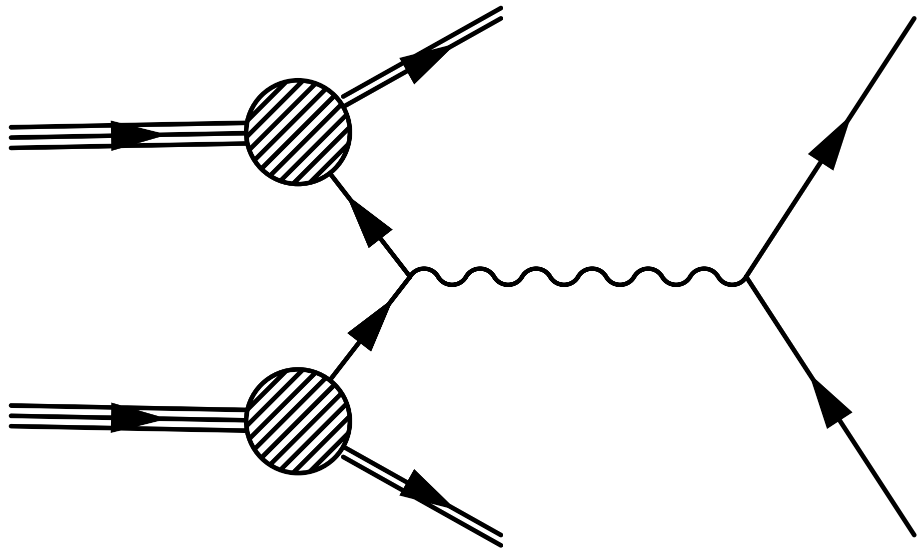
Electroweak Precision Measurements



8 TeV Measurements

High Mass Drell-Yan Cross Sections

New 3D Drell-Yan Cross Sections

Systematic Uncertainties

13 TeV Plans

Eram Rizvi

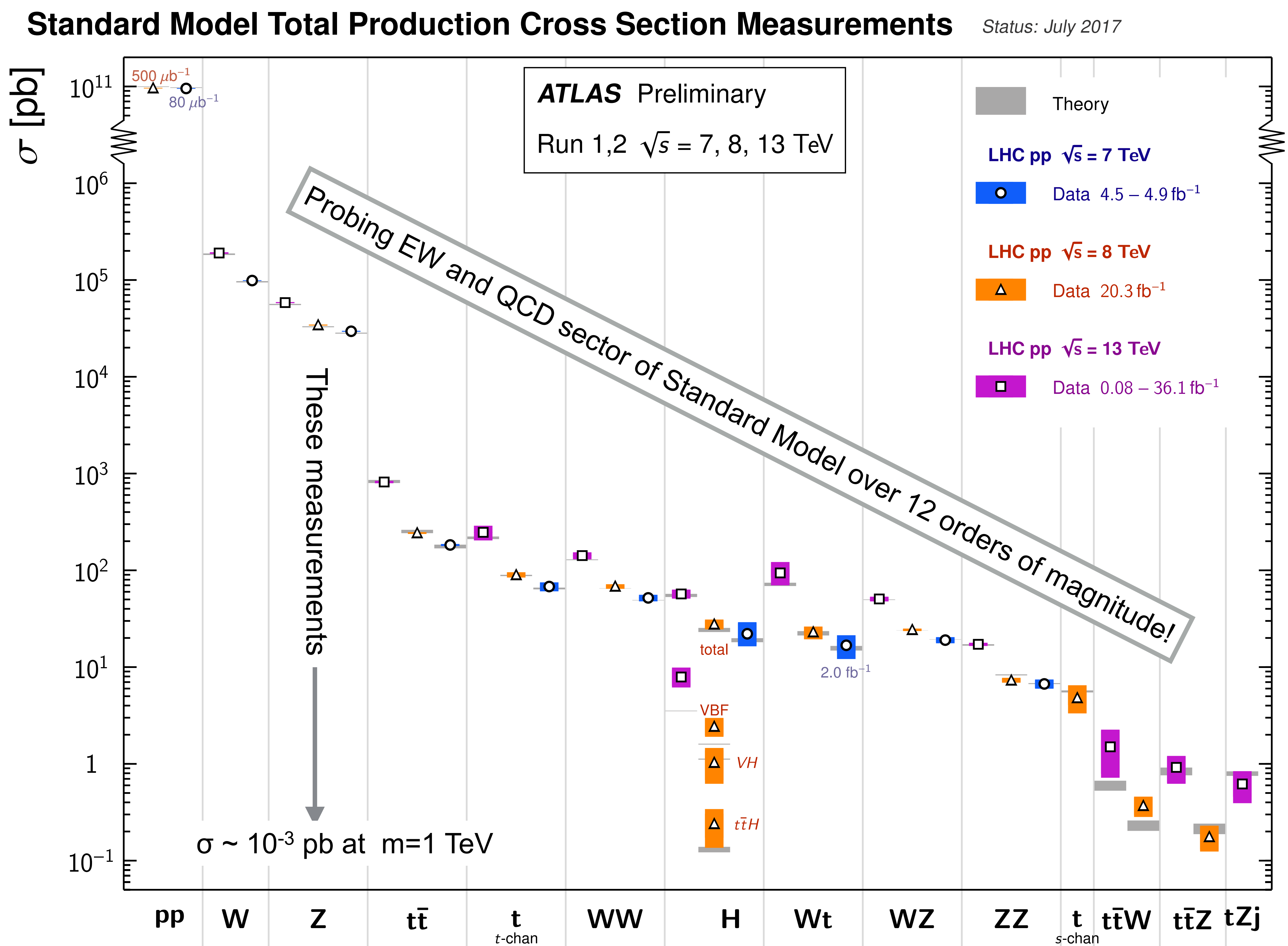
Queen Mary University of London

ATLAS EXPERIMENT

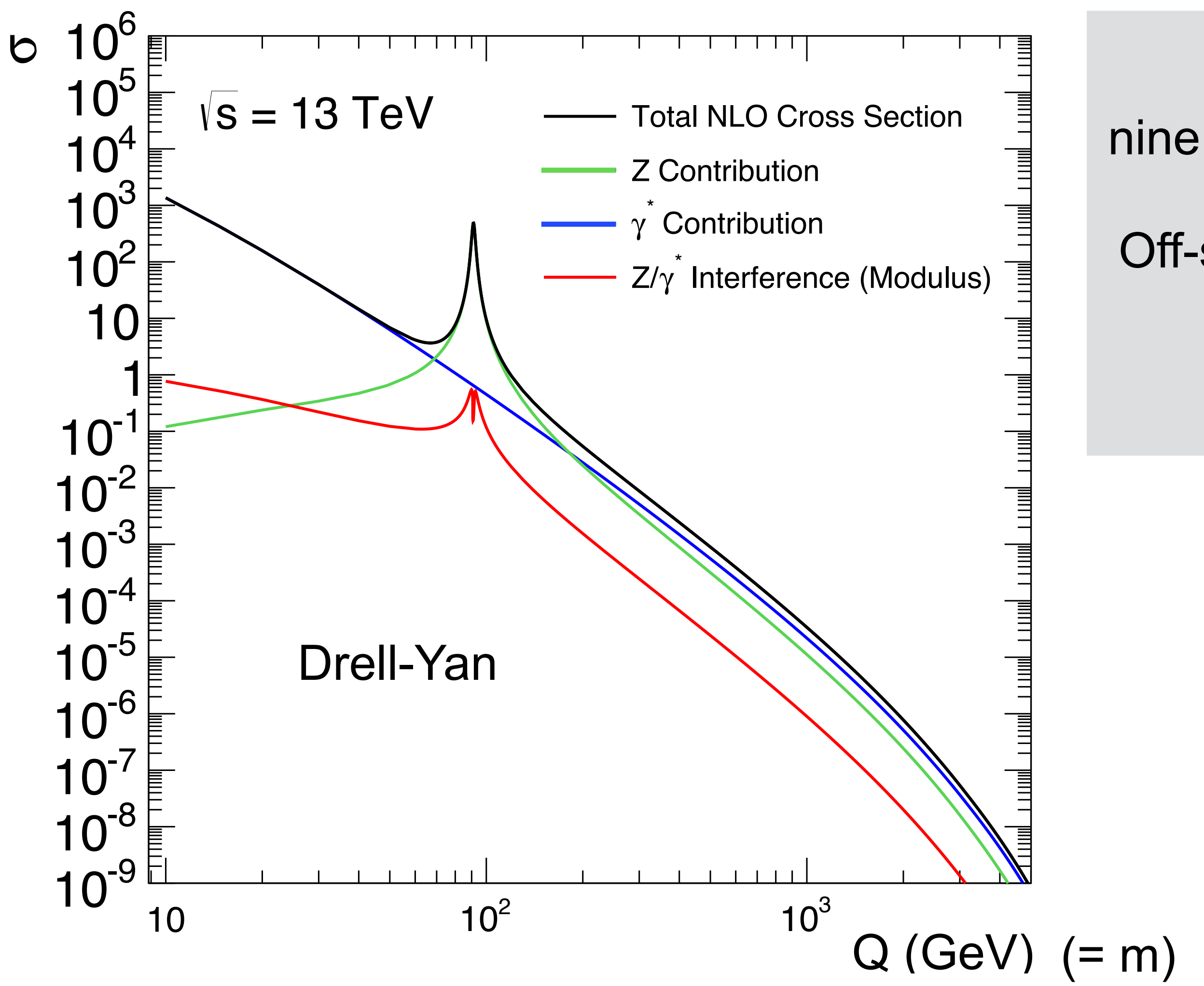
Collider Cross Talk - CERN

13th July 2017

The Standard Model



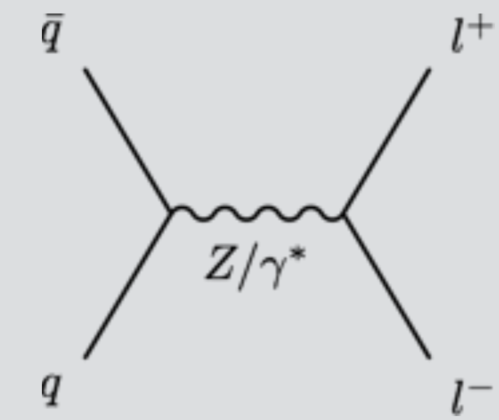
Drell—Yan & Photon Induced Dilepton Production



Drell—Yan cross section falls nine decades for m=100 GeV → 1000 GeV

Off-shell production dominated by γ* terms

Sensitive to high x antiquarks



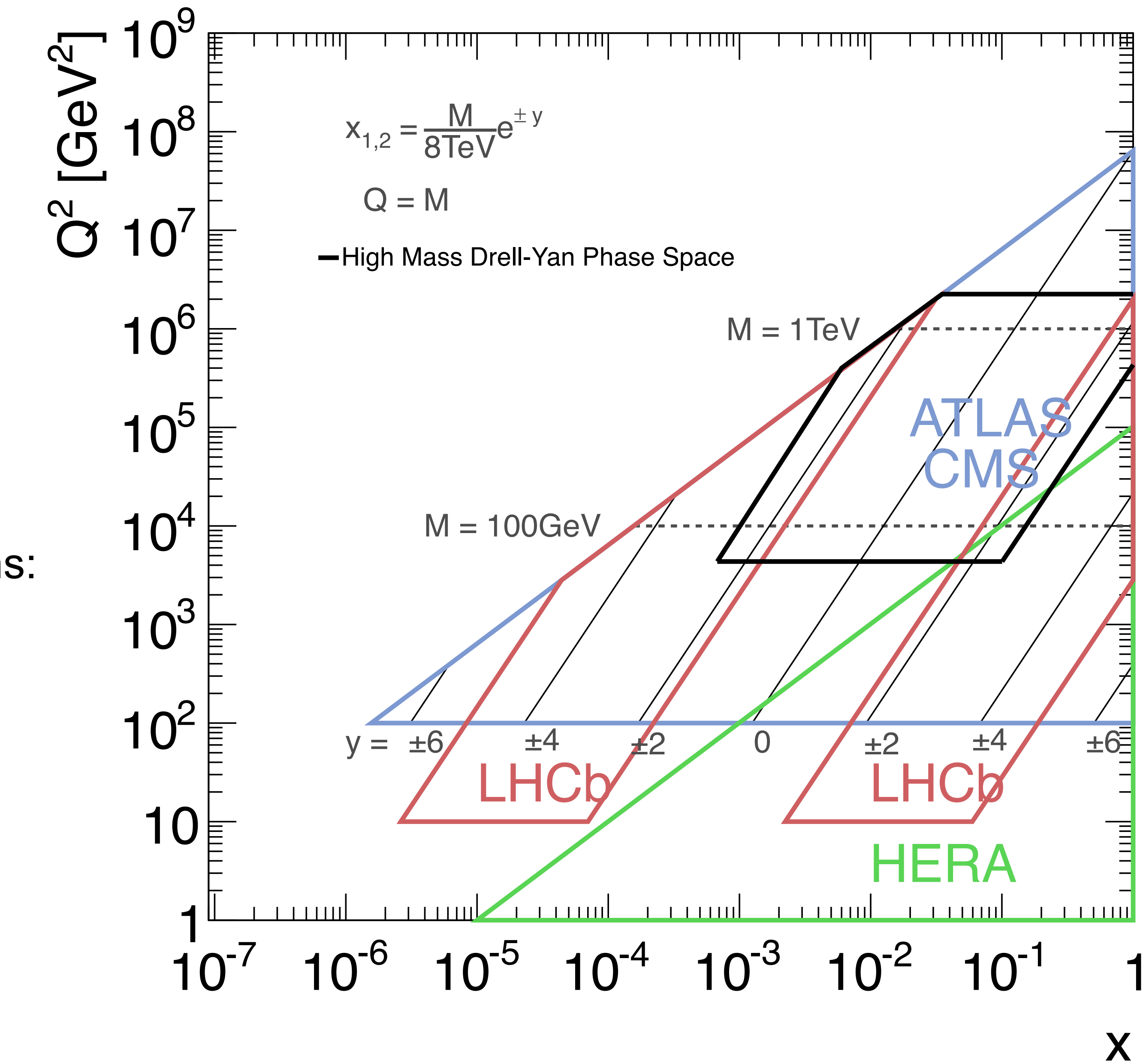
Measure single + double + triple differential cross sections:

$$\frac{d\sigma}{dm_{\ell\ell}} \qquad \frac{d^2\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|} \qquad \frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*}$$

Measurements access range of

$x > 4\times10^{-4}$

$46 \le m \le 1500$ GeV



High Mass Z/γ* Production at √s = 8 TeV

General models of new physics SM Lagrangian extended by dimension 6 operators
They describe new physics appearing at scale m > √s

- ★ new EW vector bosons
- ★ new EW fermions
- ★ EW compositeness…

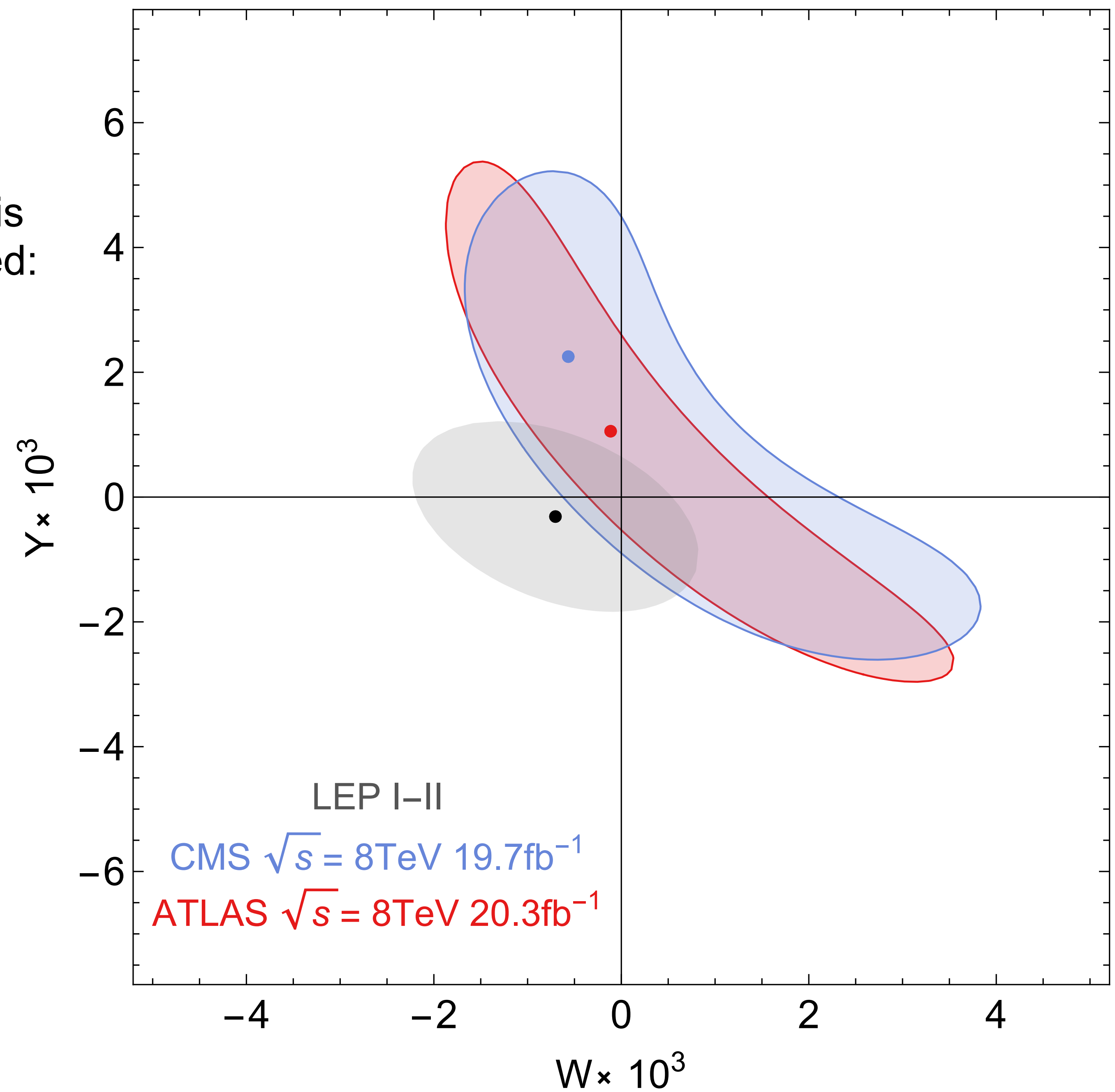
https://arxiv.org/abs/1609.08157

Effective field theory (EFT) attempts to encapsulate this
For DY production 4 propagator form-factors introduced:

S , T , Y , W

- Y and W increase with √s
- S and T do not grow with √s

LHC data can help constrain Y & W



Current constraints based on neutral current HMDY 8 TeV data

⇒ Cannot yet compete with LEP

Run-I Measurements from ATLAS

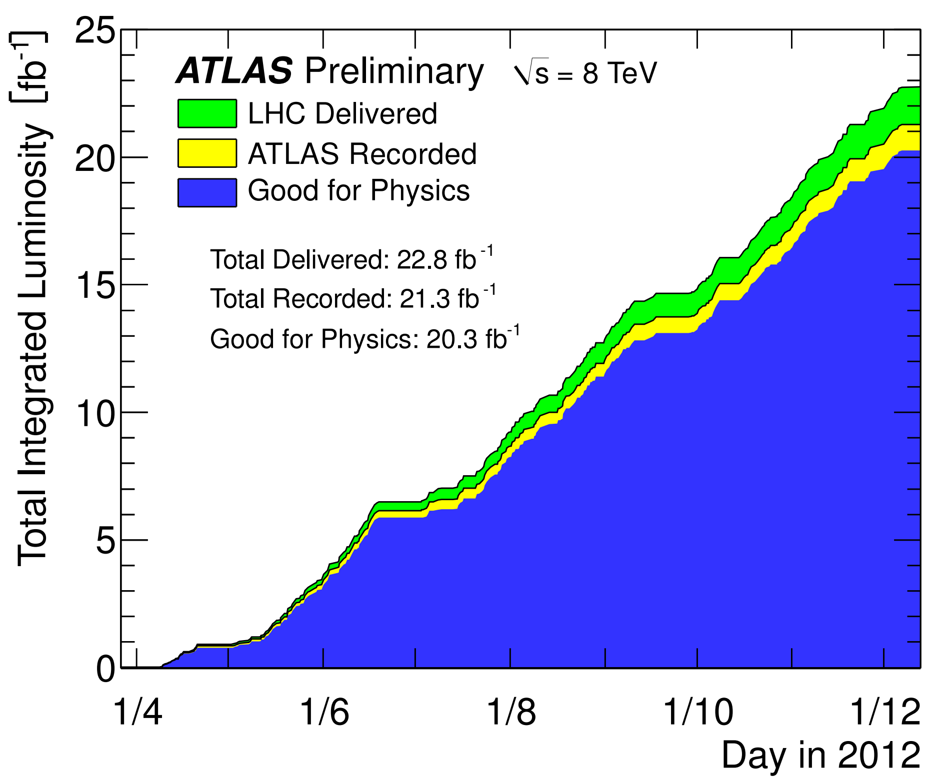
single, double and triple-differential cross sections

$$\frac{d\sigma}{dm_{\ell\ell}} \qquad \frac{d^2\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|} \qquad \frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*}$$

High mass DY 8 TeV
Neutral current - e & μ channels
116 < m < 1500 GeV

publication: JHEP 08 (2016) 009

On-shell DY 8 TeV
Neutral current - e & μ channels
46 < m < 200 GeV
Extended to high y with FCAL analysis
preliminary public plots
Expect arXiv submission ~ August



Complete 2012 data set analysed

$\int \mathcal{L}\, dt = 20.2\ fb^{-1}$

Centre of mass energy $\sqrt{s} = 8$ TeV

Previous measurement (arXiv:1305.4192) used
- $5\ fb^{-1}$
- $\sqrt{s} = 7$ TeV
- electron channel only

This analysis increases precision by factor 3!

High Mass Z/γ^* Selection

Muon Selection

- Good quality detector status (all sub-systems on)
- muon trigger fired (matched to lepton)
- ≥ 2 good quality muons
- muon $|\eta| < 2.4$
- muon $p_T > 30$ GeV
- longitudinal impact parameter $|z_0| < 10$ mm
- isolated muon $\sum p_{T,i}^{(\Delta R=0.2)}/p_T^{\mu} < 0.12$
  p_T sum of tracks within a cone size $\Delta R=0.2$ is less than 12% of muon p_T
- opposite charge
- one muon has $p_T > 40$ GeV

Electron Selection

- Good quality detector status (all sub-systems on)
- electron trigger fired (matched to lepton)
- ≥ 2 good quality “tight” electrons
- electron $|\eta| < 2.47$ excl. $1.37 < |\eta| < 1.52$
- electron $E_T > 30$ GeV
- isolated electron $\sum E_{T,i}^{(\Delta R=0.4)} < 0.022 \times E_T + 5$ GeV
  E_T sum of calo energy within a cone size $\Delta R=0.4$ is less than 2% of electron E_T with E_T scaled offset
- one electron has $p_T > 40$ GeV
- $|\Delta\eta_{ee}| < 3.5$ to suppress multijet background

Fiducial Cross Section Definition

- lepton $p_T > 30$ GeV & $p_T > 40$ GeV
- lepton $|\eta| < 2.5$
- $116 < m_{ll} < 1500$ GeV
- Unfolding to Born level lepton kinematics
  (dressed level available as a correction factor)

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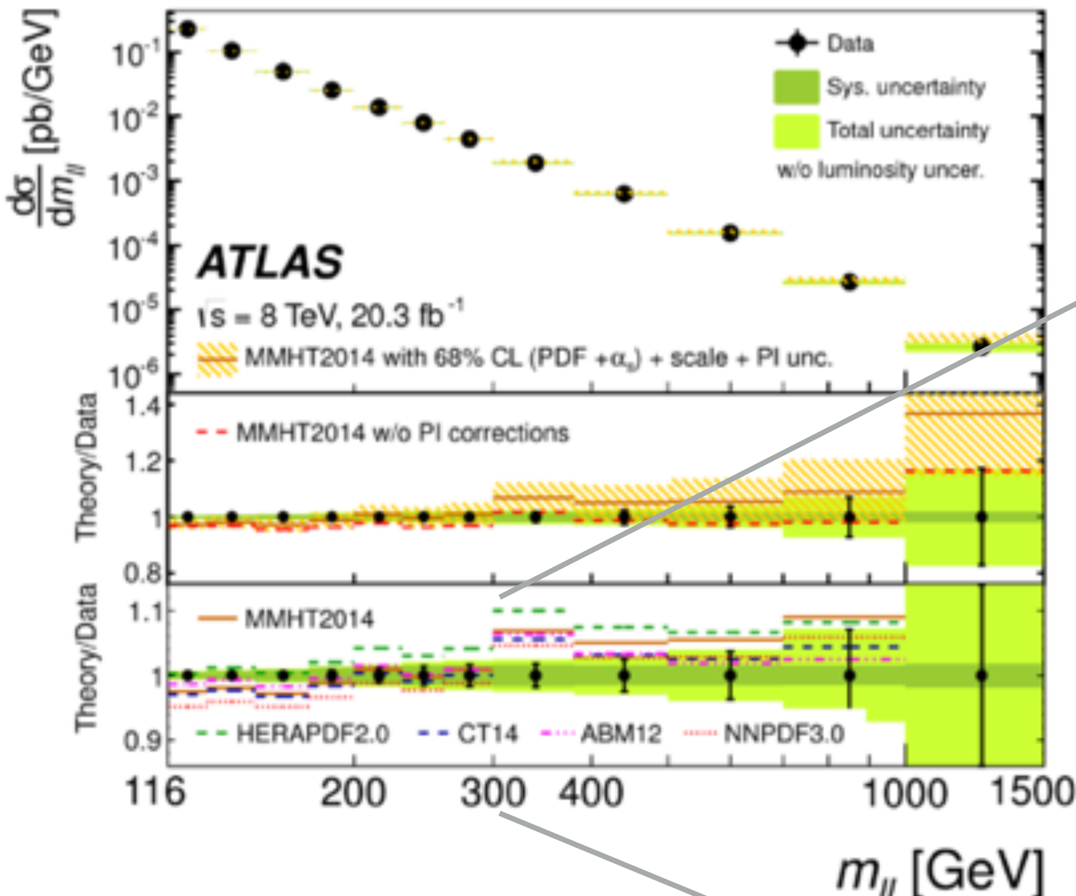
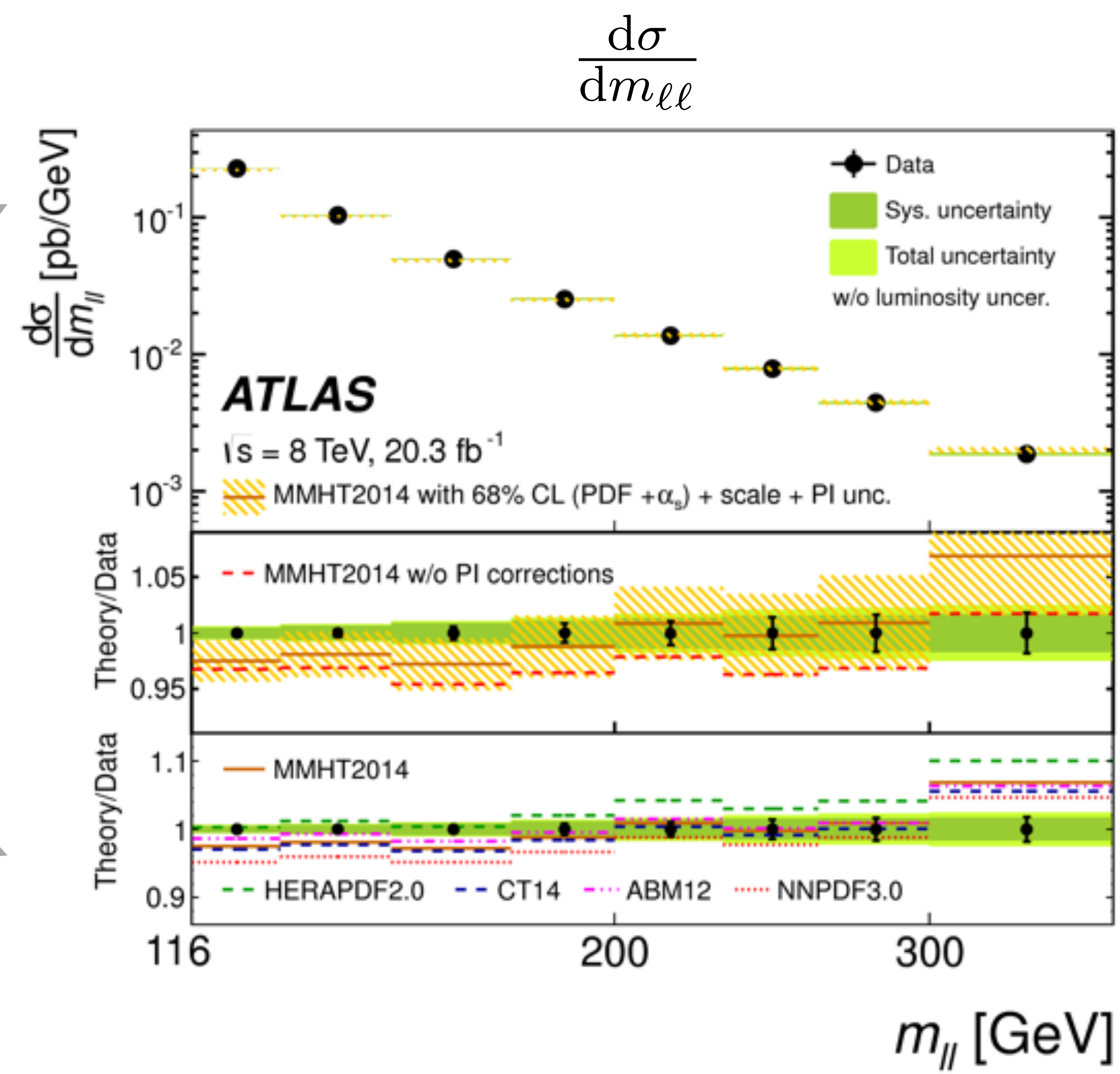
electron + muon cross sections combined
account for **35** correlated systematic uncertainties
improved result for both statistical & systematic precision

High Mass Z/γ* Cross Sections √s = 8 TeV



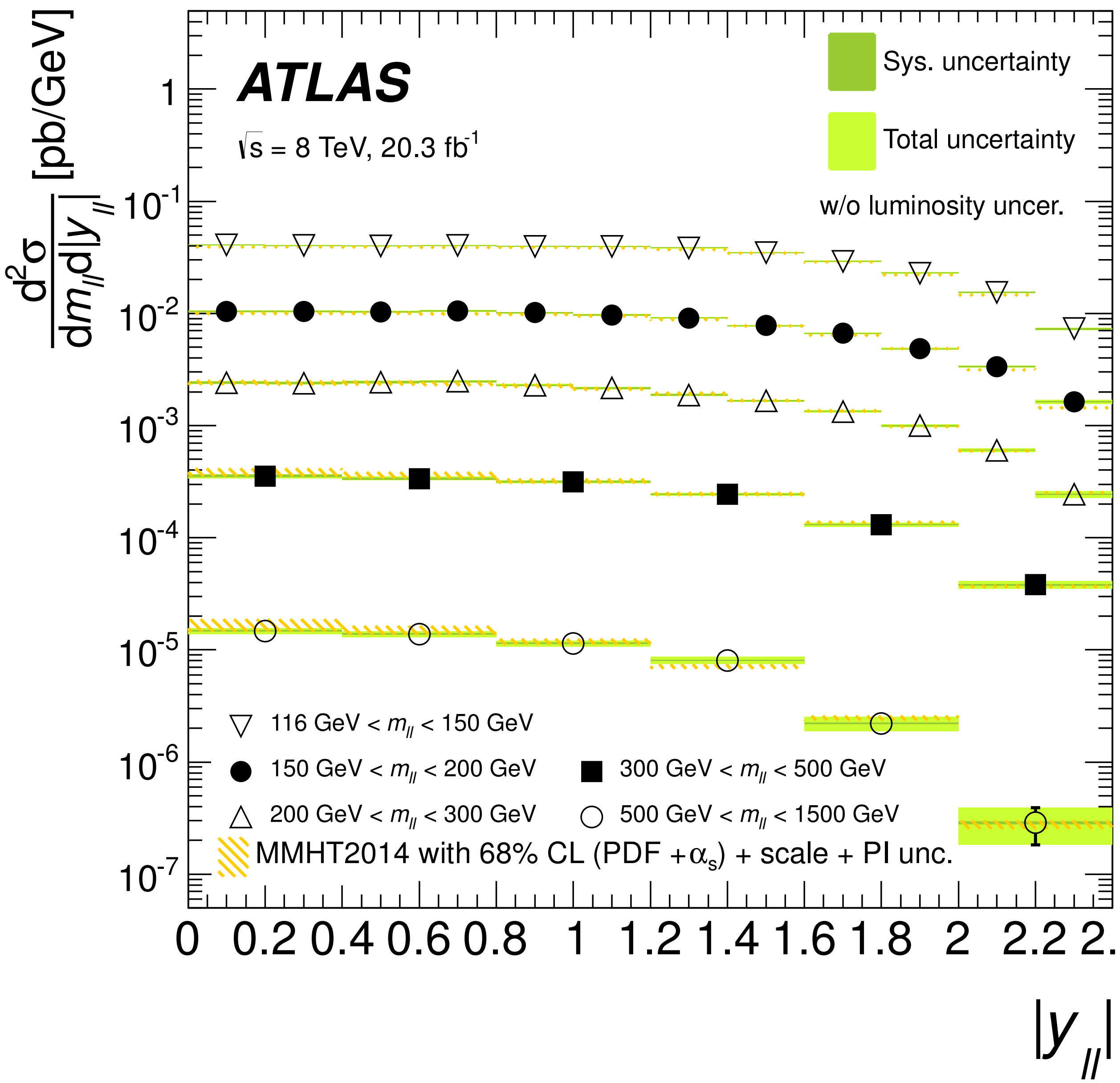


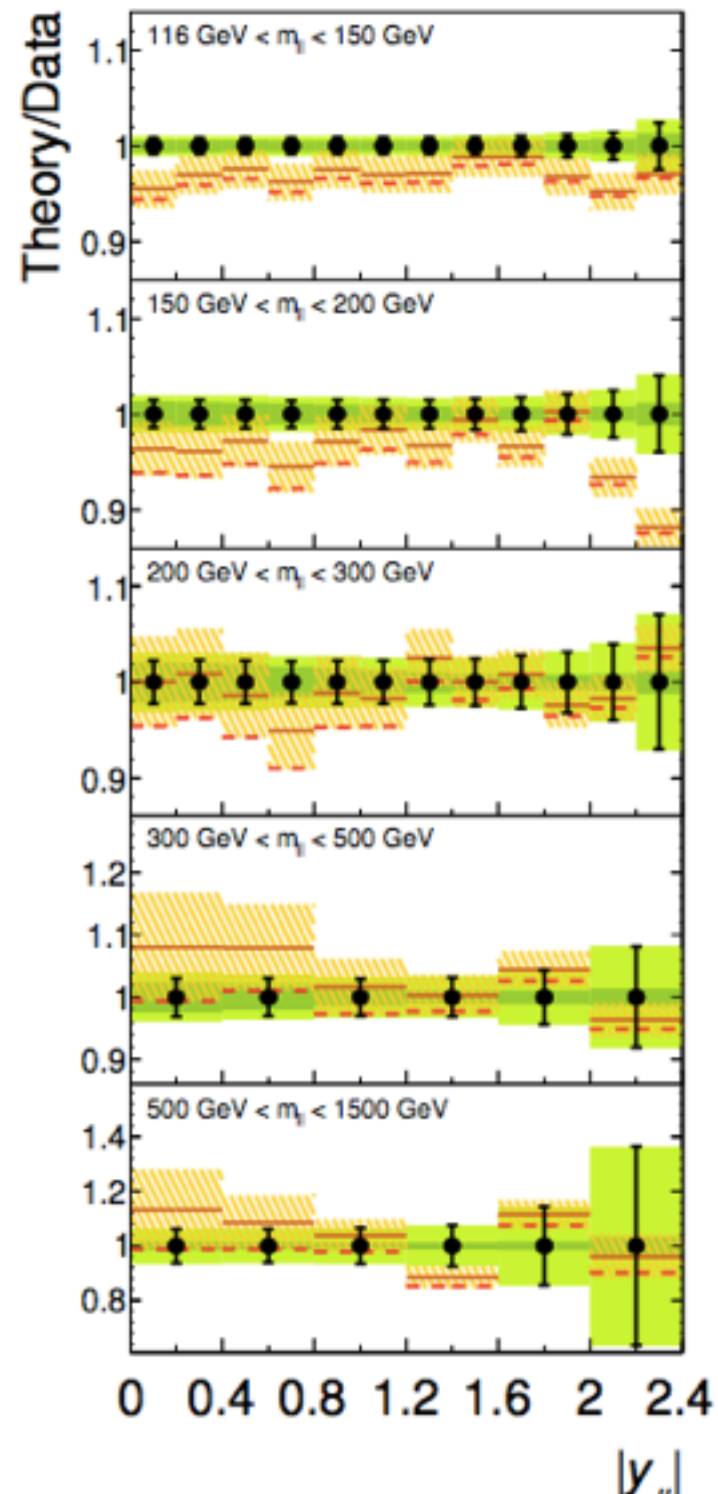
- Theory = NNLO pQCD ⊗ NLO EW + PI
- data precision better than theory uncertainty over most of the phase space
  → measurements can constrain theory
- theory generally in agreement with data
- Measurement accuracy systematically limited for m < 400 GeV

At low m observe large spread of predictions from different PDFs compared to experimental accuracy
⇒ large potential to constrain PDFs

High Mass Z/γ^* Cross Sections $\sqrt{s}$ = 8 TeV

$$\frac{d^2\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|}$$





$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}

MMHT2014 with 68% CL

(PDF + α_s) + scale + PI unc.

MMHT2014 w/o PI corrections

Cross sections are measured with 1% precision at m ~ 200 GeV (each channel)

Bin-to-bin correlated systematics can be further constrained by combining channels

For larger m combination reduces √N statistical error

Stat error dominates at large m reaching ~20%

Measurements well described by predictions over complete phase space

Performance Considerations

8 TeV cross sections for e & μ channels at m=400 GeV
Run-II statistical error will be ~ factor 3 smaller

Muon channel

$m_{\mu\mu}$ [GeV]	$\lvert y_{\mu\mu}\rvert$	$\frac{d^2\sigma}{dm_{\mu\mu}d\lvert y_{\mu\mu}\rvert}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]	δ^{trig}_{cor} [%]	δ^{reco}_{cor} [%]	δ^{MSres}_{cor} [%]	δ^{IDres}_{cor} [%]	δ^{pT}_{cor} [%]	δ^{iso}_{unc} [%]	δ^{top}_{cor} [%]	$\delta^{diboson}_{cor}$ [%]	δ^{bgMC}_{unc} [%]	$\delta^{mult.}_{cor}$ [%]	$\delta^{mult.}_{unc}$ [%]	δ^{MC}_{unc} [%]	$k_{dressed}$
300 – 500	0.0 – 0.4	3.72×10^{-4}	4.0	2.9	4.9	-0.1	-0.6	0.2	0.1	-0.2	-0.2	-2.2	-0.8	0.7	-0.5	1.2	0.2	1.036
300 – 500	0.4 – 0.8	3.28×10^{-4}	4.1	2.5	4.8	-0.1	-0.6	-0.2	-0.1	-0.3	-0.2	-1.9	-0.7	0.8	-0.4	0.7	0.2	1.036
300 – 500	0.8 – 1.2	3.09×10^{-4}	4.0	1.6	4.2	-0.1	-0.6	0.1	-0.1	-0.3	-0.2	-1.1	-0.5	0.6	-0.1	0.2	0.2	1.034
300 – 500	1.2 – 1.6	2.51×10^{-4}	4.1	1.1	4.2	-0.1	-0.6	0.0	0.1	-0.3	-0.2	-0.5	-0.3	0.5	-0.1	0.0	0.3	1.035
300 – 500	1.6 – 2.0	1.29×10^{-4}	5.7	1.2	5.8	-0.1	-0.8	-0.2	-0.1	-0.3	-0.2	-0.2	-0.3	0.6	0.0	0.0	0.4	1.040
300 – 500	2.0 – 2.4	3.93×10^{-5}	11.2	1.9	11.4	-0.1	-1.0	-0.3	-0.1	-0.5	-0.2	-0.1	-0.1	0.7	0.0	0.0	1.3	1.037

Muon trigger uncertainty required effort to reduce to 0.1% (was dominant sys)

Muon reco uncertainty could be reduced in future

Top +diboson b/g: dilepton filtered mass-binned samples needed

MC signal stats not a problem

Electron channel

m_{ee} [GeV]	$\lvert y_{ee}\rvert$	$\frac{d^2\sigma}{dm_{ee}d\lvert y_{ee}\rvert}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]	δ^{trig}_{cor} [%]	δ^{trig}_{unc} [%]	δ^{reco}_{cor} [%]	δ^{id}_{cor} [%]	δ^{iso}_{cor} [%]	δ^{iso}_{unc} [%]	δ^{Eres}_{cor} [%]	δ^{Escale}_{cor} [%]	$\delta^{mult.}_{cor}$ [%]	$\delta^{mult.}_{unc}$ [%]	δ^{top}_{cor} [%]	$\delta^{diboson}_{cor}$ [%]	δ^{bgMC}_{unc} [%]	δ^{MC}_{unc} [%]	$k_{dressed}$
300–500	0.0–0.4	3.23×10^{-4}	4.6	3.3	5.7	-0.1	0.2	-0.2	-0.8	-0.1	0.4	0.1	0.9	-1.8	0.6	-2.2	-0.8	0.8	0.3	1.080
300–500	0.4–0.8	3.34×10^{-4}	4.3	2.8	5.1	-0.1	0.2	-0.2	-0.8	-0.1	0.4	0.1	1.4	-1.1	0.6	-1.6	-0.7	0.7	0.3	1.072
300–500	0.8–1.2	3.16×10^{-4}	4.3	2.8	5.2	-0.1	0.2	-0.2	-0.8	-0.1	0.4	0.2	2.0	-0.9	0.5	-1.1	-0.6	0.7	0.3	1.058
300–500	1.2–1.6	2.30×10^{-4}	4.9	2.9	5.7	-0.1	0.2	-0.2	-0.8	-0.1	0.4	0.1	2.0	-1.6	0.5	-0.6	-0.4	0.6	0.4	1.053
300–500	1.6–2.0	1.31×10^{-4}	6.5	3.2	7.3	-0.1	0.2	-0.4	-0.9	-0.2	0.4	0.2	2.8	-0.3	0.4	-0.2	-0.2	0.5	0.6	1.047
300–500	2.0–2.4	3.62×10^{-5}	11.5	3.5	12.0	-0.1	0.2	-0.6	-1.0	-0.2	0.4	0.4	2.5	-1.3	1.0	0.0	-0.1	0.8	0.9	1.046

Energy scale - dominant systematic

leptonic decay angle in Collins-Soper frame $\cos\theta^* = \frac{p_{z,\ell\ell}}{m_{\ell\ell}|p_{z,\ell\ell}|}\frac{p_1^+p_2^- - p_1^-p_2^+}{\sqrt{m_{\ell\ell}^2 + p_{T,\ell\ell}^2}}$

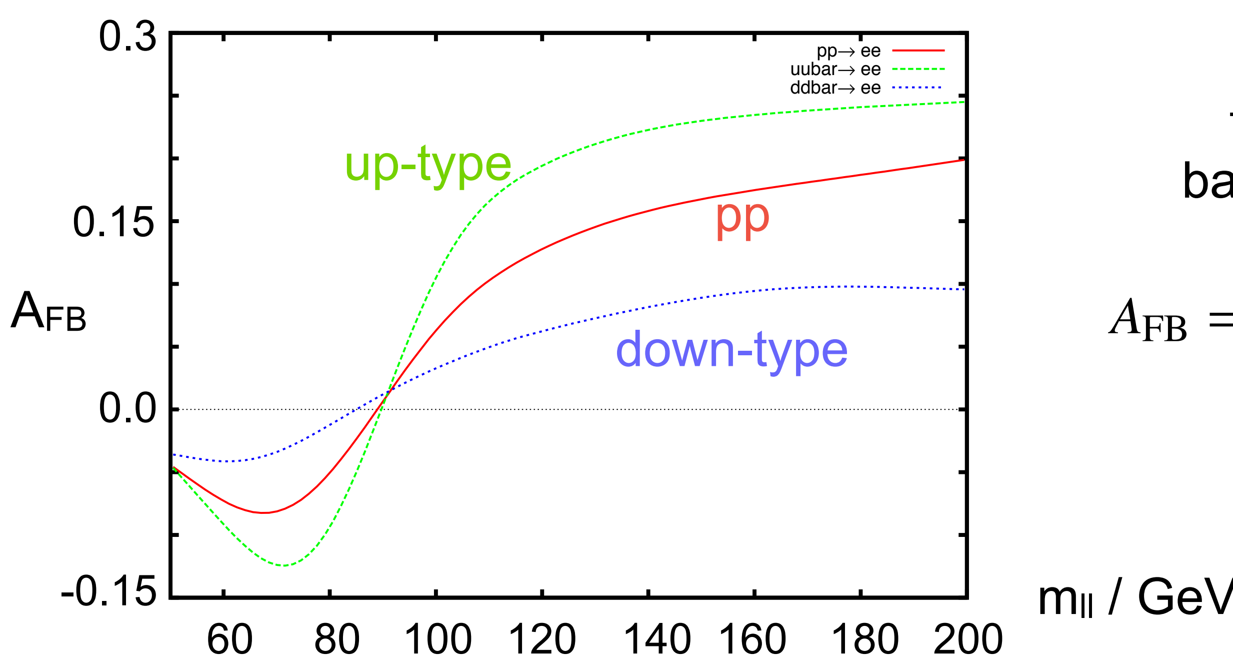
$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q P_q\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q\leftrightarrow\bar{q})\right]$$

$f_q(x,Q^2)$ = parton density functions

pure ɣ* $P_q = e_l^2e_q^2(1+\cos^2\theta^*)$

interference Z/ɣ* $+\, e_l e_q \frac{2m_{\ell\ell}^2(m_{\ell\ell}^2 - m_Z^2)}{\sin^2\theta_W\cos^2\theta_W[(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2m_Z^2]}[v_\ell v_q(1+\cos^2\theta^*) + 2a_\ell a_q\cos\theta^*]$

pure Z $+\, \frac{m_{\ell\ell}^4}{\sin^4\theta_W\cos^4\theta_W[(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2m_Z^2]}[(a_\ell^2+v_\ell^2)(a_q^2+v_q^2)(1+\cos^2\theta^*) + 8a_\ell v_\ell a_q v_q\cos\theta^*]$



forward = cos θ* > 0
backward = cos θ* < 0
Asymmetry

$$A_{FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$

Sensitive to $\sin^2\theta_W$

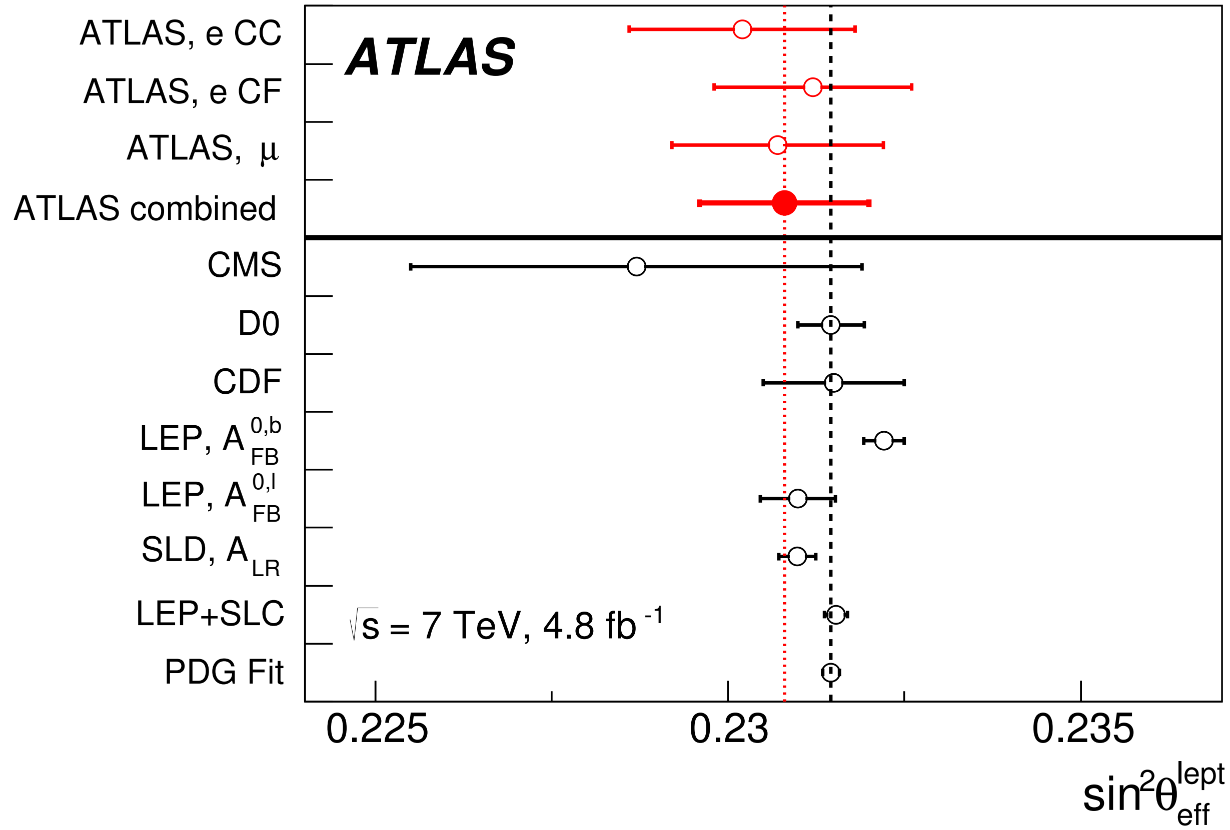
Triple Differential Z/γ* Measurement Motivation & $\sin^2\theta_W$

Previous measurement of $\sin^2\theta_W$

JHEP09(2015)049

5 fb^{-1}

$\sqrt{s}$ = 7 TeV

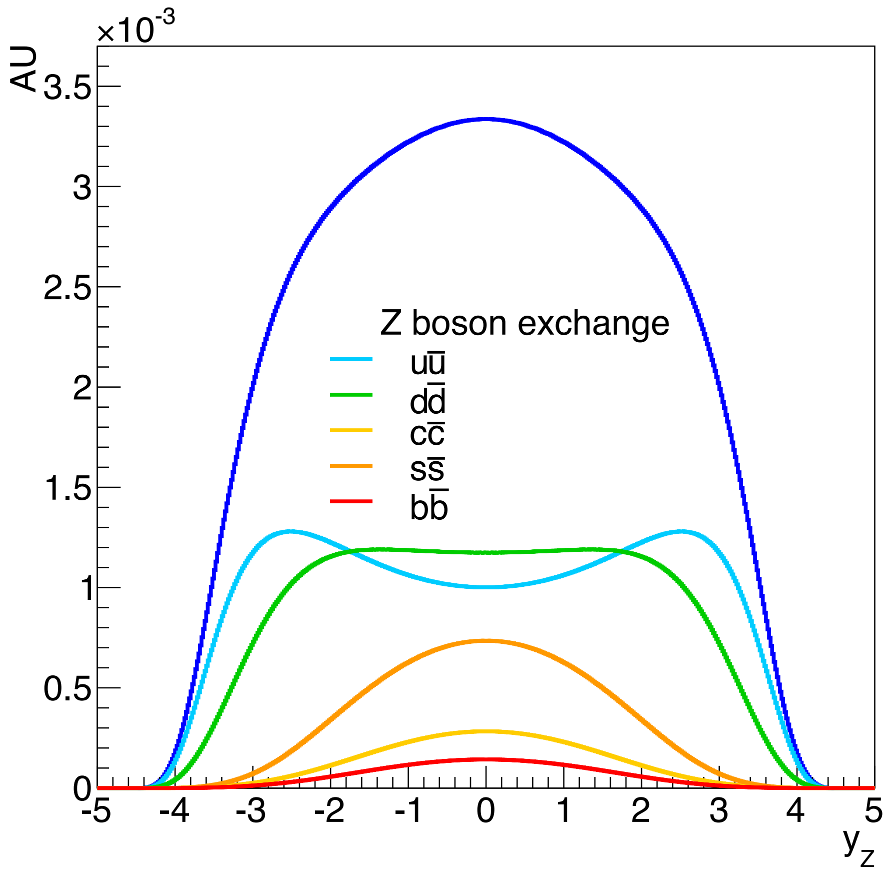


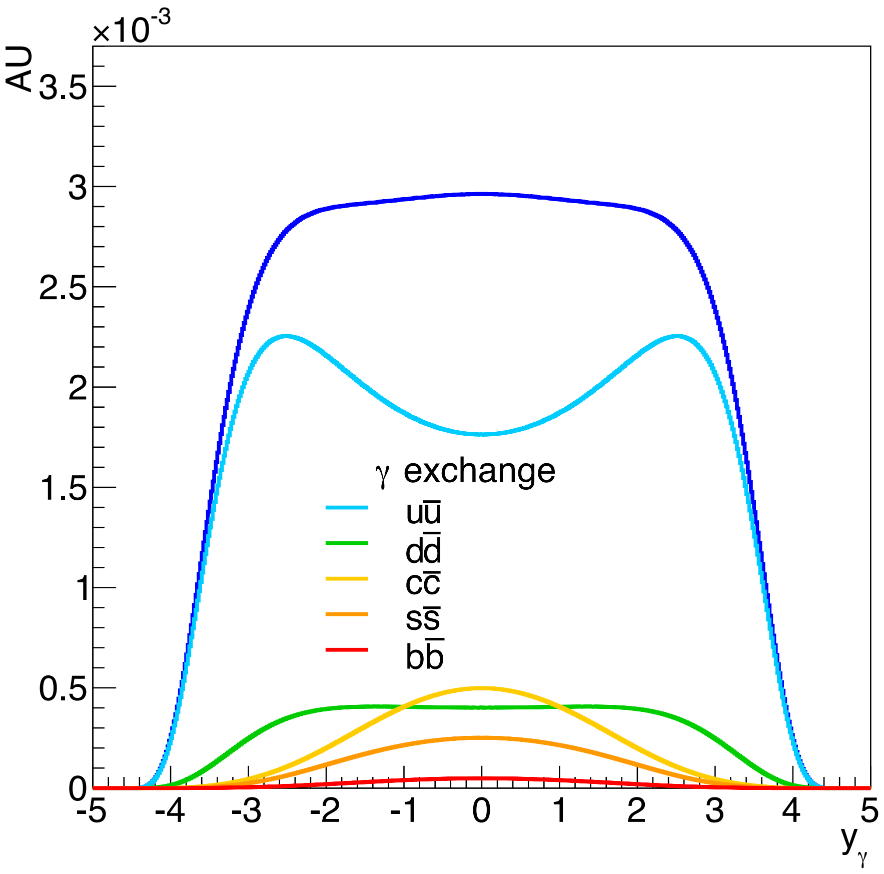
ATLAS measurement of $\sin^2\theta_W$ limited by PDF uncertainty

Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combined $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

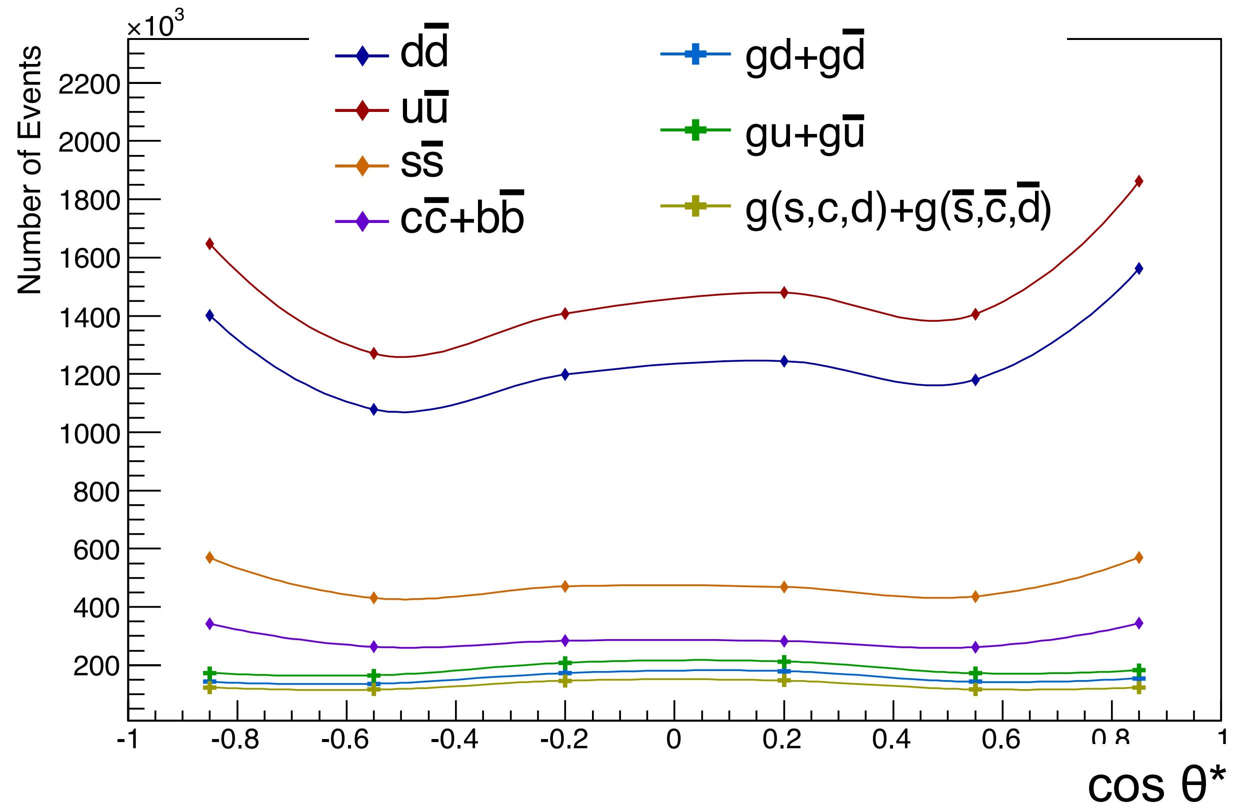
Triple Differential Z/ɣ* Measurement Motivation

y spectrum shapes changes dramatically for $m_{ll} != m_Z$
different Z and ɣ* couplings





cos θ* spectrum has sensitivity to gluon PDF via gq terms



Triple Differential Z/γ^* Selection

Muon Selection

- Good quality detector status (all sub-systems on)
- muon trigger fired (matched to lepton)
- ≥ 2 good quality muons
- muon $|\eta| < 2.4$
- muon $p_T > 20$ GeV
- longitudinal impact parameter $|z_0| < 10$ mm
- isolated muon $\sum p_{T,i}^{(\Delta R=0.2)}/p_T^{\mu} < 0.12$
  p_T sum of tracks within a cone size $\Delta R=0.2$ is less than 12% of muon p_T
- opposite charge

Central Electron Selection

- Good quality detector status (all sub-systems on)
- electron trigger fired (matched to lepton)
- ≥ 2 good quality "medium" electrons
- electron $|\eta| < 2.4$ excl. $1.37 < |\eta| < 1.52$
- electron $E_T > 20$ GeV

Fiducial Cross Section Definition

- lepton $p_T > 20$ GeV
- lepton $|\eta| < 2.5$
- $46 < m_{ll} < 200$ GeV
- Unfolding to Born level lepton kinematics
  (dressed level available as a correction factor)

High Rapidity Electron Selection

- Good quality detector status (all sub-systems on)
- electron trigger fired (matched to lepton)
- 1 good quality "tight" central electron
  - electron $|\eta| < 2.47$ excl. $1.37 < |\eta| < 1.52$
  - electron $E_T > 25$ GeV
- **1 good quality "tight" forward electron**
  - **electron $2.5 < |\eta| < 4.9$** excl. $3.0 < |\eta| < 3.4$
  - electron $E_T > 20$ GeV

Fiducial Cross Section Definition

- lepton $p_T > 25$ GeV & lepton $|\eta| < 2.5$
- lepton $p_T > 25$ GeV & lepton $2.5 < |\eta| < 4.9$
- $66 < m_{ll} < 150$ GeV
- Unfolding to Born level lepton kinematics
  (dressed level available as a correction factor)

Triple Differential Z/γ^* Binning

Central Rapidity Channel

m_{ll} =	[46, 66, 80, 91, 102, 116, 150, 200] GeV	7 bins
$\|y_{ll}\|$ =	[0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4]	12 bins
$\cos\theta^*$=	[-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0]	6 bins
	Total bins =	504
	x 2 channels	

measure in electron + muon channels
check for consistency of channels
combine both measurements
account for **~200** correlated systematic errors
improved result for both statistical & systematic precision

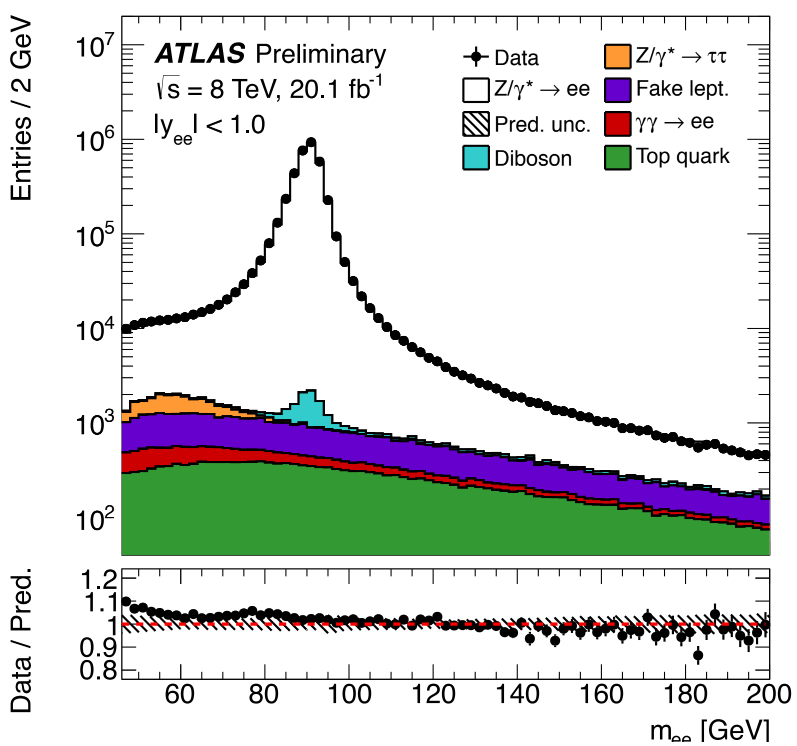
Binning choice optimised for
- control experimental bin migrations
- statistical precision
- physics sensitivity

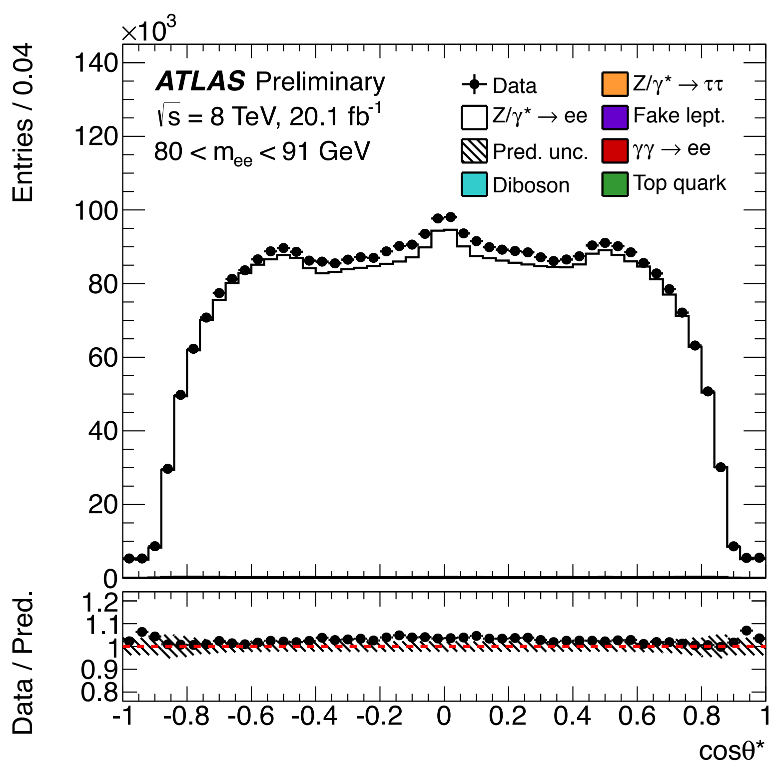
High Rapidity Channel

m_{ll} =	[66, 80, 91, 102, 116, 150] GeV	5 bins
$\|y_{ll}\|$ =	[1.2, 1.6, 2.0, 2.4, 2.8, 3.6]	6 bins
$\cos\theta^*$=	[-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0]	6 bins
	Total bins =	150

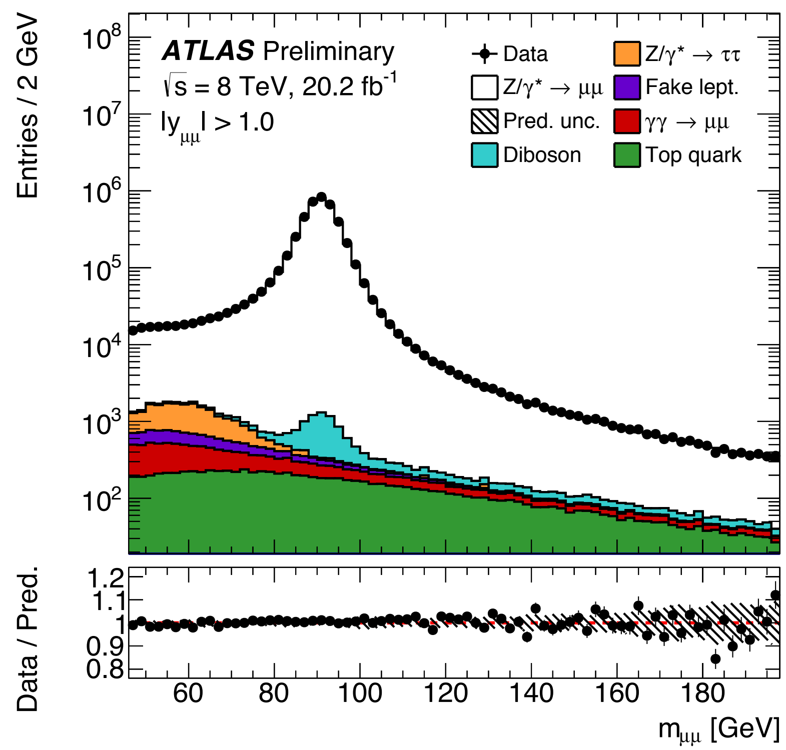
Triple-differential Z/γ* Cross Sections √s = 8 TeV

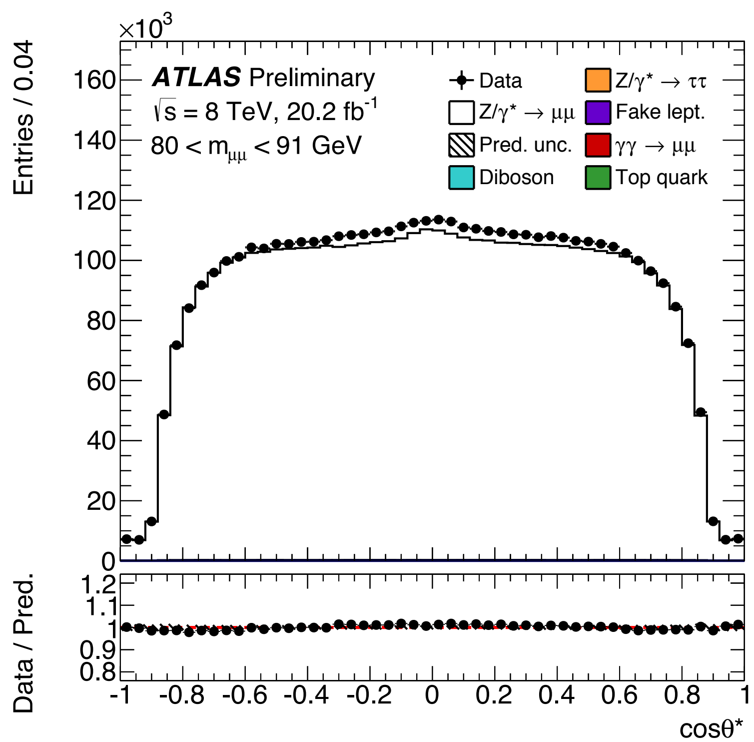
Electron Channel



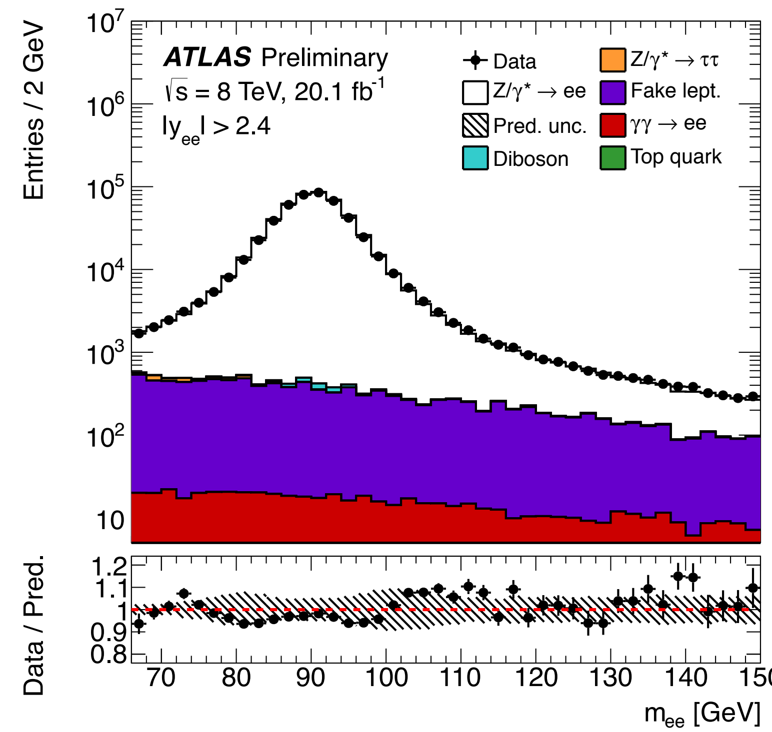


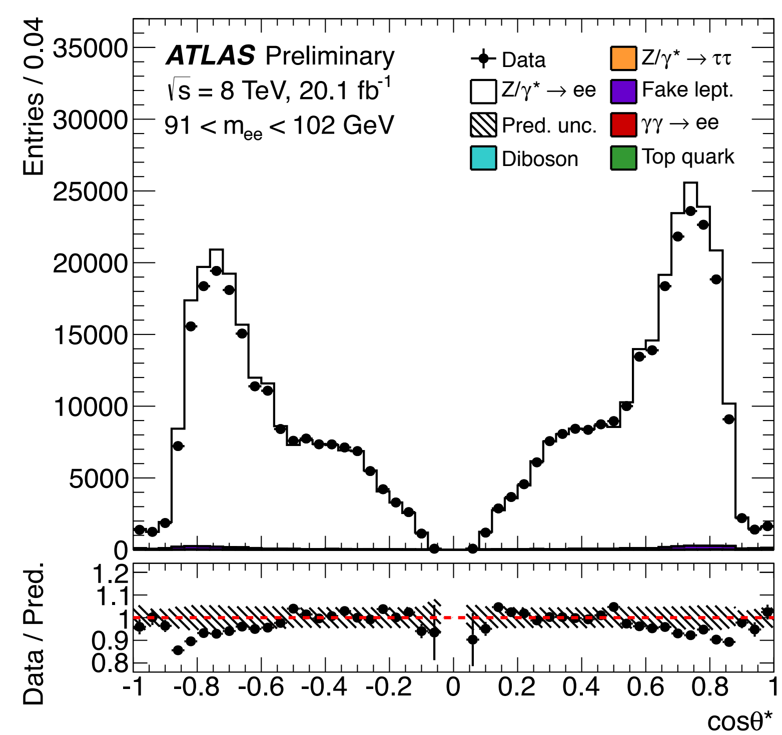
Muon Channel





High Rapidity Electron Channel





Simulation describes data well

Performance Considerations

Already good precision achieved for run-II !
Need to ensure phase-space corners are well covered e.g. boosted Zs access high pT lepton efficiencies
For run-I lepton pT ~ 200 GeV
For run-II we should reach lepton pT ~ 400 GeV

Electron Channel
Energy scale dominates error at large |cos θ*| → ~3%

efficiency error also large at at large cos θ* (even at small |y|) → ~2-3%

Muon Channel
In peak region at $m \sim m_Z$ momentum scale dominates sys error → ~0.6% compared to 0.8% stat error

Tracking misalignments ~ 1.7% cf stat error 2% at small cos θ* or large y

High Rapidity Electron Channel
Energy scale / resolution dominates error at large |cos θ*| & y → ~5% compared to ~3% stat error

Combination of channels constrains correlated systematic uncertainties

↓

Improved precision for combined central channels

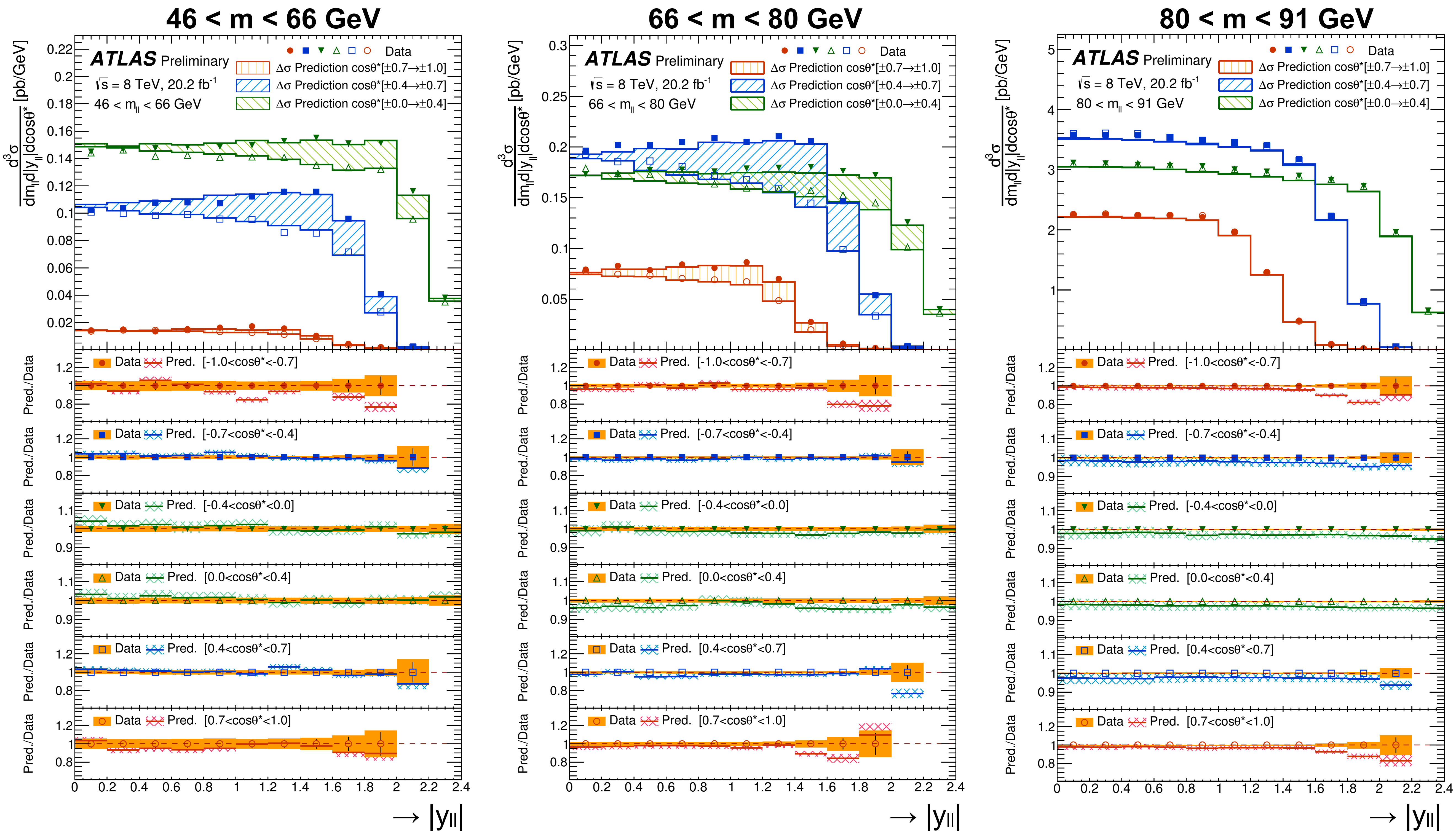
Triple-differential Z/γ* Cross Sections √s = 8 TeV

$$\frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*}$$

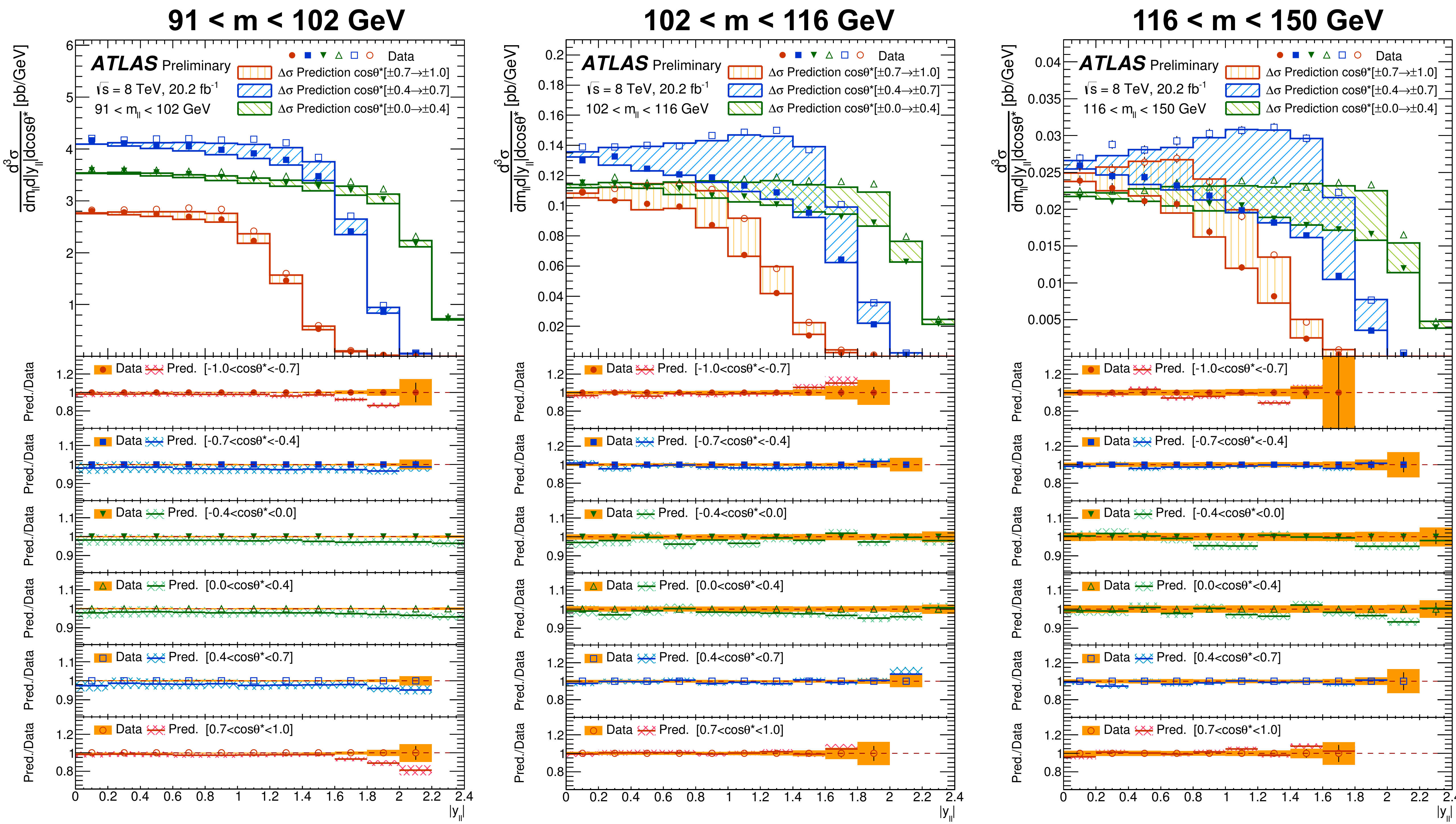
Central rapidity electron & muon combined result

Large forward-backward asymmetry at low mass, decreasing to ~zero at $m_{ll} \sim m_Z$

Upper plots: shaded regions highlight equal |cos θ*|



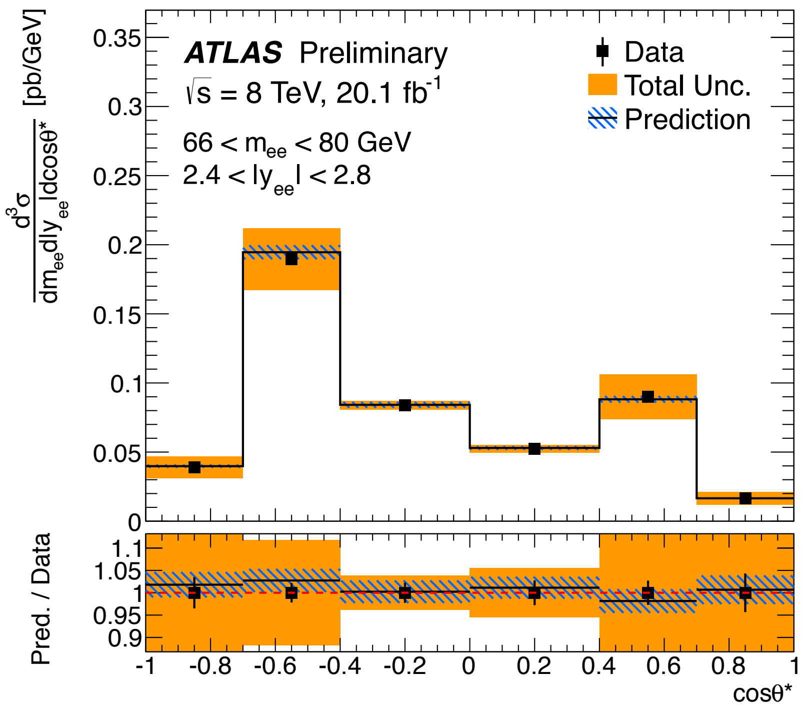
Triple-differential Z/γ* Cross Sections √s = 8 TeV

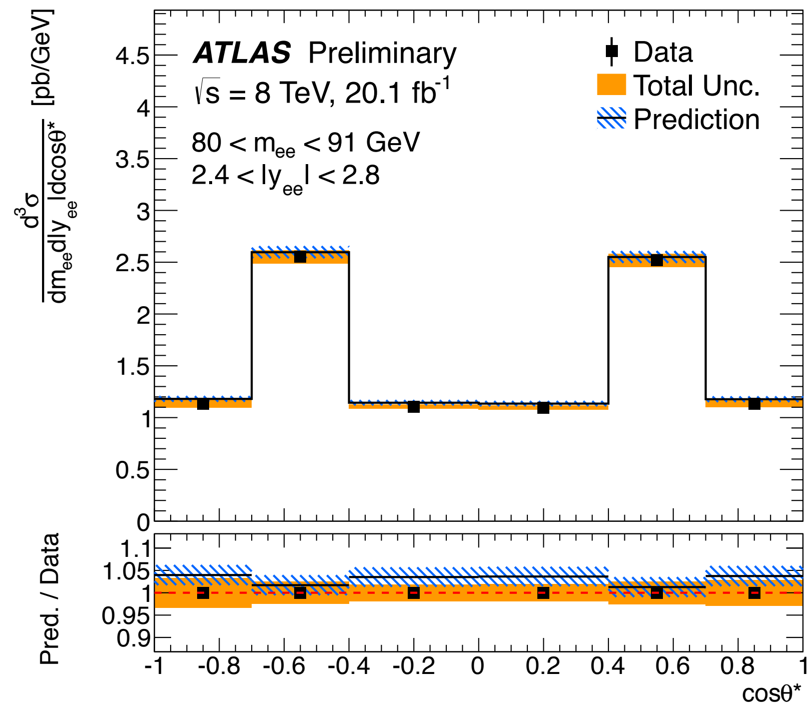


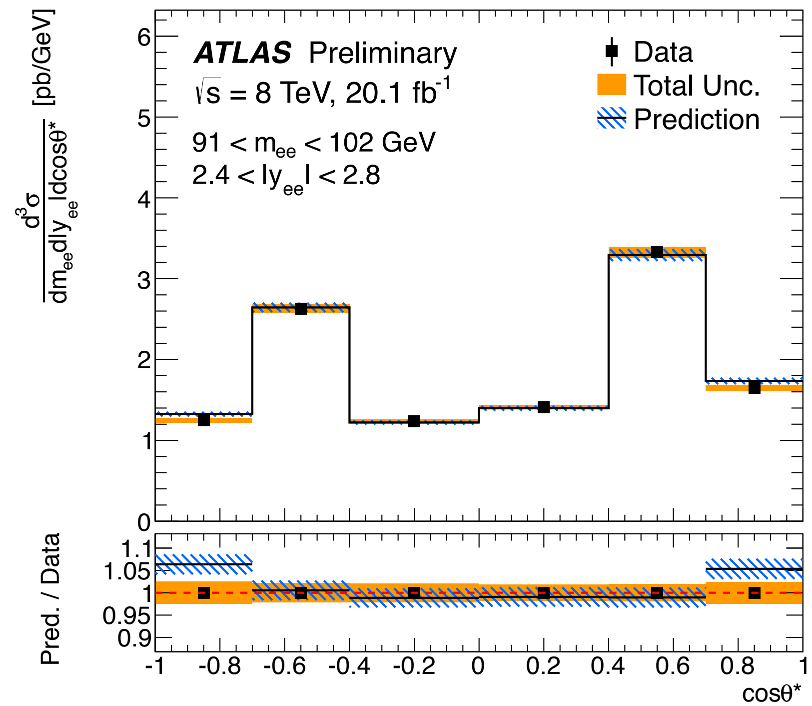
Data precision reaches ~0.5% for $m_{ll} \sim m_Z$

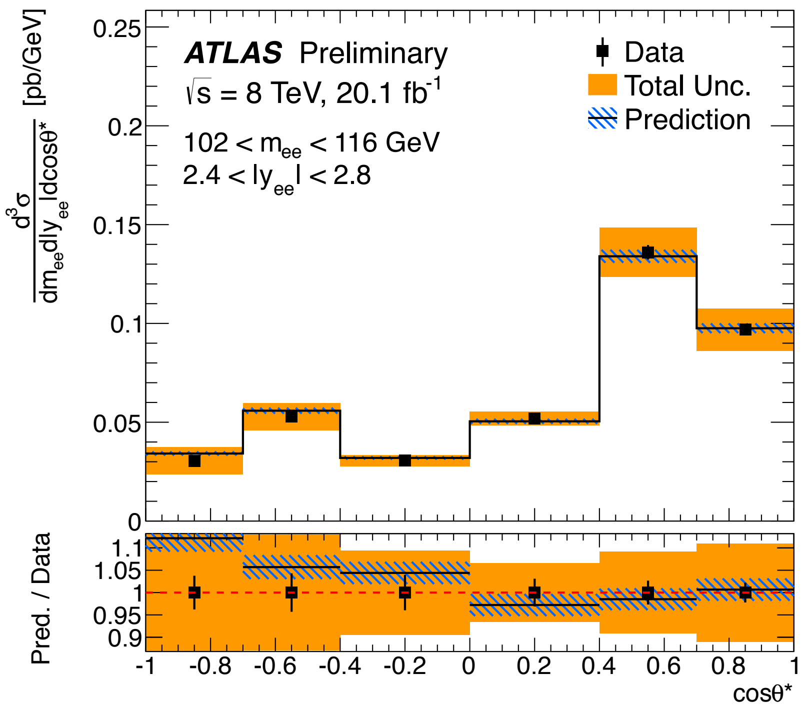
[m=150-200 GeV bin shown in back-up]

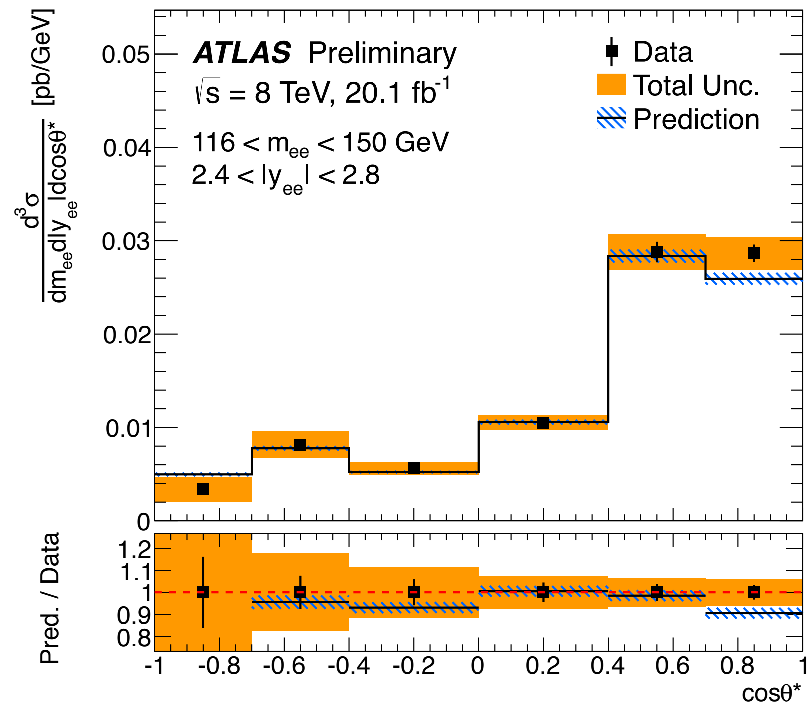
Good agreement with Powheg based predictions incl. NNLO/NLO k-factor (and Z polarisation correction)











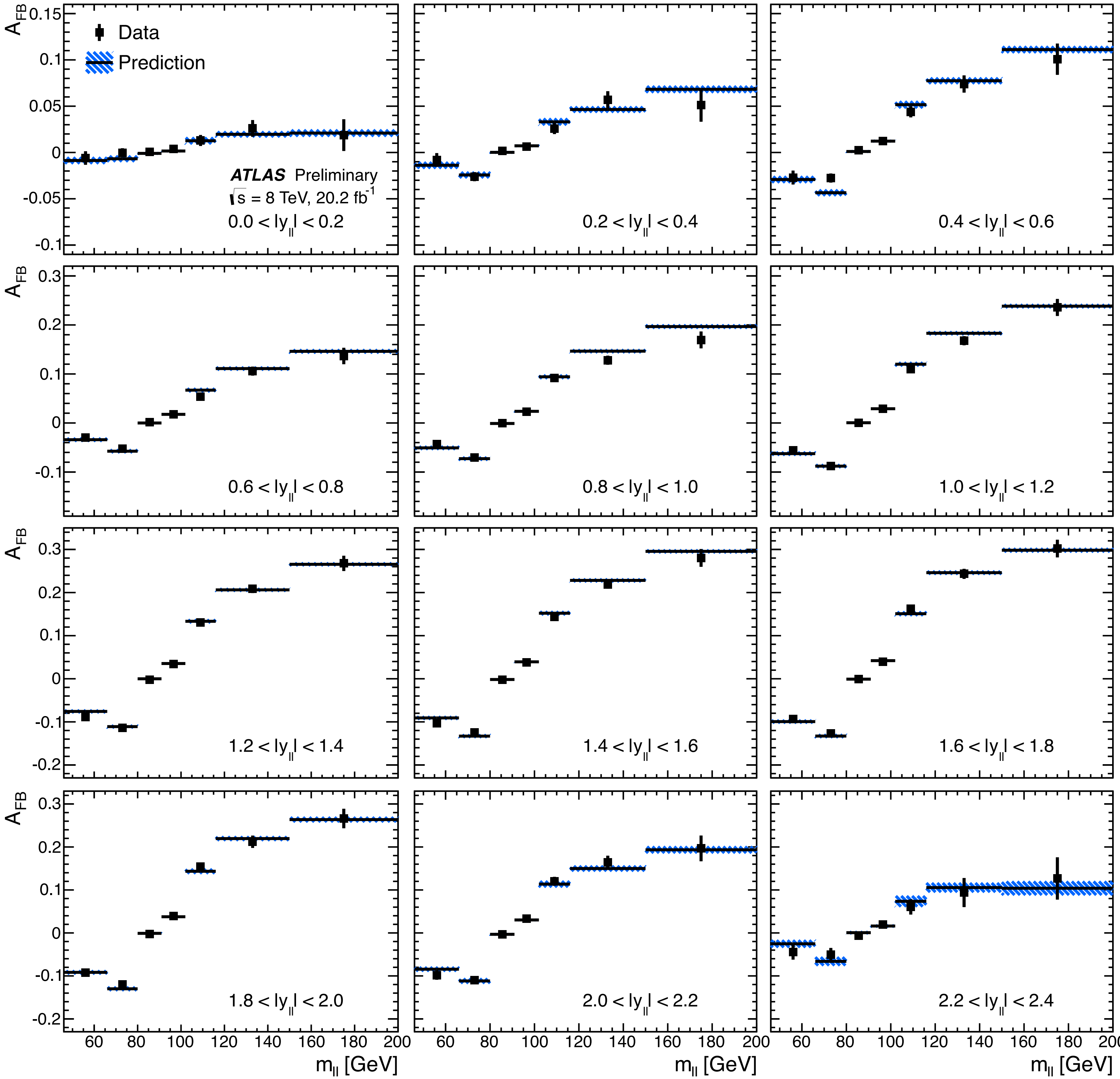
$$\frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*}$$

High rapidity channel

Showing selected bins

High y region has greatest sensitivity to $\sin^2\theta_W$ and PDFs
High y analysis shows much larger asymmetry

Forward-Backward Asymmetry



Central rapidity channel

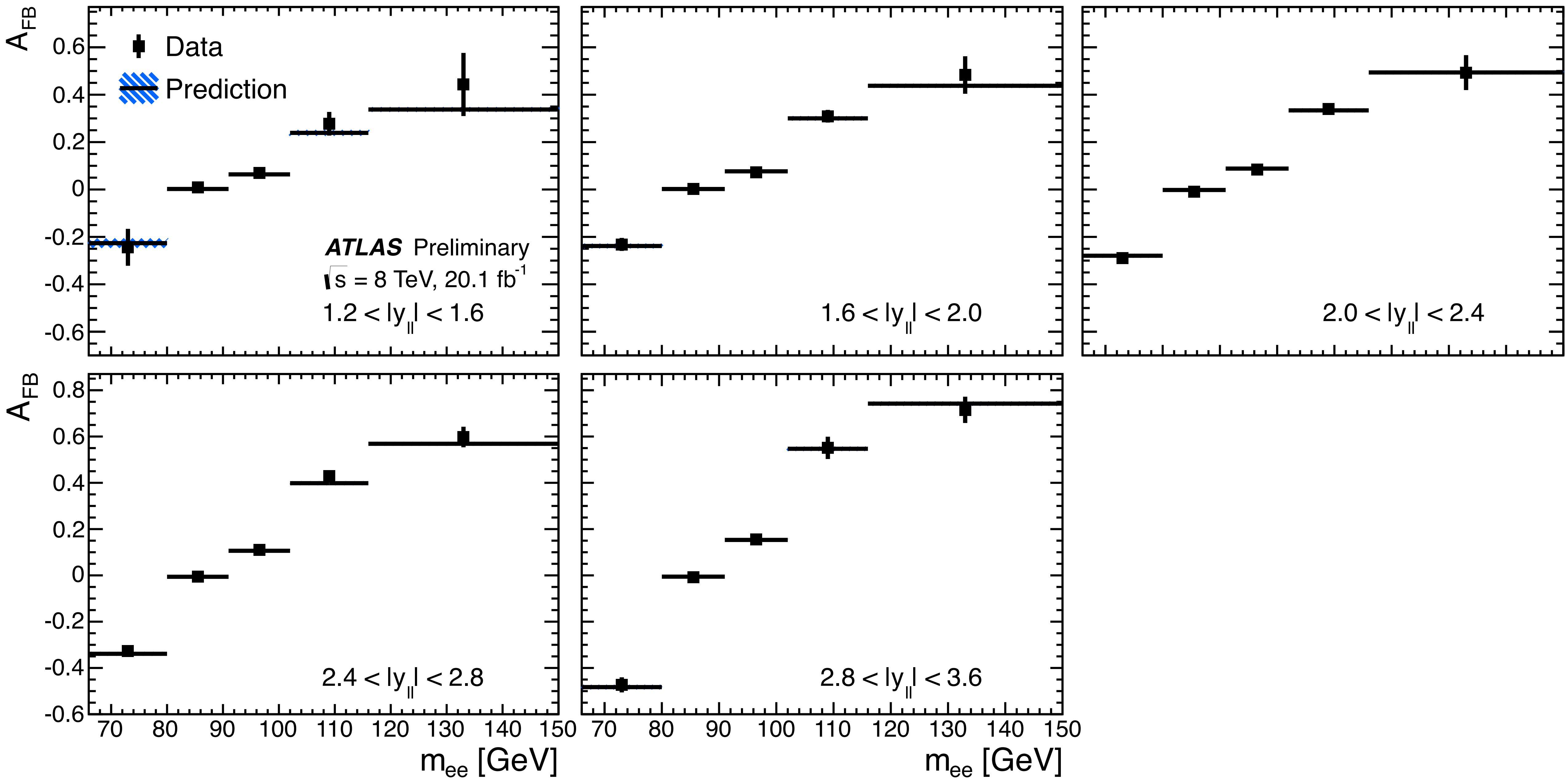
$$A_{\mathrm{FB}} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$

Note: A_{FB} derived from unfolded cross section measurements

Asymmetry increases with |y|
Due to better determination of initial quark

(high |y| access higher x valence PDF)

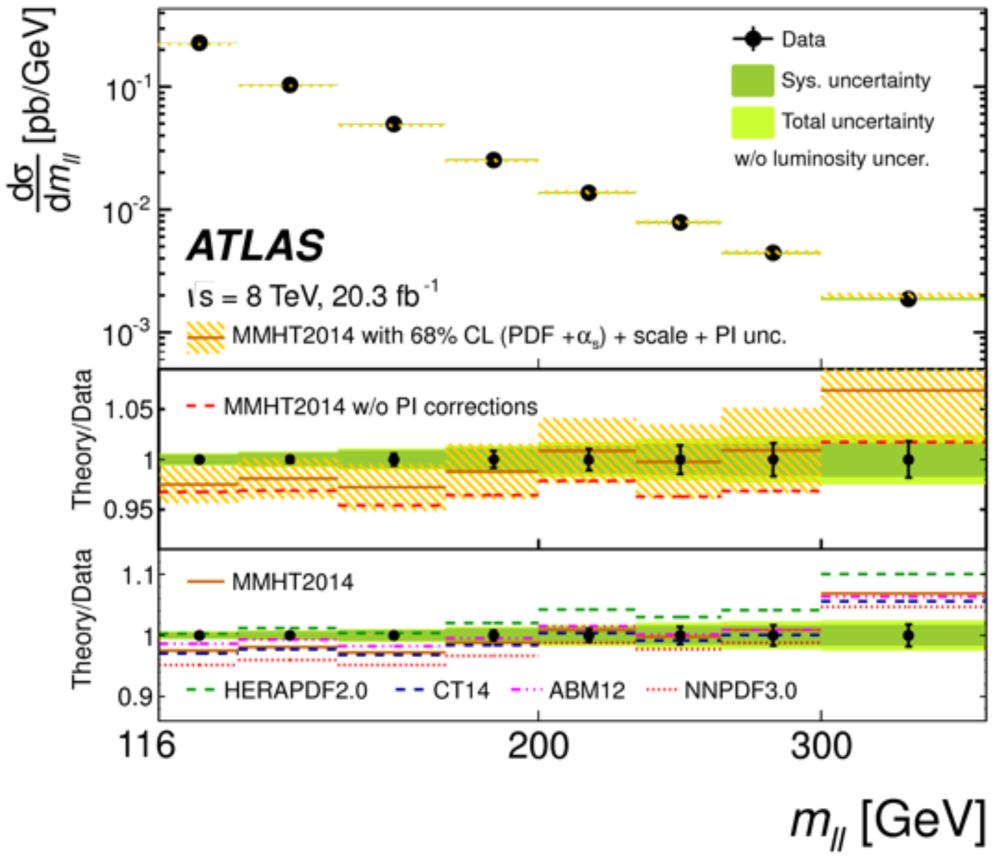
Forward-Backward Asymmetry



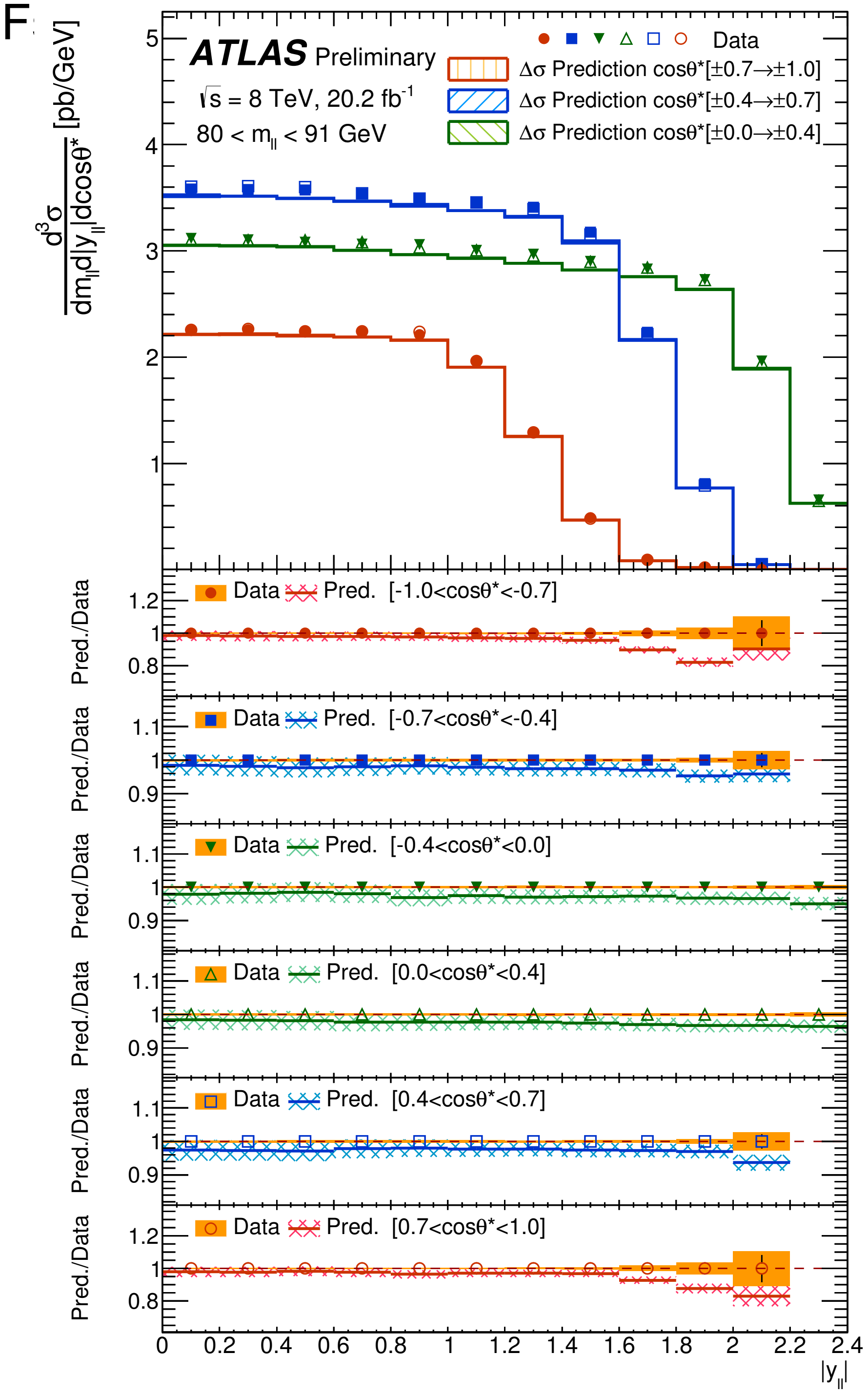
High rapidity channel

For **A_{FB}** measurements uncorrelated sources dominate:
data stats are factor 2 larger than MC stat / multijet unc / bg MC stats
correlated sources ~ factor 10 smaller

Summary - I



- Measurement of DY cross section at $\sqrt{s}$ = 8 TeV presented
- High mass phase space 116 < m < 1500 GeV
- Precision of 1% attained at low m
- Data compatible with NNLO pQCD ⊗ NLO EW
- Measurements are sensitive to PDF

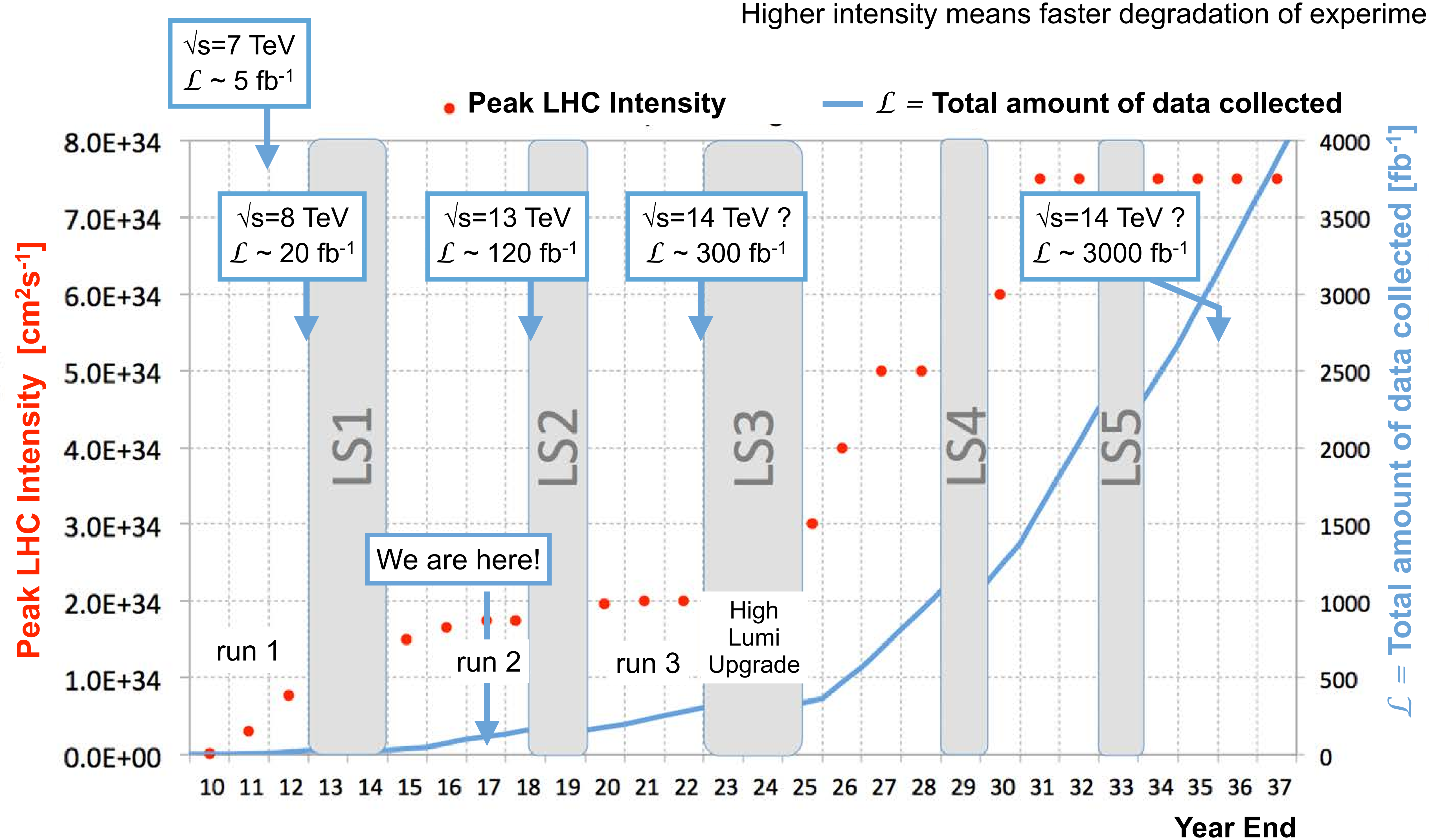


- New measurement of DY cross section at $\sqrt{s}$ = 8 TeV shown
- on-shell analysis covers phase space 46 < m < 200 GeV
- triple-differential cross sections determined
- Precision of 0.5% attained at $m = m_Z$
- Data compatible with NNLO pQCD ⊗ NLO EW
- Data to be published in ~3-4 weeks
- Plan to extract $\sin^2\theta_W$ in follow-up paper ~ 6 months

LHC Schedule to 2035

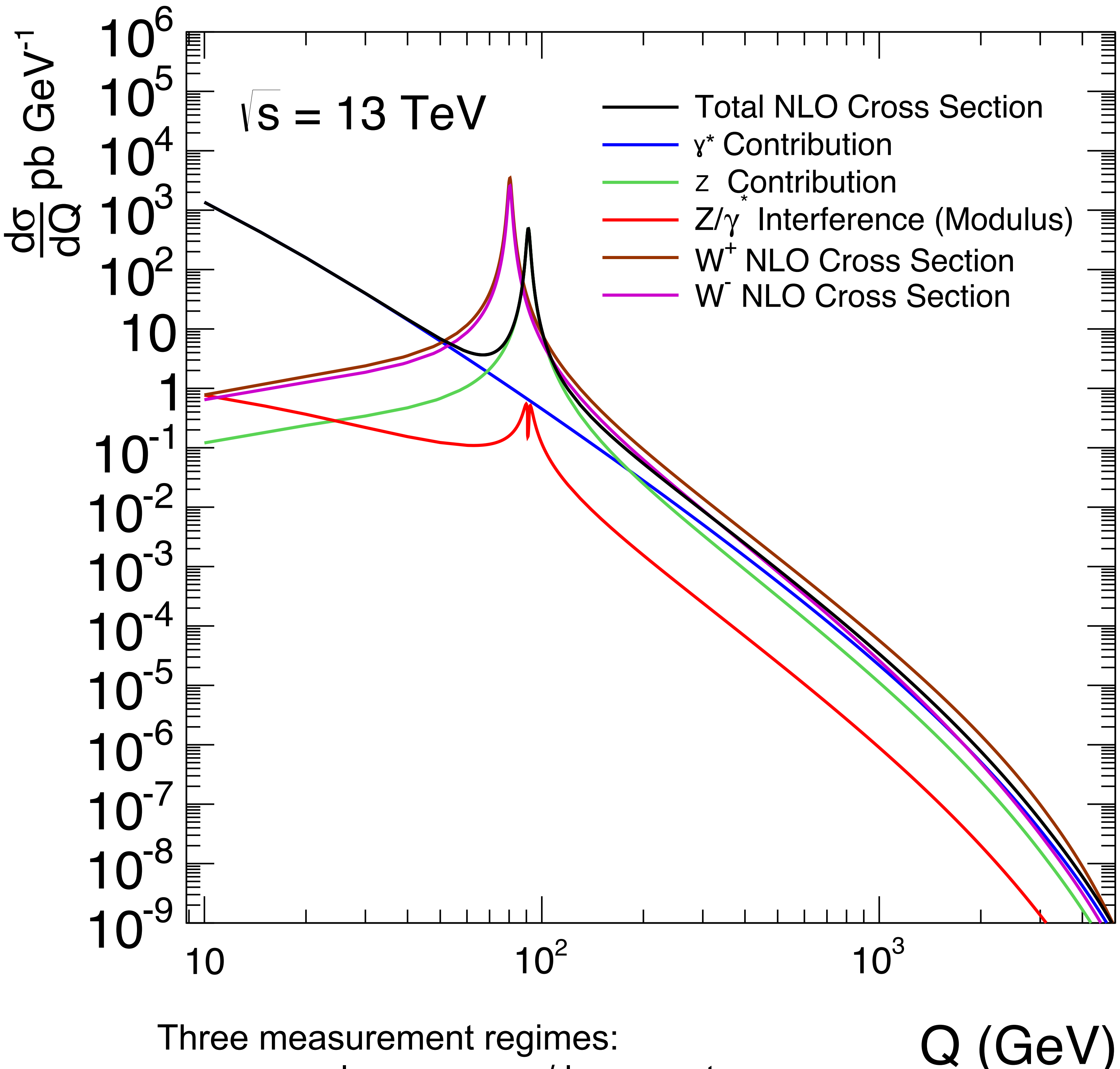
* actual schedule slipped by 1 year
e.g. LS3 starts 2023

Large increases in intensity
Requires significant changes to LHC magnets
Higher intensity means faster degradation of experiments



LS = Long Shutdown for repairs and upgrades

High Mass W/Z/γ^* Production at $\sqrt{s}$ = 13 TeV



Three measurement regimes:
$m_{\mu\mu} < m_Z$ − low muon p_T / low x partons
$m_{\mu\mu} = m_Z$ − ultra-high precision
$m_{\mu\mu} > m_Z$ − high muon p_T / new physics / high x partons

- At large Q $\sigma(W^+) > \sigma(W^-) >= \sigma(\gamma^*)$ by ~ factor 2
- Run-II total $\int L$~120 fb^{-1}
- Lumi ~ 4-5 times larger than Run-I
- Factor >2 larger cross section at 13 TeV
  ⇒ order of magnitude more data

High mass DY reaches high x region

Factor 5 higher x than on-shell Z at 8 TeV

At M=300-500 can achieve ~ 2% precision for |y| < 1

High Mass W/Z/γ* Production at √s = 13 TeV

Stringent constraints on Y & W from LEP
100 fb^{-1} of NC data $Z/\gamma^* \rightarrow l^+l^-$ reaches LEP precision
20 fb^{-1} of CC data $W \rightarrow l\nu$ surpasses LEP by factor 4!

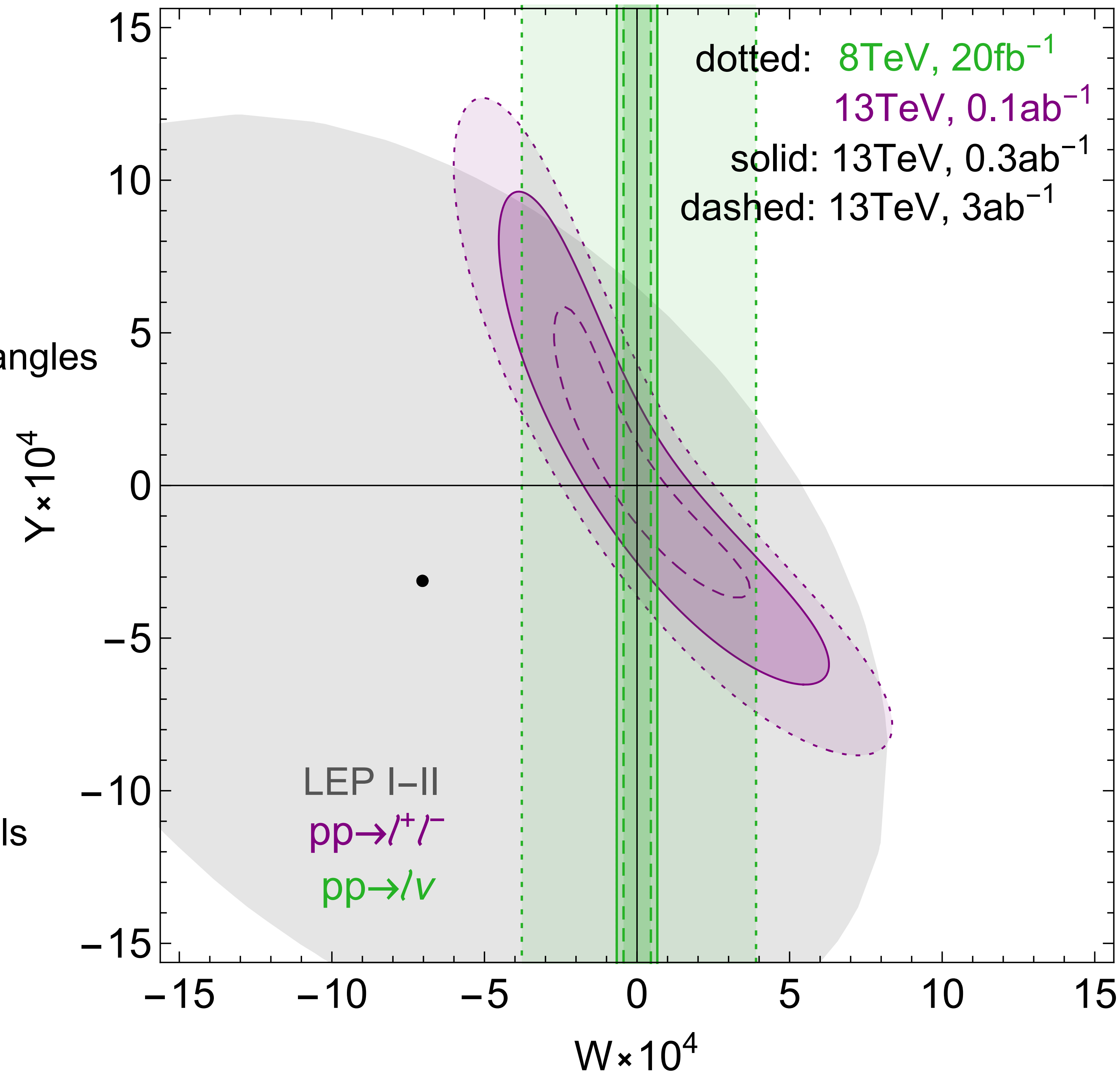
https://arxiv.org/abs/1609.08157

Discussions with Andrea / Riccardo et al
Request for unfolded cross sections
Additional gains in NC channel measuring decay angles
- cos θ*
- y_{ll}
- m_{ll}

→ triple differential cross sections

Started analysis of high mass DY cross sections in run-II @ √s=13 TeV

Simultaneous measurement in NC & CC channels

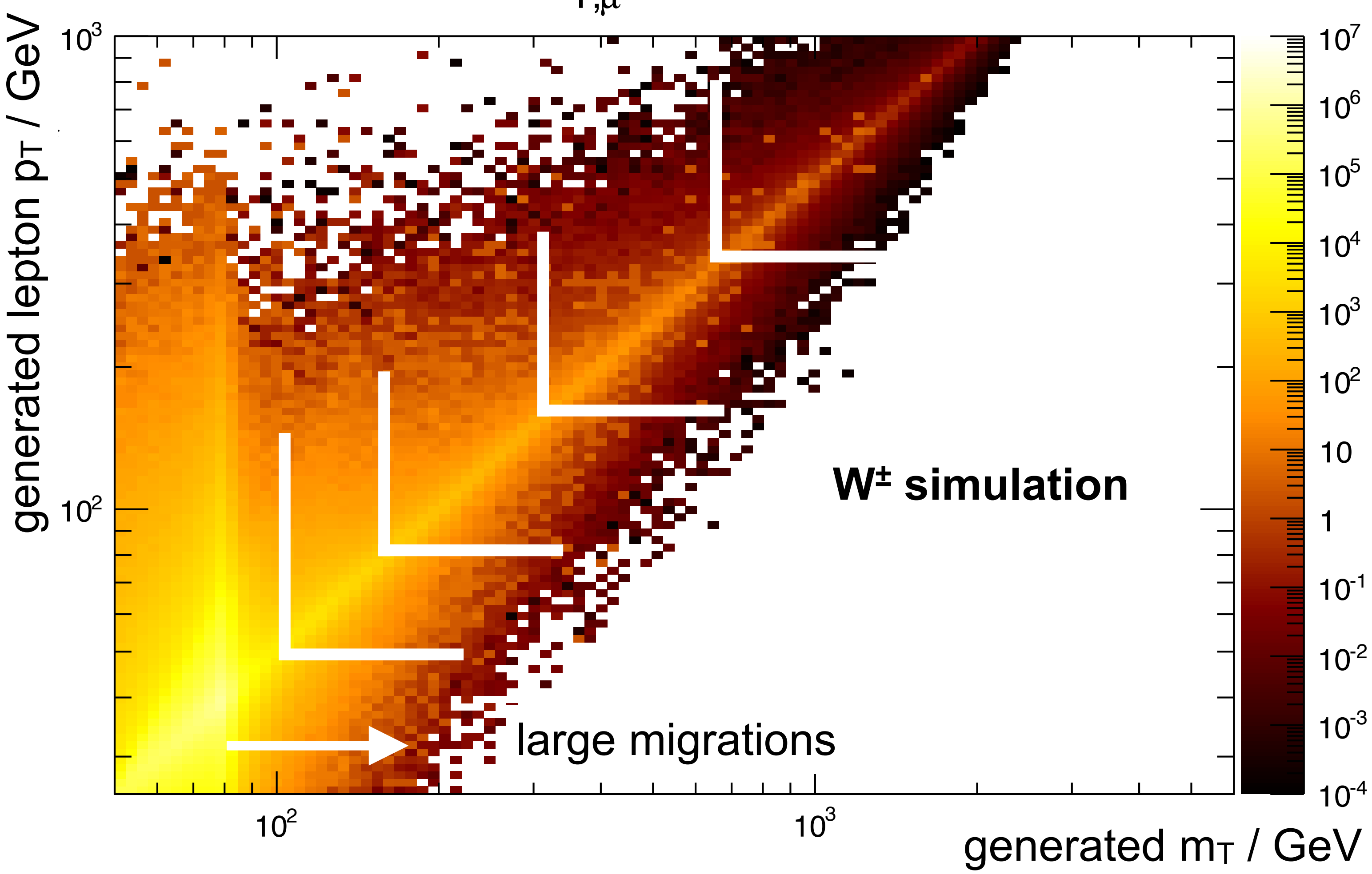


High Mass W/Z/γ^* Production at $\sqrt{s}$ = 13 TeV

Run-I precision measurements gained excellent knowledge of ATLAS detector and performance
Improved our calibration methods
Will allow us to improve detector modelling
Now have experience of highly differential measurements with leptonic decay angles
Extend measurement using FCAL to high |y|
Aim to now extend the precision region at higher m
Measure lepton decay angle also at high m

- Muon tracking misalignment uncertainties affects single-charge measurements i.e. W^+ and W^-
- Much better treatment planned for run2 analyses

$p_{T,\mu}$ vs m_T



Questions:

Neutral current channel
- exclude PI contribution?
- which angular variables?
- measure A_{FB} at high m?
- can we constrain W better with new 3D data?

Charged current channel
- is ratio of W+/W- useful?
- measure lepton charge asymmetry vs η
- measure mT for increasing lepton p_T
  control migration = wide mT bins

Missing E_T resolution is largest problem in $W^\pm$ channels
Large migrations off-peak
Good correlation of lepton p_T with m_T
Better resolution for lepton → measure mT for increasing lepton p_T cut

Backup

MC Samples

Process	Generator	Parton shower	Generator PDF	Model parameters ("Tune")
Drell–Yan	POWHEG	PYTHIA 8.162	CT10	AU2 [67]
Drell–Yan	MC@NLO 4.09	HERWIG++ 2.6.3	CT10	UE-EE-3 [39]
PI	PYTHIA 8.170	PYTHIA 8.170	MRST2004qed	4C [68]
$t\bar{t}$	POWHEG	PYTHIA 6.427.2	CT10	AUET2 [69]
$t\bar{t}$	MC@NLO 4.06	HERWIG 6.520	CT10	AUET2
Wt	MC@NLO 4.06	HERWIG 6.520	CT10	AUET2
Diboson	HERWIG 6.520	HERWIG 6.520	CTEQ6L1	AUET2

Drell—Yan signal simulated at NLO in matrix element with PS
- cross section is scaled to mass dependent NNLO calculation (FEWZ)
- includes final state photon emission (photos)
- (for cross checks MC@NLO is also used)
- 25 — 1000 x data statistics simulated

Photon Induced cross section available at LO only in pythia
- 20 — 6000 x data statistics simulated

Top production simulated at NLO and renormalised to NNLO+NNLL prediction
- 5 x data luminosity

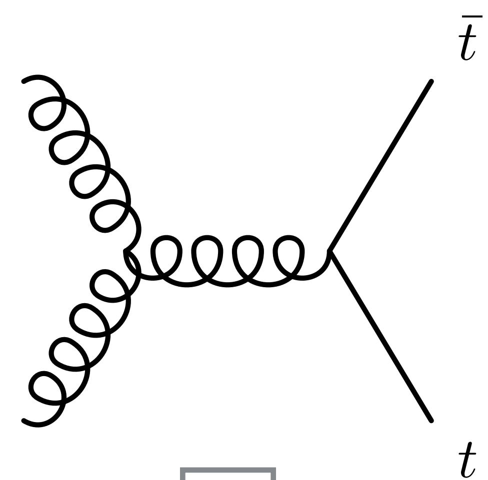
Diboson production channels simulated at LO with herwig
- 40 — 50,000 x data statistics simulated

Several sources of so called “electroweak” backgrounds yielding isolated dileptons:

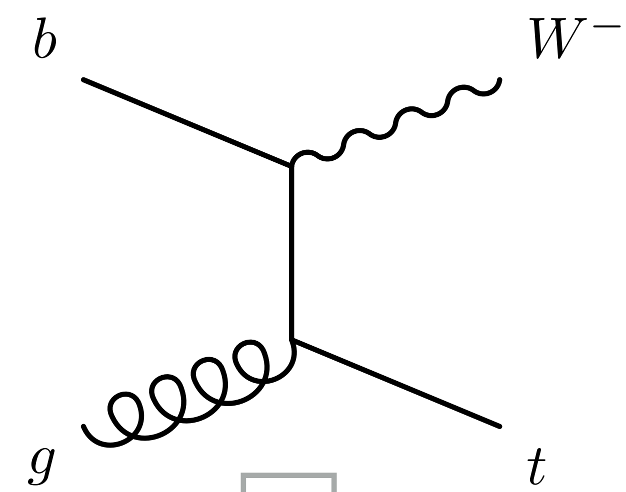
DY → tau production modes found to be negligible contribution

top background

up to 9% contribution top background
estimated from MC
validated with eμ dilepton selection
validated with two MC generators



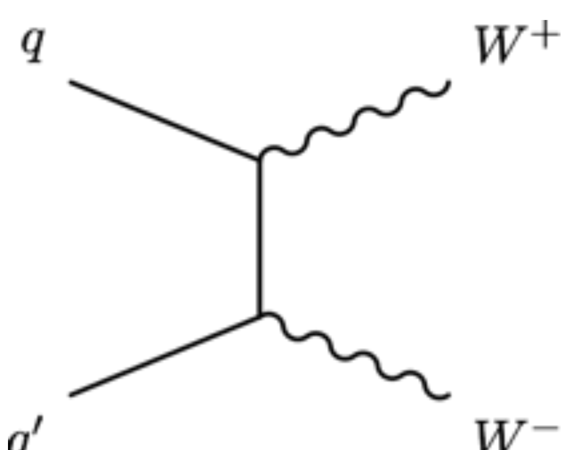
$t\bar{t}$



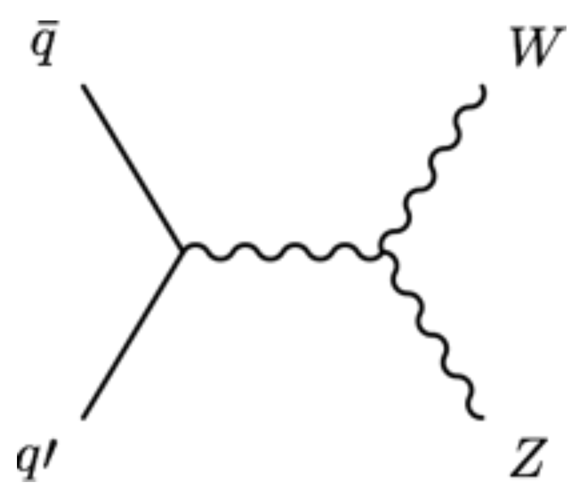
Wt

diboson background

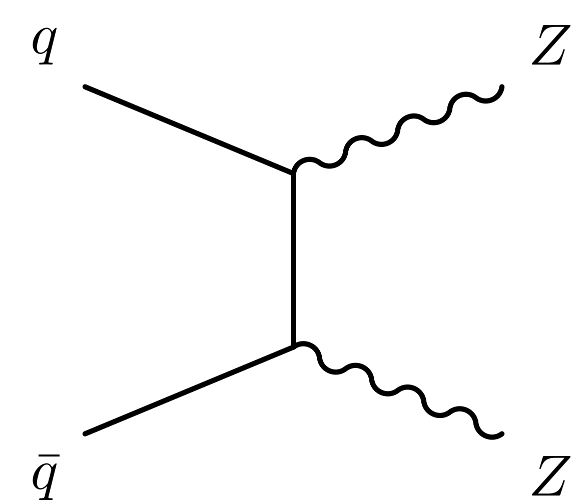
up to 2% contribution
estimated from MC



diboson (WW)



diboson (WZ)

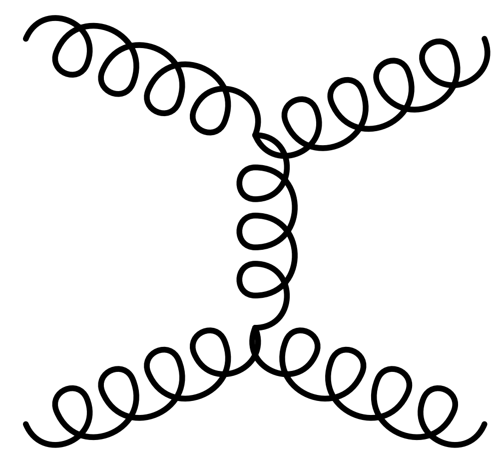


diboson (ZZ)

multijet background

multijet production dominates cross section at LHC
Also large W+jets cross section
contributes to background via:
- leptonic meson decays
- misidentification of hadron jet as calorimeter electron

soft leptons produced typically
contributing processes involve complex hadronisation simulation
⇒ use data to estimate this background



muon channel

use same sign dimuons as proxy for mulitjet b/g

dimuon pairs

A isolated opposite sign	**C** non-isolated opposite sign
B isolated same sign	**D** non-isolated same sign

$$\frac{N_A}{N_B} = \frac{N_C}{N_D}$$

assume ratio of same sign to opp sign pairs is same in isolated and in non-isolated region
<1% contribution in muon channel

electron channel

use matrix method:
N_T / N_L → "tight" / "loose" identified electrons
N_R/ N_F → "real" / "fake" electrons

dielectron pairs

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

Depends on:
f = fake rate probability (estimated from dijet data)
r = real electron efficiency (estimated from MC)

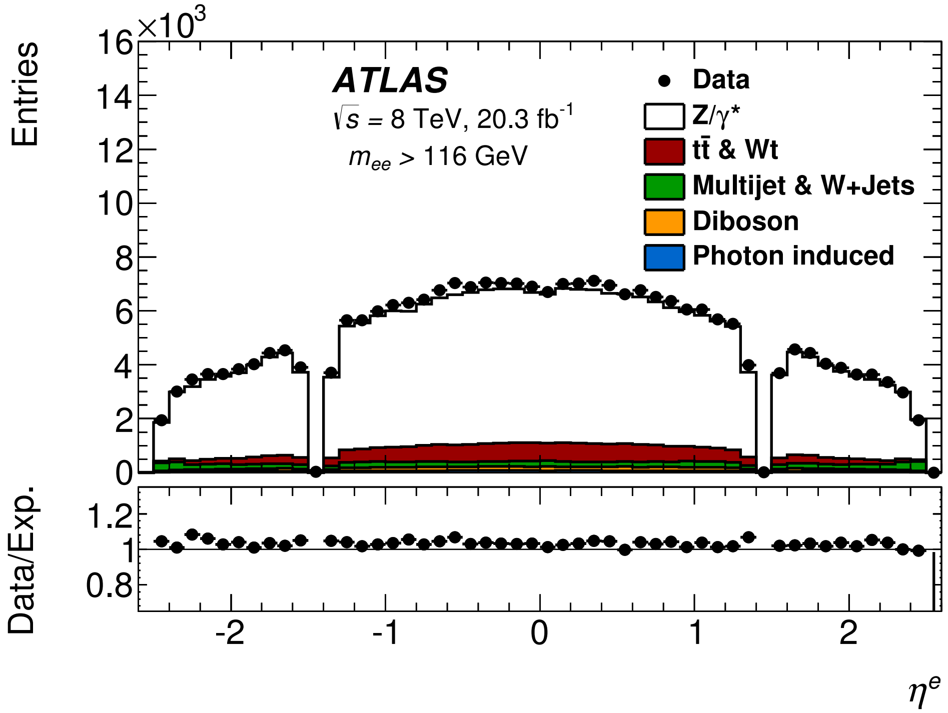
~4% contribution in electron channel

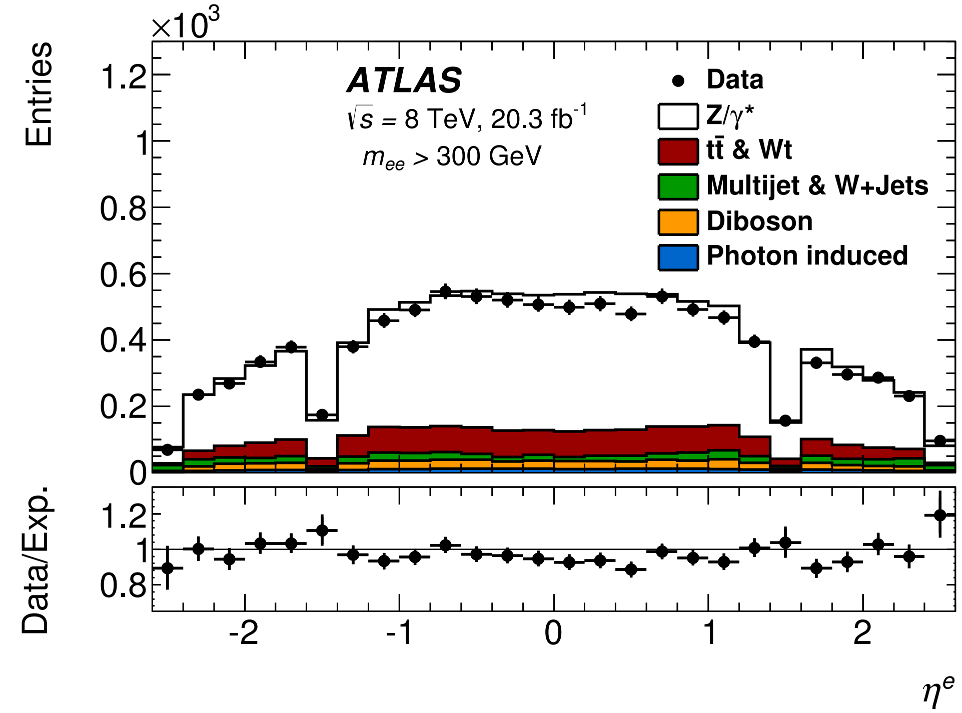
Electron Channel Control Plots

Simulation provides good description of electron data to better than 5%

m > 116 GeV | **m > 300 GeV**

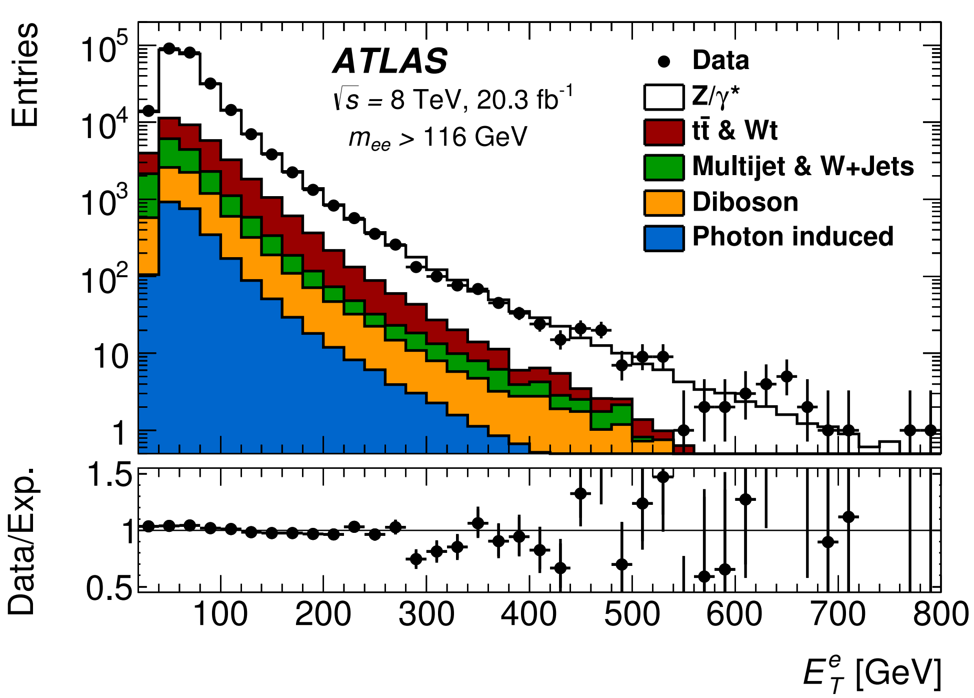
η_e

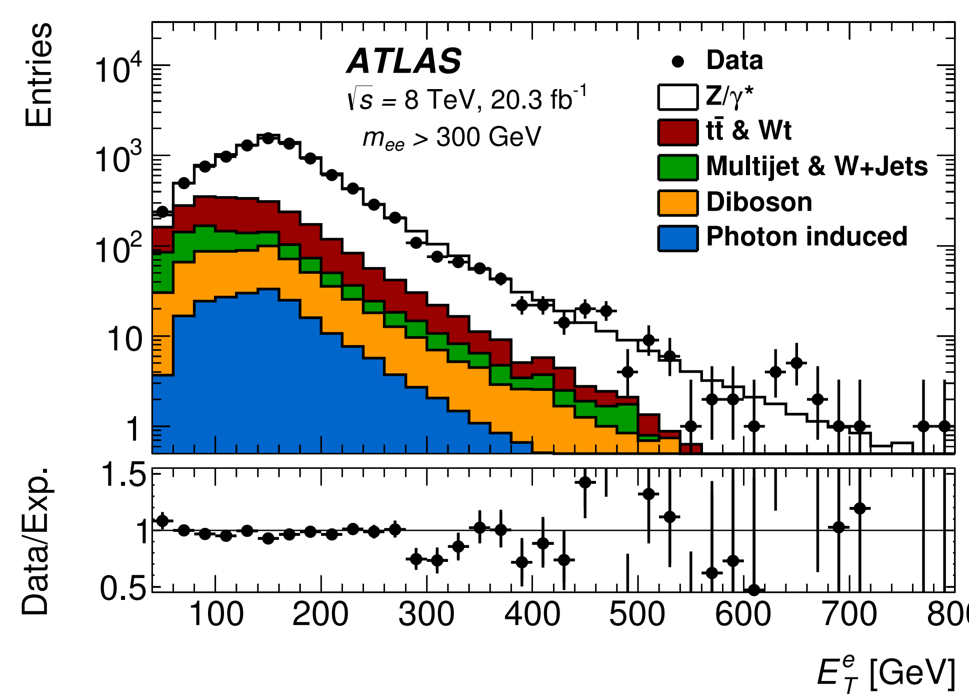




η_e

$p_{T,e}$





$p_{T,e}$

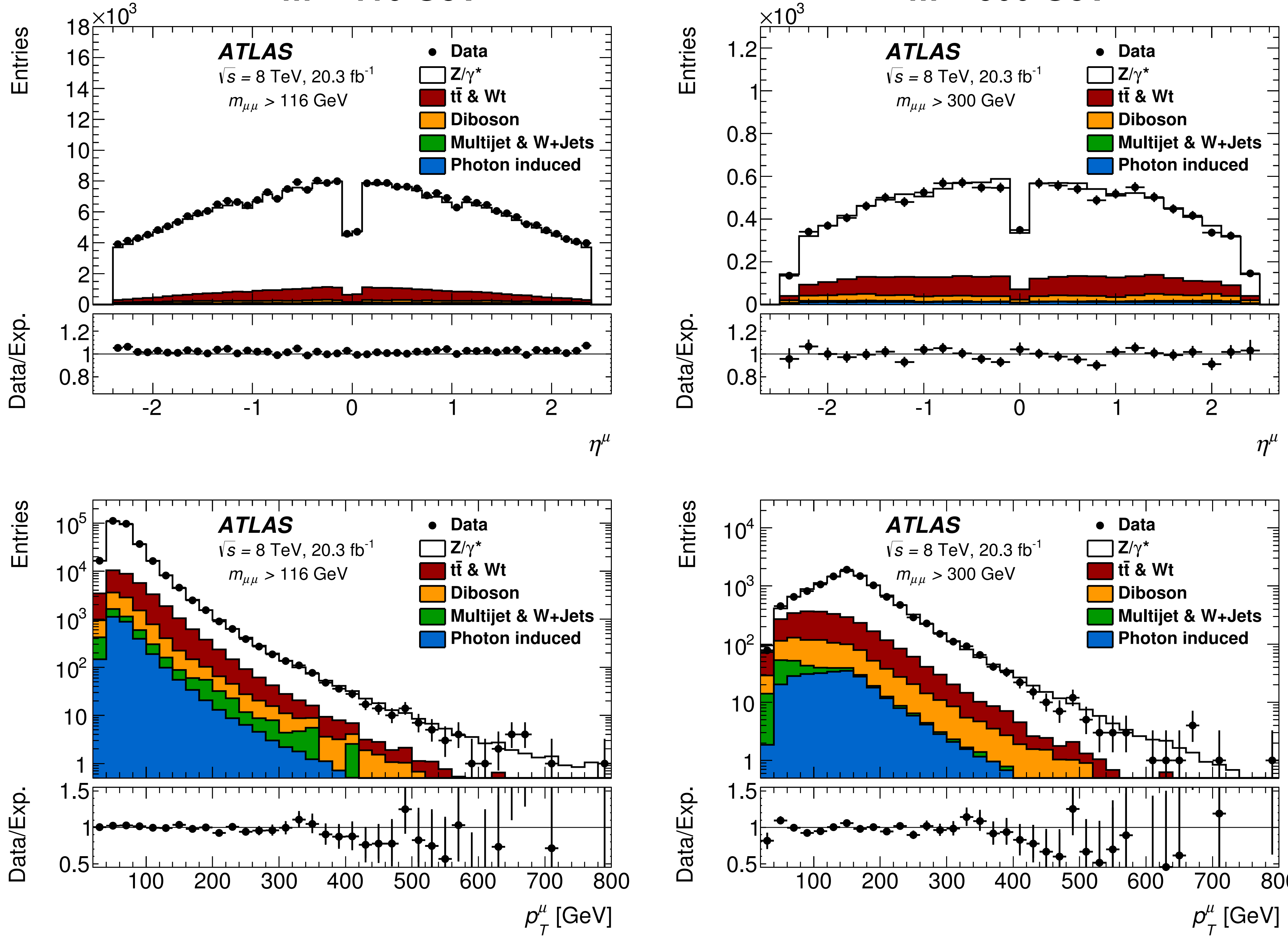
Muon Channel Control Plots

Simulation provides good description of muon data to better than 5%

m > 116 GeV | **m > 300 GeV**

η_μ

$p_{T,\mu}$



⇒ can use MC simulation to unfold for detector resolution to Born level kinematics

Electron & Muon Cross Sections and Combination

Cross Section

$$\frac{d^2\sigma}{dm_{\ell\ell}\, d|y_{\ell\ell}|} = \frac{N_{\rm data} - N_{\rm bkg}}{C_{\rm DY}\, \mathcal{L}_{\rm int}} \frac{1}{\Delta_{m_{\ell\ell}}\, 2\Delta_{|y_{\ell\ell}|}}$$ ← bin widths

C_{DY} unfolds detector resolution effects (from DY+PI signal MC)
Bin purities typically ≥ 85% (and ≥ 75% everywhere)
C_{DY} includes small extrapolations to reach common fiducial phase space:

- muon: |η| < 2.4 → |η| < 2.5
- electron: |η| < 2.47 excl. 1.37 < |η| < 1.52 → |η| < 2.5
- electron: $|\Delta\eta_{ee}| < 3.5 \rightarrow |\Delta\eta_{ee}| < \infty$ (for dmd|y| cross section only)

Combination

Combine electron & muon channel measurements in averaging procedure
Minimise difference between measurements
Taking correlated uncertainties into account

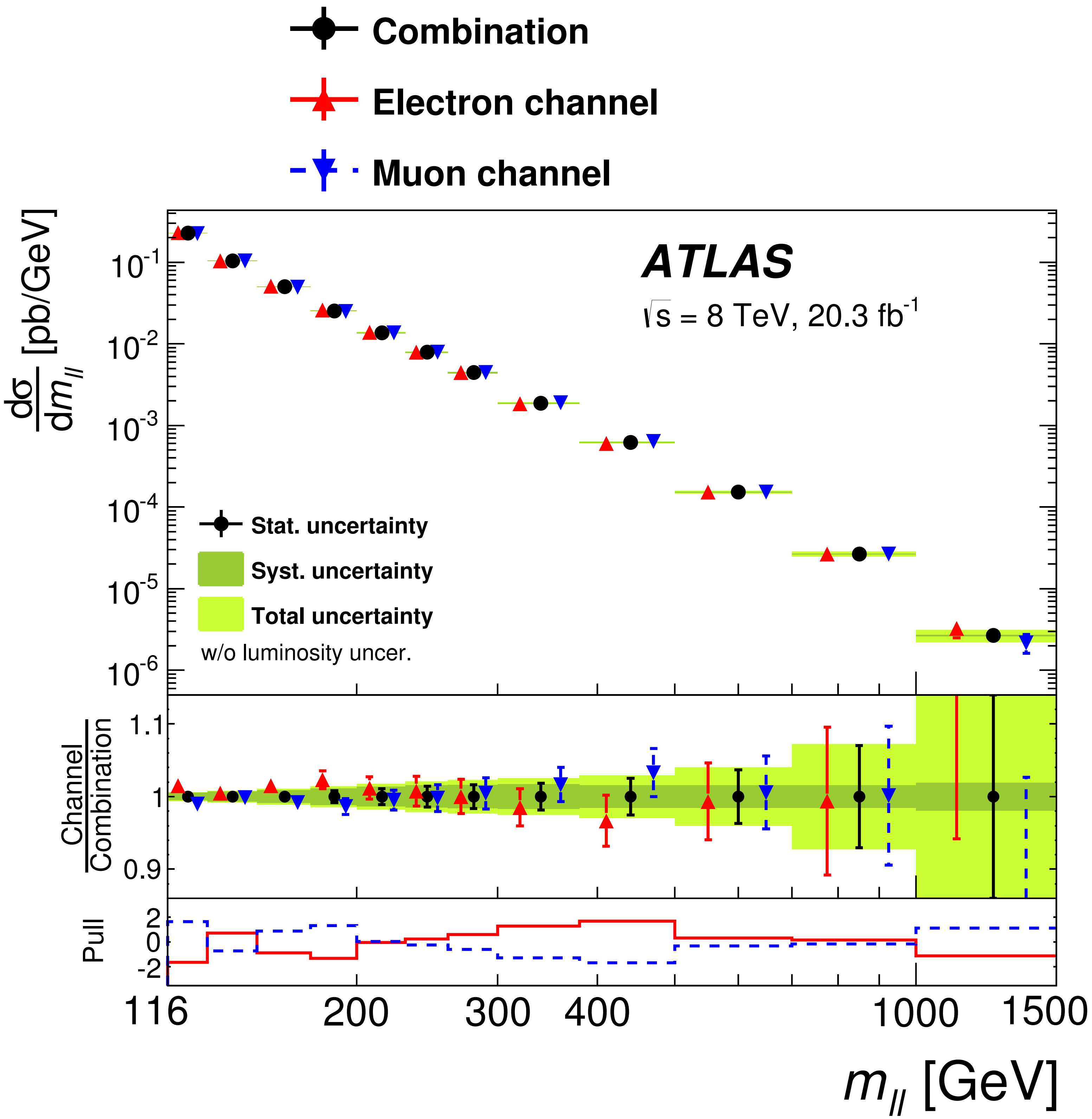
i data points
j systematic error sources

$$\chi^2_{tot}(\mathbf{m},\mathbf{b}) = \sum_i \frac{[\mu^i - m^i(1-\sum_j \gamma^i_j b_j)]^2}{\delta^2_{i,stat}\mu^i m^i(1-\sum_j \gamma^i_j b_j) + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2$$

bin-to-bin correlated error sources j = 35 including
- lepton trigger, ID, isolation efficiencies
- lepton scale and resolution uncertainties
- background contributions
- etc.…

μ^i = measurement
m^i = averaged value
γ^i_j = correlated sys uncertainty on point i from error source j
b_j = systematic error source strength
nuisance parameter left free in fit but constrained
no extra degrees of freedom due to additional constraint

Combination of Electron & Muon Channels



Cross sections are measured with 1% precision at low m (each channel)

Measurement accuracy systematically limited for m < 400 GeV

Bin-to-bin correlated systematics can be further constrained by combining channels

For larger m combination reduces √N statistical error

Stat error dominates at large m reaching ~20%

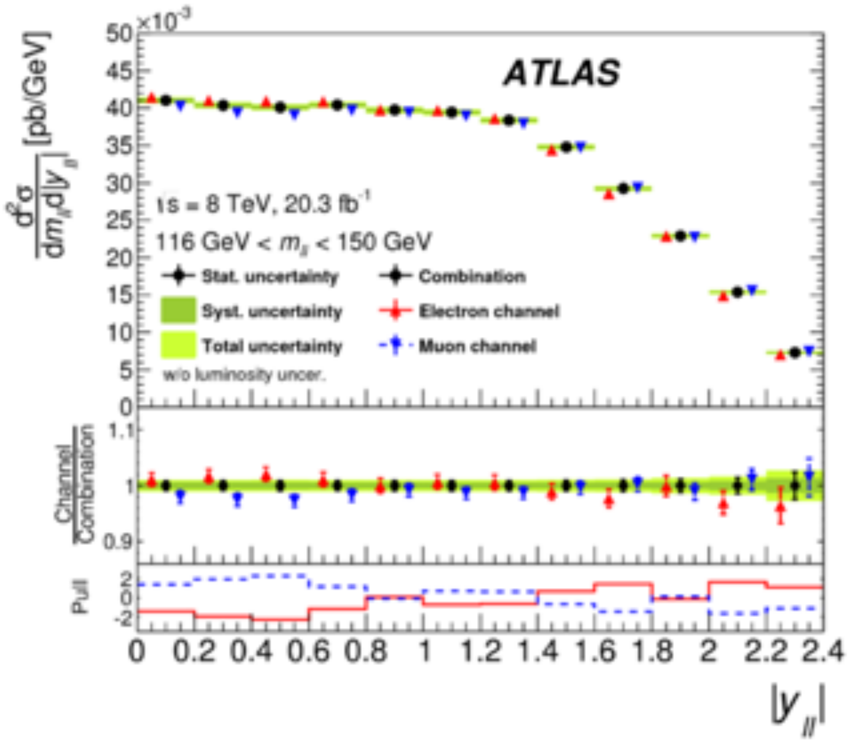
Excellent agreement between channels over full range

χ^2/ndf = 14.2 / 12 = 1.19

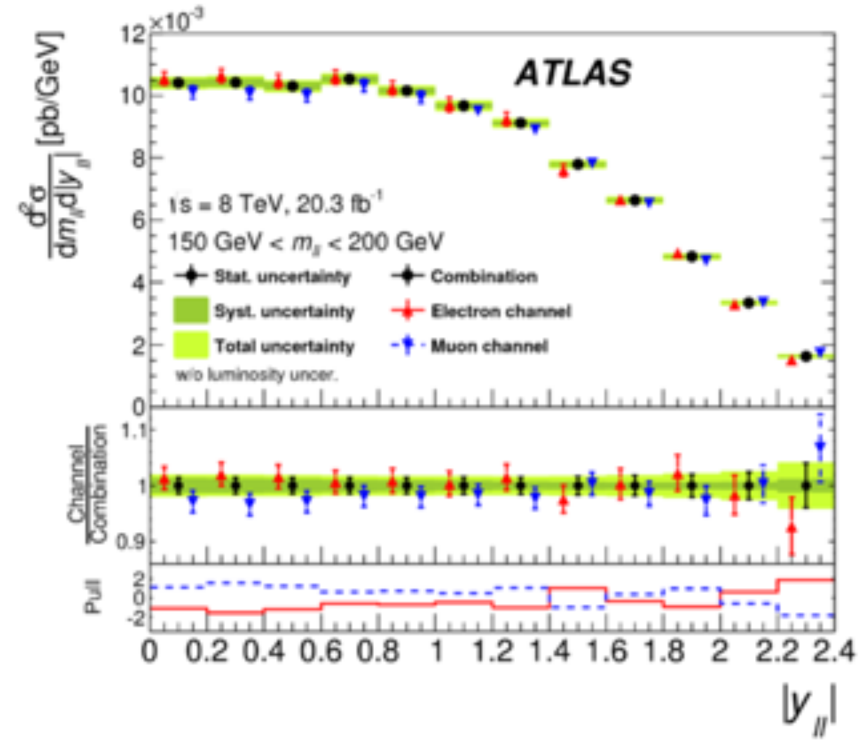
all nuisance parameters < 1 standard deviation

Combination of Electron & Muon Channels

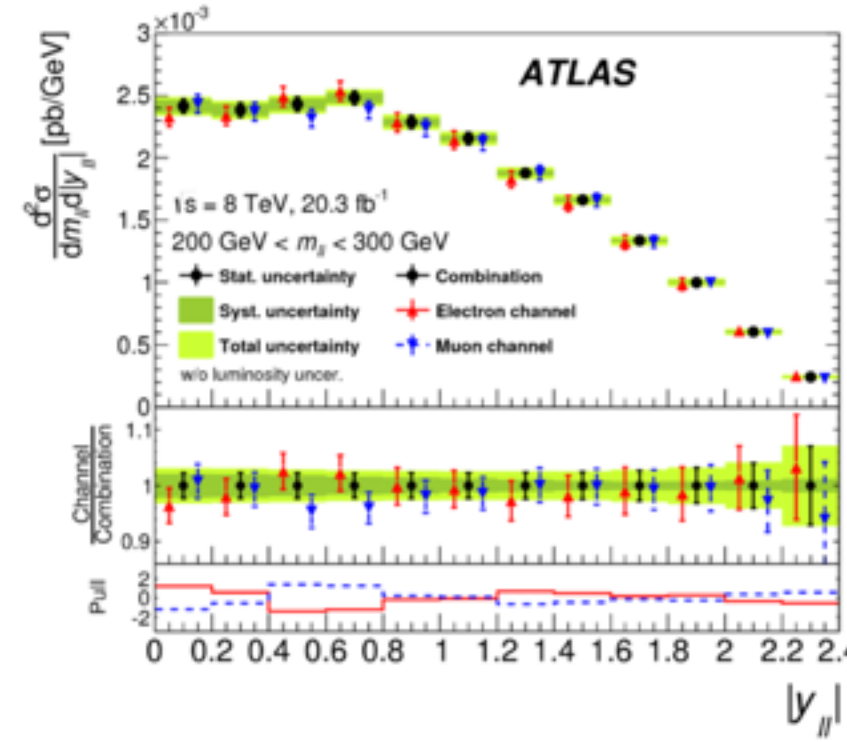
116 GeV < m < 150 GeV



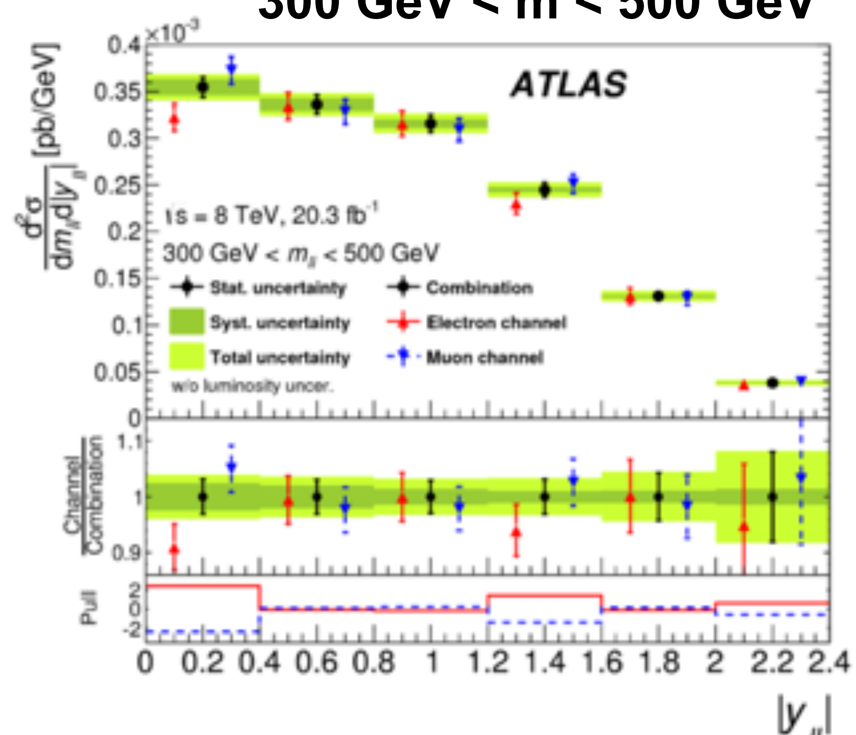
150 GeV < m < 200 GeV



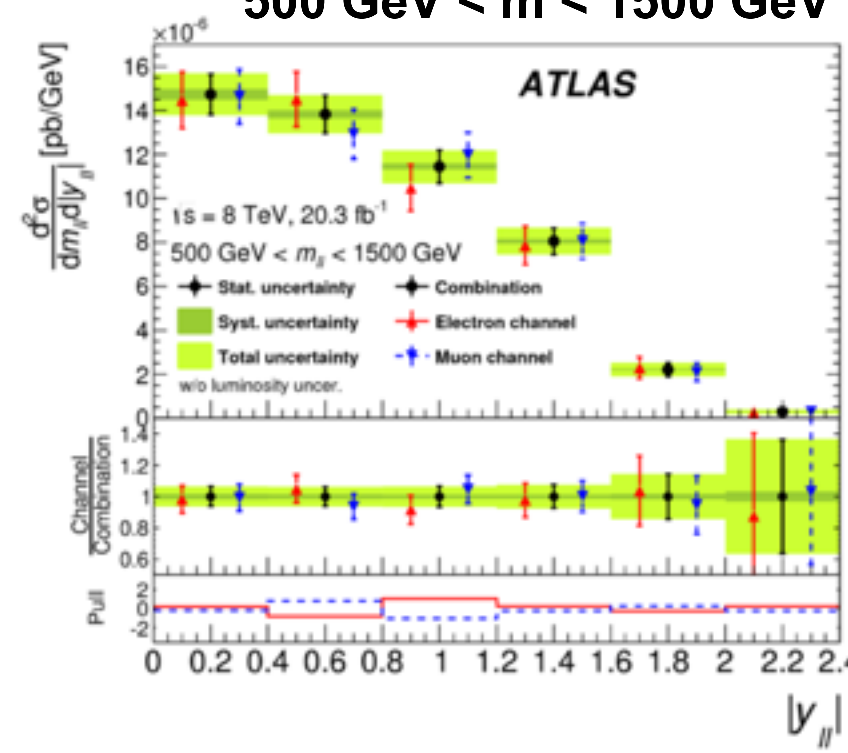
200 GeV < m < 300 GeV



300 GeV < m < 500 GeV



500 GeV < m < 1500 GeV

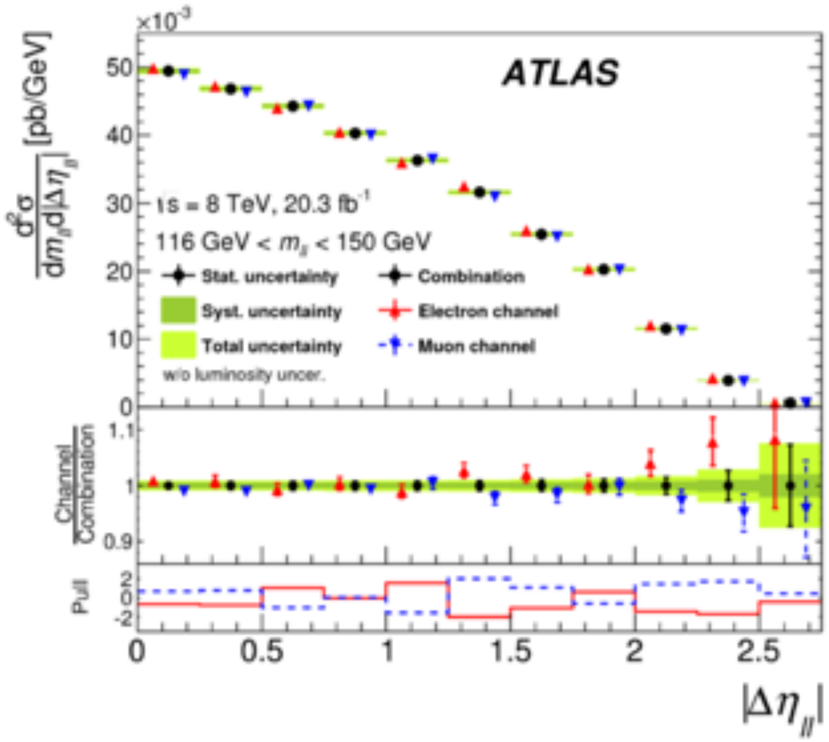


$$\frac{d^2\sigma}{dm_{ll}d|y_{ll}|}$$

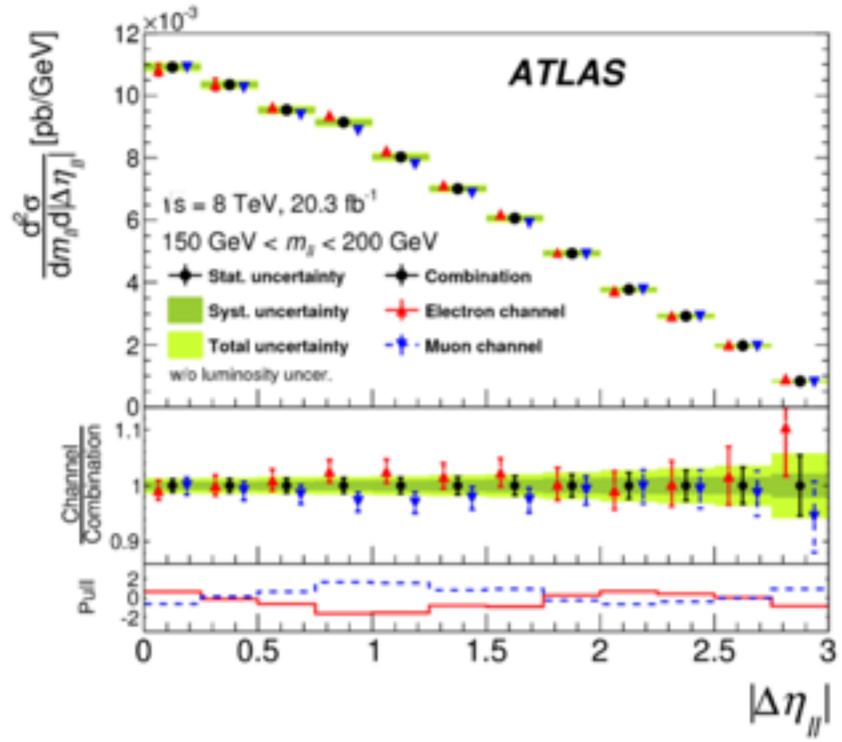
No large pulls between the measurement channels
combination χ^2/ndf = 53.1 / 48 = 1.11

Combination of Electron & Muon Channels

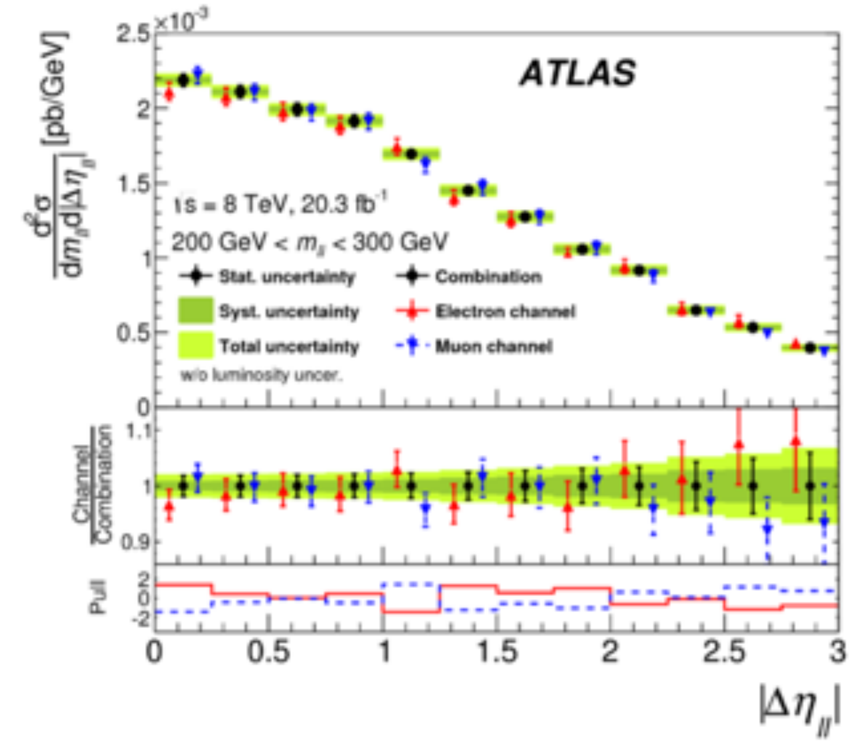
116 GeV < m < 150 GeV



150 GeV < m < 200 GeV

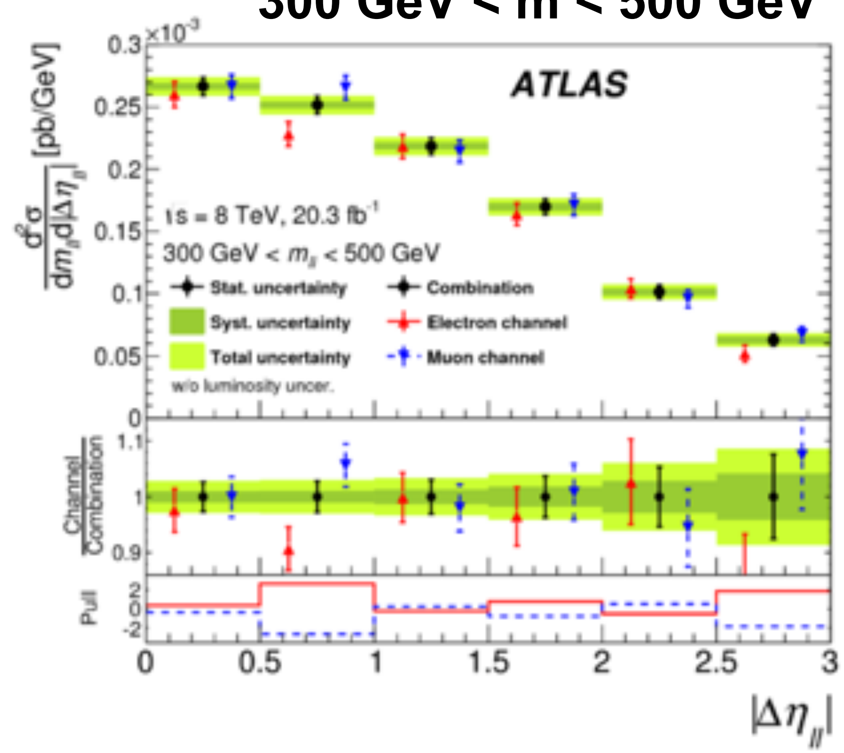


200 GeV < m < 300 GeV

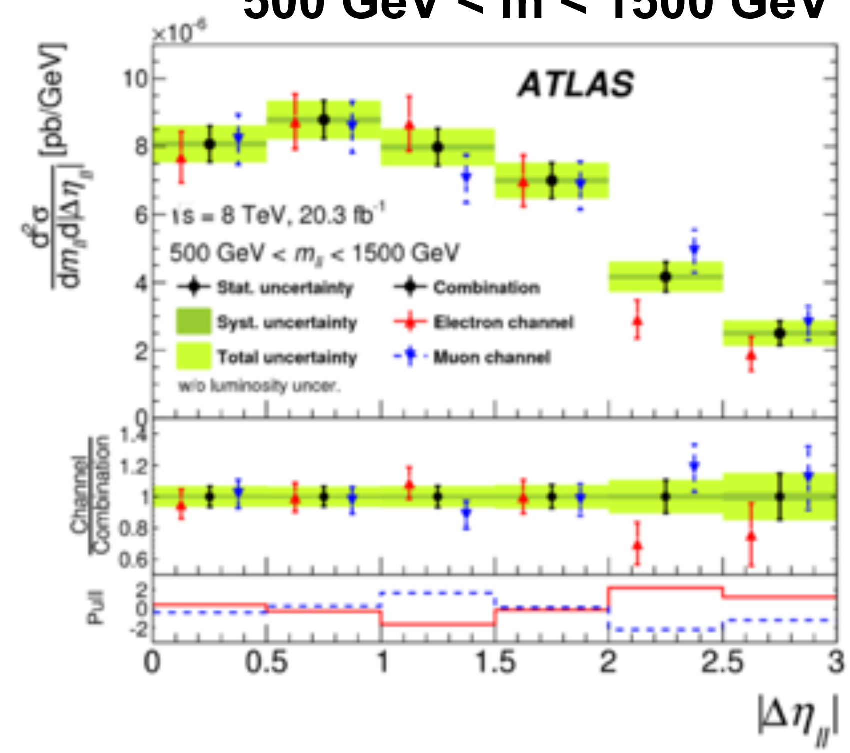


$$\frac{d^2\sigma}{dm_{ll}d|\Delta\eta_{ll}|}$$

300 GeV < m < 500 GeV

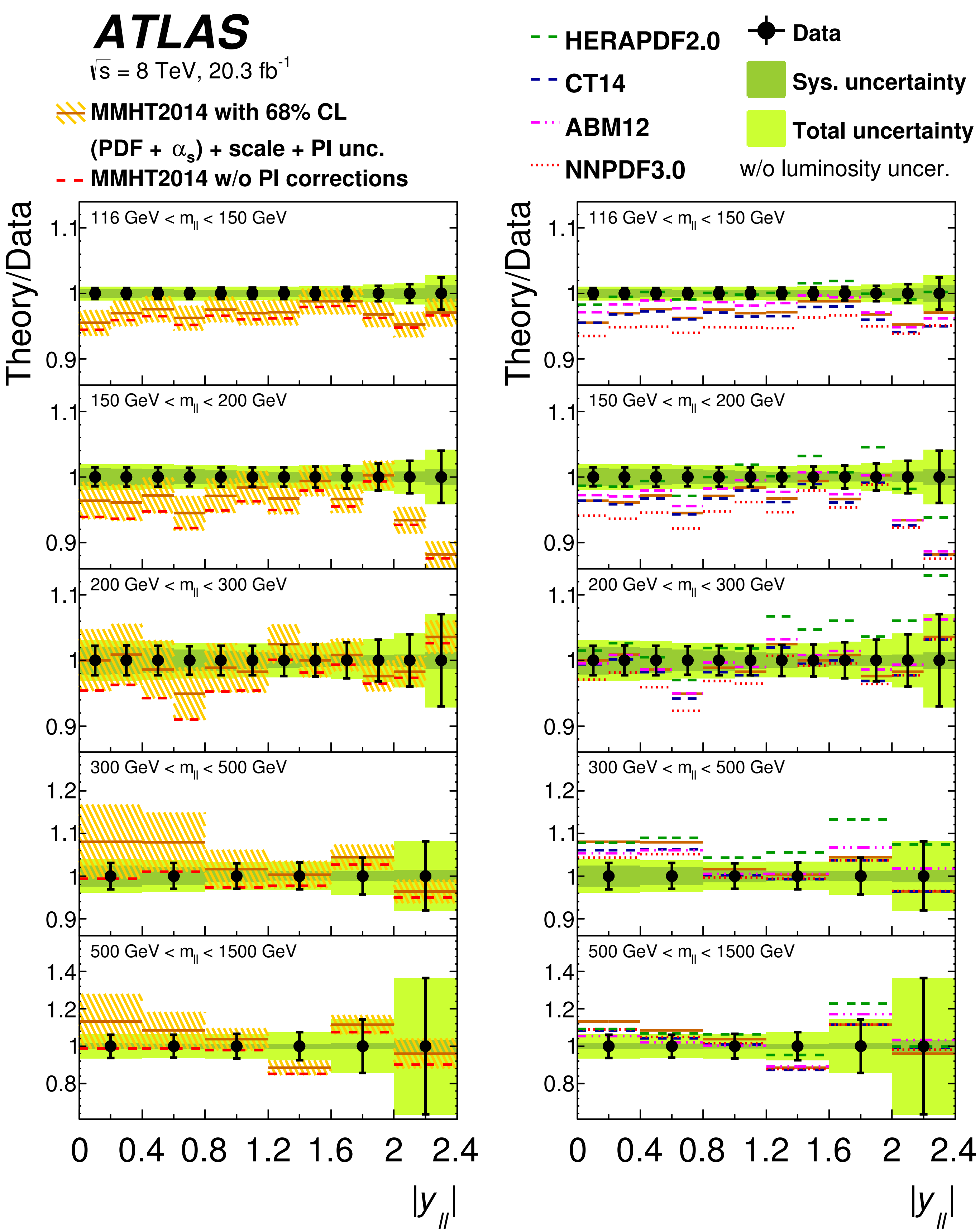


500 GeV < m < 1500 GeV



combination χ^2/ndf = 59.3 / 47 = 1.26

Combined Differential Cross Sections



$$\frac{d^2\sigma}{dm_{ll}\,d|y_{ll}|}$$

data/theory ratio

PI contribution increases with m and decreasing $|y_{ll}|$

PDF uncertainties calc'd for each PDF scaled to 68% CL
- ABM uncertainty smaller than MMHT
- CT14 , NNPDF3.0 uncertainty larger than MMHT
- HERAPDF2.0 uncertainty much larger than MMHT

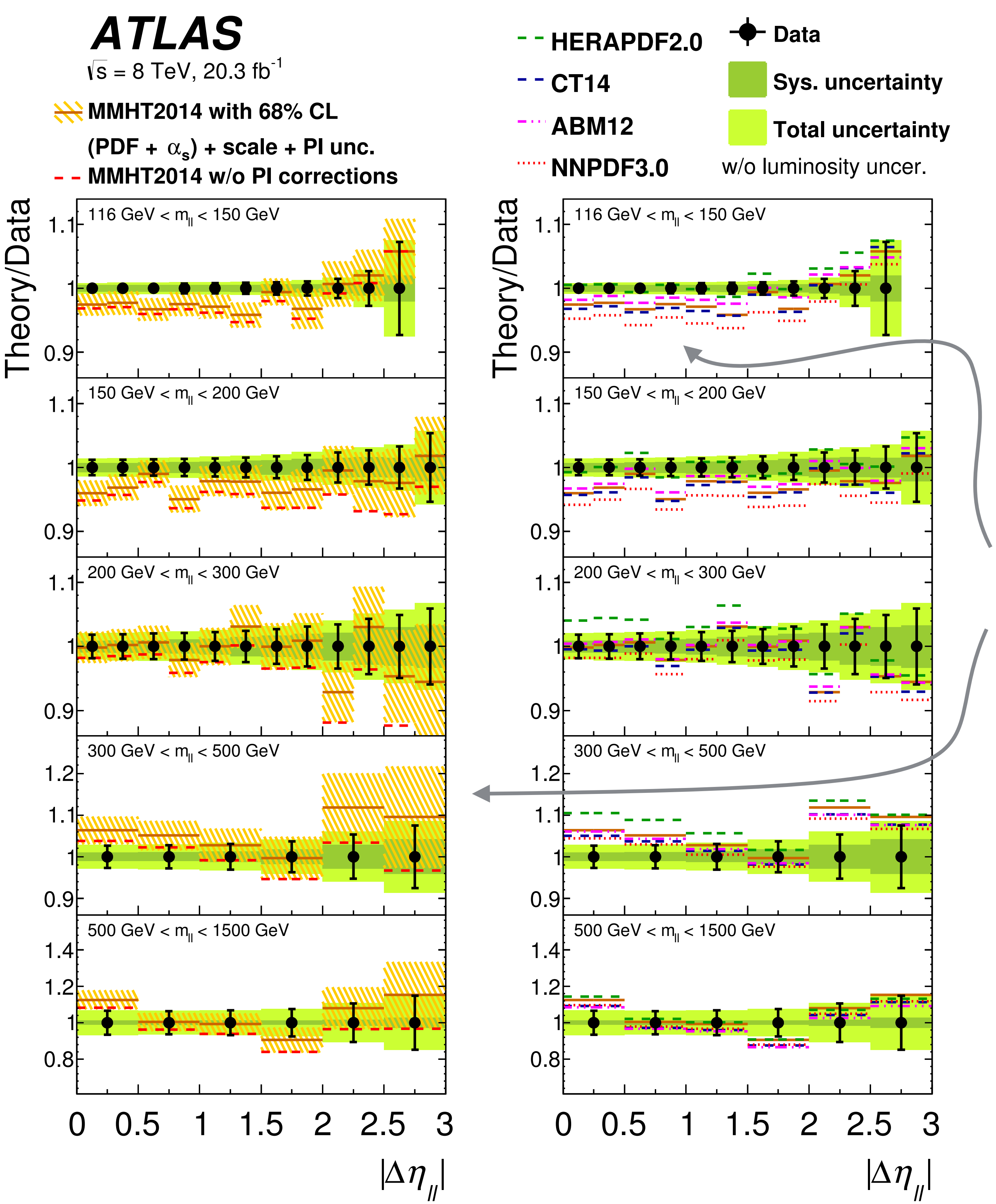
Compatibility of data to predictions with other PDFs tested with χ^2 function

	$m_{\ell\ell}$	$\lvert y_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$
MMHT2014	18.2/12	59.3/48	62.8/47
CT14	16.0/12	51.0/48	61.3/47
NNPDF3.0	20.0/12	57.6/48	62.1/47
HERAPDF2.0	15.1/12	55.5/48	60.8/47
ABM12	14.1/12	57.9/48	53.5/47

All data & theory correlated errors treated as nuisance parameters e.g. PDF eigenvectors (incl. for NNPDF)

Data in agreement with predictions:
- χ^2 probability at worst ~6%

$$\frac{d^2\sigma}{dm_{ll}d|\Delta\eta_{ll}|}$$ **data/theory ratio**



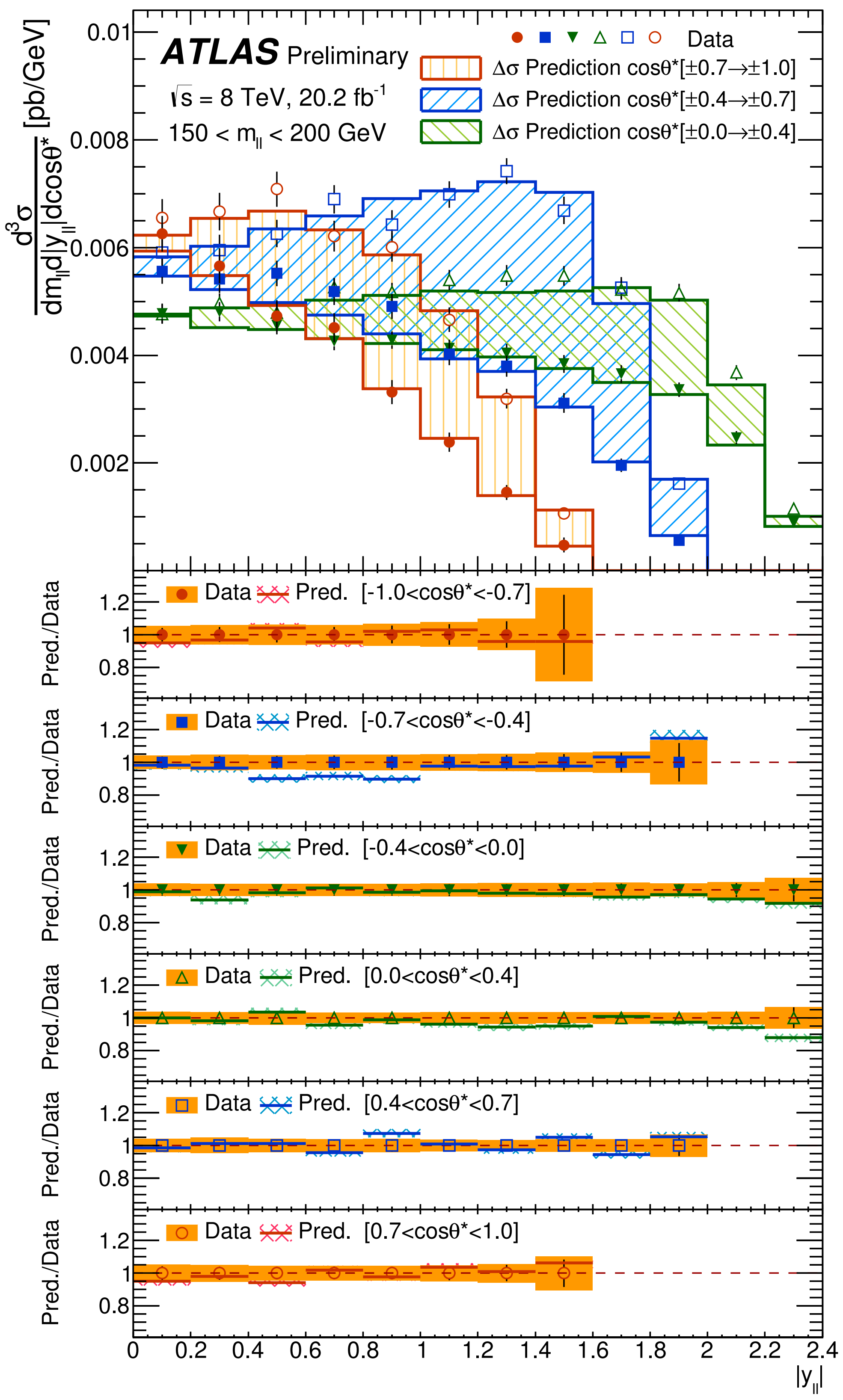
PI contribution increases with m and $|\Delta\eta_{ll}|$

Similar conclusions here:
At low m spread of PDFs is larger than data accuracy

PDF uncertainty is dominated by PI piece at large $|\Delta\eta_{ll}|$

Triple-differential Z/γ* Cross Sections √s = 8 TeV

150 < m < 200 GeV

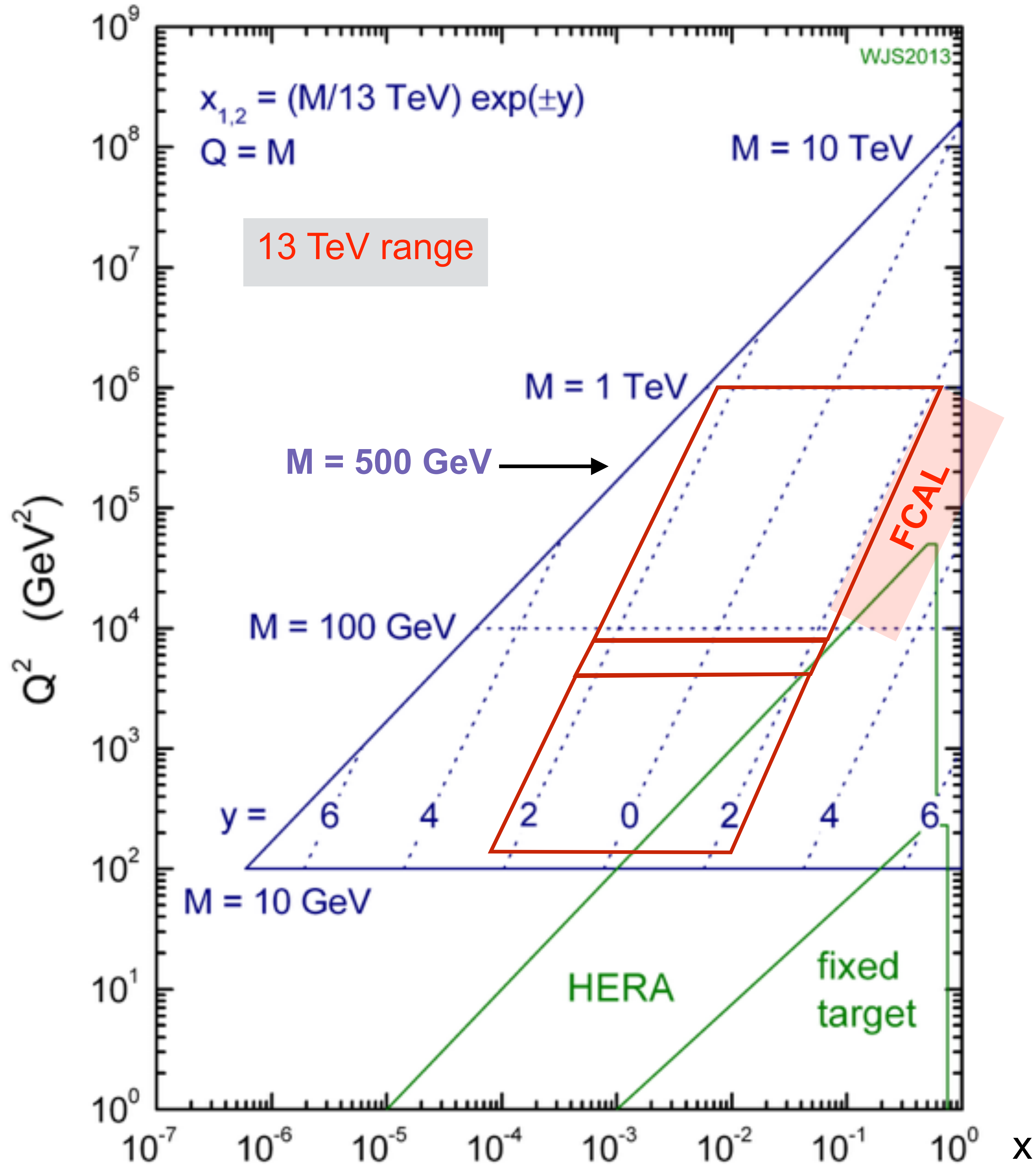


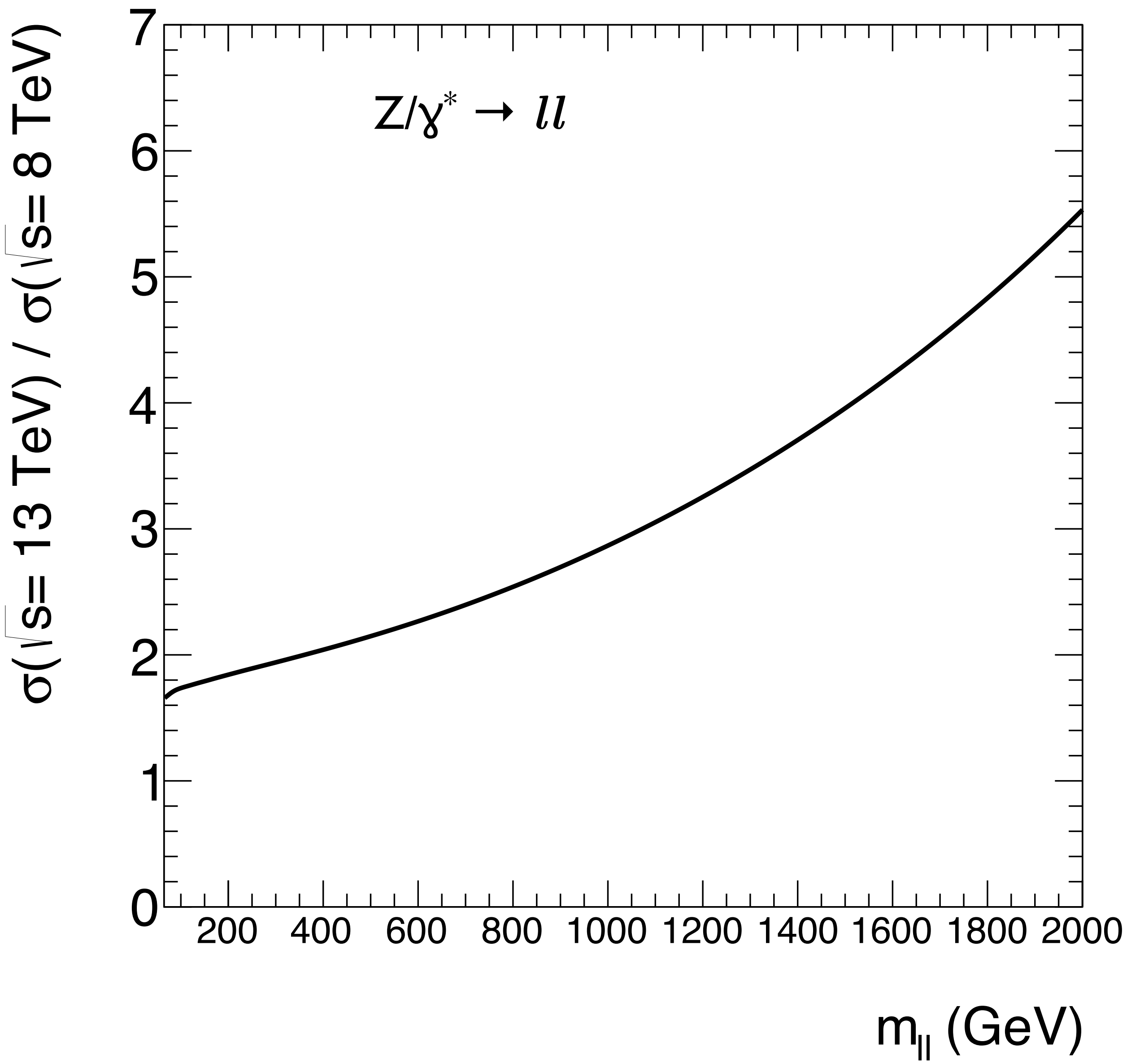
High Mass W/Z/γ^*

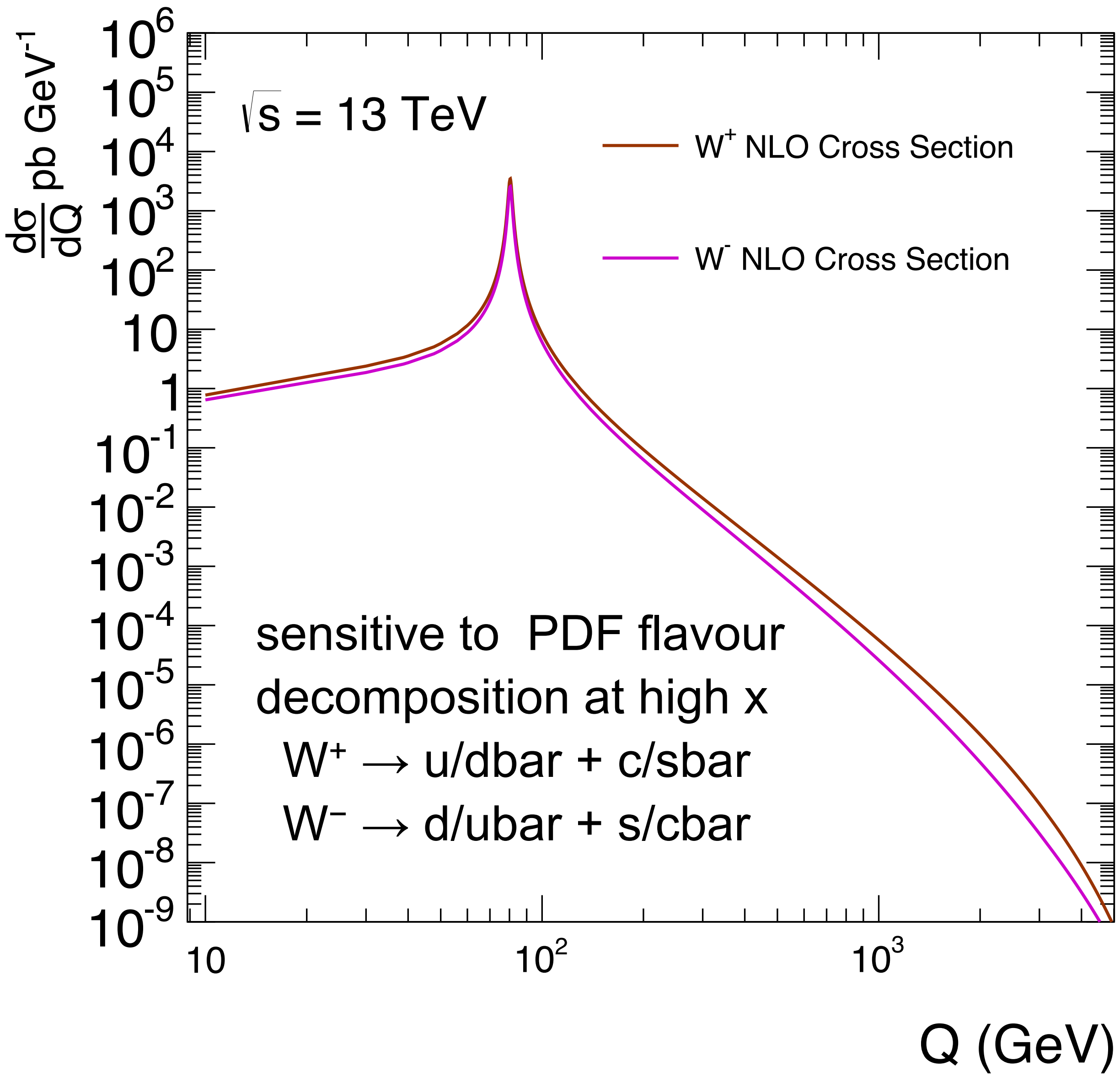
Classic problem: how to constrain PDFs at high x for BSM searches?

Measure cross sections at high rapidity

FCAL forward electrons → PDF sensitivity up to x=1 at m=500 GeV







Neutral current

Cross section enhancement > factor 5 at large m_{ll}

Similar for charged current

Charged current

First measurement off-shell high m_T $W^{\pm}$ production

Analogous to neutral current Z/γ^* measurement