Precise Phenomenology at LHC

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Instituto de Física Corpuscular

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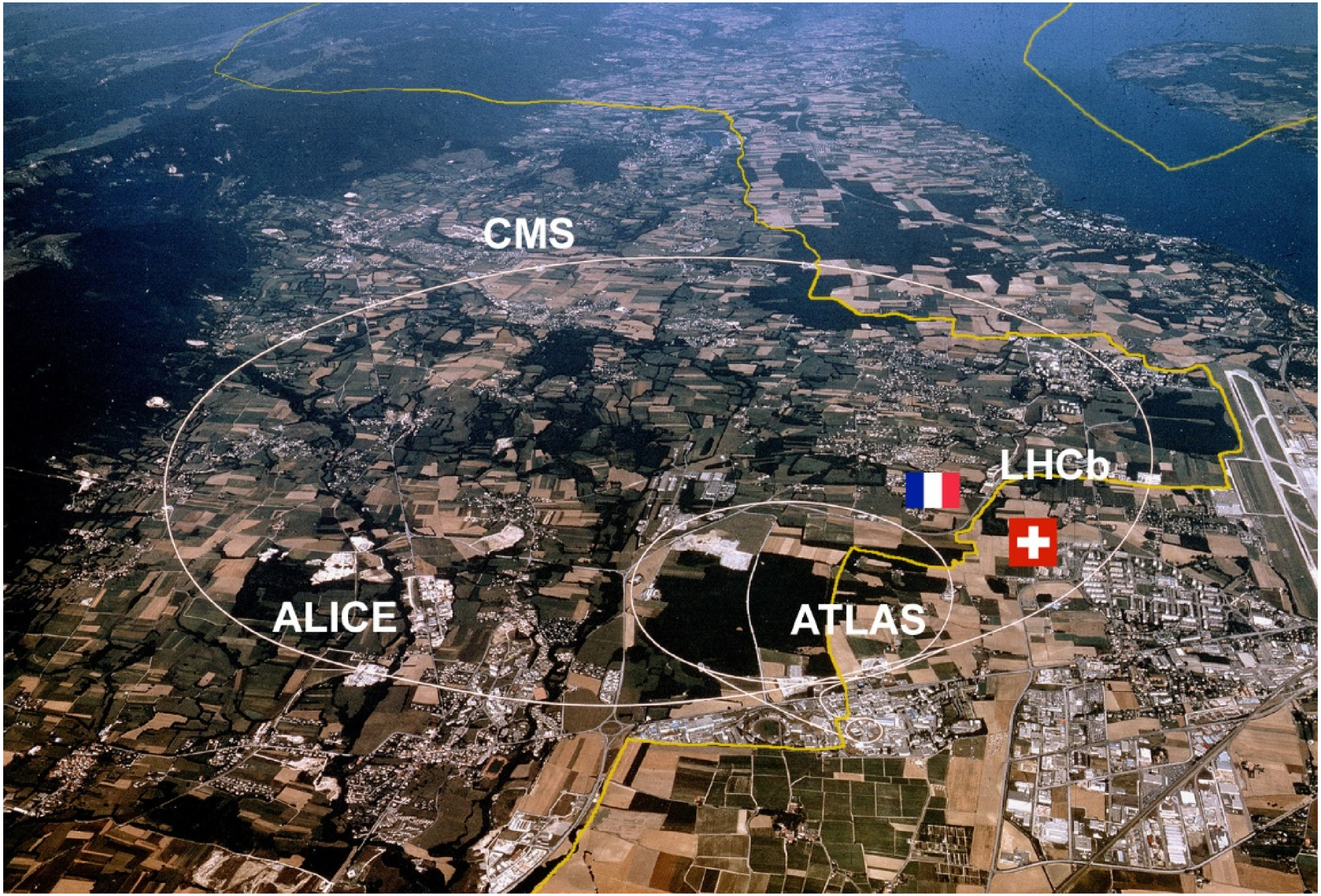
The Large Hadron Collider



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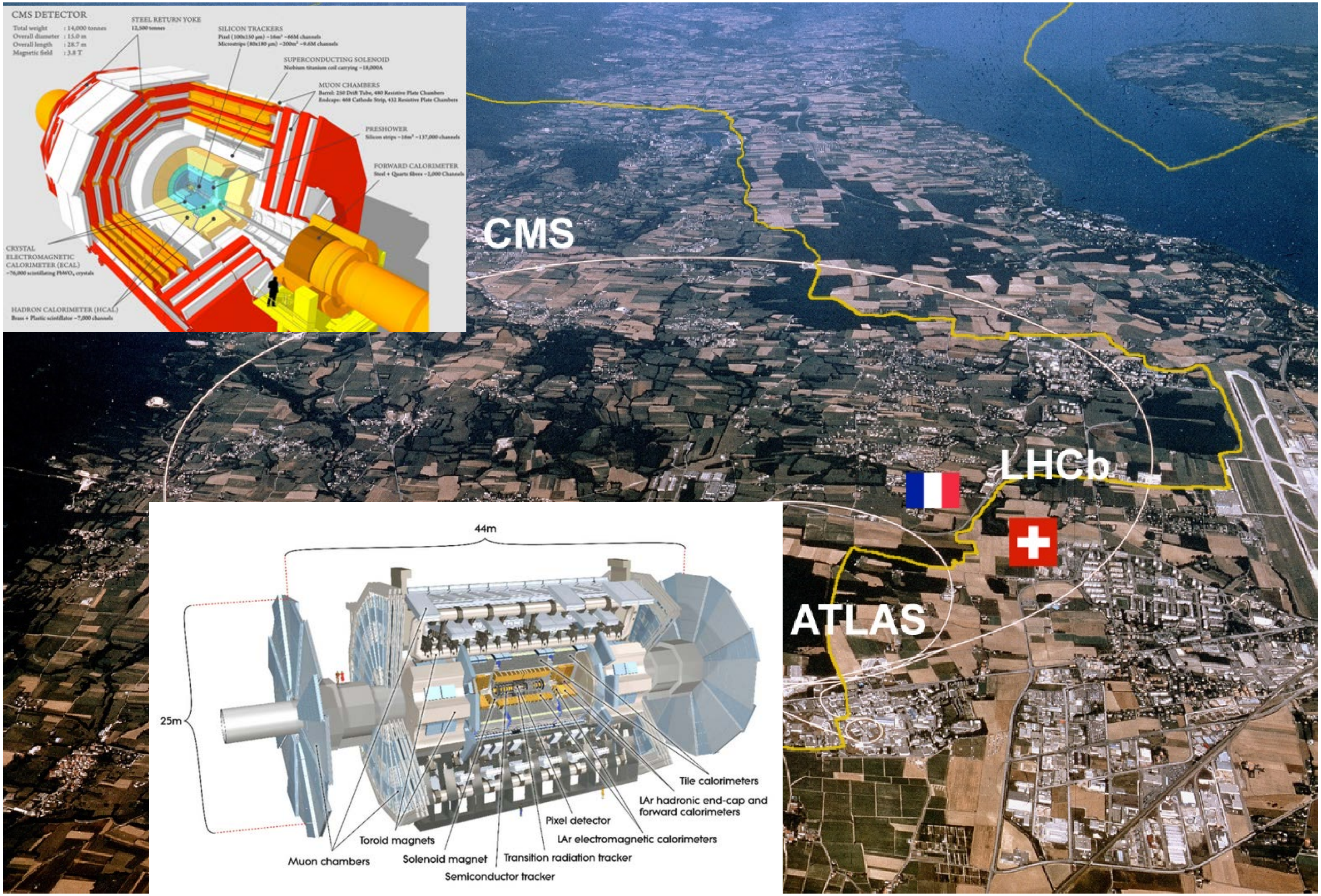

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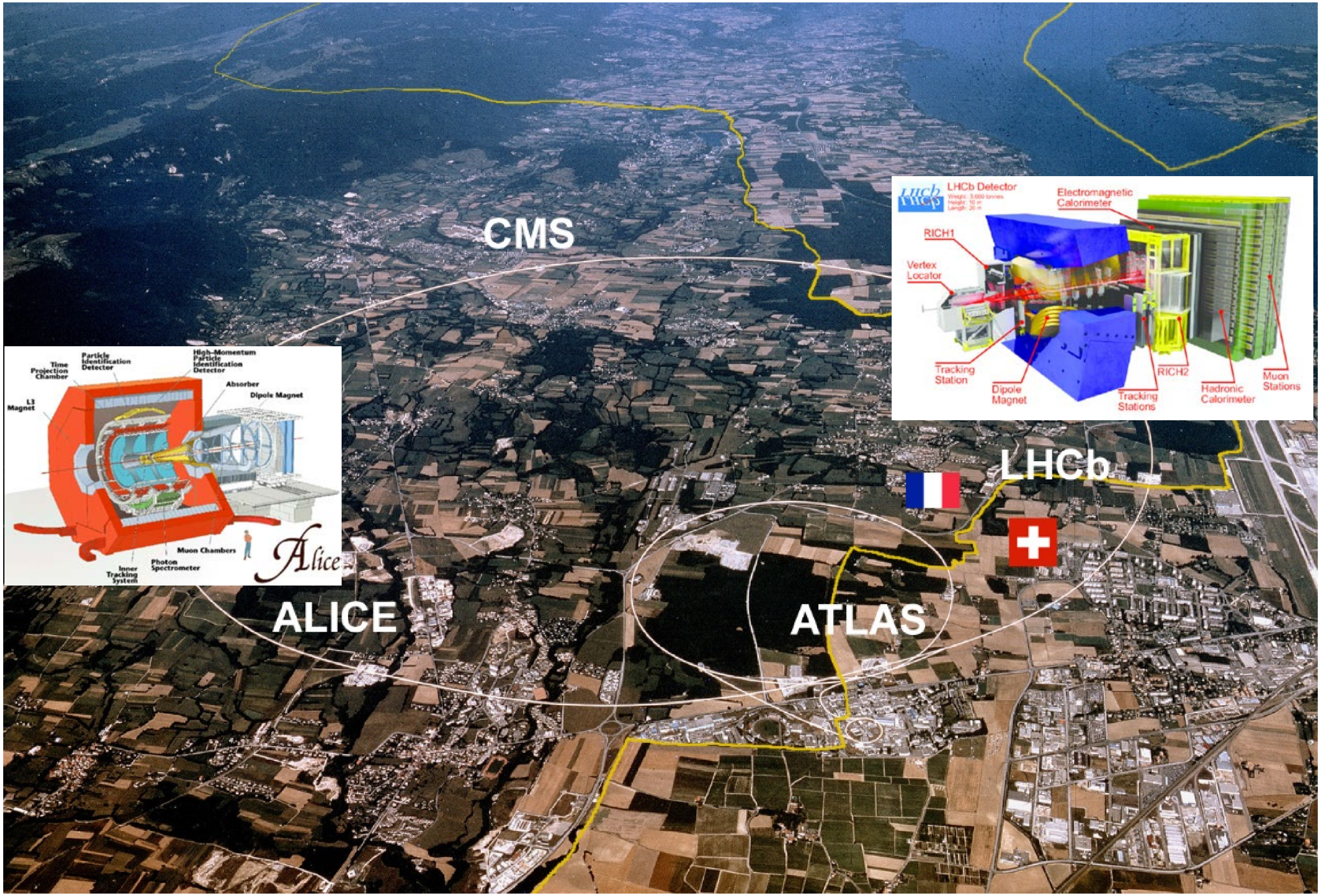
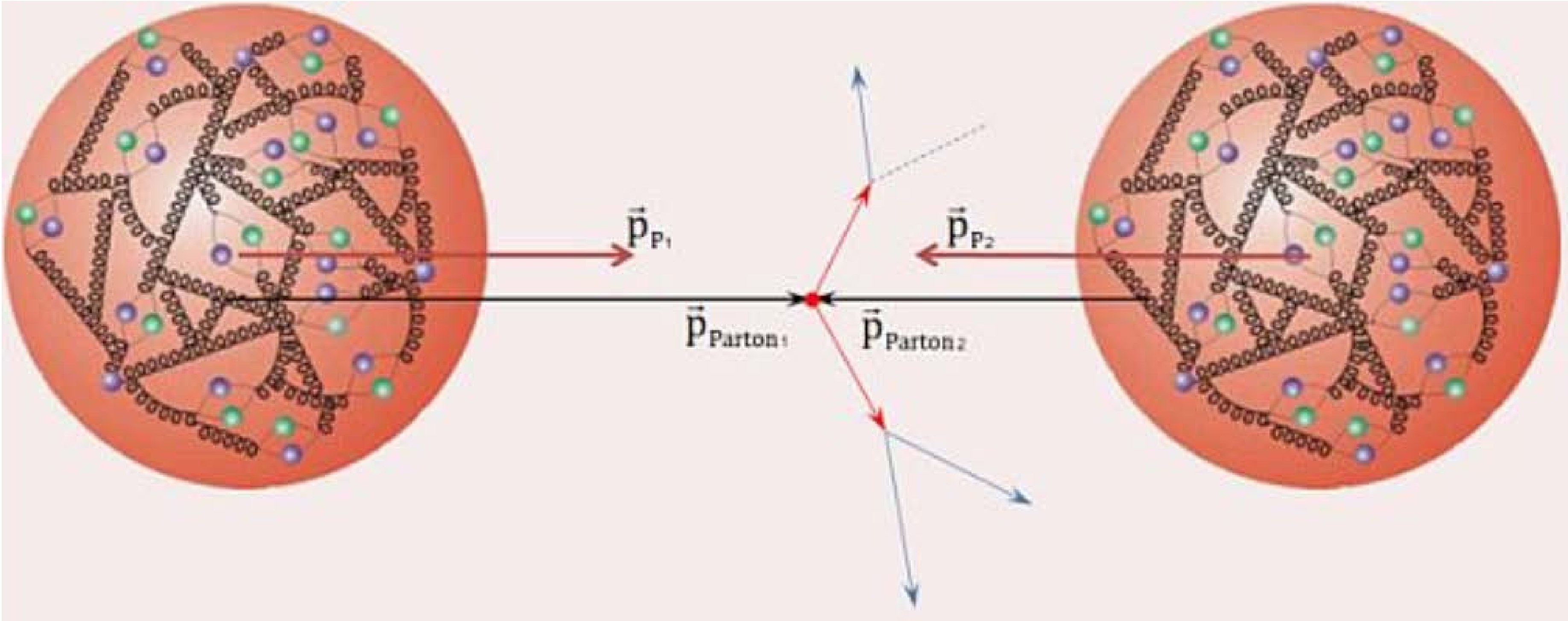


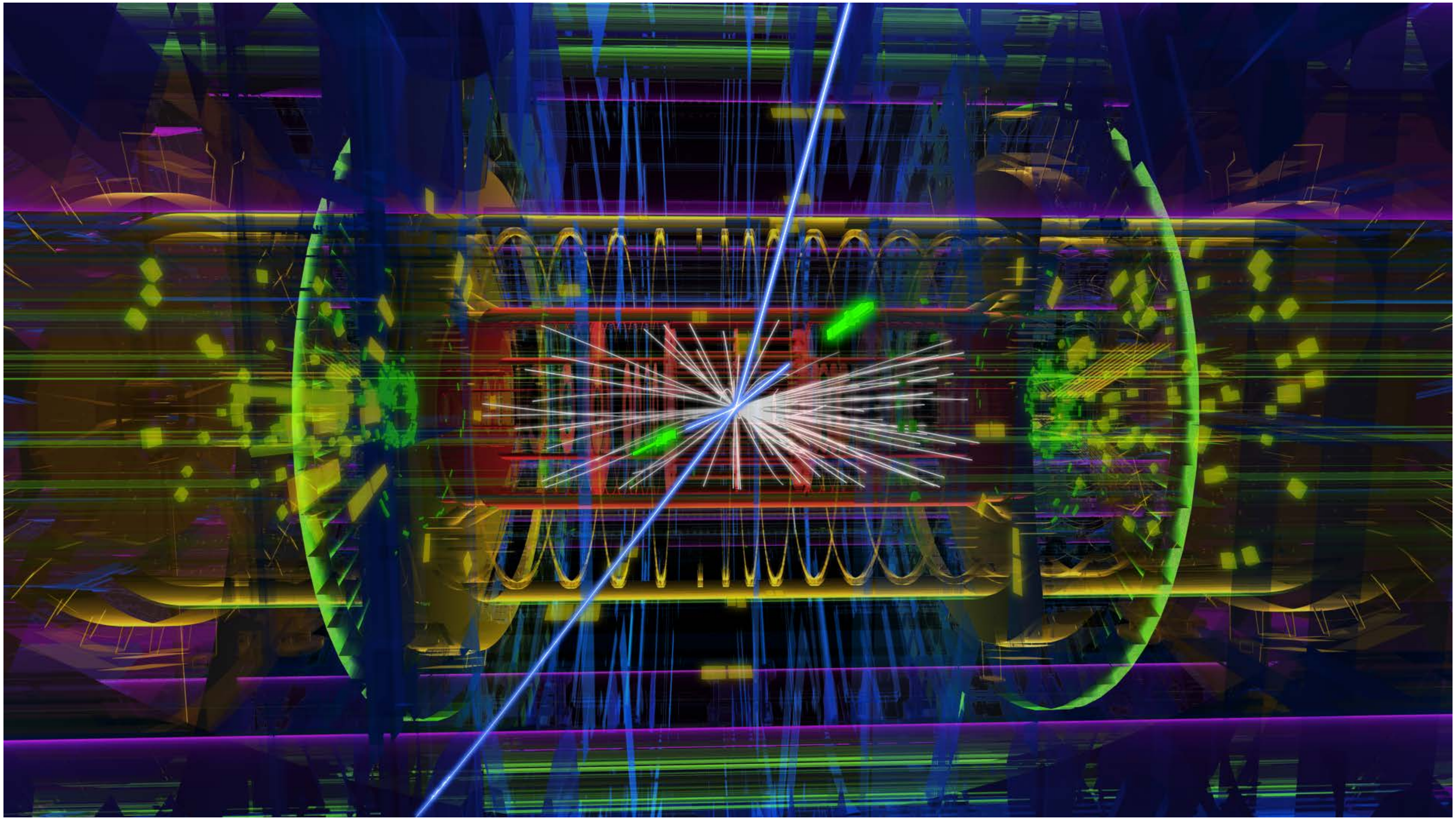
Proton Collider: Initial Proton- Proton Collision



Proton: Not only valence quarks (uud)
Gluon relevant: carry half of the energy

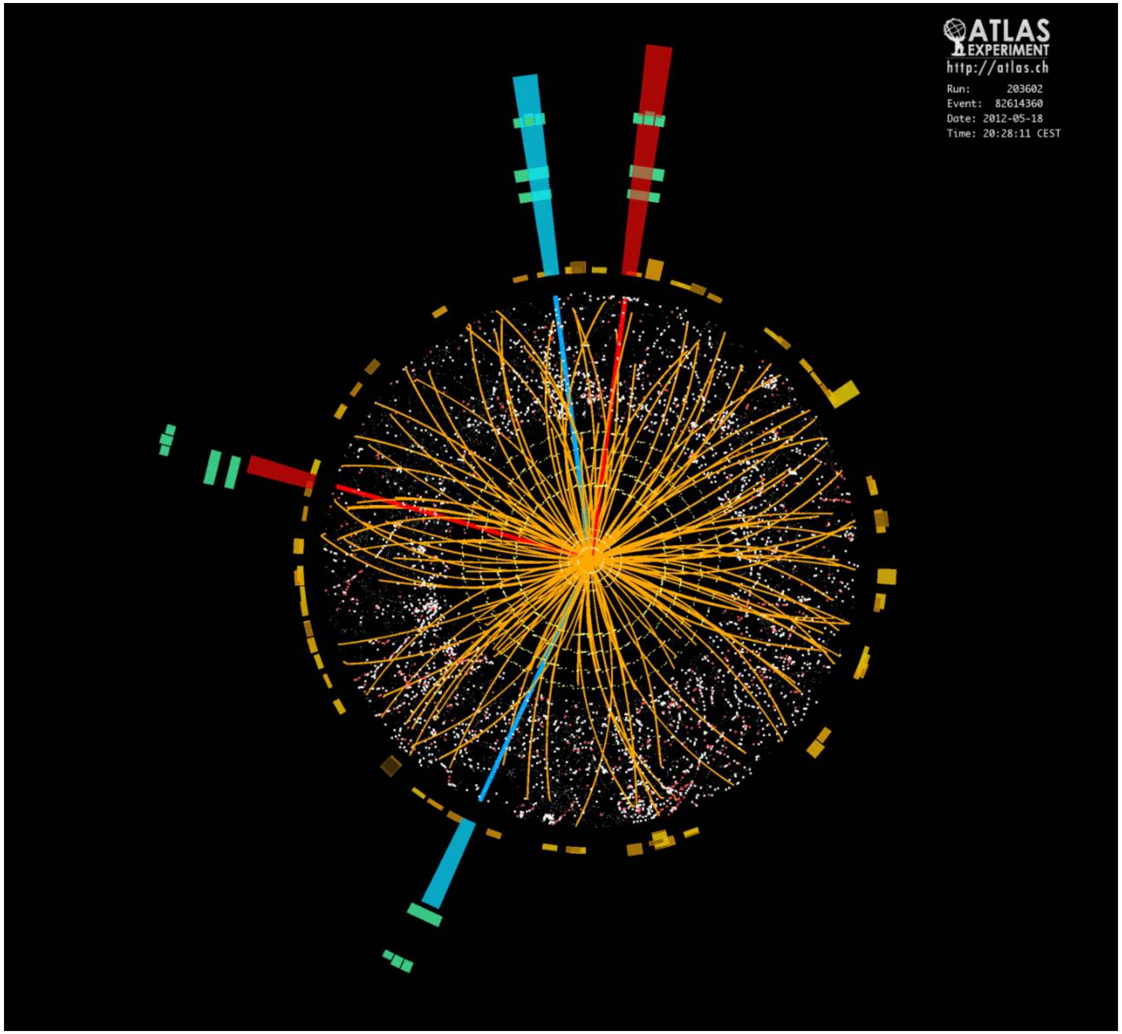
Final State: Complicated Topologies:
pp ➡ H + X ➡ 4 e + X

ATLAS: 18-May-2012, 20:28:11 CEST, run number 203602, event number 82614360



Transverse Plane

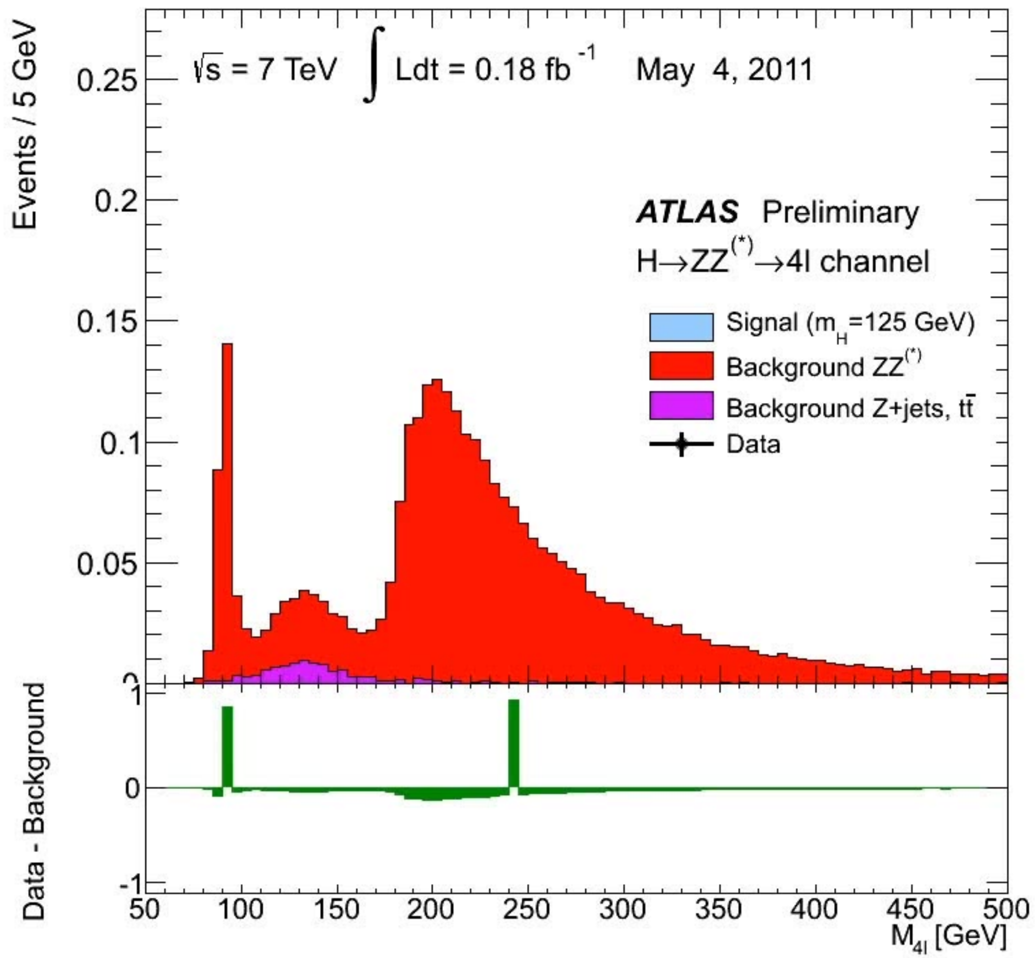
ATLAS: 18-May-2012, 20:28:11 CEST, run number 203602, event number 82614360



m(4l) = 124.5 GeV

m(2l) = 70.6 , 44.7 GeV

The Higgs Signal Evolution



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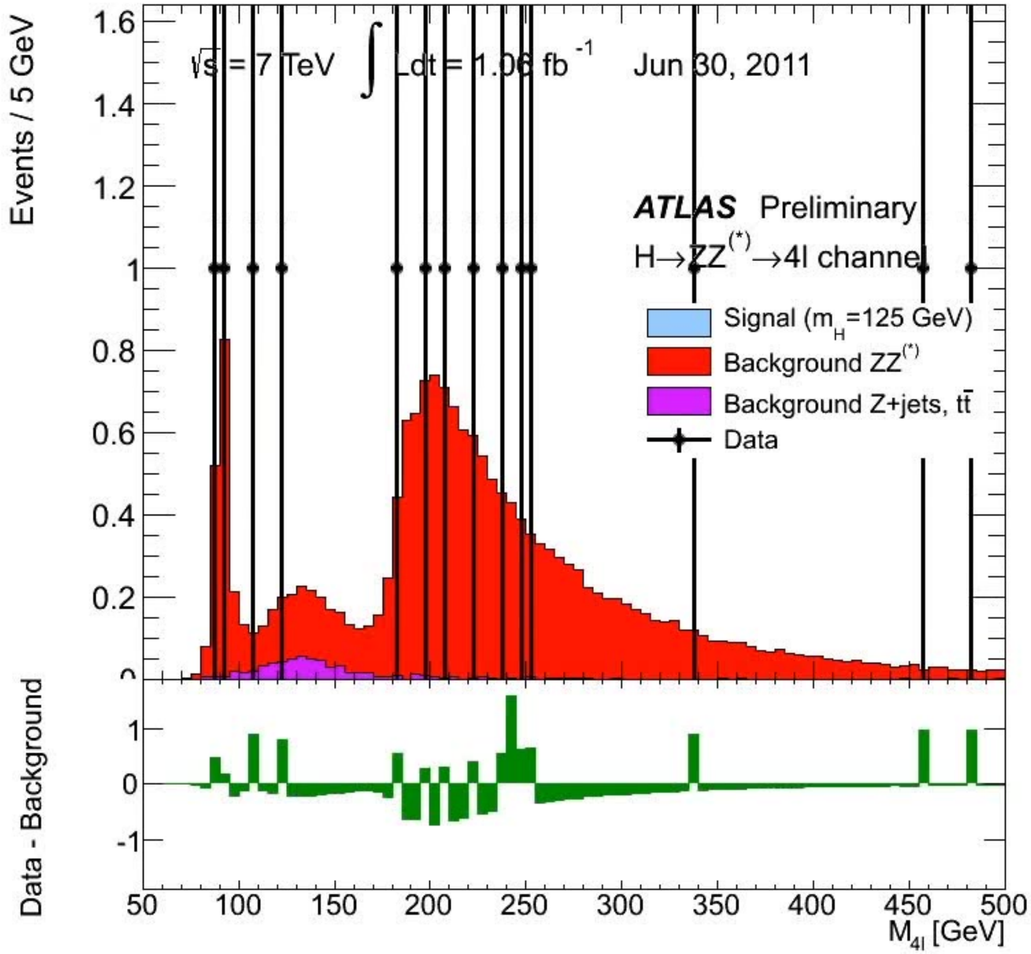

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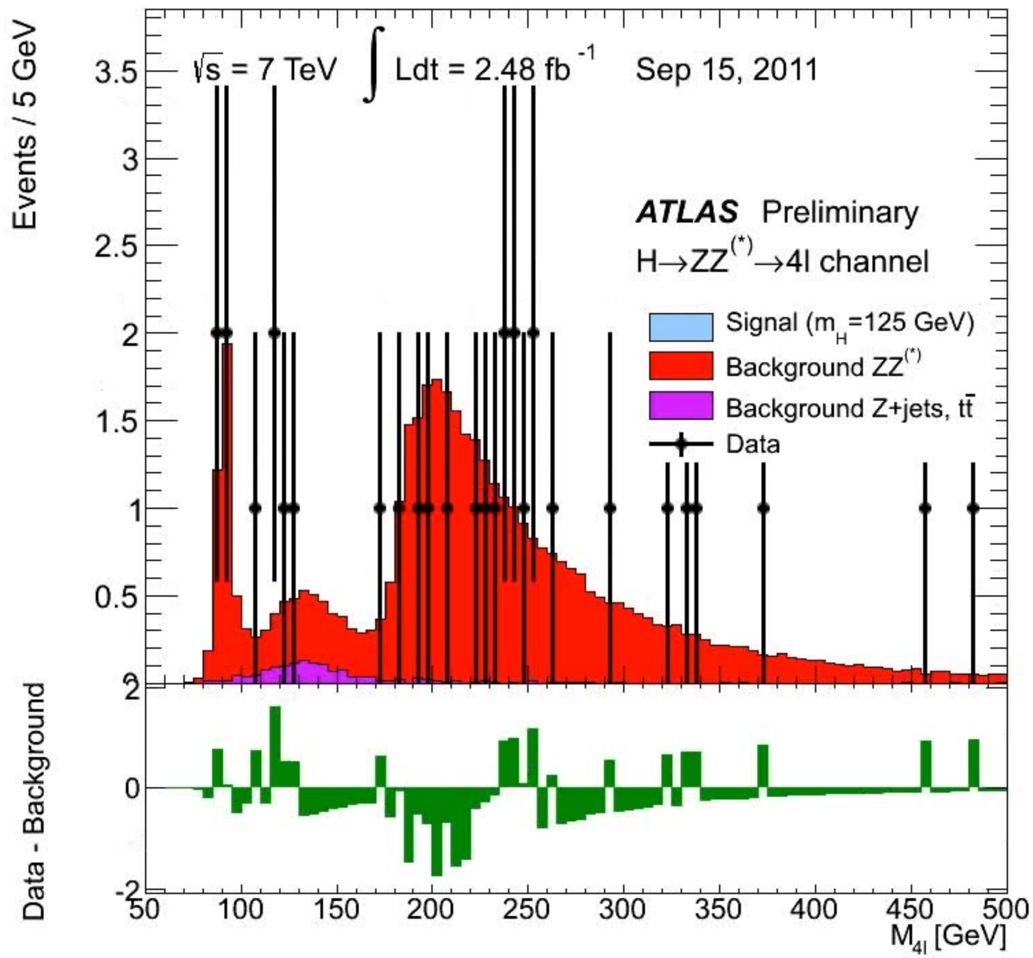

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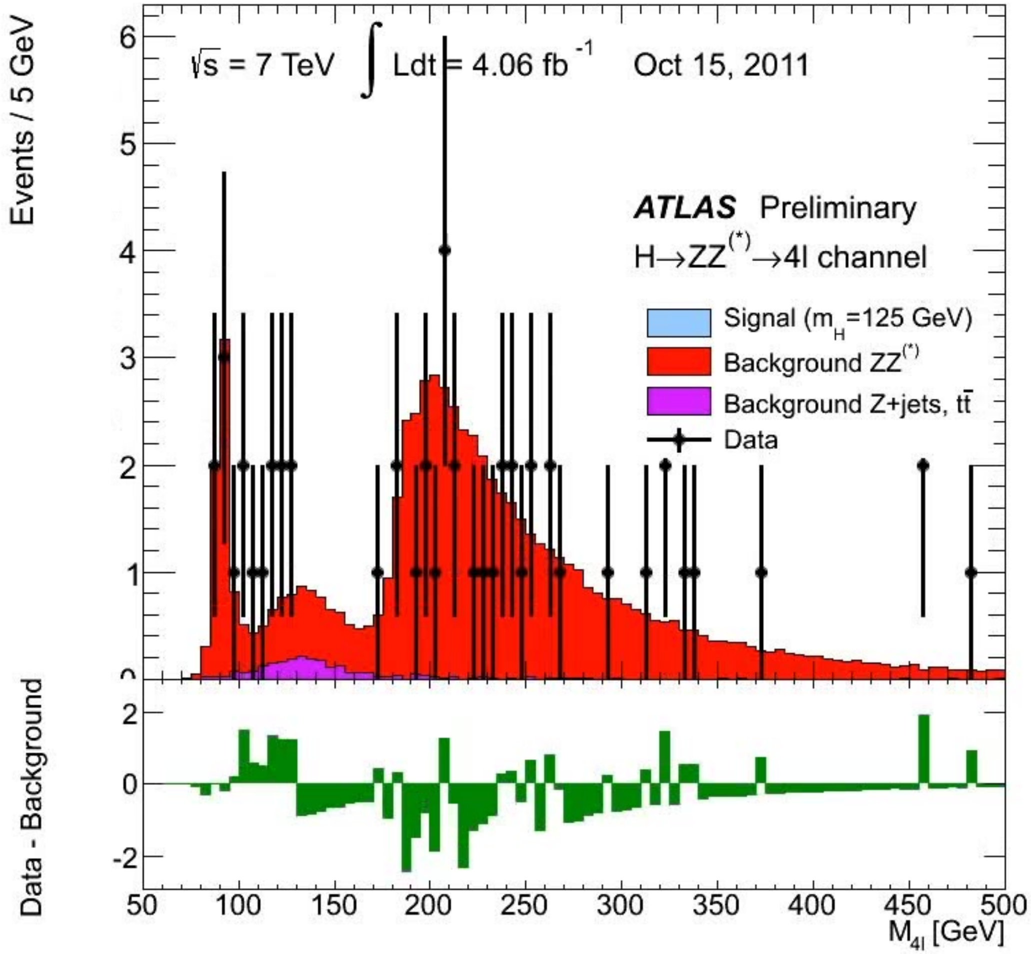

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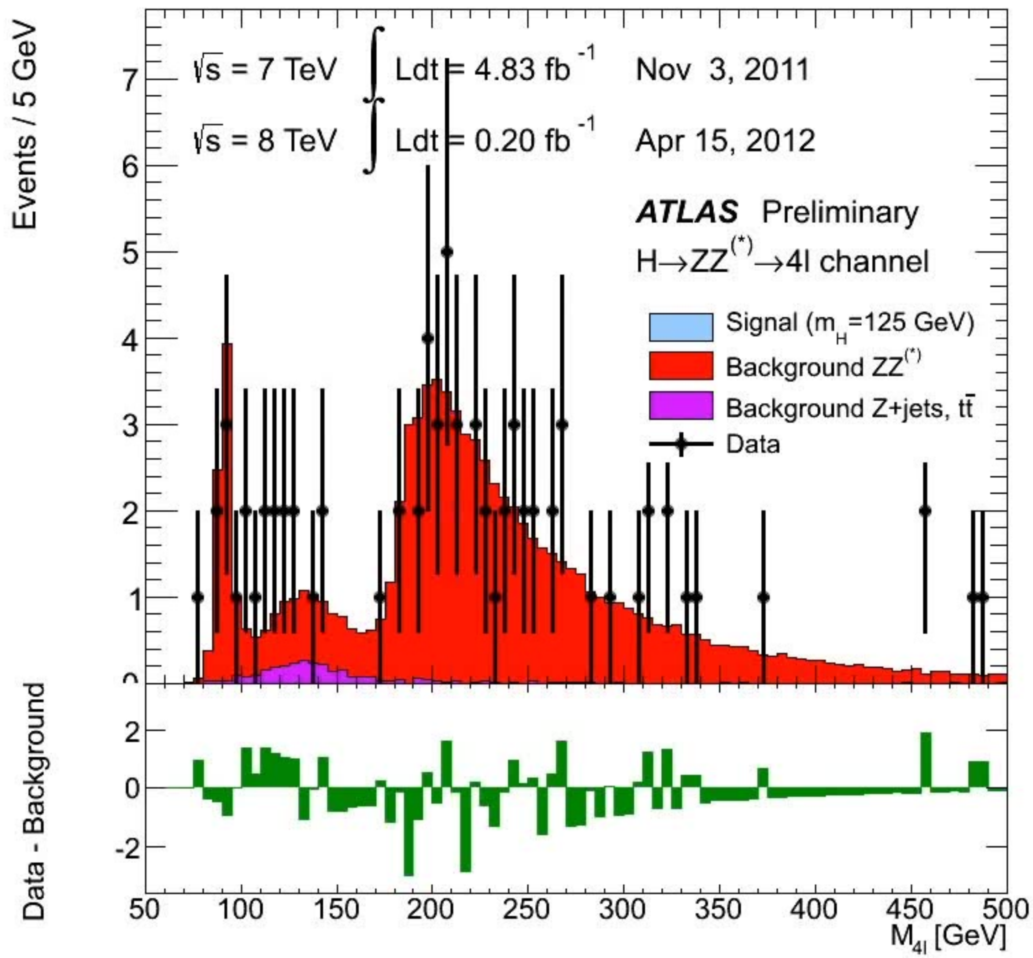

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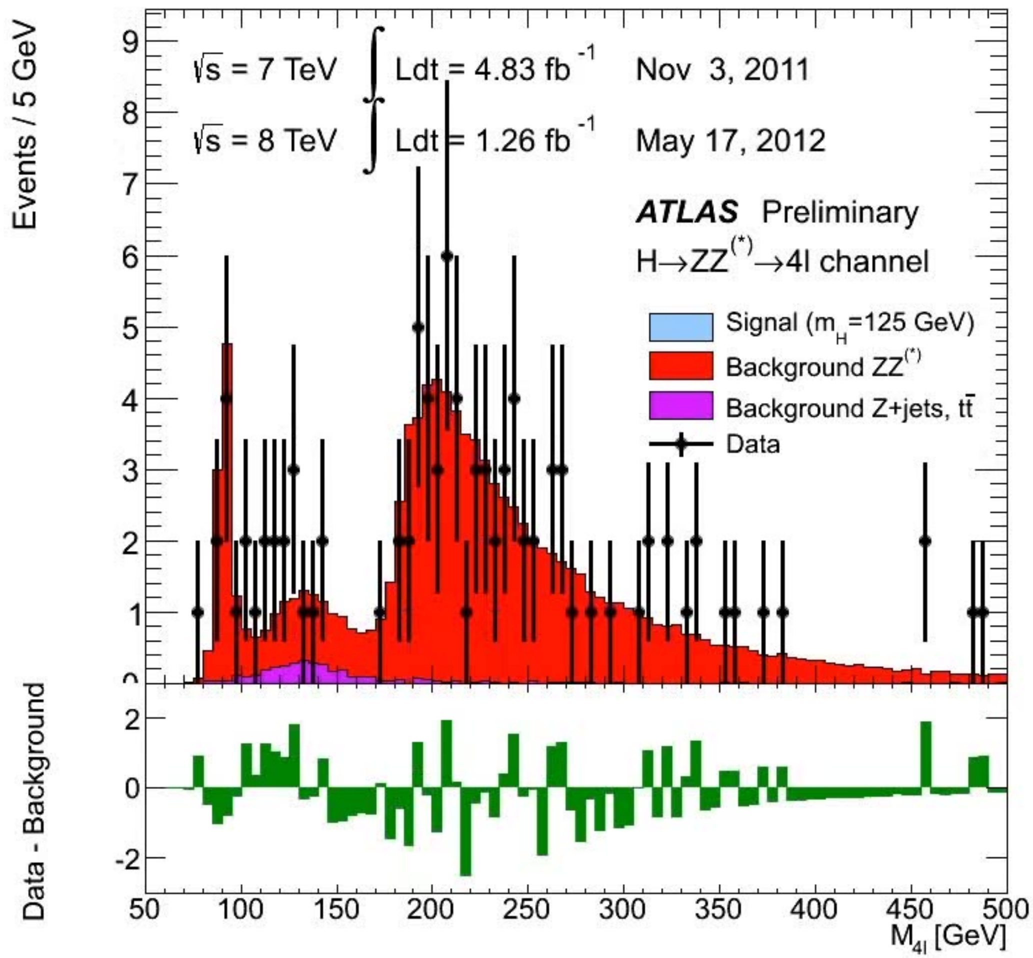

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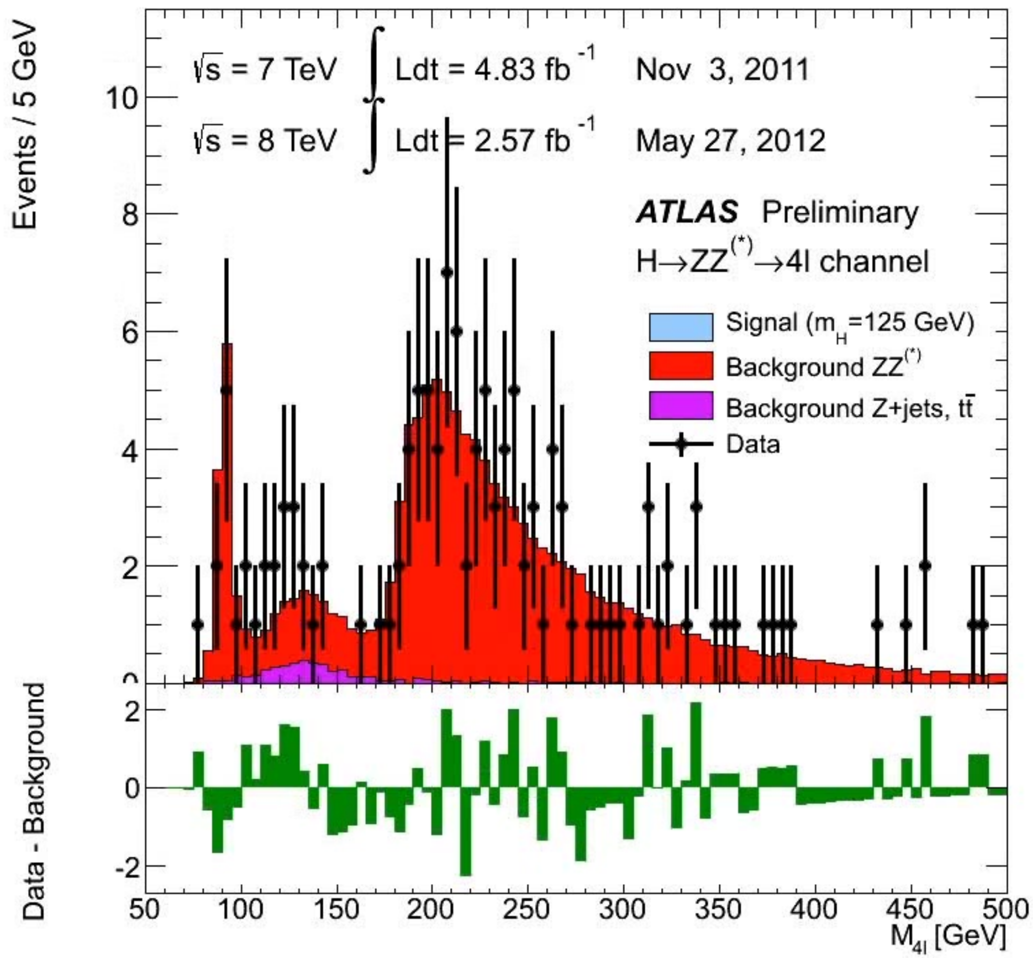

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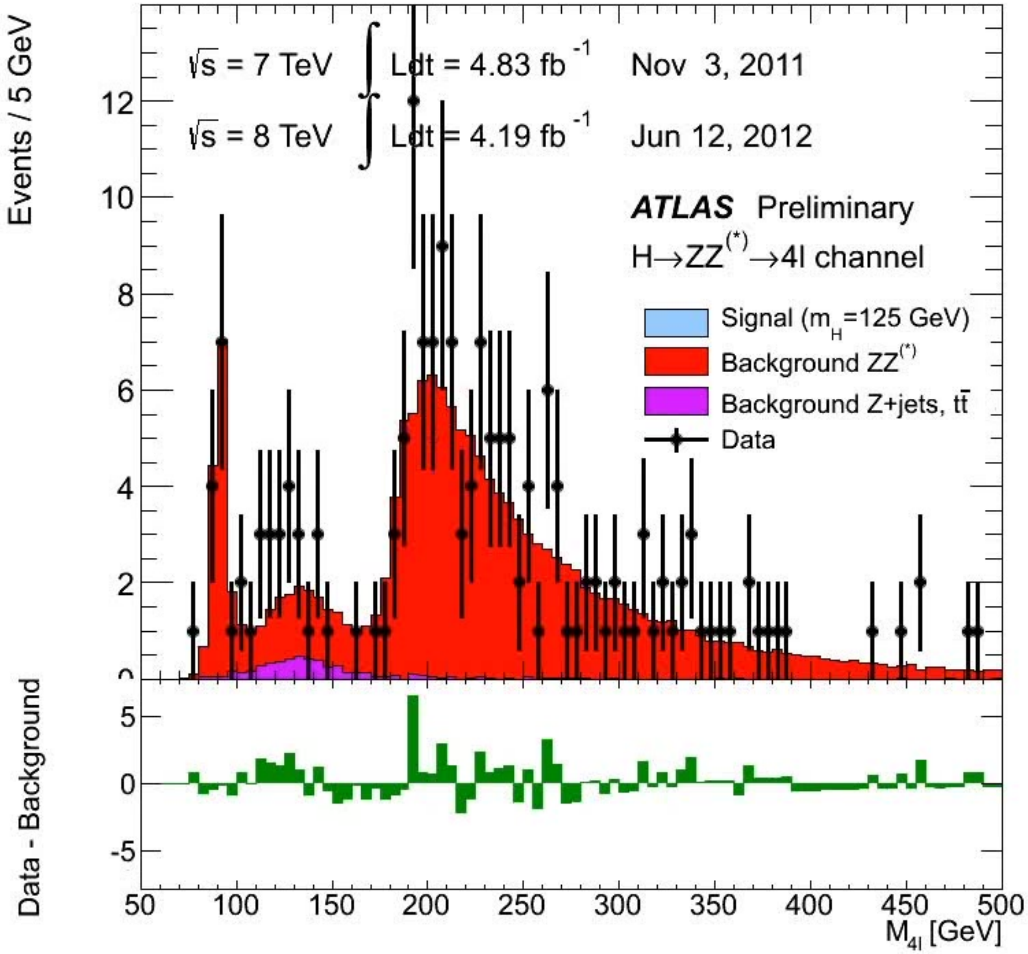

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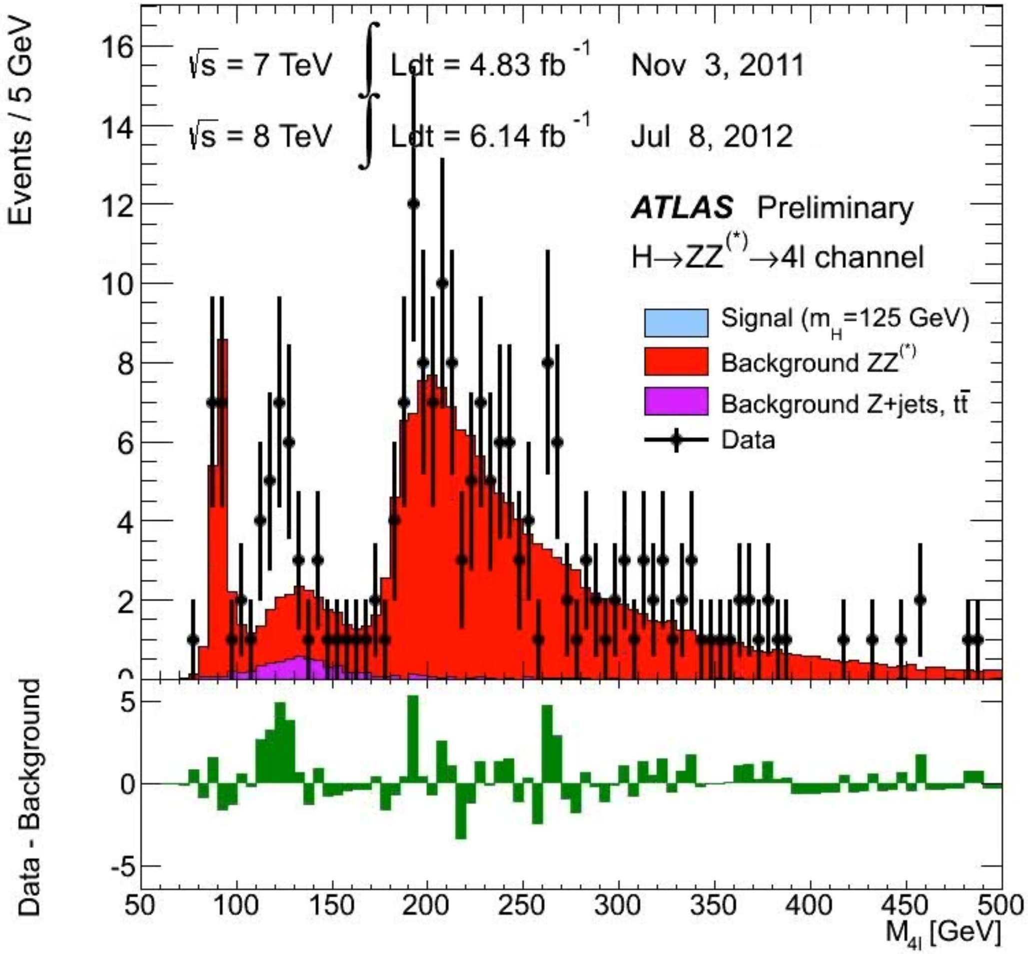

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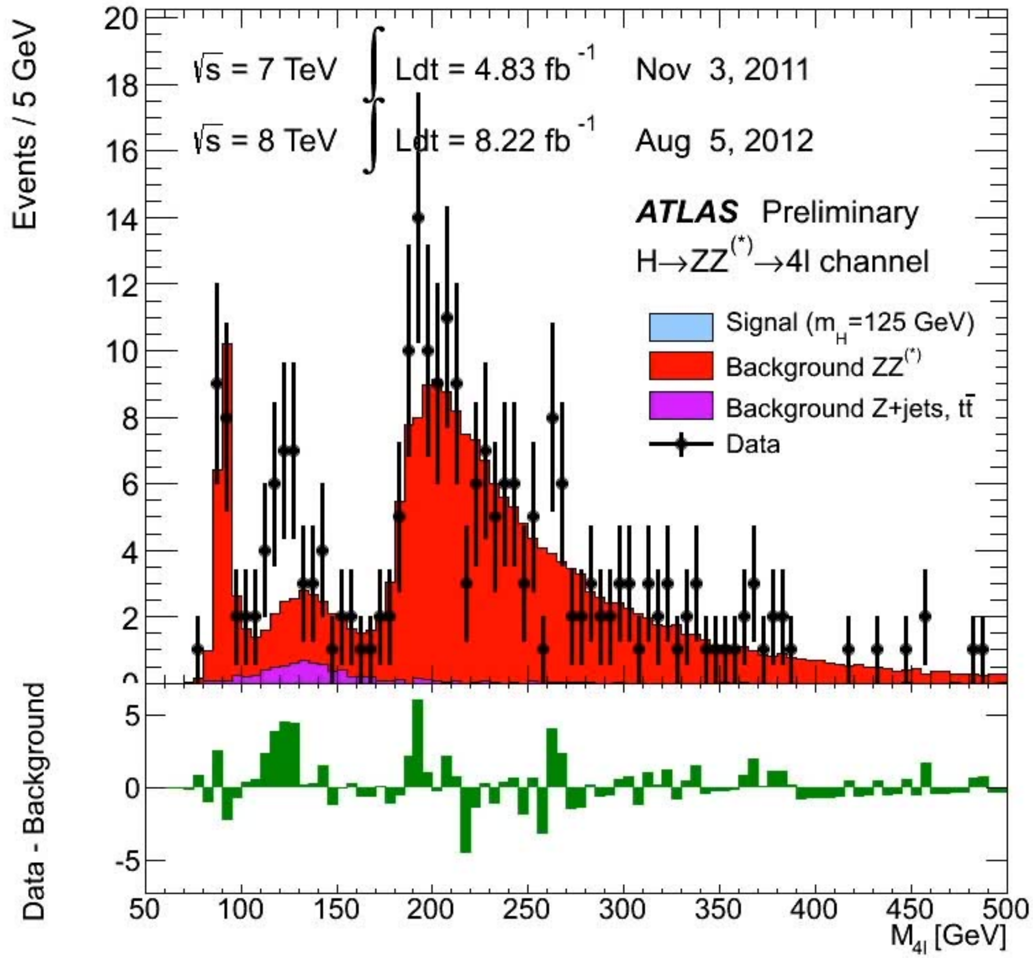

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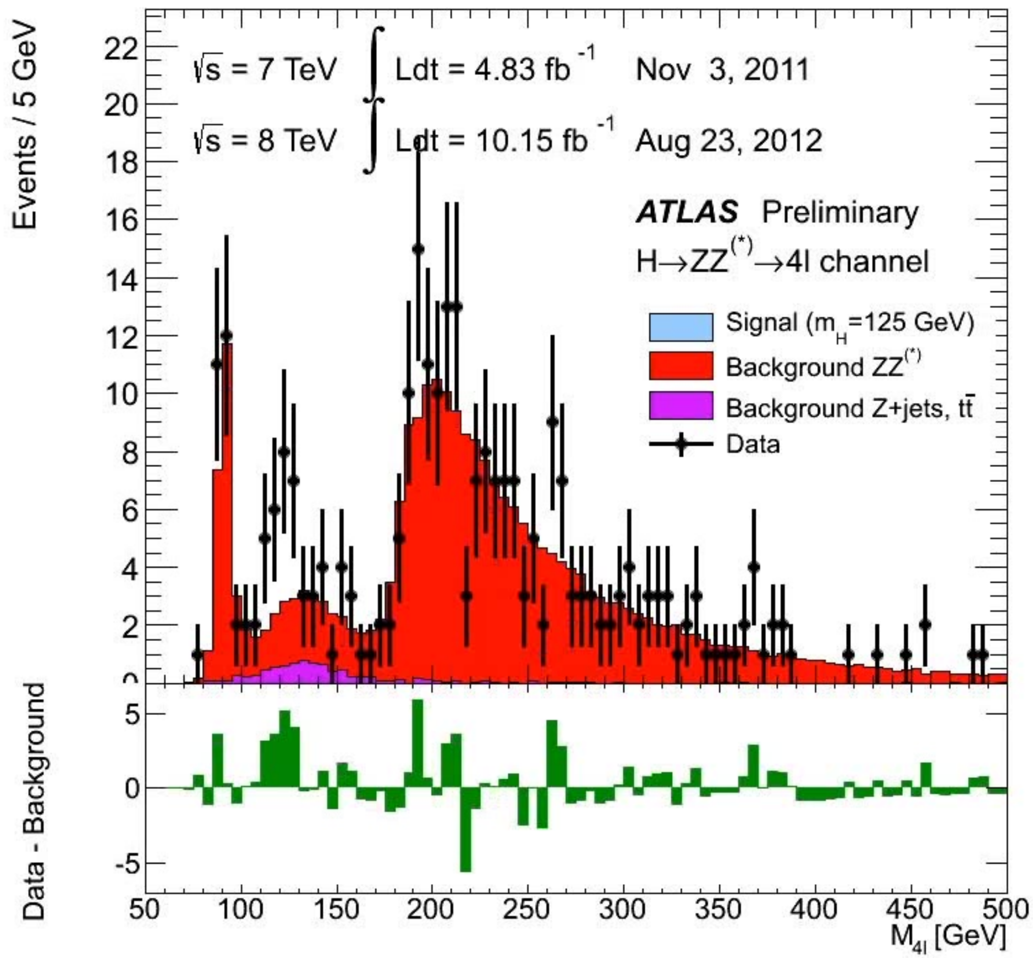

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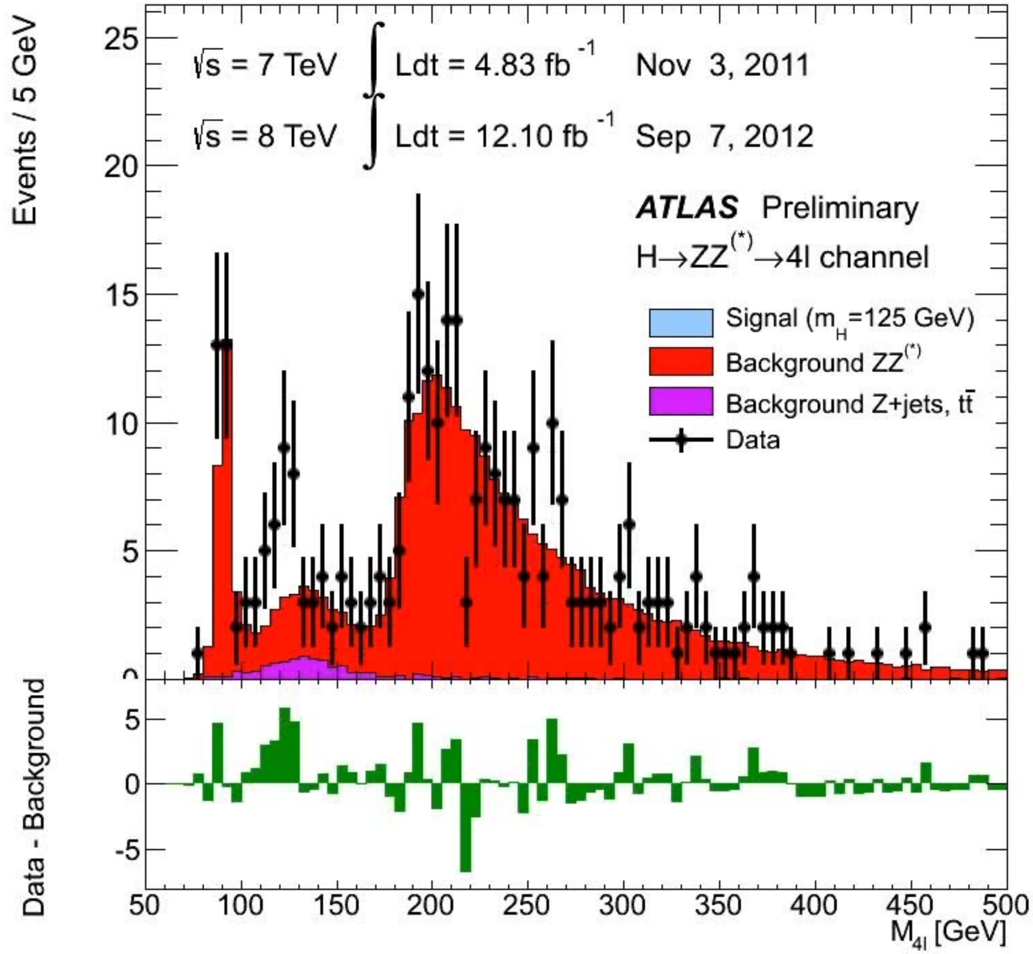

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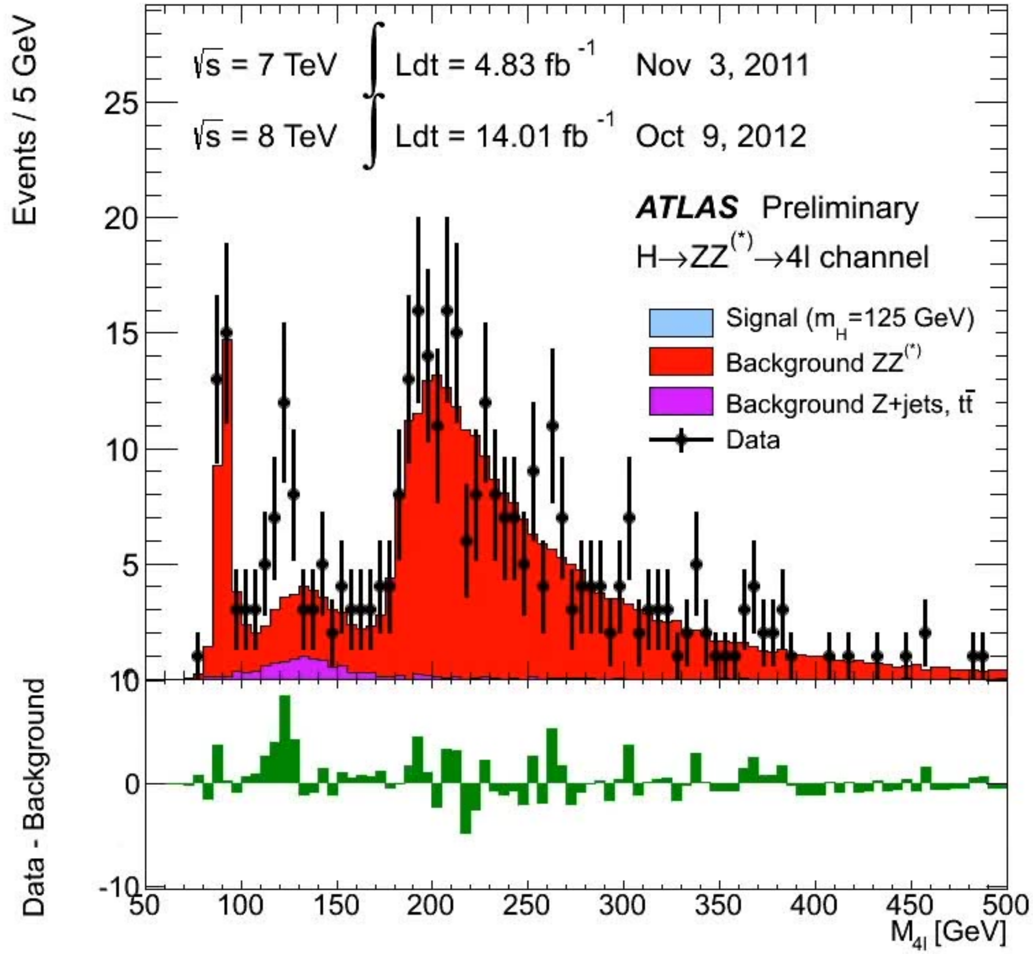

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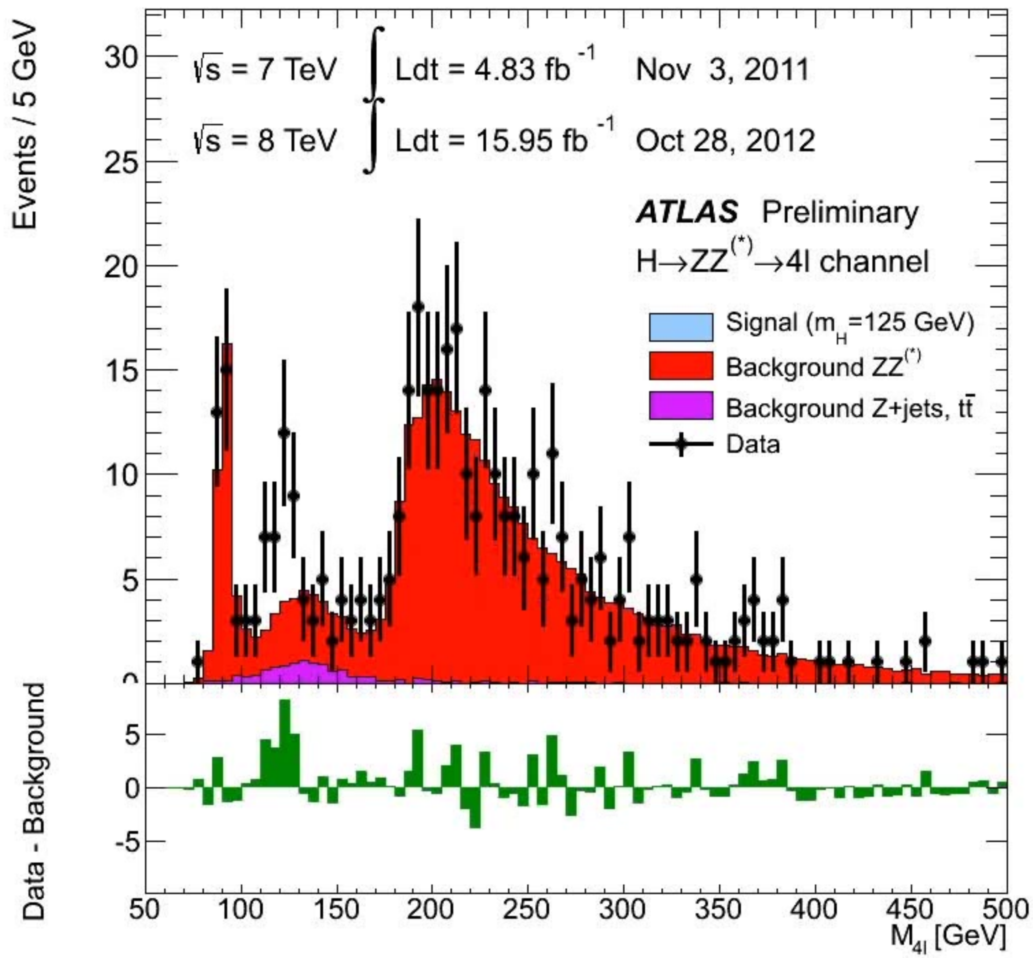

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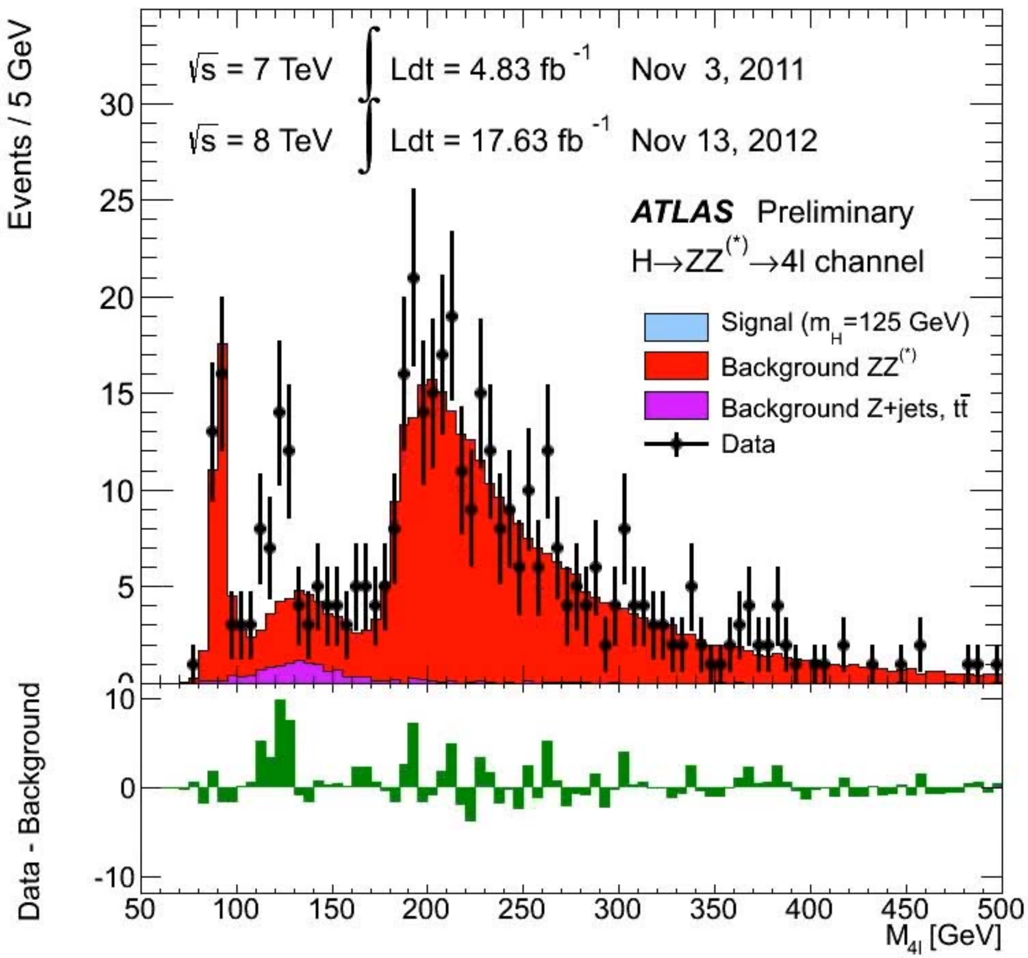

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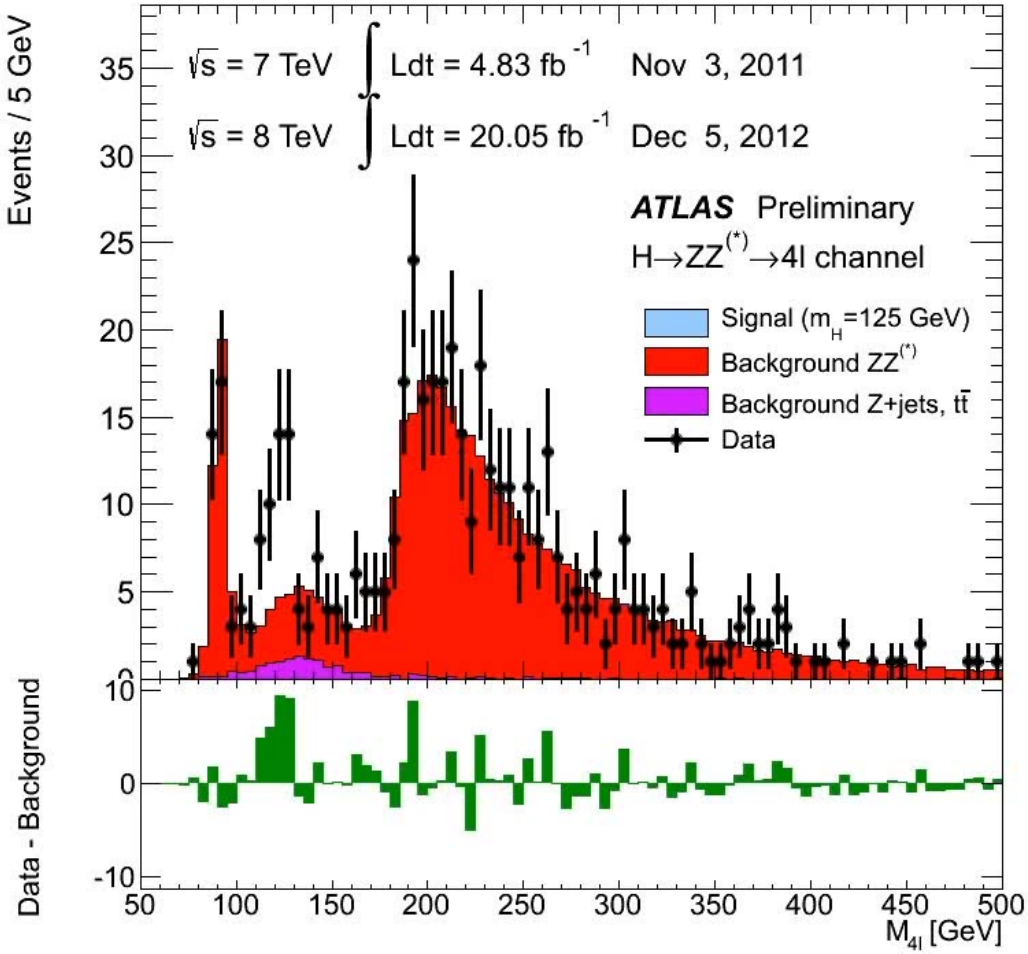

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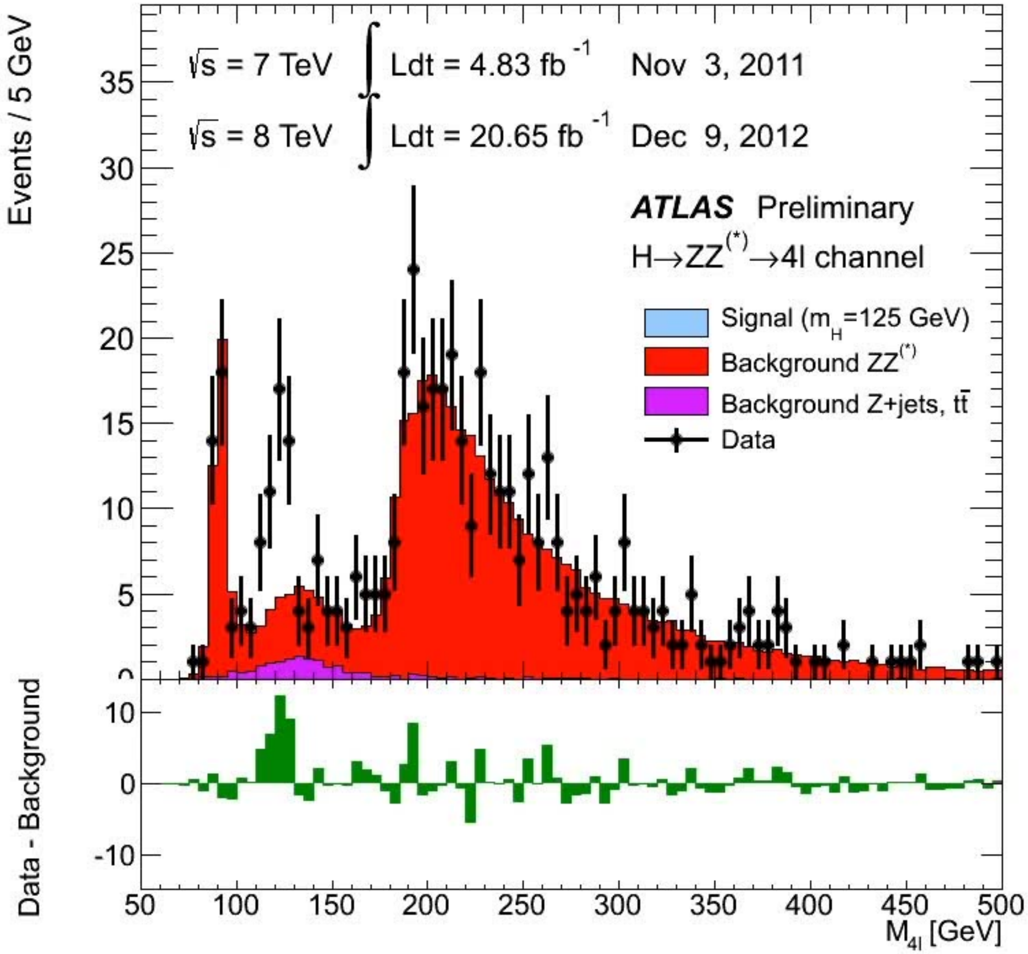

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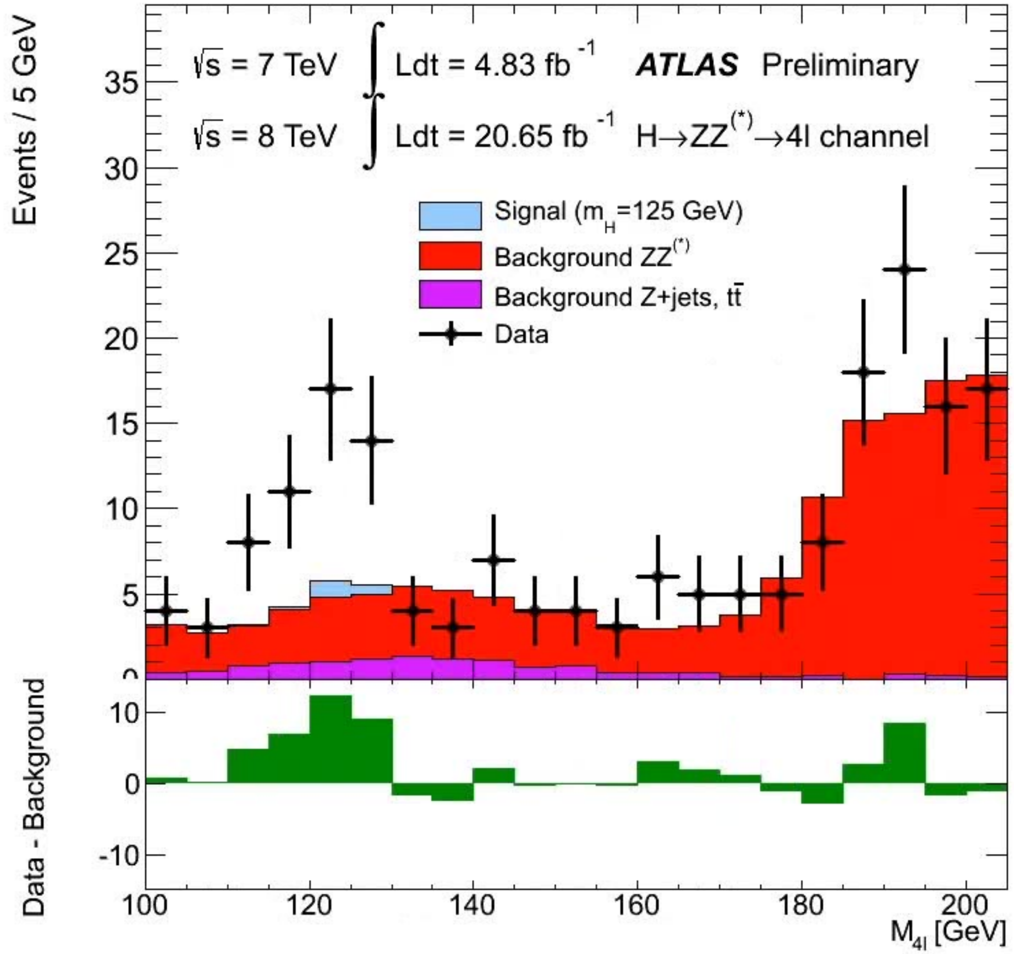

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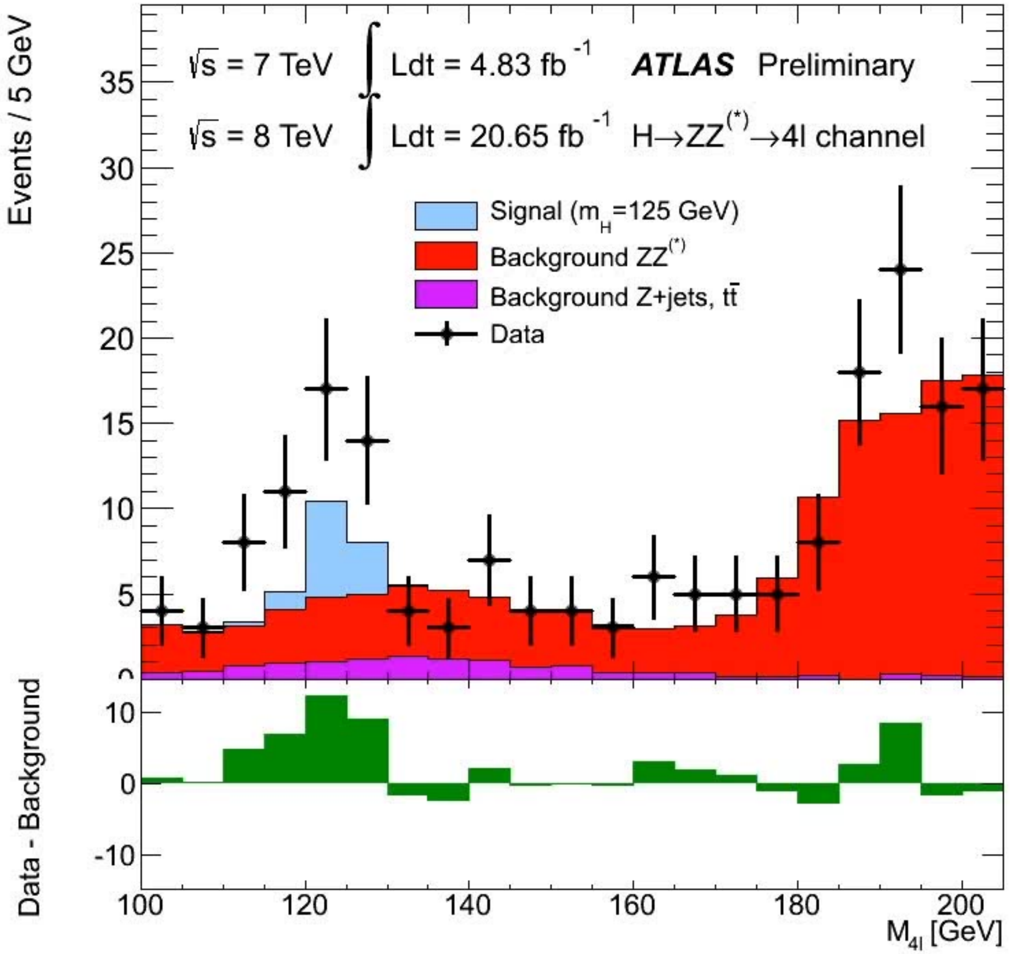

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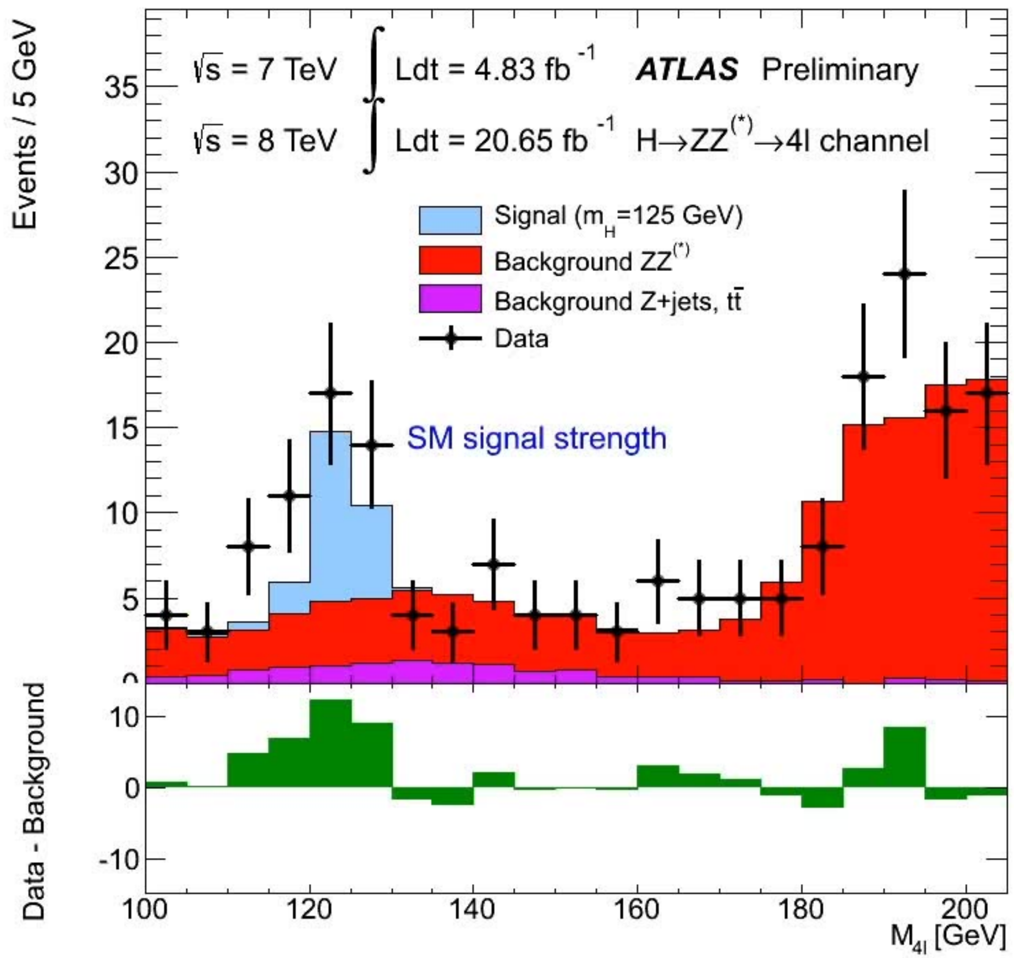
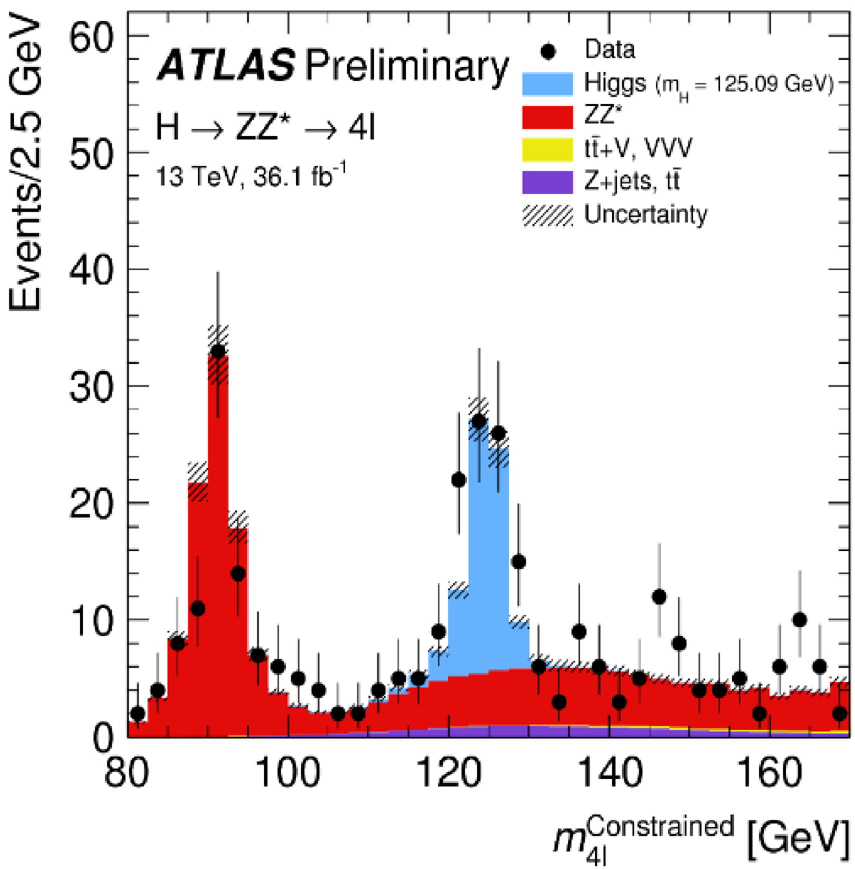
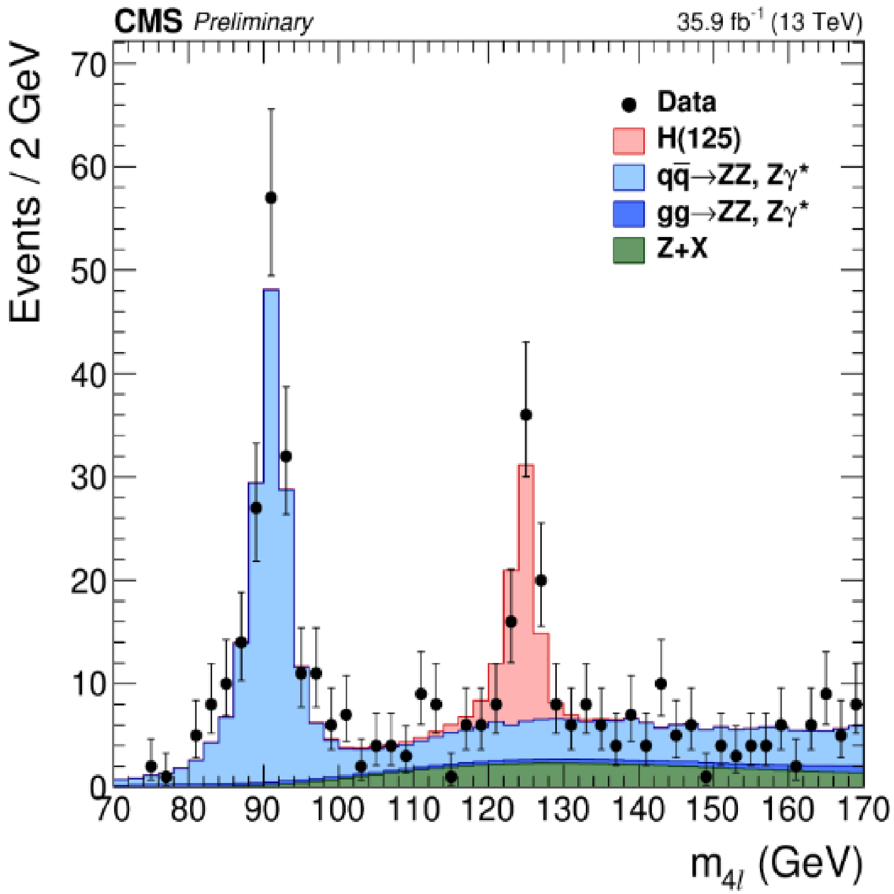


The Higgs Signal Evolution

Dr. Marc Bret Cano [Higgs Couplings 2017, Nov 6]





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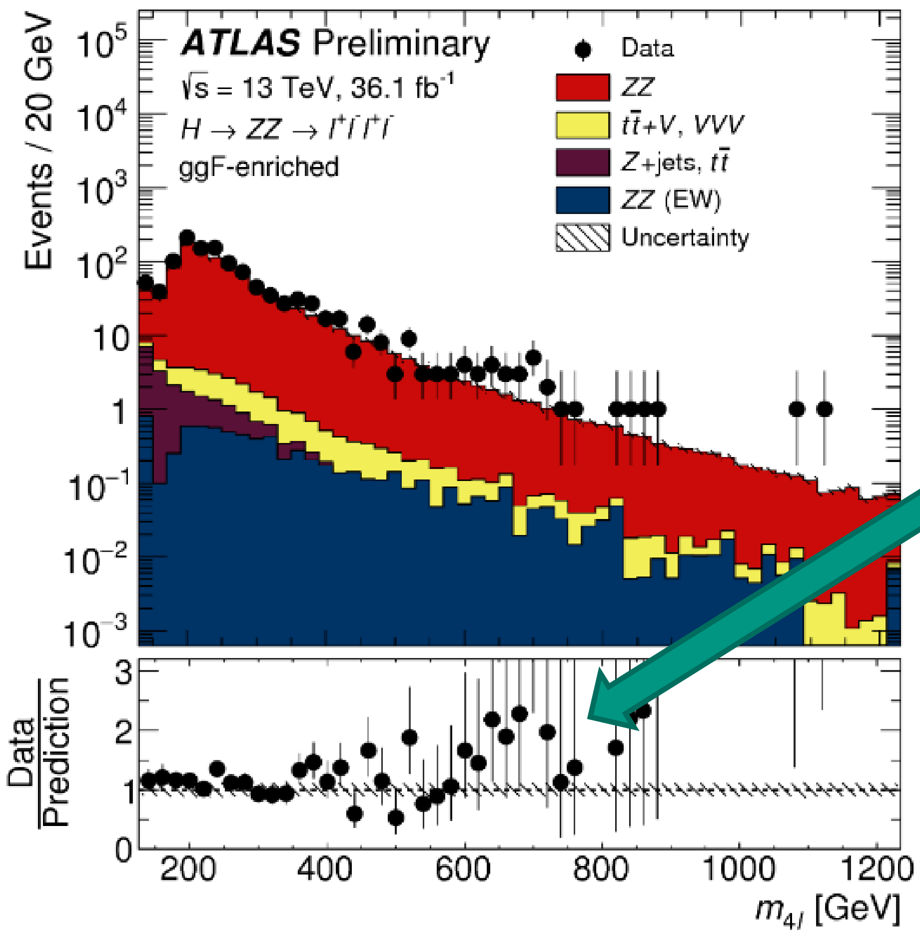
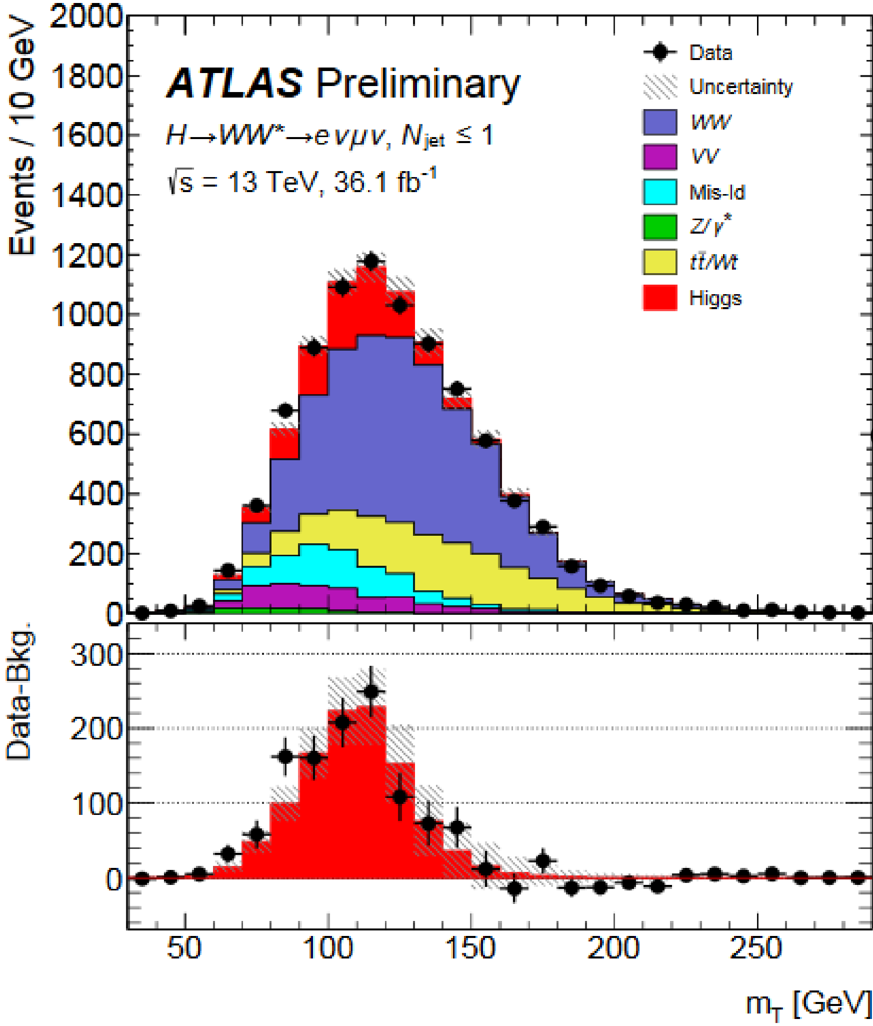


- Excess at 190 GeV gone
- 2.2 σ at 700 GeV

Precise Knowledge of Backgrounds

[ATLAS-CONF-2018-004]

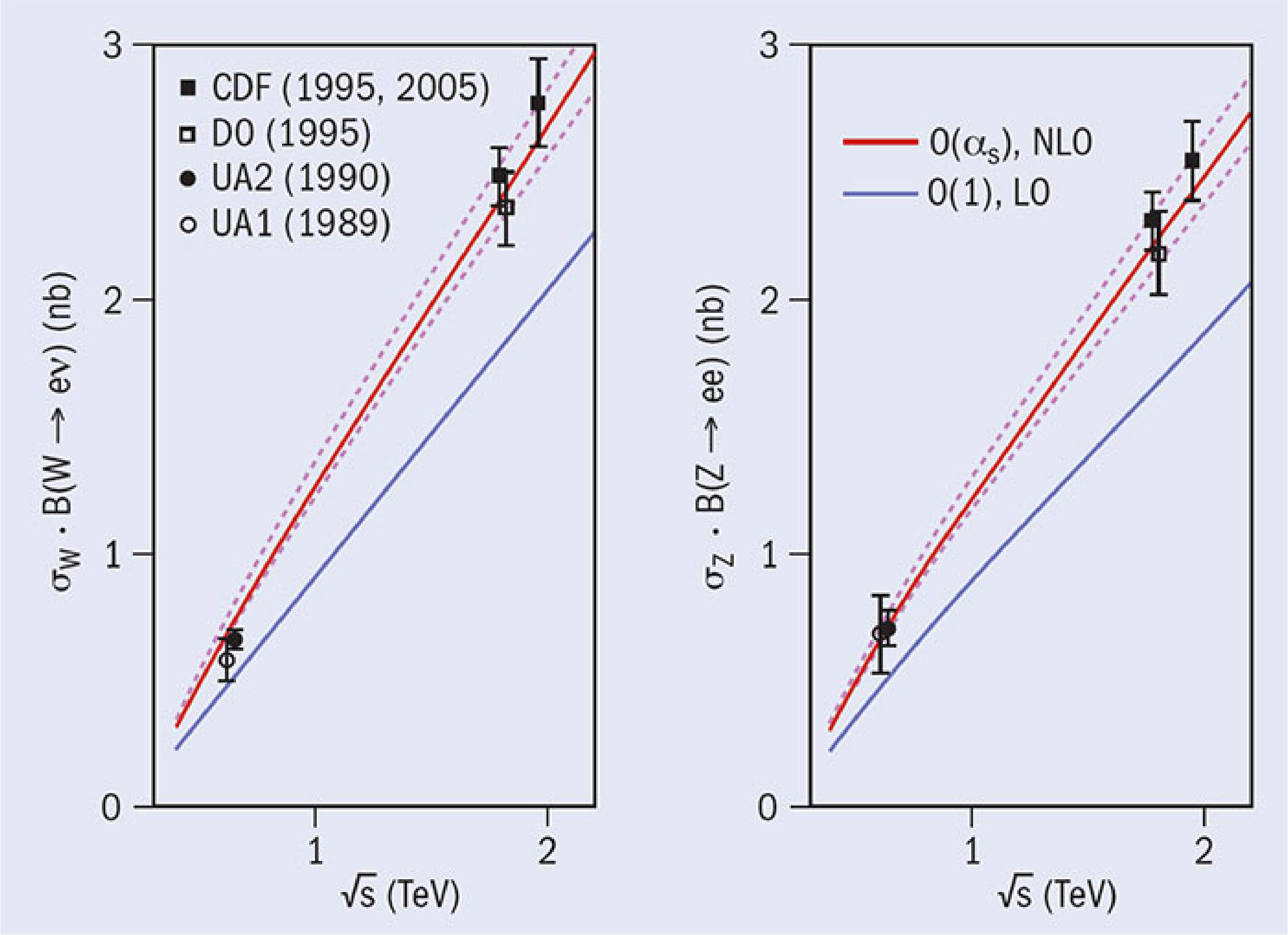


$$\frac{\sigma_{signal}}{\sigma_{background}} \propto \frac{250}{850} = 0.3$$

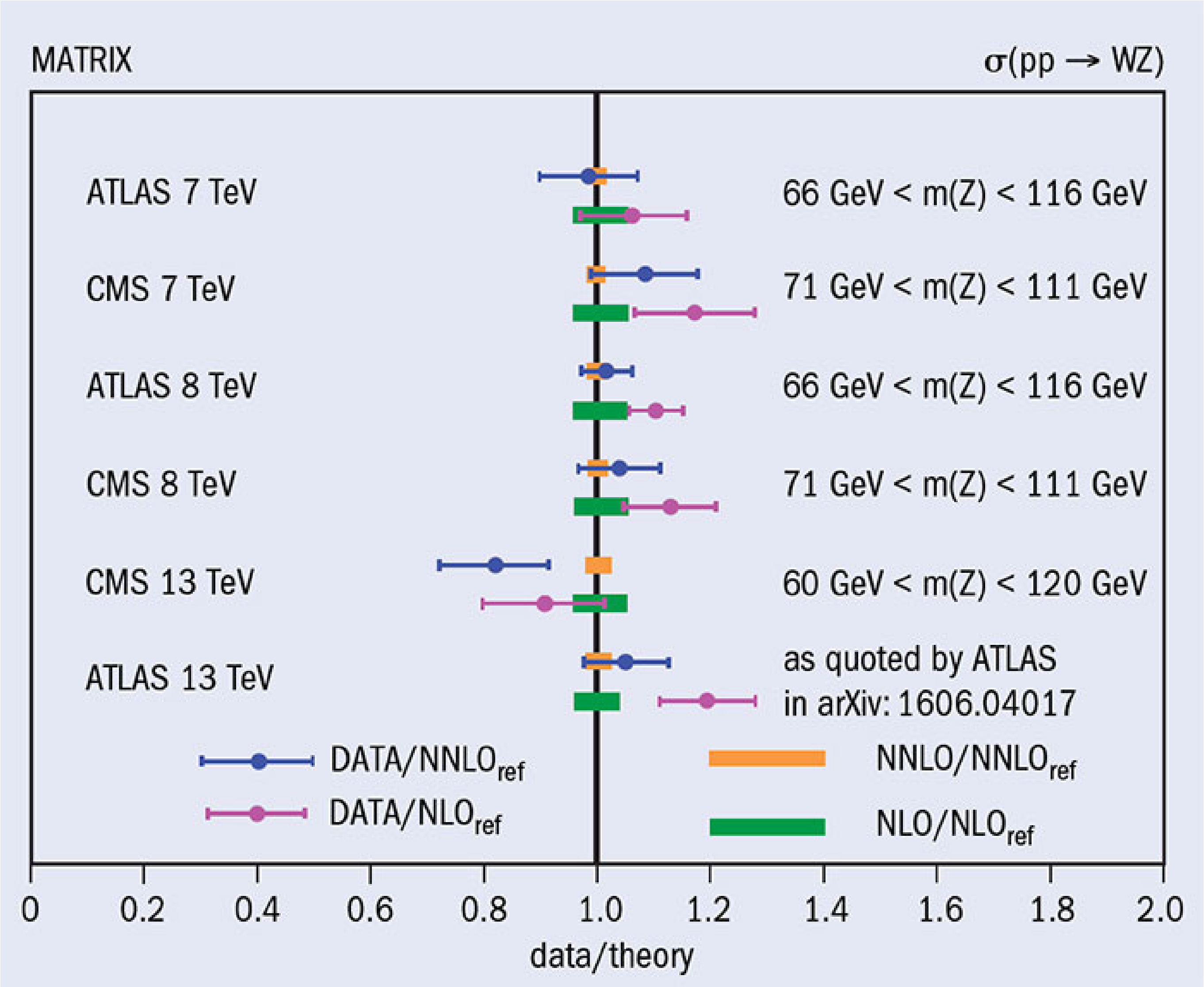
- Theoretical error of 30% in background as large as signal

⟶ No measurement

Needed Precise Theoretical Predictions



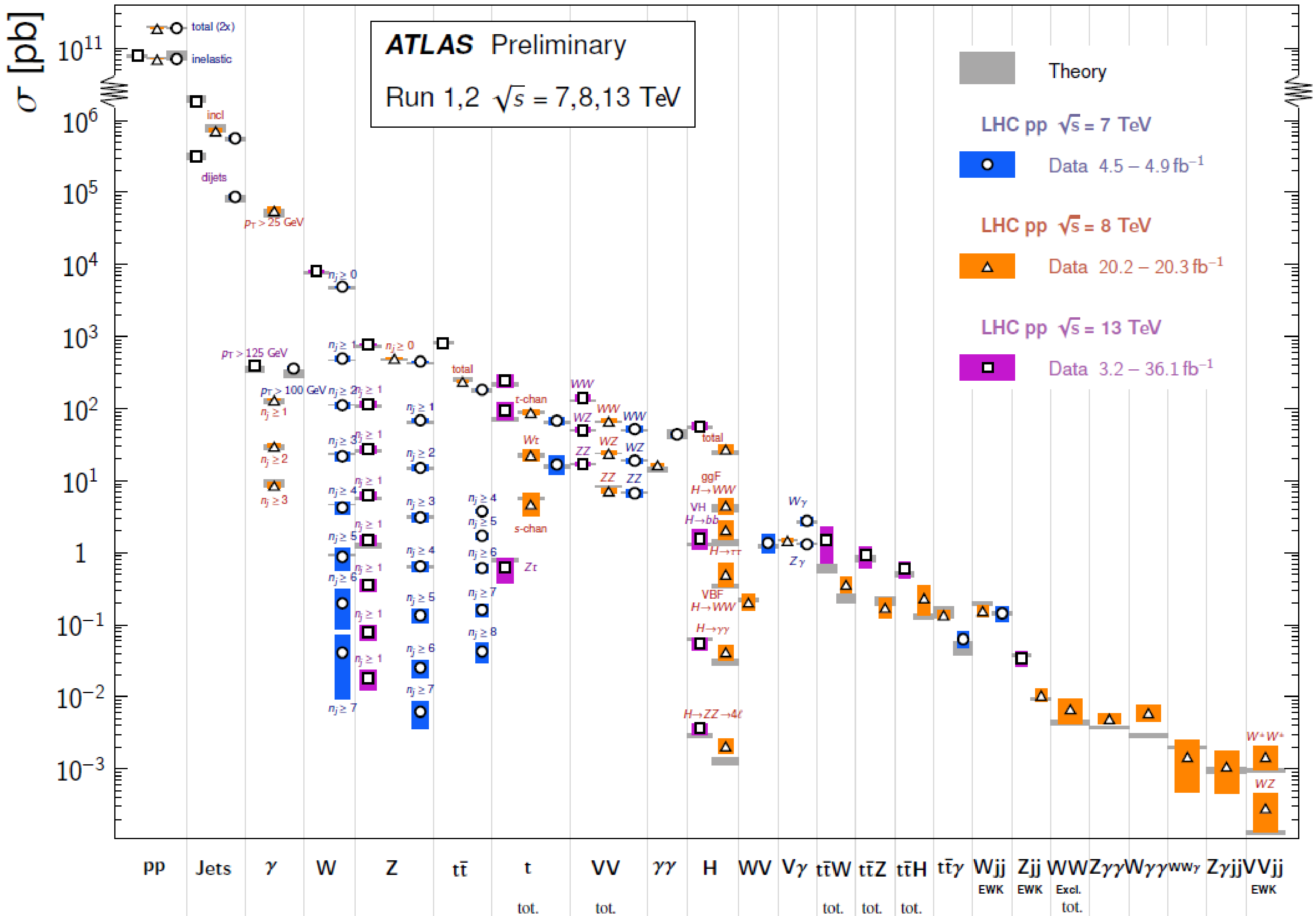
Beyond NLO: Precision frontier



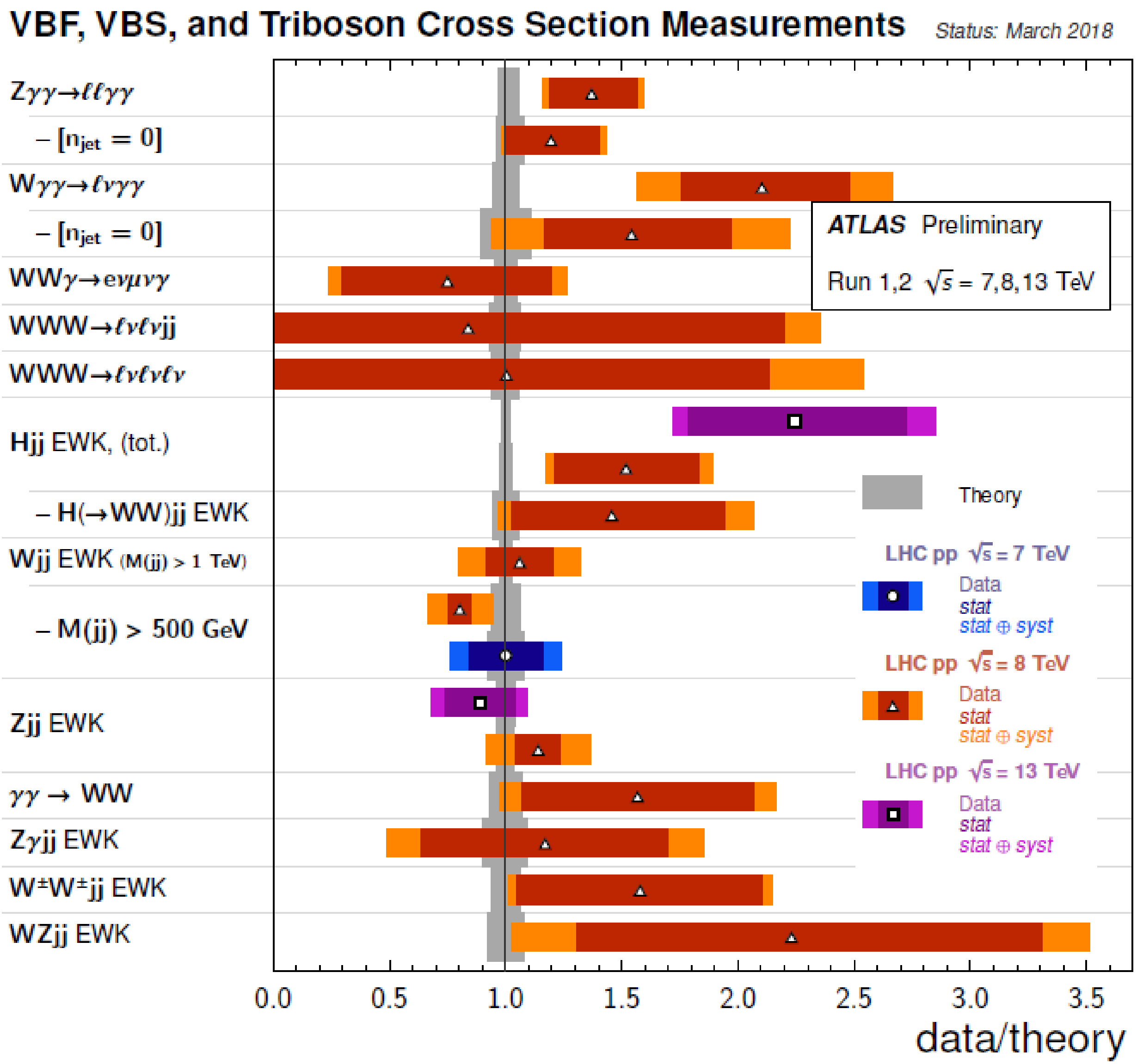
Status Theory

- LO:
  - Automatize (Madgraph, Sherpa…)
  - Public libraries (optimized code):(MCFM, VBFNLO)
- NLO QCD:
  - Automatize (MG5_aMC@NLO, Gosam/OpenLoops+ Herwig/Sherpa)
    - (processes with >4 legs in the final state, still might be challenging
    - Public libraries (MCFM, VBFNLO)
- NLO EW:
  - $2 \rightarrow 1$ (solved), many $2 \rightarrow 2$, some $2 \rightarrow 3/4$ processes
- NNLO QCD:
  - $2 \rightarrow 1$ (solved), many $2 \rightarrow 2$ processes
  - Public libraries (MATRIX, MCFM) and private codes
- NNNLO QCD:
  - $pp \rightarrow H$: via GF (effective theory) and VBF (VBF approximation)

Re-discovering the SM



Re-discovering the SM



Goal at LHC

Test Standard Model & Hints of New Physics

Method

Improve SM prediction → Reduce Theory Uncertainty

Framework to parametrize Beyond Standard Model physics → Effective Field Theory

Anomalous Couplings

⇩

Improve Sensitivity → Cuts and Observables

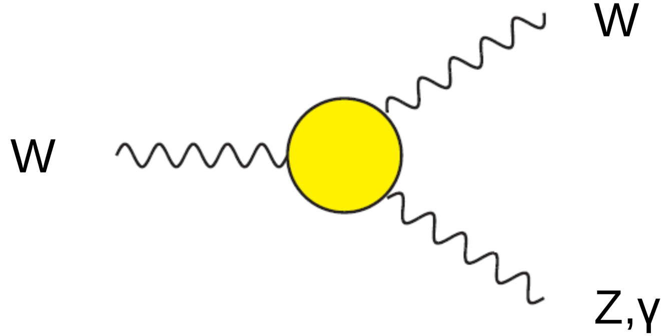
Tools

Monte Carlo tools at the precision frontier:

NLO: MG5_aMC@NLO, Gosam/OpenLoops+ Herwig/Sherpa, VBFNLO+Herwig …
NNLO: MATRIX,MCFM, DY/HNNLO,..

Anomalous Couplings via Effective Field Theory

- Search for New Physics through Anomalous couplings



- New Physics at high mass scale: Λ
- Higher-dimension terms to Lagrangian: 1/ Λ

➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_k}{\Lambda^4}\cdots$$

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger\,\hat{W}^{\mu\nu}\,(D_\nu\Phi)$$

Anomalous Couplings

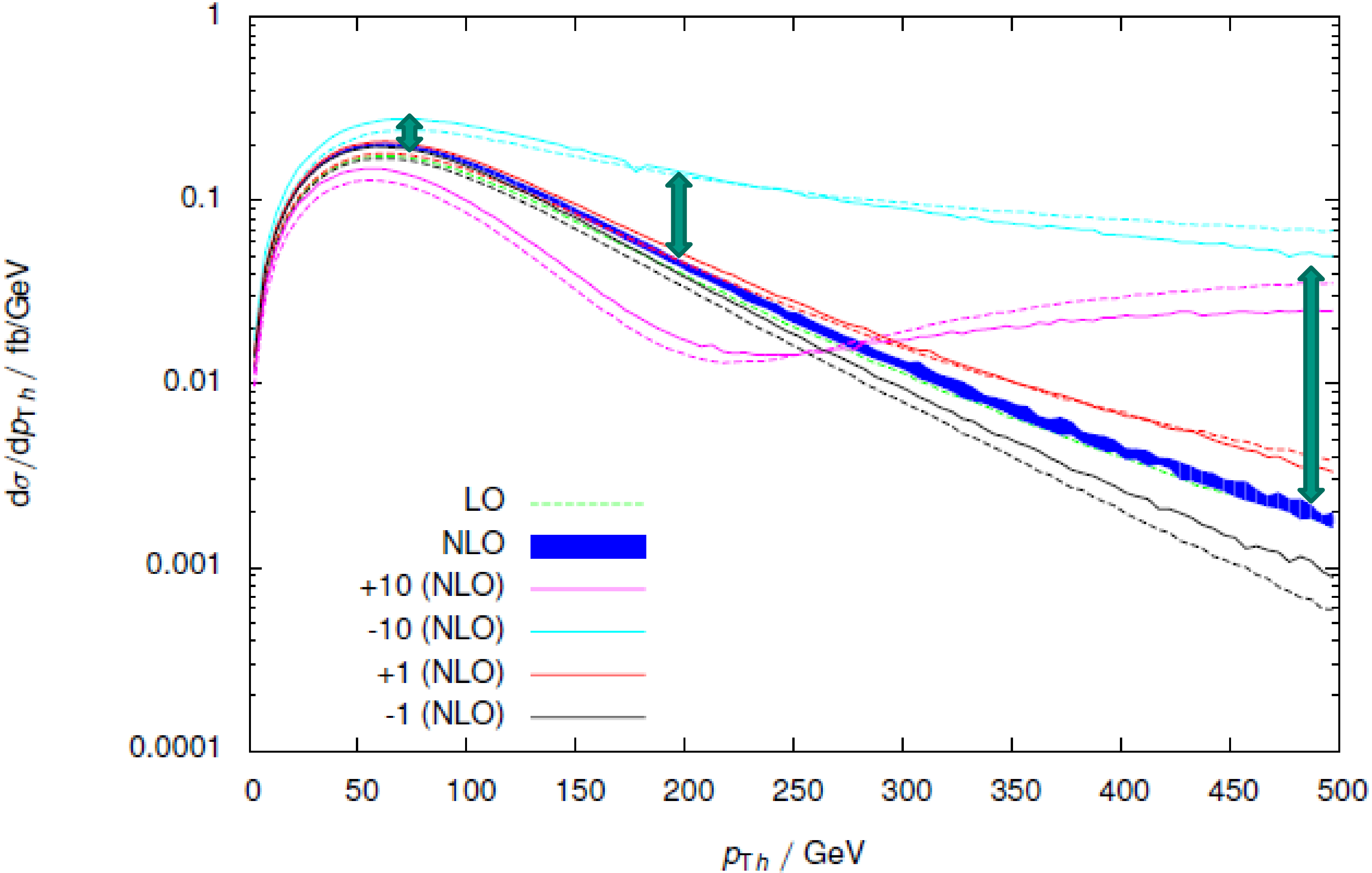
WWH Vertex:

$$\underbrace{i g m_W g^{\mu\nu}}_{\text{SM}} \underbrace{-\frac{1}{2} i \frac{f_W}{\Lambda^2} g m_W \left(-g^{\mu\nu}\left(p_h\cdot p_- + p_h\cdot p_+\right) + p_h^\nu p_-^\mu + p_h^\mu p_+^\nu\right)}_{\mathcal{O}_W}$$

$$\mathcal{O}_W = \left(D_\mu \Phi\right)^\dagger \hat{W}^{\mu\nu} \left(D_\nu \Phi\right)$$

Anomalous Couplings ⟶ Limits to f_W

[FC,Roth,Zeppenfeld,20014]



Anomalous Couplings ⟶ Limits to f_W

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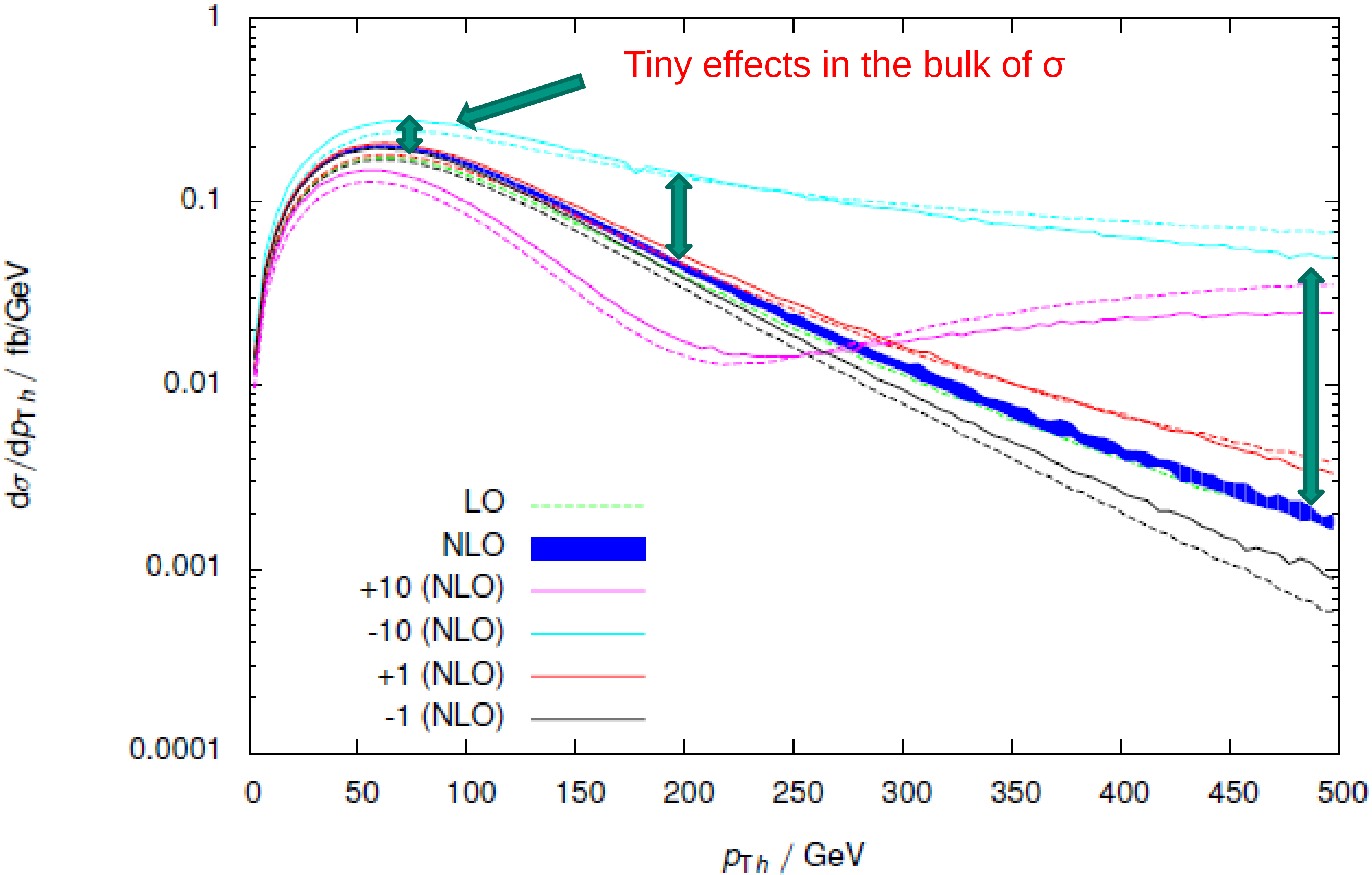

Anomalous Couplings ⟶ Limits to f_W

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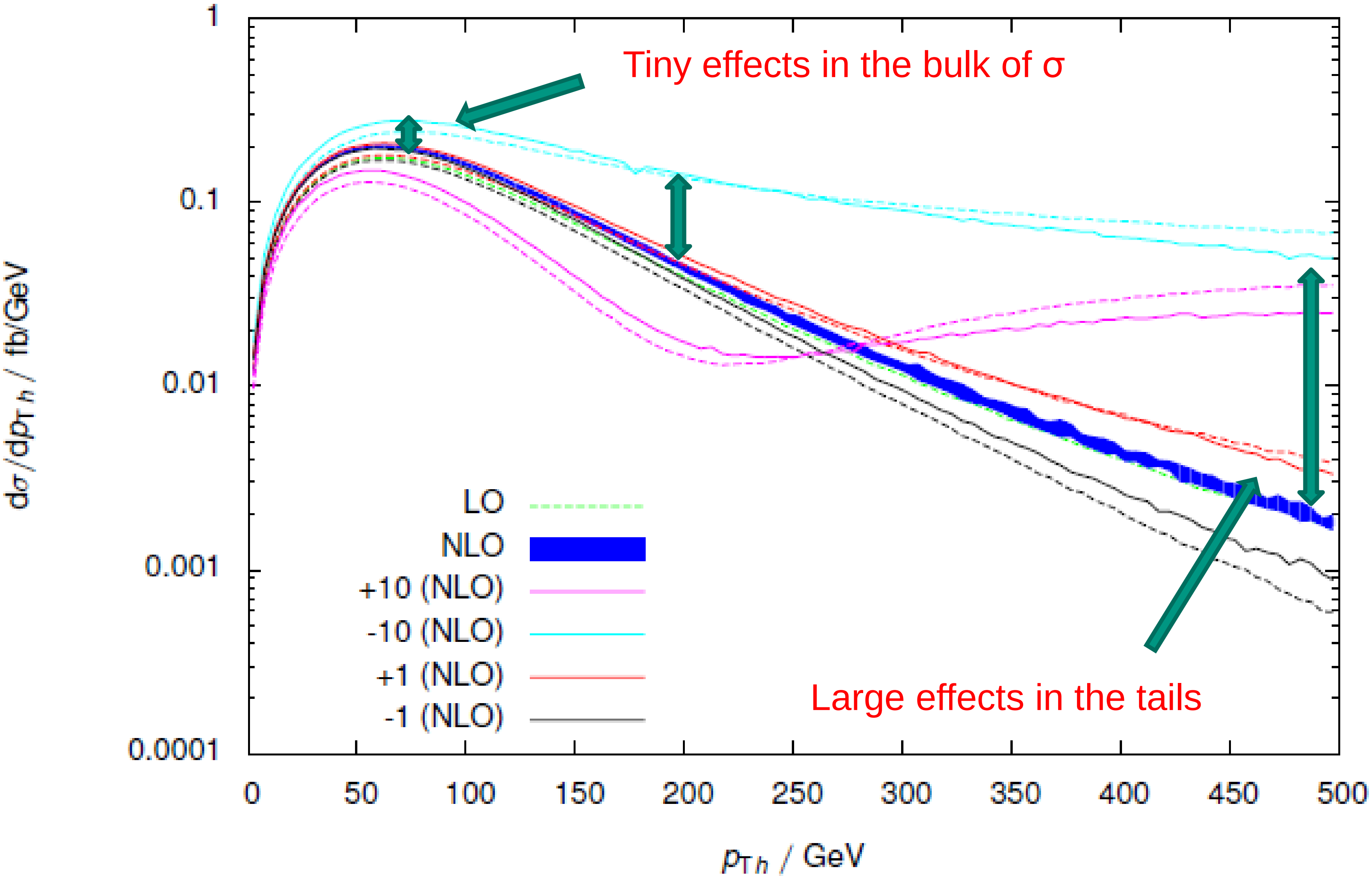
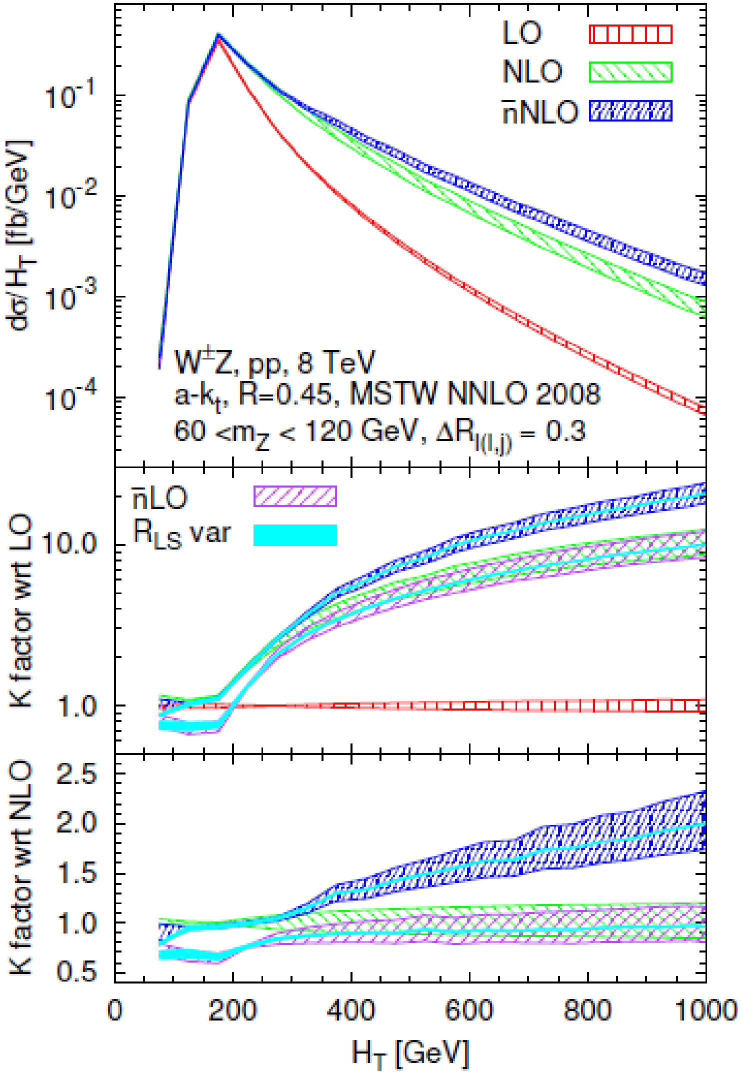


Relevant Beyond (N)LO effects

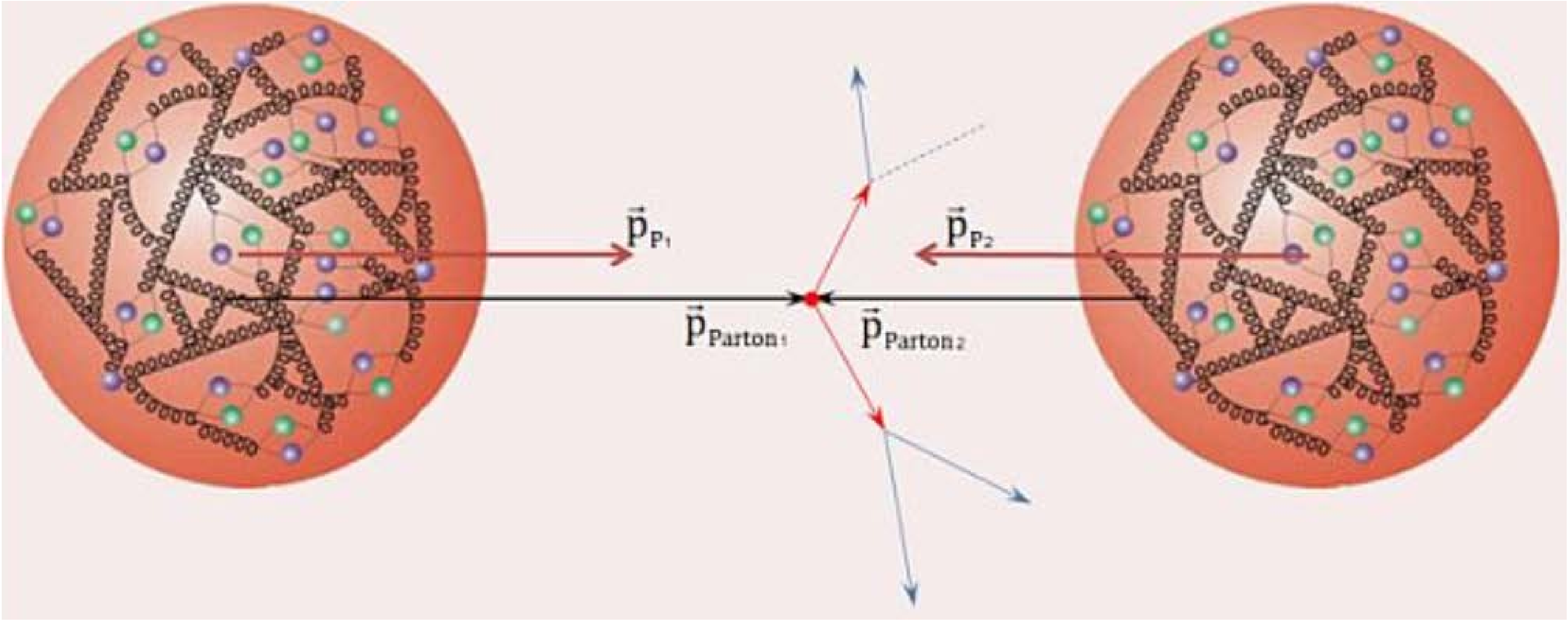
[FC,Sapeta,20012]



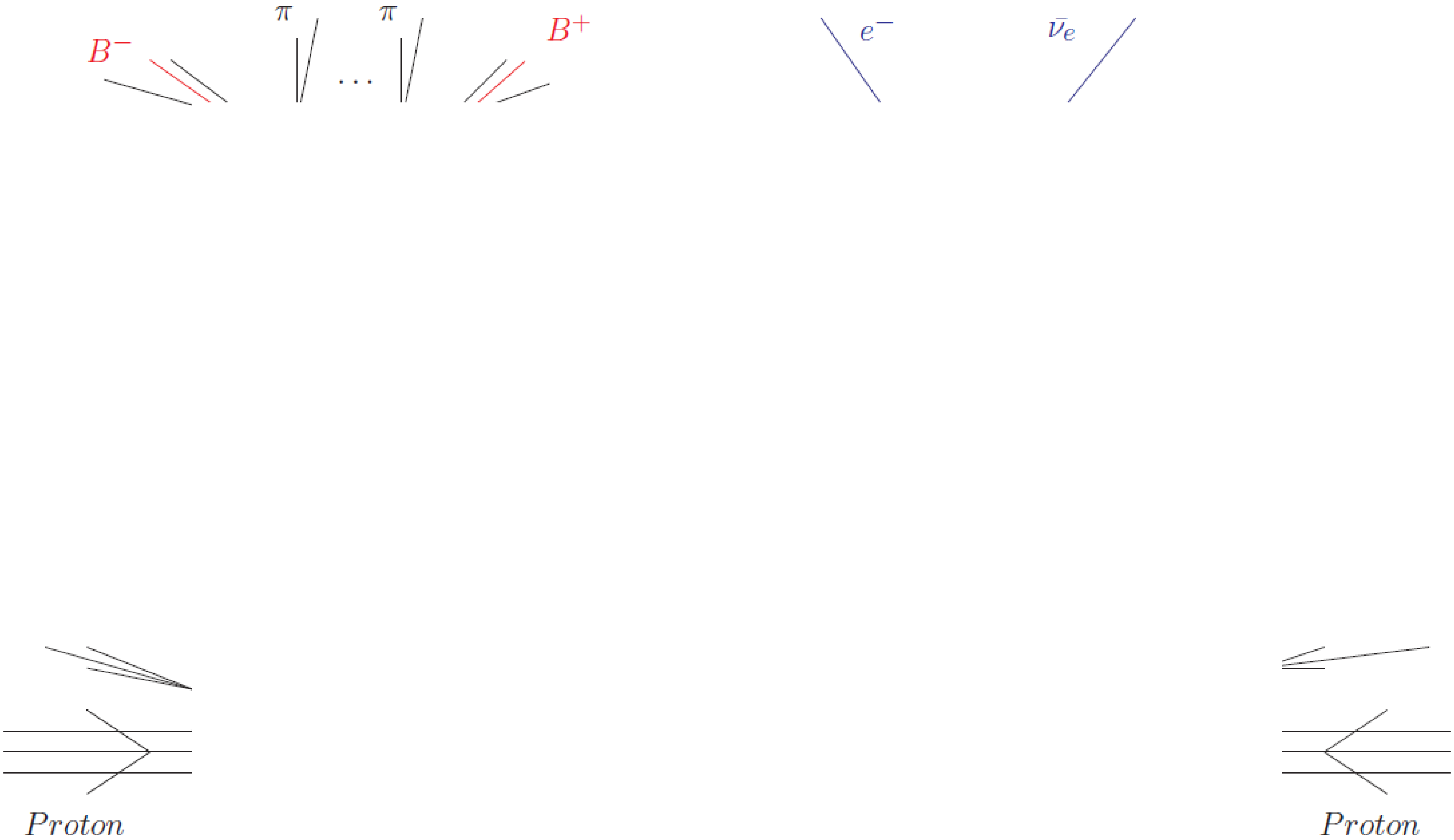
$$H_T = \sum p_{T,\mathrm{jets}} + \sum p_{T,l} + E_{T,\mathrm{miss}}$$

- Huge NLO/LO corrections
- Large NNLO/NLO corrections
- Precision is needed

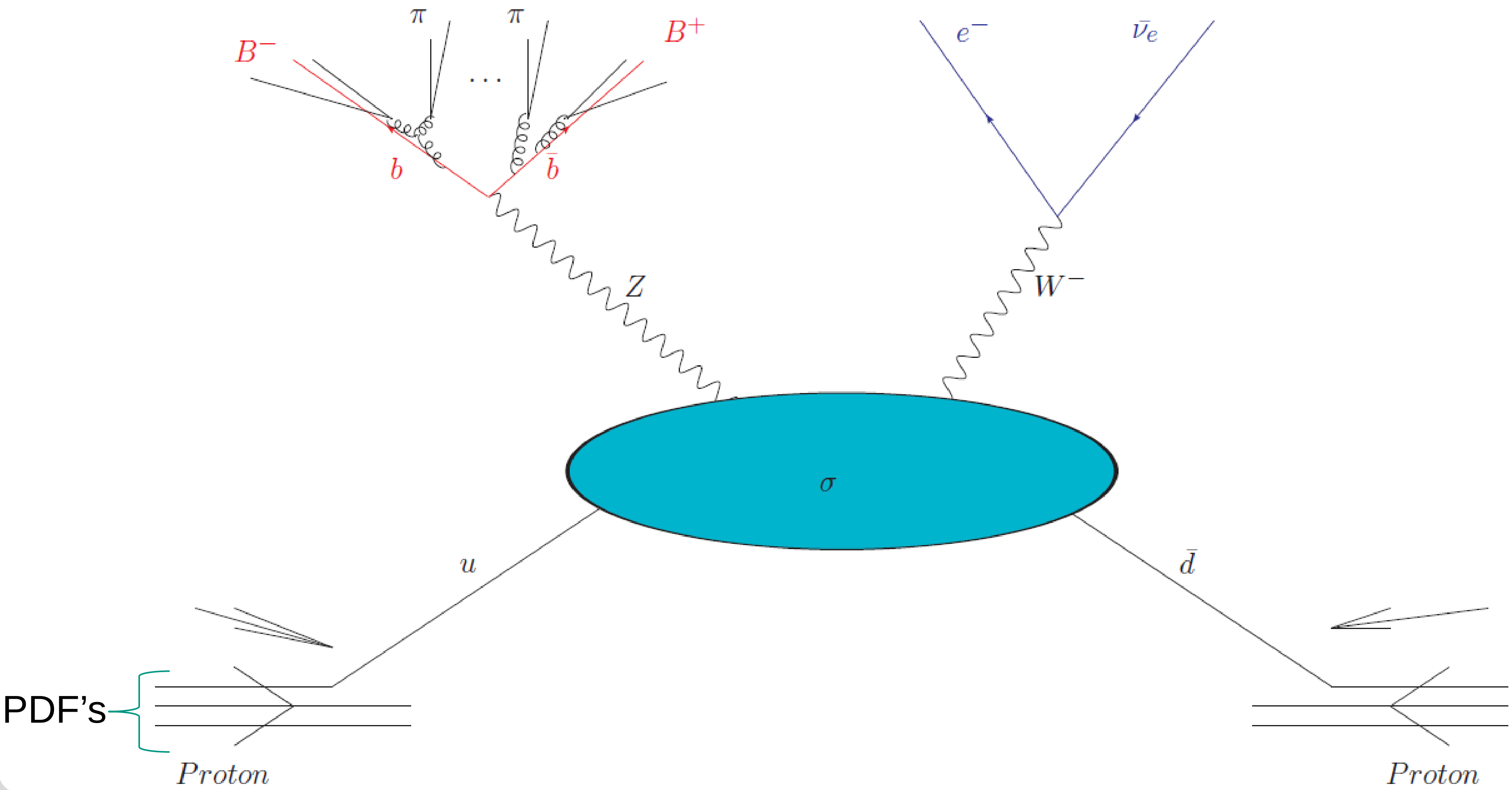
Theoretical Ingredients



Initial and Final States at LHC



Particle Content



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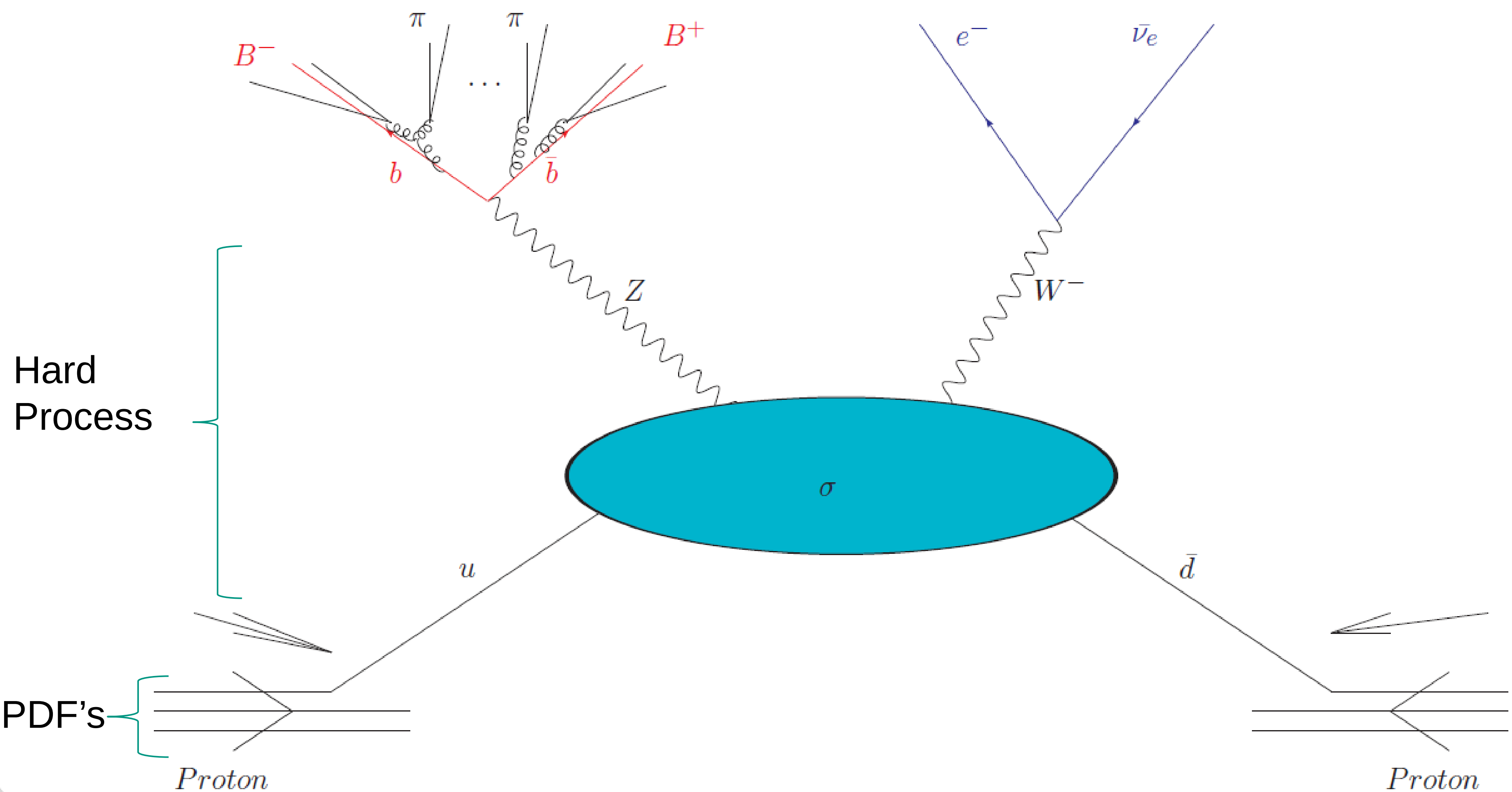

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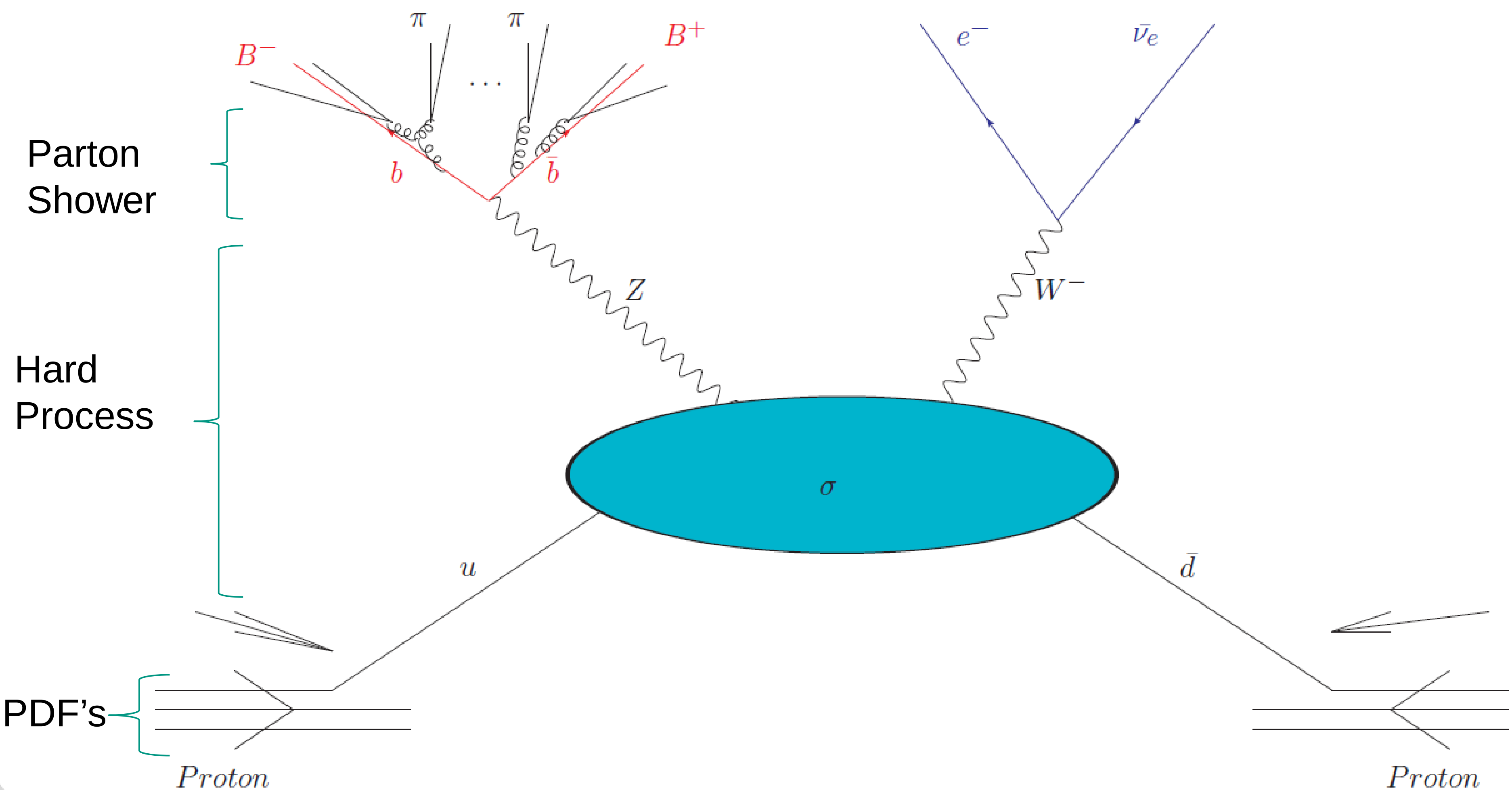

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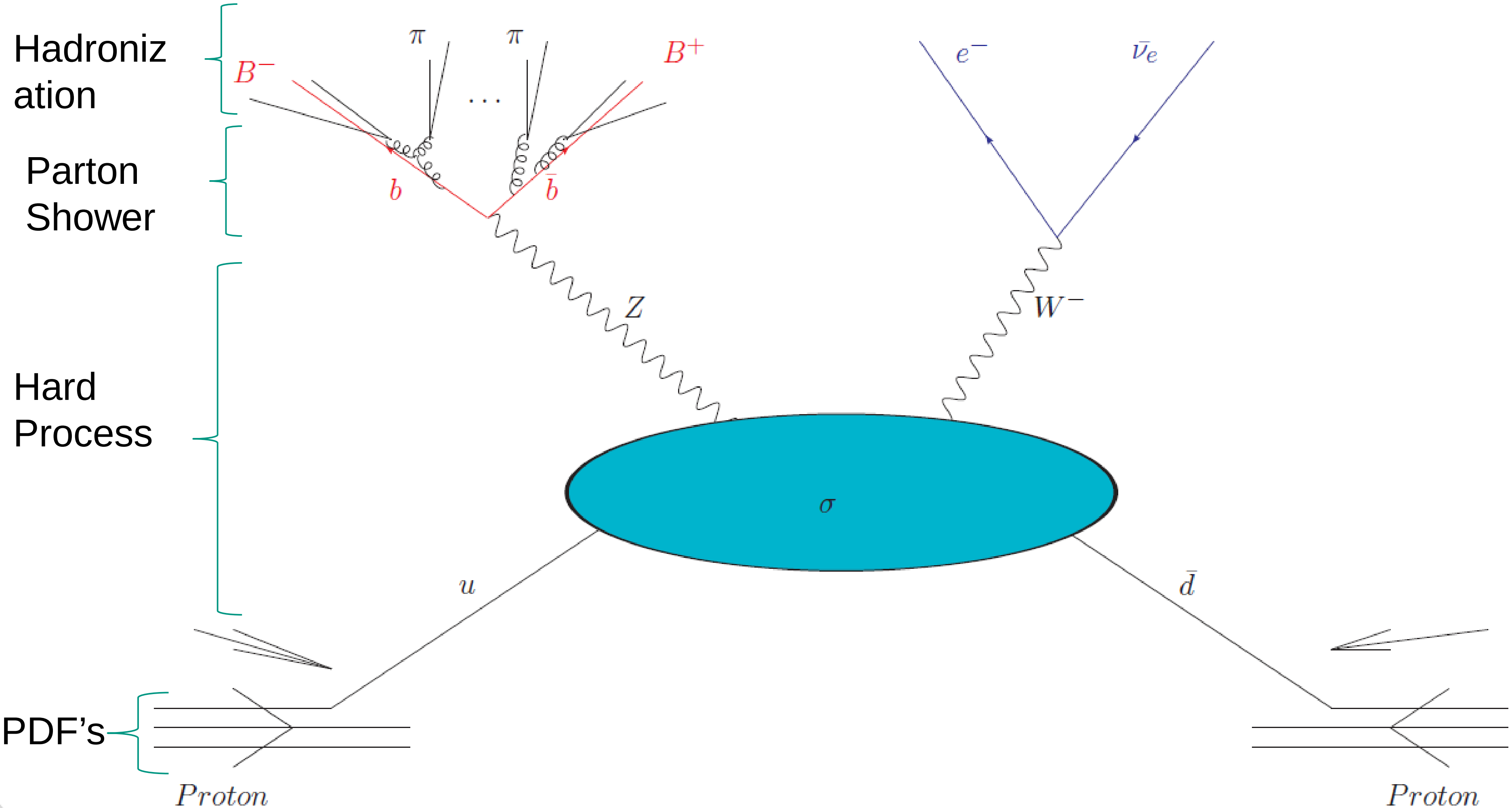
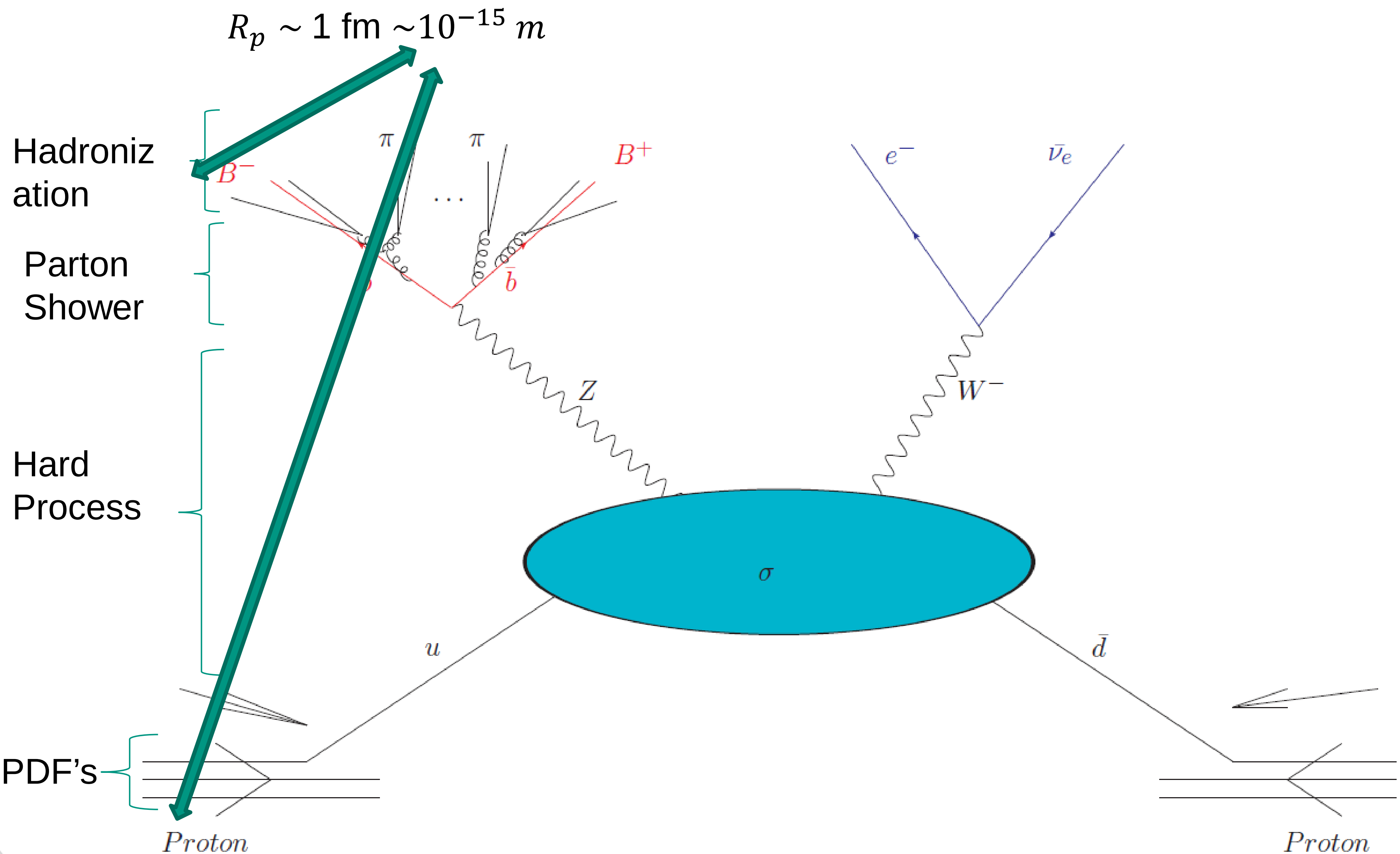


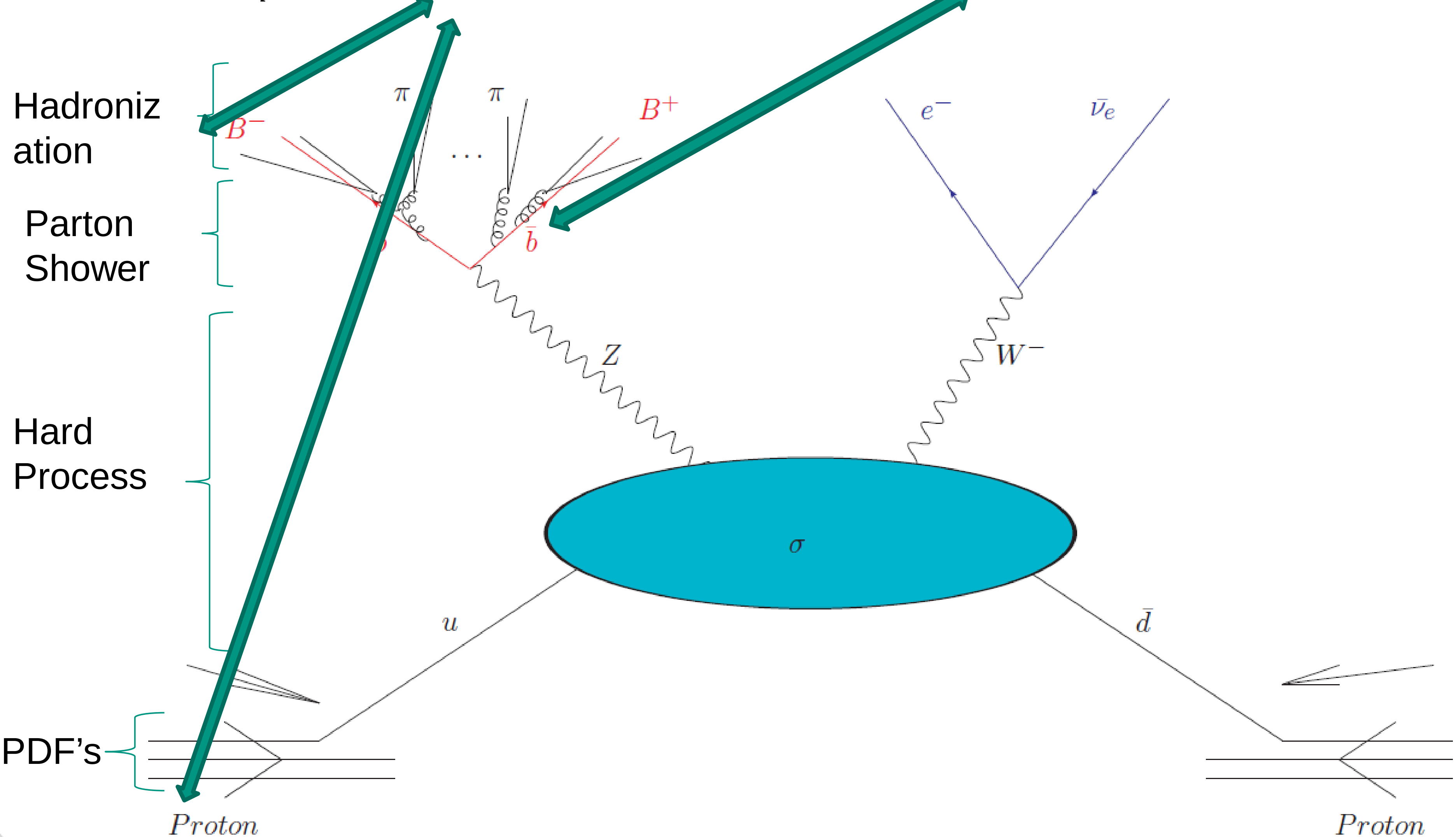
Factorization



Factorization

$R_p \sim 1$ fm $\sim 10^{-15}\, m$

1/10 GeV ~ 0.02 fm



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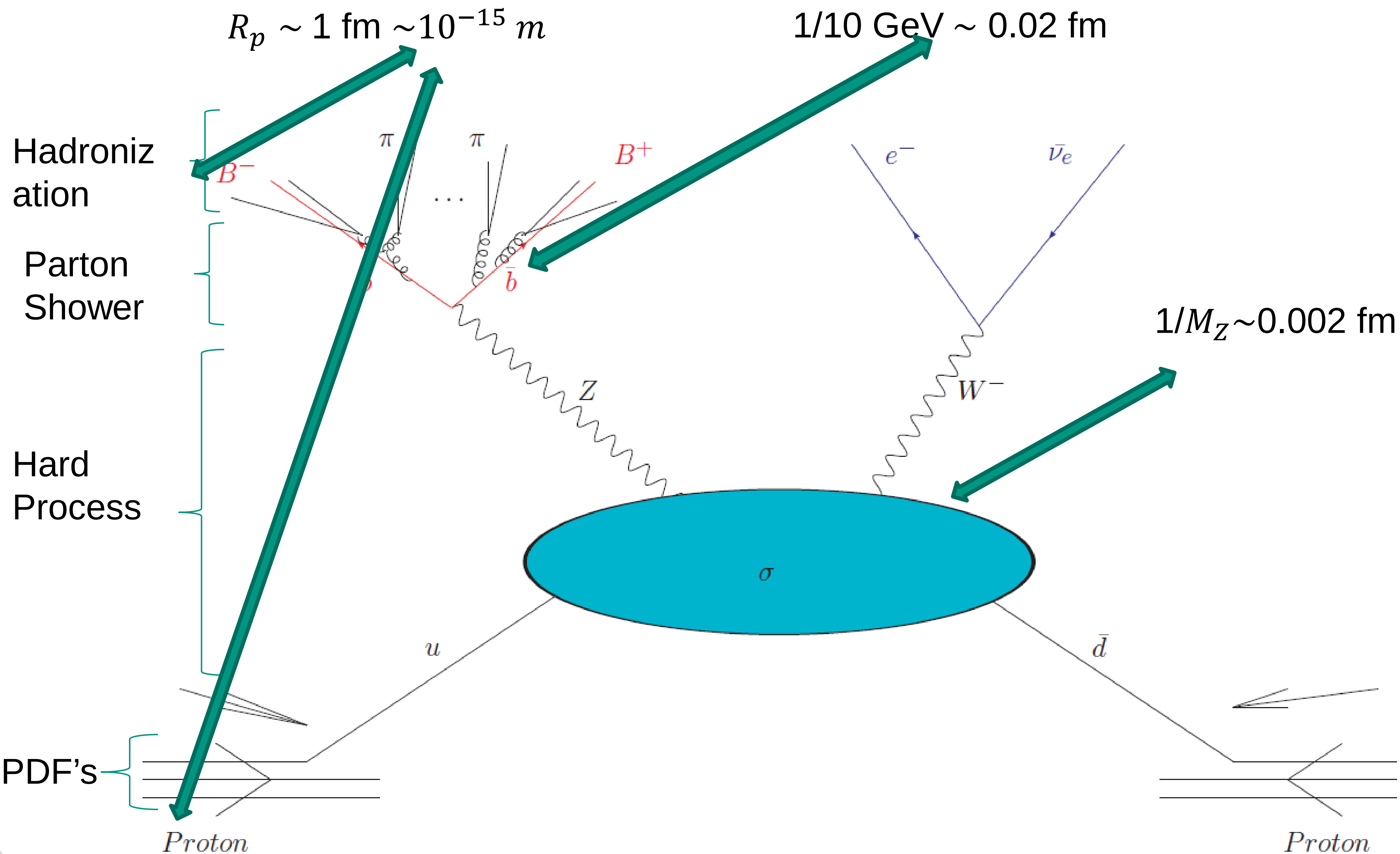


Libraries

Hadronization

Herwig, Pythia,Sherpa

Parton Shower

Hard Process

MG5_aMC@NLO

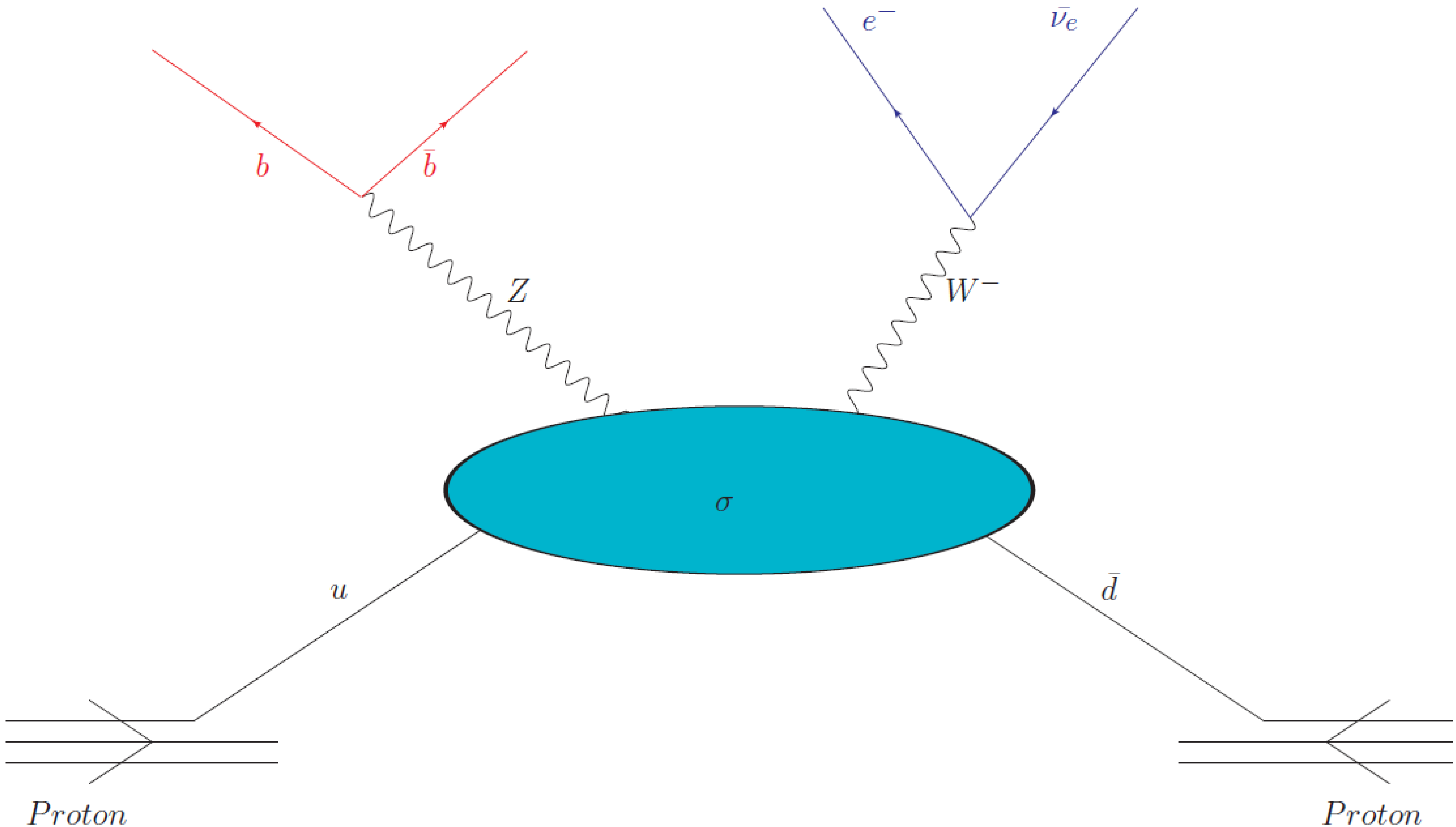
MCFM, VBFNLO

Gosam/OpenLoops/VBFNLO + Herwig/Sherpa

PDF's

ABM, CT14, MMHT14, NNPDF3.0, PDF4LHC15

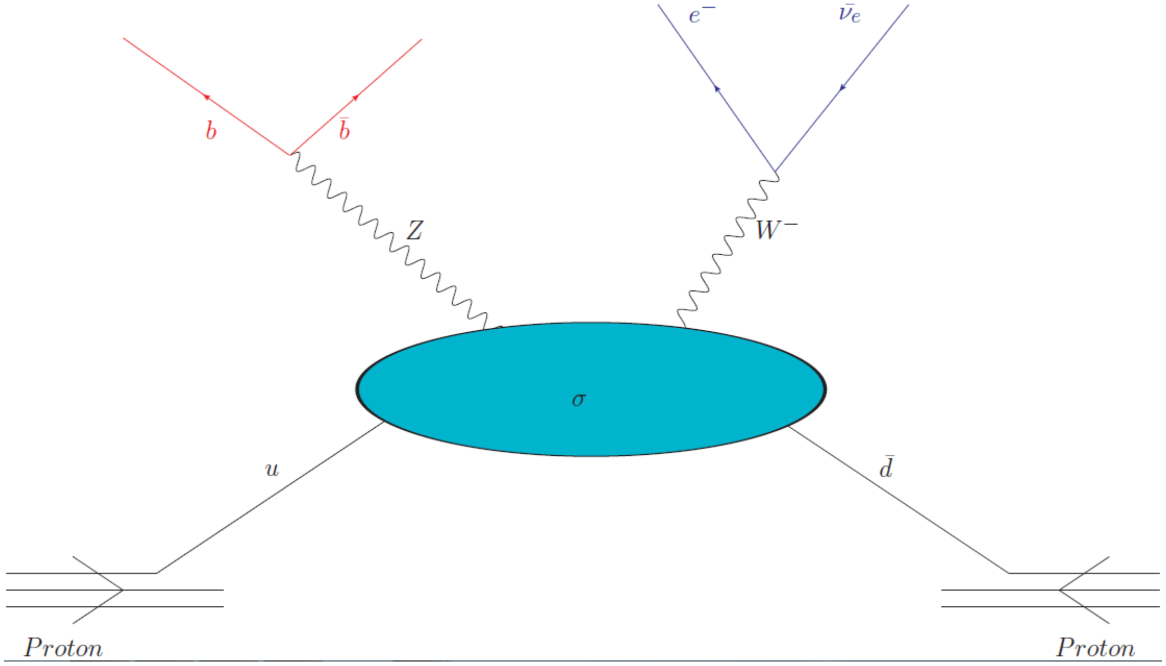
Partonic Cross Section



Cross Section at Hadron Colliders

$$\sigma(H_1 H_2 \to X) = \sum_{a,b,\tilde{X}} \int_0^1 \mathrm{d}x_a\, \mathrm{d}x_b\, f_{a/H_1}(x_a, \mu_F^2)\, f_{b/H_2}(x_b, \mu_F^2)$$

$$\times\ \sigma_{ab}(ab \to \tilde{X}; \mu_F^2)\, \Theta\,(C(X))\, F(\tilde{X} \to X)$$



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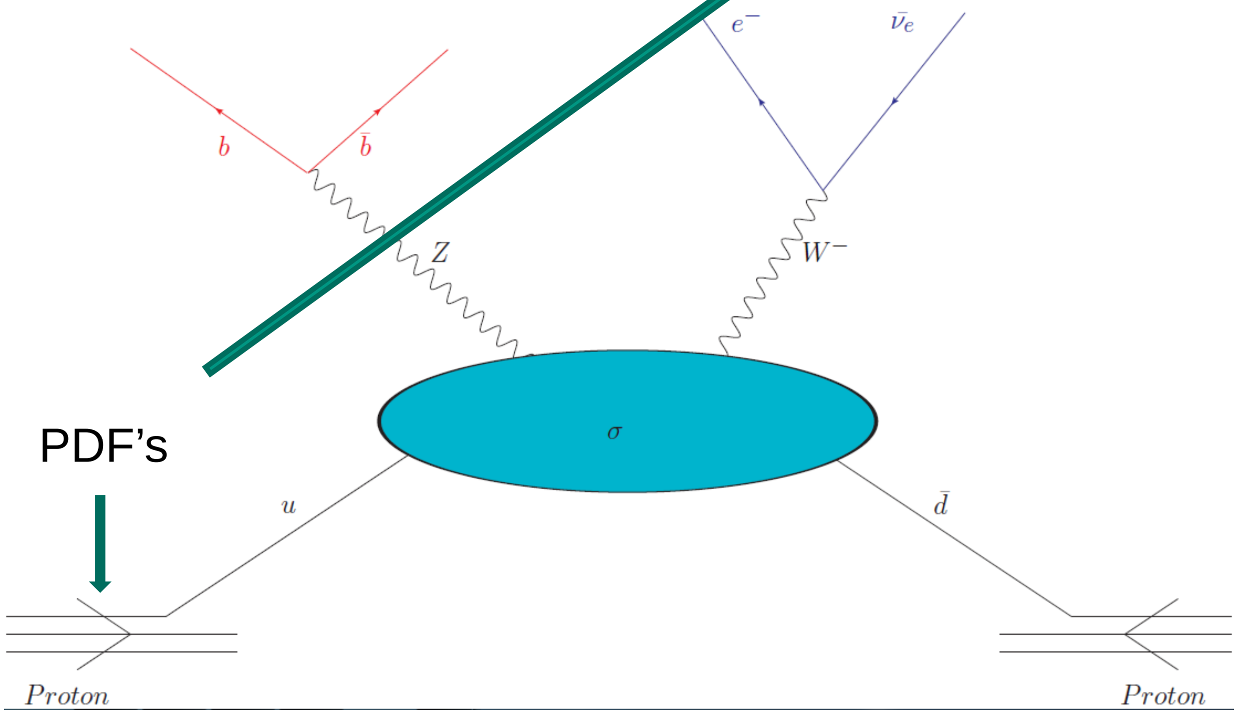
$$\times\ \sigma_{ab}(ab \to \tilde{X};\mu_F^2)\,\Theta\,(C(X))\,F(\tilde{X} \to X)$$



PDF's

Cross Section at Hadron Colliders

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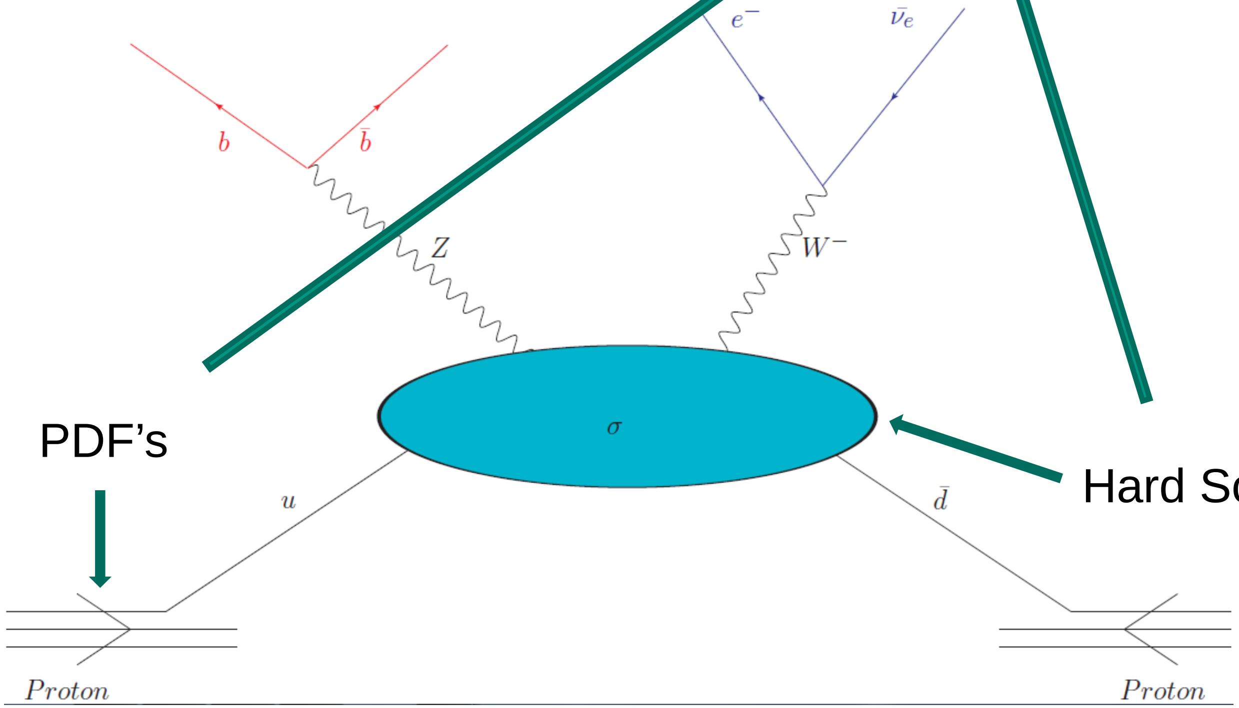
$$\text{x}\ \sigma_{ab}(ab \to \tilde{X}; \mu_F^2)\, \Theta\,(C(X))\, F(\tilde{X} \to X)$$



PDF's

Hard Scattering

Cross Section at Hadron Colliders

$$\sigma(H_1\, H_2 \to X) = \sum_{a,b,\tilde{X}} \int_0^1 \mathrm{d}x_a\, \mathrm{d}x_b\, f_{a/H_1}(x_a, \mu_F^2)\, f_{b/H_2}(x_b, \mu_F^2)$$

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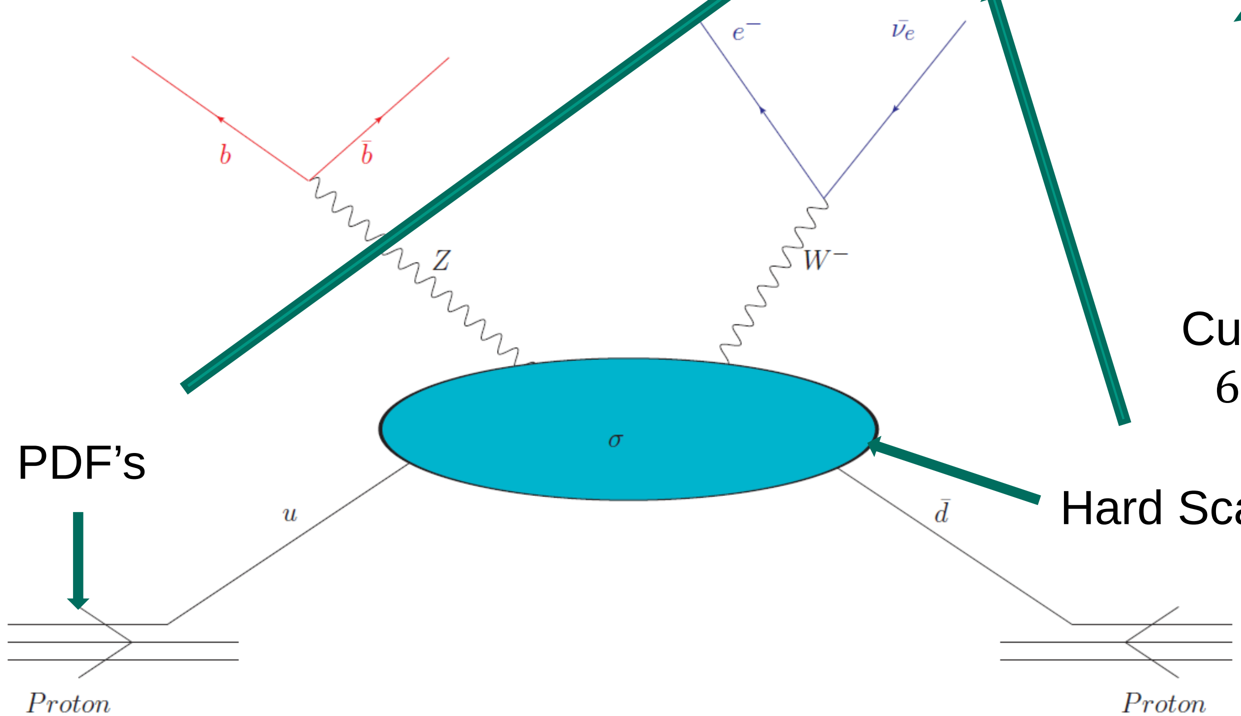


PDF's

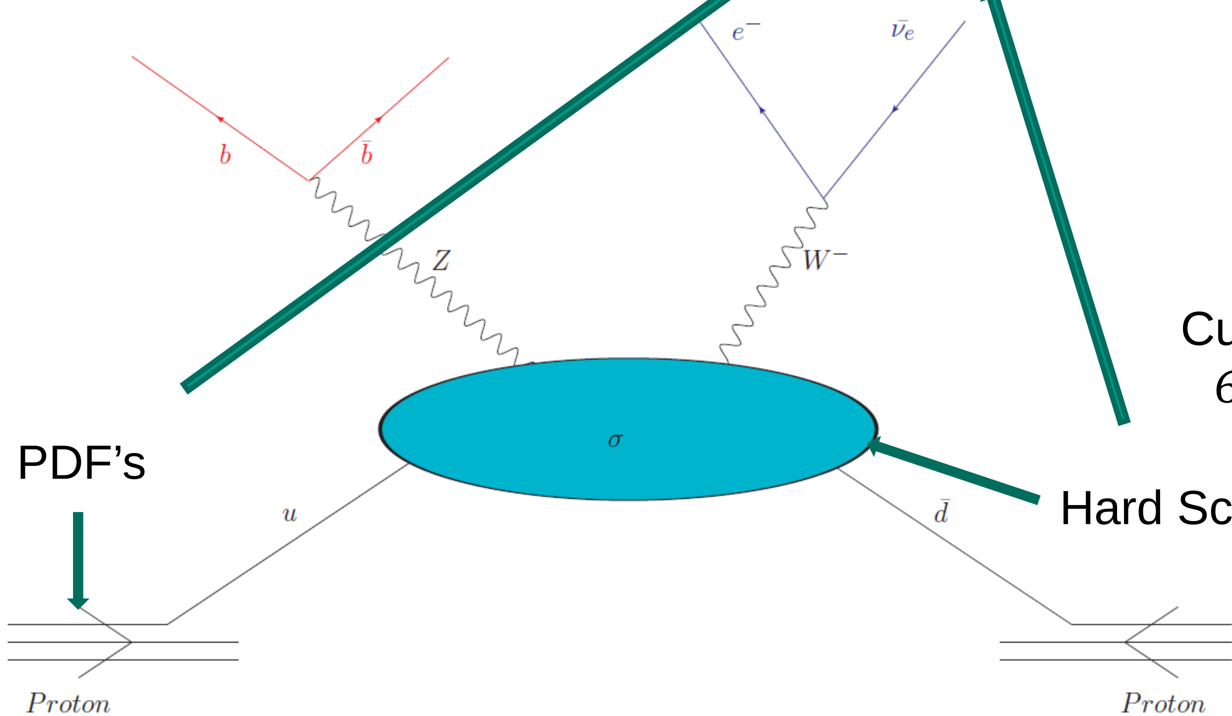
Hard Scattering

Cuts to Final State:e.g.
$60\ GeV < m_{bb} < 120\ GeV$

Cross Section at Hadron Colliders

$$\sigma(H_1\, H_2 \to X) = \sum_{a,b,\tilde{X}} \int_0^1 \mathrm{d}x_a\, \mathrm{d}x_b\, f_{a/H_1}(x_a, \mu_F^2)\, f_{b/H_2}(x_b, \mu_F^2)$$

$$\times\ \sigma_{ab}(ab \to \tilde{X}; \mu_F^2)\, \Theta\,(C(X))\, F(\tilde{X} \to X)$$



How partons recombine into Jets

Cuts to Final State:
$60\ GeV < m_{bb} < 120\ GeV$

Hard Scattering

PDF's

Perturbative Expansion of Cross Section

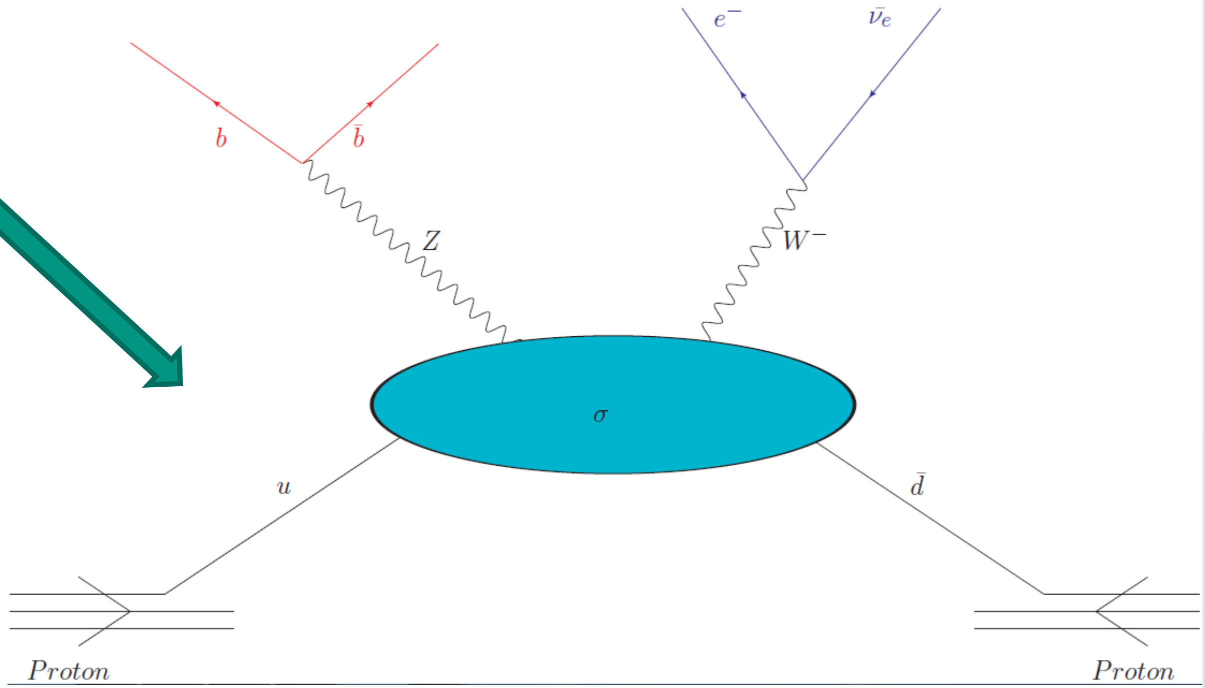
$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\,\alpha^n(\mu_{R,EW}^2)\,\sigma_{m,n}(\mu_R^2,\mu_F^2)$$

$$\alpha(M_e^2) = (137.03599911)^{-1}$$

$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0006$$

$$\sigma = \sigma^{LO} + \sigma^{NLO}_{QCD} + \sigma^{NLO}_{EW} + \sigma^{NNLO}_{QCD}$$

Leading Order

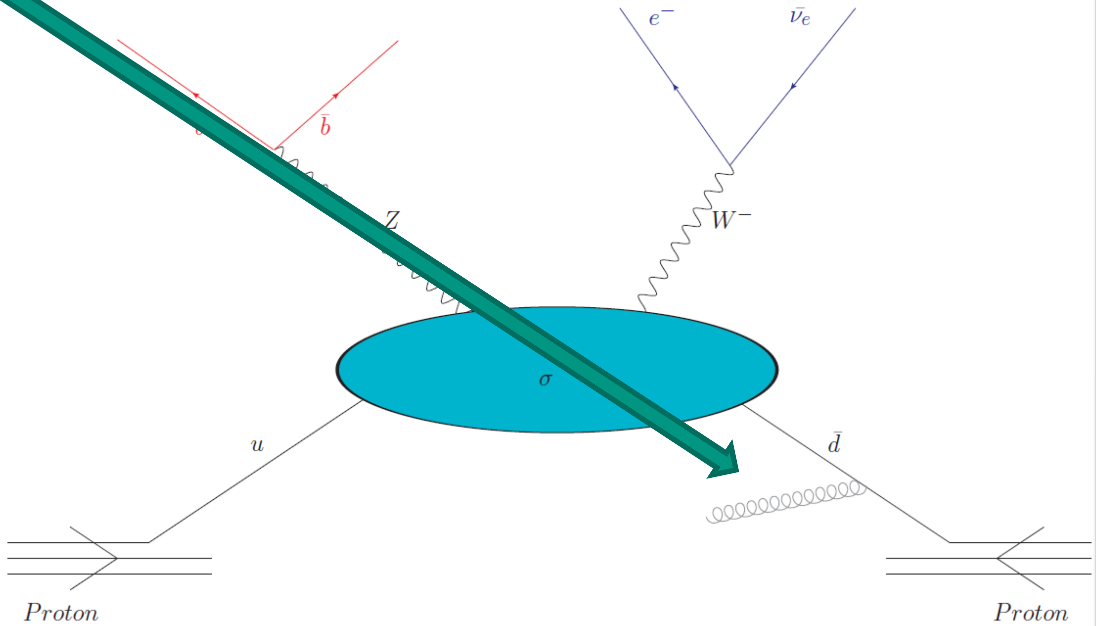


Perturbative Expansion of Cross Section

$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\, \alpha^n(\mu_{R,EW}^2)\, \sigma_{m,n}(\mu_R^2, \mu_F^2)$$

$$\sigma = \sigma^{LO} + \sigma^{NLO}_{QCD} + \sigma^{NLO}_{EW} + \sigma^{NNLO}_{QCD}$$

Next-to-Leading Order: α_S

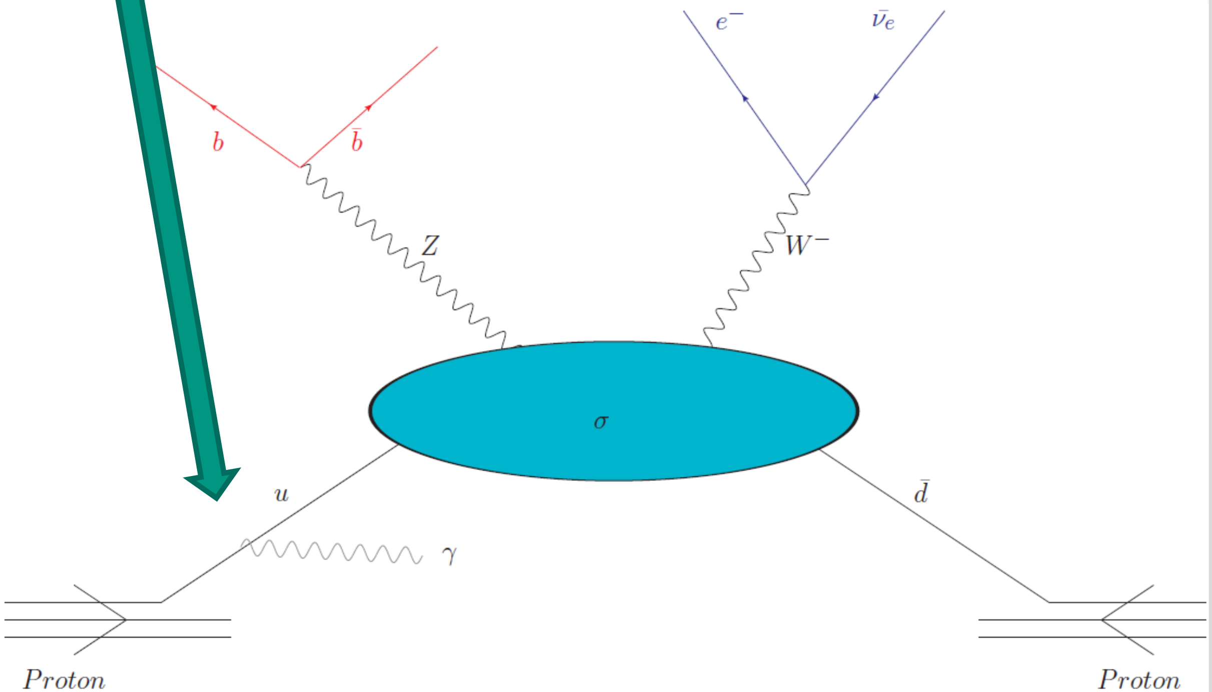


Perturbative Expansion of Cross Section

$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\,\alpha^n(\mu_{R,EW}^2)\,\sigma_{m,n}(\mu_R^2,\mu_F^2)$$

$$\sigma = \sigma^{LO} + \sigma_{QCD}^{NLO} + \sigma_{EW}^{NLO} + \sigma_{QCD}^{NNLO}$$

Next-to-Leading Order: α



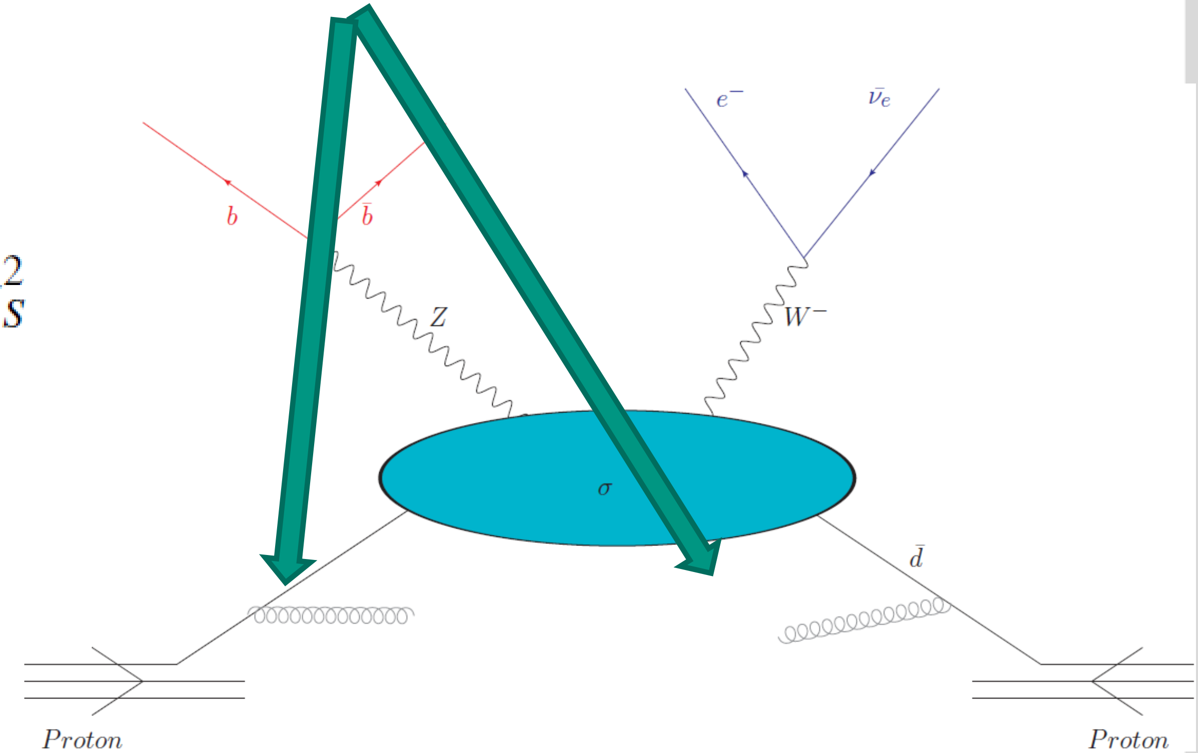
Perturbative Expansion of Cross Section

$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\,\alpha^n(\mu_{R,EW}^2)\,\sigma_{m,n}(\mu_R^2,\mu_F^2)$$

$$\sigma = \sigma^{LO} + \sigma^{NLO}_{QCD} + \sigma^{NLO}_{EW} + \sigma^{NNLO}_{QCD}$$

Next-Next-to-Leading Order: α_S^2

Note: $\alpha \approx \alpha_S^2$



Coupling Constants Run

$$\alpha(M_e^2) = (137.03599911)^{-1}$$

At NLO:

$$\alpha(Q^2) = \frac{\alpha(Q_0^2)}{1 - \frac{\alpha(Q_0^2)}{3\pi}\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

At M_Z:

$$\alpha(M_Z^2) \approx (128)^{-1}$$

- High Q $\Rightarrow$ Non-perturbative

Coupling Constants Run

$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0006$$

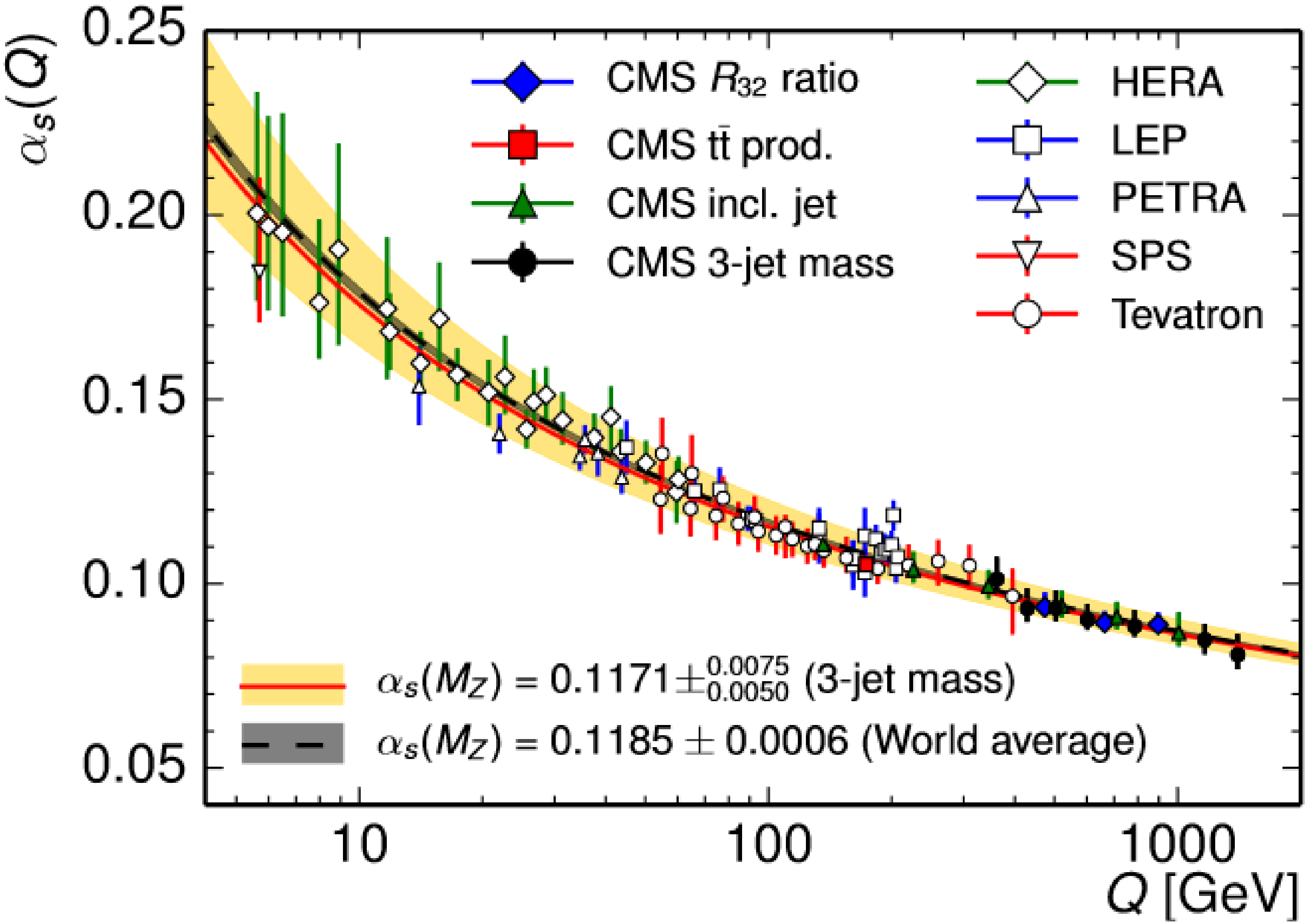
At NLO:

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + (11 - \frac{2}{3}n_f)\frac{\alpha_s(Q_0^2)}{4\pi}\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

For high Q:

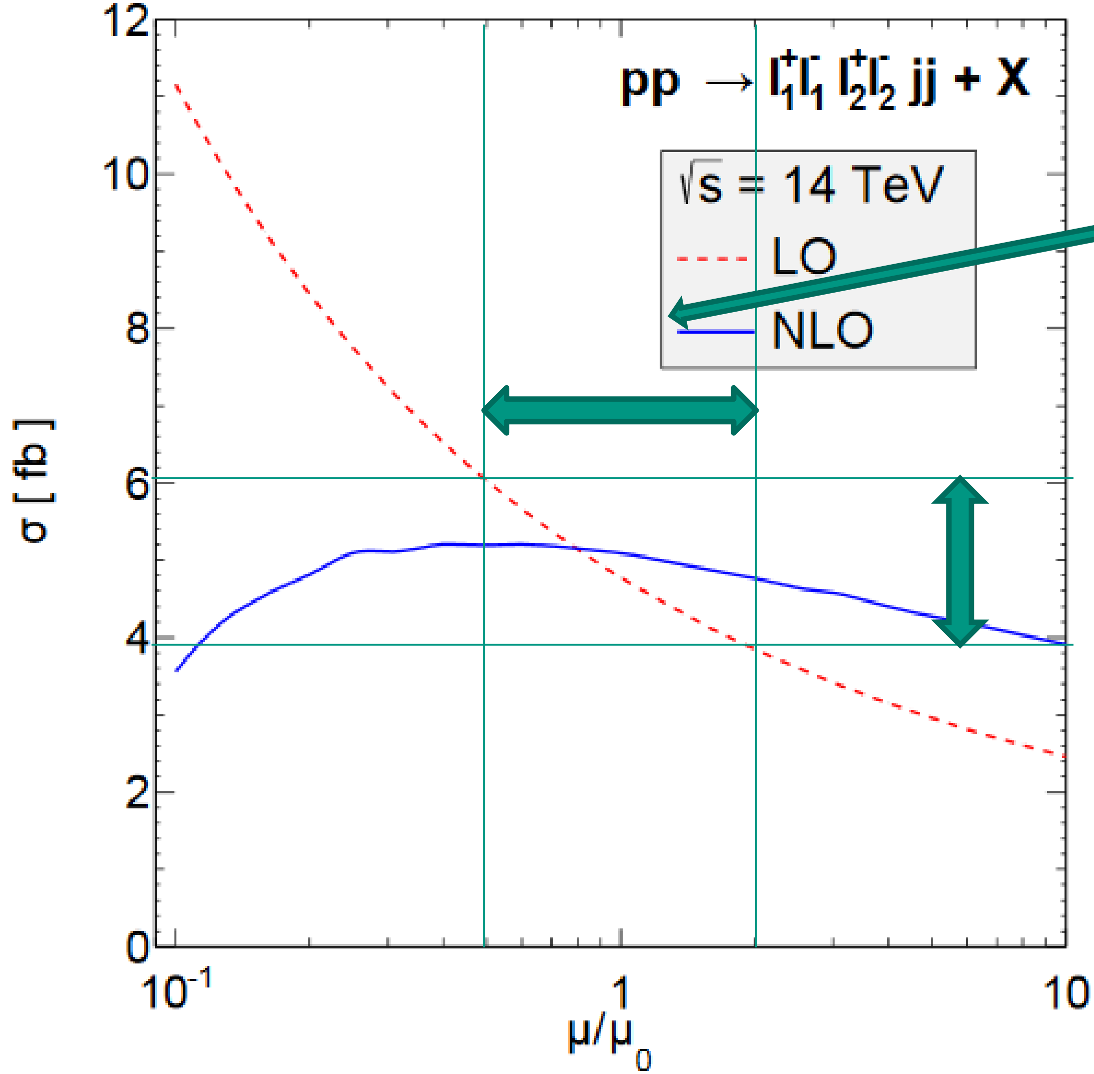
$n_f < 33/2$ $\longrightarrow$ Asymptotic Freedom

QCD Coupling Constant



Scale Uncertanty

$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\,\alpha^n(\mu_{R,EW}^2)\,\sigma_{m,n}(\mu_R^2,\mu_F^2)$$

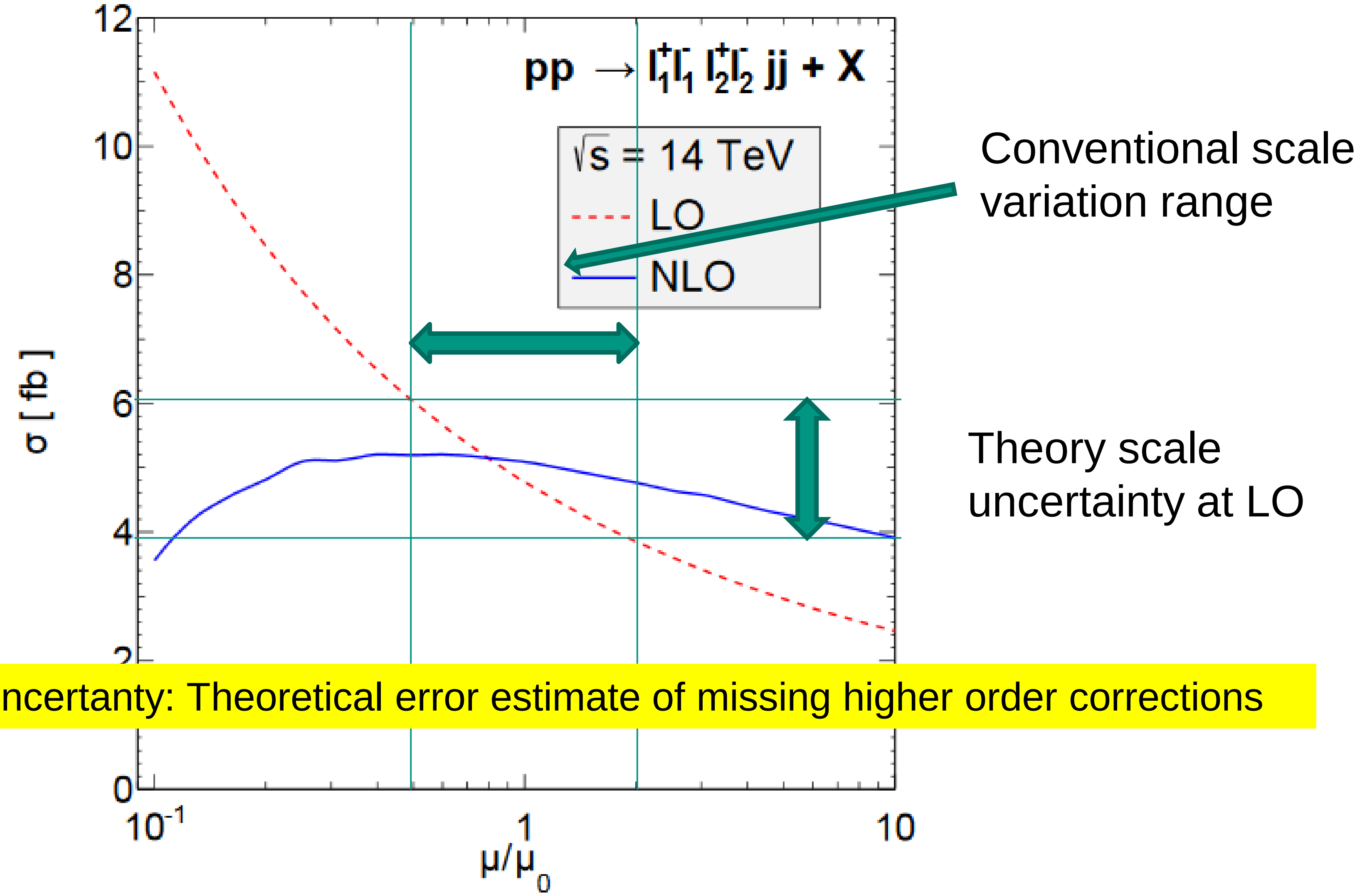


Conventional scale variation range

Theory scale uncertainty at LO

Scale Uncertanty

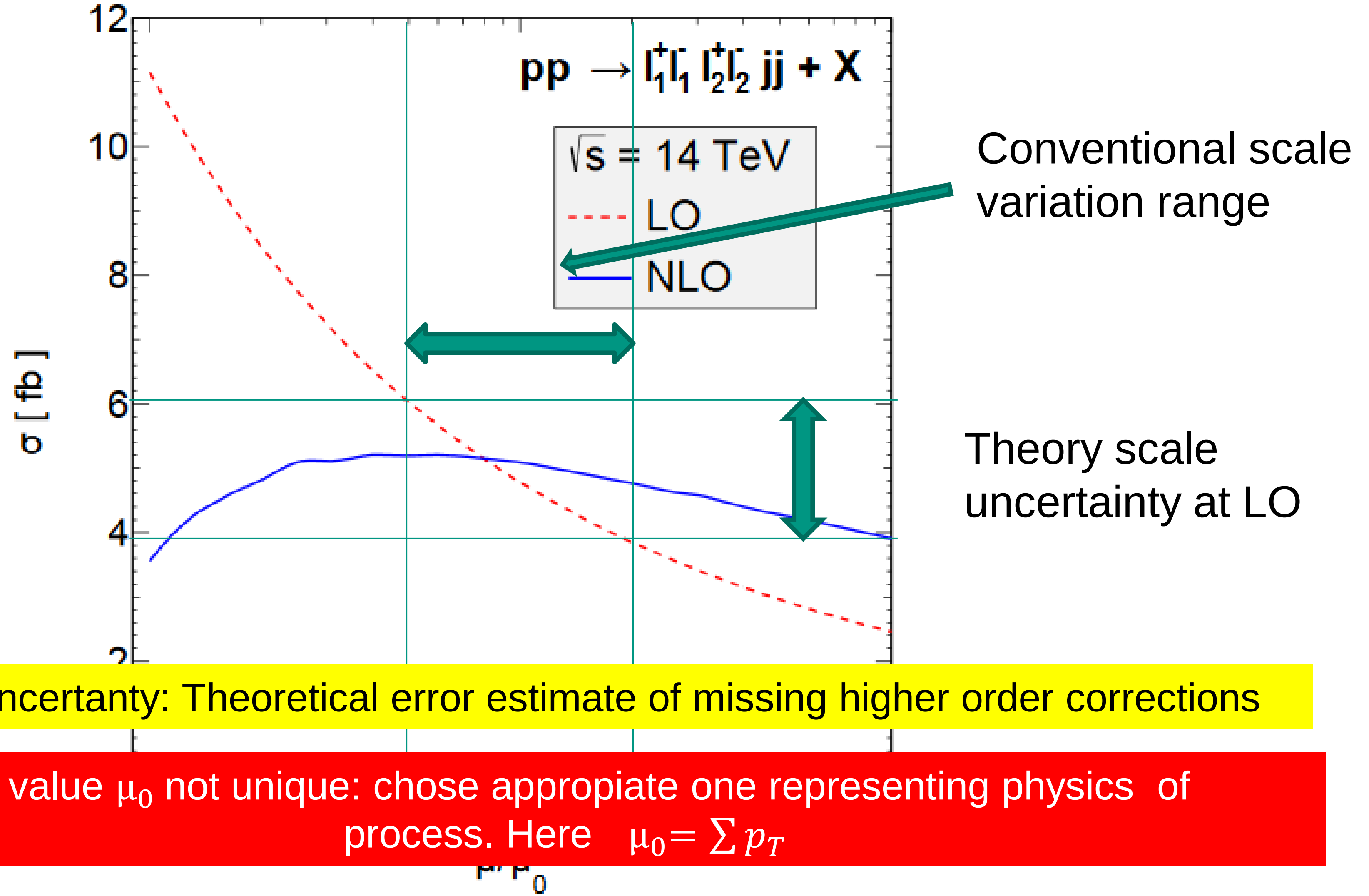
$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\,\alpha^n(\mu_{R,EW}^2)\,\sigma_{m,n}(\mu_R^2,\mu_F^2)$$



Scale Uncertanty: Theoretical error estimate of missing higher order corrections

Scale Uncertanty

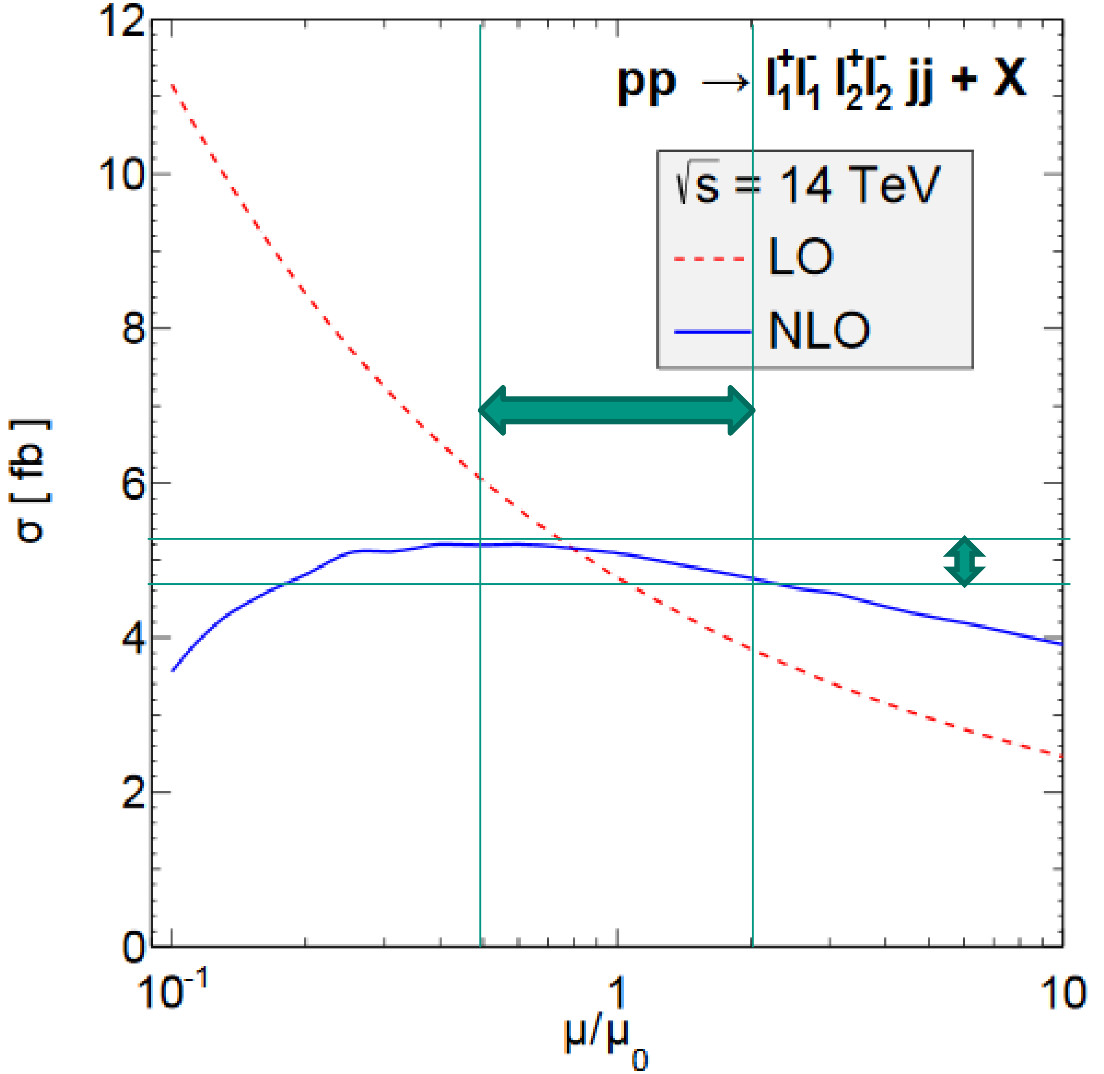
$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\, \alpha^n(\mu_{R,EW}^2)\, \sigma_{m,n}(\mu_R^2, \mu_F^2)$$



Scale Uncertanty: Theoretical error estimate of missing higher order corrections

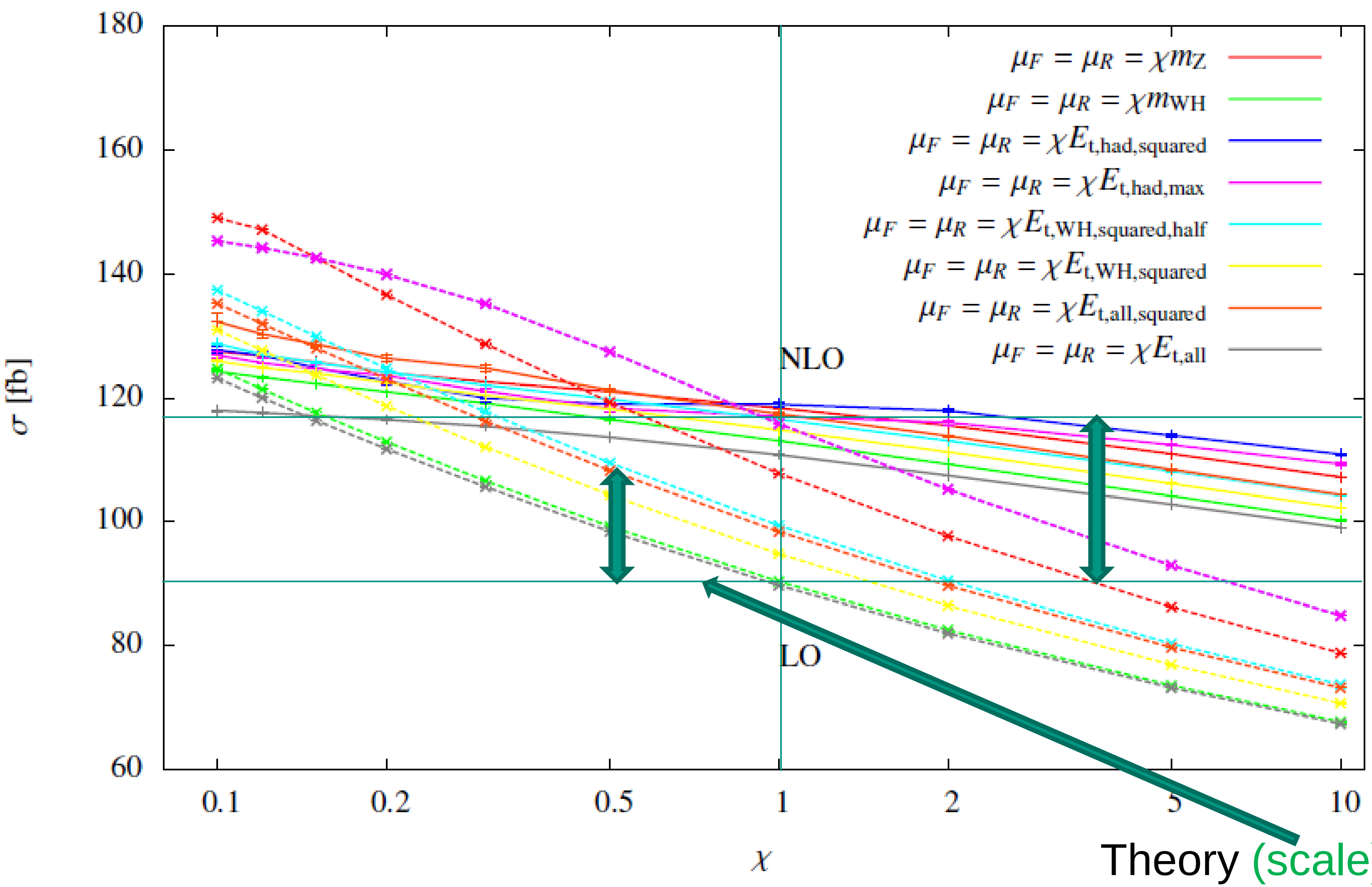
Central value μ_0 not unique: chose appropiate one representing physics of process. Here $\mu_0 = \sum p_T$

Scale Uncertainty



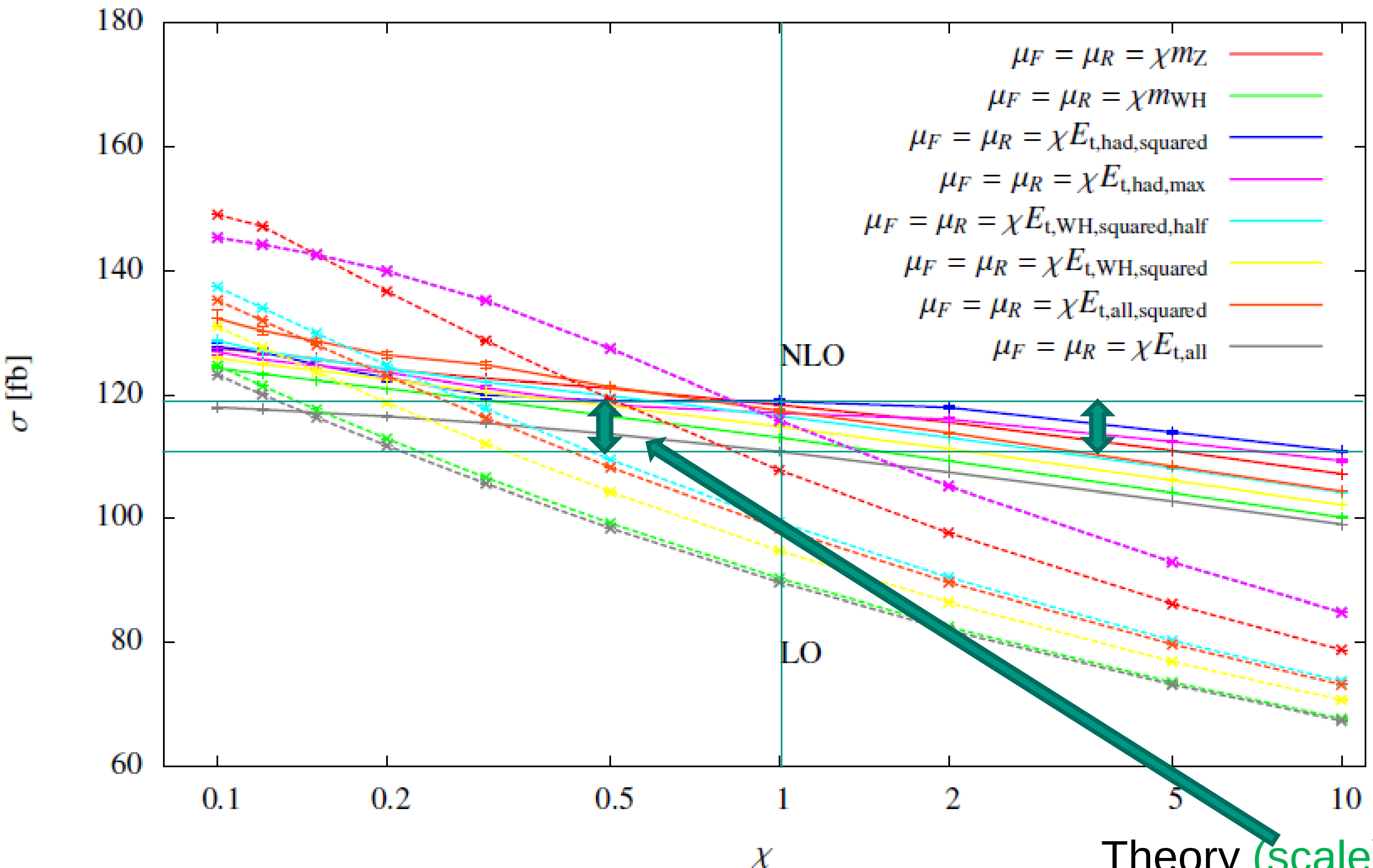
Theory scale uncertainty at NLO

Central Scale Choice Dependence



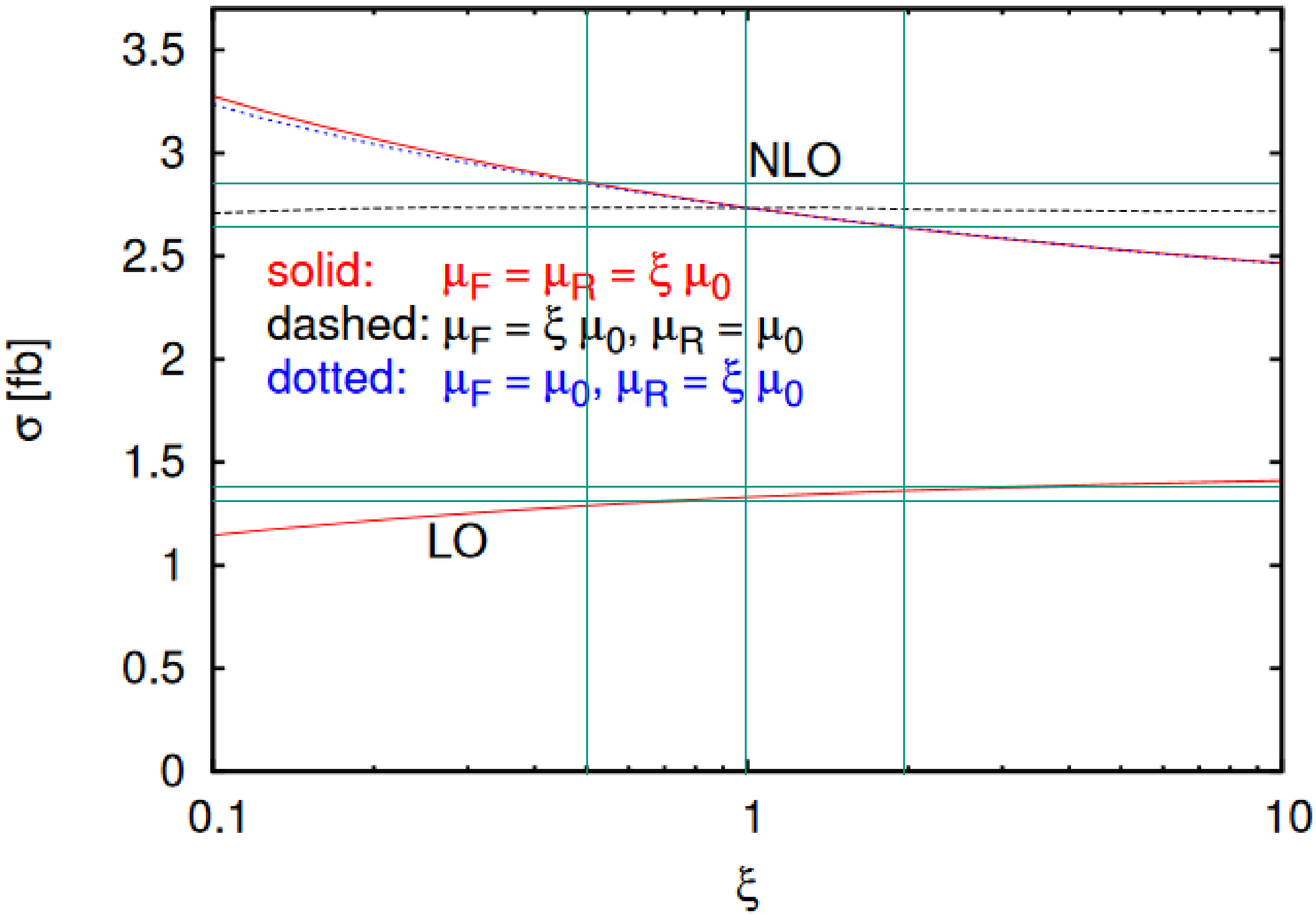
Theory (scale) uncertainty at LO

Central Scale Dependence



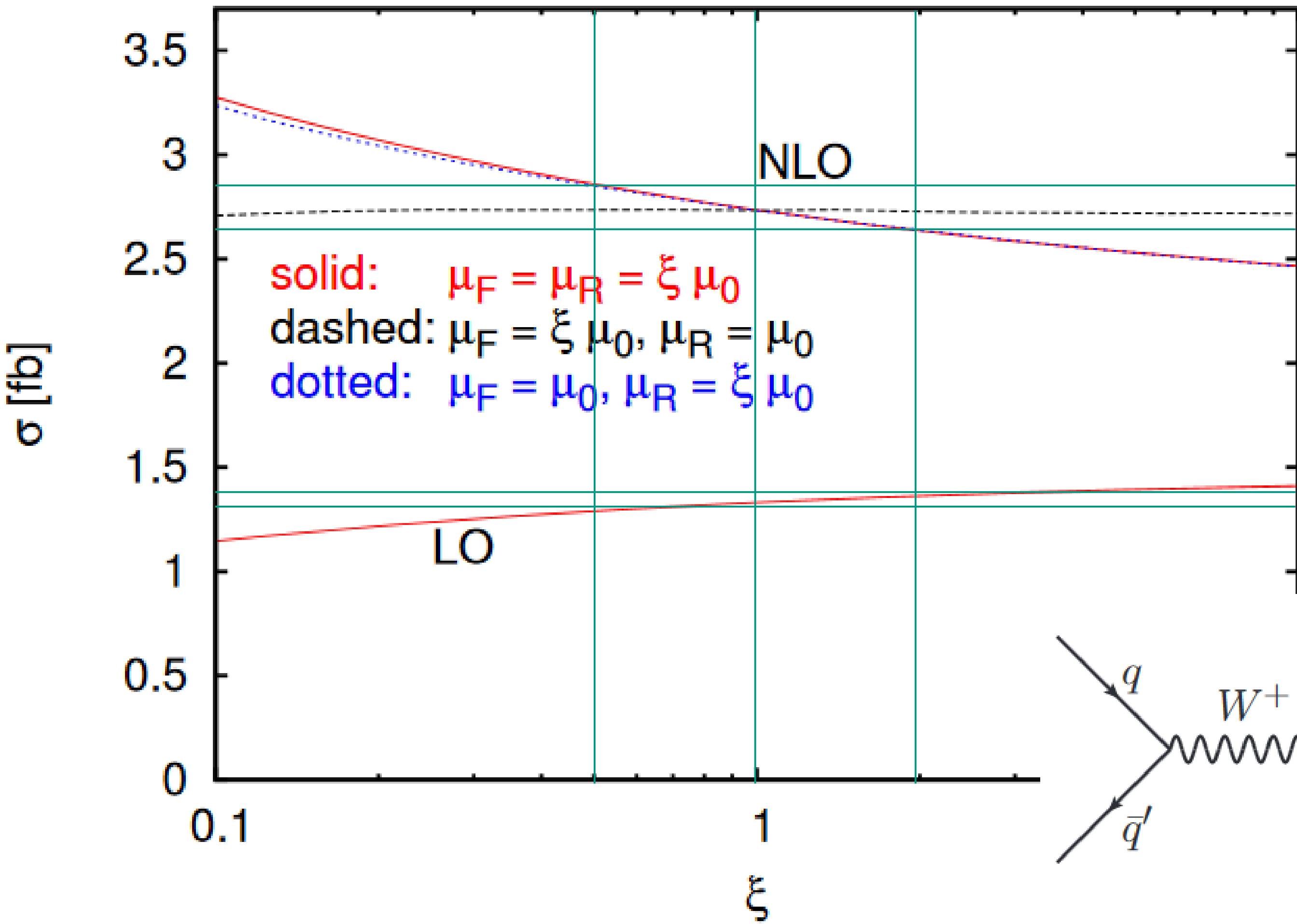
Theory (scale) uncertainty at NLO

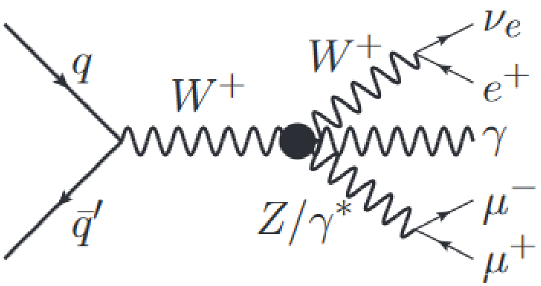
WZγ Production



- No α_S at LO: Accidental LO small scale uncertainty
- NLO/LO>2: Is perturbation theory broken? $\alpha_S(m_{WZ\gamma}) \approx 0.1$

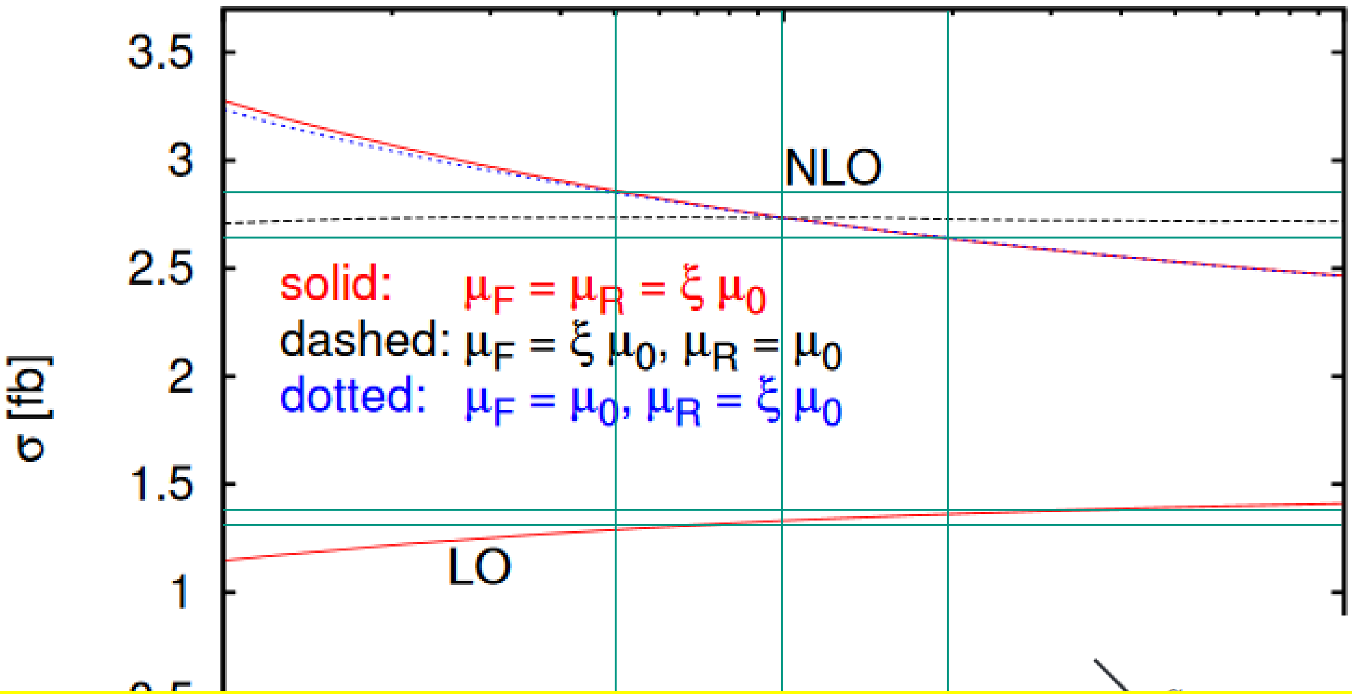
WZγ Production





- No α_s at LO: Accidental LO small scale uncertanties
- NLO/LO>2: Is perturbation theory broken? $\alpha_s(m_{WZ\gamma})\approx 0.1$

WZγ Production



CAUTION at LHC:

Scale Uncertanty: Theoretical error estimate of missing higher order corrections
Depends on the process, selection cuts…

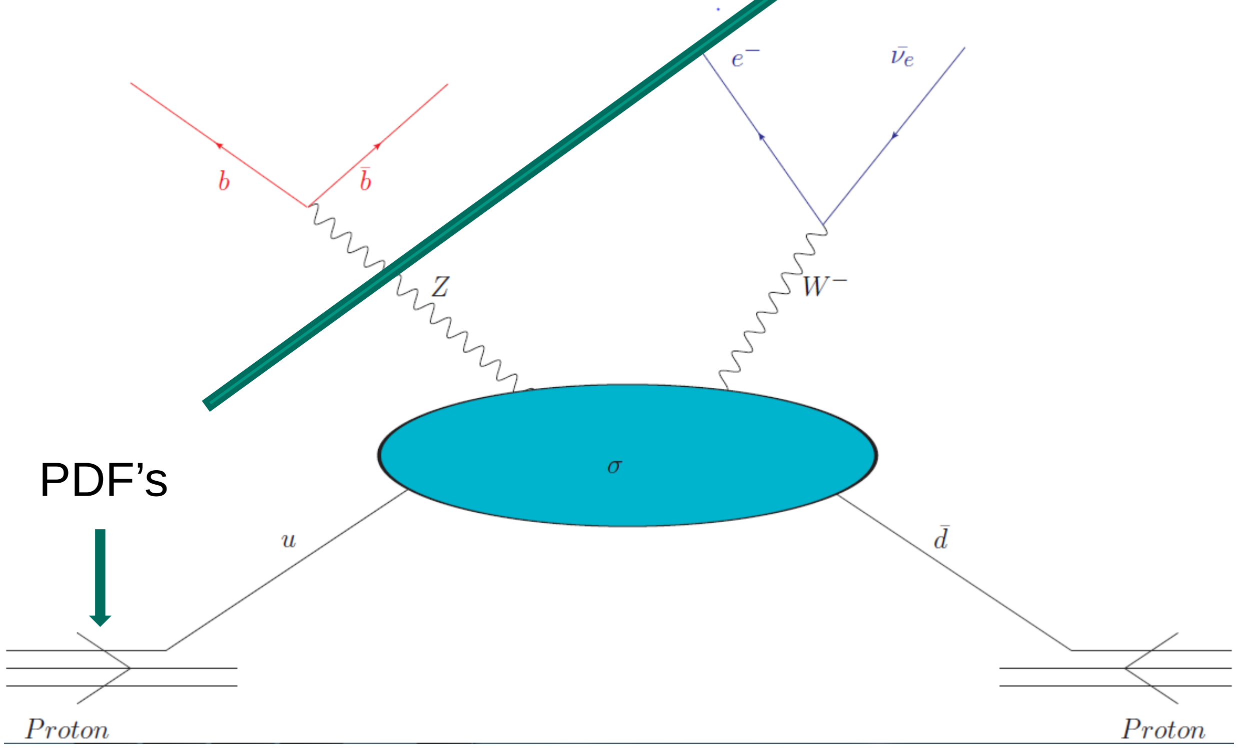
- No α_S at LO: Accidental LO small scale uncertanties
- NLO/LO>2: Is perturbation theory broken? $\alpha_S(m_{WZ\gamma}) \approx 0.1$

Cross Section at Hadron Colliders

$$\sigma(H_1\, H_2 \to X) = \sum_{a,b,\tilde{X}} \int_0^1 \mathrm{d}x_a\, \mathrm{d}x_b\, f_{a/H_1}(x_a, \mu_F^2)\, f_{b/H_2}(x_b, \mu_F^2)$$

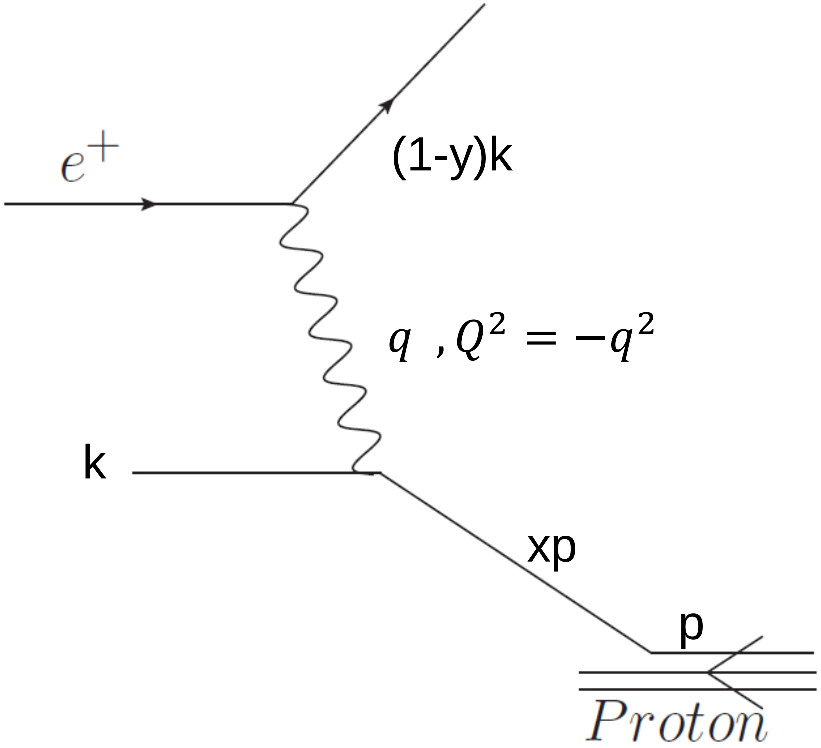
$$\times\ \sigma_{ab}(ab \to \tilde{X}; \mu_F^2)\, \Theta\,(C(X))\, F(\tilde{X} \to X)$$

PDF's



Parton Distribution Functions

DIS: Deep Inelastic Scattering



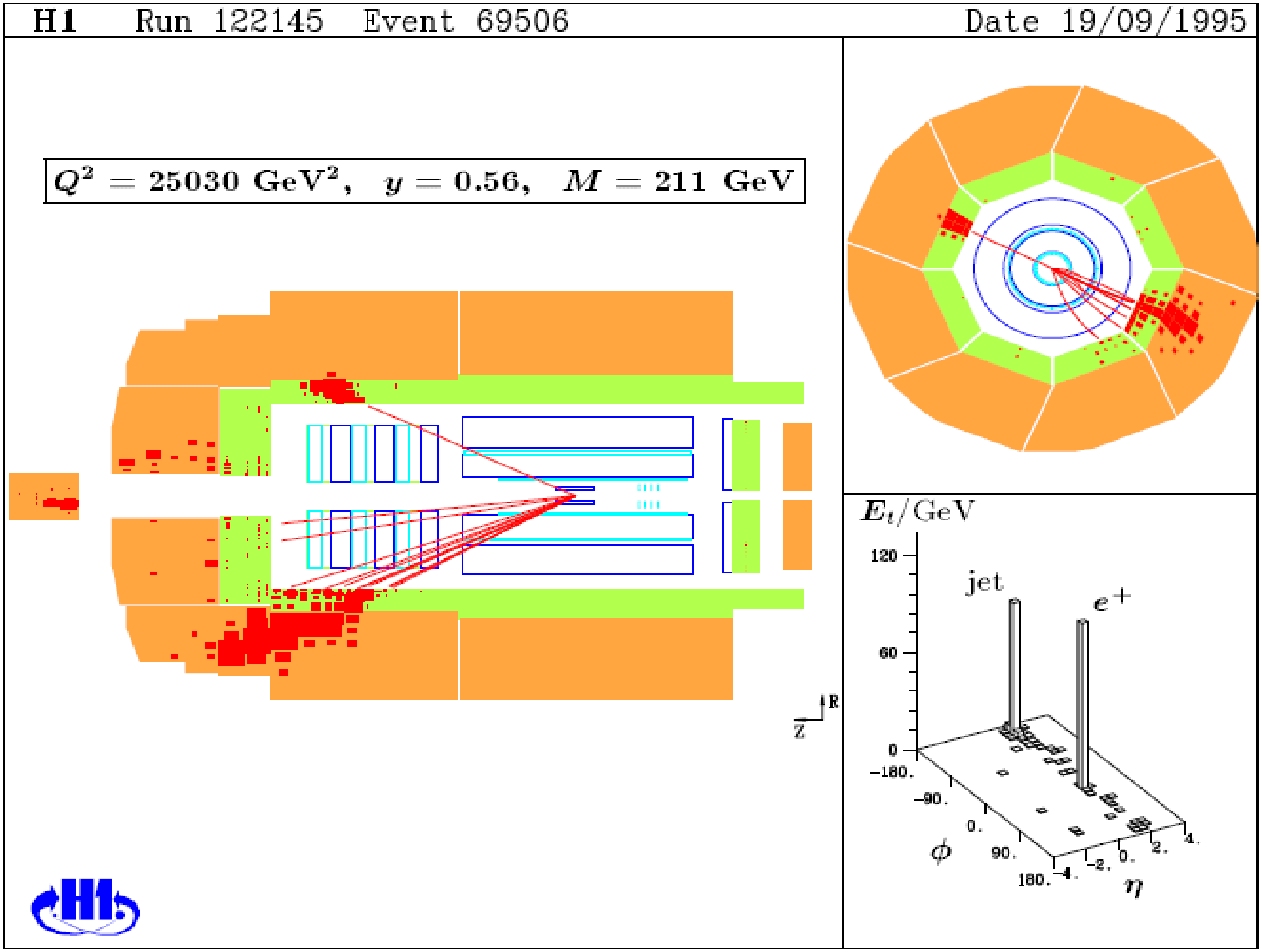
- Kinematic Relations:

$$y = \frac{p \cdot q}{p \cdot k} \qquad x = \frac{Q^2}{2\, p \cdot q} \qquad M = \sqrt{xs}$$

$$Q^2 = xys$$

- Q: photon virtuality
  - transverse resolution at which it probes proton structure
- x: longitudinal momentum fraction of parton
- y: momentum fraction lost by electron (in proton rest frame)

DIS



H1 Run 122145 Event 69506
Date 19/09/1995
$Q^2 = 25030$ GeV^2, $y = 0.56$, $M = 211$ GeV
R
Z
E_t/GeV
120
60
0
jet
e^+
−180.
−90.
0.
90.
180.
ϕ
−4.
−2.
0.
2.
4.
η

DIS

Structure Function

$$\frac{d^2\sigma^{\mathrm{em}}}{dx\,dQ^2} \approx \frac{4\pi\alpha^2}{xQ^4}\left(\frac{1+(1-y)^2}{2}F_2^{\mathrm{em}} + O(\alpha)\right)$$

$$F_2^{\mathrm{em}} = x\left(\Sigma_i Q_i^2 q_i(x)\right) = x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x) + \ldots\right)$$

- $d(x), u(x)$: Parton Distribution Functions

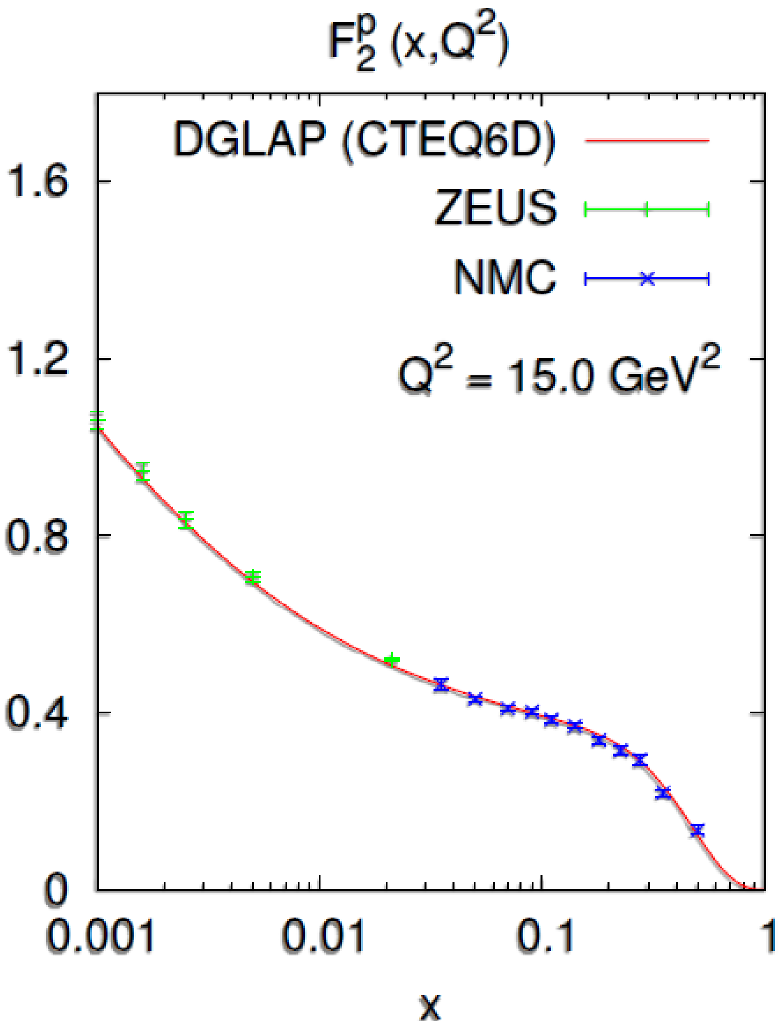
- Assuming SU(2) isospin symmetry:

neutron = proton with d $\Longleftrightarrow$ u

$$F_2^{\mathrm{p}} = x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x)\right) \qquad F_2^{\mathrm{n}} = x\left(\frac{4}{9}d(x) + \frac{1}{9}u(x)\right)$$

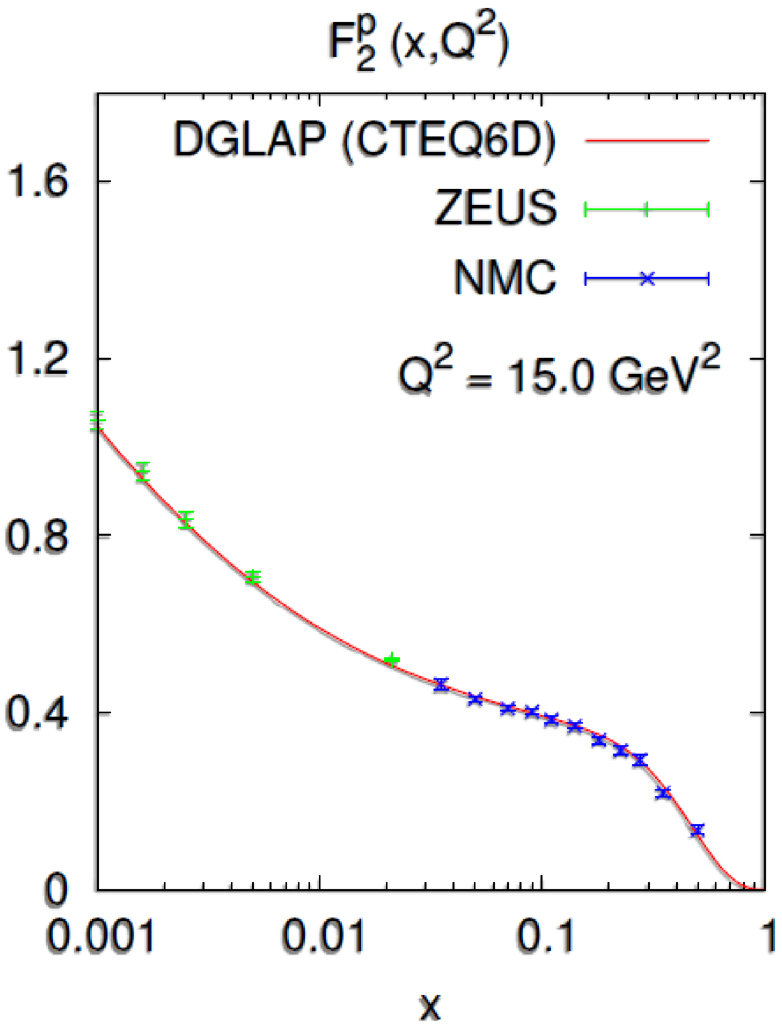
$$F_2^{\mathrm{p,n}} \longrightarrow d(x), u(x)$$

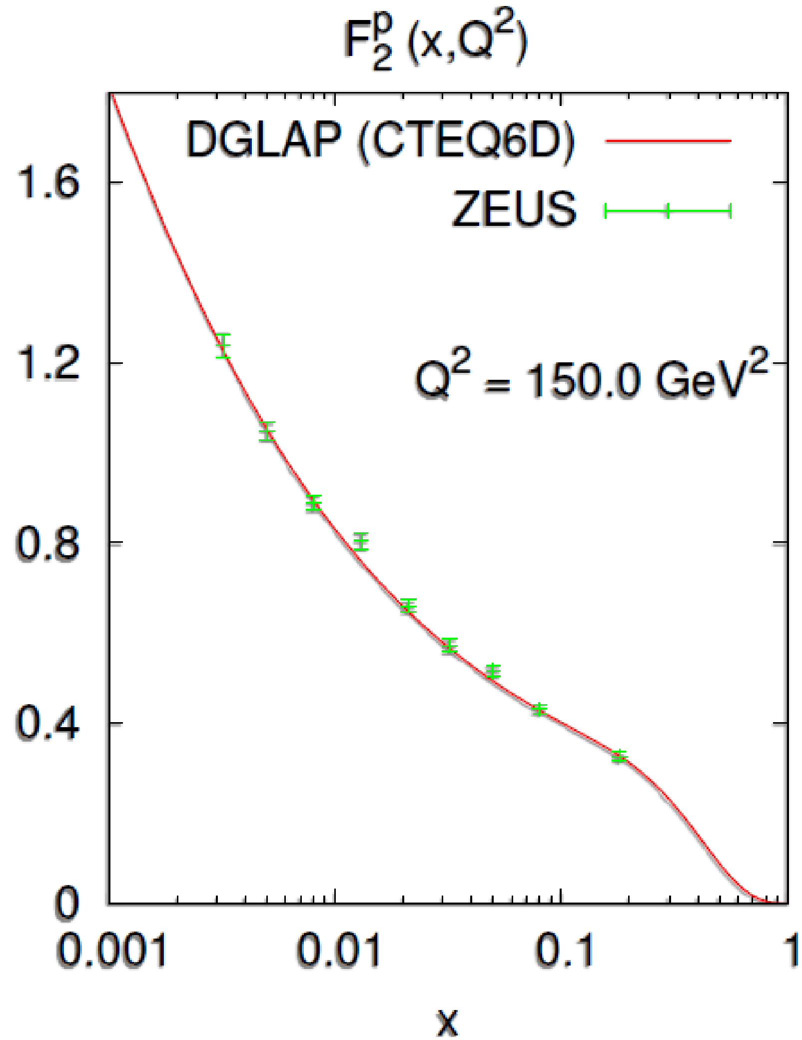
DIS and DGLAP



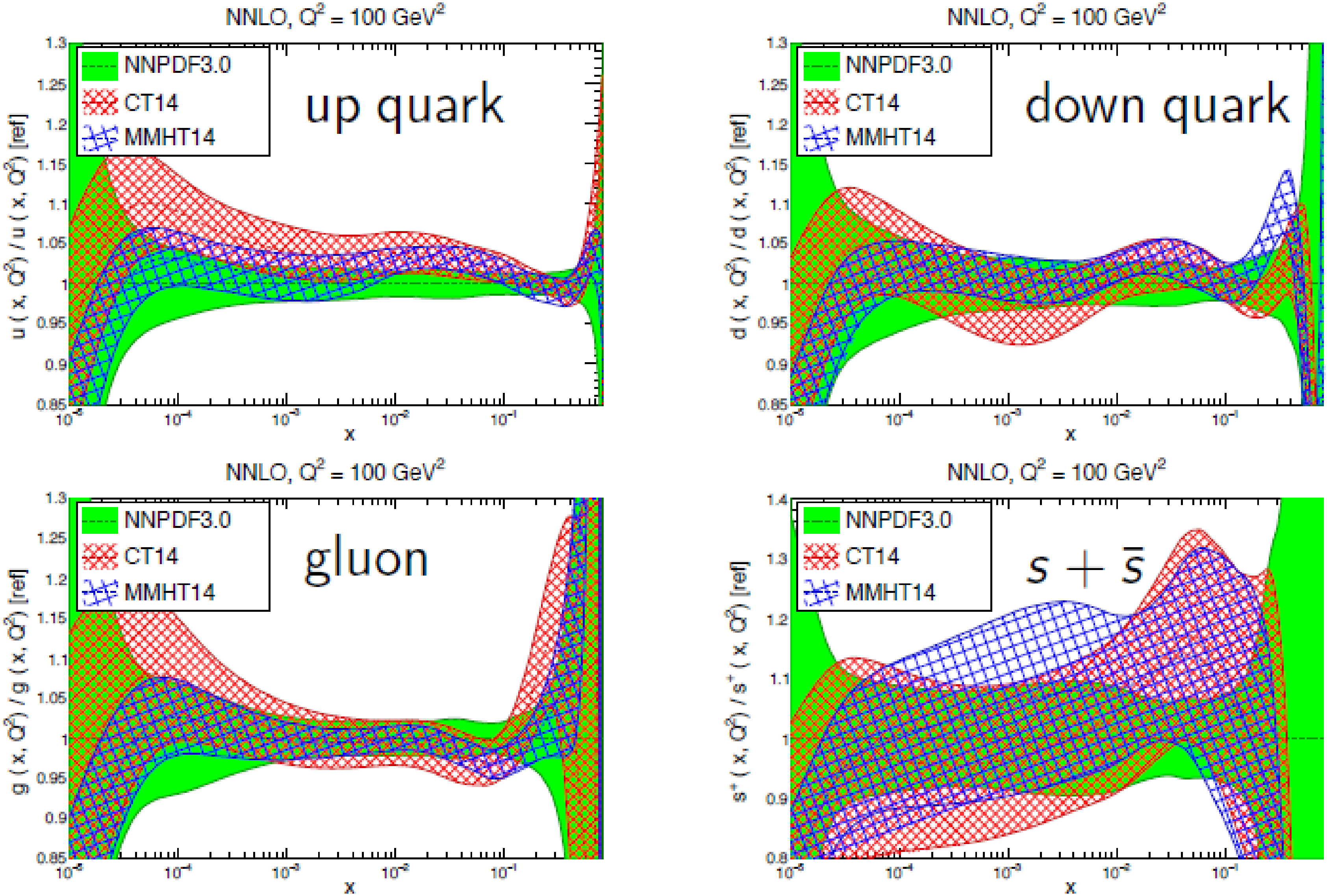
- Parton distributions run:
  - Dokshitzer-Gribov-Lipatov-Alterelli-Parisi (DGLAP)
  - $$\frac{d\,q(x,\mu^2)}{d\ln\mu^2} = \frac{\alpha_s}{2\pi}\int_x^1 dz\, K_{qq}(z)\,\frac{q(x/z,\mu^2)}{z}$$
  - $K_{qq}(z)$: Splitting kernel
    - $K_{qq}(z) = C_F \frac{1+z^2}{1-z}$

DIS and DGLAP

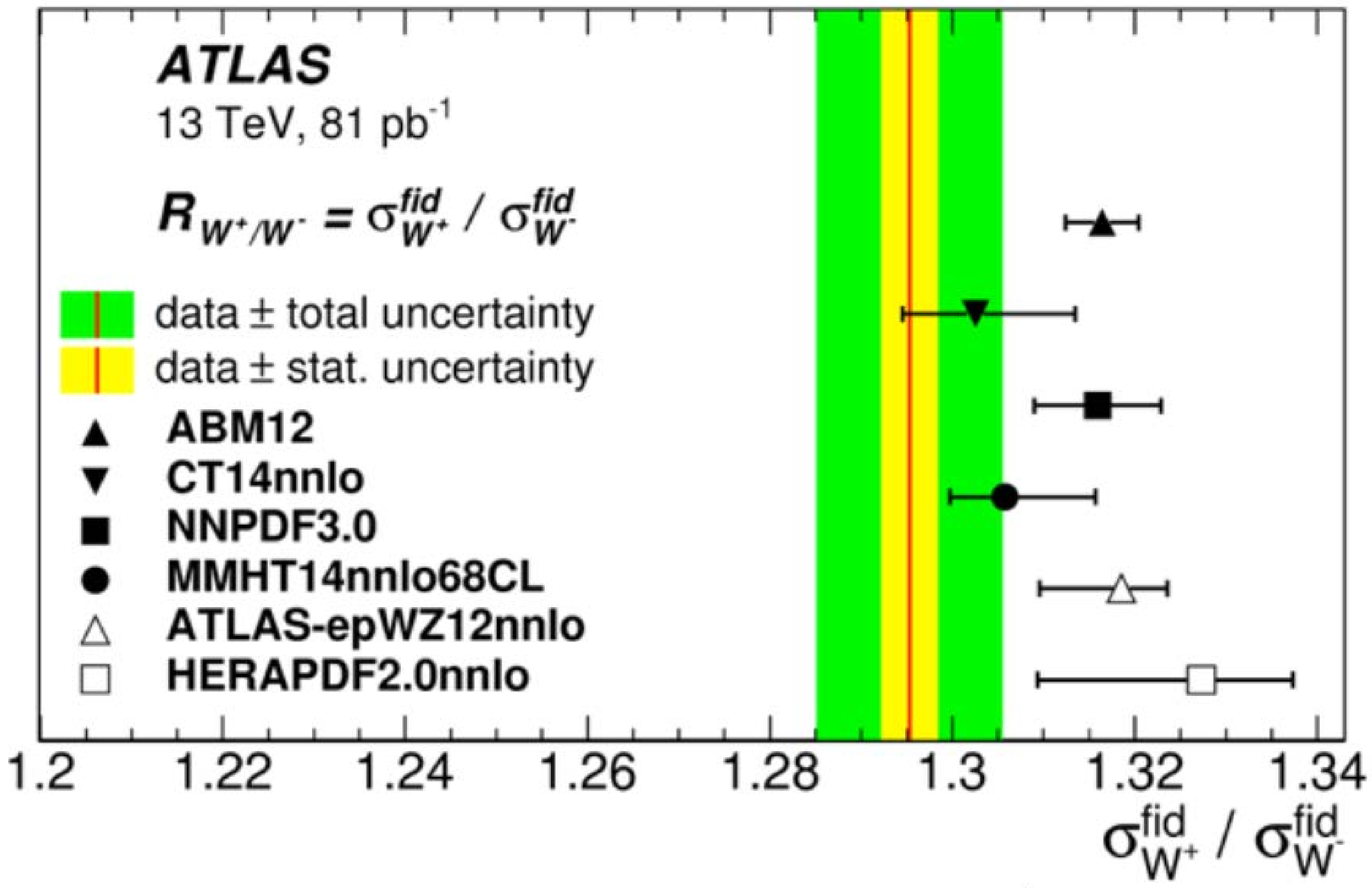




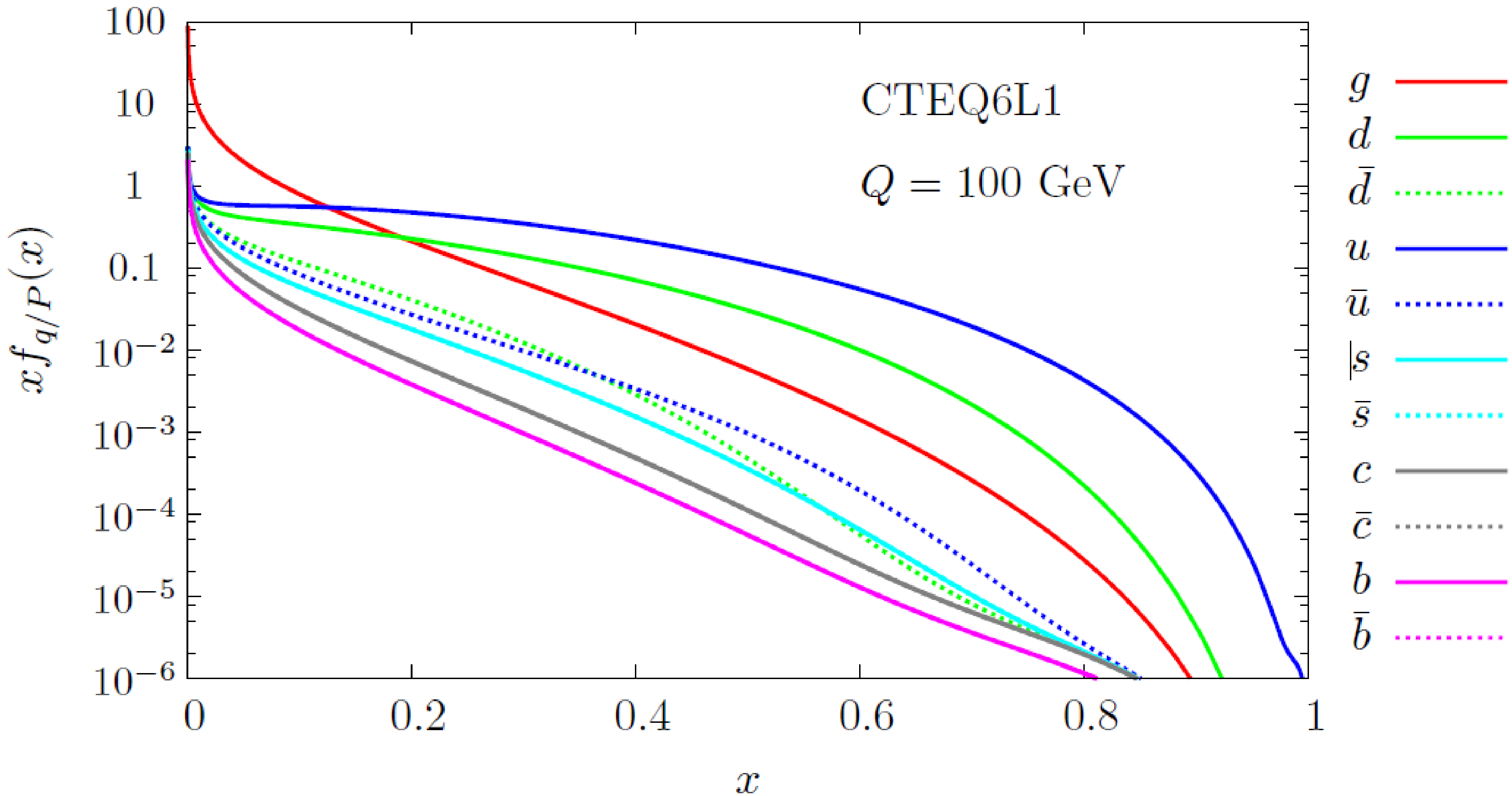
PDF's sets (ABM not shown)



Sensitivity of LHC to PDF's



PDF's overview



- Large gluon pdf's at small x: Phenomenological consequences

LHC → gluon machine

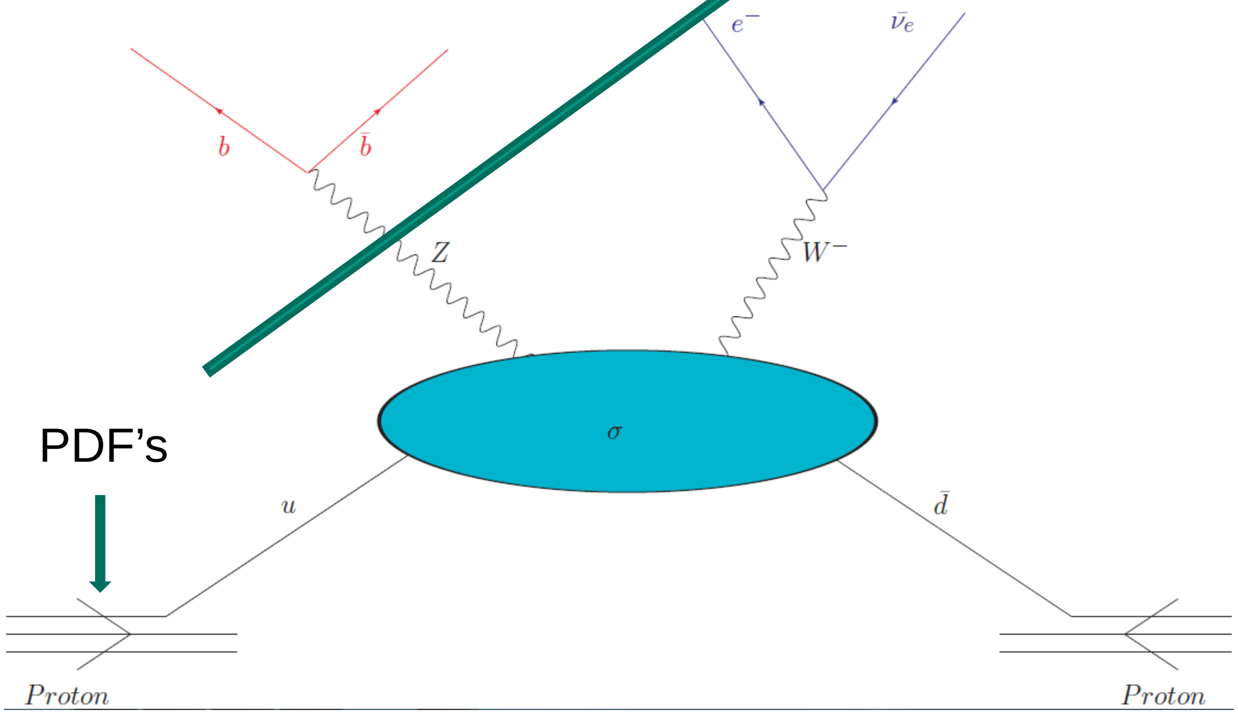
HARD PROCESS

Cross Section at Hadron Colliders

$$\sigma(H_1 H_2 \to X) = \sum_{a,b,\tilde{X}} \int_0^1 \mathrm{d}x_a\, \mathrm{d}x_b\, f_{a/H_1}(x_a, \mu_F^2)\, f_{b/H_2}(x_b, \mu_F^2)$$

$$\times\ \sigma_{ab}(ab \to \tilde{X}; \mu_F^2)\, \Theta(C(X))\, F(\tilde{X} \to X)$$

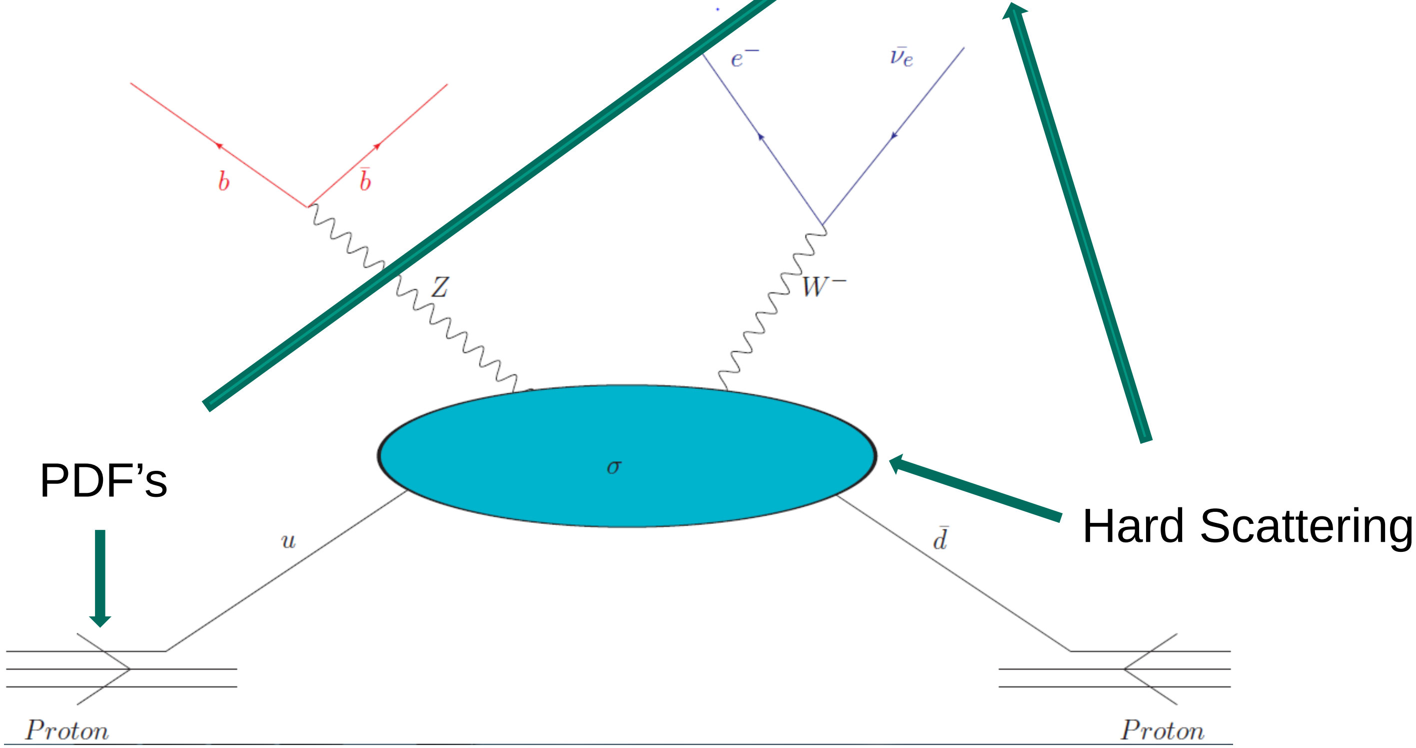
PDF's



Cross Section at Hadron Colliders

$$\sigma(H_1\,H_2 \to X) = \sum_{a,b,\tilde{X}} \int_0^1 \mathrm{d}x_a\,\mathrm{d}x_b\, f_{a/H_1}(x_a,\mu_\mathrm{F}^2)\, f_{b/H_2}(x_b,\mu_\mathrm{F}^2)$$

$$\mathrm{x}\;\; \sigma_{ab}(ab \to \tilde{X};\mu_\mathrm{F}^2)\,\Theta\,(C(X))\,F(\tilde{X}\to X)$$

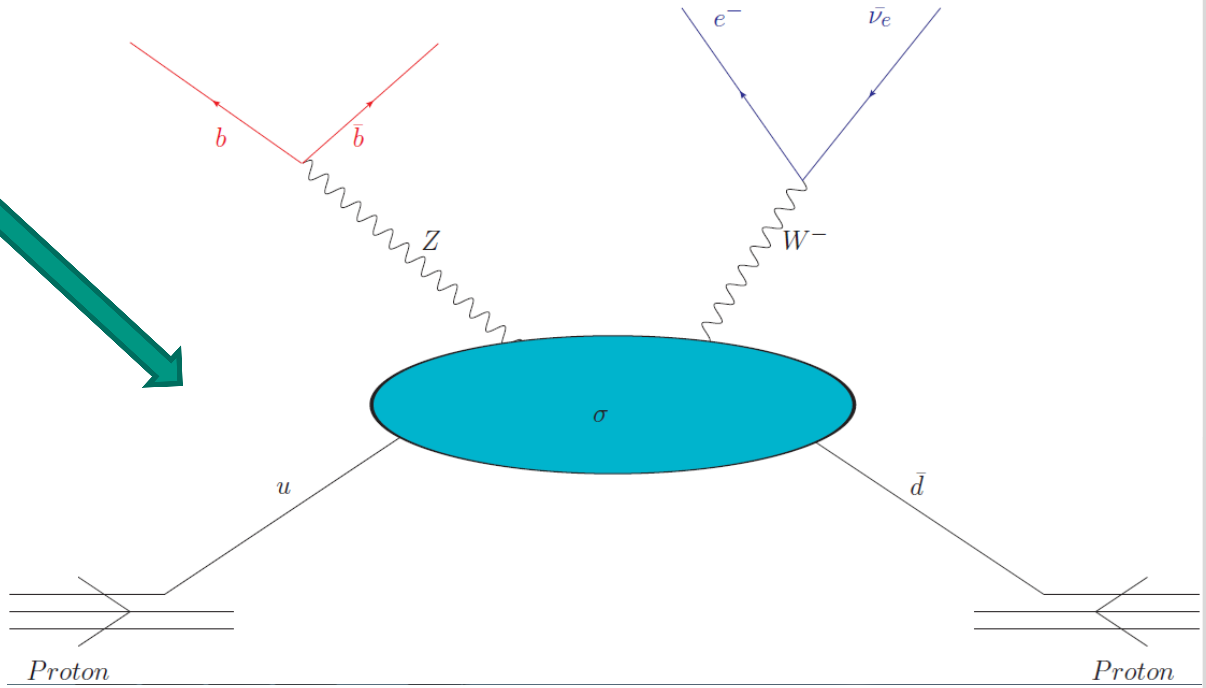


Cross Section at Hadron Colliders

$$\sigma = \sum_{m,n} \alpha_s^m(\mu_R^2)\, \alpha^n(\mu_{R,EW}^2)\, \sigma_{m,n}(\mu_R^2, \mu_F^2)$$

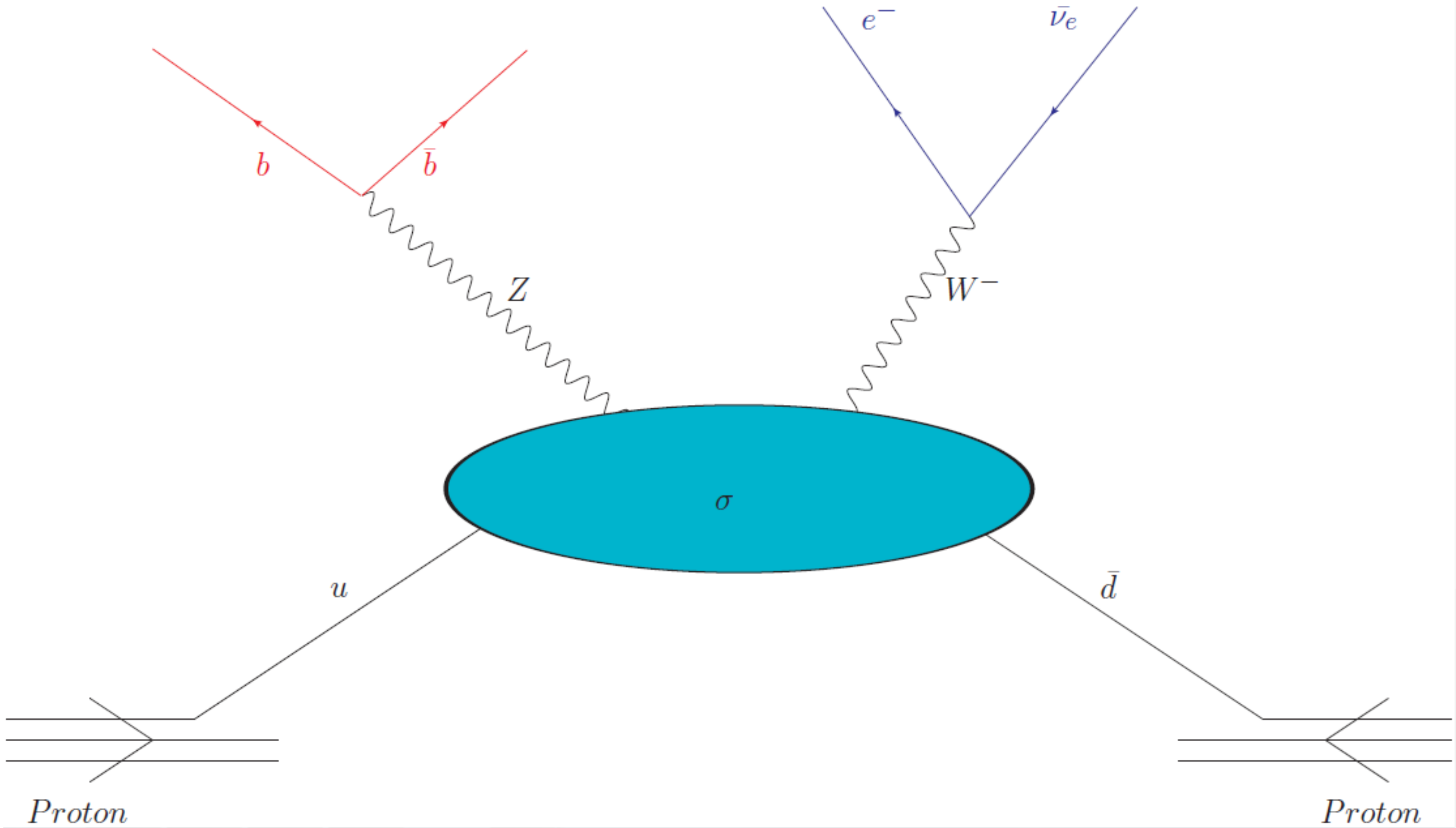
$$\sigma = \sigma^{LO} + \sigma^{NLO}_{QCD} + \sigma^{NLO}_{EW} + \sigma^{NNLO}_{QCD}$$

Leading Order



LO Cross Section

$$\sigma^{LO} = \sum_{a,b} \int_0^1 \mathrm{d}x_a \, \mathrm{d}x_b \, f_a^{LO}(x_a, \mu_F^2) \, f_b^{LO}(x_b, \mu_F^2) \, \sigma_{ab}^B$$



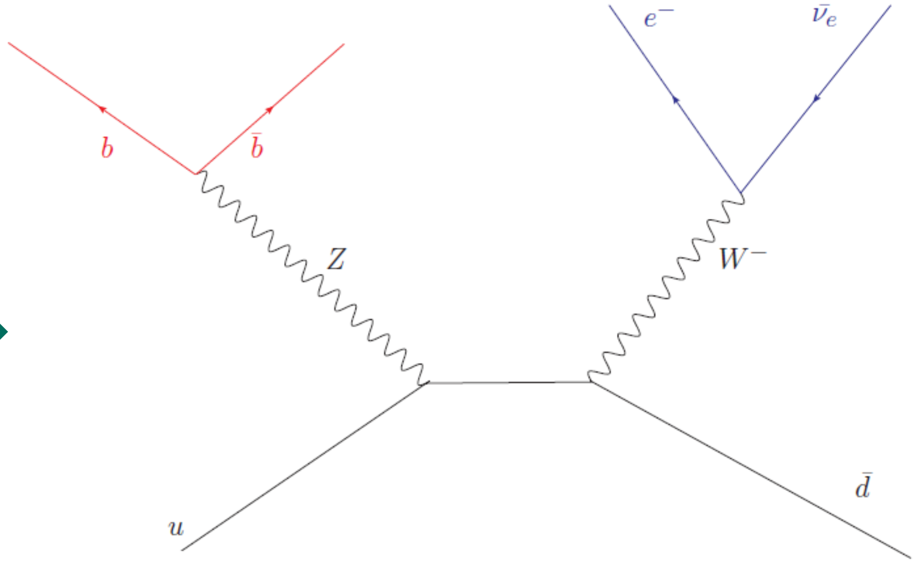
LO Cross Section

$$\sigma^{LO} = \sum_{a,b} \int_0^1 \mathrm{d}x_a\, \mathrm{d}x_b\, f_a^{LO}(x_a, \mu_\mathrm{F}^2)\, f_b^{LO}(x_b, \mu_\mathrm{F}^2)\, \sigma_{ab}^B$$

$$\sigma_{ab}^B = \frac{1}{4 p_a p_b} \sum_{\{f_n\}} \int \mathrm{d}\Phi_{2\to n} |\mathcal{M}_B|^2$$

Phase Space integration

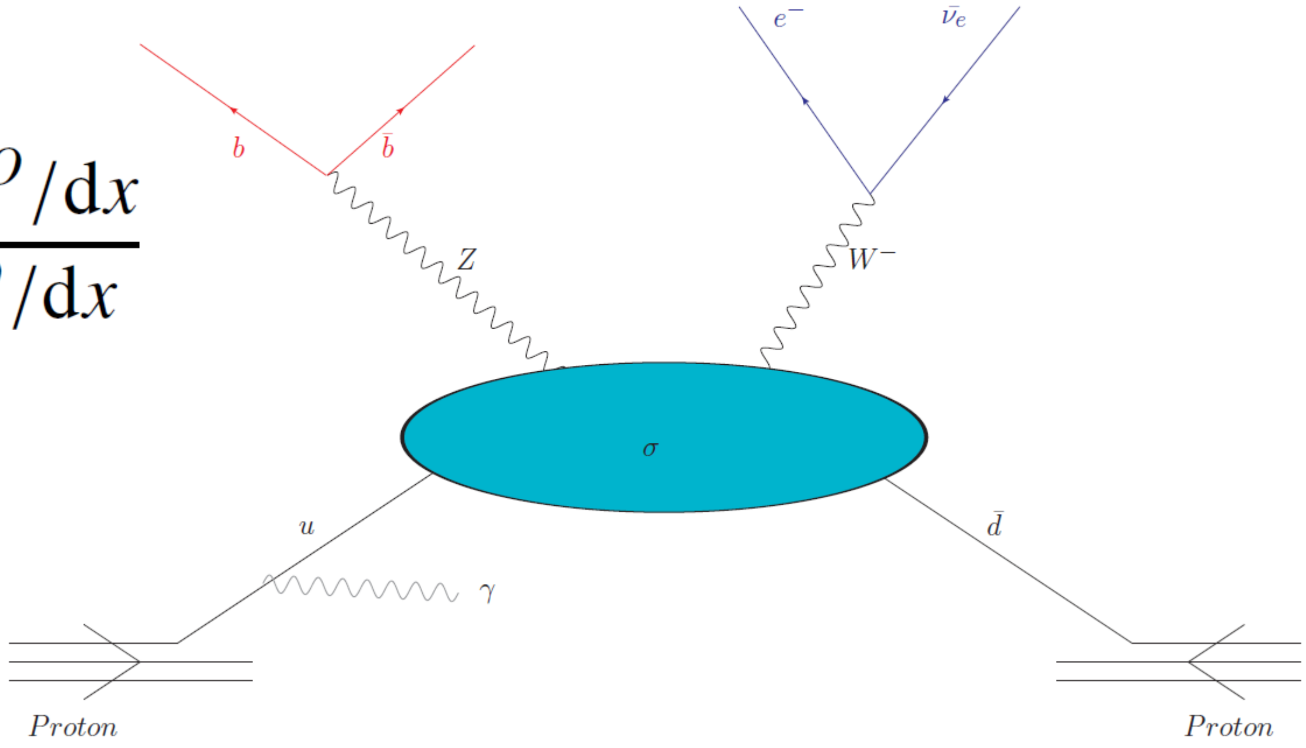
$$\mathcal{M}_B$$



NLO Cross Section

$$\sigma^{NLO} = \sum_{a,b} \int_0^1 \mathrm{d}x_a \, \mathrm{d}x_b \, f_a^{NLO}(x_a, \mu_\mathrm{F}^2) \, f_b^{NLO}(x_b, \mu_\mathrm{F}^2) \left[\sigma^B + \sigma^{\mathrm{NLO}}\right]_{ab}$$

$$K_{\mathrm{EW,LO}} = \frac{\mathrm{d}\sigma^{NLO}/\mathrm{d}x}{\mathrm{d}\sigma^{LO}/\mathrm{d}x}$$

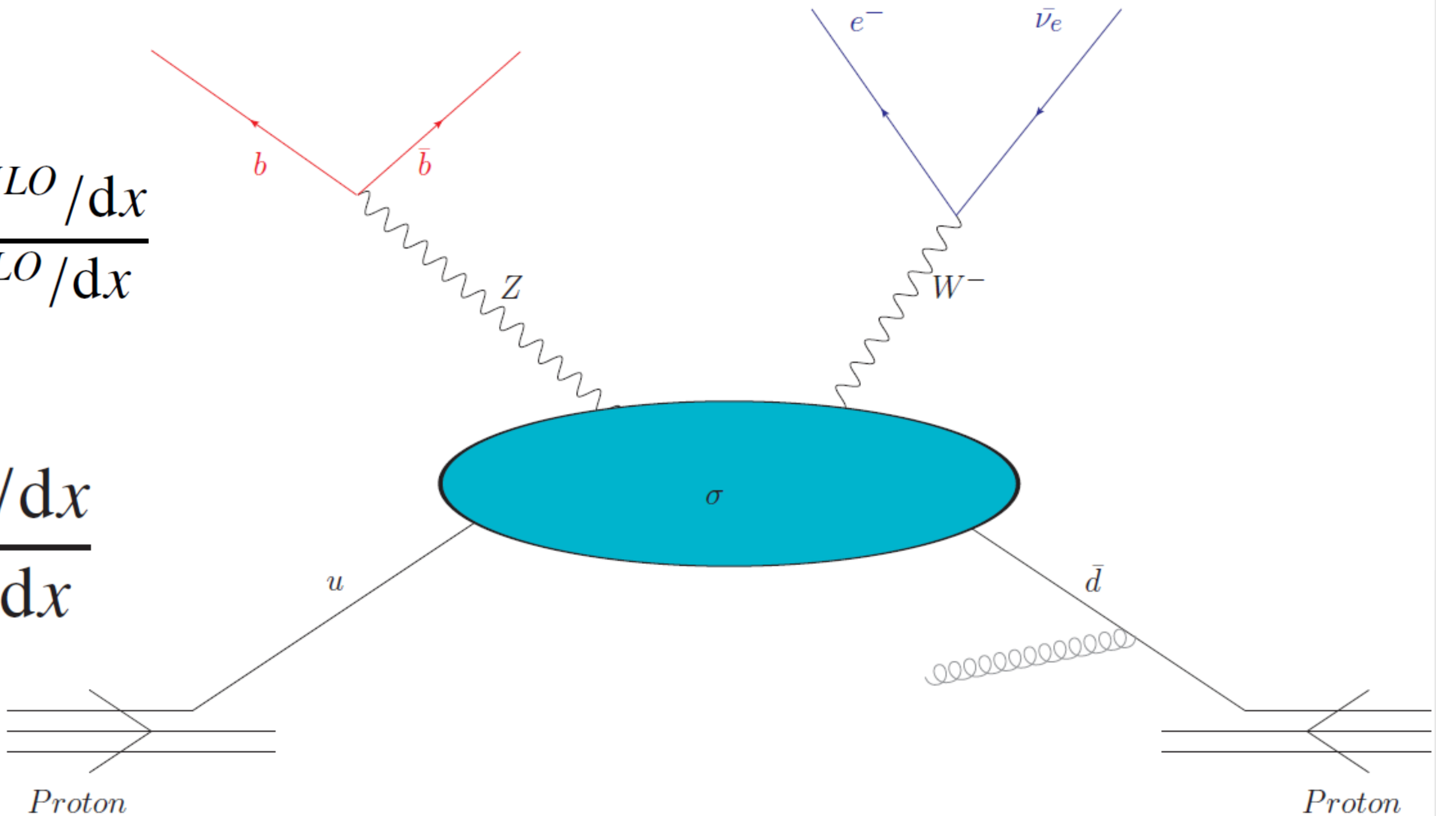


NLO Cross Section

$$\sigma^{NLO} = \sum_{a,b} \int_0^1 \mathrm{d}x_a \, \mathrm{d}x_b \, f_a^{NLO}(x_a, \mu_\mathrm{F}^2) \, f_b^{NLO}(x_b, \mu_\mathrm{F}^2) \left[\sigma^B + \sigma^{\mathrm{NLO}}\right]_{ab}$$

$$K_{\mathrm{QCD,LO}} = \frac{\mathrm{d}\sigma^{NLO}/\mathrm{d}x}{\mathrm{d}\sigma^{LO}/\mathrm{d}x}$$

$$K = \frac{\mathrm{d}\sigma^{NLO}/\mathrm{d}x}{\mathrm{d}\sigma^{LO}/\mathrm{d}x}$$

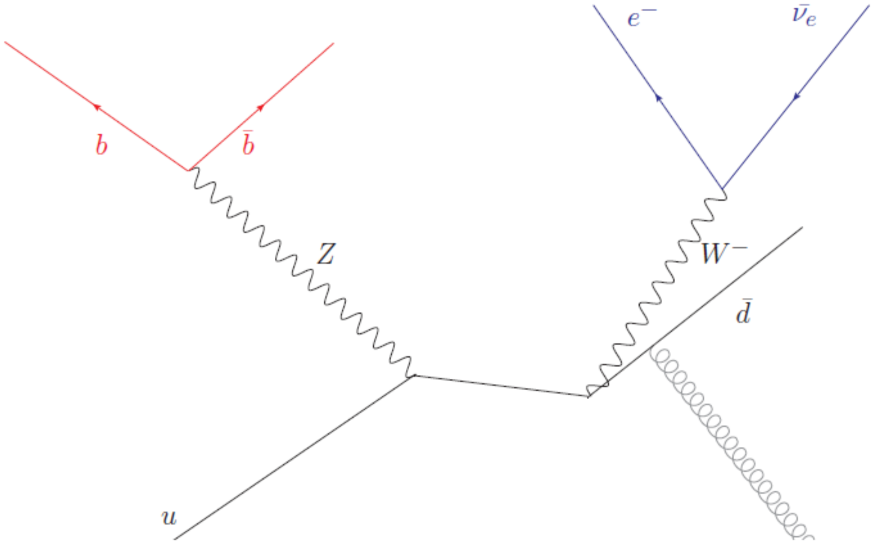


Details of NLO Calculation

$$\sigma_{ab}^{NLO} = \int_n d\sigma^V + \int_{n+1} d\sigma^R + \int_n d\sigma^C$$

$$\sigma^R = \frac{1}{4 p_a p_b} \sum_{\{f_{n+1}\}} \int d\Phi_{2\to n+1} |\mathcal{M}_{RE}|^2$$

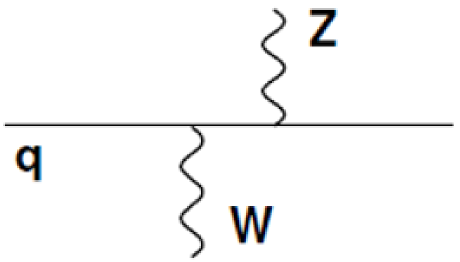
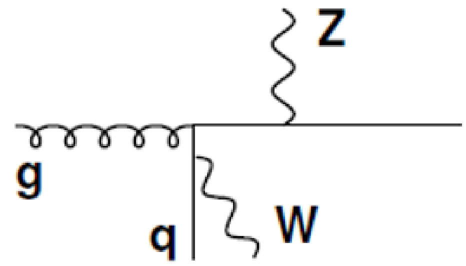
$\mathcal{M}_{RE}$ ⟶



- Initial state gluon

Implications ⟶

NLO effects

LO	NLO QCD (WZ+j at LO)
	

- Subprocesses:

$$q\bar{q}$$

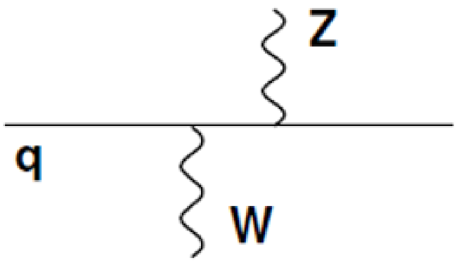
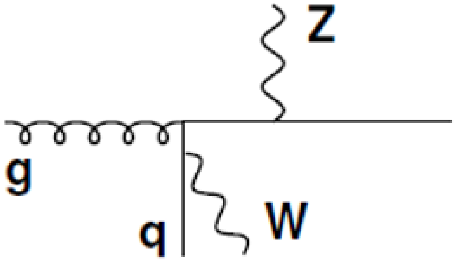
- New Subprocesses: LO

$$qg,\bar{q}g$$

- Large corrections due to gluon PDF's

$$\frac{f_g(x_a,\mu_{\mathrm{F}}^2)}{f_{\bar{q}}(x_b,\mu_{\mathrm{F}}^2)} \approx 10 \Longrightarrow \alpha_s \frac{f_g(x_a,\mu_{\mathrm{F}}^2)}{f_{\bar{q}}(x_b,\mu_{\mathrm{F}}^2)} \approx 1$$

NLO effects

LO	NLO QCD (WZ+j at LO)
	

$$\alpha_s \ln^2 \frac{p_T}{M_W}$$

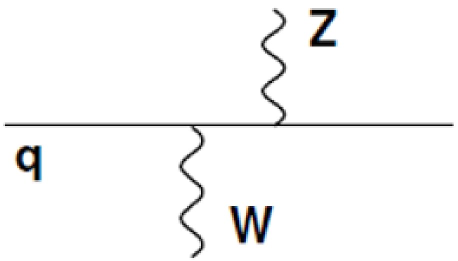
- Back to back topologies
- Soft and Collinear W Radiation

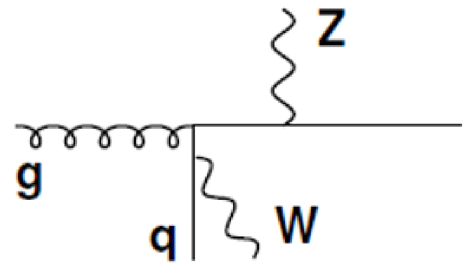
- Large corrections:

$$p_T = 1000\,\mathrm{GeV} \quad \Rightarrow \quad \alpha_s \ln^2 \frac{p_T}{M_W} \approx 0.7$$

NLO effects

LO	NLO QCD (WZ+j at LO)





- Subprocesses:

$$q\bar{q}$$

- New Subprocesses: LO

$$qg, \bar{q}g$$

- Total effect

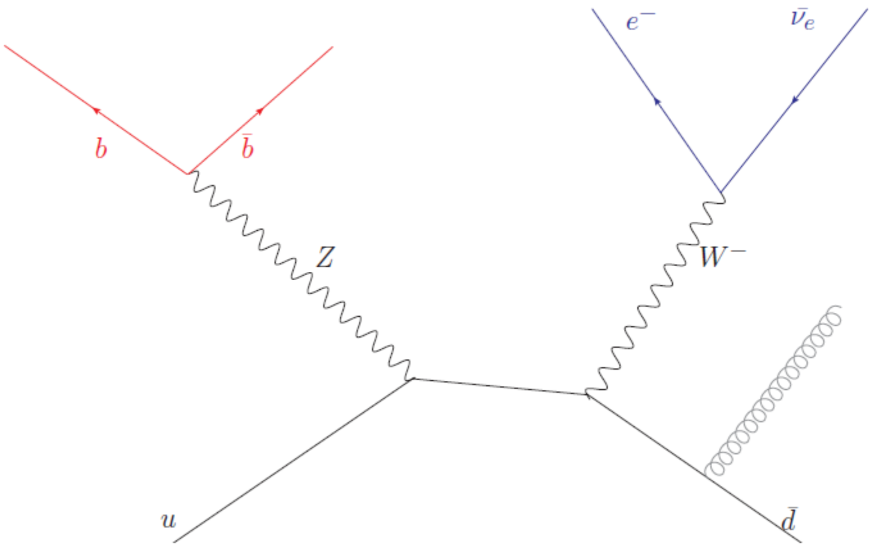
$$p_T = 1000\,\text{GeV} \Longrightarrow \frac{f_g(x_a, \mu_F^2)}{f_{\bar{q}}(x_b, \mu_F^2)} \alpha_s \ln^2 \frac{p_T}{M_W} \approx 7$$

Details of NLO calculation

$$\sigma_{ab}^{NLO} = \int_n d\sigma^V + \int_{n+1} d\sigma^R + \int_n d\sigma^C$$

$$\sigma^R = \frac{1}{4 p_a p_b} \sum_{\{f_{n+1}\}} \int d\Phi_{2\to n+1} |\mathcal{M}_{RE}|^2$$

$\mathcal{M}_{RE}$ $\Longrightarrow$

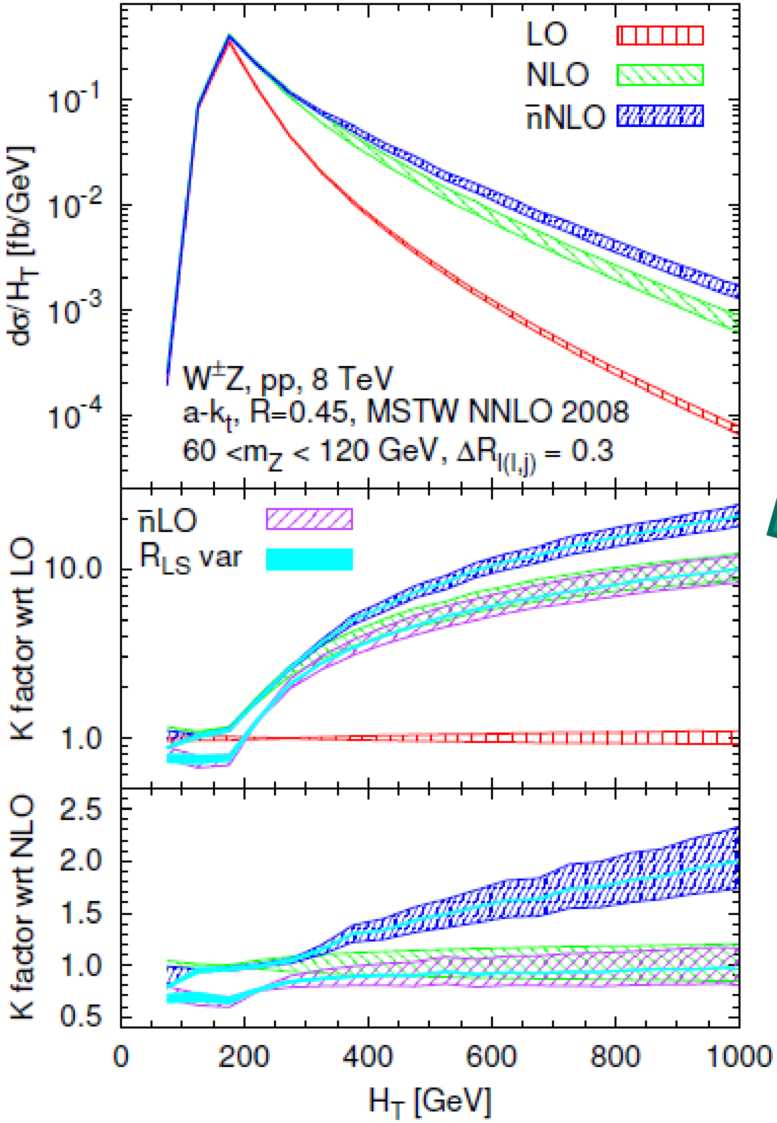


- Final state gluon:

  same initial partons $\Longrightarrow$ "only" $\alpha_s \ln^2 \frac{p_T}{M_W} \sigma^{LO}$

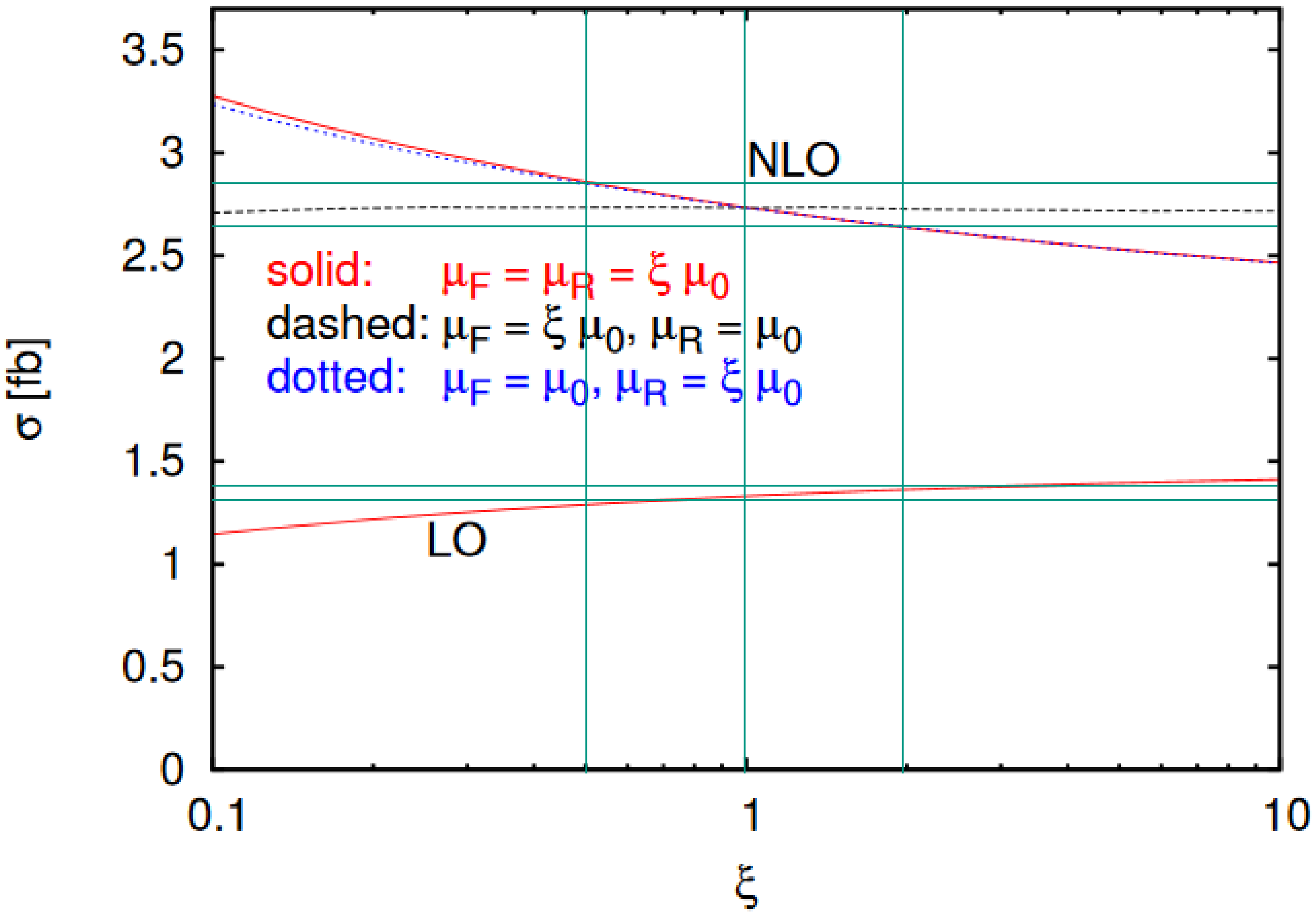
Relevant NLO effects

[FC,Sapeta,20012]



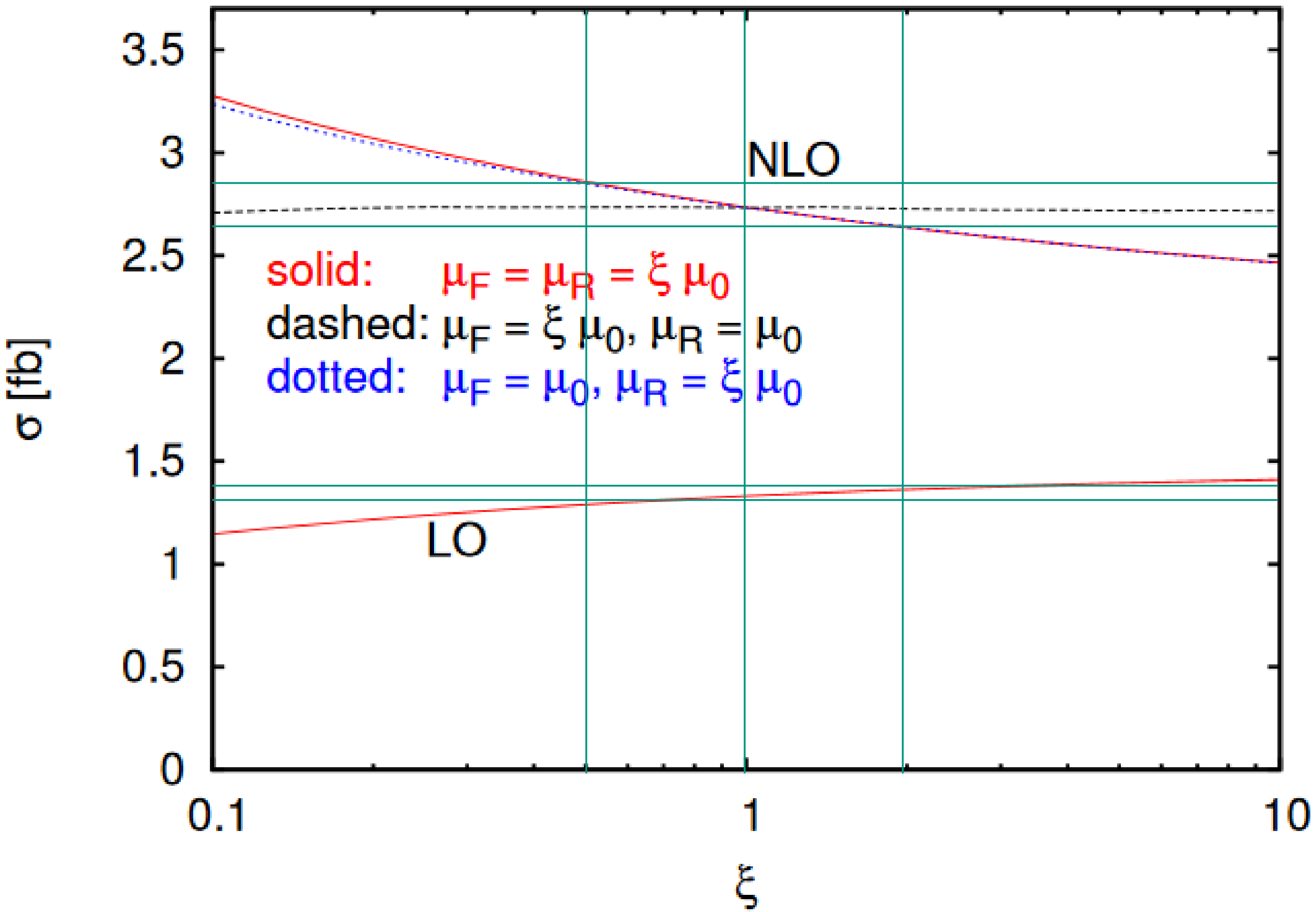
$$\frac{f_g(x_a,\mu_F^2)}{f_{\bar{q}}(x_b,\mu_F^2)}\alpha_s \ln^2 \frac{p_T}{M_W}\; \sigma^{LO}$$

WZγ Production



- NLO/LO>2: Is perturbation theory broken? $\alpha_S(m_{WZ\gamma}) \approx 0.1$

WZγ Production

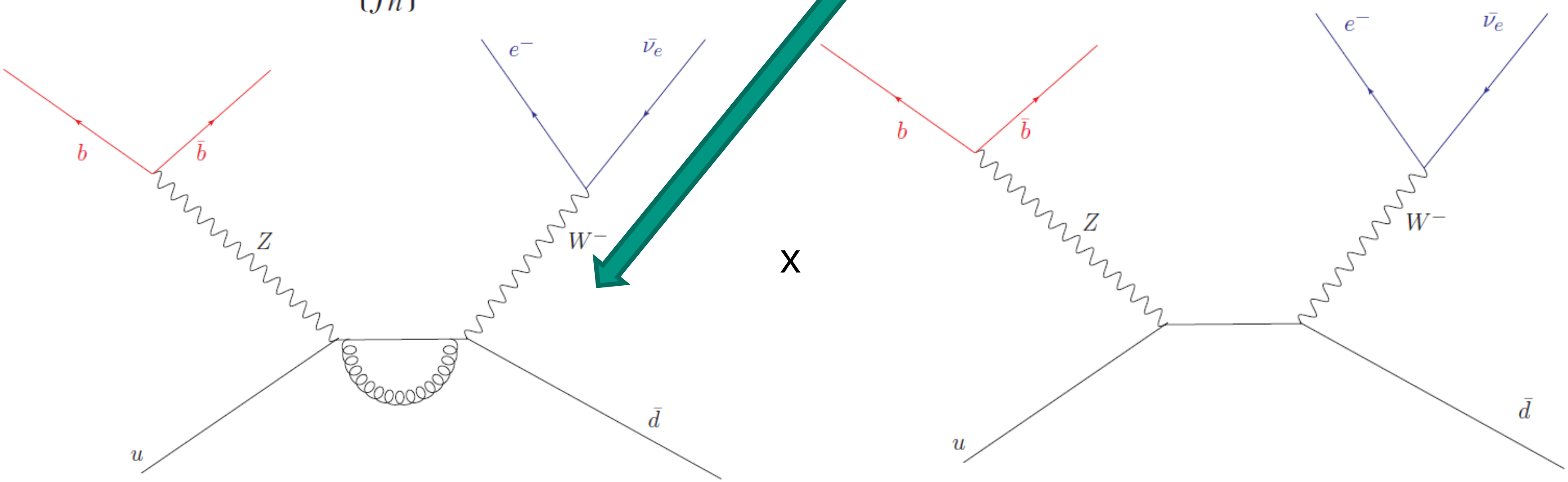


- NLO/LO>2
  - New gluon initiated processes + new kinematic topologies

Details of NLO calculation

$$\sigma_{ab}^{NLO} = \int_n d\sigma^V + \int_{n+1} d\sigma^R + \int_n d\sigma^C$$

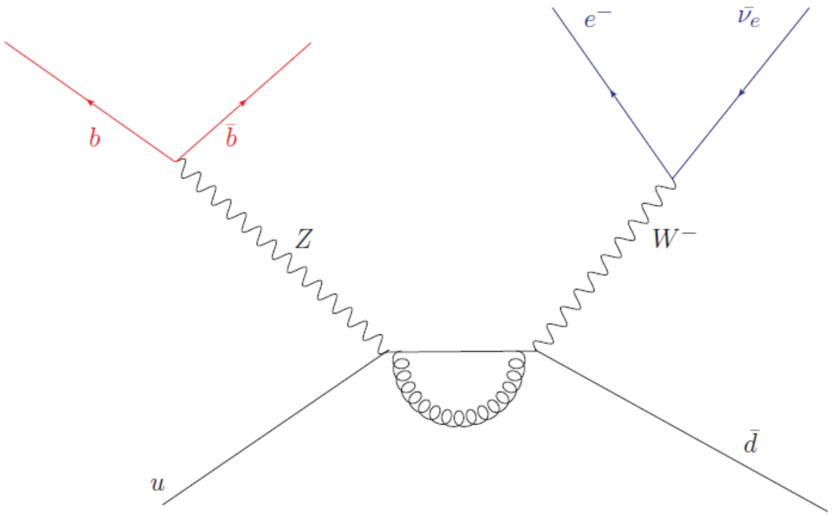
$$\sigma^V = \frac{1}{4 p_a p_b} \sum_{\{f_n\}} \int d\Phi_{2\to n}\, 2\,\mathrm{Re}\left(\mathcal{M}_V \mathcal{M}_B^*\right)$$



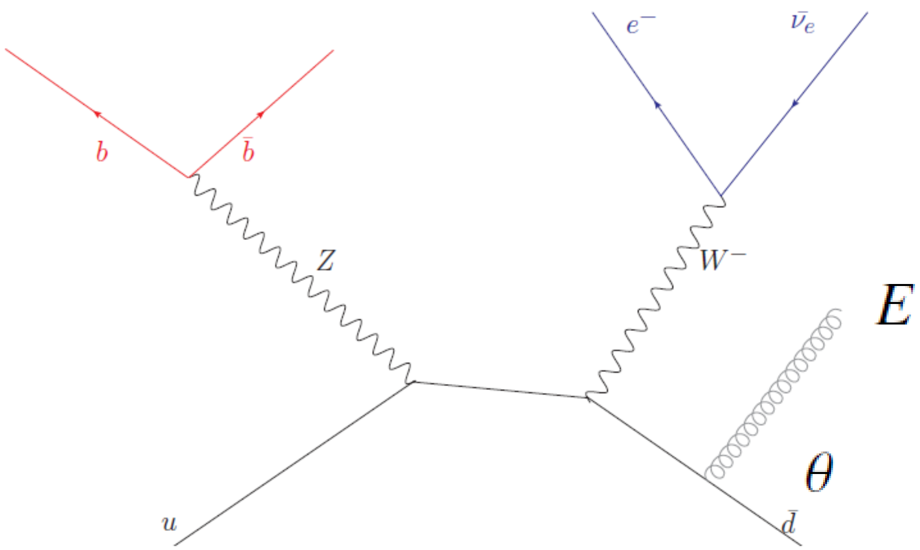
- Same initial partons and kinematics:

$\Rightarrow$ σ^V : Naturally suppressed $\Rightarrow$ $\approx \alpha_s \sigma^{LO}$

Cancellation of Divergences



$$-2\,C_F\,\frac{\alpha_s}{\pi}\,\frac{dE}{E}\,\frac{d\theta}{\theta}$$



$$+2\,C_F\,\frac{\alpha_s}{\pi}\,\frac{dE}{E}\,\frac{d\theta}{\theta}$$

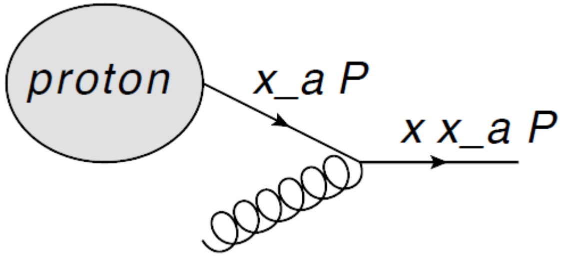
Details of NLO calculation

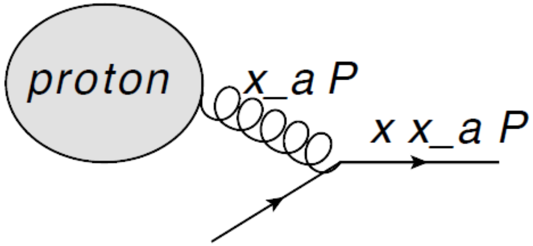
$$\sigma_{ab}^{NLO} = \int_n d\sigma^V + \int_{n+1} d\sigma^R + \int_n d\sigma^C$$

- Collinear counterterms: renormalize PDF's in $\overline{\mathrm{MS}}$

$$\mathrm{d}\sigma^{\mathrm{C}}_{ab}(p_a, p_b; \mu_F^2) = -\frac{\alpha_s}{2\pi}\frac{1}{\Gamma(1-\varepsilon)}\sum_{cd}\iint_0^1 \mathrm{d}z_a\,\mathrm{d}z_b\,\mathrm{d}\sigma^{\mathrm{B}}_{cd}(z_a p_a, z_b p_b)$$
$$\times\left\{\delta_{bd}\,\delta(1-z_b)\left[-\frac{1}{\varepsilon}\left(\frac{4\pi\mu^2}{\mu_F^2}\right)^{\varepsilon} P^{ac}(z_a)\right]\right.$$
$$\left. + \,\delta_{ac}\,\delta(1-z_a)\left[-\frac{1}{\varepsilon}\left(\frac{4\pi\mu^2}{\mu_F^2}\right)^{\varepsilon} P^{bd}(z_b)\right]\right\}$$

D = 4 – 2ε





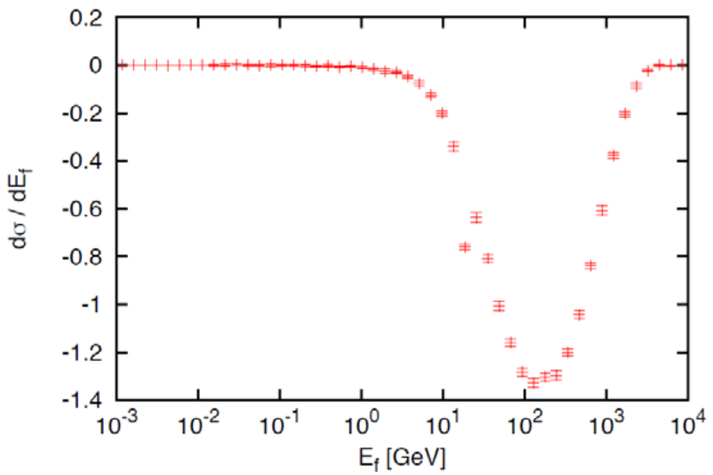
Dipole Substraction Method: [Catani,Seymour,1997]

$$\sigma_{ab}^{NLO} = \int_{n+1} \left(d\sigma^R\big|_{\varepsilon=0} - d\sigma^A\big|_{\varepsilon=0} \right) + \int_n \left(d\sigma^V + d\sigma^C + \int_1 d\sigma^A \right)_{\varepsilon=0}$$

- Add counterterm: $d\sigma^A$

$$d\sigma^A \xrightarrow[\text{region}]{\text{soft/coll.}} d\sigma^R$$

$$\int_{m+1} d\sigma^R - d\sigma^A$$



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$$\sigma_{ab}^{NLO} = \int_{n+1} \left(d\sigma^R\big|_{\varepsilon=0} - d\sigma^A\big|_{\varepsilon=0} \right) \quad + \int_n \left(d\sigma^V + d\sigma^C + \int_1 d\sigma^A \right)_{\varepsilon=0}$$

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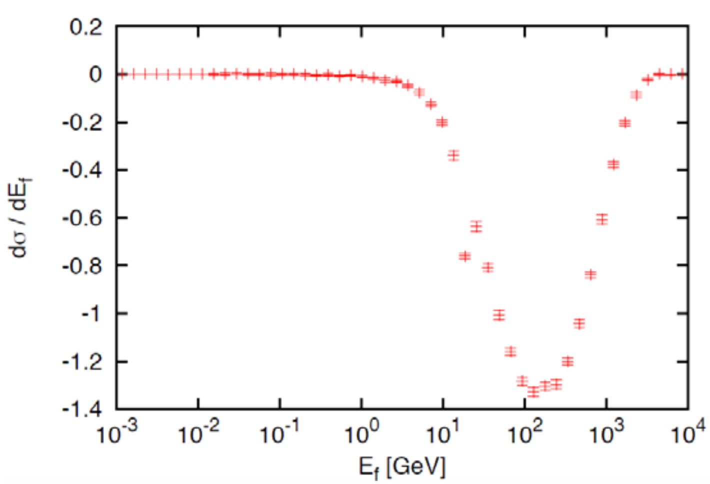


- Numerically Integrable D=4

Dipole Substraction Method: [Catani,Seymour,1997]

$$\sigma_{ab}^{NLO} = \int_{n+1} \left(\mathrm{d}\sigma^R\big|_{\varepsilon=0} - \mathrm{d}\sigma^A\big|_{\varepsilon=0} \right) + \int_n \left(\mathrm{d}\sigma^V + \mathrm{d}\sigma^C + \int_1 \mathrm{d}\sigma^A \right)_{\varepsilon=0}$$

- $\int_1 \mathrm{d}\sigma^A$: Analytically integrable

$$\int_{m+1} \mathrm{d}\sigma^{\mathrm{A}} + \int_m \sigma_m^{\mathrm{C}} = \int_m \left[\mathrm{d}\sigma^{\mathrm{B}} \otimes \boldsymbol{I}\right] + \int_0^1 \mathrm{d}x \int_m \left[\mathrm{d}\sigma^{\mathrm{B}} \otimes \left(\boldsymbol{P}(x, \mu_F^2) + \boldsymbol{K}(x)\right)\right]$$

- e.g: for V,VV,VVV production:

$$\langle \mathbf{I}(\epsilon) \rangle = |\mathcal{M}_B|^2 \frac{\alpha_s}{2\pi} C_F \left(\frac{4\pi\mu_{\mathrm{R}}^2}{-s} \right)^{\varepsilon} \Gamma(1+\varepsilon) \left[\frac{2}{\varepsilon^2} + \frac{3}{\varepsilon} + 9 - \frac{4}{3}\pi^2 \right]$$

Cancel divergences of $\mathrm{d}\sigma^V$

Dipole Substraction Method: [Catani,Seymour,1997]

$$\sigma_{ab}^{NLO} = \int_{n+1} \left(d\sigma^R \big|_{\varepsilon=0} - d\sigma^A \big|_{\varepsilon=0} \right) + \int_n \left(d\sigma^V + d\sigma^C + \int_1 d\sigma^A \right)_{\varepsilon=0}$$

- $\int_1 d\sigma^A$: Analytically Integrable

$$\int_{m+1} d\sigma^{\mathrm{A}} + \int_m \sigma_m^{\mathrm{C}} = \int_m \left[d\sigma^{\mathrm{B}} \otimes \boldsymbol{I} \right] + \int_0^1 dx \int_m \left[d\sigma^{\mathrm{B}} \otimes \left(\boldsymbol{P}(x, \mu_F^2) + \boldsymbol{K}(x) \right) \right]$$

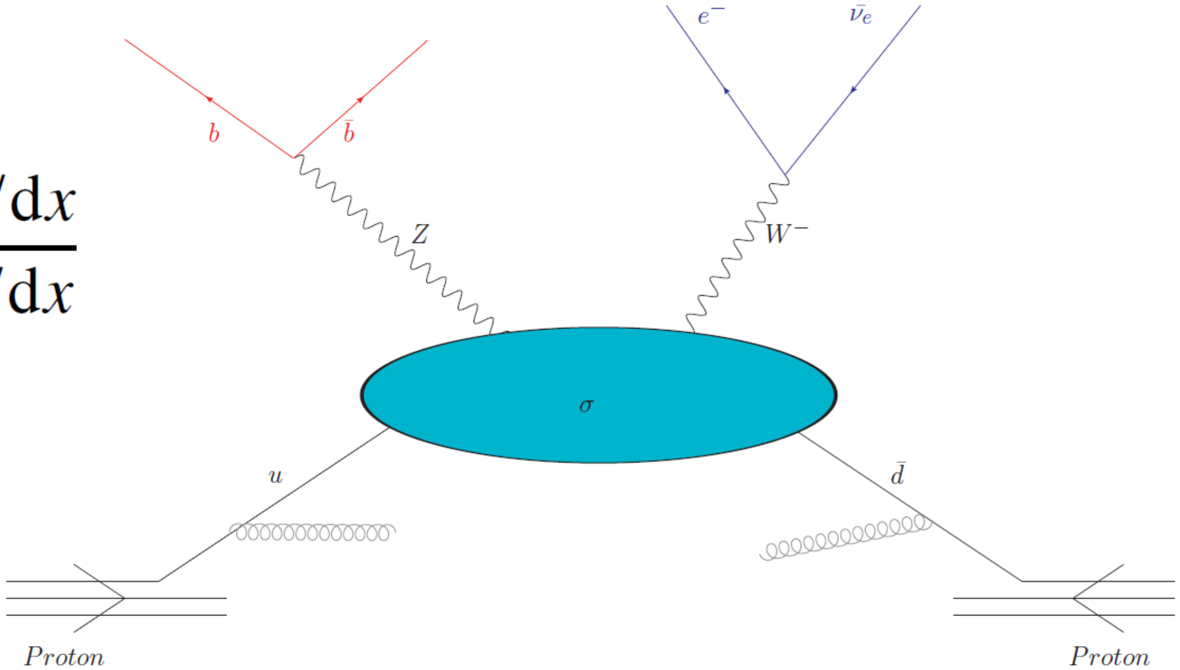
$$\langle \mathbf{I}(\epsilon) \rangle = |\mathcal{M}_B|^2 \frac{\alpha_s}{2\pi} C_F \left(\frac{4\pi\mu_F^2}{-s} \right) \Gamma(1+\varepsilon) \left[\frac{2}{\varepsilon^2} + \frac{3}{\varepsilon} + 9 - \frac{4}{3}\pi^2 \right]$$

- Numerically Integrable D=4

At NNLO:

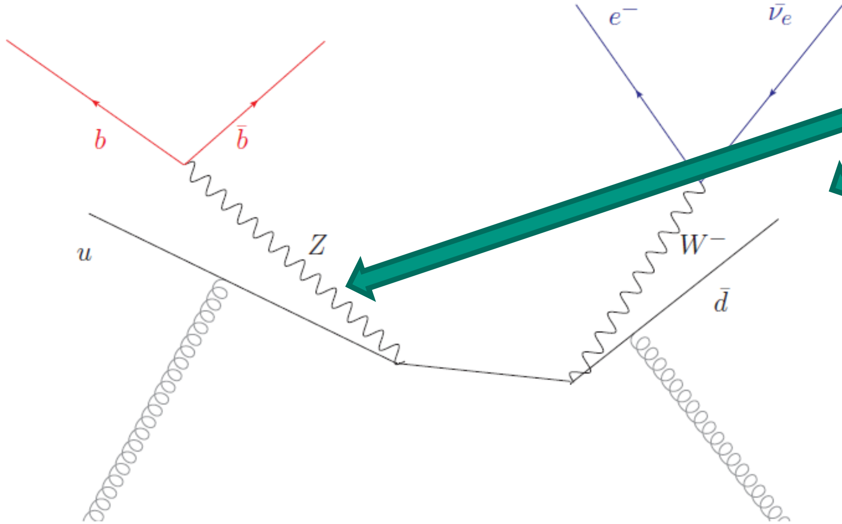
$$\sigma^{NNLO} = \sum_{a,b} \int_0^1 \mathrm{d}x_a \, \mathrm{d}x_b \, f_a^{NNLO}(x_a, \mu_\mathrm{F}^2) \, f_b^{NNLO}(x_b, \mu_\mathrm{F}^2) \left[\sigma^B + \sigma^{\mathrm{NLO}} + \sigma^{\mathrm{NNLO}}\right]_{ab}$$

$$K^2_{\mathrm{QCD,(N)LO}} = \frac{\mathrm{d}\sigma^{NNLO}/\mathrm{d}x}{\mathrm{d}\sigma^{(N)LO}/\mathrm{d}x}$$



NNLO Topologies

$$\alpha_s \ln^2 \frac{p_T}{M_W}$$



- Soft and collinear W, Z radiation

- New subprocesses:

  gg ⟹ LO process

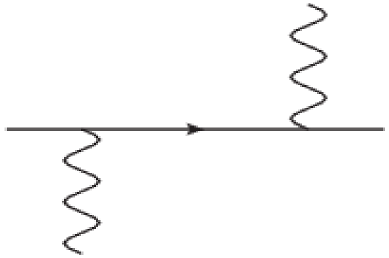
- Overall effect at small x and large momenta:

$$\frac{f_g(x_a,\mu_F^2)}{f_{\bar{q}}(x_b,\mu_F^2)}\frac{f_g(x_a,\mu_F^2)}{f_q(x_b,\mu_F^2)}\alpha_s^2 \ln^4 \frac{p_T}{M_W} > 20$$

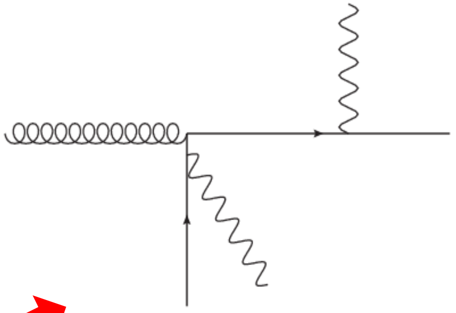
Beyond (N)LO QCD effects: for $X_1 \ldots X_n$ colorless Particles in Final State

- NLO QCD corrections large
  - New LO sub-processes
  - New topologies
- At NNLO
  - New LO sub-processes
  - New topologies
- Potentially large corrections

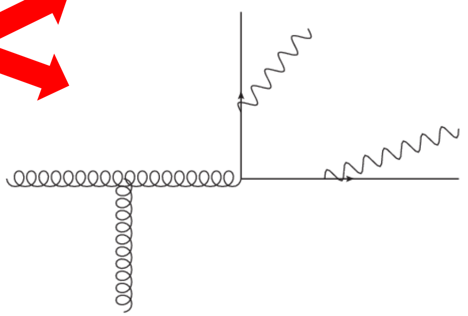
LO



NLO



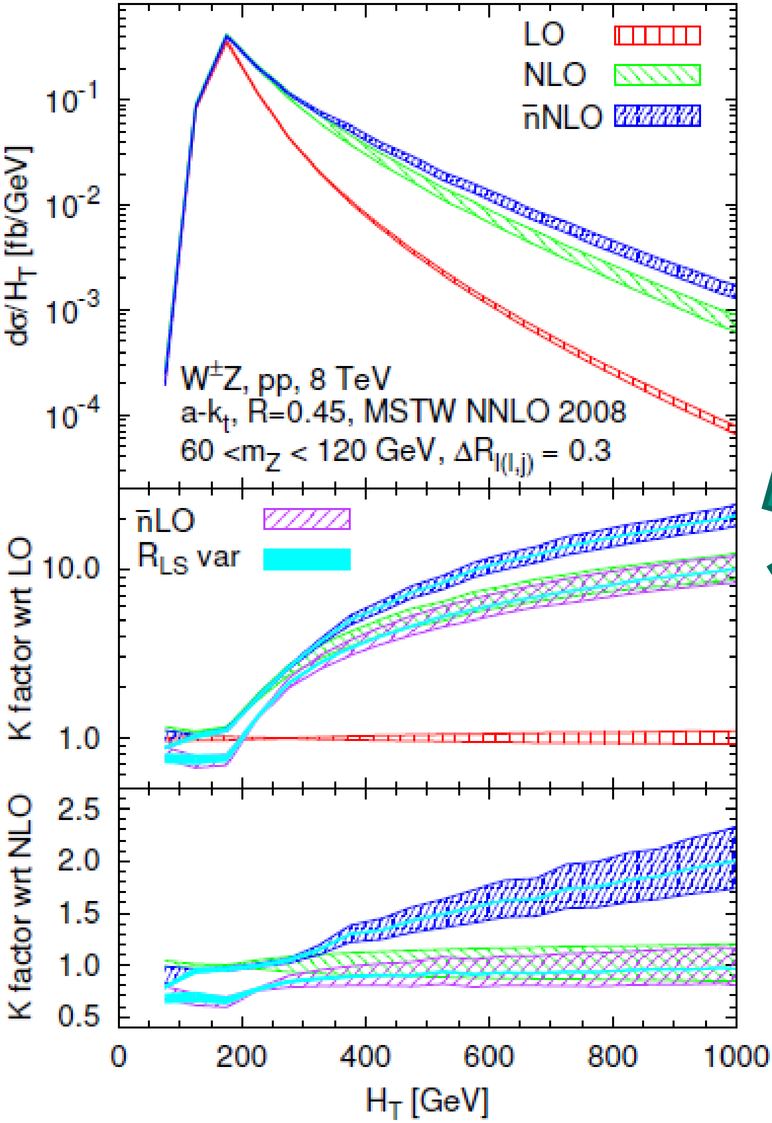
$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\,\mathrm{jet}}^2}{m_Z^2}$$



NNLO

Relevant Beyond (N)LO effects

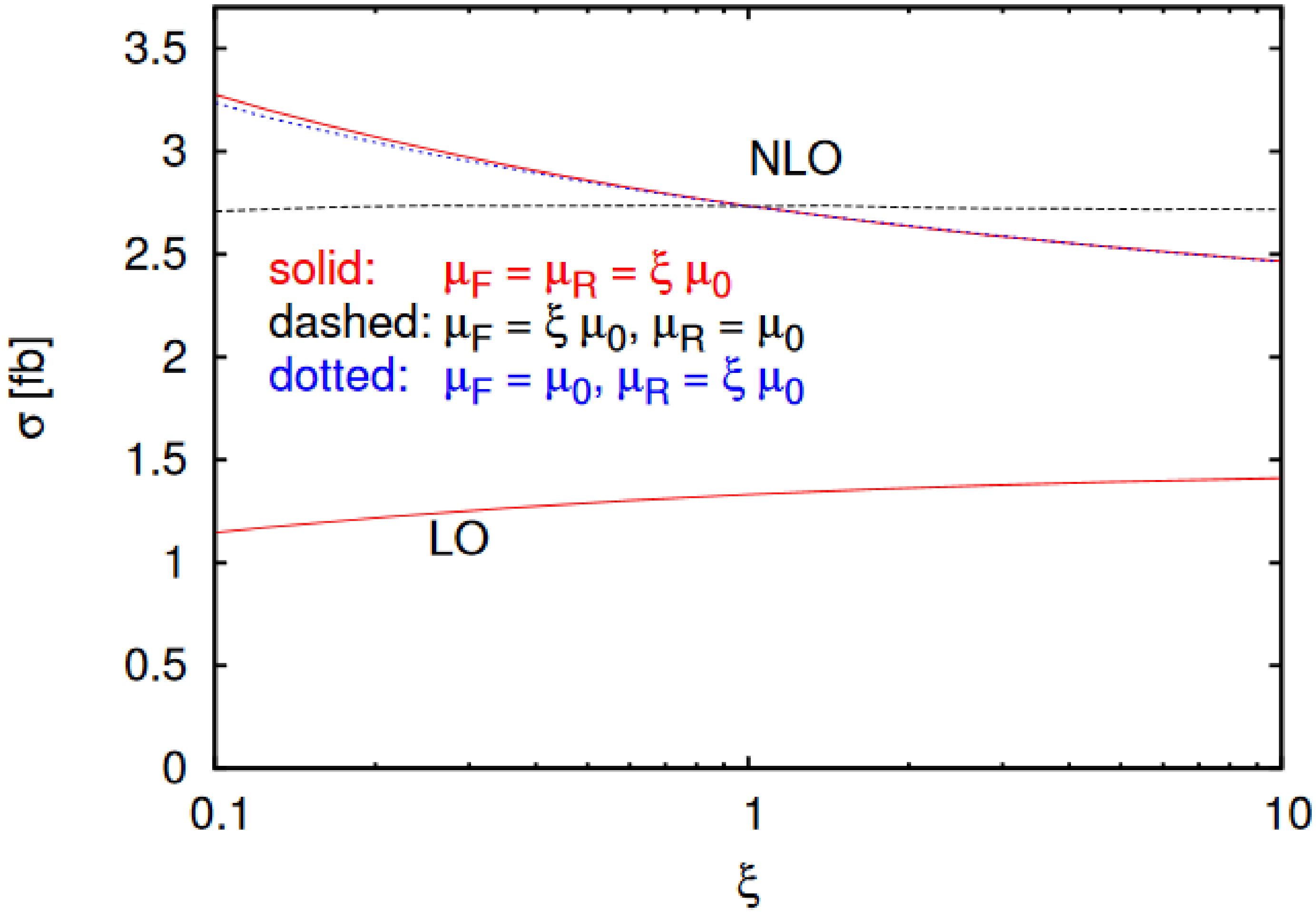
[FC,Sapeta,20012]



$$\frac{f_g(x_a,\mu_F^2)}{f_{\bar{q}}(x_b,\mu_F^2)}\frac{f_g(x_a,\mu_F^2)}{f_q(x_b,\mu_F^2)}\alpha_s^2 \ln^4 \frac{p_T}{M_W}\sigma^{LO}$$

$$\frac{f_g(x_a,\mu_F^2)}{f_{\bar{q}}(x_b,\mu_F^2)}\alpha_s \ln^2 \frac{p_T}{M_W}\ \sigma^{LO}$$

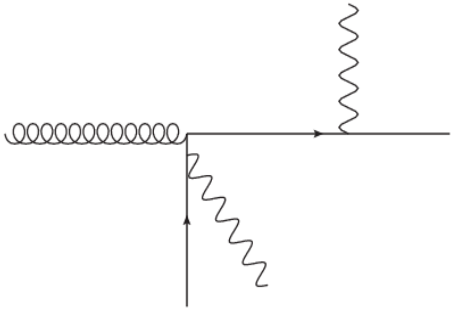
WZγ Production [FC,Rauch,Rzehak,Zeppenfeld,1011.2206]



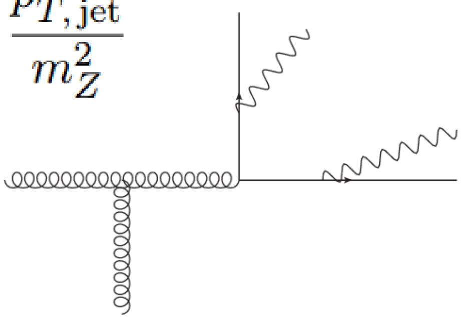
NLO QCD effects: for $X_1 \ldots . X_n\ J$ in Final State

- NLO QCD corrections large
  - New LO sub-processes
  - New topologies
- Potentially large corrections

LO



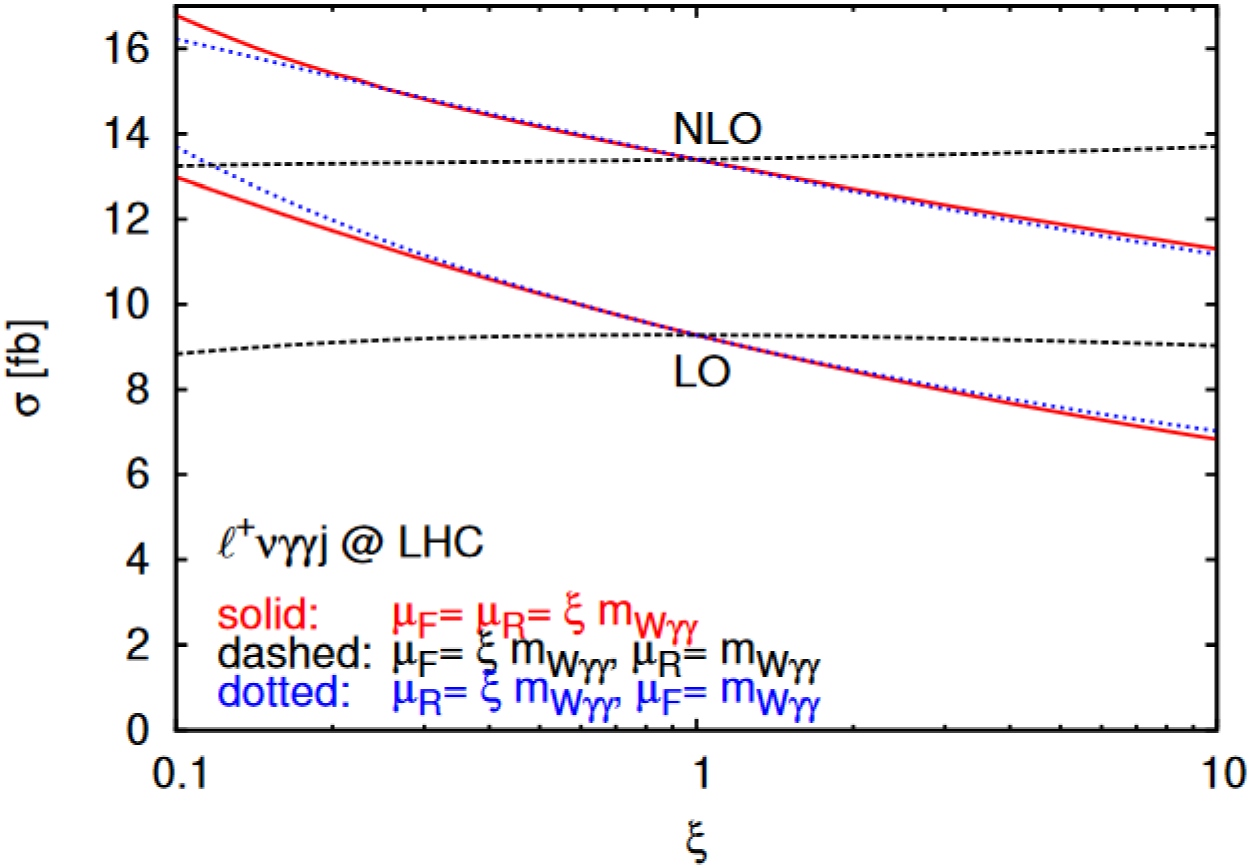
$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\mathrm{jet}}^2}{m_Z^2}$$



NLO

Wγγ + J

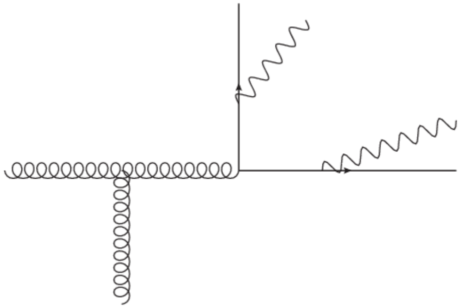
[FC,Englert,Rauch,Zeppenfeld,1106.4009]



NLO QCD effects: for $X_1 \ldots . X_n\ J\, J$ in Final State

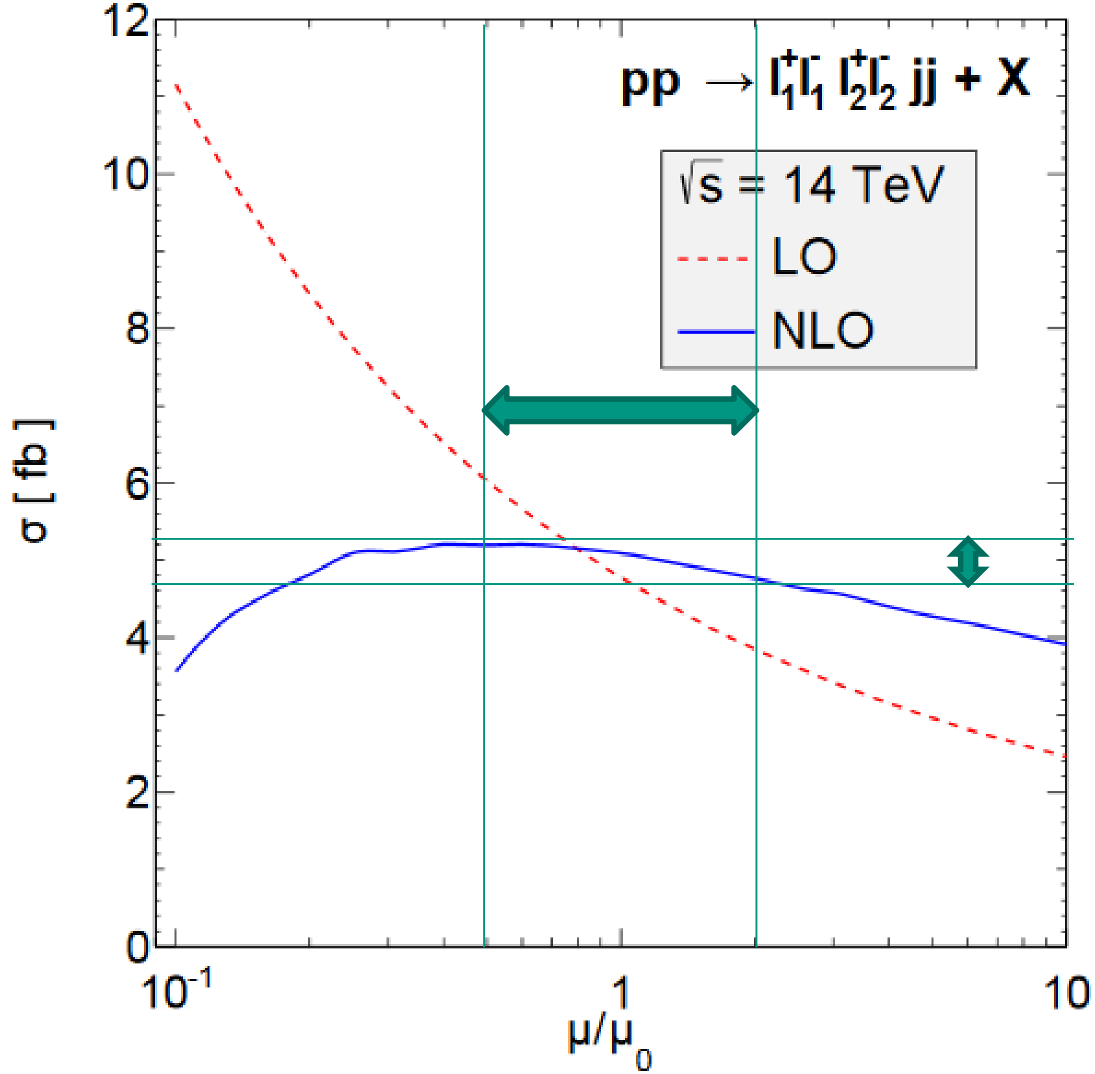
- NLO QCD corrections large
  - No New LO sub-processes (W+W+jj)
  - No New topologies

LO



- Moderate corrections

ZZjj Production [FC,Kerner,Ninhn,Zeppenfeld,1405.3972]



Theory scale uncertainty at NLO

Contents

THANK YOU FOR YOUR ATTENTION

Precise Phenomenology at LHC

Francisco Campanario
IFIC, UV-CSIC

8th IDPASC SCHOOL, 21-31 May 2018

Instituto de Física Corpuscular

Contents

- Introduction
  - The LHC
  - Results
  - Goal
  - Theoretical Ingredients
- PDF’s
- The Hard Process
- Phenomenology
- VBFNLO
- Summary

Phenomenology
VV Production

Introduction

Goal

Test Standard Model & Hints of New Physics

Method

Improve SM prediction — Reduce Theory Uncertainty

Framework to parametrize Beyond Standard Model physics → Effective Field Theory ⇓ Anomalous Couplings

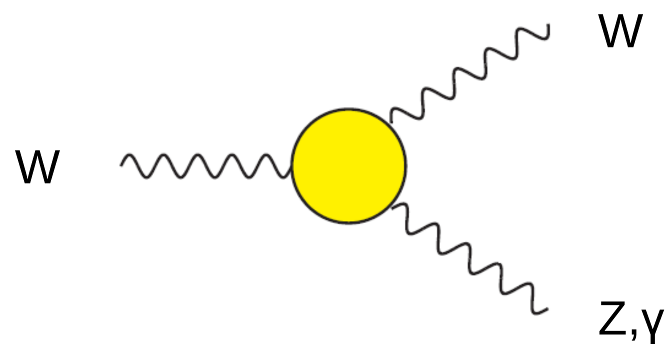
Improve Sensitivity — Cuts and Observables

Tools

VBFNLO: Diboson (+ up to 2 jet) production at NLO with AC
LoopSim: Merge NLO samples to provide approximate higher order

Di-boson production

- Background to many SM and BSM searches (including Higgs)

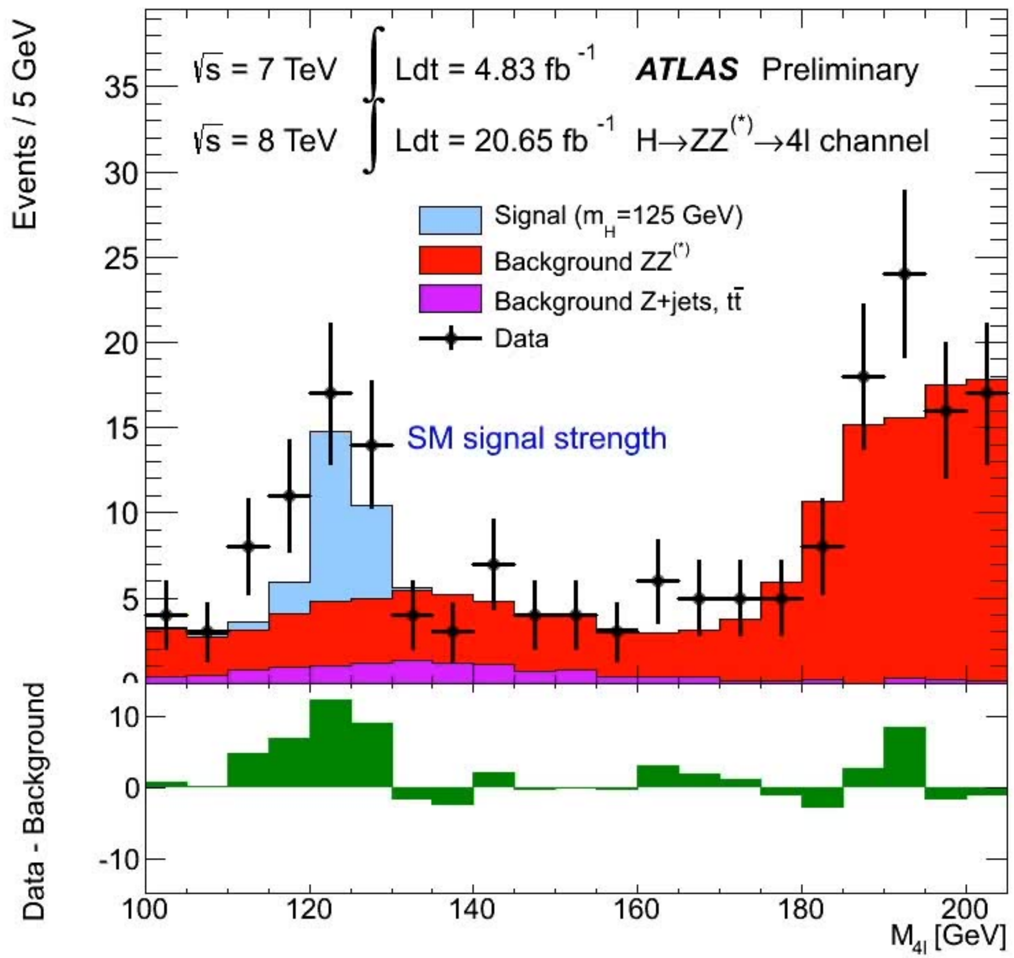


Status:

- NLO QCD known for a long time: 40-300%
- NLO EW known for almost all processes(on-shell): in tails up to 30%
- LO QCD GF induced contribution (NNLO) known: up to 20%
- NNLO QCD known: MATRIX

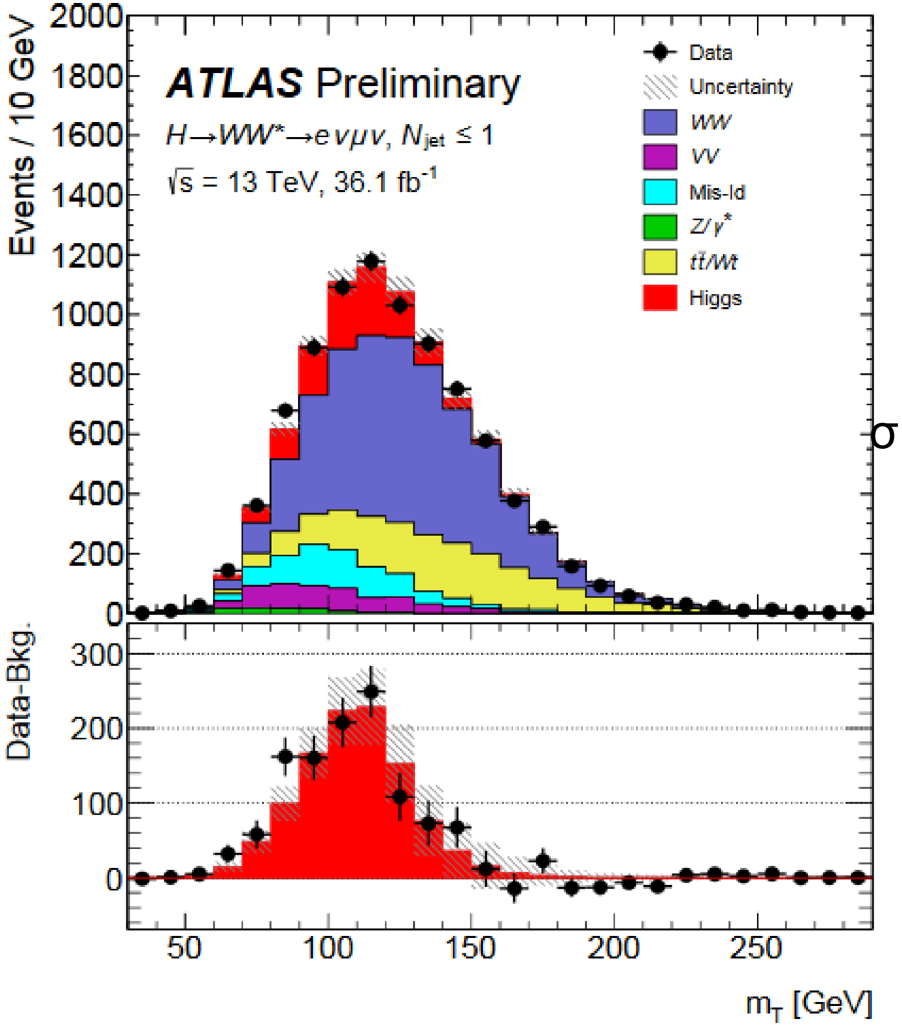
The Higgs Signal Evolution

IFIC INSTITUT DE FÍSICA CORPUSCULAR



Precise Knowledge of Backgrounds

[ATLAS-CONF-2018-004]



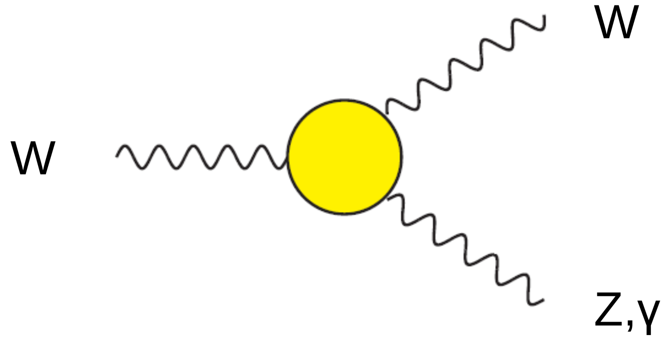
$$\frac{\sigma_{signal}}{\sigma_{background}} \propto \frac{250}{850} = 0.3$$

- Theoretical error of 30% in background as large as signal

→ No measurement

Di-boson production

- Background to many SM and BSM searches (including Higgs)
- Search for New Physics through Anomalous couplings



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- LO QCD GF induced contribution (NNLO) known: up to 20%
- NNLO QCD known: MATRIX

AC via Effective Theory

- New Physics at high mass scale: Λ
- Higher-dimension terms to Lagrangian: $1/\Lambda$

➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_k}{\Lambda^4} \cdots$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \hat{W}^{\mu\nu} \, (D_\nu \Phi)$$

Effective Theory

- New Physics at a high mass scale: Λ
- Higher-dimension terms to Lagrangian 1/ Λ^n

➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings

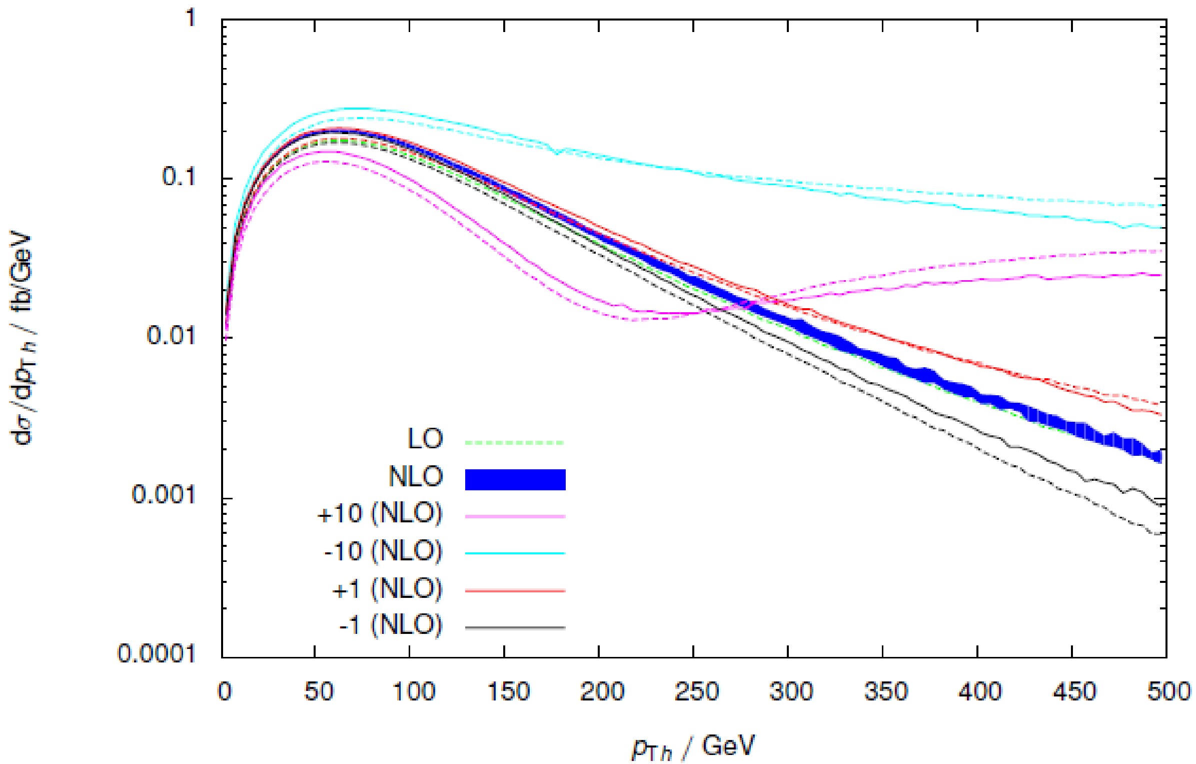
WWH Vertex:

$$\underbrace{igm_W g^{\mu\nu}}_{\text{SM}} \underbrace{-\frac{1}{2} i \frac{f_W}{\Lambda^2} g m_W \left(-g^{\mu\nu} \left(p_h \cdot p_- + p_h \cdot p_+ \right) + p_h^{\nu} p_-^{\mu} + p_h^{\mu} p_+^{\nu} \right)}_{\mathcal{O}_W}$$

Effective Theory

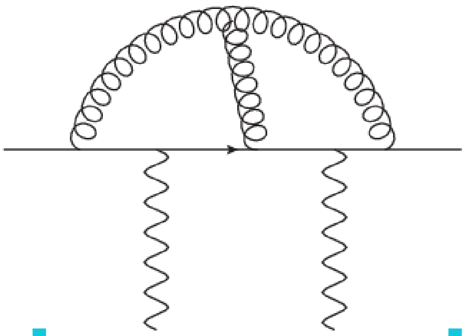
- New Physics at a high mass scale: Λ
- Higher-dimension terms to Lagrangian 1/ Λ^n

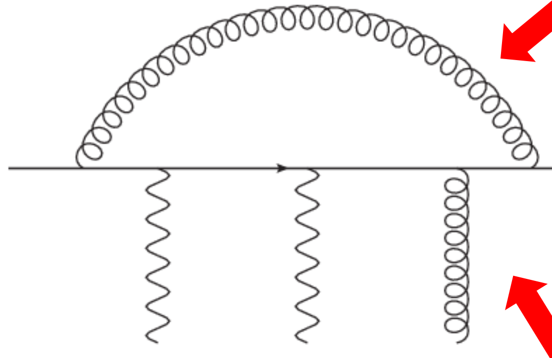
➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings

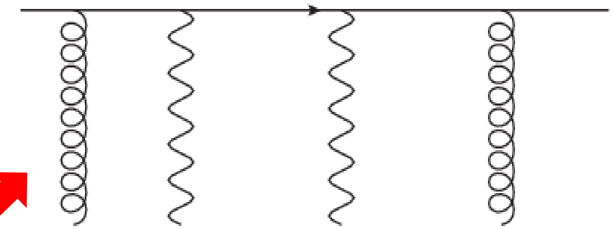


VV@NNLO

New Sub-processes:
PDF's







$$\mathcal{O}\left(\alpha_s^2 \sigma_{\mathrm{LO}}^{(A)}\right)$$

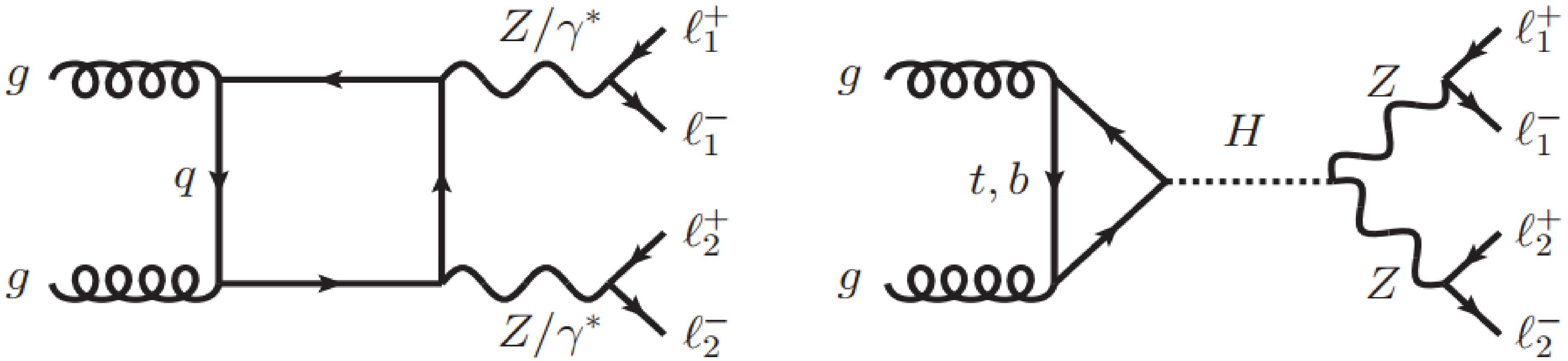
$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\mathrm{jet}}^2}{m_Z^2}$$

VVj at NLO

- IR divergences upon parton integration
- How to exploit the known NLO results for VV + n jets?
  - Merging: Sherpa, Herwig++, MG5_aMC@NLO

VV@NNLO

- Neutral Processes



GF ZZ at LO

- LO Kinematics, but gluon PDF's

LoopSim (M.Rubin,G.Salam,S.Sapeta,ArXiv:1006.2144)

Goal

- Merge processes with different multiplicity: VV, VVj,VVjj
  - Include dominant contributions of extra emissions, possibly log enhance
  - New Sub processes

Method

X $@\mathrm{NLO}$
X$j@\mathrm{NLO}$
Loop X$j@\mathrm{NLO}$ (Catani-Seymour like generated of loop kinematics)

$$V_1 \ldots V_n @\mathrm{LO} \quad + \quad V_1 \ldots V_n j @\mathrm{LO} \quad \to \quad V_1 \ldots V_n @\bar{n}\mathrm{LO}$$
$$V_1 \ldots V_n @\mathrm{NLO} \quad + \quad V_1 \ldots V_n j @\mathrm{NLO} \quad \to \quad V_1 \ldots V_n @\bar{n}\mathrm{NLO}$$

Inspired by CKKW matching

LoopSim (M.Rubin,G.Salam,S.Sapeta,ArXiv:1006.2144)

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- Merge processes with different multiplicity: VV, VVj,VVjj
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X $@\mathrm{NLO}$
X$j@\mathrm{NLO}$
Loop X$j@\mathrm{NLO}$ (Catani-Seymour like generated of loop kinematics)

$$V_1 \ldots V_n@\mathrm{NLO} \;+\; V_1 \ldots V_n j@\mathrm{NLO} \;+\; V_1 \ldots V_n jj@\mathrm{NLO} \;\rightarrow\; V_1 \ldots V_n@\bar{n}\bar{n}\mathrm{NLO}$$

Inspired by CKKW matching

ZZ@nNLO (FC,M.Rauch,S.Sapeta:ArXiv:1504.05588)

- VBFNLO: ZZ@NLO, ZZj@NLO, GFZZ@LO and GFZZj@LO [FC,Q.Li,M.Rauch,M.Spira,1211.5429] (NNNLO)

σ_{LO} [pb]	$5.0673(4)\ ^{+1.6\%}_{-2.7\%}$	$(Ref.\ [32]\text{: } 5.060\ ^{+1.6\%}_{-2.7\%})$
σ_{NLO} [pb]	$7.3788(10)\ ^{+2.8\%}_{-2.3\%}$	$(Ref.\ [32]\text{: } 7.369\ ^{+2.8\%}_{-2.3\%})$
$\sigma_{\text{NLO+LO-GF}}$ [pb]	$7.946(3)\ ^{+4.2\%}_{-3.2\%}$	
σ_{NNLO} [pb]		$(Ref.\ [32]\text{: } 8.284\ ^{+3.0\%}_{-2.3\%})$
$\sigma_{\bar{n}\text{NLO}}$ [pb]	$8.103(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	
$\sigma_{\bar{n}\text{NLO}+\bar{n}\text{LO-GF}}$ [pb]	$8.118(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	

Ref.[32]: F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhfer, A. von Manteuffel, S. Pozzorini et al.,arXiv:1405.2219

- GF 60% of total NNLO corrections
- nNLO vs NNLO 2%: within scale uncertainties

Anomalous Coupling Searches

PDF set: MSTW2008 at NNLO

Scale:

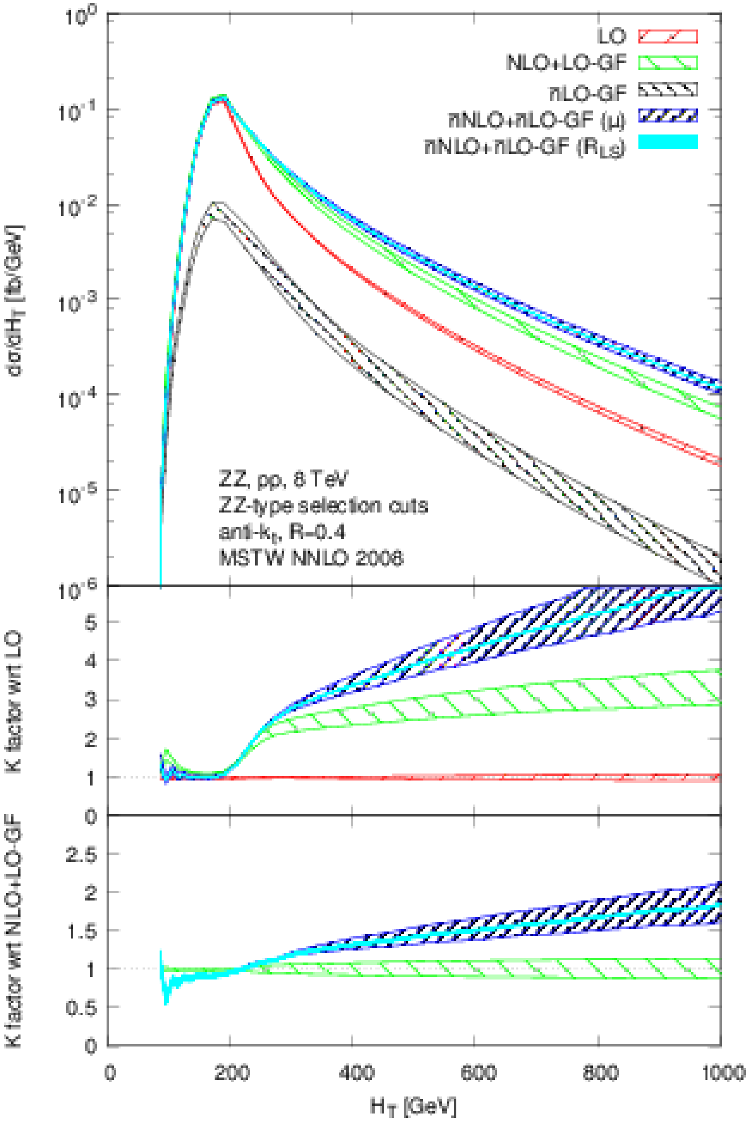
$$\mu_{F,R} = \mu_0 = \frac{1}{2}\left(\sum p_{T,\text{partons}} + \sqrt{p_{T,V_1}^2 + m_{V_1}^2} + \sqrt{p_{T,V_2}^2 + m_{V_2}^2}\right)$$

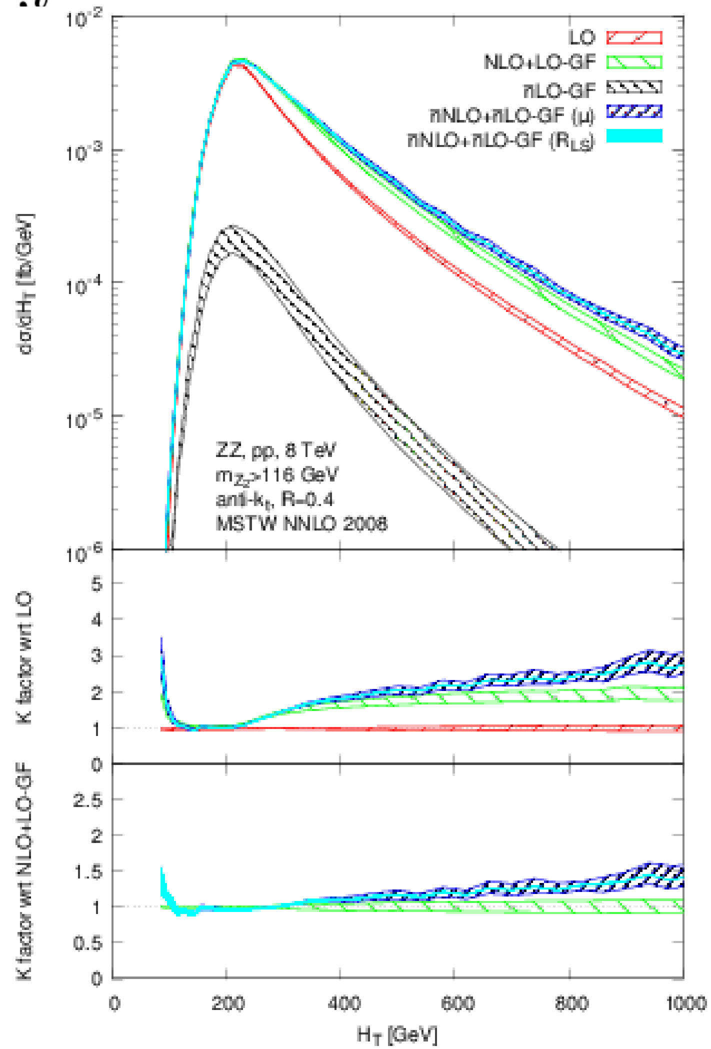
$$p_{t,\ell} > 20\,\text{GeV}\,, \qquad |\eta_\ell| < 2.5\,,$$
$$p_{t,\,\text{jet}} > 25\,\text{GeV}\,, \qquad |\eta_{\text{jet}}| < 4.5\,,$$
$$\Delta R_{\ell,\,\text{jet}} > 0.3\,, \qquad \Delta R_{\ell,\ell} > 0.2\,.$$

ZZ selection: $\quad m_{Z_1}, m_{Z_2} \in (66, 116)\,\text{GeV}\,,$

ZZ^* selection: $\quad m_{Z_1} \in (66, 116)\,\text{GeV}\,,\; m_{Z_2} \in (20, 66) \cup (166, m_{Z,\max})\,\text{GeV}\,,$

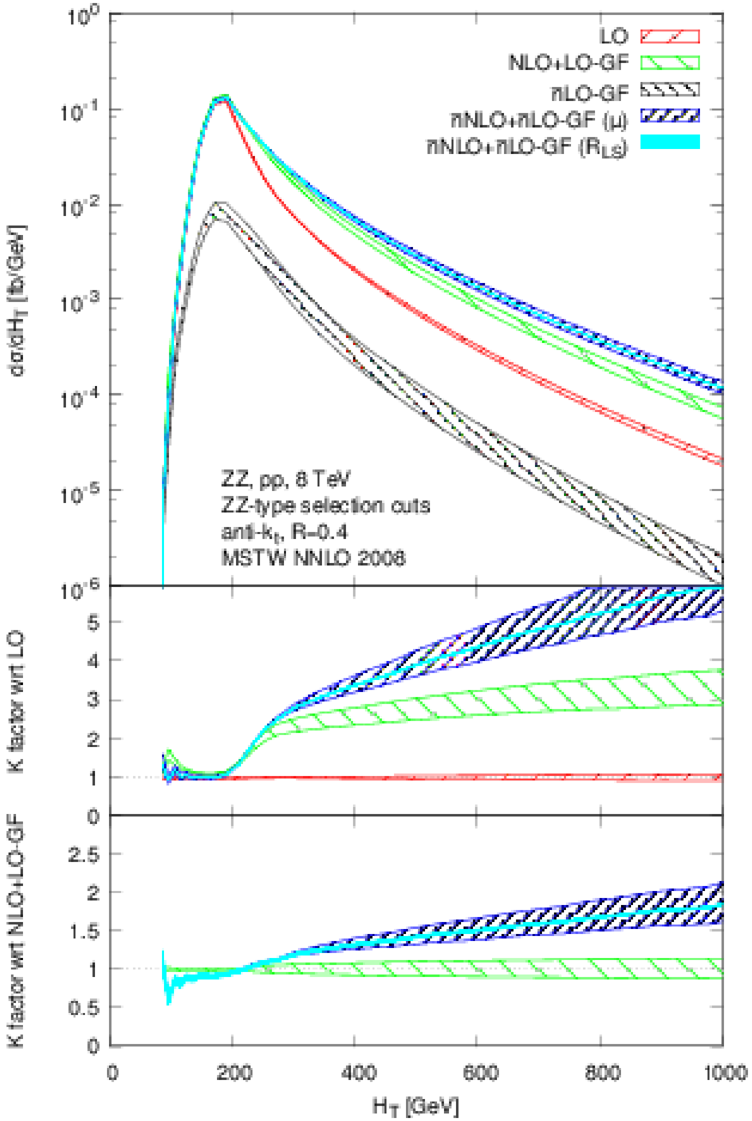
$$H_T = \sum p_{T,\text{jets}} + \sum p_{T.l}$$



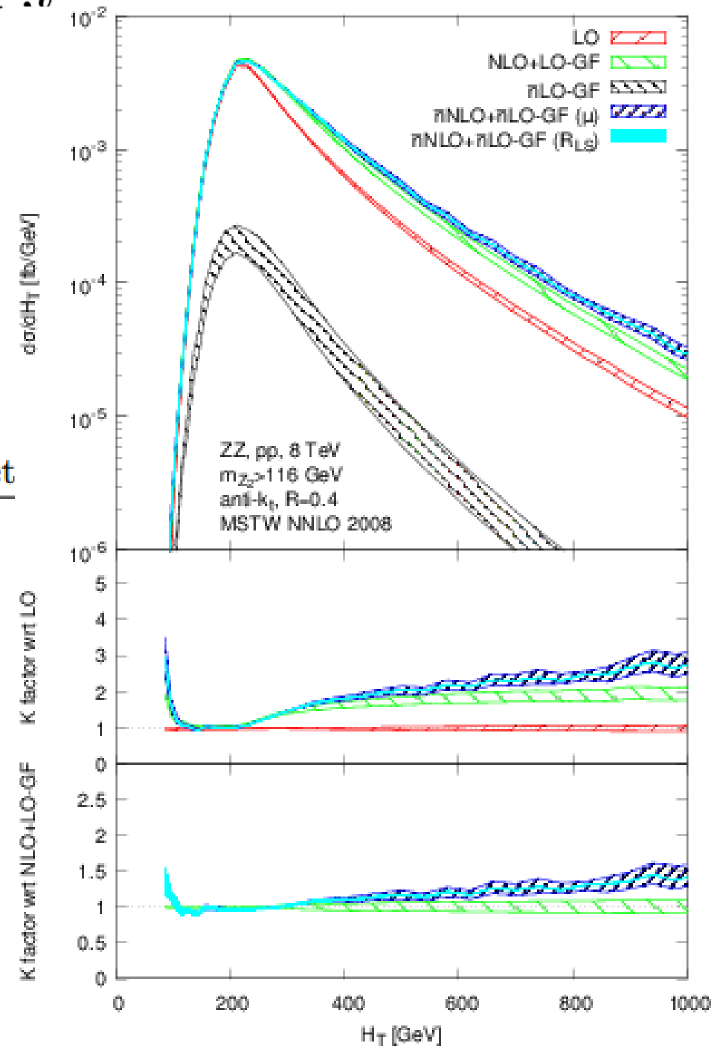


$$m_{Z_2} \in \quad (166, m_{Z,\max}) \text{ GeV}$$

$$H_T = \sum p_{T,\text{jets}} + \sum p_{T,l}$$



$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\text{jet}}^2}{m_Z^2}$$

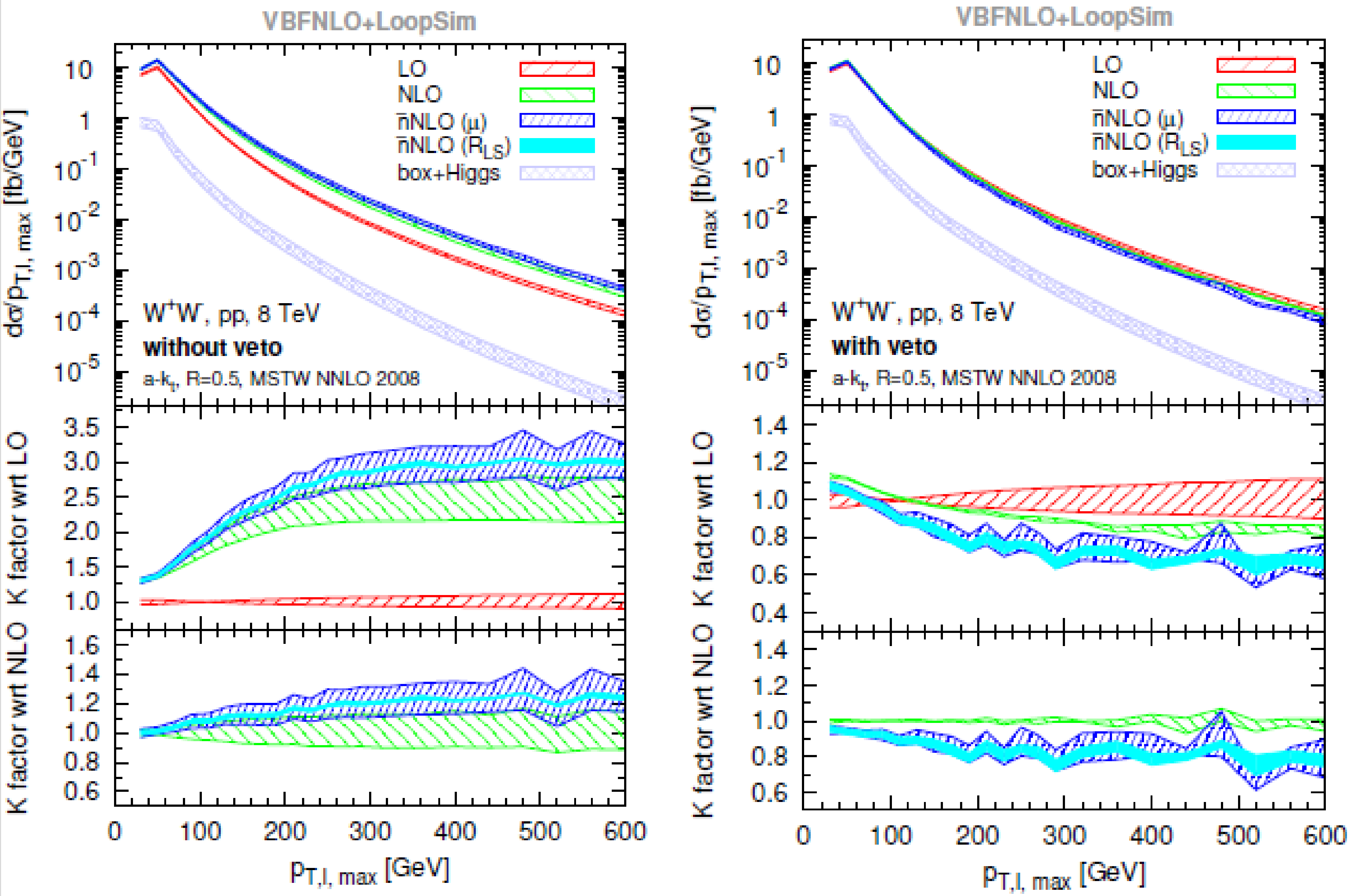


$$m_{Z_2} \in (166, m_{Z,\max}) \text{ GeV}$$

WW@nNLO (FC,M.Rauch,S.Sapeta:ArXiv:1309.7293)

- VBFNLO: WW@NLO, WWj@NLO, GF WW@LO
  - W^+W^- decaying to: $l_1^-\bar{\nu}_{l_1} l_2^+\nu_{l_2}$ and $l^-\bar{\nu}_l l^+\nu_l$
  - PDFs: MSTW NNLO 2008
  - $\mu_{F,R} = \frac{1}{2}\left\{\sum p_{T,partons} + \sqrt{p^2_{T,W} + m^2_W} + \sqrt{p^2_{T,W} + m^2_W}\right\}$
  - Cuts:

$$|y_l| < 2.5, \qquad p_{T_l} > 20\mathrm{GeV}$$
$$\mathrm{anti}-k_t, R = 0.45$$
$$|\eta_{\mathrm{jet}}| < 4.5 \quad p_{T_{\mathrm{jet}}} > 15\ \mathrm{GeV}$$
$$E_{Tprojectedmiss} > 20(45)GeV$$
$$m_{ll} > 12\mathrm{GeV}, \qquad |m_{ll} - M_Z| > 15\mathrm{GeV}$$
$$|\Delta(\phi_{ll} - \phi_{\mathrm{hardestjet,pt}>15})| < 165$$


VBFNLO+LoopSim
LO
NLO
n̄NLO (μ)
n̄NLO (R_{LS})
box+Higgs
W^+W^-, pp, 8 TeV
without veto
a-k_t, R=0.5, MSTW NNLO 2008
$d\sigma/p_{T,l,max}$ [fb/GeV]
K factor wrt LO
K factor wrt NLO
$p_{T,l,max}$ [GeV]
VBFNLO+LoopSim
W^+W^-, pp, 8 TeV
with veto
a-k_t, R=0.5, MSTW NNLO 2008

WZ@nNL (FC,S.Sapeta:ArXiv:1209.4595)

- VBFNLO: WZ@NLO, WZj@NLO, (FC,S.Kallweit,C.Englert,Spannowsky, Zeppenfeld,ArXiv:1006.0390)
  - W^+Z and W^-Z channels decaying to: $ee\mu\nu_\mu$ and $\mu\mu e\nu_e$
  - PDFs: MSTW NNLO 2008
  - $\mu_{F,R} = \frac{1}{2}\left\{\sum p_{T,partons} + \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,Z}^2 + m_Z^2}\right\}$
  - Cuts:

$$|y_l| < 2.5, \qquad p_{T_l} > 15(20)\mathrm{GeV}$$

$$60 < m_{ll} < 120\mathrm{GeV}$$

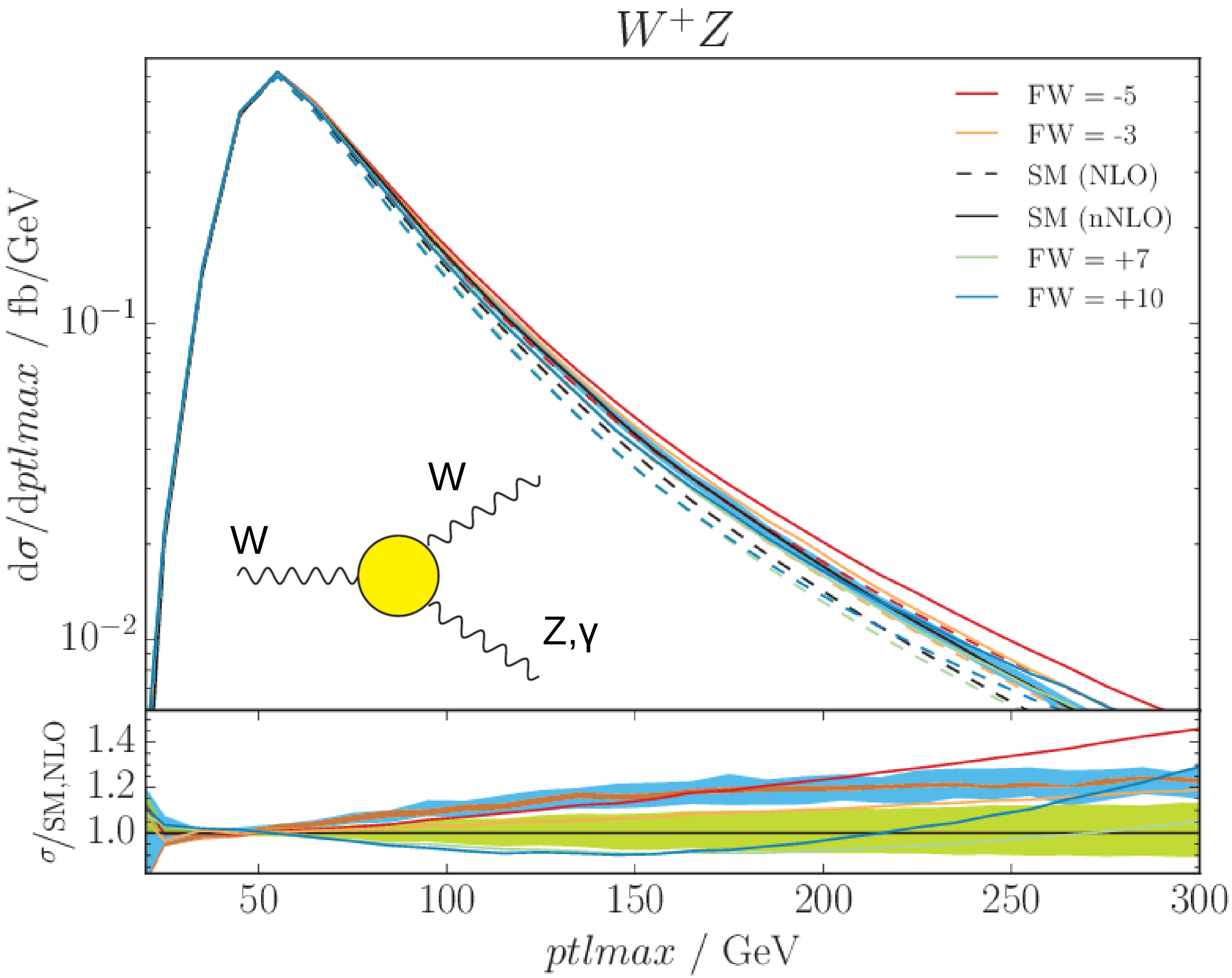
$$E_{Tmiss} > 30GeV$$

$$\mathrm{anti} - k_t,\ R = 0.45$$

$$|\eta_{\mathrm{jet}}| < 4.5 \qquad p_{T_{\mathrm{jet}}} > 30\ \mathrm{GeV}$$

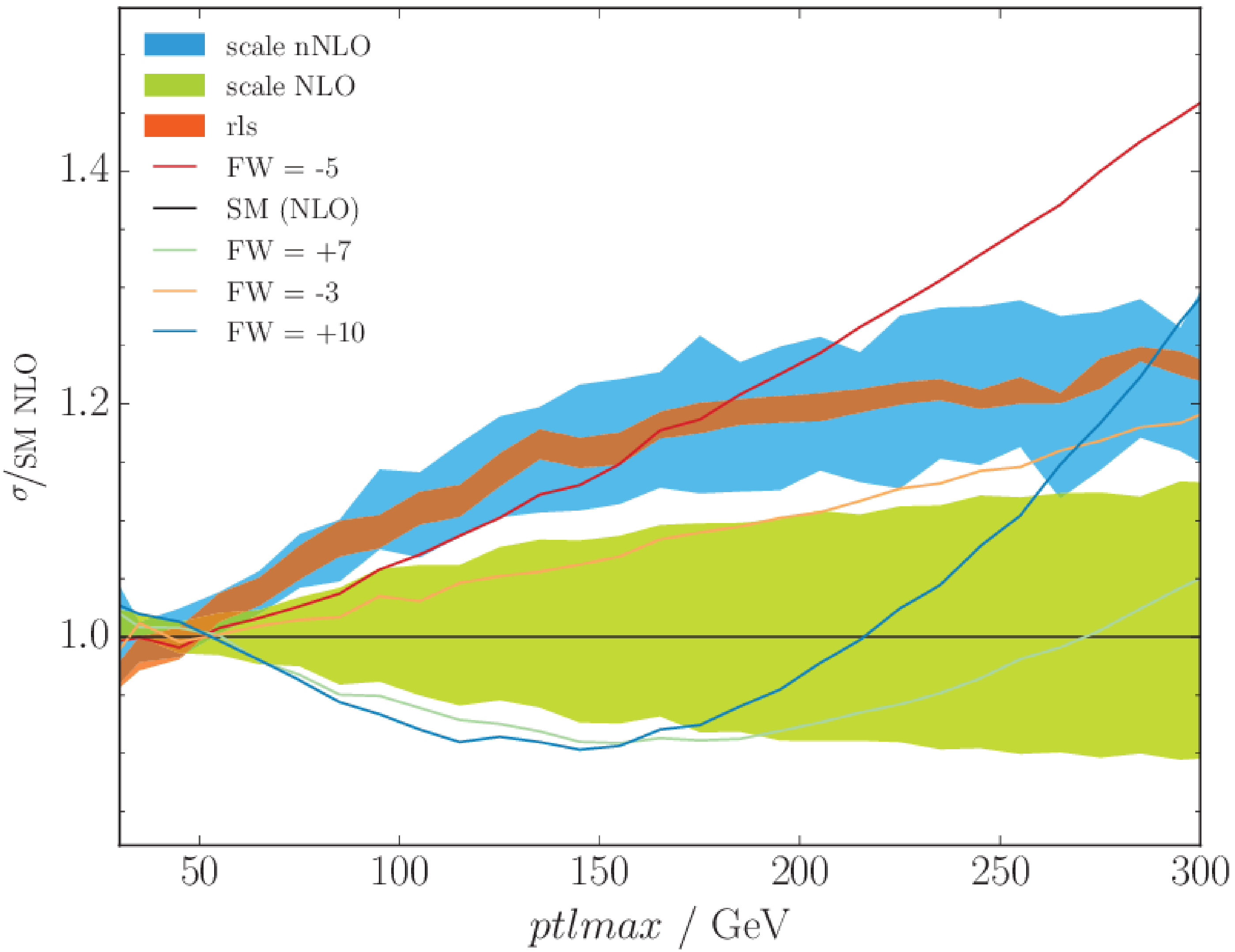
$$R_{ll(j)} > 0.3$$

NNLO QCD fakes AC effects [FC,Roth,Sapeta,Zeppenfeld,2016]

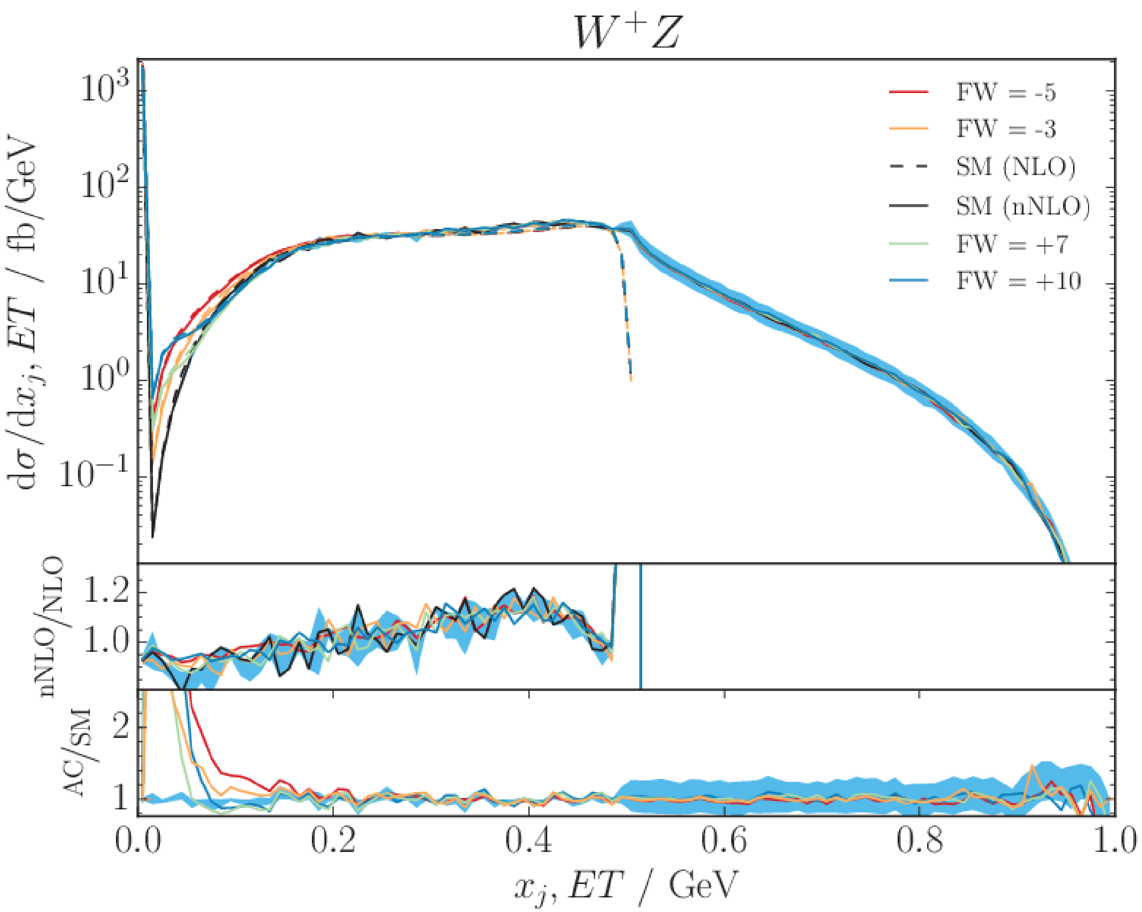


NNLO QCD fakes AC effects

[FC,Roth,Sapeta,Zeppenfeld,2016]

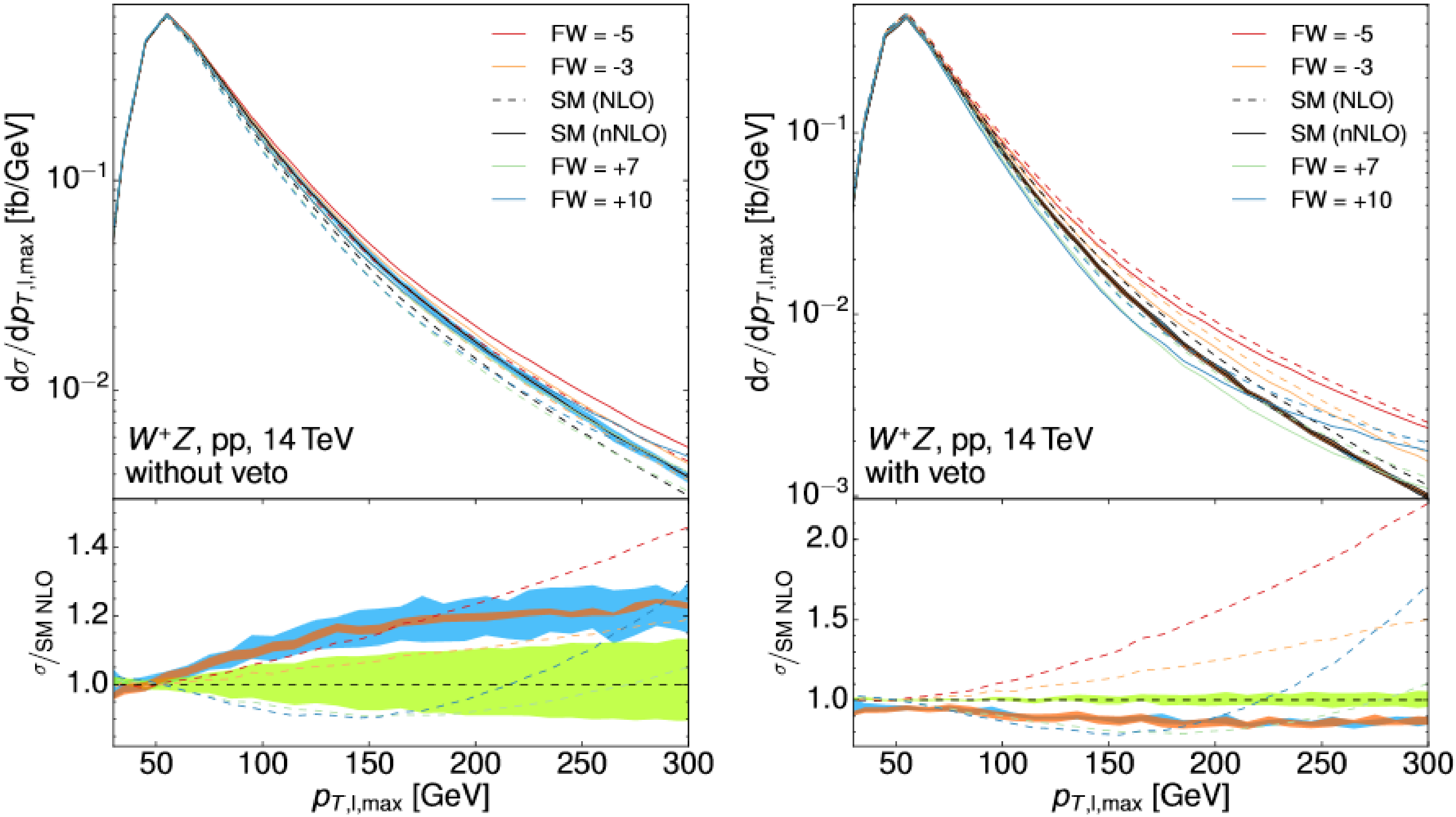


Jet Observable (FC,R.Roth,Zeppenfeld:ArXiv:1410.4840)



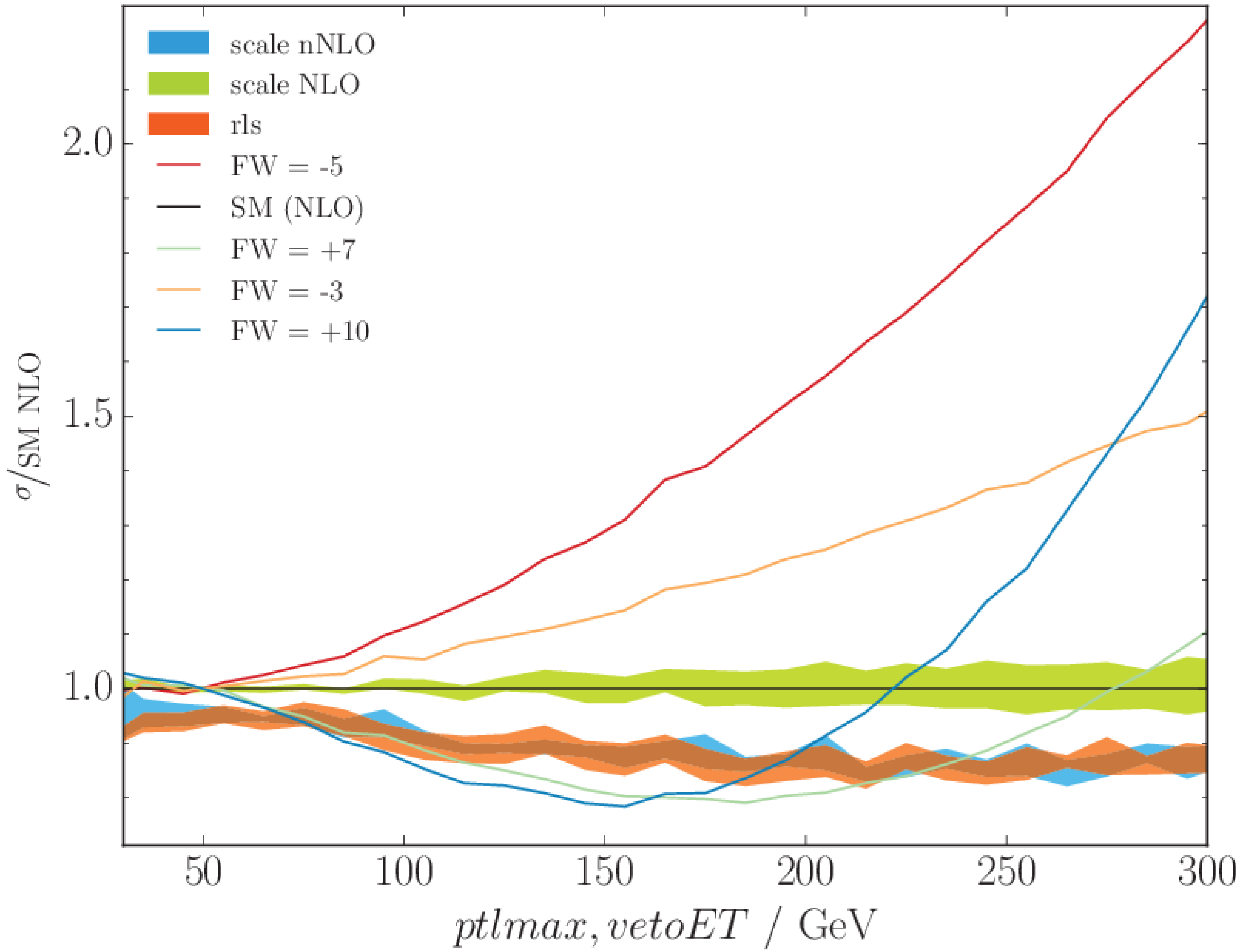
$$x_{\text{jet}} = \frac{\sum_{k \in \{\text{jets}\}} E_{T,k}}{\sum_{k \in \{\text{jets,Zs}\}} E_{T,k}}$$

WZ@nNLO + AC



FW = -5
FW = -3
SM (NLO)
SM (nNLO)
FW = +7
FW = +10
$d\sigma/dp_{T,l,max}$ [fb/GeV]
W^+Z, pp, 14 TeV
without veto
with veto
$\sigma/_{SM\ NLO}$
$p_{T,l,max}$ [GeV]

WZ@nNLO + AC



scale nNLO
scale NLO
rls
FW = -5
SM (NLO)
FW = +7
FW = -3
FW = +10
σ/SM NLO
2.0
1.5
1.0
50
100
150
200
250
300
ptlmax, vetoET / GeV

Summary

Total Cross section:

- Good agreement for ZZ at NNLO (not compared for other)

Differential Distributions

- Corrections can be large 30-100%
- Observable favoring LO kinematics: 5%
- (GF)ZZ@nLO: 50% corrections

Anamolous Couplings

- NNLO can fake AC effects
- More sophisticated analyses are needed to increase sensitivity

Outlook:

VV@nNLO+AC, VV@nnNLO, VVV@nNLO

VBFNLO: https://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=overview

LoopSim: https://loopsim.hepforge.org/

VBFLO

https://www.itp.kit.edu/vbfnlo/wiki/doku.php?id=overview

Karlsruhe Institute of Technology

VBFNLO - A parton level Monte Carlo for processes with electroweak bosons

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- Implementation Details
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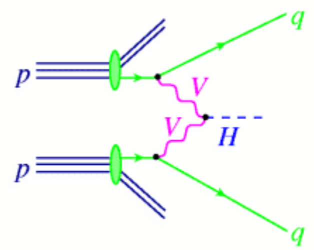
  - Anomalous Higgs Couplings



Project Description

VBFNLO is a fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production in hadronic collisions at next to leading order in the strong coupling constant. VBFNLO includes Higgs and vector boson decays with full spin correlations and all off-shell effects. In addition, VBFNLO implements CP-even and CP-odd Higgs boson via gluon fusion, associated with two jets, at the leading order one loop level with the full top-quark and bottom-quark mass dependence in a generic two Higgs doublet model.

A variety of effects arising from beyond the Standard Model physics are implemented for selected processes. This includes anomalous couplings of Higgs and vector bosons and a Warped Higgsless extra dimension model. The program offers the possibility to generate Les Houches Accord event files for all processes available at leading order.

All implemented processes can be found here.

The list of people involved in VBFNLO is here.


VBFNLO MC
Todo
Maps
Imágenes
Vídeos
Noticias
Más
Configuración
Herramientas
Aproximadamente 4.930 resultados (0,55 segundos)
Quizás quisiste decir: VENLO MC
overview[VBFNLO - A parton level Monte Carlo for processes with ...
https://www.itp.kit.edu/vbfnlo/wiki/doku.php?id=overview
Traducir esta página
6 feb. 2018 - VBFNLO is a fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production ...
Falta: ~~mc~~

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REPOLO

Implementation Details
- EWSCHEME
- Electroweak Renormalisation
- Anomalous Higgs Couplings
- Conversion to JHU notation
- aQGC conventions

Project Members

- Julien Baglio
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- Carlo Oleari
- Sophy Palmer
- Simon Plätzer
- Michael Rauch
- Robin Roth
- Heidi Rzehak
- Franziska Schissler
- Oliver Schlimpert
- Michael Spannowsky
- Malgorzata Worek
- Dieter Zeppenfeld

Iván Rosario Bonastre

Task:

EW γγjj at LHC

Interface with Herwig: VV(V)(j)

Main Developers

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Process List

The complete list of implemented production processes and decay modes in VBFNLO is summarized in the following. Except for gluon fusion, all processes are implemented in NLO QCD. For Higgs boson production plus two jets without Higgs decay the NLO electroweak corrections are also implemented. All processes can be run in the Standard Model. Several processes also allow for Beyond the Standard Model Physics effects. These options are shown in the third column.

Jump to:
Higgs boson production plus two jets via Vector Boson Fusion
Higgs boson production plus three jets via Vector Boson Fusion
Higgs boson production with a photon and two jets via Vector Boson Fusion
Single vector boson production plus two jets via Vector Boson Fusion
VBF production of two Higgs bosons and two jets
VBF production of a spin-2 particle
Vector boson pair production plus two jets via Vector Boson Fusion
Diboson production
Triple vector boson production
Double vector boson production in association with a hadronic jet
Triple vector boson production in association with a hadronic jet
WH production
W production
WH production in association with a hadronic jet
W production in association with a hadronic jet
QCD induced production of a vector boson in association with two jets
QCD induced diboson production in association with two jets
Higgs boson production plus two jets via Gluon Fusion
Gluon-induced diboson production
Gluon-induced diboson production in association with a hadronic jet

Higgs boson production plus two jets via Vector Boson Fusion

Processes with fully leptonic decays:

Process ID	Process	BSM Options
100	$\overset{(-)}{p}p \to H\,jj$	anomalous HVV couplings, MSSM
101	$\overset{(-)}{p}p \to H\,jj \to \gamma\gamma\,jj$	
102	$\overset{(-)}{p}p \to H\,jj \to \mu^+\mu^-\,jj$	
103	$\overset{(-)}{p}p \to H\,jj \to \tau^+\tau^-\,jj$	
104	$\overset{(-)}{p}p \to H\,jj \to b\bar{b}\,jj$	
105	$\overset{(-)}{p}p \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	
106	$\overset{(-)}{p}p \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	
107	$\overset{(-)}{p}p \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	

Processes with semi-leptonic decays:

Process ID	Process	BSM Options
108	$\overset{(-)}{p}p \to H\,jj \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$	anomalous HVV couplings, MSSM
109	$\overset{(-)}{p}p \to H\,jj \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$	
1010	$\overset{(-)}{p}p \to H\,jj \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	

Higgs boson production plus three jets via Vector Boson Fusion

Process ID	Process	BSM Options
110	$p \overset{(-)}{p} \to H\,jjj$	–
111	$p \overset{(-)}{p} \to H\,jjj \to \gamma\gamma\,jjj$	
112	$p \overset{(-)}{p} \to H\,jjj \to \mu^+\mu^-\,jjj$	
113	$p \overset{(-)}{p} \to H\,jjj \to \tau^+\tau^-\,jjj$	
114	$p \overset{(-)}{p} \to H\,jjj \to b\bar{b}\,jjj$	
115	$p \overset{(-)}{p} \to H\,jjj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jjj$	
116	$p \overset{(-)}{p} \to H\,jjj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jjj$	
117	$p \overset{(-)}{p} \to H\,jjj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jjj$	

Higgs boson production with a photon and two jets via Vector Boson Fusion

Process ID	Process	BSM Options
2100	$p \overset{(-)}{p} \to H\gamma\,jj$	–
2101	$p \overset{(-)}{p} \to H\gamma\,jj \to \gamma\gamma\gamma\,jj$	
2102	$p \overset{(-)}{p} \to H\gamma\,jj \to \mu^+\mu^-\gamma\,jj$	
2103	$p \overset{(-)}{p} \to H\gamma\,jj \to \tau^+\tau^-\gamma\,jj$	
2104	$p \overset{(-)}{p} \to H\gamma\,jj \to b\bar{b}\gamma\,jj$	
2105	$p \overset{(-)}{p} \to H\gamma\,jj \to W^+W^-\gamma\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\gamma\,jj$	
2106	$p \overset{(-)}{p} \to H\gamma\,jj \to ZZ\gamma\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\gamma\,jj$	
2107	$p \overset{(-)}{p} \to H\gamma\,jj \to ZZ\gamma\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\gamma\,jj$	

Diboson production

Processes with fully leptonic decays:

Process ID	Process	BSM Options
300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	anomalous HVV and gauge couplings
310	$p\overset{(-)}{p} \to W^+Z \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-$	anomalous gauge couplings
320	$p\overset{(-)}{p} \to W^-Z \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	
330	$p\overset{(-)}{p} \to ZZ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	anomalous HVV couplings
340	$p\overset{(-)}{p} \to W^+\gamma \to \ell_1^+\nu_{\ell_1}\gamma$	anomalous gauge couplings
350	$p\overset{(-)}{p} \to W^-\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\gamma$	
360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^+\ell_1^-\gamma$	anomalous HVV couplings
370	$p\overset{(-)}{p} \to \gamma\gamma$	

Processes with semi-leptonic decays:

Process ID	Process	BSM Options
301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^-\bar{\nu}_\ell$	anomalous HVV and gauge couplings
302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+\nu_\ell\,q\bar{q}$	
312	$p\overset{(-)}{p} \to W^+Z \to q\bar{q}\,\ell^+\ell^-$	anomalous gauge couplings
313	$p\overset{(-)}{p} \to W^+Z \to \ell^+\nu_\ell\,q\bar{q}$	
322	$p\overset{(-)}{p} \to W^-Z \to q\bar{q}\,\ell^+\ell^-$	
323	$p\overset{(-)}{p} \to W^-Z \to \ell^-\bar{\nu}_\ell\,q\bar{q}$	
331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^-\ell^+$	anomalous HVV couplings

Triple vector boson production

Processes with fully leptonic decays:

Process ID	Process	BSM Options
400	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\ell_3{}^+\ell_3{}^-$	
410	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\ell_3{}^+\nu_{\ell_3}$	
420	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\ell_3{}^-\bar{\nu}_{\ell_3}$	anomalous gauge couplings, Kaluza-Klein models
430	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\ell_3{}^+\nu_{\ell_3}$	
440	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3{}^-\bar{\nu}_{\ell_3}$	
450	$p\overset{(-)}{p} \to ZZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+\ell_3{}^-\ell_3{}^+$	
460	$p\overset{(-)}{p} \to W^-W^+\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\gamma$	
470	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+\gamma$	
480	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+\gamma$	
490	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+\gamma$	anomalous gauge couplings
500	$p\overset{(-)}{p} \to W^+\gamma\gamma \to \ell^+\nu_\ell\gamma\gamma$	
510	$p\overset{(-)}{p} \to W^-\gamma\gamma \to \ell^-\bar{\nu}_\ell\gamma\gamma$	
520	$p\overset{(-)}{p} \to Z\gamma\gamma \to \ell^-\ell^+\gamma\gamma$	
521	$p\overset{(-)}{p} \to Z\gamma\gamma \to \nu_\ell\bar{\nu}_\ell\gamma\gamma$	
530	$p\overset{(-)}{p} \to \gamma\gamma\gamma$	

Processes with semi-leptonic decays:

Process ID	Process	BSM Options
401	$p\overset{(-)}{p} \to W^+W^-Z \to q\bar{q}\,\ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	
402	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\,q\bar{q}\,\ell_2^+\ell_2^-$	

WH production in association with a hadronic jet

Process ID	Process	BSM Options
1600	$p\overset{(-)}{p} \to W^+Hj \to \ell^+\nu_\ell Hj$	
1601	$p\overset{(-)}{p} \to W^+Hj \to \ell^+\nu_\ell\gamma\gamma j$	
1602	$p\overset{(-)}{p} \to W^+Hj \to \ell^+\nu_\ell\mu^+\mu^- j$	
1603	$p\overset{(-)}{p} \to W^+Hj \to \ell^+\nu_\ell\tau^+\tau^- j$	
1604	$p\overset{(-)}{p} \to W^+Hj \to \ell^+\nu_\ell b\bar{b} j$	
1605	$p\overset{(-)}{p} \to W^+Hj \to W^+W^+W^- j \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar\nu_{\ell_3} j$	
1606	$p\overset{(-)}{p} \to W^+Hj \to W^+ZZj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^- j$	
1607	$p\overset{(-)}{p} \to W^+Hj \to W^+ZZj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar\nu_{\ell_3} j$	
1610	$p\overset{(-)}{p} \to W^-Hj \to \ell^-\bar\nu_\ell Hj$	anomalous gauge couplings
1611	$p\overset{(-)}{p} \to W^-Hj \to \ell^-\bar\nu_\ell\gamma\gamma j$	
1612	$p\overset{(-)}{p} \to W^-Hj \to \ell^-\bar\nu_\ell\mu^+\mu^- j$	
1613	$p\overset{(-)}{p} \to W^-Hj \to \ell^-\bar\nu_\ell\tau^+\tau^- j$	
1614	$p\overset{(-)}{p} \to W^-Hj \to \ell^-\bar\nu_\ell b\bar{b} j$	
1615	$p\overset{(-)}{p} \to W^-Hj \to W^-W^+W^- j \to \ell_1^-\bar\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar\nu_{\ell_3} j$	
1616	$p\overset{(-)}{p} \to W^-Hj \to W^-ZZj \to \ell_1^-\bar\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^- j$	
1617	$p\overset{(-)}{p} \to W^-Hj \to W^-ZZj \to \ell_1^-\bar\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar\nu_{\ell_3} j$	

QCD induced production of a vector boson in association with two jets

Process ID	Process	BSM Options
3120	$\overset{(-)}{p}p \to Z\,jj \to \ell^+\ell^-\,jj$	–
3121	$\overset{(-)}{p}p \to Z\,jj \to \nu_\ell\bar{\nu}_\ell\,jj$	
3130	$\overset{(-)}{p}p \to W^+\,jj \to \ell^+\nu_\ell\,jj$	
3140	$\overset{(-)}{p}p \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$	

QCD induced diboson production in association with two jets

Process ID	Process	BSM Options
3210	$\overset{(-)}{p}p \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	–
3211	$\overset{(-)}{p}p \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	
3220	$\overset{(-)}{p}p \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	
3230	$\overset{(-)}{p}p \to W^-Z\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\,jj$	
3250	$\overset{(-)}{p}p \to W^+W^+\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\,jj$	
3260	$\overset{(-)}{p}p \to W^-W^-\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	
3270	$\overset{(-)}{p}p \to W^+\gamma\,jj \to \ell^+\nu_\ell\gamma\,jj$	
3280	$\overset{(-)}{p}p \to W^-\gamma\,jj \to \ell^-\bar{\nu}_\ell\gamma\,jj$	
3290	$\overset{(-)}{p}p \to Z\gamma\,jj \to \ell^+\ell^-\gamma\,jj$	
3291	$\overset{(-)}{p}p \to Z\gamma\,jj \to \nu_\ell\bar{\nu}_\ell\gamma\,jj$	

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- Electroweak Renormalisation

Manual

The manual is shipped together with the program in the VBFNLO-Download in the `doc` folder. You can also download it from below.

VBFNLO Version 2.7.1

The manual for the current release is available in pdf format for download:

Manual for version 2.7.1

VBFNLO Version 2.7.0

The manual for version 2.7.0 is available in pdf format for download:

Manual for version 2.7.0,

but it can also be found on the arXiv:

arXiv:1107.4038v3

The release note for version 2.7.0 is here or on the arXiv:

arXiv:1404.3940

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Software Download

The current release is Version 2.7.1, released on 05 August 2015.

Version 2.7.1

Source tarball: VBFNLO-2.7.1.tgz August 2015)

For installation instructions see Documentation > Installation

For a list of known issues and fixes see Download > Known Issues

GitHub Repository

You can also get recent versions from our public repository at GitHub.

The tagged releases are identical to the tarballs. In the future, we will put small bug fixes to the code there also between releases, so you have faster access to those.

GitHub Repository

VBFNLO Monte Carlo Program https://www.itp.kit.edu/vbfnlo

vector-boson-fusion | higgs-production | monte-carlo-generator | particle-physics

10 commits | 3 branches | 7 releases | 1 contributor | GPL-2.0

Branch: master | New pull request | Find file | Clone or download

Releases:

Releases | Tags

Pre-release

v3.0.0beta5

1f4d9ed

3.0.0 beta 5

michael-rauch released this on 6 Feb · 0 commits to v3.0 since this release

Assets

vbfnlo-3.0.0beta5.tgz 16.2 MB

Source code (zip)

Source code (tar.gz)

Major Enhancements

- Large speed improvement in real-emission calculation of Hjjj production (processes 110-117)

Bug fixes

- Fix two bugs in NLO calculation of Hjjj production (processes 110-117)
- Fix number of active flavours in BLHA interface

First Steps:

Download:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL$ ls
vbfnlo-3.0.0beta5.tgz
```

Untar:

```
:/SCHOOL$ tar xzf vbfnlo-3.0.0beta5.tgz
```

List of content:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL$ ls
VBFNLO-3.0.0beta5  vbfnlo-3.0.0beta5.tgz
francam@lhcpheno22:~/Work/Projects/SCHOOL$ cd VBFNLO-3.0.0beta5/
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$ ls
aclocal.m4       config          GUIDELINES   m4                        phasespace
amplitudes       configure       helas        Makefile.am               README.md
AUTHORS          configure.ac    include      Makefile.dependencylist   regress
autom4te.cache   COPYING         lib          Makefile.in               src
CHANGELOG.md     doc             loops        PDFsets                   utilities
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$
```

Installation

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Installation

VBFNLO includes a GNU conforming build system for portability and an easy build and installation procedure.

Prerequisites

The basic installation requires GNU make, a FORTRAN 95 (we have tested gfortran and ifort) and a C++ compiler. VBFNLO offers the possibility of using the LHAPDF library for parton distribution functions. In order to include the electroweak corrections, the program LoopTools is required. Additionally, FeynHiggs can be linked to the code in order to calculate the Higgs boson sector of the MSSM, although a SLHA file can be used as an alternative. If the simulation of Kaluza-Klein resonances is enabled, an installation of the GNU Scientific Library GSL is required. VBFNLO can also be linked to ROOT and HepMC to produce histograms and event files in those formats.

Compilation and installation

After unpacking the source archive and entering the source directory, the configure script can be invoked with several options, a complete list being available via `./configure --help`. Among these, the most important ones are:

- `--prefix=[path]`
  Install Vbfnlo in the location given by [path].
- `--enable-processes=[list]`
  By default, the code for processes that do not contain hexagons (i.e. all processes except triboson + jet processes) is compiled. Optionally, [list] gives a comma-separated list of selected processes to be compiled. Possible process names are:
  - `vbf` — Vector boson fusion processes
  - `qcdvjj` — QCD-induced vector boson plus two jet production
  - `qcdvvjj` — QCD-induced vector boson pair plus two jet production
  - `diboson` — Double gauge boson production, including W and WH production
  - `triboson` — Triple gauge boson production
  - `dibosonjet` — Double gauge boson production with a hadronic jet, including Wj and WHj production

Configure, make, make install

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$ ./configure --prefix
=/home/RUN/SCHOOL --disable-static --enable-MPI --enable-quad CC=mpicc FC=mpifort
 CXX=mpic++
```

Installation path:

No static libraries: faster to compile

Compiler options:

--enable-MPI: allow mpi to use more than one core of the PC

-enable-quad: quadruple precision for difficult processes

FC and CC: chose compiler

Configure, make, make install

- Output:

```
================================================================

 VBFNLO 3.0.0beta5 configuration

 Processes included:
 all_except_hexagons

 NLO QCD             yes
 KK resonances       no
 Compile warnings    no
 Quad precision      yes
 MPI                 yes

 LHAPDF              no
 LOOPTOOLS           no
 FEYNHIGGS           no
 ROOT                no
 GSL                 not required
 HEPMC               no

 FORTRAN compiler    gfortran

================================================================
```

Configure, make, make install

Configure help:

```
/VBFNLO-3.0.0beta5$ ./configure --help
to adapt to many kinds of systems
```

Which processes can be selected:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$
./configure --help |grep -A10 LIST
```

List:

```
  --enable-processes=LIST Comma-separated list of processes to enable. Options
                          are: vbf, ggf, diboson, dibosonjet, triboson,
                          tribosonjet, hjjj, qcdvvjj, qcdvjj,
                          all_except_hexagons, all. Default is
                          all_except_hexagons.
  --enable-kk             --enable-kk to enable simulation of Kaluza-Klein
                          resonances
  --enable-NLO            --disable-NLO to disable next-to-leading order QCD
  --enable-MPI            --enable-MPI to use MPI parallelization
  --enable-madgraph       --enable-madgraph to include code for MadGraph
                          comparisons
```

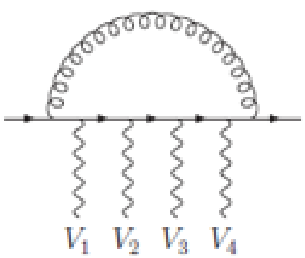
Configure, make, make install

```
./configure --prefix=/home/RUN/SCHOOL --disable-static --enable-MPI --enable-quad CC=mpicc FC=mpifort CXX=mpic++ --enable-processes=all
```

All processes selected

```
==================================================

VBFNLO 3.0.0beta5 configuration

Processes included:
all

NLO QCD              yes
KK resonances        no
Compile warnings     no
Quad precision       yes
MPI                  yes

LHAPDF               no
LOOPTOOLS            no
    GGS              no
                     no
                     not required
                     no

  N compiler         gfortran

==================================================
```

Increase compilation time:
There are
pp→ $VVjj$ at NLO QCD



Configure, make, make install

make –j8: Here 8, numbers of cores of PC

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta
 make -j8
```

make install:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$
 make install
```

Configure, make, make install

The installation path and compiler options stored in:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$
 head config.log
```

Output:

```
This file contains any messages produced by compilers while
running configure, to aid debugging if configure makes a mistake.

It was created by VBFNLO configure 3.0.0beta5, which was
generated by GNU Autoconf 2.69.  Invocation command line was

  $ ./configure --prefix=/home/RUN/SCHOOL --disable-static --enable-MPI --enable-qua
d CC=mpicc FC=mpifort CXX=mpic++ --enable-processes=diboson
```

Binary and Input Files

- Create a RUN directory somewhere and link the exe there:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$
cd /home/RUN/SCHOOL/
francam@lhcpheno22:/home/RUN/SCHOOL$ ls
bin  include  lib  share
francam@lhcpheno22:/home/RUN/SCHOOL$ mkdir RUN
francam@lhcpheno22:/home/RUN/SCHOOL$ cd RUN
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ln -s ../bin/vbfnlo
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ls
vbfnlo
```

- Copy input .dat files from the share folder

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ cp ../share/VBFNLO/*
dat .
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ls
anom_HVV.dat  histograms.dat     random.dat         vbfnlo.dat
anomV.dat     kk_coupl_inp.dat   spin2coupl.dat
cuts.dat      kk_input.dat       susy.dat
ggflo.dat     procinfo.dat       vbfnlo
```

Input Files

- Main files for SM physics:
  - vbfnlo.dat, gglo.dat, cuts.dat
  - vbfnlo.dat:
    - Process
    - Statistics
    - Energy Collider
    - EW input parameters
      - Masses….
    - Central Scale Choice

```
!   Main input file for vbfnlo

!   General parameters of the calculation
!-------------------------------------------
PROCESS                     = 100                   ! Identifier f
LOPROCESS_PLUS_JET          = false                 ! switch: LO p
LEPTONS                     = 11 -11 11 -11 11 -12  ! final state
DECAY_QUARKS                = 93                    ! final state

!
! lepton and quark numbering according to MC particle numb
! particles are given positive numbers, antiparticles nega
! decay products have to be grouped according to their par
!
! e-    ve    mu-   vm    ta-   vt    |   d     u     s     c     b
! 11    12    13    14    15    16    |   1     2     3     4     5
!
! DECAY_QUARKS = 93 includes all possible combinations of
! DECAY_QUARKS = 94 includes also b-quarks (u, u~, d, d~,
! LEPTONS      = 98 includes all possible combinations of
! LEPTONS      = 99 includes all possible combinations of
!

LO_ITERATIONS               = 4            ! number of iterations fo
NLO_ITERATIONS              = 4            ! number of iterations fo
LO_POINTS                   = 20           ! number of points for LO
NLO_POINTS                  = 20           ! number of points for re
LO_GRID                     = "grid2_1" "grid2_2" "grid2_3" "grid
NLO_GRID                    = "grid3_1" "grid3_2" "grid3_3" "grid
PHTN_GRID                   = "grid4_1" "grid4_2" "grid4_3" "grid
FLOOP_GRID                  = "grid5_1" "grid5_2" "grid5_3" "grid

NLO_SWITCH                  = false        ! switch: nlo/lo calculat
EWCOR_SWITCH                = false        ! Whether electroweak cor
FERMIONLOOP                 = 3            ! Contribution of gluon-i
                                           ! 0: none
                                           ! 1: only box diagrams
                                           ! 2: only Higgs resonance
                                           ! 3: both contributions (
NLO_SEMILEP_DECAY           = 0            ! controls whether QCD NL
                                           ! 0: leading order hadron
```

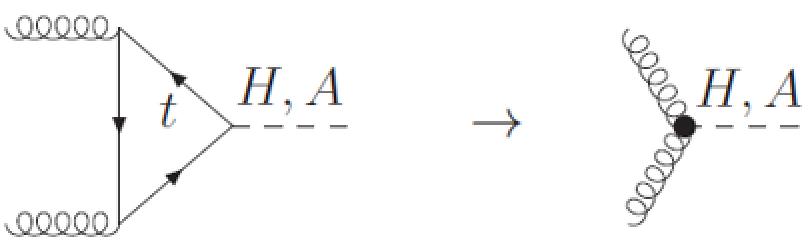
Input Files

- Main files for SM physics:
  - vbfnlo.dat, gglo.dat, cuts.dat
  - cuts.dat:
    - cuts for particles
      - Rapidity
      - PT

```
! input file for the cut parameters

!   Jet cuts
!-------------
RJJ_MIN     = 0.8d0       ! min jet-jet R separation
Y_P_MAX     = 5.0d0       ! max pseudorapidity for partons
PGENKTJET   = 1.0d0       ! exponent of generalised k_T algorithm
PT_JET_MIN = 20.0d0       ! min jet pT
Y_JET_MAX   = 4.5d0       ! max jet rapidity

!   Lepton cuts (only applied to charged leptons)
!---------------------------------------------------
Y_L_MAX     = 2.5d0       ! max lepton rapidity
PT_L_MIN    = 10.0d0      ! min lepton pT
MLL_MIN     = 15.0d0      ! min. m_ll for charged leptons
MLL_MAX     = 1d20        ! max. m_ll for charged leptons
MLL_OSONLY = true         ! m_ll cuts apply to opposite-charged lep
RLL_MIN     = 0.4d0       ! min lepton-lepton R separation
RLL_MAX     = 50.0d0      ! max lepton-lepton R separation

!   Photon cuts
!---------------
Y_G_MAX     = 1.5d0       ! max pseudorapidity for photons
PT_G_MIN    = 20d0        ! min transverse momentum for photons
RGG_MIN     = 0.6d0       ! min photon-photon R separation
RGG_MAX     = 50.0d0      ! max photon-photon R separation
PHISOLCUT   = 0.7d0       ! photon isolation cut
EFISOLCUT   = 1d0         ! efficiency of photon isolation cut

!   Additional cuts
!---------------------------------
RJL_MIN     = 0.6d0       ! min jet-lepton R separation
RJG_MIN     = 0.6d0       ! min jet-photon R separation
RLG_MIN     = 0.6d0       ! min lepton-photon R separation

MLG_MIN     = 0.0d0       ! min. m_lg for any comb. of charged lept
MLG_MAX     = 1.d20       ! max. m_lg for any comb. of charged lept

PTMISS_MIN = 0.0d0        ! minimal missing transverse momentum
                          ! (pt of neg. sum of 4-momenta of all vi
```

Input Files

- Main files for SM physics:
  - vbfnlo.dat, gglo.dat, cuts.dat
  - ggflo.dat:
    - Specific for GFHjj processes
      - Eff vs Full Theory
      - Model SM or BSM
      - Switch on sub-processes



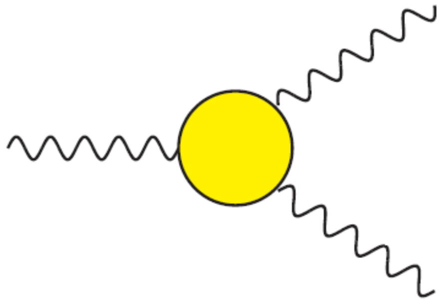

```
!**********************************************
!  This is the main input file for GGFLO
!----------------------------------------------
!  author   : Michael Kubocz
!  modified : 03.03.2011
!**********************************************


!------------------------- loop particle(s) ------
Q_LOOP        = 3          ! 0 : effective theory
                           ! 1 : top-loop
                           ! 2 : bottom-loop (varies w
                           ! 3 : top loop + bottom loo

!------------------------- subprocess choice -----
SUBPRQQ       = true      ! quark-quark scattering
SUBPRQG       = true      ! quark-gluon scattering
SUBPRGG       = true      ! gluon-gluon scattering

!--------------- Mixing between different Higgs b
HIGGS_MIX     = 0          ! whether higgs mixing is t
CP_EVEN_MOD   = 1d0        ! changes the strength of t
CP_ODD_MOD    = 1d0        ! changes the strength of t

!Further important parameters are present in the f
!have to be changed there:

!PROCESS        41xx Identifier for gluon fusion (
!MODEL, HTYPE
!TOPMASS
!BOTTOMMASS
!     .
!     .
!     .
!...see vbfnlo.dat !
```

Input Files

- Other files:
  - histograms.dat, random.dat, procinfo.dat
    - Random.dat
      - chose initial seed number: by default 0
    - Procinfo.dat
      - List of processes
    - Histograms.dat
      - Change range of plotted histograms (Save compilation time)
      - Smearing & errors

```
!! This input file allows the user to alter the his
!! enable smearing between adjacent bins and enable

SMEARING    = true                    ! enable or disab
SMEAR_VALUE = 0.10d0                  ! bin fraction wh

!! Error calculation for gnuplot histograms
CALC_ERROR_GNUPLOT = false            ! calculate per b

!! Error calculation for root histograms defined in
!! (an error estimation for the histograms in rootu
CALC_ERROR_ROOT = false               ! calculate per b

!!
!! Error calculation for raw histogram data files
!!
!! Format for 1D data files:
!! x    y    y-error
!!
!! Format for 2D data files:
!! x    y    z    z-error
!!
CALC_ERROR_1D       = true            ! calculate per b
CALC_ERROR_2D       = false           ! calculate per b

!!
!! Modify histogram ranges for x-axis
!!

!! 1D Histograms:
!! FORMAT = <min> <max>
! HIST_ID1         =    0D0 250D0      !  pT of taggin
! HIST_ID2         =    0D0 500D0      !  pT of taggin
! HIST_ID3         =    0D0 200D0      !  pT of taggin
! HIST_ID4         =    -5D0 5D0       !  y of tagging
! HIST_ID5         =    -5D0 5D0       !  y of tagging
! HIST_ID6         =    -5D0 5D0       !  y of tagging
! HIST_ID7         =    0D0 500D0      !  pT_max of al
! HIST_ID8         =    0D0 200D0      !  pT_min of al
! HIST_ID9         =    0D0 5D0        !  |eta|_max of
! HIST_ID10        =    0D0 5D0        !  |eta|_min of
-UU-:----F1  histograms.dat    Top L1      (Fundament
```

Input Files



- Main files for BSM physics:

```
anom_HVV.dat   kk_coupl_inp.dat   spin2coupl.dat
anomV.dat      kk_input.dat       susy.dat
```

Anomalou coupling Paraters

Kaluza-Klein and Spin models

MSSM

Running the Code

- Running (store output into a file):

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ls
anom_HVV.dat  ggflo.dat          kk_input.dat  spin2coupl.dat  vbfnlo.dat
anomV.dat     histograms.dat     procinfo.dat  susy.dat
cuts.dat      kk_coupl_inp.dat   random.dat    vbfnlo
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ mpirun -np 4 vbfnlo > LOG.proc100_s
tat20_LO.out &
```

- Output:

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ls histograms.* LOG.proc100_stat20_
LO.out gri* xsec*
grid2_1.out.1  grid2_1.out.3  histograms.dat  LOG.proc100_stat20_LO.out
grid2_1.out.2  grid2_1.out.4  histograms.gp   xsection.out

histograms.dir:
hist_noerror.gp  hist_witherror_1d.gp  Kfac  LO  NLO
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$
```

Running the Code

- grid2_1.out.X : MonteCarlo grid of random number. One can store it for next run, if parameter has not been changed

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ cp grid2_1.out.4 grid2_1
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$
```

- Cross section result: xsection.out

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ head xsection.out
   2525.1423327782900          2.0474729506923652
   0.0000000000000000          0.0000000000000000
```

- More Detail information of the Run in

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ls LOG.proc100_stat20_LO.out
LOG.proc100_stat20_LO.out
```

  - Evolution of cross section per iteration
  - Cuts, input parameters

grep –A10 “iteration “ LOG*

```
accumulated statistics:
integral =  2.526406E+03,  sigma = 8.685E+01,  chi^2/iteration = 1.137E-13

MONACO:  grid written to file grid2_1.out.1

MONACO input parameters:
ndim =  9,  ncall =     256k,   rtype = 0
--
iteration  2:
integral =  2.517866E+03,  sigma = 1.211E+01
efficacy = 2.196E-02,  raw efficacy = 6.304E-04
f_positive = 5.790E-1,  f_zero = 4.210E-1,  f_negative = 0.000E+0
accumulated statistics:
integral =  2.518029E+03,  sigma = 1.199E+01,  chi^2/iteration = 9.485E+03

MONACO:  grid written to file grid2_1.out.2

MONACO input parameters:
ndim =  9,  ncall =     512k,   rtype = 0
--
iteration  3:
integral =  2.519003E+03,  sigma = 4.462E+00
efficacy = 6.445E-02,  raw efficacy = 6.097E-04
f_positive = 7.485E-1,  f_zero = 2.515E-1,  f_negative = 0.000E+0
accumulated statistics:
integral =  2.518885E+03,  sigma = 4.182E+00,  chi^2/iteration = 1.529E-02

MONACO:  grid written to file grid2_1.out.3

MONACO input parameters:
ndim =  9,  ncall =       1M,   rtype = 0
--
iteration  4:
integral =  2.527116E+03,  sigma = 2.348E+00
efficacy = 3.209E-02,  raw efficacy = 5.977E-04
f_positive = 8.057E-1,  f_zero = 1.943E-1,  f_negative = 0.000E+0
accumulated statistics:
integral =  2.525142E+03,  sigma = 2.047E+00,  chi^2/iteration = 1.481E+00

MONACO:  grid written to file grid2_1.out.4

 result (LO):    2525.1423327782900       +-    2.0474729506923652       fb
```

Plots: histograms.gp or individually in histograms.dir

- Generating the plots:

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ gnuplot histograms.gp
Warning: empty y range [0:0], adjusting to [-1:1]
Warning: empty y range [0:0], adjusting to [-1:1]
Warning: empty y range [0:0], adjusting to [-1:1]
Warning: empty y range [0:0], adjusting to [-1:1]
```

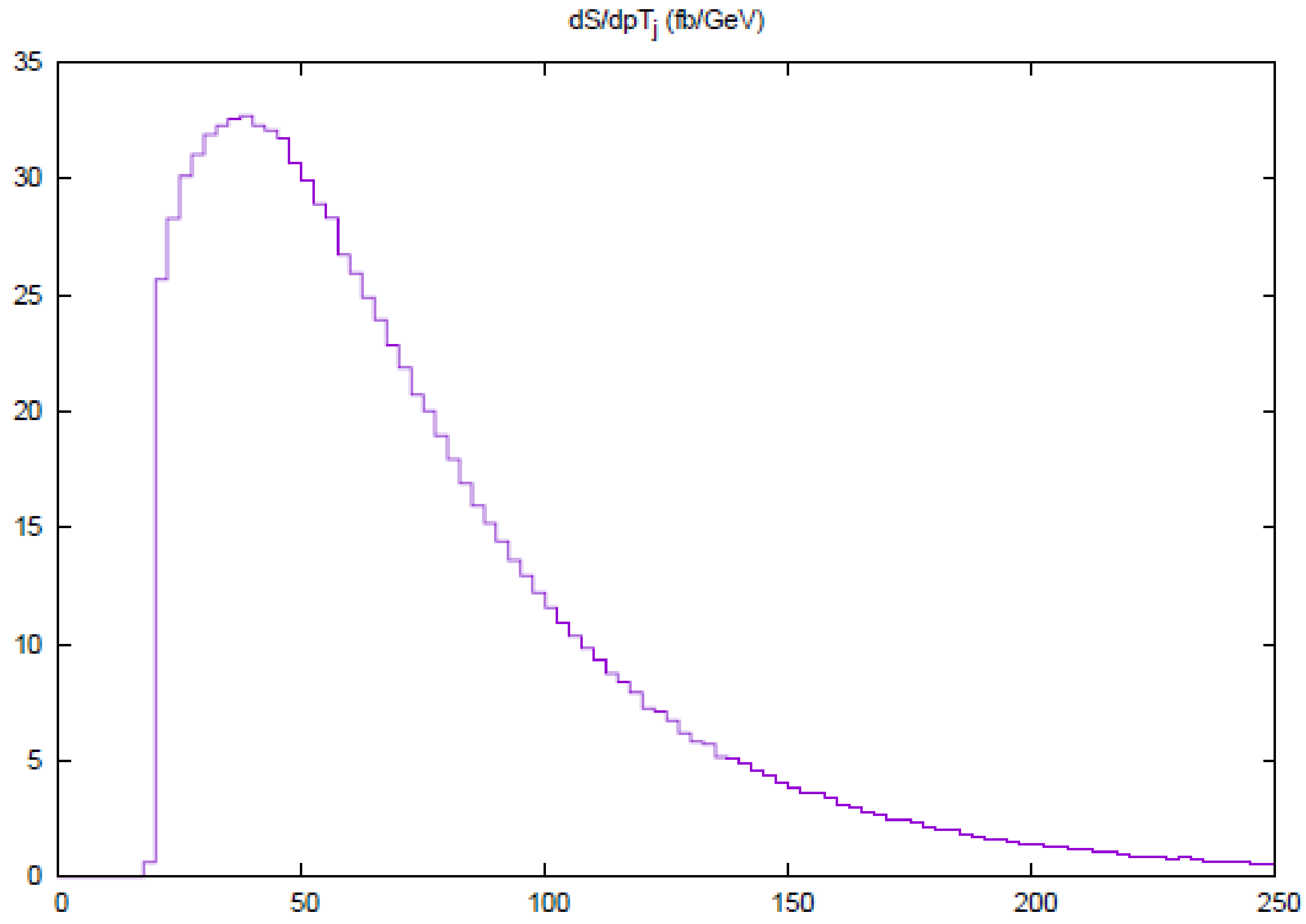
- The ouput: histograms.ps

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ ls histograms.
histograms.dat  histograms.dir/ histograms.gp   histograms.ps
```

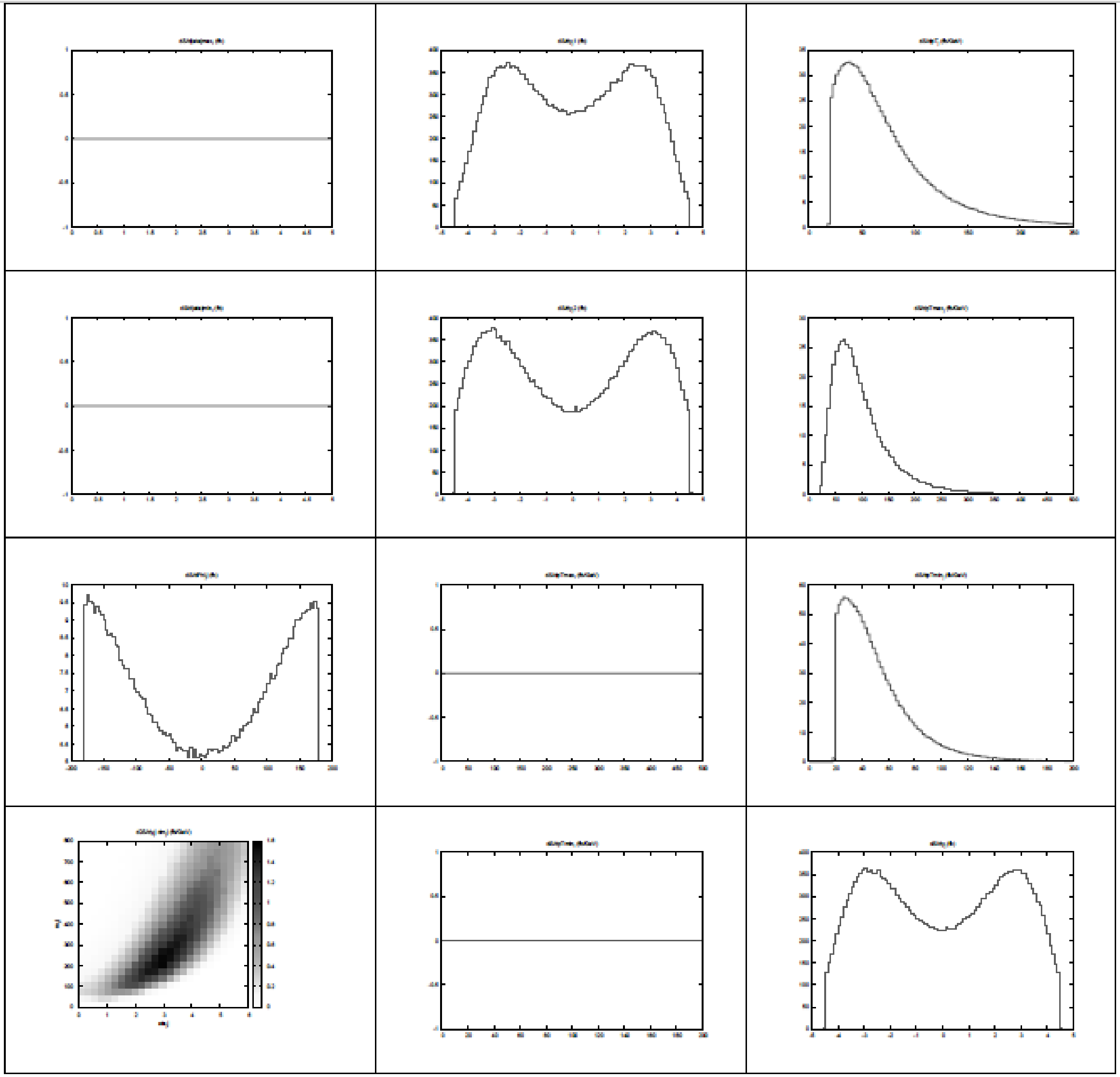
- Opening the file:

```
francam@lhcpheno22:/home/RUN/SCHOOL/RUN$ gv histograms.ps
```

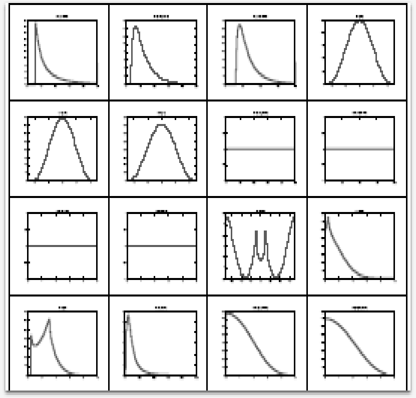
Default Plots: Limited amount



Default Plots: Limited amount



Adding New histograms: GF HJJJ



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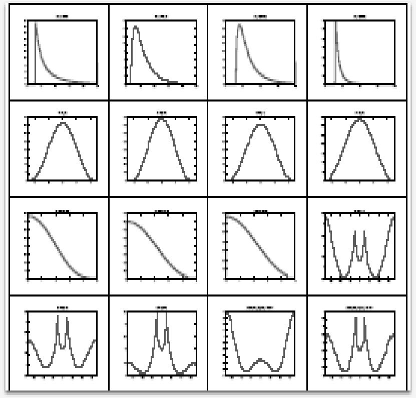

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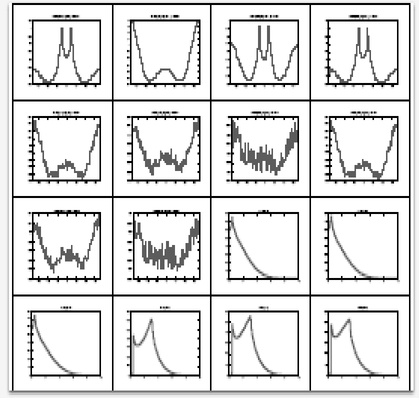

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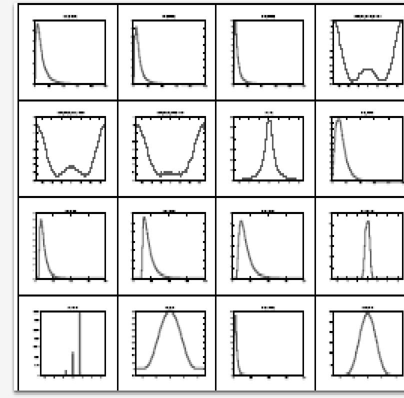

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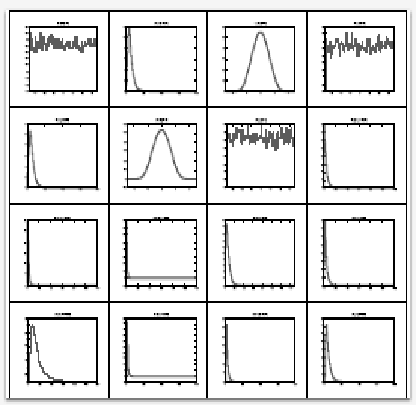
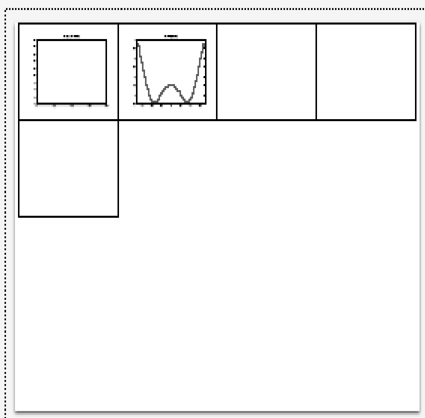


80



85

Adding New Histograms:

- Source code: utilities/histograms.F

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$ l
amplitudes/       doc/       lib/     PDFsets/      src/
autom4te.cache/   helas/     loops/   phasespace/   utilities/
config/           include/   m4/      regress/
```

- Define the new histograms:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$ grep -i  "call createhist" utilities/histograms.F
*      call CreateHist(ID, title, #bins, min, max)
       call CreateHist(1, "dS/dpT_j (fb/GeV)",100,0d0,250d0)    !pT of tagging jets
       call CreateHist(2, "dS/dpTmax_j (fb/GeV)",100,0d0,500d0) !pT of tagging jet with higher pT
       call CreateHist(3, "dS/dpTmin_j (fb/GeV)",100,0d0,200d0) !pT of tagging jet with lower pT
       call CreateHist(4, "dS/dy_j (fb)",100,-5d0,5d0)        !y of tagging jets
       call CreateHist(5, "dS/dy_j1 (fb)",100,-5d0,5d0)       !y of tagging jet with higher pT
       call CreateHist(6, "dS/dy_j2 (fb)",100,-5d0,5d0)       !y of tagging jet with lower pT
       call CreateHist(7, "dS/dpTmax_l (fb/GeV)",100,0d0,500d0)     !pT_max of all leptons
       call CreateHist(8, "dS/dpTmin_l (fb/GeV)",100,0d0,200d0)     !pT_min of all leptons
       call CreateHist(9, "dS/d|eta|max_l (fb)",100,0d0,5d0)  !|eta|_max of all leptons
```

Adding histograms: histograms.F

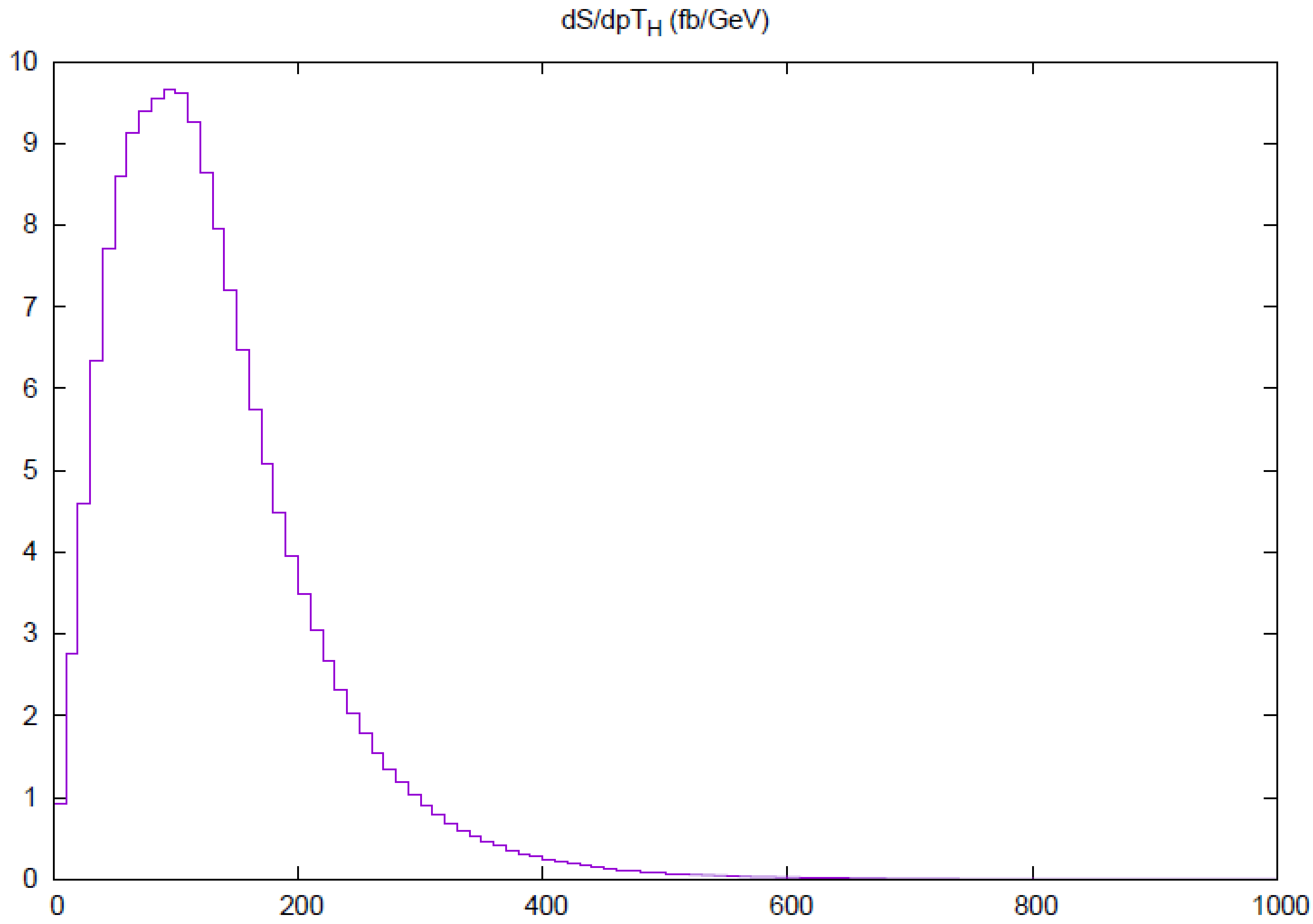
- Filling the histogram with the observable:

```
francam@lhcpheno22:~/Work/Projects/SCHOOL/VBFNLO-3.0.0beta5$ grep -i  "call FillHist" utilities/histograms.F
         call FillHist( 1, jets(5,tag1), dw*0.5d0, NLO)
         call FillHist( 1, jets(5,tag2), dw*0.5d0, NLO)
         call FillHist( 2, jets(5,tag1), dw, NLO)
         call FillHist( 3, jets(5,tag2), dw, NLO)
            call FillHist( 1, jets(5,1), dw*0.5d0, NLO)
            call FillHist( 2, jets(5,1), dw, NLO)
            call FillHist( 1, jets(5,2), dw*0.5d0, NLO)
            call FillHist( 3, jets(5,2), dw, NLO)
         call FillHist( 4, jets(6,tag1), dw*0.5d0, NLO)
         call FillHist( 4, jets(6,tag2), dw*0.5d0, NLO)
```

- Higgs observables:

```
******************
* pT of the Higgs boson
******************
!      if (n_jets.eq.3) then
         CALL legoy(v(0:3,1),pH_T,yH,phiH)
         call FillHist( 69, pH_T, dw, NLO)
         call FillHist( 75, yH, dw, NLO)
* Higgs Jet correlations
         do i = 0,3
            temp(i)=v(i,1)+jets(i,1)
         enddo
         call legoy(temp,pthj,yhj,phihj)
         call FillHist(76, pthj, dw, NLO)
         call FillHist(77, yhj, dw, NLO)
         call FillHist(78, phihj* 180d0 / Pi, dw, NLO)
** Tau observable
```

PT Higgs in GF HJJJ Production: Preliminary



Future Developments VBFNLO

- Interface with Herwig → Parton Shower and Hadronization
  - Iván Rosario Bonastre, et al.
- Electroweak Corrections

- New GF induced processes
  - HJJJ (B)SM
  - HH pair at NLO (B)SM
    - Jonathan Ronca et al.

Summary

LHC complicated machine

PDF’s, Hard Process, Parton Showers and Hadronization

Factorization of different parts is crucial

Precision is needed to find hints of new physics

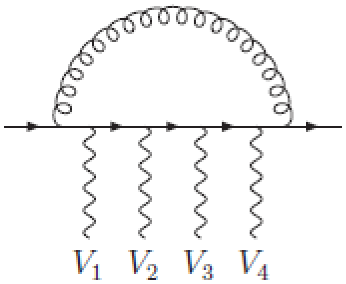
→ NLO, NNLO QCD & EW NLO needed

There are many public tools to do phenomenology

VBFNLO, one of the group

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES



$$= \mathcal{M}_{V_1 V_2 V_3 V_4,\tau} = g_\tau^{V_1 f} g_\tau^{V_2 f} g_\tau^{V_3 f} g_\tau^{V_4 f} \frac{g_0^2}{(4\pi)^2} \mathcal{C}_{ij}^{V_1 V_2 V_3 V_4} \mathcal{M}_\tau^{ij},$$

$$\mathcal{M}_\tau = \mathcal{M}_\tau^{D=4} + (D-4)\mathcal{M}_\tau^{DR},$$

$\mathcal{M}_\tau^{DR} \rightarrow$ Rational Terms coming from $\gamma^\mu \gamma_\mu = D$ contractions

These terms are written:

$$\mathcal{M}_\tau^{(D=4,DR)} = \sum_{i,j,\tau} \mathrm{SM}_{i,\tau}\, \mathrm{F1}_j,$$

$\mathrm{SM}_{i,\tau}$: Standard matrix elements along the quark line

$$\mathrm{SM}_{1,\tau} = \bar{u}(k_2)\gamma^{\mu_4}\gamma^{\mu_3}\gamma^{\mu_2}\gamma^{\mu_1}\not{p}_4\not{p}_3\not{p}_2\omega_\tau u(k_1), \quad \omega_\pm = \frac{1 \pm \gamma^5}{2}$$

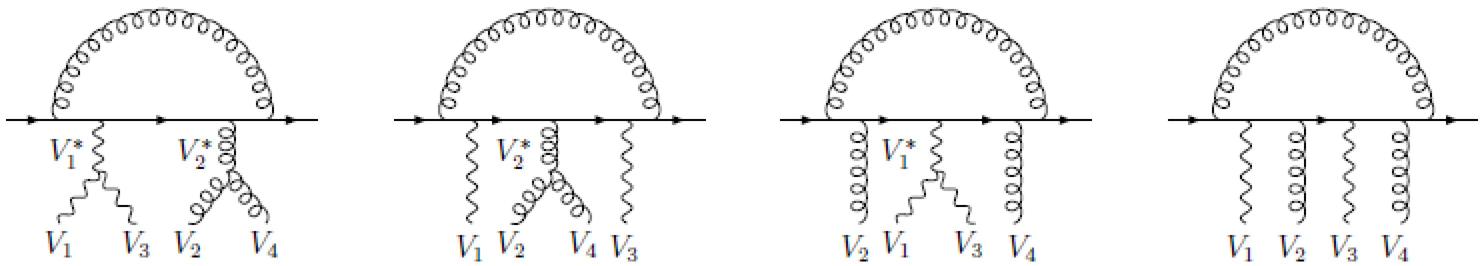
$$\mathrm{F1}_j = \sum_k \mathrm{F}_k \prod_{m,n} p_m \cdot \epsilon(p_n),$$

F_k: Functions with loop information ($B_0, C_0, \ldots F_{ij}$)

$\boxed{\mathcal{M}_\tau^{D=4} \quad \& \quad \mathcal{M}_\tau^{DR} \text{ : Full Result}}$

$$\mathcal{M}_\tau^{D=4} = \widetilde{\mathcal{M}}_\tau + \frac{\mathcal{M}_\tau^1}{\epsilon} + \frac{\mathcal{M}_\tau^2}{\epsilon^2},$$

$$(D-4)\mathcal{M}_\tau^{DR} = \widetilde{\mathcal{N}}_\tau + \frac{\mathcal{N}_\tau^1}{\epsilon},$$



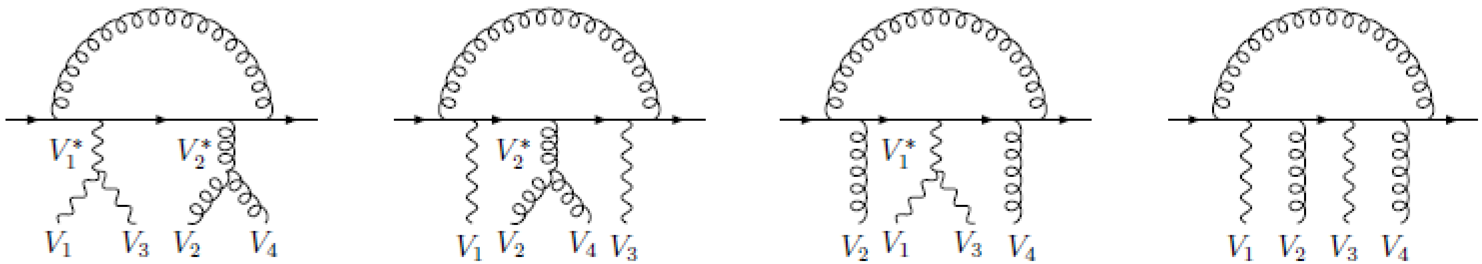
- Effective current approach

$$A_{V_1 V_2 V_3 V_4,\tau} = J^{\mu_1}_{V_1^*} J^{\mu_2}_{V_2^*} \mathcal{M}_{\mu_1\mu_2,\tau} \equiv \mathcal{M}_{V_1^* V_2^*,\tau},$$

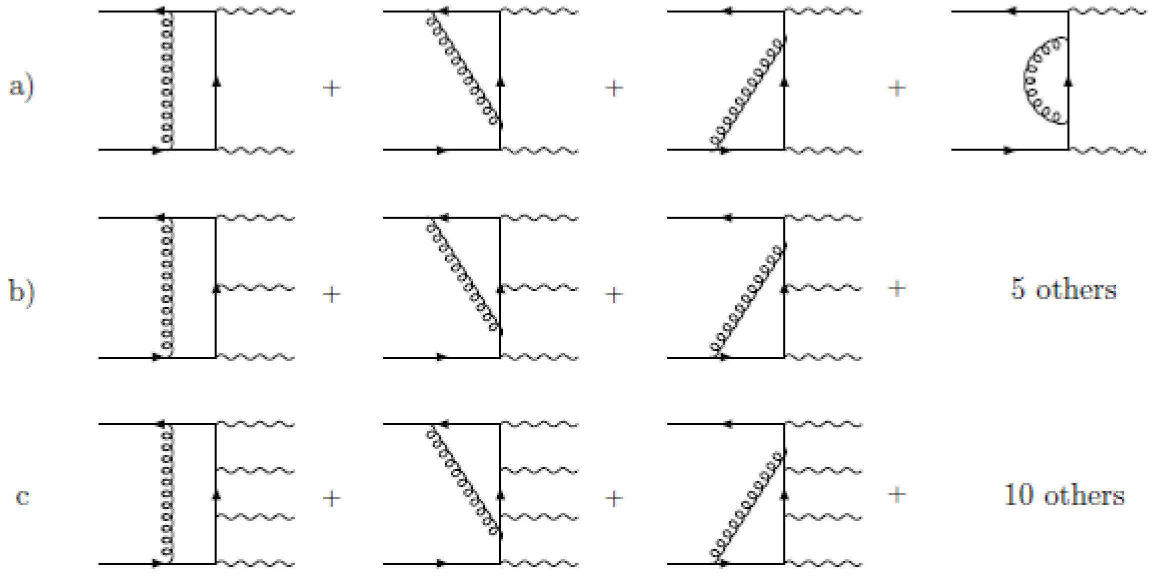
$$J^{\mu_1}_{V_1^*}(q_1) = \frac{-I}{q_1^2 - M^2_{V_1^*} - I\, M_{V_1^*}\Gamma_{V_1^*}} \left(g^{\mu_1}_{\mu} - \frac{q_1^{\mu_1} q_{1\mu}}{q_1^2 - M^2_{V_1^*} - I\, M_{V_1^*}\Gamma_{V_1^*}} \right) \Gamma^{\mu}_{V_1^* V_1 V_3}$$

12 Universal Blocks $\approx$ 5000

Code: Fast to compile & Easy to handle, e.g. numerical uncertainties



Building Blocks:



[FC 1105.0920]

- Ward Identities Gauge Test: $(\epsilon(p_i) \to p_i)$

```
hexline=penline(1)-penline(2)
penline=boxline(1)-boxline(2)
```

- Divergent pieces factorize against born amplitude

$$\begin{aligned}\mathcal{M}_{V_1\ldots V_n,\tau} \quad = \quad & g_\tau^{V_1 f} \ldots g_\tau^{V_n f} C_F \frac{\alpha_s(\mu)}{4\pi} \Big(\widetilde{\mathcal{M}}_V + \\ & + \left(\frac{4\pi\mu^2}{-s}\right)^\epsilon \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{10-D}{2\epsilon} \right] \mathcal{M}^B_{V_1\ldots V_n,\tau} \Big)\end{aligned}$$

- Renormalization scale independence

For on-shell massless particles(g,γ), transversality must be used$(\epsilon(p_i) \cdot p_i = 0)$

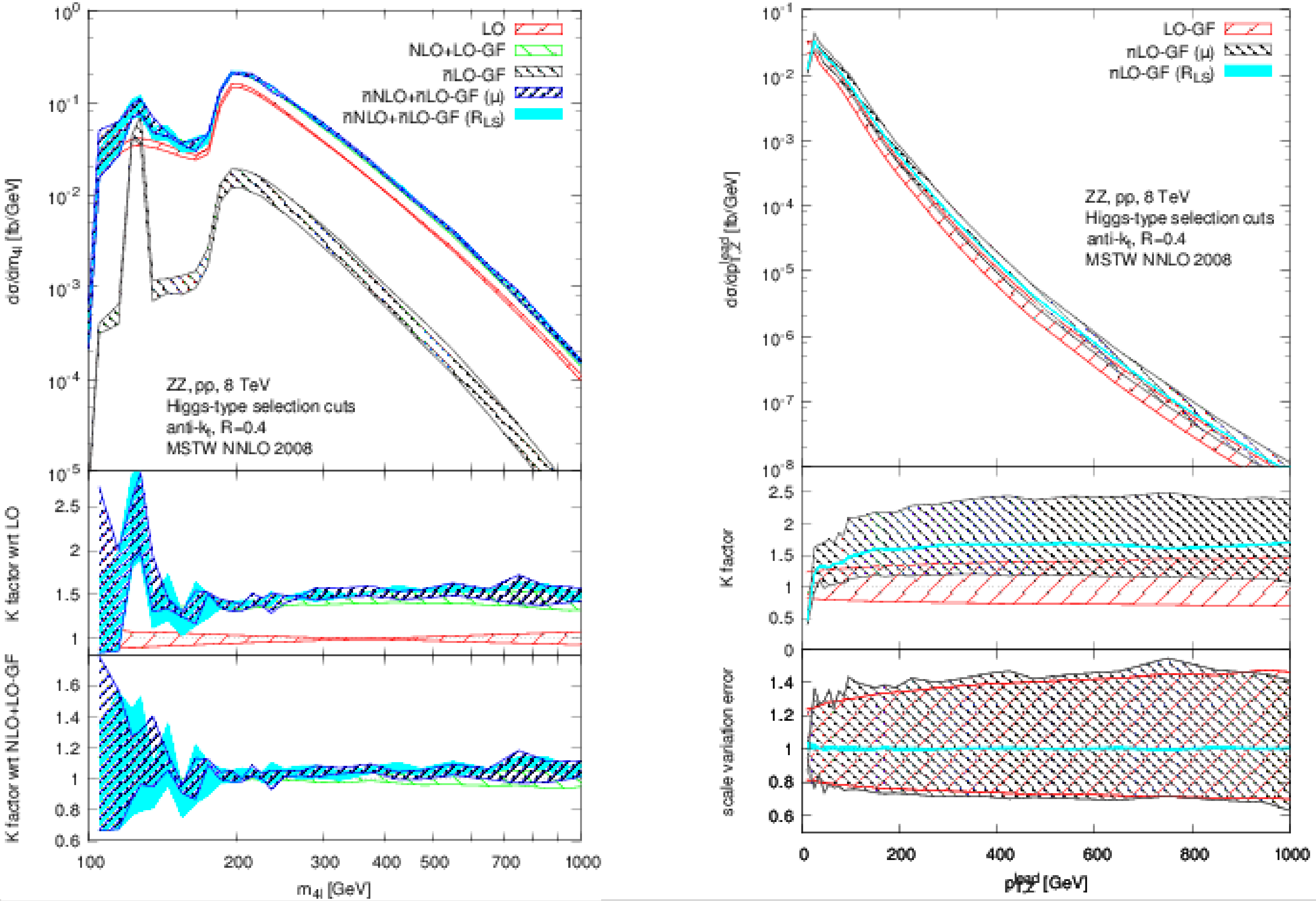
VV

Higgs Searches

$$p_{t,e} > 7\,\text{GeV}\,, \qquad |\eta_e| < 2.5\,,$$
$$p_{t,\mu} > 5\,\text{GeV}\,, \qquad |\eta_\mu| < 2.4\,,$$
$$p_{t,\ell_{\text{hardest}}} > 20\,\text{GeV}\,, \qquad m_{4\ell} > 100\,\text{GeV}\,,$$
$$p_{t,\ell_{\text{second-hardest}}} > 10\,\text{GeV}\,,$$

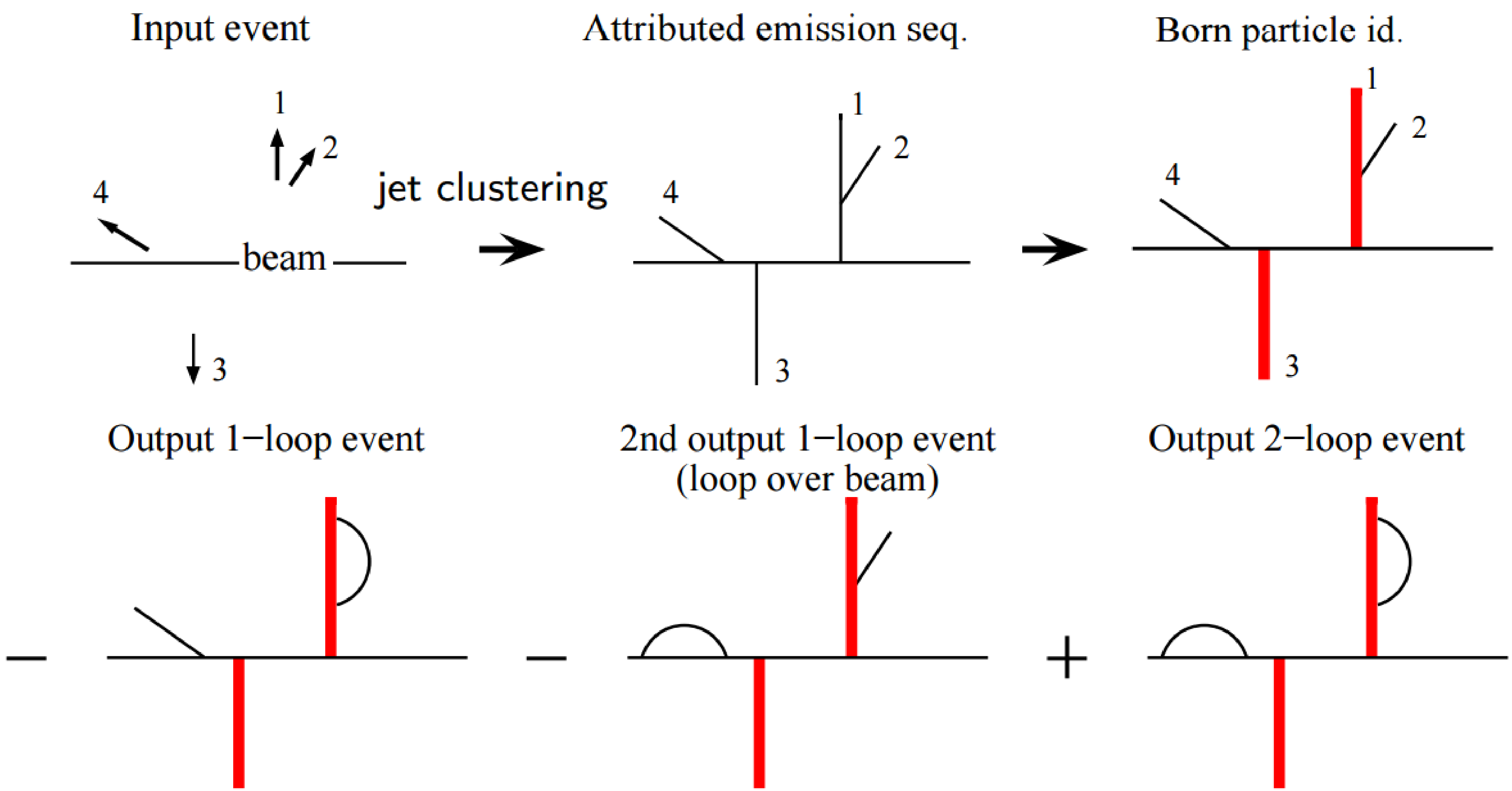
$$40 < m_{\ell\ell} < 120\,\text{GeV} \qquad \text{for the } \ell\ell \text{ pair with mass closer to } m_Z,$$
$$12 < m_{\ell\ell} < 120\,\text{GeV} \qquad \text{for the other } \ell\ell \text{ pair},$$
$$m_{\ell\ell} > 4\,\text{GeV} \qquad \text{for any oppositely-charged pair of leptons.}$$

M_{4l} & $p_{T,Z}^{lead}$



LO
NLO+LO-GF
ñLO-GF
ñNLO+ñLO-GF (μ)
ñNLO+ñLO-GF (R_LS)
ZZ, pp, 8 TeV
Higgs-type selection cuts
anti-k_t, R=0.4
MSTW NNLO 2008
dσ/dm_4l [fb/GeV]
K factor wrt LO
K factor wrt NLO+LO-GF
m_4l [GeV]
LO-GF
ñLO-GF (μ)
ñLO-GF (R_LS)
dσ/dp_T,Z^lead [fb/GeV]
K factor
scale variation error
p_T,Z^lead [GeV]

LoopSim



Sum of weights = 0 (Unitarity)

Ingredients

VBFNLO:

ZZ@NLO ZZj@NLO

GF ZZ@LO GF ZZj@LO

Note that GF ZZ@LO contributes at NNLO and

GF ZZj@LO contributes at NNNLO

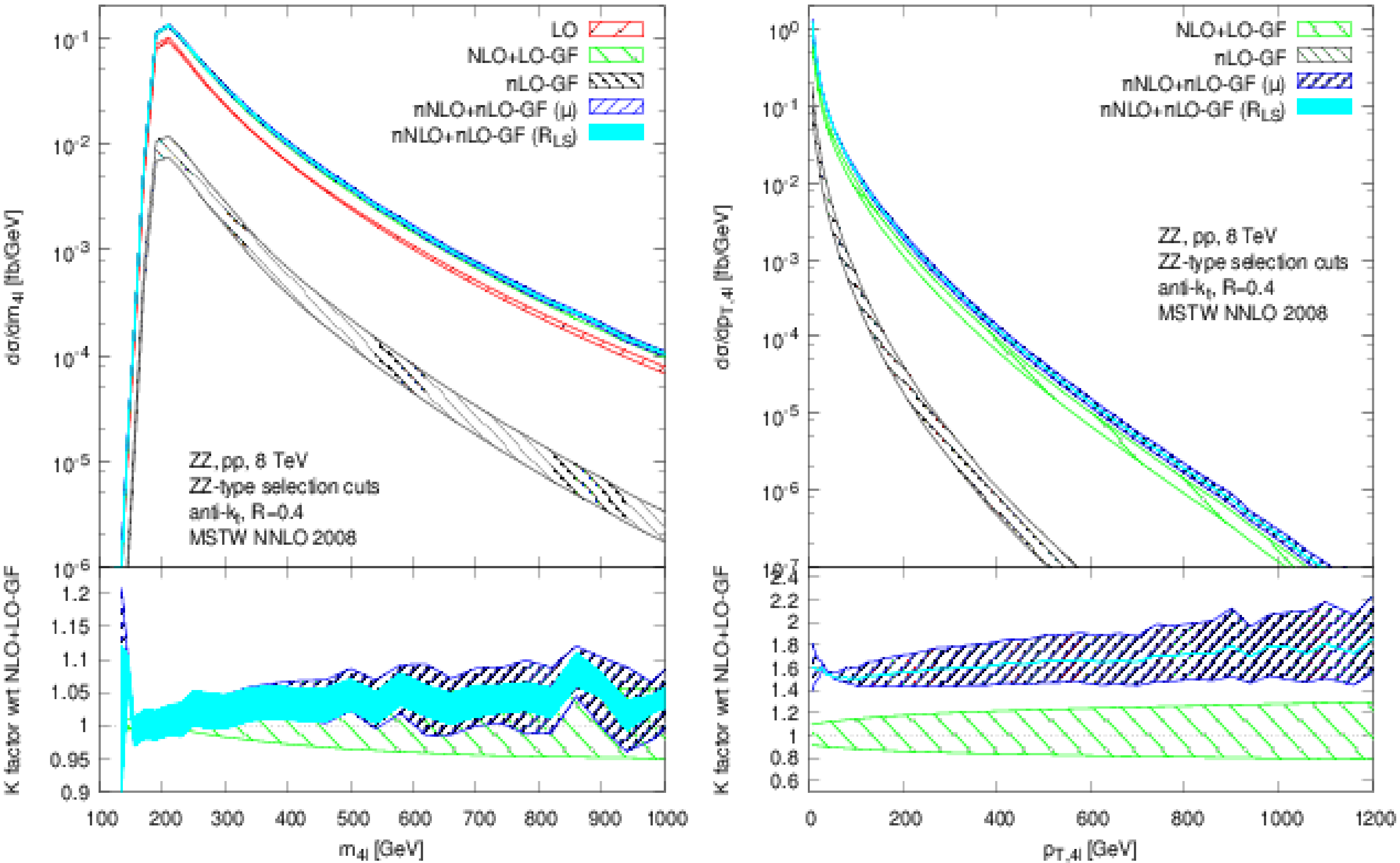
Merging Convention:

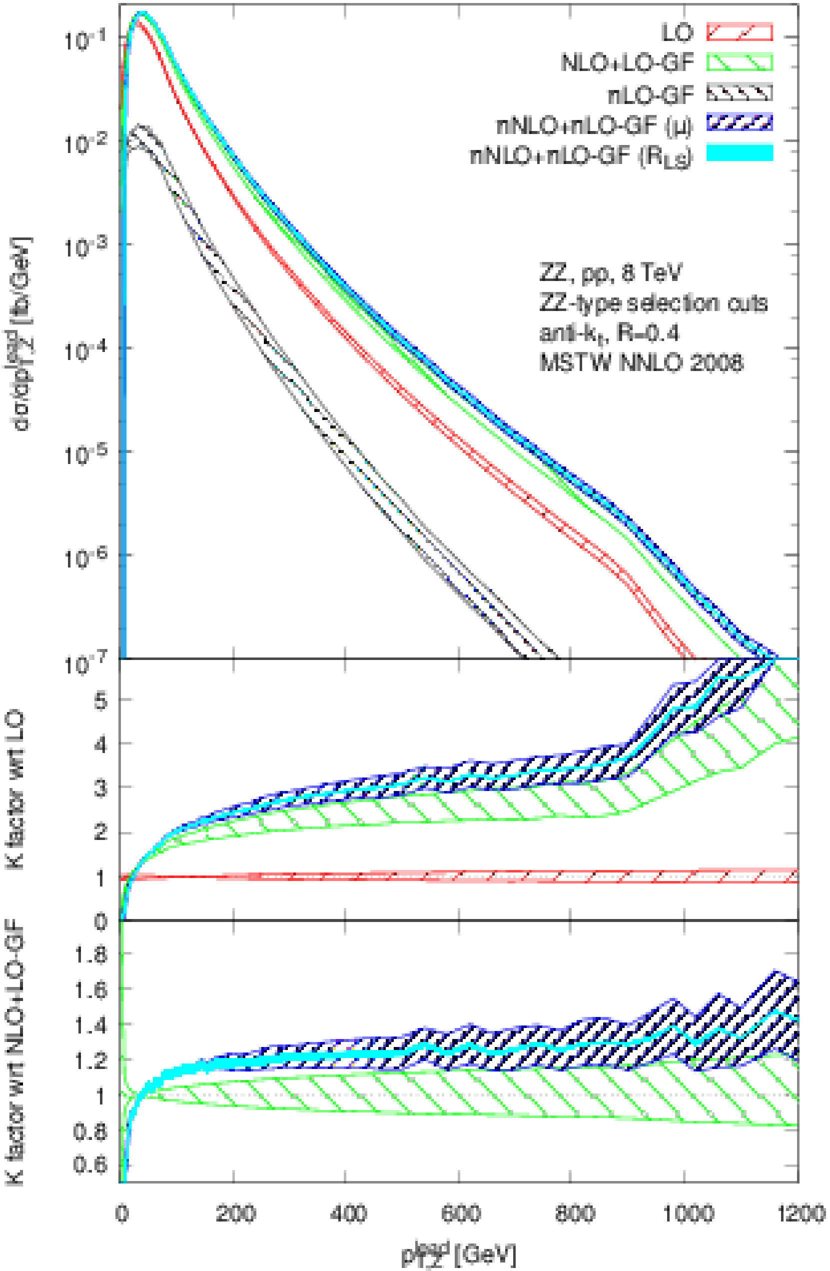
GF ZZ@LO + GF ZZj@LO = GF ZZ@nLO

ZZ@NLO + ZZj@NLO + GF ZZ@LO = ZZ@nNLO

ZZ

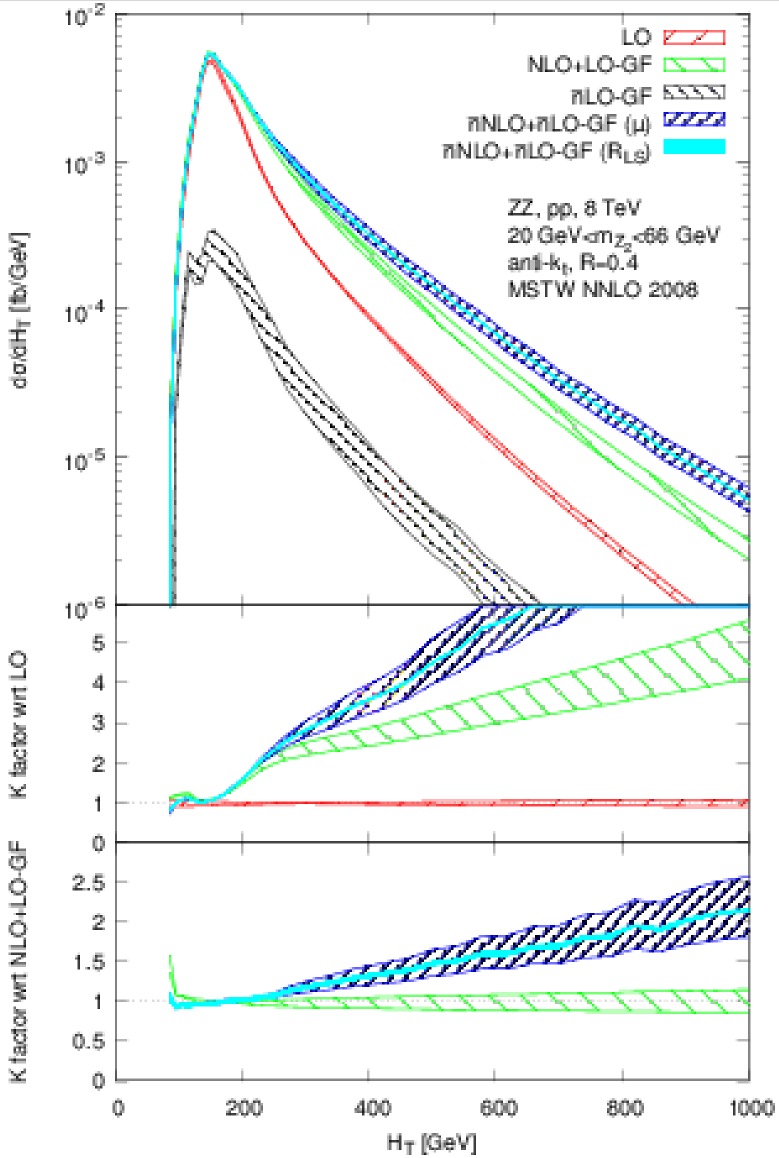
4 lepton observables



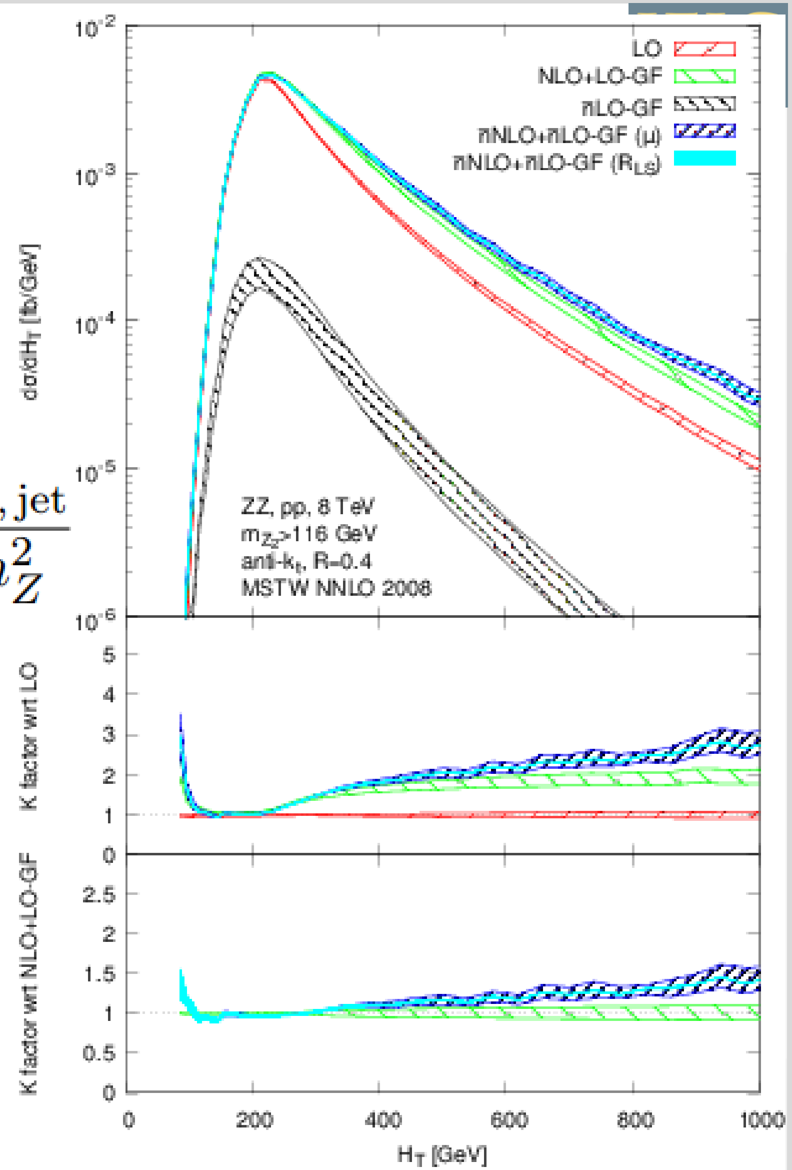


$$m_{\ell\ell}^2 \simeq \frac{1}{4} p_{T,Z}^2 \Delta R_{\ell,\ell}^2$$

$$p_{T,Z} \lesssim 10\, m_{\ell\ell}$$



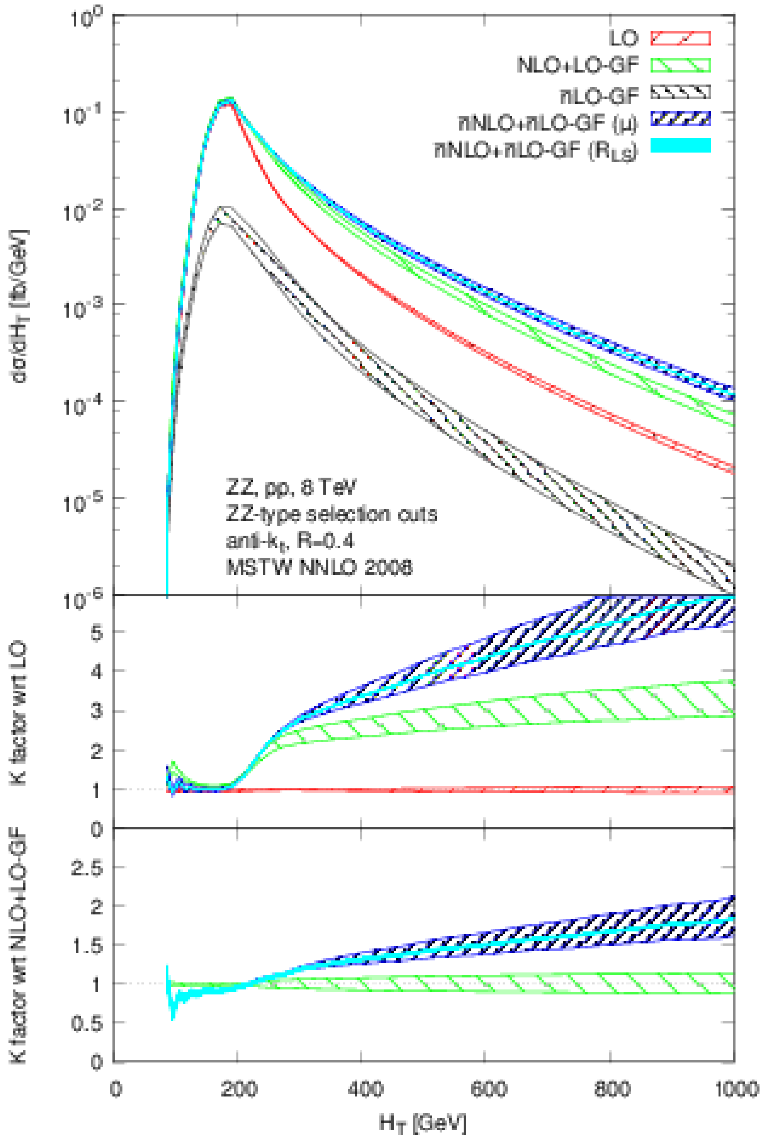
$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\text{jet}}^2}{m_Z^2}$$



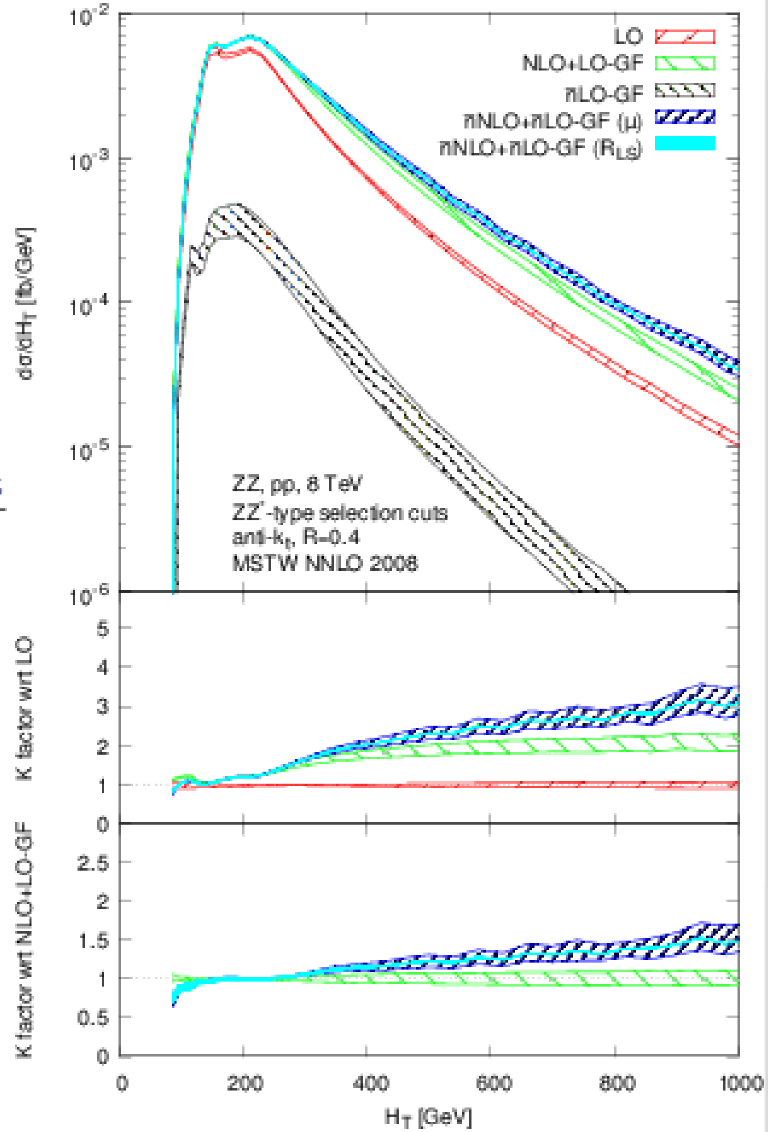
$m_{Z_2} \in (20, 66)\,\text{GeV}$

$m_{Z_2} \in (166, m_{Z,\max})\,\text{GeV}$

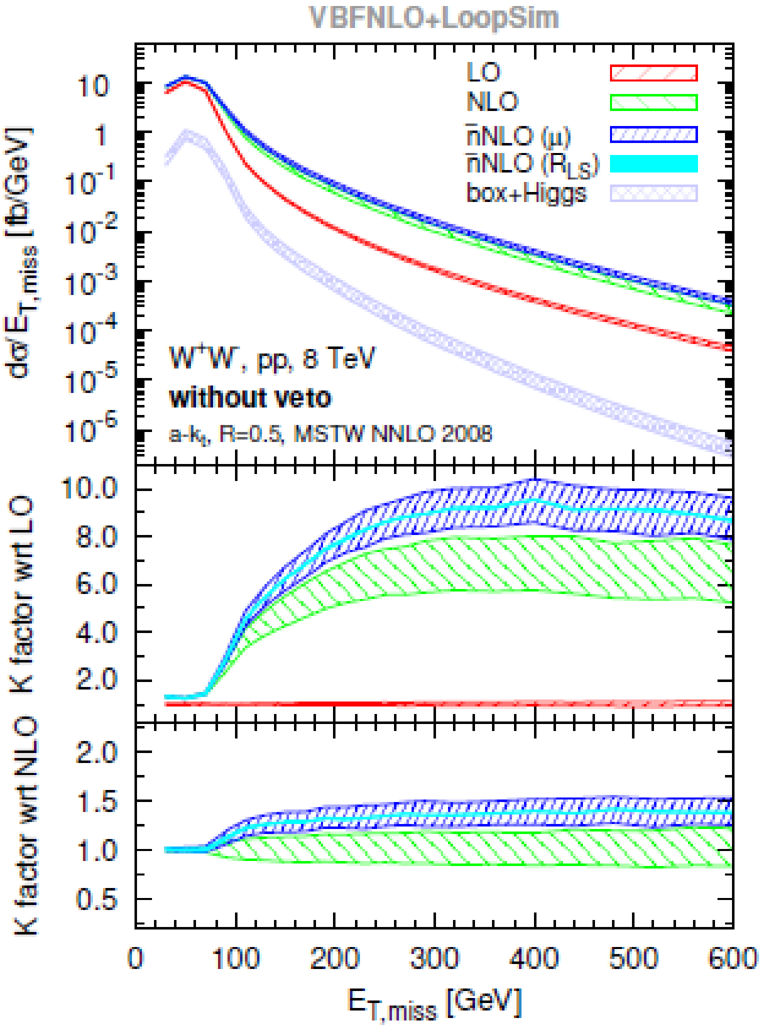
$$H_T = \sum p_{T,\text{jets}} + \sum p_{T,l}$$

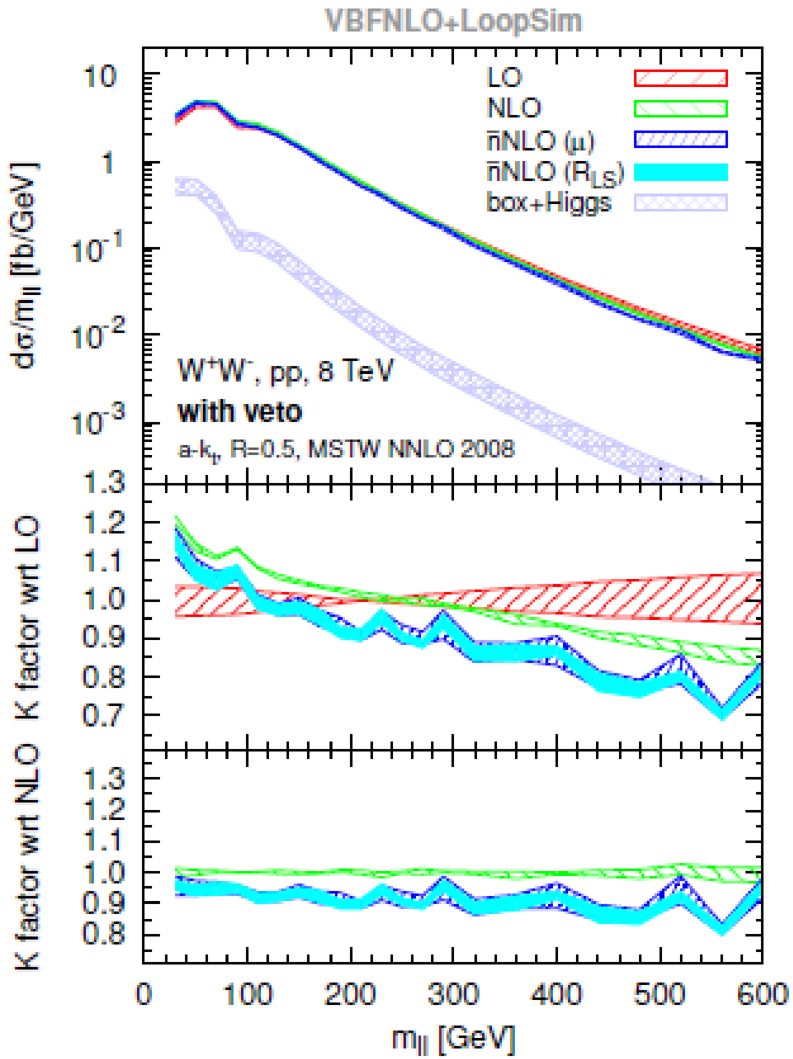


$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\text{jet}}^2}{m_Z^2}$$

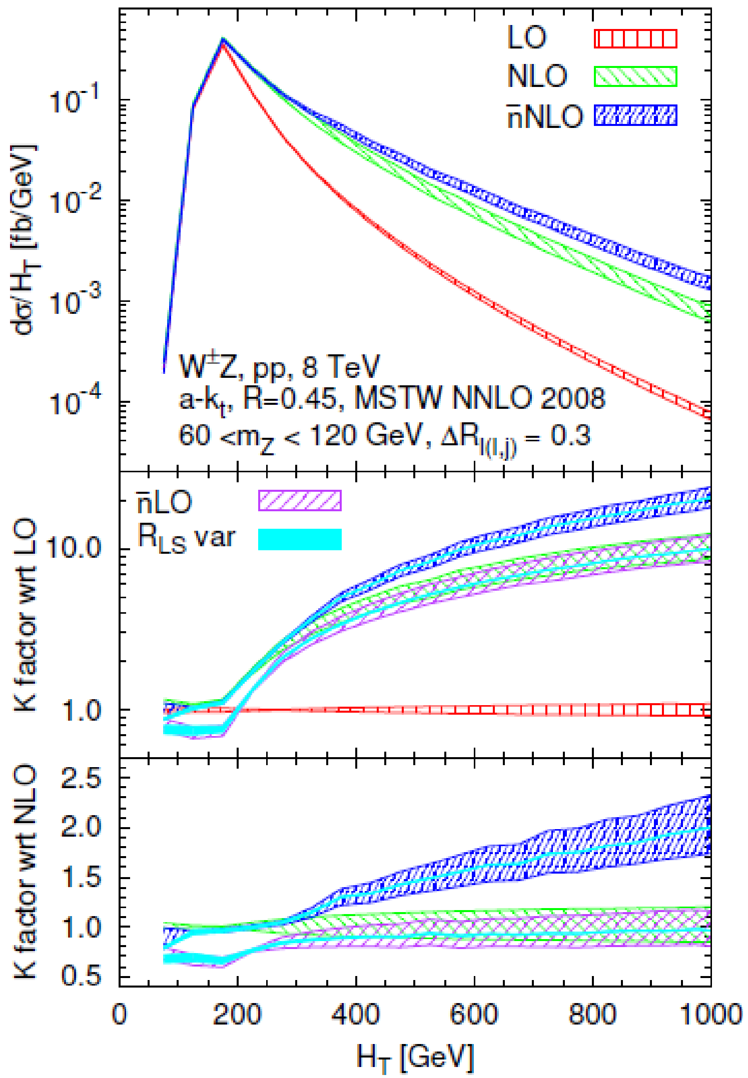


WW


VBFNLO+LoopSim
LO
NLO
n̄NLO (μ)
n̄NLO (R_LS)
box+Higgs
W⁺W⁻, pp, 8 TeV
without veto
a-k_t, R=0.5, MSTW NNLO 2008
dσ/E_T,miss [fb/GeV]
K factor wrt LO
K factor wrt NLO
E_T,miss [GeV]

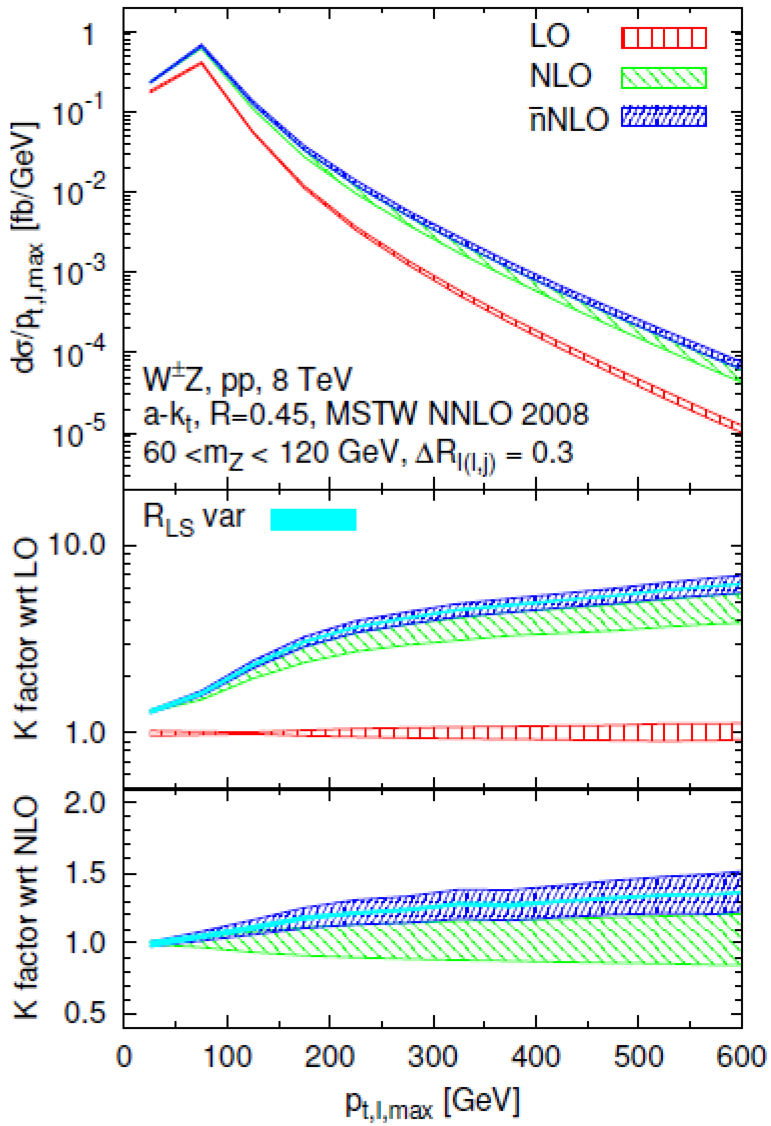

VBFNLO+LoopSim
LO
NLO
n̄NLO (μ)
n̄NLO (R_LS)
box+Higgs
W⁺W⁻, pp, 8 TeV
with veto
a-k_t, R=0.5, MSTW NNLO 2008
dσ/m_ll [fb/GeV]
K factor wrt LO
K factor wrt NLO
m_ll [GeV]

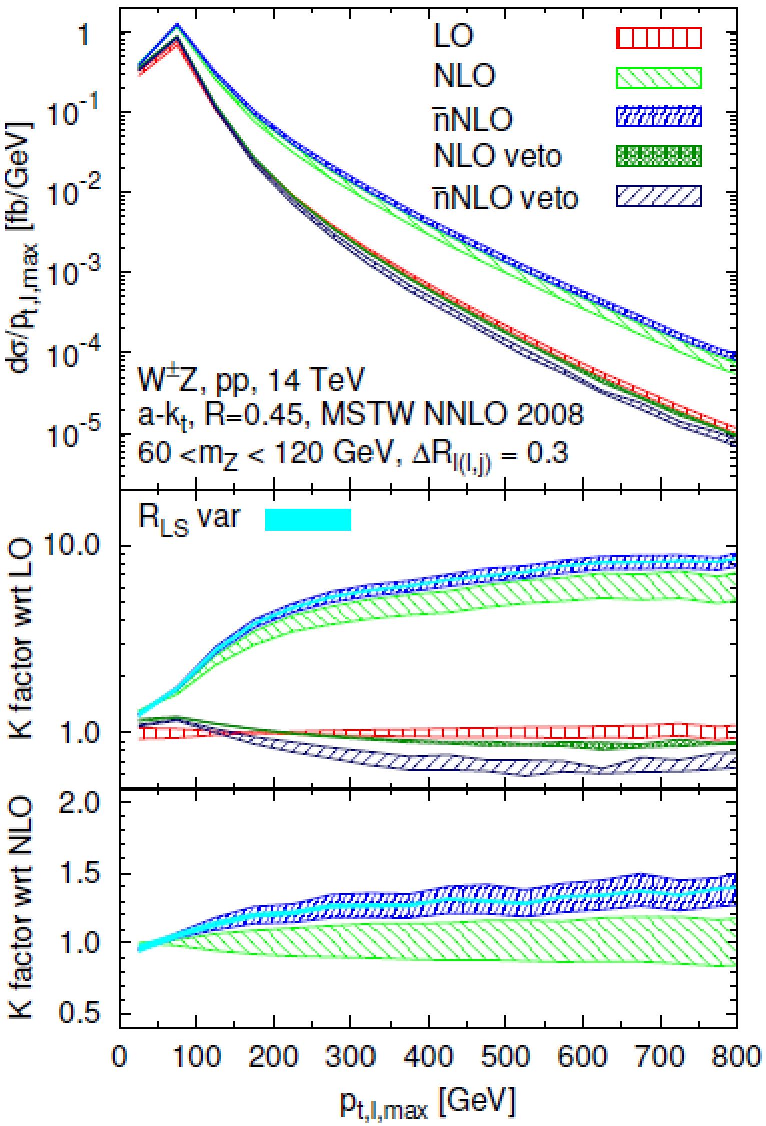
WZ



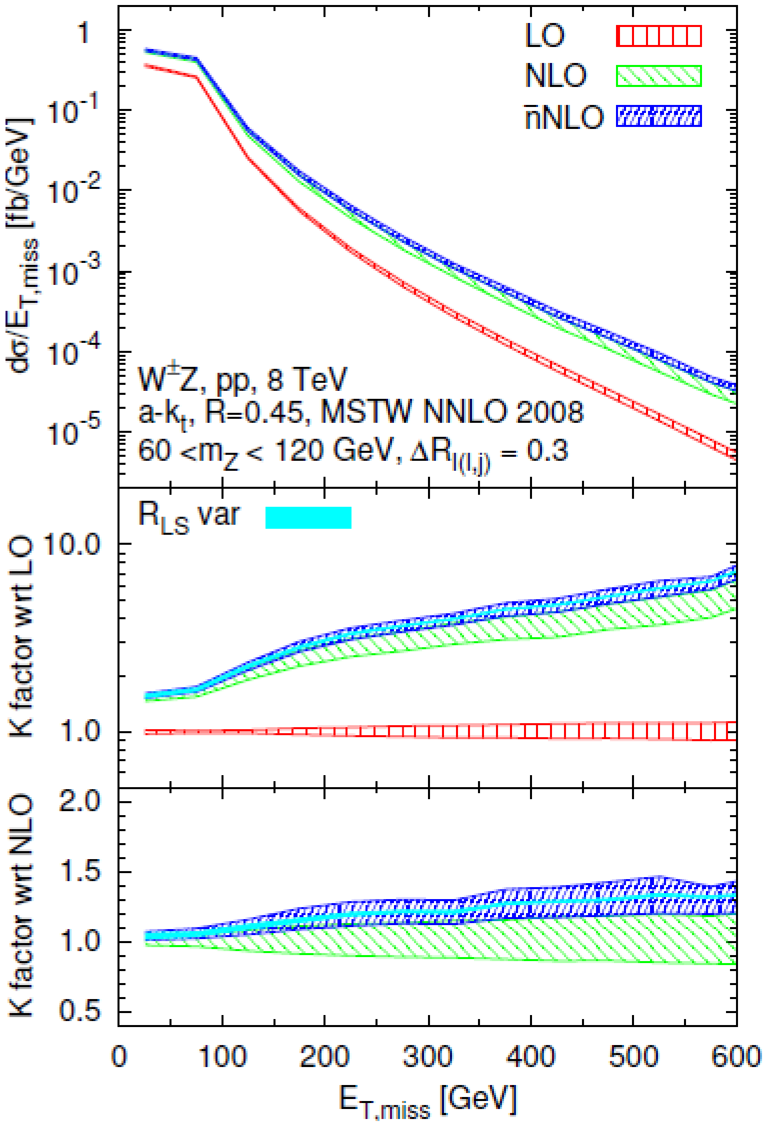
$$H_T = \sum p_{T,\text{jets}} + \sum P_{T,l} + E_{T,\text{mis}}$$

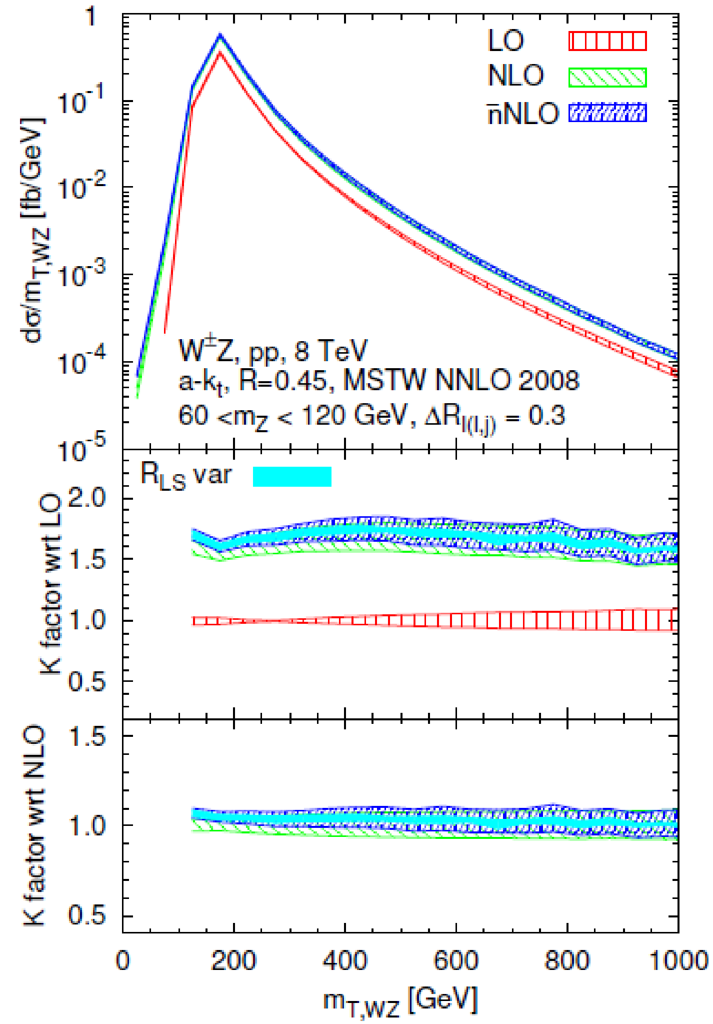
- Huge K-factors from LO to NLO
- Good agreement between $\bar{n}$LO and NLO at large H_T values
- Large $\bar{n}$NLO corrections
- Small R_{LS} uncertainties at large H_T
- Marginal reduction of scale uncertainties





- $\bar{n}$NLO corrections beyond scale uncertainty
- $\bar{n}$NLO with veto: Large corrections, larger scale uncertainties

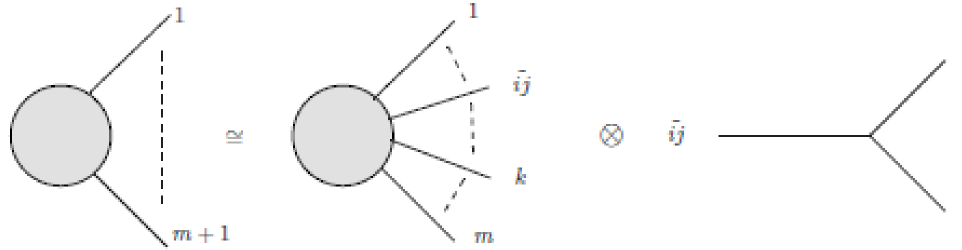

LO
NLO
n̄NLO
W±Z, pp, 8 TeV
a-kt, R=0.45, MSTW NNLO 2008
60 <mZ < 120 GeV, ΔRl(l,j) = 0.3
dσ/ET,miss [fb/GeV]
RLS var
K factor wrt LO
K factor wrt NLO
ET,miss [GeV]


LO
NLO
n̄NLO
W±Z, pp, 8 TeV
a-kt, R=0.45, MSTW NNLO 2008
60 <mZ < 120 GeV, ΔRl(l,j) = 0.3
dσ/mT,WZ [fb/GeV]
RLS var
K factor wrt LO
K factor wrt NLO
mT,WZ [GeV]

Ingredients at NLO

$|\mathcal{M}_{m+1}|^2$ factorizes if partons i, j are collinear or one of them is soft:

$$d\sigma^A \propto \sum_{\substack{\text{pairs}\\ i,j}} \sum_{k \neq i,j} \mathcal{D}_{ij,k}$$



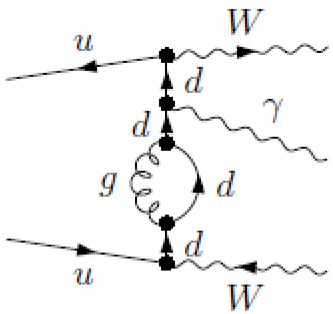
$$\mathcal{D}_{ij,k} = -\frac{1}{2p_a p_i} \underbrace{\frac{1}{x_{ij,k}}}_{\substack{\text{if } i,j, \text{ or } k\\ \text{in initial state}}} {}_m\langle\, 1, \ldots, m| \underbrace{\frac{T_k \cdot T_{ij}}{T_{ij}^2} V_{ij,k}}_{\text{spin and colour correlation}} \underbrace{|1, \ldots, m\rangle_m}_{\mathcal{M}_m}$$

$V_{ij,k}$ depends on dipole type.

e.g. initial state $g \to q\bar{q}$ with final state spectator:

$${}_m\langle s|V_k^{ai}|s'\rangle_m = 8\pi\mu^{2\epsilon}\alpha_S T_R[1 - \epsilon - 2x_{ik,a}(1 - x_{ik,a})]\delta_{ss'}$$

TECHNICAL DETAILS:
NUMERICAL ISSUES AT NLO



$$I = \int \frac{dl}{2\pi} \frac{\gamma^\alpha(\not{p}_1 + \not{l})\gamma_\alpha}{(p_1+l)^2 l^2} =$$

$$= \gamma^\alpha \not{p}_1 \gamma_\alpha \int \frac{dl}{2\pi} \frac{1}{(p_1+l)^2 l^2} + \gamma^\alpha \gamma_\beta \gamma_\alpha \int \frac{dl}{2\pi} \frac{l^\beta}{(p_1+l)^2 l^2}$$

$$B_0(p_1) = I_2(p_1) = \int \frac{dl^n}{2\pi} \frac{1}{(l^2)(l+p_1)^2} = \int \frac{dl^n}{2\pi} \frac{1}{N_0 N_1}$$

with

$$N_0 = l^2, \qquad N_1 = (l+p_1)^2$$

$$I_3^{\mu_1}(p_1^2, p_2^2, p_1 \cdot p_2) = p_1^{\mu_1} C_1 + p_2^{\mu_1} C_2$$

Contracting with $p_1^{\mu 1}$ or $p_2^{\mu 1}$ $\rightarrow$ **Recursion Relations**

$$\begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} B_0(1) - B_0(0) - r_1 C_0 \\ B_0(2) - B_0(1) - (r_2 - r_1) C_0 \end{pmatrix} = \begin{pmatrix} R_1 \\ R_2 \end{pmatrix}$$

$$C_1 = (\Delta^{(3)})^{(-1)} (\tilde{Z}_{11} R_1 + \tilde{Z}_{12} R_2)$$
$$C_2 = (\Delta^{(3)})^{(-1)} (\tilde{Z}_{12} R_1 + \tilde{Z}_{22} R_2)$$

If $\Delta^{(3)}$ small $\rightarrow$ Cancellations and lost of precision.

$\Delta^{(3)} = 4(p_1^2 p_2^2 - p_1 p_2^2);$ $\mathrm{detAbs}^{(3)} = 4(abs(p_1^2 p_2^2) + abs(p_1 p_2^2))$

$x = \frac{\Delta^{(3)}}{\mathrm{detAbs}^{(3)}}$ order of cancellation.

1 digit $\rightarrow \frac{100-99}{199} = 5 * 10^{-3} < x < \frac{900-91}{191} = 4.6 * 10^{(-2)}$

2 digit $\rightarrow \quad 5 * 10^{-4} < x < \quad 4.6 * 10^{(-3)}$

Precision for C_0, C_{ij} for $x = 4.6 * 10^{(-6)}$:

Integral	Precision
C_0	dble -5 digits =11 digits
C_1, C_2	C_0 -5 digits=6 digits
C_{11}, C_{12}	C_0-2(5 digits)=1 digits

Point instable: Gauge test $\geq \mathbf{10^{-6}}$

- Pentagons: $\sim 2/1000$
- Hexagons: 2%-10%

$\boxed{\text{Instabilites due to small Gram determinants in C and D functions}}$

$\det/|\det| \approx \mathbf{10^{(-5)}}$ $\longrightarrow$ cancellation of 3-5 digits expected

D's, up to Rank 3 $\longrightarrow$ 9-15 digits loss over 16 of Dble precision

- For Hexagons:

1/3 pts fails the gauge test for an accuracy of $\mathbf{10^{-1}}$

$\boxed{\text{We need more digits for those} \longrightarrow \text{Quadruple precision}}$

Point unstable: Gauge test $\geq 10^{-6}$

- Pentagons: $\sim$2/1000
- Hexagons: 2%-10%

$\boxed{\text{Instabilities due to small Gram determinants in C and D functions}}$

If Gauge test Failed(10% of the times)

1) QUAD only to determine $C_0, D_0, C_{ij}, \ldots$(10% of the CPU)
Gauge test failed: 10% $\rightarrow$ 0.2% (0.02%,0.0008%,0)

2) Full QUAD for 0.2%
Gauge test failed: 0.2% $\rightarrow$ 0.1% (0.007%,0)

From 400% $\rightarrow$ 50% CPU time in adition.
$\Delta < 10^{-6} \rightarrow$ Routines for small Gram Determinants.

However, QUAD $\sim$ 40 times slower than Dble precision!!!!

First: Evaluate Dble Precision and apply Gauge Test

If Gauge test Failed(10% of the times)

Option 1

1) Revaluation with QUAD precision

Option 2

1) QUAD only to determine C_0,D_0,C_{ij},...(10% of the CPU)

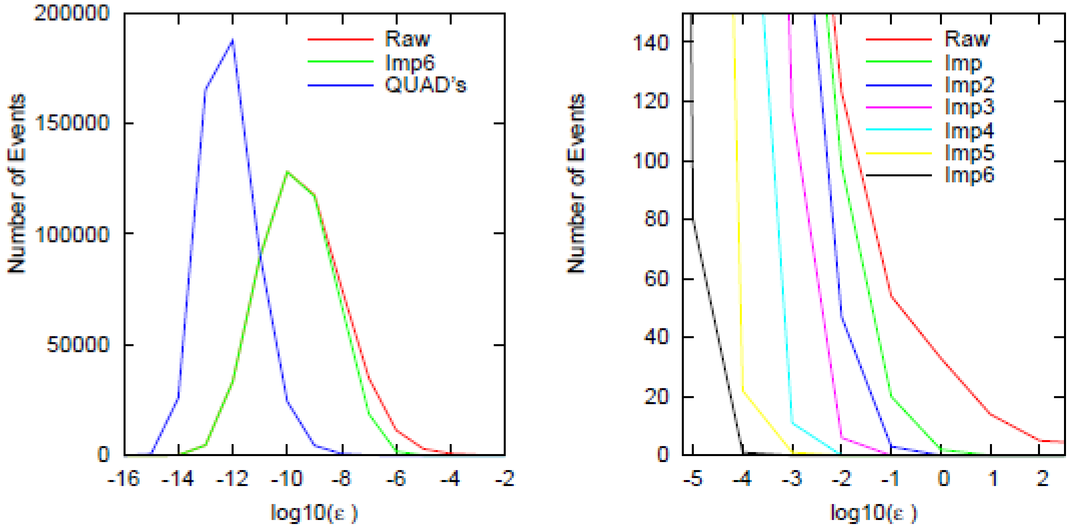
Gauge test failed: 10% $\rightarrow$ 0.2% (0.02%,0.0008%,0)

2) Full QUAD for 0.2%

Gauge test failed: 0.2% $\rightarrow$ 0.1% (0.007%,0)

From 400% $\rightarrow$ 50% CPU time in addition

For 5 10^5 cut-accepted points with VBFNLO for EW pp$\to$WWjj



ϵ=abs((QUAD-Dbl))/abs(QUAD)

Imp(,2,3,n): Gauge test $\leq 10^{(-1,-2,-3,n)} \to$ Dble=QUAD

References VV@LHC

VBFNLO:

https://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=overview

LoopSim:

https://loopsim.hepforge.org/

NNLO QCD

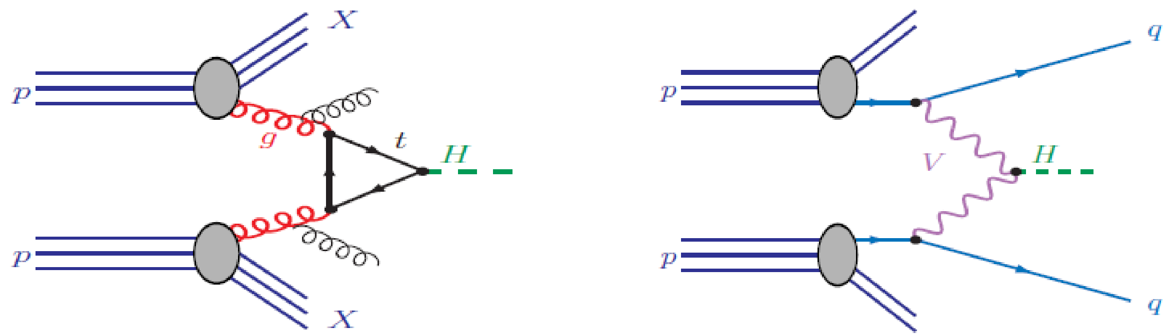
- γγ :Catani, Cieri, de Florian, Ferrera, Grazzini 2011]
- W γ /Zγ: Grazzini, Kallweit, Rathlev, Torre 2013, Grazzini, Kallweit, Rathlev 2015
- ZZ :Cascioli et al. '14, Grazzini, Kallweit, Rathlev 2015
- WW: [Gehrmann et al. 2014

GF LO

- γγ: D. A. Dicus and S. S. D. Willenbrock, Phys. Rev. D 37 (1988) 1801
- Zγ : J. J. van der Bij and E. W. N. Glover, Phys. Lett. B206 (1988) 701,
- ZZ: . E. Glover and J. van der Bij, Phys.Lett. B219 (1989) 488
- WW: T. Binoth, M. Ciccolini, N. Kauer and M. Kramer, JHEP 12 (2006) 046.

NLO EW(on-shell):

- WW/WZ: E. Accomando and A. Kaiser, Phys.Rev. D73 (2006) 093006.
- W γ / Zγ: E. Accomando, A. Denner, and C. Meier, Eur.Phys.J.C47 (2006) 125–146
- ZZ A. Bierweiler, T. Kasprzik, and J. H. Kühn,arXiv:1305.5402, J.Baglio, N.D.Li, M. Weber Phys. Rev.D 88 (2013) 113005.



GF H+2J:

- Background to WBF
- Sensitive to: CP-structure and coupling of fermions
- NLO known within Effective Theory[Campbell,Ellis,Zanderighi hep-ph/0608194]
- LO known for the full Theory [Del Duca et al.hep-ph/0105129;FC,Kubocz,Zeppenfeld 1011.3819]

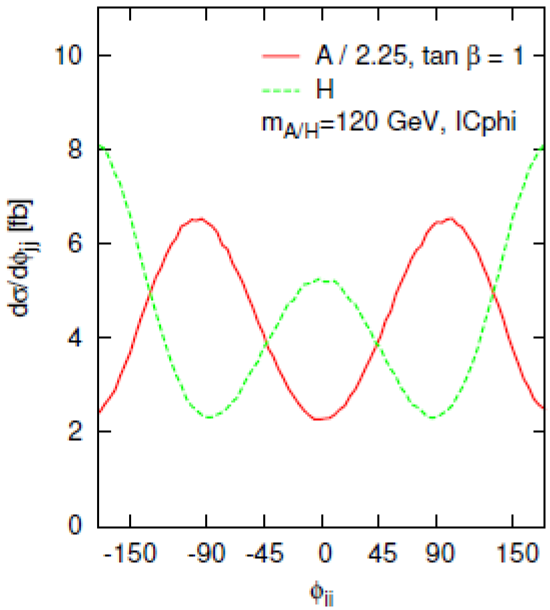
GF H+3J:

- Background to WBF process[1] (CJV strategies known at NLO)

[1] [Figy,Hankele,Zeppenfeld 0710.5621; FC,Figy,Platzer,Sjodahl 1308.2932]

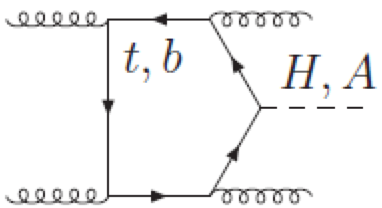
- NLO corrections known within Effective Theory [Cullen et al. 1307.4737]
- Here: LO corrections for the full Theory [FC,Kubocz 1306.1830; 1402.1154]
- Soft radiation: Distort CP-sensitive distributions?

- sensitive to the $\mathcal{CP}$-structure $\rightarrow$ azimuthal angle correlation



$$\phi_{jj} = \phi_F - \phi_B$$

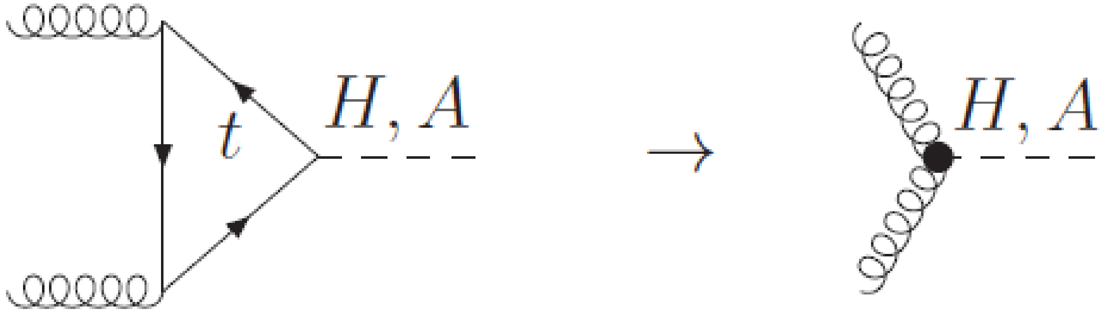
$$\mathcal{L}_{\text{Yukawa}} = y_q\,\overline{q}\,q\,H + \mathrm{i}\tilde{y}_q\overline{q}\gamma_5\,q\,A$$



"LO": one loop $2 \rightarrow 3$ process of $\mathcal{O}(\alpha_s^4)$

$$Y_q = \frac{m_q}{v}$$

- bottom-quark: suppressed
- top-quark: effective theory



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{H^0 gg} + \mathcal{L}_{A^0 gg} = \frac{1}{v}\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} H + \frac{1}{v}\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} A$$

- Validity: $m_{\text{Higgs}} < m_t$ and $p_T^j < m_t$
- If used correcty $\rightarrow$ powerful tool
- bottom loops: Not described (Important in BSM)

$\Phi = H \cos\alpha + A \sin\alpha$

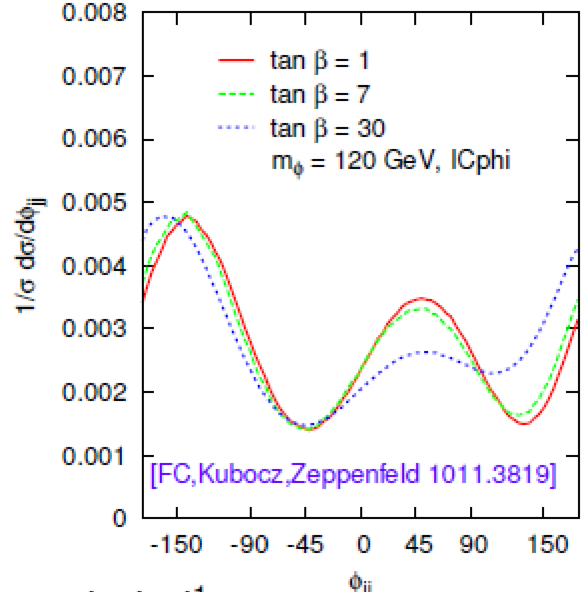
Min: $\tan\Delta\phi_{jj} = -\frac{2y_t}{3\tilde{y}_t}\cot\alpha$

$\circ\ \frac{y_q}{\tilde{y}_q} = \frac{3}{2}$ and $\alpha = 45°$

Min: $\Delta\phi_{jj} = -45°$

Type II HDM(MSSM): $\tilde{y}_b = -\frac{m_b}{v}\tan\beta$

$\rightarrow$ distortion for large $\tan\beta$



- For 50 fb^{-1} and $\tilde{y}_q = y_q^{SM} \rightarrow \alpha > 40°$ excluded[1]

[1] [Dolan,Harris,Jankowiak,Spannowsky 1406.3322]