W Physics at ATLAS

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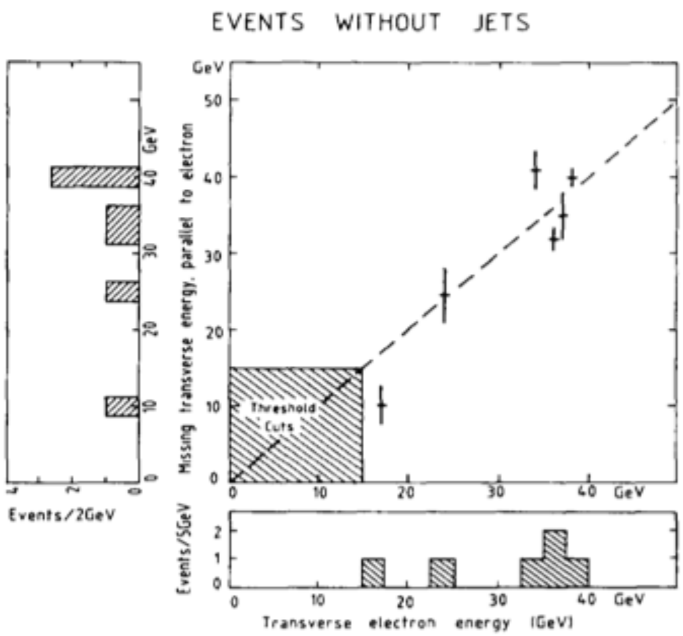
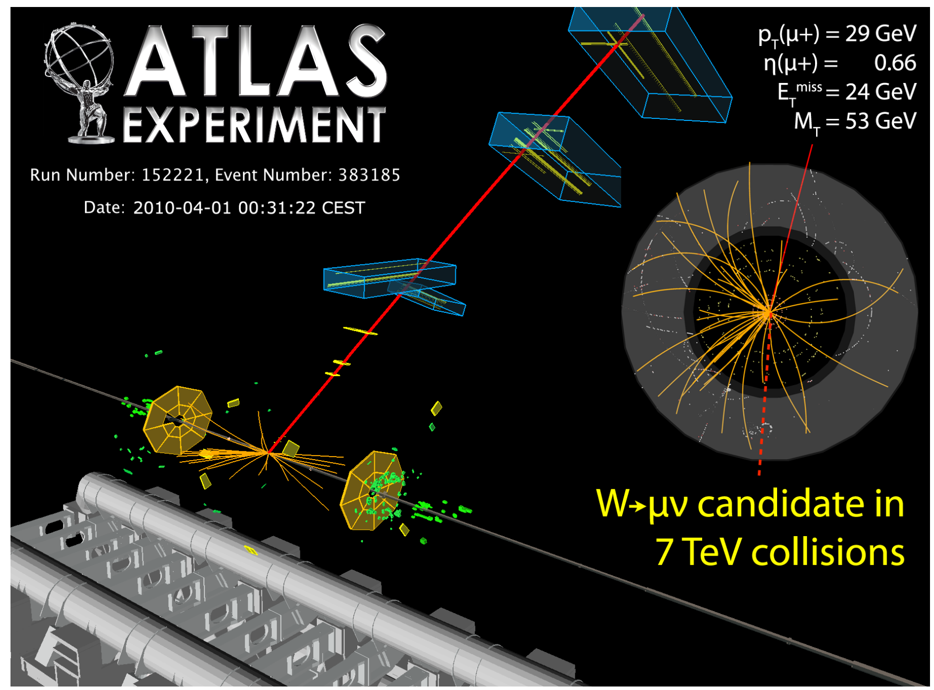
A Familiar Particle in a New Setting



- **W → lν at CERN in 1982**
  - → *Observation (with Z) establishes the Standard Model*

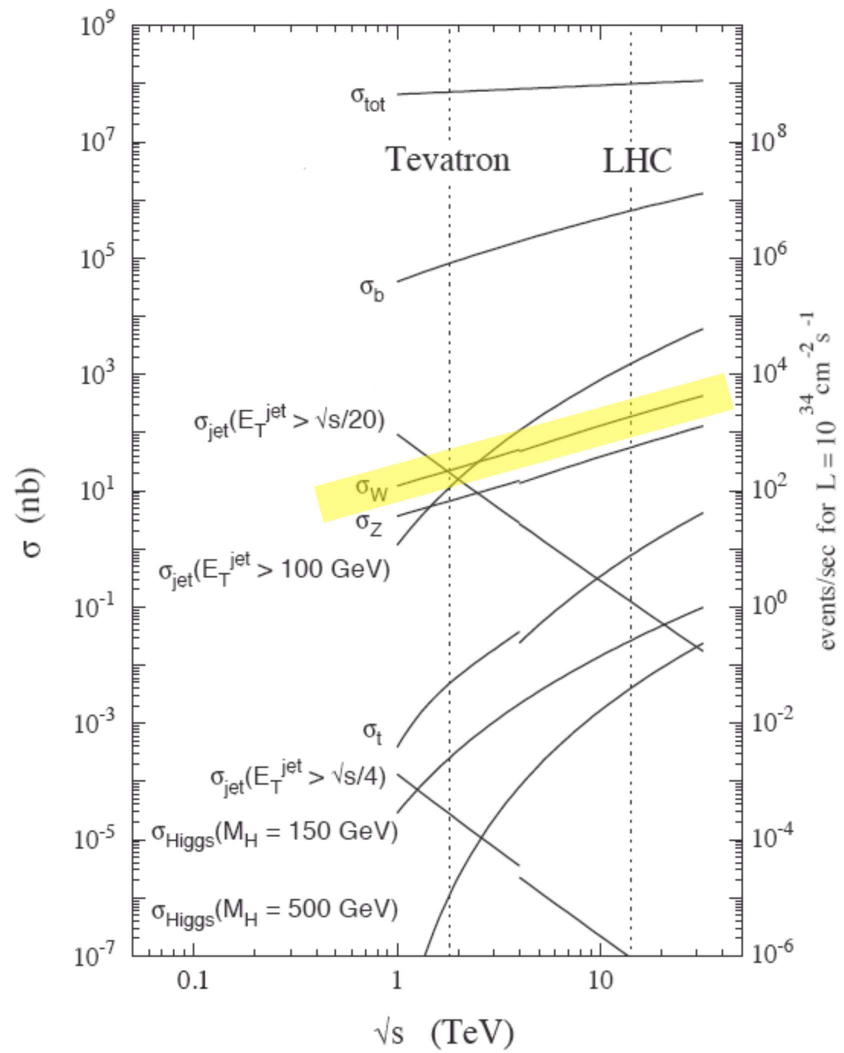
- **W → lν at CERN in 2010**
  - → *First source of high momentum leptons*
  - → *Standard Model in new energy regime*



From the Familiar to the Unknown

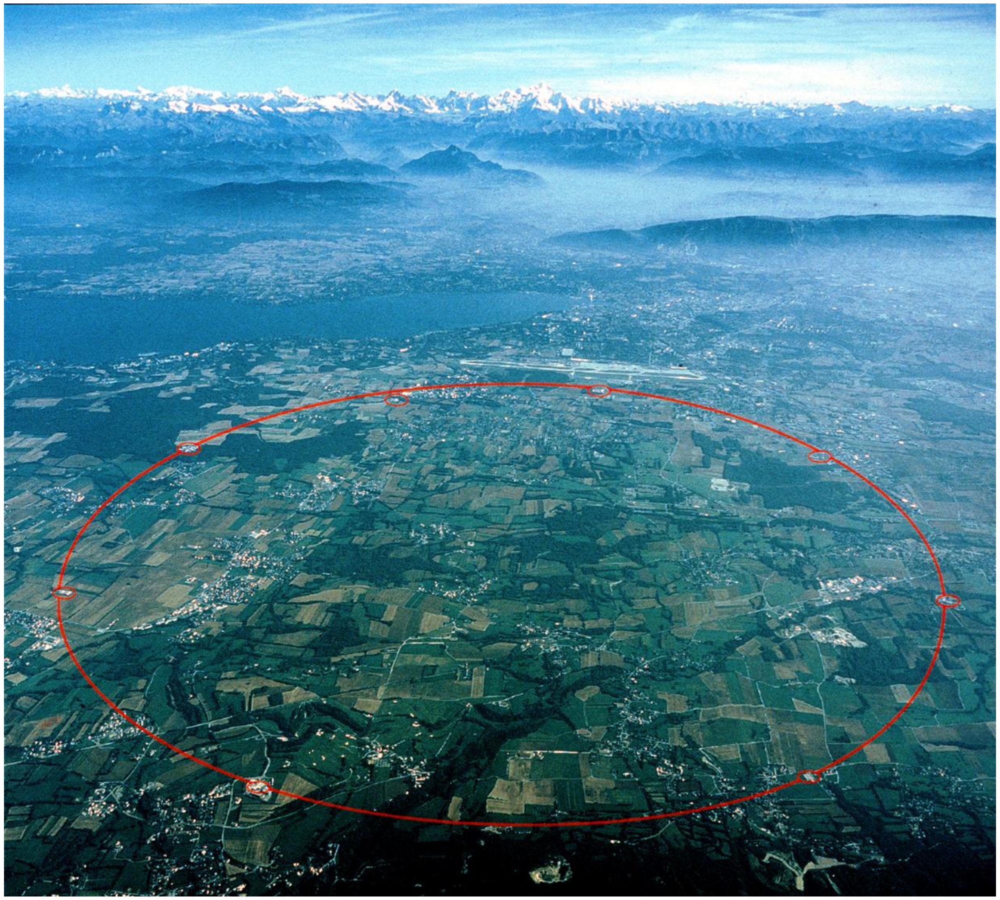
(We hope)

- Search for physics beyond what we know must be based on a solid understanding of the detector and the Standard Model
- W signature
  - → *Charged leptons*
  - → *Missing energy (from weakly-interacting neutrals)*
  - → *Modeling of pp collisions*
- Leptons flag electroweak interactions in a sea of strong interactions (jets)
  - → *Generically, something new could participate in either interaction, or both*
  - → *But leptonic signatures are easier to distinguish from background*
- Weakly-interacting neutrals pretty interesting, too

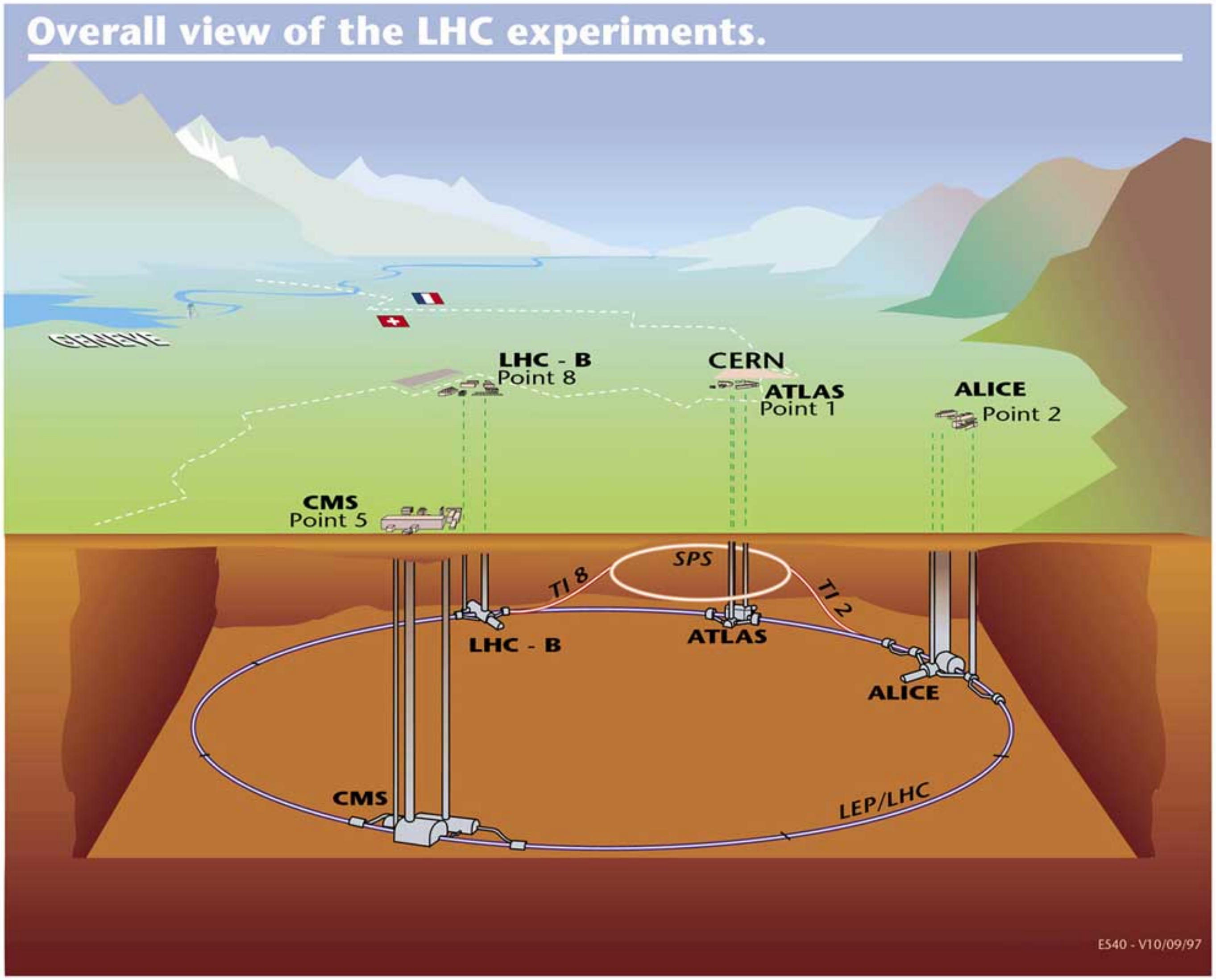


Overview

- The LHC and the ATLAS detector
- W candidate sample
  - → *Lepton definitions*
  - → *Backgrounds*
- Measurements
  - → *Inclusive cross section*
  - → *Charge asymmetry*
  - → *Differential ($d\sigma/dP_T$)*

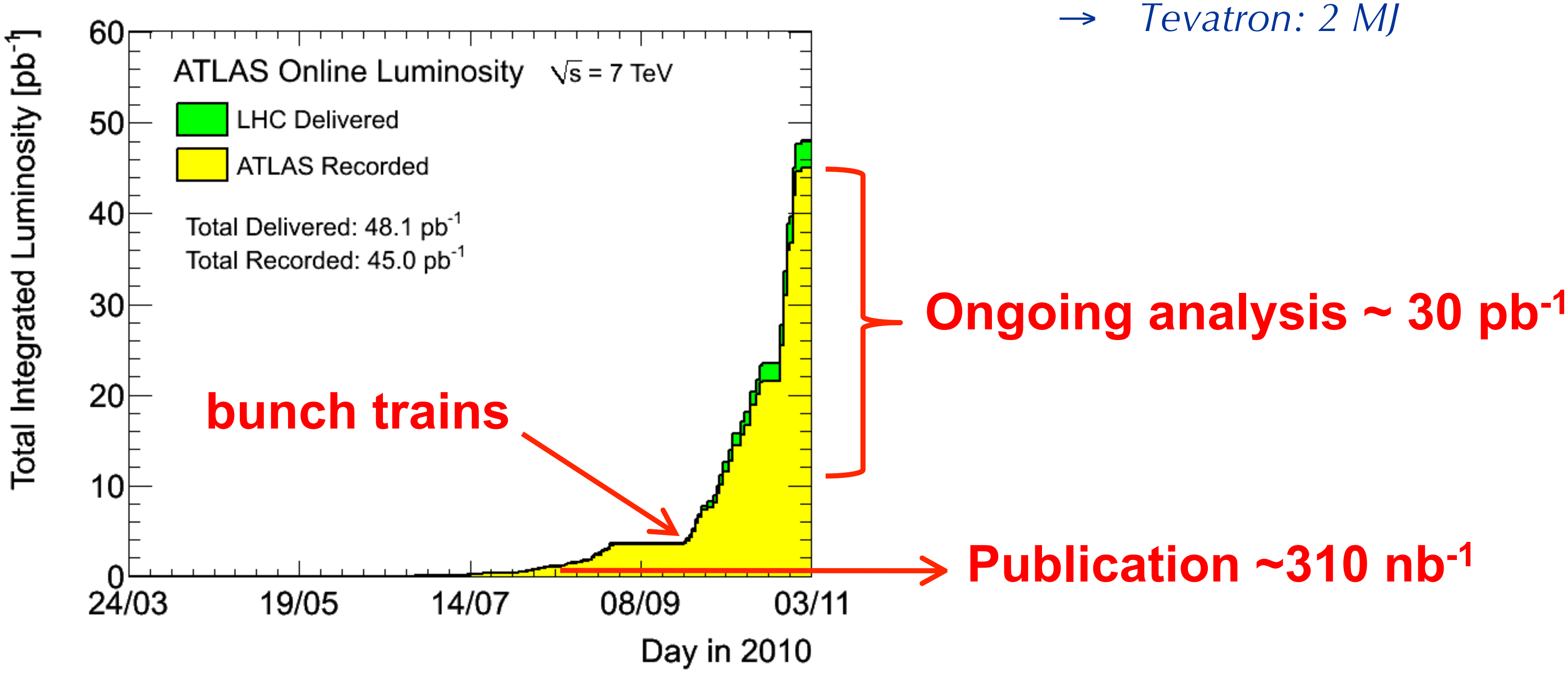


The LHC at CERN

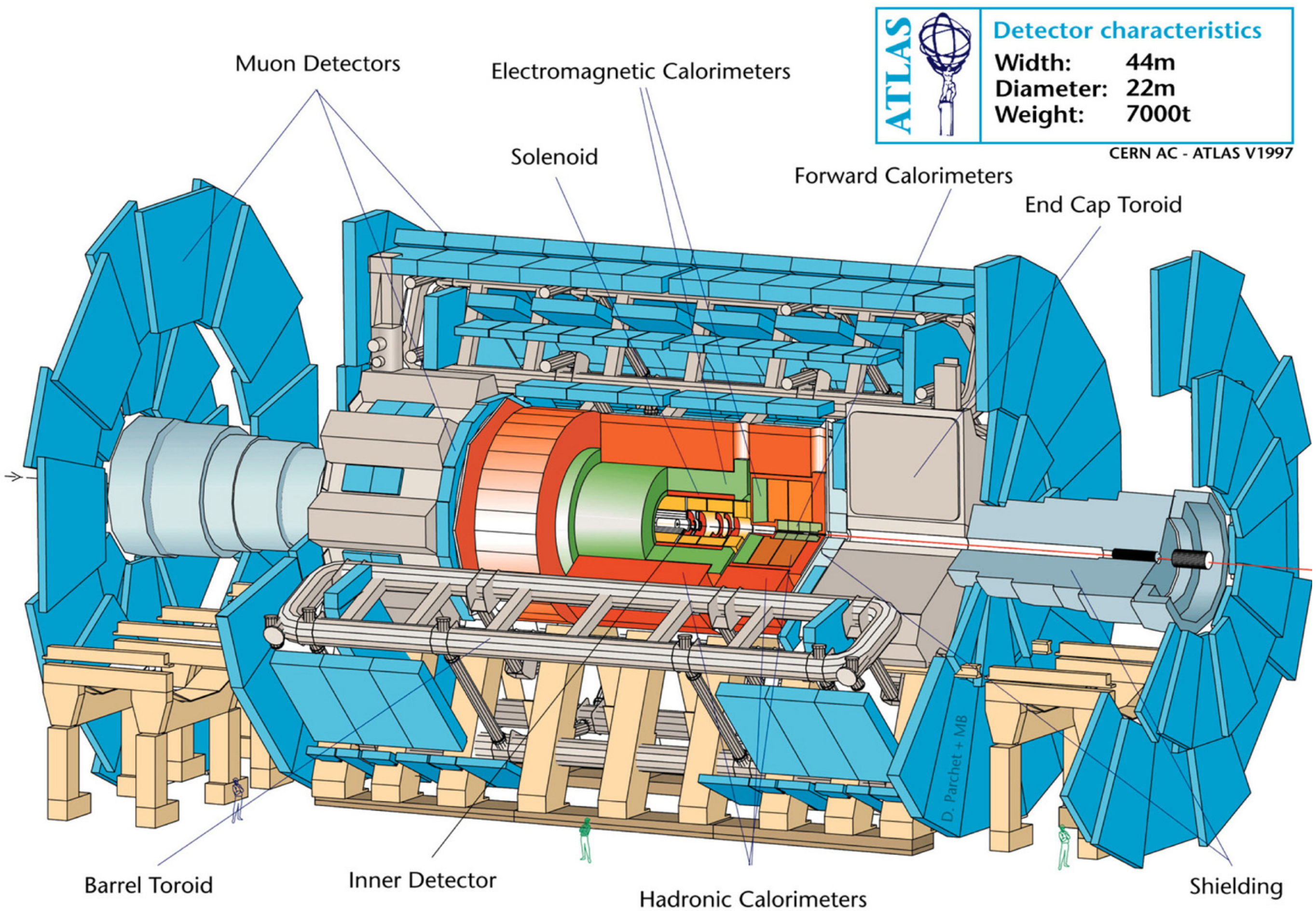


LHC @ 7 TeV

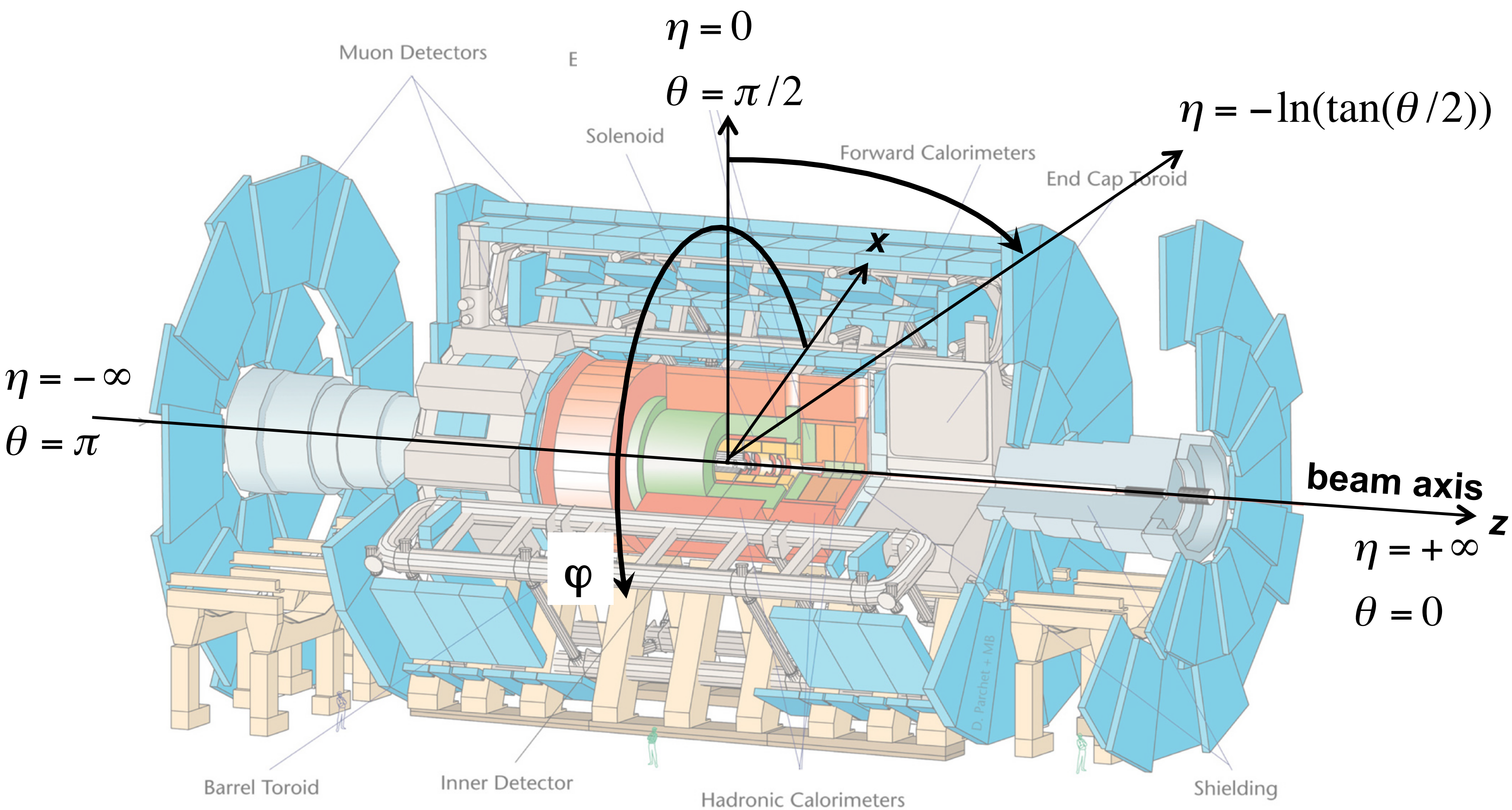
- Rapid LHC startup
- 2010 Instantaneous luminosity record = 2.1 x 10^{32} $cm^{-2}s^{-1}$
  - → *Tevatron record ~ 4x10^{32} $cm^{-2}s^{-1}$*
- 2 → 368 bunches
  - → *2808 possible*
- ~10^{11} p/bunch
- > 20 MJ stored energy
  - → *Tevatron: 2 MJ*



The ATLAS Detector



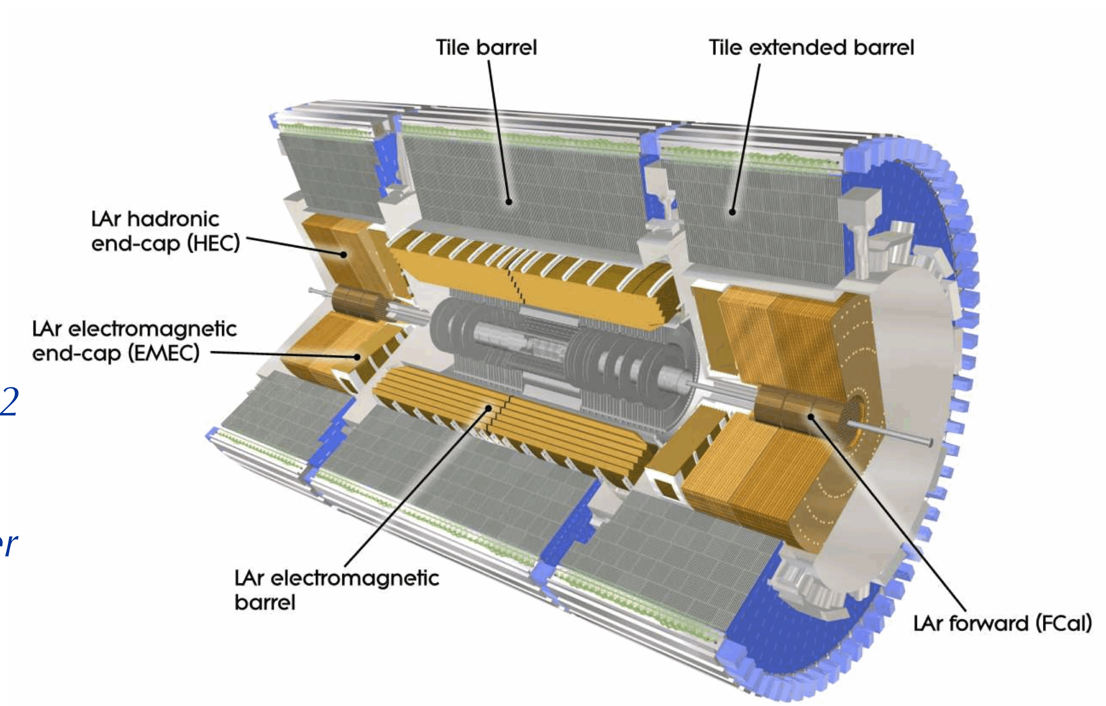
Hadron Collider Kinematics



$\vec{p}_T = (p_x, p_y)$ $\quad p_T = p\sin\theta, \quad E_T = E\sin\theta$ $\quad \vec{E}_T^{miss} = -\sum_{\text{clusters}\, i} E_i \hat{n}_i$

Electrons in ATLAS

- EM calorimeter cluster, possibly matched to inner detector (ID) track
- $E_T > 20$ GeV, $|\eta| < 2.47$
  - → *exclude gap between barrel and endcap $1.37 < |\eta| < 1.52$*
- "Loose" selection
  - → *shower shape in middle layer of calorimeter*
- "Medium" selection
  - → *add fine-granularity shower shape and track match*
- "Tight" selection
  - → *add E/p, more track quality, high-threshold TRT hits, conversion veto*



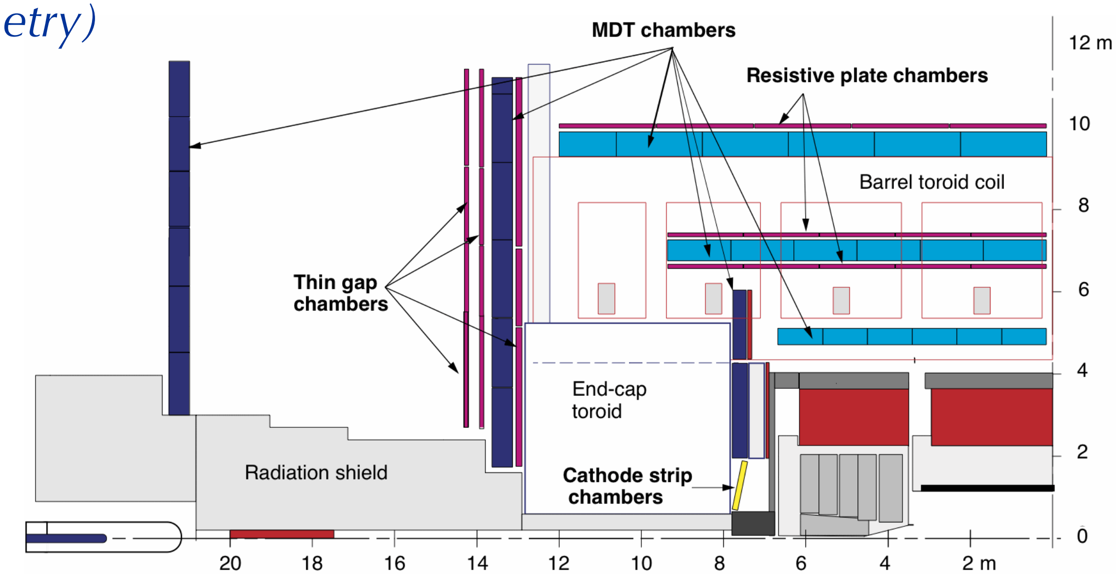
- Trigger: Level 1 (hardware) requires coarse-granularity cluster with $|\eta| < 2.5$ and $E_T > 10$ GeV

Muons in ATLAS

- Combined muon: matched inner detector (ID) and muon spectrometer (MS) track
- Selection:
  - → p_T *(combined) > 15 GeV*
  - → p_T *(MS) > 10 GeV*
  - → $|p_T(MS) - p_T(ID)| < 15$ *GeV*
  - → $|\eta| < 2.4$ *(trigger geometry)*

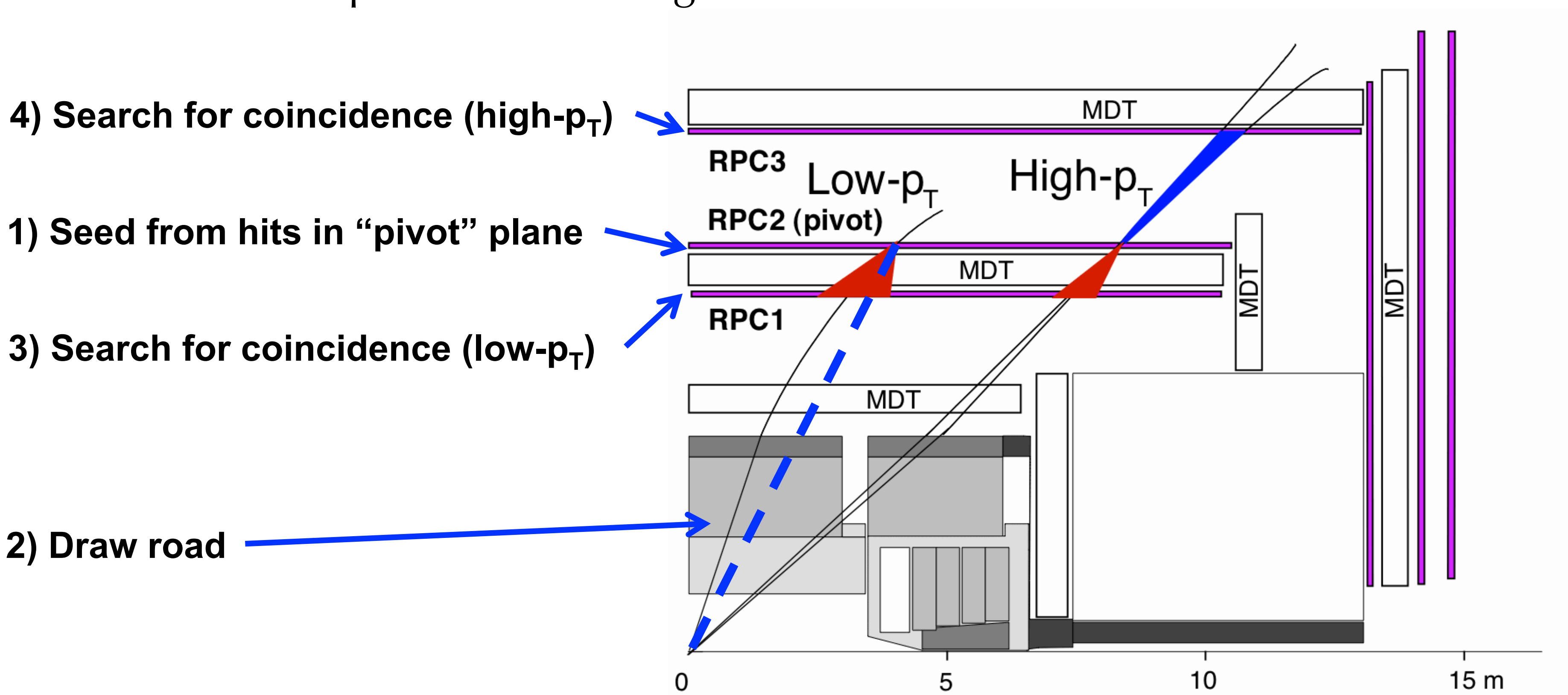
reject decays in flight (applies to the p_T (MS) and $|p_T(MS) - p_T(ID)|$ cuts)

- Trigger: L1 (hardware)
  - → $p_T > 6$ *GeV*



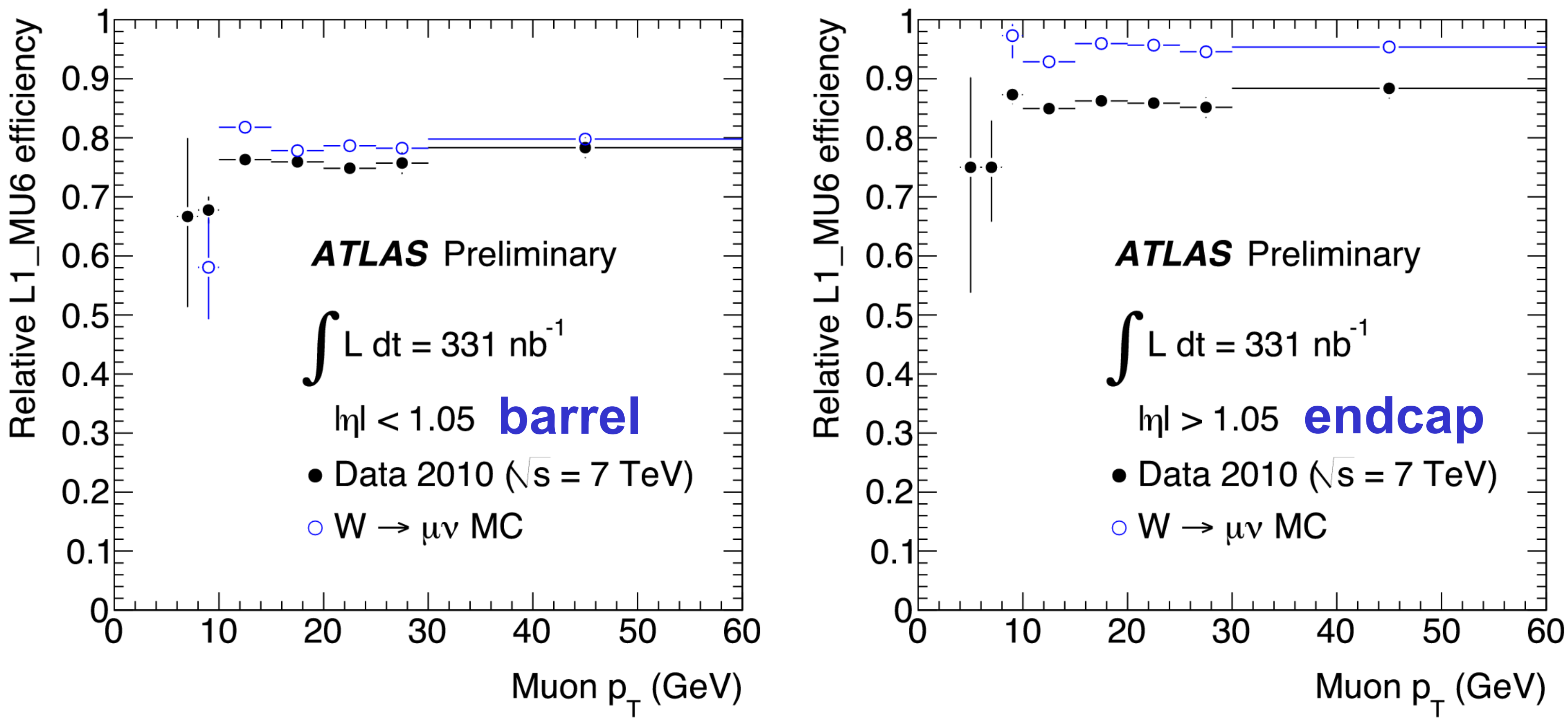
Level 1 Muon Trigger

- Collisions (ultimately) at almost 40 MHz, write to disk at 200 Hz
- Three-stage trigger: Level 1, Level 2, and "Event Filter"
- Level 1 implemented through on-detector electronics



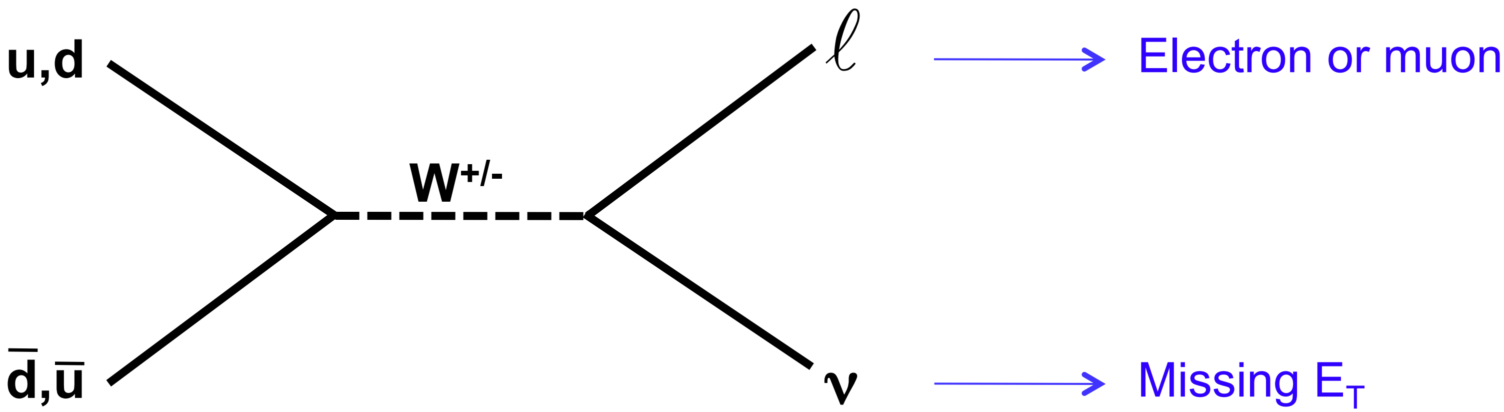
Muon Trigger Performance

- **L1 trigger (6 GeV threshold)** for first papers – HLT not commissioned
- Measure trigger efficiency for reconstructed muons in orthogonal (calo) trigger



- Inefficiency in barrel = gaps in geometry
- Endcap: some TGC inefficiencies not modeled, uncalibrated trigger roads

W Production at the LHC



Cross section:

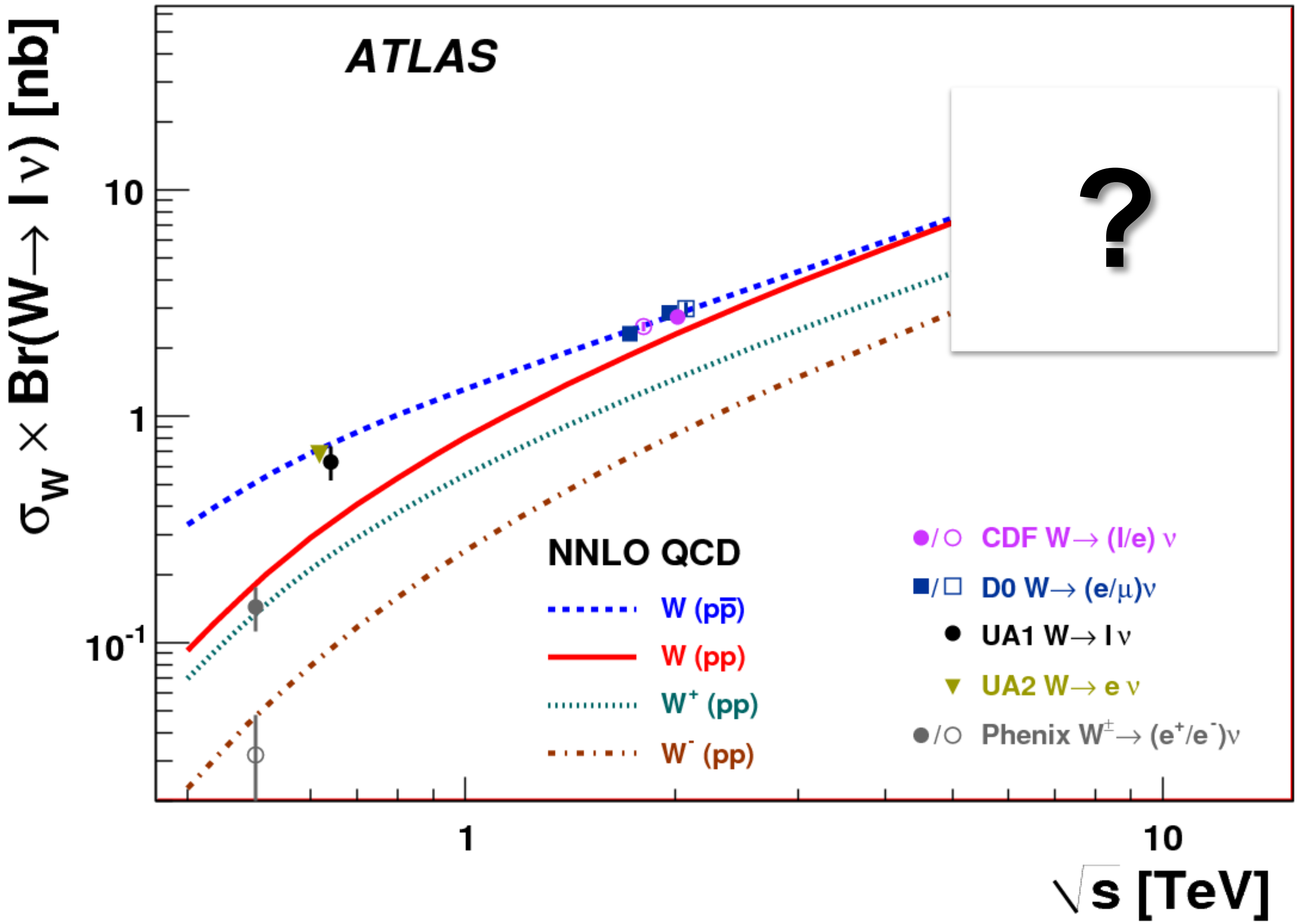
$$\sigma = \frac{N_{\text{cand}} - N_{\text{background}}}{A_W \times C_W \times \int \mathcal{L}\, dt}$$

- A_W x C_W = fraction of signal expected to pass selection
- $\int \mathcal{L}$ dt = integrated lumi.

Backgrounds:

- Z → ee,μμ
- W → τν
- Z → ττ
- tt with t → Wb, W → ln
- "QCD"
  - heavy quark decays
  - hadronic "fakes"

W Cross Section Measurement



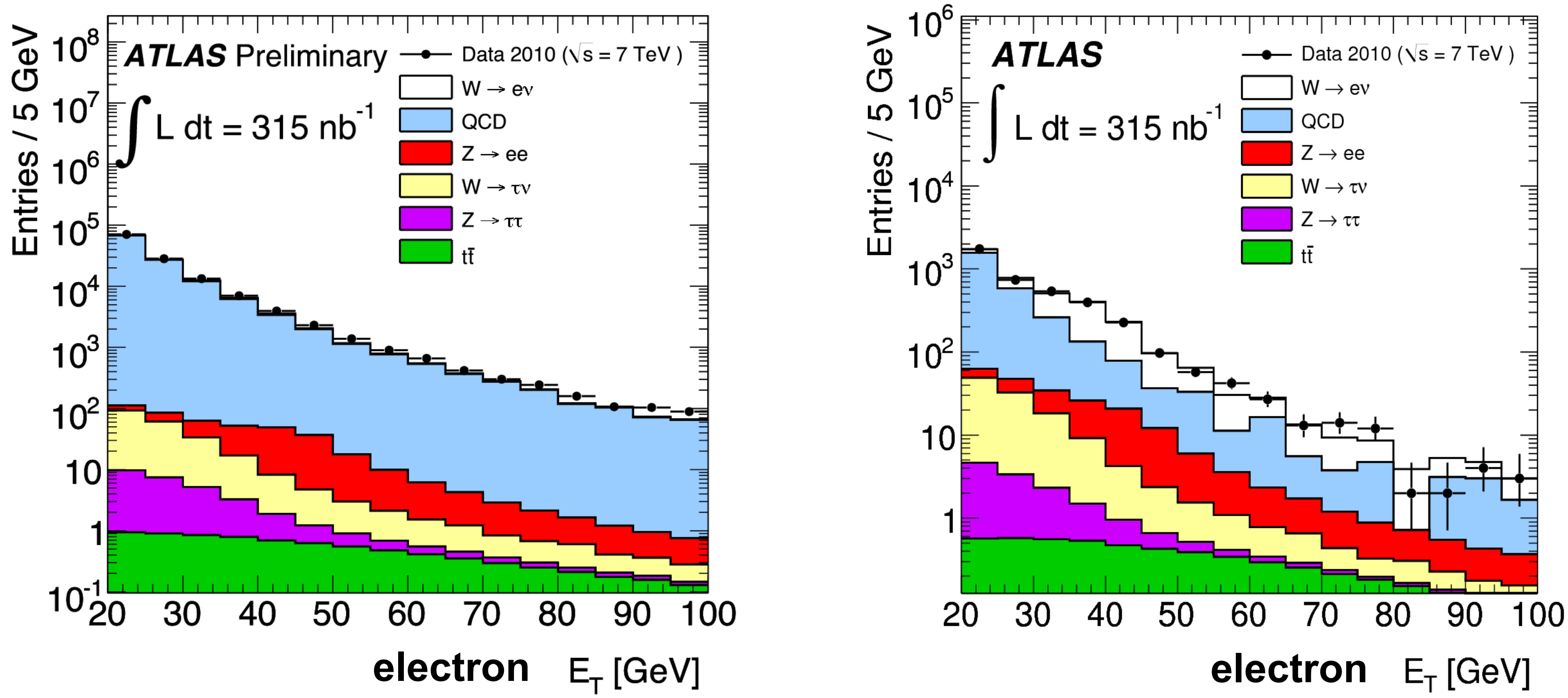
Event Selection

electron		muon	
L1 trigger: E_T > 10 GeV		L1 trigger: p_T > 6 GeV	
E_T	> 20 GeV	p_T	> 20 GeV
$\|\eta\| < 1.37$ or	$1.52 < \|\eta\| < 2.47$	$\|\eta\|$	< 2.4
pass "tight" criteria		isolated from other charged particles	
E_T^{miss}	**> 25 GeV**		
transverse mass M_T	**> 40 GeV**		

The High-p_T Electron Data

Electrons with E_T > 20 GeV in events firing L1 electron trigger:

"Loose" electrons → "Tight" electrons

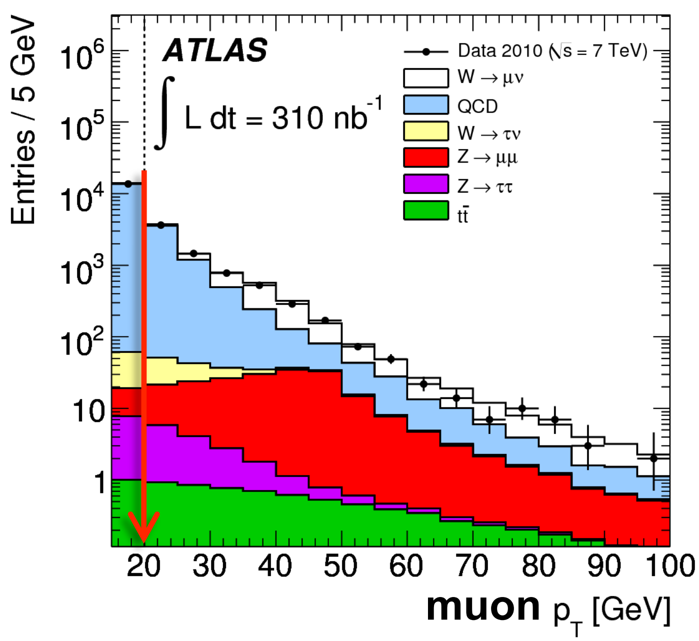


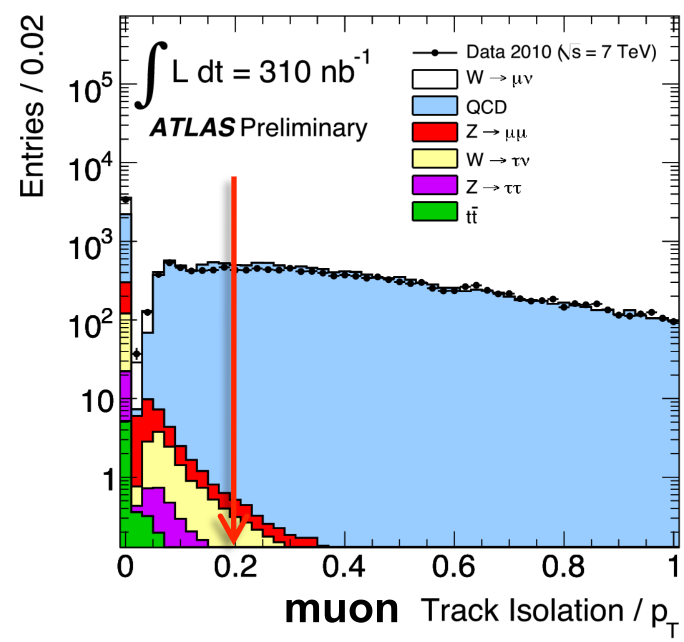
The High-p_T Muon Data

- Muons with p_T > 15 GeV in events firing L1 trigger
- Refine muon selection:
  - → *$p_T > 20$ GeV*
  - → *Relative Track Isolation*

$$\text{iso} = \left(\sum_{\text{tracks in cone}} p_T^{\text{track}} \right) / p_T^{\mu} < 0.2$$

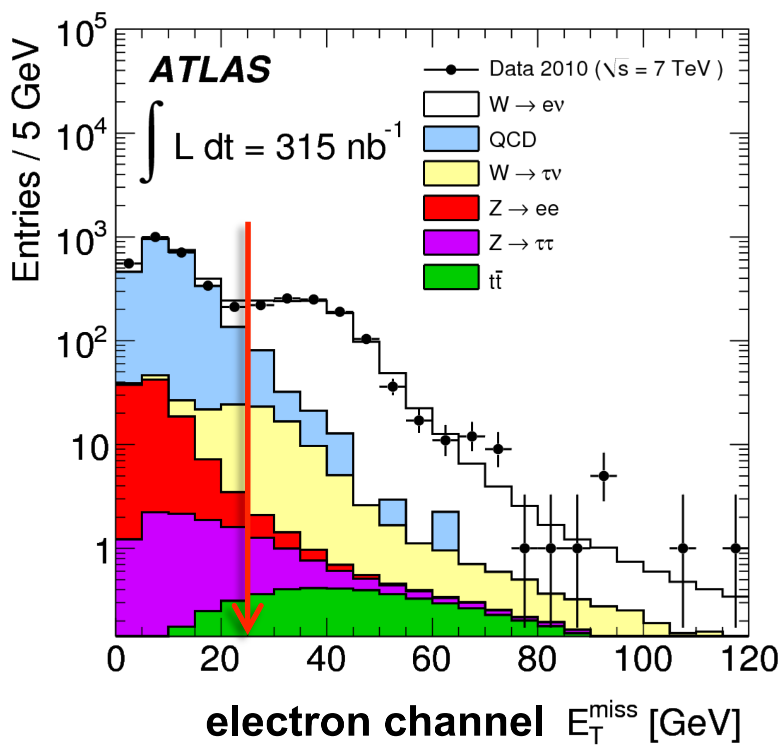
$$\text{in cone if } \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 0.4$$

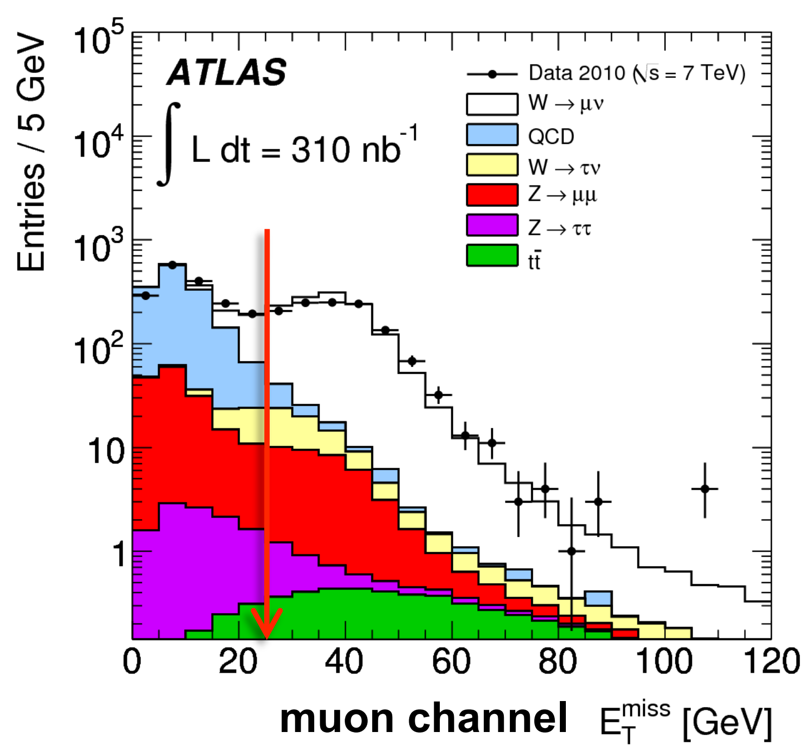




Selecting the W signal (II)

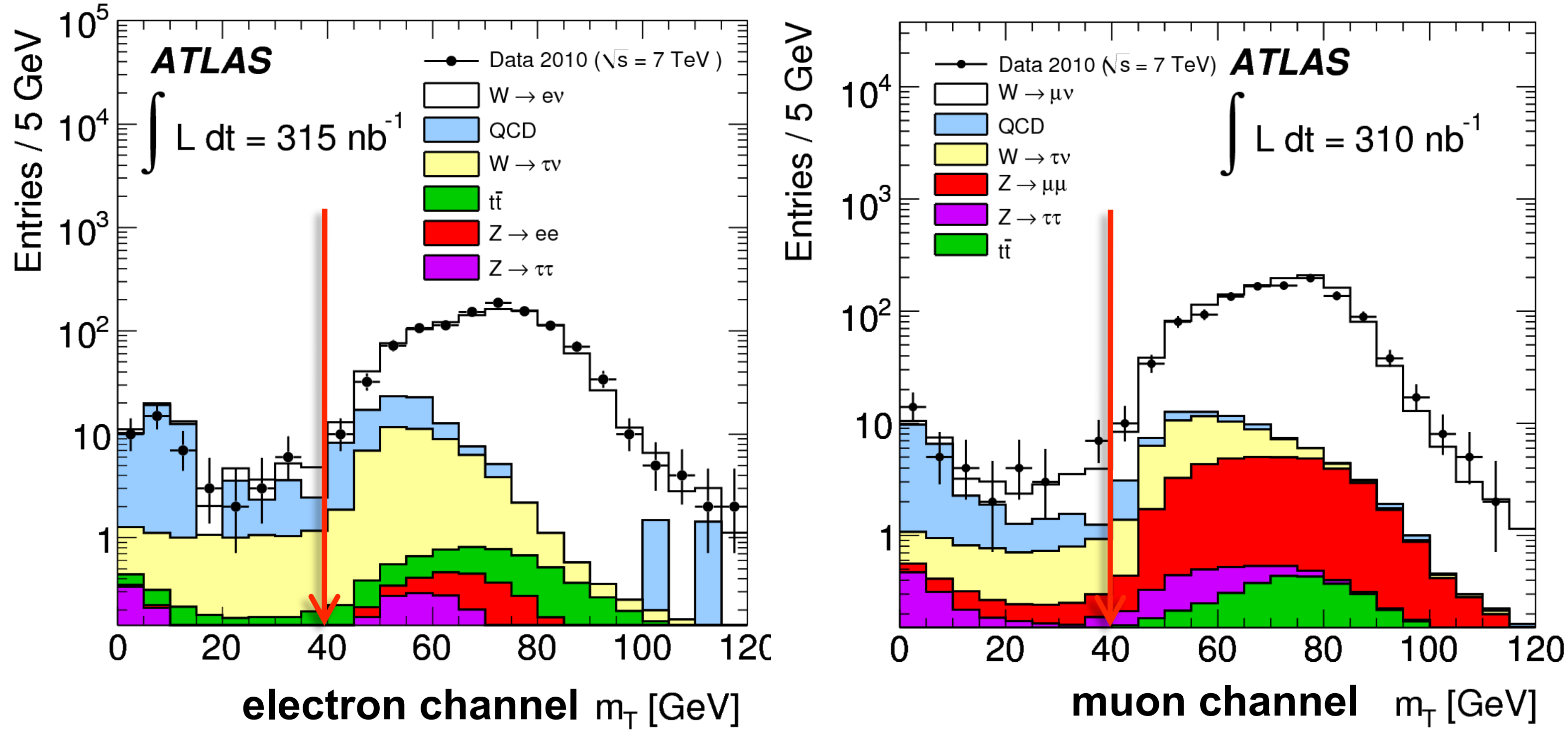
- Missing Transverse Energy $$\vec{E}_T^{miss} = -\sum_{\text{clusters}\, i} E_i \hat{n}_i - \vec{p}_T^{\,\mu} + E_{loss}^{\mu} \hat{p}_T^{\mu}$$
- Reduce backgrounds by requiring $\mathbf{E_T^{miss} > 25}$ **GeV**





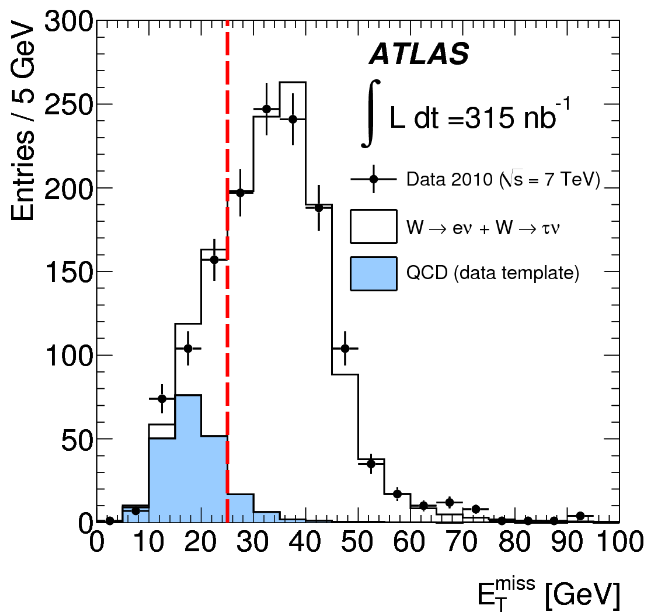
Selecting the W signal (III)

- 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 $\mathbf{M_T > 40}$ **GeV**



Yield: **1069** candidates **1181** candidates

Backgrounds to $W \rightarrow e\nu$



- **"Electroweak" backgrounds** ($Z \rightarrow ee$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, ttbar): **33.5 ± 3.0** (stat+sys) events
- **N_{QCD} = 28 ± 3 (stat) ± 10 (sys)** events
- **QCD: Template fit to E_T^{miss}** distribution (after all other requirements)
  - → *$W \rightarrow e\nu$ and $W \rightarrow \tau\nu$ templates from simulation*
  - → *QCD template from data*
    - Some electron ID cuts reversed, veto events with isolated electrons
  - → *Systematic*
    - Vary requirements for QCD template
    - Restrict fit range

Backgrounds to $W \rightarrow \mu\nu$

- **"Electroweak" backgrounds** ($Z \rightarrow \mu\mu$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, ttbar) **77.6 ± 5.4** (stat+sys) events
- **Cosmics: 1.7 ± 0.8** event
- **QCD: 21.1 ± 9.8** (stat+sys) events
  - → N_{all} *candidates before isolation req.*
    - N_{isol} pass
    - N_{QCD} are from QCD, $N_{non\text{-}QCD}$ are not
  - → *Apply isolation requirement, with different efficiencies from each sample*
    - Measure $\varepsilon_{non\text{-}QCD}$ (i.e. signal efficiency) from Zs
    - Measure ε_{QCD} in QCD-dominated data ($15 < p_T^{\mu} < 20$ GeV), and extrapolate to $p_T^{\mu} > 20$ GeV using simulated dijet events
  - → *Solve, and* $\varepsilon_{QCD} N_{QCD}$ *is the pred. background*
  - → *Systematic from extrapolation of* ε_{QCD}, *significant statistical uncertainty, too*

$$N_{all} = N_{non-QCD} + N_{QCD}$$
$$N_{isol} = \varepsilon_{non\text{-}QCD} N_{non\text{-}QCD} + \varepsilon_{QCD} N_{QCD}$$

$W \rightarrow \ell \nu$ Acceptance

channel	A_W	C_W	acceptance x efficiency
electrons	0.462 ± 0.014	0.659 ± 0.046	**0.304 ± 0.023**
muons	0.480 ± 0.014	0.758 ± 0.030	**0.364 ± 0.018**

- Factorize acceptance times efficiency
  - → *A_W = geometric & kinematic acceptance (measured at truth level)*
    - From Pythia 6.4 (LO)
  - → *C_W = detection efficiency*
    - GEANT 4 simulation of ATLAS, corrected to data
- Common systematic uncertainty on A_W is 3%
  - → *Dominated by PDF dependence*
  - → *Includes LO-NLO differences*
- Systematic uncertainties on C_W = 7% for electrons and 4% for muons
  - → *Reconstruction and trigger (μ) efficiencies*
  - → *Energy / momentum scale/resolution*

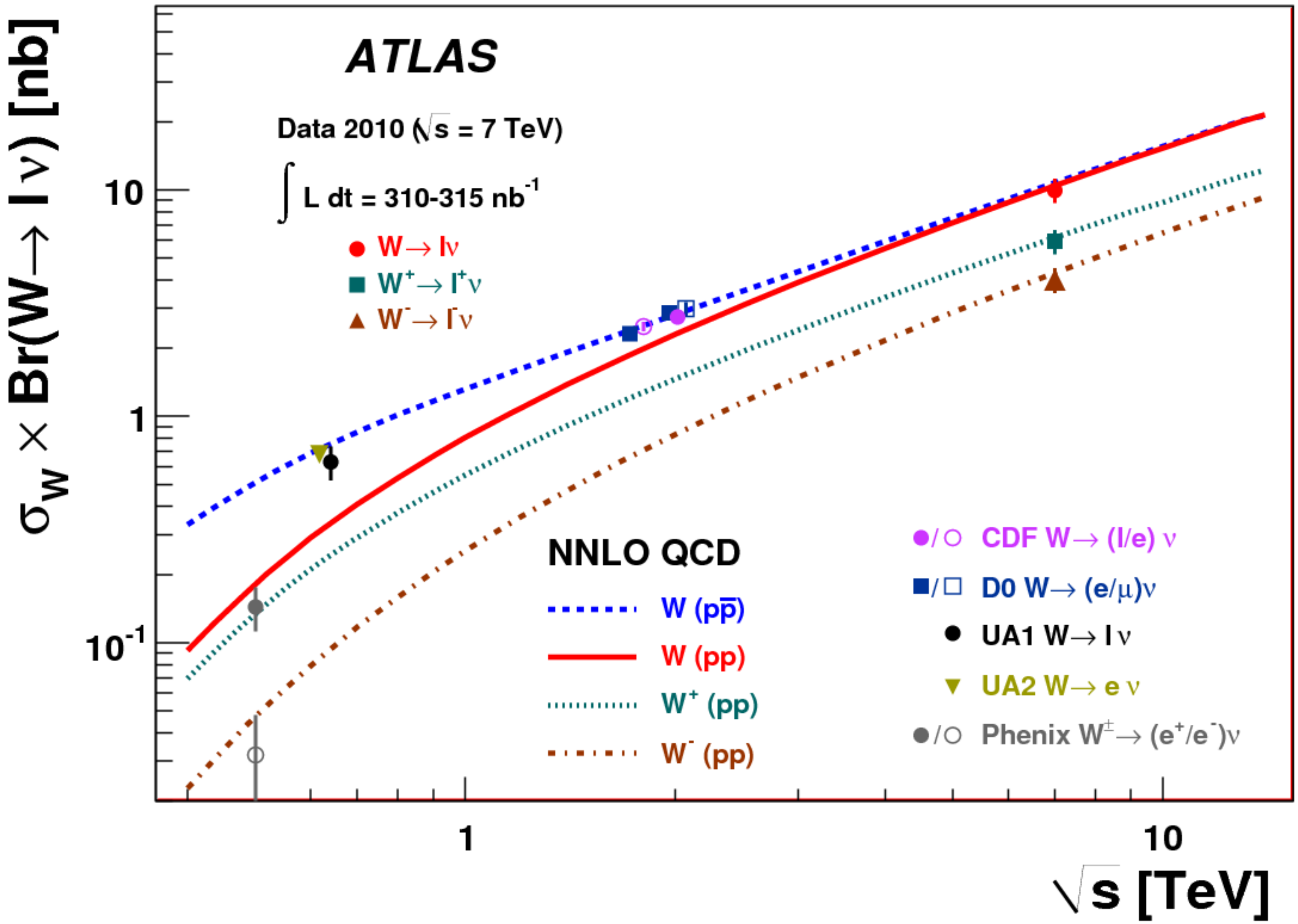
W Cross Section Results

channel (lumi)	N_{cand}	$N_{background}$	cross section (nb)
electron (315 nb^{-1})	1069	61.5 ± 10.8	10.5 ± 0.3 (stat) ± 0.8 (sys) ± 1.1 (lum)
muon (310 nb^{-1})	1181	100.4 ± 11.2	9.6 ± 0.3 (stat) ± 0.5 (sys) ± 1.1 (lum)
combined	2250	-	**10.0 ± 0.2 (stat) ± 0.5 (sys) ± 1.1 (lum)**

- Cross section times branching ratio BR($W \rightarrow \ell \nu$)
- Theoretical prediction:
  - → *10.46 ± 0.02 nb*
  - → *FEWZ w/ MSTW2008 pdfs*
- Luminosity uncertainty is 11%

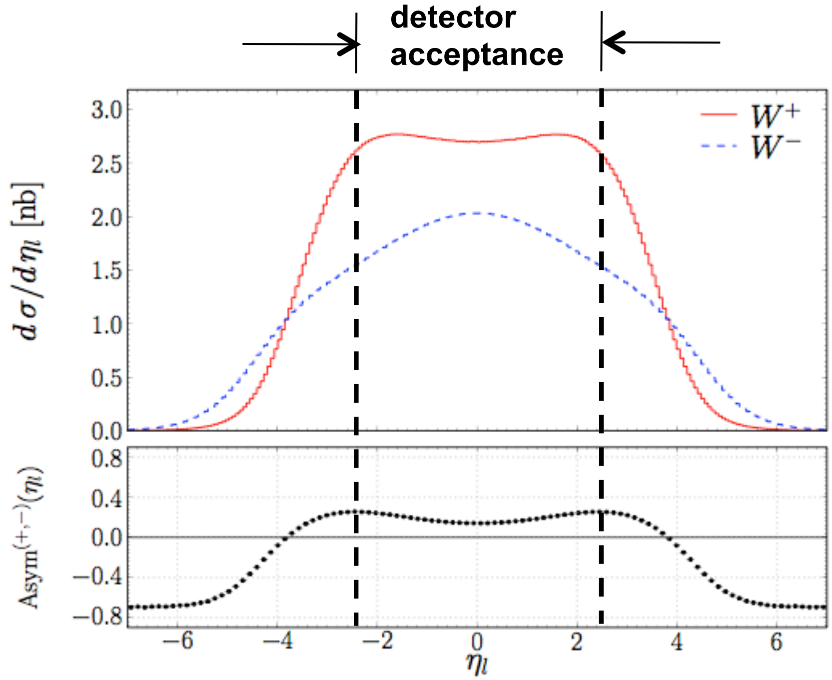
$$\sigma = \frac{N_{\text{cand}} - N_{\text{background}}}{A_W \times C_W \times \int \mathcal{L}\, dt}$$

W Cross Section in Context



W^+-W^- Charge Asymmetry

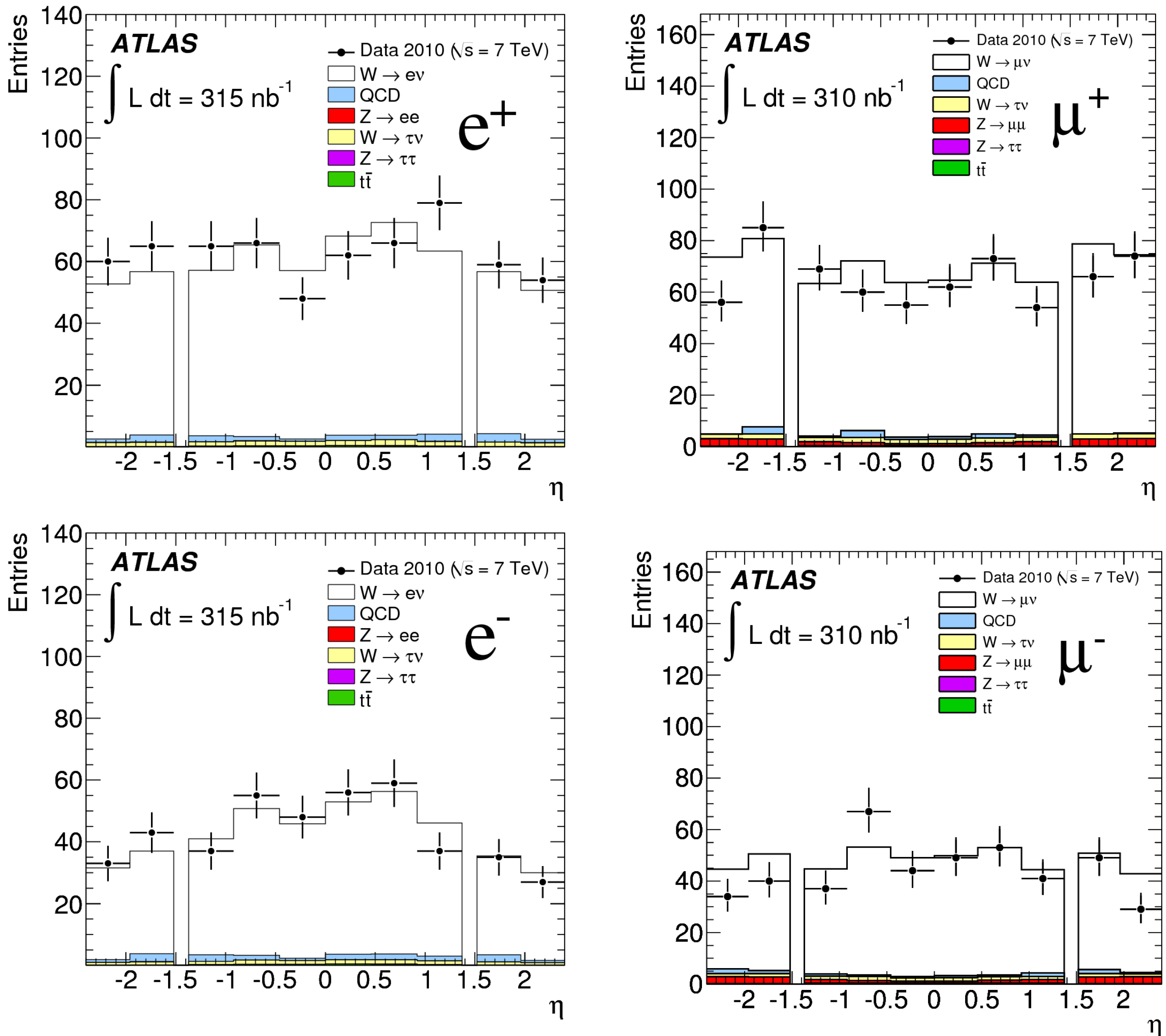
- W^+ favored in proton-proton collisions in eta-dependent way
  - → *twice as much u as d in the proton, harder u-quark PDF*



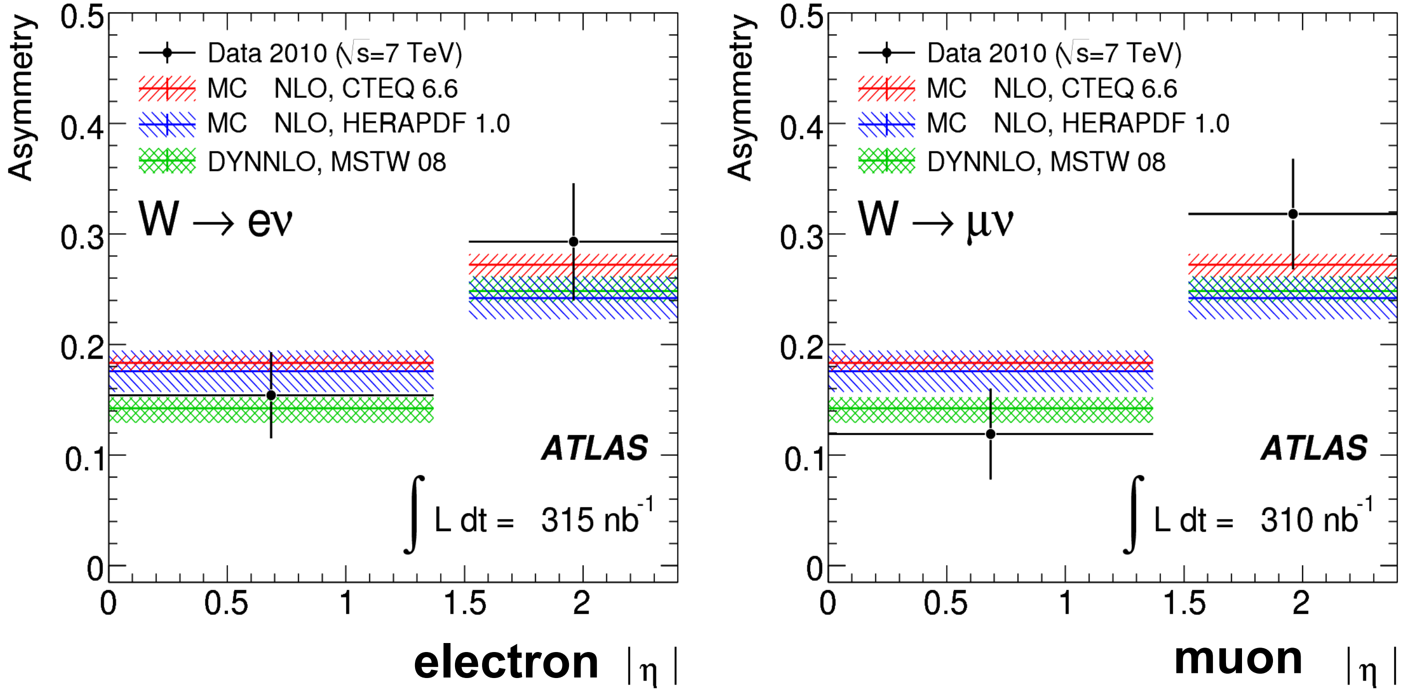
$$A = \frac{\sigma^{\ell^+} - \sigma^{\ell^-}}{\sigma^{\ell^+} + \sigma^{\ell^-}}$$

from F. Fayette et al., Eur. Phys. J. C63 (2009) 33,
by way of M. Boonekamp

Charge Asymmetry Inputs



Charge Asymmetry Results

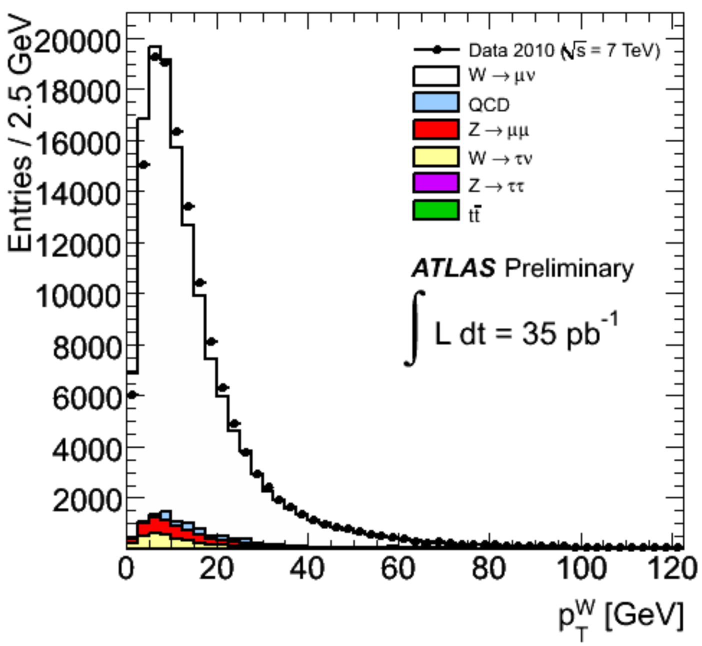


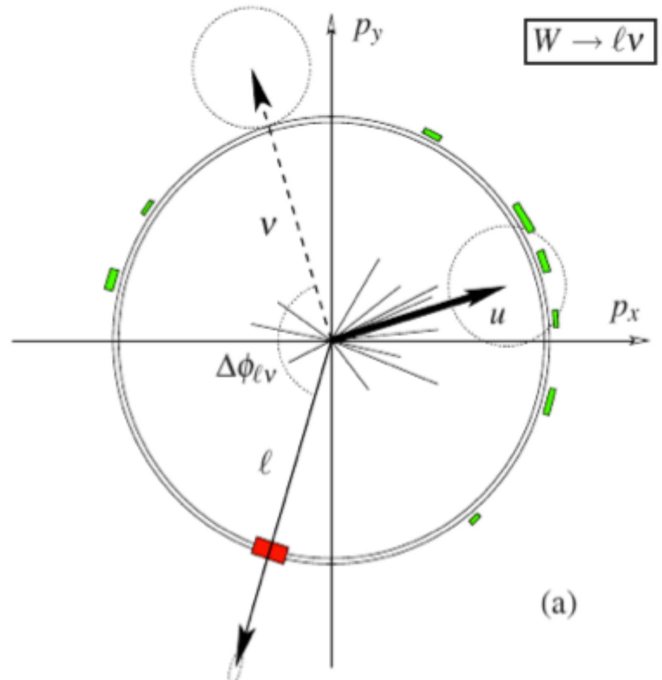
$$A = \frac{\sigma^{\ell^+} - \sigma^{\ell^-}}{\sigma^{\ell^+} + \sigma^{\ell^-}}$$

integral combined result	**0.20 ± 0.02** (stat) **± 0.01** (sys)
MC@NLO with CTEQ6.6	$0.218^{+0.008}_{-0.009}$
MC@NLO with HERAPDF 1.0	0.202 ± 0.019
DYNNLO with MSTW 08	$0.184^{+0.011}_{-0.012}$

$W\ p_T$

- In progress: $d\sigma/dp_T$ for the W
- Characterize hadronic recoil system (vector *u*)





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

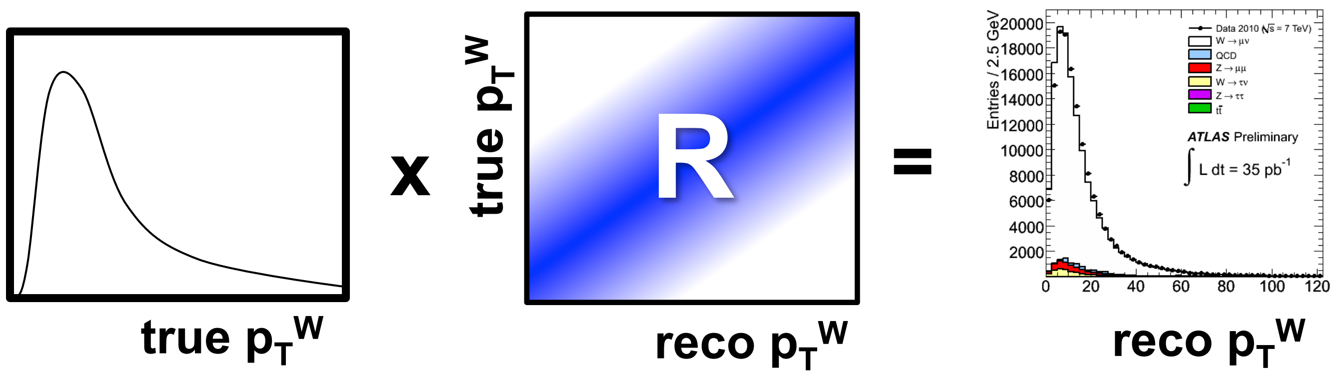
$$\vec{p}_T^{\,W} = \vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu} = \cancel{\vec{p}_T^{\,\ell} - \vec{p}_T^{\,\ell}} - \vec{u}$$

W mass →

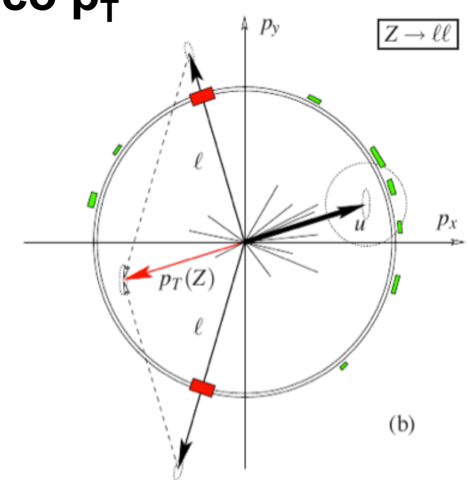
$$M_T = \sqrt{2(p_T^{\mu})(p_T^{\nu})(1-\cos(\varphi^{\mu}-\varphi^{\nu}))}$$

W p_T Response Matrix

- Calorimeter resolution → measured and reconstructed W p_T may be quite different
  - → *Related by a **Response Matrix R***

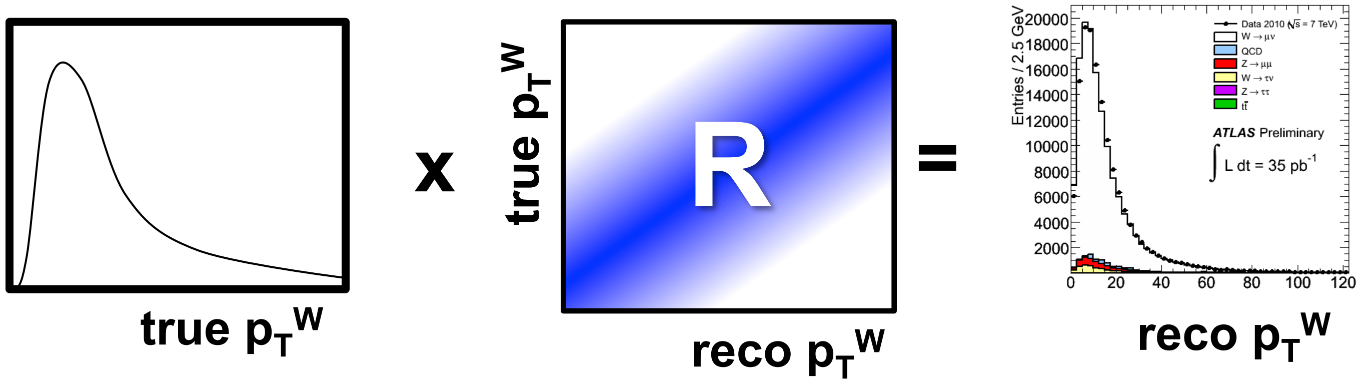


- Can build response matrix from W Monte Carlo events
  - → *Have both true and reconstructed W p_T*
  - → *But, accurate modeling of recoil?*
- Better: build from Z data
  - → *"Truth" from Z p_T reconstructed from leptons*
  - → *"Reco" from hadronic recoil*
  - → *Correct for slight differences in W and Z kinematics (sum E_T)*

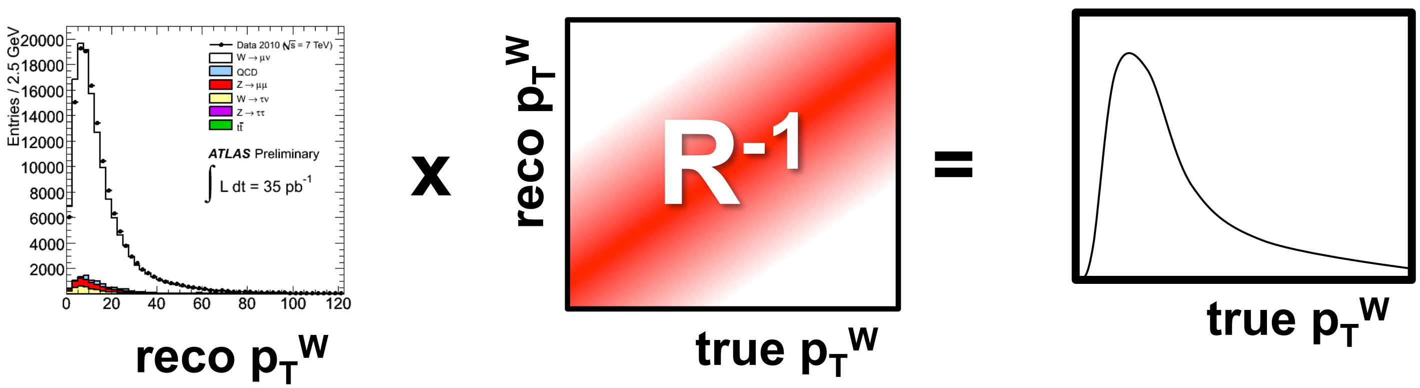


W p_T Unfolding

- Response Matrix R relates measured and reconstructed W p_T



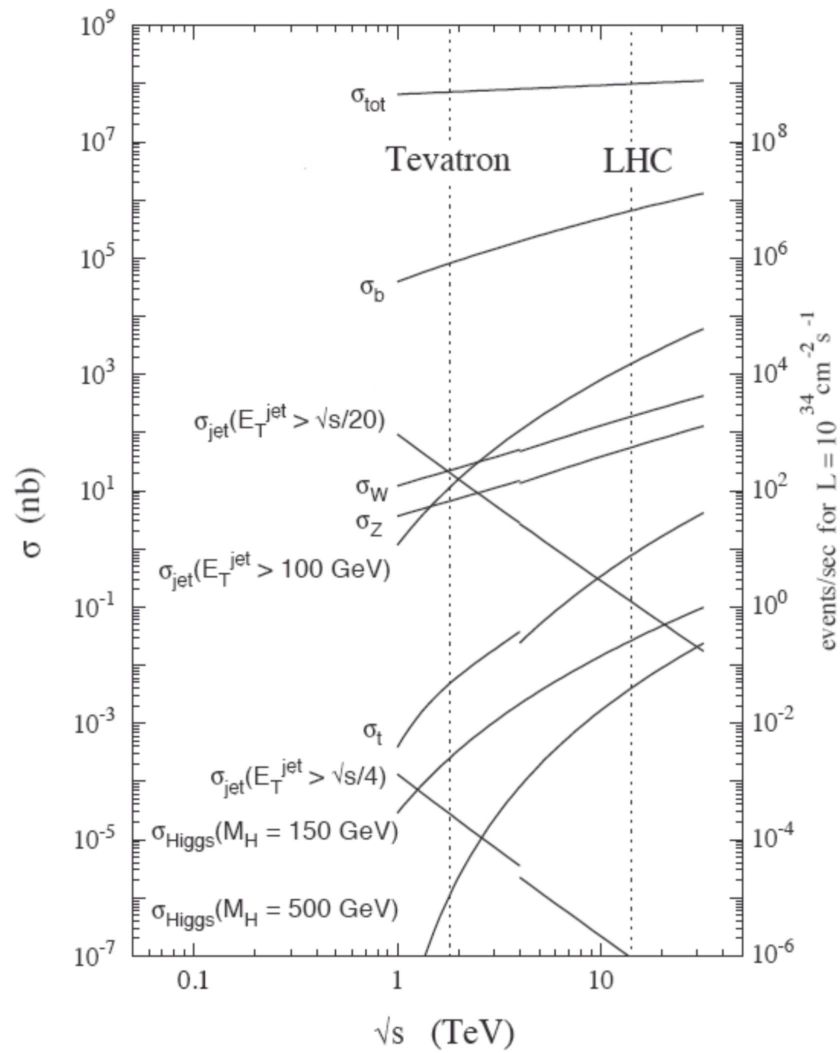
- Can "unfold": invert matrix, map back to truth



- Measurement to be completed in coming weeks

Summary of W Measurements

- Benchmark high-p_T electroweak processes at the LHC by characterizing W production at ATLAS
  - → *Inclusive cross section*
  - → *Lepton charge asymmetry*
  - → *$d\sigma/dp_T$*
- Feeds back into physics
  - → *Standard Model*
    - PDFs
    - QCD modeling (perturbative and non-perturbative)
  - → *Detector response*
    - Hadronic recoil and E_T^{miss}
    - High-p_T electrons and muons

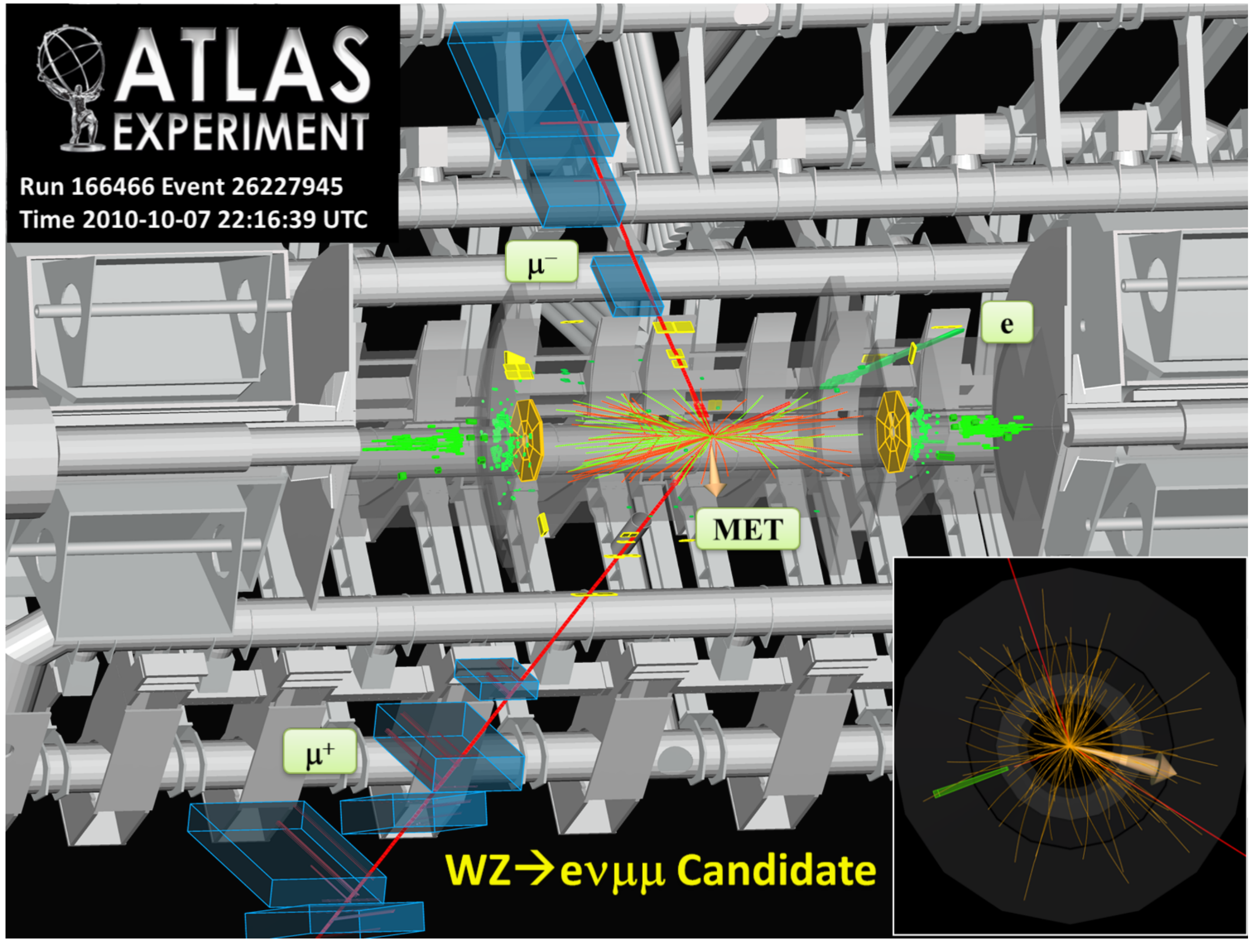


WZ candidate event

- Rarer processes (σ_{WZ} = 18 pb) are beginning to appear

$M_{\mu\mu}$ = 96 GeV
M_T (e-E_T^{miss})
= 57 GeV

$P_T(\mu^+)$ = 65 GeV
$P_T(\mu^-)$ = 40 GeV
P_T(e) = 64 GeV
E_T^{miss} = 21 GeV



What's next

- Build on knowledge from W sample
  - → *Better modeling of signals and backgrounds*
  - → *Understanding of muons, electrons, E_T^{miss}*
  - → *Go after multilepton signals*
    - Start from WZ (for example), test for supersymmetry or anomalies in the triple gauge boson coupling
  - → *Longer term: search for very massive particles*
    - Still anchor event selection on leptons for trigger, background rejection
    - New event topologies?
- Representatives from experiments and accelerator are meeting now at Chamonix
  - → *$\sqrt{s}$ = 7 or 8 TeV?*
  - → *run through 2012 or stop at the end of 2011 to go for 14 TeV?*

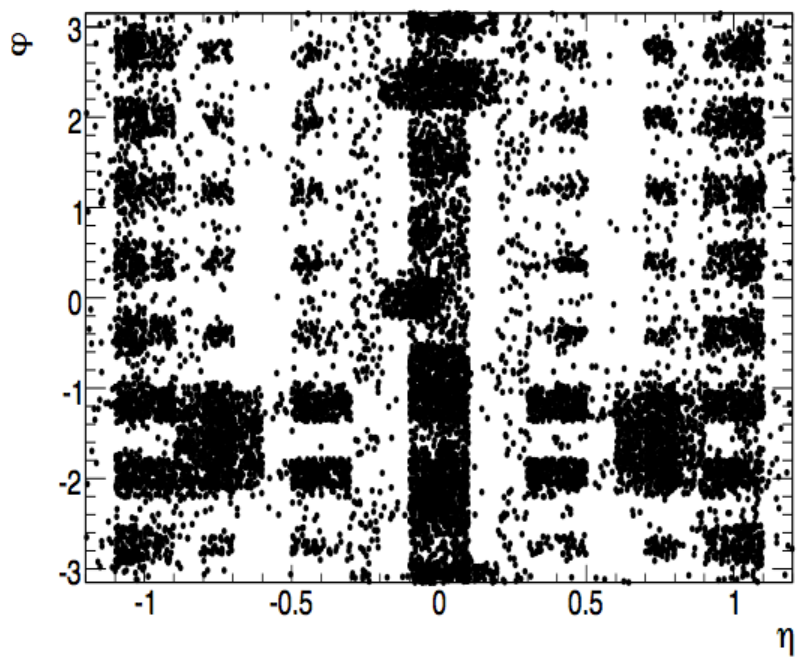
Backup

More on Electrons

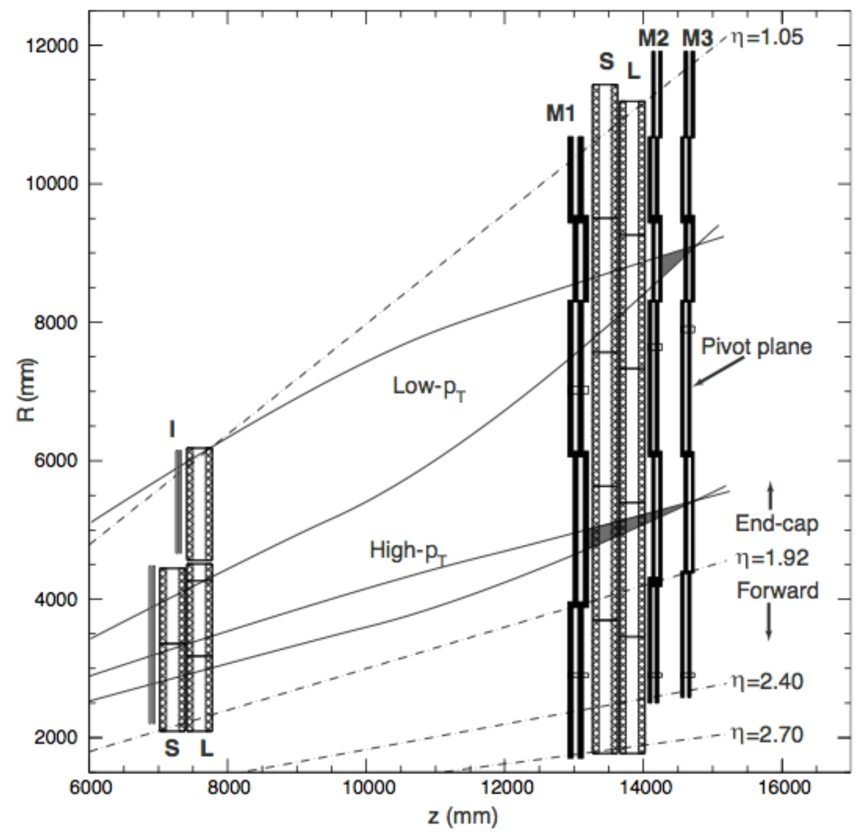
- Trigger: sliding-window algorithm using reduced-granularity clusters $\Delta\eta \times \Delta\varphi$ = 0.1 x 0.1
- Offline reconstruction: sliding window of 3x5 cells or 0.075 x 0.125 in $\eta \times \varphi$
  - → *Electron = cluster with E_T > 2.5 GeV and matched track with p_T > 0.5 GeV*
- Reconstruction: exact requirements vary with E_T and $|\eta|$, but three categories:
- Loose electrons
  - → *Fiducial: $|\eta| < 2.37$ and exclude $1.37 < |\eta| < 1.52$*
  - → *Shower shape in middle (largest) layer of calorimeter: cluster width in η*
  - → *Hadronic leakage: E_T(innermost later of HCAL) / cluster E_T*
- Medium electrons: loose +=
  - → *Shower shape in innermost (finely segemented in η) layer of calorimeter*
  - → *Track match ($\Delta\eta$)*
  - → *Track quality (pixel, SCT hits and impact parameter)*
- Tight electrons: medium +=
  - → *High-threshold hits in transition-radiation tracker (TRT); hit in innermost pixel layer*
  - → *E/p*
- http://cdsweb.cern.ch/record/1273197/files/ATLAS-CONF-2010-005.pdf

Muon L1 Trigger

Holes in Barrel Trigger Acceptance



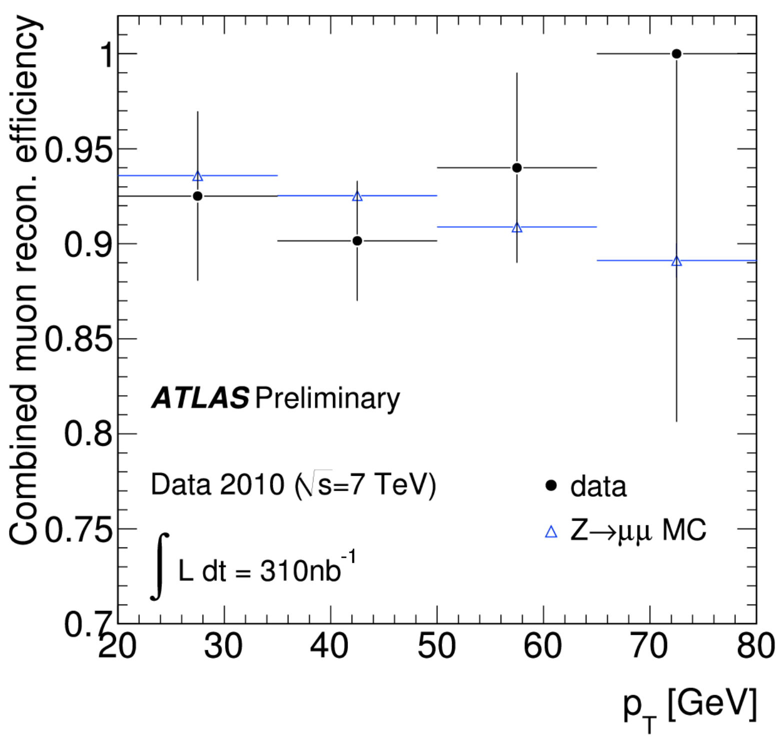
Endcap L1 Trigger (TGC)

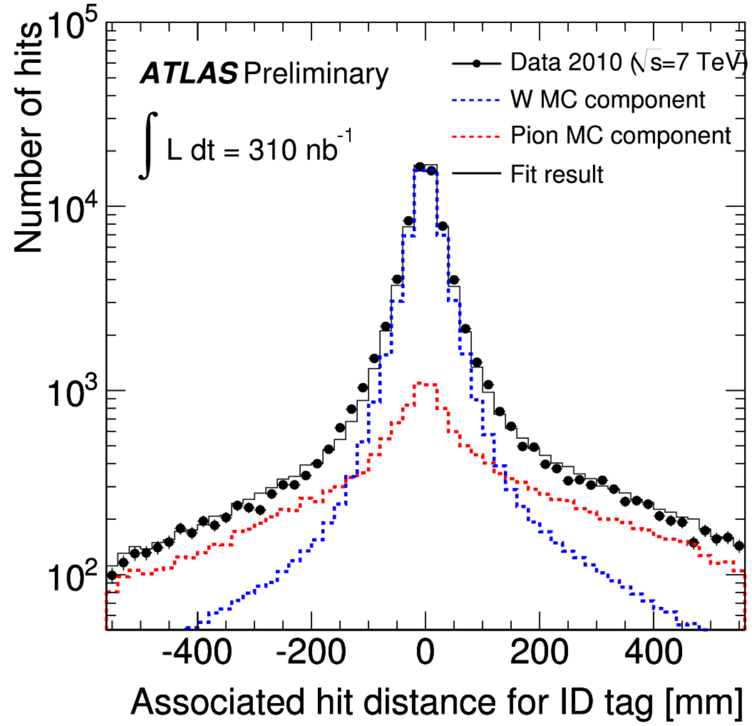


Muon High Level Trigger

- On L1 accept, location of muon (Region of Interest or RoI, about $\Delta\eta$ x $\Delta\varphi$ = 0.1 x 0.1 in barrel, smaller in endcap) sent to Level 2
- Level 2: full-granularity reconstruction of muon within RoI
  - → *Spectrometer segment finding by LUT*
  - → *ID track match included*
- Event Filter (Level 3): identical to offline reconstruction
- Improving momentum resolution → better background rejection
- Work ongoing
  - → *Alignment, algorithm optimisation*

Muon Reconstruction Efficiency





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 x 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