

W/Z Production in ATLAS

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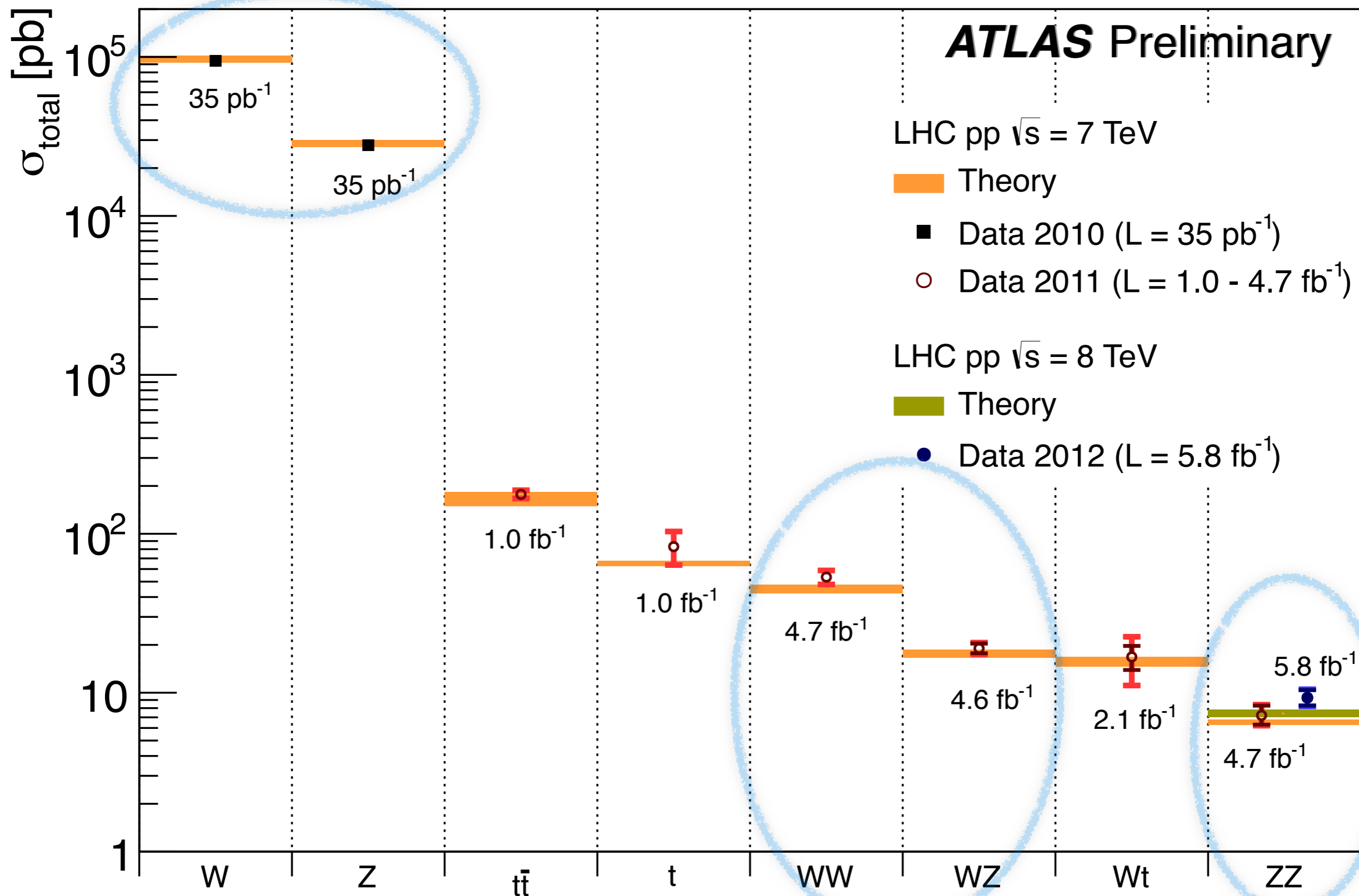


**On behalf of
the ATLAS Collaboration**

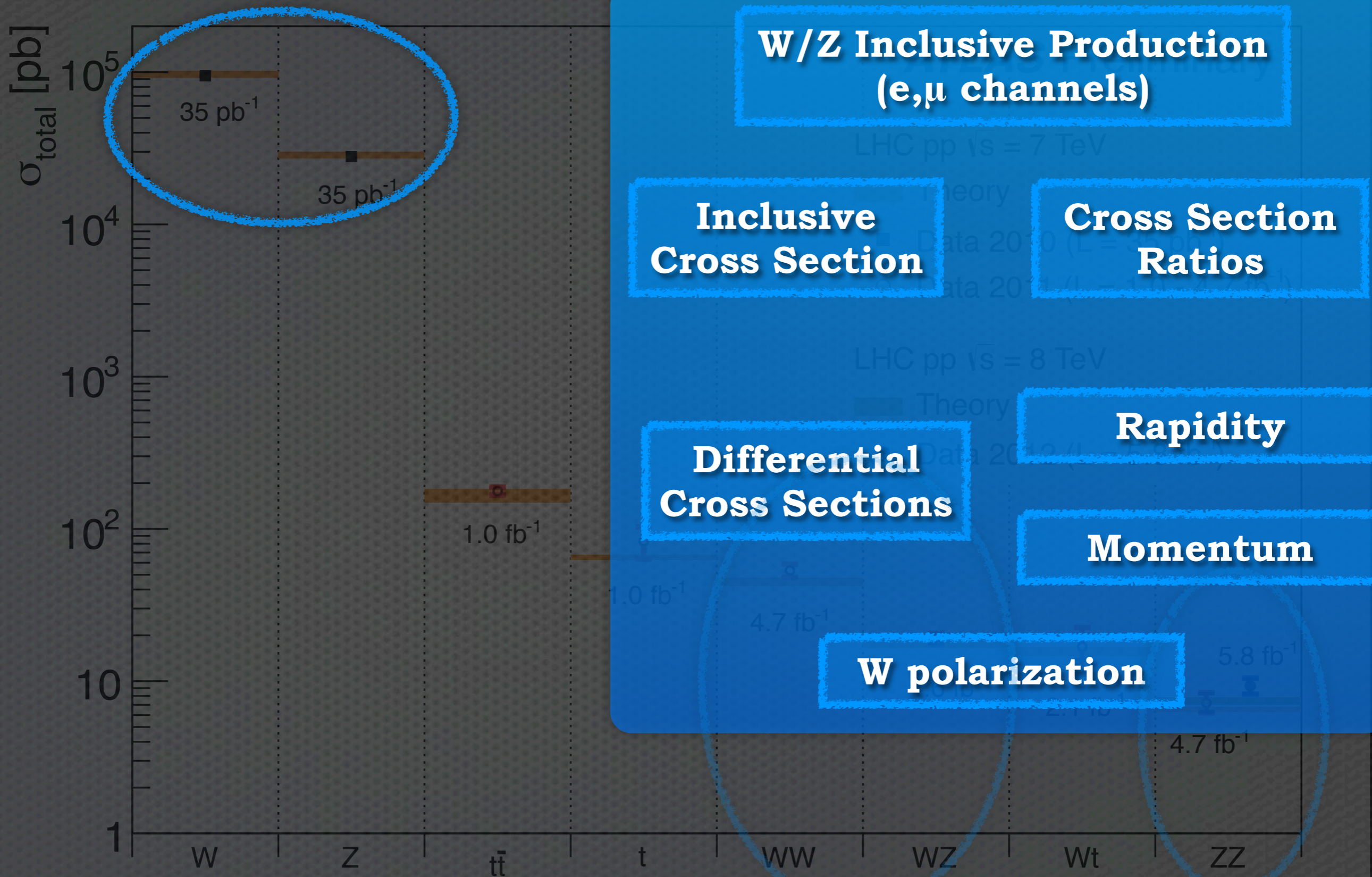
QCD@LHC 2012

Aug 20, 2012

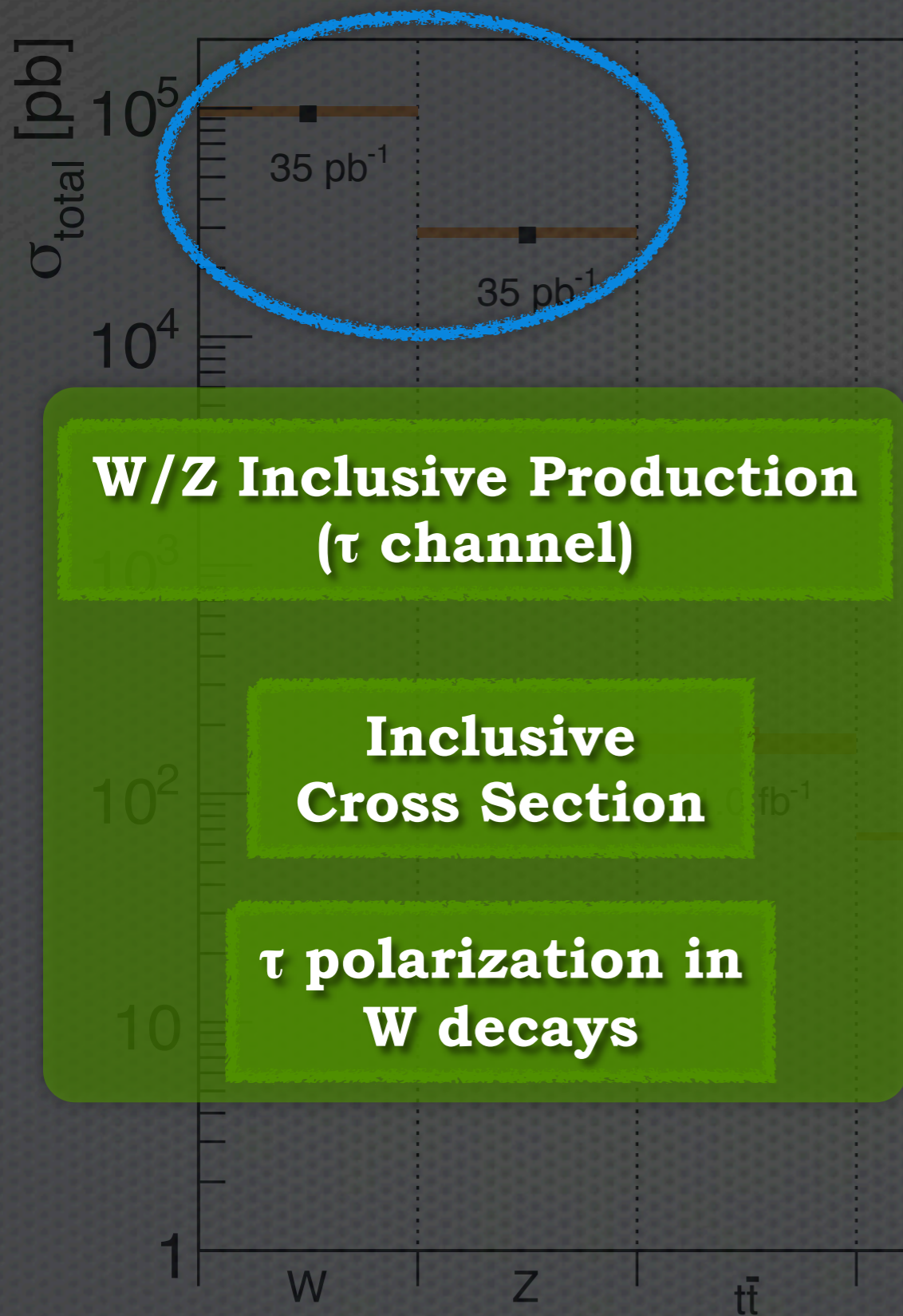
Production cross sections in ATLAS



Production cross sections in ATLAS



Production cross sections in ATLAS



**W/Z Inclusive Production
(τ channel)**

**Inclusive
Cross Section**

**τ polarization in
W decays**

**W/Z Inclusive Production
(e, μ channels)**

**Inclusive
Cross Section**

**Cross Section
Ratios**

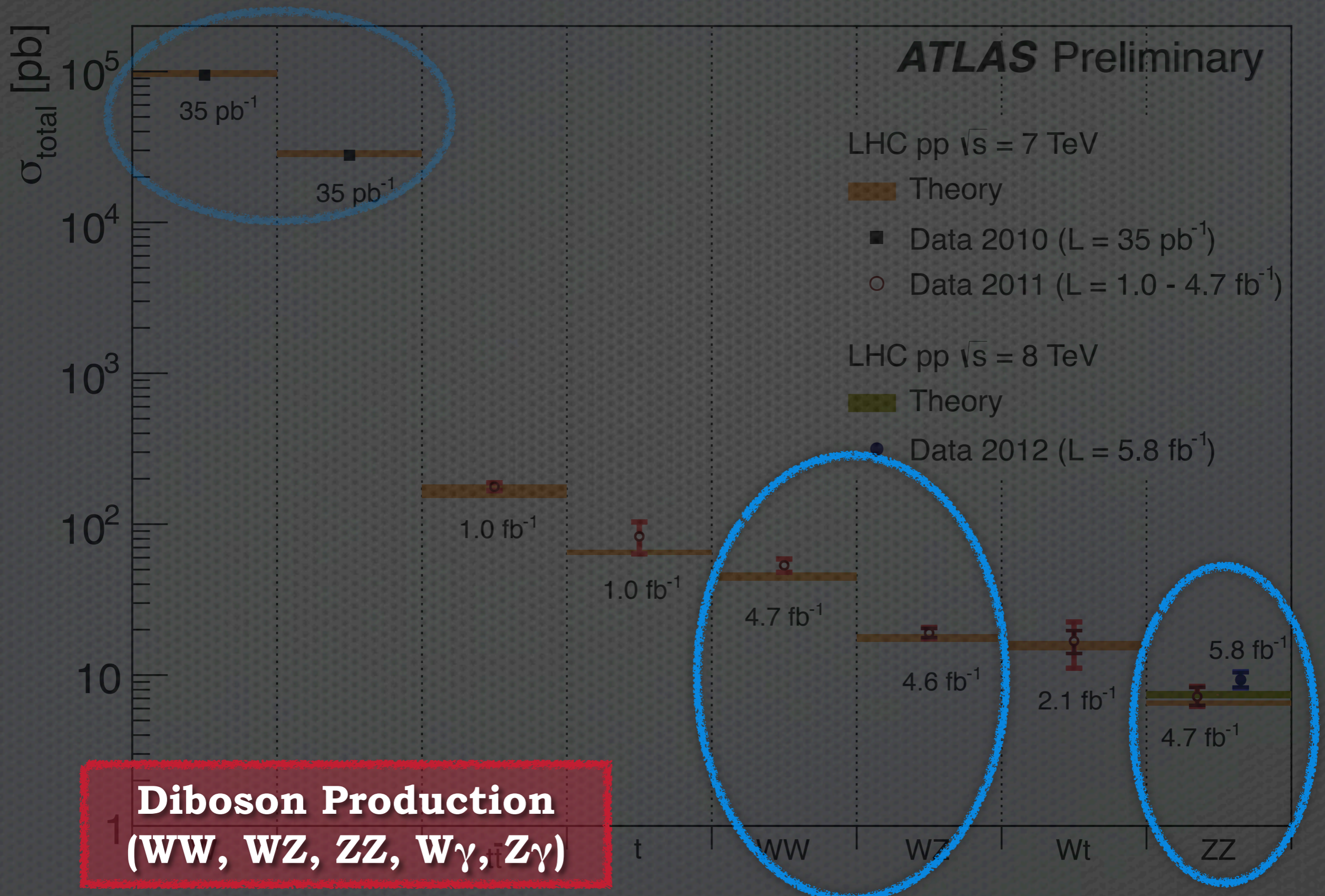
**Differential
Cross Sections**

Rapidity

Momentum

W polarization

Production cross sections in ATLAS





$$pp \rightarrow W + X$$

$$\begin{cases} \rightarrow e \nu \\ \rightarrow \mu \nu \end{cases}$$

W/Z inclusive production in e/ μ channel



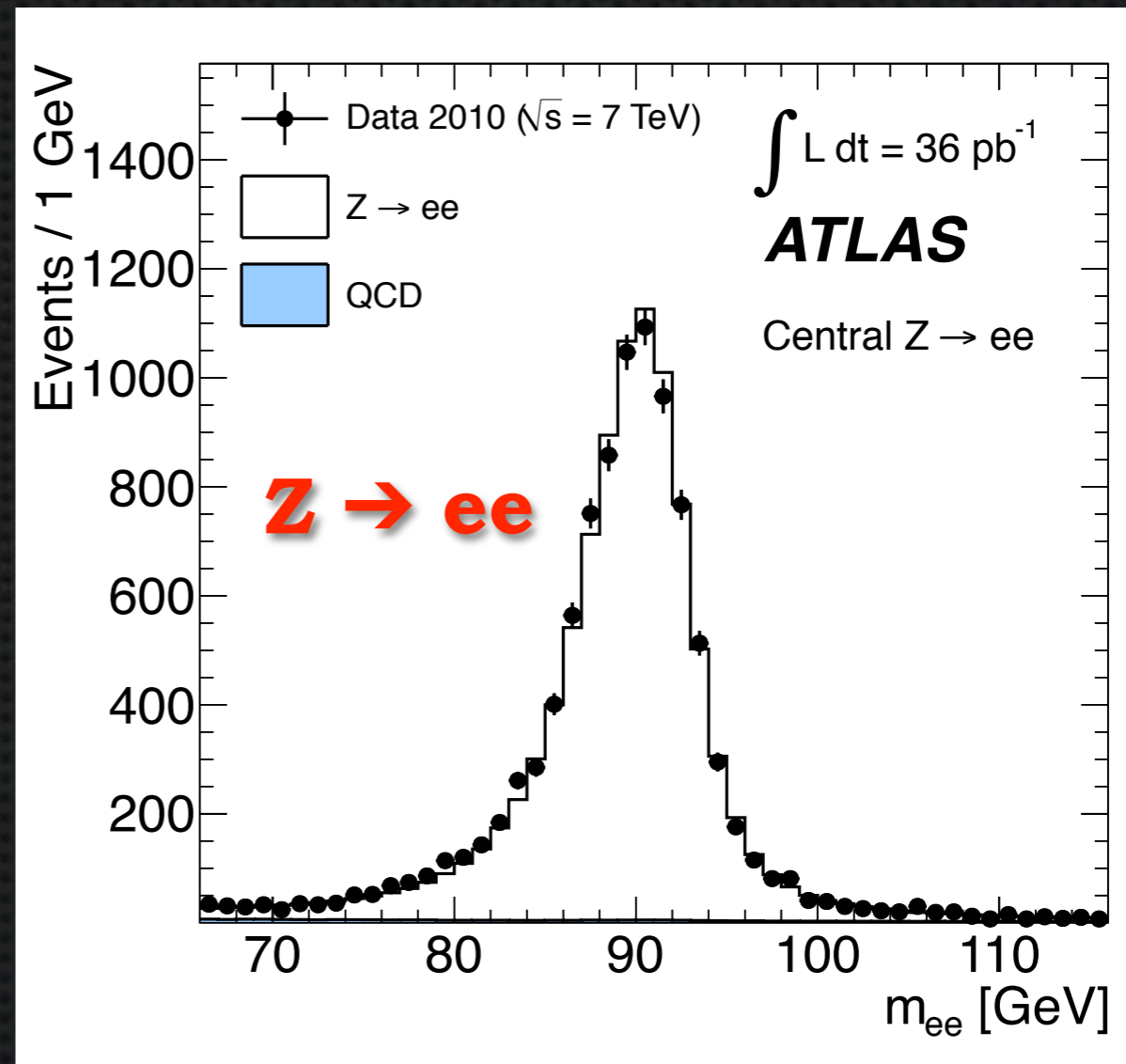
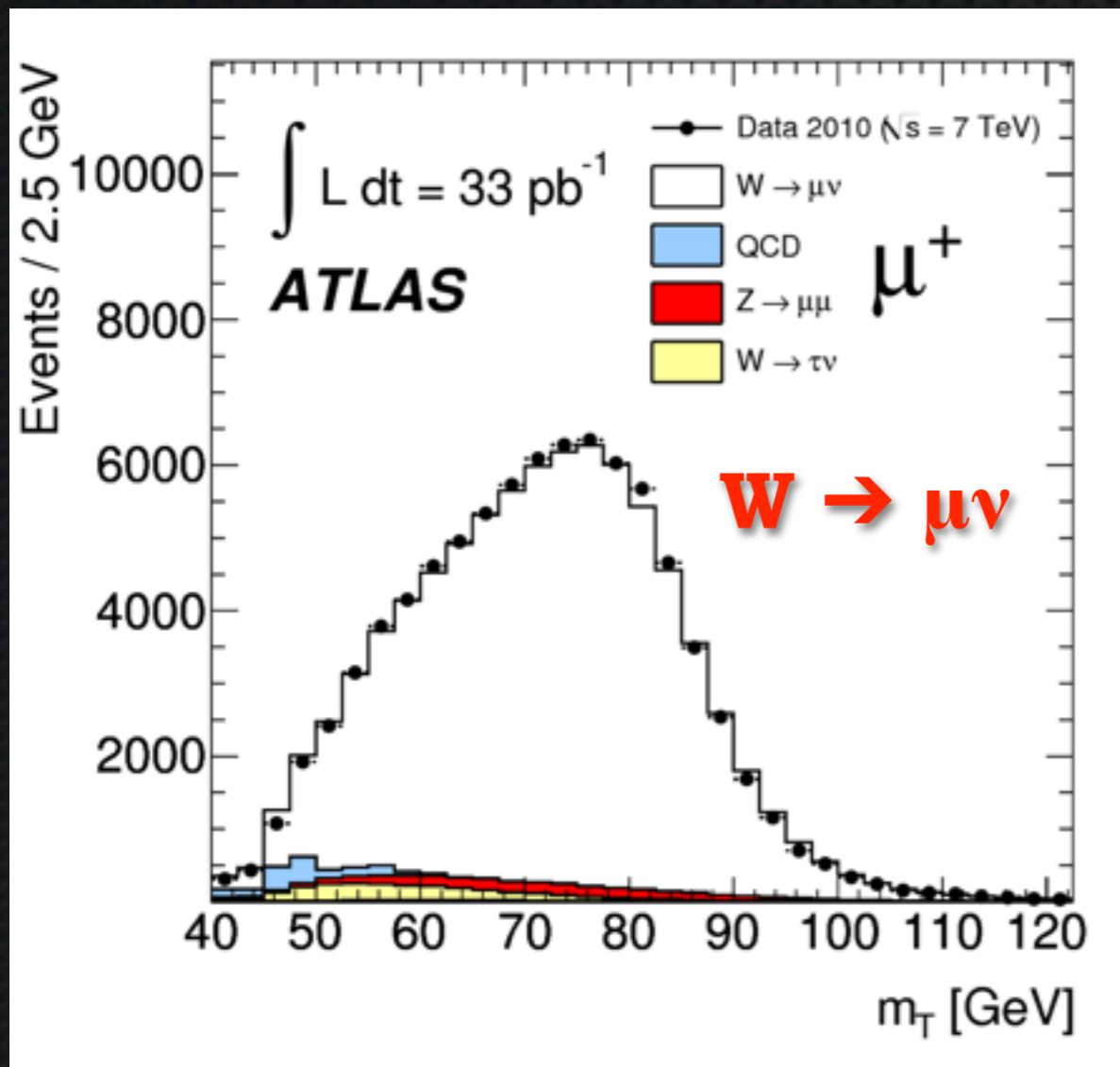
$$pp \rightarrow Z + X$$

$$\begin{cases} \rightarrow ee \\ \rightarrow \mu \mu \end{cases}$$

W/Z inclusive cross section measurements

- ATLAS has recently published precision measurements with 2010 data

Phys. Rev. D85 (2012) 072004



Much larger datasets are now available

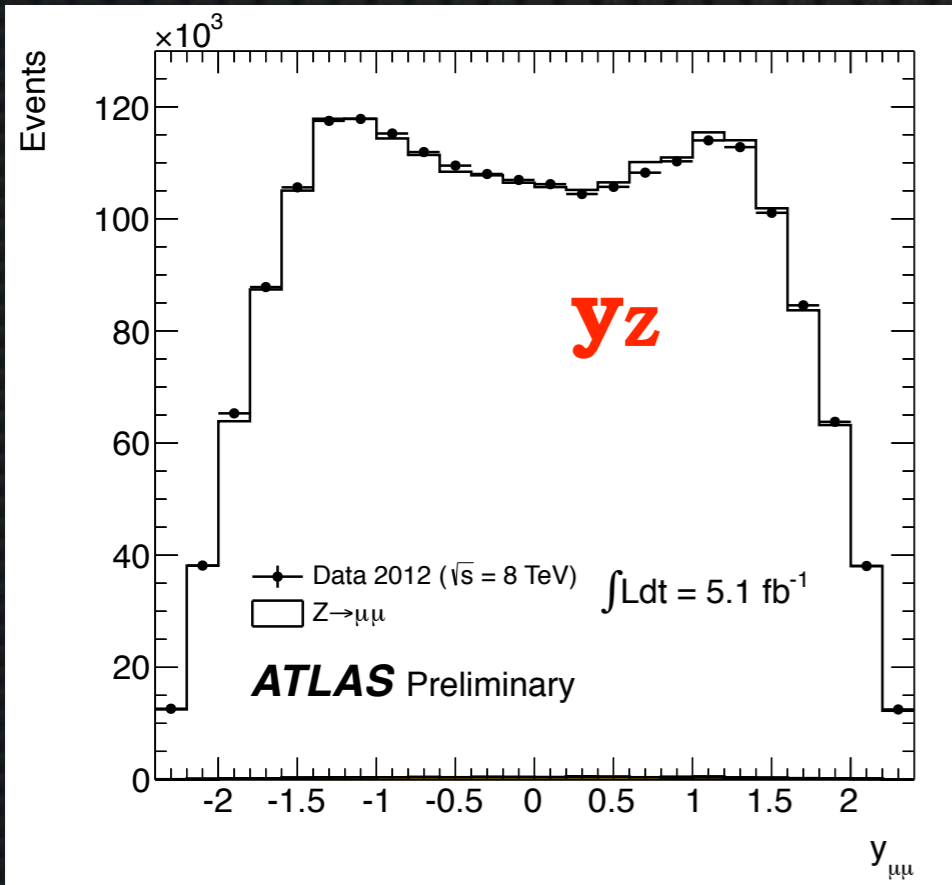
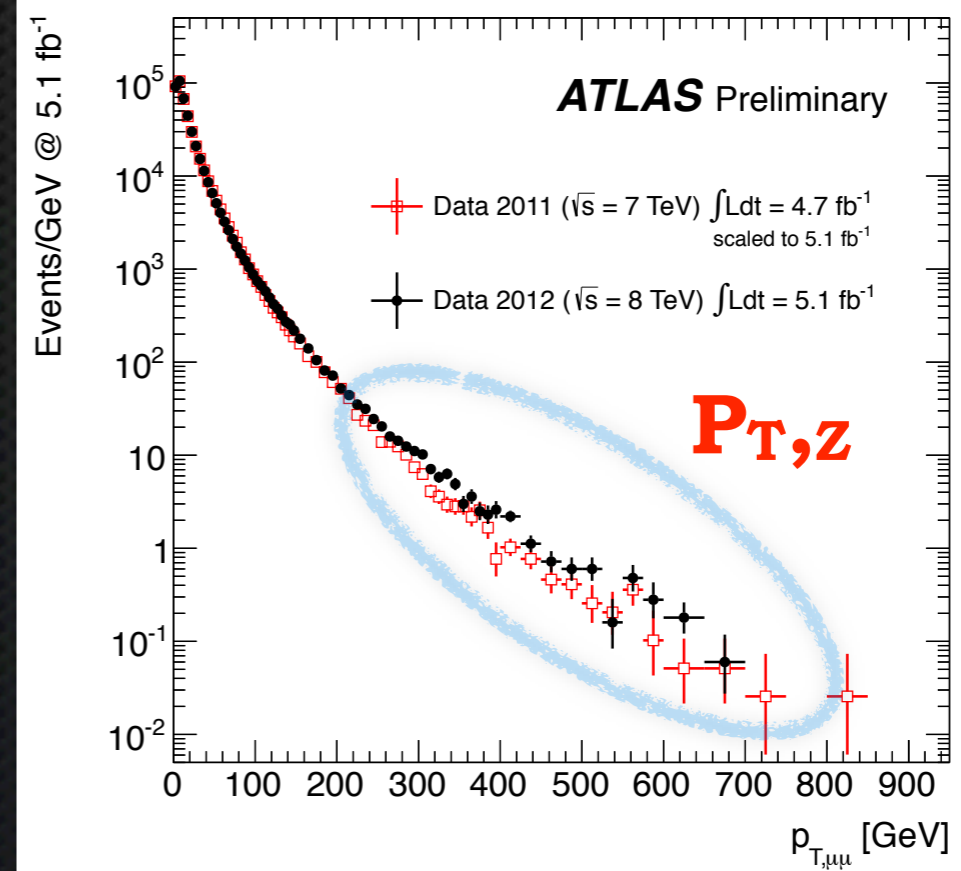
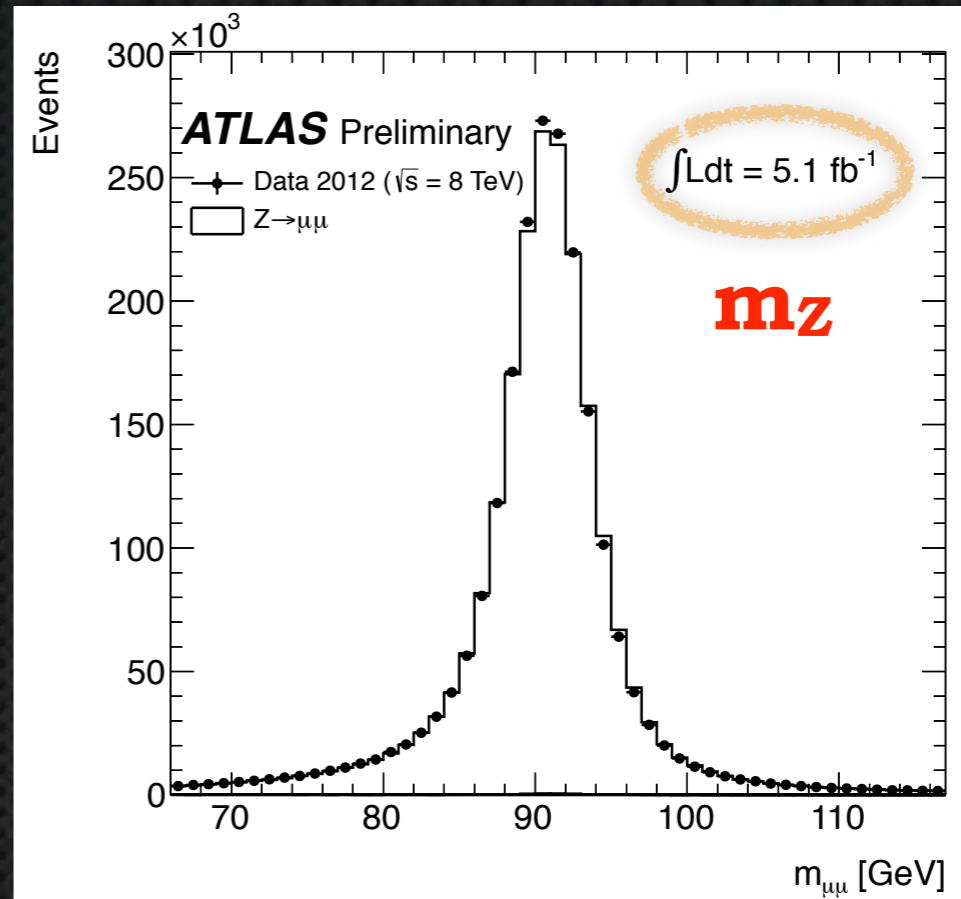
$$\sqrt{s} = 7 \text{ TeV}, 5 \text{ fb}^{-1} \left\{ \begin{array}{l} W \rightarrow e/\mu \nu : \sim 25 \text{ Million} \\ Z \rightarrow ee/\mu\mu : \sim 3 \text{ Million} \end{array} \right. + \sqrt{s} = 8 \text{ TeV} \sim 12 \text{ fb}^{-1}$$

Z production at $\sqrt{s} = 8 \text{ TeV}$

Z boson observation at
 $\sqrt{s} = 8 \text{ TeV}$
 $Z \rightarrow \mu\mu$

POWHEG+PYTHIA 8 MC
CT 10.0

Distributions normalized
to data



Fiducial phase space

$W \rightarrow e\nu$:

$$p_{T,e} > 20 \text{ GeV}, |\eta_e| < 2.47,$$

excluding $1.37 < |\eta_e| < 1.52$,

$$p_{T,\nu} > 25 \text{ GeV}, m_T > 40 \text{ GeV};$$

$W \rightarrow \mu\nu$:

$$p_{T,\mu} > 20 \text{ GeV}, |\eta_\mu| < 2.4,$$

$$p_{T,\nu} > 25 \text{ GeV}, m_T > 40 \text{ GeV};$$

$Z \rightarrow ee$:

$$p_{T,e} > 20 \text{ GeV}, \text{ both } |\eta_e| < 2.47,$$

excluding $1.37 < |\eta_e| < 1.52$,

$$66 < m_{ee} < 116 \text{ GeV};$$

Forward $Z \rightarrow ee$: $p_{T,e} > 20 \text{ GeV}$, one $|\eta_e| < 2.47$,

excluding $1.37 < |\eta_e| < 1.52$,

other $2.5 < |\eta_e| < 4.9$,

$$66 < m_{ee} < 116 \text{ GeV};$$

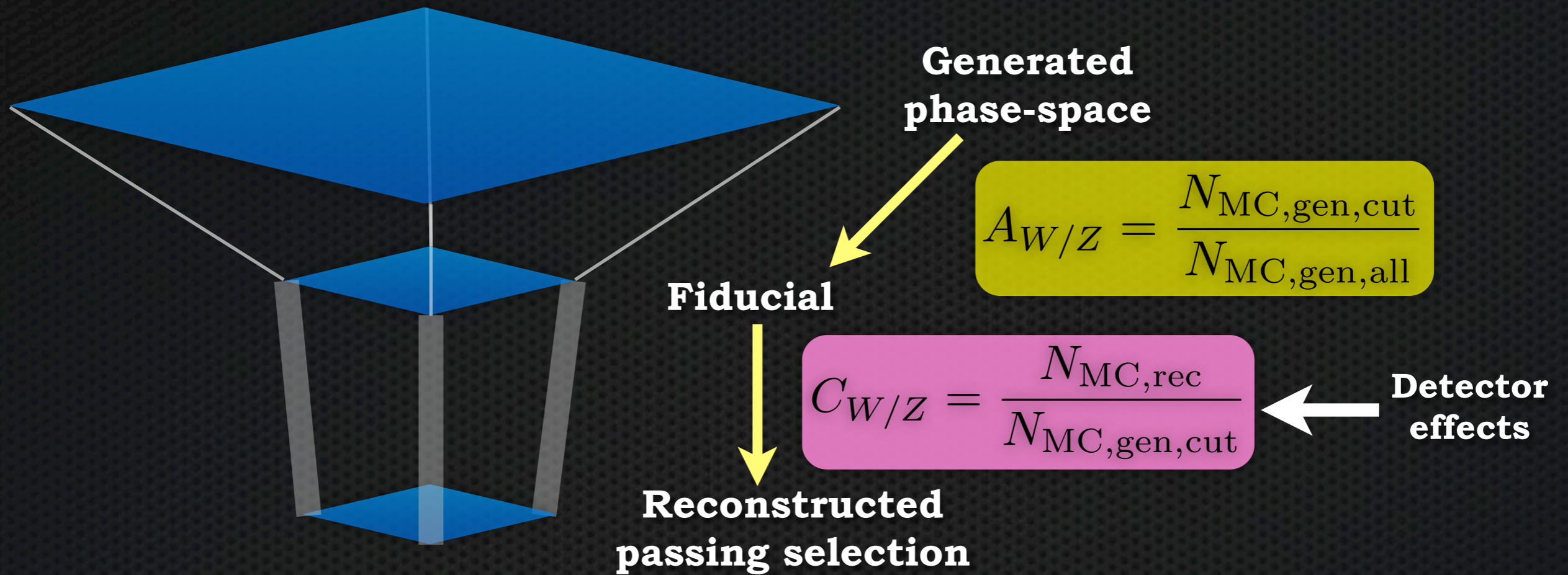
$Z \rightarrow \mu\mu$:

$$p_{T,\mu} > 20 \text{ GeV}, \text{ both } |\eta_\mu| < 2.4,$$

$$66 < m_{\mu\mu} < 116 \text{ GeV}.$$



Fiducial cross section



$$\sigma_{\text{fid}} = \frac{N - B}{C_{W/Z} \cdot L_{\text{int}}}$$

$$\sigma_{\text{tot}} = \sigma_{W/Z} \times BR(W/Z \rightarrow \ell\nu/\ell\ell) = \frac{\sigma_{\text{fid}}}{A_{W/Z}}$$

Monte Carlo Samples

Physics process	Generator	$\sigma \cdot \text{BR}$ [nb]	
$W^+ \rightarrow \ell^+ \nu$ ($\ell = e, \mu$)	MC@NLO	6.16 ± 0.31	NNLO
$W^- \rightarrow \ell^- \bar{\nu}$ ($\ell = e, \mu$)	MC@NLO	4.30 ± 0.21	NNLO
$Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} > 60$ GeV, $\ell = e, \mu$)	MC@NLO	0.99 ± 0.05	NNLO
$W \rightarrow \tau\nu$	PYTHIA	10.46 ± 0.52	NNLO
$Z/\gamma^* \rightarrow \tau\tau$ ($m_{\tau\tau} > 60$ GeV)	PYTHIA	0.99 ± 0.05	NNLO
$t\bar{t}$	MC@NLO	$0.165^{+0.011}_{-0.016}$	\approx NNLO
WW	HERWIG	0.045 ± 0.003	NLO
WZ	HERWIG	0.0185 ± 0.0009	NLO
ZZ	HERWIG	0.0060 ± 0.0003	NLO
Dijet (e channel, $\hat{p}_T > 15$ GeV)	PYTHIA	1.2×10^6	LO
Dijet (μ channel, $\hat{p}_T > 8$ GeV)	PYTHIA	10.6×10^6	LO
$b\bar{b}$ (μ channel, $\hat{p}_T > 18$ GeV, $p_T(\mu) > 15$ GeV)	PYTHIA	73.9	LO
$c\bar{c}$ (μ channel, $\hat{p}_T > 18$ GeV, $p_T(\mu) > 15$ GeV)	PYTHIA	28.4	LO

QCD normalized with data-driven techniques

Details on MC Simulation

- ✦ **Signal and background models:**
 - ✦ **LO MC:**
 - ✦ PYTHIA 6.4 with MRST LO* PDF
 - ✦ HERWIG with MRST LO* PDF
 - ✦ **NLO MC:**
 - ✦ MC@NLO with CTEQ 6.6 (+ HERWIG for hadronization and parton shower)
 - ✦ POWHEG with CTEQ 6.6 (+ HERWIG)
 - ✦ **Final state QED radiation**
 - ✦ PHOTOS
 - ✦ **Minimum bias and underlying event**
 - ✦ ATLAS tunes from first data
 - ✦ **Pile-up simulation:**
 - ✦ Overlay of simulated minimum bias events over hard-scattering
 - ✦ **Transverse momentum of W and Z reweighted to match data**
- ✦ **ATLAS detector response**
 - ✦ GEANT4

Uncertainties: Electron channel

	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
Trigger	0.4	0.4	0.4	<0.1
Electron reconstruction	0.8	0.8	0.8	1.6
Electron identification	0.9	0.8	1.1	1.8
Electron isolation	0.3	0.3	0.3	—
Electron energy scale and resolution	0.5	0.5	0.5	0.2
Non-operational LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	0.0	0.1	0.1	0.6
QCD background	0.4	0.4	0.4	0.7
Electroweak+ $t\bar{t}$ background	0.2	0.2	0.2	<0.1
E_T^{miss} scale and resolution	0.8	0.7	1.0	—
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.6	0.6	0.6	0.3
Total experimental uncertainty	1.8	1.8	2.0	2.7
$A_{W/Z}$ theoretical uncertainty	1.5	1.7	2.0	2.0
Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity	3.4			



Extrapolation

(1.8% in 2011)

Uncertainties: Muon channel

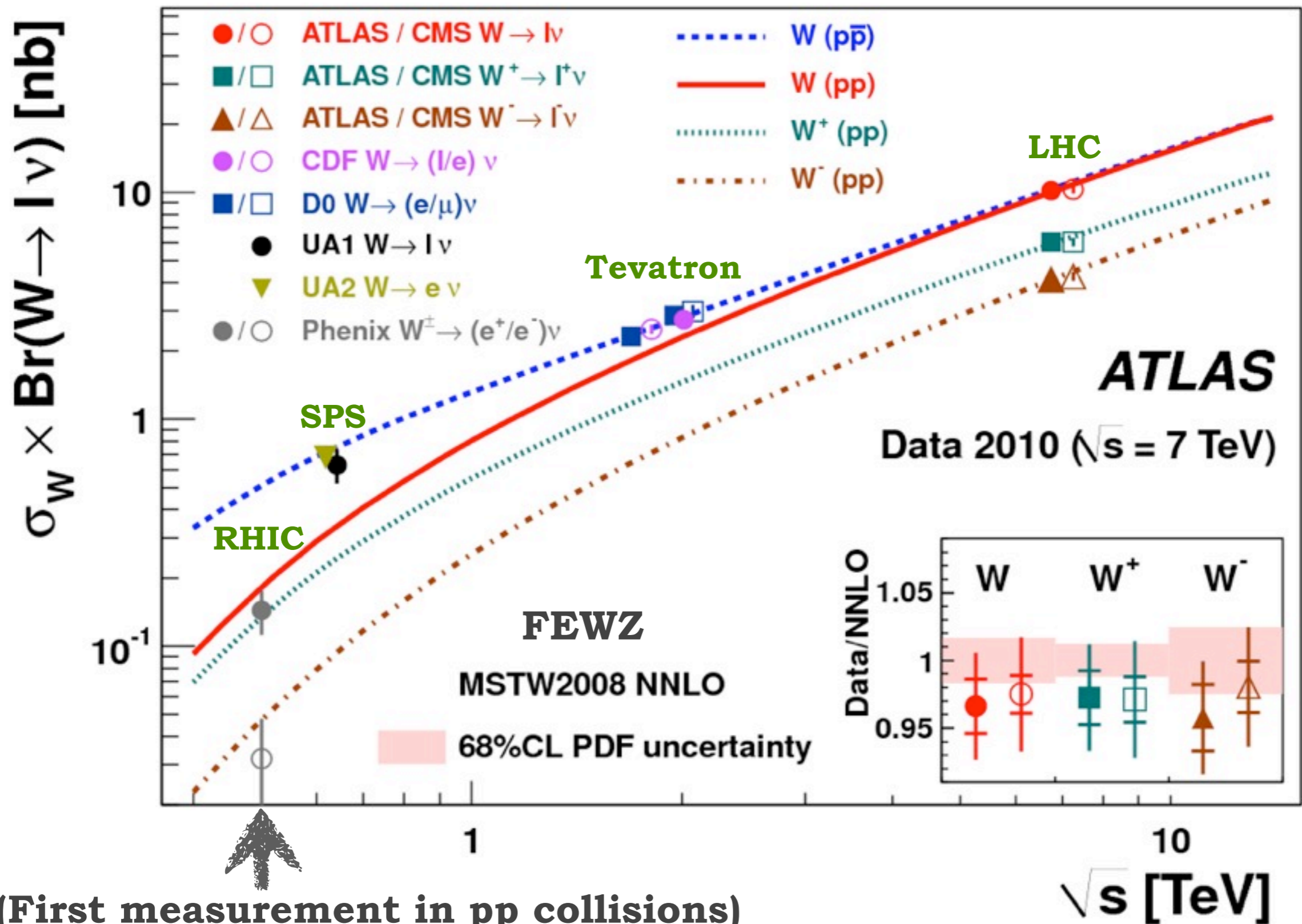
	$\delta\sigma_{W\pm}$	$\delta\sigma_{W+}$	$\delta\sigma_{W-}$	$\delta\sigma_Z$
Trigger	0.5	0.5	0.5	0.1
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_T resolution	0.04	0.03	0.05	0.02
Muon p_T scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Electroweak+ $t\bar{t}$ background	0.4	0.3	0.4	0.02
E_T^{miss} resolution and scale	0.5	0.4	0.6	-
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.8	0.8	0.7	0.3
Total experimental uncertainty	1.6	1.7	1.7	0.9
$A_{W/Z}$ theoretical uncertainty	1.5	1.6	2.1	2.0
Total excluding luminosity	2.1	2.3	2.6	2.2
Luminosity	3.4			



Extrapolation

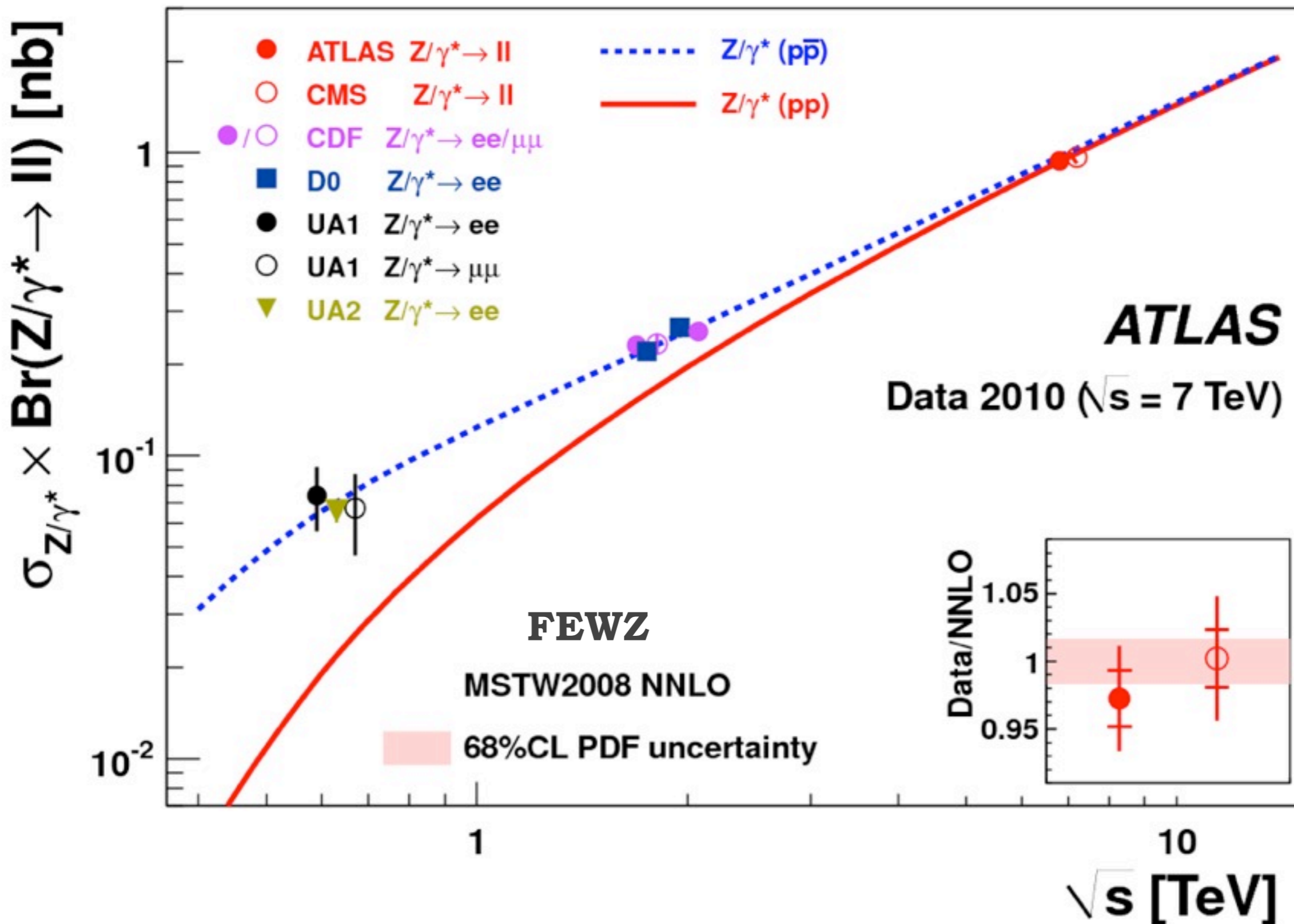
(1.8% in 2011)

W inclusive cross section



(First measurement in pp collisions)

Z inclusive cross section



Fiducial W and Z Cross Sections

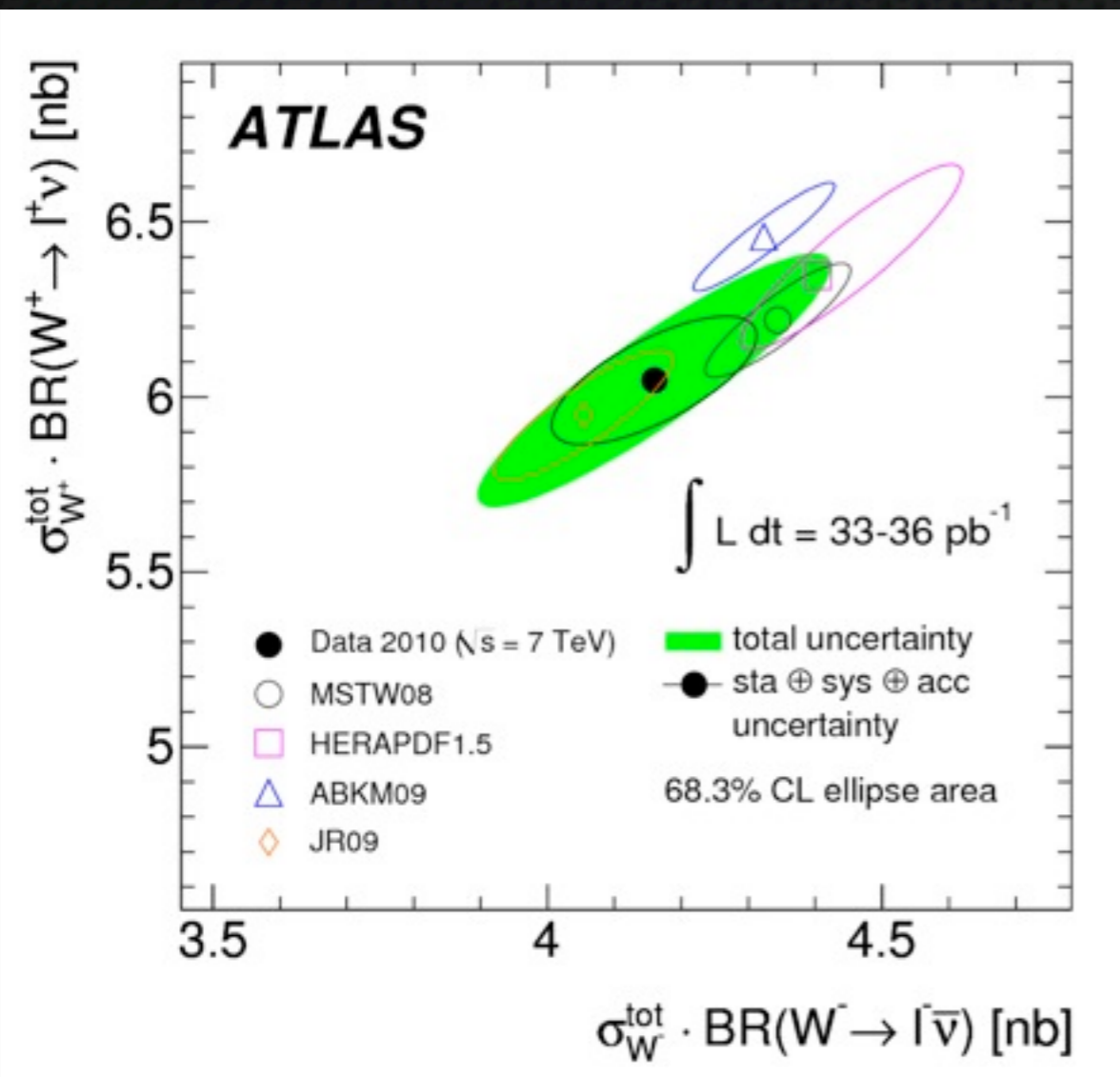
Phys. Rev. D85 (2012) 072004

ATLAS measures fiducial cross sections

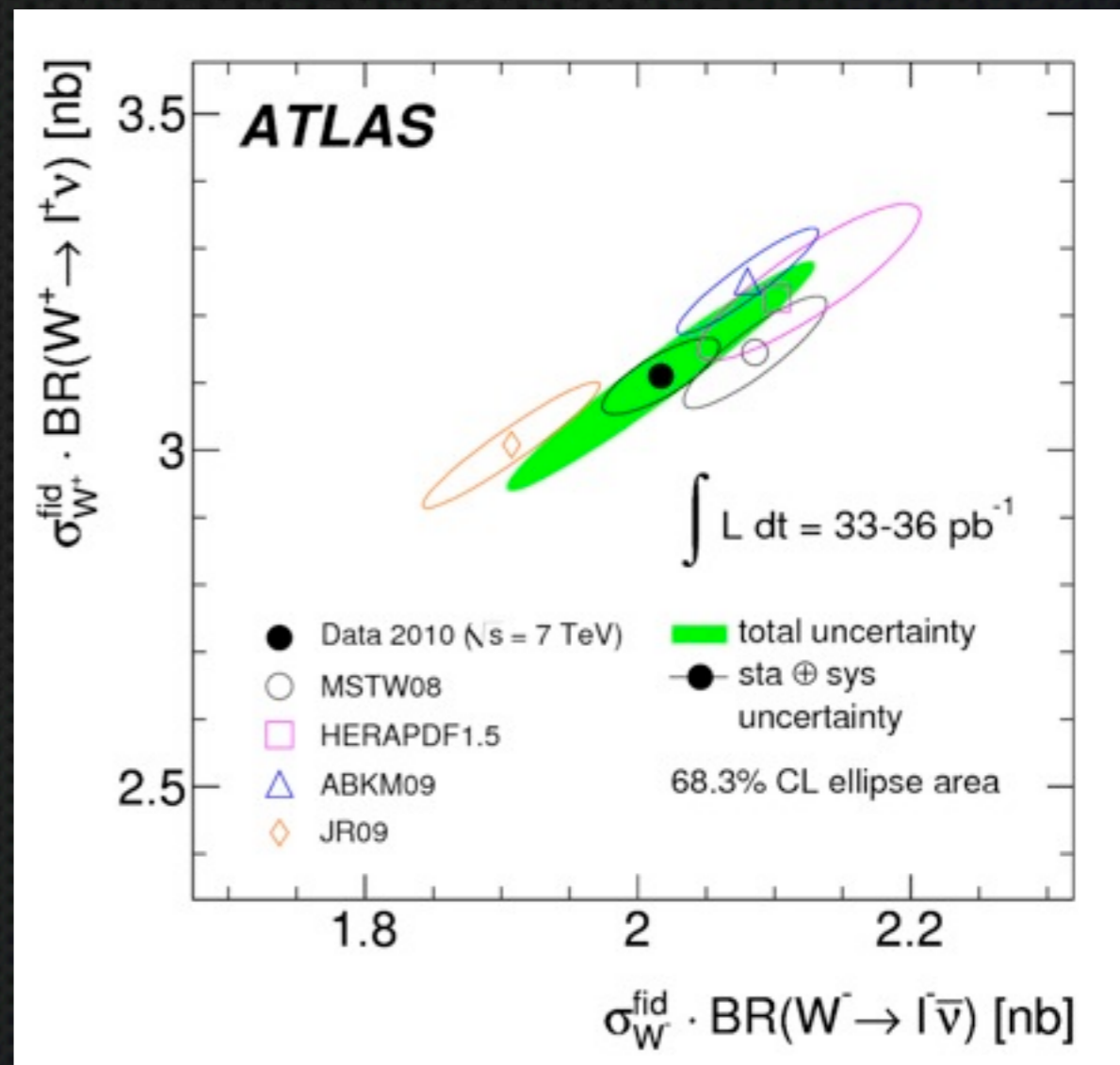
No theoretical uncertainty from extrapolation outside experimental acceptance

σ_{Total} : W^+ versus W^-

σ_{Fiducial} : W^+ versus W^-



FEWZ = DYNNLO ~ 0.5%



FEWZ = DYNNLO ~ 1%

■ Luminosity 3.4%

Some differentiation between PDF sets already observed now

JR09 seems to be the most discrepant

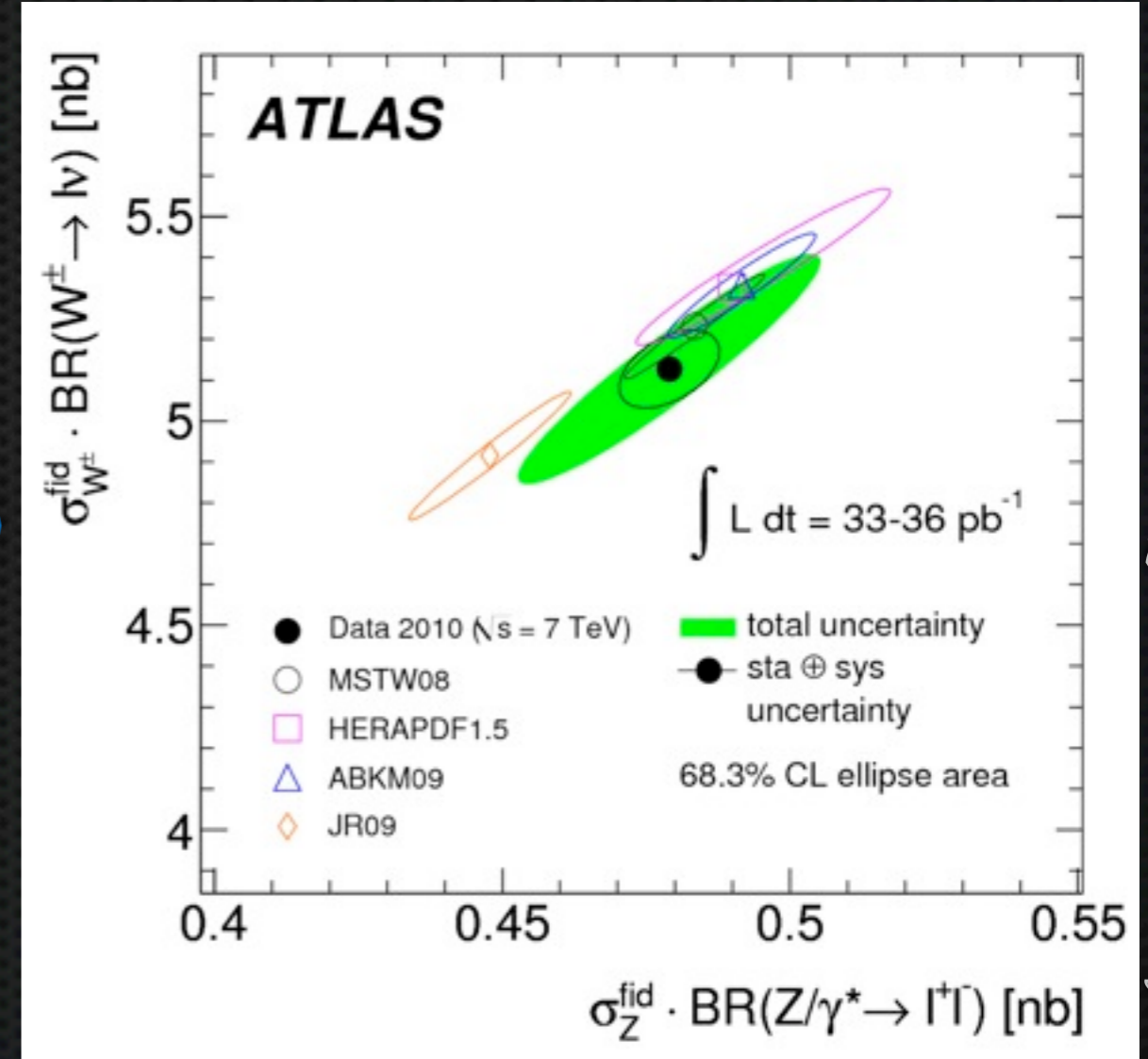
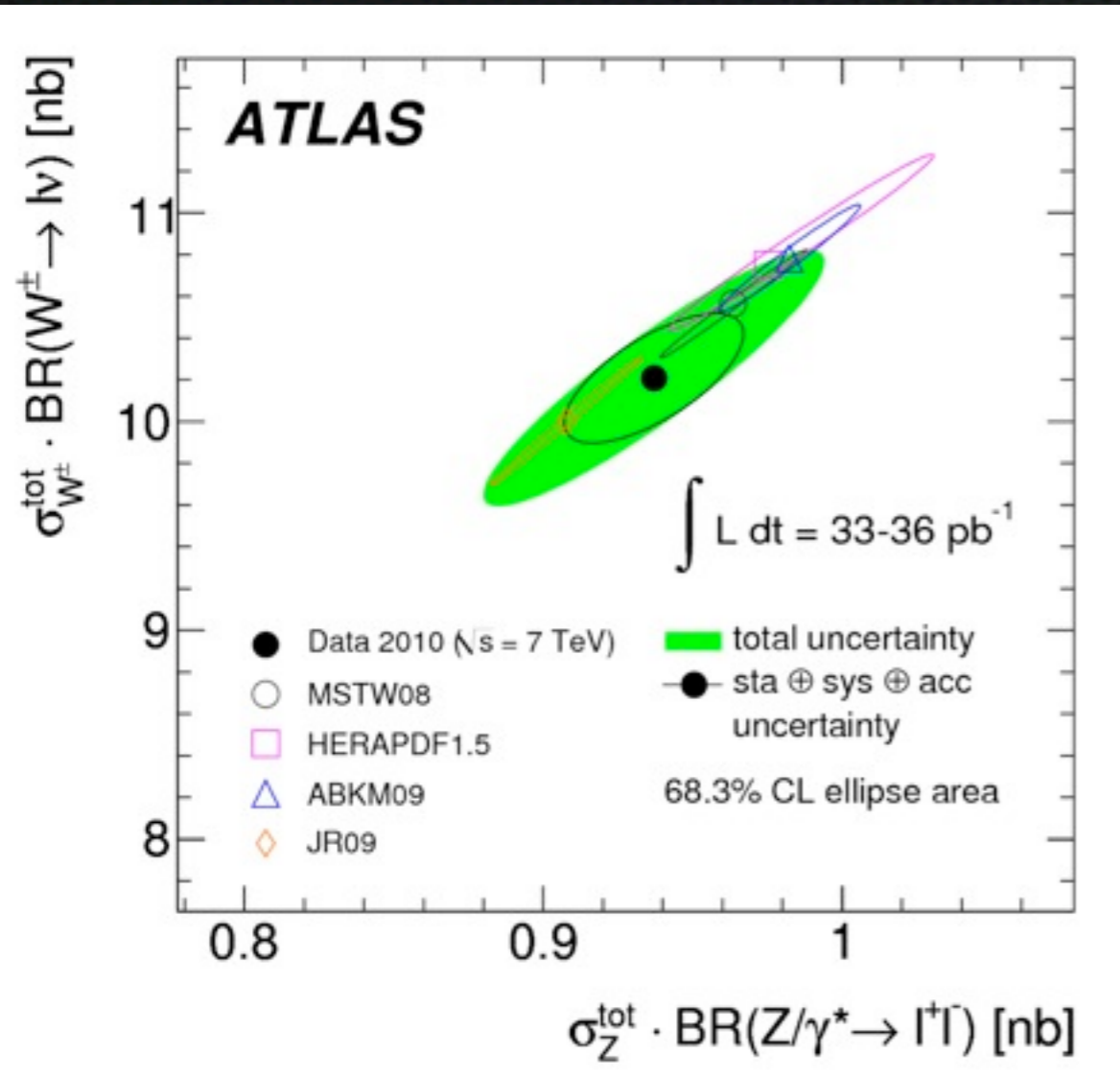
Fiducial W and Z Cross Sections

Phys. Rev. D85 (2012) 072004

- **ATLAS measures fiducial cross sections**
- No theoretical uncertainty from extrapolation outside experimental acceptance

$\sigma_{\text{Total}}: W^\pm$ versus Z

$\sigma_{\text{Fiducial}}: W^\pm$ versus Z



■ Luminosity 3.4%

Some differentiation between PDF sets already observed now

JR09 seems to be the most discrepant

Lepton Universality

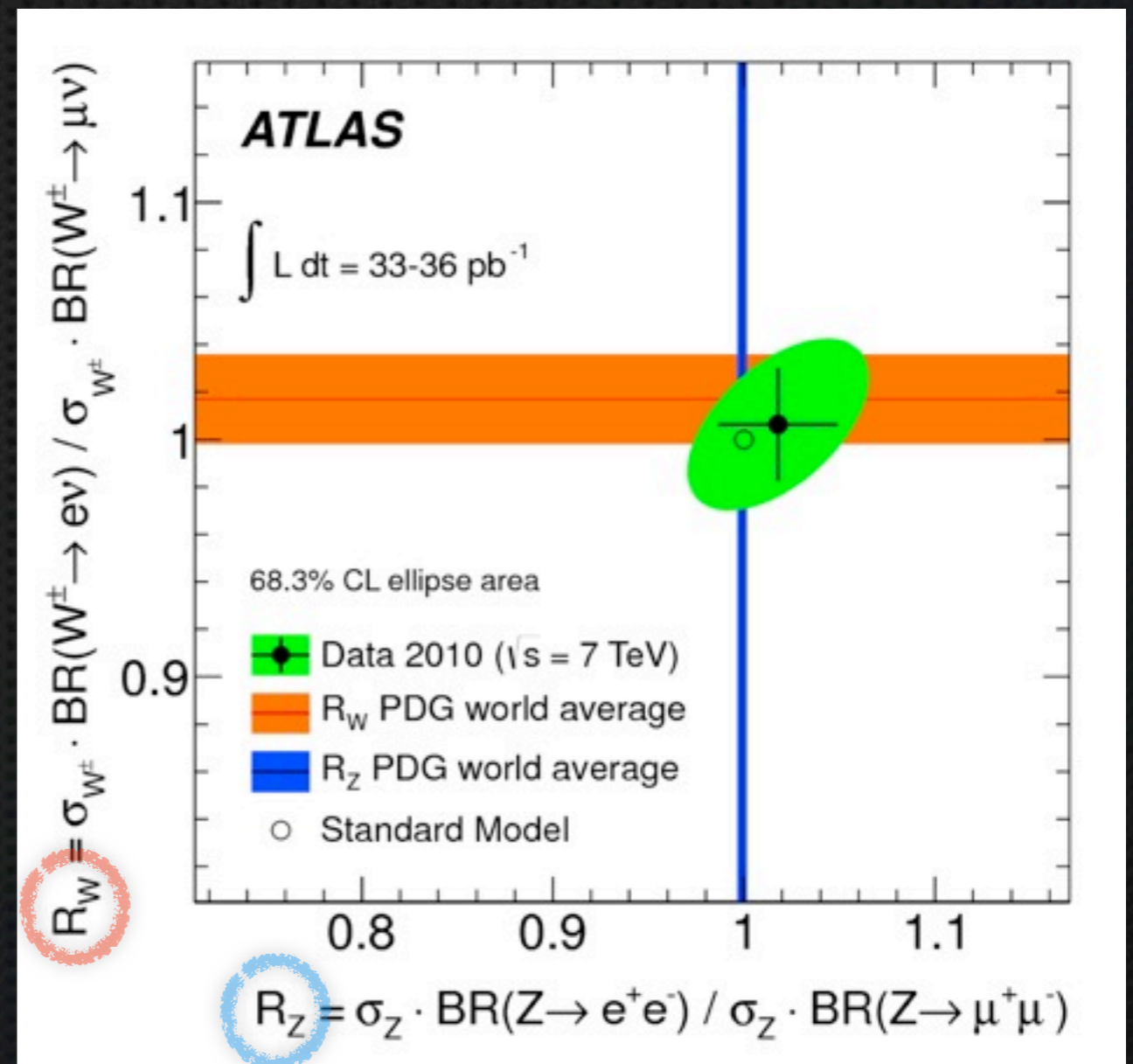
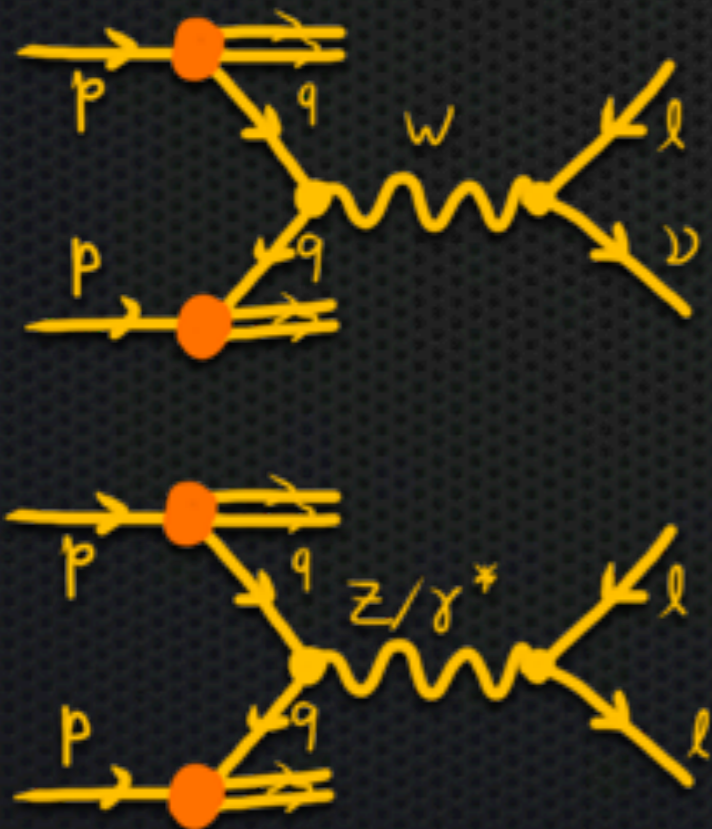
Phys. Rev. D85 (2012) 072004

$$R_W = \frac{\sigma_W^e}{\sigma_W^\mu} = \frac{Br(W \rightarrow e\nu)}{Br(W \rightarrow \mu\nu)} = 1.006 \pm 0.004 \text{ (sta)} \pm 0.006 \text{ (unc)} \pm 0.023 \text{ (cor)} = 1.006 \pm 0.024$$

$$R_Z = \frac{\sigma_Z^e}{\sigma_Z^\mu} = \frac{Br(Z \rightarrow ee)}{Br(Z \rightarrow \mu\mu)} = 1.018 \pm 0.014 \text{ (sta)} \pm 0.016 \text{ (unc)} \pm 0.028 \text{ (cor)} = 1.018 \pm 0.031$$

✦ **Result already close to best measurement (R_W)**

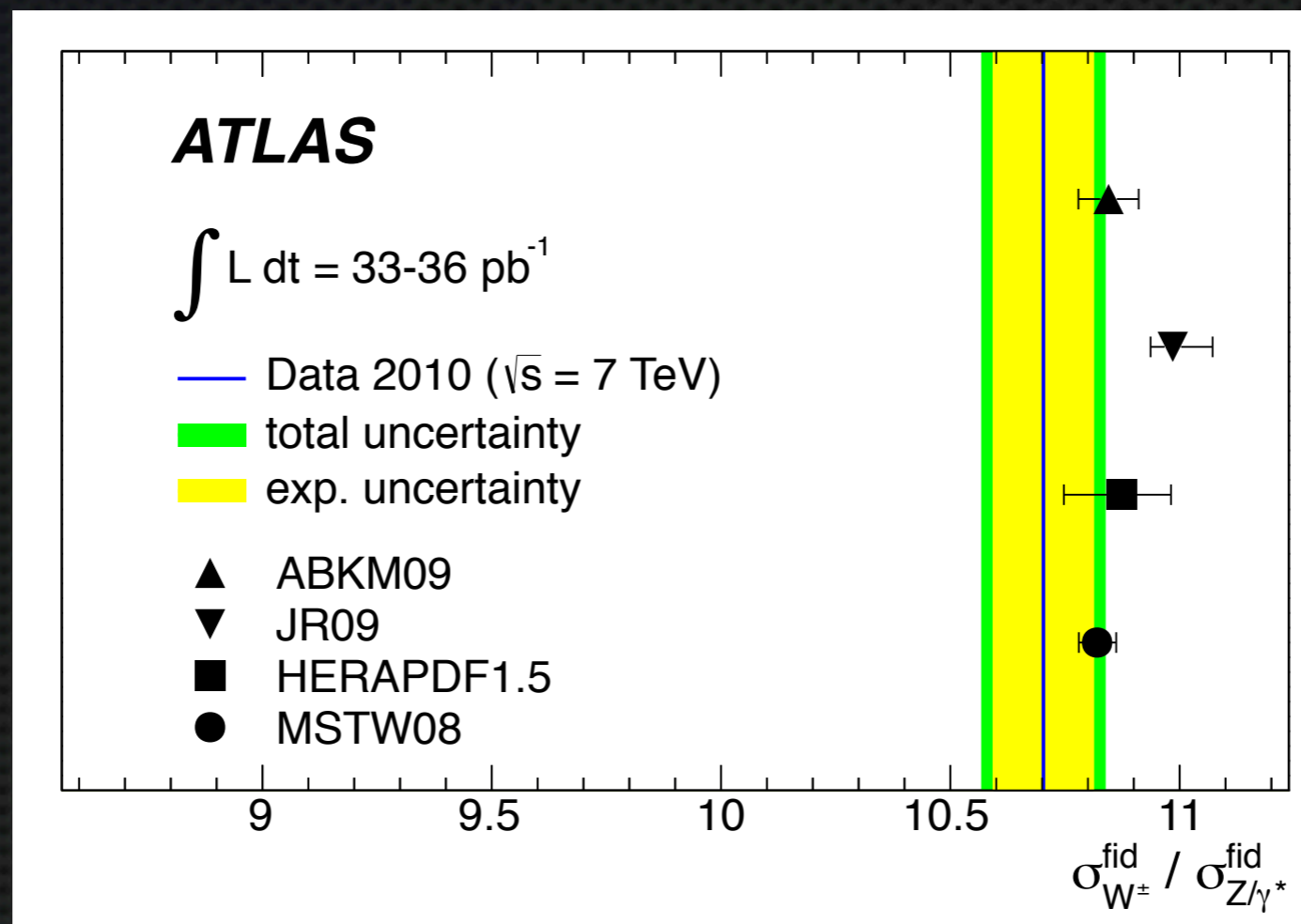
- ✦ PDG: 1.9%
- ✦ This measurement: 2.4%



Ratio W and Z Cross Sections

Phys. Rev. D85 (2012) 072004

Benefits from experimental and theoretical systematics cancellation



$\sigma \times \mathcal{B}$

W^\pm/Z

σ^{fiducial}

$10.703 \pm 0.078 \text{ (sta)} \pm 0.110 \text{ (sys)} \pm 0.008 \text{ (acc)}$

1.3%

σ^{total}

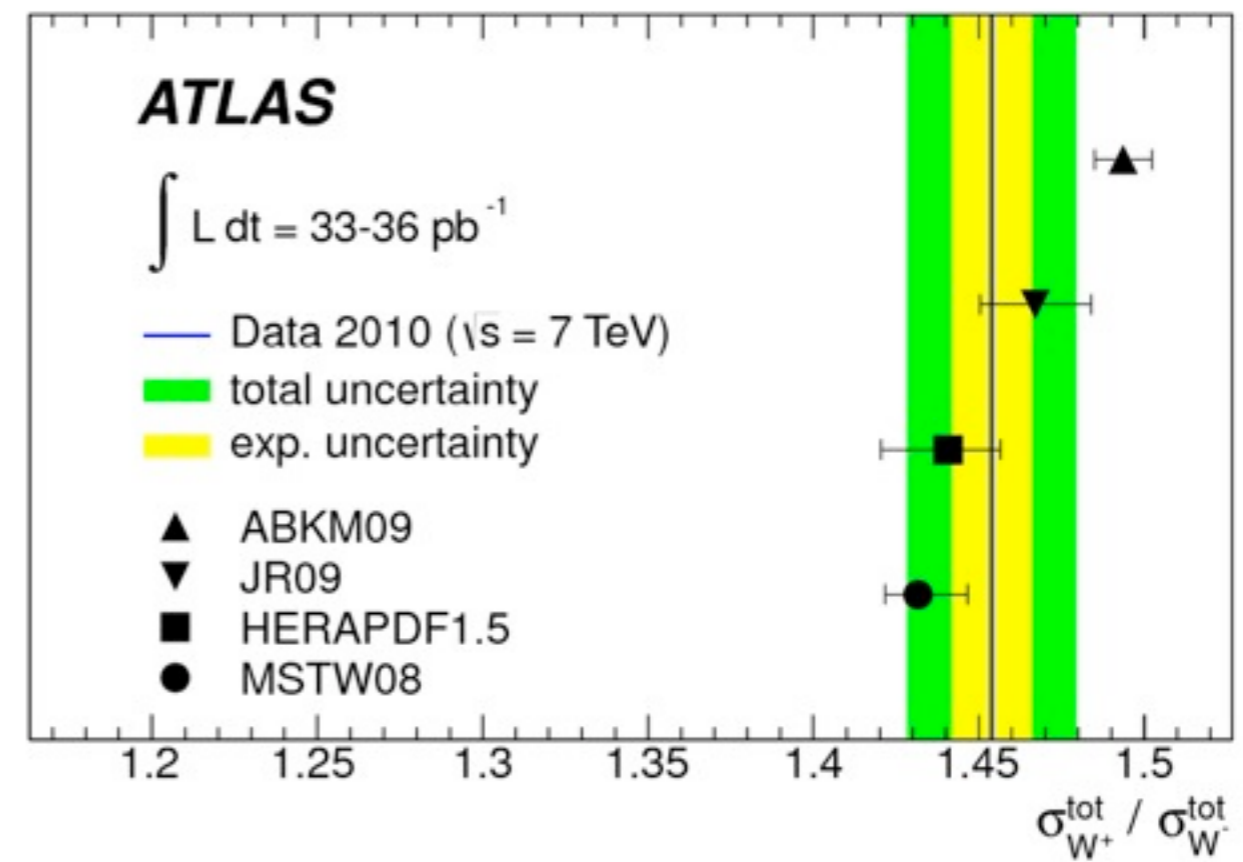
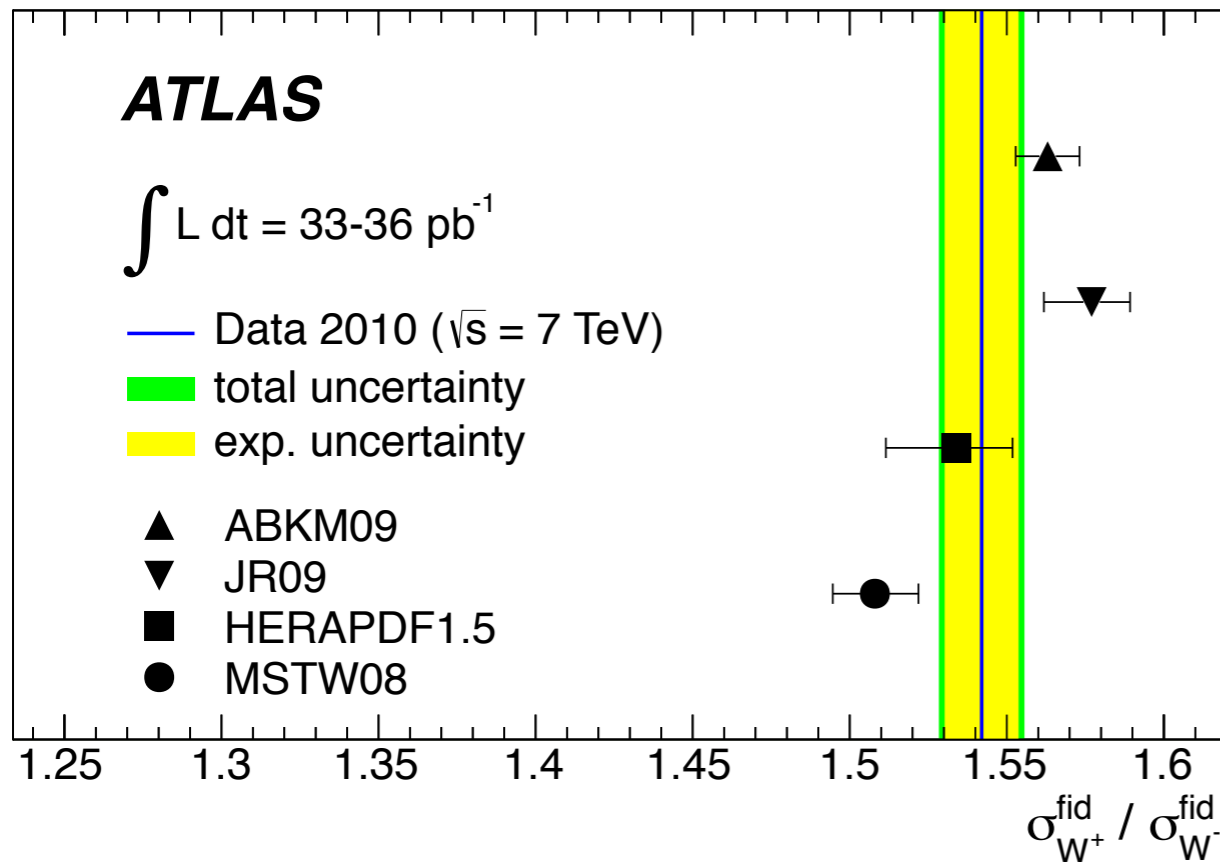
$10.893 \pm 0.079 \text{ (sta)} \pm 0.110 \text{ (sys)} \pm 0.116 \text{ (acc)}$

1.6%

Cross Section Ratio W^+/W^-

Phys. Rev. D85 (2012) 072004

Benefits from experimental and theoretical systematics cancellation



$\sigma \times \mathcal{B}$

W^+/W^-

σ^{fiducial}

$1.542 \pm 0.0007 \text{ (sta)} \pm 0.012 \text{ (sys)} \pm 0.0001 \text{ (acc)}$

0.9%

σ^{total}

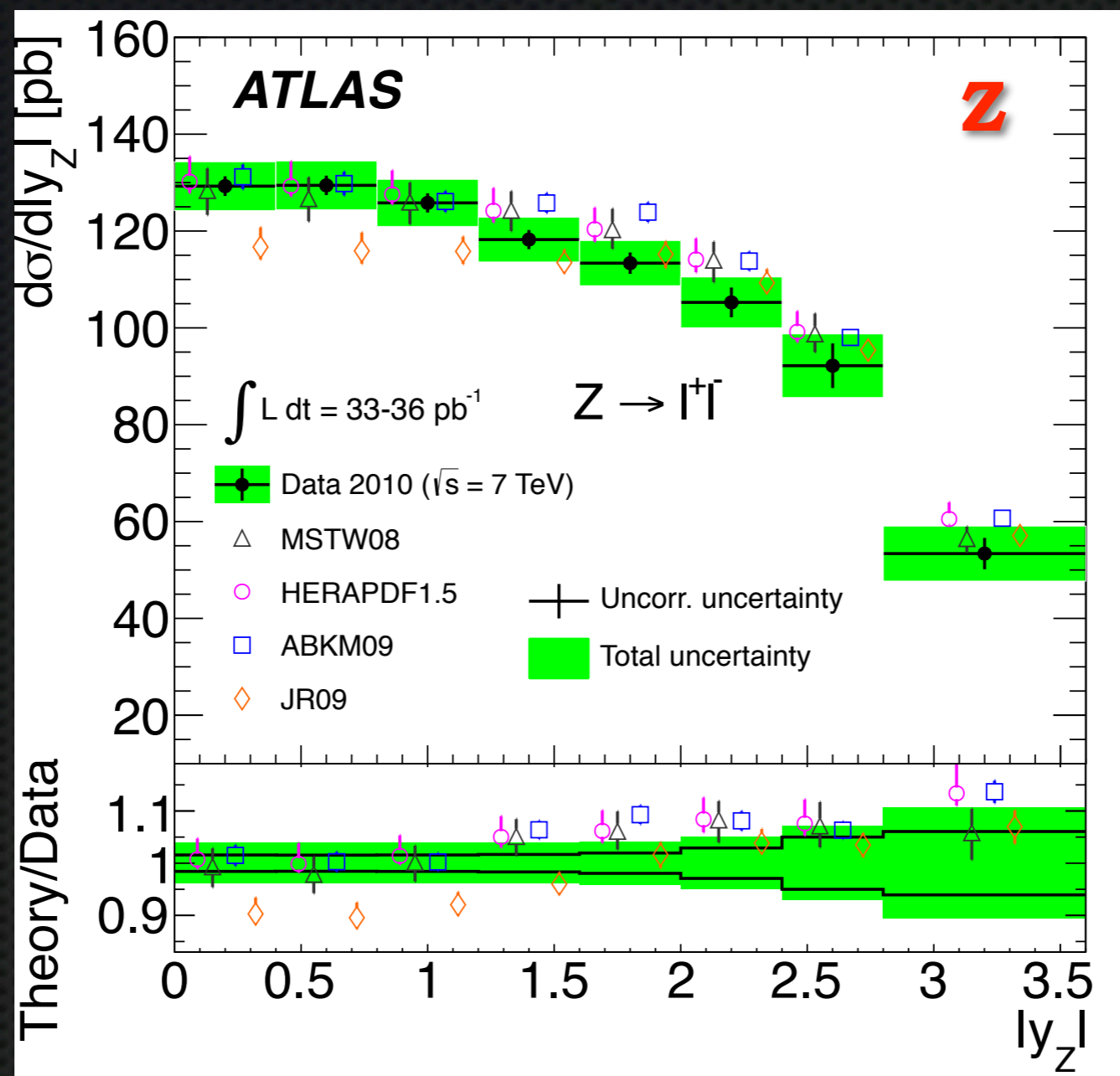
$1.454 \pm 0.0006 \text{ (sta)} \pm 0.012 \text{ (sys)} \pm 0.0222 \text{ (acc)}$

1.8%

W/Z Production in ATLAS -- QCD@LHC 2012 -- Joao Guimaraes

$d\sigma_Z/dy_Z$ versus NNLO PDF predictions

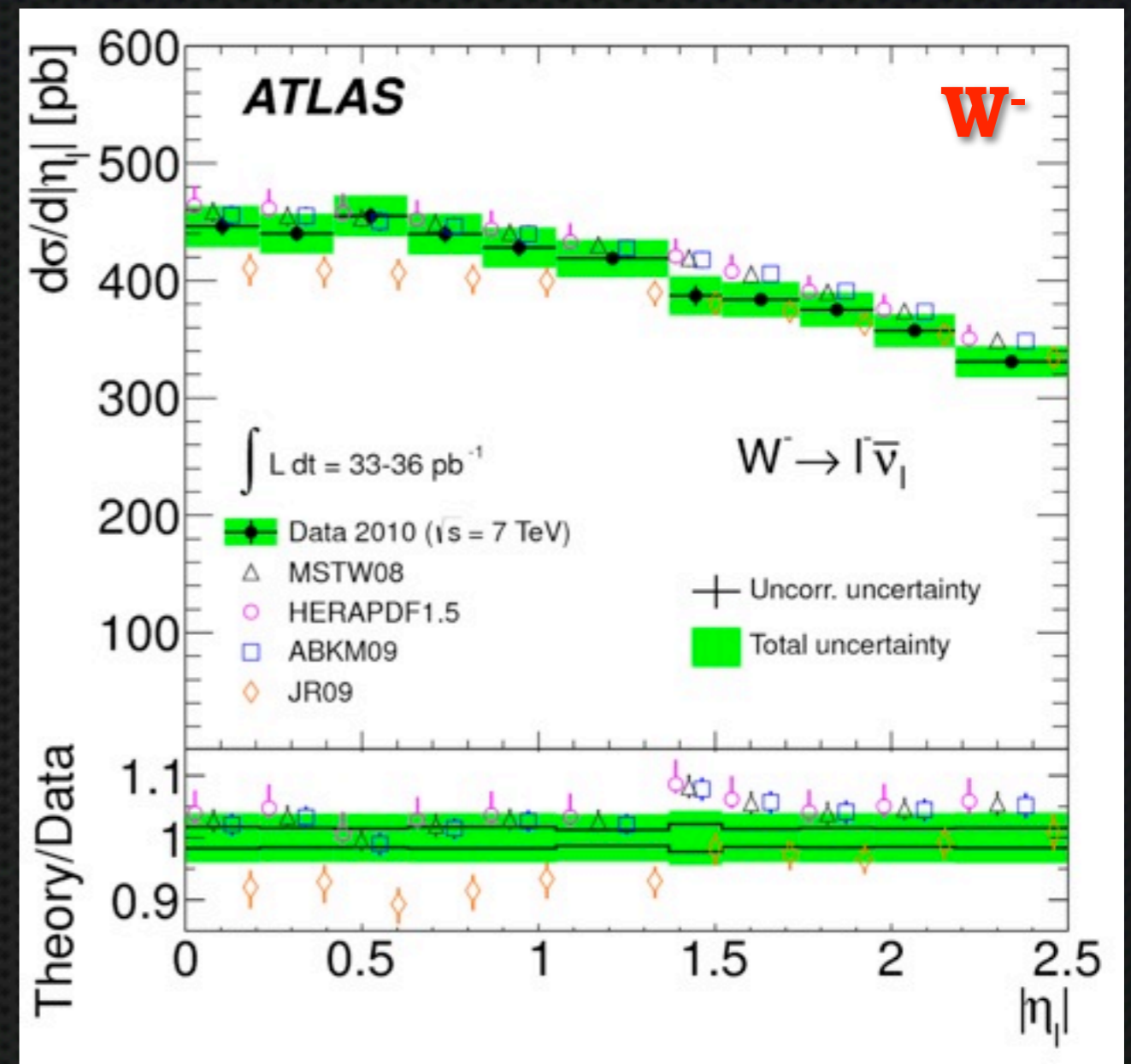
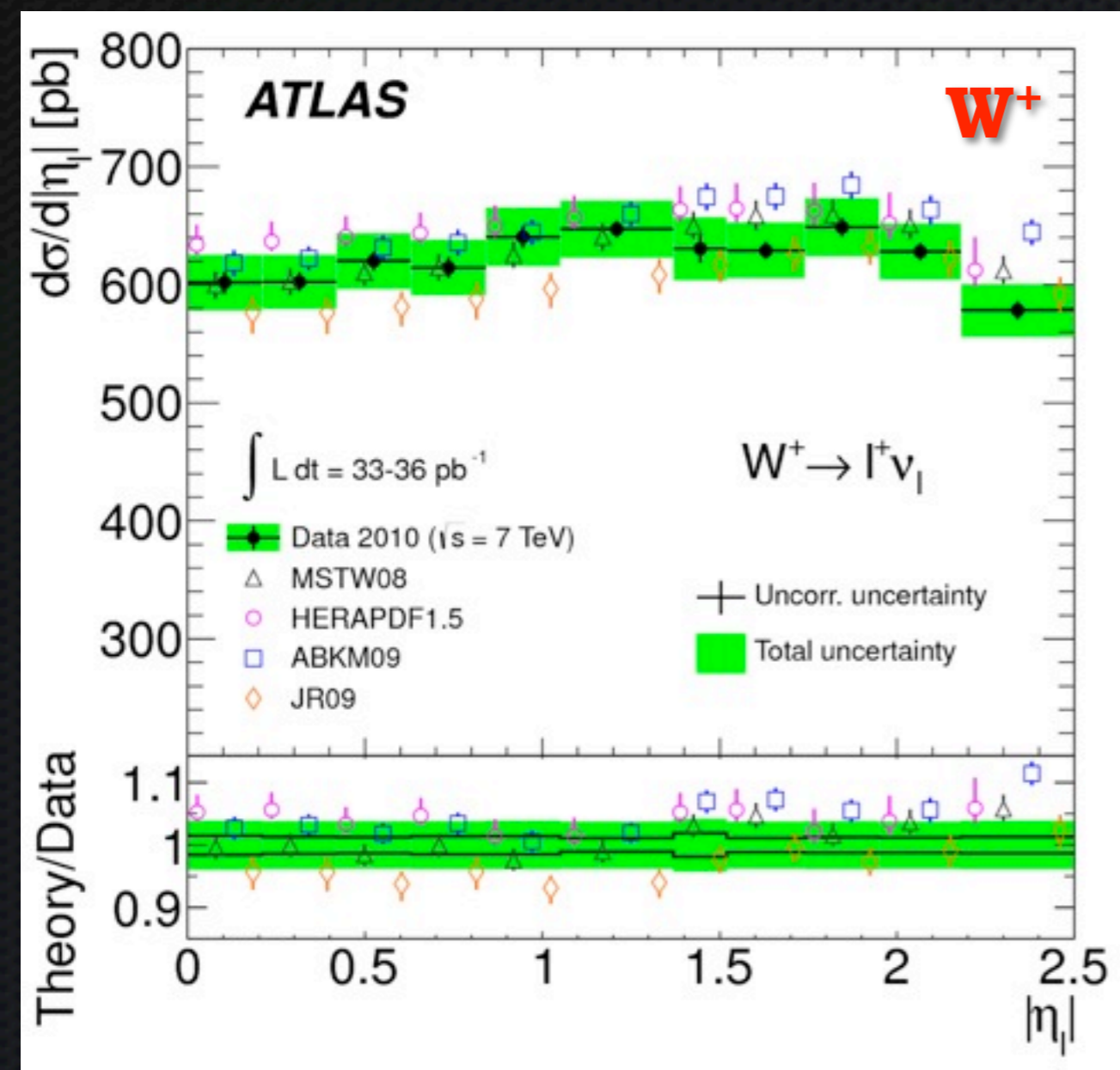
Phys. Rev. D85 (2012) 072004



- **Broadly well described by predictions**
- **Can impact PDF central values and uncertainties**
 - Information on d , u and s decomposition at $x \sim 0.01$
 - Full covariance matrix available

$d\sigma_W/d\eta_l$ versus NNLO PDF predictions

Phys. Rev. D85 (2012) 072004

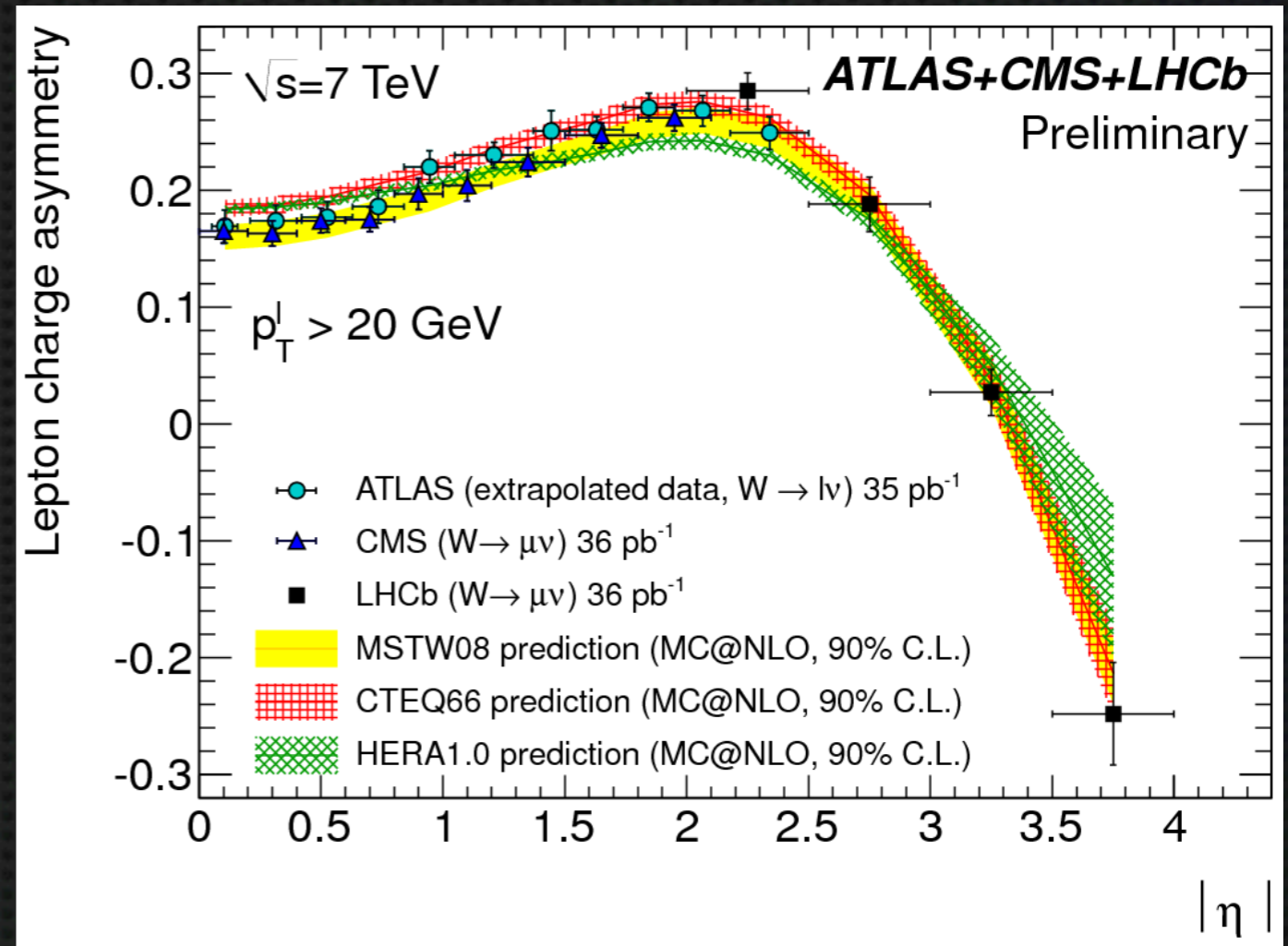
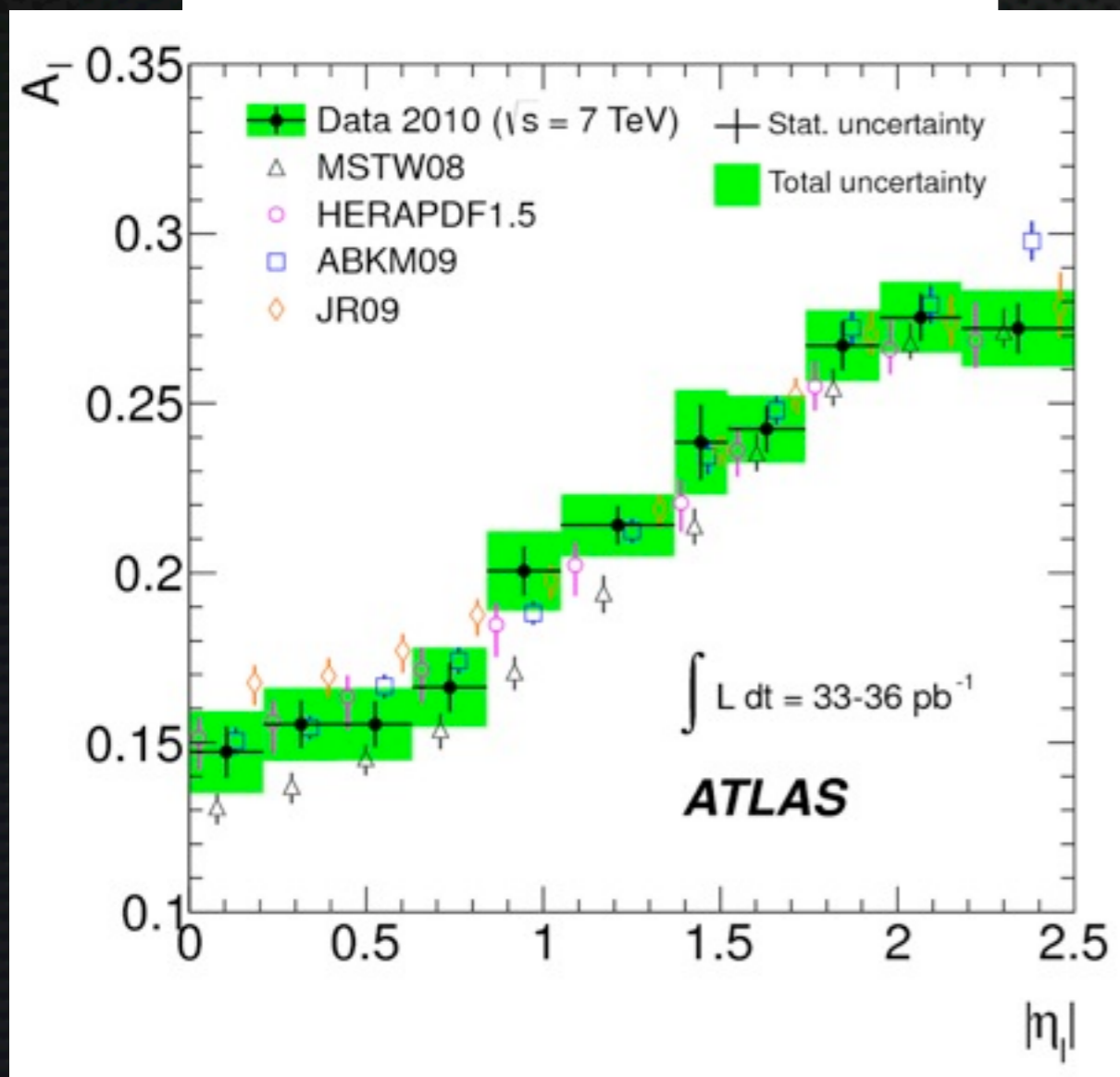


- ✦ Broadly well described by predictions
- ✦ Can impact PDF central values and uncertainties
 - ✦ Information on u_v and d_v PDFs
 - ✦ Full covariance matrix available

W-Lepton Charge Asymmetry

$$A(\eta_e) = \frac{d\sigma_{W^+}(\eta_e) - d\sigma_{W^-}(\eta_e)}{d\sigma_{W^+}(\eta_e) + d\sigma_{W^-}(\eta_e)}$$

ATLAS-CONF-2011-129

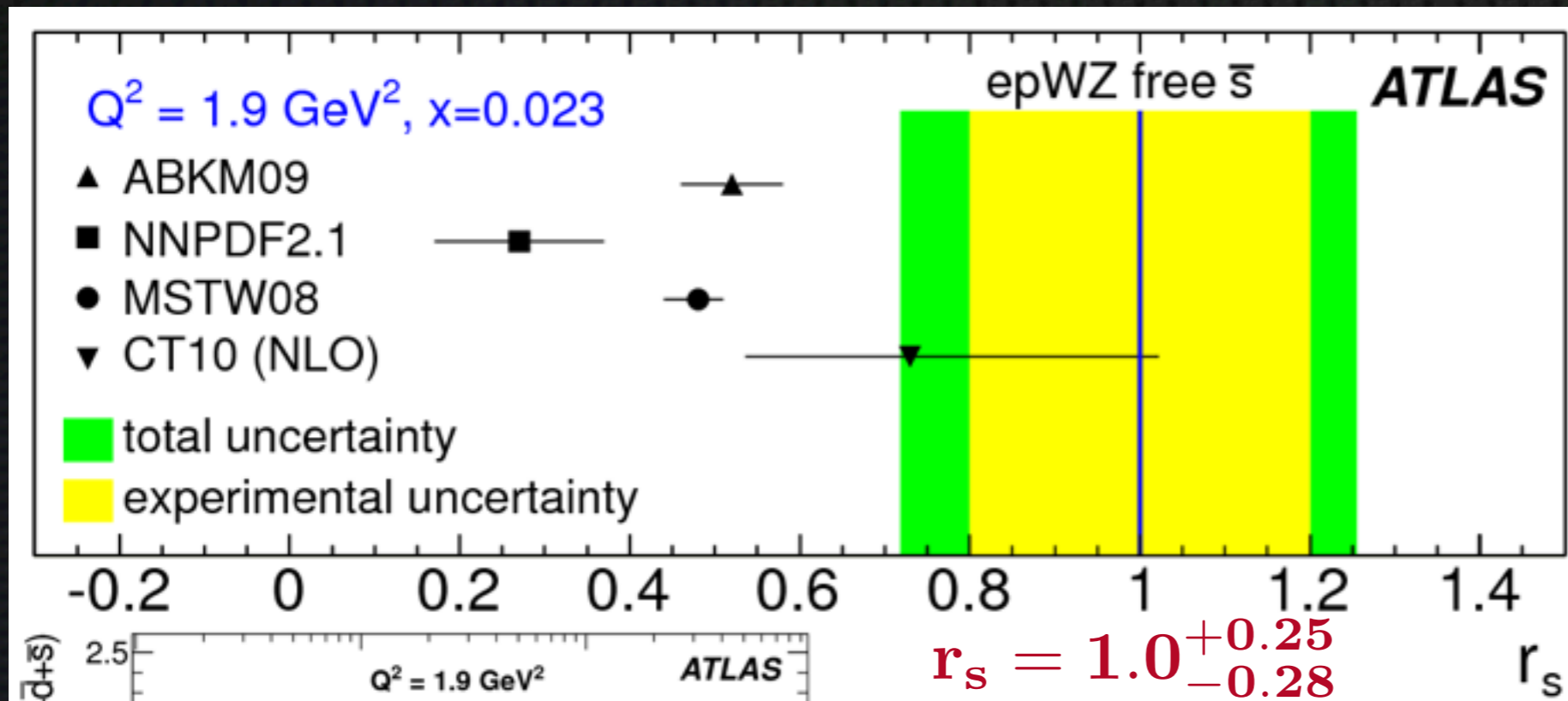


First LHC combined plot (LHC EWK WG)

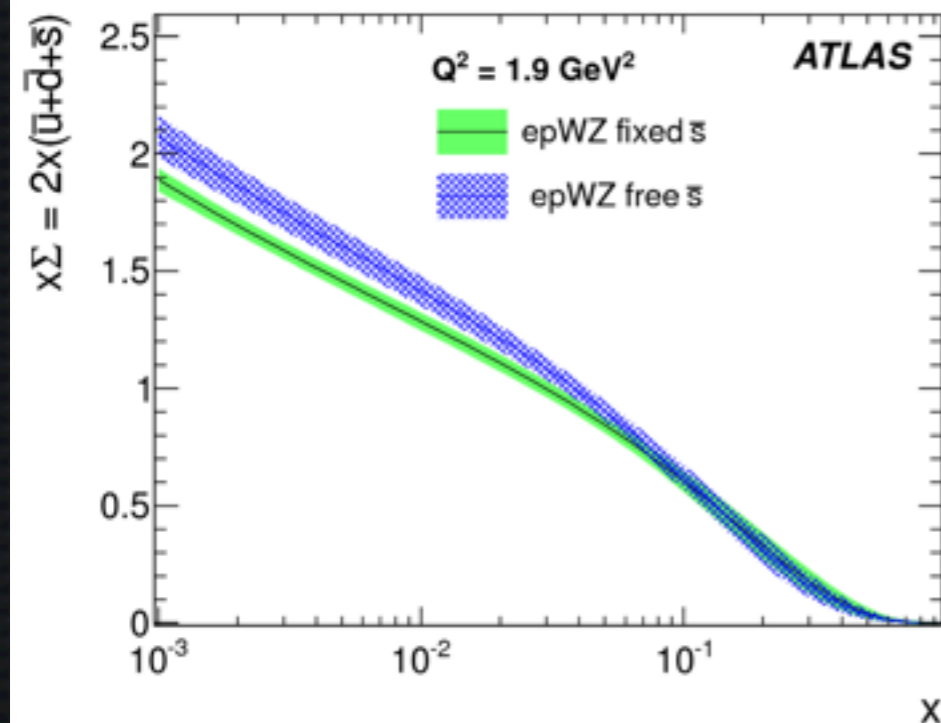
Strangeness in the Proton

Phys.Rev.Lett. 109 (2012) 012001

- Fit ATLAS differential distributions for W^+ , W^- and Z with HERA $e^\pm p$ data
 - NNLO pQCD analysis



$$r_s = \frac{0.5(s + \bar{s})}{\bar{d}}$$

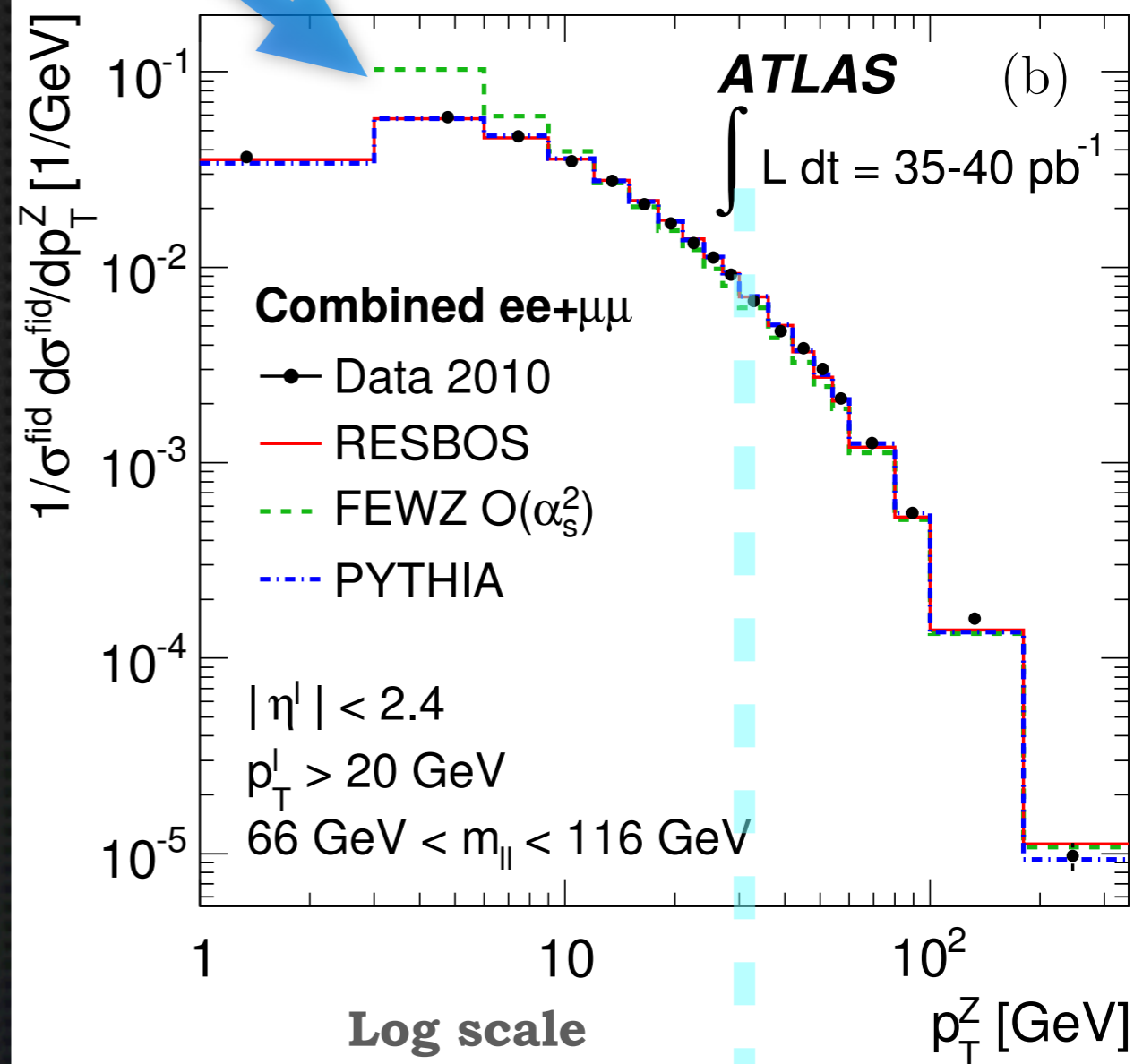
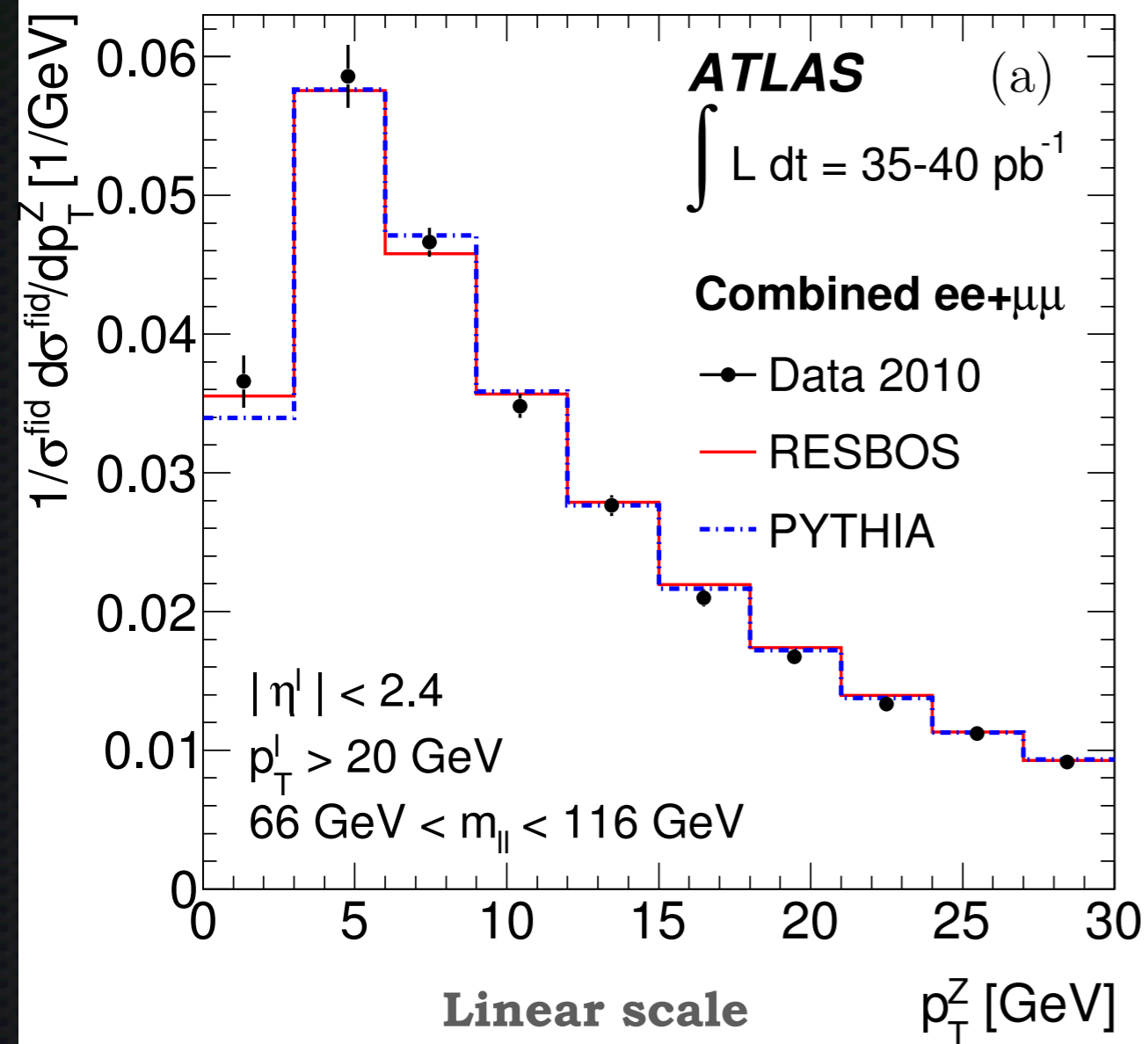


- Fit results:**
- Light quark sea at low x is flavor symmetric
 - Total sea enhancement of 8%

Transverse momentum distribution of Z/γ^* bosons

Electron and muon channel combined

FEWZ
diverges
at low p_T



Transverse momentum distribution of Z/γ^* bosons

Predictions: FEWZ v2.0 + MSTW08

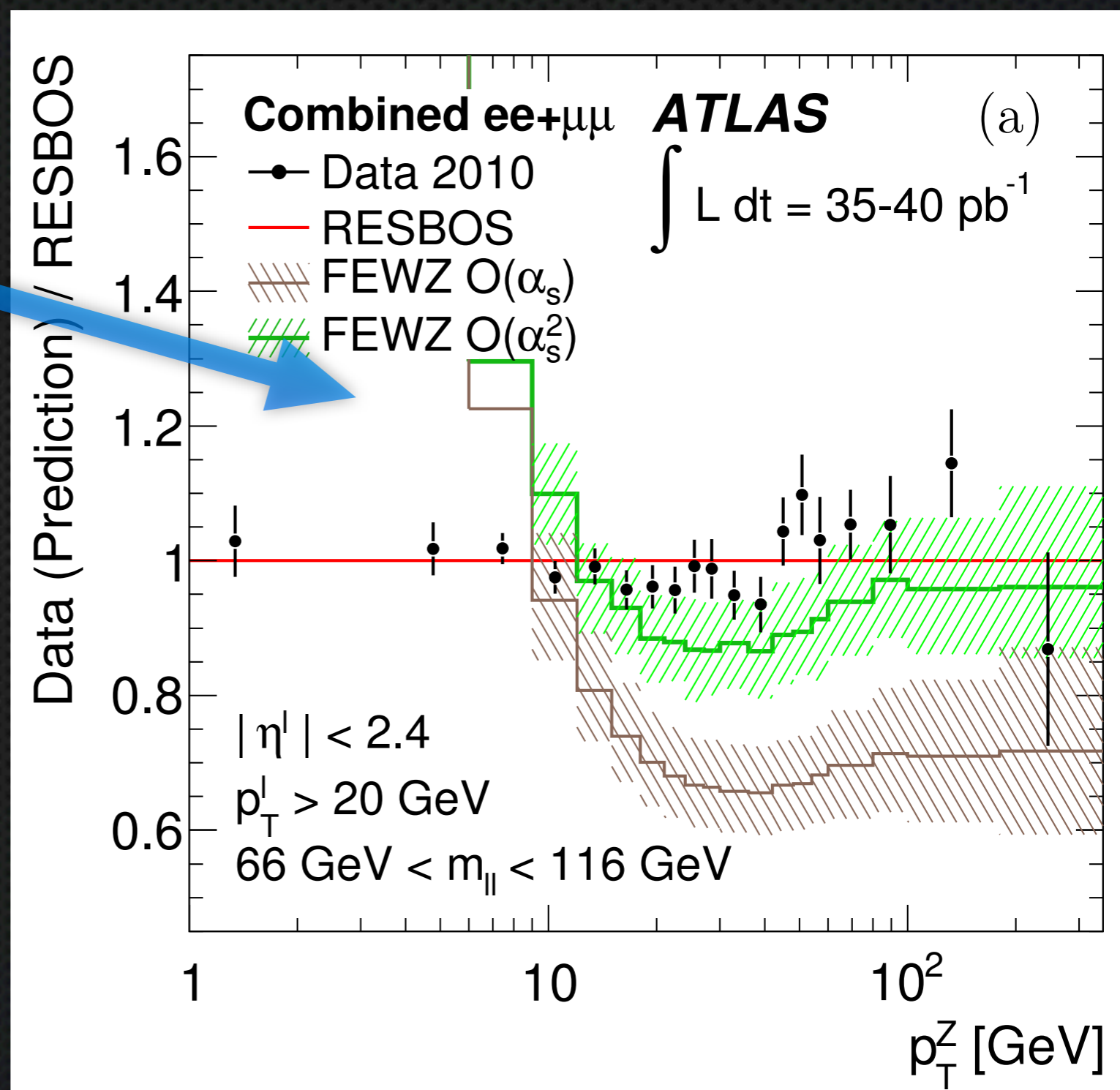
Fiducial measurement

Ratio to RESBOS

FEWZ
diverges
at low p_T
(multiple soft gluon
emissions)



RESBOS:
Matches soft gluon
resummation at low p_T
with fixed order pQCD
calculation

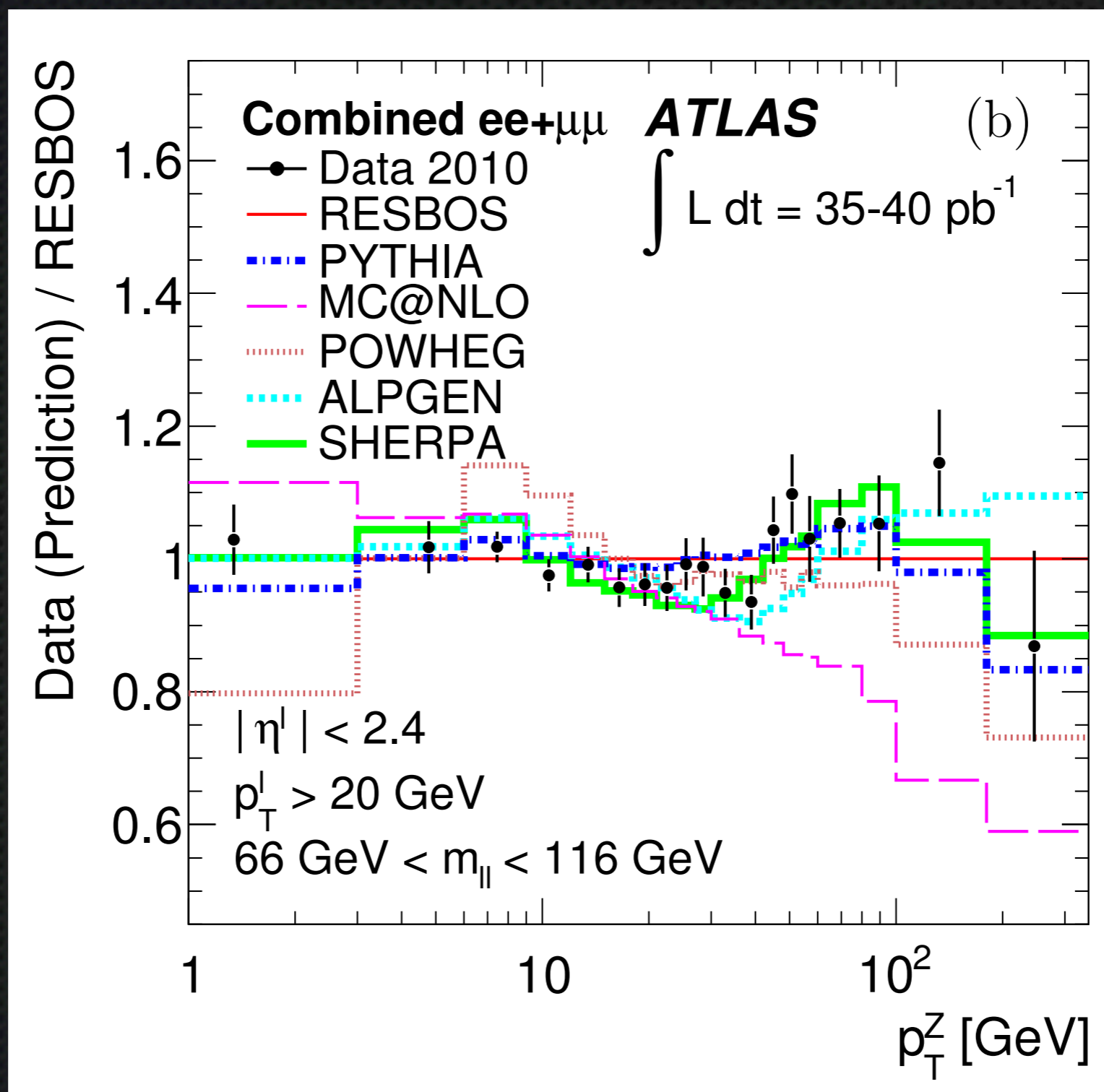


Transverse momentum distribution of Z/γ^* bosons

Predictions: Different event generators

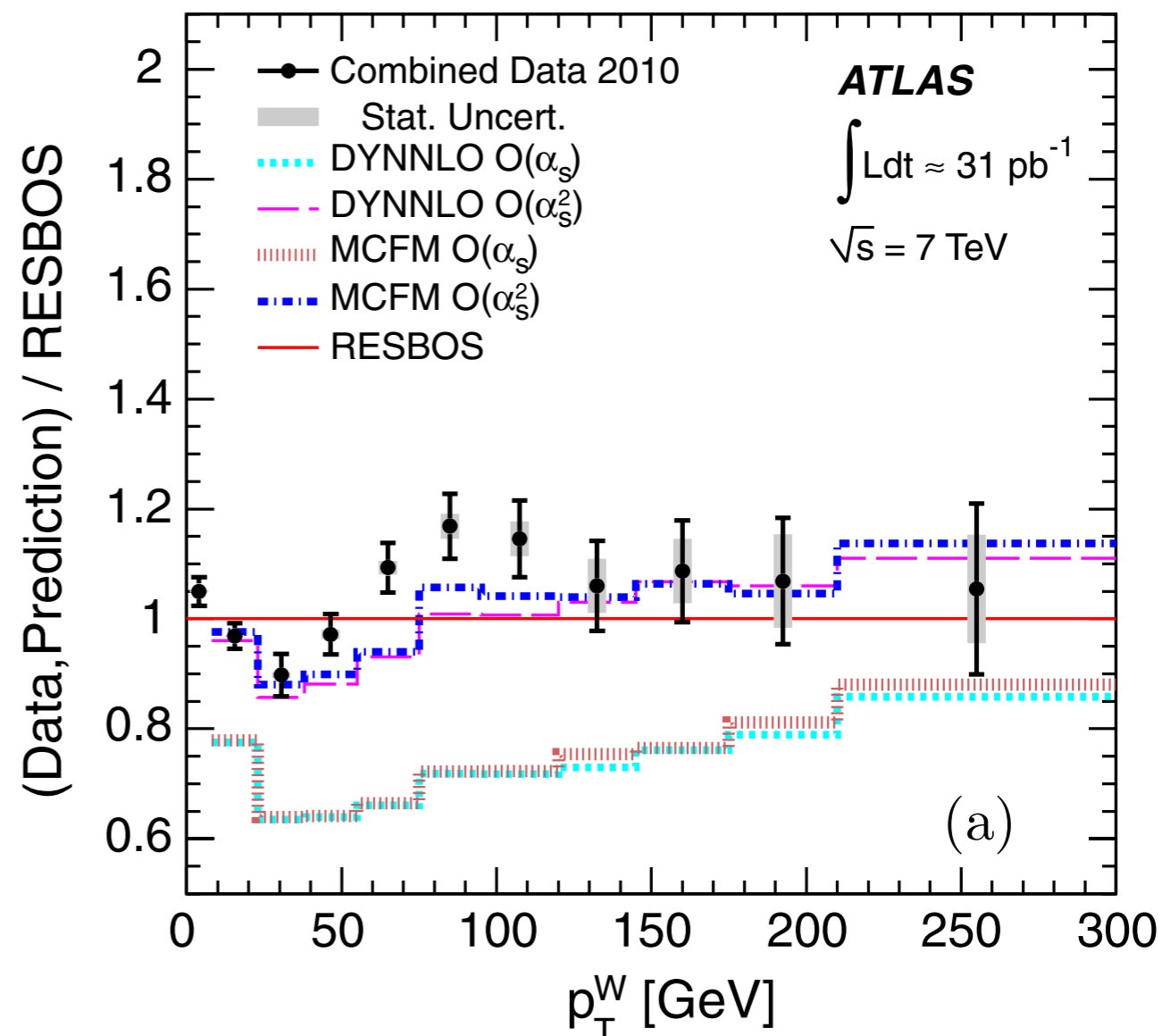
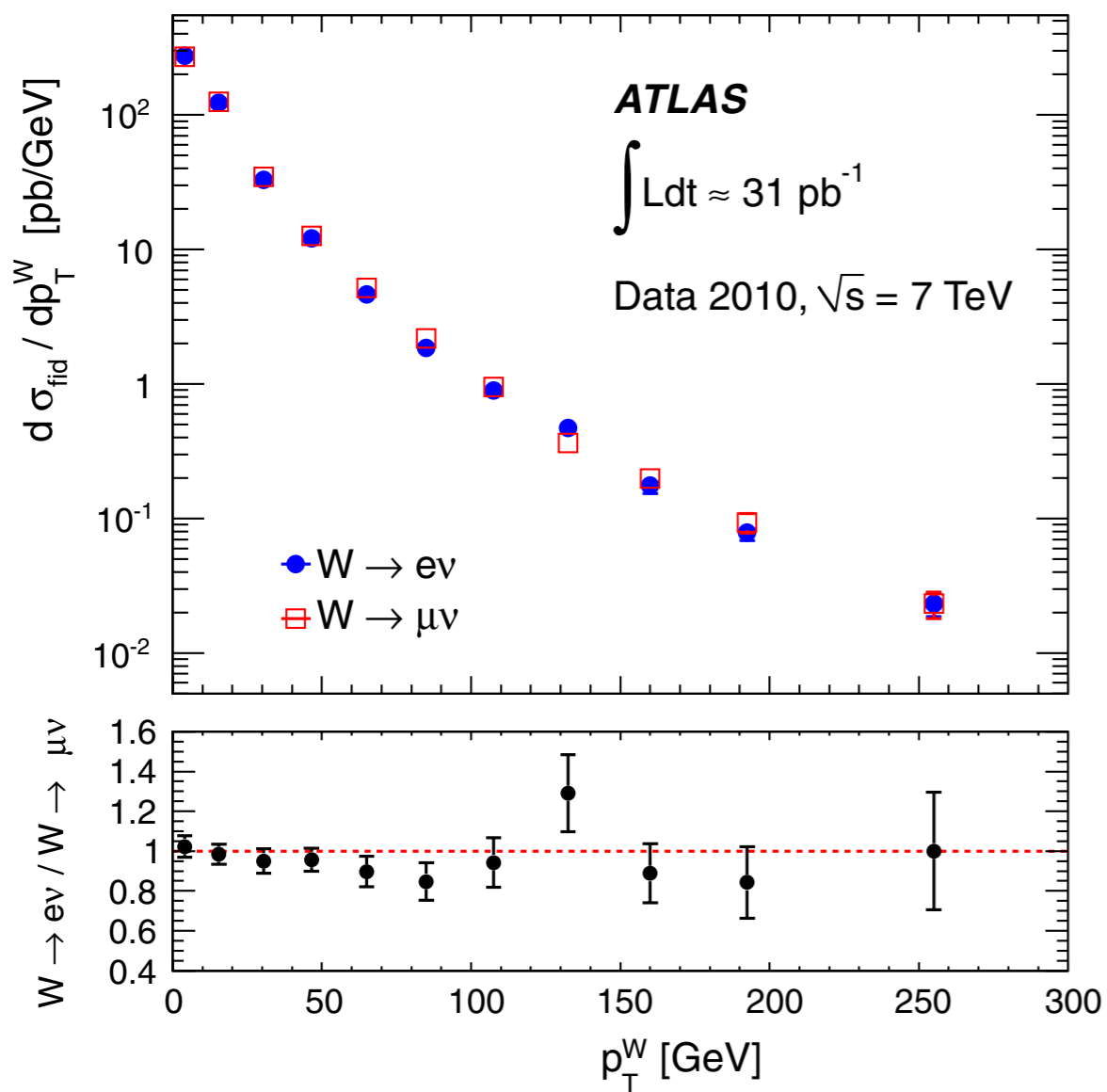
Fiducial measurement

Ratio to RESBOS



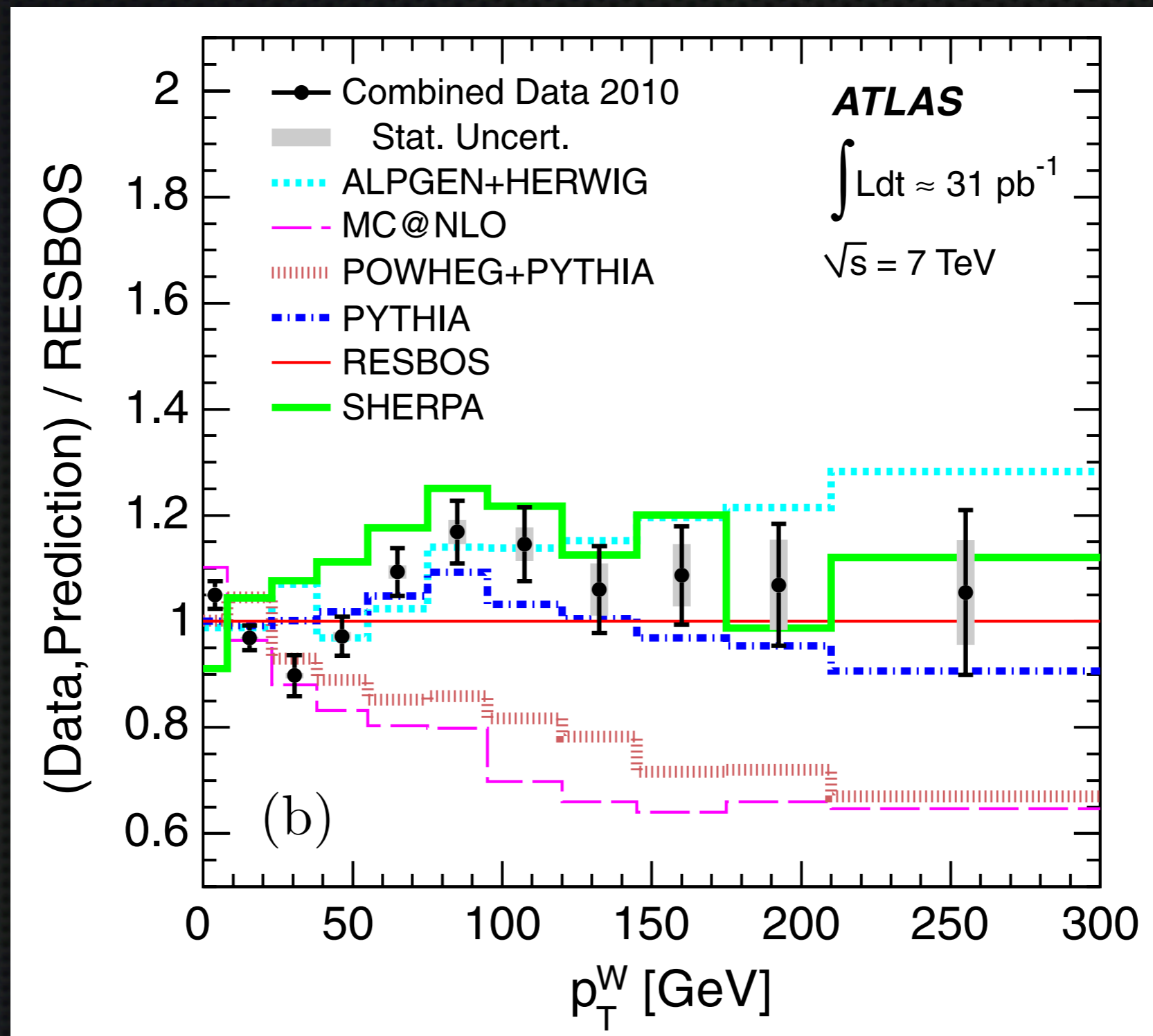
Transverse momentum distribution of W bosons

Phys.Rev. D85 (2012) 012005



Transverse momentum distribution of W bosons

Phys.Rev. D85 (2012) 012005

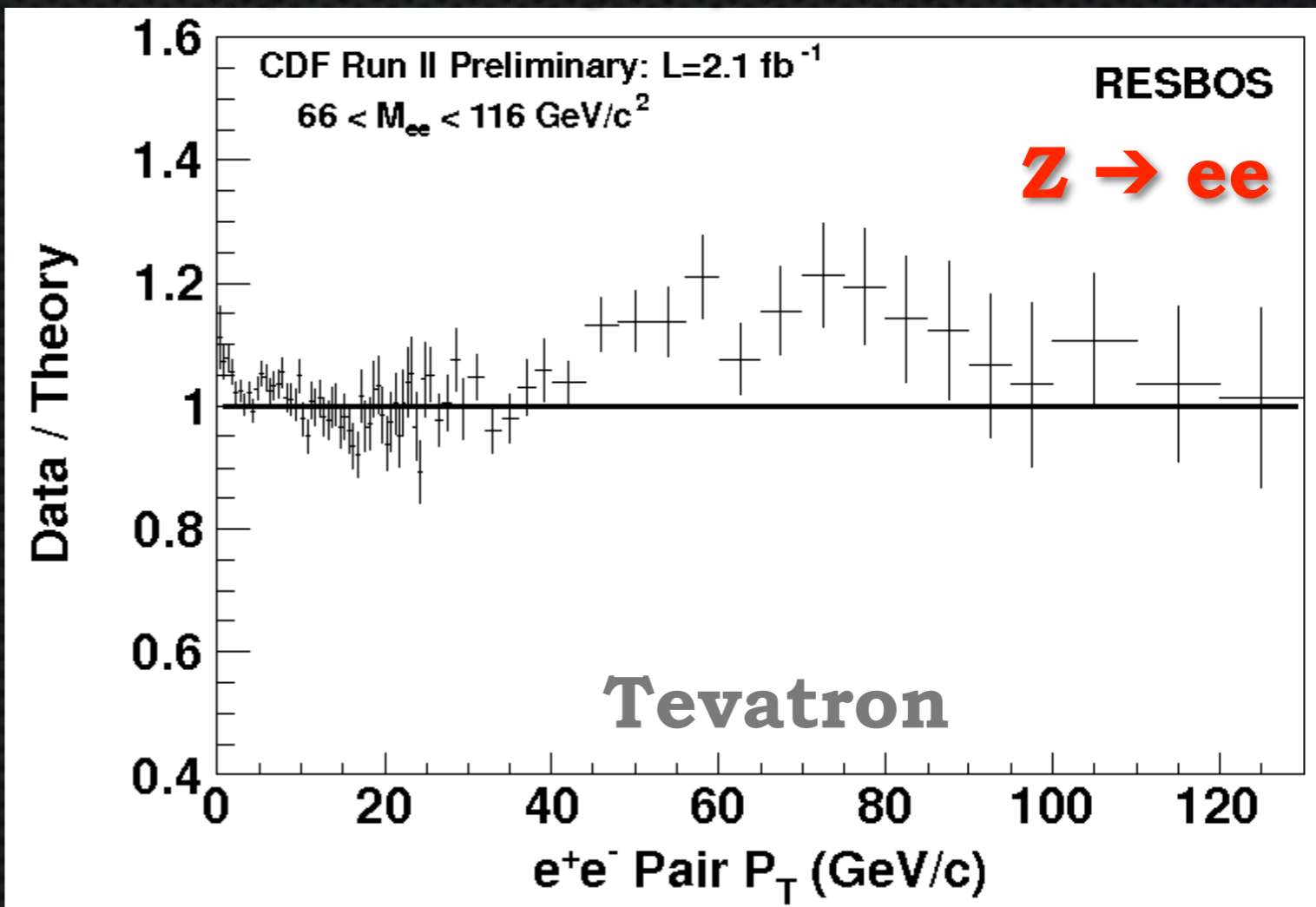
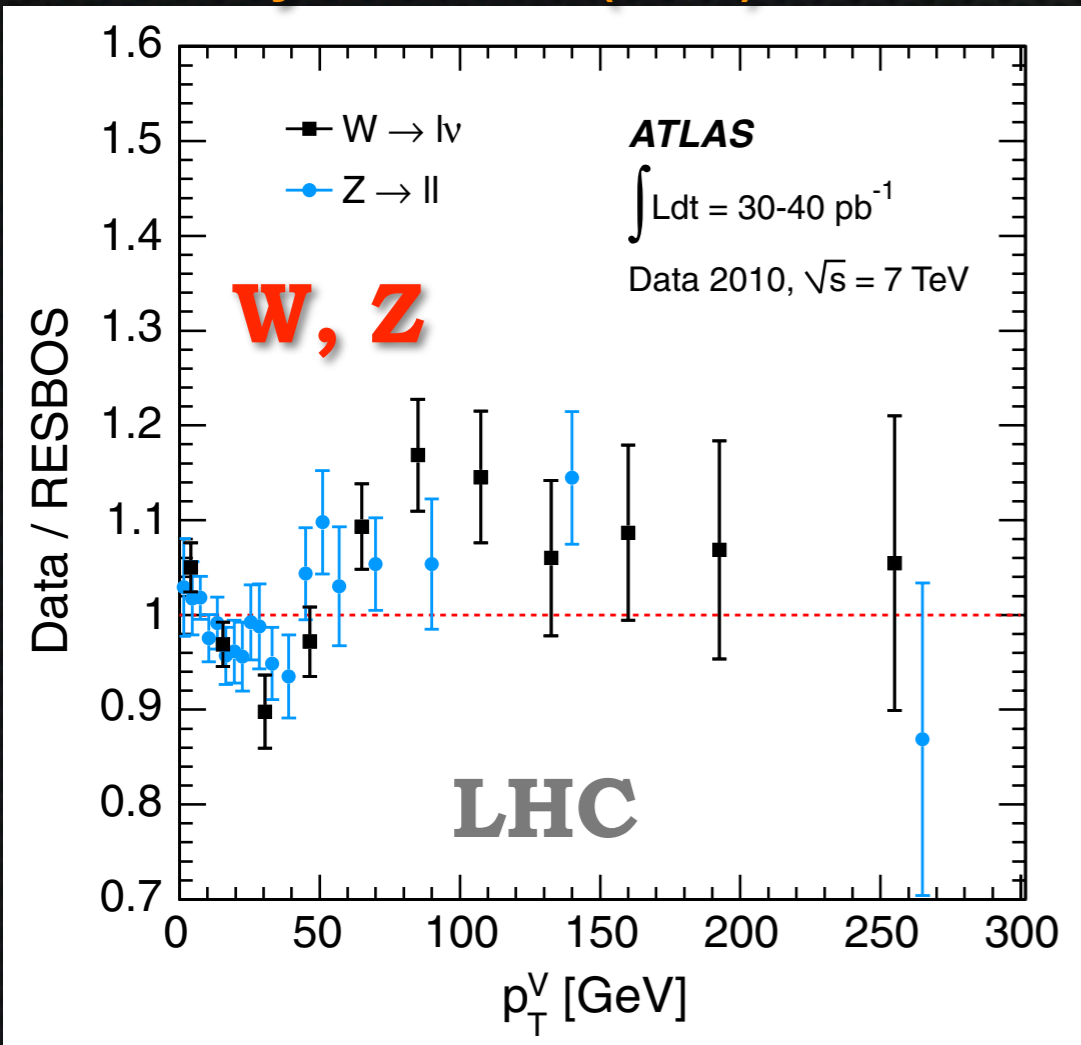


Measurement of Z and W P_T

- Fully unfolded differential distributions
- Comparison with RESBOS

Phys.Rev. D85 (2012) 012005

<http://www-cdf.fnal.gov/physics/ewk/2011/zpt21/cdf10699/>



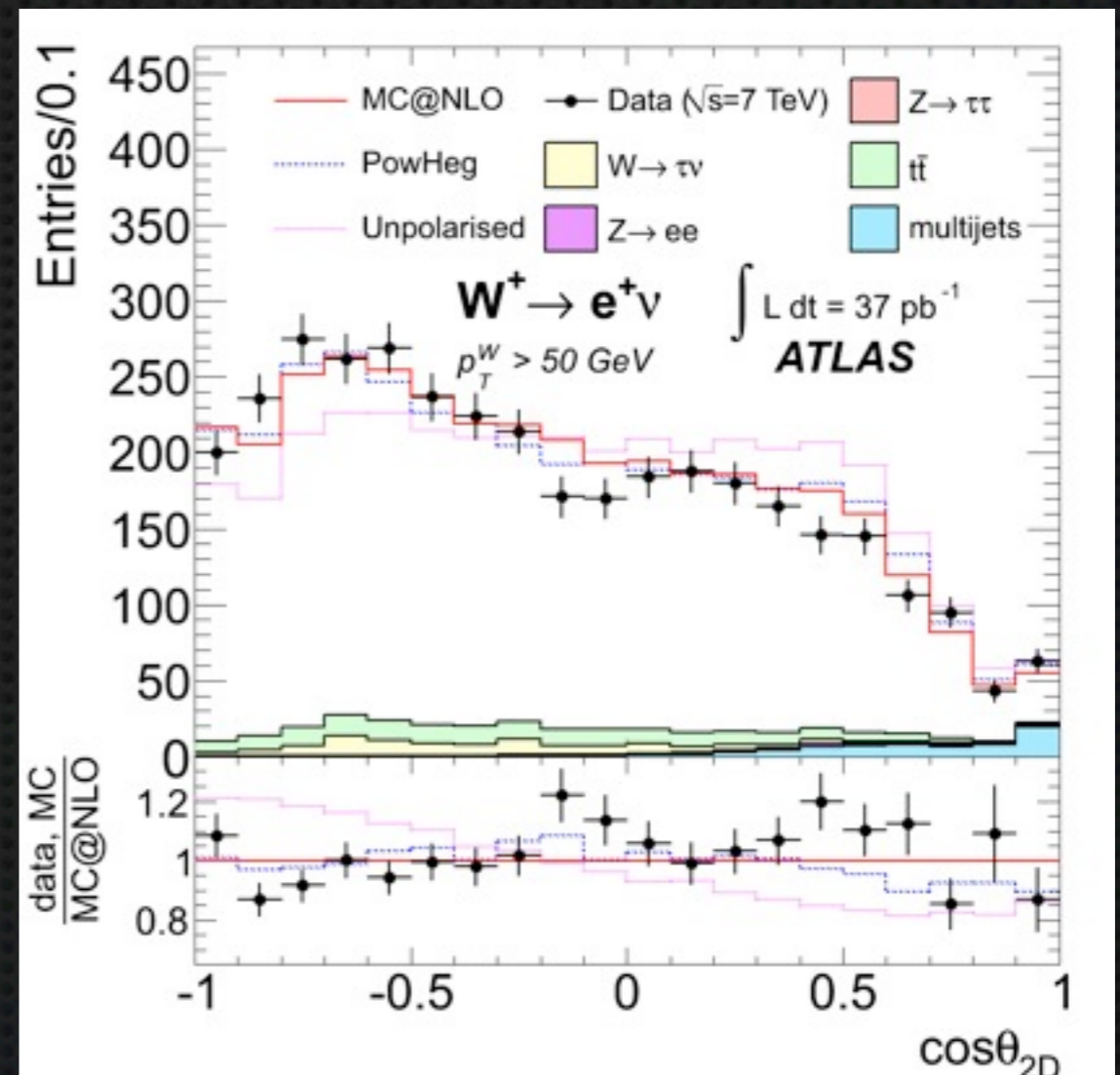
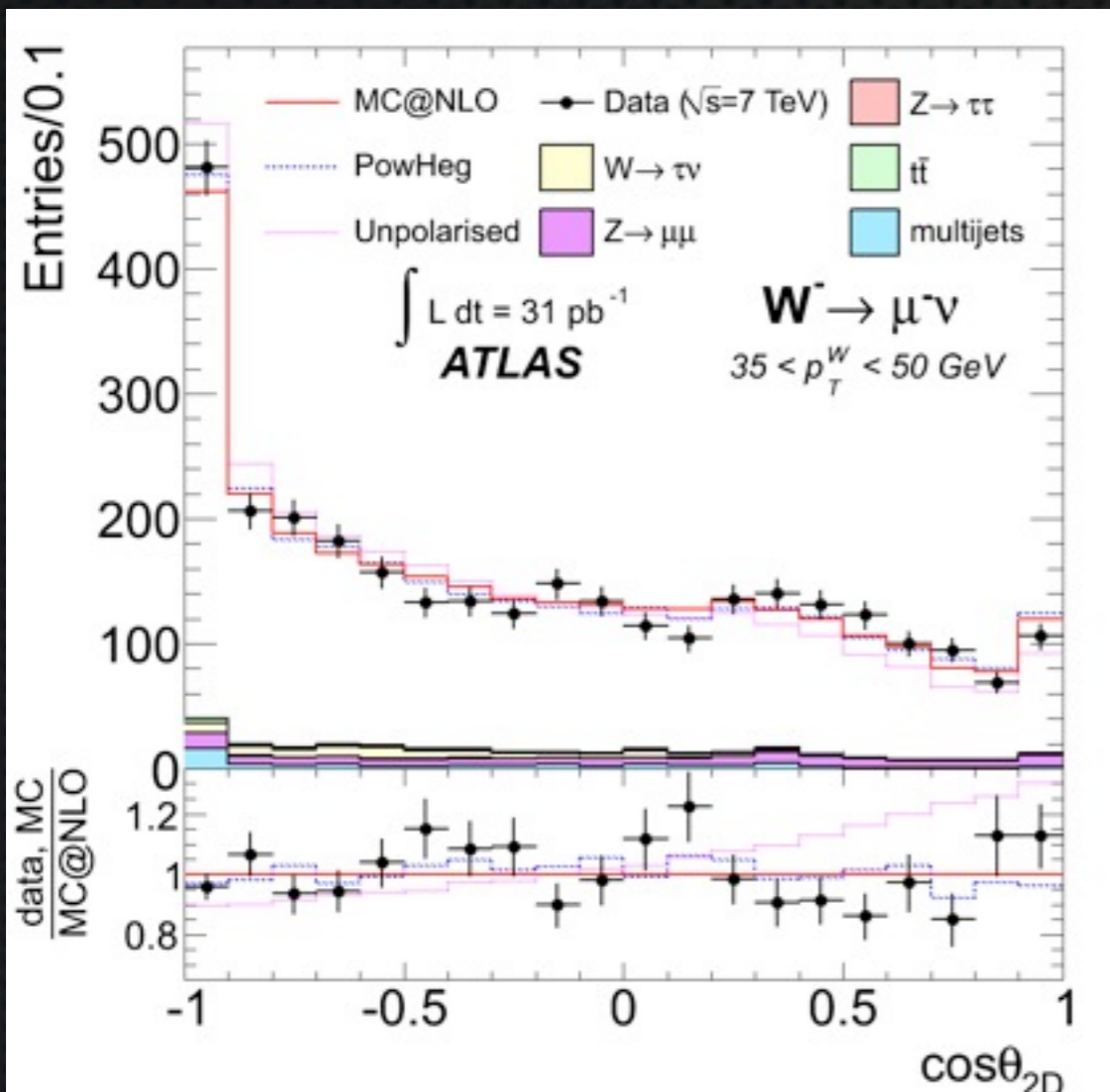
RESBOS tuned to Tevatron data (but not to LHC yet)

W Boson Polarization

Eur. Phys. J. C72 (2012) 2001

$$\cos \theta_{2D} = \frac{\vec{p}_T^{\ell*} \cdot \vec{p}_T^W}{|\vec{p}_T^{\ell*}| |\vec{p}_T^W|}$$

Angle between:
 P_T lepton in W rest frame
AND
 $P_T(W)$ in lab rest frame

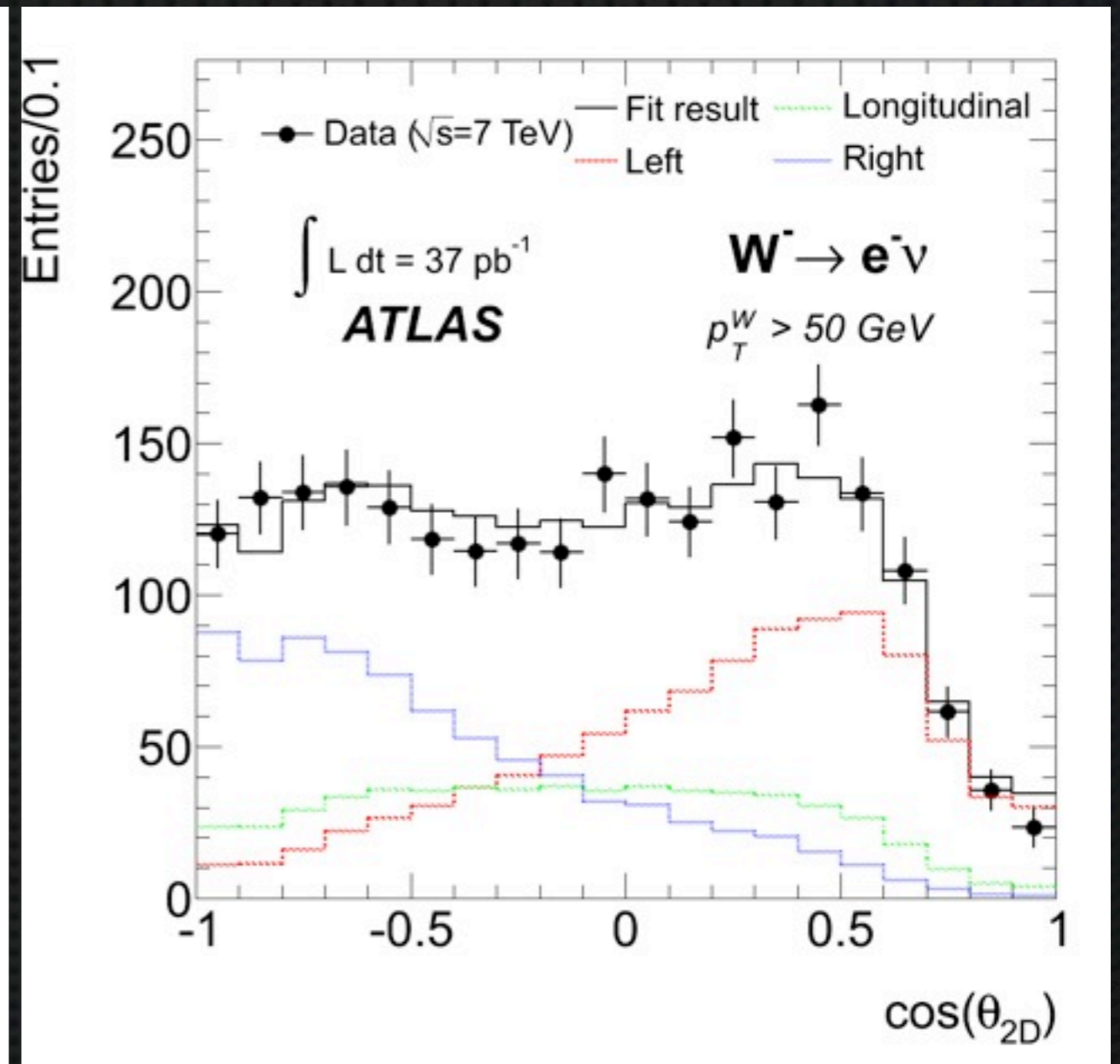
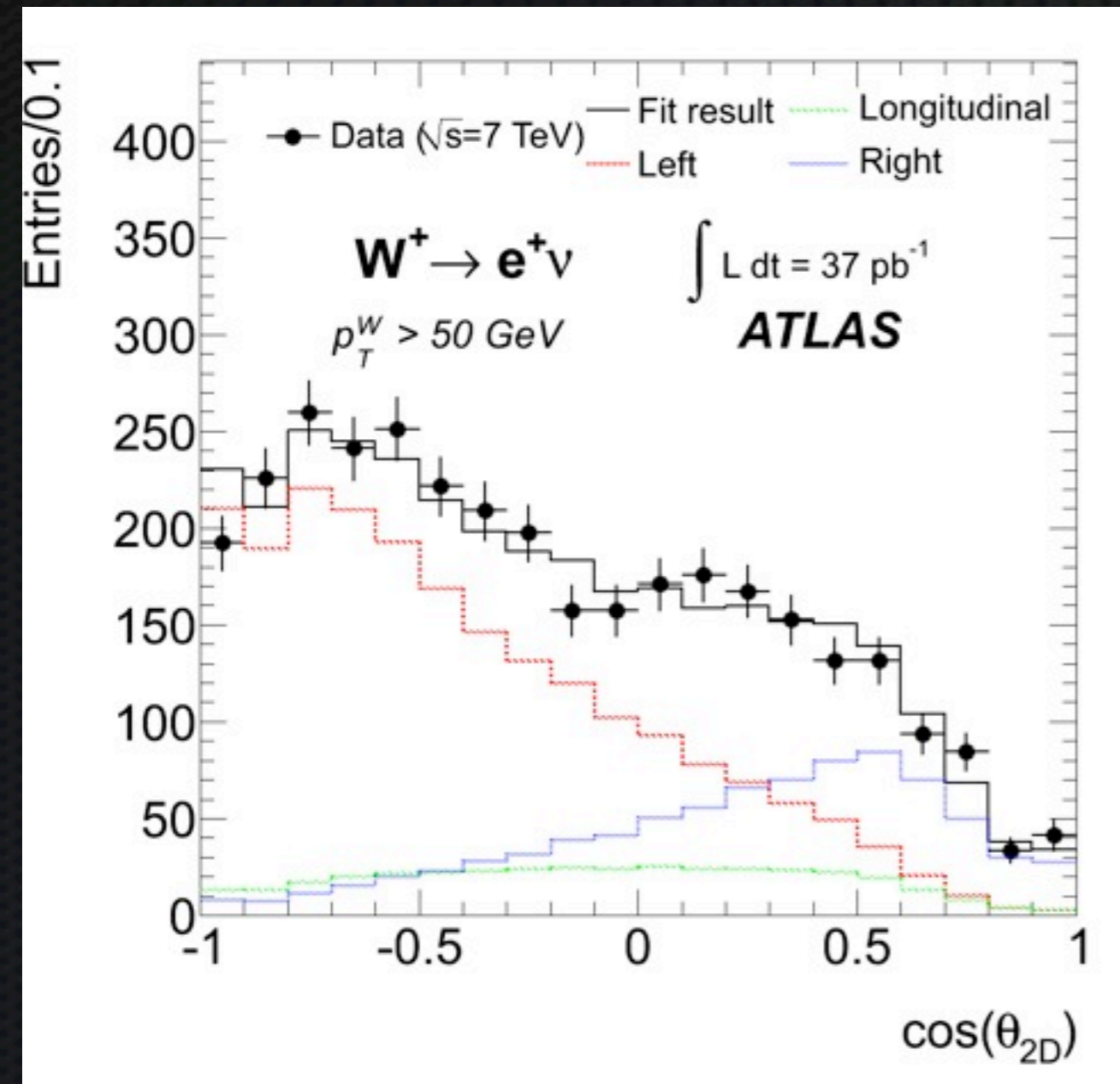


Signal:

- MC@NLO 3.4.2 + HERWIG (CTEQ 6.6)
- POWHEG 1.0 + PYTHIA

Uncertainties:
MSTW08 and HERAPDF 1.0

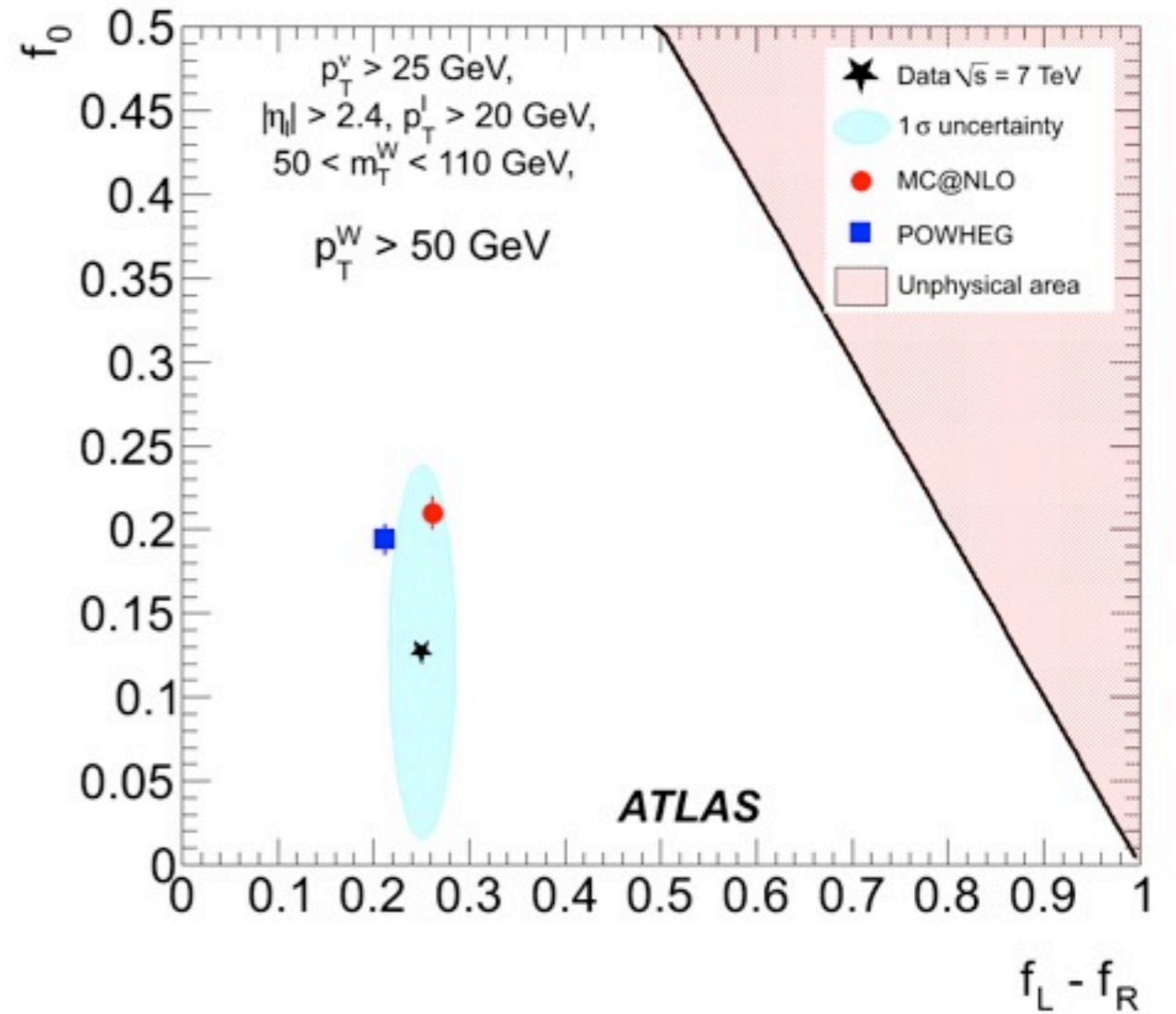
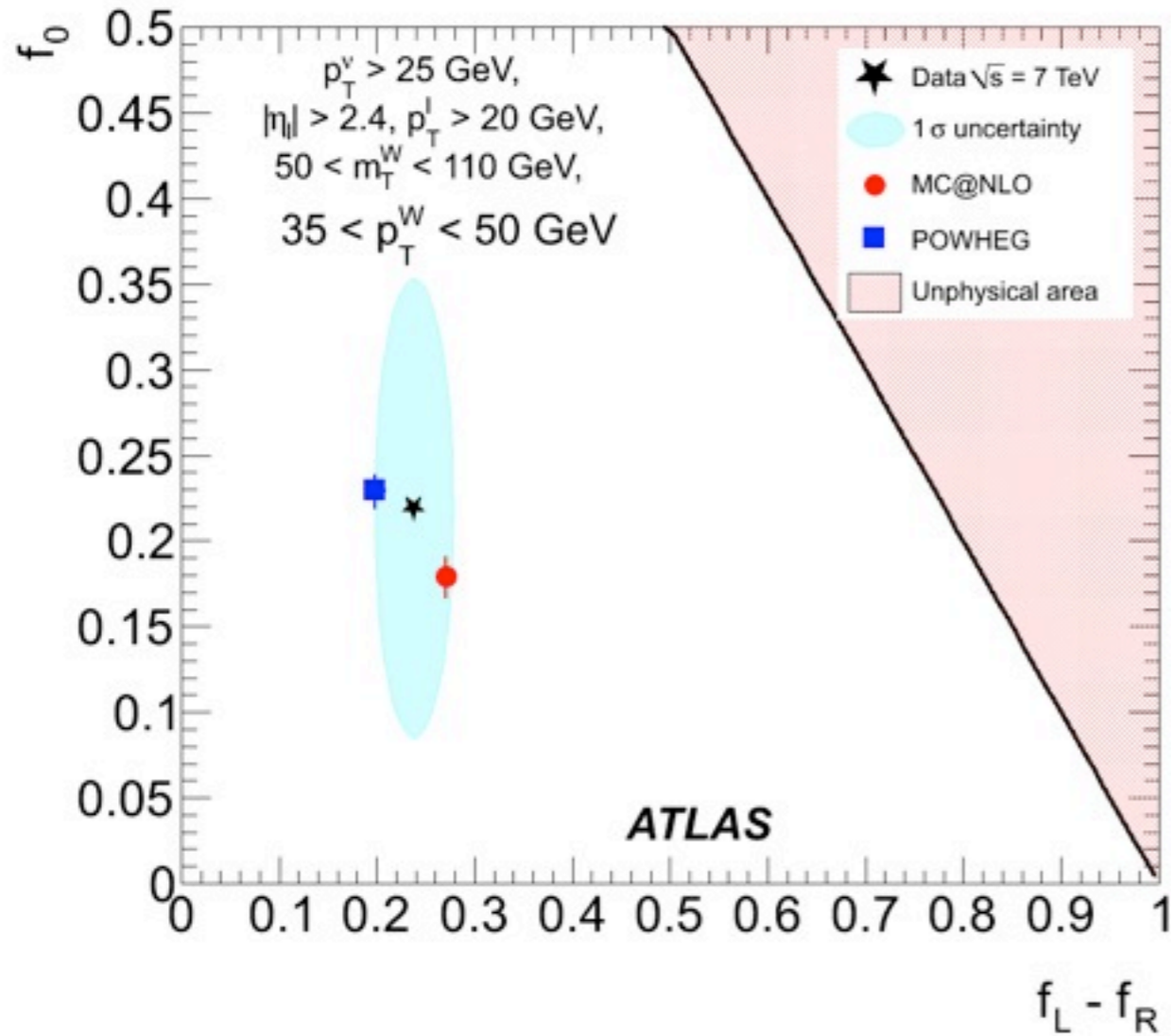
W Polarization fits



Templates from MC@NLO after background subtraction

W Boson Polarization

Eur. Phys. J. C72 (2012) 2001



	$f_L - f_R$ (%)	
	$35 < p_T^W < 50 \text{ GeV}$	$p_T^W > 50 \text{ GeV}$
Data	$23.8 \pm 2.0 \pm 3.4$	$25.2 \pm 1.7 \pm 3.0$
MC@NLO	27.1 ± 0.7	26.2 ± 0.5
POWHEG	19.9 ± 1.0	21.2 ± 0.8



$$pp \rightarrow W + X$$

$$\quad \searrow$$

$$\quad \tau \nu$$

W/Z inclusive production in τ channel

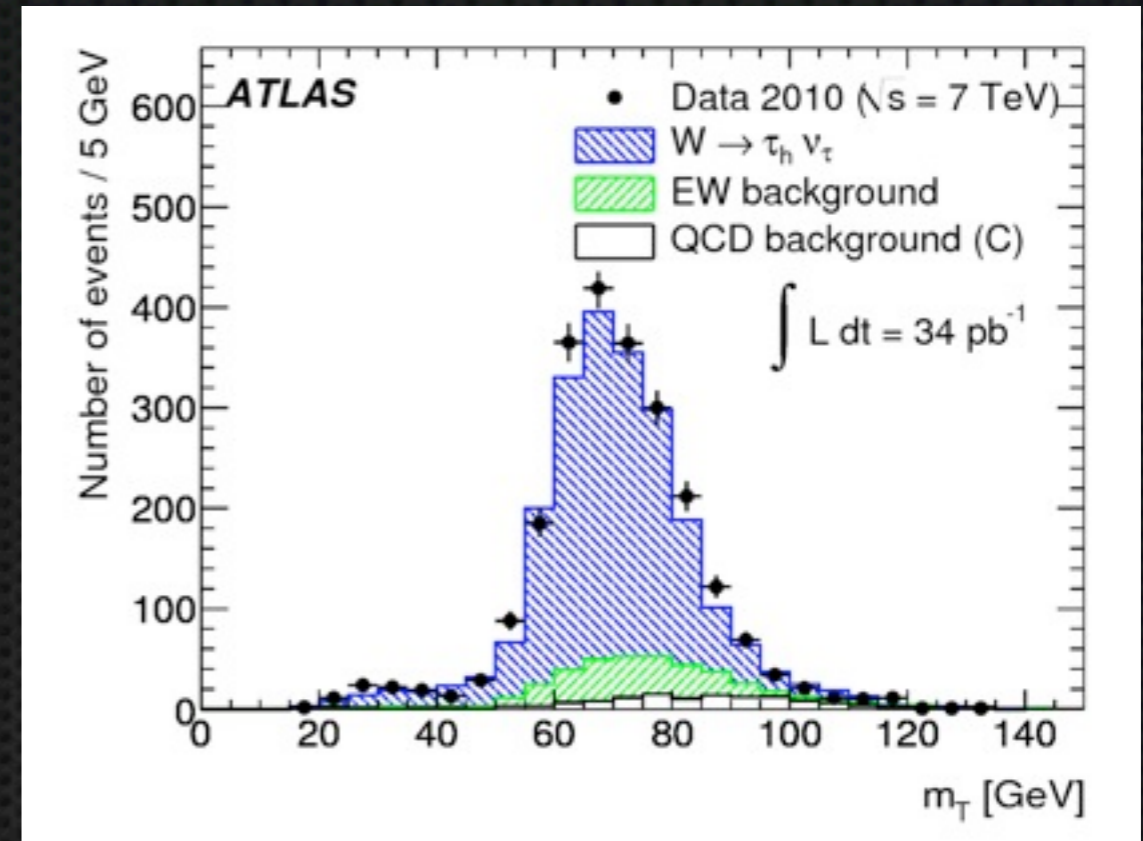
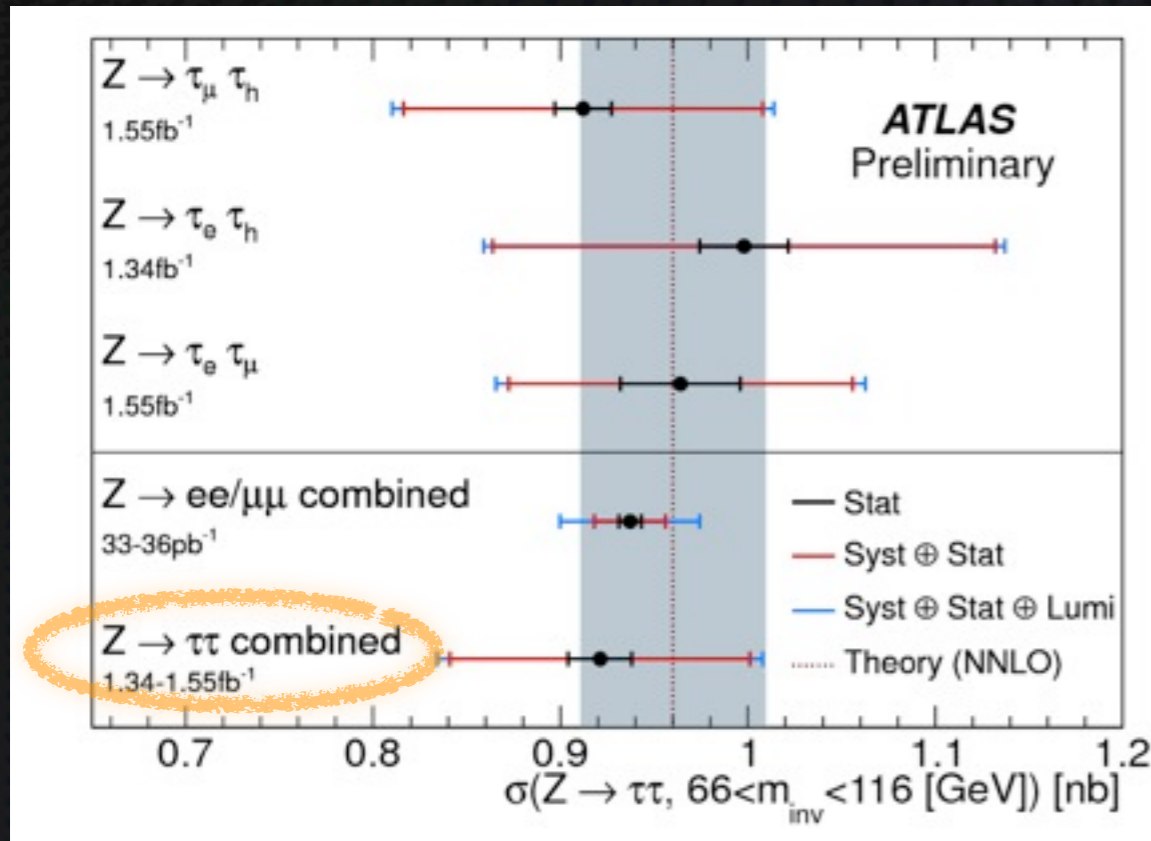


$$pp \rightarrow Z + X$$

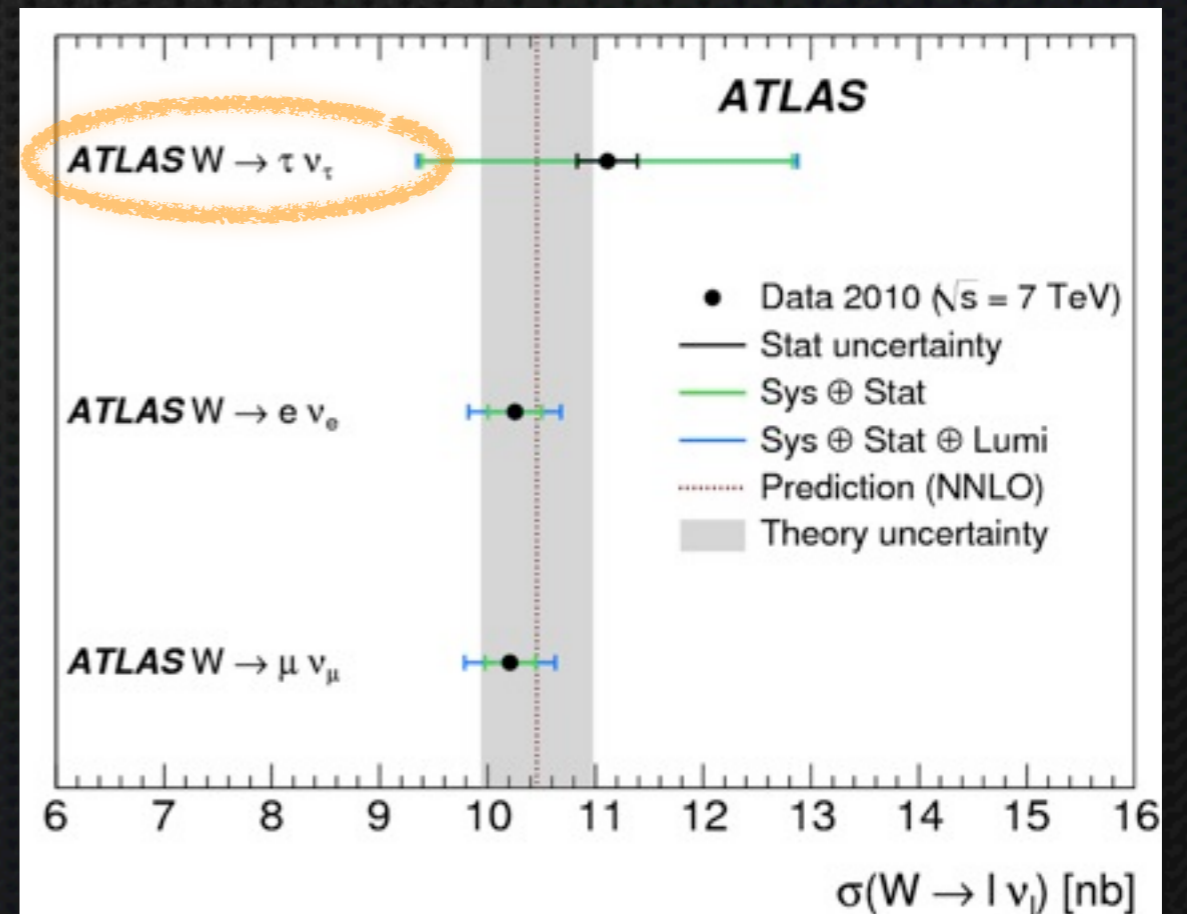
$$\quad \searrow$$

$$\quad \tau \tau$$

Z → ττ and W → τν Cross Section



- ✦ **Excellent tau identification**
 - ✦ **Z → ττ cross section**
 - ✦ **W → τν cross section**
- ✦ **Good prospects for new physics searches with taus**



Tau Polarization in W decays

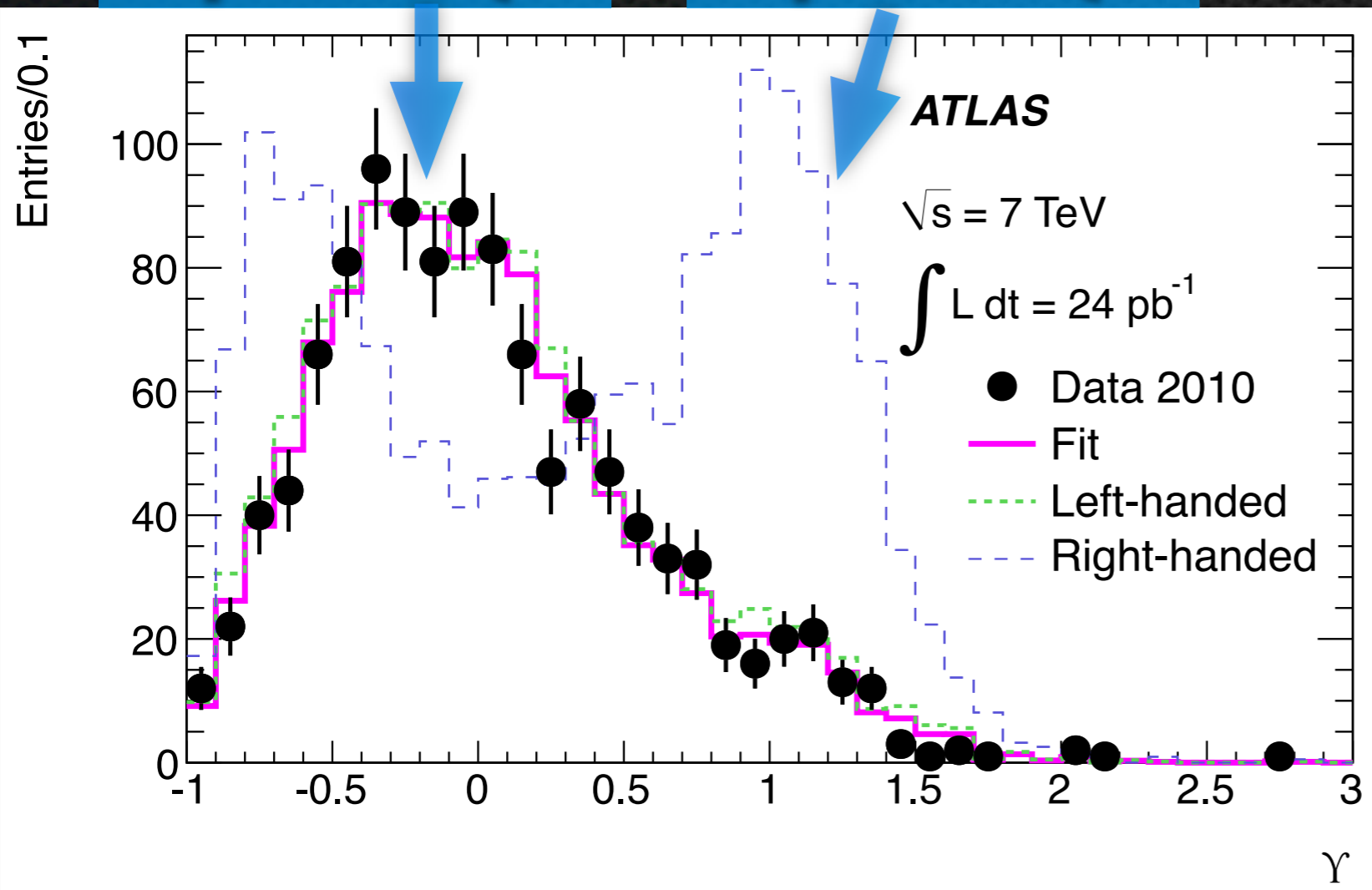
Eur.Phys.J. C72 (2012) 2062

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Process	P_τ Prediction
$W^\pm \rightarrow \tau\nu$	-1
$H^\pm \rightarrow \tau\nu$	+1
$Z \rightarrow \tau\tau$	≈ -0.15
$H \rightarrow \tau\tau$	0

Transversely polarized ρ

Longitudinally polarized ρ

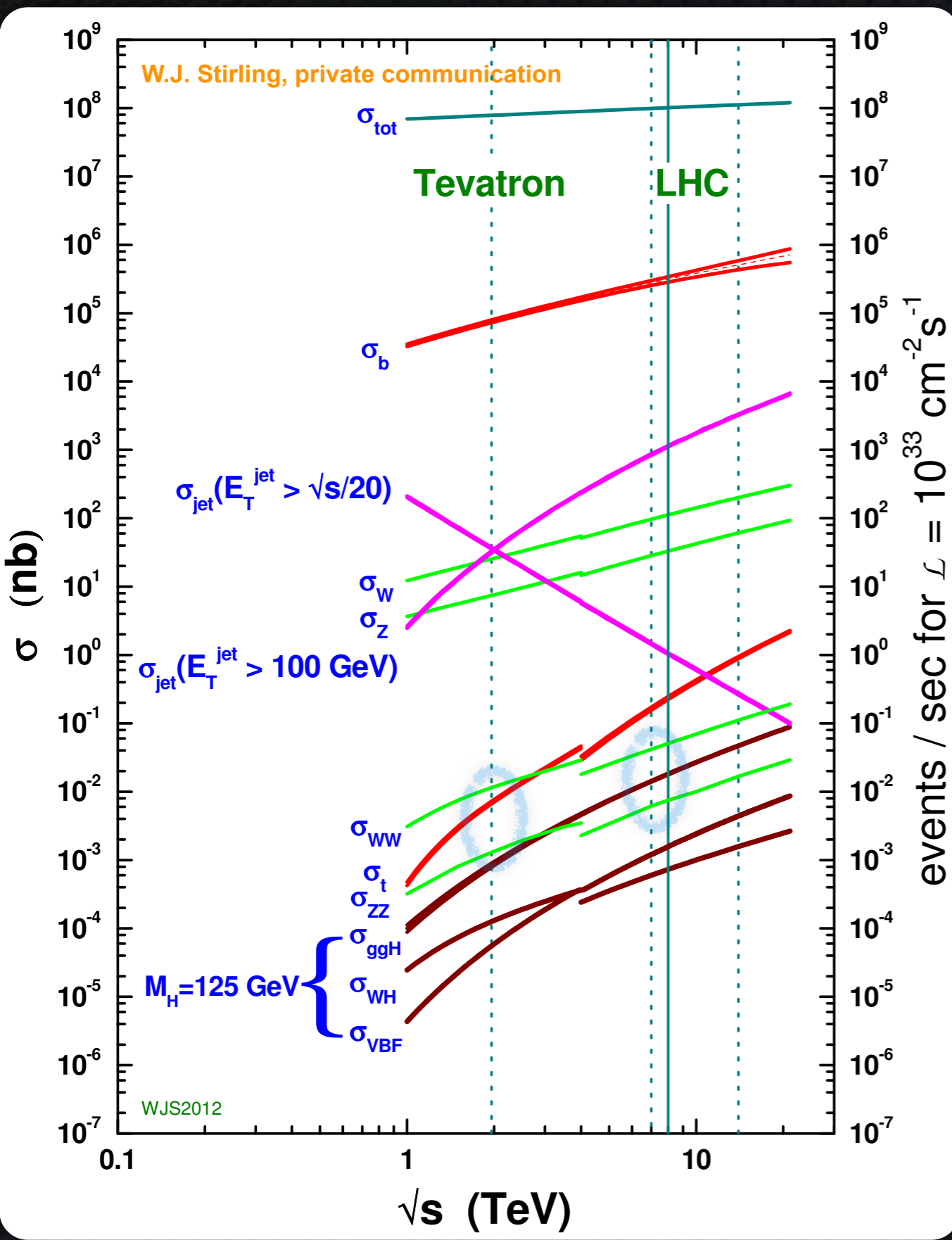


$$\tau \rightarrow \rho^- \nu_\tau \rightarrow \pi^- \pi^0 \nu_\tau$$

BR = 25.94 ± 0.09%

$$\Upsilon = \frac{2p_T^{\text{trk}}}{p_T^\tau} - 1 \approx \frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T}$$

$$P_\tau = -1.06 \pm 0.04 \text{ (stat)}_{-0.07}^{+0.05} \text{ (syst)}$$

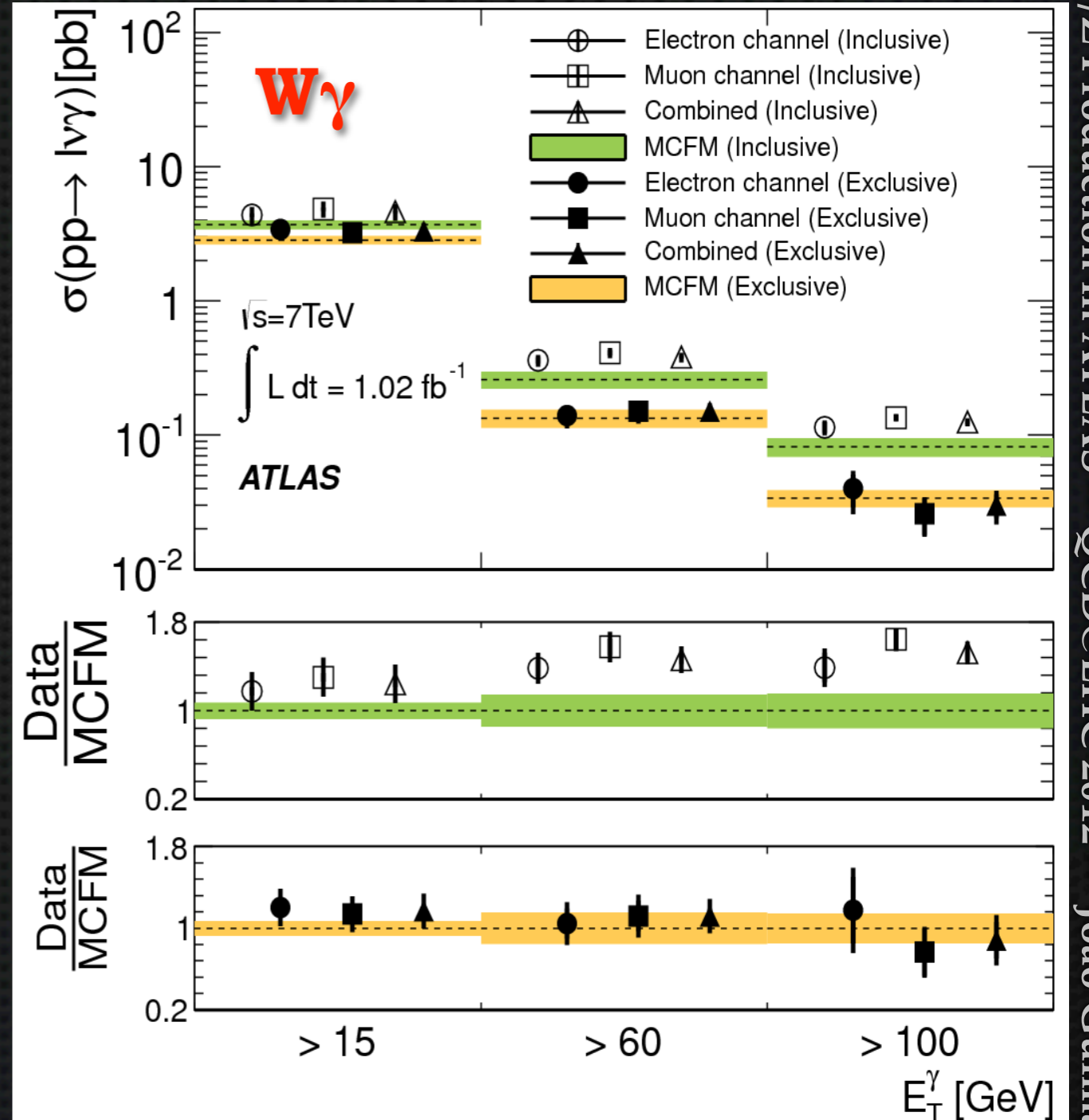
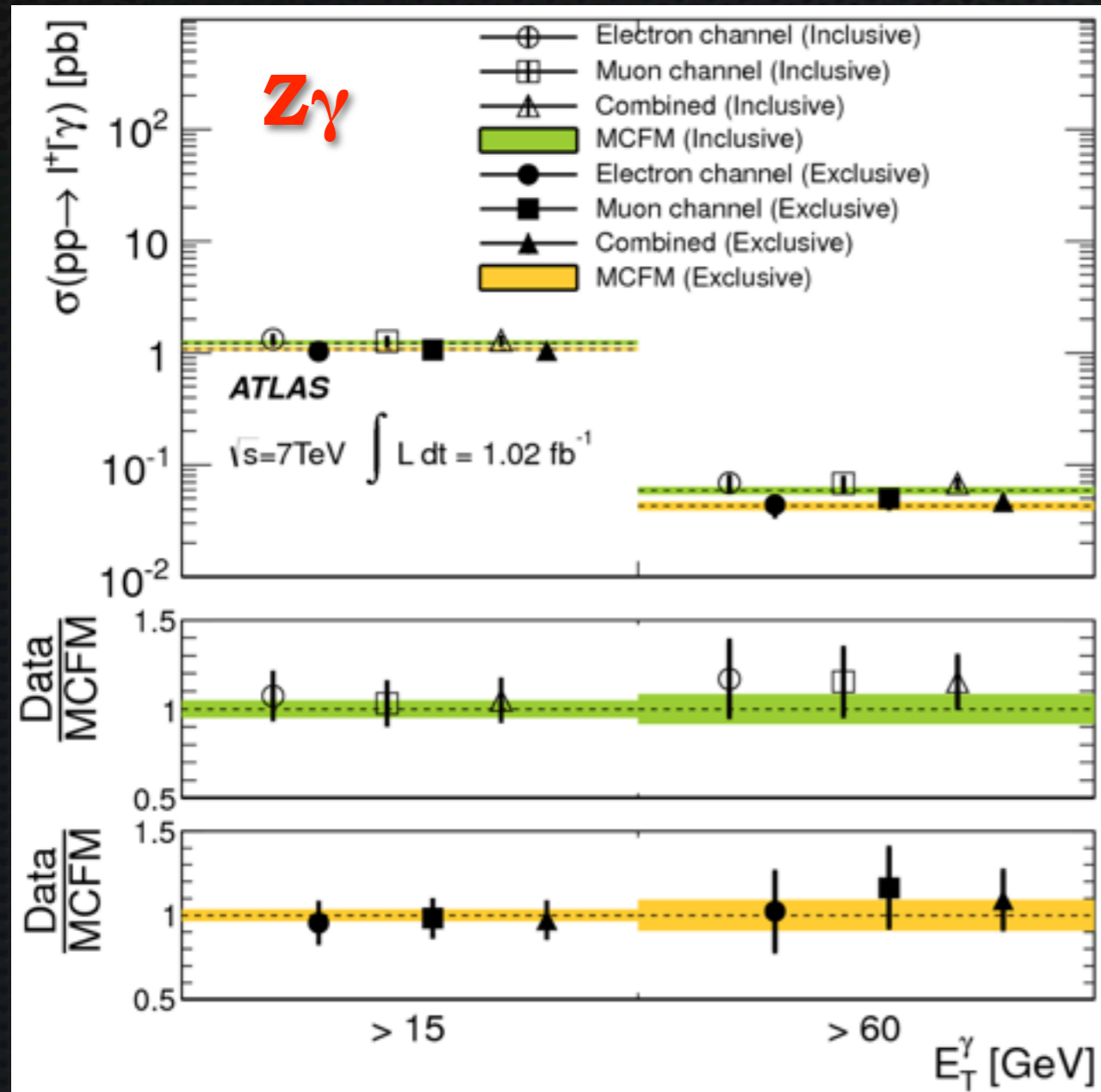


Diboson Production

- ✦ Fundamental test of Standard Model
 - ✦ Triple gauge couplings (TGC)
 - ✦ Probe for new physics
 - ✦ Resonances with diboson final states
- ✦ Higgs hunting
 - ✦ Background to Higgs

Dibosons: $W\gamma/Z\gamma$

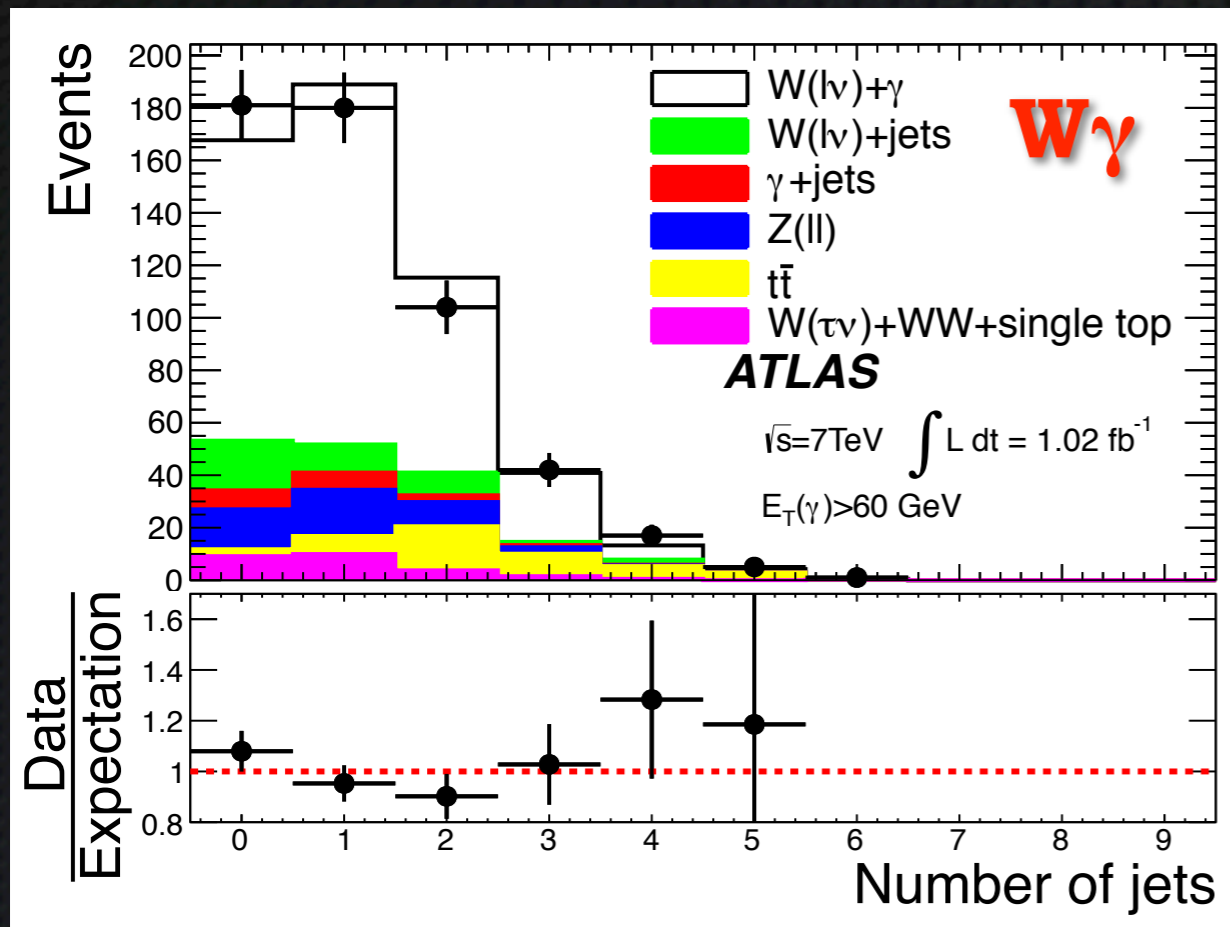
ATLAS: arXiv:1205.2531



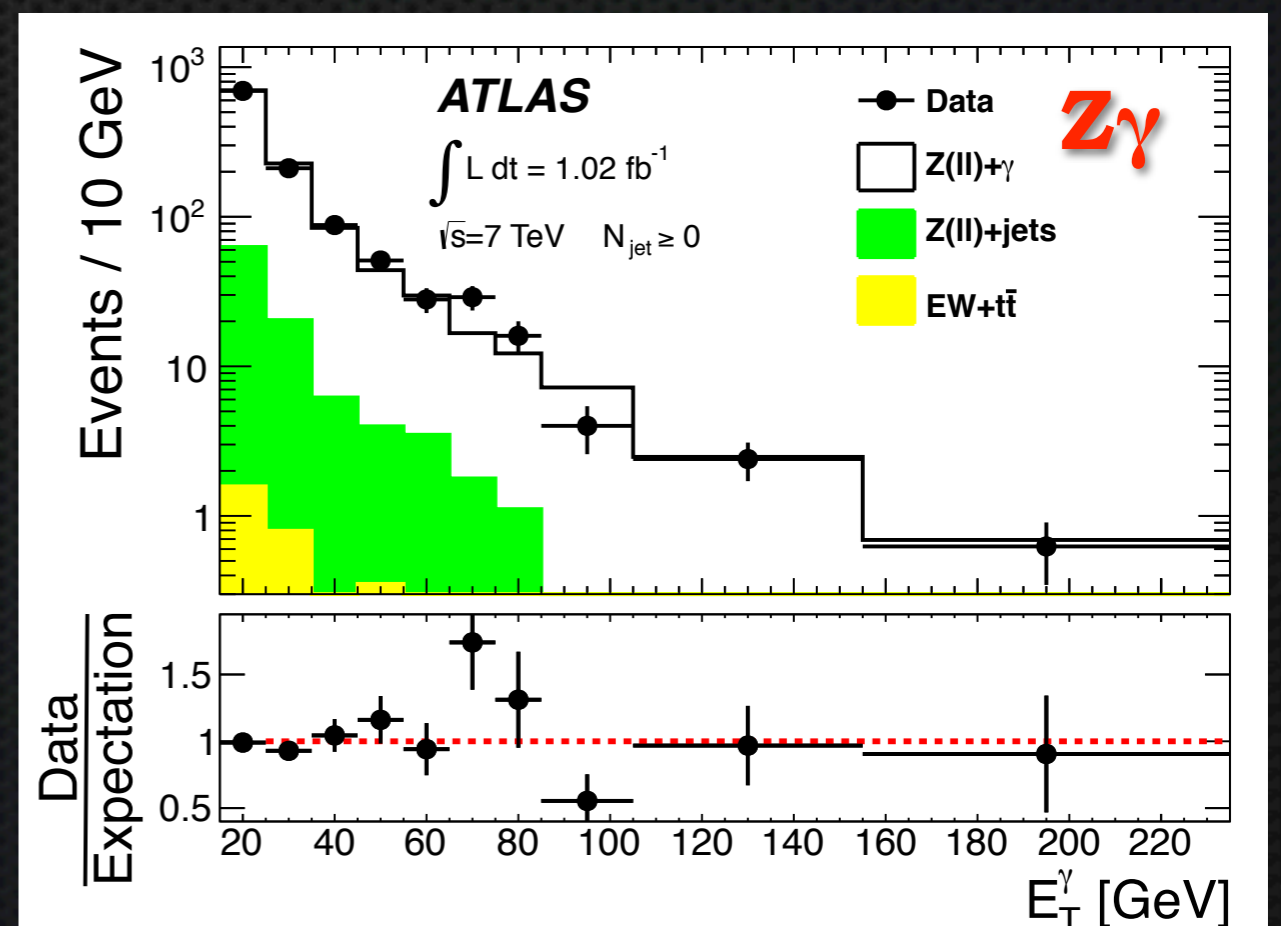
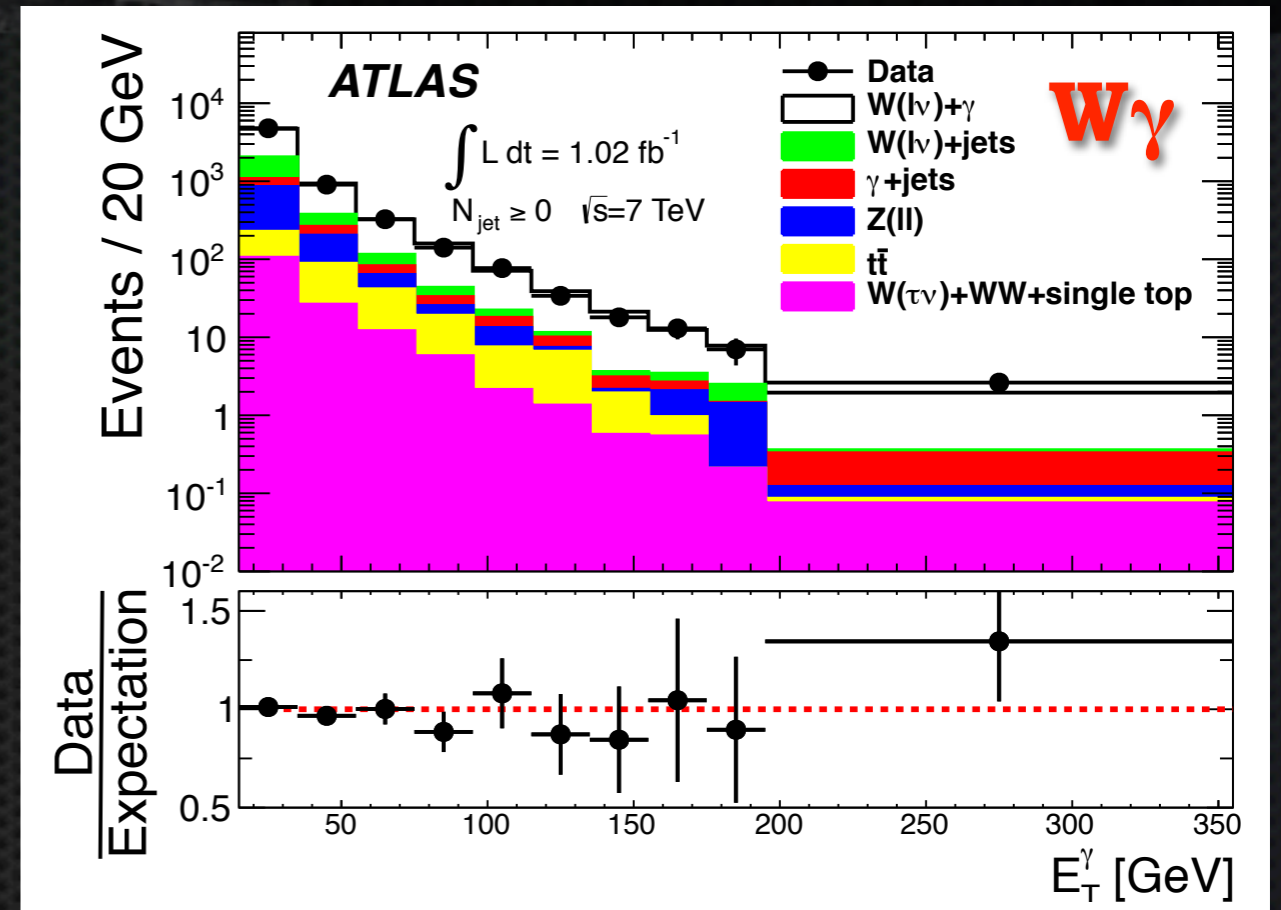
$W\gamma$: Agreement with NLO MCFM calculation is poor
Exclusive calculation ($N_{\text{jet}}=0$) looks good

Dibosons: $W\gamma/Z\gamma$

ATLAS: arXiv:1205.2531



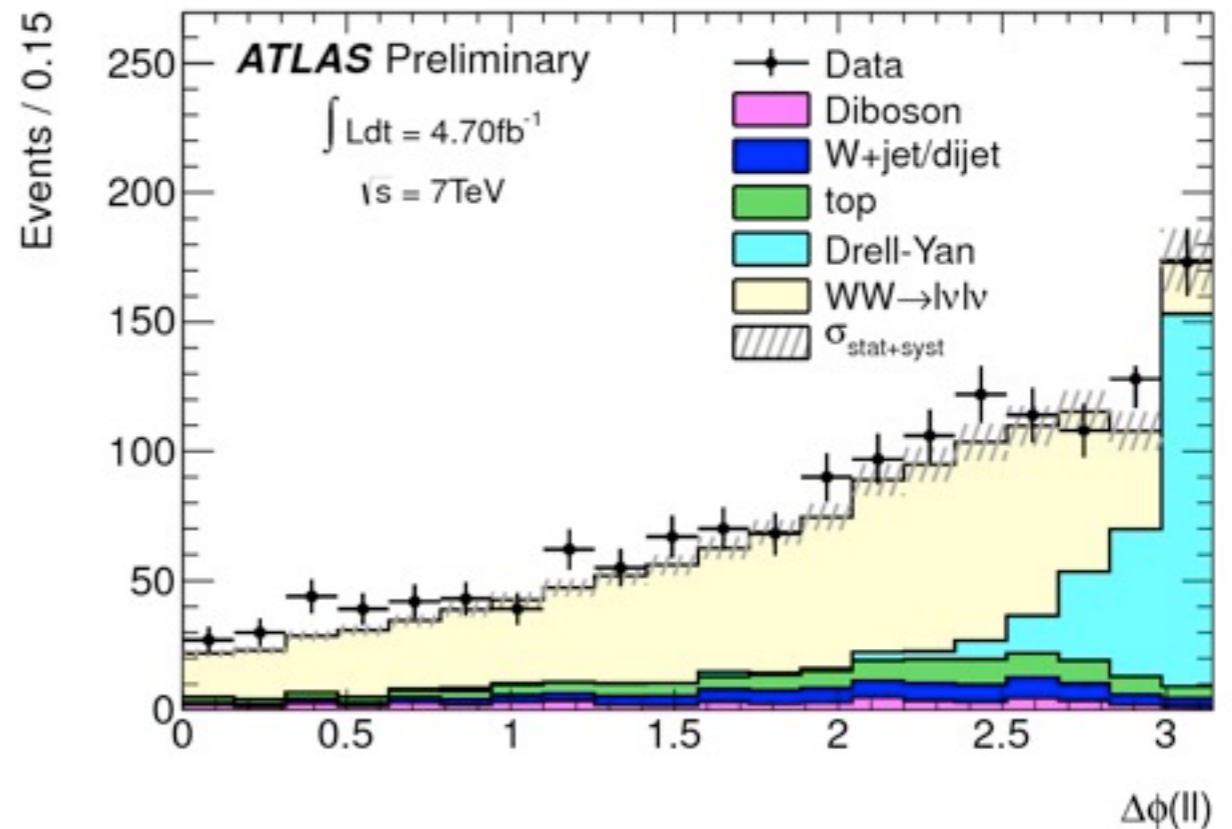
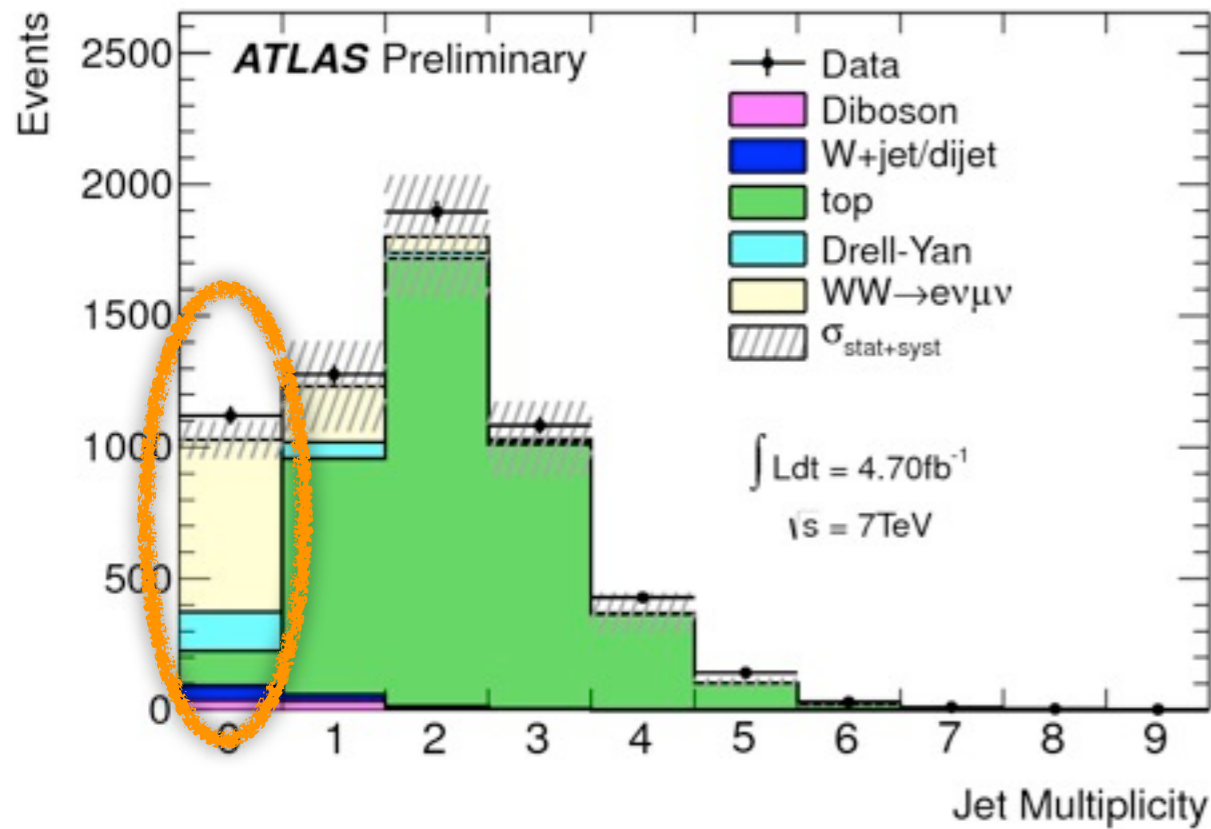
**W+jets and Z+jets simulated with
 ALPGEN + 5 partons and
 SHERPA + 3 partons**



Dibosons: WW @ 7 TeV

ATLAS-CONF-2012-025

$$\sqrt{s} = 7 \text{ TeV}$$



	N_{observed}	N_{bkg}	$\sigma_{\text{measured}} \text{ (pb)}$	$\sigma_{\text{NLO}} \text{ (pb)}$
WW	1524	531 ± 51	$53.4 \pm 2.1 \pm 4.5 \pm 2.1$	45.1 ± 2.8

Theory: MC@NLO with CT10 (similar to MCFM)

$gg \rightarrow WW$ contributes 2.9%

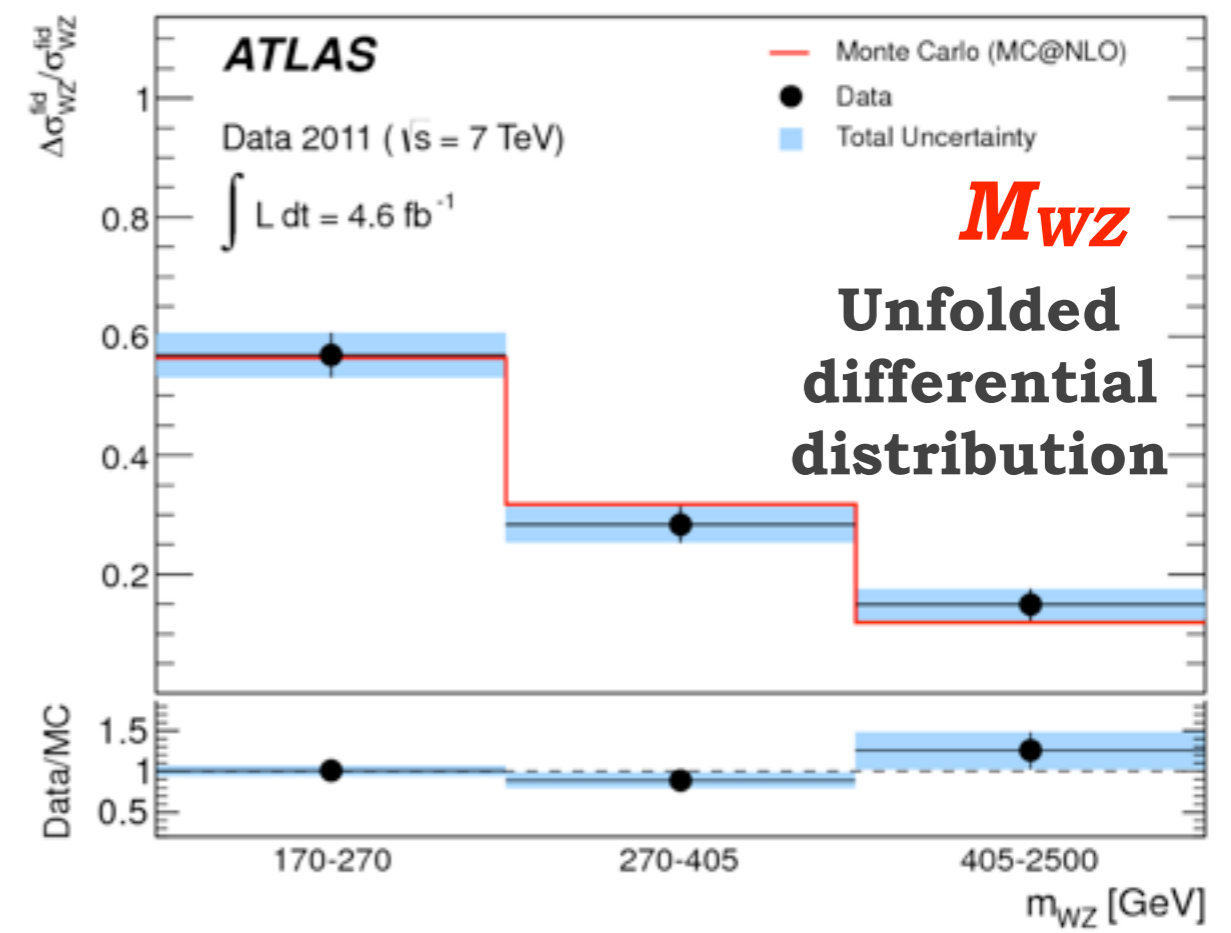
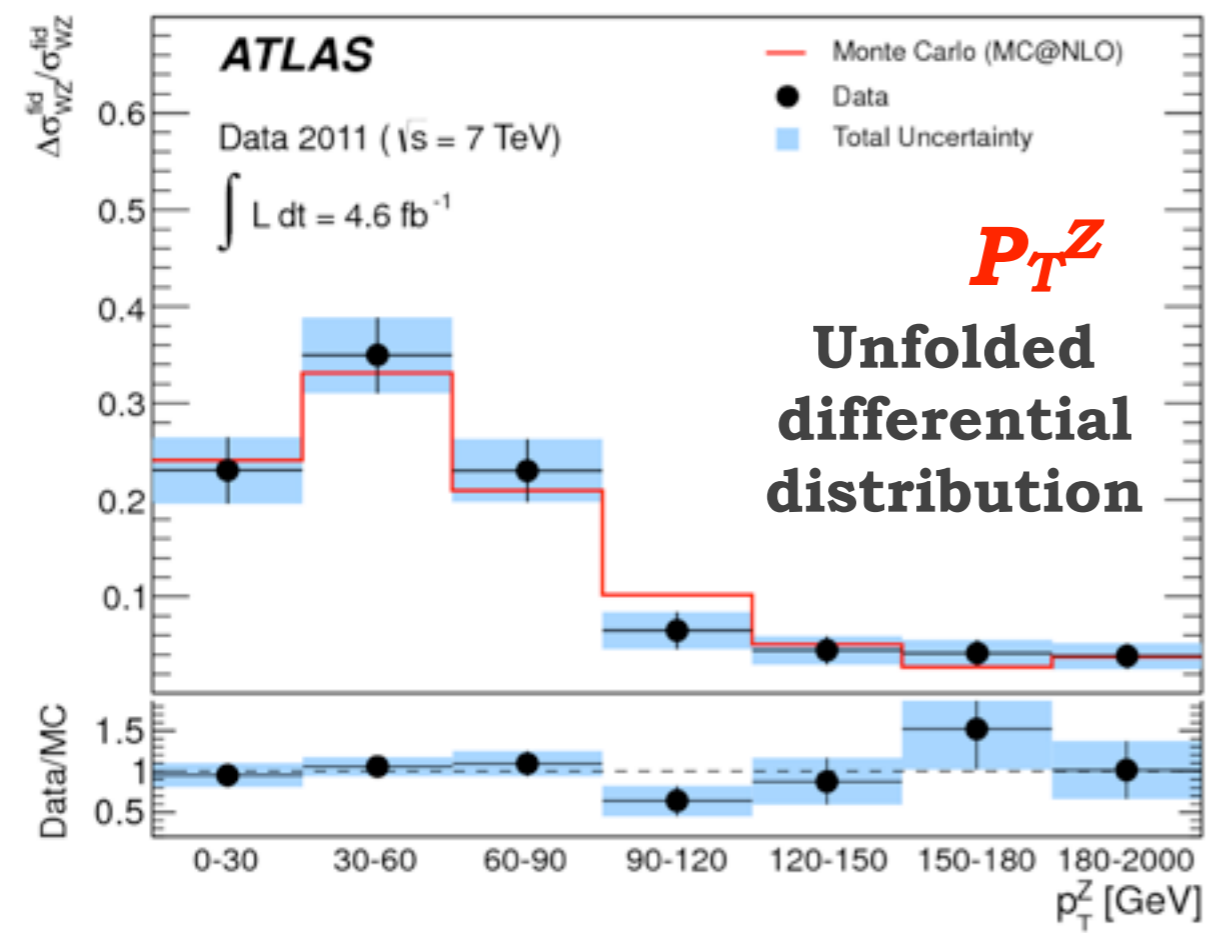
Higgs @ $m_H = 125 \text{ GeV}$ (3%), VBS and DPS (0.1%) neglected

W/Z Production in ATLAS -- QCD@LHC 2012 -- Joao Guimaraes



Dibosons: WZ @ 7 TeV

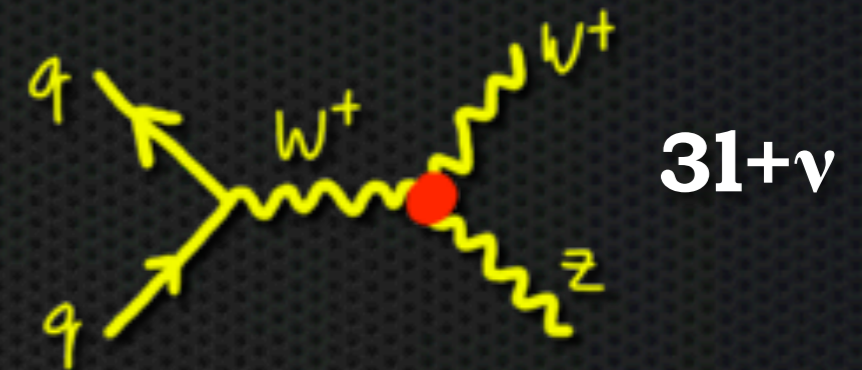
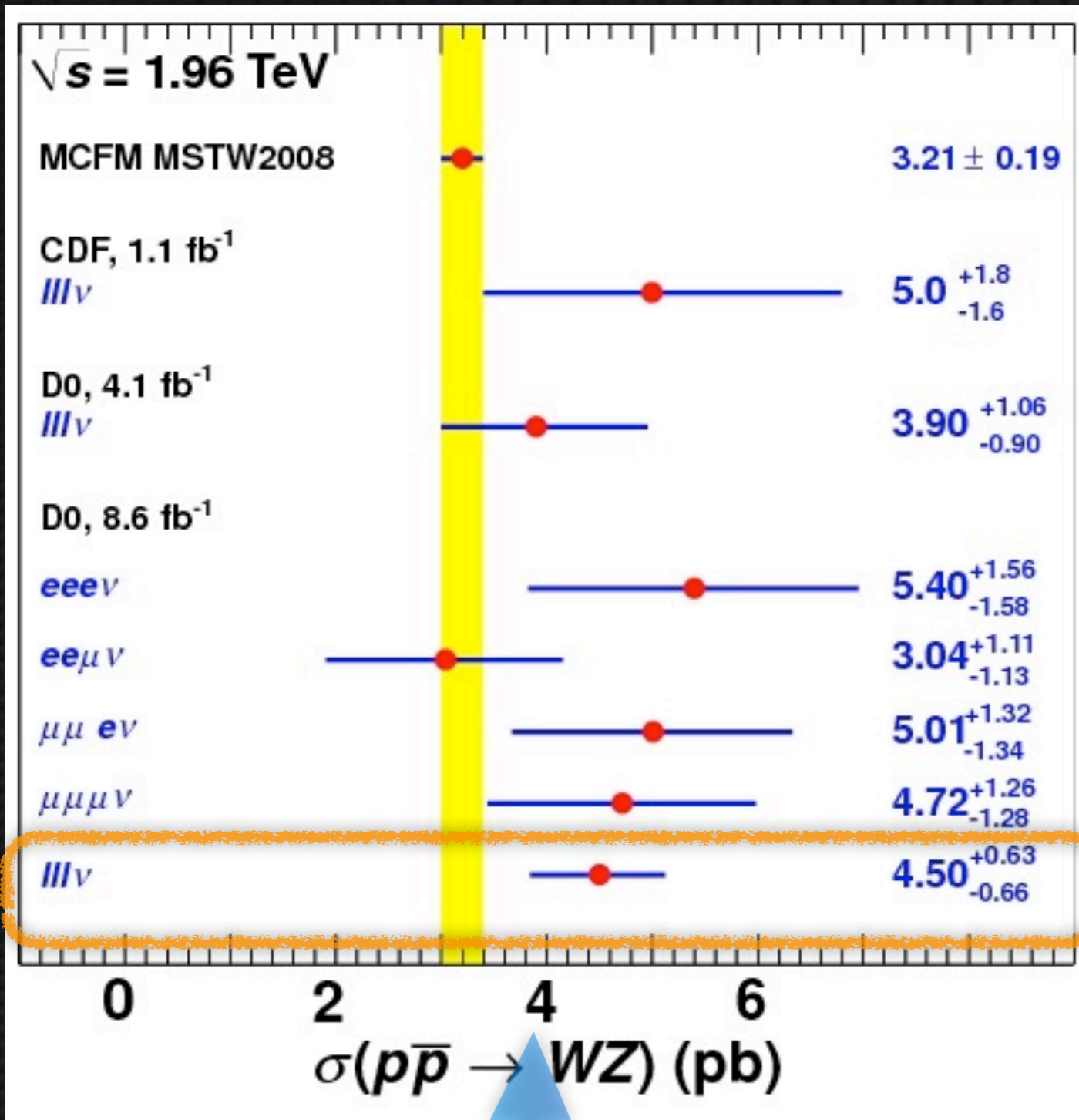
Differential cross sections:



WZ	N_{observed}	N_{bkg}	σ_{measured} (pb)	σ_{NLO} (pb)
ATLAS	317	68 ± 10	$19.0^{+1.4}_{-1.3} \pm 0.9 \pm 0.4$	$17.6^{+1.1}_{-1.0}$

Theory: MCFM + CT10 (calculation with MSTW08 agrees within ~3%)
Uncertainty: - CT10 error set
 - Factorization and renormalization scale

Dibosons: WZ at Tevatron



Phys. Rev. D 85, 112005 (2012)

CDF, 7.1 fb⁻¹: $\sigma_{WZ} = 3.93^{+0.60}_{-0.53} \text{ pb}$

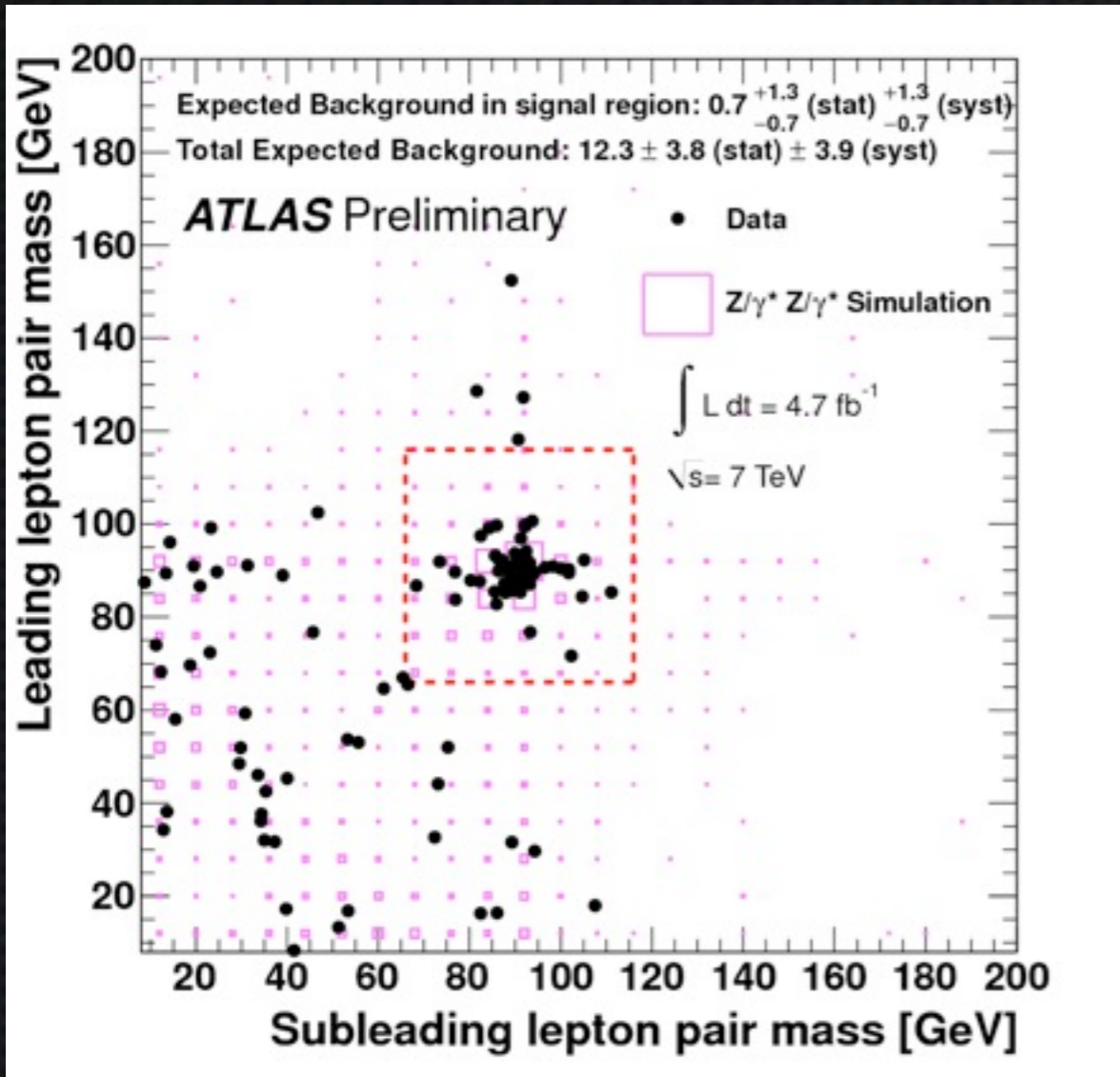
arXiv:1202.6629

Dibosons: ZZ @ 7 TeV

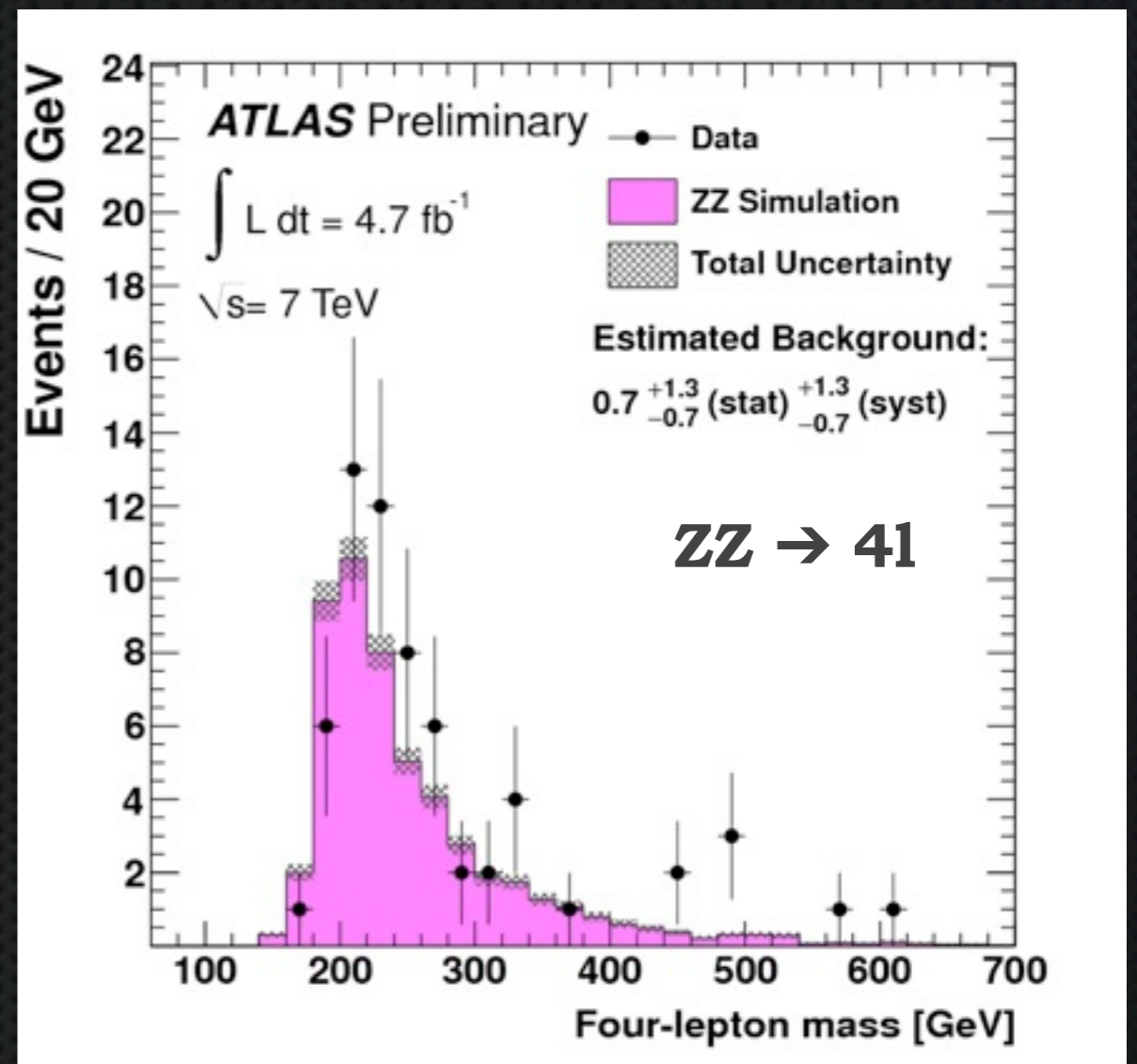
ATLAS-CONF-2012-027

ZZ → 4 leptons (eeee, μμμμ, eeμμ)

66 < M_{Z1} < 116 GeV



66 < M_{Z2} < 116 GeV

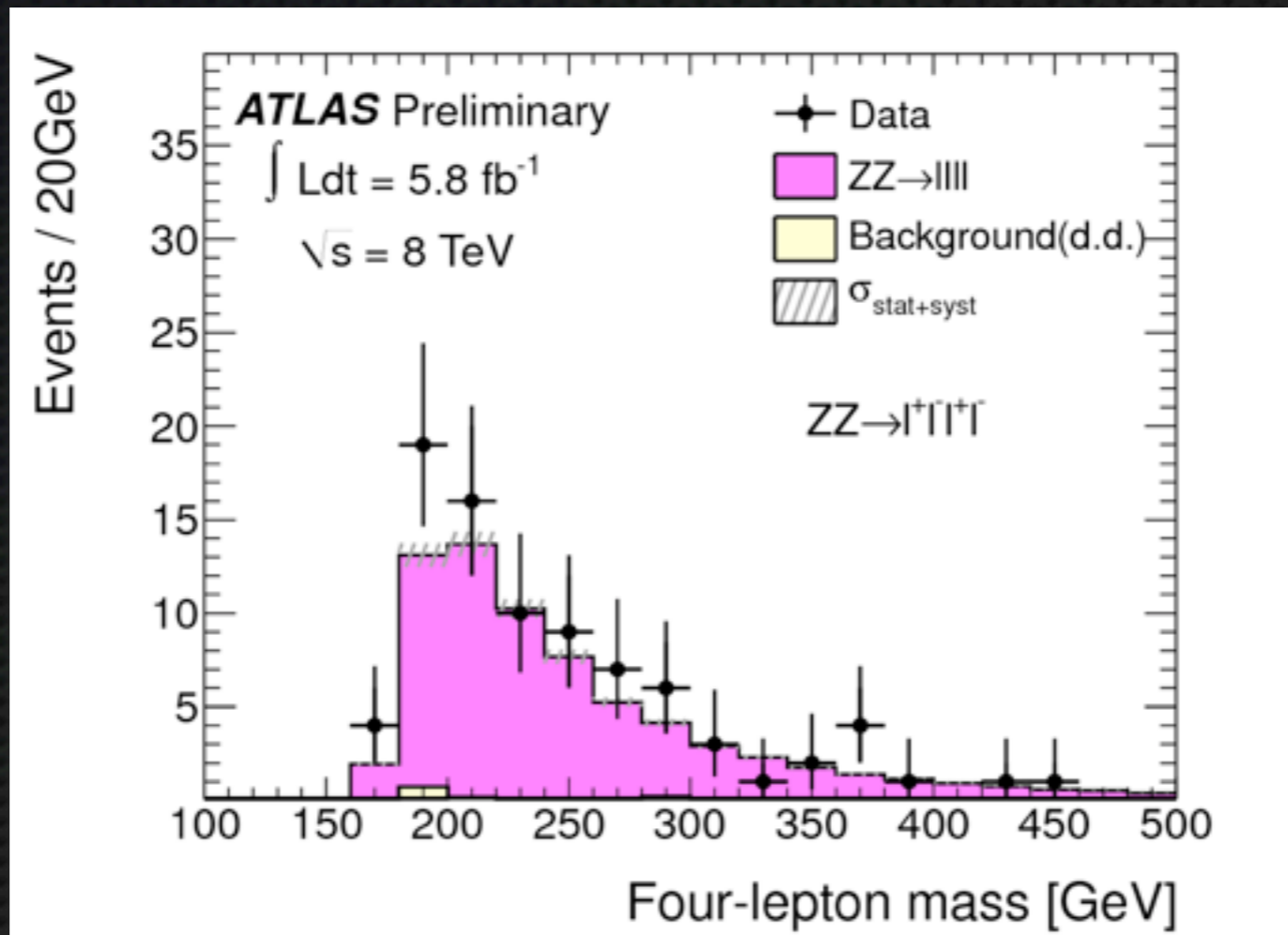


Theory: MCFM+MSTW08

ZZ	N _{obs(4l)}	N _{signal(4l)}	N _{bkg(4l)}	σ _{measured} (pb)	σ _{NLO} (pb)
ATLAS	62	53.2 ± 2.2	0.7 ± 2.1	7.2 ^{+1.1} _{-0.9} ^{+0.4} _{-0.3} ± 0.3	6.5 ^{+0.3} _{-0.2}

Dibosons: ZZ @ 8 TeV

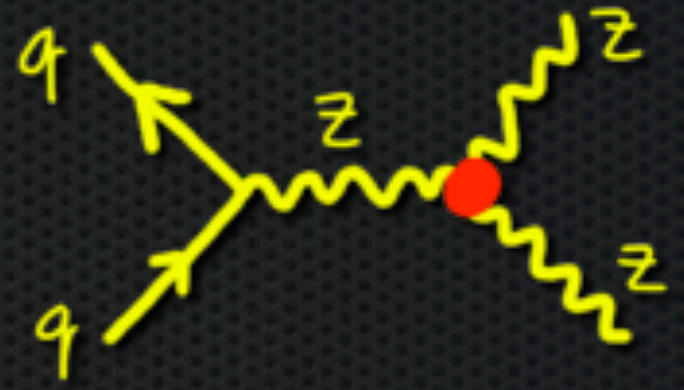
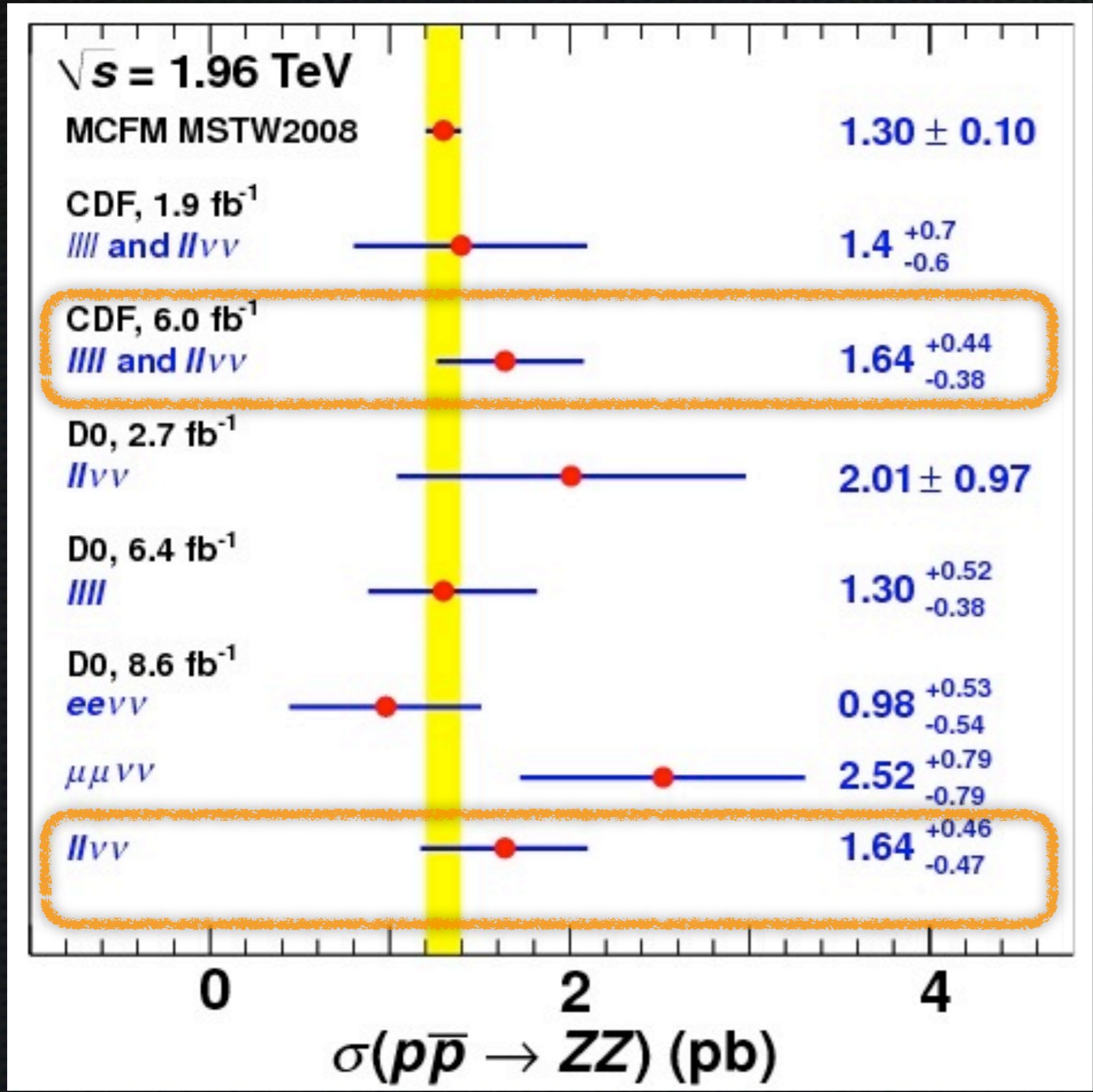
$ZZ \rightarrow 4$ leptons ($eeee, \mu\mu\mu\mu, ee\mu\mu$)



Theory: MCFM + CT10
(NLO $qq \rightarrow ZZ$ and LO $gg \rightarrow ZZ$)

ZZ	$N_{\text{obs}(4l)}$	$N_{\text{signal}(4l)}$	$N_{\text{bkg}(4l)}$	$\sigma_{\text{measured}} \text{ (pb)}$	$\sigma_{\text{NLO}} \text{ (pb)}$
ATLAS	85	70.5 ± 1.7	1.5 ± 1.3	$9.3^{+1.1}_{-1.0} {}^{+0.4}_{-0.3} \pm 0.3$	7.4 ± 0.4

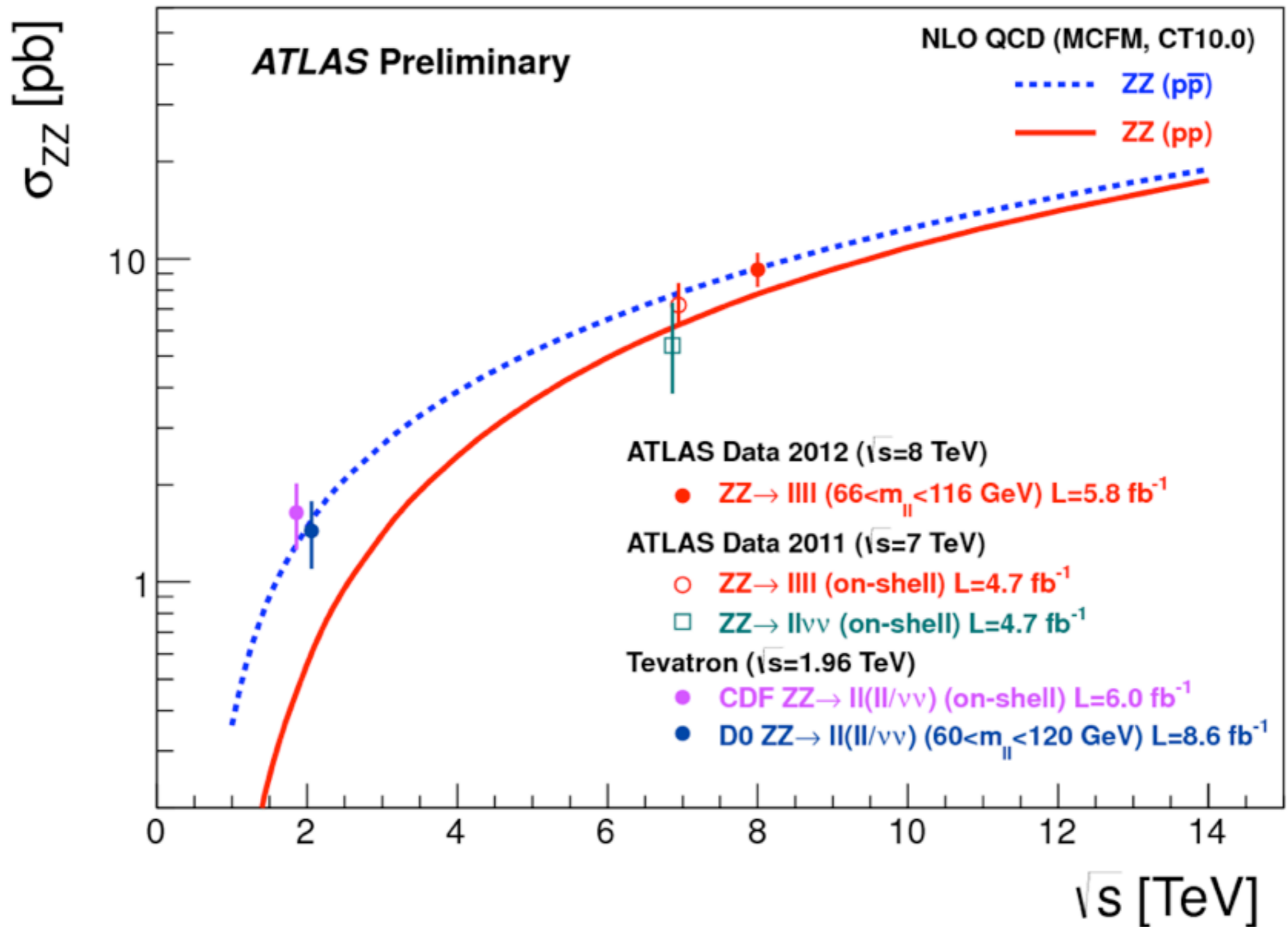
Dibosons: ZZ @ Tevatron



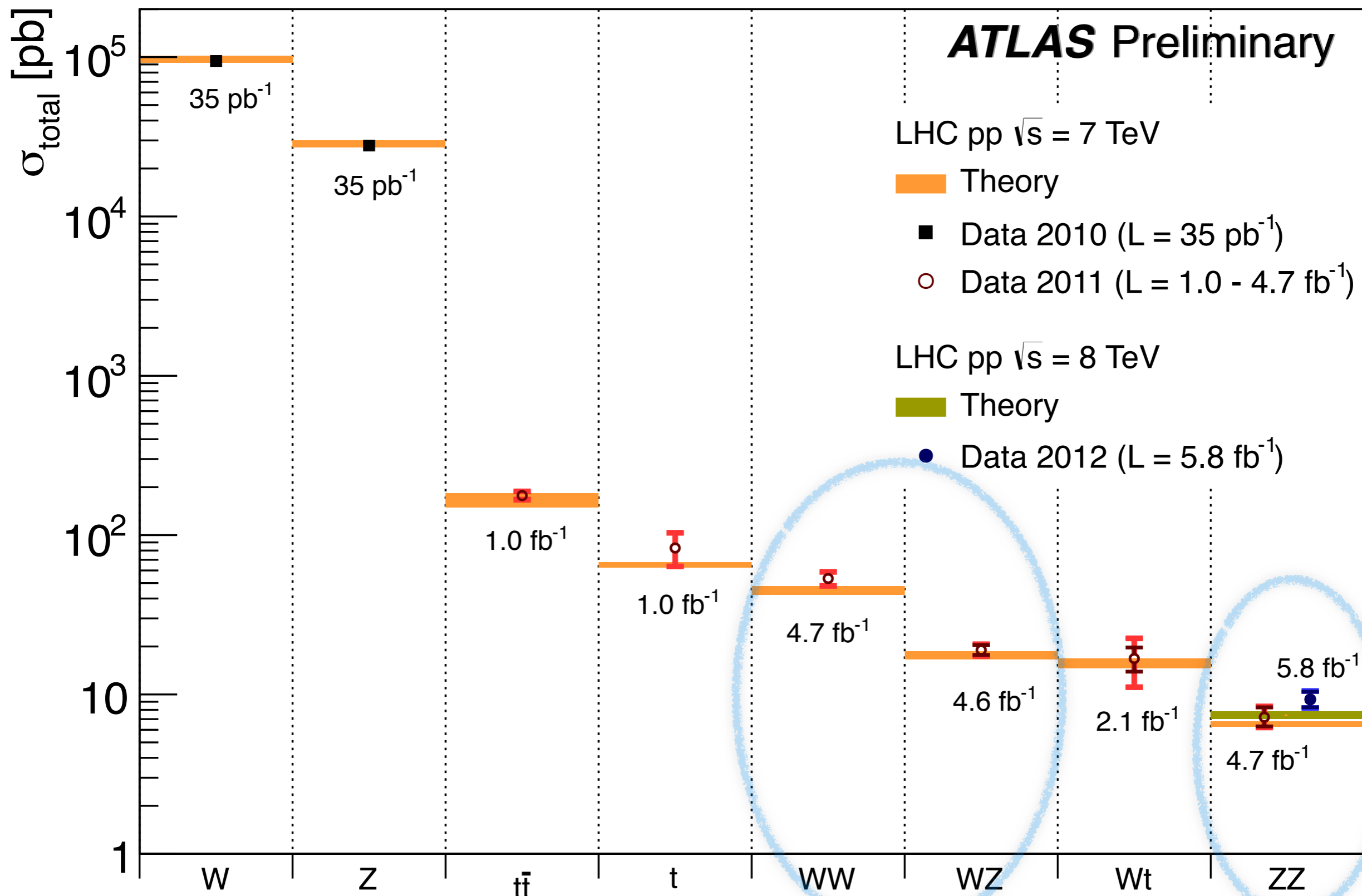
PRL 108, 101801 (2012)

Phys. Rev. D 85, 112005 (2012)

Dibosons: ZZ Overview



W/Z Production in ATLAS



- **ATLAS program well underway towards precision physics with W and Z bosons**
 - 1-2% uncertainties have been achieved
 - Stable ground for new physics searches
- **Agreement with theory across orders of magnitude is impressive**
 - Higher order calculations for dibosons needed
 - Next range of measurements will challenge theoretical predictions
- **Anything else we should be measuring?**
 - DY differential cross sections to come soon

For W+jets see talk tomorrow by Mishra

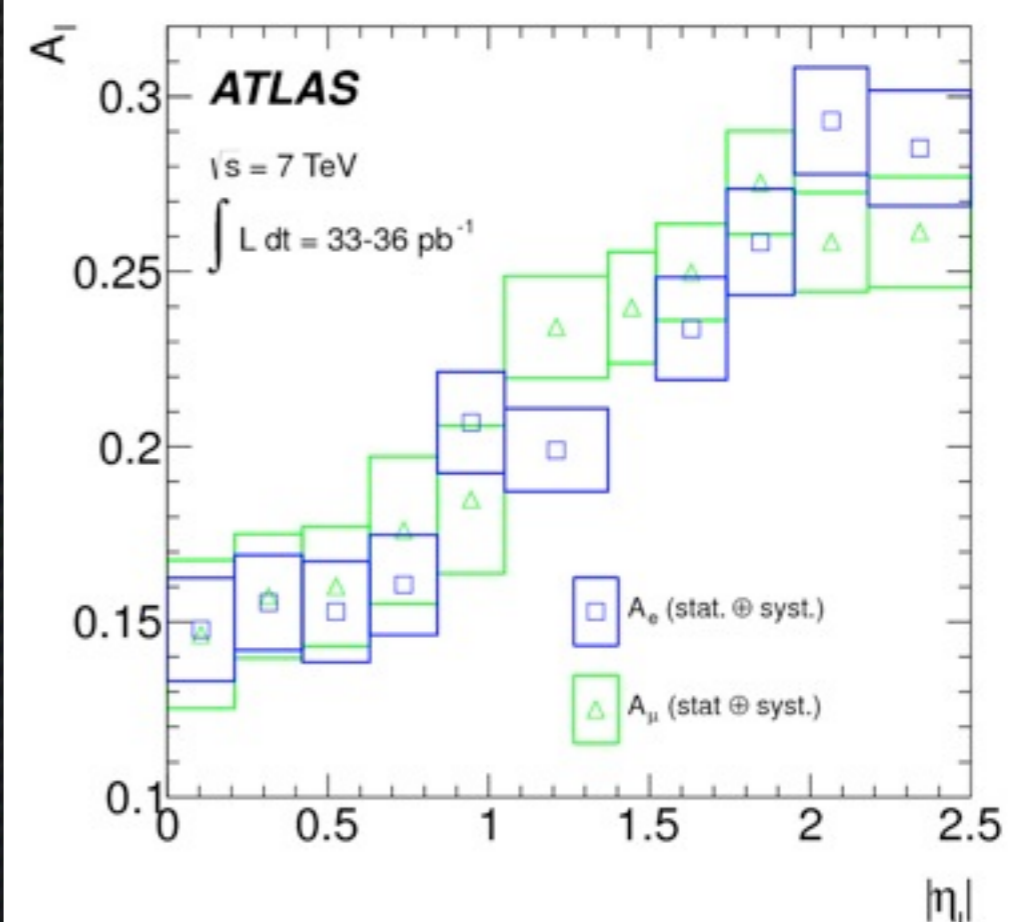
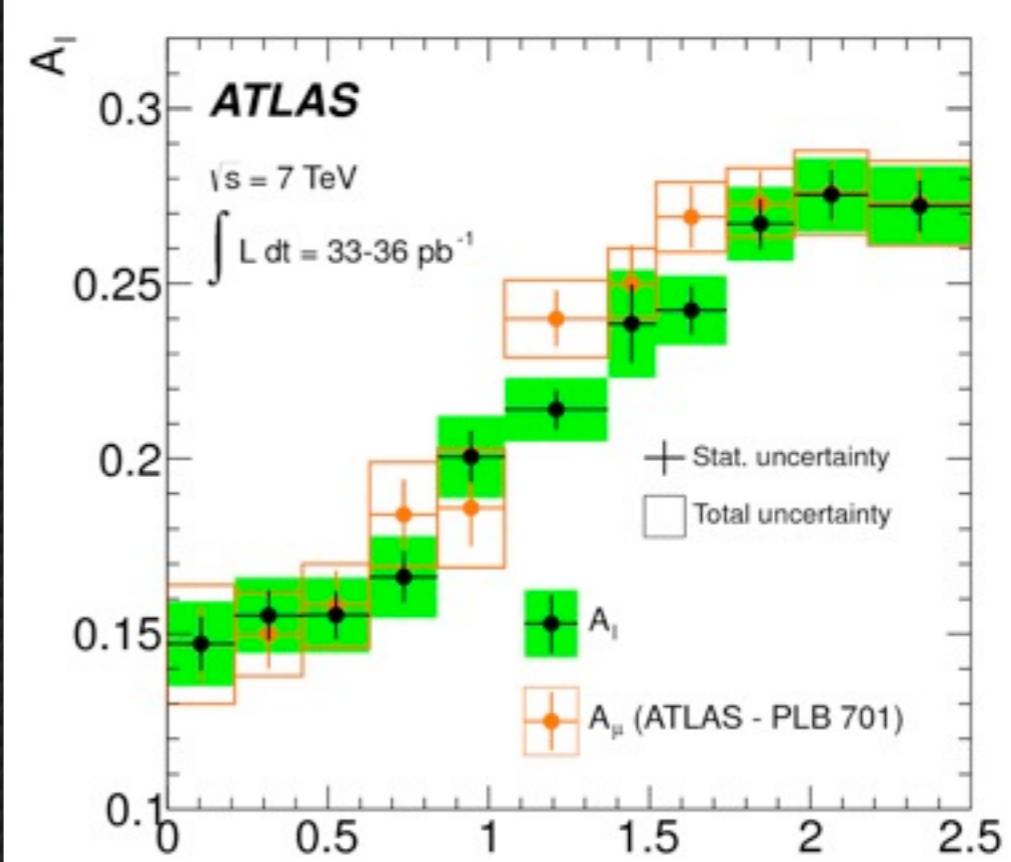


Extra Slides

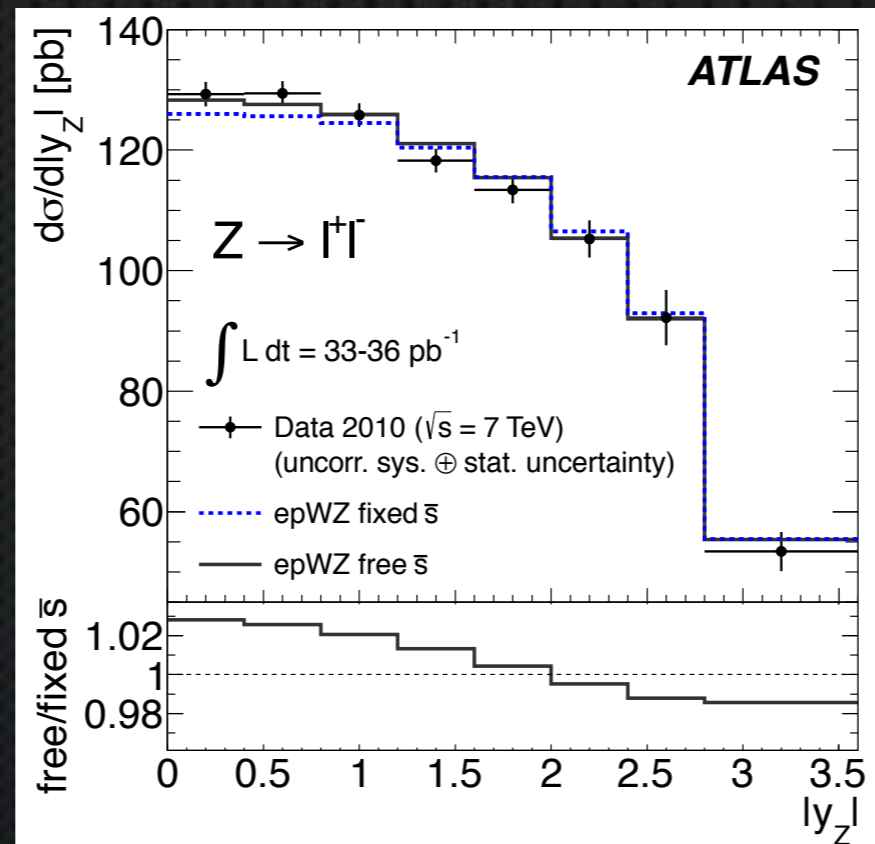
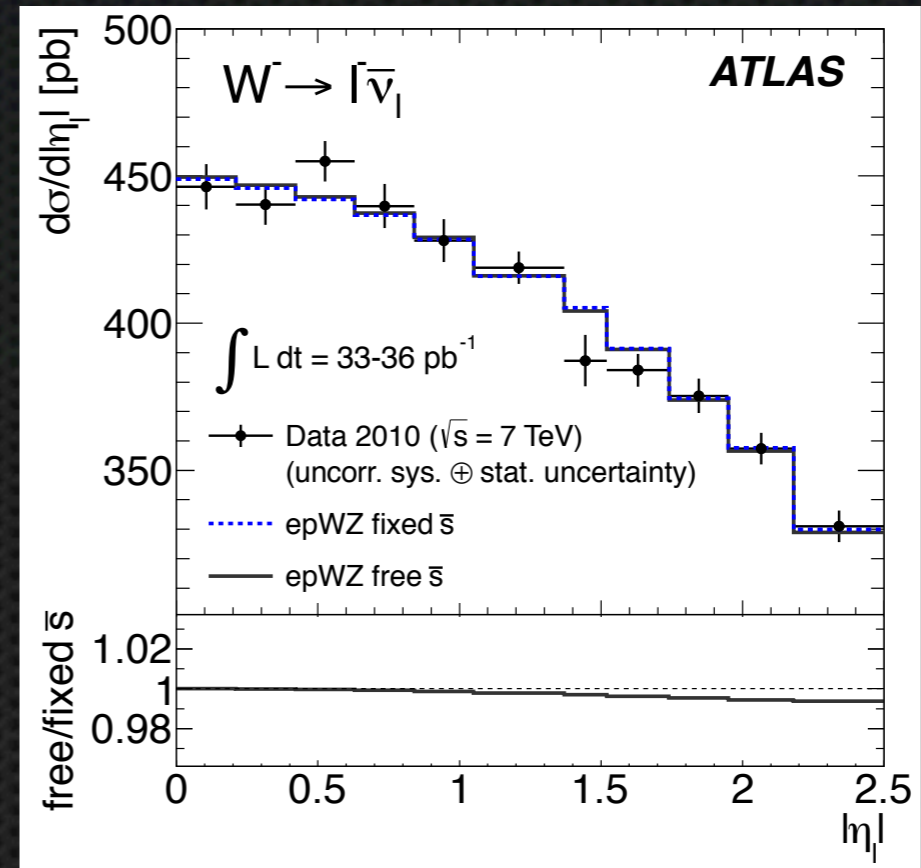
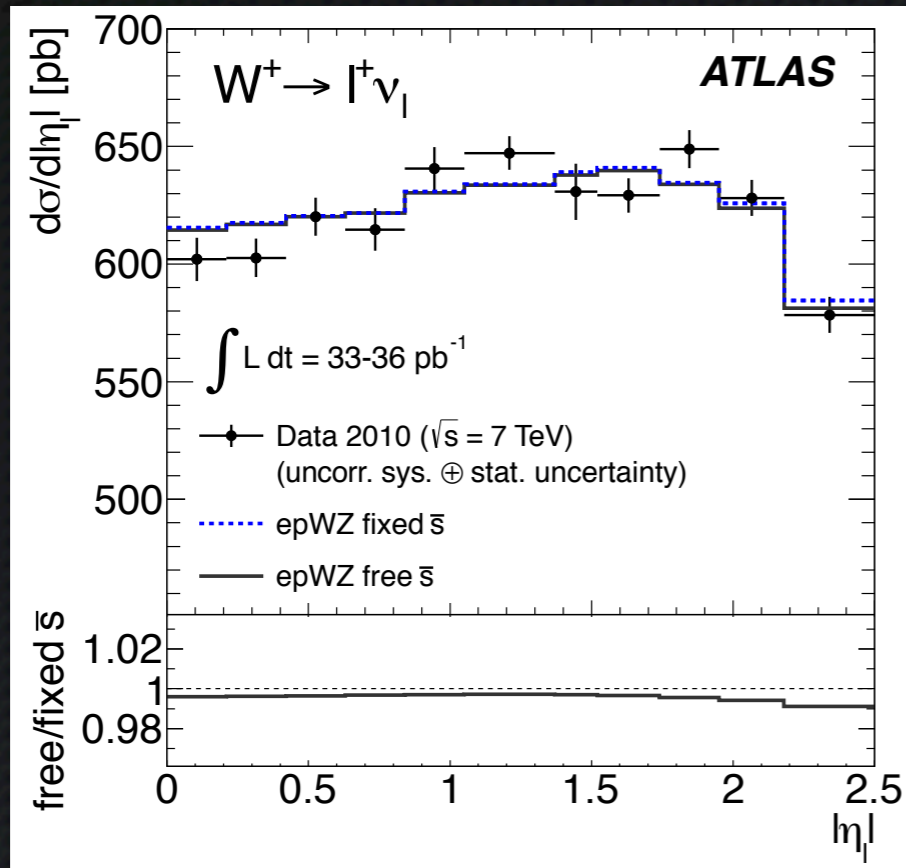
W charge asymmetry: Comparison with first publication

Change in systematic uncertainties and correction factors

- efficiency scale-factor
- MET
- momentum scale corrections
- boson p_T reweighting
- theoretical CW

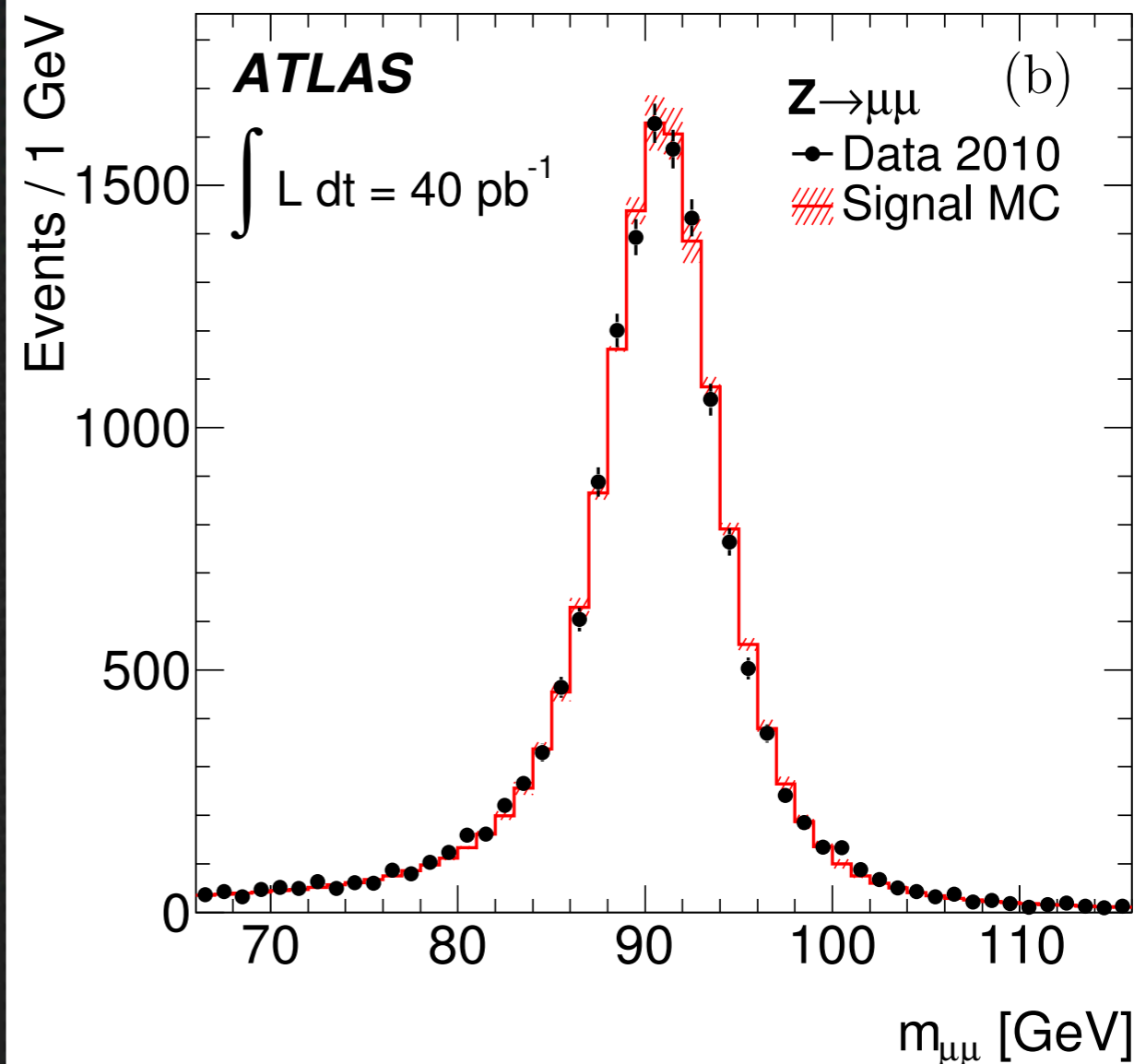
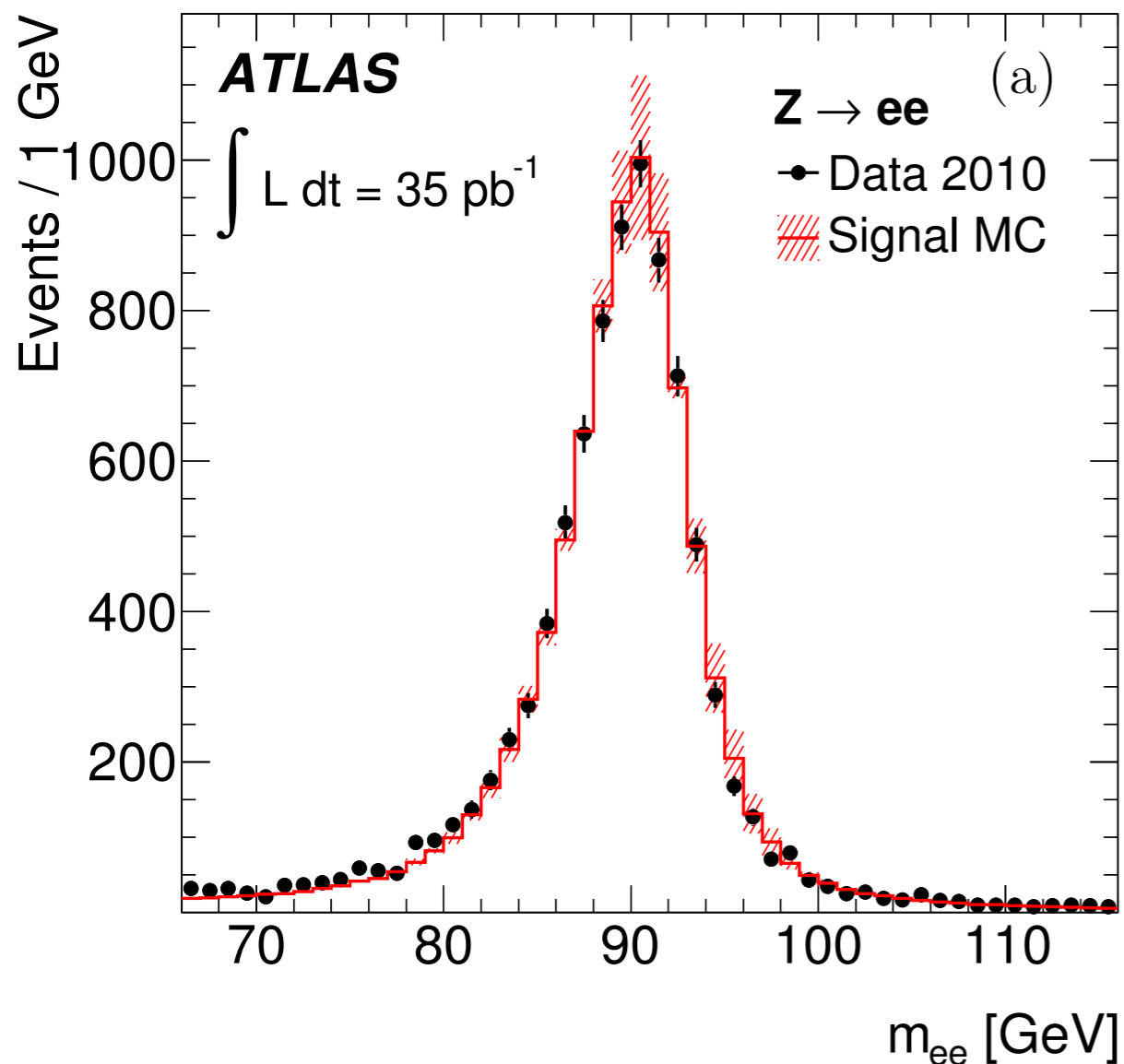


Strangeness fits



Transverse momentum distribution of Z/γ^* bosons

Phys.Lett. B705 (2011) 415-434



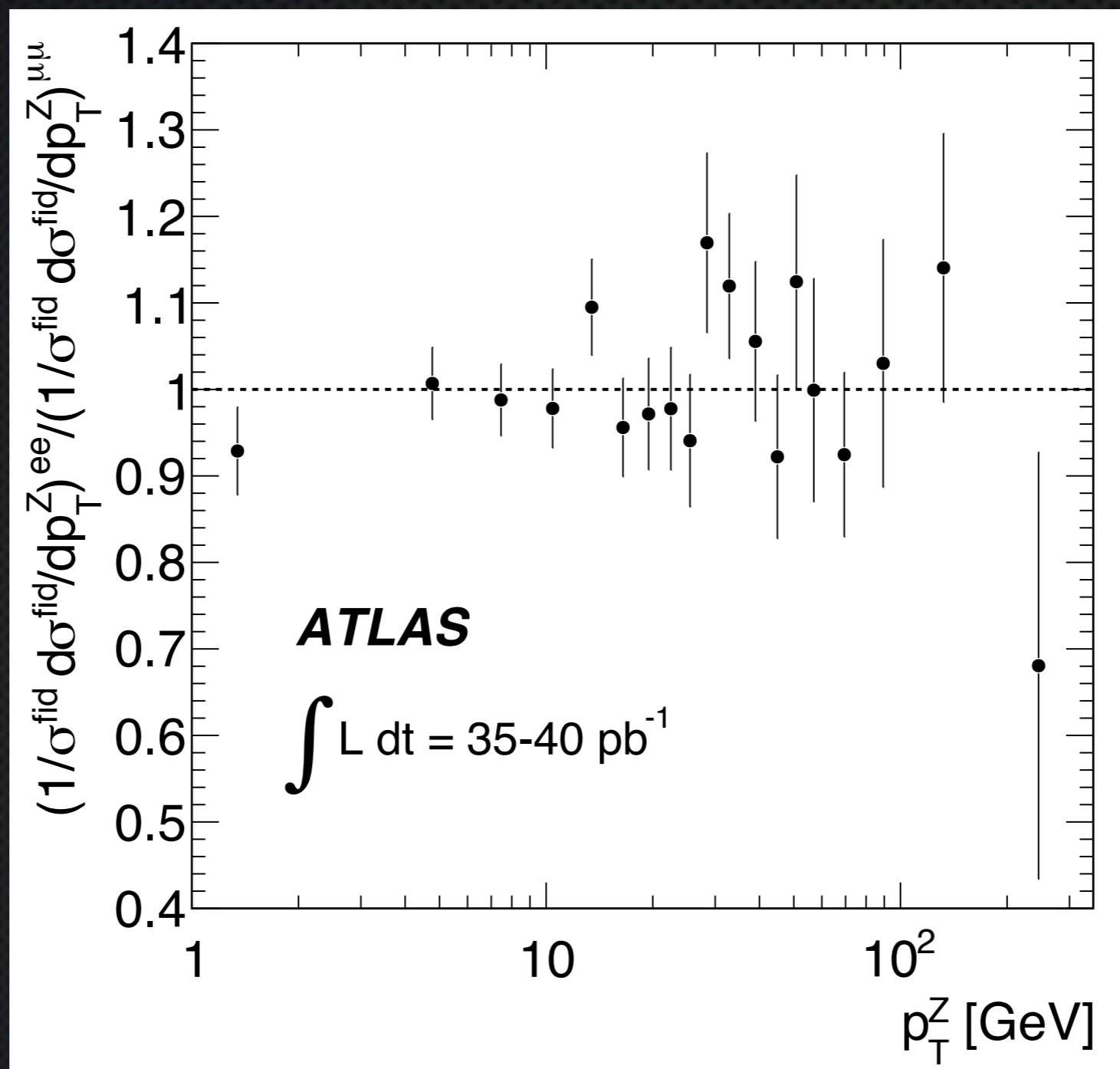
Background: 1.5%

Background: 0.4%

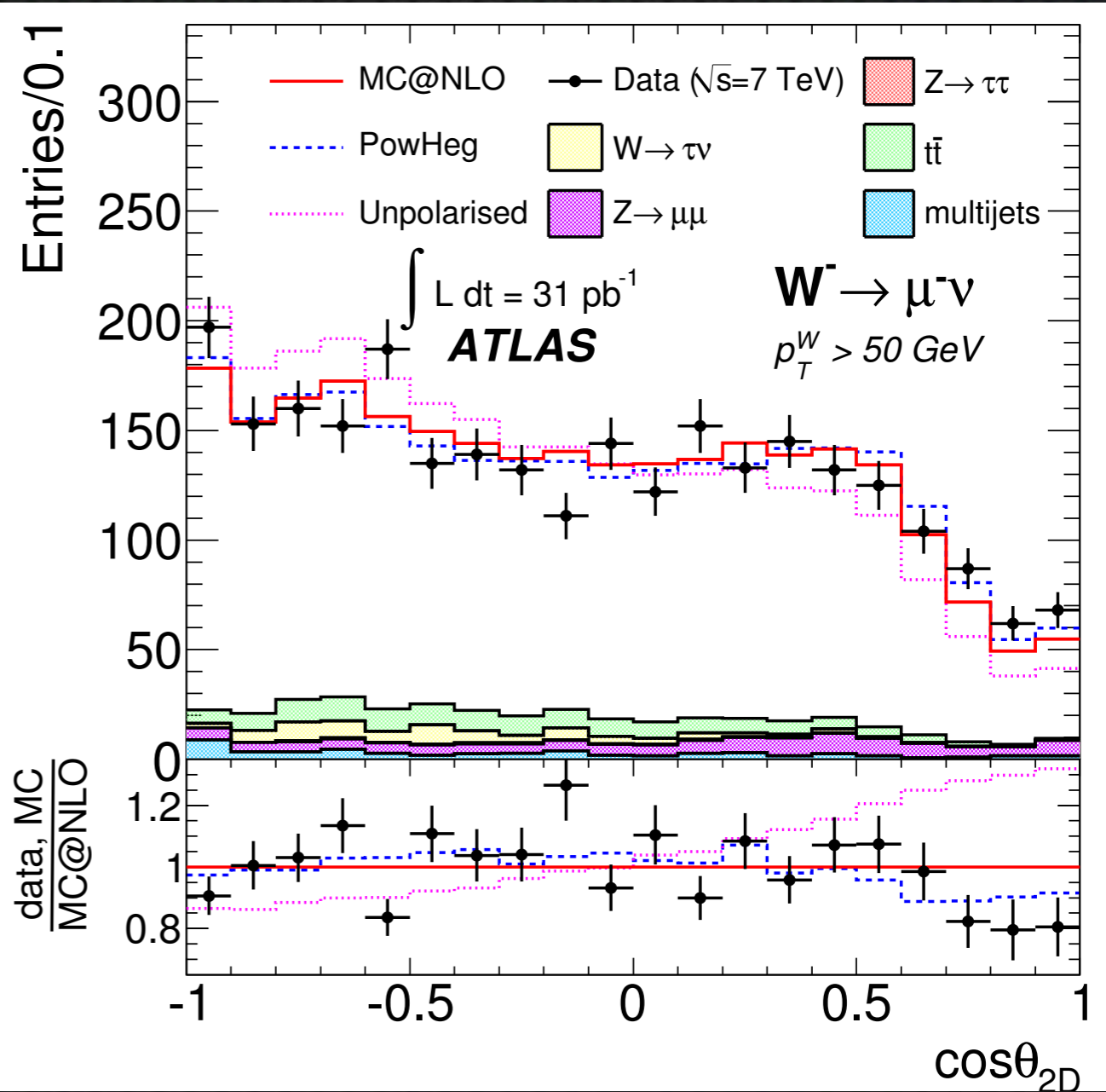
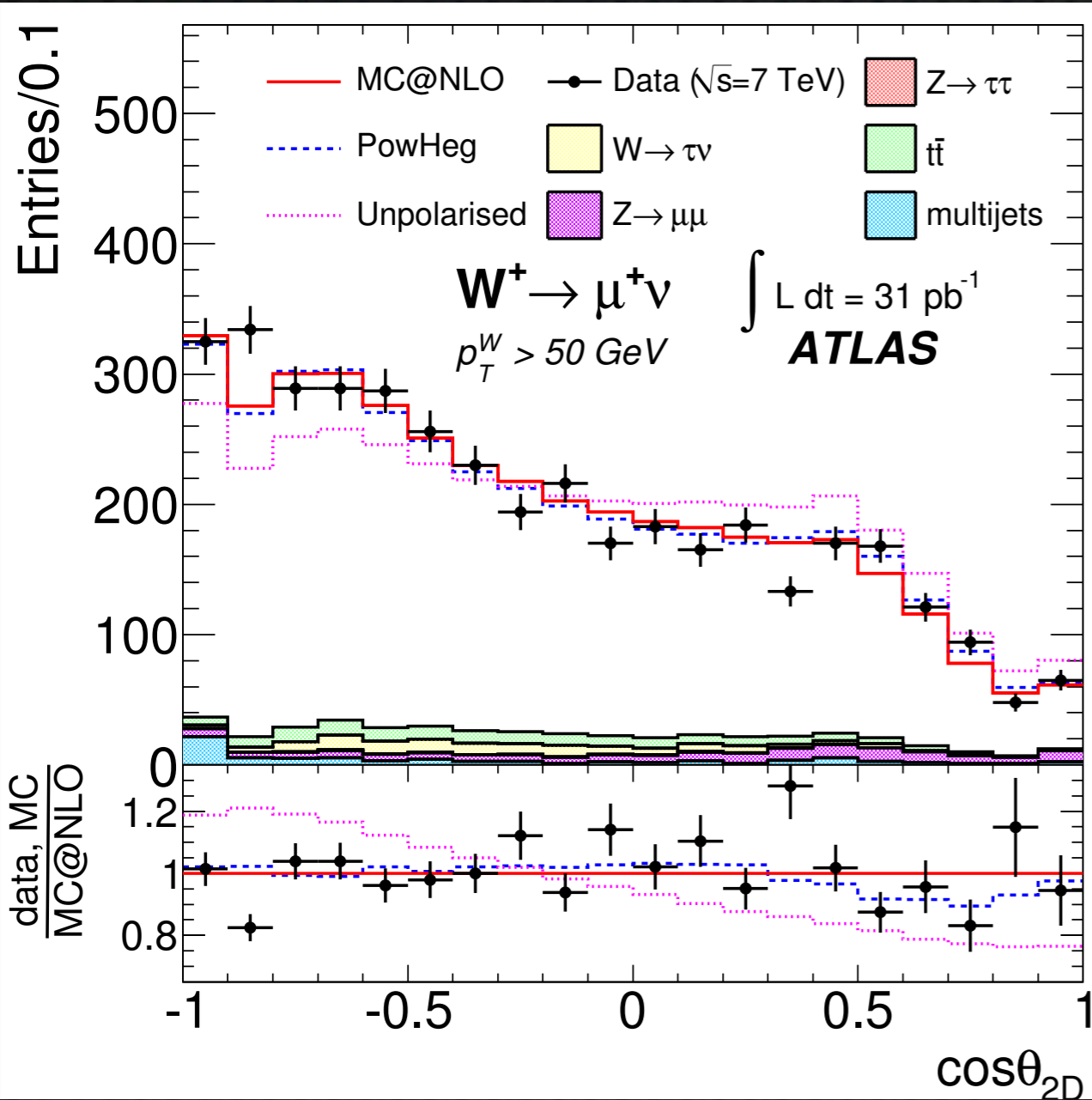
Signal MC: Pythia 6.1 normalized to NNLO (FEWZ)

Transverse momentum distribution of Z/γ^* bosons

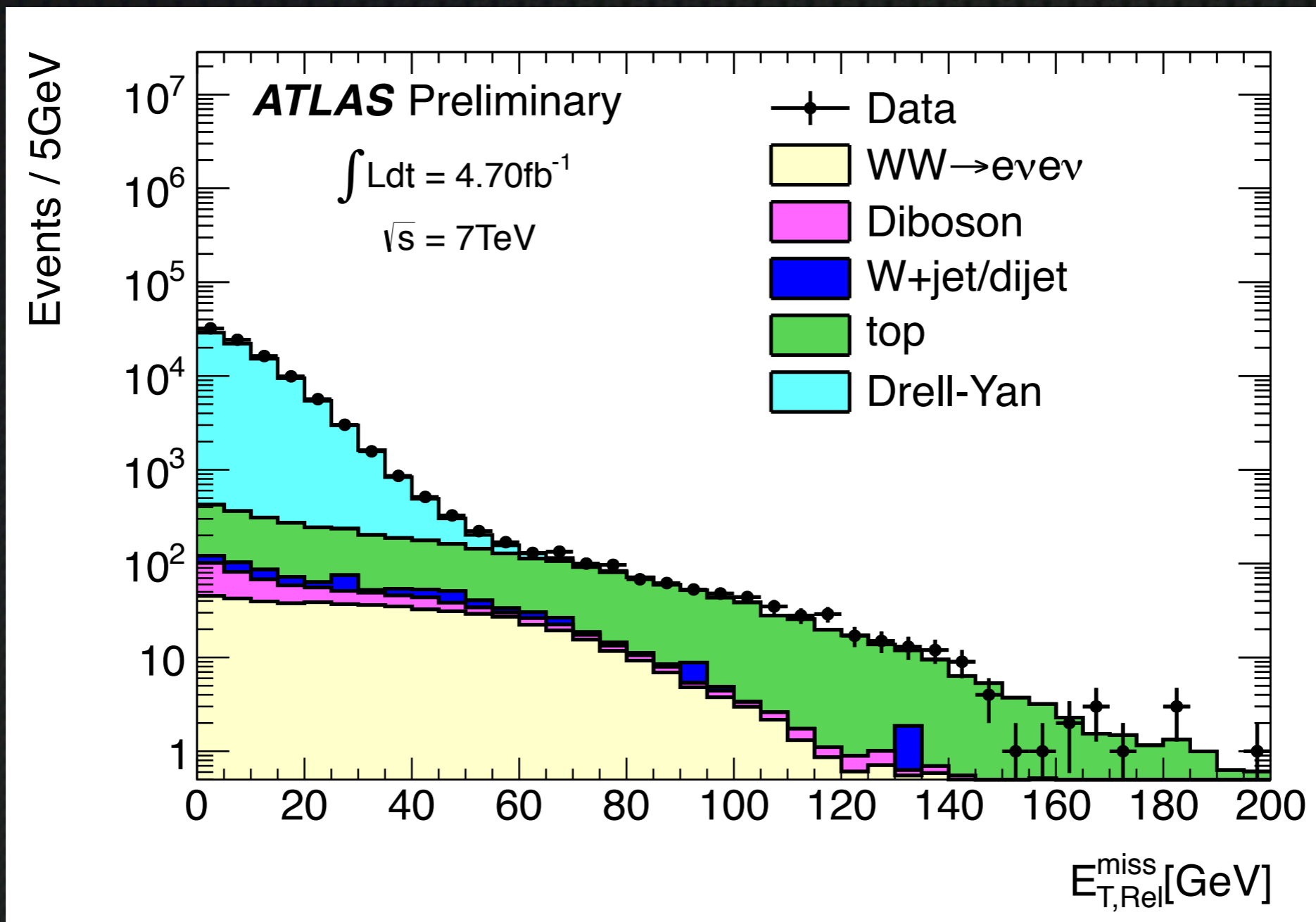
Comparison of electron- and muon- channel result

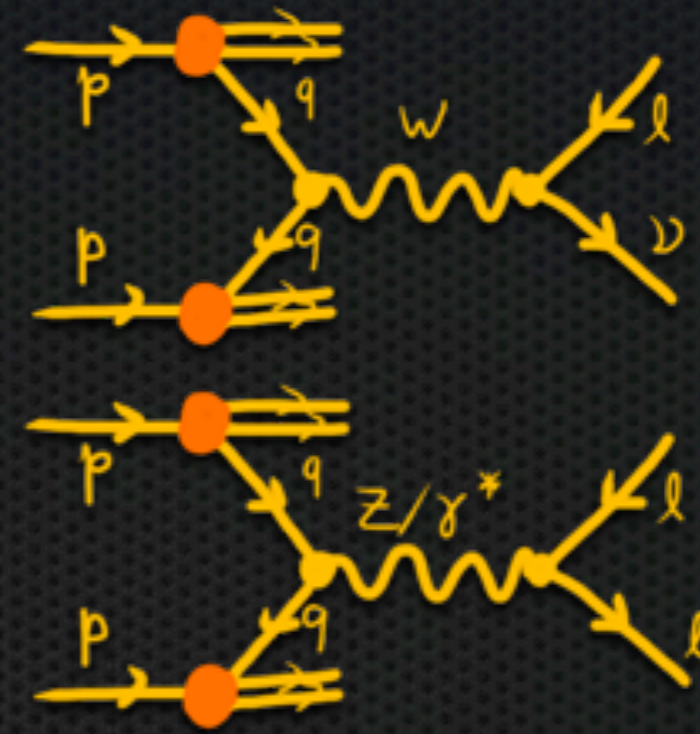
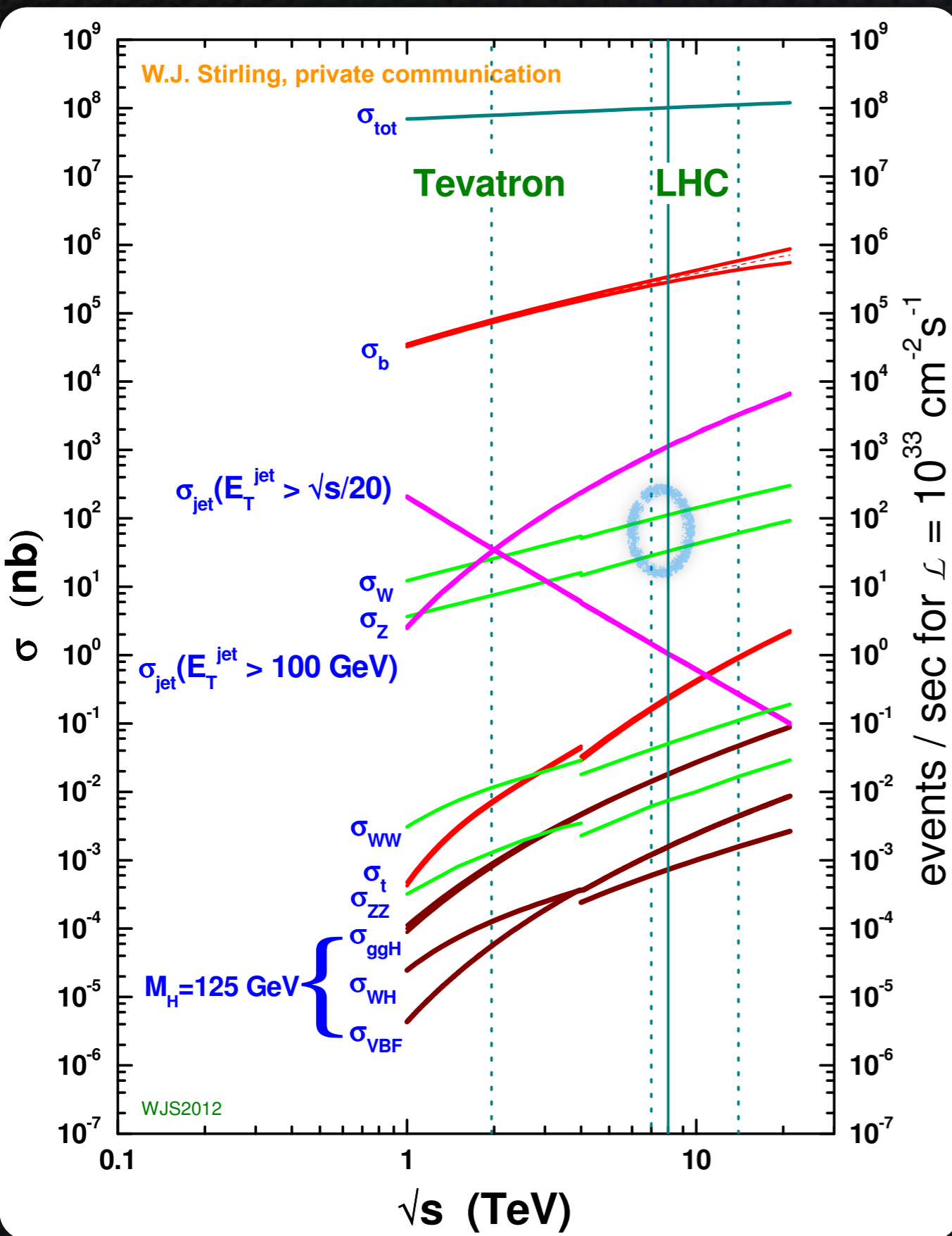


W Boson Polarization



Dibosons: WW-- Missing energy distribution





W and Z Production

- ✦ Performance measurements
- ✦ SM tests at TeV scale
- ✦ Proton PDFs
- ✦ Backgrounds for searches

Current Luminosity at 8 TeV

