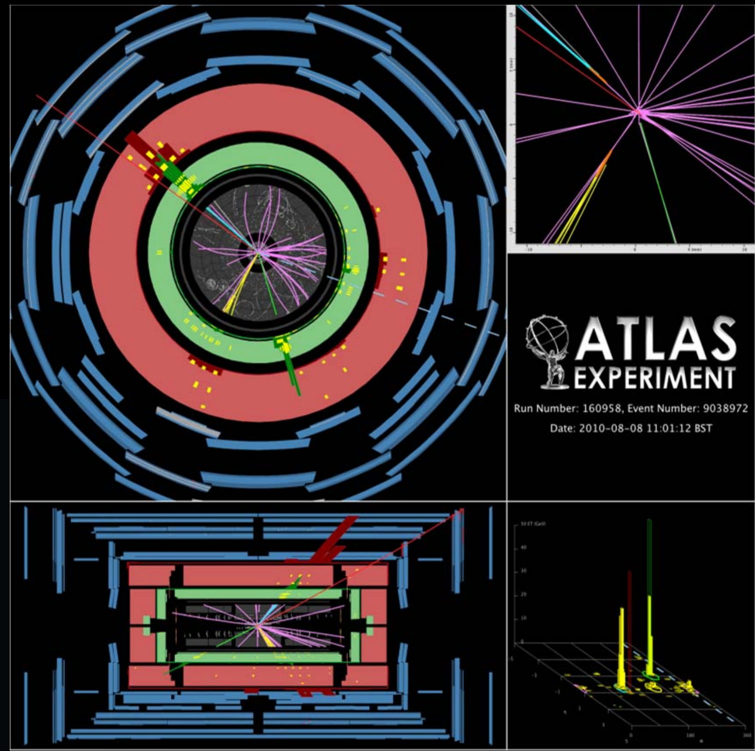
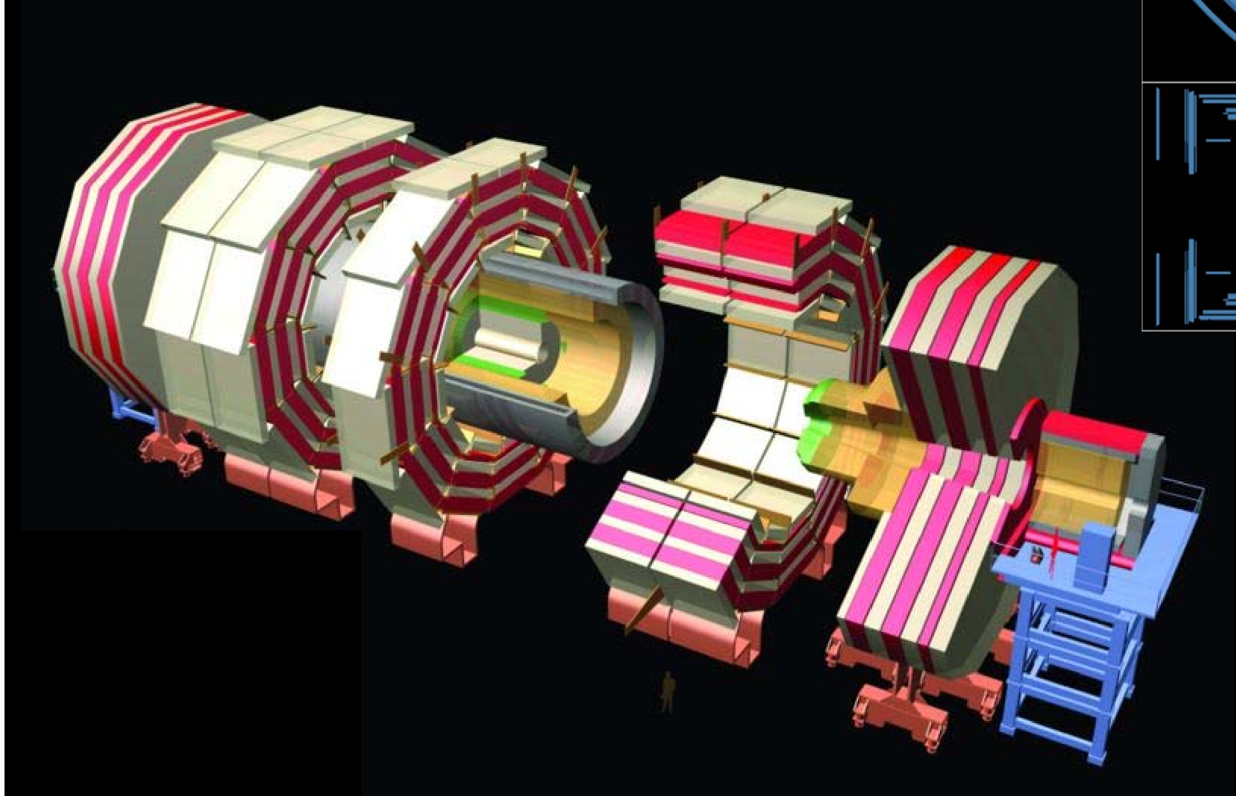
Electroweak and Top Quark Physics at the LHC





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Brief Notes on the Electroweak Theory

The Electroweak Lagrangian

Gauge group $SU(2)_L \times U(1)_Y$

Coupling constants g and g’

Gauge bosons W^1_μ, W^2_μ, W^3_μ and B_μ

Physical boson fields after SSB A_μ (photon) and W^+_μ, W^-_μ, Z_μ (weak bosons)

Weinberg’s mixing angle $\tan\theta_W \equiv g'/g$

Electric charge $e \equiv g\sin\theta_W$

The Electroweak Lagrangian density after SSB

$$\begin{aligned}\mathcal{L}_{\rm EWK} &= \mathcal{L}_{\rm gauge} \\ &+ \mathcal{L}_{\rm EWSB} \\ &+ \mathcal{L}_{\rm kin\text{-}leptons} \\ &+ \mathcal{L}_{\rm kin\text{-}quarks} \\ &+ \mathcal{L}_{\rm Yukawa}\end{aligned}$$

The Gauge Sector

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$ gauge kinetic terms

$$= -\frac{1}{2}W^{-}{}_{\mu\nu}W^{+\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$ vector boson kinetic terms

$$+\ ig\cos\theta_W \left[\left(W^{-}{}_{\mu\nu}W^{+\mu} - W^{+}{}_{\mu\nu}W^{-\mu} \right) Z^{\nu} + Z_{\mu\nu}W^{+\mu}W^{-\nu} \right]$$ ZWW

$$+\ ig\sin\theta_W \left[\left(W^{-}{}_{\mu\nu}W^{+\mu} - W^{+}{}_{\mu\nu}W^{-\mu} \right) A^{\nu} + F_{\mu\nu}W^{+\mu}W^{-\nu} \right]$$ γWW

$$+\ g^2\cos^2\theta_W \left[Z_\mu Z_\nu W^{-\mu}W^{+\nu} - Z_\mu Z^\mu W^{-}{}_{\nu}W^{+\nu} \right]$$ ZZWW

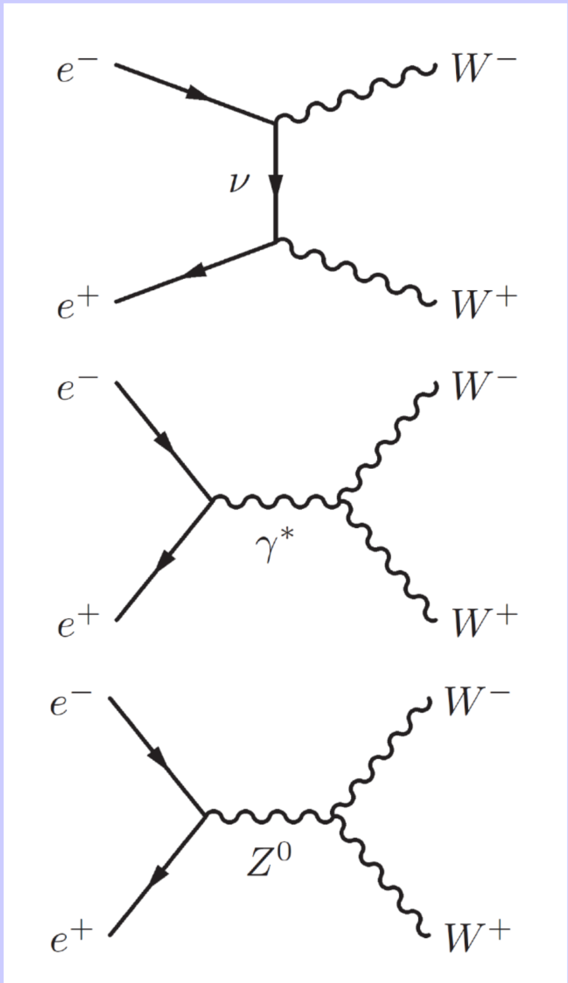
$$+\ g^2\sin^2\theta_W \left[A_\mu A_\nu W^{-\mu}W^{+\nu} - A_\mu A^\mu W^{-}{}_{\nu}W^{+\nu} \right]$$ γγWW

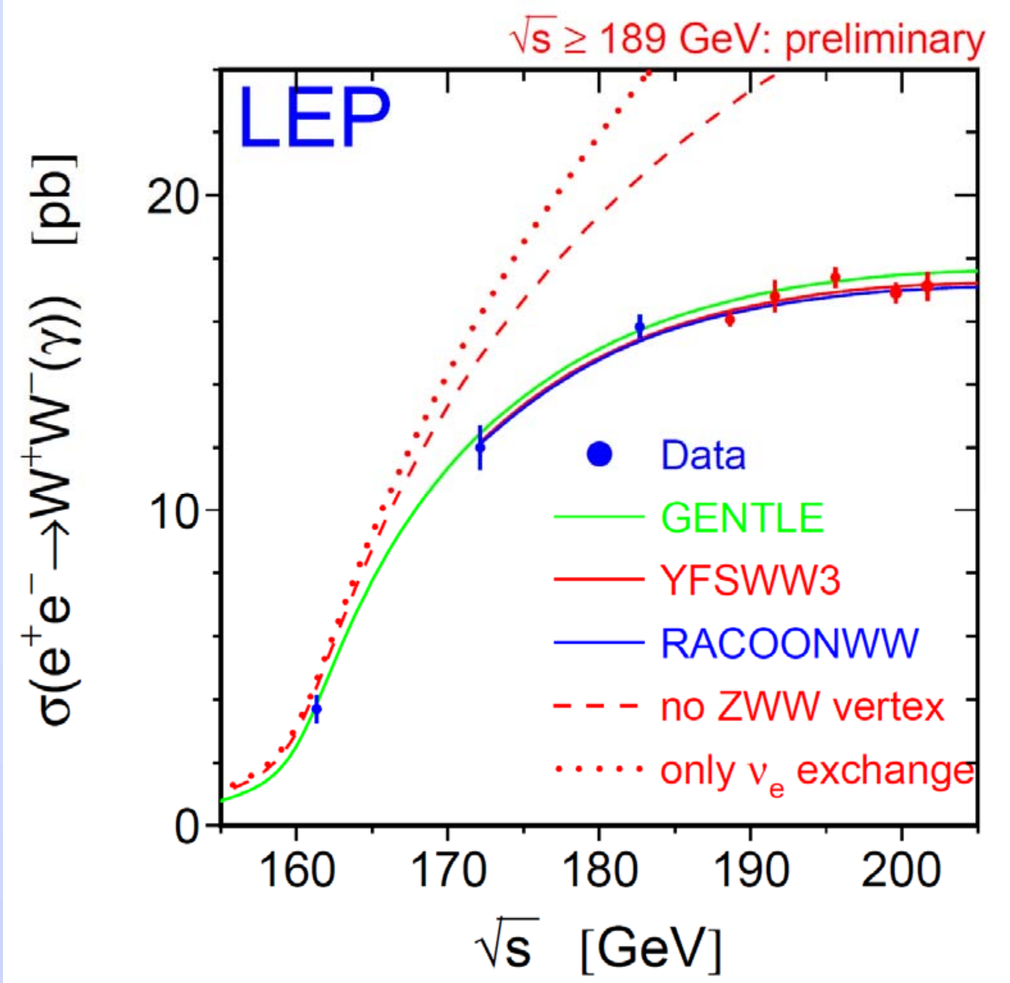
$$+\ g^2\cos\theta_W\sin\theta_W \left[\left(Z_\mu A_\nu + Z_\nu A_\mu \right) W^{-\mu}W^{+\nu} - 2\,Z_\mu A^\mu W^{-}{}_{\nu}W^{+\nu} \right]$$ γZWW

$$+\ \frac{g^2}{2} W^{-}{}_{\mu}W^{+}{}_{\nu} \left[W^{-\mu}W^{+\nu} - W^{-\nu}W^{+\mu} \right]$$ WWWW

Tree-level triple and quartic gauge couplings are central predictions of the Electroweak theory

The Gauge Sector





Clear observation of triple gauge couplings at LEP-2

The Higgs Sector

$$\mathcal{L}_{\rm EWSB} = (\mathcal{D}_\mu\phi)^\dagger(\mathcal{D}^\mu\phi) - \lambda\left[(\phi^\dagger\phi)^2 - v^2\phi^\dagger\phi\right]$$

$$= \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_H^2 h^2$$

Higgs boson kinetic and mass terms

$$+ m_W^2 W^-{}_\mu W^{+\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu$$

electroweak boson mass terms

$$+ \frac{2m_W^2}{v}W^-{}_\mu W^{+\mu}h + \frac{m_Z^2}{v}Z_\mu Z^\mu h + \frac{m_W^2}{v^2}W^-{}_\mu W^{+\mu}h^2 + \frac{m_Z^2}{2v^2}Z_\mu Z^\mu h^2$$

$$- \frac{m_H^2}{2v}h^3 - \frac{m_H^2}{8v^2}h^4 + \left(\mathrm{Cte} = \frac{m_H^2 v^2}{8}\right)$$

coupings to bosons
and self-couplings
of the Higgs boson

$$\mathcal{L}_{\rm Yukawa} = \sum_j\left(\Gamma_{uj}\,\overline{Q^j}{}_L\widetilde{\phi}\,u_{jR} + \Gamma_{dj}\,\overline{Q^j}{}_L\phi\,d'{}_{jR}\right) + \sum_\ell \Gamma_\ell\,\overline{L^\ell}{}_L\phi\,\ell_R + \mathrm{h.\ c.}$$

$$= \sum_f\left(m_f\,\overline{f}f + \frac{m_f}{v}\,\overline{f}fh\right)$$

fermion mass terms and
couplings of the Higgs boson
to fermions

Electroweak Relations

- electroweak boson masses

$$m_W \equiv \frac{gv}{2} \quad \text{and} \quad m_Z \equiv \frac{gv}{2\cos\theta_W}$$

v = 246 GeV
is the vacuum
expectation value (VEV)
of the Higgs field

- electroweak relation between electroweak bosons masses

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$$ **= 1** (at tree-level)

define $$s_W^2 \equiv 1 - \frac{m_W^2}{m_Z^2}$$

- three parameters of the electroweak theory are precisely measured

the Fermi constant	$G_F = 1.166\,37(1) \times 10^{-5}\,\mathrm{GeV}^{-2}$
the QED fine structure constant	$\alpha_{\mathrm{QED}}^{-1}(m_Z^2) = 128.940\,(5)$
the mass of the Z boson	$M_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$

$$g^2 = \frac{4\pi\alpha_{\mathrm{QED}}}{\sin^2\theta_W}$$

- link with the Fermi theory

$$\alpha_{\mathrm{QED}} = \frac{\sqrt{2}}{\pi} G_F m_W^2 \sin^2\theta_W$$

$$m_W^2 = \frac{A_0^2}{\sin^2\theta_W} \quad \text{with} \quad A_0 = \left(\frac{\pi\alpha_{\mathrm{QED}}}{\sqrt{2}G_F}\right)^{1/2} \simeq 38.433\ \mathrm{GeV}$$

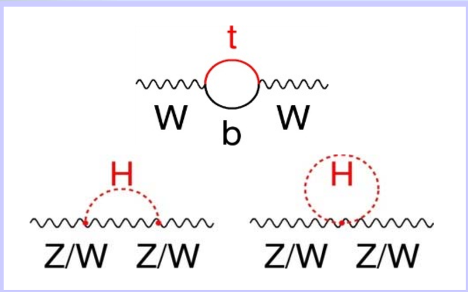
Radiative Corrections

Electroweak radiative corrections

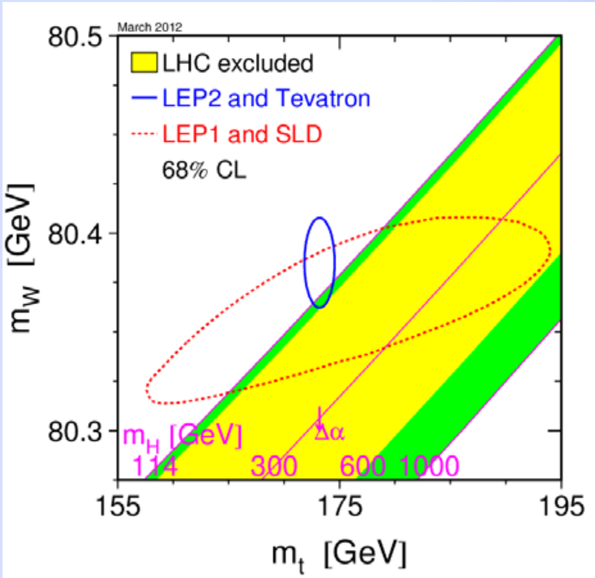
physical quantities $M_W^2 = m_W^2\,(1+\Delta r\,), \quad \bar{\rho} = 1 + \Delta\rho \quad \text{and} \quad \sin^2\theta_W^{\text{eff}} = s_W^2\,(1+\Delta\kappa)$

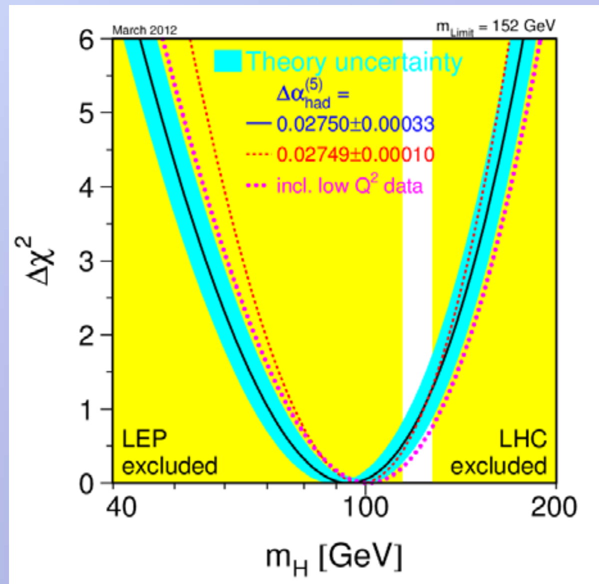
$\Delta\rho_t \simeq 0.01 \times [m_t/175 \ \ \text{GeV}]^2$

$\Delta\rho_H \simeq -0.0015 \times \log(m_H/M_W)$



the three electroweak radiative correction parameters are of the order of the percent and involve contributions from top quark and Higgs boson loops





- Precision measurements of m_W and m_{top} are crucial for testing the EW theory
  - a 1 GeV shift on m_{top} translates into a 10 GeV shift on m_H

The Lepton Sector

left-handed doublets

$$L^{\ell}{}_{L} \equiv \frac{1}{2}(1-\gamma^5)\begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}$$

right-handed singlets

$$\ell_R \equiv \frac{1}{2}(1+\gamma^5)\,\ell$$

three families

$$\begin{aligned}
\mathcal{L}_{\text{kin-leptons}} &= \sum_{\ell}\; i\,\overline{L^{\ell}}{}_{L}\gamma^\mu \mathcal{D}_\mu L^{\ell}_{L} \;+\; i\,\overline{\ell}_R\gamma^\mu\mathcal{D}_\mu\ell_R \\
&= \sum_{\ell}\; i\,\overline{\nu}_\ell\gamma^\mu\partial_\mu\nu_\ell \;+\; i\,\overline{\ell}\gamma^\mu\partial_\mu\ell \;-\; e\,\overline{\ell}\gamma^\mu\ell\,A_\mu \\
&\quad + \frac{g}{2\sqrt{2}}\left[\,\overline{\ell}\gamma^\mu(1-\gamma^5)\nu_\ell\,W^{-}{}_{\mu} + \overline{\nu}_\ell\gamma^\mu(1-\gamma^5)\ell\,W^{+}{}_{\mu}\,\right] \\
&\quad + \frac{g}{2\cos\theta_W}\;\overline{\nu}_\ell\gamma^\mu\frac{1}{2}(1-\gamma^5)\nu_\ell\,Z_\mu \\
&\quad + \frac{g}{2\cos\theta_W}\left[\sin^2\theta_W\,\overline{\ell}\gamma^\mu(1+\gamma^5)\ell + (-\frac{1}{2}+\sin^2\theta_W)\,\overline{\ell}\gamma^\mu(1-\gamma^5)\ell\right] Z_\mu
\end{aligned}$$

The QuarkSector

left-handed doublets

$$Q^j{}_L \equiv \frac{1}{2}(1-\gamma^5)\begin{pmatrix} u_j \\ d'_j \end{pmatrix}$$

right-handed singlets

$$u_{jR} \equiv \frac{1}{2}(1+\gamma^5)\,u_j$$

$$d'_{jR} \equiv \frac{1}{2}(1+\gamma^5)\,d'_j$$

$$\begin{aligned}
\mathcal{L}_{\text{kin-quarks}} = \sum_j \; & i\,\overline{Q^j}_L\gamma^\mu\mathcal{D}_\mu Q^j{}_L \;+\; i\,\overline{u}_{jR}\gamma^\mu\mathcal{D}_\mu u_{jR} \;+\; i\,\overline{d}_{jR}\gamma^\mu\mathcal{D}_\mu d_{jR} \\
= \; & i\,\overline{\mathbf{u}}\gamma^\mu\partial_\mu\mathbf{u} + i\,\overline{\mathbf{d}}\gamma^\mu\partial_\mu\mathbf{d} \;+\; \frac{2}{3}e\,\overline{\mathbf{u}}\gamma^\mu\mathbf{u}A_\mu \;-\; i\,\frac{1}{3}e\,\overline{\mathbf{d}}\gamma^\mu\mathbf{d}A_\mu \\
& + \frac{g}{2\sqrt{2}}\left[\,\overline{\mathbf{d}}\mathbf{V}_{\text{CKM}}{}^\dagger\gamma^\mu(1-\gamma^5)\mathbf{u}\,W^-{}_\mu + \overline{\mathbf{u}}\gamma^\mu(1-\gamma^5)\mathbf{V}_{\text{CKM}}\mathbf{d}\,W^+{}_\mu\,\right] \\
& + \frac{g}{2\cos\theta_W}\left[-\frac{2}{3}\sin^2\theta_W\,\overline{\mathbf{u}}\gamma^\mu(1+\gamma^5)\mathbf{u} + \left(+\frac{1}{2}-\frac{2}{3}\sin^2\theta_W\right)\overline{\mathbf{u}}\gamma^\mu(1-\gamma^5)\mathbf{u}\right]Z_\mu \\
& + \frac{g}{2\cos\theta_W}\left[\;\frac{1}{3}\sin^2\theta_W\,\overline{\mathbf{d}}\gamma^\mu(1+\gamma^5)\mathbf{d} + \left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)\overline{\mathbf{d}}\gamma^\mu(1-\gamma^5)\mathbf{d}\;\right]Z_\mu
\end{aligned}$$

The CKM matrix V_{CKM} (complex unitary 3x3 matrix: 4 real parameters) links flavor and mass eigenstates of down-type quarks

d' = V_{CKM} d

source of CP violation in the SM

Couplings of the Z boson

Feynman rules at tree level

vertex function at the *Zff* vertex

$$V^{\mu}_{Z^0 f\bar{f}} = -i\, C^{1/2} \bar{f}\gamma^{\mu}\left[R_f(1+\gamma^5) + L_f(1-\gamma^5) \right] f = -i\, C^{1/2}\bar{f}\gamma^{\mu}\left[v_f - a_f\,\gamma^5 \right] f$$

with $C = \dfrac{g^2}{4\cos^2\theta_W}$ and $\begin{cases} v_f = T^3_f - 2Q_f \sin^2\theta_W \\ a_f = T^3_f \end{cases}$

Vector and Axial-Vector couplings of the Z boson to fermions

$\sin^2\theta_W = 0.2312$

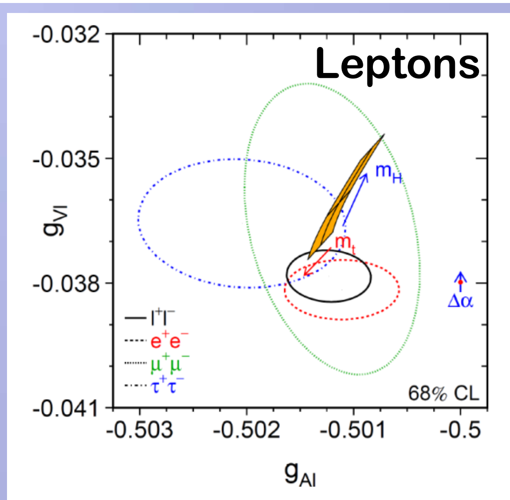
Fermion	$v_f = T^3_f - 2Q_f \sin^2\theta_W$	$a_f = T^3_f$	L_f	R_f	$v_f^2 + a_f^2$
$\nu_e,\, \nu_\mu,\, \nu_\tau$	$1/2$	$1/2$	$1/2$	0	$1/2$
$e,\, \mu,\, \tau$	$-\,1/2 + \;\; 2\,\sin^2\theta_W \simeq -0.038$	$-1/2$	$\simeq -0.269$	$\simeq +0.231$	$\simeq 0.251$
$u,\, c,\, t$	$1/2 - 4/3\,\sin^2\theta_W \simeq +0.192$	$1/2$	$\simeq +0.346$	$\simeq -0.154$	$\simeq 0.287$
$d,\, s,\, b$	$-\,1/2 + 2/3\,\sin^2\theta_W \simeq -0.346$	$-1/2$	$\simeq -0.423$	$\simeq +0.077$	$\simeq 0.370$

Effective couplings

$$\begin{cases} g_{Vf} = \sqrt{\rho}\,\left(T^3_f - 2Q_f \sin^2\theta^{\rm eff}_W\right) \\ g_{Af} = \sqrt{\rho}\; T^3_f \end{cases}$$

left-right asymmetry $\mathcal{A}_f \equiv \dfrac{2\, g_{Vf}\, g_{Af}}{g_{Vf}{}^2 + g_{Af}{}^2}$

forward-backward asymmetry at the Z pole (in e^+e^- collisions) $A^{0\,f}_{\rm FB} \equiv \dfrac{3}{4}\mathcal{A}_e \mathcal{A}_f$



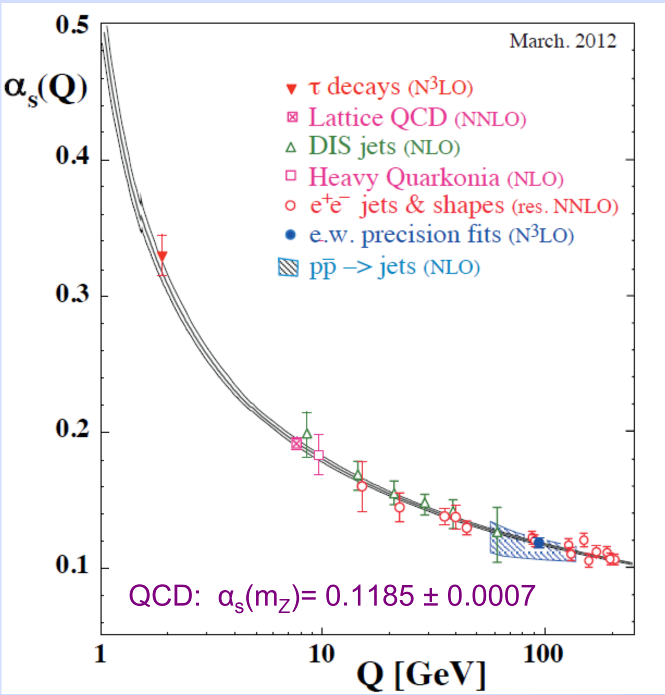
The Standard Model

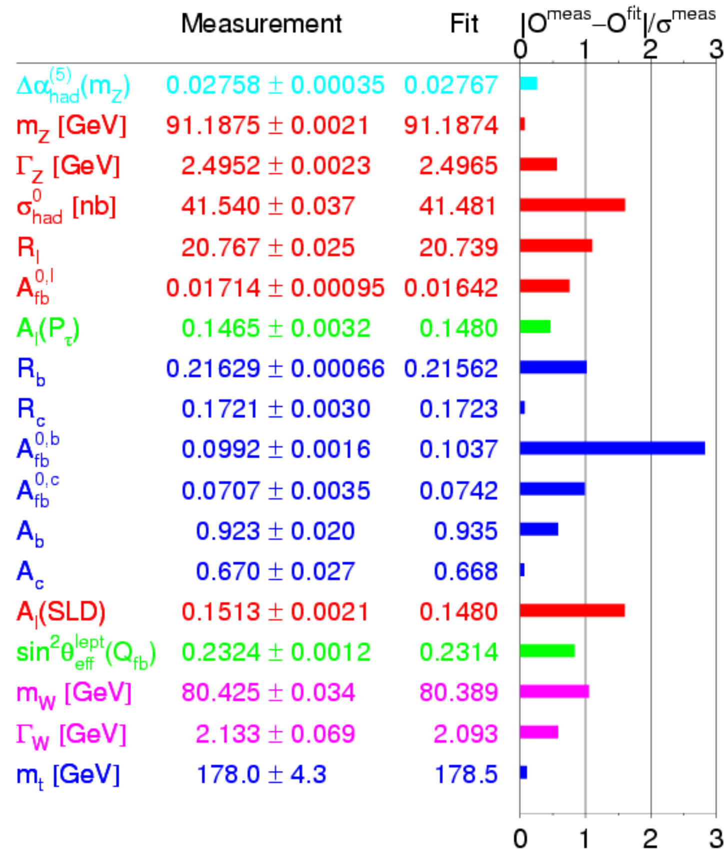
The Standard Model

- a very predictive model
- 17 parameters (masses, couplings, CKM)

  all measured experimentally
- prediction of the top quark mass
- constraints on the Higgs boson mass

Strong coupling constant





Electroweak fit

The Top Quark

The top quark *t*

- is the SU(2)$_L$ partner of the bottom quark *b*
  - third generation of quarks
  - weak isospin +½ member of doublet (Y=1/6)
  - color triplet with electric charge +2/3e
- is the heaviest known fundamental particle

  $m_{top} \approx 174$ GeV

  - 40 times heavier than the bottom quark!
- is the only quark with "natural" mass
  - Yukawa coupling to the Higgs field close to 1

$$m_{\rm top} = y_t v/\sqrt{2} \approx 174\,{\rm GeV} \Rightarrow y_t \approx 1$$

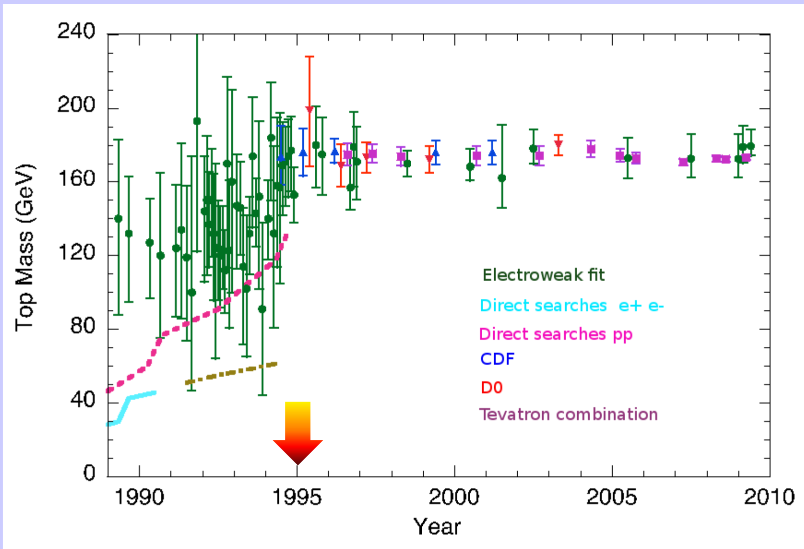
(this suggests that the top quark plays a special role in the spontaneous breaking of the electroweak symmetry)

  - the top quark coupling to the Higgs field is much stronger than that of any other fermion. It is involved in the main production mode of the Higgs boson at the LHC (gluon fusion) and in its decay to photons
- decays almost exclusively as $t \to b\, W^+$

$$\Gamma\left(t \to bW^+\right) = \frac{\alpha}{16 s_W^2} \left|V_{tb}\right|^2 \frac{m_{\rm top}^3}{m_W^2} \left[1 - 3\frac{m_W^4}{m_{\rm top}^4} + 2\frac{m_W^6}{m_{\rm top}^6}\right]$$

~1.5 GeV
(> Λ_{QCD})

- is the only quark that decays before it has time to hadronize
  - top decay time: ~5 x10^{-25} s ; typical hadronization time: ~2 x10^{-24} s

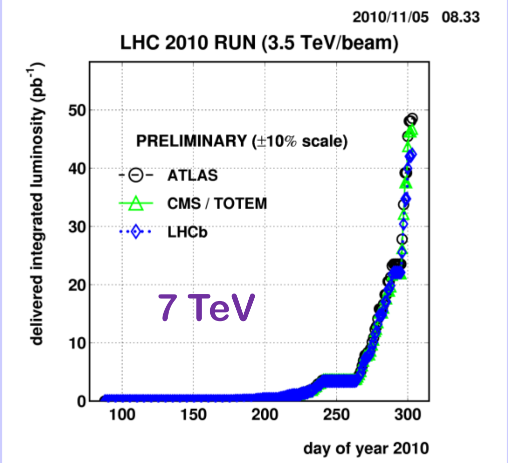


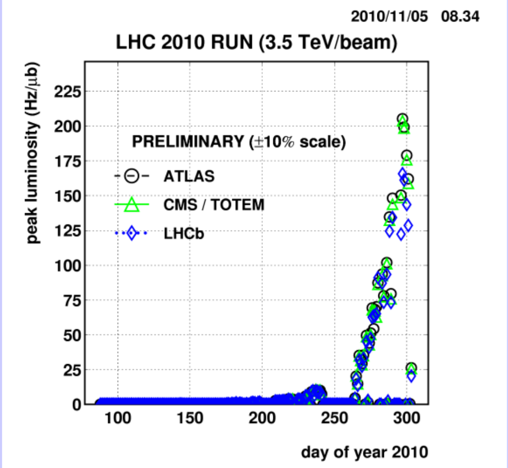
prediction of the top quark mass and discovery


LHC

LHC Running

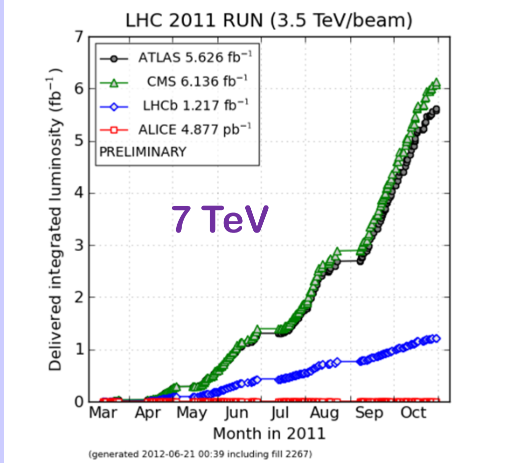
2010

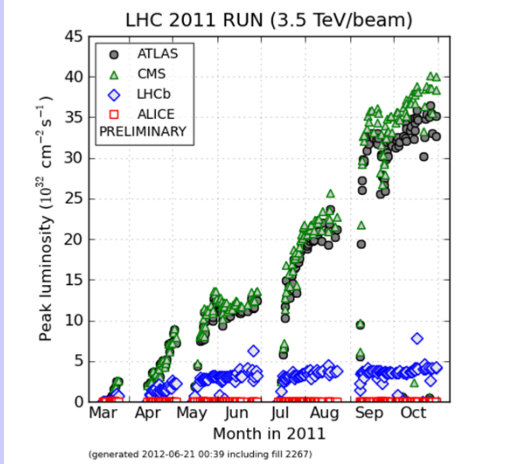




50 pb^{-1} at 7 TeV

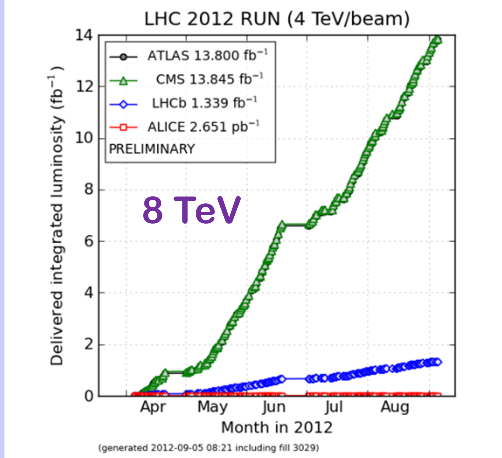
2011

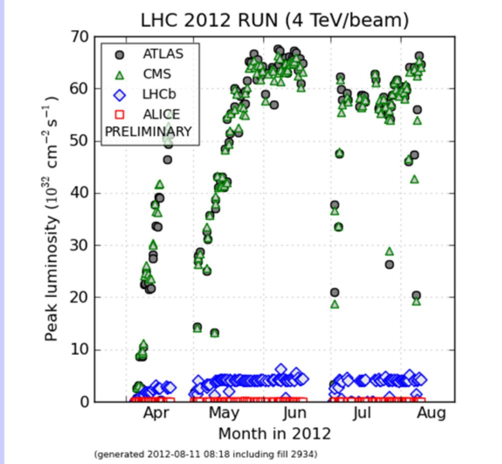




5 fb^{-1} at 7 TeV

2012





> 14 fb^{-1} at 8 TeV

instantaneous luminosity unit
10^{33} cm^{-2} s^{-1} = 1 Hz/nb

http://lpc.web.cern.ch/lpc/

LHC Running

- **In 2010, ~ 50 pb^{-1}/ exp. at 7 TeV**

  many electroweak measurements
  are using data corresponding to ~40 pb^{-1}
  with *clean conditions*
  at the end of the run: $L \sim 2 \times 10^{32}\ cm^{-2}s^{-1}$

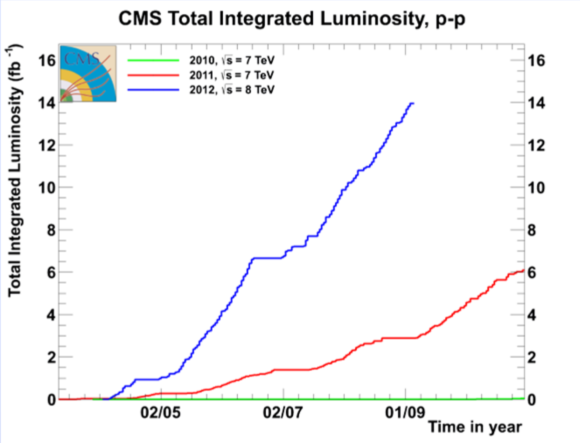
- **In 2011, ~ 6 fb^{-1}/exp. at 7 TeV**

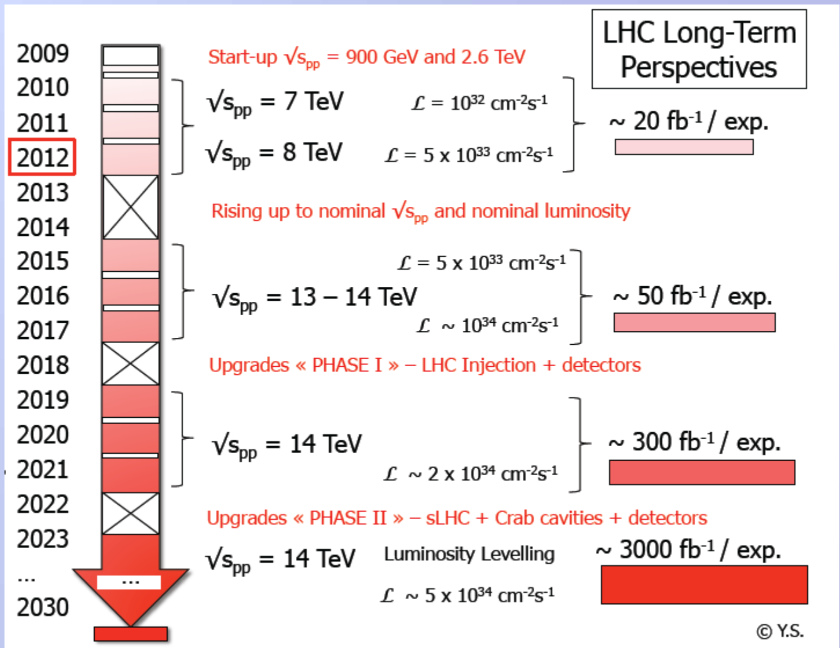
  × 130 in integrated luminosity
  with respect to 2010!
  instantaneous luminosity increase by steps
  (number of bunches, β^*, emittance…)
  from $L \sim 2 \times 10^{32}\ cm^{-2}s^{-1}$ to $L \sim 4 \times 10^{33}\ cm^{-2}s^{-1}$
  × 20 in peak luminosity
  with respect to 2010!

- **In 2012, already 14 fb^{-1}/exp. at 8 TeV**

  already × 2 in integrated luminosity
  with respect to 2011
  steady instantaneous luminosity
  in the range L = 6-7 $\times 10^{33}\ cm^{-2}s^{-1}$
  × 1.5 in peak luminosity
  with respect to the end of 2011

  expect between 20 and 30 fb^{-1}/exp.
  at the end of the run

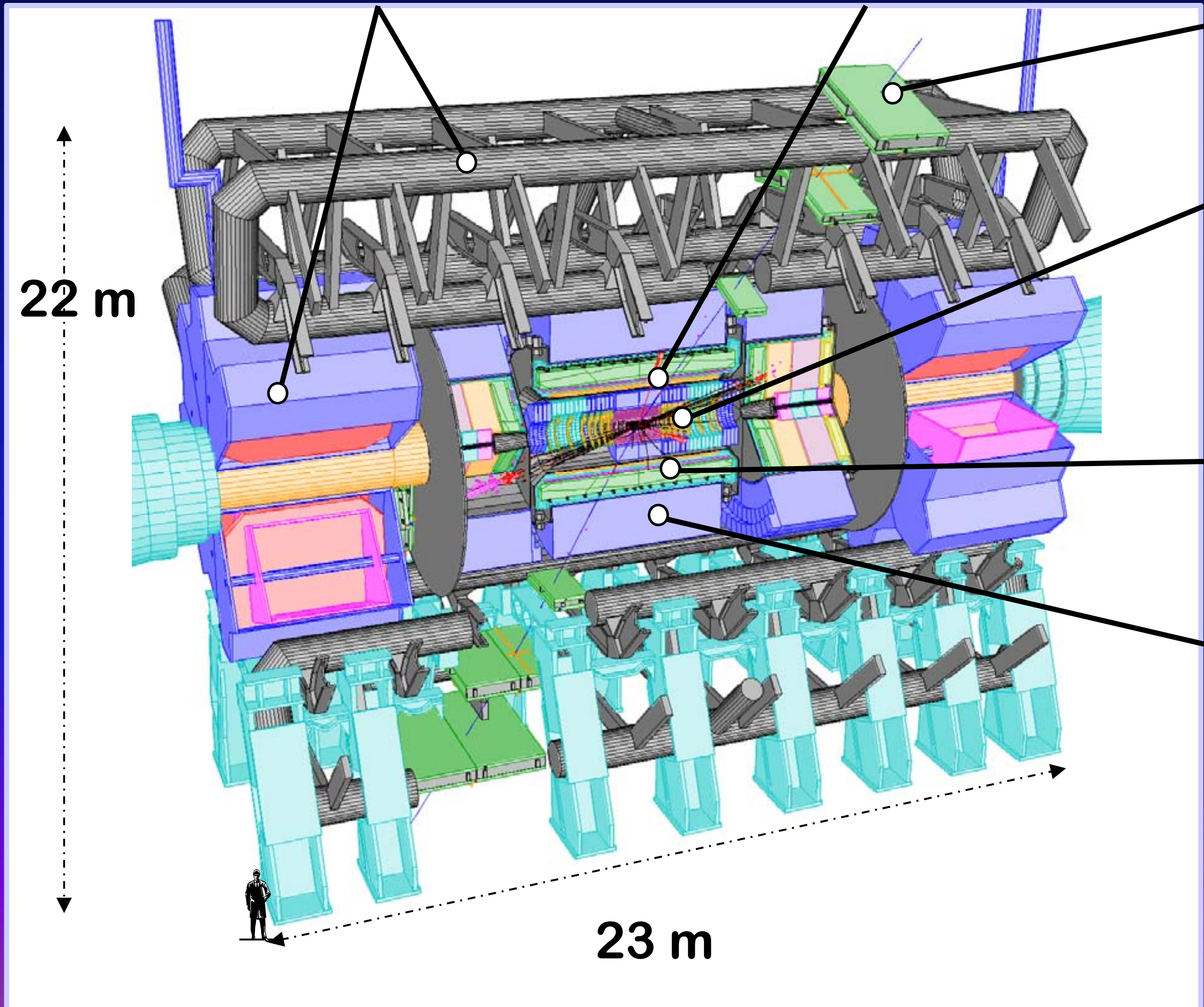




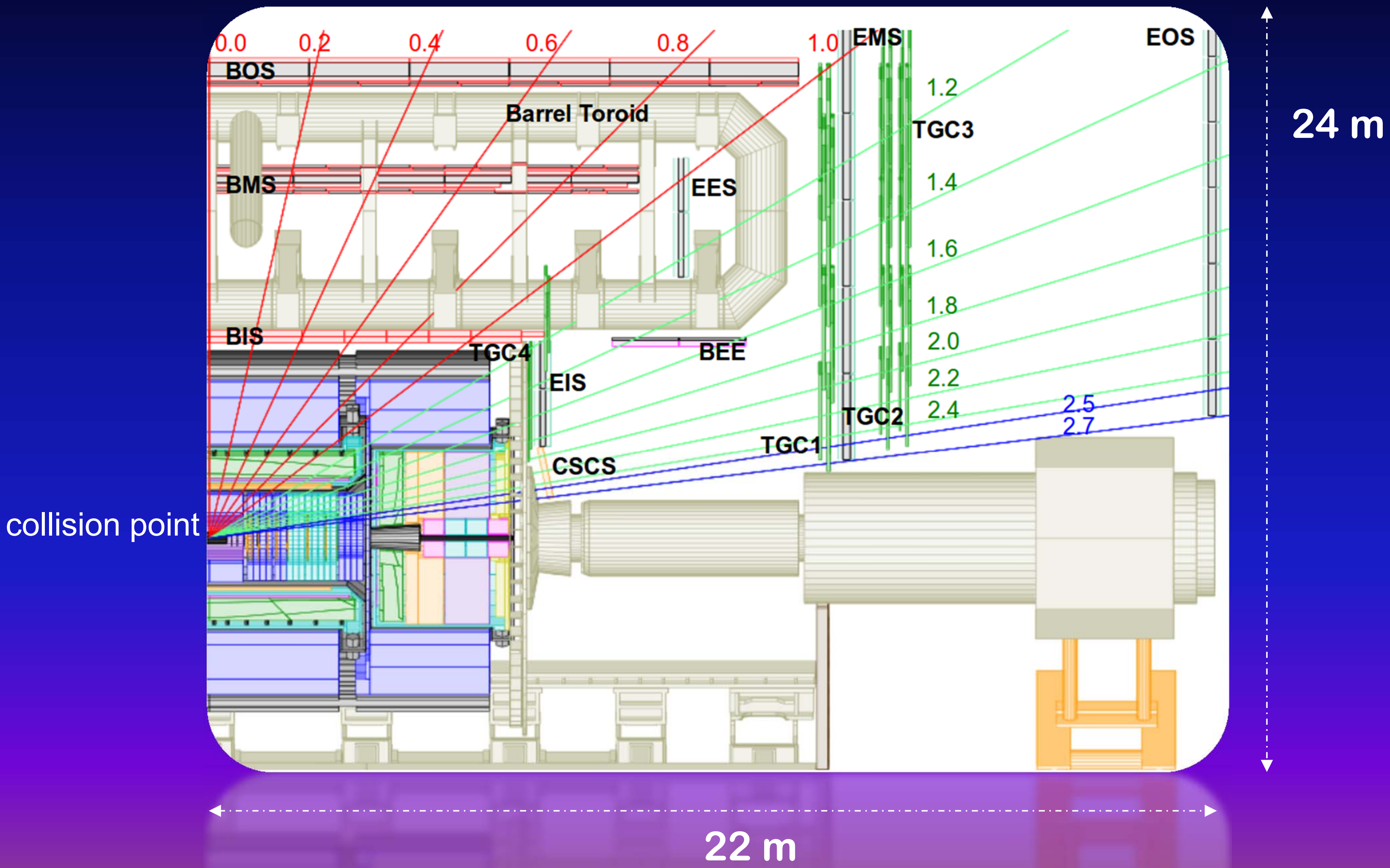
LHC Experiments

ATLAS

Weight : 7000 t
Diameter : 25 m
Length: 44 m
Solenoid: 2 Tesla, Toroid: 3-8 T.m

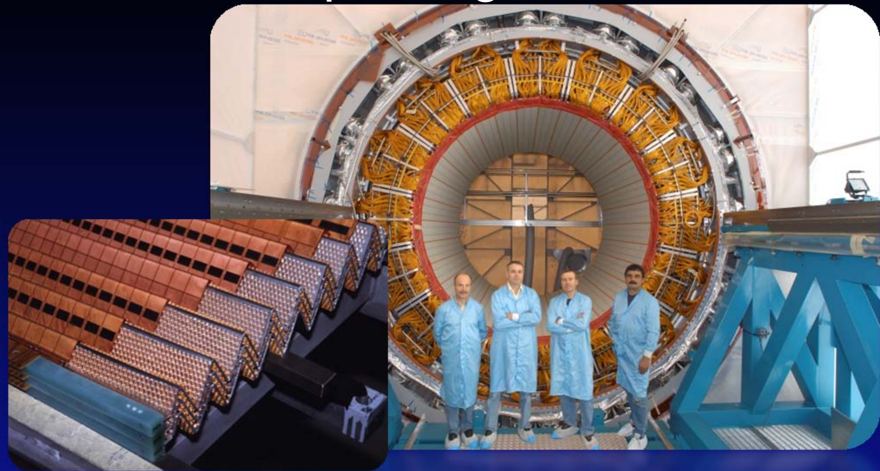


ATLAS

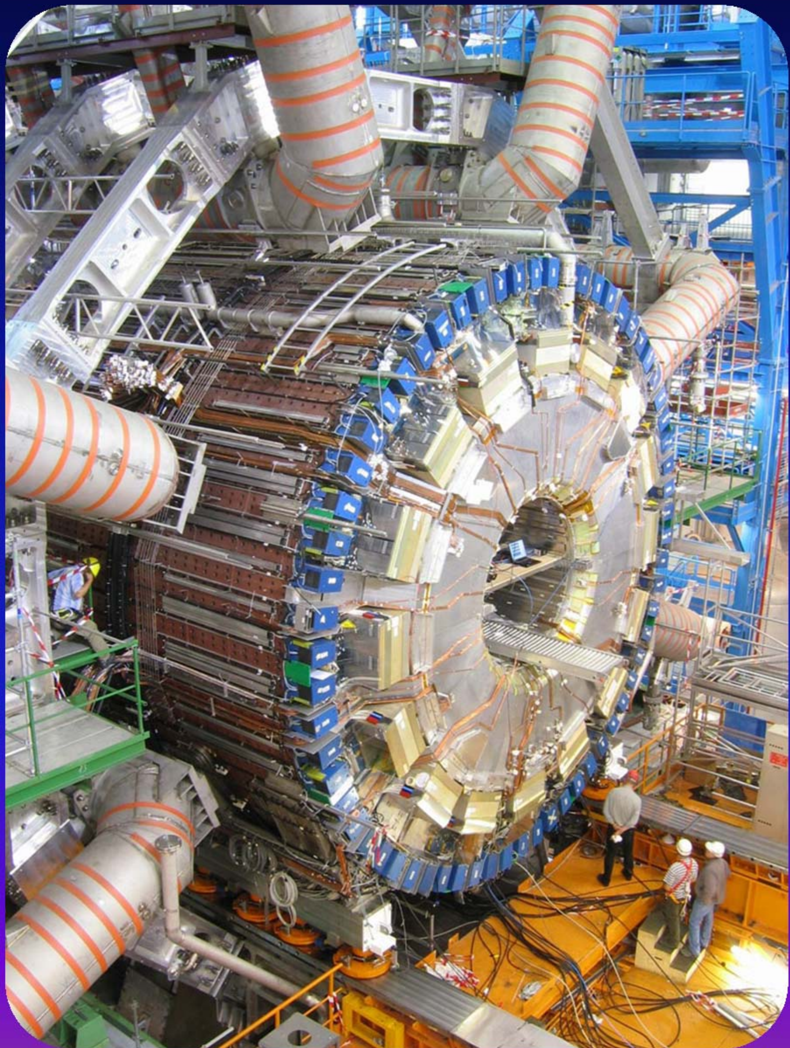

0.0
0.2
0.4
0.6
0.8
1.0
EMS
EOS
BOS
Barrel Toroid
1.2
TGC3
BMS
EES
1.4
1.6
1.8
BIS
2.0
TGC4
BEE
EIS
2.2
2.4
TGC2
2.5
2.7
TGC1
CSCS
collision point
24 m
22 m

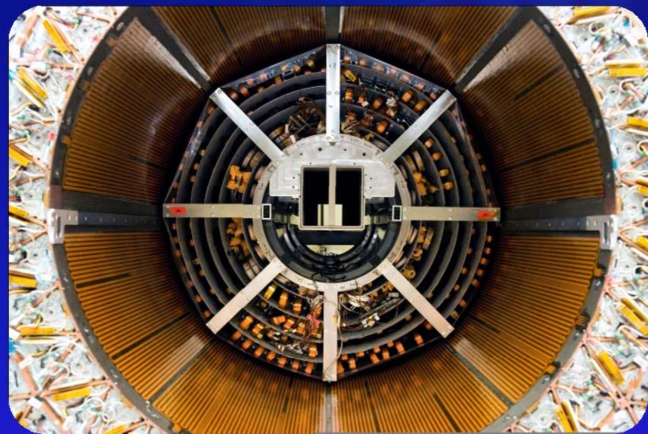
ATLAS

Liquid Argon Calorimeter



Barrel toroid & Calorimeters

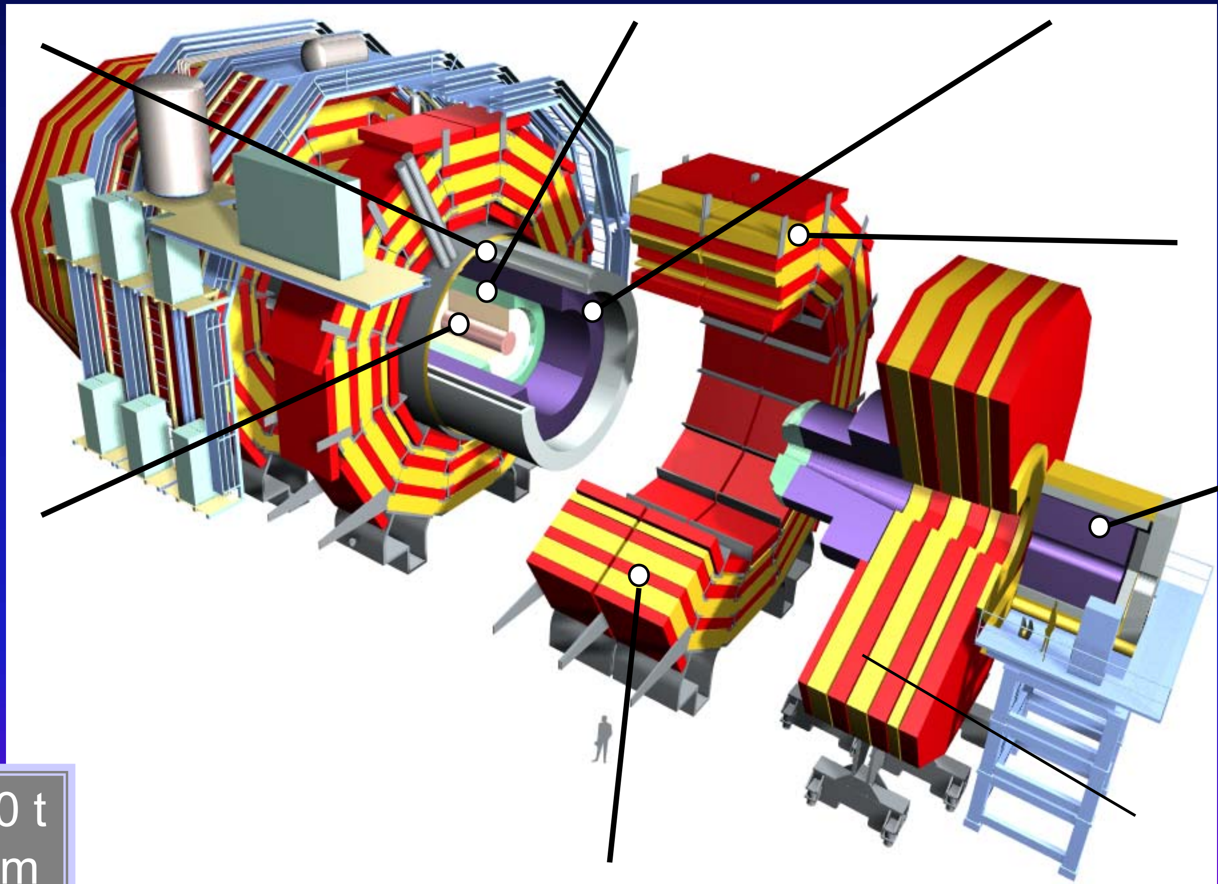




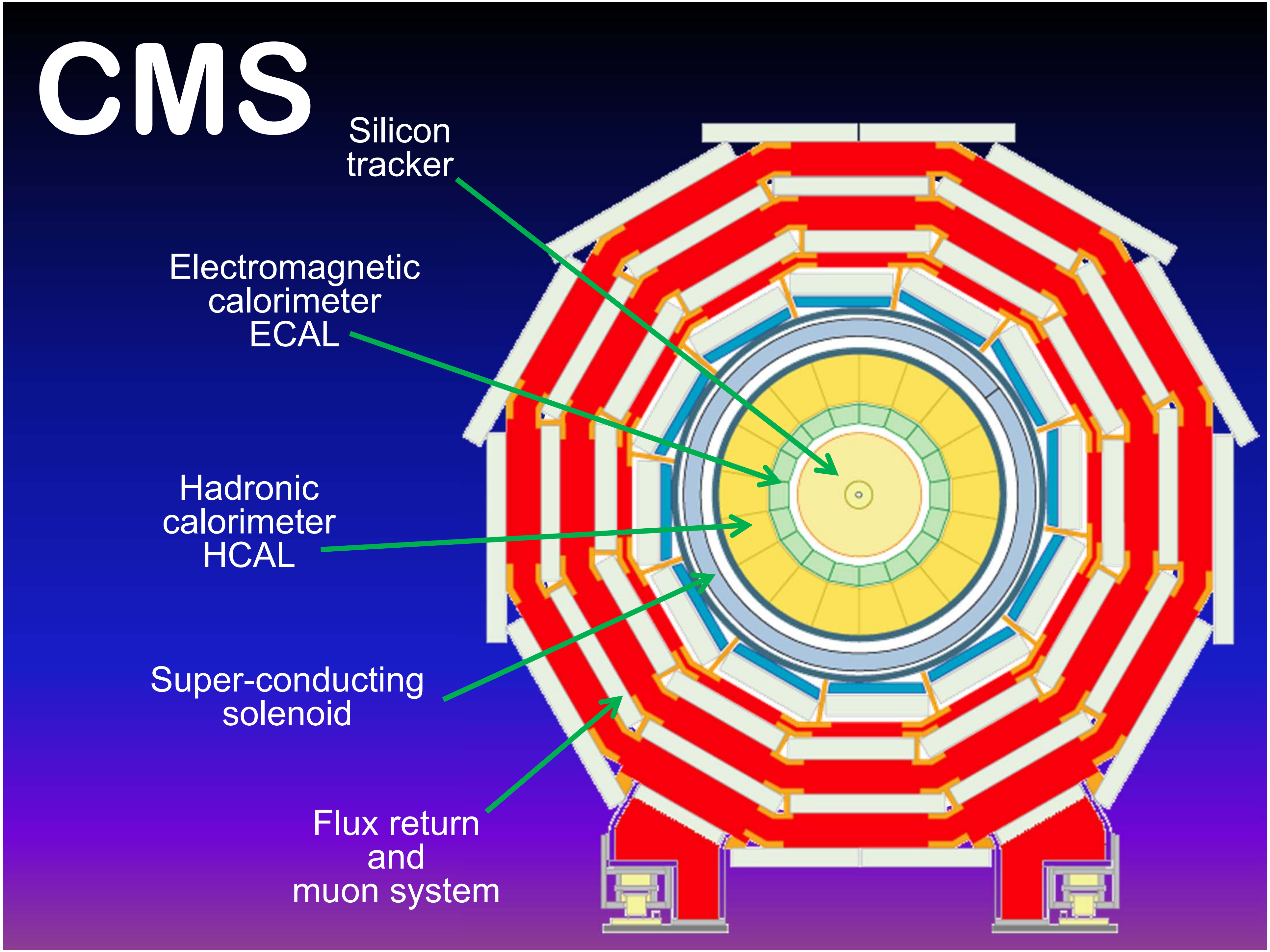
SCT
&
TRT

Pixel
Detector

CMS

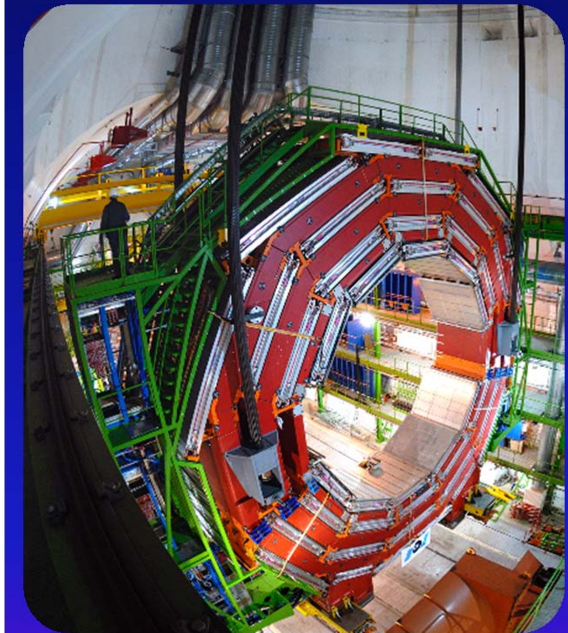


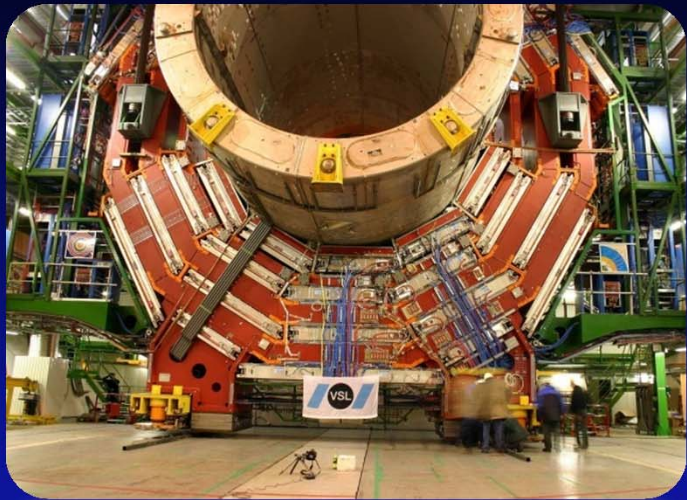
Weight : 12500 t
Diameter : 15 m
Length: 20 m
B field: 3.8 Tesla


CMS
Silicon tracker
Electromagnetic calorimeter ECAL
Hadronic calorimeter HCAL
Super-conducting solenoid
Flux return and muon system

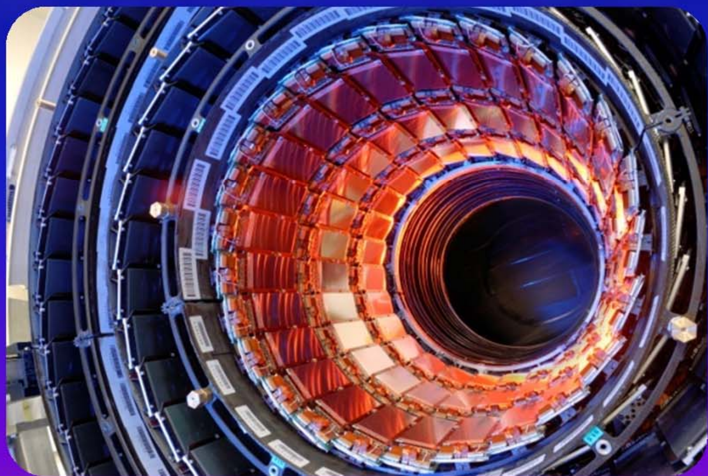
CMS

Muon system



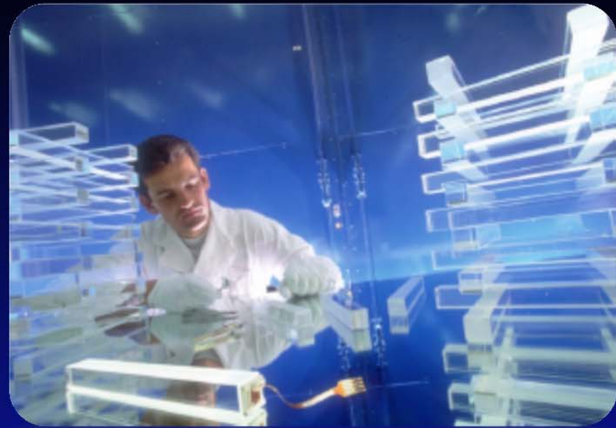


Solenoid 3.8 Tesla



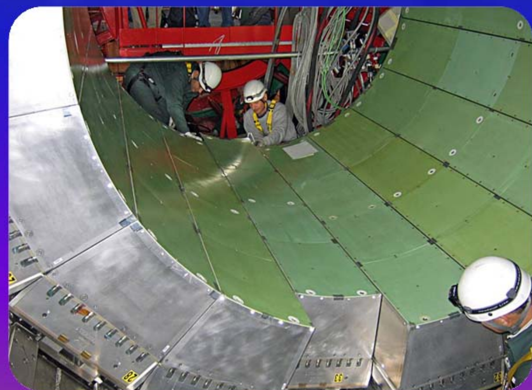
Silicon tracker

ECAL



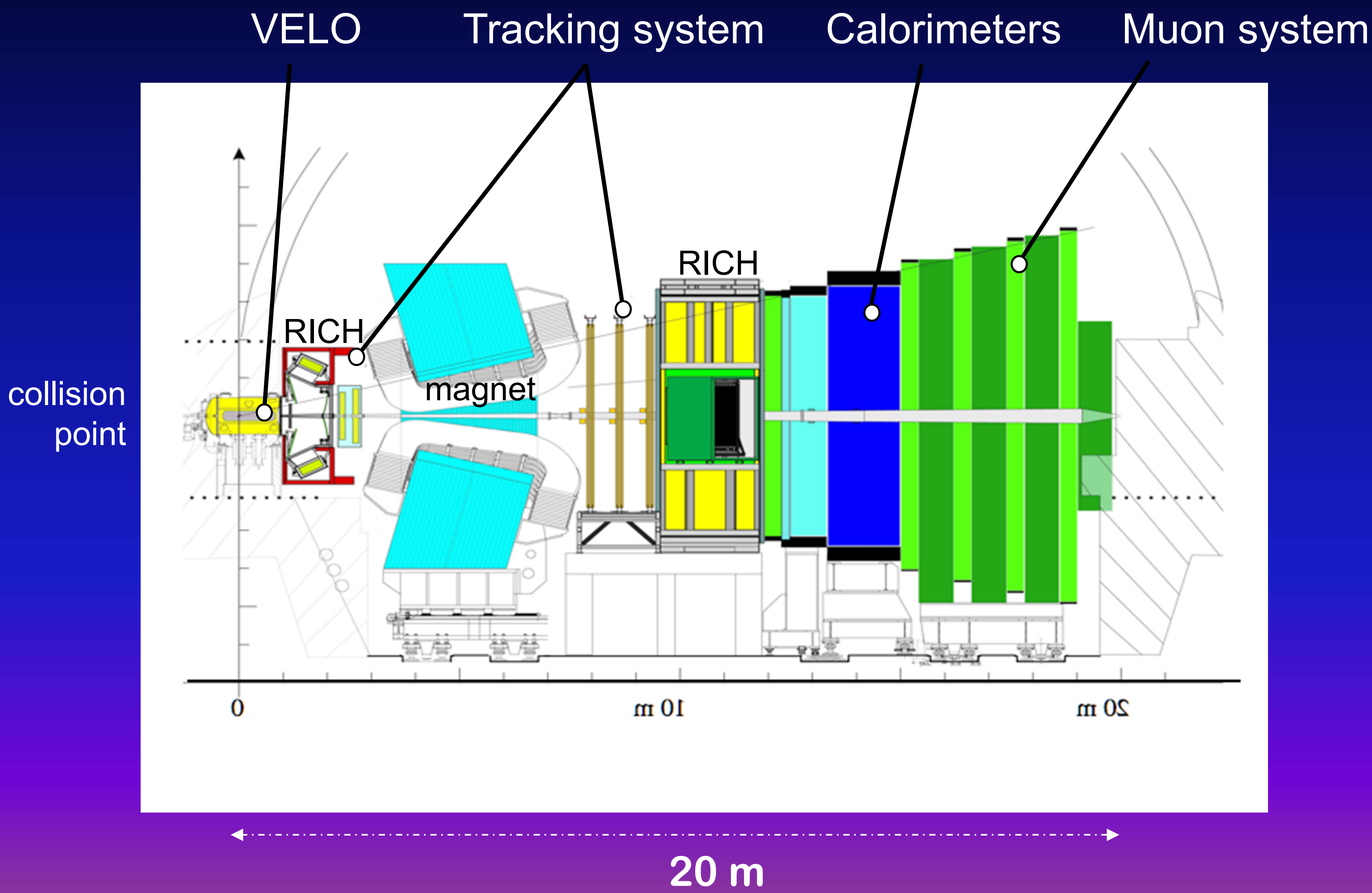
crystals

one 200-crystal module

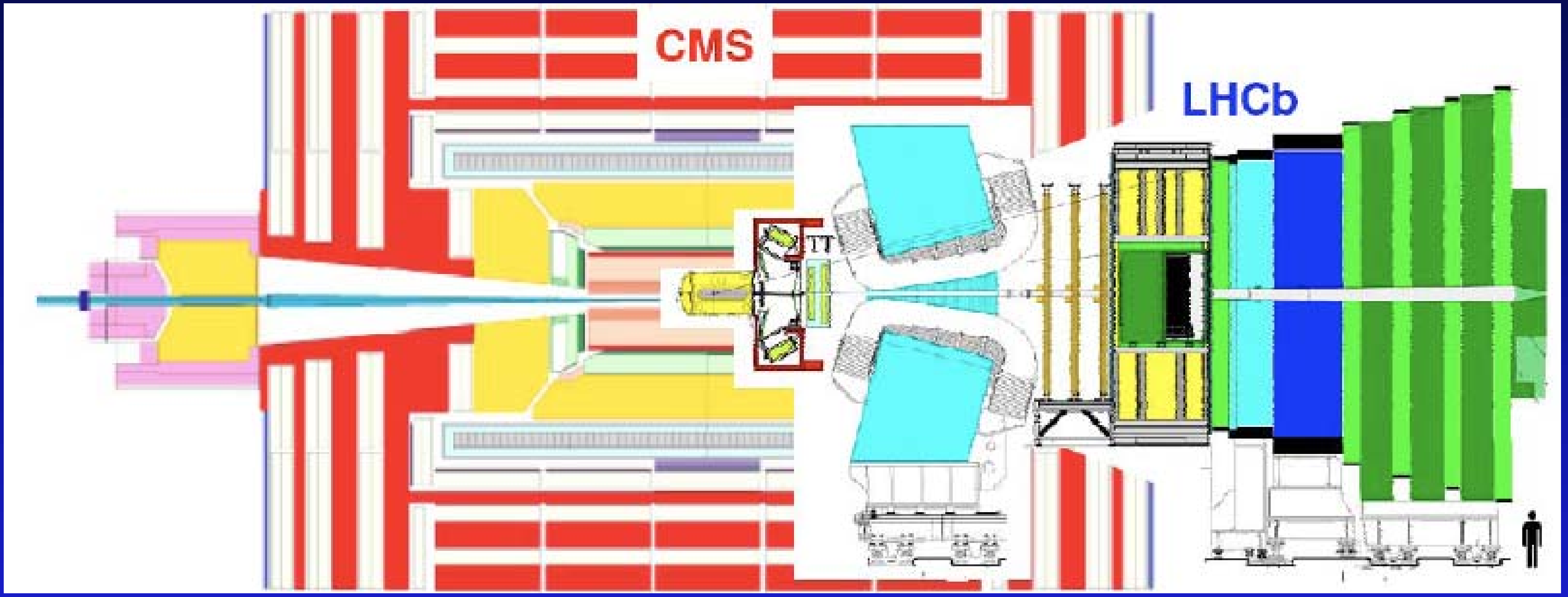


36 super-modules

LHCb


VELO
Tracking system
Calorimeters
Muon system
RICH
magnet
RICH
collision point
0
20 m

LHCb

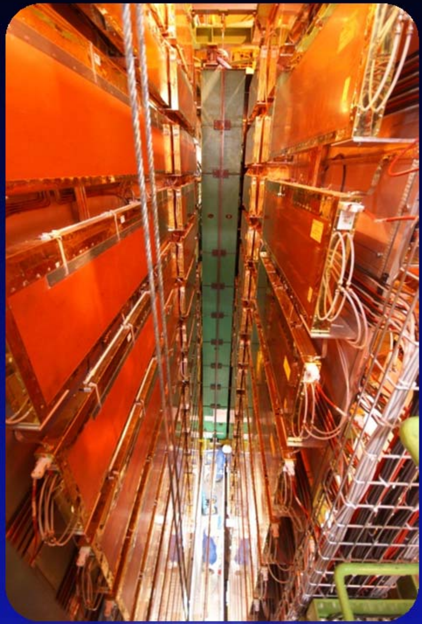


Measurements extended up to $|\eta(\mu)|=4.9$

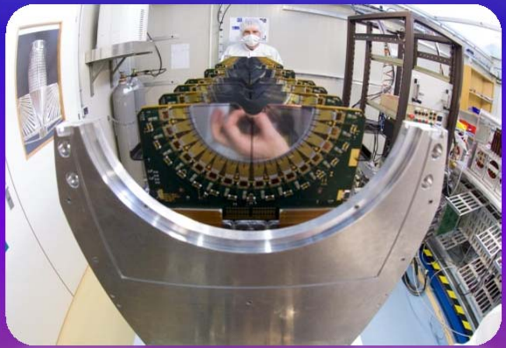
LHCb

Magnet

Muon system

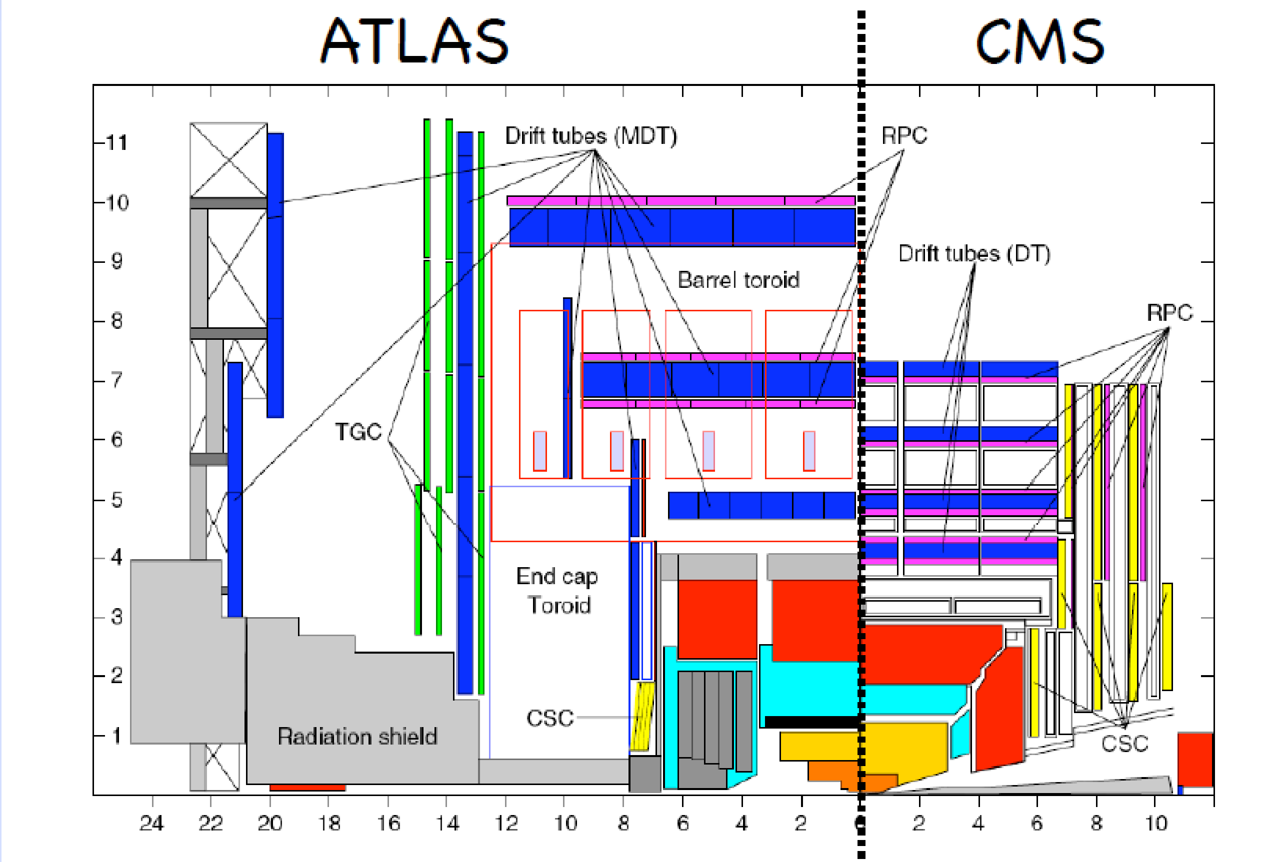


Vertex Locator (VELO)



Inner and outer tracker

Muon Spectrometers



ATLAS and CMS muon spectrometers use similar technologies:

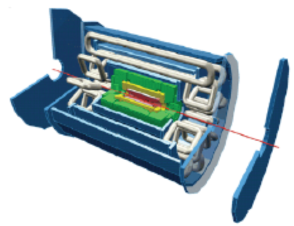
Drift Tubes for precision position measurements

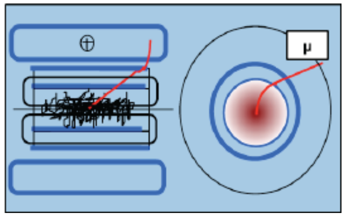
Resistive Plate Chambers for fast triggering

ATLAS and CMS

ATLAS

ATLAS A Toroidal LHC ApparatuS





4 magnets

Three SC air toroids

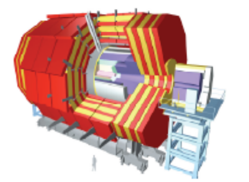
An inner 2T solenoid

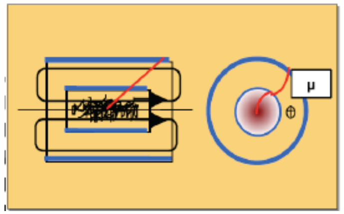
	ATLAS	CMS
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • $B = 2$T • $\sigma(p_T) \sim$ **3.8%** (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • $B = 3.8$T • $\sigma(p_T) \sim$ **1.5%** (at 100 GeV, $\eta = 0$)
MAGNETS	• Solenoid + Air-core muon toroids • Calorimeters outside field • 4 magnets	• Solenoid • Calorimeters inside field • 1 magnet
EM CALORIMETER	• Pb / Liquid argon accordion • $\sigma(E) \sim$ **10–12% / $\sqrt{E}$ $\oplus$ 0.2–0.35%** • Uniform longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E) \sim$ **3–5.5% / $\sqrt{E}$ $\oplus$ 0.5%** • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. & Cu-liquid argon • $\sigma(E) \sim$ **45% / $\sqrt{E}$ $\oplus$ 1.3%** (Barrel)	• Brass / scintillator • $\sigma(E) \sim$ **100% / $\sqrt{E}$ $\oplus$ 8%** (Barrel)
MUON	• Monitored drift tubes + CSC (fwd) • $\sigma(p_T) \sim$ **10.5 / 10.4%** (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes + CSC (fwd) • $\sigma(p_T) \sim$ **13 / 4.5%** (1 TeV, $\eta = 0$) (standalone / combined with tracker)

Ann.Rev.Nucl.Part.Sci.56:375-440,2006.

CMS

CMS Compact Muon Solenoid





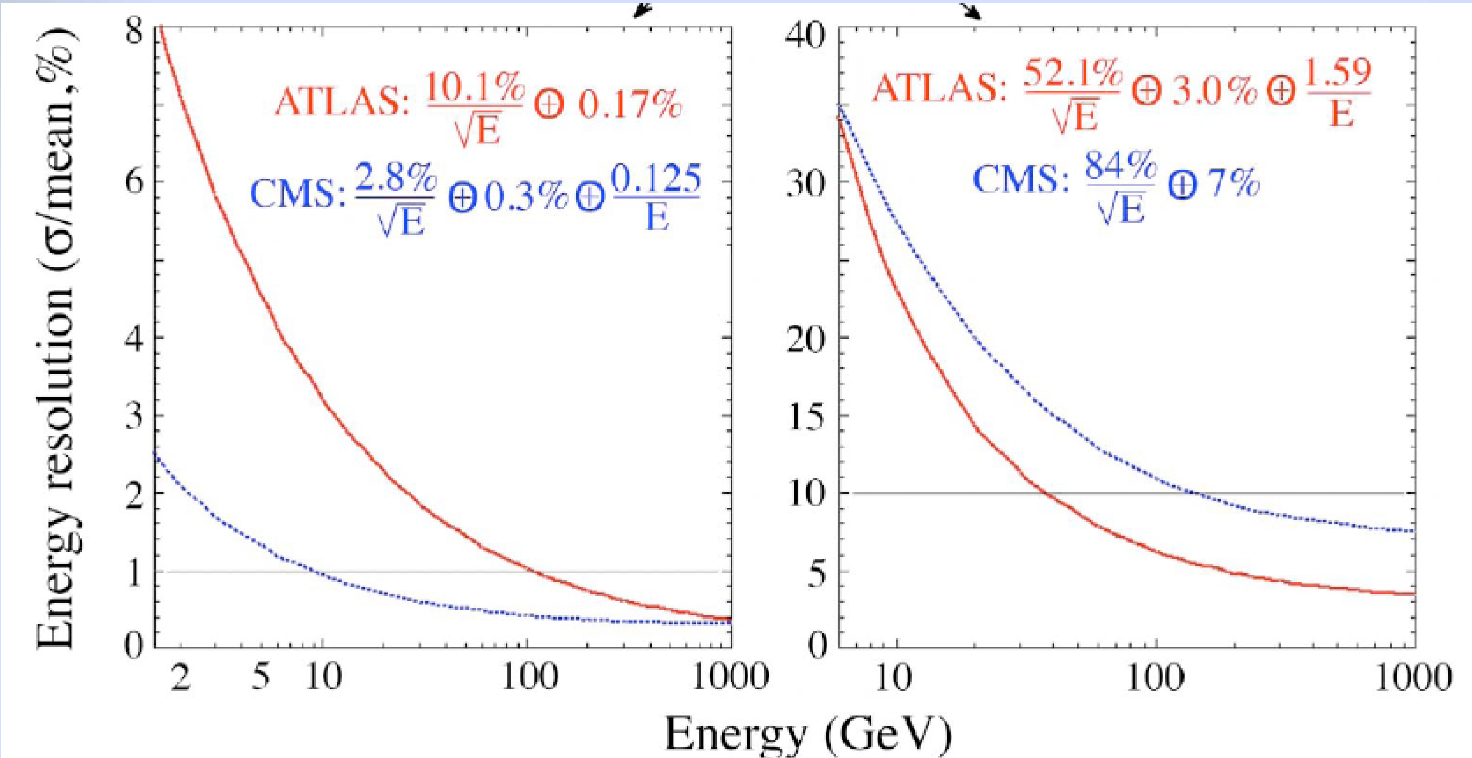
1 magnet

3.8T solenoid

Relevant for electroweak and top physics

ATLAS	CMS
σ/p_T (tracker) ~ $3.8 \times 10^{-4}\, p_T \oplus 0.001$	σ/p_T (tracker) ~ $1.5 \times 10^{-4}\, p_T \oplus 0.005$
σ/E (EM cal) ~ $10\%/\sqrt{E(\text{GeV})} \oplus 0.3\%$	σ/E (EM cal) ~ $3\%/\sqrt{E(\text{GeV})} \oplus 0.5\%$
σ/E (HA cal) ~ $50\%/\sqrt{E(\text{GeV})} \oplus 3\%$	σ/E (HA cal) ~ $100\%/\sqrt{E(\text{GeV})} \oplus 8\%$

ATLAS & CMS: Calorimetry



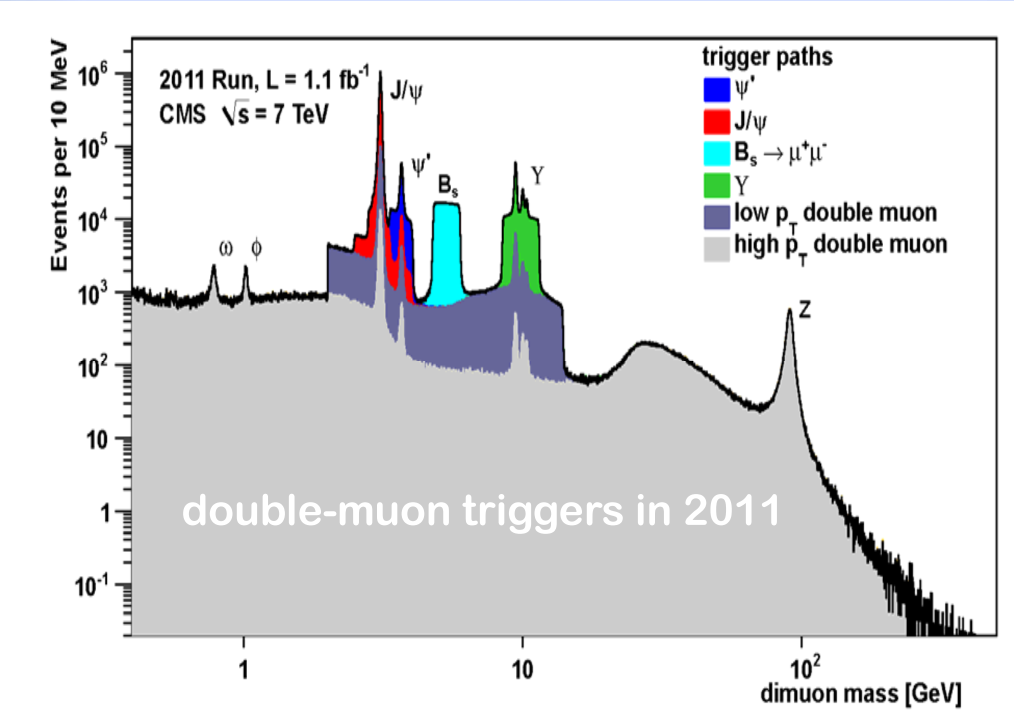
- CMS ECAL has superior energy resolution, but its calibration is subtle
- ATLAS EMC has excellent uniformity and linearity, plus longitudinal shower sampling

- ATLAS has good hadron calorimetry, for jet and missing ET measurements
- CMS compensates relatively mediocre hadron calorimetry by energy flow techniques

Basics Objects for Electroweak and Top Physics Analysis

Triggering

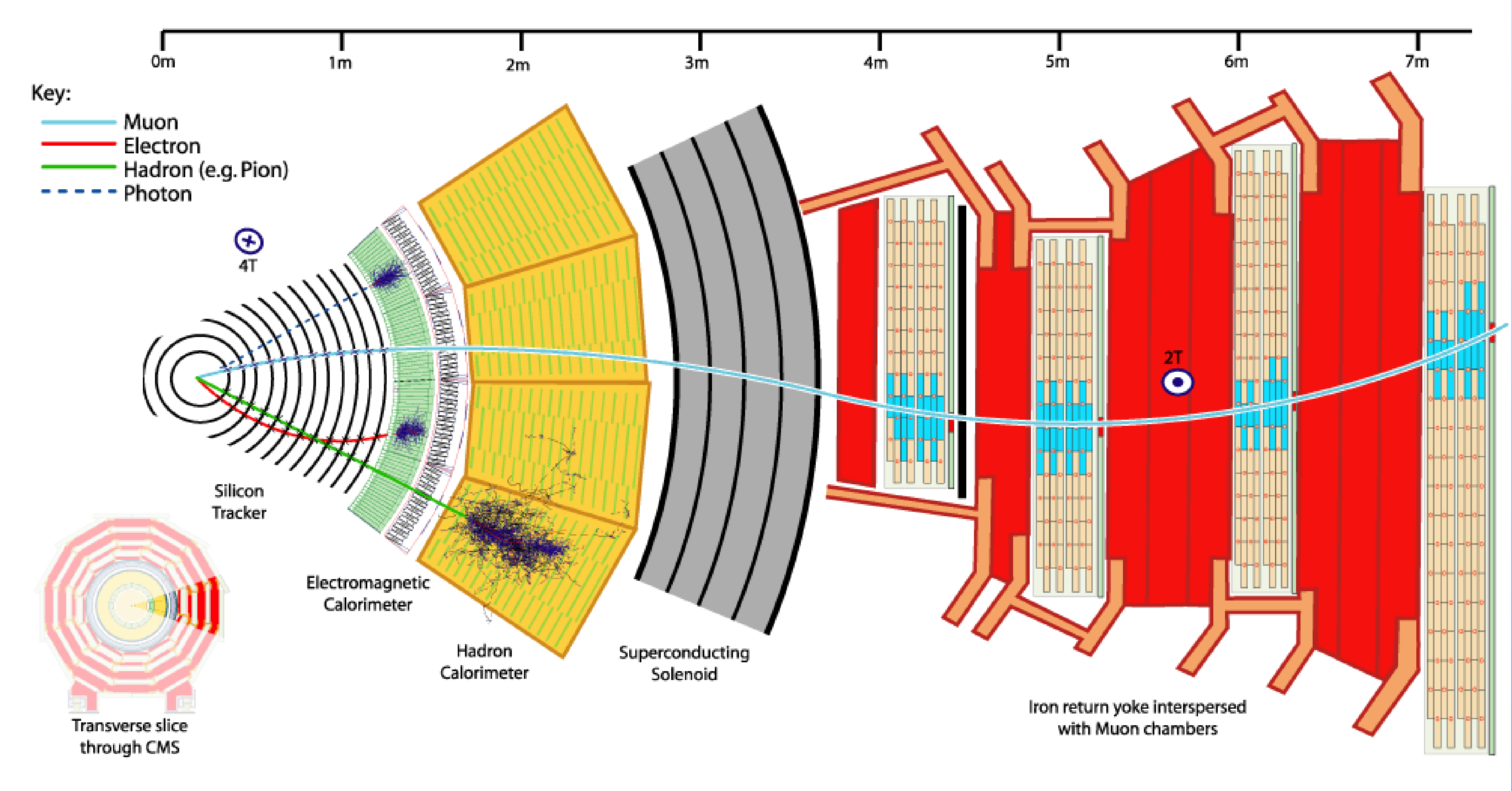
- **2010, single-lepton (e and μ) triggers for W and Z analyses**
  - electrons at L1: $E_T > 5$ or 8 GeV
  - muons at L1: $p_T > 7$ GeV
  - HLT thresholds up to $p_T > 17$ GeV, below typical offline cut of 20 GeV
  - e+τ trigger for the Z $\rightarrow \tau\tau$ analysis



- **2011, single-lepton triggers**
  - higher and higher p_T thresholds!
  - stringent identification and isolation criteria on electrons at HLT level
- **2011, lepton+«object» triggers**
  - lepton+central-jet, lepton+MET, etc.
- **2011, double-lepton triggers**
  - thresholds typically 8, 13 GeV (muons)
  - thresholds typically 8, 17 GeV (electrons)

trigger is a major issue
for inclusive W analyses in 2011-2012
especially in the electron channel

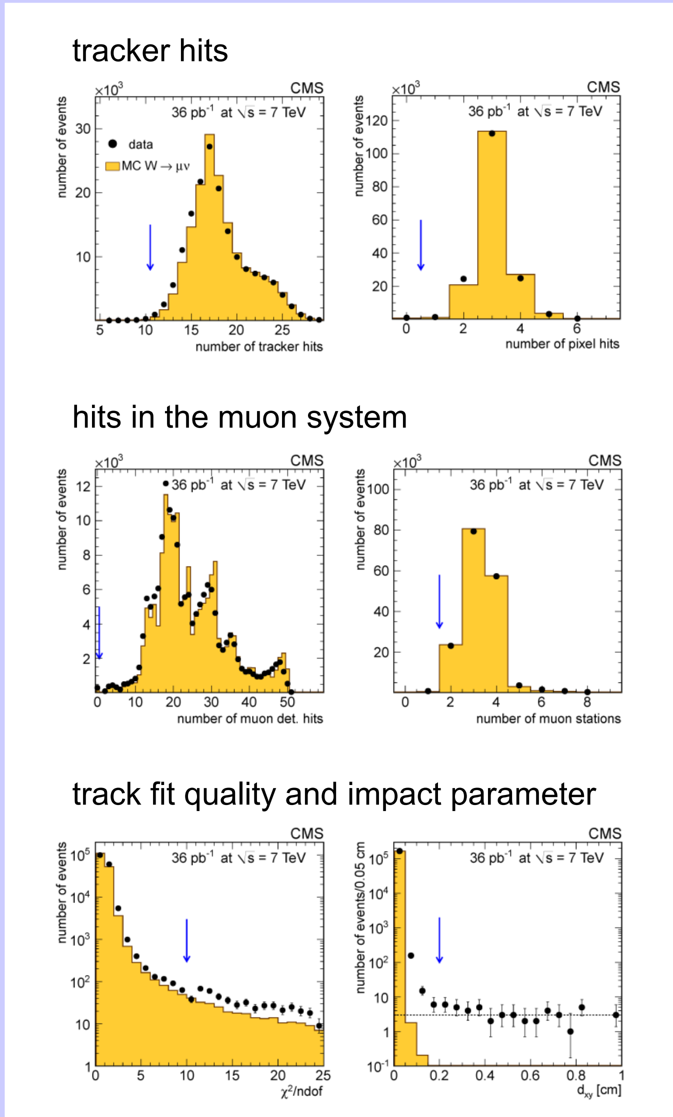
Physics Objects



Muons from W and Z

typically p_T > 20 GeV and $|\eta|$ < 2.4

- **ATLAS**
  - standalone reconstruction in muon spectrometer
  - calorimeter muon
  inner detector track associated with MIP deposit
  - combined muon
  refit of the entire track taking into account energy losses in calorimeters
  typical pT resolution for EWK studies is 3%
- **CMS**
  - inner tracking (3.8 T B-field)
  typical pT resolution for EWK studies is 1.5%
  - match with muon spectrometer
  - quality criteria
  number of hits, track fit, impact parameter, etc.
- **Charge mis-assignment negligible**
  measured from cosmic rays

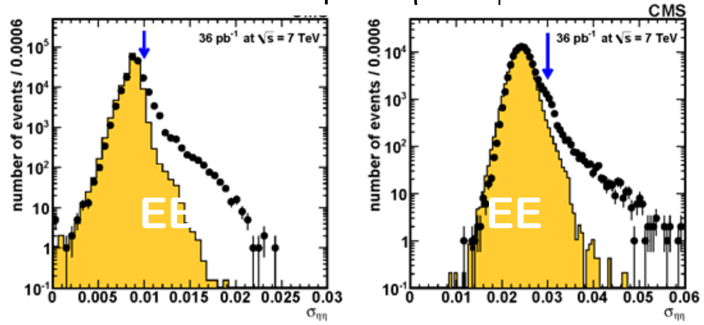


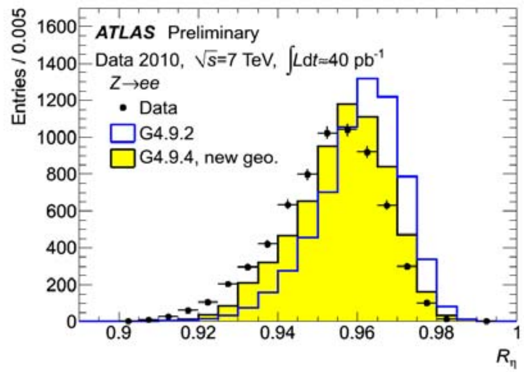
Electrons from W and Z

typically $p_T > 25$ GeV and $|\eta| < 2.5$

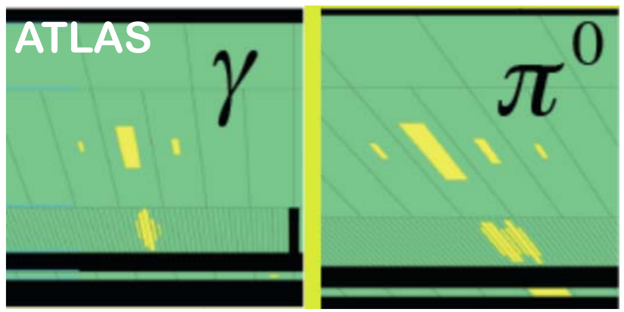
- **Excellent energy resolution**
  - typical energy resolution in EM Calorimeter for electrons in electroweak studies is 1-3%
- **Special electron tracking**
  - Gaussian Sum Filter (GSF): fitting technique that accounts for possible Bremsstrahlung emission in tracker silicon and support structure
  - provides a way to assess electron track quality (fraction of energy lost along trajectory)
  - good track-cluster matching
- **Charge assignment**
  - several charge determination methods
  - typical mis-assignment ~0.1-1%
- **Identification**
  - based on cluster shape and track matching
  - ATLAS: shower sampling + pointing capabilities
  - ATLAS: use of TRT for pion rejection
  - CMS: relative isolation in tracker, ECAL and HCAL $\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)} < 0.3$ and H/E
  - several working points with tabulated efficiency/purity (typically: loose, medium, tight)

CMS: cluster shape in η and ϕ

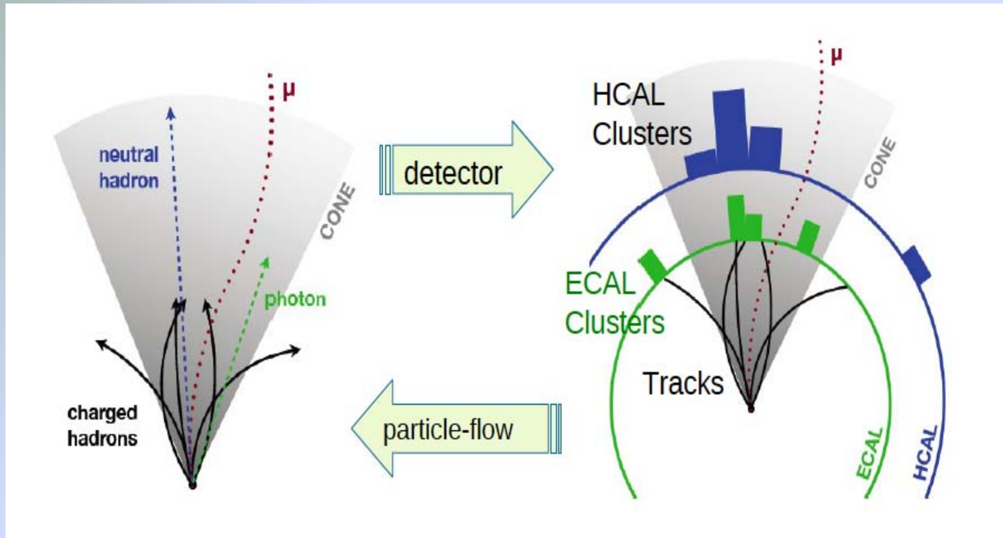




ratio 3x7 over 7x7



CMS: Particle-Flow



CMS has

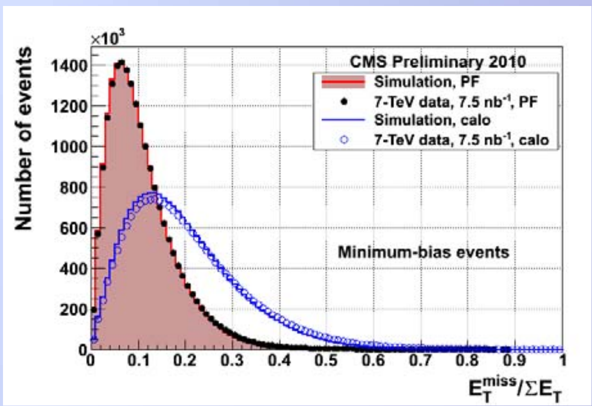
- **excellent tracker resolution**

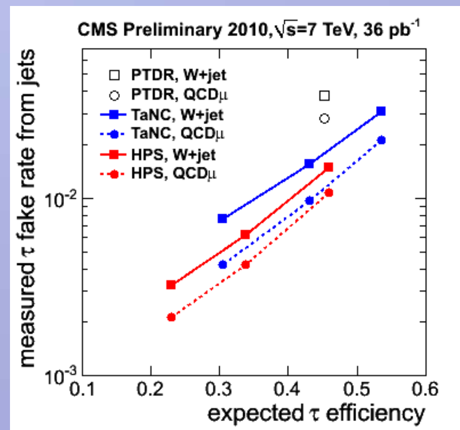
  down to momenta of 100 MeV
- **high EM calorimeter granularity**

  small Molière radius of $PbWO_4$

HCAL energy resolution is mediocre
but, in multijet events, only ~10% of the energy
is carried out by neutral stable hadrons

due to **large tracker volume**
and **high magnetic field** (3.8 T),
charged particles get separated
in calorimeters





Particle Flow algorithm in CMS

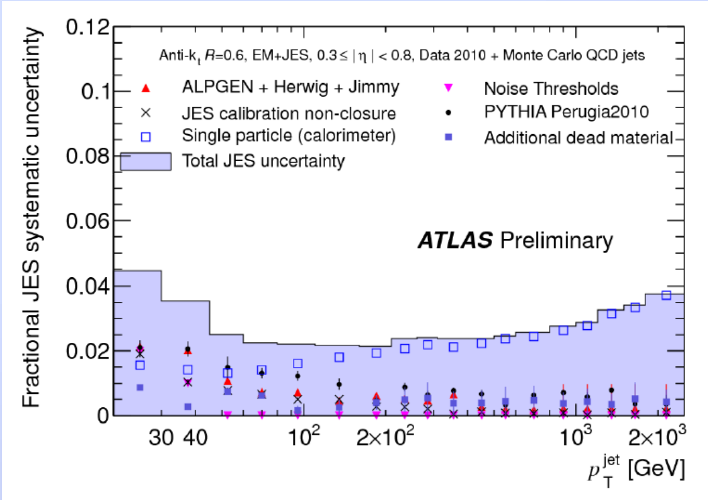
spectacular improvement in

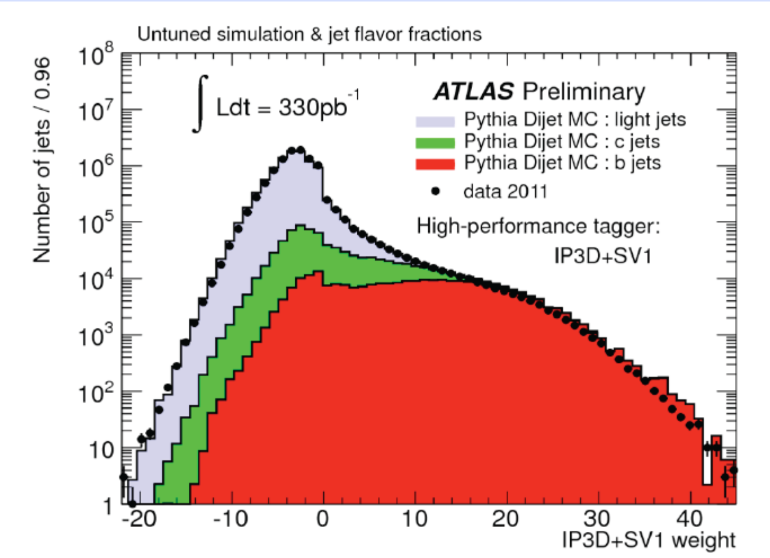
- jet energy and angular resolution
- jet composition
- MET resolution and angular resolution
- tau reconstruction and identification

Jets and B Tagging

Jets W/Z and top analyses

- jets clustered from
  - calorimeter towers (ATLAS)
  - lists of Particle Flow candidates (CMS)
- anti-kT jet algorithm with
  - $\Delta R < 0.4$ and $\Delta R < 0.6$ (ATLAS)
  - $\Delta R < 0.5$ (CMS)
- typical scale uncertainty is <3%
- typical jet energy resolution is 10-15%

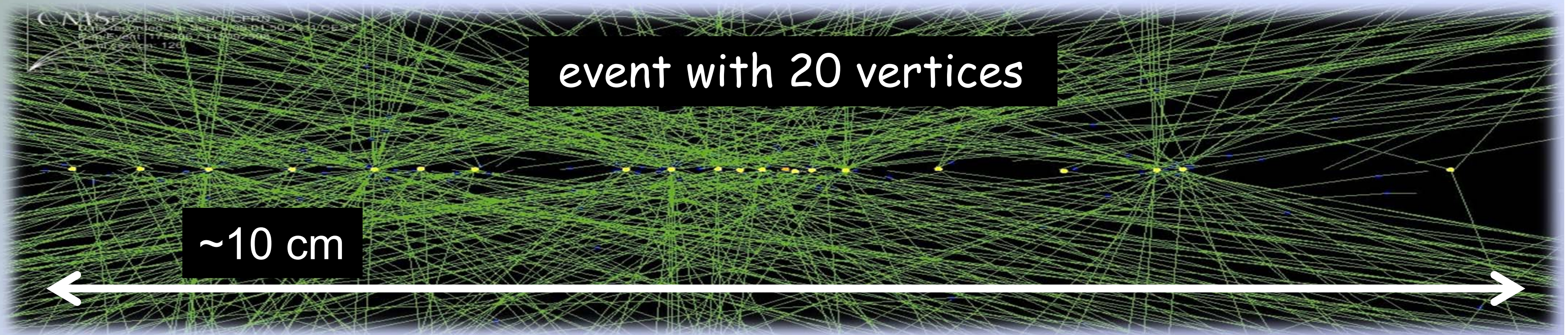




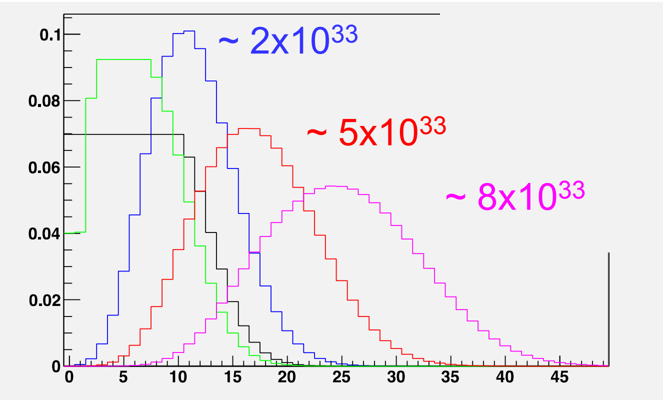
B tagging for W/Z and top analyses

- several different algorithms to identify the presence of long-lived B-particles in the jet
  - 3D impact parameter
  - track counting (above some impact parameter threshold)
  - secondary vertex finding
- use of sophisticated multivariate discriminants
- define working points wither based on efficiency or purity
- proven performances based on data studies

Pile-Up

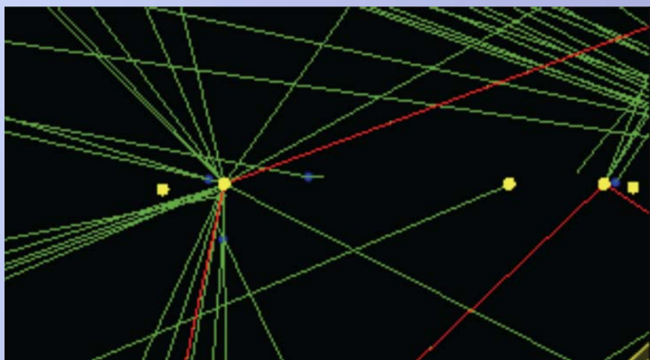


number of vertices: effect of in-time pile-up



Pile-up events affect

- jet energy
- missing transverse energy
- isolation variables

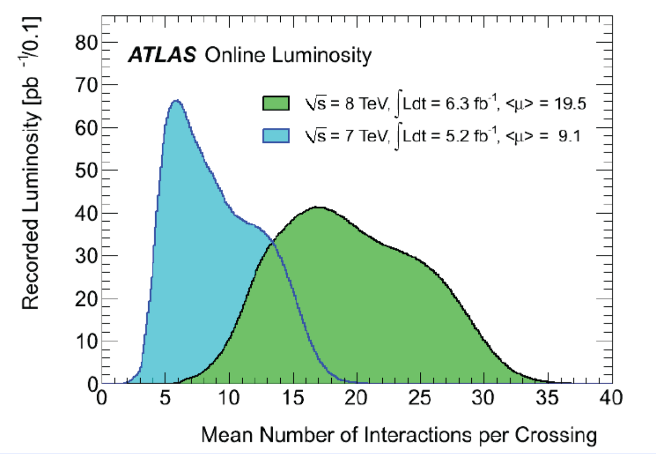


The two Z candidates in this event are…
5 cm apart!

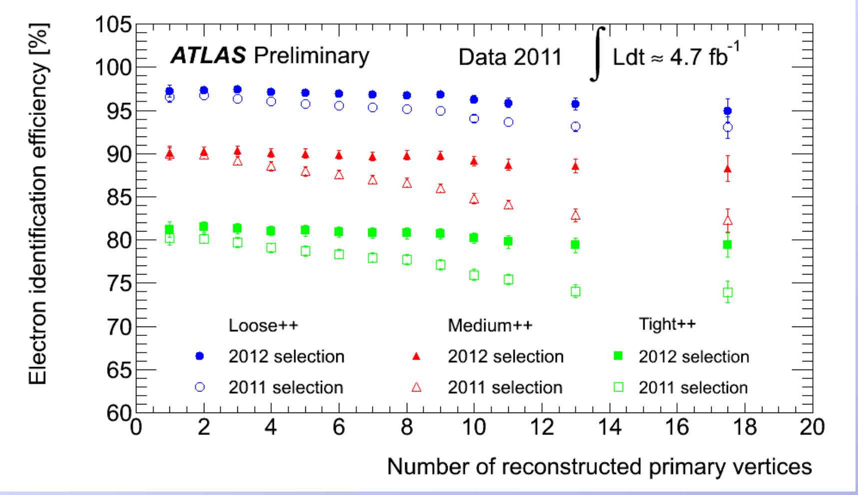
Other concerns

- off-time pile-up
- multi-parton interactions

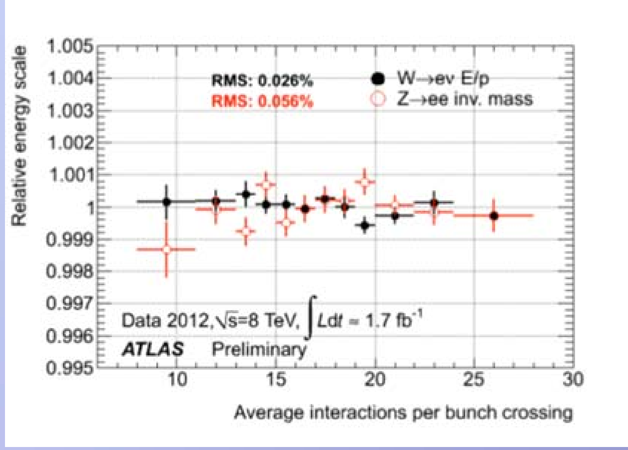
Coping with High Pile-up



energy corrections for isolation and jets

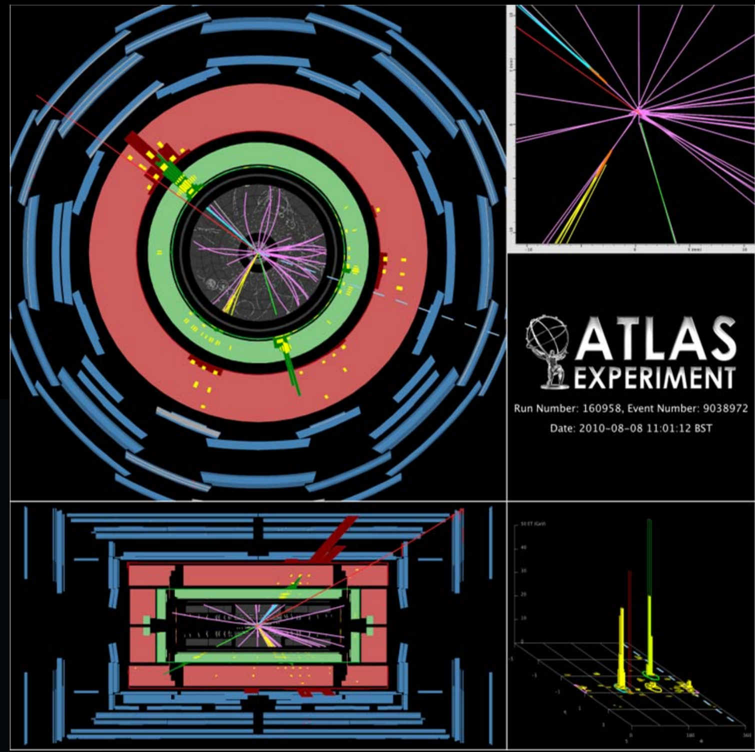


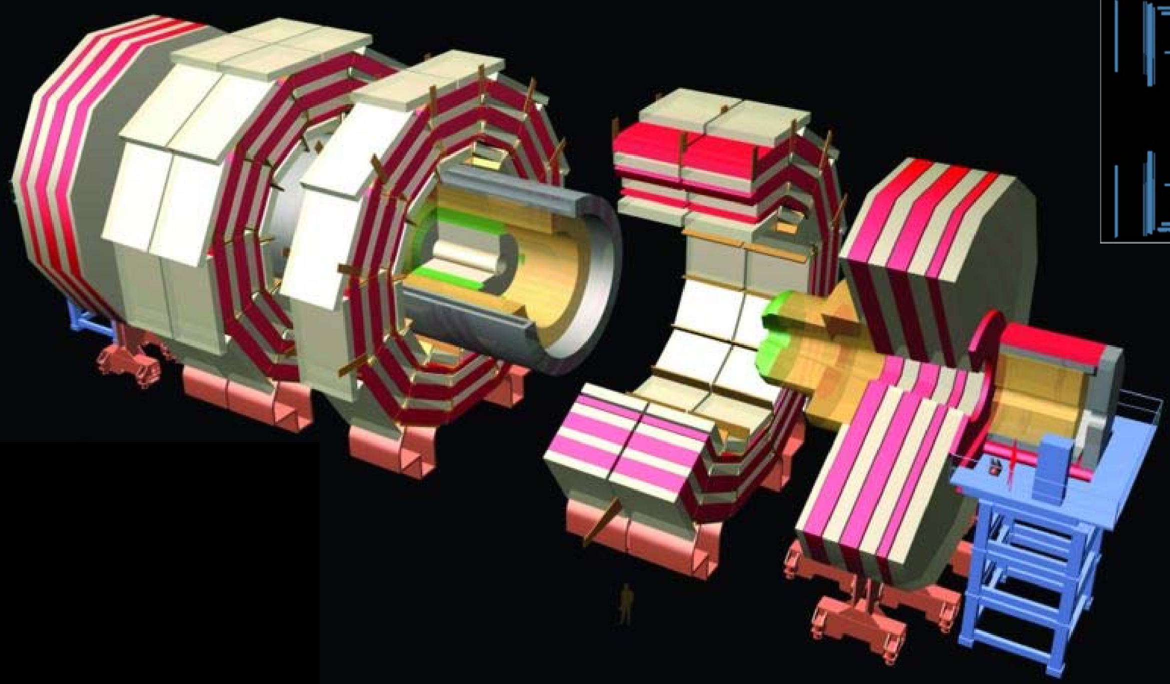
- already in 2011 and 2012
  LHC design values
  are exceeded in terms
  of instantaneous luminosity
- both ATLAS and CMS are able
  to cope with the very high level
  of pile-up for
  - jet energy corrections
  - isolation variables
  (not so well for missing transverse energy)
- precision W physics requires
  special low luminosity runs



lepton selection insensitive to pile-up

Electroweak and Top Quark Physics at the LHC





Part 2: Inclusive Cross Sections

Gautier Hamel de Monchenault
CEA-Saclay IRFU-SPP

Ecole d'été de Gif
Septembre 2012

Weak Boson Production at the LHC

Physics with W & Z Bosons

W and Z Bosons

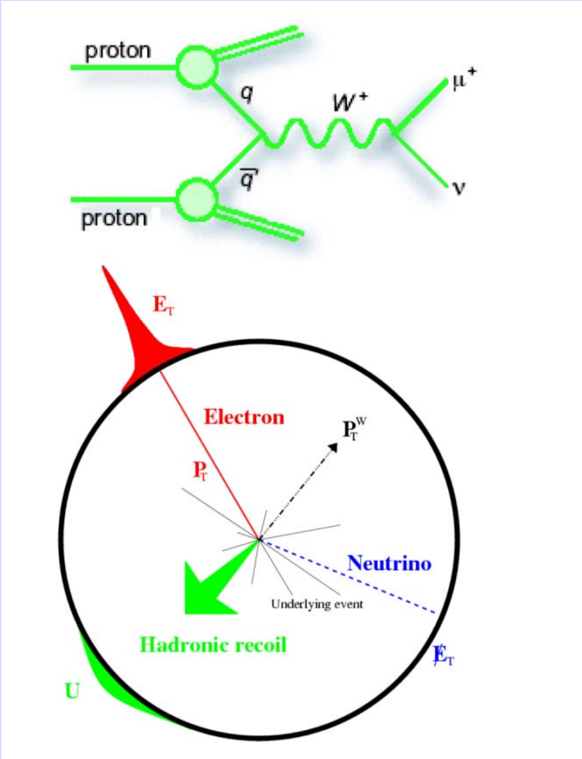
- discovered and first studied by UA1 and UA2 at the CERN SppS in the 80's
- Z boson studied in great details at LEP-1 and SLC
- many measurements on the W & Z bosons at LEP-2 and the Tevatron

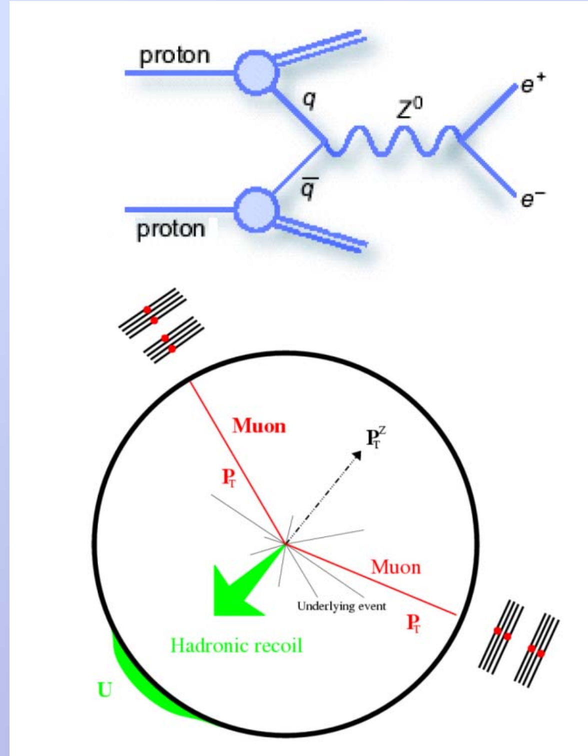
Interest for the W and Z physics at the LHC?

- tests electroweak interactions with more SM precision measurements
  - left/right couplings of quarks (including light quarks) and leptons
  - probe (anomalous?) gauge couplings
  - test unitarity of gauge interactions at high energy
- precision measurements of the W boson mass
  - related to the top quark and Higgs boson mass through radiative corrections
- interplay with strong interactions (QCD)
  - W and Z as probes of the parton densities (PDFs)
  - tests of QCD models in associated W and Z productions with jets
- the W and Z as Standard Candles
  - exploit leptonic final states (including tau channels) for trigger, calibration, alignment, energy scale, luminosity monitoring, etc.
- W and Z processes are backgrounds for many processes (top pair and single top production, Higgs and SUSY, LED, new gauge bosons, new strong interactions)
  - it is essential to master SM processes before claiming any discovery

W/Z Production and Detection

- Main production via quark-antiquark annihilation
- Detection via leptonic decays

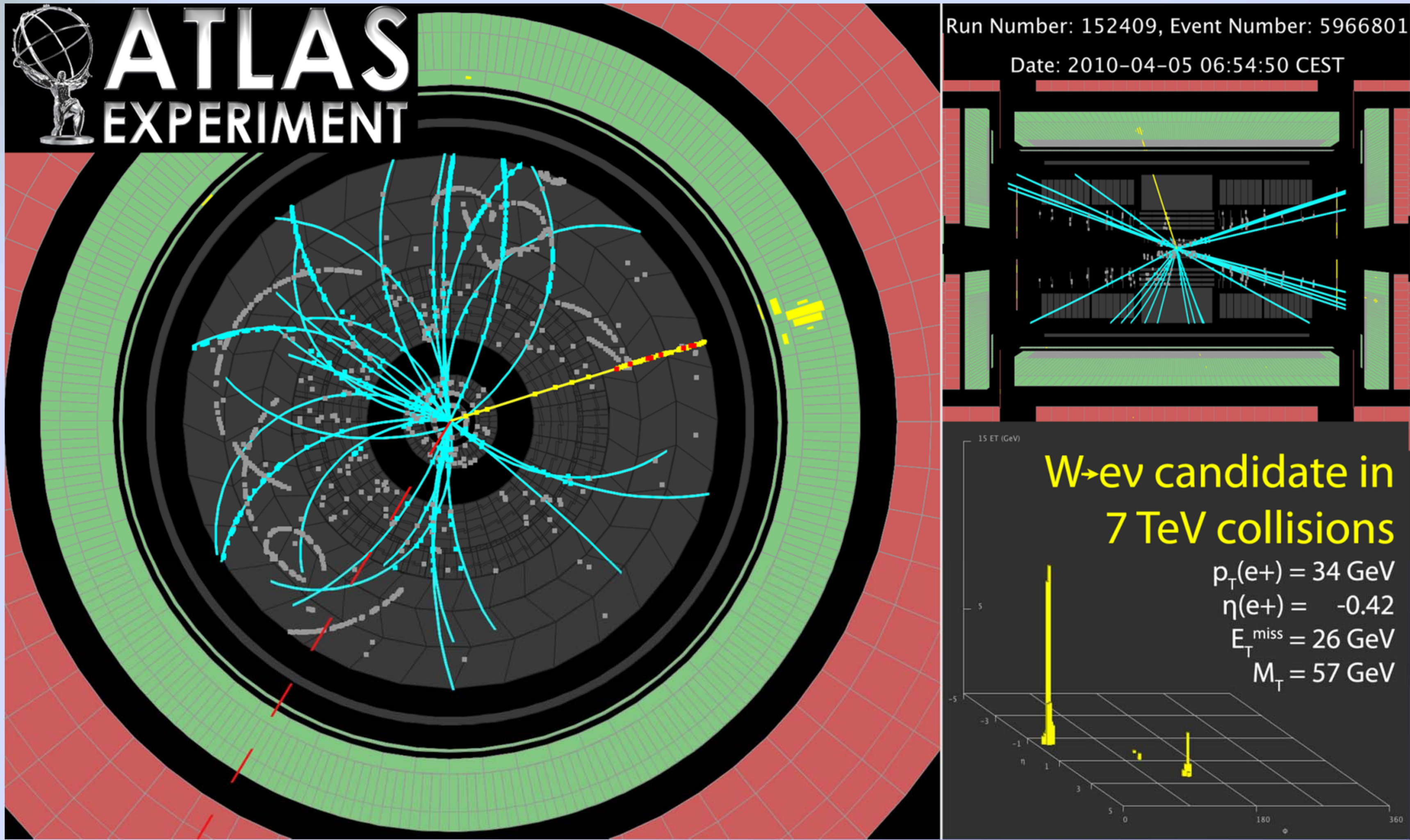




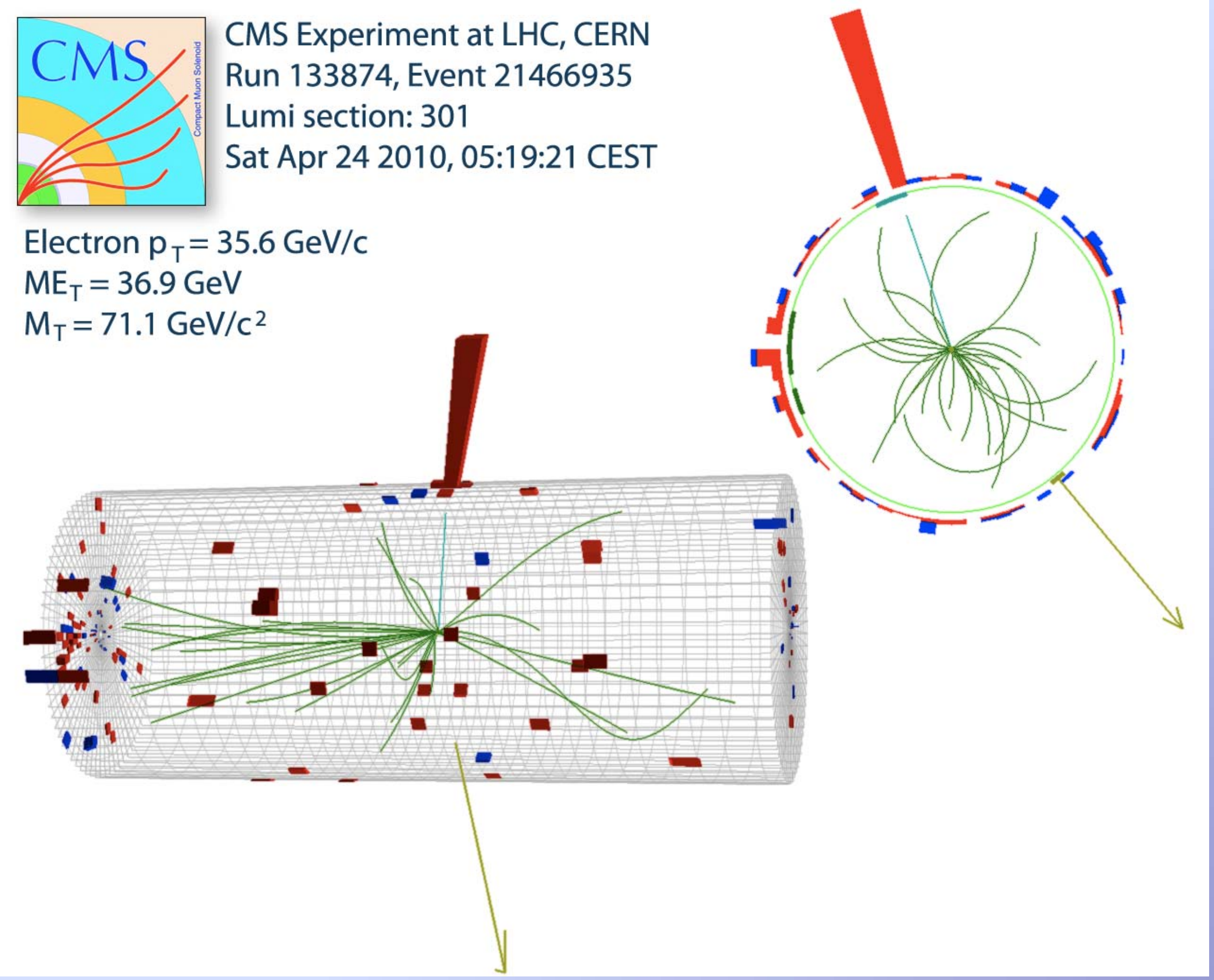
W signature
- high-p_T isolated lepton
- missing transverse energy E_T^{miss}

Z signature
- two high-p_T isolated lepton
  with same flavor (e,μ) & opposite sign

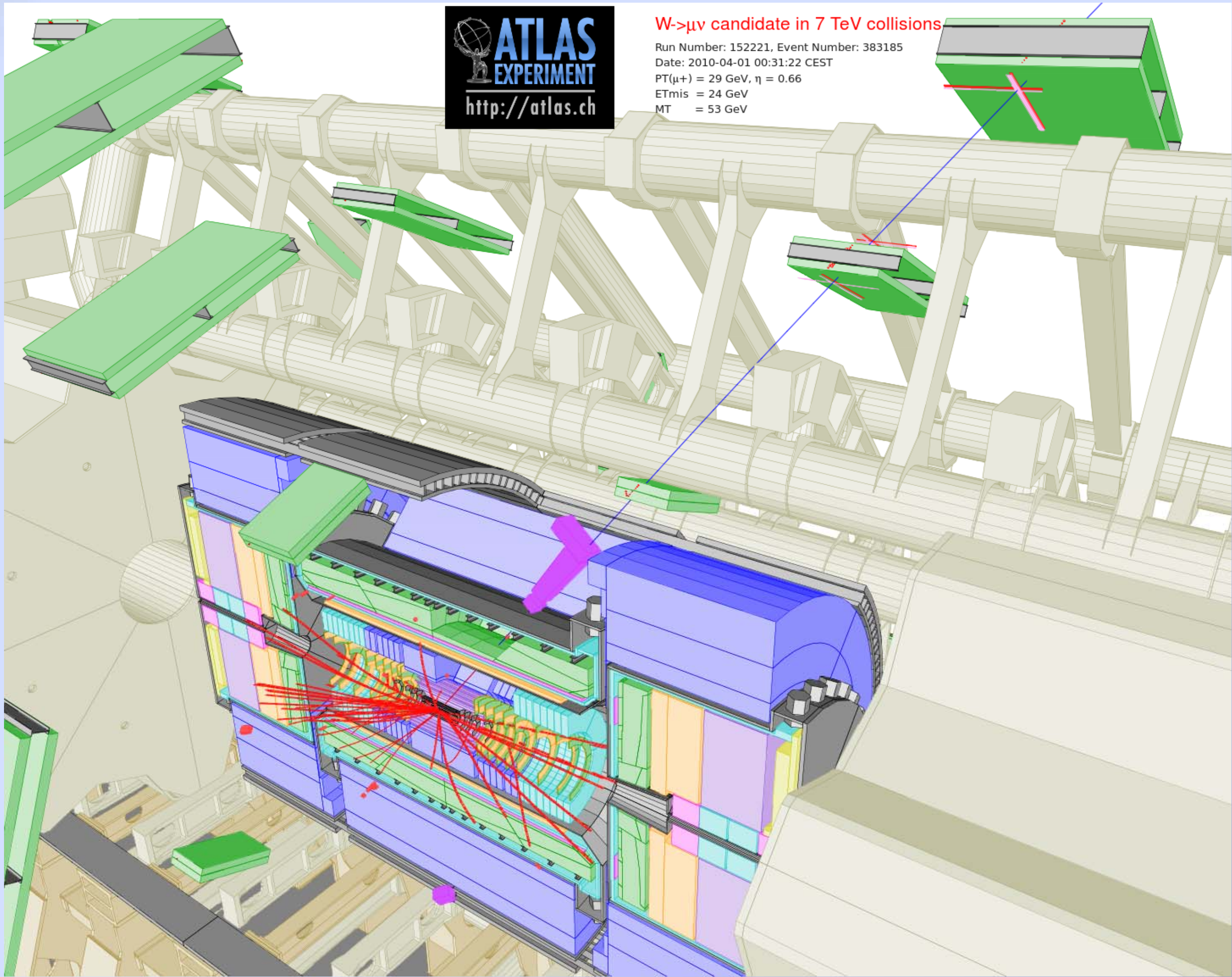
W → eν Candidate



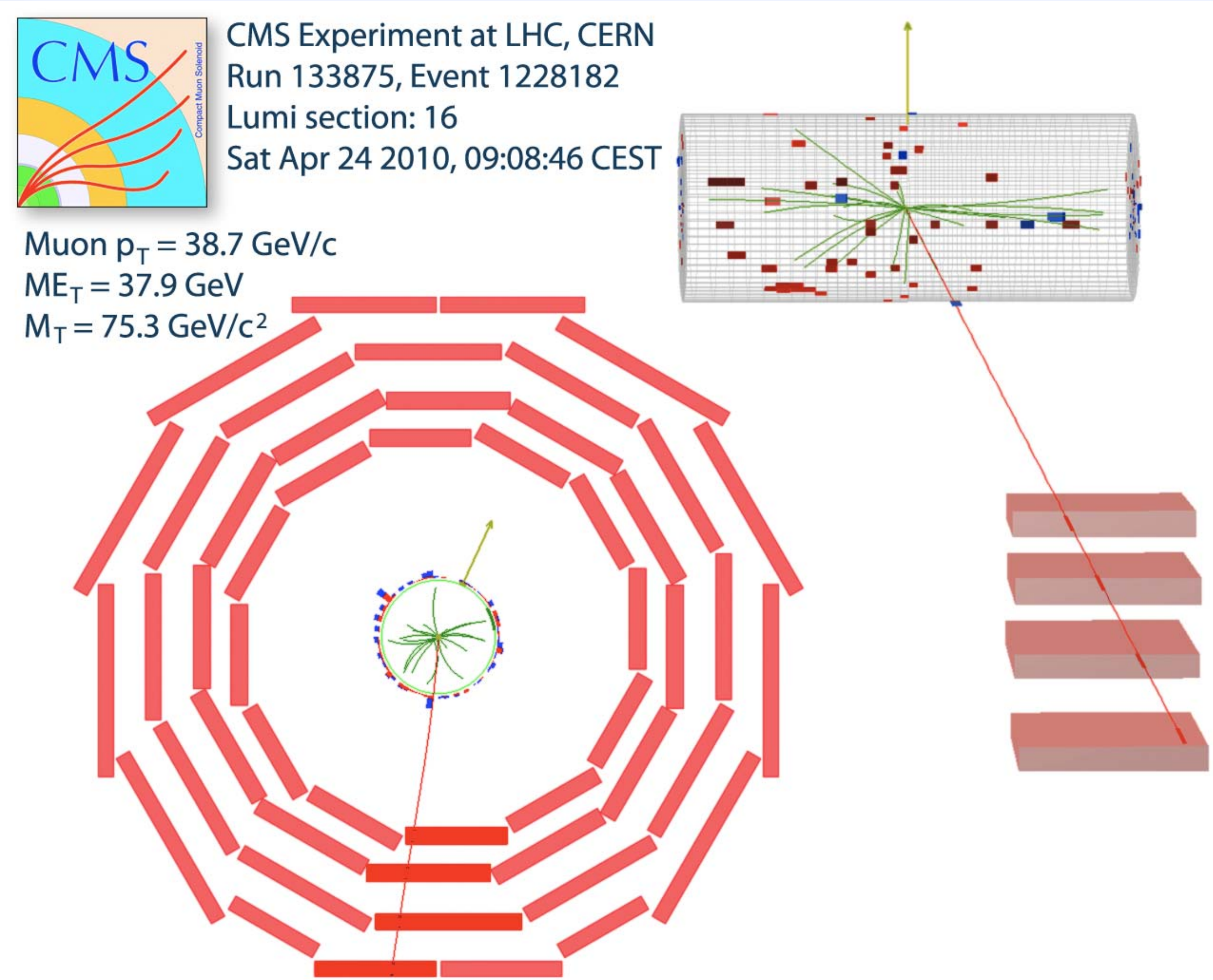
W → eν Candidate



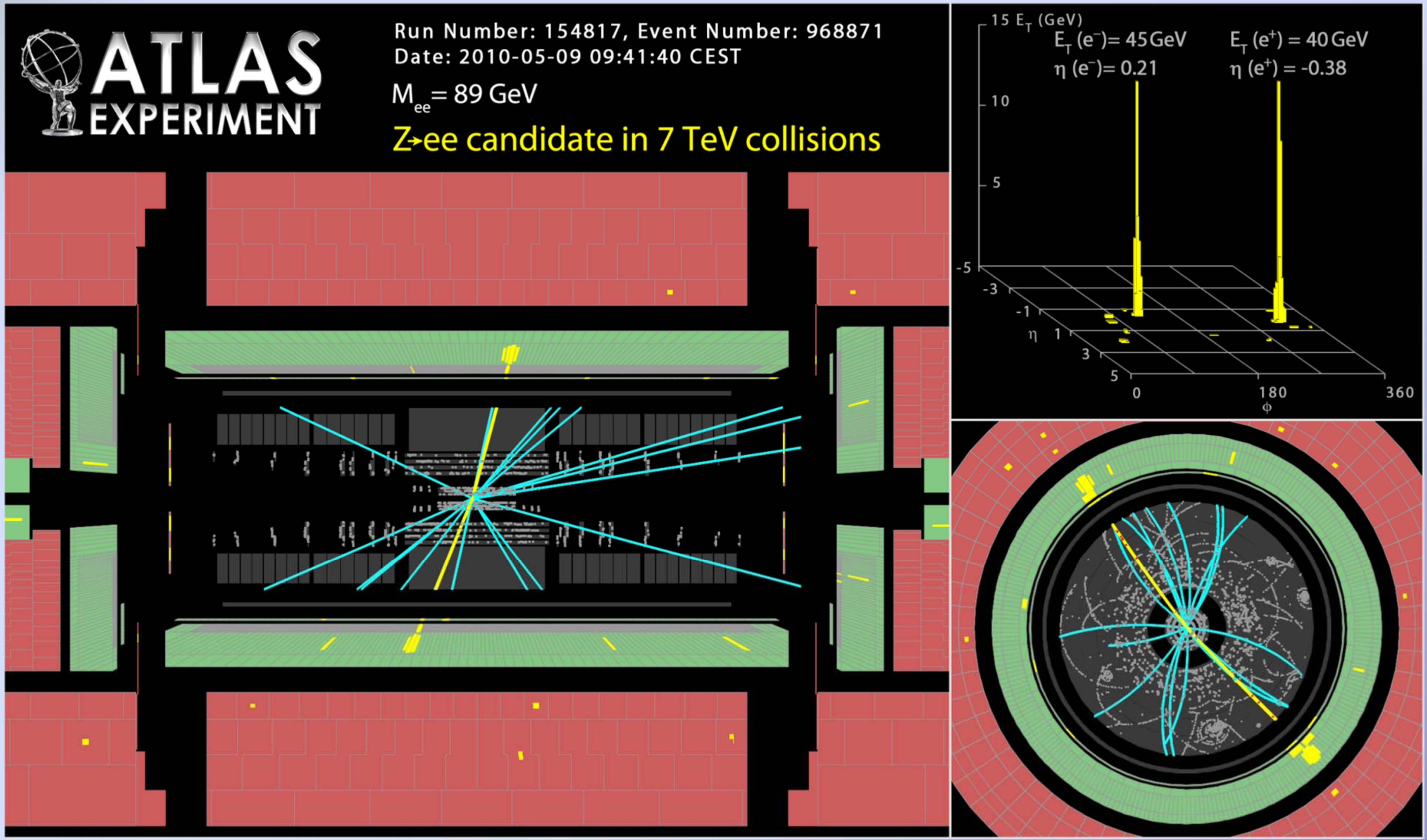
W → μν Candidate



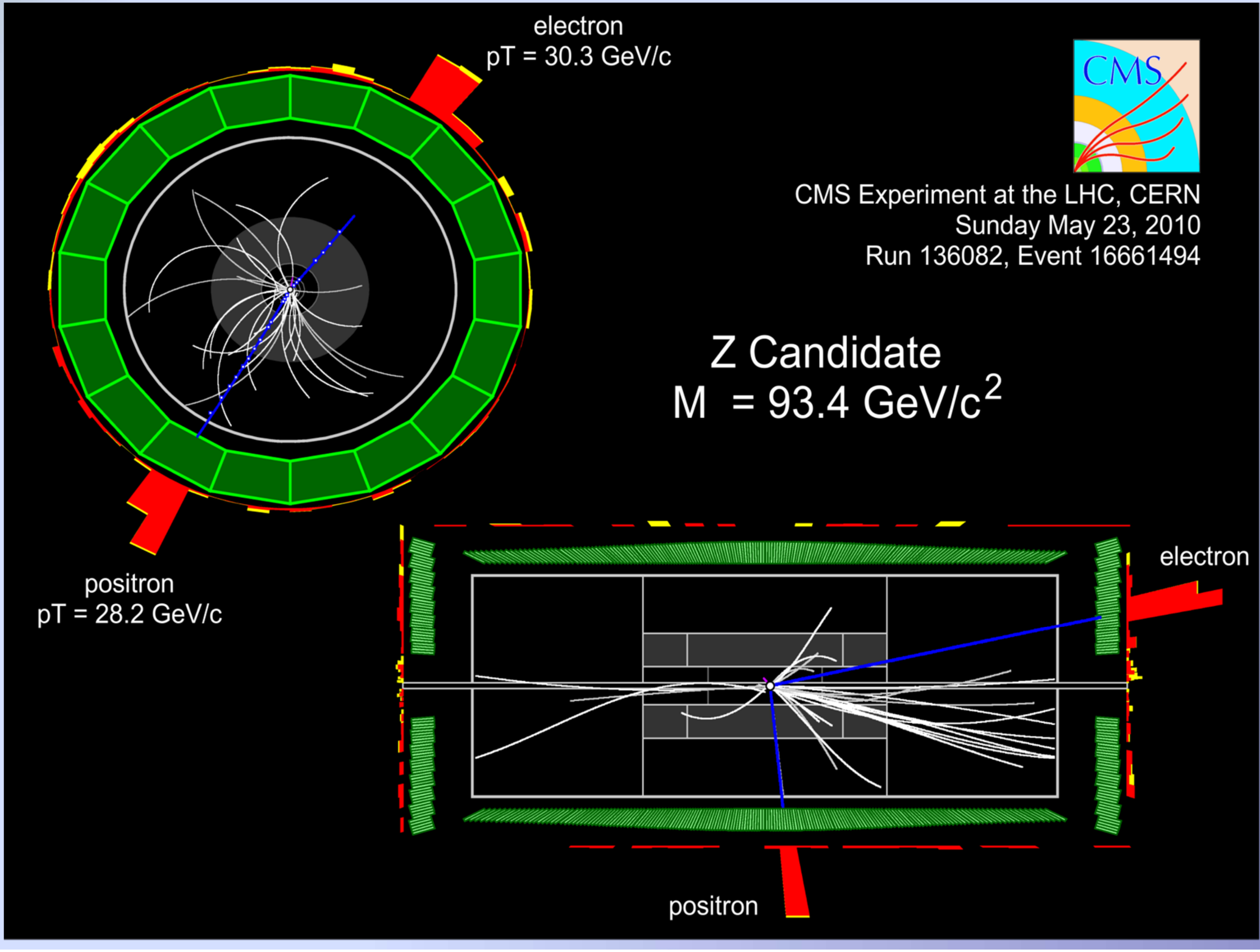
W → μν Candidate



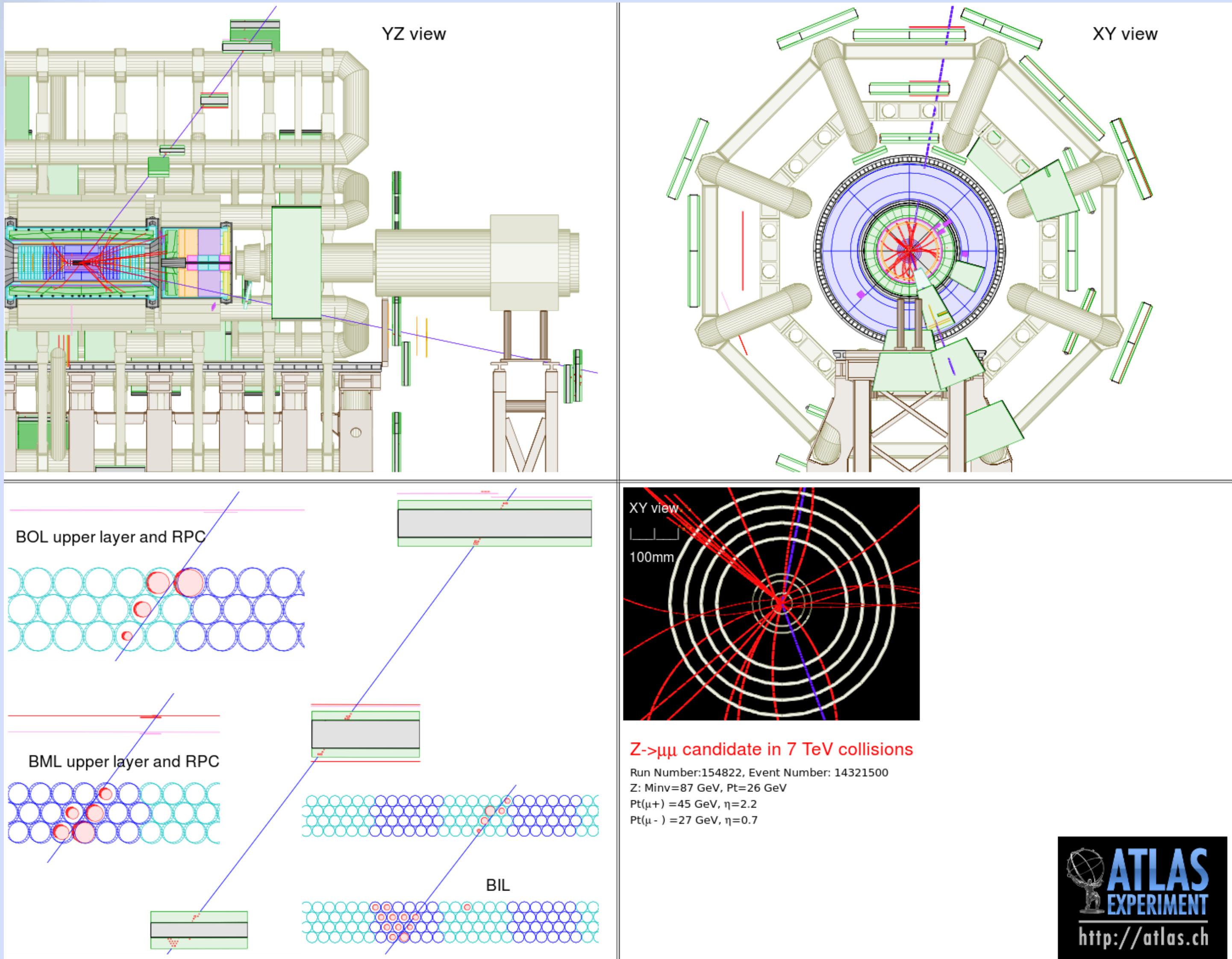
$Z \rightarrow ee$ Candidate



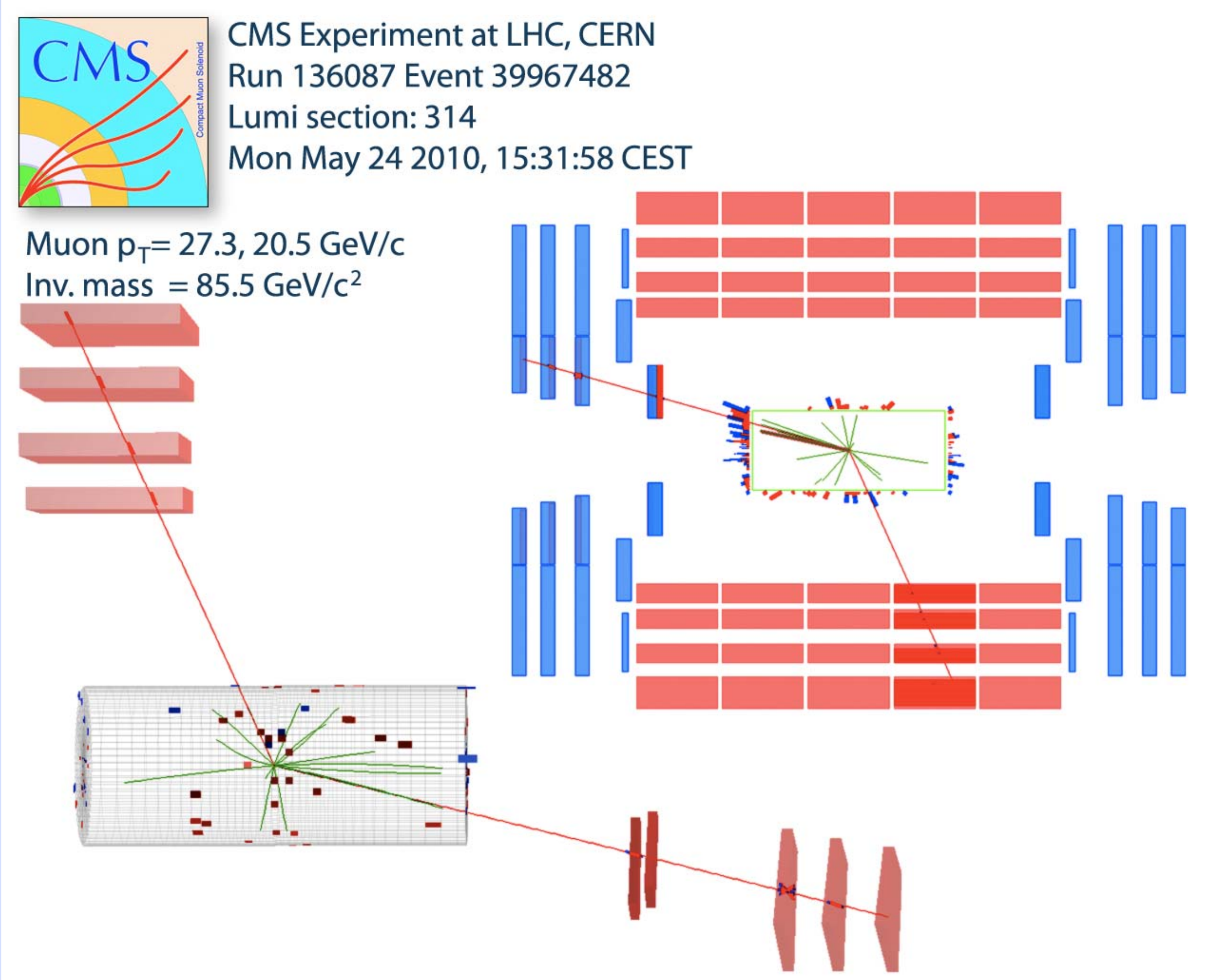
Z → ee Candidate



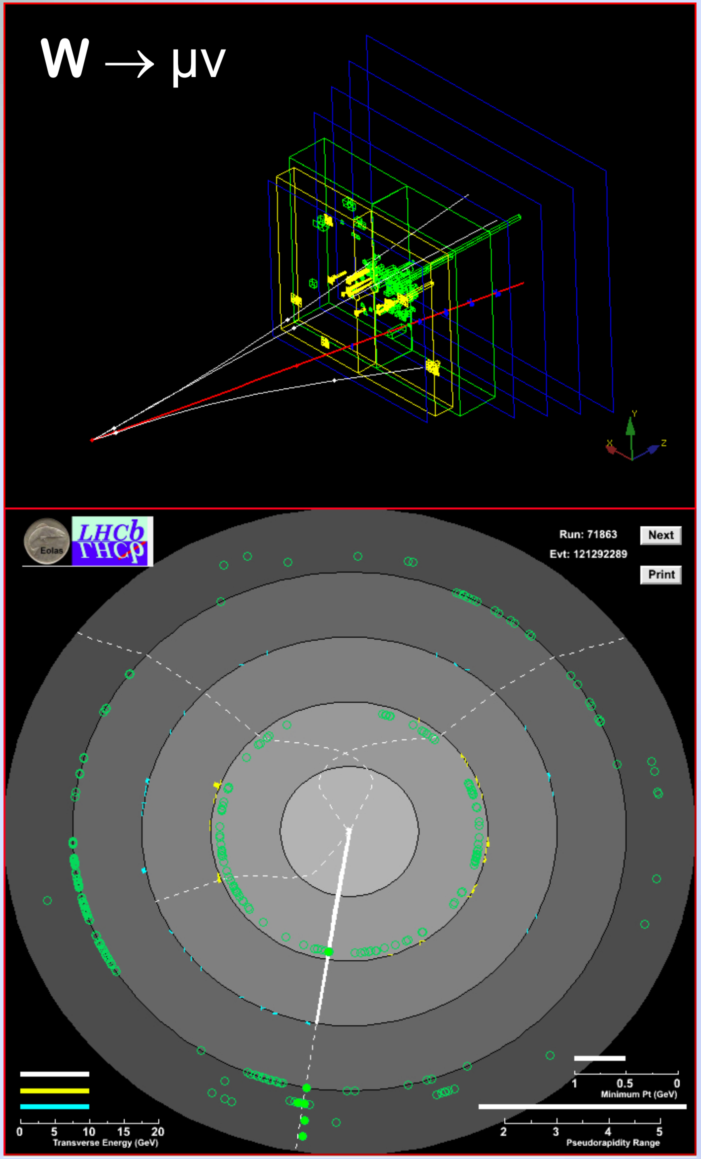
Z → μμ Candidate



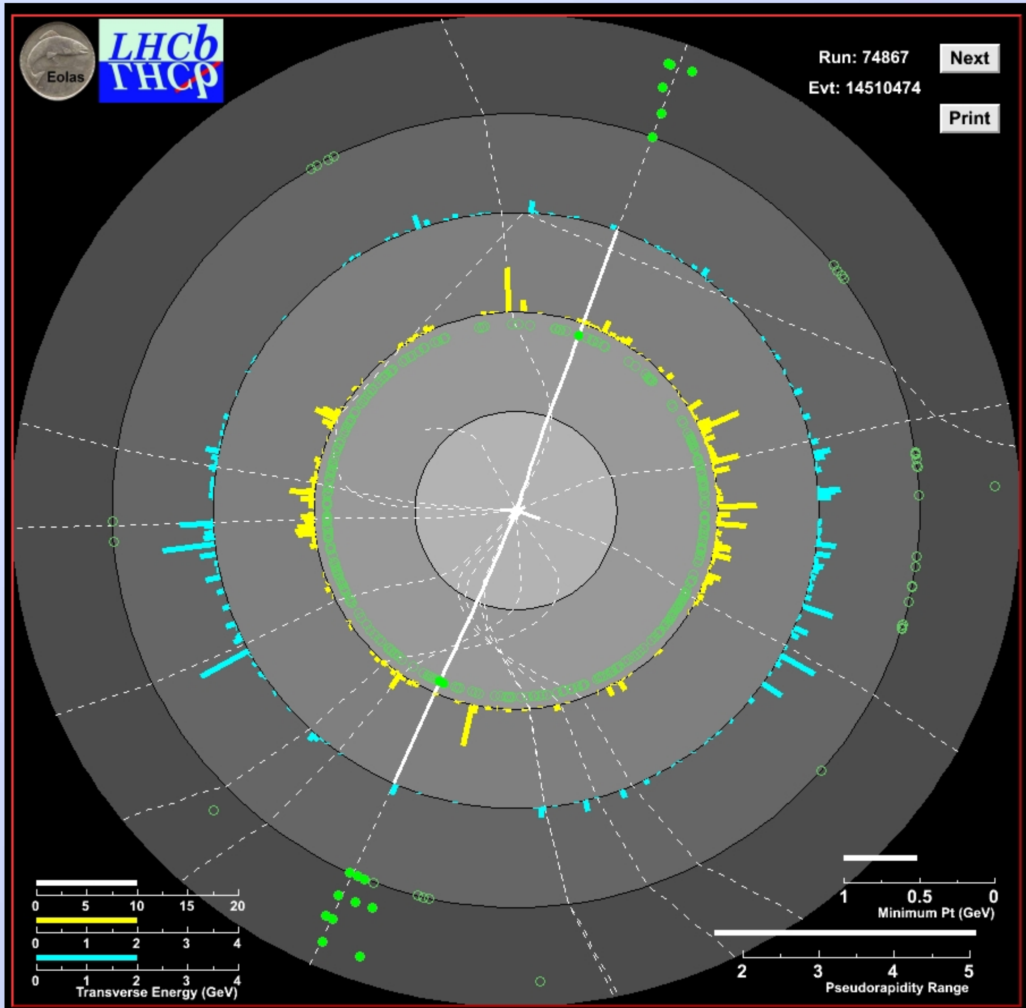
$Z \rightarrow \mu\mu$ Candidate



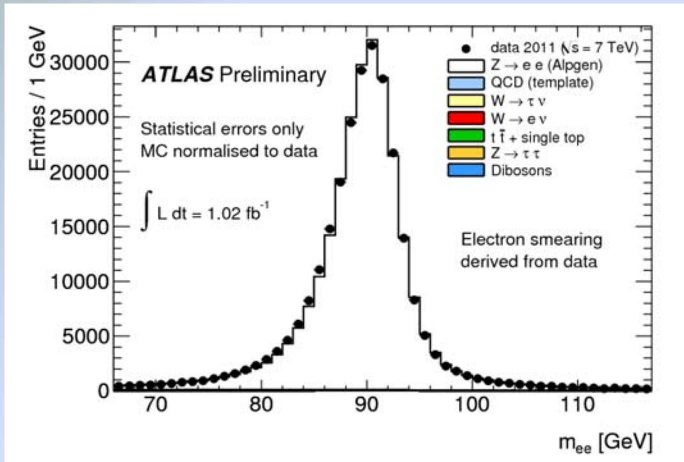
Electroweak Bosons in LHCb

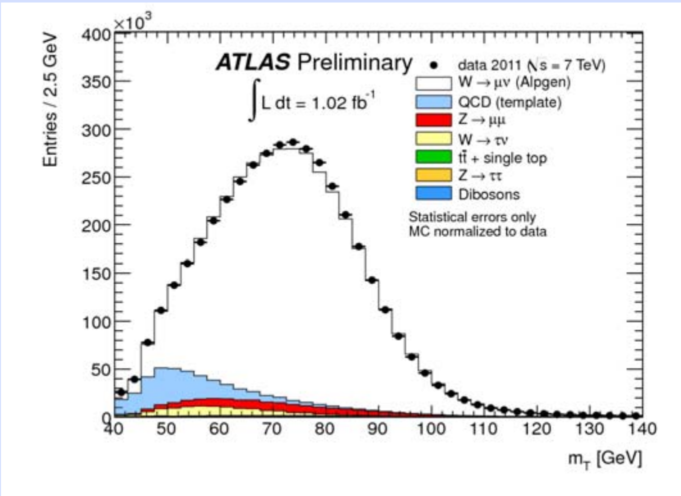


Z → μμ



Experimental Methods





Z: Dilepton invariant mass

$$m_{\ell\ell} = [2\,(E(\ell_1)E(\ell_2) - \vec{p}(\ell_1)\cdot\vec{p}(\ell_2))]^{1/2}$$

W: Transverse mass

The longitudinal momentum of the neutrino is unknown. Define the transverse mass:

$$m_{\rm T} = [\ 2\,p_{\rm T}(\ell)\,p_{\rm T}(\nu)\ (\ 1 - \cos\Delta\phi(\ell,\nu)\ )\ ]^{1/2}$$

with $p_{\rm T}(\nu) = E_{\rm T}^{\rm miss}$

Note: using a W mass constraint, one can obtain the longitudinal momentum of the neutrino, up to a two-fold ambiguity

$$p_{\rm L}(\nu) = \frac{1}{2{p_{\rm T}}^2(\ell)}\left[\,p_{\rm L}(\ell)\times A\ \pm\ p(\ell)\sqrt{B}\,\right]$$

$$\begin{aligned} A &= m_W^2 - m_{\rm T}^2 + 2\,p_{\rm T}(\nu)\,p_{\rm T}(\ell)\ , \\ B &= A^2 - 4\,{p_{\rm T}}^2(\ell)\,{p_{\rm T}}^2(\nu) \\ &= (\,m_W^2 - m_{\rm T}^2\,)\ [\ m_W^2 + 2\ (\ p_{\rm T}(\nu)\,p_{\rm T}(\ell) + \vec{p_{\rm T}}(\nu)\cdot\vec{p_{\rm T}}(\ell)\ )\ ] \end{aligned}$$

(B=0 if $m_T > m_W$)

typically, keep the solution with smallest absolute value

Parton Kinematics

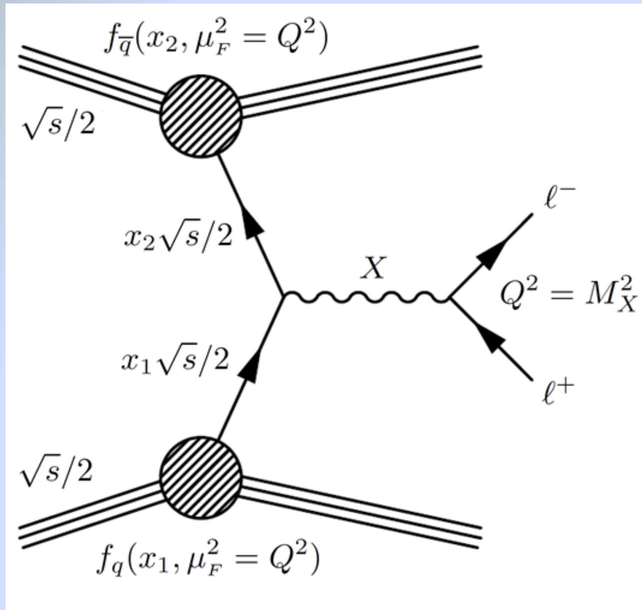
Rapidity of 4-vector $P(E, p_X, p_Y, p_Z)$

$$y \equiv \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$$

kinematic variable such that

$$\mathrm{d}y/\mathrm{d}p_z = 1/E$$

(differences in rapidity are invariant under longitudinal Lorentz boosts)



Hard scattering seen as interaction between two partons

$$a(x_1) + b\,(x_2) \rightarrow X$$

√s = center of mass energy

Parton system (at leading order) in lab frame

$$E = (x_1 + x_2)\sqrt{s}/2$$
$$p_z = (x_1 - x_2)\sqrt{s}/2$$

one gets $Q^2 = E^2 - p_z^2 = x_1 x_2 s$

and $y = \frac{1}{2} \ln \frac{x_1}{x_2}$

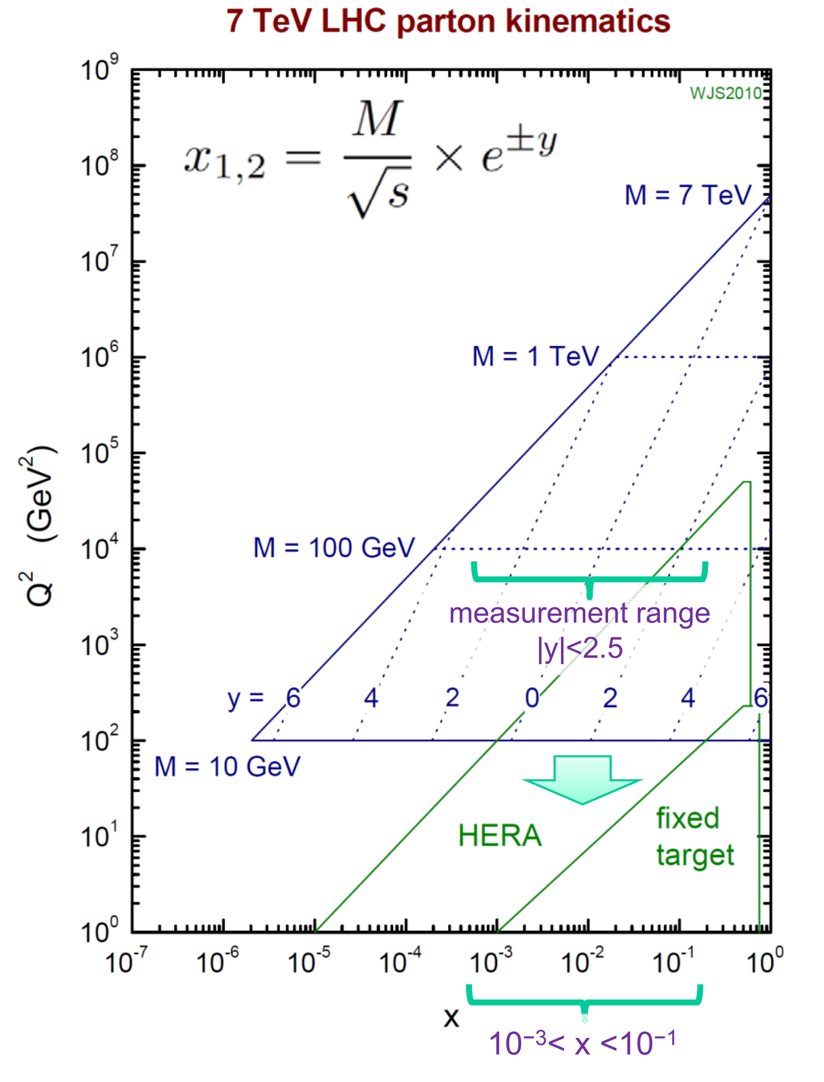
x Bjorken: fraction of the longitudinal momentum carried out by the parton

Simple case of a boson of mass M produced in the s channel

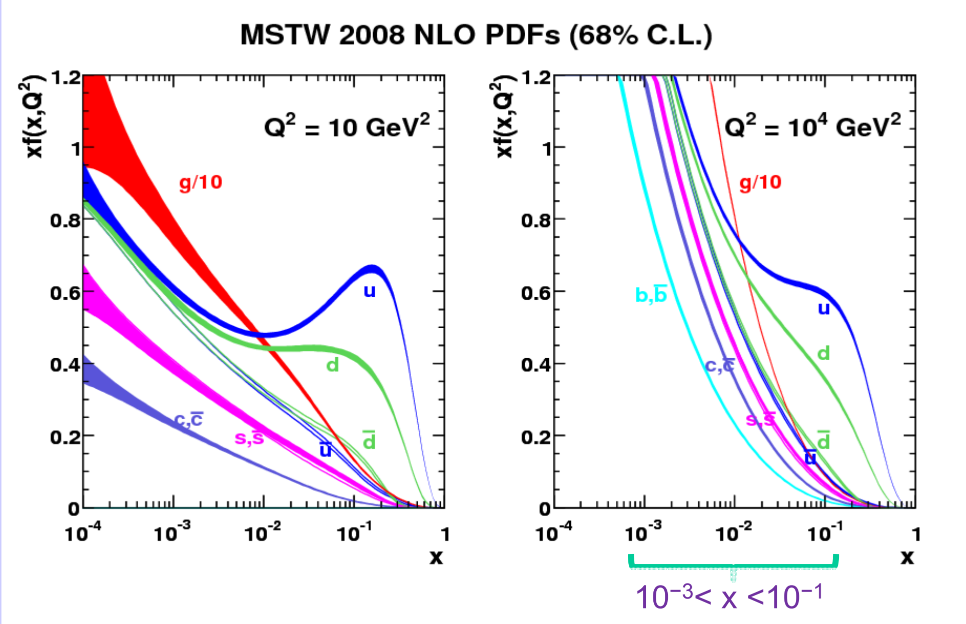
$$x_{1,2} = \frac{M}{\sqrt{s}} \times e^{\pm y}$$

for a given mass *M*, the rapidity *y* relates *M* to the Bjorken *x* values of the quark (x_1) and the anti-quark (x_2)

Parton Kinematics



the parton structure of the proton is encoded in the **parton density functions** (PDFs)



valence
$$u_V = u - \overline{u}$$
$$d_V = d - \overline{d}$$

sea
$$2 \times (\overline{u} + \overline{d} + \overline{s})$$
$$\overline{d} - \overline{u}$$

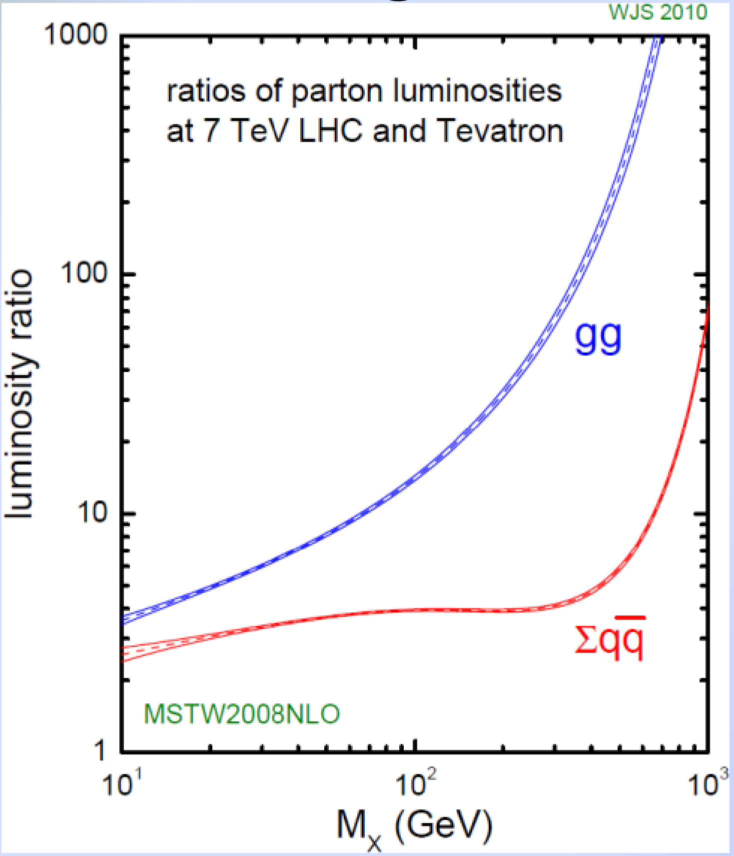
strangeness $s + \overline{s}$

low Q^2 data (HERA) dominate the PDF estimation

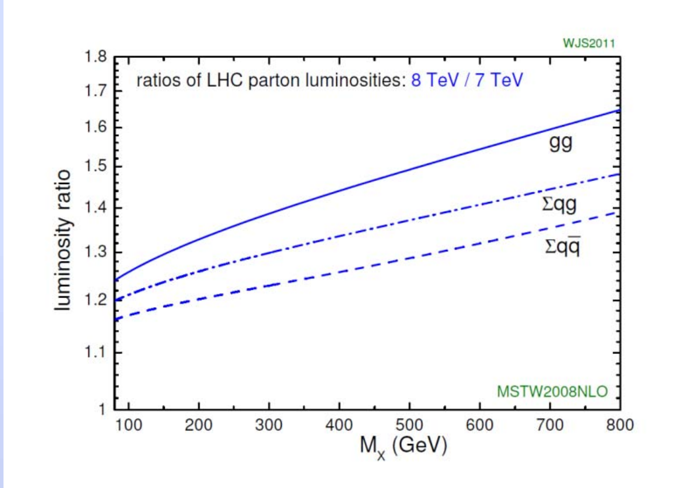
heavy quarks (c,b) are treated perturbatively

Parton Luminosities

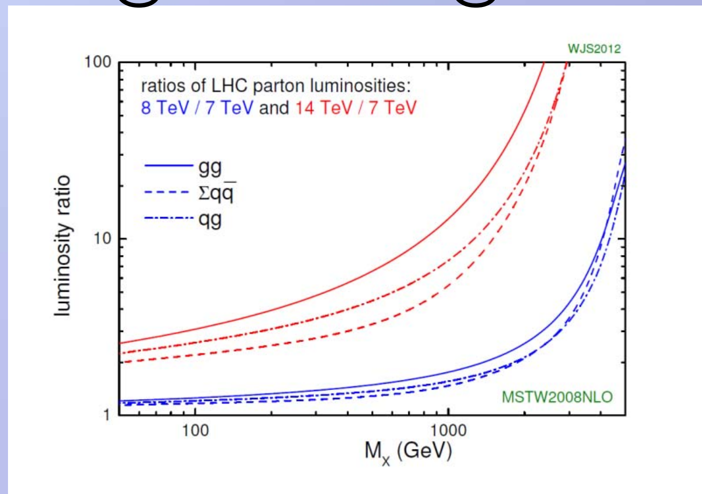
Tevatron → LHC@7TeV



LHC@7TeV → LHC@8TeV



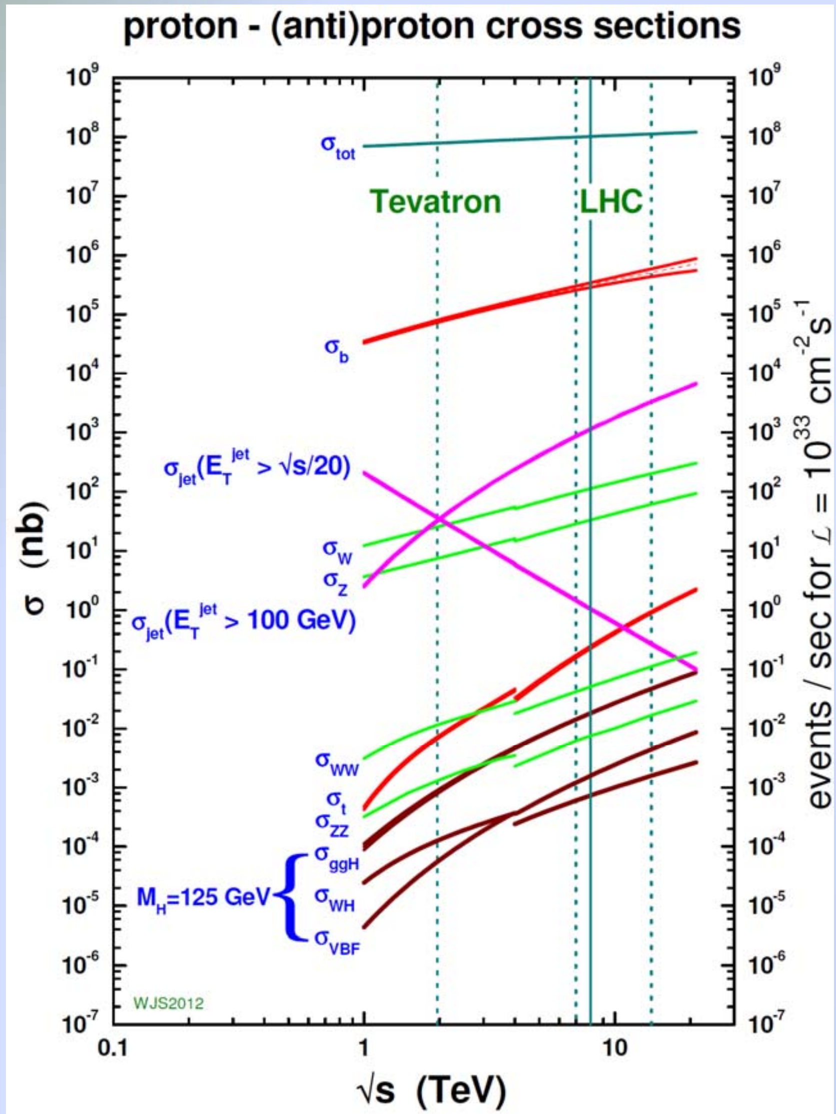
LHC@7TeV → LHC@14TeV



The gluon-gluon luminosity increases
much more that the quark luminosity

- top quark pair production and Higgs production by **gluon fusion** are dominant at the LHC

Cross Sections at Colliders



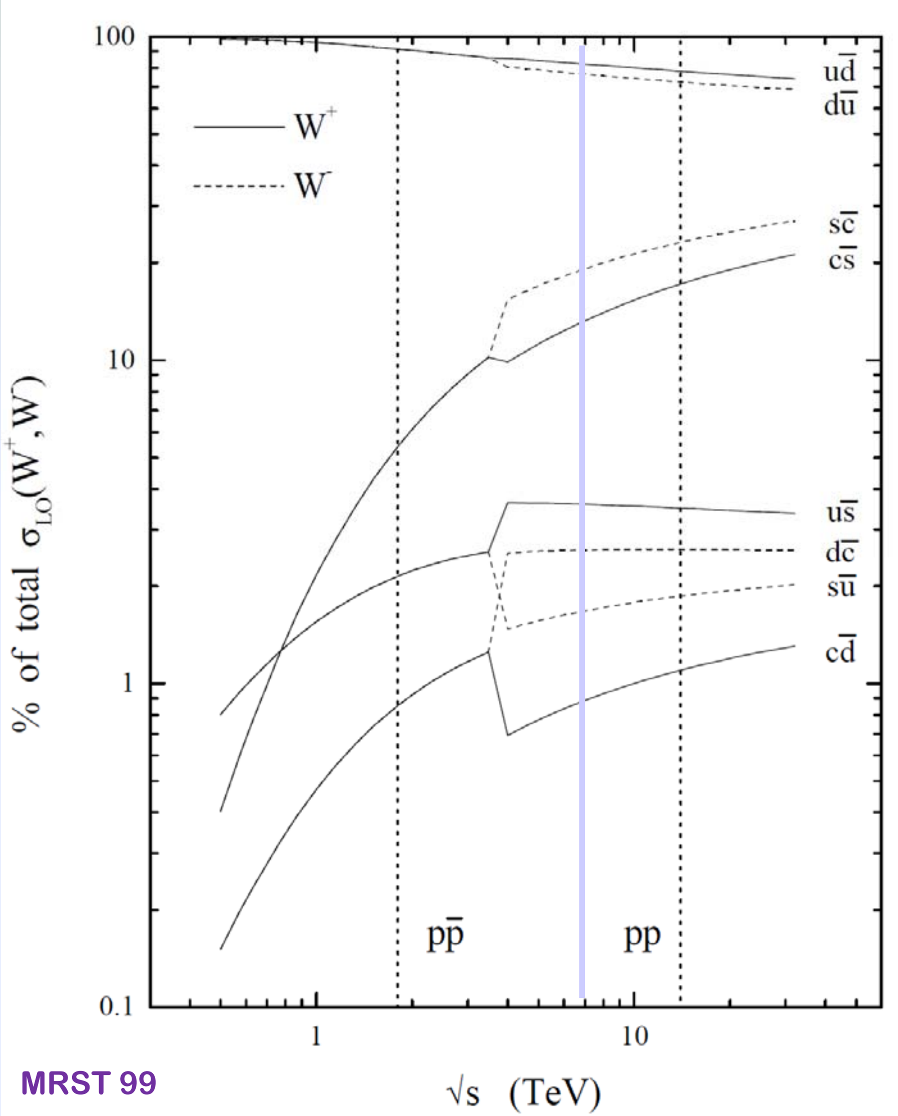
Cross sections in pp collisions at 7 TeV

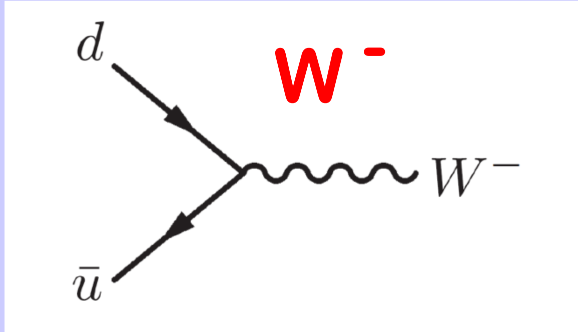
- **total**: **110 mb**
  - elastic: 40 mb
  - inelastic: 60 mb
  - diffractive: 12 mb
- **b-quark pair: 0.4 mb**
- **W and Z**: **100 nb** and **30 nb**
  (3 times larger than at Tevatron)
- **top quark pair**: **160 pb**
  (20 times larger than at Tevatron)
- **125-GeV Higgs boson**: **20 pb**

- **W & Z cross sections in leptonic mode**
  expect
  σ(W) × B(W → lν) ~10 nb
  and
  σ(Z) × B(Z → ll) ~ 1 nb

with acceptances of ~0.5 (W) or ~0.4 (Z)
5 000 000 W per lepton channel per fb^{-1}
500 000 Z per lepton channel per fb^{-1}

Flavor in W Production





At the LHC

W production is charge asymmetric

expect

$\sigma(\mathbf{W^+})/\sigma(\mathbf{W^-}) \sim \mathbf{2}$

if only **valence quark** + **sea antiquark**

but

involved parton fractions are low

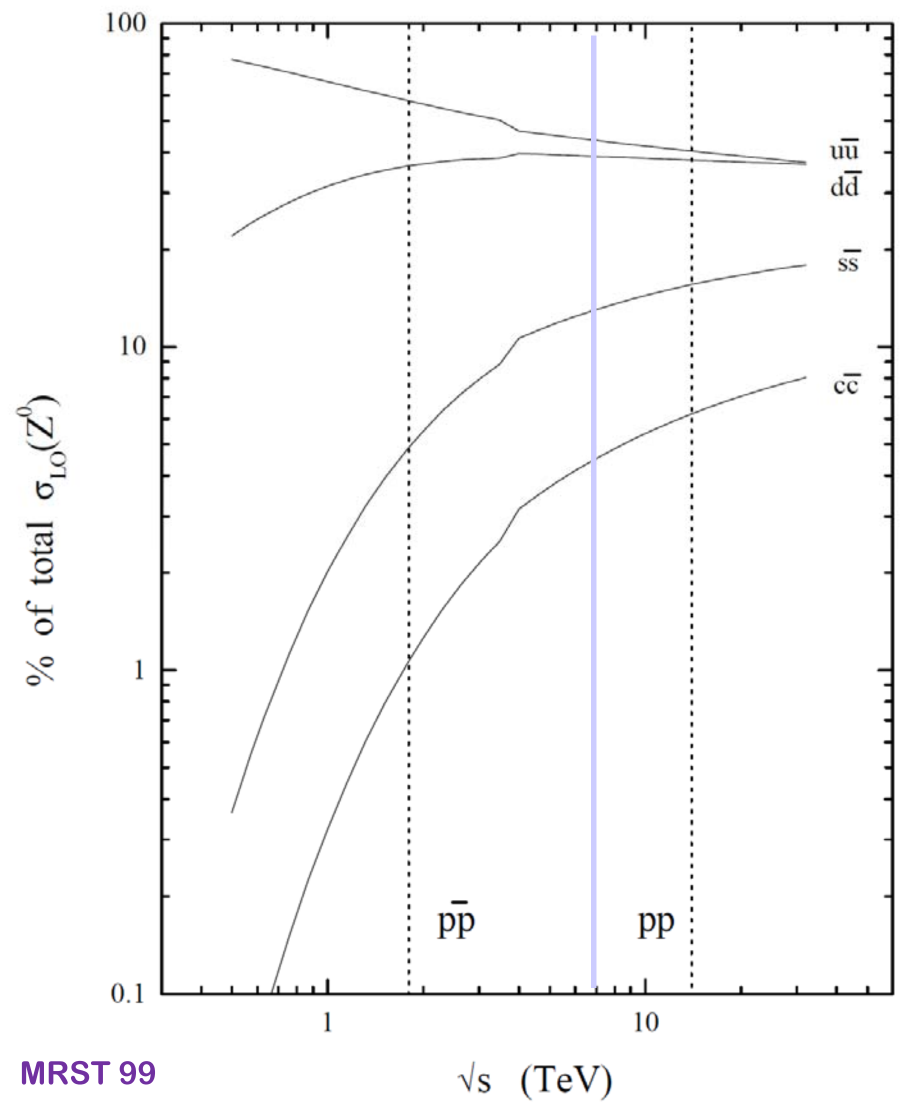
($10^{-3} < x < 10^{-1}$)

annihilation of a **sea quark** and a **sea anti-quark** is significant:

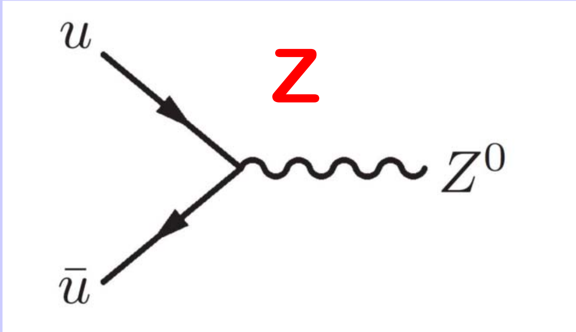
$\sigma(\mathbf{W^+})/\sigma(\mathbf{W^-}) \sim \mathbf{1.4}$

charge asymmetry strongly depends on rapidity (see later)

Flavor in Z Production



MRST 99



the **strange** density as a large impact on both W and Z production rates (10-20%) but proton strangeness is poorly known

LHC W and Z data can improve PDFs

- constraints on u, d sea (anti)quarks
- constraints on strangeness
- constraints on heavy quark content
- crucial for reducing PDF uncertainties in searches

without LHC improvements on PDFs many measurement are bound to stay limited by PDF uncertainties

Cross Section Calculations

Key theoretical tool:

the Factorization Theorem

$$\sigma_{pp\to X} = \sum_{a,b=q,\bar{q},g} \int \mathrm{d}x_1 \mathrm{d}x_2\, f_a(x_1,\, \mu_F^2) f_b(x_2,\, \mu_F^2) \times \hat{\sigma}_{ab\to X}\left(Q^2 = x_1 x_2 s,\, \alpha_S(\mu_R),\, \frac{Q^2}{\mu_F^2},\, \frac{Q^2}{\mu_R^2},\, \ldots\right)$$

the **parton-level cross section** describing the hard scattering is computed perturbatively at the LO and NLO

$$\hat{\sigma}(\alpha_S, \mu_F, \mu_R) = [\alpha_S(\mu_R)]^{n_\alpha} \left[\hat{\sigma}^{(0)} + \frac{\alpha_S}{2\pi} \hat{\sigma}^{(1)}(\mu_F, \mu_R) + \left(\frac{\alpha_S}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F, \mu_R) + \ldots \right]$$

leading order

next-to-leading order

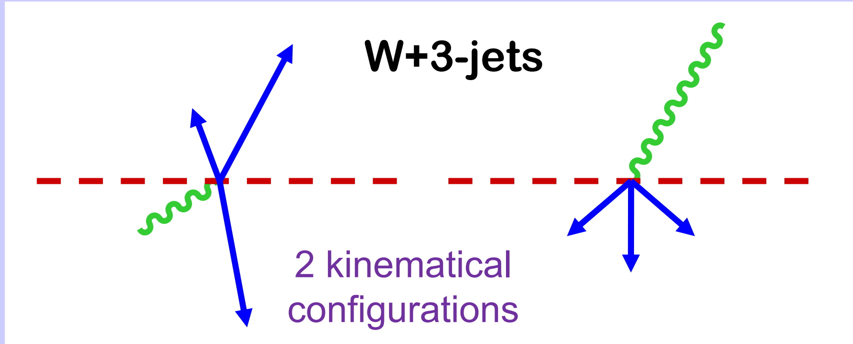
next-to-next-to-leading order

Which QCD Scale ?

typically, take $\mu_F = \mu_R = \mu$

for inclusive W take $\mu = m_W$

in more complicated processes there are often several 'reasonable' choices



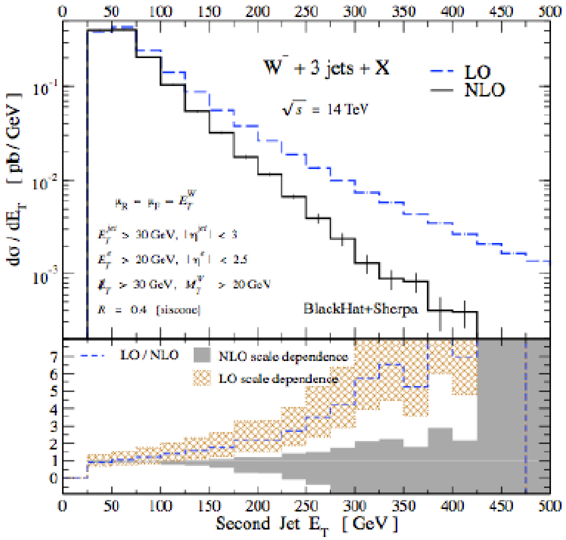
Example: W+3-jets

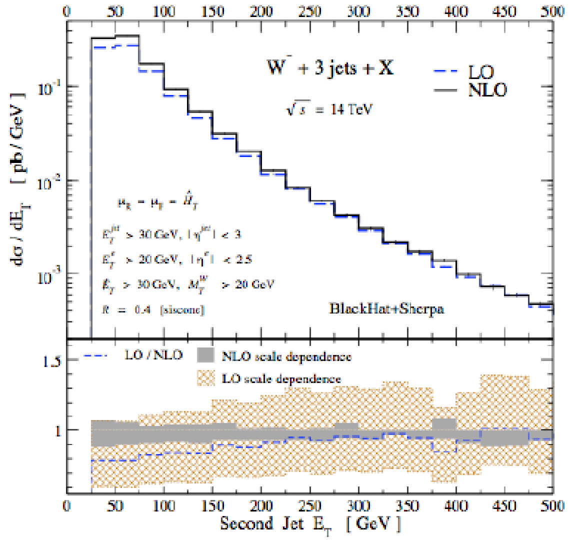
because LHC has greater dynamic range than Tevatron

the renormalization scale used at Tevatron turns to be a bad choice at LHC

Scale used at Tevatron

$$\mu = E_T^W$$





A better scale for LHC

$$\mu = \hat{H}_T$$

H_T takes account of different kinematical configurations

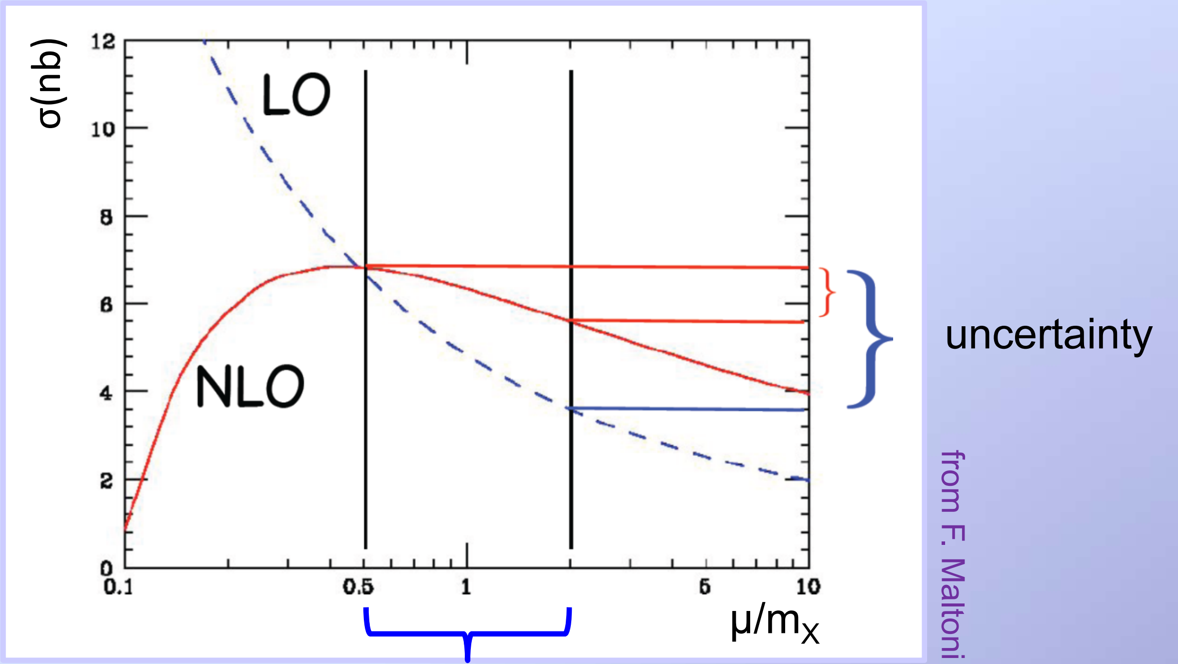
$$E_T{}^W = \sqrt{m_W^2 + p_T{}^W}$$

BlackHat+Sherpa

$$\hat{H}_T = p_T{}^W + \sum E_T{}^{\text{parton}}$$

Scale Uncertainties

Typical behavior of a cross section calculation
as a function of scale variations

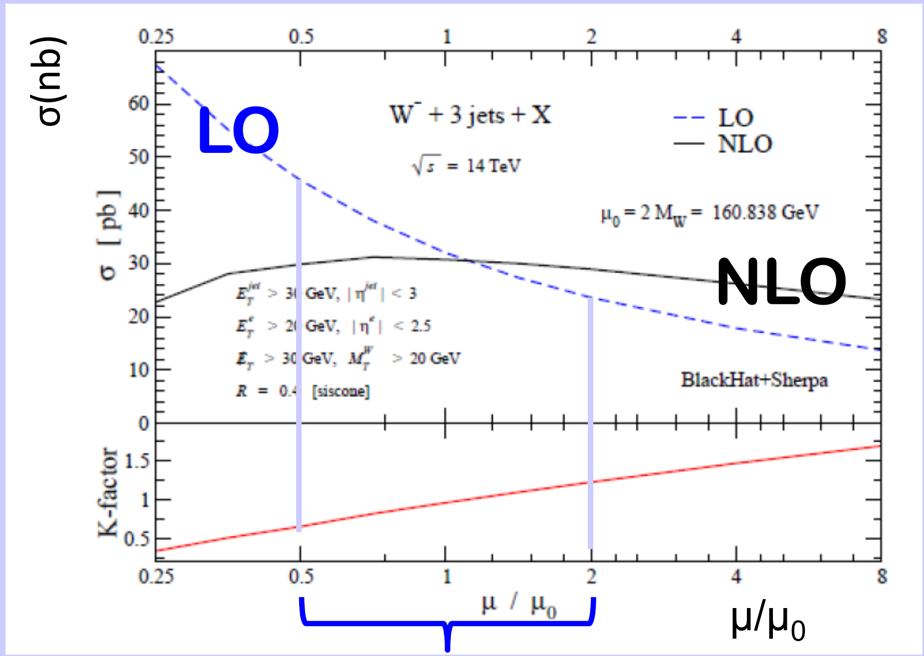


assume that “reasonable” scale variation is μ/m_X from ½ to 2

- **LO** calculation: rough estimate of the cross section
  LO predictions are only qualitative due to poor convergence of the expansion in α_S
- **NLO** calculation: good estimate of the cross section, rough estimate of the uncertainty
- **NNLO** calculation: refined estimate of the cross section, good estimate of the uncertainty

Scale Uncertainties

A concrete example: W + 3-jets



LO uncertainty

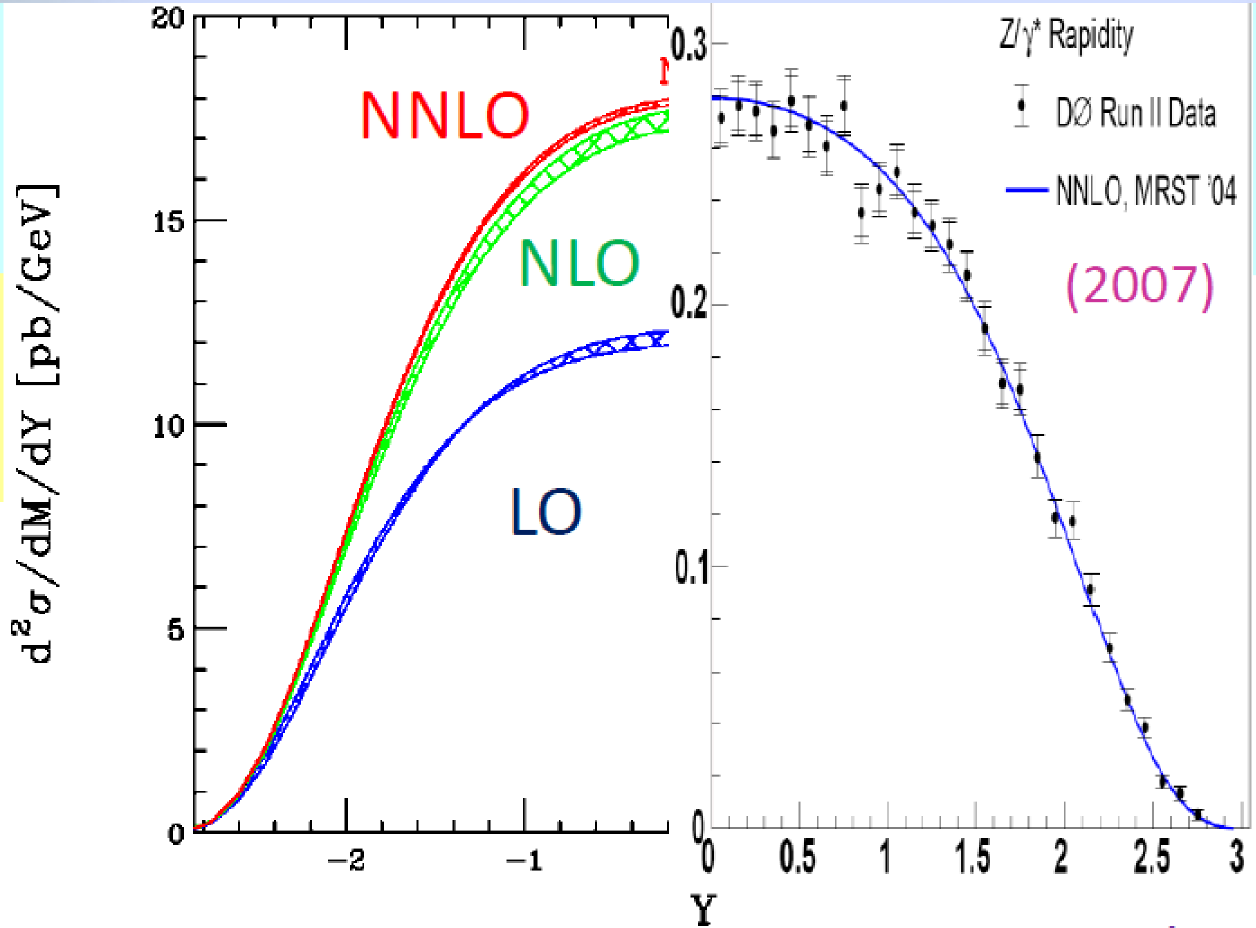
- calculation BlackHat+Sherpa
- $\mu_0 = 2\ m_W$

assume that "reasonable" scale variation is μ/m_X from ½ to 2

- **LO** calculation: rough estimate of the cross section
  LO predictions are only qualitative due to poor convergence of the expansion in α_S
- **NLO** calculation: good estimate of the cross section, rough estimate of the uncertainty
- **NNLO** calculation: refined estimate of the cross section, good estimate of the uncertainty

From LO to NNLO

example: Z rapidity distribution at Tevatron

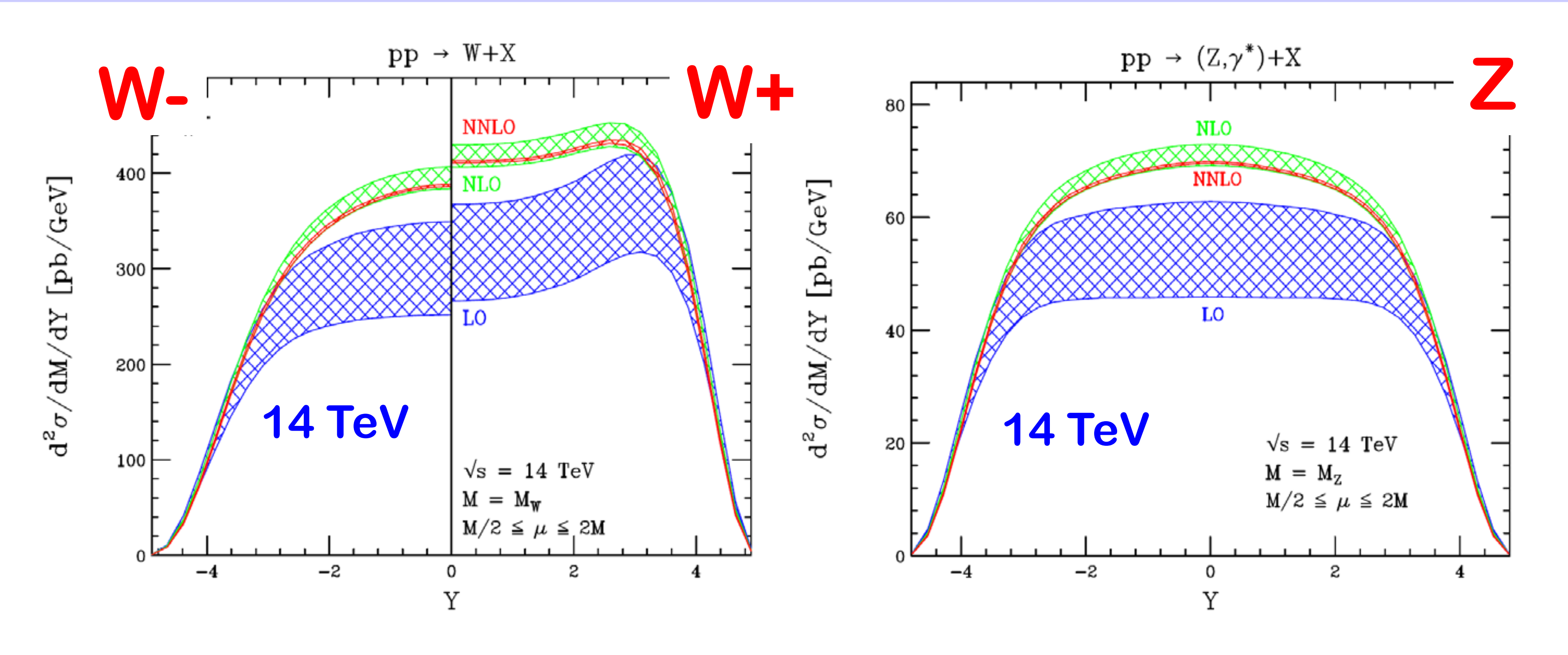


process with n_α=0,
still ~50% correction,
LO → NLO

When NLO calculations are not available, use so-called **K-factors**, either global or parameterized as a function of a kinematic variable

Rapidity Distributions

Higher order QCD (α_s) corrections from LO to NLO can modify cross section predictions by 30-40%!
with strong effects on the kinematics



from 14 TeV down to 7 TeV
at 7 TeV the rapidity plateau is at ~ 40 pb/GeV

W and Z: Theory Tools

- **Accurate theoretical NLO+ predictions exist**
  Many tools are available:
  - QCD MC generators
    (LO: PYTHIA, HERWIG, NLO: POWHEG, MC@NLO...)
  - LO-matched multi-jet generators
    (ALPGEN, MADGRAPH, SHERPA…)
    which will become NLO-matched in the next future
  - NNLO QCD cross-section calculations
    (RESBOS, FEWZ, DYNNLO…)
    effects NLO to NNLO are 3-4% on inclusive cross sections, smaller on acceptances
- **QED & electroweak corrections**
  - not negligible at this level of precision
    (HORACE…)
- **Parton density functions (PDF)**
  - differential distributions are sensitive to PDFs
  - several sets are available at LO and NLO
    (MSTW08, CT10, HERAPDF1.5, NNPDF2.1…)

W and Z Physics at the LHC

Why W and Z studies at the LHC?

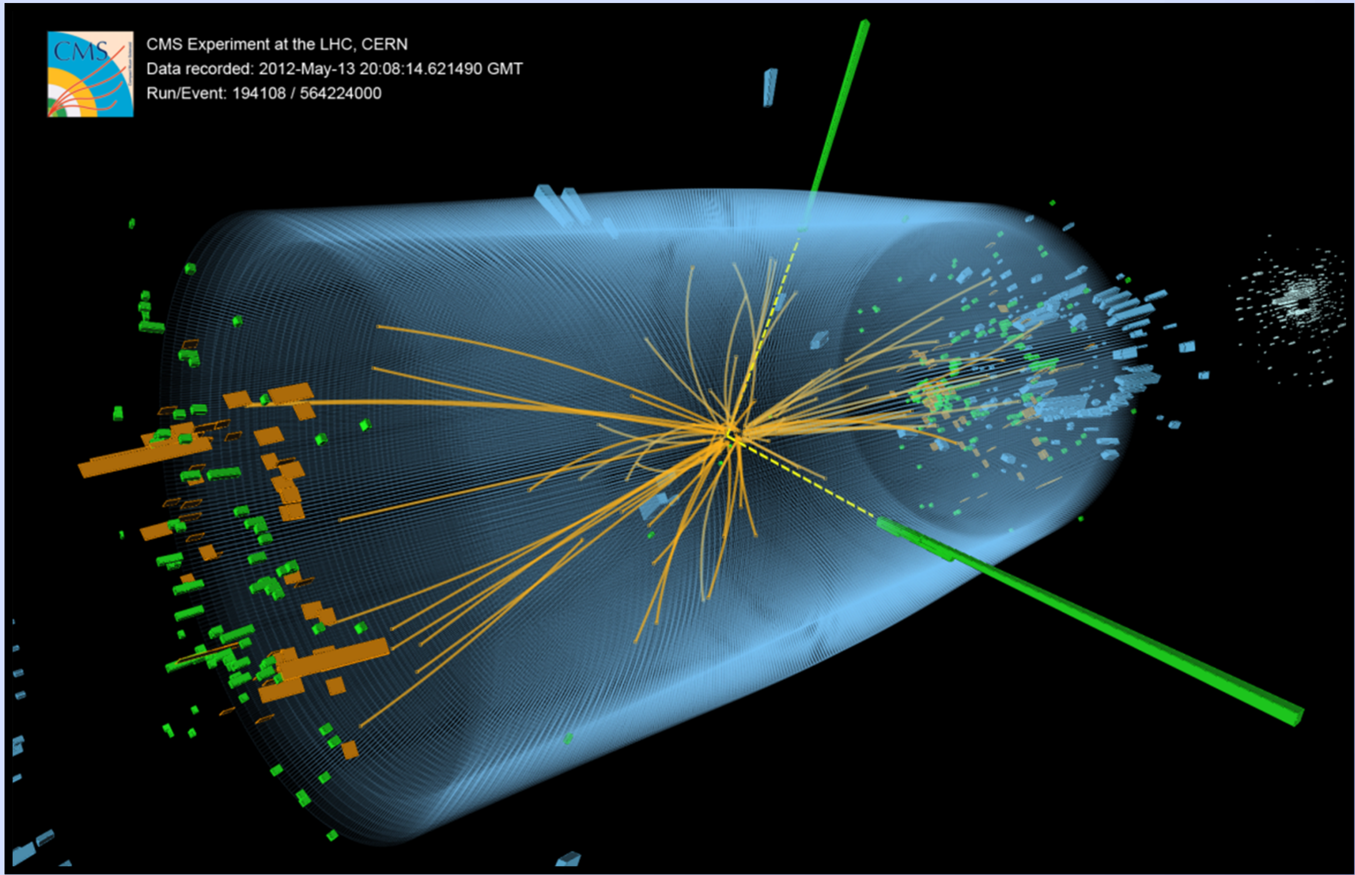
- **Processes with W and Z as “backgrounds”**
  for top physics and searches
  Higgs and New Physics
- **W and Z special samples for detector calibrations**
  trigger, identification, resolution, efficiencies, …

What can W and Z Studies at the LHC add on the Physics?

- **Higher collision energy**
  - implies larger cross sections and enlarged phase space for multi-boson production
  - allows to study processes inaccessible at lower energy collider,
    e.g., W+n-jets, 3V, 4V… production (with V=W, Z, or γ)
- Probe triple and quartic gauge couplings
- Check perturbative QCD dynamics
- Thanks to complementarity between ATLAS/CMS and LHCb
  study QCD at smaller x values : $x \sim M_X/\sqrt{s}$

Electroweak and Top Backgrounds to Higgs Searches

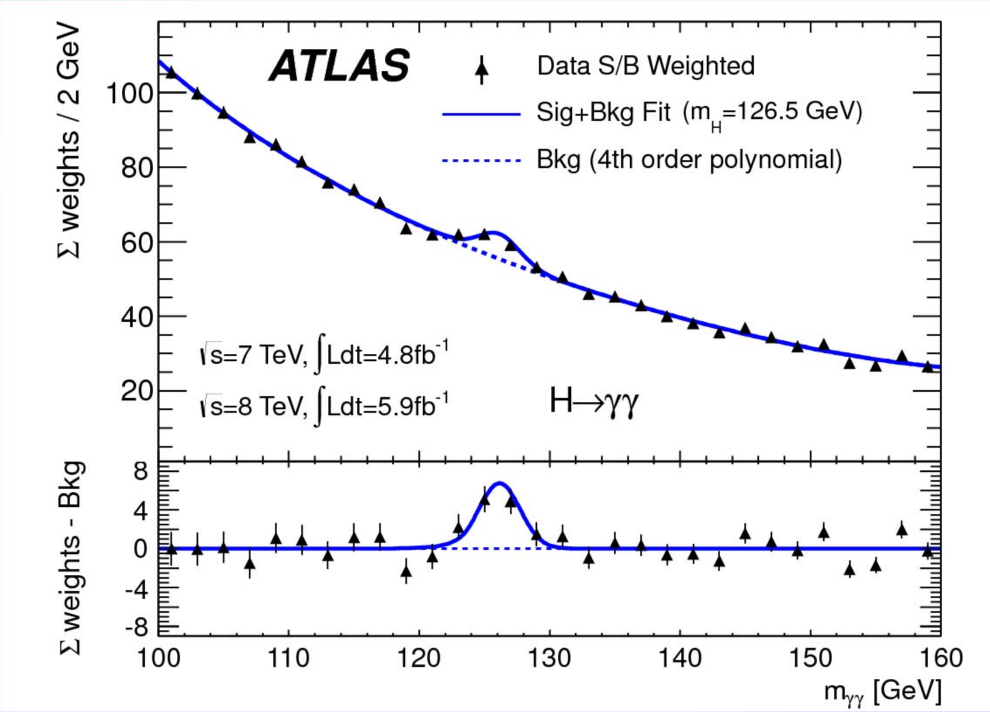
Electroweak and top backgrounds



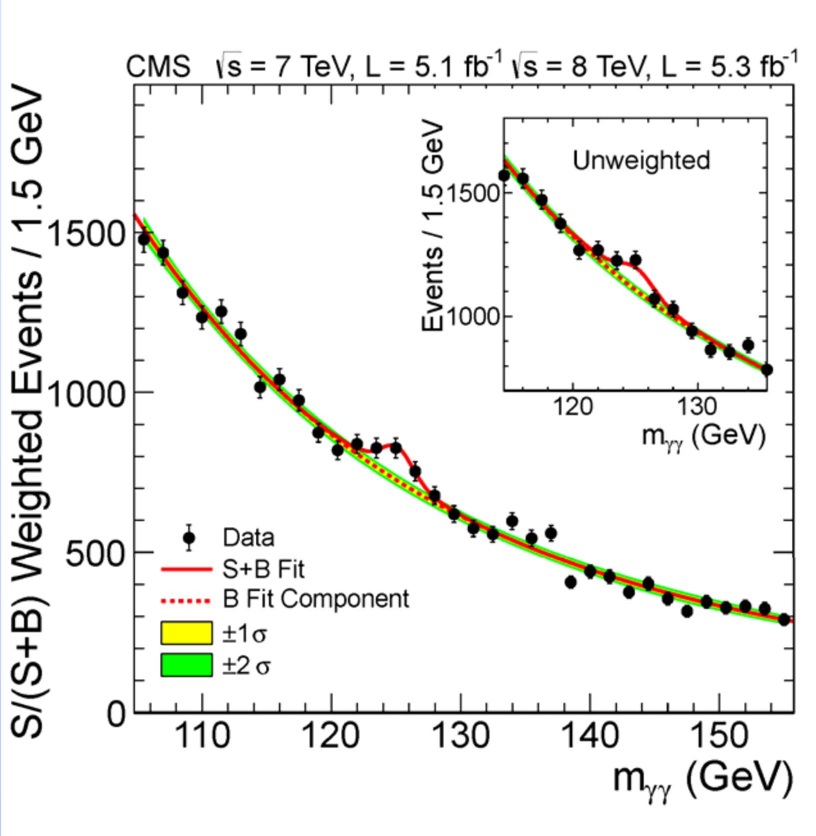
an event in CMS with two high-energy isolated photons: Higgs boson or di-photon QED production ?

Higgs in two gamma

ATLAS



CMS



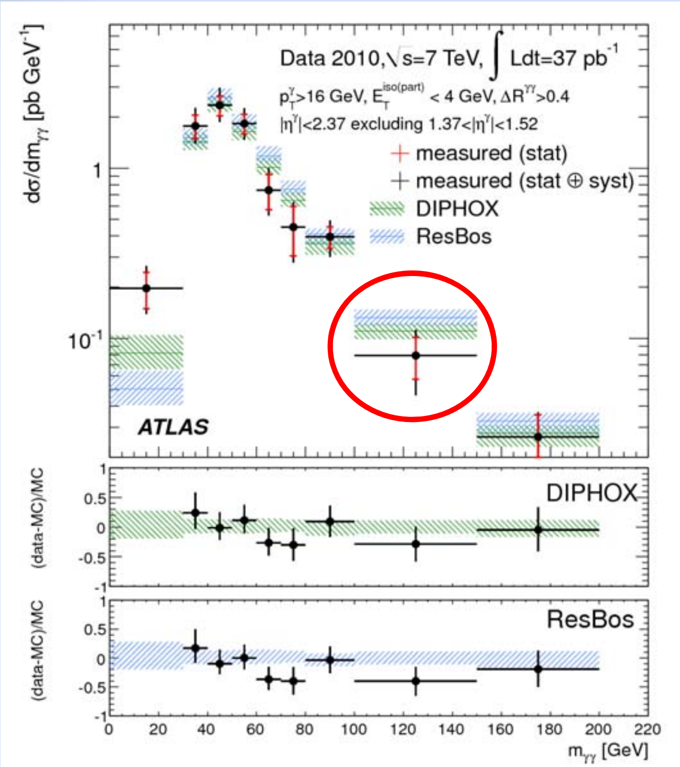
one of the main backgrounds is di-photon QED production

QED/QCD Di-Photons

Study of **QED/QCD di-photon production** in ATLAS and CMS

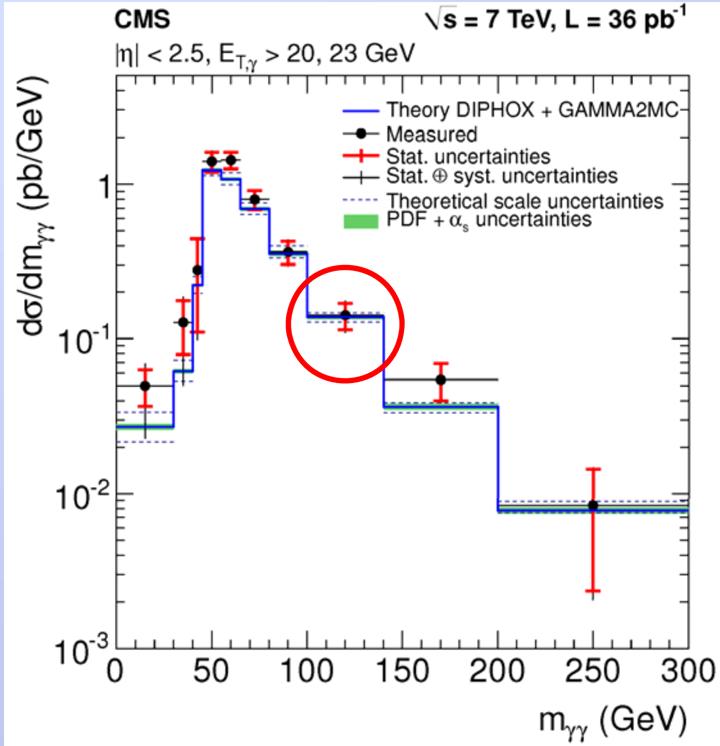
ATLAS

PRD85 (2012) 012003



CMS

JHEP 01 (2012) 133

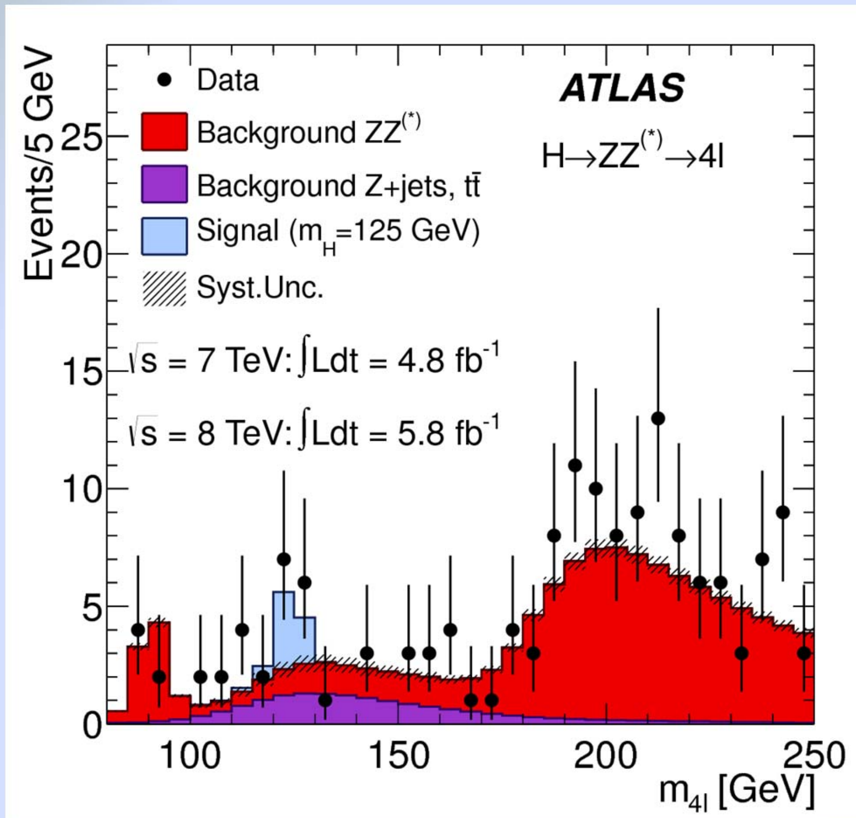


distributions are background-subtracted and corrected for resolution effects

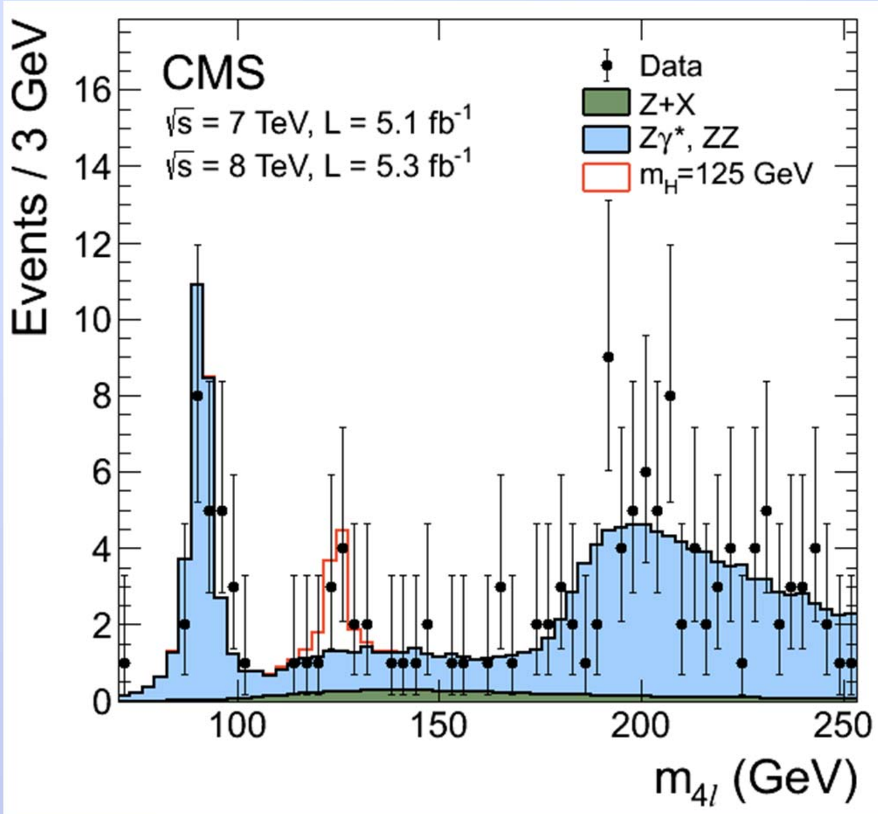
→ **good understanding** of the level of irreducible background in Higgs to gamma-gamma

Higgs in ZZ*

ATLAS



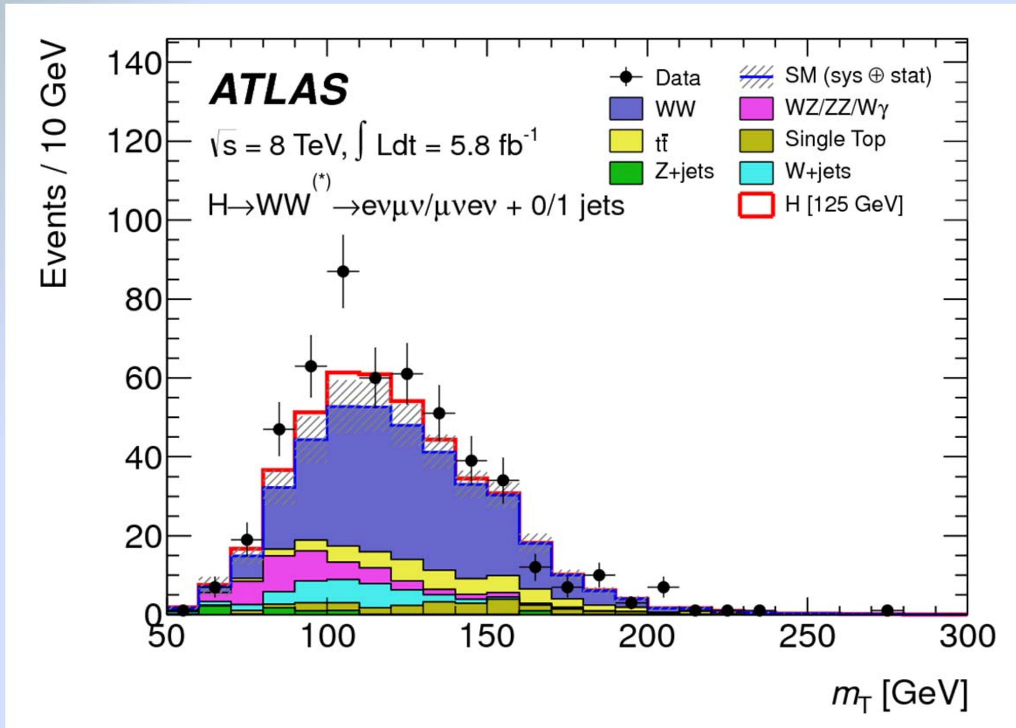
CMS



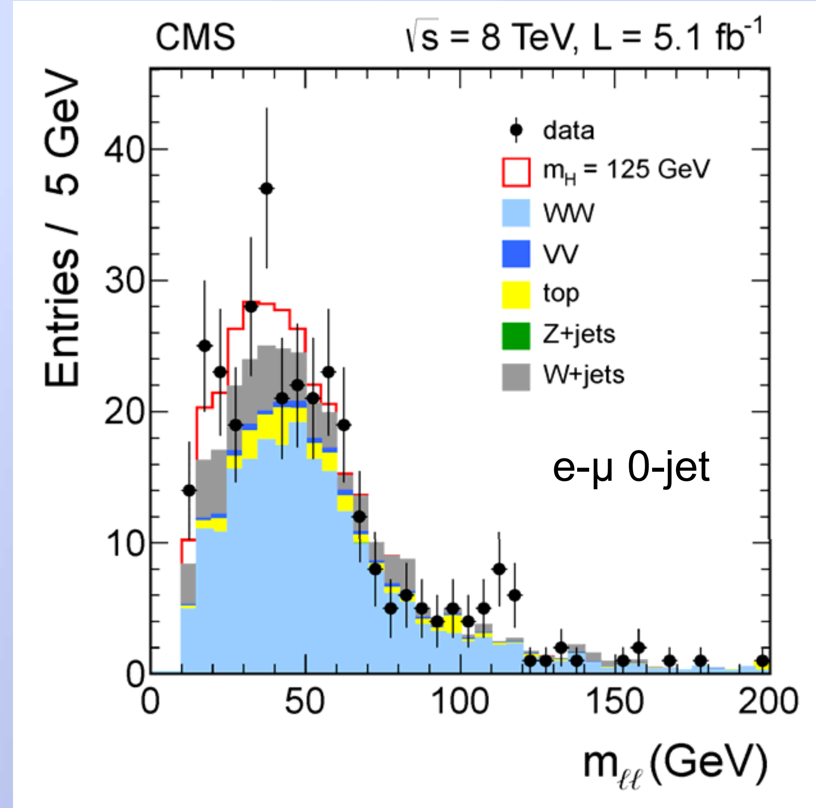
The main backgrounds are electroweak:
Z, ZZ*, Z+bb, Z+jets

Higgs in WW*

ATLAS



CMS

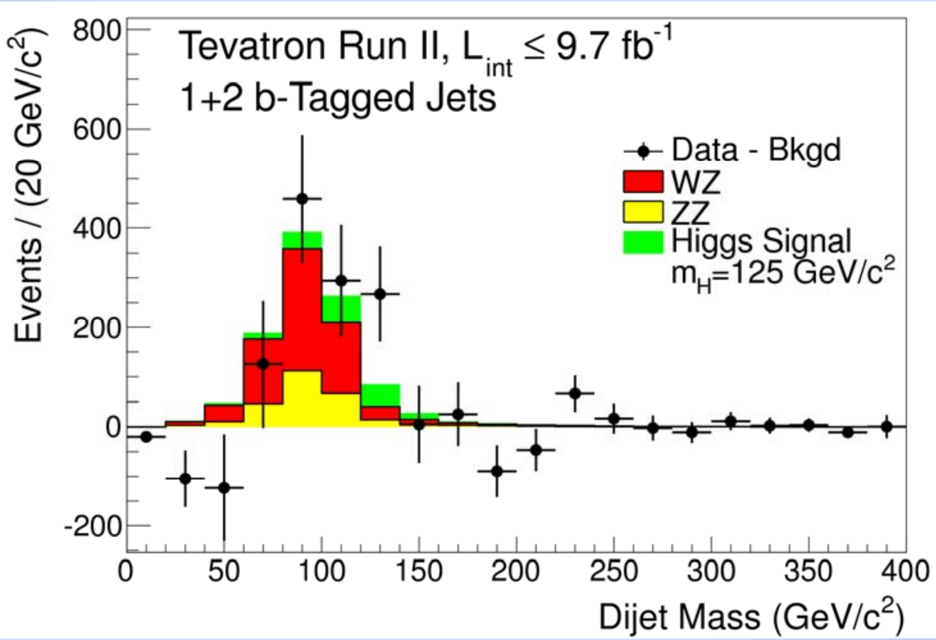


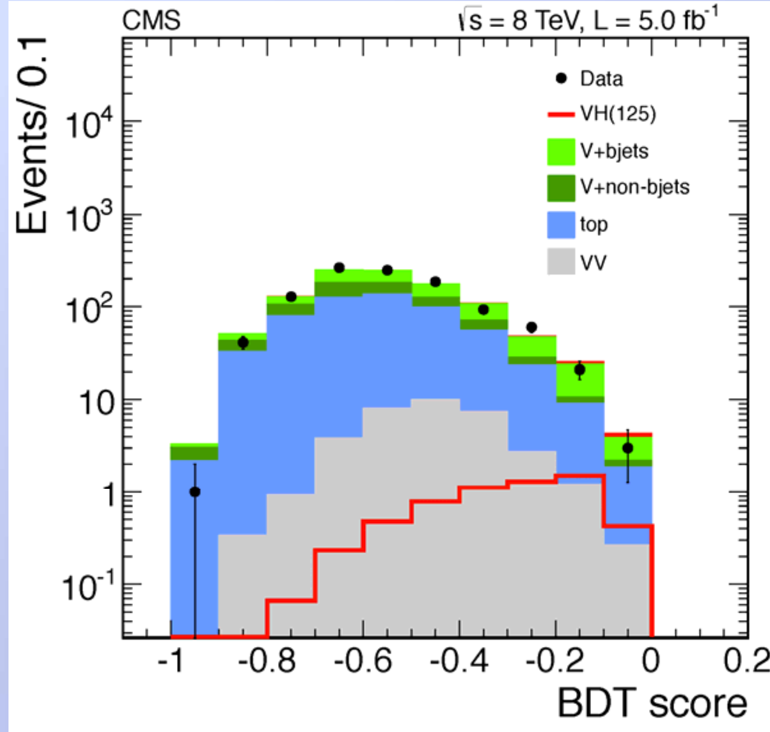
The main backgrounds are electroweak WW, W+jets, Wγ/WZ/ZZ and top quark pair production

Higgs en b-bbar

CDF+D∅

CMS





The main backgrounds are electroweak V+b-jets, V+jets, WZ and ZZ and top quark pair production

Inclusive W and Z Cross Sections

Cross Section Master Formula

Master formula

cross section x branching fraction

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

signal yield

acceptance

efficacity

luminosity

Signal extraction

cut & count

$$N = N_{\mathrm{tot}} - N_{\mathrm{bkg}}$$

number of selected signal event (background subtracted)

the signal yield can also be extracted from more complex likelihood fits (background templates)

Data-driven efficiency determination

strategy

$$A \times \varepsilon = F \times \rho$$

$$F = A \times \varepsilon_{\mathrm{sim}}$$

fraction of events selected in the signal Monte-Carlo simulation
incertainty : theory (incl. PDF)

$$\rho = \varepsilon / \varepsilon_{\mathrm{sim}}$$

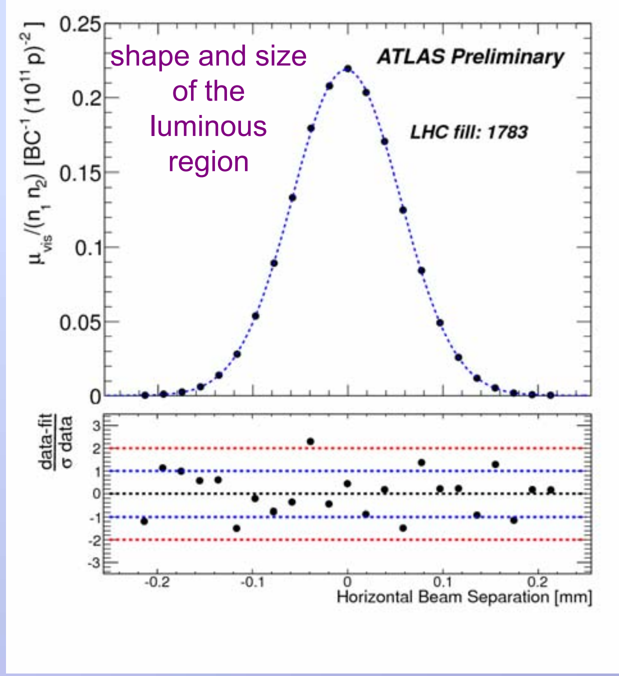
efficiency ratios
incertainty : experimental

Fiducial cross sections

perform the measurement within acceptance (=define generator level cuts for which A~1)
→ minimize theory uncertainties due to extrapolation to the full acceptance

Luminosity Measurement

- **Relative luminosity**
  several methods and algorithms used to determine the interaction rate per bunch crossing every few seconds with statistical precision better than 1%
  Exploit special minimum bias triggers:
  - rate zero counts in Forward Calorimeters
  - count of pixel track segments
  - count of pile-up vertices
  - etc.
- **Calibration of total visible cross section**
  - from dedicated **Van der Meer scans**
- **Absolute luminosity**
  - inferred from direct measurements of LHC parameters (e.g. bunch intensities)



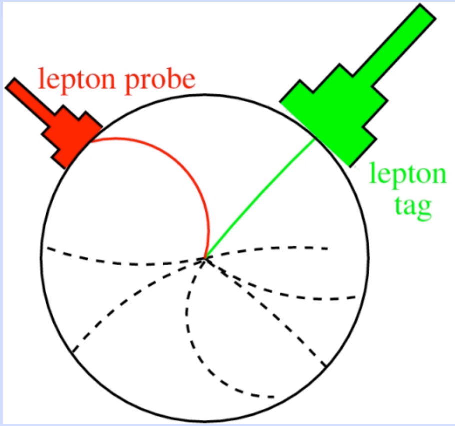
Van de Meer scan
specific interaction rate versus nominal beam separation

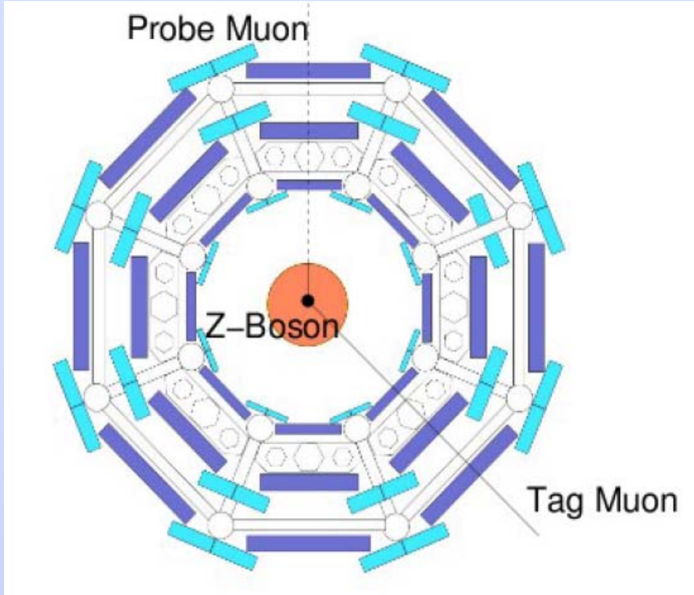
depending on the experiment and the period
(i.e., the method used to measure the luminosity variations versus time and the quality of its calibration with VdM scans)
luminosity errors in ATLAS and CMS are of the order of 3 to 6%

luminosity measurements are dominated by systematic uncertainties specific to the method used
Many cross checks are performed, including with W and Z Standard Candles

Z as Calibration Sample

Tag and Probe: a method to determine lepton selection efficiencies from data

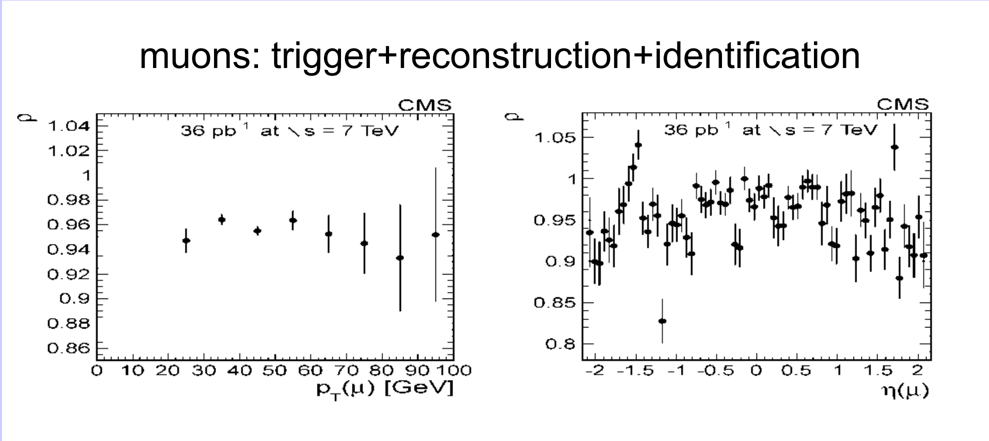




Select Z candidate events in data with:

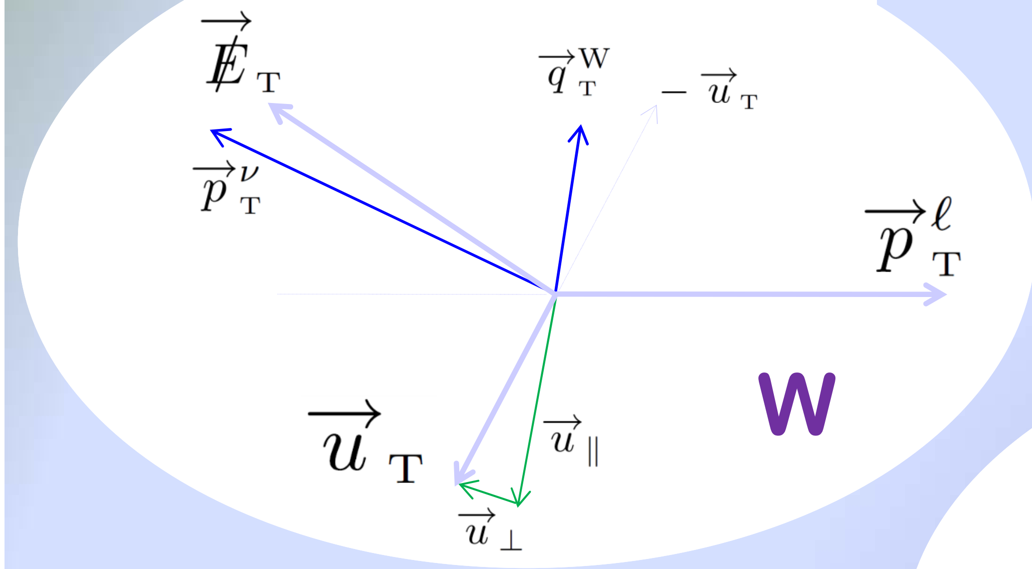
- one lepton satisfying tight selection criteria (the **tag**)
- a second lepton selected with loose criteria (the **probe**)
- use the probe to determine trigger, reconstruction, identification and isolation efficiencies
- derive **data/MC correction factors** as a function of p_T and η

Efficiency correction factors ρ



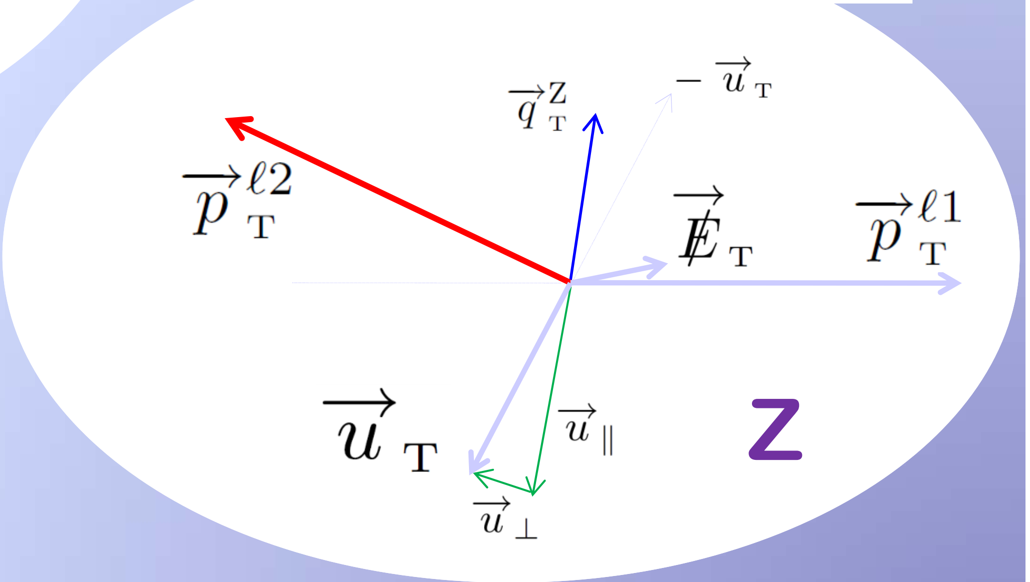
Hadronic recoil in W and Z events

$$\vec{u}_{\mathrm{T}} = -\vec{\not{E}}_{\mathrm{T}} - \vec{p}^{\,\ell}_{\mathrm{T}}$$



- **Simulation of recoil affected by**
  - underlying event
  - pile-up
  - instrumental backgrounds
  - detector calibration, energy resolution

$$\vec{u}_{\mathrm{T}} = -\vec{\not{E}}_{\mathrm{T}} - \Sigma_{\ell}\, \vec{p}^{\,\ell}_{\mathrm{T}}$$



strategy →

Use the **Z sample** for **MC/data event-by-event corrections**, parameterized as a function of the boson transverse momentum

Inclusive W: muon channel

Fiducial cuts
- $p_T > 25$ GeV
- $|\eta| < 2.1$

DY veto
- no other muon candidate with $p_T > 7$ GeV and $|\eta| < 2.4$

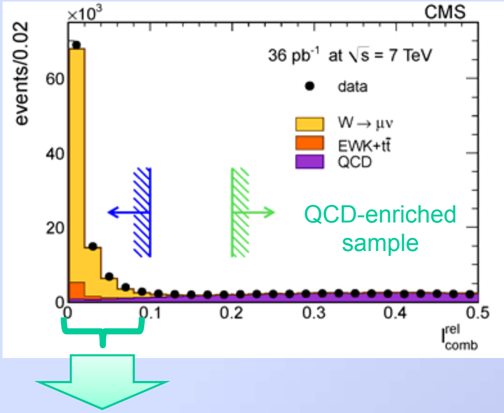
Use of Z sample
- E_T^{miss} from recoil
- momentum scale

Signal extraction
- from MET distribution
- templated fit
- data-driven QCD
- other backgrounds from MC

140 757 ± 383 W candidates

84 091 W^+ & 56 666 W^-

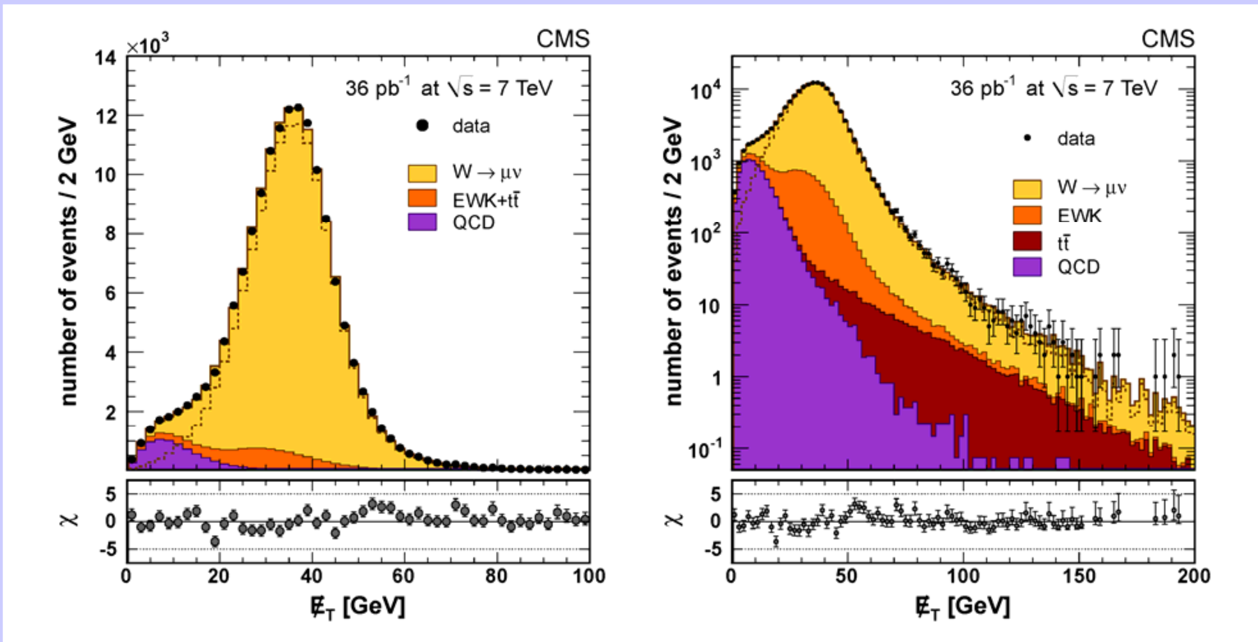
isolation variable



signal region

QCD-dominated control sample
- invert isolation criteria
- QCD template shape scaled to signal region as a function of isolation

JHEP 10 (2011) 132



Inclusive W: electron channel

Fiducial cuts
- $E_T > 25$ GeV
- $|\eta| < 2.5$

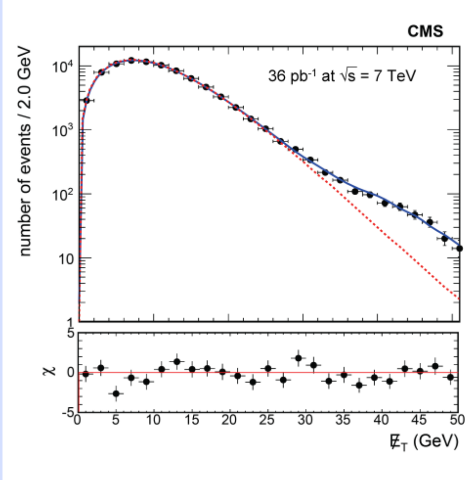
Stringent electron selection

DY veto
- no other electron candidate (loose selection) with $E_T > 20$ GeV and $|\eta| < 2.5$

Use of Z sample
- E_T^{miss} from recoil
- energy scale

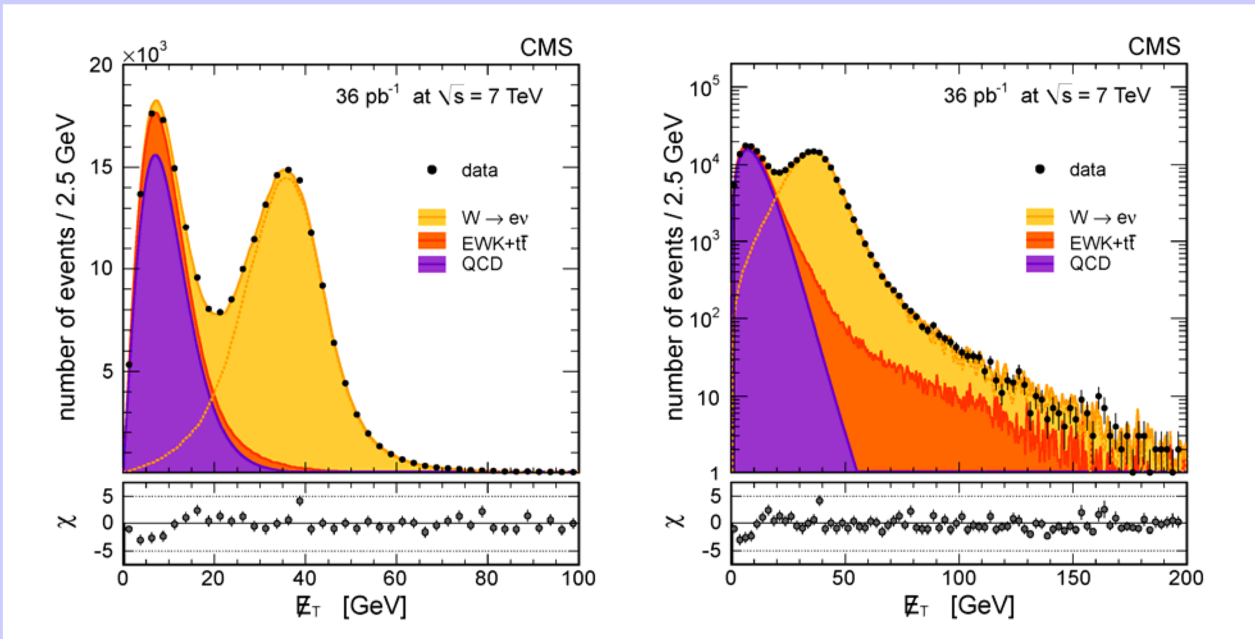
Signal extraction
- from MET distribution
- parameterized fit
- data-driven QCD
- other backgrounds from MC

135 982 ± 388 W candidates
81 286 W^+ & 54 703 W^-



QCD-dominated control sample
- invert track-matching criteria
- QCD background parameterized as modified Rayleigh function

JHEP 10 (2011) 132



Inclusive Z: muon channel

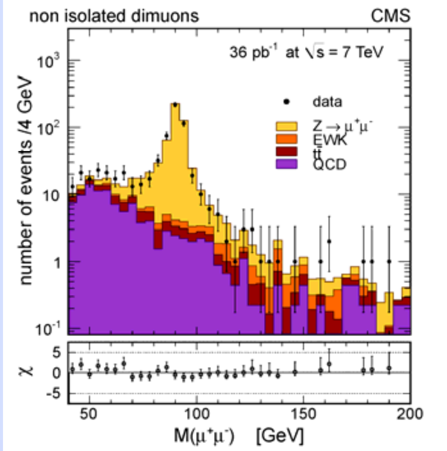
Fiducial cuts
- $p_T > 20$ GeV
- $|\eta_1| < 2.1$ and $|\eta_2| < 2.4$
- $60 < M(\mu\mu) < 120$ GeV

Standard muon selection

Almost background-free
- EWK and top backgrounds from simulation

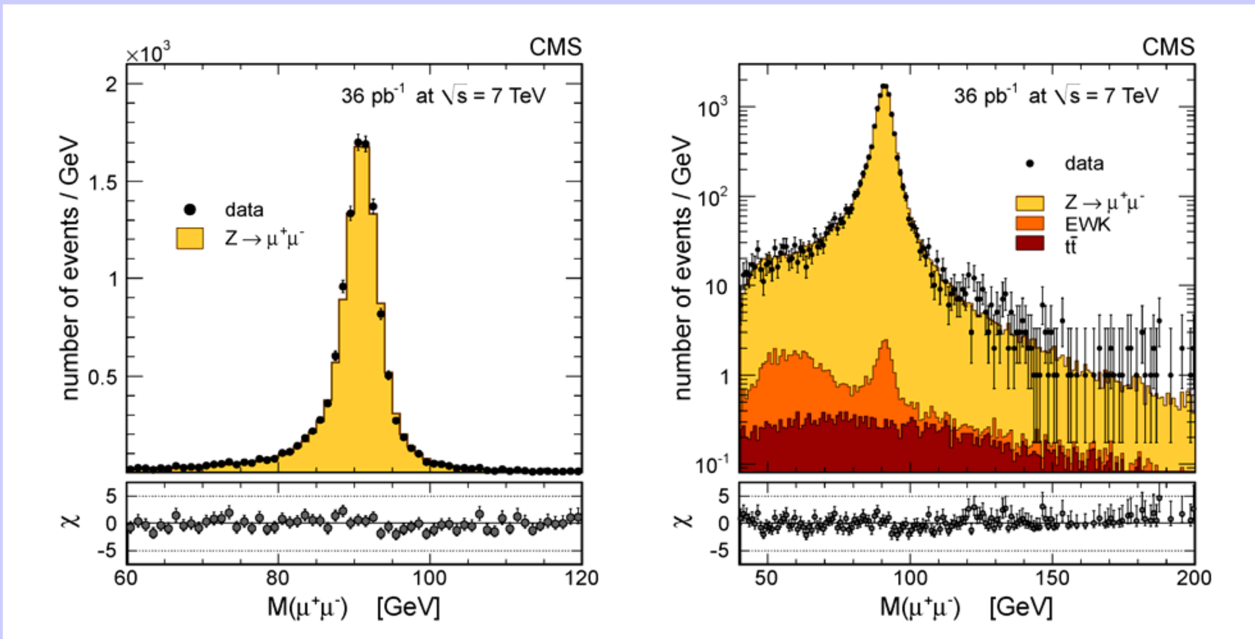
Signal extraction
- simultaneous fit of yields and muon efficiencies
- five exclusive categories of events

13 728 ± 121 Z candidates in "Golden" category



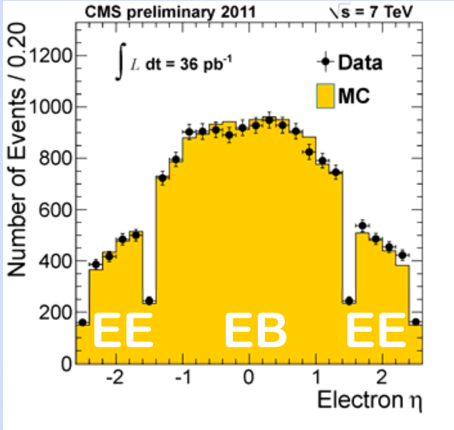
Control sample to determine isolation efficiency
(category of events with one non-isolated Global Muon)

JHEP 10 (2011) 132



Inclusive Z: electron channel

Fiducial cuts
- $E_T > 25$ GeV
- $|\eta| < 2.5$
- $60 < M(ee) < 120$ GeV

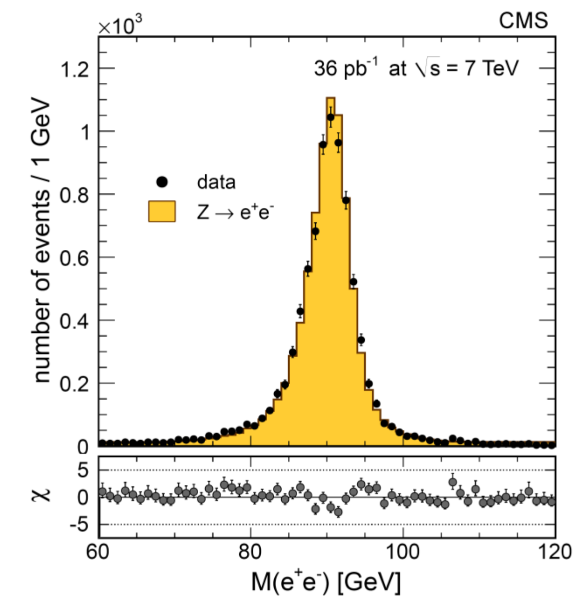


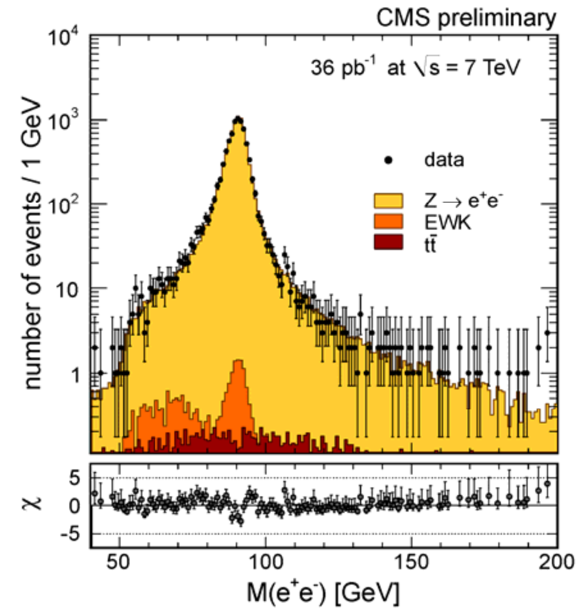
pseudo-rapidity of ECAL clusters

Same electron selection as W analysis

Almost background-free with this electron selection
- QCD and W+jets from data (with three methods) consistent with zero
- other backgrounds from simulation

JHEP 10 (2011) 132





Signal extraction
- cut and count
- efficiencies from Tag and Probe

8 406 ± 92 Z candidates

Acceptance and Efficiencies

Acceptance

POHWEG + CT10

Process	$A_{W,Z}$	
	$\ell = e$	$\ell = \mu$
$W^+ \to \ell^+\nu$	0.5017 ± 0.0004	0.4594 ± 0.0004
$W^- \to \ell^-\overline{\nu}$	0.4808 ± 0.0004	0.4471 ± 0.0004
$W \to \ell\nu$	0.4933 ± 0.0003	0.4543 ± 0.0003
$Z \to \ell^+\ell^-$	0.3876 ± 0.0005	0.3978 ± 0.0005

all results are given in the fiducial region
and in the full acceptance

Quantity	CTEQ	MSTW	NNPDF
$A_{W^+}(e)$	0.5017	0.5016	0.5036
$A_{W^-}(e)$	0.4808	0.4855	0.4804
$A_W(e)$	0.4933	0.4951	0.4942
$A_Z(e)$	0.3876	0.3892	0.3872
$A_{W^-}(e)/A_{W^+}(e)$	0.9583	0.9488	0.9626
$A_Z(e)/A_W(e)$	0.7857	0.7853	0.7880
$A_{W^+}(\mu)$	0.4594	0.4587	0.4617
$A_{W^-}(\mu)$	0.4471	0.4519	0.4472
$A_W(\mu)$	0.4543	0.4559	0.4557
$A_Z(\mu)$	0.3978	0.3990	0.3973
$A_{W^-}(\mu)/A_{W^+}(\mu)$	0.9732	0.9614	0.9778
$A_Z(\mu)/A_W(\mu)$	0.8756	0.8761	0.8796

Efficiencies

	ϵ_{sim}	$\epsilon_{sim} \times \rho$
$W^+ \to e^+\nu$	$(76.04 \pm 0.03)\%$	$(73.7 \pm 1.0)\%$
$W^- \to e^-\overline{\nu}$	$(76.94 \pm 0.03)\%$	$(73.2 \pm 1.0)\%$
$W \to e\nu$	$(76.40 \pm 0.02)\%$	$(73.5 \pm 0.9)\%$

	ϵ_{sim}	$\epsilon_{sim} \times \rho$
$W^+ \to \mu^+\nu$	$(89.19 \pm 0.03)\%$	$(85.4 \pm 0.8)\%$
$W^- \to \mu^-\overline{\nu}$	$(89.19 \pm 0.03)\%$	$(84.1 \pm 0.8)\%$
$W \to \mu\nu$	$(89.19 \pm 0.03)\%$	$(84.8 \pm 0.8)\%$

	ϵ_{sim}	$\epsilon_{sim} \times \rho$
$Z \to e^+e^-$	$(66.74 \pm 0.07)\%$	$(60.9 \pm 1.1)\%$

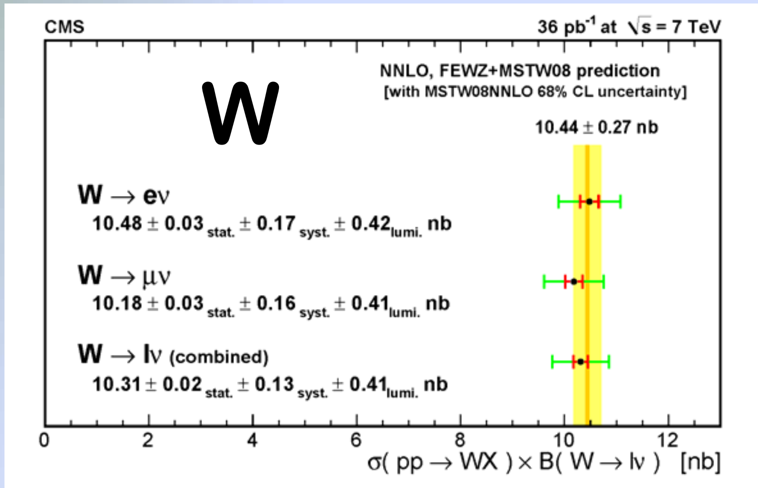
	ϵ_{sim}	$\epsilon_{sim} \times \rho$
$Z \to \mu^+\mu^-$	$(89.21 \pm 0.05)\%$	$(87.1 \pm 1.1)\%$

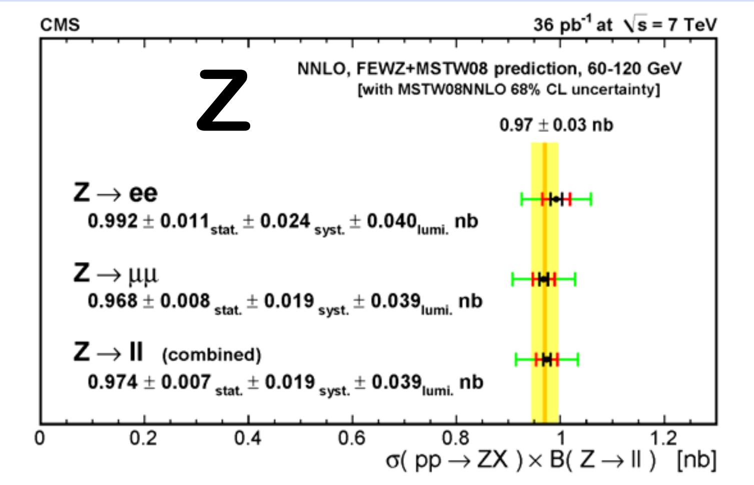
Systematic Uncertainties

Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.3	0.9	1.8	n/a
Trigger prefiring	n/a	0.5	n/a	0.5
Energy/momentum scale & resolution	0.5	0.22	0.12	0.35
$\not\!\!E_T$ scale & resolution	0.3	0.2	n/a	n/a
Background subtraction / modeling	0.35	0.4	0.14	0.28
Trigger changes throughout 2010	n/a	n/a	n/a	0.1
Total experimental	1.5	1.1	1.8	0.7
PDF uncertainty for acceptance	0.6	0.8	0.9	1.1
Other theoretical uncertainties	0.7	0.8	1.4	1.6
Total theoretical	0.9	1.1	1.6	1.9
Total (excluding luminosity)	1.7	1.6	2.4	2.0

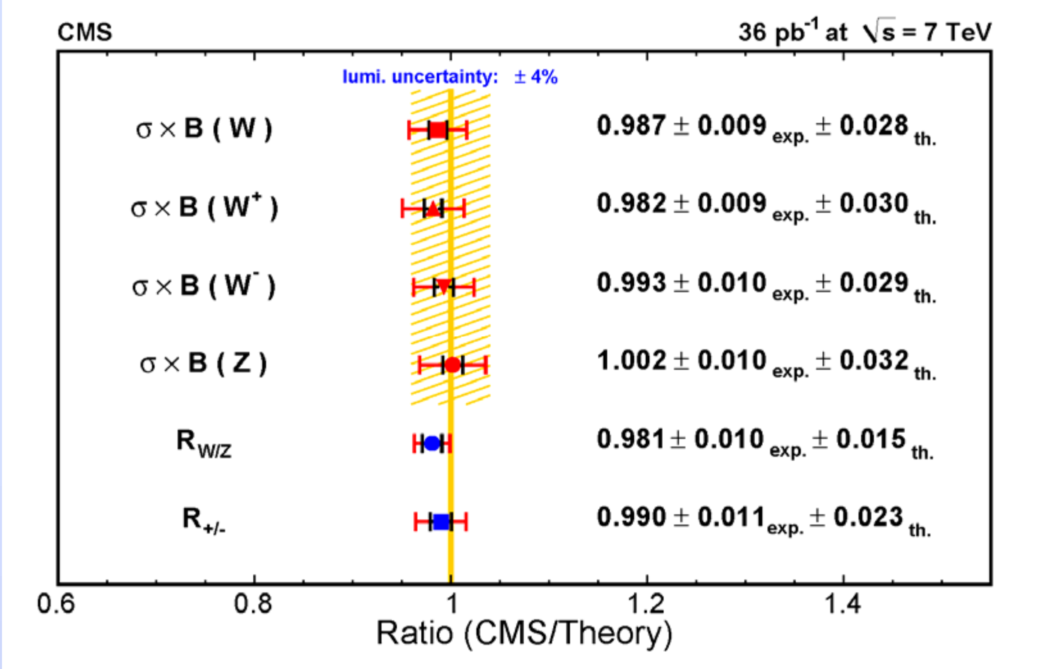
- **experimental uncertainties** are reduced thanks to the use of data-driven techniques to control background and signal shapes, and efficiencies
- **theoretical uncertainties** on acceptance include:
  PDFs (use of PDF4LHC prescription) ; ISR/higher-order effects (RESBOS vs POWHEG) ;
  EWK/FSR effects (HORACE vs Pythia) ; factorization/renormalization scales (FEWZ) ;
  EWK corrections (HORACE)

W and Z Inclusive Cross Sections





JHEP 10 (2011) 132



- ratios are not affected by luminosity uncertainty
- W+/W- is sensitive to PDFs
  (→ W lepton charge asymmetry)
- the theory prediction for W/Z is quite precise

ATLAS: W Signal Yields

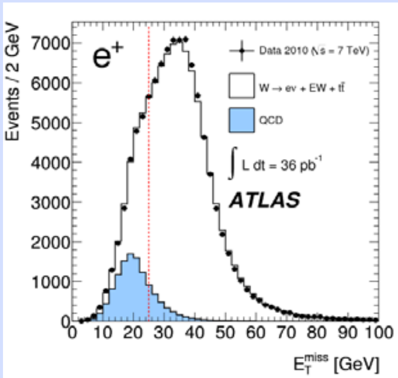
PRD85 (2012) 072004

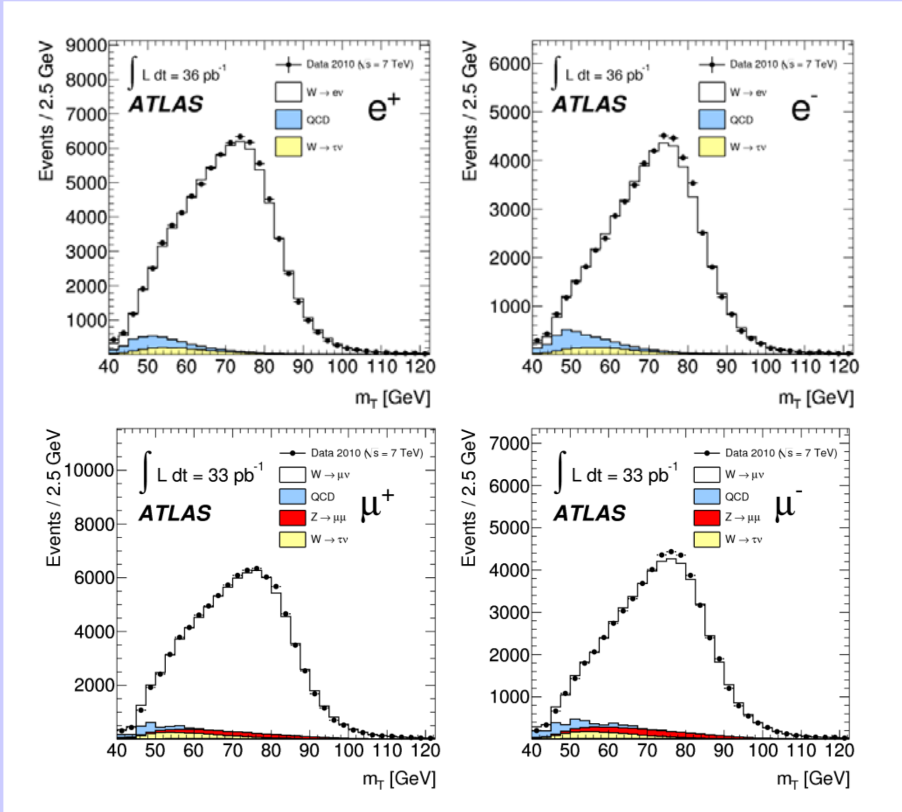
Different strategy

obtain pure samples of W events using requirements on E_T^{miss} and m_T

Fiducial cuts

- $p_T > 20$ GeV
- $|\eta| < 2.47$ (2.4) for e (μ)
- $E_T^{miss} > 25$ GeV
- $m_T > 40$ GeV





electrons

	N	B	$C_{W/Z}$	$A_{W/Z}$
W^+	77885	5130 ± 350	0.693 ± 0.012	0.478 ± 0.008
W^-	52856	4500 ± 240	0.706 ± 0.014	0.452 ± 0.009
$W^\pm$	130741	9610 ± 590	0.698 ± 0.012	0.467 ± 0.007

muons

	N	B	$C_{W/Z}$	$A_{W/Z}$
W^+	84514	6600 ± 600	0.796 ± 0.016	0.495 ± 0.008
W^-	55234	5700 ± 600	0.779 ± 0.015	0.470 ± 0.010
$W^\pm$	139748	12300 ± 1100	0.789 ± 0.015	0.485 ± 0.007

ATLAS: Z Signal Yield

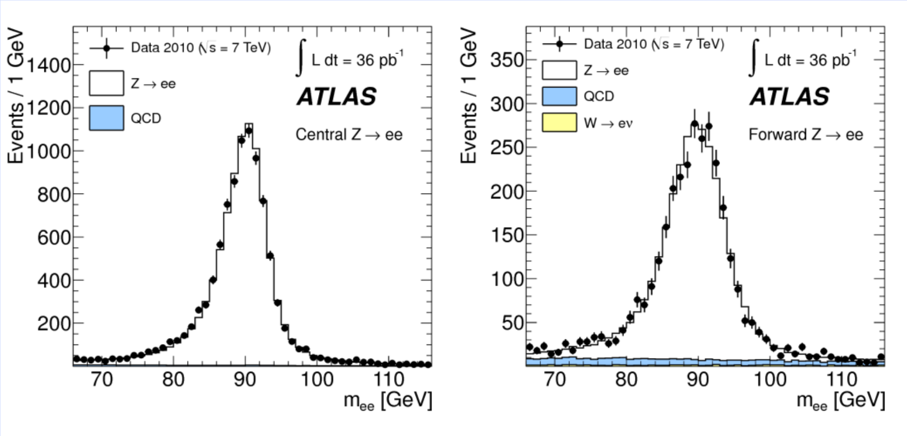
Fiducial cuts
- p_T > 20 GeV
- $|\eta|$ < 2.47 (2.4) for e (μ)
- 66 < $M(\mu\mu)$ < 116 GeV

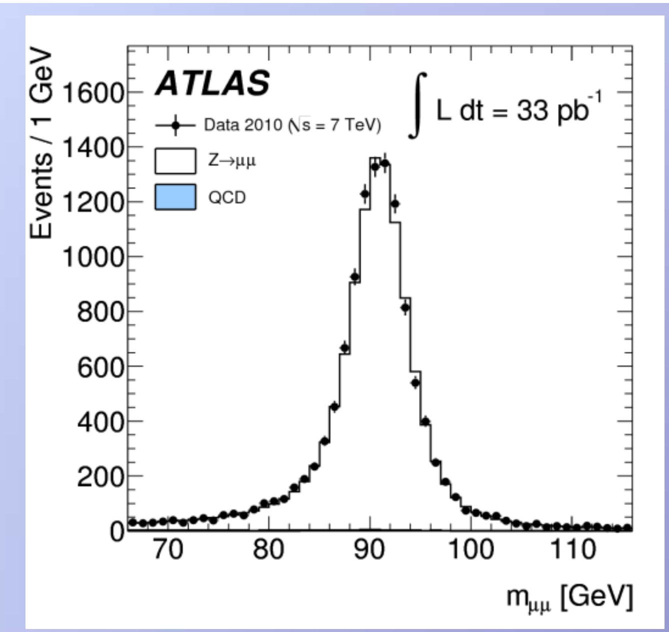
Electrons
- central: both e with $|\eta|$ < 2.47
- forward: one e with 2.5 < $|\eta|$ < 4.9

9 725 Z candidates
$C_{W/Z}$ = 0.618 ± 0.016
A = 0.447 ± 0.009

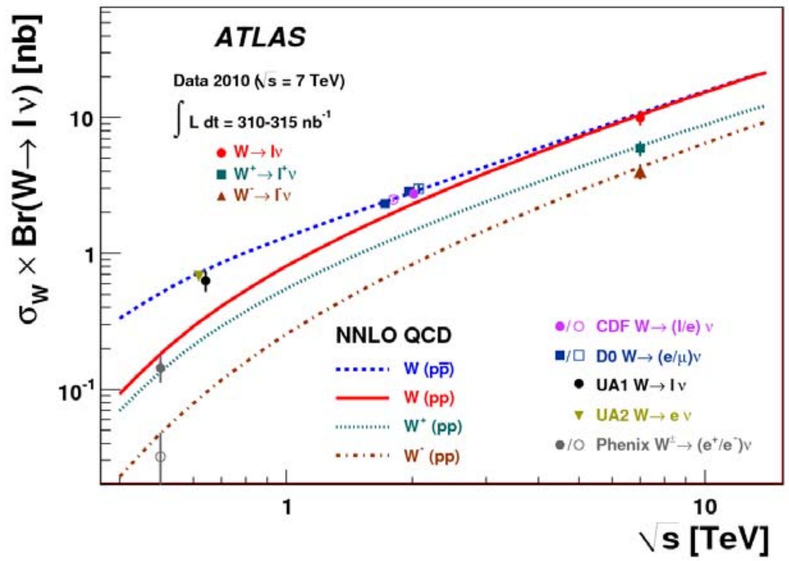
Muon
- $|\eta|$ < 2.4

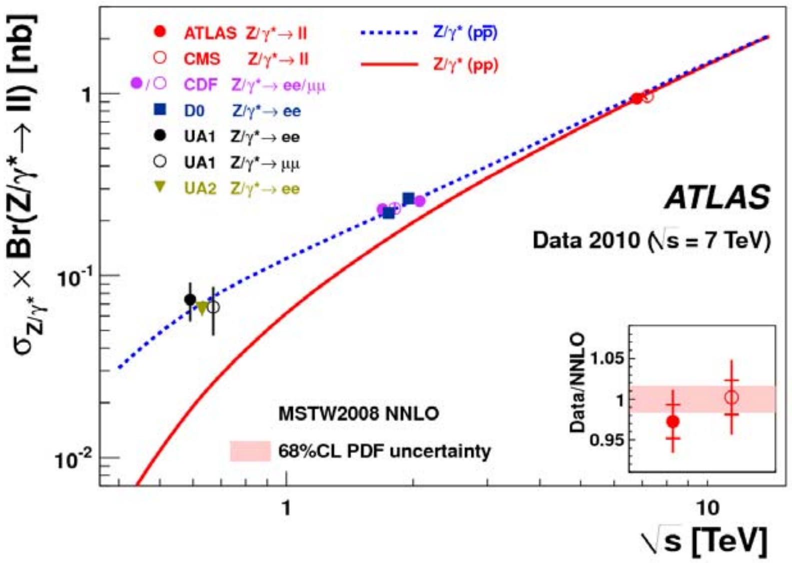
11 709 Z candidates
$C_{W/Z}$ = 0.782 ± 0.007
A = 0.487 ± 0.010

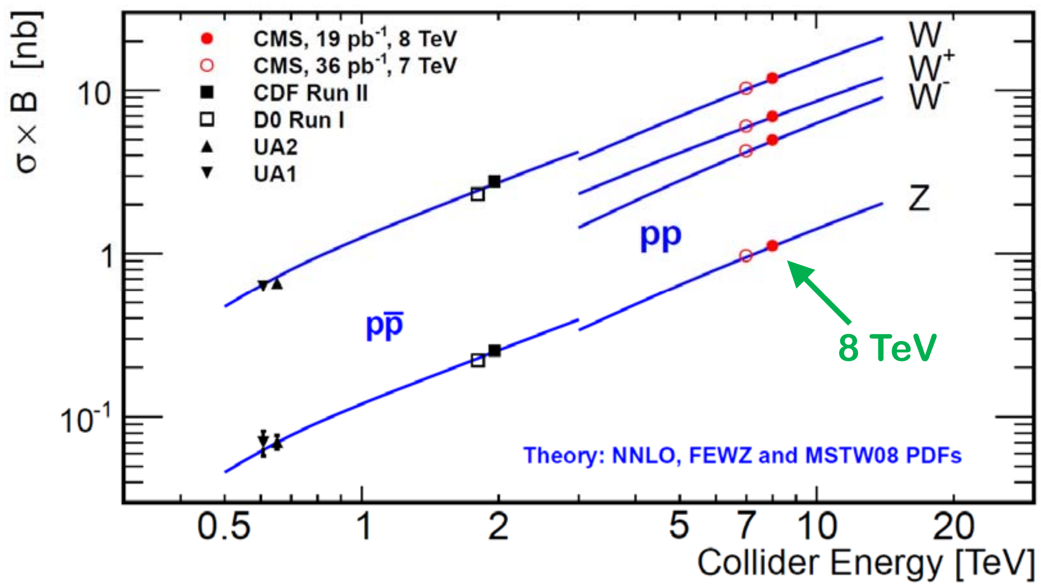




W & Z Cross Sections

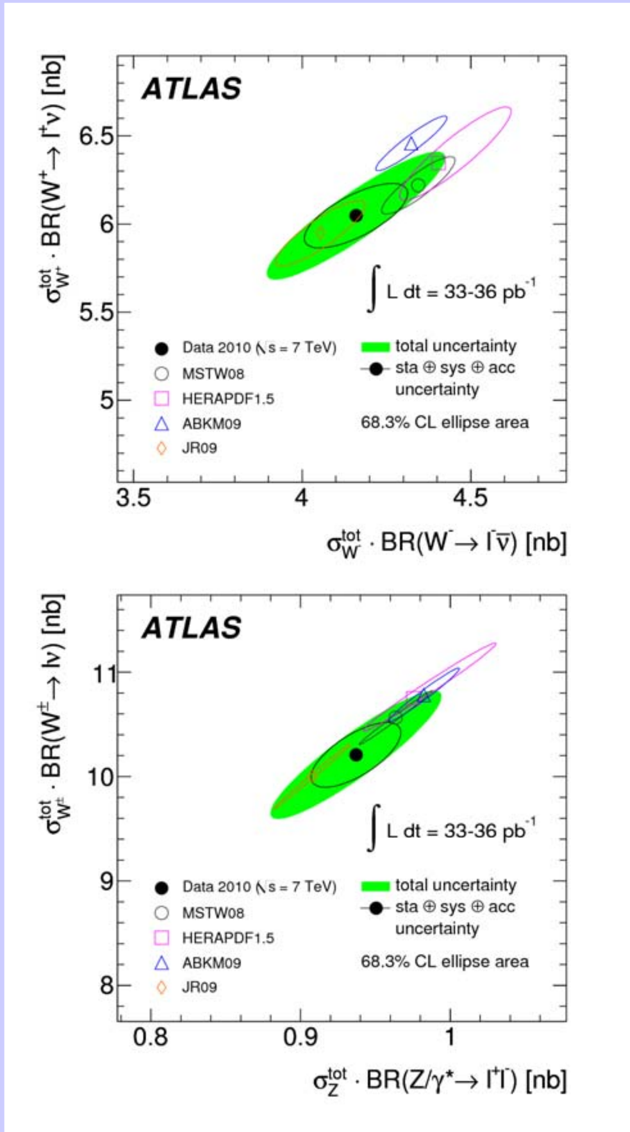


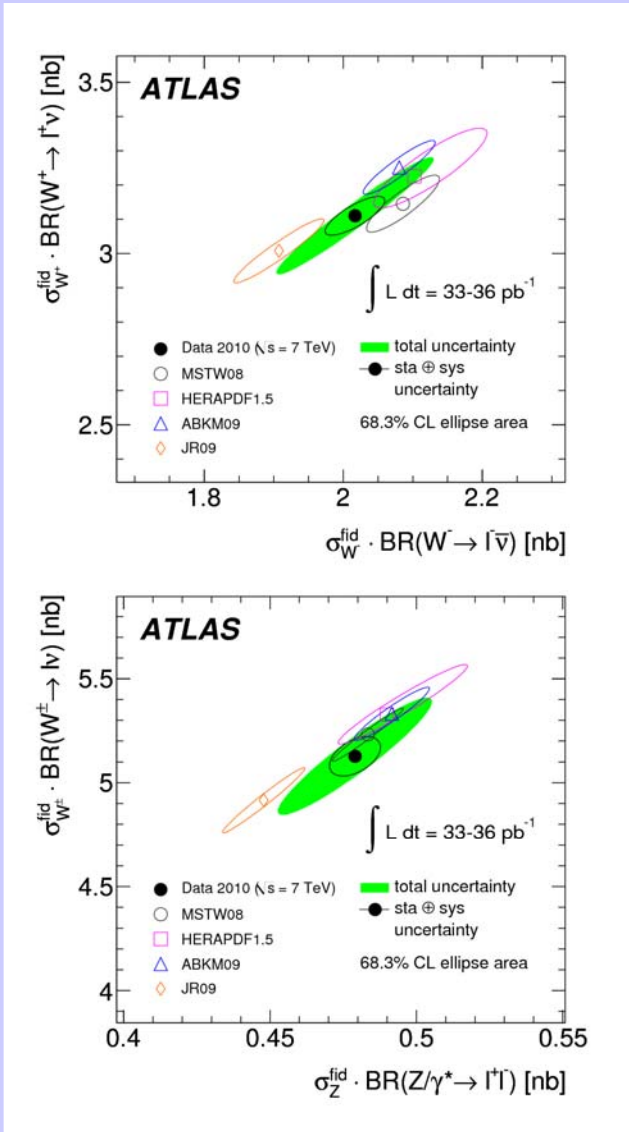




Excellent agreement
with NNLO
theory predictions
(7 and 8 TeV)

Fiducial Cross Sections





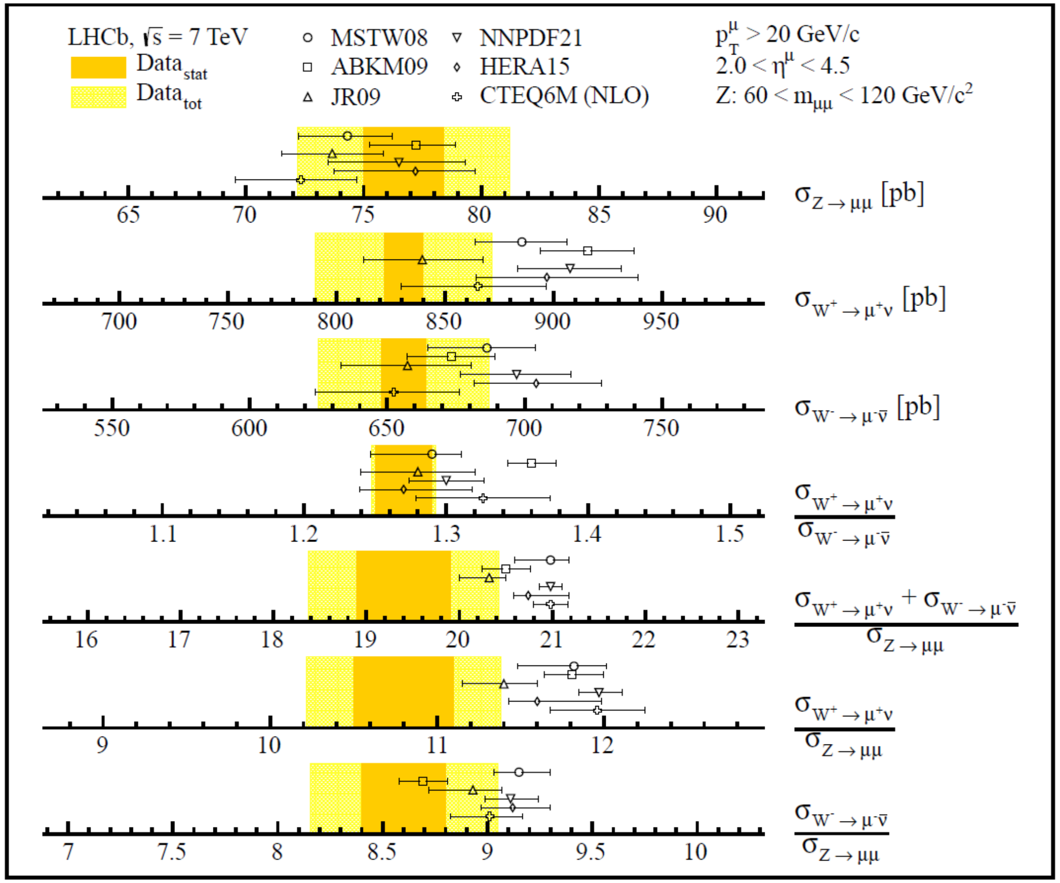
Both ATLAS and CMS provide fiducial cross sections

No theoretical uncertainty from extrapolation outside experimental acceptance

Luminosity becomes dominant source of uncertainty

Much better sensitivity for tests of PDF sets

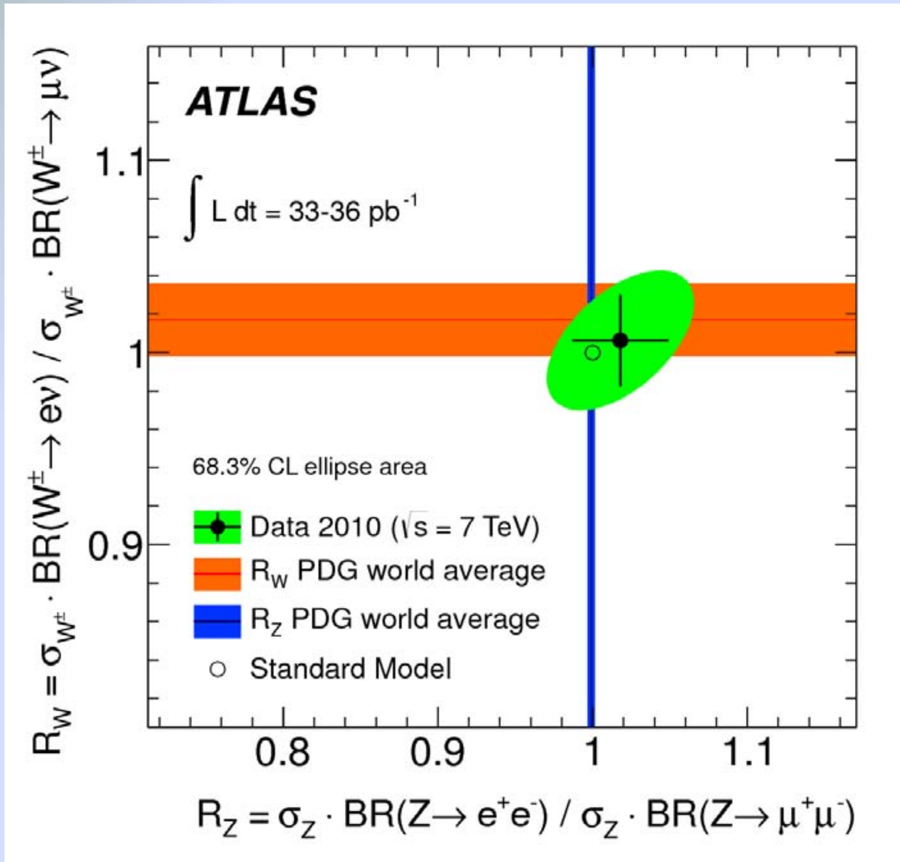
LHCb: Fiducial Cross Sections



Large discrepancies in W and Z boson production at high rapidity (including in luminosity-independent ratios)

This indicates that PDF sets for valence quarks and sea (anti)quarks need retuning at large and low x values

Test of Lepton Universality



$$R_W = \frac{\sigma_W^e}{\sigma_W^\mu} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)}$$

$R_W = 1.006 \pm 0.024$

World Average: 1.017 ± 0.019

$$R_Z = \frac{\sigma_Z^e}{\sigma_Z^\mu} = \frac{Br(Z \to ee)}{Br(Z \to \mu\mu)}$$

$R_Z = 1.018 \pm 0.031$

World Average: 0.9991 ± 0.0024

Result already close to best measurement for R_W