ATLAS Results

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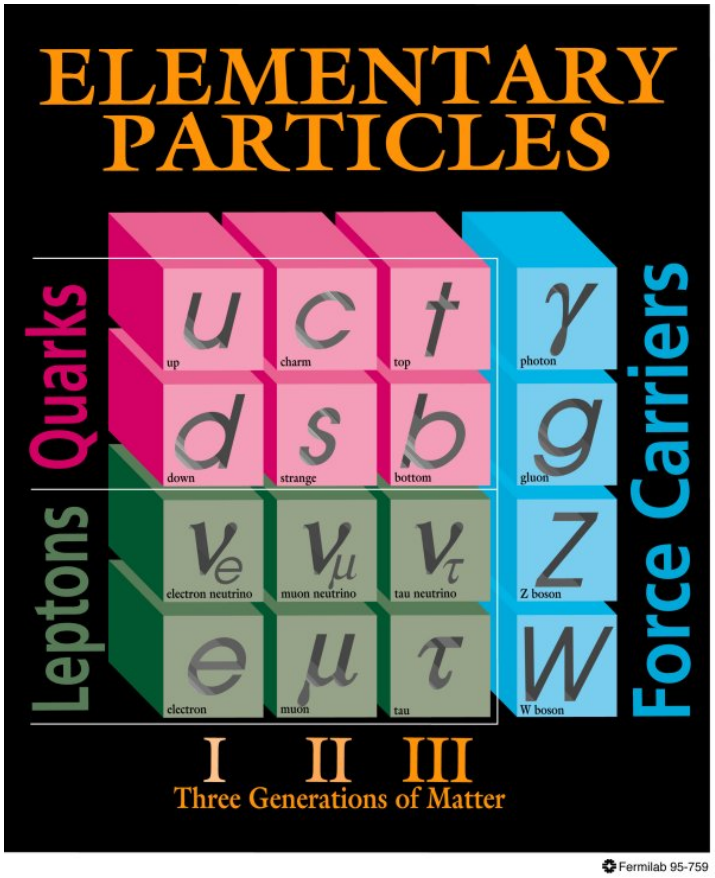
Introduction

- What kinds of things does ATLAS measure?
- How are these measurements related to one another?
- What do we learn about how the universe works?
- What is interesting right now?

- Too much to cover in 2 hours, so while I'll try to give a good sense of the breadth of the measurements being done at ATLAS, this "overview" is necessarily biased toward
  - → *Topics I've worked on or want to work on*
  - → *Or that I think are really interesting*

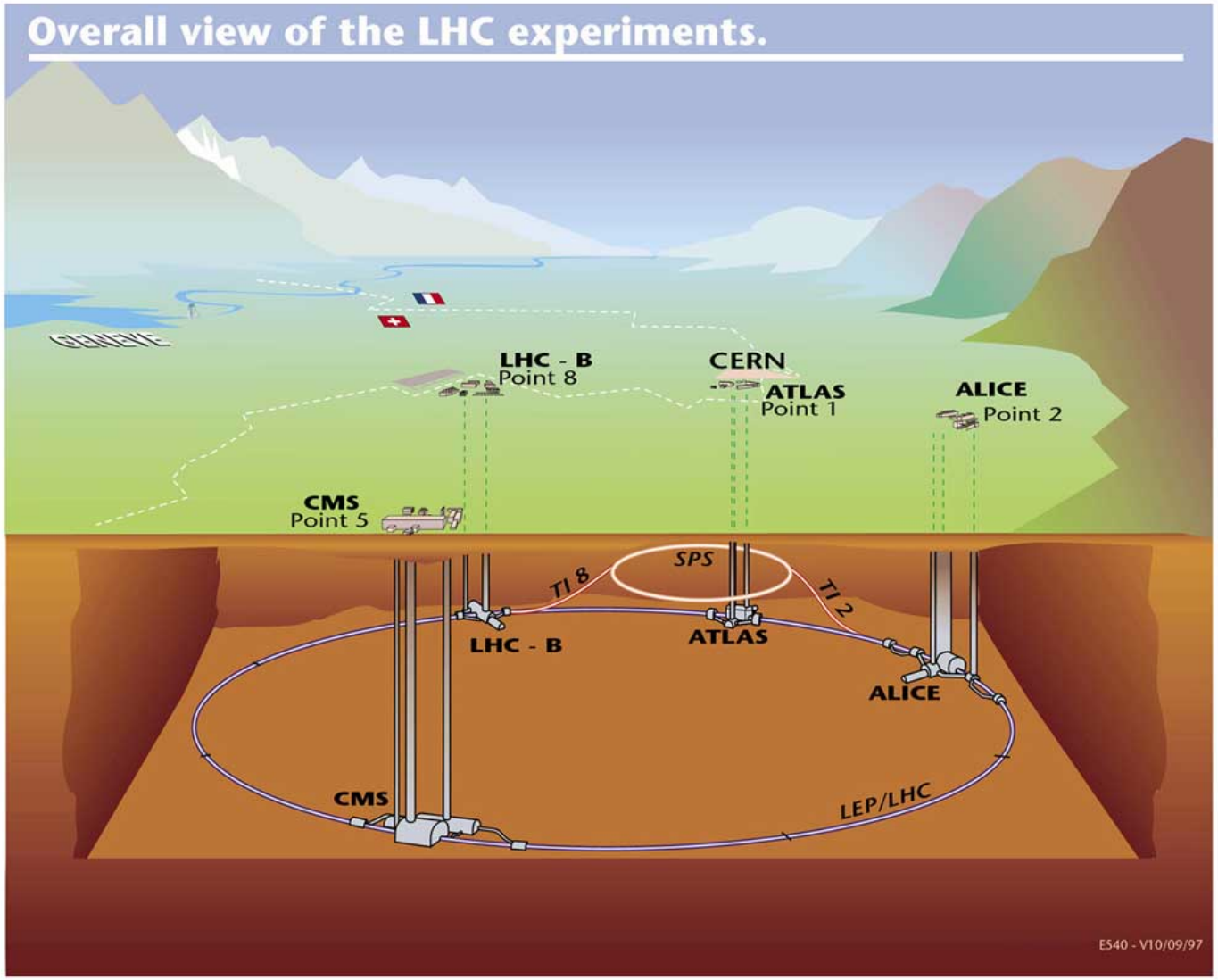
Part I: leptons (both charged and neutral) and all things electroweak
Part II: photons, quarks, and QCD!

The Standard Model



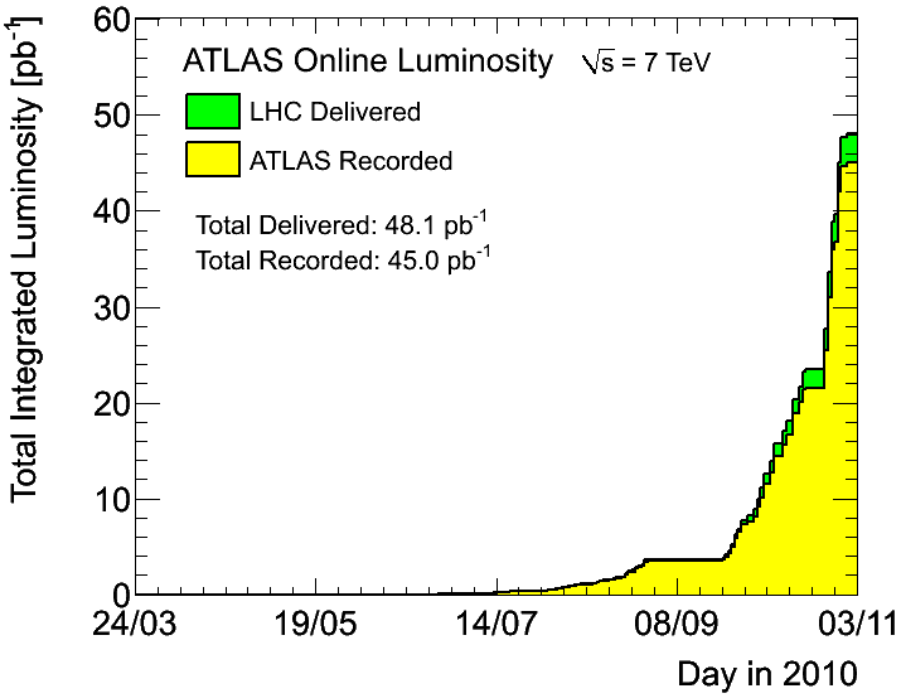
What happens when you throw the Standard Model at a collider detector?

The LHC at CERN



The 2010 run at 7 TeV

- Rapid LHC startup
- 2010 Instantaneous luminosity record = 2.1 x 10^{32} $cm^{-2}s^{-1}$
  - → *Tevatron record ~ 4x10^{32} $cm^{-2}s^{-1}$*

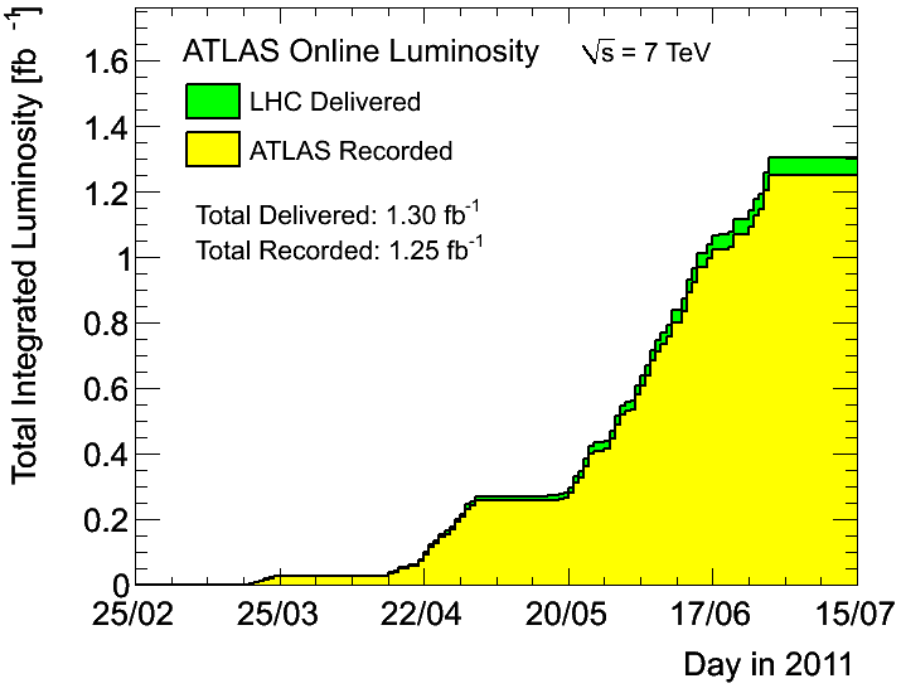


- 2 → 368 bunches
  - → *2808 possible*
- ~10^{11} p/bunch
- > 20 MJ stored energy
  - → *Tevatron: 2 MJ*

Stable 30-35 pb^{-1}
Analysis ongoing

The 2011 Run, So Far

- Rapid lumi. evolution continues
- 2011 Instantaneous luminosity record = 1.26 x 10^{33} $cm^{-2}s^{-1}$
  - → *Tevatron record ~ 4x10^{32} $cm^{-2}s^{-1}$*



- 75 → 50 ns bunch spacing
  - → *1380/2808 bunches filled*
- Up to 62 pb^{-1} / fill
- Expect up to 4 fb^{-1} by end of the year

> 1 fb^{-1} and integrating!
Analysis ramping up

The ATLAS Detector

Muon Detectors

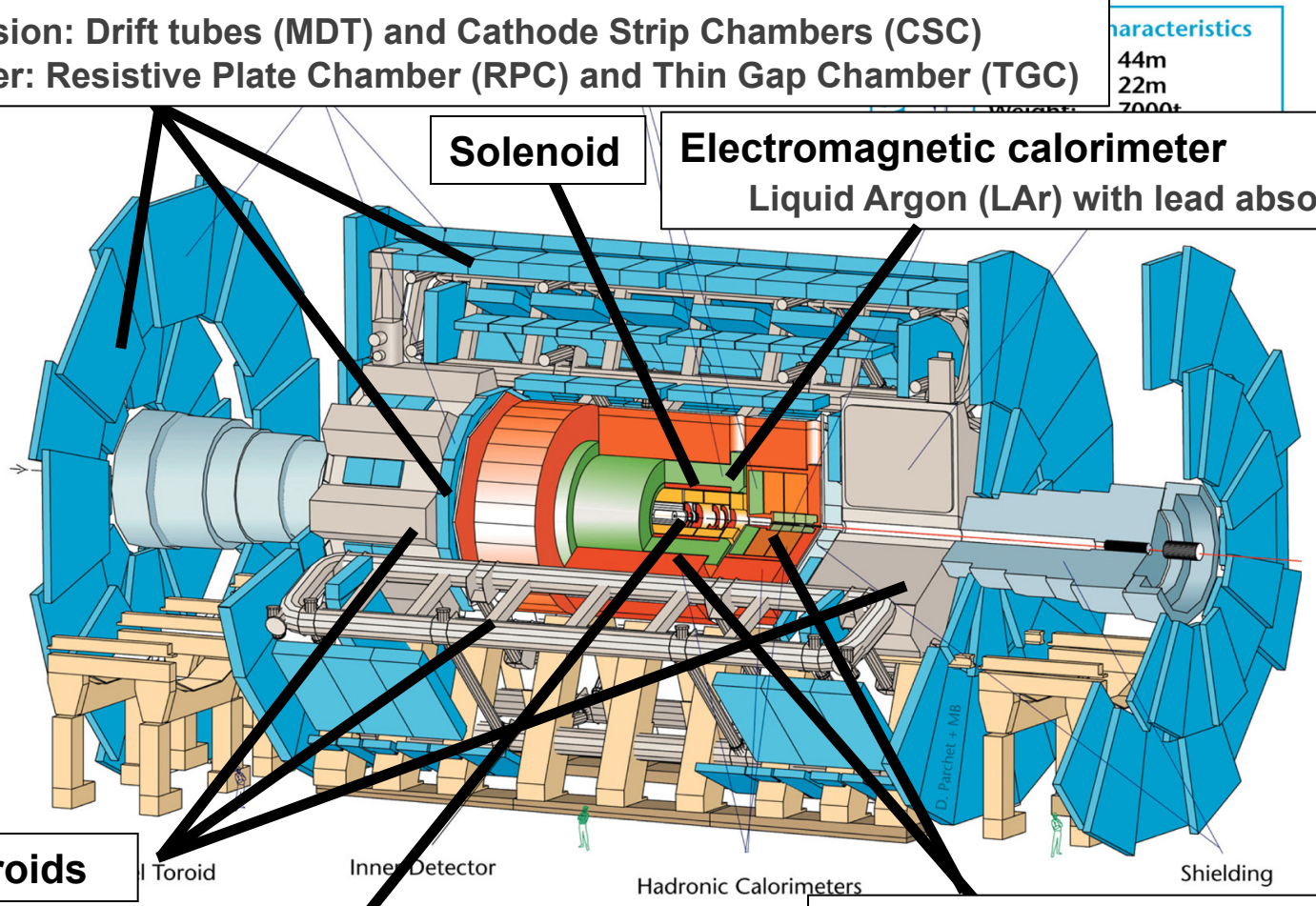
Precision: Drift tubes (MDT) and Cathode Strip Chambers (CSC)

Trigger: Resistive Plate Chamber (RPC) and Thin Gap Chamber (TGC)

Solenoid

Electromagnetic calorimeter

Liquid Argon (LAr) with lead absorber



Toroids

Inner Detector (tracking):

Pixels (silicon)

SCT (silicon strips)

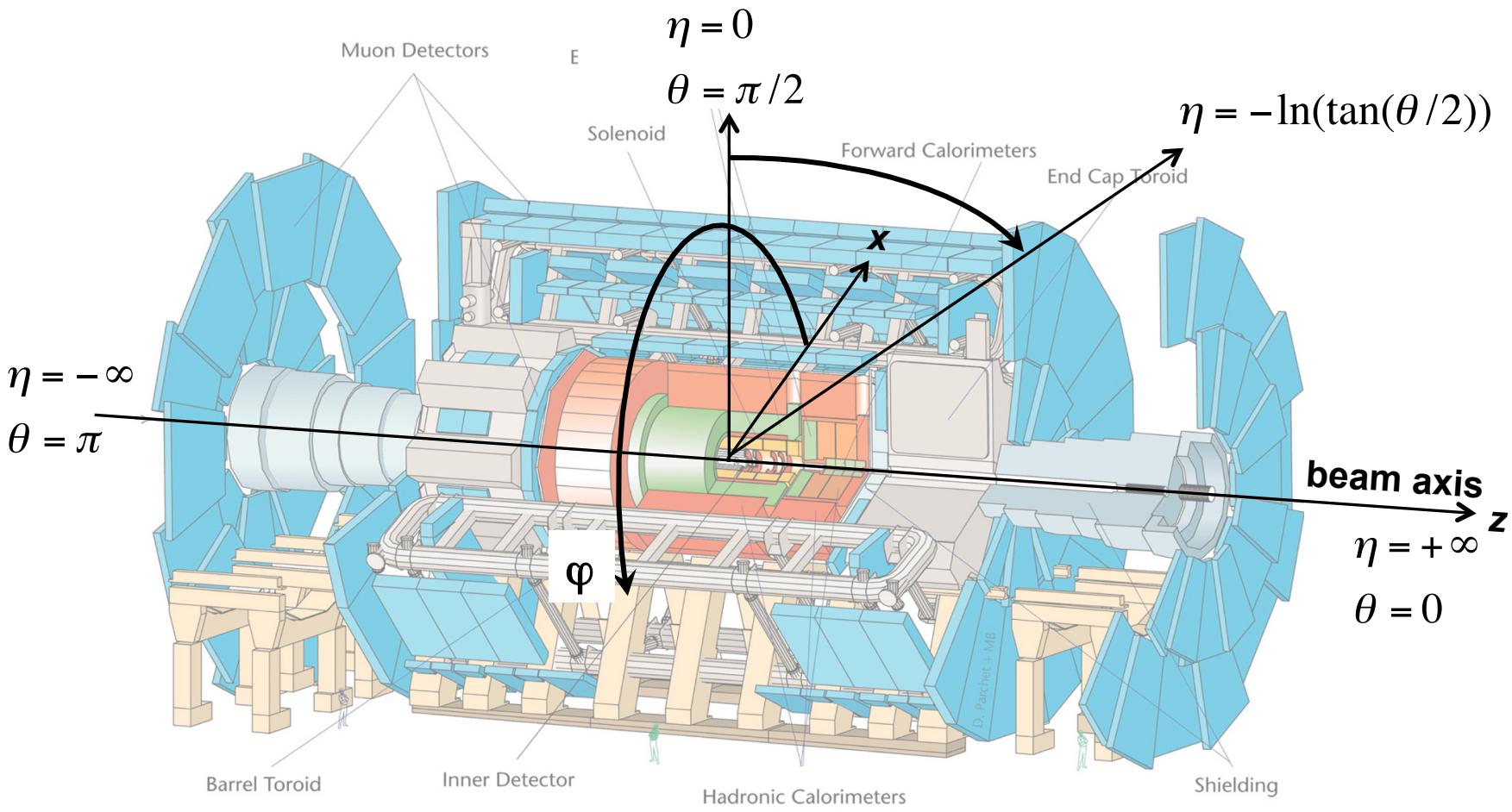
TRT (straw tubes / ionization)

Hadronic calorimeter

Steel absorber + scintillator

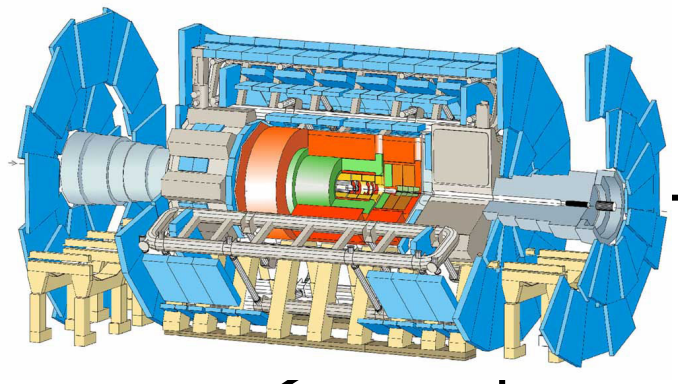
LAr with copper/tungsten absorber

Hadron Collider Kinematics



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

The ATLAS Trigger System



Level One (hardware)
limited info, calo + muon
(55 kHz (design: 75 → 100)**)**

triggers

Region of Interest Builders

Level Two (software)
full granularity, partial readout
(3.5 → **4 kHz)**

triggers

Event Builder

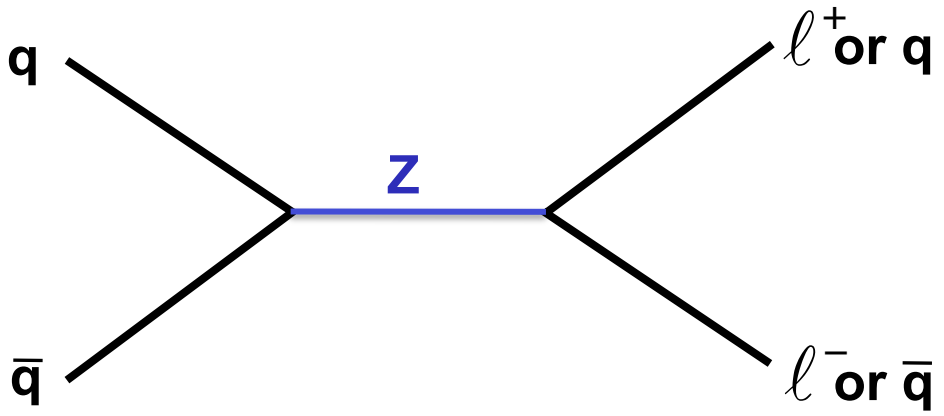
Event Filter (software)
full granularity, full readout
(200 → **400 Hz)**

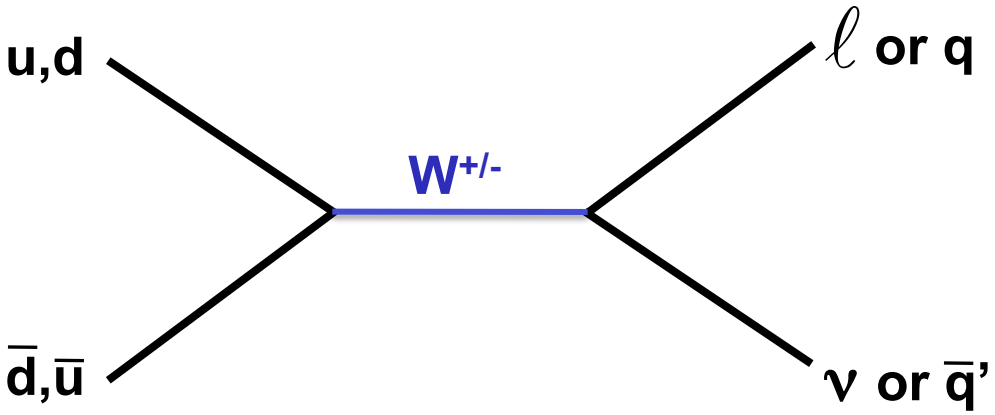
to tape

triggers

The W and Z Bosons

- Weak force carriers
- Spin 1 bosons
- $M_W = 80.399 \pm 0.023$ GeV
- $M_Z = 91.1876 \pm 0.0002$ GeV

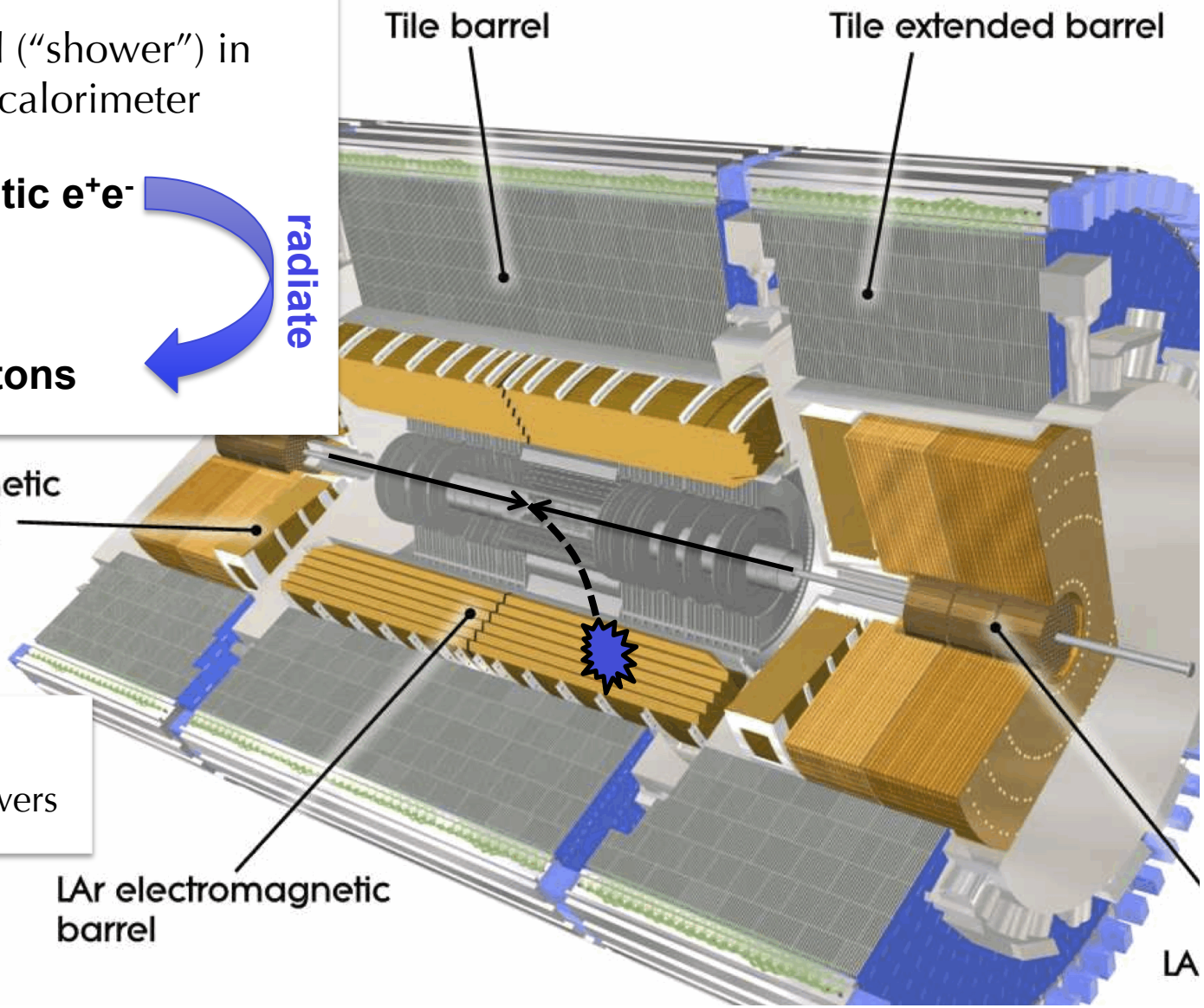




Focus on leptonic signatures

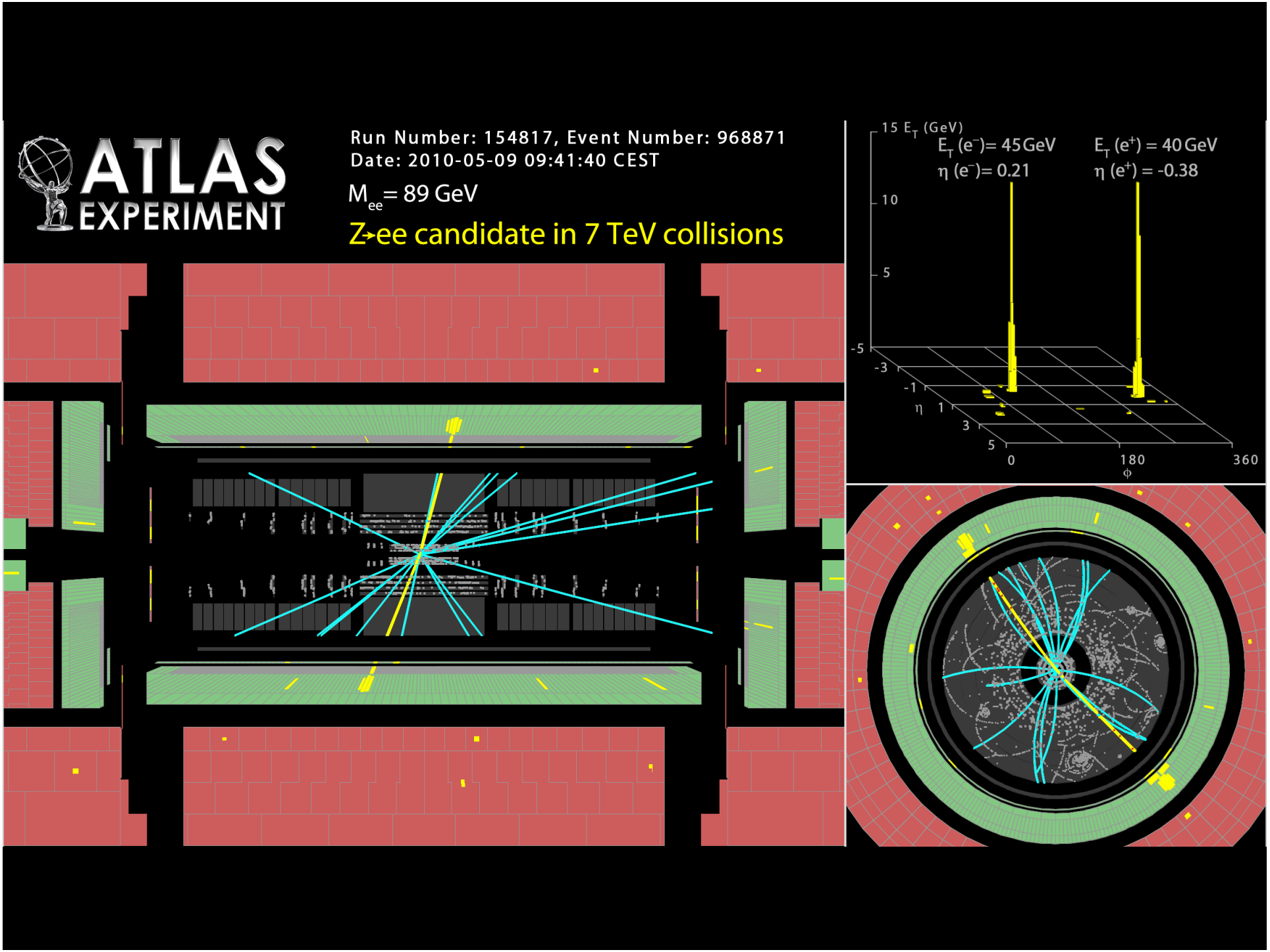
Electrons and Photons in ATLAS

- Track in inner detector
- Energy deposited ("shower") in electromagnetic calorimeter



22 X_0 deep (or more)

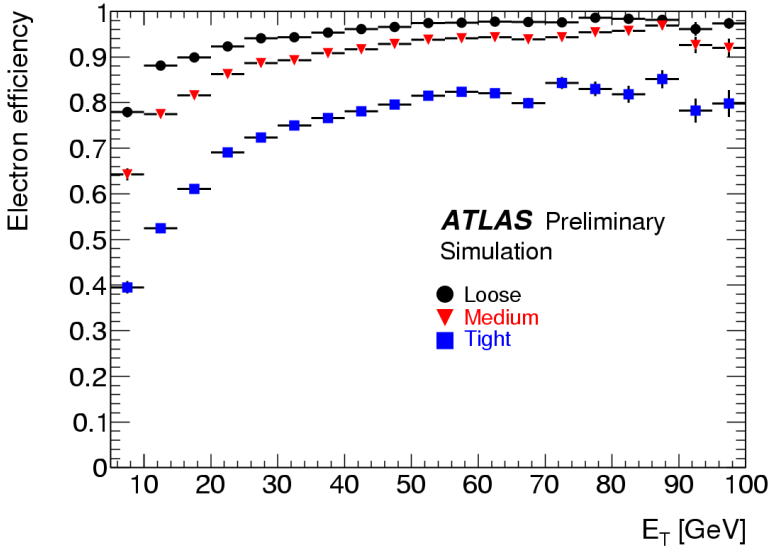
→ fully contained showers


ATLAS
EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e^-)= 45 GeV
E_T (e^+) = 40 GeV
η (e^-)= 0.21
η (e^+) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ

Electrons in ATLAS

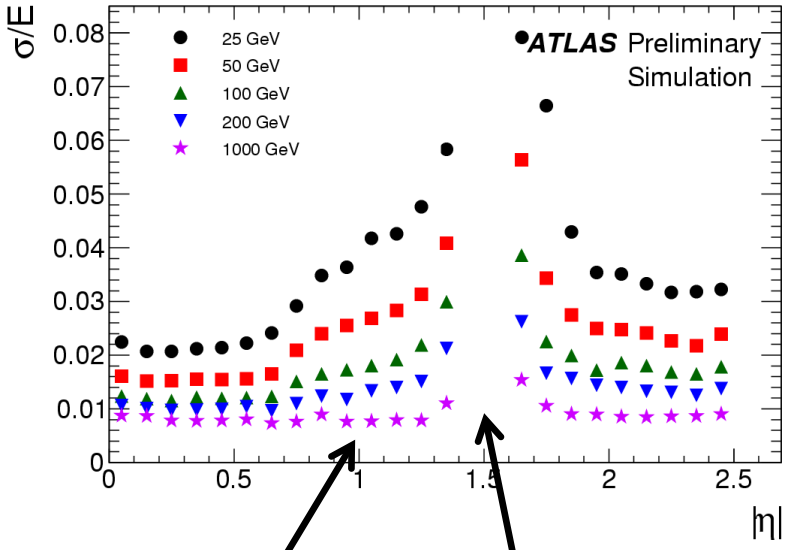
Loose electrons are basically just a calo cluster
Medium electrons have a track and pass more shower shape cuts
Tight electrons get the works, incl. transition radiation and a conversion veto

electron efficiency



electron resolution

$$\sigma(E) = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

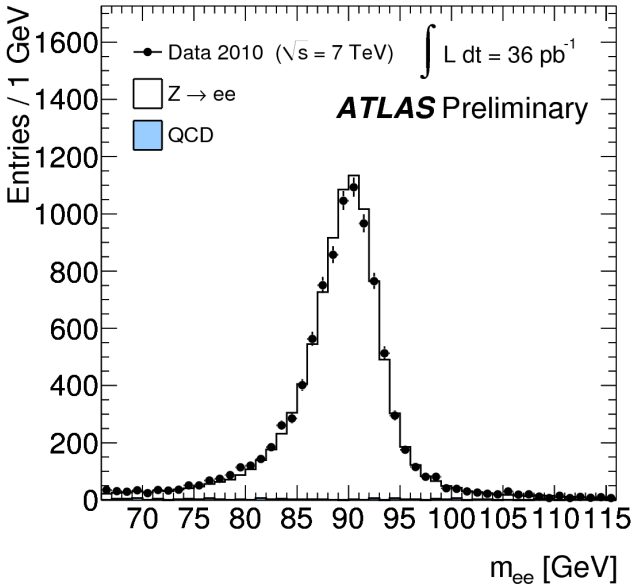


resolution degraded by additional material

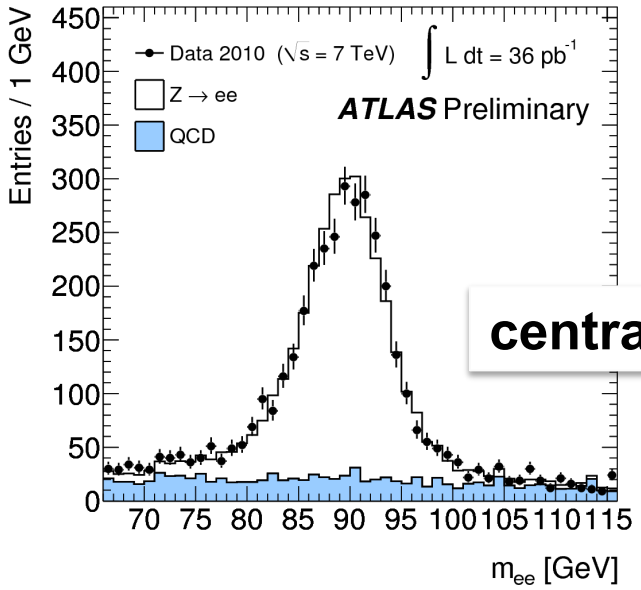
calorimeter crack

(caveat: 2010 baselines)

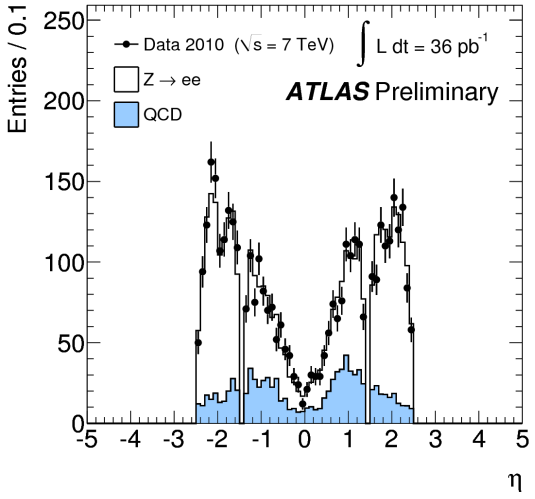
$Z \rightarrow ee$ data (2010)

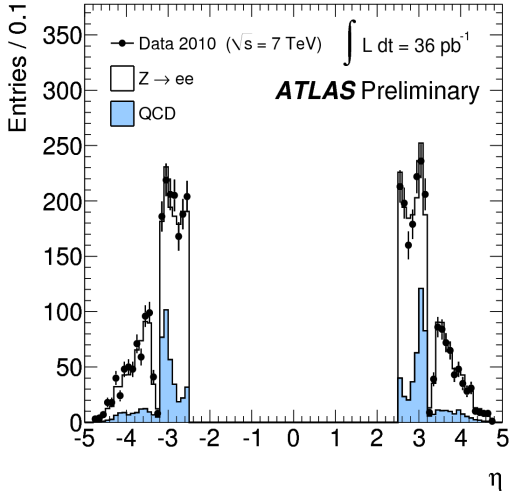


central-central



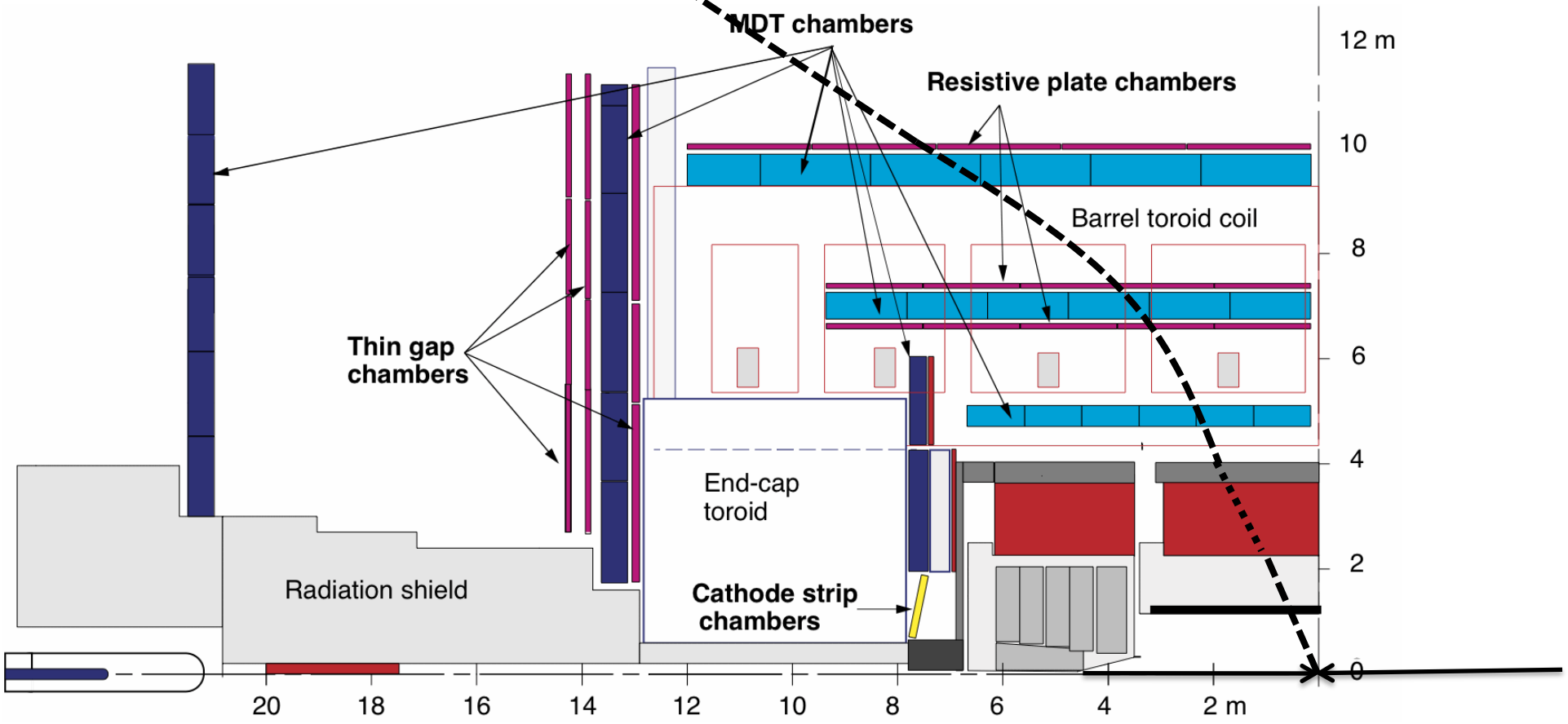
central-*forward*



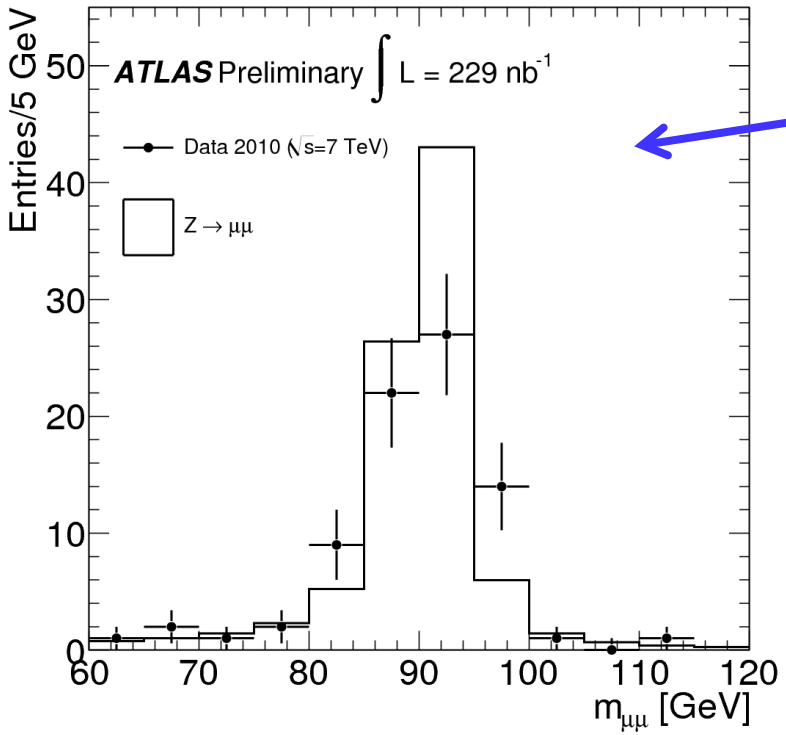


Muons in ATLAS

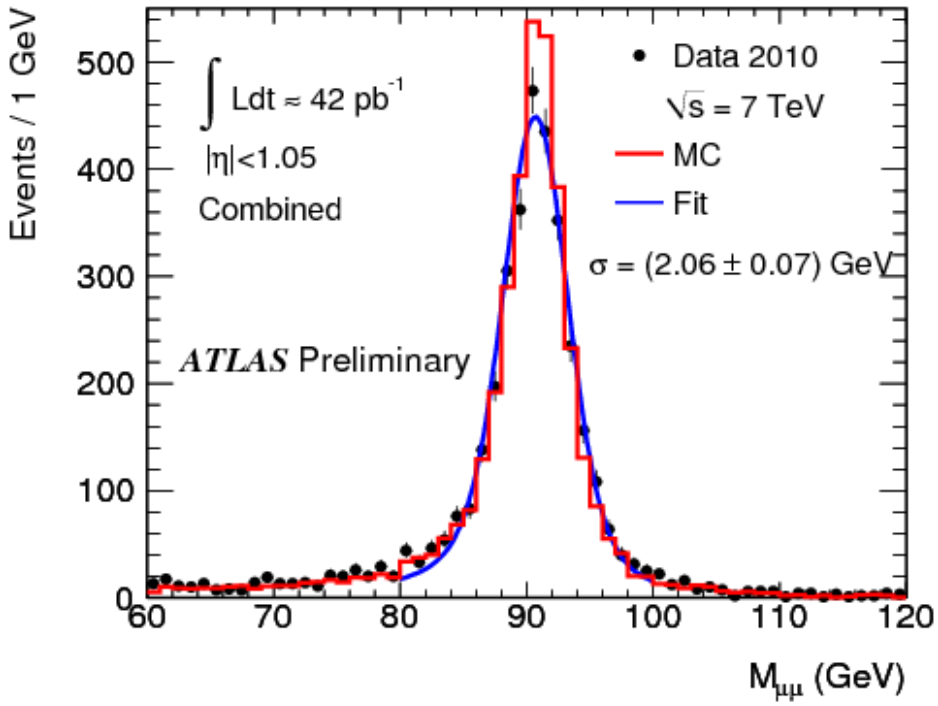
Match tracks from inner detector (ID) and muon spectrometer (MS)



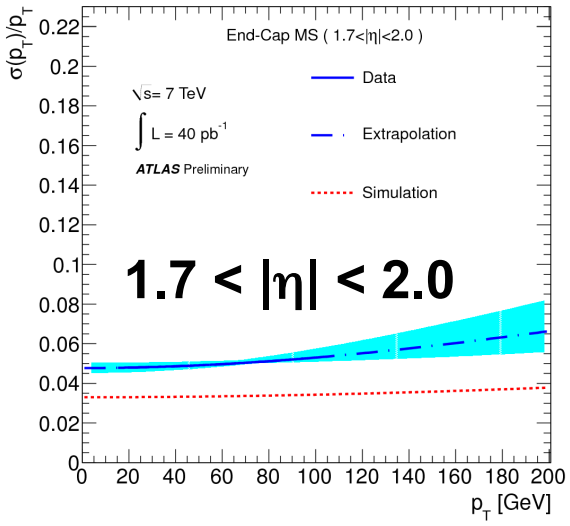
Muon resolution in $Z \rightarrow \mu\mu$ data

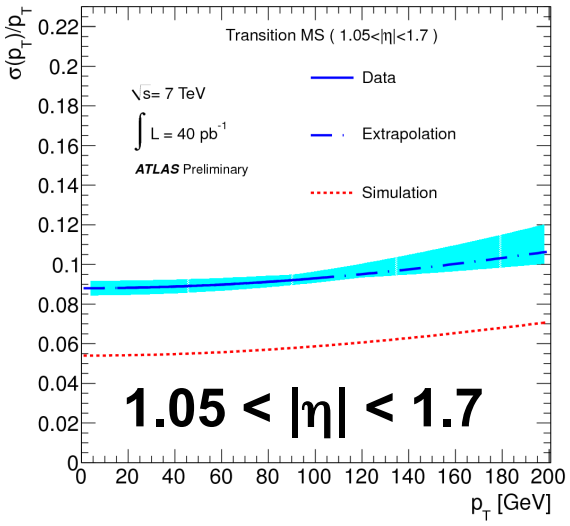


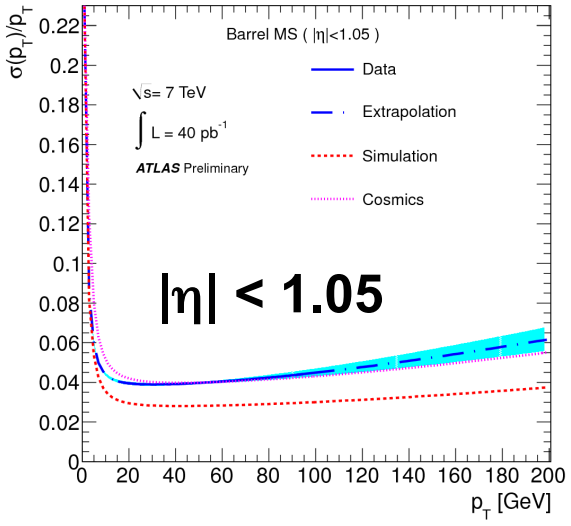
summer 2010

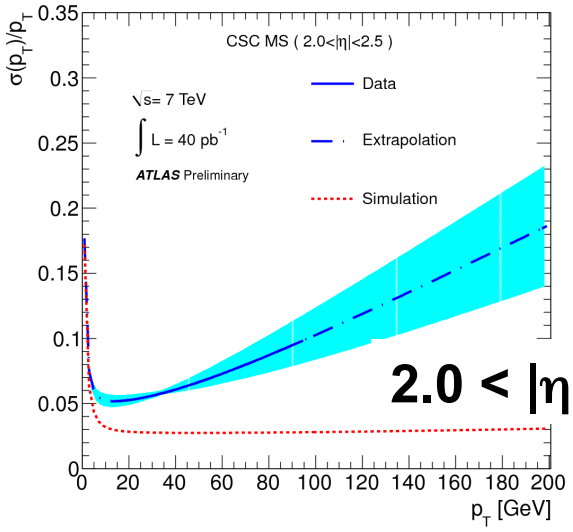


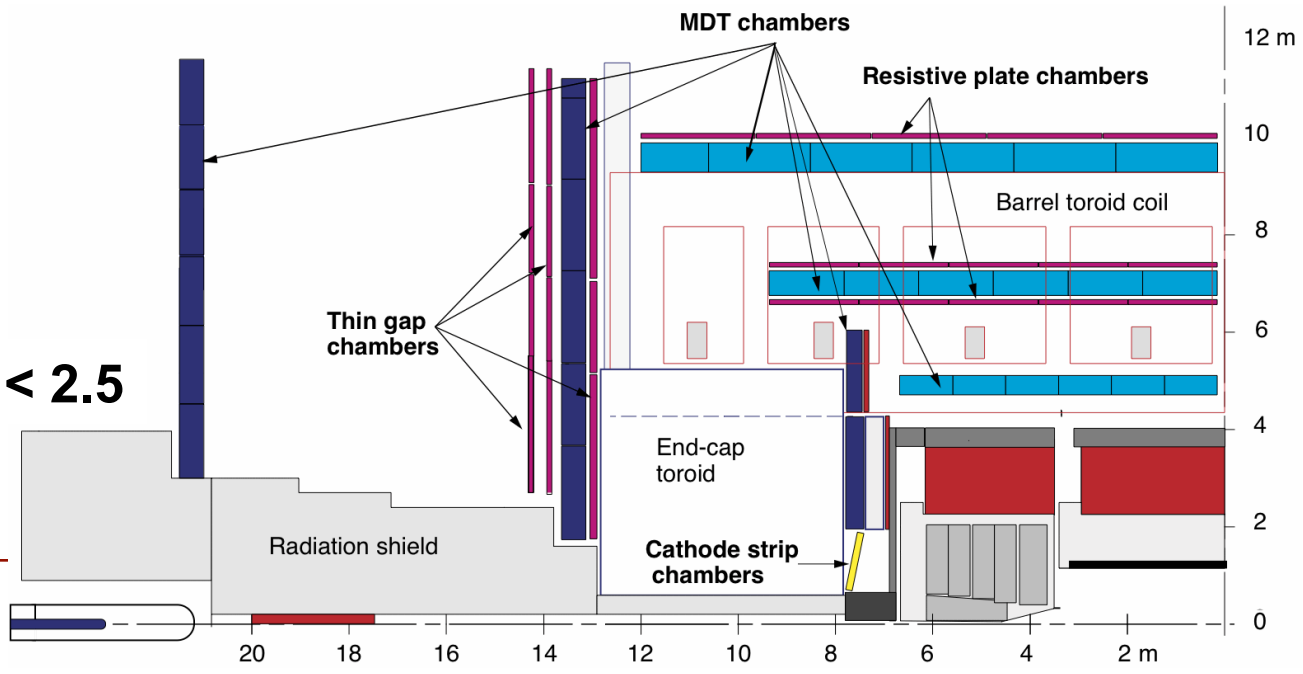
Muon Performance: Resolution



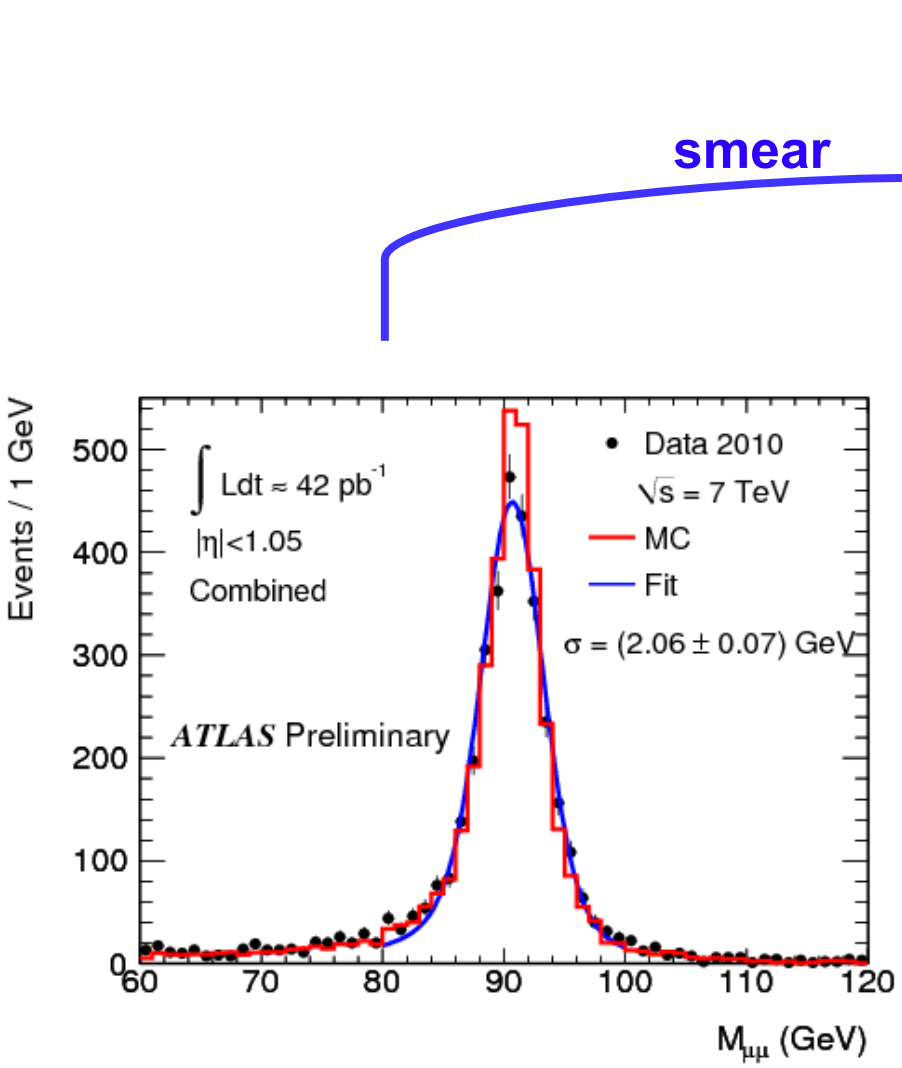




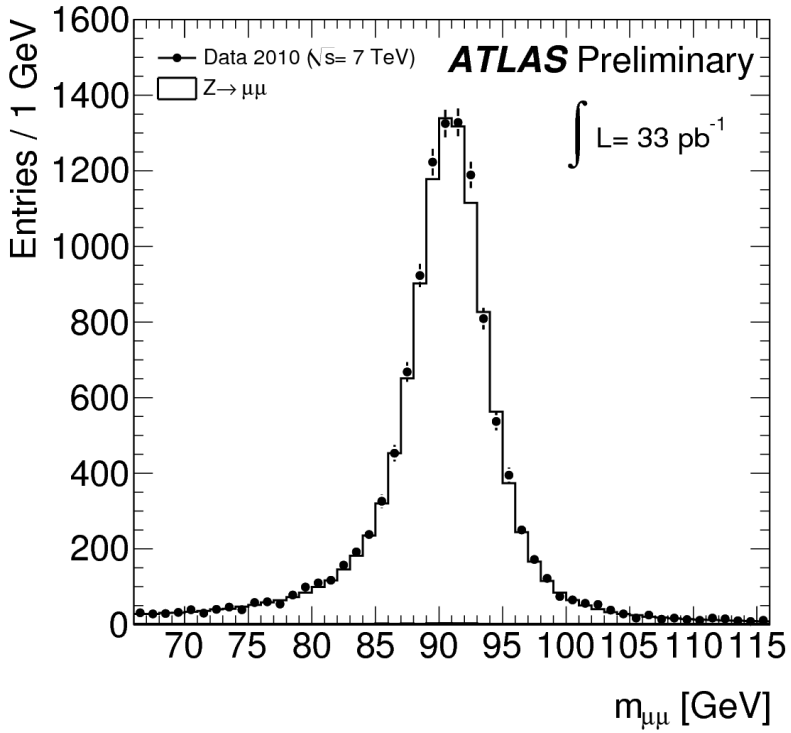




$Z \rightarrow \mu\mu$ data



smear



$Z \rightarrow ll$ cross section results

Cross section:

$$\sigma\ (pb) = \frac{N_{\text{cand}} - N_{\text{background}}}{(A_Z \times C_Z) \times (\mathcal{L}(pb^{-1}))}$$

- A_Z x C_Z = fraction of signal expected to pass selection
- $\mathcal{L}$ = integrated luminosity

Dominant systematics:

- lepton ID & reco
- (not scale & resolution)

measured

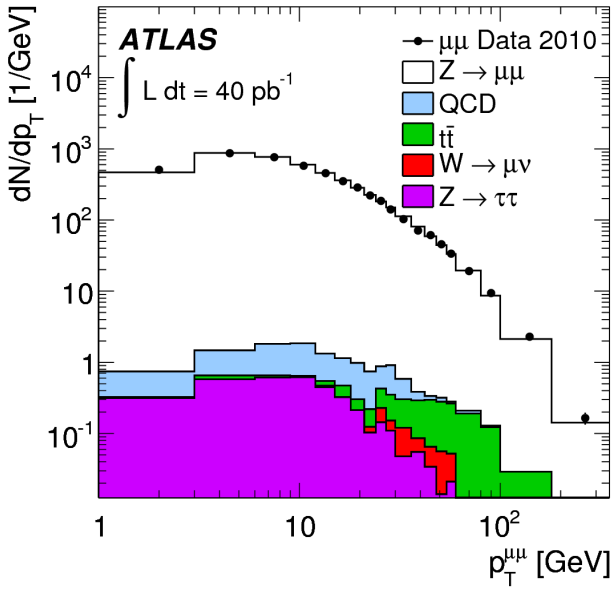
	$\sigma^{\text{tot}}_{Z/\gamma^*} \cdot \text{BR}(Z/\gamma^* \rightarrow \ell\ell)$ [nb], $66 < m_{ee} < 116$ GeV
Z/γ^*	$0.945 \pm 0.006(\text{sta}) \pm 0.011(\text{sys}) \pm 0.032(\text{lum}) \pm 0.038(\text{acc})$

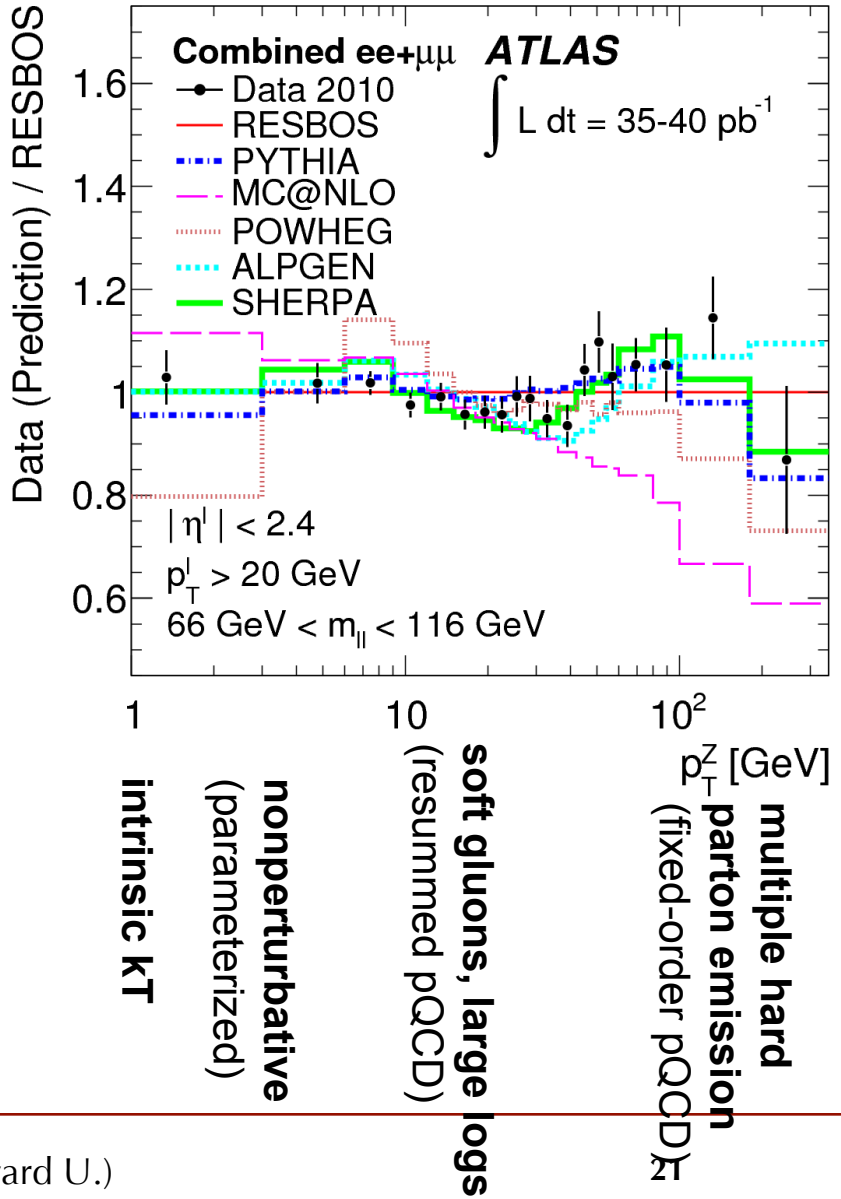
predicted: 0.964 ± 0.018 nb

$Z\ p_T$

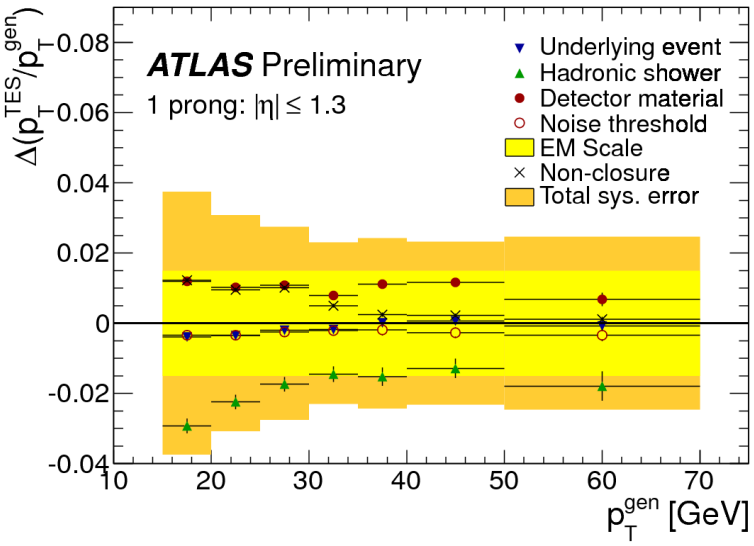
- $p_T^Z = 0$ (zero) at LO in QCD
- physics driving p_T^Z changes qualitatively with p_T^Z
- Notoriously difficult to calculate
- Measure it!

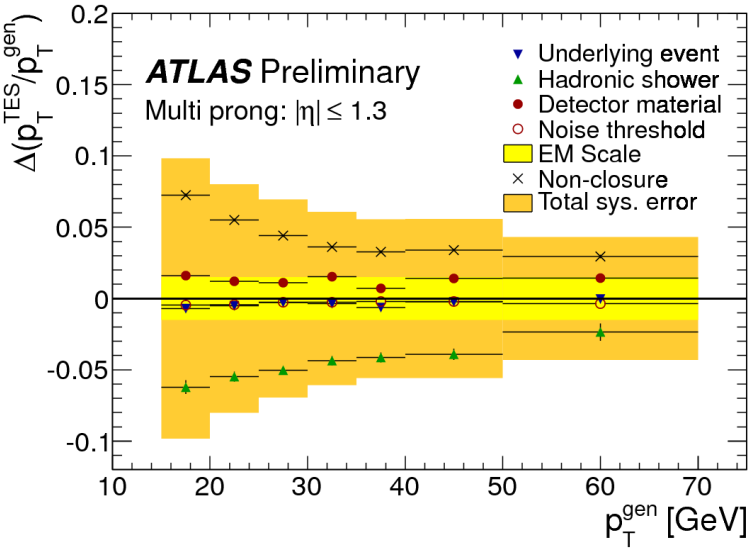
→ *dilepton p_T*

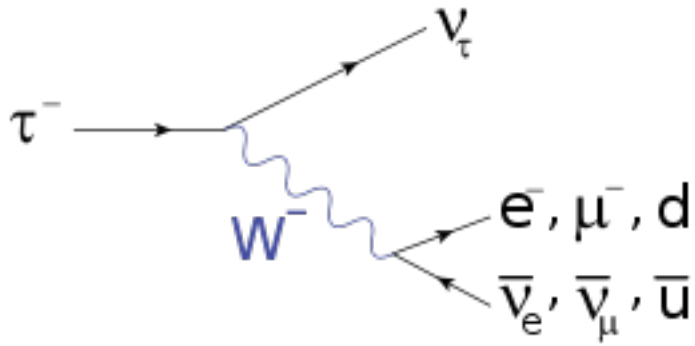




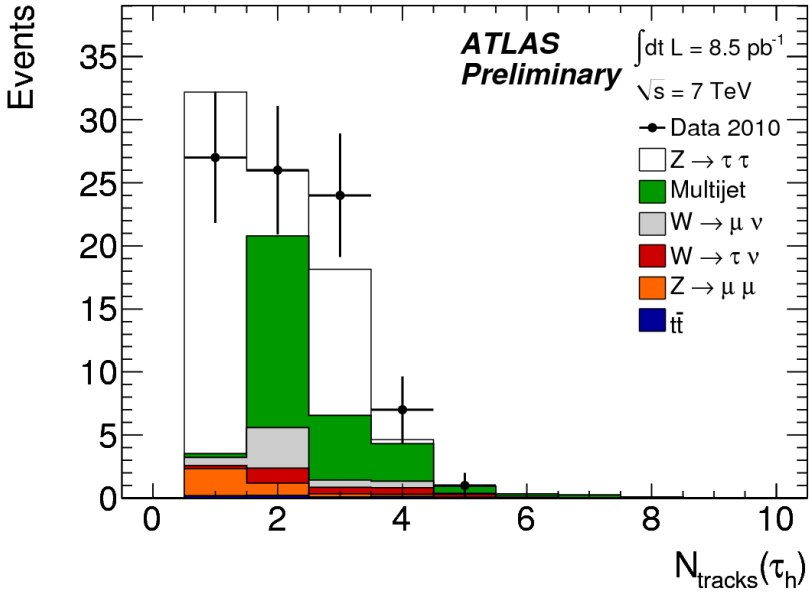
Taus in ATLAS







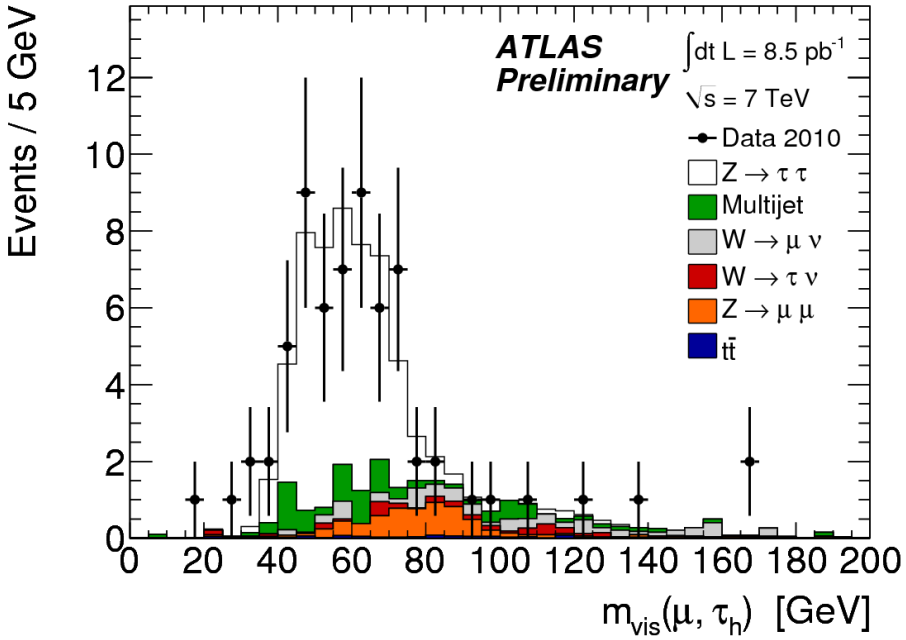
hadronic signature: **narrow jet with 1 or 3 tracks**
efficiency ~50-60%

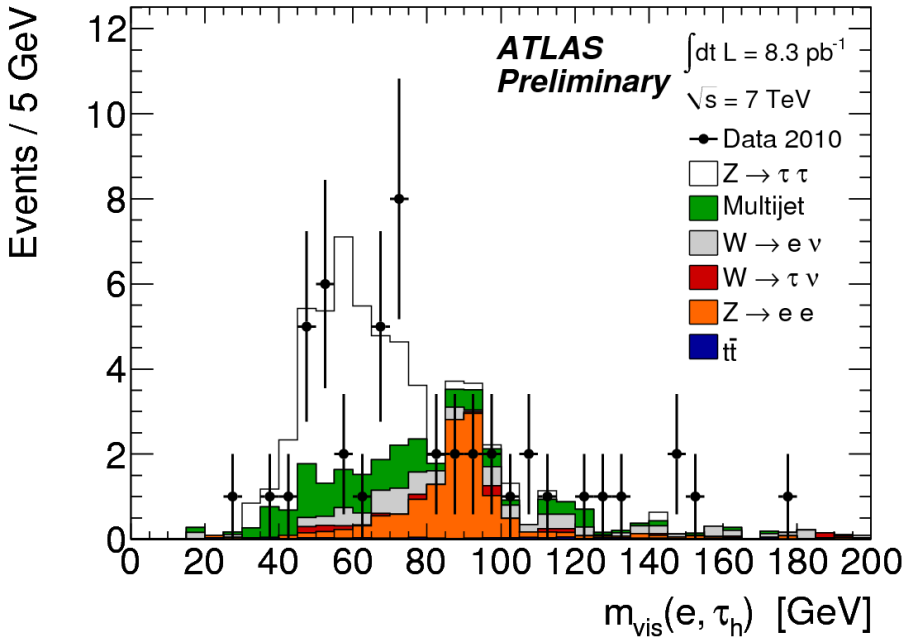


$Z \rightarrow \tau\tau$ observation

muon channel
expect 39.9 ± 1.8(stat.) ± 6.7(syst.)
observe 41.1 ± 7.1(stat.) ± 2.1(bkg. est.)

electron channel
expect 24.5 ± 1.4(stat.) ± 7.9(syst.)
observe 17.2 ± 5.4(stat.) ± 1.7(bkg. est.)

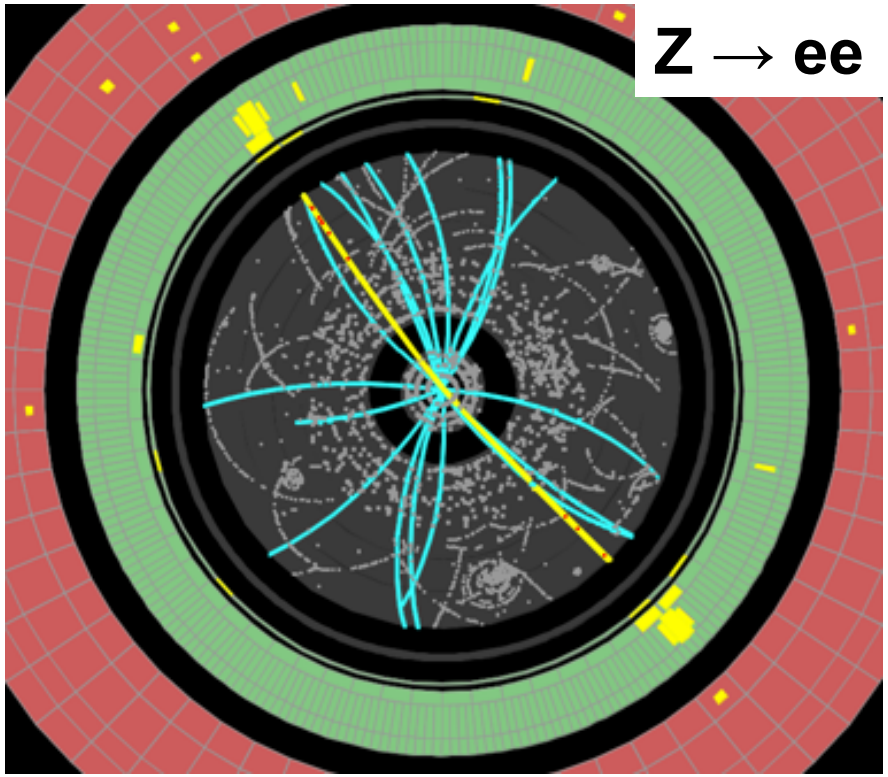


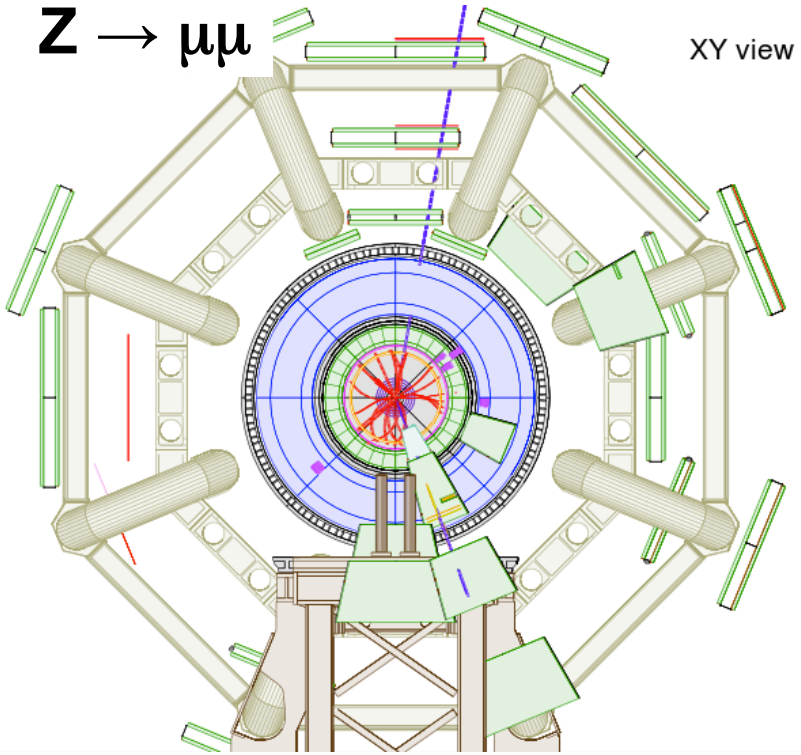


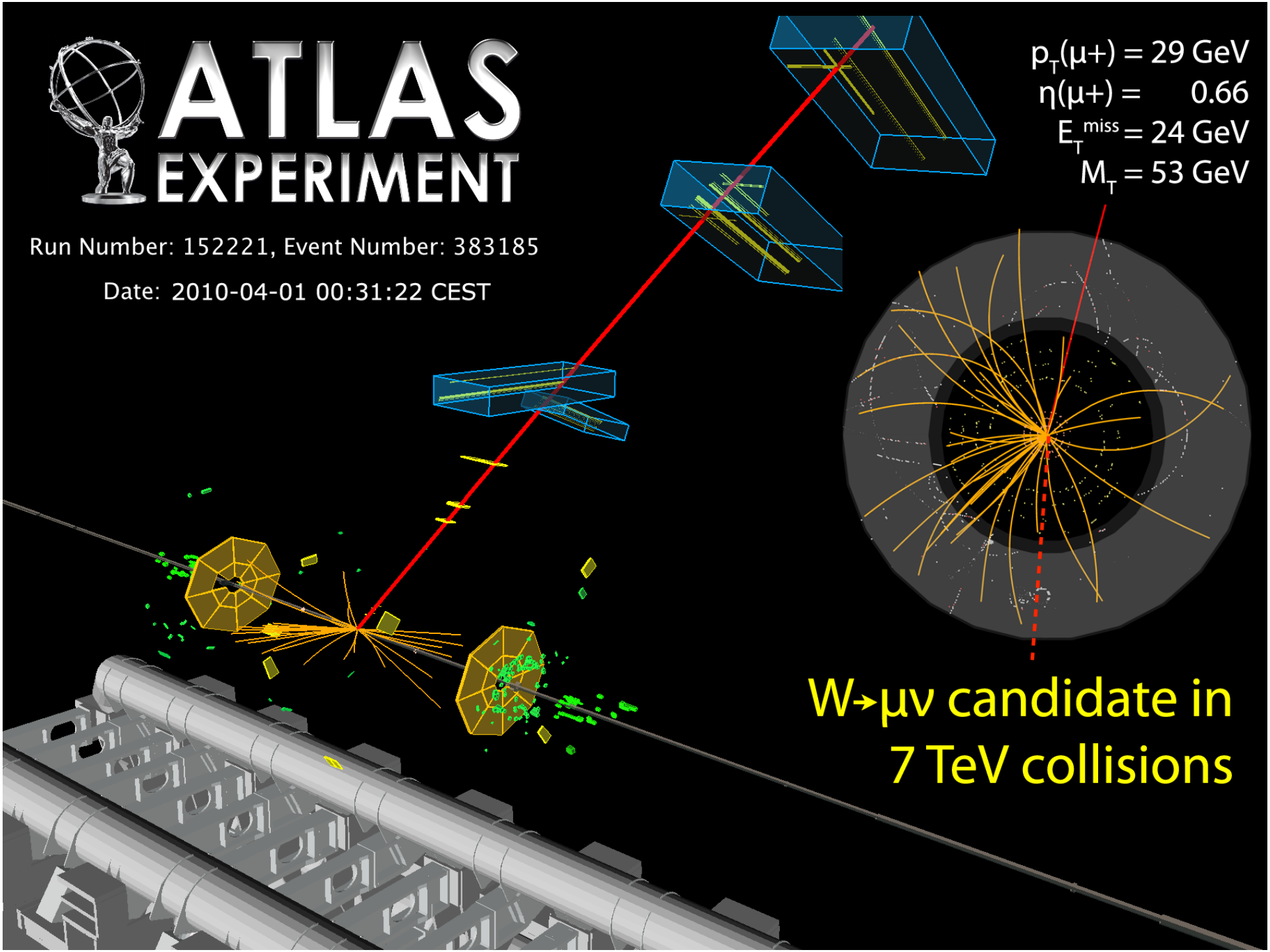
visible mass m_{vis} = invariant mass of tau "jet" and electron or muon

Experimental Calibrations w/ Z

- Unfortunately named but ubiquitous "tag+probe" method
- Great signal/background ratio allows partial ID on second lepton

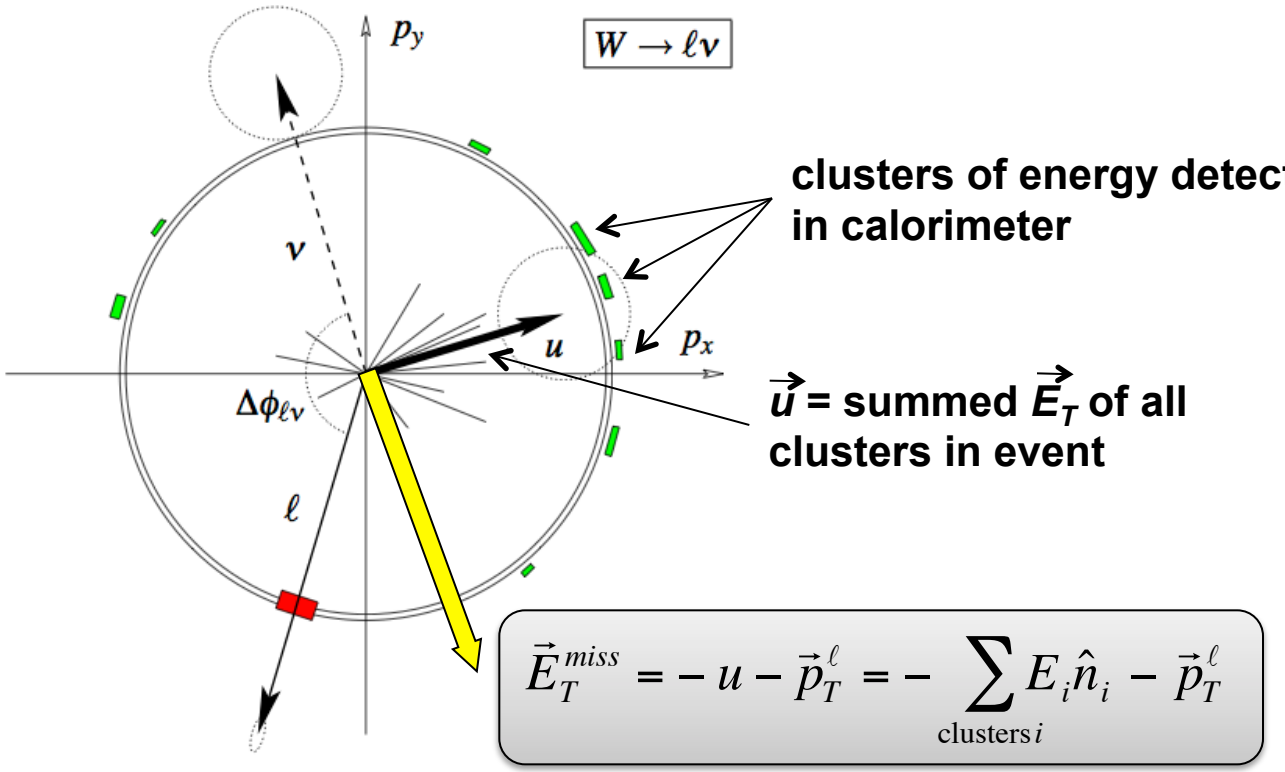





ATLAS
EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV
W→μν candidate in
7 TeV collisions

Missing Transverse Energy

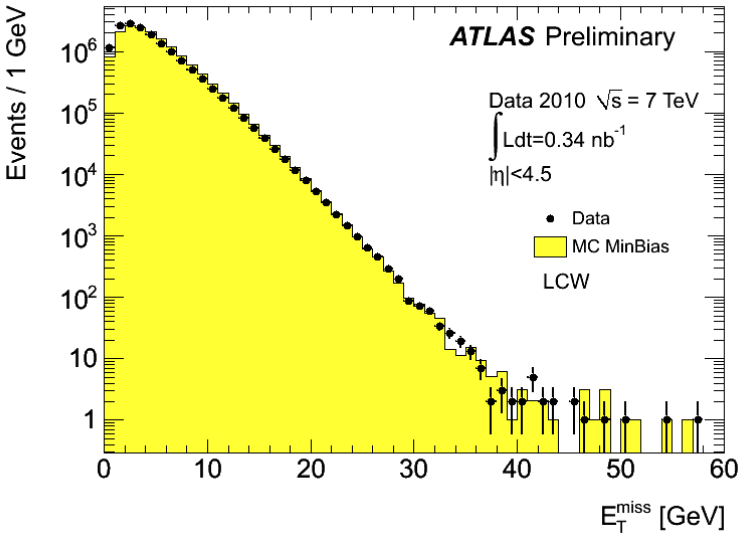
Detect neutrino (or other weakly interacting neutral) by invoking conservation of momentum in the plane transverse to the beam

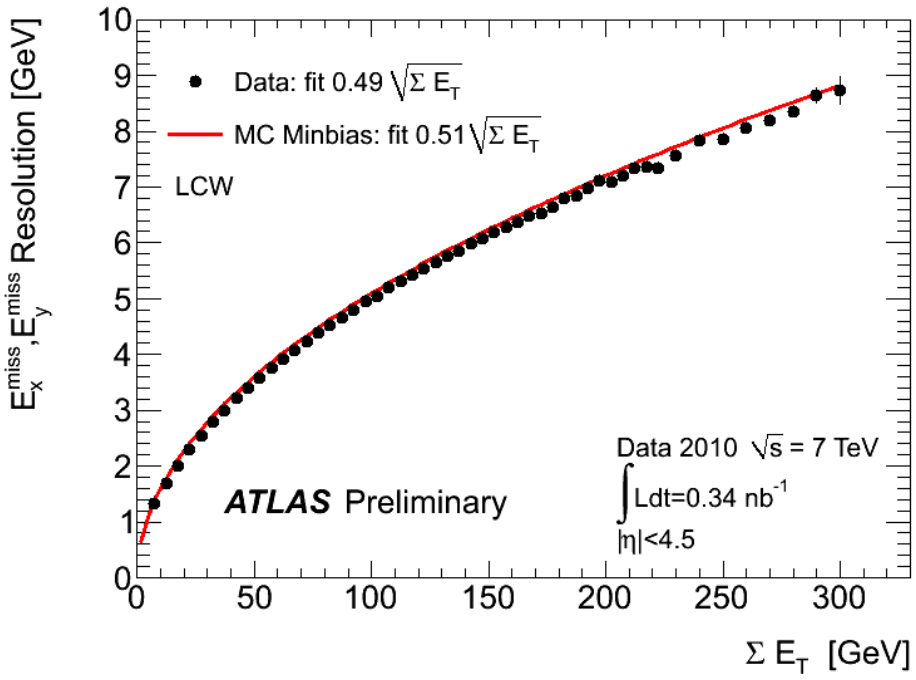


E_T^{miss} Performance – first data

- All calo clusters treated equally
- Calibrate with minimum bias events
- SumET = 100 GeV ⇒ σ = 5 GeV
- SumET = 1600 GeV ⇒ σ = 20 GeV

$$\sigma_{E_T^{miss}} = \alpha\sqrt{\sum E_T}$$

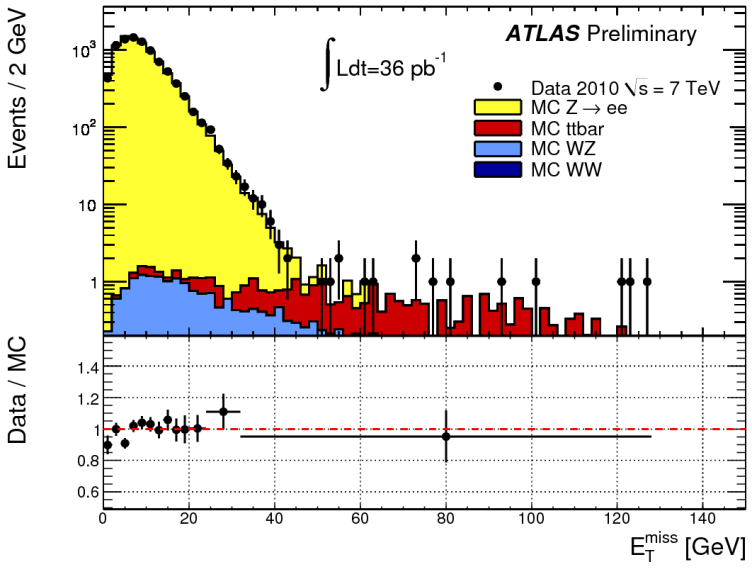


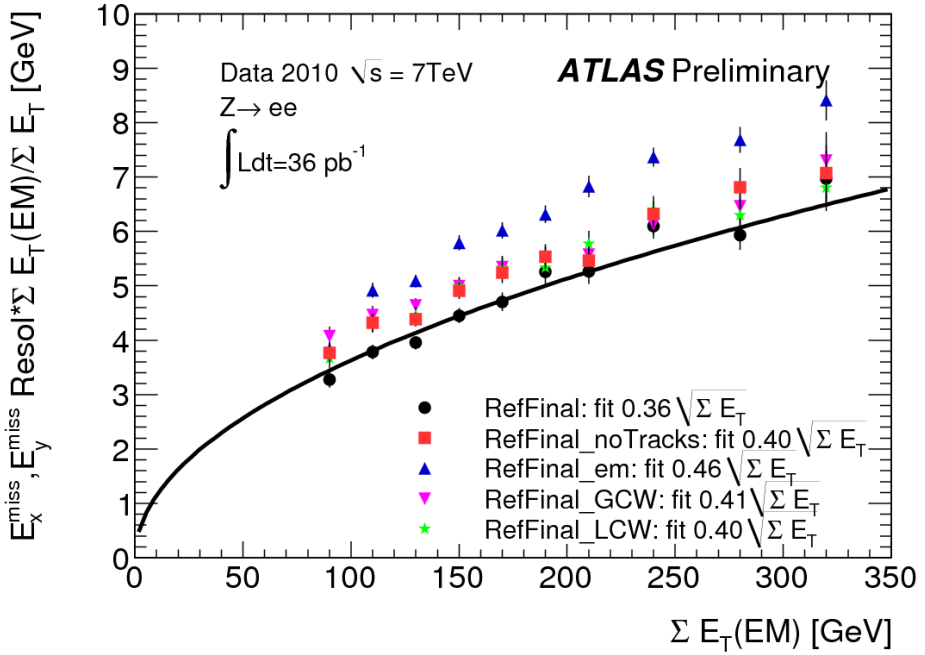


E_T^{miss} Performance – Z

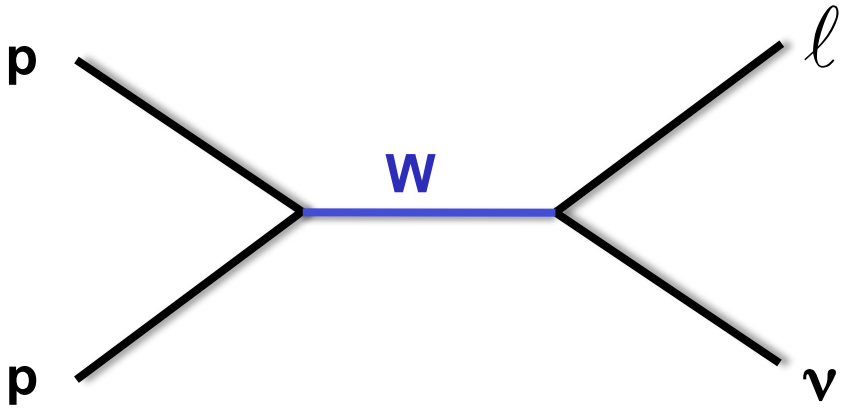
- Associate calo. cells with particular objects (jet, electron) and calibrate to best knowledge
- Calibrate with Z events (no ν)
- SumET = 100 GeV ⇒ σ = 3.6 GeV
- SumET = 1600 GeV ⇒ σ = 14 GeV

$$\sigma_{E_T^{miss}} = \alpha\sqrt{\sum E_T}$$





W Selection & Cross Section



→ Electron or muon
E_T (p_T) > 20

→ Missing E_T > 25

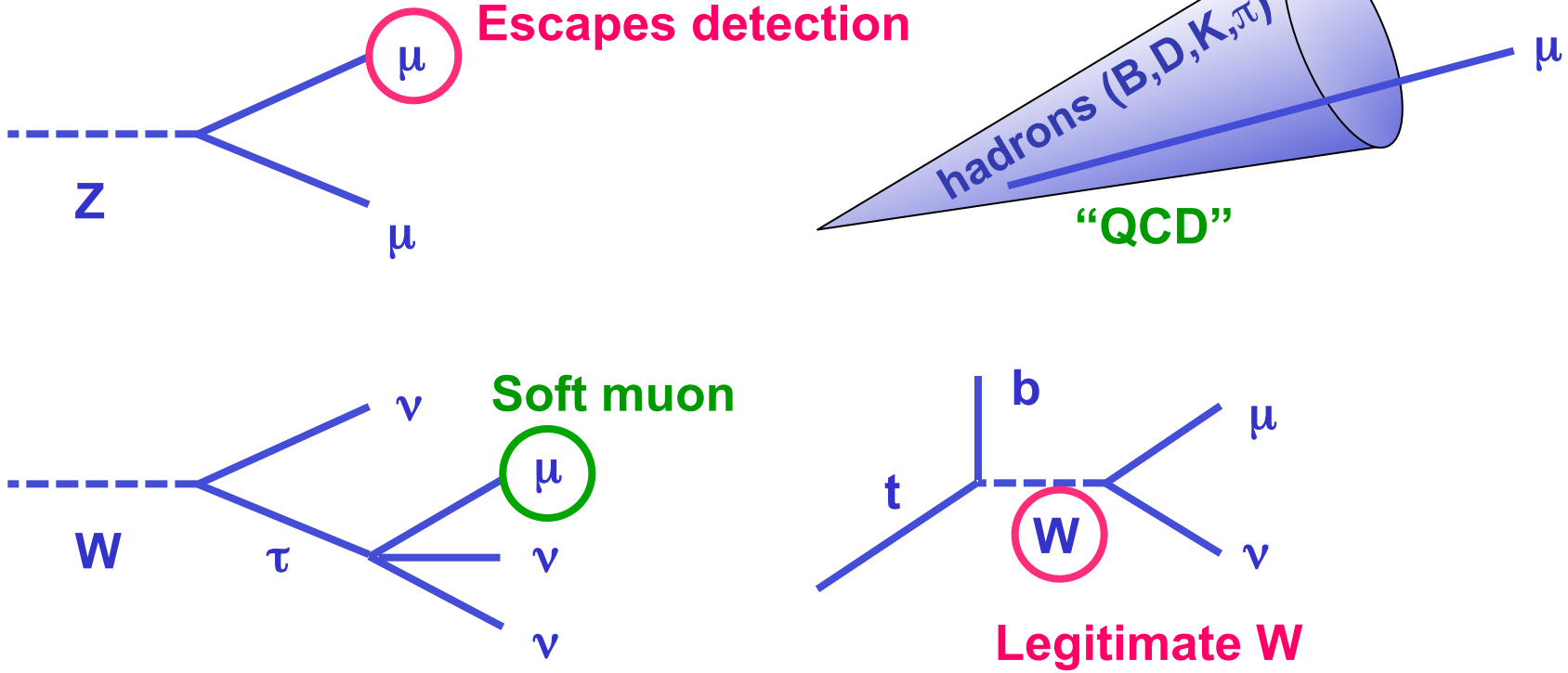
Cross section:

$$\sigma\ (pb) = \frac{N_{\text{cand}} - N_{\text{background}}}{(A_W \times C_W) \times (\mathcal{L}(pb^{-1}))}$$

- A_W x C_W = fraction of signal expected to pass selection
- $\mathcal{L}$ = integrated luminosity

Backgrounds to W

- Looks like signal, but is not!

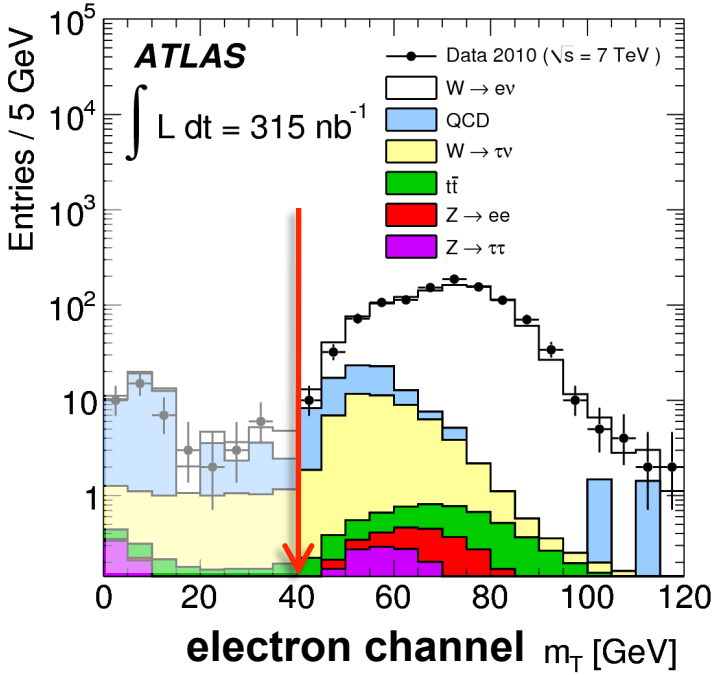


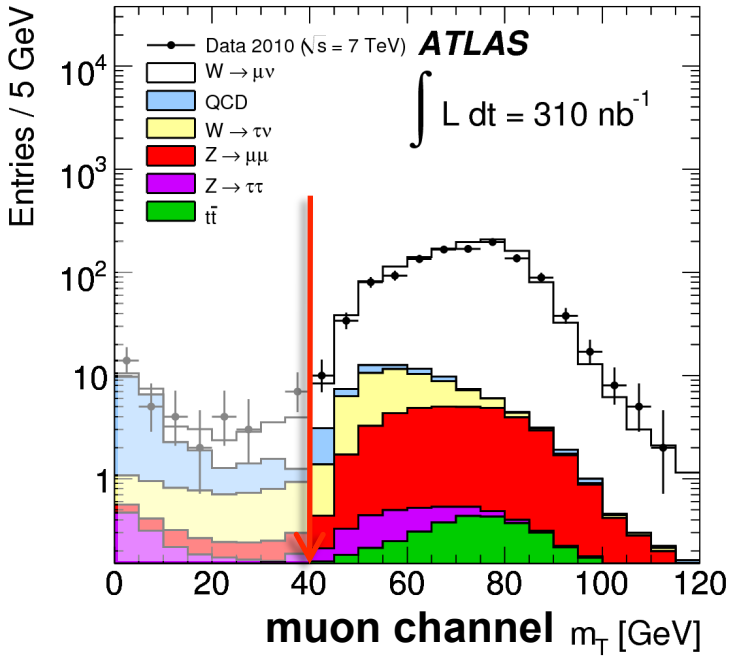
- Estimate using data and simulation
- In the end, 10% or less of candidate sample

$$\sigma = \frac{N_{\text{cand}} - N_{\text{background}}}{A_W \times C_W \times \int \mathcal{L}\, dt}$$

The W Candidate Sample

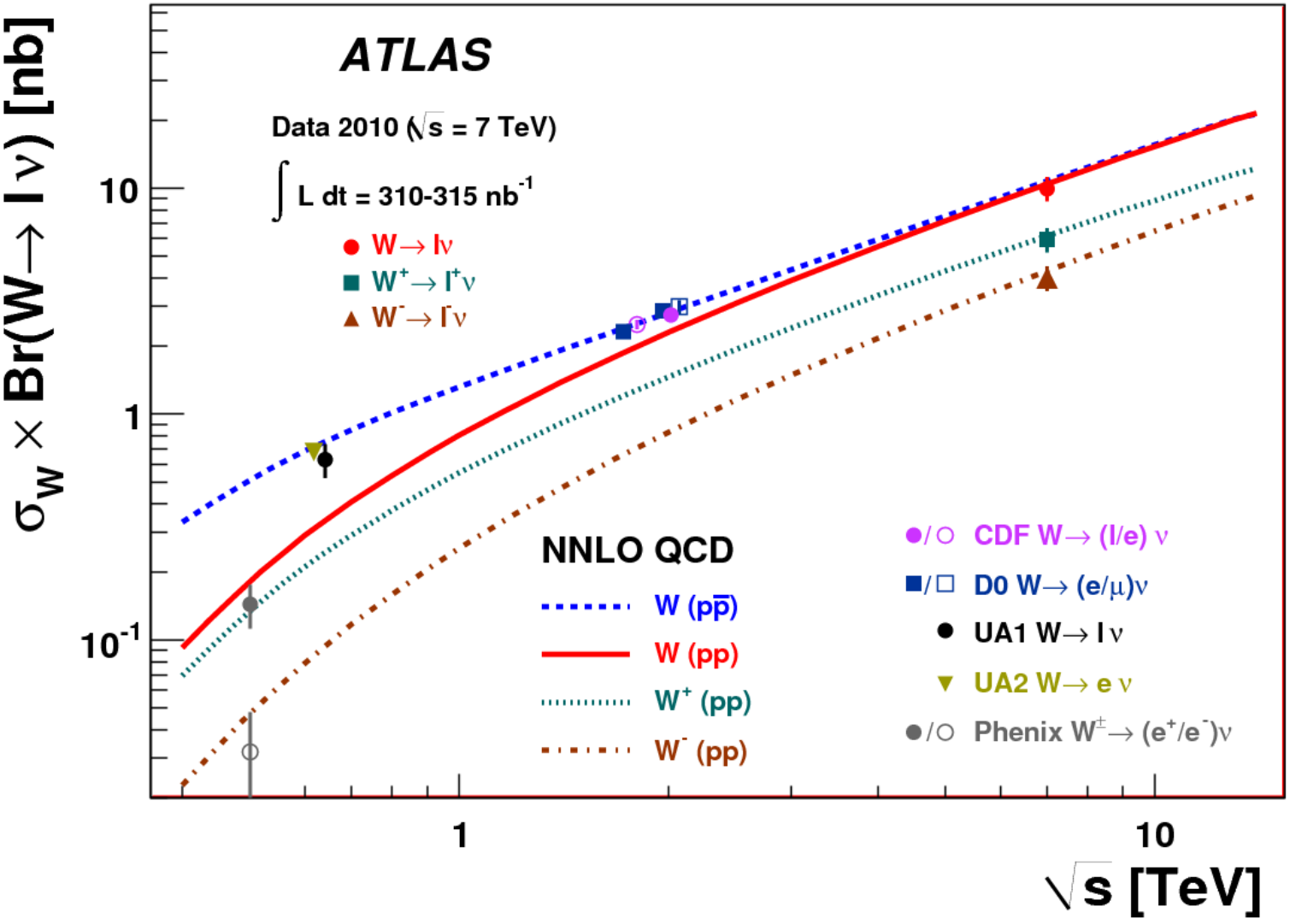
- Transverse mass $M_T = \sqrt{2(p_T^{\mu})(E_T^{\text{miss}})(1-\cos(\varphi^{\mu} - \varphi^{E_T^{\text{miss}}}))}$
- Clean up sample with **M_T > 40 GeV**





Yield: **1069** candidates **1181** candidates $\sigma = \dfrac{N_{\text{cand}} - N_{\text{background}}}{A_W \times C_W \times \int \mathcal{L}\, dt}$

W Cross Section in Context



W cross section results (2010 final)

measured

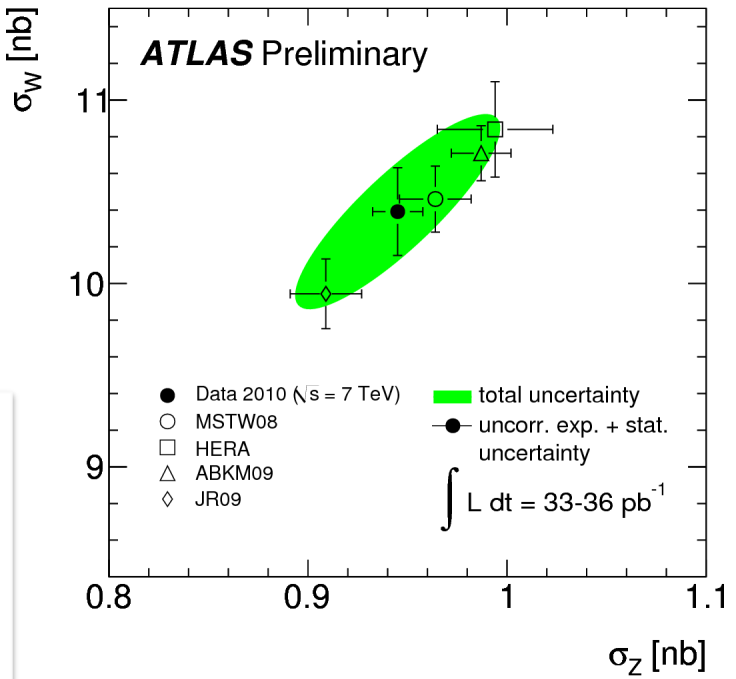
	$\sigma^{tot}_{W^{(\pm)}} \cdot BR(W \to \ell\nu)$ [nb]
W^+	$6.257 \pm 0.017(sta) \pm 0.152(sys) \pm 0.213(lum) \pm 0.188(acc)$
W^-	$4.149 \pm 0.014(sta) \pm 0.102(sys) \pm 0.141(lum) \pm 0.124(acc)$
W	$10.391 \pm 0.022(sta) \pm 0.238(sys) \pm 0.353(lum) \pm 0.312(acc)$

predicted

	MSTW08
W^+	6.16 ± 0.11
W^-	4.30 ± 0.08
W	10.46 ± 0.18

Leading systematics:

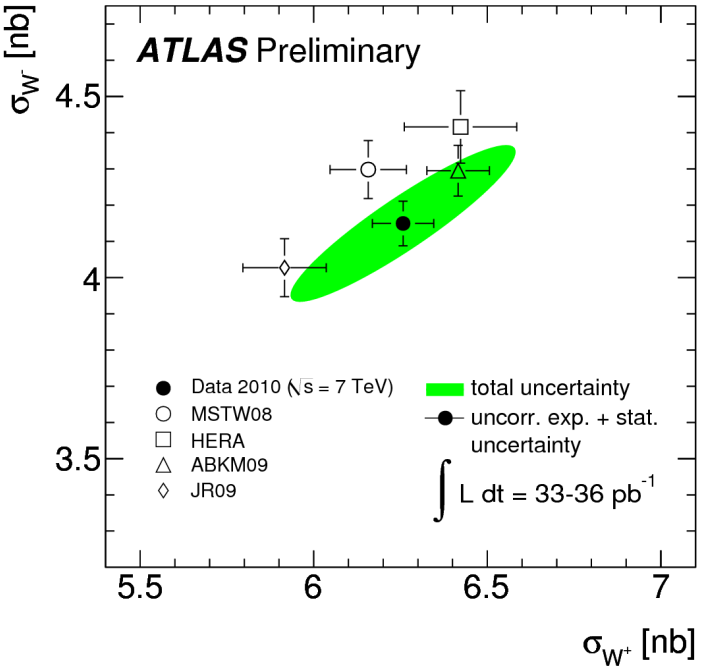
- E_T^{miss} resolution & scale
- Lepton trigger efficiency
- Integrated luminosity



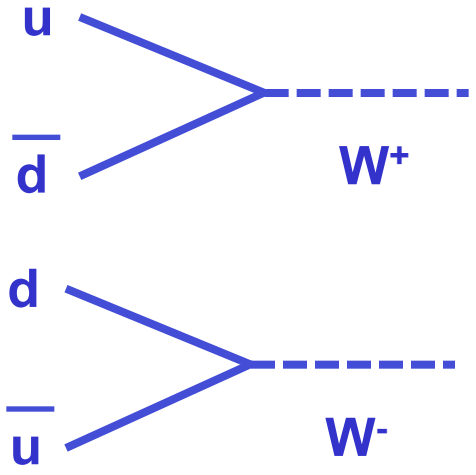
Deeper look at W production

Actually colliding the partons within the protons

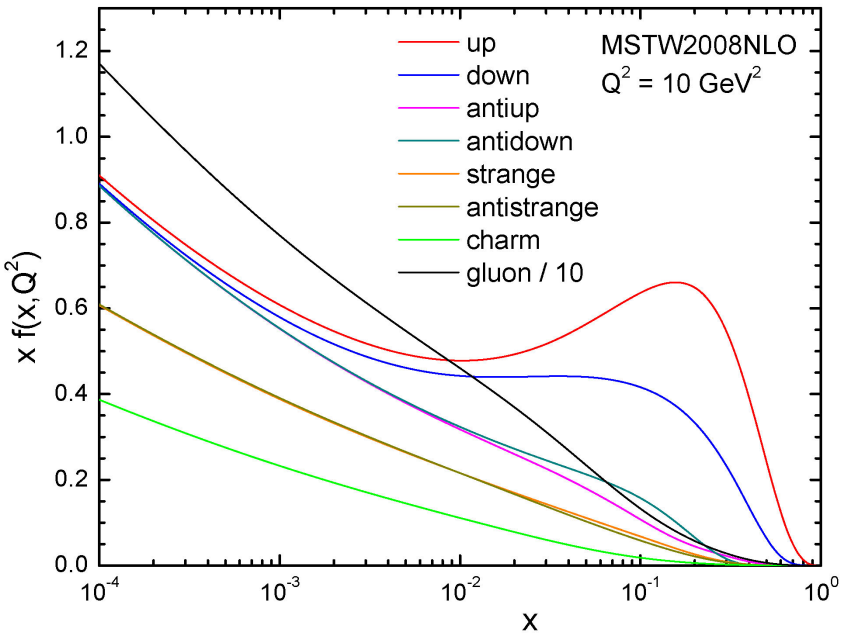
$$\sigma_{\mathrm{W}} = \sum_{q} \int dx_1 dx_2 f_q(x_1) f_{\overline{q'}}(x_2) \times \sigma_{q\overline{q'}}$$

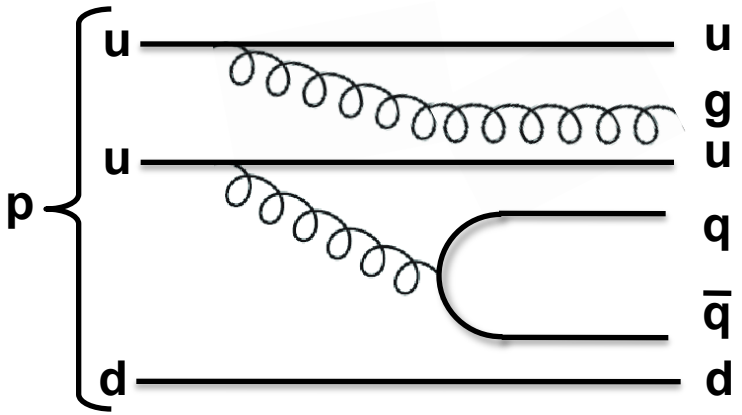


Leading diagrams for inclusive W:



Parton Distribution Functions (PDFs)





- ***x*** = fraction of proton momentum carried by a ***parton***
- ***parton*** = up, down, gluon, antiquarks, strange, charm, bottom…
- In the proton, up and down are ***valence*** quarks, and everything else is the ***sea***
- High momentum = small scale

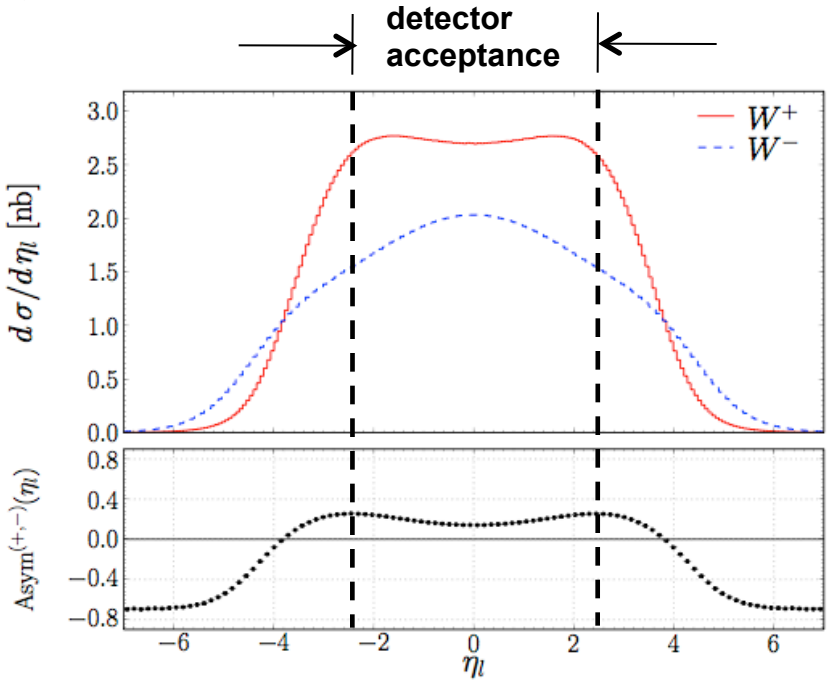
W^+-W^- Charge Asymmetry

- Twice as much up as down → W^+ favored
- up quark carries more momentum on average → W+ production boosted forward
- Measure asymmetry as a function of lepton angle

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

- Many uncertainties cancel

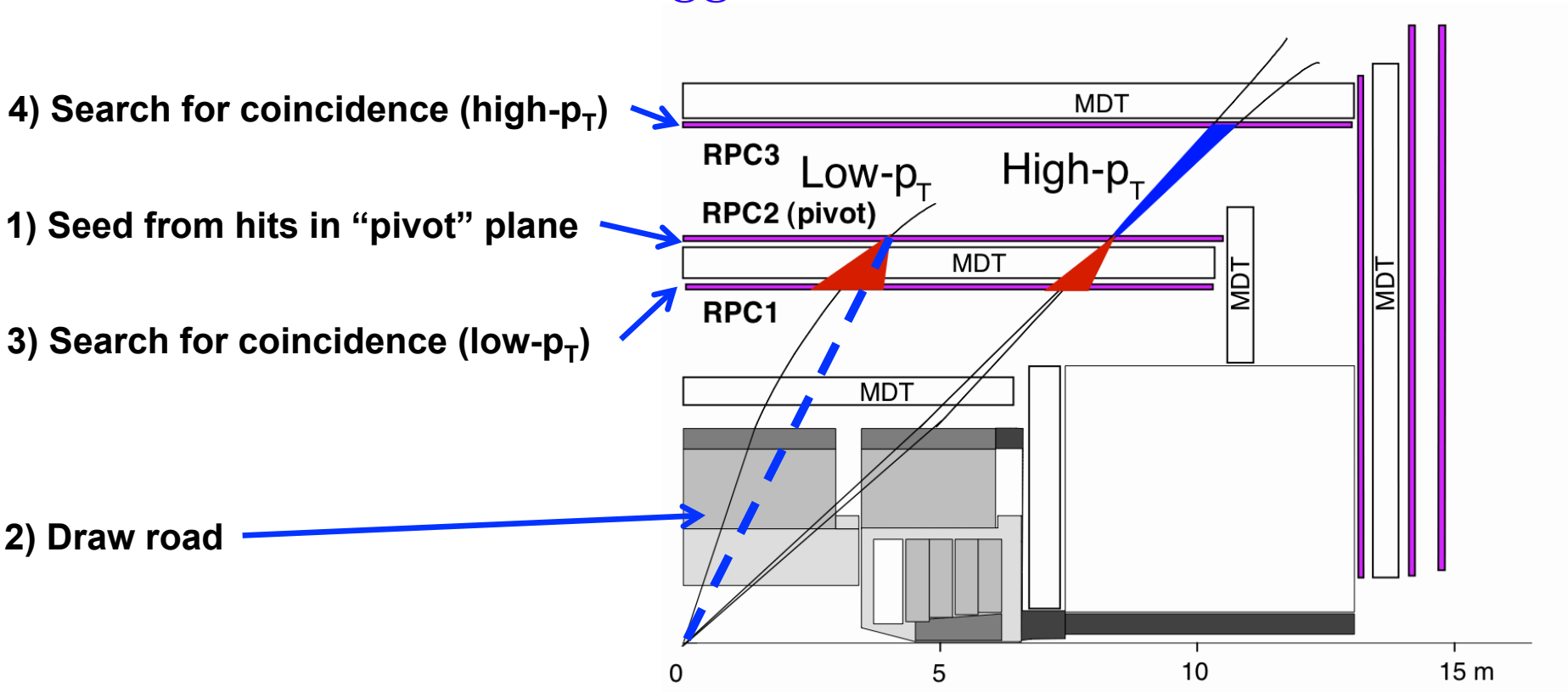
$$A = \frac{\sigma^{\ell^+} - \sigma^{\ell^-}}{\sigma^{\ell^+} + \sigma^{\ell^-}}$$



F. Fayette et al., Eur. Phys. J. C63 (2009) 33

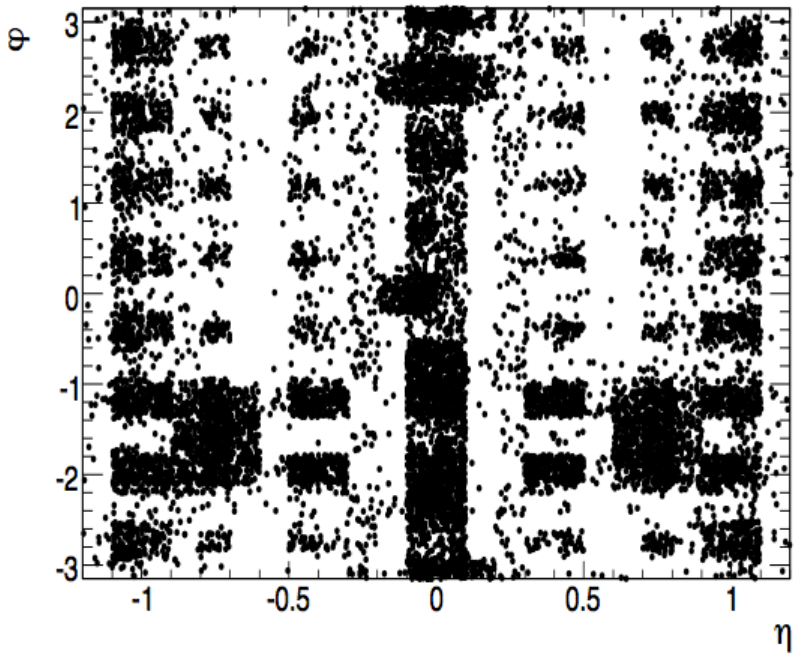
Muon Performance: Trigger

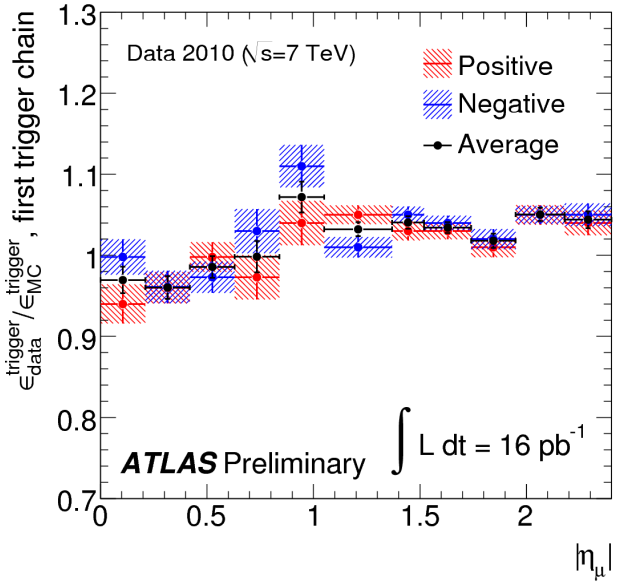
The Level 1 Muon Trigger

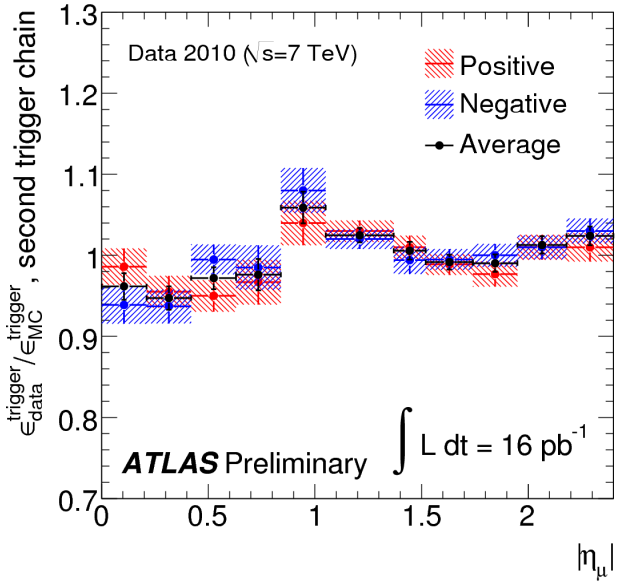


Muon Performance: Trigger

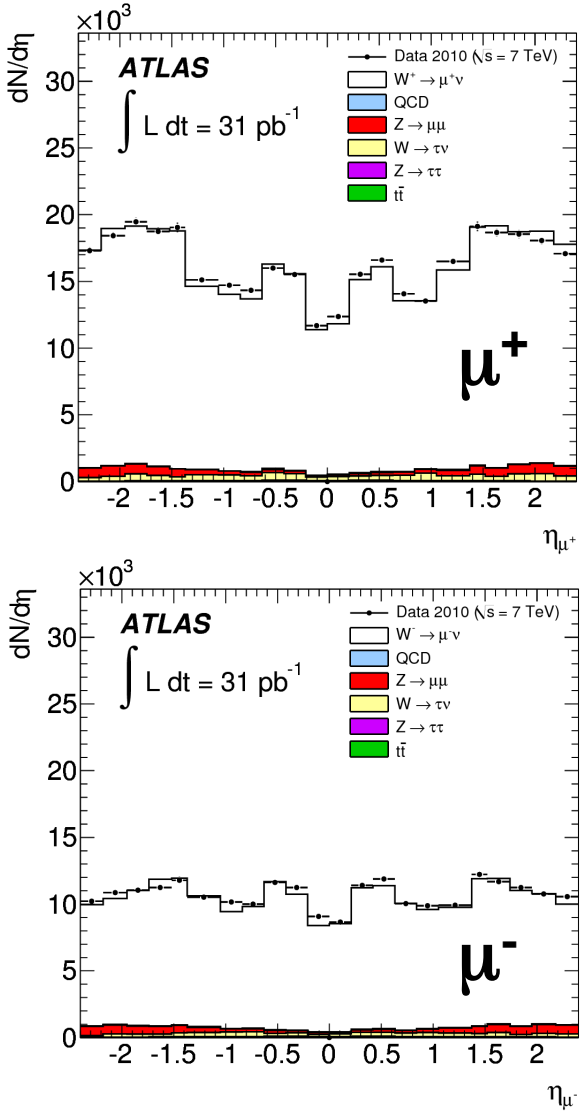
Holes in Barrel Trigger Acceptance

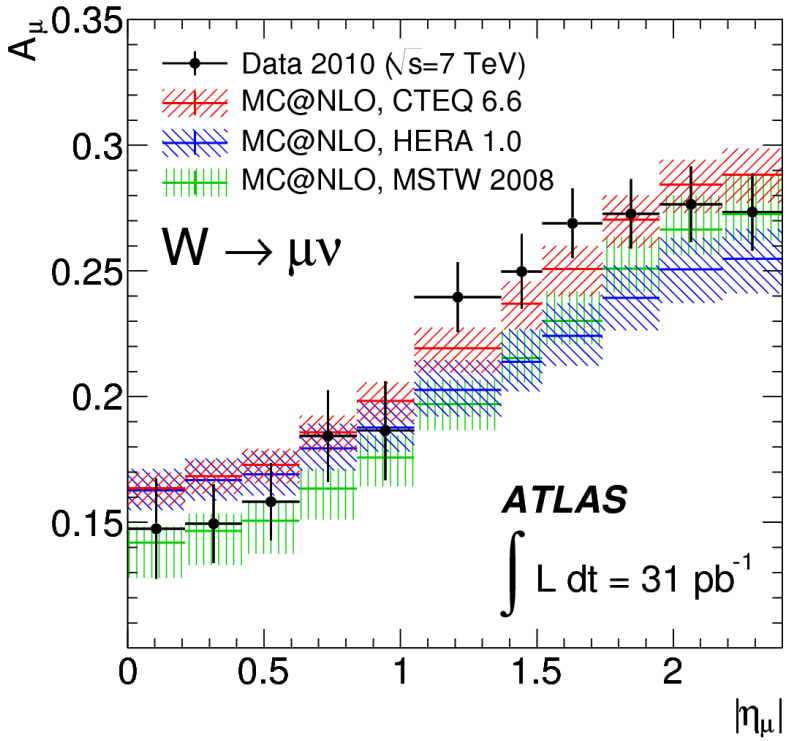






W Asymmetry Results





Test PDF models:

χ^2/dof =

CTEQ6.6: **9.16/11**

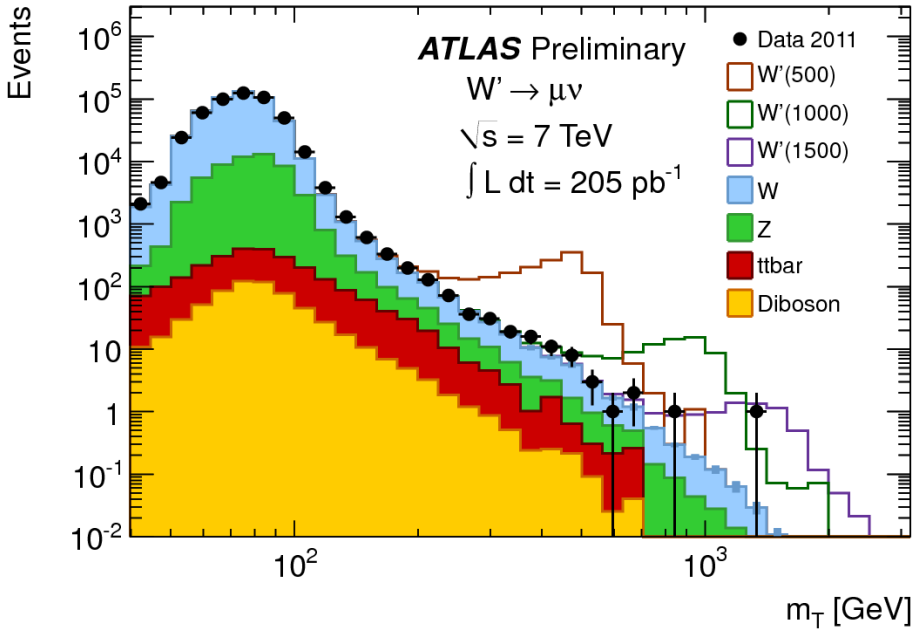
HERA 1.0: **35.81/11**

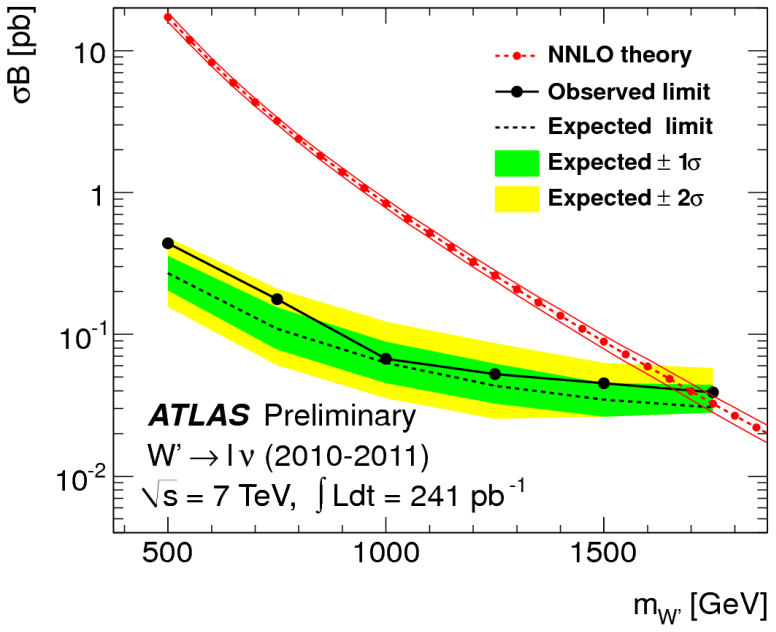
MSTW2008: **27.31/11**

$$A = \frac{\sigma^{\ell^+} - \sigma^{\ell^-}}{\sigma^{\ell^+} + \sigma^{\ell^-}}$$

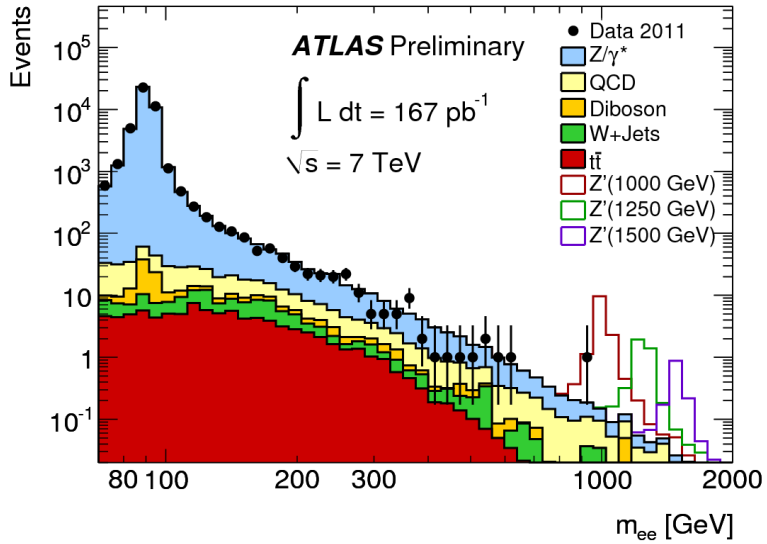
W′ and Z′ searches

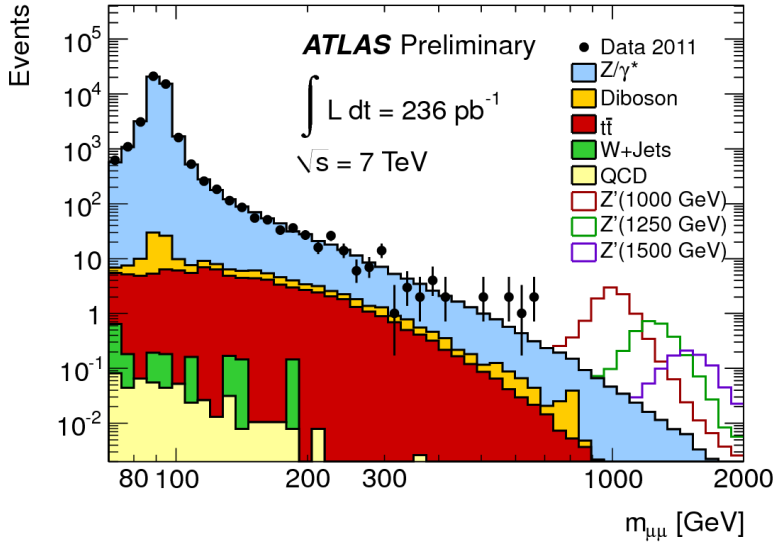
- Experimental appeal: simple extension of W and Z measurements
- Physics appeal: actually appears in many models
- **W′ with 2011 data:**
  - → ***exclude Sequential Standard Model $M_{W'} < 1.7$ TeV at 95% CL***
  - → *(combined limit from 2010+2011 data)*



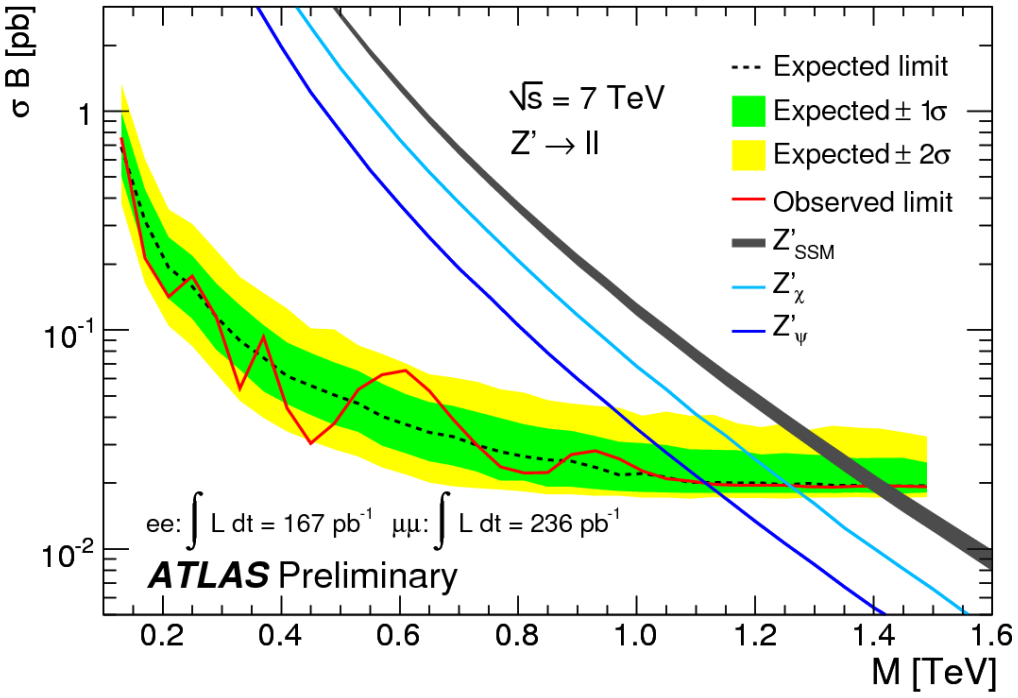


W′ and Z′ searches





- **Exclude Sequential Standard Model $M_{Z'} < 1.4$ TeV at 95% CL**
- Sensitive to any narrow neutral state
  - → *E6 new bosons (below), RS spin-2 graviton, spin-1 technimeson*



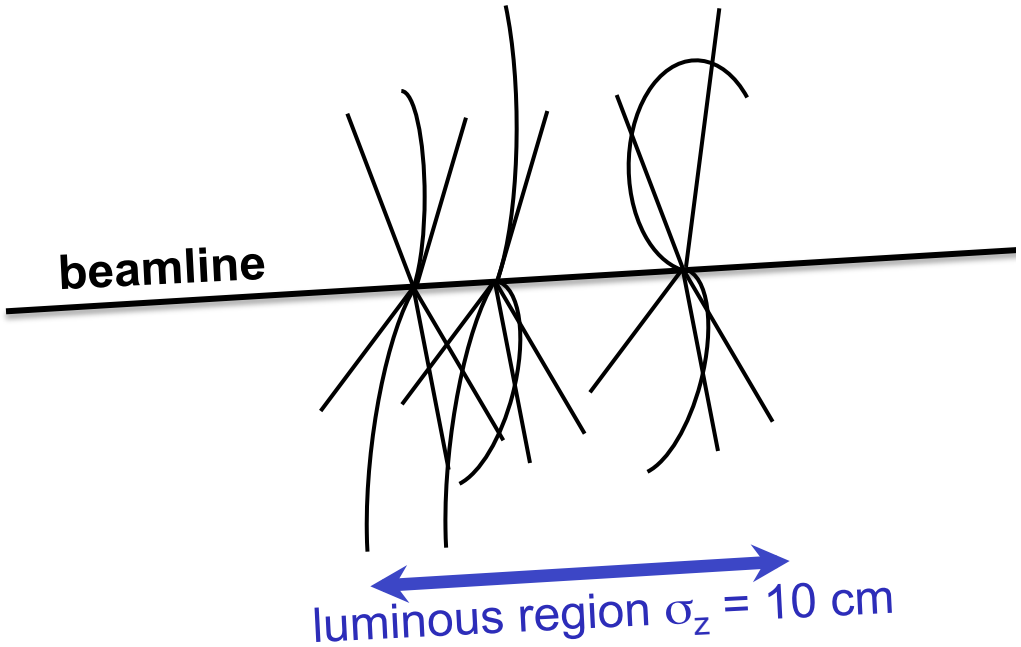
Intermission

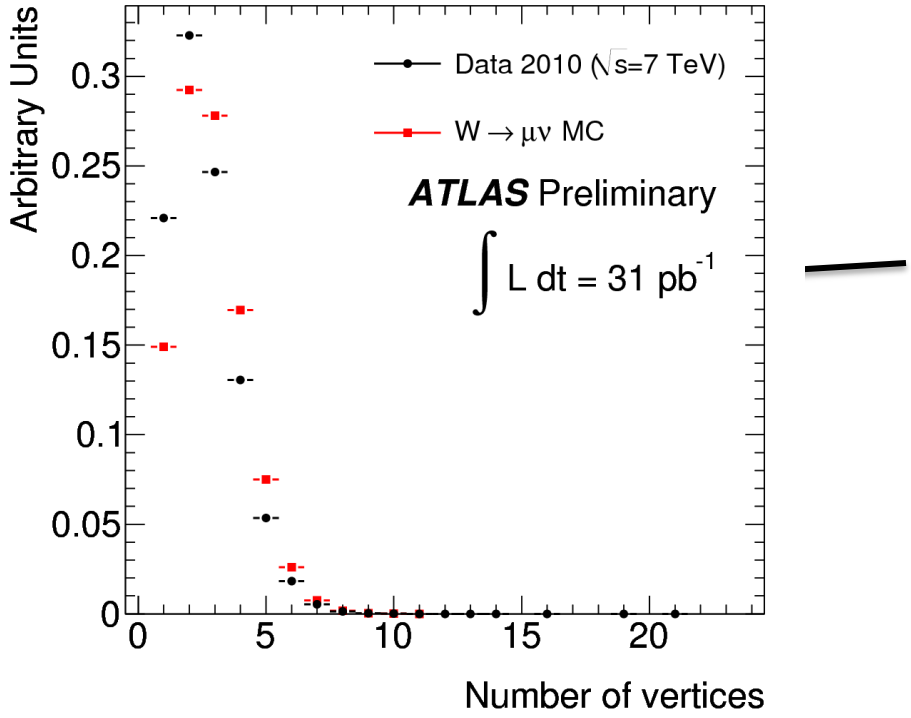
- Leptonic signatures
  - → *Flag presence of W or Z boson*
    - electroweak interaction, EWSB?
  - → *Efficient triggering and good S/B*
    - good for precision tests of QCD
- Tomorrow:
  1. *Continue with dibosons*
  2. *photons, gluons, and quarks*

Backup

Pileup

- Multiple interactions per bunch crossing
- Count primary vertices as a proxy for counting interactions
  - → *2.2 vertices / bunch crossing (avg) for 2010 data*
- Significant improvement in modeling of E_T^{miss}





LHC design parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

From http://cdsmedia.cern.ch/img/CERN-Brochure-2009-003-Eng.pdf

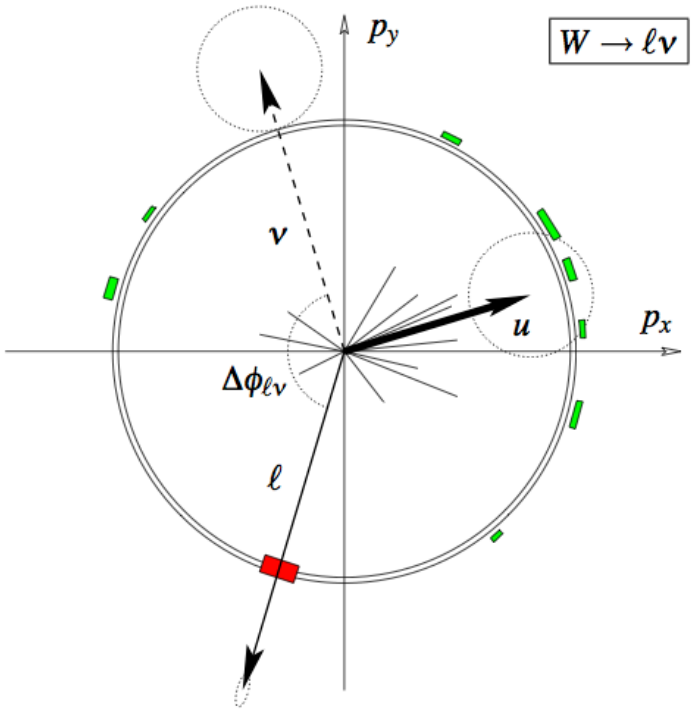
The Atlas Detector, in Numbers

- Tracker: precision tracking to $|\eta| = 2.5$
  - → *3d spacepoints from semiconductor tracking: 3 pixel layers, SCT is 4 double-layers (SAS)*
  - → *TRT is 4 mm diameter straw tubes (Xenon), providing 36 additional R-φ (or z-φ) points*
- Calorimetry
  - → *LAr barrel from 1.5 < R < 2m, 22 X_0 deep*
  - → *10 λ (interaction lengths) active, >11 total*
  - → *HCAL from 2.3 < R < 4.3 m, 7.4λ by itself*
  - → *total coverage to almost $|\eta| = 5$*
- Magnets
  - → *Solenoid field 2T*
  - → *Toroid field bending power 1 < $\int B \cdot dl$ < 7.5 T· m*
- Muons
  - → *Three MDT planes measure R-z using 3mm diameter tubes (Ar/CO_2)*
    - Nominal single-hit precision 80 μm
  - → *Forward precision by CSC (MWPC strip-wire-strip) 2 < $|\eta|$ < 2.7*
    - Designed to be functional at expected rates of > 150 Hz/cm^2
  - → *RPC and TGC: fast 2d spacepoints for triggering and second (phi) coordinate*

Fact Sheet

- 1 event ~ 1 MB ESD, 150 kB AOD
- 75 → 50 ns bunch spacing this spring
  - → *25 ns under discussion but unlikely for pp colliding beams before 2012*
- Current data volume is ~ 400 MBytes/hour
- We will keep the raw for 3~4 week (~ TBytes) and then delete them

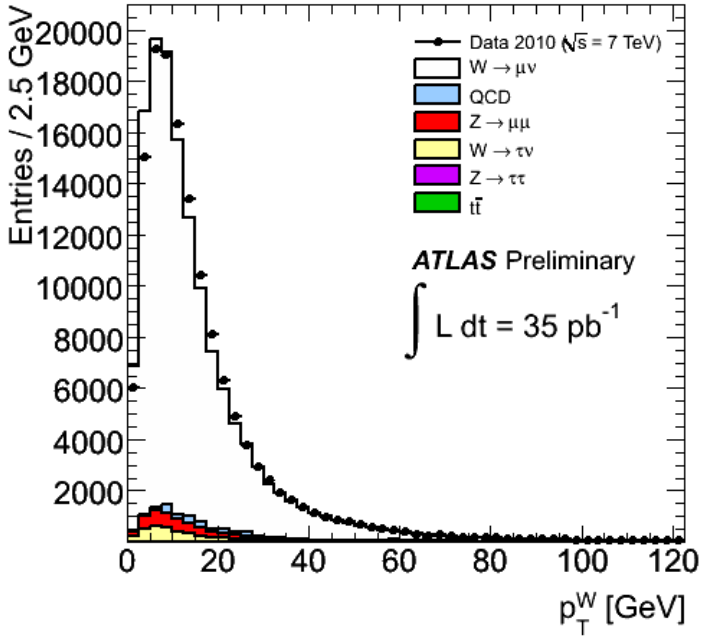
Next W Measurements: W p_T



- Measure via hadronic recoil
  - → *challenging to model*
- Test nonperturbative QCD calculations
- Calibration of neutrino momentum measurement (aka E_T^{miss})

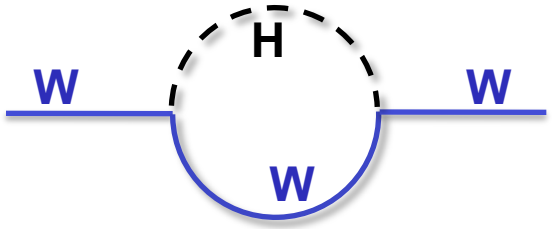
$$\vec{p}_T^{\,\nu} = \vec{E}_T^{\,\text{miss}} = -\vec{p}_T^{\,\ell} - \vec{u}$$

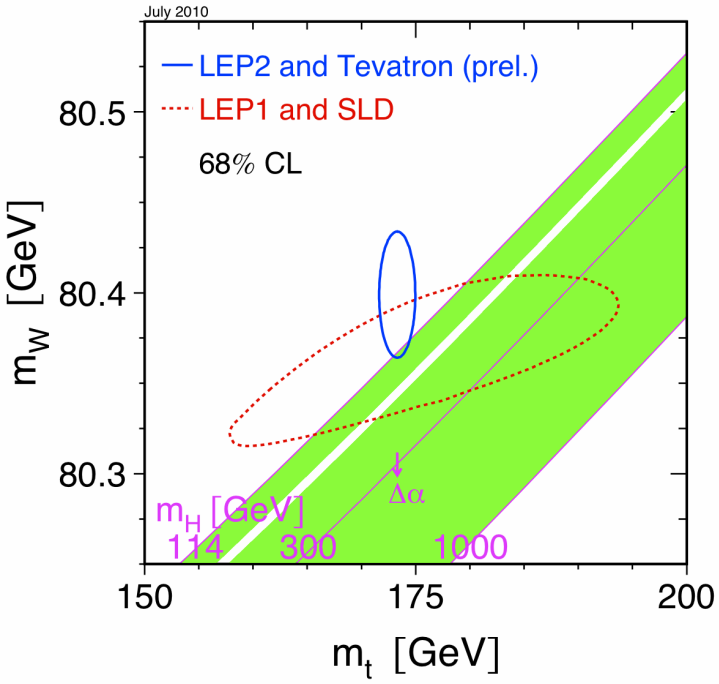
$$\vec{p}_T^{\,W} = \vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu} = \cancel{\vec{p}_T^{\,\ell} - \vec{p}_T^{\,\ell}} - \vec{u}$$

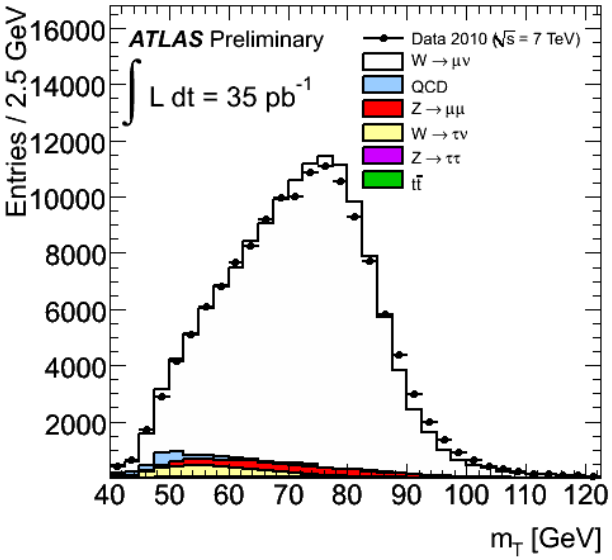


Next W measurements: W mass

- New particles influence via quantum loops
- Strong constraint on Higgs mass
- Heavy particle ⇒ strong coupling







- Measure via fit of p_T^l or M_T^W
- Current world avg M_W = 80 399 ± 23 MeV
- Projected ATLAS M_W precision 100 MeV (initial) → < 10 MeV (ultimate)