Course on Physics at the LHC

LIP Lisbon, February - June 2015

The Standard Model of Particle Physics at LHC

J. Varela

Program

The standard model of particle physics	Prof. João Varela (LIP, IST)	23, 26 February
Statistical methods in data analysis	Dr. Pedrame Bargassa (LIP)	2 March
Detector physics and experimental methods	Dr. Michele Gallinaro (LIP), Dr. Pedro Silva (CERN)	9, 16 March
Top quark physics	Dr. Michele Gallinaro (LIP), Prof. António Onofre (LIP, UM))	23, 30 March, 13 April
Standard model Higgs and beyond	Dr. Pedro Silva (CERN), Dr. André David (CERN), Dr. Patricia Muino (LIP), Dr. Ricardo Gonçalo (LIP)	20, 27 April 4, 11 May
Supersymmetry	Dr. Pedrame Bargassa (LIP)	18, 25 May
B physics and rare decays	Dr. Nuno Leonardo (LIP)	1 June
Matter at high density and temperature	Prof. João Seixas (LIP, IST), Dr. Pietro Faccioli (LIP)	8, 15 June

The lectures will take place on Mondays, between 17:00 and 18:30 at LIP, Av. Elias Garcia, 14 r/c, 1000 Lisbon - Portugal

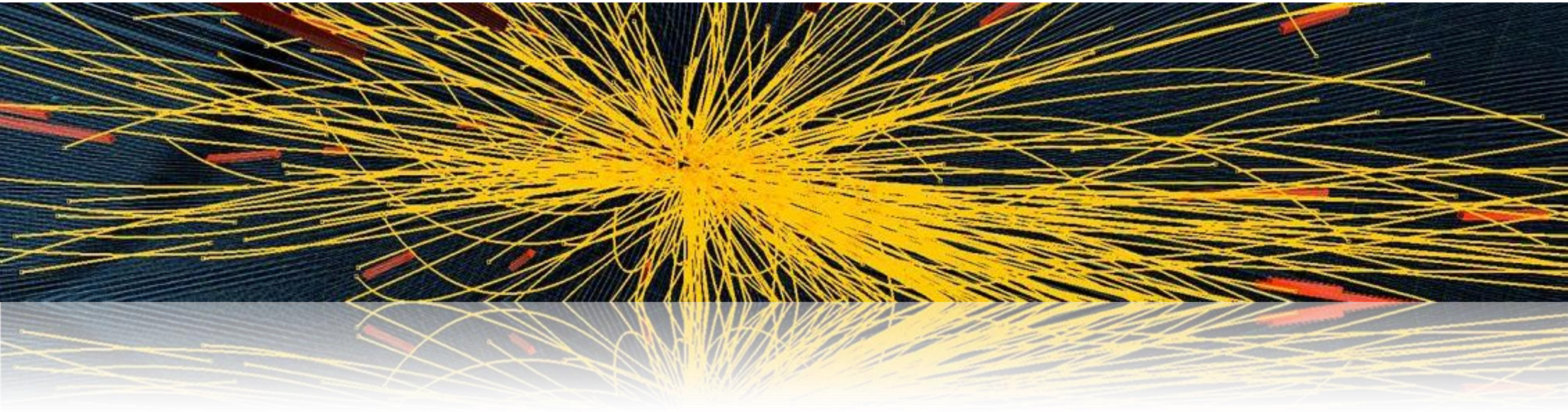
More info at
http://idpasc.lip.pt/LIP/events/2015_lhc_physics

Course coordinator: João Varela, Michele Gallinaro (LIP, IST)

The Standard Model at LHC

1. Hadron interactions
2. QCD and parton densities
3. Monte Carlo generators
4. Luminosity and cross-section measurements
5. Minum bias events
6. Jet physics
7. W and Z physics

Hadron Interactions



Natural units

$$\hbar = 1,\ c = 1$$

$$\hbar c = 197.3 \text{ MeV fm}$$
$$(\hbar c)^2 = 0.3894 \text{ GeV}^2 \text{ mb}$$

Four-vector kinematics

$$p = (E, \vec{p}\,)$$

$$p^2 = E^2 - \vec{p}^{\,2} = m^2$$

$$\beta = p/E,\ \gamma = E/m$$

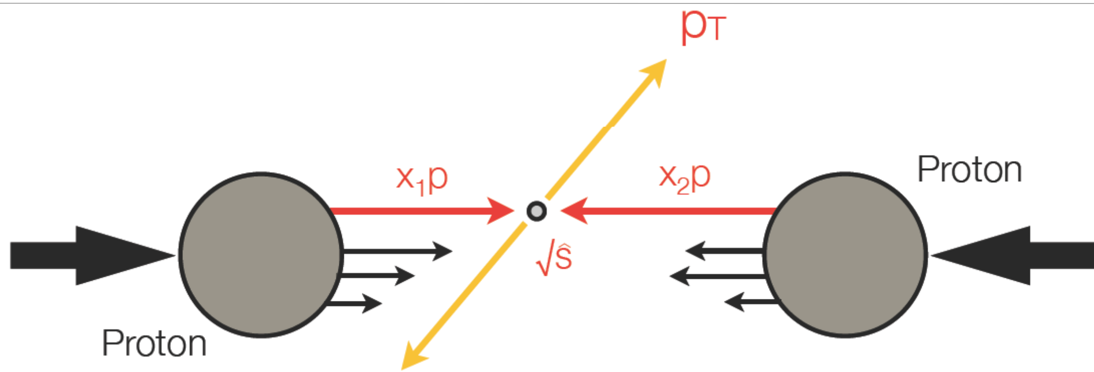
Lorentz invariance

$$p_1 \cdot p_2 = E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2$$

Cross-sections should be function of scalar products of 4-vectors

4-vector scalar product Lorentz invariant

Kinematical variables

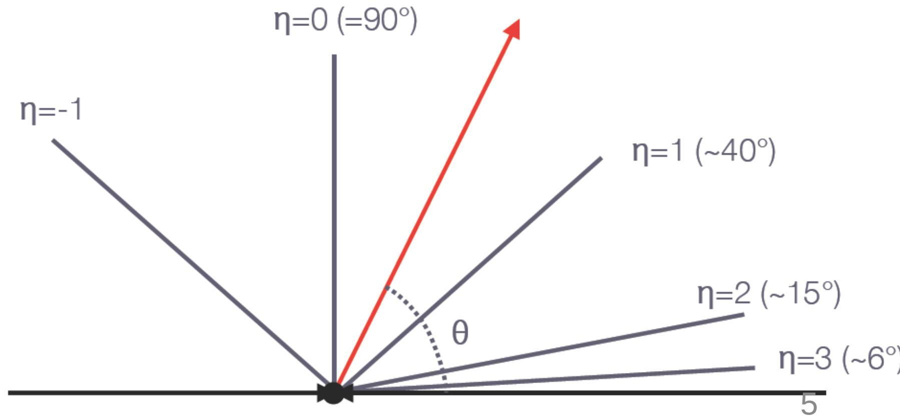


Schematic
proton-proton scattering

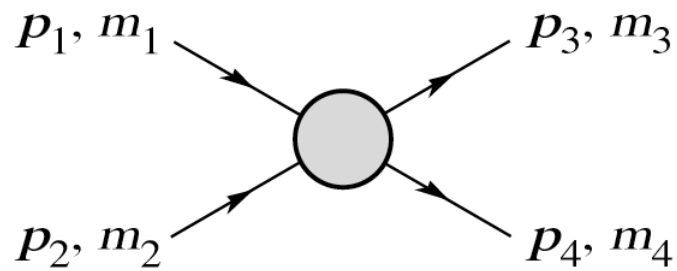
Relevant kinematic variables:

- Transverse momentum: p_T
- Rapidity: $y = ½ \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan ½\theta$
- Azimuthal angle: φ

Pseudorapidity



Invariant mass



Invariant Mass:

$$M^2 = (p_1 + p_2)^2$$
$$= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$
$$= m_1^2 + m_2^2 + 2E_1E_2(1 - \vec{\beta}_1\vec{\beta}_2)$$

Center of mass energy

Center-of-mass Energy:

$$E_{\rm cm} = \left[(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2\right]^{\frac{1}{2}}$$

Particle 2 at rest:

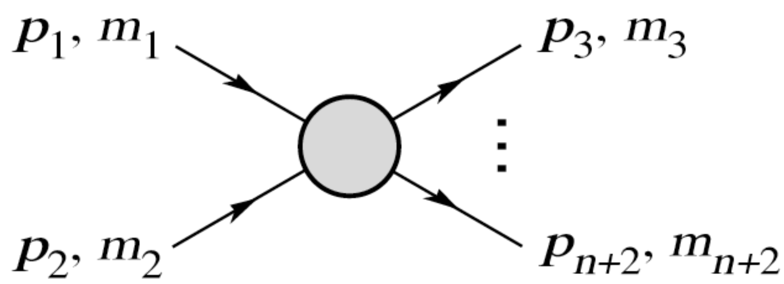
$$\sqrt{s} = \quad E_{\rm cm} = \left[m_1^2 + m_2^2 + 2E_1 m_2\right]^{\frac{1}{2}}$$

Particle Collider:

$[E_1 = E_2;\ \vec{p}_1 = -\vec{p}_2;\ m_1 = m_2 \approx 0]$

$$E_{\rm cm} = 2E$$

Cross section
Matrix element
Phase space



Differential
Cross Section:

Matrix element

$$d\sigma = \frac{(2\pi)^4 |\mathscr{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}}$$

$$\times \; d\Phi_n(p_1 + p_2;\; p_3, \ldots, p_{n+2})$$

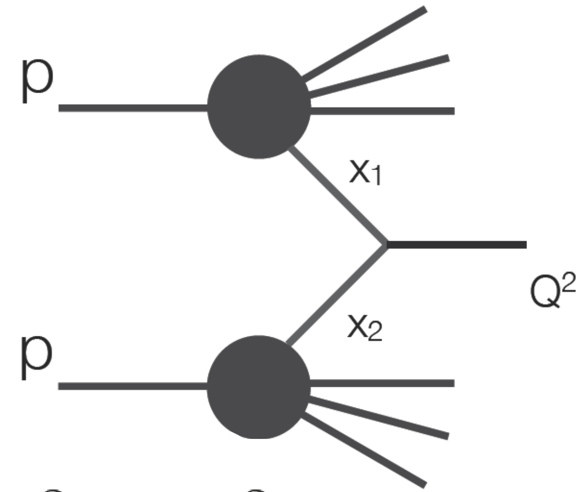
n-body
phase space

$$d\Phi_n = \ldots$$

$$\ldots = \delta^4 \left(P - \sum_{i=1}^{n} p_i\right) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

with $P = p_1 + p_2$

Parton distributions
Bjorken-x



Proton-proton cross section

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \; f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$

$x_{1,2}$: Bjorken-x

fractional momentum of parton
involve in hard process

Q^2 : scale; spacial resolution

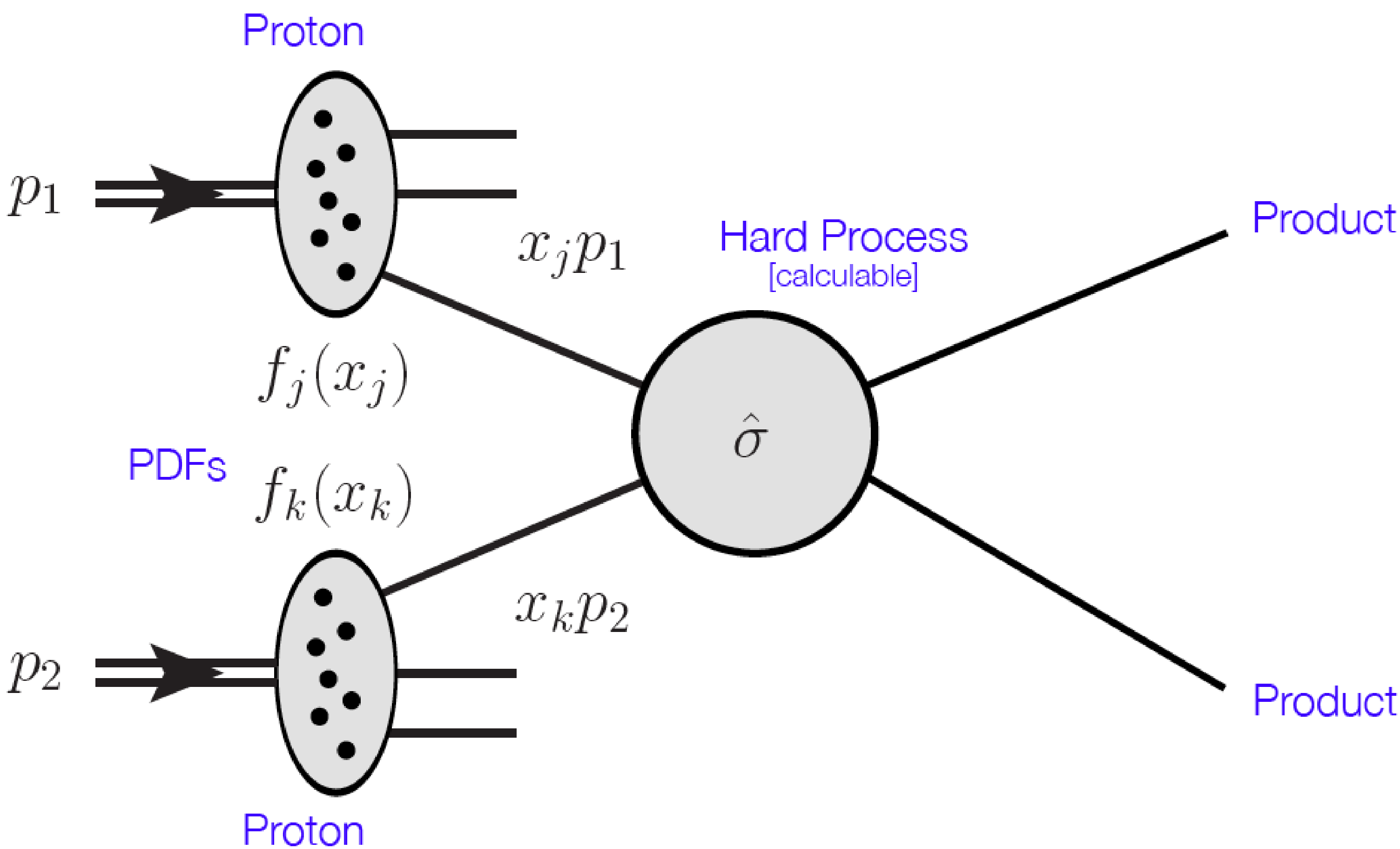
invariant parton-parton mass

f : Parton Distribution function

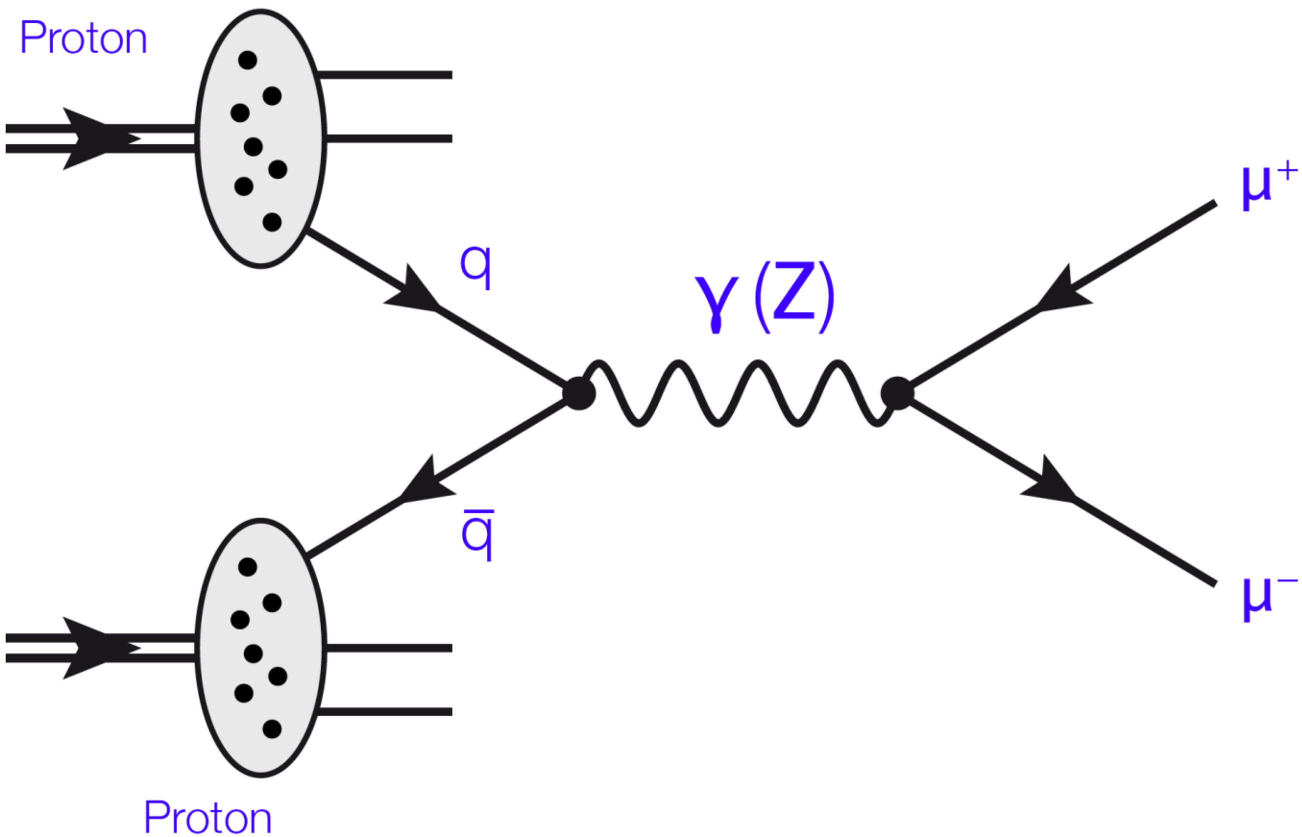
Parton content:

$f(x,Q^2) = q(x,Q^2)$ or $g(x,Q^2)$

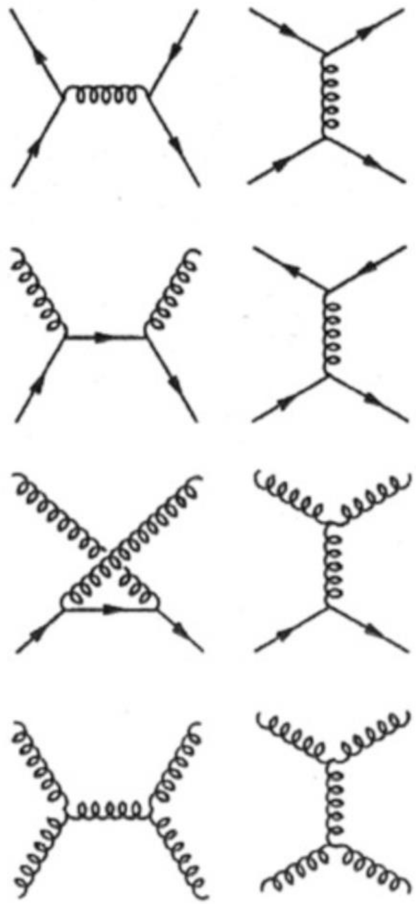
Proton-proton scattering



Example: Drell-Yan Process



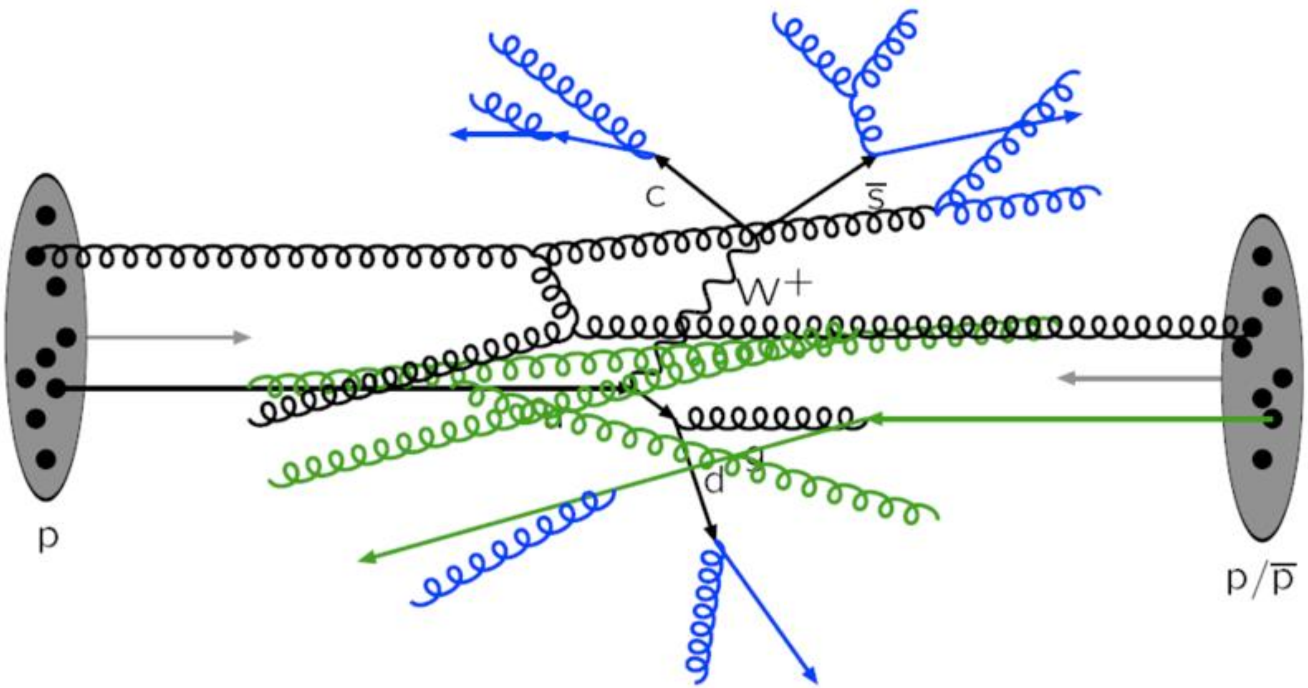
QCD Matrix Elements



Subprocess	$\lvert\mathcal{M}\rvert^2/g_s^4$	$\lvert\mathcal{M}(90^\circ)\rvert^2/g_s^4$
$\left.\begin{matrix} qq' \to qq' \\ q\bar{q}' \to q\bar{q}' \end{matrix}\right\}$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^{\,2}}$	2.2
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^{\,2}}+\frac{\hat{s}^2+\hat{t}^{\,2}}{\hat{u}^2}\right)-\frac{8}{27}\,\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\,\frac{\hat{t}^{\,2}+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^{\,2}}+\frac{\hat{t}^{\,2}+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\,\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \to gg$	$\frac{32}{27}\,\frac{\hat{u}^2+\hat{t}^{\,2}}{\hat{u}\hat{t}}-\frac{8}{3}\,\frac{\hat{u}^2+\hat{t}^{\,2}}{\hat{s}^2}$	1.0
$gg \to q\bar{q}$	$\frac{1}{6}\,\frac{\hat{u}^2+\hat{t}^{\,2}}{\hat{u}\hat{t}}-\frac{3}{8}\,\frac{\hat{u}^2+\hat{t}^{\,2}}{\hat{s}^2}$	0.1
$qg \to qg$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^{\,2}}+\frac{\hat{s}^2+\hat{t}^{\,2}}{\hat{u}^2}+\frac{\hat{u}^2+\hat{t}^{\,2}}{\hat{s}^2}+3\right)$	30.4

Proton-Proton Scattering @ LHC

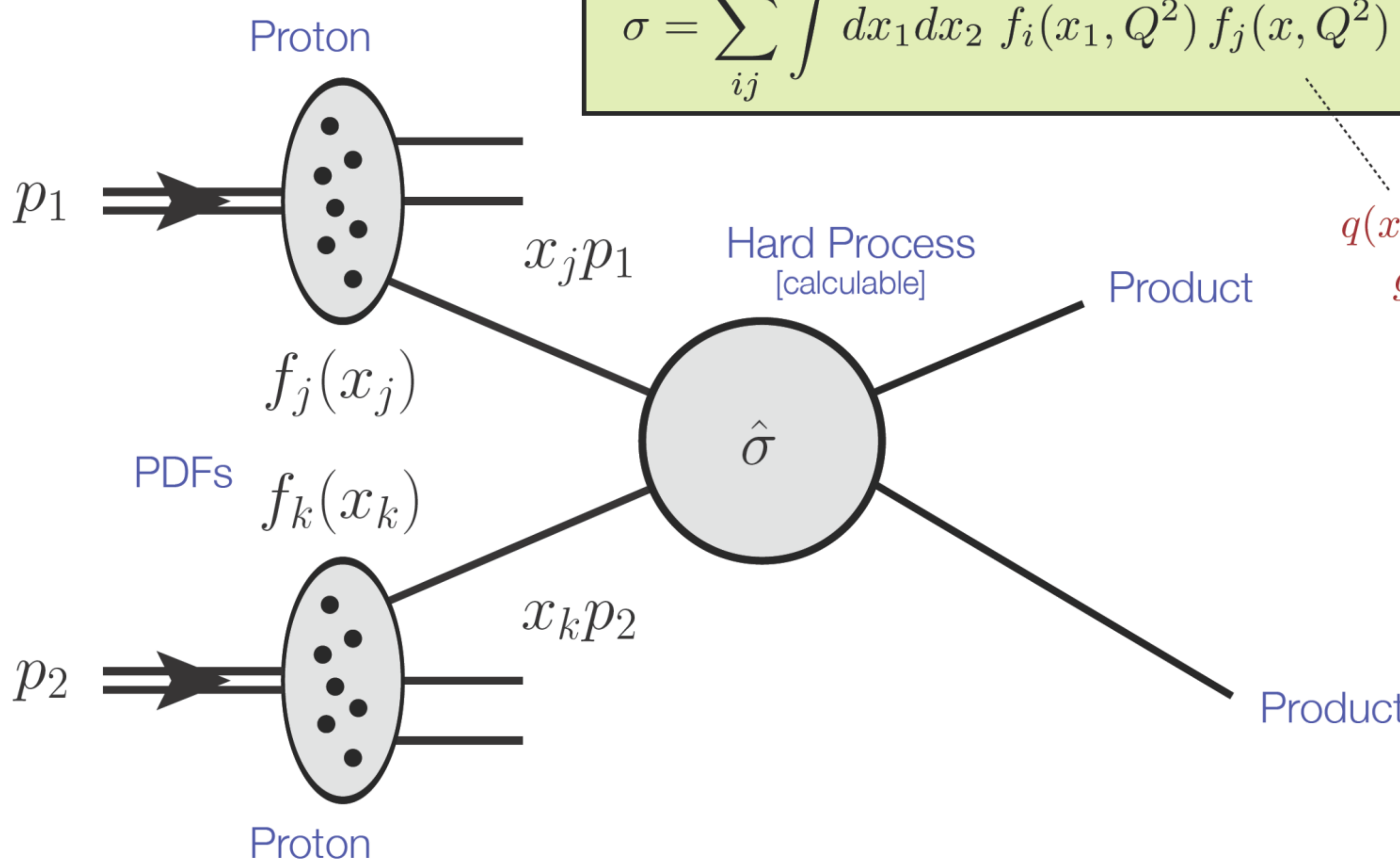
- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



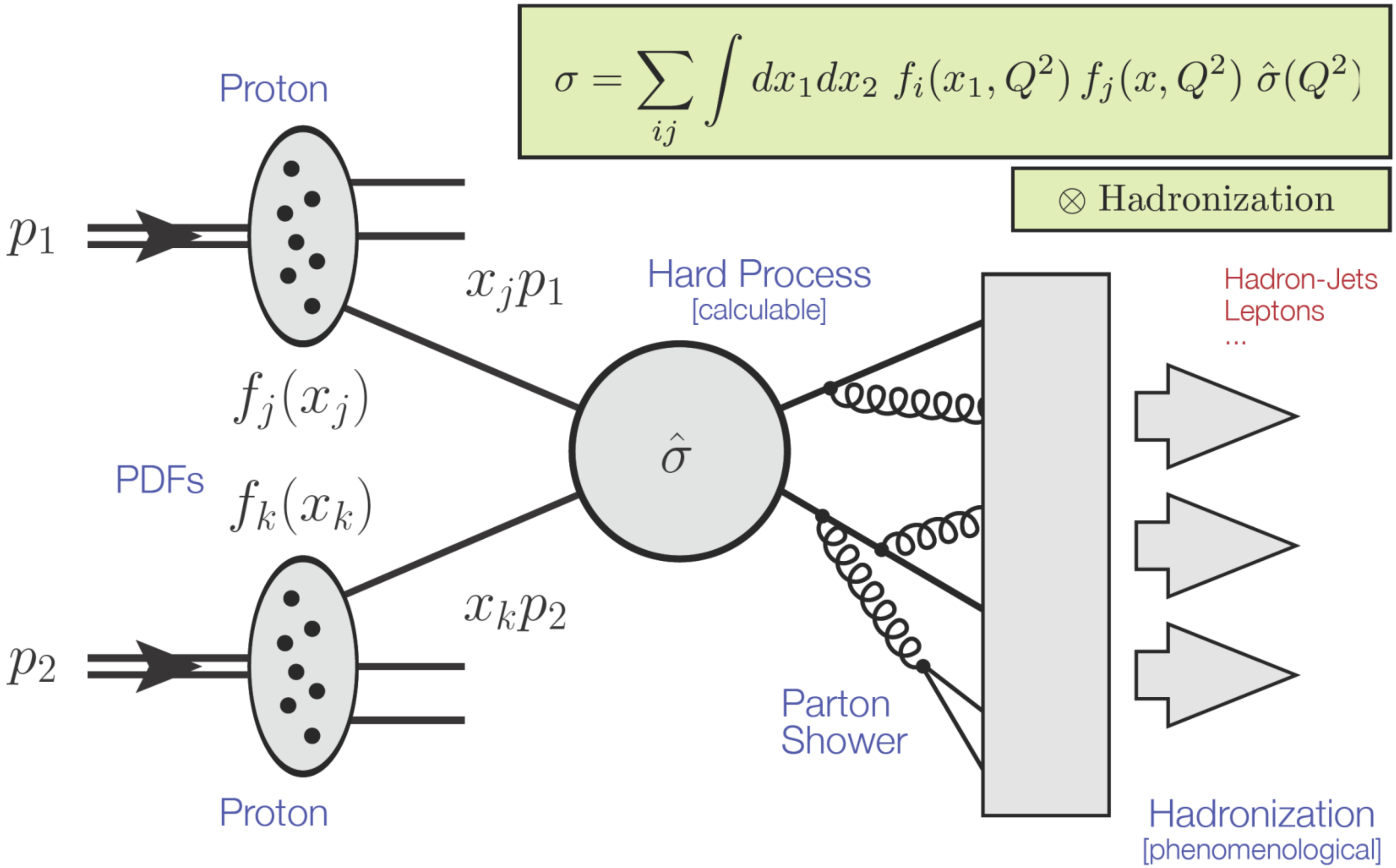
Proton-Proton Scattering @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$

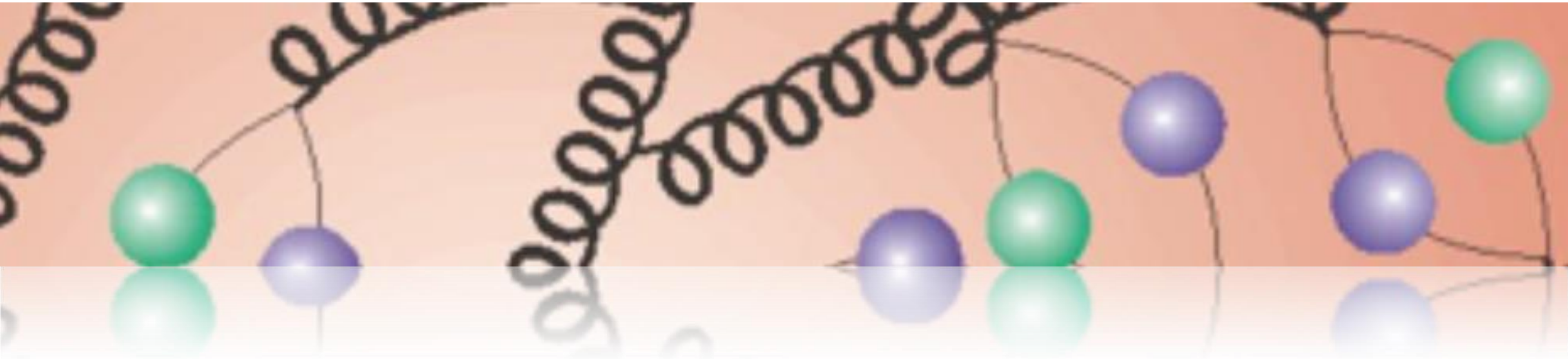
$q(x, Q^2)$
$g(x, Q^2)$



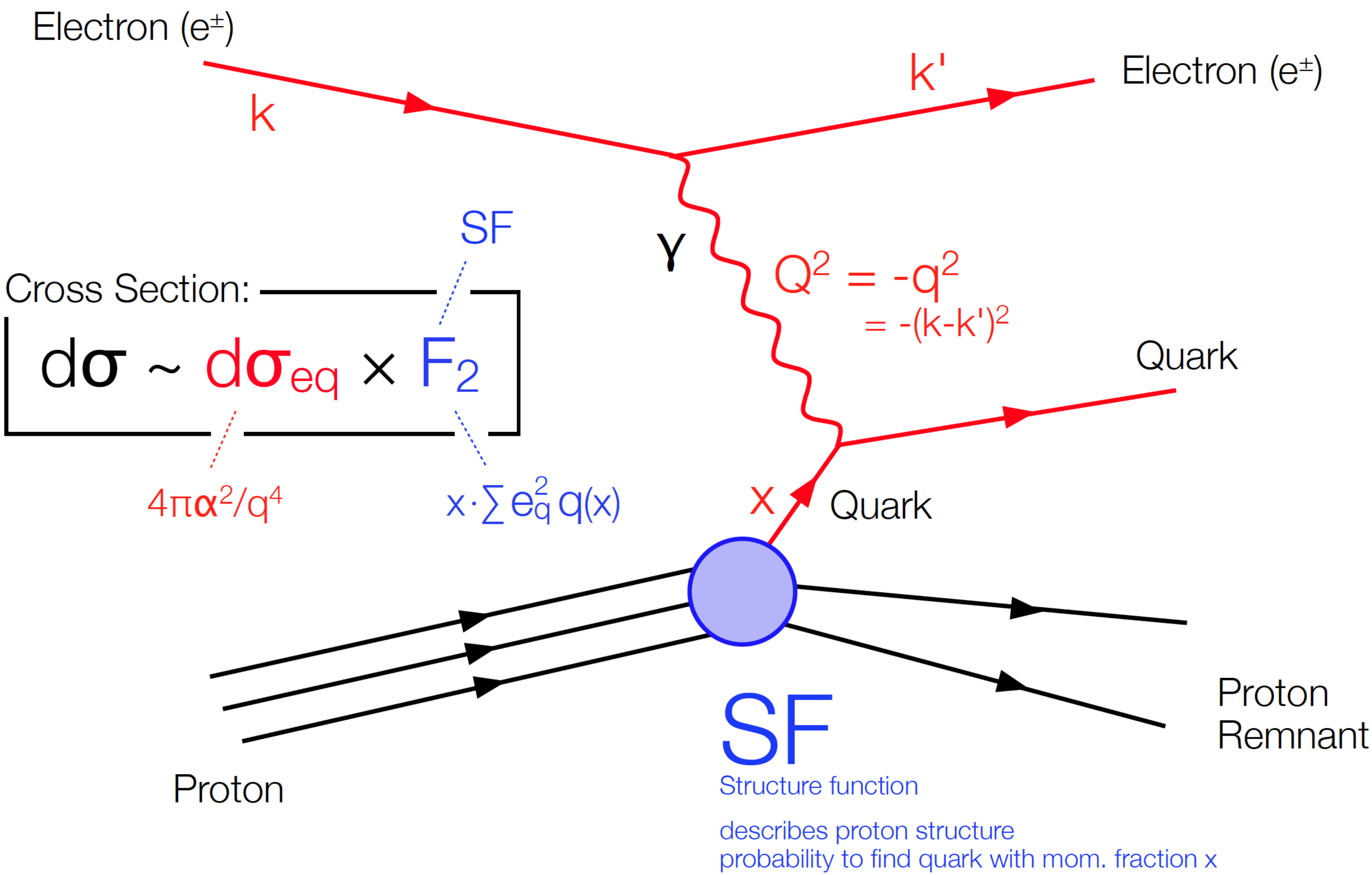
Proton-Proton Scattering @ LHC



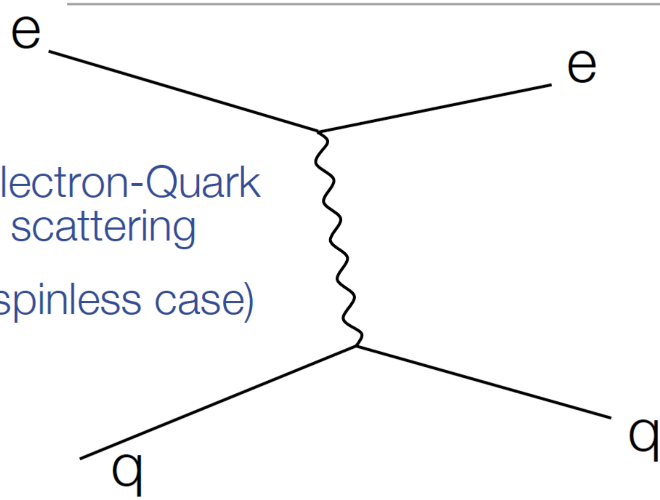
QCD & parton densities



Lepton-proton scattering



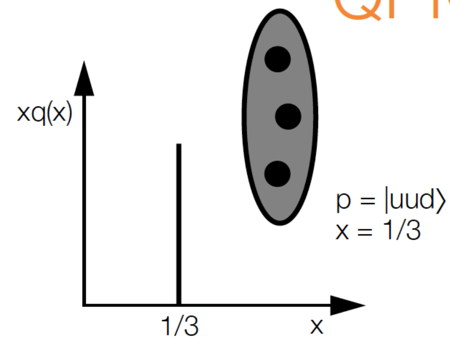
Structure Function F_2



Electron-Quark scattering

(spinless case)

Naive QPM

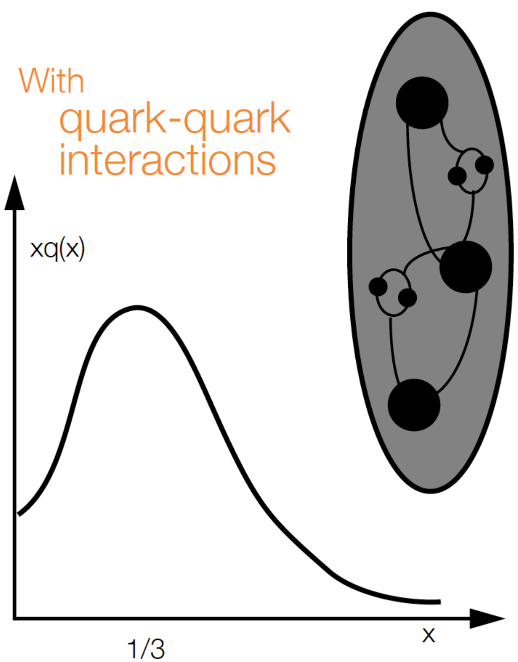


$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

Rutherford scattering on pointlike target

$$\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4}[2e_u^2 + e_d^2] = \frac{4\pi\alpha^2}{q^4}$$

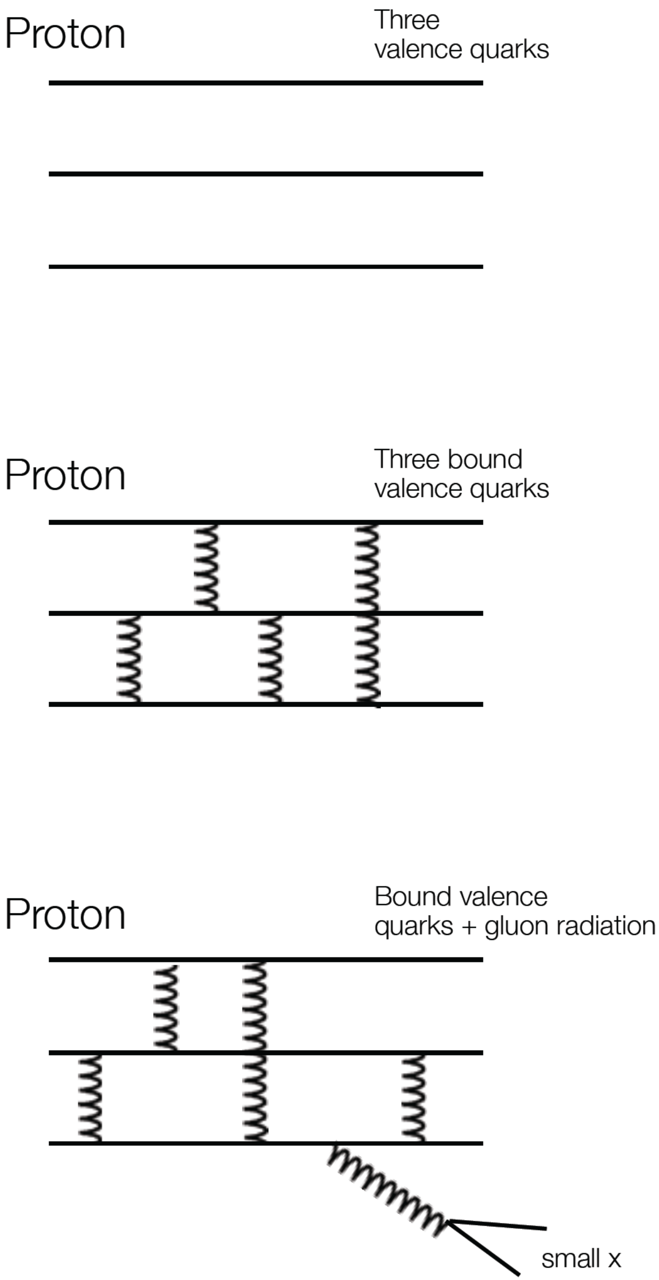
With quark-quark interactions

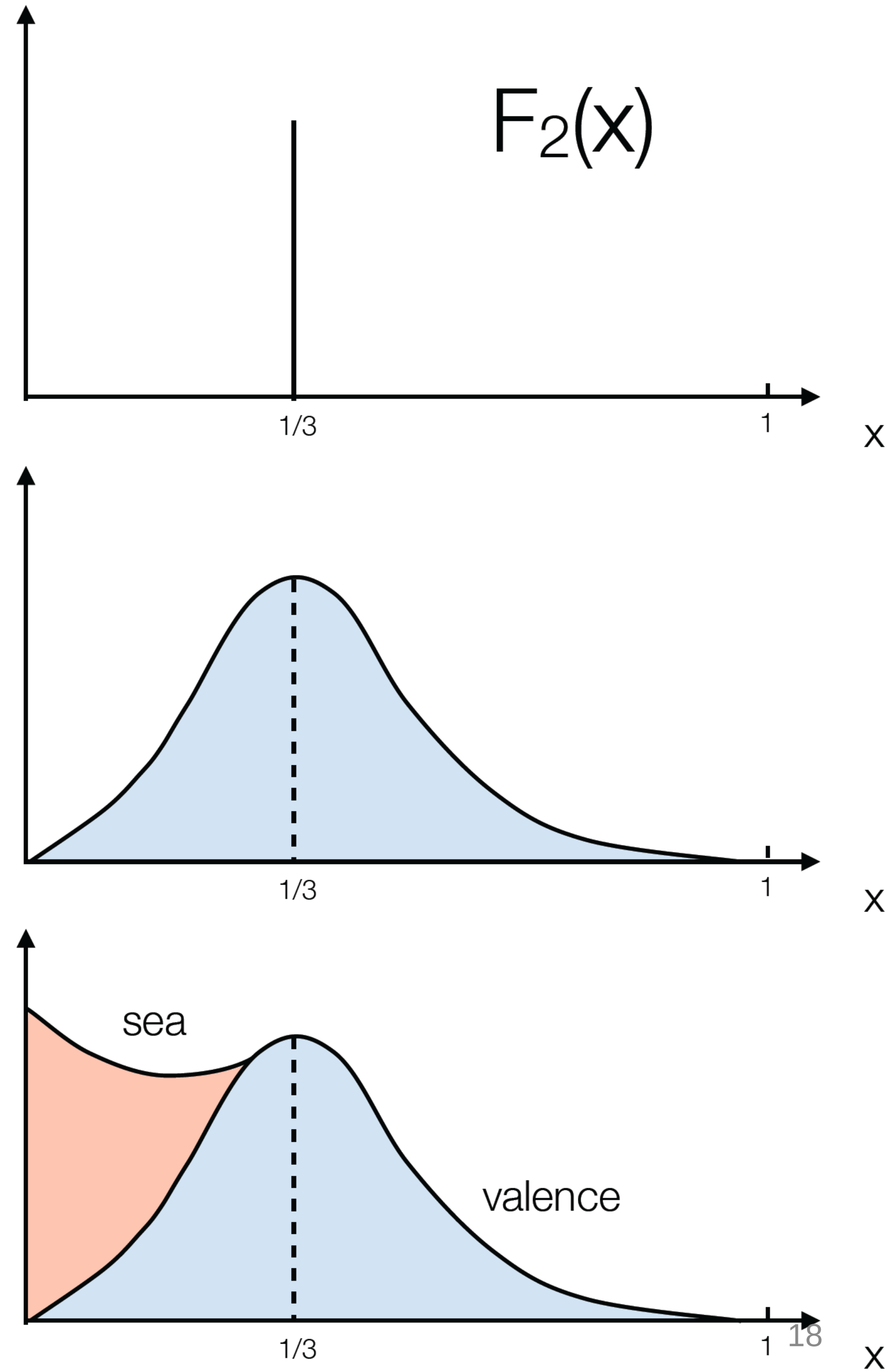


$$\frac{d\sigma(ep)}{dx\,dq^2} = \frac{4\pi\alpha^2}{q^4}[e_u^2 u(x) + e_d^2 d(x) + \ldots]$$

$$= \frac{4\pi\alpha^2}{q^4}\frac{F_2(x)}{x}$$

QPM: Structure Functions F_2 independent of Q^2

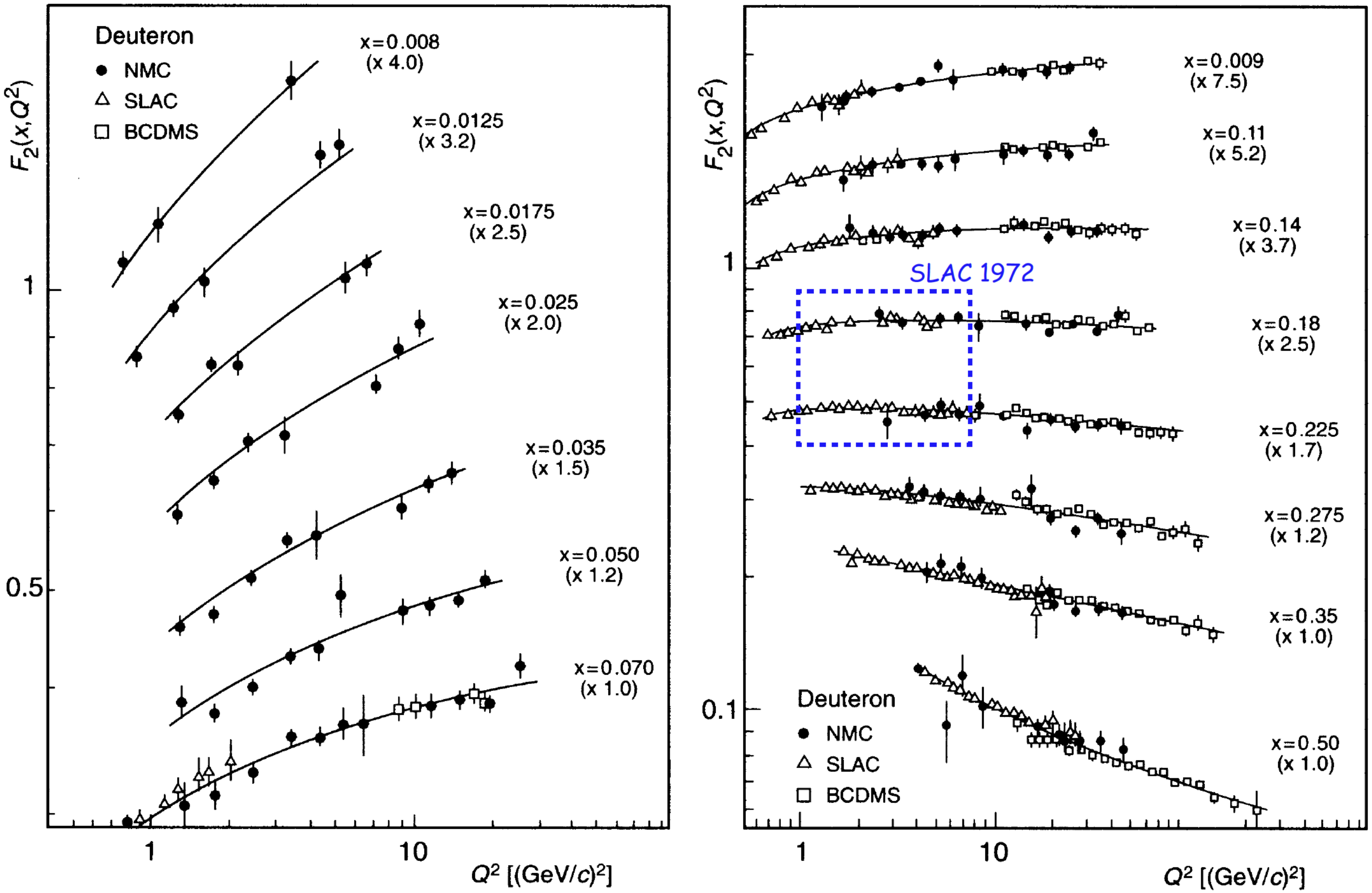




[see e.g. Halzen/Martin]

Scaling violation

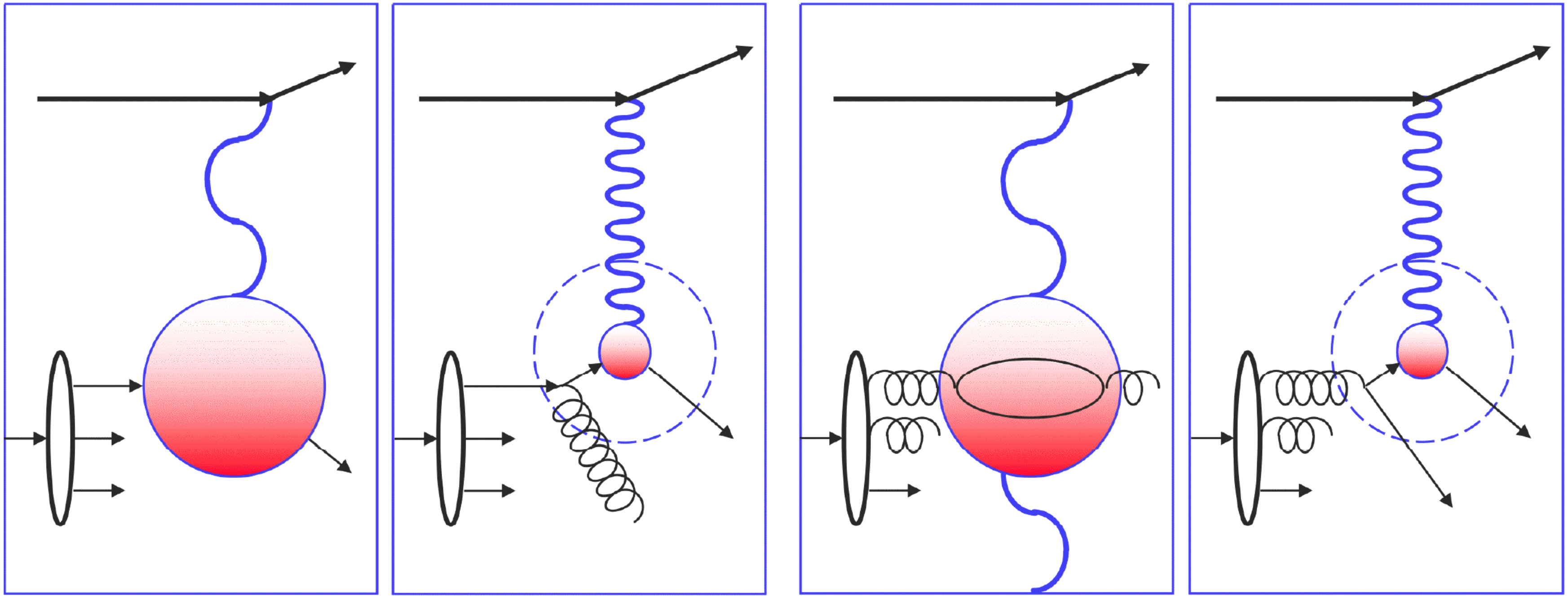
$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$



Scaling violation

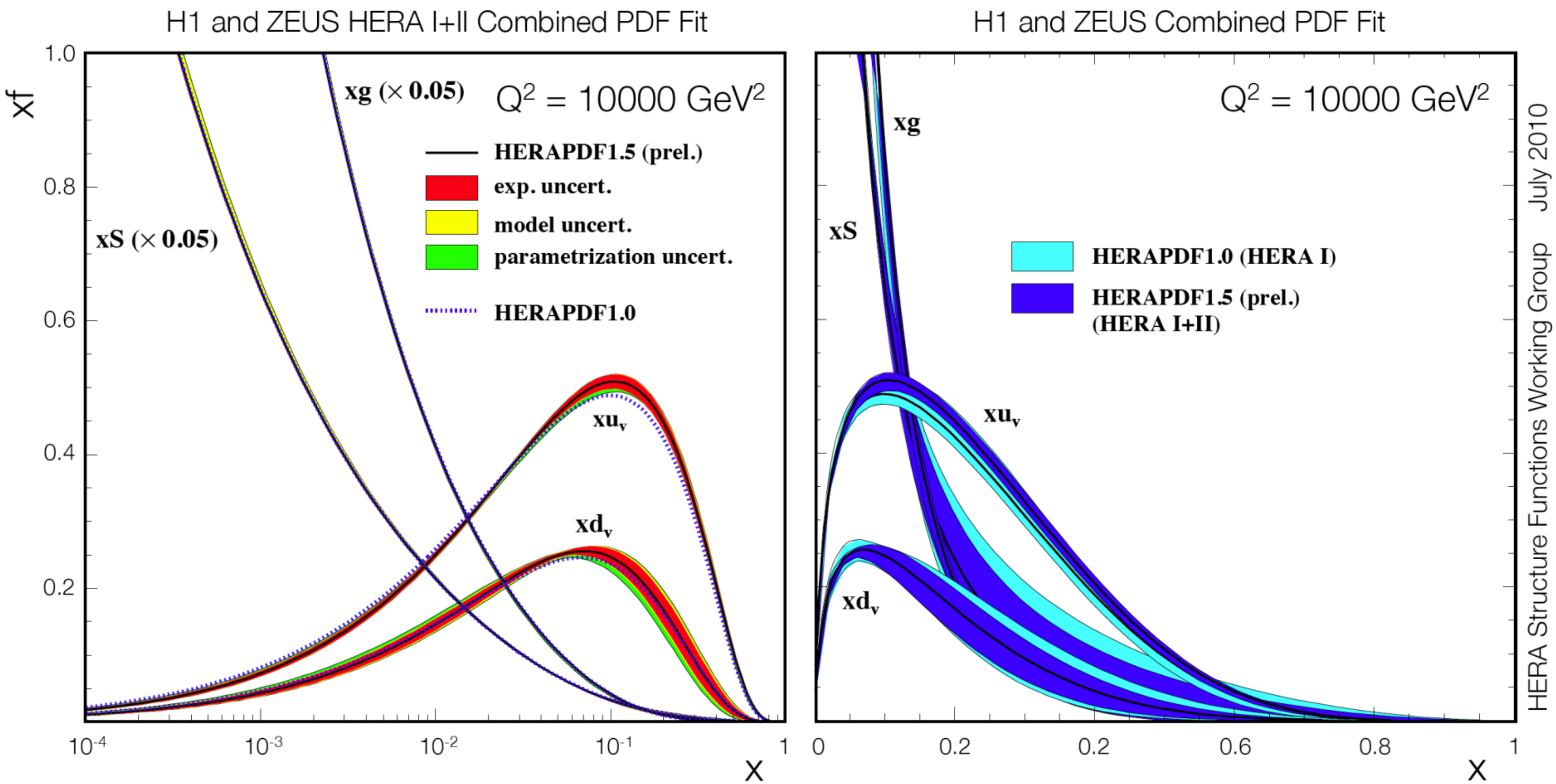
Proton quark dominated:
$Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

Proton gluon dominated:
$Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x

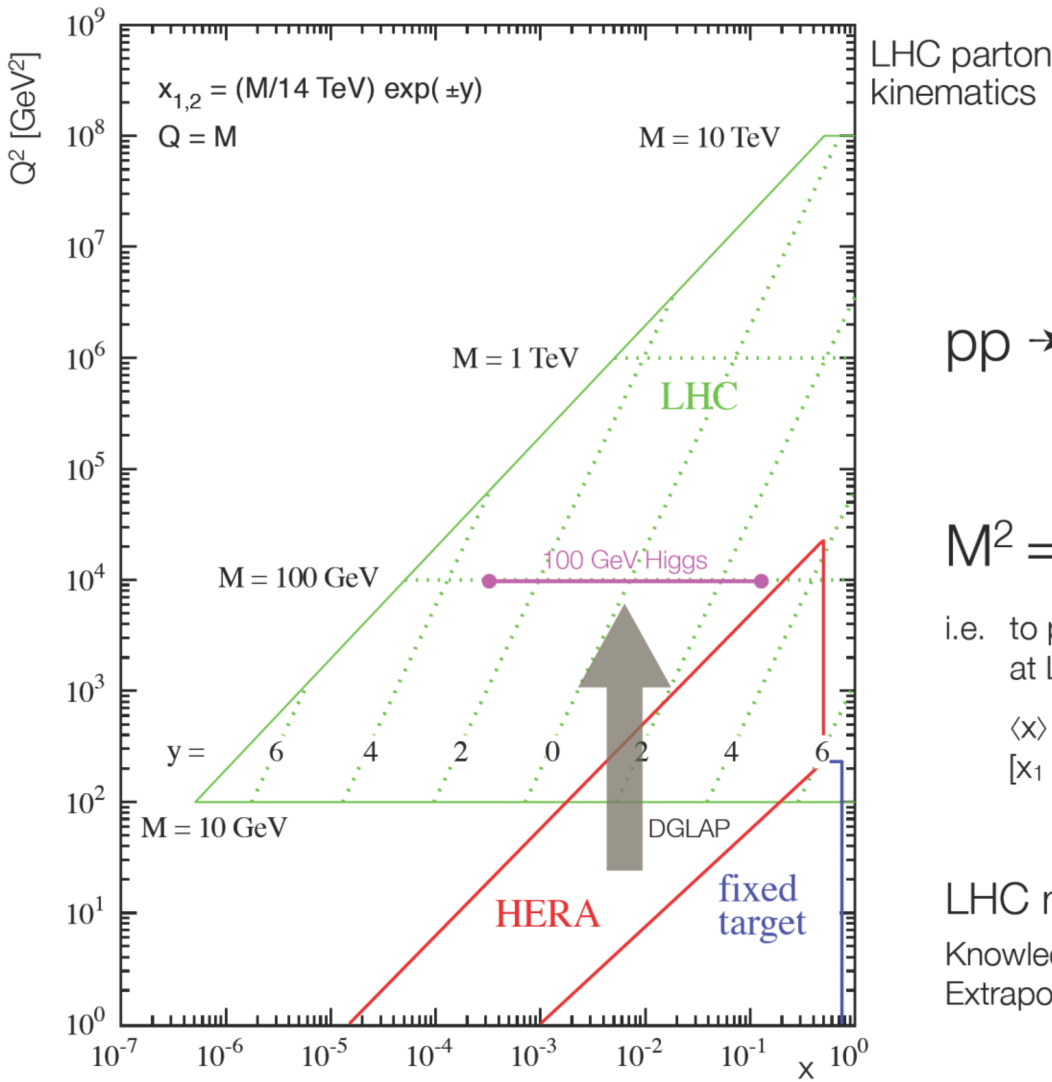


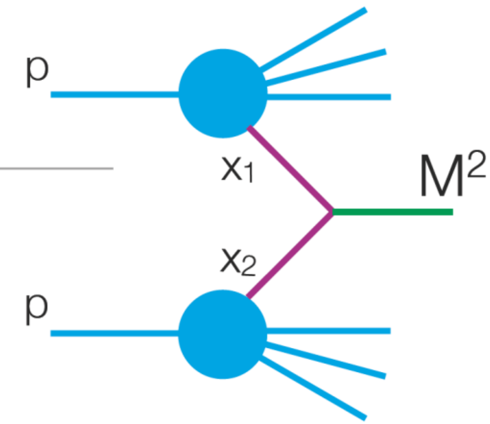
Q^2-evolution described by DGLAP Equations

Proton parton densities



Particle production @ LHC





$pp \to X_M$ + remnants

X_M: particle with mass M
e.g. Higgs

$$M^2 = x_1 x_2 \cdot s$$

i.e. to produce a particle with mass M
at LHC energies ($\sqrt{s}$ = 14 TeV)

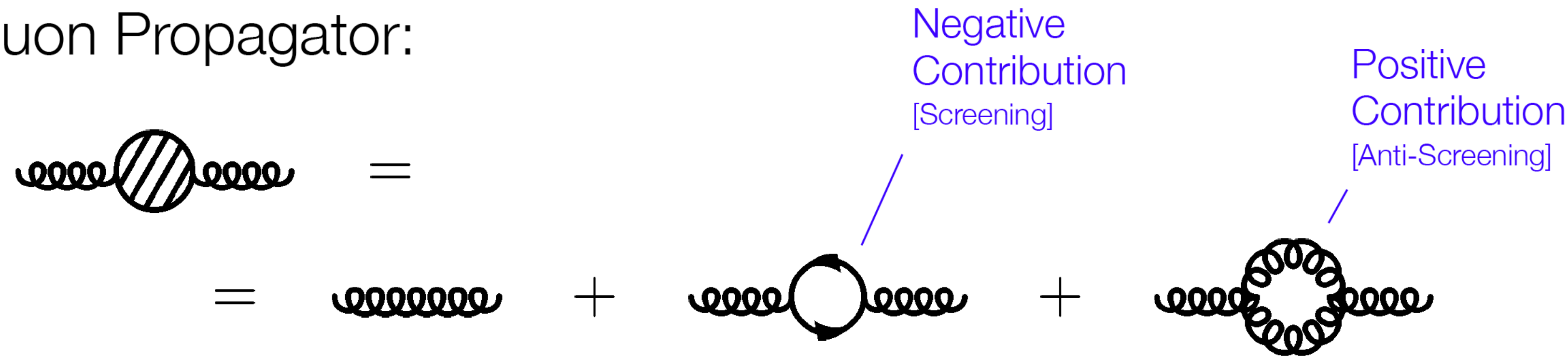
$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$
[$x_1 = x_2$: mid-rapidity]

LHC needs:

Knowledge of parton densities
Extrapolation over orders of magnitudes

Running Coupling α_s

Gluon Propagator:



$+ \ \cdots$

Yields

Running Coupling:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \log \frac{Q^2}{\mu^2}}$$

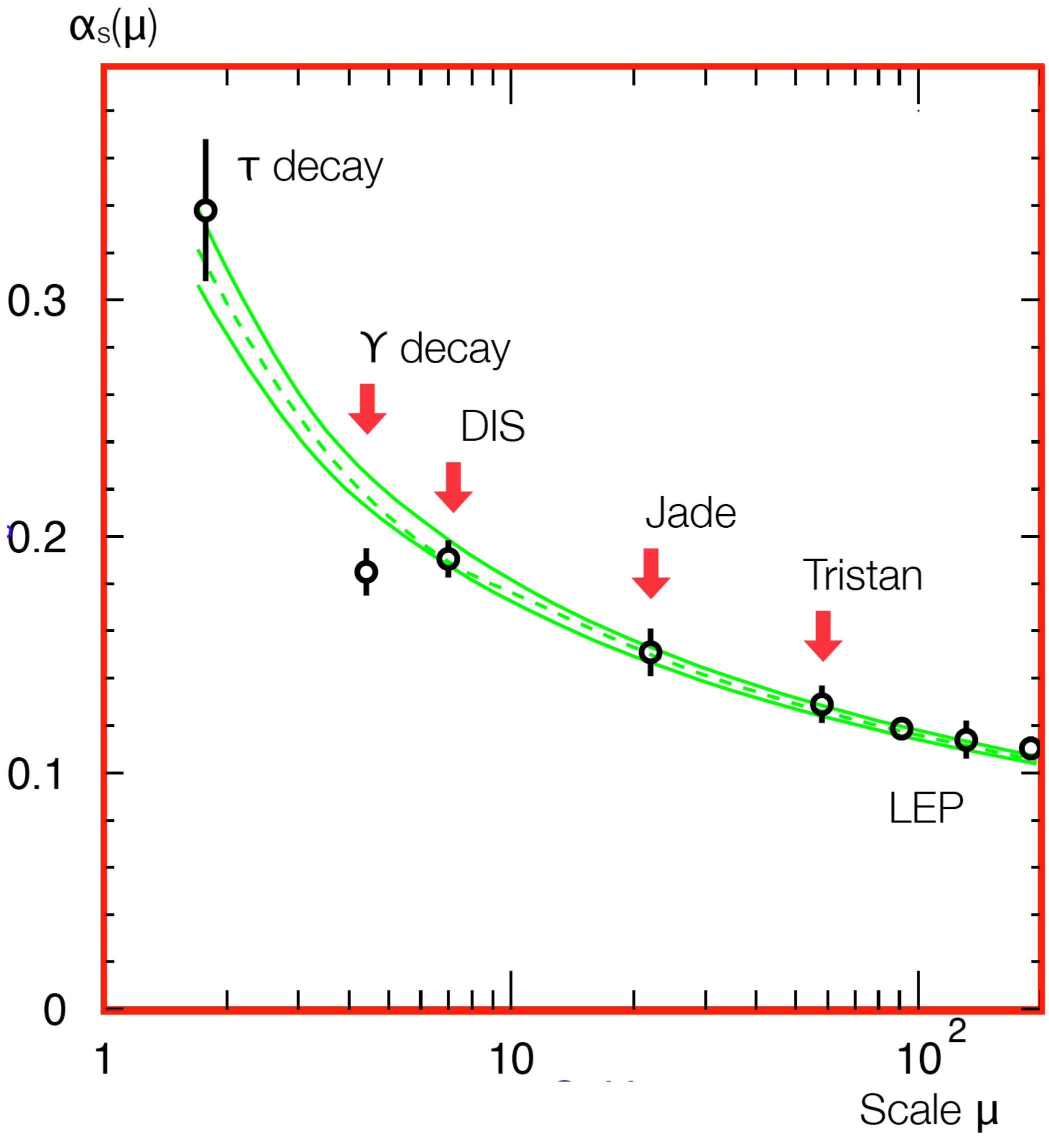
Positive Sign !

QED:

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \log \frac{Q^2}{\mu^2}}$$

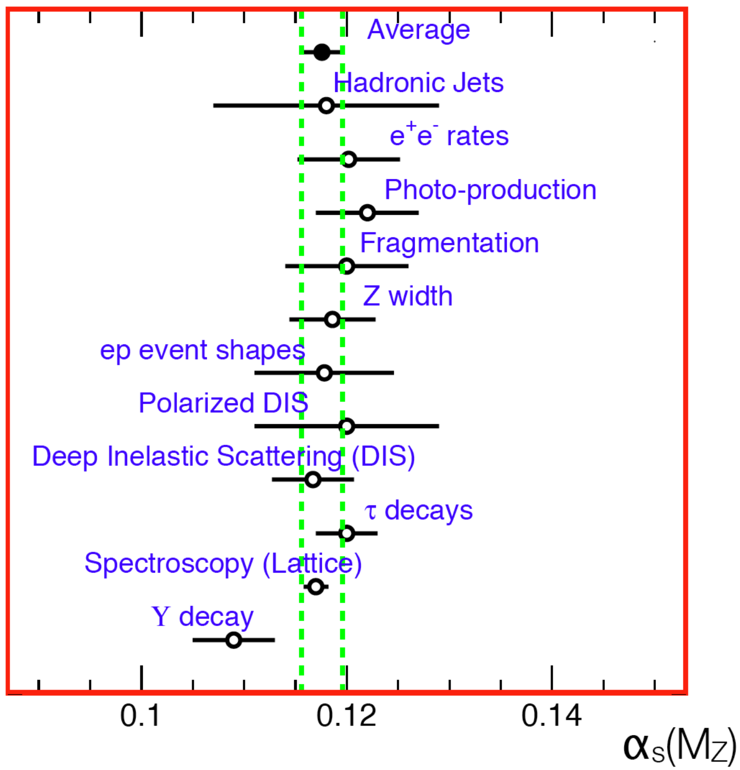
Negative Sign !

Running Coupling α_s

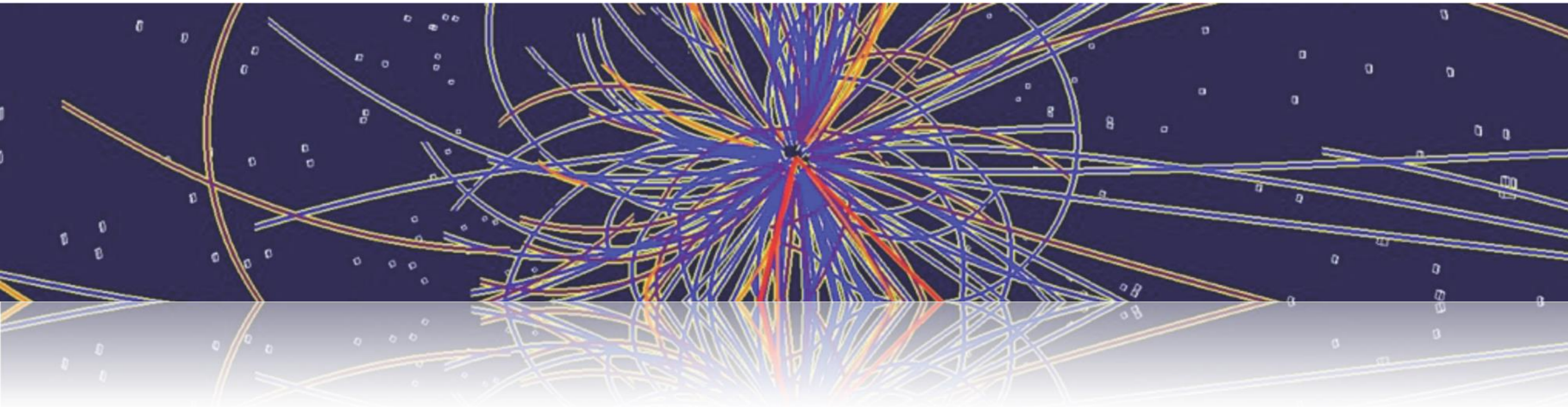


PDG ’08

[Summary of exp. results]



Monte Carlo Generators



From Partons to Jets

From partons to
color neutral hadrons:

Fragmentation:

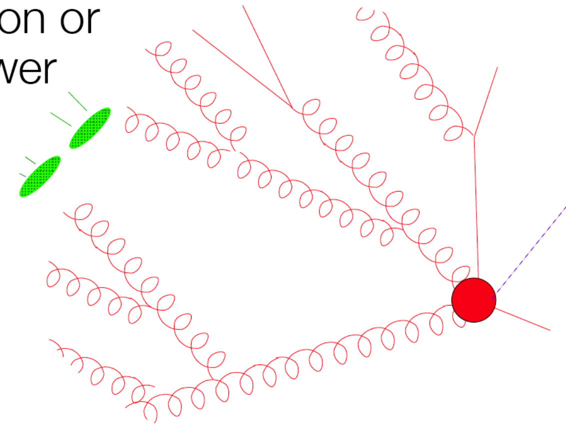
Parton splitting into other partons
[QCD: re-summation of leading-logs]
["Parton shower"]

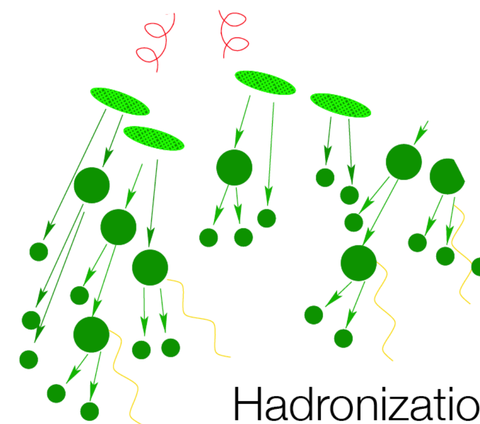
Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]

Fragmentation or
Parton Shower





Hadronization &
Decays

Monte Carlo overview

Monte Carlo simulation ...

Numerical process generation based on random numbers

Method very powerful in particle physics

Event generation programs:

Pythia, Herwig, Isajet
Sherpa ...

Hard partonic subprocess + fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response of all produced particles ...

MC simulations in particle physics

Event Generator
simulate physics process
(quantum mechanics: probabilities!)

↓

Detector Simulation
simulate interaction with detector material

↓

Digitization
translate interactions with detector into realistic signals

↓

Reconstruction/Analysis
as for real data

Event Generator types

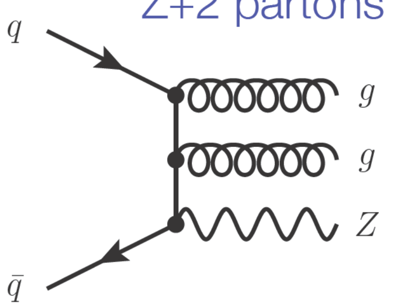
Type II : Leading order matrix element, parton shower & merging

i.e.: MEs for 2 ➛ n processes (e.g. W/Z + jets)
PS with LO generator [Pythia or Herwig]

Examples: ALPGEN, MadGraph, Sherpa

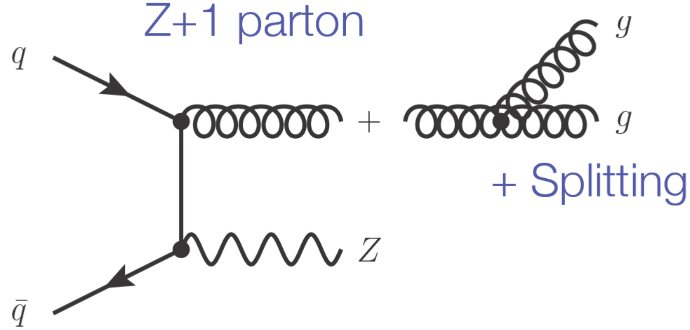
Challenge: Remove overlap between jets from ME and jets from parton shower [MLM matching, CKKW]

Z+2 partons



Overlap?

Z+1 parton



ME+PS

- Herwig
- Pythia
- SingleTop, TopRex
- Phantom
- AcerMC
- GRAPPA
- CompHEP

ME+PS+merging

- Alpgen
- MadGraph
- Sherpa

NLO+PS

- MC@NLO
- POWHEG

[F. Maltoni]

Pythia sub-processes

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g \gamma^*_T \to f_i \bar{f}_i$
136	$g \gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

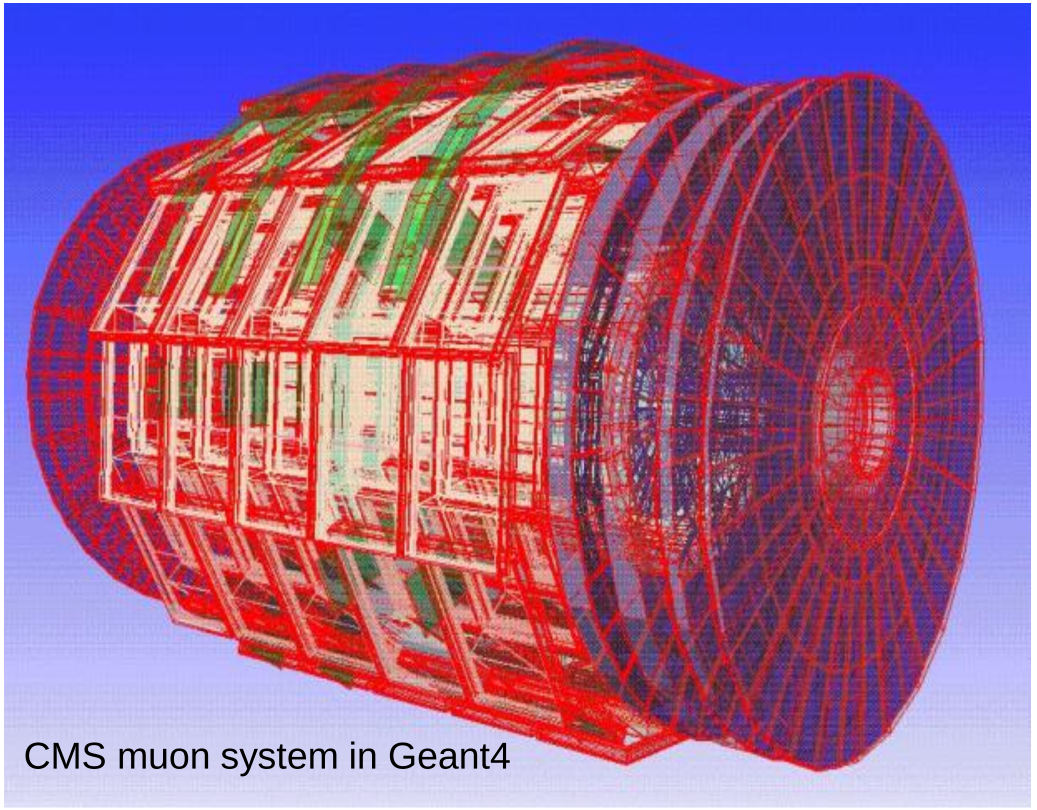
Detector simulation

GEANT
Geometry And Tracking

Detailed description of detector geometry
[sensitive & insensitive volumes]

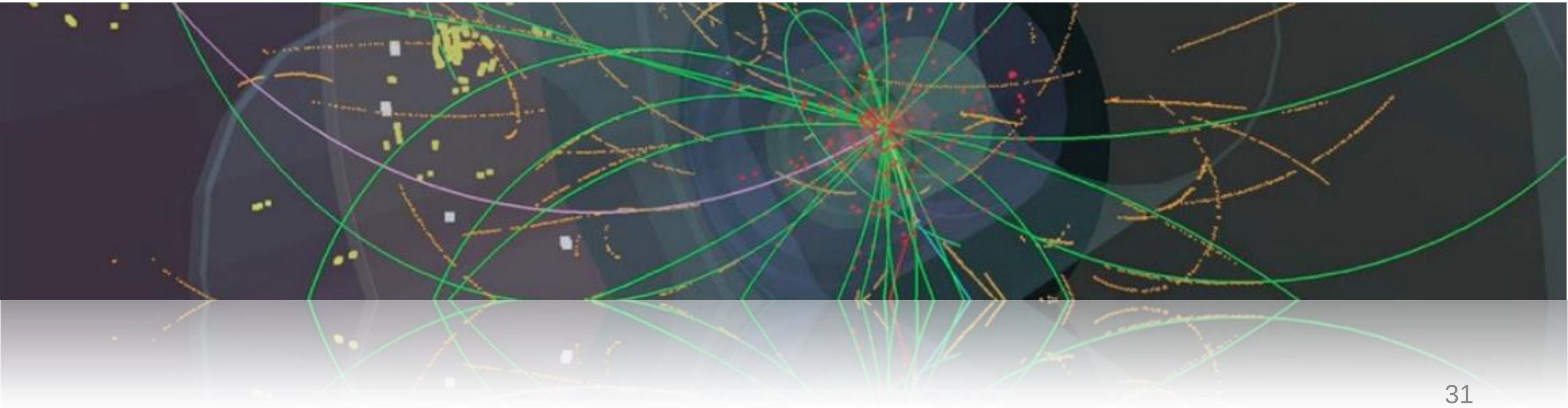
Tracking of all particles through detector material ...

➛ Detector response


CMS muon system in Geant4

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C^{++}]

Luminosity and cross-section measurements



Cross section & Luminosity

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

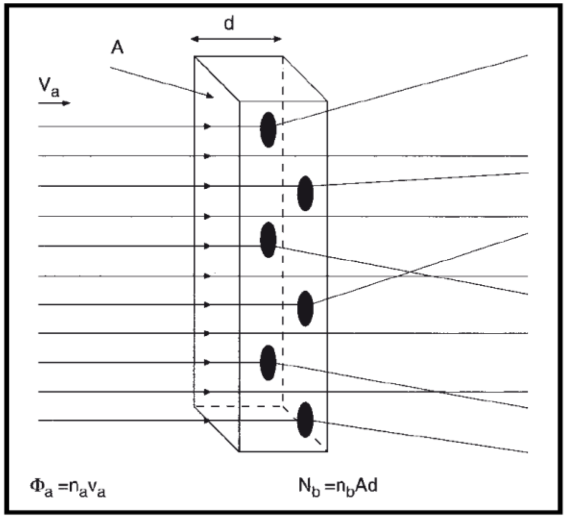
Luminosity

determined by accelerator, triggers, …

Efficiency

many factors, optimized by experimentalist

Cross section & Luminosity



$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

Φ_a : flux
n_a : density of particle beam
v_a : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

$\dot{N}$: reaction rate
N_b : target particles within beam area
σ_a : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

$$\dot{N} \equiv L \cdot \sigma$$

$$N = \sigma \cdot \underbrace{\int L\, dt}_{\text{integrated luminosity}} \qquad \sigma = N/L$$

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

$$L = f \frac{nN_aN_b}{A} = f \frac{nN_aN_b}{4\pi\sigma_x\sigma_y}$$

LHC:

N_x	~	10^{11}
A	~	.0005 mm^2
n	~	2800
f	~	11 kHz
L	~	10^{34} cm^{-2} s^{-1}

N_a : number of particles per bunch (beam A)
N_b : number of particles per bunch (beam B)
U : circumference of ring
n : number of bunches per beam
v : velocity of beam particles
f : revolution frequency
A : beam cross-section
σ_x : standard deviation of beam profile in x
σ_y : standard deviation of beam profile in y

Luminosity determination @ LHC

Absolute Methods:

Accuracy: 10%

Determination from LHC parameters; van-der-Meer separation scans ...
Rate measurement for standard candle processes ...

LHC Examples:

Rate of pp ➛ Z/W ➛ $\ell\ell/\ell\nu$ [needs: electroweak cross sections]

Accuracy: 5-10%
[PDF knowledge, ...]

Rate of pp ➛ $\gamma\gamma$ ➛ $\mu\mu$, ee [needs: QED & photon flux]

Accuracy: 1% ?
[TDR; needs forw. tagging]

Optical theorem: $\sigma_{tot} \sim \mathrm{Im}\, f(0)$ [needs: forward elastic and total inel. x-sec]
Elastic scattering in Coulomb region ...

Accuracy: 5-10%
[needs σ_{tot}; needs forw. instrumentation]
TOTEM

Combination of the above ...

Accuracy: 2-3%

Relative Methods:

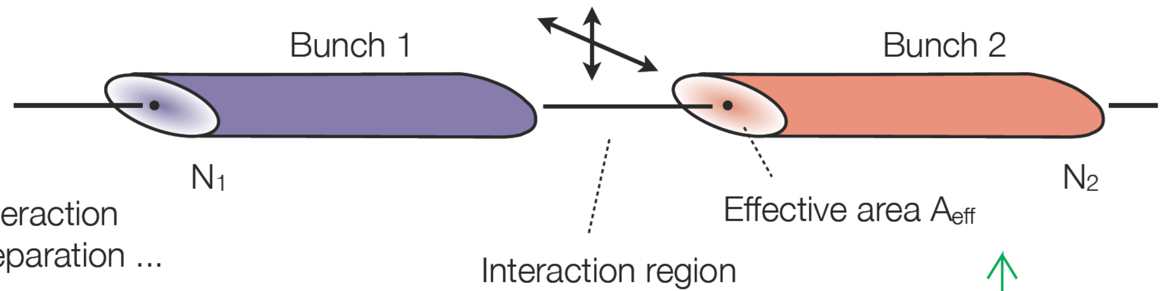
Particle counting; **LUCID @ ATLAS; HF, Pixels @ CMS**
[needs to be calibrated for absolute luminosity]

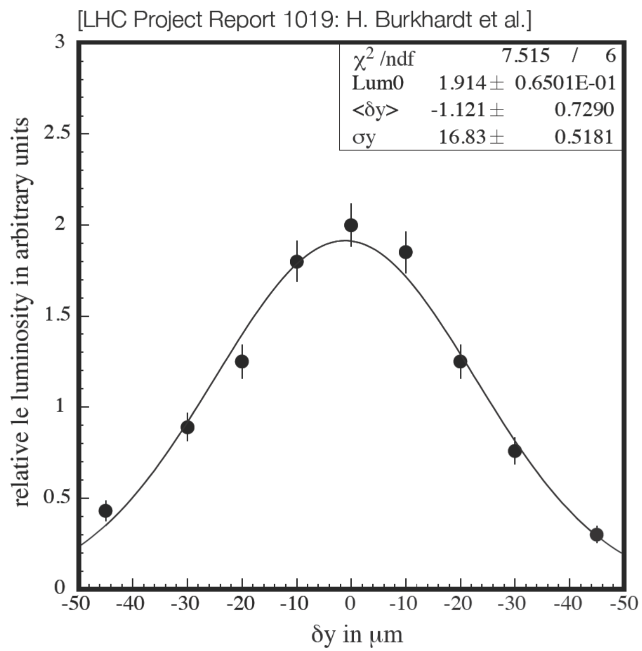
Aim: Luminosity accuracy of 2-3% ...

Van-der-Meer separation scan

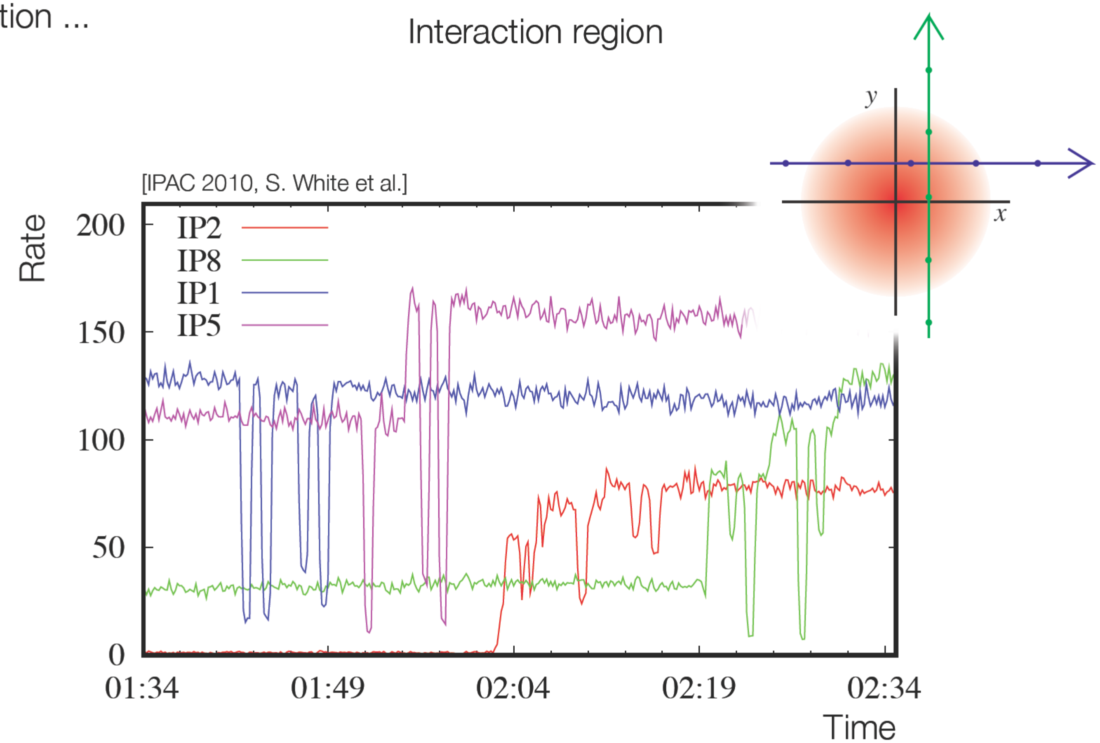
Determine beam size ...

measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...





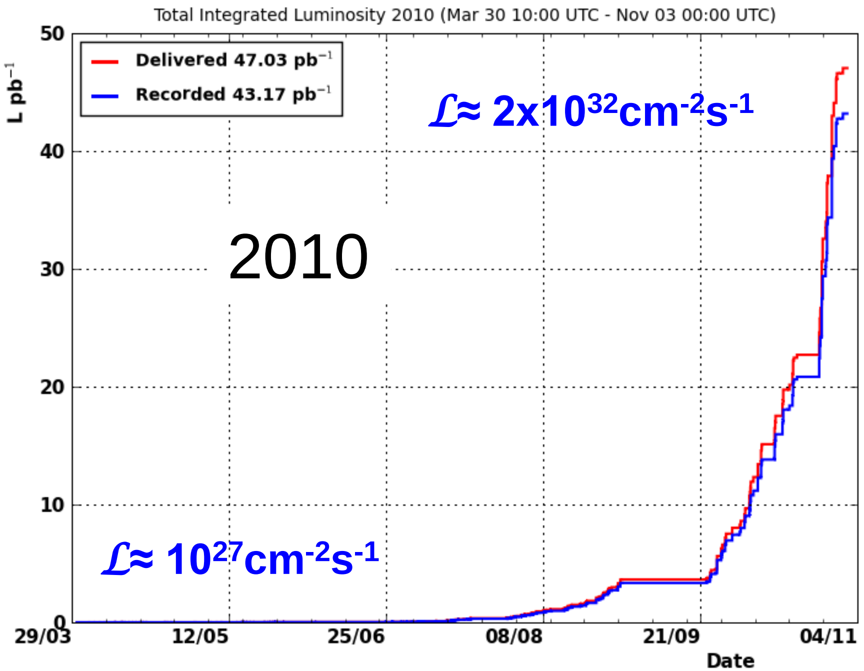
$$\frac{L}{L_0} = \exp\left[-\left(\frac{\delta_x}{2\sigma_x}\right)^2 - \left(\frac{\delta_y}{2\sigma_y}\right)^2\right]$$

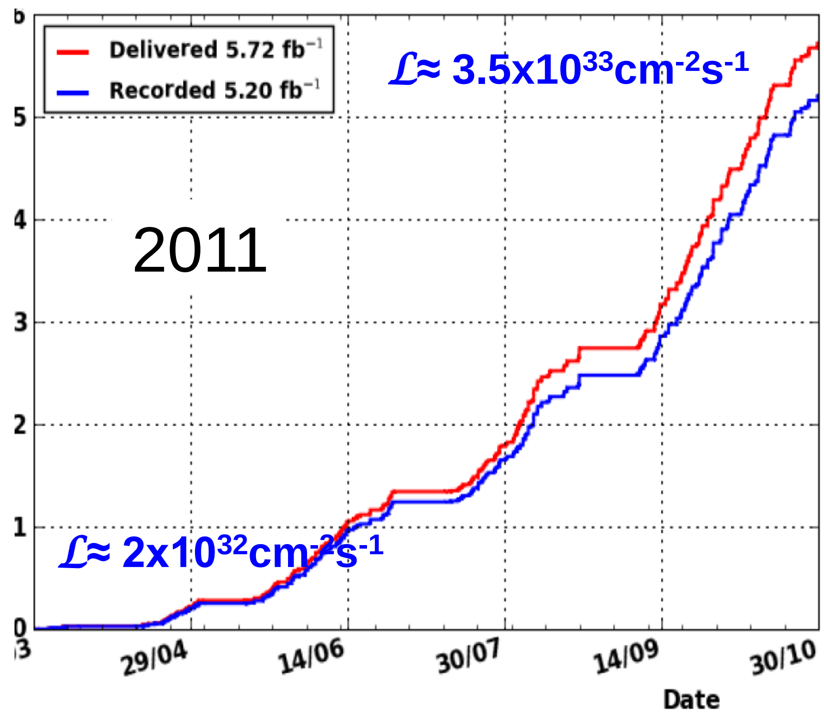


First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].

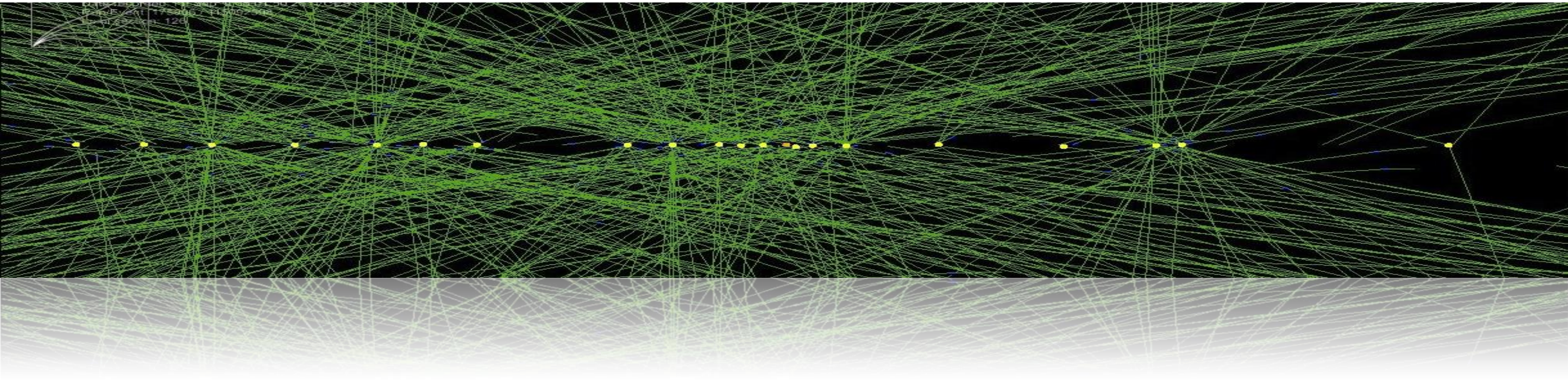
Instantaneous and integrated Luminosity

	Instantaneous (max)	Integrated
2010:	$2.x10^{32}$ cm^{-2}s^{-1}	47 pb^{-1}
2011:	$3.5x10^{33}$ cm^{-2}s^{-1}	5.7 fb-1





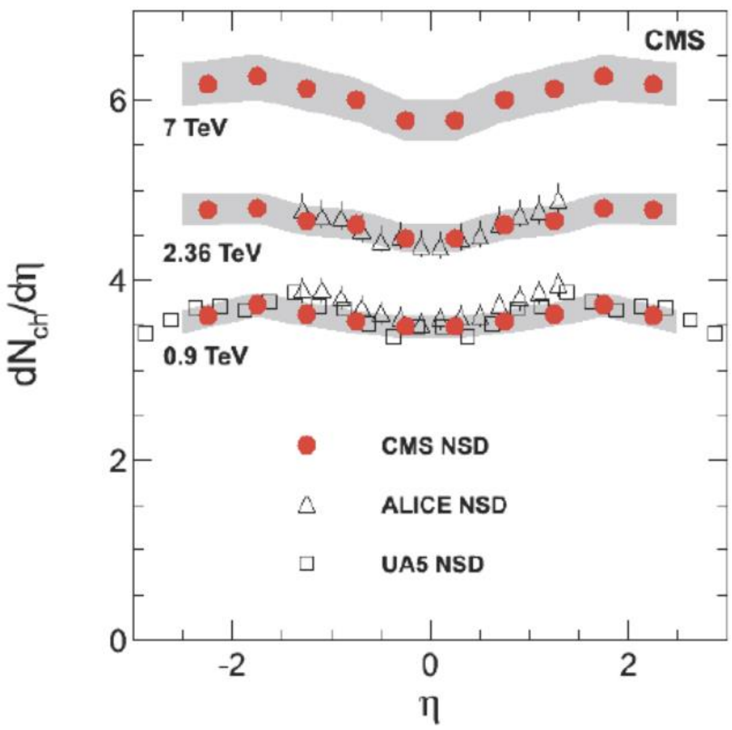
Minimum bias events

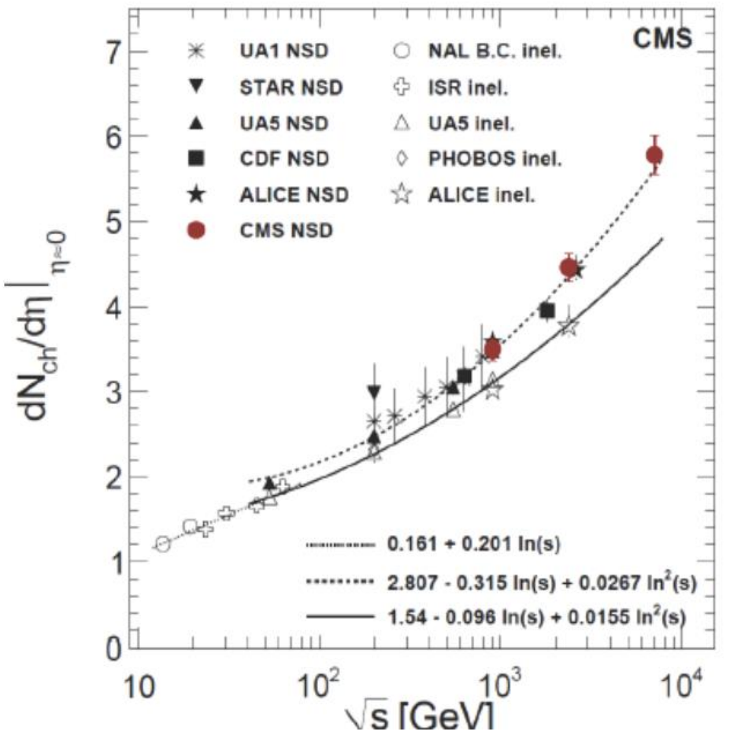


Characteristics of inelastic p-p collisions

Particle density in minimum bias events

Soft QCD (PT threshold on tracks: 50 MeV)

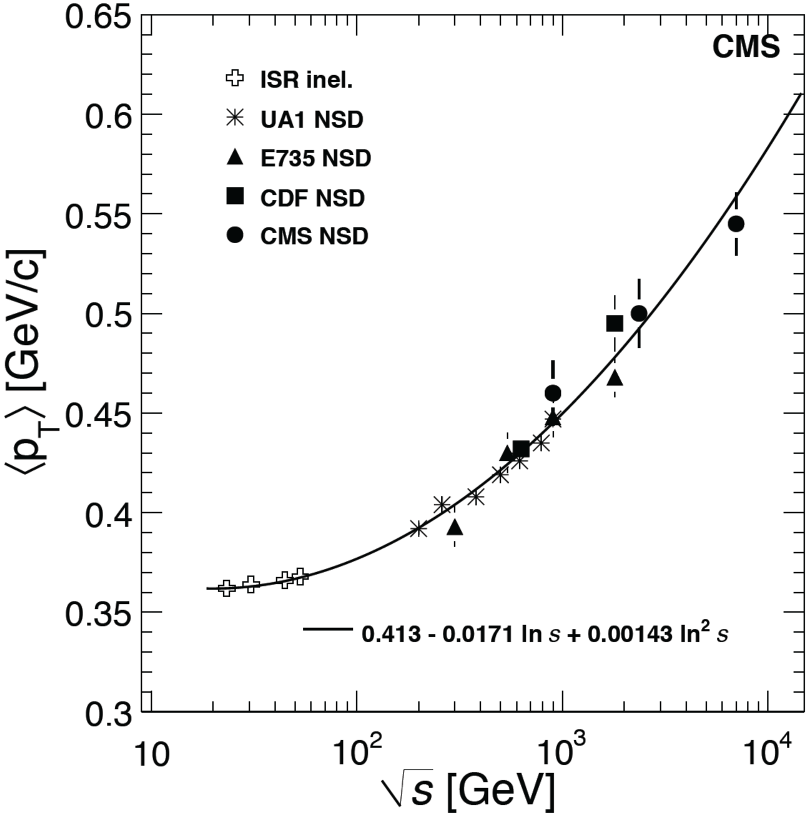




Particle density in data rises faster than in model predictions.
Tuning of MC generators was needed.

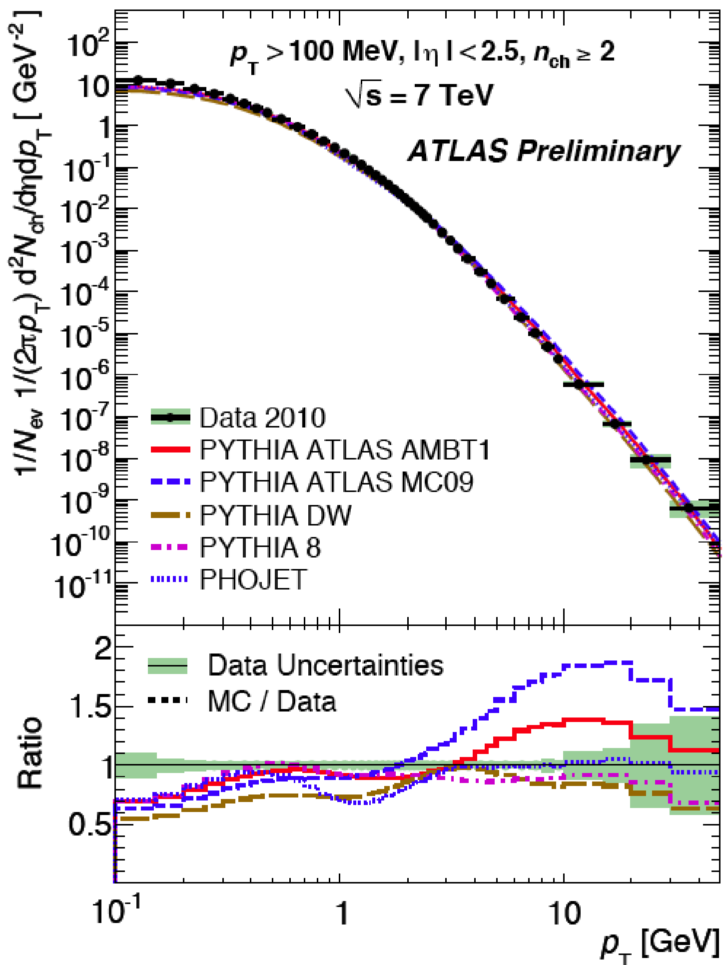
Charged particle p_T spectrum

$<p_T> = 0.545$
$\pm$ 0.005 (stat.)
$\pm$ 0.015 (syst.) GeV/c

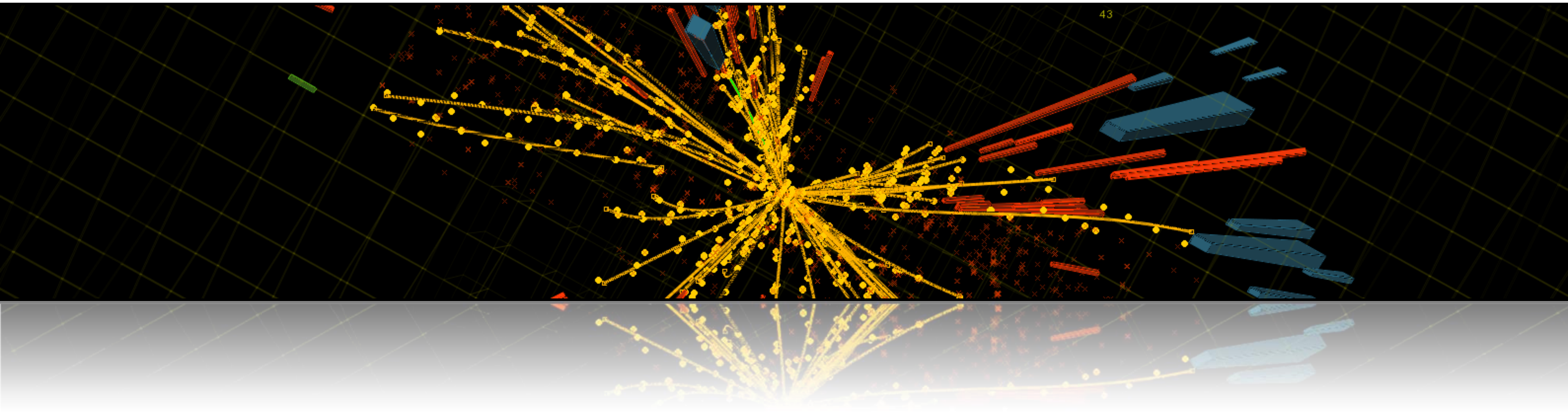


dN_{ch}/dp_T

p_T > 100 MeV
$|\eta| < 2.5$
$N_{ch} \geq 2$

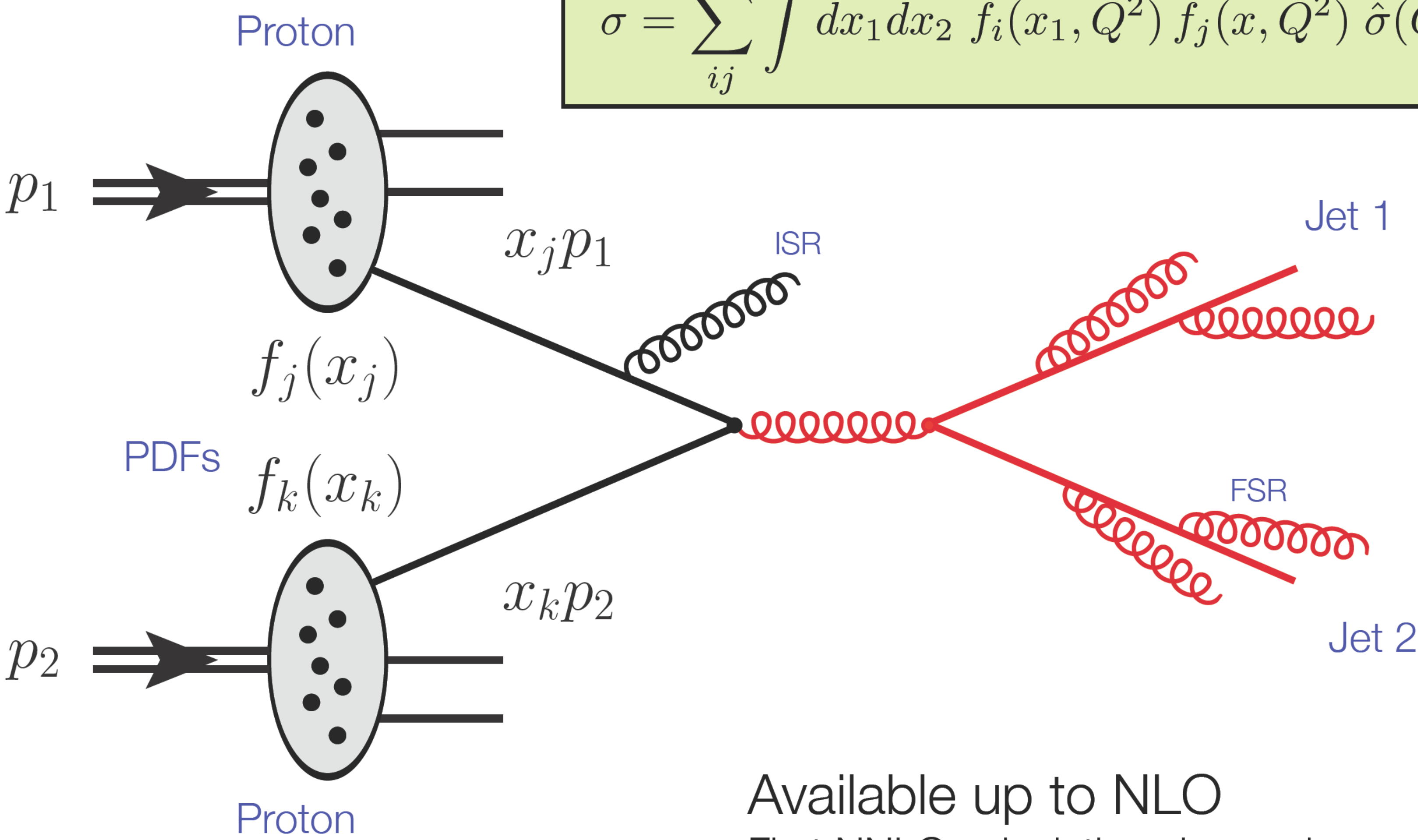


Jet physics



Jet production @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$



Available up to NLO

First NNLO calculations becoming available ...

Higher orders

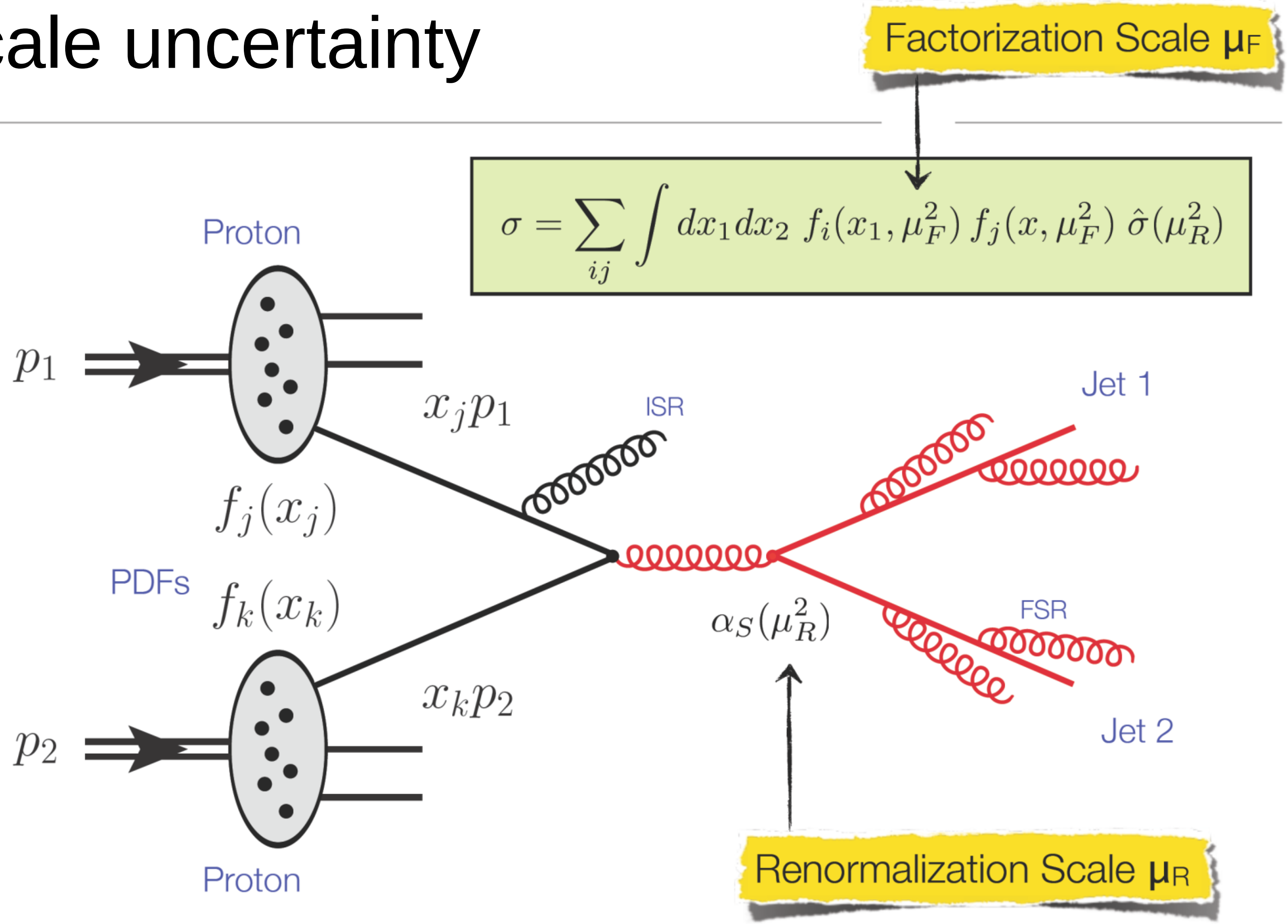
At least next-to-leading order (NLO) required
to compare to precision measurements
[First NNLO calculations becoming available ...]

Various divergencies; artifacts of perturbation theory;
the full theory gives finite results ...
[But we don't know how to solve it]

Ultraviolet (UV) divergences, i.e. at very large momenta
Solution: renormalization; choice of correct scale ...
["Status of peaceful coexistence with divergences", S.D. Drell]

Infrared (IR) divergences, i.e. at very small momenta
Solution: cancellations, factorization, IR-safe observables

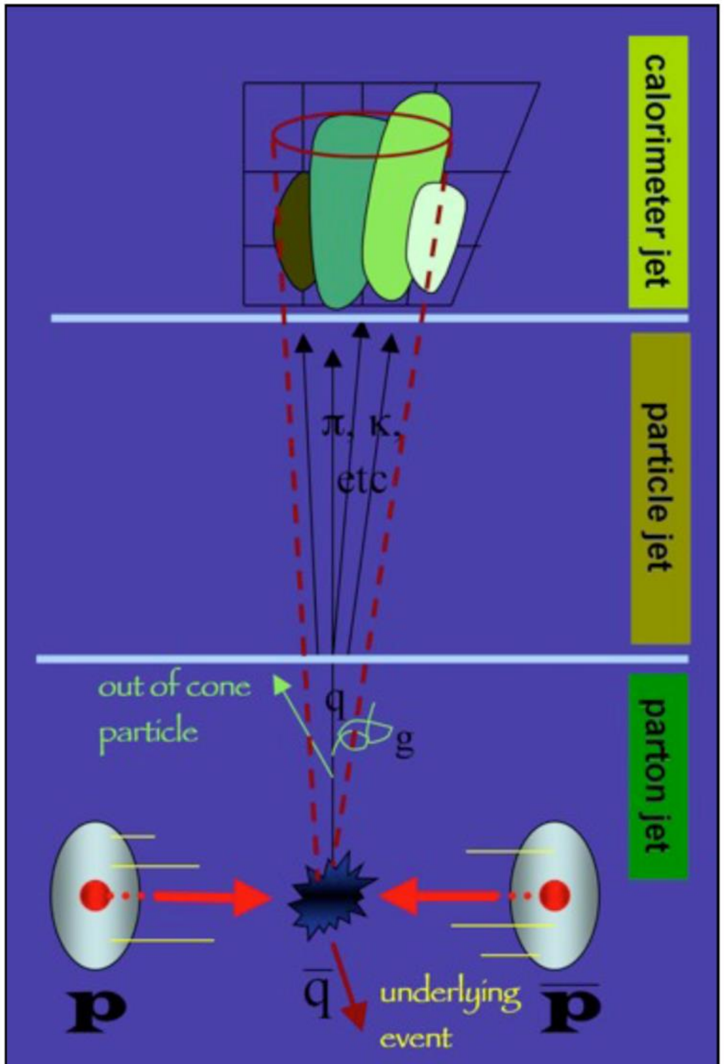
Scale uncertainty

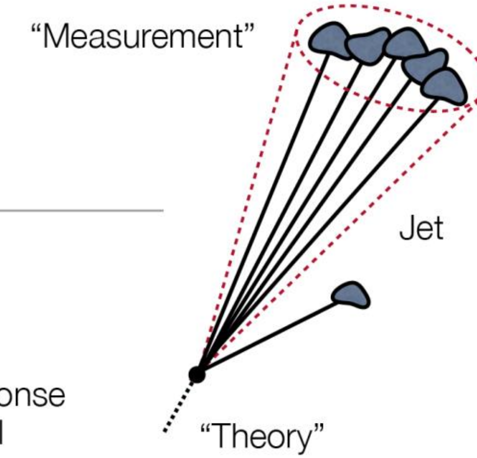


The default renormalization and factorization scales (μ_R and μ_F respectively) are defined to be equal to the p_T of the leading jet in the event

Scale uncertainty estimation: vary μ_R, μ_F within [μ_R/2, 2μ_R] and [μ_F/2, 2μ_F]

Jet properties measurement





Calorimeter Jet

[extracted from calorimeter clusters]

Understanding of detector response
Knowledge about dead material
Correct signal calibration
Potentially include tracks

From measured energy to particle energy

Compensate energy loss due to neutrinos, nuclear excitation ...

Hadron Jet

[might include electrons, muons ...]

Hadronization
Fragmentation
Parton shower
Particle decays

From particle energy to original parton energy

Compensate hadronization; energy in/outside jet cone
...

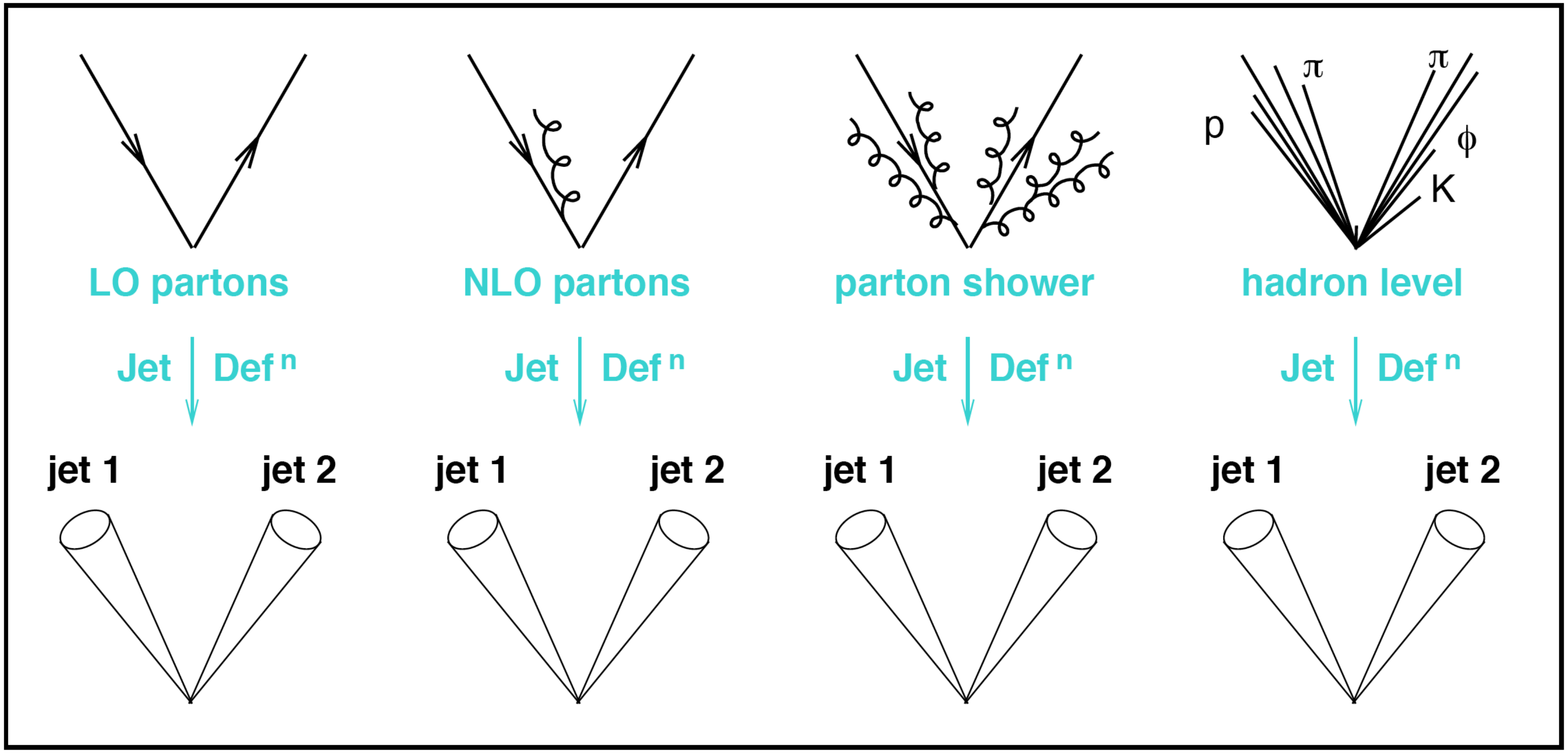
Parton Jet

[quarks and gluons]

Proton-proton interactions
Initial and final state radiation
Underlying event

Needs Calibration

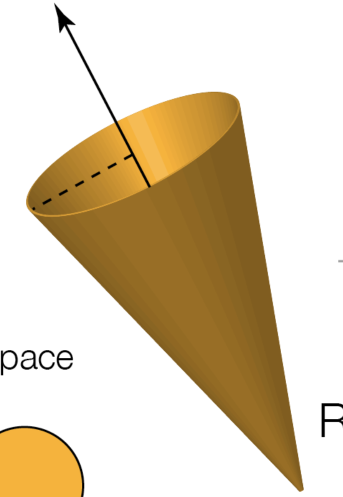
Jet properties measurement



Jets may look different at different levels

Robust jet definition ➛ stable on all jet levels

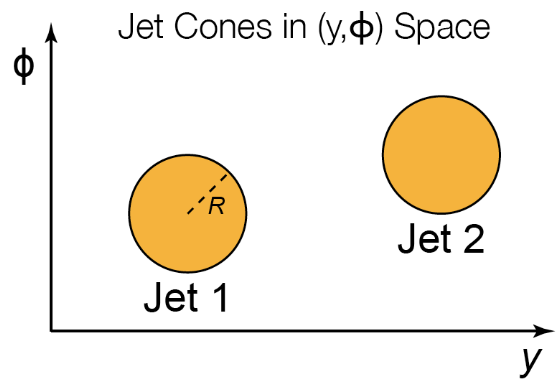
Jet reconstruction



Iterative cone algorithms:

Jet defined as energy flow within a cone of radius R in (y,ϕ) or (η,ϕ) space:

$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$



Sequential recombination algorithms:

Define distance measure d_{ij} ...

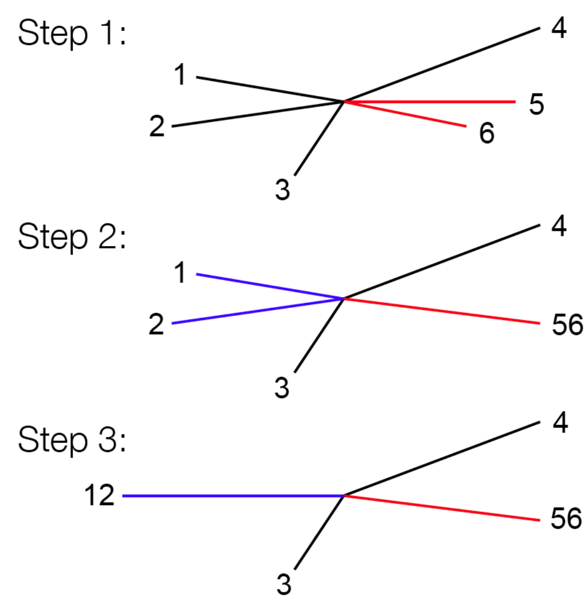
Calculate d_{ij} for all pairs of objects ...

Combine particles with minimum d_{ij} below cut ...

Stop if minimum d_{ij} above cut ...

e.g. k_T-algorithm:
[see later]

$$d_{\mathrm{ij}} = \min\left(k_{\mathrm{T,i}}^2, k_{\mathrm{T,j}}^2\right) \frac{\Delta R \mathrm{ij}}{R}$$



Sequential recombination

Jet algorithms performance

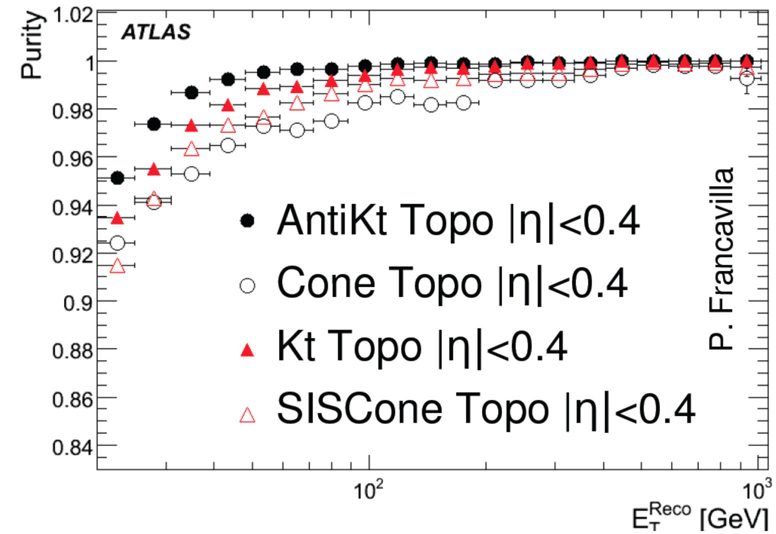
Anti-kt clustering algorithm:

in distance formula
replace P_T^2 by P_T^{2p}

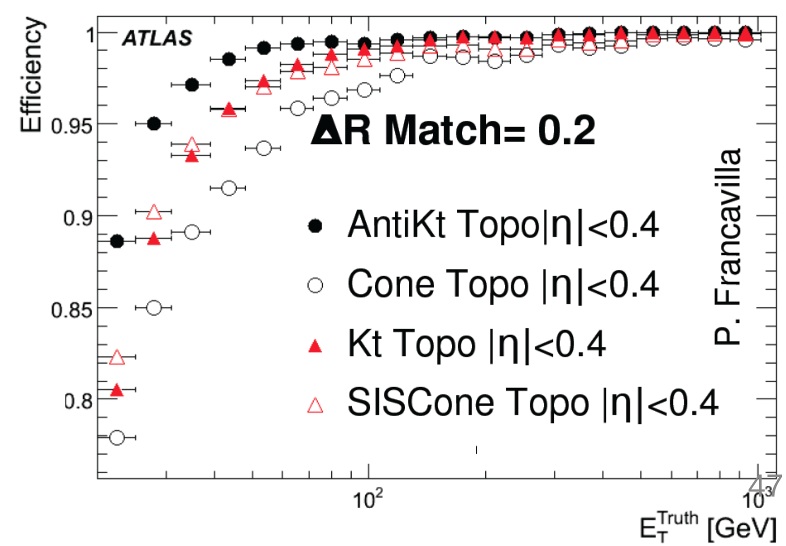
p=1 : standard Kt
p=-1 : anti-Kt

$$D_{ij} = \min(P_{Ti}^2, P_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}$$

Purity = $N^{Reco}_{Matched}$ / N^{Reco}

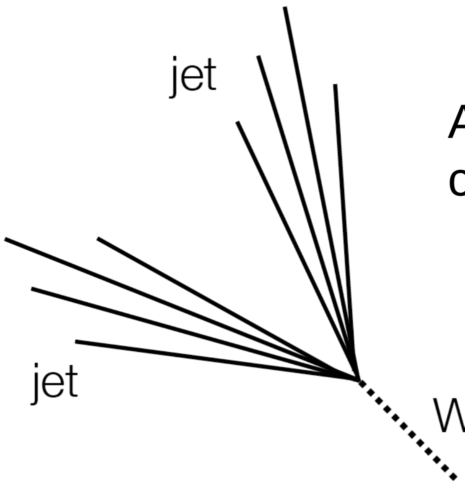


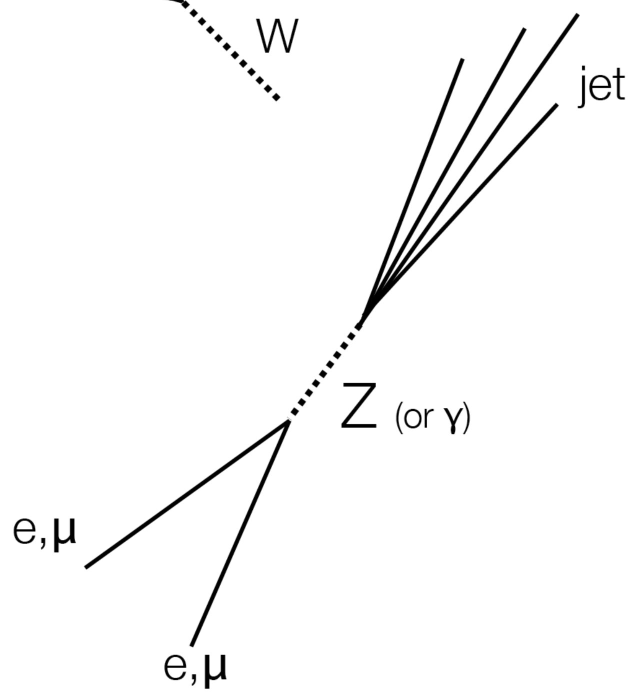
Efficiency = $N^{Truth}_{Matched}$ / N^{Truth}

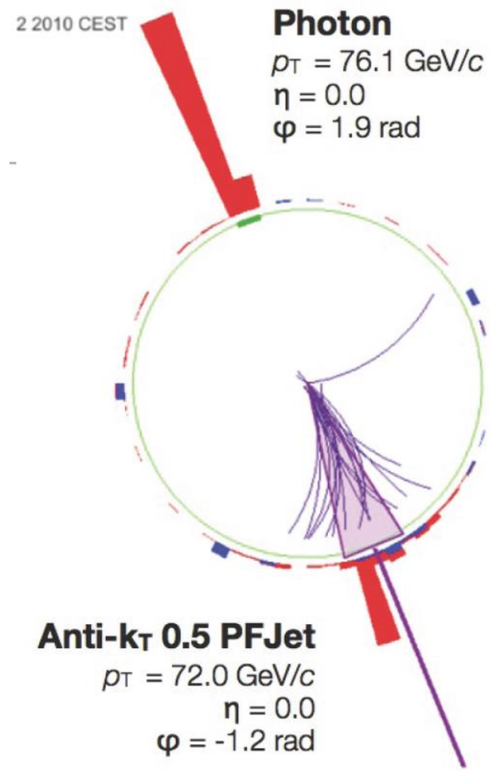


Jet energy calibration

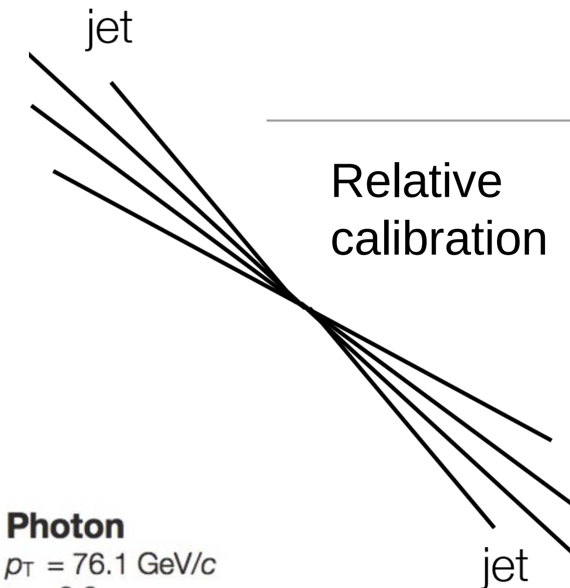
Absolute calibration





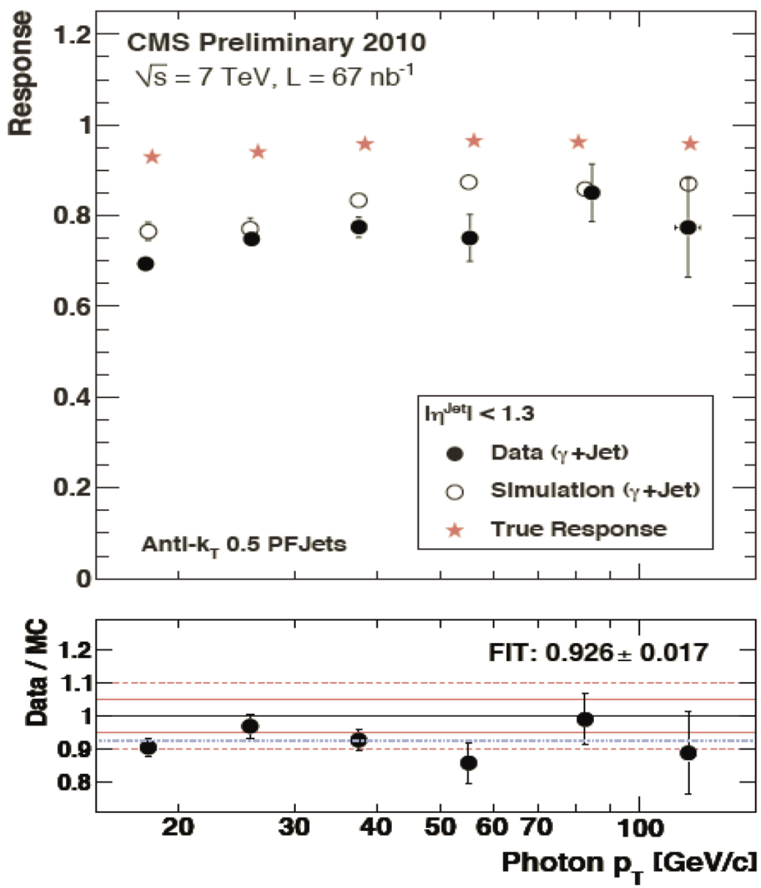


Relative calibration

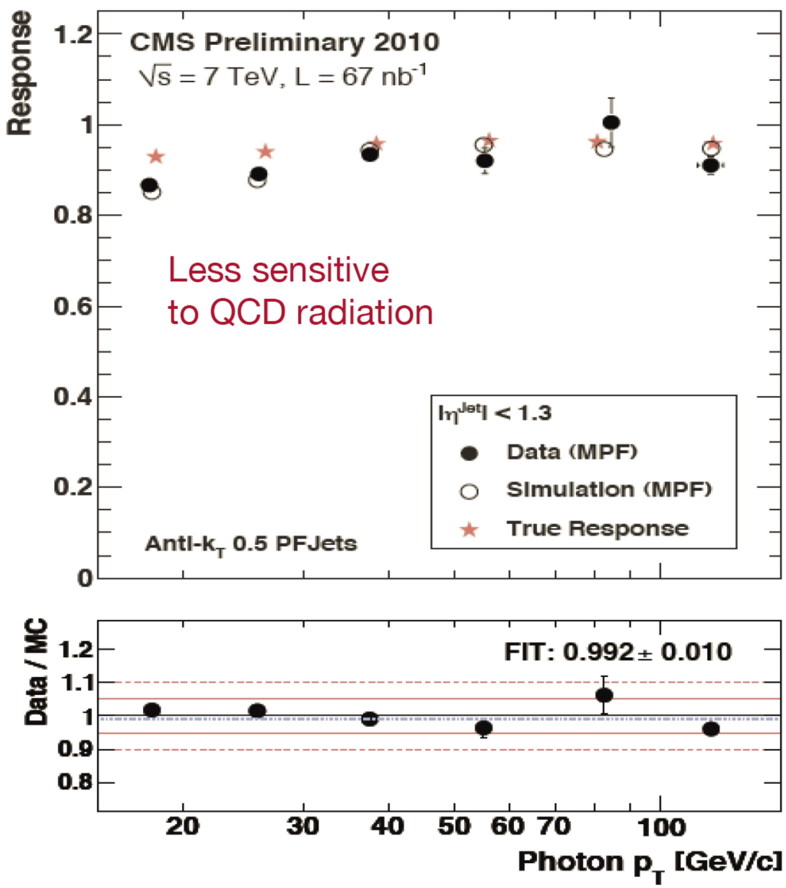


Jet energy calibration

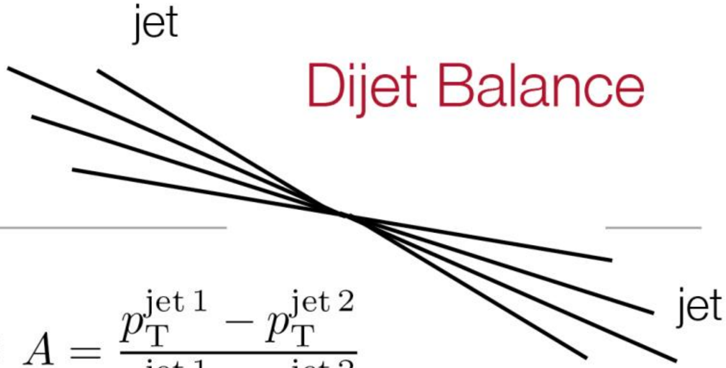
Simple Photon+jet balance
Bias due to soft veto on second jet



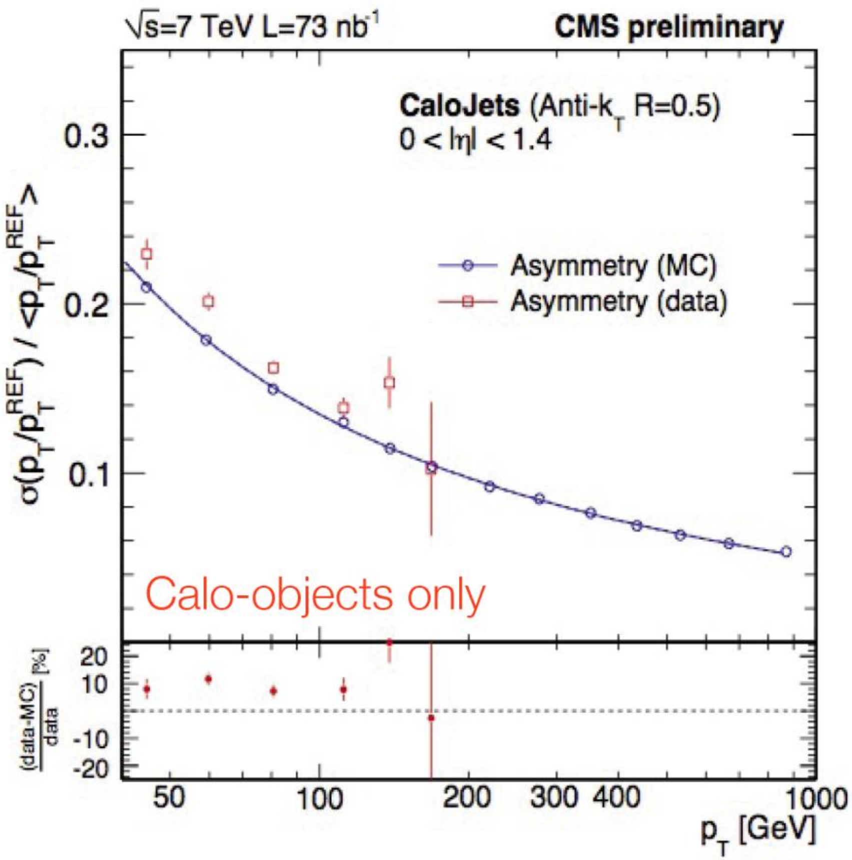
MET projection fraction method
Sums over non-photon E_T for balance

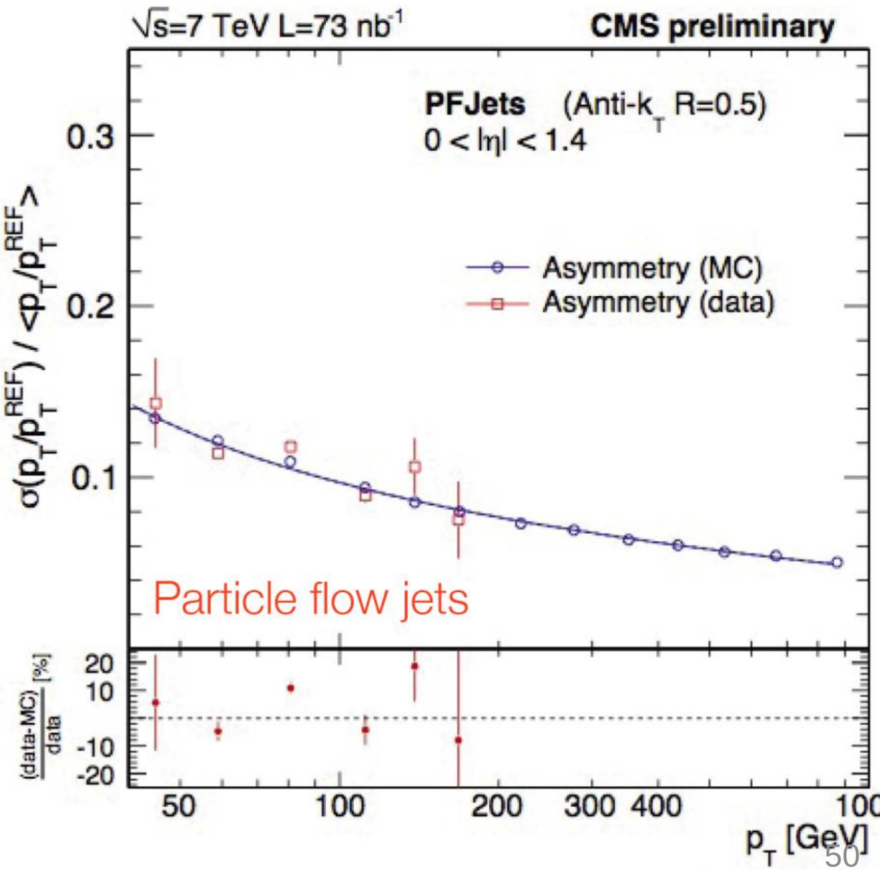


Jet energy resolution



Resolution: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$ using p_T asymmetry: $A = \frac{p_T^{\text{jet}\,1} - p_T^{\text{jet}\,2}}{p_T^{\text{jet}\,1} + p_T^{\text{jet}\,2}}$



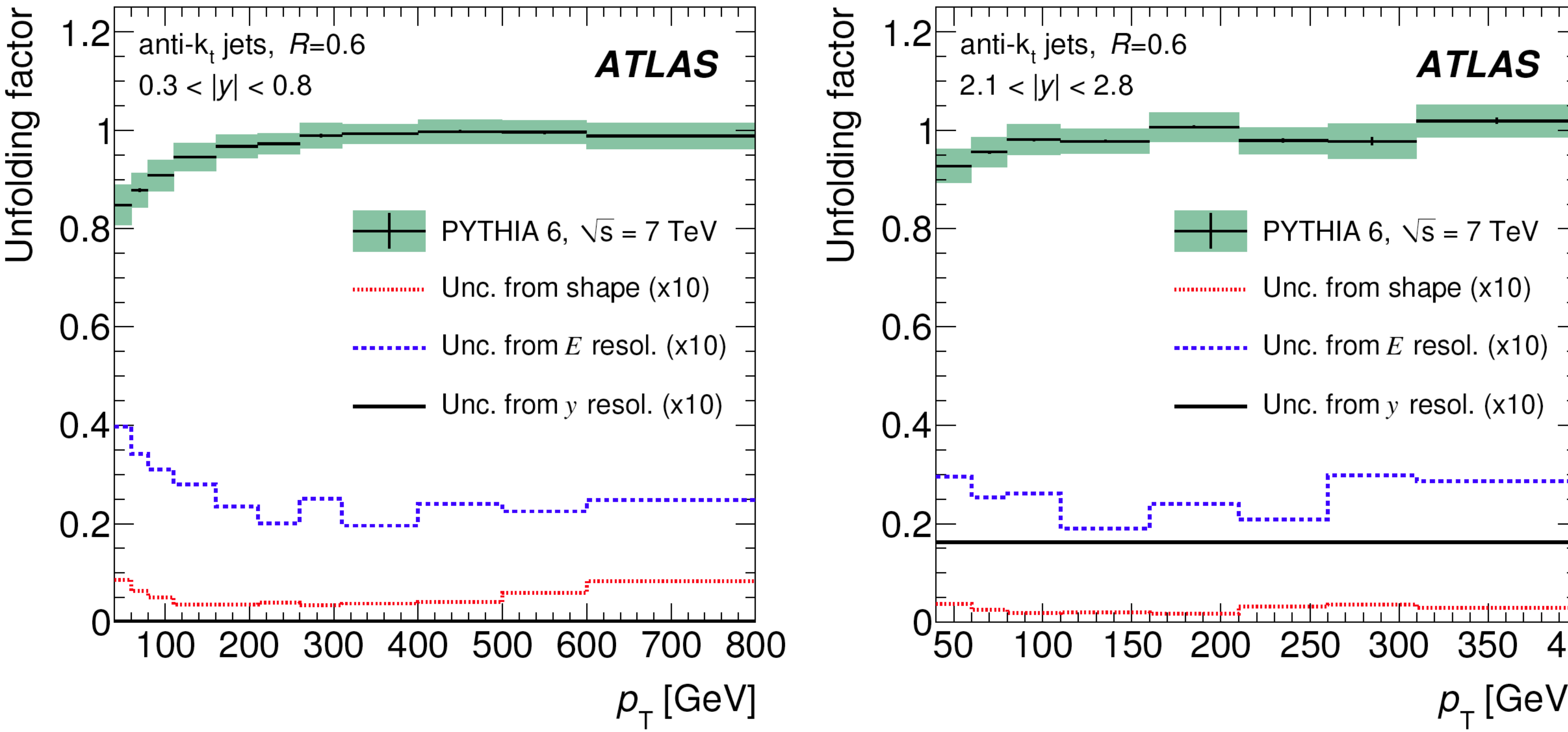


['bin-by-bin' unfolding]

Resolution unfolding

Measured spectrum =
Real spectrum □ Experim. resolution

$$N_{\text{part}} = N_{\text{meas}} \cdot \frac{N_{\text{part}}^{\text{MC}}}{N_{\text{meas}}^{\text{MC}}}$$



[ATLAS Collaboration; arXiv:1009.5908v2; Fig. 8]

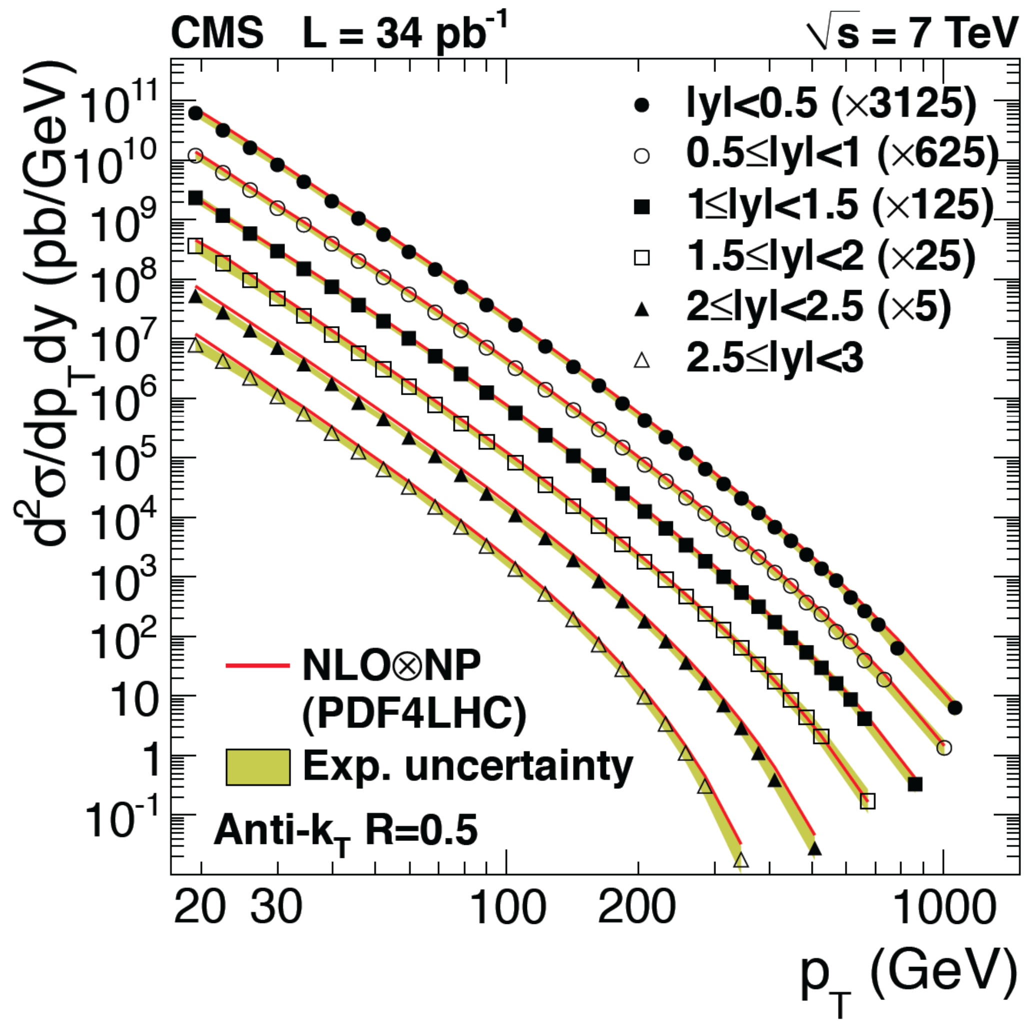
Inclusive jet cross-section

Cross section is huge
(~ Tevatron x 100)

Very good agreement with NLO QCD over nine orders of magnitude

PT extending from 20 to 500 GeV

Main uncertainty:
Jet Energy Scale (3-4%)



Inclusive jet cross-section

[ATLAS Collaboration; arXiv:1009.5908v2; Tab. 1]

$0 < \|y\| < 0.3$									
p_{T} [GeV]	60-80	80-110	110-160	160-210	210-260	260-310	310-400	400-500	500-600
Measured cross section [pb/GeV]	3.5e+04	7.9e+03	1.4e+03	2.7e+02	43	22	8.8	2.0	–

NLO

$0.3 <$

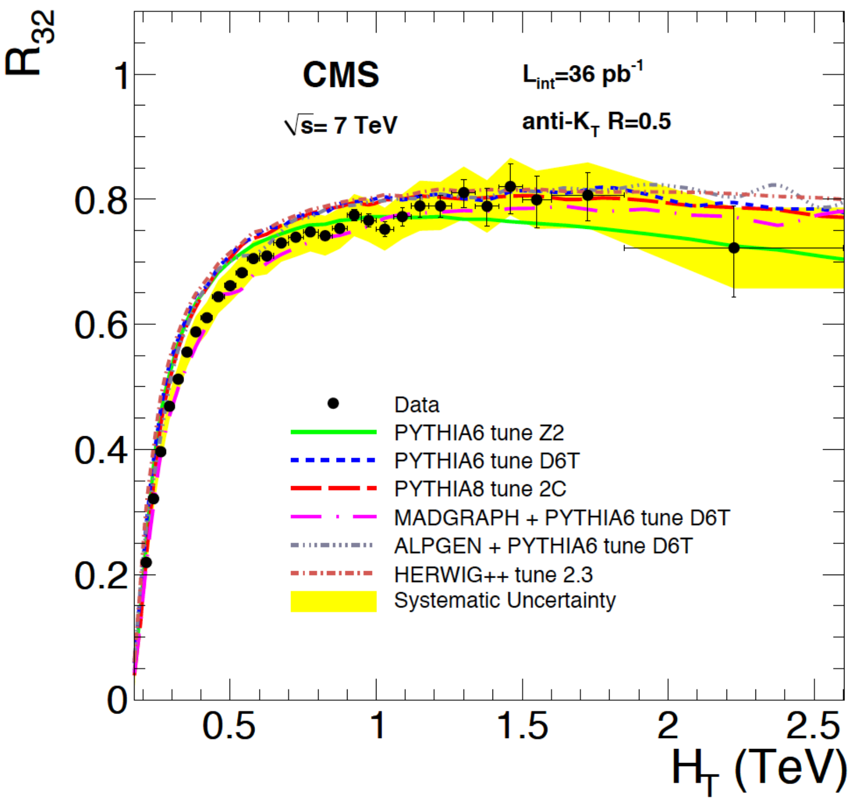
NLO

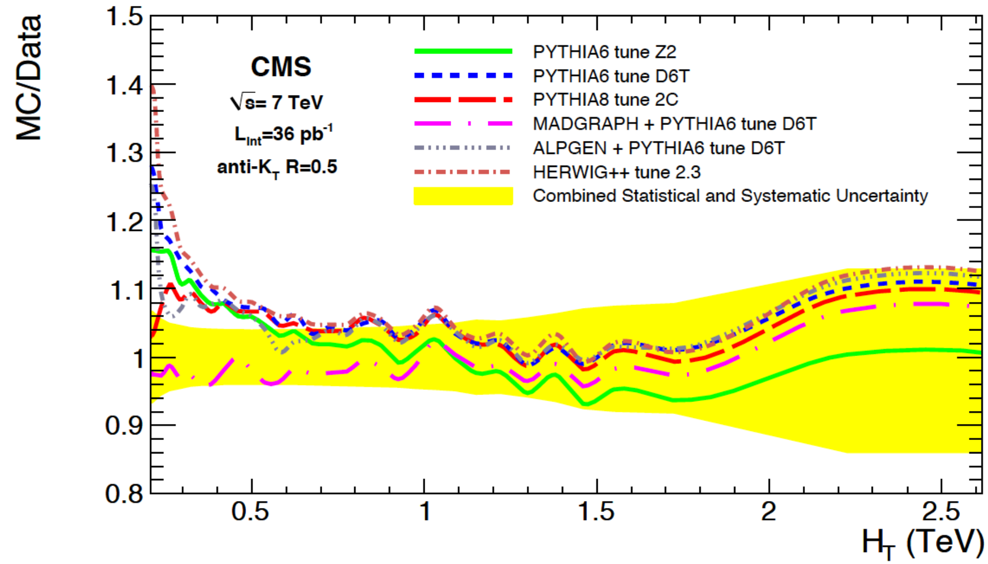
Table
pQCD
the me
where

$0 < \|y\| < 0.3$	
p_{T} [GeV]	60-80
Measured cross section [pb/GeV]	3.5e+04
NLO pQCD (CTEQ 6.6) × non-pert. corr. [pb/GeV]	4.1e+04
Non-perturbative correction	0.92
Statistical uncertainty	0.011
Absolute JES uncertainty	$^{+0.25}_{-0.22}$
Unfolding uncertainty	0.04
Total systematic uncertainty	$^{+0.3}_{-0.2}$
PDF uncertainty	0.02
Scale uncertainty	$^{+0.006}_{-0.04}$
α_s uncertainty	0.03
Non-perturbative correction uncertainty	$^{+0.06}_{-0}$
Total theory uncertainty	$^{+0.07}_{-0.05}$

Inclusive jet cross sections: 3-jet / 2-jet ratio

hep-ex 1106.0647, PLB 702 (2011) 336

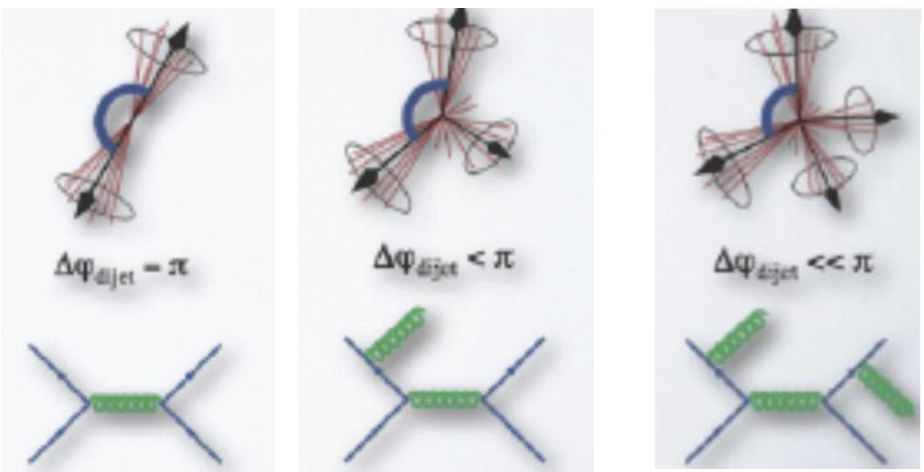


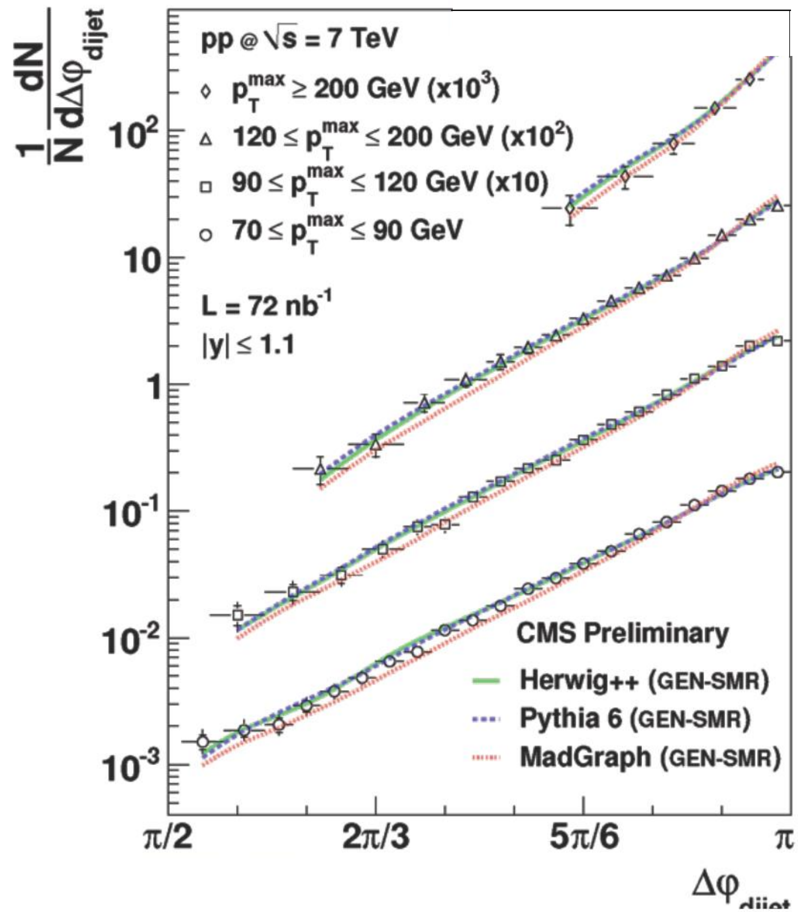


$$H_{\mathrm{T}} = \sum_{i=1}^{N} p_{\mathrm{T}i}$$

Jets: angular correlations

Difference in azimuth of the two leading jets
Probe of QCD high-order processes
Very slight dependence on JES
No dependence on luminosity





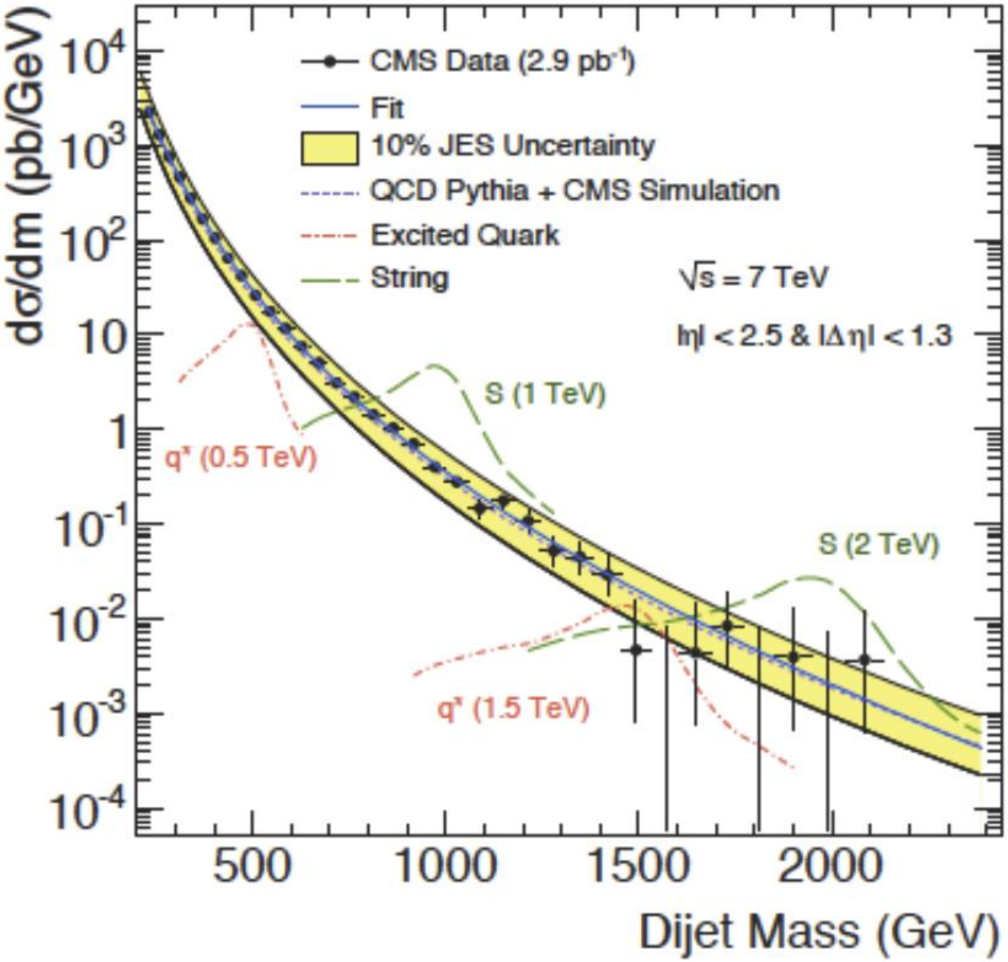
Dijet mass

Very early search for numerous resonances BSM:
string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons

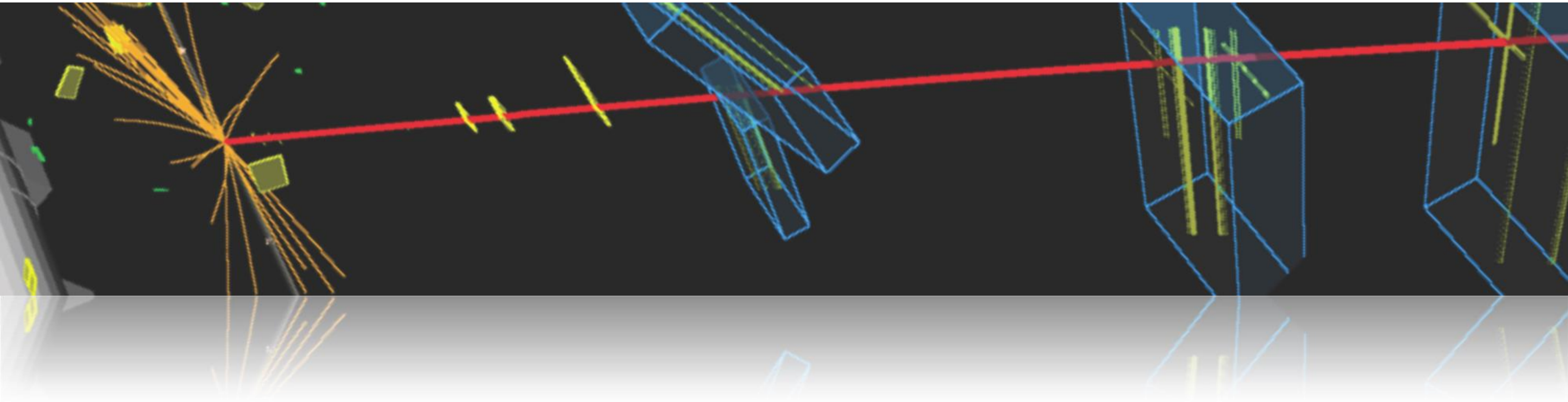
Four-parameter fit to describe QCD shape:

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1-\frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^{B}};$$

$$B = p_2 + p_3\left(m/\sqrt{s}\right)$$

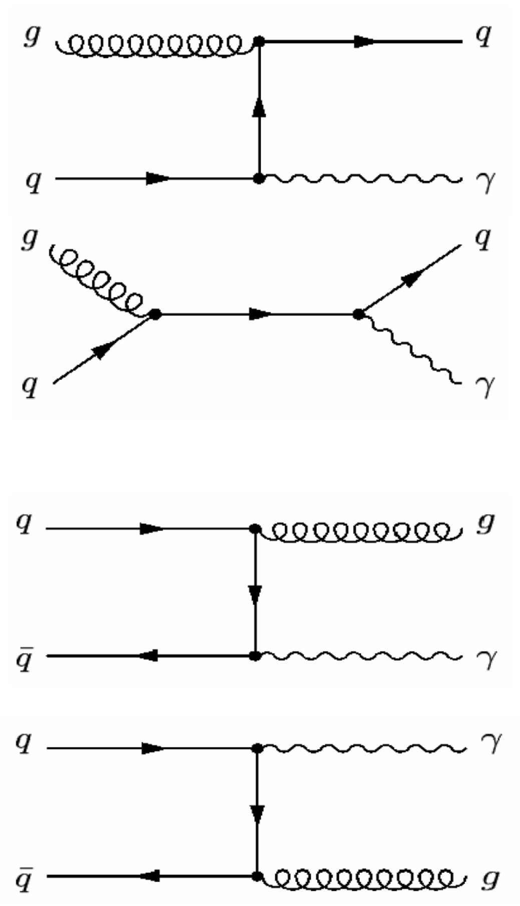


W and Z bosons

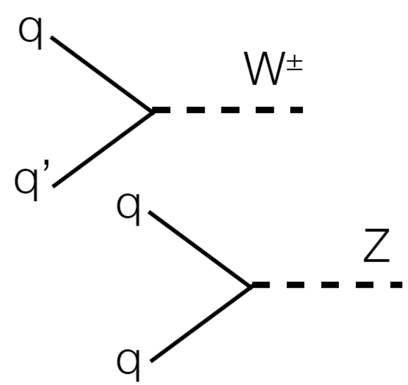


Vector boson production

Direct γ-production:



Singel W/Z production:



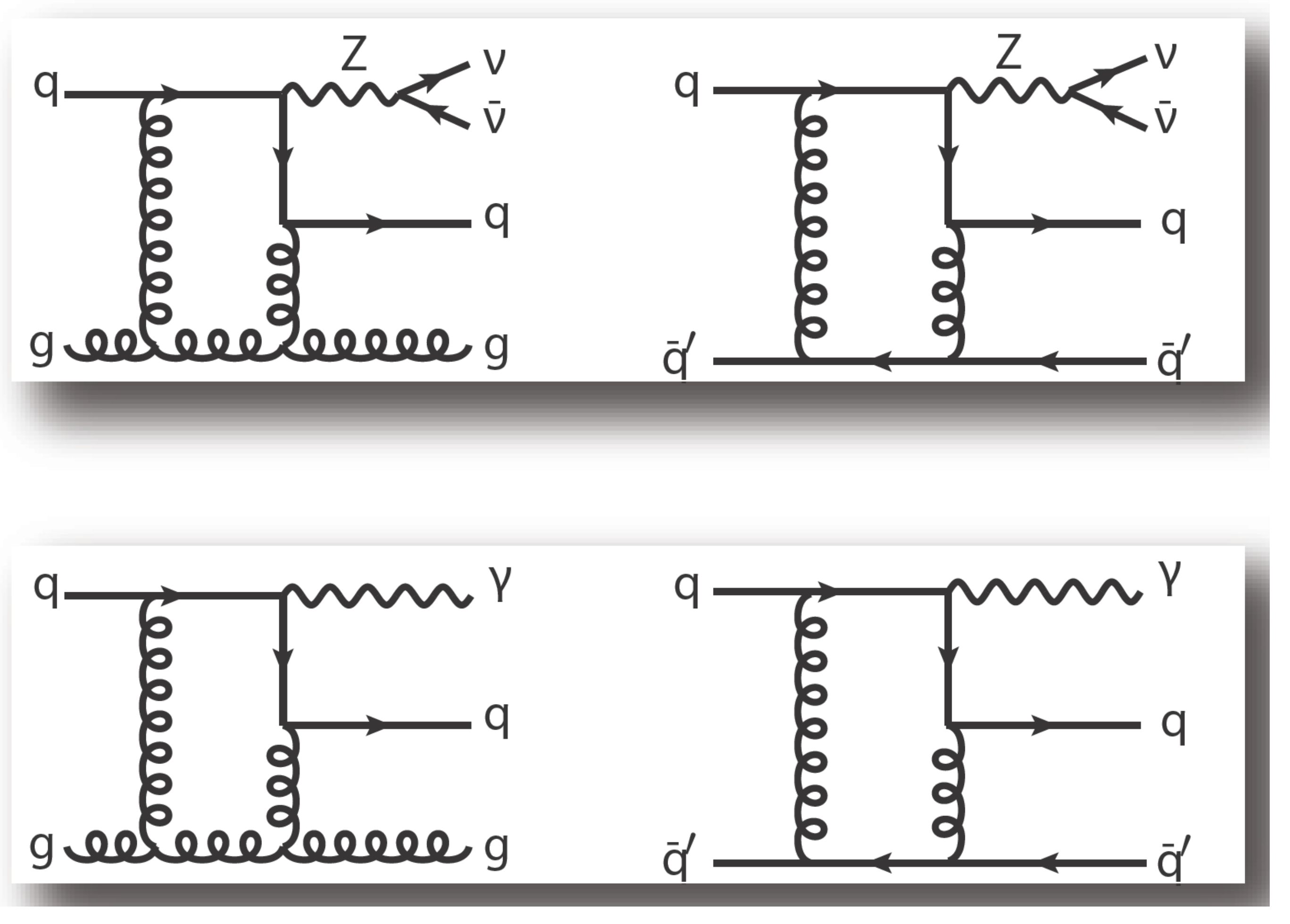
W production: $\begin{cases} u\bar{d} \to W^+ \\ d\bar{u} \to W^- \end{cases}$
(main contributions)

Z production: $\begin{cases} u\bar{u} \to Z \\ d\bar{d} \to Z \end{cases}$
(main contributions)

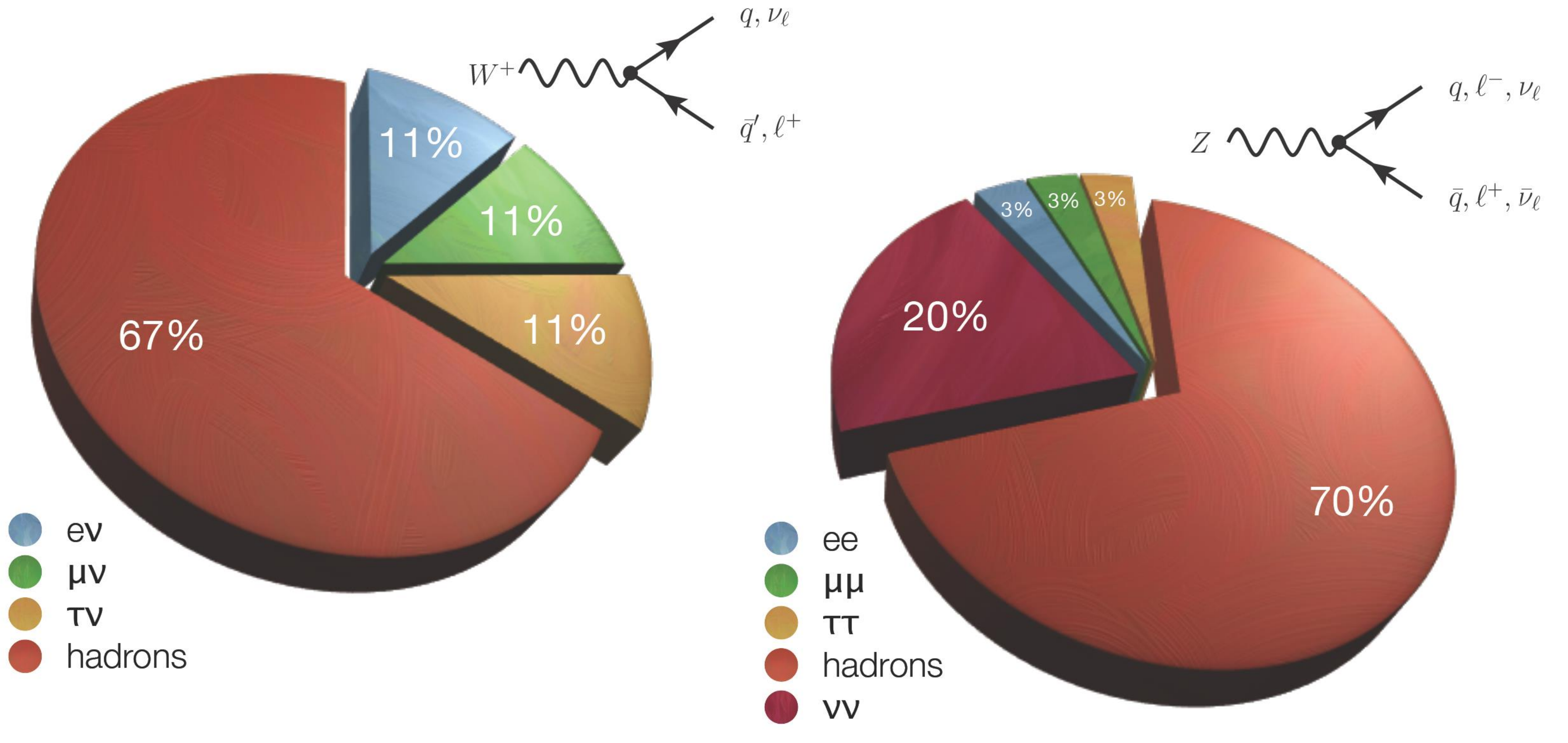
- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

➥ Constraints on sea and gluon distributions

Examples of high-order processes



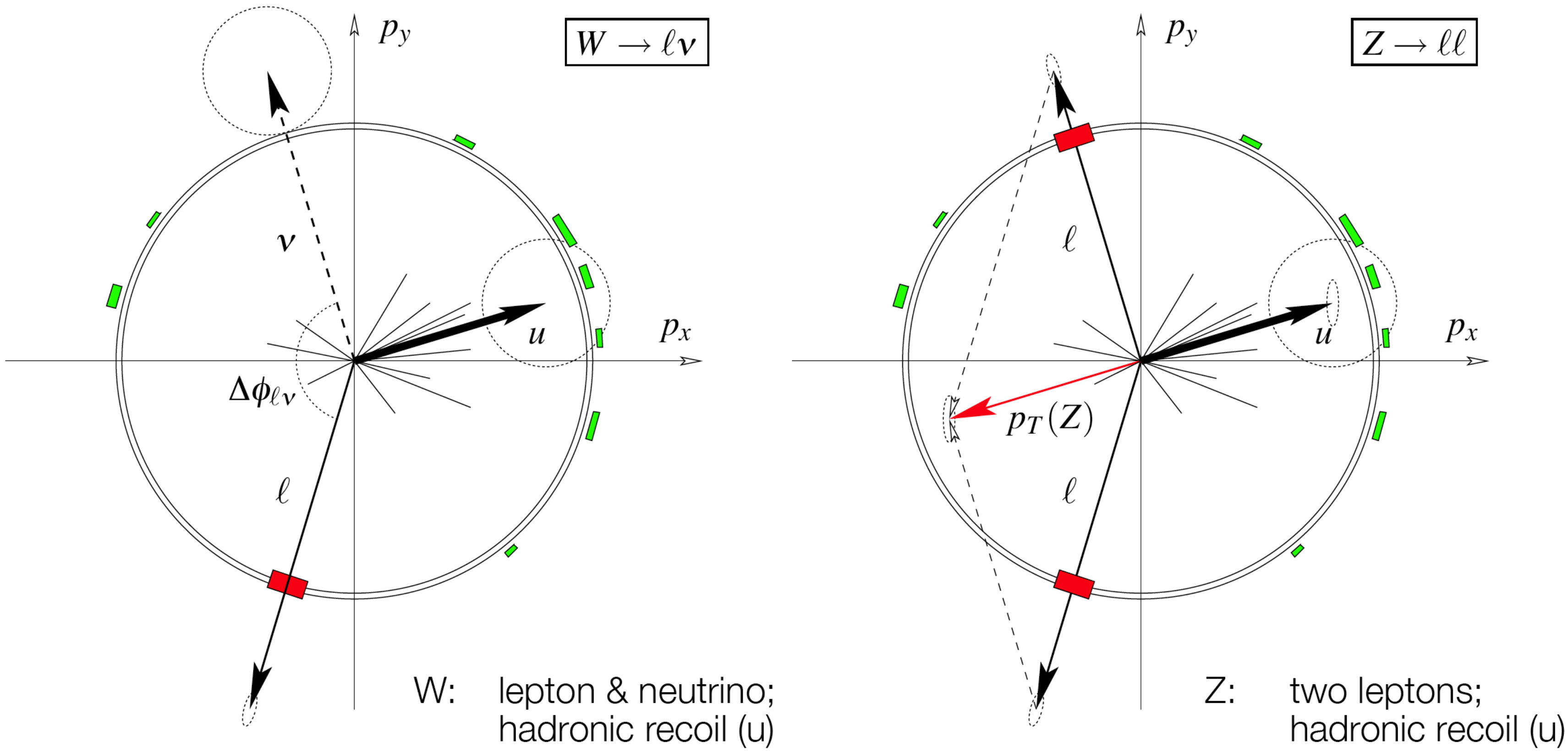
W and Z boson decays



Leptonic decays (e/μ): very clean, but small(ish) branching fractions
Hadronic decays: two-jet final states; large QCD dijet background
Tau decays: somewhere in between…

W and Z boson signatures

[CERN-OPEN-2008-020]



Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

Isolated High-p_T Leptons

Starting point for many hadron collider analyses:
isolated high-p_T leptons ➛ discriminate against QCD jets ...

QCD jets can be mis-reconstructed
as leptons ("fake leptons")

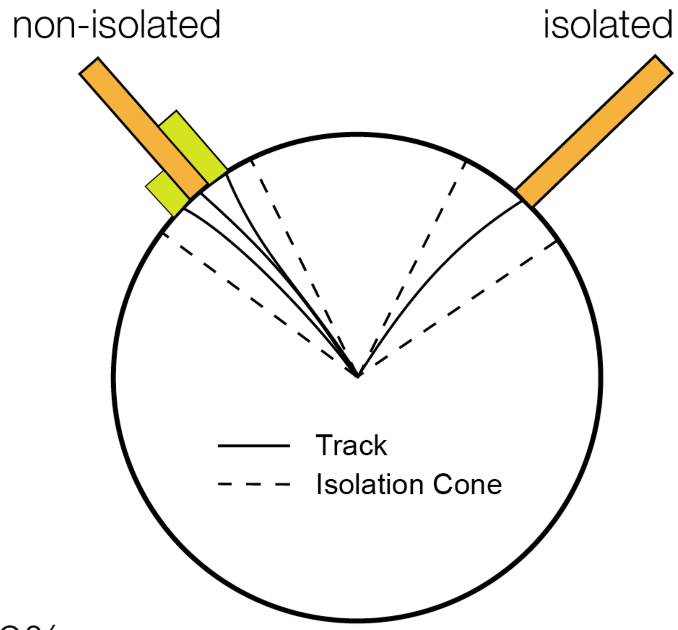
QCD jets may contain real leptons
e.g. from semileptonic B decays [$B \to l\nu X$]

➛ soft and surrounded by other particles

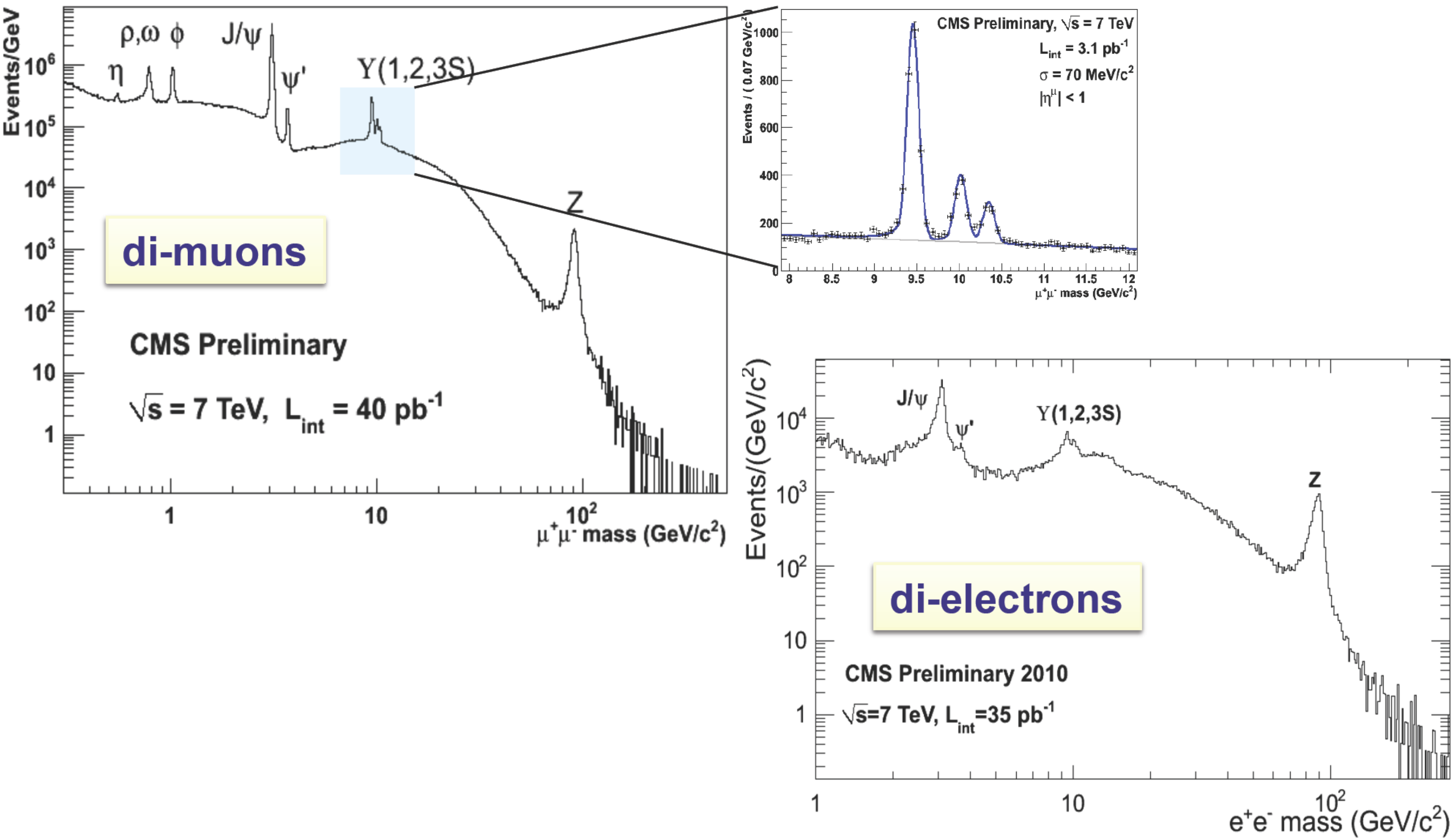
"Tight" lepton selection ...

Require e/μ with p_T > (at least) 20 GeV
Track isolation, e.g. $\sum p_T$ of other tracks
in cone of ΔR=0.1 less than 10% of lepton p_T

Calorimeter isolation, e.g. energy deposition
from other particles in cone of ΔR=0.2 less than 10%



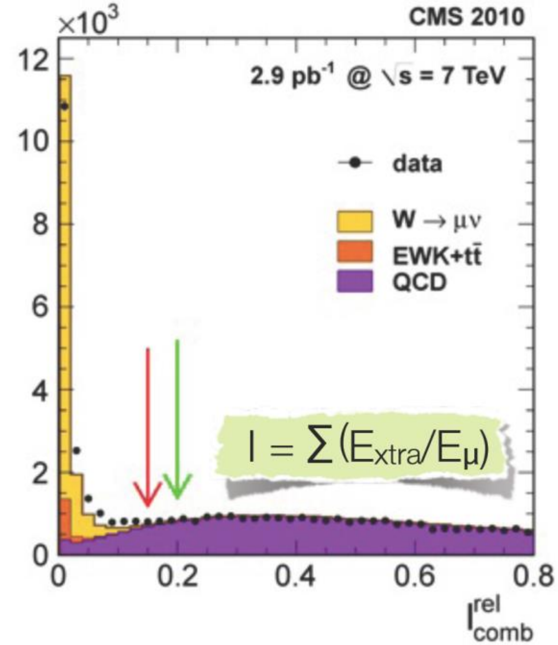
Dilepton mass spectrum at 7 TeV

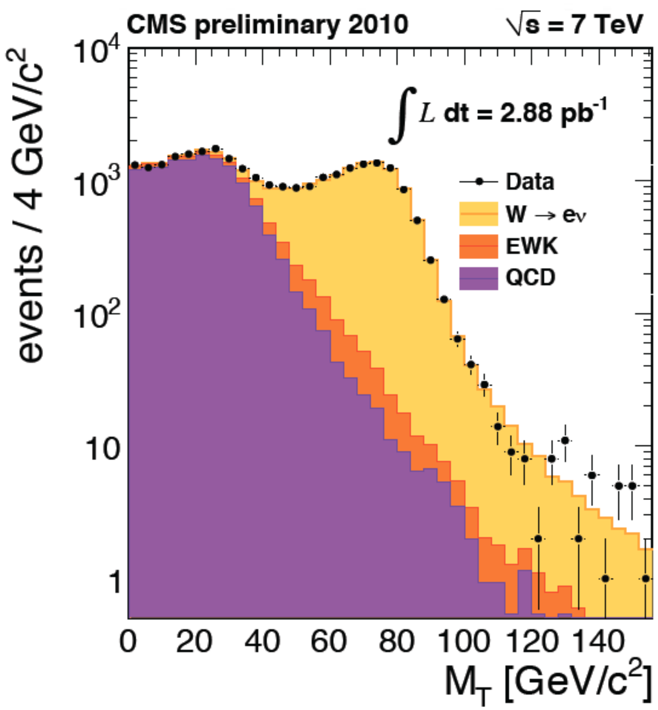


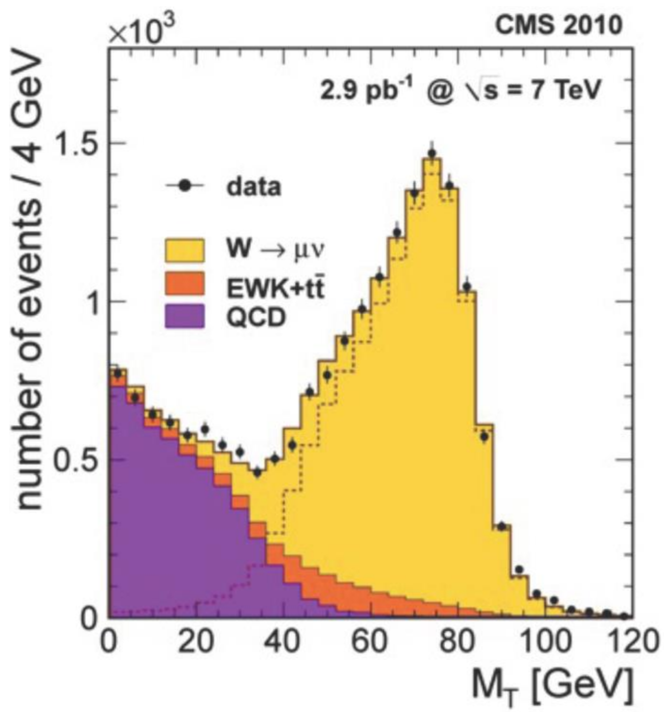
Example: CMS W Analysis

Select isolated electrons and muons ...
[muons: p_T>9 GeV; electrons: p_T>20 GeV]

Investigate transverse mass ...
[Use $E_{T,miss}$; $M_T = (p_{lep} + E_{T,miss})^{½}$]



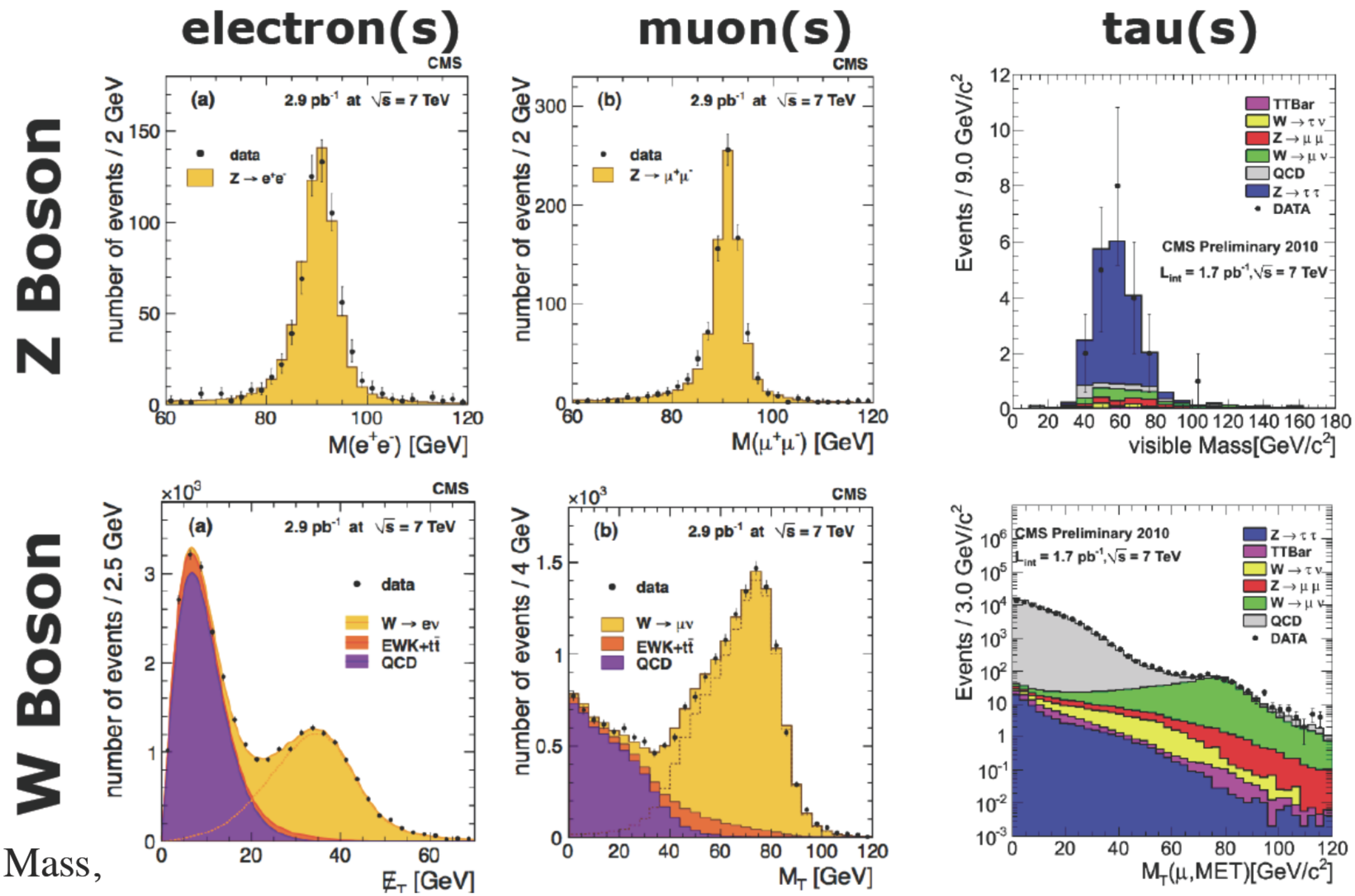




The W signal yield is extracted from a binned likelihood fit to the M_T distribution. Three different contributions:

- W signal
- QCD background
- other (EWK) backgrounds.

W/Z production at 7 TeV

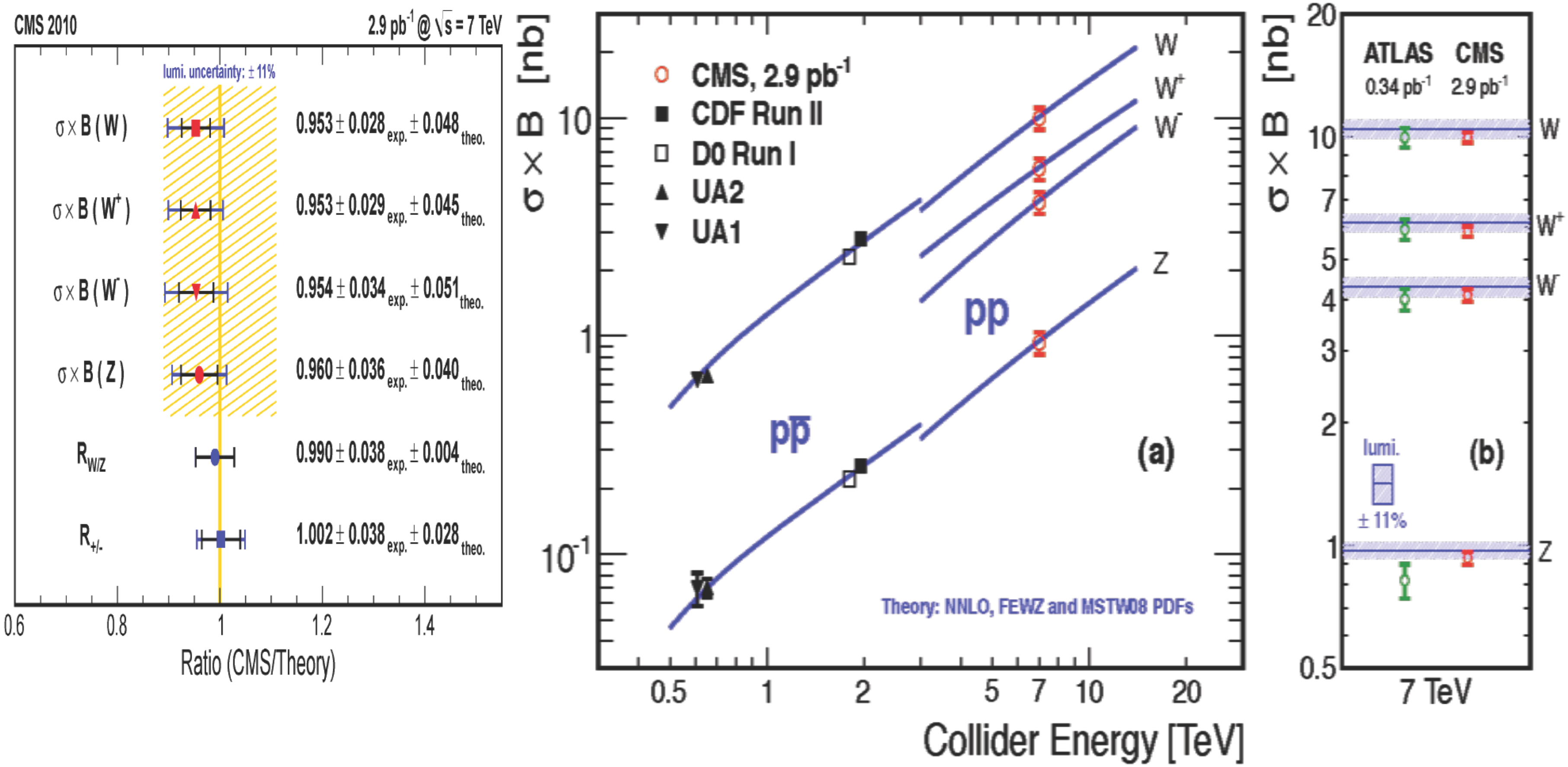


Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}}$$

W, Z cross-section v.s. √s

hep-ex 1012.2466, JHEP 01 (2011) 080



W+/W- charge asymmetry

NNLO cross sections:
scale uncertainties very small

W rapidity: asymmetry
[sensitivity to PDFs]

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

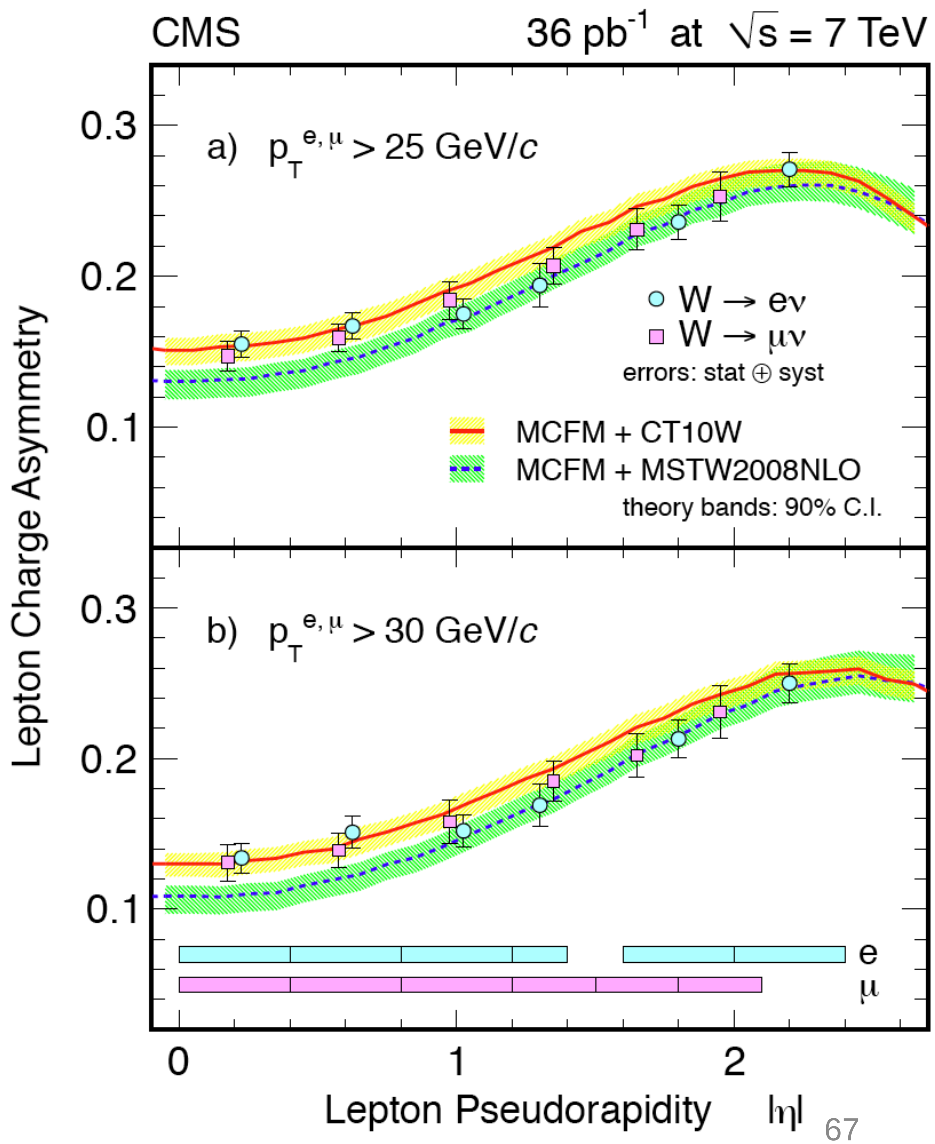
Proton-Proton Collider:

symmetry around y=0 ...

PDFs:

u(x) > d(x) for large x ...
more W^+ at positive rapidity

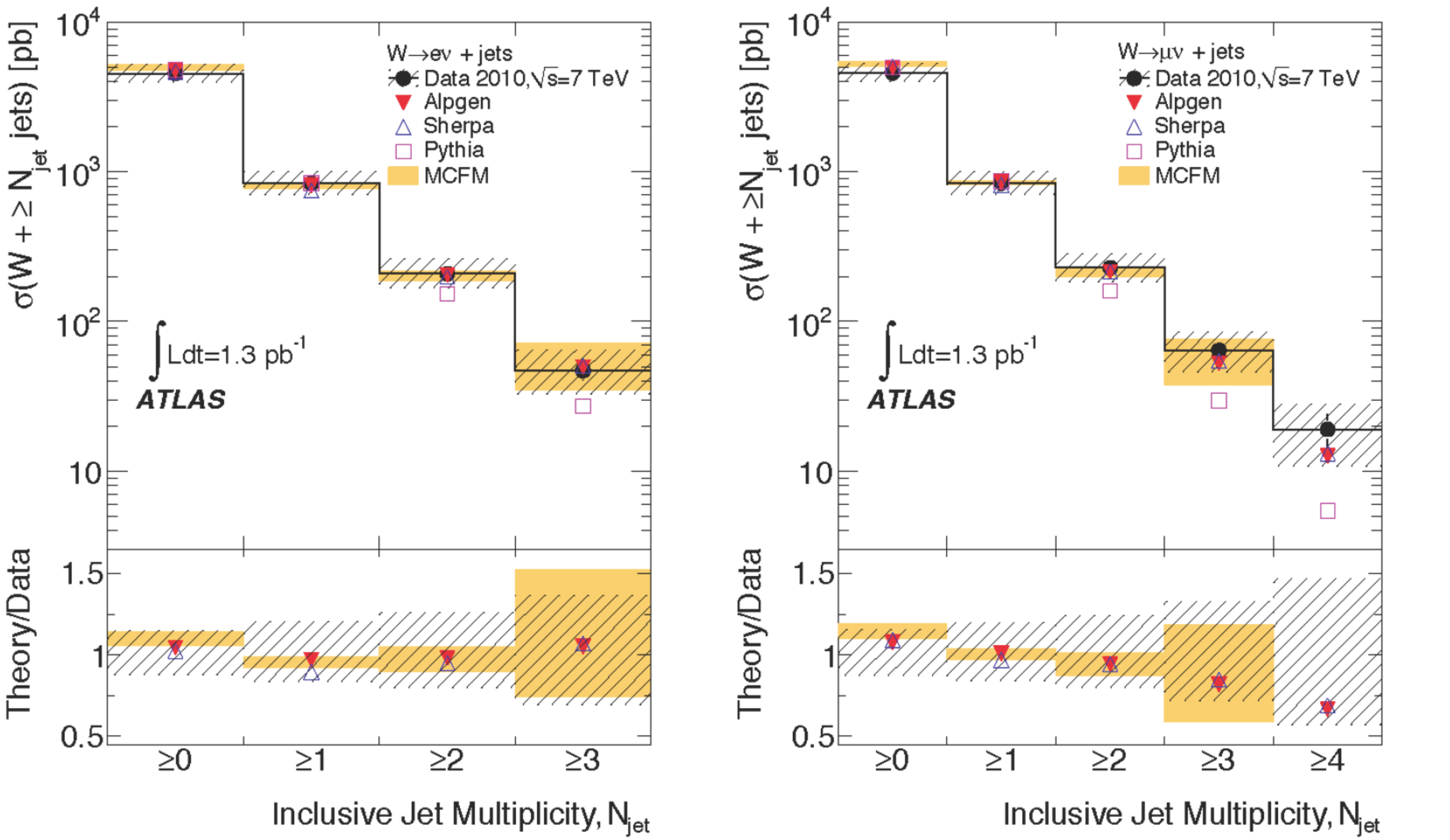
d/u ratio < 1 ...
always more W^+ than W^-



W + Jets multiplicity

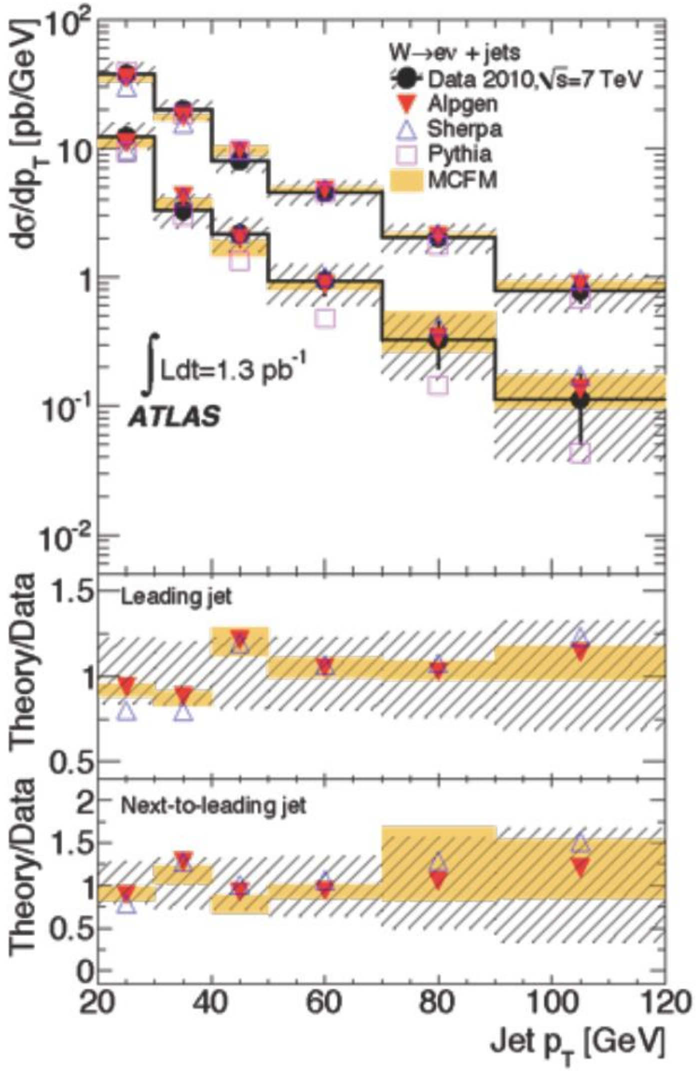
$|\eta| < 2.8$ and $p_T > 20$ GeV

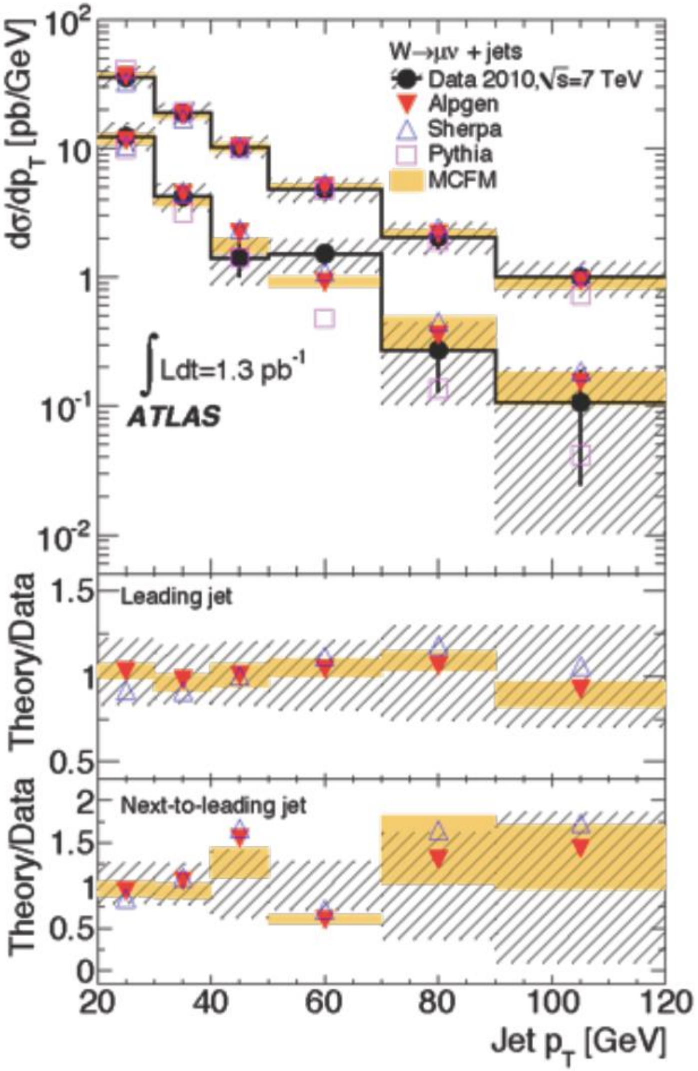
arXiv:1012.5382



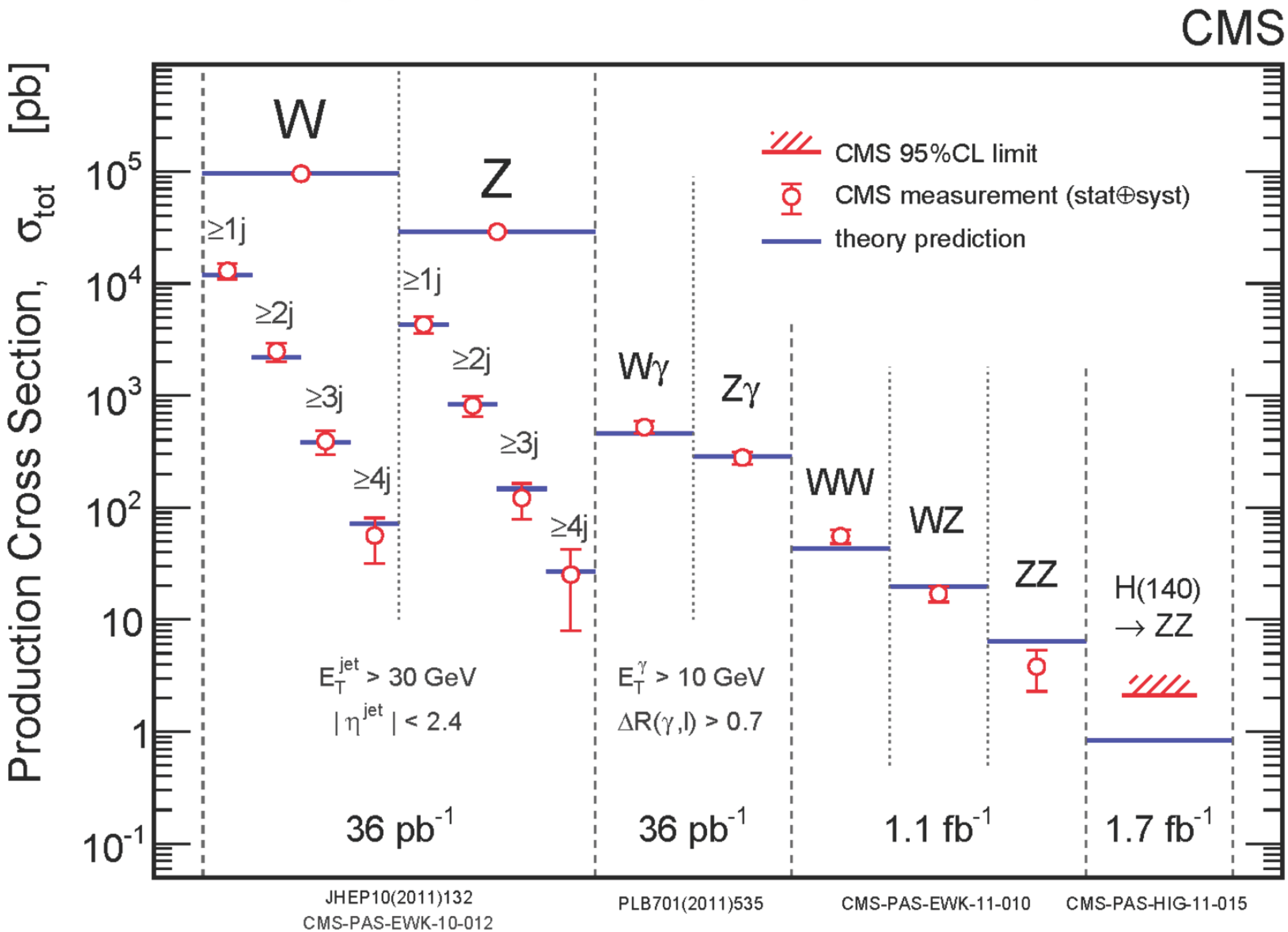
W + Jets P_T

Tails are important in several Exotica and SUSY searches





SM processes measured at LHC



W Mass Determination

Very challenging measurement

Template method:

Fit templates (from MC simulation) with different m_W to data

➛ W mass from best fit

Requires very good modeling of physics & detector

Present

systematic uncertainties:

[DØ-Experiment]

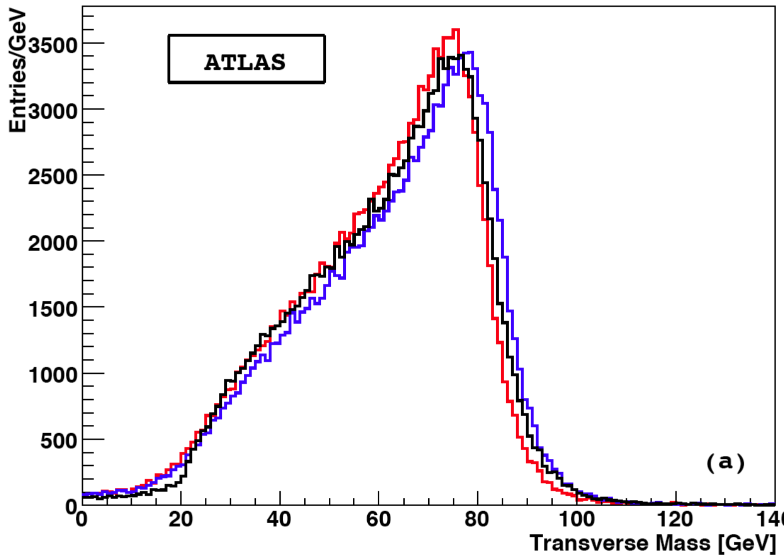
Lepton energy scale: 34 MeV

➛ calibrated to known Z mass
[calorimeter: 3.6% for 50 GeV]

Hadronic recoil: 6 MeV

W production model [PDFs, ...]: 12 MeV

Templates for
$m_W = 80.4 \pm 1.6$ GeV



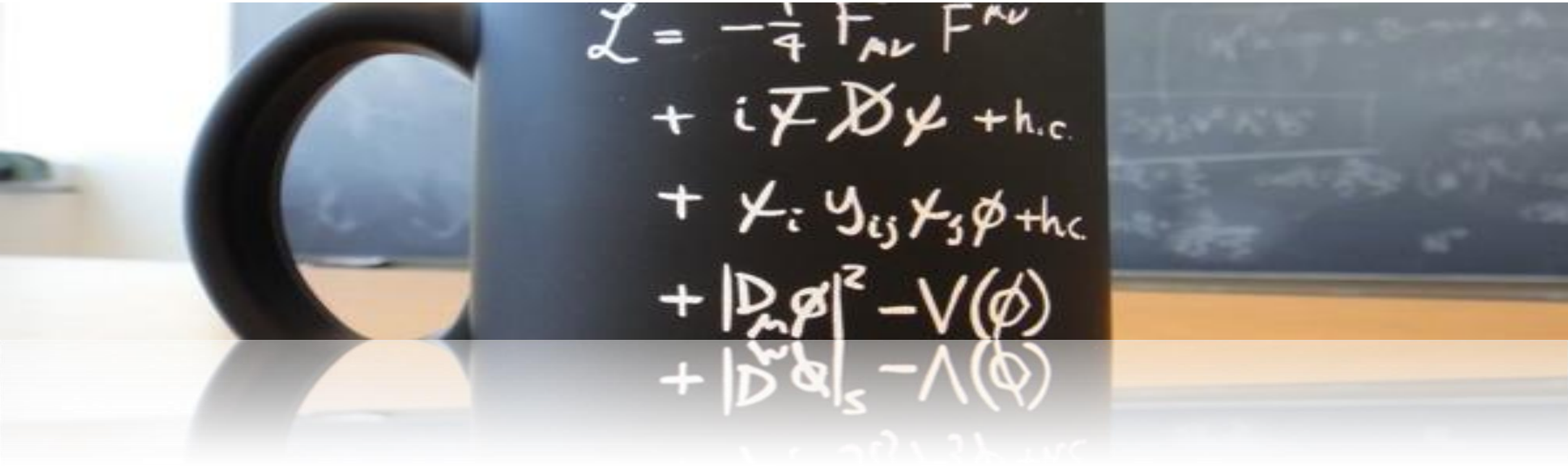
[CERN-OPEN-2008-020]

Ultimate LHC goal:
m_W uncertainty of 15 MeV
[via combination]

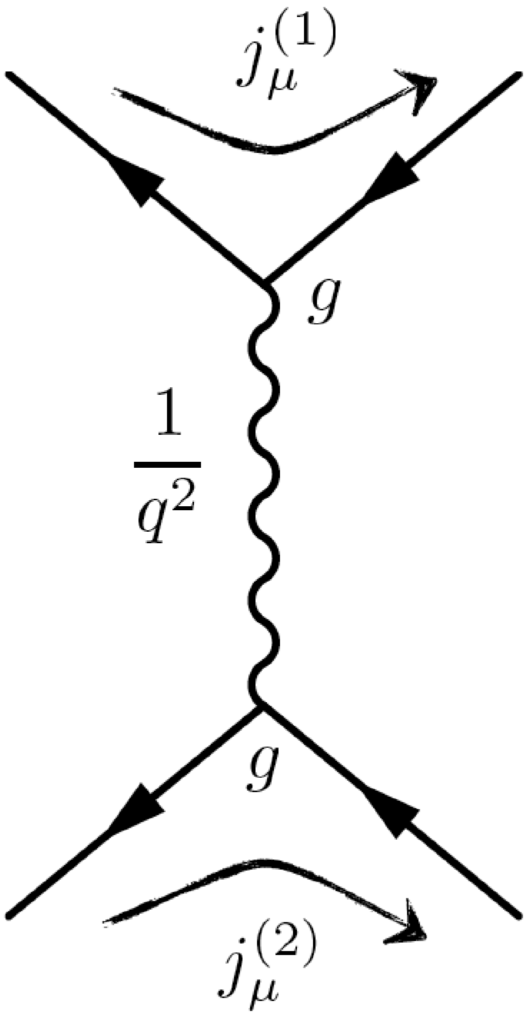
End of Lecture 3

Additional material

Electroweak theory



Cross section: using Feynman diagrams



Fermi's Golden Rule

$$\boxed{W_{\text{fi}} = 2\pi \, |M_{\text{fi}}|^2 \cdot \frac{dN}{dE_{\text{f}}}}$$

Transition probability

Matrix element

Phase space

4-vector current

$$M_{\text{fi}} = -i \int j_\mu^{(1)} \cdot \left(\frac{1}{q^2}\right) \cdot j_\mu^{(2)} d^4x$$

Propagator

$$\sigma \;\sim\; |M_{\text{fi}}|^2$$

$$\sim\; g^4 \cdot \left(\frac{1}{q^4}\right)$$

From the Lagrangian to cross sections

$$\boxed{\sigma \sim \langle\, f\,|\mathbf{S}|\, i\,\rangle^{\,2}}$$

Inelastic
Cross Section
[for | i⟩ ≠ | f⟩]

$$[\mathrm{Def.}:\ |\, t = +\infty\,\rangle \equiv \mathbf{S}|\, t = -\infty\,\rangle\,]$$

Time Evolution

From Schrödinger-Equation
[Dirac picture]

$$|\, t\,\rangle = |\, t_0\,\rangle - i\int_{t_0}^{t} \mathrm{d}t'\, \mathbf{H}'(t')|\, t'\,\rangle$$

$$\mathbf{H}'(t) = -\int \mathcal{L}'(x,t)\,\mathrm{d}^3x$$

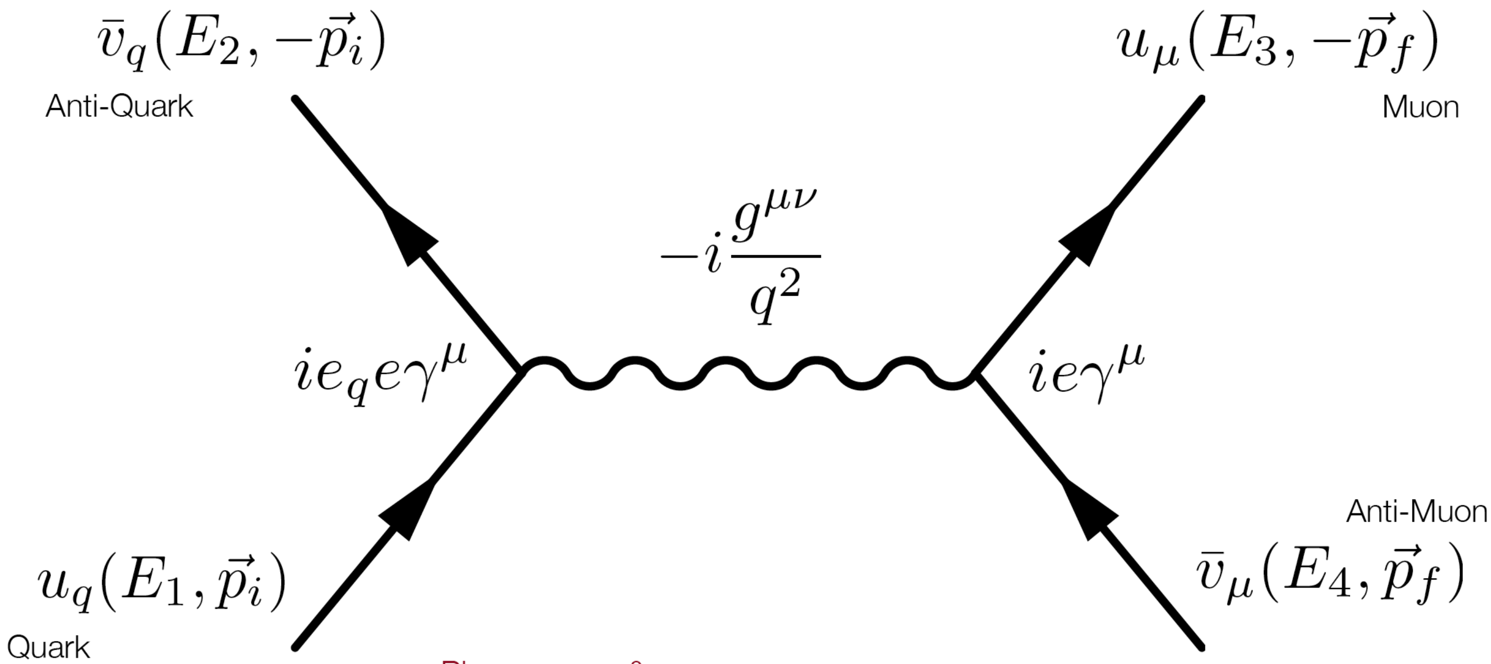
Lagrangian
of Interaction

Matrix element

$$\langle\, f\,|\mathbf{S}|\, i\,\rangle \cong \delta_{fi} - i\int_{-\infty}^{\infty} \mathrm{d}t' \langle\, f\,|\mathbf{H}'(t')|\, i\,\rangle$$

➡ Feynman rules

Example: Drell-Yan Process

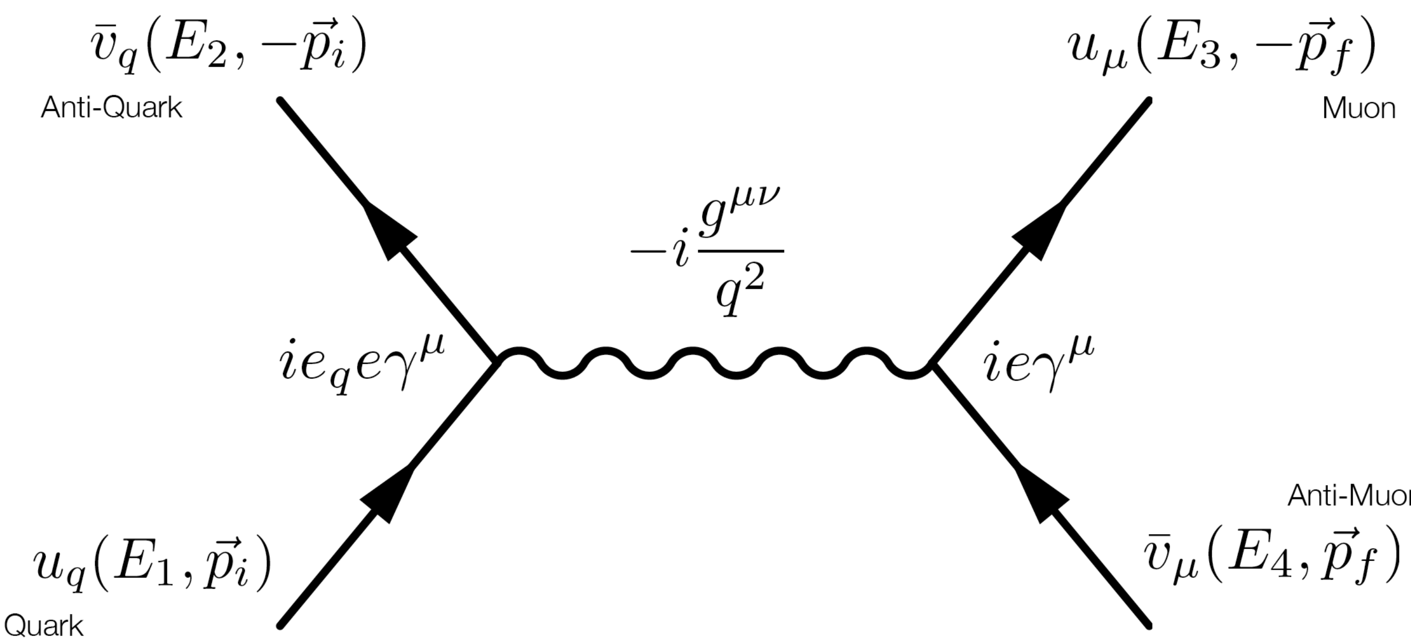


Phase space & delta functions ...

Squared Matrix element

$$\frac{d\sigma}{d\Omega} = \frac{1}{s \cdot 64\pi^2} \cdot \frac{|\vec{p}_f|}{|\vec{p}_i|} \cdot \overline{|M_{fi}|^2}$$

Example: Drell-Yan Process

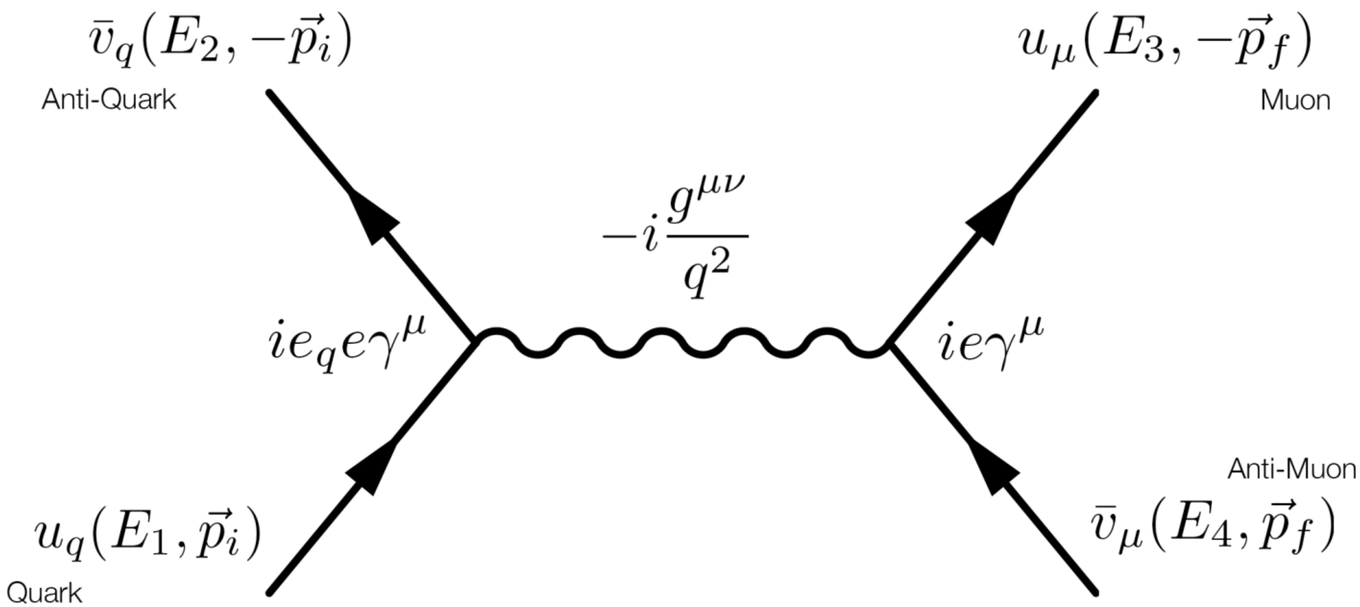


Averaging over initial spins

Summing over initial and final spins

$$\boxed{|M_{fi}|^2 = \frac{1}{(2s_q+1)^2} \cdot \sum_{s_q, s'_q} \sum_{s_\mu, s'_\mu} |M_{fi}|^2}$$

Example: Drell-Yan Process



Couplings Anti-Quark Anti-Muon

$$M_{fi} = -\frac{e_q e^2}{q^2}\bar{v}_q\gamma_\mu u_q \cdot \bar{v}_\mu\gamma^\mu u_\mu$$

Propagator Quark Muon

Example: Drell-Yan Process

$$\overline{|M|^2}_{q\bar{q}\to\mu\mu} = 2e_q^2 e^4 \cdot \frac{t^2+u^2}{s^2}$$

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{32\pi^2} e_q^2 \cdot \frac{1}{s} \cdot \frac{t^2+u^2}{s^2}$$

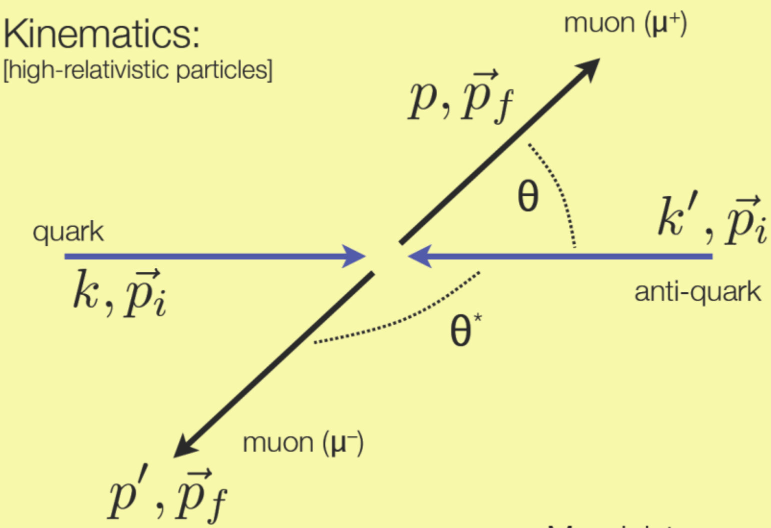
$$= \frac{e^4}{64\pi^2} e_q^2 \cdot \frac{1}{s} \cdot (1+cos^2\theta)$$

with $e^2 = 4\pi\alpha$

$$\boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha}{4s} e_q^2 \cdot (1+cos^2\theta)}$$

[θ in CMS frame]

Kinematics:
[high-relativistic particles]



Mandelstam variables

$$s = (k+k')^2 = 4E_i^2$$

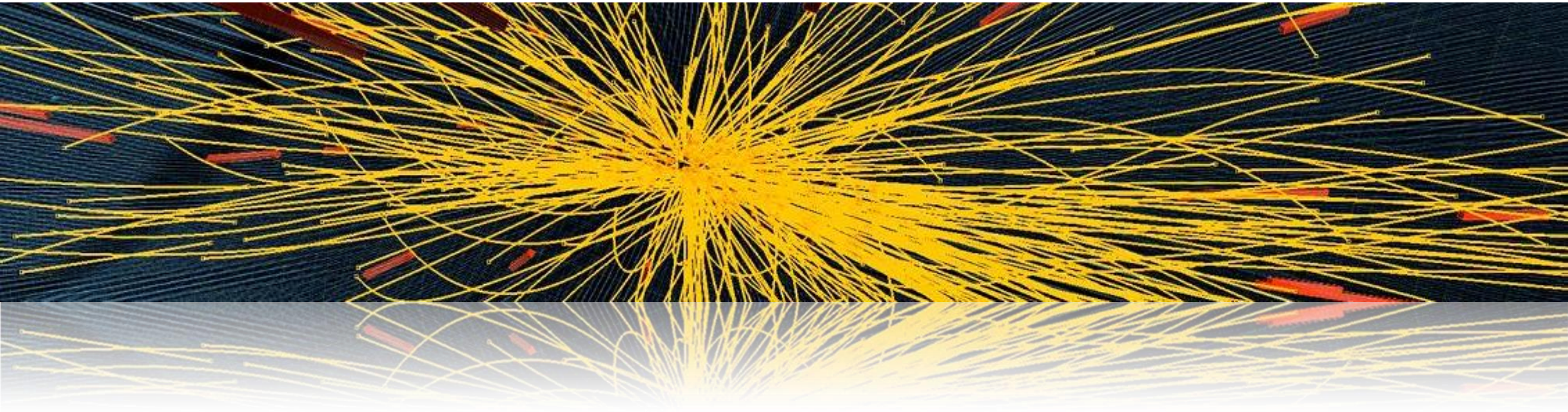
$$t = (k-p)^2 \approx -2kp \approx -2E_i^2(1-\cos\theta^*)$$

$$\approx -\frac{s}{2}(1+\cos\theta)$$

$$u = (k-p')^2 \approx -2kp' \approx -2E_i^2(1-\cos\theta)$$

$$\approx -\frac{s}{2}(1-\cos\theta)$$

Hadron Interactions



Reference frames

$$p = (E, \vec{p}\,)$$

Particle momentum as seen in laboratory frame ...

$$p^* = (E^*, \vec{p}^{\,*})$$

Particle momentum as viewed from a frame moving with velocity β_f ...

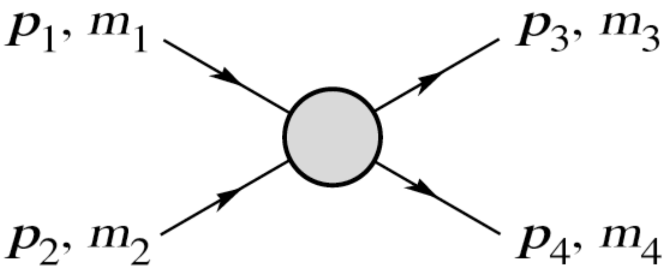
Lorentz transformation

Lorentz Transformation:

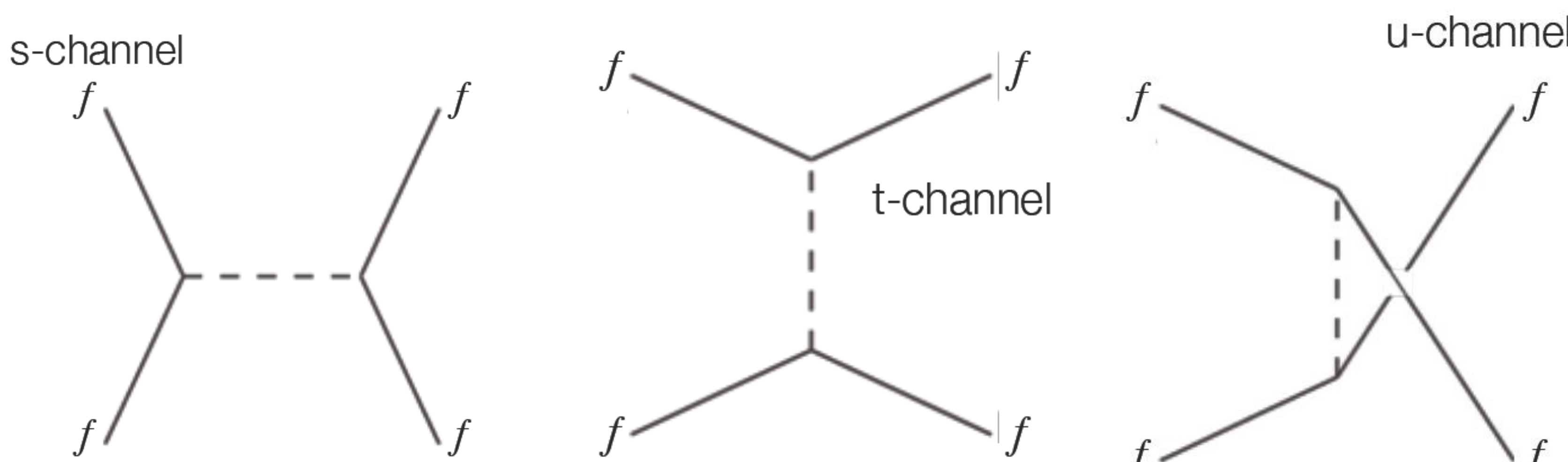
$$E^* = \gamma_f \cdot E - \gamma_f \beta_f \cdot p_{||}$$
$$p_{||}^* = \gamma_f \cdot p_{||} - \gamma_f \beta_f \cdot E$$
$$p_T^* = p_T$$

with $\gamma_f = (1 - \beta_f^2)^{-\frac{1}{2}}$

Mandelstam variables
Feynman diagrams

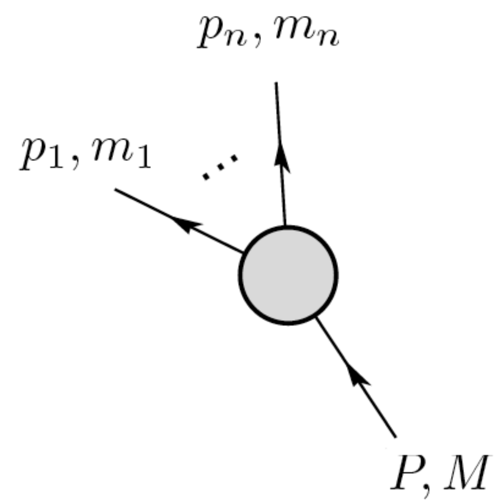


$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$



$$\sigma \propto \frac{t^2 + u^2}{s^2} \qquad \sigma \propto \frac{s^2 + u^2}{t^2} \qquad \sigma \propto \frac{s^2 + t^2}{u^2}$$

Particle decays



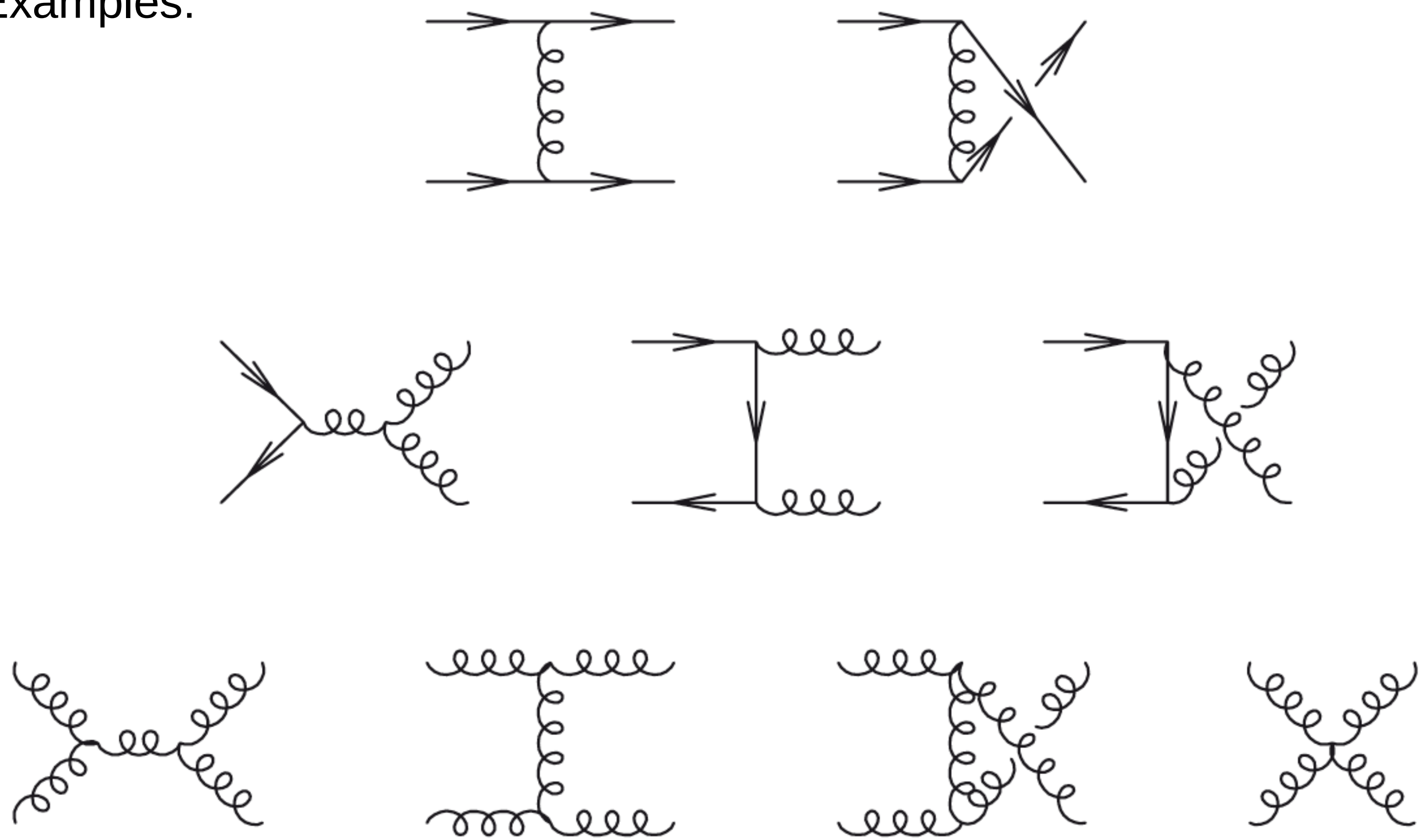
Partial
Decay Rate:

$$d\Gamma = \frac{(2\pi)^4}{2M} \, |\mathscr{M}|^2$$

$$\times \;\; d\Phi_n \left(P;\; p_1, \, \ldots, \, p_n\right)$$

Hard processes with quarks and gluons

Examples:



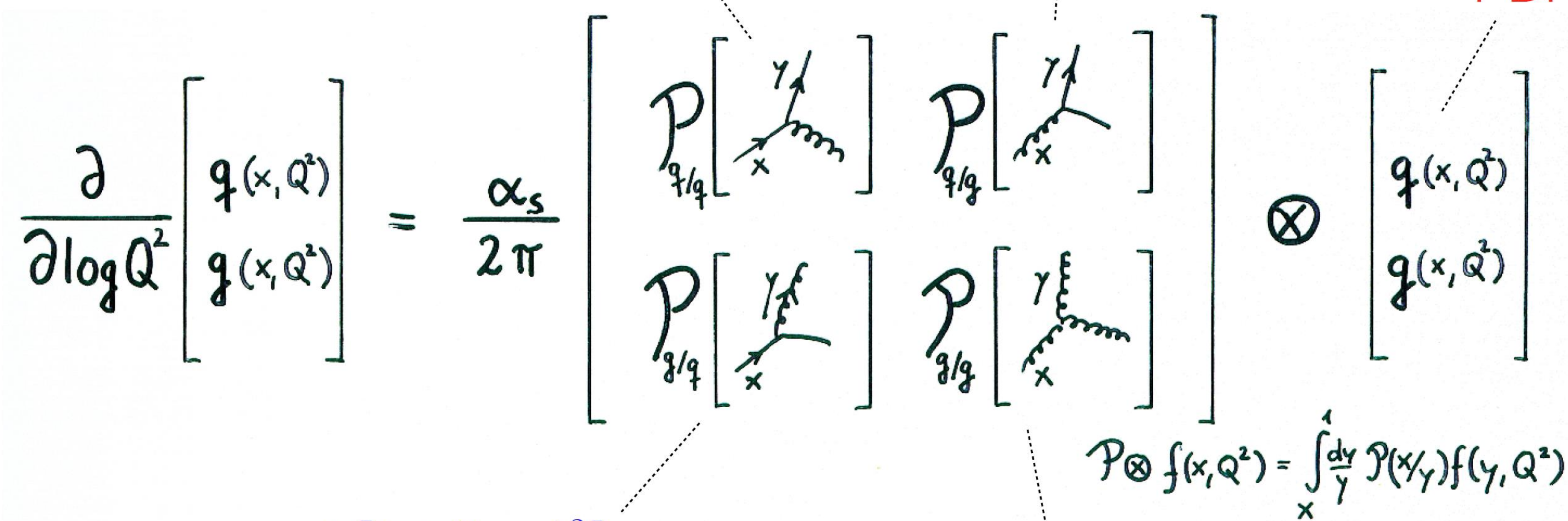
Q^2 evolution equations

[DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli, Parisi]

$$\frac{4}{3}\left[\frac{1+z^2}{1-z}\right]$$

$$\frac{1}{2}\left[z^2+(1-z^2)\right]$$

PDFs

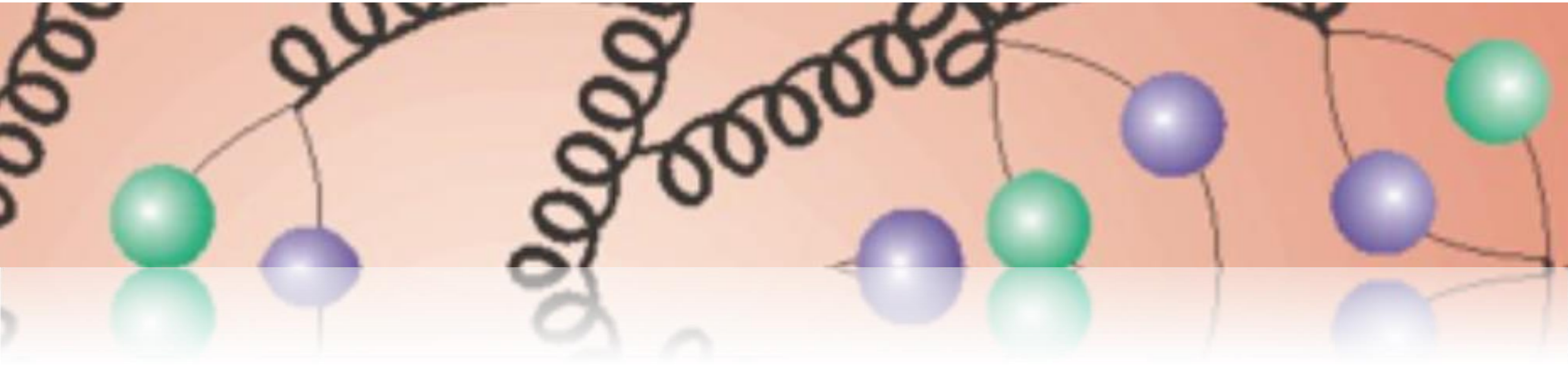


$$\frac{4}{3}\left[\frac{1+(1-z)^2}{z}\right]$$

$$6\left[\frac{z}{1-z}+\frac{1-z}{z}+z(1-z)\right]$$

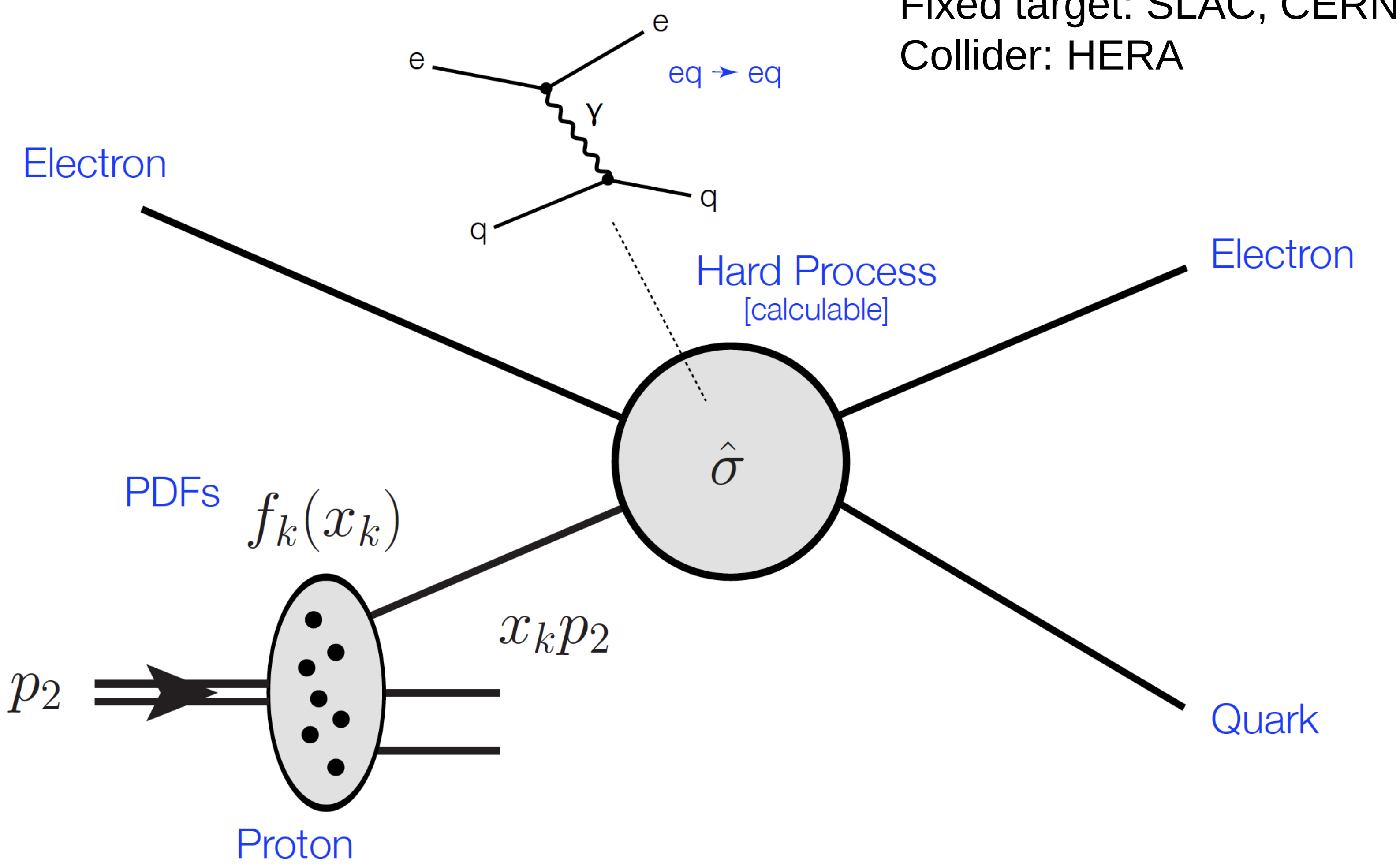
[z: momentum fraction of radiated parton]

QCD & parton densities



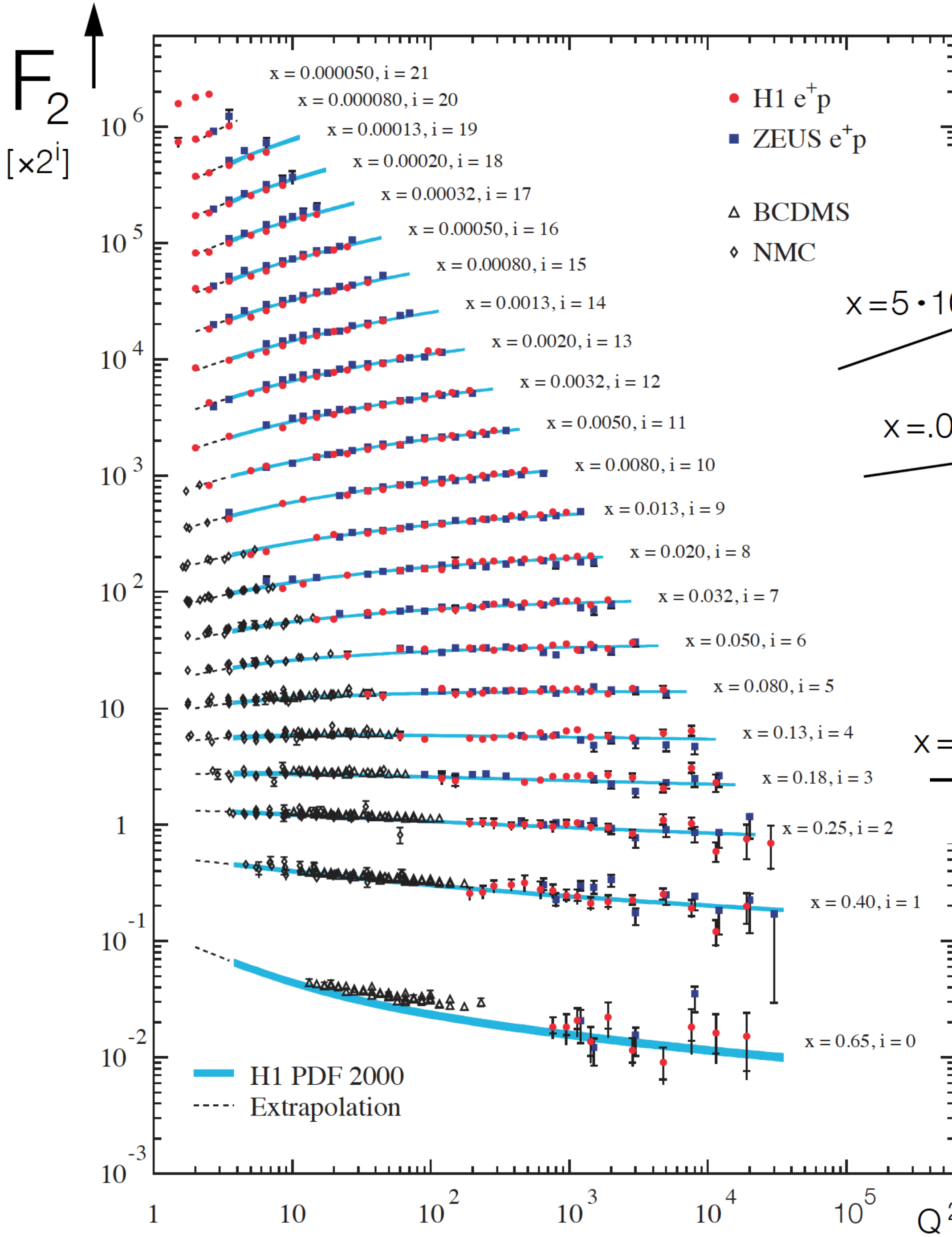
Lepton-proton scattering

Fixed target: SLAC, CERN
Collider: HERA



Scaling Violations

[HERA & fixed target data]



$x=5\cdot10^{-3}$

$x=.013$

$x=.18$

$x=.65$

Precision: 2-3%
[bulk region]

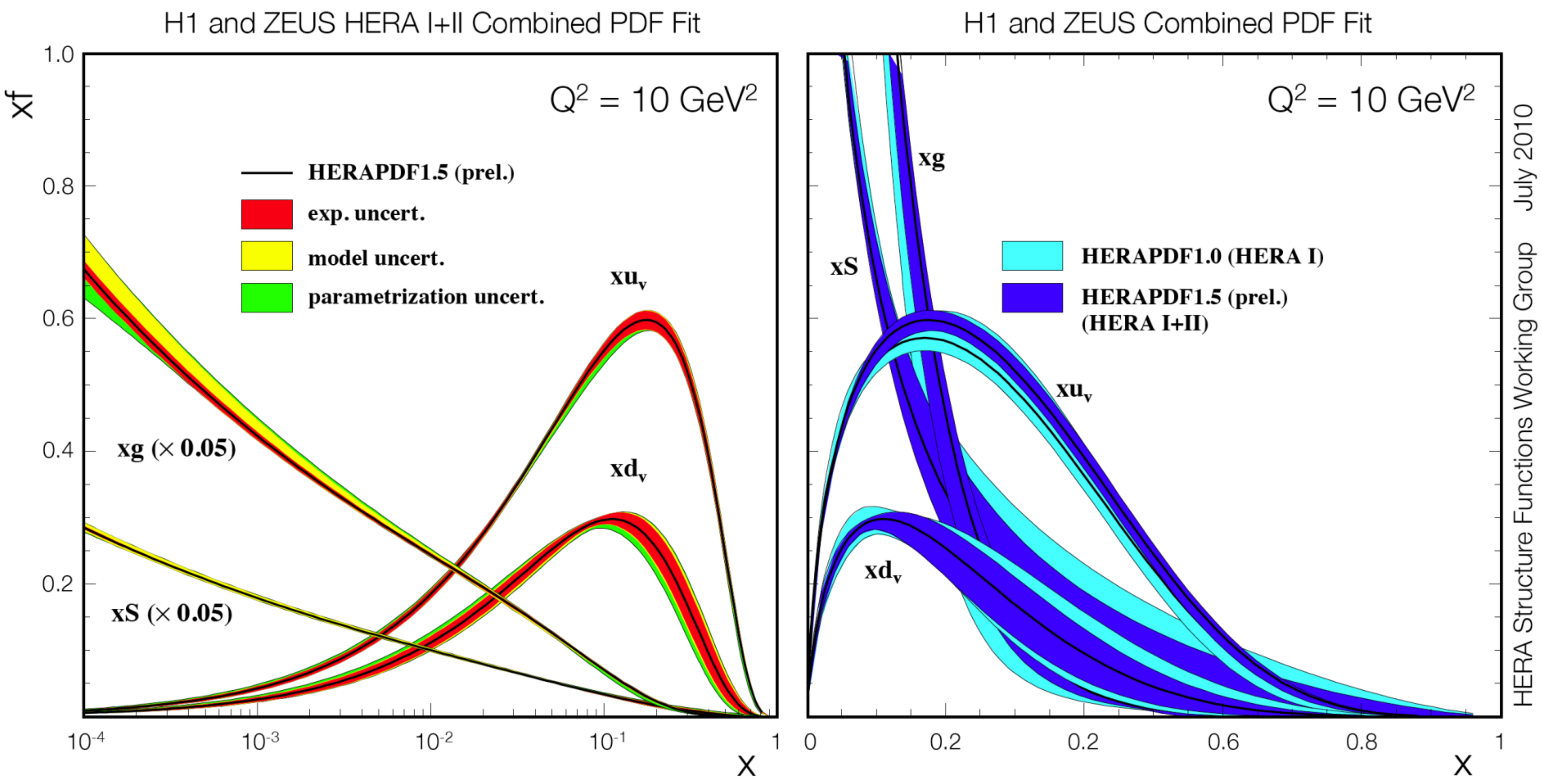
For $x < 10^{-2}$:

$$\frac{dF_2}{d\log Q^2} \sim g(x,Q^2)\cdot\alpha_s(Q^2)$$

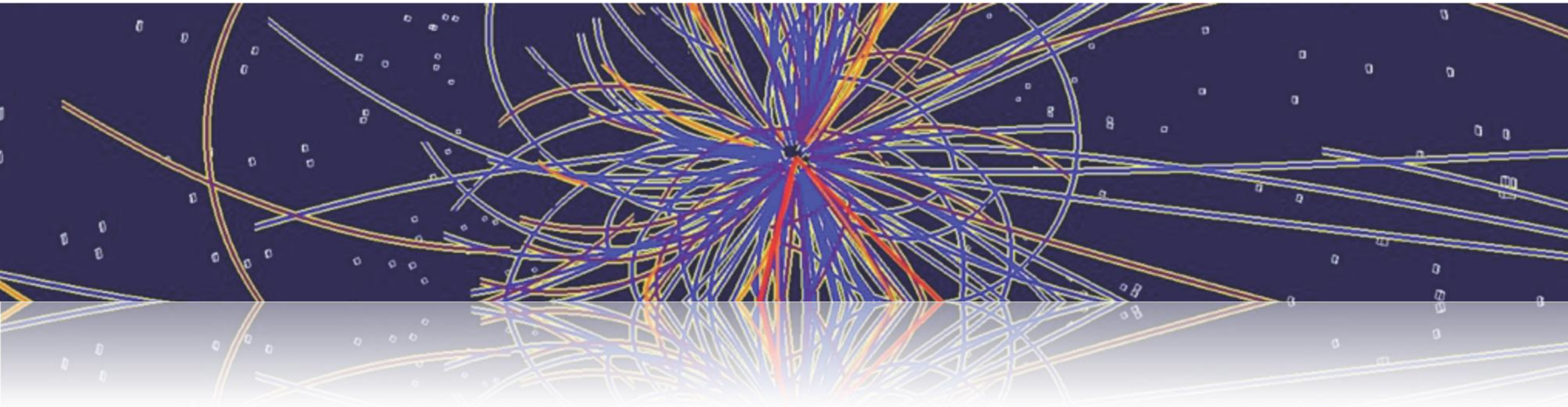
NLO QCD Fits:

Quark densities
Gluon density
Strong coupling α_s

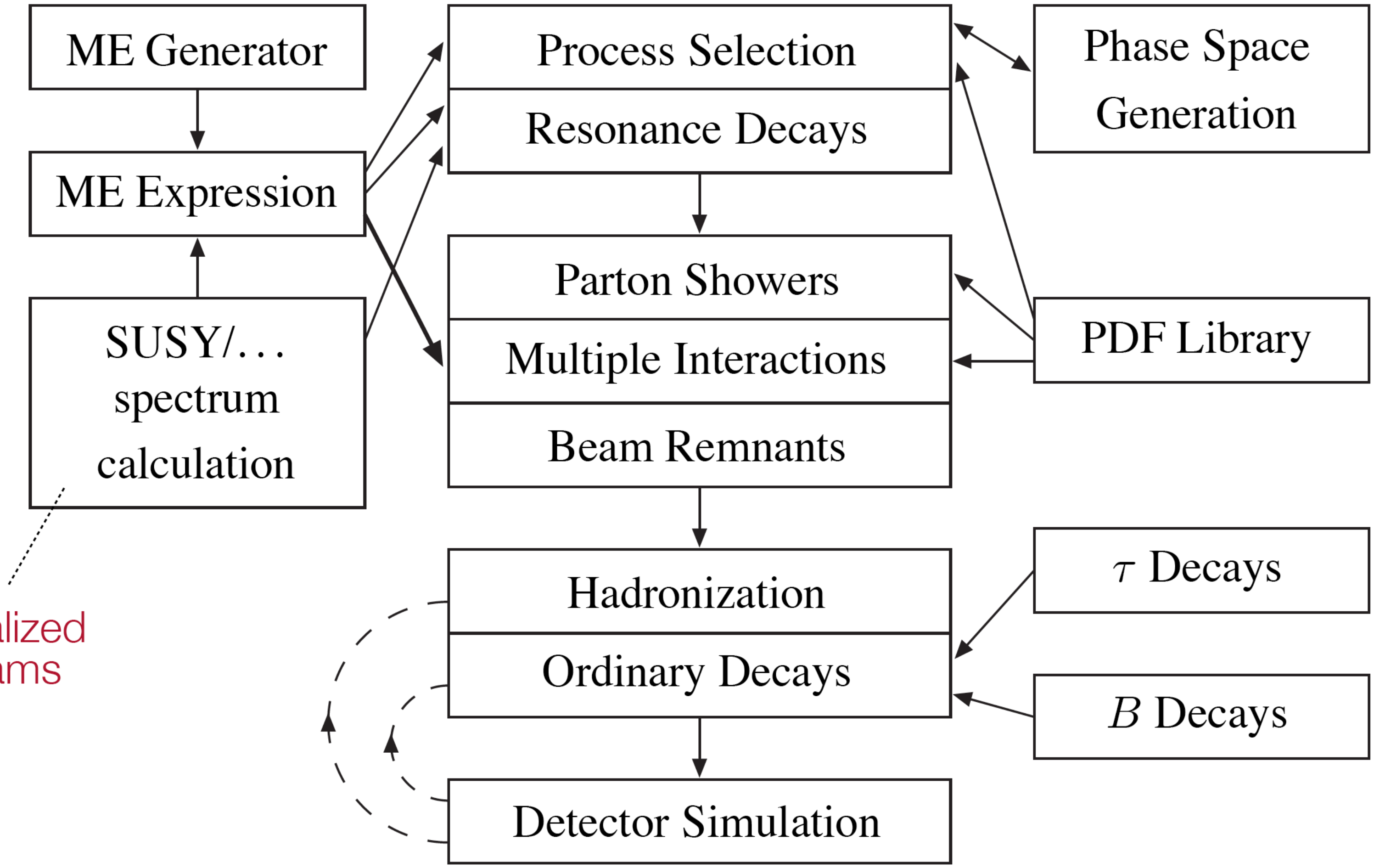
Proton parton densities



Monte Carlo Generators



Monte Carlo overview



Use
specialized
programs

Monte Carlo interfacing

Many specialized processes already available in Pythia ...

but, processes usually only implemented in lowest non-trivial order ...

Need external programs that ...

- include higher order loop corrections or, alternatively, do kinematic dependent rescaling
- allow matching of higher order ME generators
  [otherwise need to trust parton shower description ...]
- provide correct spin correlations often absent in Pythia ...
  [e.g. top produced unpolarized, while $t \to bW \to bl\nu$ decay correct]
- simulate newly available physics scenarios ...
  [appear at rapid pace; need for many specialized generators]

Les Houches Accord ...

Specifies how parton-level information about the hard process and sequential decays can be encoded and passed on to a general-purpose generator.

Les Houches generator files

Specialized Generator
[➛ Hard Process]

↓

Les Houches Interface

↓

Herwig, Pythia

[Resonance Decays]
Parton Showers
Underlying Event
Hadronization
Ordinary Decays

Specialized Generators:
[some examples]

AcerMC	:	ttbb, ...
ALPGEN	:	W/Z + ≤ 6j, nW + mZ + kH + ≤ 3j, ...
AMEGIC++	:	generic LO
CompHEP	:	generic LO
GRACE [+Bases/Spring]	:	generic LO [+ some NLO loops]
GR@PPA	:	bbbb
MadCUP	:	W/Z+ ≤ 3j, ttbb
HELAS & MadGraph	:	generic LO
MCFM	:	NLO W/Z+ ≤ 2j, WZ, WH, H+ ≤ 1j
O'Mega & WHIZARD	:	generic LO
VECBOS	:	W/Z+ ≤ 4j

From Partons to Jets

[T. Gleisberg et al., JHEP02 (2004) 056]

Parton splitting

$$d\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)dz$$

Splitting probability
determined by splitting functions $P_{q\to qg}$

$$P_{\mathrm{q}\to\mathrm{qg}} = \frac{4}{3}\frac{1+z^2}{1-z}$$

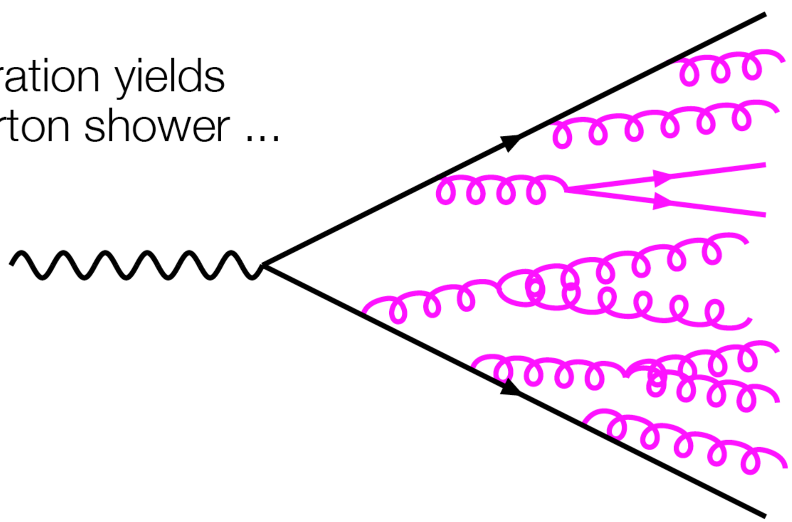
$$P_{\mathrm{g}\to\mathrm{gg}} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$

$$P_{\mathrm{g}\to\mathrm{q\bar{q}}} = \frac{n_f}{2}(z^2+(1-z)^2)$$

Same splitting functions
as used for PDF evolution

z : fractional momentum of radiated parton
n_f : number of quark flavours

Iteration yields
parton shower ...



Need soft/collinear cut-offs to
avoid non-perturbative regions ...
[divergencies!]

Details model-dependent

e.g. $Q > m_0 = \min(m_{ij}) \approx 1$ GeV,
$z_{min}(E,Q) < z < z_{max}(E,Q)$ or
$p_\perp > p_{\perp min} \approx 0.5$ GeV

Hadronization models

Non-perturbative transition from partons to hadrons ...
[Modeling relies on phenomenological models available]

Models based on MC simulations
very successful:

Generation of complete final states ...
[Needed by experimentalists in detector simulation]

Caveat: tunable ad-hoc parameters

Most popular MC models:

Pythia : Lund string model
Herwig : Cluster model

Lund String Model

Lund String Model

[Andersson et al., Phys. Rep. 97 (1983) 31]

QCD potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(1/r^2)}{r} + kr$$

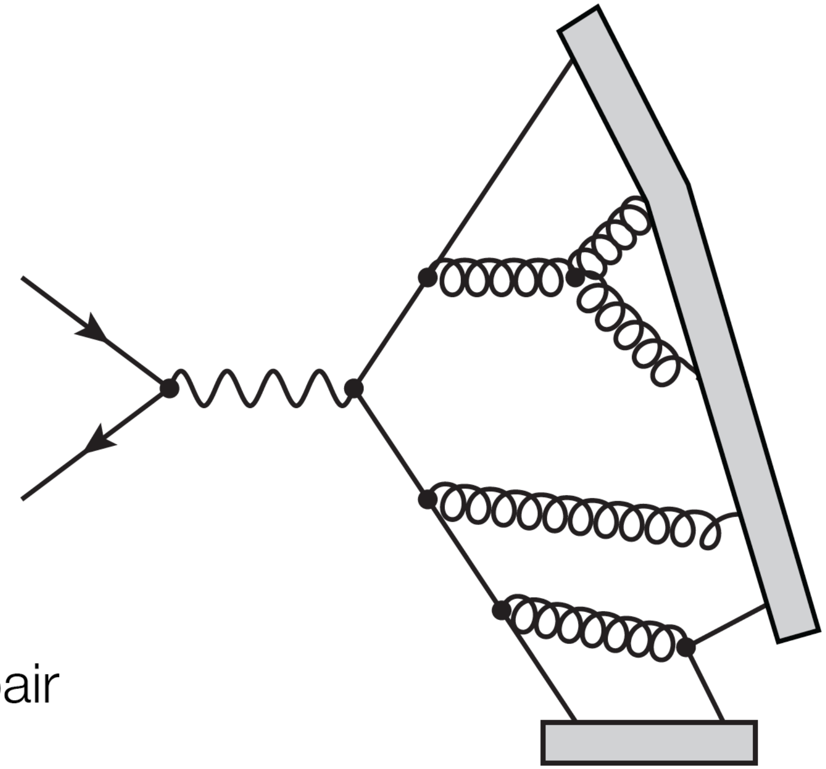
String formation between initial quark-antiquark pair

String breaks up if potential energy large enough new quark-antiquark pair

Gluons = 'kinks' in string

At low energy: hadron formation

Very widely used ...
[default in Pythia]



After: Ellis et al.,
QCD and Collider Physics

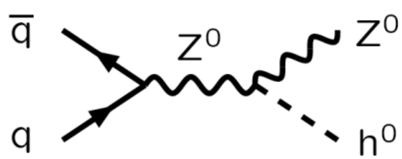
Overview of MC generators

Structure of basic generator process [by order of consideration]

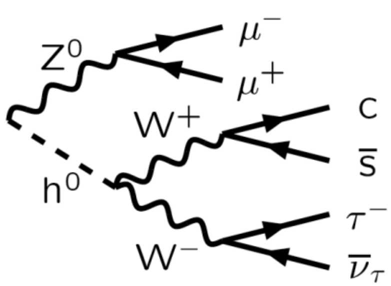
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled; at small

Matrix elements (ME)

1. Hard subprocess:
   $|M|^2$, Breit Wigners, PDFs

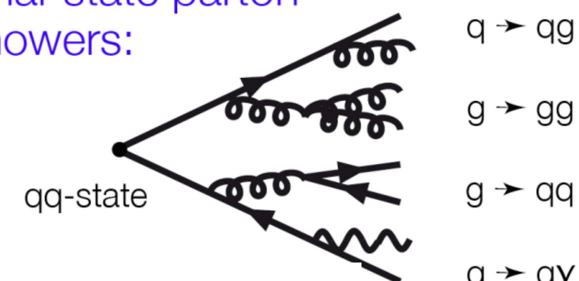


2. Resonance decays:
   Includes particle correlations

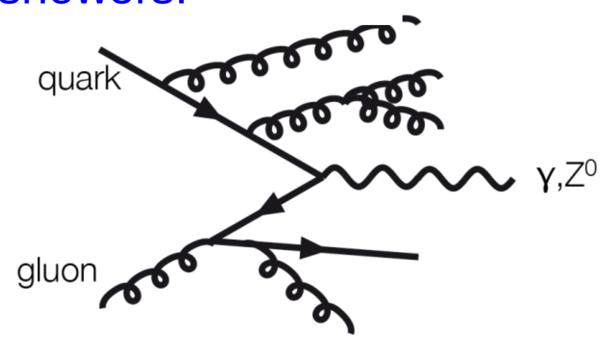


Parton Shower (PS)

3. Final-state parton
   showers:



4. **Initial-state parton
   showers:**



[from G.Herten]

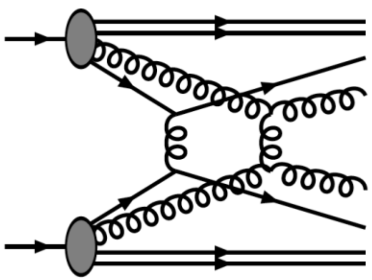
Overview of MC generators

Structure of basic generator process [by order of consideration]

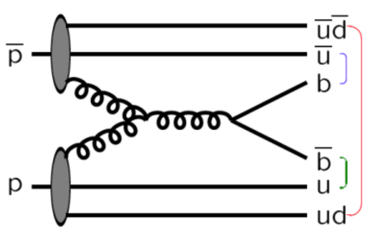
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled; at small

Underlying Event (UE)

5. Multi-parton interaction:

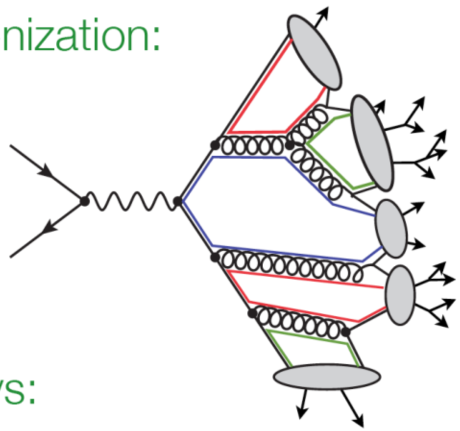


6. Beam remnants:

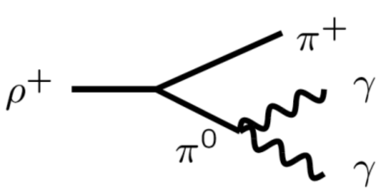


Stable Particle State

7. Hadronization:

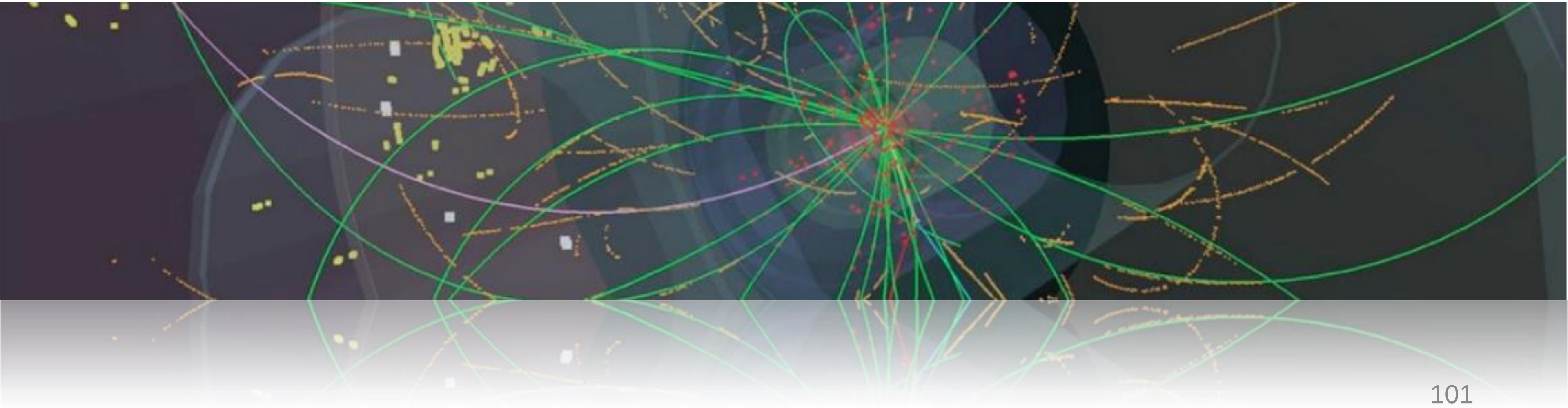


8. Decays:



[from G.Herten]

Luminosity
and cross-section measurements



Cross section & Luminosity

Luminosity
[Machine parameter]

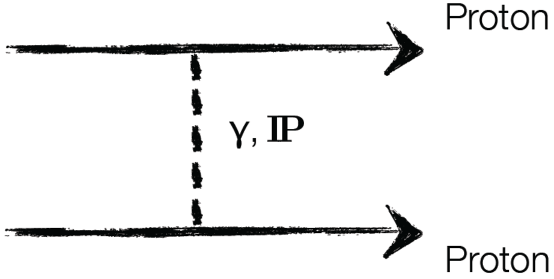
$$\dot{N} = L \cdot \sigma$$

Event Rate
[Measured]

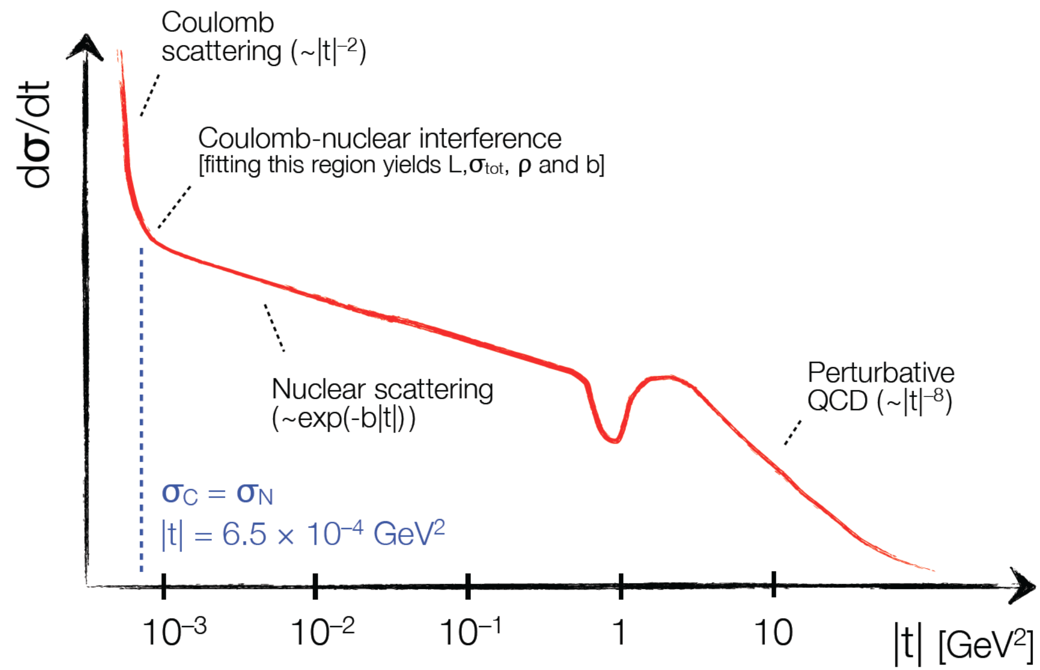
Cross Section

Luminosity and elastic scattering

Elastic Scattering:



$$t = (p_i - p_i') \sim p^2\theta^2$$



Elastic Scattering at low t is sensitive to exactly known Coulomb amplitude ...

Shape of elastic scattering distribution can also be used to determine total cross section, σ_{tot}, and the parameters ρ and b ...

Perform fit to:

$$\frac{dN}{dt} = L\left(\underbrace{\frac{4\pi\alpha^2}{|t|^2}}_{\text{Coulomb Scattering}} - \underbrace{\frac{\alpha\rho\sigma_{\text{tot}}e^{\frac{-b|t|}{2}}}{|t|}}_{\text{Coulomb/nuclear Interference}} + \underbrace{\frac{\sigma^2_{\text{tot}}(1+\rho^2)e^{-b|t|}}{16\pi}}_{\text{Nuclear Scattering}}\right)$$

with:

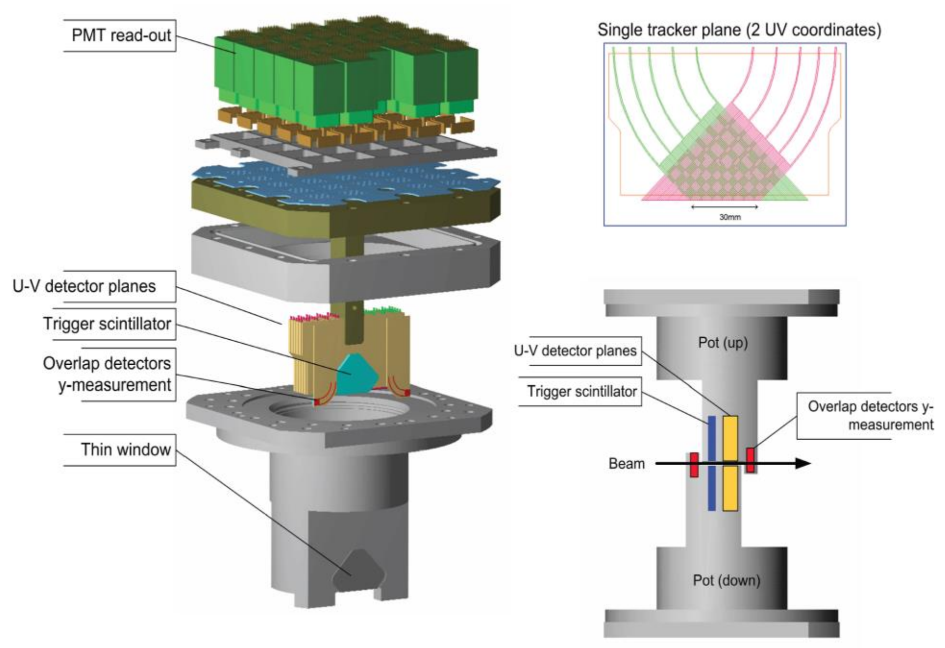
ρ : ratio of the real to imaginary part of the elastic forward amplitude

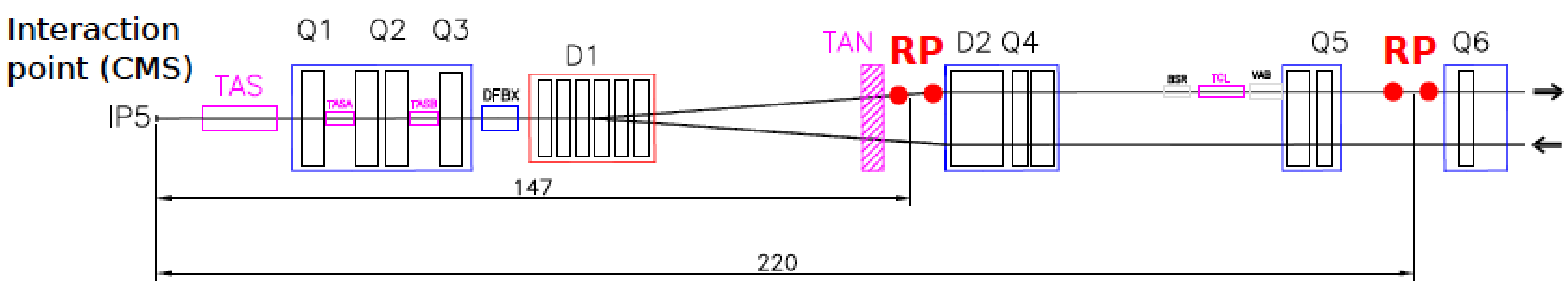
b : nuclear slope

σ_{tot} : total pp ➛X cross section

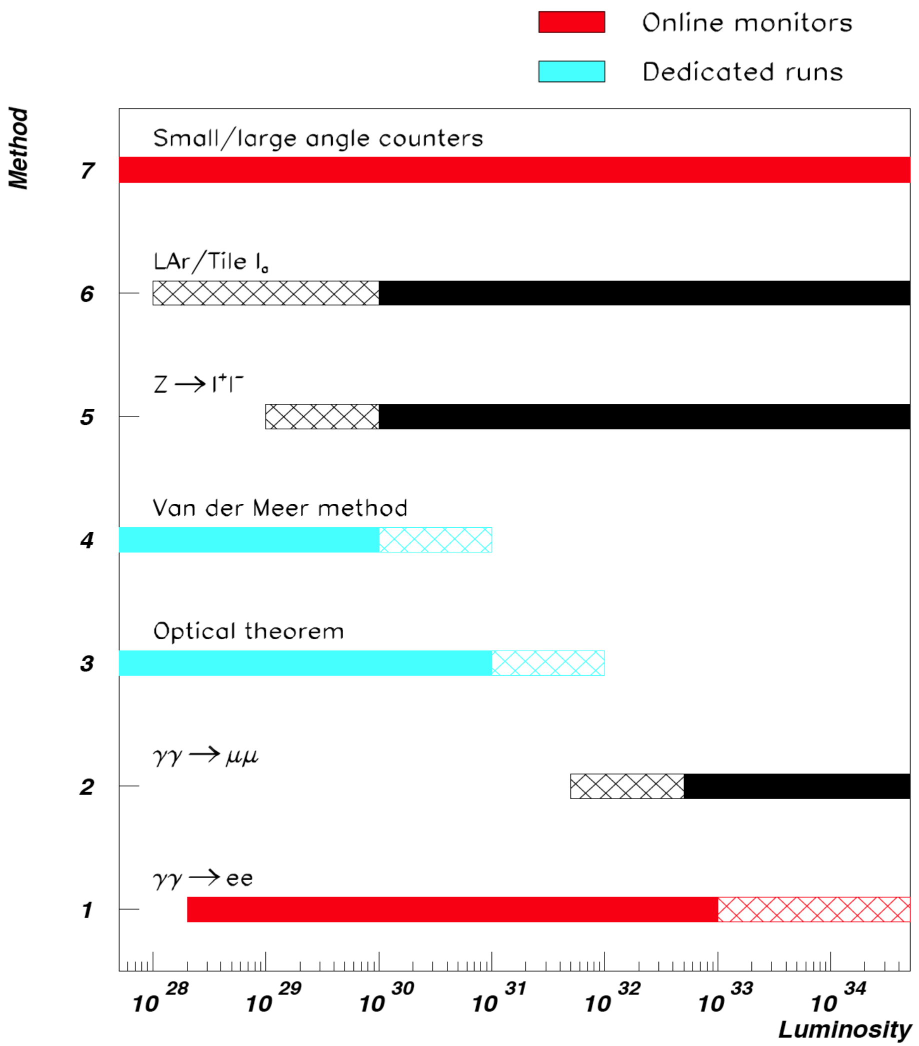
Roman Pots (Totem and Alfa)

- Measurement of p-p elastic scattering
- Roman Pots used to move detectors near to stable beam.





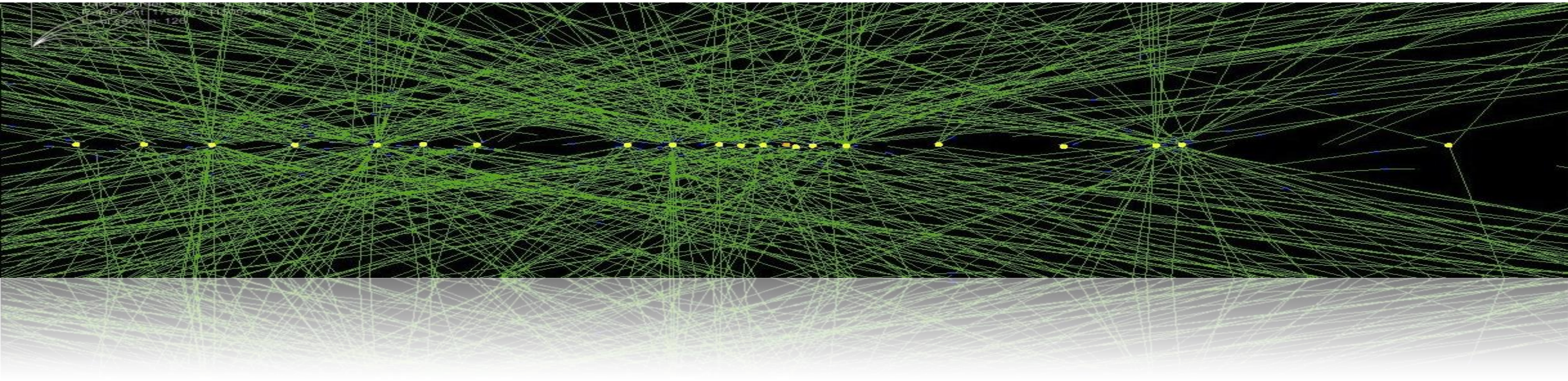
Luminosity determination @ LHC



Methods as
summarized in ATLAS TDR

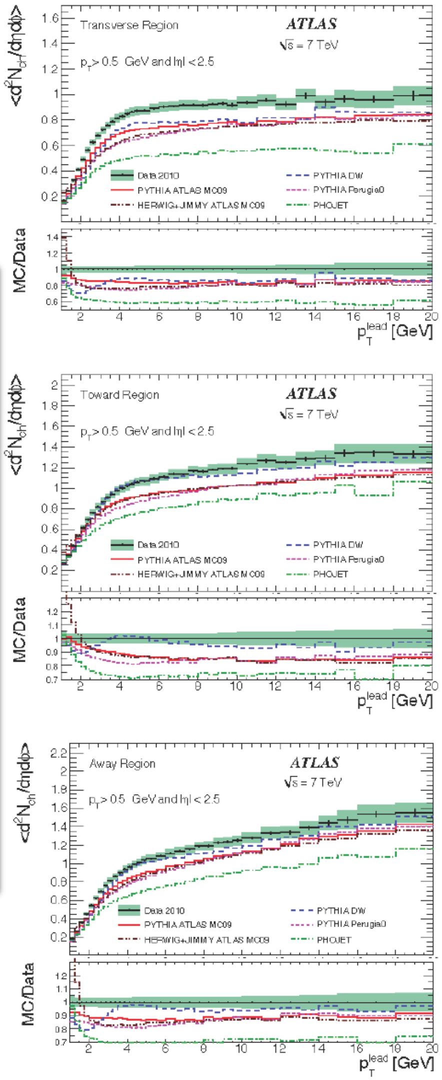
[ATLAS Technical Design Report, Vol. I]

Minimum bias events

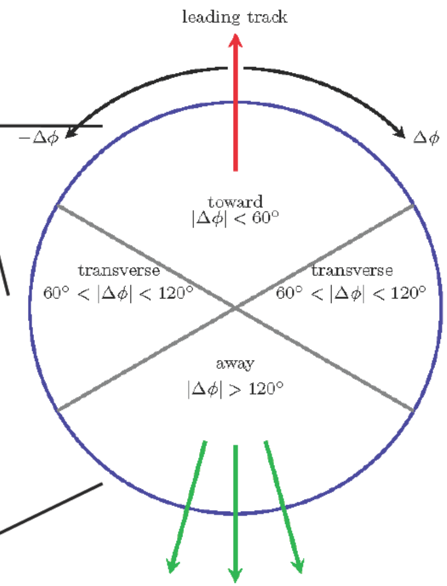


Underlying event

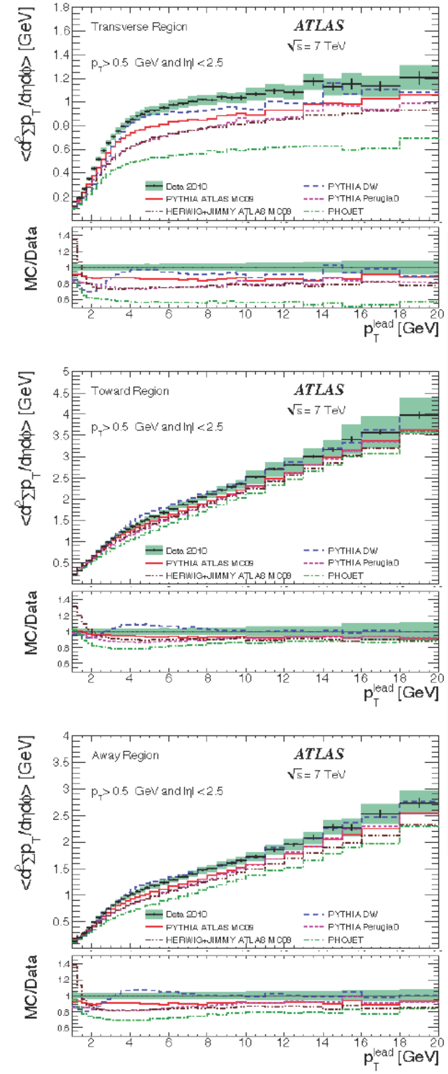
Multiplicity vs P_T



Particle momentum flow in regions defined wrt leading track



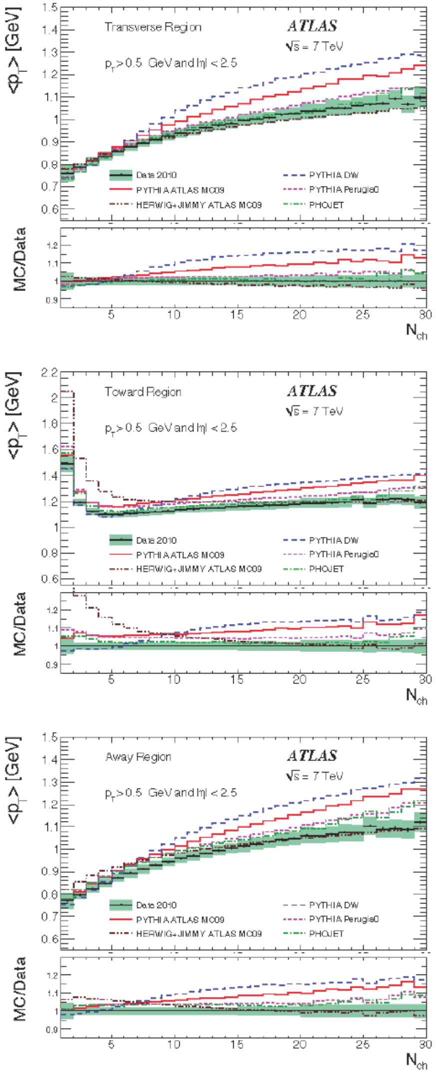
arXiv:1012.0791



Sum P_T vs P_T

Underlying event

Mean P_T vs Multiplicity

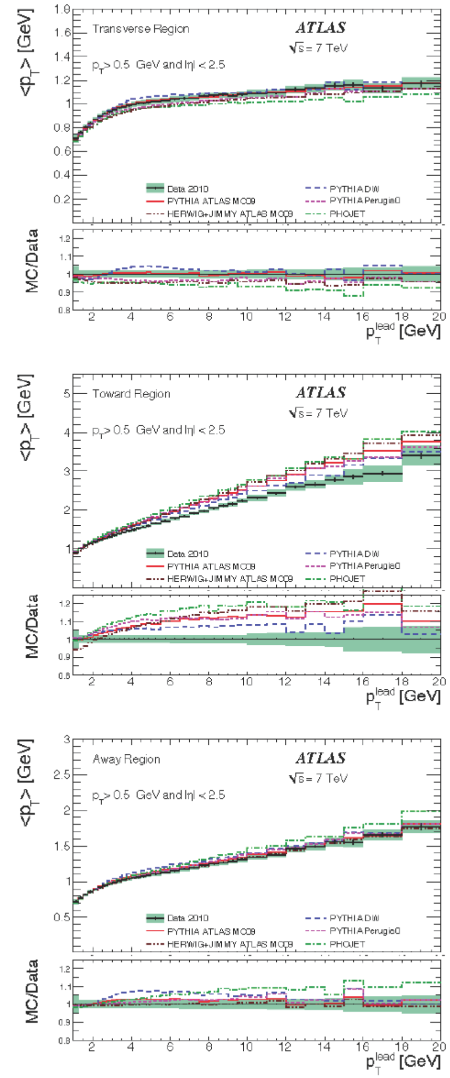


From these comparisons: determine best "tunes" for underlying event.

In practice: tuning of soft QCD model in PYTHIA

Tuning is important for data-MC agreement further down; particle isolation (e.g. in lepton identification) and missing energy (ME_T)

Mean P_T vs P_T



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