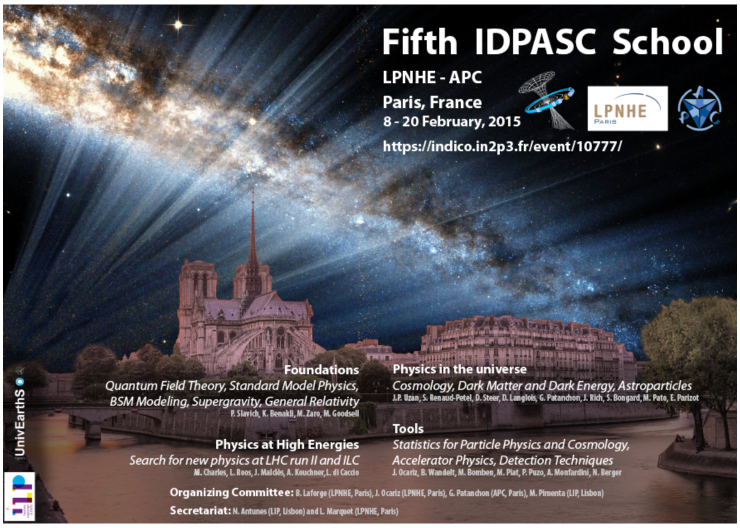
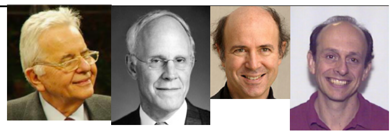
Beyond the Standard Model @ ATLAS & CMS

Lucia Di Ciaccio

Université de Savoie & CNRS/IN2P3-LAPP

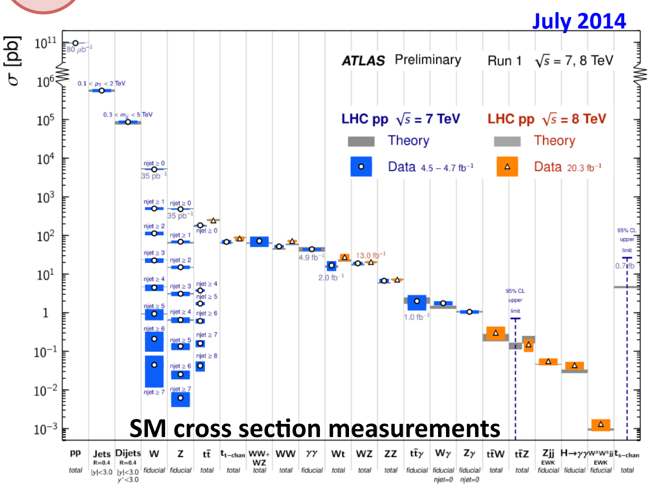


Standard Model (SM): EW + pQCD

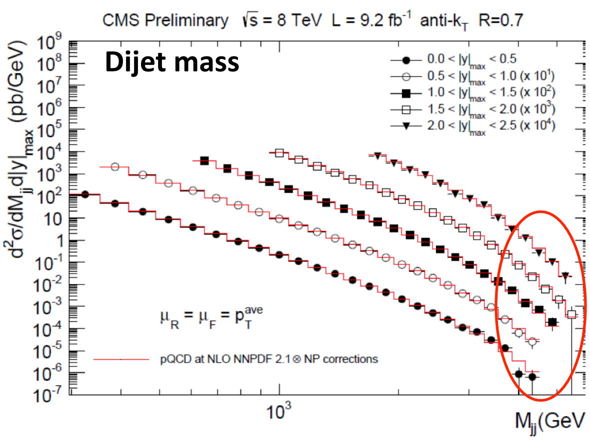


Renormalizable **Q**uantum **F**ield Theory with spontaneously broken local gauge invariance describing electroweak (EW) + strong interactions (QCD)

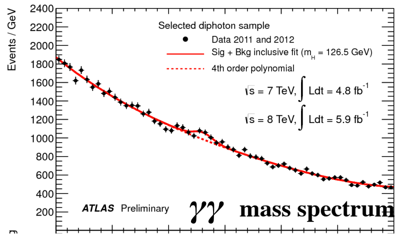
Amazily successful in describing precisely data from experiments

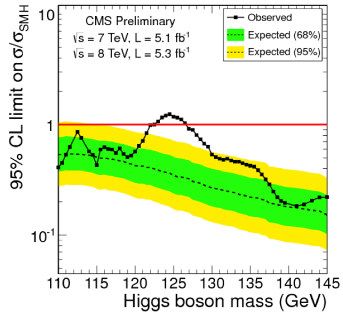


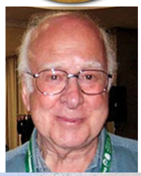
CMS-PAS-SMP-14-002

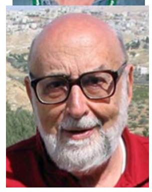


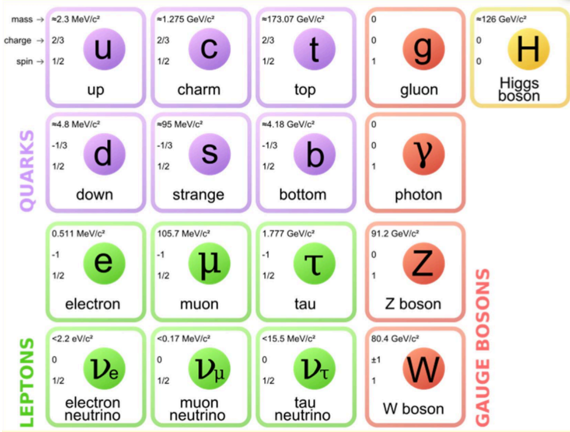
The list of fundamental constituents of SM is now complete !









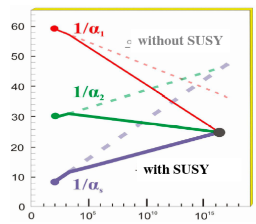


Should particle physicists go/return on holidays forever ?

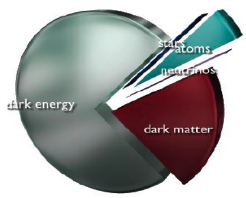
… Unfortunately/Fortunately .. not

Still many open questions !!

- **Mass origin :**
  - ~~* Does the Higgs boson exist ?~~ → which are the "Higgs" bosons properties?
  - * How precisely electroweak symmetry breaking is implemented in nature?
  - * Fine tuning of the Higgs mass → Supersymmetry? Composite Higgs ? Extra Dimensions?



- **Gravity is not included in SM:**
  - * ExtraDimensions ?
- **Unification of the fundamental interactions:**
  - * Supersymmetry? GUT?
- **What is the Dark Matter /Energy composing the Universe?**
  - * Supersymmetry? ExtraDimensions ?



- **Why the prevalence of matter on antimatter ?**
  - * CP violation phenomena in :
    - B physics ?
    - ν sector ?

Motivation to look for physics Beyond the SM

… still more questions !!

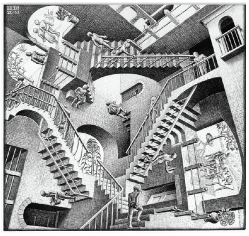
- how to accommodate the experimental result that ν have a mass?
- why gravity is so weak $G_F/G_N \sim 10^{32}$?
- why 3 families of fermions? Are there more ?
- why mass hierarchy $m_{top}/m_{up} \sim 10^4$?
- are quarks and leptons really 'elementary'?
- why charge quantization?
- can quark and gluons be deconfined in a quark-gluon plasma ?

… and many more

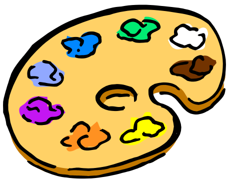
Is Standard Model a low energy approximation of a more fundamental theory?

If yes, which one? → BSM

SUSY?



Extra-Dimensions?



Technicolor ?

We hope to find the answers by studying particle collisions @ very high energy

Probing the TeV region with pp collisions

How to discover New Physics (NP)

One recipe @ LHC

- **Scatter high energy probes with high luminosity**
- **Select, identify and measure basic outgoing objects**
  - **NP Models** may suggest the signatures to look for
- **Calibrate, align, correct for measured efficiencies**
- **Compute expectations from all that is known (need to evaluate the "SM Background",data & MC)**
  - Mesure yields of Background
  - Evaluate **NP Signal** (model)
- **Evaluate experimental and theory uncertainties**
- **Compare data with "theory": any departure from the expectations?**
- **Yes:**
  Interpret in the context of NP models
  and p  **s**

OUTLINE OF THIS LECTURE

→ The LHC machine

→ The detector

→ Understand the detector

→ & the Standard Model

→ Statistical tools

→ An example: Dilepton Resonance search

The LHC: design parameters (proton-proton)

The rate of events is :
R(Hz) = L(cm^{-2} s^{-1}) * σ(cm^{2})

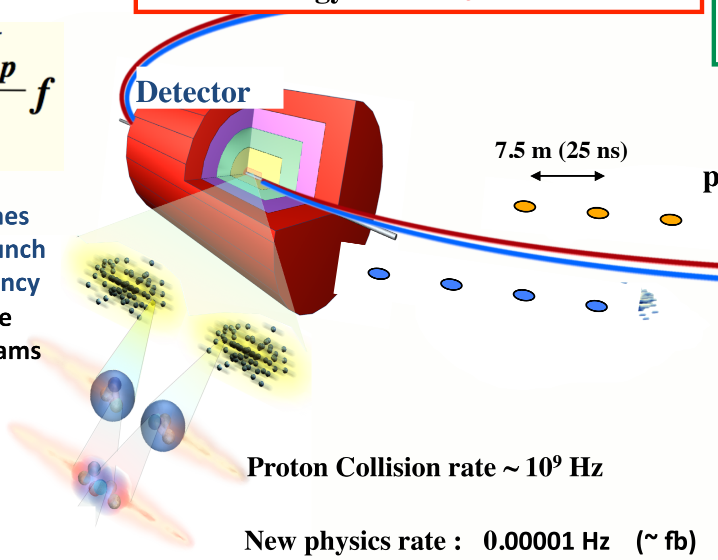
Energy $\sqrt{s}$ = 14 TeV
Luminosity L = 10^{34} cm^{-2} s^{-1}
Number of bunches = 2808
~ 10^{11} protons/bunch
Stored energy ~ 350 MJ/beam

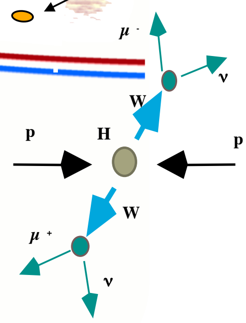
factor ≈ 100 w.r.t. previous machines

! 200 MJ to melt 1 ton of copper

$$L \propto B \frac{N_p N_p}{A_{xy}} f$$

B = number of bunches
N_p = number of p/bunch
f = revolution frequency
A_{xy} = area in the plane transverse to the beams



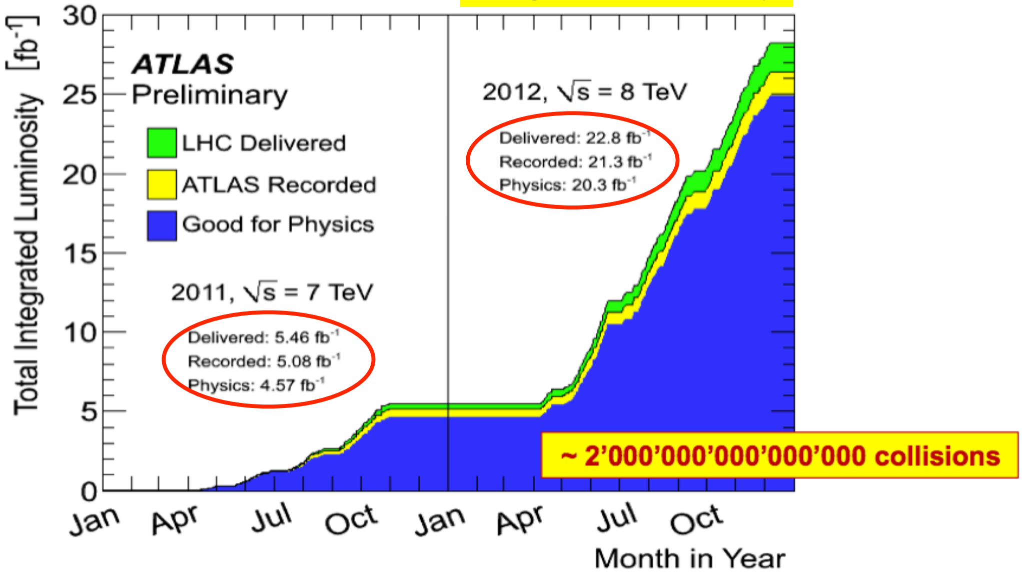


New physics rate : 0.00001 Hz (~ fb)

The LHC: reached performance (proton-proton)

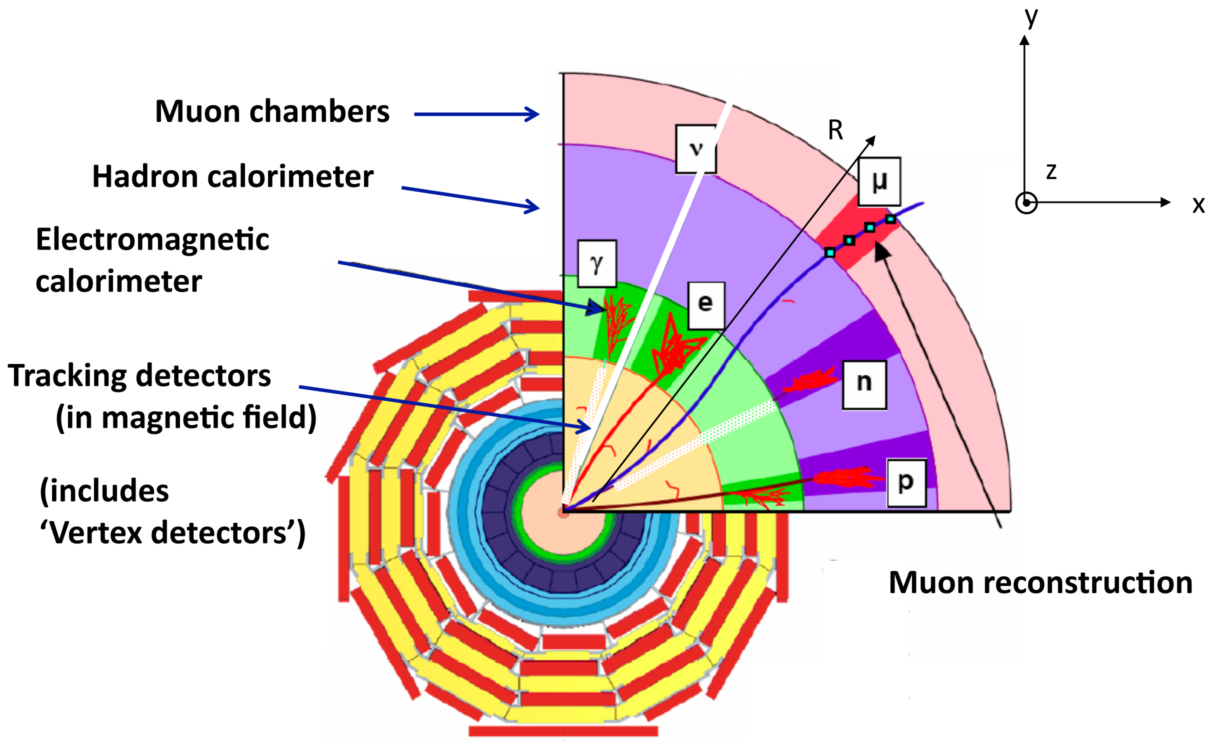
$N_{events} = \sigma \int L\, dt$

Integrated Luminosity



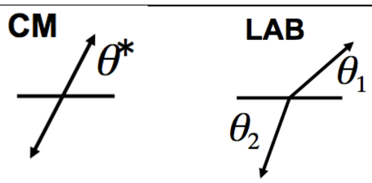
The experiments record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!

Multipurpose detector: typical layout @ colliders



Variables used in the analysis of *pp* collisions

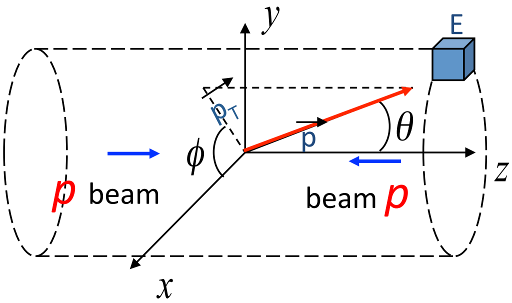
- **LAB system ≠ parton-parton Center of Mass (CM) system**
- **Boost of parton-parton CM along beam line "unknown"**



- **p of a particle is not invariant under Lorentz transformation along z**

→ **focus on transverse quantities (i.e. in the plane ⊥ to the beam):**

- **Transverse momentum** $\vec{p}_T = \vec{p} \sin\theta$
- **Transverse energy** $E_T = E \sin\theta$

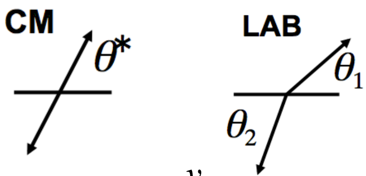


NB • **p_T is invariant under a Lorentz transformation (boost) along z axis**

NB • **when m « E → $p_T \approx E_T$**

Variables used in the analysis of *pp* collisions

- **θ is not invariant under Lorentz boost along z**

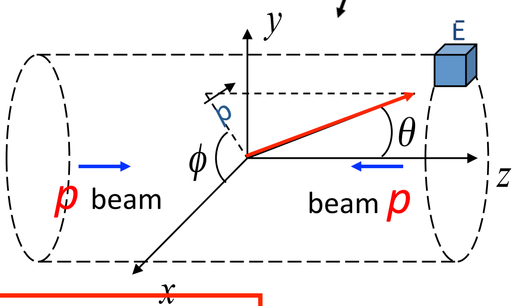


→ Use 'rapidity':

- rapidity $y \equiv \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

  or pseudorapidity(*) $\eta \equiv -\ln(\tan\frac{\theta}{2})$

- azimuthal angle φ



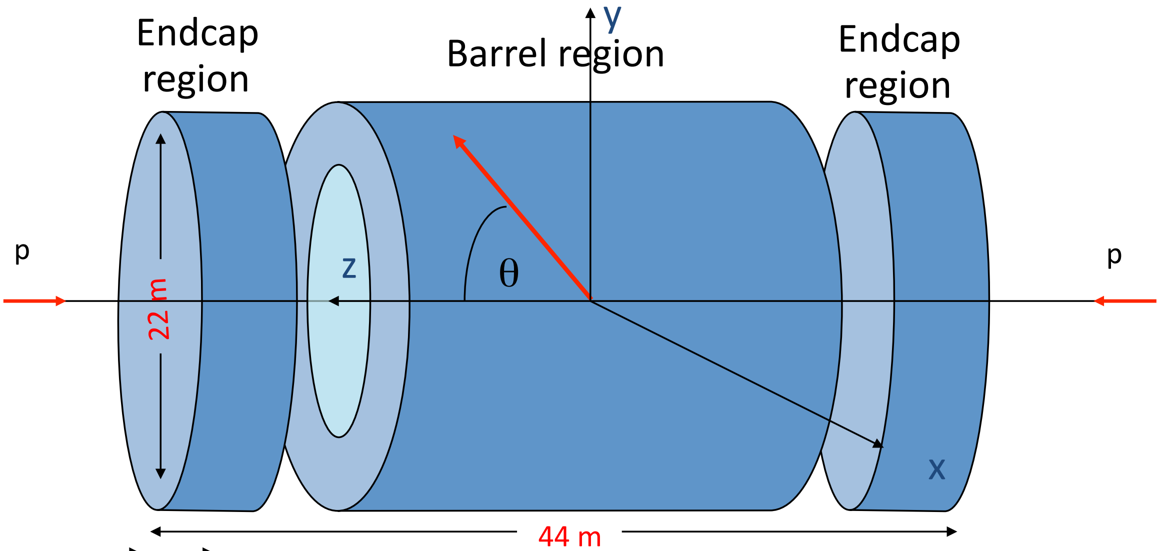
Δy, φ : invariant under Lorentz boosts along z

Bottom line: particles described by p_T, y, φ

- **"Angular distance" between two particles:** $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$

NB (*) **m « E → Y ≈ η**

Recap: Generic detector (dimensions ATLAS) and variables



$\vec{p}_T \equiv \vec{p} \sin\theta$: momentum transverse to the beam direction

$y \equiv$ rapidity $\qquad y \equiv 0.5 * \ln((E+p_z)/(E-p_z))$

$\eta \equiv$ pseudorapidity $\qquad \eta \equiv -\ln(\tan(\theta/2))$

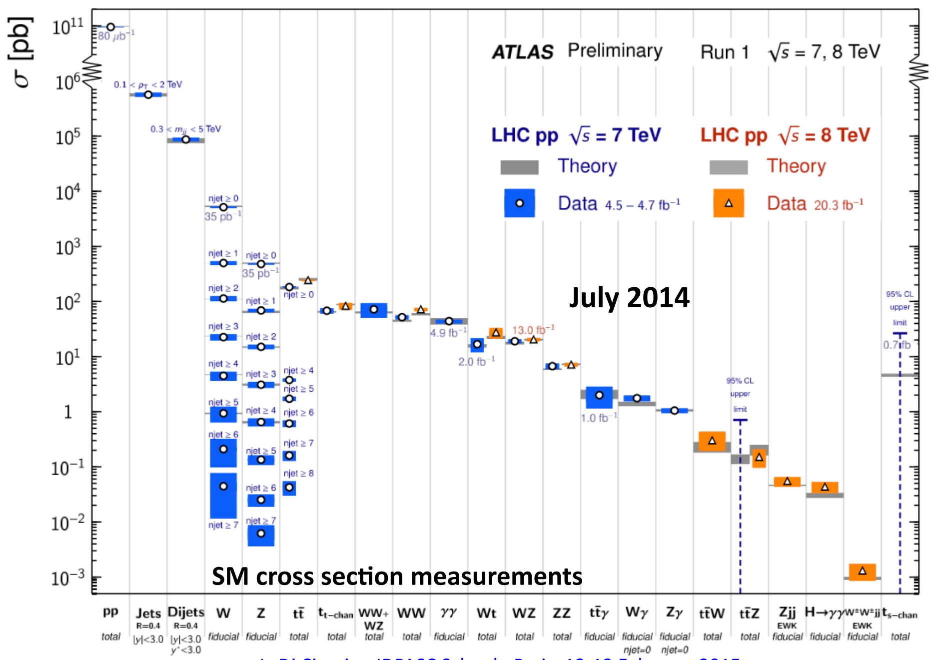
for massless particles : $\eta \cong y$

(In the central region, hadron η distribution is approximately flat at fixed p_T)

Understand the SM @ LHC

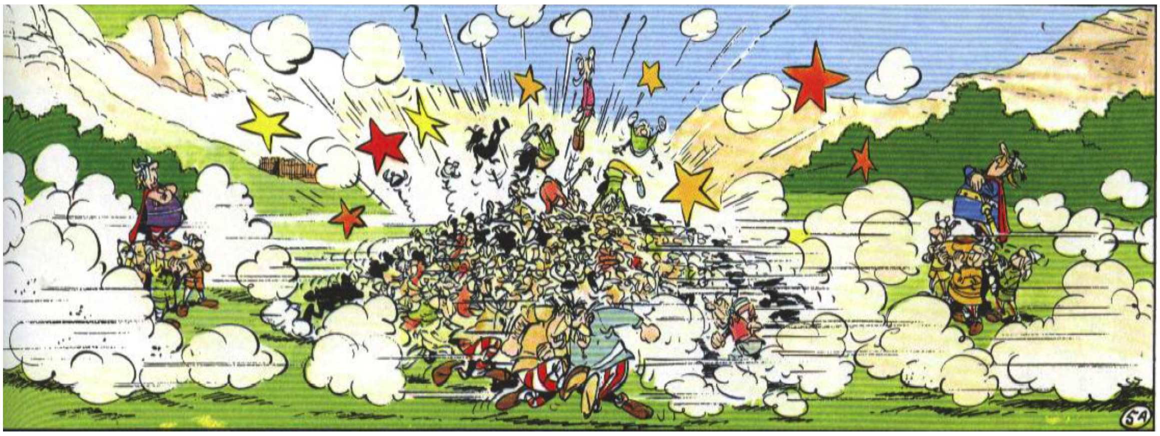
- **Strong (QCD) processes (soft and hard)**
- **Electroweak (EWK) processes**

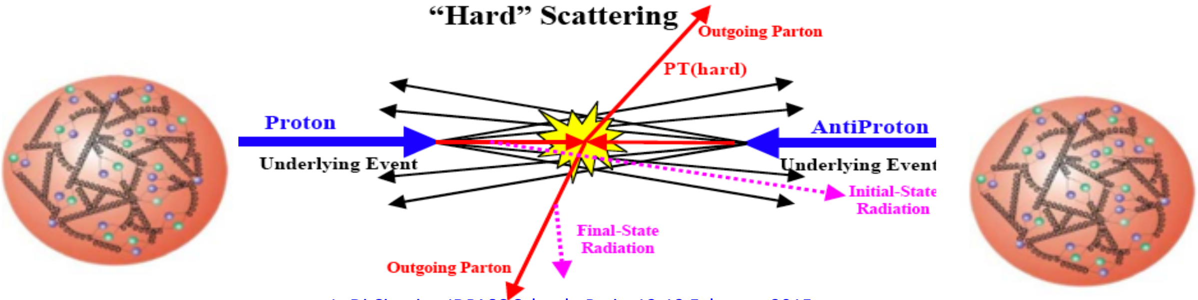
Cross sections of more than 22 SM (hard scattering) processes



Proton-proton interactions @ very high energy

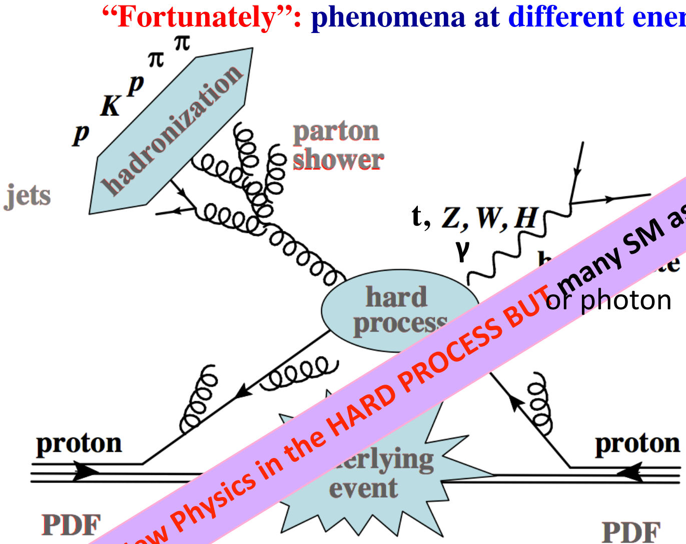
Protons are complex objects





A Complex Picture

"Fortunately": phenomena at different energy scales Q factoriz



We look for New Physics in the HARD PROCESS BUT many SM aspects must be understood

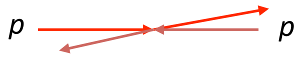
PDF = Parton Density Functions
(describing the momentum distribution of partons in proton)

→ separation between phenomena @ high- and small-Q scale
he former are computed exactly, the latter are approximated or modeled

The factorisation scale μ_F arbitrarily separates hard from soft scales

pp collisions

~ 25% ELASTIC collisions : $\sigma_{elastic} \approx$ 20 - 25 mb



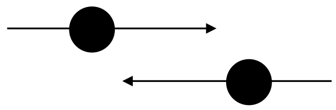
~ 75% INELASTIC collisions : $\sigma_{inelastic} \approx$ 80 - 85 mb

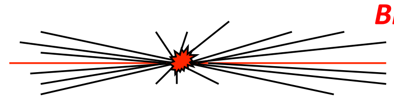
* Most of them occur at **large distance**

→ **low** momentum transfer from initial to final state (**soft collisions**)

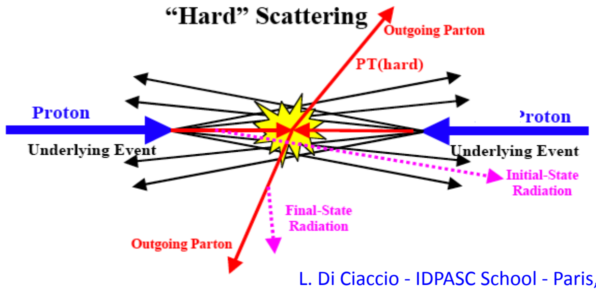
→ final state particle with large longitudinal momentum but **small** p_T

(Minimum Bias type)





*** High p_T processes are a small fraction of the total inelastic pp cross section.**

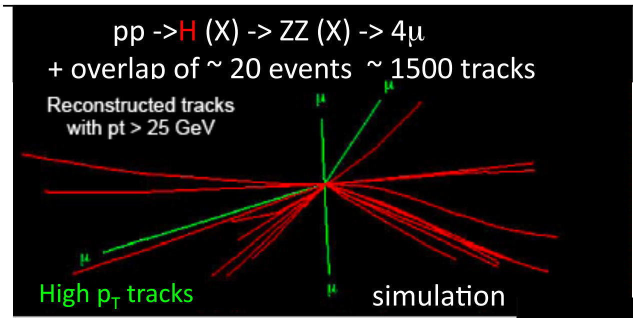


They are accompanied by:

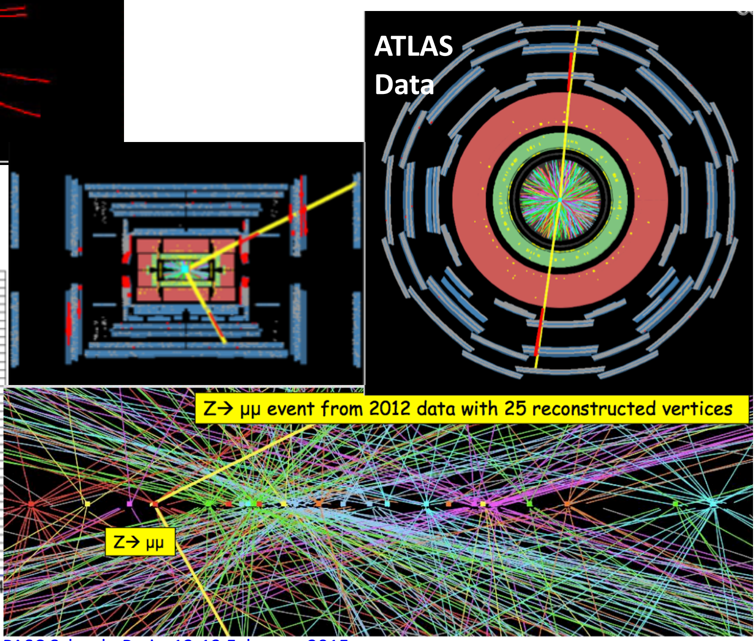
Initial/Final State Radiation(ISR/FSR)

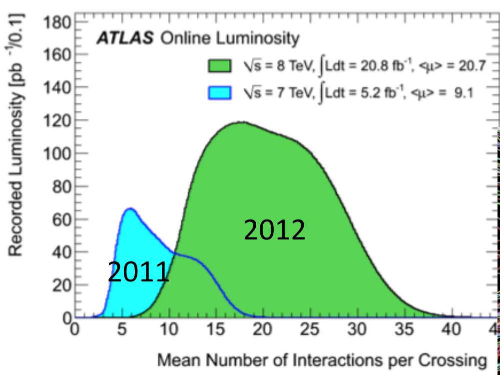
- **Underlying event (UE):**
  - **Spectator parton fragments**
  - **MultiPartonInteraction(MPI)**

"Superimposed soft collisions" = Pile UP



The **high pt events** is accompanied by soft collisions = Pile UP (PU)

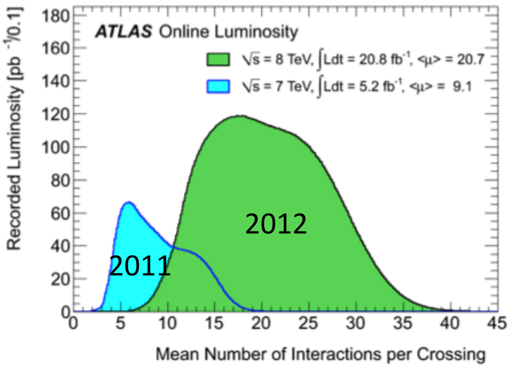


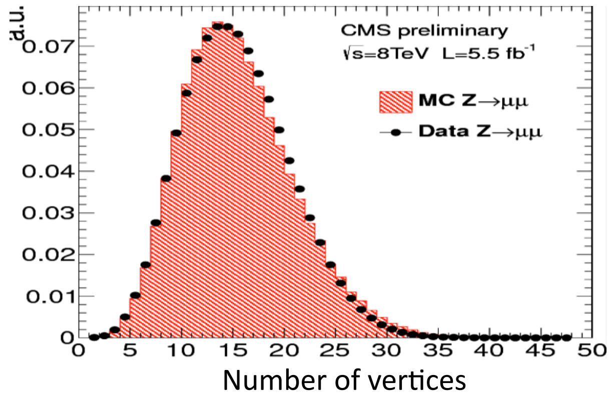


Pile Up (PU) : a challenge

Number of primary vertices NPV characterizes the "In time Pile Up"

Mean number of interactions $<\mu>$ characterizes the "In&Out of time Pile Up"

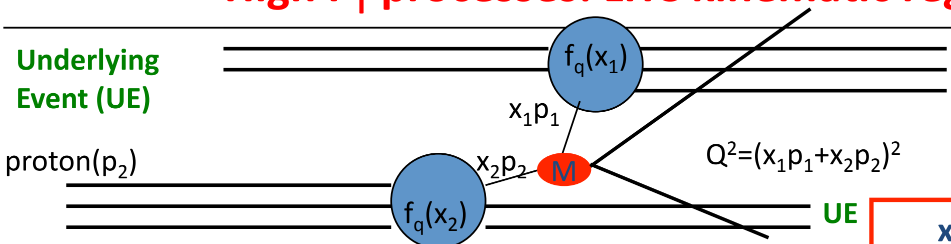




Recipe to make analyses 'robust' wrt PU effects :

- **Select particles, jets etc. coming from primary vertex with highest p_T tracks (need precise vertexing)**
- **Exploit jet characteristics**
- **Subtract average PU energy in isolation cones**
- **Include PU in the simulation (if not → reweight NPV, $<\mu>$ distributions)**

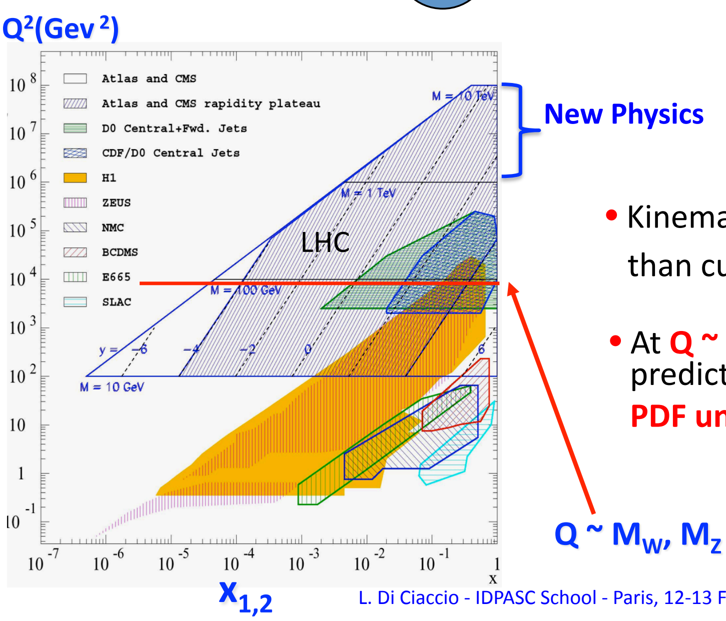
High P_T processes: LHC kinematic regime



$x_{1,2}=(M/\sqrt{s})\ e^{\pm y_{cm}}$

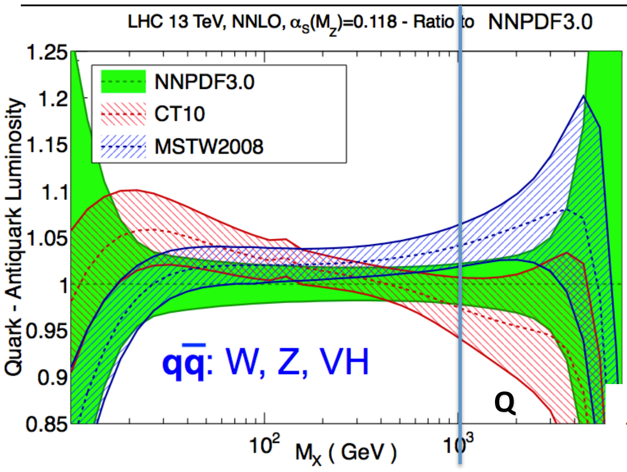
$Q=M$

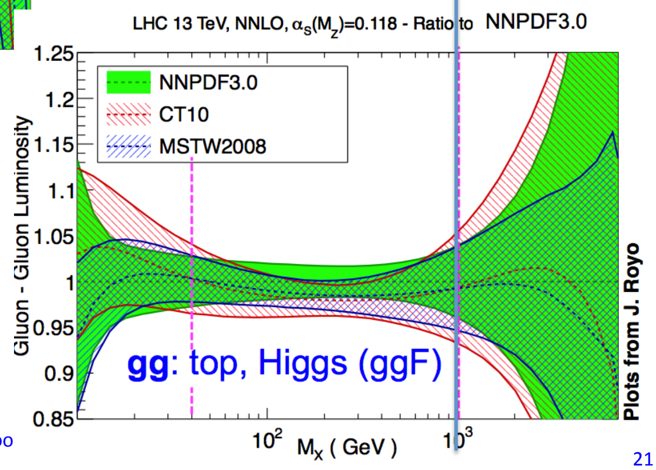
$y_{cm}=1/2\ \ln(E\text{-}pz)/(E+pz)$



- Kinematic regime for LHC much broader than currently explored
- At **Q ~ TeV** **New Physics** cross-section predictions dominated by **PDF uncertainties @ high-x**

High P_T processes: how well we know PDF?





For **physics BSM** important to measure !

p-p Cross Sections

total cross section

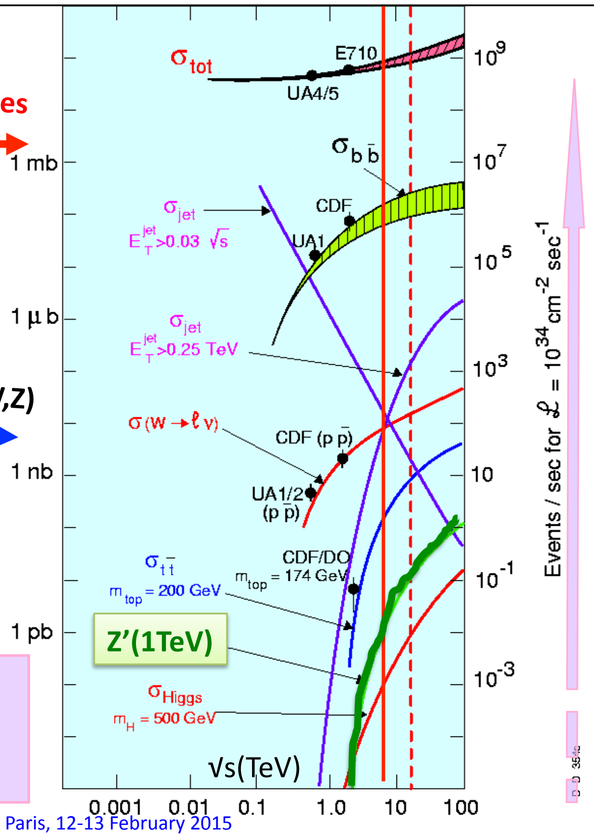
$\sigma \sim 10^{-25}$ cm^2 = 100 mb (strong interaction)

QCD processes

Electroweak (W,Z)

$\sigma \sim 10^{-33}$ cm^2 = 10 nb (electroweak interaction)

New Physics



Many orders of magnitude between New Physics and 'known processes
→ **On line trigger and selection**

Understand the detector

- Searches have signatures that involve a combination of
  - * leptons
  - * jets
  - * Missing Transverse Energy (MET)
- The reconstruction of these objects must be well mastered as well as the efficiency of the reconstruction and the calibration of the objects together with the uncertainties
- Here two examples of objects are briefly shown:

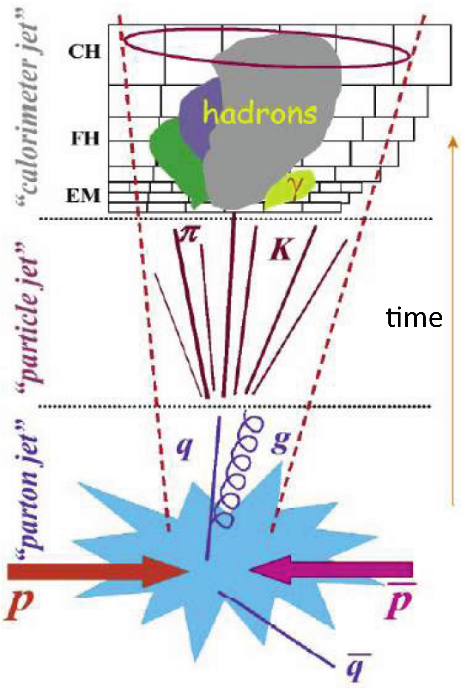
Jets

Missing Transverse Energy

Important for **BSM searches**

Jets

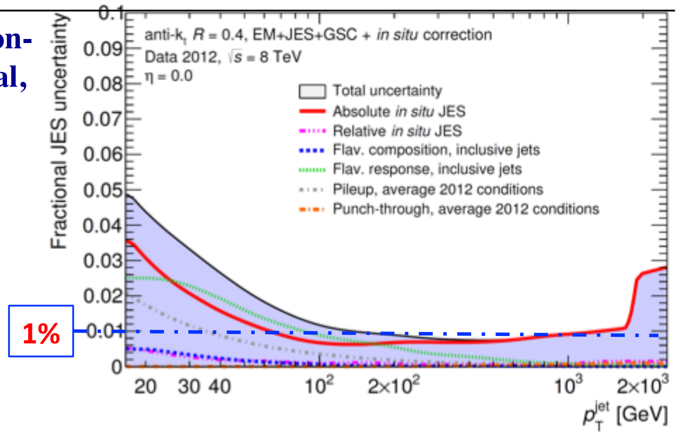
- Quarks and gluons manifest as jets (of hadrons). "Jets are universal".
- A jet is defined by the jet algorithm: different algorithms → (Slightly) different jets
- The jet algorithm is run on detector objects (clusters, tracks) or on stable hadrons
- A jet algorithm is characterized by:
  - a metric (measure of distance)
  - a resolution parameter
  - procedure of recombination
- A good jet algorithm is:
  - safe to higher order effects, i.e. a soft IR (E->0) or collinear (θ->0) gluon radiation do not change jet quantities
  - detector independent
  - fast
- Jet algorithms: cone, midpoint cone, JetClu (unsafe)
  SISCone, k_T, anti-k_T (safe)

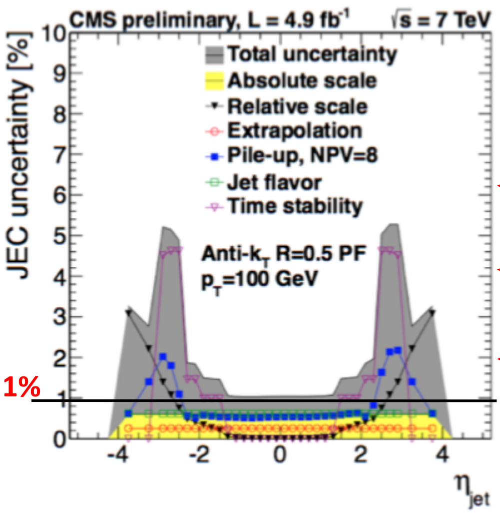


See Salam, arXiv:0906.1833 for a review on jet algorithms

Jet Energy Calibration & JES uncertainty

- **Jet Energy Calibration corrects for non-compensating calorimeters, dead material, out- close of-cone effects, pile-up**
- **Validations: in-situ checks using p_T balance jet-jet or with respect to well-calibrated objects (i.e γ-jet, Z-jet data, ..)**





- **JES uncertainty depends on constituent input to jet algorithm (smaller for ParticleFlow jets)**
- **JES uncertainty higher in forward region wrt end/cap region (extrapolation di-jet balance)**
- **Uncertainty due to Pile-Up depends on the number of primary vertices NPV**

Missing Transverse Energy

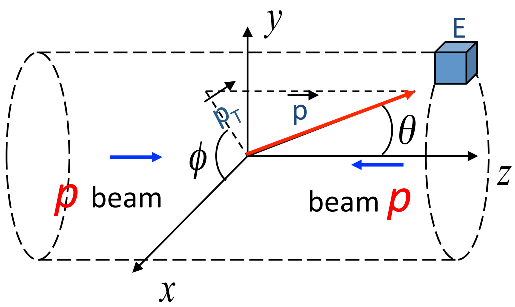
Important variable in searches:

- $\Sigma_i \vec{p}_T^{\,i} \approx 0$ $\quad \Sigma_{i\,vis} \vec{p}_T^{\,i} + \Sigma_i \vec{p}_{T\,invis}^{\,i} \approx 0$

This allows to evaluate the $\vec{p}_T$ of particles not detected (ν)

$\Sigma_i \vec{p}_{T\,invis}^{\,i}$ = "Missing p_T" = $-\Sigma_{i\,vis} \vec{p}_T^{\,i} \approx -\Sigma_{i\,vis} \vec{E}_T^{\,i}$ = MET

- **Missing Transverse Energy :**
  $\vec{MET} = -\Sigma_{vis} \vec{E}_T$



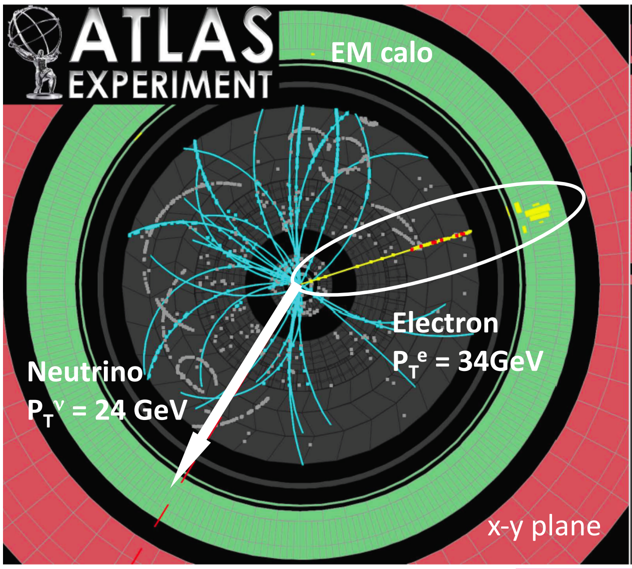
Missing Transverse Momentum is also defined

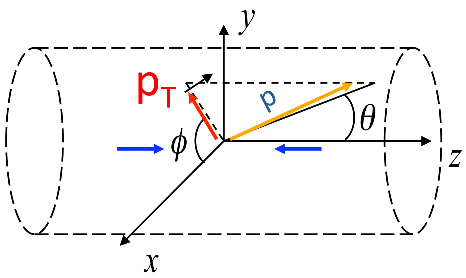
NB
- p_T is a vector when m « E → $p_T \approx E_T$
- a direction is "affected" to $\vec{E}_T$

Example: neutrino detection (production of a W boson)

p p → Electron + ν + $h^{(1)}$ + $h^{(2)}$ + …

W





$$\vec{p}_{T\ initial} = \vec{p}_{T\ final} = 0$$

Need to add an additional non-measured contribution (p_T^{ν}) to get 0

$$\vec{p}_{T\ final} = \vec{p}_T^{\,e} + \Sigma_h \vec{p}_T^{\,h} + \vec{p}_T^{\,\nu} = 0$$

⇓

Missing energy

$$|\vec{E}_{Tmiss}| \equiv |\vec{p}_{T\nu}| = E_\nu = -\,|\vec{p}_T^{\,e} + \Sigma_h \vec{p}_T^{\,h}|$$

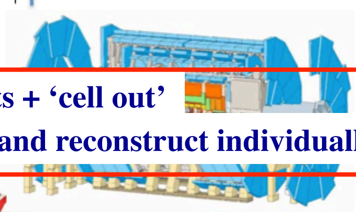
Inputs to Missing ET

Electrons / Photons / Jets / Taus

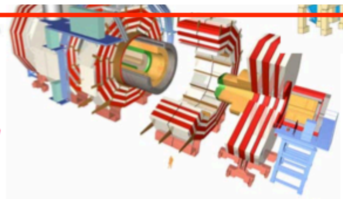
- Overlap resolution needed for calorimeter-based signals
- Object quality cuts change MET
- Use best calibration for each

Muons

- Use good reconstructed muons
- Possible source of fake MET
- Avoid double-counting signal in calorimeters



ATLAS. Sums of e + γ + μ + jets + soft jets + 'cell out'
CMS. Particle Flow approach: identify and reconstruct individually each particle



Remaining Clustered Energy

- Important to use all real signals in calorimeters, but ignore noise
- Need to derive calibration for soft signals

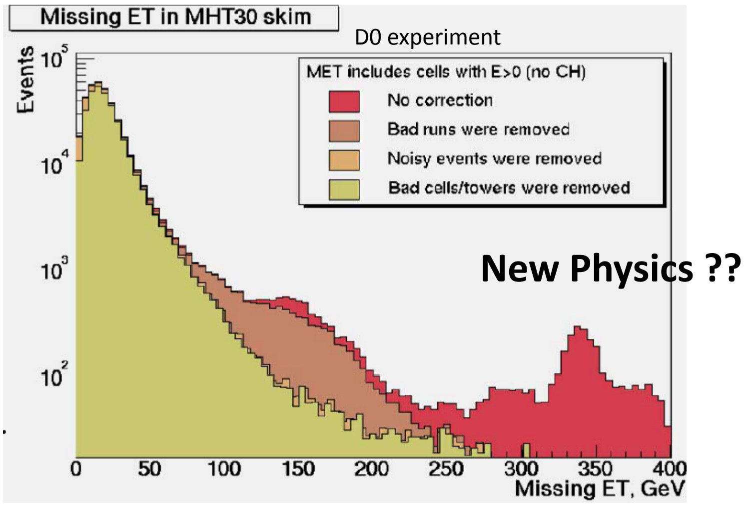
Data Quality/ Monitoring

- Physics analyses must exclude/ understand data with detector problems

Understand the MET

First need to **understand precisely detector response**. Here remove :

- 'bad' runs (i.e. detector not completely operational)
- 'bad' events (noise in some detector regions or cells)
  & correct for 'dead' region or cells



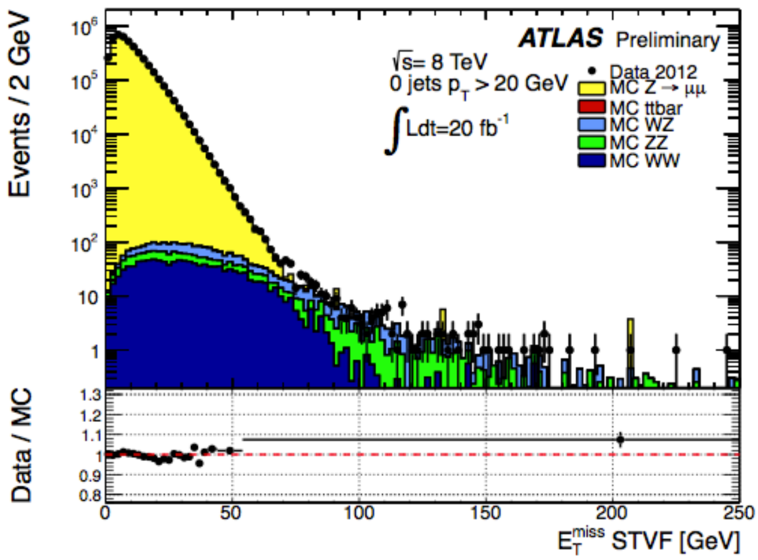
Not to forget: reject cosmics, beam-gas & beam halo events ('machine background')

The simulation here is of little help → Need to use from data

Missing Transverse Energy : E_T^{miss}

$$E_T^{miss} = |\vec{p}_T^{\,miss}| \qquad \vec{p}_T^{\,miss} = -\sum_{vis} \vec{p}_T$$

E_T^{miss} performance measured in $Z \rightarrow \mu\mu$ events (clean final state, no intrinsic E_T^{miss})



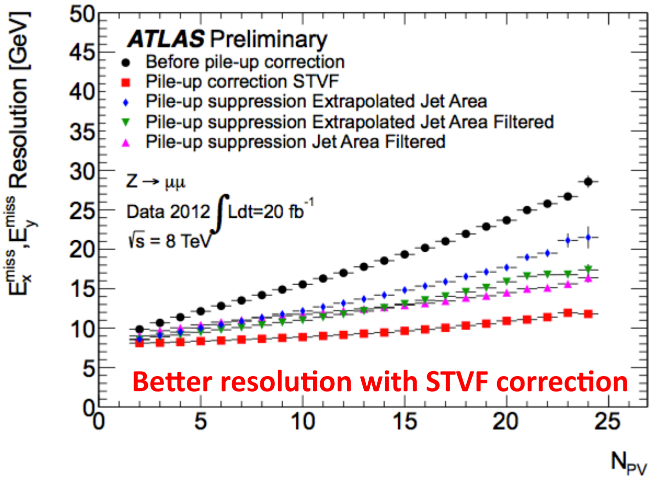
STVF=Soft Term Vertex Fraction

MET reconstruction performance: mitigation of PU

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

$$E_{x(y)}^{miss} = -\sum_{particles} E_{x(y)}$$

- To mitigate PU effect :
  Use Jet Vertex Fraction (JVF) to filter PU jets (JVF, same as STVF for track matched to jets)
  Multiply soft term of MET by Soft-Term Vertex-Fraction
- In events with no MET (**Z→μμ**) the width of Emiss x(y) gives an estimation of the MET resolution



$$\mathrm{STVF} = \frac{\sum_{i \in \mathrm{PV0}} p_T^{\mathrm{track}\ i}}{\sum_j p_T^{\mathrm{track}\ j}}$$

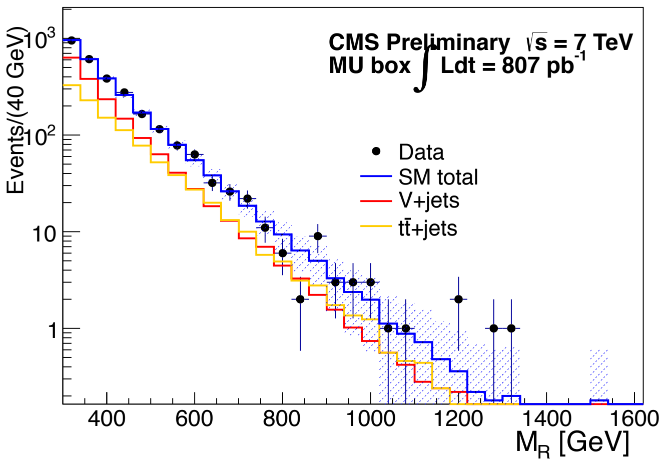
Understand the Physics Background → SM !

After understanding the detector response ("reducible backgrounds") and PU filters, there are physics processes which give the **same signature** (often "irreducible backgrounds" but also "reducible backgrounds")

Example: search for a signature " MET + jets "

Background 1: Z + jets
with the Z decays to neutrinos
→ the MET is genuine!

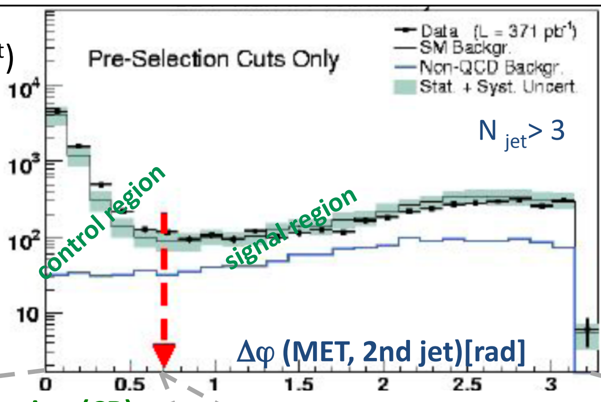
Background 2: t-tbar
with one of the two W's decays to a tau and a neutrino

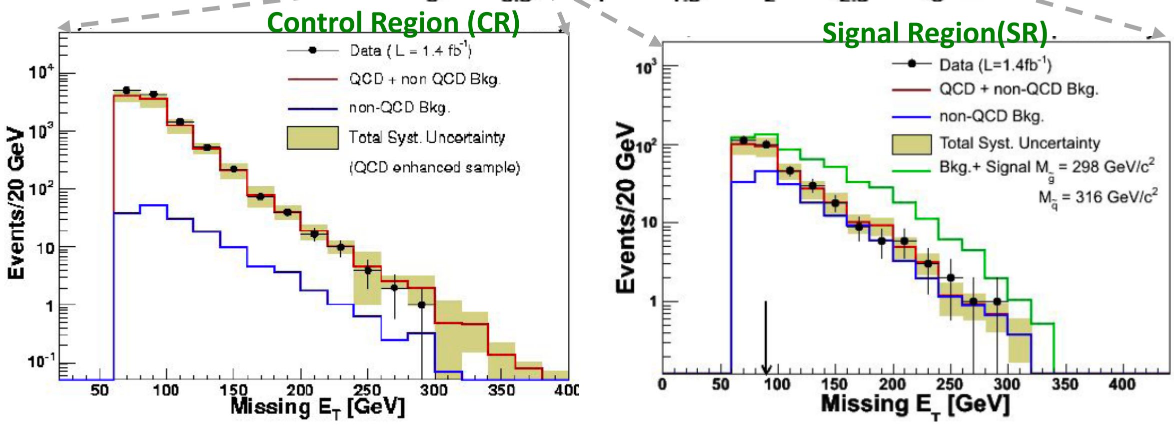


Need to measure SM processes and use data to be confident in "extreme" phase space regions

Another example: control of "QCD background"

- After preselection cuts (p_T^{jet})
- Use $\Delta\varphi$ (jet, MET)
  to suppress and
  to understand jet BKG



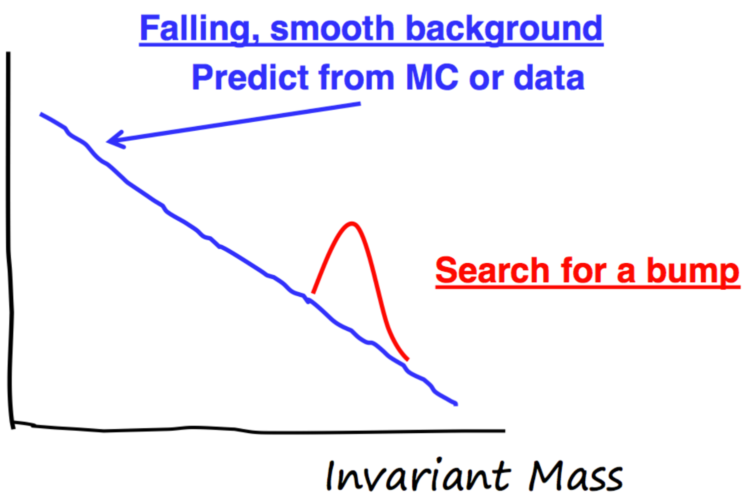


An example of analysis: Heavy Resonance search → l+ l-

Taken as example since "Clean signature"

<u>**BUT Experimental Challenge**</u>:

➢ Understanding detector performance in region with no (little) control sampl

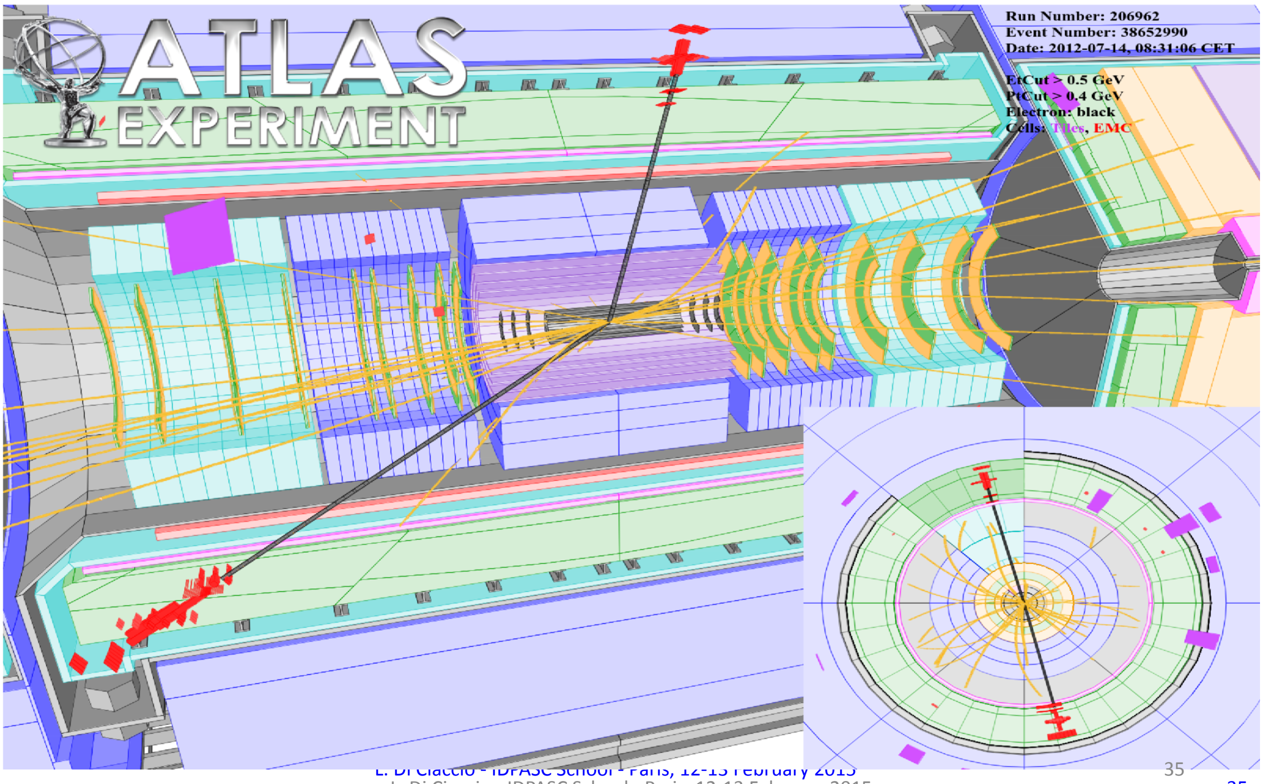


C. Issever

Detector resolution:

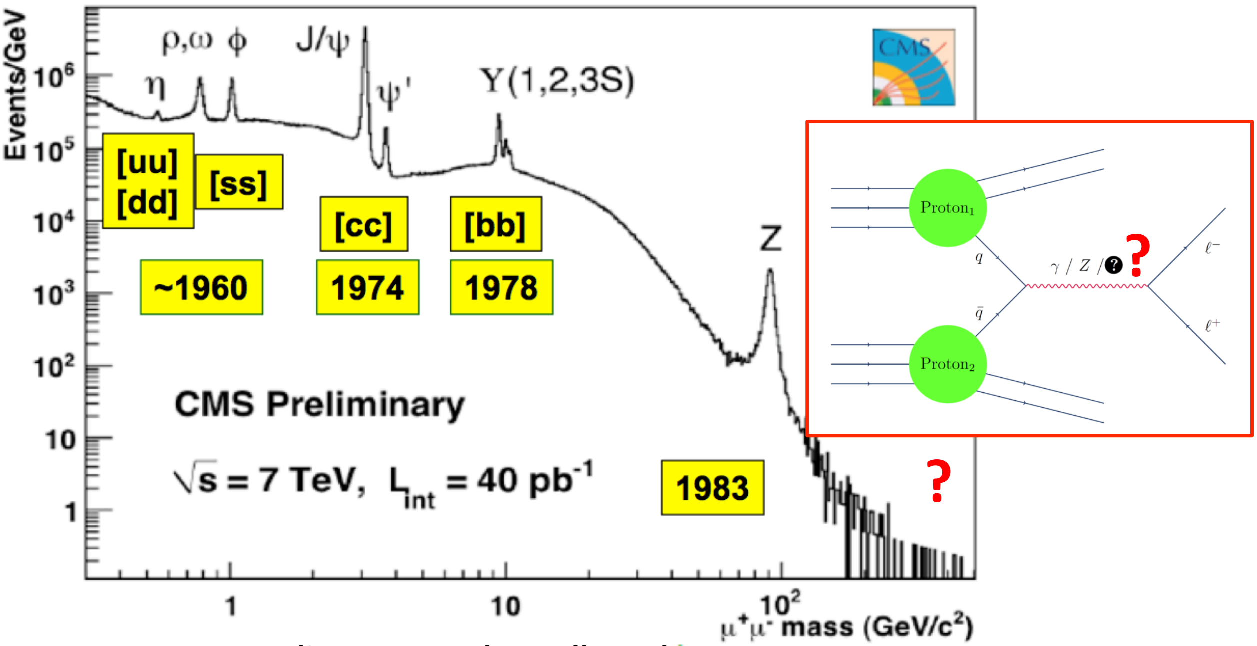
NB for muons deteriorates with mass; for electrons the opposite

Di-electron Event (m_{ee} =1541GeV)



Dilepton Resonance study

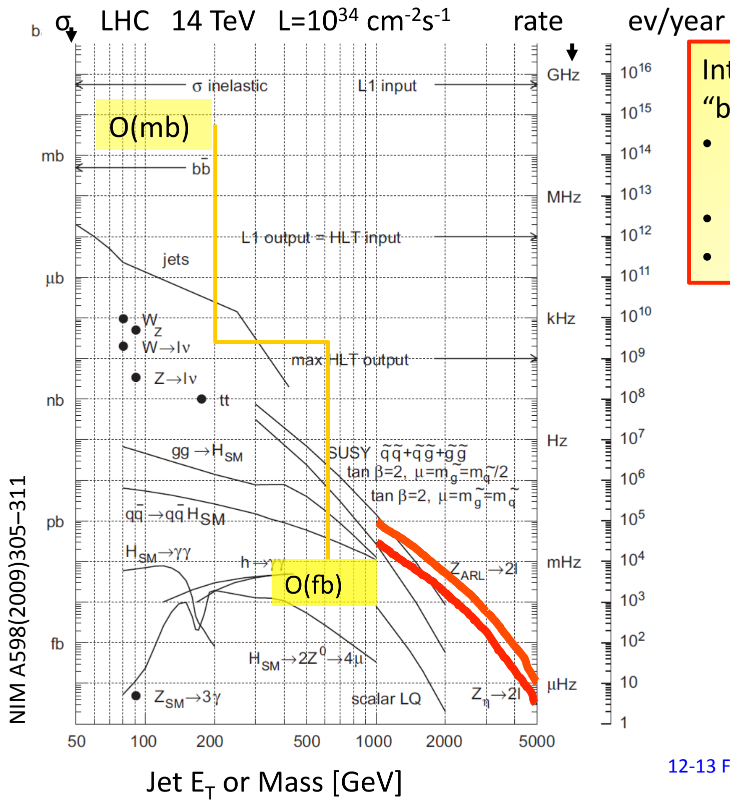
The di-muon spectrum recalls a long period of particle physics:



Data carresponding to ~ 40 pb-1 collected

→ Rediscovery of the the Standard Model **→ Search for new physics**

First Step: Trigger

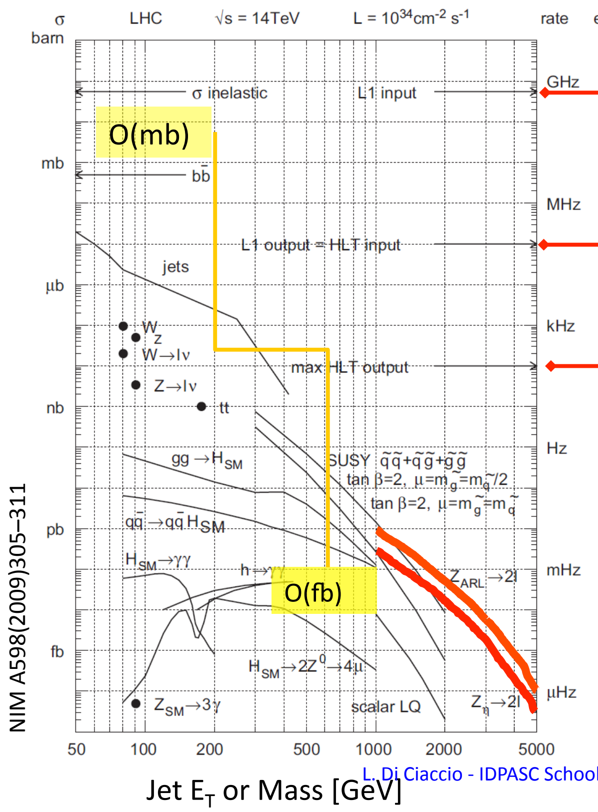


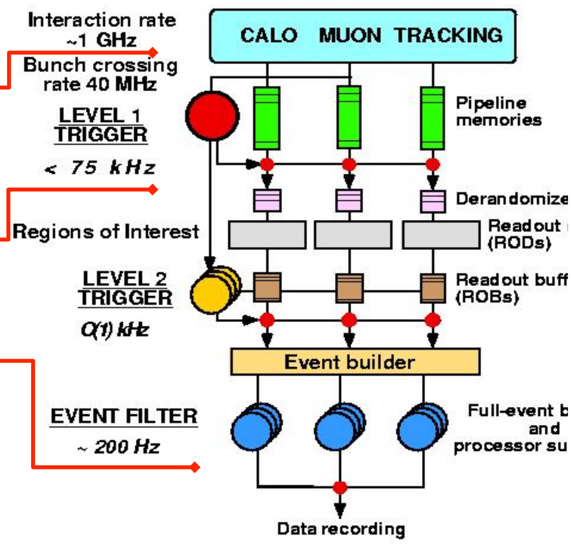
Interesting physics swamped by "background"

- Cross section for new physics:
    - ~10^{12} times lower !!
- Need to filter → TRIGGER SYSTEMS
- Carefully decide what to record)

C. Issever

First Step: Trigger





Dilepton Heavy Resonance study: trigger

ATLAS (PRD 90 (2014) 052005)

ee channel

- Diphoton trigger
- $E_T > 35$ GeV and $E_T > 25$ GeV

μμ channel

- Single muon triggers
- $E_T > 24$ GeV or $E_T > 36$ GeV

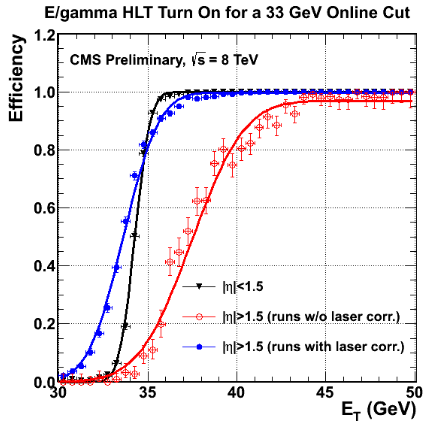
CMS (CMS-EXO-12-061)

ee channel

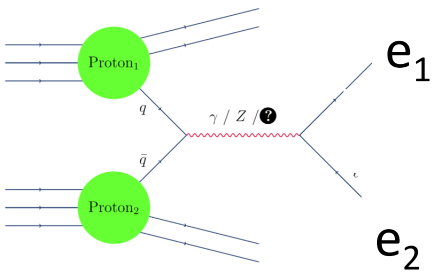
- Dielectron trigger
- Both clusters with $E_T > 33$ GeV

μμ channel

- single muon trigger
- $E_T > 40$ GeV



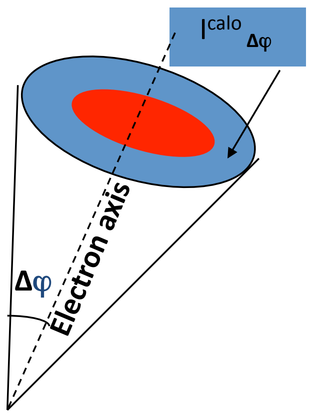
Dilepton Heavy Resonance : ee channel selection



ATLAS	CMS
$E_T^1 > 40$GeV $\|\eta\| < 2.47$	$E_T^1 > 35$GeV
$E_T^2 > 30$GeV $\|\eta\| < 2.47$	$E_T^2 > 35$GeV

Use isolation to reduce jets faking electrons

$I^{calo,\,trk}_{\Delta\varphi}$ = Sum of Transverse Energy or Transverse momentum in a cone $\Delta\varphi$ **minus** Transverse energy or Transverse Momentum of electron



	ATLAS	CMS
leading	$I^{calo}_{0.2} < 0.7\% \cdot E_T + 5$ GeV	$I^{tracker}_{0.3} < 5$ GeV
subleading	$I^{calo}_{0.2} < 2.2\% \cdot E_T + 6$ GeV	$I^{calo}_{0.3} < 3\% \cdot E_T$

Dilepton (Heavy) Resonance : μμ channel selection

ATLAS

- Single muon triggers
- $p_T > 25$ GeV
- $|\eta|<2.4$
- Suppress cosmic rays
  - $|d_0| < 0.2$ mm
  - $|z_0\text{-}z(\text{vertex})|<1$ mm
- Suppress jets faking μ's
  - $\sum p_T(\Delta R<0.3) < 5\%\cdot p_T$
- Require opposite charge

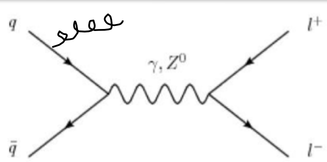
CMS

- Single muon trigger
- $p_T > 45$ GeV
- $|\eta|<2.4$
- Suppress cosmic rays
  $|d_0| < 0.2$ mm
  $|z_0\text{-}z(\text{vertex})|<24$ cm
- Suppress jets faking μ's
  - $\sum p_T(\Delta R<0.3) < 10\%\cdot p_T$
  - $|z_0\text{-}z(\text{vertex})|< 0.2$mm
- Require opposite charge

Dilepton Heavy Resonance : ee channel background

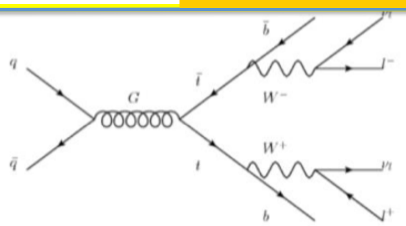
Dominant, from MC

2nd, contribution from data (matrix method)

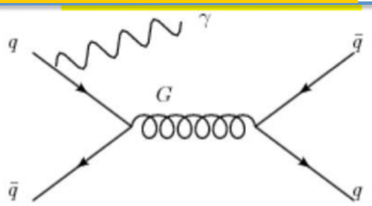


Z (+ jets) n

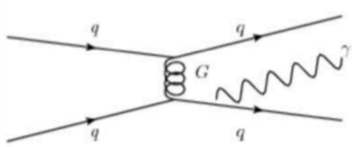
γγ non resonant



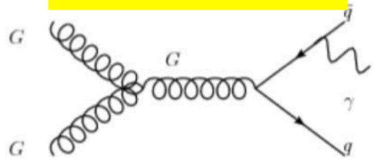
Top pairs semileptonic



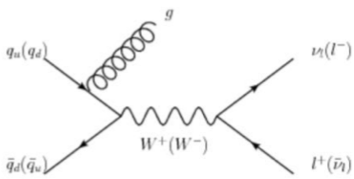
Dijets



Dijets



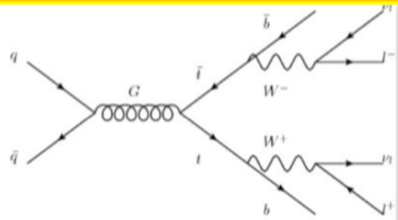
Dijets



W + jets

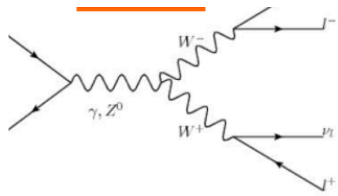
Dilepton (Heavy) Resonance : ee channel background

2nd, contribution from MC/Data

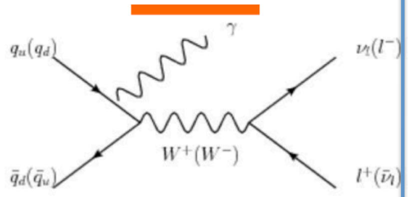


Top pairs leptonic

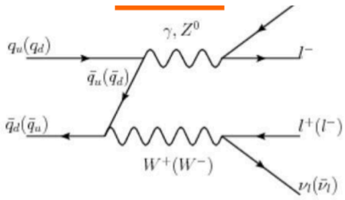
Dibosons : 3nd, contribution from MC



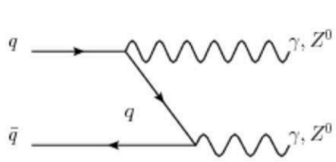
(b) WW



(c) Wγ

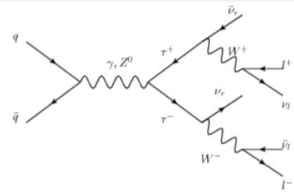


(d) WZ, Wγ



(e) ZZ,Zγ,γγ

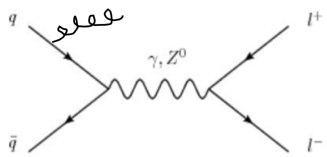
Small MC



Z → τ τ → e+ e- (+ jets)

Dilepton (Heavy) Resonance : μμ channel background

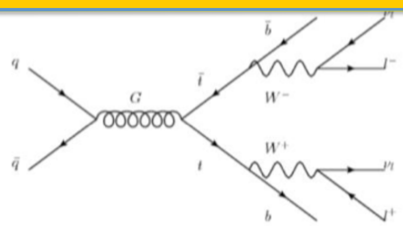
Dominant, from MC



Z (+ jets) n

γγ non resonant

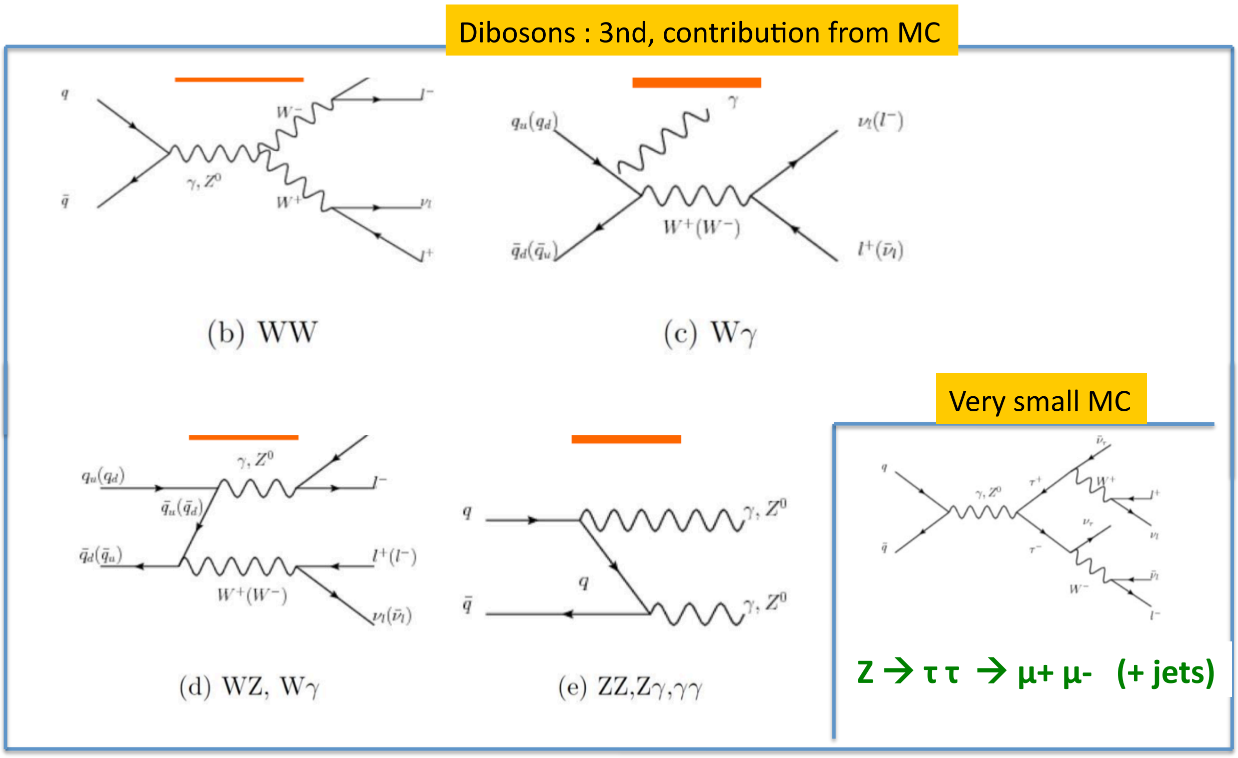
2nd, contribution from MC/Data



Top pairs leptonic

Dijets background is negligible

Dilepton (Heavy) Resonance : μμ channel background



Recap: Dilepton Heavy Resonance : background

- SM Drell-Yan: $\gamma^*/Z \to l^+l^-$
  - shape taken from Monte Carlo
  - normalisation taken from Z peak in data
- t-tbar:
  - where tt goes to e+e-, mu+mu-
  - est. from MC, cross-checked in data
  - also includes Z->ττ, WW, WZ
- Jet Background:
  - di-jet, W+jet events where the jets are misidentified as electrons/muons
- Cosmic Ray Background:
  - muons from cosmic rays
  - estimated <0.1 event after vertex and angular difference requirements

ee and μμ

ee

μμ

Dilepton Heavy Resonance : event yield

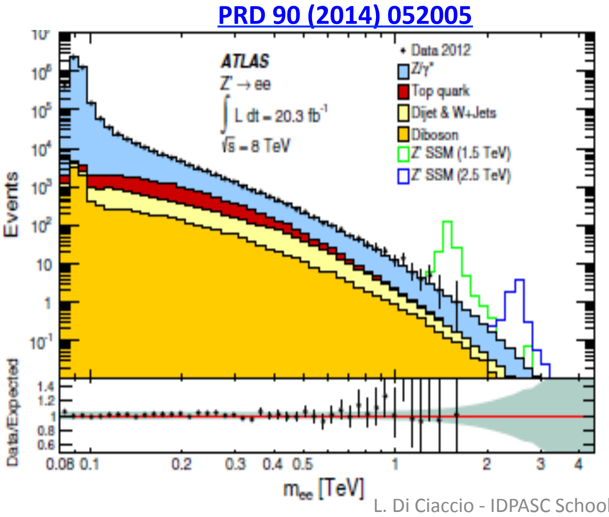
m_{ee} [GeV]	110–200	200–400	400–800	800–1200	1200–3000	3000–4500
Z/γ^*	122000 ± 7000	14000 ± 800	1320 ± 70	70 ± 5	10.0 ± 1.0	0.008 ± 0.004
Top	8200 ± 700	2900 ± 500	200 ± 80	3.1 ± 0.8	0.16 ± 0.08	< 0.001
Diboson	1880 ± 90	680 ± 40	94 ± 5	5.9 ± 0.4	1.03 ± 0.06	< 0.001
Dijet & W+jet	3900 ± 800	1290 ± 320	230 ± 70	9.0 ± 2.3	0.9 ± 0.5	0.002 ± 0.004
Total	136000 ± 7000	18800 ± 1000	1850 ± 120	88 ± 5	12.1 ± 1.1	0.011 ± 0.005
Observed	136200	18986	1862	99	9	0

$m_{\mu\mu}$[GeV]	110–200	200–400	400–800	800–1200	1200–3000	3000–4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.1	0.034 ± 0.022
Top	7100 ± 600	2300 ± 400	160 ± 80	3.0 ± 1.7	0.17 ± 0.15	< 0.001
Diboson	1530 ± 180	520 ± 130	64 ± 16	4.2 ± 2.1	0.69 ± 0.30	0.0024 ± 0.0019
Total	120000 ± 8000	13700 ± 1100	1180 ± 130	56 ± 6	8.2 ± 1.2	0.036 ± 0.023
Observed	120011	13479	1122	49	8	0

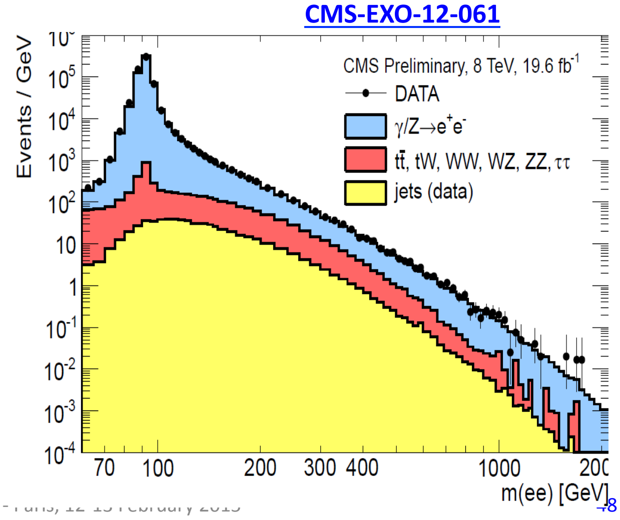
Heavy Resonance: dilepton channel

❖ Predicted by:
- ➢ Heavy gauge boson(s) Z'(W'): **GUT theories**
- ➢ Kaluza-Klein excitations: **Randall-Sundrum Extra-dimensions**

PRD 90 (2014) 052005



CMS-EXO-12-061



Dilepton (Heavy) Resonance : systematic uncertainties

N/A = not applicable

Source ($m_{\ell\ell} = 2$ TeV)	Dielectrons Signal	Dielectrons Backgr.	Dimuons Signal	Dimuons Backgr.
Normalization		N/A		N/A
PDF variation		11%		12%
PDF choice		7%		6%
α_s		3%		3%
Electroweak corr.		2%		3%
Photon-induced corr.		3%		3%
Beam energy		3%		3%
Resolution		< 3%		3%
Dijet and W + jets		5%		N/A
Total		15%		15%

Source ($m_{\ell\ell} = 3$ TeV)	Dielectrons Signal	Dielectrons Backgr.	Dimuons Signal	Dimuons Backgr.
Normalization		N/A		N/A
PDF variation		30%		17%
PDF choice		22%		12%
α_s		5%		4%
Electroweak corr.		4%		3%
Photon-induced corr.		6%		4%
Beam energy		5%		3%
Resolution		< 3%		8%
Dijet and W + jets		21%		N/A
Total		44%		23%

Shape (remember slide 21)

Dilepton (Heavy) Resonance : event yield

m_{ee} [GeV]	110–200	200–400	400–800	800–1200	1200–3000	3000–4500
Z/γ^*	122000 ± 7000	14000 ± 800	1320 ± 70	70 ± 5	10.0 ± 1.0	0.008 ± 0.004
Top	8200 ± 700	2900 ± 500	200 ± 80	3.1 ± 0.8	0.16 ± 0.08	< 0.001
Diboson	1880 ± 90	680 ± 40	94 ± 5	5.9 ± 0.4	1.03 ± 0.06	< 0.001
Dijet & W+jet	3900 ± 800	1290 ± 320	230 ± 70	9.0 ± 2.3	0.9 ± 0.5	0.002 ± 0.004
Total	136000 ± 7000	18800 ± 1000	1850 ± 120	88 ± 5	12.1 ± 1.1	0.011 ± 0.005
Observed	136200	18986	1862	99	9	0

$m_{\mu\mu}$ [GeV]	110–200	200–400	400–800	800–1200	1200–3000	3000–4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.1	0.034 ± 0.022
Top	7100 ± 600	2300 ± 400	160 ± 80	3.0 ± 1.7	0.17 ± 0.15	< 0.001
Diboson	1530 ± 180	520 ± 130	64 ± 16	4.2 ± 2.1	0.69 ± 0.30	0.0024 ± 0.0019
Total	120000 ± 8000	13700 ± 1100	1180 ± 130	56 ± 6	8.2 ± 1.2	0.036 ± 0.023
Observed	120011	13479	1122	49	8	0

Are the observed number consistent with background?

Are the observed number consistent with background?

Many way to answer → Statistics Lectures

- An experiment expects **49** events [from SM processes] and observes **56** events.
  - The observation is within "1σ" of the expectation. One in three experiments would do this. Not an observation.

The standard for discovery has been set (ad hoc) at "5σ" $p=2.9\times10^{-7}$

- **Question 1** : what does the observation of 56 events imply for all new physics processes?
  - An upper limit on the **number of observed events** from these processes
  - Thus, an **upper limit on their cross section**
  - Assuming we know the cross section as a function of some unknown parameter, e.g. the mass, a **lower limit on the mass**
- **Question 2:** what does the expectation of 49 events [from SM processes] imply ?
  - Same as before for the **number of expected events** [from SM processes]

Upper limit on the number of observed events

- If an experiment finds **0** candidate events, the "**95% CL upper limit on the average number of events**", **μ,** assuming a Poisson probability distribution function (pdf) is obtained by solving for **μ**

$$0.95 = \mathrm{CL} = \sum_{n=1}^{\infty} \frac{e^{-\mu}\mu^n}{n!} \qquad 1-\mathrm{CL} = 1-\sum_{n=1}^{\infty} \frac{e^{-\mu}\mu^n}{n!} = e^{-\mu}$$

Solve for **μ**

probability to observe **n > 0** events — probability to observe **0** events

$$\mu = -\ln(1-\mathrm{CL});\ \ \mathrm{CL}=0.95\ \ (0.90) \rightarrow \mu = 3.0\ \ (2.3)$$

- If N_D is the **number of events observed in data (s+b),** repeat the exercise

$$0.95 = \mathrm{CL} = \sum_{n=N_D+1}^{\infty} \frac{e^{-\mu}\mu^n}{n!} \qquad 1-\mathrm{CL} = \sum_{n=0}^{N_D} \frac{e^{-\mu}\mu^n}{n!}$$

Solve for **μ** and obtain

probability to observe **n >** N_D events

μ = $N^{upper\ limit}$

Acceptance, efficiency and upper limit on cross-section

"acceptance", α = fraction of events passing the kinematic (phase space)
Selection requirements, e.g. they have two electrons with p_T>25 GeV, |η|<2.4)

"efficiency", ε fraction of events within the acceptance that actually get reconstructed

Example:

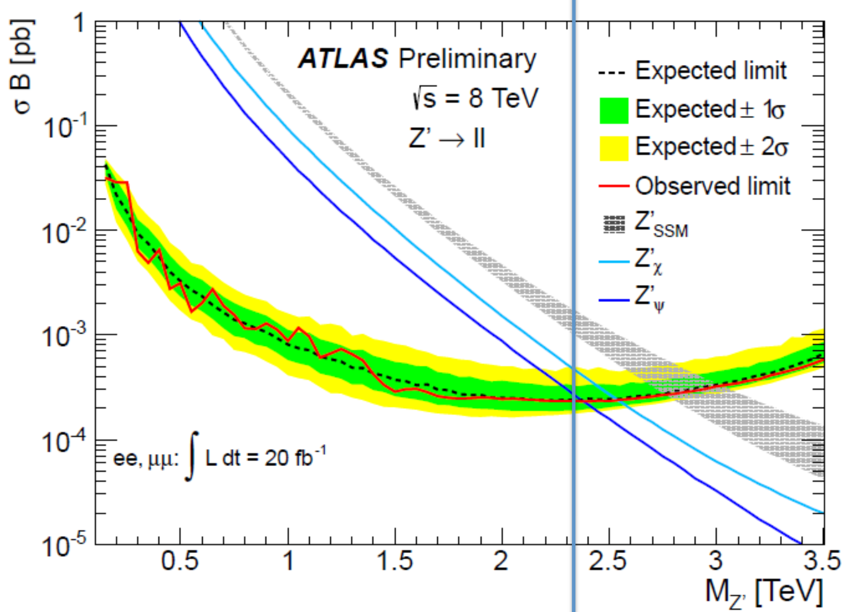
	ATLAS	CMS
ee channel	Axε(m = 2 TeV) = 73%	Axε(m = 2.5 TeV) = 67%

The **95% upper limit** on the cross section for the production of this new particle X

$$\sigma^{\text{upper limit}}(pp \to X) = \frac{N^{\text{upper limit}}}{\alpha\ \varepsilon\ L}$$

Example

Comparison with model prediction



Red line:

obained from data (N_D solving for **μ**)

Black dashed line:
obained from MC (N_{MC}, bkg only, solving for **μ**)

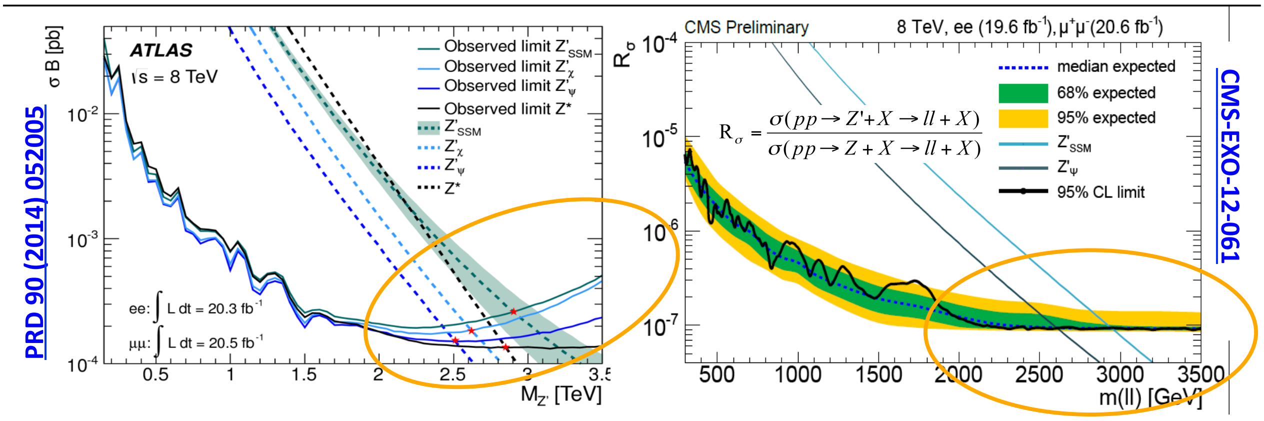
Blue and Grey:

Cross section calculations in a **given model**

σ model (Z'_χ) > measured limit
→ mass range is excluded

σ model (Z'_χ) < measured limit
cannot conclude

Heavy Resonance: dilepton channel



$$R_\sigma = \frac{\sigma(pp \to Z'+X \to ll+X)}{\sigma(pp \to Z+X \to ll+X)}$$

- ATLAS set limits on a Z' with the width (3% of mass), CMS sets limit on narrow Z'

Model	ATLAS (TeV)	CMS (TeV)
Z'_{SSM} (3% width)	2.90	2.96
Z'_{ψ} (0.5%) E6	2.51	2.60
Z'_{χ} (1.2%)	2.62	
RS G^* (k/M_{pl} =0.1)	2.68	
Z* (3.4%)	2.85	

Conclusions

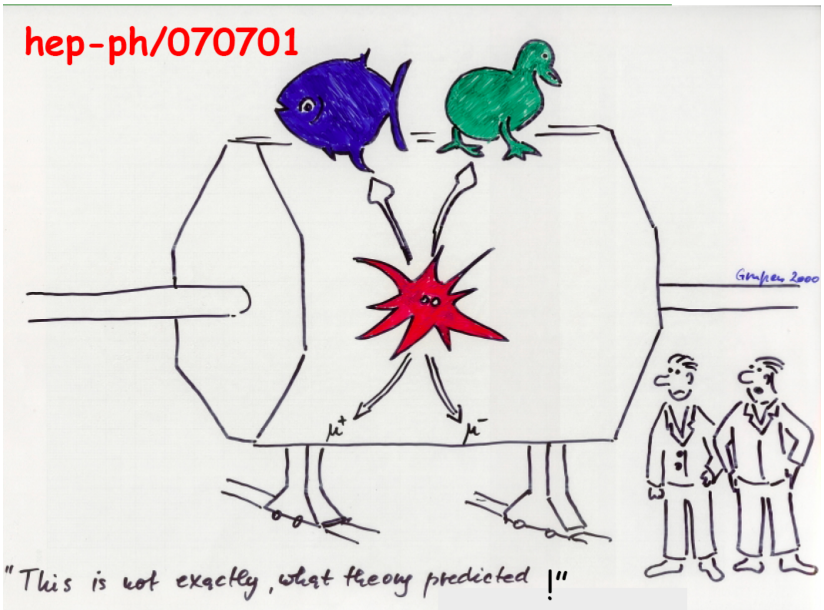
LHC is a discovery machine

To make discoveries one needs (5 ingredients, at least):

1) a well working accelerator and detector
2) understand the detector response
3) understand the SM (PDF and all that)

Nouvelle Physique ?

4) Guides from our friends theoreticians



5) A bit of luck

THE End of Lecture 1

Next lecture I'll talk about results