LHC Measurements Sensitive to the Proton Structure

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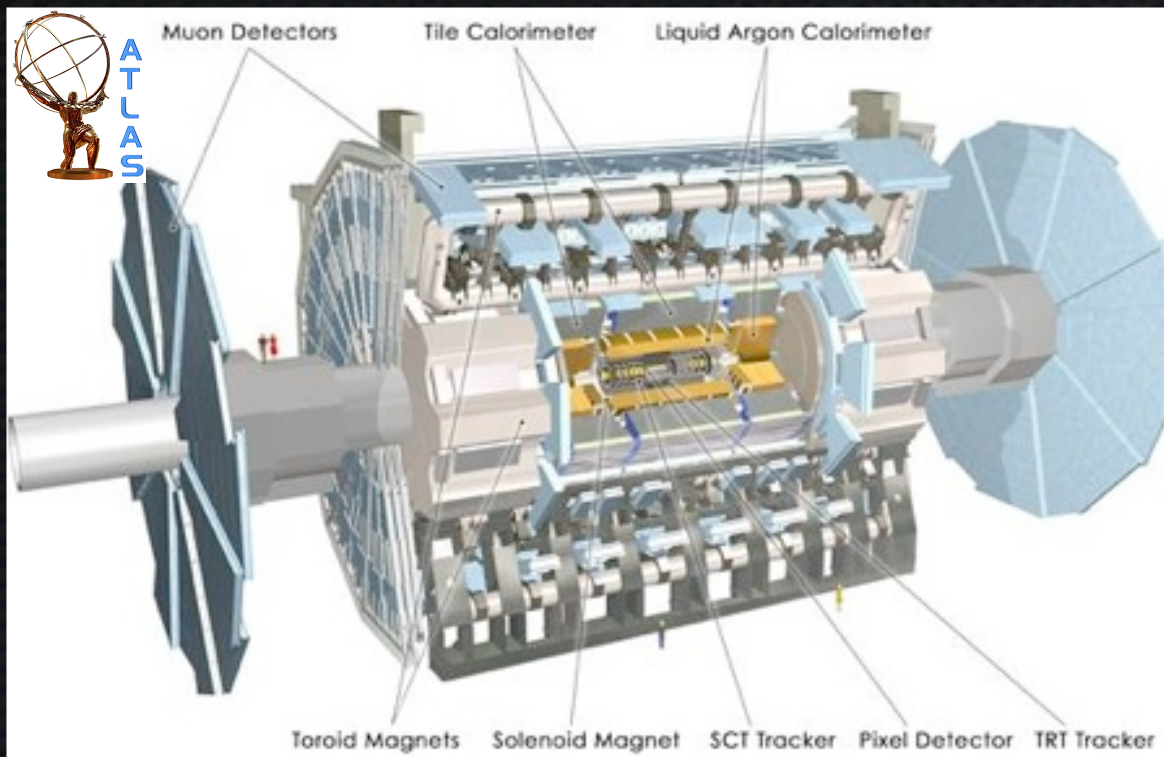
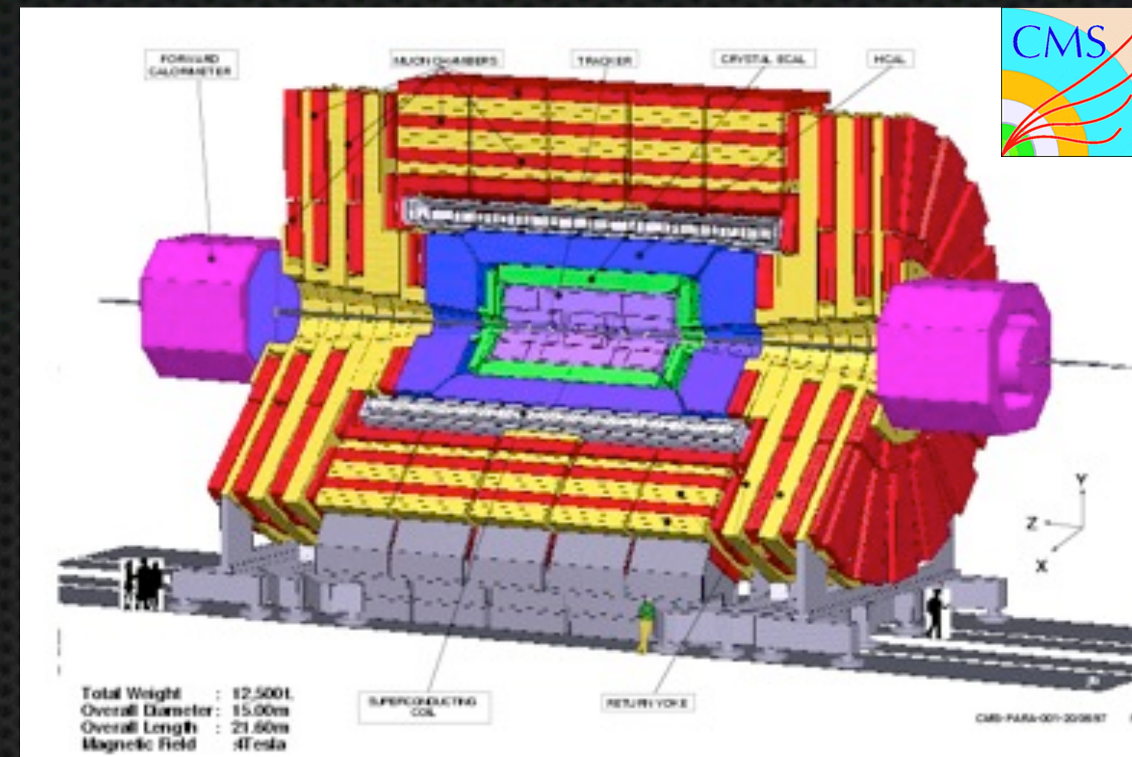
Results included from:
ATLAS, CMS, LHCb

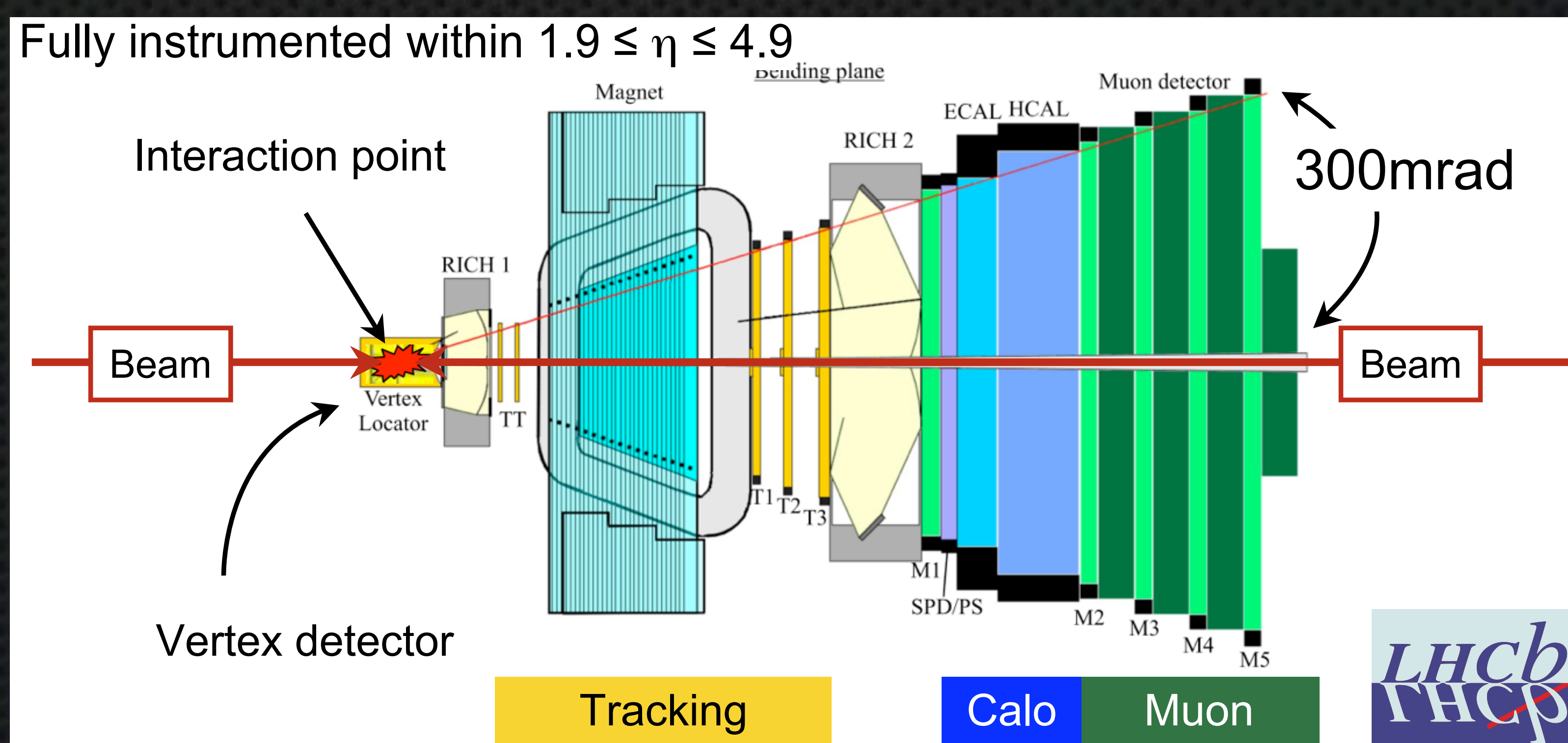
Proton Structure in the LHC Era, DESY

October 24, 2012

The Experiments







Outline

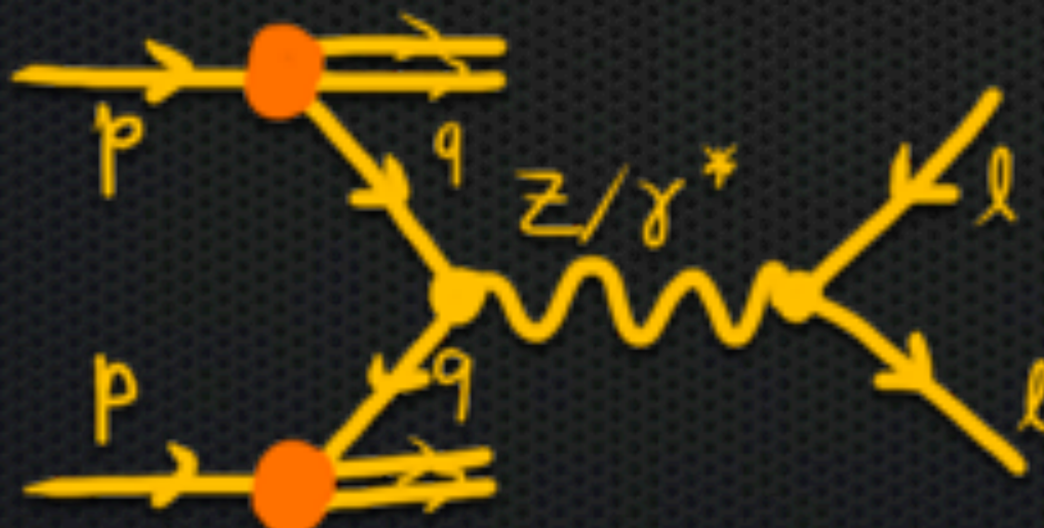
- W and Z production at LHC
  - Inclusive and differential cross sections
- W+HF
- Drell-Yan production
- Inclusive jet production
- Dijet production

W/Z inclusive production in e/μ channel

$pp \rightarrow W + X$

$\quad \hookrightarrow e\,\nu$

$\quad \hookrightarrow \mu\,\nu$



$pp \rightarrow Z + X$

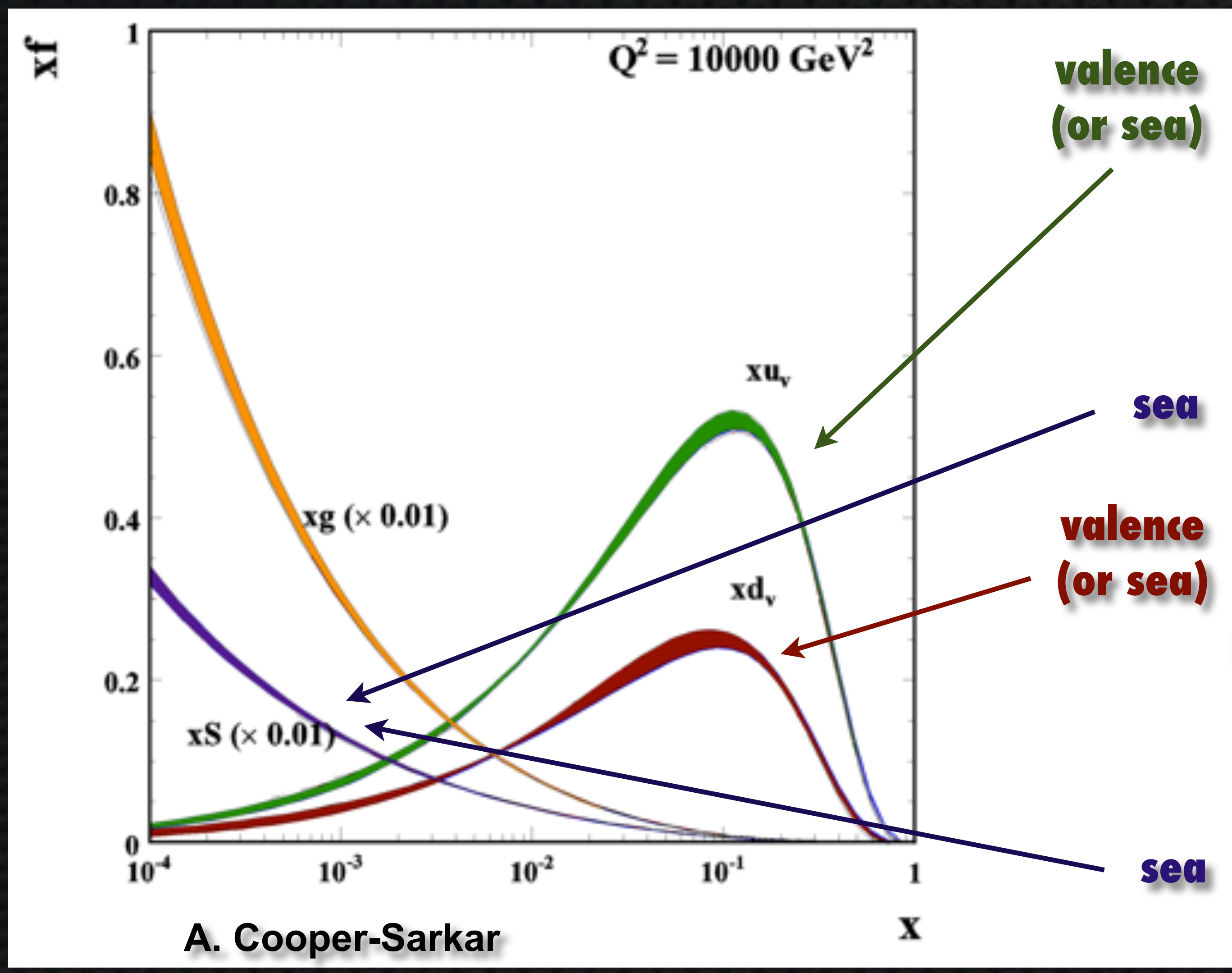
$\quad \hookrightarrow ee$

$\quad \hookrightarrow \mu\,\mu$

Hadronic W Production

$$\sigma_W = \Sigma_q \int dx_1 dx_2 f_q(x_1) f_{\bar{q}}(x_2) \times \hat{\sigma}_{q\bar{q}}$$

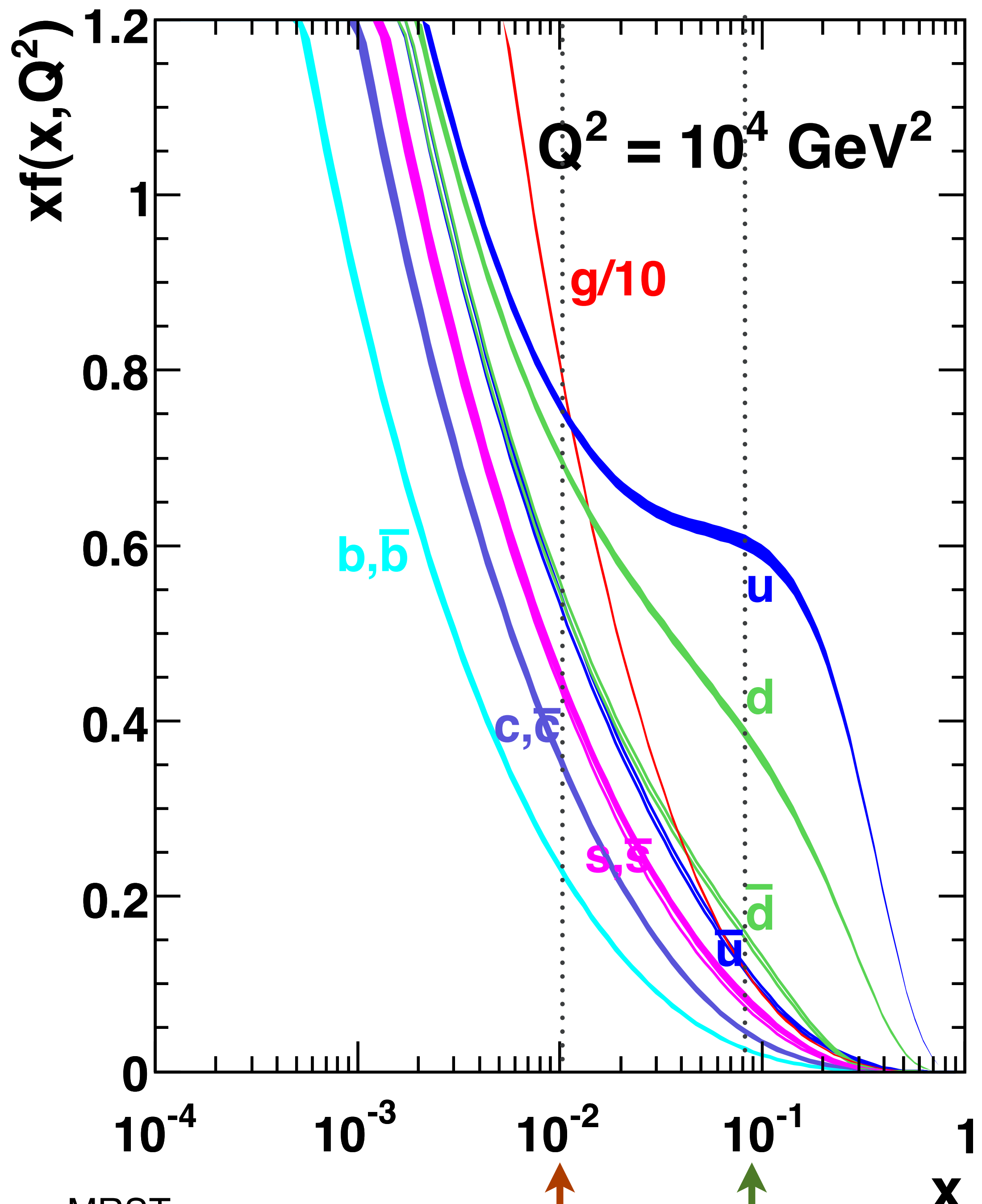
total x-sec   parton distribution functions   parton x-sec



$$M_W^2 = x_1 x_2 s$$

Additional valence u compared to d => W^+ production favored over W^-

W^+ and W^- Rapidity



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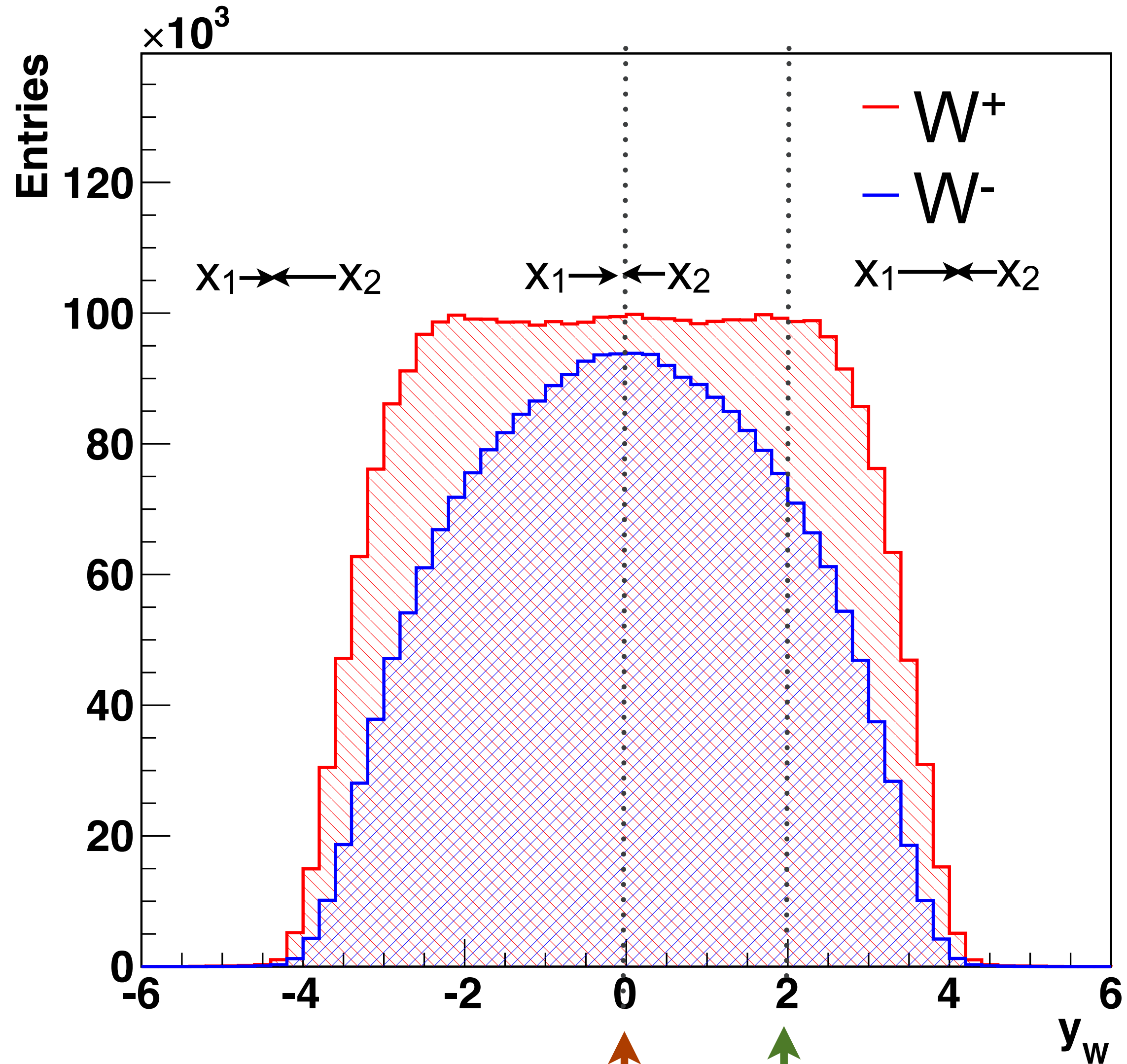
C14 (2000) 133

y~0 y~2



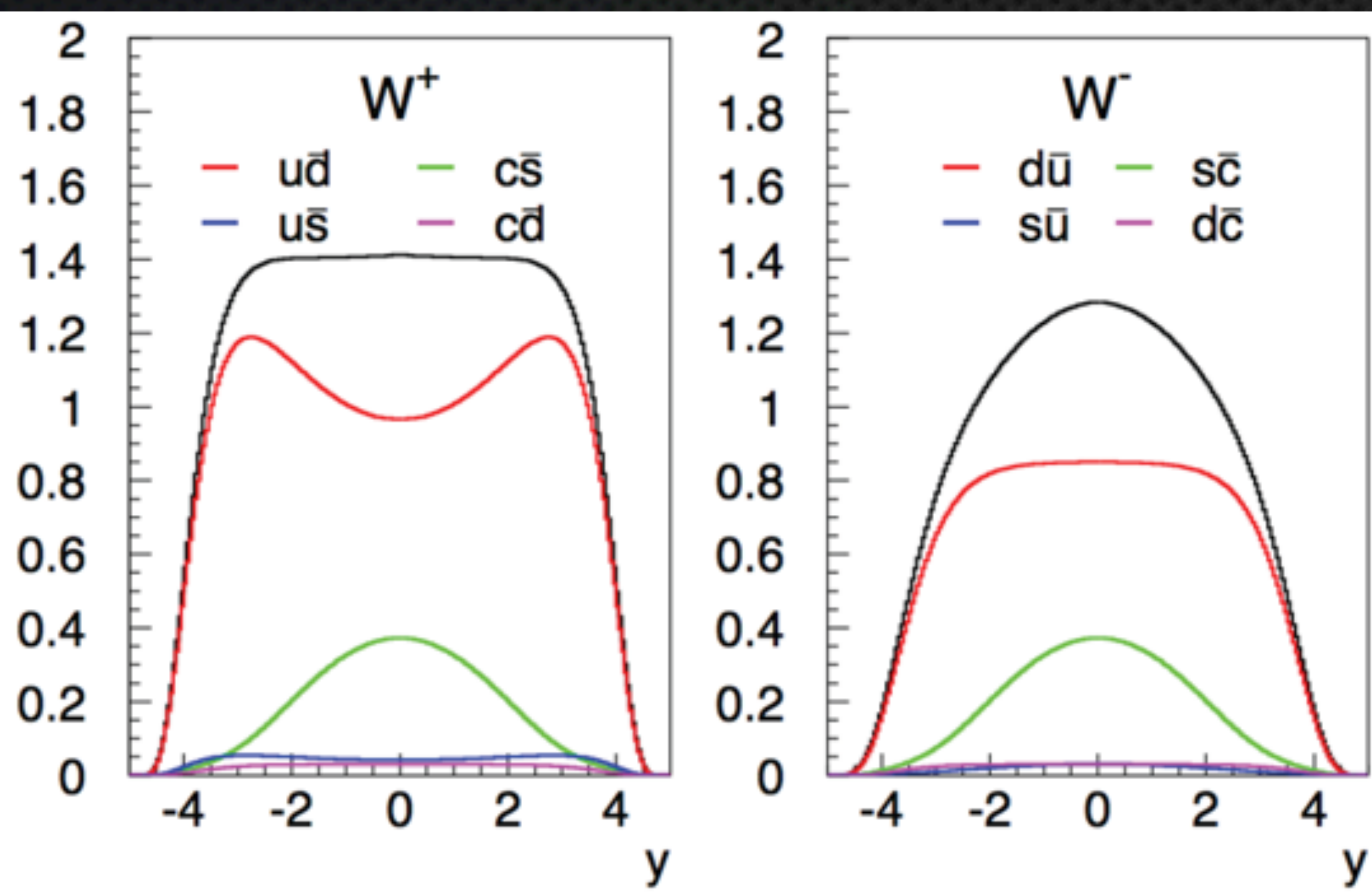
$$x_{1,2} = \frac{m_W}{\sqrt{s}} \cdot e^{\pm y}$$

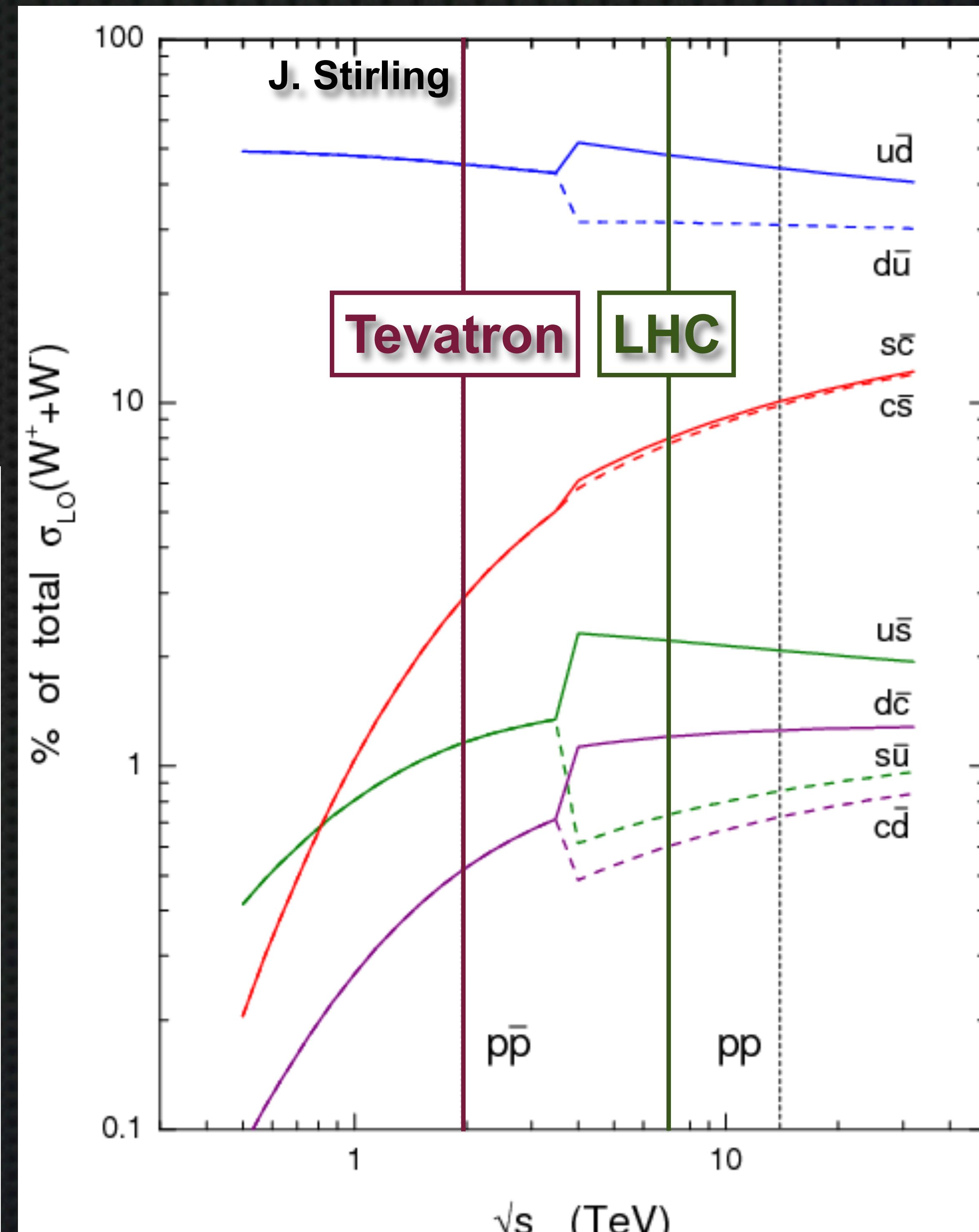
y~0 y~2

Rapidity dependence of W^+/W^- production sensitive to differences in u and d

Flavor Decomposition

- **Dominant W production mode is *ud* quark annihilation**
  - Valence *u* gives broader structure in *y* for W^+
- **Significant contribution of sea quarks**
  - Total about 30%, particularly at low y

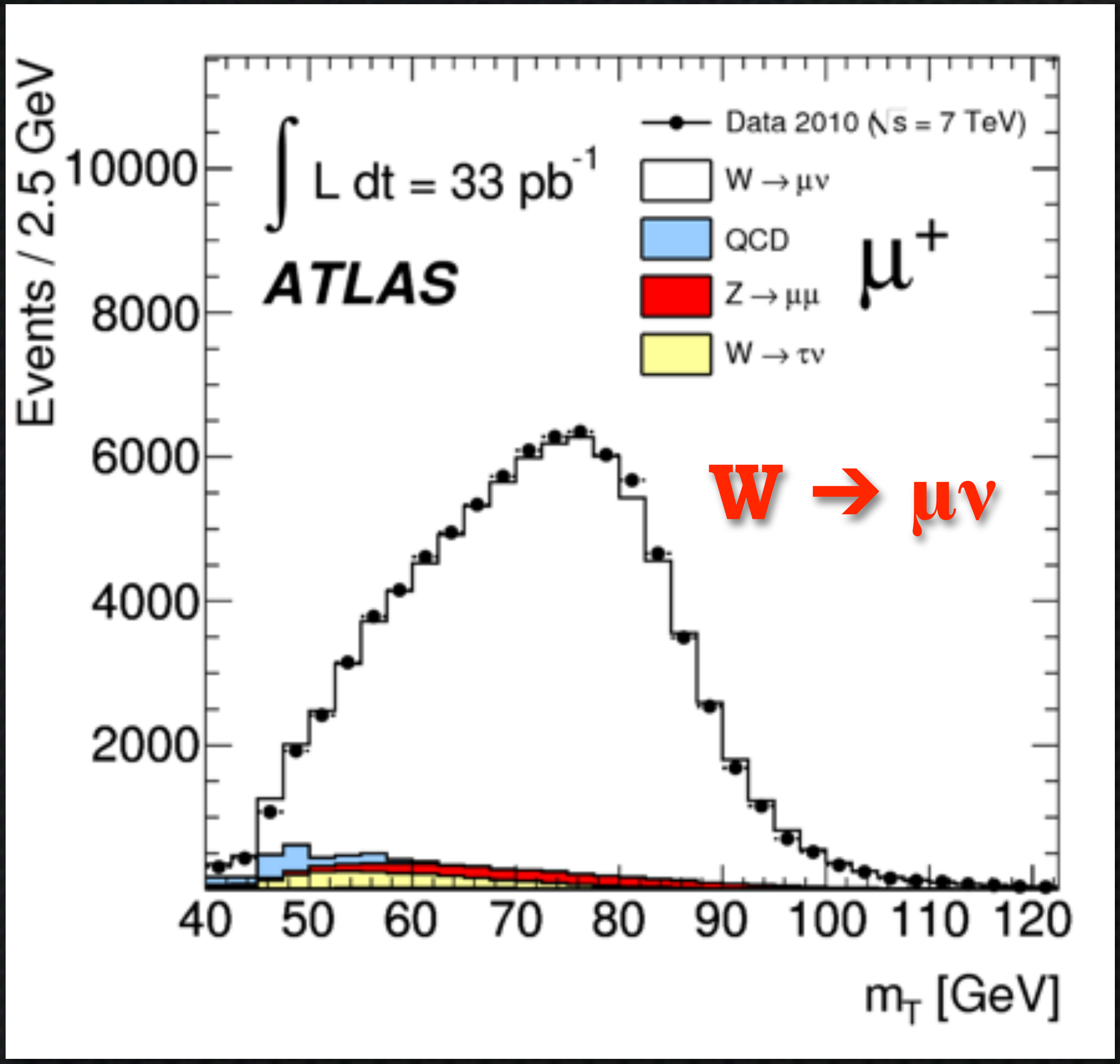




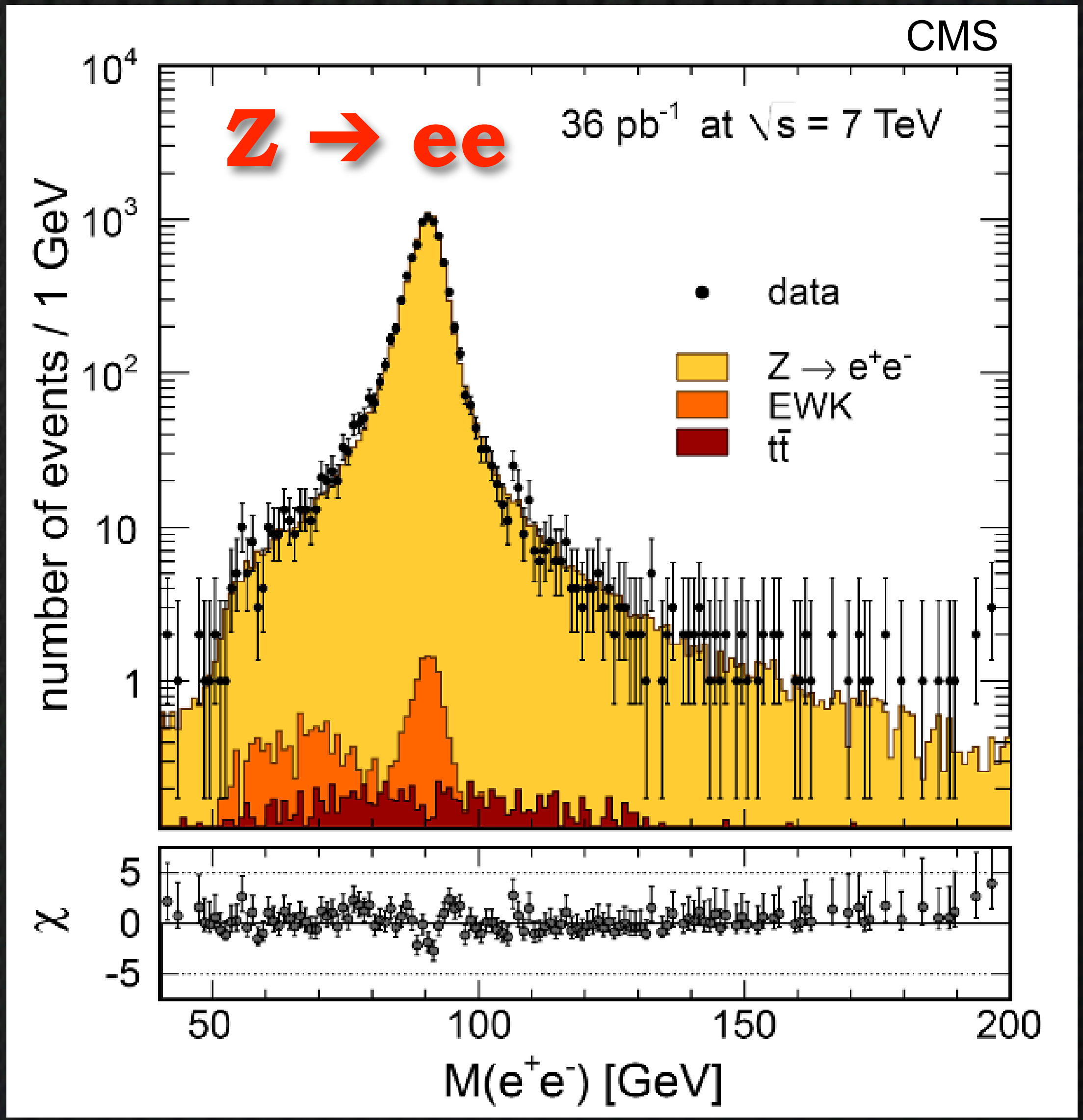
W/Z cross section measurements

- **ATLAS, CMS and LHCb published precision measurements with 2010 data --> relatively recent publications**

Phys. Rev. D85 (2012) 072004



JHEP 10 (2011) 132



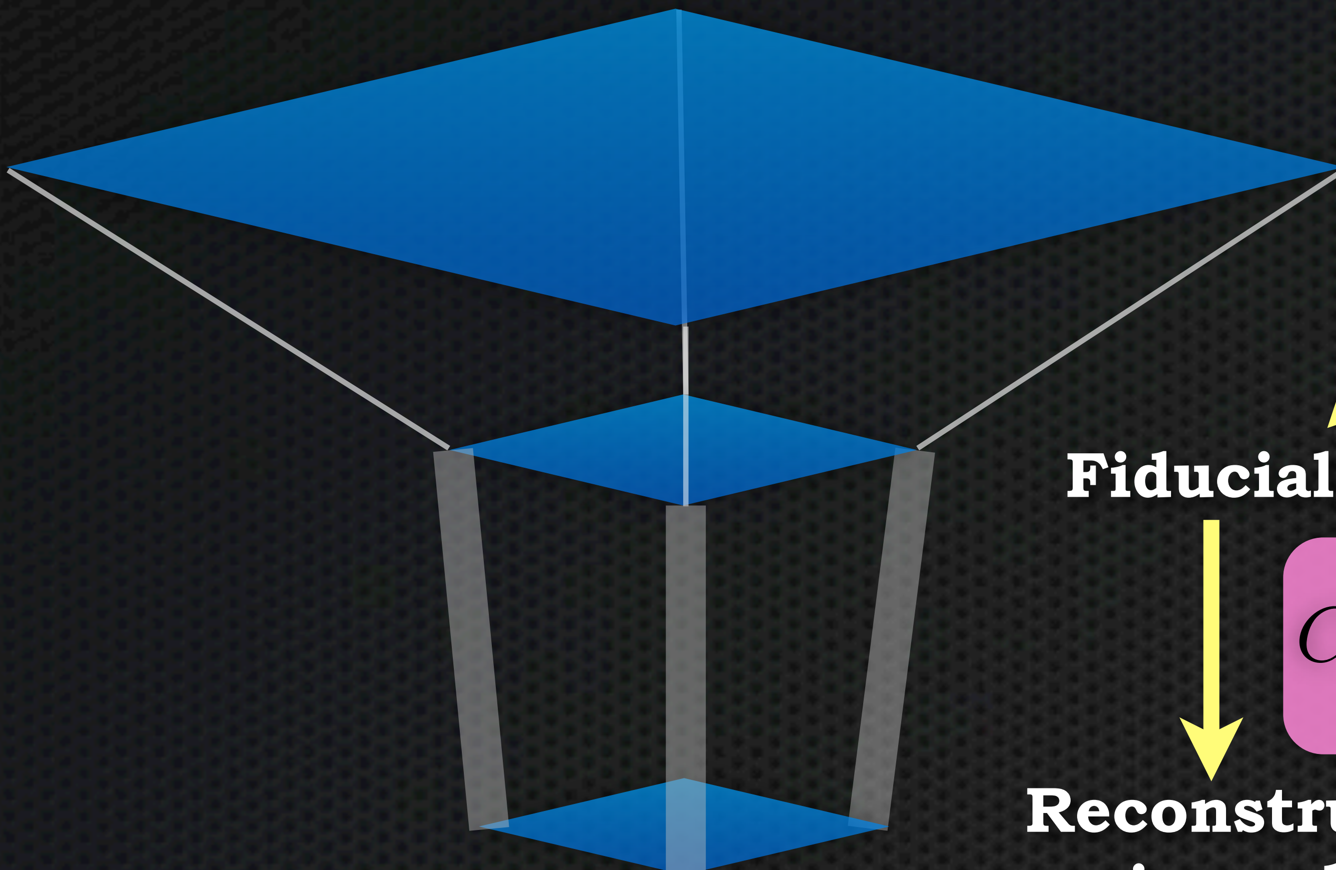
Much larger datasets are now available

$\sqrt{s}$ = 7 TeV, 5 fb^{-1} $\begin{cases} W \rightarrow e/\mu\ \nu : \sim 25 \text{ Million} \\ Z \rightarrow ee/\mu\mu : \sim 3 \text{ Million} \end{cases}$ + $\sqrt{s}$ = 8 TeV ~6 fb^{-1}

Fiducial phase space

$W \to e\nu$:	$p_{T,e} > 20$ GeV, $\lvert\eta_e\rvert < 2.47$,
	excluding $1.37 < \lvert\eta_e\rvert < 1.52$,
	$p_{T,\nu} > 25$ GeV, $m_T > 40$ GeV;
$W \to \mu\nu$:	$p_{T,\mu} > 20$ GeV, $\lvert\eta_\mu\rvert < 2.4$,
	$p_{T,\nu} > 25$ GeV, $m_T > 40$ GeV;
$Z \to ee$:	$p_{T,e} > 20$ GeV, both $\lvert\eta_e\rvert < 2.47$,
	excluding $1.37 < \lvert\eta_e\rvert < 1.52$,
	$66 < m_{ee} < 116$ GeV;
Forward $Z \to ee$:	$p_{T,e} > 20$ GeV, one $\lvert\eta_e\rvert < 2.47$,
	excluding $1.37 < \lvert\eta_e\rvert < 1.52$,
	other $2.5 < \lvert\eta_e\rvert < 4.9$,
	$66 < m_{ee} < 116$ GeV;
$Z \to \mu\mu$:	$p_{T,\mu} > 20$ GeV, both $\lvert\eta_\mu\rvert < 2.4$,
	$66 < m_{\mu\mu} < 116$ GeV.

Fiducial cross section



Generated phase-space

$$A_{W/Z} = \frac{N_{\mathrm{MC,gen,cut}}}{N_{\mathrm{MC,gen,all}}}$$

Fiducial

$$C_{W/Z} = \frac{N_{\mathrm{MC,rec}}}{N_{\mathrm{MC,gen,cut}}}$$

Detector effects

Reconstructed passing selection

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

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

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
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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)

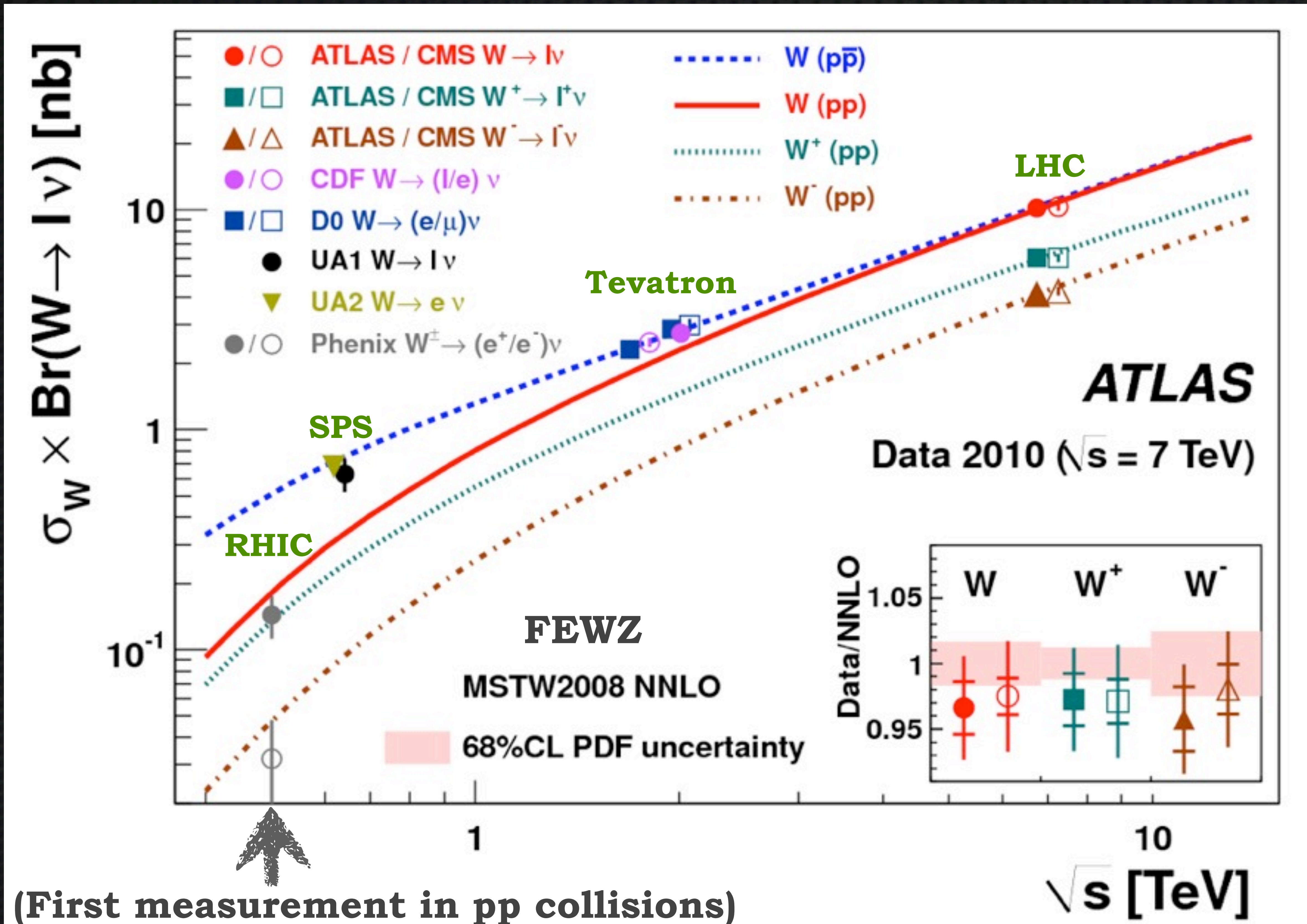
Uncertainties: Muon channel

	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
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
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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			

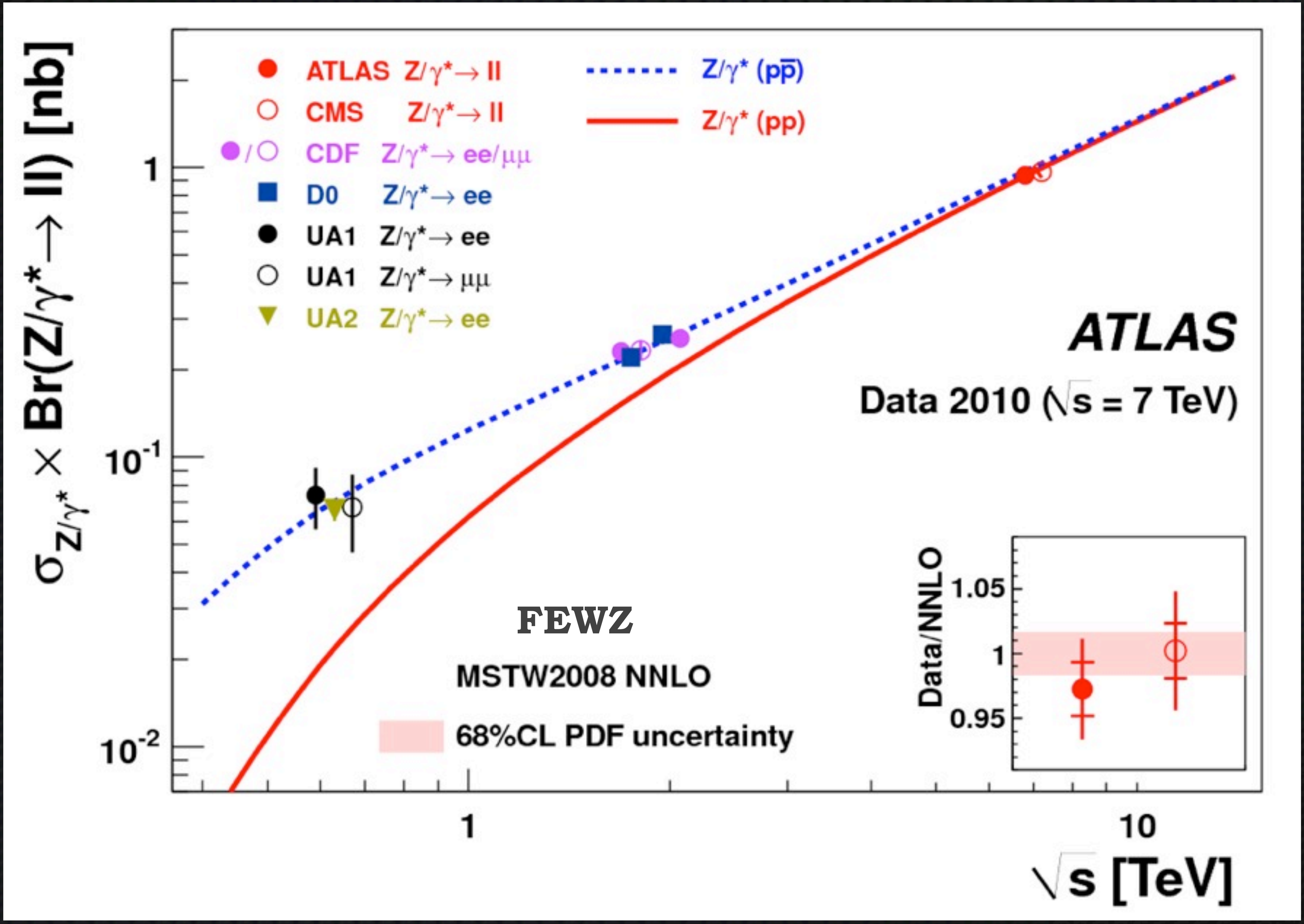
Extrapolation

(1.8% in 2011)

W inclusive cross section



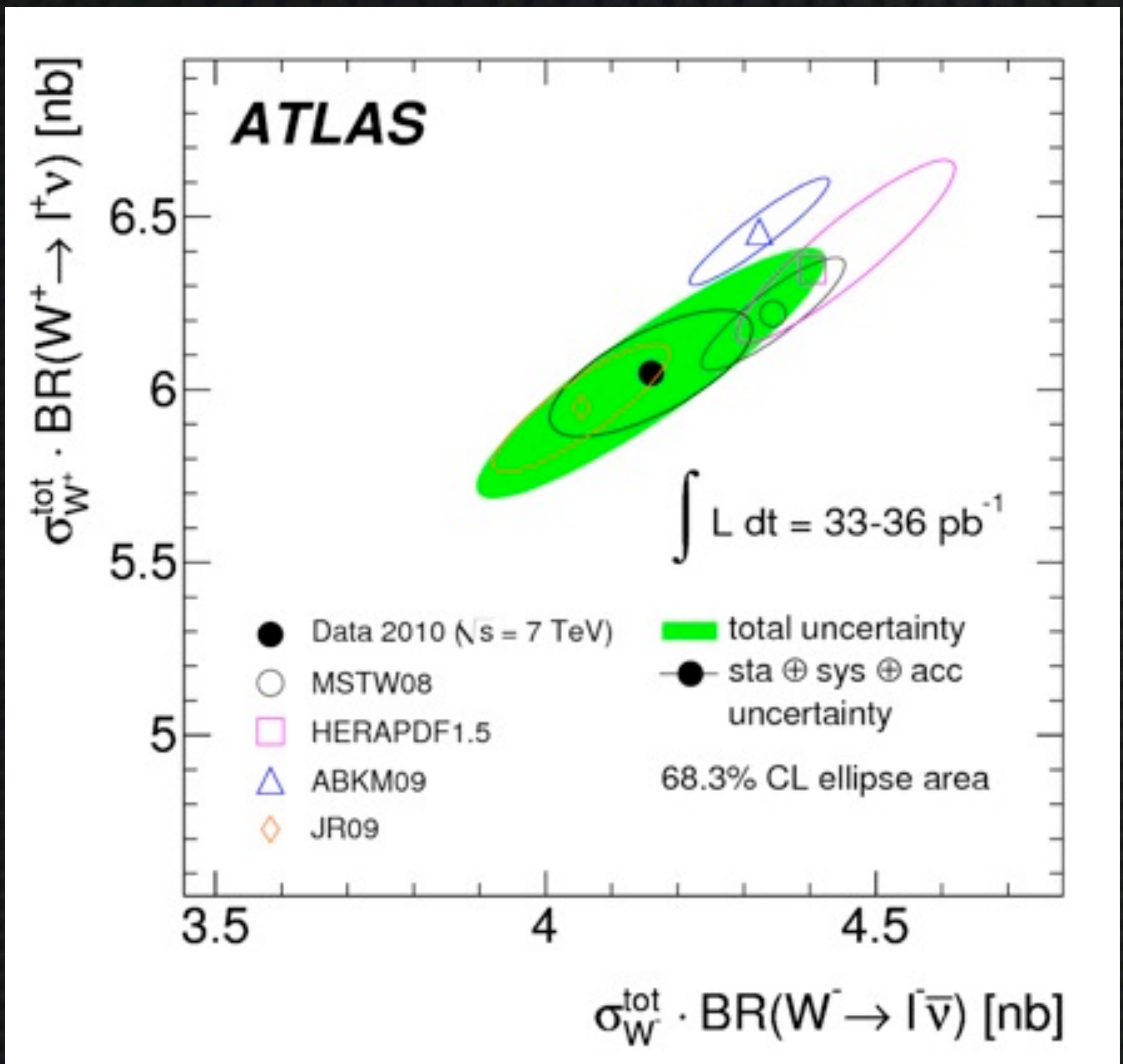
Z inclusive cross section



Fiducial W and Z Cross Sections

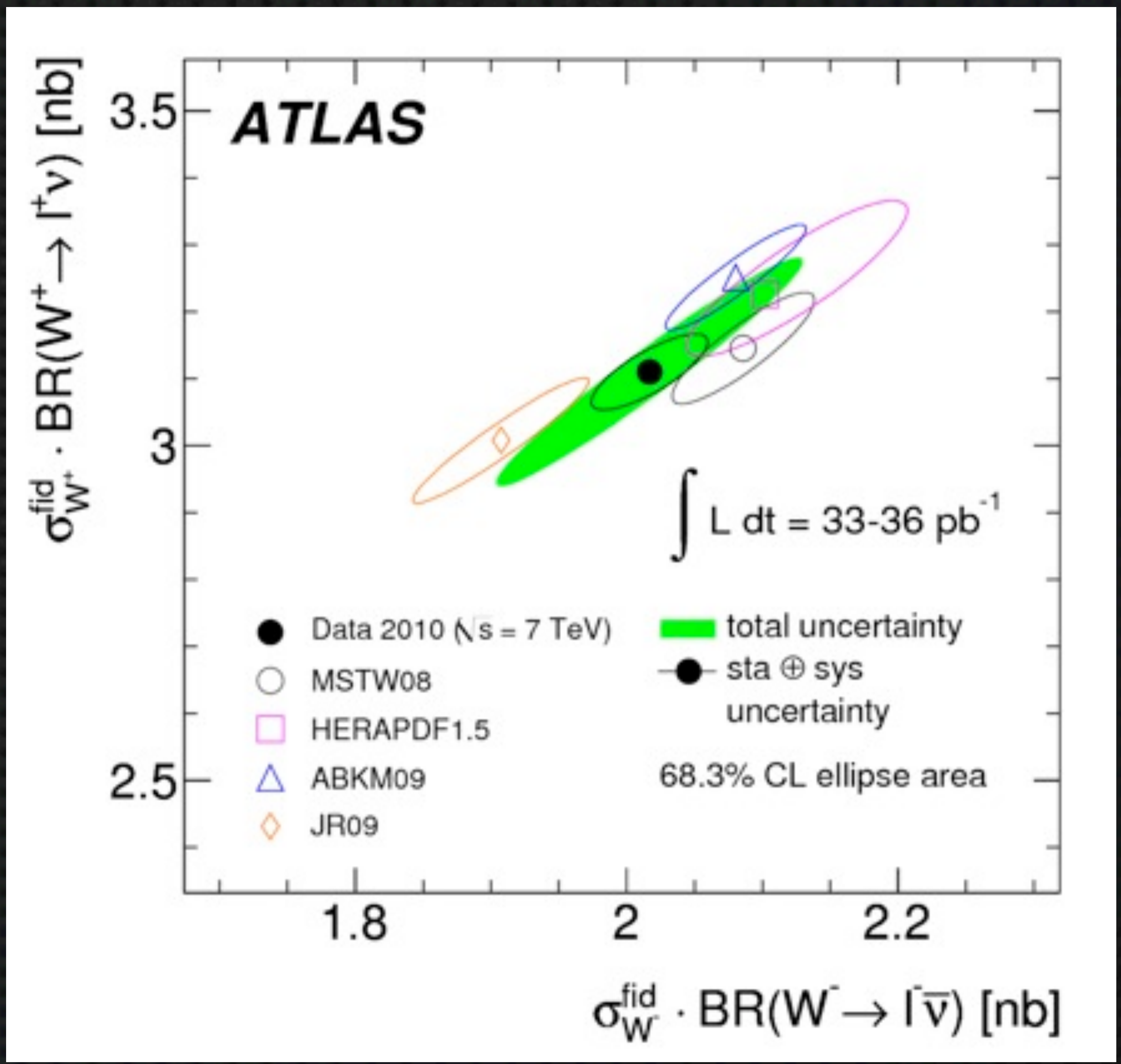
- **ATLAS measures fiducial cross sections** — Phys. Rev. D85 (2012) 072004
  - No theoretical uncertainty from extrapolation outside experimental acceptance

σ_{Total}: W^+ versus W^-



FEWZ = DYNNLO ~ 0.5%

$\sigma_{Fiducial}$: W^+ versus W^-



FEWZ = DYNNLO ~ 1%

Luminosity 3.4%

Some differentiation between PDF sets already observed now

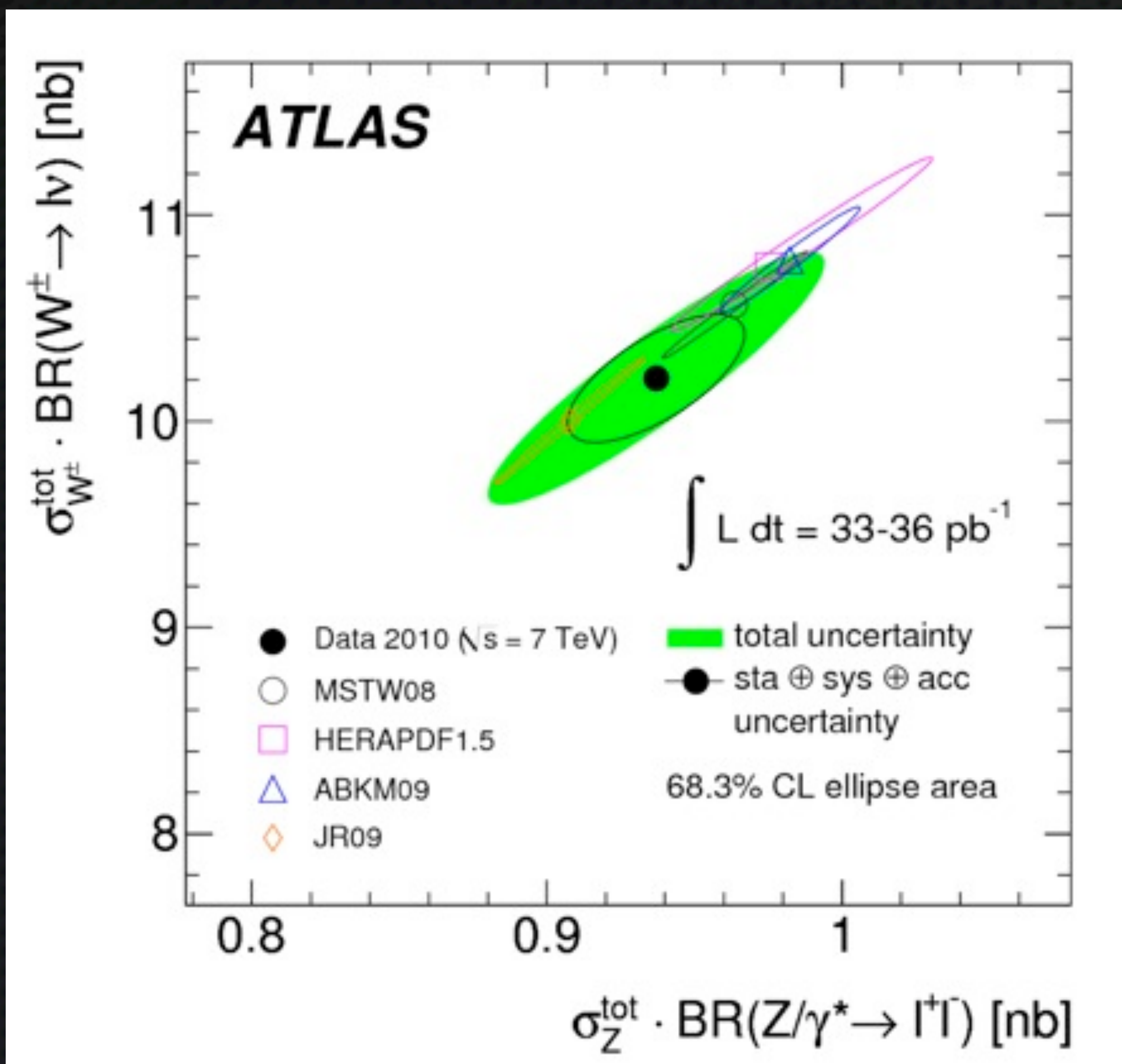
JR09 seems to be the most discrepant

Fiducial W and Z Cross Sections

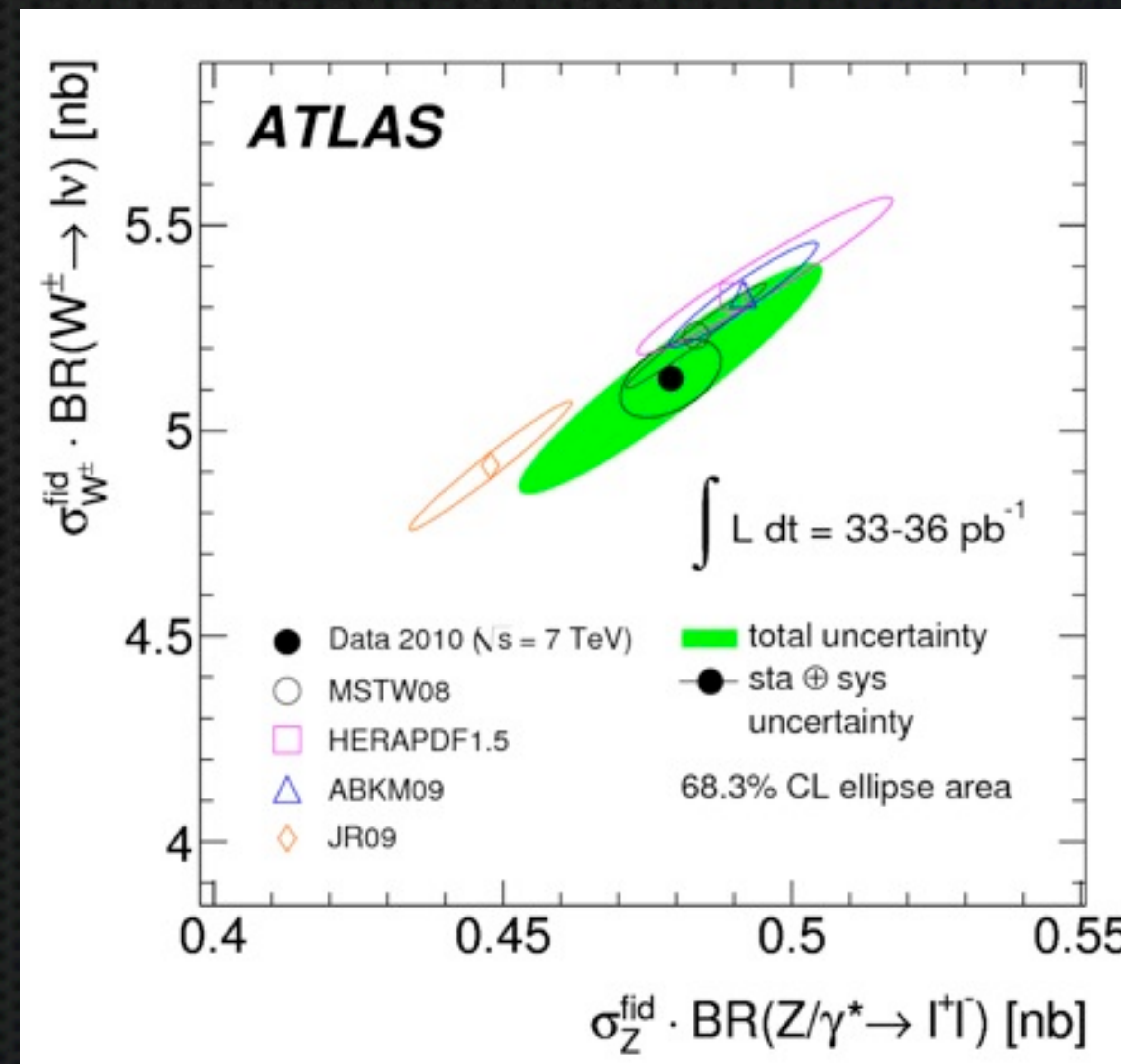
- **ATLAS measures fiducial cross sections**
  - No theoretical uncertainty from extrapolation outside experimental acceptance

Phys. Rev. D85 (2012) 072004

σ_{Total}: $W^{\pm}$ versus Z



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



Luminosity 3.4%

Some differentiation between PDF sets already observed now

JR09 seems to be the most discrepant

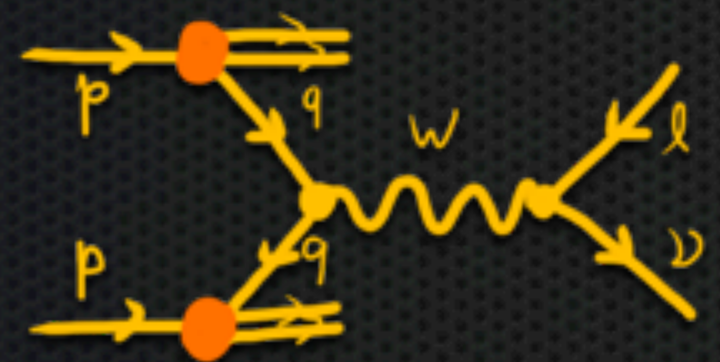
Lepton Universality

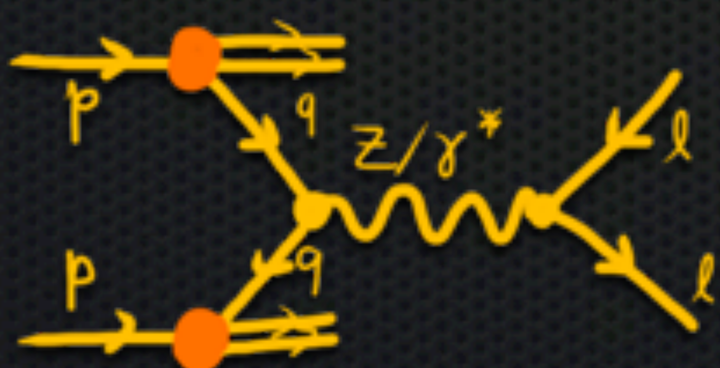
Phys. Rev. D85 (2012) 072004

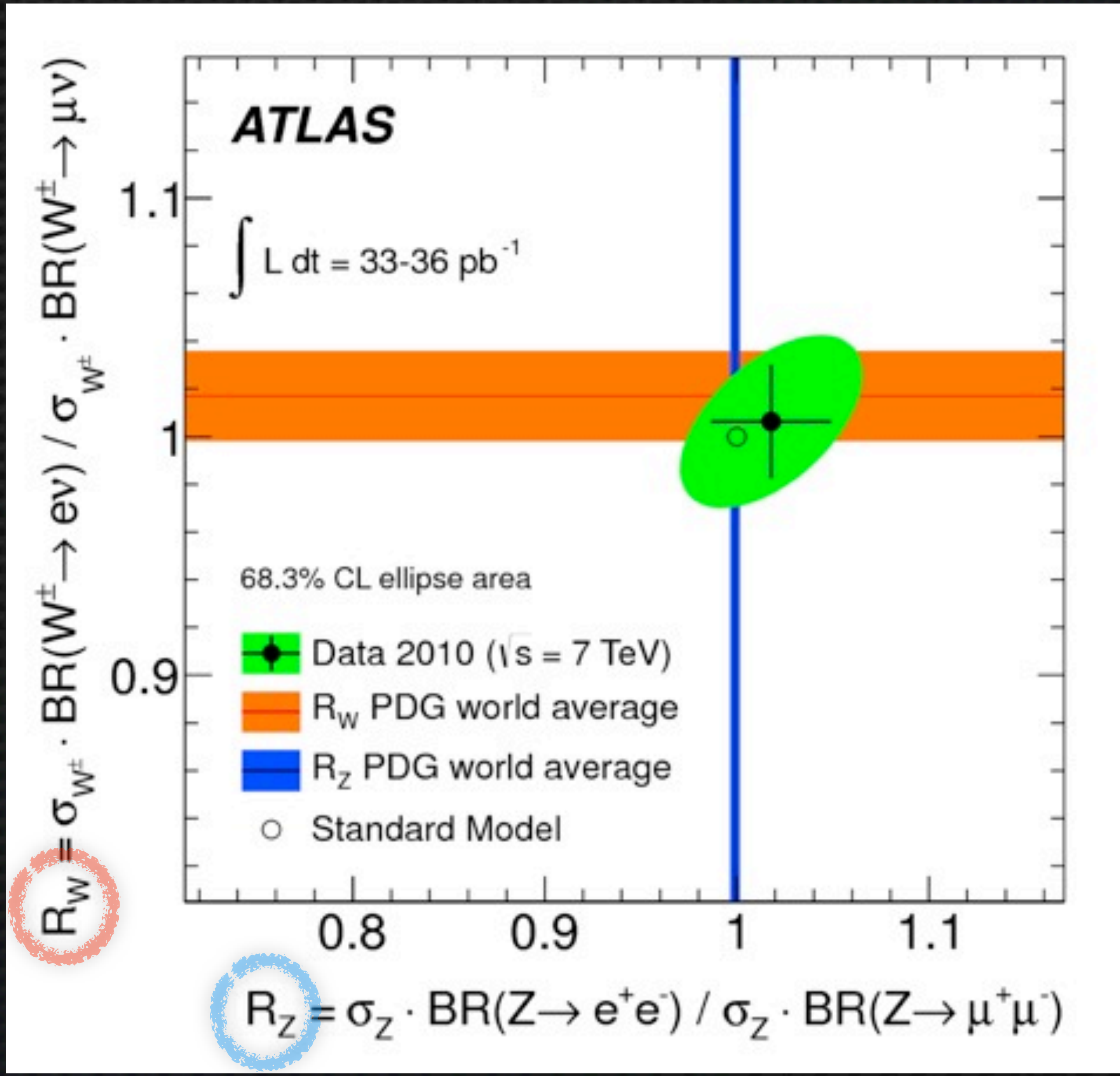
$$R_W = \frac{\sigma^e_W}{\sigma^\mu_W} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)} = 1.006 \pm 0.004\,(\mathrm{sta}) \pm 0.006\,(\mathrm{unc}) \pm 0.023\,(\mathrm{cor}) = 1.006 \pm 0.024$$

$$R_Z = \frac{\sigma^e_Z}{\sigma^\mu_Z} = \frac{Br(Z \to ee)}{Br(Z \to \mu\mu)} = 1.018 \pm 0.014\,(\mathrm{sta}) \pm 0.016\,(\mathrm{unc}) \pm 0.028\,(\mathrm{cor}) = 1.018 \pm 0.031$$

- **Result already close to best measurement (R_W)**
  - **PDG: 1.9%**
  - **This measurement: 2.4%**





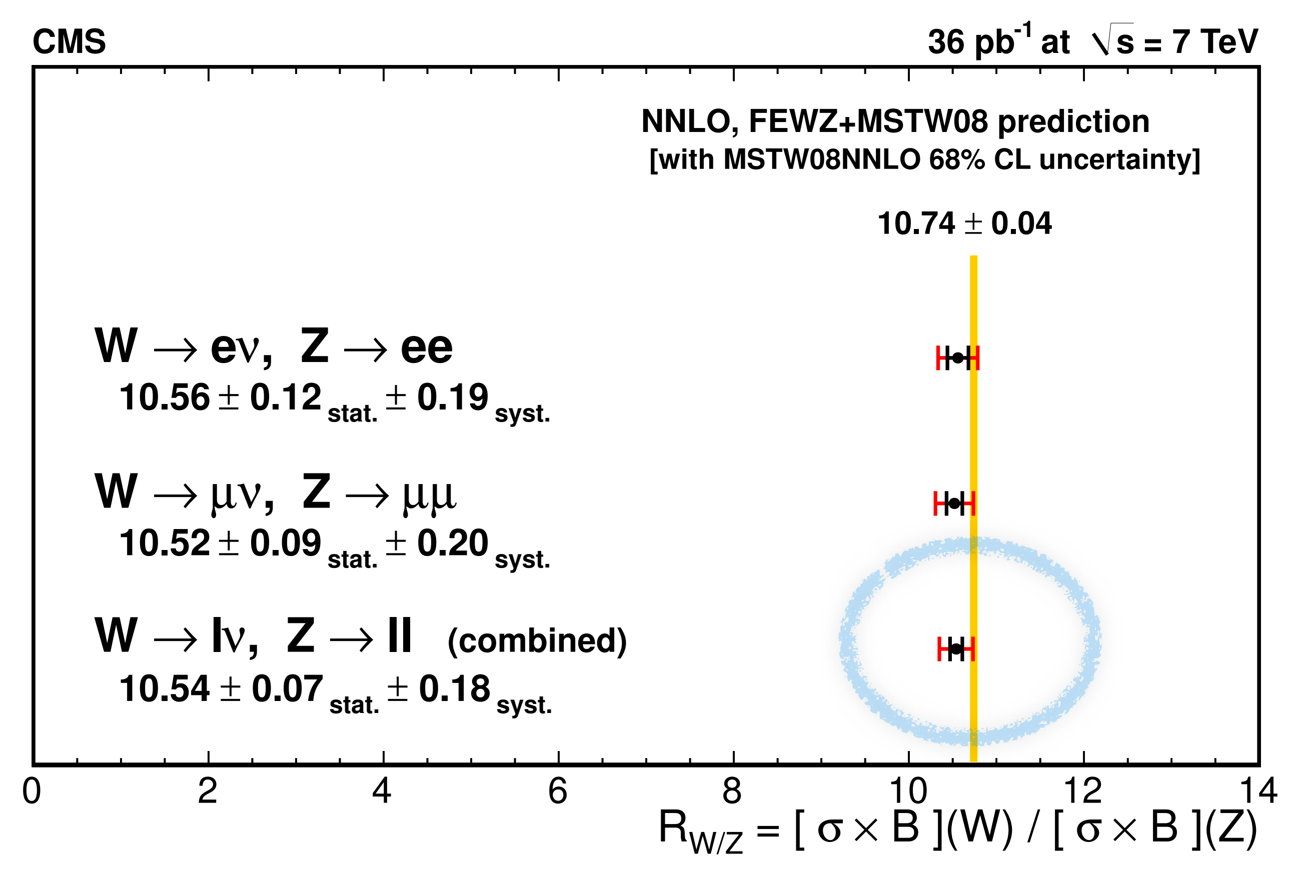


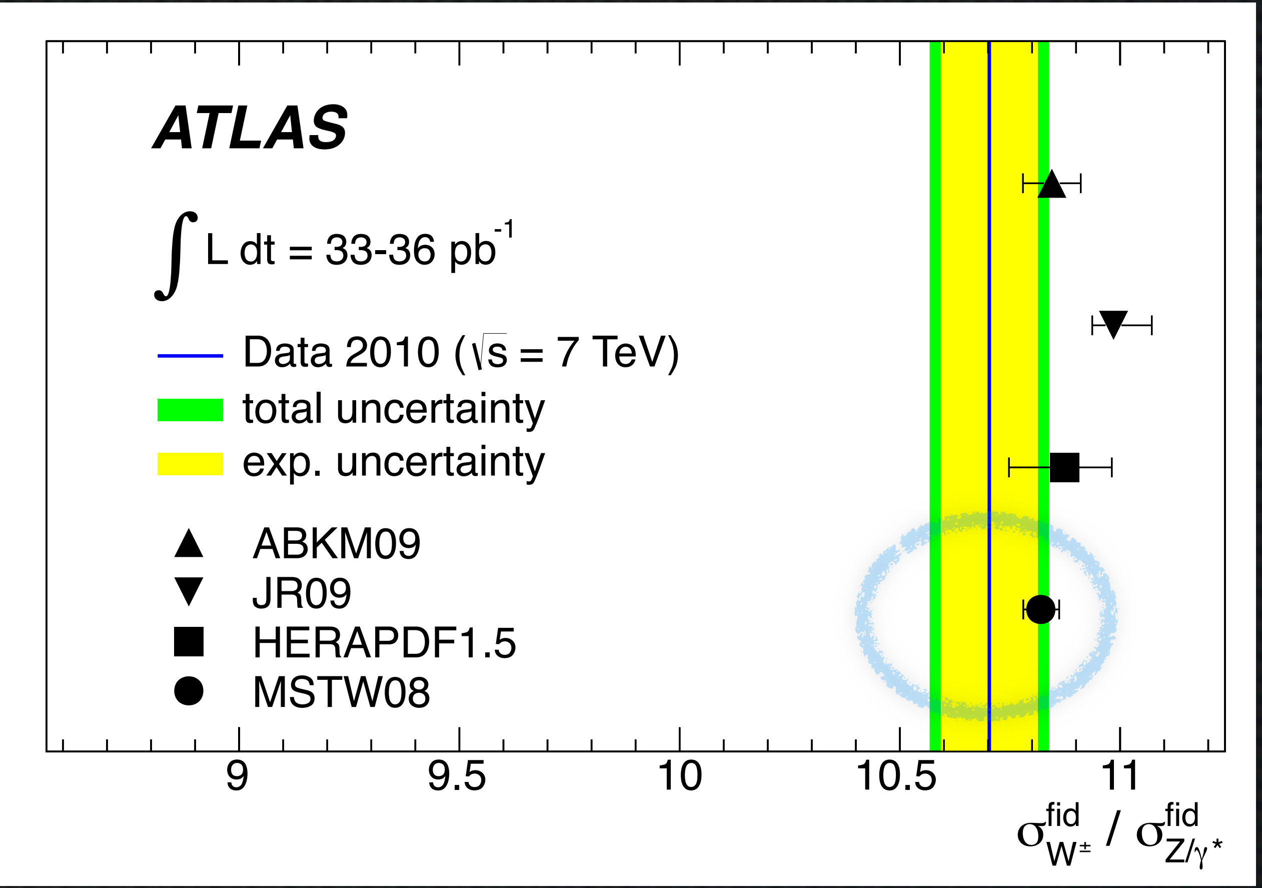
Ratio W and Z Cross Sections

Benefits from experimental and theoretical systematics cancellation

JHEP 10 (2011) 132

Phys. Rev. D85 (2012) 072004



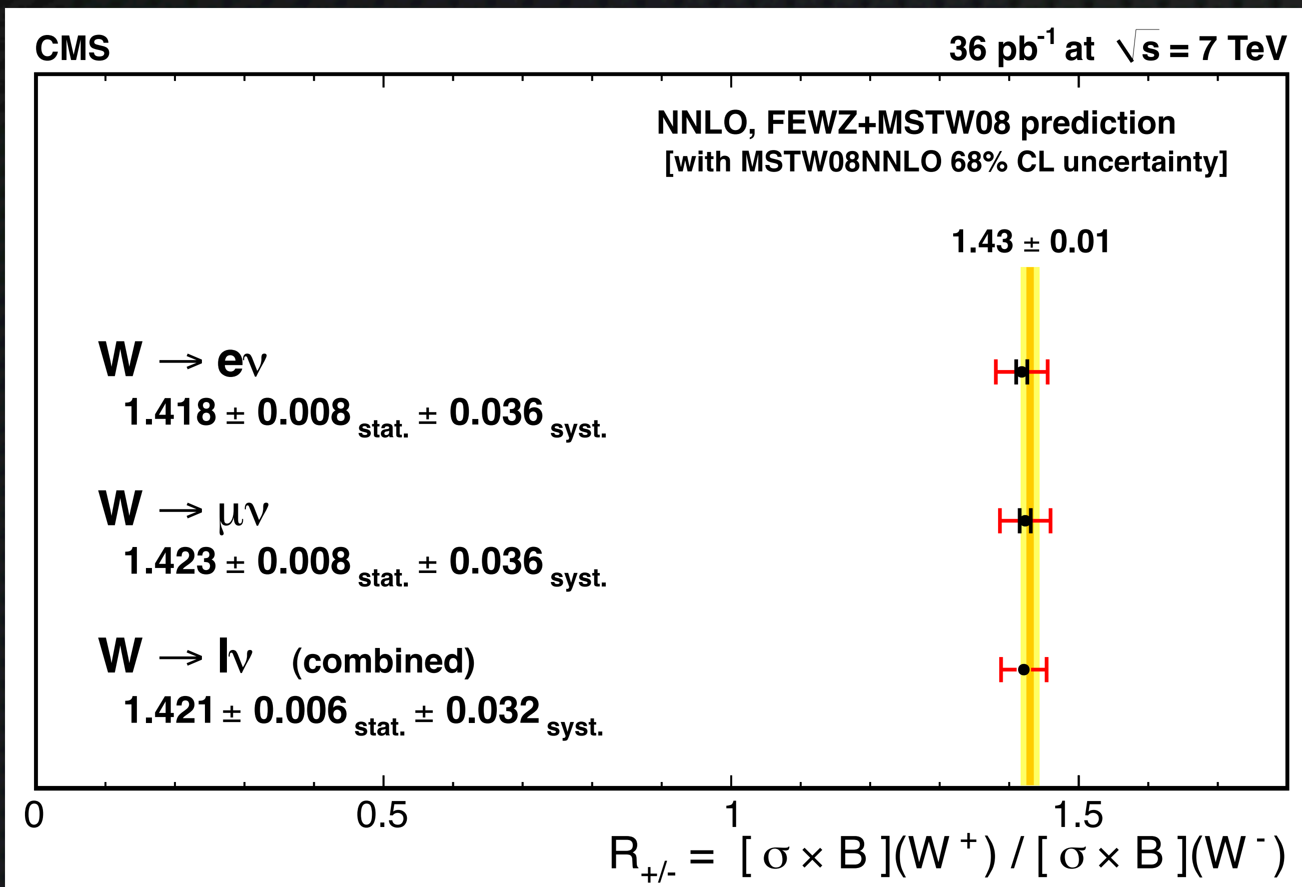


$\sigma^{tot}\times\mathcal{B}$	$W^{\pm}/Z$	
CMS	10.54 ± 0.07 (sta) ± 0.08 (sys) ± 0.16 (theo)	
ATLAS	10.893 ± 0.079 (sta) ± 0.110 (sys) ± 0.116 (acc)	1.6%
ATLAS $\sigma_{fiducial}$	10.703 ± 0.078 (sta) ± 0.110 (sys) ± 0.008 (acc)	1.3%

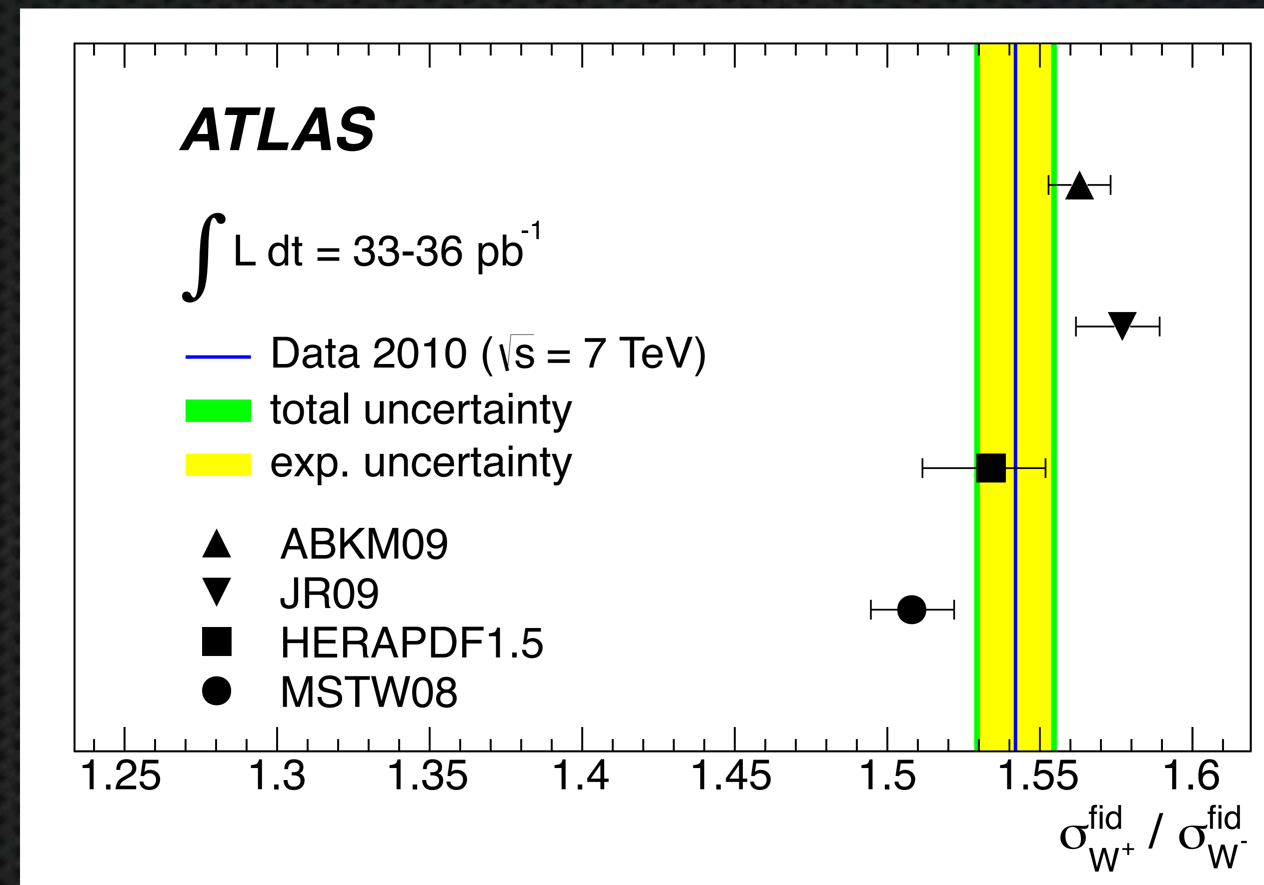
Cross Section Ratio W^+/W^-

Benefits from experimental and theoretical systematics cancellation

JHEP 10 (2011) 132



Phys. Rev. D85 (2012) 072004



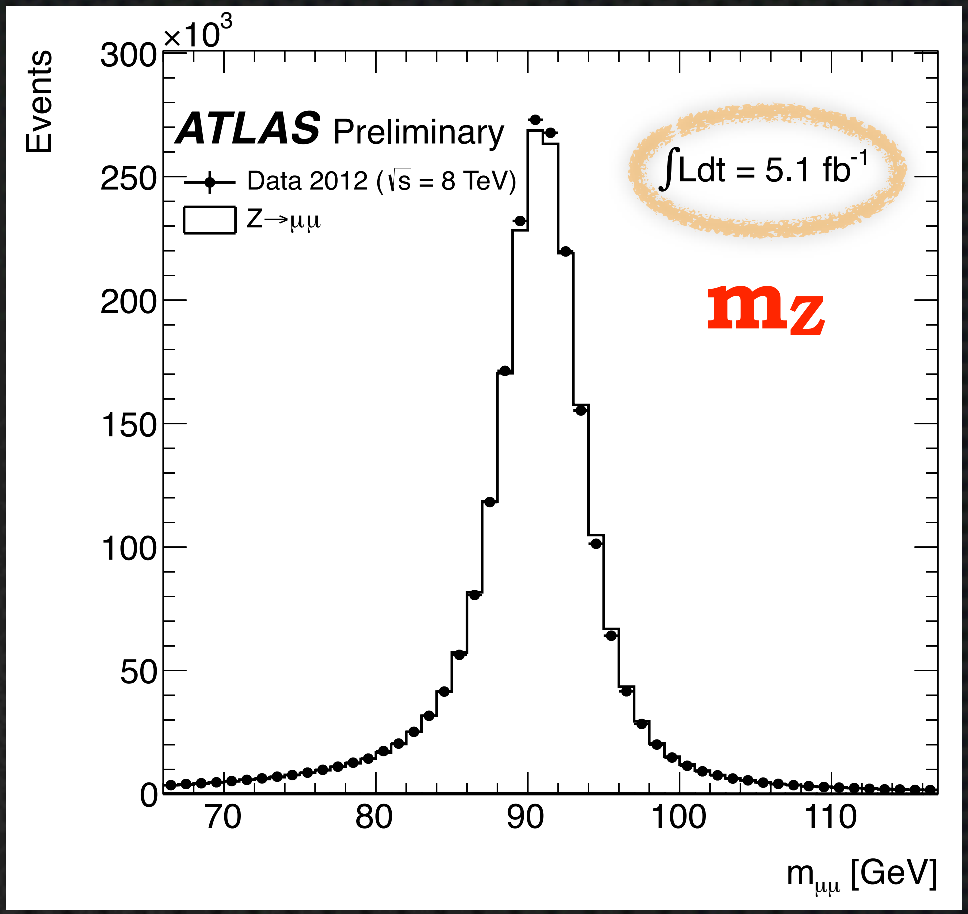
$\sigma^{tot} \times \mathcal{B}$	W^+/W^-	
CMS	1.421 ± 0.006 (sta) ± 0.014 (sys) ± 0.029 (the)	
ATLAS	1.454 ± 0.006 (sta) ± 0.012 (sys) ± 0.022 (acc)	1.8%
ATLAS $\sigma_{fiducial}$	1.542 ± 0.007 (sta) ± 0.012 (sys) ± 0.001 (acc)	0.9%

New

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

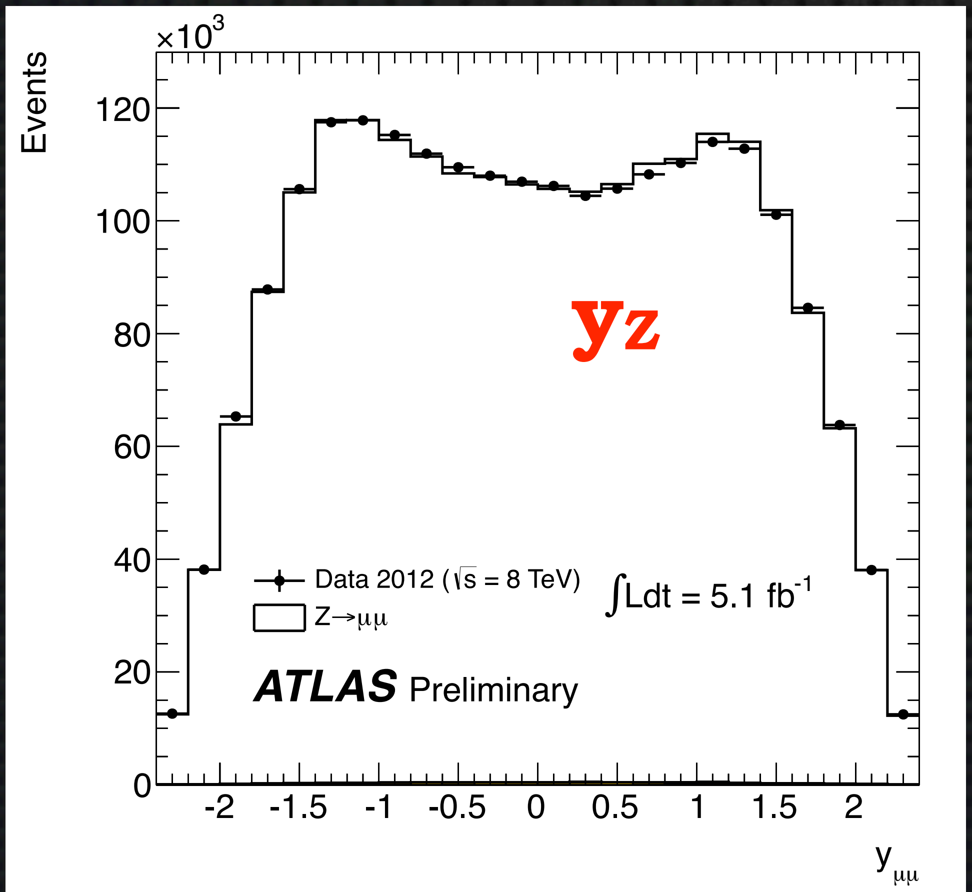
Z boson observation at $\sqrt{s}$ = 8 TeV

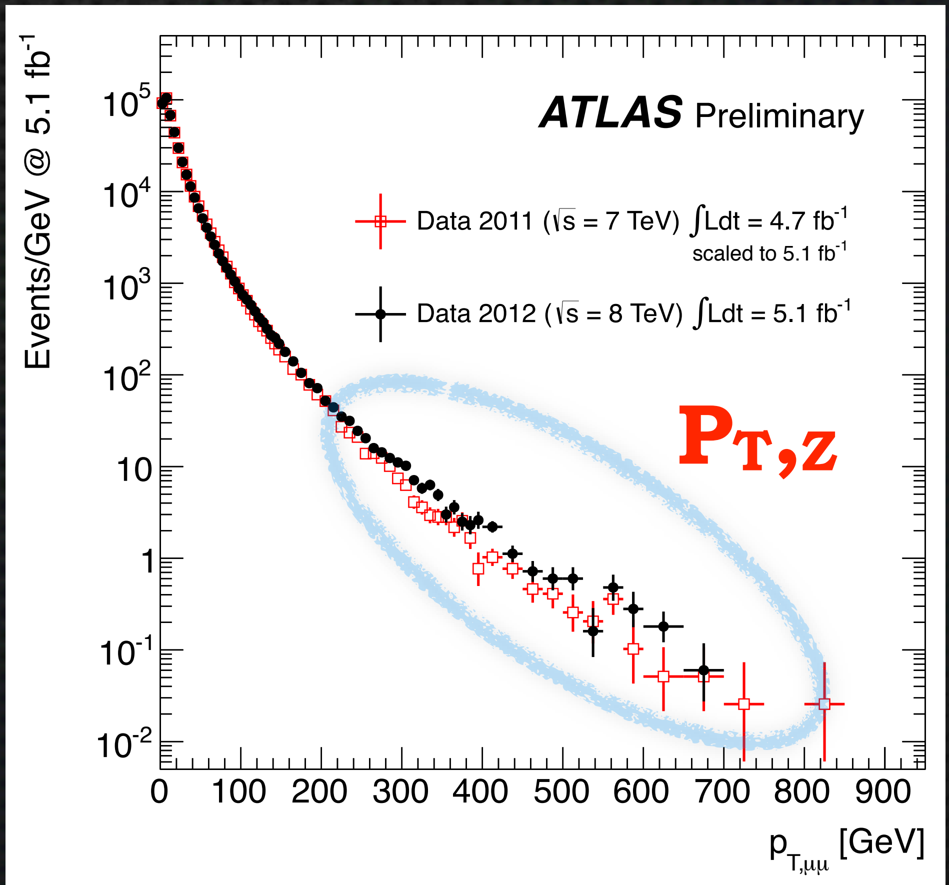
Z → μμ



POWHEG+PYTHIA 8 MC
CT 10.0

Distributions normalized to data

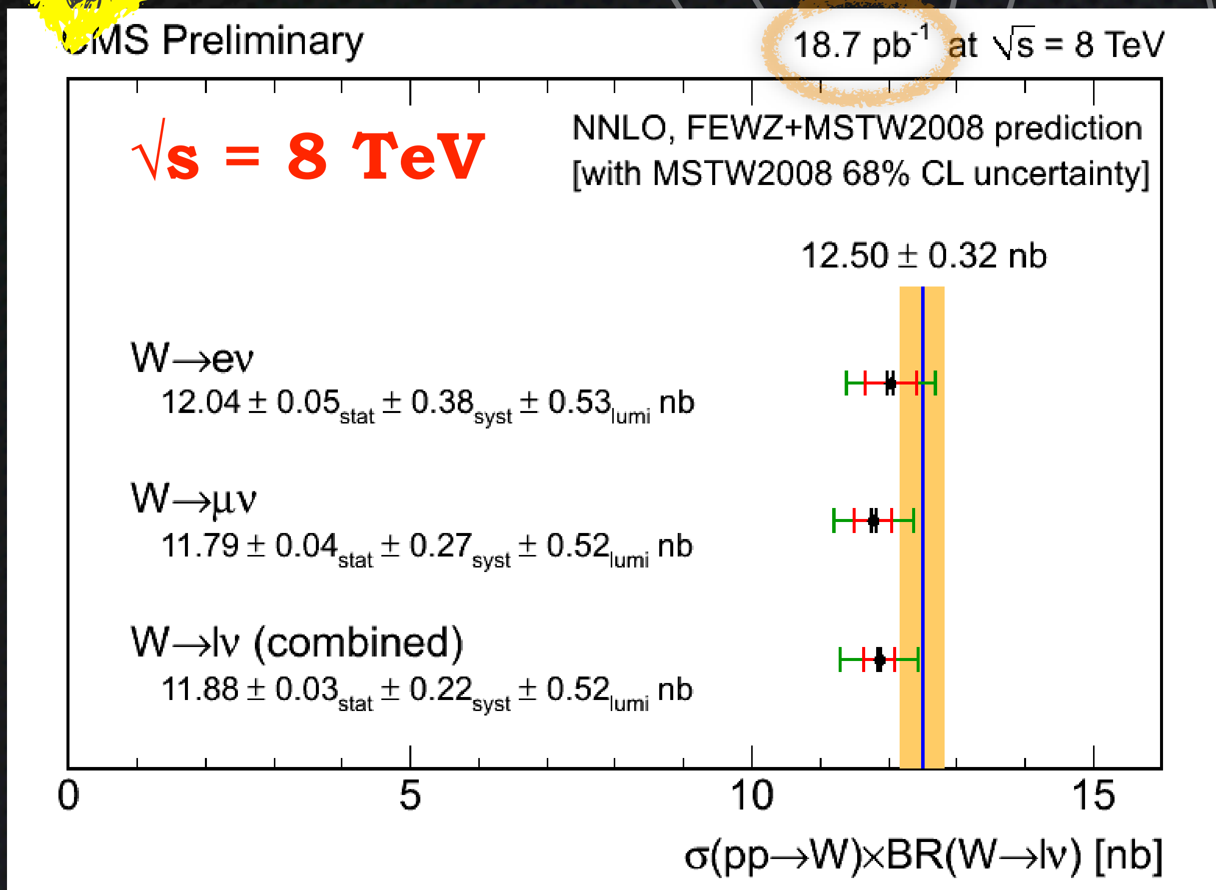


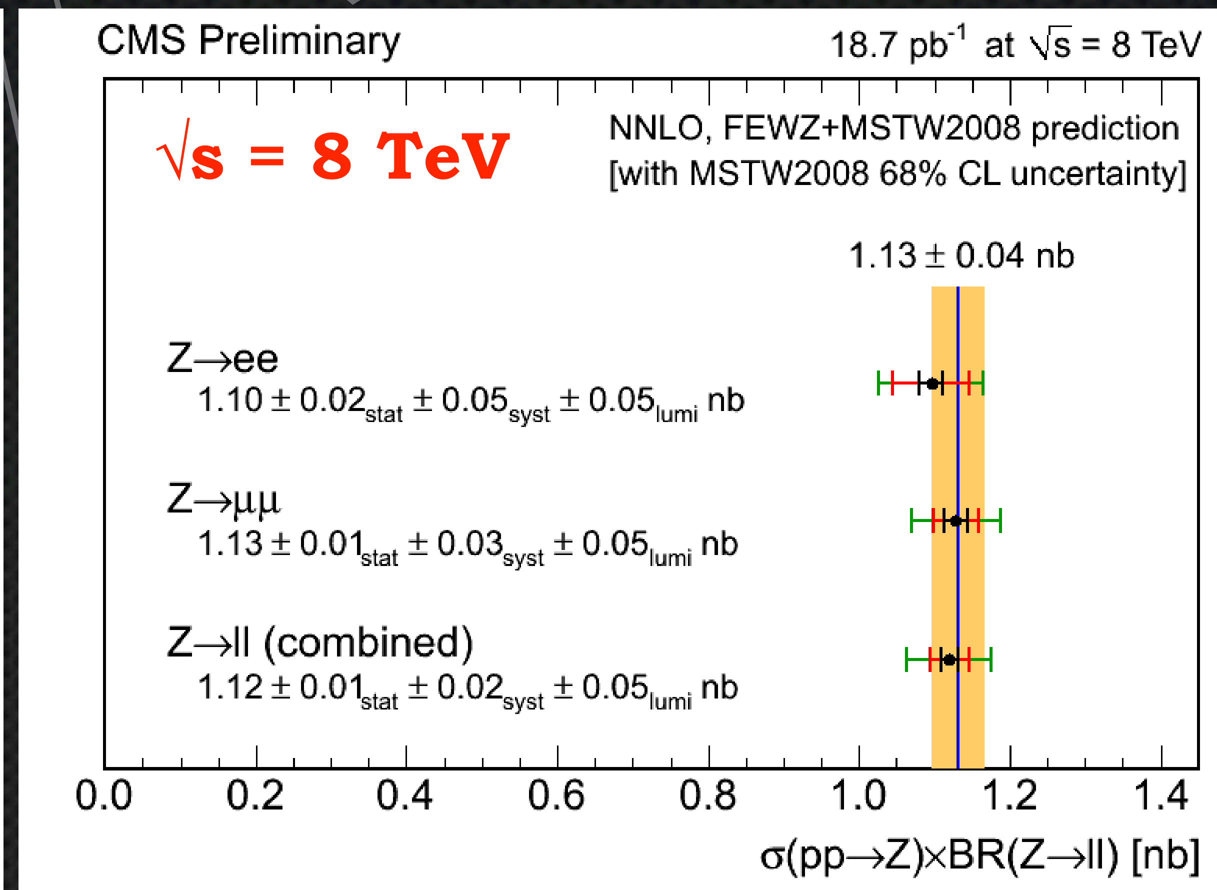


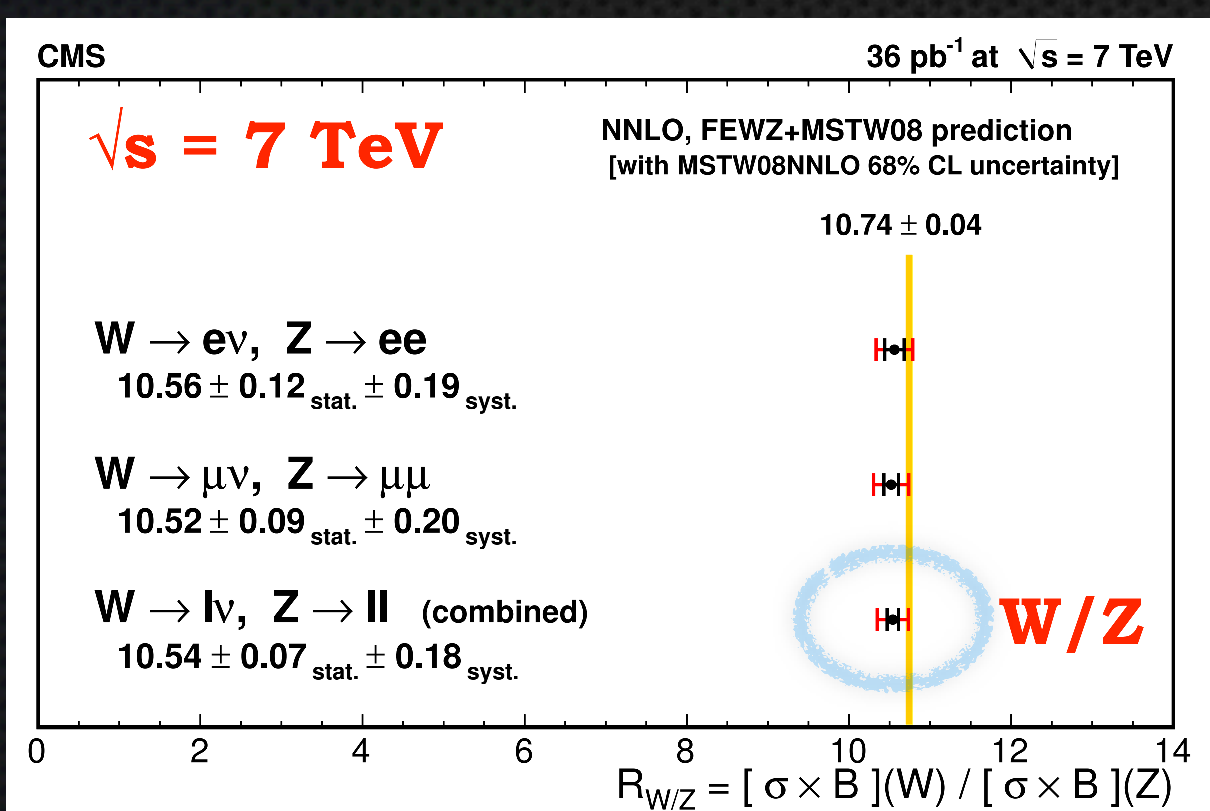
New

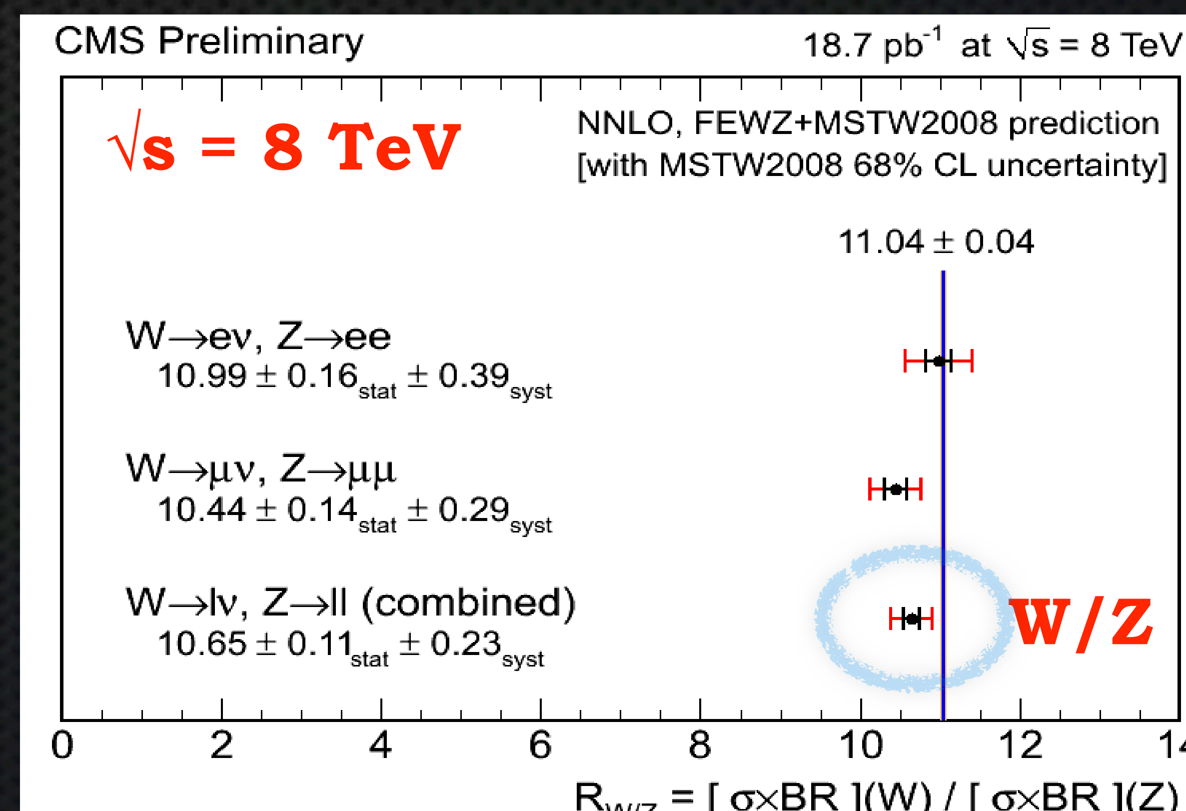
W and Z production at $\sqrt{s}$ = 8 TeV

CMS-PAS-12-011





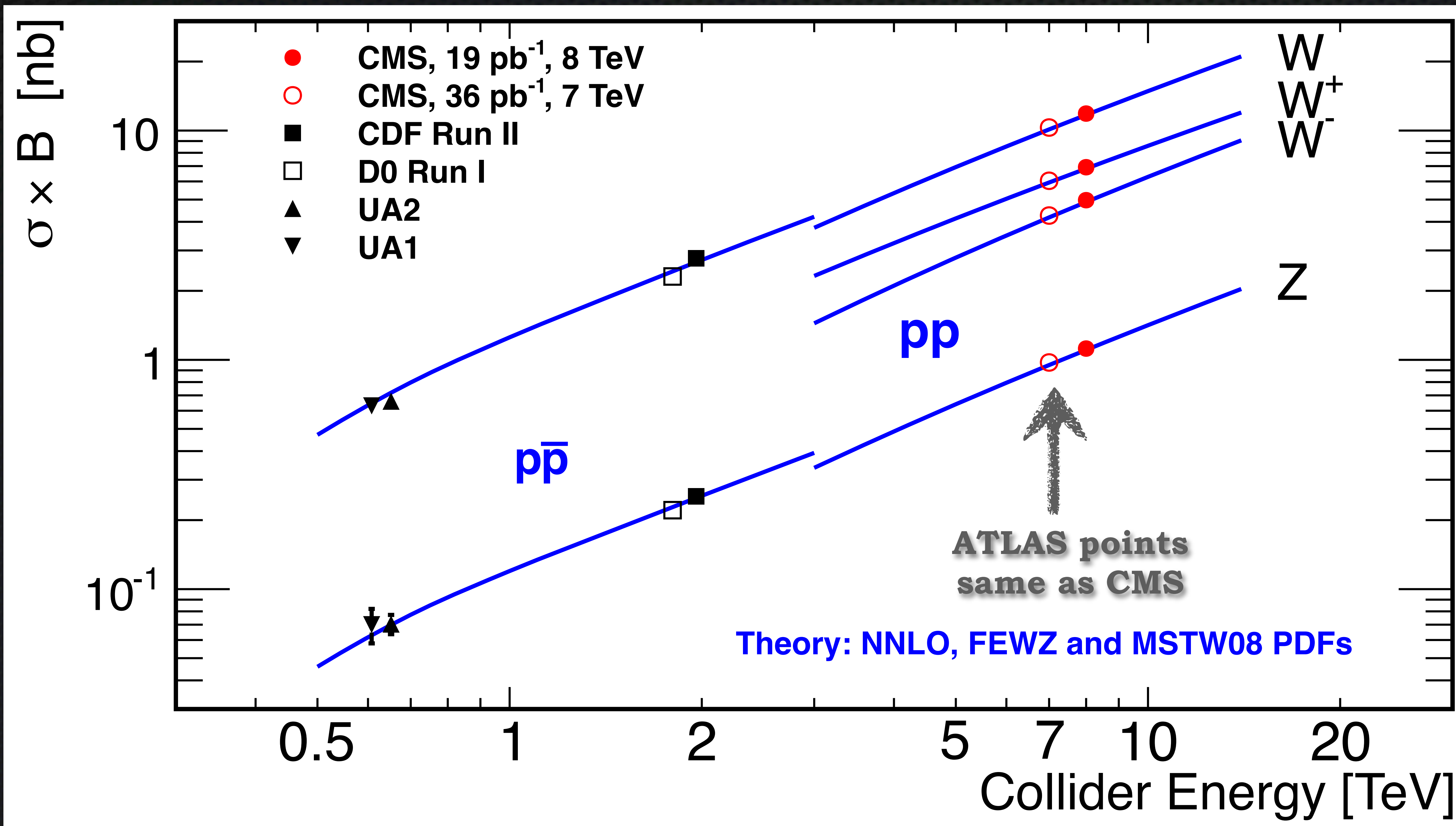




W and Z Inclusive Cross Sections

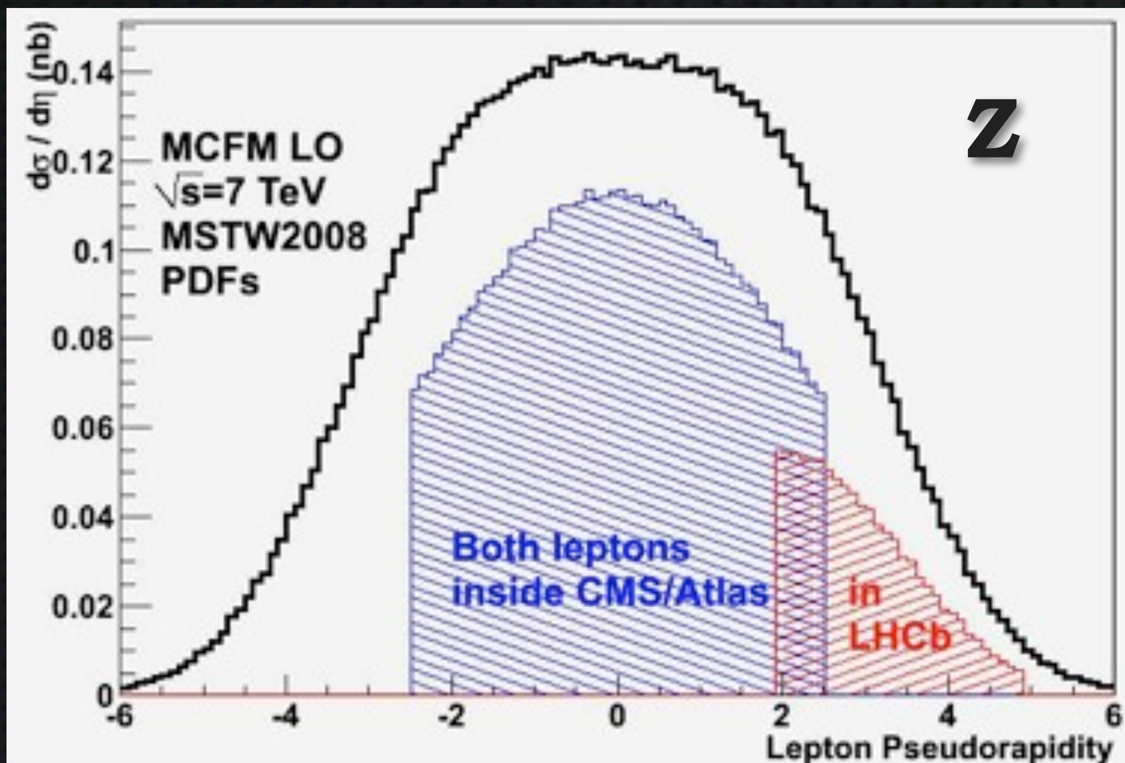
New

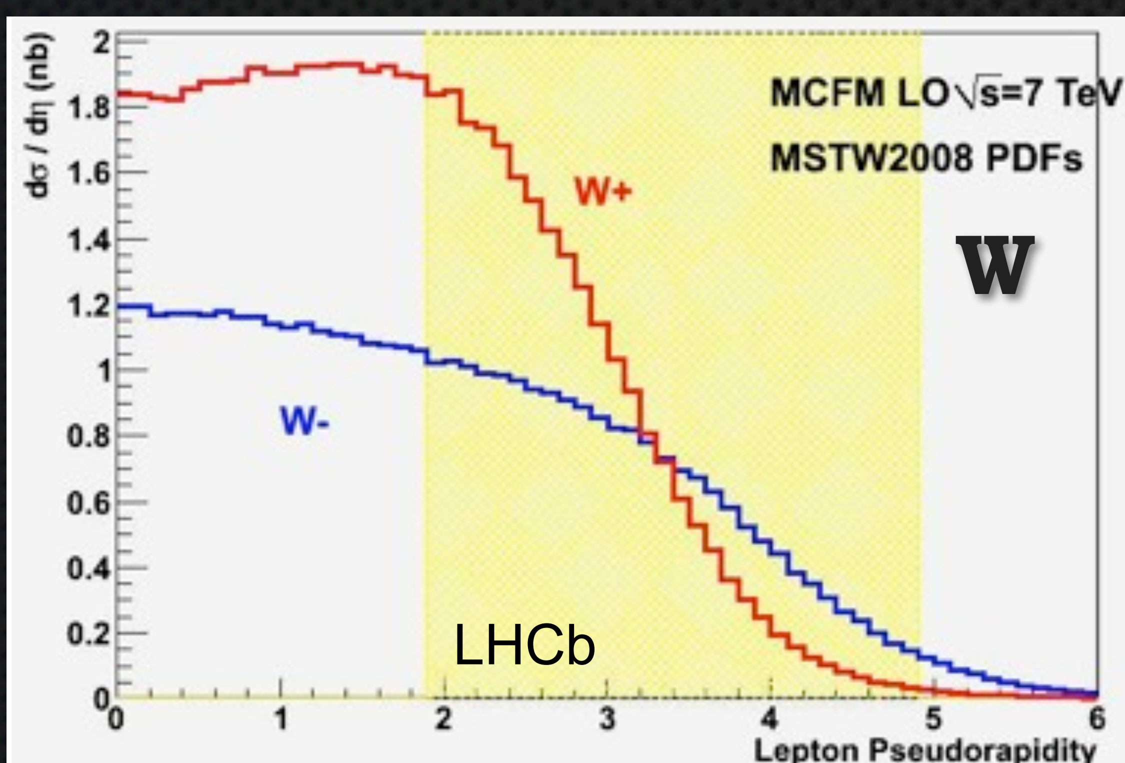
CMS-PAS-12-011

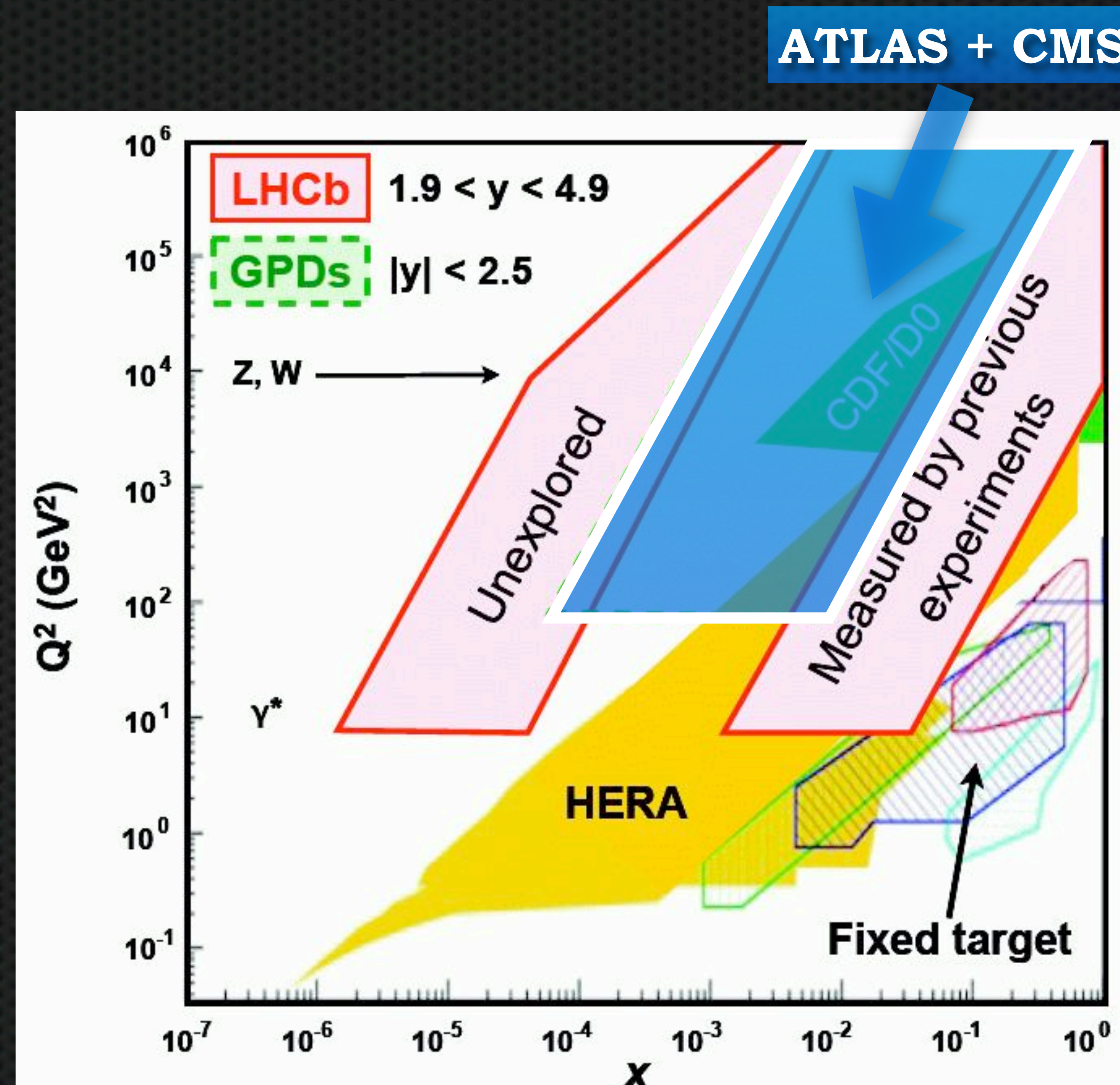


W and Z Production at LHCb

LHCb: Measurements extended up to |η₁| = 4.9



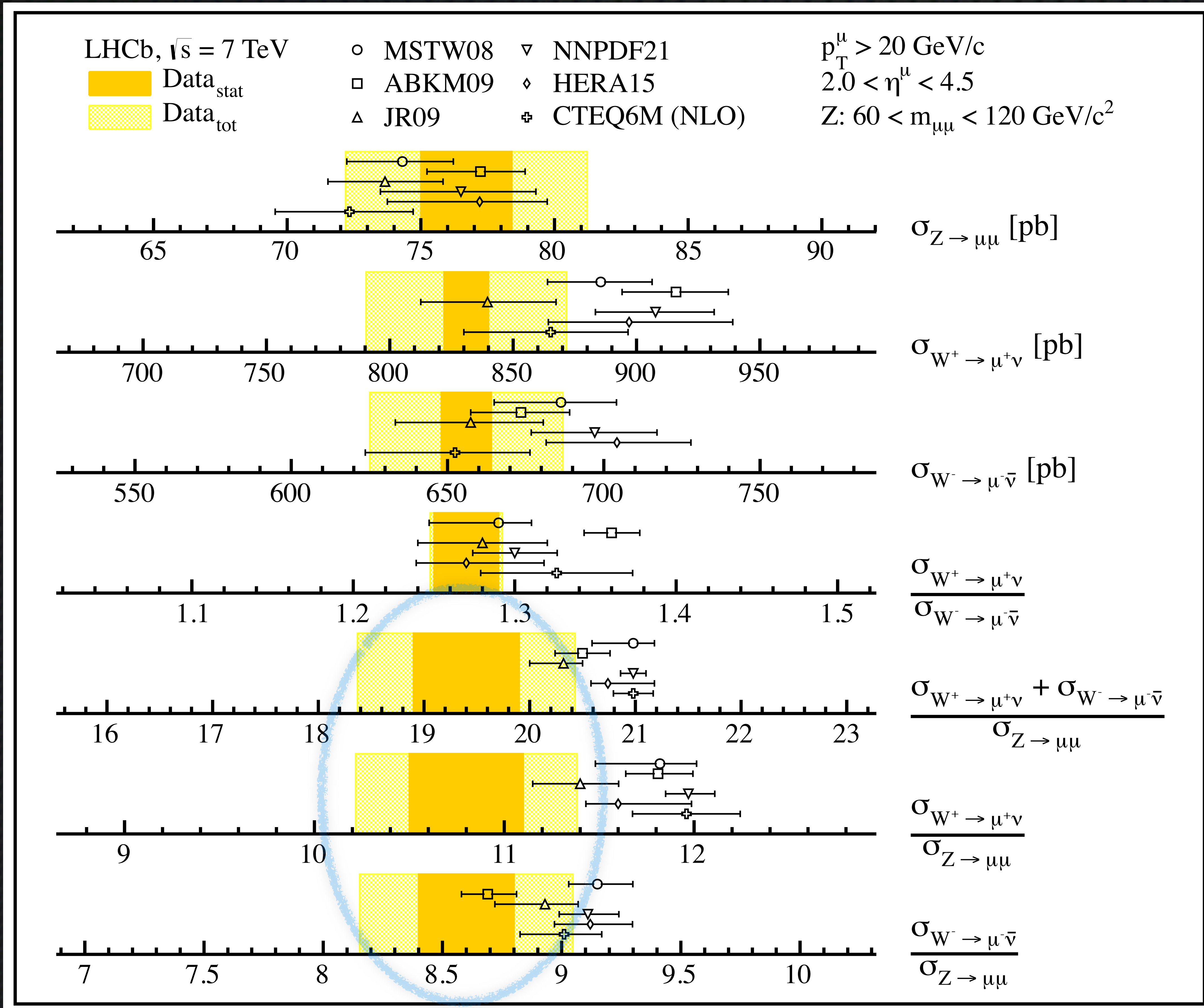




Important for PDF constraints

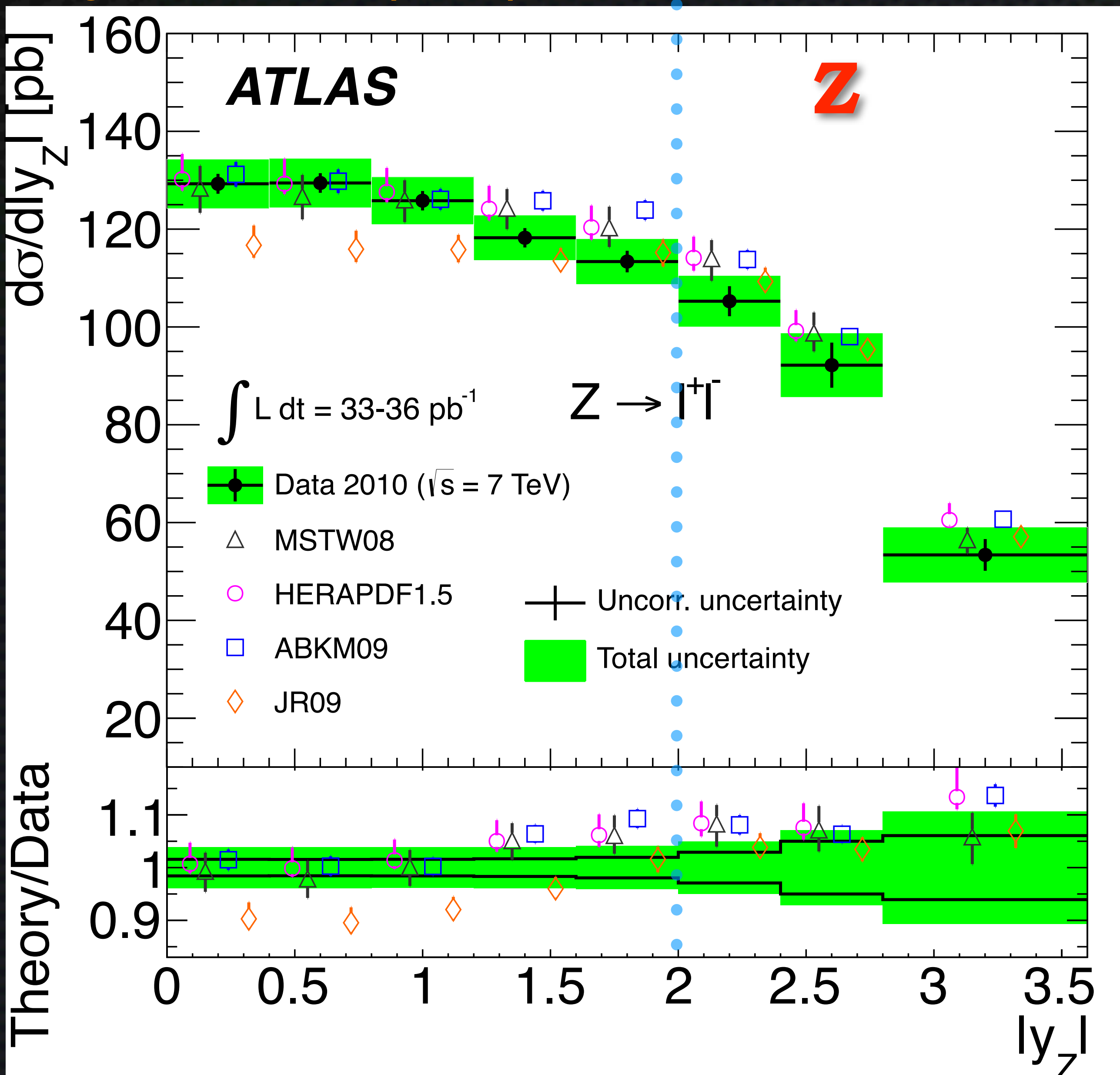
W and Z Production at LHCb

JHEP 06 (2012) 058

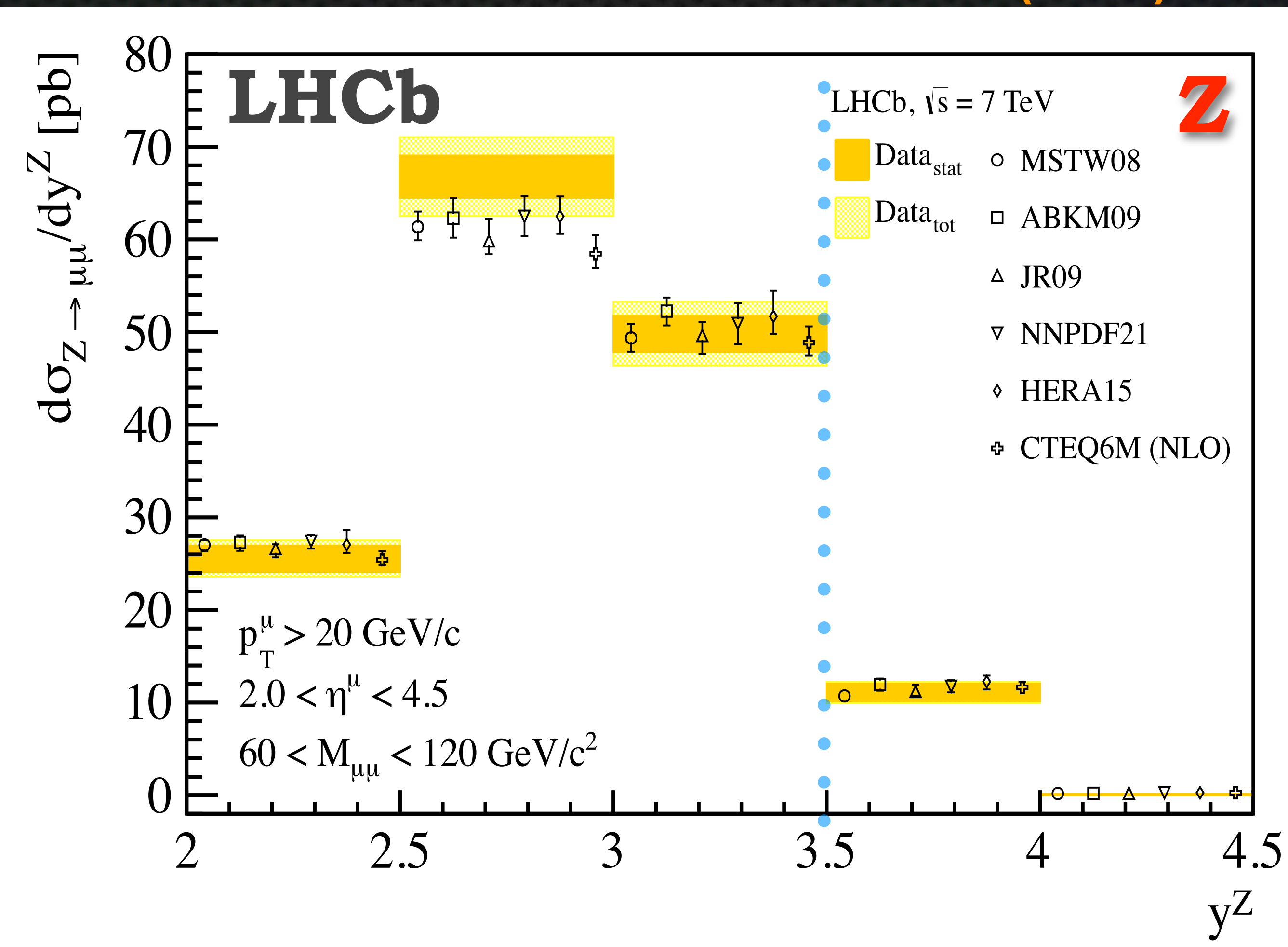


$d\sigma_Z/dy_Z$ versus NNLO PDF predictions

Phys. Rev. D85 (2012) 072004



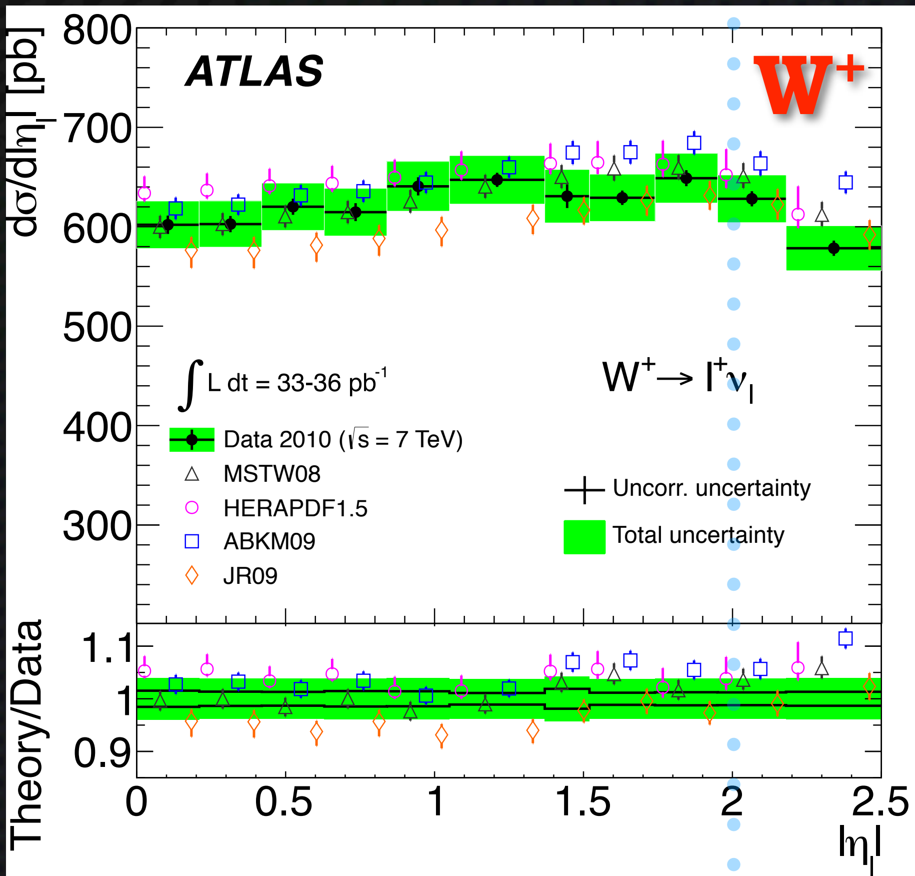
JHEP 06 (2012) 058

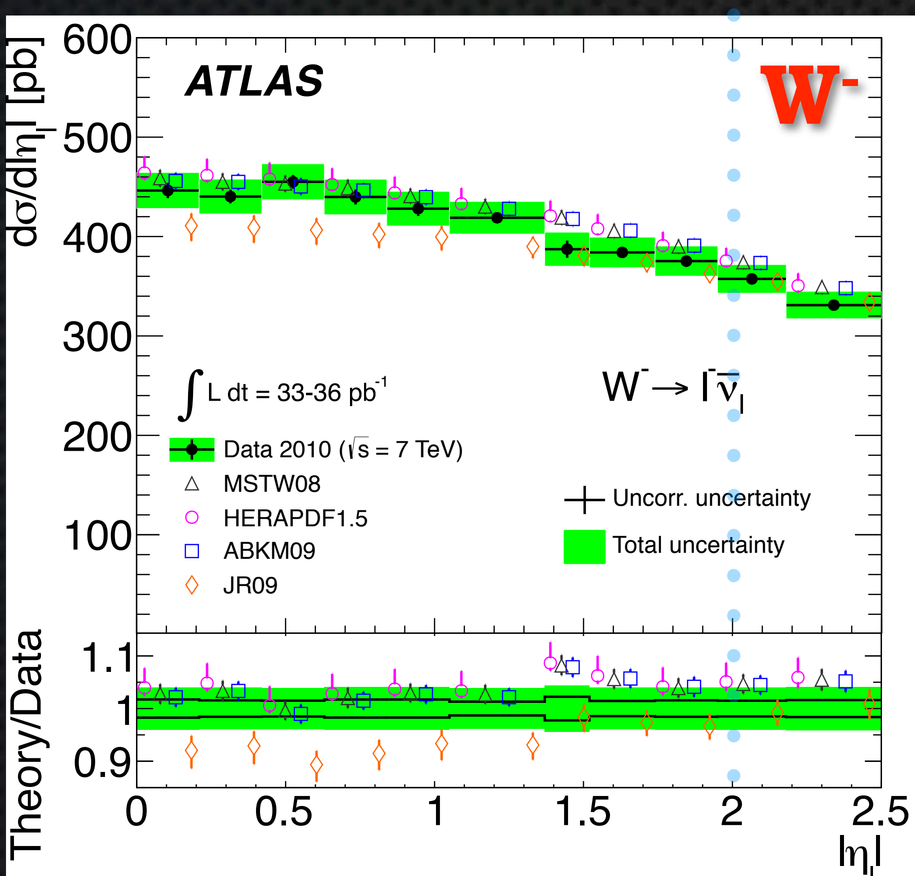


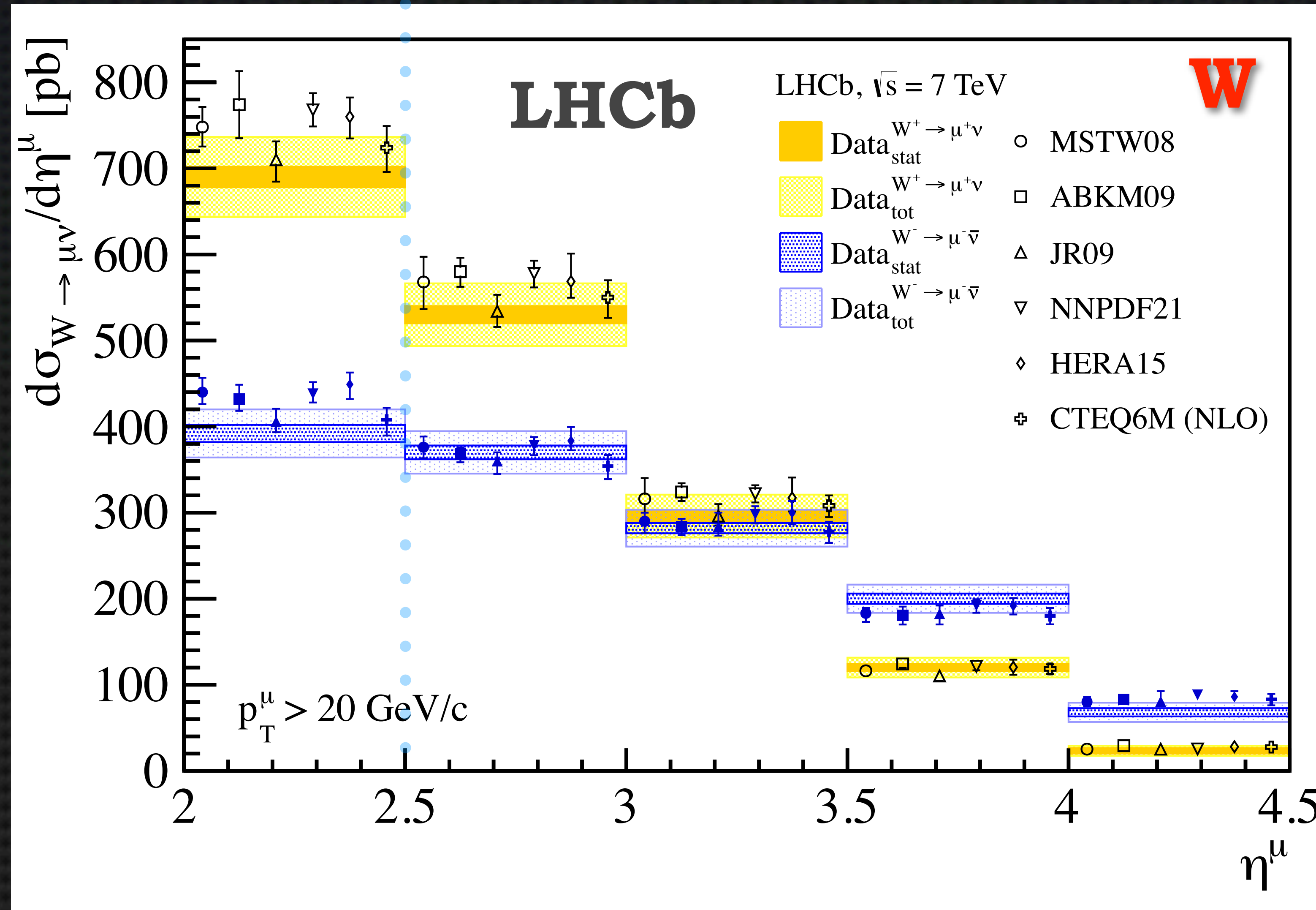
CMS Z rapidity measurement:
Phys. Rev. D 85 (2012) 032002

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

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



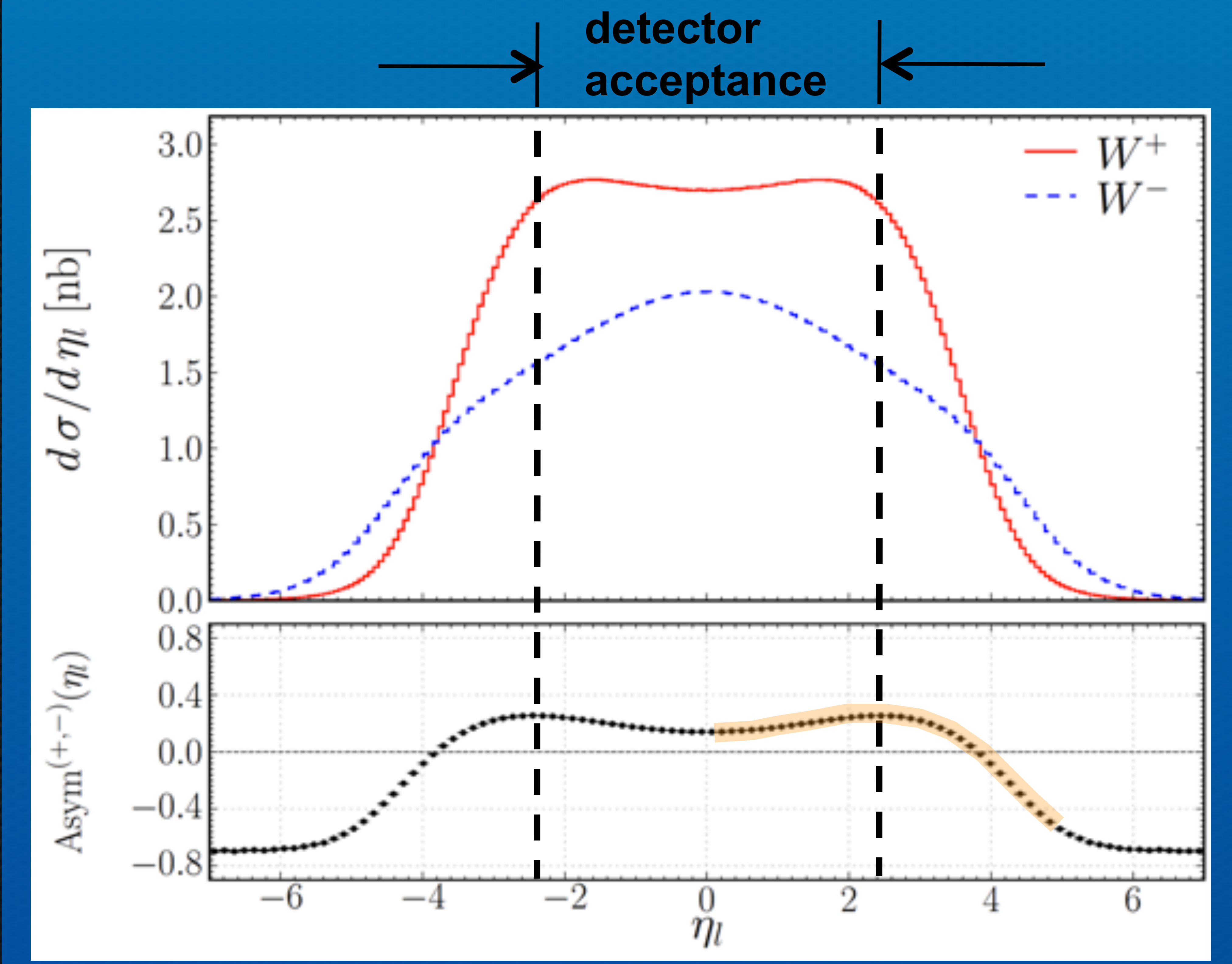




- **Broadly well described by predictions**
- **Can impact PDF central values and uncertainties**
  - **Information on u_v and d_v PDFs**

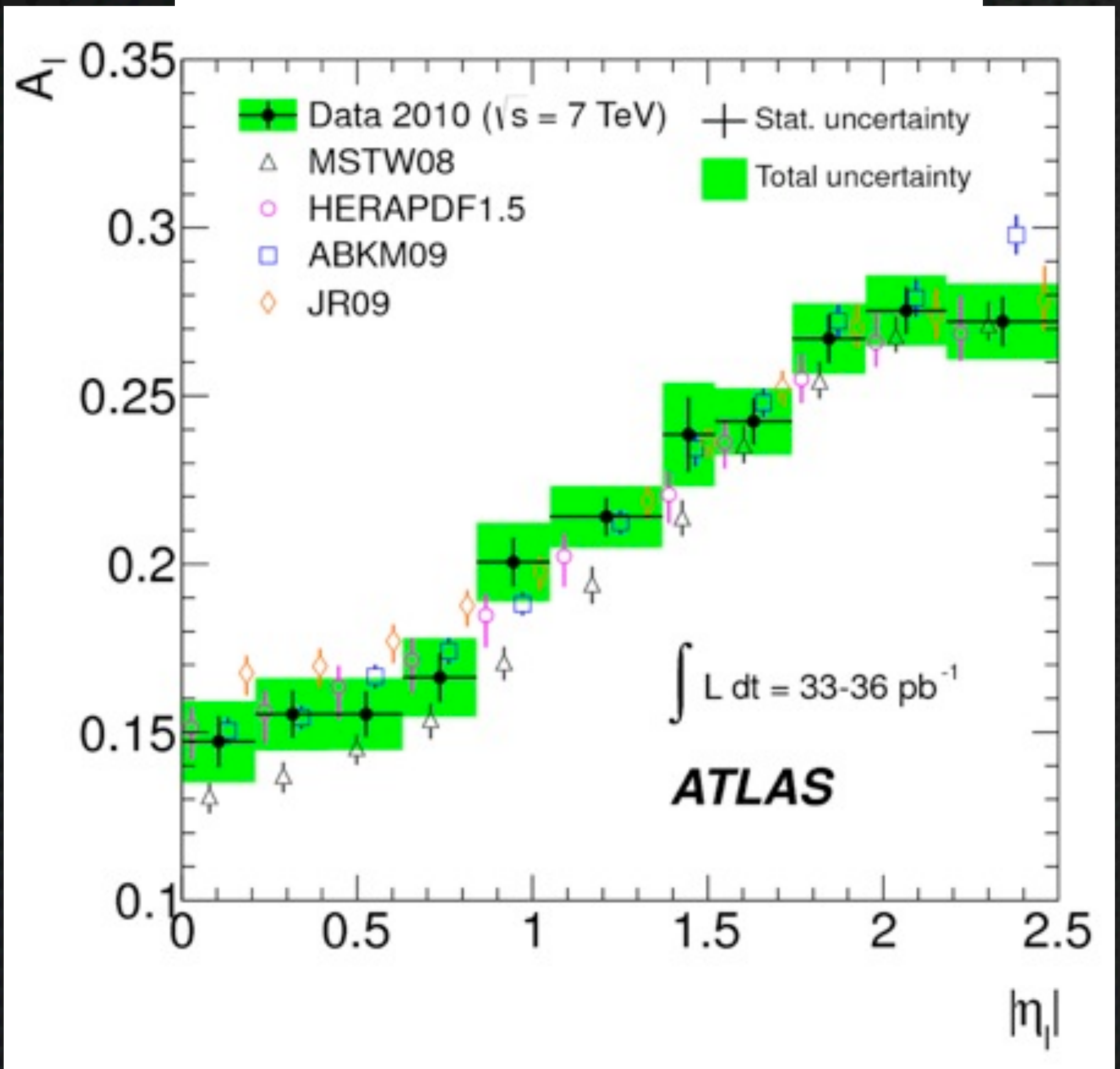
W-Lepton Charge Asymmetry

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

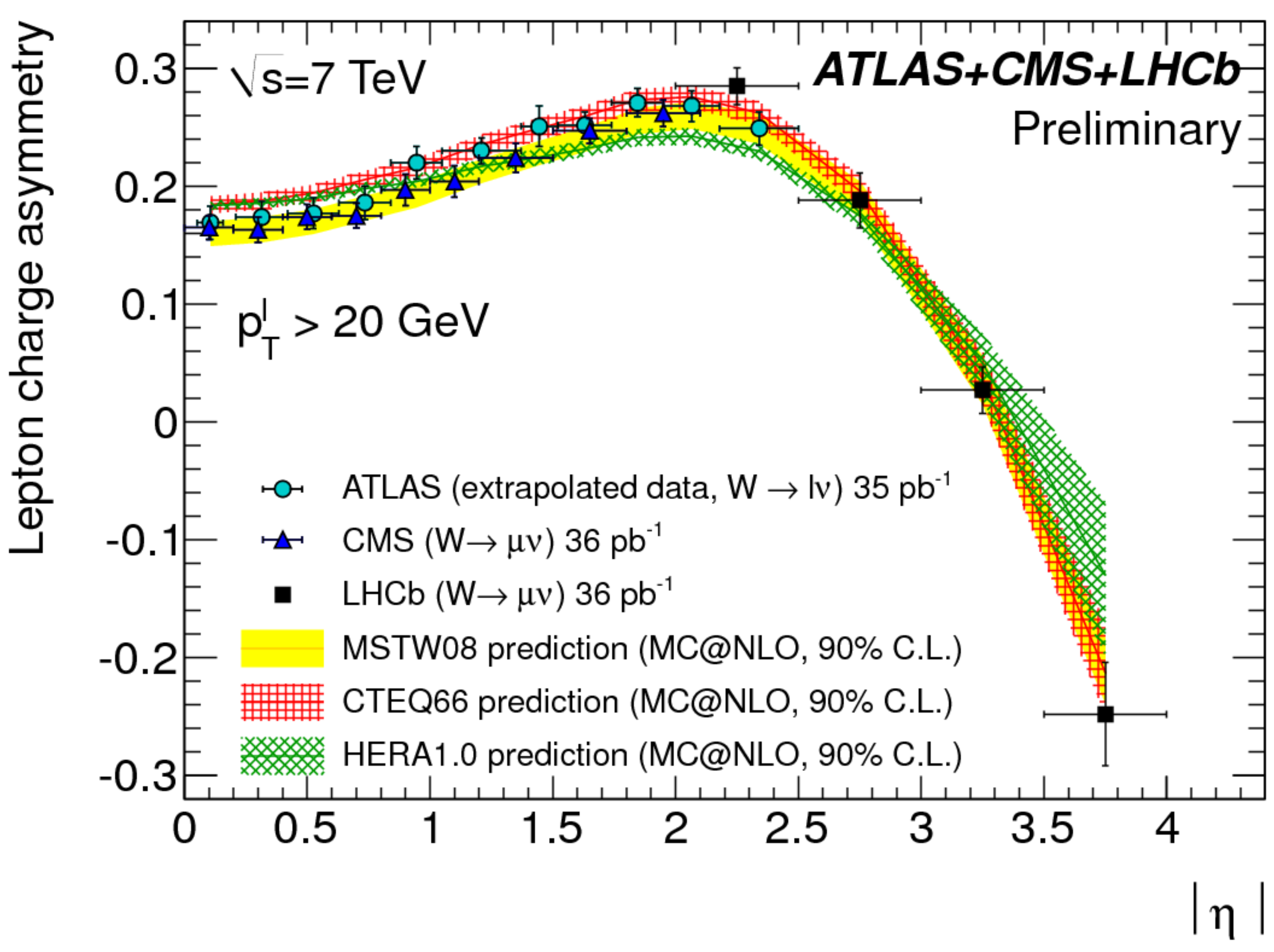


W-Lepton Charge Asymmetry

$$A(\eta_\ell) = \frac{d\sigma_{W+}(\eta_\ell) - d\sigma_{W-}(\eta_\ell)}{d\sigma_{W+}(\eta_\ell) + d\sigma_{W-}(\eta_\ell)}$$



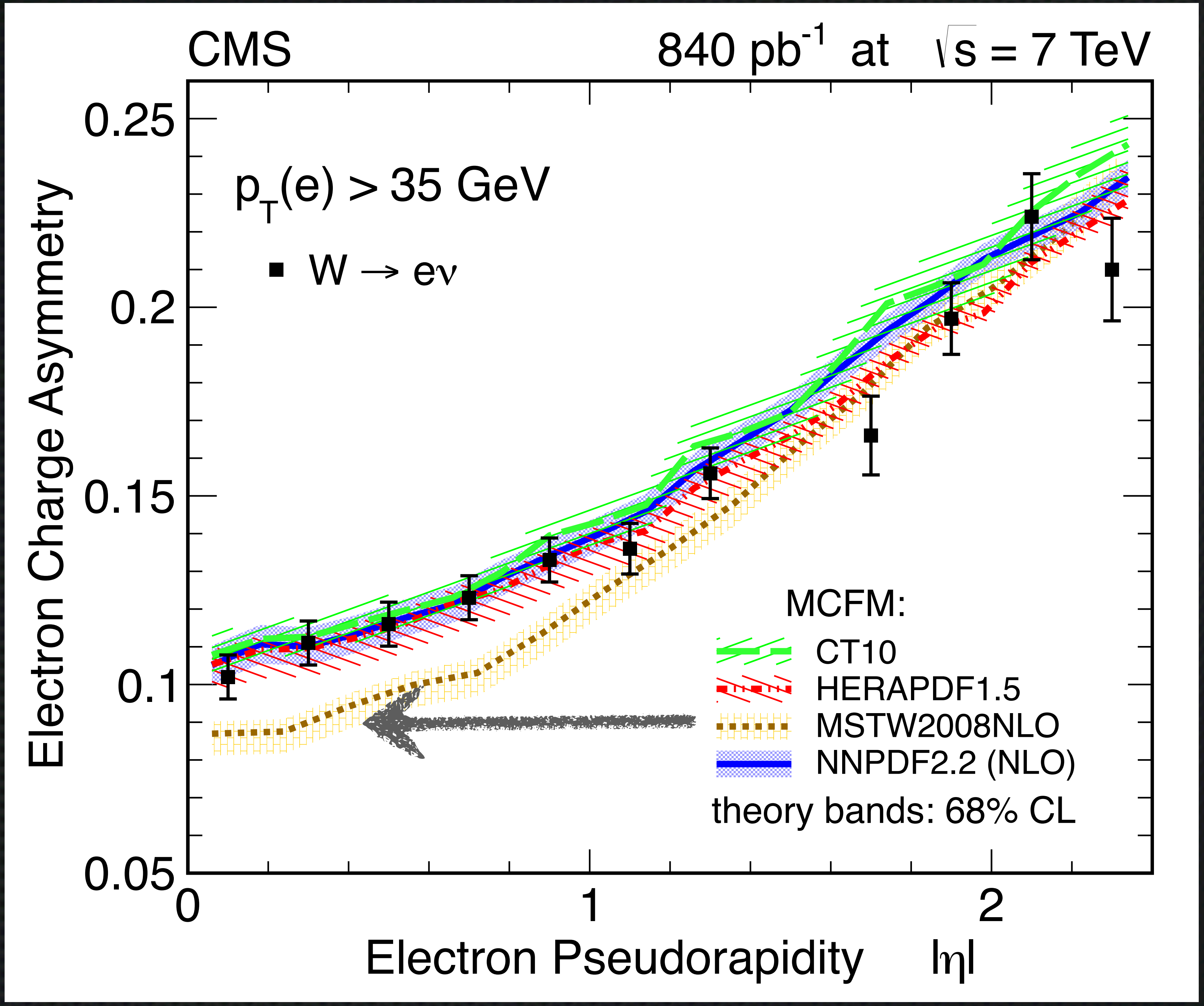
ATLAS-CONF-2011-129



First LHC combined plot (LHC EWK WG)

W charge asymmetry: update

arXiv:1206.2598



Discrimination between PDF at low |η|

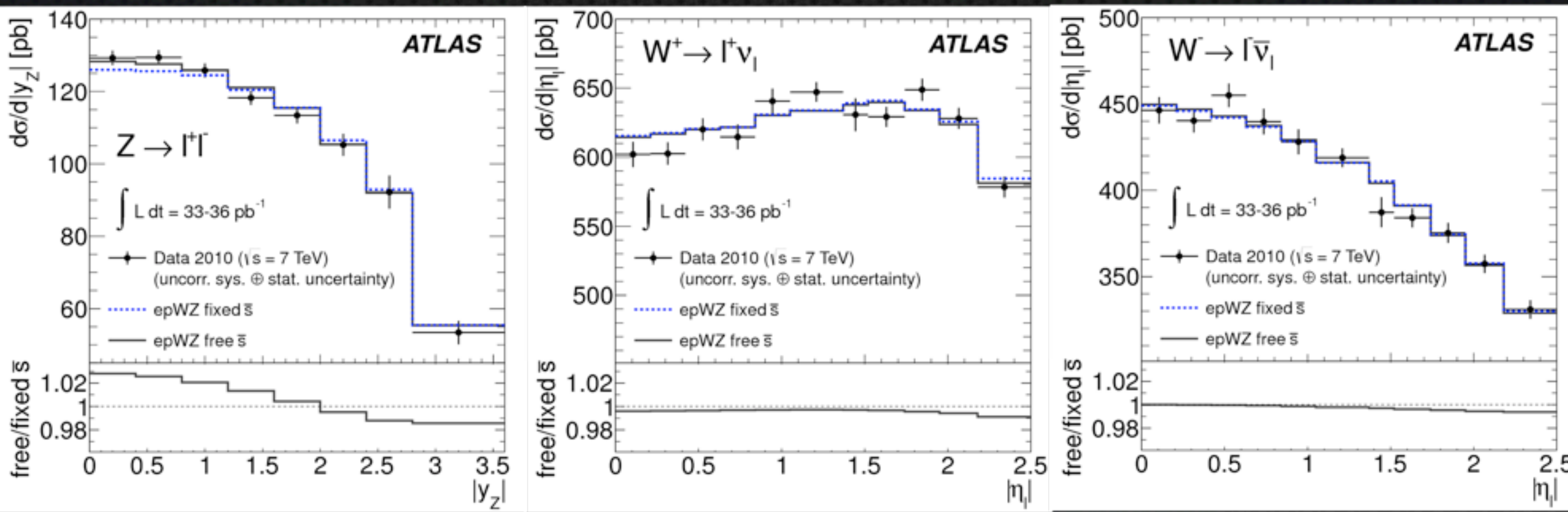
Strangeness in the Proton (from W and Z data)

Phys.Rev.Lett. 109 (2012) 012001

- **QCD fit of ATLAS differential distributions for W^+, W^- and Z with HERA $e^{\pm}p$ DIS data**
  - **NNLO pQCD analysis**
    - **HERAFitter framework with MCFM+APPLGRID NLO QCD**
    - **Corrected to NNLO QCD using k factors**

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

r_s = 0.5 fixed: χ^2/ndf = 44.5/30
r_s free: χ^2/ndf = 33.9/30



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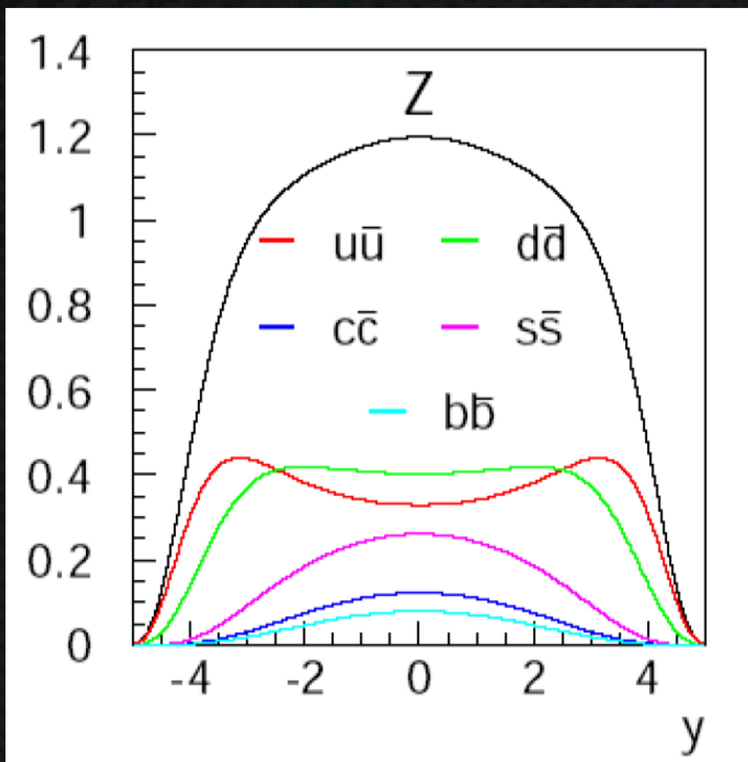
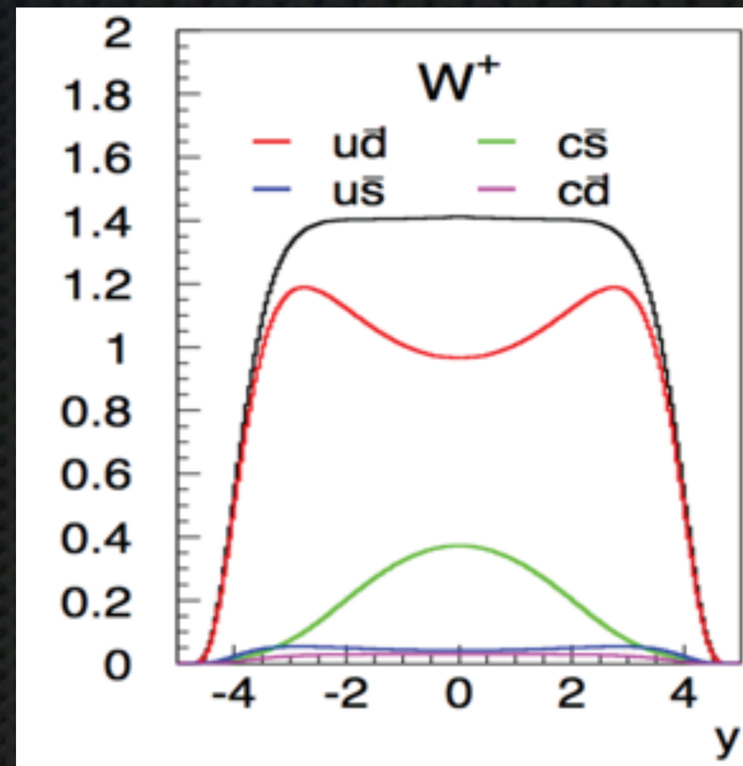
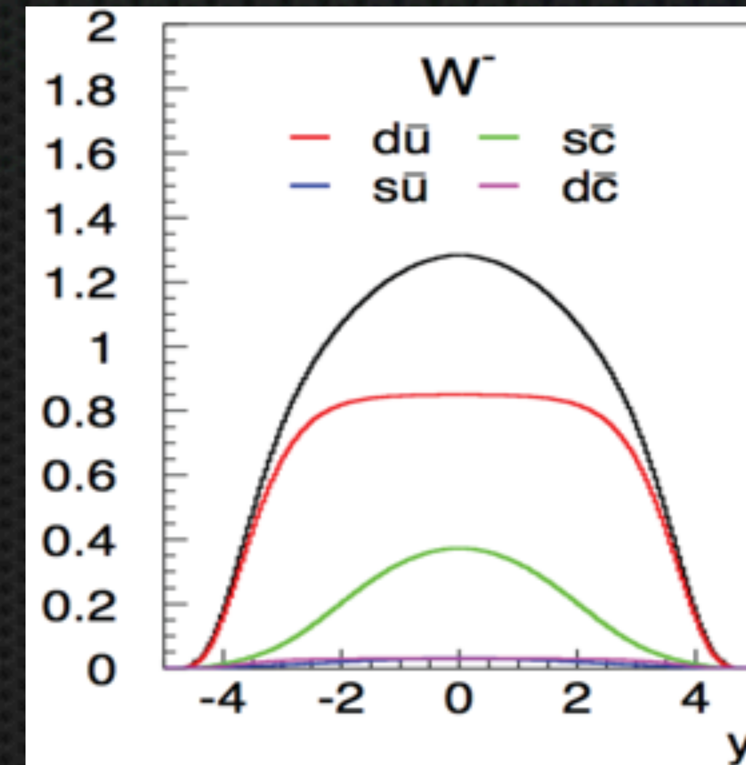
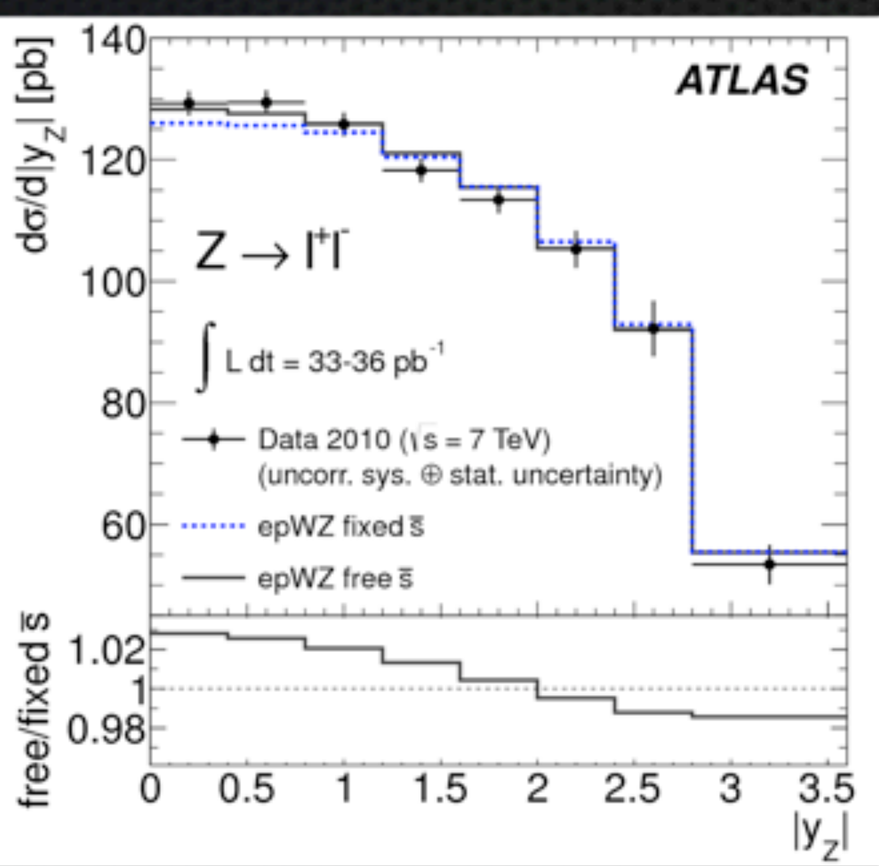
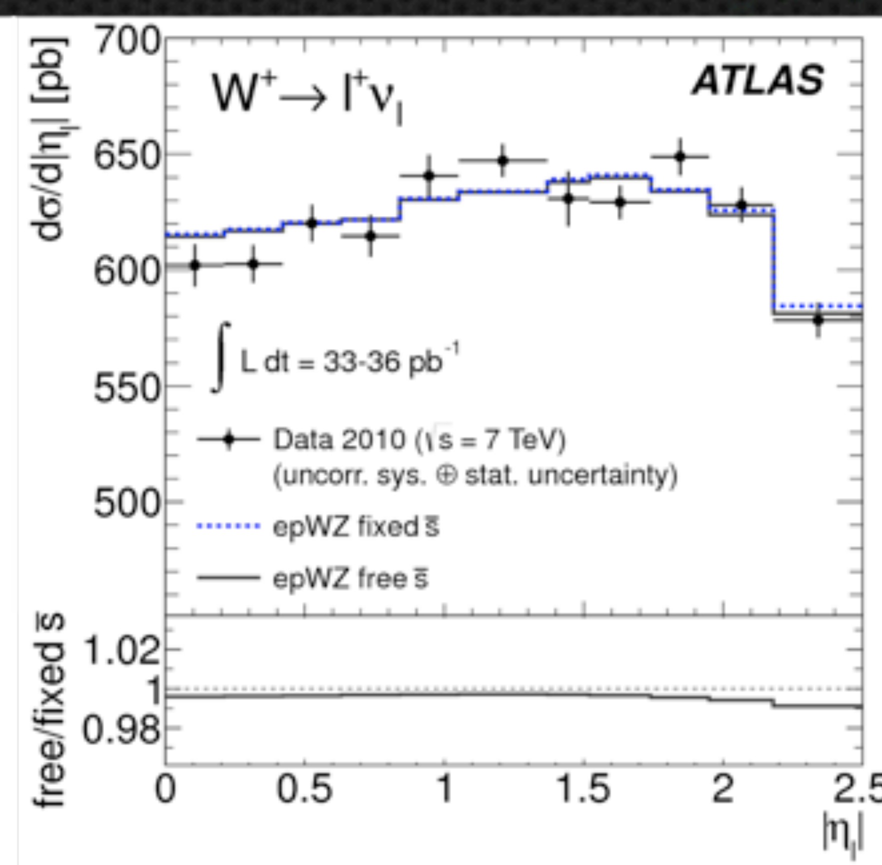
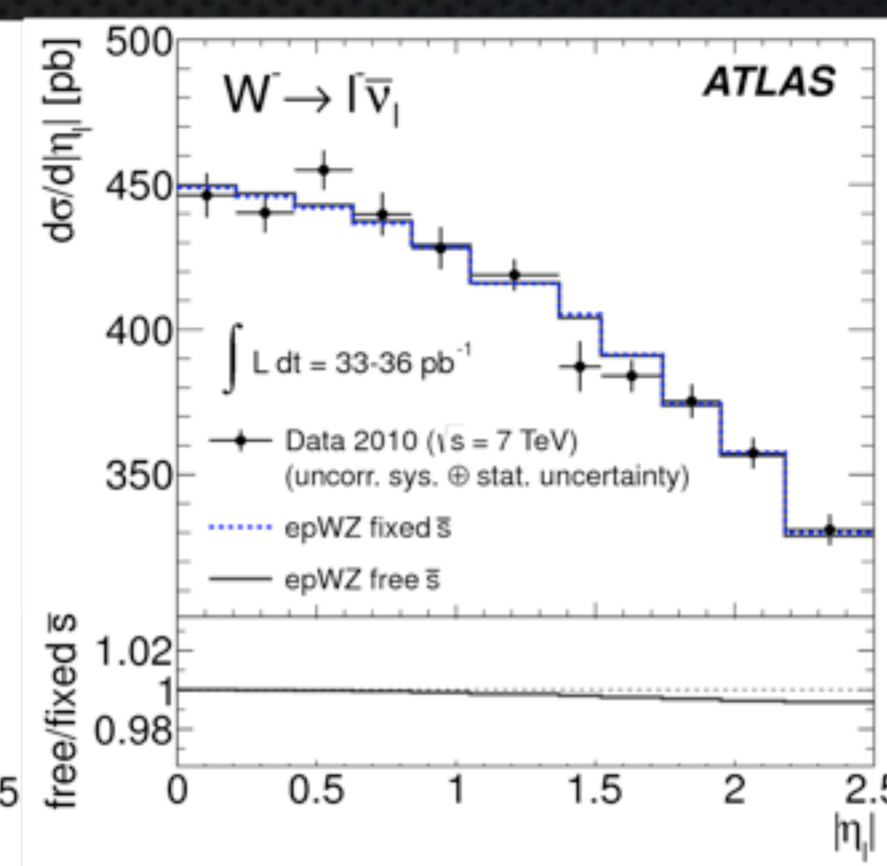








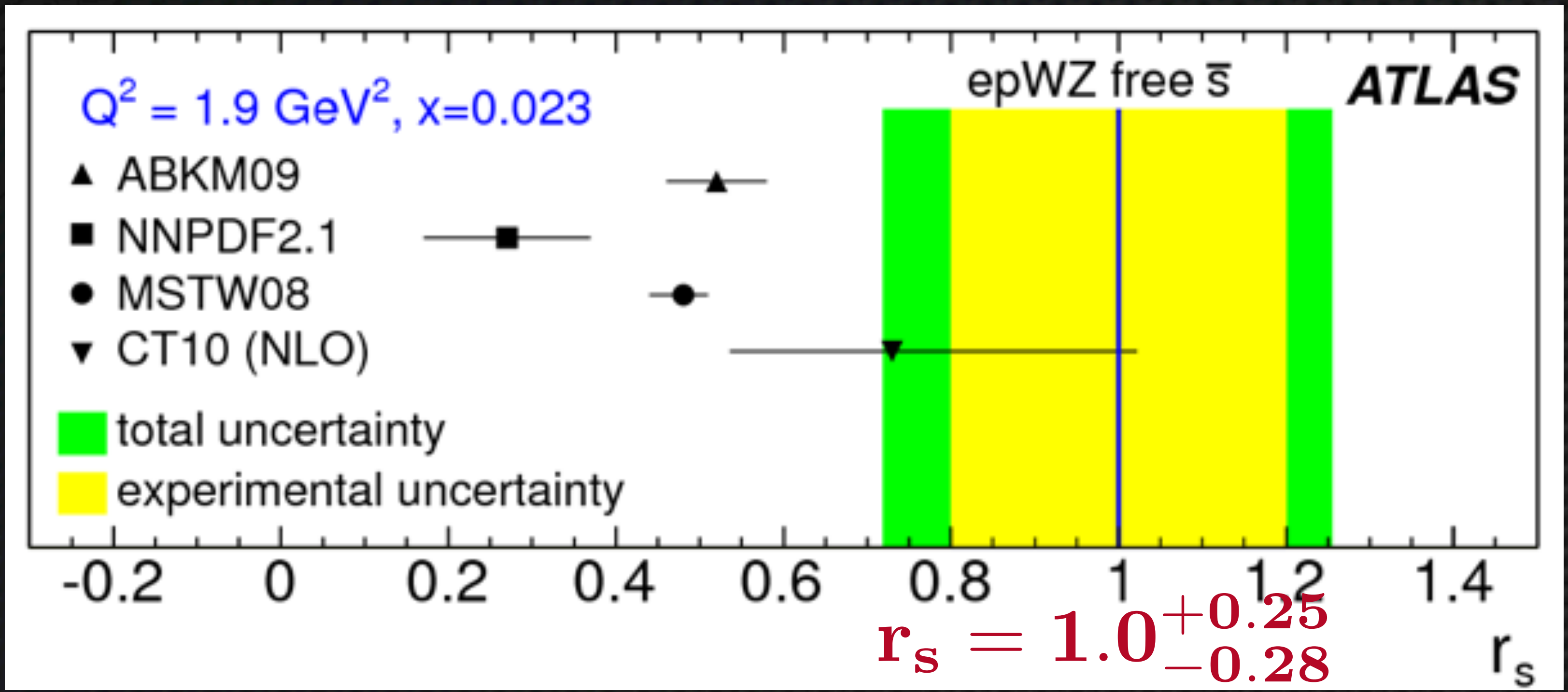




Strangeness in the Proton

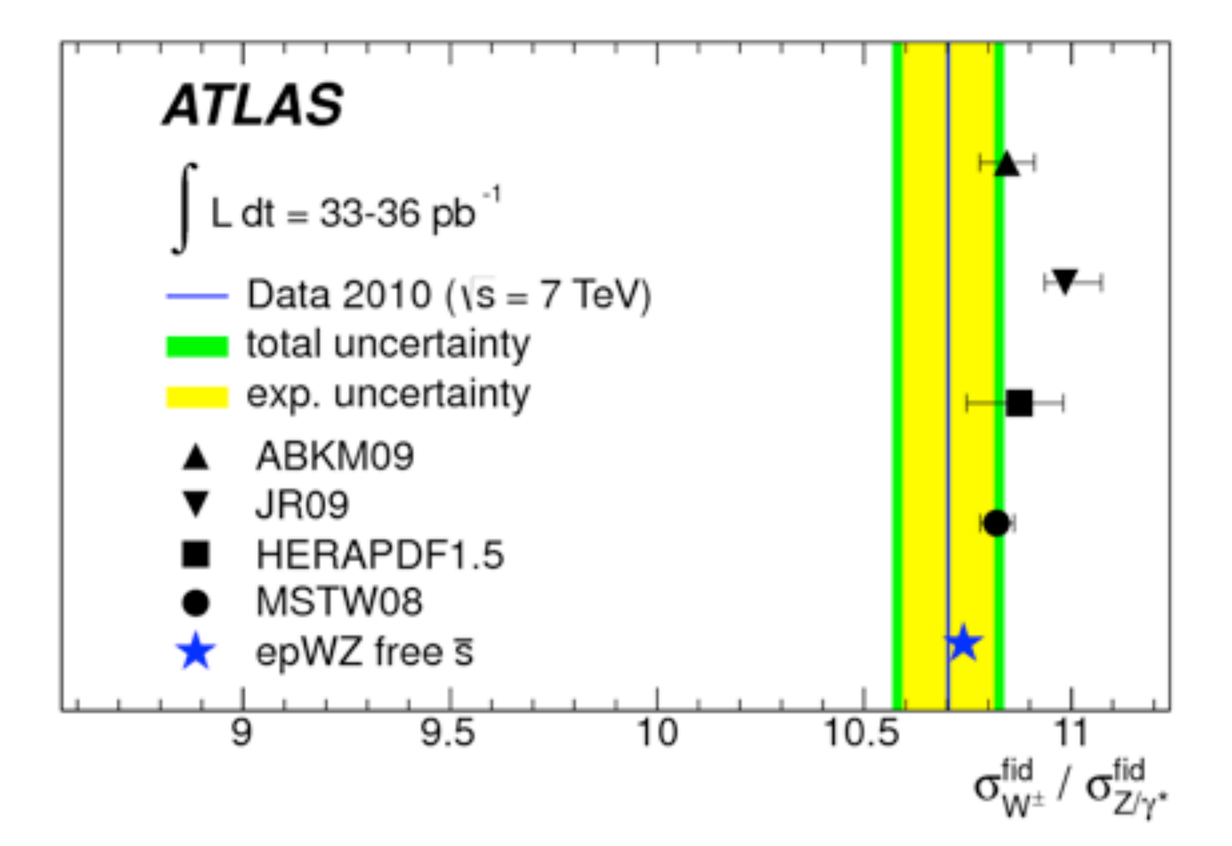
Phys.Rev.Lett. 109 (2012) 012001

- **No strange sea suppresion observed**



$r_s = 1.0^{+0.25}_{-0.28}$

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

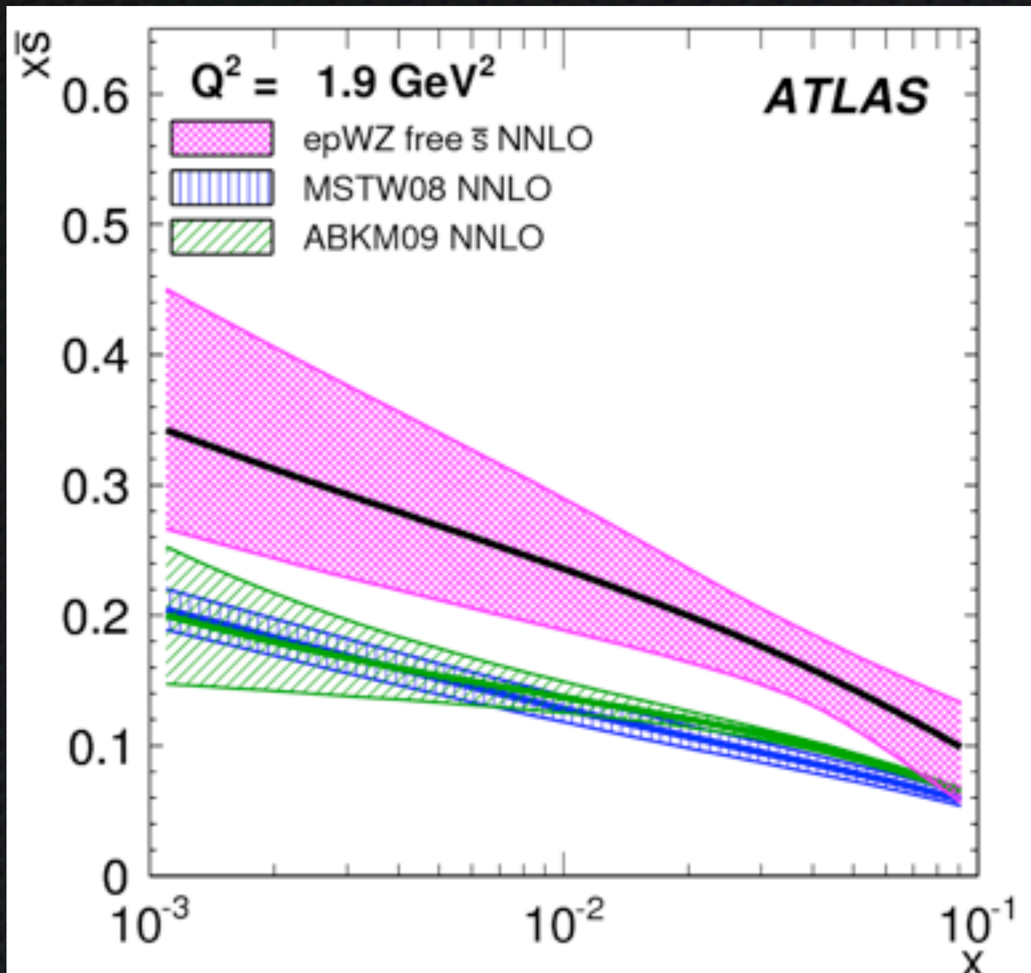


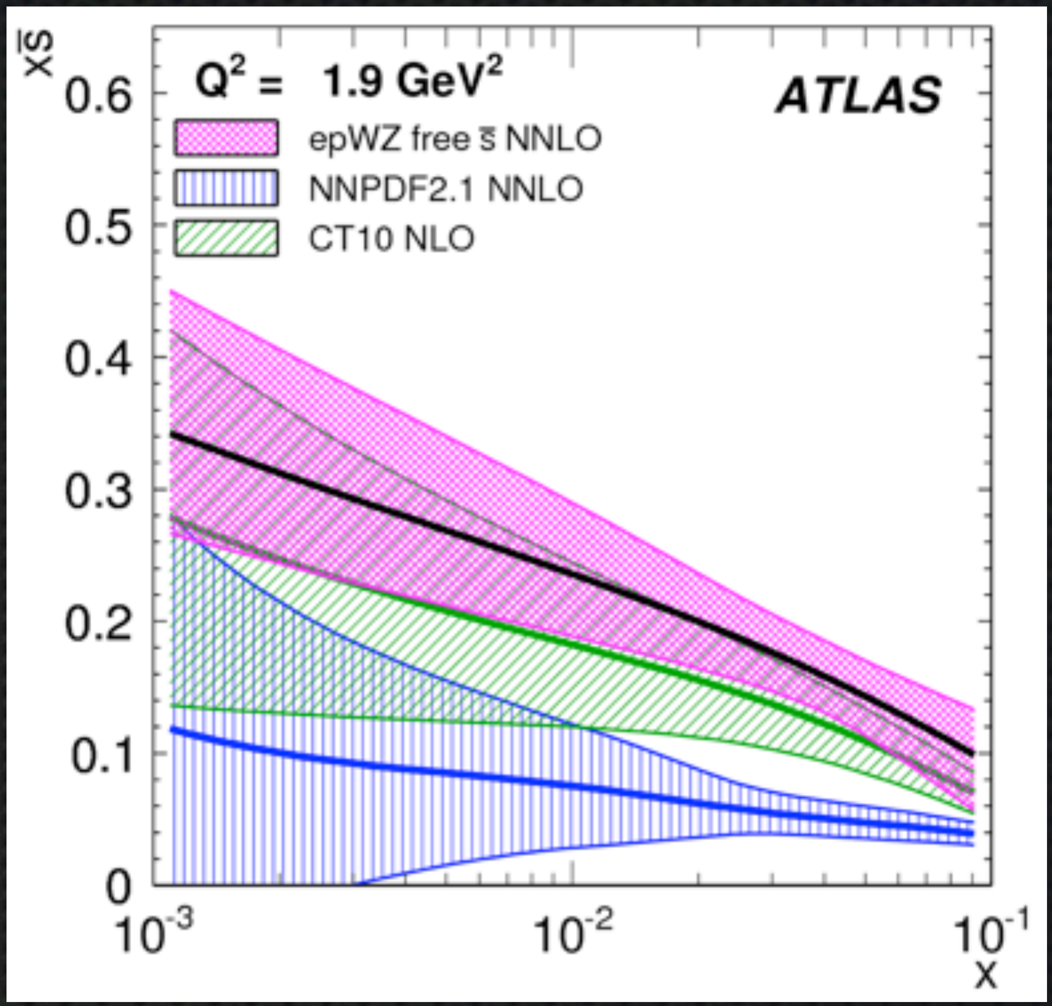
Fit results:

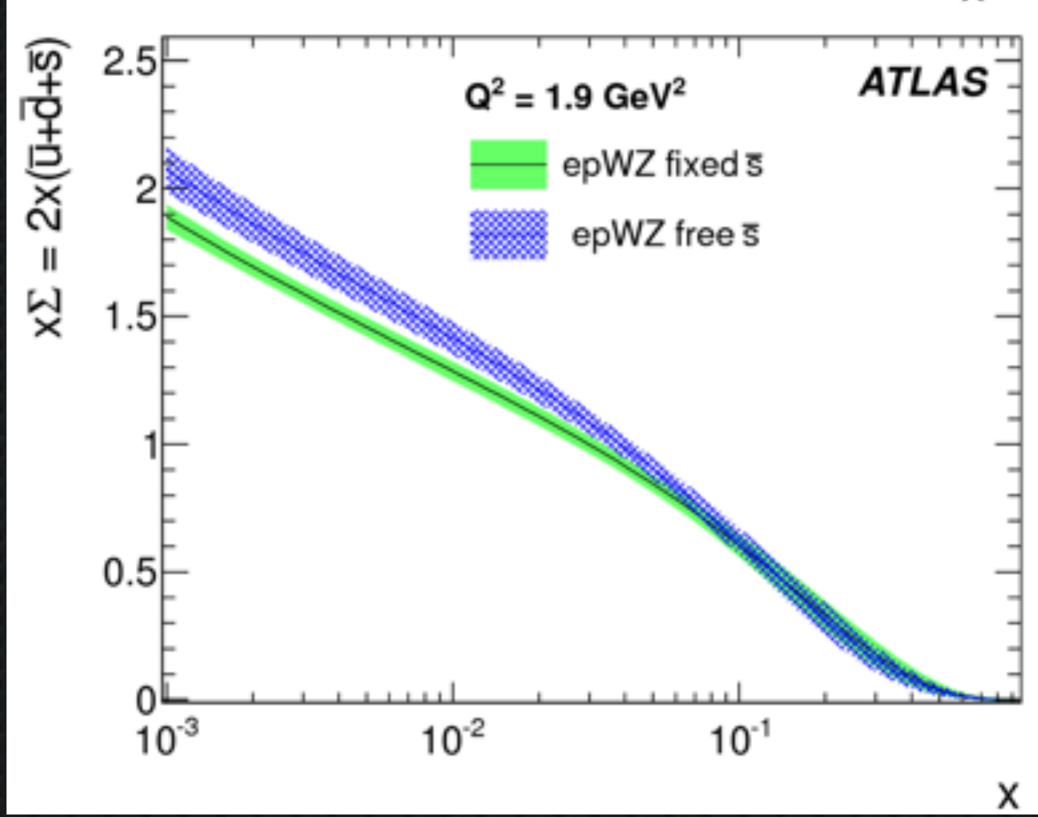
- **Light quark sea at low *x* is flavor symmetric** (x ~0.023, Q^2 = 1.9 GeV^2)

Strangeness in the Proton (from W and Z data)

Phys.Rev.Lett. 109 (2012) 012001







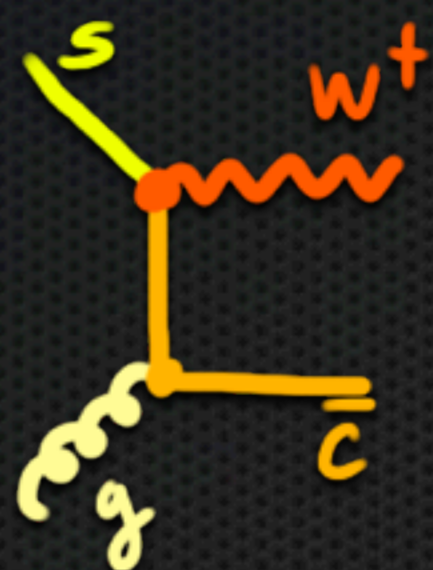
Fit results:

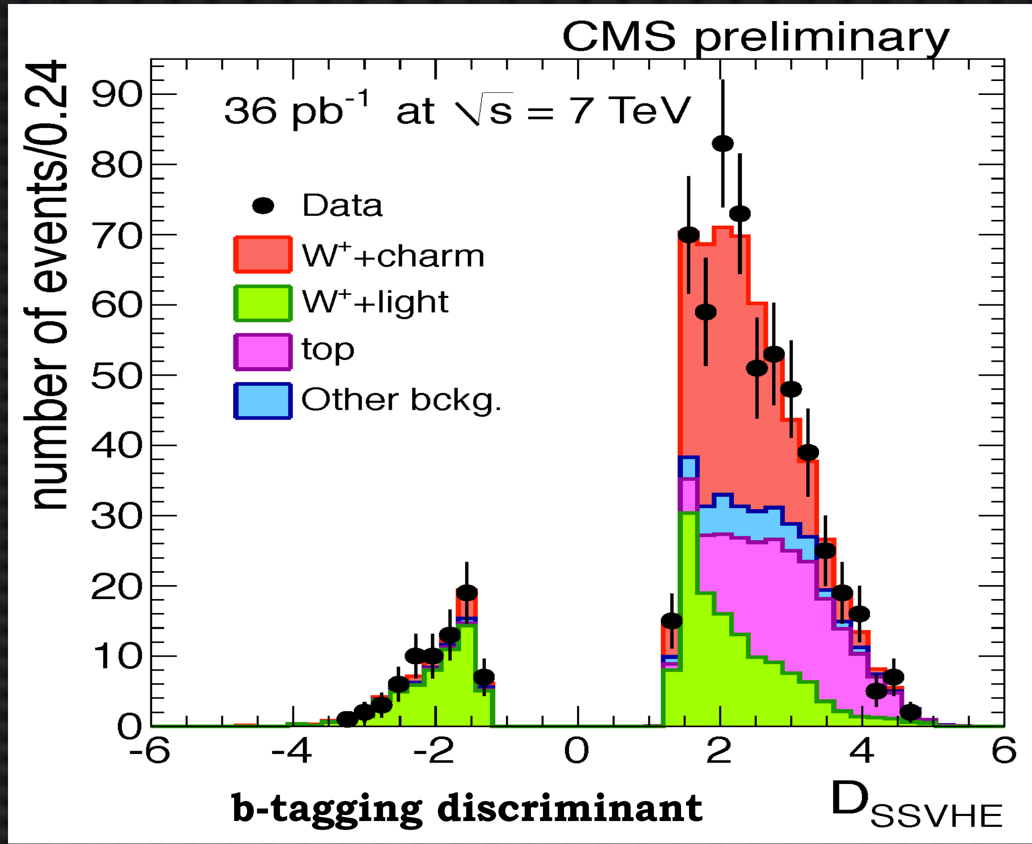
- Light quark sea at low x is flavor symmetric (x ~0.023, Q^2 = 1.9 GeV^2)
- Total sea enhancement of 8%

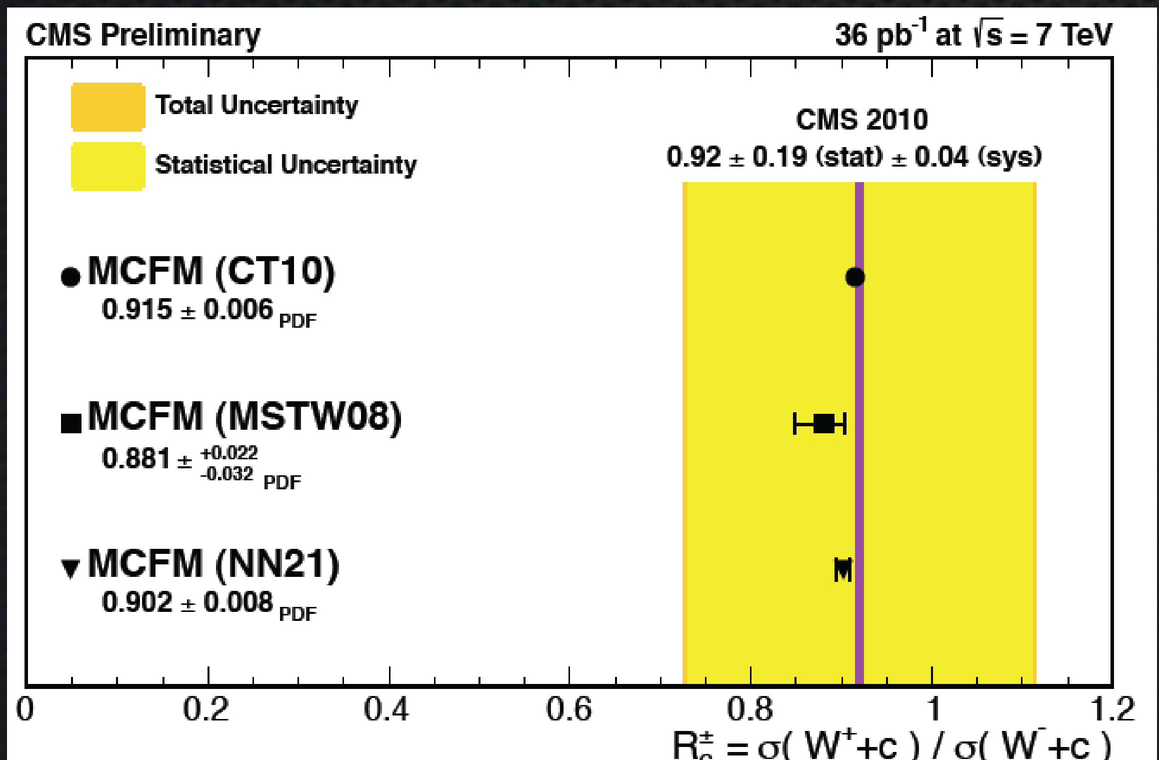
W + Charm Production at LHC

Direct probe of the strange PDF

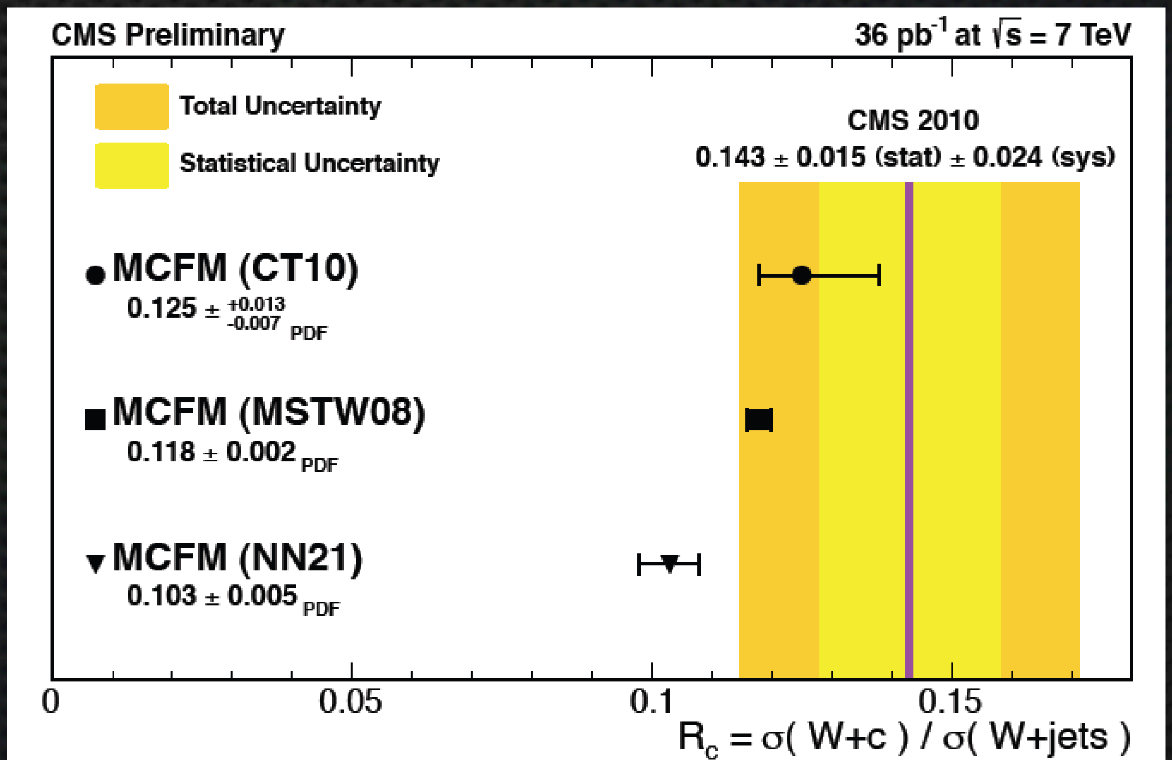
~10% of W+jets events have charm







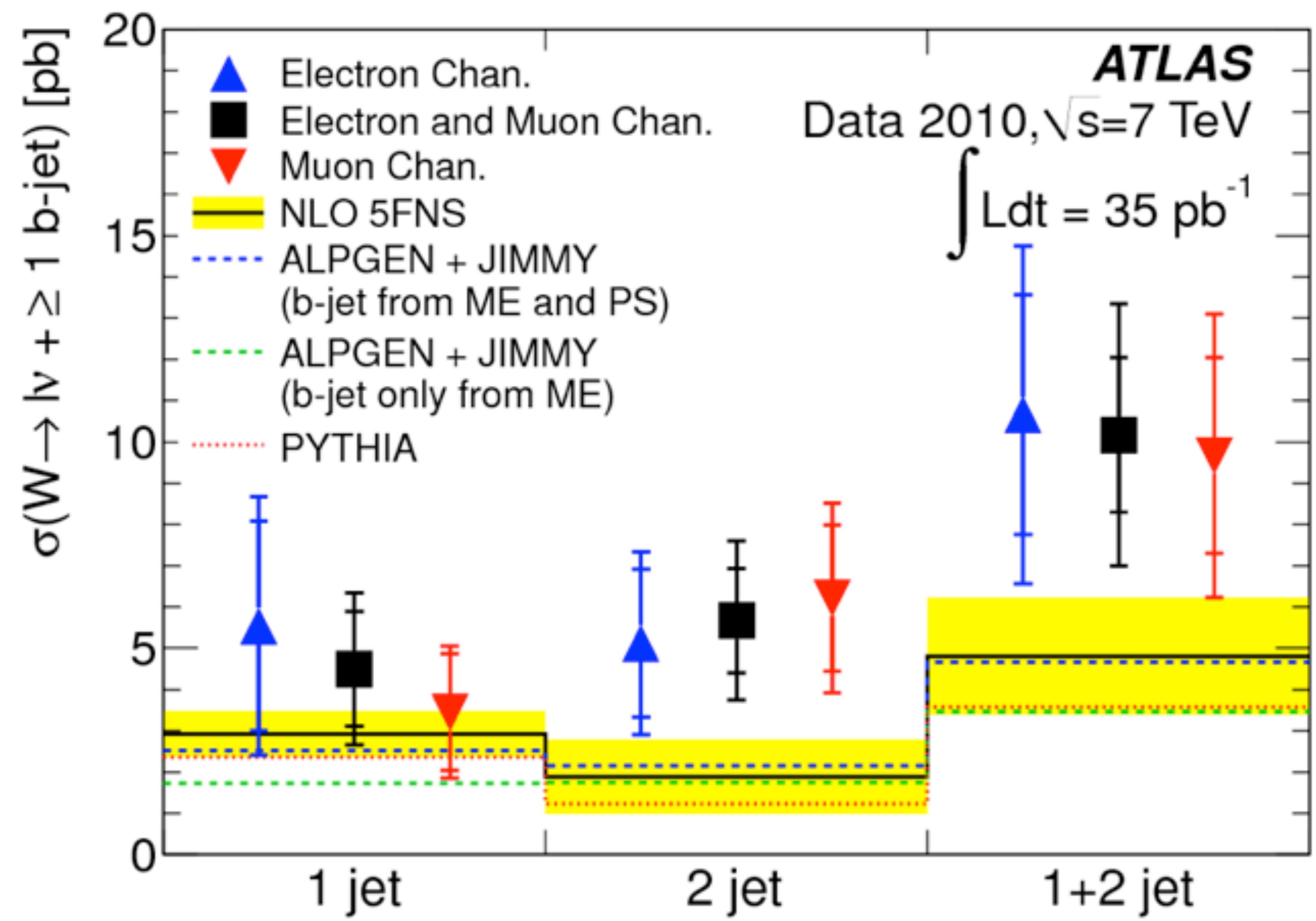
$$\frac{\sigma\left(W^{+}+charm\right)}{\sigma\left(W^{-}+charm\right)}=0.92\pm0.19\left(stat.\right)\pm0.04\left(syst.\right)$$



$$\frac{\sigma\left(W+charm\right)}{\sigma\left(W+jets\right)}=0.142\pm0.015\left(stat.\right)\pm0.024\left(syst.\right)$$

W + b Production at LHC

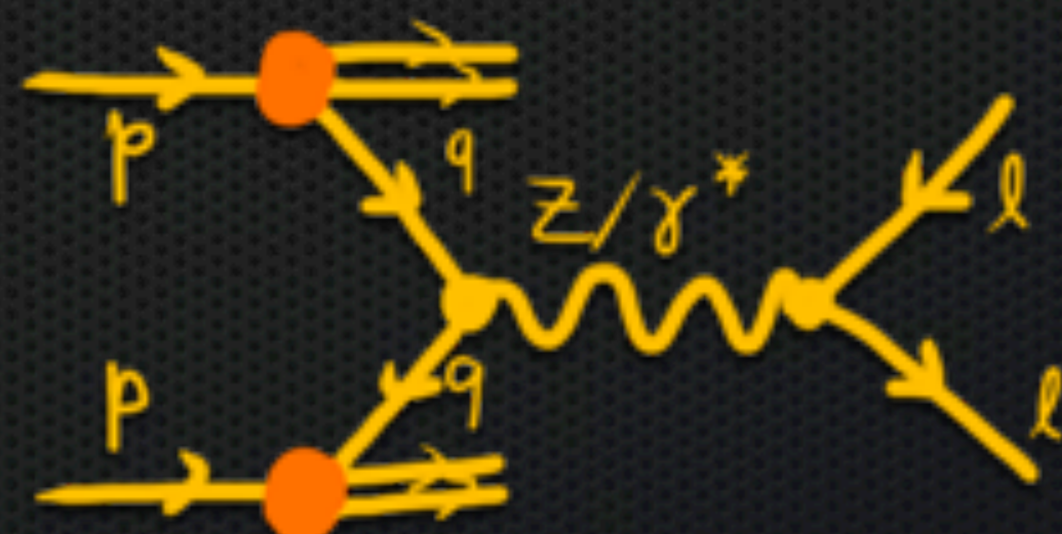
Important background for Higgs and top



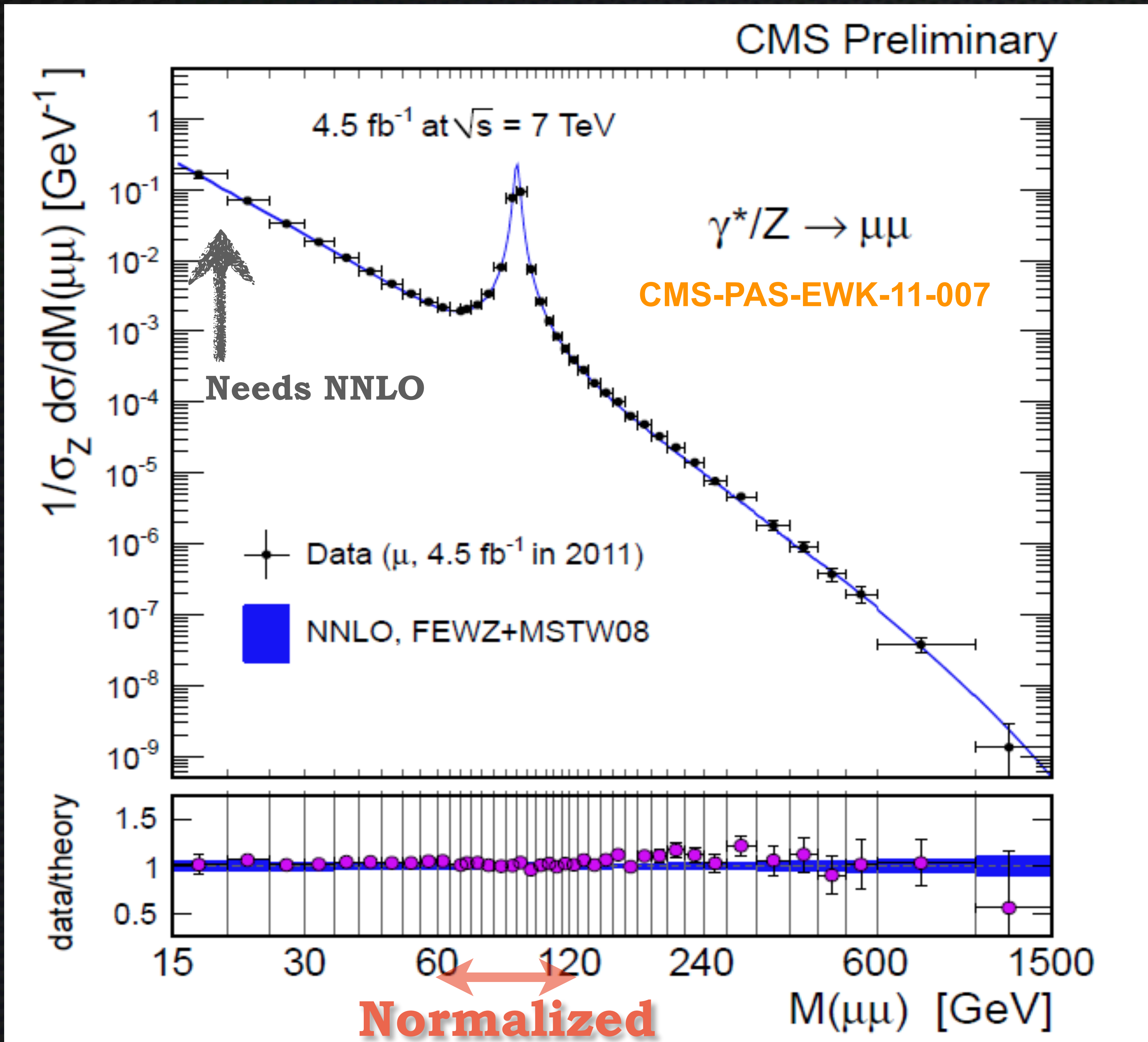
PDF uncertainties: ~ 7%

Agreement with theoretical expectations at 1.5 σ level

Drell-Yan Production



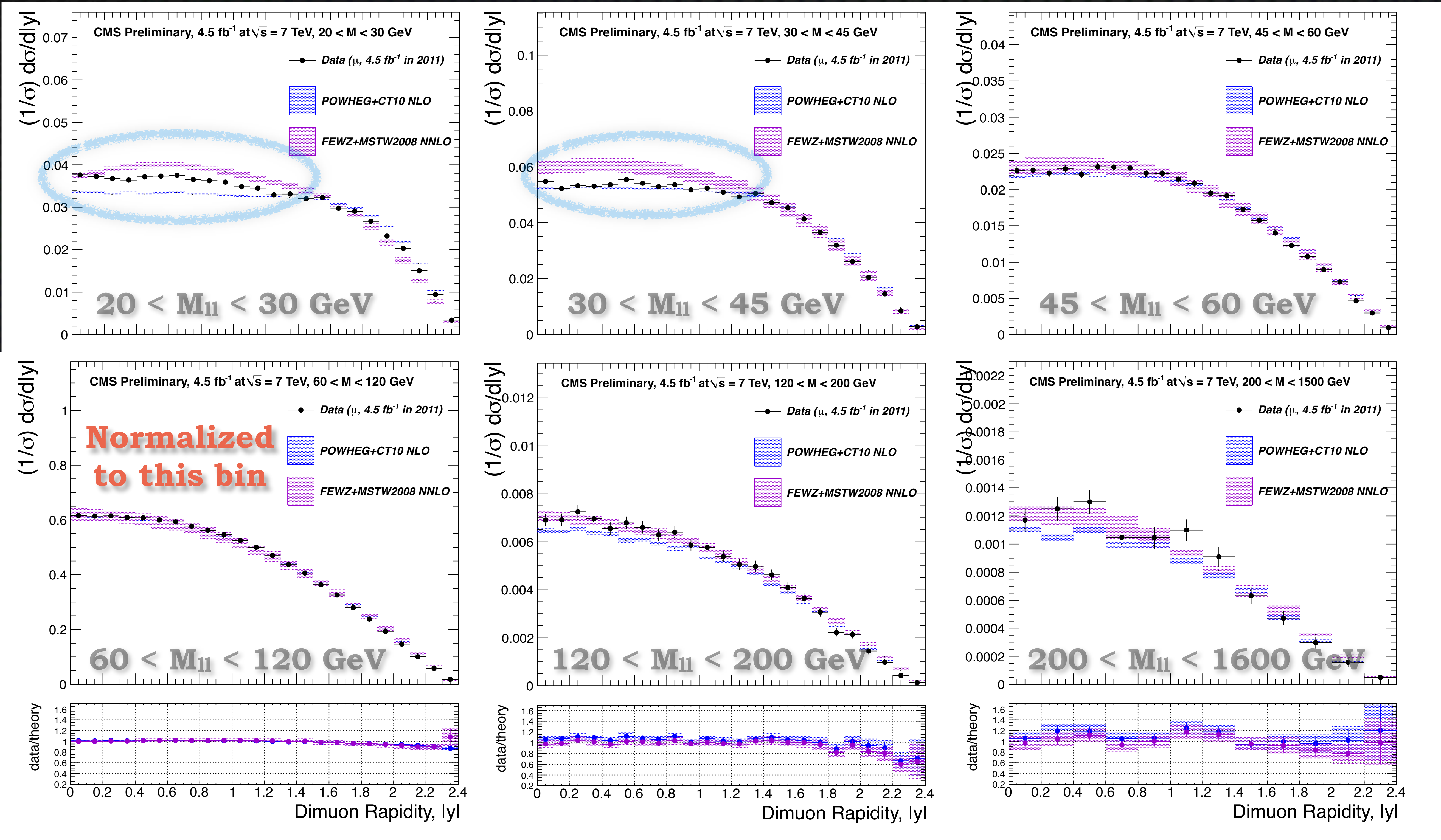
Drell-Yan Production at LHC



Low-mass DY constraints **low-x** region

DY double-differential cross section (CMS)

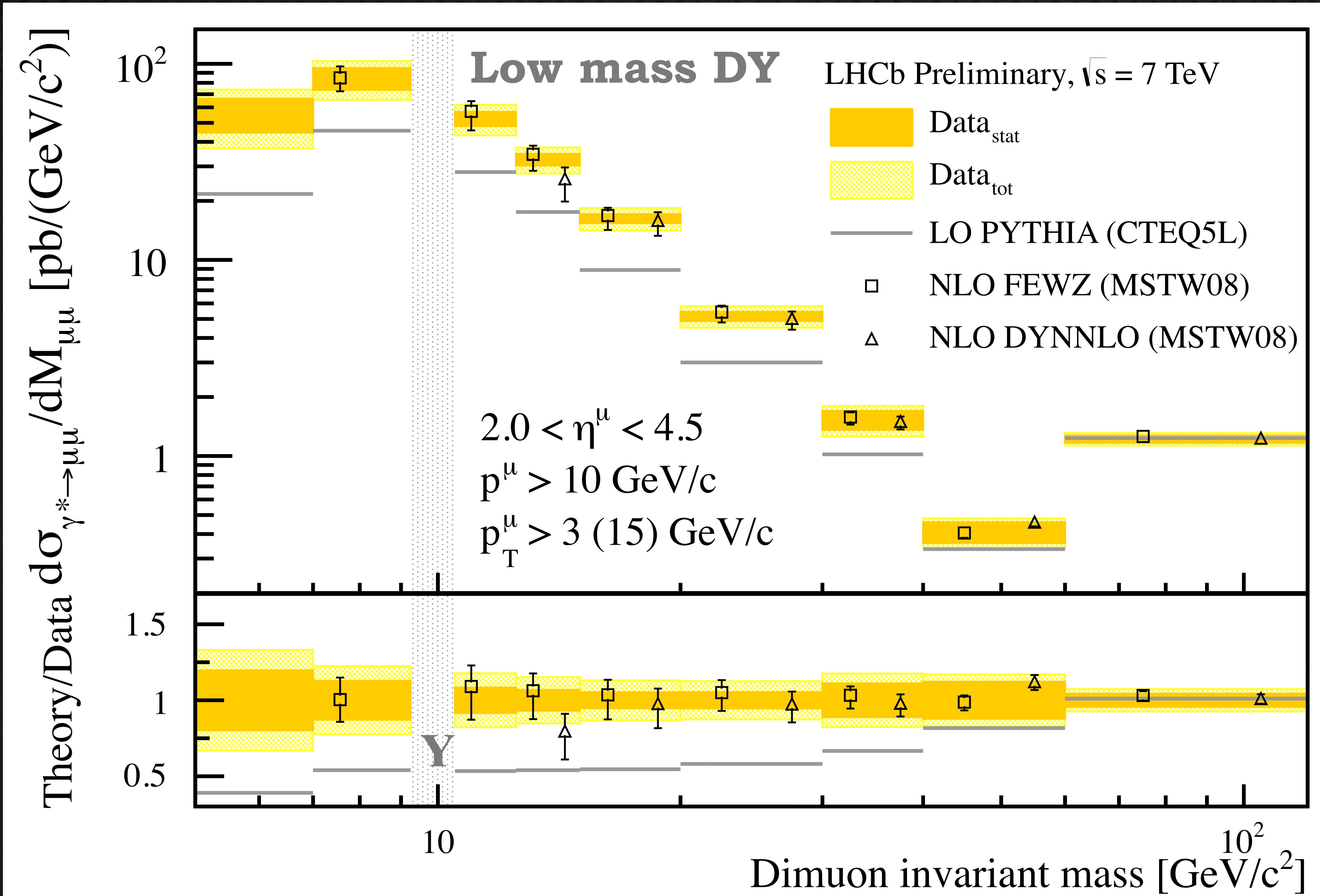
CMS-PAS-EWK-11-007



Significant differences between data, POWHEG NLO and FEWZ NNLO calculations at low mass

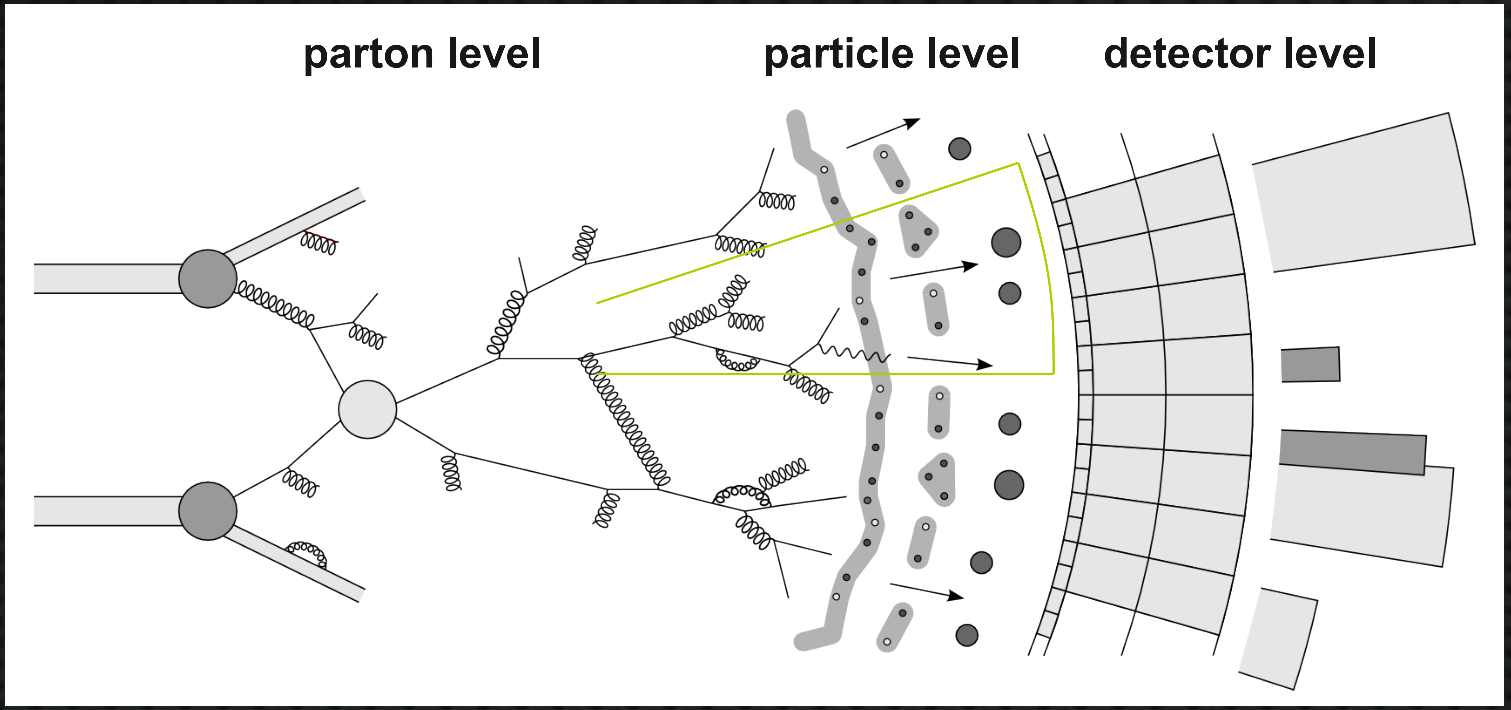
Drell-Yan production in forward region (LHCb)

LHCb-CONF-2012-013



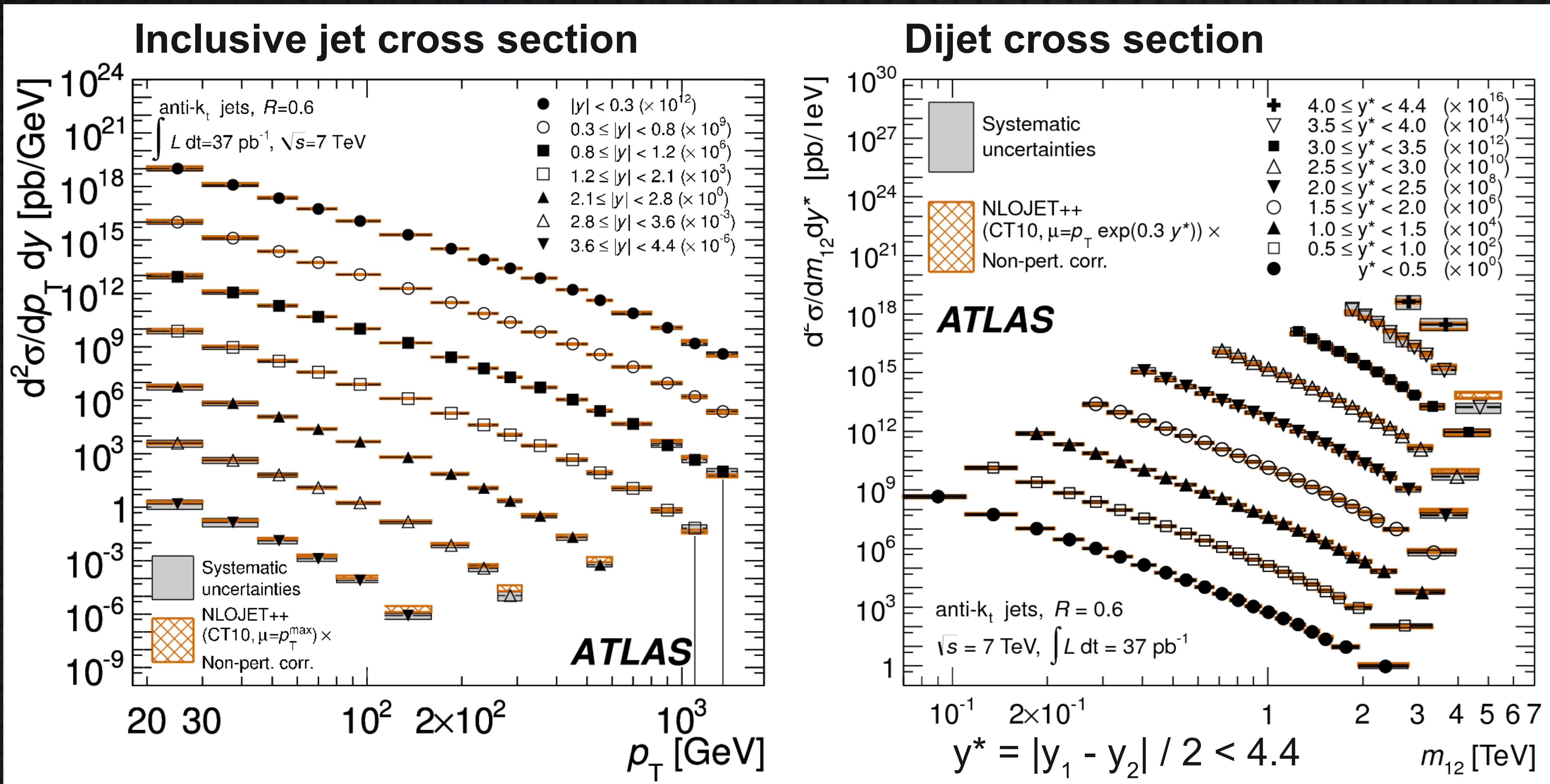
Jet Production

Jet Measurements

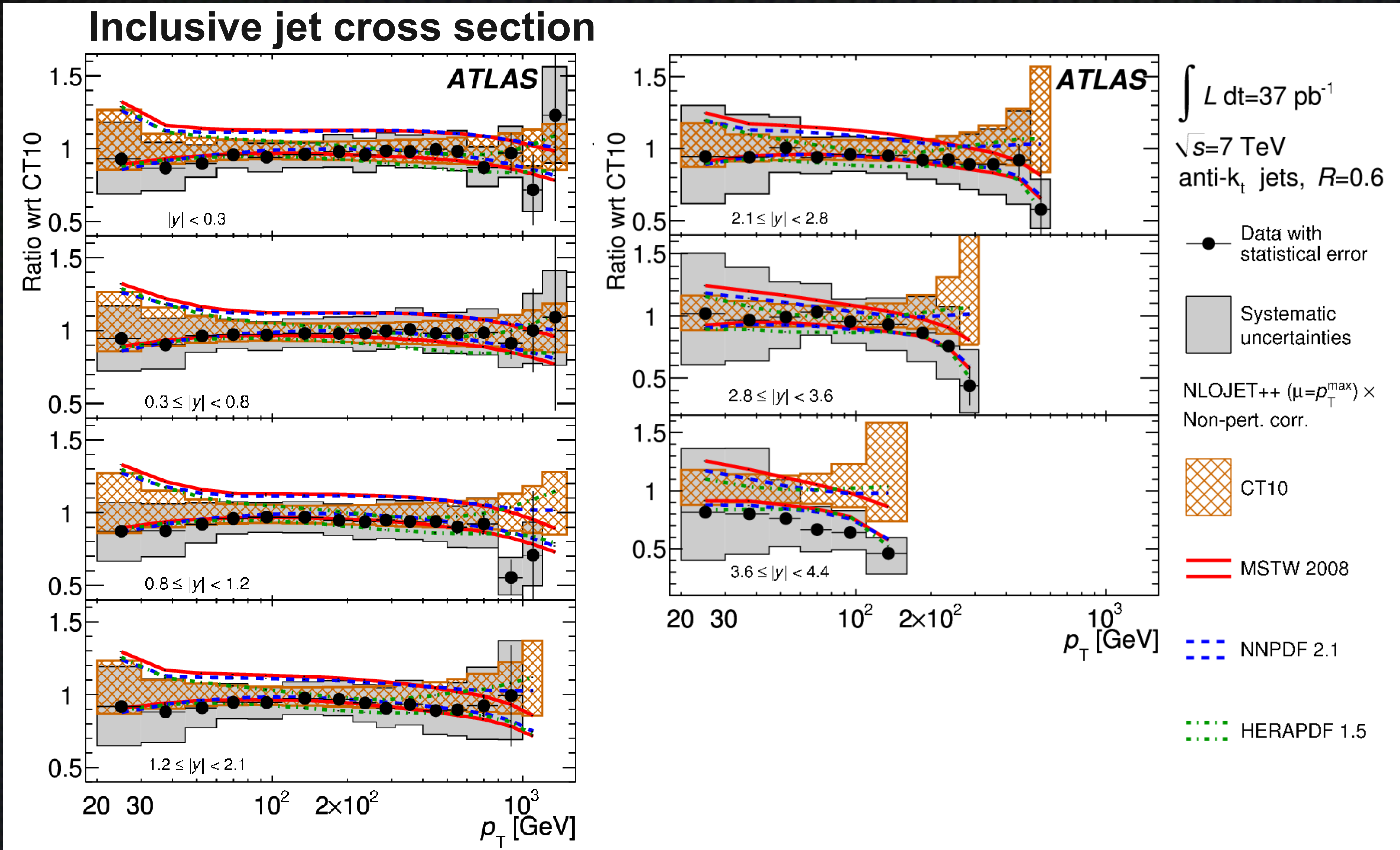


- **Jet algorithm:**
  - anti-kt with distance parameter R=0.4 and R=0.6
    - Defined at parton, particle and detector lever
  - Measurement
    - Unfolding data from detector effect (--> particle level)
  - Predictions:
    - NLO pQQCD with non-perturbative corrections
    - Compare different generators, tunes and PDFs

Inclusive Jet and Dijet Cross Sections at 7 TeV



Inclusive Jet and Dijet Cross Sections at 7 TeV



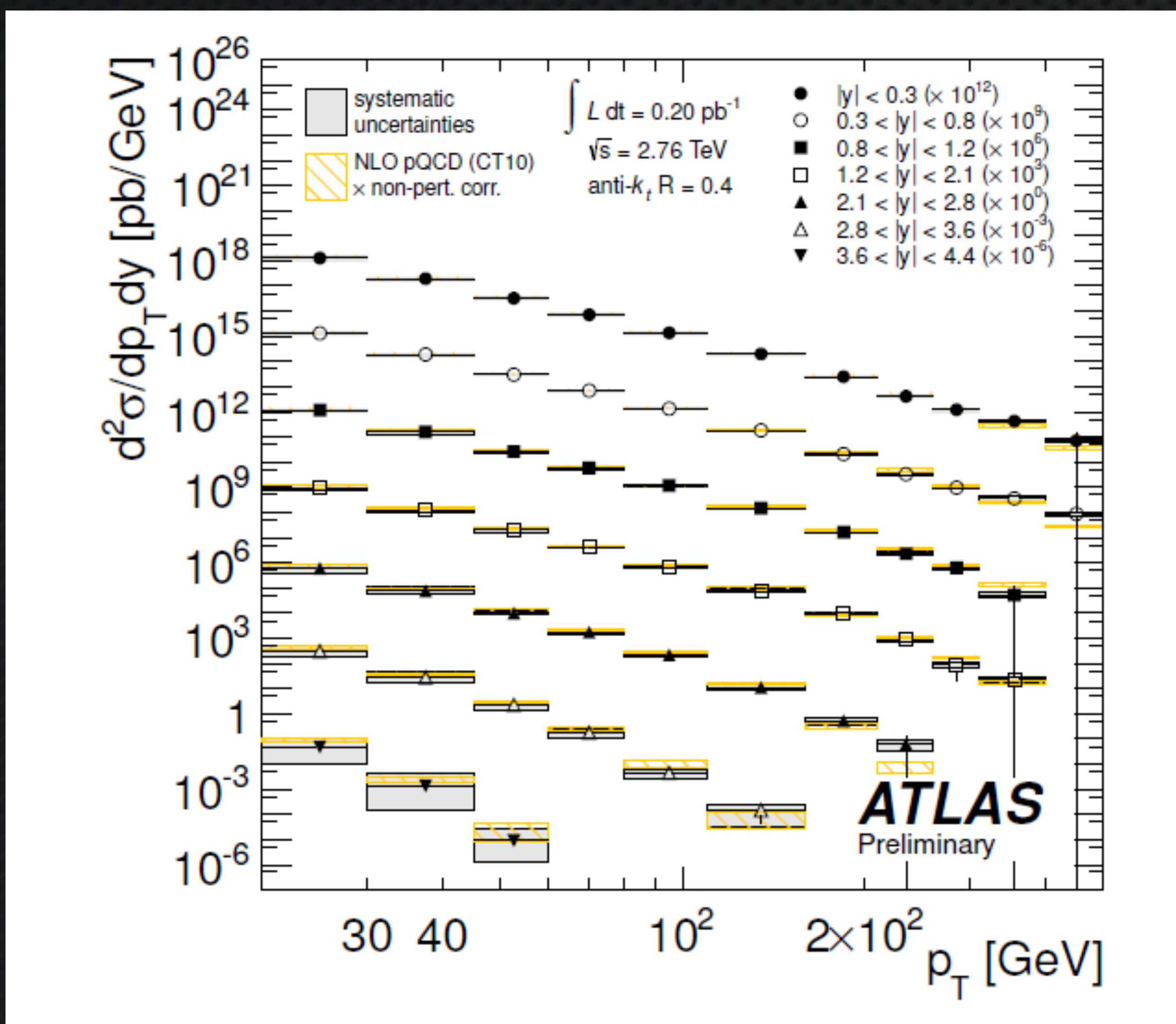
Good general agreement

Inclusive jet cross section at 2.76 TeV

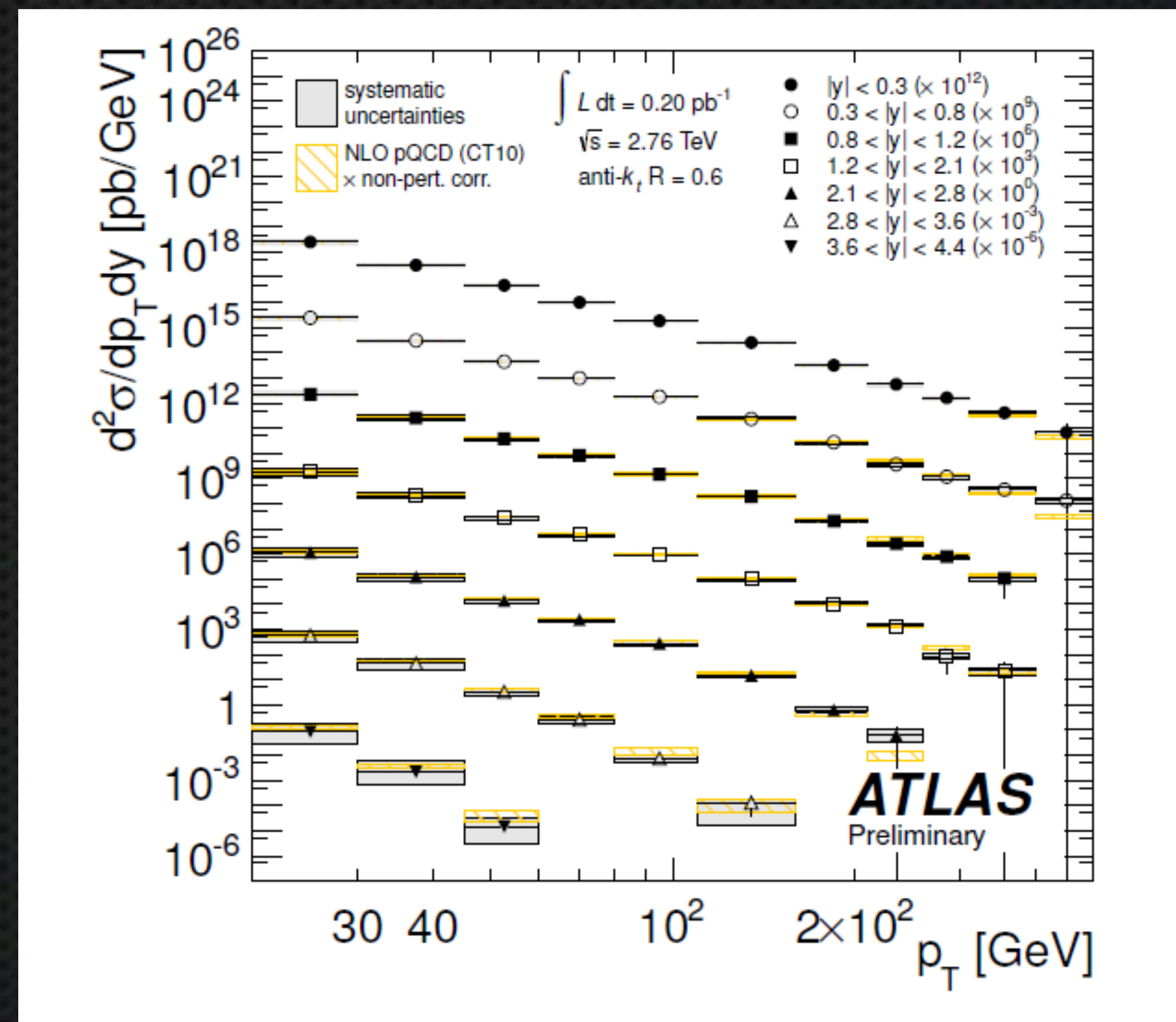
ATLAS-CONF-2012-128

Measurement made in the kinematic regions:
20 ≤ pT <430 GeV and |y| < 4.4

R=0.4



R=0.6



Luminosity uncertainty: 2.8%

Inclusive jet cross section at 2.76 TeV

ATLAS-CONF-2012-128

Systematic uncertainties

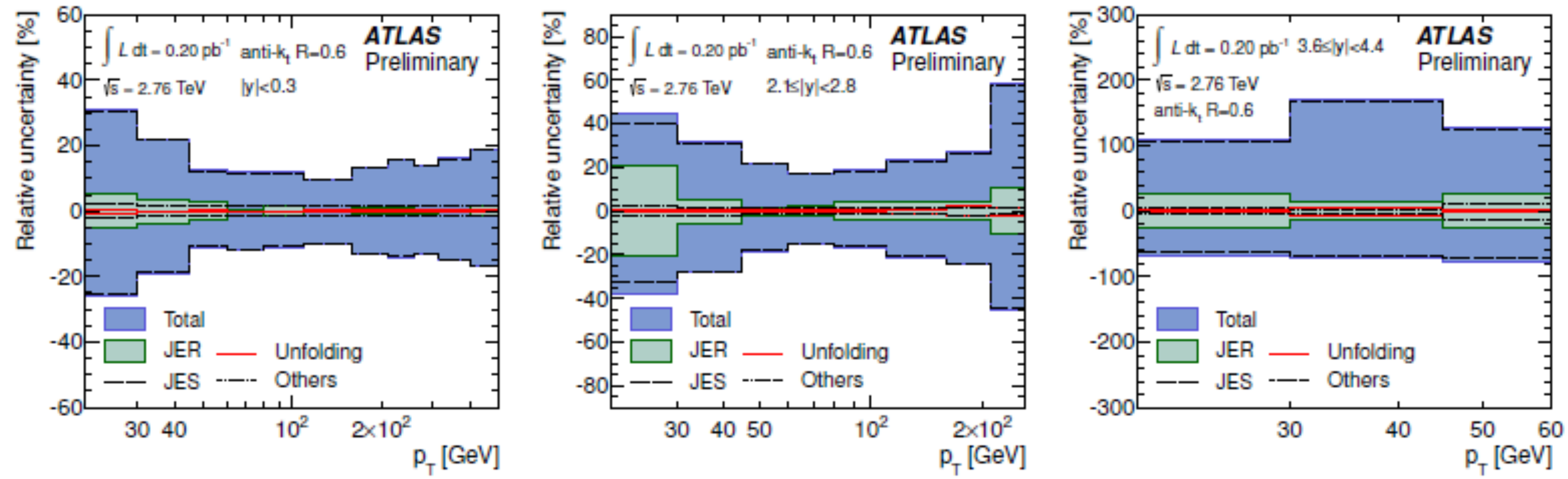
Uncertainty source	$\|y\|$ bins							Correlation to 7 TeV
	0-0.3	0.3-0.8	0.8-1.2	1.2-2.1	2.1-2.8	2.8-3.6	3.6-4.4	
Trigger efficiency	u_1	u_1	u_1	u_1	u_1	u_1	u_1	N
Jet reconstruction eff.	83	83	83	83	84	85	86	Y
Jet selection eff.	u_2	u_2	u_2	u_2	u_2	u_2	u_2	N
JES1: Noise thresholds	1	1	2	3	4	5	6	Y
JES2: Theory UE	7	7	8	9	10	11	12	Y
JES3: Theory showering	13	13	14	15	16	17	18	Y
JES4: Non-closure	19	19	20	21	22	23	24	Y
JES5: Dead material	25	25	26	27	28	29	30	Y
JES6: Forward JES generators	88	88	88	88	88	88	88	*
JES7: E/p response	32	32	33	34	35	36	37	Y
JES8: E/p selection	38	38	39	40	41	42	43	Y
JES9: EM + neutrals	44	44	45	46	47	48	49	Y
JES10: HAD E-scale	50	50	51	52	53	54	55	Y
JES11: High p_T	56	56	57	58	59	60	61	Y
JES12: E/p bias	62	62	63	64	65	66	67	Y
JES13: Test-beam bias	68	68	69	70	71	72	73	Y
JES15: Forward JES detector	89	89	89	89	89	89	89	*
Jet energy resolution	76	76	77	78	79	80	81	Y
Jet angle resolution	82	82	82	82	82	82	82	Y
Unfolding: Closure test	74	74	74	74	74	74	74	N
Unfolding: Jet matching	75	75	75	75	75	75	75	N
Luminosity	87	87	87	87	87	87	87	N

Calorimeter and jet reconstruction common to both analyses at 7 TeV and 2.76 TeV

Jet energy scale (JES) systematics are largely correlated between the two analyses

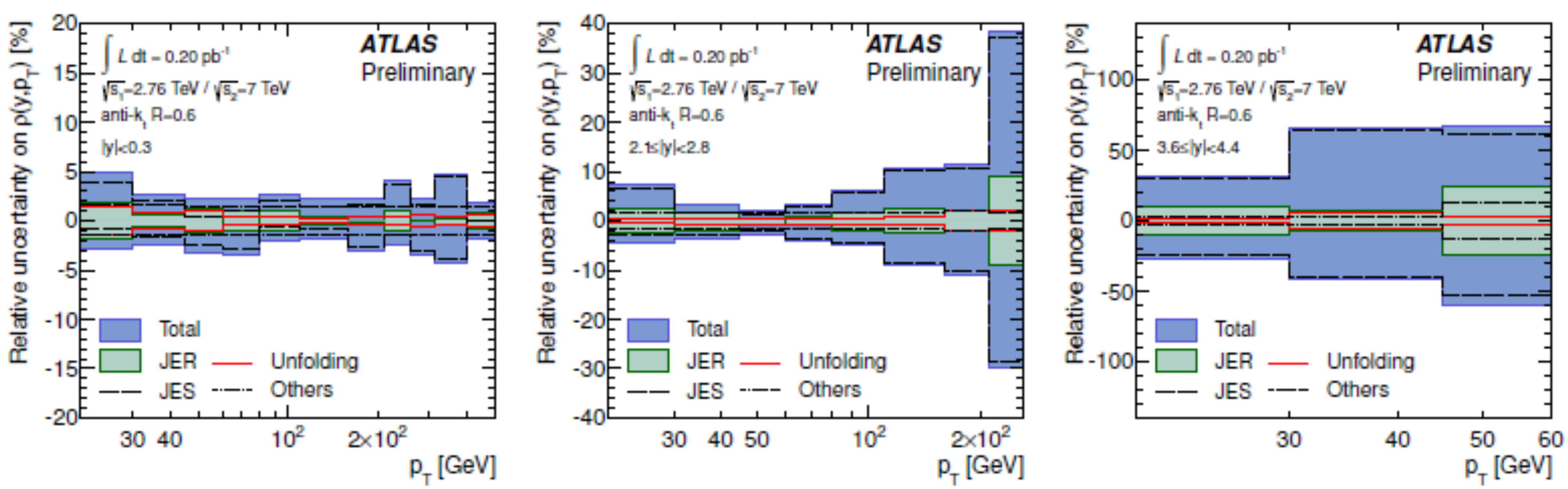
Inclusive jet cross section at 2.76 TeV

Uncertainties on 2.76TeV jet cross section



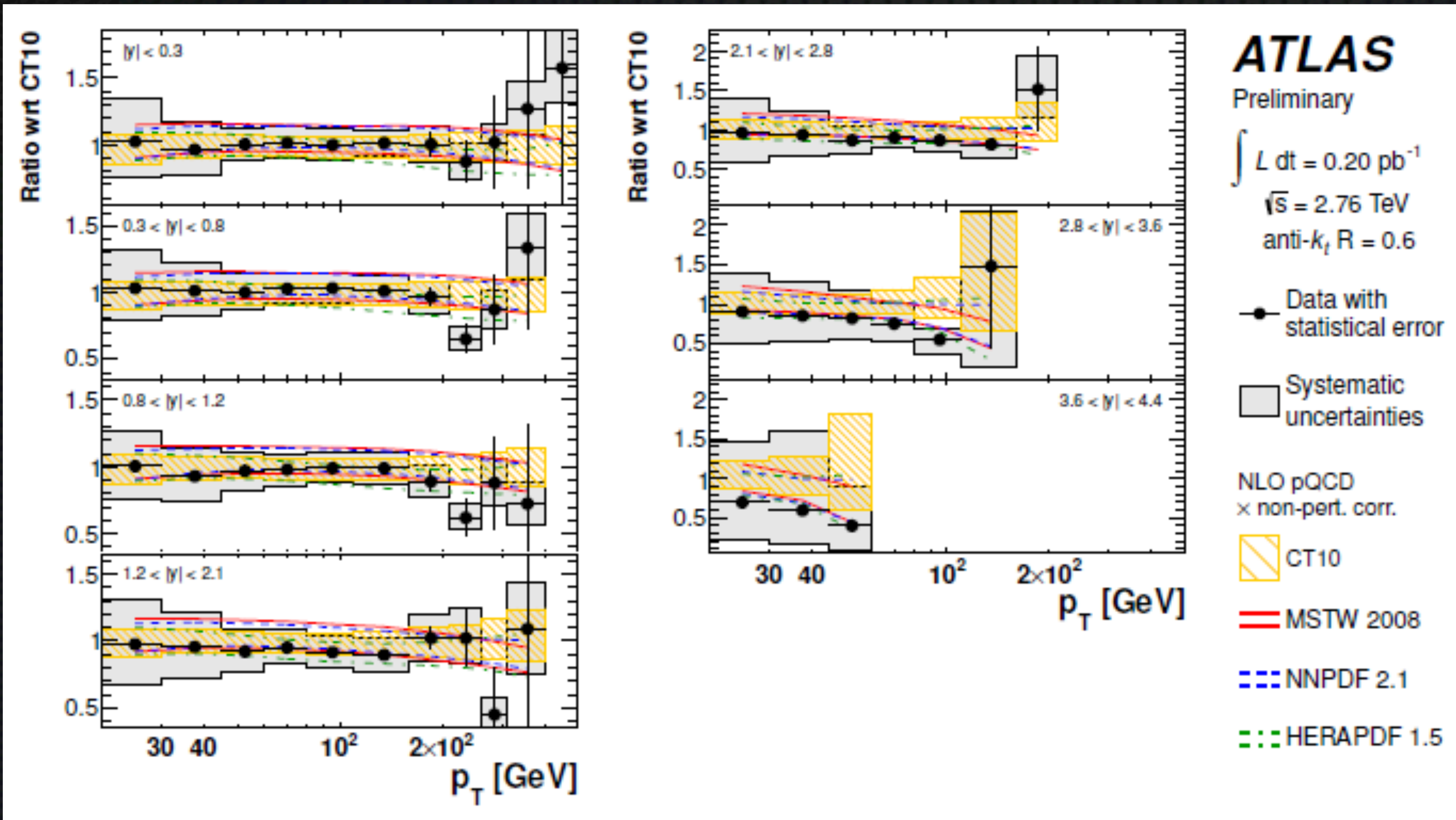
(a) $|y| < 0.3$ (b) $2.1 \leq |y| < 2.8$ (c) $3.6 \leq |y| < 4.4$

Uncertainties on the ratio 2.76 TeV to 7 TeV jet cross sections



(d) $\rho(y, p_T), |y| < 0.3$ (e) $\rho(y, p_T), 2.1 \leq |y| < 2.8$ (f) $\rho(y, p_T), 3.6 \leq |y| < 4.4$

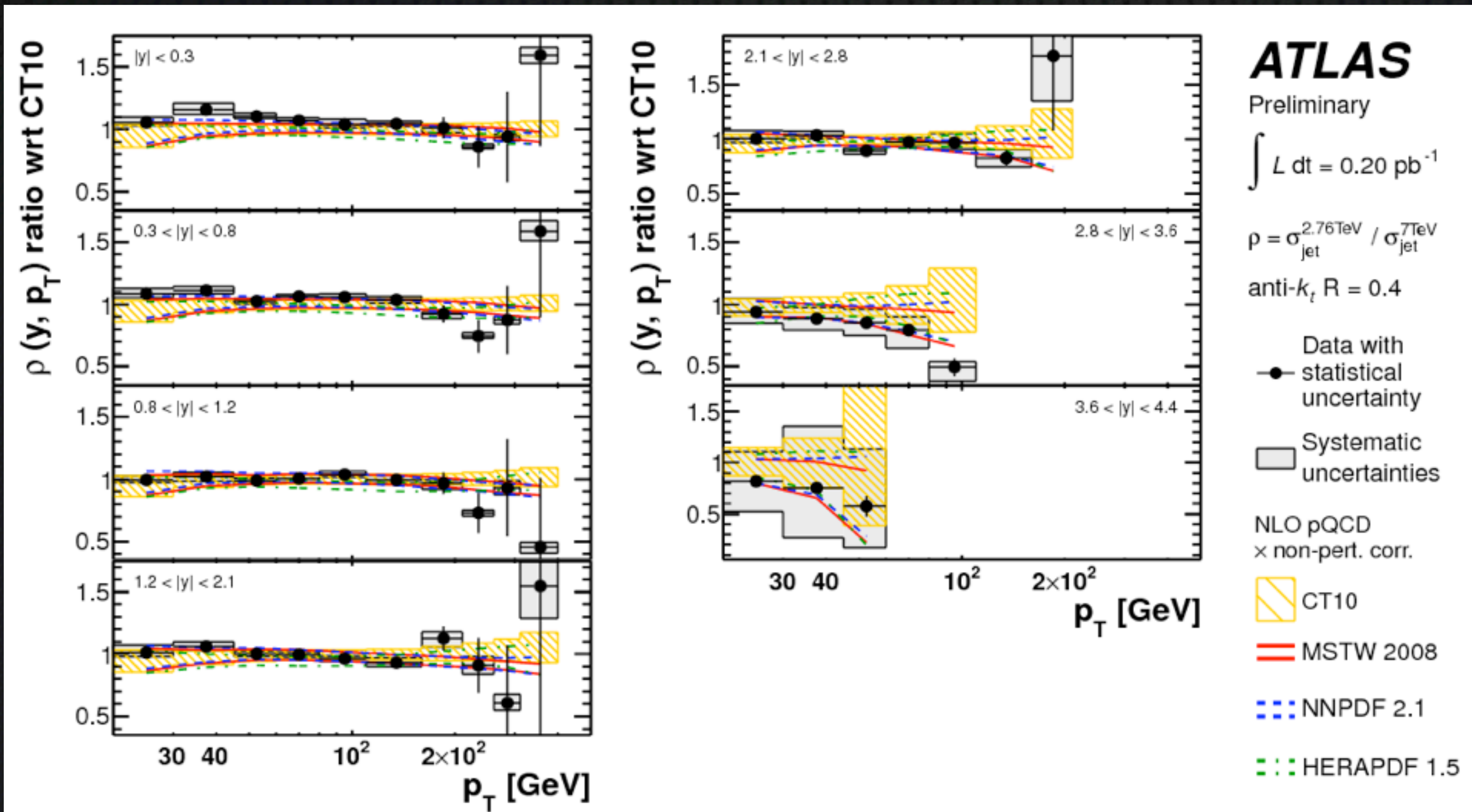
Inclusive jet cross section at 2.76 TeV



Systematic uncertainties are large ==> not easy to assess PDF impact

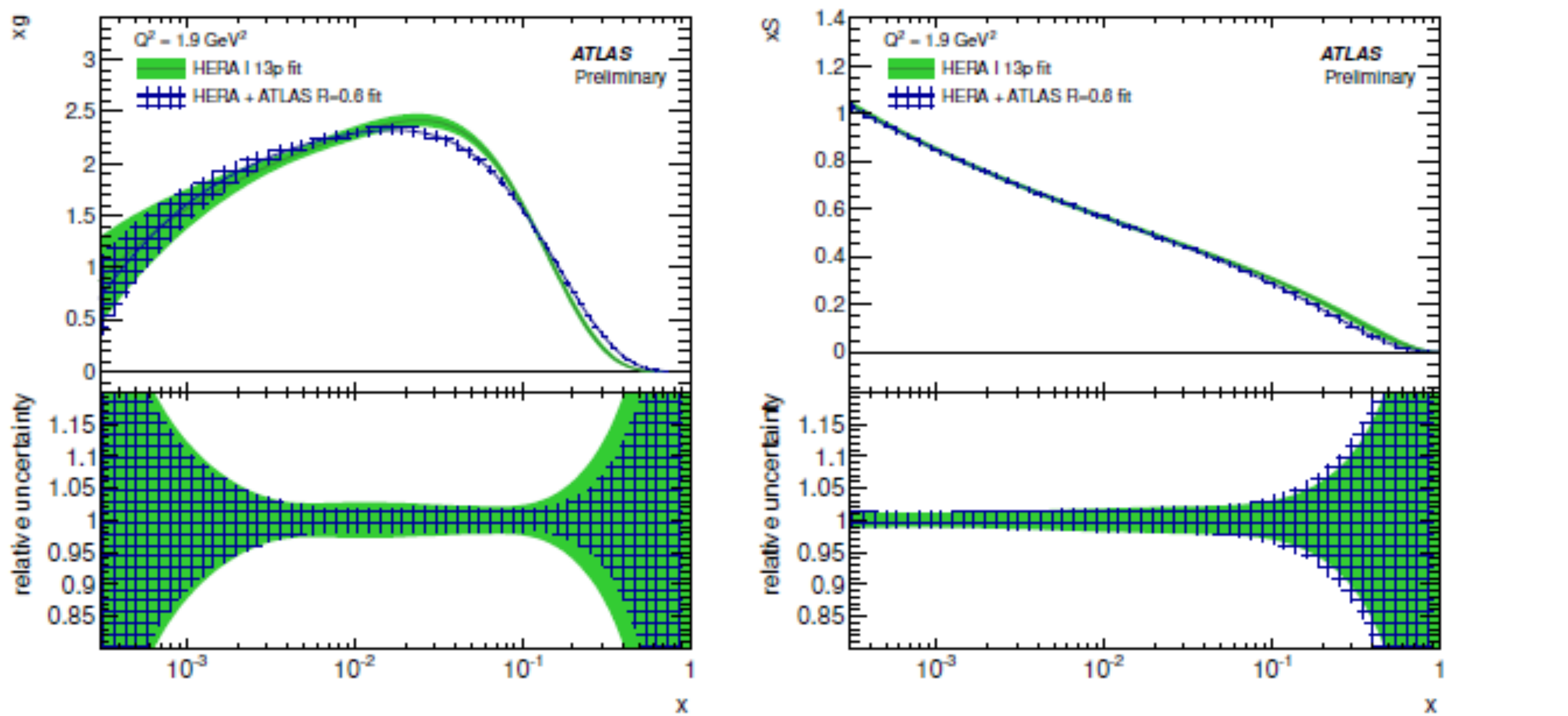
Cross section ratio 2.76 TeV/7 TeV

- **Ratio of experimental uncertainties is reduced and generally smaller than the theory uncertainty**



Assessment of effect on PDFs

Fit HERA data together with ATLAS 7 TeV and 2.76 TeV data

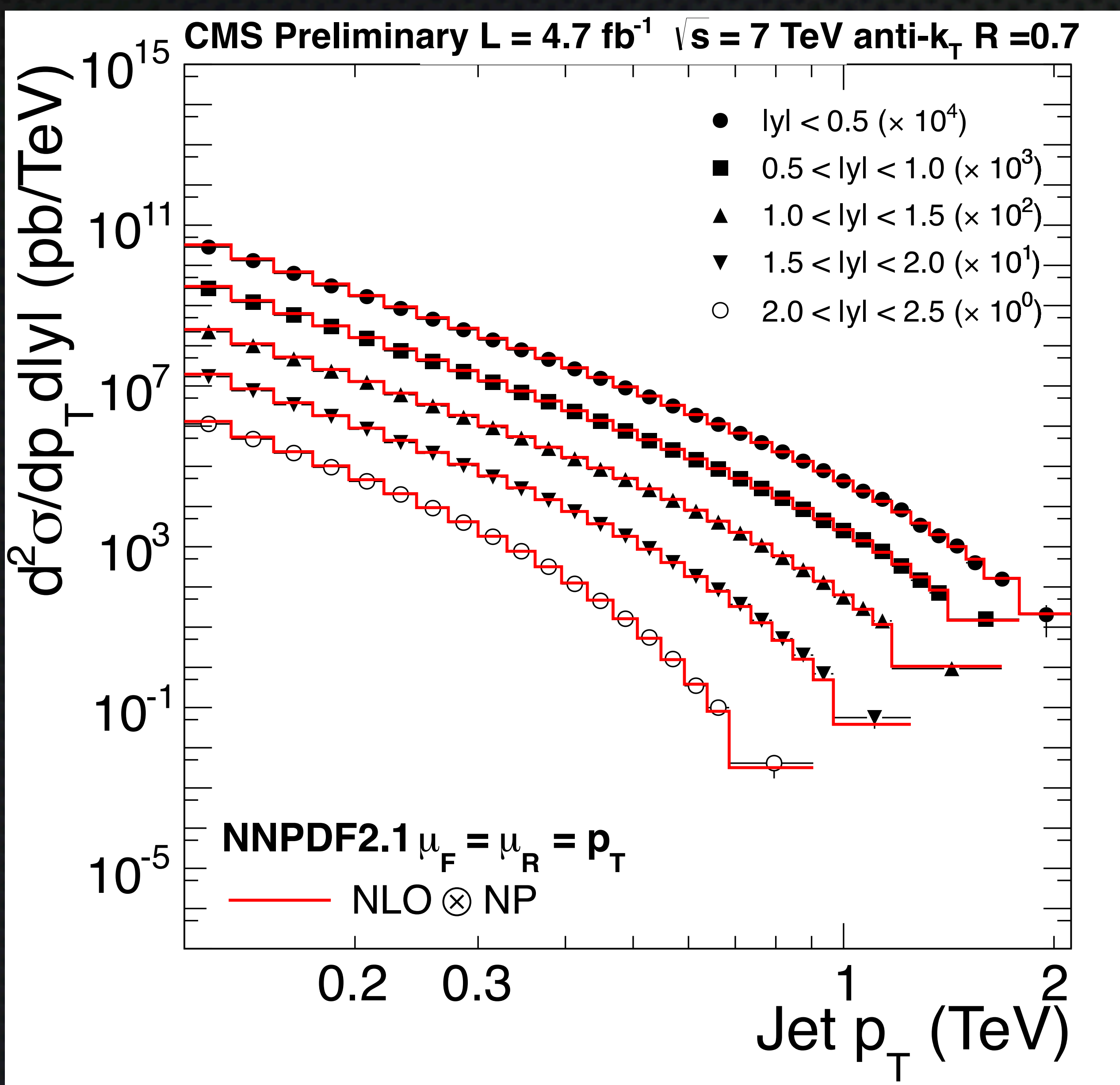


(a) xg (b) xS

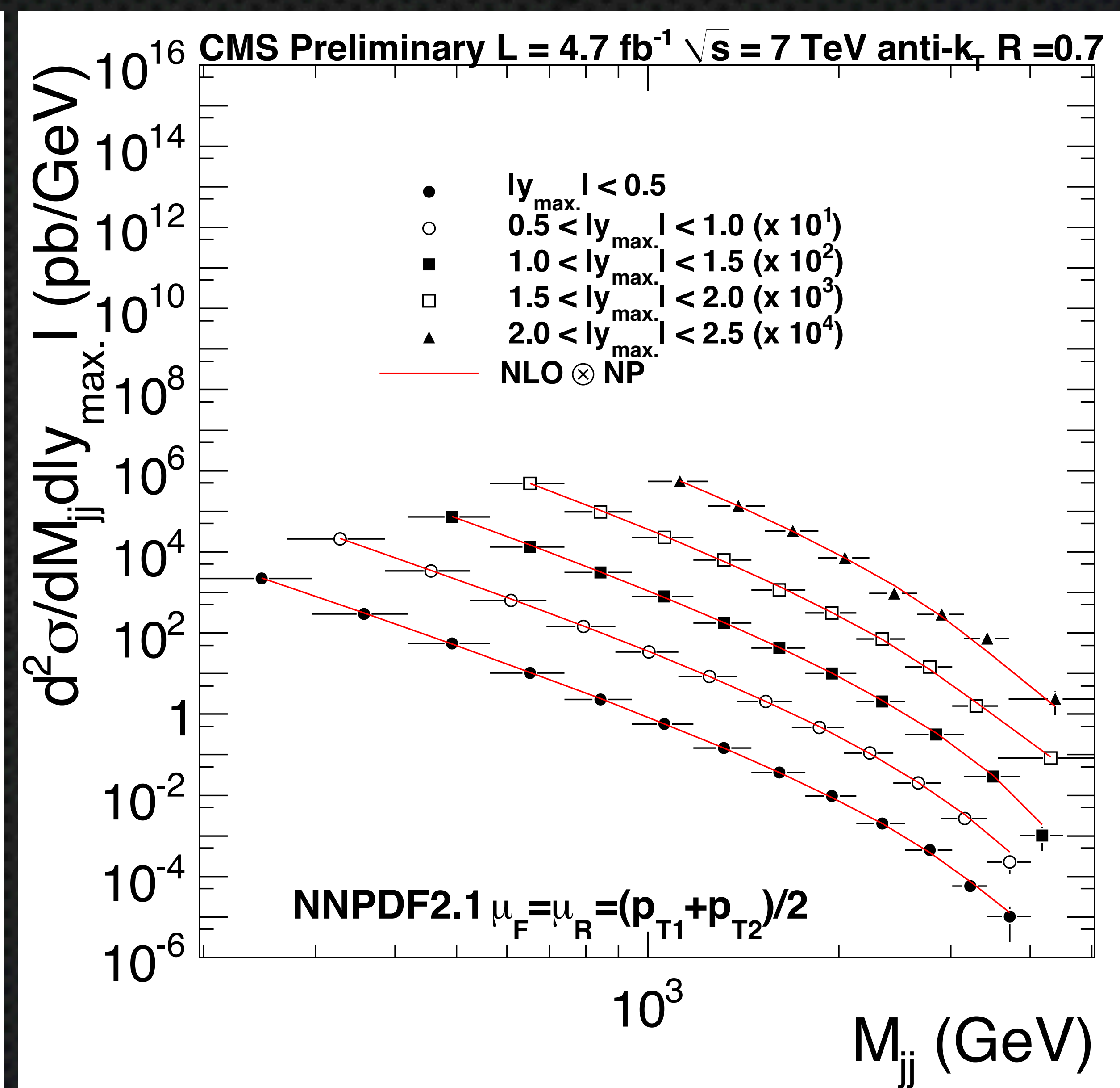
Jet cross sections at CMS

Double differential cross sections

Inclusive



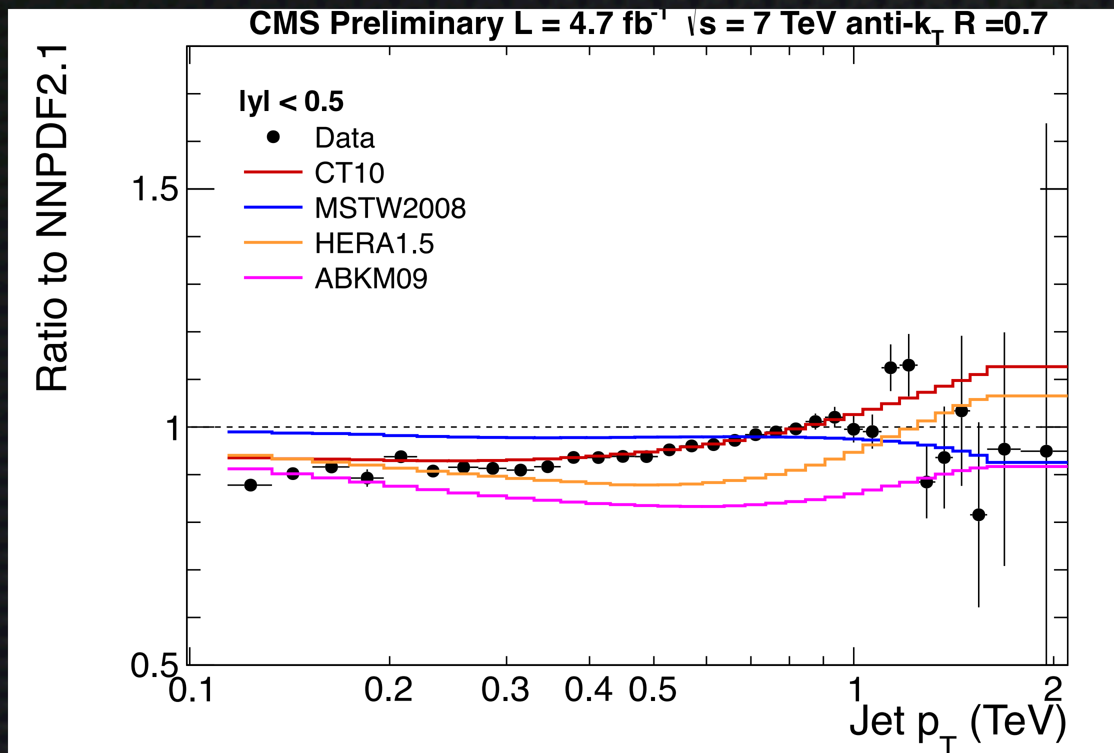
Dijets

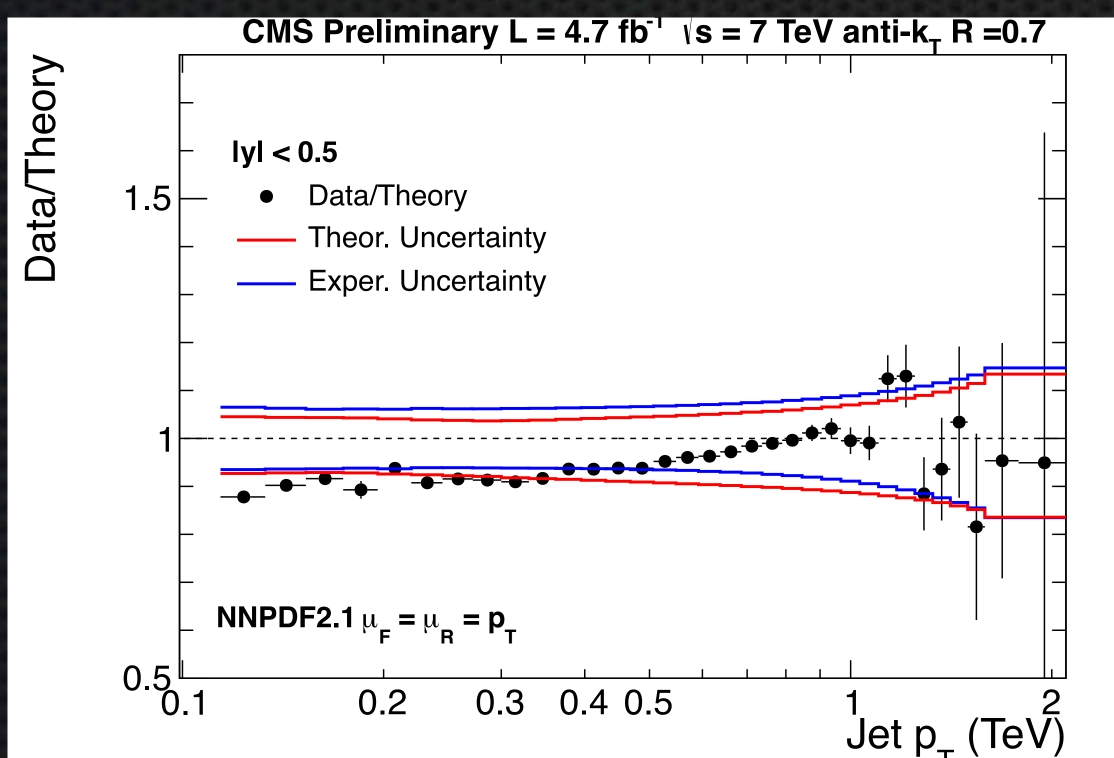


Using full dataset at 7 TeV

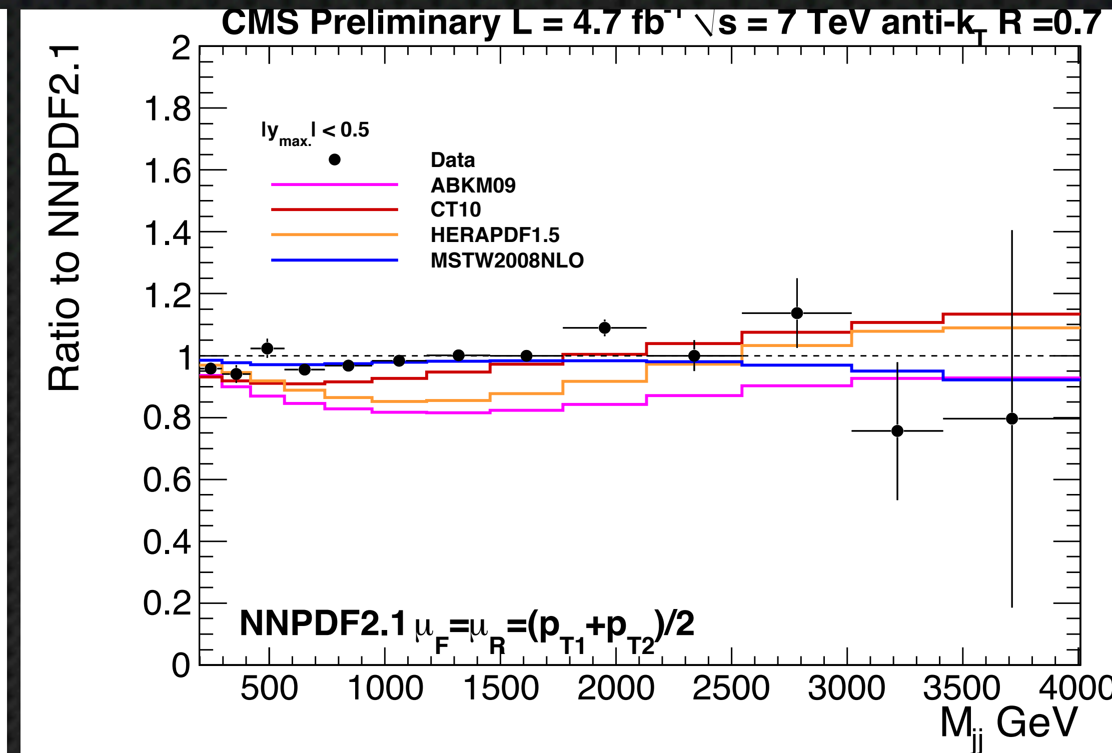
Jet cross sections at CMS

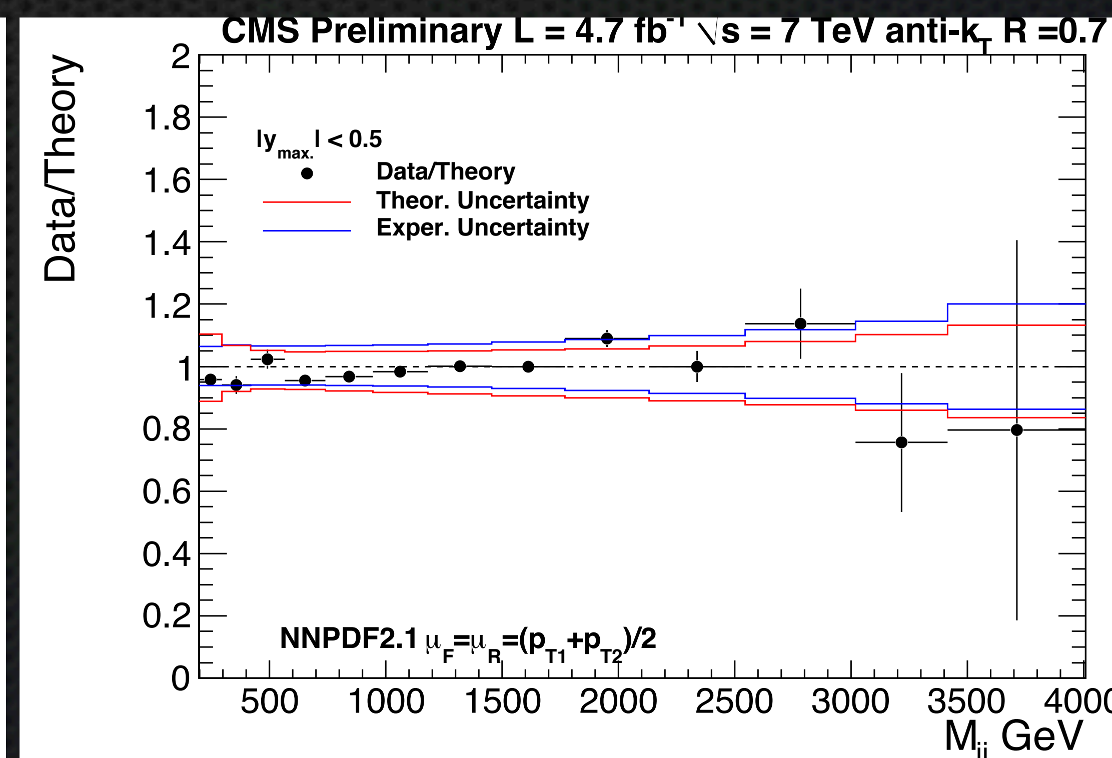
Inclusive





Dijets

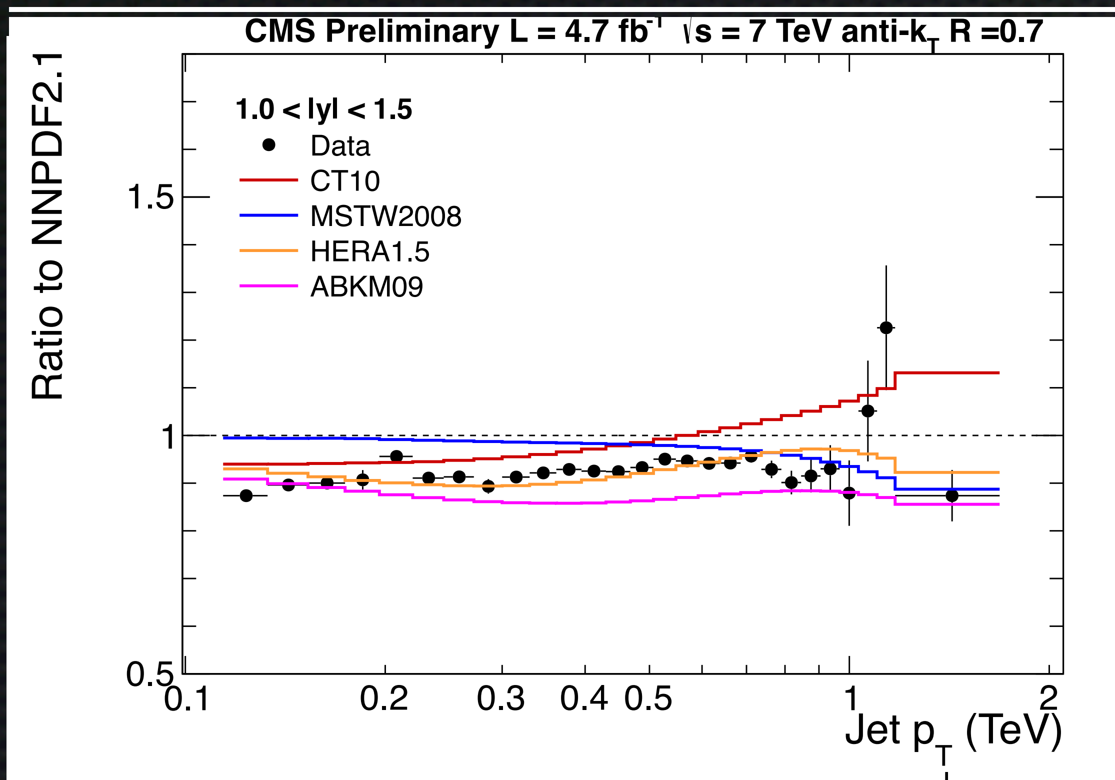


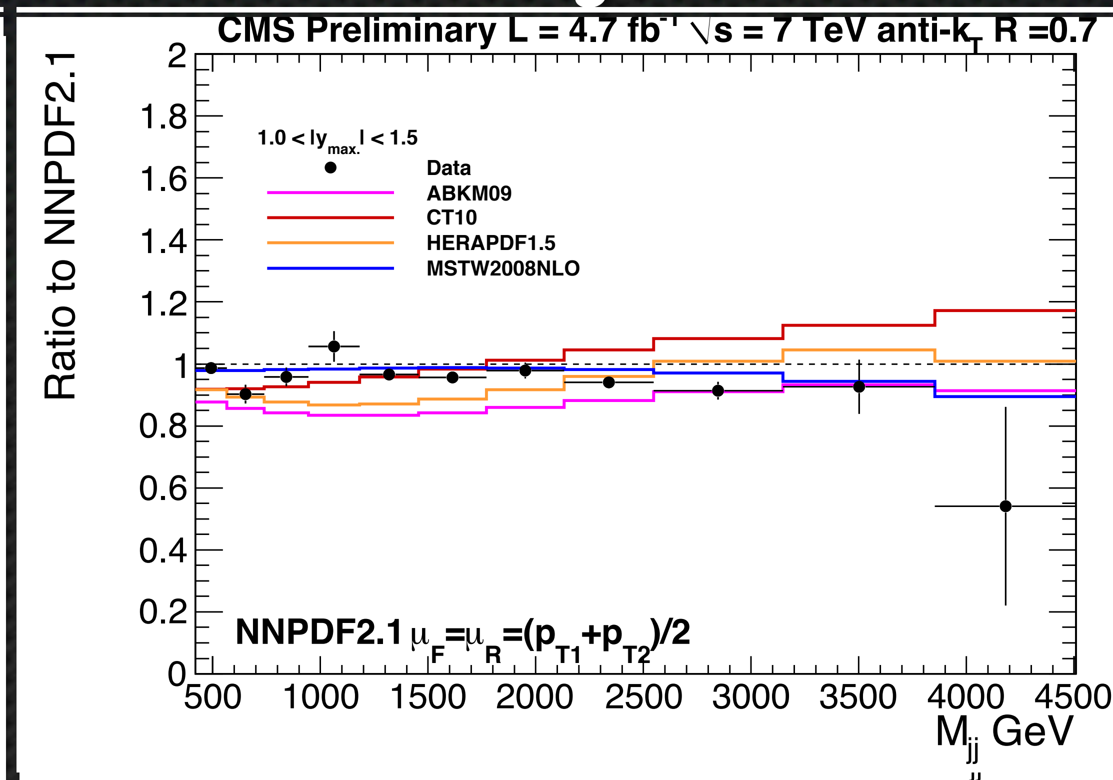


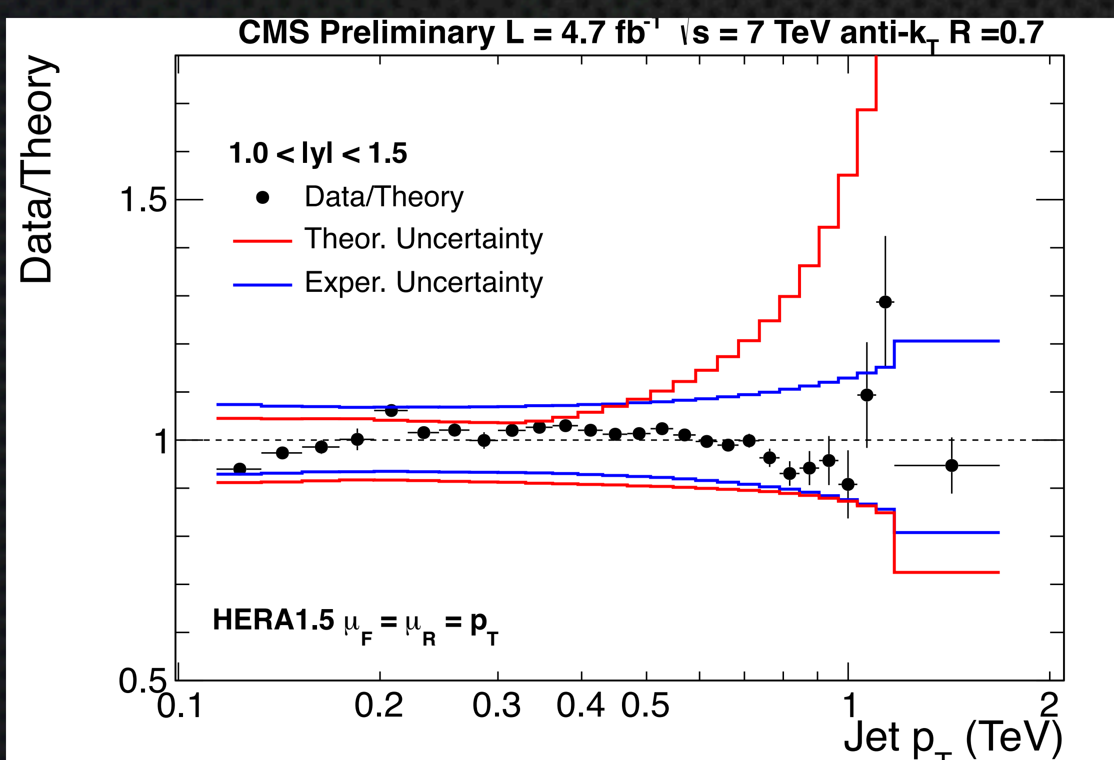
Jet cross sections at CMS

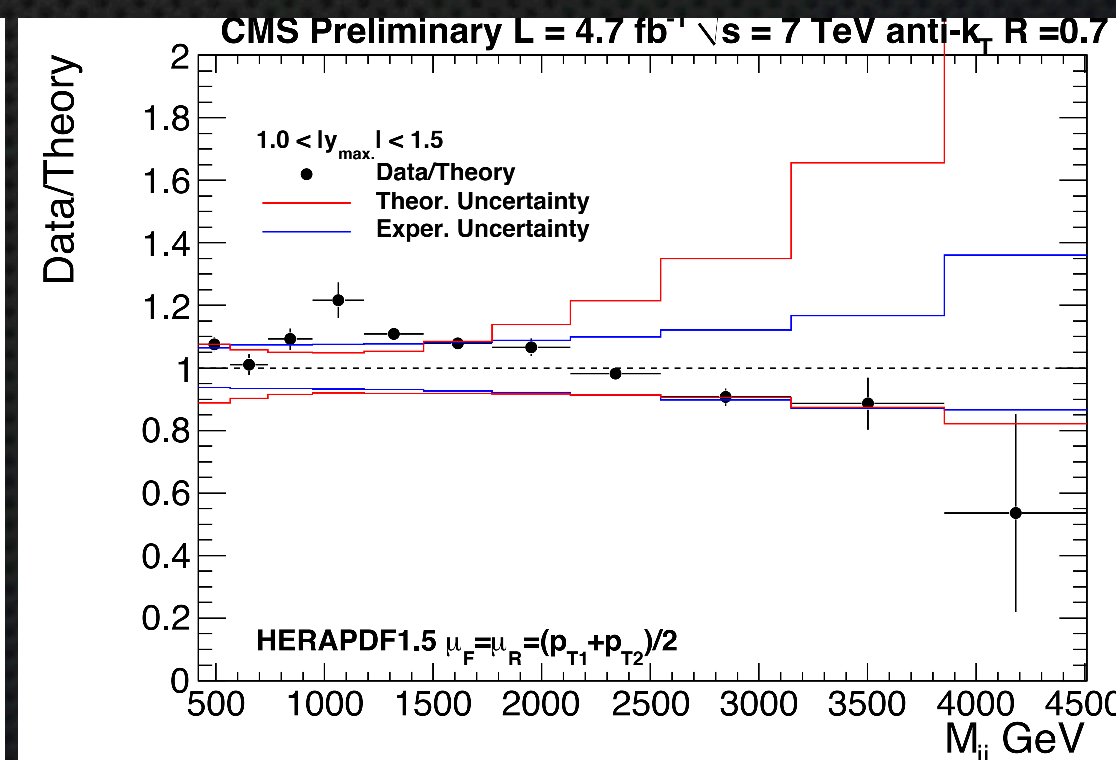
Inclusive

Dijets









Conclusions

- Large Hadron Collider program well underway towards precision physics
  - PDF uncertainties are still a major systematic uncertainty for many physics analysis
- ATLAS, CMS and LHCb are already providing interesting constraint to PDFs
  - W and Z production
  - W+heavy flavor
  - Drell-Yan production
  - Inclusive jet production
  - Dijet production
  - Photon inclusive production
- Much more data available
  - Expect significant improvements in the near future

Extra Slides

The LHCb Experiment

VELO: 21 (R+φ) silicon stations
- Movable:7mm when stable beams

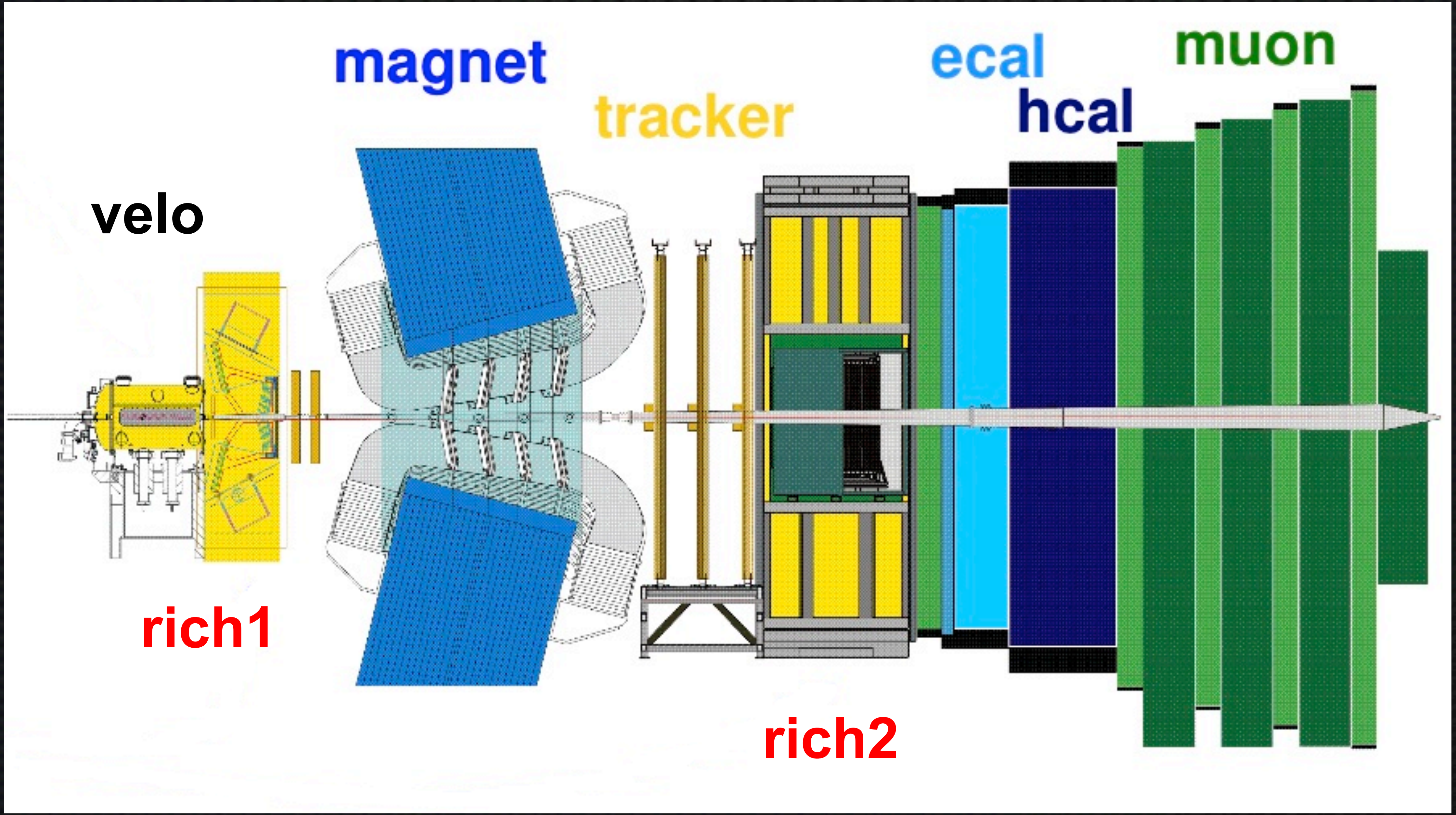
RICH1: C_4F_{10} + AEROGEL
- π/K separation for 2<p<60 GeV

Tracking: Si + straw tubes + 4Tm
- $\delta p/p$=0.45%

RICH2: CF_4
- π/K separation for 20<p<100 GeV

CALO:
- ECAL: lead+scintillating tiles
- HCAL: iron+scintillation tiles

MUON
MWPC+GEM: π/μ separation



CMS: W and Z cross sections at $\sqrt{s}$ =8 TeV

A. Kropivnitskaya

- CMS requested special LHC conditions during luminosity ramp up period to achieve low pile-up events (~5) for good MET resolution at W:
  - ➔ LHC separate beams in transverse plane to reduce effective overlap
  - ➔ separation was periodically adjust to keep instantaneous $\mathcal{L}_{inst}$ ~ 3E32 – 6E32 $cm^{-2}s^{-1}$
  - ➔ Integrated $\mathcal{L}$ = 18.8 pb^{-1}
  - ➔ Special HLT menu with low thresholds: 22 GeV for e and 15 GeV for μ
  - ➔ minimal ID/Iso requirement to suppress background

Event Selection:

e-channel:
E_T > 25 GeV and |η|< 2.5, exclude 1.4442 < |η| < 1.566 (barrel/forward transition)
W ➔ eν: Reject events with 2nd e with E_T > 20 GeV

μ-channel:
p_T > 25 GeV and |η| < 2.1
W ➔ μν: Reject events with 2nd μ with p_T > 10 GeV

Z→ll: 60 GeV < M_{ll} < 120 GeV

The dominant source of systematic uncertainty:
- Experimental:
  - Luminosity (4.4%) for absolute cross sections
  - Lepton efficiency (1-3%)
  - Theoretical uncertainty in acceptance (2-3%)
- Theoretical:
  - PDFs
  - Higher order QCD corrections
  - Higher order electroweak corrections

Monte Carlo Samples

Physics process	Generator	$\sigma\cdot$ BR [nb]	
$W^+ \to \ell^+\nu$ ($\ell = e, \mu$)	MC@NLO	6.16±0.31	NNLO
$W^- \to \ell^-\bar{\nu}$ ($\ell = e, \mu$)	MC@NLO	4.30±0.21	NNLO
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} > 60$ GeV, $\ell = e, \mu$)	MC@NLO	0.99±0.05	NNLO
$W \to \tau\nu$	PYTHIA	10.46±0.52	NNLO
$Z/\gamma^* \to \tau\tau$ ($m_{\tau\tau} > 60$ 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

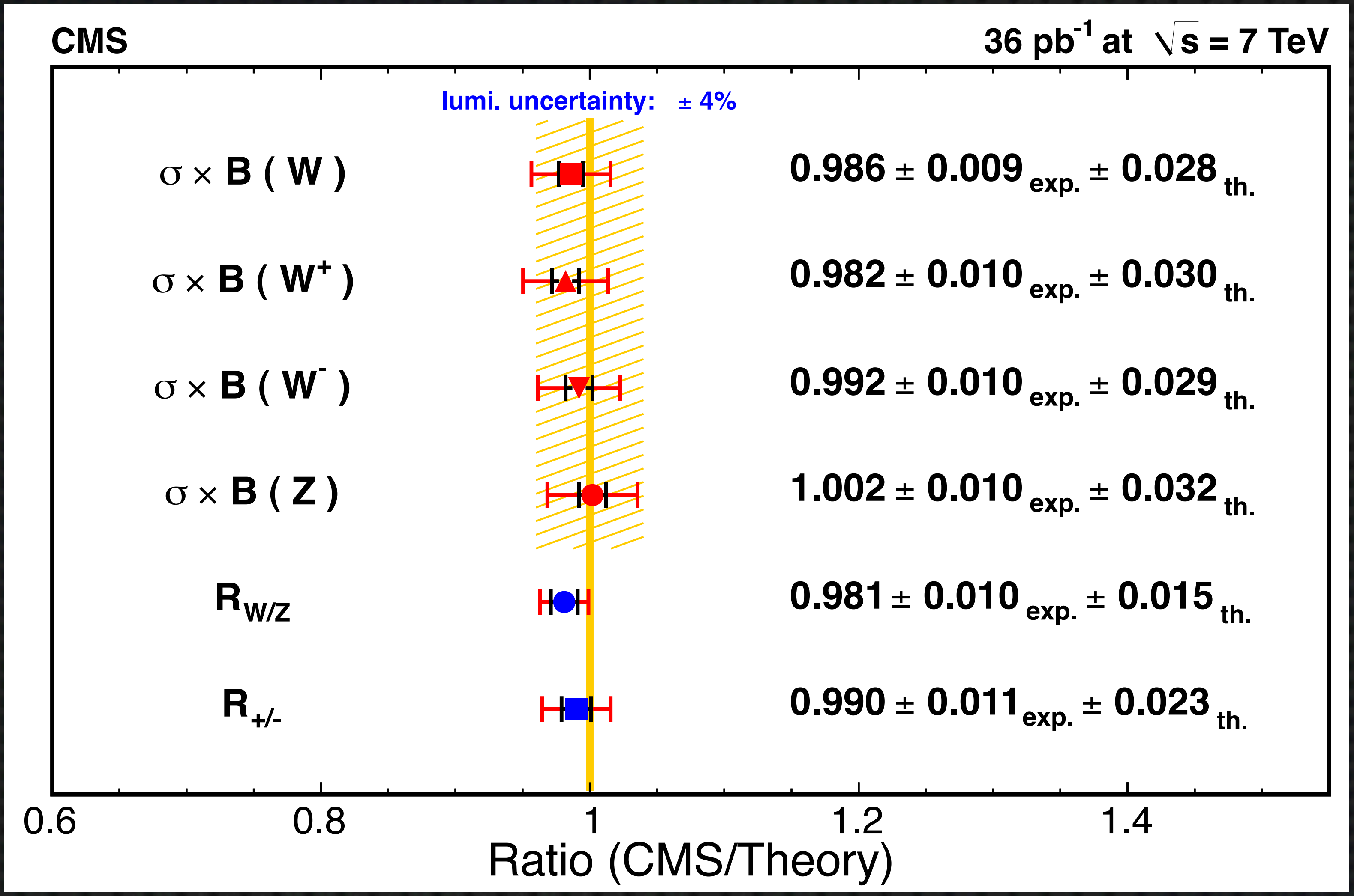
W/Z Inclusive: ATLAS Systematics

- **Detailed systematic uncertainties**
  - **Luminosity: 3.4%**

Electron channels (%)	$W^\pm$	W^+	W^-	Z
Trigger	0.4	0.4	0.4	<0.1
Reconstruction	0.8	0.8	0.8	1.6
Identification	0.9	0.8	1.1	1.8
Isolation	0.3	0.3	0.3	—
Energy scale and resolution	0.5	0.5	0.5	0.2
Defective LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	<0.1	0.1	0.1	0.6
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.8	0.7	1.0	—
Pile-up	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
QCD Background	0.4	0.4	0.4	0.7
EWK+$t\bar{t}$ Background	0.2	0.2	0.2	<0.1
$C_{W/Z}$ Theor. uncertainty	0.6	0.6	0.6	0.3
Total Exp. uncertainty	**1.8**	**1.8**	**2.0**	**2.7**
$A_{W/Z}$ Theor. uncertainty	1.4	1.6	1.9	1.9
Total excluding Luminosity	2.3	2.4	2.8	3.3

Muon channels (%)	$W^\pm$	W^+	W^-	Z
Trigger	0.5	0.5	0.5	0.1
Reconstruction	0.4	0.3	0.3	0.6
Isolation	0.2	0.1	0.2	0.3
p_{T} Resolution	0.04	0.03	0.05	0.02
p_{T} Scale	0.4	0.6	0.6	0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.5	0.4	0.6	-
Pile-up	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
QCD Background	0.6	0.5	0.8	0.3
EWK+$t\bar{t}$ Background	0.4	0.3	0.4	0.02
$C_{W/Z}$ Theor. uncertainty	0.8	0.8	0.7	0.3
Total Exp. uncertainty	**1.6**	**1.7**	**1.7**	**0.9**
$A_{W/Z}$ Theor. uncertainty	1.4	1.6	2.0	2.0
Total excluding Luminosity	2.1	2.3	2.6	2.2

CMS Cross Section Measurements



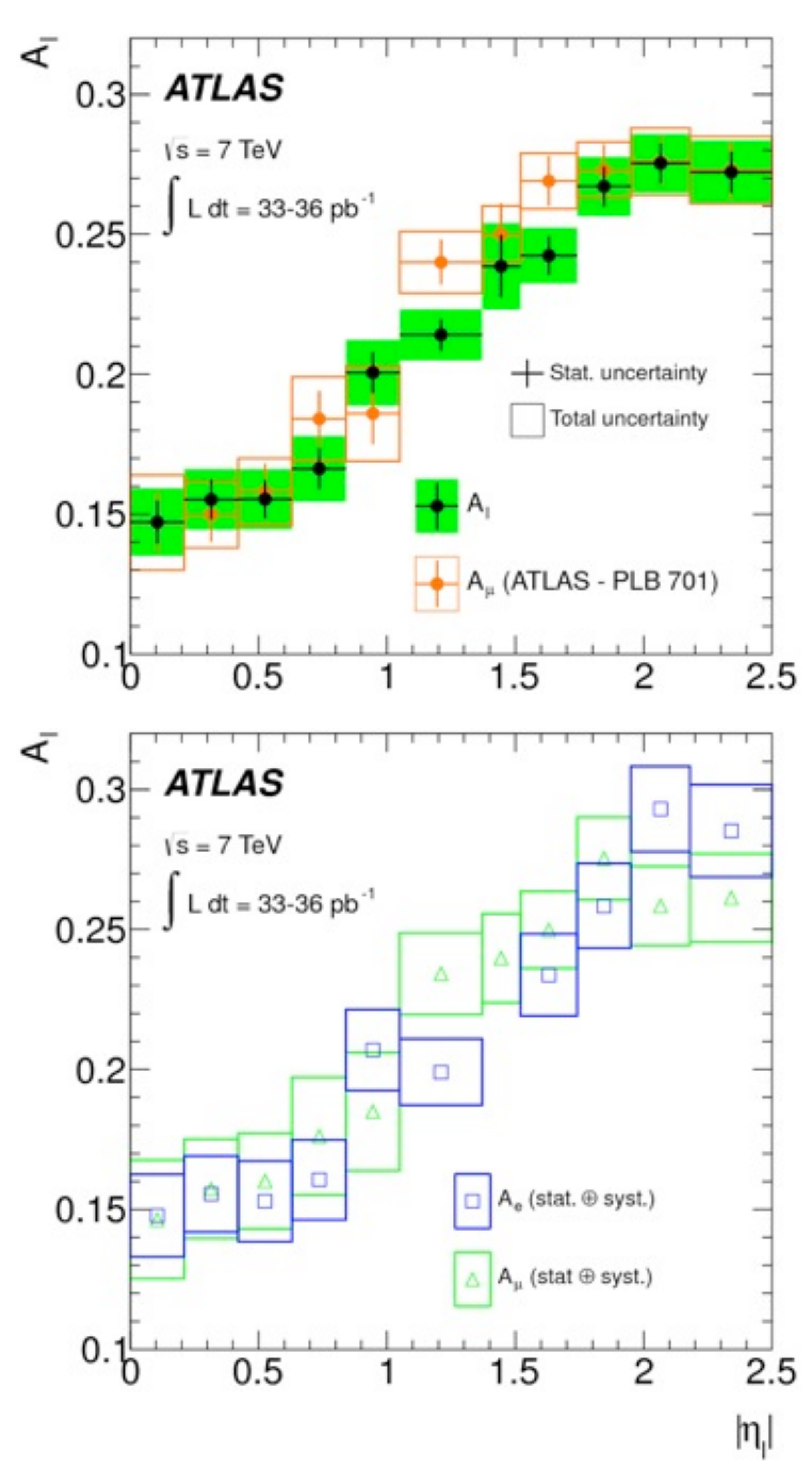
W/Z Inclusive: CMS Systematics

- **Detailed systematic uncertainties**
  - **Luminosity: 4%**

Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.4	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	1.6	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)	1.8	1.6	2.4	2.0

W charge asymmetry: Comparison with first publication

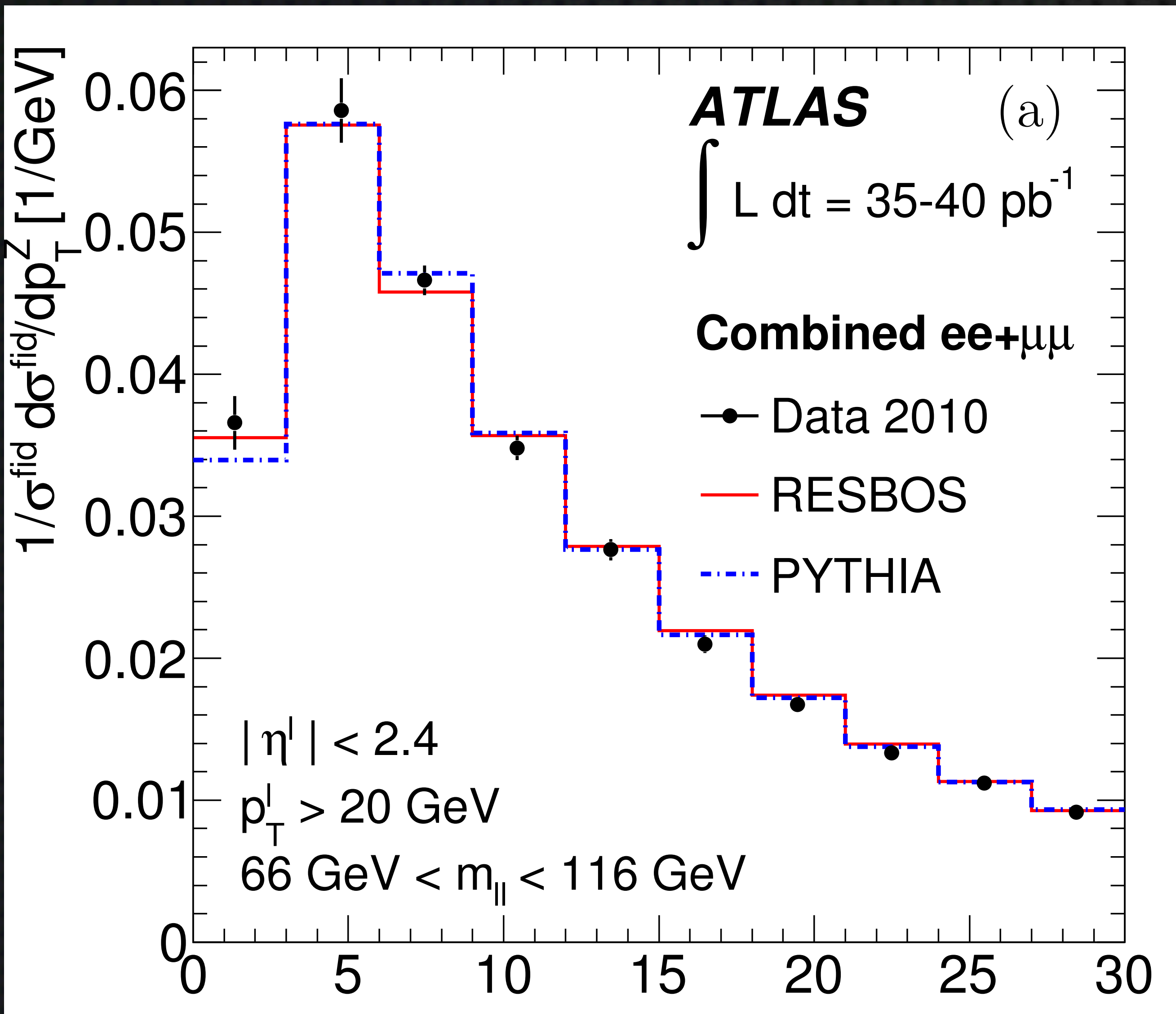
- **Change in systematic uncertainties and correction factors**
  - efficiency scale-factor
  - MET
  - momentum scale corrections
  - boson p_T reweighting
  - theoretical CW



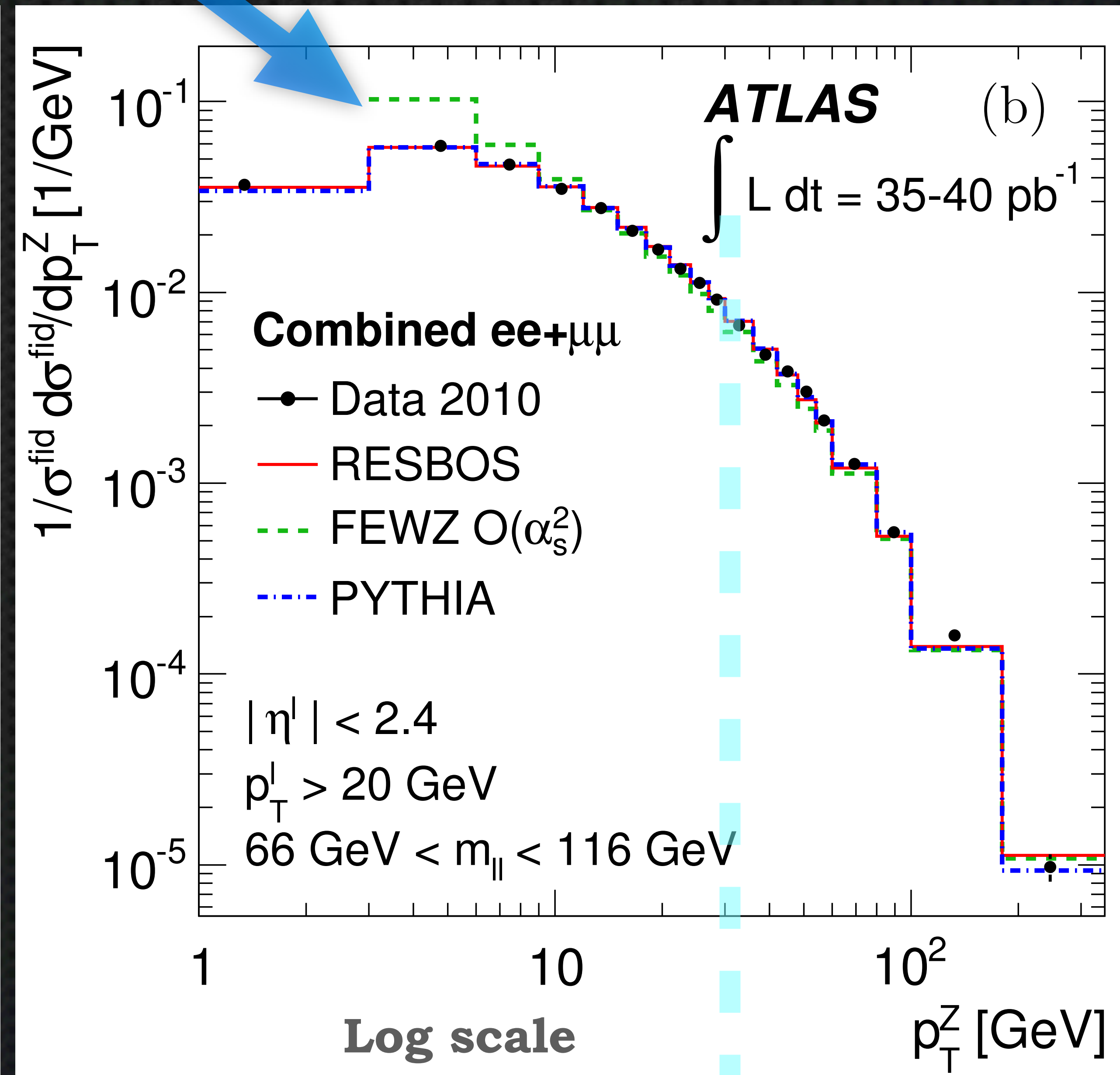
Transverse momentum distribution of Z/γ* bosons

Electron and muon channel combined

FEWZ diverges at low p_T



Linear scale



Log scale

Transverse momentum distribution of Z/γ* bosons

Predictions: FEWZ v2.0 + MSTW08

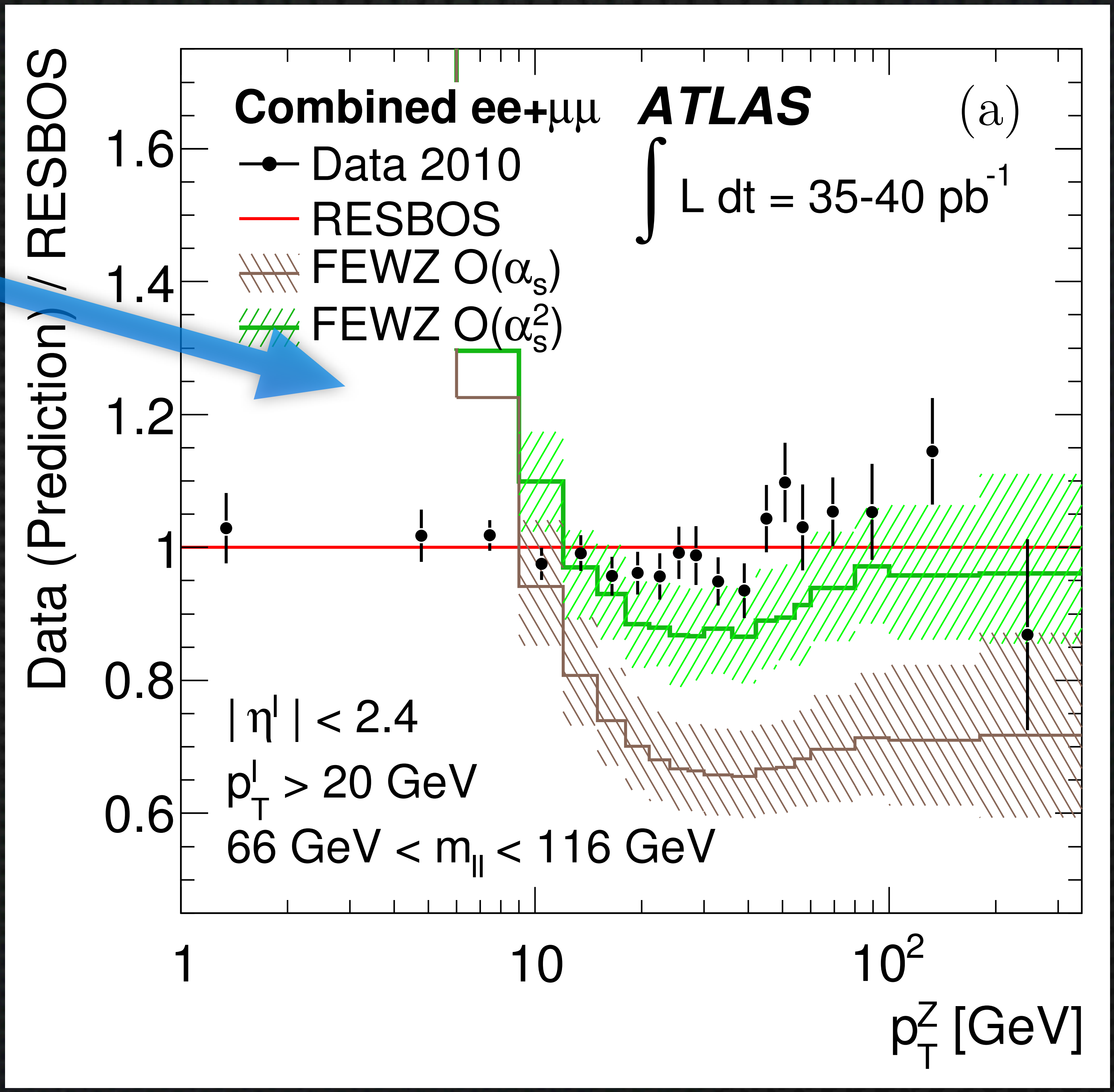
Fiducial measurement

FEWZ diverges at low p_T

(multiple soft gluon emissions)

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

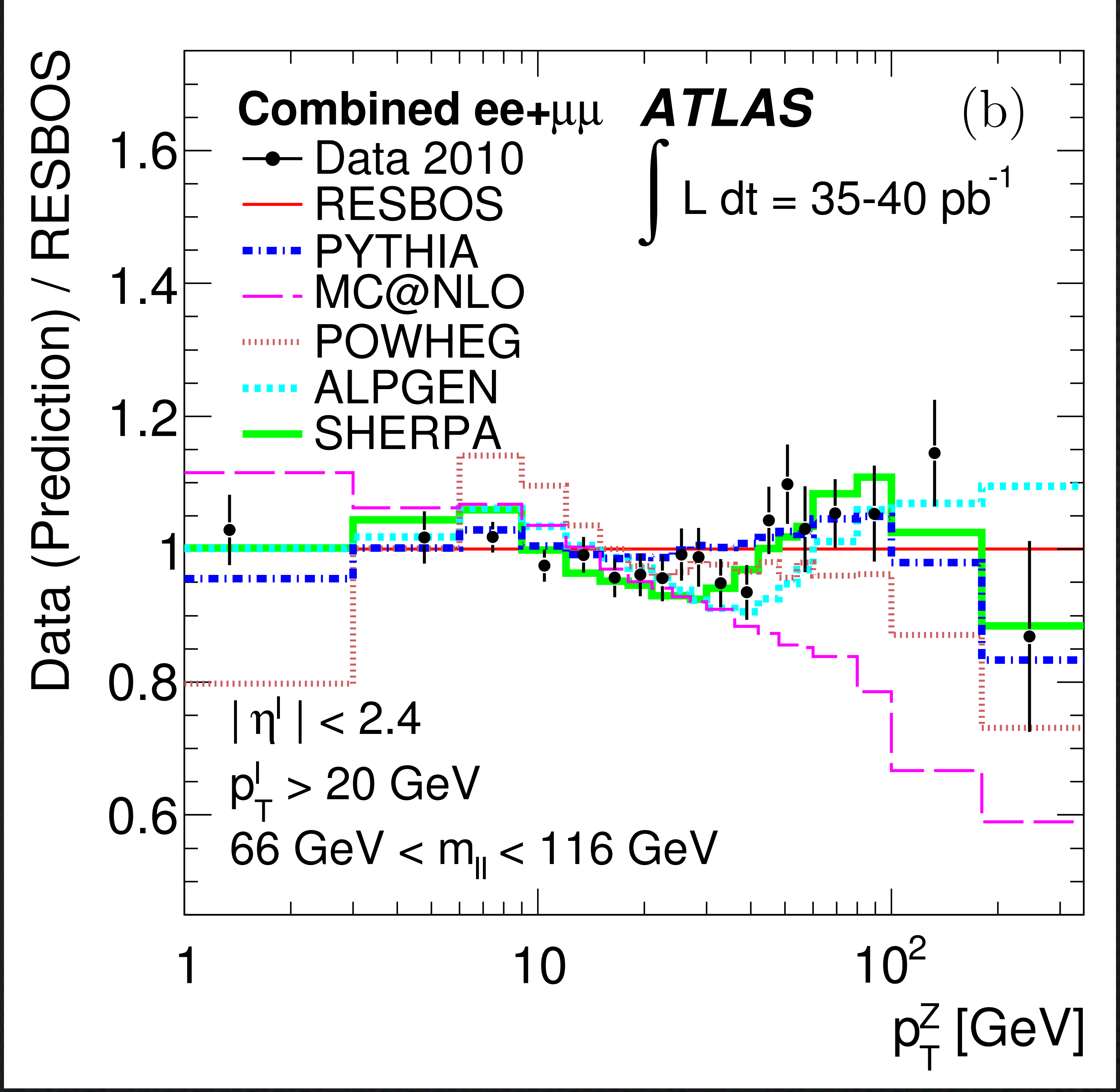
Ratio to RESBOS



Transverse momentum distribution of Z/γ* bosons

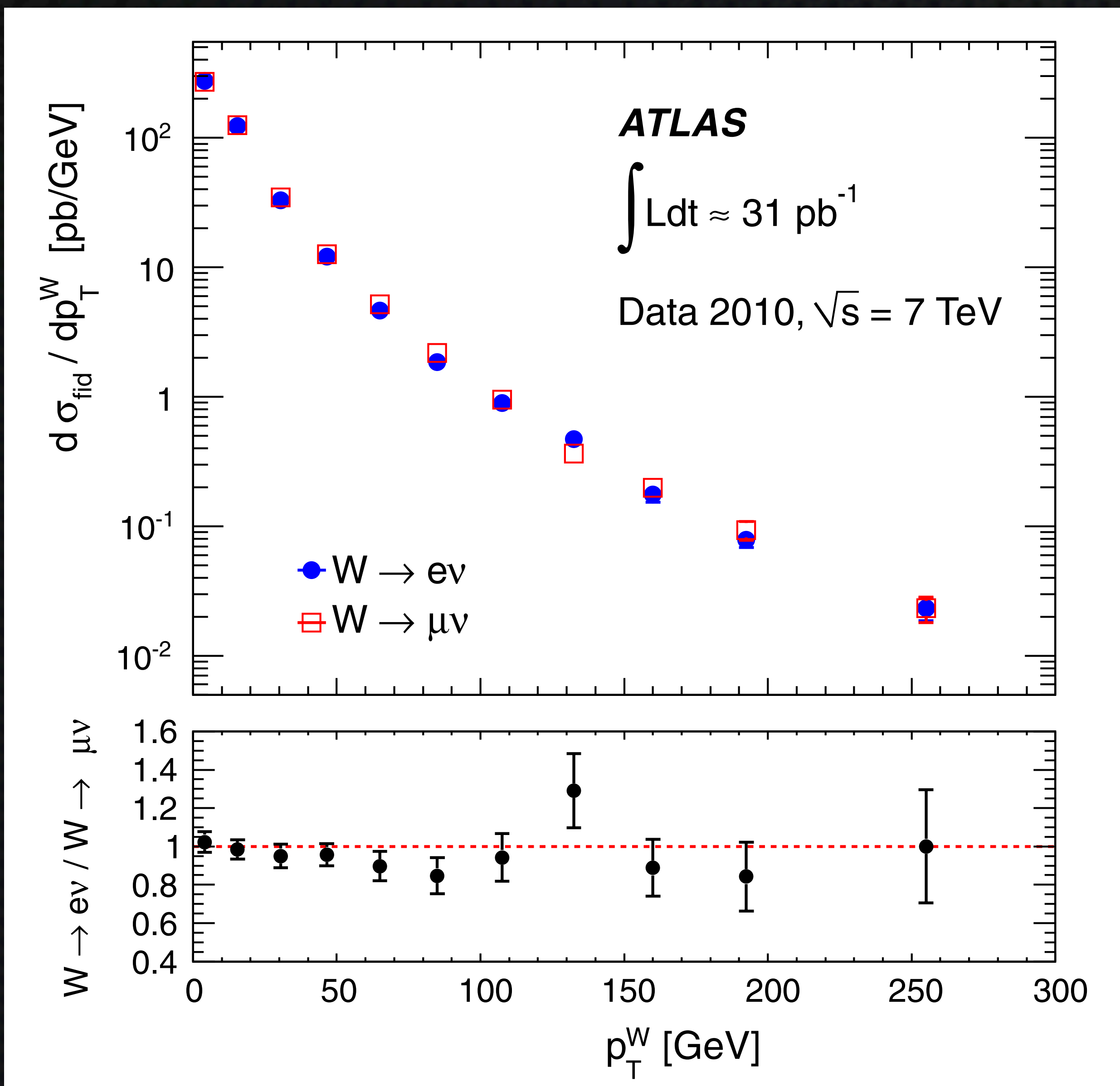
Predictions: Different event generators **Fiducial measurement**

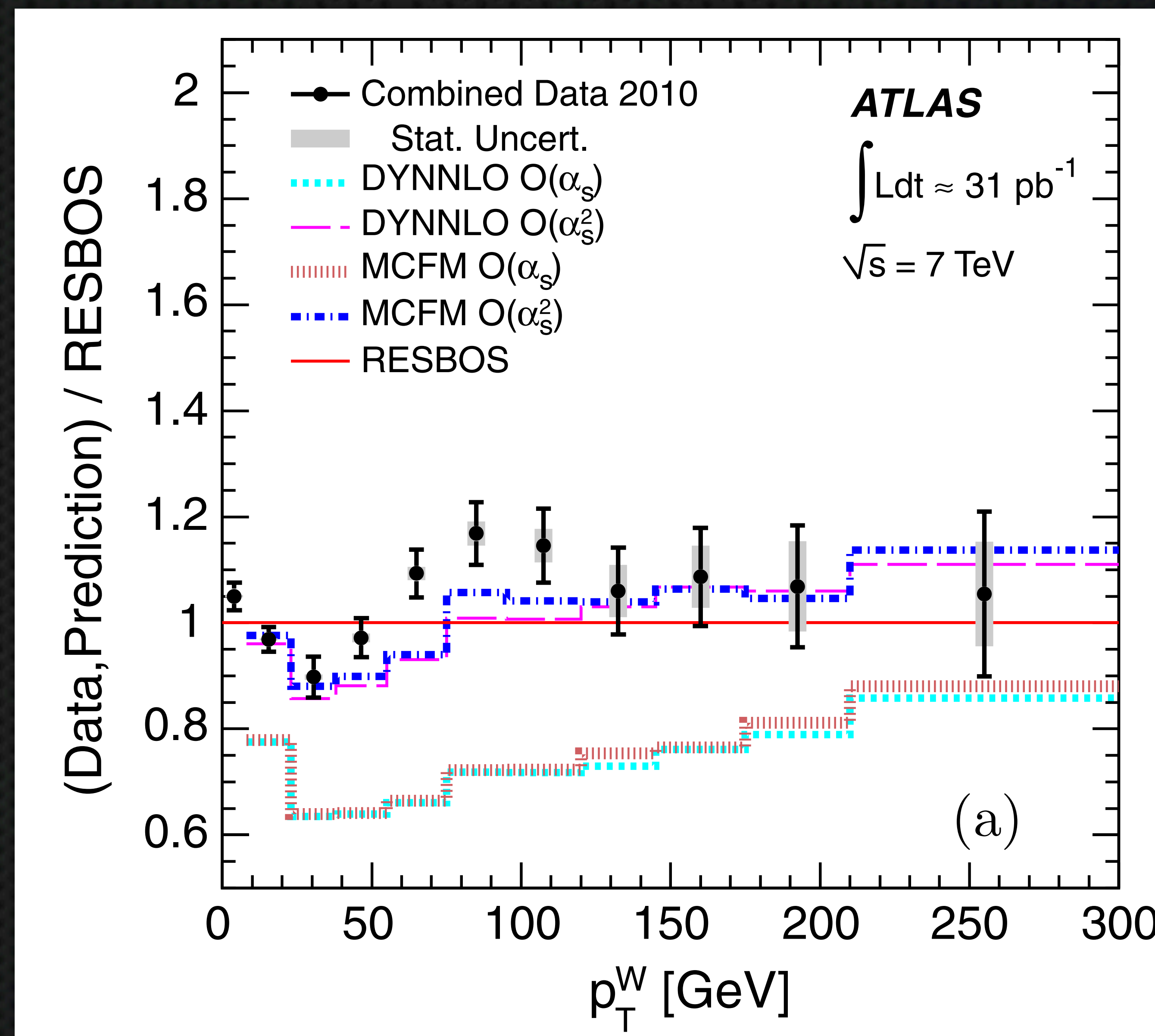
Ratio to RESBOS



Transverse momentum distribution of W bosons

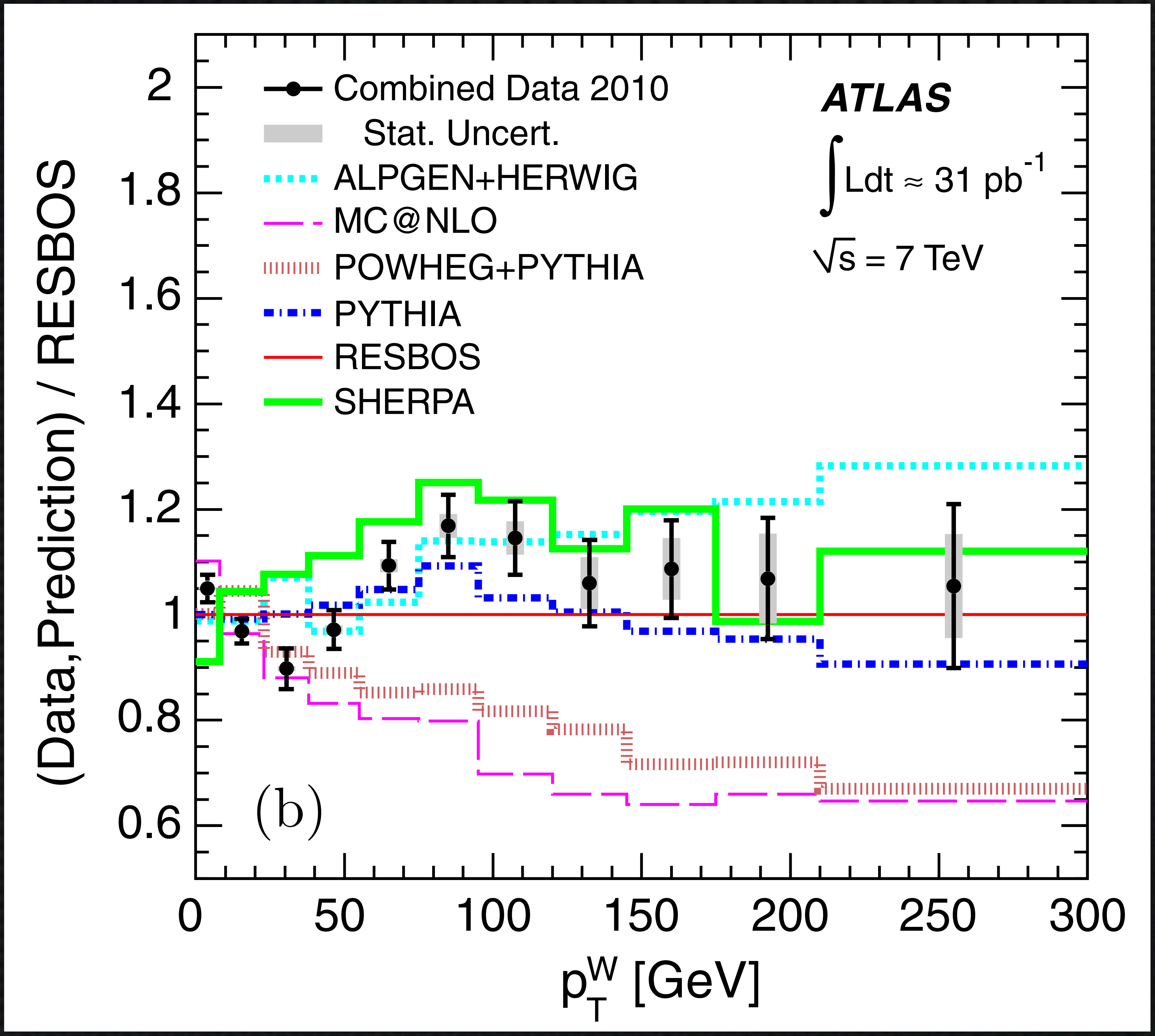
Phys.Rev. D85 (2012) 012005



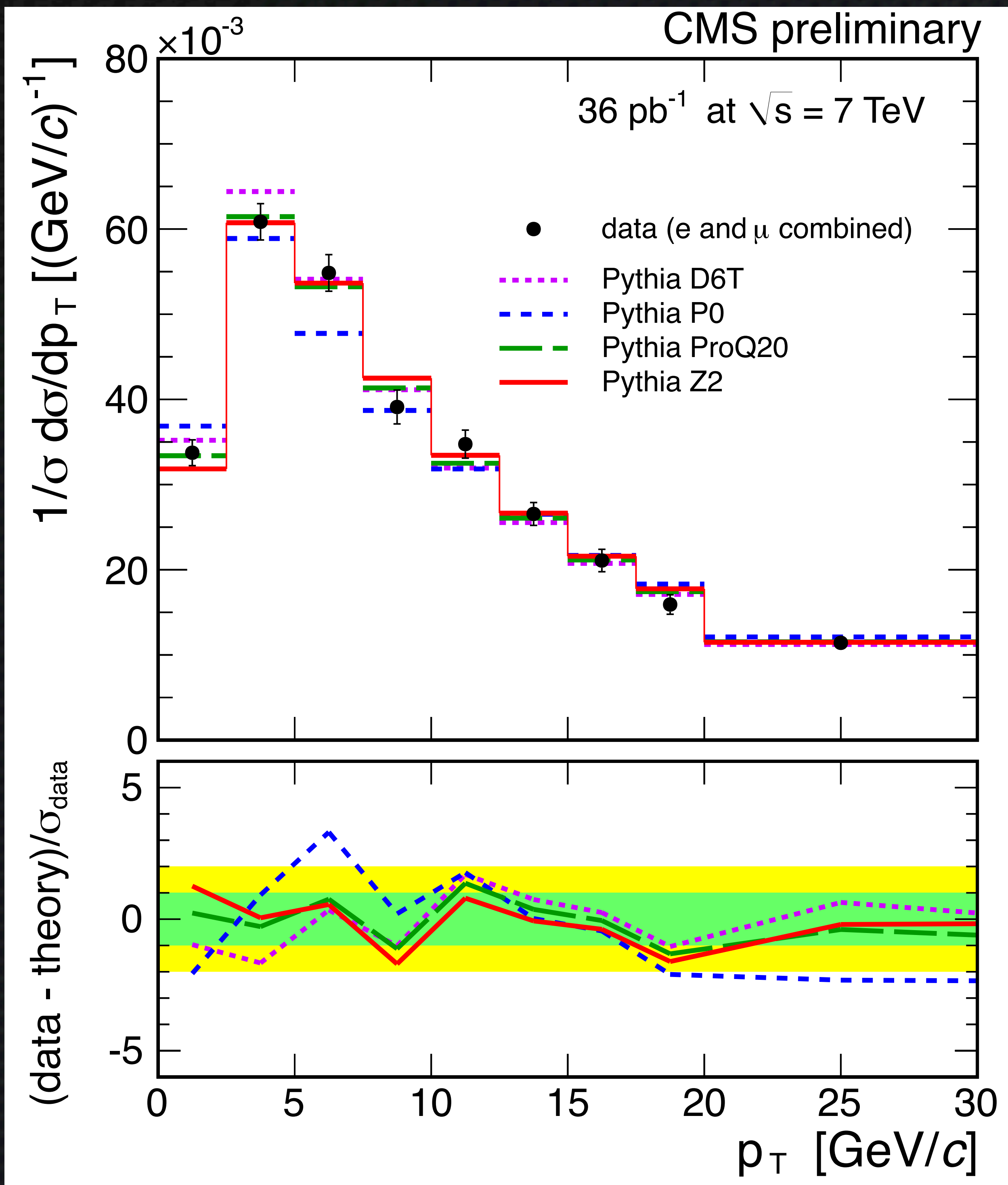


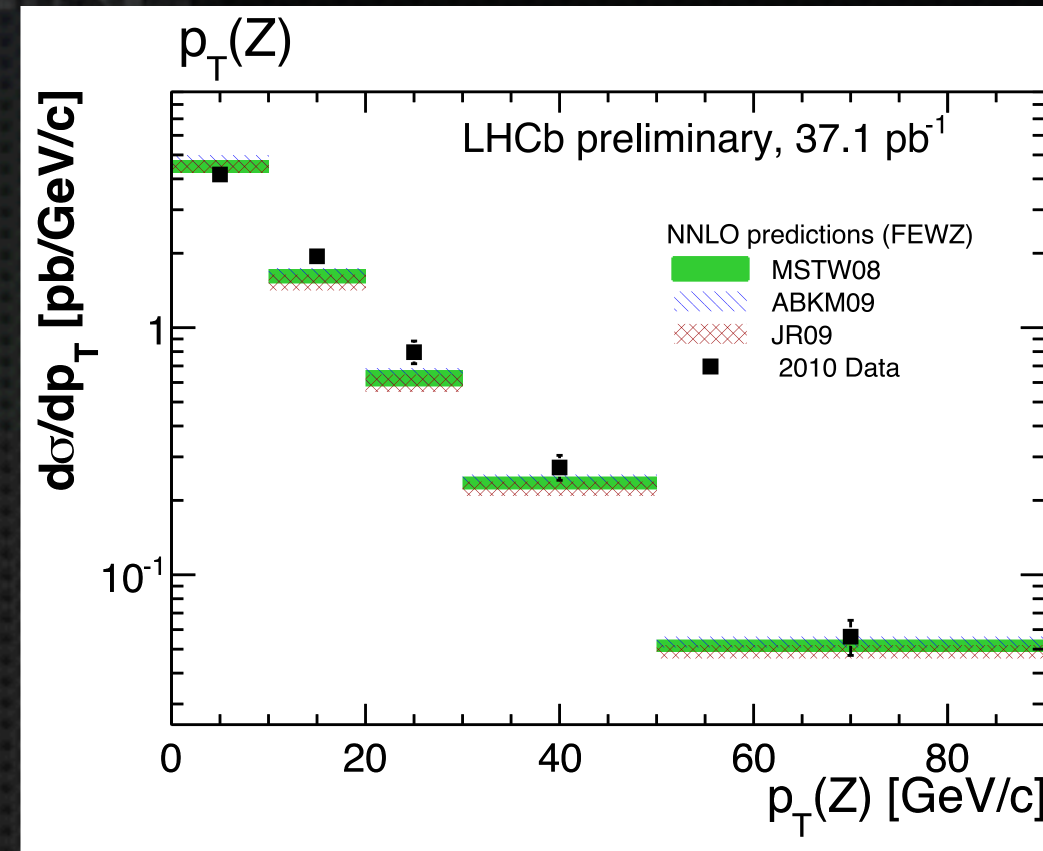
Transverse momentum distribution of W bosons

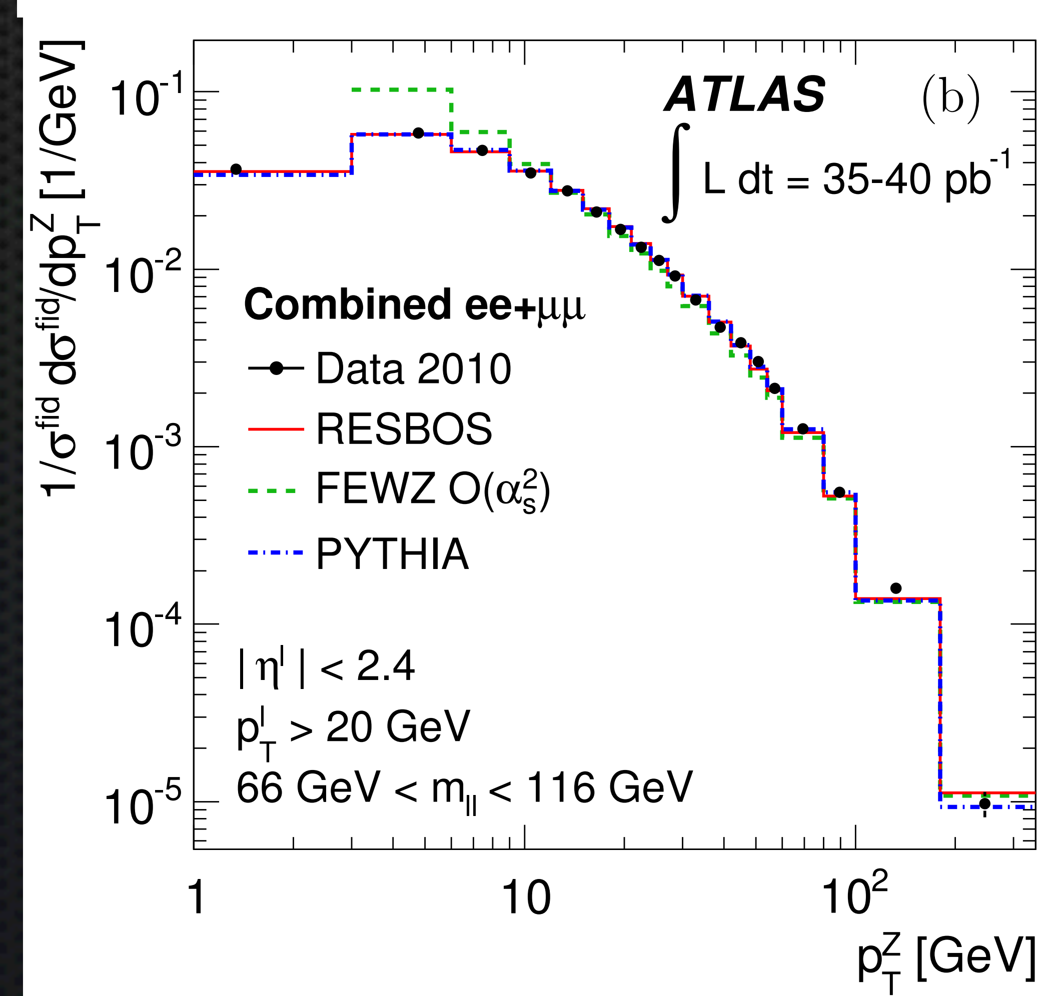
Phys.Rev. D85 (2012) 012005



Z Transverse Momentum at LHC







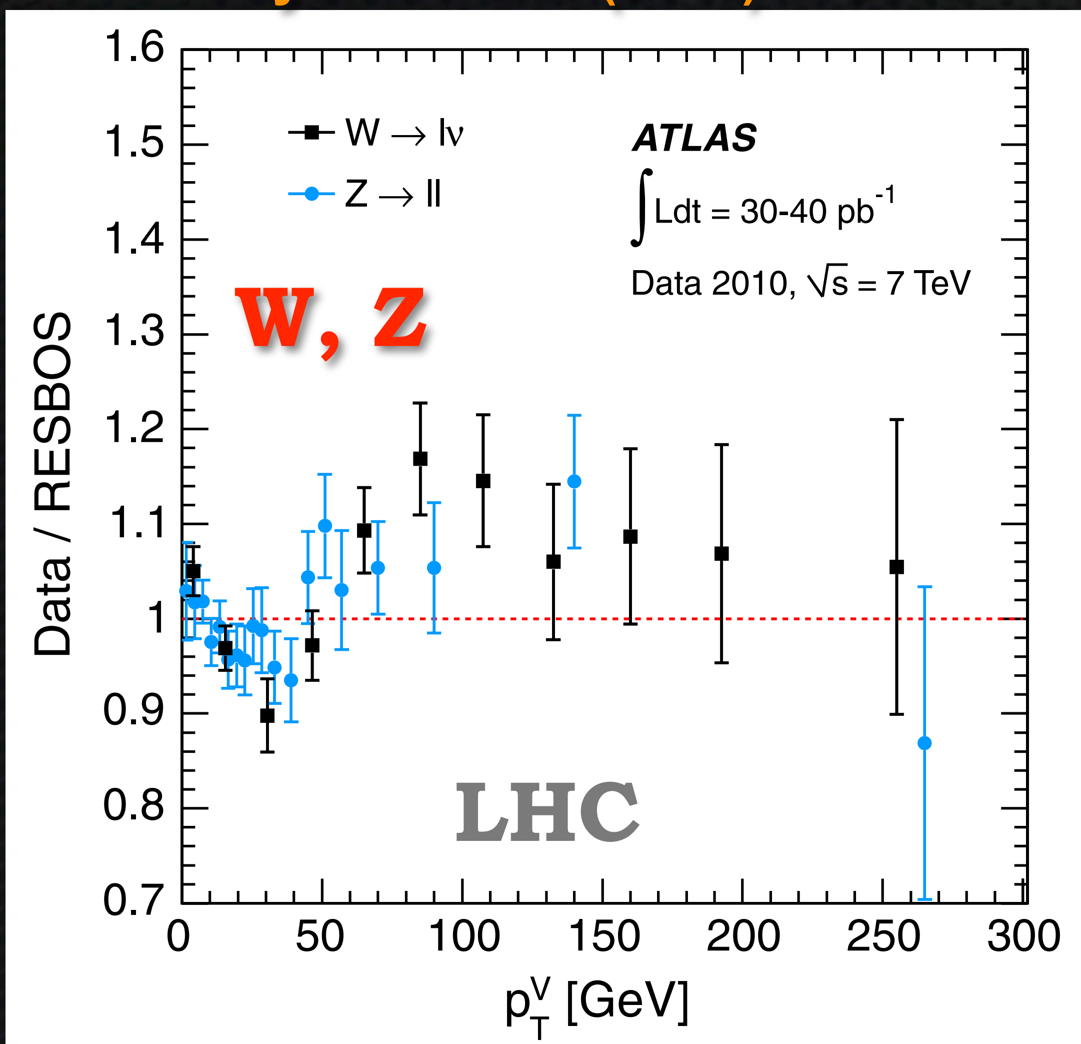
- **Predictions describe the data well in the full range**

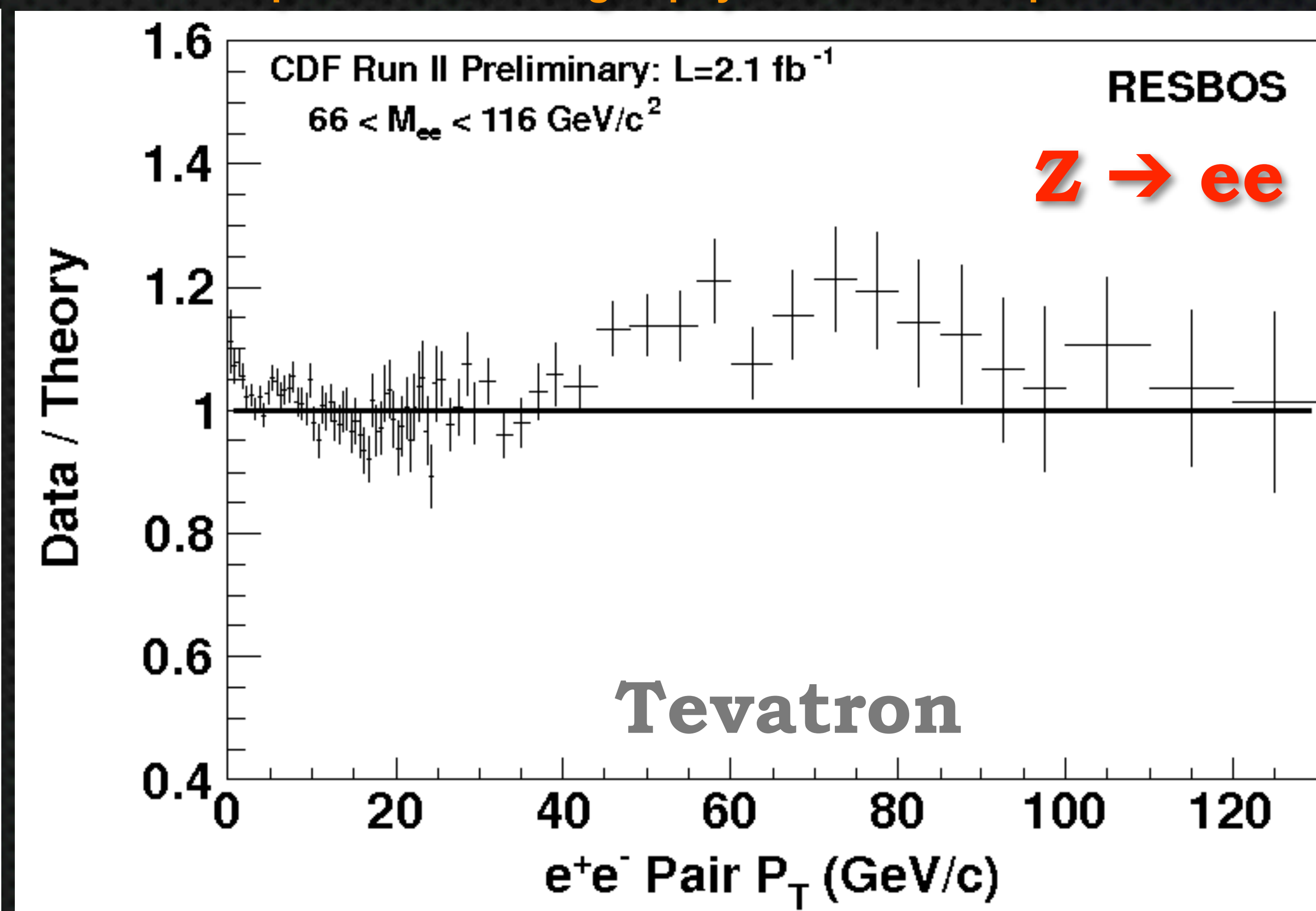
Measurement of Z and W P_T

- **Fully unfolded differential distributions**
  - **Comparison with RESBOS**

Phys.Rev. D85 (2012) 012005

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



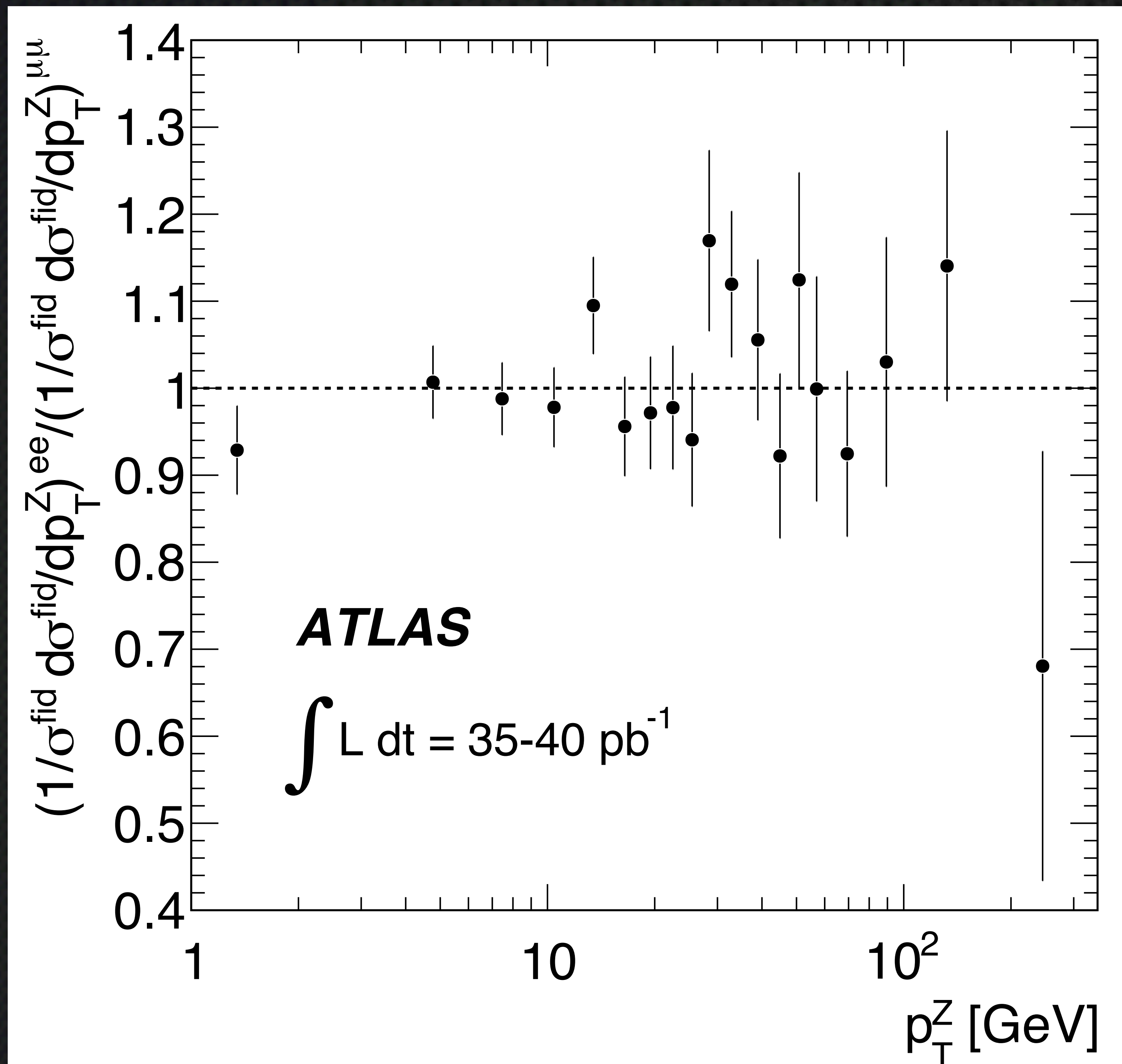


CMS Z P_T measurement:
Phys. Rev. D 85 (2012) 032002

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

Transverse momentum distribution of Z/γ* bosons

Comparison of electron- and muon- channel result

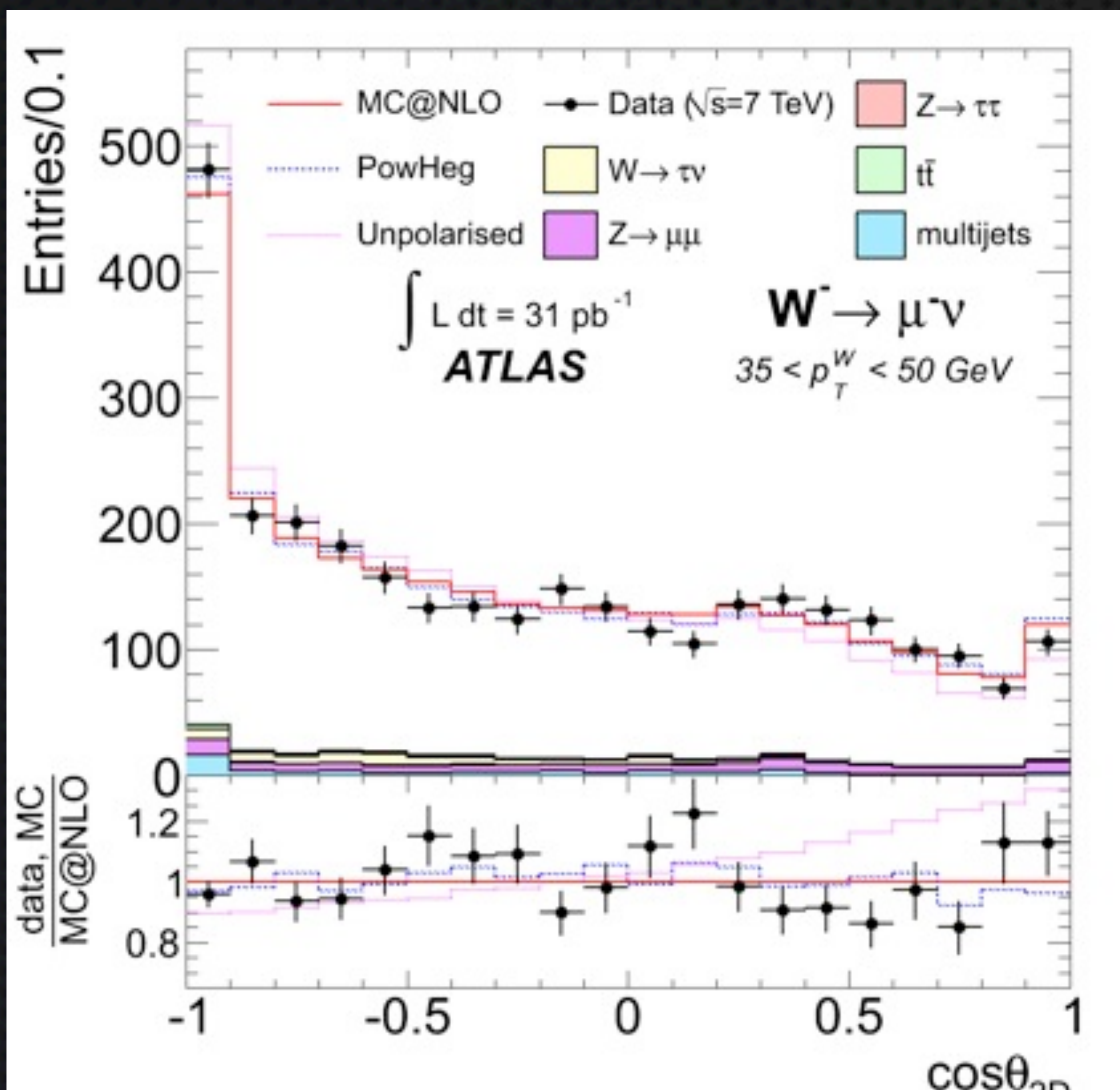


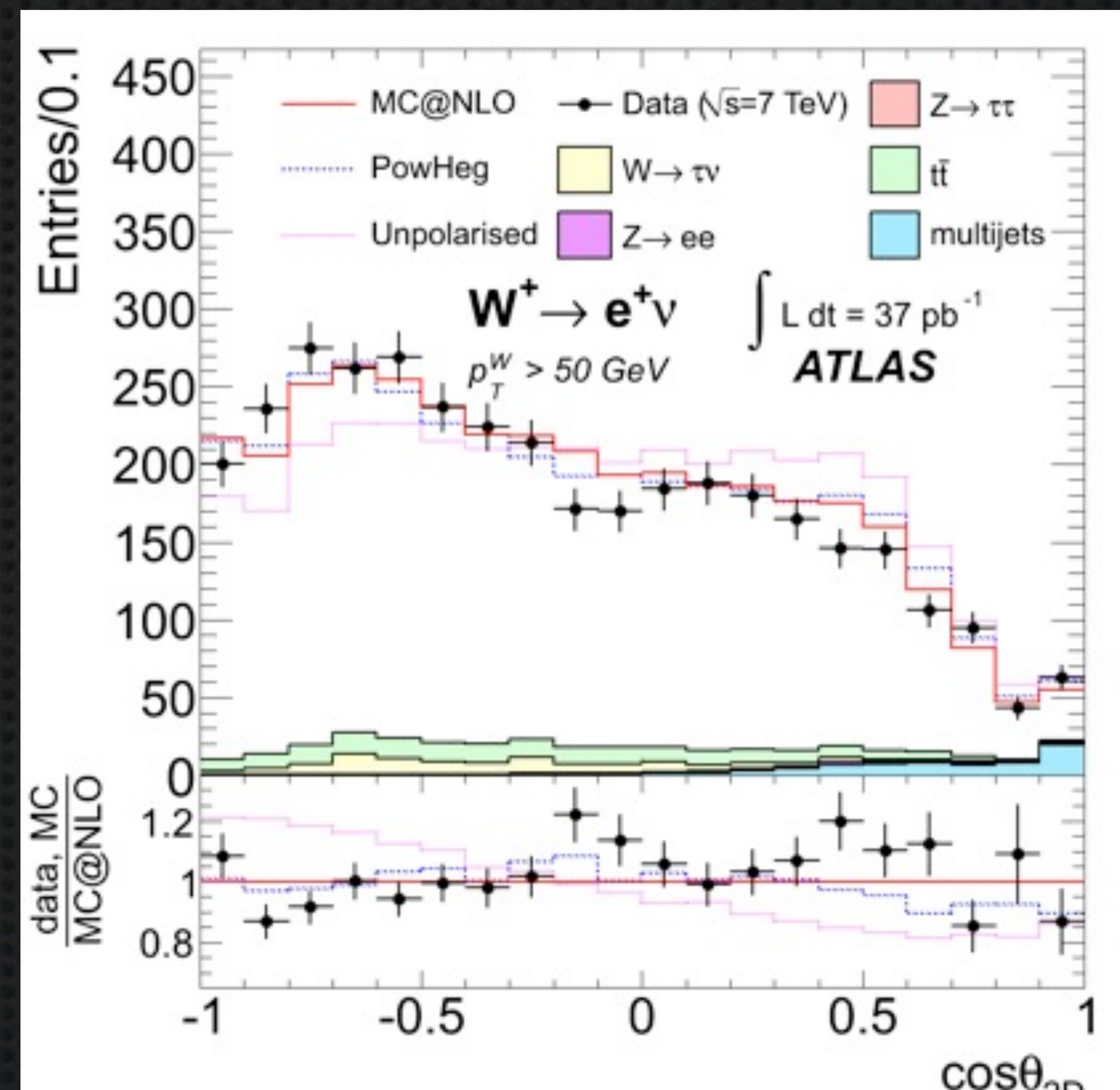
W Boson Polarization

Eur. Phys. J. C72 (2012) 2001

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

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





Signal:
- **MC@NLO 3.4.2 + HERWIG**
- **POWHEG 1.0 + PYTHIA**

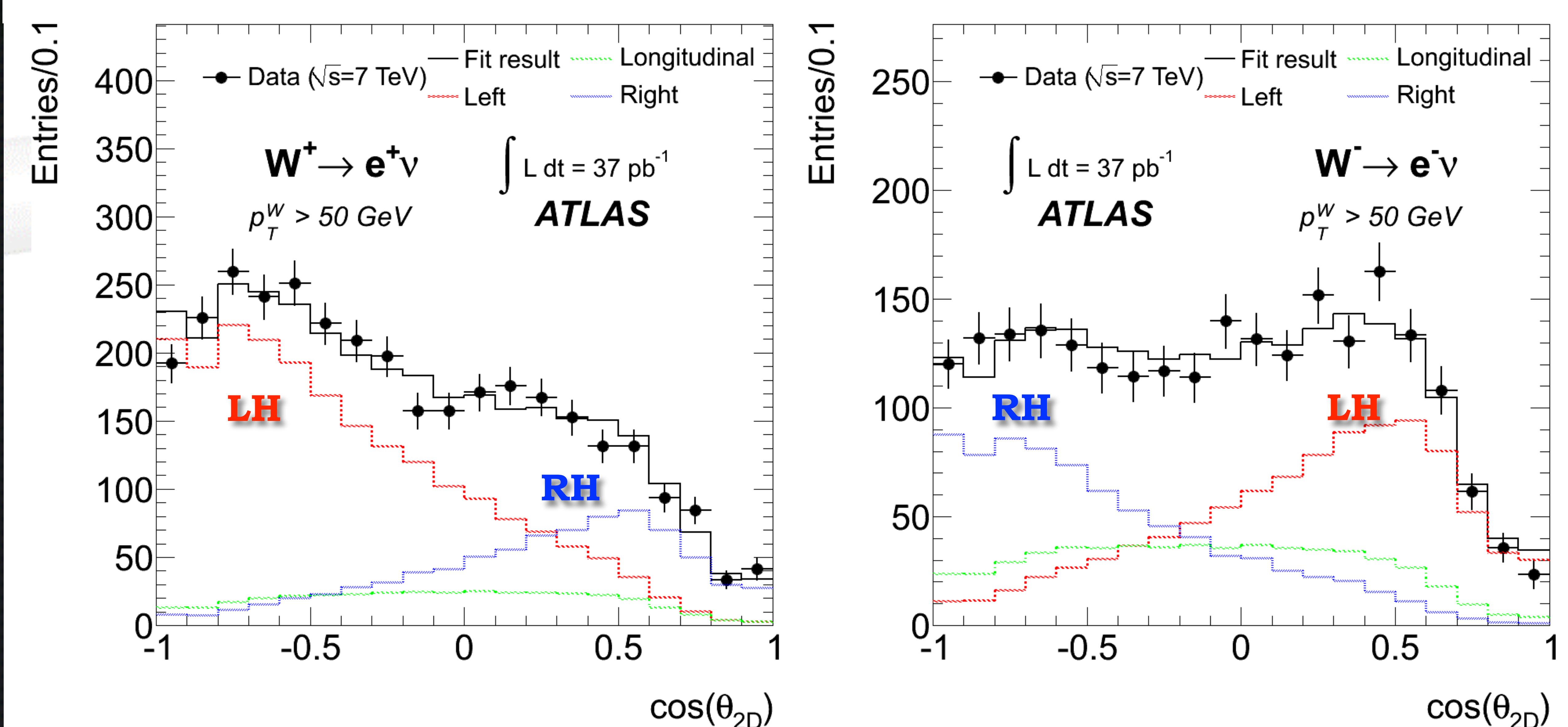
(CTEQ 6.6)

Uncertainties:
MSTW08 and HERAPDF 1.0

W Polarization

Eur. Phys. J. C72 (2012) 2001

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

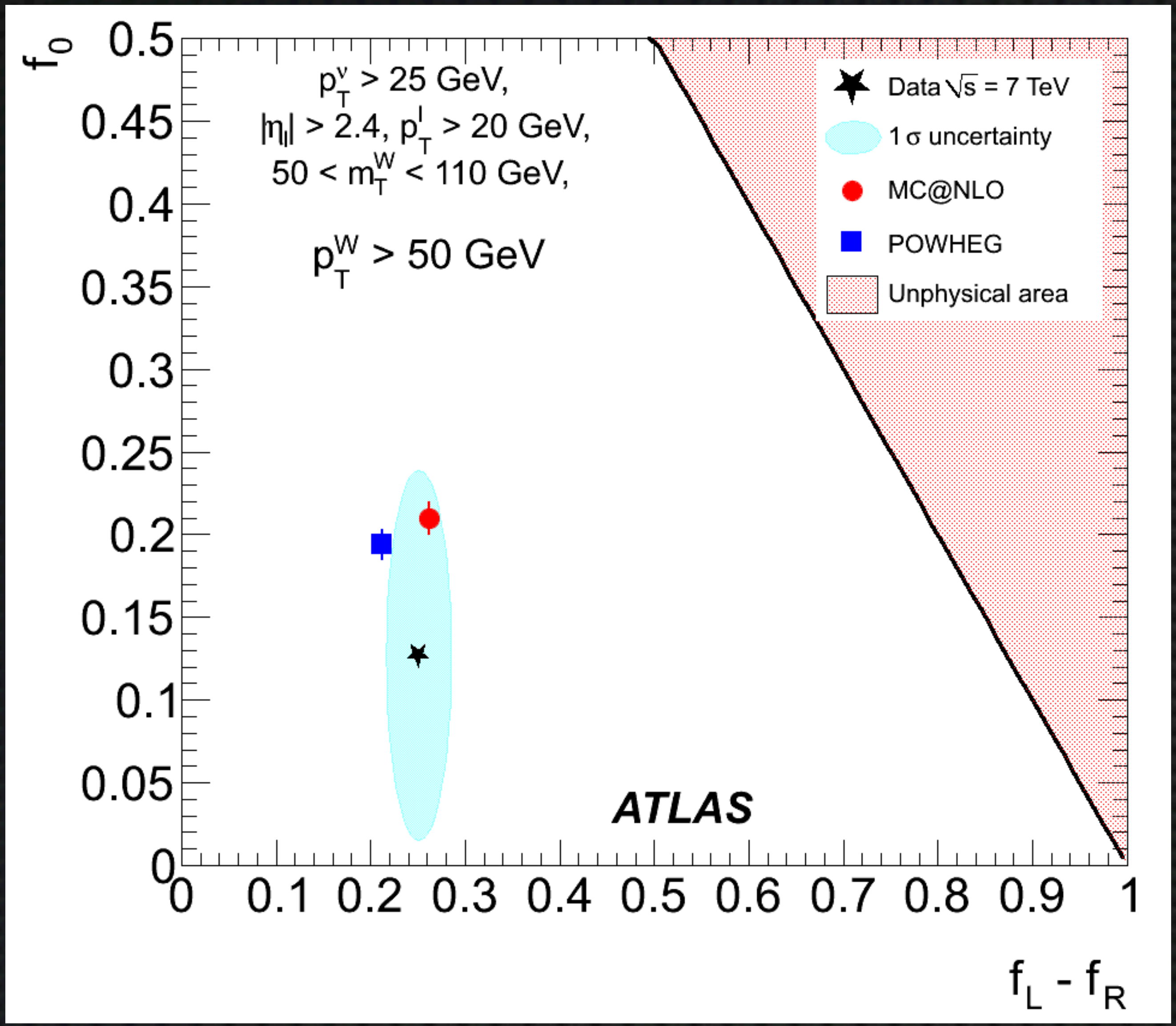


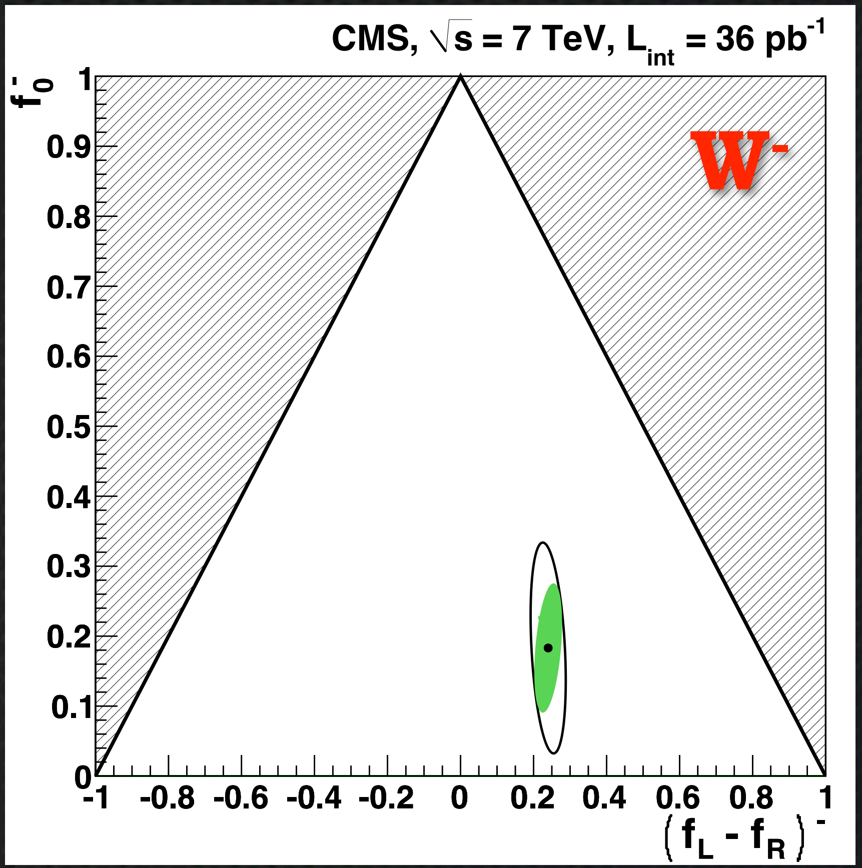
Templates from MC@NLO after background subtraction

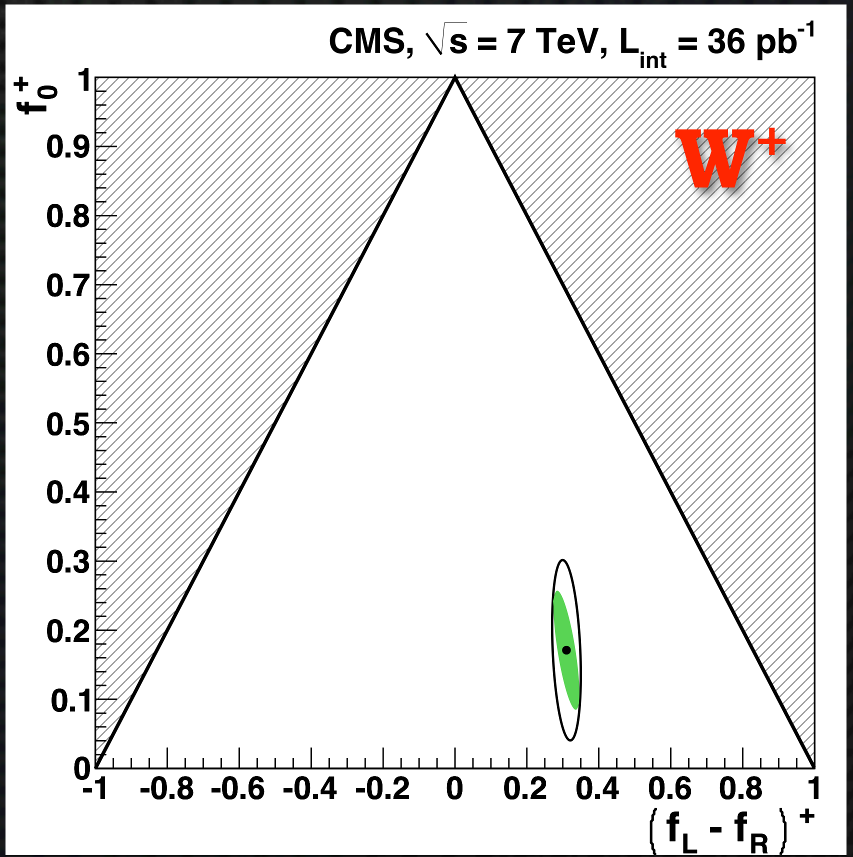
W Boson Polarization

Eur. Phys. J. C72 (2012) 2001

Phys. Rev. Lett. 107 (2011) 021802







	$f_L - f_R$ (%)	
	$35 < p_T^W < 50$ GeV	$p_T^W > 50$ 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

Event selection in tau polarization analysis

- 24 pb-1 from 2010 data with tau (16 GeV) + Missing E_T (22 GeV) trigger
- Offline: single-track tau with p_T > 20 GeV and Missing ET greater than 30 GeV
- Reject events with jet activity in region between the central and endcap detectors
- Reject events with electron or muon greater than 15 GeV E_T
- Reject events with jet activity along direction of event Missing E_T
- Require Missing ET significance > 6

$$S_{E_{\mathrm{T}}^{\mathrm{miss}}} = \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sigma(E_{\mathrm{T}}^{\mathrm{miss}})}$$

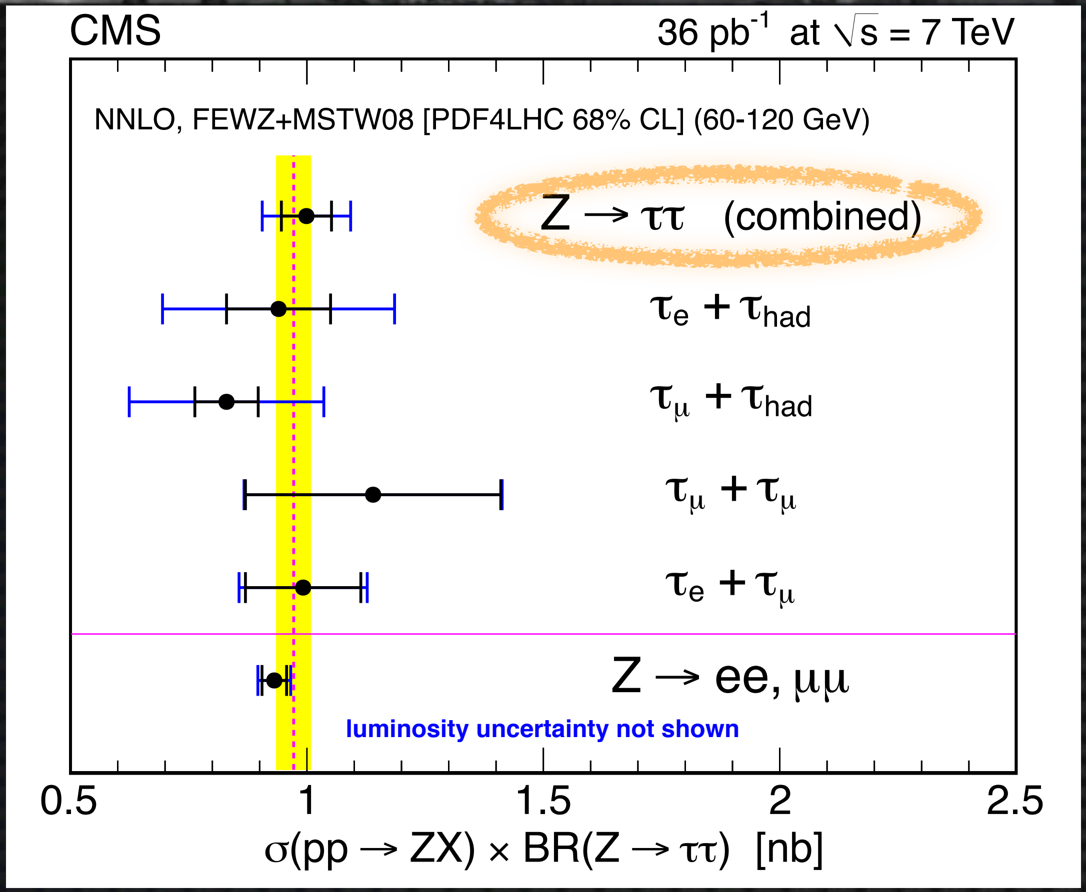
Based on ATLAS W-> τν cross section measurement: Phys. Lett. B 706, 276 (2012)

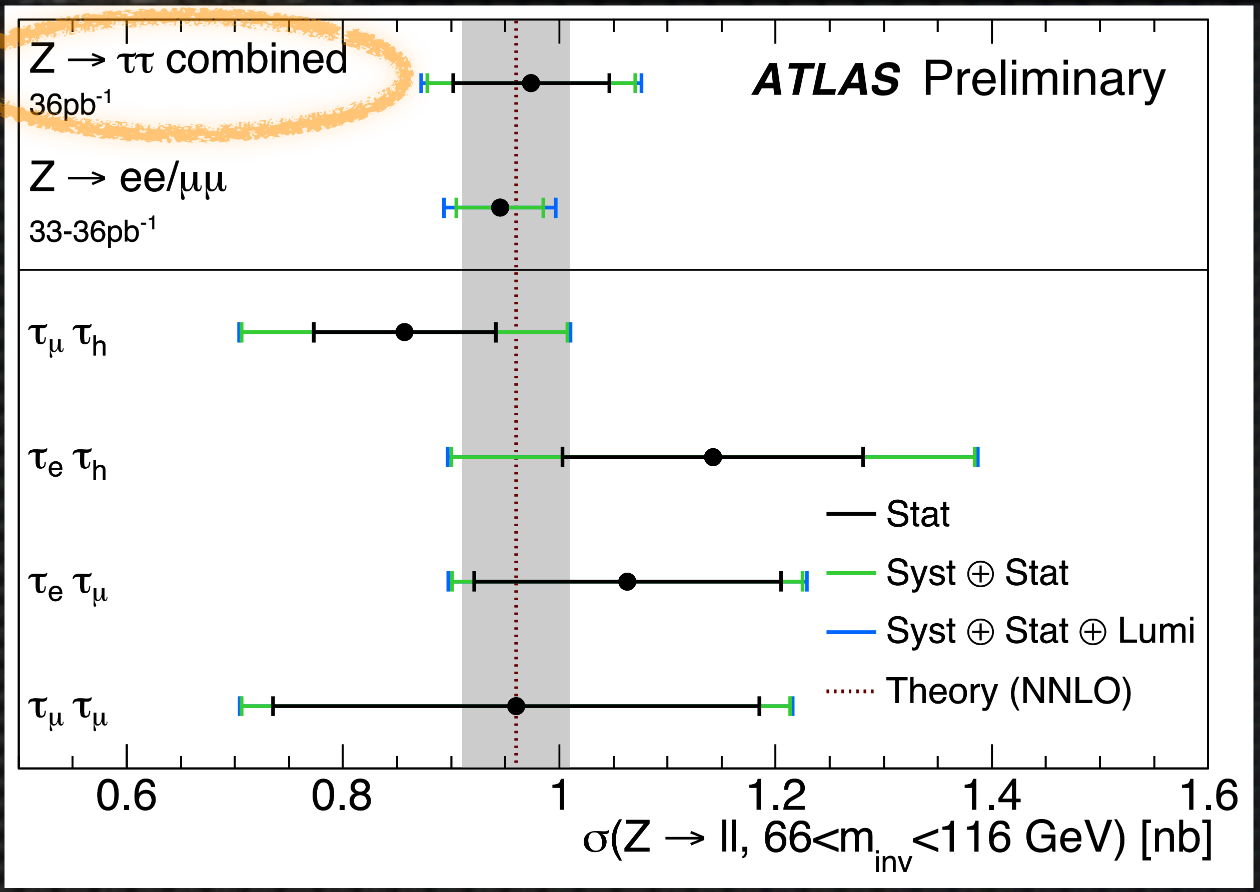
$$pp \longrightarrow W + X$$
$$\hookrightarrow \tau\ \nu$$

W/Z inclusive production in τ channel

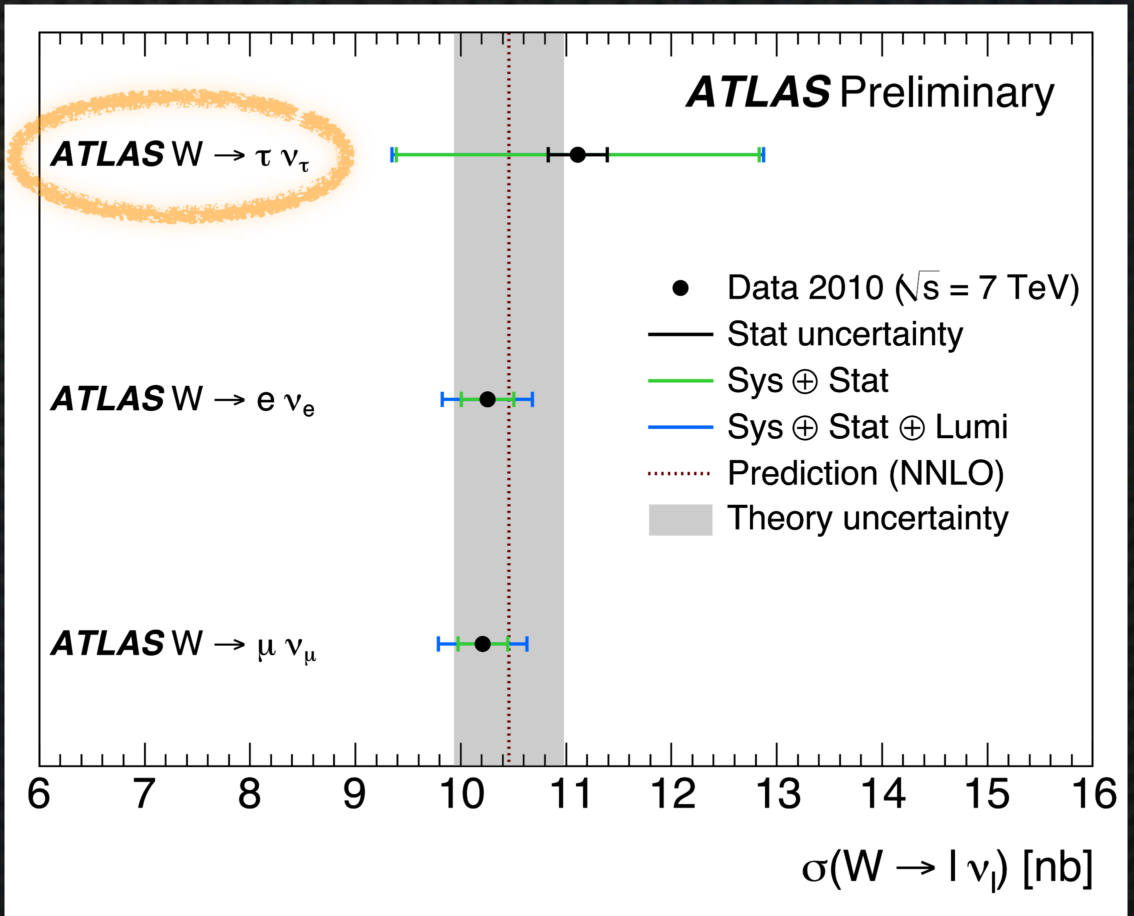
$$pp \longrightarrow Z + X$$
$$\hookrightarrow \tau\ \tau$$

Z→ττ and W→τν Cross Section

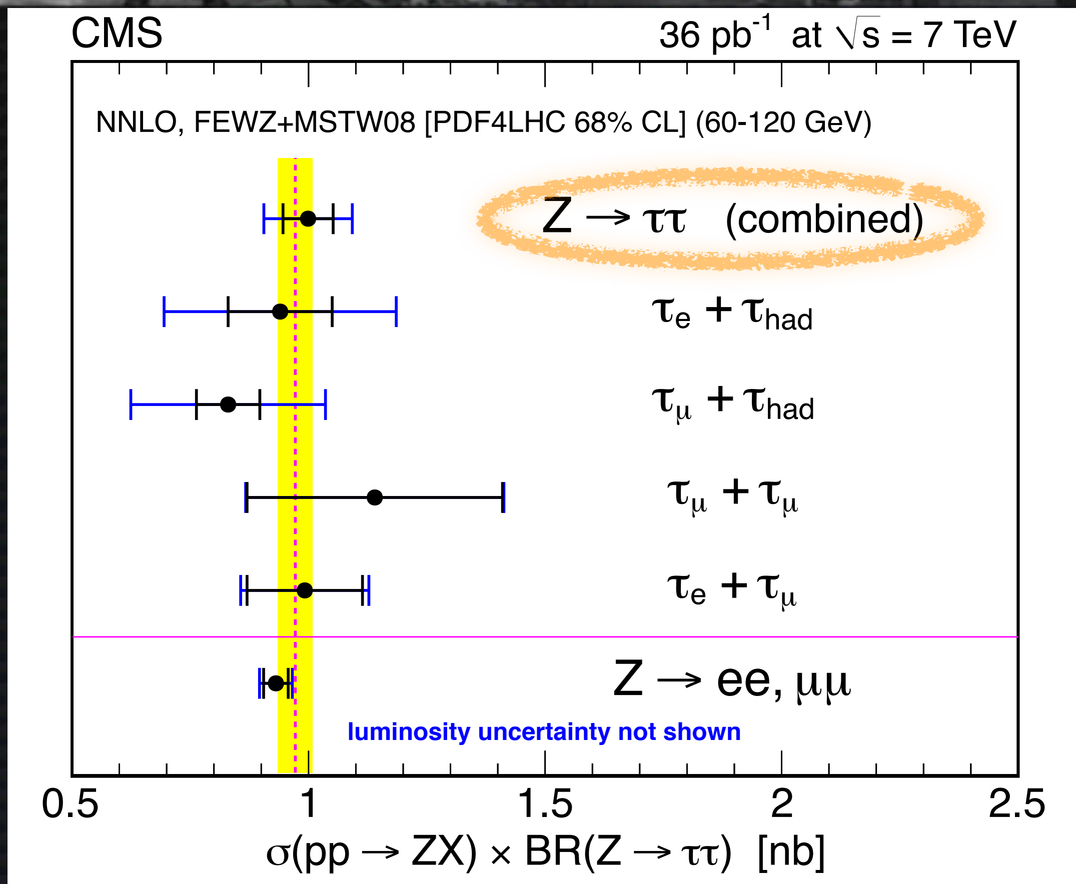


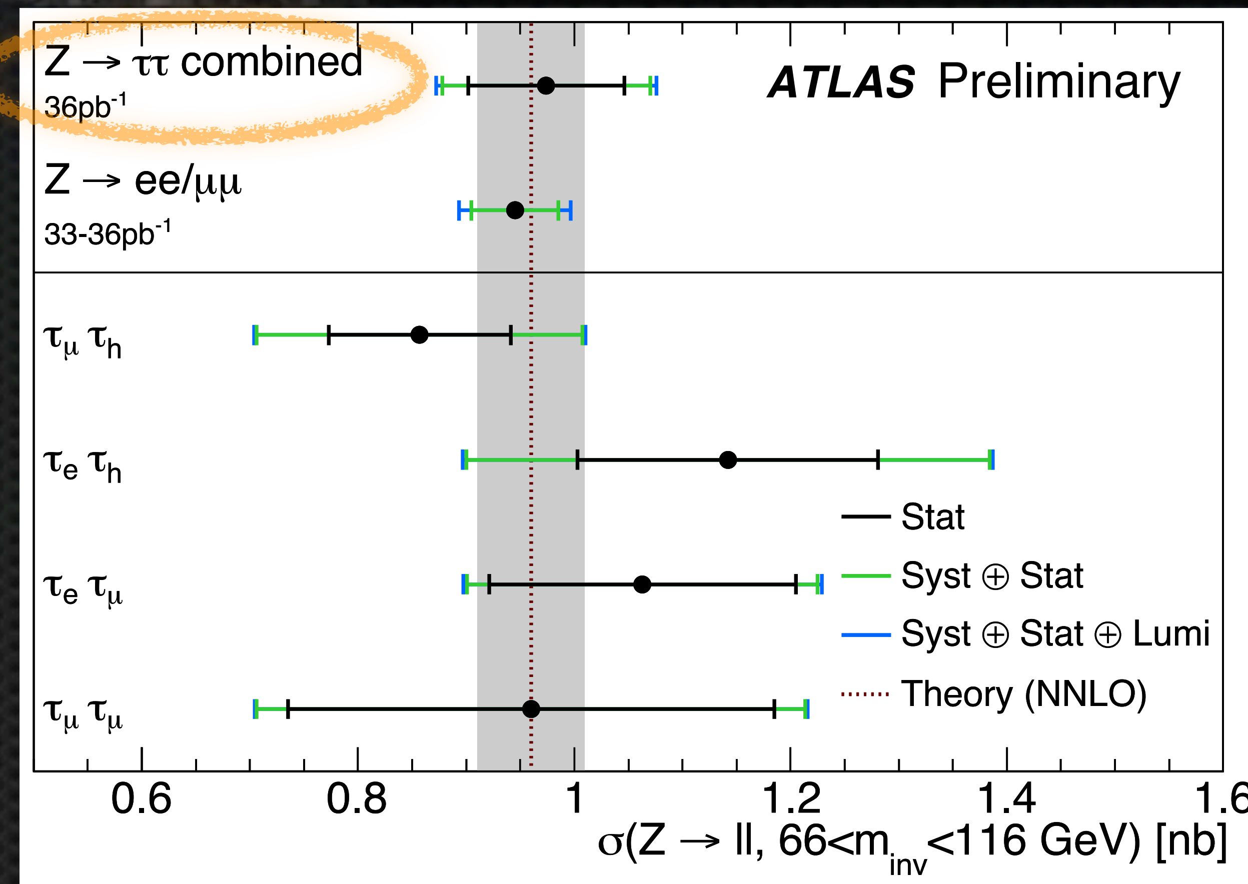


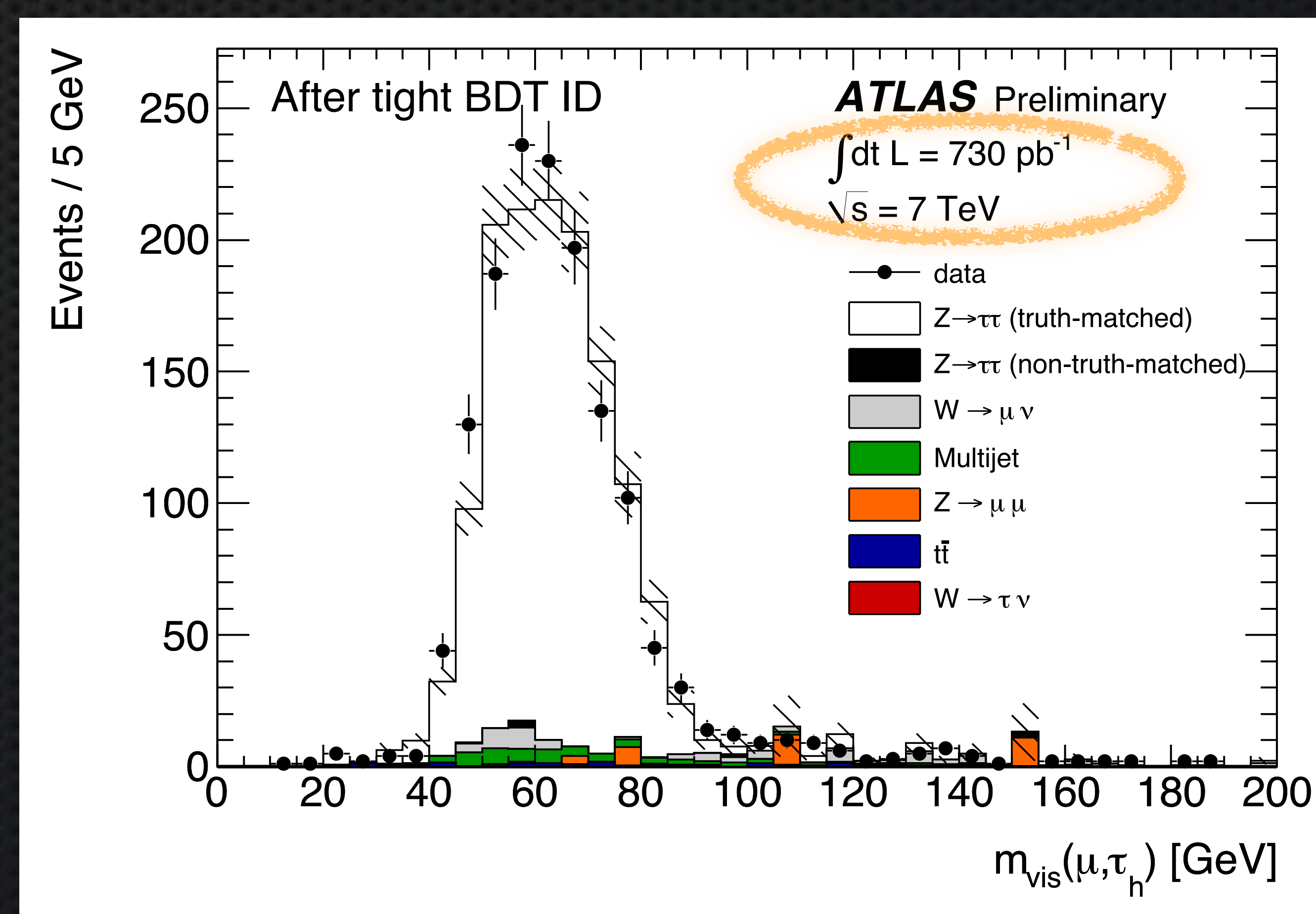
- **Excellent tau identification at LHC**
- **Z→ττ cross section**
  - **CMS: Published**
  - **ATLAS: New**
- **W→τν cross section**
  - **ATLAS: New**
- **Good prospects for new physics searches with taus**



Z→ττ and W→τν Cross Section







- **Excellent tau identification at LHC**
- **Z→ττ cross section**
  - **CMS: Published**
  - **ATLAS: New**
- **W→τν cross section**
  - **ATLAS: New**
- **Good prospects for new physics searches with taus**

Tau Polarization

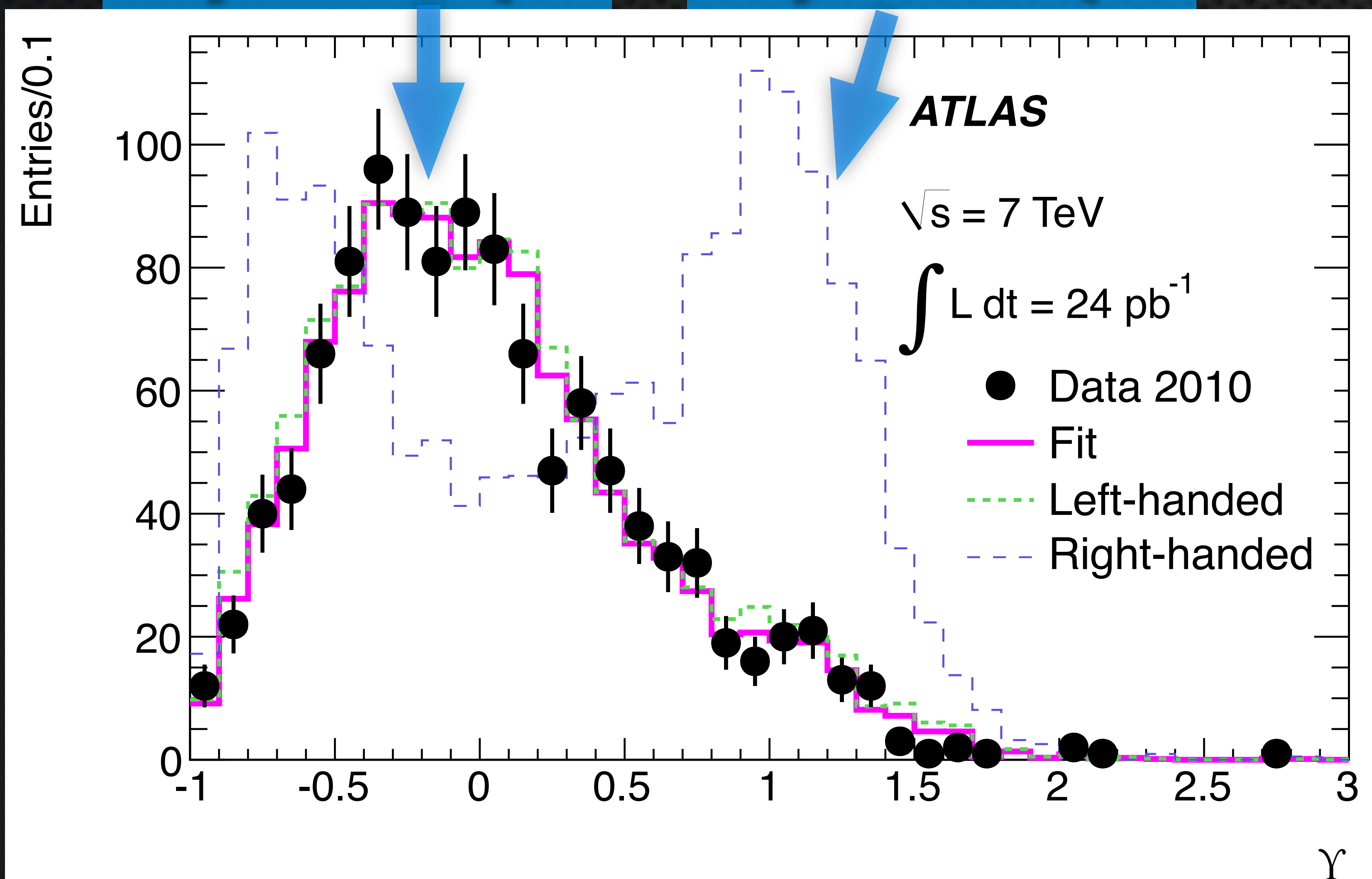
Eur.Phys.J. C72 (2012) 2062

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

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

Transversely polarized ρ

Longitudinally polarized ρ



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

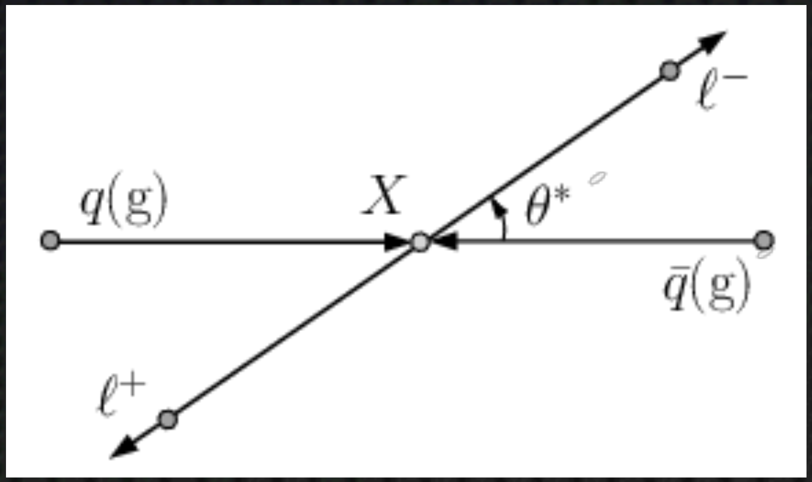
BR = 25.94 ± 0.09%

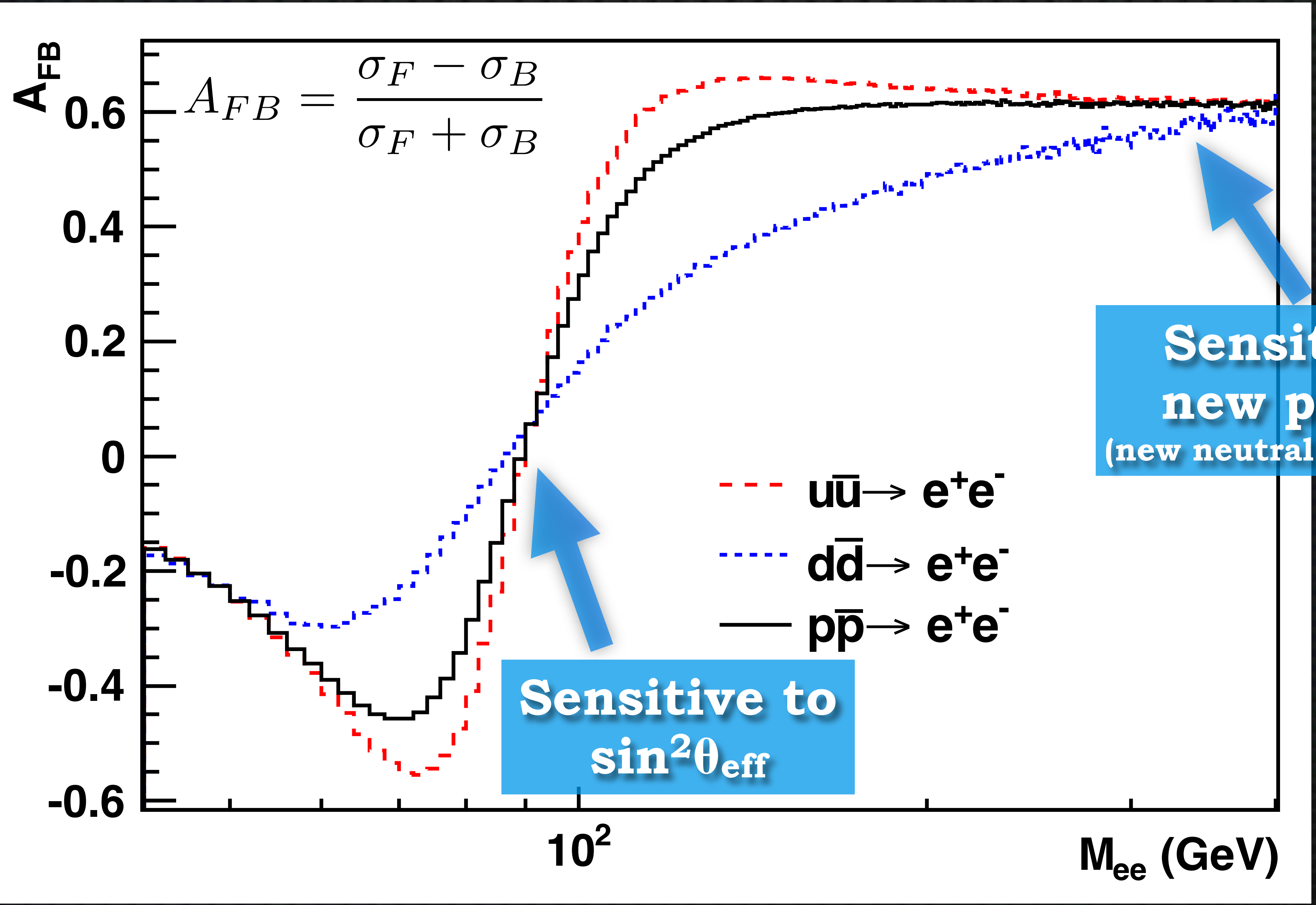
$$\Upsilon = \frac{2p_T^{trk}}{p_T^\tau} - 1 \approx \frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T}$$

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

Z forward-backward asymmetry

at Hadron Colliders

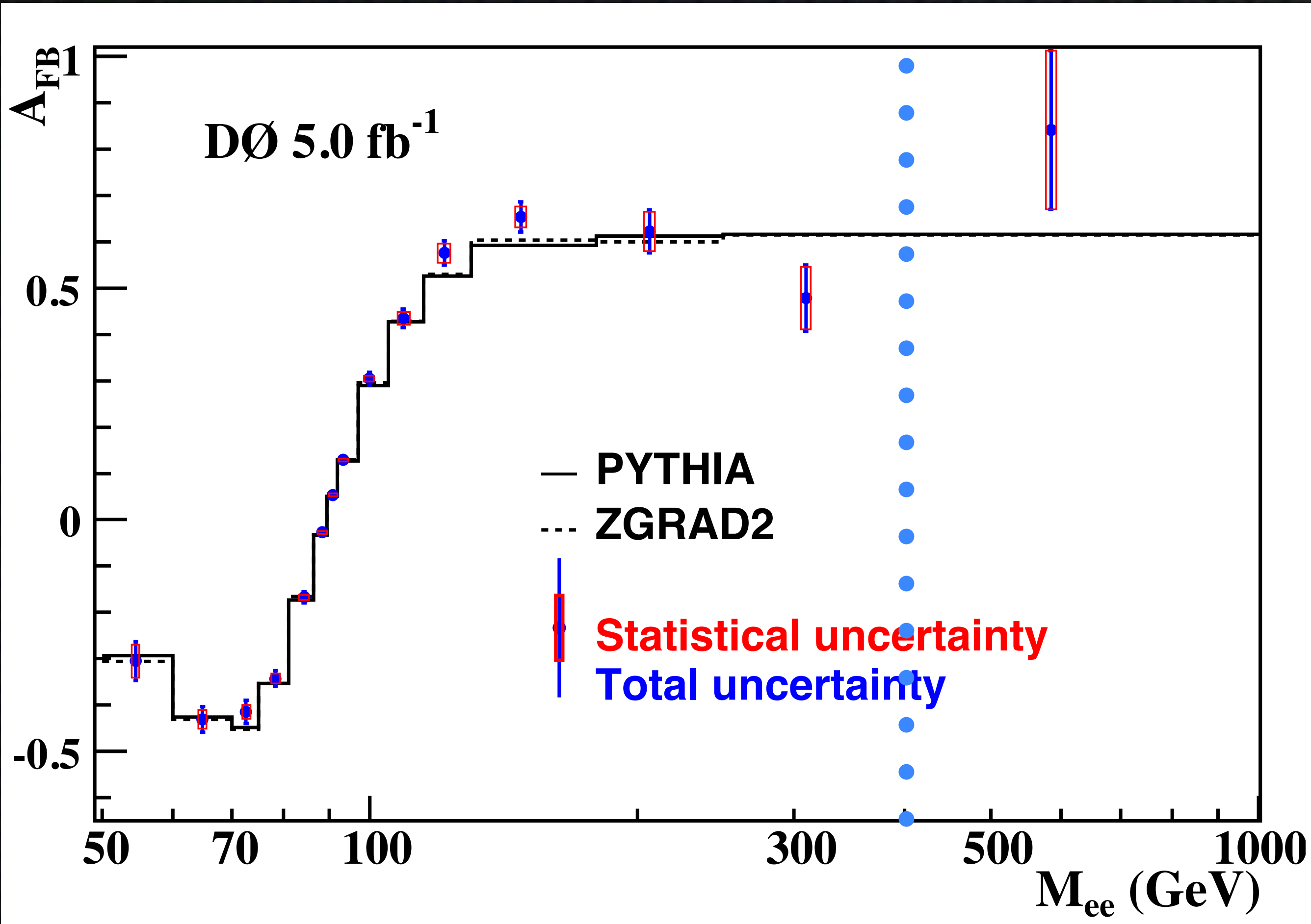




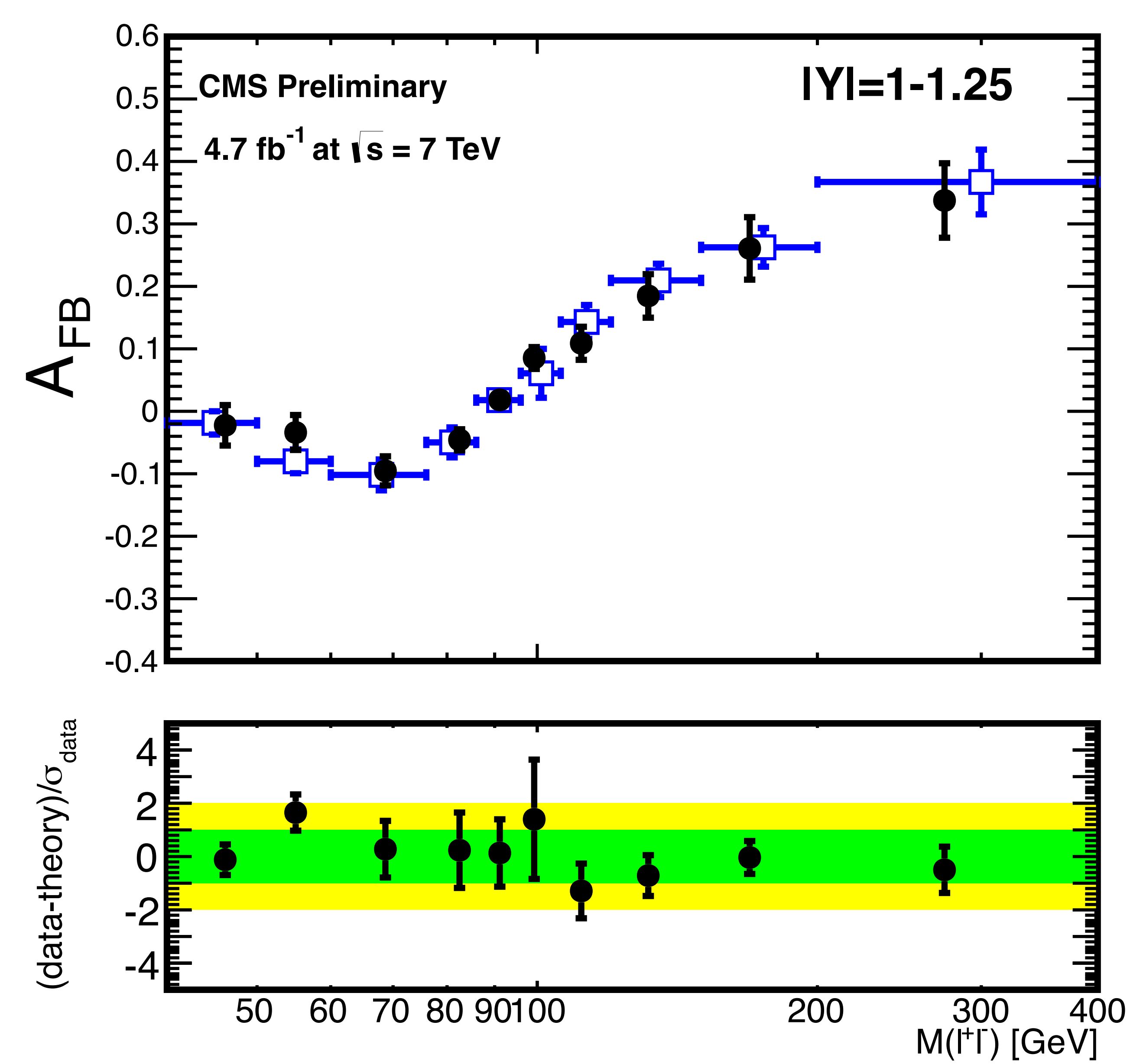
Z forward-backward asymmetry

at Hadron Colliders

Phys. Rev. D 84, 012007 (2011)



CMS PAS EWK-11-004

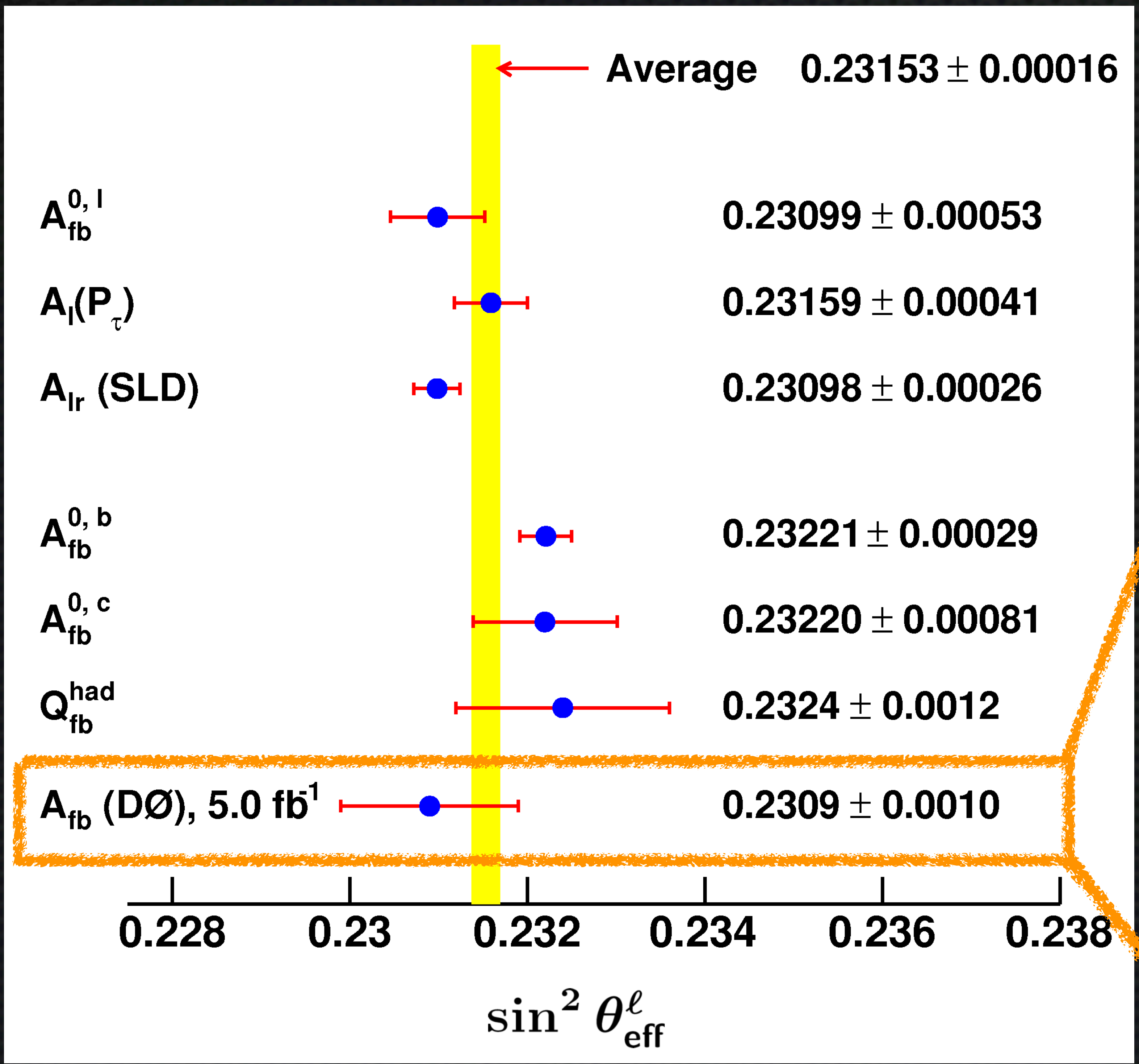


Unfolded AFB agrees well with theoretical predictions

No evidence for new physics at high-mass

Effective Weak Mixing Angle

D0



0.2309 ± 0.0008 (stat) ± 0.0006 (syst)

Most precise measurement from Z to light-quark coupling

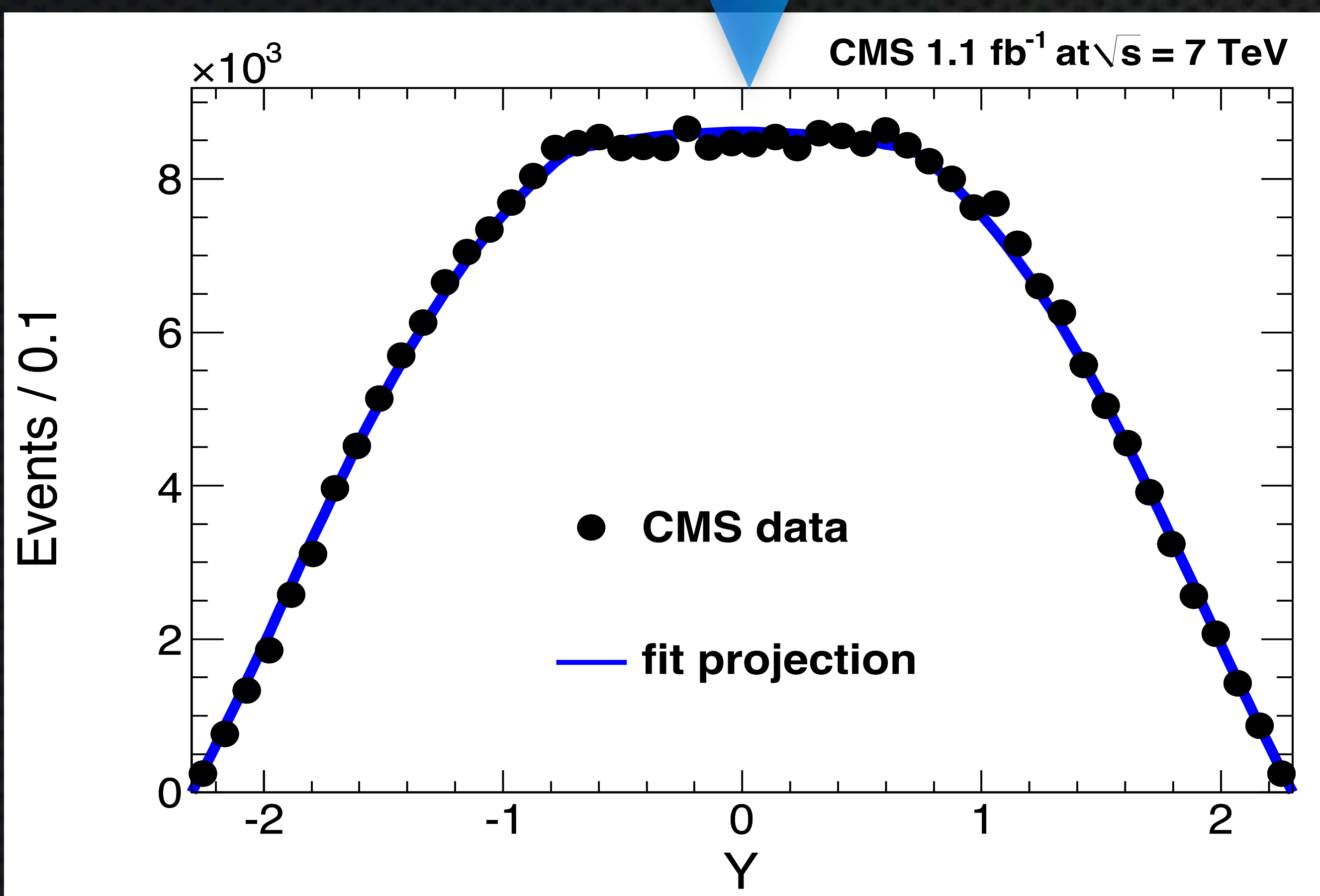
Statistical uncertainty still dominant

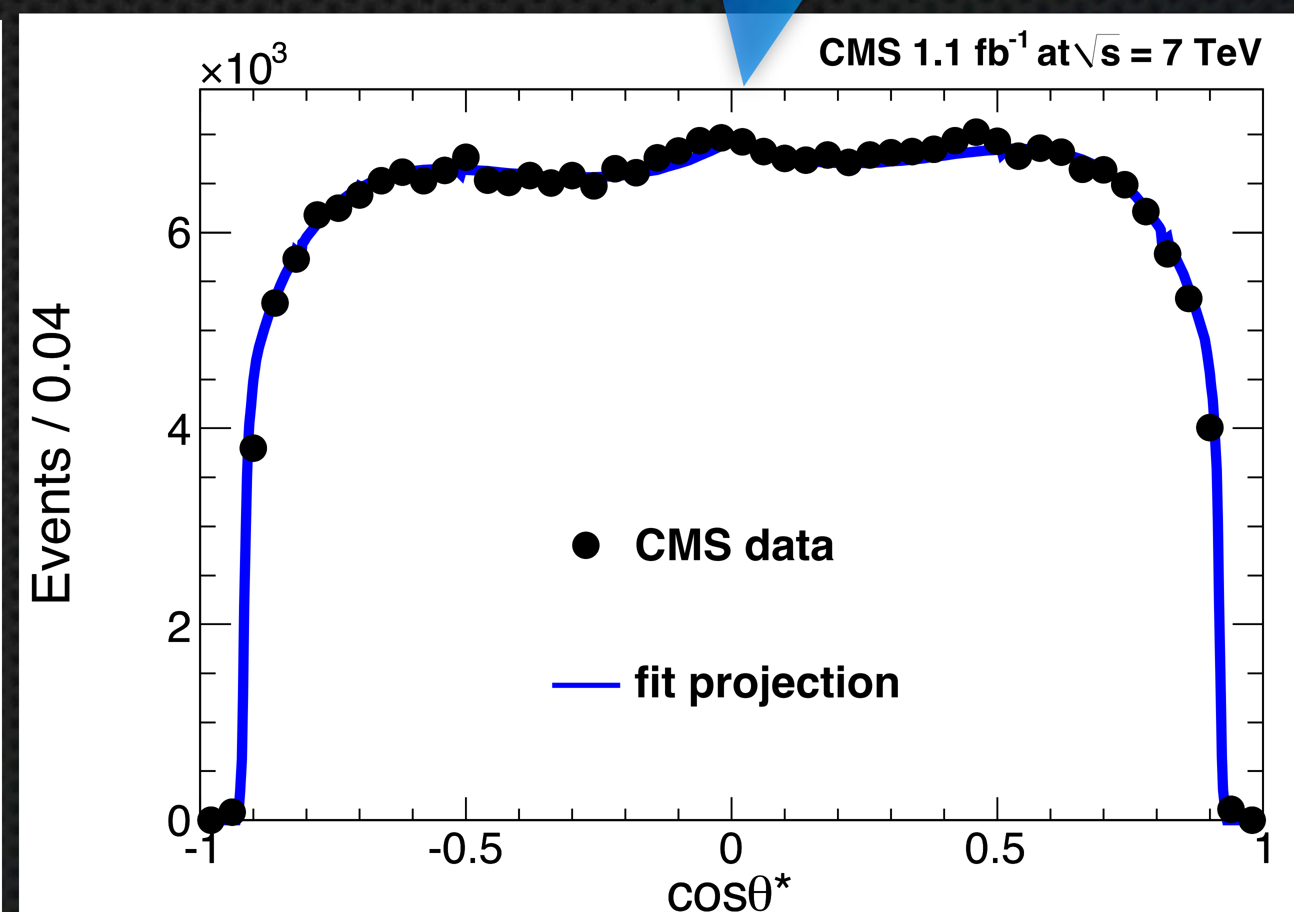
Dominant systematic uncertainty PDF uncertainty (0.00048)

Effective Weak Mixing Angle

CMS: First measurement at the LHC

Extracted from $Z/\gamma^* \rightarrow \mu\mu$ data using unbinned maximum likelihood fit: di-lepton rapidity, invariant mass and $\cos\theta^*_{CS}$





$$\sin^2\theta_{eff} = 0.2287 \pm 0.0020\ (stat) \pm 0.0025\ (syst)$$

Major systematics: PDF, FSR and detector alignment

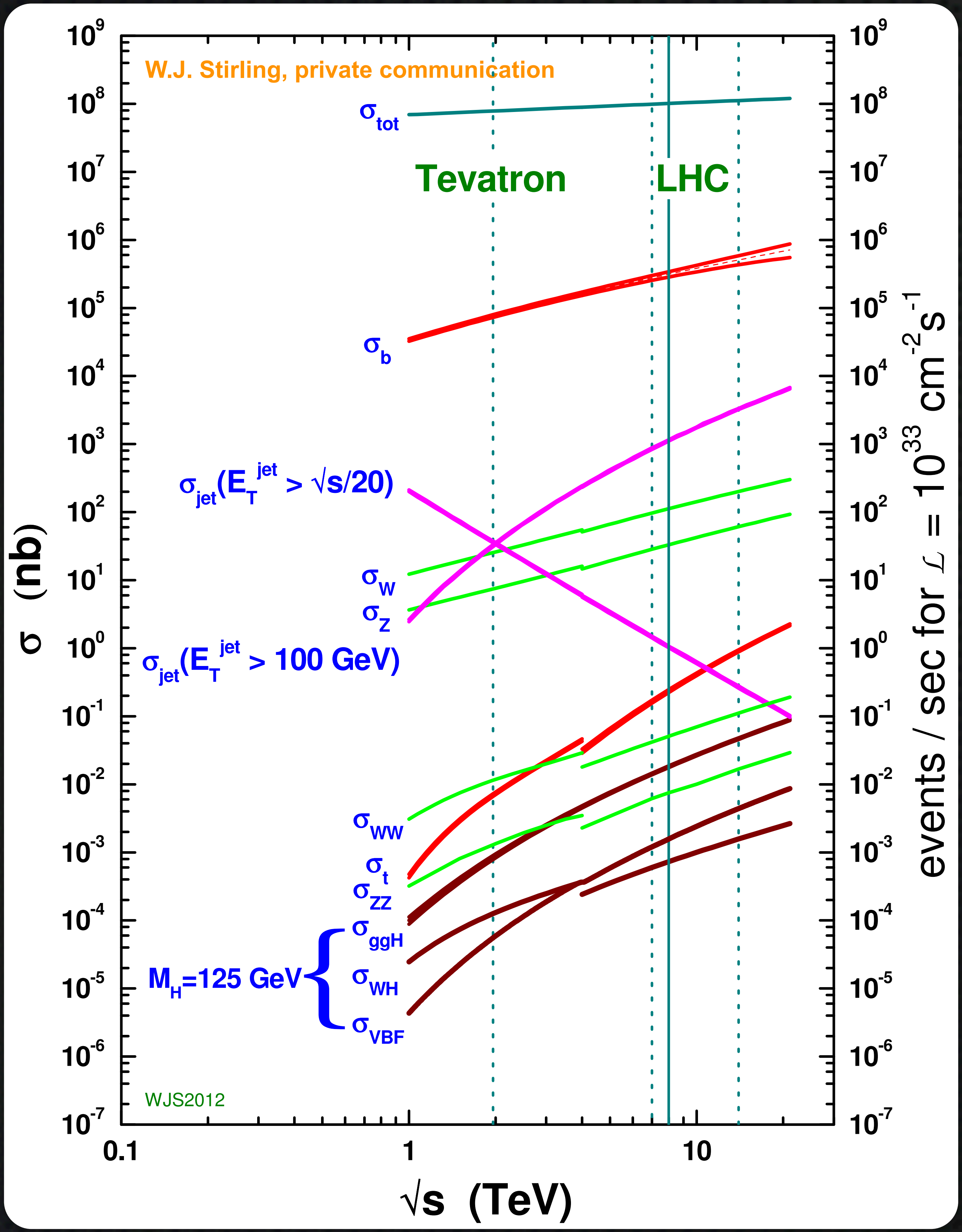
Phys. Rev. D 84 (2011) 112002

Production rates at Hadron Colliders

Tevatron timeline

W: 1988
Z: 1988

Top: 1994
WW: 2005
WZ: 2007
ZZ: 2008



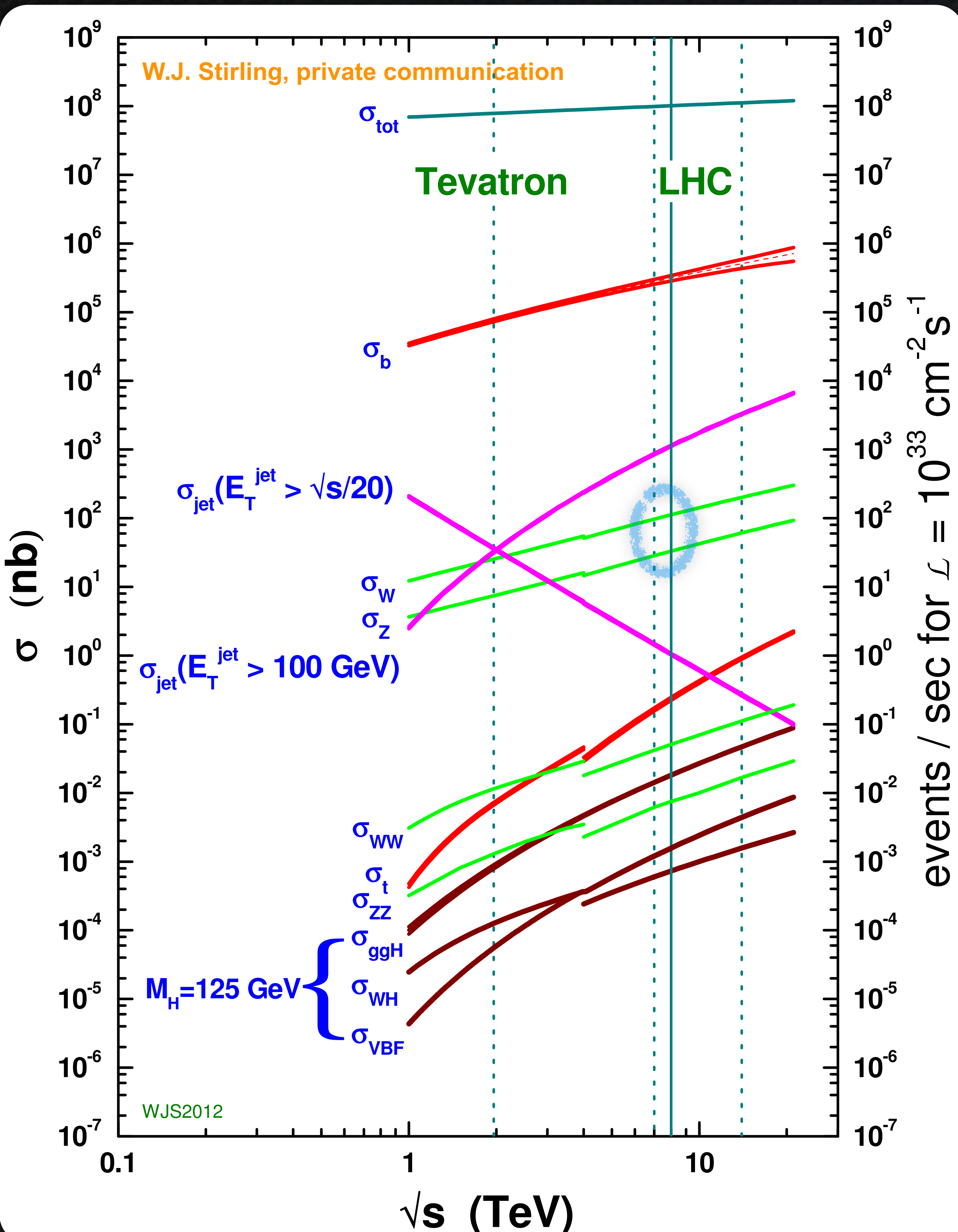
LHC timeline

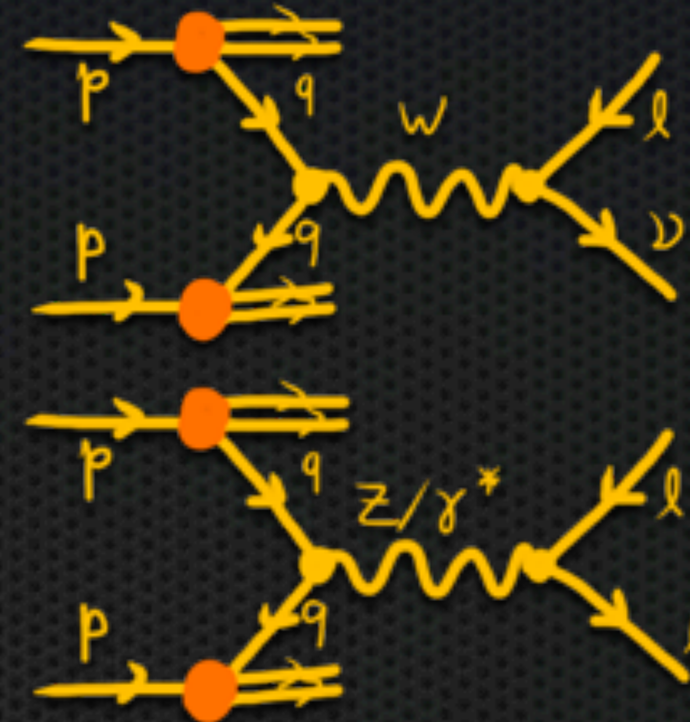
W: May 2010
Z: Jun 2010

Top: Jul 2010

WW: Dec 2010
WZ: Mar 2011
ZZ: Jul 2011

H: Last week?

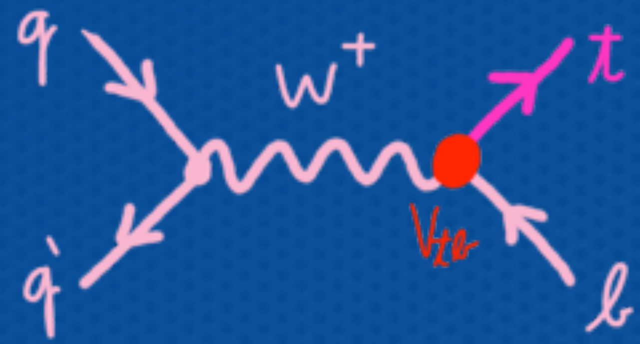
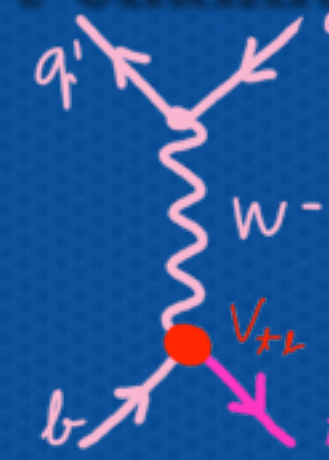
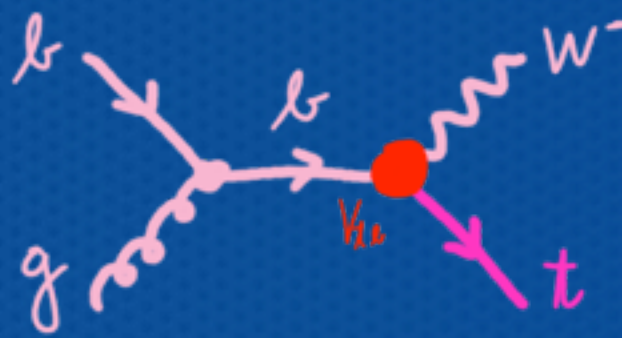




W and Z Production

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

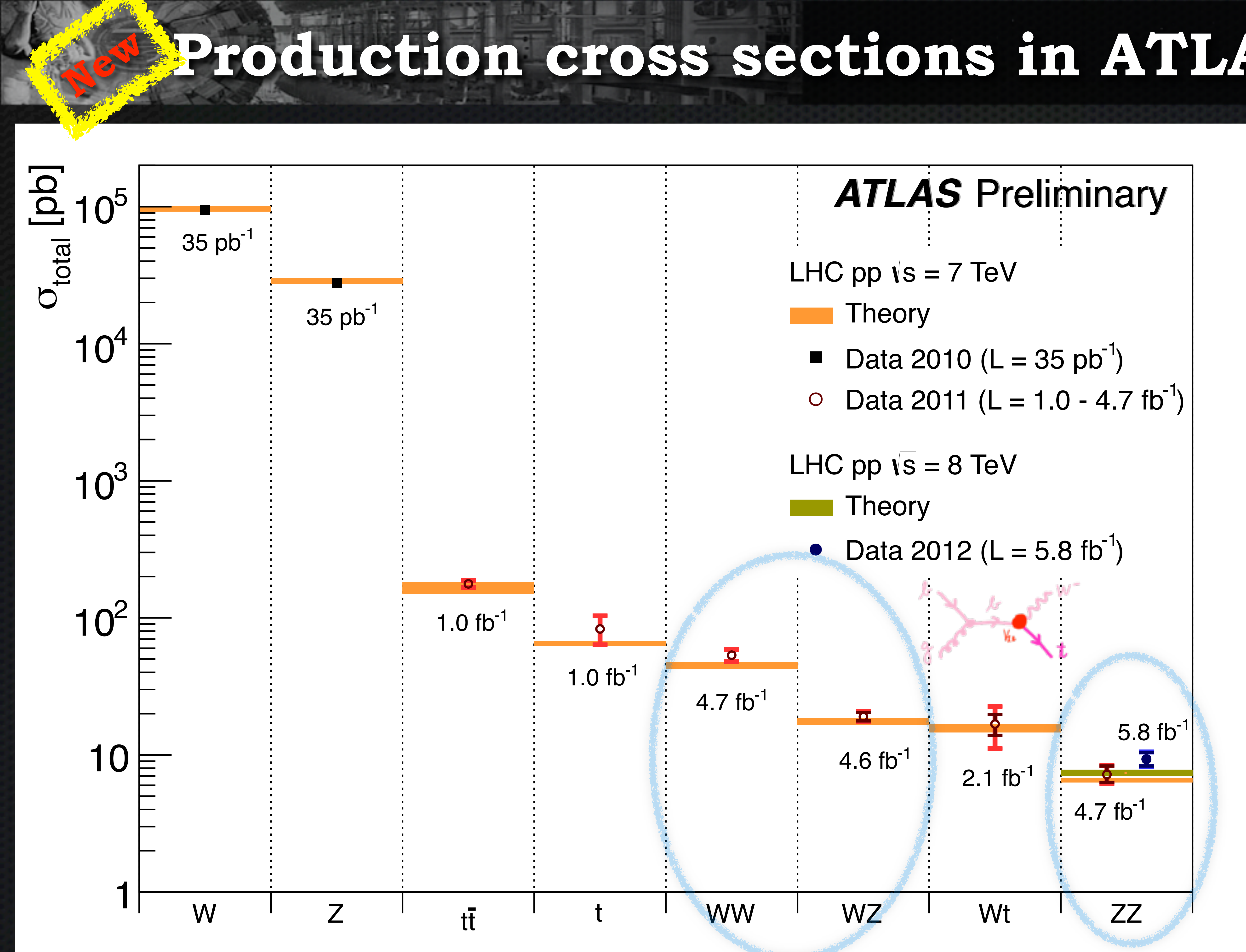
Electroweak Top Production at Hadron Colliders

σ(NNLO) (pb) (m_{top} = 172.5 GeV)	s-channel 	t-channel 	Wt-channel 
Tevatron @ 1.96 TeV	1.04 ± 0.4	2.26 ± 0.12	0.28 ± 0.06
LHC @ 7 TeV	4.6 ± 0.2	$64.6^{+2.7}_{-2.0}$	15.7 ± 1.1

Very difficult at LHC

Not possible at Tevatron

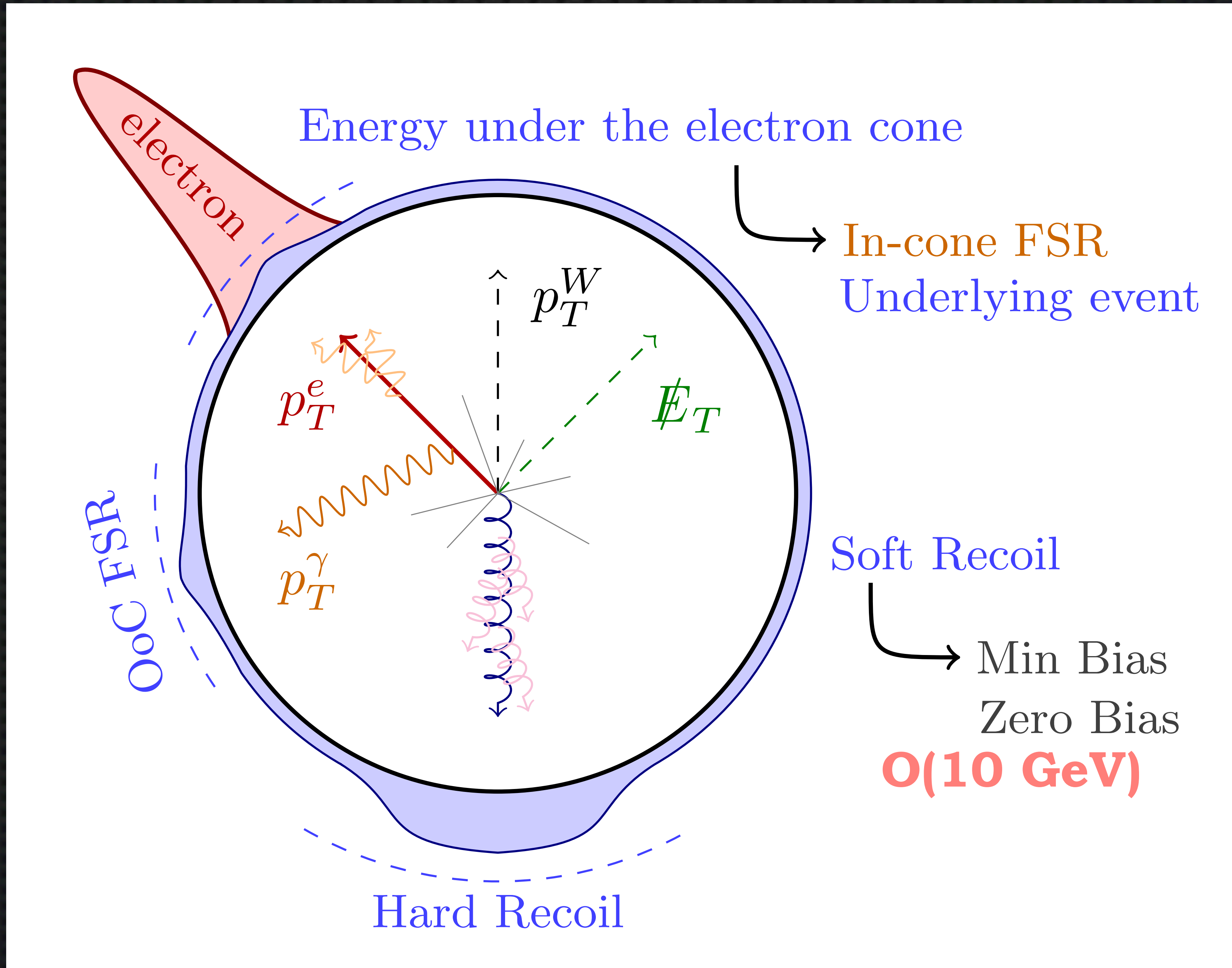
Production cross sections in ATLAS



New W Boson Mass at the Tevatron

Constraints Higgs mass: $\Delta m_t = 0.9$ GeV $\leftrightarrow$ $\Delta m_W \approx 5$ MeV

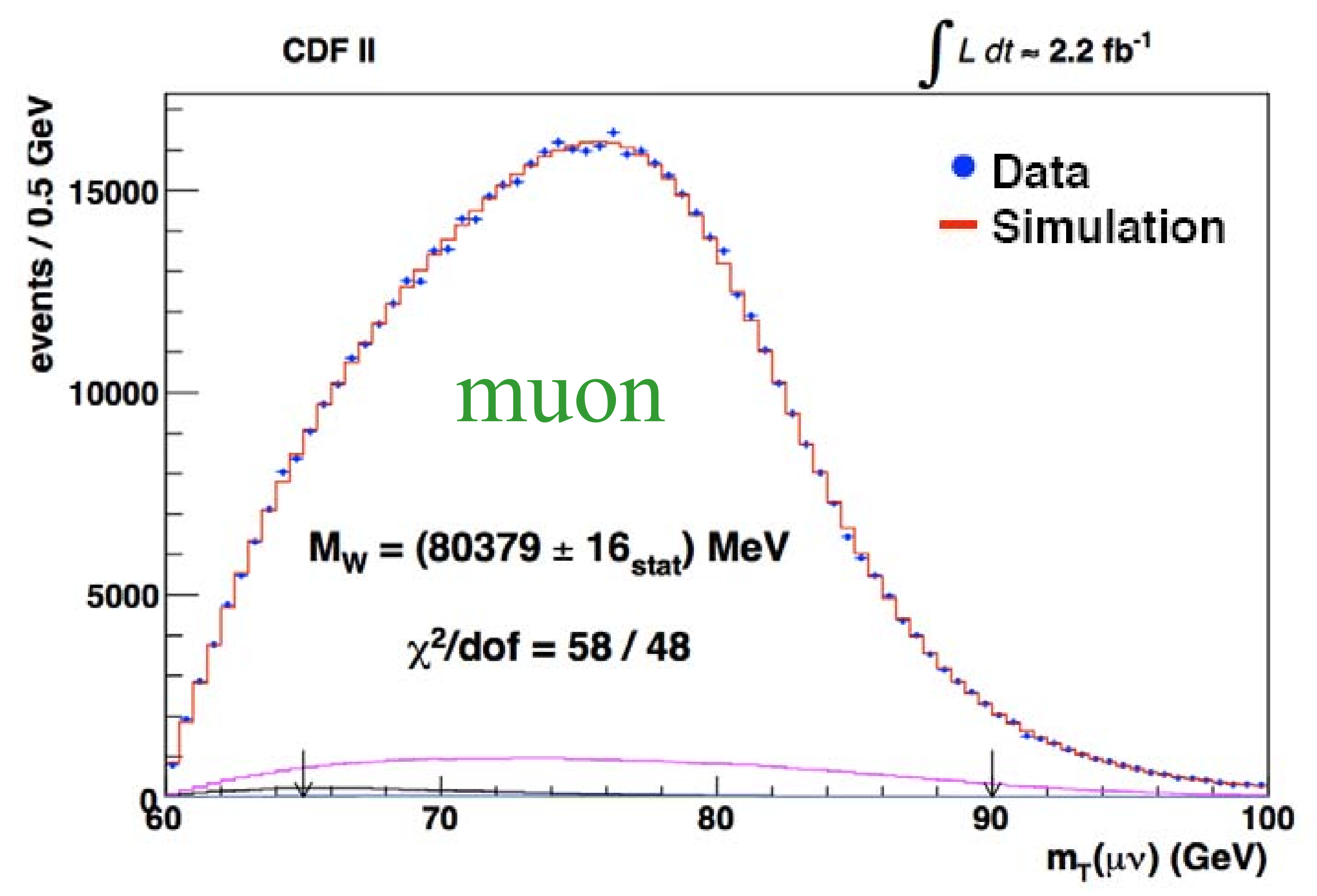
Need excellent understanding of detector and MC simulation



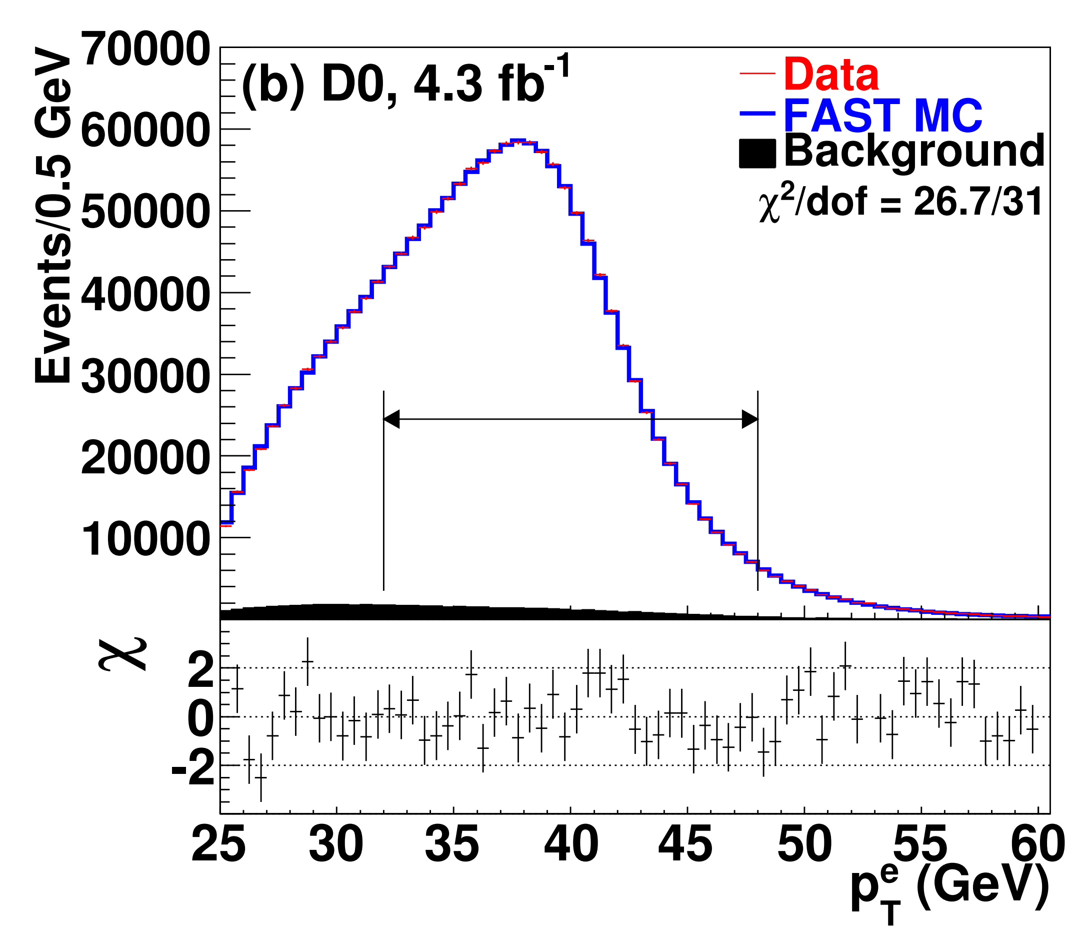
O(10 GeV)

New W Boson Mass at the Tevatron

PRL 108, 151803 (2012)



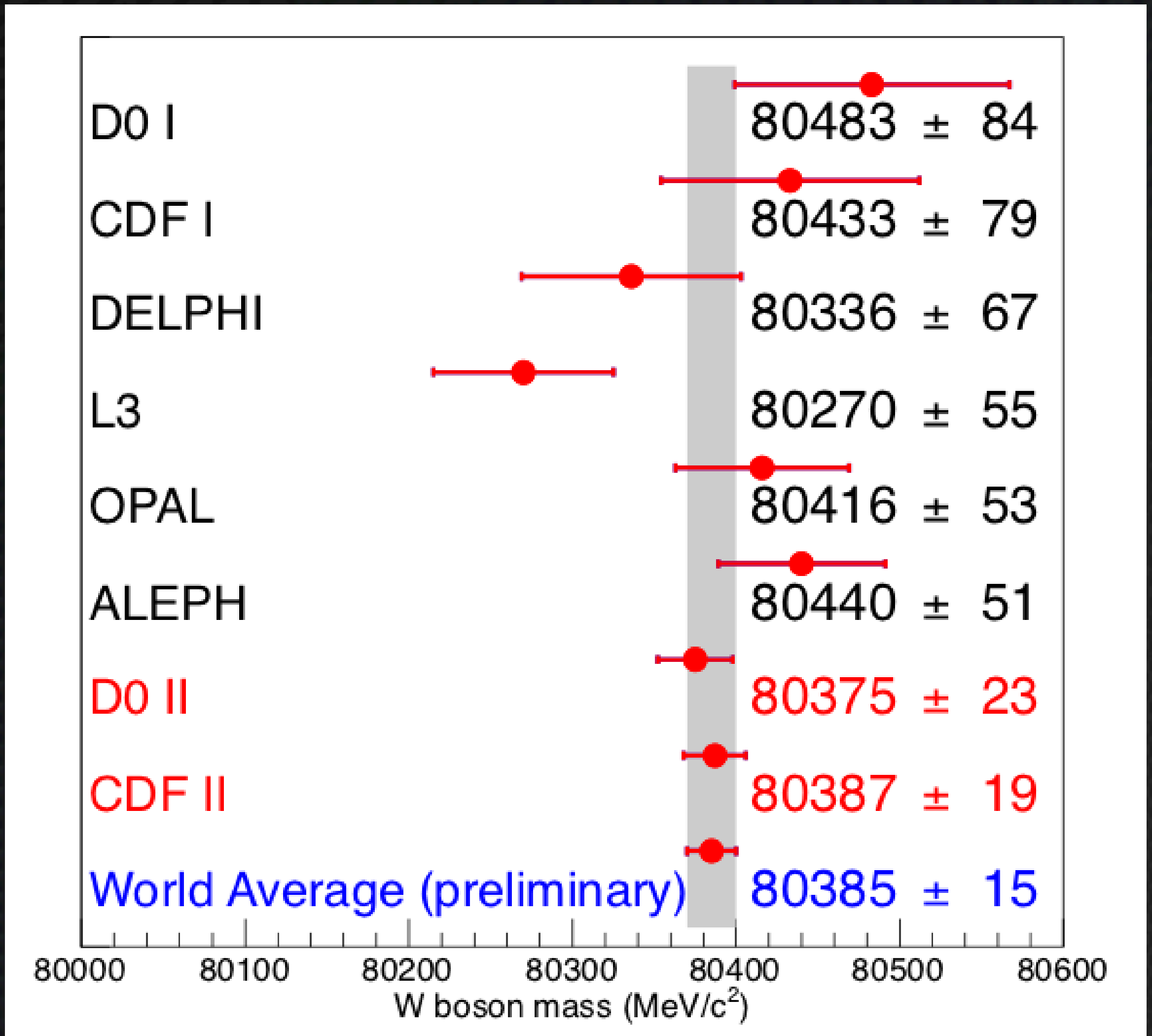
Phys. Rev. Lett. 108, 151804 (2011)

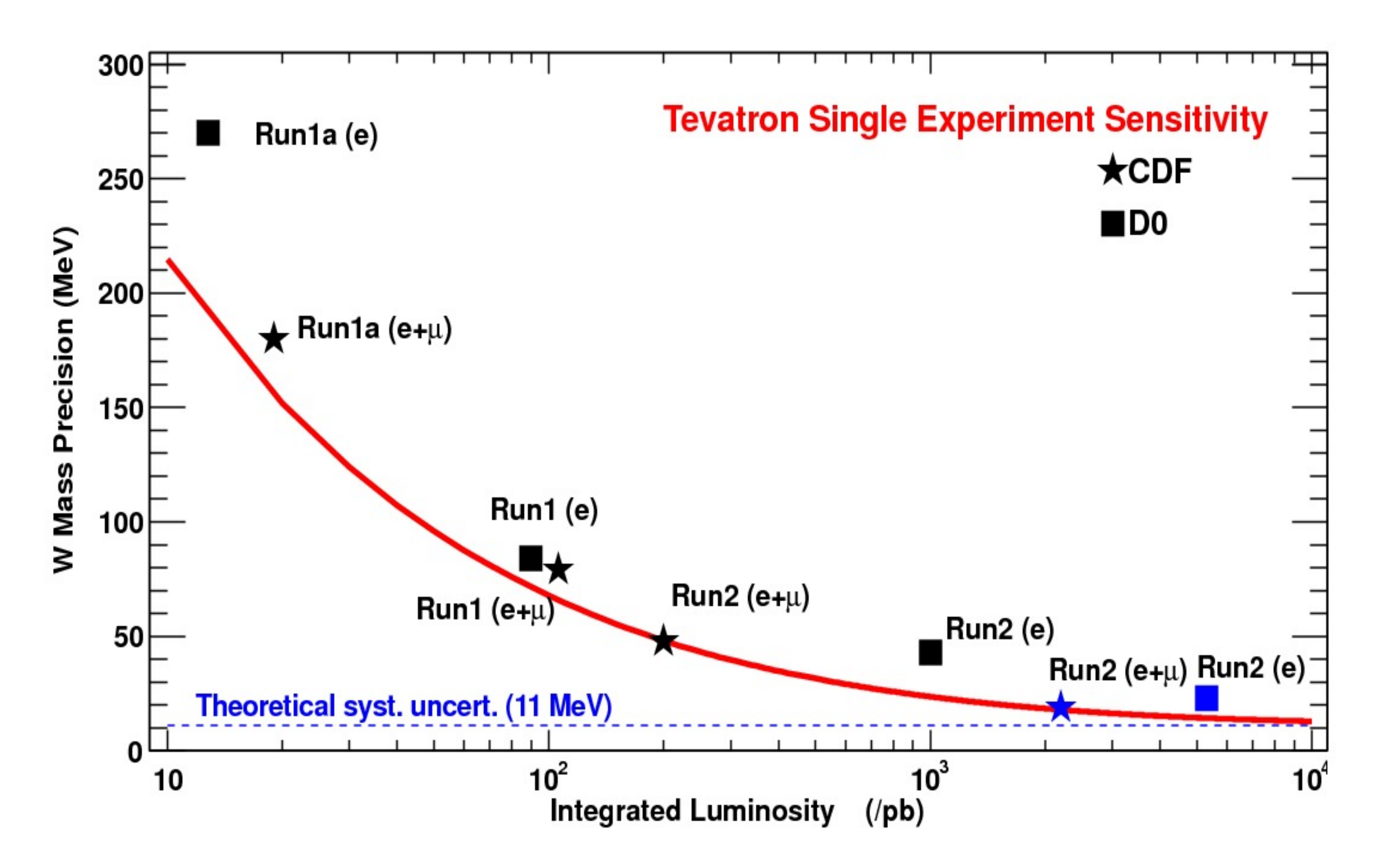


Fits transverse mass, lepton p_T and neutrino p_T

Uses both e and μ	Uses only e
2.2 fb^{-1}	4 + 1 fb^{-1}
1.1 M W events	1.7 M W events
Δm_W(sys) = 18 MeV (e)	Δm_W(sys) = 22 MeV (e)
Δm_W(sys) = 16 MeV (μ)	

W Boson Mass





Dominant uncertainties:

Parton distribution functions: 10-14 MeV

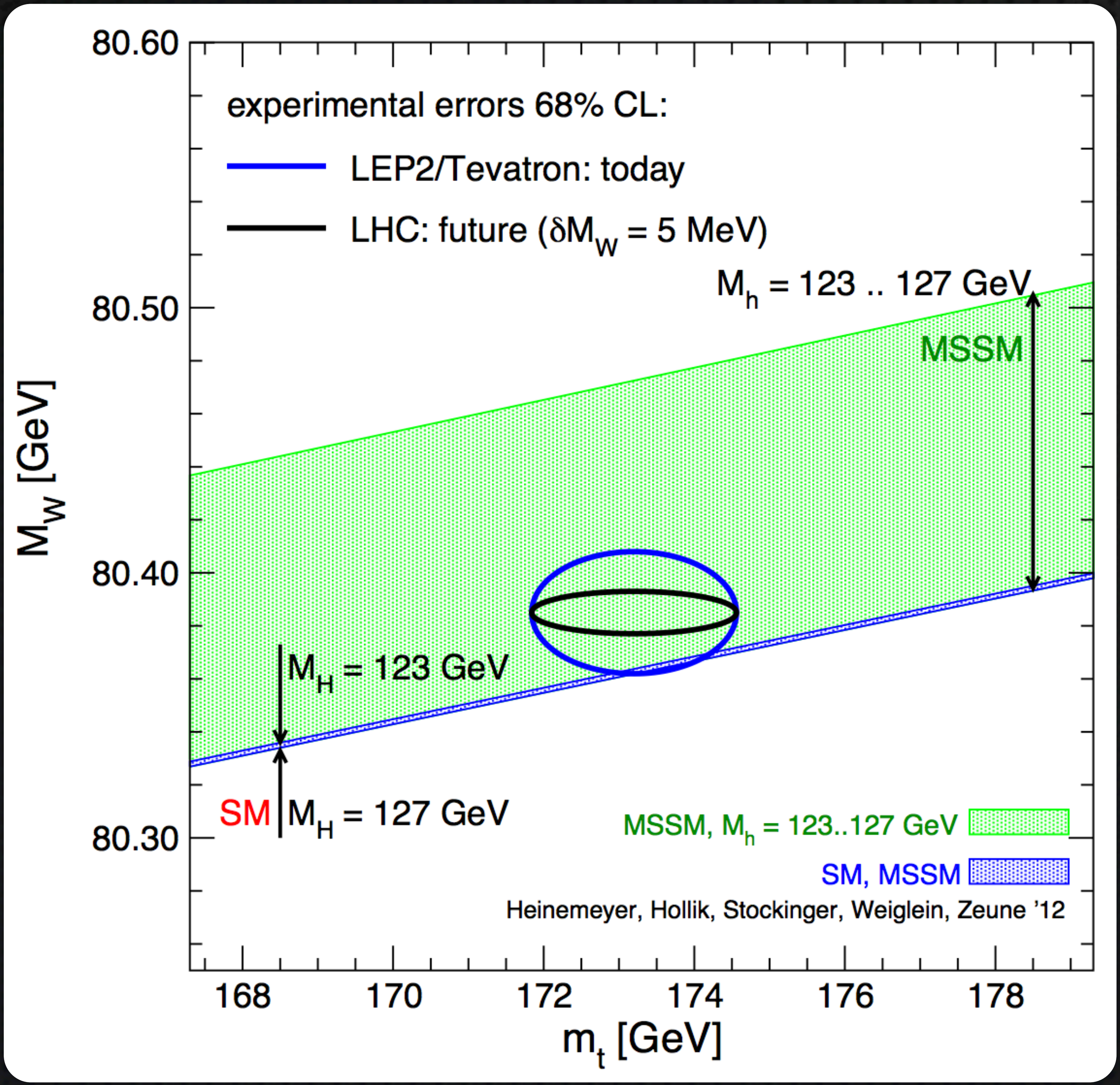
Lepton calibration: 16 MeV (D0) / 5 MeV (CDF)

Improvements still to come

More than double statistics with full run II dataset

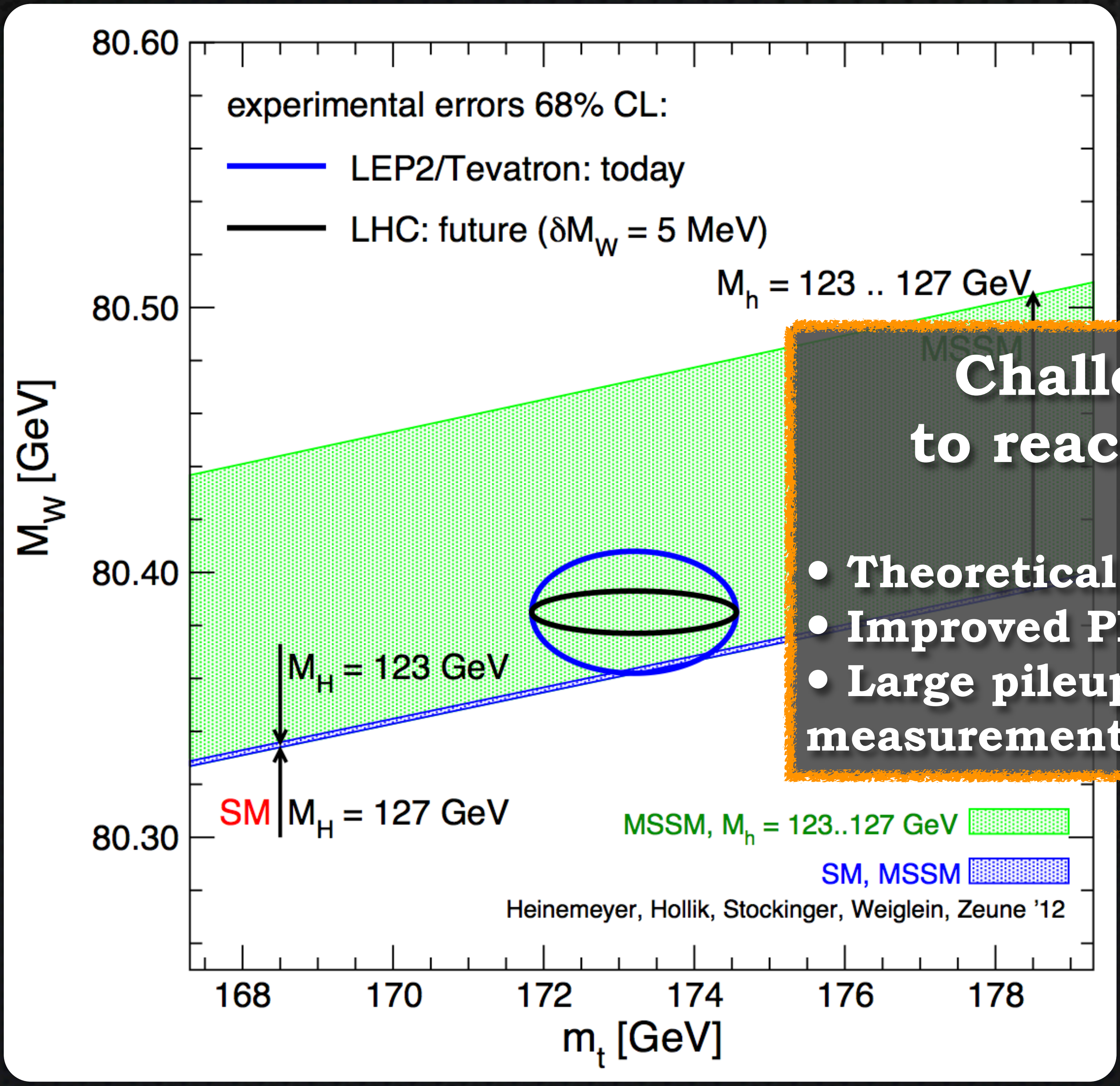
Precision Electroweak Constraints

- **Disentangle if "observed" Higgs boson is SM or SUSY-like**



Precision Electroweak Constraints

- **Disentangle if "observed" Higgs boson is SM or SUSY-like**



Challenges for LHC to reach ΔM_W =5 MeV

- Theoretical understanding of $P_T(W)$
- Improved PDFs (strangeness)
- Large pileup affecting measurement of soft recoil