LHC results on electroweak and Higgs physics

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CTEQ @ PITT

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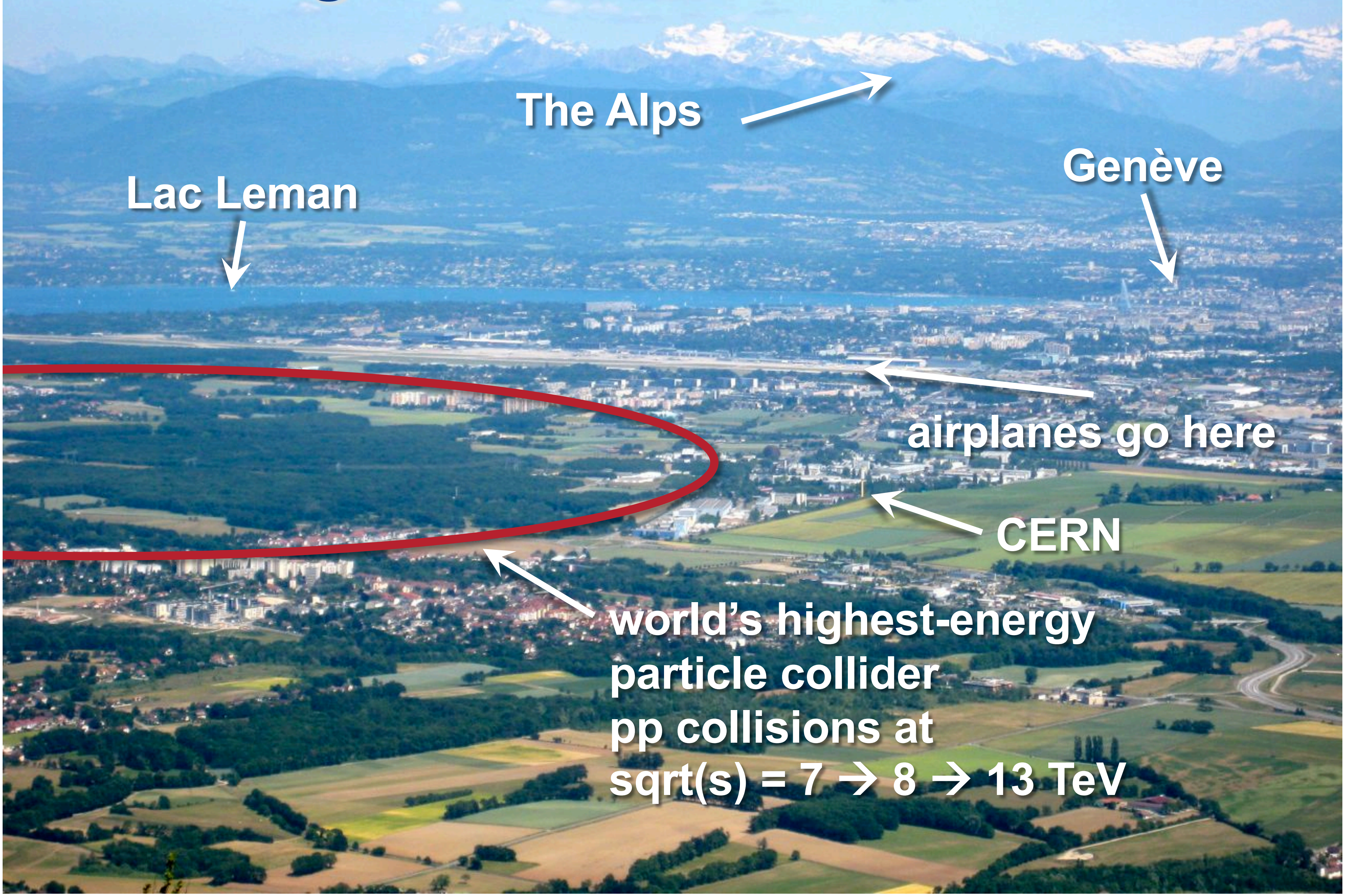
Introduction

- Electroweak physics has been a cornerstone of collider physics since discovery of W and Z bosons in the early 80s
  - → *Higgs boson is an inextricable part of this*
- The last time I lectured at this school (2011), the Higgs boson had yet to be observed
- As the dataset has increased, focus on increased precision and search for increasingly rare processes

- Rather than trying to cover exhaustively the dynamic landscape of all measurements, focus on key examples
- Also talk about detector performance: results chosen to illustrate concepts, don't necessarily represent the state-of-the-art performance

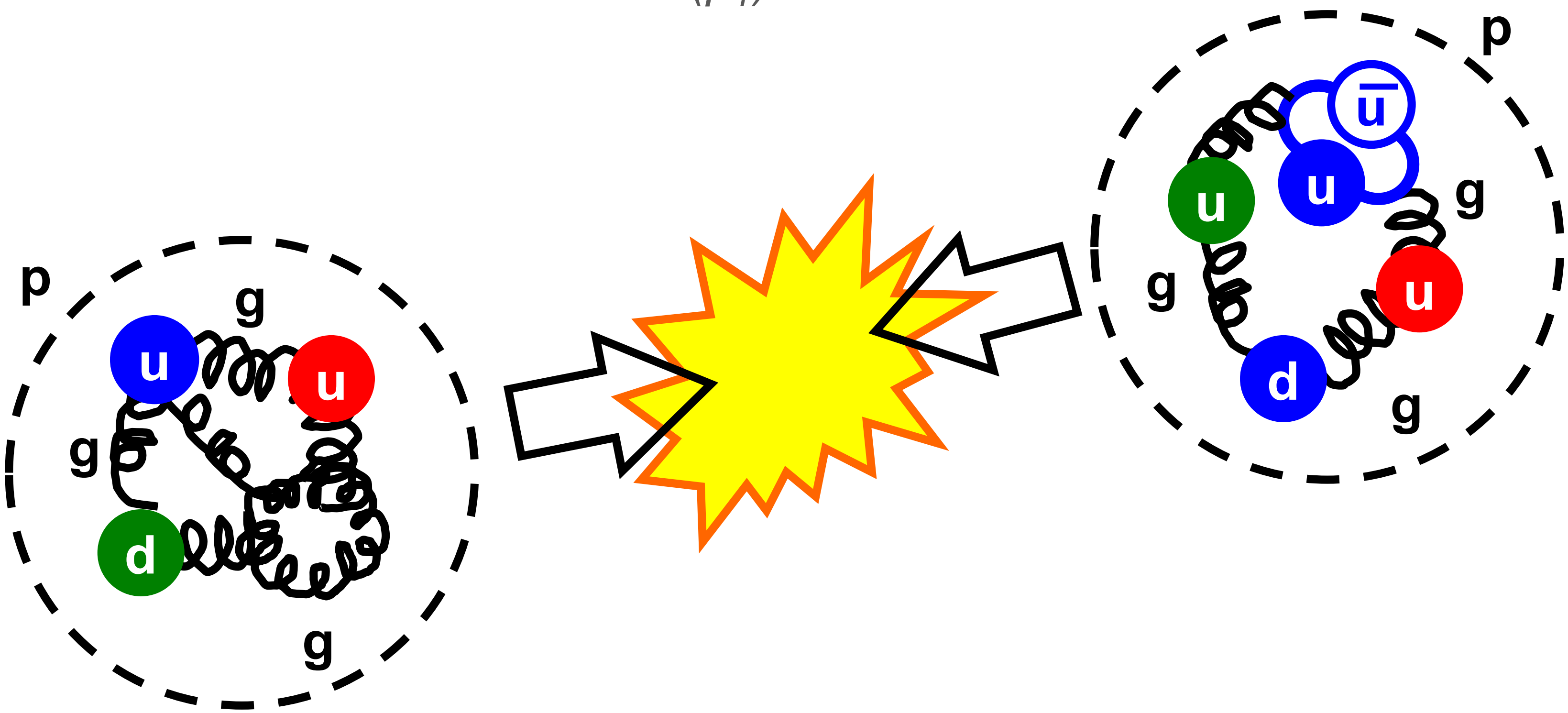
- My career at hadron colliders: CDF (Tevatron), ATLAS, now CMS
  - → *I am also excited to talk about silicon detectors at the discussion sections*
- Mistakes, opinions, and biases are all my own

The Large Hadron Collider, CERN



Colliding protons

- High energies ←→ small distance scales at the LHC
- Proton is not a point particle: quarks, gluons, even antiquarks
  → *Most collision events **gluon-gluon***
- Don't know momentum carried by individual partons (p_Z)
  → *use transverse momentum (p_T)*



Rapidity and pseudorapidity ("η")

Rapidity *y* is a Lorentz-invariant way to express the polar angle of a particle

CTEQ2011 Schellman

$$y \equiv \quad \tfrac{1}{2}\left(\frac{E+p_{\parallel}}{E-p_{\parallel}}\right)$$

$$E = \quad \tfrac{1}{2}e^{y}\sqrt{m^2+p_T^2}$$

Lorentz Invariant Phase Space can be written as

$$\frac{d^3p}{2E} = d\phi \; d\cos\theta \; p^2 dp = d\phi dy dp_T^2 = 2\pi dy dp_T^2$$

In frame where $p_z = 0$,

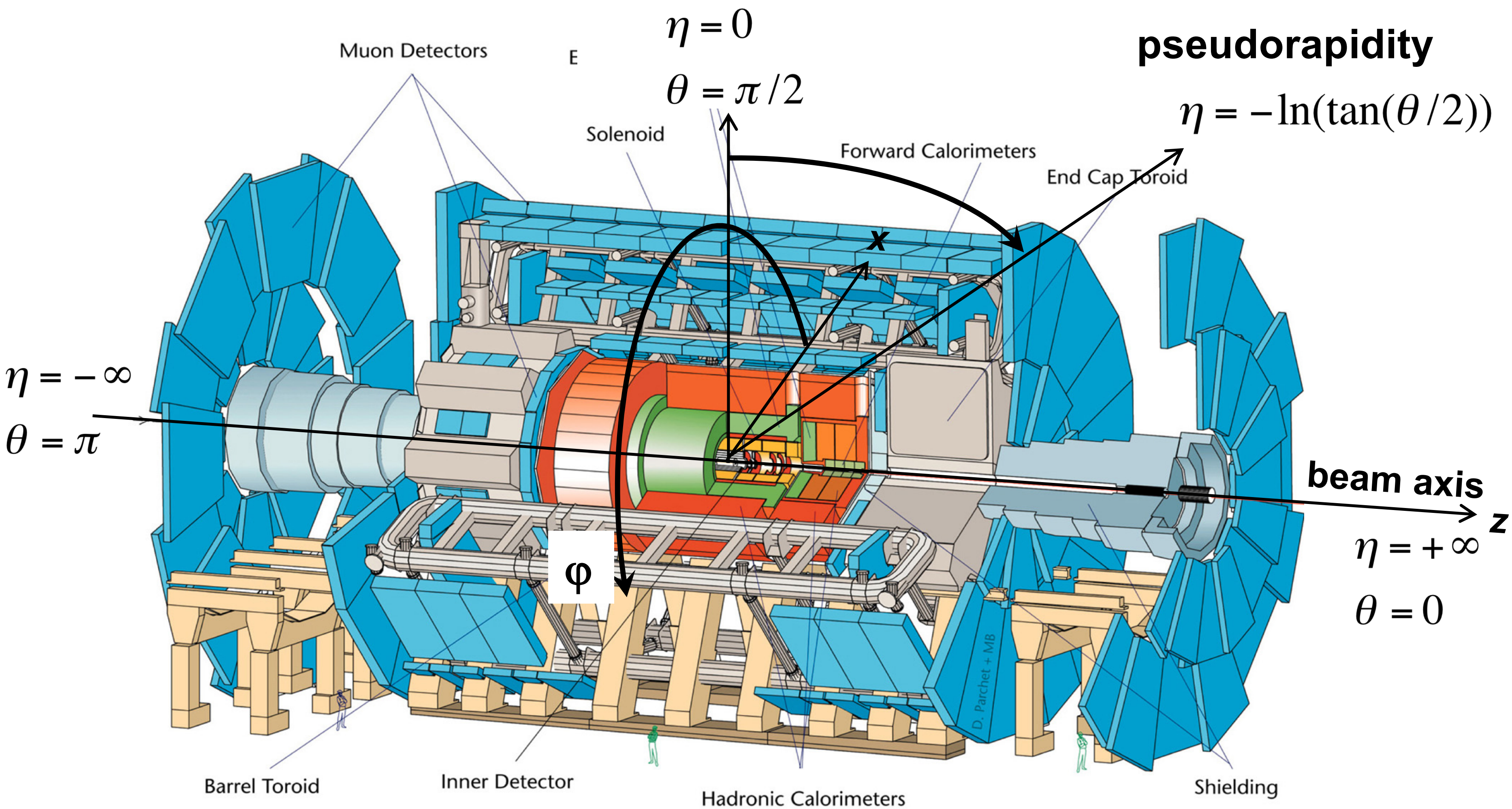
$$\delta y \approx \delta\theta + \mathcal{O}(\delta\theta)^3$$

equivalent to small variations in the polar angle θ.

For massless particles, the rapidity reduces to the pseudorapidity

$$\eta = -\ln(\tan\theta/2)$$

Hadron Collider Kinematics



$\vec{p}_T = (p_x, p_y) \qquad p_T = p\sin\theta, \quad E_T = E\sin\theta$

Collider physics units

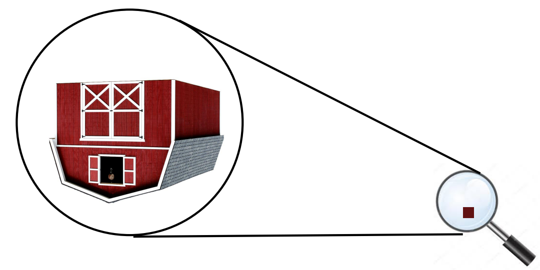
- **Energy measured in eV**
  - → *Energy acquired by electron accelerated through 1 Volt*
  - → ***1 GeV*** *= 10^9 eV = $1.6\text{x}10^{-10}$ Joules*
- The rest follows from the famous equation

$$E^2 = p^2c^2 + m^2c^4$$

  - → *Momentum in* ***GeV/c***
  - → *Mass in* ***GeV/c²***
  - → *Typically set* ***c = 1***
- **Then work with four-vectors:**

$$p = (E, -p_x, -p_y, -p_z)$$

- **Integrated luminosity measured in inverse femtobarn**



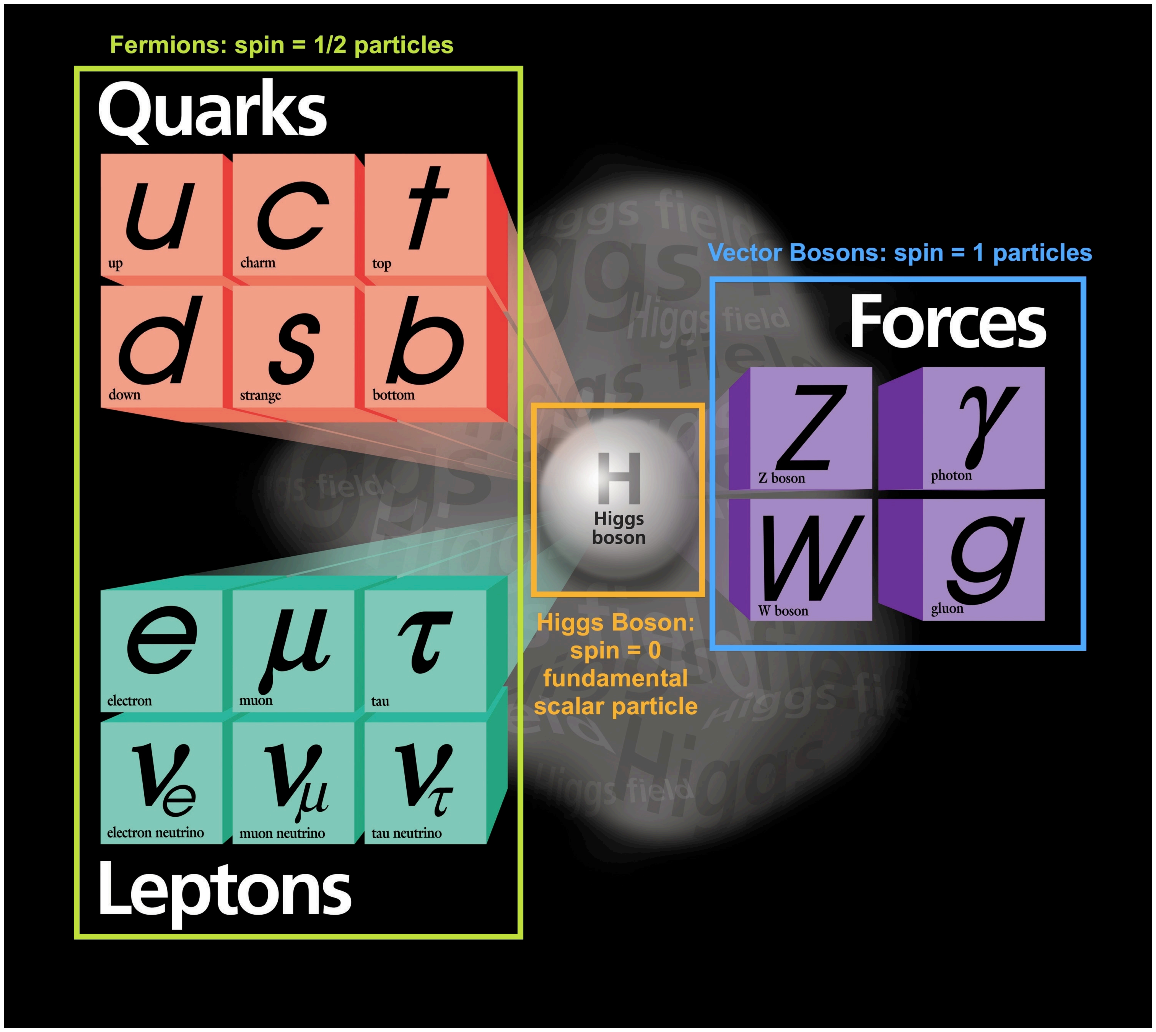
- Cross sections are measured in *barns* (with *one barn* being a very large cross section)
  - → *Typical (interesting) cross sections at LHC are pico- and femto- barns*
  - → *That's 10^{-12} and 10^{-15}*
- Quantify "amount of data" by number of events for a process with a particular cross section

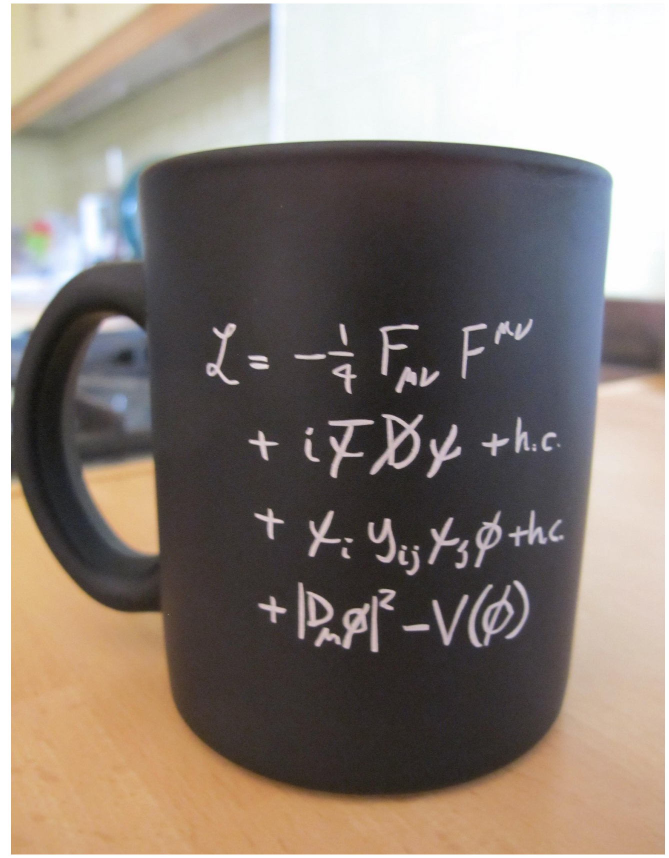
$$N = \left(\int \mathcal{L}dt\right)\sigma \text{ so } \int \mathcal{L}dt = N/\sigma$$

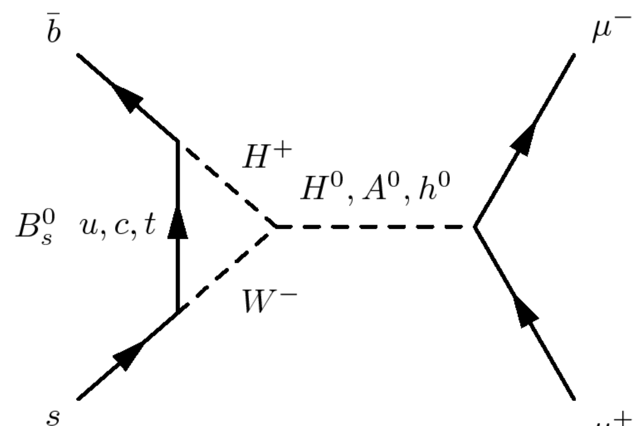
Slide inspired by Heidi Schellman's 2011 lectures

The Standard Model: Theorist View

Fermions and bosons are building blocks, complexity is in interactions

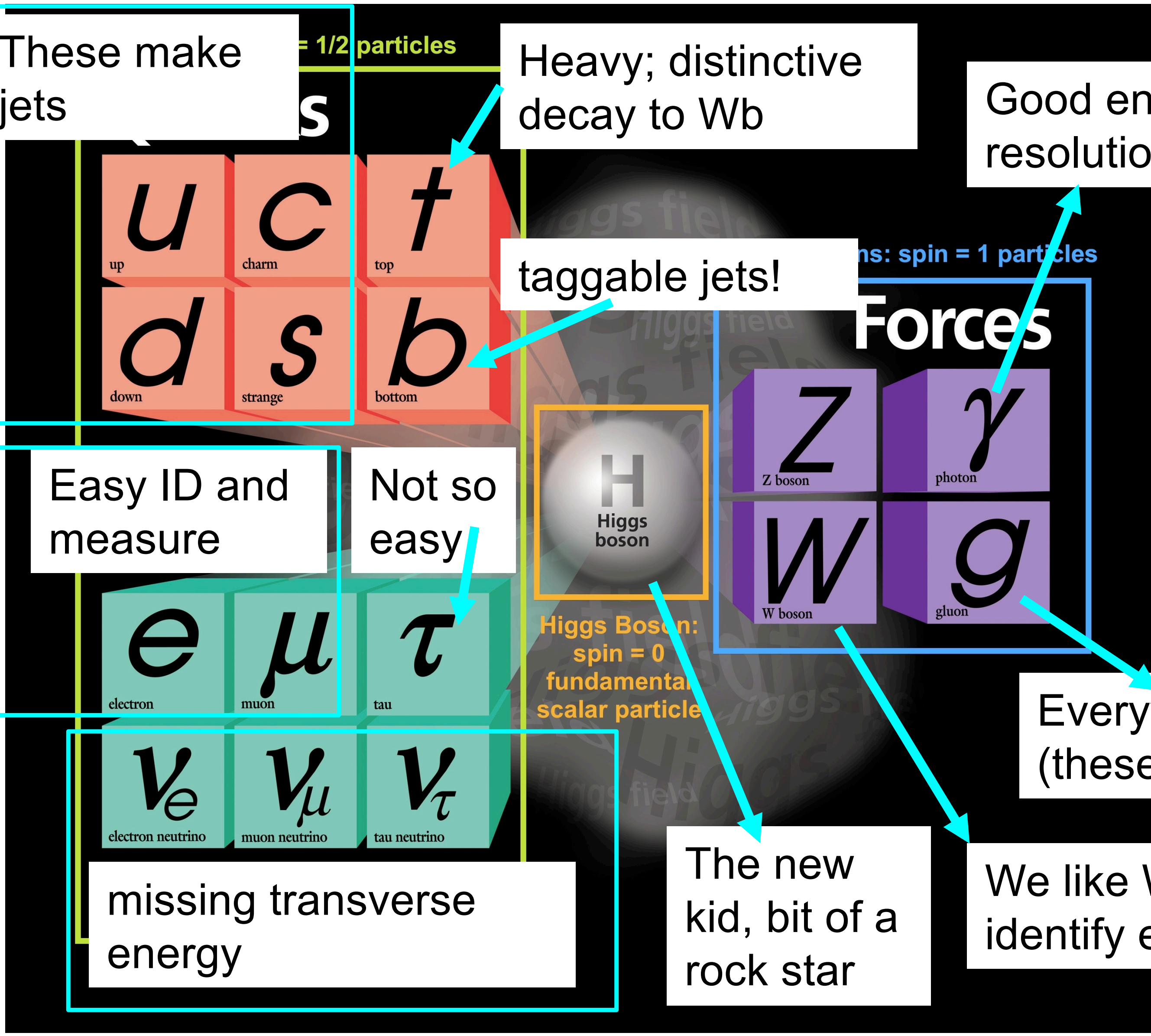






Hadron Collider Experimentalist's View

Every particle has a personality



These make jets

Heavy; distinctive decay to Wb

taggable jets!

Easy ID and measure

Not so easy

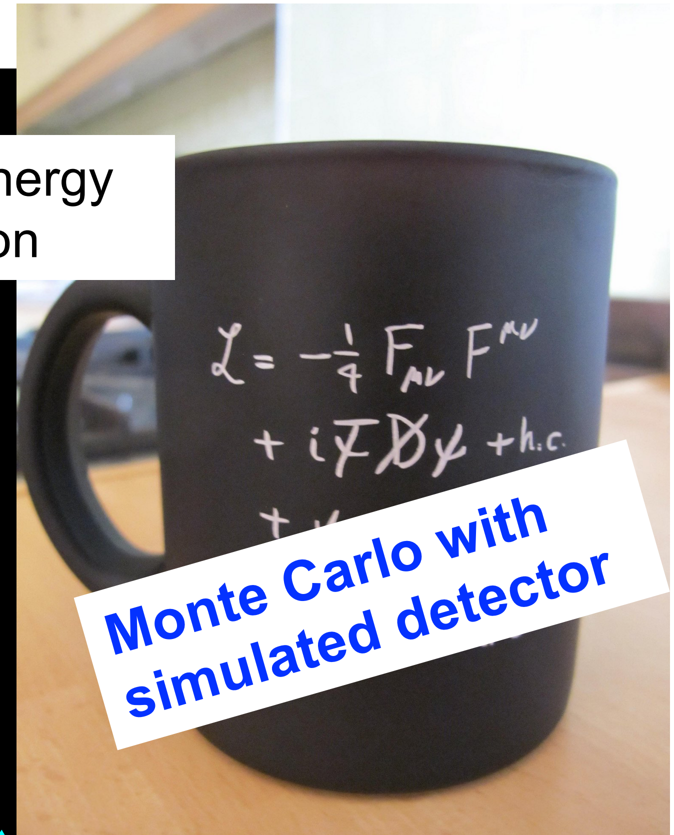
missing transverse energy

The new kid, bit of a rock star

Good energy resolution

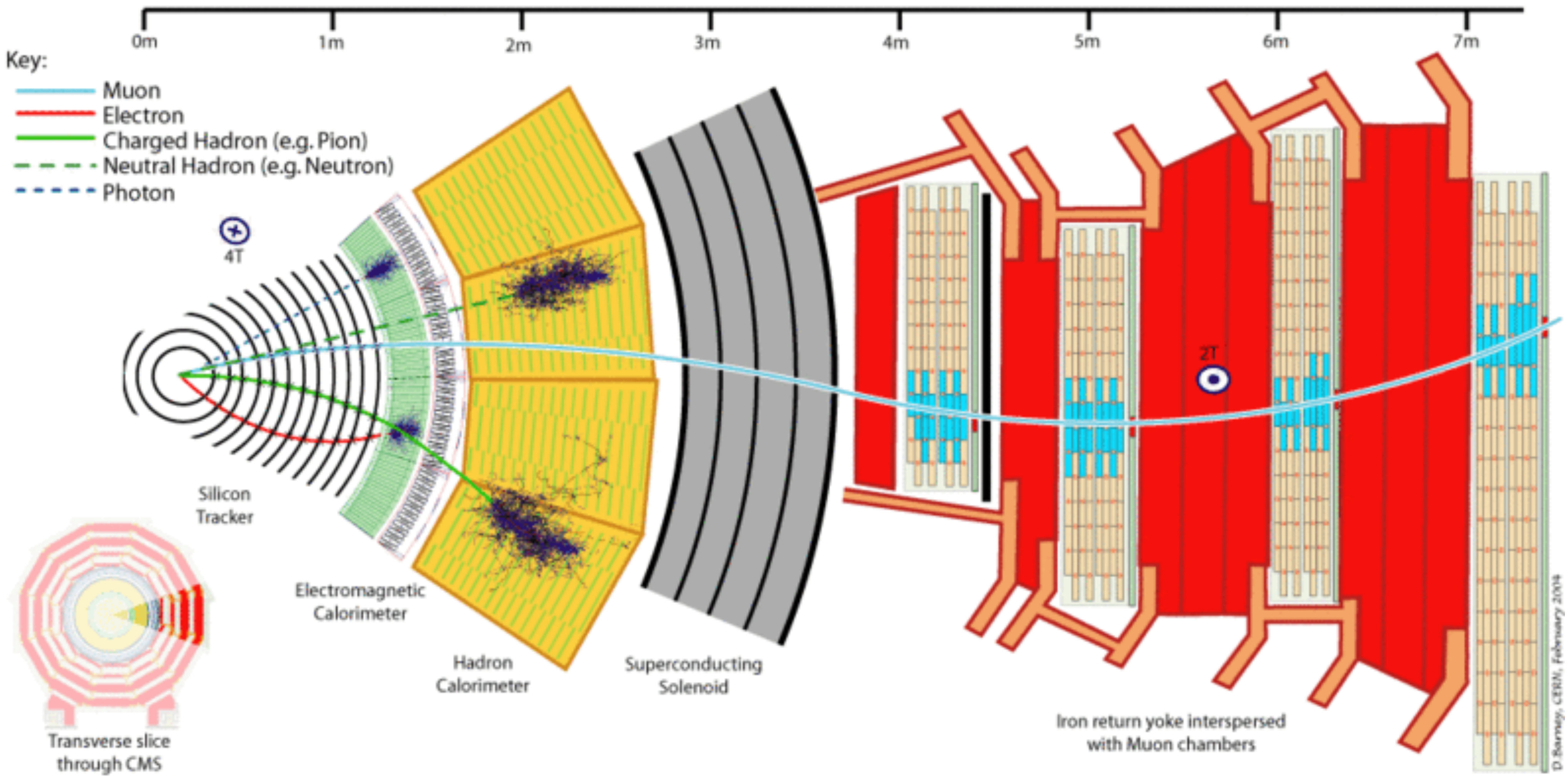
Everywhere... so many gluons... (these make more jets)

We like Ws and Zs: easy to identify experimentally



Monte Carlo with simulated detector

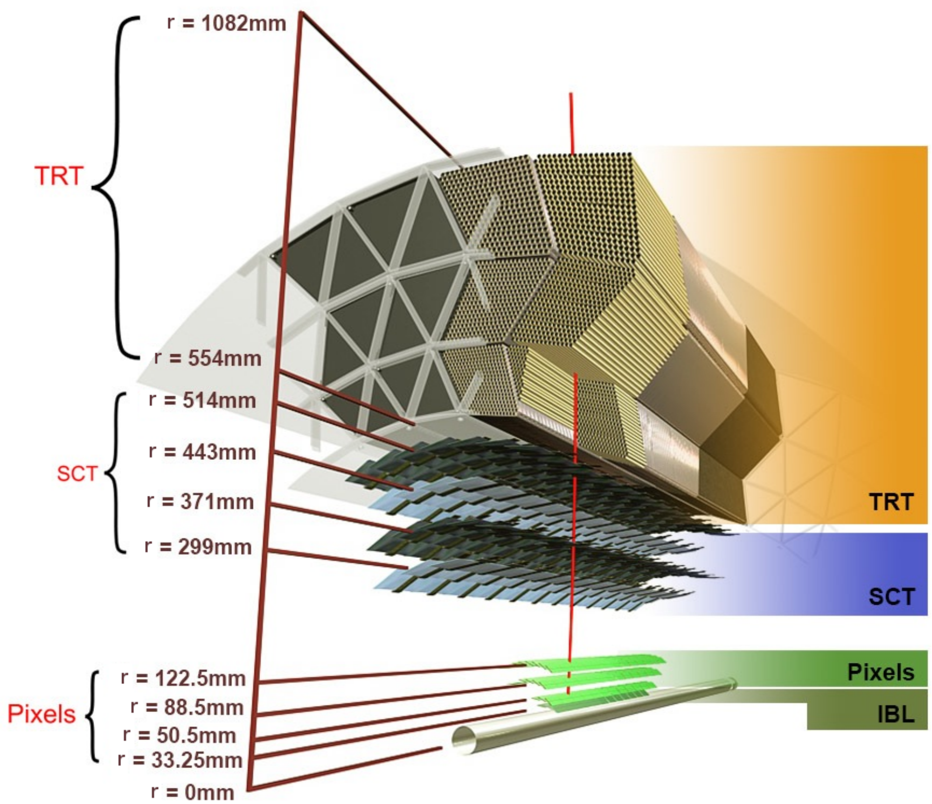
How we reconstruct particles

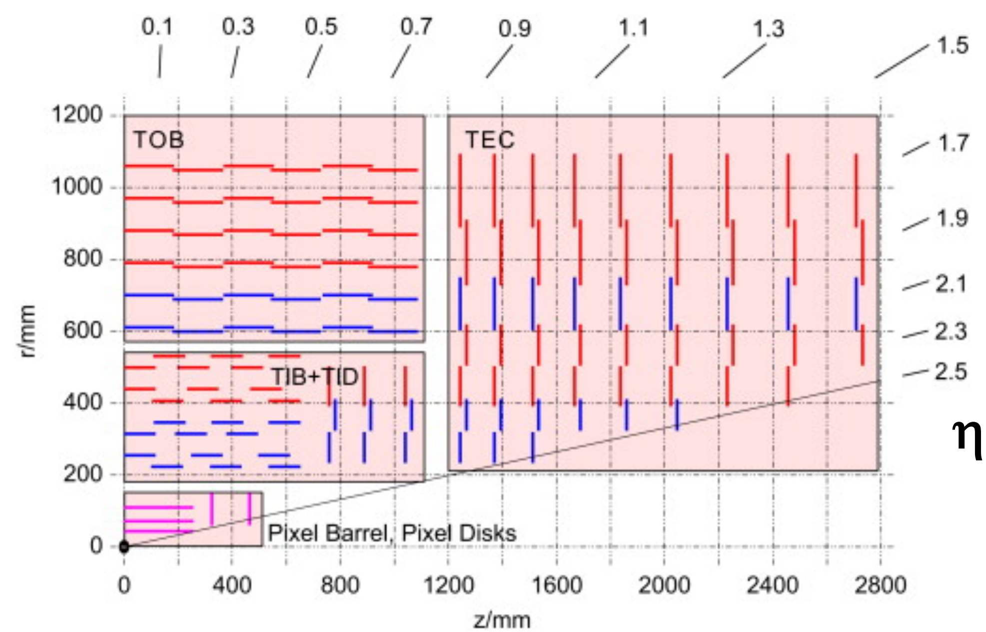


Charged particle tracking

- Radiation conditions and occupancy (granularity) requirements ⇒ silicon semiconductor detectors closest to the interaction point:
  - → *Strips: charge collection implants run the length of the detector*
  - → *Pixels: segmented in 2d detector plane, typical size 100 x 150 μm^2 (current CMS)*
- ATLAS (left): innermost layers silicon semiconductor (4 strip + 4 pixel), outer layers Transition Radiation Tracker (TRT): 4 mm straw tubes filled Xenon, pion/electron discrimination using x-ray photons from interstitial material

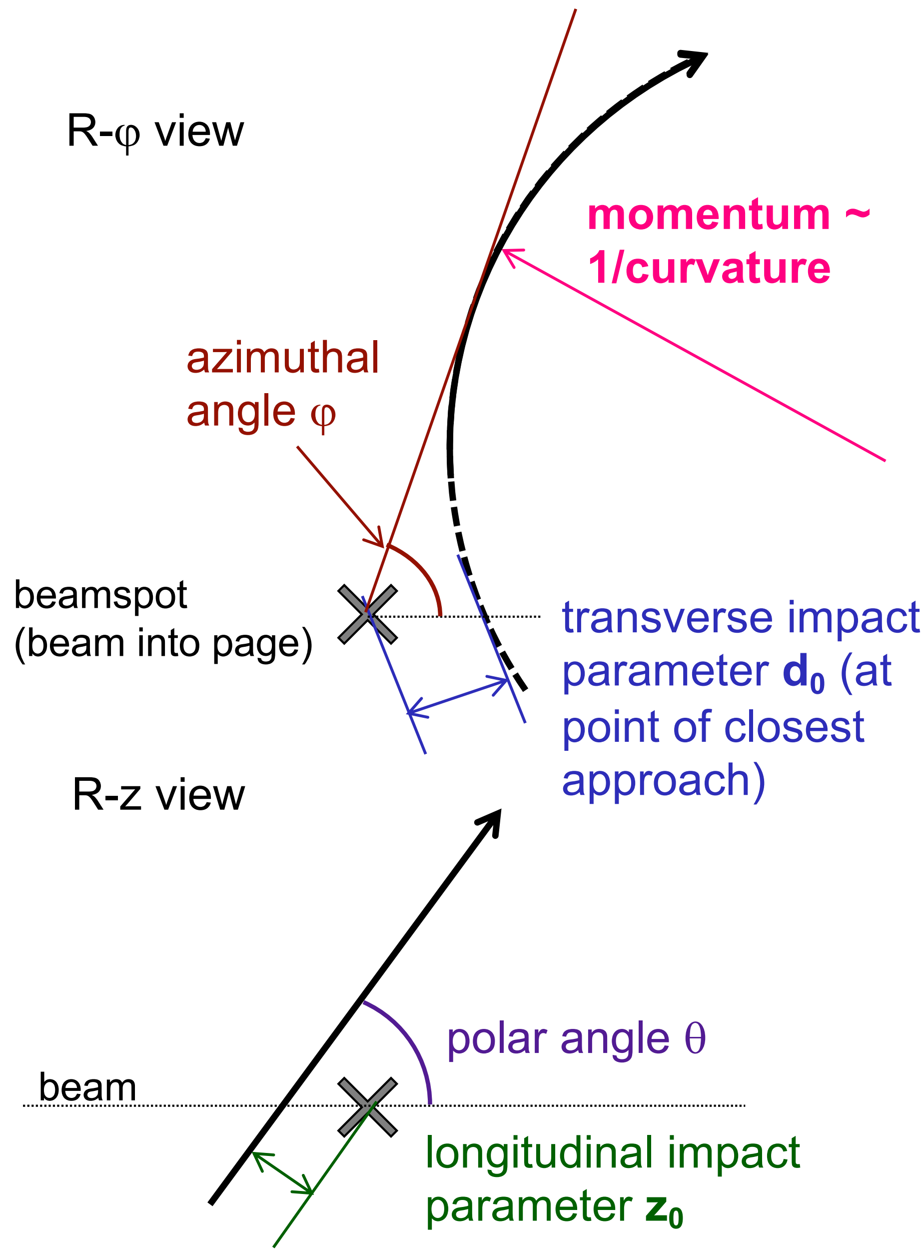
CMS (right): all silicon: 3-4 pixel layers and 8-14 strip layers



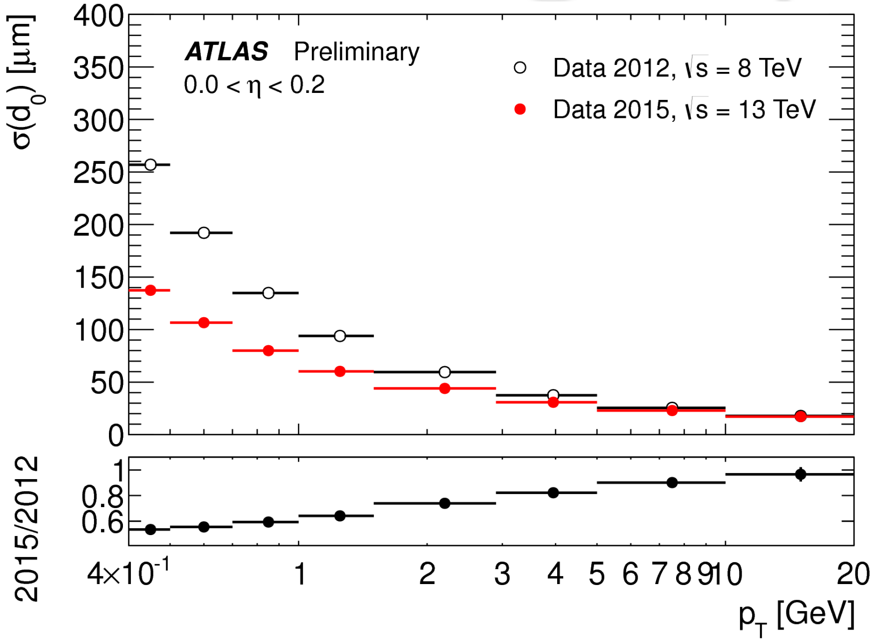


Charged particle tracking

- Tracks bend in magnetic field produced by solenoid
- Helical trajectory defined by 5 track parameters
  - → *2 impact parameters (d_0, z_0)*
    - Critical to vertexing
    - Performance determined by pitch and radius of innermost tracker layers
  - → *2 angles (θ, φ)*
  - → *curvature/momentum p*
    - Performance determined by "lever arm": distance over which trajectory measured



Charged particle tracking

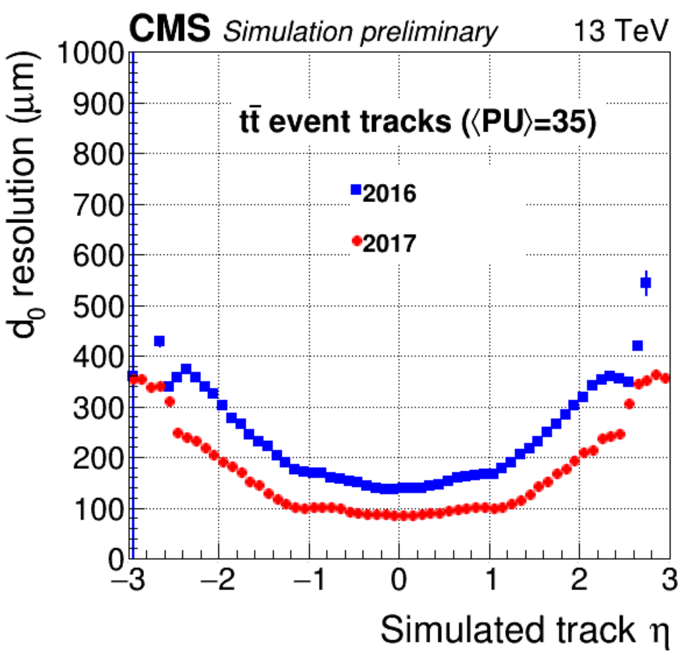


Adding a layer at smaller radius (red points) improves impact parameter resolution

- → *Multiple scattering affects tracks with $p_T \lesssim 10$ GeV*

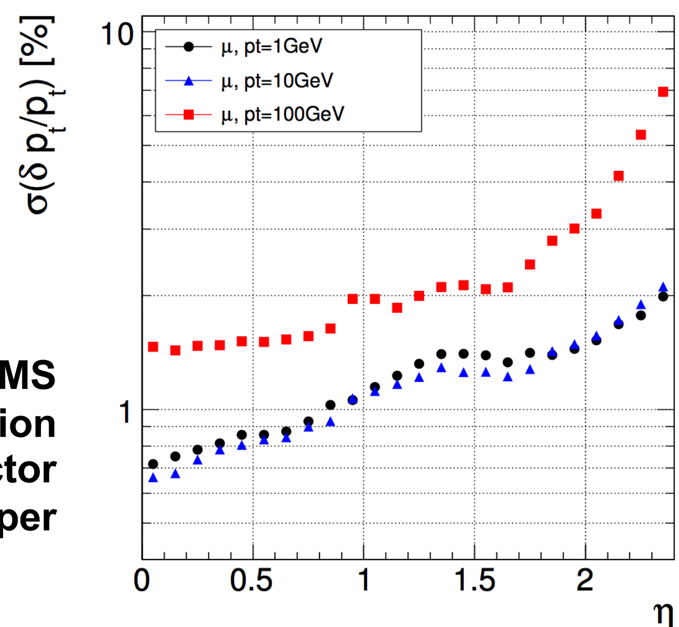
Conversely, momentum resolution gets better at lower momentum (to a point)

- → *Harder to measure curvature of straighter tracks*



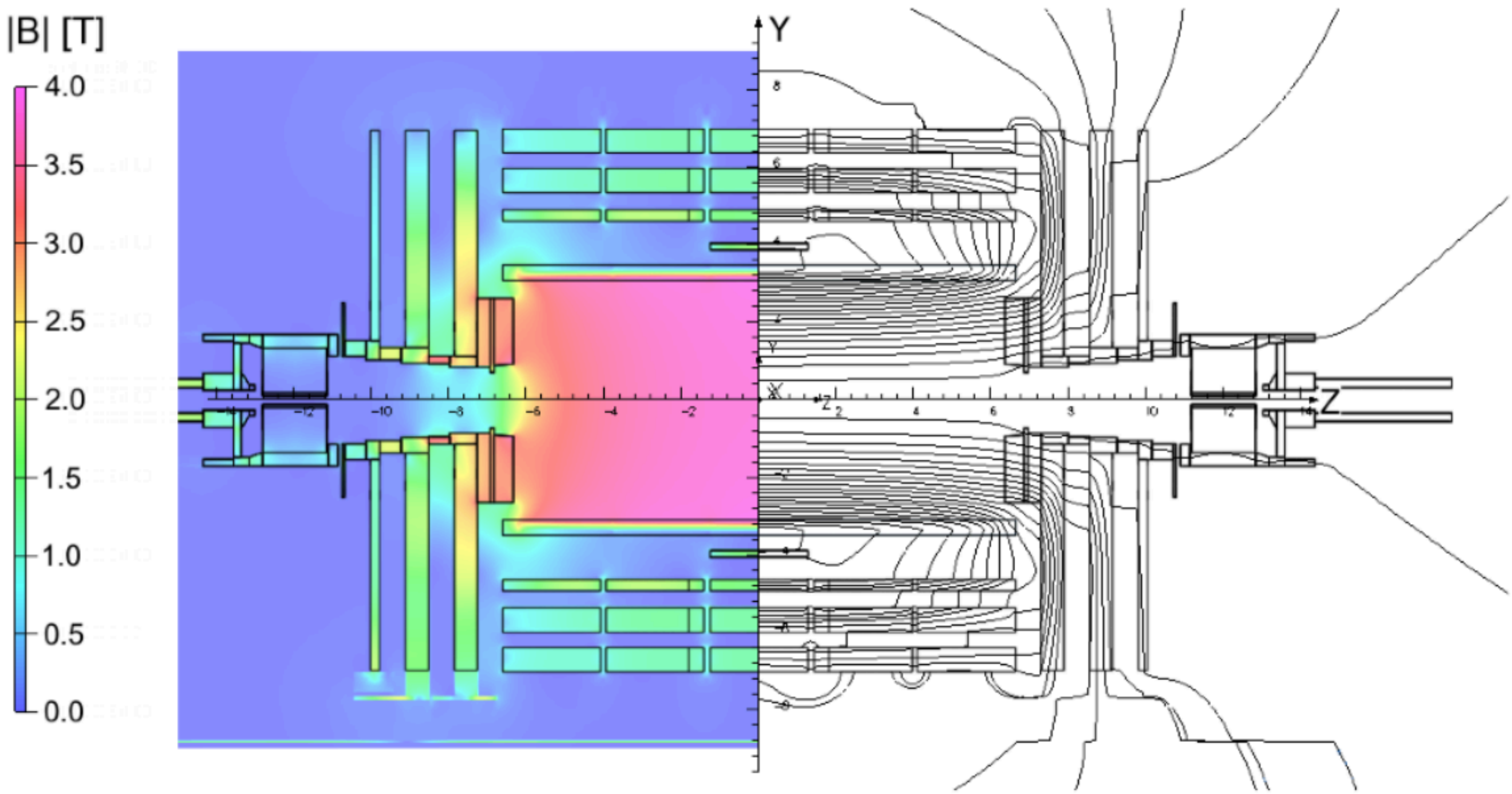
ATLAS added the IBL in 2014, CMS replaced their entire pixel detector in early 2017

CMS simulation from detector paper



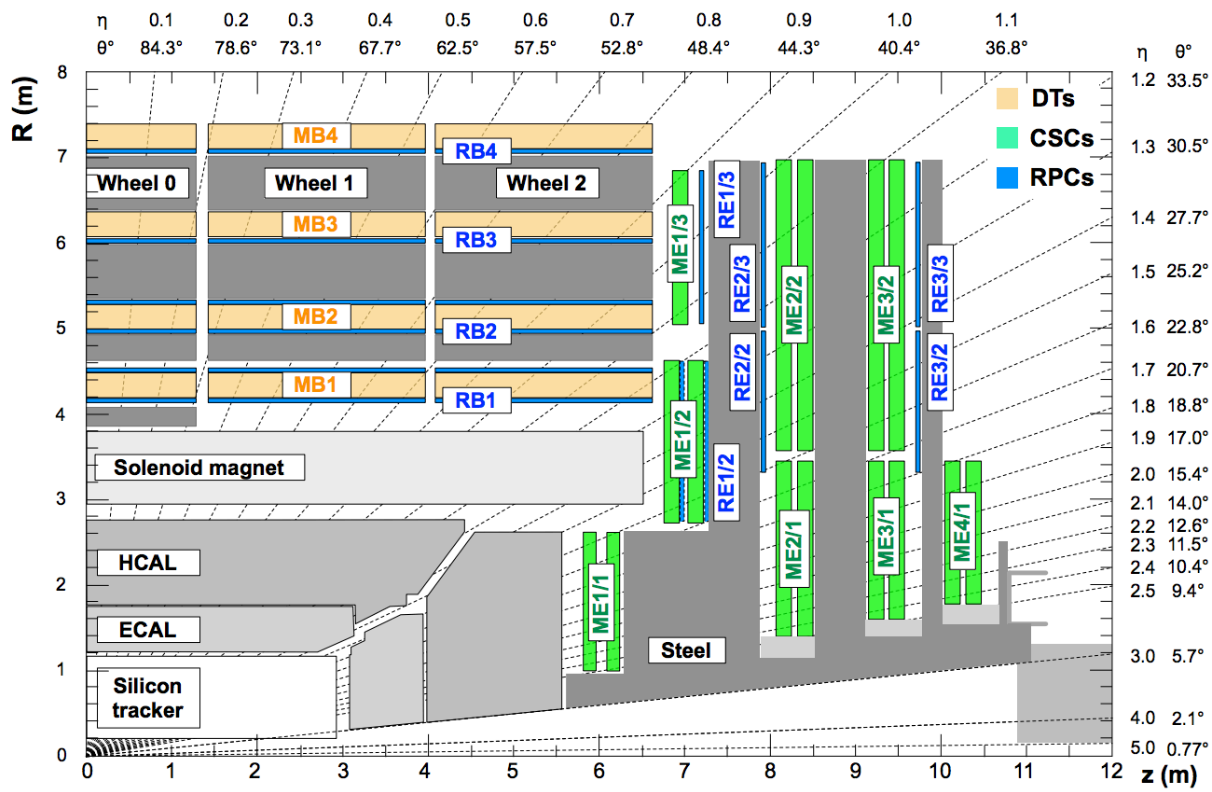
Muons and magnetic fields

- Muons traverse the entire detector: ATLAS and CMS link tracks in two detectors, each with an independent momentum measurement
  - → *Solenoid: 2 Tesla, 2.4m diameter (ATLAS); 3.8 Tesla, 6m diameter (CMS)*
  - → *ATLAS toroids produce magnetic field with field lines around the Z axis*
  - → *CMS uses iron to direct flux return outside the solenoid, concentrating the field lines*

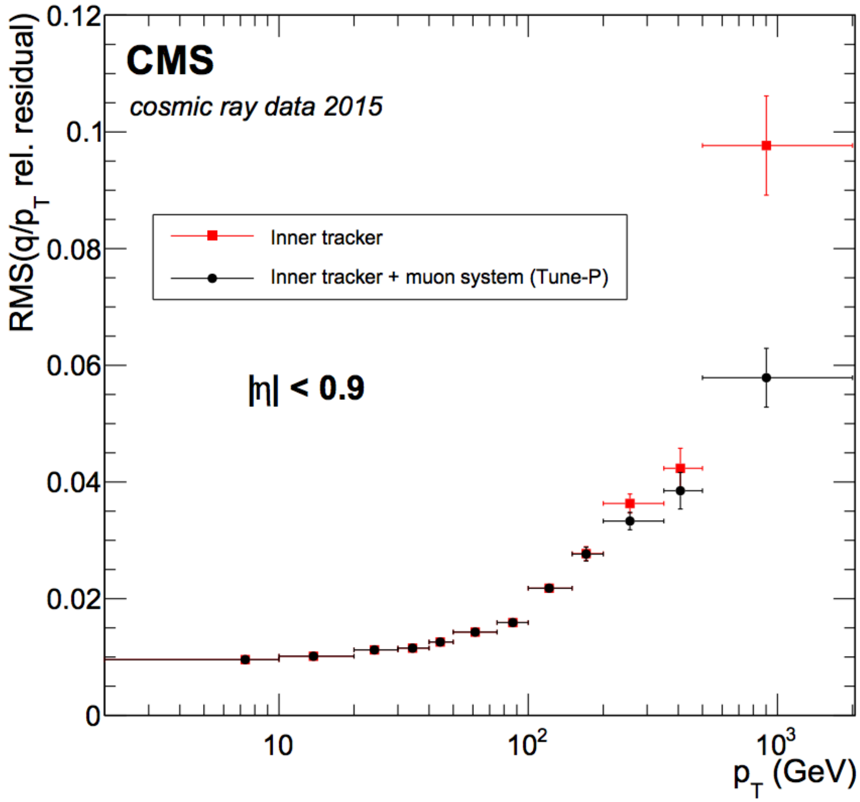


Muons and magnetic fields

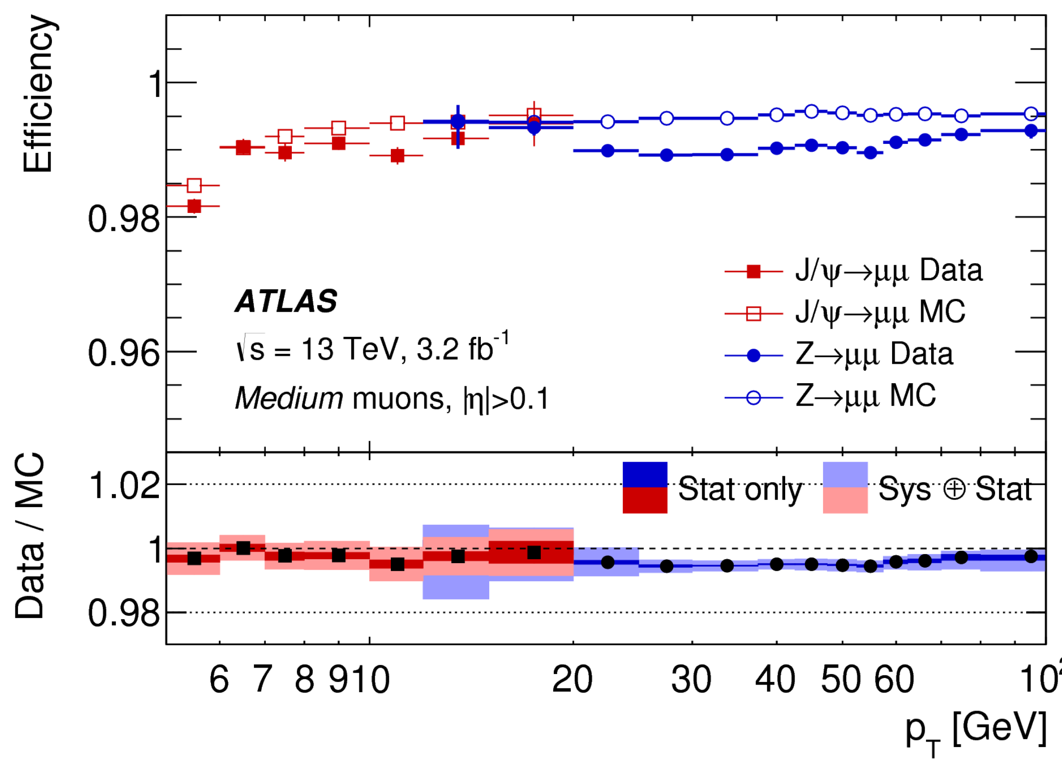
- Muon detectors track charged particles using gas ionization
  - → *Lower rate and easier radiation environment but need to cover more area*
- ATLAS, CMS work on similar principles; CMS described here (1306.6905)
- Drift tubes for precision: 200-300 μm single-hit resolution (~100 μm per station)
  - → *Position measured by time to drift to wire*
- RPCs for speed
  - → *E field tuned to operate in "avalanche" mode*
  - → *~1 cm resolution*
  - → *3 ns time resolution and fast response (vs up to 400 ns for drift tubes; compare 25 ns collision spacing)*
- CSCs split the difference
  - → *Tolerate higher event rates in forward region*
  - → *40-150 μm resolution per station*



Muon performance



- Improved momentum resolution for highest-p_T muons
- Efficient reconstruction
  - → *And well-understood: total uncertainty 1% or less*
- Calibrated using two-body decays

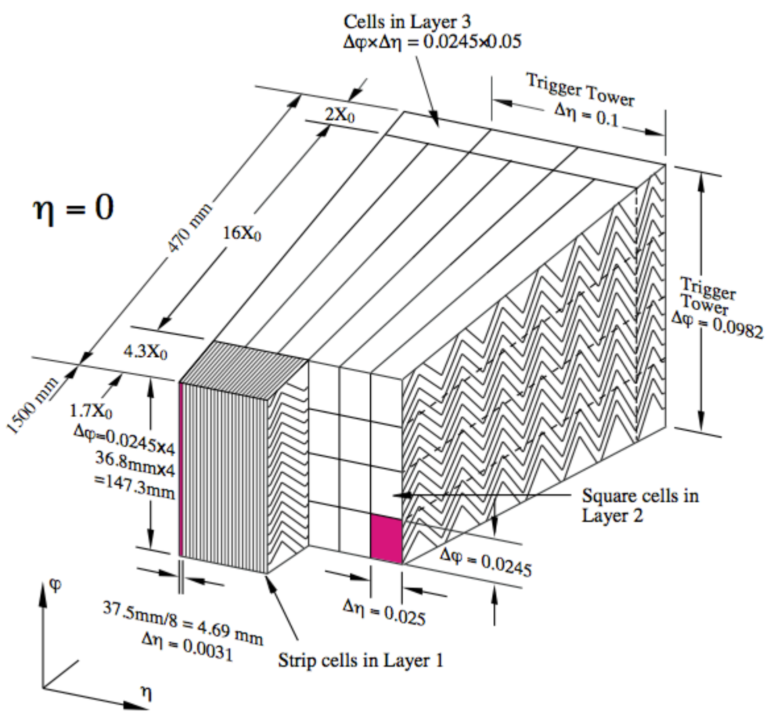


- Background rejection is a key feature of muons but harder to quantify: strong dependence on details of selection (number of hits, isolation, etc)

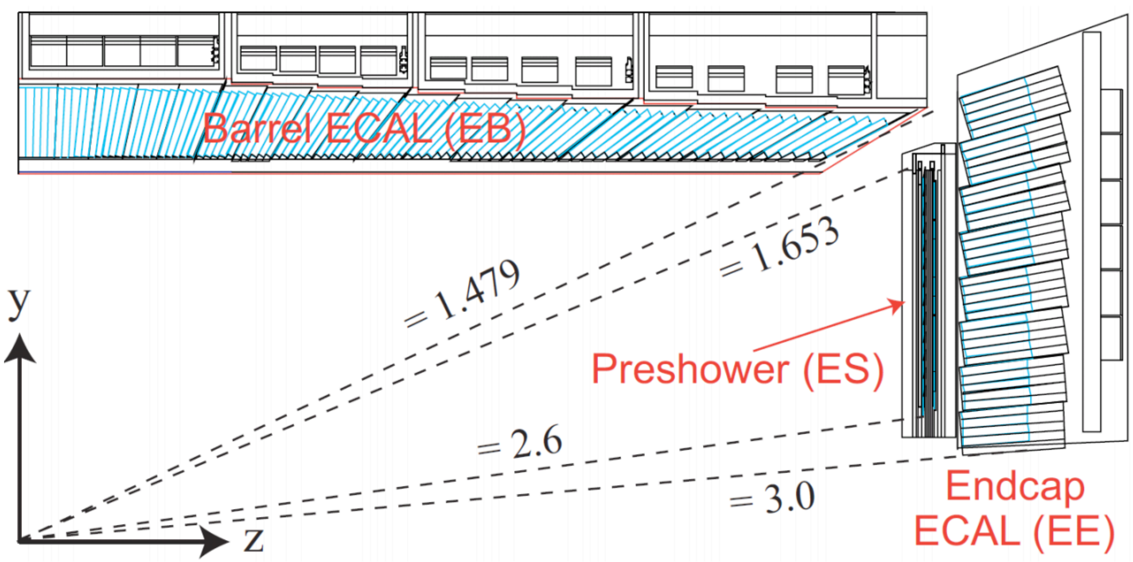
CMS 1804.04528
ATLAS PERF-2015-10

Photons, electrons, and ECALs

- Electromagnetic calorimeters from high-Z material (i.e. lead) to maximize electromagnetic interaction
- ATLAS and CMS made fundamentally different choices
  - → *ATLAS for background rejection ($\pi \rightarrow \gamma\gamma$ in particular) using segmentation of electrodes; liquid argon for active material (ionization signal)*
  - → *CMS for energy resolution: lead tungstate ($PbW0_4$) crystals are dense (absorber) and produce scintillation light (active material)*

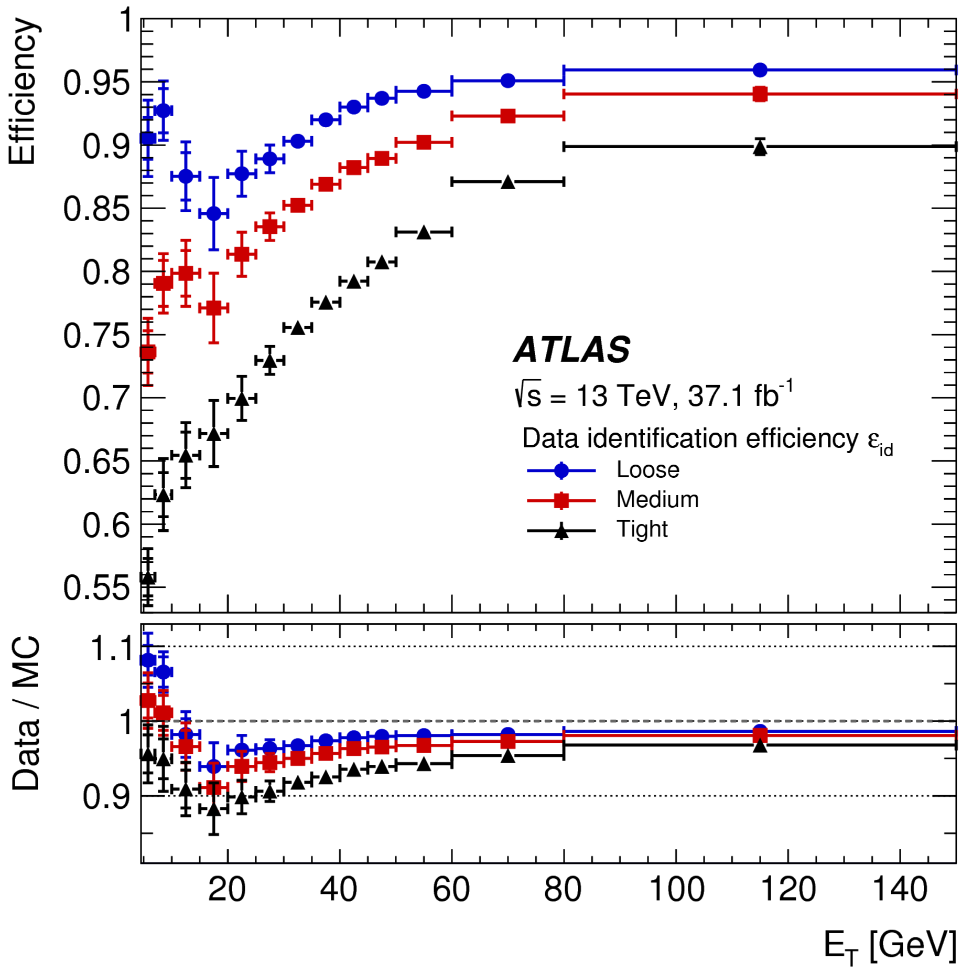


ATLAS

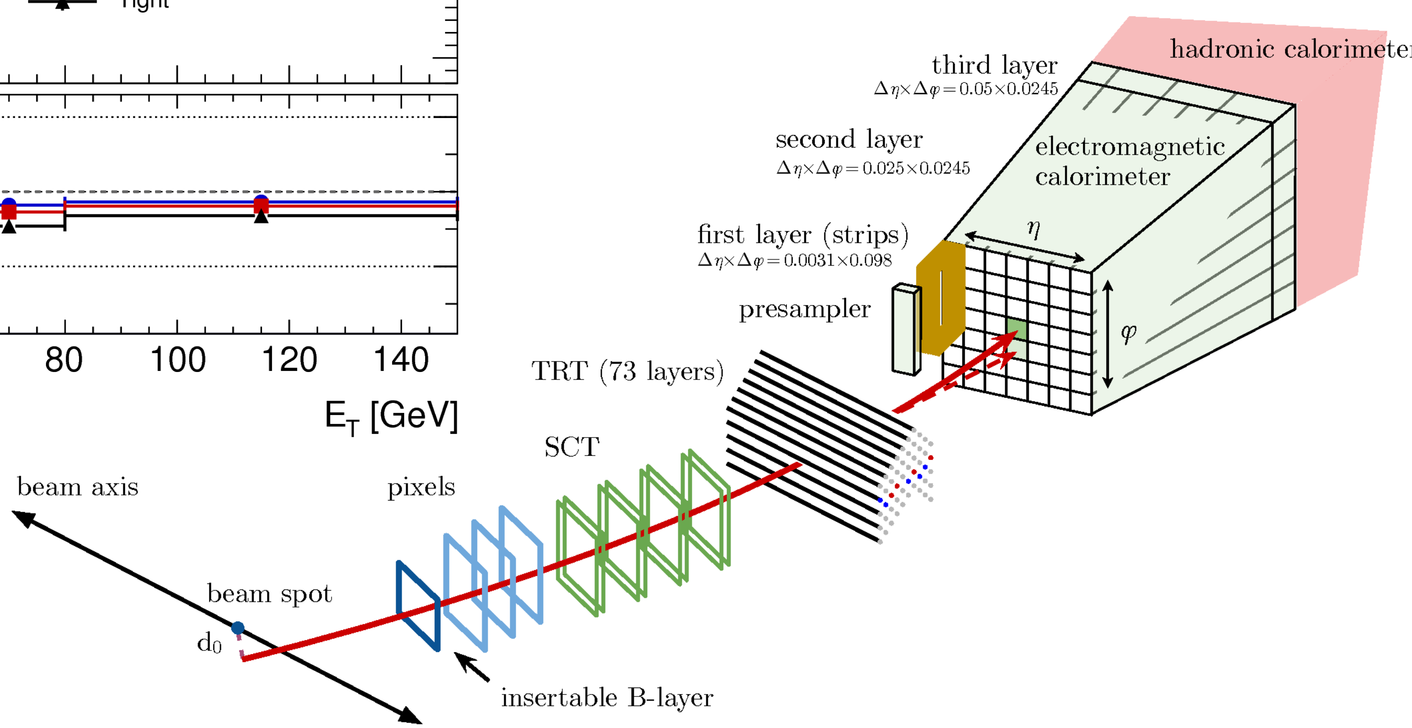


CMS

Electrons



- Combine tracks in inner detector with clustered energy deposits in electromagnetic calorimeter
- Tradeoff in background rejection and efficiency

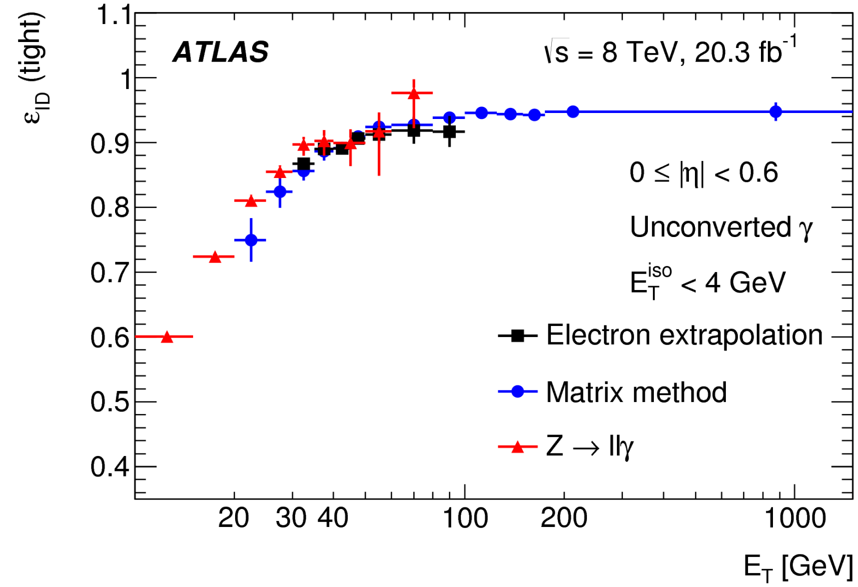


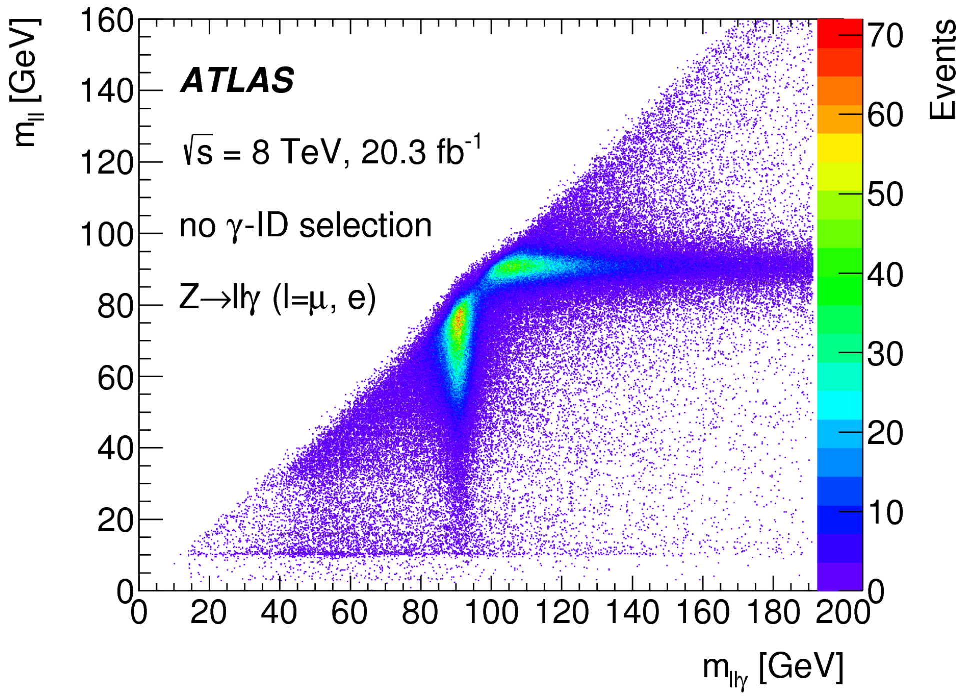
ATLAS PERF-2017-01

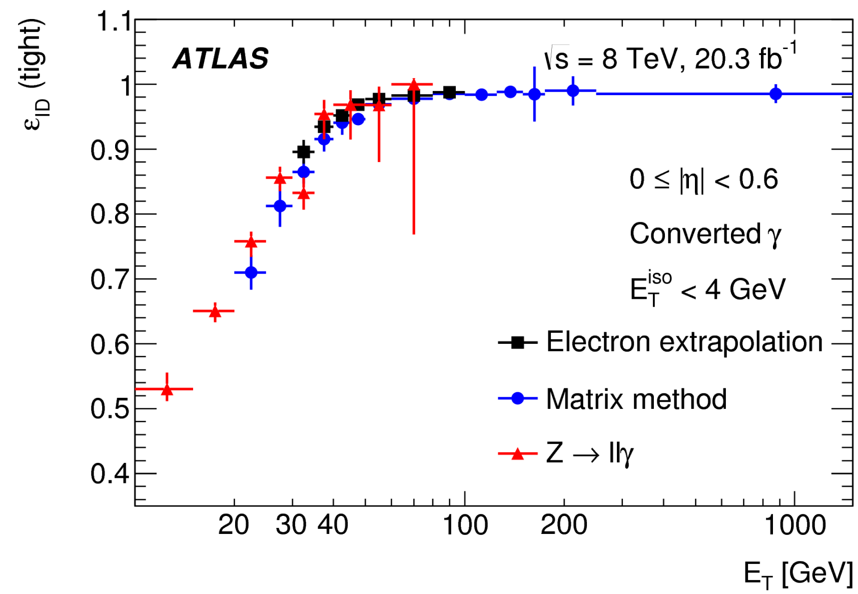
Photons

Reconstruct both converted and unconverted photons

→ *Converted have two tracks, particularly important for CMS, which has more material in the tracker: **≥ 20%of photons** in $H \to \gamma\gamma$ convert before reaching the calorimeter*



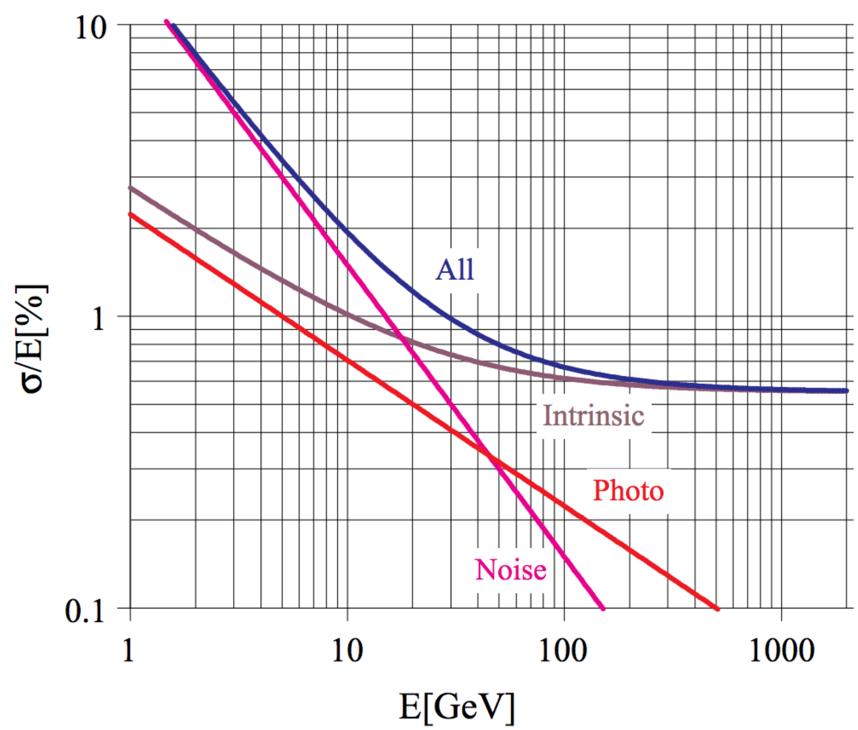




ATLAS PERF-2013-04

Photons

- Energy scale (error on the mean): known to 0.1% -- 0.3% for energies relevant to H $\rightarrow \gamma\gamma$
- Energy resolution (width of the distribution): around 1%



photon energy resolution (from CMS detector paper)

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$$

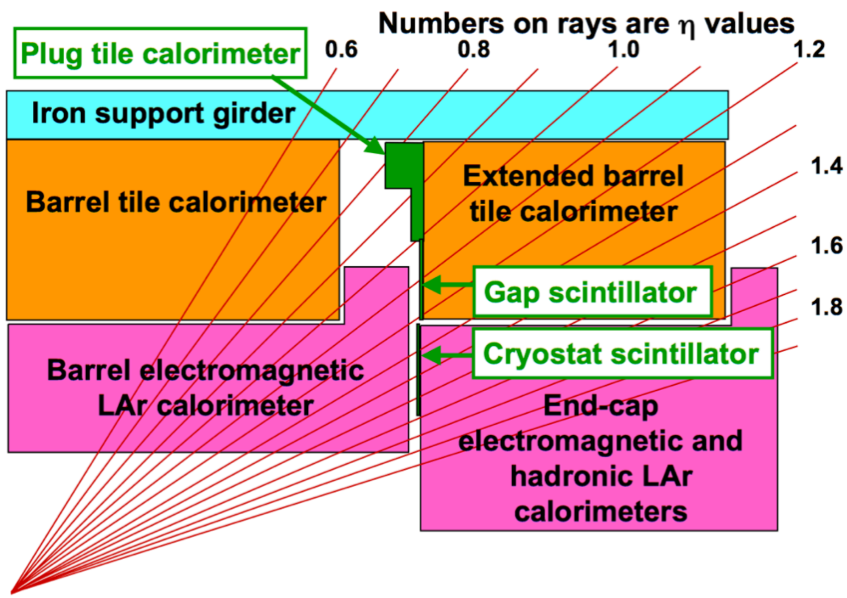
Stochastic term "photo" : photon counting

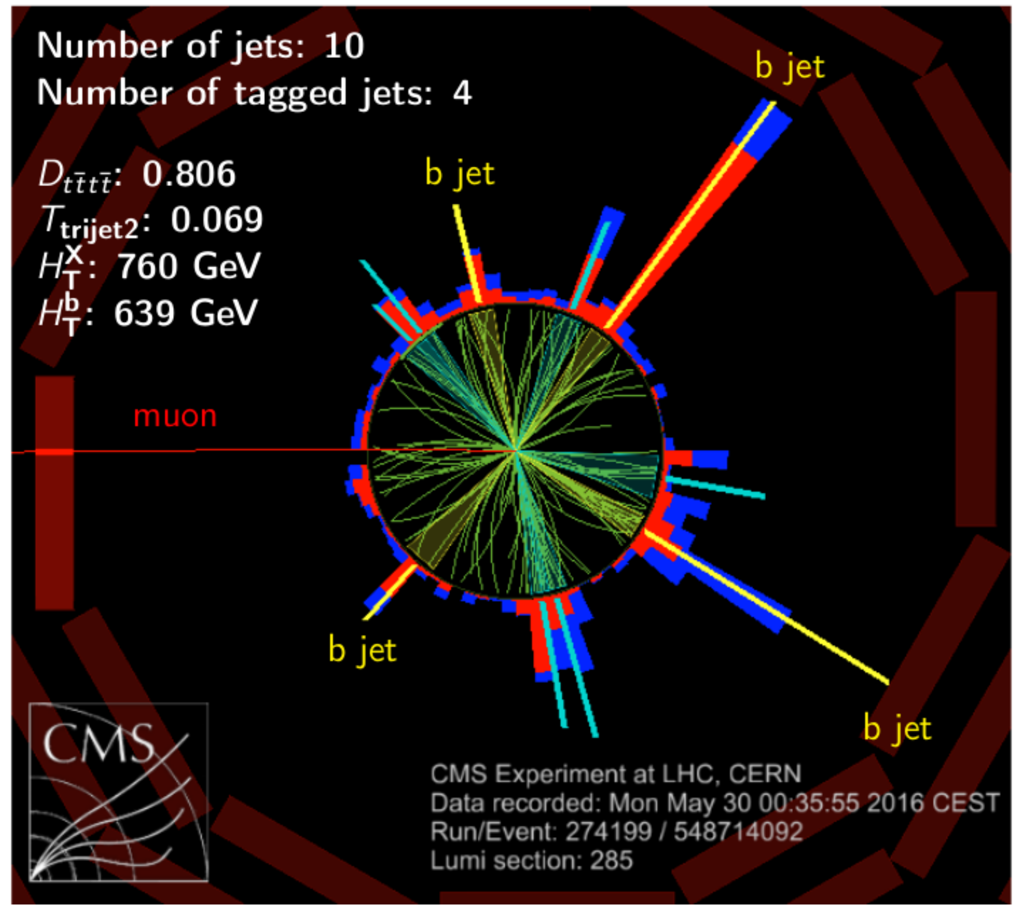
Noise term: electronics + digitization

Constant term: nonuniform light collection, intercalibration errors, energy leakage from back of crystal

HCAL and jets

- Hadron calorimeter designed to be as massive as possible to stop all particles, reconstruct hadron showers



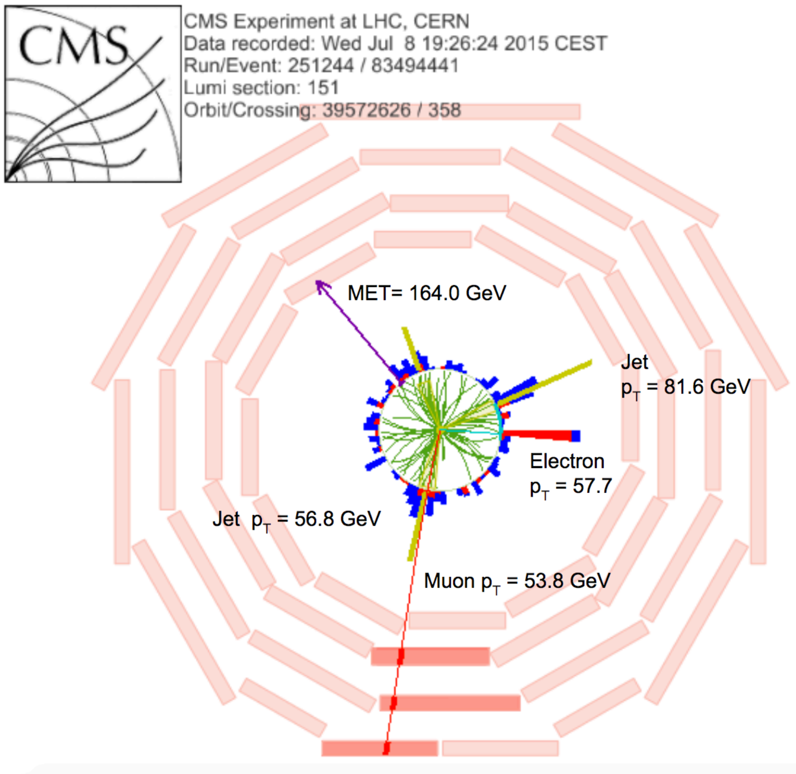


Reconstruct jets using **anti-k_t algorithm**, but this reflects our intuition of localized energy deposit from fragmentation and hadonization of a high-pT quark or gluon

Missing Transverse Momentum

Detect **neutrino** (or other weakly interacting neutral) by invoking conservation of momentum in the plane transverse to the beam

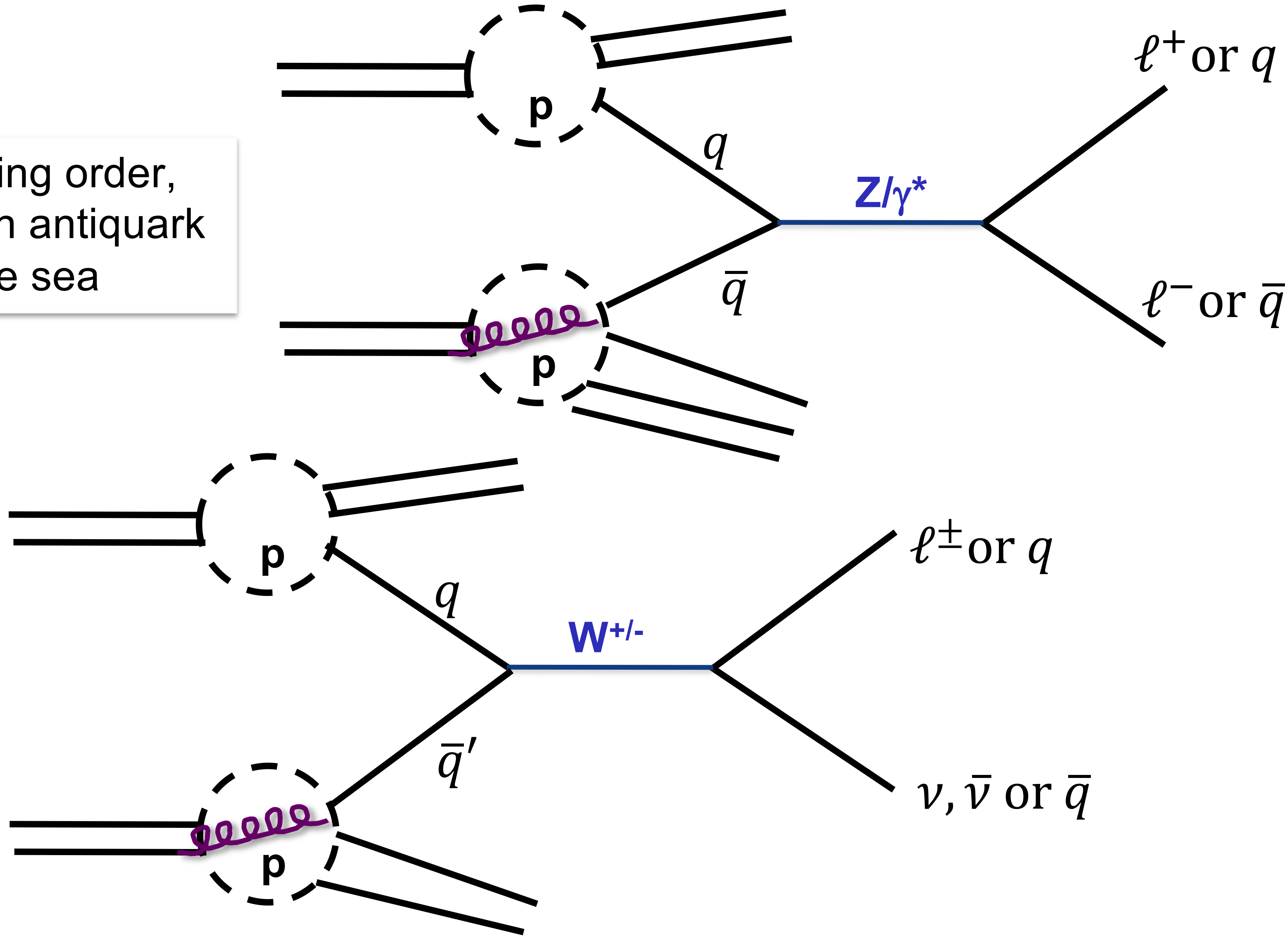
Resolution of unclustered part driven by stochastic effects: scales as $\sqrt{\Sigma E_T}$



$$\vec{p}_T^{miss} = -1 \cdot \left[\sum_{\text{jets } j} \vec{p}_T^{\,j} + \sum_{\text{leptons } \ell} \vec{p}_T^{\,\ell} + \sum_{\text{photons } \gamma} \vec{p}_T^{\,\gamma} + \sum_{\text{unclustered } u} \vec{p}_T^{\,u} \right]$$

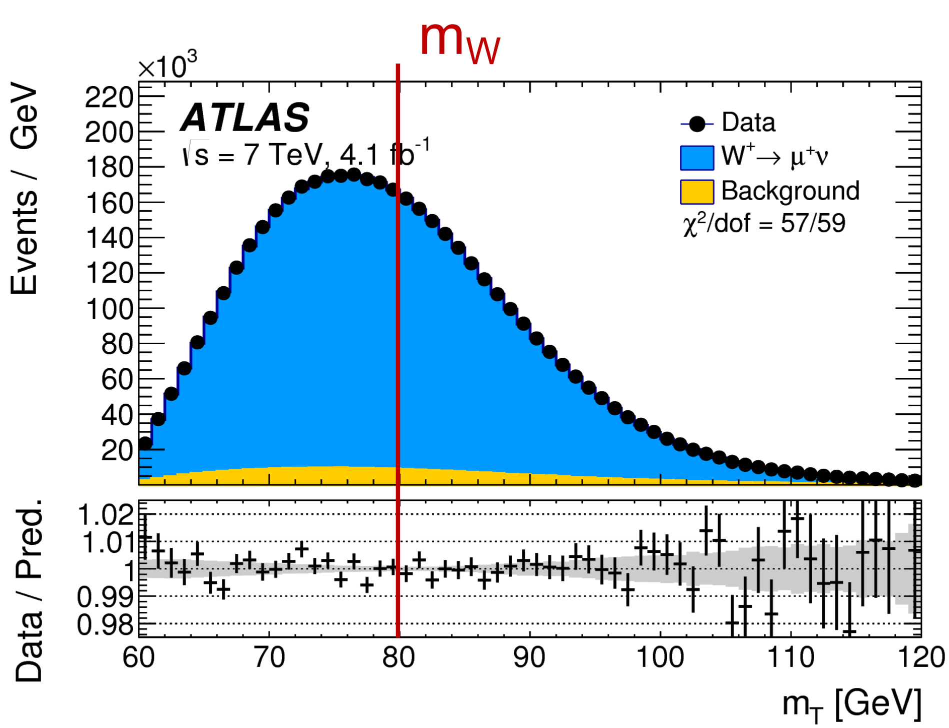
Building blocks: W and Z

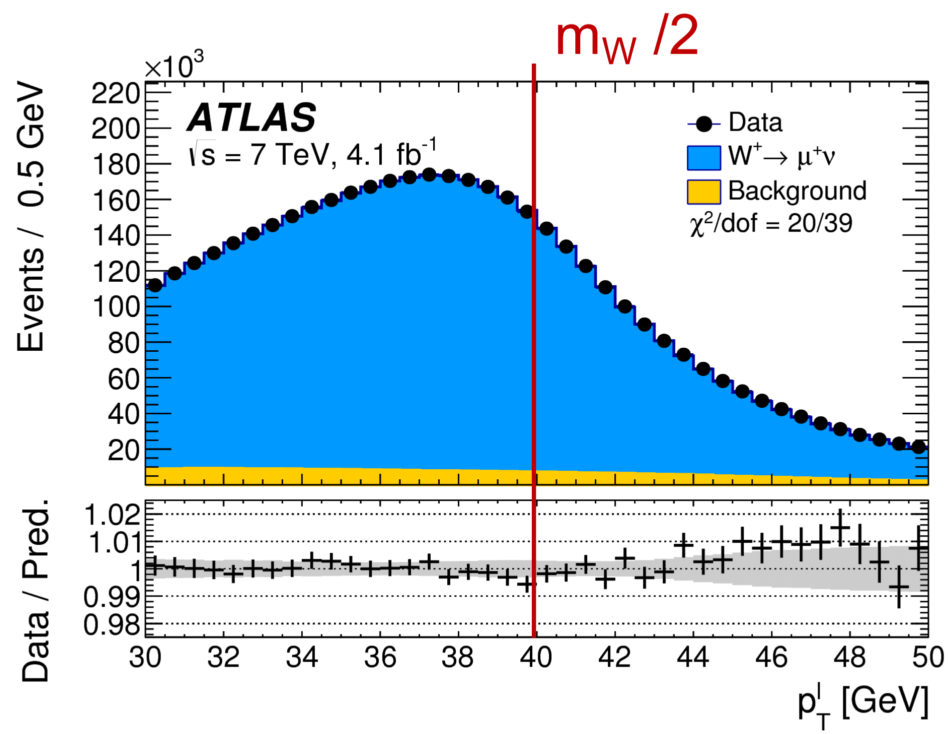
At leading order, need an antiquark from the sea



W Mass

- ATLAS measurement with 7 TeV data (just under 5 fb^{-1})
  - → *Not statistically limited*
- Fit to lepton p_T and transverse mass $m_T = \sqrt{2 p_T^{\ell} p_T^{miss}(1 - \cos\Delta\varphi)}$
  - → *Kinematic edges at $m_W/2$ and m_W*
  - → *Convoluted with detector resolution,*

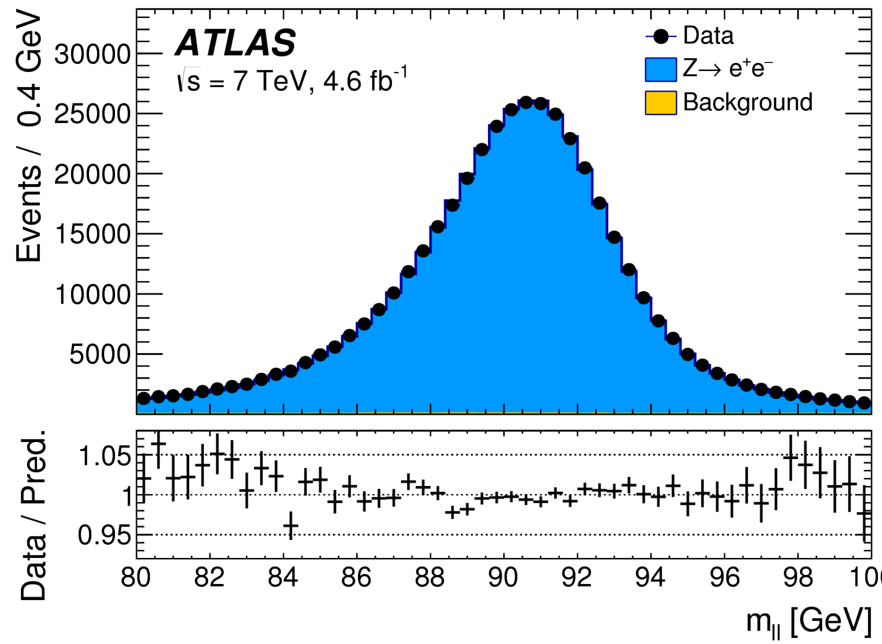




(ATLAS STDM-2014-18)

W Mass

- Use Z events to model detector response, particularly recoil (unclustered energy)
  - → *Similar production and kinematics*
- Sensitive to charm and strange quark content of the proton
  - → *25% of W production involves 2nd-generation quark*



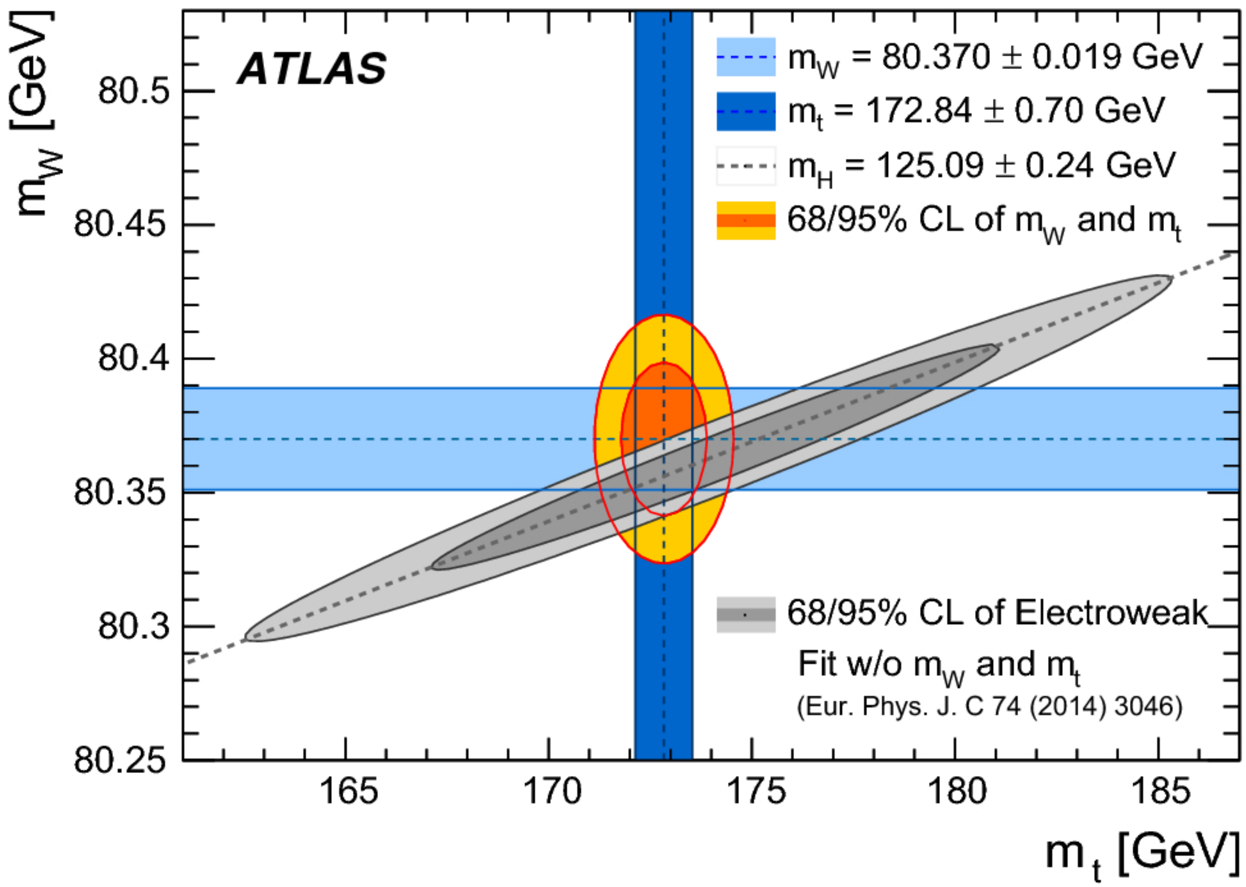
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

(ATLAS STDM-2014-18)

W mass

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

- Fundamental test of internal consistency of Standard Model



(ATLAS STDM-2014-18)

Weak mixing angle from DY A_{FB}

- Weak mixing angle is a free parameter of the SM

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

- Measure **effective weak mixing angle** (includes EW corrections and is lepton-flavor dependent)

$$\sin^2\theta_{\mathrm{eff}}^{f} = \kappa_f \sin^2\theta_W$$

- Theoretical expression for asymmetry:

$$A_{\mathrm{FB}}^{\mathrm{true}}(m_{\ell\ell}) = \frac{6a_\ell a_\mathrm{q}(8v_\ell v_\mathrm{q} - Q_\mathrm{q}KD_m)}{16(v_\ell^2 + a_\ell^2)(v_\mathrm{q}^2 + a_\mathrm{q}^2) - 8v_\ell v_\mathrm{q} Q_\mathrm{q} K D_m + Q_\mathrm{q}^2 K^2 (D_m^2 + \Gamma_\mathrm{Z}^2/m_\mathrm{Z}^2)}$$

vector and axial couplings of fermions (leptons and quarks) to Z

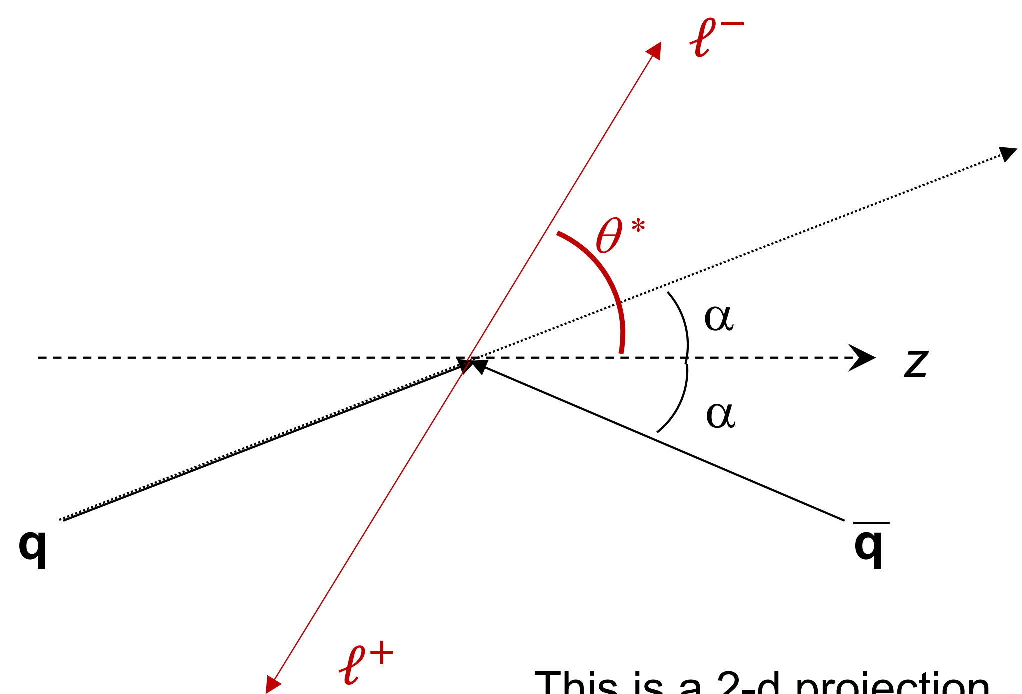
$v_f = a_f\left(1 - 4\left|Q_f\right|\sin^2\theta_{\mathrm{eff}}^{f}\right)$ where Q_f is the fermion charge

(CMS SMP-16-007)

Weak mixing angle from DY A_{FB}

- Ratios and asymmetries are powerful measurements because uncertainties on the total yield cancel to first order
- Define "forward" direction as $\cos\theta^* > 0$, where θ^* is defined in the Collins-Soper frame
  → *Parton p_T is small compared to other momenta so this is close to the lab frame*
- Valence quarks, but antiquarks only from the sea → momentum asymmetry → quark direction more likely to be in the direction of dilepton system boost
  → *Calculate $\cos\theta^*$ under this assumption*
  → *Account for dilution*
- Measured asymmetry defined

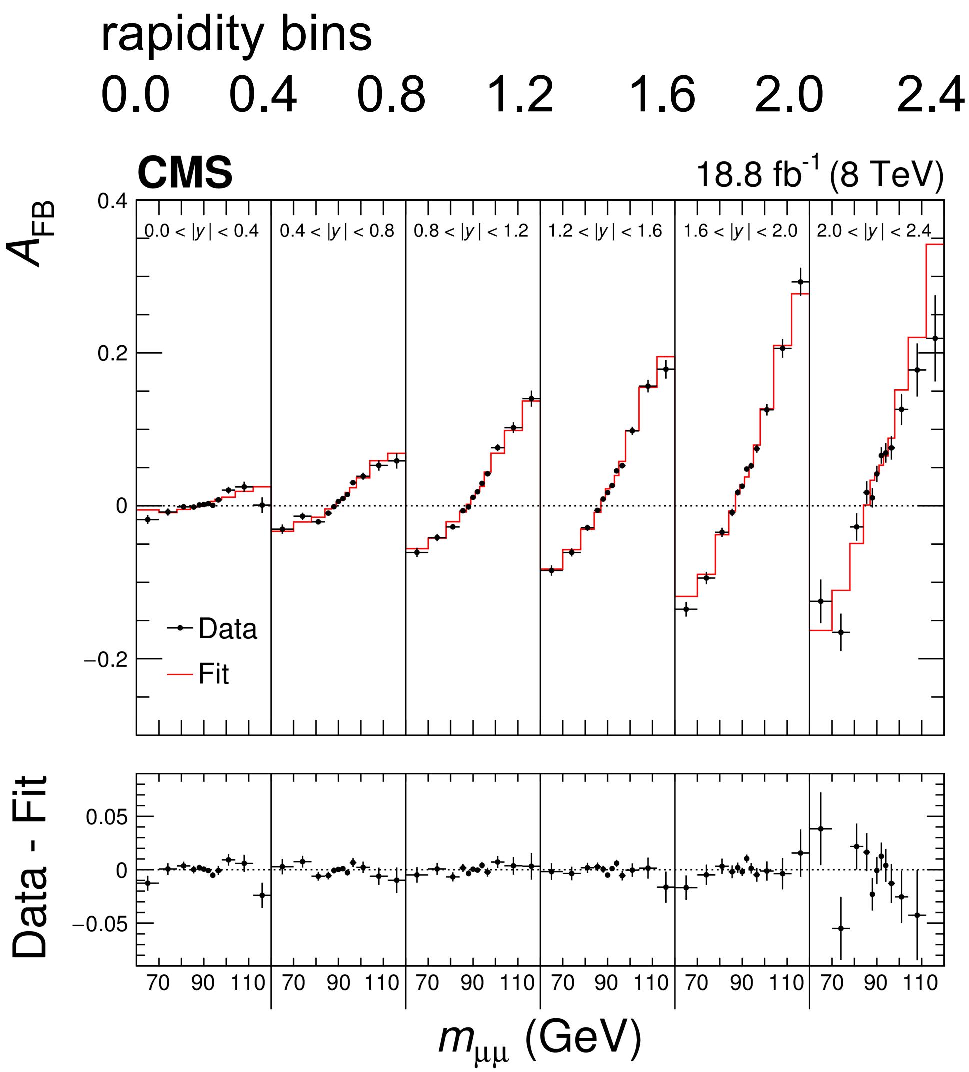
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



This is a 2-d projection but that's all we need

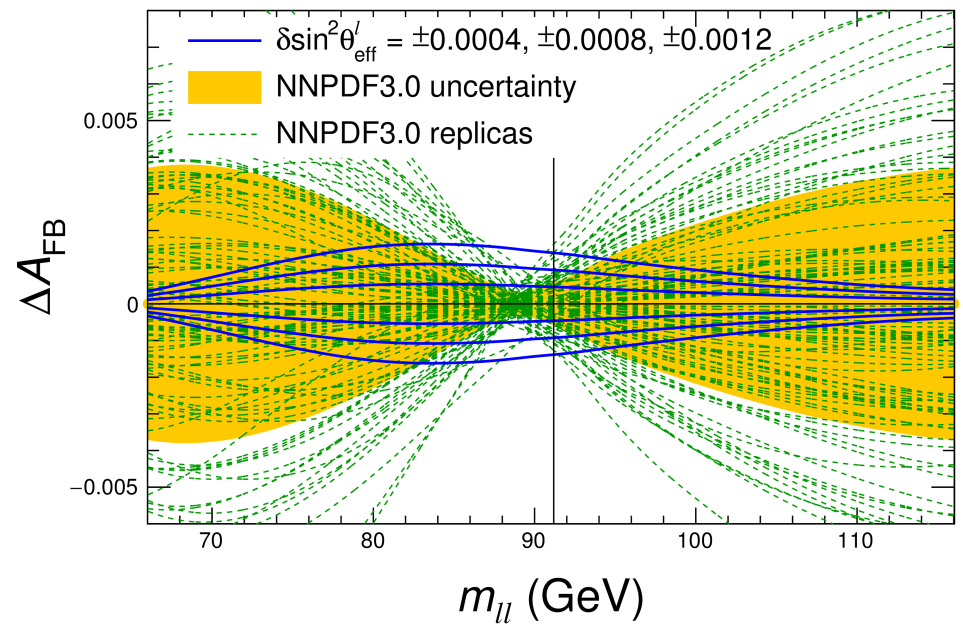
(CMS SMP-16-007)

Weak mixing angle from DY A_{FB}



- Asymmetry largest for furthest-forward leptons, away from Z peak

  → *But changes in $\sin^2(\theta_{eff}^l)$ most evident near the Z peak*



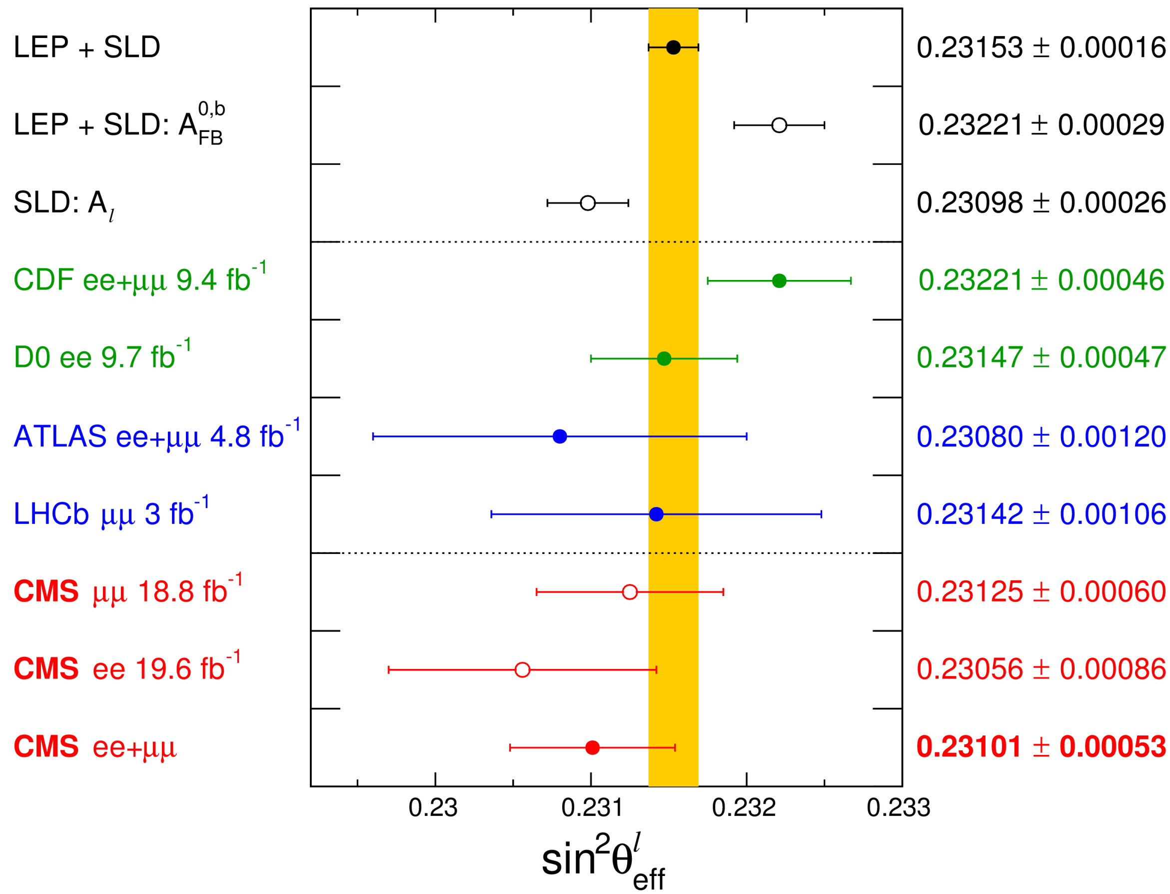
- Sensitivity to PDF model also evident

(CMS SMP-16-007)

Weak mixing angle from DY A_{FB}

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF})$$

- Limiting systematic is PDFs, statistical uncertainty from Monte Carlo
- Recall percent-level uncertainties on lepton ID: reduced to per-mil effect
- PDF replicas weighted by how well the model agrees with data
  - → *Final result is a χ2-weighted average over the replicas, uncertainty is the weighted RMS*
  - → *PDF uncertainty reduced by factor 2, still dominant*



(CMS SMP-16-007)

Cross section, simple view

- Cross section formula

$$\sigma = \frac{N - B}{A\, \varepsilon \int \mathcal{L} dt}$$

N = number of events observed in selected data
B = estimated background
A = Acceptance
ε = Efficiency
$\int \mathcal{L} dt$ = Integrated luminosity

Acceptance A purely from theory

$$\mathrm{A} = \frac{N(\text{kinematic})}{N(\text{total})}$$

Fraction of total events that pass kinematic selection (fiducial volume)

Efficiency ε brings in detector effects (measure using simulated events and detector)

$$\varepsilon = \frac{N(\text{reconstructed})}{N(\text{kinematic})}$$

Fraction of events in fiducial volume that pass all event selection

Cross section, simple view

- Cross section formula

$$\sigma = \frac{N - B}{A\, \varepsilon\, \mathcal{L}}$$

N = number of events observed in selected data
B = estimated background
A = Acceptance
ε = Efficiency
L = Integrated luminosity

- Uncertainties follow by error propagation with the statistical uncertainty $\delta N = \sqrt{N}$

$$(\delta\sigma)^2 = \frac{N}{(A\varepsilon\mathcal{L})^2} + \left(\frac{\delta B}{A\varepsilon\mathcal{L}}\right)^2 + \left(\frac{\delta A}{A}\right)^2 \sigma^2 + \left(\frac{\delta \varepsilon}{\varepsilon}\right)^2 \sigma^2$$

If the *absolute* uncertainty on your background is larger than your signal, no sensitivity
(to see this, divide through by σ^2)

Fractional uncertainty on the acceptance and efficiency apply to the cross section

Cross section, modern view (I)

- Likelihood fit takes into account both the nominal expected signal and systematic uncertainties as nuisance parameters
  - → *We say that the nuisance parameters are "profiled"*
- Models the probability to observe a certain number of events in a certain bin

$$\mathcal{L}(\mu, B(\boldsymbol{\theta})) \propto P(N_{obs}|\mu S(\boldsymbol{\theta}) + B(\boldsymbol{\theta})) \prod_i \exp\left(\frac{(\theta_i - \theta_i^0)^2}{\sigma_i^2}\right)$$

Poisson distribution describing the predicted and observed yield in each bin

Expectation is sum of signal S and background(s) B

- Both a function of nuisance parameters θ
- Signal strength μ "floats" unconstrained

$$\mu = \sigma_{\text{measured}}/\sigma_{\text{predicted}}$$

(To extend to multiple bins, take a product of Poisson distributions)

Product of gaussians, one per (uncorrelated) source of uncertainty

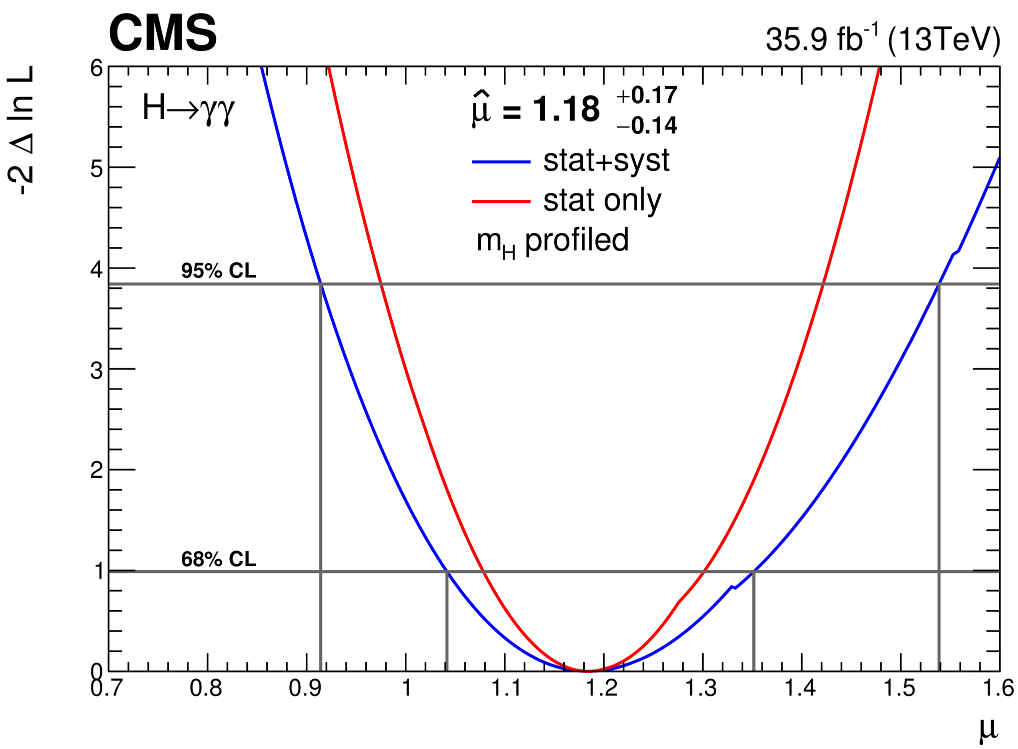
- The θ_i are allowed to vary in the fit, but we say that they are "constrained" by this gaussian
- θ_i^0 is the nominal value of the uncertain parameter
- σ_i is the uncertainty on parameter i

Cross section, modern view (II)

- Can fit for parameters other than cross section
- Equivalent to maximizing the likelihood: minimize negative log likelihood

  → *Simplify computation*

$$-\log \mathcal{L} = -\big(\mu S(\boldsymbol{\theta}) + B(\boldsymbol{\theta})\big) + N_{obs} \log\big(\mu S(\boldsymbol{\theta}) + B(\boldsymbol{\theta})\big) + \sum_i \frac{\left(\theta_i - \theta_i^0\right)^2}{\sigma_i^2} + \text{constants}$$



- A typical likelihood scan
- Well-behaved: quadratic shape
- Central value at minimum
- Read 1- and 2-sigma uncertainty from points where $-2\log\mathcal{L}$ has increased by 1 and 4

backup