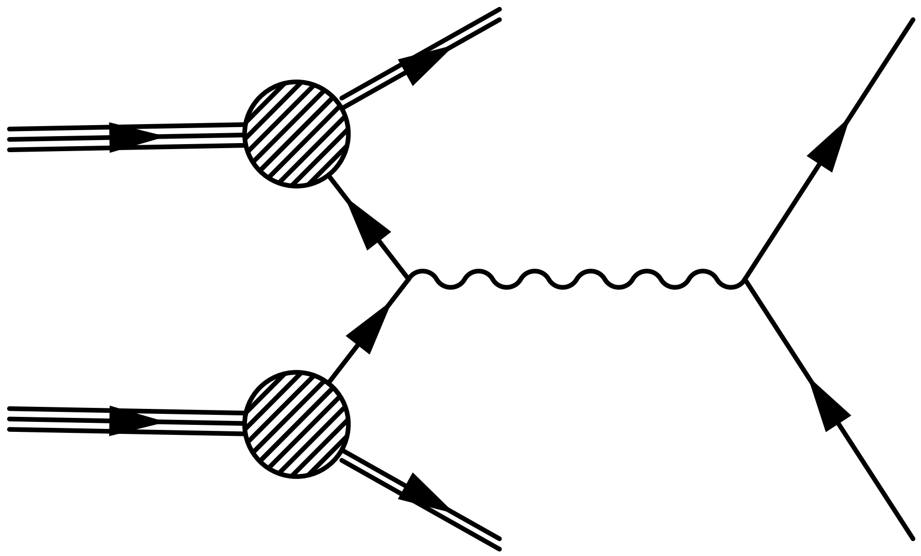
Precision EW Measurements from ATLAS
Extracting $\sin^2\theta_{eff}$



Introduction

Why measure $\sin^2\theta_{eff}$?

New triple-diffl Drell-Yan Cross Sections $d^3\sigma$

Systematic Uncertainties

Extraction of $\sin^2\theta_{eff}$

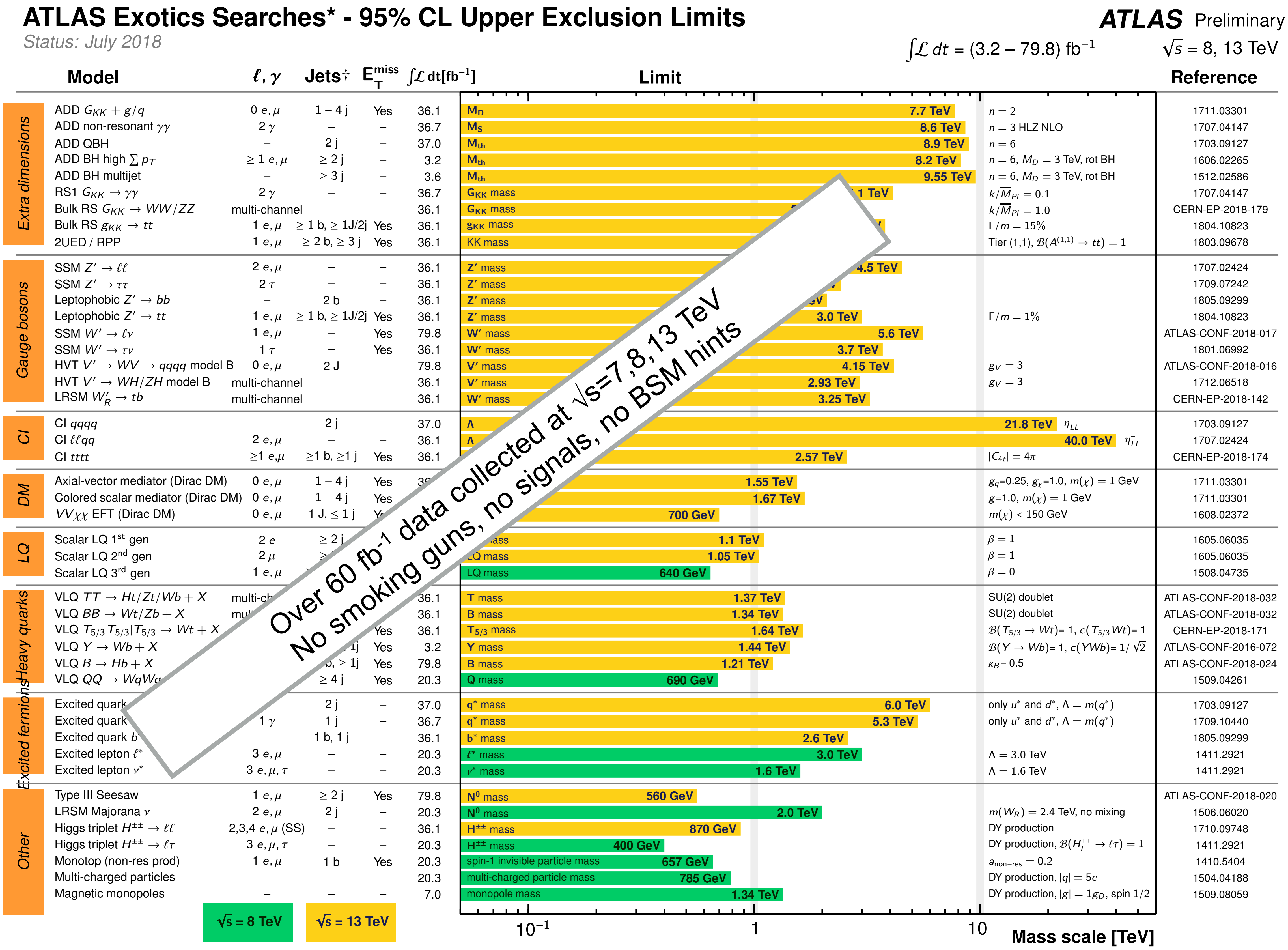
Measurement of the Drell-Yan triple differential cross section
in pp collisions at $\sqrt{s}$ = 8 TeV
http://dx.doi.org/10.1007/JHEP12(2017)059
arXiv:1710.05167

HepData tables:
https://www.hepdata.net/record/ins1630886

Eram Rizvi

UCL Seminar
26th October 2018

New Physics Searches



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass	[illegible]	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	[illegible]	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass	[illegible]	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass	[illegible]	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass	4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass	[illegible]		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass	[illegible]		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	79.8	🟨 W' mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	🟨 W' mass	3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	79.8	🟨 V' mass	4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	🟨 W' mass	3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η^-_{LL}	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ	40.0 TeV	η^-_{LL}	1707.02424
	CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 [illegible]	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	[illegible]	🟨 [illegible]	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	[illegible]	🟨 [illegible]	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	[illegible]	[illegible]	🟨 [illegible]	700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	[illegible]	[illegible]	🟨 [illegible]	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	[illegible]	[illegible]	[illegible]	🟨 LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	[illegible]	[illegible]	[illegible]	🟩 LQ mass	640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	[illegible]	[illegible]	[illegible]	36.1	🟨 T mass	1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	[illegible]	[illegible]	[illegible]	36.1	🟨 B mass	1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	[illegible]	[illegible]	Yes	36.1	🟨 $T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	[illegible]	[illegible]	Yes	3.2	🟨 Y mass	1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	[illegible]	[illegible]	Yes	79.8	🟨 B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	[illegible]	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark [illegible]	[illegible]	2 j	–	37.0	🟨 q^* mass	6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark [illegible]	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark b^*	–	1 b, 1 j	–	36.1	🟨 b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	🟨 N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	1710.09746
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass	657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass	1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

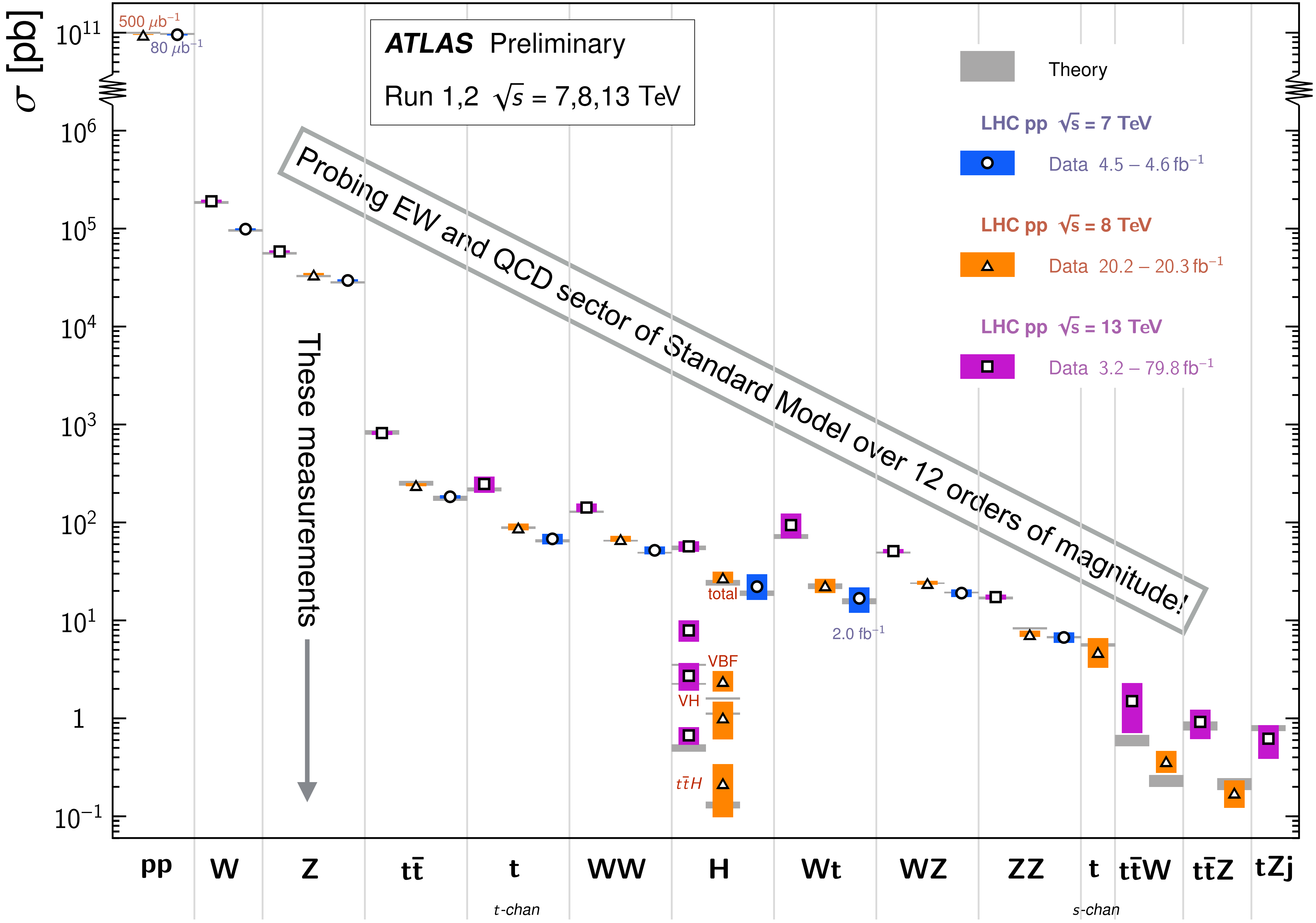
Over 60 fb^{-1} data collected at $\sqrt{s}$=7,8,13 TeV
No smoking guns, no signals, no BSM hints

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

The Standard Model

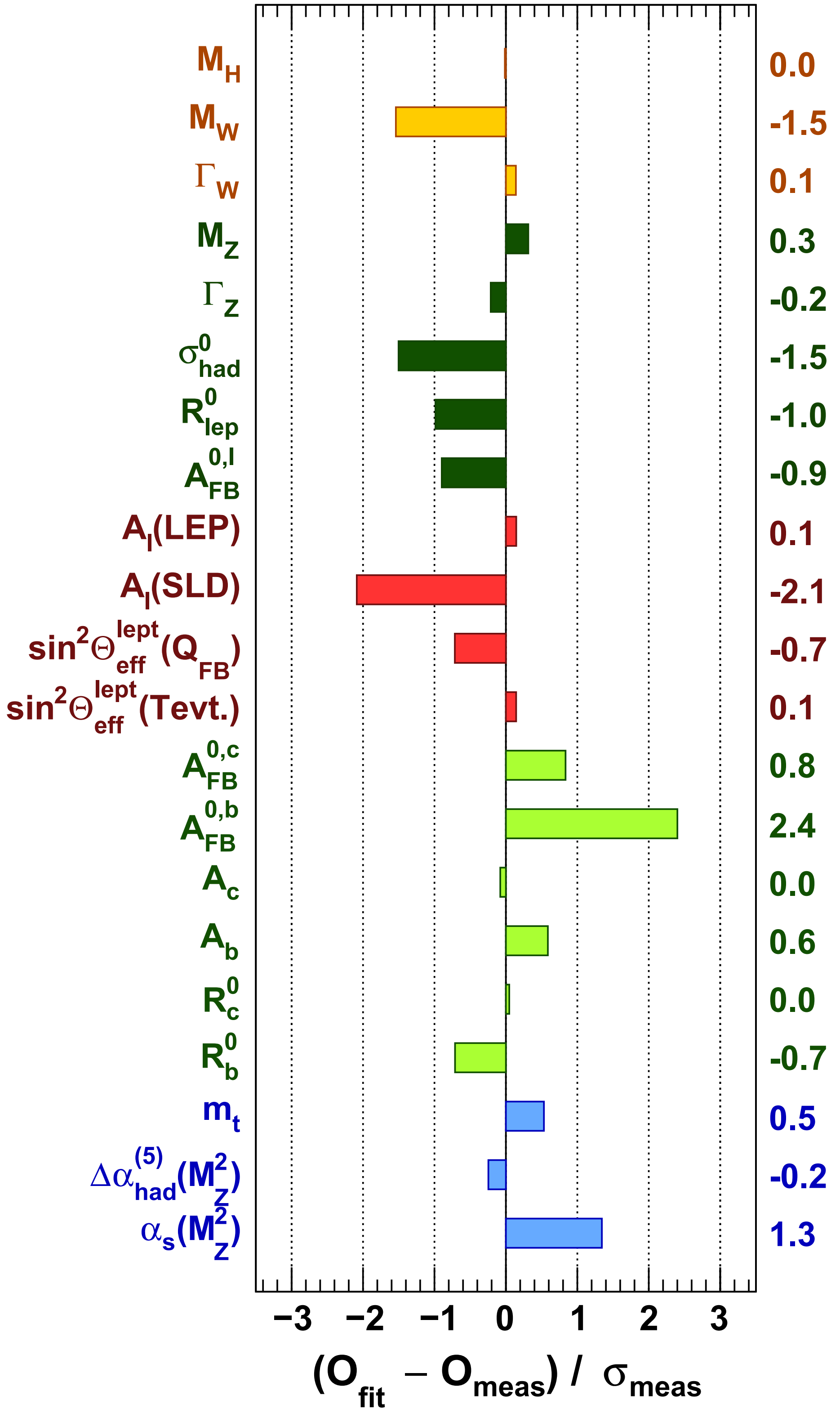
Standard Model Total Production Cross Section Measurements *Status: July 2018*



Electroweak Precision Observables - $\sin^2\theta_{eff}$

GFitter 2018

Global EW fit of all precision data



With known m_h EW sector of SM is over-constrained

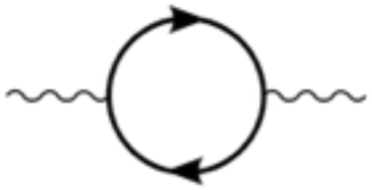
- m_Z = 91.1876 GeV
- $G_\mu = 1.16637 \times 10^{-5}$ GeV^{-2}
- $\alpha_{QED}(0) = 1/137.035$
- …. several others ….

$\sin^2\theta_W$ is a fundamental SM parameter of the SM
Specifies the mixing between EM and weak fields
Relates the Z and W couplings g_Z and g_W (and their masses)

At leading order $\sin^2\theta_W = 1 - \frac{g_W^2}{g_Z^2} = 1 - \frac{m_W^2}{m_Z^2}$

Higher order EW corrections modify this to an effective mixing angle dependent on fermion flavour ***f***

$$\sin^2\theta^f_{\rm eff} = (1 - \frac{m_W^2}{m_Z^2}) \cdot (1 + \Delta r)$$

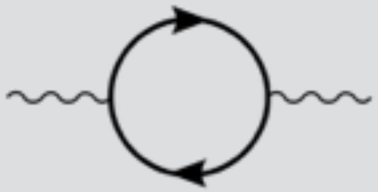


EW scheme dependent corrections incorporated into $\Delta r \rightarrow \Delta r(m_H, m_{top}, \ldots)$

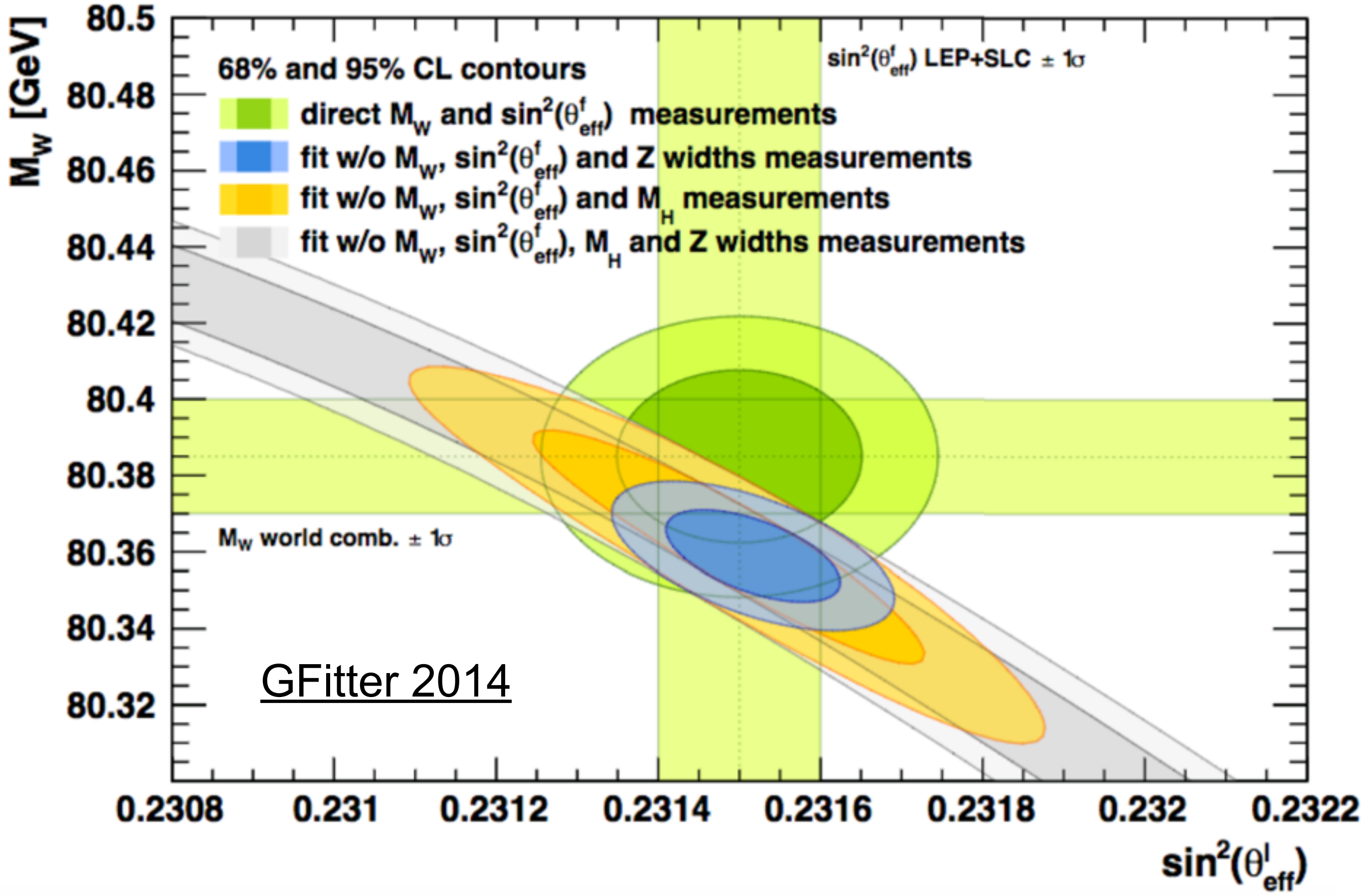
Electroweak Precision Observables - $\sin^2\theta_{eff}$

$$\sin^2\theta^f_{\rm eff} = (1 - \frac{m_W^2}{m_Z^2}) \cdot (1 + \Delta r)$$

EW scheme dependent corrections incorporated into $\Delta r \rightarrow \Delta r(m_H\,,\, m_{top}\,,\, \text{new physics})$



In context of EFT extension to SM EW oblique parameters S, T, U, Y, W incorporate new BSM dim-6 operators in self-energy terms



$\sin^2\theta_{eff}$ precision ± 50×10^{-5} equivalent to ± 25 MeV in m_W

Measurement of one observable can predict the other
$m_W \Leftrightarrow \sin^2\theta_W$

$$m_{\rm W}^2 = \frac{\pi\alpha(0)}{\sqrt{2}G_\mu \sin^2\theta_{\rm W}} \frac{1}{1-\Delta r}$$

m_W and $\sin^2\theta_{eff}$ allows self-consistency check of SM
New physics hidden in the higher order corrections ??
Valuable test in absence of direct BSM signals

Final Precision on $\sin^2\theta_{eff}$

LEP:	± 29×10^{-5}
SLD:	± 26×10^{-5}
CDF+D0:	± 35×10^{-5}

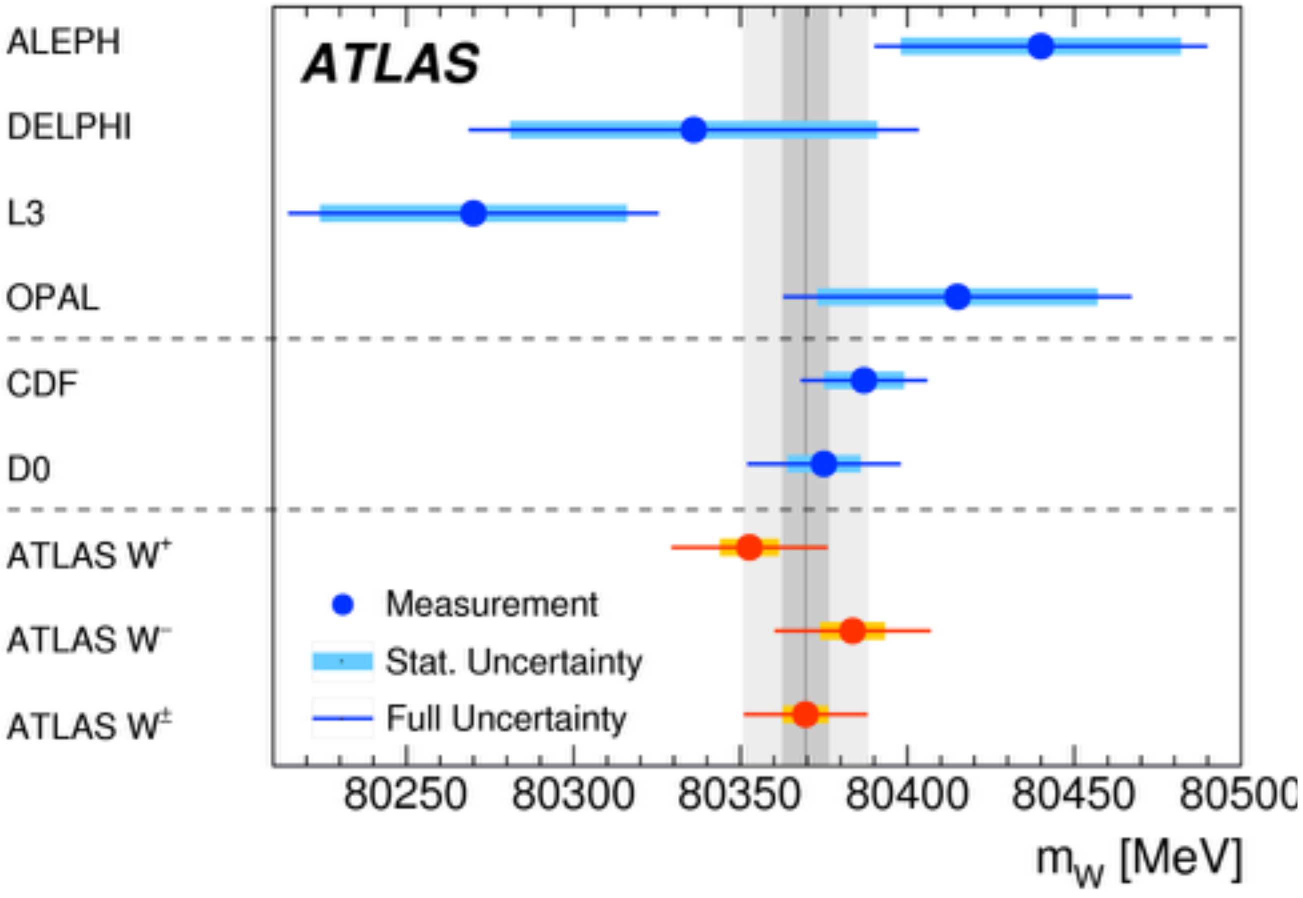
First LHC results on $\sin^2\theta_{eff}$

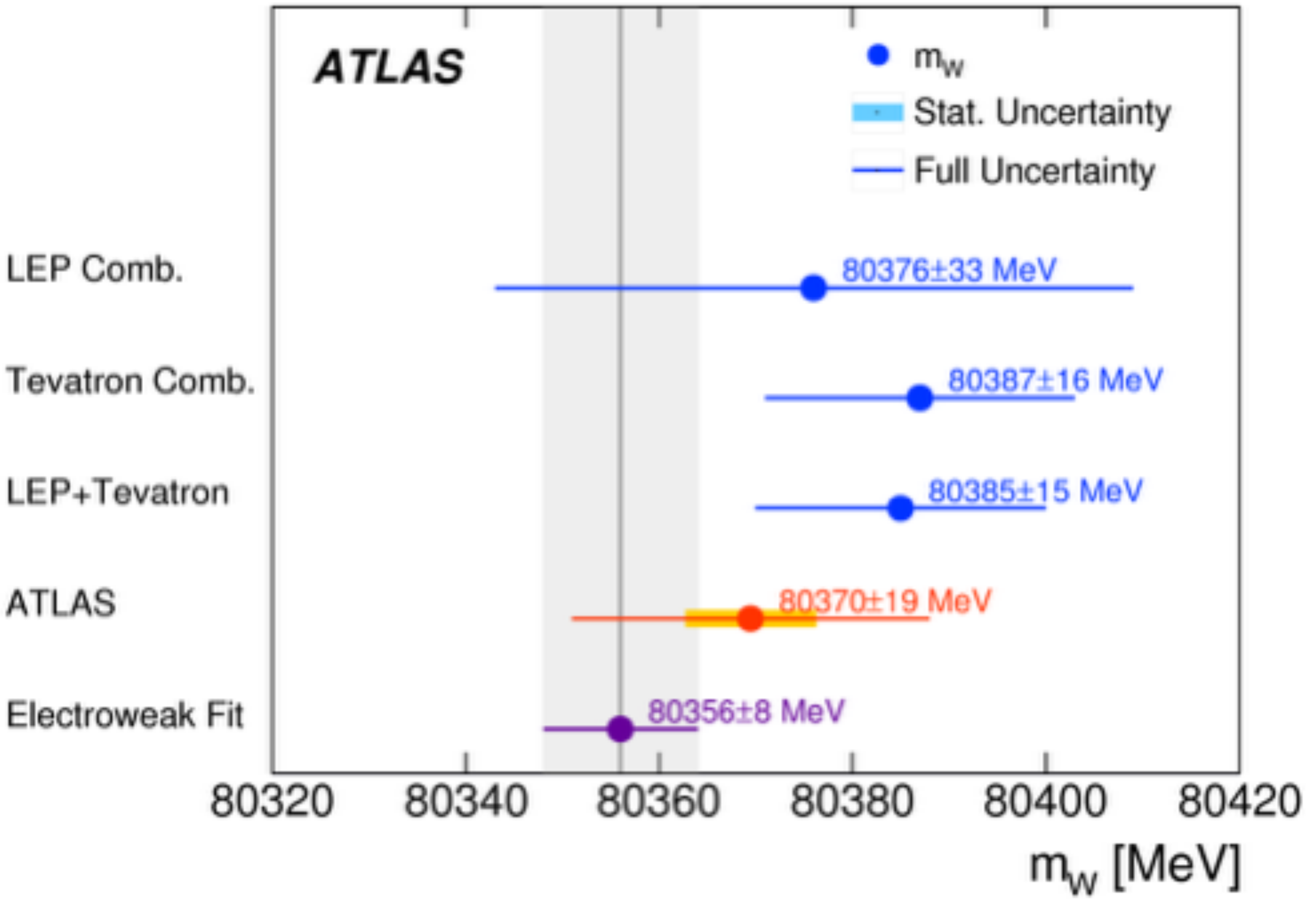
CMS(7TeV):	± 320×10^{-5}
ATLAS(7TeV):	± 120×10^{-5}

Electroweak Precision Observables - m_W

arXiv:1701.07240

New ATLAS measurement of m_W reaches ±19 MeV precision





ATLAS approaches precision of combined LEP + Tevatron measurement
Theory prediction from EW fit has uncertainty ±8 MeV

Electroweak Precision Observables - $\sin^2\theta_{eff}$

Physics Reports 427 (2006) 257–454

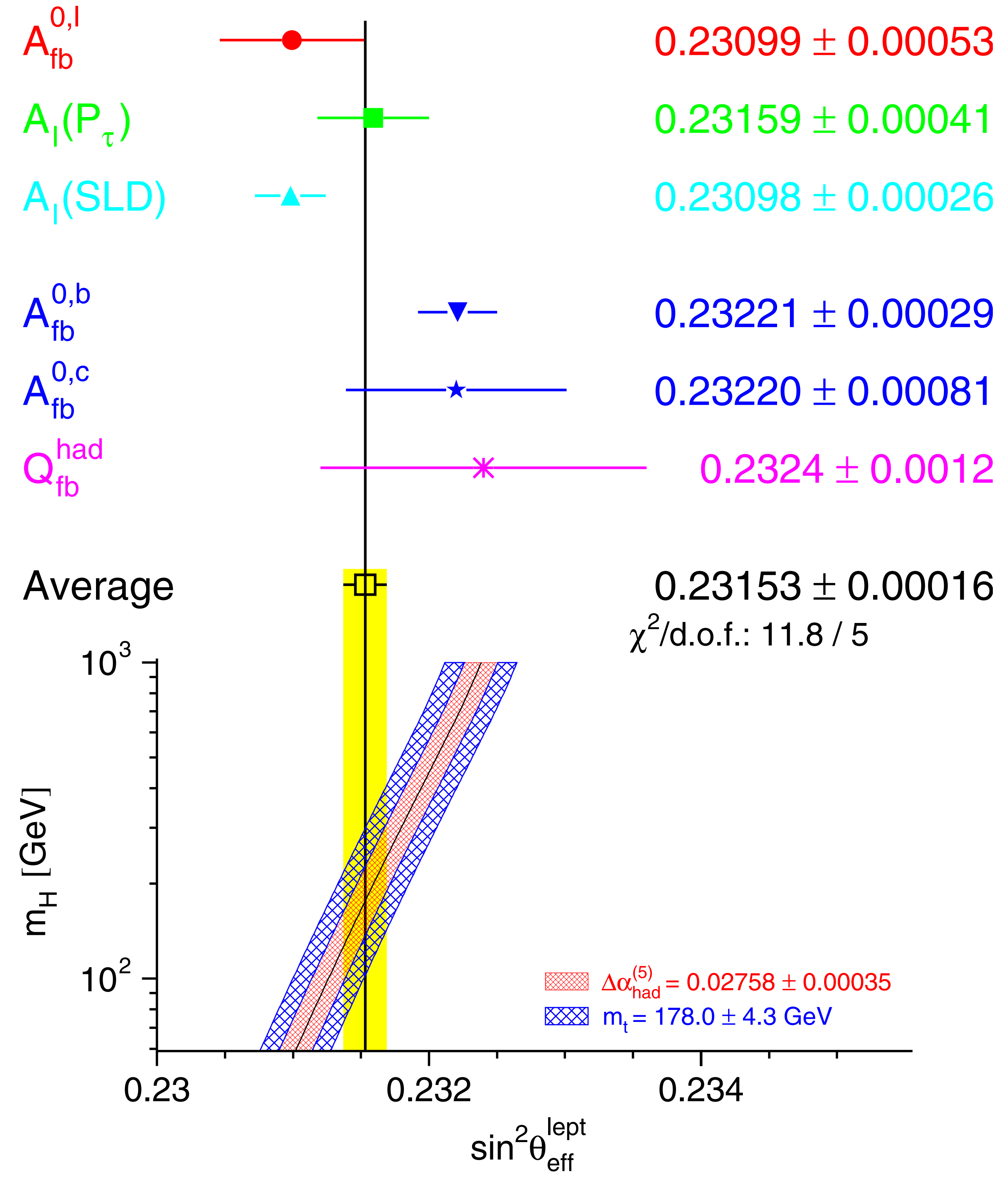
Previous generation of $\sin^2\theta_W$ measurements LEP/SLD

Several different observables and asymmetries used

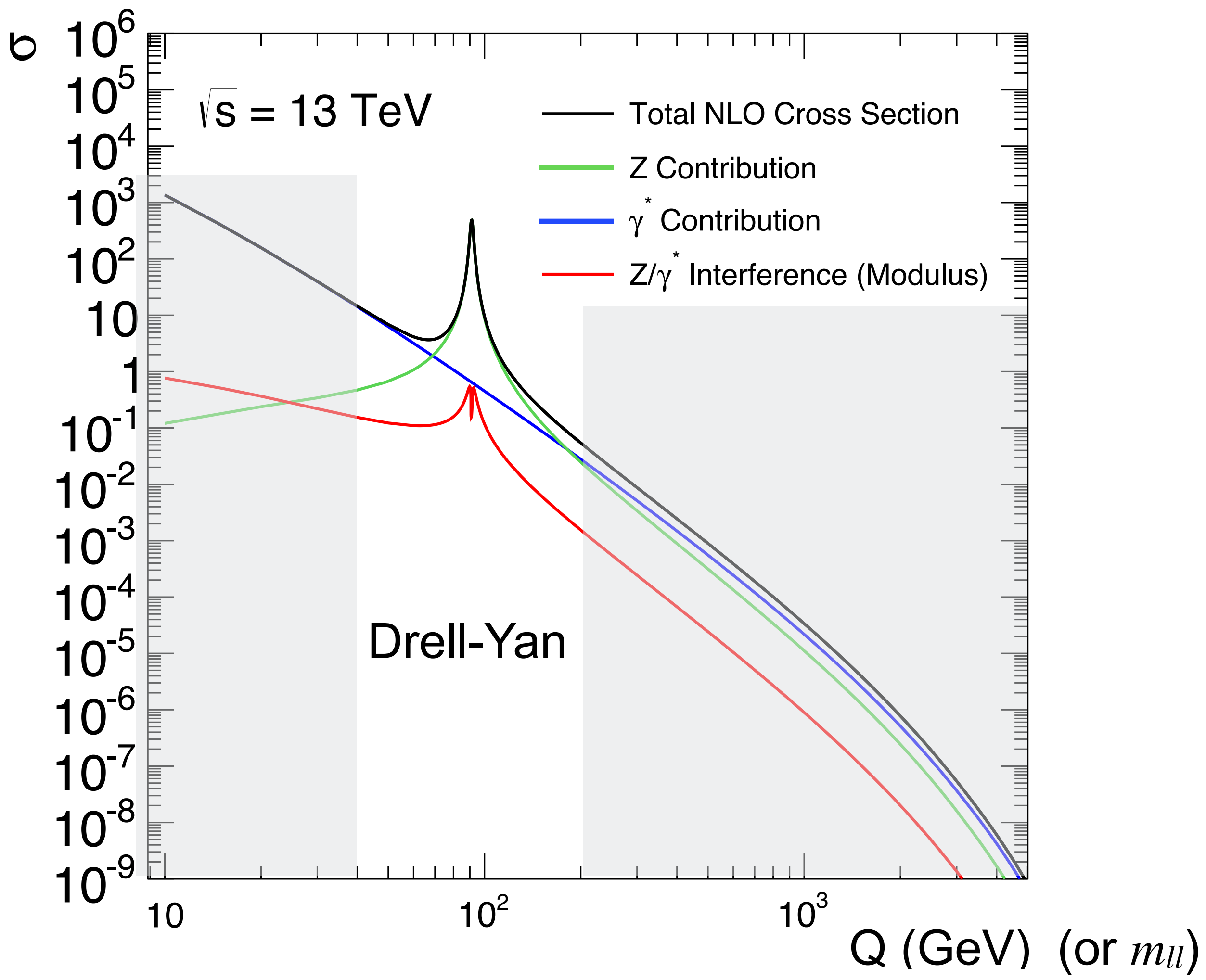
A_l = polarisation L/R asymmetry at SLD

$A_{FB}^{0,b}$ = forward/backward asymmetry in Z→bb

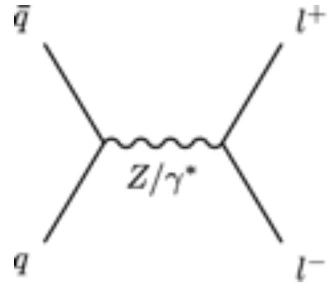
Long-standing 3.2σ discrepancy between LEP and SLD



Drell—Yan Measurement at ATLAS



Drell—Yan cross section
Large event rates and clean final-state
allow high experimental precision



Measure triple differential cross sections: $\dfrac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*}$

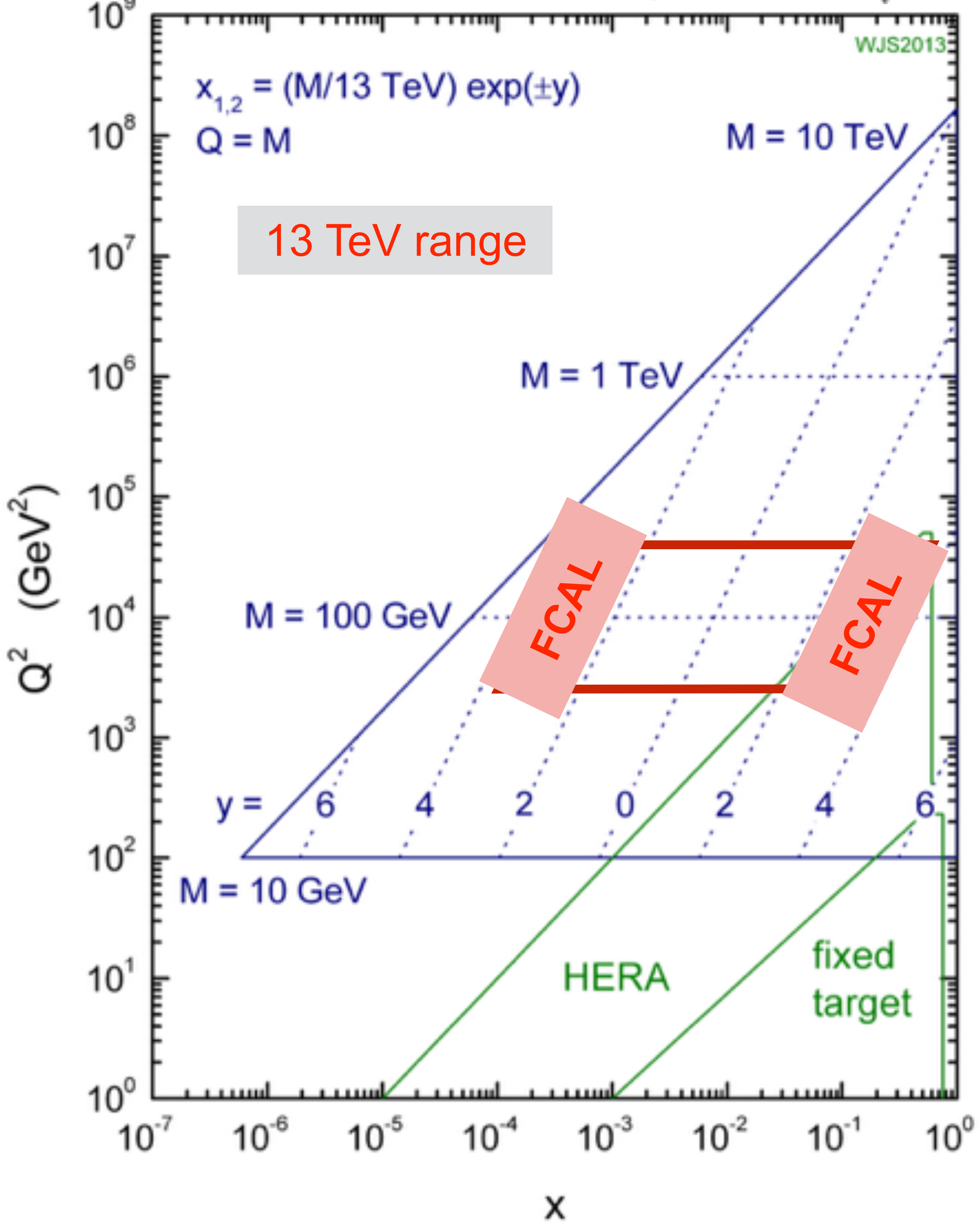
Can be integrated to derive $\dfrac{d\sigma}{dm_{\ell\ell}}$ $\dfrac{d^2\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|}$

Measurements access range of

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

$0 < |y| < 3.6$

$46 \leq m \leq 200$ GeV



Triple-differential Z/ɣ* Measurement Motivation

leptonic decay angle in Collins-Soper frame $\cos\theta^* = \frac{p_{\mathrm{Z},\ell\ell}}{m_{\ell\ell}|p_{\mathrm{Z},\ell\ell}|}\frac{p_1^+p_2^- - p_1^-p_2^+}{\sqrt{m_{\ell\ell}^2 + p_{\mathrm{T},\ell\ell}^2}}$ lepton and quark angle or anti-lepton / anti-quark angle

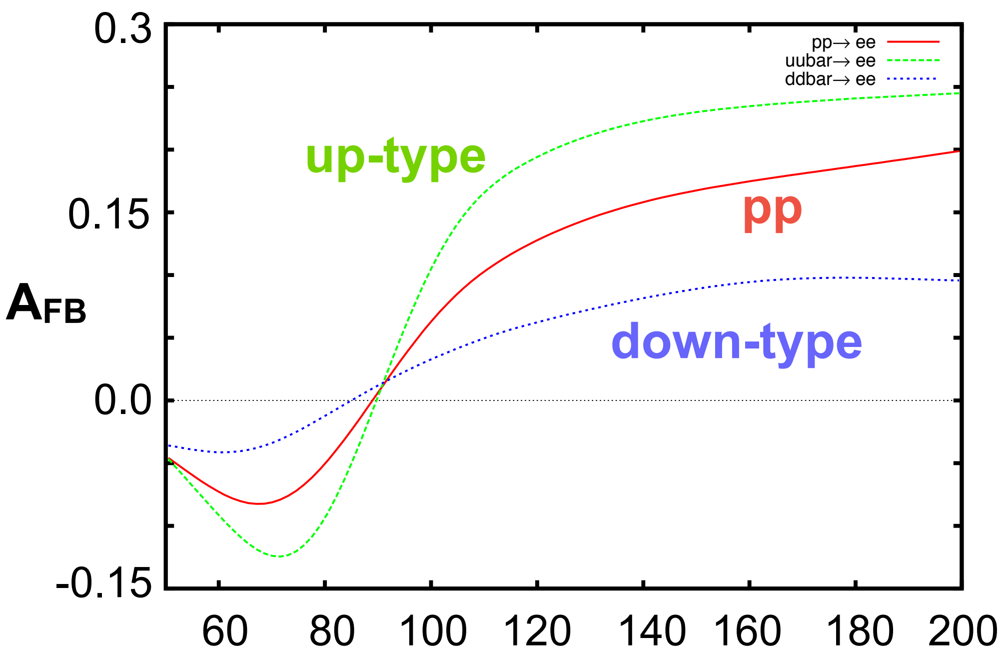
$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}y_{\ell\ell}\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q P_q\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q\leftrightarrow\bar{q})\right]$$

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

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

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

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



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

Asymmetry

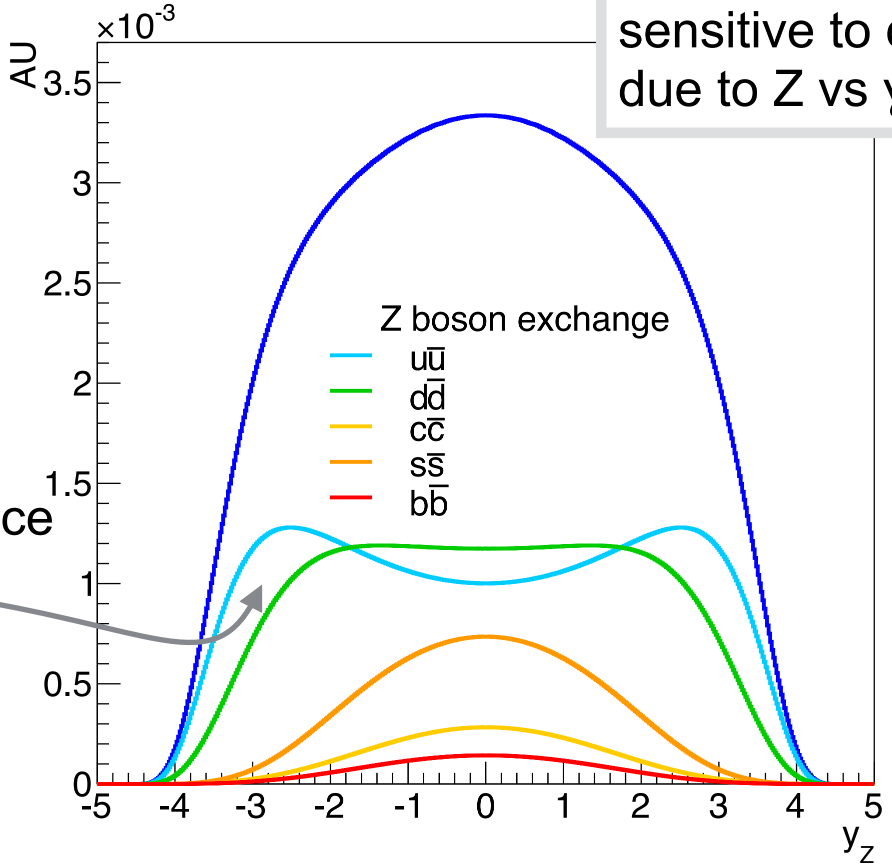
$$A_{\mathrm{FB}} = \frac{\mathrm{d}^3\sigma(\cos\theta^* > 0) - \mathrm{d}^3\sigma(\cos\theta^* < 0)}{\mathrm{d}^3\sigma(\cos\theta^* > 0) + \mathrm{d}^3\sigma(\cos\theta^* < 0)}$$

Sensitive to $\sin^2\theta_W$
Sensitive to PDFs $f(x,Q^2)$

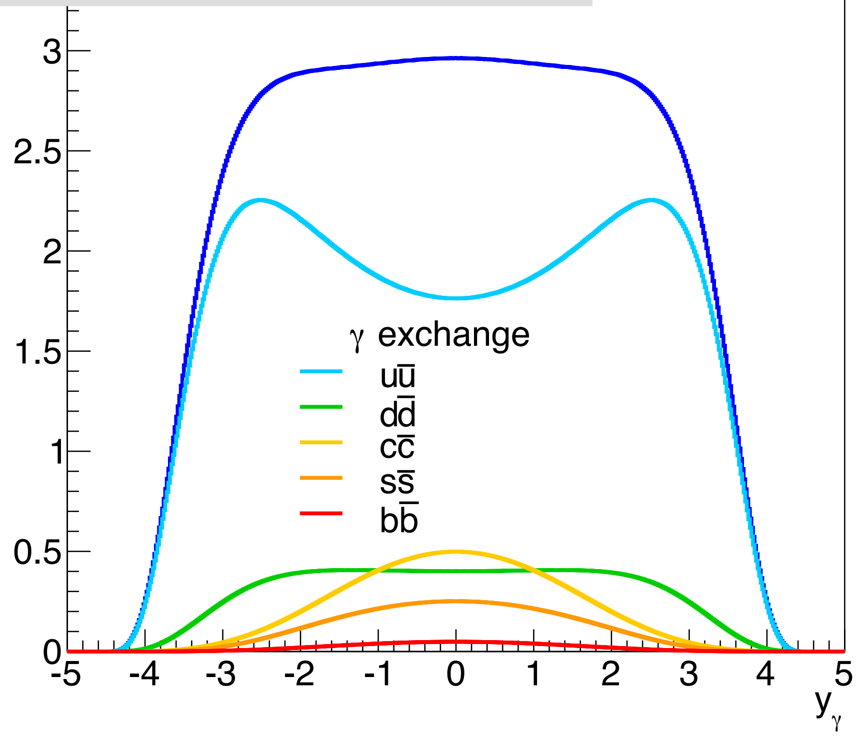
Zll vertex more sensitive than Zqq to $\sin^2\theta_W$
(by factor ~ 5u − 20d,s)

Triple-differential Z/γ^* Measurement Motivation

In different m regions
y spectrum shape changes
dramatically for $m_{ll} \neq m_Z$



sensitive to difference in u-type and d-type due to Z vs γ^* couplings on- and off-shell



Sensitivity to u_v & d_v valence quarks at |y| > 1

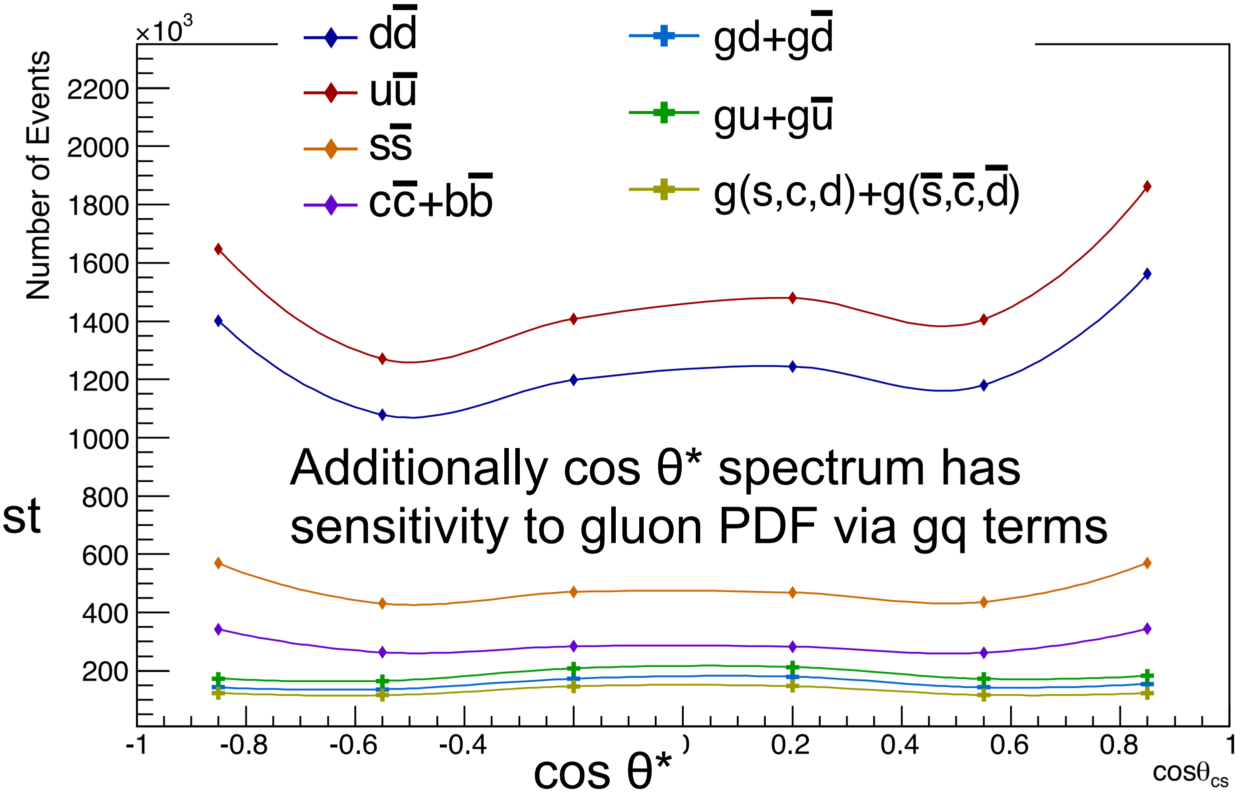
y dependence measures x distribution of PDFs

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

At LHC direction of incoming quark is unknown
Therefore there is ambiguity in defining θ*
(not a problem at Tevatron)
Ambiguity dilutes A_{FB}
Dilution is reduced at large |y| due to valence quark boost

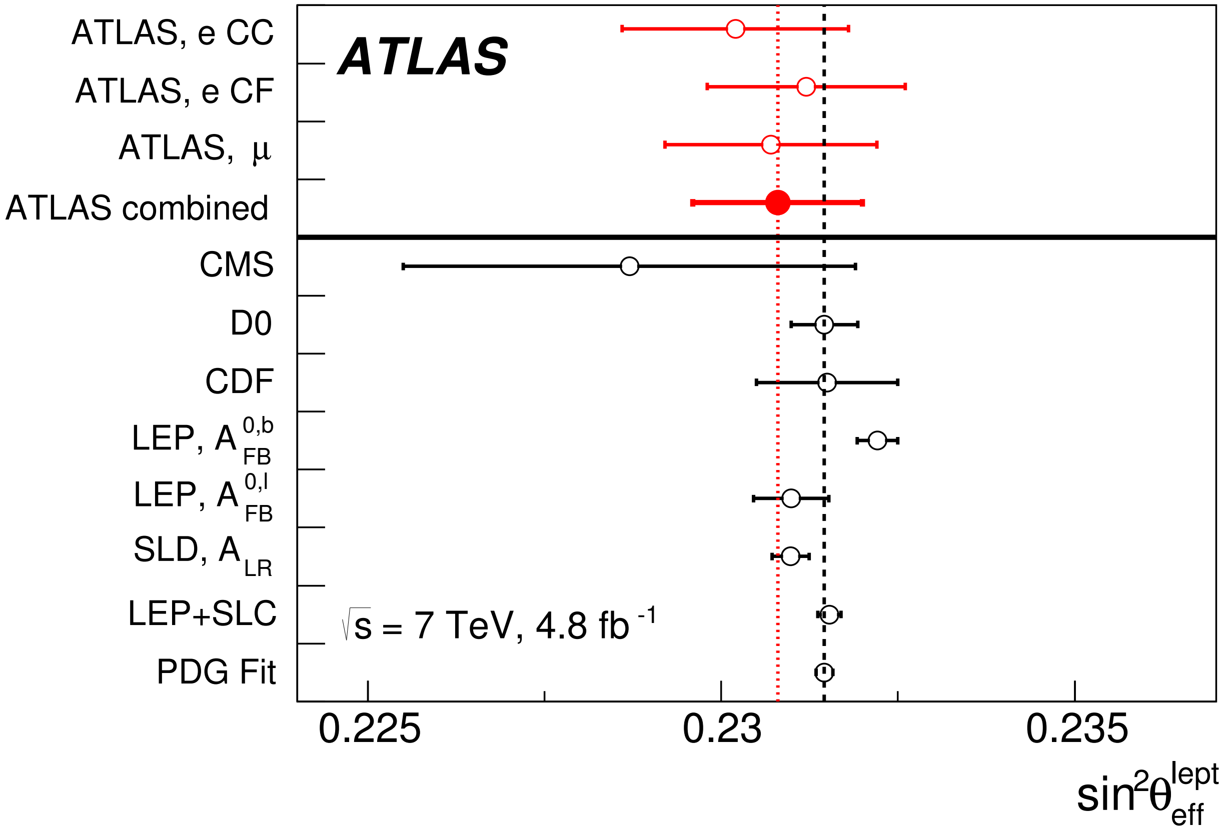
⇒ greater sensitivity to $\sin^2\theta_{eff}$ at larger y

zero sensitivity at y=0



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

Triple-differential Z/ɣ* Measurement Motivation



Previous ATLAS measurement of $\sin^2\theta_W$

JHEP09(2015)049

5 fb^{-1}
$\sqrt{s}$ = 7 TeV

Uncertainty Source	CC electrons x10^{-5}	CF electrons x10^{-5}	Muons x10^{-5}	Combined x10^{-5}
PDF	100	100	90	90
MC statistics	50	20	50	20
Elec energy scale	40	60	—	30
Elec energy res.	40	50	—	20
Muon energy scale	—	—	50	20
higher order corrs	30	10	30	20
Other source	10	10	20	20

ATLAS measurement of $\sin^2\theta_{eff}$ limited by PDF uncertainty
Values are in units of 10^{-5} of $\sin^2\theta_{eff}$

Run-I Measurements from ATLAS

triple-differential cross sections d³σ = $\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}|y_{\ell\ell}|\mathrm{d}\cos\theta^*}$

On-shell DY 8 TeV
Neutral current - e & μ channels
46 < m < 200 GeV
Extended to high y with FCAL analysis

arXiv:1710.05167
Hepdata

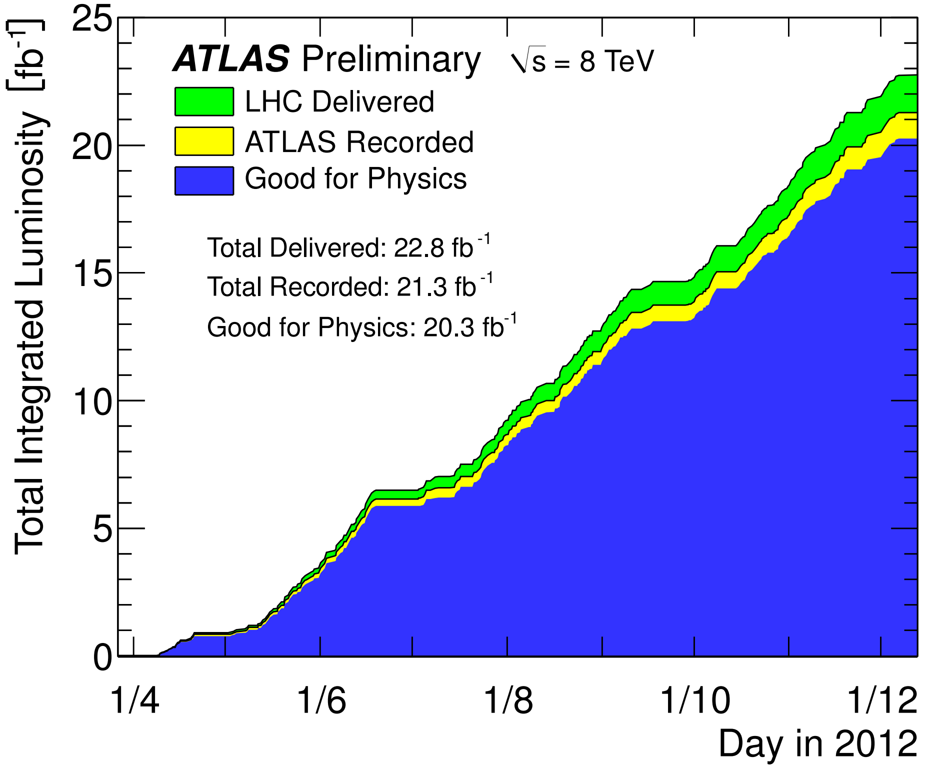
Use d³σ to derive
ancillary measurements
for purely visual purposes

A

A_{FB}(m,|y|)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}}$$

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



Complete 2012 data set analysed

Centre of mass energy √s = 8 TeV

$\int\mathcal{L}\,\mathrm{d}t = 20.2\ \mathrm{fb}^{-1}$

7M di-electron events (CC)
9M di-muon events (CC)
1M forward di-electron events (CF)

ATLAS Z/γ^* $d^3\sigma$ Cross Section $\sqrt{s}$ = 8 TeV

JHEP12(2017)059

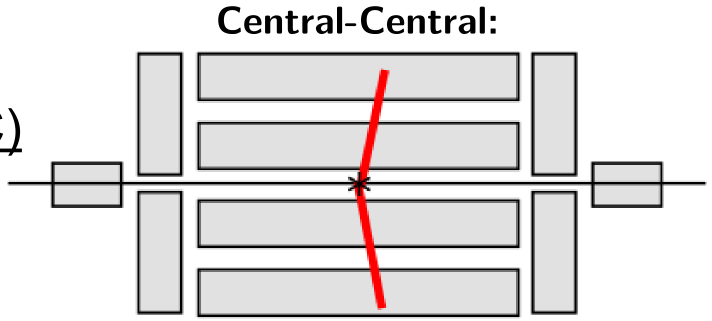
Muon Selection

- ≥ 2 isolated muons
- muon $|\eta| < 2.4$
- muon $p_T > 20$ GeV
- opposite charge

Central Electron Selection

- ≥ 2 good quality “medium” electrons
- electron $|\eta| < 2.4$ excl. $1.37 < |\eta| < 1.52$
- electron $E_T > 20$ GeV

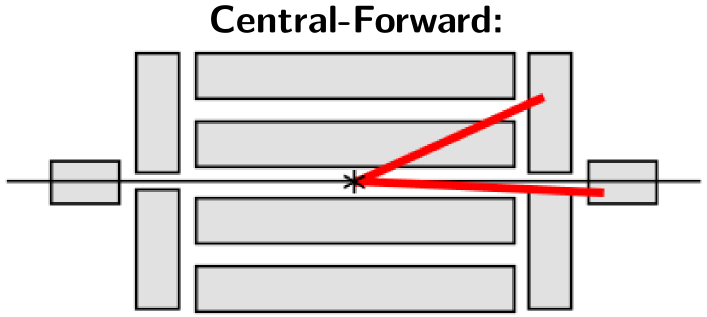
Central-central topology (CC)
Two leptons with $|\eta| < 2.4$



Forward Electron Selection

- 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

Central-forward topology (CF)
One electron with $|\eta| < 2.4$
One electron with $2.5 < |\eta| < 4.9$



Identical dataset and almost identical selection as ATLAS angular coefficients analysis (see later)

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 typically <1% in peak region
dominates error at large |cos θ*| → ~3%

efficiency error typically <0.5% in peak region
larger 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%
upto 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

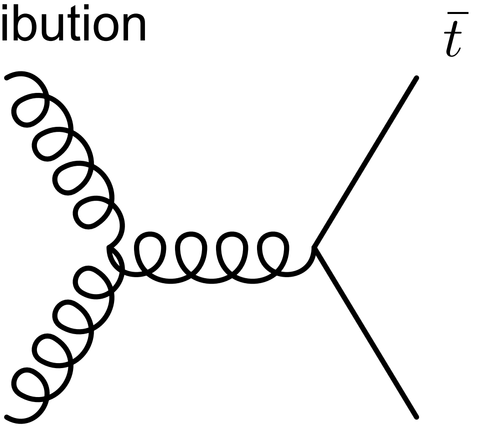
Combination of channels constrains correlated systematic uncertainties

Improved precision for combined central channels

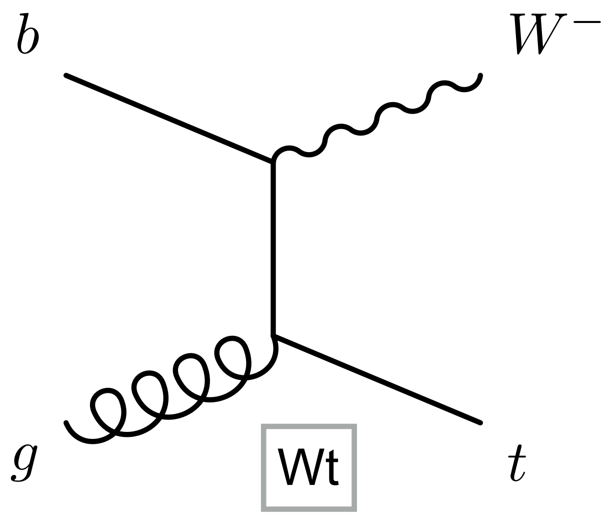
Electroweak Backgrounds

Several sources of so-called “electroweak” backgrounds yielding isolated leptons pairs:
DY → tau production modes found to be negligible contribution

top background
2-10% contribution top (largest at high cos θ*)
below 5% for high y channel
background estimated from MC

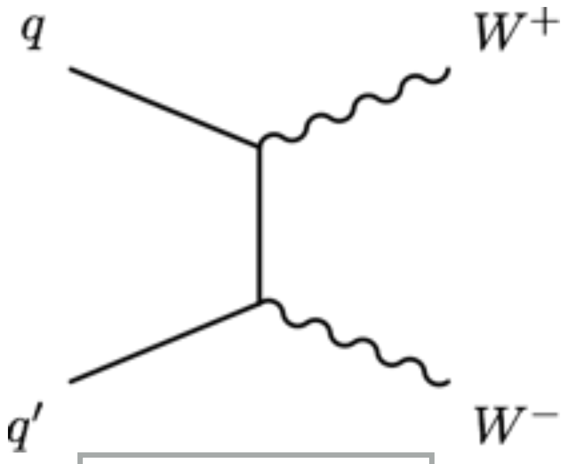


$t\bar{t}$

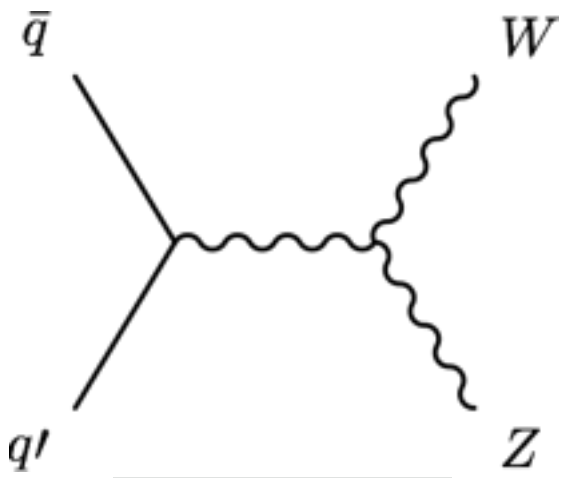


Wt

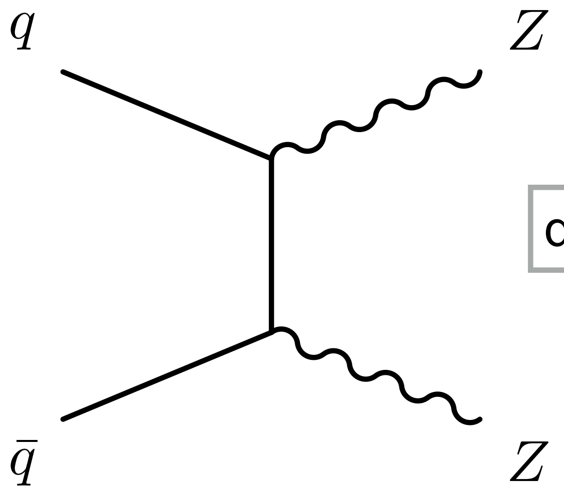
diboson background
3-6% contribution
estimated from MC



diboson (WW)



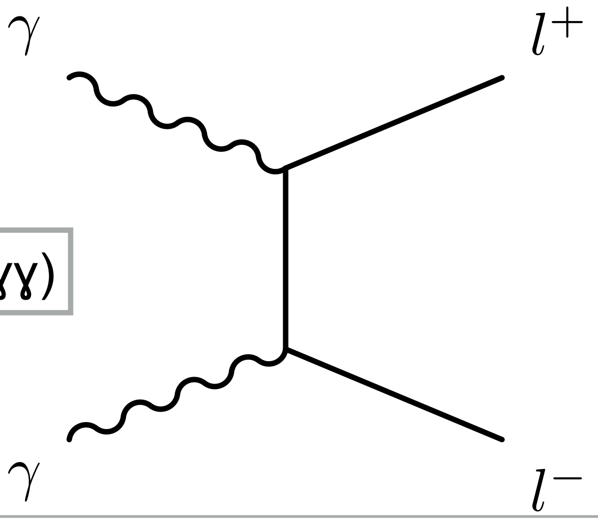
diboson (WZ)



diboson (ZZ)

photon induced background
2-5% contribution (largest at large m)
background estimated from MC

photon induced (γγ)

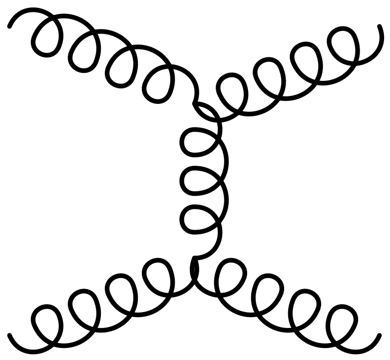


Triple-differential Z/γ* Cross Sections √s = 8 TeV

multijet background

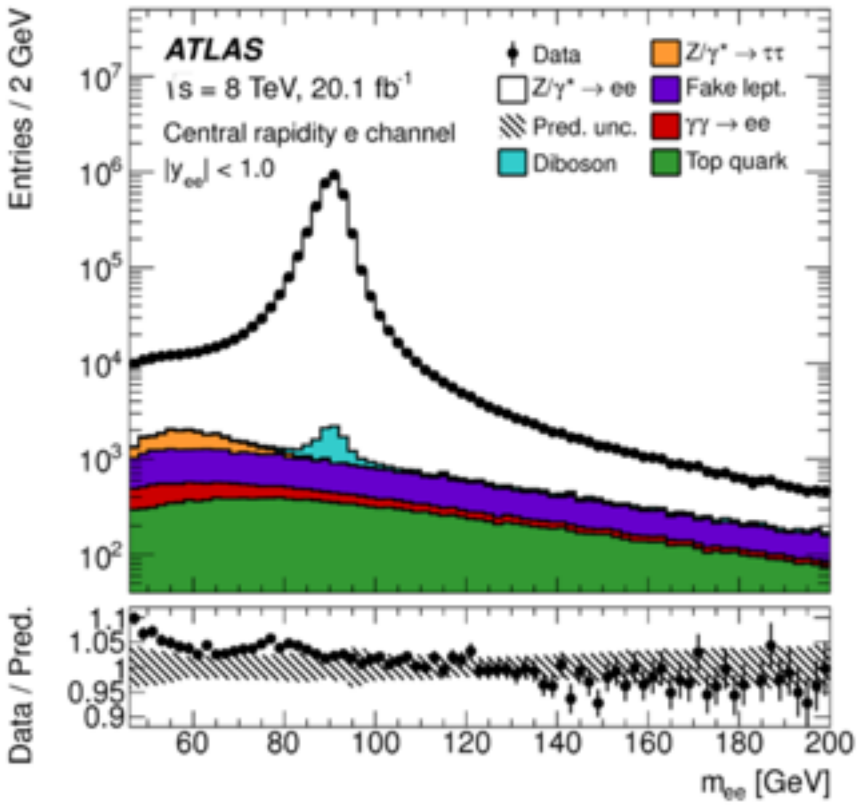
multijet production has large cross section at LHC
contributes to background via:
- b,c quark leptonic meson decays
- misidentification of hadron jet as calorimeter electron

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

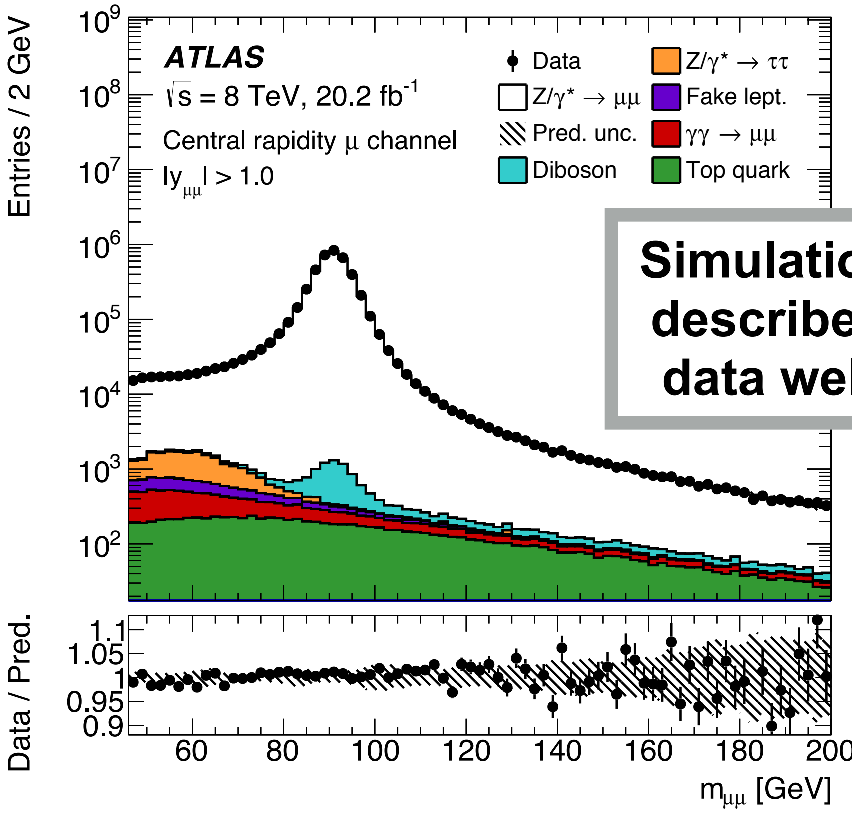


electron / muon channel at m ~ m_Z b/g is <0.1%
significant off-peak upto to 15% low m_{ee}
less than 5% everywhere in muon channel

Electron Channel

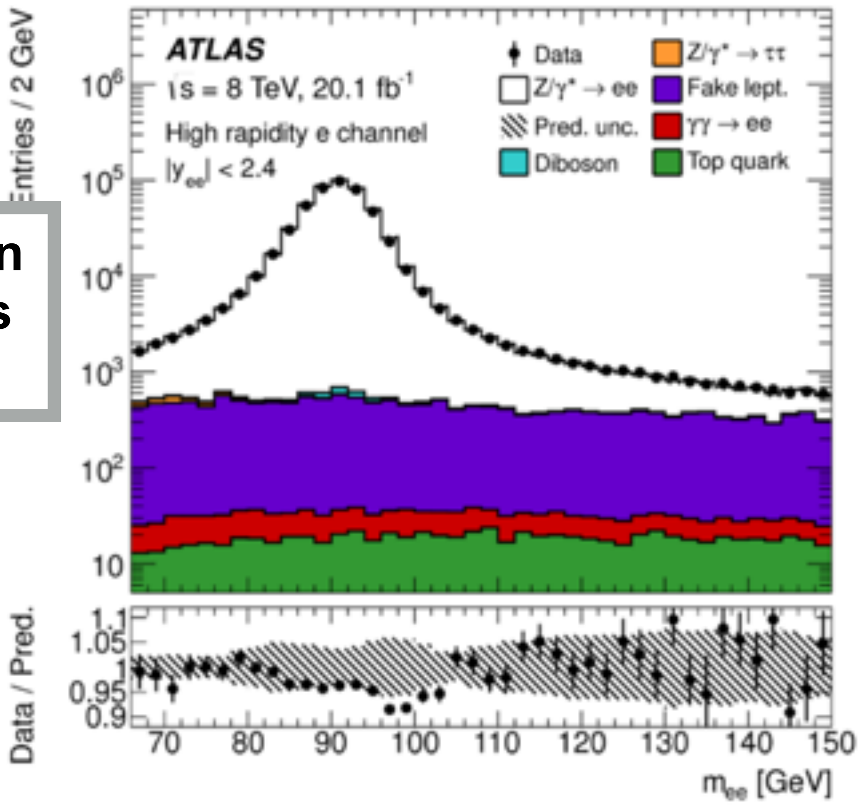


Muon Channel



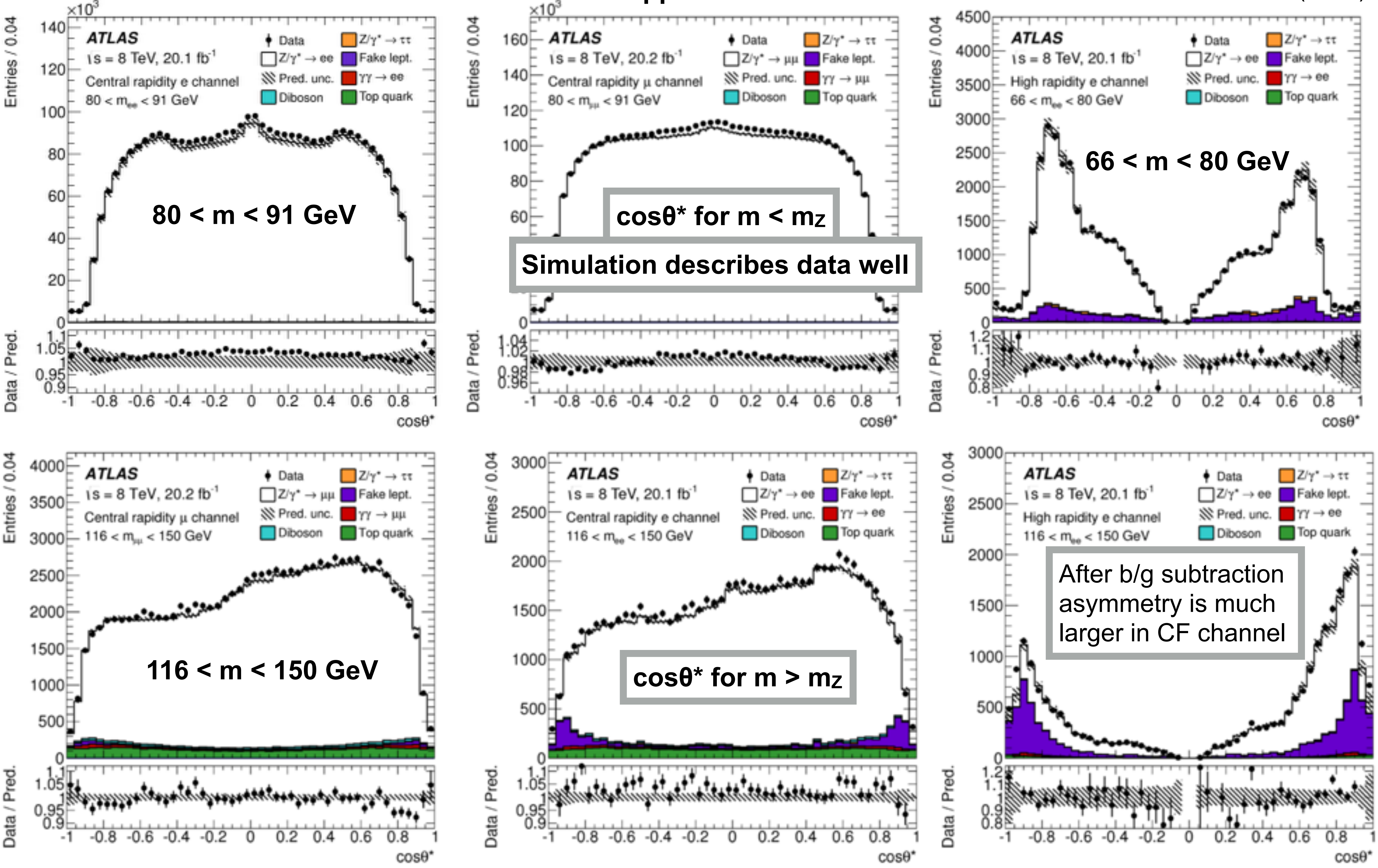
Simulation describes data well

High Rapidity Electron Channel



ATLAS Z/γ^* $d^3\sigma$ Cross Section $\sqrt{s} = 8$ TeV

ee channel **μμ channel** **forward channel** JHEP12(2017)059



80 < m < 91 GeV

cosθ* for m < mZ

Simulation describes data well

66 < m < 80 GeV

116 < m < 150 GeV

cosθ* for m > mZ

After b/g subtraction asymmetry is much larger in CF channel

https://link.springer.com/article/10.1007%2FJHEP12%282017%29059

Triple-differential Z/γ* Binning

Central Rapidity Channel

m_{ll} =	[46, 66, 80, 91, 102, 116, 150, 200] GeV	7 bins
$\lvert y_{ll}\rvert$ =	[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 θ^*=	[-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0]	6 bins
	Total bins =	504

x2 channels

measure in electron + muon channels
check for consistency of channels
combine both measurements
account for **331** 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
$\lvert y_{ll}\rvert$ =	[1.2, 1.6, 2.0, 2.4, 2.8, 3.6]	6 bins
cos θ^*=	[-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0]	6 bins
	Total bins =	150

Triple-differential Z/γ^* Unfolding & Combination

Unfolding

Remove influence of ATLAS detector by unfolding
Use ATLAS detector simulation to quantify event resolution migrations and efficiency losses
Define the particle-level phase space of the final quoted result

CC 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)

CF fiducial cross section definition

- lepton p_T > 25 GeV & lepton $|\eta|$ < 2.5
- lepton p_T > 20 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)

Cross sections unfolded using iterative Bayesian unfolding

$$\left.\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\ell}\,\mathrm{d}|y_{\ell\ell}|\,\mathrm{d}\cos\theta^*}\right|_{l,m,n} = \mathcal{M}^{lmn}_{ijk} \cdot \frac{N^{\text{data}}_{ijk} - N^{\text{bkg}}_{ijk}}{\mathcal{L}_{\text{int}}} \frac{1}{\Delta_{m_{\ell\ell}} \cdot 2\Delta_{|y_{\ell\ell}|} \cdot \Delta_{\cos\theta^*}}$$

i,j,k = reco bin indices
l,m,n = Born bin indices
$\mathcal{M}$ = inverted response matrix
Δ = bin widths in each variable

Triple-differential Z/ɣ* Unfolding & Combination

Combination

Combine CC electron & muon channel measurements in averaging procedure
Minimise difference between two 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 including
- lepton trigger, ID, isolation efficiencies
- lepton scale and resolution uncertainties
- background contributions
- etc.…

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

Method allows cross-calibration of systematics between e and μ channels
Improves statistical and systematic precision

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

Integrated single differential cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}}$$

electron & muon CC channels combined

electron/muon combination gives
χ^2/ndf = 12.8/7

Prediction from Powheg with CT10 PDFs

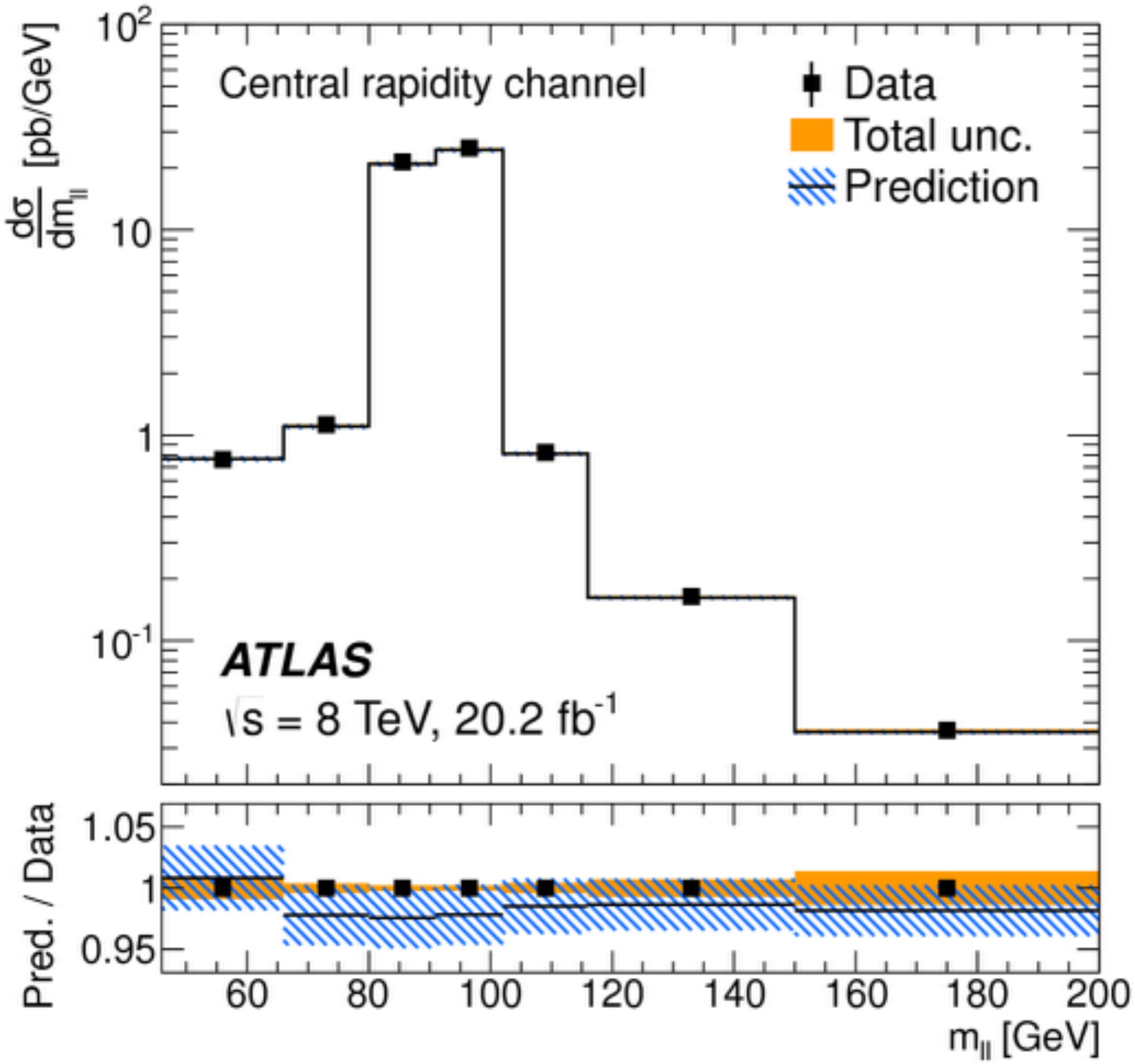
Partial NNLO (QCD) + NLO (EW) k-factors included:
  → 1-dimensional in m_{ll}

Calculated with FEWZ in G_μ EW scheme
  → k-factor ~ 1.03

Powheg has known mismodelling of A_0 angular polarisation coefficient (goes negative)
  → reweighted vs $p_{T,Z}$ and y_{ll}

Computed with DYNNLO

$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}|y_{\ell\ell}|}$ 2d cross sections in back-up



orange band: data uncertainty (excl. lumi ± 1.9%)
blue band: MC stat + PDF uncertainty
(CT10 68% eigenvectors)

Triple-differential Z/γ^* Cross Sections $\sqrt{s}$ = 8 TeV

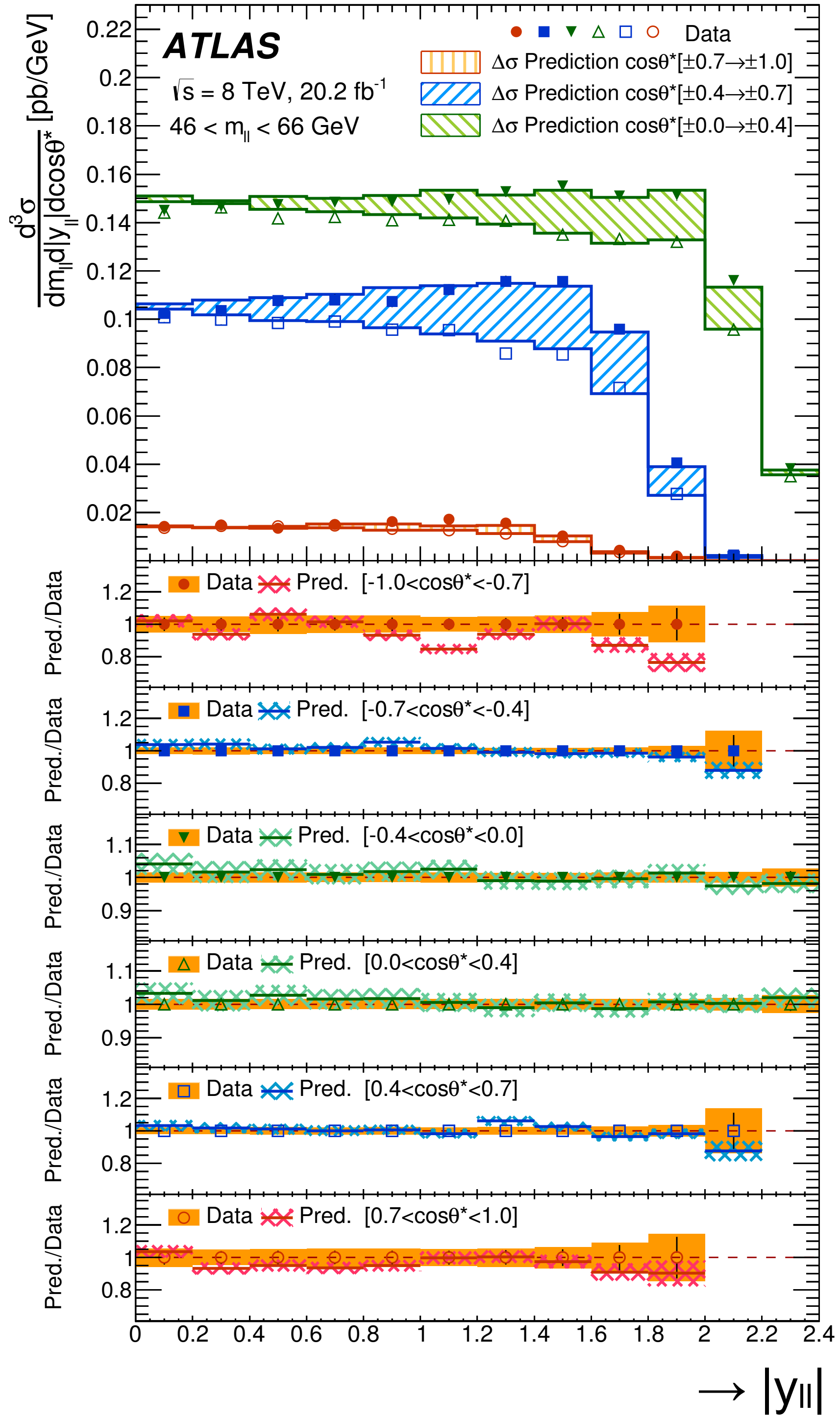
$$\frac{d^3\sigma}{dm_{\ell\ell}\,d|y_{\ell\ell}|\,d\cos\theta^*}$$

Central rapidity electron & muon combined result

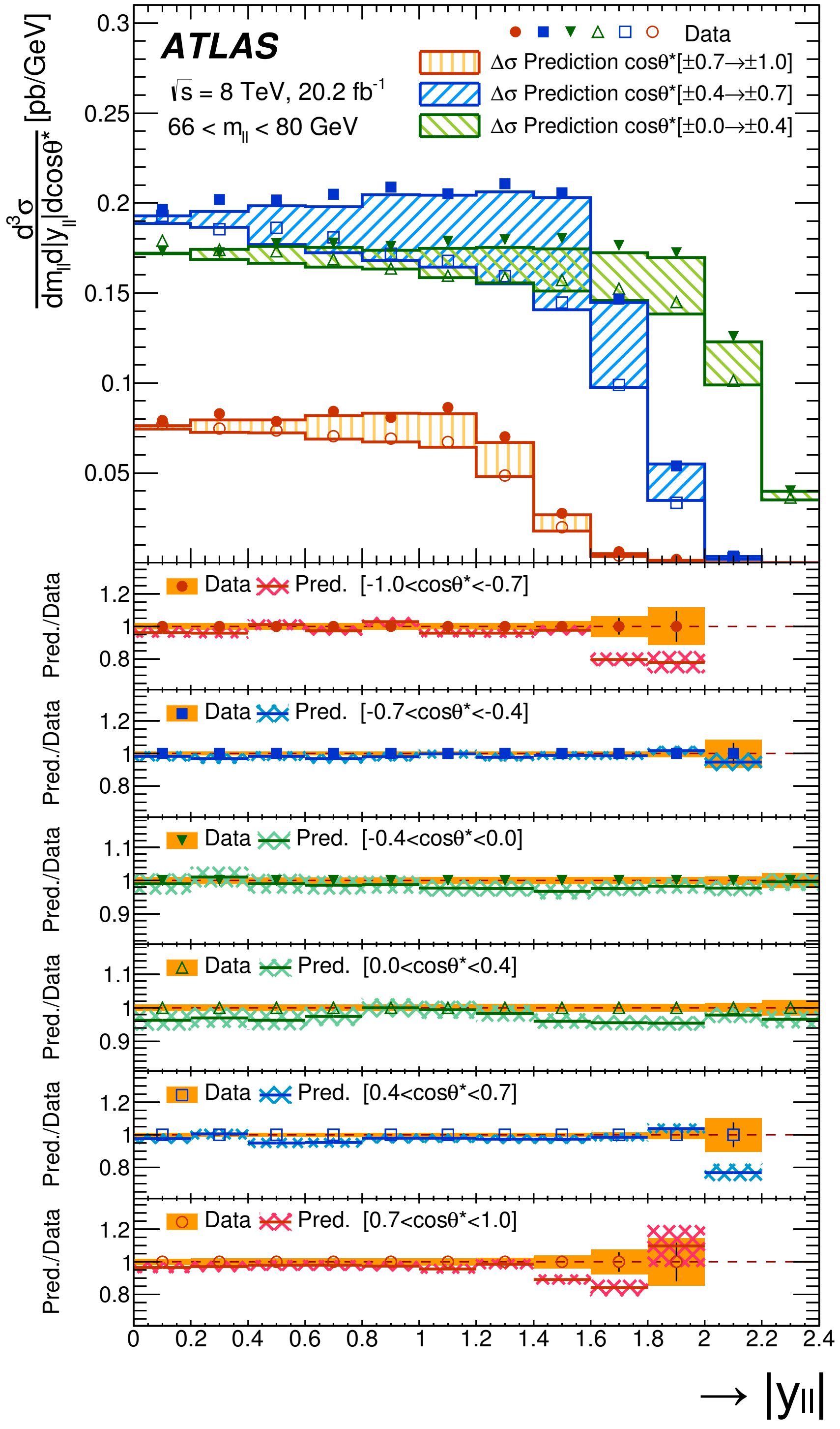
Large forward-backward asymmetry at low mass, decreasing to ~zero at $m_{ll} \sim m_Z$

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

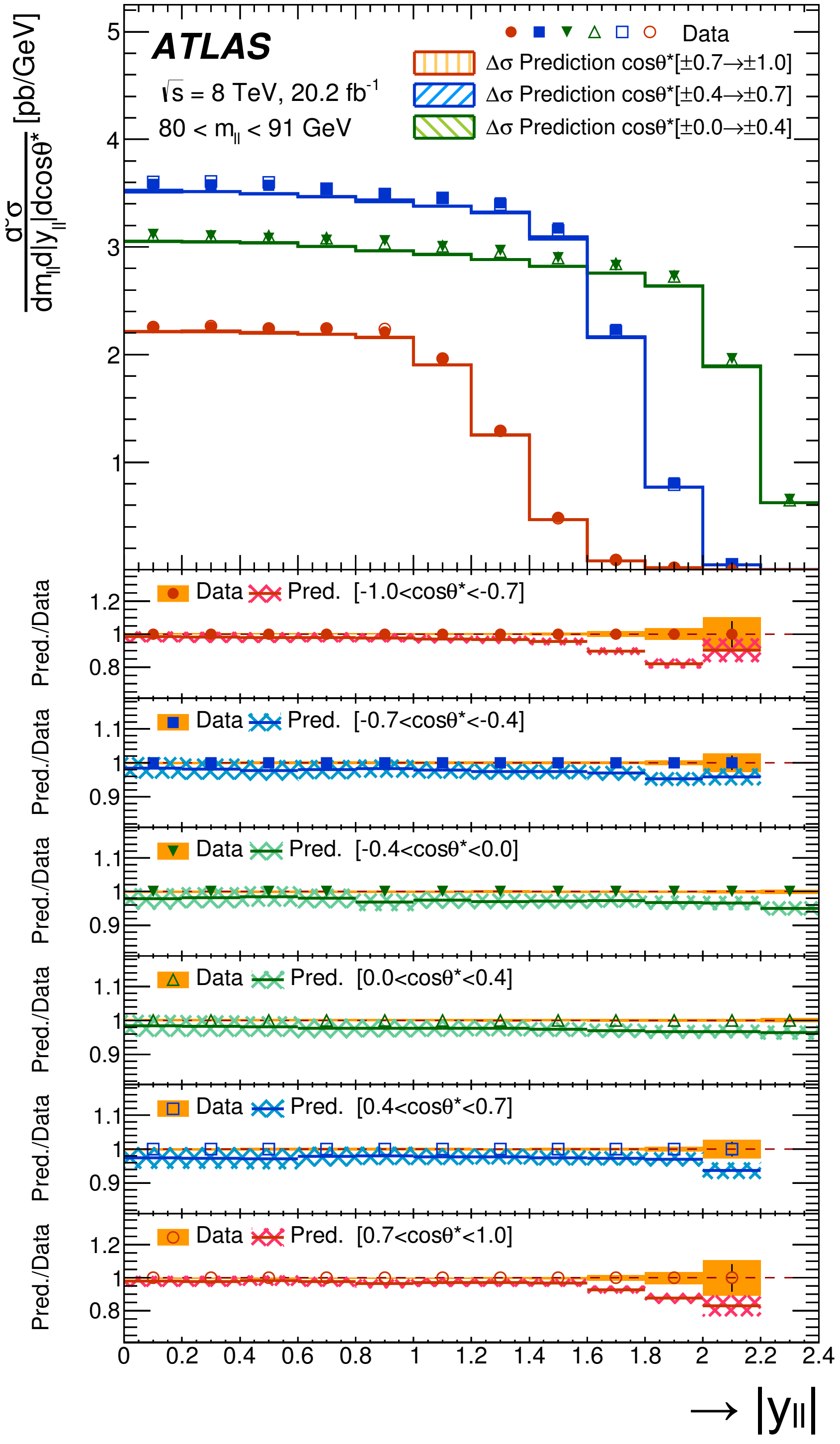
46 < m < 66 GeV



66 < m < 80 GeV



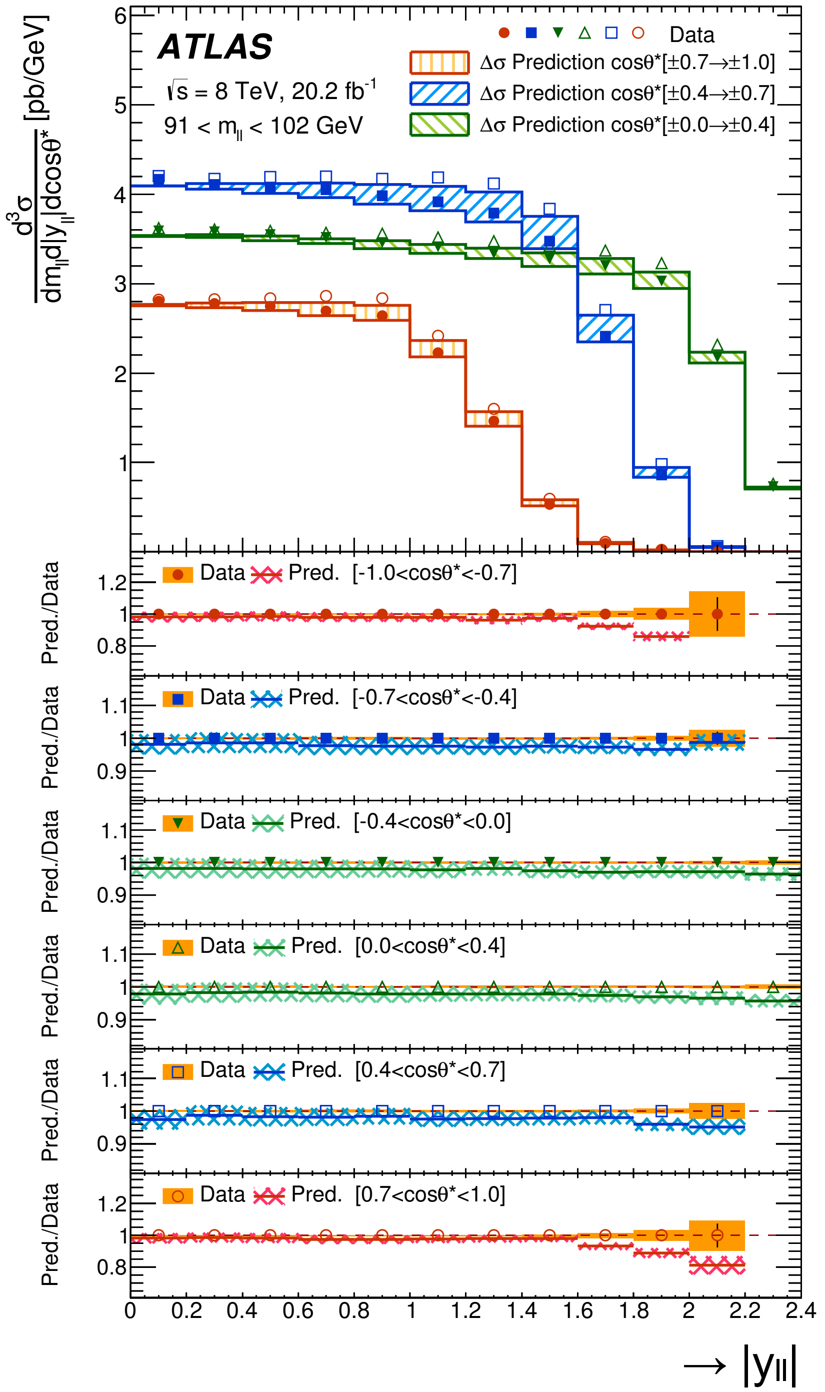
80 < m < 91 GeV

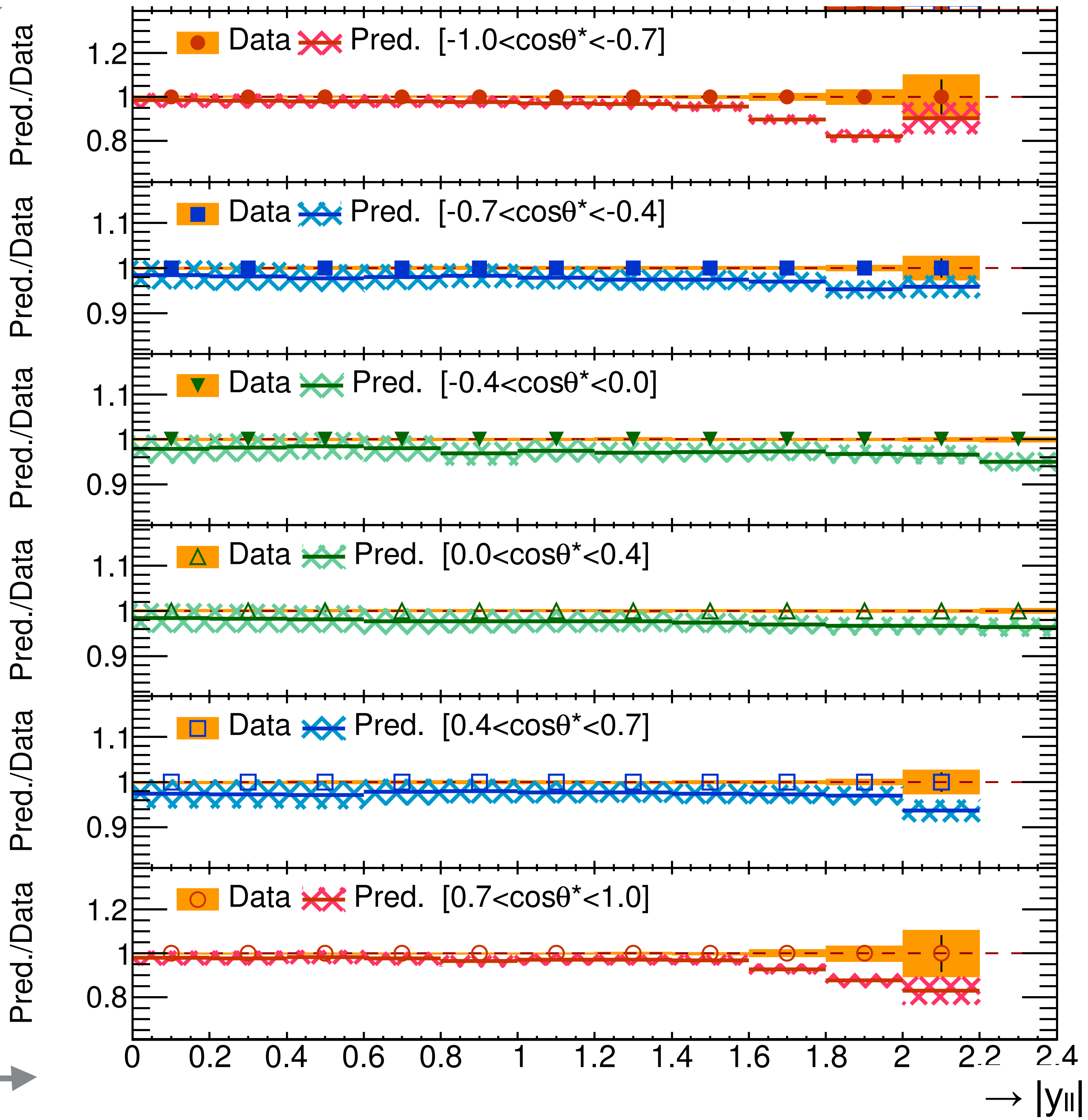


Triple-differential Z/γ^* Cross Sections $\sqrt{s}$ = 8 TeV

electron / muon combination gives χ^2/ndf = 489.4 / 451

91 < m < 102 GeV

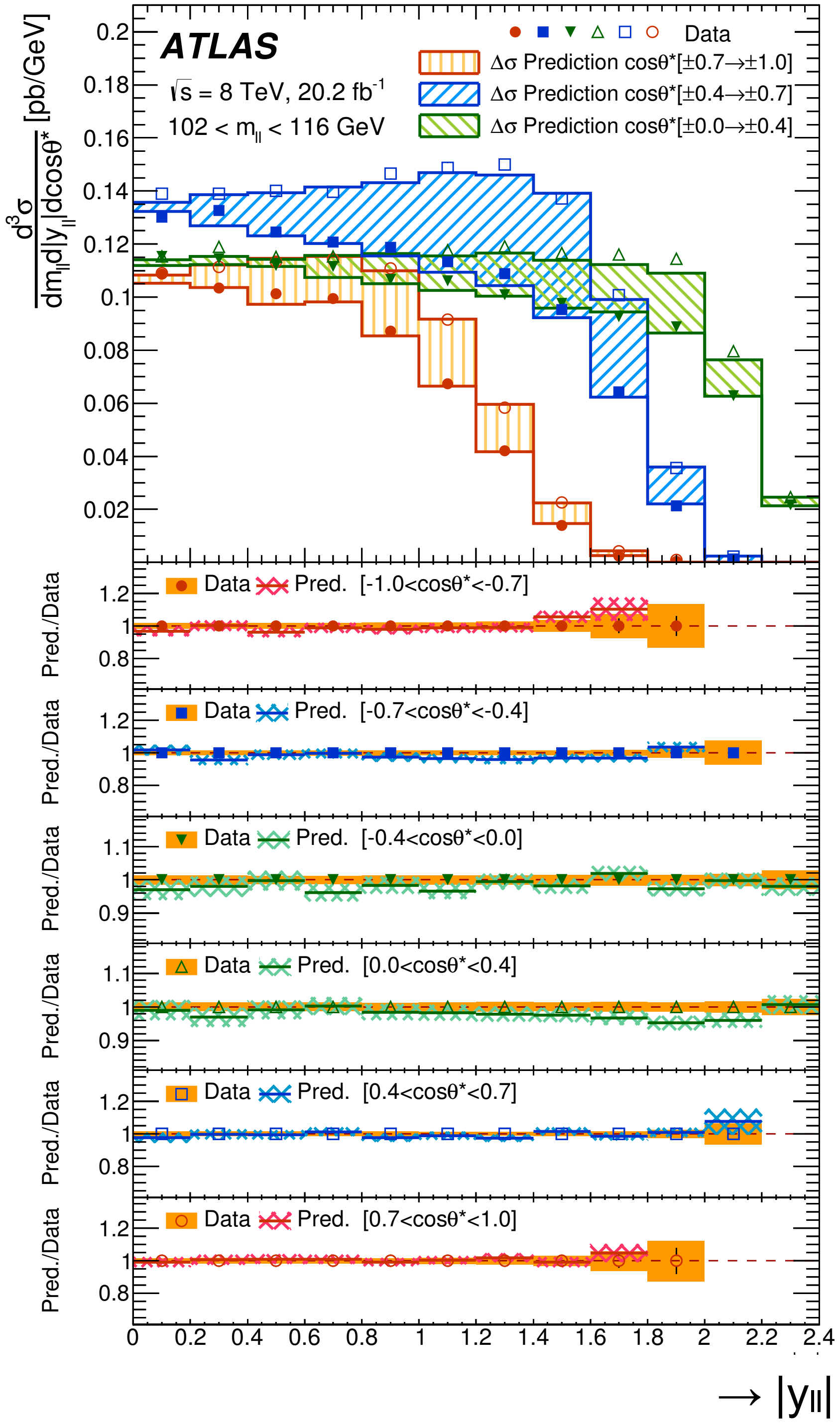




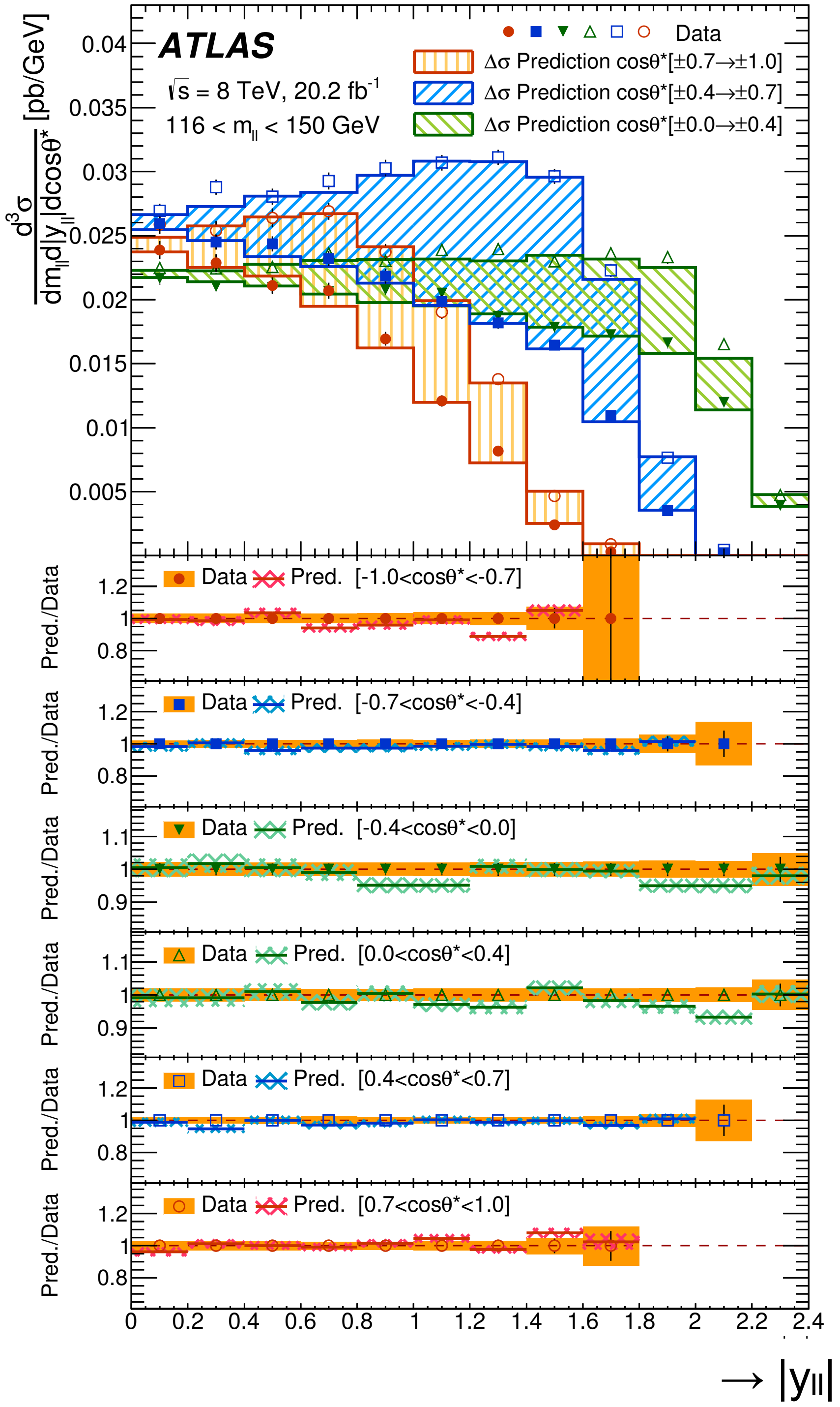
Data precision reaches ~0.5% for $m_{ll} \sim m_Z$
Good agreement with Powheg based predictions incl. NNLO/NLO k-factor (and A_0 polarisation correction)
Interesting features at high |y| + large |cos θ*| ≈ 1 ….

Triple-differential Z/γ^* Cross Sections $\sqrt{s}$ = 8 TeV

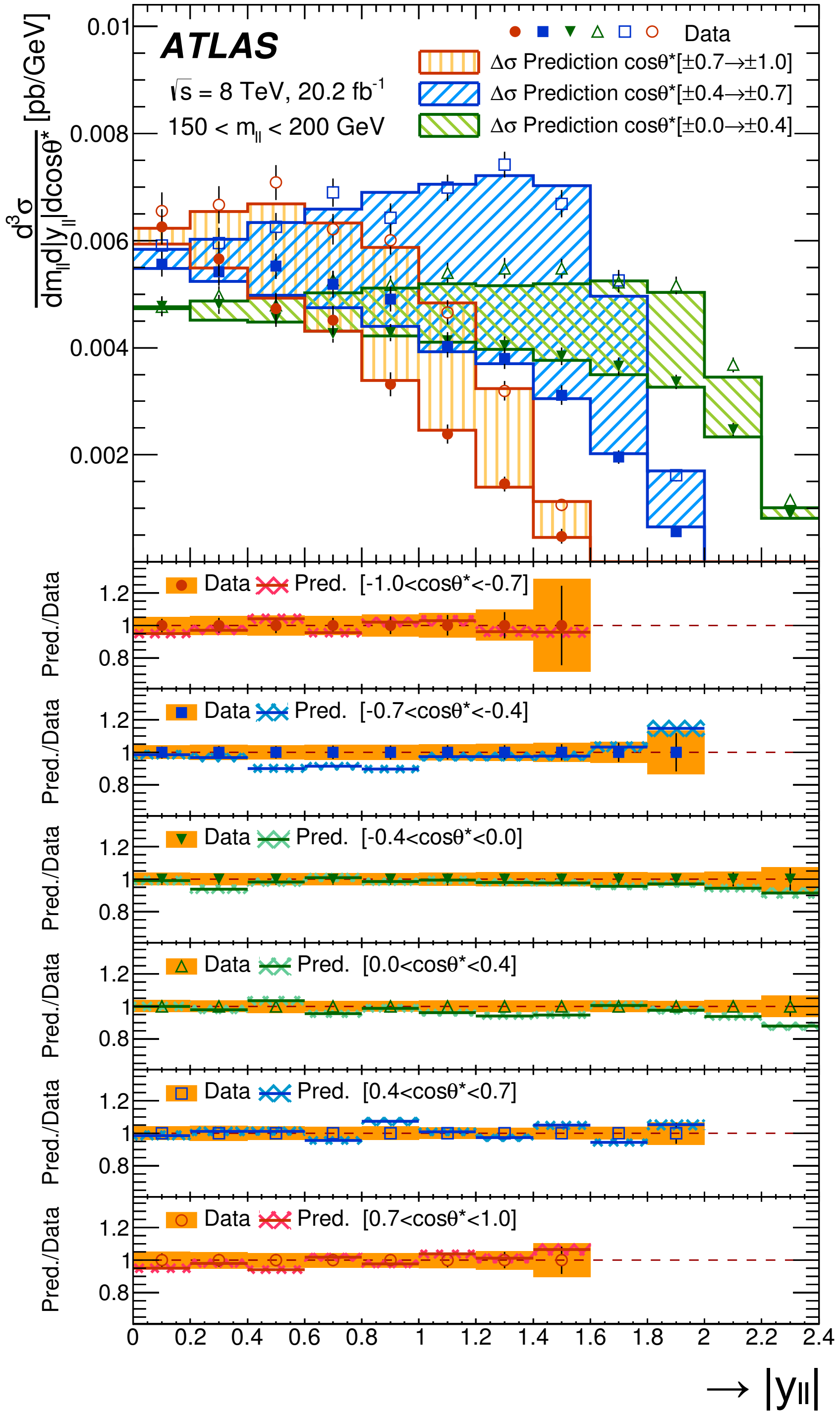
102 < m < 116 GeV



116 < m < 150 GeV

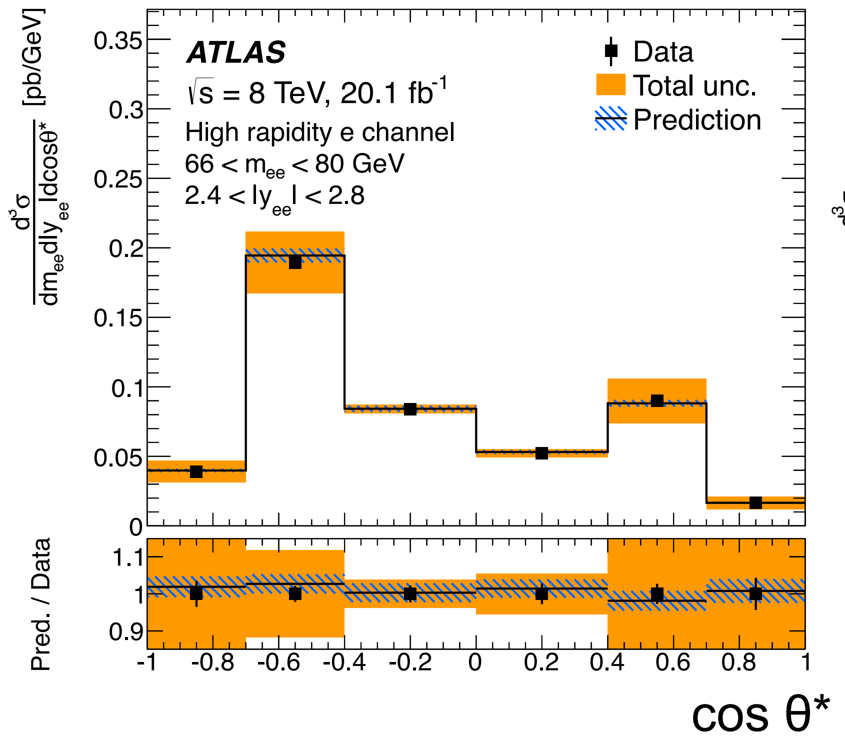


150 < m < 200 GeV

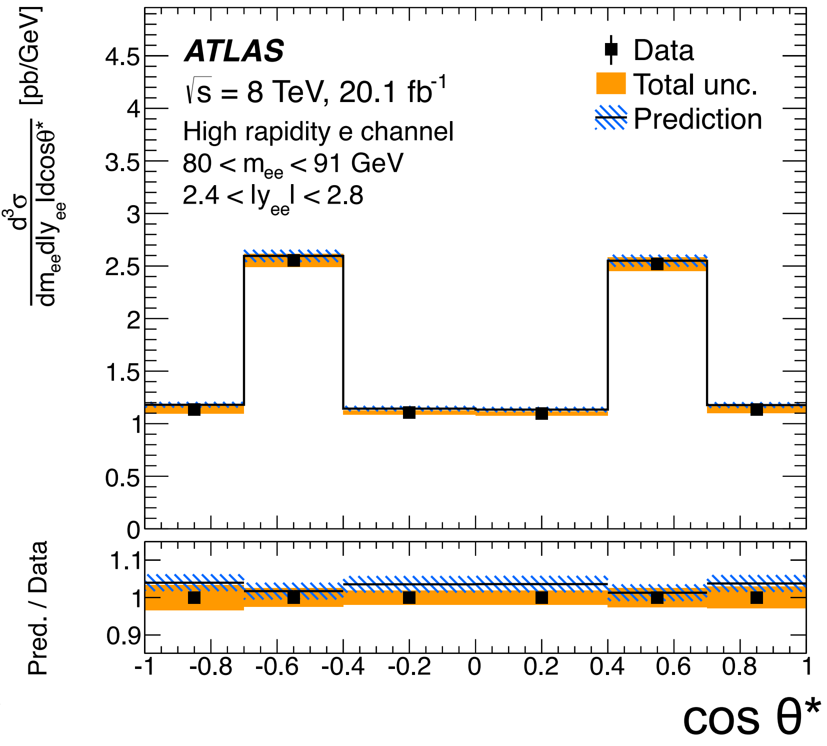


Triple-differential Z/γ* Cross Sections √s = 8 TeV

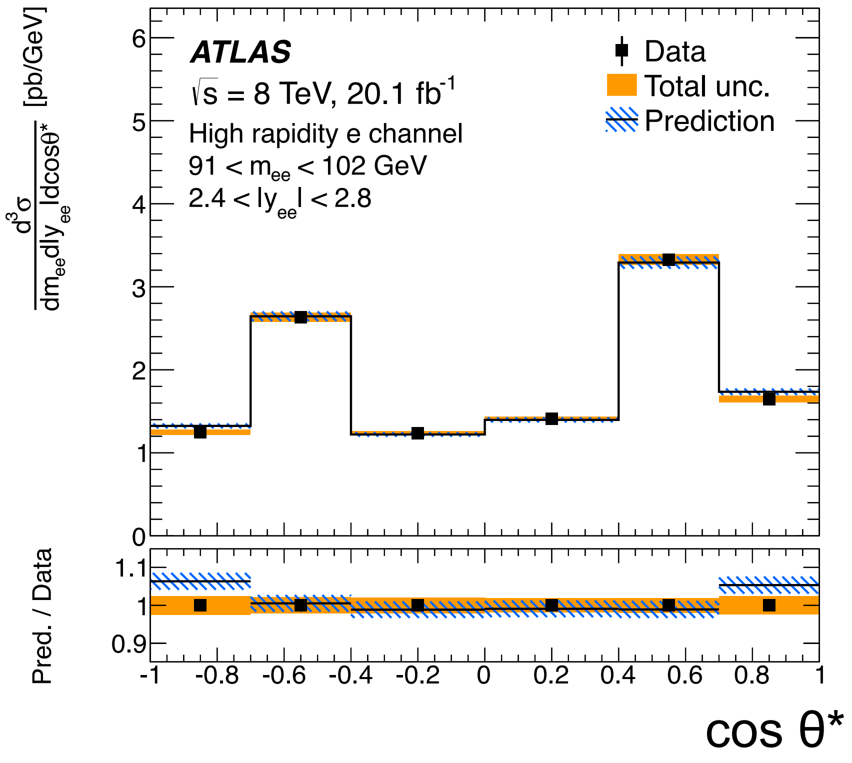
66 < m < 80 GeV



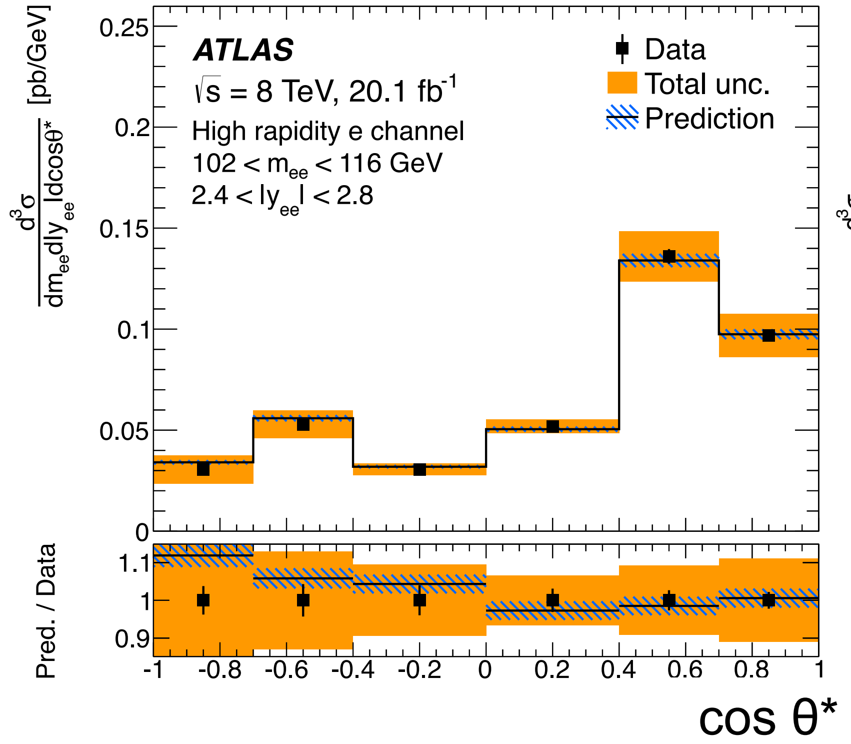
80 < m < 91 GeV



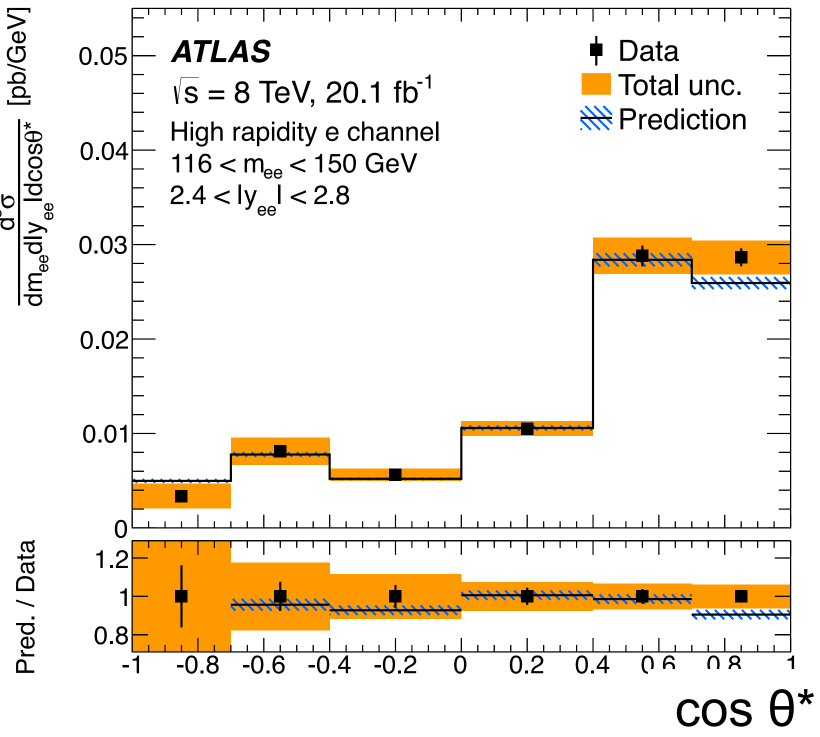
91 < m < 102 GeV



102 < m < 116 GeV



116 < m < 150 GeV



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

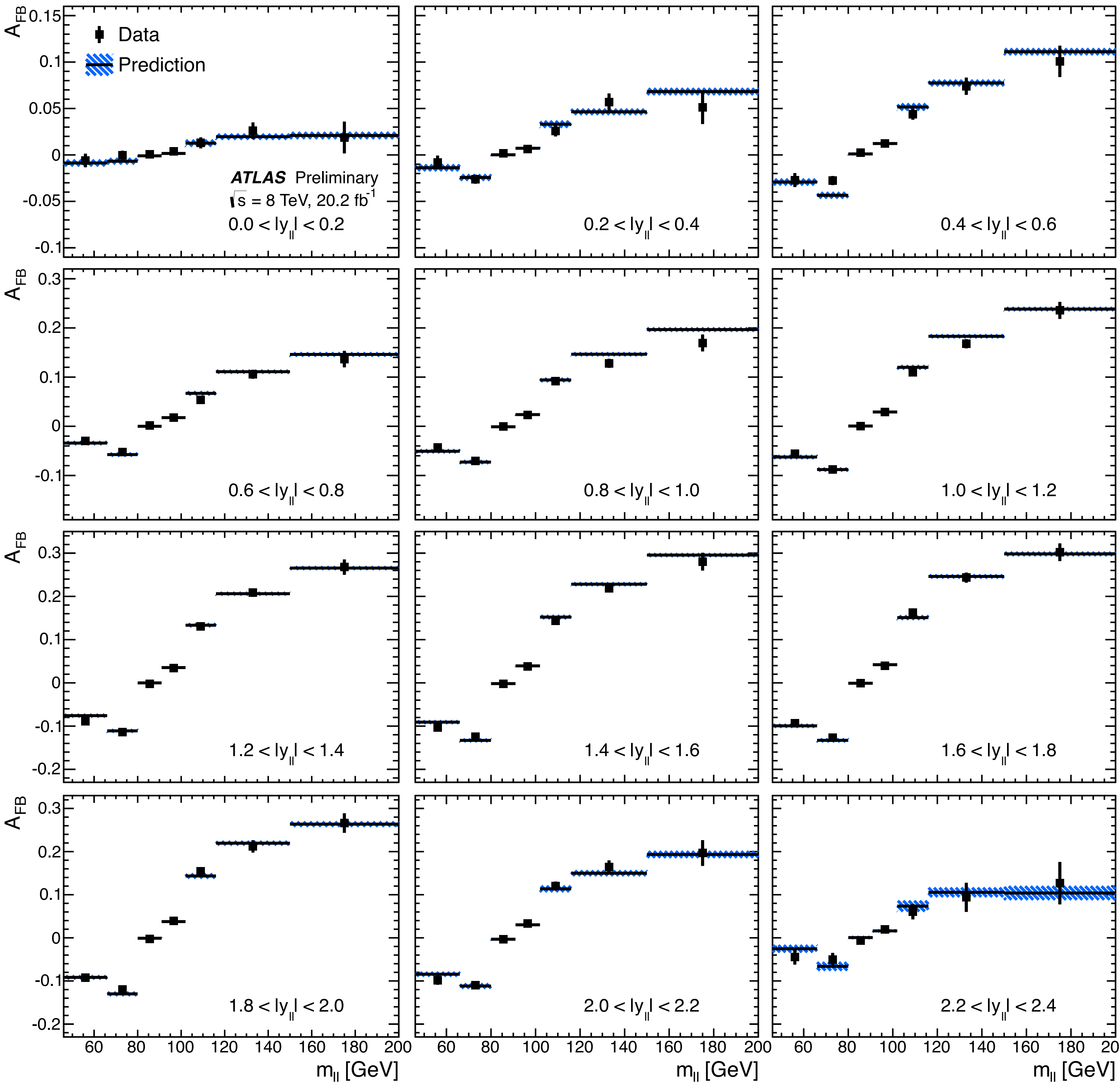
High rapidity channel

Showing selected bins

2.4 < |y| < 2.8

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

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

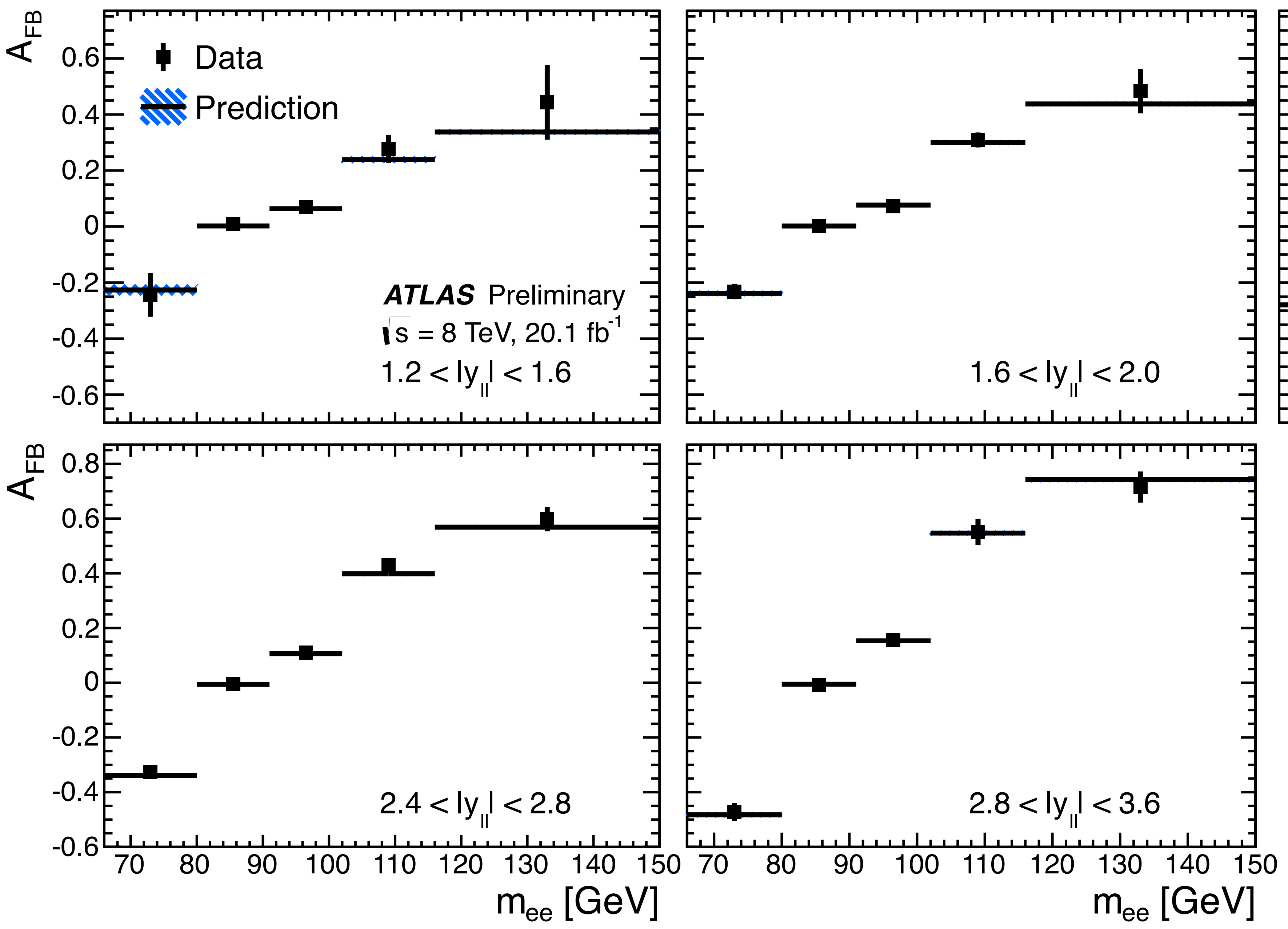
Note: A_{FB} derived from unfolded cross section measurements

symmetric uncertainties cancel in A_{FB}
Scale, resolution, backgrounds

Asymmetry increases with |y|
Due to better determination of initial quark direction (less dilution)

(high |y| access higher x valence PDF)

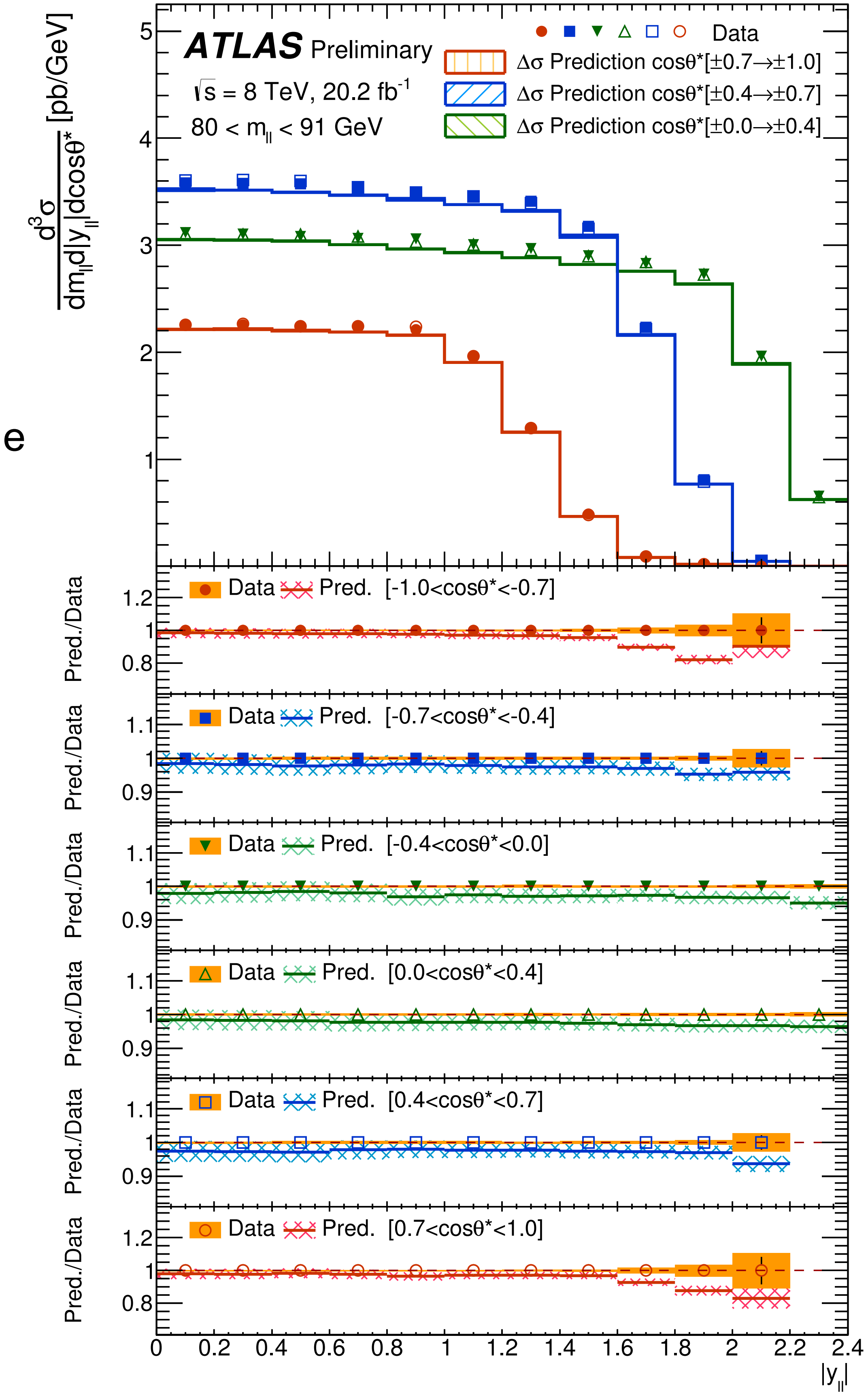
Forward-Backward Asymmetry — high rapidity



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



- New $d^3\sigma$ measurement of DY cross section at $\sqrt{s}$ = 8 TeV available
- on-shell analysis covers phase space 46 < m < 200 GeV
- Precision of 0.5% attained at $m = m_Z$
- Data compatible with NNLO pQCD ⊗ NLO EW
- Data available on HepData with full systematic breakdown

Now extract $\sin^2\theta_{eff}$ using this data

Method of using unfolded $d^3\sigma$ cross sections never used before

Extracting $\sin^2\theta_{eff}$

Typically experiments measure A_{FB}
→ unfold detector effects / dilution → fit for $\sin^2\theta_{eff}$
→ or, perform detector level template fits to A_{FB}
→ estimate PDF uncertainties on extraction

At LHC / Tevatron largest uncertainty ~ PDFs
worse at LHC due to pp collisions
worse at larger √s due to lower x (more dilution)

D0 + CDF combination 2017

$$\begin{aligned} \sin^2\theta^{\rm lept}_{\rm eff} = 0.23148 \ &\pm 0.00027 \quad ({\rm stat.}) \\ &\pm 0.00005 \quad ({\rm syst.}) \\ &\pm 0.00018 \quad ({\rm PDF}) \end{aligned}$$

ATLAS 7 TeV

$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.2308 \pm 0.0005({\rm stat.}) \pm 0.0006({\rm syst.}) \pm 0.0009({\rm PDF}) = 0.2308 \pm 0.0012({\rm tot.})$$

CMS 8 TeV

$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$
$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.23101 \pm 0.00052.$$

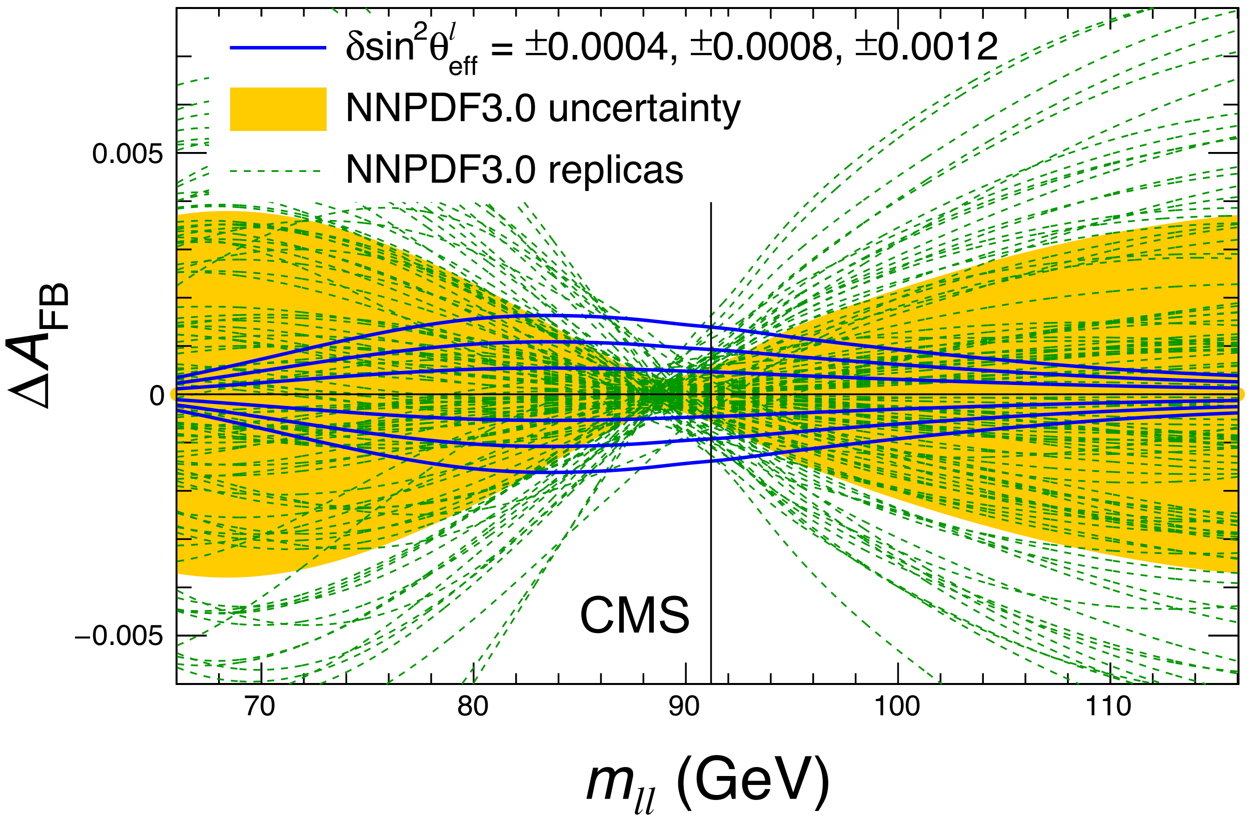
LHCb 7 & 8 TeV

$$\sin^2\theta^{\rm eff}_{\rm W} = 0.23142 \pm 0.00073({\rm stat}) \pm 0.00052({\rm sys}) \pm 0.00056({\rm theo})$$

dominated by PDF

Extracting $\sin^2\theta_{eff}$ — PDF Profiling

Variation of A_{FB} from PDF replicas and $\sin^2\theta_W$



$\sin^2\theta_W$ variations correlated across m spectrum
PDF variations anti-correlated about m=91

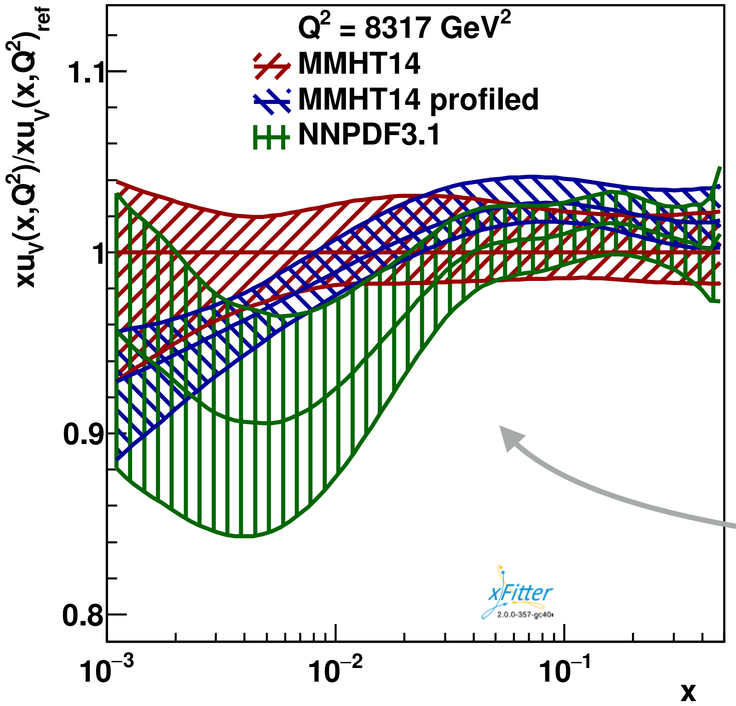
These correlations can be exploited
Use data to constrain PDFs → reduce uncertainty

For NNPDF incompatible replicas rejected by data

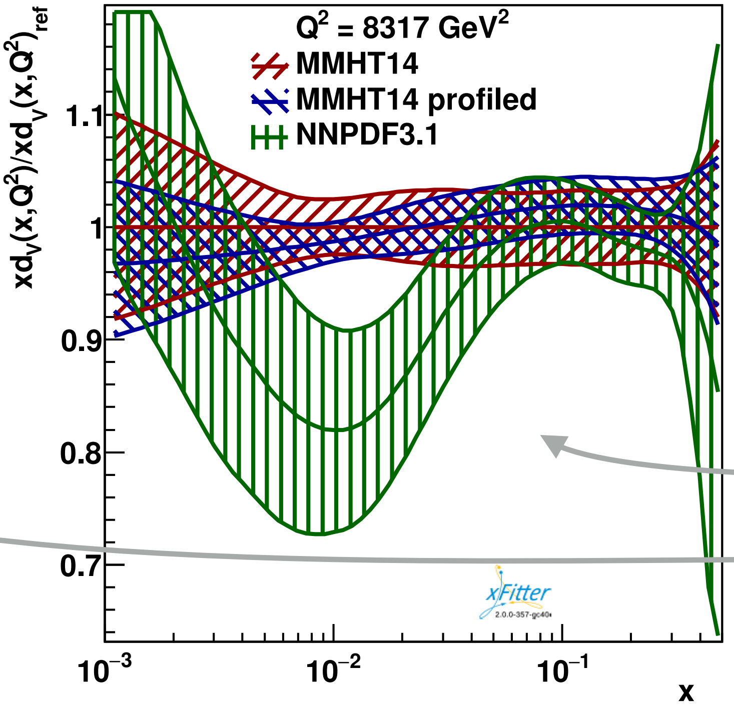
Other PDF sets: uncertainties given as eigenvector variations
Introduce nuisance parameters for each PDF eigenvector
Fit data + PDF nuisance parameters to constrain PDFs

Approximation to performing full PDF fit to data

u_V compared to MMHT reference



d_V compared to MMHT reference



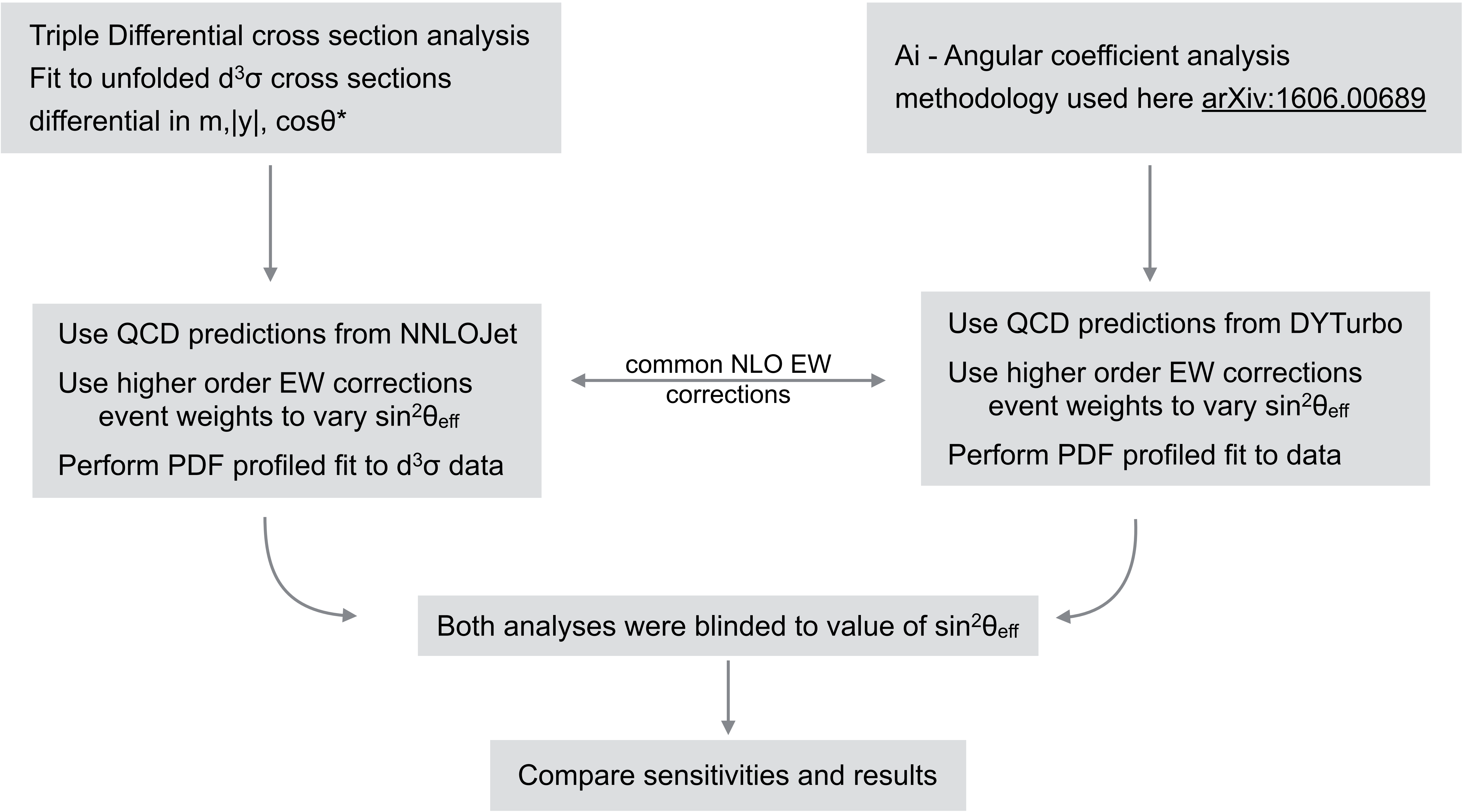
Example of profiling using $d^3\sigma$ pseudo-data
Pseudo-data produced with NNPDF set
Predictions generated using MMHT
Pseudo-data are profiled using predictions
Profiled PDFs move towards MMHT

Profiling works for u_V but fails for d_V where
PDF set has insufficient flexibility
→ use several PDF sets

Extracting $\sin^2\theta_{eff}$

ATLAS-CONF-2018-037/

ATLAS uses 2 methods (same data set / similar selections):



Triple Differential cross section analysis
Fit to unfolded $d^3\sigma$ cross sections
differential in m,|y|, cosθ*

Ai - Angular coefficient analysis
methodology used here arXiv:1606.00689

Use QCD predictions from NNLOJet

Use higher order EW corrections event weights to vary $\sin^2\theta_{eff}$

Perform PDF profiled fit to $d^3\sigma$ data

common NLO EW corrections

Use QCD predictions from DYTurbo

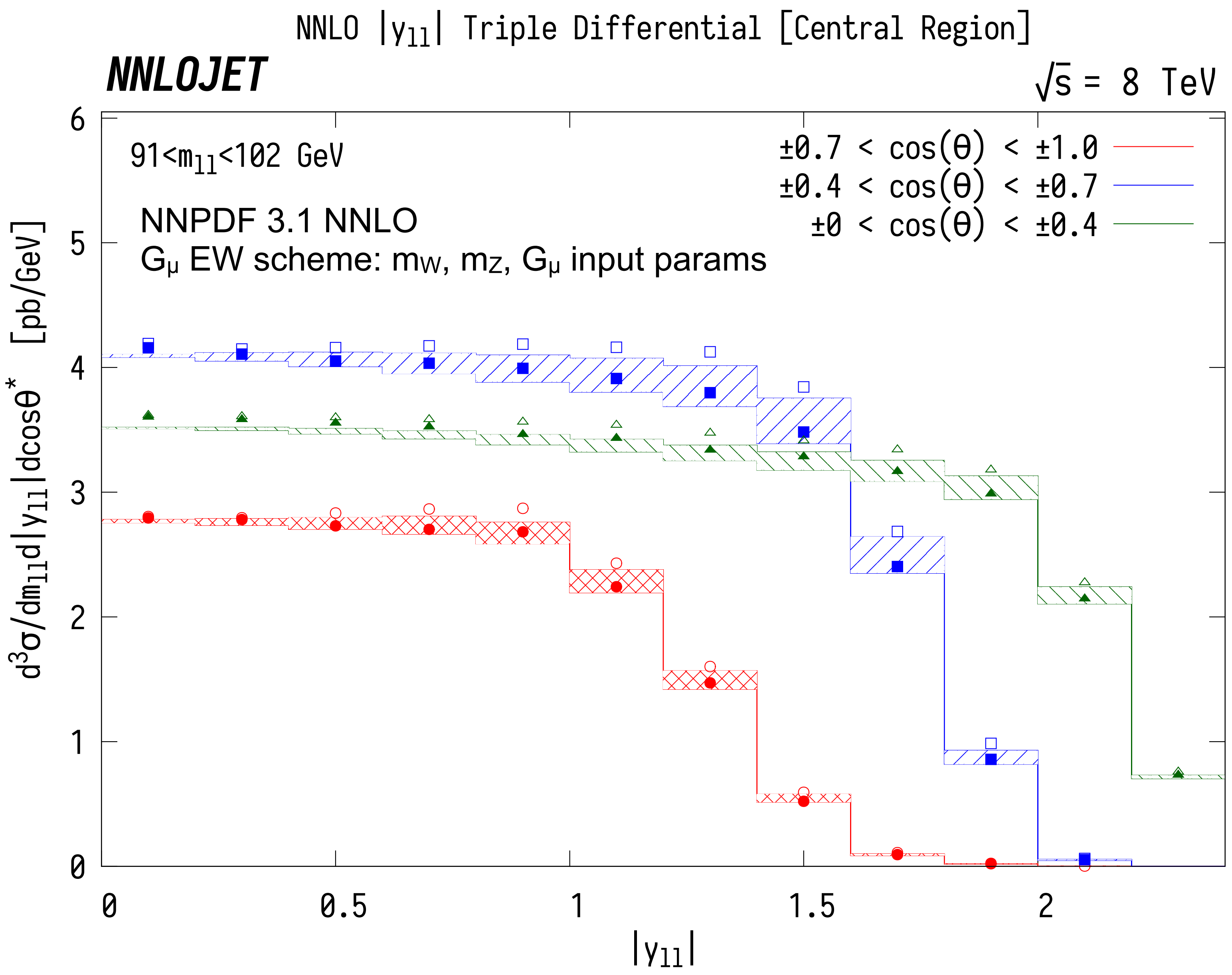
Use higher order EW corrections event weights to vary $\sin^2\theta_{eff}$

Perform PDF profiled fit to data

Both analyses were blinded to value of $\sin^2\theta_{eff}$

Compare sensitivities and results

Extracting $\sin^2\theta_{eff}$ — $d^3\sigma$



LHC EW Working Group:
https://indico.cern.ch/event/707971/

Parton level event generator at NN(N)LO QCD using antenna subtraction

Processes available:
- pp → H, H+J,
- Z, Z+J,
- $W^\pm$, $W^\pm$J,
- VH,
- dijets
- ep → 1,2J
- e^+e^- → 3J ...

Comparisons to NNLOjet - collaboration with IPPP (Nigel Glover & Duncan Walker)

Provide **fiducial** NNLO QCD predictions for varying $\sin^2\theta_W$

Full set of NNLO predictions = ~3-4 days grid time

Applfast interface under development (for PDF uncertainties)

QCD scale uncertainties μ_R & μ_F ~0.5% …

…but larger dependence observed in some kinematic regions…

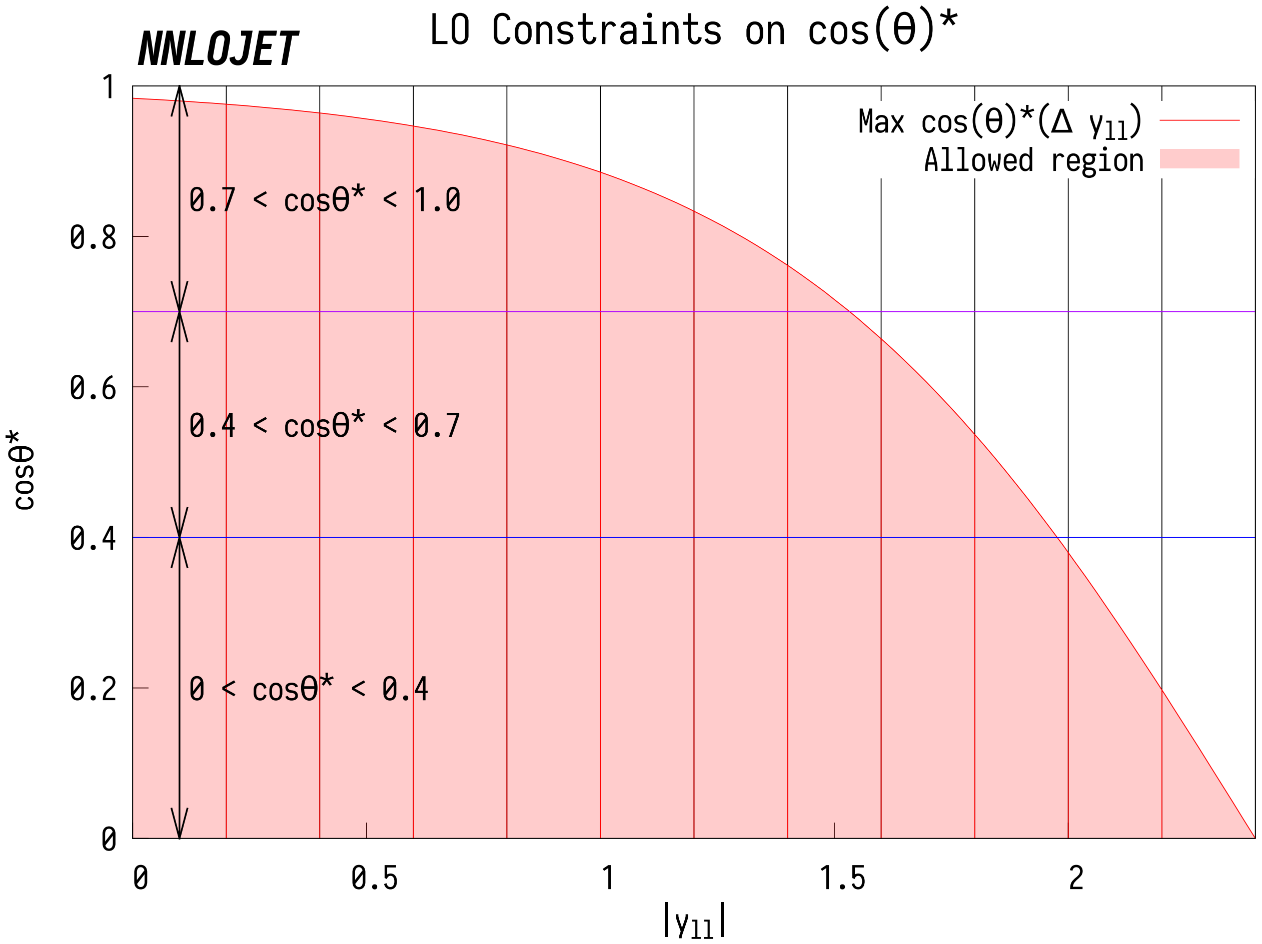
Extracting $\sin^2\theta_{eff}$ — $d^3\sigma$

Slides from Duncan Walker

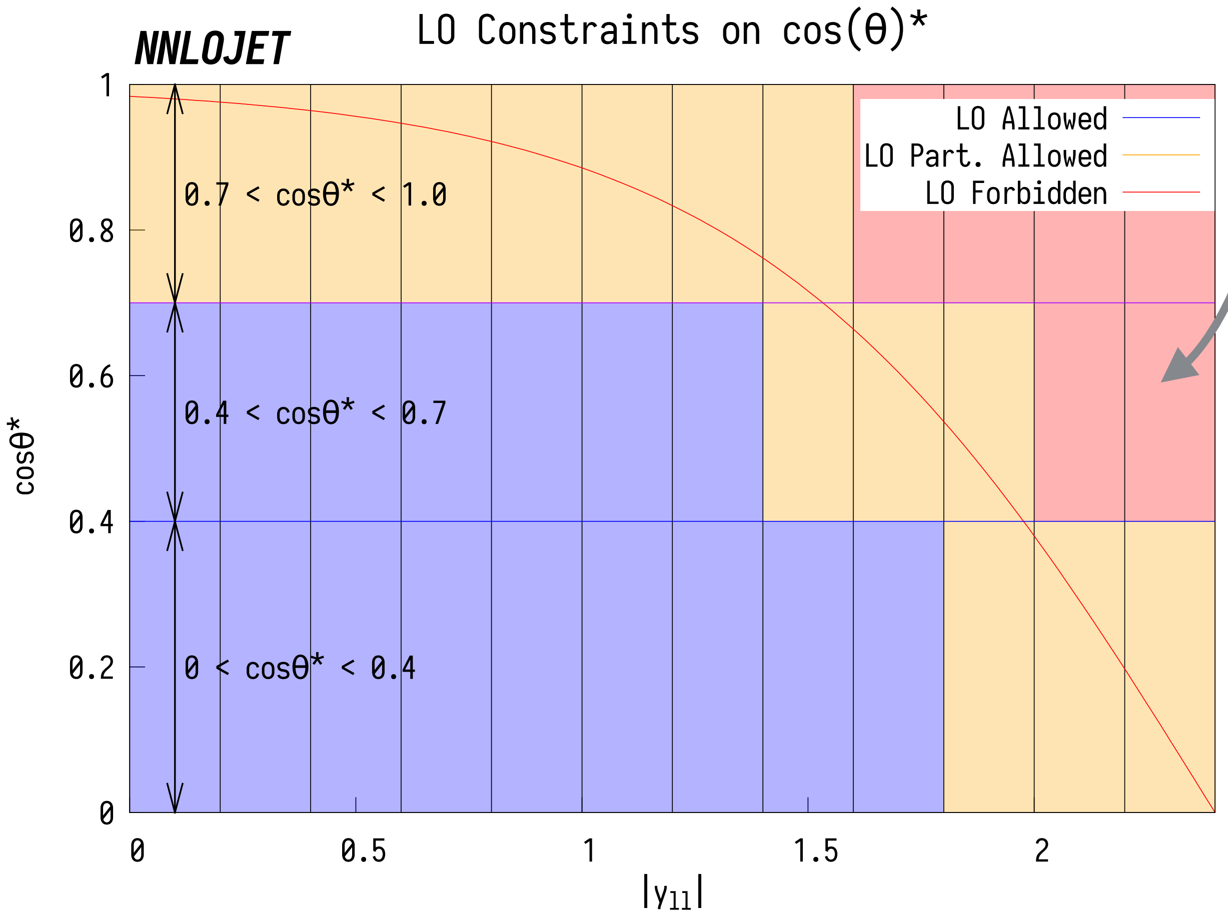
Using LO kinematics, we can write $\cos\ \theta^*$ a function of the difference in rapidities of the leptons:

$$\cos\ \theta^* = \frac{\sinh(\Delta y_{ll})}{1+\cosh(\Delta y_{ll})} \rightarrow \cos\ \theta^* \leq \frac{\sinh(2(y_l^{max} - |y_{ll}|))}{1+\cosh(2(y_l^{max} - |y_{ll}|))}$$

Constraints on Δy_{ll} from the cuts give constraints on $\cos\ \theta^*$. Only NLO in these bins at $\mathcal{O}(\alpha_S^2) \rightarrow$ use NNLO ZJ calculation?



Region corresponds to Z recoiling against jet



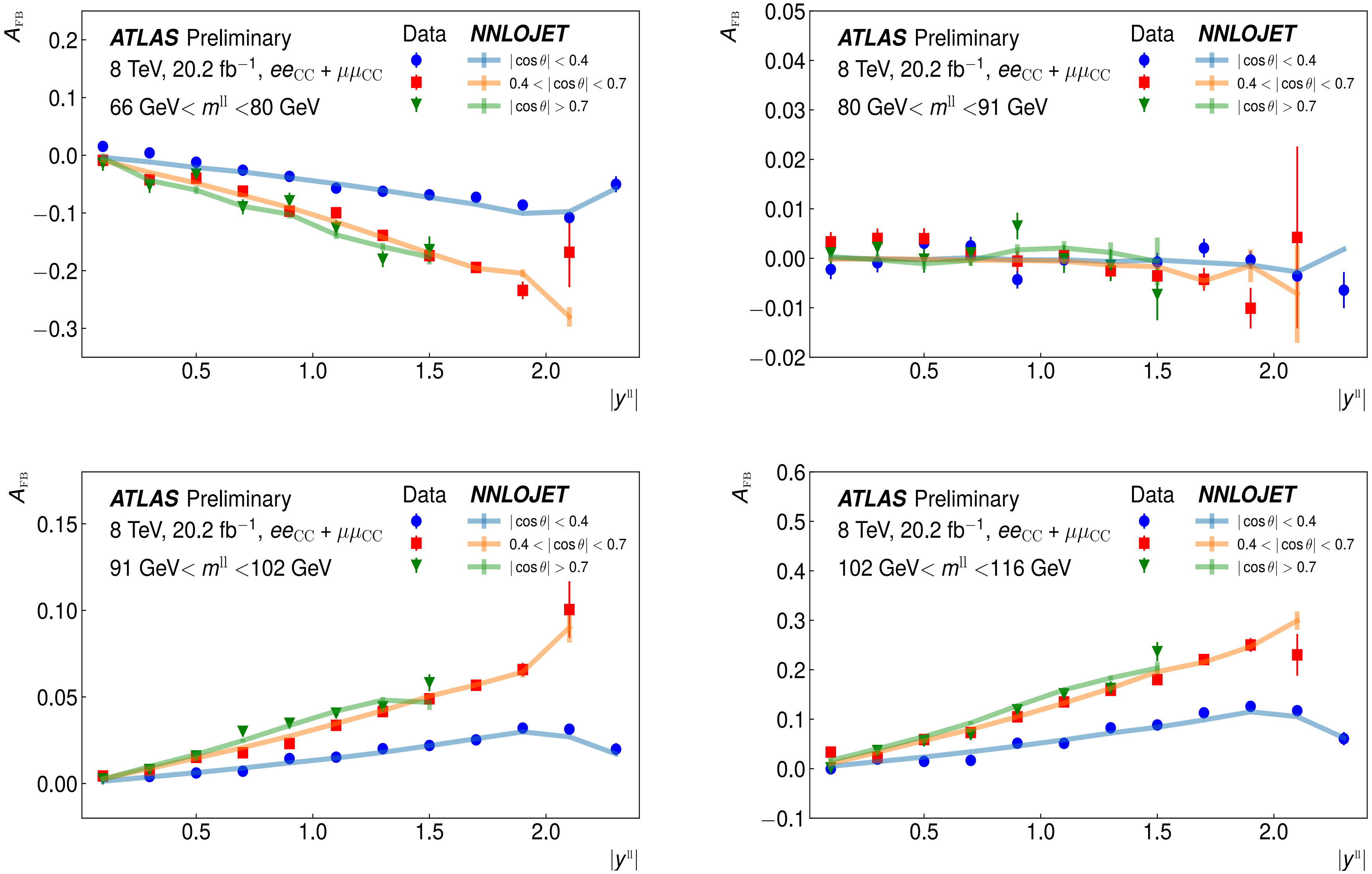
Observe large theory stat & scale errors in “forbidden region” predictions

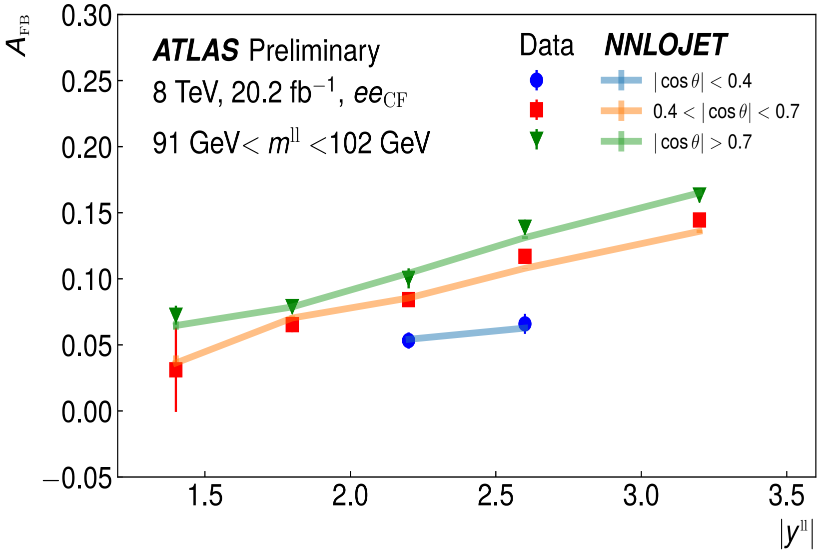
⇒ Use differential A_{FB} in “forbidden region”
Scale uncertainty cancels in A_{FB}
All data points can be used in fit

scale choice $\mu^2 = m^2 + p^2_{T,ll}$
Equivalent to m^2 at LO
Apt choice for recoil jet topology

Extracting $\sin^2\theta_{eff}$ — $d^3\sigma$

ATLAS-CONF-2018-037/





Data	***NNLOJET***	
●	━	$|\cos\theta| < 0.4$
■	━	$0.4 < |\cos\theta| < 0.7$
▼	━	$|\cos\theta| > 0.7$

Triple differential $A_{FB}(m,|y|, \cos\theta^*)$

$|A_{FB}|$ increases with y

A_{FB} negative $m<m_Z$

Smallest for cos θ* ~ 0

Use predictions of differential $A_{FB}(m,|y|, \cos\theta^*)$ from NNLOjet
i.e. defined in slices of equal |cosθ*|

Apply identical event reweighting to vary $\sin^2\theta_{eff}$
for NLO EW effects in Improved Born Approximation (IBA)

Extracting $\sin^2\theta_{eff}$ — Angular Coefficients

ATLAS-CONF-2018-037/

ATLAS uses 2 methods (same data set / similar selections):

- Perform fit to unfolded A_{FB} from $d^3\sigma$ cross sections differential in m,|y|, cosθ*
- Ai - Angular coefficient analysis (methodology used here arXiv:1606.00689)

Angular Coefficients

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$

$$+\frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$

$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}$$

factorised production dynamics from decay kinematics

Full 5d cross section decomposed into
9 polynomials & 9 coefficients $A_i(m,y,pT)$
Description is complete to all orders in QCD
- only in full phase space of decay leptons

$$A_{FB} = \frac{8}{3}A_4$$

in full phase space

A_3 and A_4 related to $\sin^2\theta_{eff}$
(A_3 contributes for
$p_{T,Z}$ > 100 GeV)

Using y and m binned data allows PDFs to be profiled Bin data in m, |y|

CC (x2 channels):
m:- {70, 80, 100, 125} GeV
|y|:- {0.0, 0.8, 1.6, 2.5}

CF
m:- {80, 100} GeV
|y|:- {1.6, 2.5, 3.6}

Extracting $\sin^2\theta_{eff}$ — Angular Coefficients

Analysis method uses folded MC templates in full phase-space

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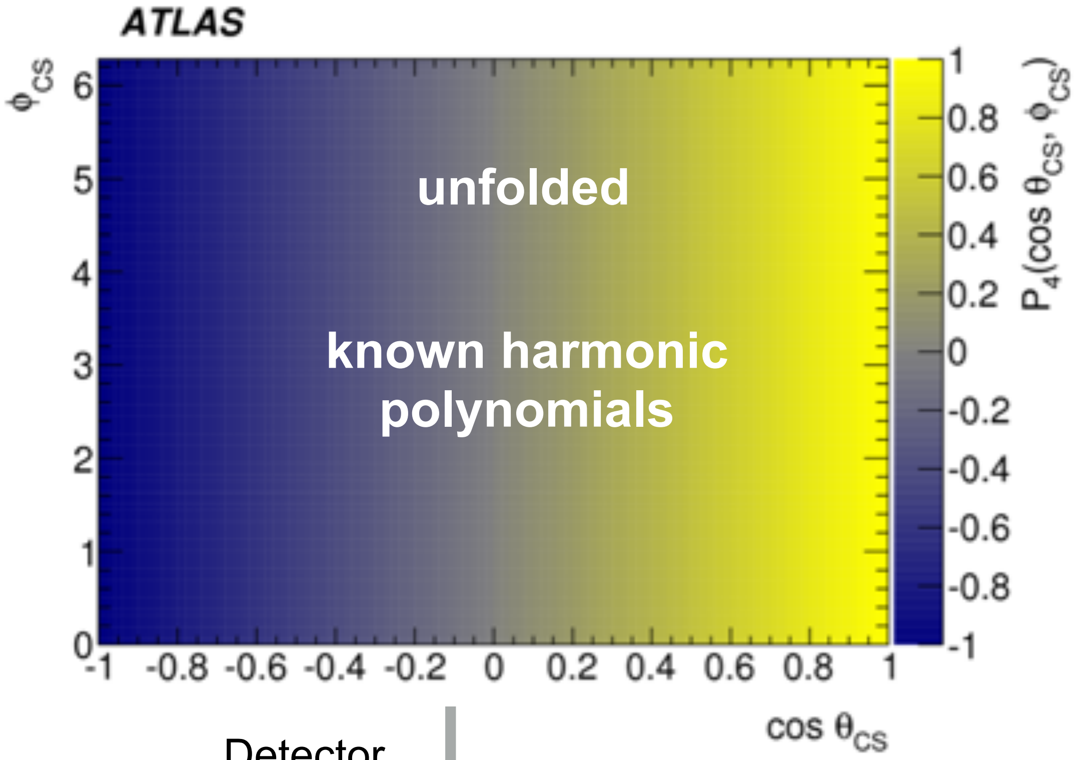
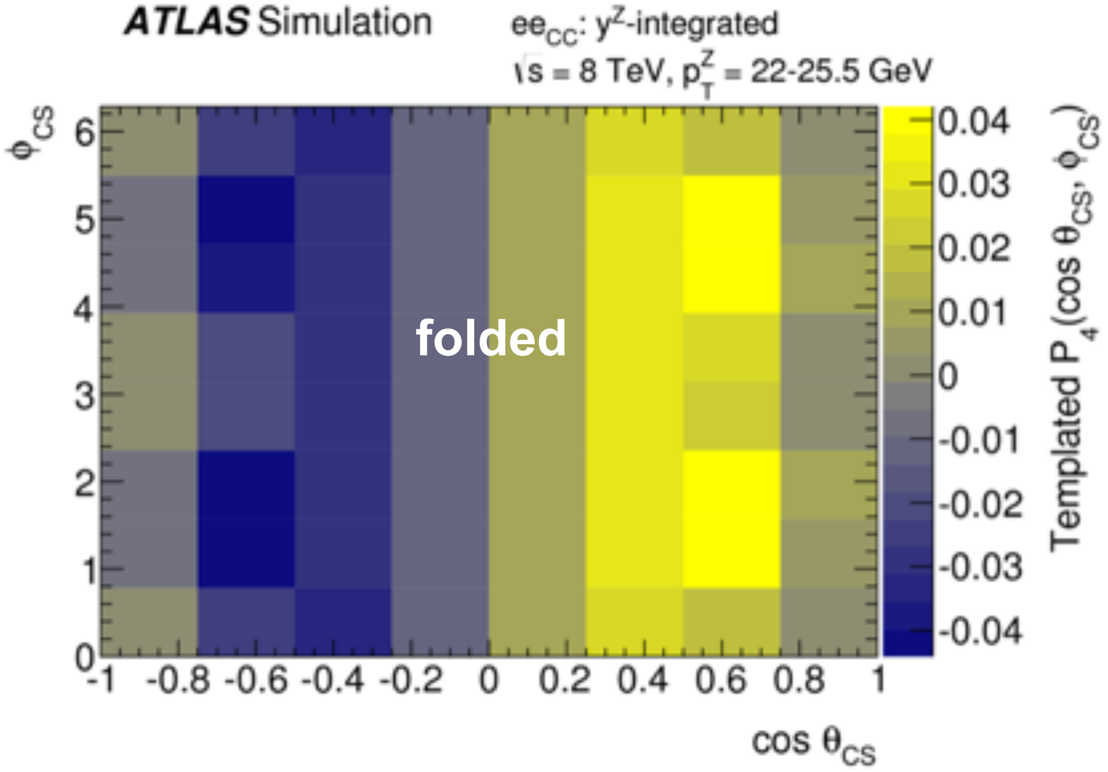


unfolded

known harmonic polynomials

Detector simulation

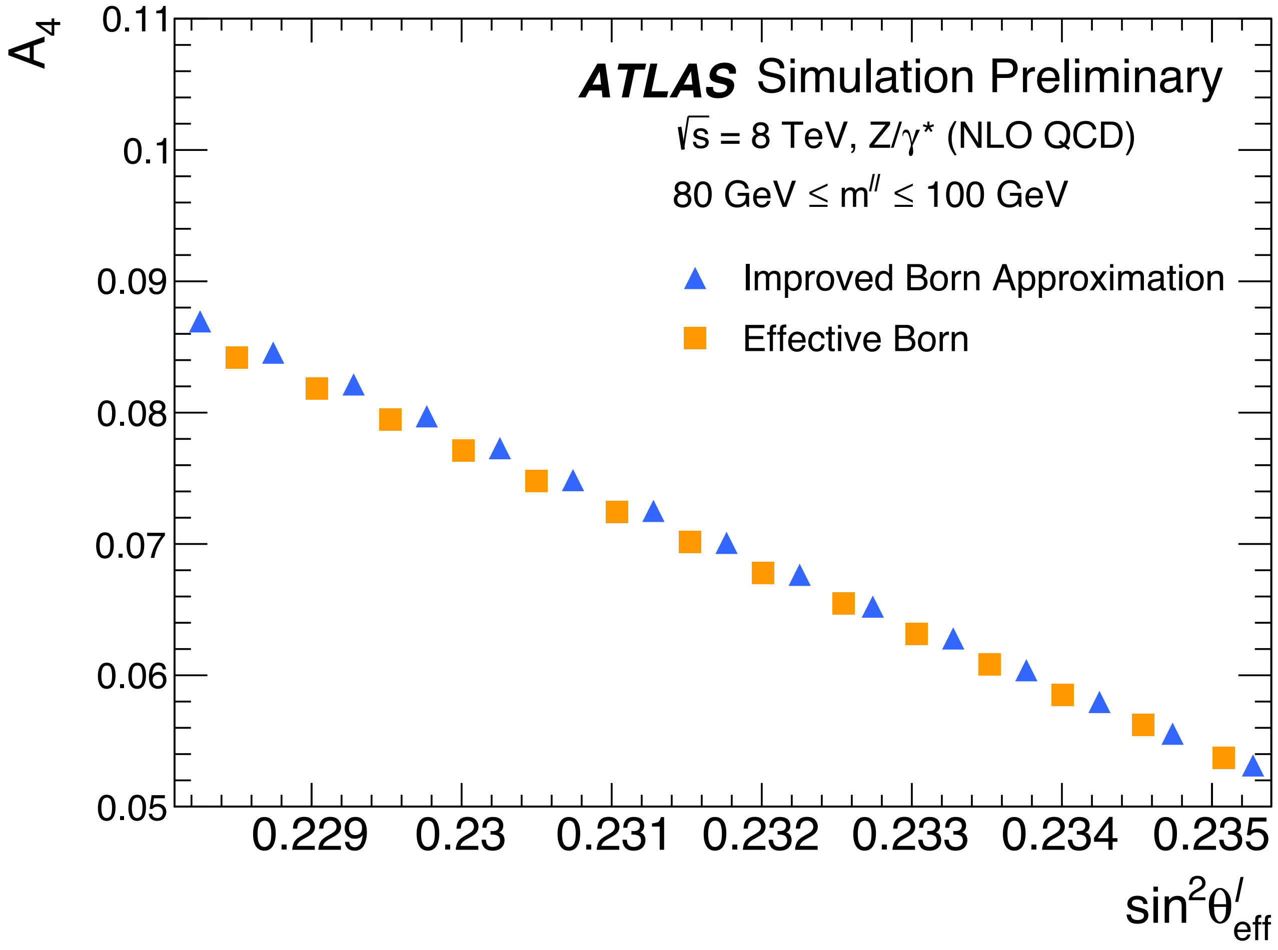


folded

Perform likelihood fits to folded templates on m & |y| bins
Use event-wise reweighting to vary $\sin^2\theta_{eff}$ in templates
Like performing analytic interpolation:

- known harmonic polynomials fitted to data
- reduces PDF sensitivity

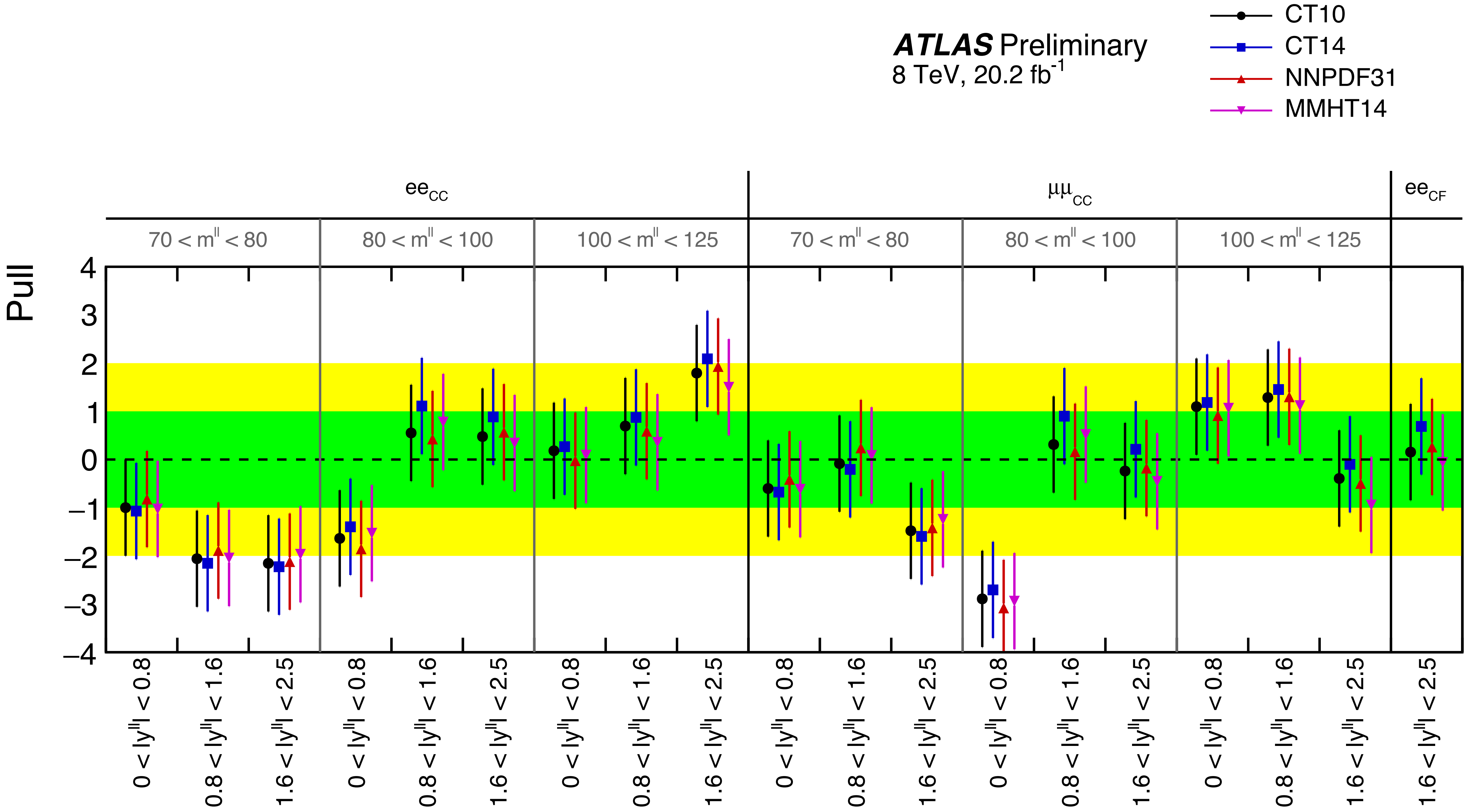
Use linear interpolation model to extract $\sin^2\theta_{eff}$



Extracting $\sin^2\theta_{eff}$ — Angular Coefficients

ATLAS-CONF-2018-037/

Consistency checks: pull of $\sin^2\theta_{eff}$ for different data sub-sets



Extracting $\sin^2\theta_{\text{eff}}$ — Angular Coefficients

ATLAS-CONF-2018-037/

Uncertainties on $\sin^2\theta_{\text{eff}}$ x 10^{-5}

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_{T}^{Z} modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

Extracted value / uncertainties of $\sin^2\theta_{\text{eff}}$ from $d^3\sigma$ agrees with angular analysis
Better precision from CF channel than CC (higher sensitivity / less dilution)
Dominated by PDF uncertainty
Sizeable uncertainty from data statistics

ATLAS $\sin^2\theta_{\mathrm{eff}}$ $\sqrt{s}$ = 8 TeV

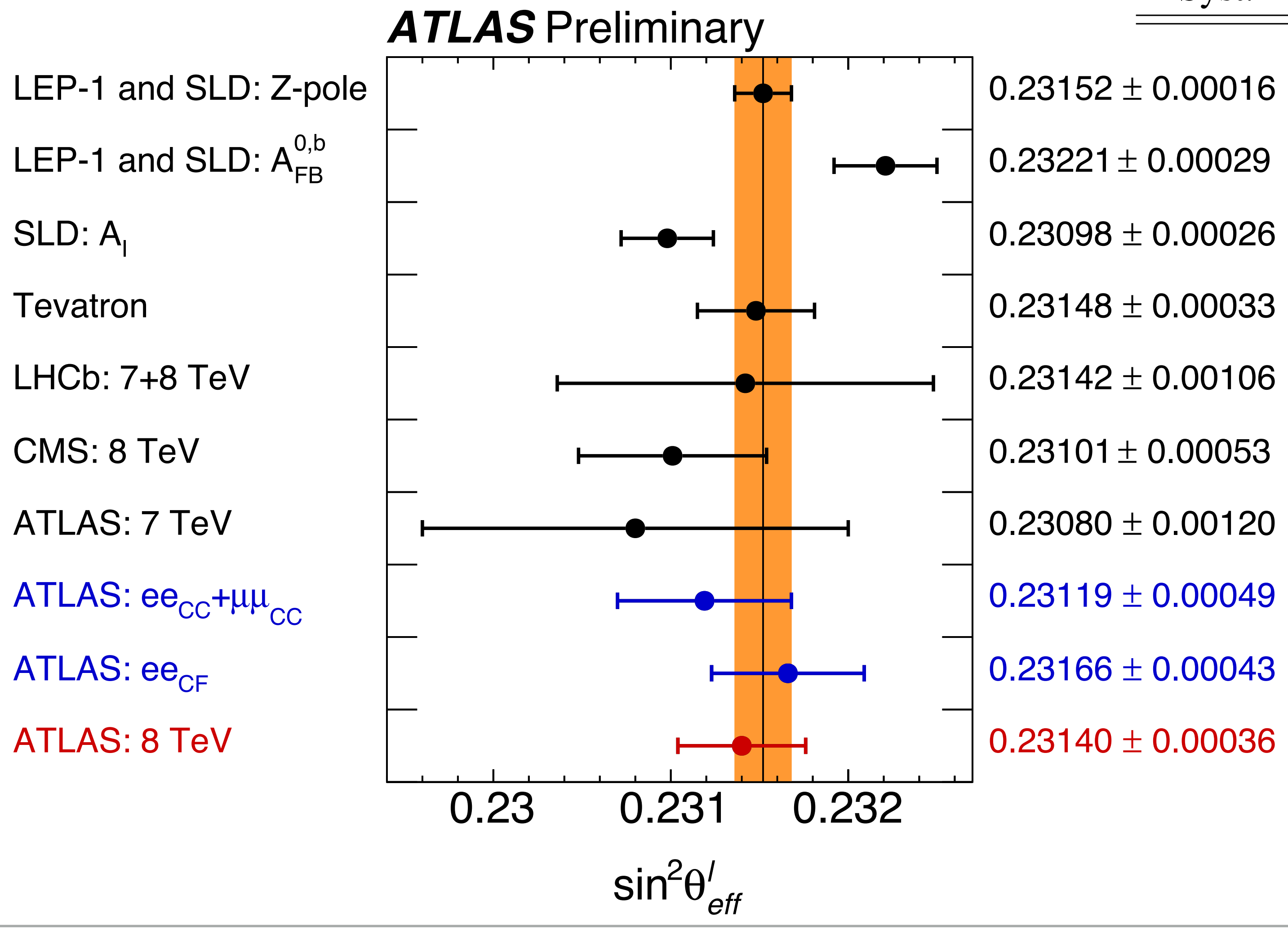
ATLAS-CONF-2018-037/

$$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23140 \pm 0.00021\,(\mathrm{stat.}) \pm 0.00024\,(\mathrm{PDF}) \pm 0.00016\,(\mathrm{syst.})$$

ATLAS reaches precision of single LEP/SLD experiments and combined CDF/D0 precision

	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^{\ell}_{\mathrm{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

x 10^{-5}



Preliminary result
Released at ICHEP 2018

Summary - II

ATLAS determination of $\sin^2\theta_{\text{eff}}$ is nearing completion

Timescale - aim for final publication spring 2019

More detailed validation of DYTurbo vs NNLOjet

cross sections have larger
PDF sensitivity allowing
in-situ PDF constraints

Triple Differential cross-section method:

- Use NNLO Z+j predictions in “forbidden region” ?
- use mixed method:
  - fit $A_{FB}(m,|y|,|\cos\theta^*|)$ for $|\cos\theta^*| < 0.4$ & $m < 66$ GeV
  - fit $d^3\sigma$ for $m > 66$ GeV & $|\cos\theta^*| < 0.4$
  - (we already did this and find PDF uncertainty is reduced!)
- using full $d^3\sigma$ in fit yields smallest PDF uncertainty
- perform complete NNLO QCD fit (not PDF profiling)

angular coefficients reduce
PDF sensitivity through
known harmonic polynomials

Angular coefficients method:

- adjust to $d^3\sigma$ experimental selection
- evaluate statistical uncertainty with bootstraps
- a few experimental checks to complete (SFs etc)
- PDF profiling tests
- PDF reweighting tests
- include A_3 ?

Project is actively pursued in LPCC Electroweak Working Group: ATLAS / CMS / LHCb / Theory

Much to be gained from LHC combination
- LHCb has higher y acceptance (but lower luminosity)
- CMS measurement has no ‘forward’ acceptance but complementary central channel

Now have 150 fb^{-1} of data at $\sqrt{s}=13$ TeV → factor 15 higher statistical sample (incl factor 2 from cross section)
…but larger $\sqrt{s}$ means lower x → worse dilution

Backup

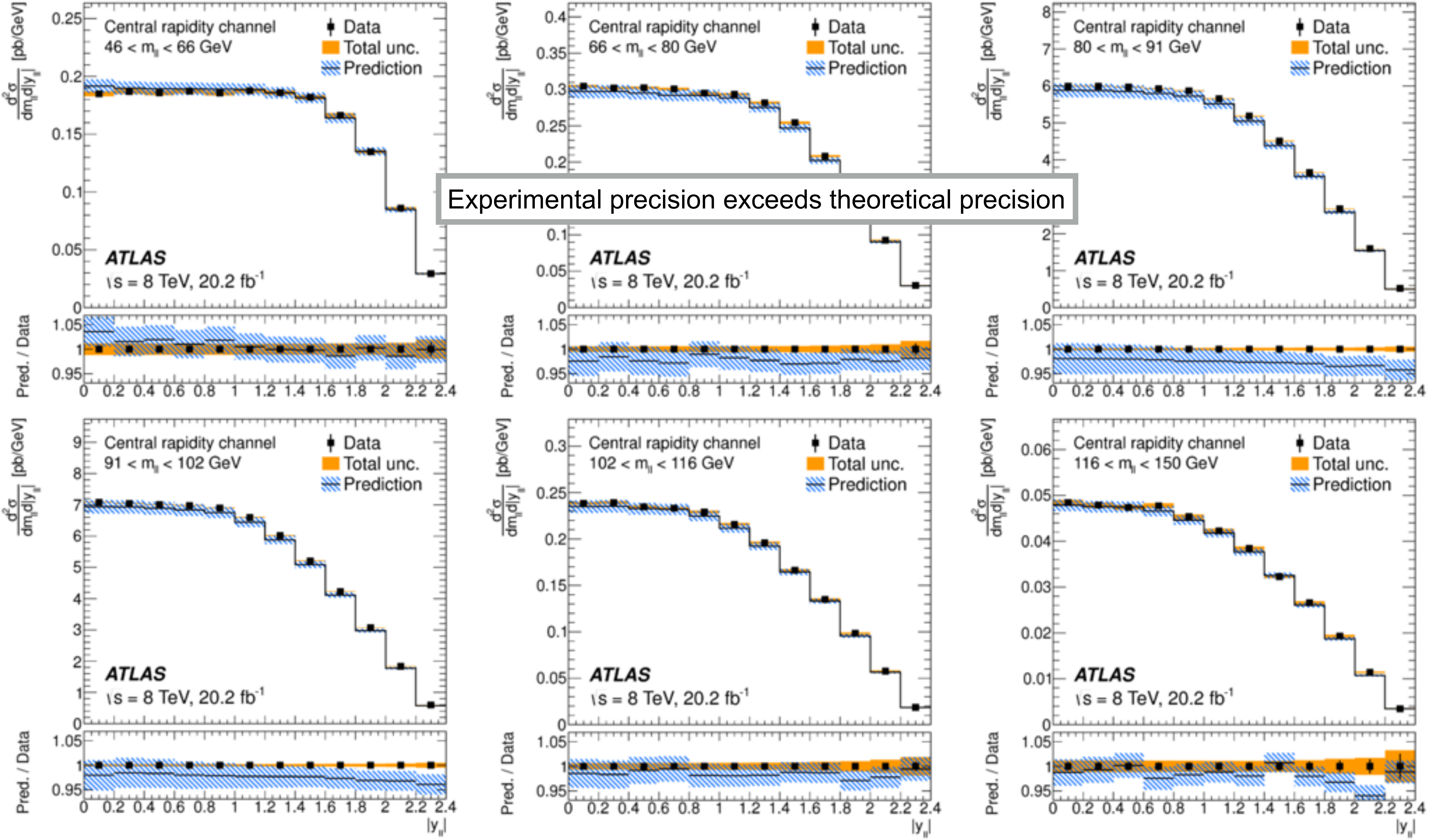
Double-differential Z/γ* Cross Sections √s = 8 TeV

Integrated double-differential cross section

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

electron & muon channel combination

χ^2/ndf = 103.4/84



Experimental precision exceeds theoretical precision

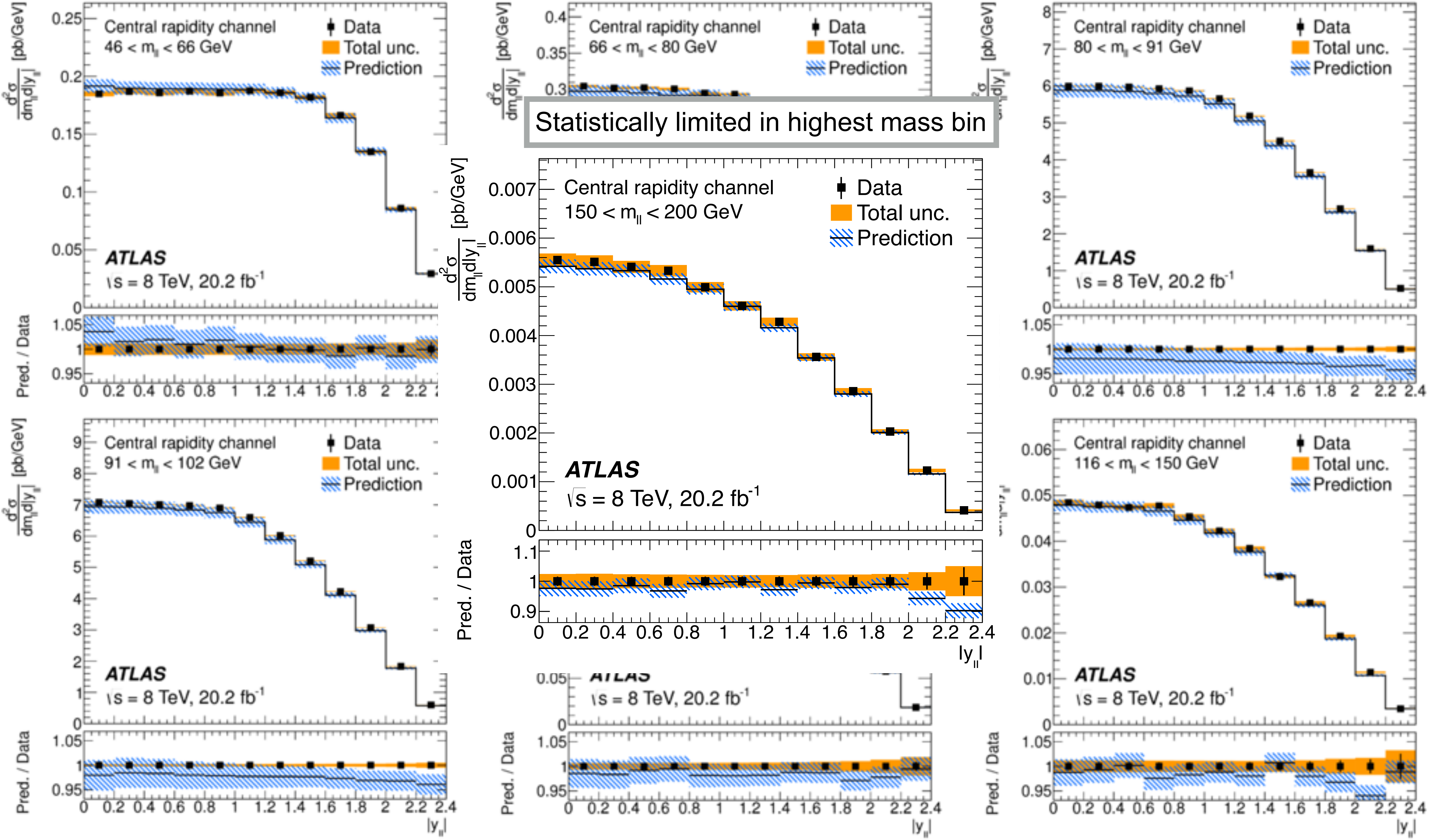
Double-differential Z/γ* Cross Sections √s = 8 TeV

Integrated double-differential cross section

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

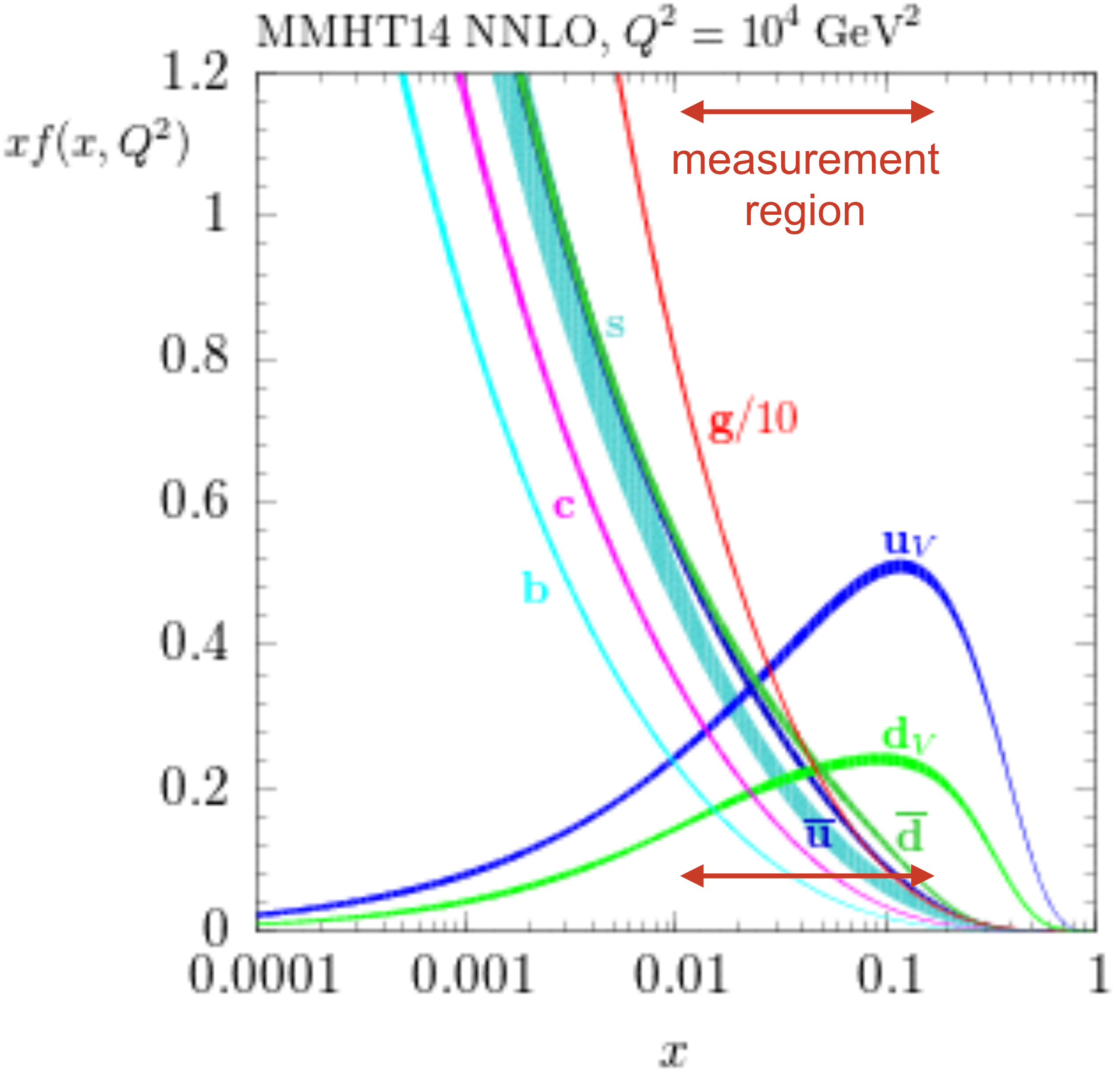
electron & muon channel combination

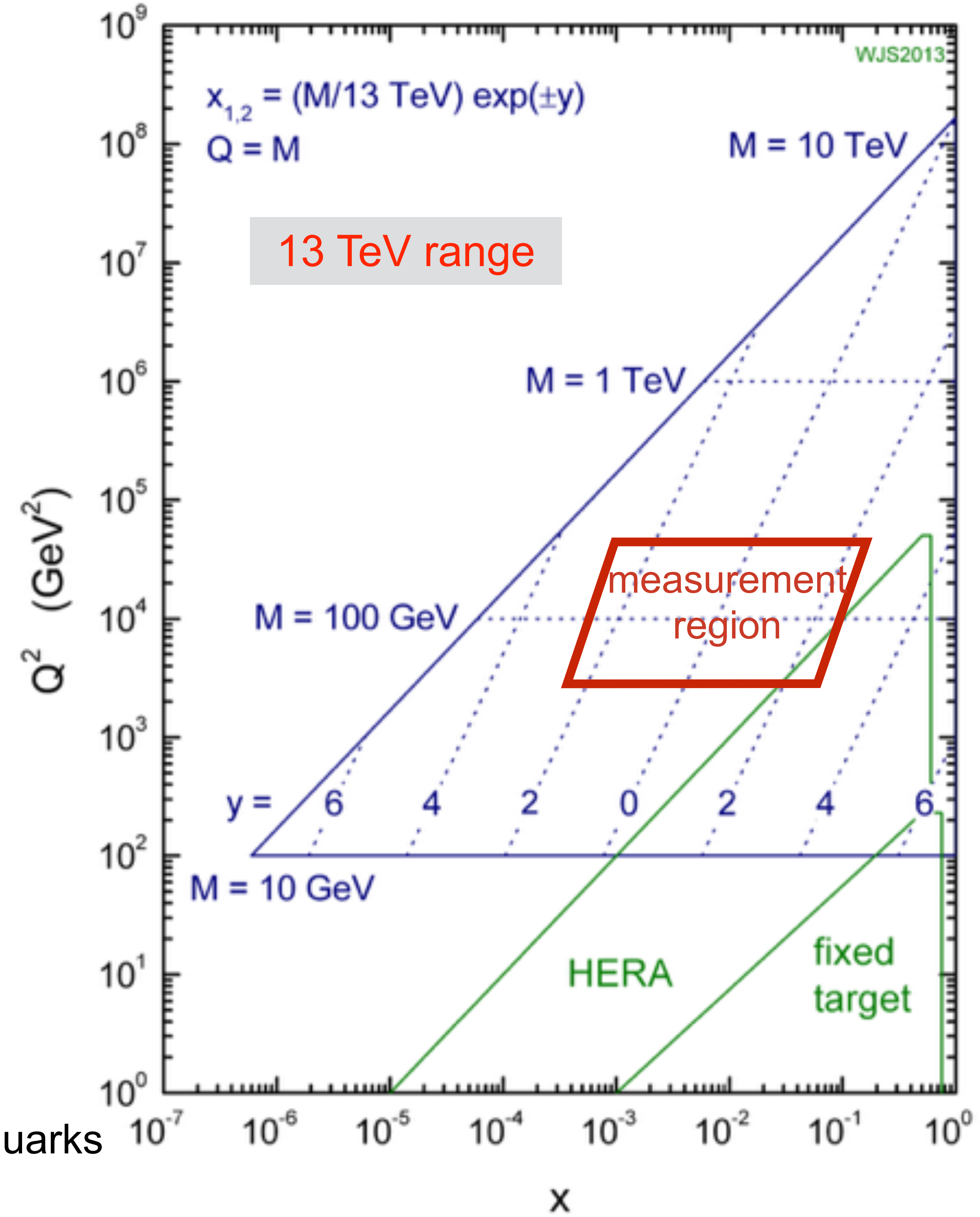
χ^2/ndf = 103.4/84



Statistically limited in highest mass bin

Extracting $\sin^2\theta_{eff}$ — PDFs





parton momentum fraction of proton

In pp Drell-Yan collisions we do not know direction of incoming quark → ambiguity in defining cos θ*

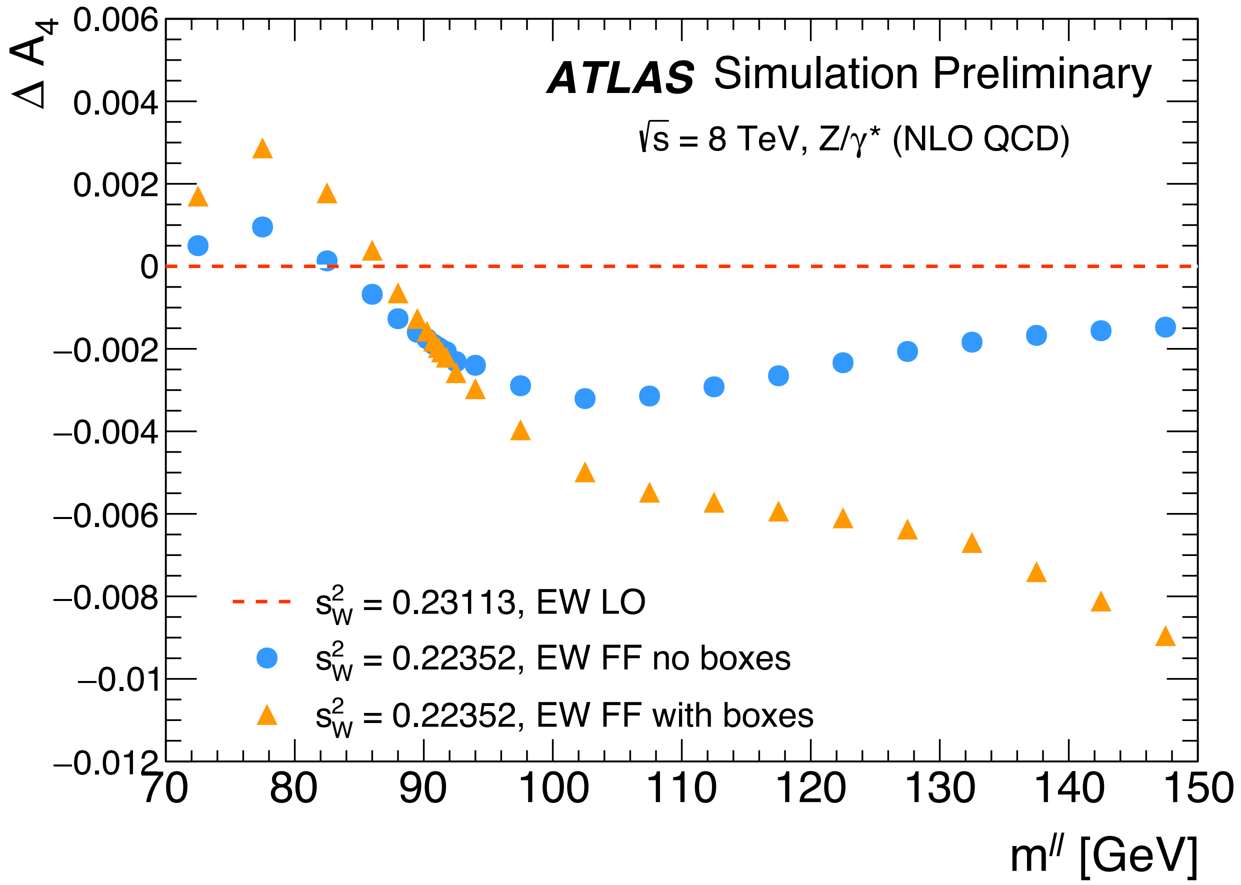
Rely on valence quarks! At high x quarks dominate not anti-quarks

$$x_{1,2} = \frac{m}{\sqrt{s}} \exp^{\pm y}$$

Large |y| → large x
less dilution

NLO EW Corrections

Change to A4 using NLO corrections



NNLO QCD predictions determined using LO EW theory

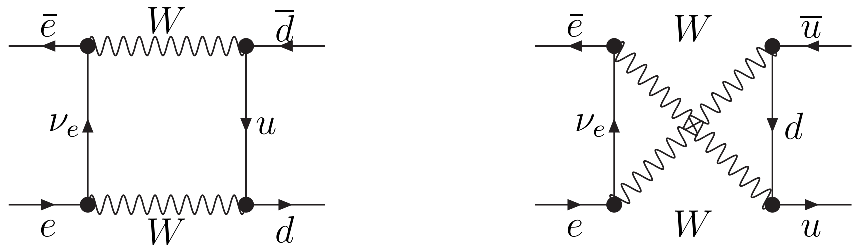
Close to Z pole:

- QED corrections can be factorised from higher order EW corrections

Improved Born Approximation absorbs NLO EW effects into form factors

Initial / final state QED/QCD radiative effects are factorised

weak boson box diagrams

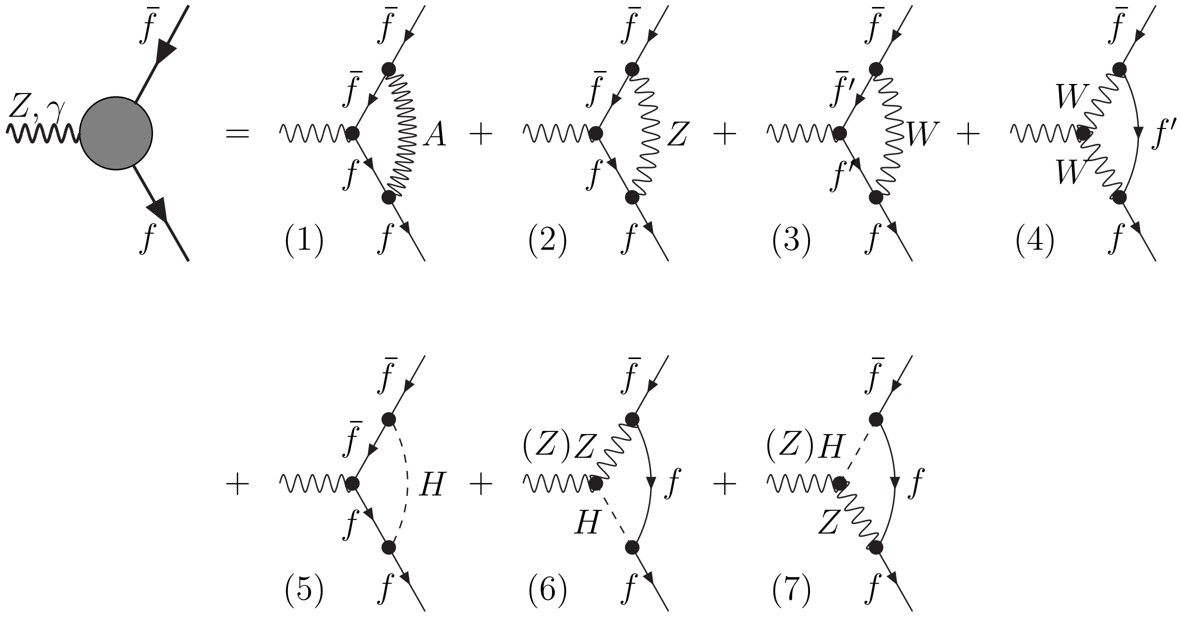


calculation performed using DIZET library 6.21

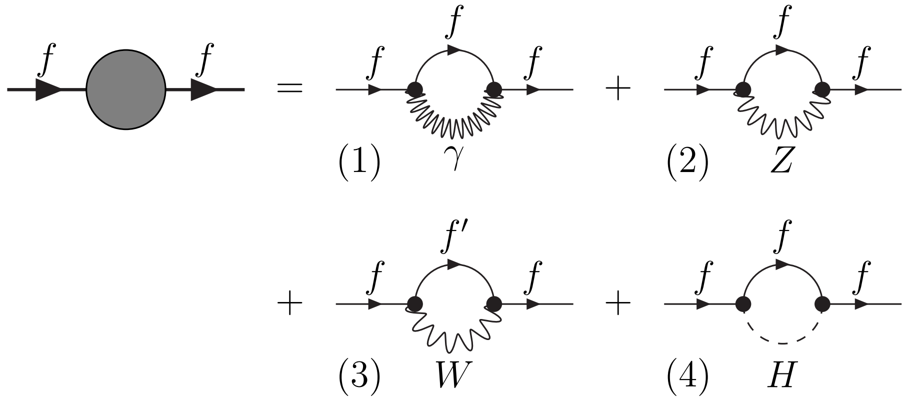
Parameter	Value	Description
	Measured	
m_Z	91.1876 GeV	Mass of Z boson
m_H	125.0 GeV	Mass of Higgs boson
m_t	173.0 GeV	Mass of top quark
m_b	4.7 GeV	Mass of b quark
$1/\alpha(0)$	137.0359895(61)	QED coupling constant in Thomson limit
G_μ	$1.166389(22) \cdot 10^{-5}$ GeV^{-2}	Fermi constant from muon lifetime
	Calculated	
m_W	80.353 GeV	Mass of W boson
$\sin^2\theta_W$	0.22351946	On mass-shell-value of weak mixing angle
$\alpha(m_Z^2)$	0.00775995	
$1/\alpha(m_Z^2)$	128.86674175	
$ZPAR(6) - ZPAR(8)$	0.23175990	$sin^2\theta^{\ell}_{eff}(m_Z^2)$ (e,μ,τ)
$ZPAR(9)$	0.23164930	$sin^2\theta^{u}_{eff}(m_Z^2)$ (up quark)
$ZPAR(10)$	0.23152214	$sin^2\theta^{d}_{eff}(m_Z^2)$ (down quark)

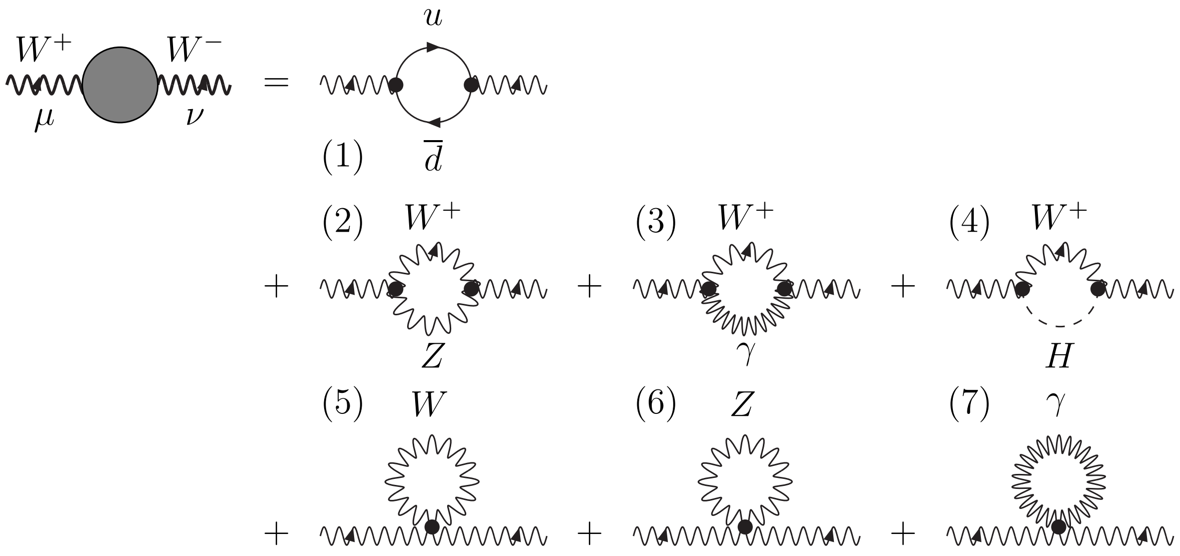
NLO EW Corrections

Z→ ff corrections

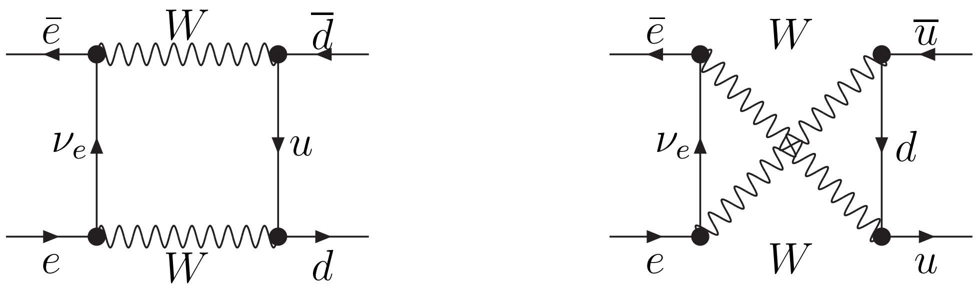


fermionic self-energy corrections



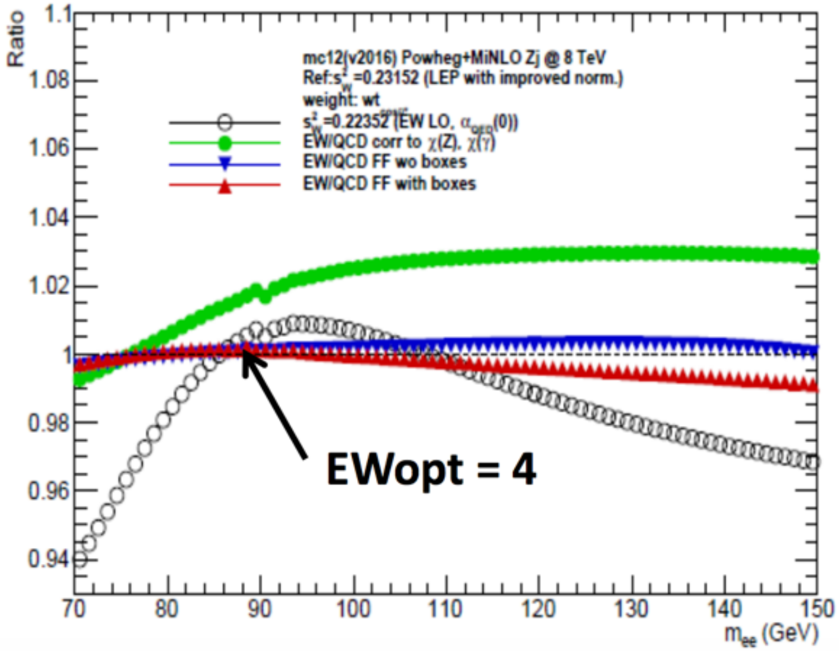


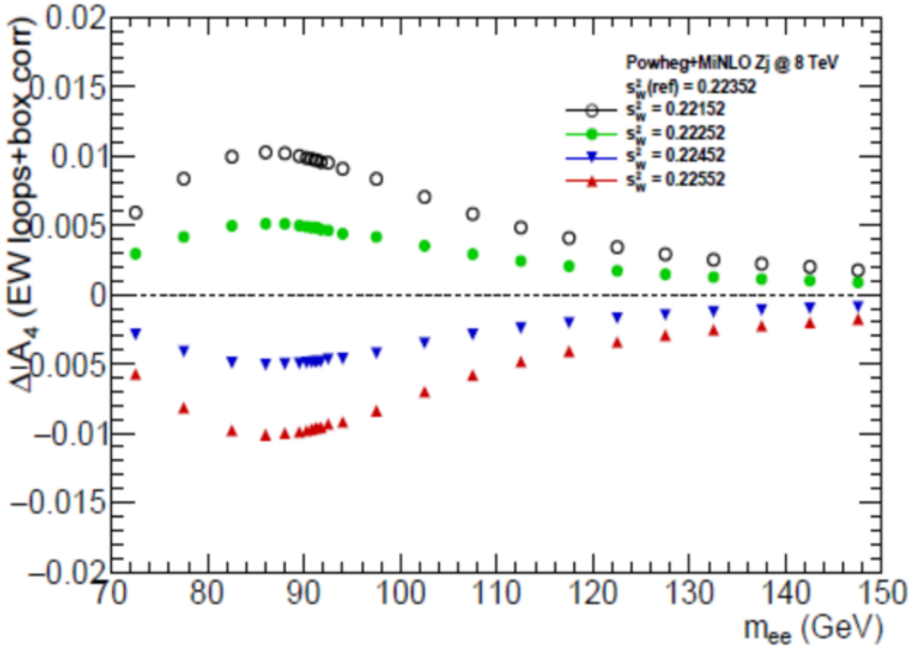
boson self-energy corrections



W and Z box diagrams

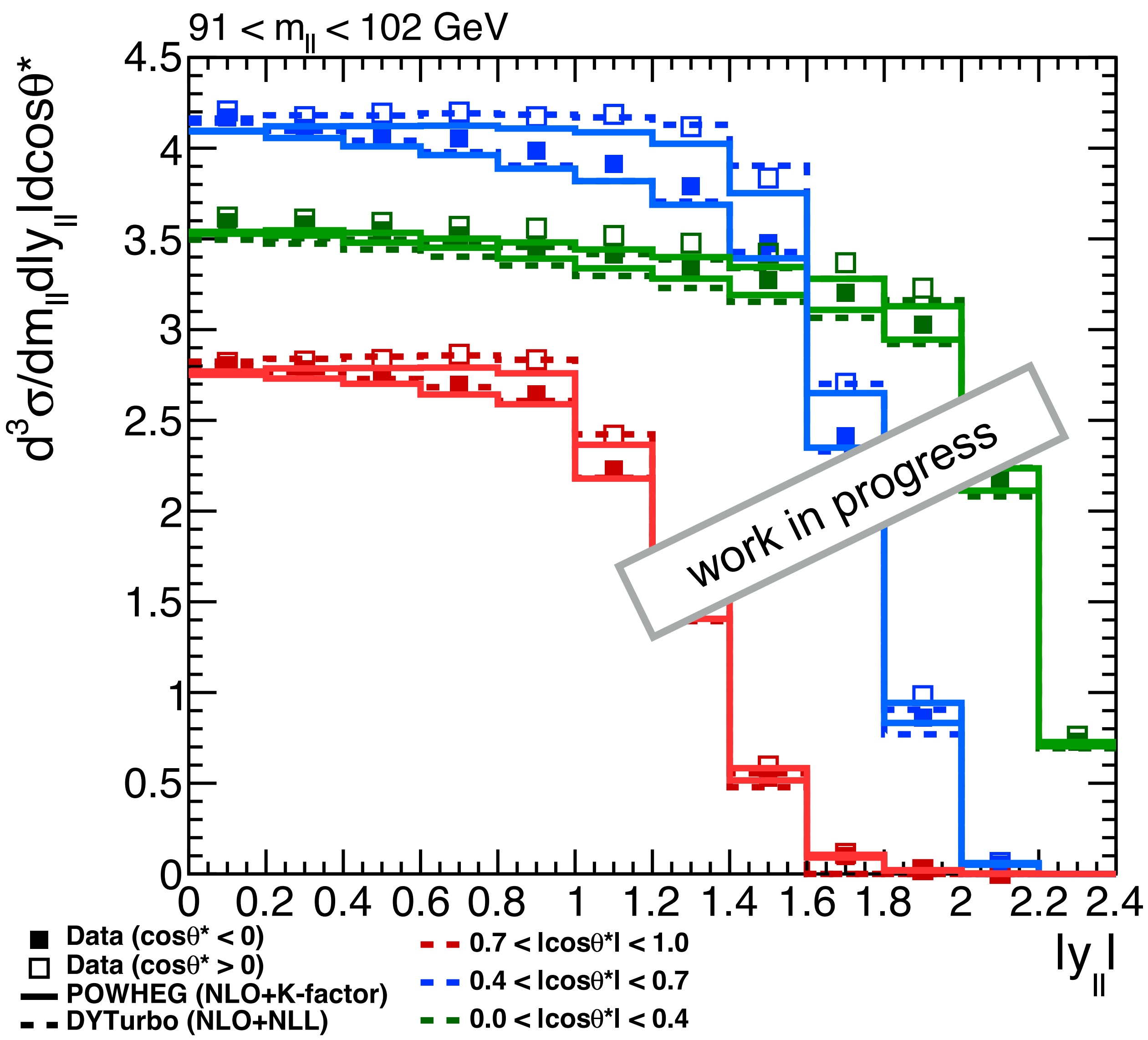
EW Corrections



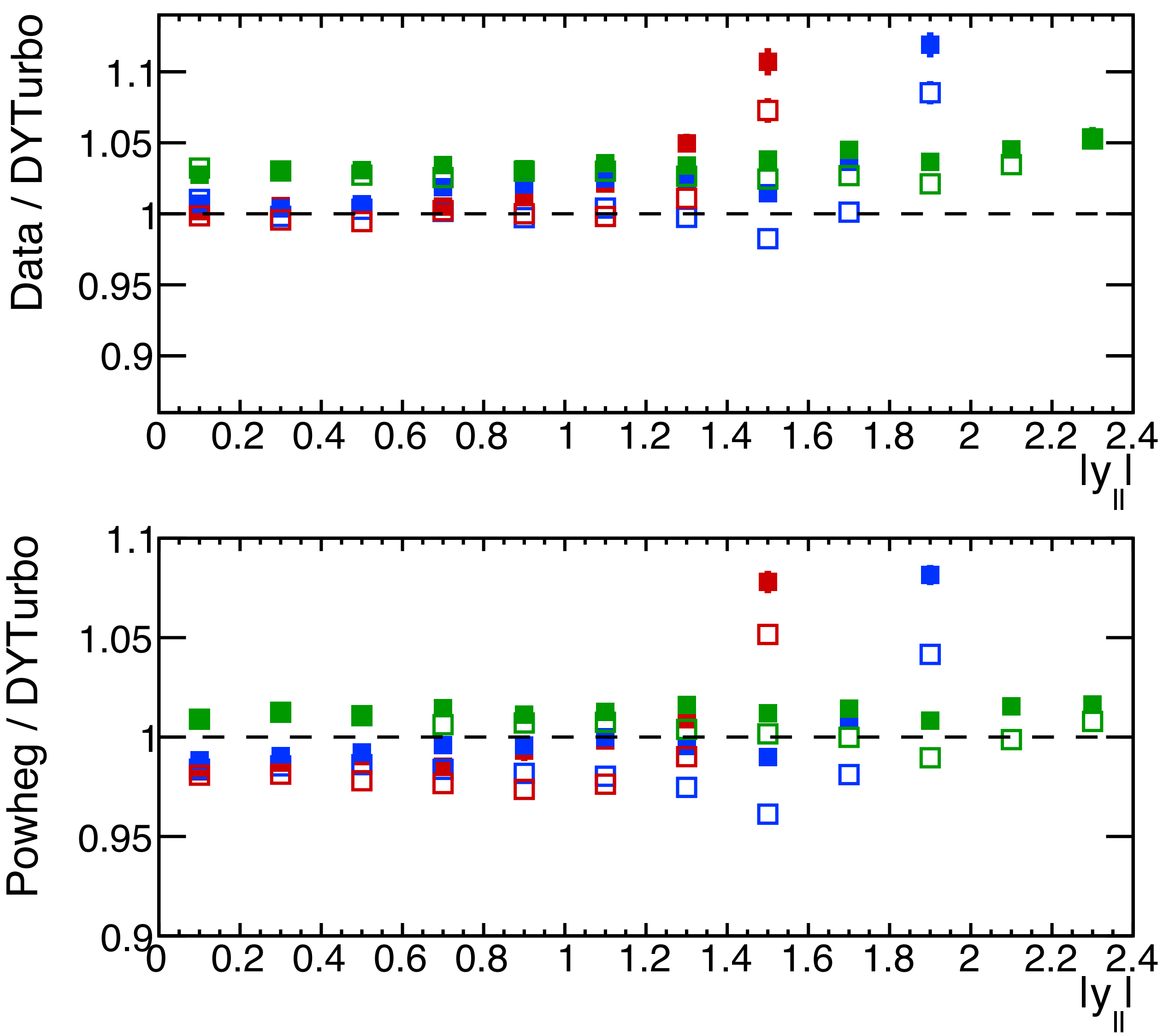


- Existing MC samples used for analysis are missing higher order EW corrections
- Factorize gauge invariant set of EW corrections from QCD, and interface with existing MC samples via “after-burn” approach
  - Interface to DIZET and KKMC libraries adapted to pp collisions, developed for LEP, to compute EW form factors
    - Exact O(α) + higher order terms
    - Dependent on event kinematics s, t = s*(1-cosθ)/2
  - Insert as event weights in MC sample
- Weights can also be embedded for effective (LO) EW scheme
    - Difference between this and EW FF is quoted to be ~22*10^{-5} for Tevatron and CMS (studies ongoing to confirm)
- Allows us to study EW effects at the per-mil level, and scan $\sin^2\theta_W$ within a single MC sample
- Studies to be done cross-checking with PowhegEW generator
- More detailed info here. **Will have dedicated talk in next meeting from Elzbieta!**

Extracting $\sin^2\theta_{eff}$ — QCD predictions



DYTurbo - Stefano Camarda



Initial comparisons of DYTurbo (NLO+NLL) with Powheg (NLO x [NNLO ⊗ NLO EW] k-factor)

Prediction code needs tuning / optimisation for:

- integration time & precision for fiducial $d^3\sigma$
- large QCD scale μ_R & μ_F dependence observed in some kinematic regions
- optimisation of resummation scale μ_{Resum} in NLL

Could indicate improved resummation is needed (move to NNLL?)

Extracting $\sin^2\theta_{eff}$ — QCD predictions

New ATLAS method:

Perform QCD & EW fit to $d^3\sigma$ cross sections differential in m,|y|, cosθ*

Ai - Angular coefficient analysis (methodology used here arXiv:1606.00689)

Target precision on $\sin^2\theta_{eff}$ about 30×10^{-5} (total uncertainty) :

- use large 20 fb^{-1} luminosity data sample at $\sqrt{s}$=8TeV
- include FCAL forward electron kinematic region - better sensitivity
- use unfolded $d^3\sigma$ to gain PDF sensitivity
- perform simultaneous fit to PDFs and $\sin^2\theta_{eff}$ on same data

Method combine best NNLO QCD & NLO EW predictions
Use xFitter framework to perform χ^2 fits
Use method of PDF profiling to optimise PDF eigenvalues arXiv:1402.6623
Account for correlated experimental systematics
Scan for optimum value of $\sin^2\theta_{eff}$

Ingredient list: State-of-the-art fiducial QCD predictions ⊗ NLO EW corrections

NLO (+ NLL ?)
NNLO (+ NNLL ?)

$d^3\sigma$ measurement is inclusive in $p_{T,Z}$
but resummations may be important in some kinematic regions

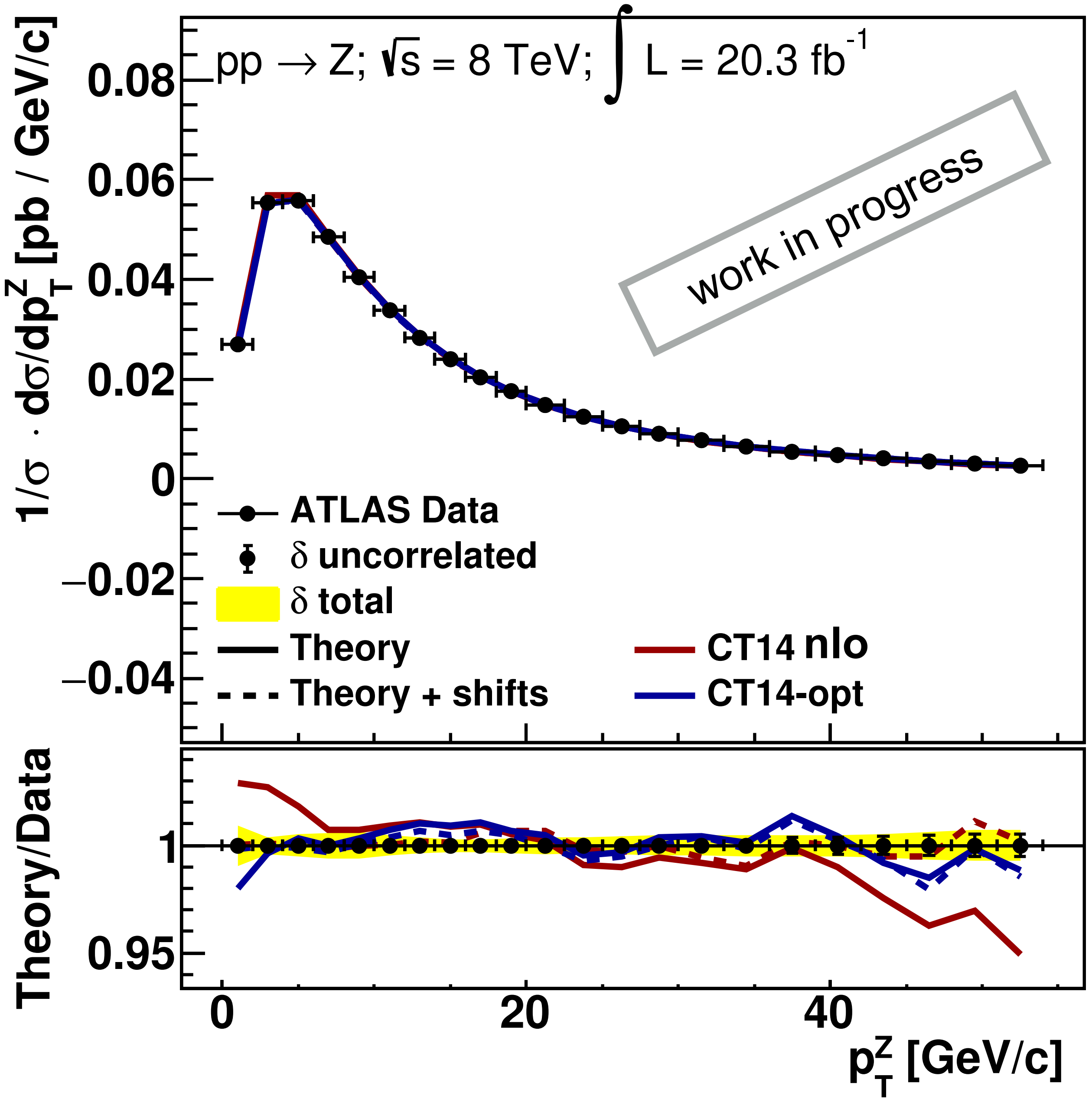
Toolkits:

DYTurbo : (NLO + NLL) or (NNLO + NNLL) resummation for small $p_{T,Z}$ predictions
MCFM: NLO
DYres:
Powheg: NLO + PS
NNLOjet: ??

This is very much work-in-progress !
Can illustrate status since $d^3\sigma$ cross sections are published

Extracting $\sin^2\theta_{eff}$ — QCD predictions

DYTurbo - Stefano Camarda
xFitter - Sasha Glazov & co



Tune resummation calculation on ATLAS 8 TeV Z p_T data

- non-perturbative parameter g
- μ_R & μ_F & μ_{Resum}

Default settings
$\mu_R = \mu_F = \mu_{Resum} = 0.5\ m_{ll}$
$g = 1.0\ GeV^2$

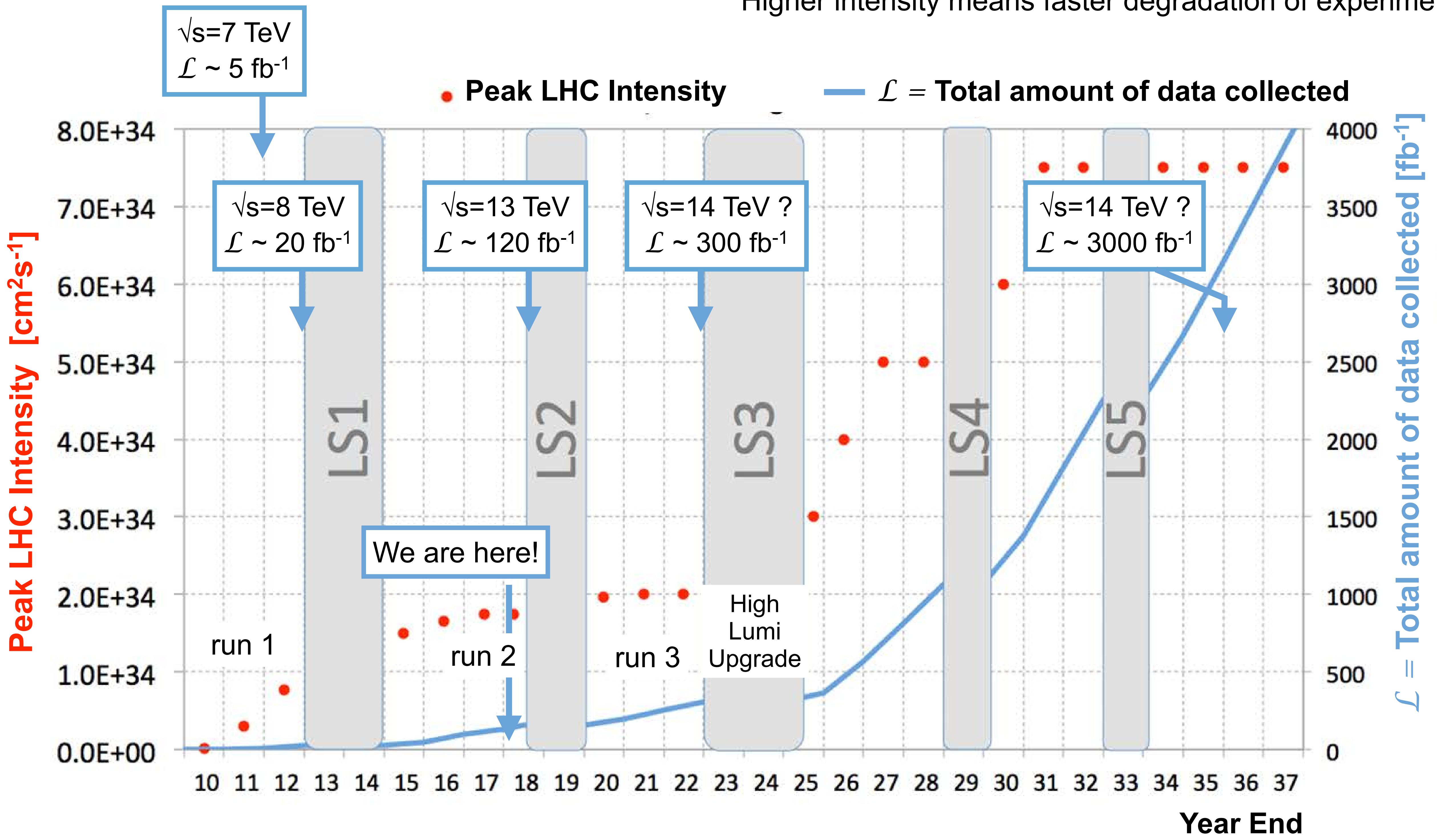
Initial optimisation prediction
$\mu_R = 0.34 \times m_{ll}$
$\mu_F = 0.49 \times m_{ll}$
$\mu_{Resum} = 0.41 \times m_{ll}$
$g = 1.04\ GeV^2$

Alternatively - switch to using A_{FB} in some regions where scale errors are large?

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



$\sqrt{s}$=7 TeV
$\mathcal{L}$ ~ 5 fb^{-1}

$\sqrt{s}$=8 TeV
$\mathcal{L}$ ~ 20 fb^{-1}

$\sqrt{s}$=13 TeV
$\mathcal{L}$ ~ 120 fb^{-1}

$\sqrt{s}$=14 TeV ?
$\mathcal{L}$ ~ 300 fb^{-1}

$\sqrt{s}$=14 TeV ?
$\mathcal{L}$ ~ 3000 fb^{-1}

We are here!

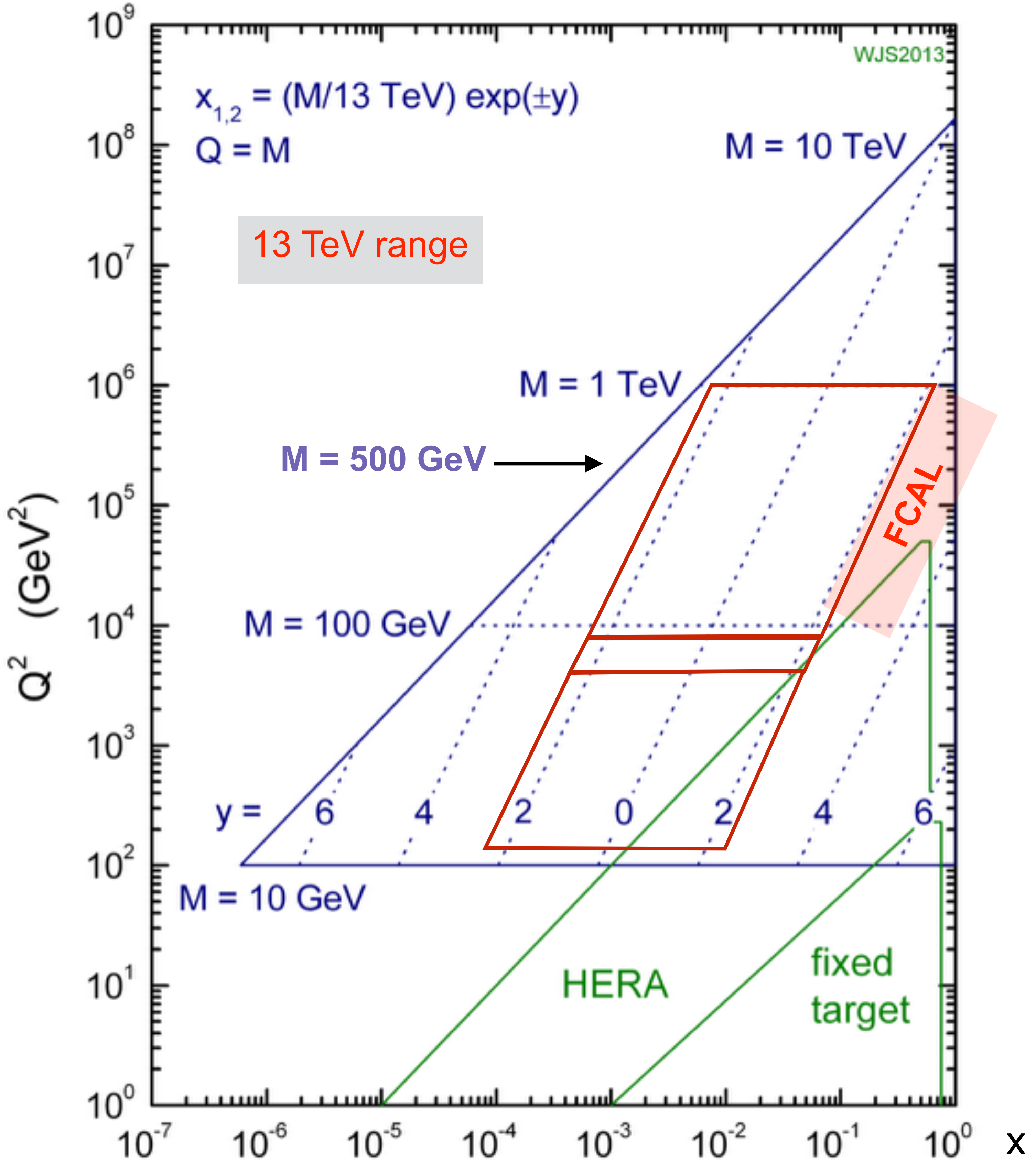
LS = Long Shutdown for repairs and upgrades

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



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…

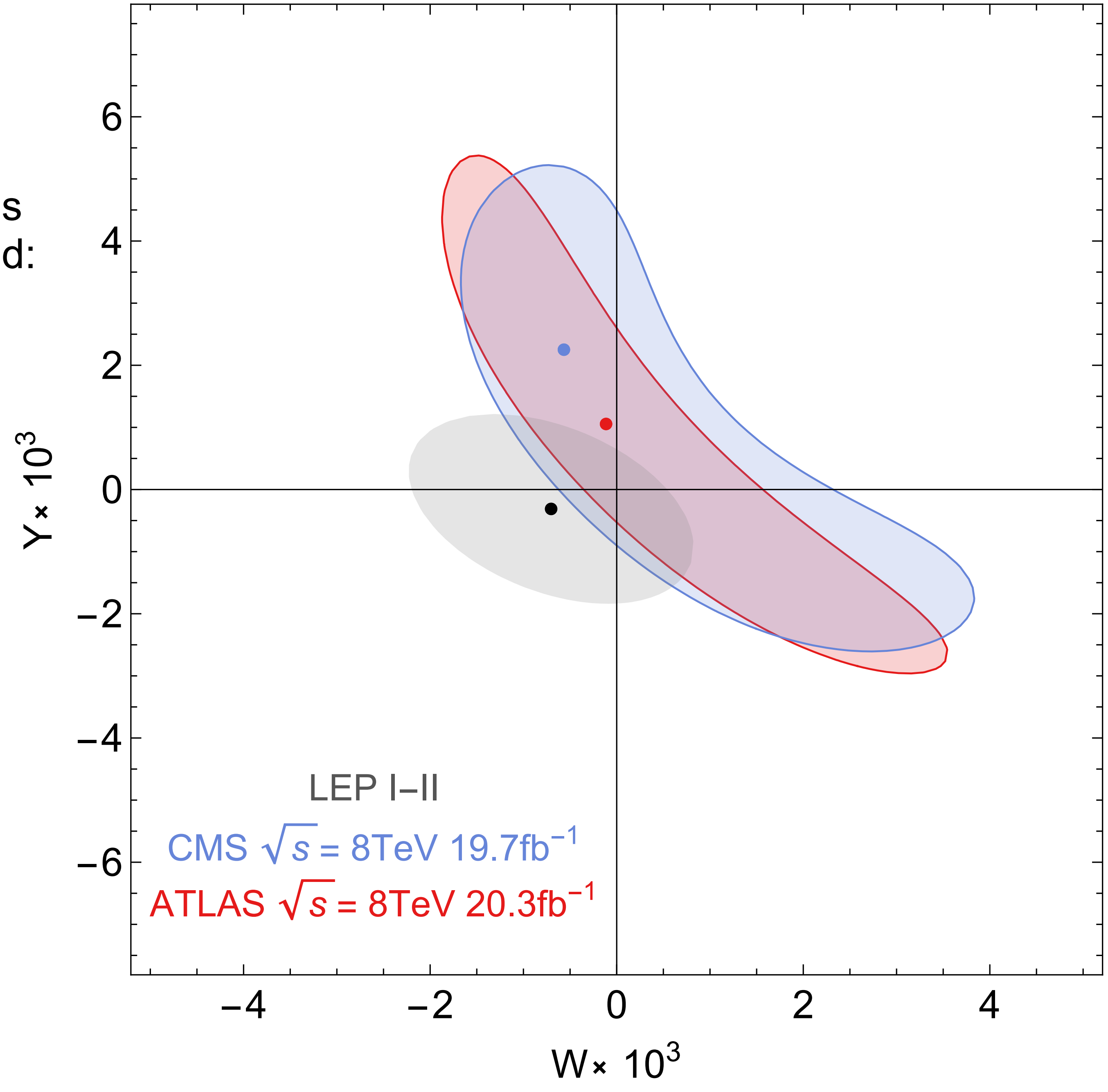
https://arxiv.org/abs/1609.08157

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

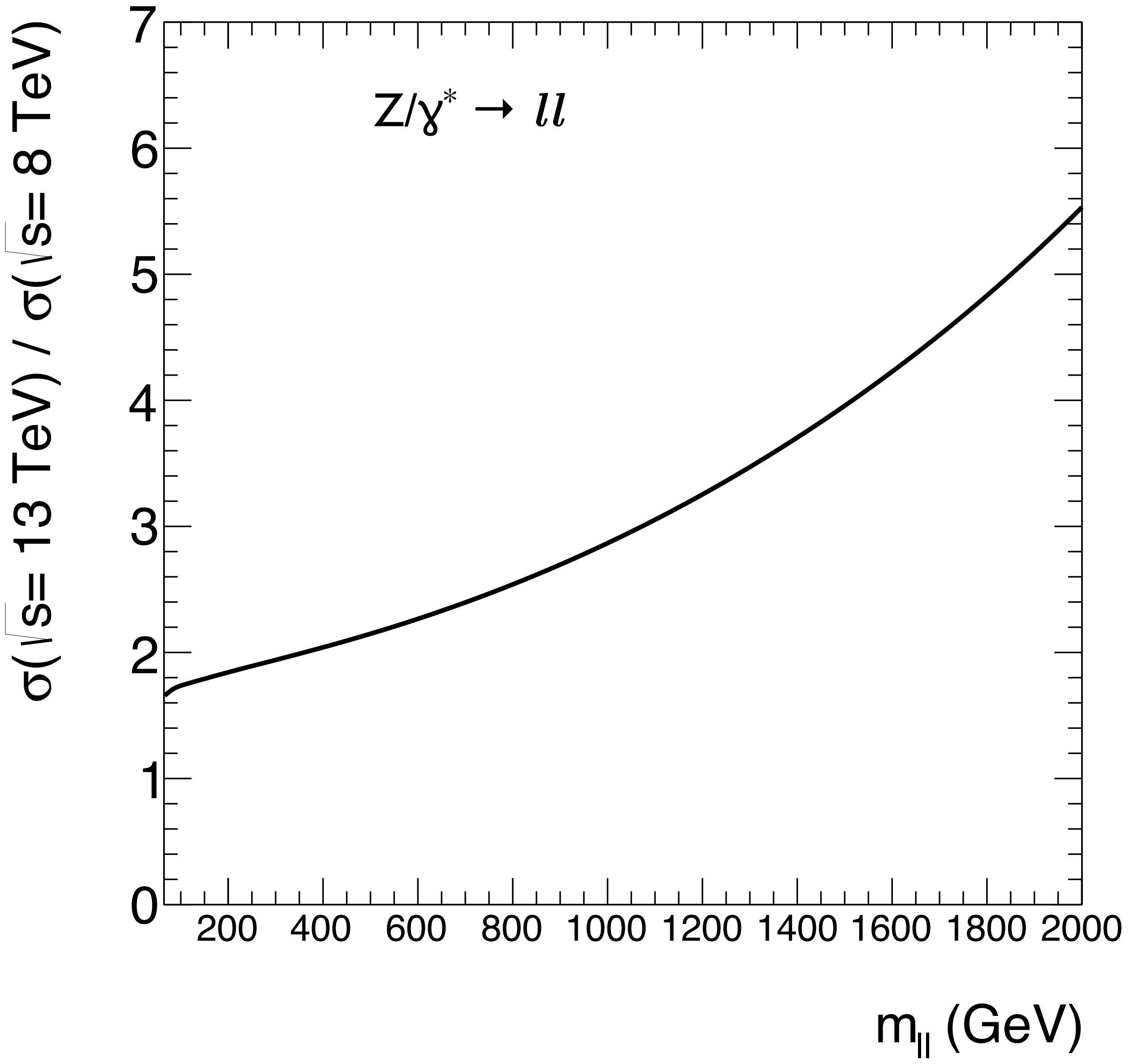
LHC data can help constrain Y & W

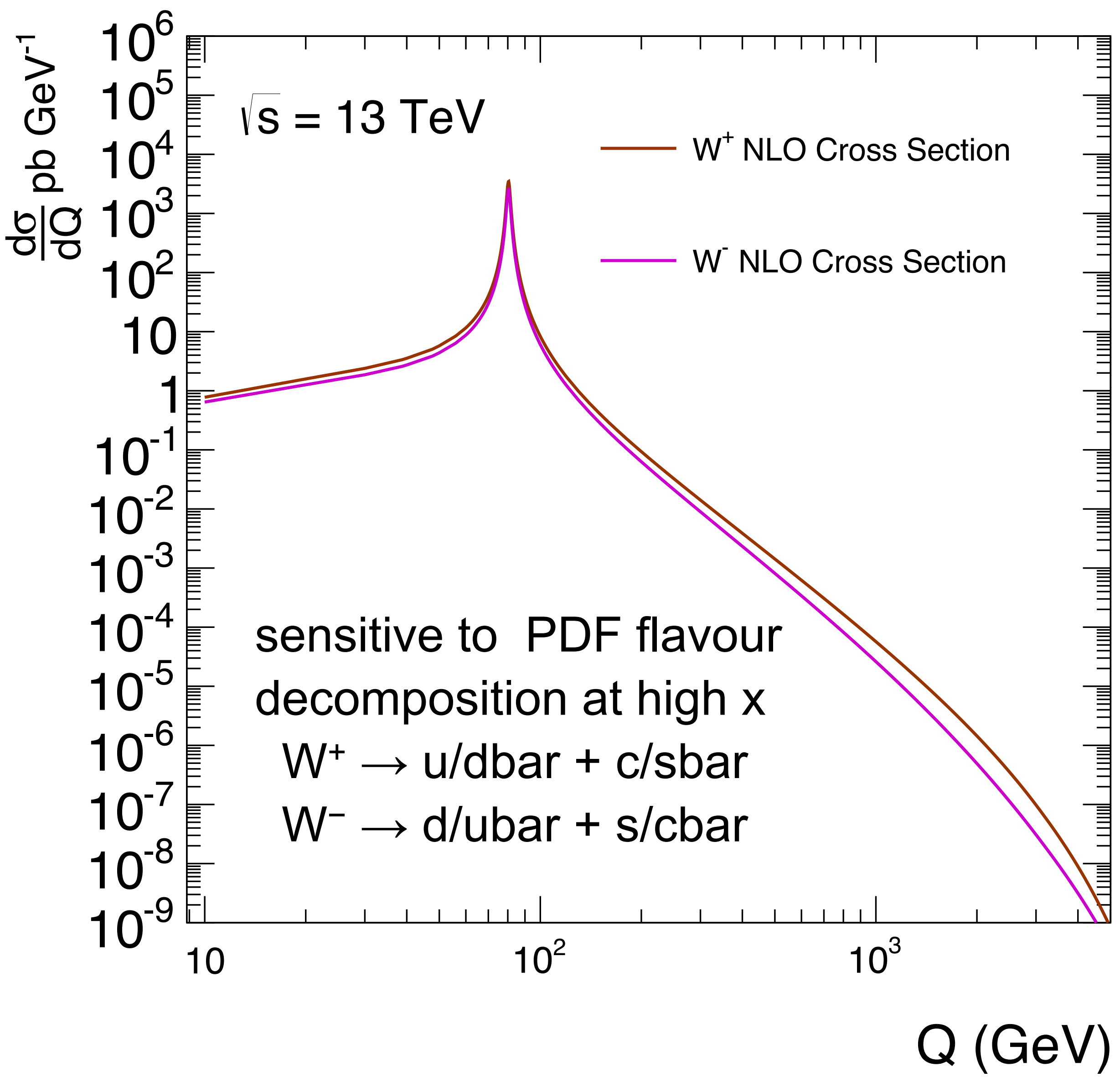


Current constraints based on neutral current HMDY 8 TeV data

⇒ Cannot yet compete with LEP

High Mass W/Z/ɣ* Inclusive Cross Sections





sensitive to PDF flavour decomposition at high x

$W^+ \rightarrow$ u/dbar + c/sbar

$W^- \rightarrow$ d/ubar + s/cbar

Neutral current

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

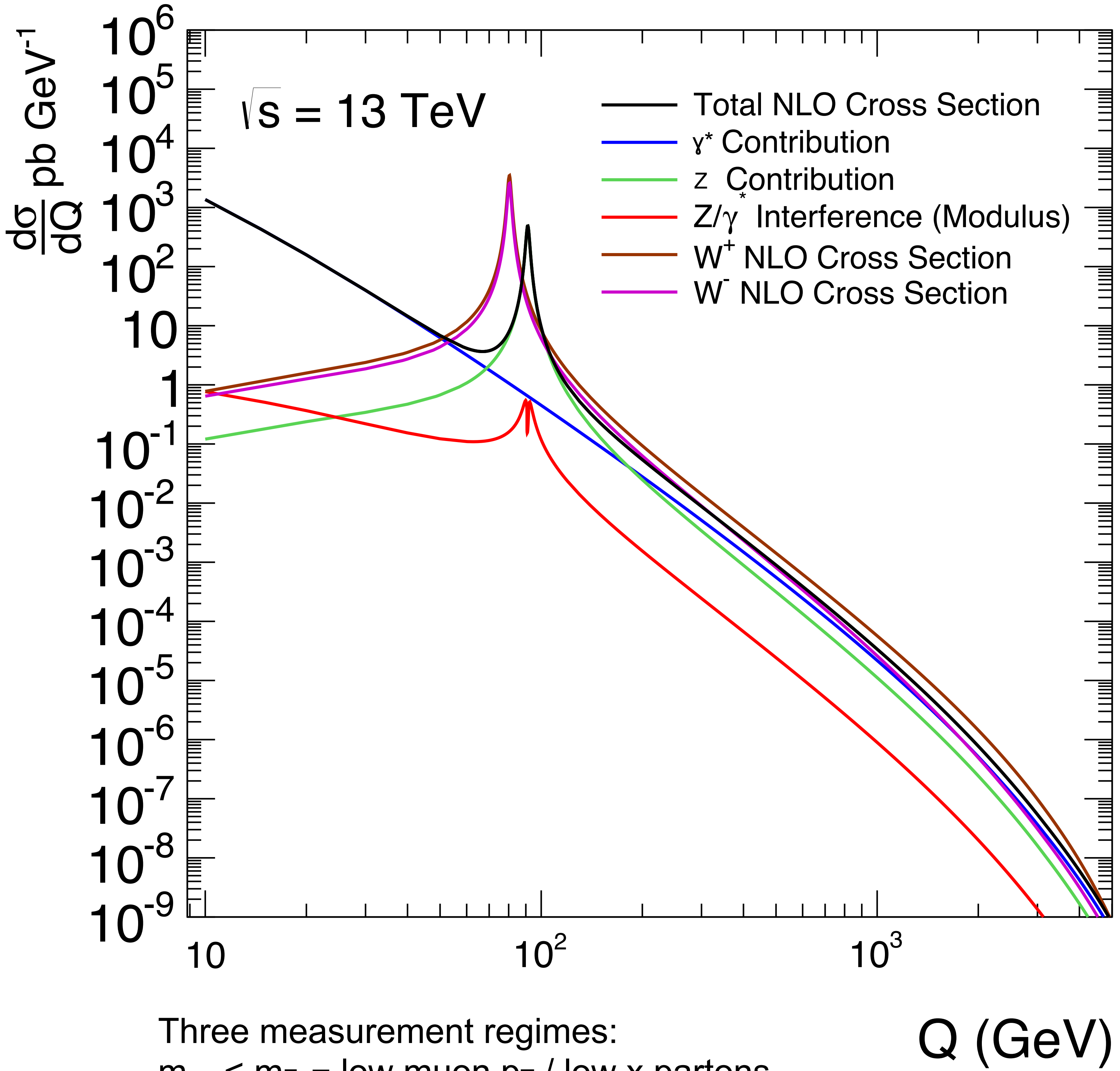
Similar for charged current

Charged current

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

Analogous to neutral current Z/γ^* measurement

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



- At large Q $\sigma(W^+) > \sigma(W^-) >= \sigma(\gamma^*)$ by ~ factor 2
- Run-II total ∫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

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

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

Stringent constraints on Y & W from LEP
100 fb^{-1} of NC data Z/γ^* → l^+l^- reaches LEP precision
20 fb^{-1} of CC data W → lν 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 @ $\sqrt{s}$=13 TeV

Simultaneous measurement in NC & CC channels