LHC and Tevatron Results (1)

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6th CERN - Latin-American School of High-Energy Physics, Natal 2011

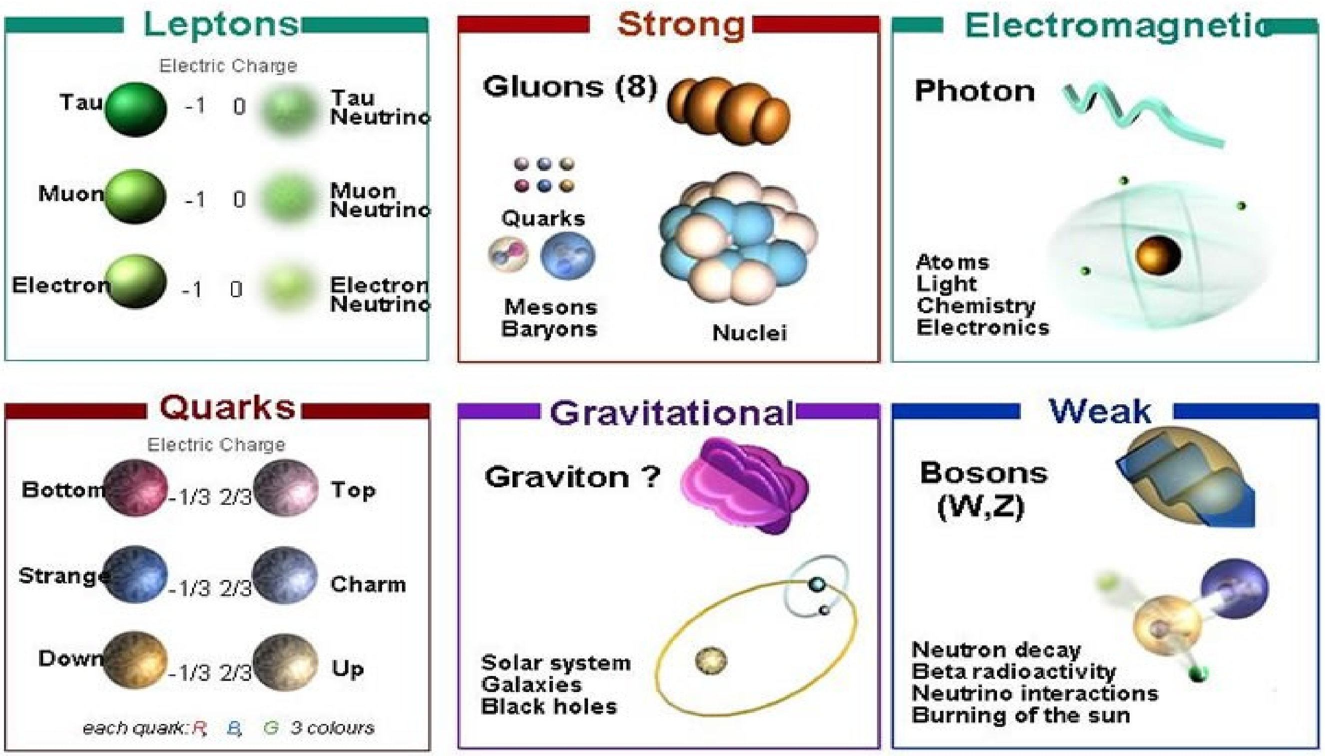
Disclaimers

- The physics output of the LHC experiments has been huge, particularly in the last months
  - It is very difficult to cover all those high quality results in detail in three school lectures
  - The weight of Tevatron results will be necessarily minimal in these lectures, mostly due to lack of time
  - Ditto for Heavy Ion results
- I have tried to balance simplicity and completeness, trying to be as useful and self-contained as possible. I'll do my best, but this may be difficult in some cases
- Since I belong to the CMS Collaboration, I may be a bit biased in the choice of figures to illustrate the different analyses
  - This does not mean that the results of other experiments (and ATLAS in particular) are less important/accurate

Outline

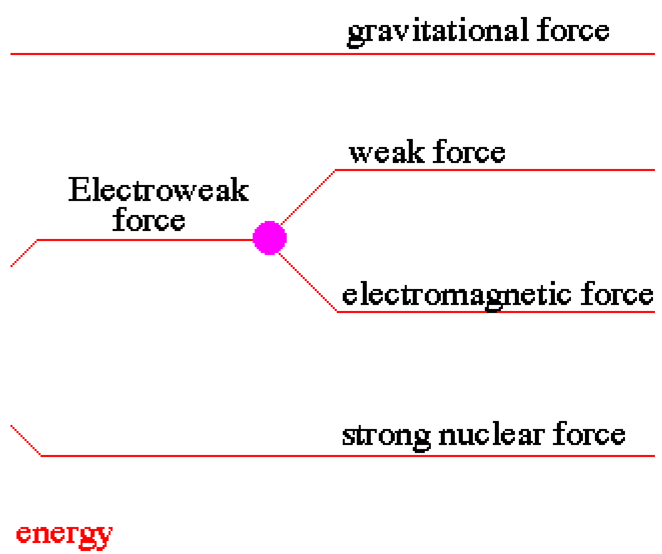
- Hadrons colliders, detectors, environment
  - Introduction
  - The LHC
  - The LHC detectors
  - The current performance and understanding of LHC detectors

What we know experimentally



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

And our theoretical understanding



?

$Z, W^{\pm}$

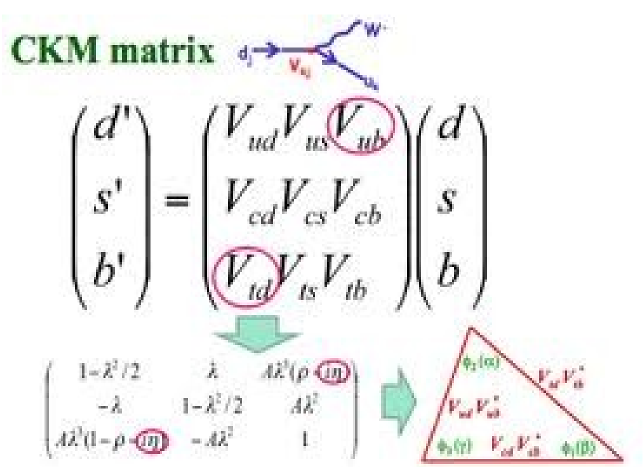
γ

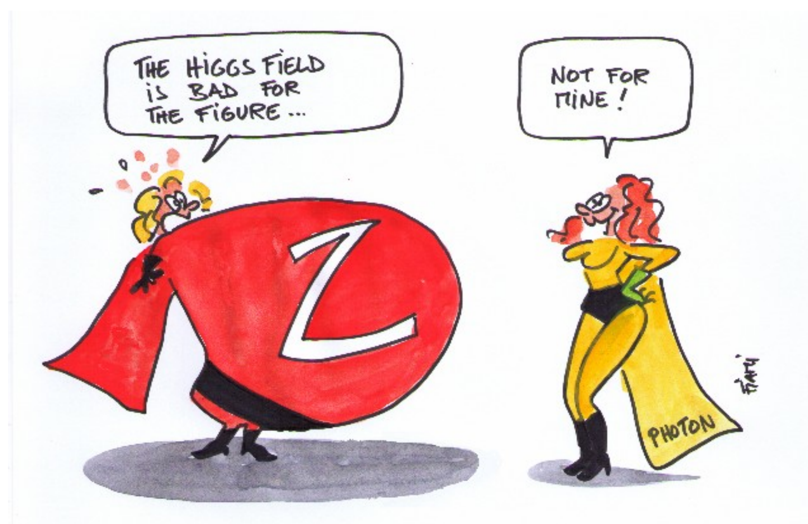
g

→ **Electroweak unification**

Strong force

SM





Some experimental limitations of the SM

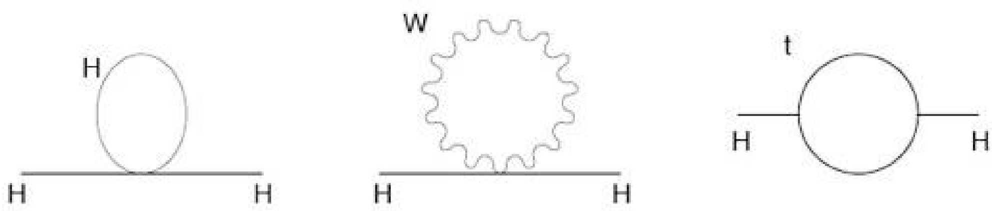
Where is the Higgs?

Not enough CP violation

What about dark matter?

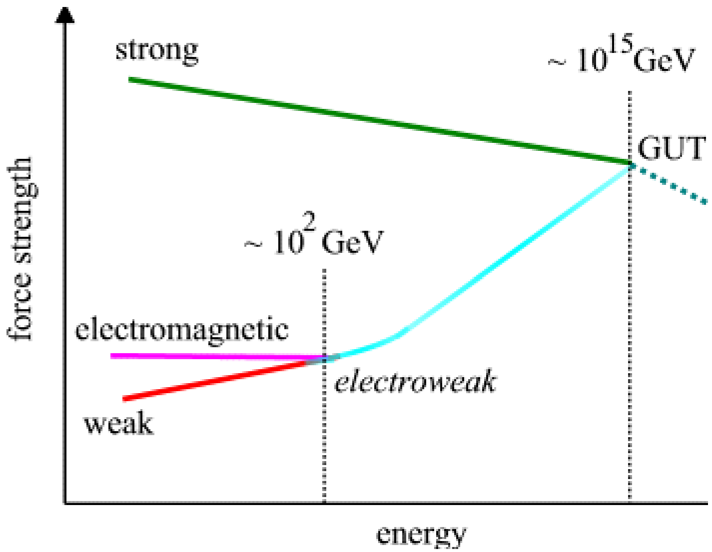
Is SM the right place for neutrino masses?

Some theoretical limitations of the SM

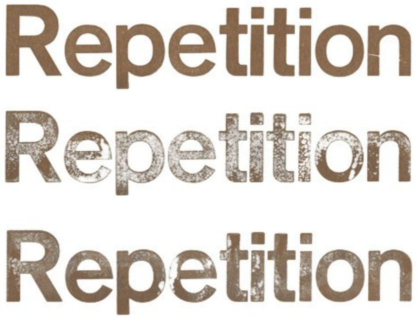


Hierarchy problem (m_H < 1 TeV is 'unnatural')

It does not even consider the gravitational force as part of the game

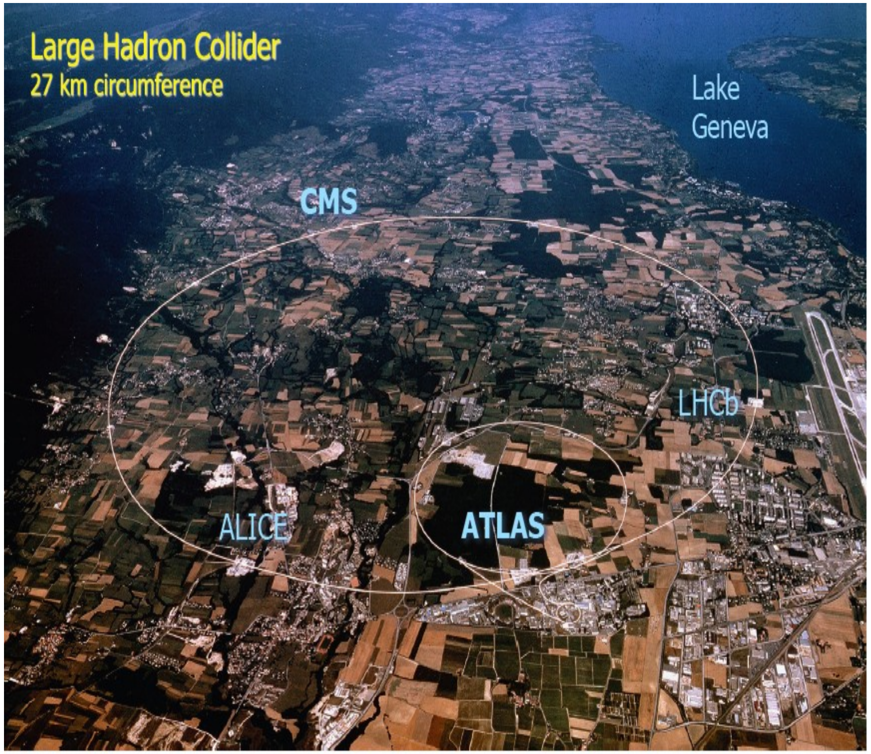


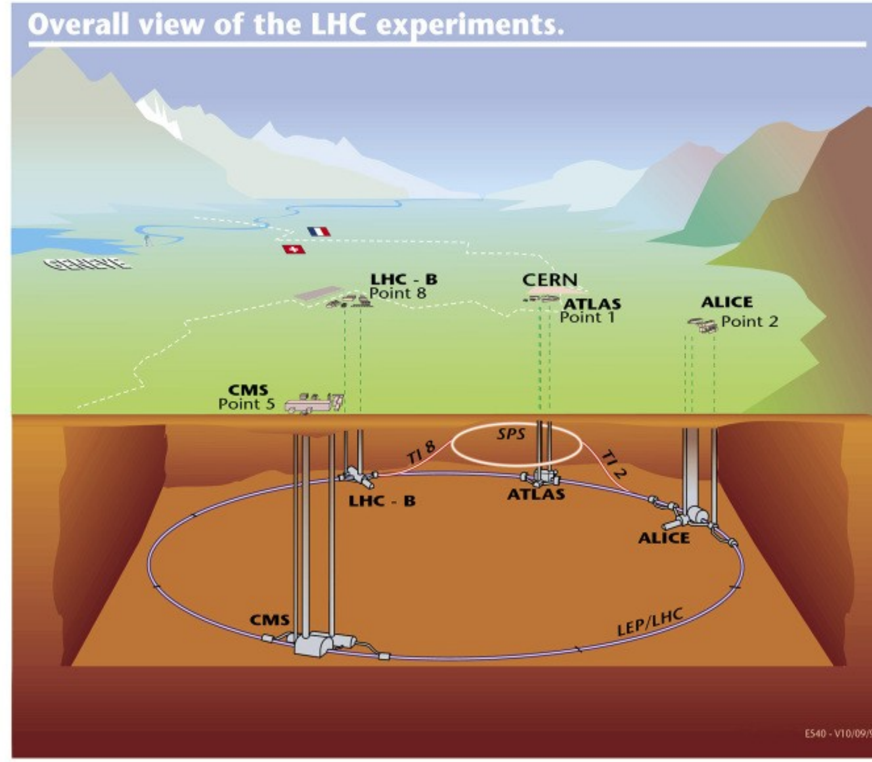
Why several fermion families? Why three? Why so many parameters (19)?



Strong interactions are not really “unified” within the SM

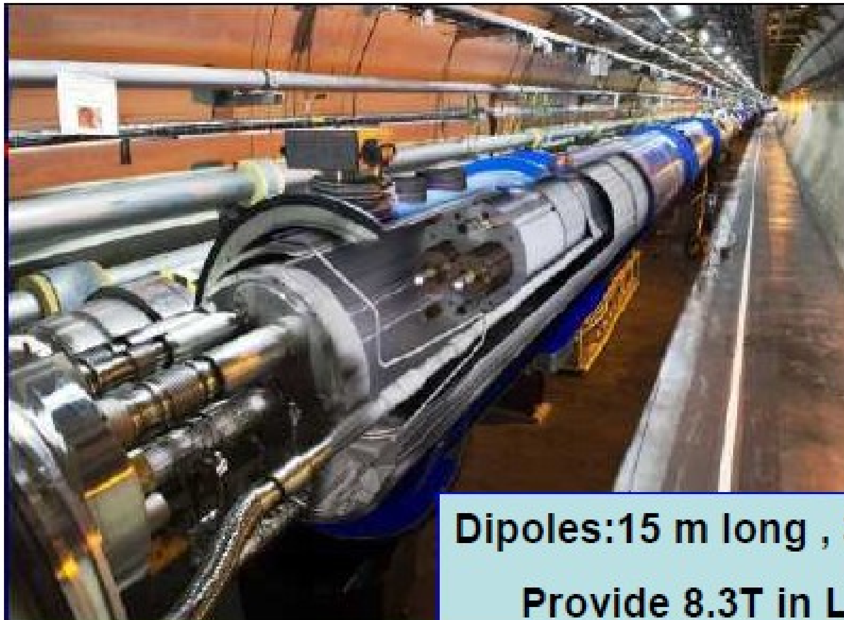
The Large Hadron Collider (LHC)





- Major objective: discover/study the Higgs particle:
  - For all masses up to 1 TeV in a Standard Model scenario
- It is designed to look for generic new physics signals at the TeV scale:
  - High center-of-mass energy (>~ 1 TeV) in collisions between elementary constituents

The Large Hadron Collider (LHC)

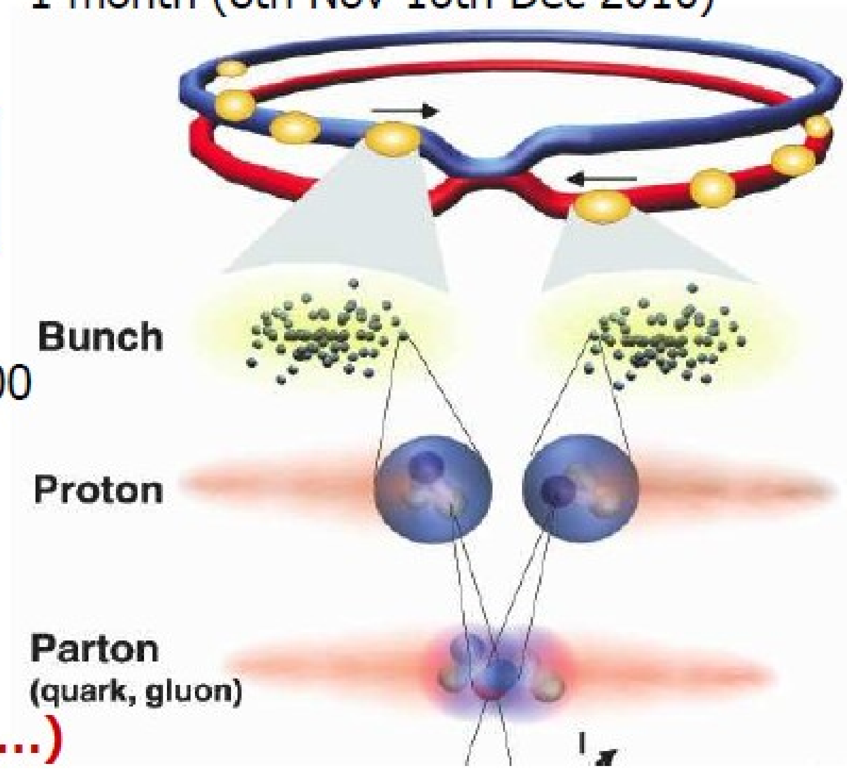


Dipoles:15 m long , 35 Ton

Provide 8.3T in LHC

Proton-proton collisions at √s = 7 TeV
From March 30th until 6th November
(initial tests & physics at √s = 0.9, 2.36 TeV by end 2009)

Pb-Pb collisions at 2.76 TeV/nucleon during 1 month (8th Nov-16th Dec 2010)



Largest superconducting magnet system: ~8000 magnets (1232 dipoles, 400 quadrupoles,….) refrigerated with liquid He at 1.9 K

Great technological challenge in many aspects (magnets, cryogenics, vaccuum, …)

The Large Hadron Collider (LHC)

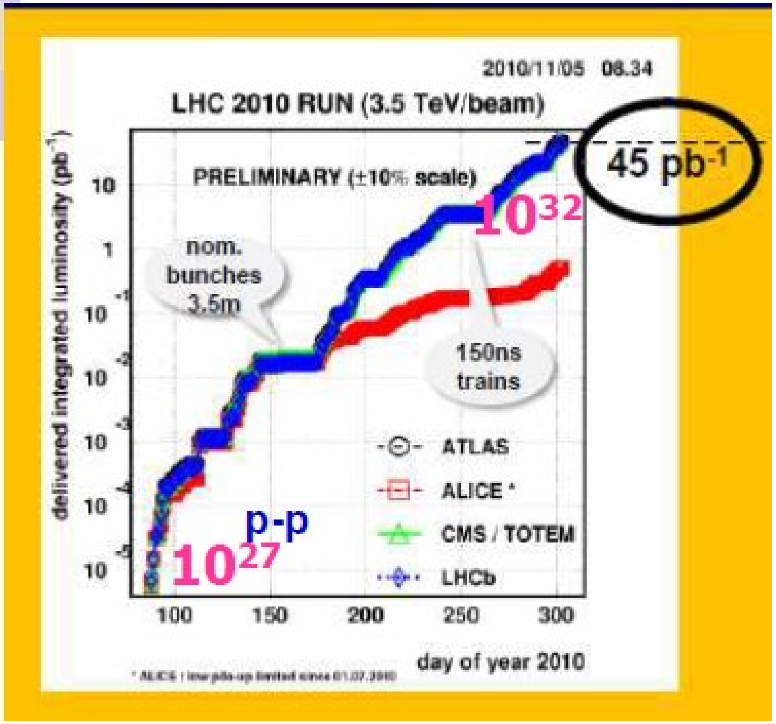
Parameter (pp Run)	2010	Nominal
Beam Energy	3.5 TeV	7 TeV
Inst. Luminosity	2. 10^{32} cm^{-2} s^{-1}	10^{34} cm^{-2} s^{-1}
Squeeze	3.5 m	0.55 m
Transverse emittance	2-3 μm rad	3.75 μm rad
Protons / bunch	Up to 1.2 10^{11}	1.15 10^{11}
Bunch separation	150 ns [a]	25 ns
Nb of bunches	368	2808

(a) Fills at 75 ns and 50 ns have also been achieved but mostly not for physics

Excellent understanding of the machine achieved!!

Five orders of magnitude in peak lumi in 200 days!!!

LHC Delivered Lumi:
- 47 pb^{-1} pp
- 9.5 μb^{-1} Pb-Pb



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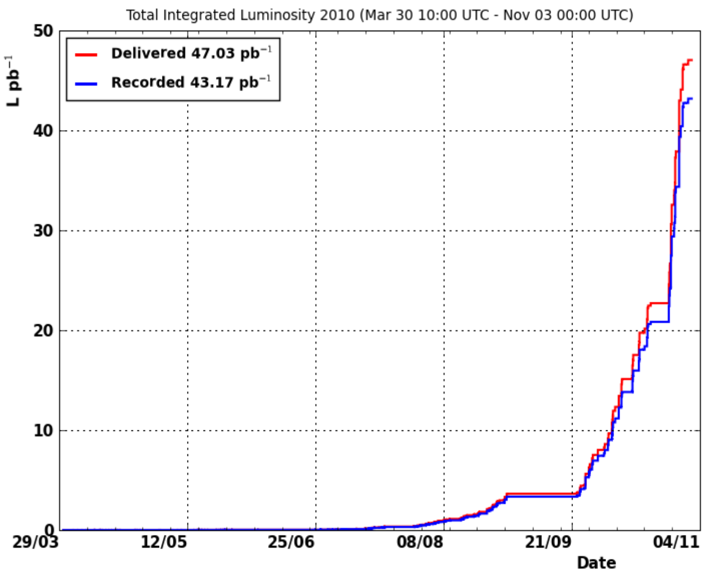
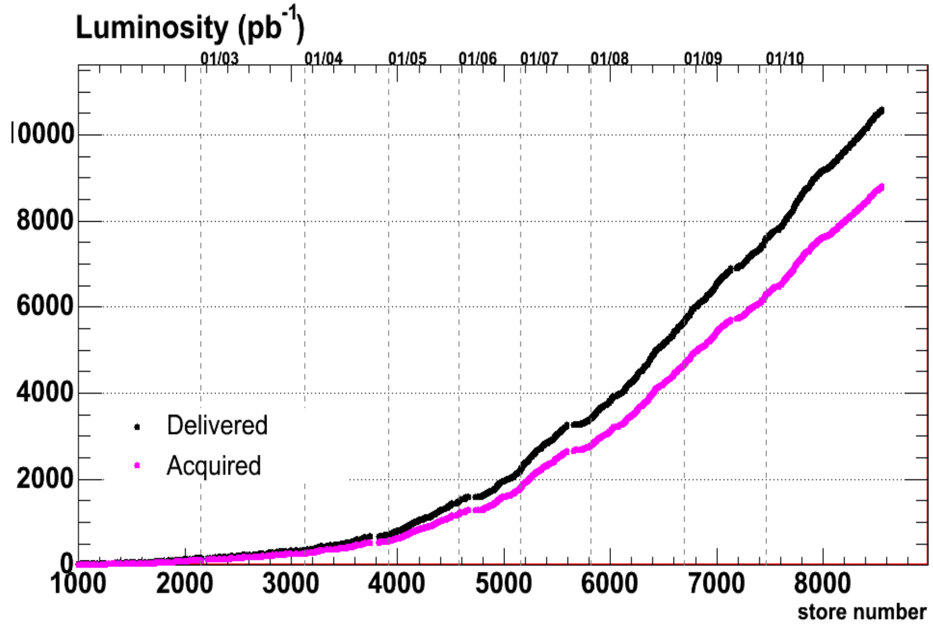
LHC vs Tevatron

- Proton-proton collider
- Max. $\sqrt{s}$ = 14 TeV (currently $\sqrt{s}$=7 TeV)
- Peak luminosity 10^{34} cm^{-2} s^{-1} (already reached: 2 10^{32} cm^{-2} s^{-1})

- Proton-antiproton collider
- Max. $\sqrt{s}$ = 1.96 TeV
- Peak luminosity ~ 4 10^{32} cm^{-2} s^{-1}

LHC vs Tevatron





- > 40 pb^{-1} / experiment delivered in 2010
- ≳ 1 fb^{-1} / experiment (ATLAS, CMS) expected in 2011

- > 10 fb^{-1} / experiment delivered until 2010 (factor of 250 with respect to current LHC integrated luminosity)
- This should increase to 12 fb^{-1} or so until September 2011 (end of Tevatron)

Despite the limited integrated luminosity, the LHC is expected to beat already Tevatron in most new particle searches ≳ 1 TeV (see next slides)

Proton-proton collisions

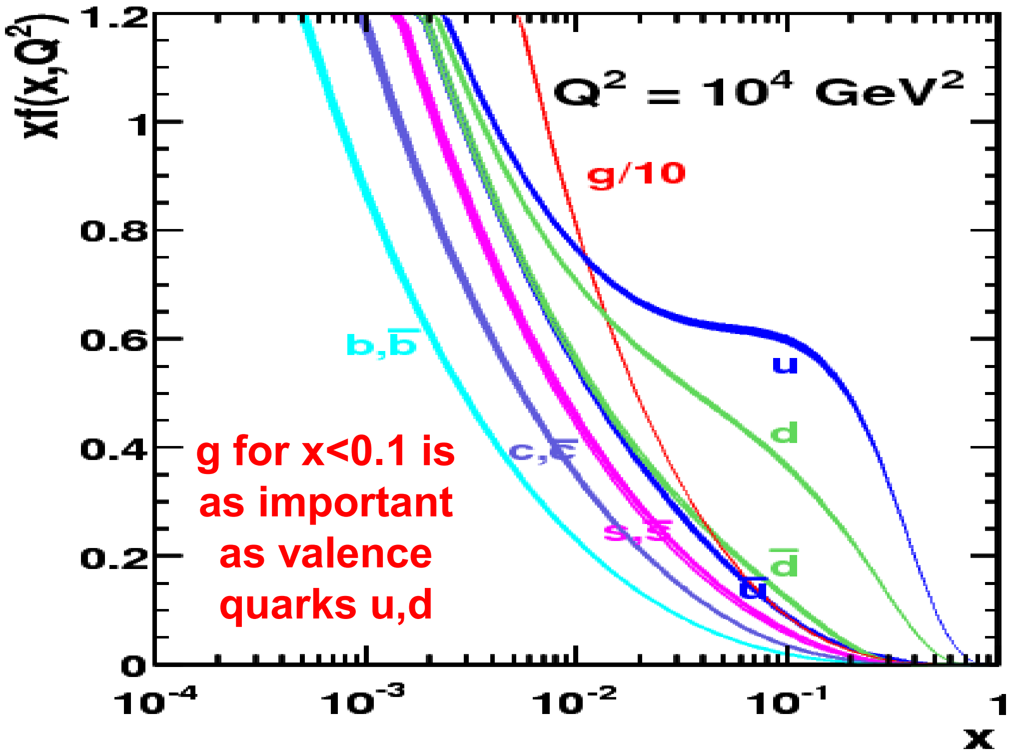
- Let us exploit the factorization properties of the cross section in terms of parton distribution functions (pdfs) and the hard elementary process. For a process AB → H (at leading order):

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

- 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 or gluons

- 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 Q is predicted



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Cross sections and parton luminosities

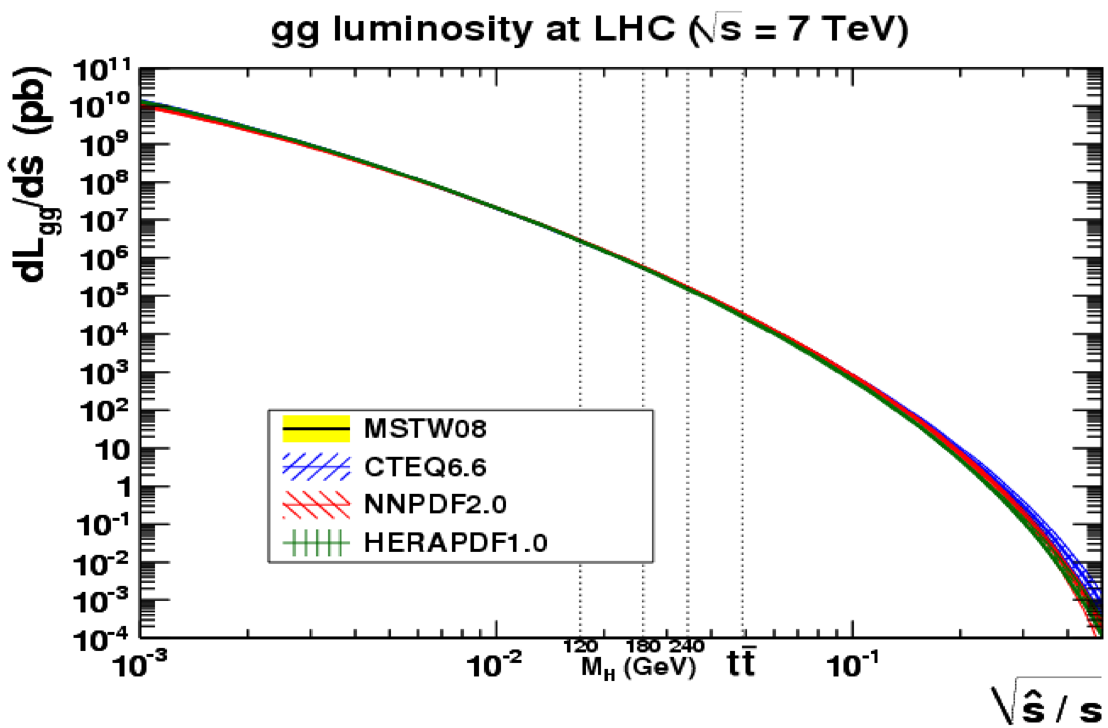
- For a process AB→H+X, the hard interaction scale is $\bar{s} = x_{partonA}\, x_{partonb}\, s$, and we can rewrite the expression as:

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

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

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



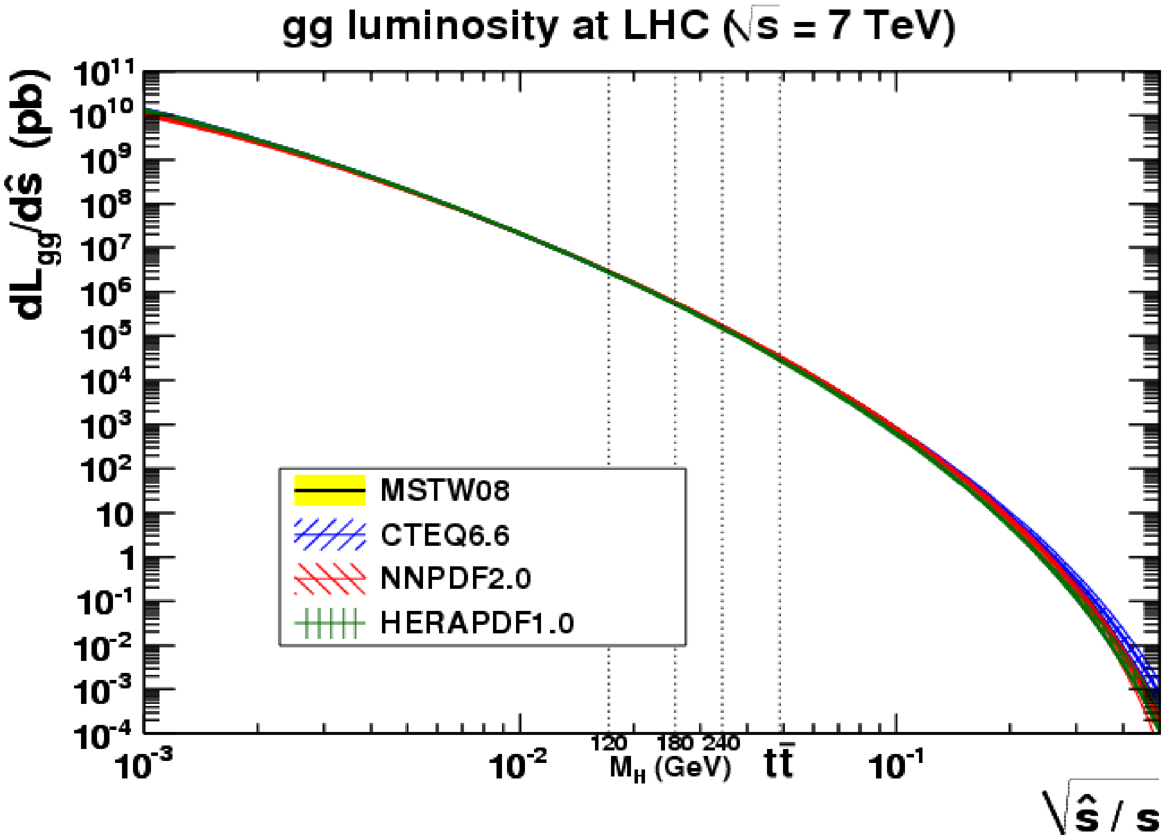
What do we expect for a new resonance?

- If H is a narrow resonance, with mass M, width Γ ($M^2 = x_A\, x_B\, s$):

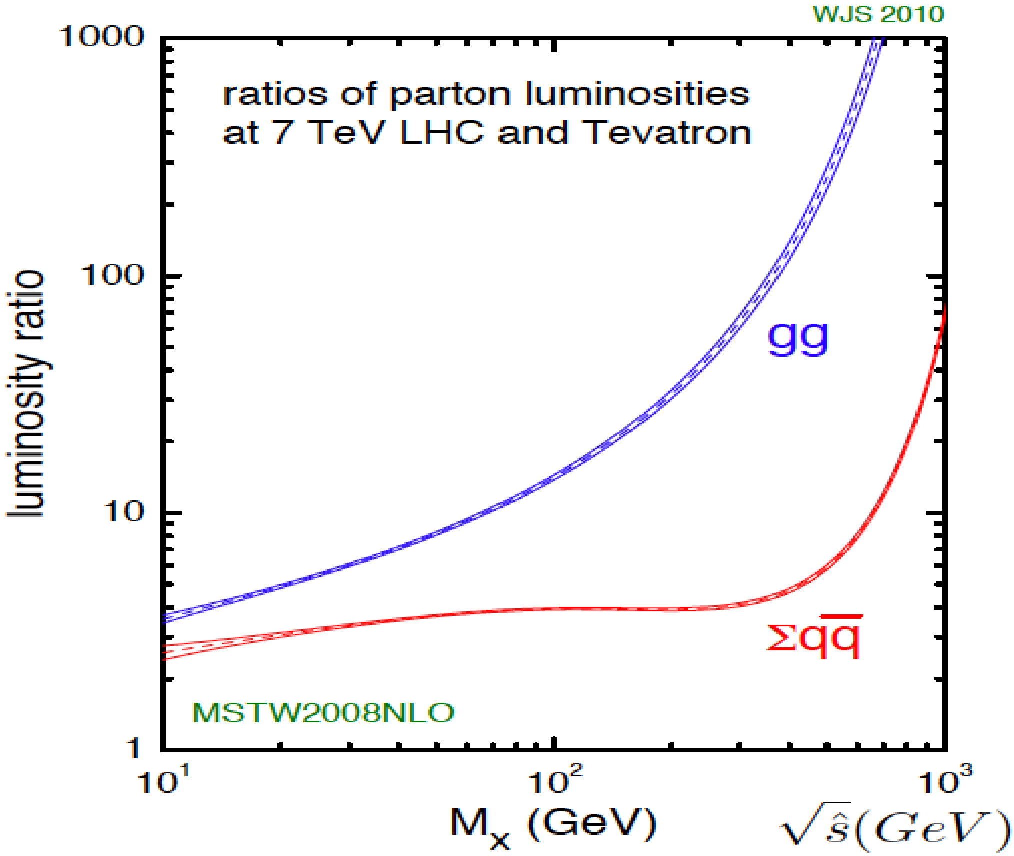
$$\sigma(pp \to H+X) \approx \sum_{A,B} \frac{dL_{AB}}{d\hat{s}}(\hat{s}=M^2)\; M\,\Gamma\,\sigma(AB\to H)$$

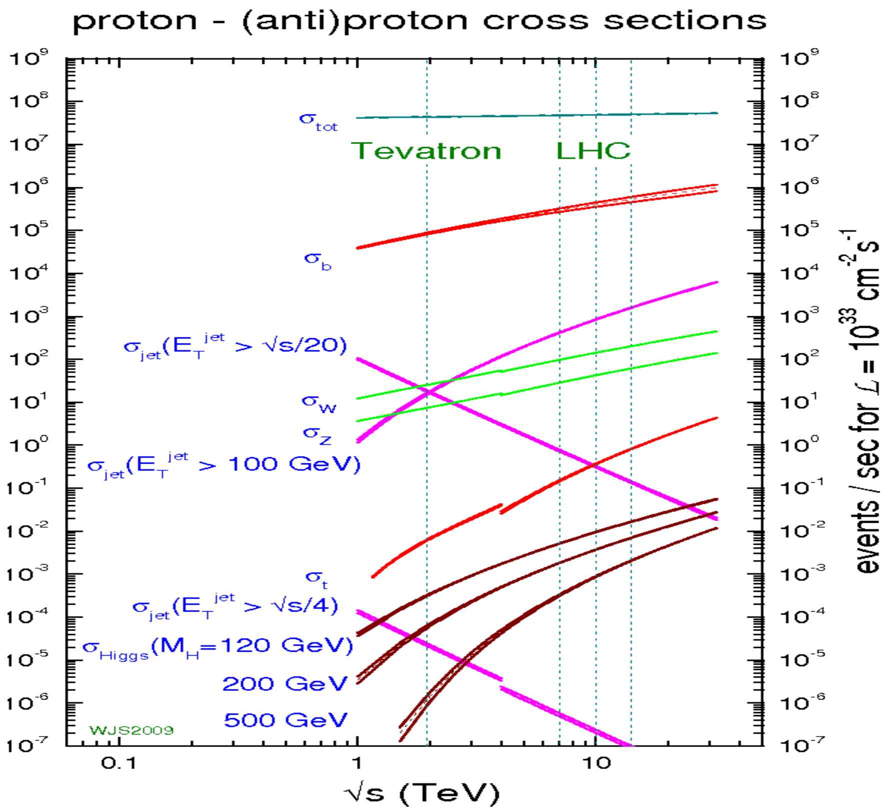
dL_{AB}/dM^2 (M) is the 'parton luminosity function' at the mass M.

Since σ(AB→H) it does not depend on the center-of-mass energy, it is enough to use dL_{AB}/dM^2 (M) to compare the physics reach of different colliders



LHC vs Tevatron





- Cross sections via $q\bar{q} \rightarrow X$ at LHC 3 times larger than at Tevatron
- Cross sections via $gg \rightarrow X$ at LHC 10-100 times larger than at Tevatron
- Reach for $pp \rightarrow X$ with mass(X)> 500 GeV much, much larger at LHC

LHC @ CERN (Geneva)

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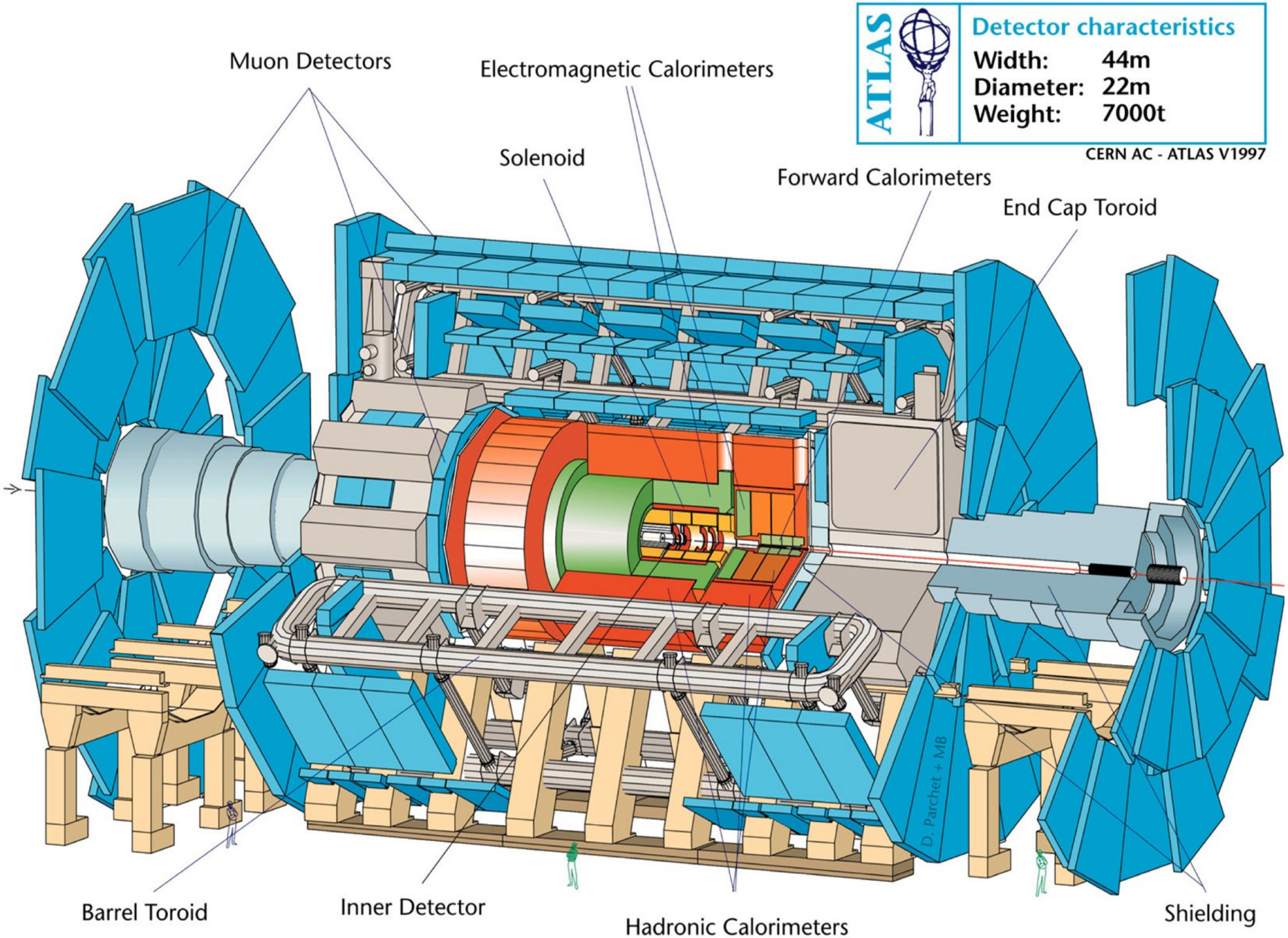
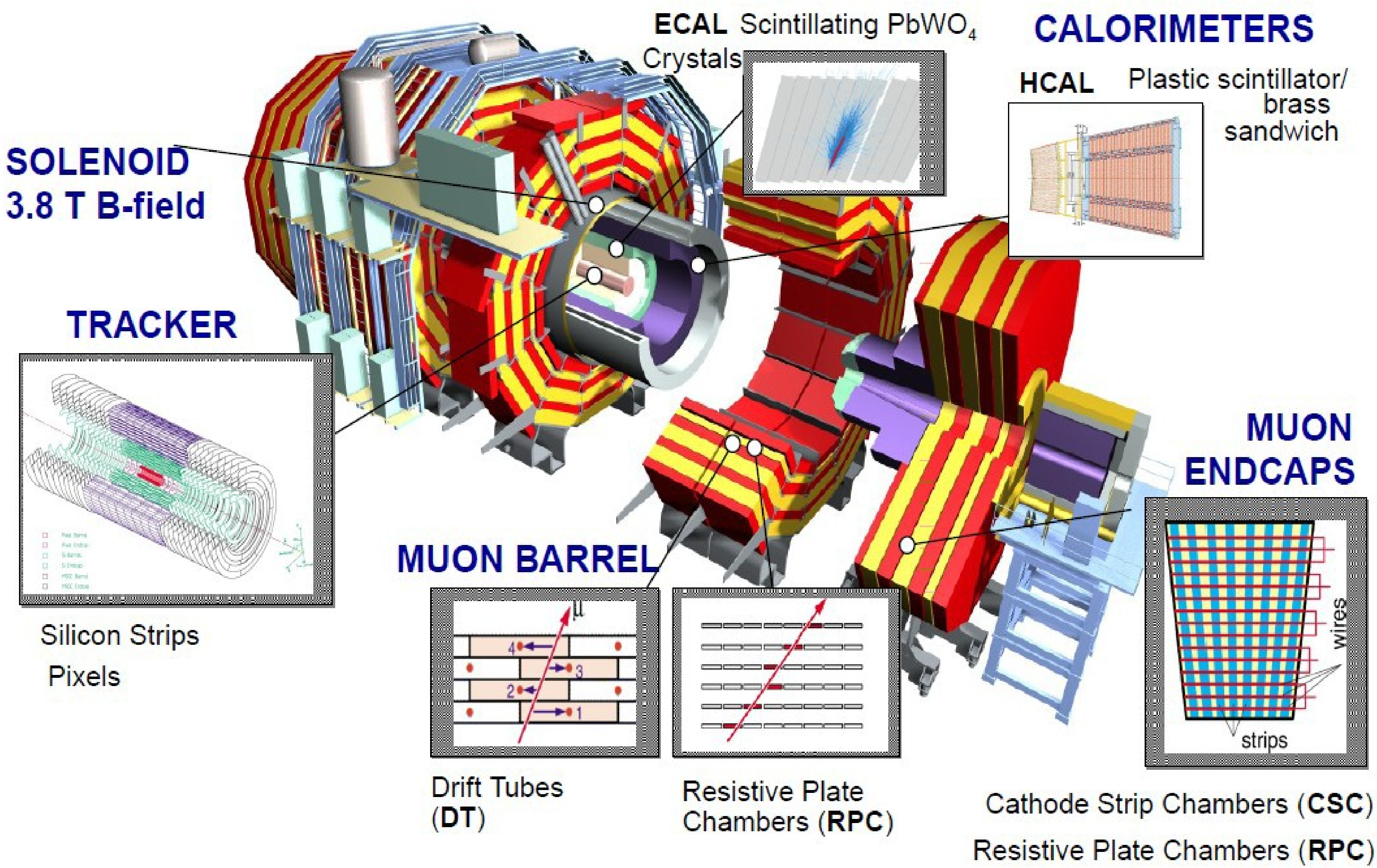
LHC multipurpose detectors: ATLAS



LHC multipurpose detectors: CMS



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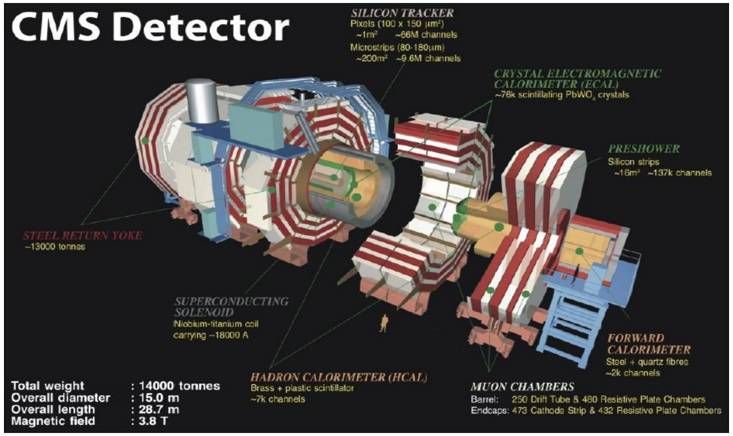
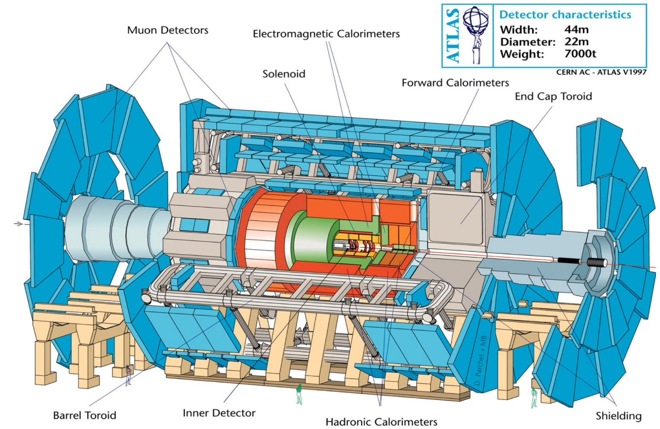
The ATLAS and CMS design goals

- 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

ATLAS vs CMS. Some differences

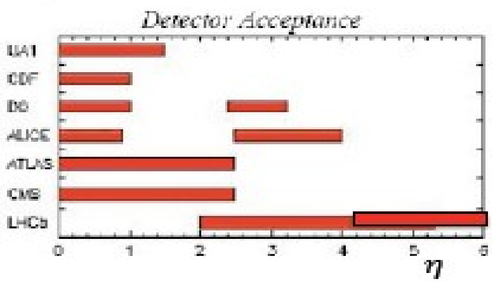




- CMS has a huge and powerful solenoid (3.8 T) covering tracker and calorimeters, and a huge silicon tracker volume (1.2 m radius). ATLAS has a less powerful solenoid (2T), silicon up to 0.5 m radius and a transition radiation tracker up to 1.2 m radius. CMS has better resolution in inner tracking.
- 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 redundant muon trigger systems.
- ATLAS has a precise electromagnetic lead-liquid argon calorimeter, with high granularity and sampling. CMS has a crystal calorimeter ($PbWO_4$), with an excellent energy resolution.
- ATLAS has a very precise, granular hadron calorimeter. CMS has a more conventional, hermetic calorimeter. ATLAS has better hadron calorimetry.

Studies in the b sector at LHC: LHCb

LHCb is General Purpose Detector
in the forward direction ($2 < \eta < 6$)
(designed to take data @ 2×10^{32} cm^{-2}s^{-1})



LHCb is fully instrumented to provide:

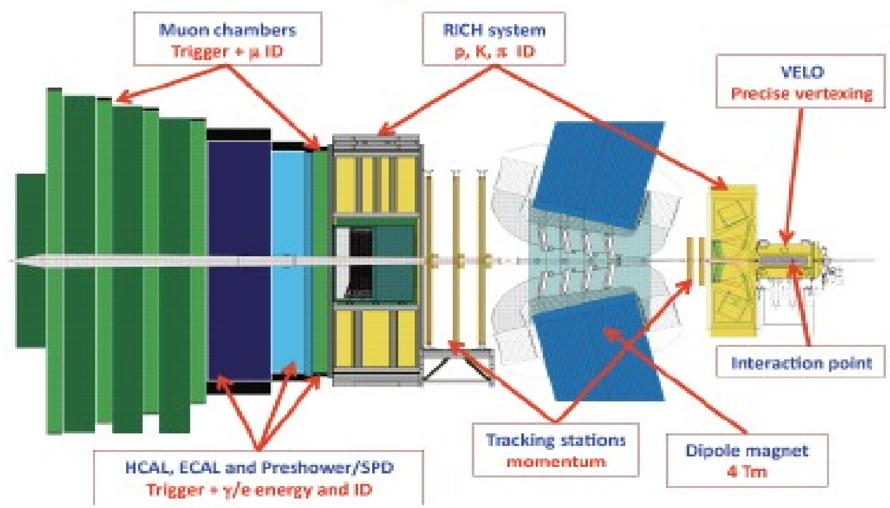
- *Vertexing*
- *Tracking*
- *PID (hadron, muon, electron, photon)*

&

Flexible Trigger to low P_t particles

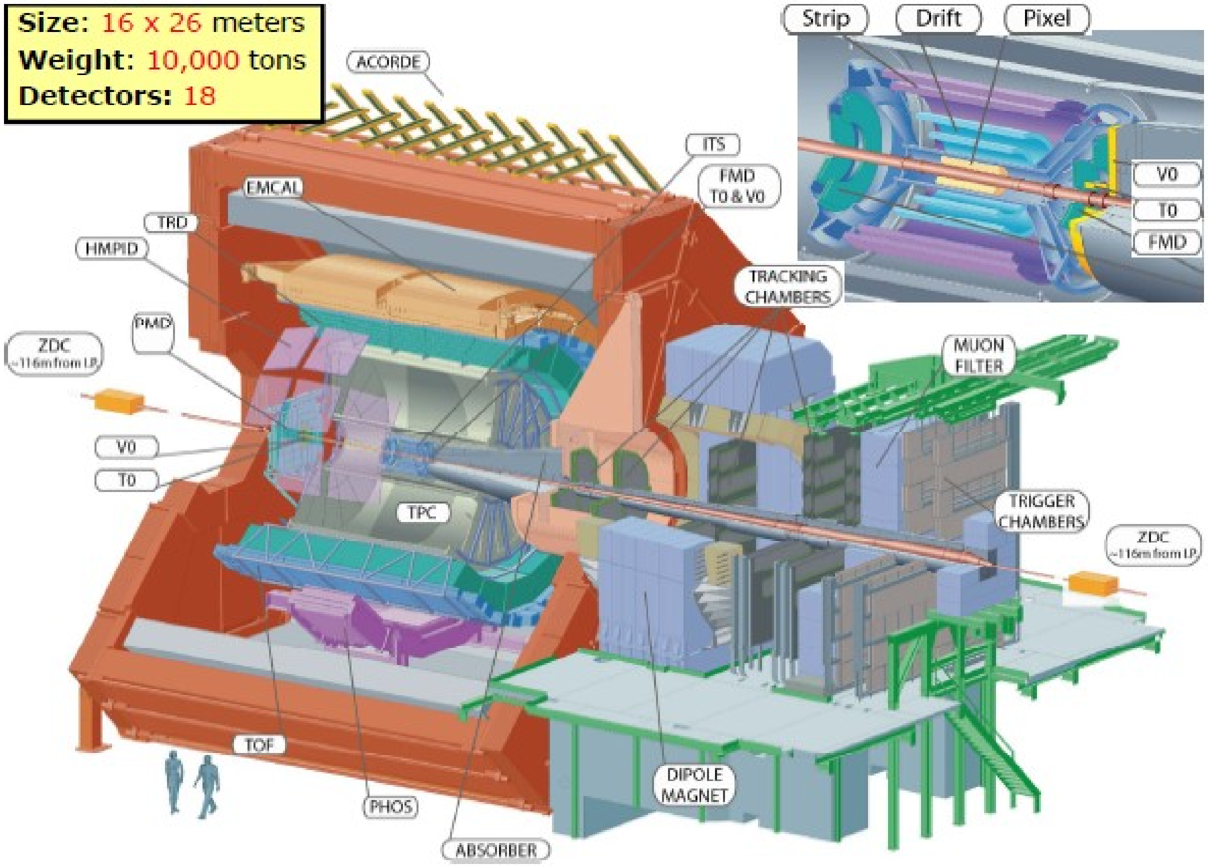
In particular well suited for flavour physics:

- *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, ...)

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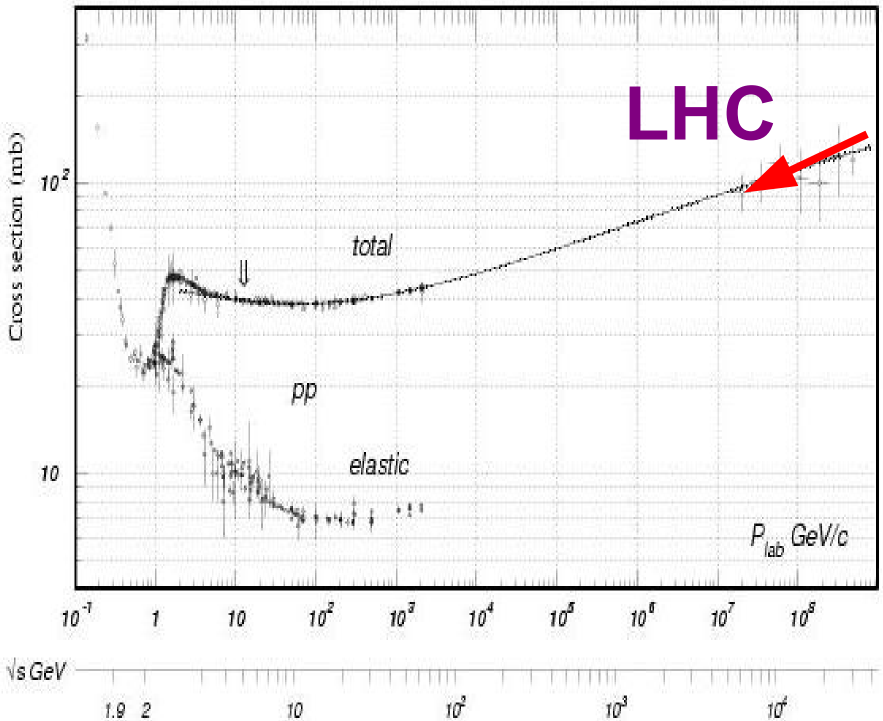
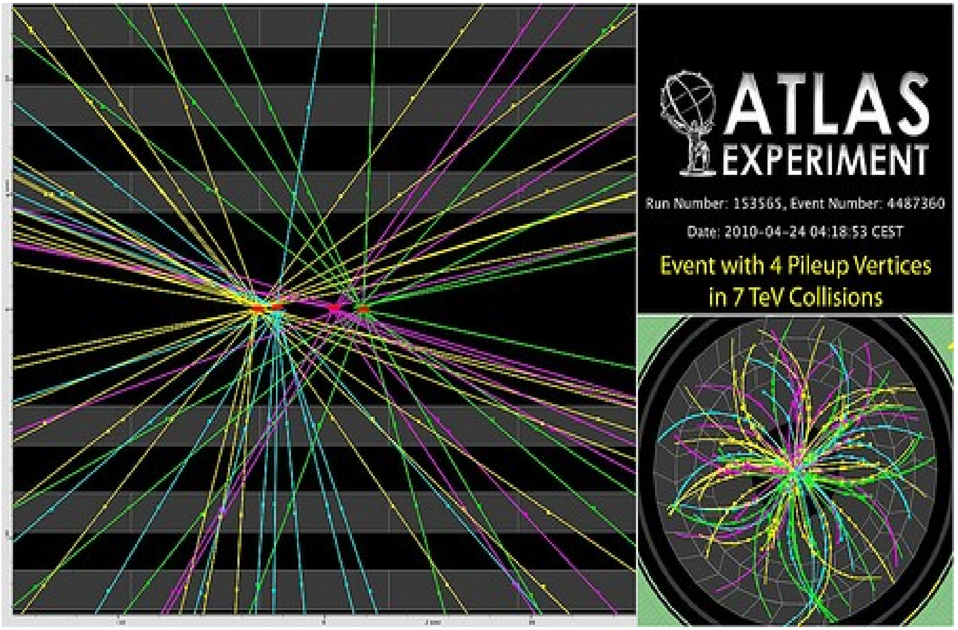
Trigger systems

Life is not easy for experiments...

- The total inelastic hadron-hadron cross section is enormous





$$\sigma\,(inelastic, \sqrt{s} = 7\,TeV) \sim 100\ mb$$

$$\sim 2 * 10^{7}\ events\ /second\ at\ a\ luminosity\ of\ 2 * 10^{32}\ cm^{-2}\ s^{-1}\ \ in\ 2010$$

$$1\ crossing/150\ ns \Rightarrow \sim 3\ events\ /crossing \Rightarrow '\ PILEUP\ '$$

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Triggering

- We can not register all events from all crossings, ~20 MHz ($2*10^7$ events per crossing). We have to choose only the relevant crossings in terms of physics.

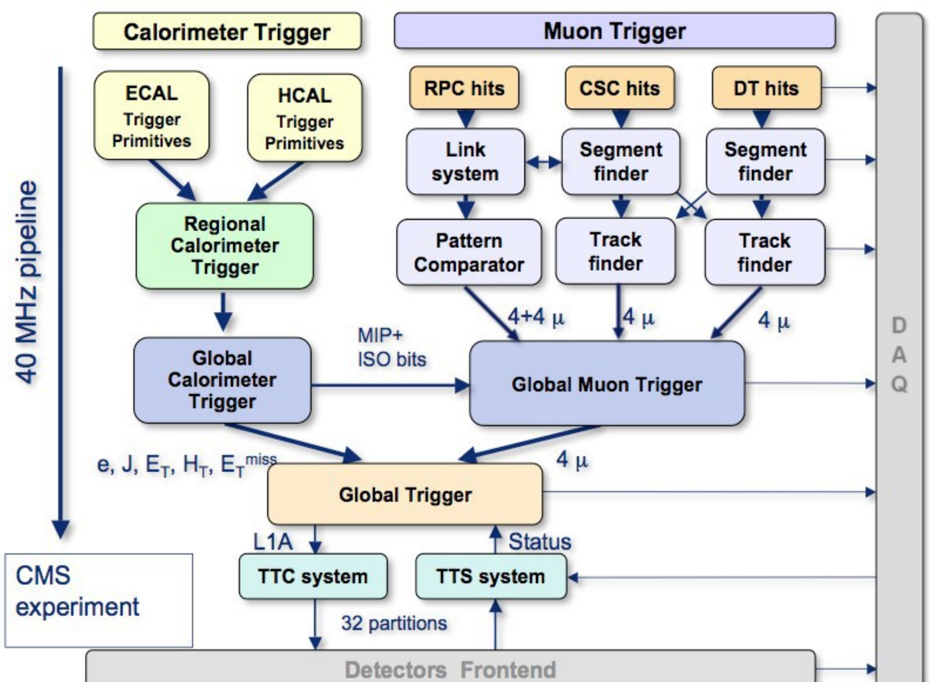
- This is done by trigger systems that decide if a collision should be recorded or not
  - There is always a 'Level-1' trigger implemented via custom hardware processors near the detector that pick up parts of the raw event information.
  - Later, there are higher level triggers, either of hardware type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

- Which are the constraints?
  - What matters is what is called 'throughput' (bytes/second), ~ 100 MB/s; in practice, for typical event sizes (1 MB/event, like those of ATLAS/CMS), one can not record more than ~ 300 events/second
  - Level-1 triggers get stuck for output rates > 100 kHz or so

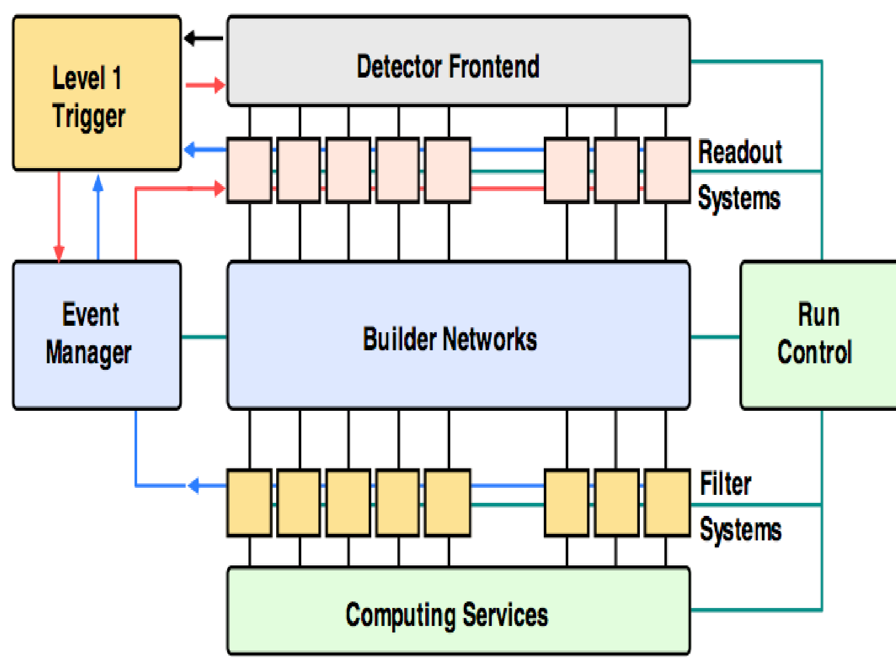
Triggering well is critical

- Level-1 systems should reduce the rate by a factor of 10^3 and higher levels by another factor of 10^3 at 10^{33} cm^{-2} s^{-1}. This is critical and challenging:
  - At Level-1 this is due to the limited precision of the available information
  - At higher levels, where more information is available, time is nevertheless more limited (~ 40 ms for CMS High Level trigger)

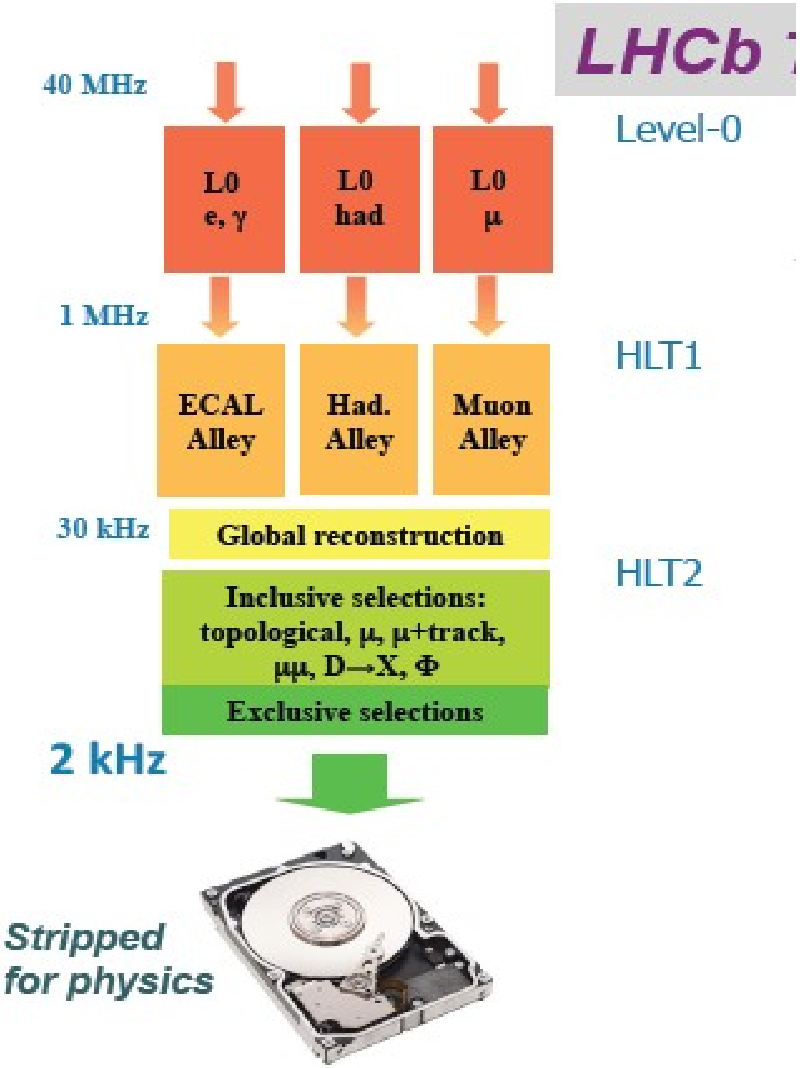
CMS Level-1



CMS HLT

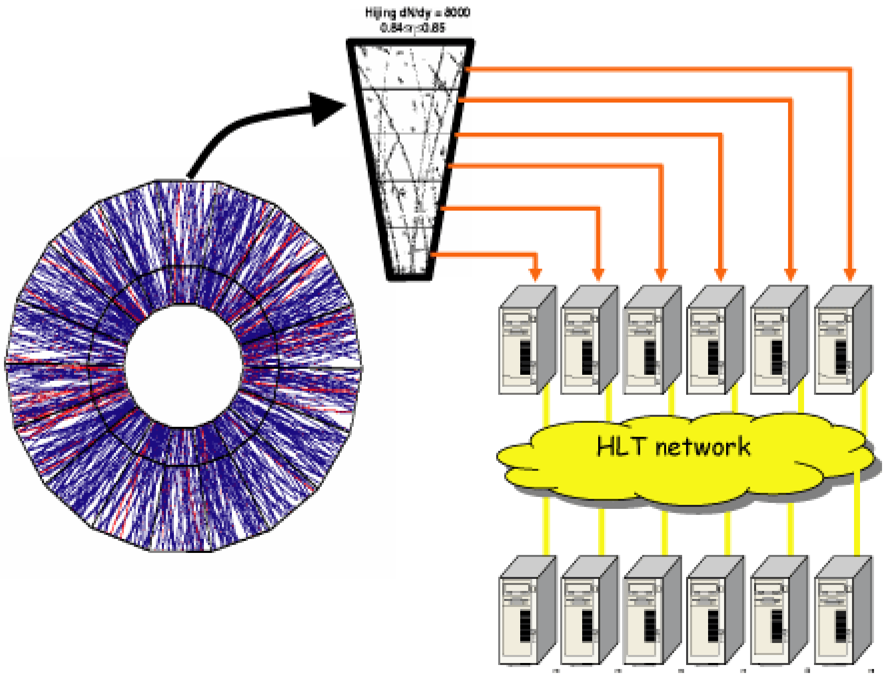


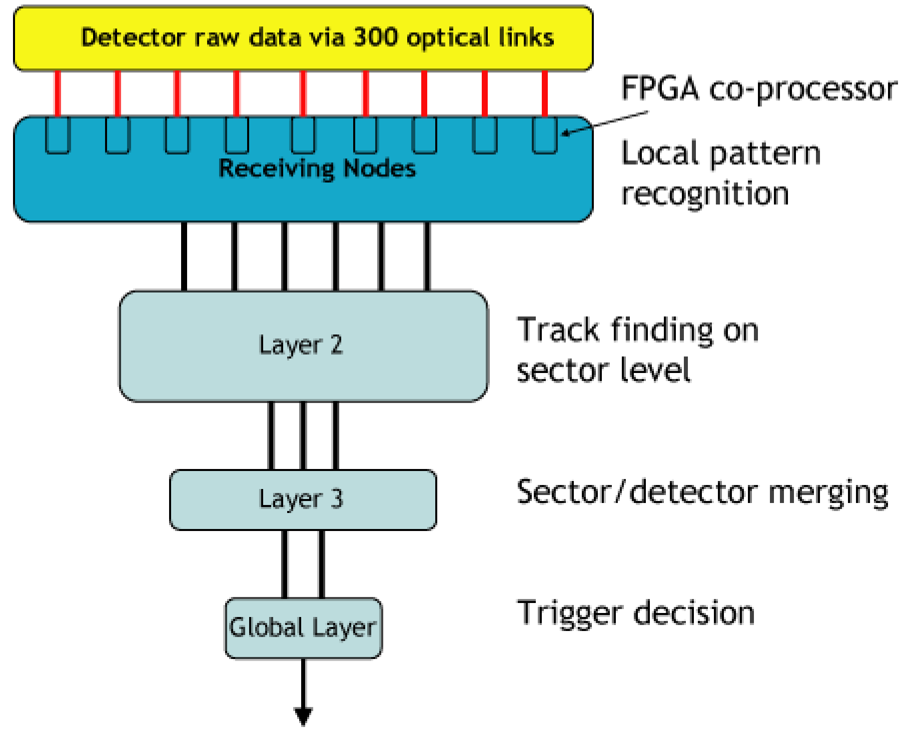
LHCb trigger system



- LHCb is also structured in two trigger levels (L0 and HLT). It presents a few challenging differences:
  - L0 output rate 10 times larger (1 MHz)
  - Final output rate is 2000 Hz
- The differences with respect to ATLAS and CMS are anyway not so big, taking into account that what matters is not the event rate, but the throughput rate (bytes/second)

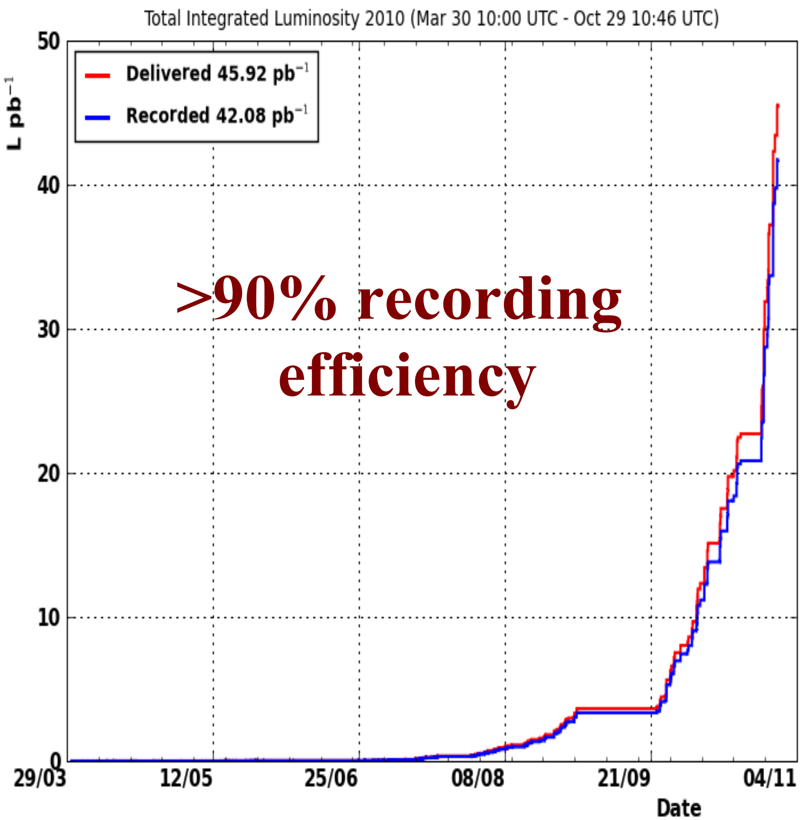
ALICE trigger system

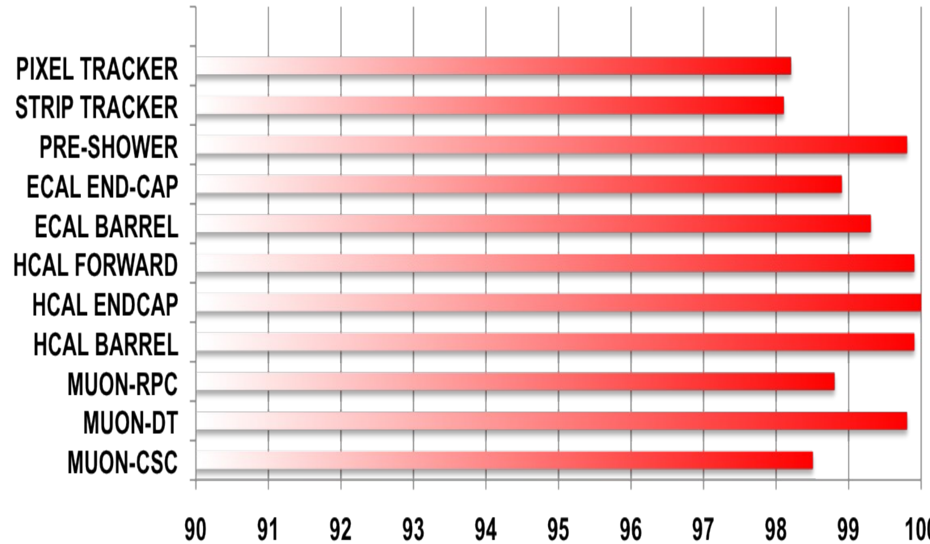




- ALICE has a typical trigger logic, but with special constraints: less collision rate, but huge events (ion interactions), long readout time for their precise gas tracking chamber (Track Projection Chamber)
  - Sophisticated "trigger hand shaking" at the early levels
  - The High Level Trigger system does the tracker reconstruction regionally via parallel processing

And we take data efficiently (CMS)





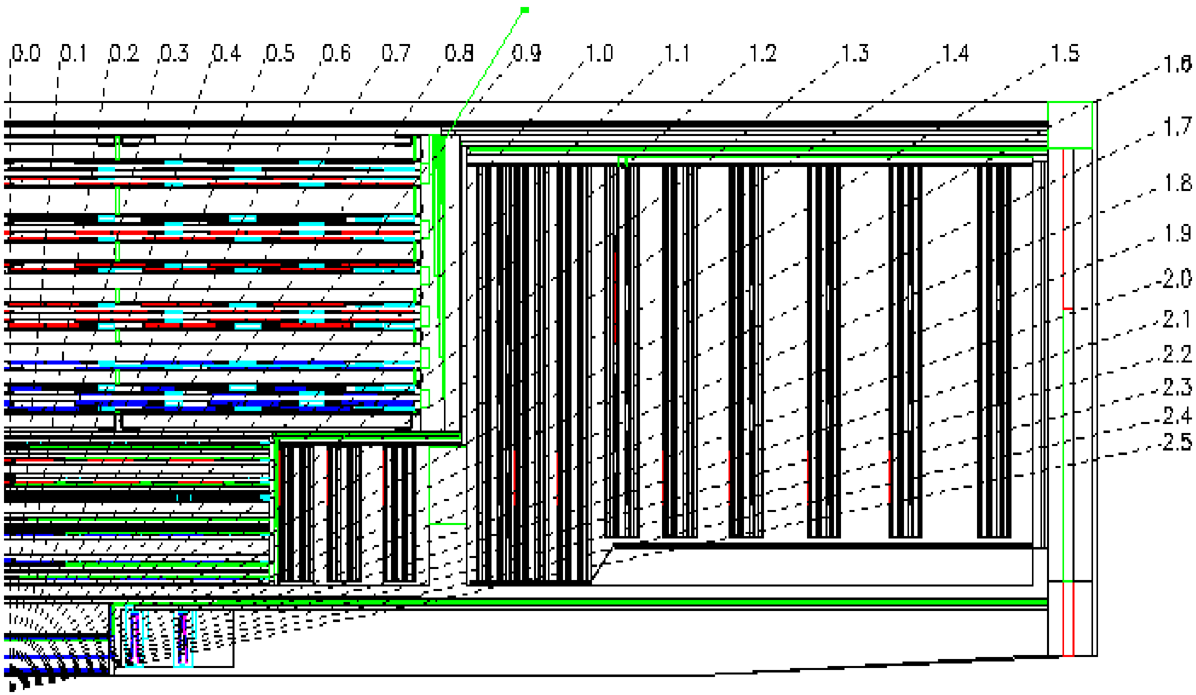
	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

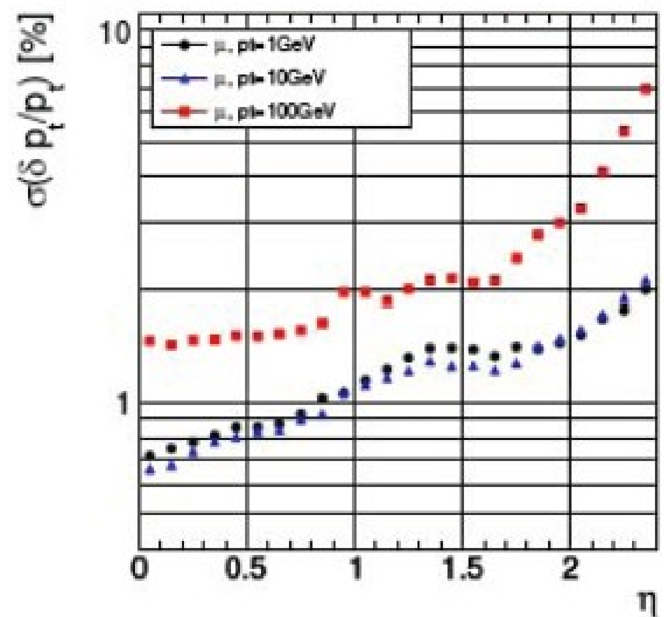
- ~ 45 pb^{-1} delivered, ~40 pb^{-1} collected, >98% operational detector
- Also in essentially 'nominal' conditions: Level-1 trigger rates > 50 kHz, HLT rates > 300 Hz

SIMILAR FIGURES FOR THE OTHER LHC EXPERIMENTS

Tracking performance at the LHC

CMS inner tracking system

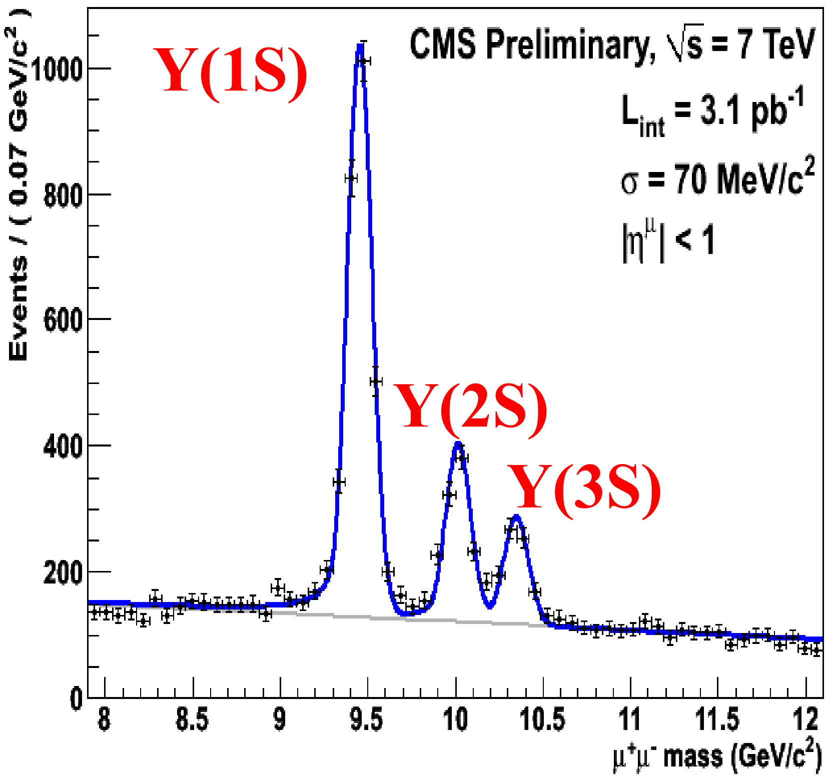


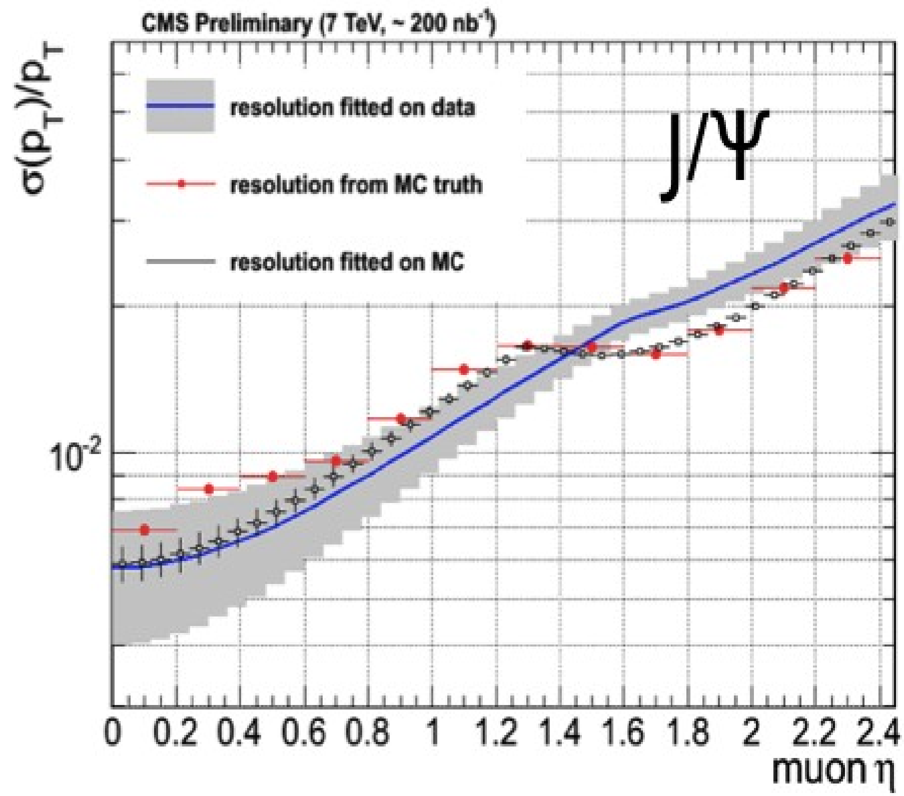


A huge, ultra-precise silicon tracker system:

- For $p_T \leq 100$ GeV, $\Delta p_T / p_T \approx 0.5\text{-}2\%$ ($|\eta|<1.6$)
  - 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
- $\Delta z \approx 20\text{-}40$ μm resolution at very high p_T ($|\eta|<2$)

CMS: tracking performance





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

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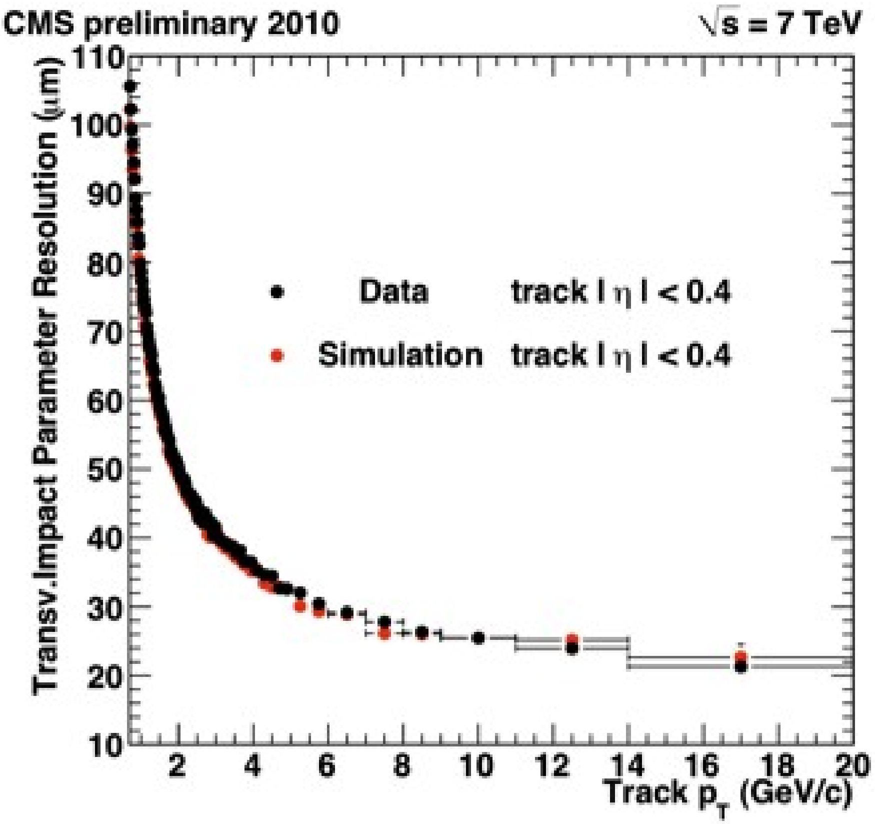
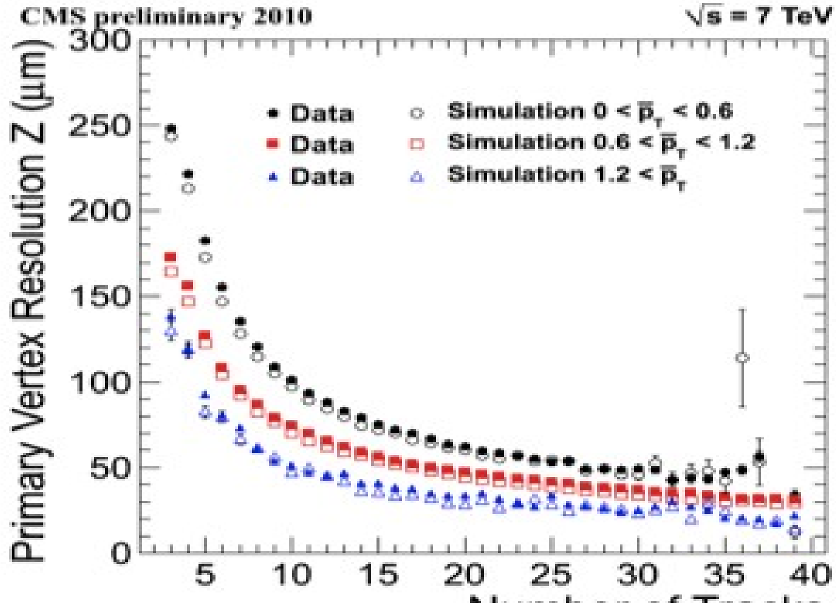
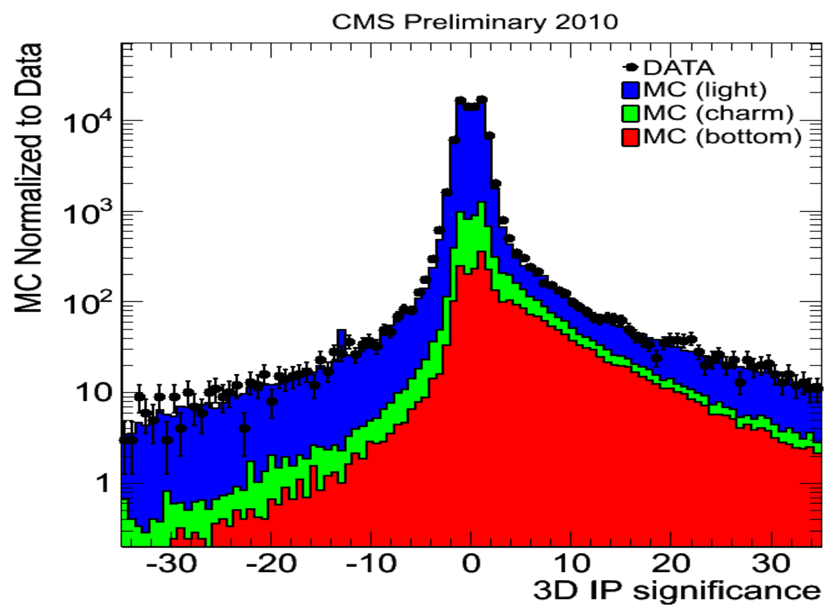
CMS: tracking performance







- High accuracy of impact parameter and vertex measurements, in reasonable agreement with simulations => b-tagging already operational !!

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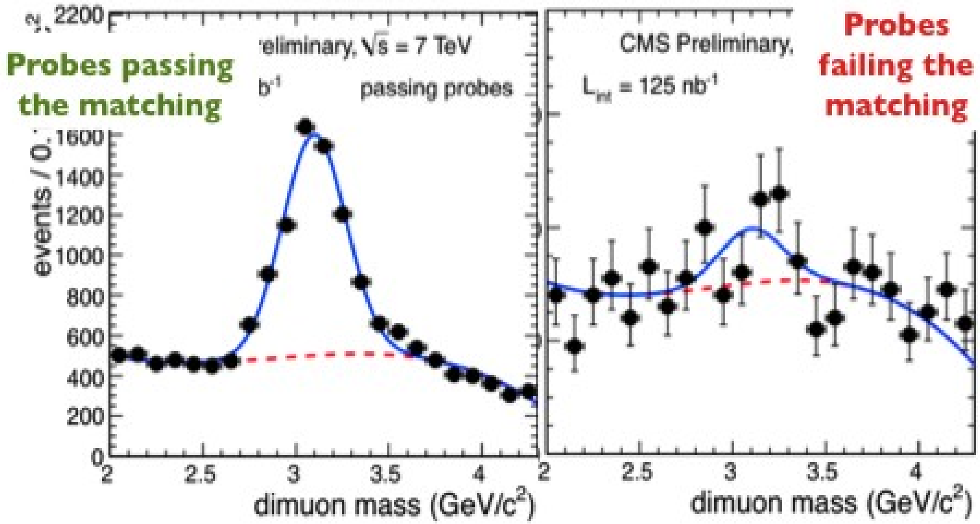
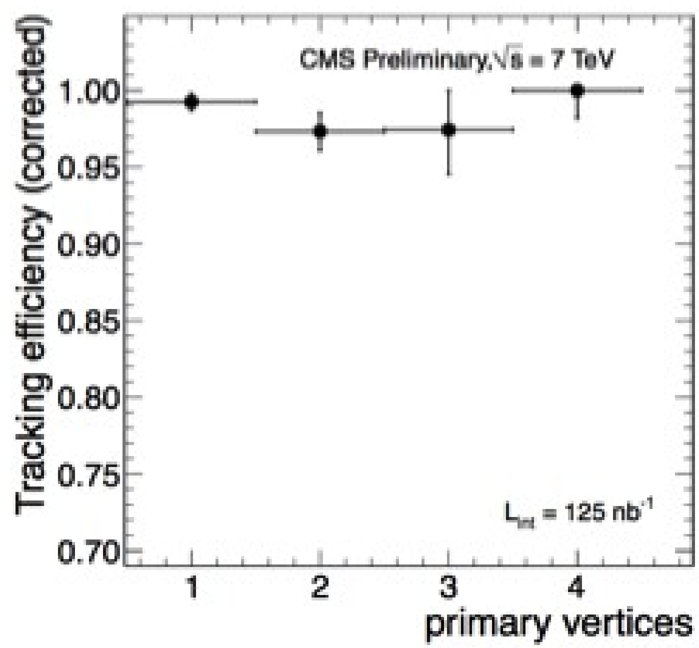
CMS: tracking performance

J/Psi Tag and probe



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



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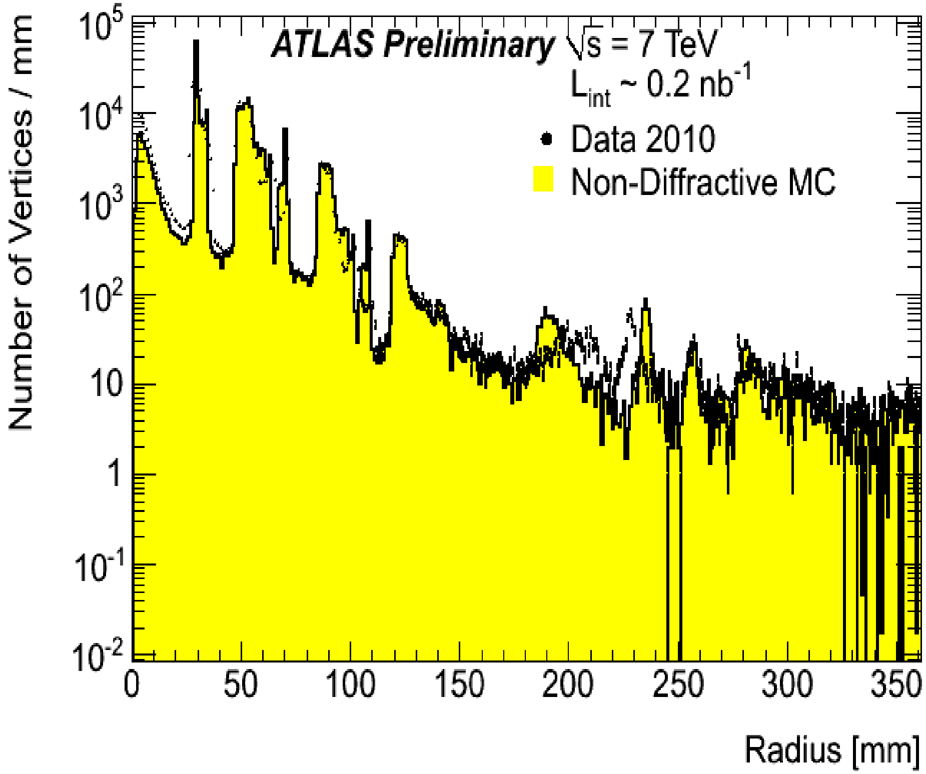
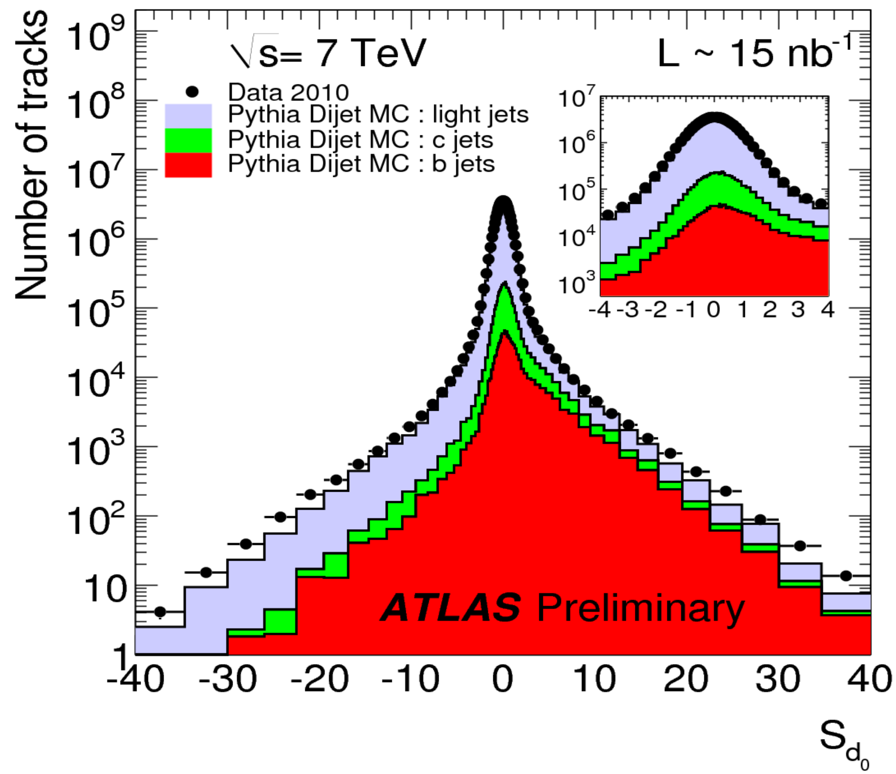
ATLAS: similar level of understanding



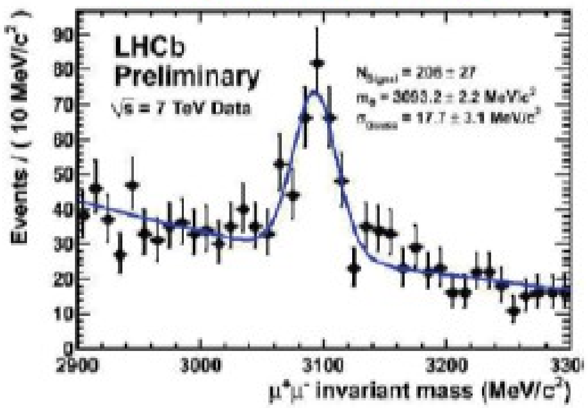


- Rather impressive level of reproducibility of the tracker material in simulations:
  - This is important to account for effects like multiple scattering or electron bremsstrahlung
- Plus good understanding of position resolution in the tracker:
  - Impact parameters in agreement with simulations, b-tagging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

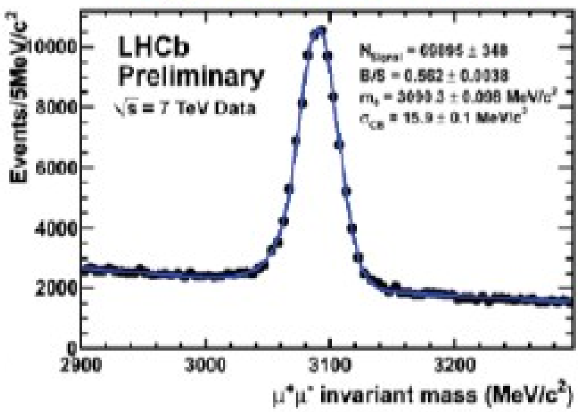
LHCb tracking resolution

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

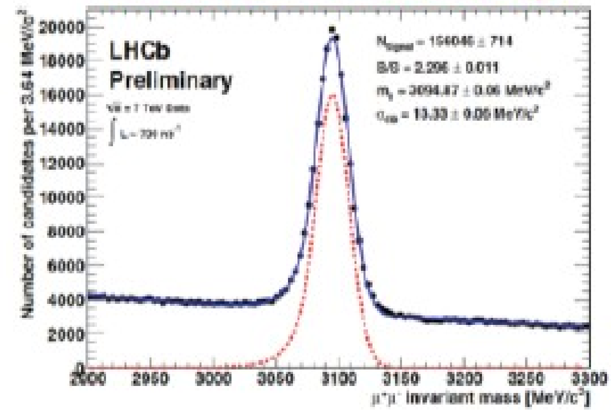
May: σ ~ 18 MeV/c^2



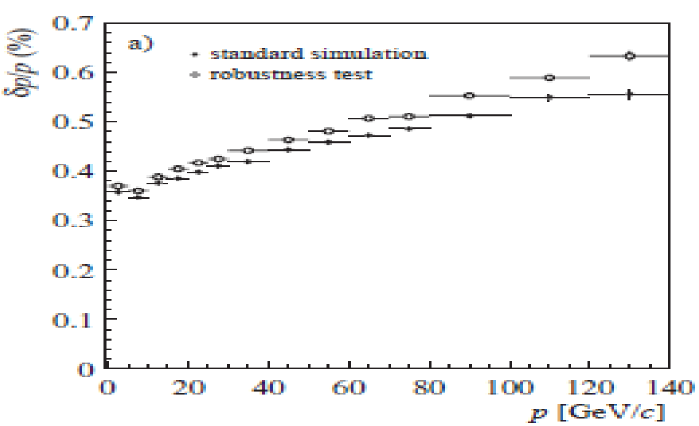
August: σ ~ 16 MeV/c^2



November: σ ~ 13 MeV/c^2

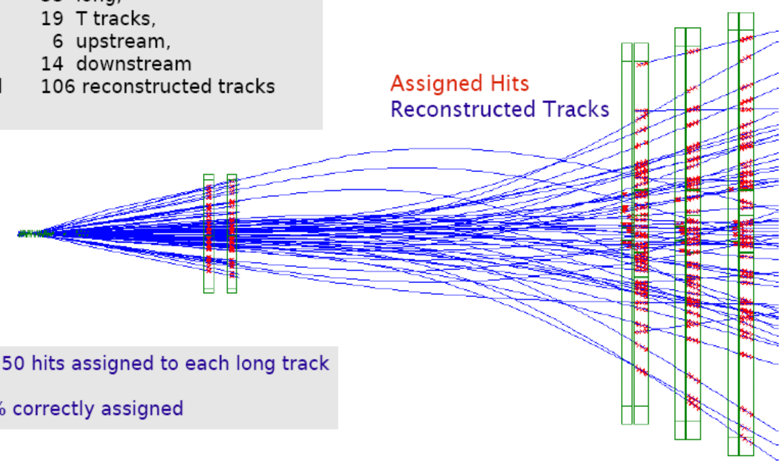


- **Many tracking detectors, high B field, long level arm → excellent resolution**



Average # of tracks in b-events:

	34	VELO,
	33	long,
	19	T tracks,
	6	upstream,
	14	downstream
Total	106	reconstructed tracks

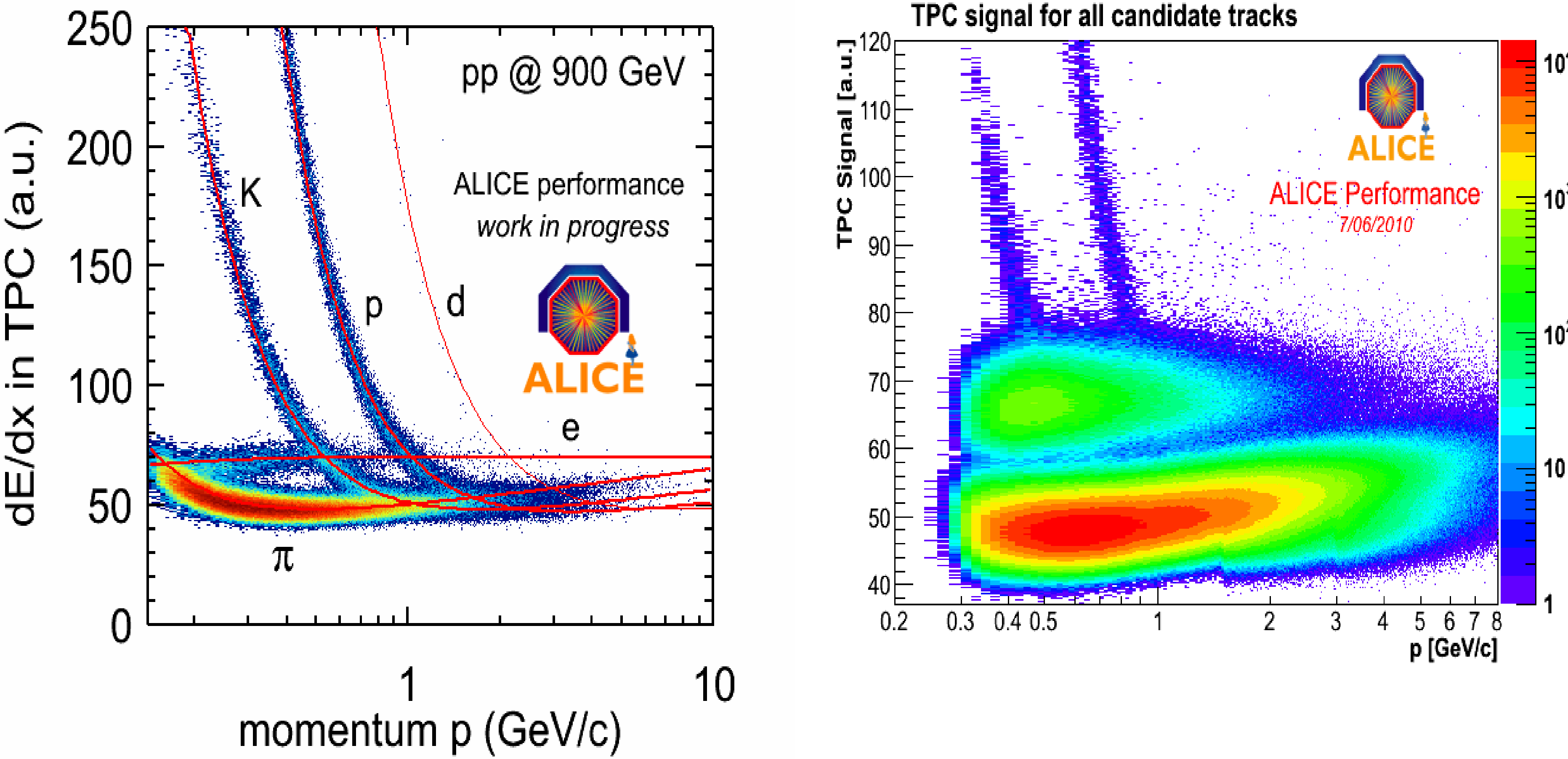


20 to 50 hits assigned to each long track

98.7% correctly assigned

Performance of dedicated particle-id detectors at LHC

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)

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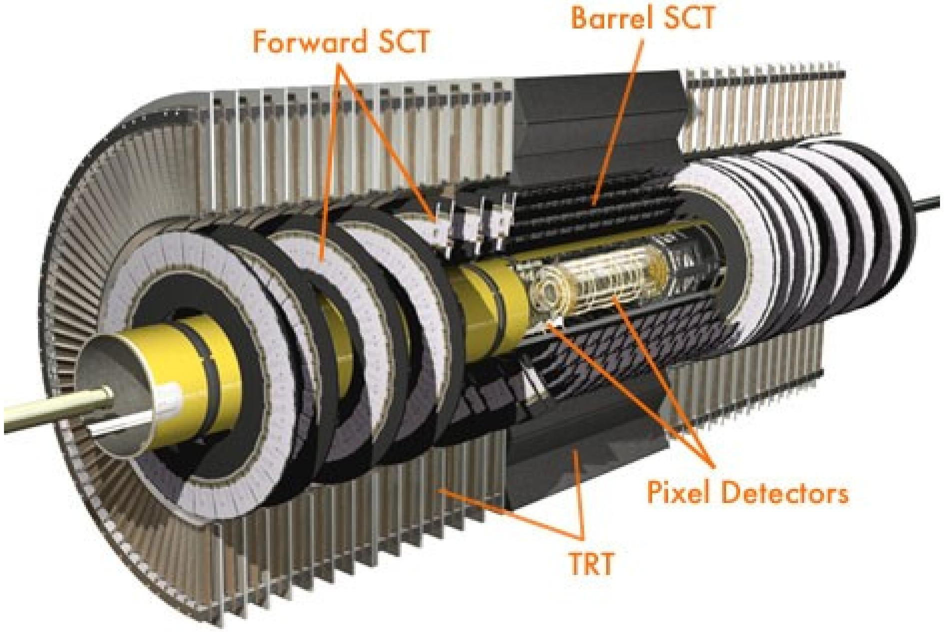
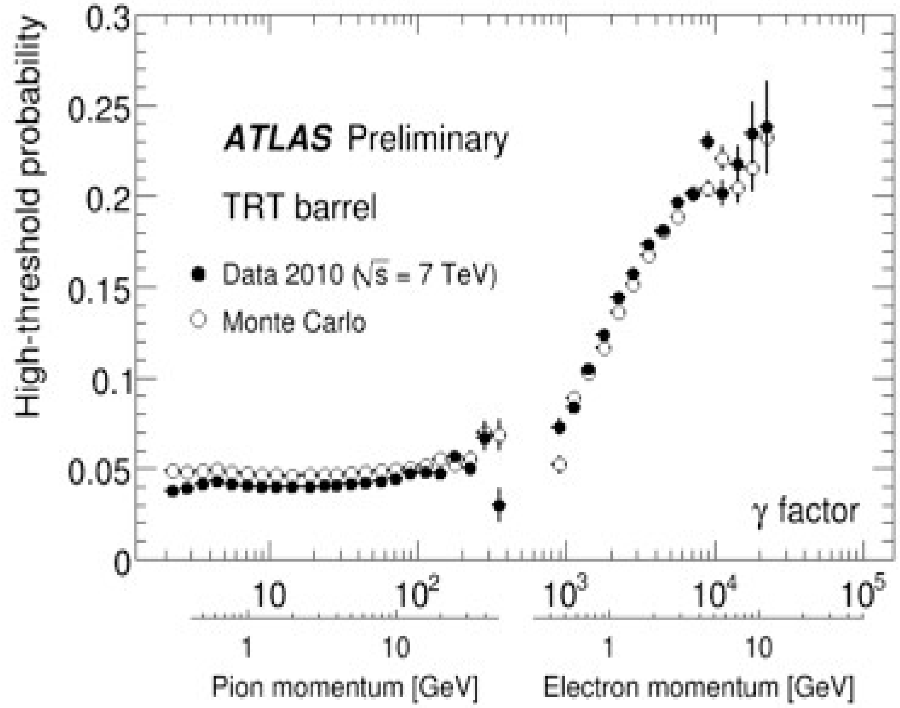
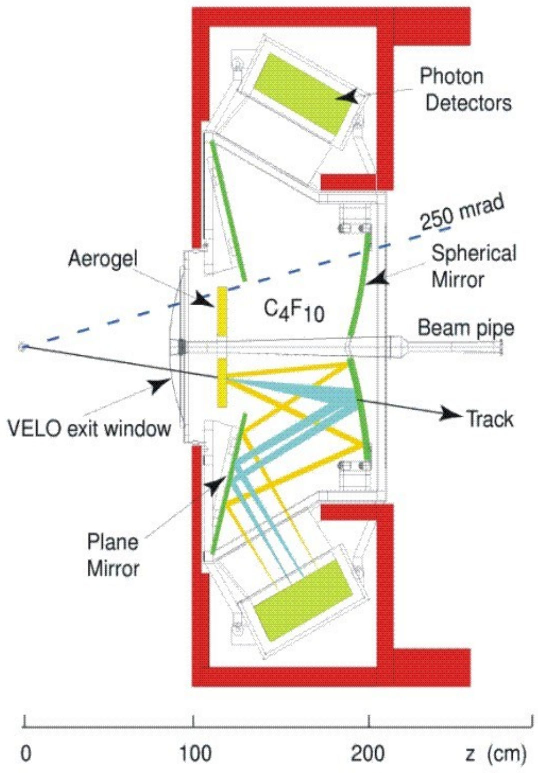
ATLAS: e/p separation using TRT

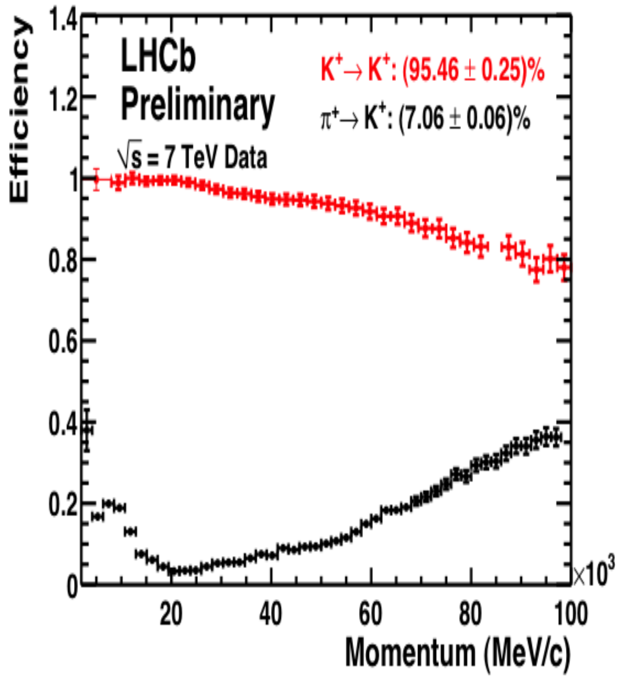


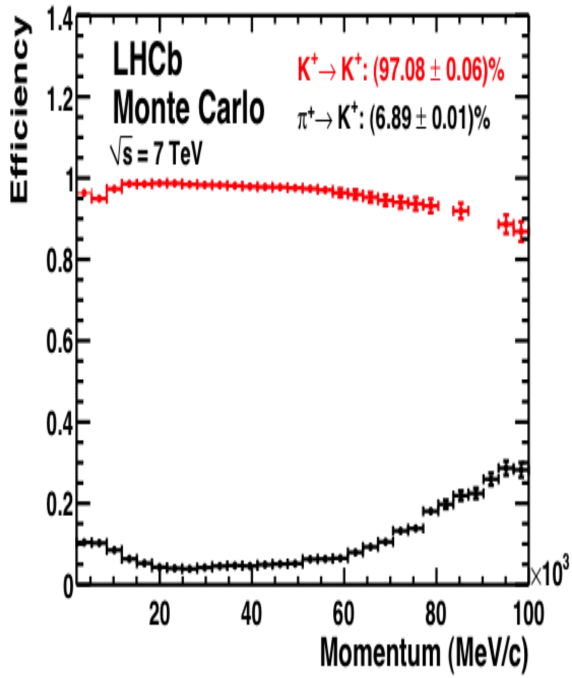


- Half of the radius of ATLAS tracking is filled with a Transition Radiation Tracker detector (TRT) (straw tubes mostly filled with Xe)
- Besides measuring the trajectory coordinates with decent precision (170 μm), it can differentiate electrons and pions in the 1-100 GeV momentum range (charged particles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

RICH detectors



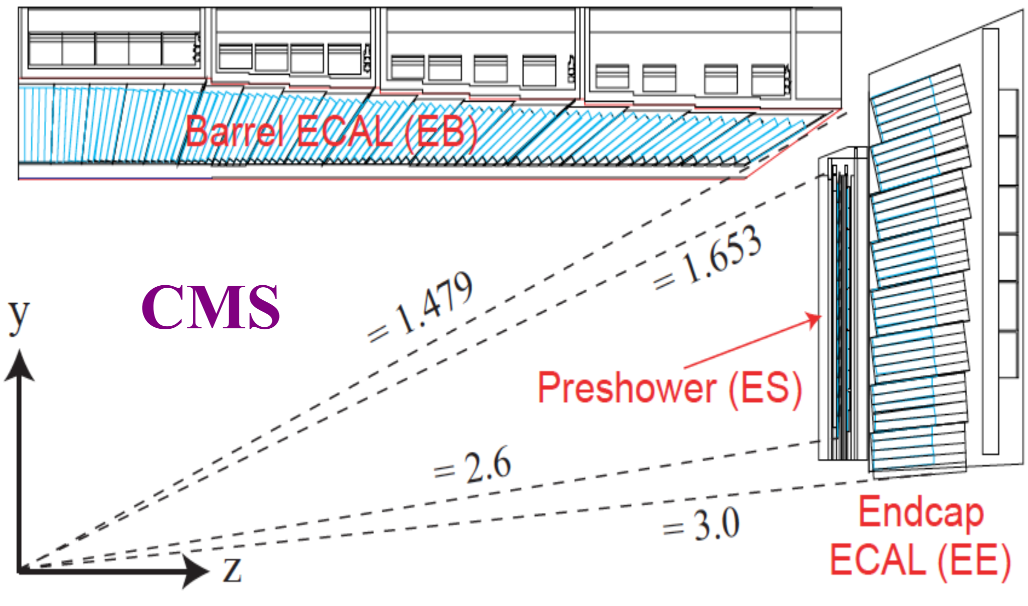


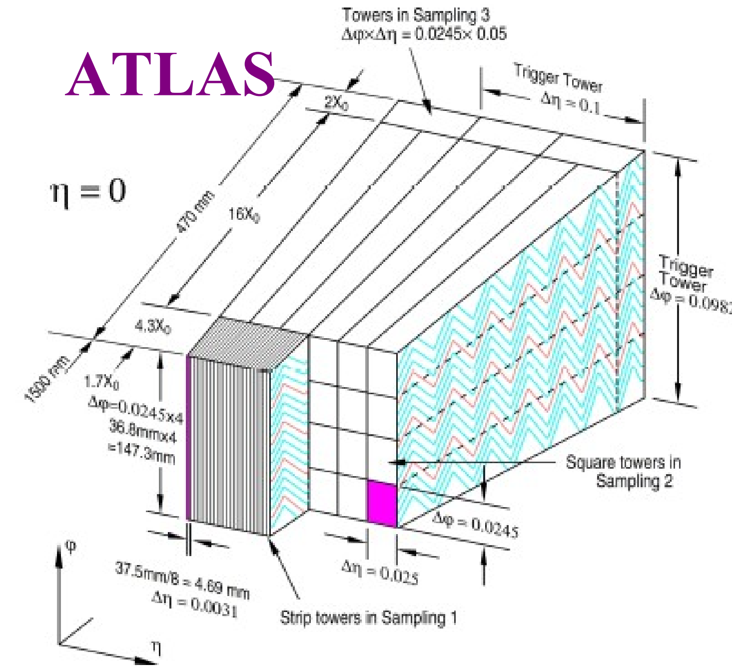


- Ring Imaging Cherenkov detectors (RICH) are typically used (at LHC) to differentiate pions and kaons in order to:
  - Do dedicated studies for strange production, ... (ALICE)
  - Identify exclusive bottom and charm decays (LHCb)
- Rather good agreement between data and MC expectations (LHCb)

Electron and photon resolution and performance at the LHC

Electromagnetic Calorimeters





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

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

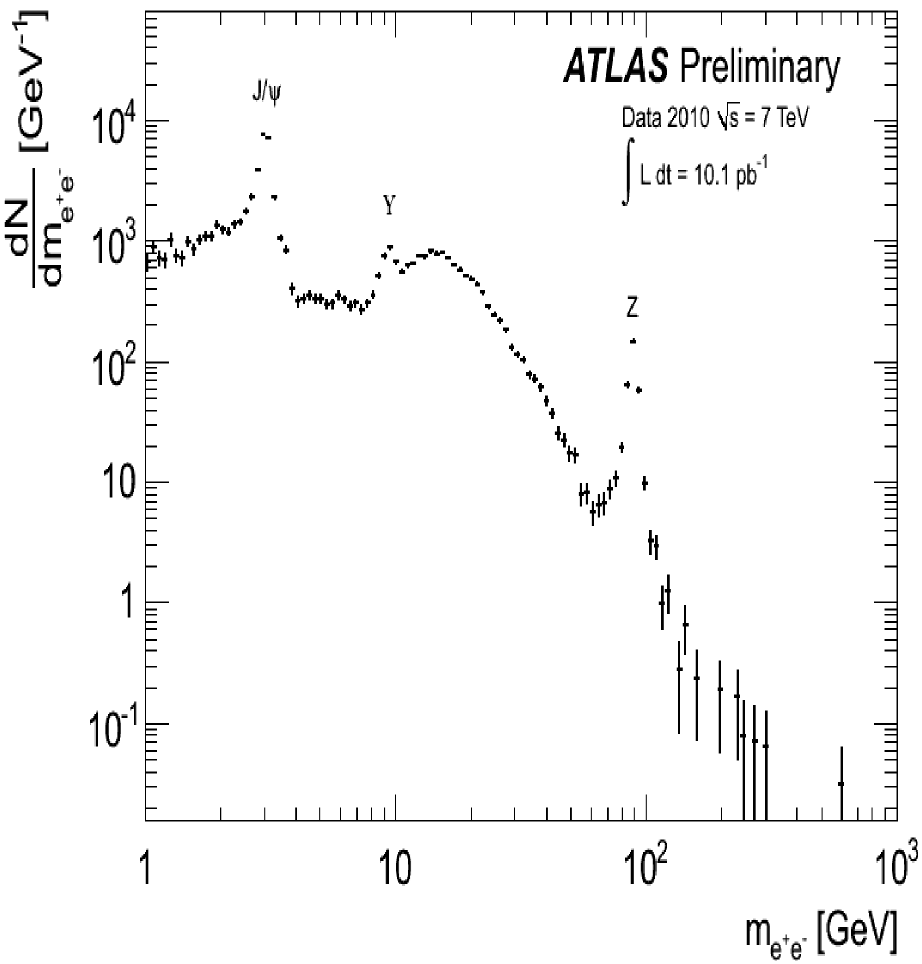
- ATLAS: a liquid argon calorimeter (active medium) with good resolution, fine segmentation ($\pi^0 \rightarrow \gamma\gamma$ rejection) and photon pointing capabilities:

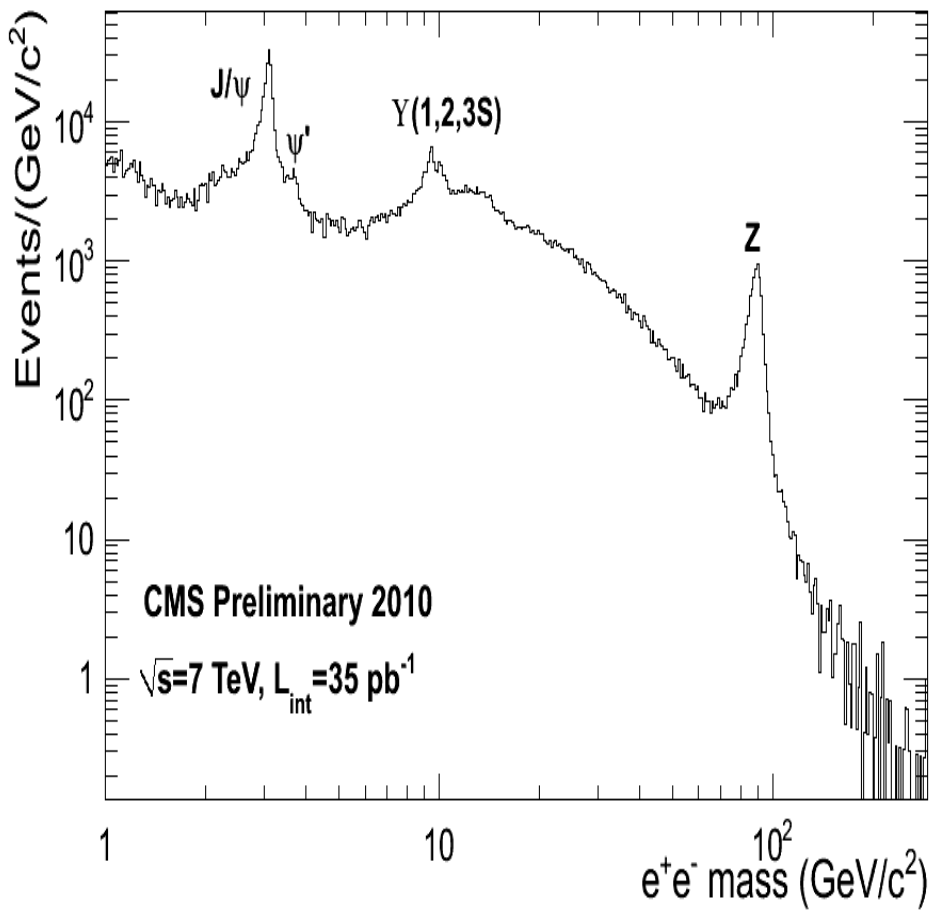
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{10\,\%}{\sqrt{E}}\right)^2 + (0.7\,\%)^2$$

(E in GeV)

ATLAS and CMS: electrons

Good resolution confirmed in data





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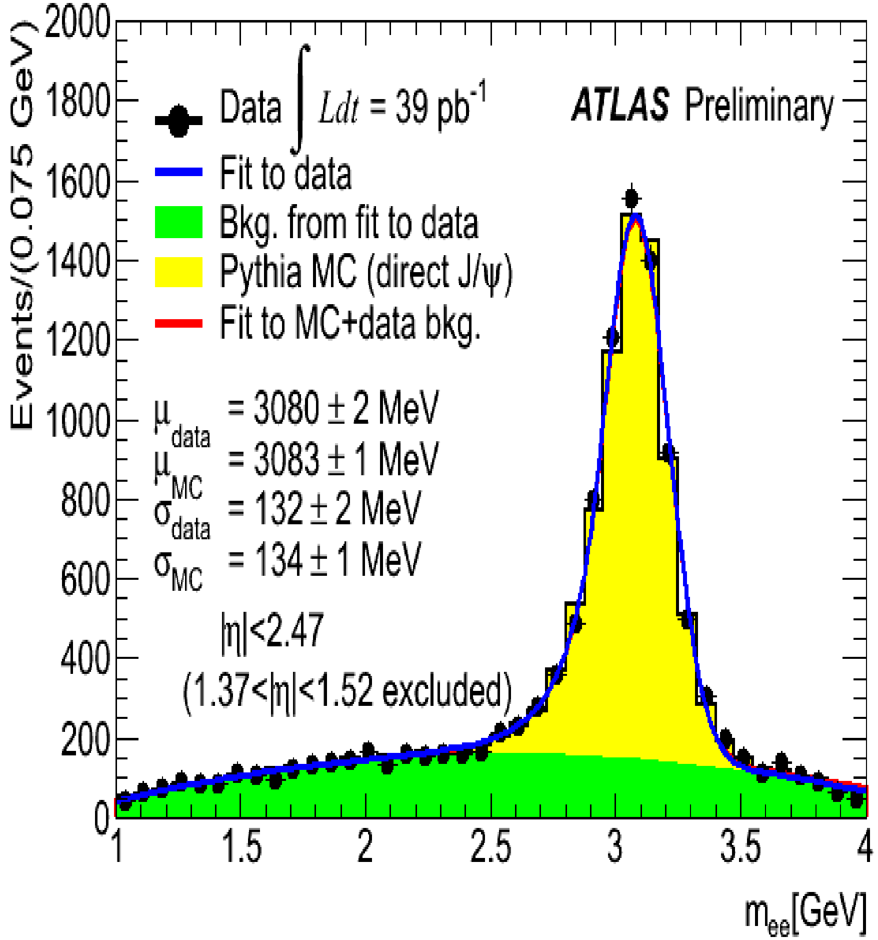
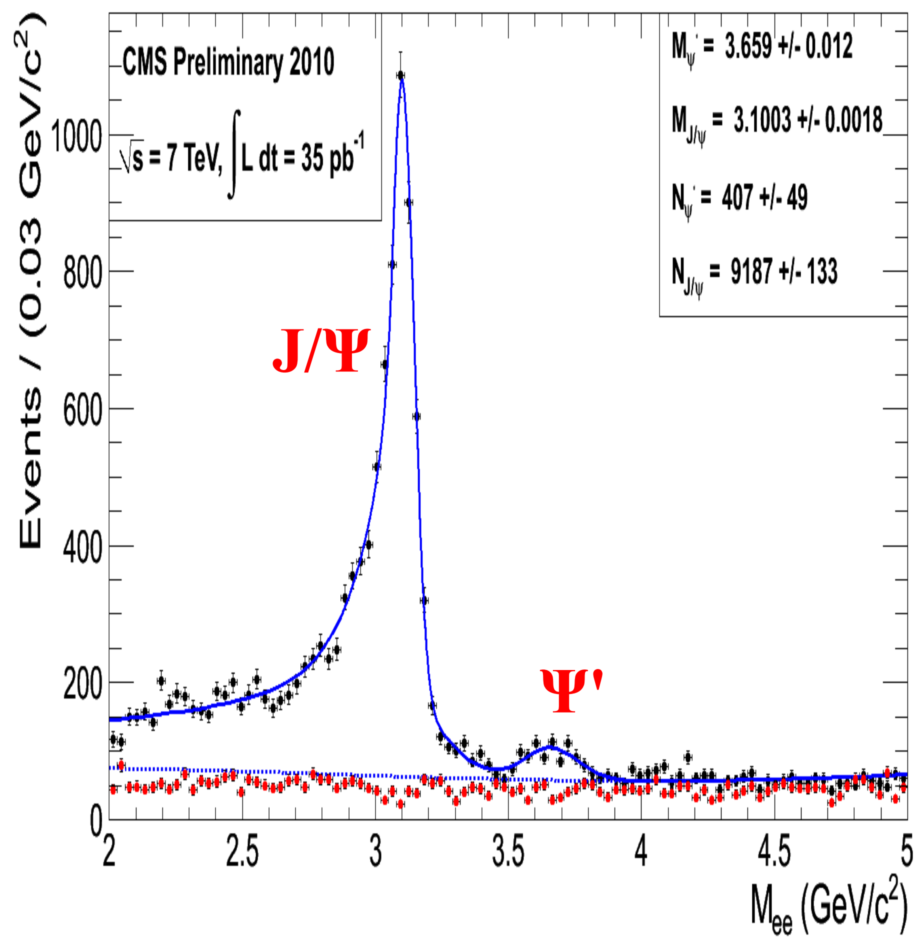
ATLAS and CMS: electrons

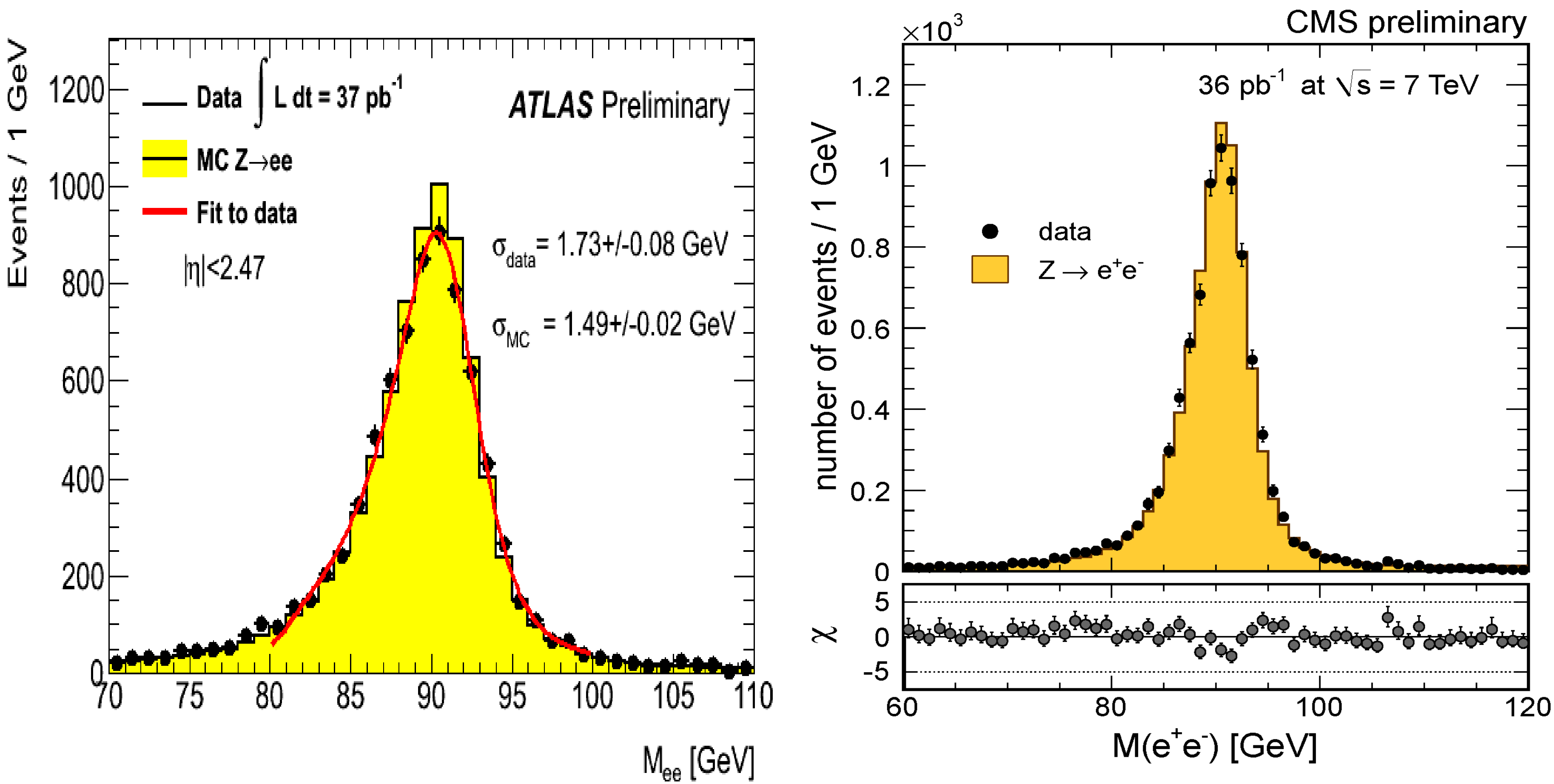
Both for low masses ...



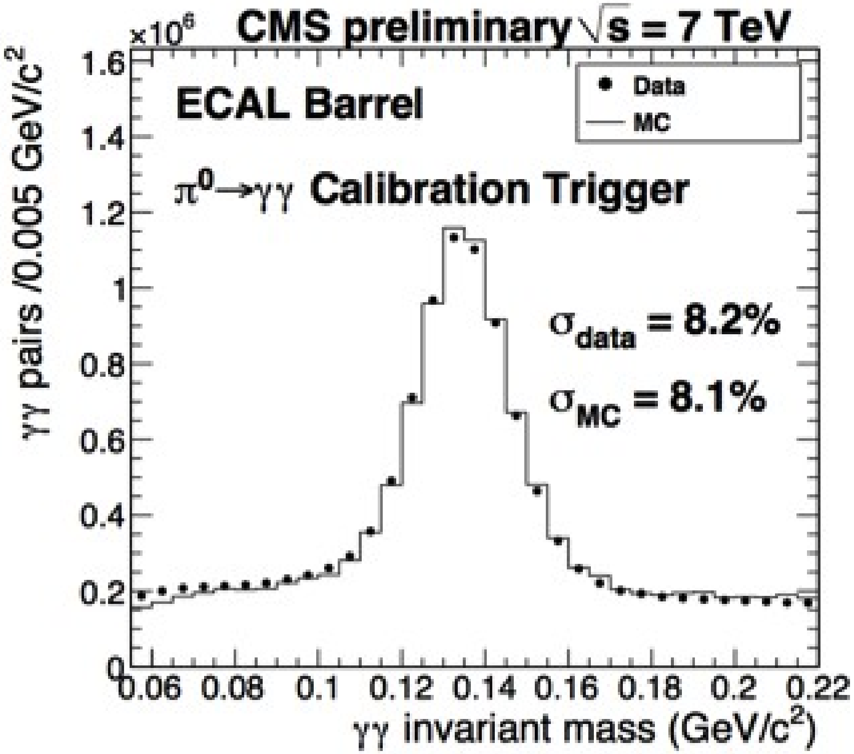


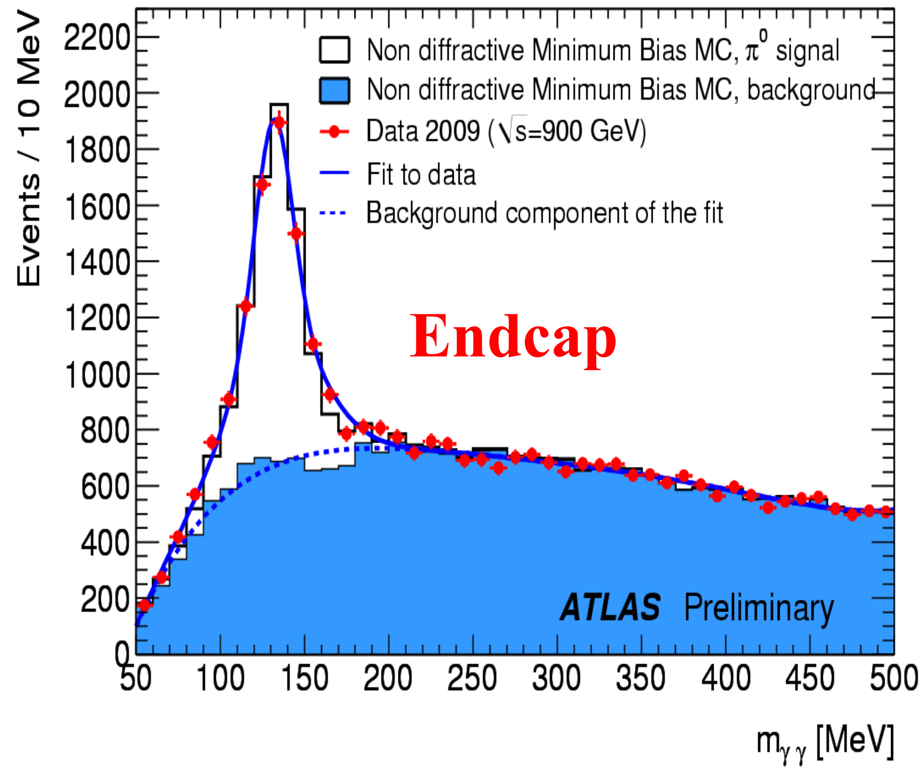
ATLAS and CMS: electrons

… and at high energies as well



ATLAS and CMS: photons



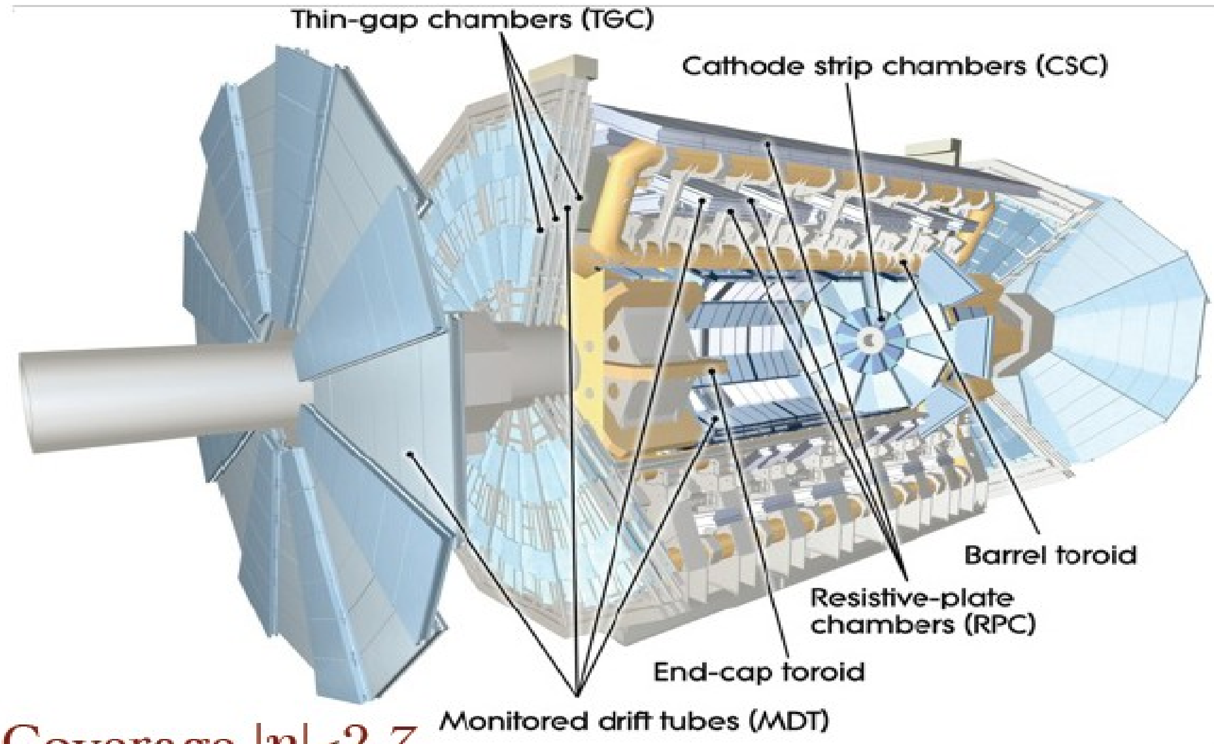


Good agreement with expectations

Muon resolution and performance at the LHC

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)



Coverage $|\eta|<2.7$

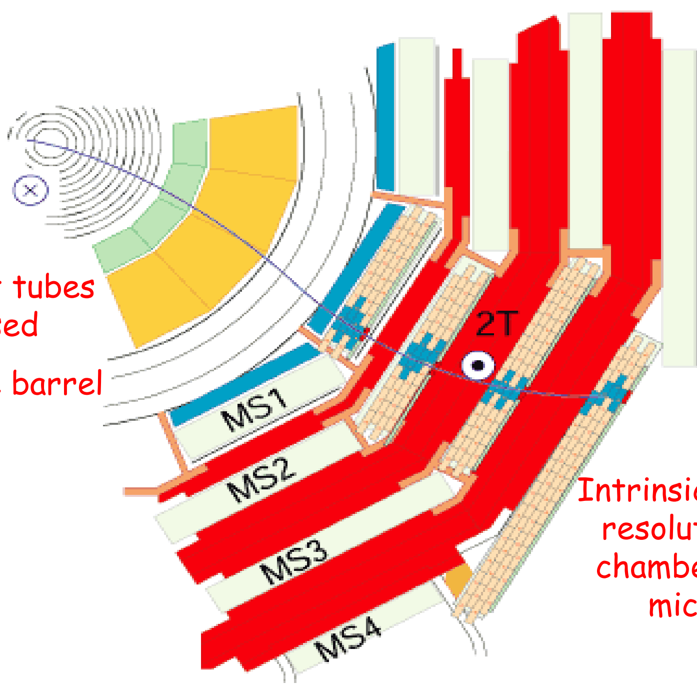
Intrinsic position resolution per chamber better than 100 microns (good alignment is critical)

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

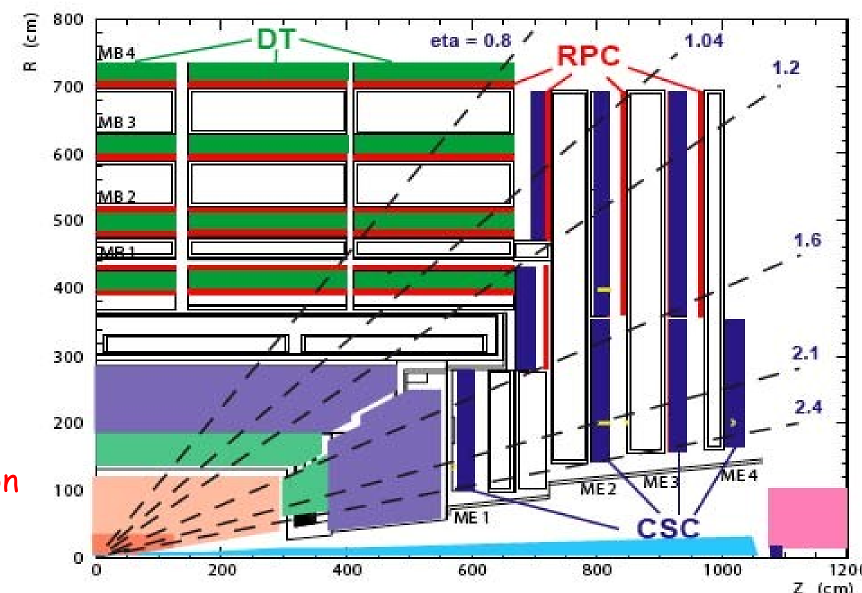
- The CMS muon system (barrel and also endcap) is optimized for:
  - Robust, efficient and redundant muon triggering system (chambers+RPCs)
  - Efficient muon identification and reconstruction (|η|<2.4, redundant coverage)
  - Precise measurement (< 10%) for TeV momenta (good alignment + level arm)



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

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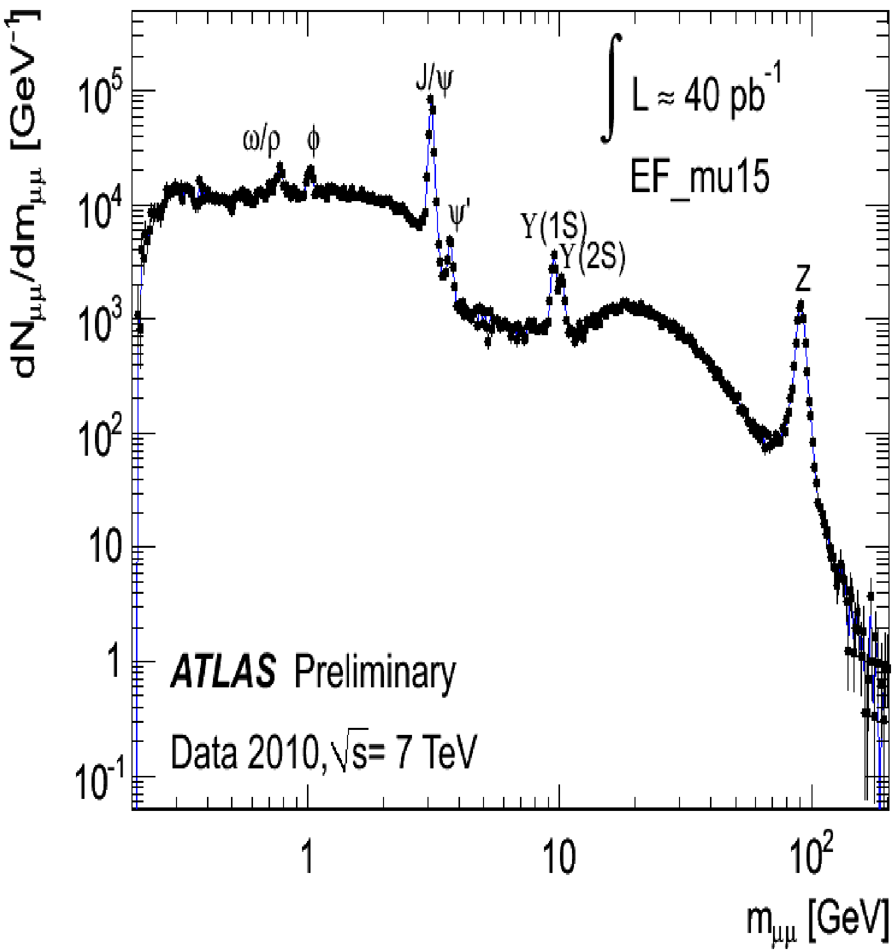
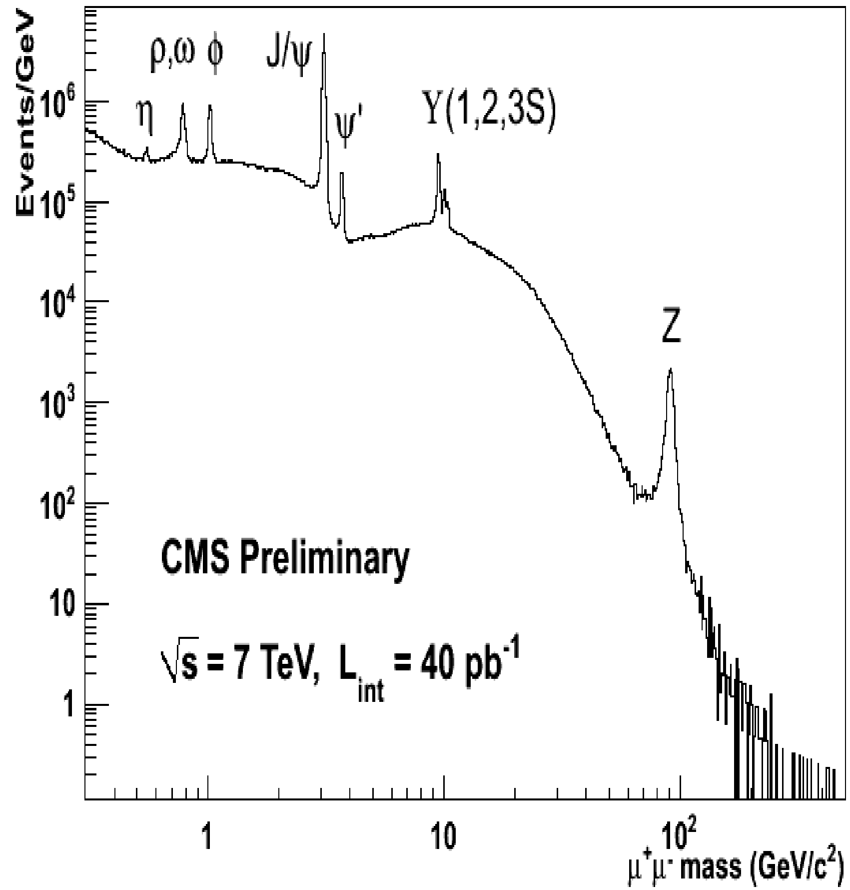
ATLAS and CMS: muons

Good resolution confirmed in data





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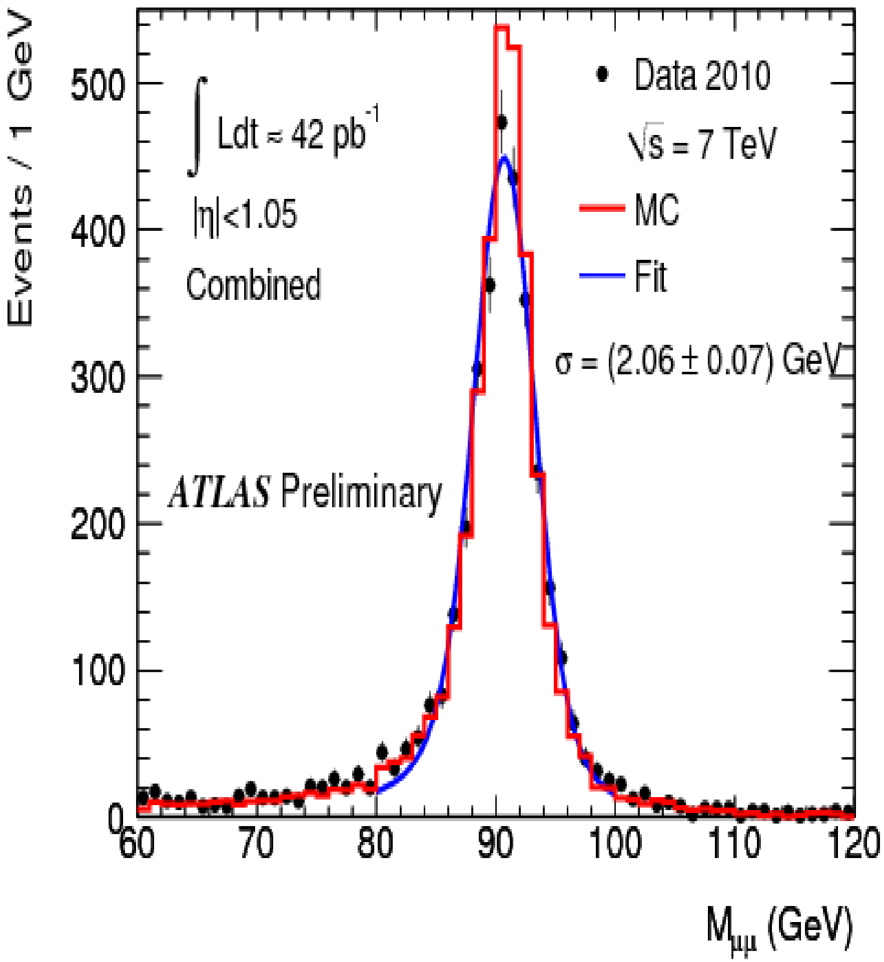
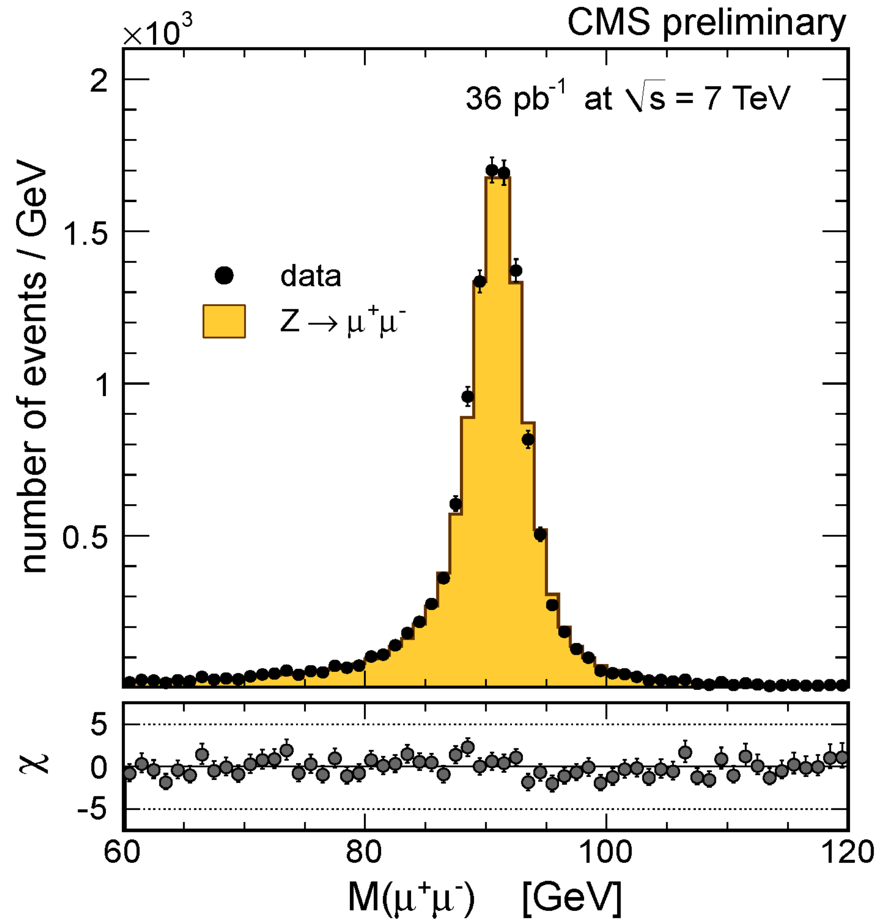
ATLAS and CMS: muons

… and at high energies as well ...





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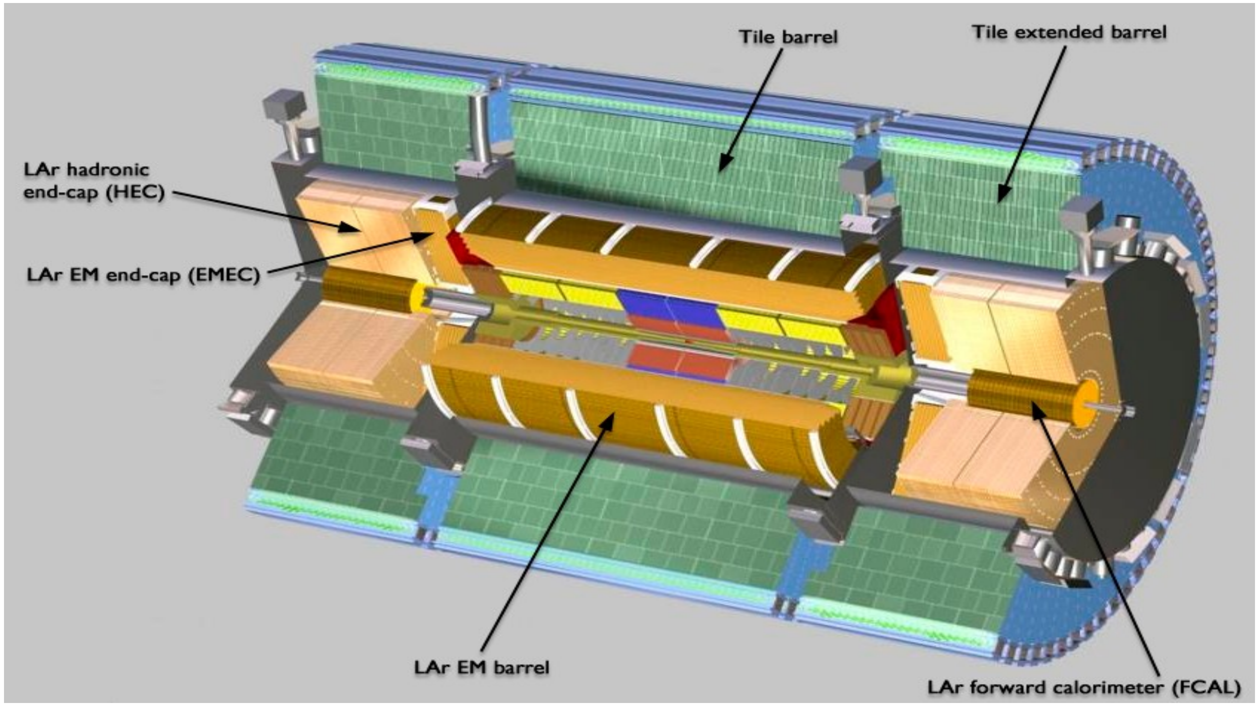
Hadron calorimetry and jet performance at the LHC

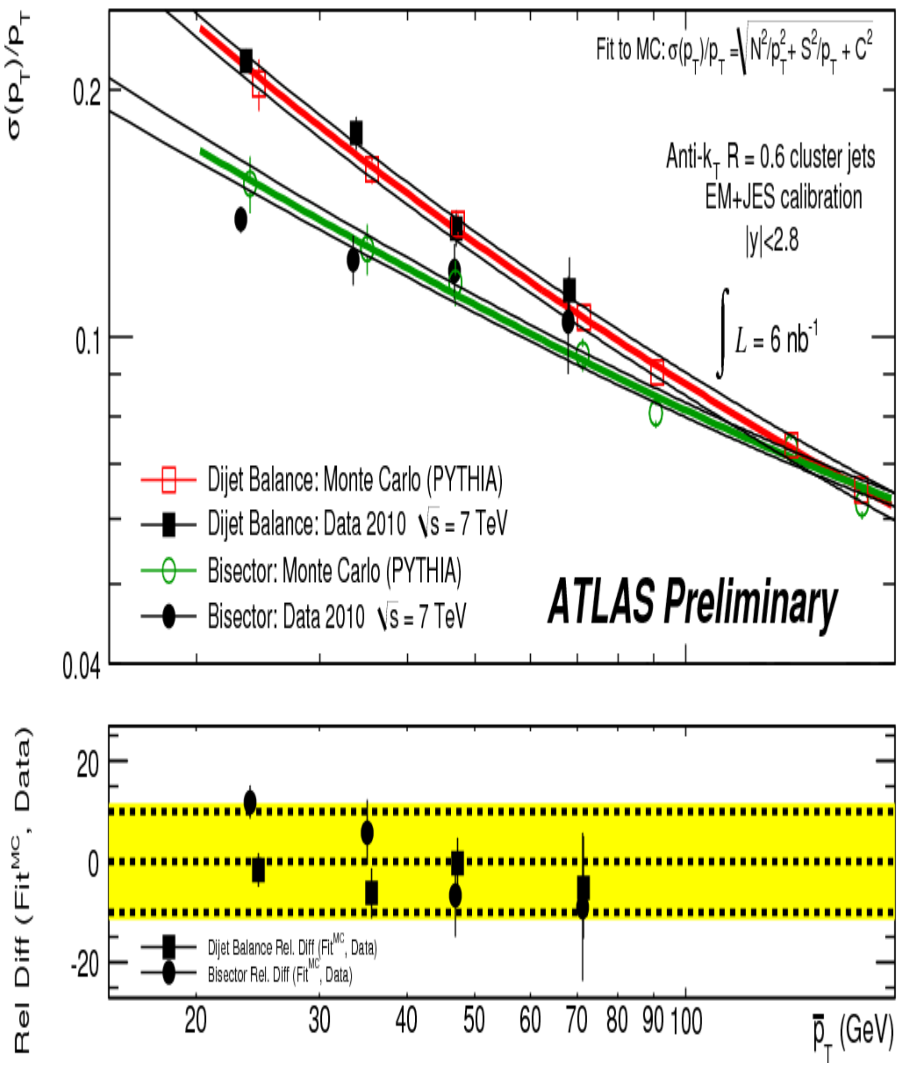
ATLAS: precise calorimetric jets

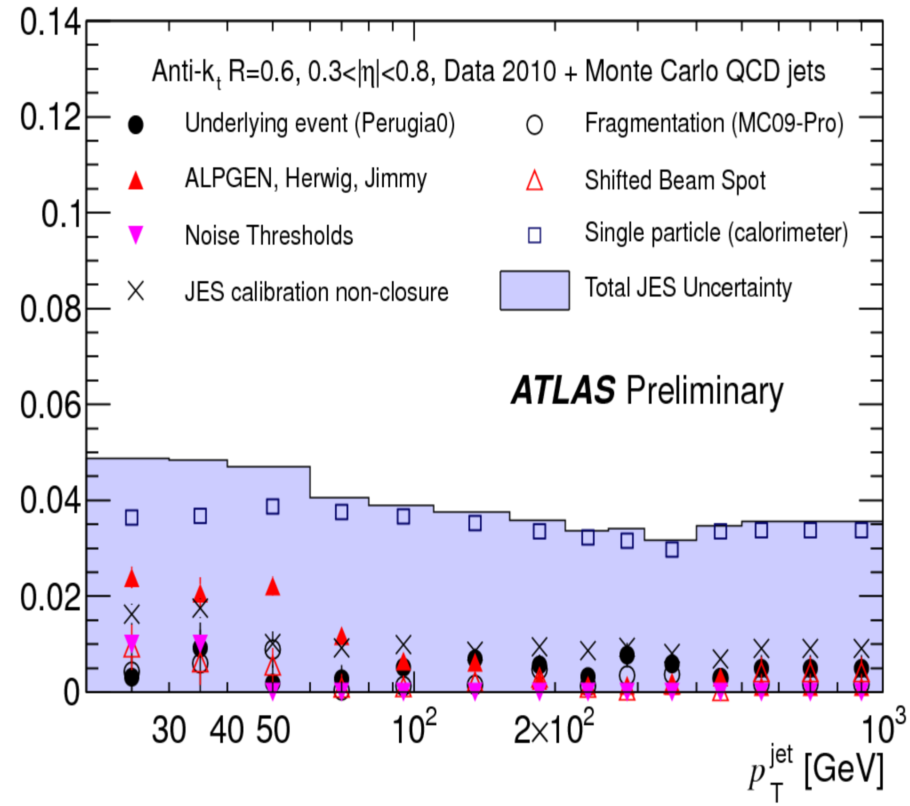


- Hadron calorimetry: Iron-plastic scintillator tile calorimeter (barrel); extremely hermetic and segmented, with a very linear response (<2% deviations)
- Jet energy resolution:

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

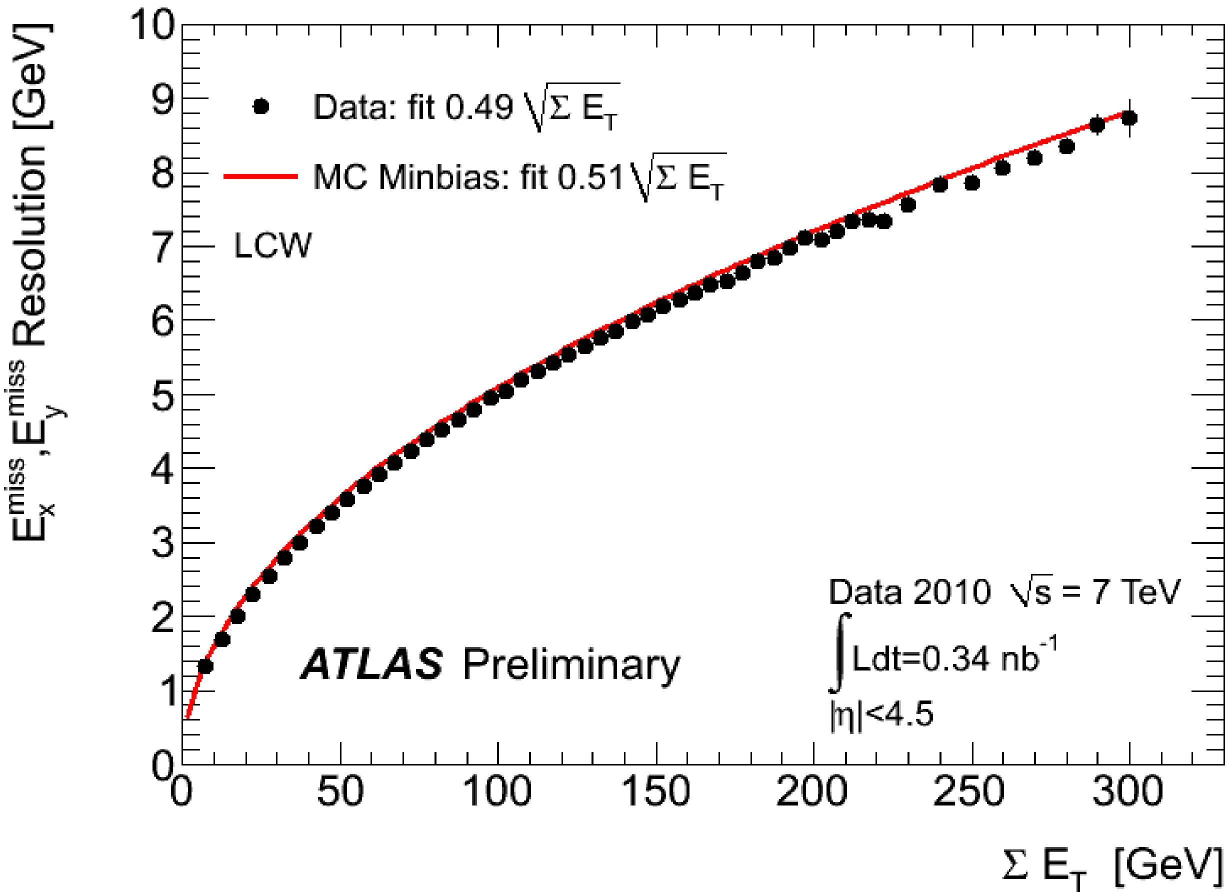
ATLAS: precise calorimetric jets





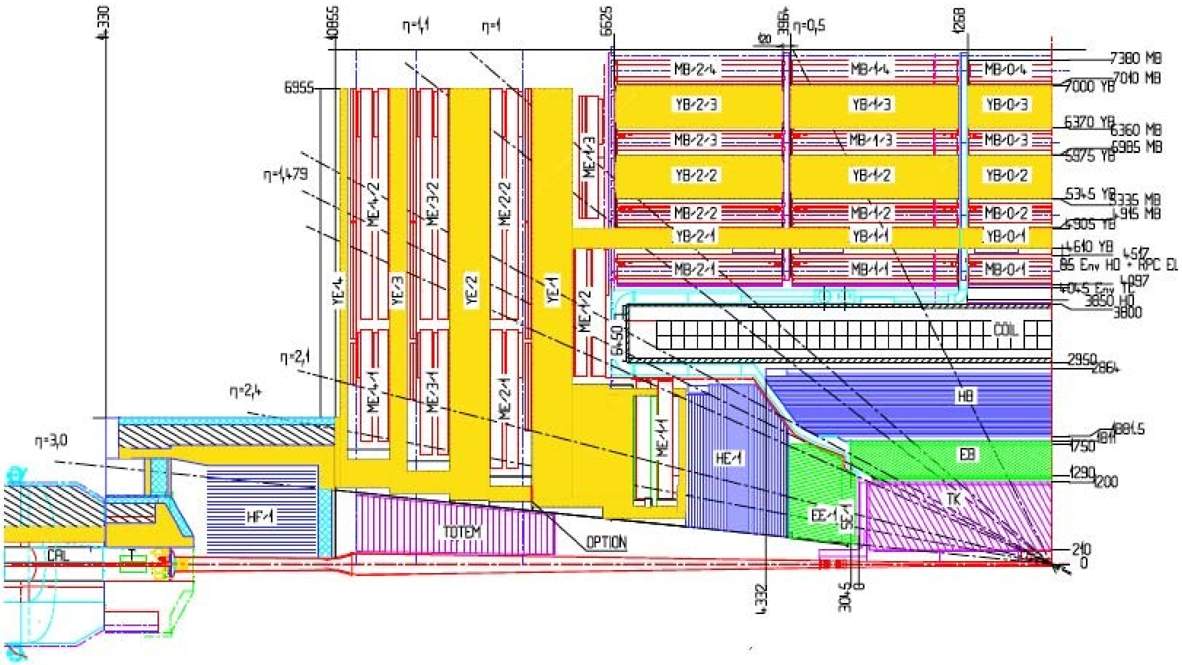
- Jet resolution according to expectations
- Scale uncertainties < 5%

ATLAS: precise calorimetric E_T^{miss}



- Missing E_T resolution according to expectations

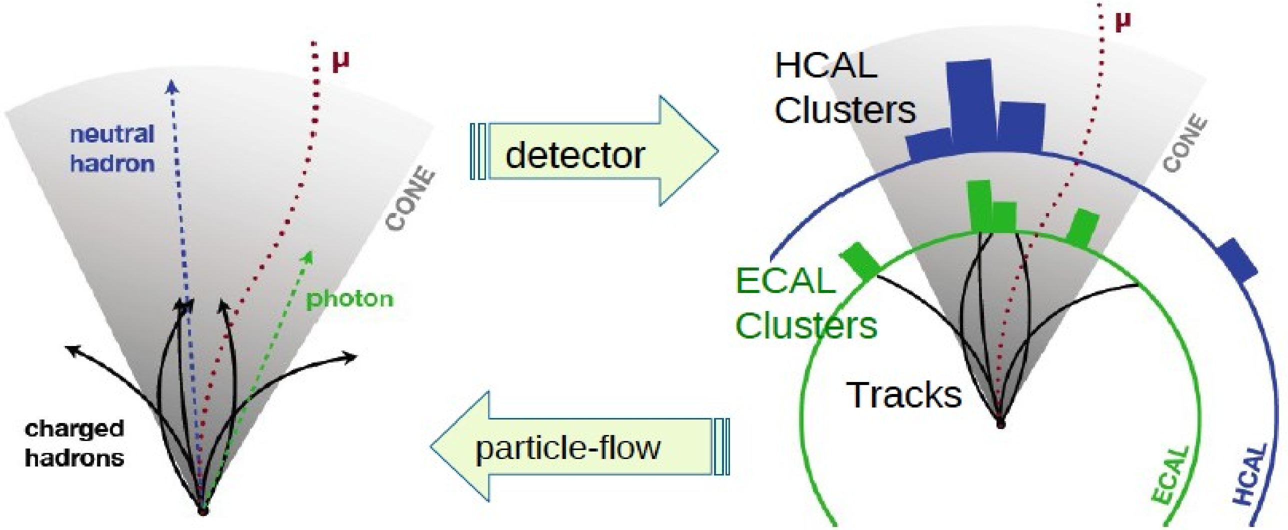
CMS Hadronic Calorimetry



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

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

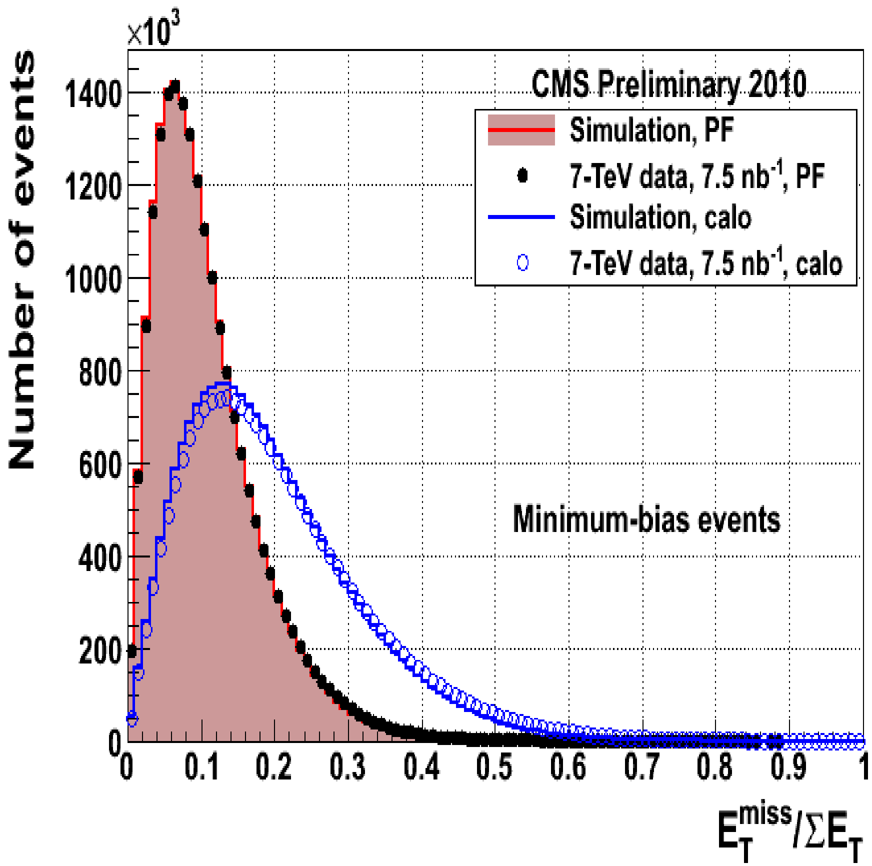
CMS: particle-flow techniques

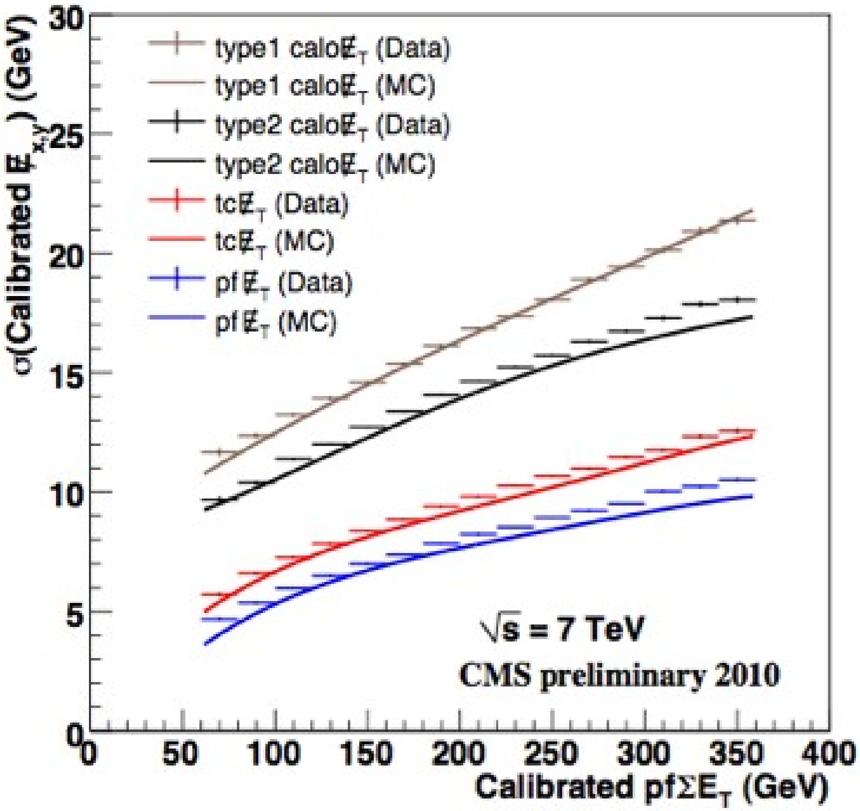


- In CMS, charged particles get well separated due to the huge tracker volume and the high magnetic field (3.8 T)
- CMS has an excellent tracking resolution, able to go to down to very low momenta (~few hundred MeVs)
- CMS has also an excellent electromagnetic calorimeter with good granularity
- In multijet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

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

CMS: particle-flow techniques





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

Summary

- The LHC accelerator has shown an excellent performance in 2010
- The LHC detectors have accompanied this performance with an also excellent behavior, confirmed with the first data taken in 2010
- This already suggests high quality physics results with those data. This will be discussed in the next two lectures