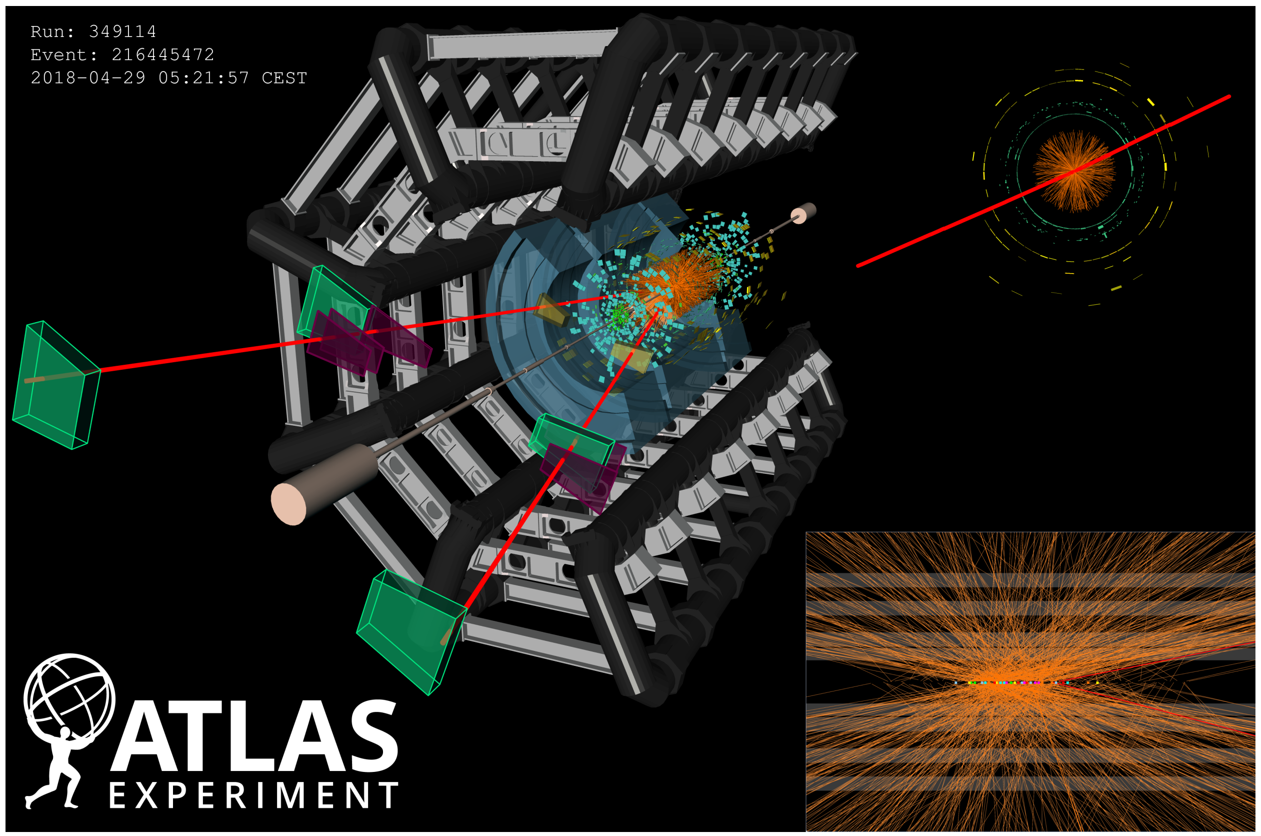
PDF and BSM Effects in High Mass Tails



- High mass Z/γ^* production
- High mass $W^{\pm}$ production
- Weak couplings
- PDFs x EFT

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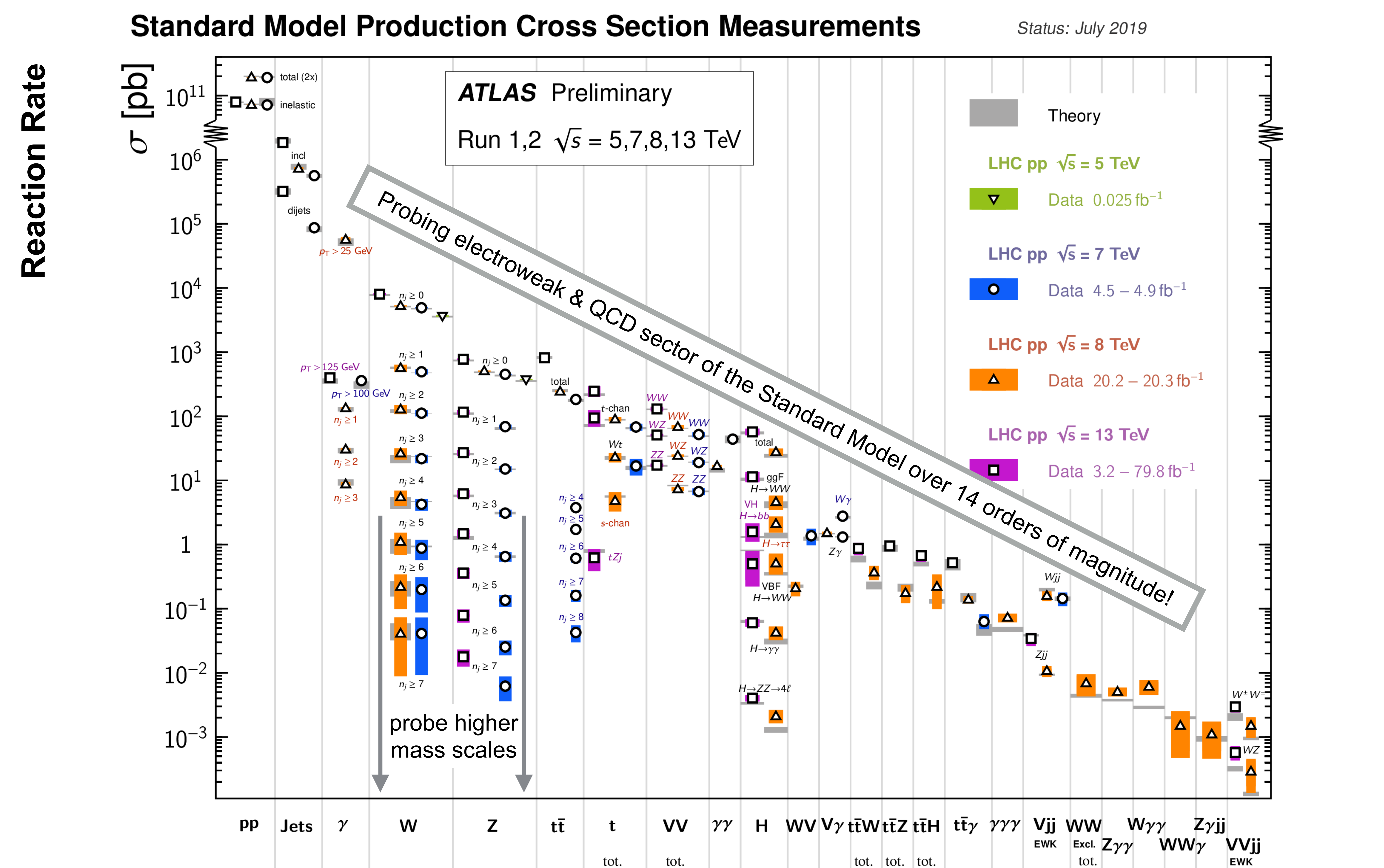
ATLAS EXPERIMENT

Ultimate Precision at Hadron Colliders
Paris-Saclay, France
5th December 2019

The Standard Model - Verified by ATLAS

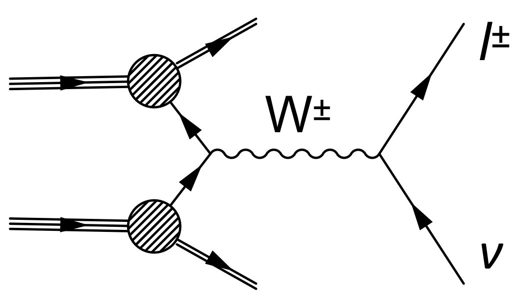


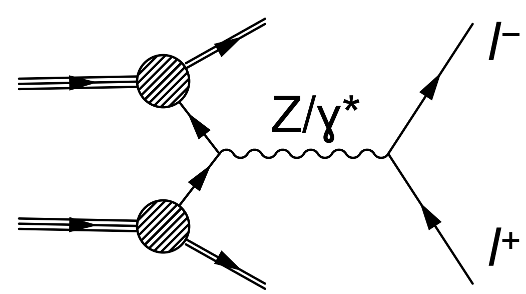
Standard Model W/Z production measurements cover range of topics

All LHC predictions rely on parton distribution functions (PDFs):
- quark/gluon content of proton
- Higgs discovery rests on precision PDF measurements

W/Z production = Drell-Yan lepton production

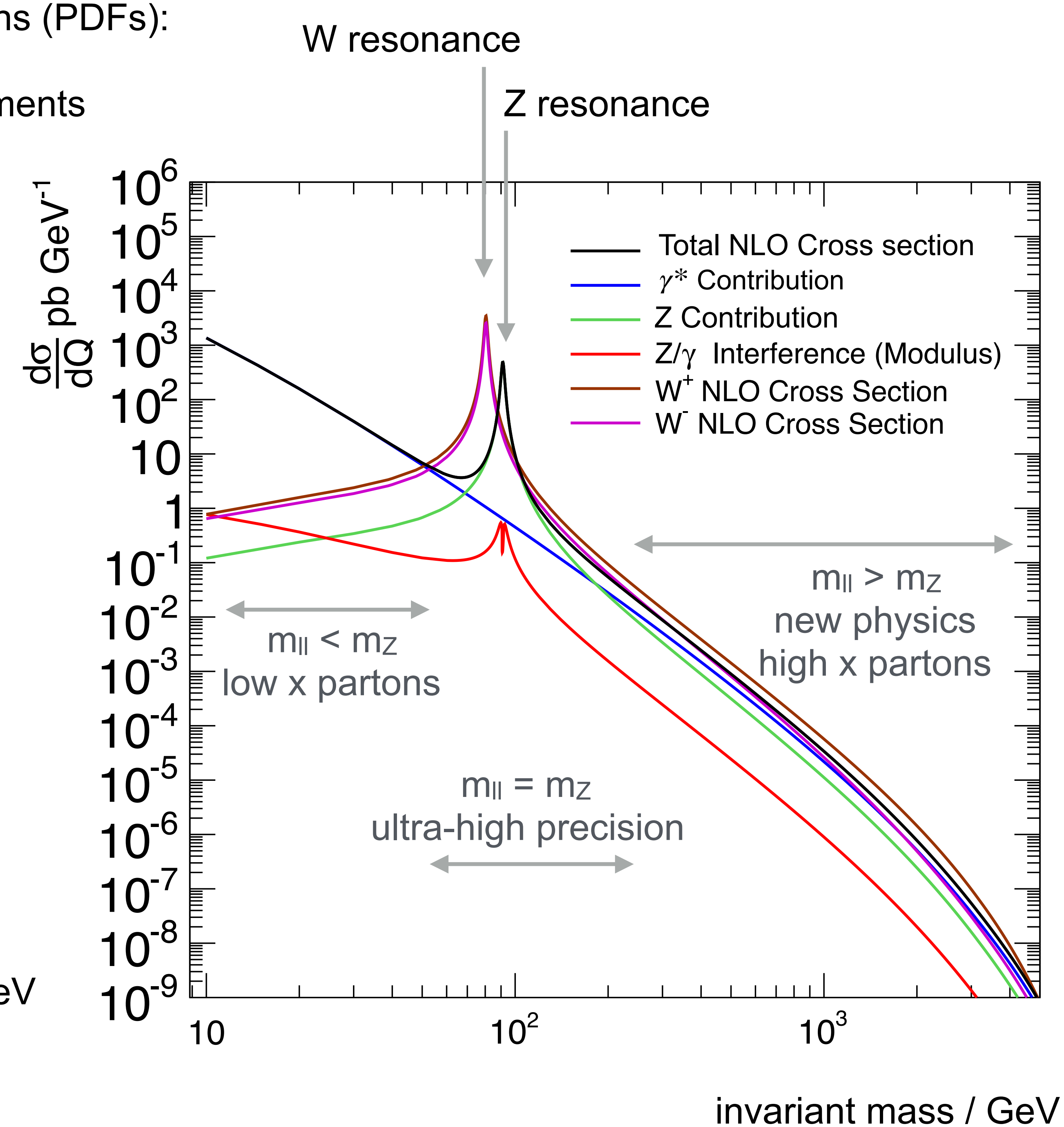
charged current / neutral current





Clean signature - low backgrounds
High cross section - large event samples
→ precise tests of Standard Model

- At large Q $\sigma(W^+) > \sigma(W^-) >= \sigma(\gamma^*)$ by ~ factor 2
- Run-III total $\int L \sim 300\ fb^{-1}$
- Lumi ~ 10 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



High Mass W/Z/γ*

run-I: ATLAS / CMS run-I measurements published
run-II: CMS published / ATLAS in progress

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

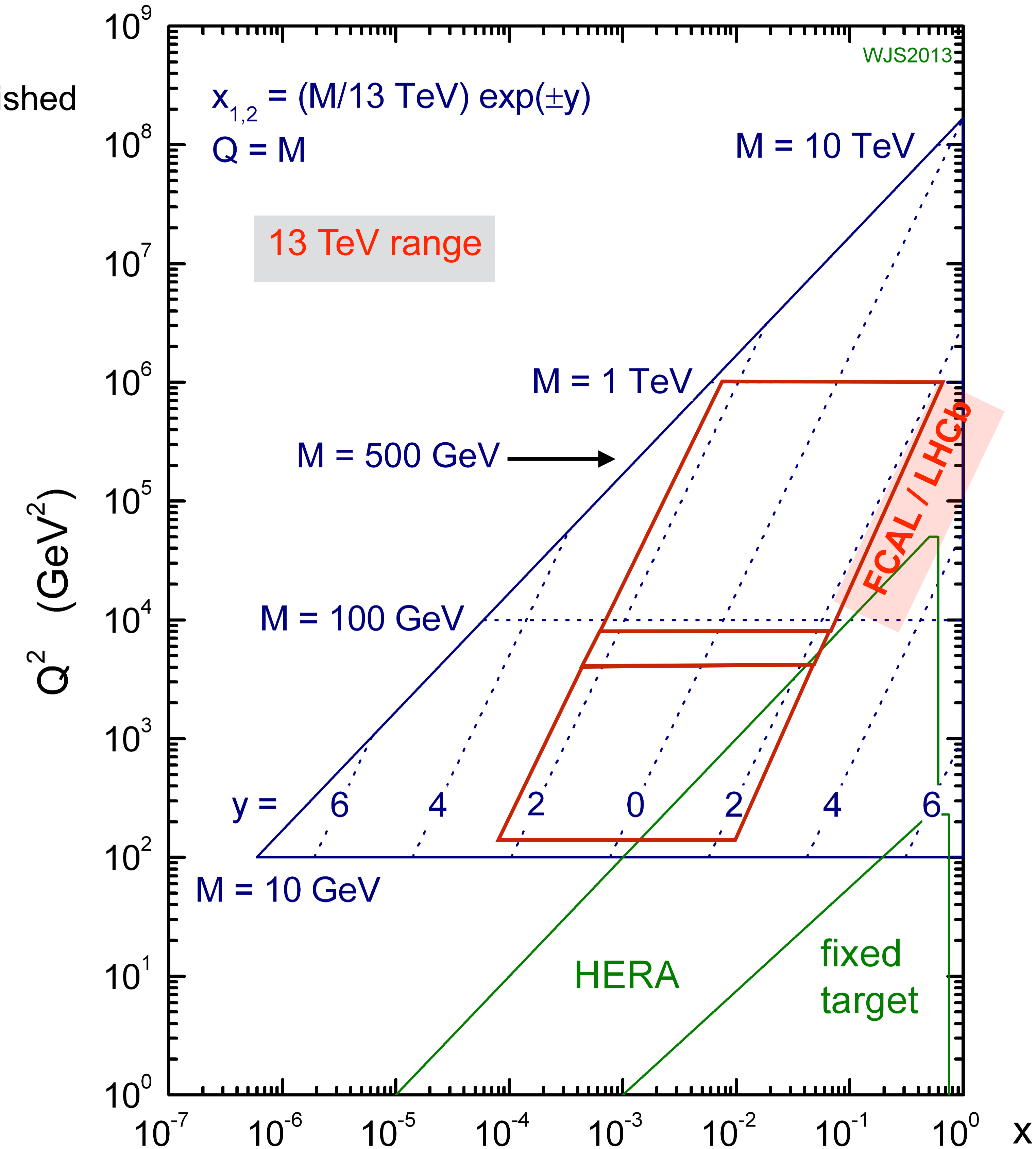
Measure cross sections at high rapidity

ATLAS FCAL forward electrons → PDF sensitivity up to x=0.5 at m~500 GeV

LHCb has forward acceptance

HL-LHC will extend tracking to |y|<4

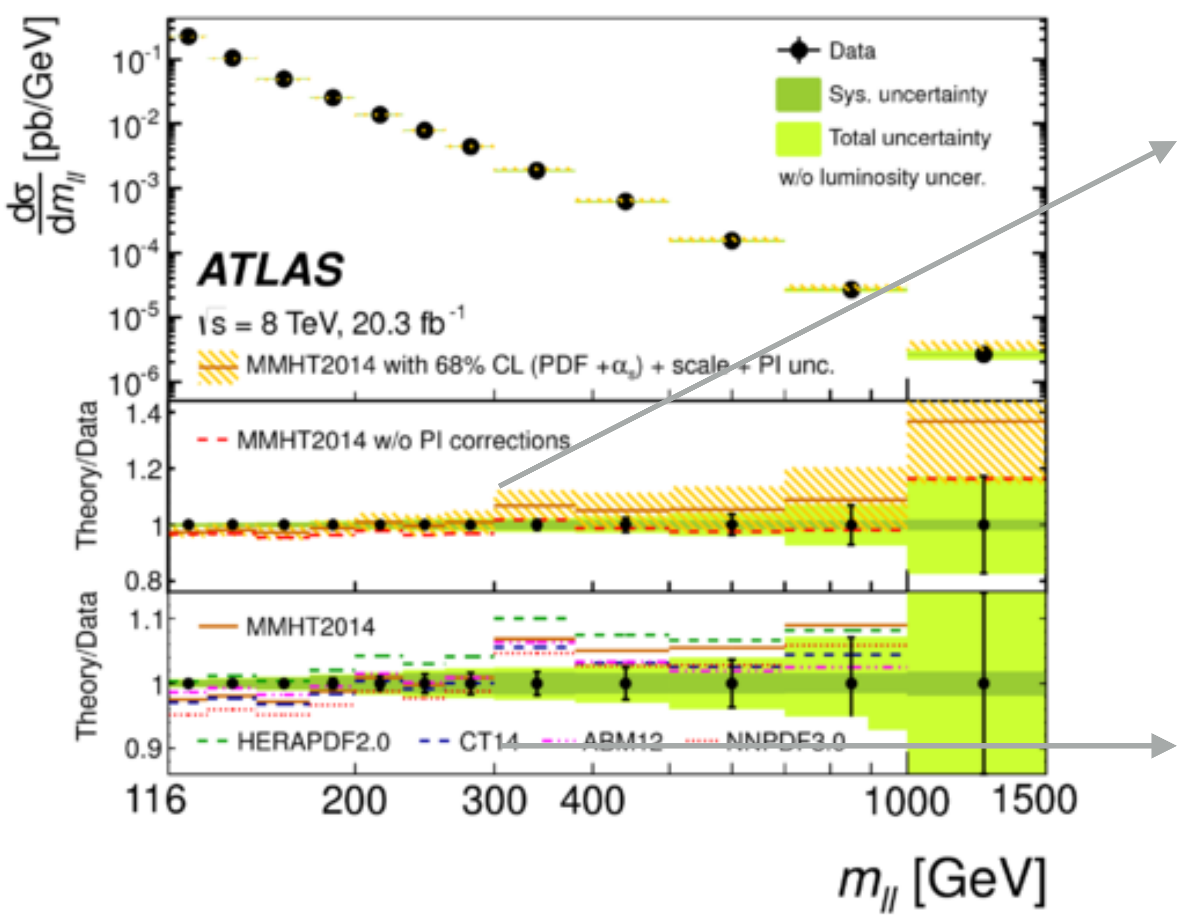
$t\bar{t}$ background much larger at √s=13 TeV



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

Fiducial Cross Section Definition

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



$$\frac{d\sigma}{dm_{\ell\ell}}$$

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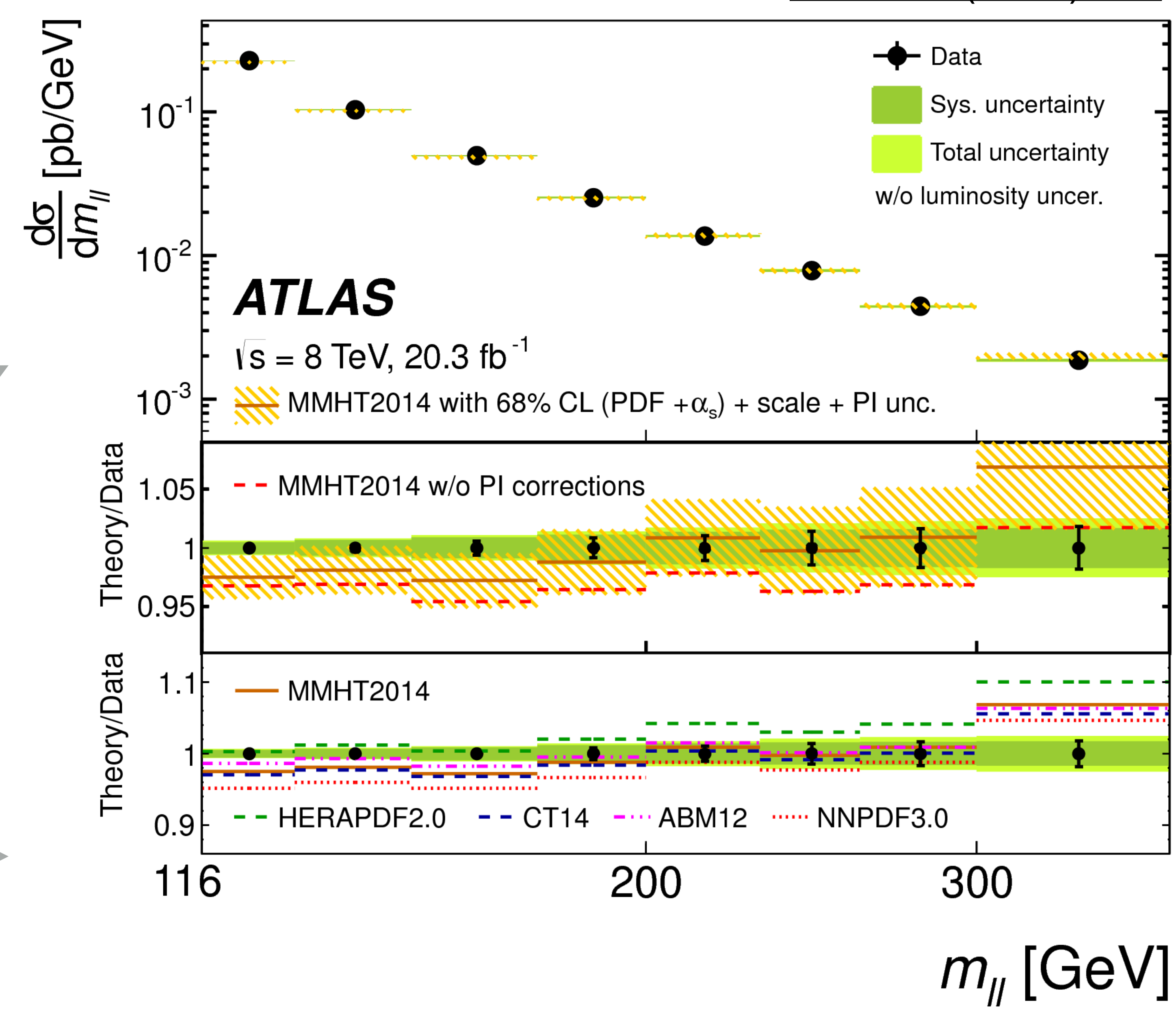

- Theory = NNLO pQCD ⊗ NLO EW + PI
- Theory generally in agreement with data
- Measurement systematically limited m < 400 GeV

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

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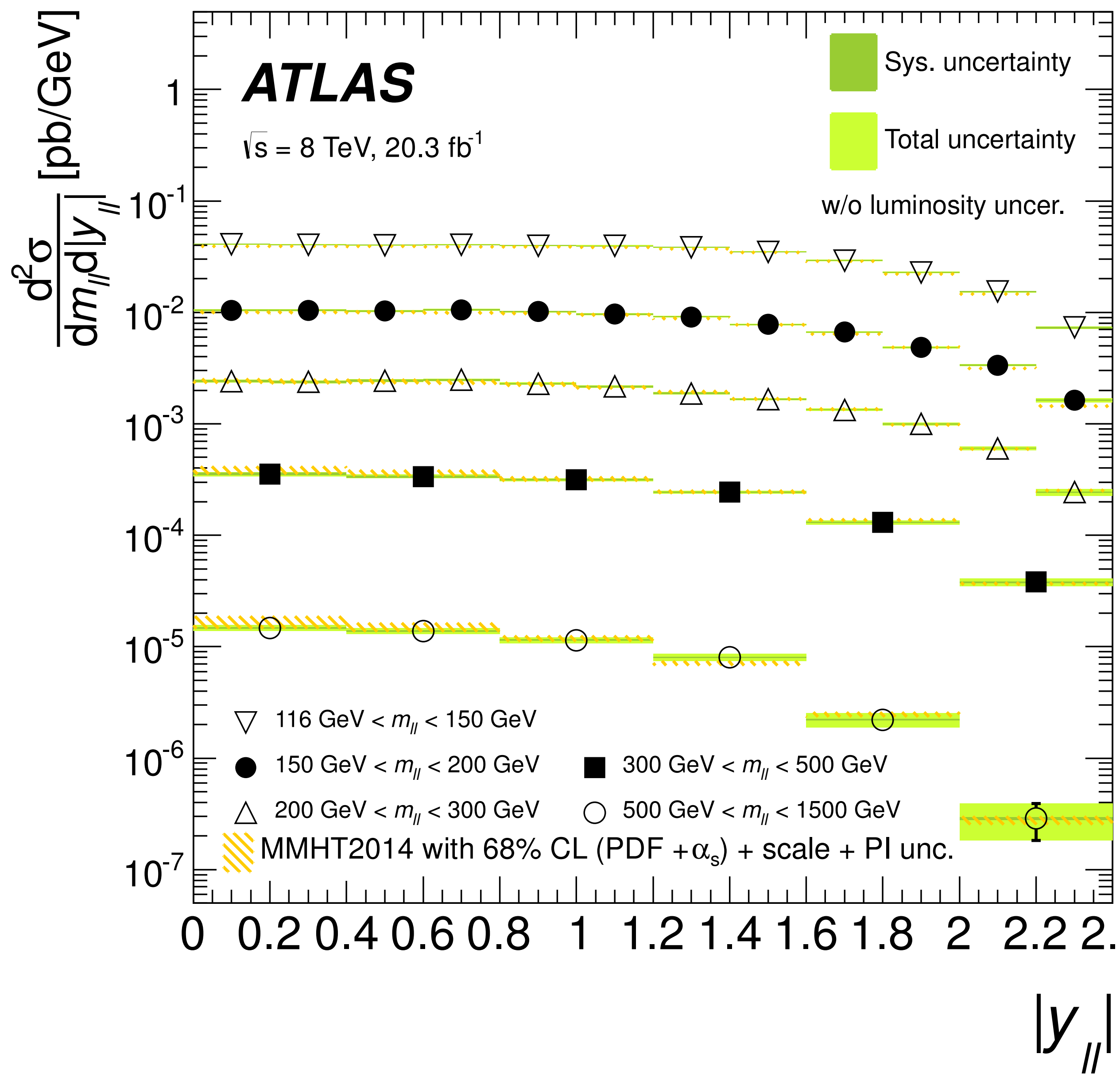
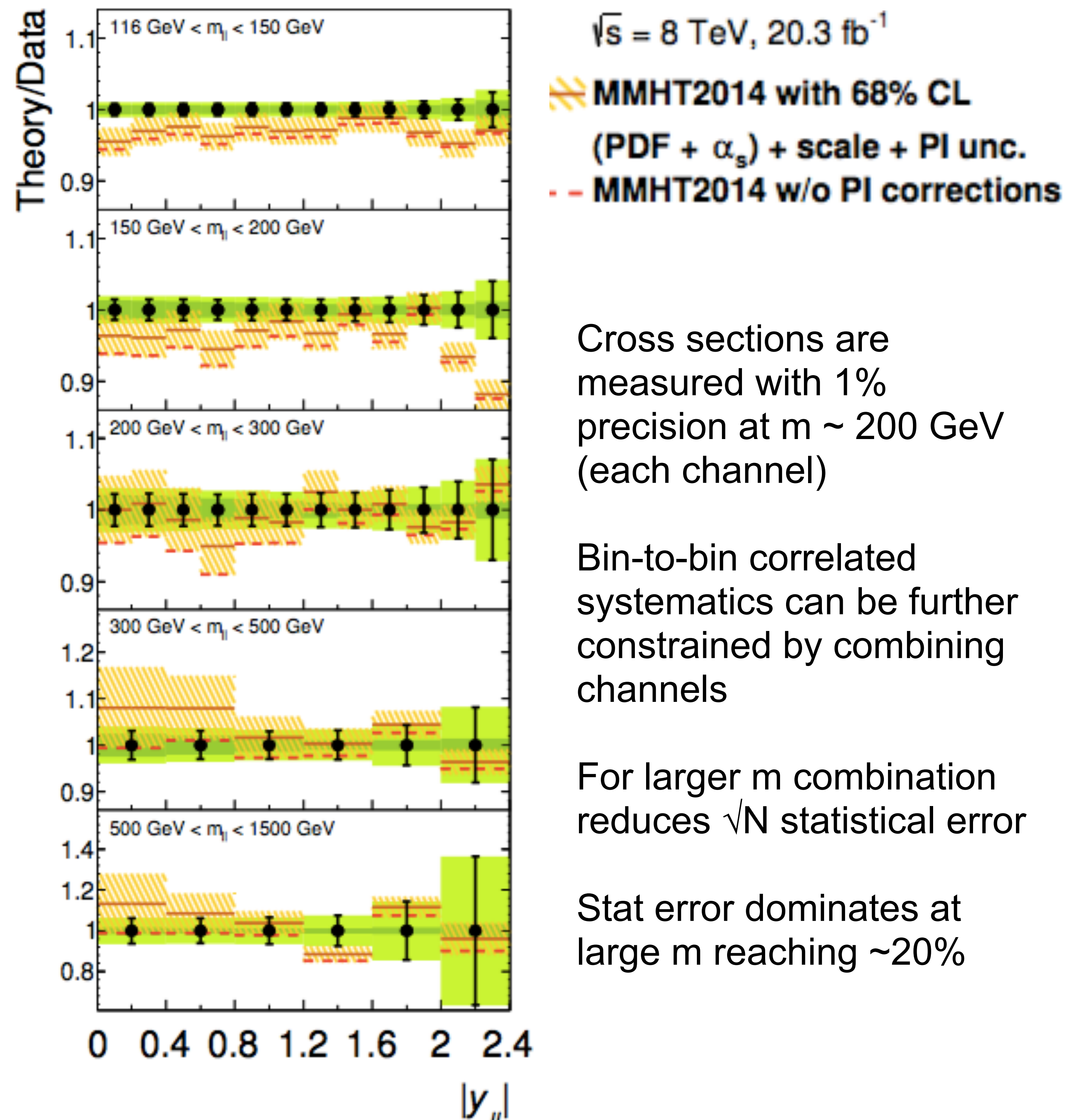
$$\frac{d^2\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|}$$





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 $\sqrt{s}$ = 8 TeV

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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]	$\|y_{\mu\mu}\|$	$\frac{d^2\sigma}{dm_{\mu\mu}d\|y_{\mu\mu}\|}$ [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]	$\|y_{ee}\|$	$\frac{d^2\sigma}{dm_{ee}d\|y_{ee}\|}$ [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

For run-II can achieve ~ 2% precision for |y| < 1 at m=300-500

Performance Considerations $\sqrt{s}$ = 8 TeV

$m_{\mu\mu}$ [GeV]	$\frac{d\sigma}{dm_{\mu\mu}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]	$\delta^{\text{trig}}_{\text{cor}}$ [%]	$\delta^{\text{reco}}_{\text{cor}}$ [%]	$\delta^{\text{MSres}}_{\text{cor}}$ [%]	$\delta^{\text{IDres}}_{\text{cor}}$ [%]	$\delta^{\text{pT}}_{\text{cor}}$ [%]	$\delta^{\text{iso}}_{\text{cor}}$ [%]	$\delta^{\text{top}}_{\text{cor}}$ [%]	$\delta^{\text{diboson}}_{\text{cor}}$ [%]	$\delta^{\text{bgMC}}_{\text{unc}}$ [%]	$\delta^{\text{mult.}}_{\text{cor}}$ [%]	$\delta^{\text{mult.}}_{\text{unc}}$ [%]	$\delta^{\text{MC}}_{\text{unc}}$ [%]	k_{dressed}
116 – 130	2.25×10^{-1}	0.5	0.6	0.8	-0.1	-0.4	-0.1	-0.1	-0.4	-0.1	-0.3	-0.1	0.0	0.0	0.1	0.1	1.055
130 – 150	1.04×10^{-1}	0.6	0.7	0.9	-0.1	-0.4	-0.1	0.0	-0.3	-0.1	-0.5	-0.1	0.1	0.0	0.1	0.1	1.047
150 – 175	4.94×10^{-2}	0.8	0.9	1.2	-0.1	-0.4	0.0	0.0	-0.2	-0.1	-0.7	-0.2	0.1	-0.1	0.1	0.1	1.043
175 – 200	2.51×10^{-2}	1.1	1.2	1.6	-0.1	-0.5	0.0	0.0	-0.2	-0.1	-1.0	-0.3	0.1	-0.1	0.2	0.1	1.040
200 – 230	1.37×10^{-2}	1.4	1.5	2.0	-0.1	-0.5	0.0	-0.1	-0.2	-0.1	-1.2	-0.4	0.2	-0.1	0.3	0.2	1.037
230 – 260	7.87×10^{-3}	1.8	1.6	2.5	-0.1	-0.5	0.0	0.1	-0.3	-0.1	-1.3	-0.4	0.3	-0.1	0.5	0.2	1.036
260 – 300	4.45×10^{-3}	2.1	1.7	2.7	-0.1	-0.6	0.0	-0.1	-0.2	-0.2	-1.4	-0.5	0.3	-0.1	0.5	0.2	1.037
300 – 380	1.90×10^{-3}	2.3	1.9	3.0	-0.1	-0.6	0.1	0.0	-0.3	-0.2	-1.4	-0.6	0.4	-0.2	0.7	0.2	1.035
380 – 500	6.40×10^{-4}	3.2	1.8	3.7	-0.1	-0.7	-0.1	-0.1	-0.2	-0.3	-1.2	-0.5	0.5	-0.1	0.8	0.2	1.037
500 – 700	1.54×10^{-4}	5.0	2.0	5.4	-0.1	-0.8	-0.1	0.0	-0.2	-0.4	-0.9	-0.5	0.6	-1.3	0.0	0.2	1.036
700 – 1000	2.66×10^{-5}	9.6	2.1	9.8	-0.1	-0.8	-0.5	-0.1	-0.4	-0.5	-0.5	-0.5	0.8	-1.3	0.0	0.4	1.040
1000 – 1500	2.17×10^{-6}	26.0	2.7	26.2	-0.1	-1.1	-0.1	-1.0	-0.3	-0.6	-0.4	-0.6	1.5	-1.4	0.0	0.4	1.043

Muon channel

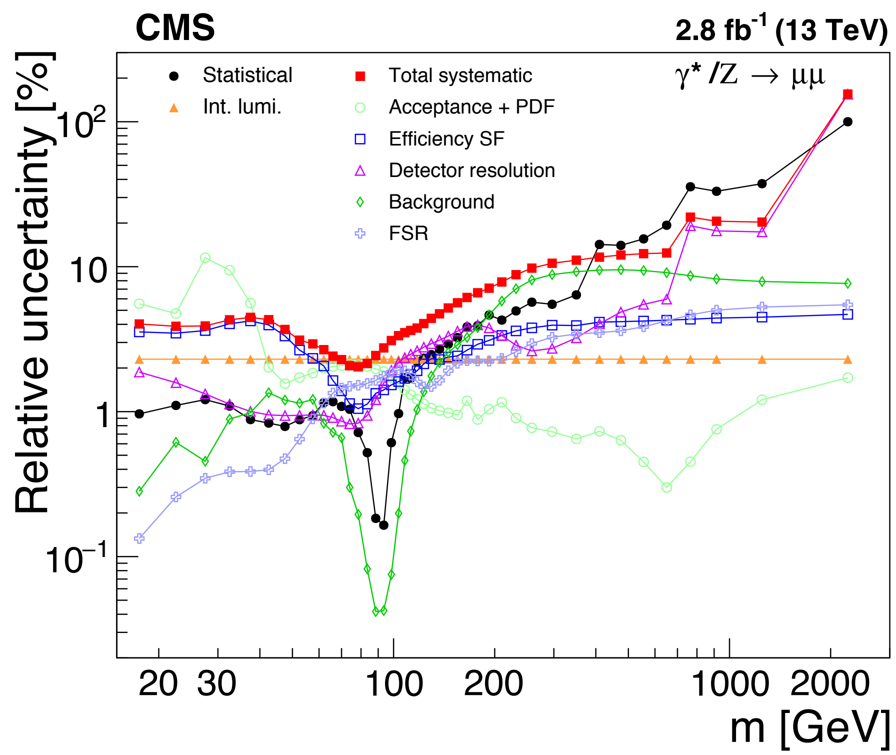
multijet uncertainties under control

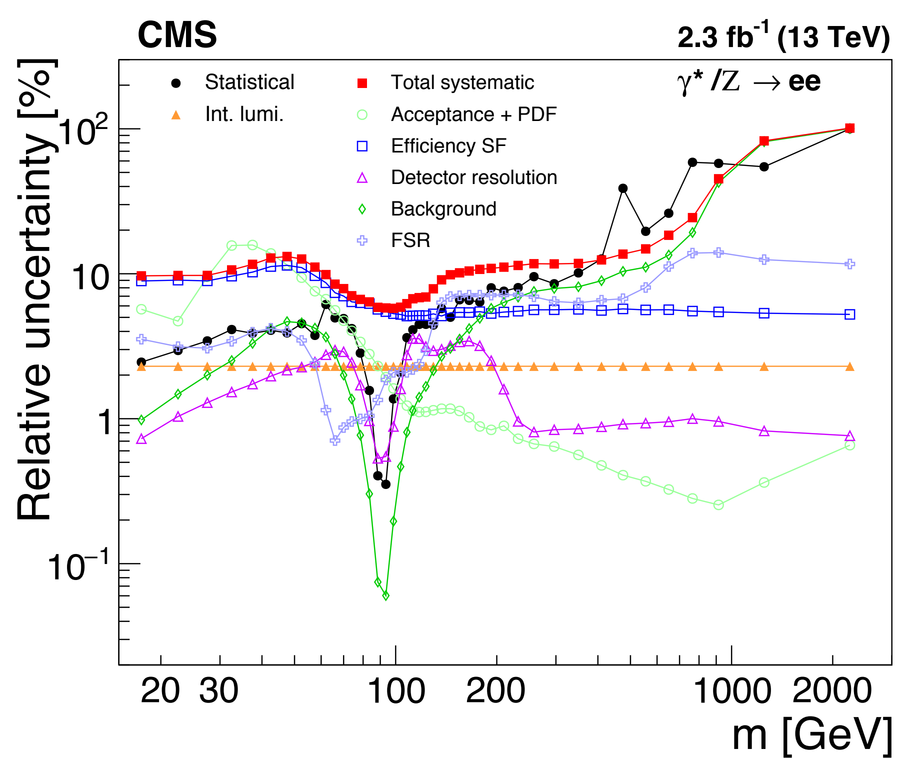
Electron channel

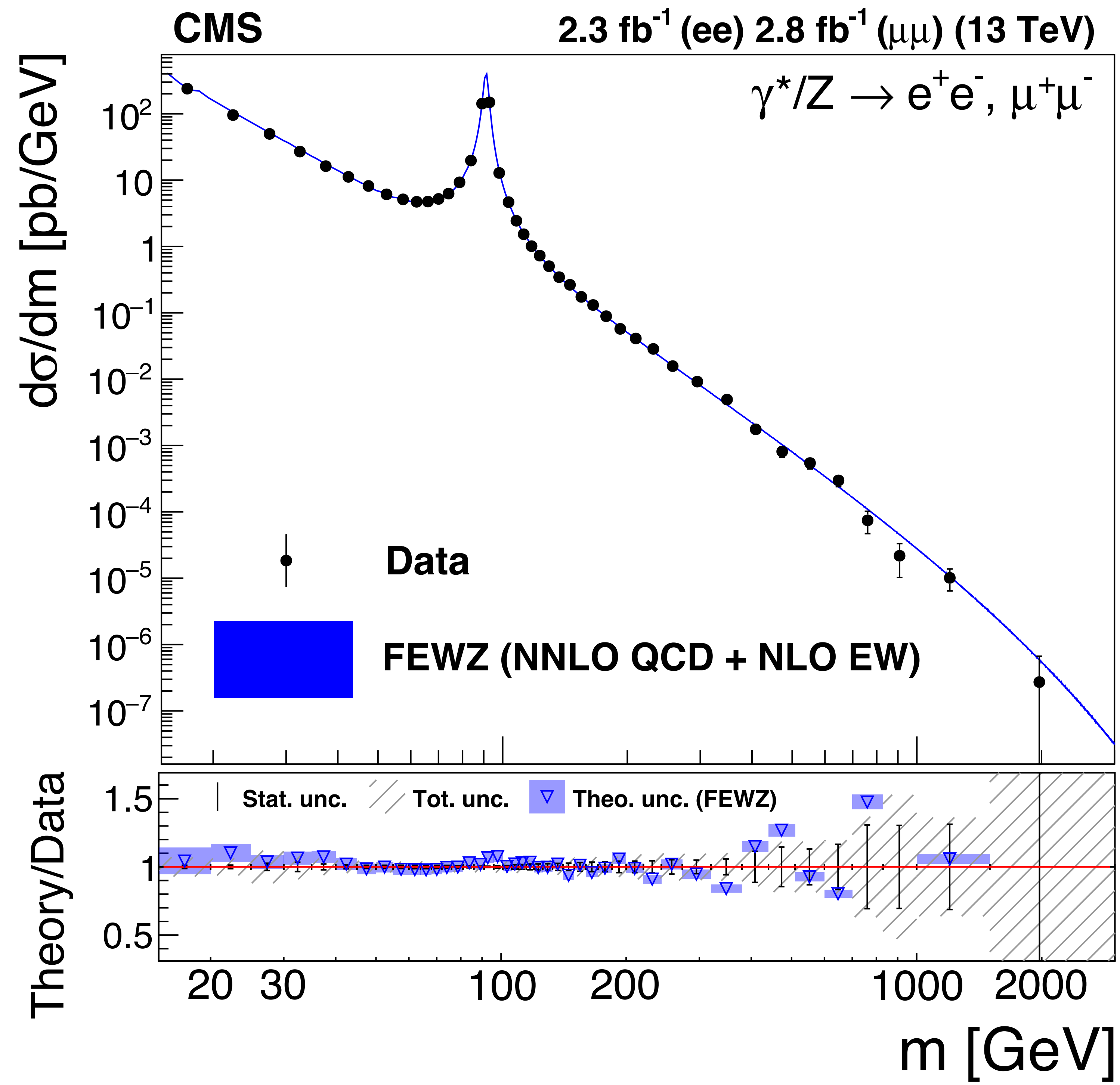
m_{ee} [GeV]	$\frac{d\sigma}{dm_{ee}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]	$\delta^{\text{trig}}_{\text{cor}}$ [%]	$\delta^{\text{trig}}_{\text{unc}}$ [%]	$\delta^{\text{reco}}_{\text{cor}}$ [%]	$\delta^{\text{id}}_{\text{cor}}$ [%]	$\delta^{\text{iso}}_{\text{cor}}$ [%]	$\delta^{\text{iso}}_{\text{unc}}$ [%]	$\delta^{\text{Eres}}_{\text{cor}}$ [%]	$\delta^{\text{Escale}}_{\text{cor}}$ [%]	$\delta^{\text{mult.}}_{\text{cor}}$ [%]	$\delta^{\text{mult.}}_{\text{unc}}$ [%]	$\delta^{\text{top}}_{\text{cor}}$ [%]	$\delta^{\text{diboson}}_{\text{cor}}$ [%]	$\delta^{\text{bgMC}}_{\text{unc}}$ [%]	$\delta^{\text{MC}}_{\text{unc}}$ [%]	k_{dressed}
116–130	2.31×10^{-1}	0.5	0.8	1.0	-0.1	0.0	0.0	-0.3	0.0	0.0	0.1	0.5	-0.5	0.1	-0.3	-0.1	0.0	0.1	1.047
130–150	1.05×10^{-1}	0.7	1.0	1.2	-0.1	0.0	-0.1	-0.4	0.0	0.1	0.1	0.4	-0.7	0.2	-0.5	-0.2	0.1	0.1	1.046
150–175	5.06×10^{-2}	0.8	1.3	1.6	0.0	0.1	-0.1	-0.5	0.0	0.1	0.1	0.4	-0.8	0.3	-0.7	-0.2	0.1	0.1	1.047
175–200	2.60×10^{-2}	1.2	1.6	2.0	-0.1	0.1	-0.1	-0.6	0.0	0.1	0.0	0.5	-0.9	0.3	-0.9	-0.3	0.2	0.1	1.052
200–230	1.39×10^{-2}	1.5	2.0	2.5	-0.1	0.1	-0.1	-0.7	0.0	0.2	0.1	0.7	-1.2	0.4	-1.1	-0.4	0.2	0.2	1.053
230–260	7.95×10^{-3}	2.0	2.2	3.0	-0.1	0.1	-0.2	-0.7	-0.1	0.2	0.1	1.0	-1.1	0.4	-1.3	-0.4	0.3	0.2	1.056
260–300	4.43×10^{-3}	2.4	2.3	3.3	-0.1	0.1	-0.2	-0.7	-0.1	0.2	0.1	0.9	-1.3	0.5	-1.3	-0.6	0.4	0.2	1.058
300–380	1.84×10^{-3}	2.6	2.5	3.6	-0.1	0.2	-0.2	-0.8	-0.1	0.3	0.1	1.3	-1.1	0.4	-1.4	-0.6	0.4	0.2	1.063
380–500	5.99×10^{-4}	3.6	2.7	4.5	-0.1	0.2	-0.2	-0.8	-0.2	0.5	0.1	1.6	-1.4	0.5	-1.1	-0.6	0.5	0.2	1.067
500–700	1.52×10^{-4}	5.3	2.6	6.0	-0.1	0.2	-0.2	-0.8	-0.2	0.7	0.1	2.0	-0.7	0.5	-0.7	-0.6	0.5	0.3	1.075
700–1000	2.64×10^{-5}	10.2	3.3	10.7	-0.2	0.4	-0.2	-0.8	-0.3	1.4	0.1	2.3	-0.6	0.8	-0.4	-0.6	0.7	0.4	1.085
1000–1500	3.23×10^{-6}	22.5	5.8	23.2	-0.7	0.9	-0.2	-0.8	-0.3	3.5	0.0	2.8	-1.9	1.6	-0.3	-0.6	2.1	0.2	1.100

High Mass Z/γ* Cross Sections √s = 13 TeV

arXiv:1812.10529







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

General models of new physics SM Lagrangian extended by dimension 6 operators
They describe new physics appearing at scale $m > \sqrt{s}$

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

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

S , T , Y , W

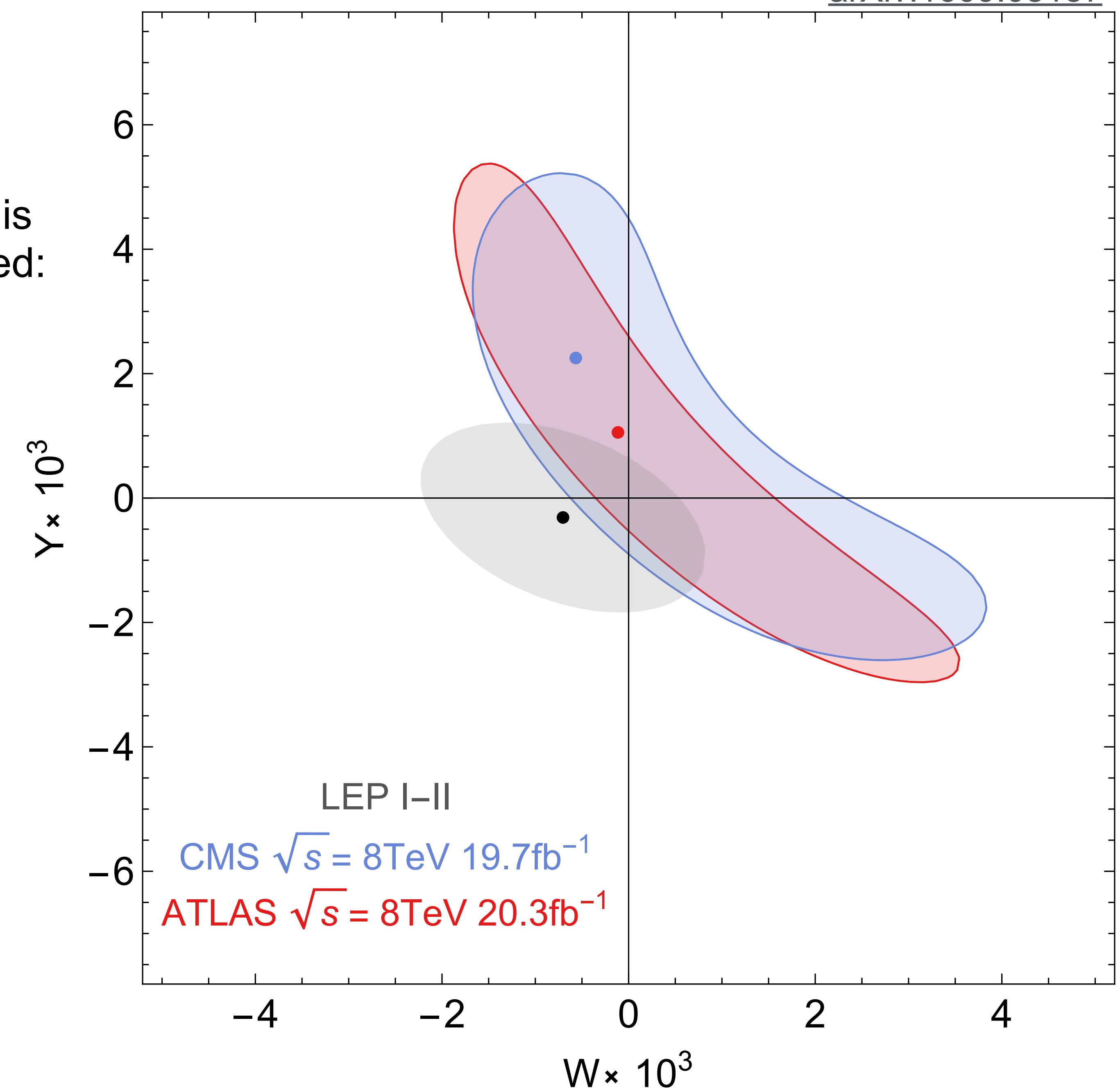
- Y and W increase with $\sqrt{s}$
- S and T do not grow with $\sqrt{s}$

LHC data can help constrain Y & W

Current constraints based on neutral current HMDY 8 TeV data

⇒ Cannot yet compete with LEP

arXiv:1609.08157



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

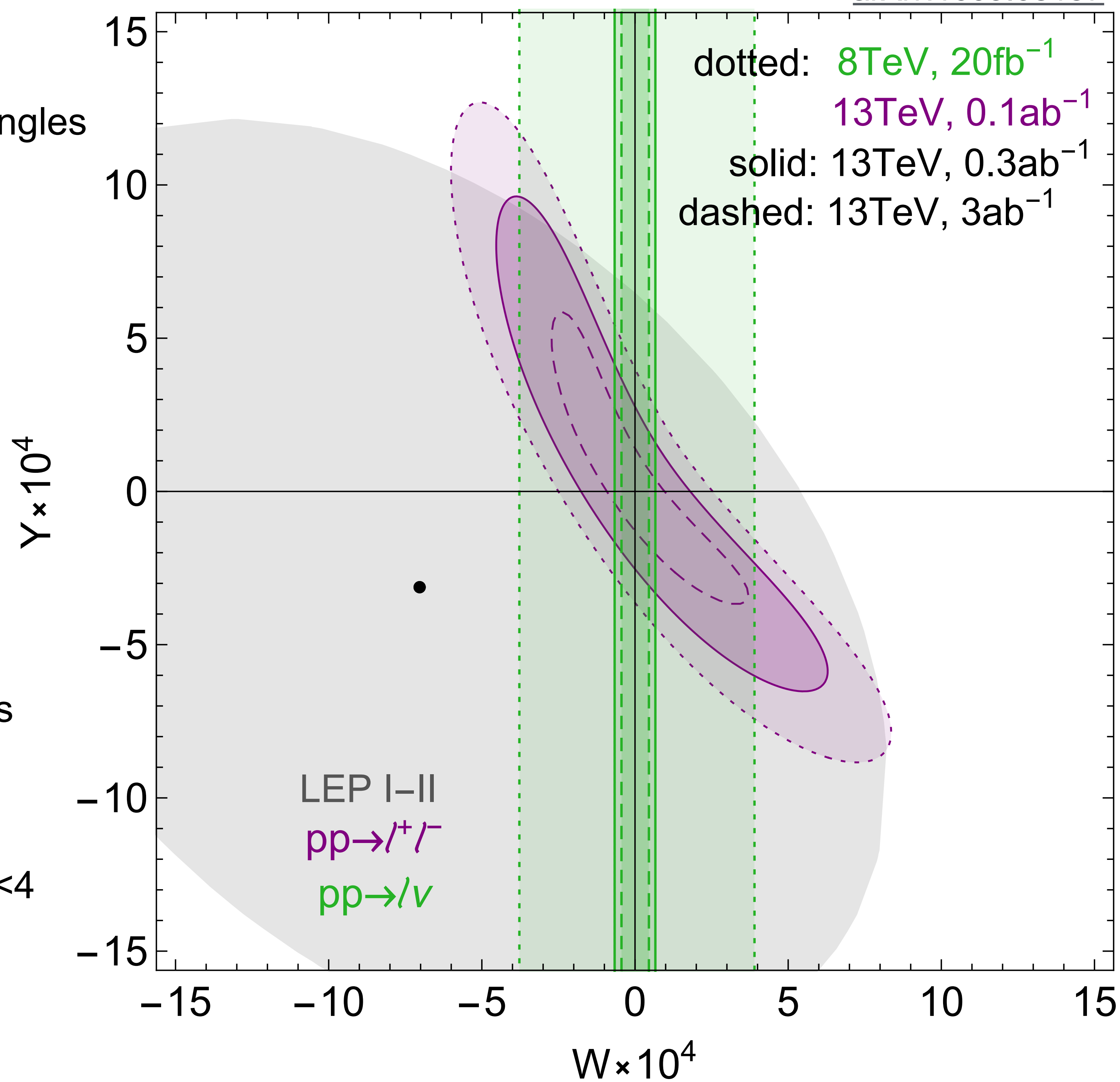
Discussions with authors
Request for unfolded cross sections
Additional gains in NC channel measuring decay angles

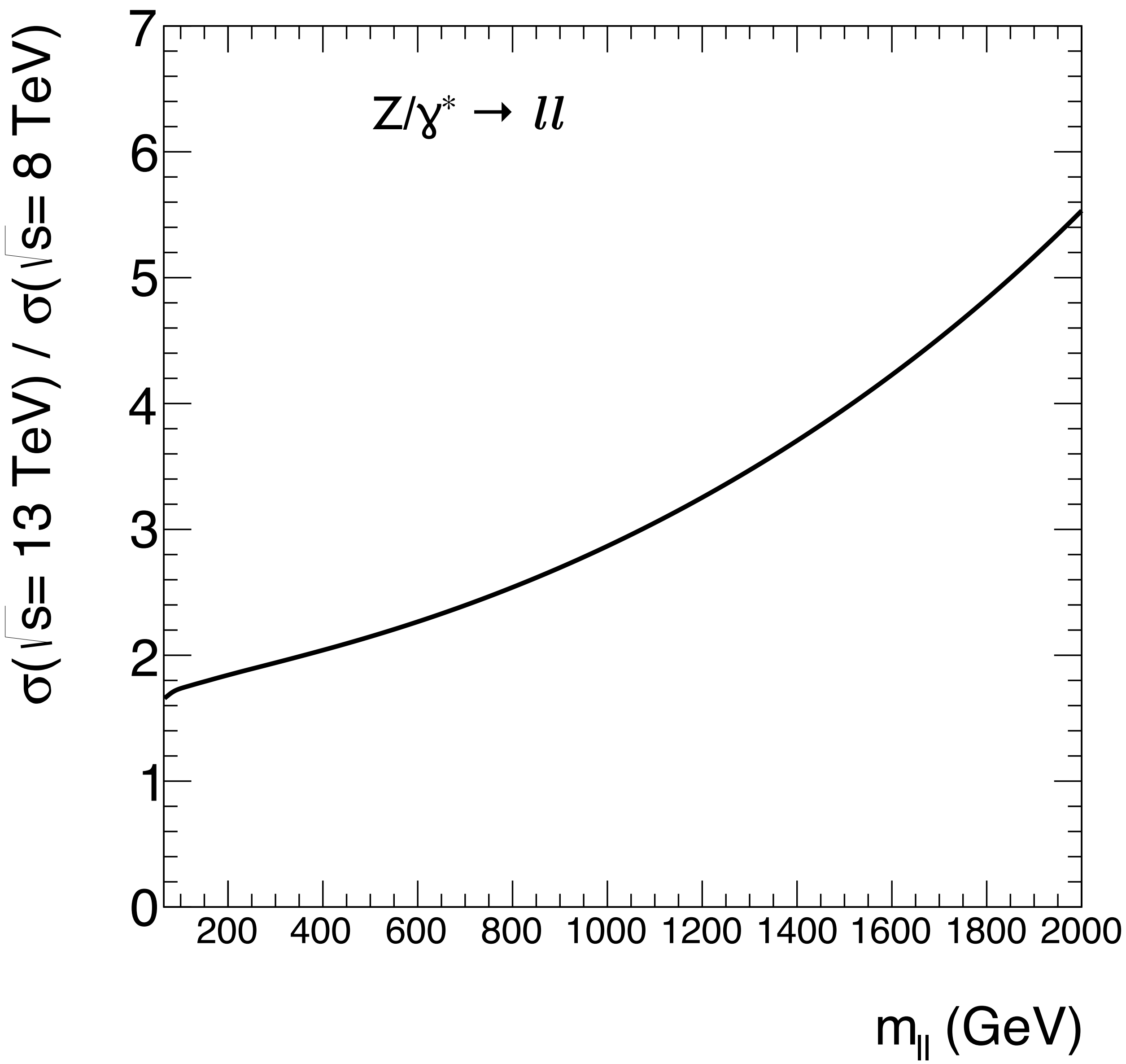
- $\cos\theta^*$
- y_{ll}
- m_{ll}

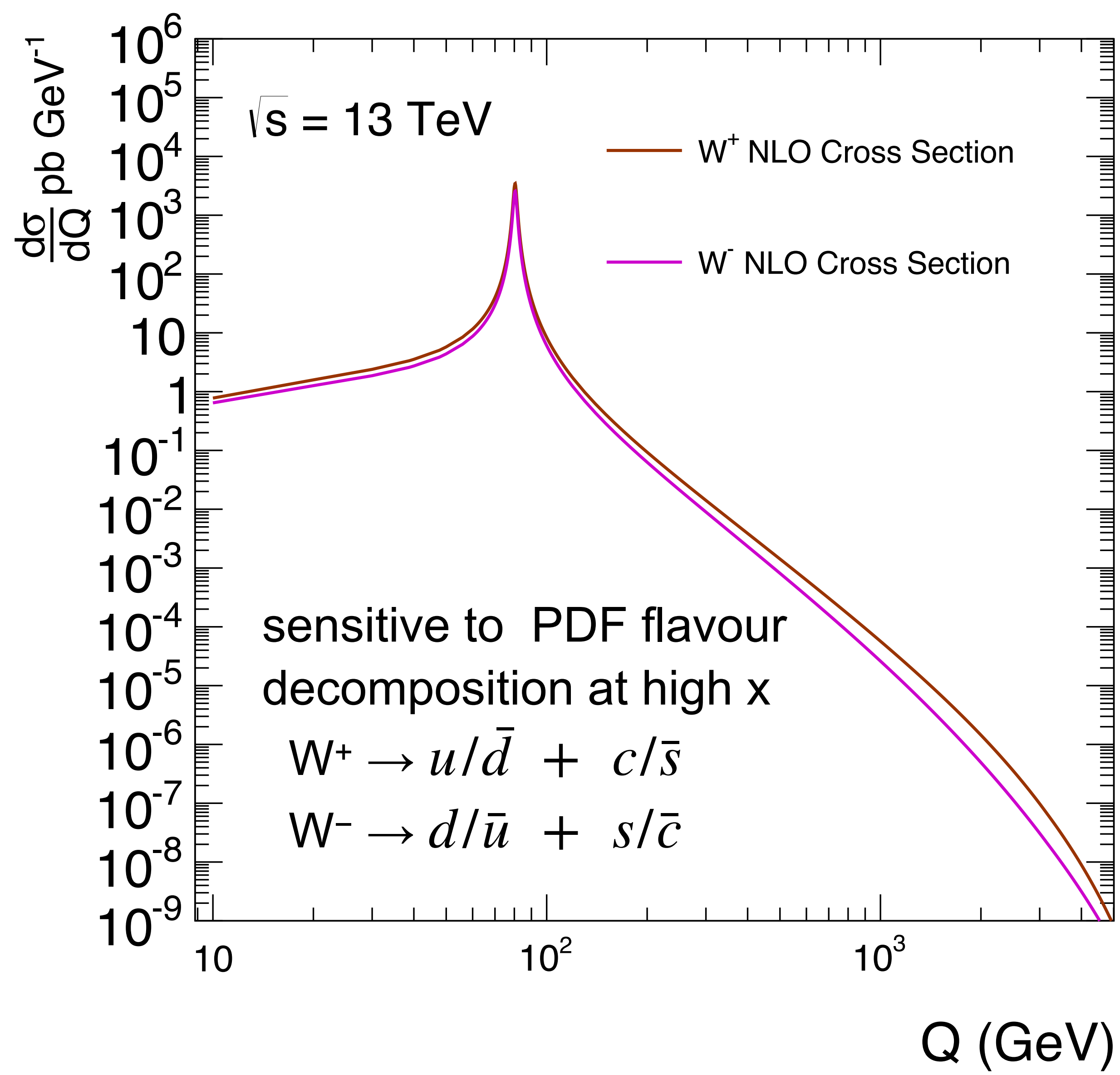
→ do other observables enhance sensitivity?

- ATLAS full run-II cross sections @ $\sqrt{s}$=13 TeV
- Simultaneous measurement in NC & CC channels
- Profit from coherent systematics in both channels
- Extend neutral current to higher rapidity FCAL |y|<4

arXiv:1609.08157







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± production
Analogous to neutral current Z/γ* measurement

First measurement of off-shell W production
run-II ~4% stat error for W production at m_T = 1 TeV

Measure W± charge asymmetry $A(m_T)$

$$A(m_T) = \frac{(\frac{d\sigma^+}{d\eta} - \frac{d\sigma^-}{d\eta})}{(\frac{d\sigma^+}{d\eta} + \frac{d\sigma^-}{d\eta})} \simeq \frac{u}{d}(x)$$

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

NC Channel - Madgraph sensitivity search: isolate SM-EFT operators which influence DY cross sections

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}^{(6)} \qquad \mathscr{L}^{(d)} = \sum_{i=1}^{n_d} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathscr{O}^{(d)}$$

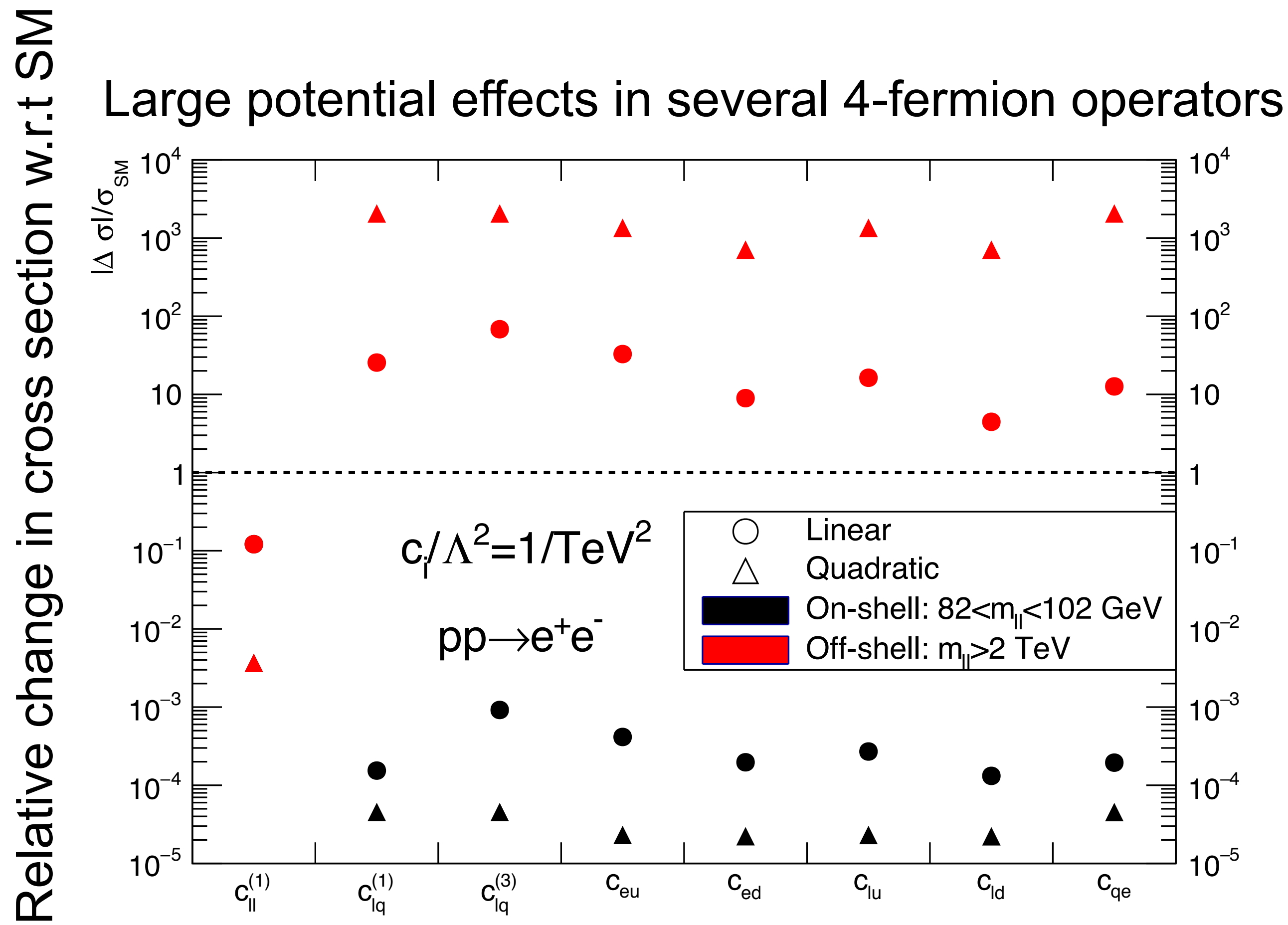
$$\sigma = |A_{\rm SM} + \sum_{i=1} \frac{c_i}{\Lambda^2} A_i|^2$$

Extended EFT lagrangian yields amplitudes, A
Cross sections generate interference terms:

$$\text{SM} \otimes \text{EFT} \sim A_{\rm SM} \times \frac{A_i}{\Lambda^2}$$

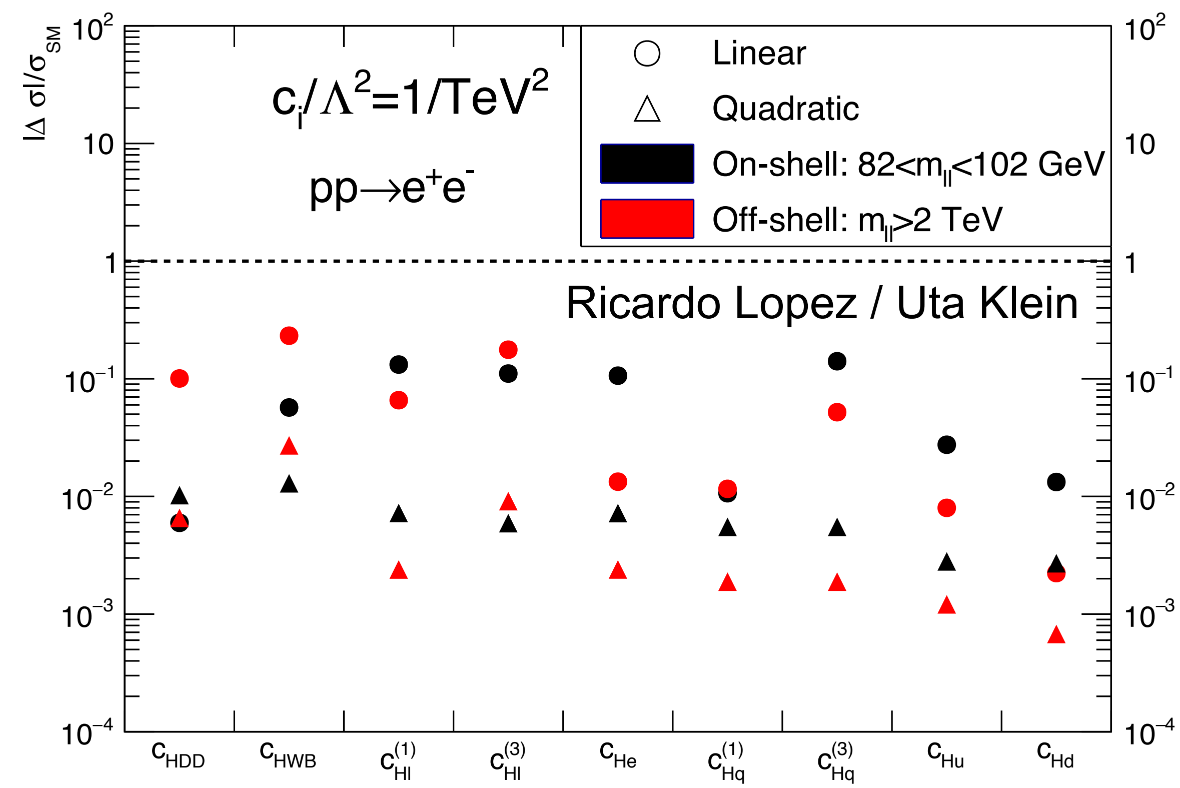
$$\text{EFT} \otimes \text{EFT} \sim \sum_{i \neq j} \frac{A_i A_j}{\Lambda^4}$$ usually neglected similar magnitude to d=8

Large potential effects in several 4-fermion operators



(a) 4-fermion operators

Modest effects in several Higgs operators



(b) Higgs-related operators

Towards Global EFT Fit

Similar illustration of SM-EFT sensitivity combinations
Test diboson, higgs and single boson production processes
Use published measurement uncertainties
Predictions from Madgraph
Over-estimated uncertainties for CC DY production at high m_T

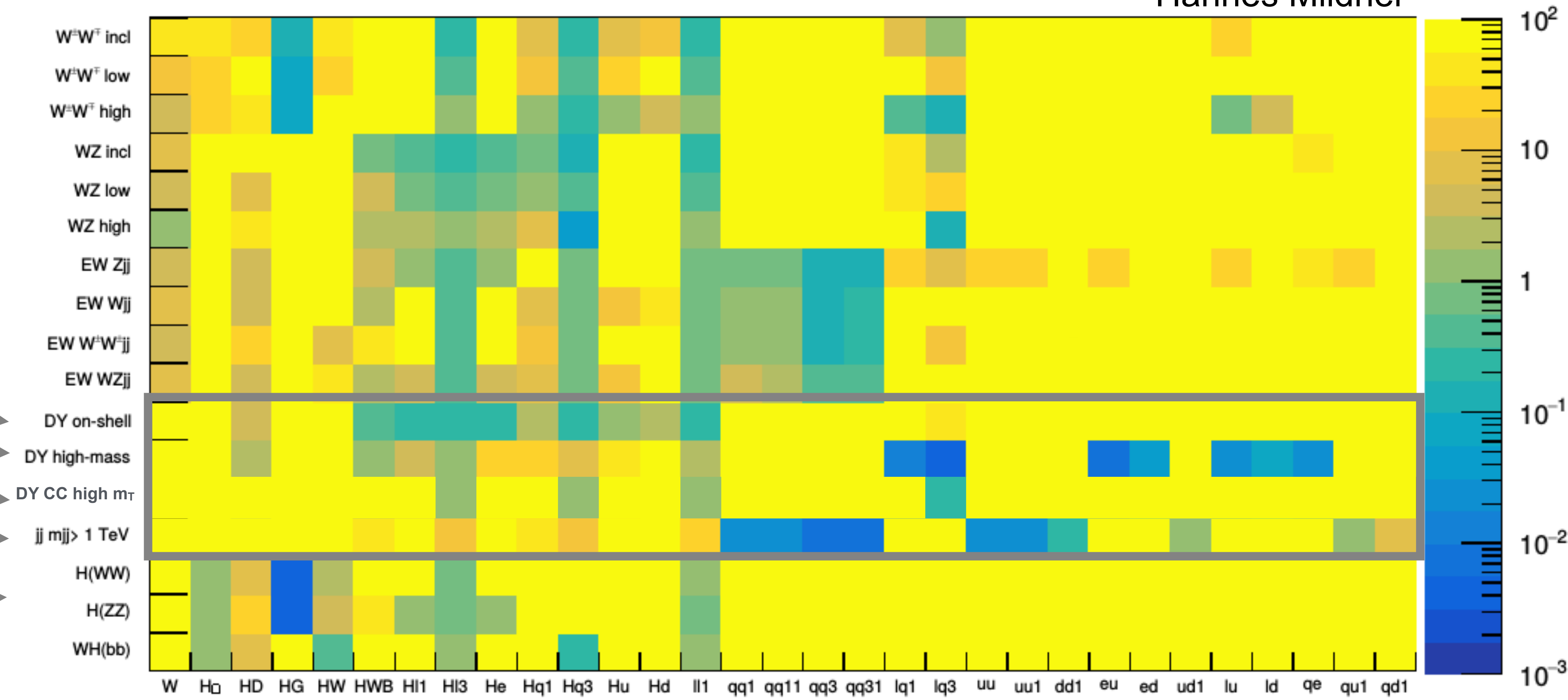
Measurement sensitivity:

$$\frac{\delta^{tot}}{\sigma^{SM} - \sigma^{SM+EFT}}$$

smaller values = higher sensitivity

Check EFT operators (Λ~1 TeV)
High sensitivity in
- NC on-shell Drell-Yan
- NC high mass Drell-Yan
- CC high m_T Drell-Yan
- dijets production
- H→WW
- H→ZZ

Hannes Mildner



- Strong constraints on 4-fermion operators
- Complementarity between NC / CC / dijet → can break degeneracies

> Need to have
Details of analysis selection (cuts) → RIVET
Details of unfolded results (+correlations) → HEPData
Good example: W/Z precision (→ PDF fits)

Work ongoing with LHC EWWG group

High Mass $W/Z/\gamma^*$ Production: Tau channel

ATLAS / CMS typically measure electron / muon leptonic decay modes
tau modes more difficult
- 1 and 3-prong hadronic tau decays difficult to trigger / identify
- leptonic decays yield soft electrons / muons below trigger thresholds (10% for p_T > 30 GeV)
- leptonic modes have 34% branching fraction

⇒ low overall selection efficiency

Measurement of Z and W production with tau decay should become easier at high scales
Leptonic modes have larger transverse momenta → exceed ~30 GeV trigger

Theorists often ask for measurements separated by lepton flavour including taus
Not clear how sensitive such a measurement would be - no studies (yet)

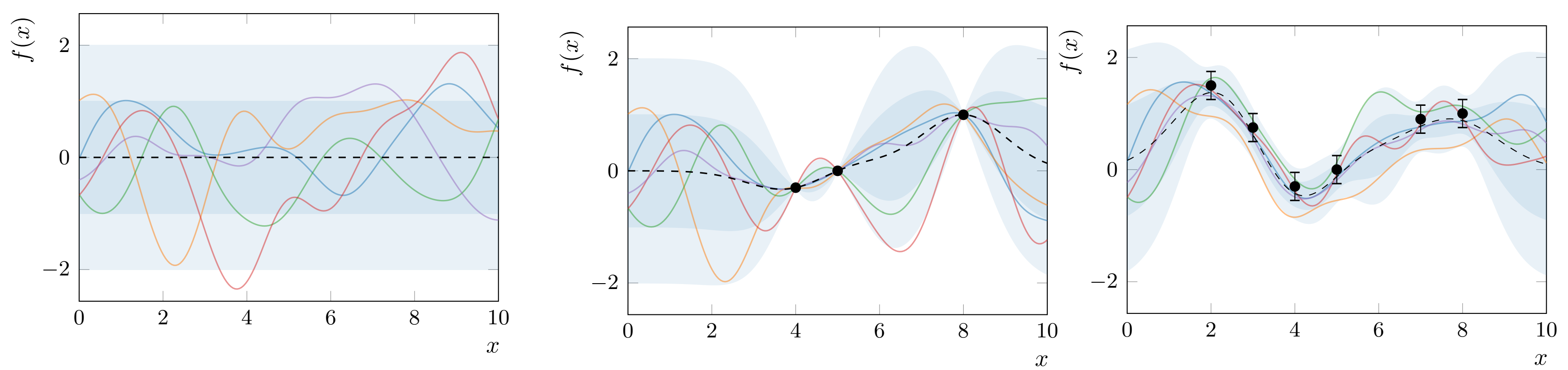
Could test lepton universality at Q ~ 1TeV?
Access to additional EFT operators?
Fewer assumptions on flavour symmetry…

Additional question:
Currently apply lepton vetos in CC high mass measurements
Suppresses Z and $t\bar{t}$ background
Also suppresses real EW corrections: real W and Z radiation
Is this wise in EFT interpretations?

Unfolding using Gaussian Processes

Adam Bozson , Glen Cowan arXiv:1811.0124

Proposal of new unfolding method using Gaussian processes and Bayesian regression
Gaussian processes - distributions over functions giving broad range non-parametric functions
Underlying truth distribution estimated as mode of posterior function



GP with zero mean and unit variance and several sampling functions and posteriors with added data
GP entirely defined by mean and covariance - governed by kernel function

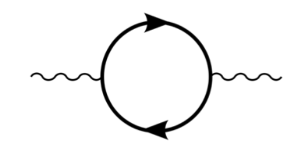
Unfolding always leads to trade-off in bias / variance of unfolded measurement controlled by regularisation
Regularisation defined by the covariance or choice of the kernel function

Posterior distribution is a GP → can be evaluated at arbitrary points
Therefore unfolded distribution can be re-binned at will, if kernel function is known
Can directly compare results from different experiments

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

$\sin^2\theta_W$ is a fundamental 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: $$\sin^2\theta^f_{\text{eff}} = (1 - \frac{m_W^2}{m_Z^2}) \cdot (1 + \Delta r)$$

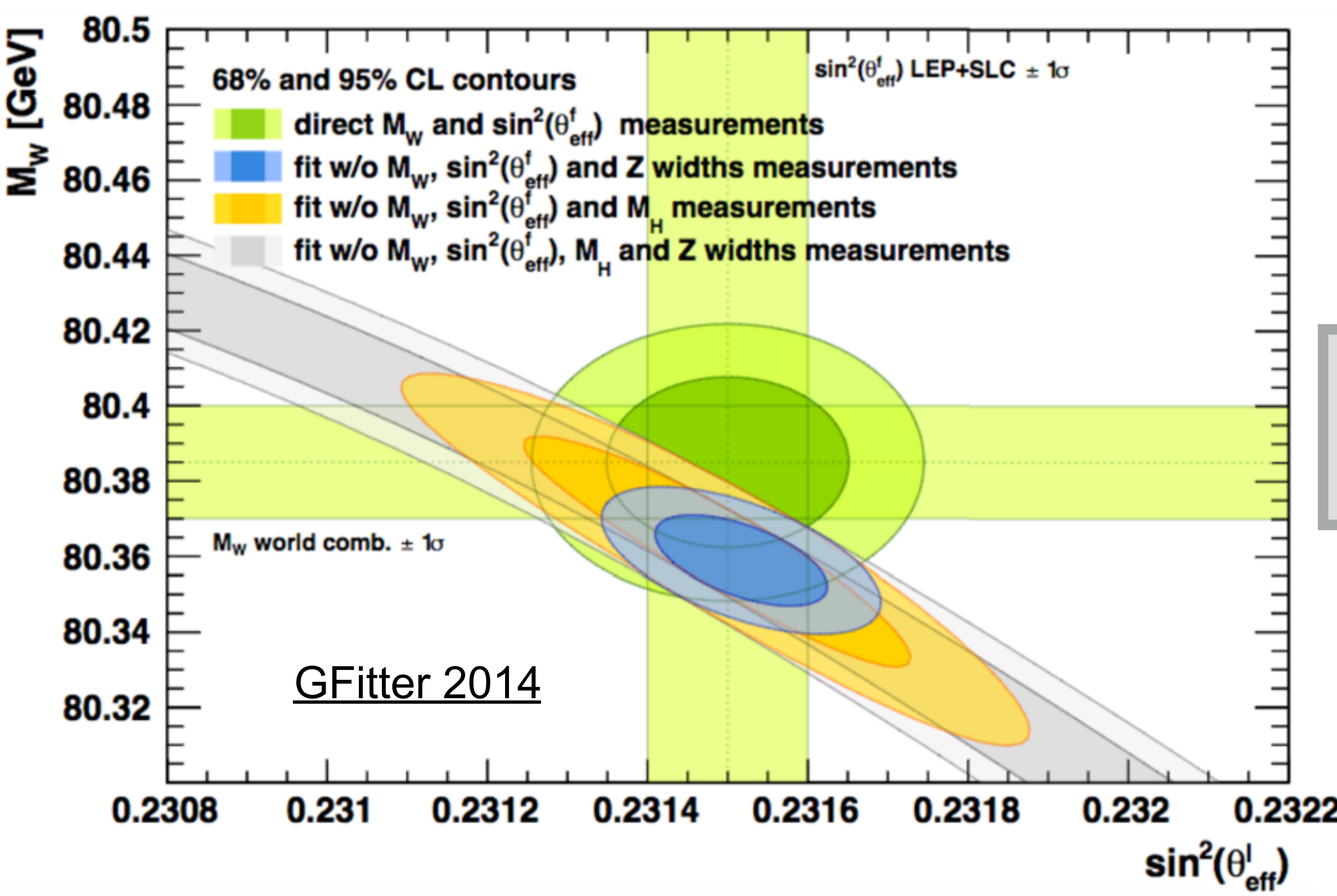
Δr encapsulates radiative corrections
New physics can appear in loops

$\Delta r \rightarrow \Delta r$ (m_Z, G_μ, m_{higgs}, m_{top}, new physics)

With known m_h EW sector of SM is over-constrained

- m_Z = 91.1876 GeV
- G_μ = 1.16637 x 10^{-5} GeV^{-2}
- $\alpha_{QED}(0)$ = 1/137.035

$$m_W^2 = \frac{\pi\alpha(0)}{\sqrt{2}G_\mu \sin^2\theta_W}\frac{1}{1-\Delta r}$$



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

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

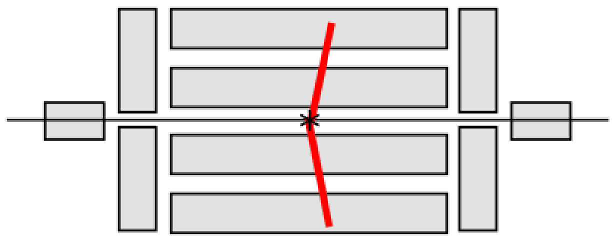
ATLAS $\sin^2\theta_{eff}$ $\sqrt{s}$ = 8 TeV

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

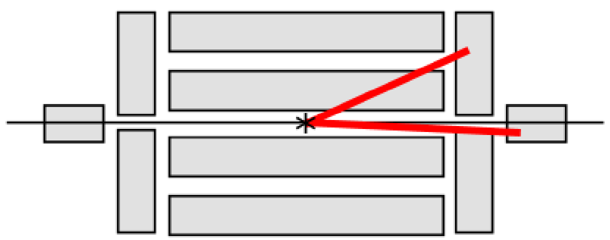
ATLAS-CONF-2018-037/

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

Central-Central:



Central-Forward:



Better precision from Central-Forward channel than Central-Central (higher sensitivity / less dilution)
Dominated by PDF uncertainty
Sizeable uncertainty from data statistics

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

ATLAS — ATLAS-CONF-2018-037/

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

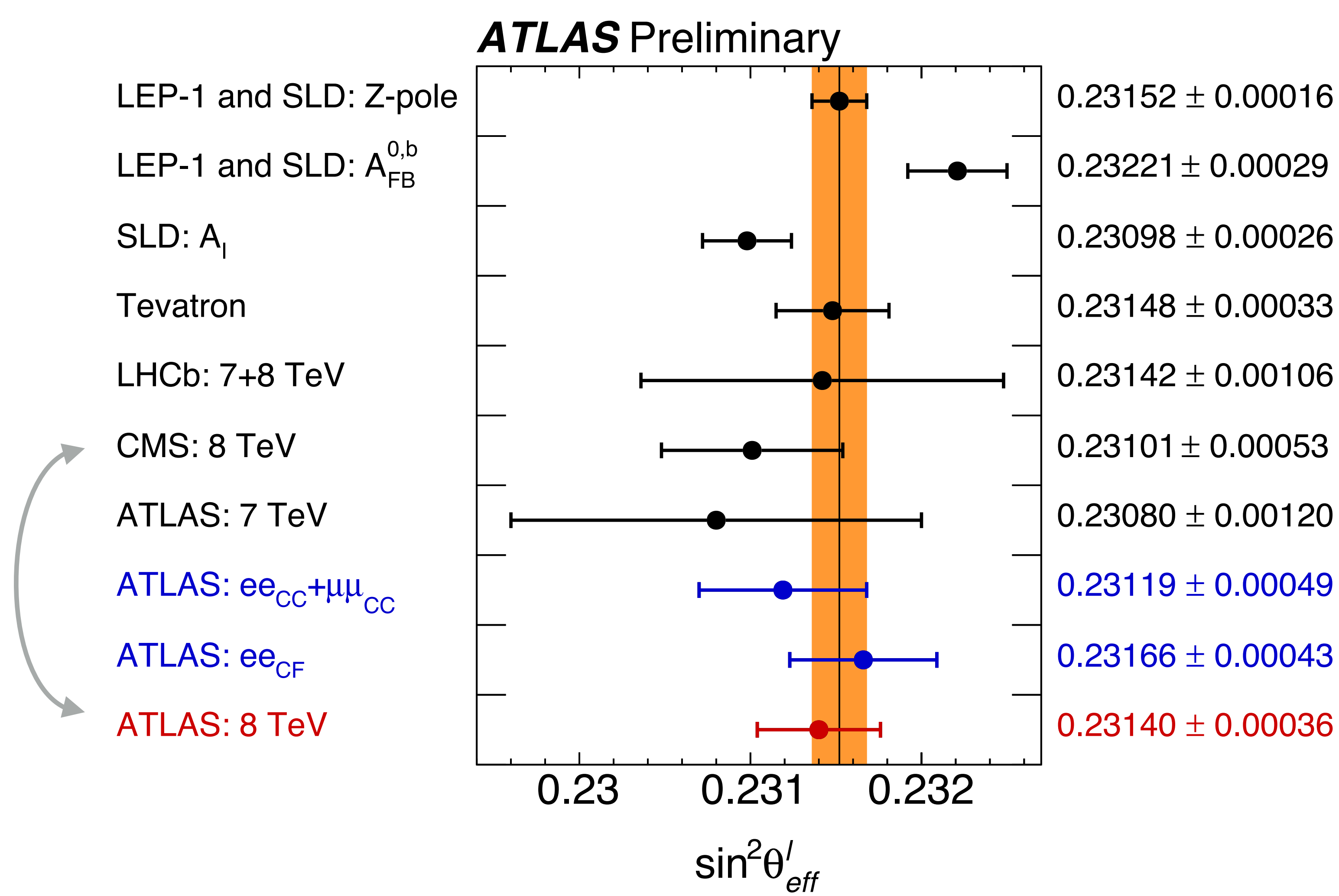
$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

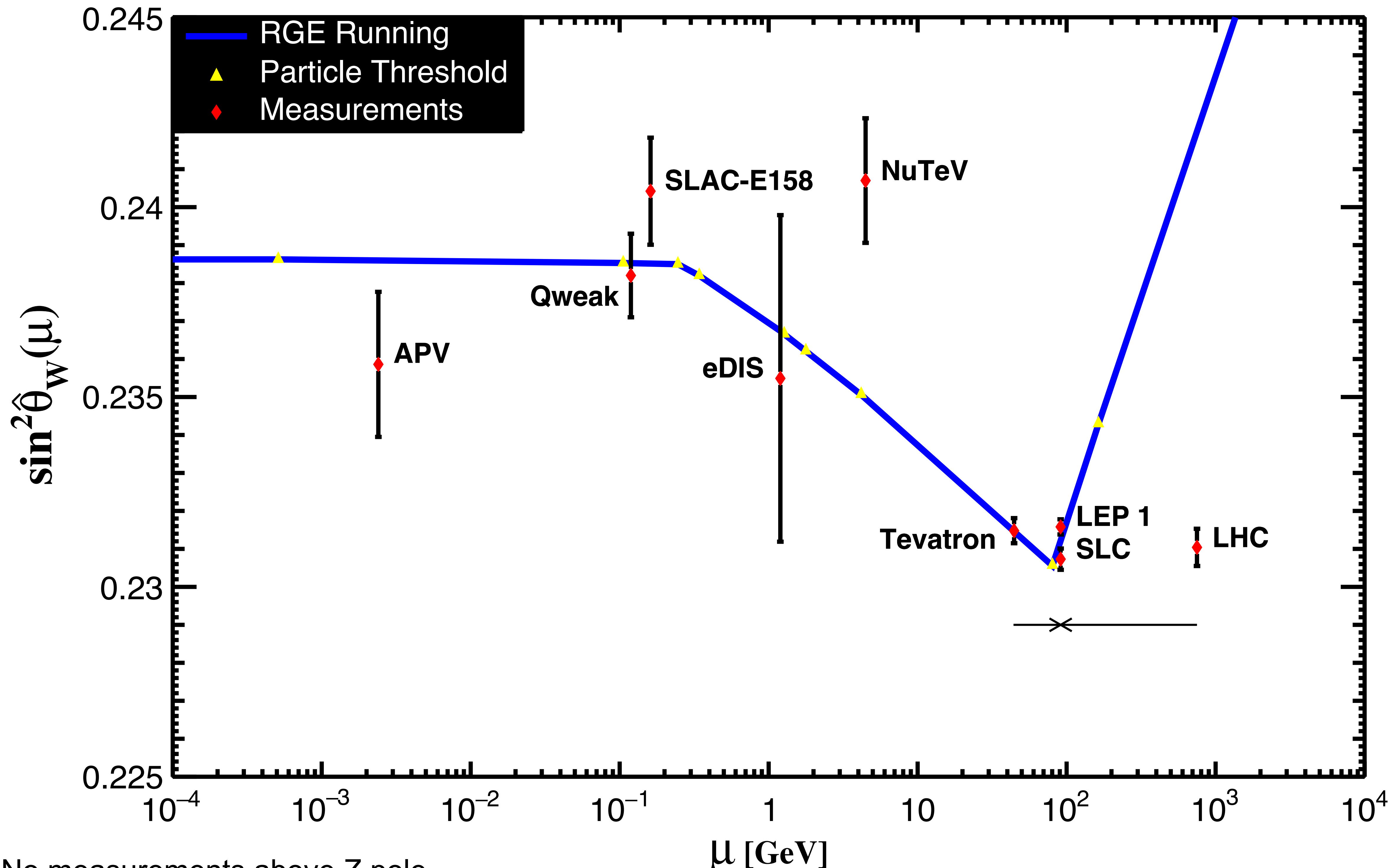
CMS — arXiv:1806.00863

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

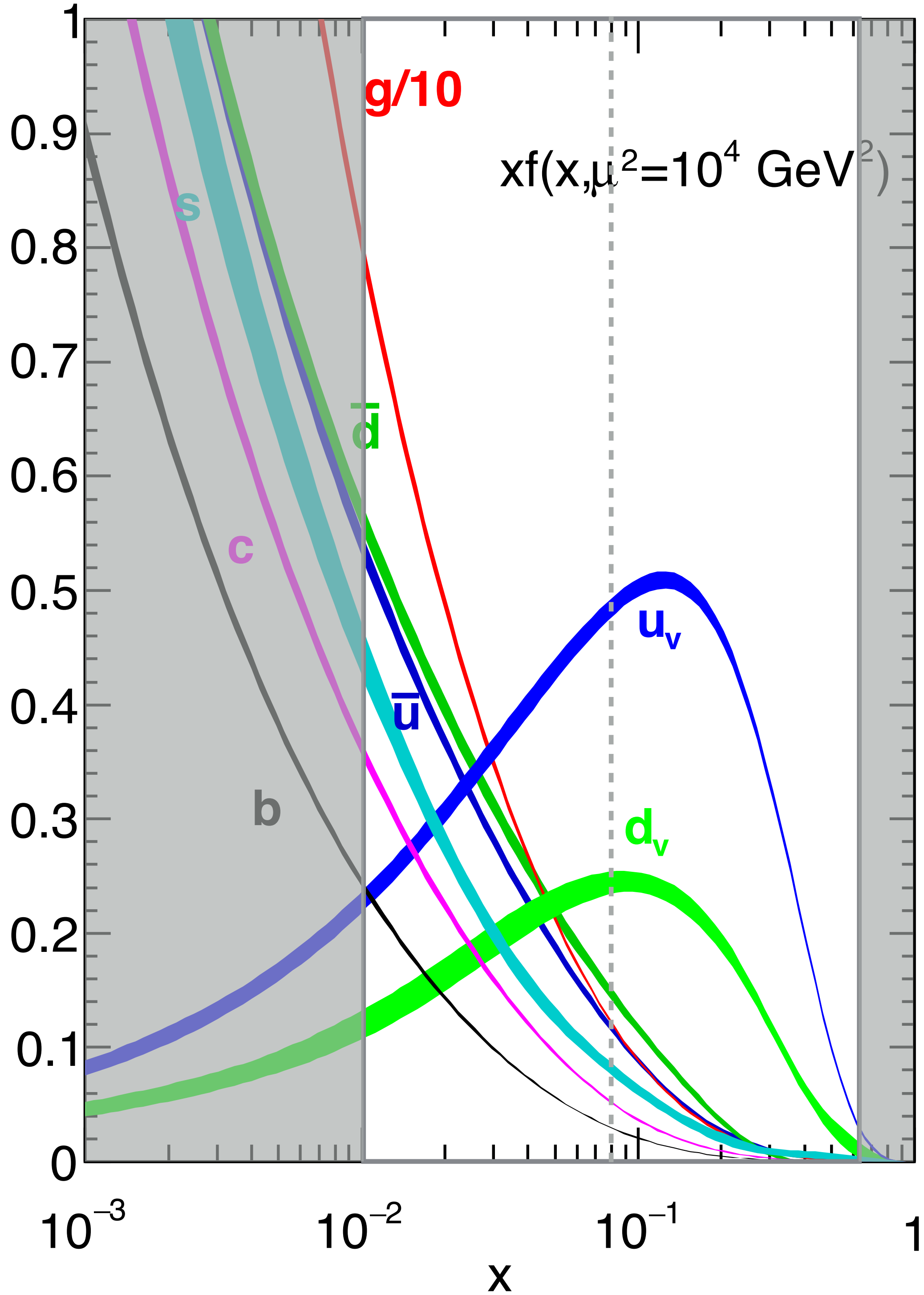
	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^{\ell}_{\text{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

x 10^{-5}





No measurements above Z pole
Can we measure scaling at high mass?
Experimentally constrained by rapidly falling cross sections



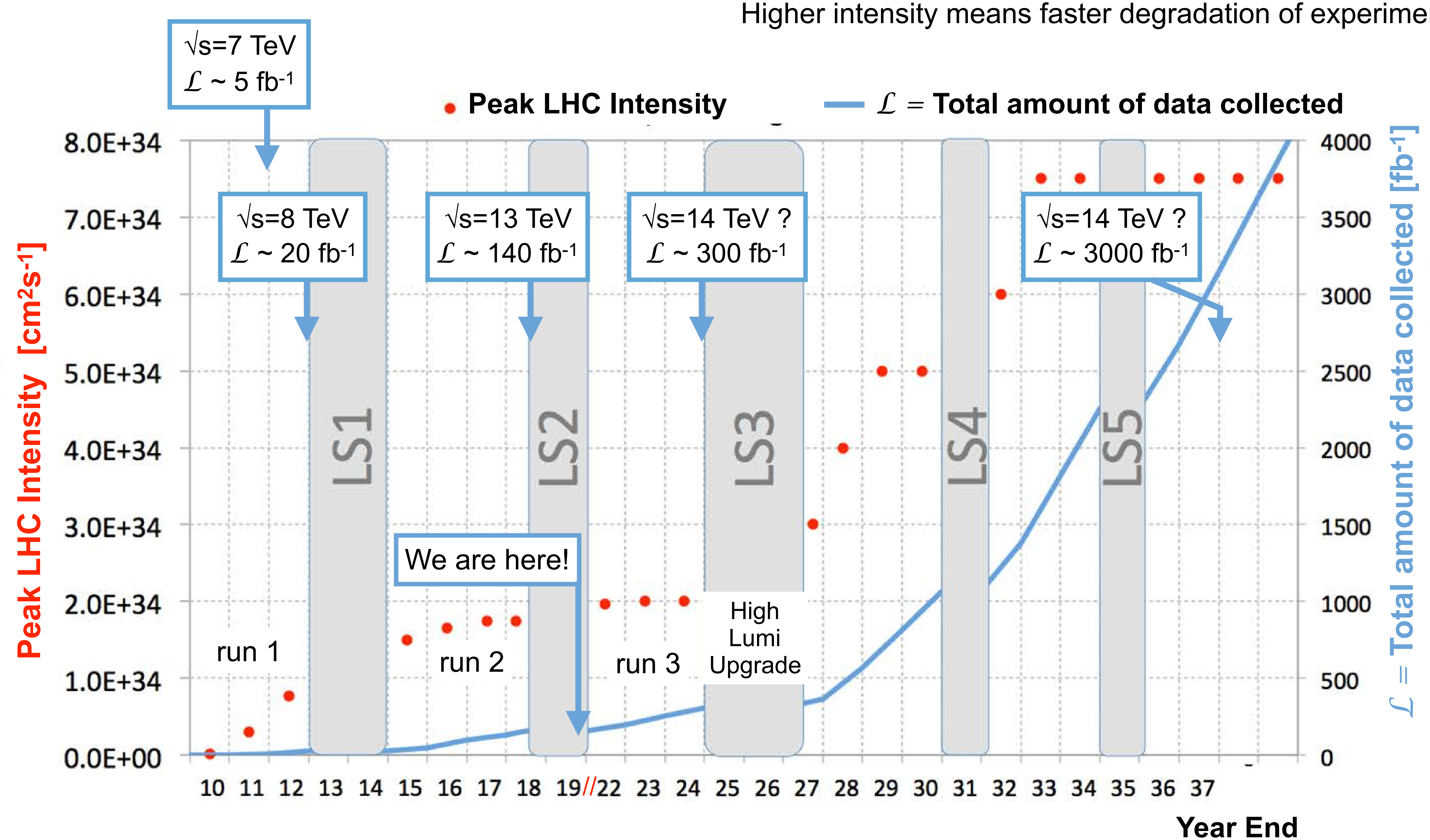
$\sin^2\theta_W(Q)$ at high scales
→ lower dilution at higher m: probe valence region

What is interplay between $\sin^2\theta_W(Q)$ and EFT?

LHC Schedule to 2035

* actual schedule slipped by ~1 year
e.g. LS3 starts 2024?

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

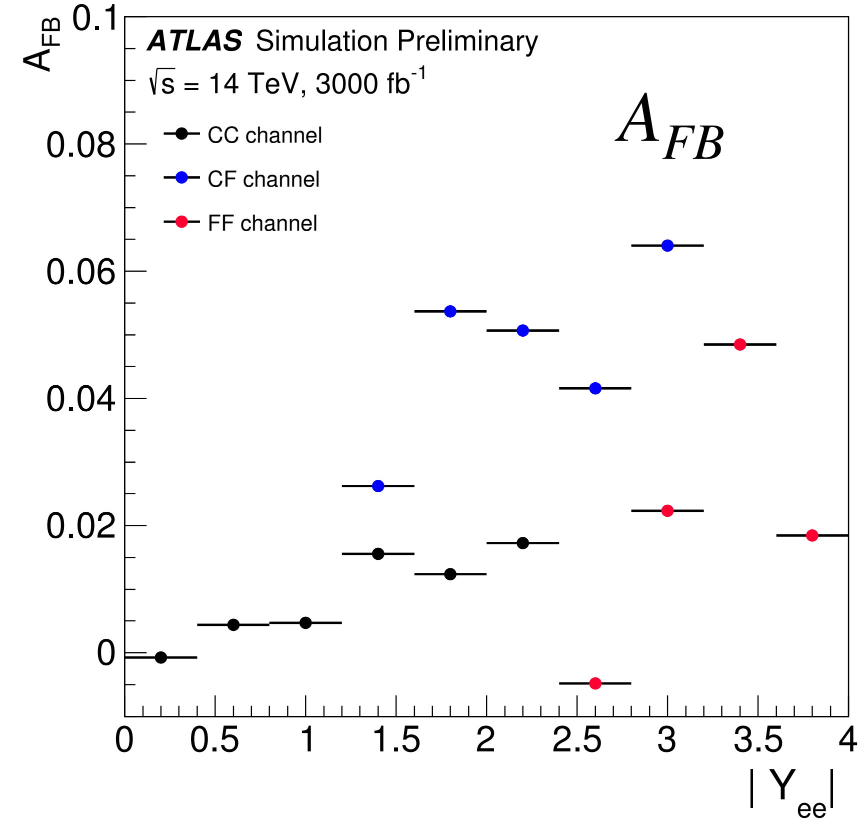


LS = Long Shutdown for repairs and upgrades

HL-LHC Prospects: $\sin^2\theta_W$

ATL-PHYS-PUB-2018-037

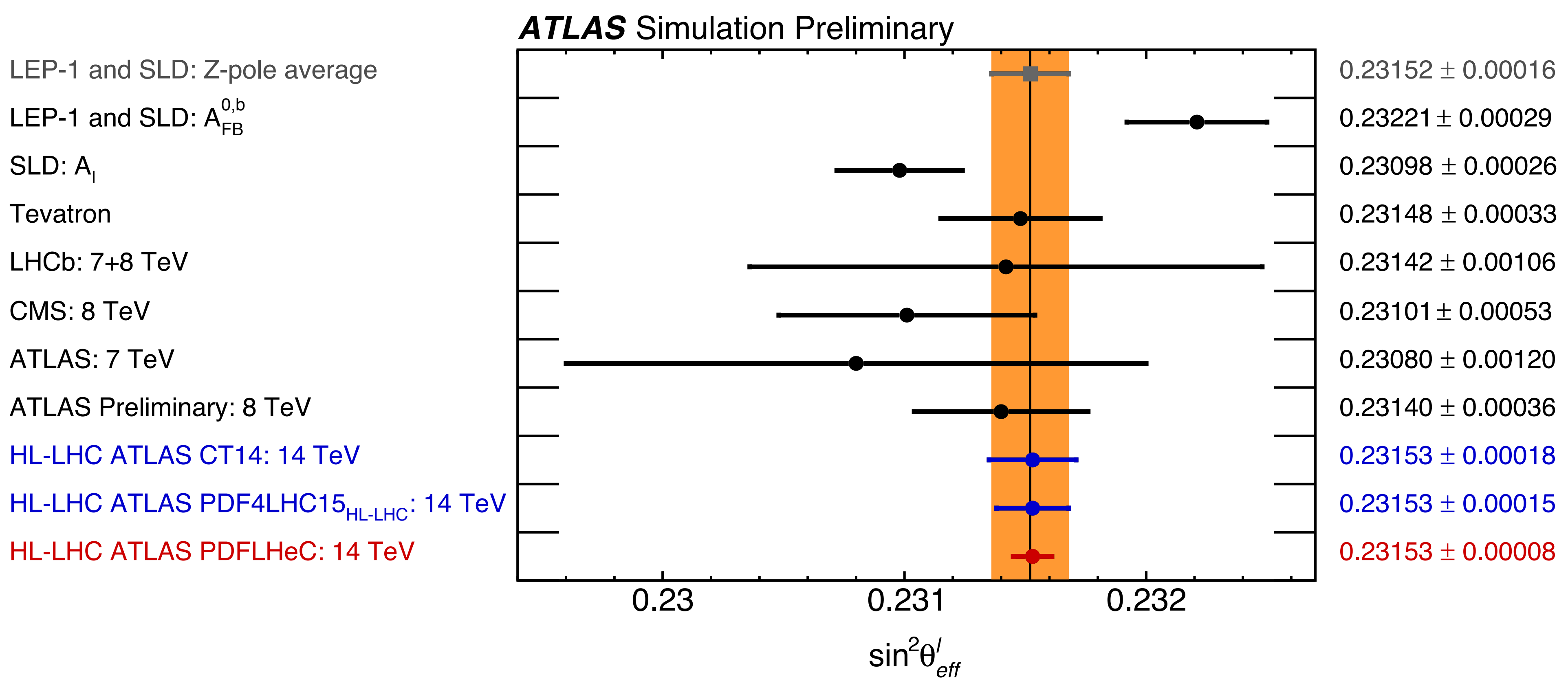
$\int\mathcal{L}$ = 3000 fb^{-1} taken at $\sqrt{s}$=14 TeV
Tracking for |η| < 4.2
→ 540m Z CC events
→ 210m Z CF events → best sensitivity
→ 150m Z FF events → new channel



Perform fit for $\sin^2\theta_W$ with PDF profiling
→ reach $\Delta\sin^2\theta_W = 18\times10^{-5}$

Use HL-LHC pseudo-data to simulate PDF improvements
→ reach $\Delta\sin^2\theta_W = 15\times10^{-5}$

Use LHeC pseudo-data to simulate PDF improvements
→ reach $\Delta\sin^2\theta_W = 8\times10^{-5}$



Summary

Open questions

- Which observables to measure in high mass NC & CC Drell-Yan production?
- Understand uncertainties in ATLAS / CMS measurements
- Can we measure NC & CC Drell-Yan in tau channel?
- Safe to apply lepton vetos - reject backgrounds (and rejects real EW emission)?
- Do we learn anything new in measuring $\sin^2\theta_W$ at large Q ?

Things to do

Publish full uncertainty tables uncombined in e / μ channels
Attempt tau channel measurement
Extend measurements to larger |y| for run-II and HL-LHC
Machinery to perform combined PDF x EFT fits under development

Backup

Triple Differential Z/γ* Measurement Motivation

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

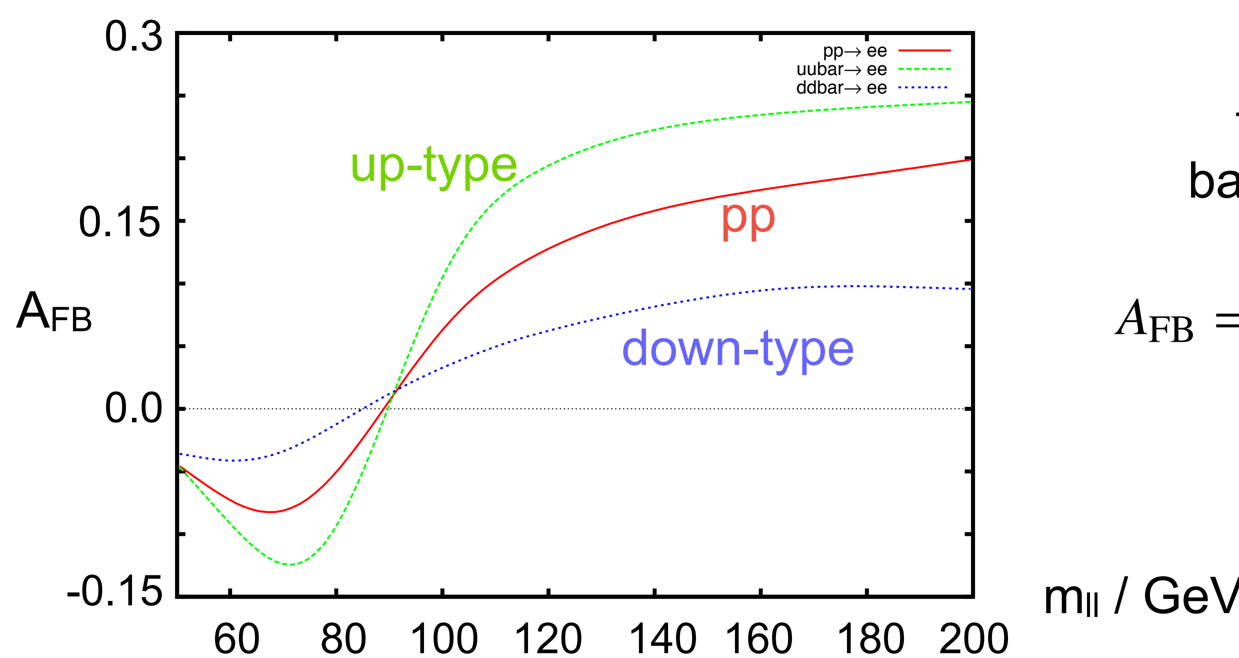
$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q P_q\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q\leftrightarrow\bar{q})\right]$$

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

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

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

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

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

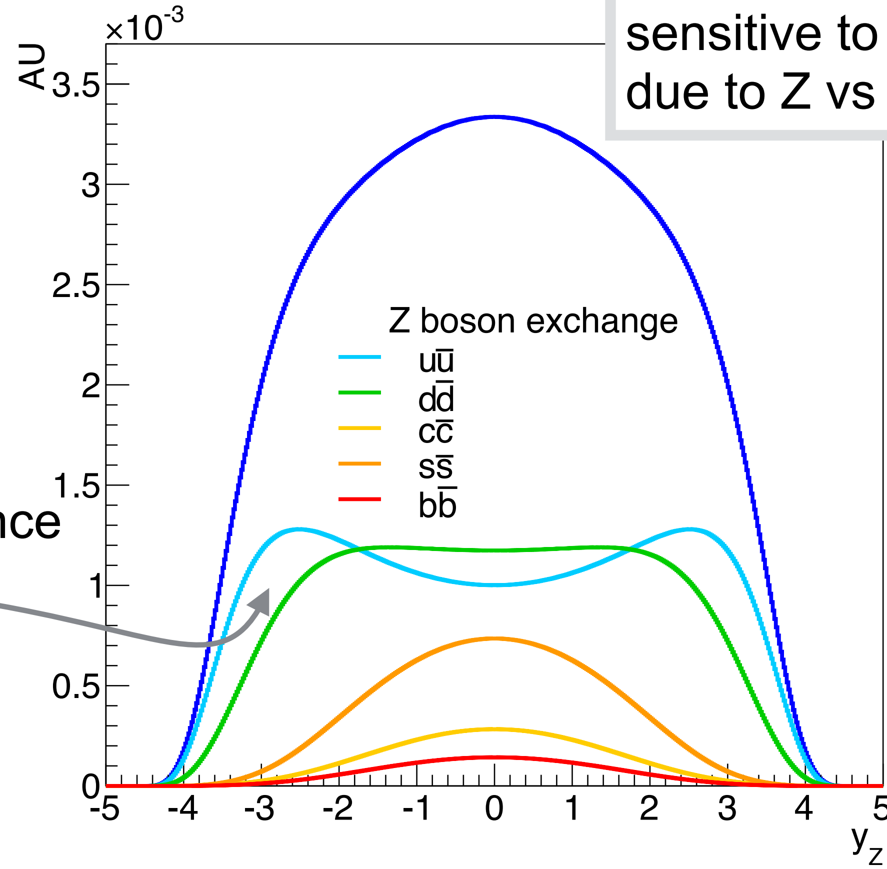
Sensitive to $\sin^2\theta_W$

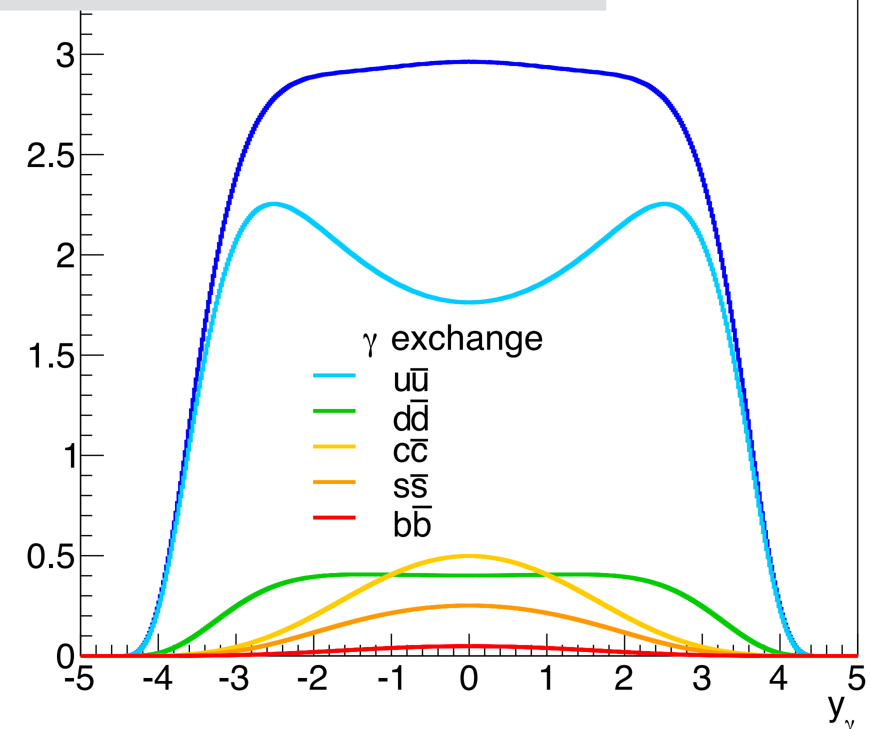
Triple-differential Z/γ* Measurement Motivation

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

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

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



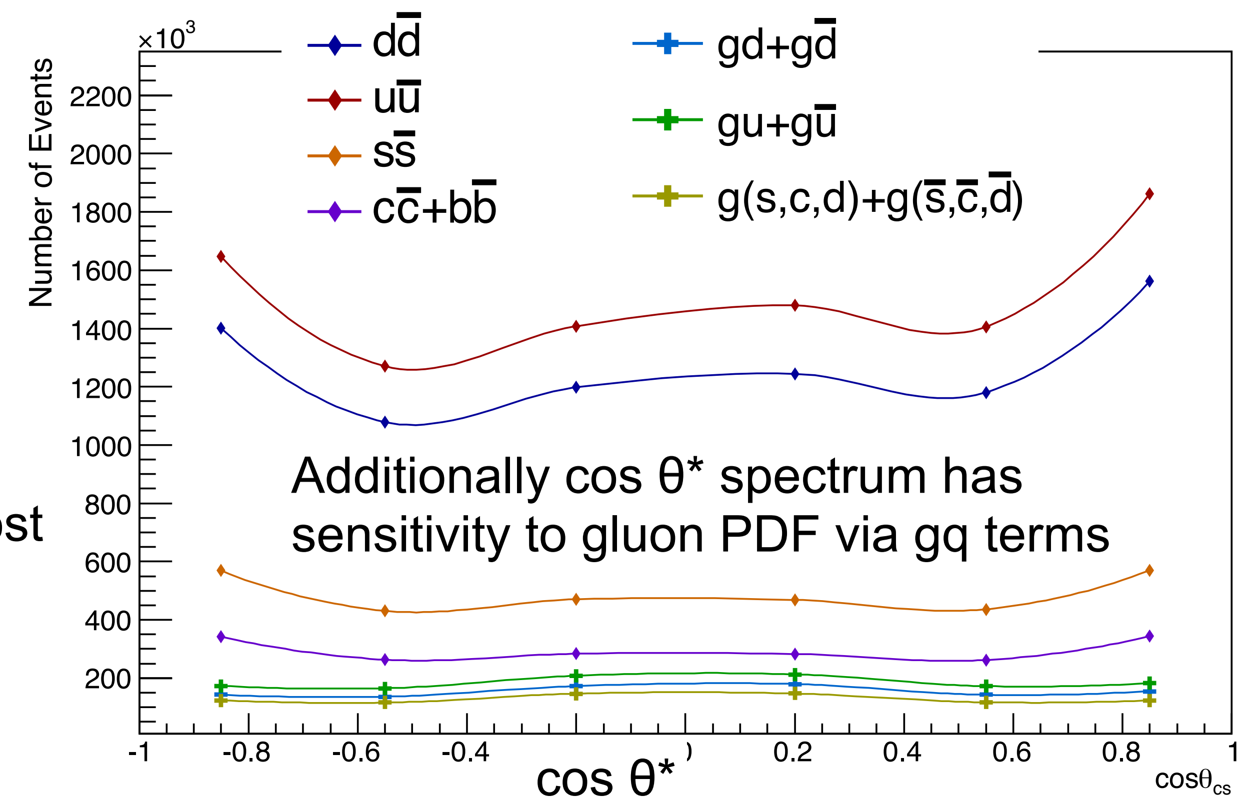


y dependence measures x distribution of PDFs

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

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/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
$\lvert y_{ll} \rvert$ =	[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
$\cos\theta^*$ =	[-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
$\lvert y_{ll} \rvert$ =	[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

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

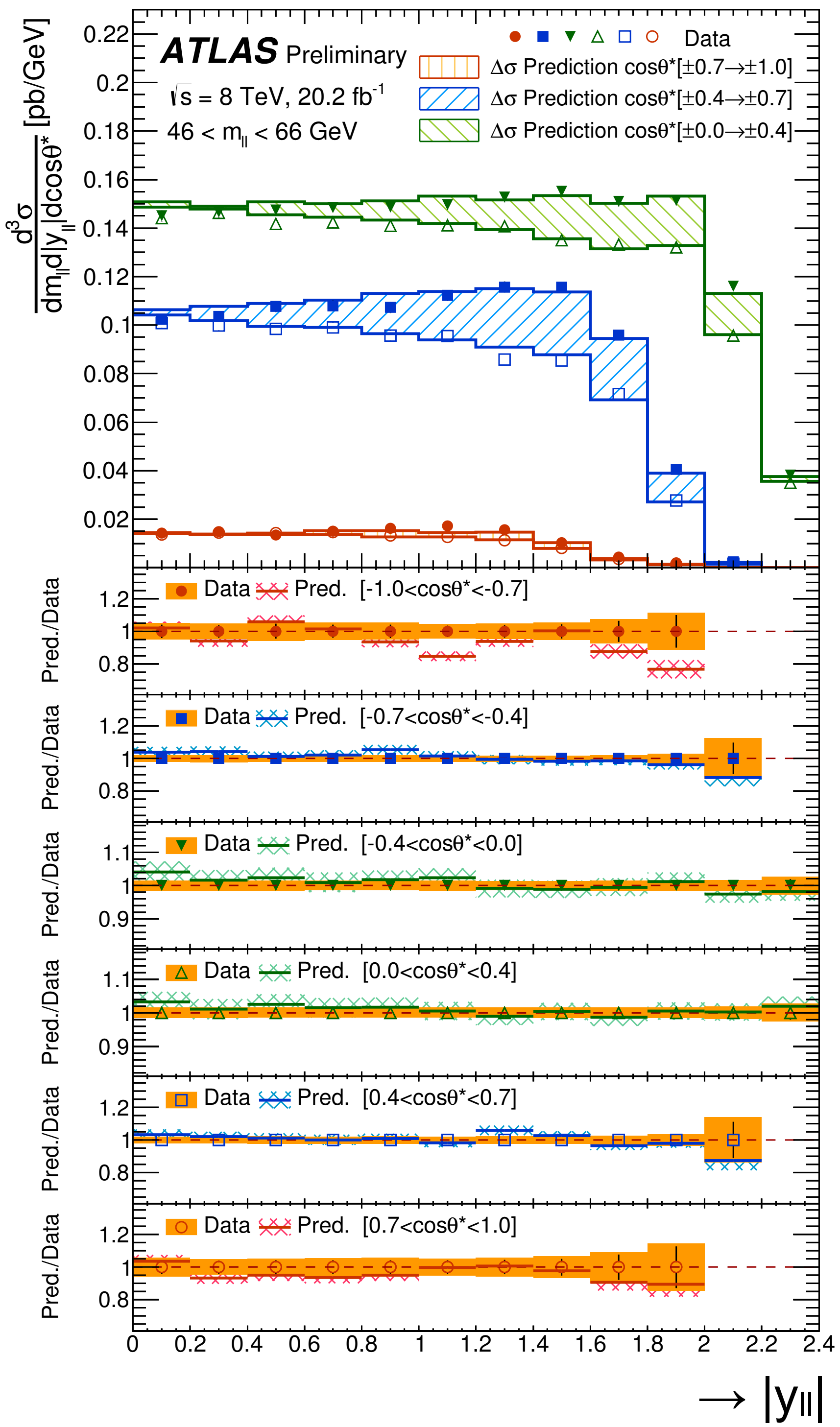
$$\frac{d^3\sigma}{dm_{\ell\ell}\,d|y_{\ell\ell}|\,d\cos\theta^*}$$

Central rapidity electron & muon combined result

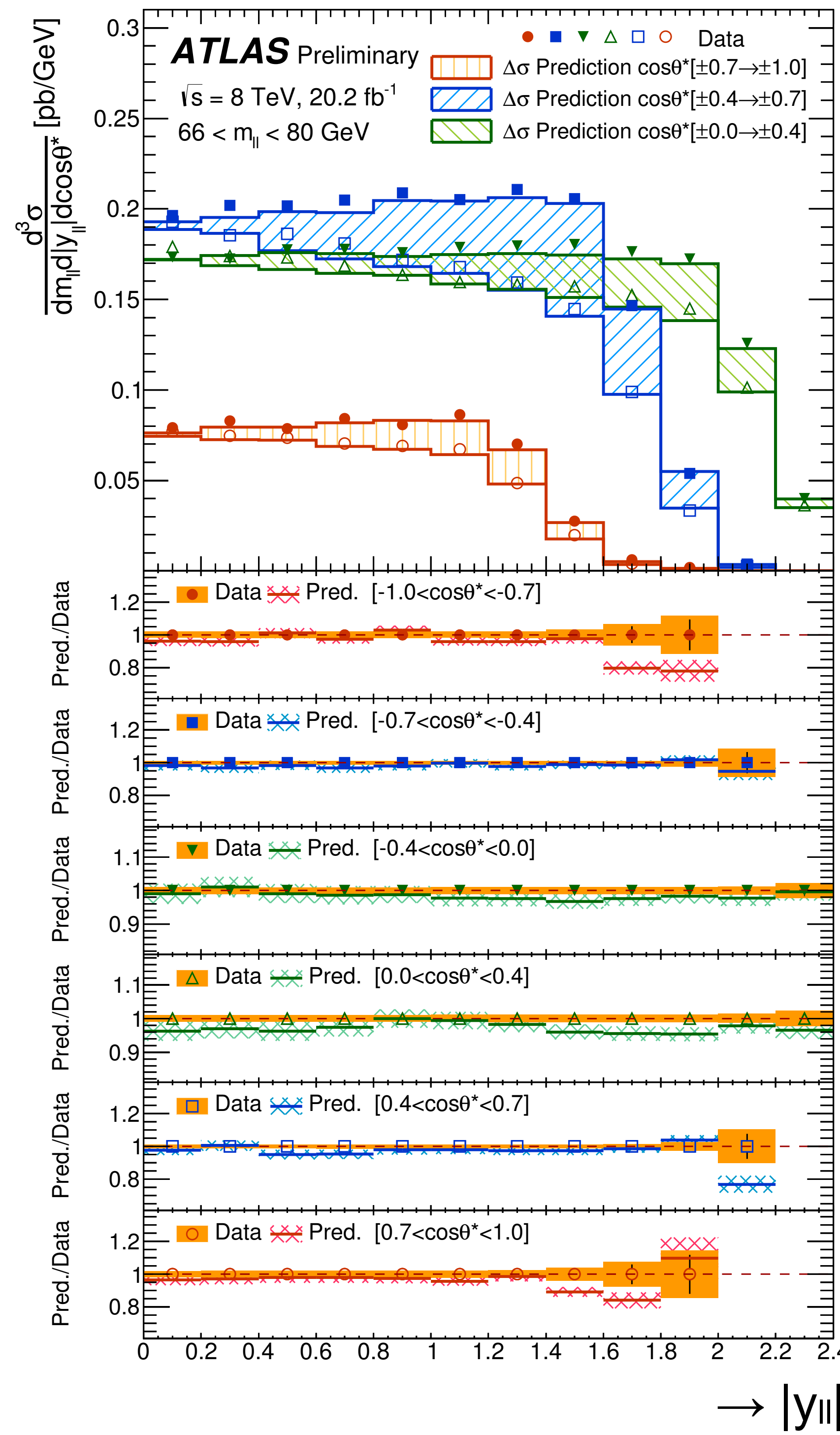
Large forward-backward asymmetry at low mass, decreasing to ~zero at $m_{ll} \sim m_Z$

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

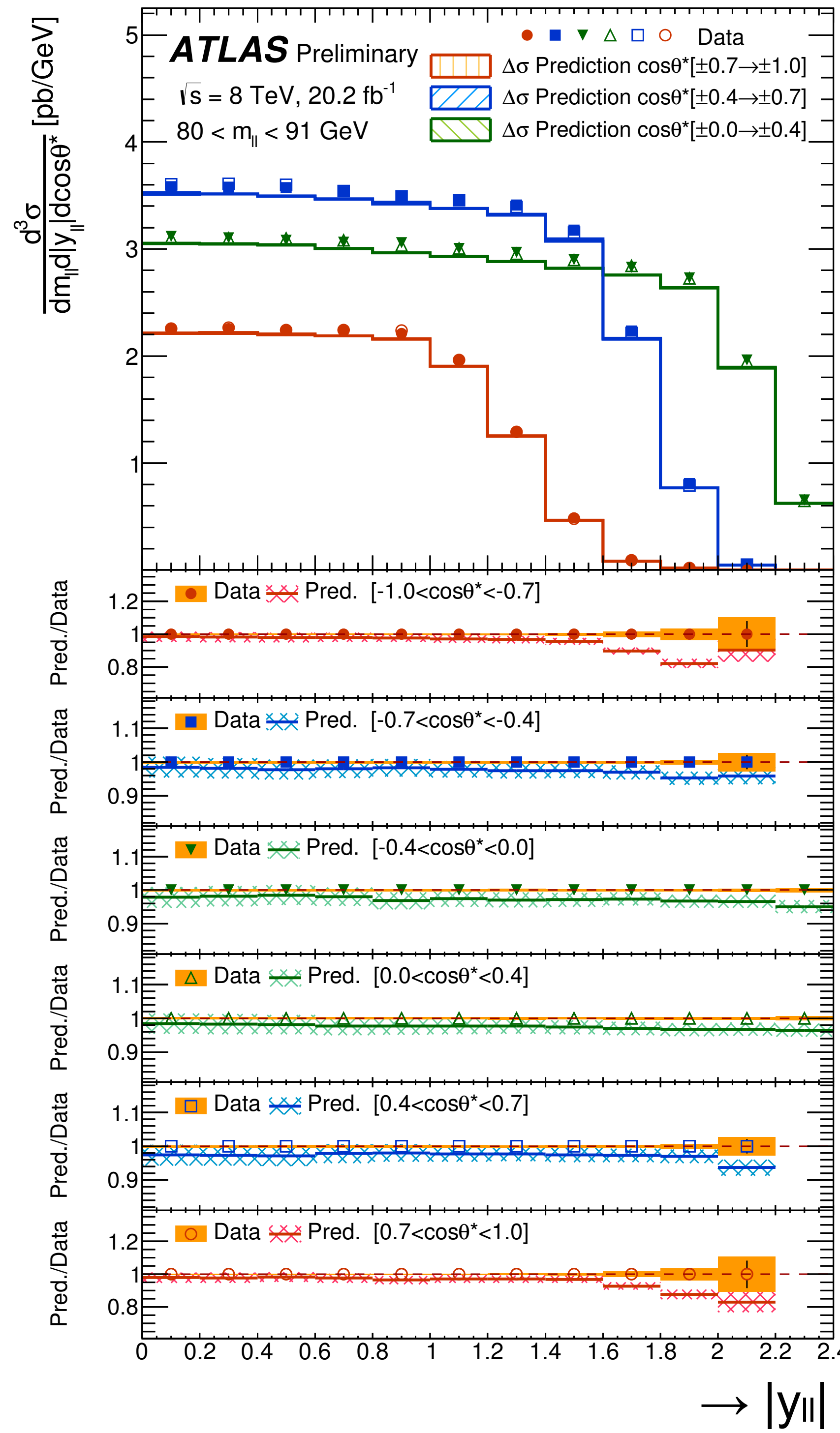
46 < m < 66 GeV



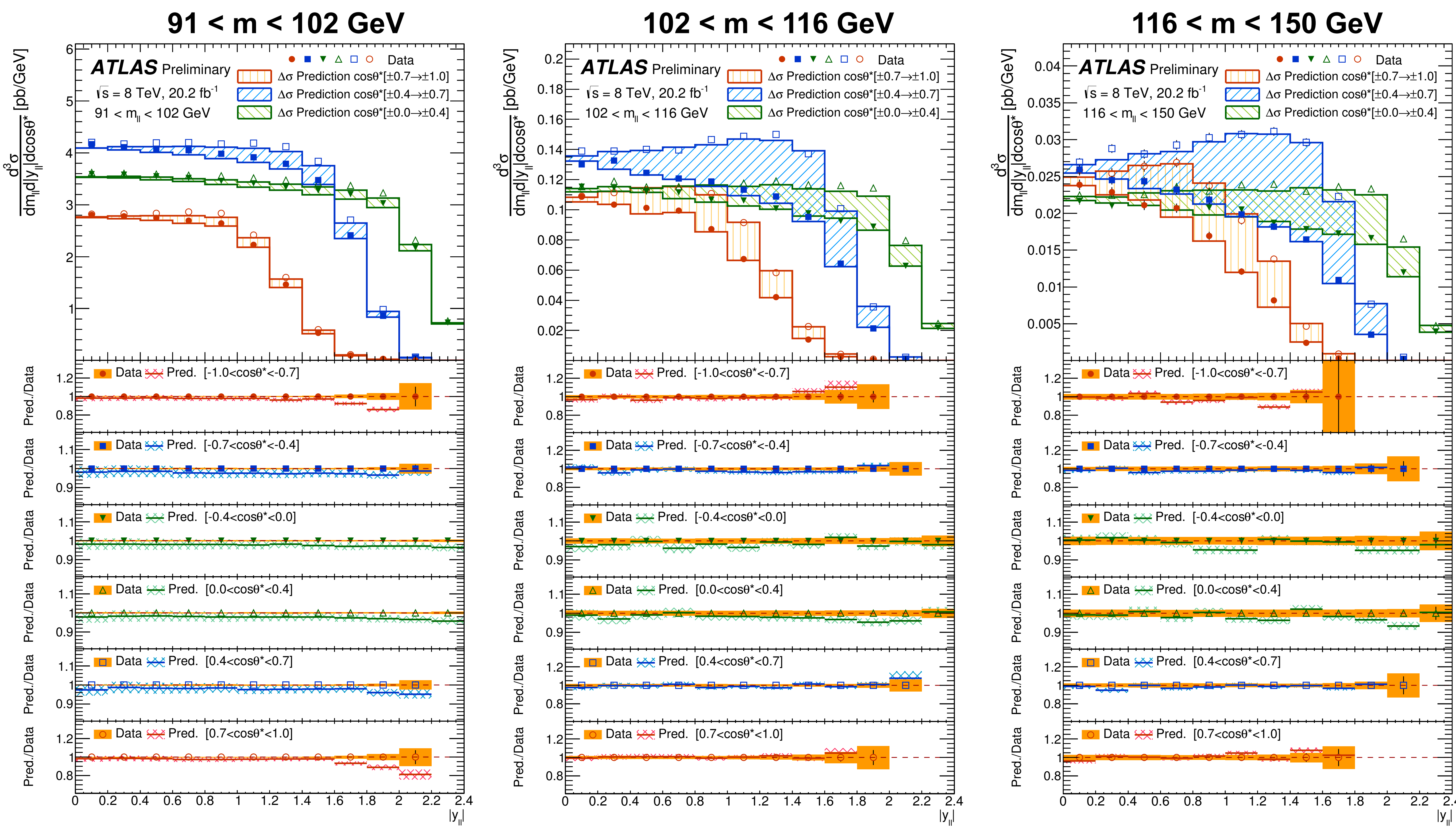
66 < m < 80 GeV



80 < m < 91 GeV



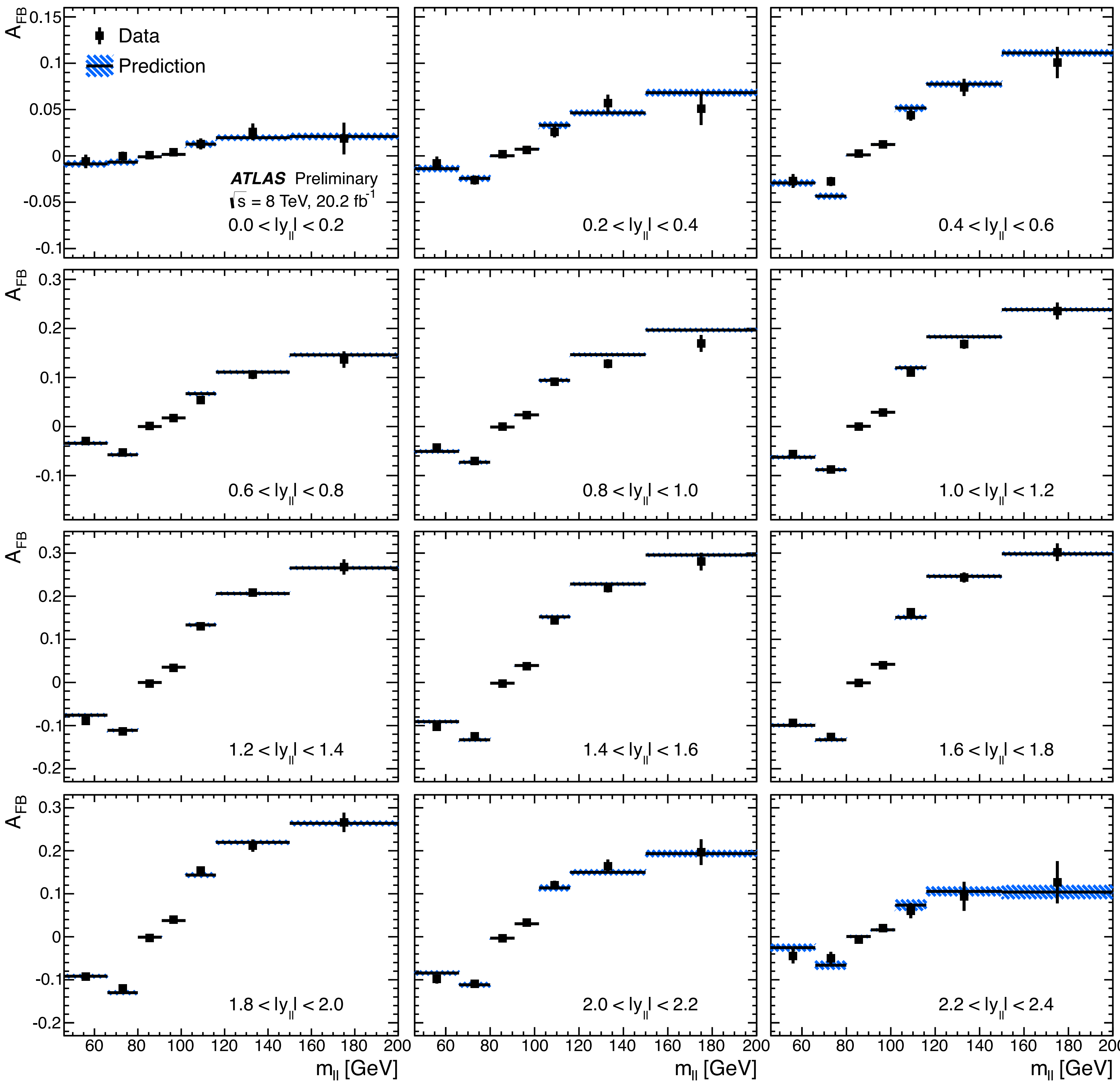
Triple-differential Z/γ* Cross Sections √s = 8 TeV



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)



Central rapidity channel

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

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

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

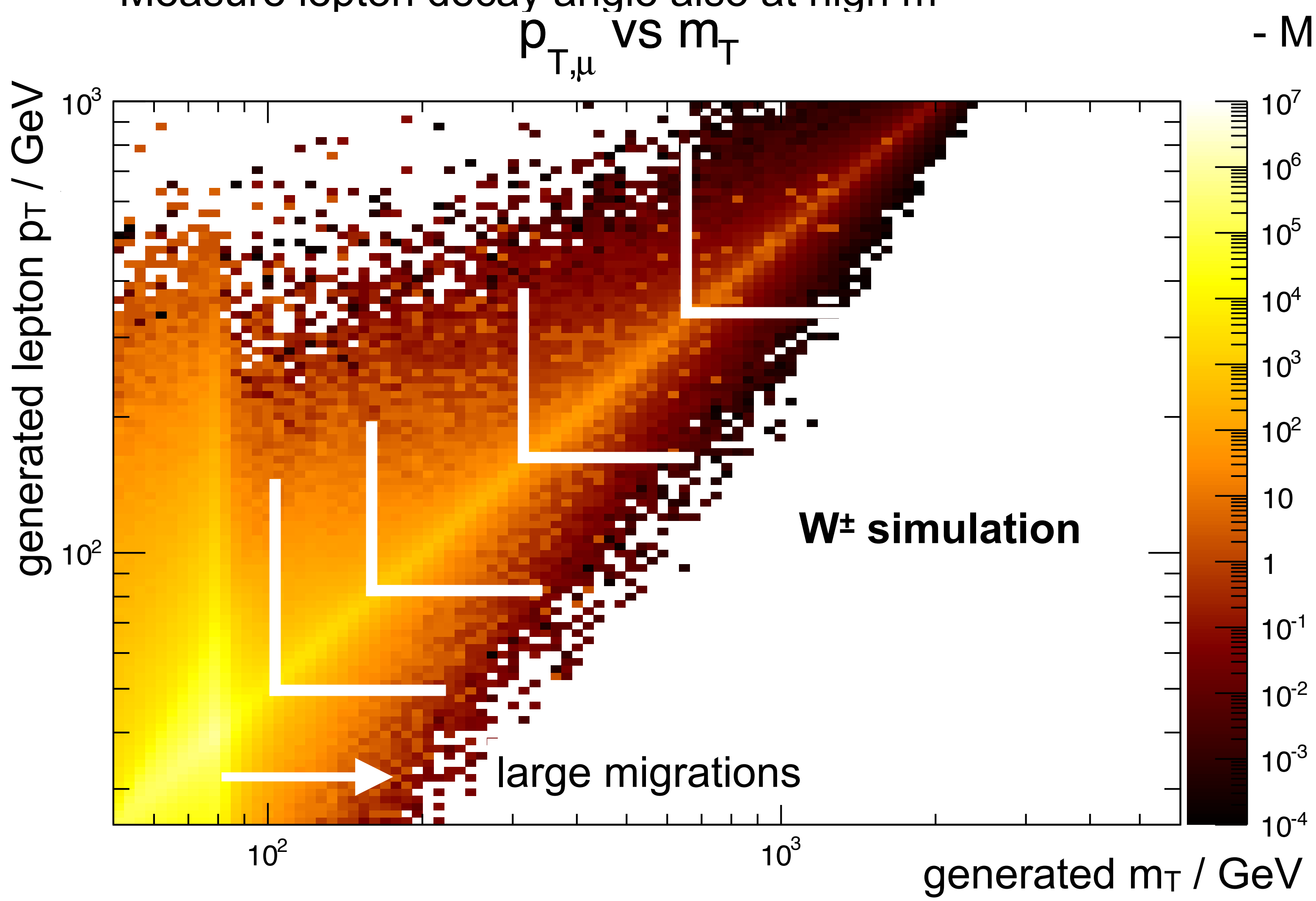
(high |y| access higher x valence PDF)

High Mass W/Z/γ* Production at √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



Questions:

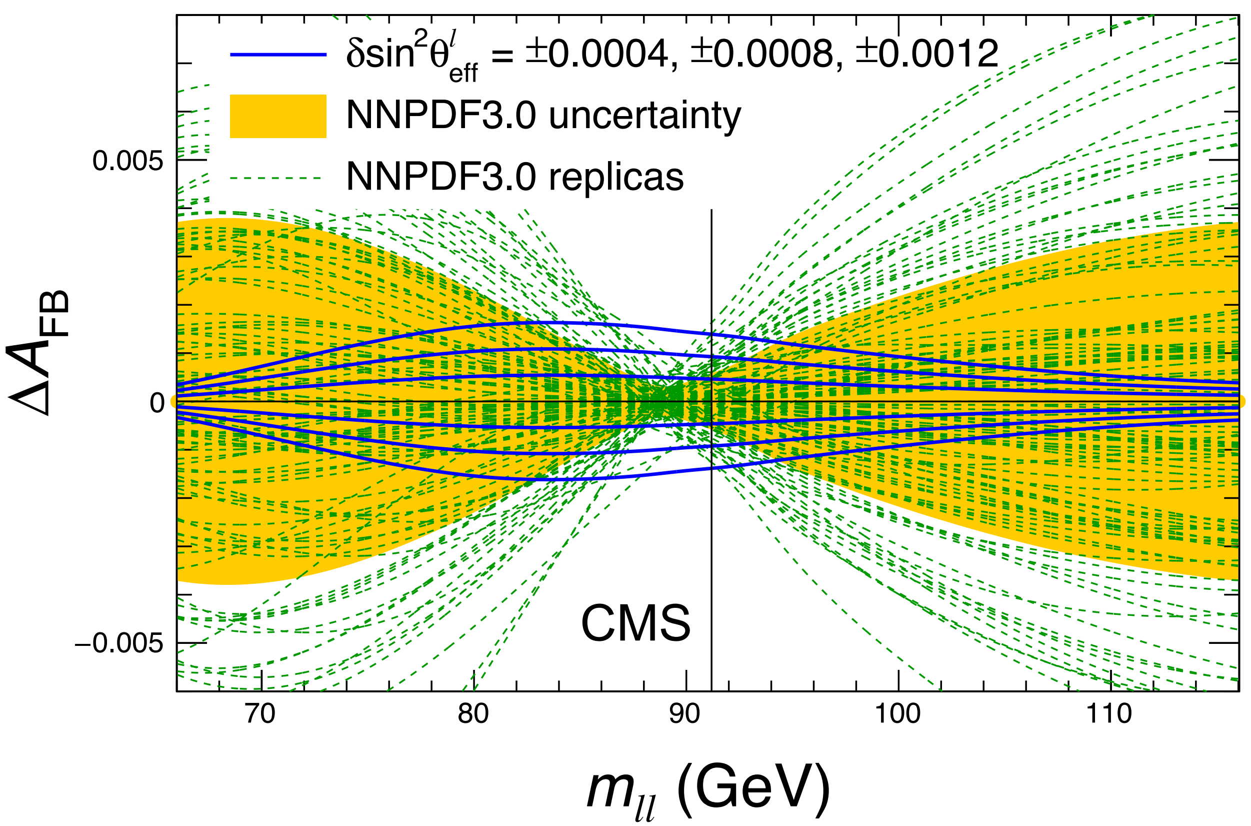
Neutral current channel
- exclude PI contribution?
- which angular variables?
- measure A_{FB} at high m?
- can we constrain W better with new 3D data?

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± 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

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

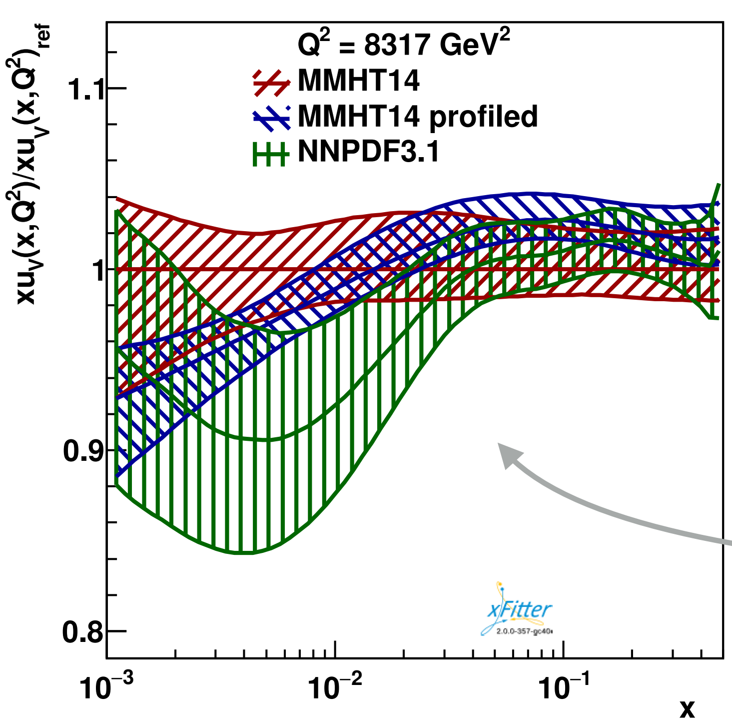
These correlations can be exploited
Use data to constrain PDFs → reduce uncertainty

For NNPDF incompatible replicas rejected by data

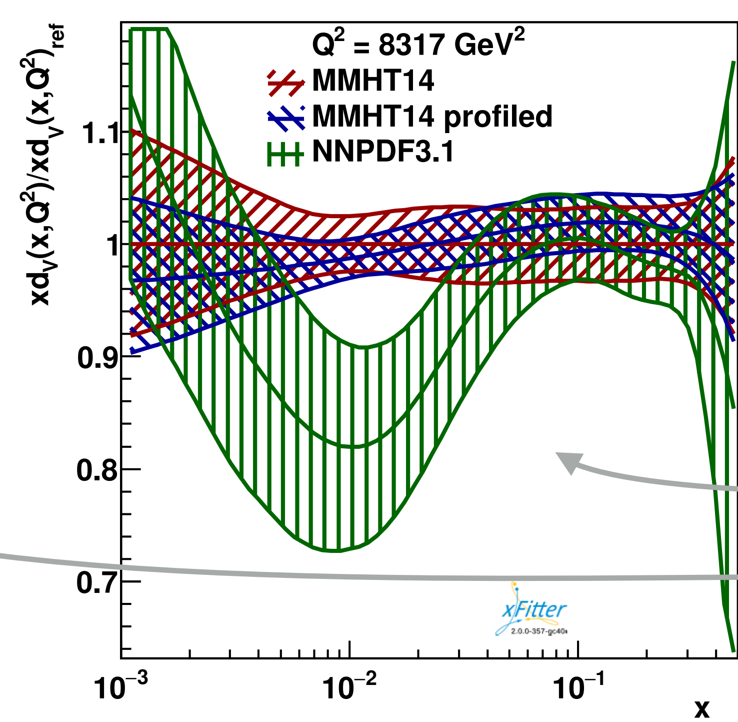
Other PDF sets: uncertainties given as eigenvector variations
Introduce nuisance parameters for each PDF eigenvector
Fit data + PDF nuisance parameters to constrain PDFs

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