LHC Physics: machine, detectors and performance

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TAE 2019, Benasque

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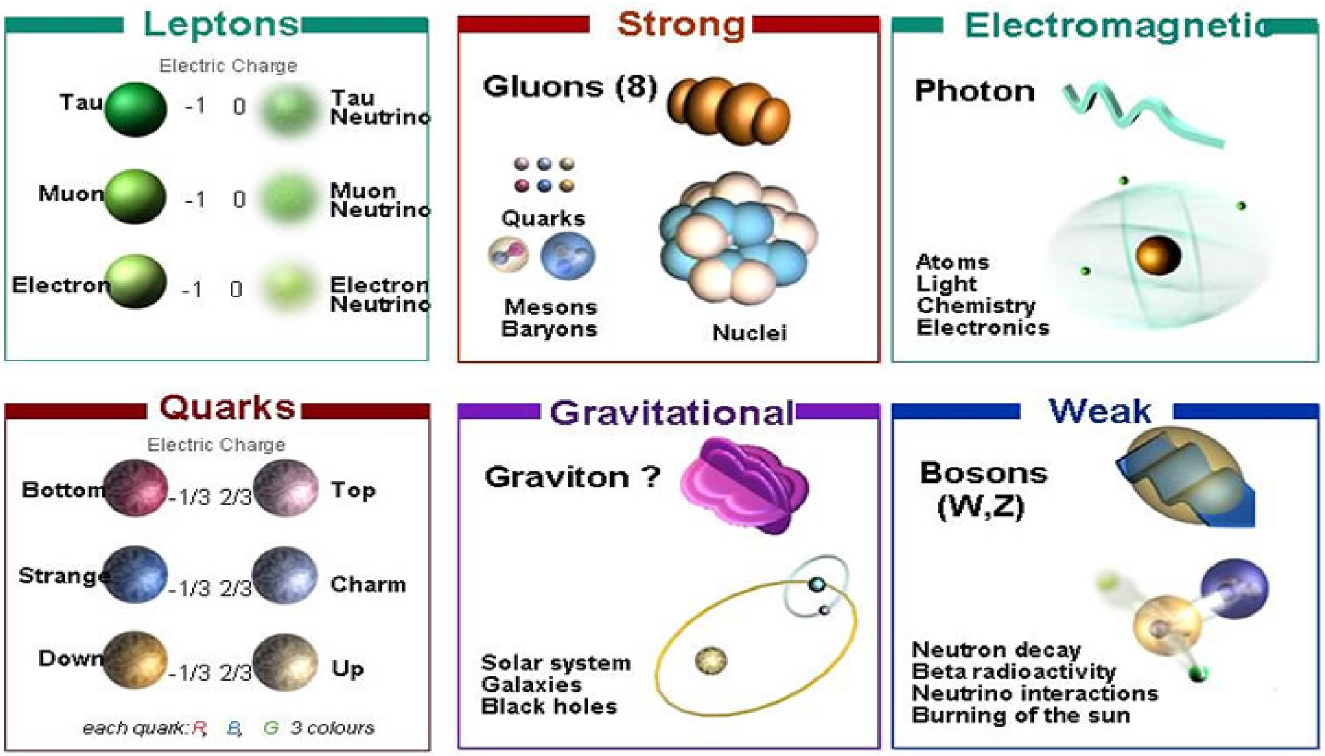
Disclaimer

- The LHC physics program program is huge
  - Many first-class projects embedded in just one experiment: searches for new physics at high and low scales, Higgs, top, electroweak, QCD studies, b-physics, heavy-ion physics, … Very difficult to cover everything in adequate detail in a few school lectures
  - Will have to be selective, excluding material from very interesting sectors, like heavy Ions or b/c quark physics (likely covered by other lectures in this school)
- Trying to be simple, focusing on specific topics
  - Better to explain a few key points, instead of giving too comprehensive talks
  - Tried to include references for all plots in the physics part (talks 2-4)
- I belong to the CMS Collaboration, so I may be a bit biased in the choice of figures to illustrate the different analyses
  - This does not mean in any way that the results of other experiments (and ATLAS in particular) are less important or relevant. Typically ATLAS and CMS reach similar results in most fronts

Outline

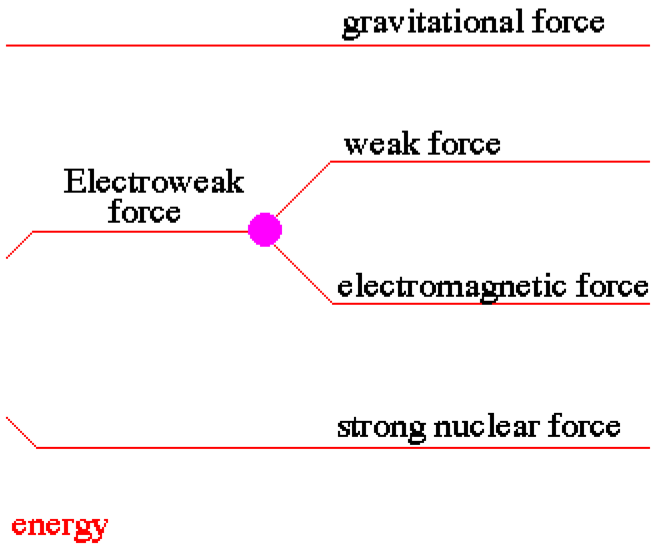
- **The LHC collider, detectors, environment**
  - **Introduction**
  - **The LHC**
  - **The LHC detectors**
  - **Performance and understanding of LHC detectors**

What we know experimentally



- Matter and interactions that manifest down to distances of order 10^{-3}-10^{-4} fm (~ $\hbar$ /(0.2-1 TeV))

Our theoretical understanding



?

Z,W$^{\pm}$

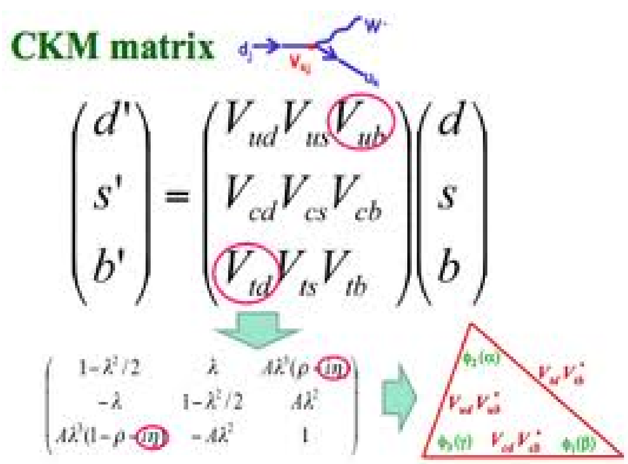
γ

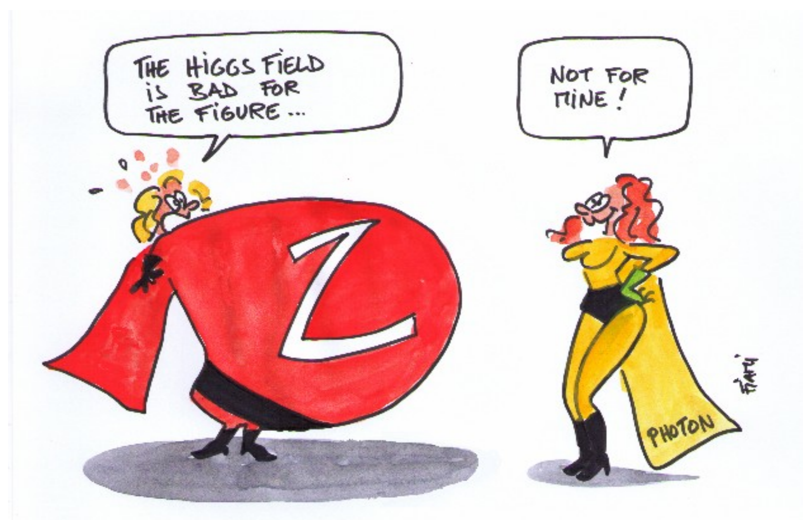
g

→ Electroweak unification

Strong force

SM





Experimental facts uncovered by the SM

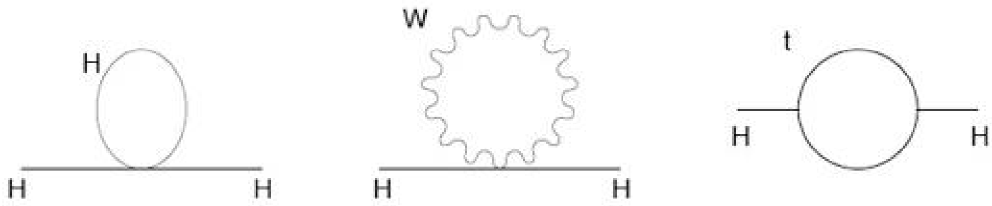
Higgs nature: fundamental, composite, ...

Not enough CP violation

What about dark matter?

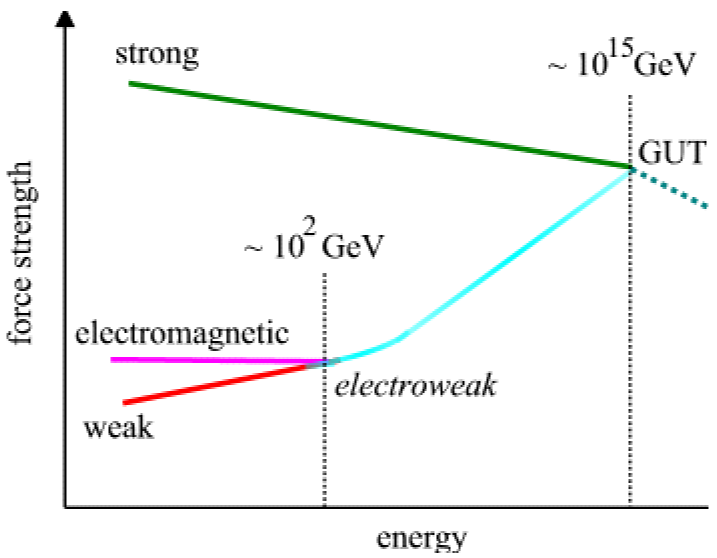
Origin of neutrino masses / oscillations

Theoretical issues raised by the SM



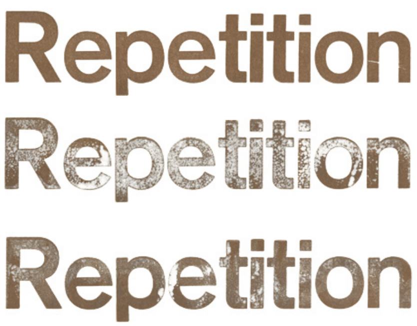
Hierarchy problem (m_H < 1 TeV looks like 'unnatural')

The SM does not even consider the gravitational force as part of the game



Strong interactions not really “unified” within the SM

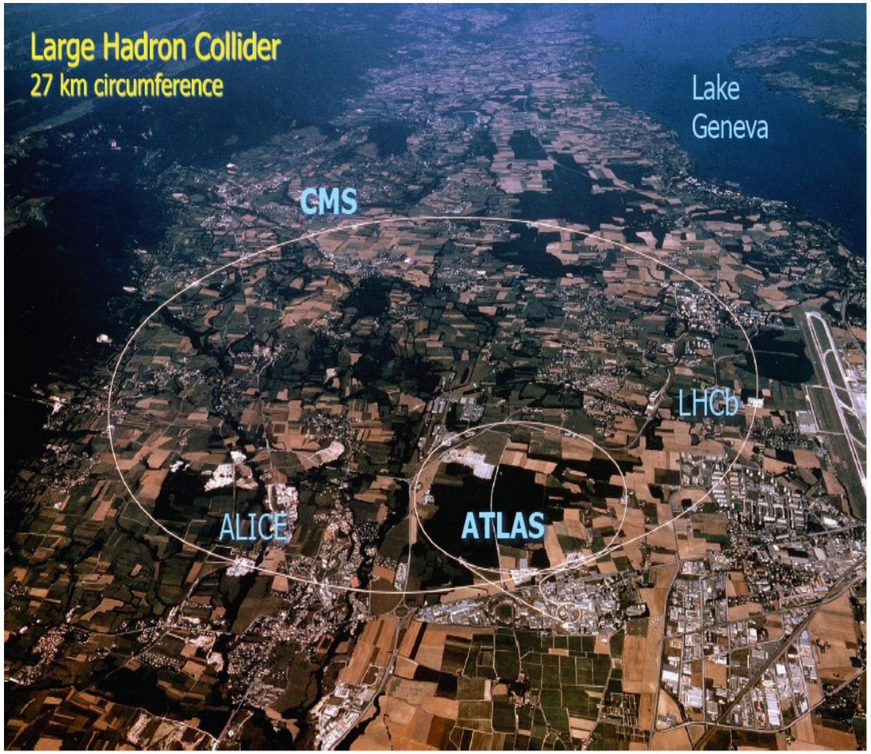
- Why several fermion families?
- Why three?
- Why so many parameters (19+7)?

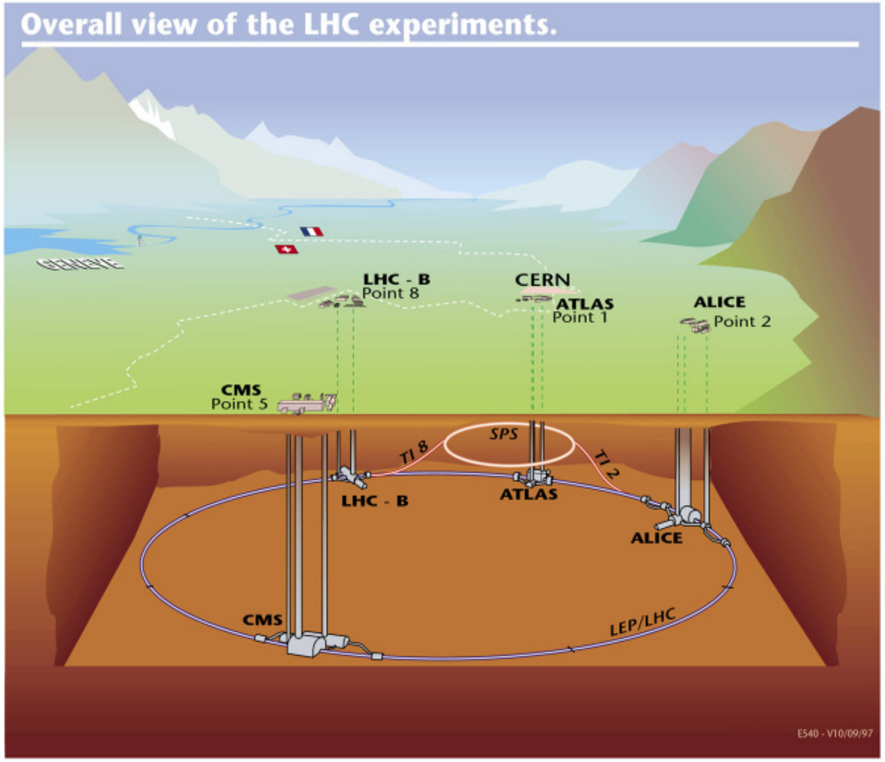


LHC @ CERN (Geneva)

- High luminosity hadron collisions at the highest energies (pp → $\sqrt{s}$=7,8,13 TeV):
  - 2 multi-purpose experiments (ATLAS,CMS)
  - 1 experiment dedicated to b/c quarks (CP violation; “multipurpose” in forward region)
  - 1 experiment dedicated to heavy-ion collisions (QCD at high density/temperature)

LHC objectives at highest energies





- Major first objective: discover the Higgs particle, **DONE!**
- Designed to look for generic new physics signals at the TeV scale:
  - High center-of-mass energy ($\gtrsim$1 TeV) in collisions between elementary constituents
- Precision physics, searching for deviations from the SM behavior:
  - Factory of W,Z, top and heavy quarks, …, and now Higgses

Luminosity, cross sections, ...

$$N = L\,\sigma$$

N: number of events for a given process (per time unit)

L: luminosity $\equiv$ number of proton encounters per time and area units

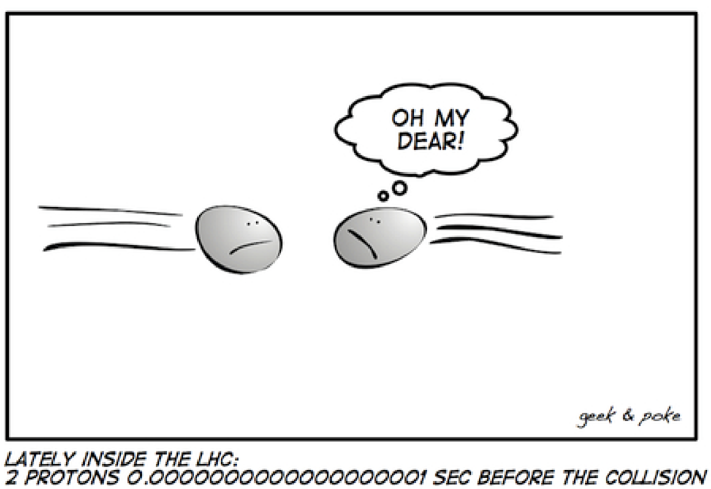
Typical units: [$cm^{-2}s^{-1}$]

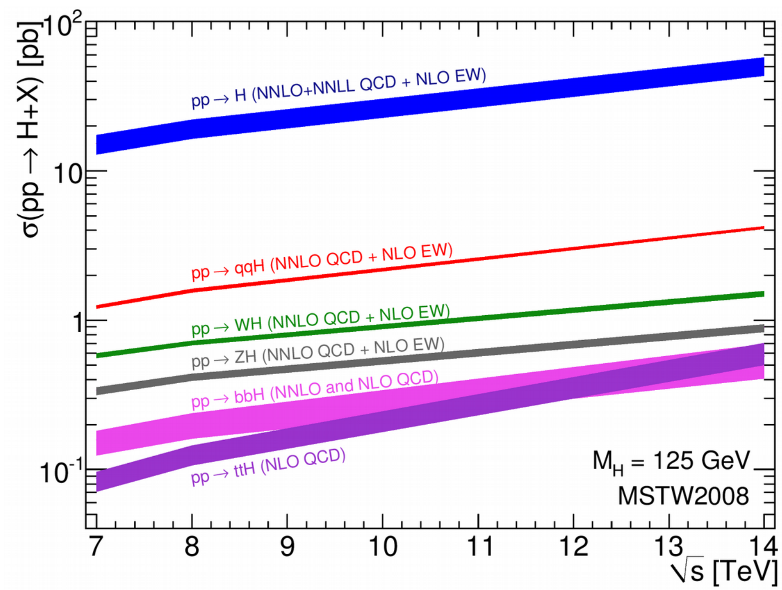
$\int$ (L dt): integrated luminosity

Typical units: [pb^{-1}], [fb^{-1}], ...

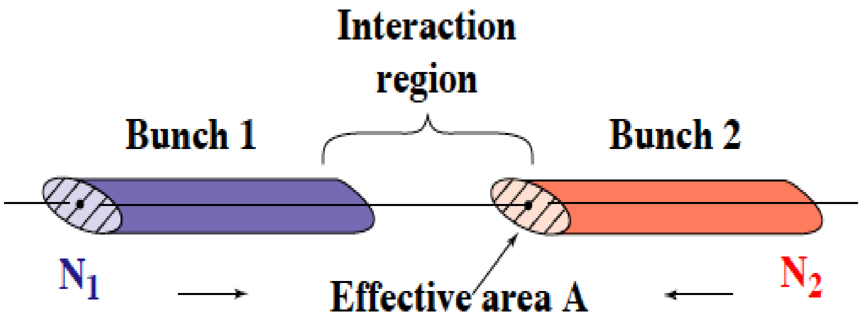
σ : cross section of the process (CALCULABLE FROM THEORY)

Some typical units: [mb], [nb], [pb], [fb], ...





Luminosity in head-on collisions

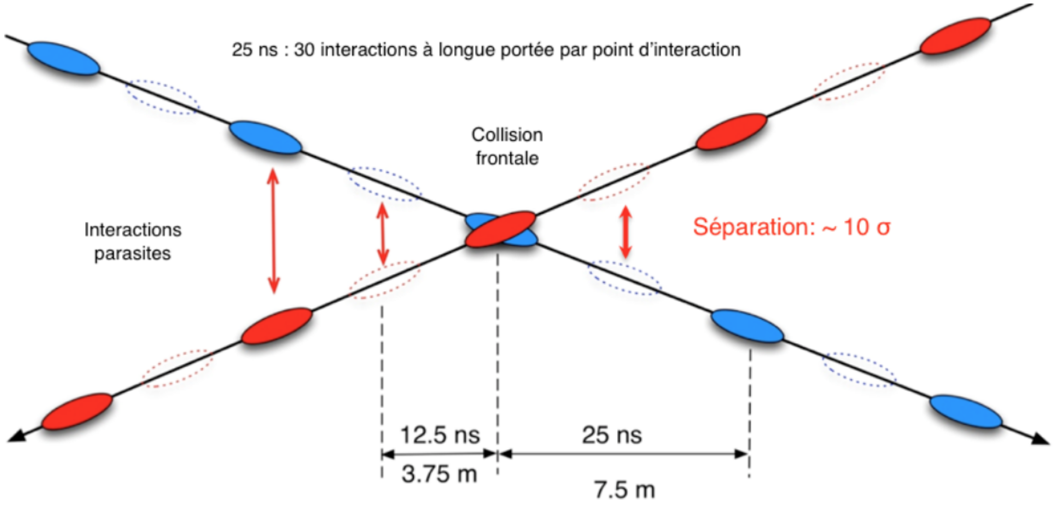


$$L = \frac{N_{pp}}{A} \equiv N_{pp} \int dx \int dy \, \rho_1(x,y) \rho_2(x,y)$$

N_{pp}: number of proton encounters per unit time
A: effective area of crossing

$\rho_{1,2}(x,y)$: transverse proton densities in beams 1,2 at point (x,y)

Luminosity in real life (crossing angle)



$$L = \left(n_b N^2 f F\right) \int dx \int dy \, \rho_1(x,y) \rho_2(x,y)$$

n_b : number of bunches

N : number of protons per bunch

f : beam frequency

F : geometrical factor due to crossing angle α ➜ $F = \left[1 + \left(\frac{\sigma_\parallel}{\sigma_\perp} \frac{\alpha}{2}\right)^2\right]^{-1/2}$

$\sigma_\perp$: transverse widths of beams (~20 microns at LHC)

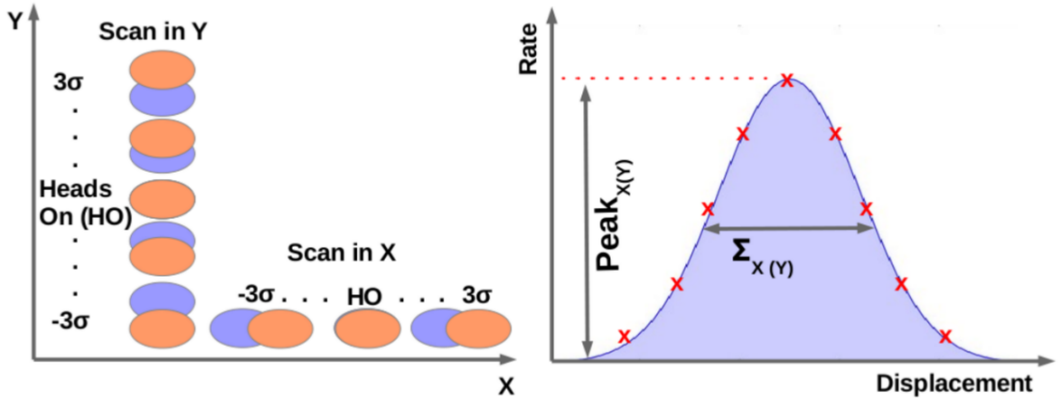
σ_z : longitudinal width of beam (~10 cm at LHC)

Measurement of luminosity

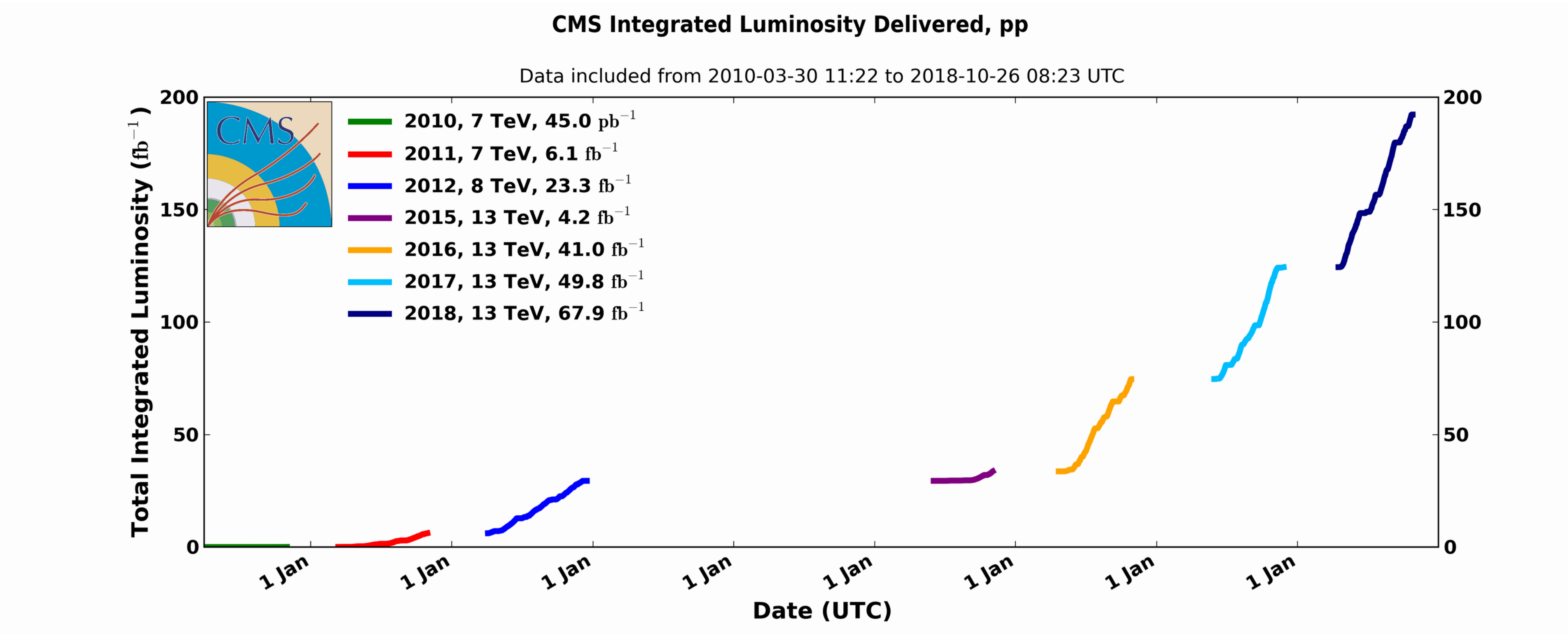
- One possibility is to measure a reference cross section very precisely known within the SM. Then: $L = N / \sigma_{ref}$
  - This is the method employed in ee colliders (ee scattering at low Q^2 (forward regions, precision < 1%) or in past hadron colliders (forward/minmum bias events, typical precisions ≈10%)
- At LHC, the best precision is obtained by measuring directly beam currents and the effective area vis relative transverse displacement of the beams, the so-called "Van-der-Meer scans":
  - **(Current) precision ≈2%**

$$L = \frac{n_b N^2 f F}{4\pi \sigma_x \sigma_y} \rightarrow (n_b N^2 f F) \int dx \int dy \, \rho_1(x,y) \rho_2(x,y)$$

$\rho_{1,2}(x,y)$: beam densities



LHC delivered luminosities



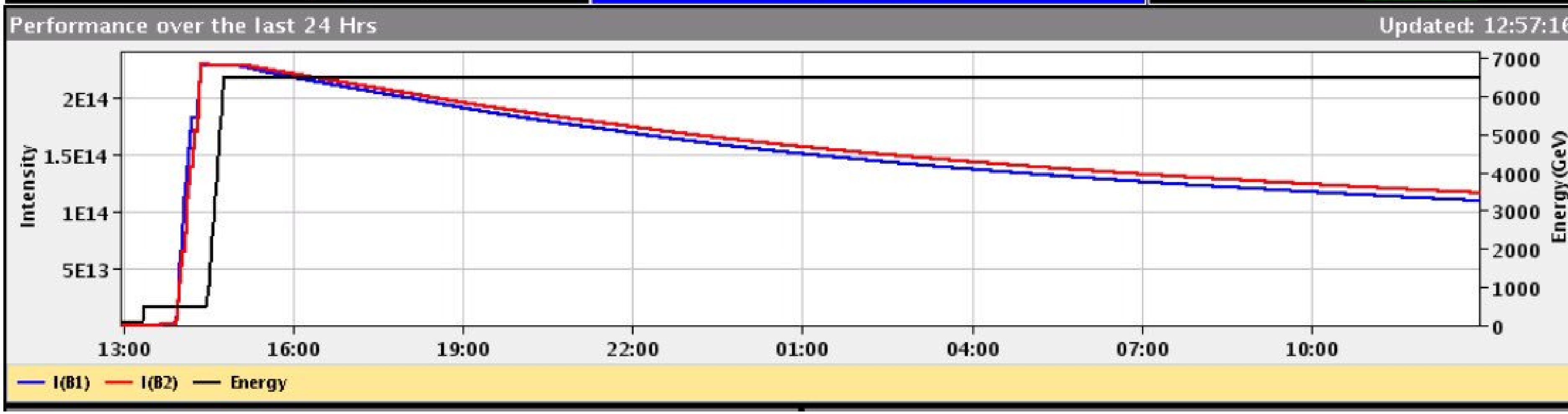
- $\approx$5 fb^{-1} "collected and validated" at $\sqrt{s}$=7 TeV
- $\approx$20 fb^{-1} "collected and validated" at $\sqrt{s}$=8 TeV
- $\approx$140 fb^{-1} "recorded and validated" at $\sqrt{s}$=13 TeV

Last LHC fill in Run2

10-Nov-2017 12:57:17 Fill #: 6371 Energy: 6499 GeV I(B1): 1.09e+14 I(B2): 1.16e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	NOT_READY	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	3965.888	2.556	3921.101	325.501
BRAN Luminosity [(ub.s)^-1]	3854.5	2.3	4095.6	184.4
Fill Luminosity (nb)^-1	677024.688	201.846	663571.938	25885.467
Beam 1 BKGD	0.231	0.331	1.429	0.000
Beam 2 BKGD	2.715	0.005	1.787	0.002

LHCb VELO Position IN Gap: -0.0 mm STABLE BEAMS TOTEM: PHYSICS



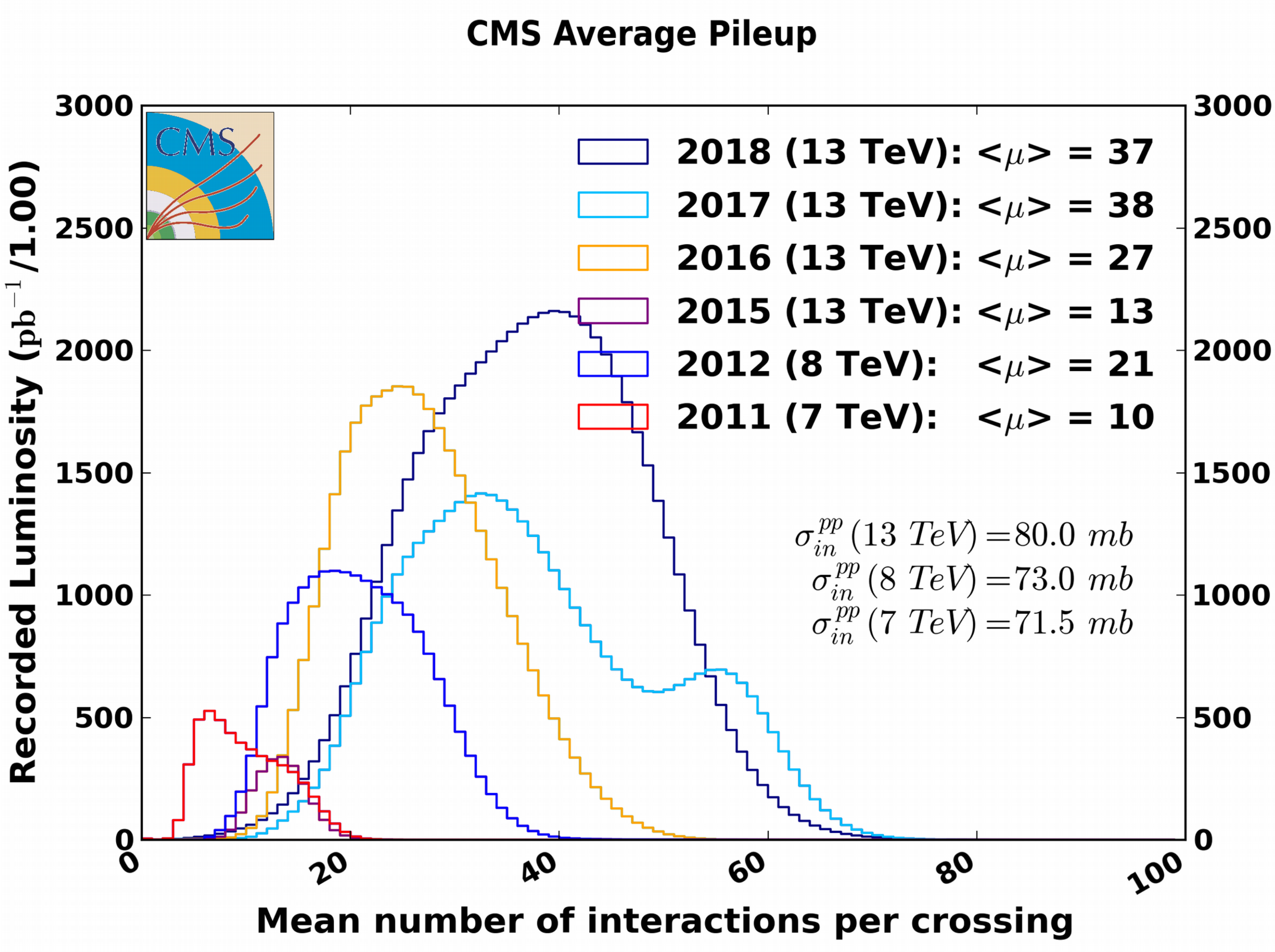
- ≈0.7 fb^{-1} delivered to both ATLAS and CMS in this last fill
- Luminosity at beginning of fill ≈ (2*2)*4000 $(\mu b.s)^{-1}$ ≈ 2×10^{34} $(cm^2.s)^{-1}$

Some relevant rates at LHC

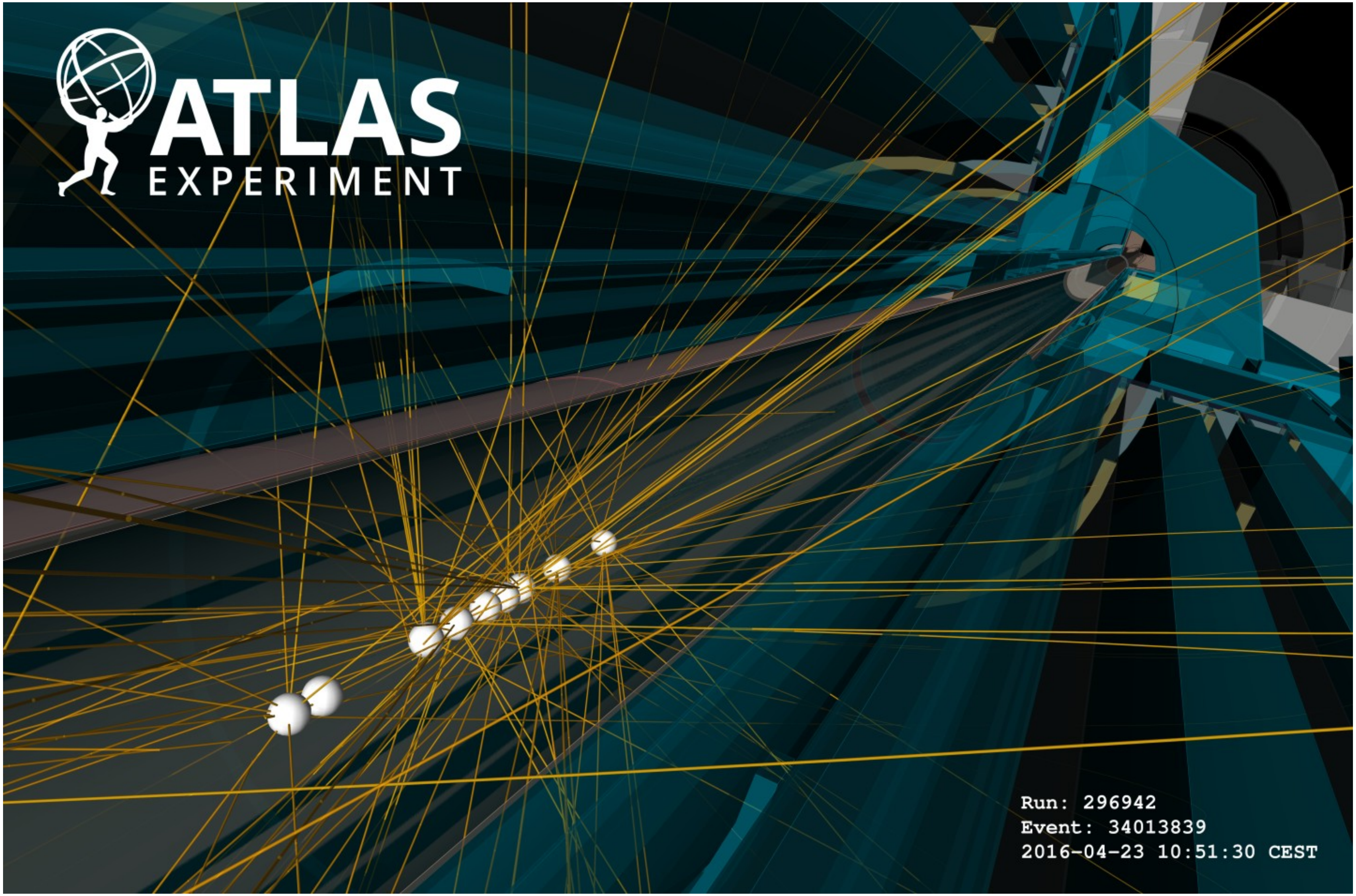
- Nominal instantaneous LHC luminosity (we already reached twice that) is 10^{34} $cm^{-2}s^{-1}$:

  - 10^{34} cm^{-2} = 10 nb^{-1} and the ttbar cross section at $\sqrt{s}$=13 TeV is ≈1 nb:
    - ≈ 10 #$t\bar{t}$ / second at nominal LHC !!
  - The total Higgs cross section at $\sqrt{s}$=13 TeV is ≈50 pb:
    - ≈ 0.5 #H / second at nominal LHC !!
  - The total inelastic cross section at $\sqrt{s}$=13 TeV is ≈80 mb; time between bunches is 25 ns:
    - Rate of "recordable" collisions ≈800 MHz at nominal LHC !!
    - #visible collisions per bunch crossing ≈800 MHz * 0.025 μs = 20 events !!

'Pileup'


CMS Average Pileup
2018 (13 TeV): <μ> = 37
2017 (13 TeV): <μ> = 38
2016 (13 TeV): <μ> = 27
2015 (13 TeV): <μ> = 13
2012 (8 TeV): <μ> = 21
2011 (7 TeV): <μ> = 10
$\sigma_{in}^{pp}(13\ TeV) = 80.0\ mb$
$\sigma_{in}^{pp}(8\ TeV) = 73.0\ mb$
$\sigma_{in}^{pp}(7\ TeV) = 71.5\ mb$
Recorded Luminosity (pb^{-1}/1.00)
Mean number of interactions per crossing
0
500
1000
1500
2000
2500
3000
0
20
40
60
80
100

‘Pileup’


ATLAS
EXPERIMENT
Run: 296942
Event: 34013839
2016-04-23 10:51:30 CEST

Trigger systems

Triggering

- We can not register all the necessary information of all events from all crossings: 1/25 ns = 40 million of crossings/second = 40 MHz !!
  - Neiher time to receive all the signals, nor time to build the event, nor time to reset the detector for the next crossing.
  - So we have to be clever and choose only the “relevant” crossings for physics (usually this implies rejecting a large fraction of events with low visible activity: “minimum bias”)

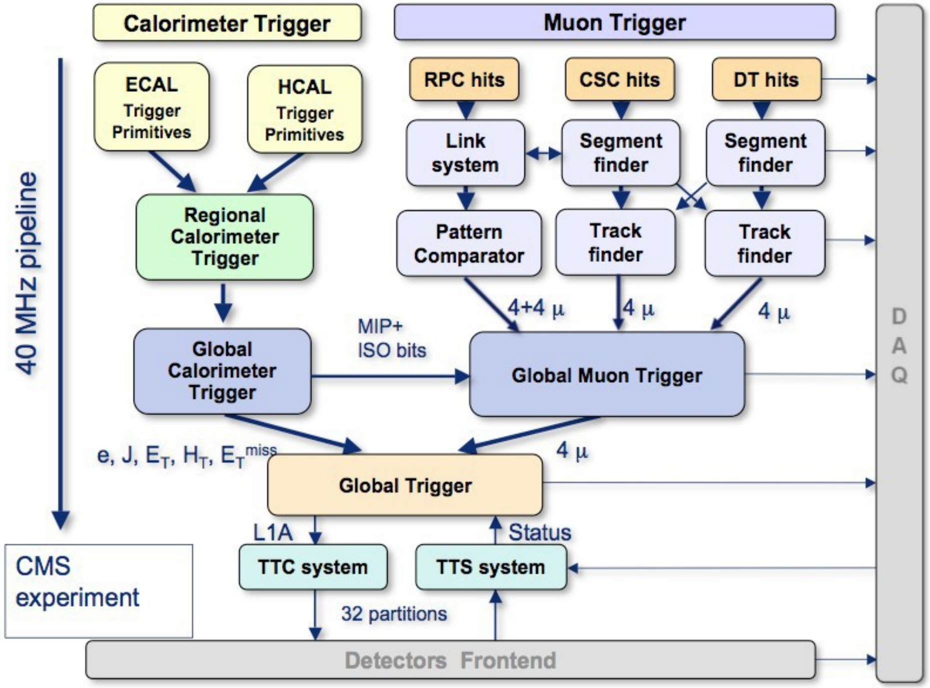
- This is done by trigger systems that decide whether signals around the bunch collision time should be recorded or not:
  - There is always a 'Level-1' trigger implemented via custom hardware processors near the detector. It picks up only part of the full raw event information.
  - Later, there are higher level triggers, either of hardware type (but using more information: Level-2 of ATLAS) or of software type (using the full event information and standard computer CPUs: HLT).

- Which are the constraints?
  - What matters is what is called 'throughput' (bytes/second), ~ 0.1-1 GByte/s; in practice, for typical event sizes (1 MB/event, like those of ATLAS/CMS), one can not record more than ≈1000 events/second (≈1 GB/second)
  - Also Level-1 triggers get stuck for output rates > 0.1-1 GHz or so

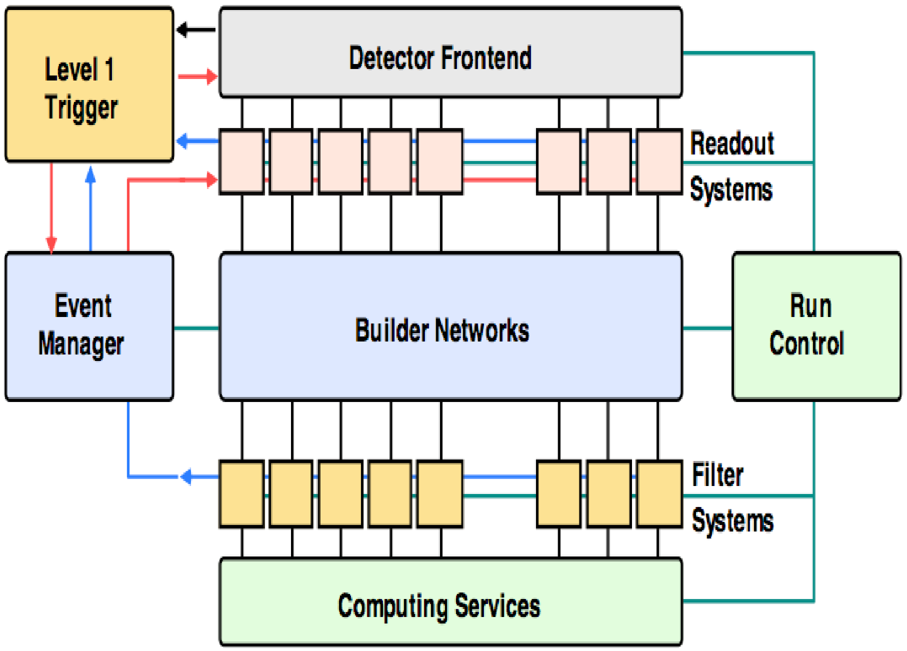
Triggering well is critical

- Level-1 systems should reduce the rate from 40 MHz to ≈100 kHz, and higher levels down to ≈1 kHz. This is critical and challenging (numbers refer to Phase 1 LHC):
  - At Level-1 this is due to the limited precision of the available information
    - ≈4 ms to make a decision
  - At higher levels, where more information is available, time is nevertheless more limited
    - ≈100 ms to make a decision

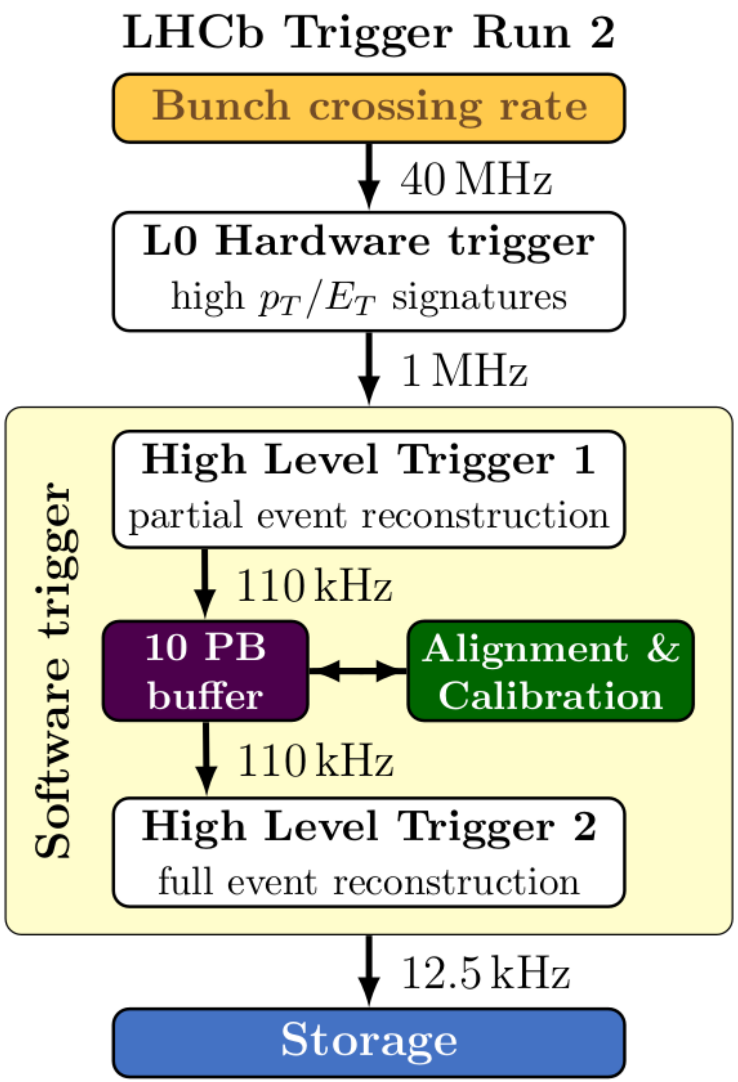
CMS Level-1 (Run 1)



CMS HLT



LHCb trigger system (Run 2)

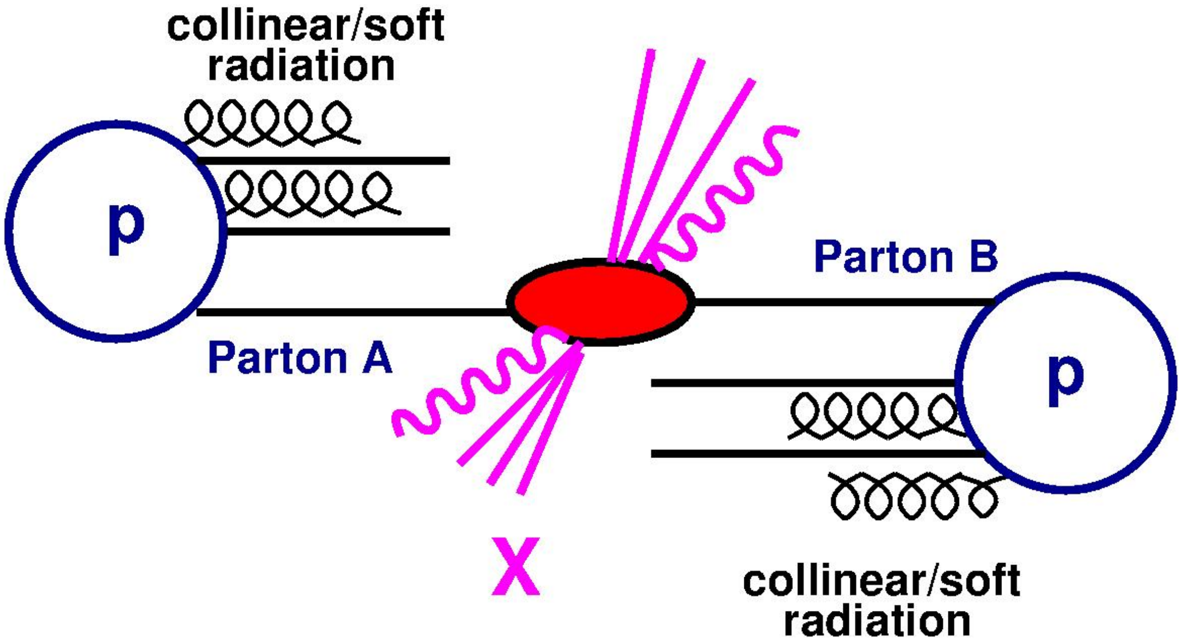


- LHCb is also structured in two trigger levels (L0 and HLT). Event rate is ≈10 times higher than at ATLAS/CMS:
  - L0 output rate ≈1 MHz
  - Final output rate is 12.5 kHz
- Note that the technical differences with respect to ATLAS and CMS are anyway not so big,. What matters is not the event rate, but the throughput rate (MB/s):
  - Event size ≈10 times smaller at LHCb

Physics at LHC and back-of-the envelope calculations

Describing physics at the LHC

Hard scattering process



Factorization:

$$\sigma\left(pp\to X;Q^2\right)=\sum_{A,B}\int dx_A\int dx_B\, pdf_{p\to j}\left(x_A,Q^2\right)\ pdf_{p\to B}\left(x_B,Q^2\right)\ \sigma\left(AB\to X;Q^2\right)$$

$pdf_{p\to C}\left(x_C;Q_0^2\right)$ *from experiment, evolution with* Q^2 *according to QCD*

$\sigma\left(AB\to X;Q^2\right)$ *calculable from theory*

Cross sections and parton luminosities

- For a process AB→X, the hard interaction scale is $\hat{s} = x_{partonA}\, x_{partonB}\, s$, and we can rewrite the expression as:

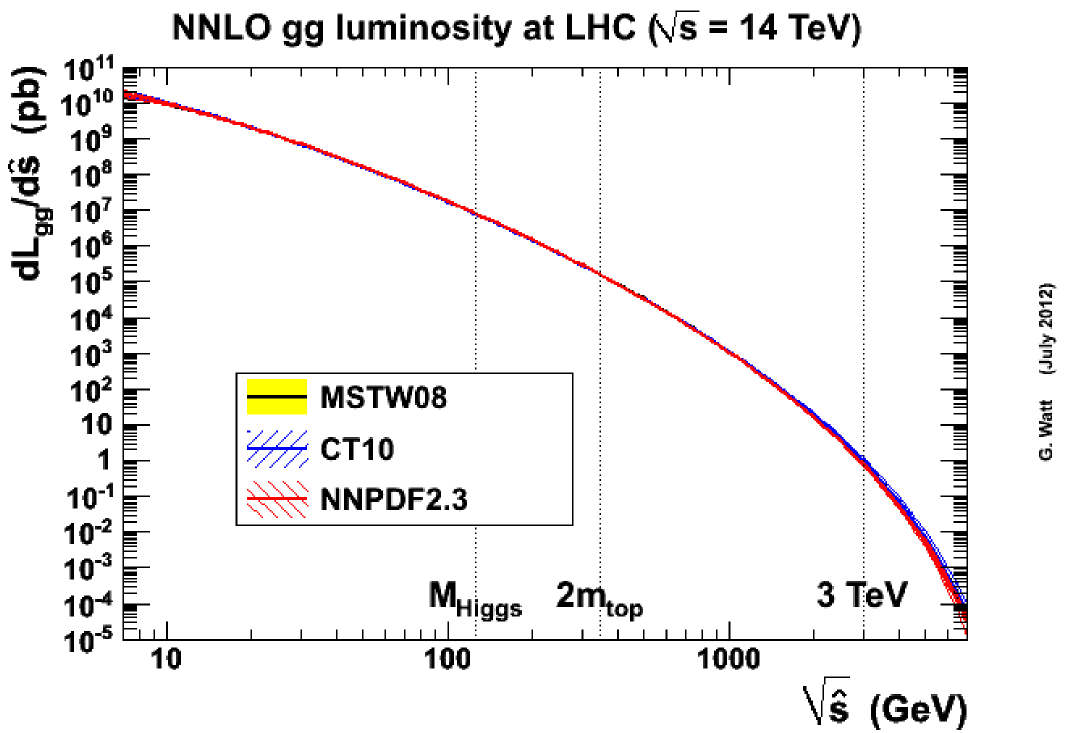
$$\sigma(pp \to X) = \sum_{A,B} \int d\hat{s}\, \frac{dL_{AB}}{d\hat{s}}\, \sigma(AB \to X)$$

$$where\ \frac{dL_{AB}}{d\hat{s}}(\hat{s}) = \frac{1}{1+\delta_{AB}} \int_{\frac{\hat{s}}{s}}^{1} \frac{dx}{sx}\, pdf_{p\to A}(x, Q^2)\, pdf_{p\to B}\left(\frac{\hat{s}}{sx}, Q^2\right)$$

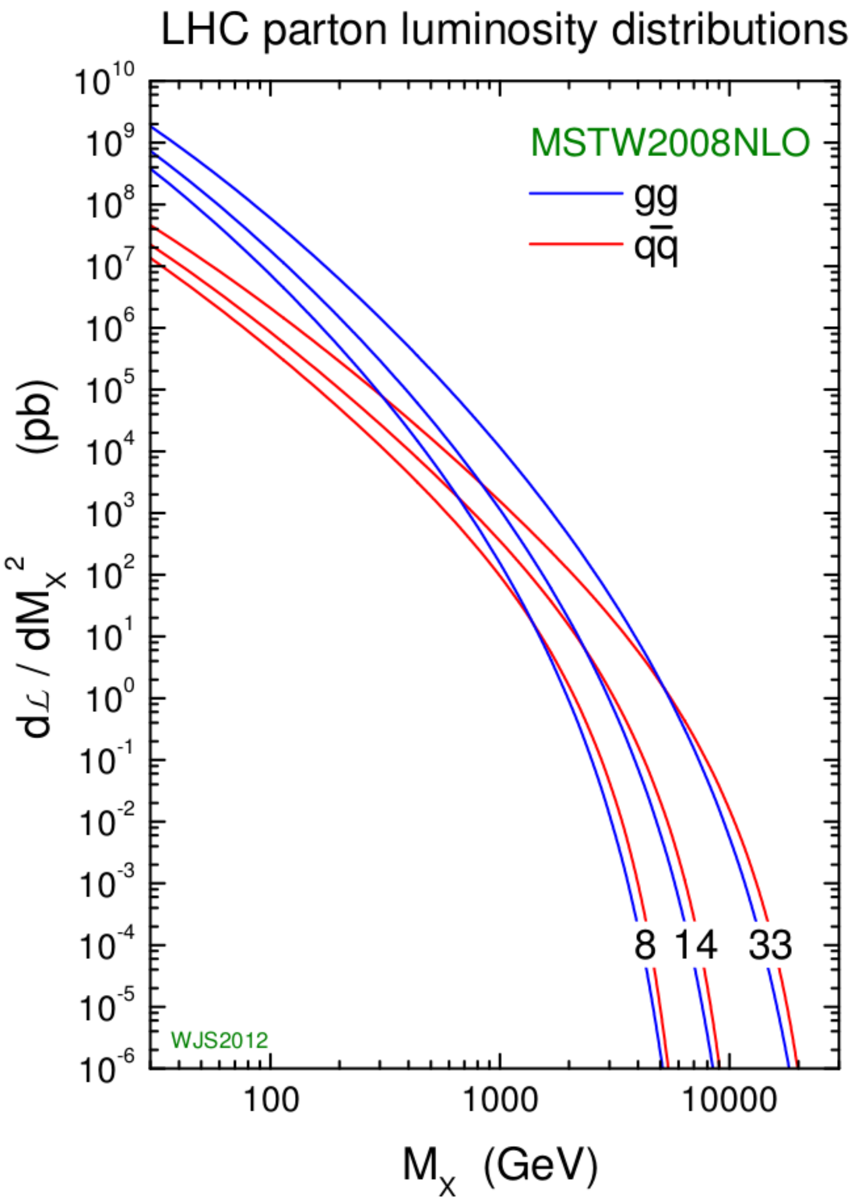
$[dL_{AB}/dM^2](M)$ is the 'parton luminosity function' at the mass M.

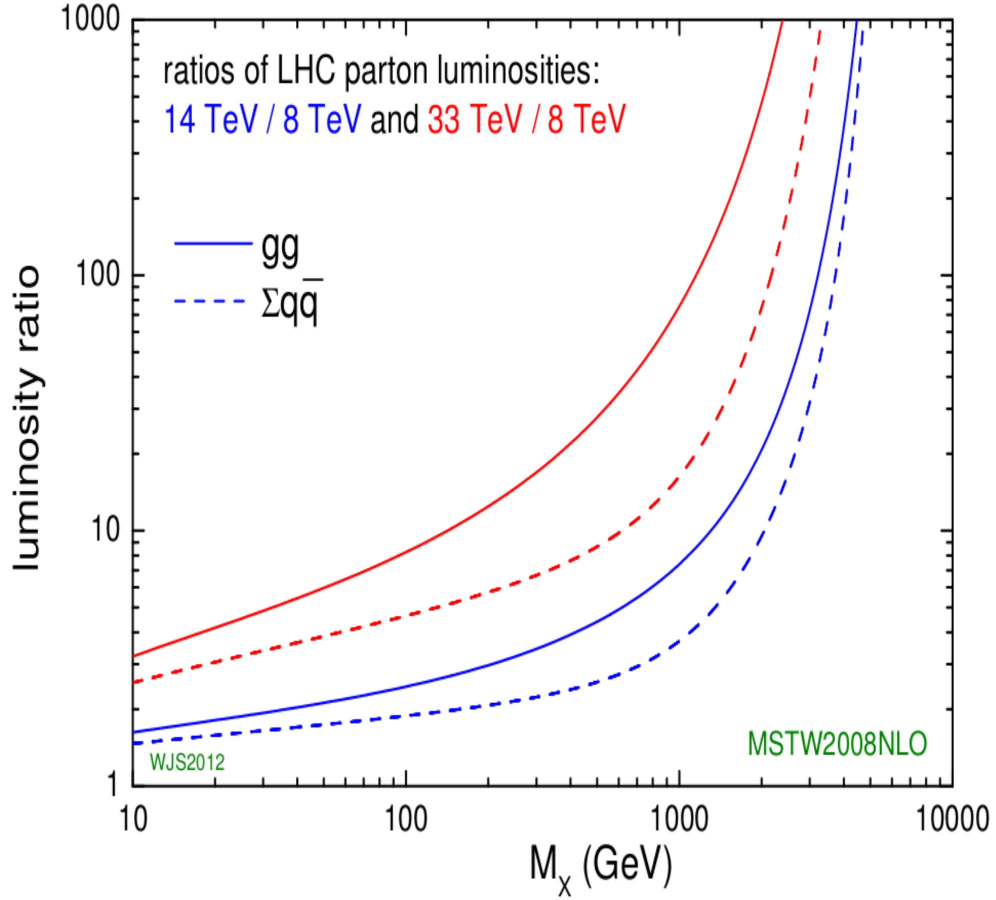
This plot allows back-of-the-envelop estimates of cross sections at a hadron collider

Note that both σ and PDFs can be given to higher QCD precision (NNLO in this example)



Parton Luminosity functions and ratios



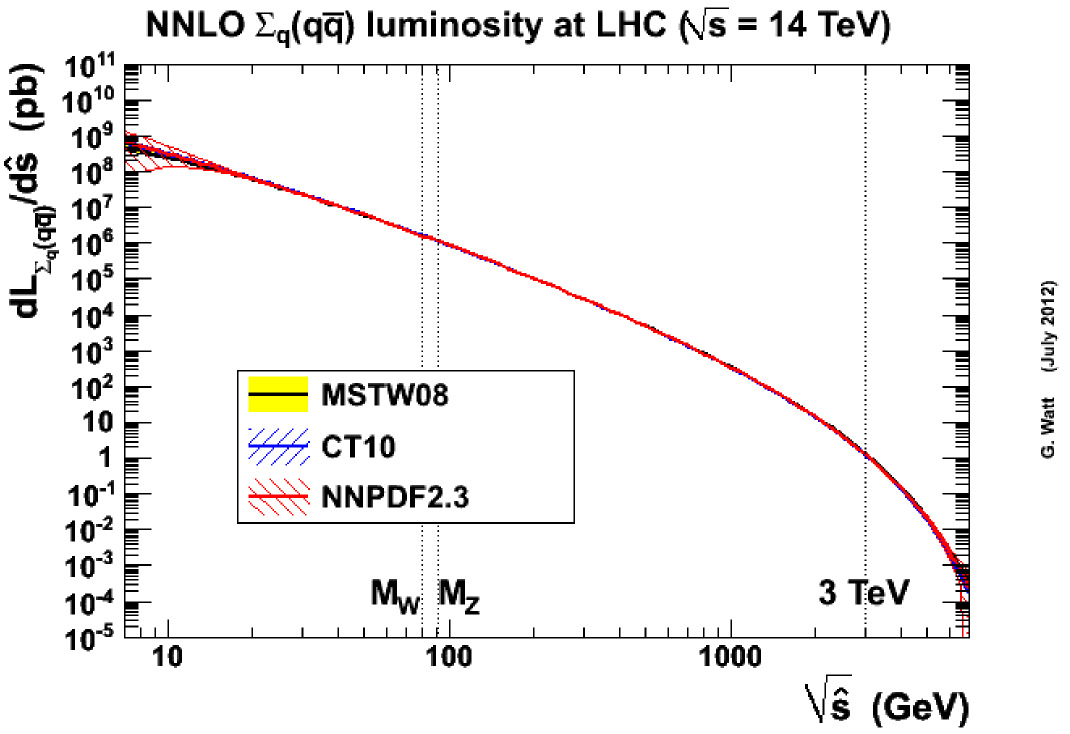


What do we expect for a narrow resonance?

- If we ntegrate its Breit-Wigner shape:

$$\sigma(pp\to X)=\sum_{A,B}\int d\hat{s}\left[\frac{dL_{AB}}{d\hat{s}}\ \sigma(AB\to X)\right](\hat{s})\to$$

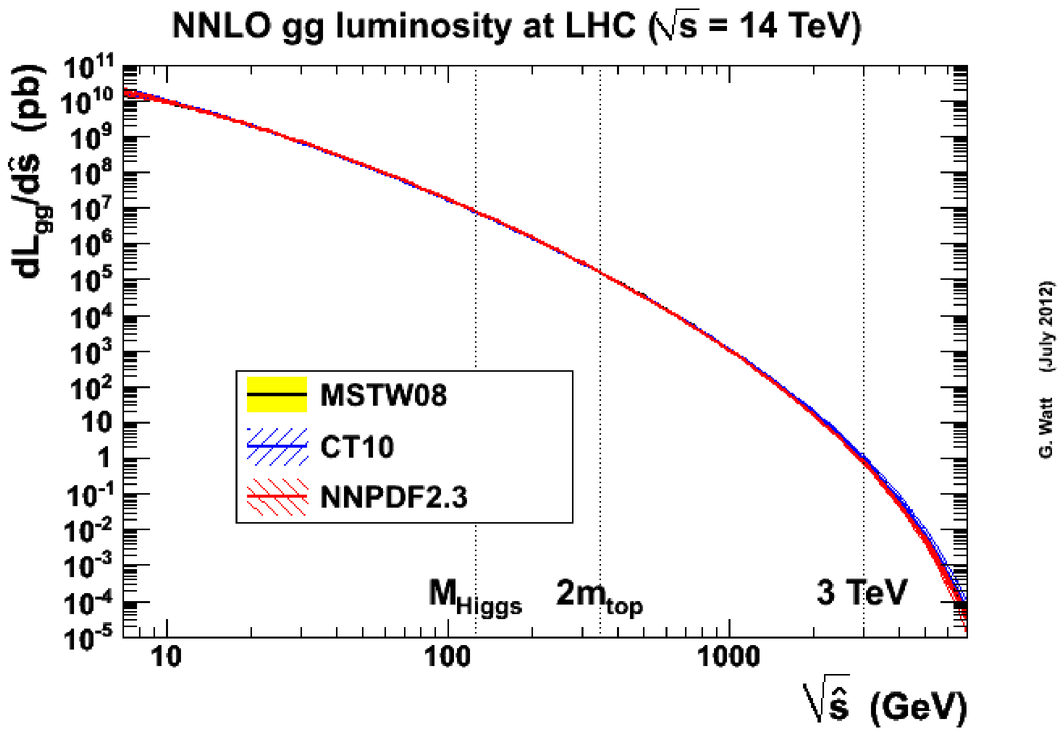
$$\sigma(pp\to X)\approx\sum_{A,B}\left[\frac{dL_{AB}}{d\hat{s}}\ M\Gamma\sigma(AB\to X)\right]_{\hat{s}=M^2}$$



What do we expect for a narrow resonance?

- If X is a narrow resonance of spin J, coupling to gluons, with width/mass ratio Γ/M:

$$\sigma\left(pp \rightarrow X\right) \approx \frac{dL_{gg}}{d\hat{s}}\left(\hat{s}=M^2\right)\ \left(2J+1\right)\frac{\pi^2}{8}\frac{\Gamma}{M}Br\left(X \rightarrow gg\right)$$



For the SM Higgs boson:

- **M≈125 GeV**
- **Γ≈4 MeV**
- **Br(H→gg) ≈ 10%**
- **(dL/ds)≈10^7 pb**

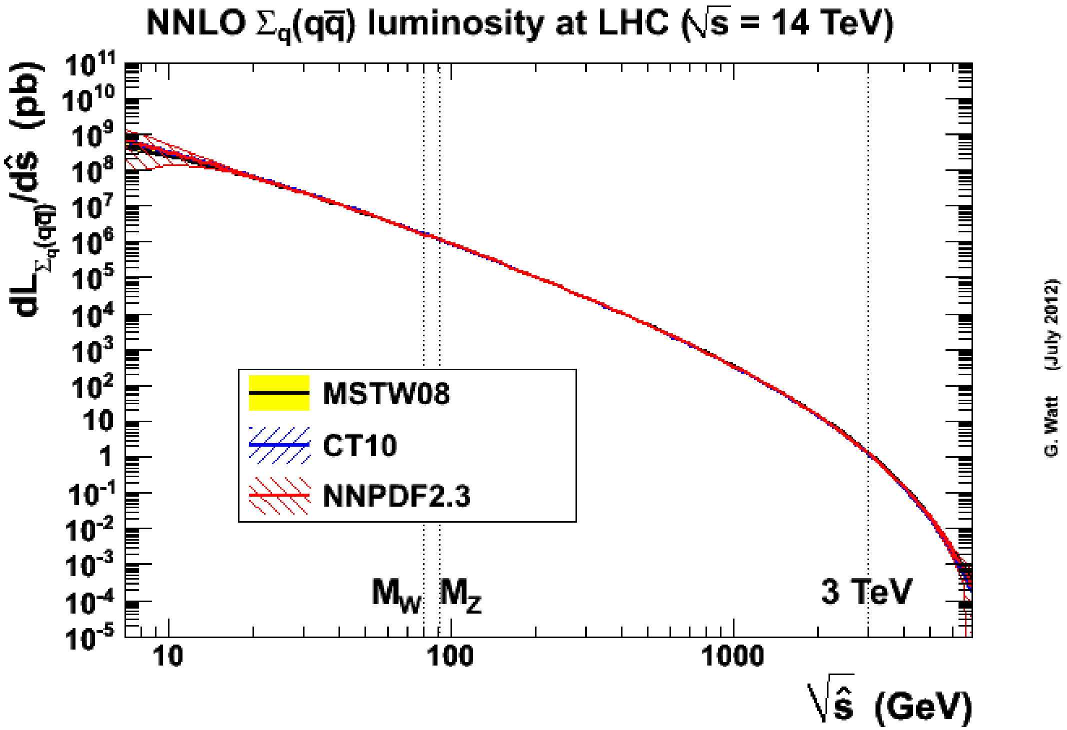
→σ(pp→H)~40 pb

(≈55 pb from precise calculations)

What do we expect for a narrow resonance?

- If X is a narrow resonance of spin J, coupling to quarks, with width/mass ratio Γ/M:

$$\sigma(pp \to X) \approx \frac{dL_{\sum_q (q\bar{q})}}{d\hat{s}}(\hat{s}=M^2)\ (2J+1)\frac{4\pi^2}{3}\frac{\Gamma}{M}Br(X\to q\overline{q'})$$



For the W boson:

- **$M \approx 80.4$ GeV**
- **$\Gamma \approx 2.1$ GeV**
- **$Br(W \to ud) \approx 1/3$**
- **$(dL/ds) \approx 2\times106$ pb**

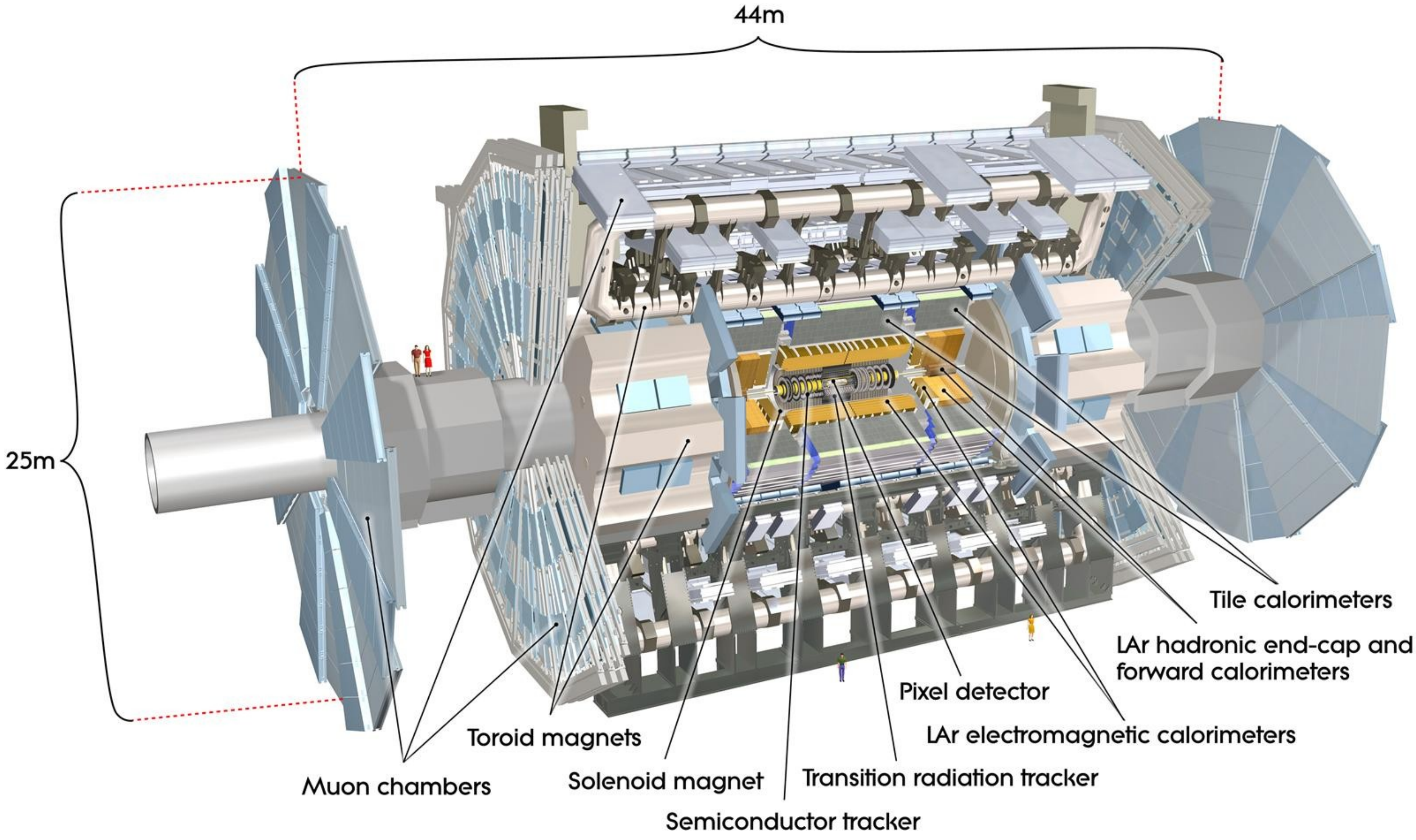
$\to \sigma(pp \to W) \sim 230$ nb

(≈190 nb from precise calculations)

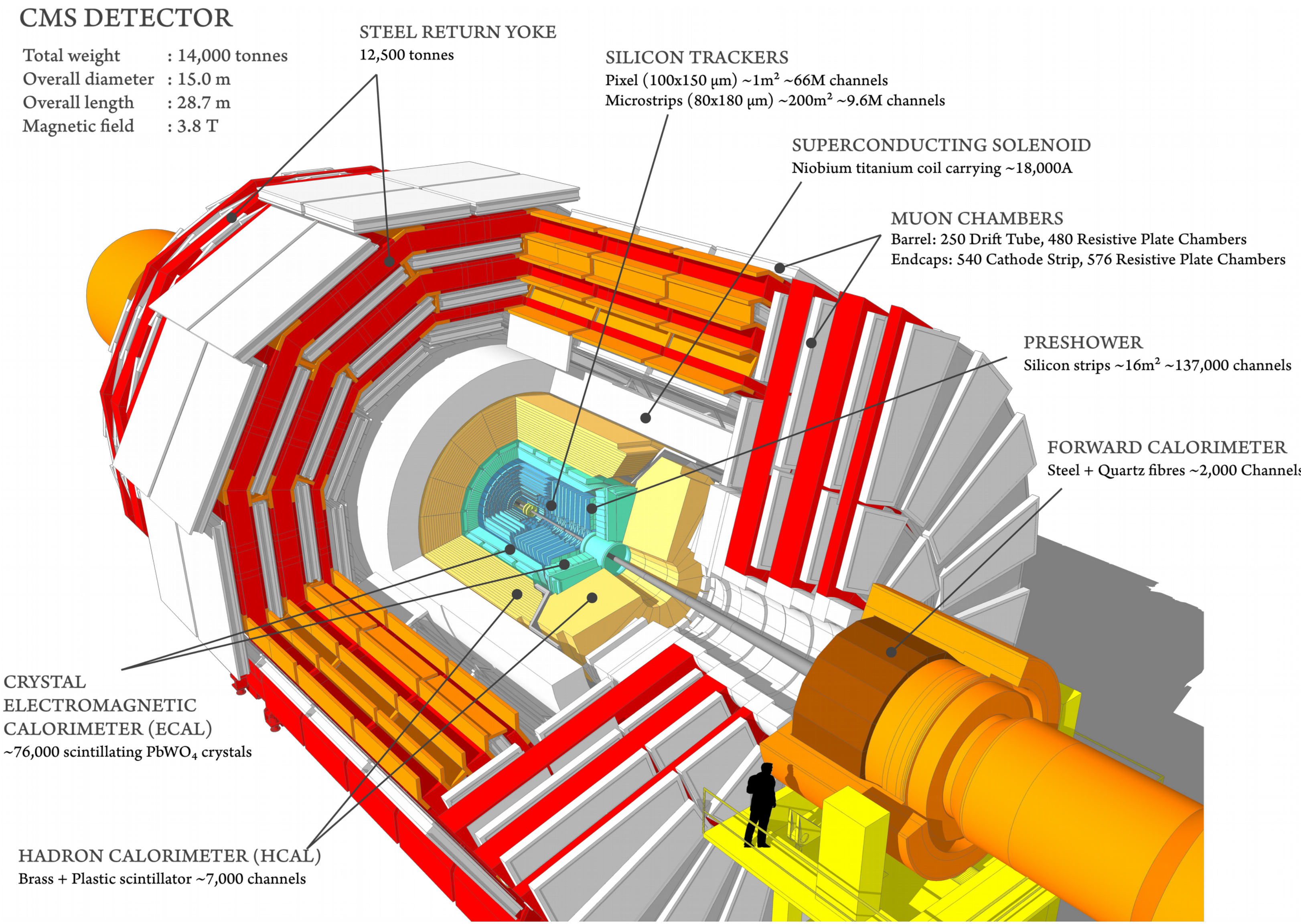
(Note that the Br in the equation refers to just 1 quark flavor, while the parton luminosity function shown above sums over the contributions from all flavors)

Detectors

LHC multipurpose detectors: ATLAS



LHC multipurpose detectors: CMS



ATLAS/CMS design goals

- Good muon identification and momentum resolution:
  - Redundant measurements to avoid reconstruction inefficiencies
  - $\Delta M_{\mu\mu} / M_{\mu\mu} \approx 1\%$ at 100 GeV
  - Unambiguous determination of the charge for $p^T_\mu < 1$ TeV

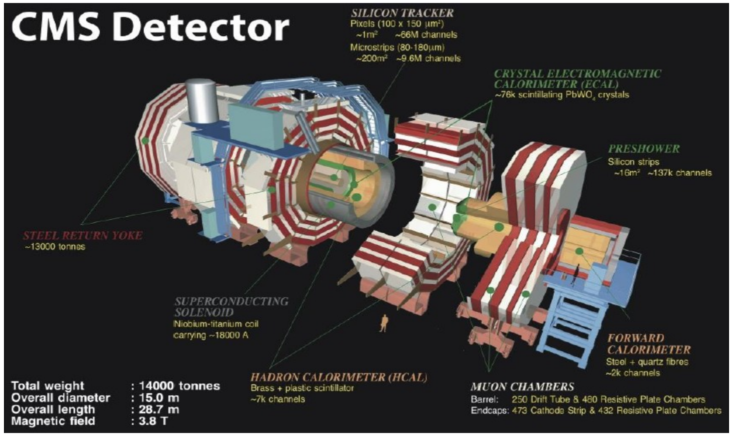
- Precise and efficient inner tracking, including vertex capabilities:
  - Efficient triggering and offline tagging of taus and b-jets
  - Pixel detectors close to the interaction region

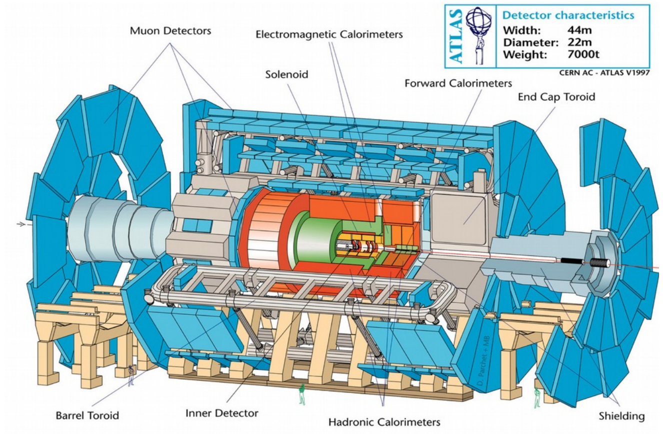
- Good electromagnetic identification and photon/electron energy resolution:
  - $\Delta M_{ee} / M_{ee}$, $\Delta M_{\gamma\gamma} / M_{\gamma\gamma} \approx 1\%$ at 100 GeV
  - Large coverage and good granularity, π^0 rejection

- Good jet and missing transverse energy resolution:
  - Hermetic coverage, fine lateral segmentation

Significantly better than previous generation detectors (Tevatron) !!

ATLAS vs CMS





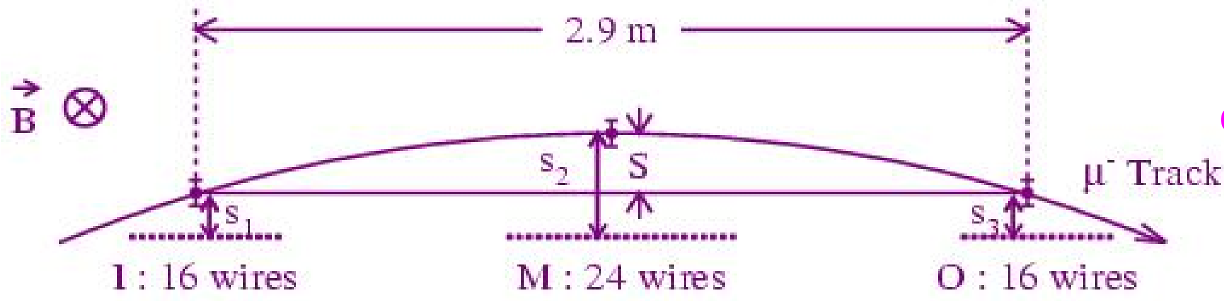
- CMS has a huge and powerful solenoid (3.8 T) covering tracker and calorimeters, and a huge silicon tracker volume (1.2 m radius). ATLAS has a less powerful solenoid (2T), silicon up to 0.5 m radius and a transition radiation tracker up to 1.2 m radius. CMS has a slightly better momentum resolution from inner tracking
- ATLAS has external air toroids for precise muon measurement up to $|\eta|=3$. CMS measures muons precisely in inner tracker($|\eta|<2.5$), less precisely in the return iron yoke of their solenoid, but it has more redundant muon trigger systems.
- ATLAS has a precise electromagnetic lead-liquid argon calorimeter, with high granularity and longitudinal sampling capabilities. CMS has a crystal calorimeter ($PbWO_4$), with an excellent energy resolution also at relatively low energies.
- ATLAS has a very precise, granular hadron calorimeter. CMS has a more conventional, hermetic calorimeter. ATLAS has better hadron calorimetry.

Tracking and muon performance at the LHC

Intrinsic resolution in ALL tracking detectors

Intrinsic uncertainty: position measurements over a distance L

$$sagitta = \frac{L^2}{8R}; \qquad \Delta\, sagitta \approx constant$$



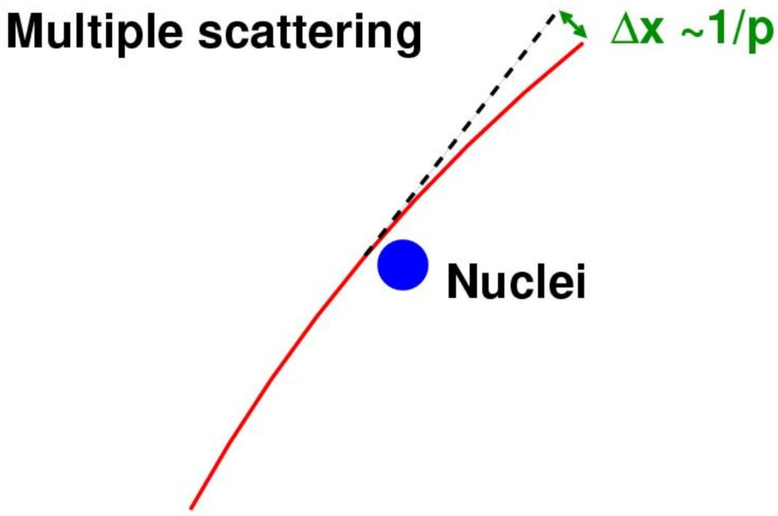
(L3 LEP detector example)

$$p(GeV) = 0.3 \;\; q \;\; B(T) \;\; R(m) \Rightarrow$$

$$\frac{\Delta p_T}{p_T} = \frac{\Delta R}{R} = \frac{\Delta\, sagitta}{sagitta} \propto p_T; \qquad also:\ \frac{\Delta p_T}{p_T} \propto [B \;\; L^2]$$

Other uncertainties

Additional uncertainties due to multiple scattering

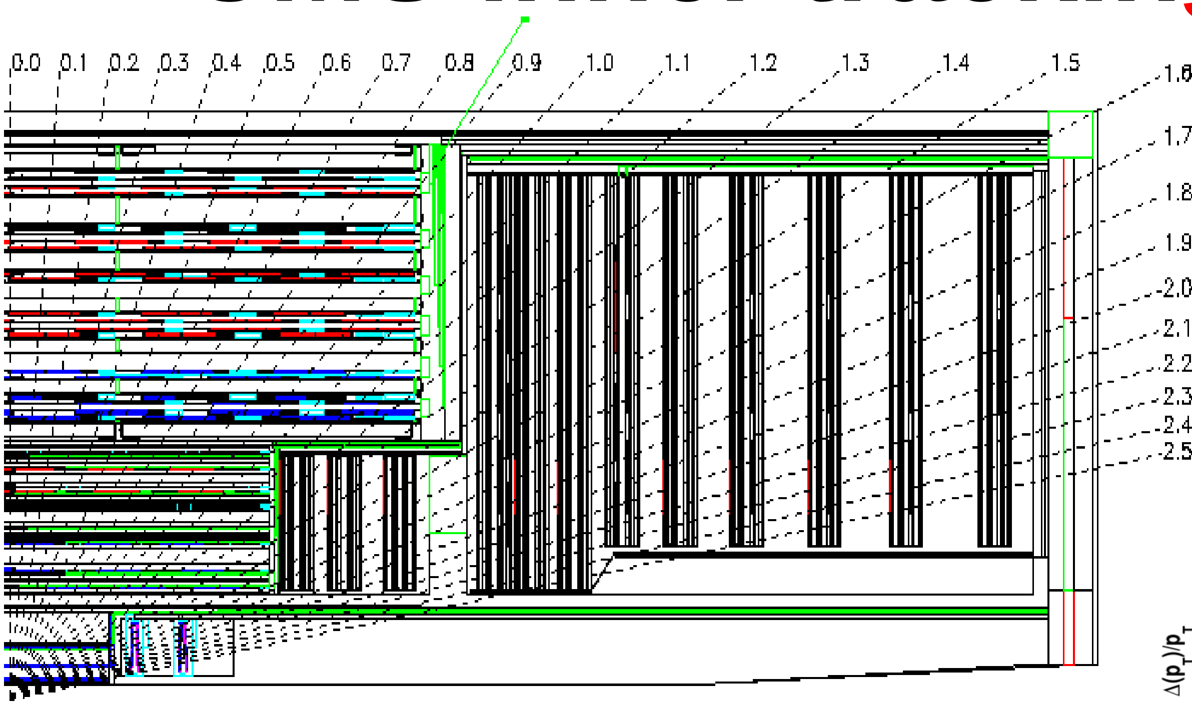


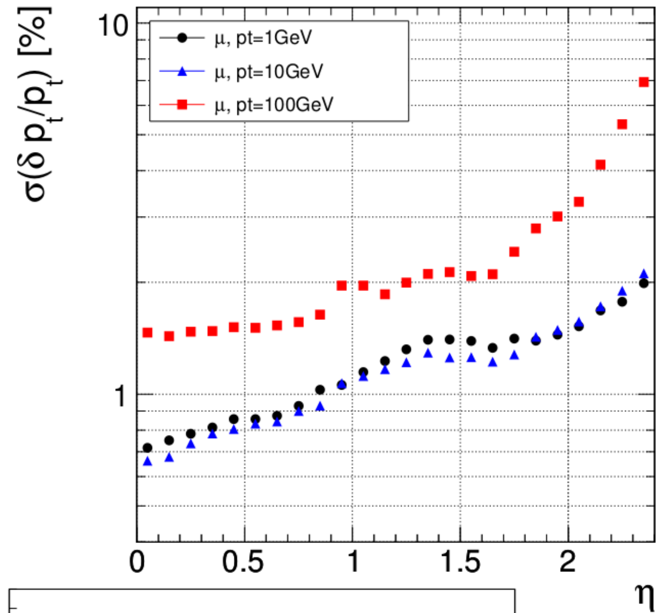
$$\Delta\, sagitta\Big|_{MS} \propto \Delta\, position\Big|_{MS} \propto \frac{1}{p} \Rightarrow$$

$$\frac{\Delta p}{p}\Bigg|_{MS} = \frac{\Delta\, sagitta}{sagitta} = constant$$

$$\frac{\Delta p}{p}\Bigg|_{all} = \kappa\, p \;\oplus\; \beta$$

CMS inner tracking system

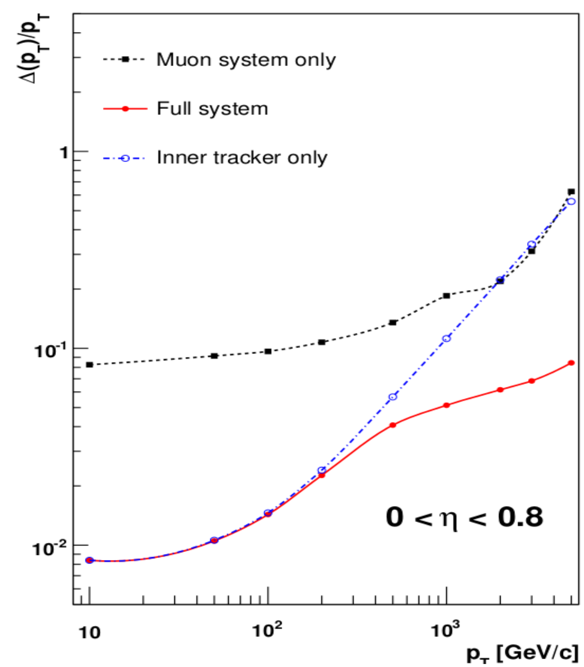




A huge, ultra-precise silicon tracker system:

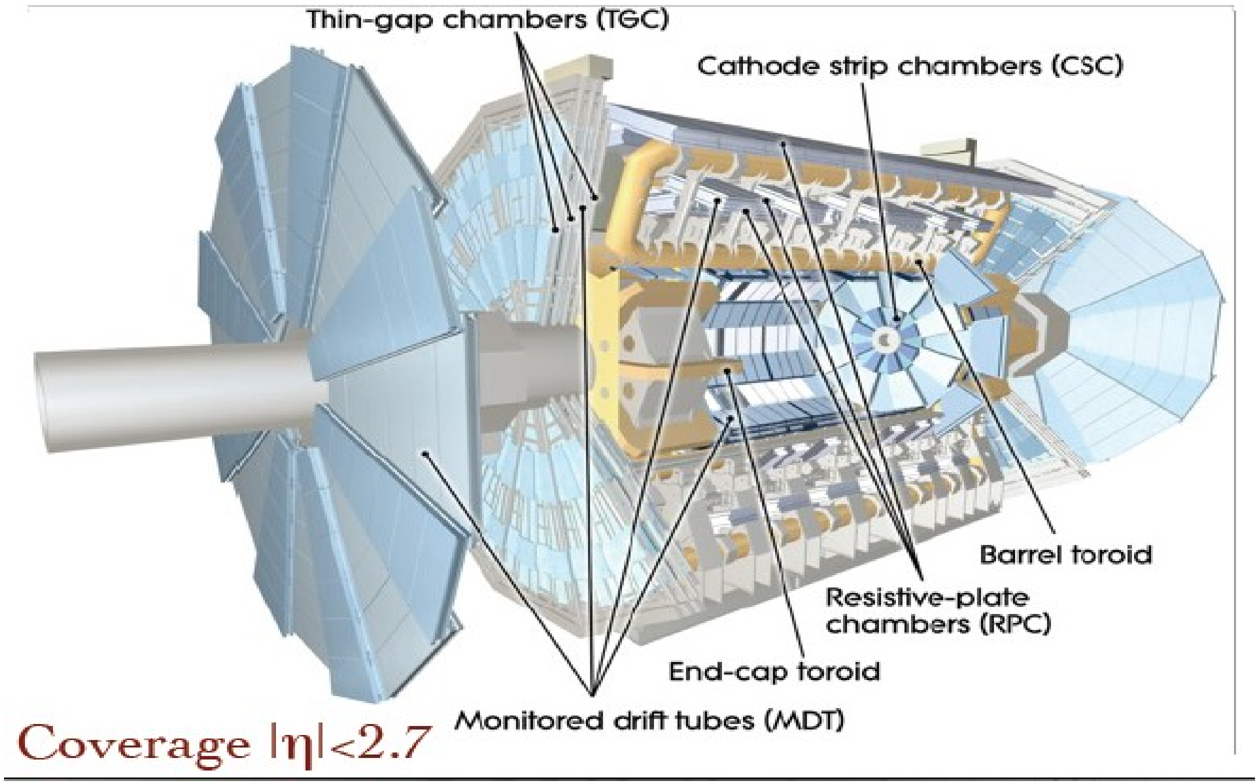
- For $p_T \leq 100$ GeV, $\Delta p_T / p_T \approx 0.5$-$2\%$ ($|\eta|<1.6$)
  - Muon resolution dominated by inner tracking resolution for $p_T <\approx 100$ GeV

- $\Delta d_{xy} \approx 10$ μm resolution at very high p_T
- $\Delta z \approx 20$-40 μm resolution at very high p_T ($|\eta|<2$)



ATLAS: a precise muon system

- The ATLAS muon system (barrel and also endcap) is optimized for:
  - Precise muon identification and stand-alone momentum measurement, even at very high rapidities and up to TeV momenta (<10% resolution)
  - Muon triggering (RPCs in barrel, TGCs in endcaps)



Intrinsic position resolution per chamber better than 100 microns (good alignment is critical)

Air toroids of 4 Tesla (no material between chamber layers to keep high resolution)

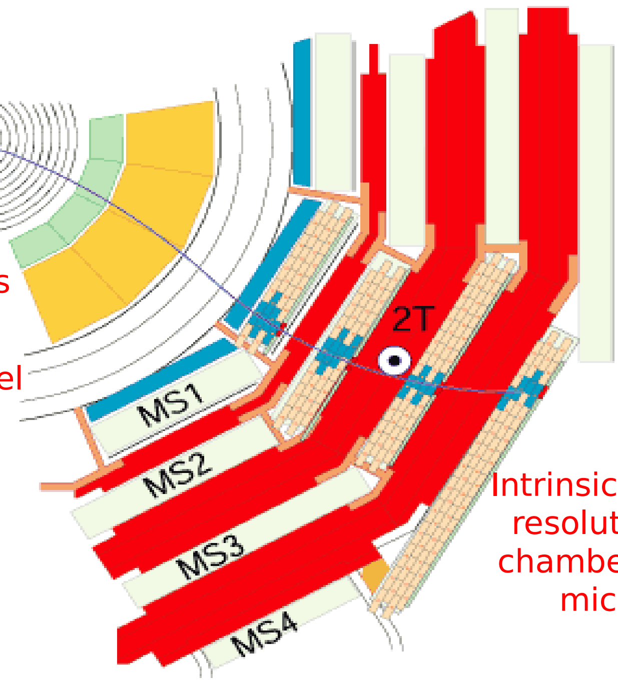
Air toroids in the endcap ensure good momentum resolution even at very high rapidities

CMS: a special muon system

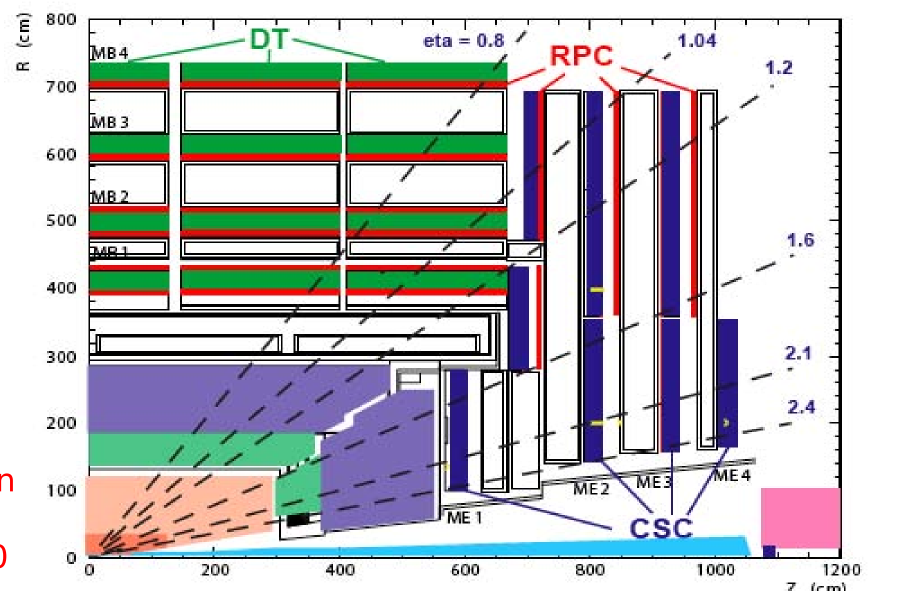
- The CMS muon system (barrel and also endcap) is optimized for:
  - Robust, efficient and redundant muon triggering system (chambers+RPCs)
  - Efficient muon identification and reconstruction ($|\eta|<2.4$, redundant coverage)
  - Precise measurement (< 10%) for TeV momenta (good alignment + level arm)

Drift tubes used

in the barrel



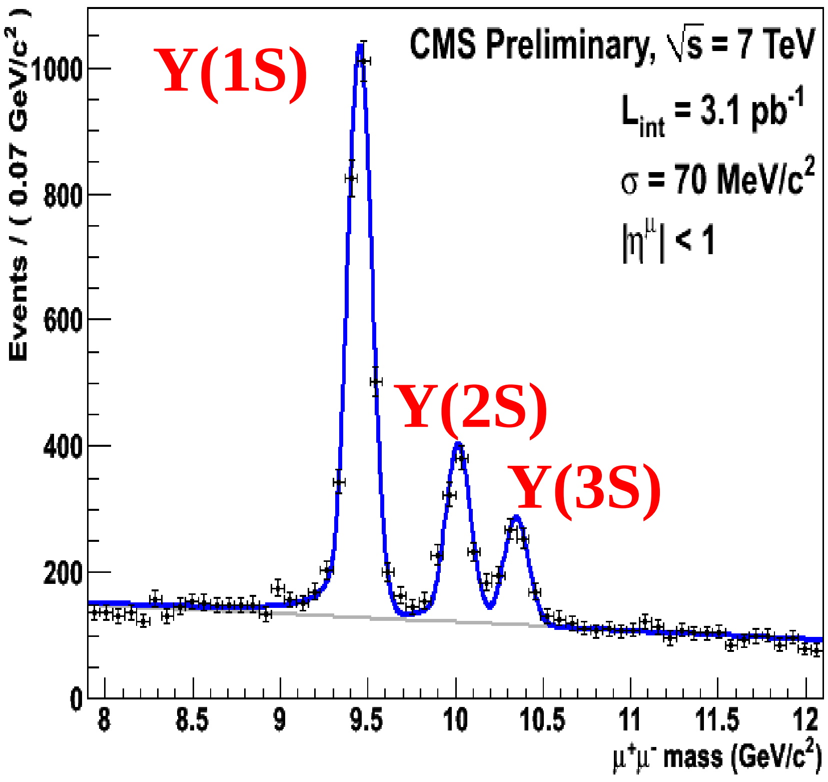
Intrinsic position resolution per chamber ~ 100 microns

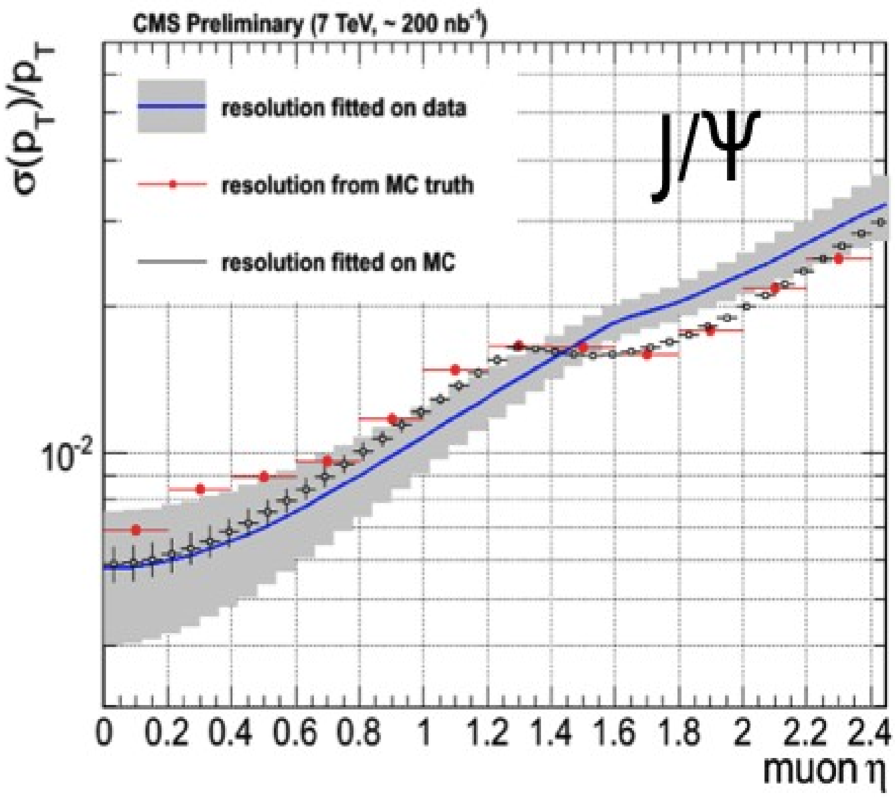


Cathode Strip Chambers (CSC) used in the end-caps

RPCs for fast timing and trigger response

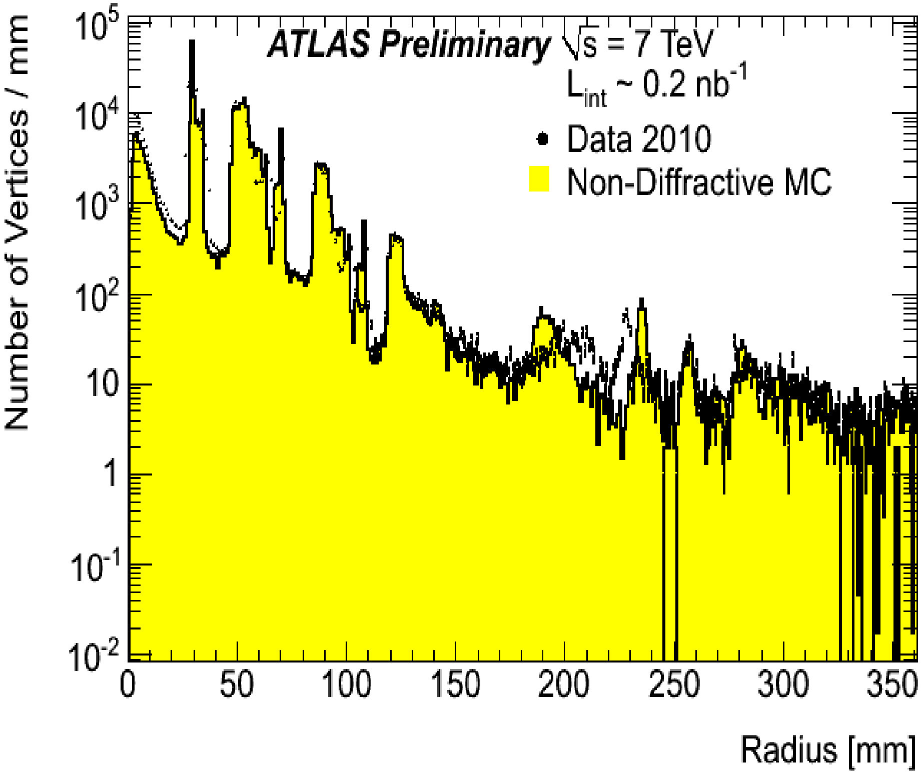
Tracking momentum resolution

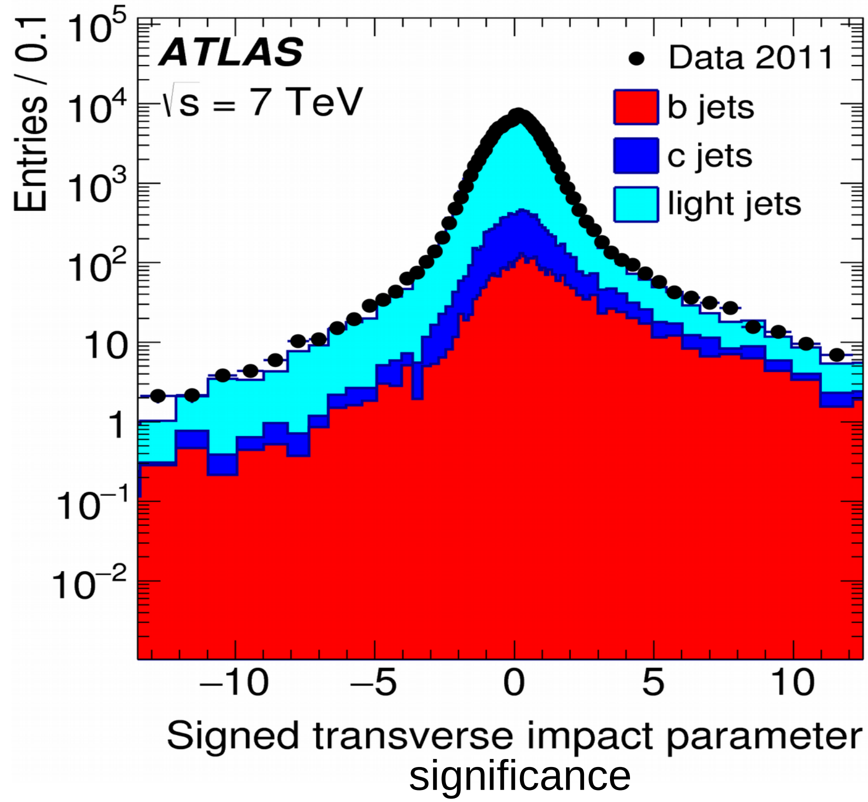




- Tracker resolution working 'almost' as in the simulation
- Resolutions extracted directly from data (narrow resonance widths)

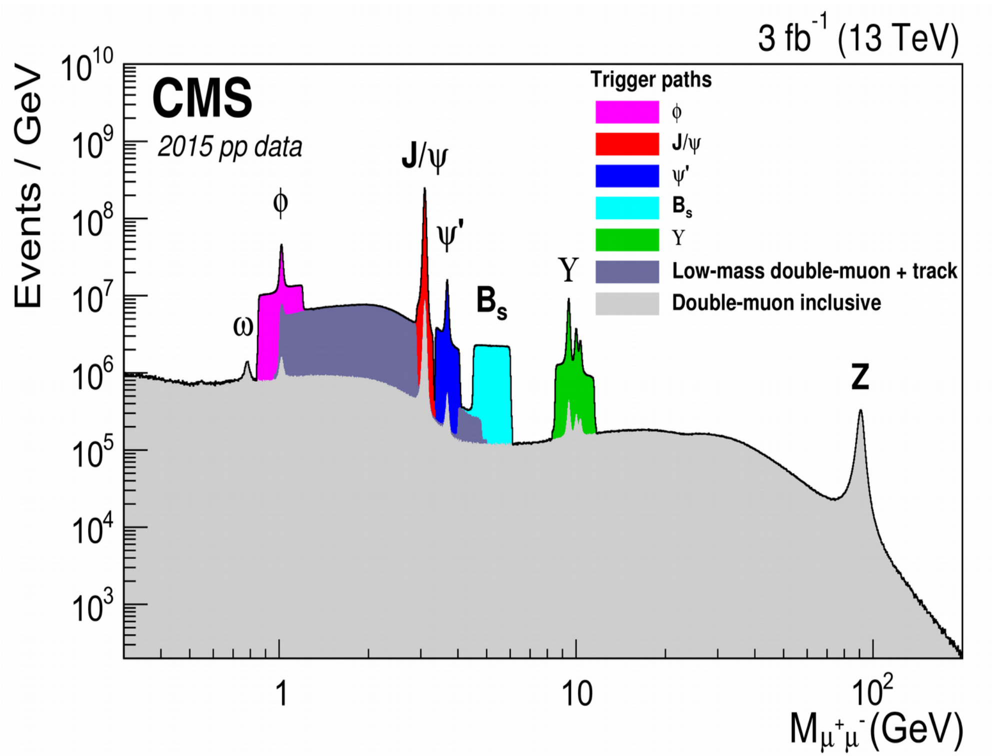
More: tracker material, vertexing

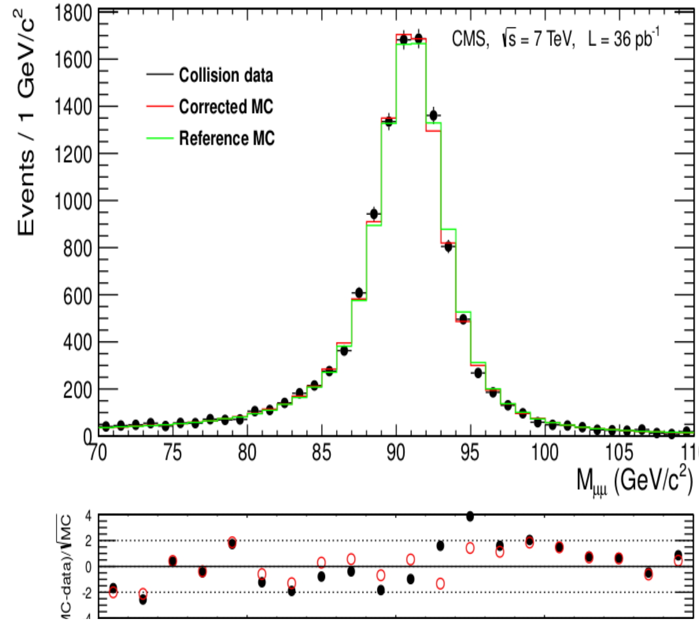


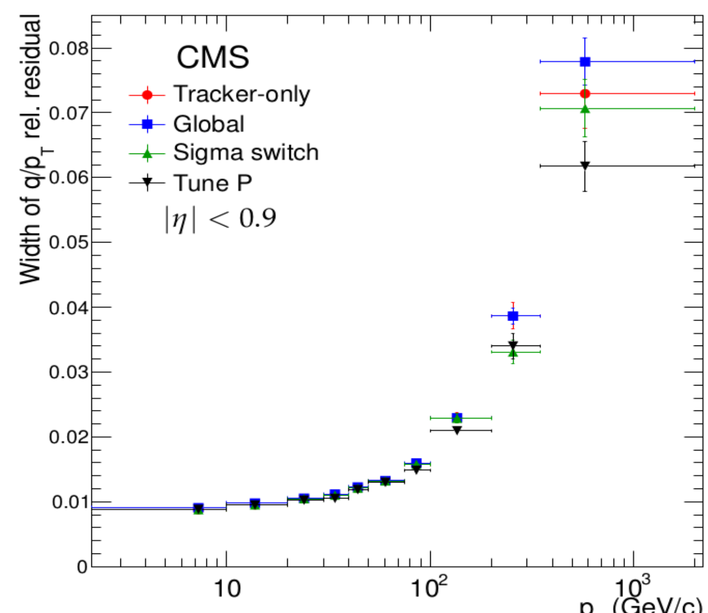


- Rather impressive level of reproducibility of the tracker material in simulations:
  - Important to account for effects like multiple scattering or electron bremsstrahlung
- Plus good understanding of position resolution in the tracker:
  - Impact parameters in agreement with simulations, excellent b-tagging capabilities

CMS: track/muon resolution





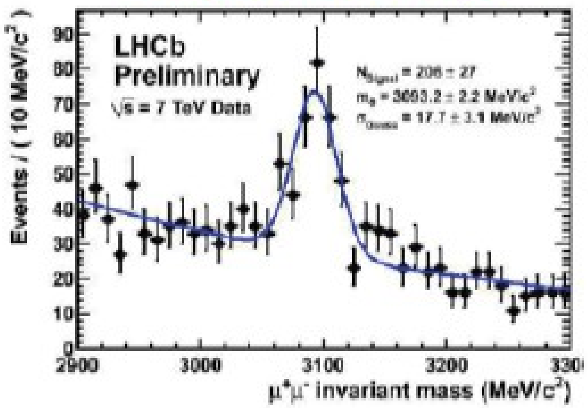


- Tracker resolution working 'almost' as expected from detector simulations
- Resolutions/corrections extracted directly from data: narrow resonances at low momenta (J/Ψ), Z boson at EWK scale, cosmics at very high momenta
- Detector alignment critical at very high p_T (≲100 μm between inner tracker and muon chambers)

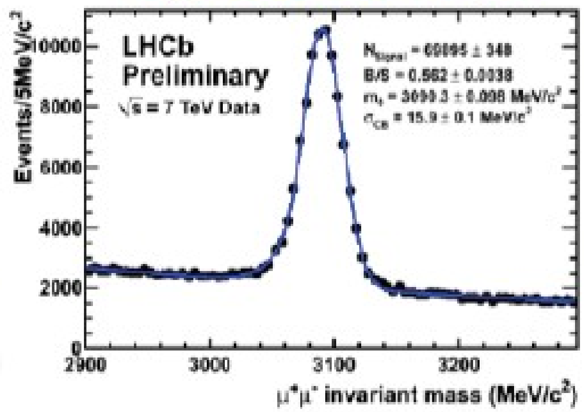
LHCb tracking resolution

Evolution of J/ψ → $\mu^+\mu^-$ mass resolution with time (MC ~ 12 MeV/c^2)

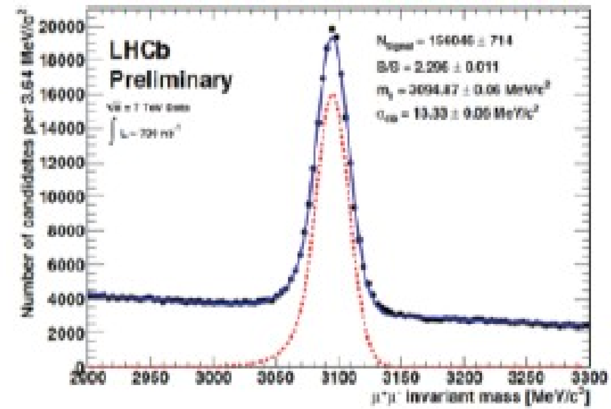
May: σ ~ 18 MeV/c^2



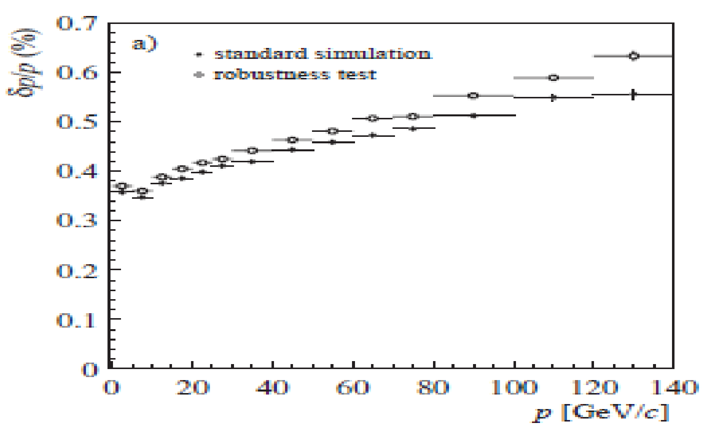
August: σ ~ 16 MeV/c^2



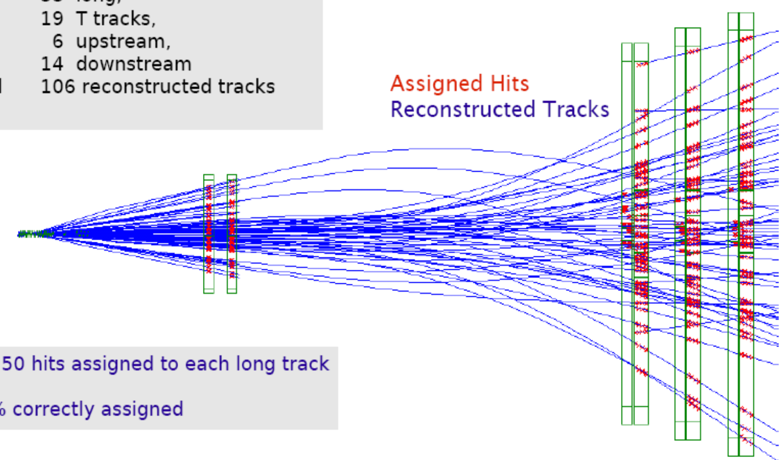
November: σ ~ 13 MeV/c^2



- **Many tracking detectors, high B field, long level arm → excellent resolution**



Average # of tracks in b-events:
34 VELO,
33 long,
19 T tracks,
6 upstream,
14 downstream
Total 106 reconstructed tracks



20 to 50 hits assigned to each long track

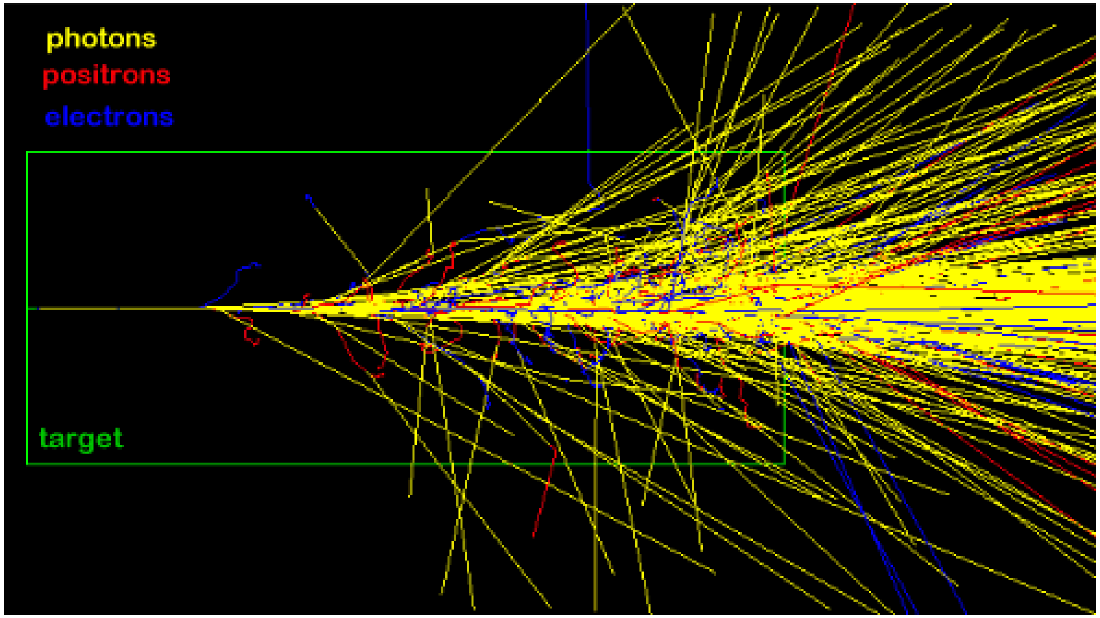
98.7% correctly assigned

Electron and photon resolution and performance at the LHC

Intrinsic resolution in ALL calorimeters

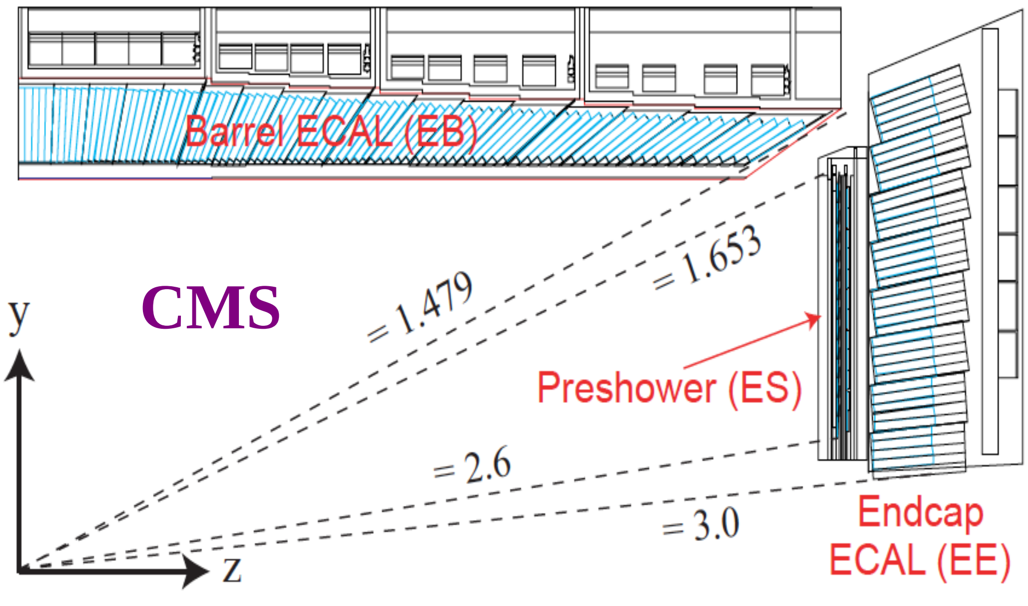
At the end of the cascade, N particles with typical ionization

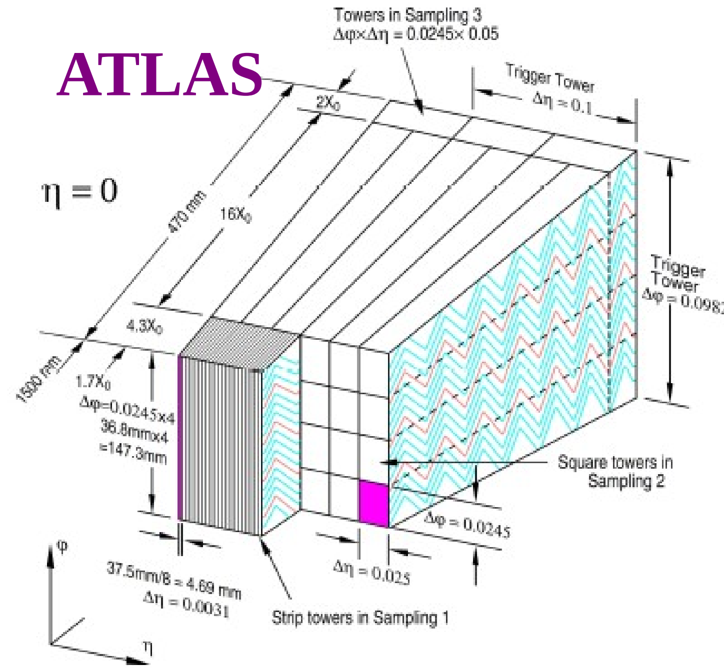
Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.



$$E \propto N < E_c > \Rightarrow \Delta E \propto \sqrt{N}\,; \qquad \frac{\Delta E}{E} = \frac{\kappa}{\sqrt{E}}$$

Electromagnetic Calorimeters





- CMS: a crystal calorimeter (Pb WO_4) with extremely good resolution, granularity and low noise (+preshower in the endcaps):

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\,\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.3\,\%)^2$$

- ATLAS: a liquid argon calorimeter (active medium) with good resolution, fine segmentation ($\pi^0 \rightarrow \gamma\gamma$ rejection) and photon pointing capabilities:

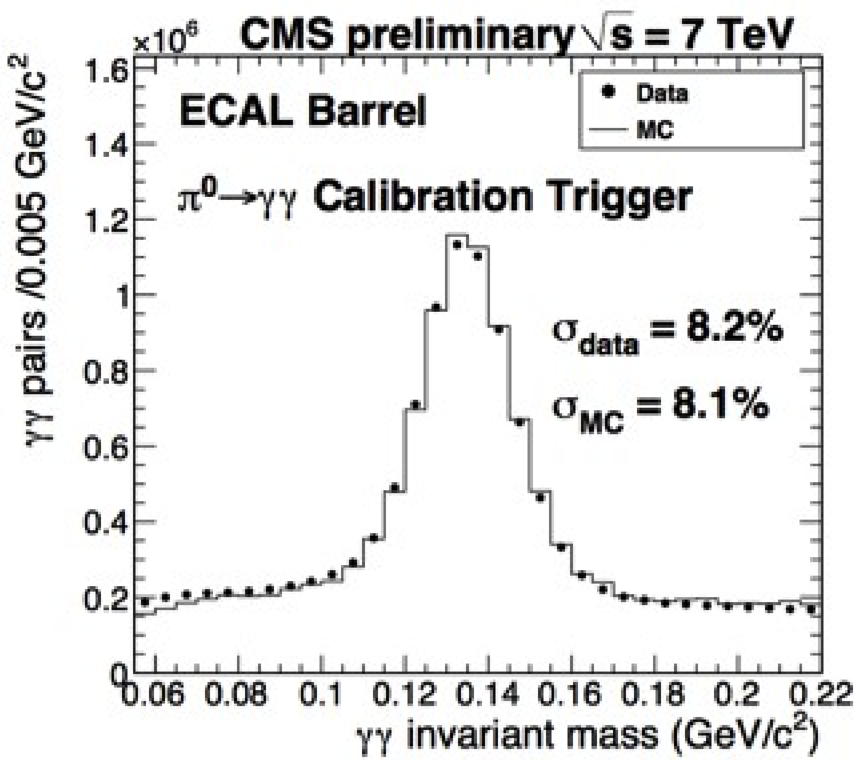
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{10\,\%}{\sqrt{E}}\right)^2 + (0.7\,\%)^2$$

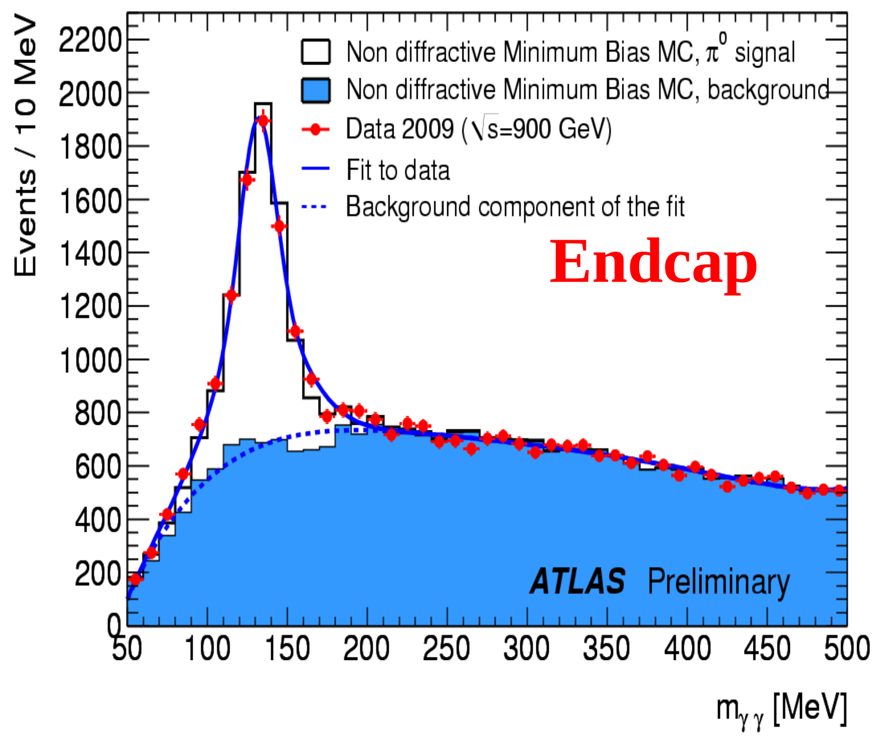
(E in GeV)

ATLAS and CMS: photons

Intrinsic resolution ($\Delta E/E \propto A/\sqrt{E}$ at GeV energies) understood on low energy resonances

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{B}{E}\right)^2 + (C)^2$$

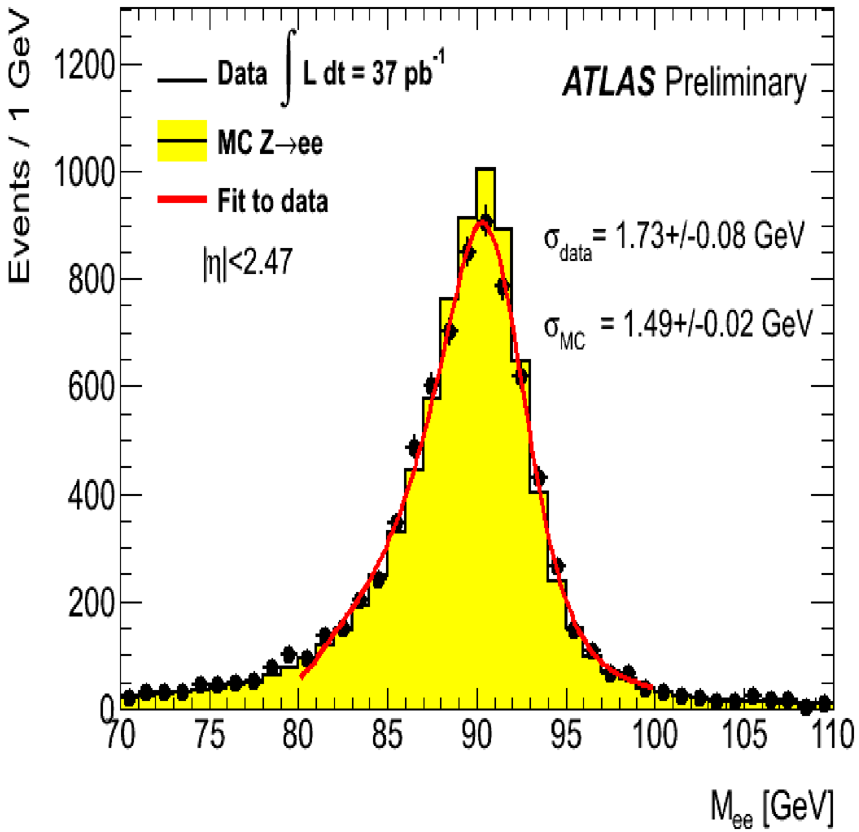


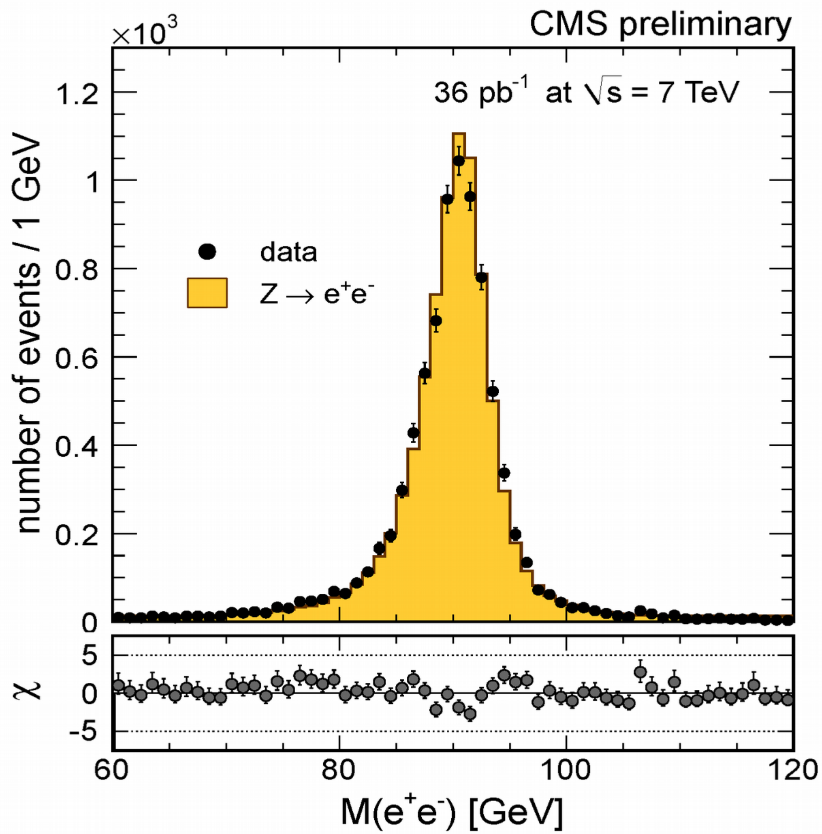


ATLAS and CMS: electrons

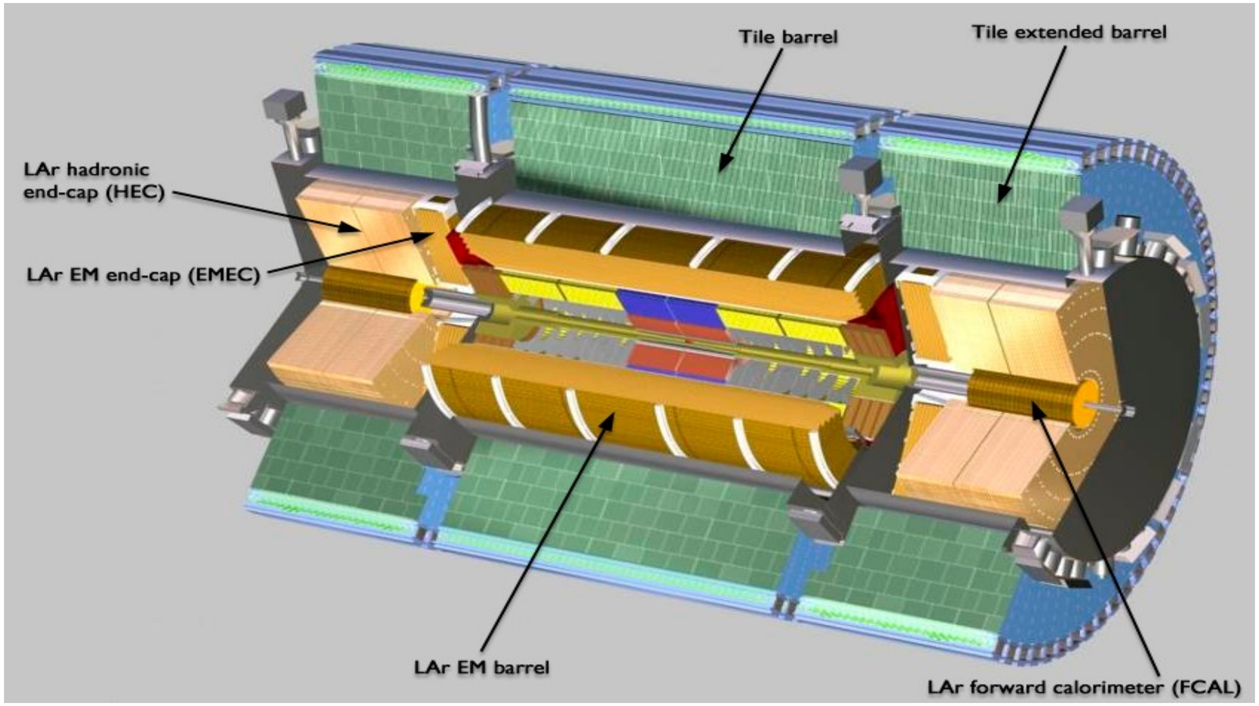
Independent term calibrated at Z peak (ΔE/E≈C at high E)

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{B}{E}\right)^2 + (C)^2$$





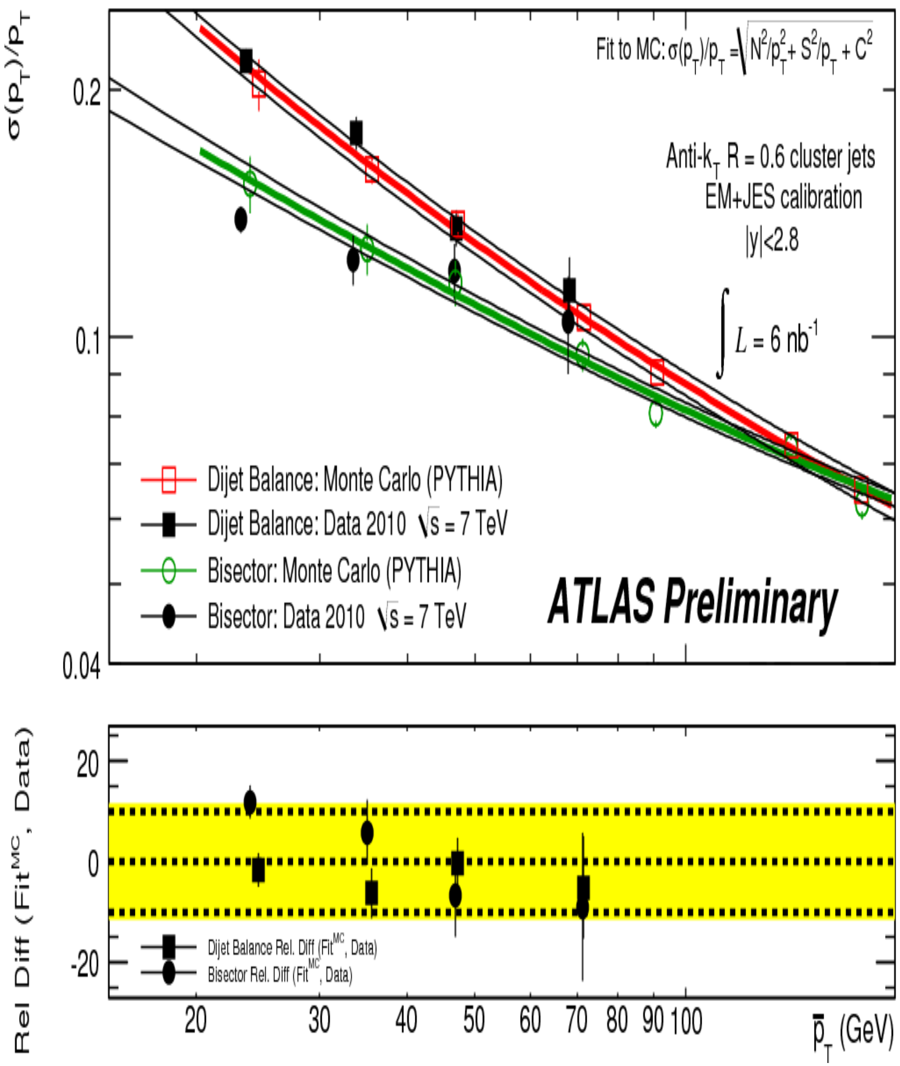
ATLAS: precise hadron calorimetry

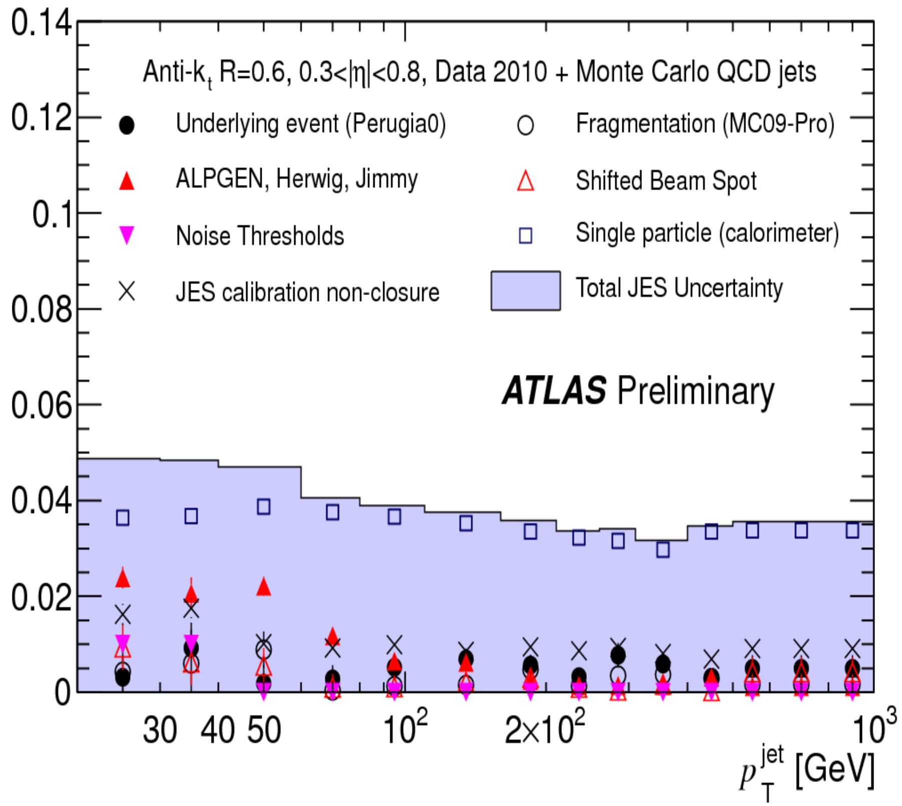


- Hadron calorimetry: Iron-plastic scintillator tile calorimeter (barrel); extremely hermetic and segmented, with a very linear response (<2% deviations)
- Jet energy resolution:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{0.5}{\sqrt{E}}\right)^2 + (3\%)^2$$

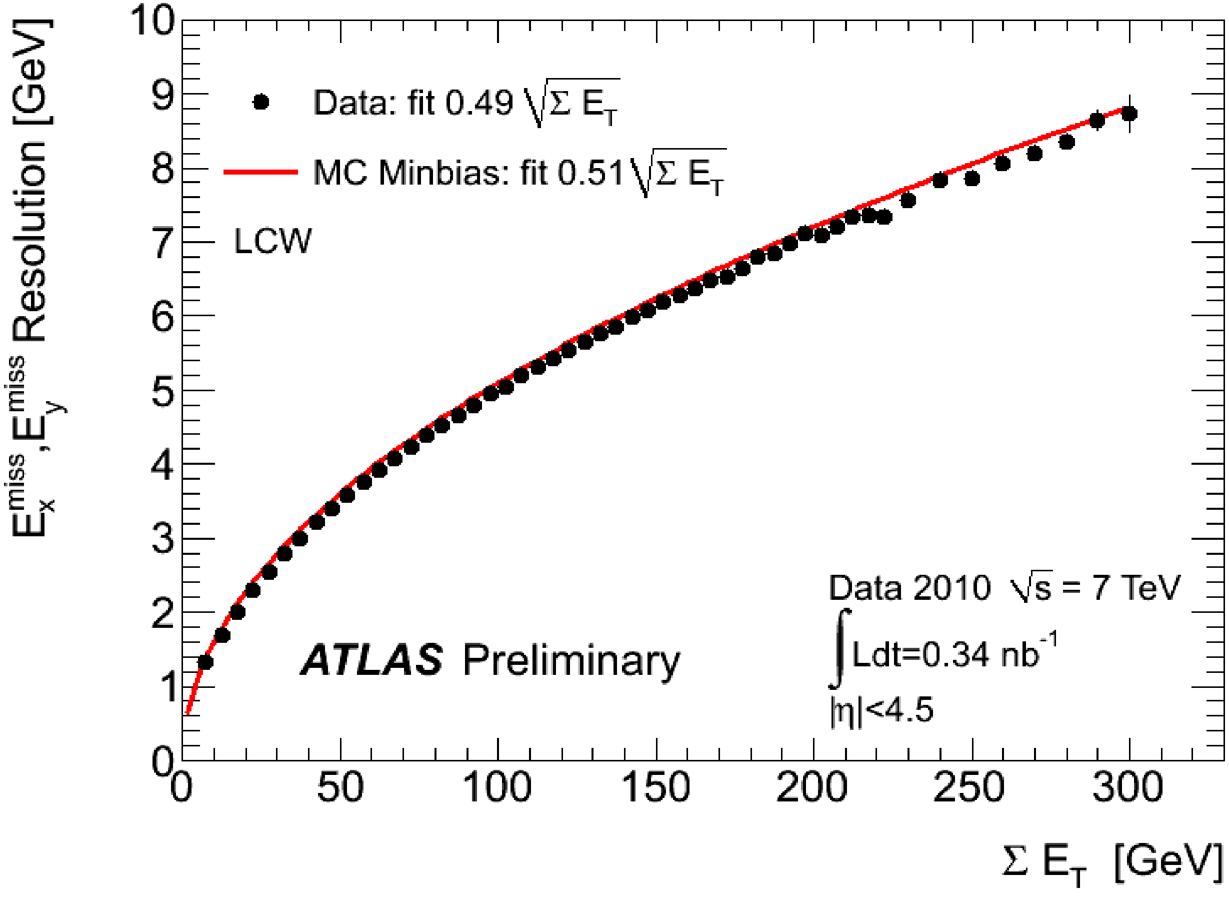
ATLAS: precise calorimetric jets





- Jet resolution according to expectations
- Scale uncertainties < 5% already in early LHC data

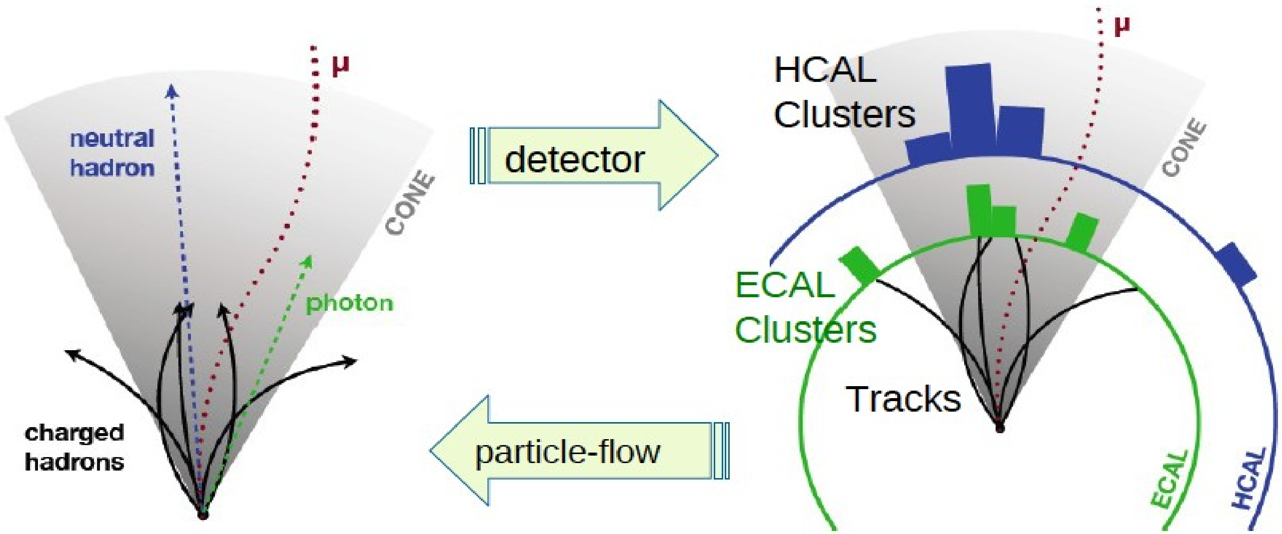
ATLAS: precise calorimetric E_T^{miss}



- Missing E_T resolution according to expectations

Performance for Physics: some advanced tools

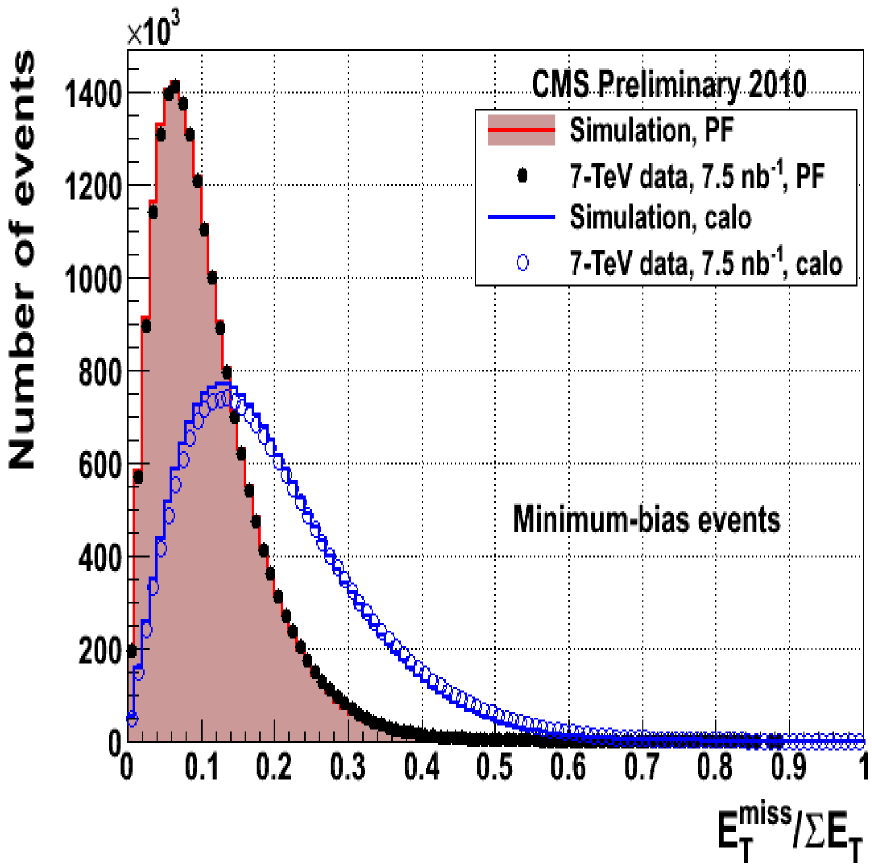
CMS: particle-flow techniques

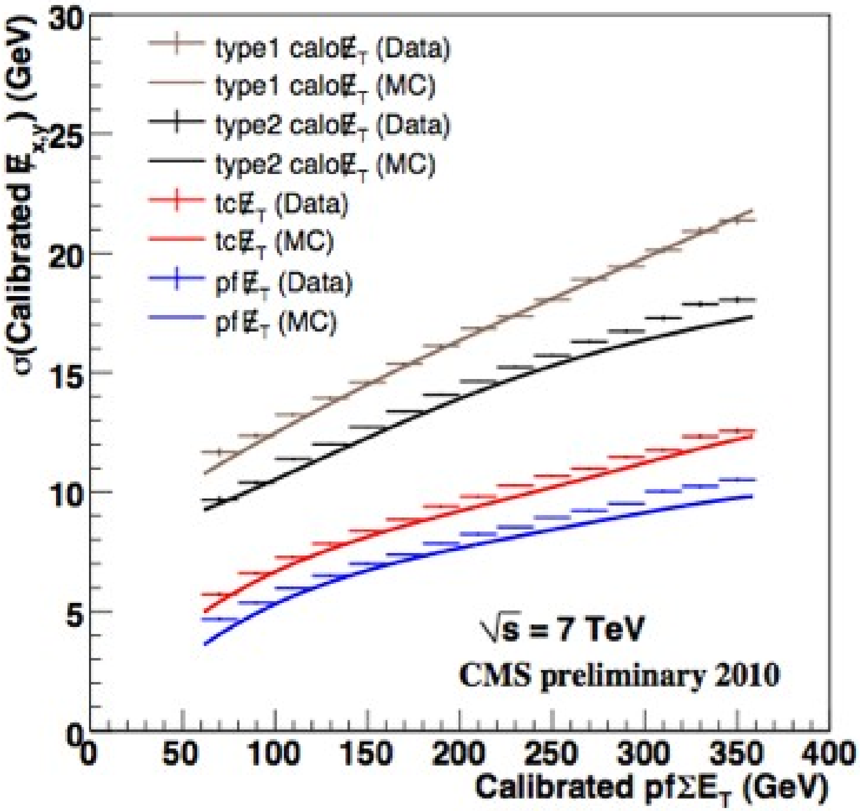


- In CMS, charged particles get well separated due to the huge tracker volume and the high magnetic field (3.8 T)
- CMS has an excellent tracking resolution, able to go to down to very low momenta (~few hundred MeVs)
- CMS has also an excellent electromagnetic calorimeter with good granularity
- In multijet events, only 10% of the energy corresponds to neutral (stable) hadrons

Big improvement in energy resolution and identification using particle-flow techniques

Particle-flow techniques

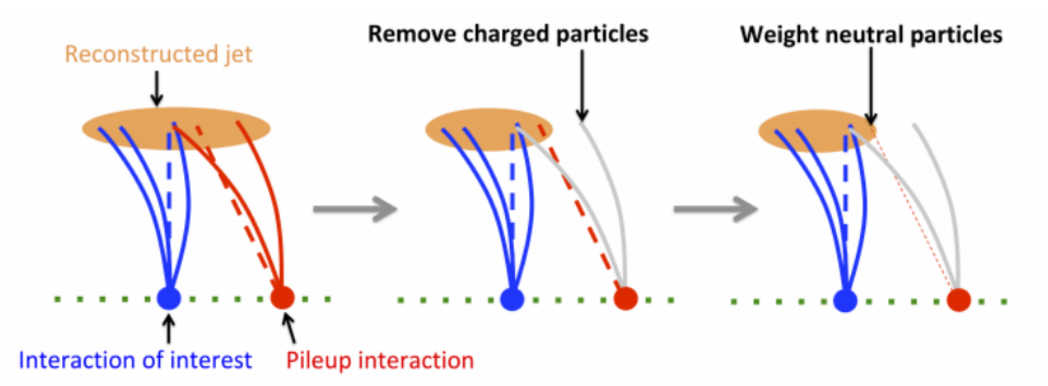


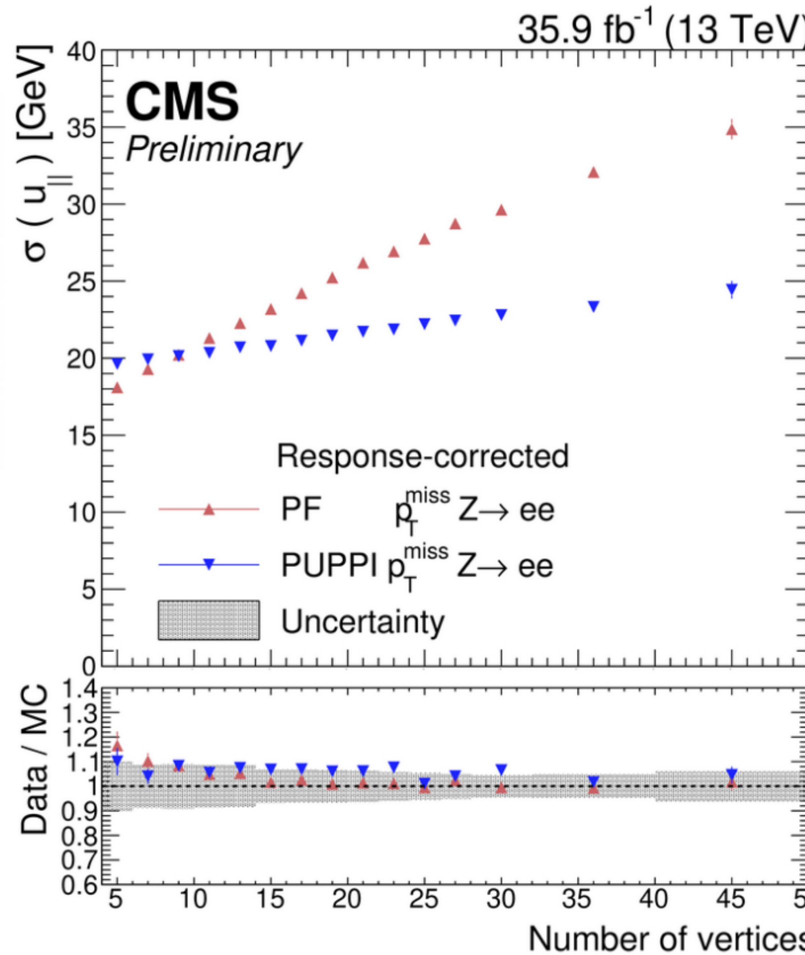


- Factor of two improvement in energy resolution with respect to measurements using CMS calorimeter information only.

Pileup mitigation (CMS)

- PUPPI: 'PileUp Per-Particle Identification'

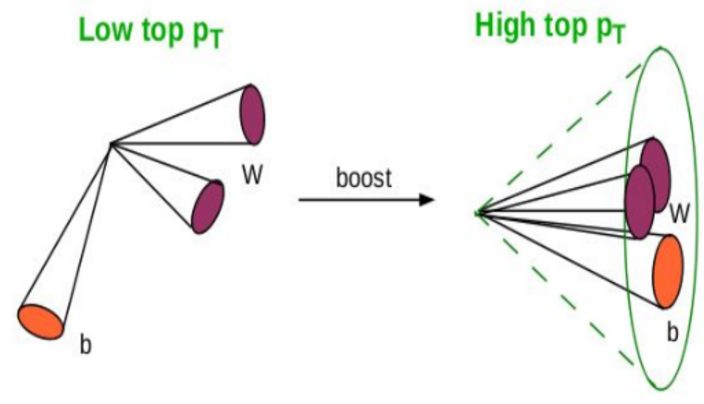


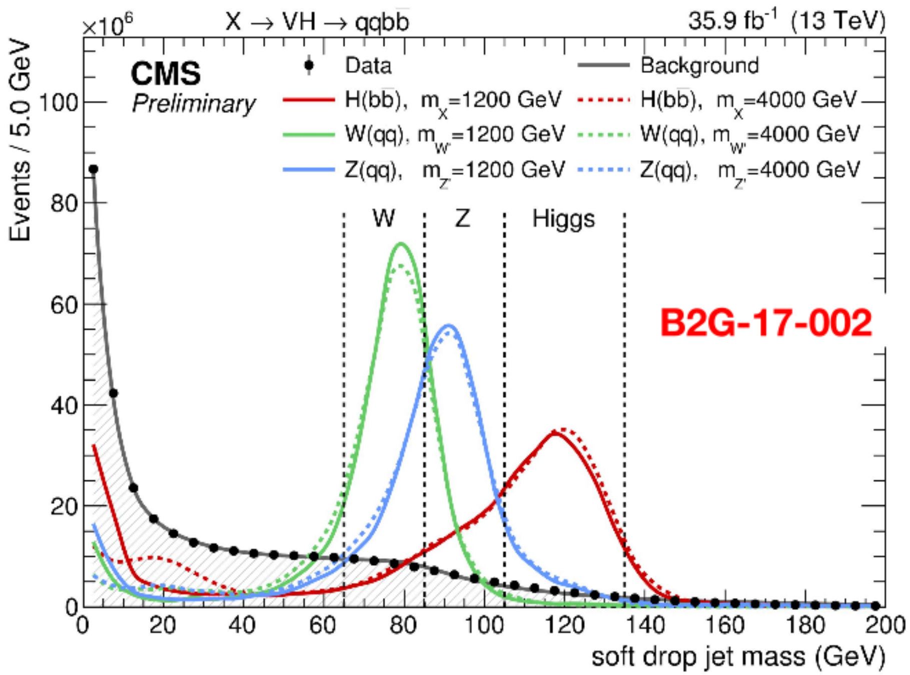


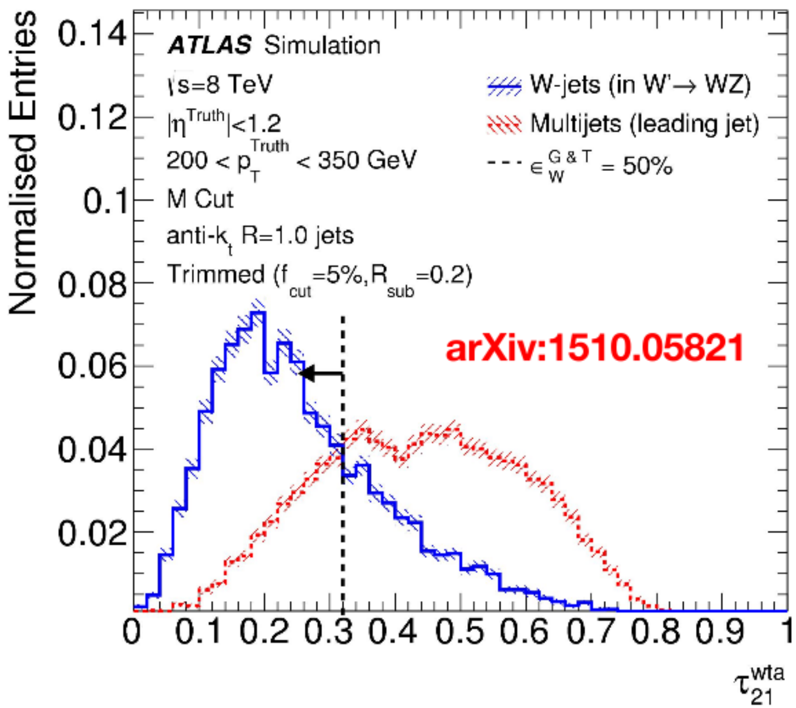
- Neutral particles from pileup are at a higher angular distance and have lower p_T →weight them according to this
- Main advantage: performance almost independent of pileup

Boosted signatures, jet substructure

- **Very active field: lots of ideas, variables, methods**
- **Basic strategy (oversimplifying):**
  - a) use wide jets to start with (typical radius in jet algorithms): ~ 0.8 - 1.0
  - b) "drop" soft/far activity to better disentangle the core of individual particles ("grooming")
  - c) Test best consistency with a 1, 2, ..., N jet structure ("sub-jetiness", D_2)

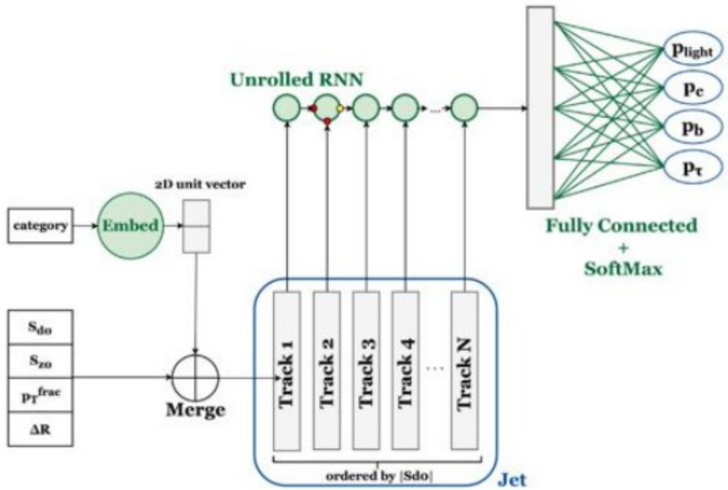




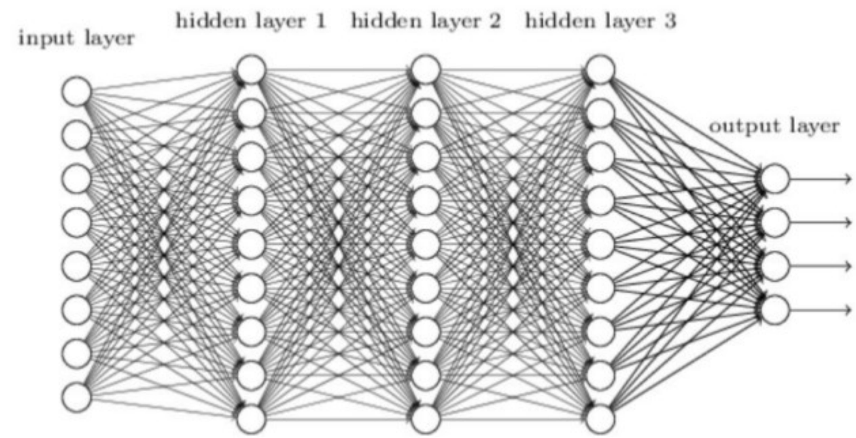


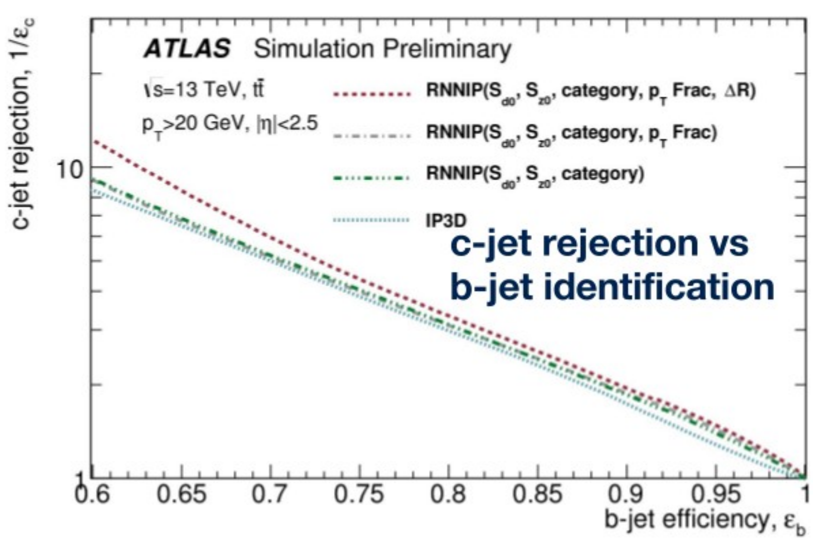
Multivariate methods, deep learning

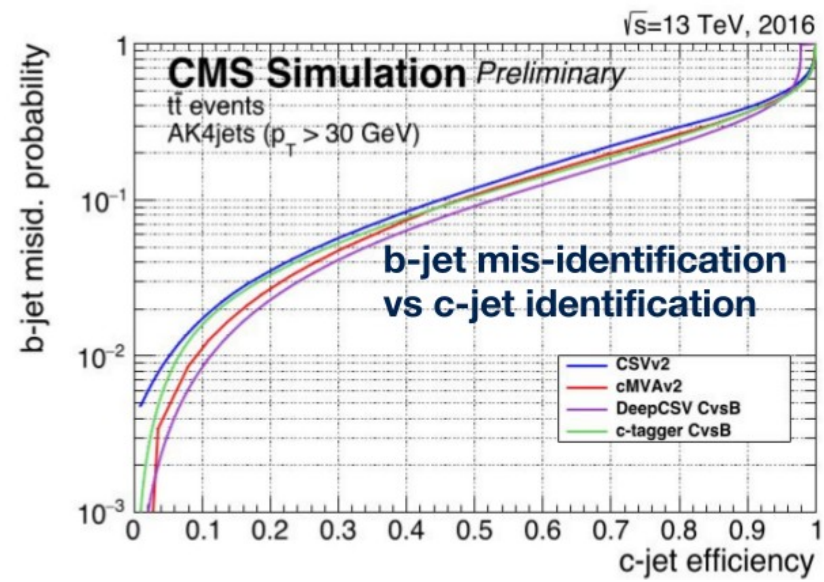
'Recurrent neural networks' in ATLAS (ATL-PHYS-PUB-2017-003)



'Deep Neural Network' in CMS (CMS-DP-2017-005)







Outlook

- The LHC accelerator has shown an excellent performance over the years
- The LHC detectors have accompanied this performance with an also excellent behavior
- This already suggests high quality physics results with those data. To be discussed in the next lectures

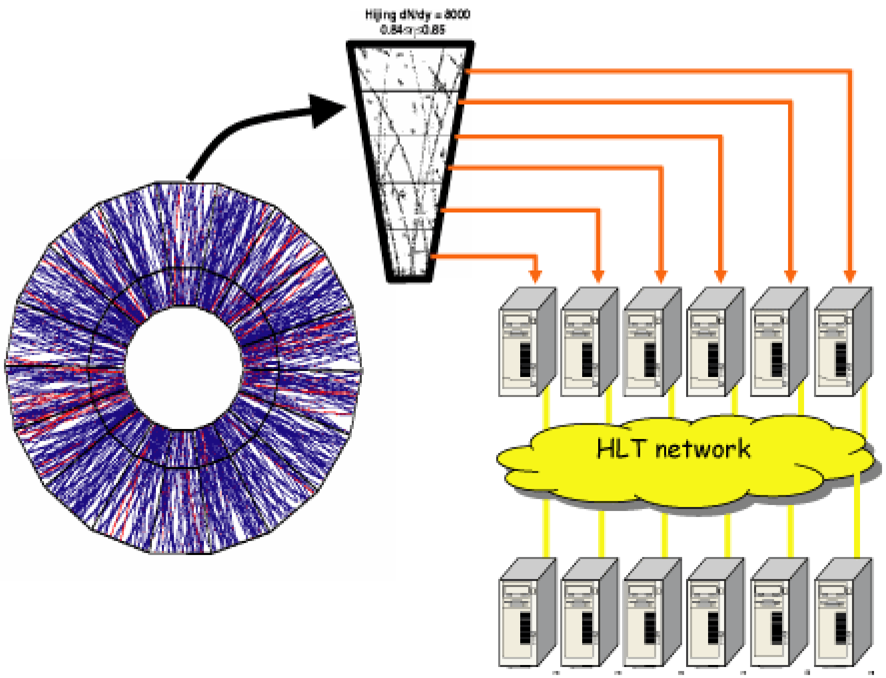
BACKUP

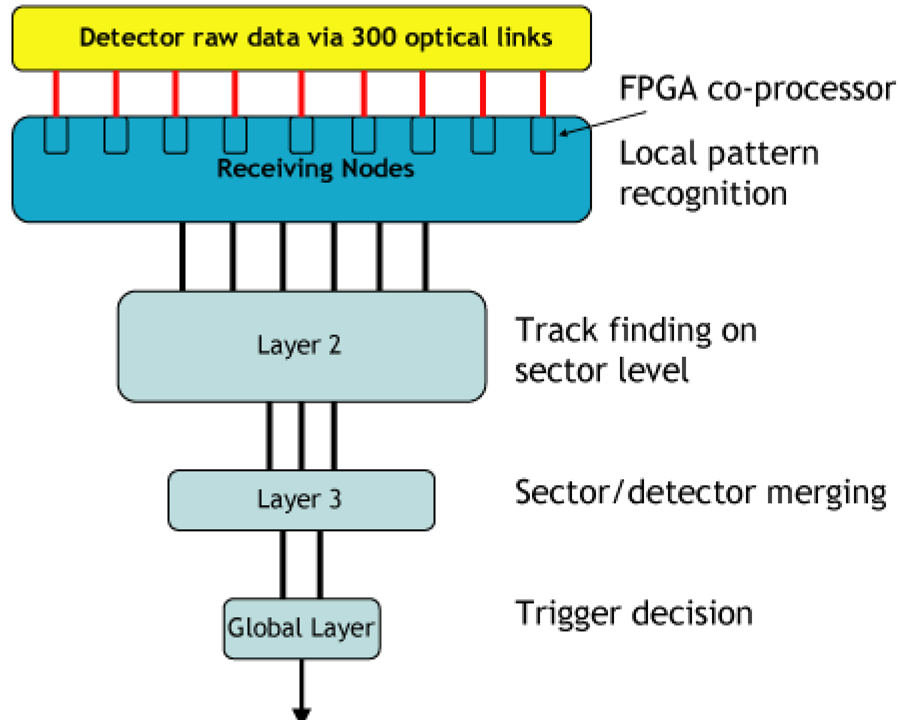
Luminosity (accelerator view)

$$L = \frac{n_b \; N^2 \; f \; F \; \gamma}{4\pi\beta^* \epsilon}$$

n_b: number of bunches
N: number of protons per bunch
f: beam frequency
n_b: number of bunches
F: loss factor due to crossing angle
γ: gamma factor (E/m of protons)
β^*: amplitude funcion at interaction point (after focusing magnets)
ϵ: normalized emittance

ALICE trigger system





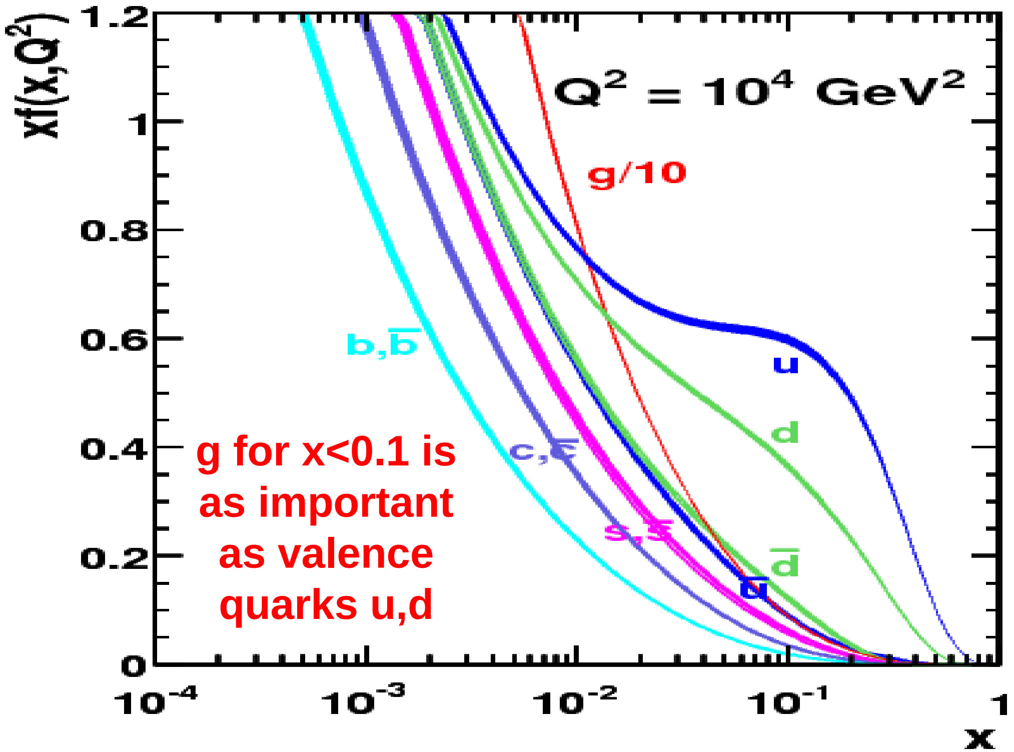
- ALICE (and also the other LHC experiments working in Heavy-Ion mode) has special trigger constraints: less collision rate, but huge events (ion interactions):
  - Long readout time for their precise gas tracking chamber (Track Projection Chamber)
  - Sophisticated "trigger hand shaking" at the early levels
  - The High Level Trigger system: tracker reconstruction regionally via parallel processing

Proton-proton collisions

- Let us exploit the factorization properties of the cross section in terms of parton distribution functions (pdfs) and the hard elementary process. For a process AB → H (at leading order):

$$\sigma(pp \rightarrow H+X;Q) = \sum_{A,B} \int dx_A \int dx_B \, pdf_{p\rightarrow A}(x_A,Q^2) \; pdf_{p\rightarrow B}(x_B,Q^2) \; \sigma(AB \rightarrow H;Q)$$

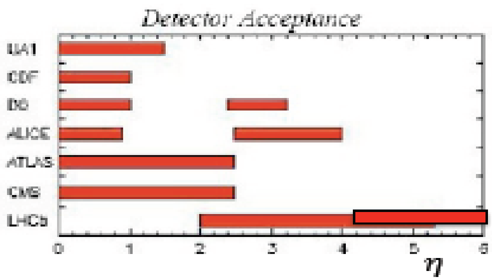
- Here x_A and x_B are the parton momentum fractions from each proton carried by the partons A and B. A and B can be quarks, antiquarks, gluons (…, even photons evolved with QED)
- In general Q is the typical energy scale involved in the AB → H process
- PDFs are universal (they can be determined at any experiment) and their evolution with Q² is predicted



Studies in the b sector at LHC: LHCb

LHCb is General Purpose Detector in the forward direction ($2 < \eta < 6$)

(designed to take data @ $2 \times 10^{32}\ cm^{-2}s^{-1}$)



LHCb is fully instrumented to provide:

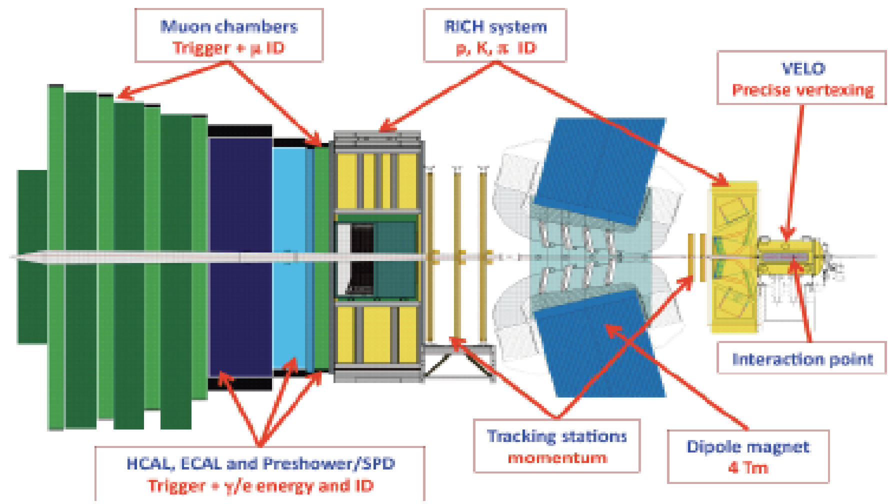
- Vertexing
- Tracking
- PID (hadron, muon, electron, photon)

&

Flexible Trigger to low P_t particles

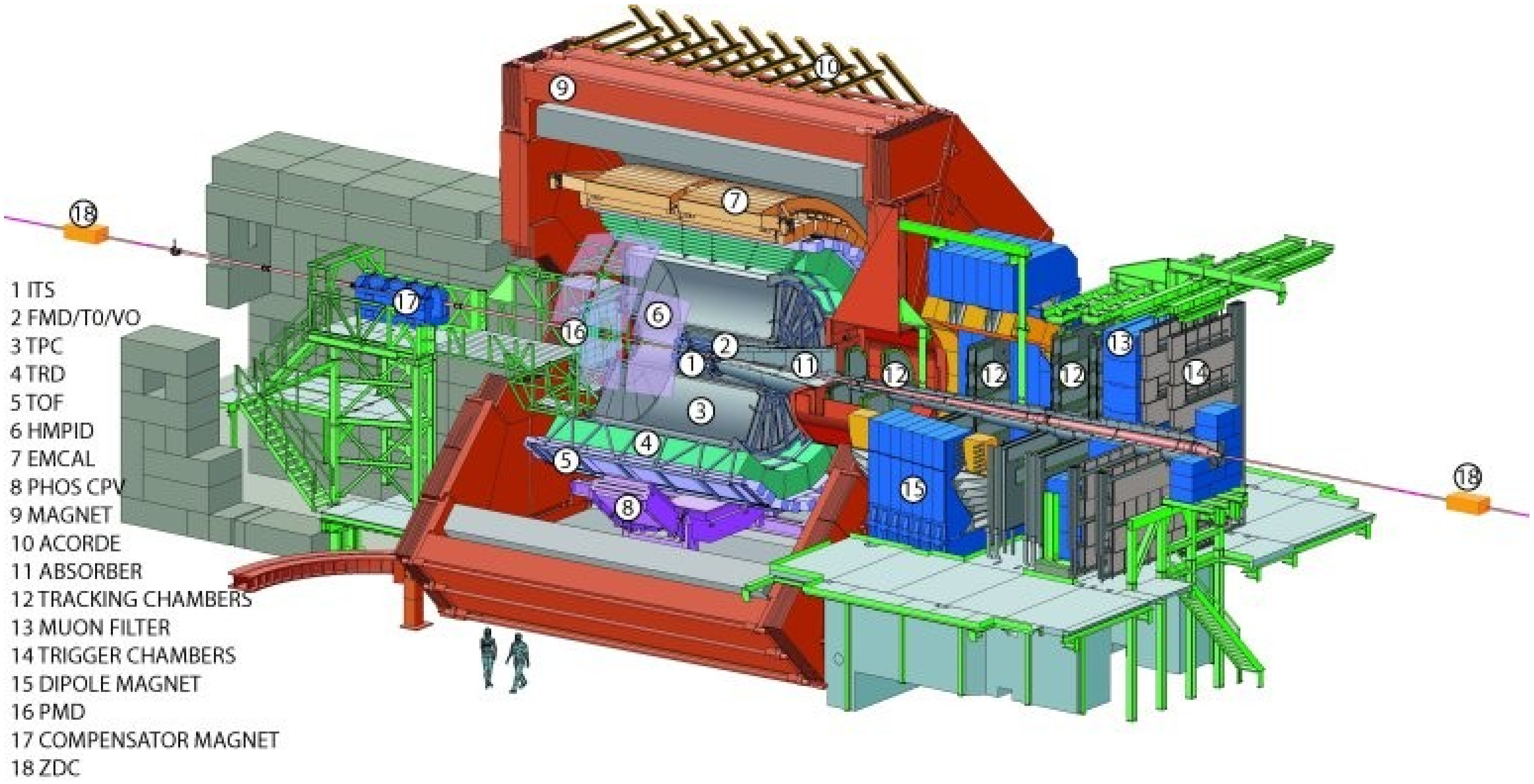
In particular well suited for flavour physics:

- Large bb (& cc) cross sections
- All B hadron species available
- Long decay flight ~ 1cm for b hadrons



(Andrey Golutvin, talk at La Thuile 2011)

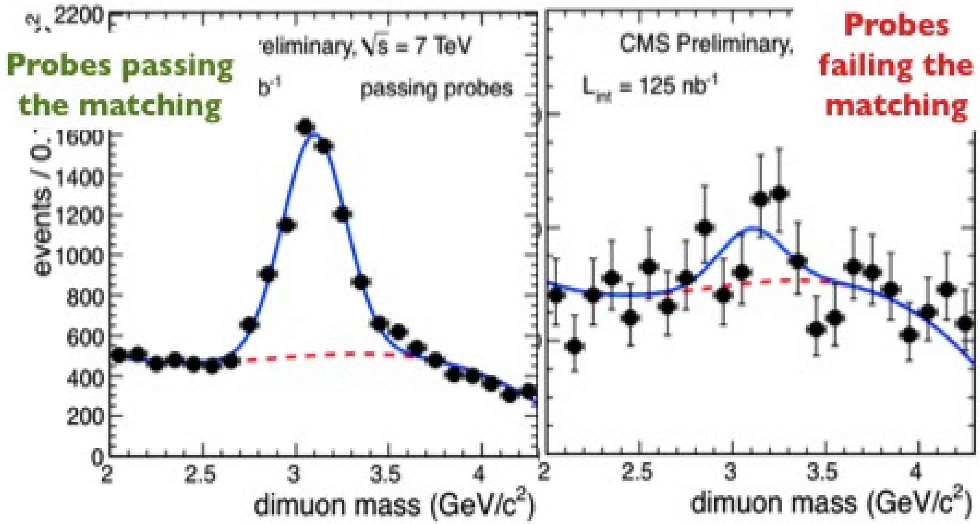
Heavy ion collisions at LHC: ALICE



- Many different sub-detectors, some of them covering small solid angle, but very specialized in particle identification/counting for heavy ion collisions (TPC(dE/dX), TOF, RICH counters, TRD, ...)

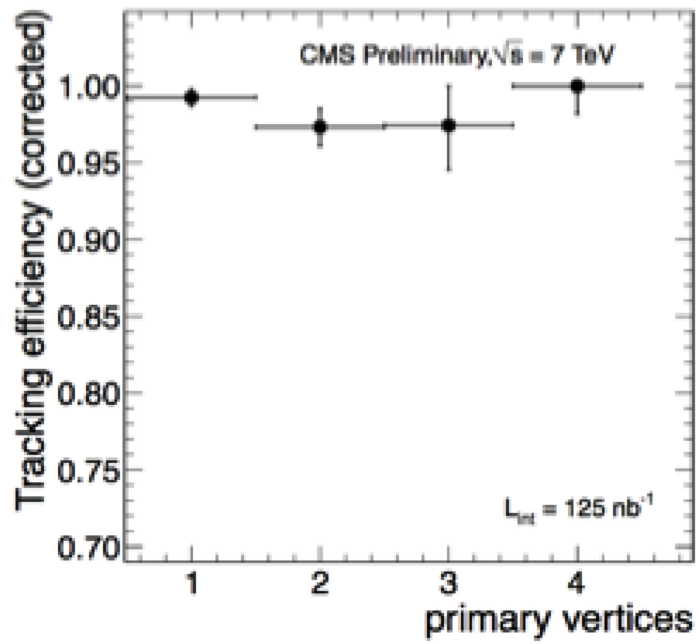
CMS: tracking performance

J/Psi Tag and probe

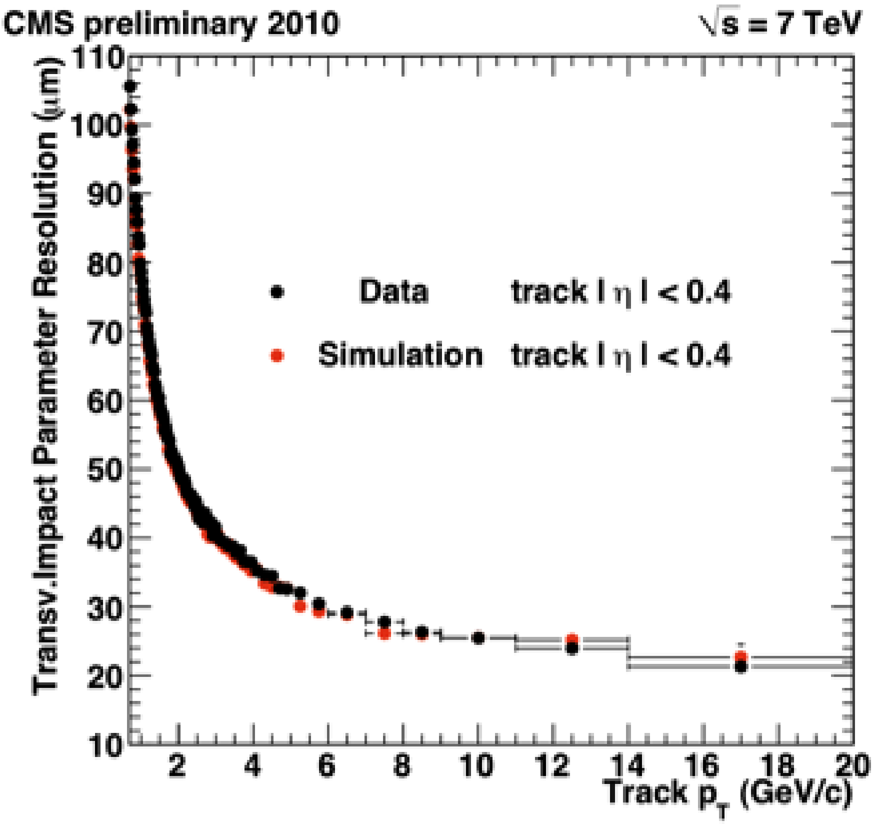


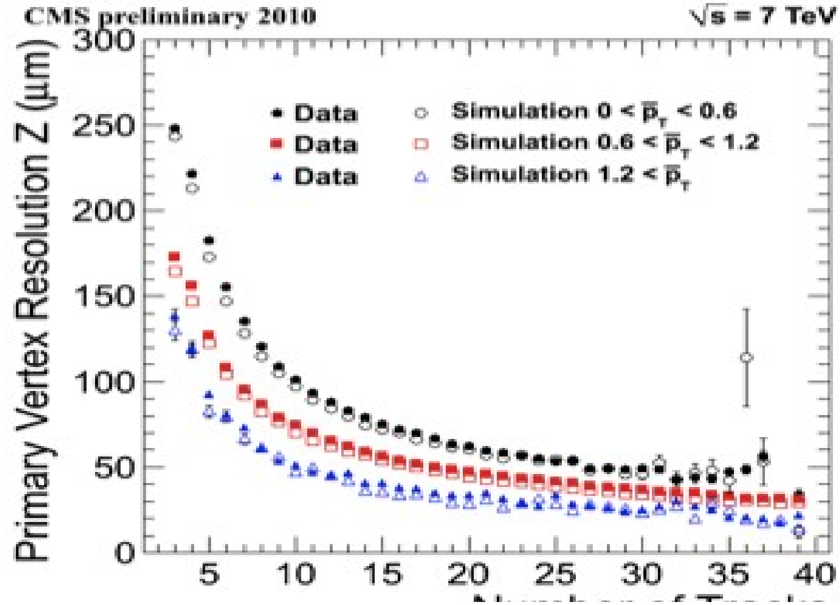
Region	Data Eff. (%)	Sim Eff. (%)	Data/Sim
$0.0 \le \lvert\eta\rvert < 1.1$	$100.0^{+0.0}_{-0.3}$	$100.0^{+0.0}_{-0.1}$	$1.000^{+0.001}_{-0.003}$
$1.1 \le \lvert\eta\rvert < 1.6$	$99.2^{+0.8}_{-1.0}$	$99.8^{+0.1}_{-0.1}$	$0.994^{+0.009}_{-0.010}$
$1.6 \le \lvert\eta\rvert < 2.1$	$97.6^{+0.9}_{-1.0}$	$99.3^{+0.1}_{-0.1}$	$0.983^{+0.009}_{-0.010}$
$2.1 \le \lvert\eta\rvert < 2.4$	$98.5^{+1.5}_{-1.6}$	$97.6^{+0.2}_{-0.2}$	$1.010^{+0.015}_{-0.016}$
Combined	$98.8^{+0.5}_{-0.5}$	$99.2^{+0.1}_{-0.1}$	$0.996^{+0.005}_{-0.005}$

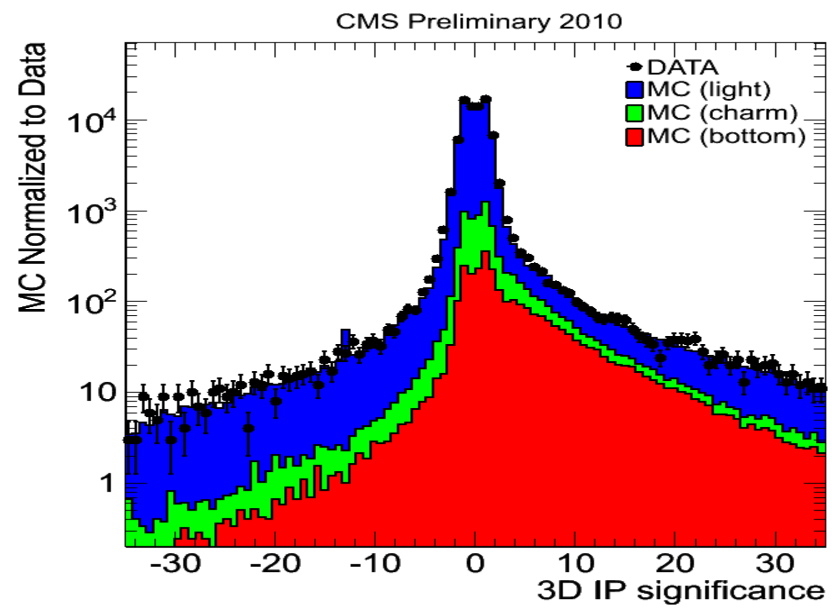
- Very high efficiency of tracking (measured also in data on J/Ψ samples). Even in the presence of pileup!



CMS: tracking performance



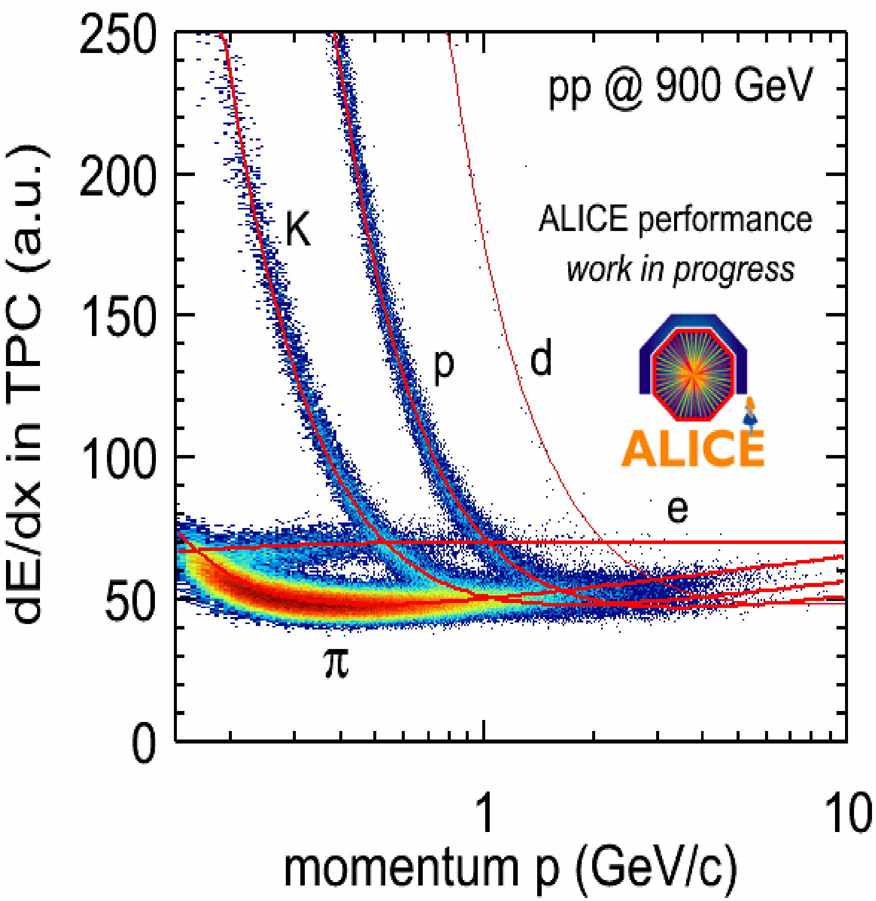


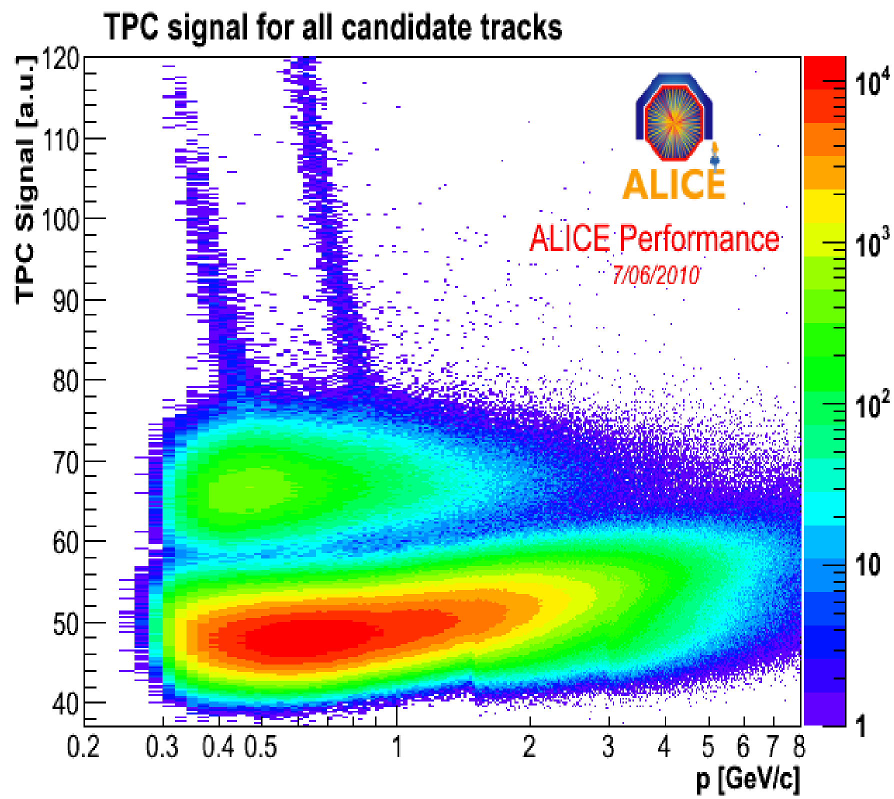


- High accuracy of impact parameter and vertex measurements, in reasonable agreement with simulations

Performance of dedicated particle-id detectors at LHC (initial LHC data in plots)

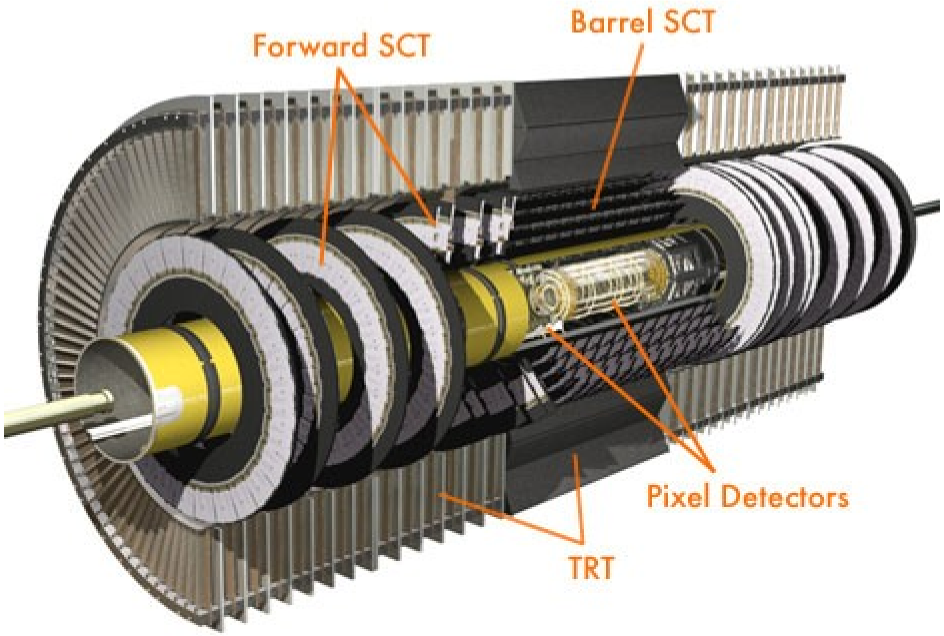
ALICE dE/dx

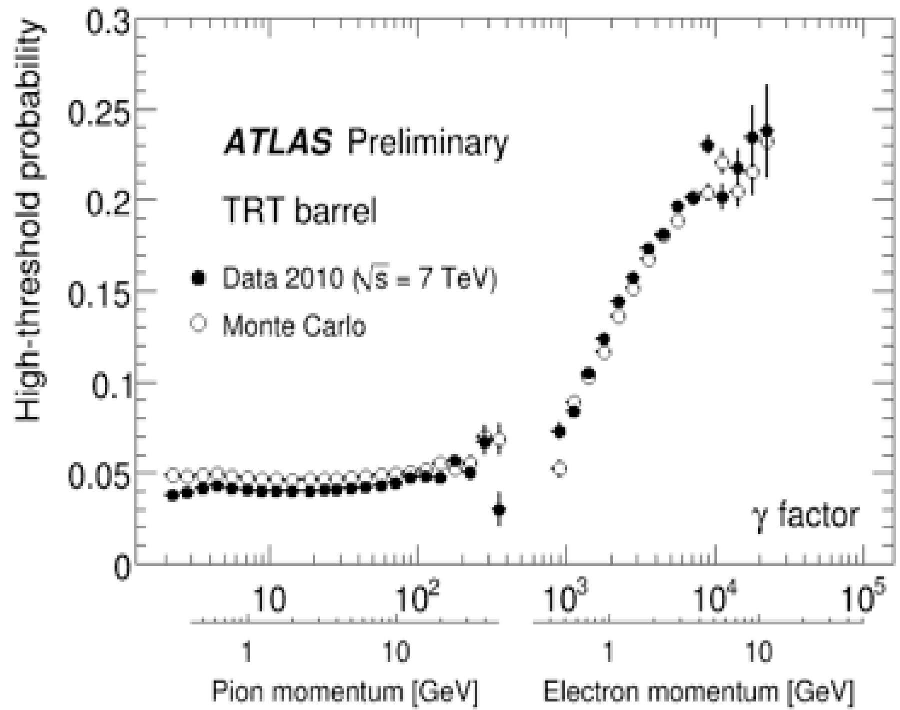




- Most effective sampling of the energy loss per unit length (dE/dx) in the TPC chamber (> 100 points per track)
- Good separation between electrons and pions (in relativistic regime)

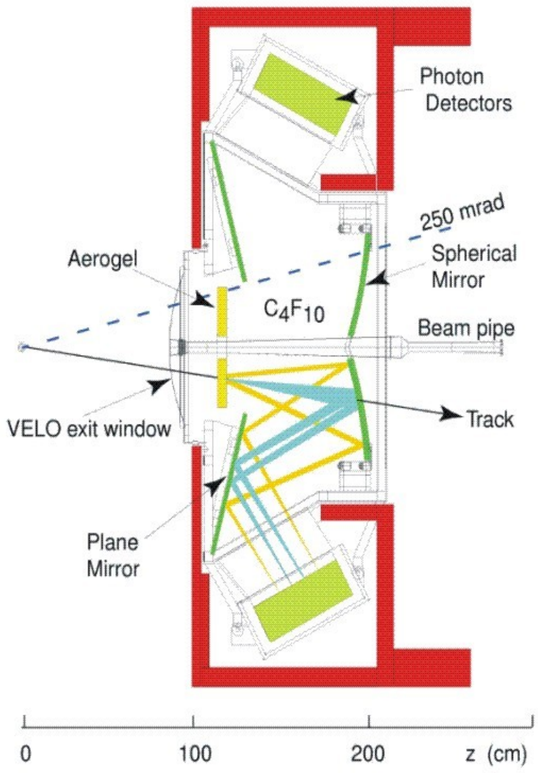
ATLAS: e/p separation using TRT

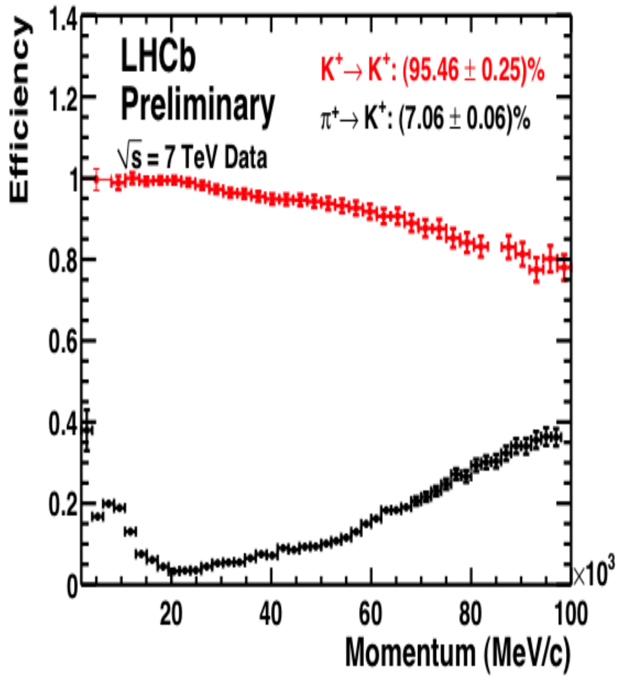


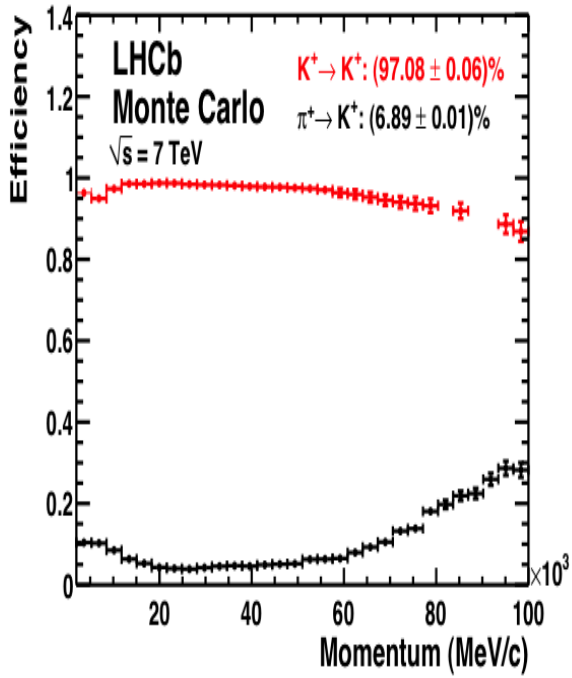


- Half of the radius of ATLAS tracking is filled with a Transition Radiation Tracker detector (TRT) (straw tubes mostly filled with Xe)
- Besides measuring the trajectory coordinates with decent precision (170 μm), it can differentiate electrons and pions in the 1-100 GeV momentum range (charged particles emitting significant X-ray radiation when traversing the different media for $\gamma = E/m \gtrsim 1000$)

RICH detectors



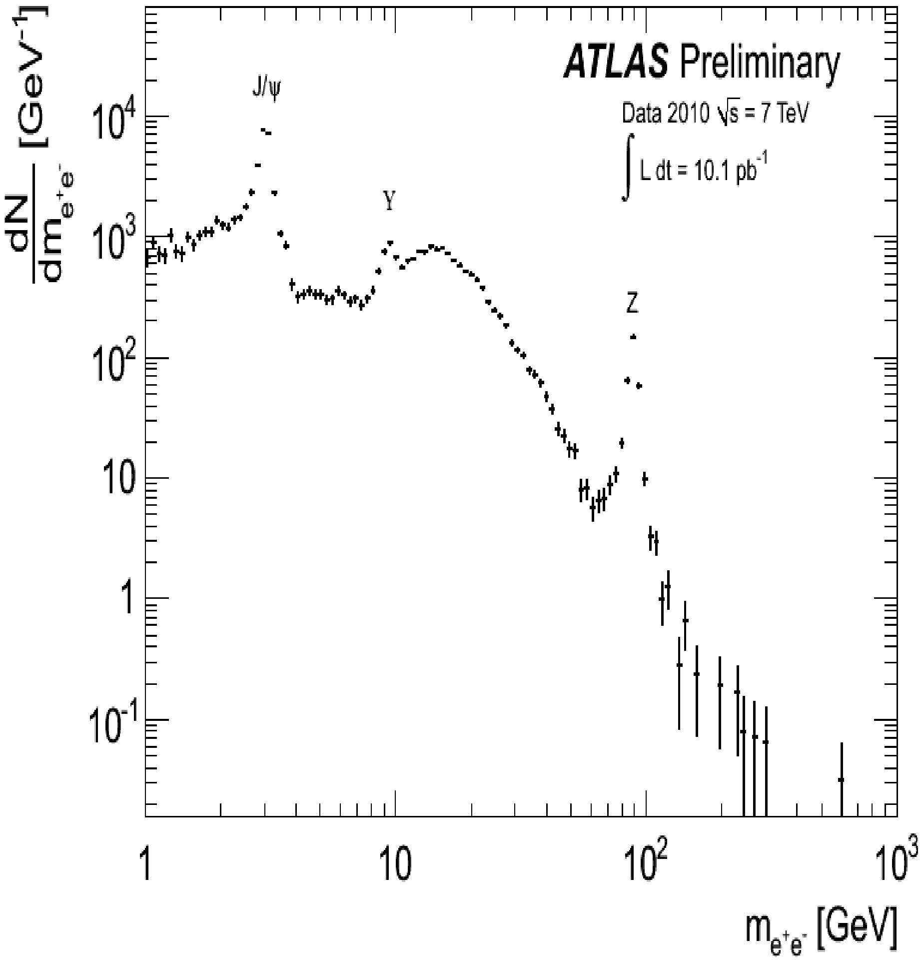


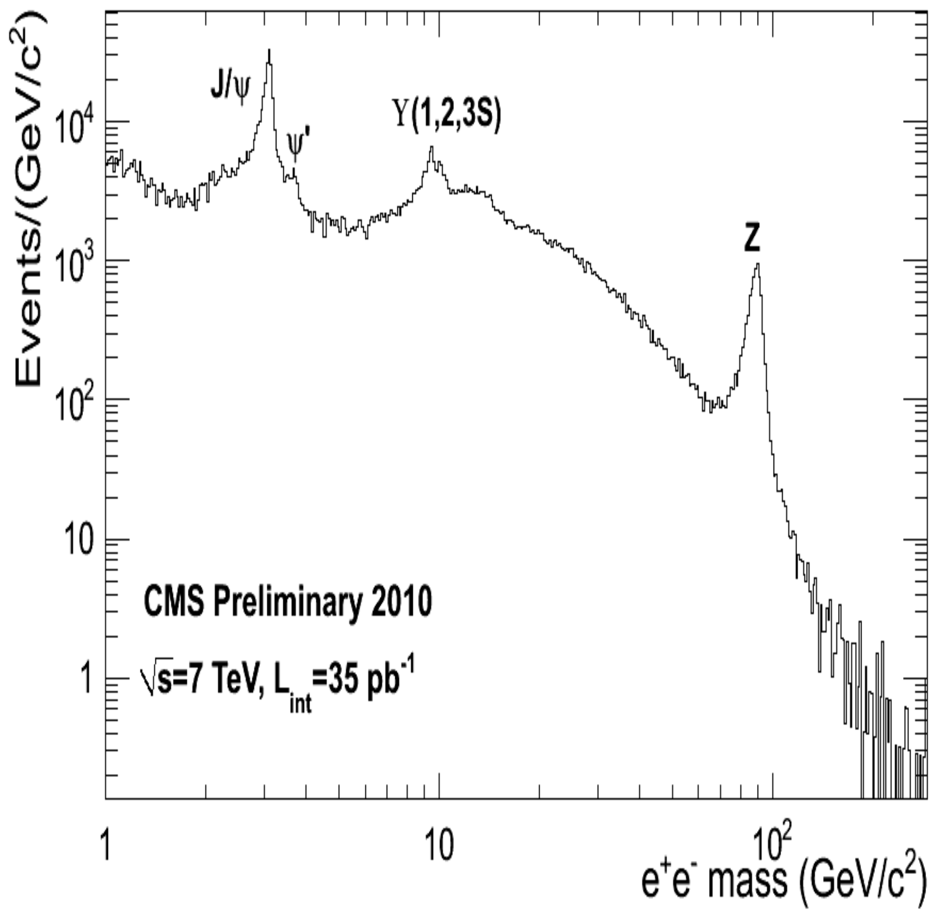


- Ring Imaging Cherenkov detectors (RICH) are typically used (at LHC) to differentiate pions and kaons in order to:
  - Do dedicated studies for strange production, ... (ALICE)
  - Identify exclusive bottom and charm decays (LHCb)
- Rather good agreement between data and MC expectations (LHCb)

ATLAS and CMS: electrons

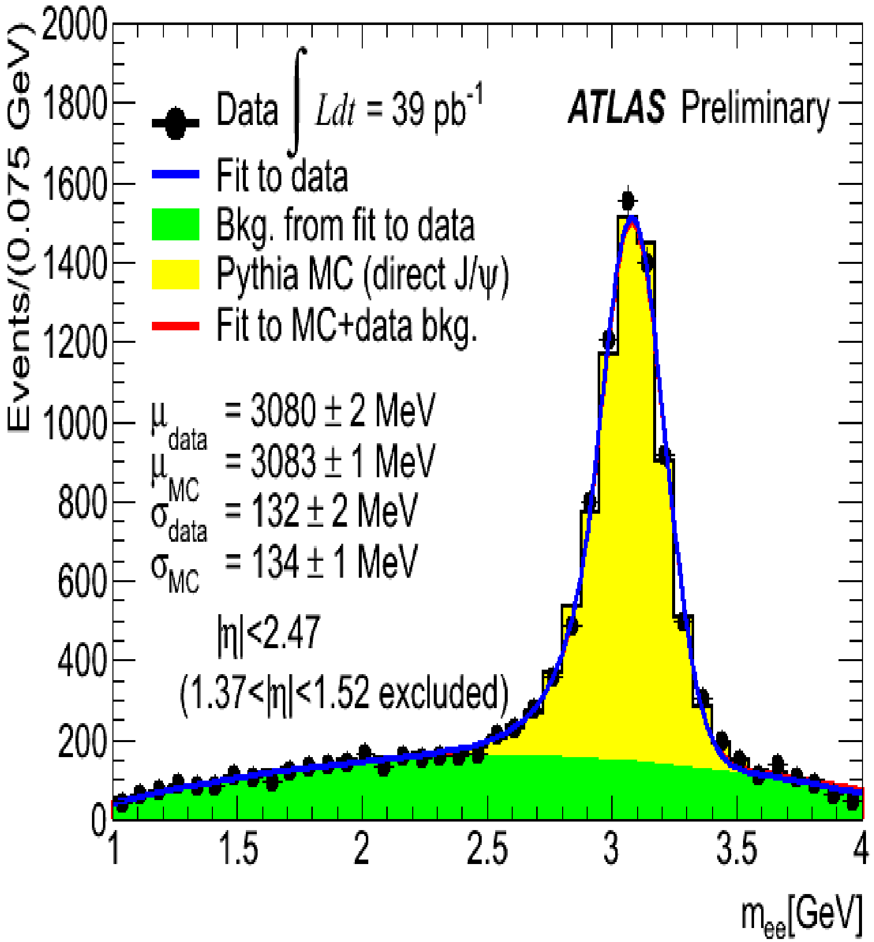
Good resolution confirmed in data already in Run1

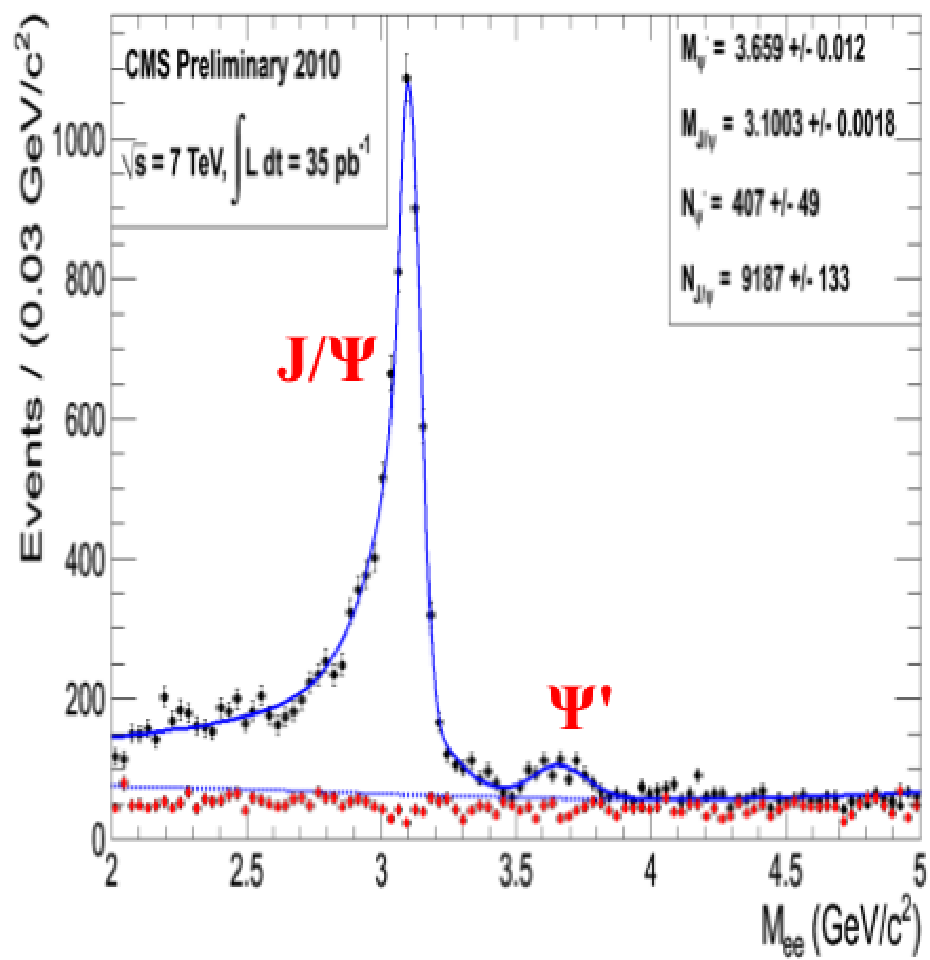




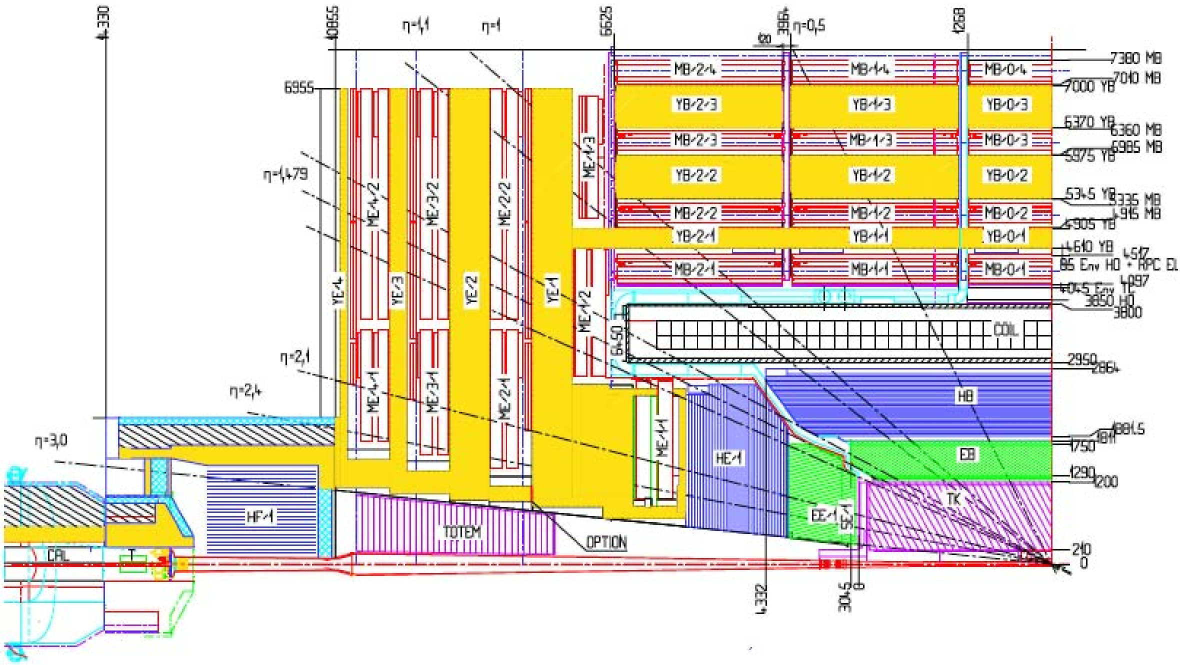
ATLAS and CMS: electrons

Good resolution confirmed in data already in Run1, both at low masses ...





CMS Hadronic Calorimetry



- Scintillator-brass/steel tile calorimeter: compact, hermetic, good segmentation and coverage (|η|<5.2)
- Jet transverse energy resolution (using ECAL+HCAL only, barrel):

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{1.25}{\sqrt{E}}\right)^2 + \left(\frac{5.6}{E}\right)^2 + (3.3\,\%)^2$$