The ATLAS experiment

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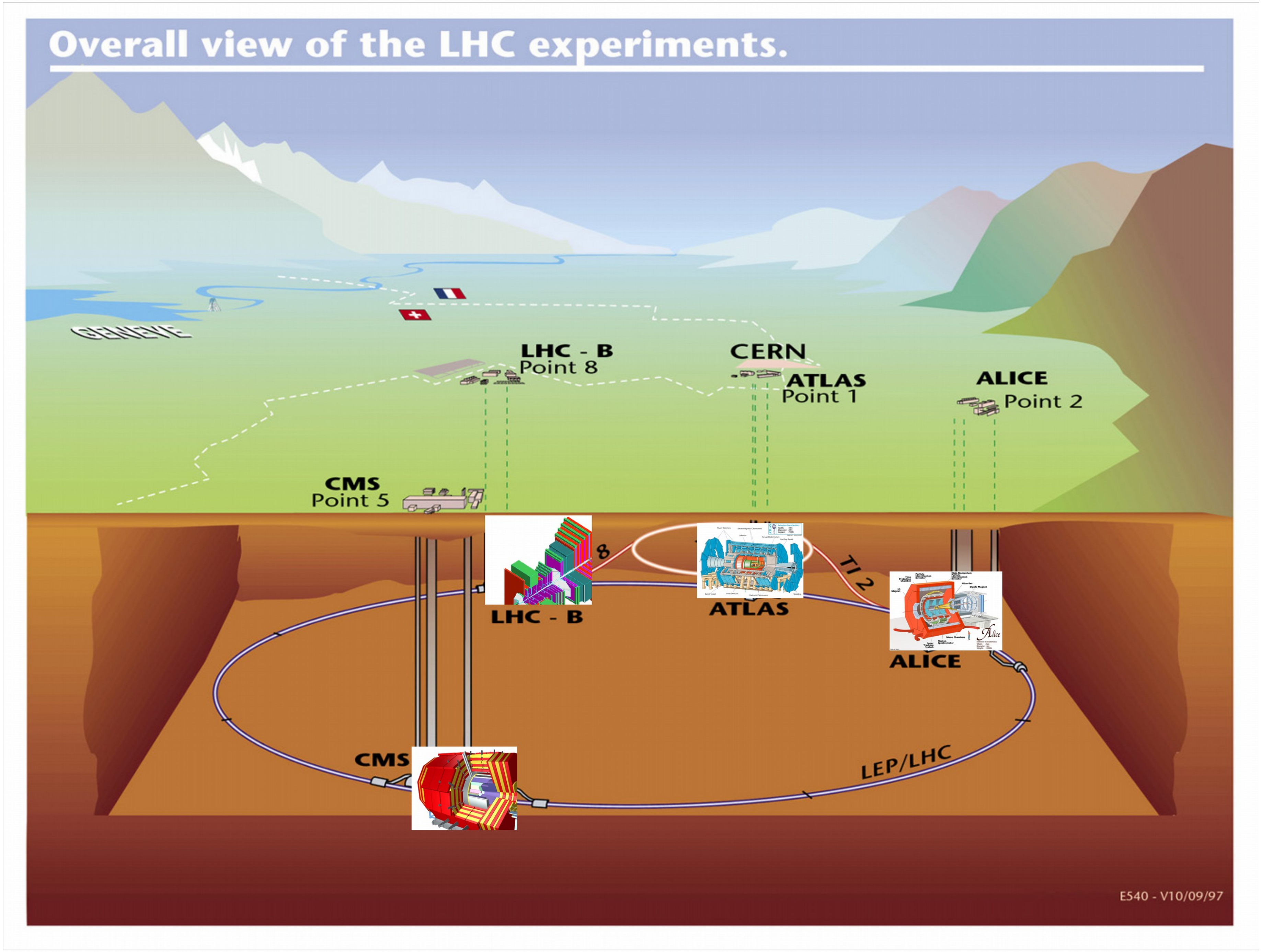
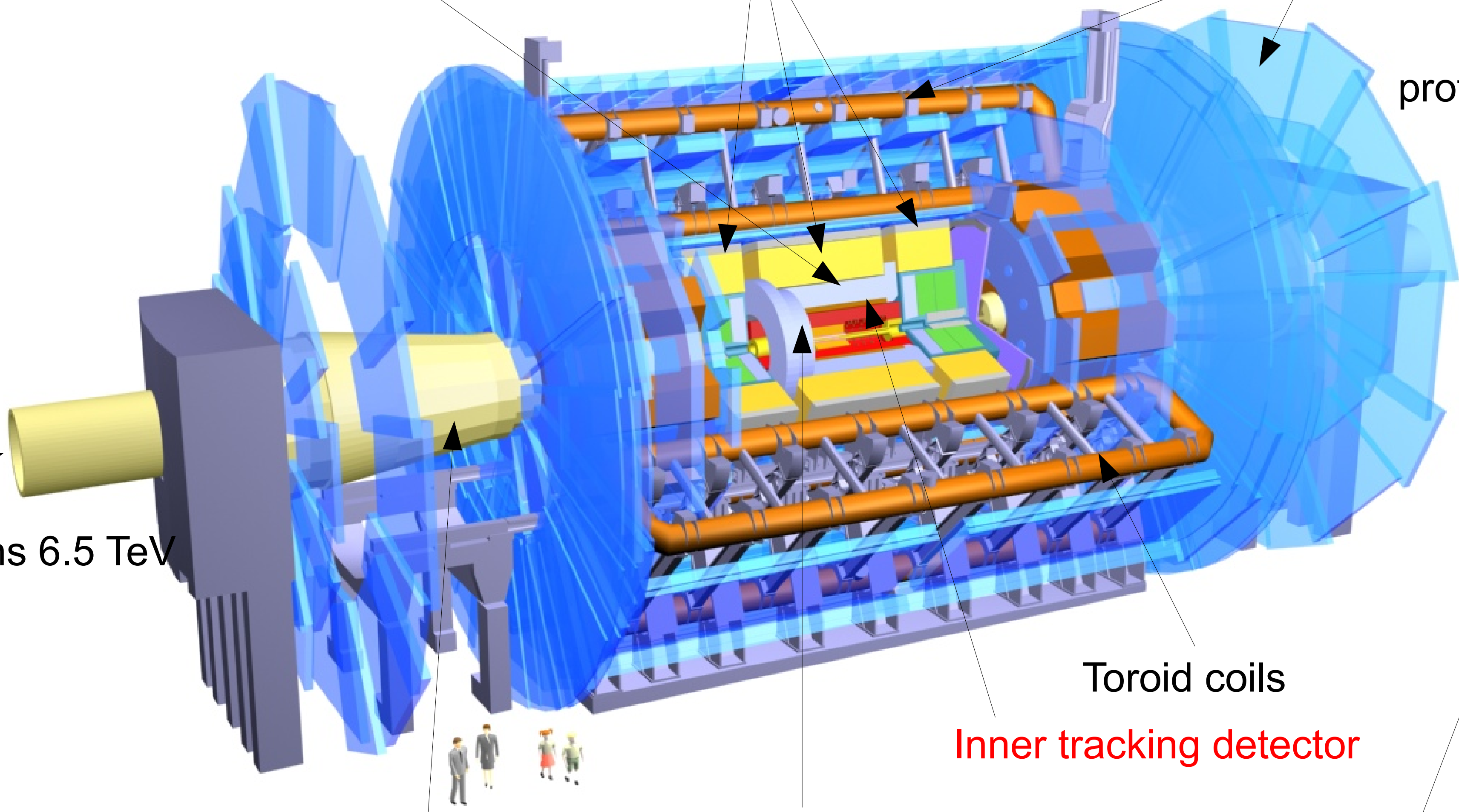
Overview

- ATLAS detector
- Tile Calorimeter performance in Run-1
- Higgs boson discovery & current status


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

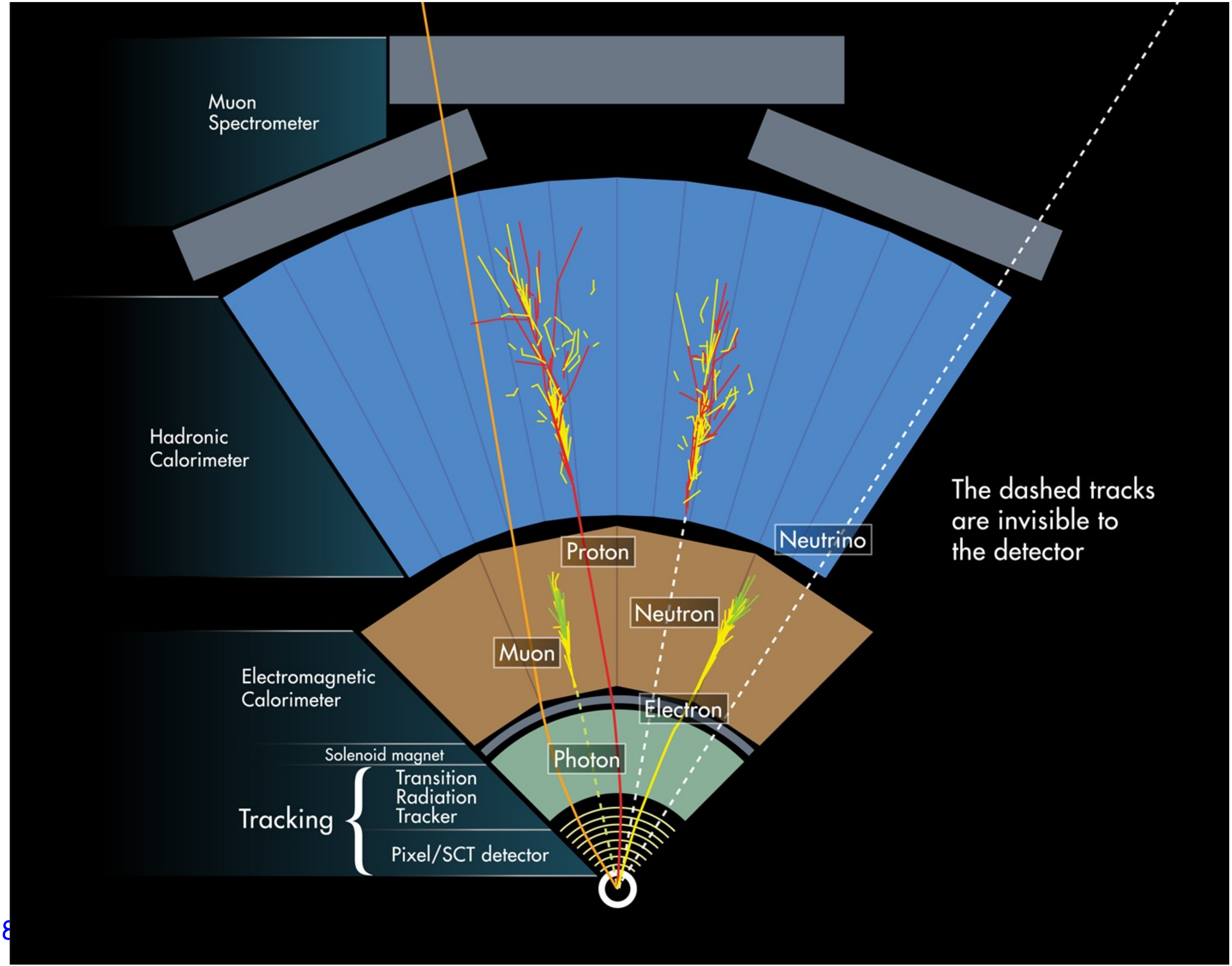
ATLAS experiment



Detector requirements

- Very good electromagnetic calorimetry for precise measurement and identification of e/γ, complemented with hadron calorimeters to jointly measure jet energies and missing transverse energy (MET)
- Large acceptance in pseudorapidity and full coverage in azimuth
- Efficient tracking at high luminosities & pile-up
  - lepton momentum measurement
  - primary and secondary vertex identification
- High precision muon momentum measurement, ideally combined with inner detector and (outer) muon spectrometer
- Trigger and particle measurement with as low as possible transverse momenta thresholds, needed for high efficiency of many physics processes measurements

Principles of particle measurements

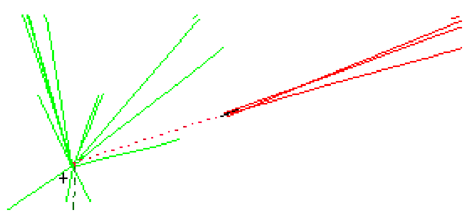


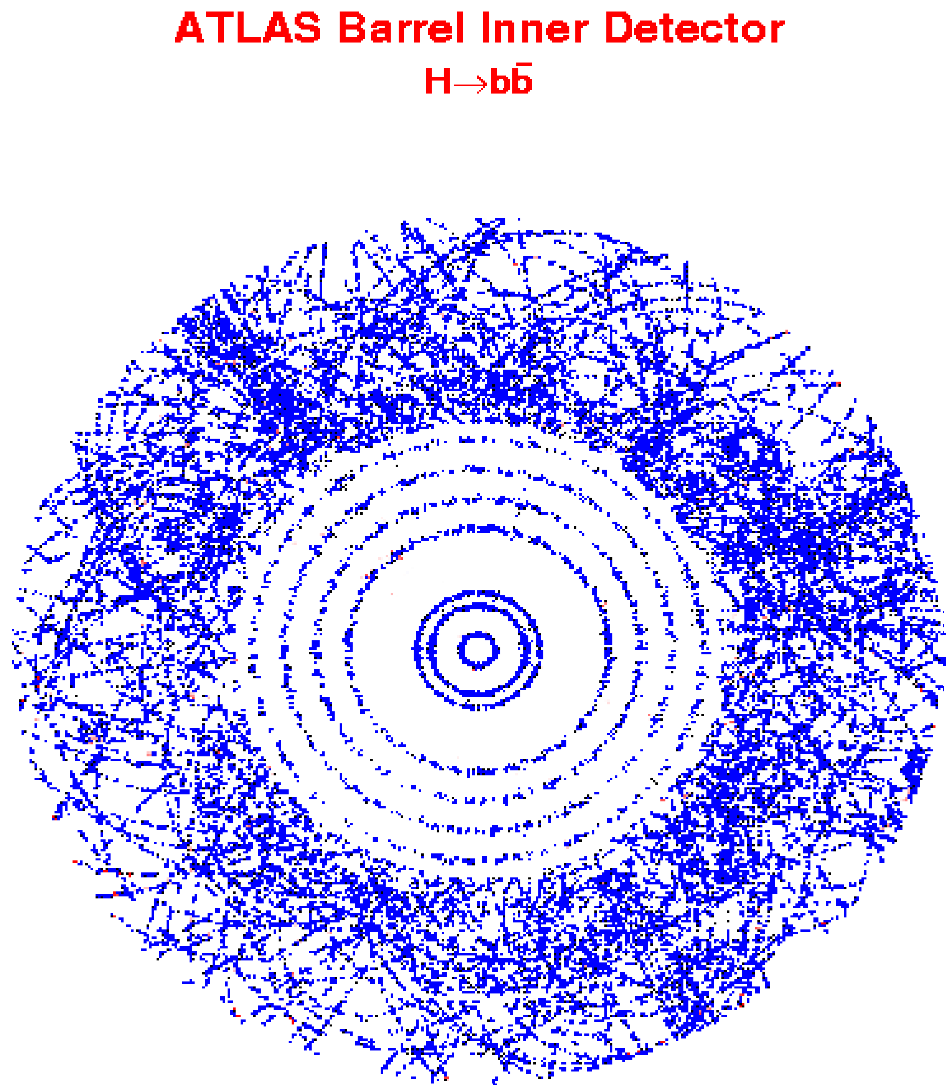
ATLAS magnet systems

- Central solenoid
  - provides 2 T field in the inner detector, tracks of charged particles are curved in the R-φ plane
  - radius of 1.25 m, length of 5.3 m
- Toroids
  - located in the outermost part of ATLAS detector
  - air-core toroids in order to minimize the multiple scattering
  - charged particle tracks are curved in the R-z plane
  - consist of 8 large coils (25 m long) in the central (barrel) part, providing the field of 0.5 T; complemented with end-cap coils providing 1 T field on each side

Track reconstruction

Challenges imposed by large amount of hits from many charged particles, originating from multiple interactions (pile-up)





Particle momentum measurement

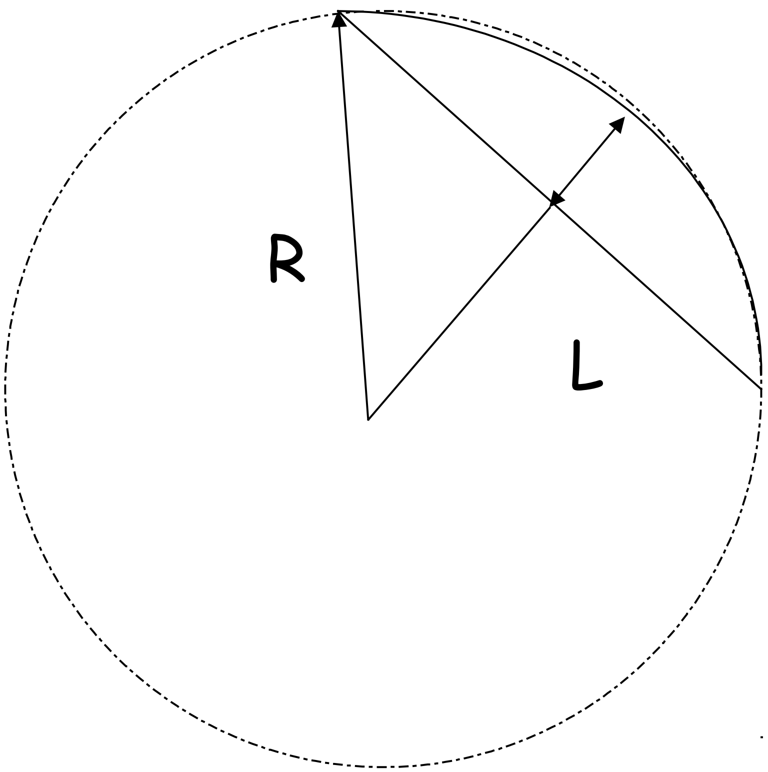
$$\text{sagitta} = R - \sqrt{R^2 - (L/2)^2} \simeq R - R\left(1 - \frac{1}{2}\frac{L^2}{4R^2}\right) = \frac{L^2}{8R}$$

$$0.3BR = p \Rightarrow R = \frac{p}{0.3B}$$

$$\text{sagitta} = \frac{0.3}{8}\int B dl \cdot L \frac{1}{p}$$

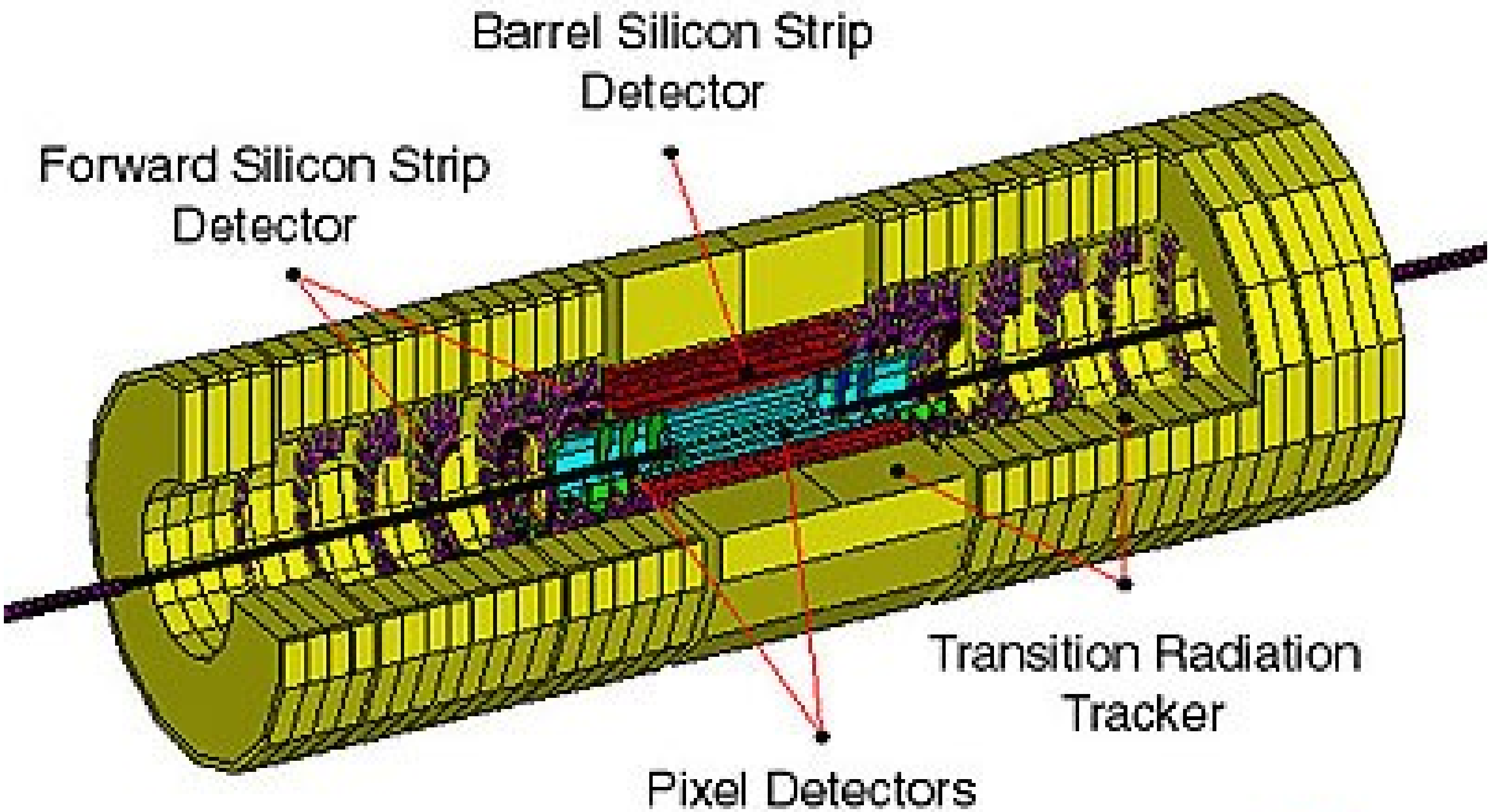
$$p = 1\ \text{TeV}$$
$$L = 5m$$
$$\int B dl = 8\ \text{Tm}$$

$$\text{sagitta} = \frac{0.3}{8} 8\,\text{Tm} \cdot 2.5m \frac{1}{1000\ \text{GeV}} = 750\ \mu\text{m}$$



So, if we require the measurement precision of 10% for a 1 TeV muon, we need to measure sagitta with only 75 µm uncertainty

Inner detector (1)



Inner detector (2)

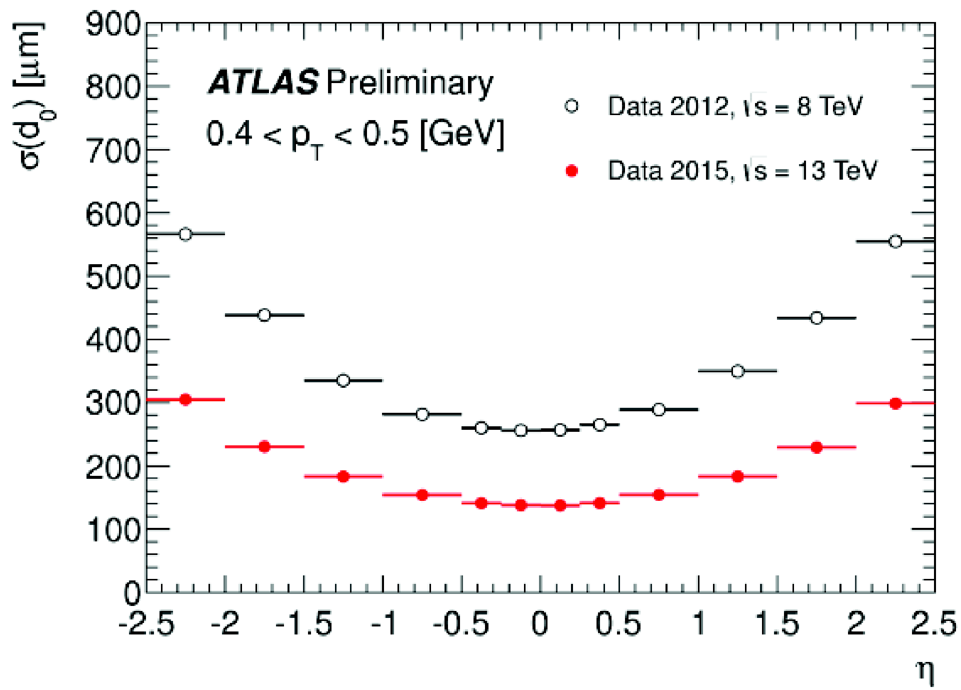
- Originally, ID consisted of three layers:
  - silicon pixel detectors
    - 3 radial layers in the central part, 2x5 discs in the forward region; total area of 2.3 m^2
    - binary readout, ~10^8 readout channels
    - resolution $\sigma(z) \approx 70\ \mu m$, $\sigma(R\varphi) = 12\ \mu m$
  - silicon strip detectors (SCT)
    - 4 radial layers in the central part, 2x9 discs in the forward region; total area of about 60 m^2
    - binary readout, ~10^7 readout channels
    - expected resolution in central part $\sigma(z) \approx 580\ \mu m$, $\sigma(R\varphi) = 16\ \mu m$, similarly in forward region $\sigma(R) \approx 580\ \mu m$, $\sigma(R\varphi) = 16\ \mu m$

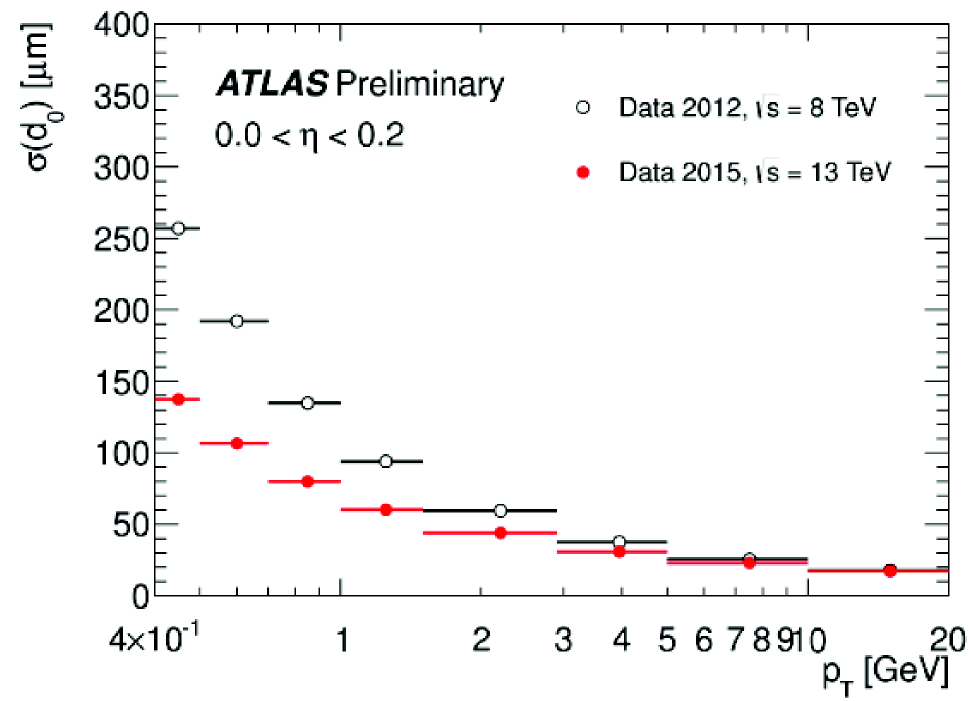
Inner detector (3)

- transition radiation tracker (TRT)
  - straw tubes filled with gas mixture (70% Xe, 20% CO_2, 10% CF_4)
  - space resolution of 170 μm per straw, based on drift time measurement
  - 2 thresholds enable to distinguish between ionization and transition radiation (→ electron identification)

Inner detector (4)

- Innermost pixel layer (B-layer) added in Run-2:
  - 1st layer of pixels, only 33 mm far from the beam line
  - improves the vertex identification and impact parameter measurement, needed for better reconstruction decaying particles; also improves b-tagging





Muon system (1)

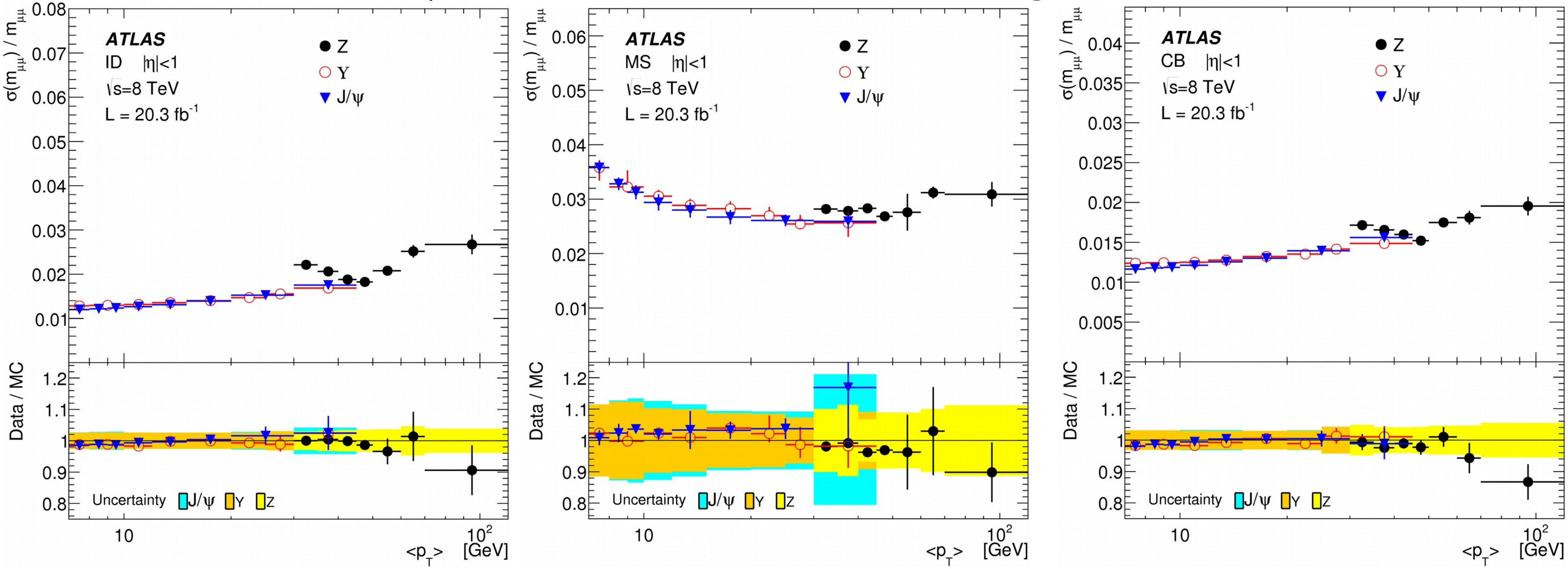
- MS provides precise measurement of muon tracks in the toroidal magnetic field
  - monitored drift tubes (MDT)
    - three layers along radius
    - provide precise measurement of 1 coordinate, $\sigma(z)$ = 80 μm
  - cathode strip chambers (CSC)
    - radiation-resistant proportional wire chambers
    - located in the transition region between the central and forward part of the detector
    - 4 layers, resolution ~ 60 μm

Muon system (2)

- Trigger chambers:
  - collision identification
  - trigger on muons at different pT thresholds
  - provide measurement of the 2nd coordinate for the muon track reconstruction (1st coordinate comes from muon chambers), resolution typically 5-10 mm
- Trigger chambers types:
  - resistive plate chambers (RPC) – 3 layers in the central part, resolution 1 cm x 1 ns
  - thin gas chambers (TGC) – forward region

Combined muon reconstruction

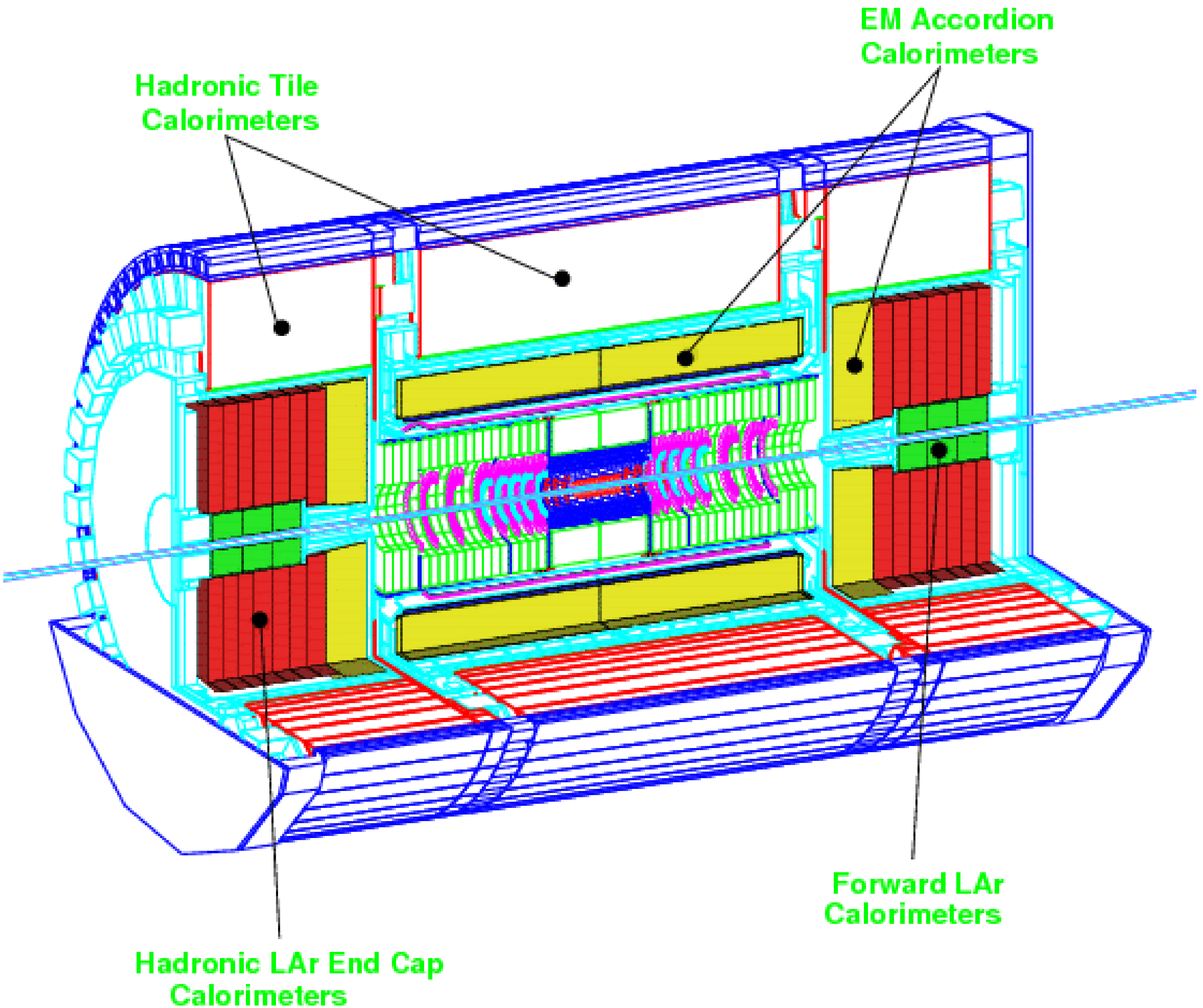
- Ideally, muons are measured in the inner detector as well as in the muon system. The track (and hence the muon momentum) is then determined from combined fit
  - example for central muons ($|\eta| < 1$) as reconstructed with ID only, MS only and combined (Run-1)
    - ID more important at lower momenta, MS at higher momenta



Calorimeters (1)

- Calorimeters measure the energy and direction of jets.
- Due to the almost full 4π coverage, they also provide the information on the missing transverse energy
  - MET implies the presence of neutrinos or other particles escaping detection in the reconstructed event
- Calorimeters in the central part
  - EM sampling calorimeters (LAr + Pb)
  - hadronic Tile calorimeter (scintillator + steel)
- Calorimeters in the forward region are all based on LAr technology
  - EM end-cap (LAr + Pb)
  - hadronic end-cap (LAr + Cu)
  - forward calorimeter (LAr + Cu, LAr + W)

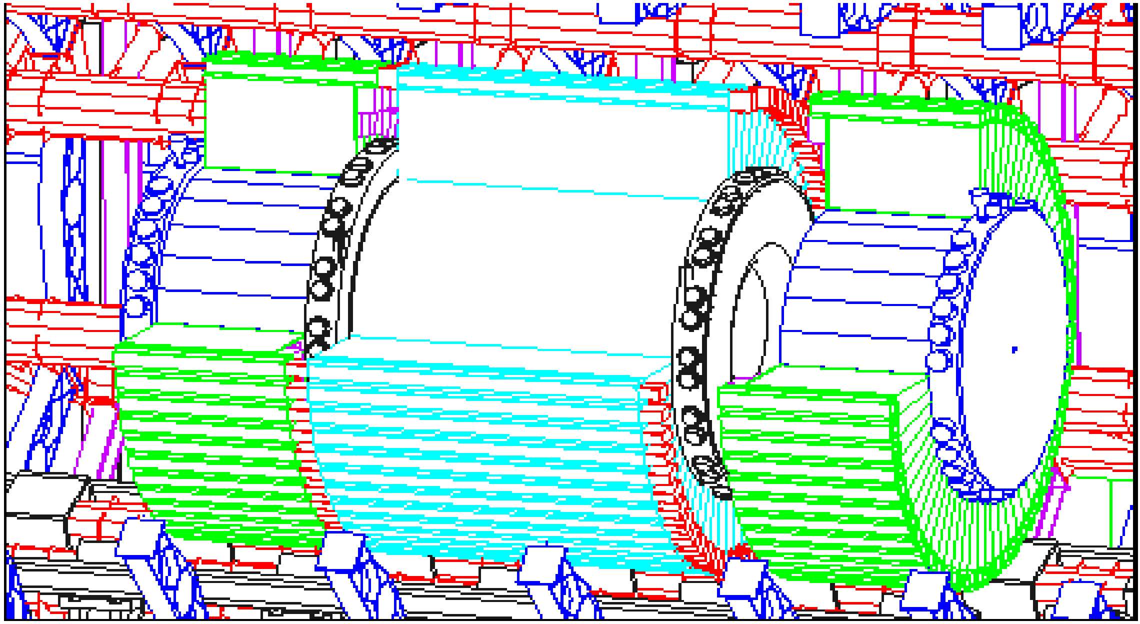
Calorimeters (2)



Tile Calorimeter

Tile Calorimeter (1)

- Total length ~12 m, total weight 2900 tons
- 5000 readout cells, each cell read-out by 2 channels
- Split into Long Barrel ($|\eta| < 1.0$) and Extended Barrel ($0.8 < |\eta| < 1.7$)

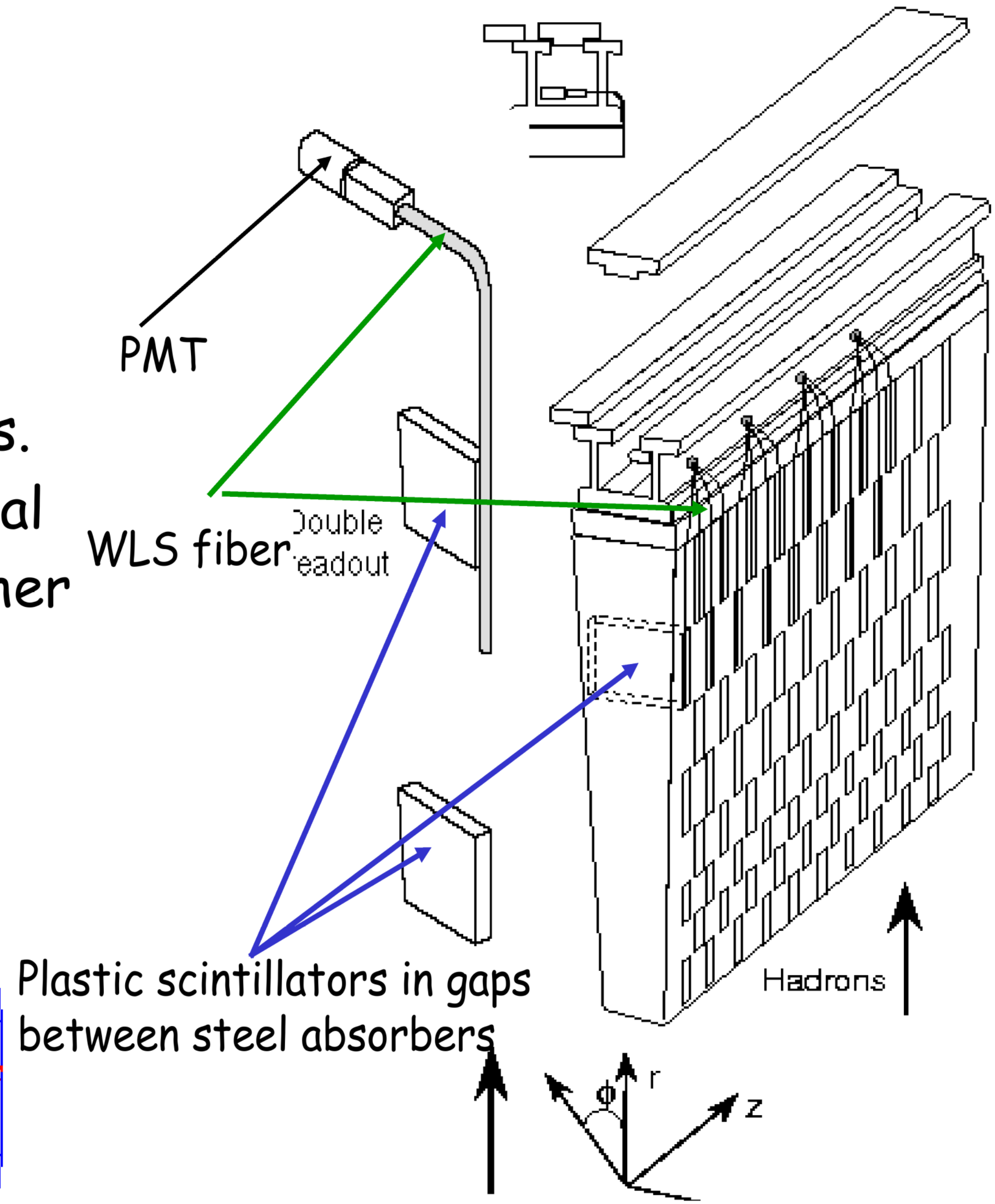


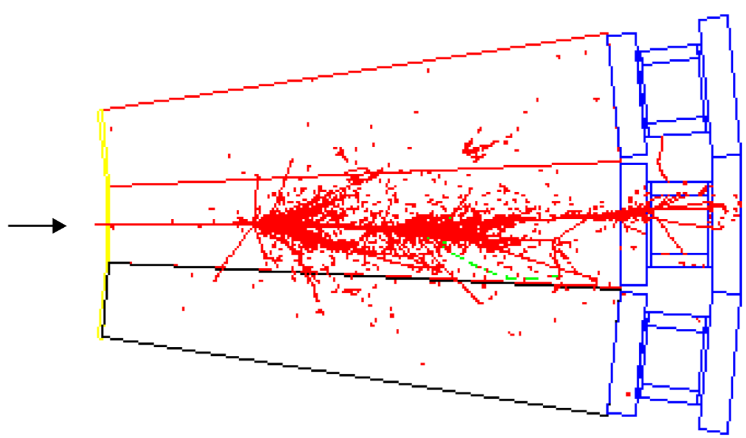
- Each barrel consist of 64 modules ($\rightarrow \Delta\varphi = 0.1$)
- Cell segmentation:
  - 3 radial layers ($1.5\lambda_{int}$, $4.1\lambda_{int}$, $1.8\lambda_{int}$ in Long Barrel; $1.5\lambda_{int}$, $2.6\lambda_{int}$, $3.3\lambda_{int}$ in Extended Barrel)
  - $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (1st and 2nd radial layer), $\Delta\eta \times \Delta\varphi = 0.2 \times 0.1$ (3rd layer)

Tile Calorimeter (2)

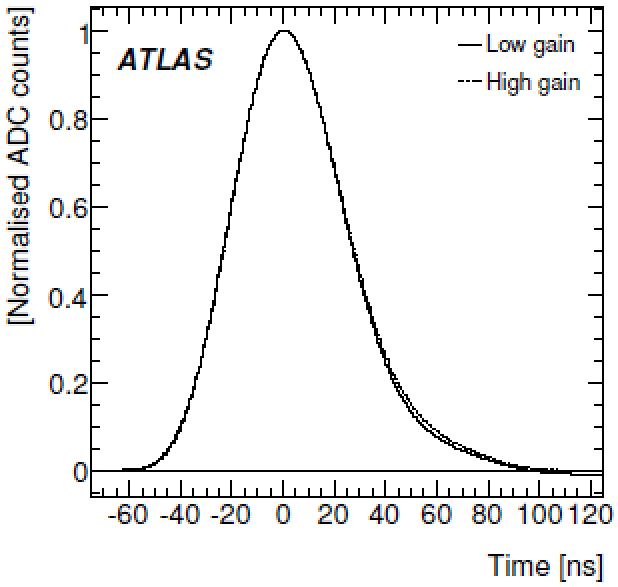
- Incoming high-energy hadrons produce showers of secondary particles

- Scintillating light induced by charged particles is collected on both sides of tiles by WLS fibers. Photomultiplier convers the optical signal into electrical that is further shaped and digitized.





Signal reconstruction & calibration (1)



- Since the signal is shaped (FWHM 50 ns), integral is proportional to its amplitude
  - analog signal sampled every 25 ns, 7 samples used for signal reco
  - amplitude reconstructed using Optimal Filtering algorithm (~pulse shape fit)

$$A = \sum_{i=1}^{n=7} a_i S_i, \qquad A\tau = \sum_{i=1}^{n=7} b_i S_i, \qquad p = \sum_{i=1}^{n=7} c_i S_i$$

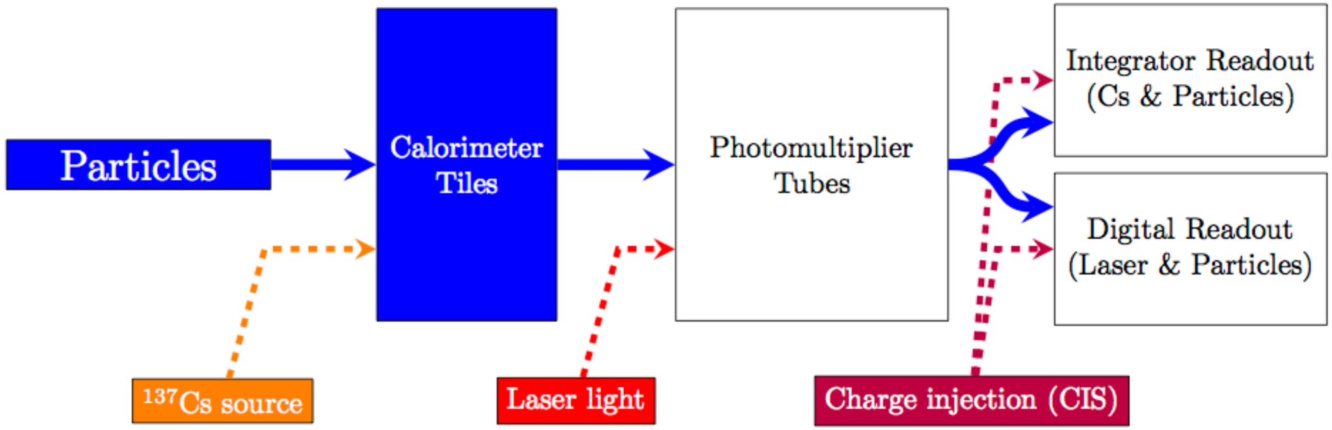
- Signal amplitude is calibrated to EM scale using multi-step procedure and the knowledge of electron response in beam tests (C_{TB}).

$$E_{channel} = A[ADC] \cdot C_{Cs} \cdot C_{laser} \cdot C_{CIS}[pC/ADC] / C_{TB}[pC/GeV]$$

  - individual constants stand for the corresponding calibration system

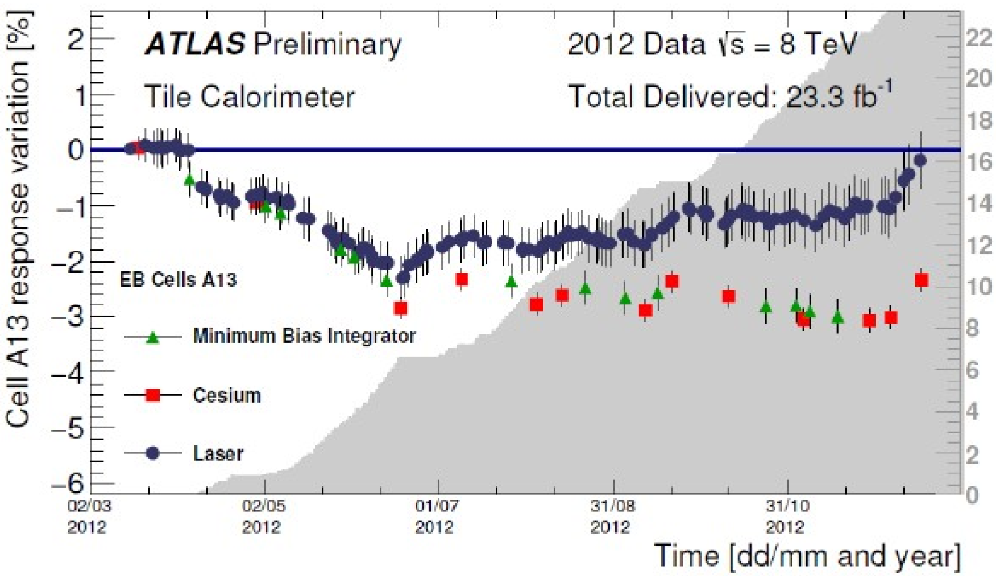
Signal reconstruction & calibration (2)

- Three calibration systems (Cs, laser, charge injection), each sensitive to different parts of the signal propagation.



- Integrator readout is also used to validate the EM scale in pp collisions

- Combined calibration show gain dependence on the beam conditions, Cs and integrator data are mutually compatible



Tilecal Run-1 results (1)

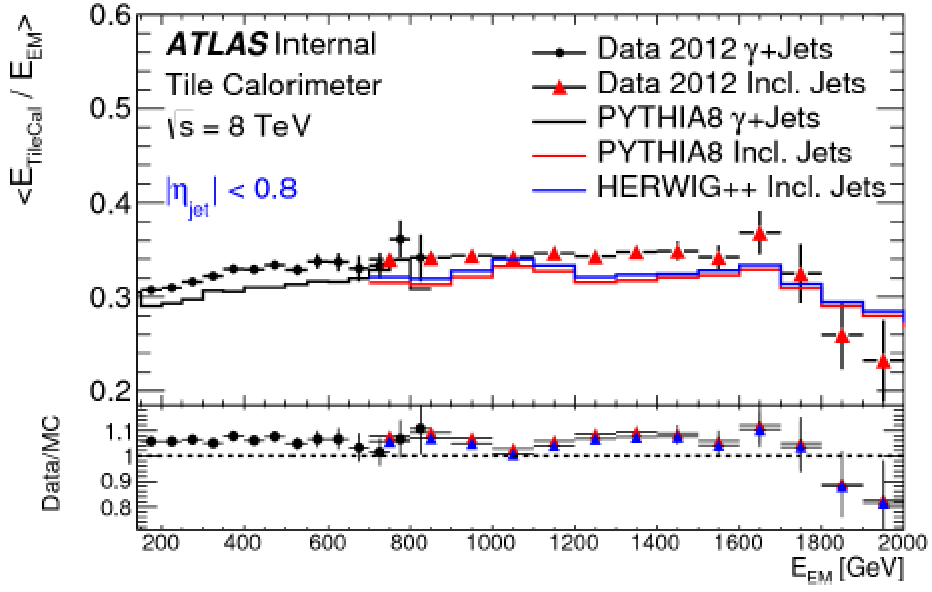
- EM scale validation with cosmic muons, collision muons, isolated hadrons and jets
- Collision muons – select high p_T muons from W boson decays, we measure truncated mean in each cell and compare to MC prediction (R = data/MC).

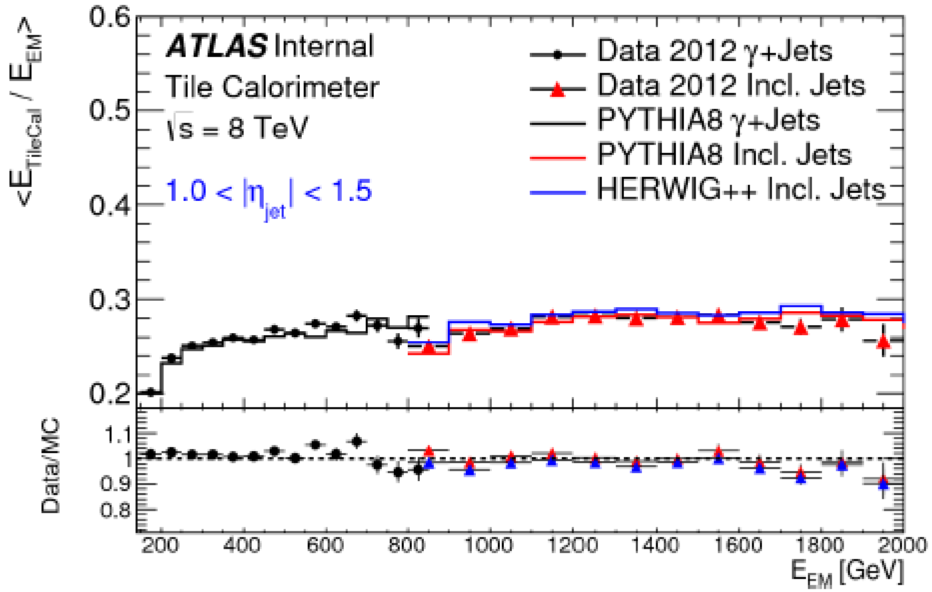
	R_{2011}	R_{2012}
LB-A	0.996±0.006	1.003±0.006
LB-BC	1.001±0.004	1.005±0.005
LB-D	1.031±0.009	1.028±0.008
EB-A	1.007±0.013	1.025±0.008
EB-B	1.001±0.006	1.012±0.007
EB-D	1.008±0.010	1.012±0.010

  - good stability across the years
  - indication of slight overcalibration in 3rd LB layer
  - similar results obtained also with cosmic muons

Tilecal Run-1 results (2)

- Jet energy fraction measured in Tilecal for uncalibrated jets (EM scale only) in the large p_T range
  - energy fraction increases from 25% (p_T = 140 GeV) to 30% (p_T = 2 TeV)
  - MC simulations describe this trend well, data show a larger fraction of the total jet energy in the central barrel (LB) compared to MC.

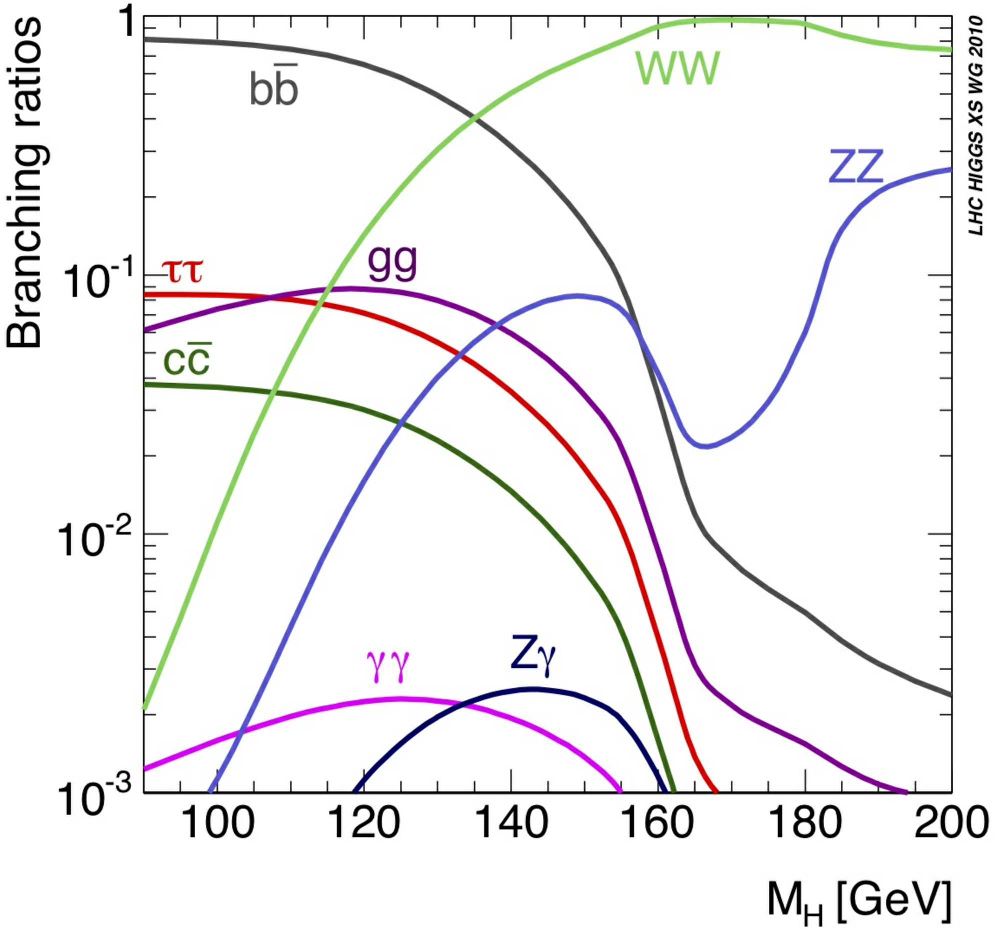




Higgs boson

Higgs boson in Standard model

- The theory predicts all Higgs boson properties except of its mass. For instance, the decay strengths (BR)...

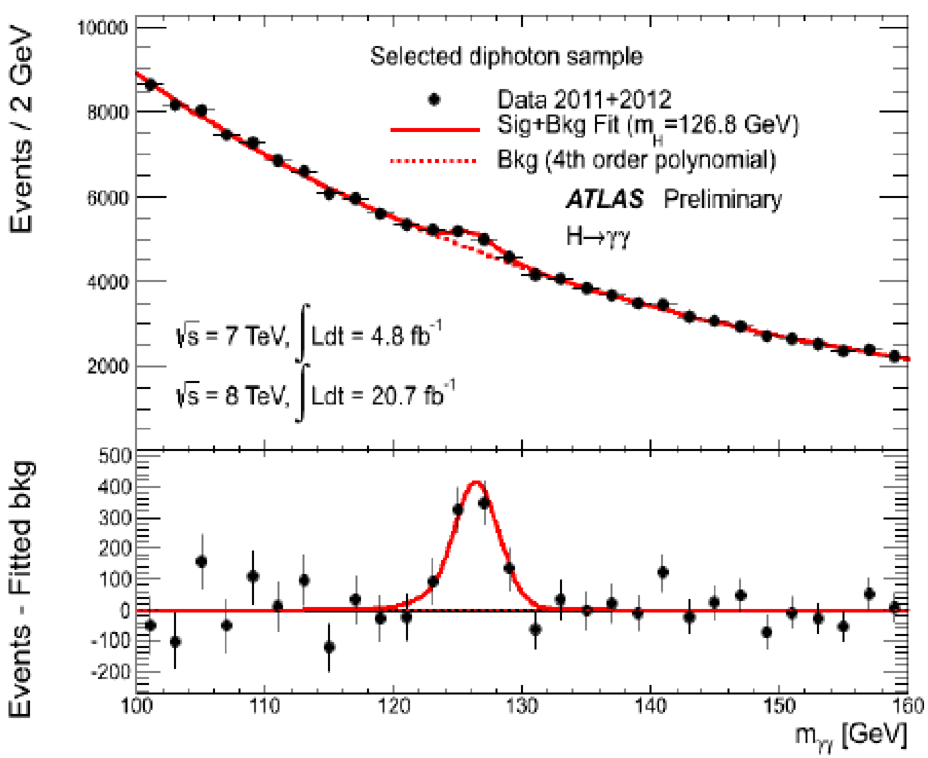


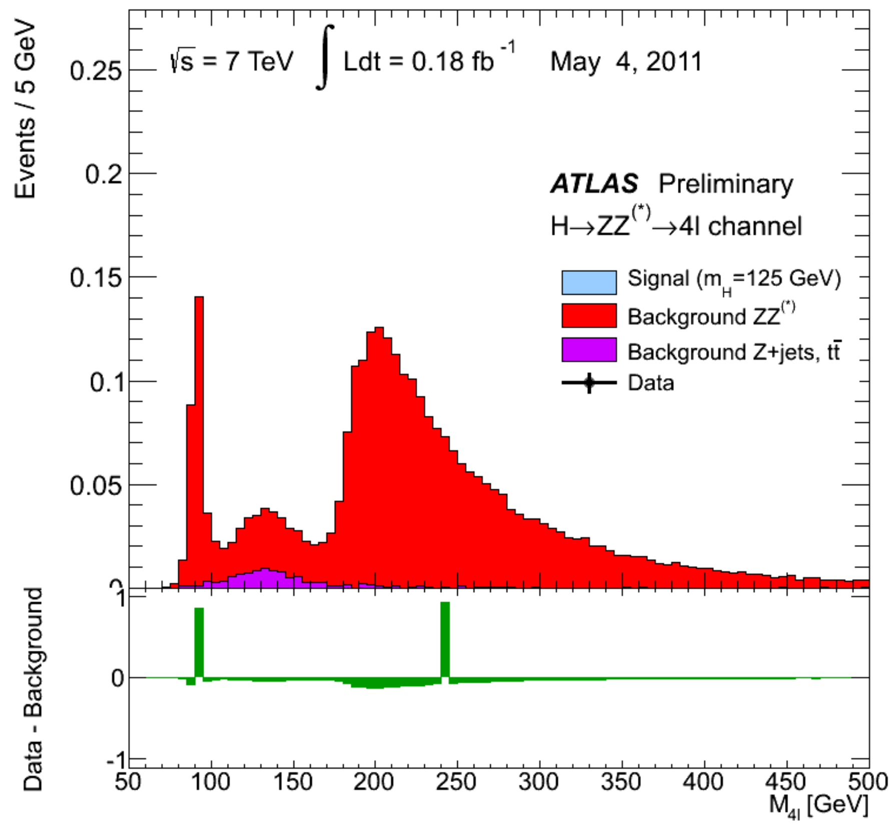
- This theory of electro-weak interactions was formulated in 1967. Note W, Z bosons were discovered at SPS (CERN) much later in 1983.

- Higgs boson was finally discovered at LHC in 2012.

Higgs boson discovery (1)

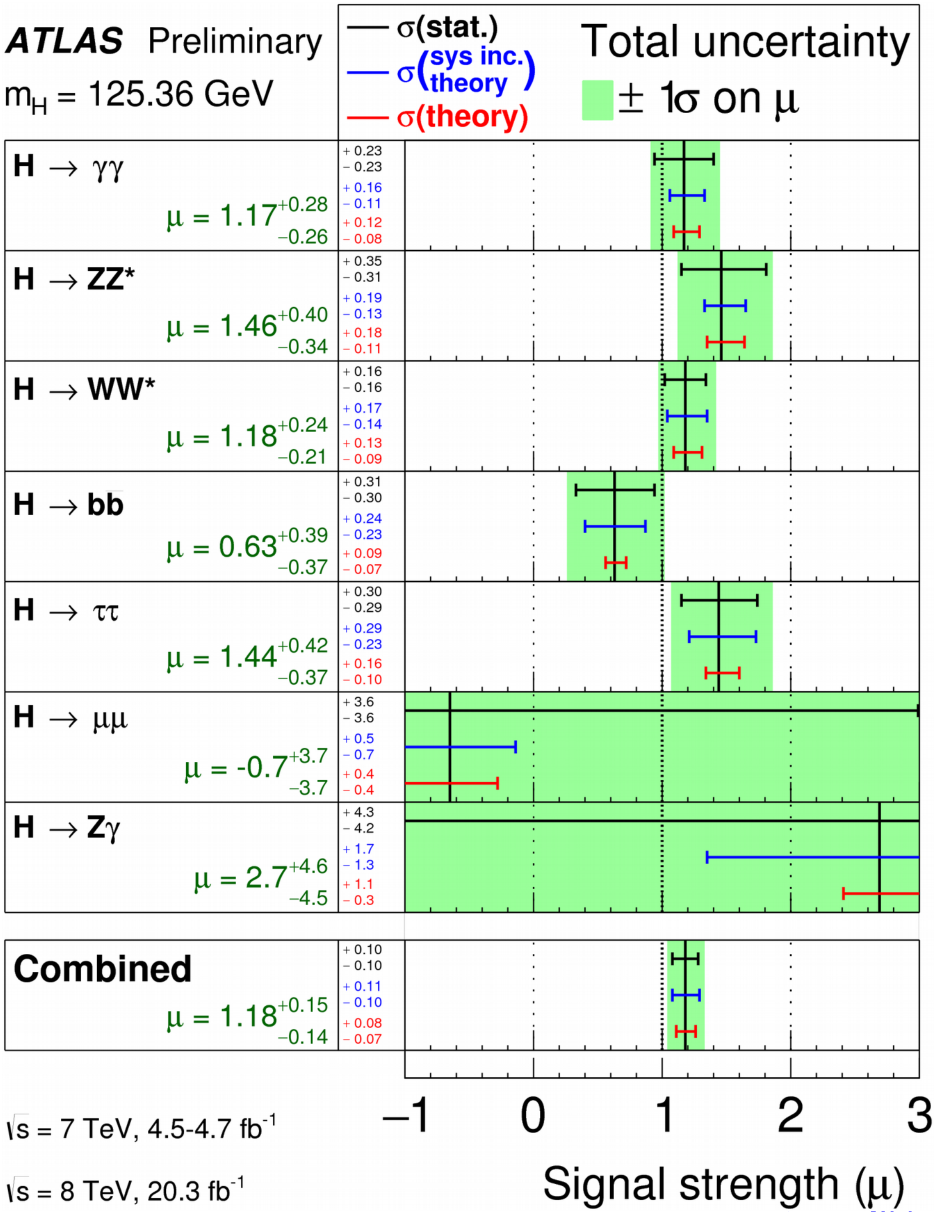
- In 2012, ATLAS and CMS experiments reported invariant mass peaks in γγ and 4ℓ final states (and an excess of events in WW → ℓνℓν) consistent with a new scalar particle with m~125 GeV

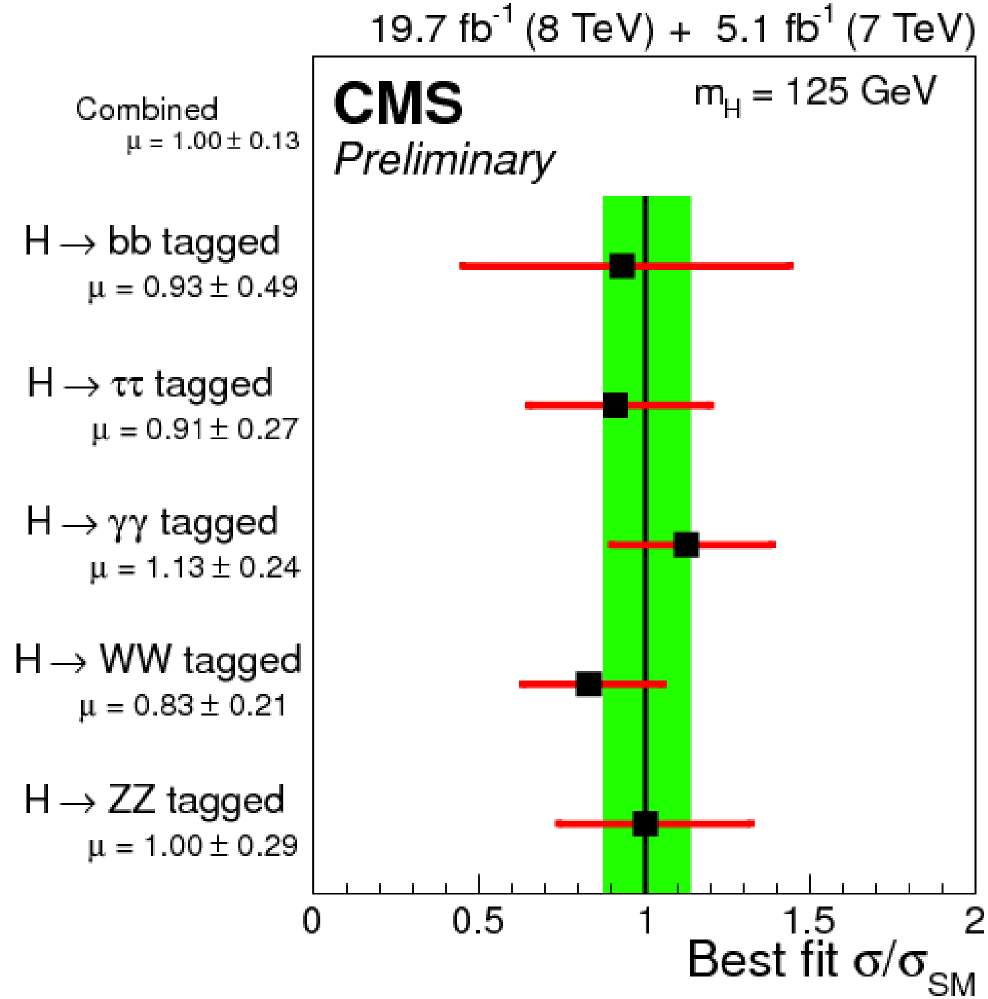




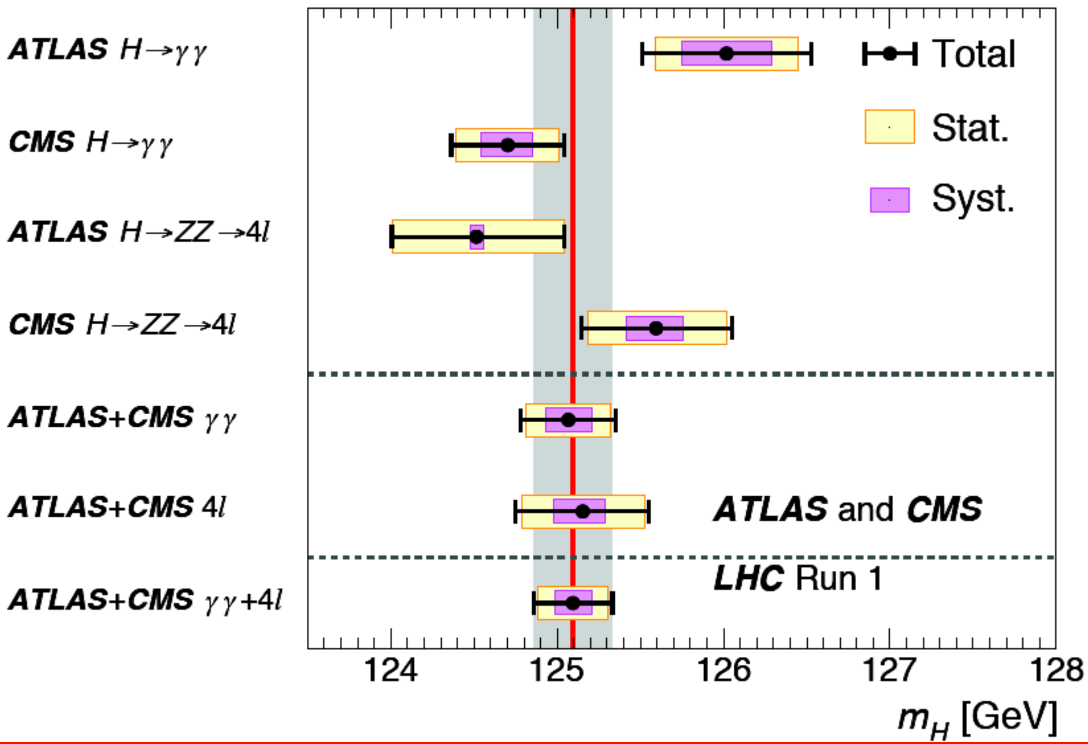
Higgs boson discovery (2)

- Results after LHC Run-1





Higgs boson discovery (3)

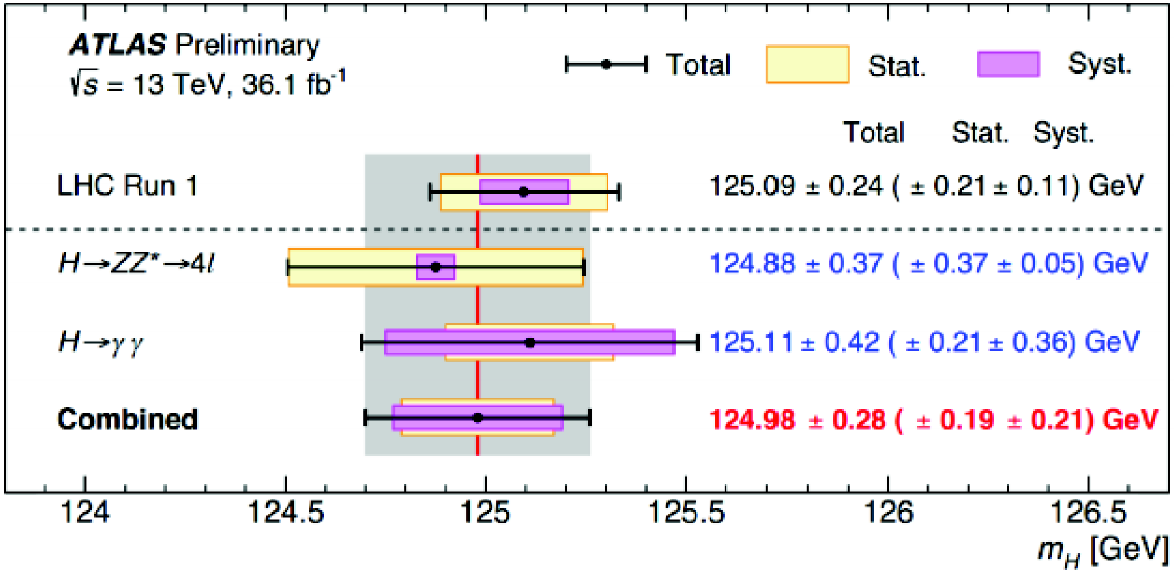


$$\mathbf{m_H = 125.09 \pm 0.24\ (\pm 0.21\ stat \pm 0.11\ syst)\ GeV}$$

- Is it really the Standard model Higgs boson?
  - need to determine more precisely the coupling constants to individual particles, as well as to determine CP etc.
  - search for anomalous decays (e.g. LFV $H \to \tau+\mu$ or $H \to \tau+e$) not predicted by Standard model

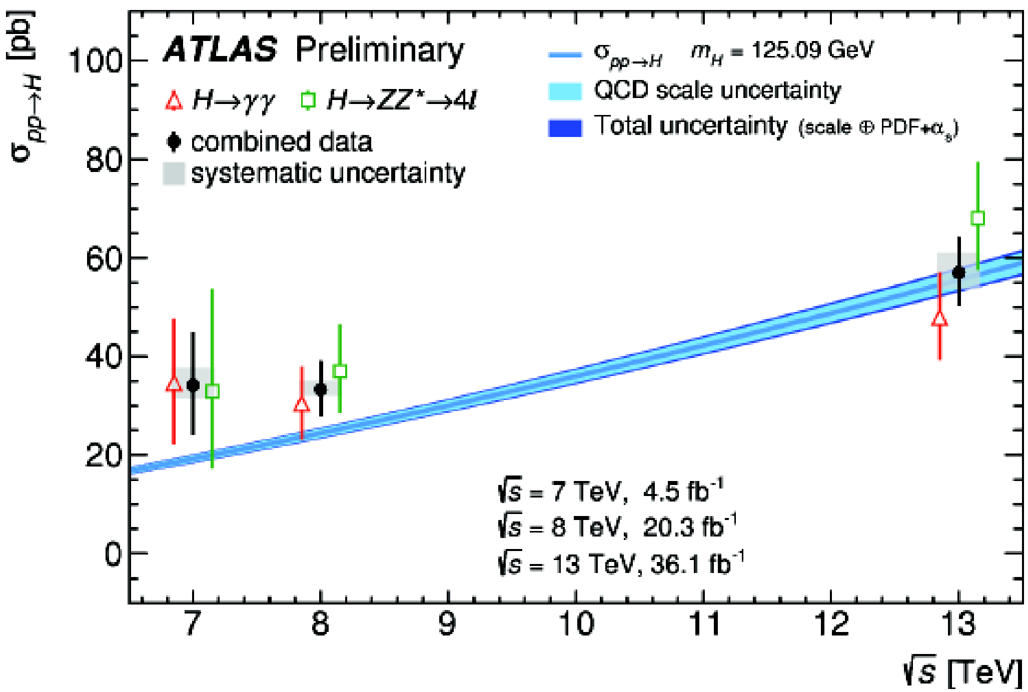
Preliminary Run-2 Higgs boson results (1)

- (Re)measurement of the Higgs boson mass in Run-2



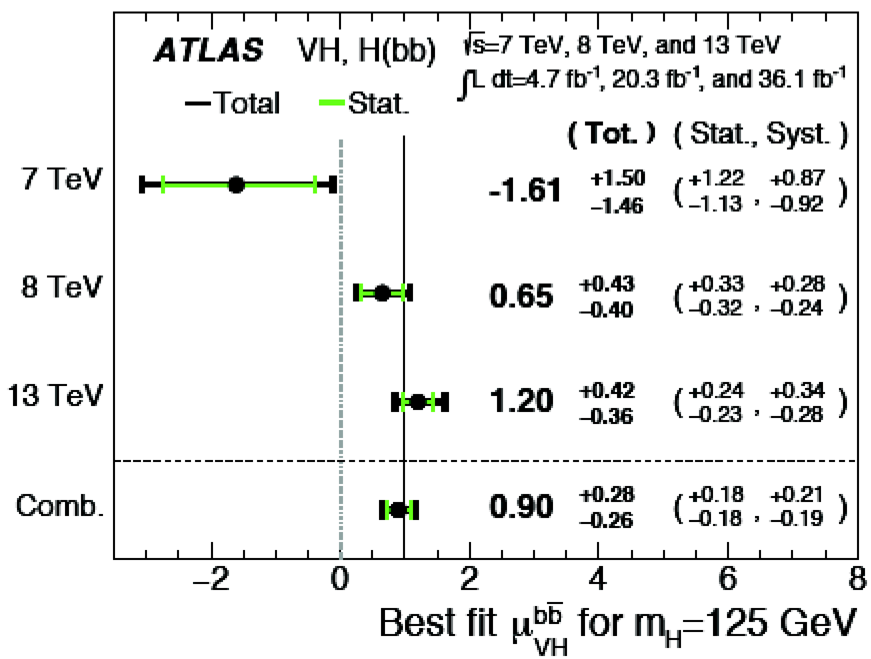
compatible with Run-1, no surprise

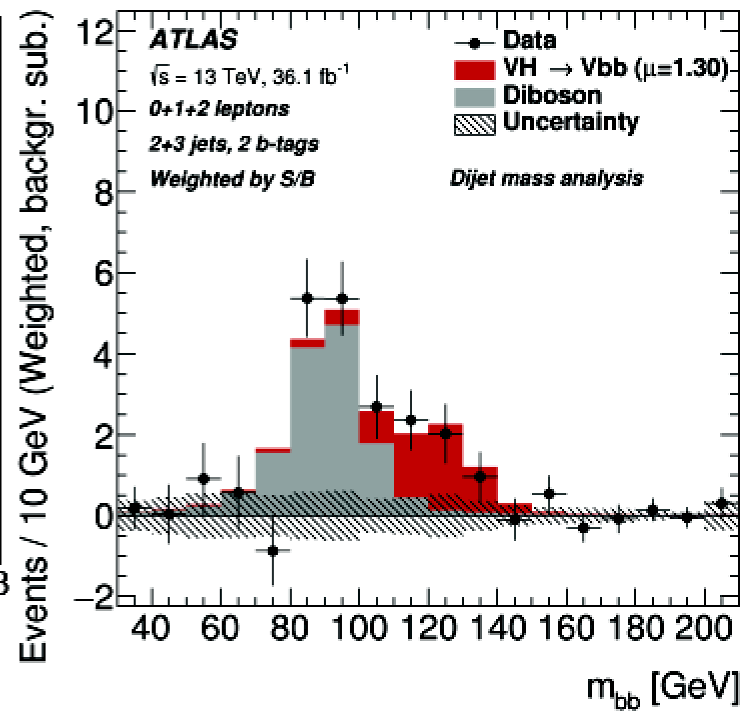
- Cross-section measurement in HZZ(4ℓ) and Hγγ channels



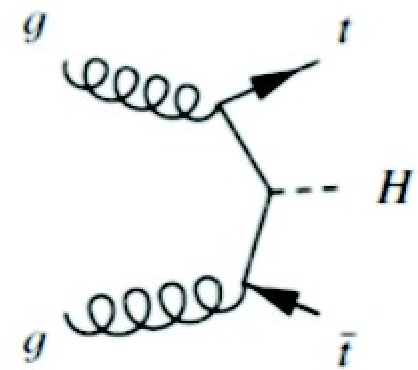
Preliminary Run-2 Higgs boson results (2)

- Evidence for Hbb coupling
  - measured significance 3.5σ, after combination with Run-1 results





Preliminary Run-2 Higgs boson results (3)



- Evidence for ttH production
  - complex final states, depends on the Higgs boson decays: bb, γγ, 4ℓ, multi-lepton (WW → ℓνℓν or ℓνqq, $\tau_\ell\tau_\ell$, ZZ → ℓℓνν or ℓℓqq)
  - many categories and signal regions
  - measured signal strength μ (relative to SM prediction)
  - combined significance ATLAS 4.2σ, CMS 3.2σ

μ	ATLAS	CMS
bb	0.8 ± 0.6	0.72 (lep) ± 0.45 0.9 (had) ± 1.5
ML	1.6 ± 0.5	1.23 ± 0.45
$\gamma\gamma$	0.6 ± 0.7	2.2 ± 0.9
4l	<1.9 (95% CLs limit)	0 + 1.2
Combination	**1.2 +/-0.3 (combination)**	**1.18 +/- 0.3 (global fit)**

Preliminary Run-2 Higgs boson results (4)

- Many other results available
  - total and differential cross-section measurements in various channels
  - spin and CP results
  - upper limits on other decay couplings ($H \rightarrow Z\gamma$, $H \rightarrow \mu\mu$)
- … or coming very soon
  - $H \rightarrow \tau\tau$

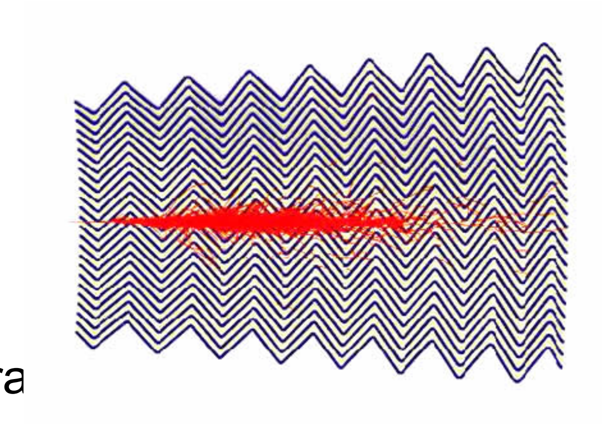
Summary on Higgs boson studies

- We have evidence of the Higgs boson couplings to WW, ZZ, γγ, ττ, bb, tt.
  - note that all 3rd generation charged fermion couplings have already been observed
- Still need to
  - measure other couplings and improve the uncertainty on the already measured ones
  - search for anomalous decays (e.g. LFV $H \rightarrow \tau e, \tau\mu$)
  - continue searching for other Higgs bosons and/or decays, e.g. those predicted by beyond Standard model theories

Eagerly awaiting 2018 data-taking and full Run-2 results

BACKUP

Centrální EM kalorimetr (1)



- Sendvič Pb+LAr
  - struktura harmoniky
  - 4 radiální části:
    - pre-sampler (1 cm LAr)
      - co nejblíže magnetu, korekce na energii ztra
    - pre-shower ($6X_0$), alias sampling 1
      - velmi jemná segmentace $\Delta\eta x\Delta\varphi$=0.003x0.1
      - rozlišení e/γ/π^0/jet
    - sampling 2 ($16X_0$)
      - $\Delta\eta x\Delta\varphi$=0.025x0.025
    - sampling 3 ($2X_0$)
      - $\Delta\eta x\Delta\varphi$=0.05x0.025

Centrální EM kalorimetr (2)

- Rekonstrukce energie:

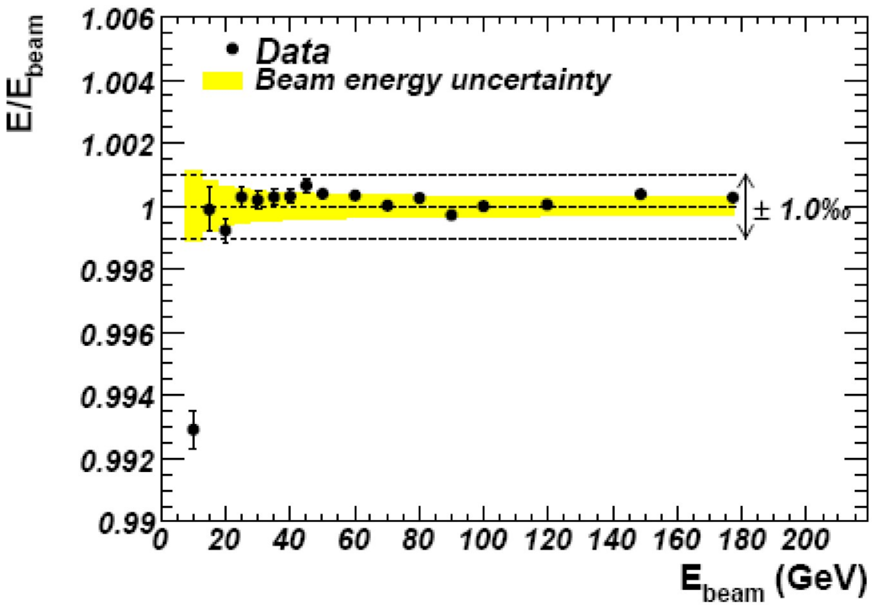
$$E = \text{offset} + W_0 E_0 + W_{01}\sqrt{E_0 E_1} + \lambda(E_1 + E_2 + E_3) + W_3 E_3$$

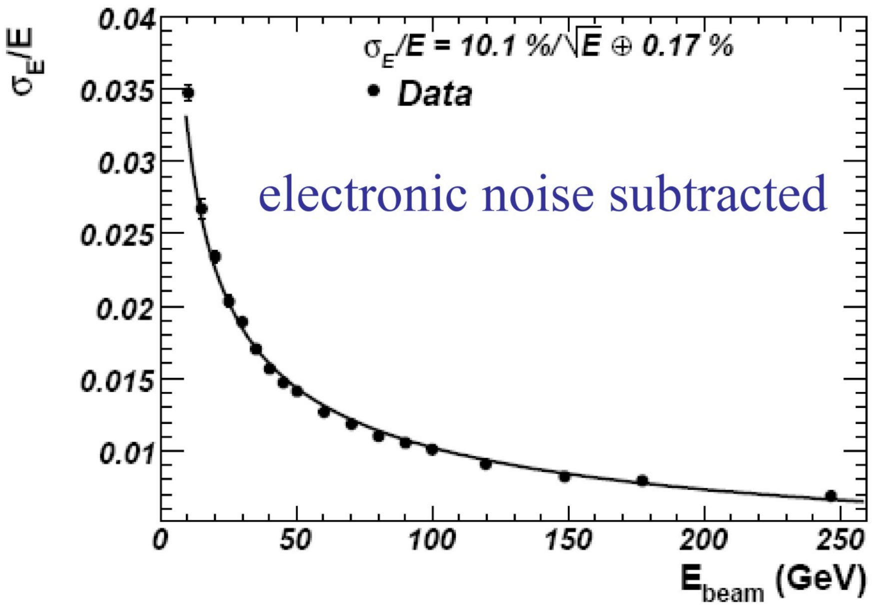
upstream energy loss

Eloss between pre-sampler and pre-shower

energy leakage

- Linearita a rozlišení:



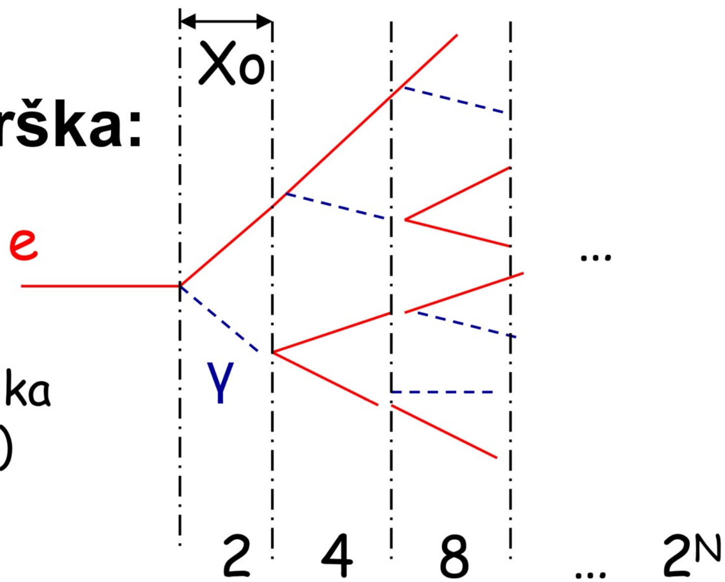


Pár slov o kalorimetrech

- Princip spršky, délka kalorimetru
- Celkový signál, úměrný součtu délek drah (v aktivním médiu), je také úměrný celkové energii primární částice
- Hadronové spršky, kompenzace
- Rozlišení kalorimetru
- In-situ kalibrace hadronového kalorimetru

Délka kalorimetru

- **Elmg. sprška:**



X_0 je radiační délka
(5.6 mm pro olovo)

$$\frac{E}{2^N} = \varepsilon$$

$$\frac{7\,\mathrm{TeV}}{2^N} = 10\,\mathrm{MeV}$$

$$2^N = 7 \cdot 10^5 \Rightarrow N \approx 20$$

- Jak dlouhý potřebuji kalorimetr ?
  - velmi naivně: 20 $\mathbf{X_0}$ na částici o energii 7 TeV
  - korekce:
    - střední volná dráha fotonu 9/7 $\mathbf{X_0}$ (vysokoenergetická limita produkce párů)
    - brzdné záření má netriviální energetické rozlišení, ….

Elektromagnetický kalorimetr pro ATLAS má hloubku 25 $\mathbf{X_0}$

Signál a celková energie

- Celková délka drah sekundárních částic

$$T(X_0) = E(primary)/\varepsilon$$

(viz. předchozí stránka), kalorimetr je tedy lineární detektor !!

  - triviální pro homogenní elmg. kalorimetr
  - platí i pro sendvičový (sampling) kalorimetr, kde v aktivním médiu detekuji pouze zlomek $T(X_0)$

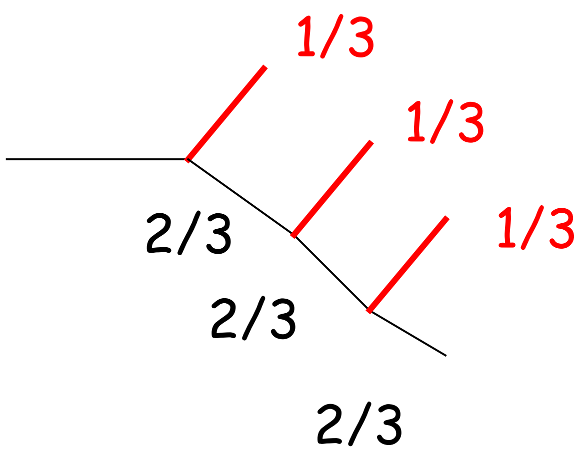
Hadronové spršky (1)

- Při silné interakci hadronu s jádrem vznikají další částice, především $\pi^{\pm}$, π^0
  - $\pi^0 \to \gamma\gamma$, vzniká tedy čistě elmg sprška
  - ostatní hadrony dále tvoří hadronovou část
- Velmi naivně: ⅓ sekundárních částic představují π^0

$$f_{em} = 1/3 + (2/3)\cdot(1/3) + (2/3)^2\cdot(1/3) + \ldots$$

$$f_{em} = 1/3 \cdot \left(1 + \frac{2}{3} + \left(\frac{2}{3}\right)^2 + \left(\frac{2}{3}\right)^3 + \ldots + \left(\frac{2}{3}\right)^N\right)$$

$$f_{em} = 1/3 \cdot \frac{1 - \left(\frac{2}{3}\right)^N}{1 - \frac{2}{3}} = 1 - \left(\frac{2}{3}\right)^N$$



Hadronové spršky (2)

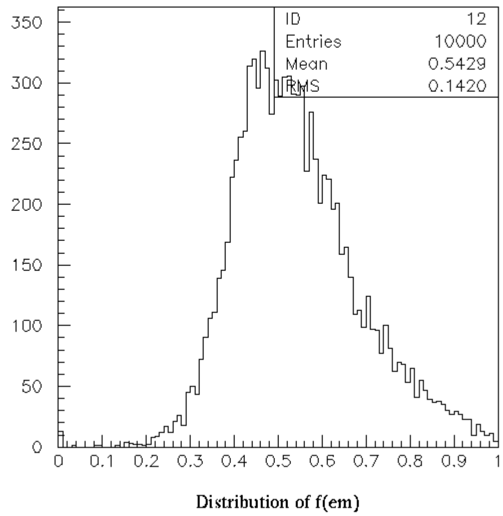
- Počet sekundárních interakcí N je konečný (tj. $f_{em} < 1$) a závisí na energii. Navíc $f_{\pi 0} < ⅓$.
  - N je úměrné délce spršky a ta logaritmicky roste s primární energií (Wigmans):

$$f_{em} = 0.1 \cdot \ln(E[\mathrm{GeV}])$$

  - Gabriel, Groom:
    - E0 = energie nutná k vytvoření π^0
    - k souvisí s multiplicitou a $f_{\pi 0}$
    - typické hodnoty:
      - $k \approx 0.83$, $E_0 \approx 1$ GeV (π), $E_0 \approx 2.7$ GeV (p)
      - hodnoty mírně závisí na Z absorbátoru

$$f_{em} = 1 - \left(\frac{E}{E_0} \right)^{(k-1)}$$

- Pozor: f_{em} navíc silně fluktuuje event-to-event !!



Hadronové spršky (3)

- Problém: čistě hadronová část sestává z několika komponent:
  - vysoko-energetické hadrony tvořící spršku
  - pomalé ionizující nabité hadrony
  - pomalé neutrony
  - neviditelná energie (nepřispívá k měřenému signálu !)
    - rozbití jader
    - uniklé částice (μ, ν)

proto obecně e/h > 1

- Díky tomu je měřený signál od hadronů obecně složitější funkcí energie:

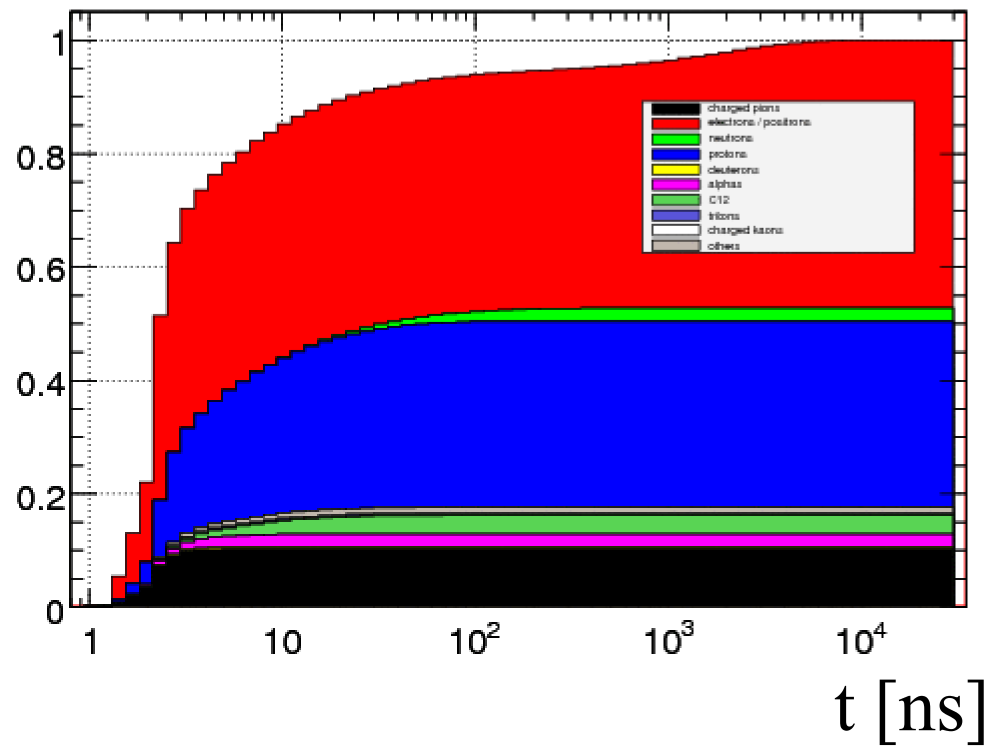
$$\frac{e}{\pi} = \frac{e}{e \cdot f_{em} + h\,(1 - f_{em})} = \frac{e/h}{1 + (e/h - 1) f_{em}}$$

Kompenzace (1)

- Kompenzovaný kalorimetr má e/h = 1
- Možnosti kompenzace:
  - hardware:
    - vhodný výběr materiálu absorbátoru (např: U), více pomalých neutronů (ZEUS, D0)
    - vhodný výběr aktivního média, citlivého na neutrony (př. plastický scintilátor, obsahuje hodně H)
    - potlačení odezvy elmg. části (vložením fólie s nízkým Z mezi absorbátor a aktivní médium, pohlcení Comptonovských elektronů)
  - offline korekce:
    - vážení odezvy jednotlivých cel podle hustoty energie (idea: elmg. část je kompaktní, takové cely vážíme faktorem=1, ostatní faktorem > 1). Vyžaduje dobrou granularitu kalorimetru.

Kompenzace (2)

- Kompenzace záleží i na čtení signálu:
  - signál od pomalých neutronů přichází později
  - příklad: časový vývoj signálu od různých typů částic v hadronové spršce v Tilecalu
    - Geant4 MC
    - 50 GeV π



Rozlišení kalorimetru

- Vývoj spršky je statistický proces, tj. počet sekundárních částic (nebo celková délka $T(X_0)$) fluktuuje:
  - $E \sim N \Rightarrow \sigma(E) \sim \sqrt{N} \Rightarrow$ sampling člen A

$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}}$$

  - další členy:
    - elektronický šum B: nezávisí na energii, pouze na počtu cel
    - konstatní člen C: špatná inter-kalibrace, podélný únik energie, nekompenzovaný kalorimetr (e/h≠1)

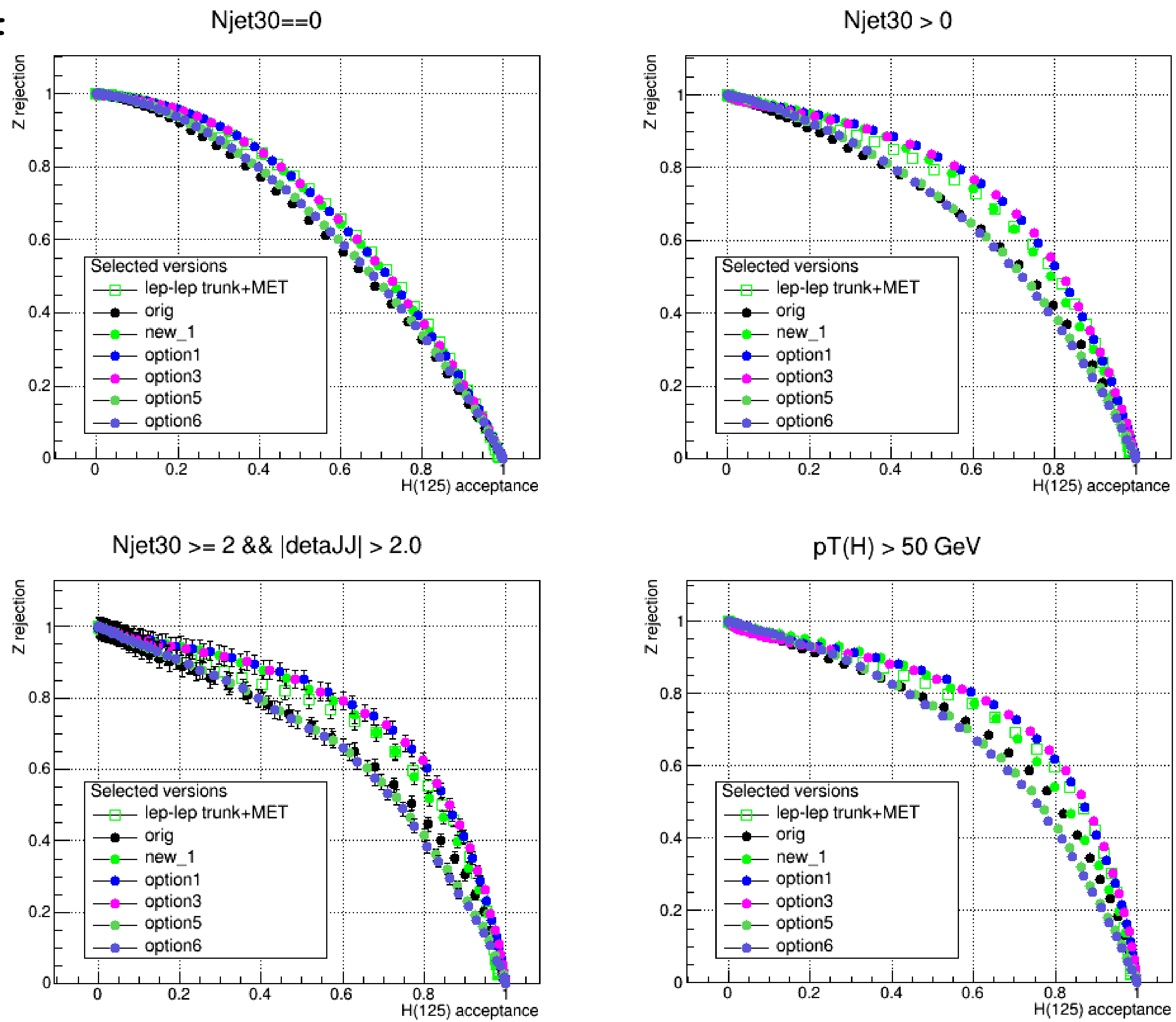
$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

In-situ kalibrace hadronového kalorimetru

- Využití přesnějšího elmg. kalorimetru:
  - vyrovnání energie v případech typu γ+jet, Z+jet
- Využití invariantní hmoty známých částic:
  - případy typu W $\rightarrow$ jet+jet
- Měření E/p pro izolované částice při nižších energiích:
  - např. $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{0}$, měření hybnosti $\tau^{\pm}$ ve vnitřním detektoru

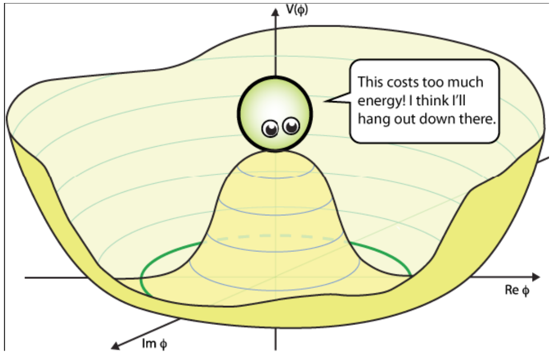
Run-2 mass reco studies in H → τ+τ

- Performance of MMC – H/Z separation power



Proč potřebujeme Higgsův boson

- Standardní model funguje „dobře", dává předpovědi odpovídající měřeným údajům. Je založen na lokální kalibrační symetrii, která generuje nehmotné částice (bosony i fermiony) - ale my víme že mají hmotu
  - Řešení: spontánní narušení symetrie + Higgsův mechanismus → hmotové členy v základních rovnicích Standardního modelu + Higgsův boson

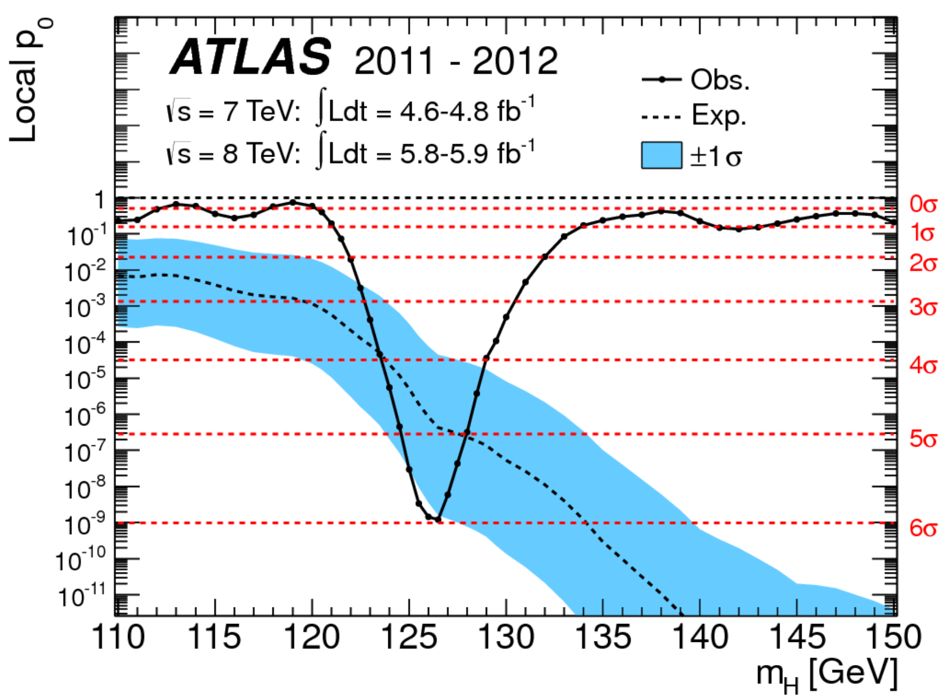


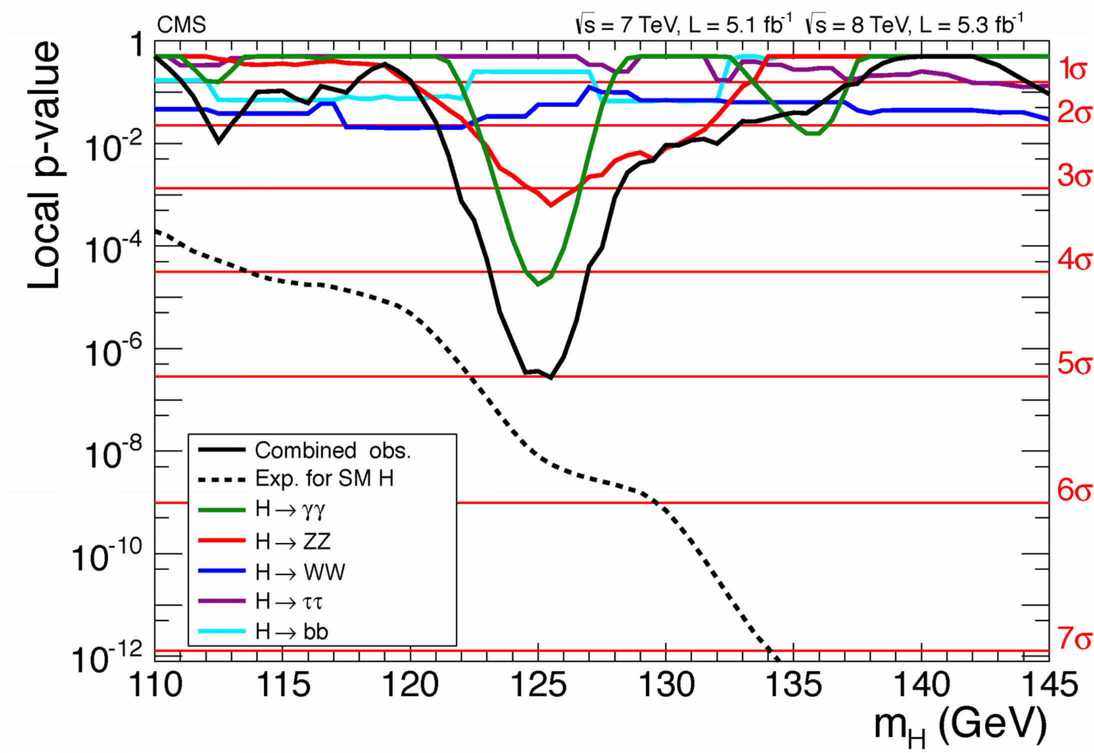
  - zavedení Higgsova bosonu řeší současně divergenci účinných průřezů na stromové úrovni. Jedná se o nutnou podmínku renormalizace SM.
- Teorie předpovídá vlastnosti Higgsova bosonu s výjimkou hmoty (volný parametr teorie)

Objev Higgsova bosonu v roce 2012

- Experimenty ATLAS a CMS oznámily objev nové částice (bosonu) s hmotou ~125 GeV a s vlastnostmi odpovídajícími Higgsově bosonu ze SM

- Objev byl založen především na měření v kanálech $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, $H \to WW \to 2\ell + 2\nu$





O rok později...