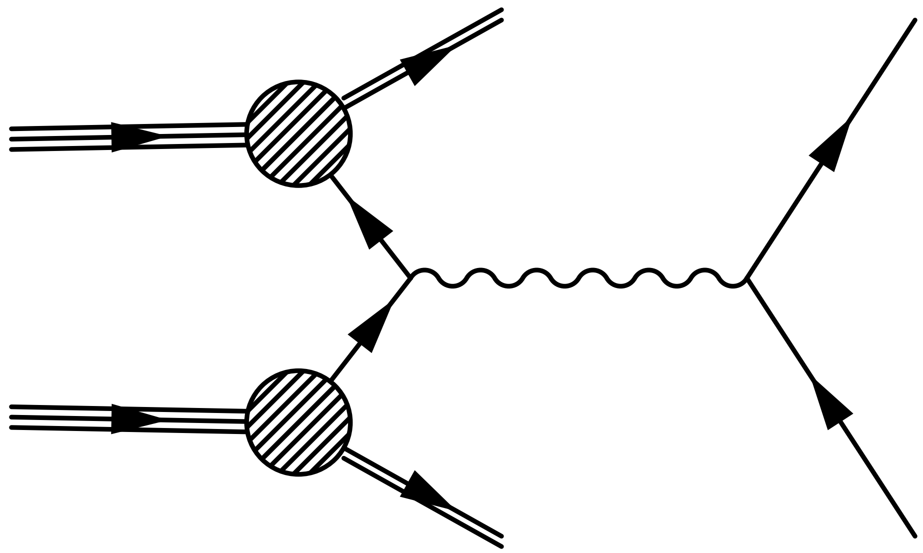
High Mass Drell-Yan and the Photon PDF



8 TeV Measurement

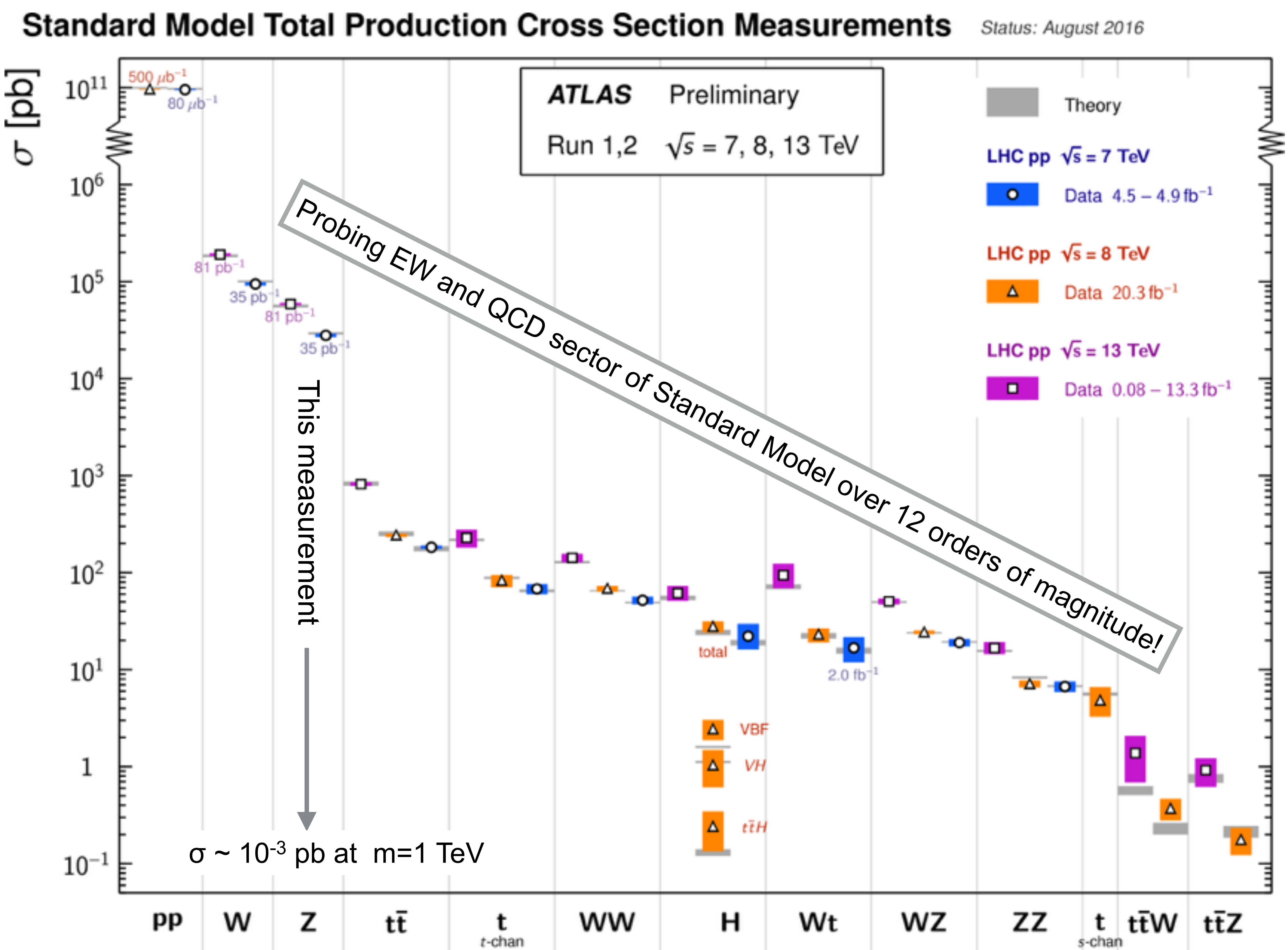
- Introduction
- ATLAS & LHC Performance
- Selections
- Background Estimations
- Differential Cross Sections
- Photon PDF Constraints

arXiv:1606.01736
10.1007/JHEP08(2016)009

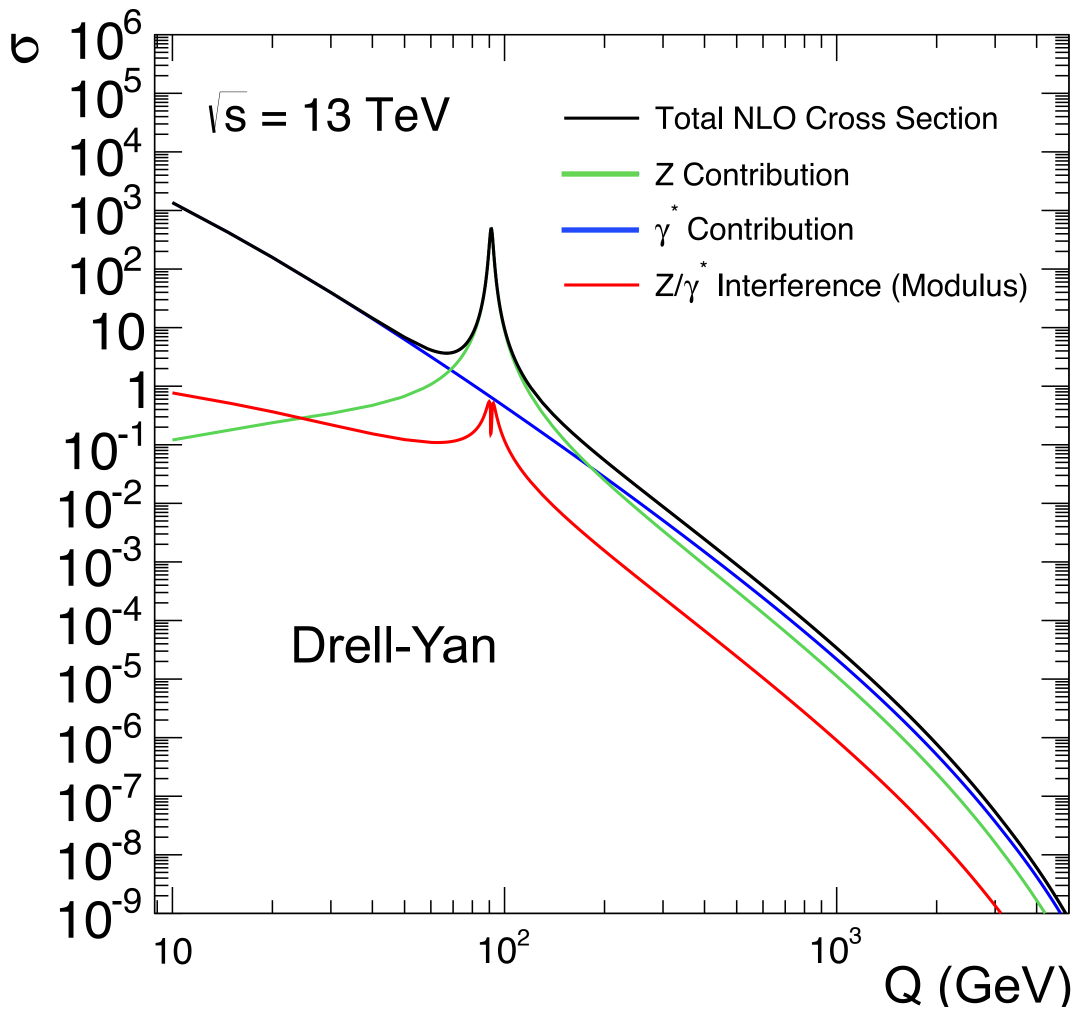
Eram Rizvi

QCD@LHC , Zurich
22nd August 2016

The Standard Model



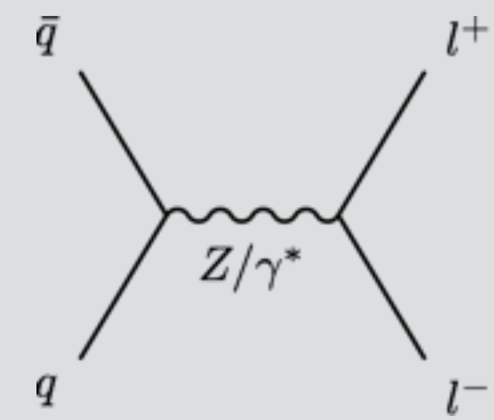
Drell—Yan & Photon Induced Dilepton Production

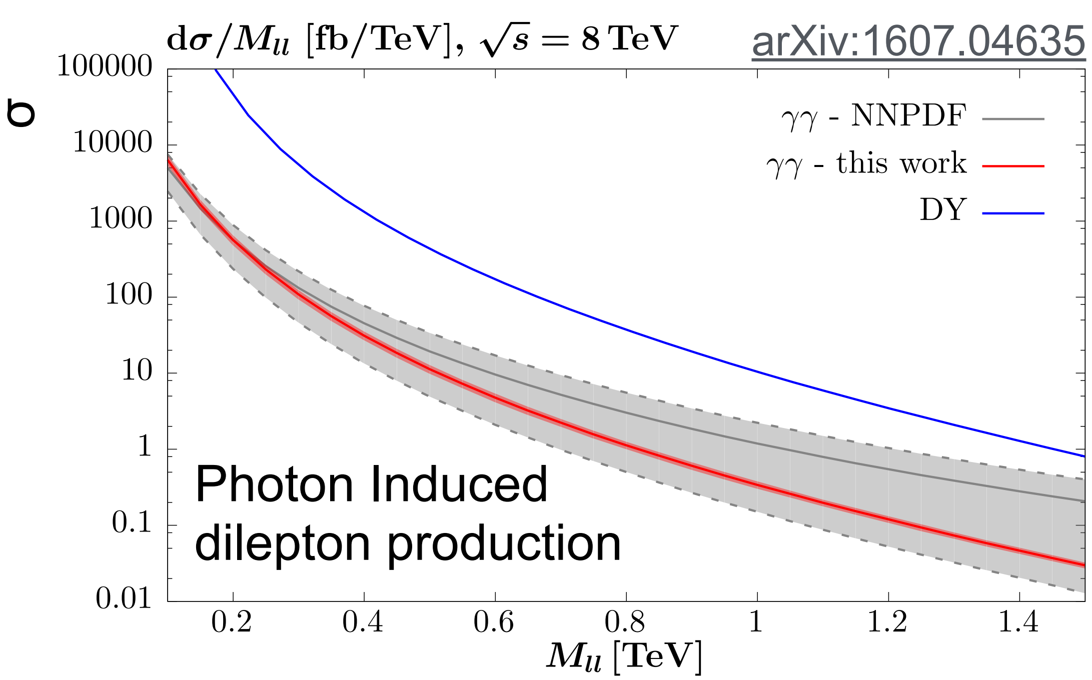


Drell—Yan cross section falls nine decades from 100 GeV → 1000 GeV

Off-shell production dominated by γ* terms

Sensitive to high x antiquarks

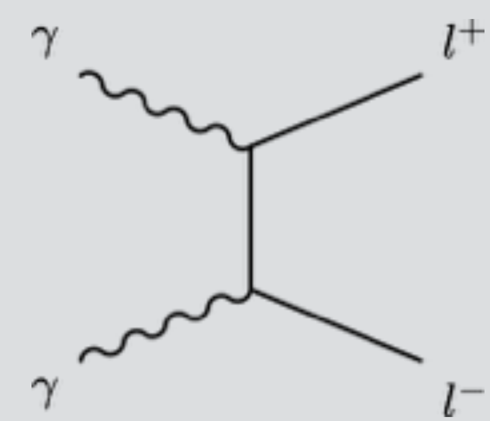




Photon induced production of lepton pairs up to 1-10% of Drell—Yan contribution

Sensitive to photon content of proton

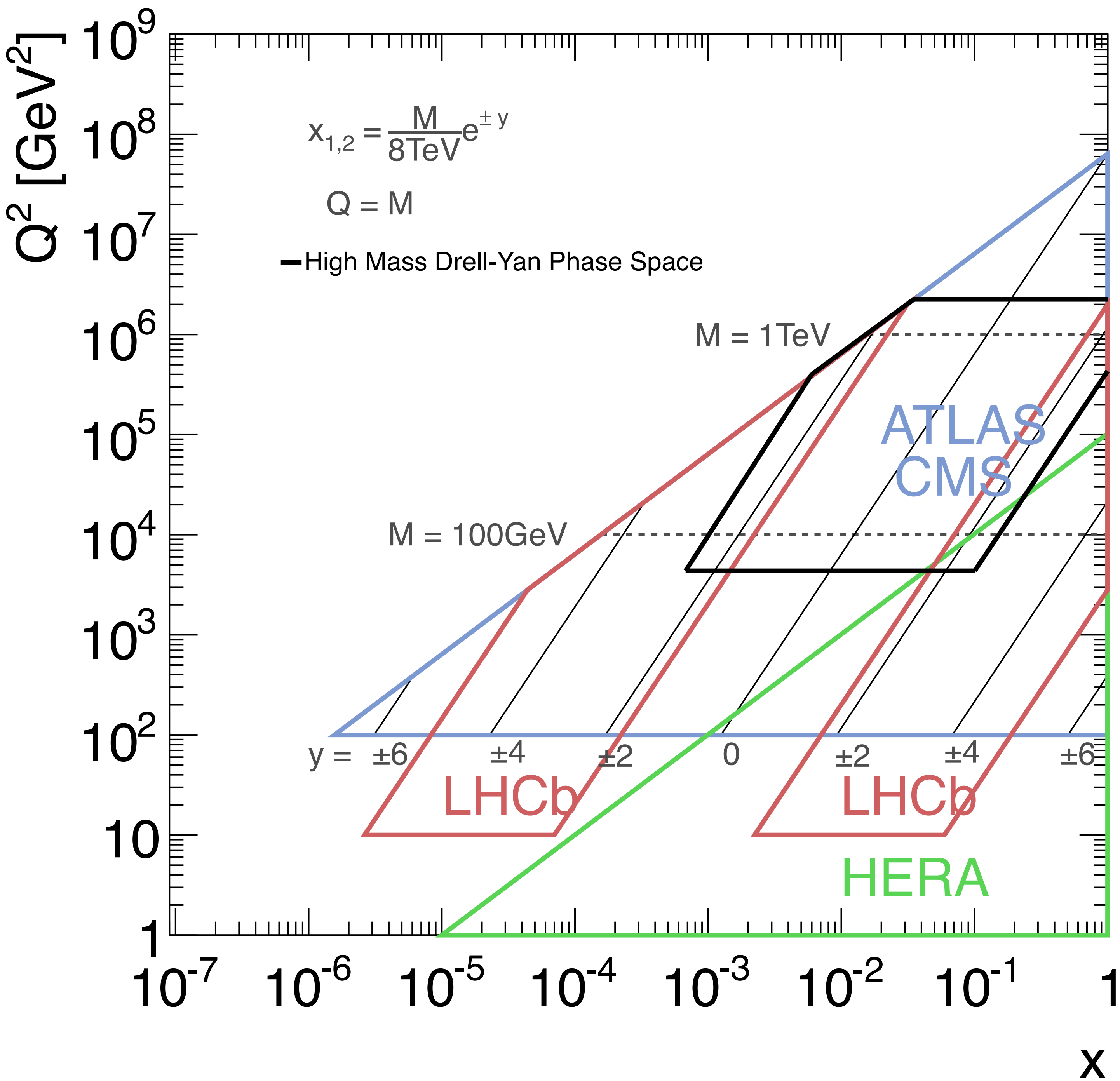
Larger at high $\Delta\eta_{ll}$ dilepton pseudorapidity separation

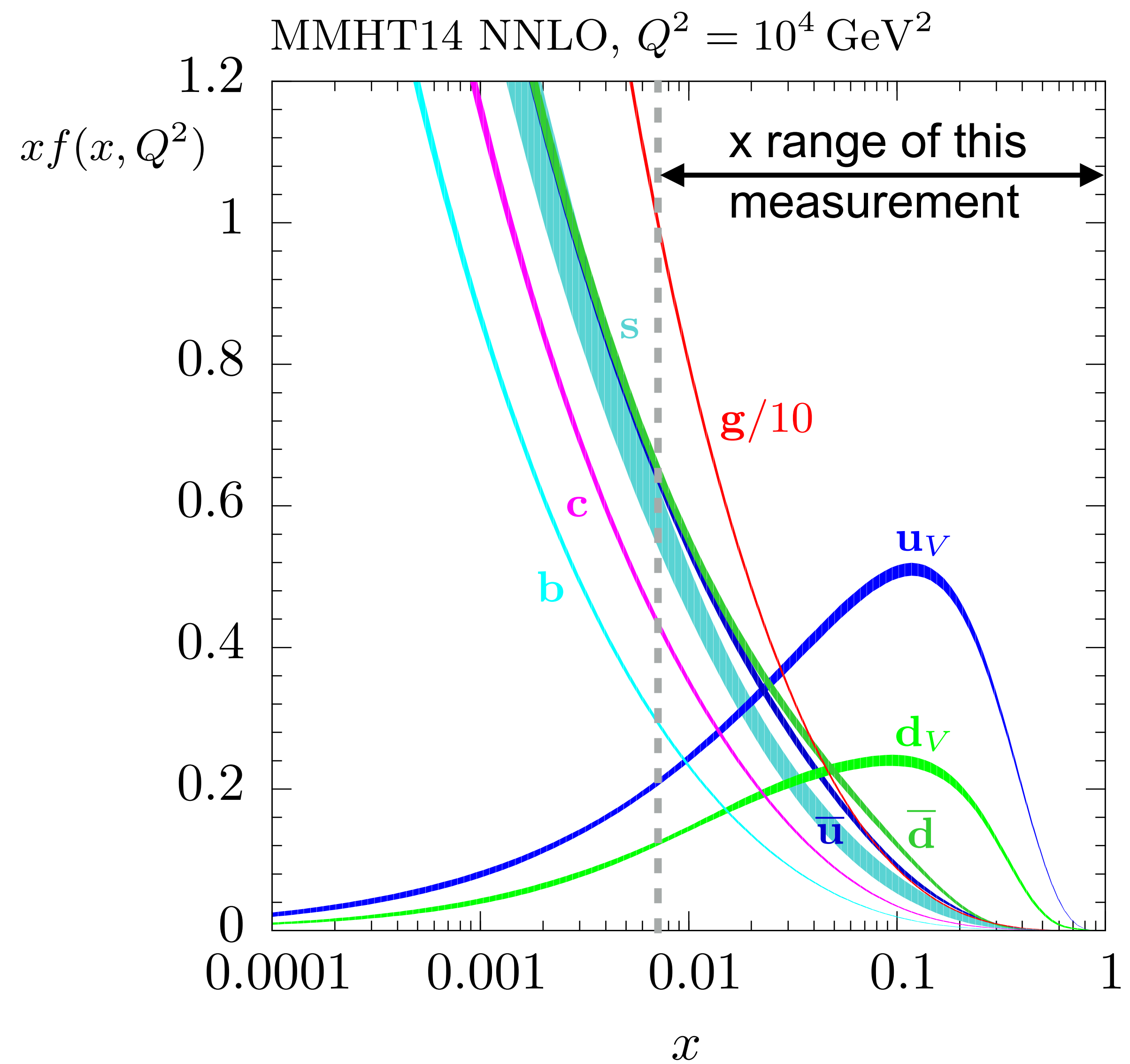


Measure double and single differential cross sections:

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

Kinematic Range of Measurement





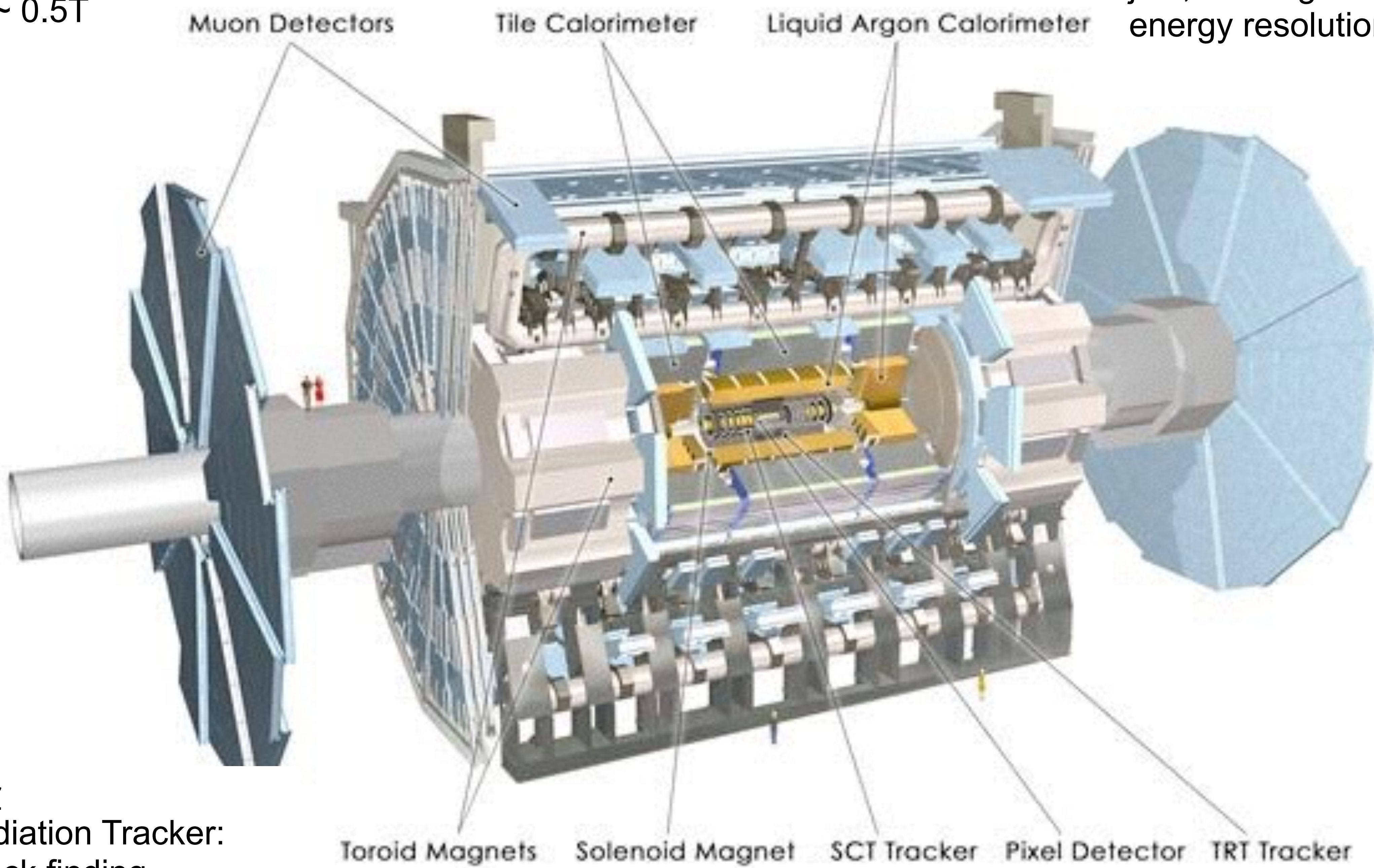
Measurement accesses region of

$x > 7\times10^{-3}$

$116 \leq Q \leq 1500$ GeV

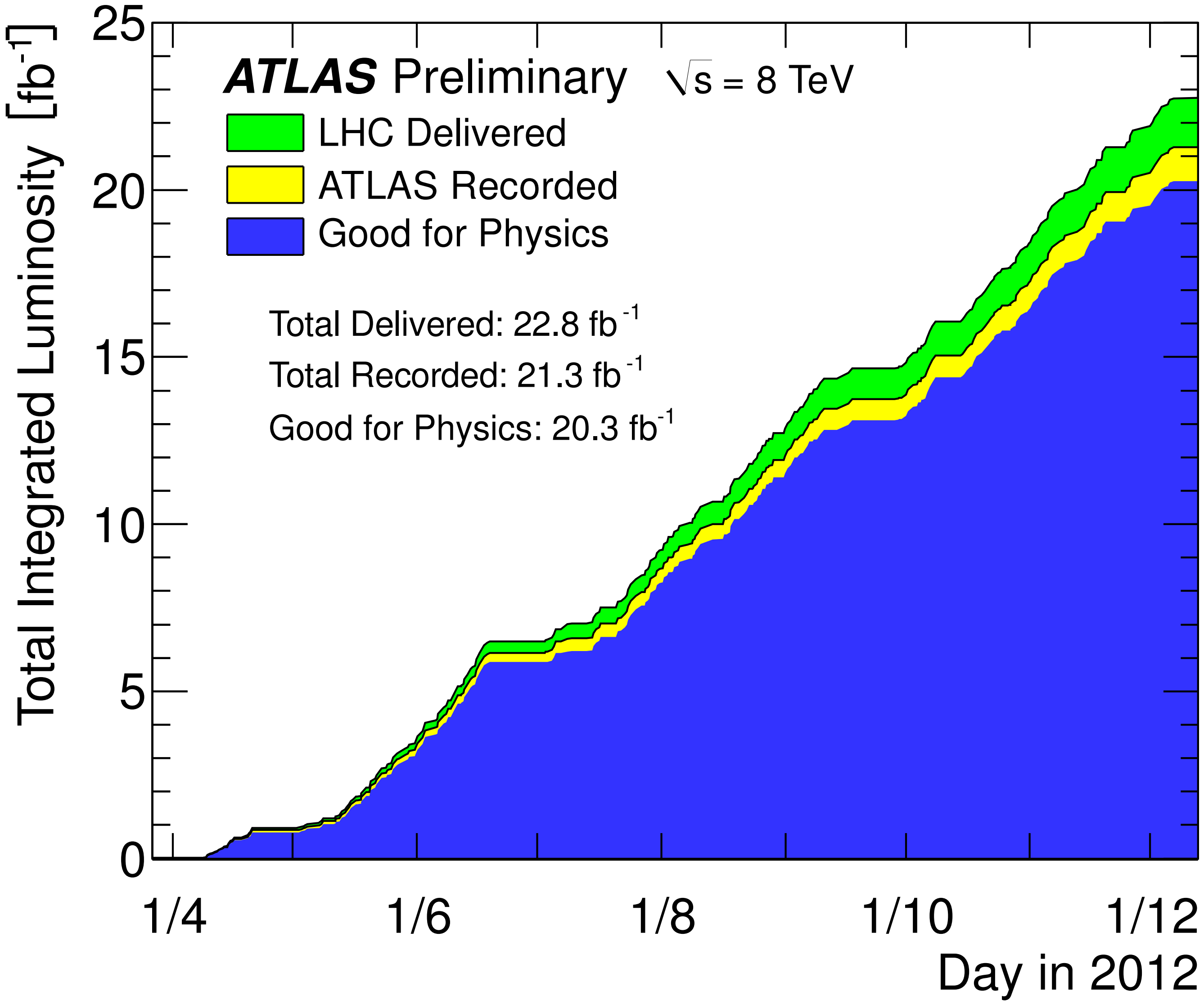
Muon system
Momentum resolution: ~3% up to 10% at p_T = 1 TeV
Momentum scale precision <0.2%
trigger system & precision tracking
toroidal B-field ~ 0.5T
$|\eta|<2.7$

Calorimeters
coverage $|\eta|<4.9$
electrons, photons,
jets, missing energy
energy resolution: <2%



Inner detector
Transition Radiation Tracker:
particle ID, track finding
silicon strips: momentum
silicon pixels: secondary vertex
solenoidal B-field = 2T for $|\eta|<2.5$

Data Analysed



Complete 2012 data set analysed

$\int \mathcal{L}\, dt = 20.3\ fb^{-1}$

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

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

This analysis increases precision by factor 3!

approximate signal samples

m>70 GeV	~6M events
m>116 GeV	~100k events
m>300 GeV	~4k events
m>500 GeV	~500 events

High Mass Selection

Muon Selection

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

Electron Selection

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

Fiducial Cross Section Definition

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

MC Samples

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

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

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

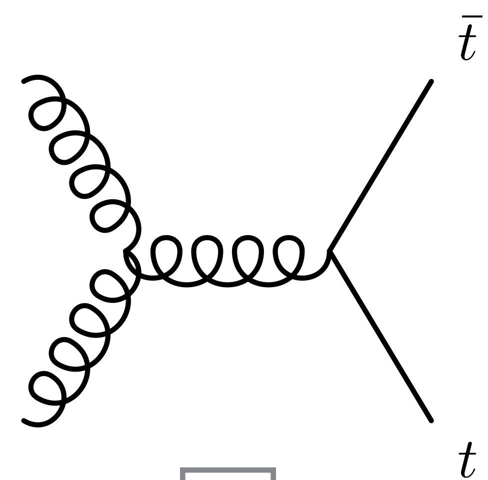
Top production simulated at NLO and renormalised to NNLO+NNLL prediction
- 5 x data luminosity

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

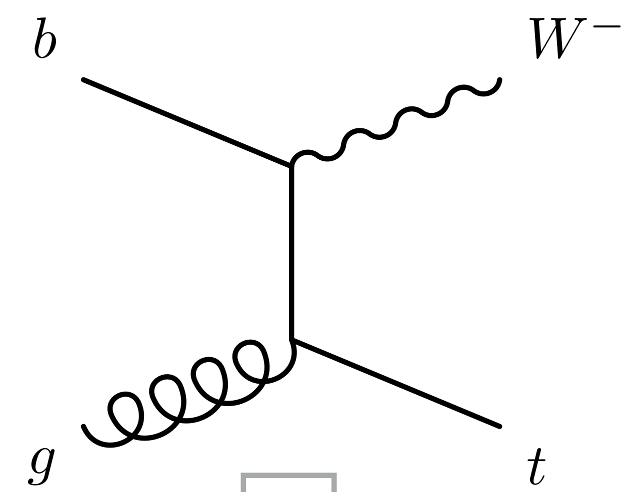
Several sources of so called “electroweak” backgrounds yielding isolated dileptons:

DY → tau production modes found to be negligible contribution

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

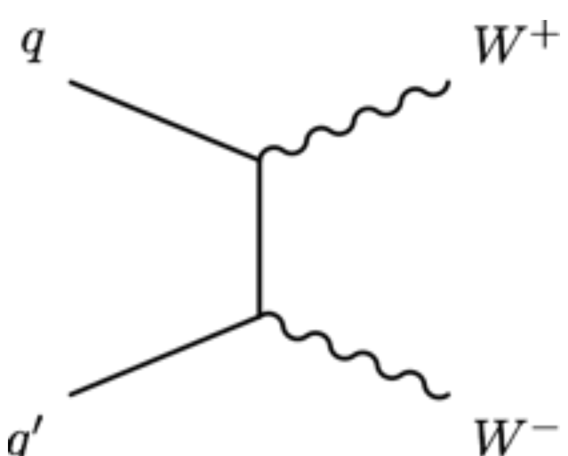


$t\bar{t}$

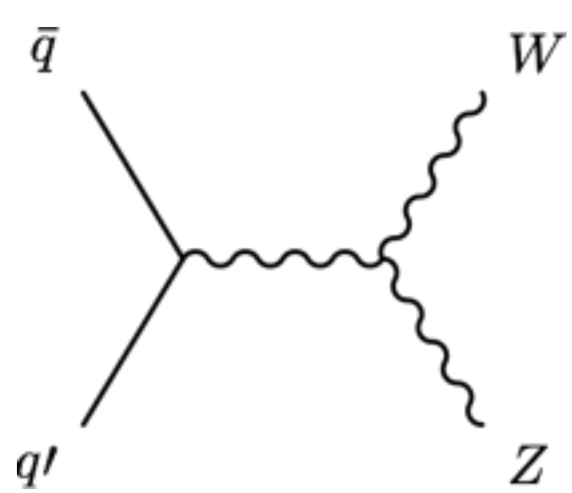


Wt

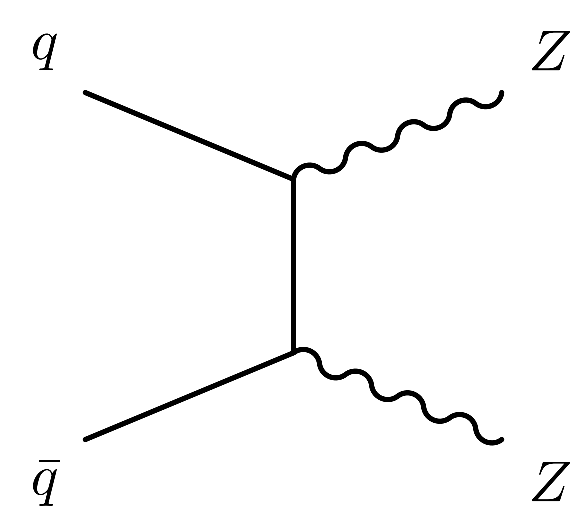
diboson background
up to 2% contribution
estimated from MC



diboson (WW)



diboson (WZ)



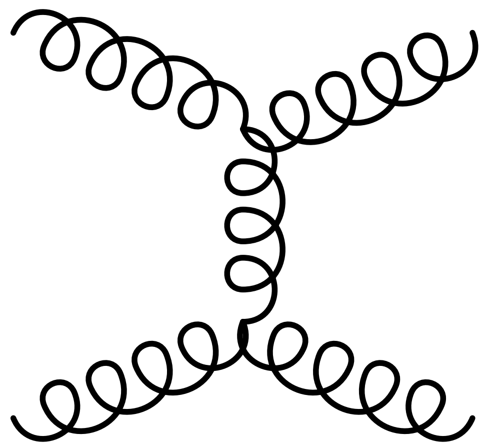
diboson (ZZ)

multijet background

multijet production dominates cross section at LHC
Also large W+jets cross section
contributes to background via:

- leptonic meson decays
- misidentification of hadron jet as calorimeter electron

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



muon channel

use same sign dimuons as proxy for mulitjet b/g

dimuon pairs

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

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

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

electron channel

use matrix method:

N_T / N_L → "tight" / "loose" identified electrons
N_R/ N_F → "real" / "fake" electrons

dielectron pairs

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

Depends on:

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

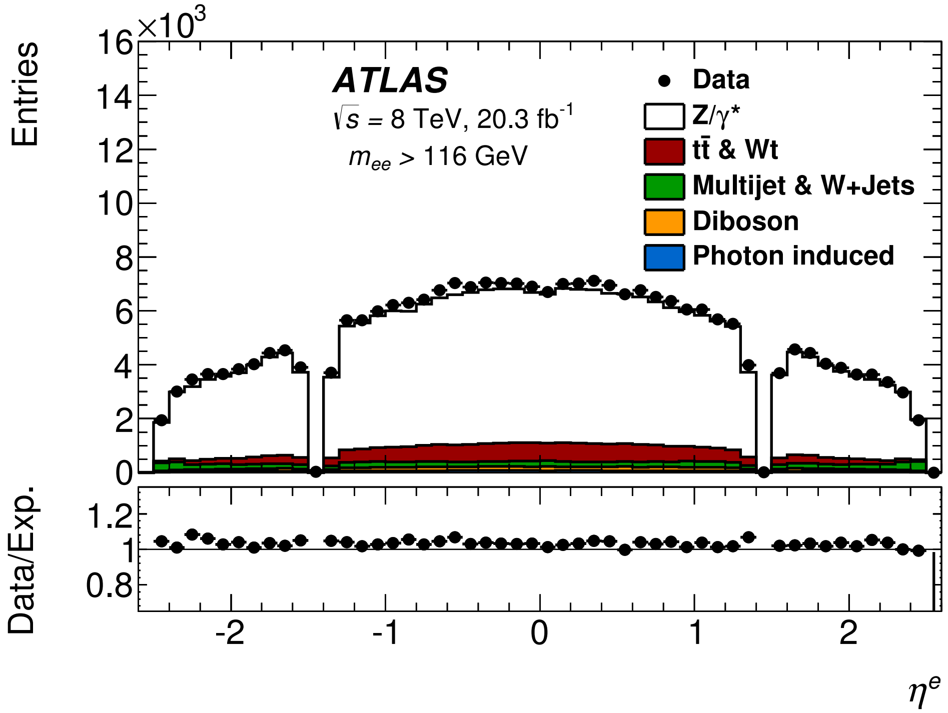
~4% contribution in electron channel

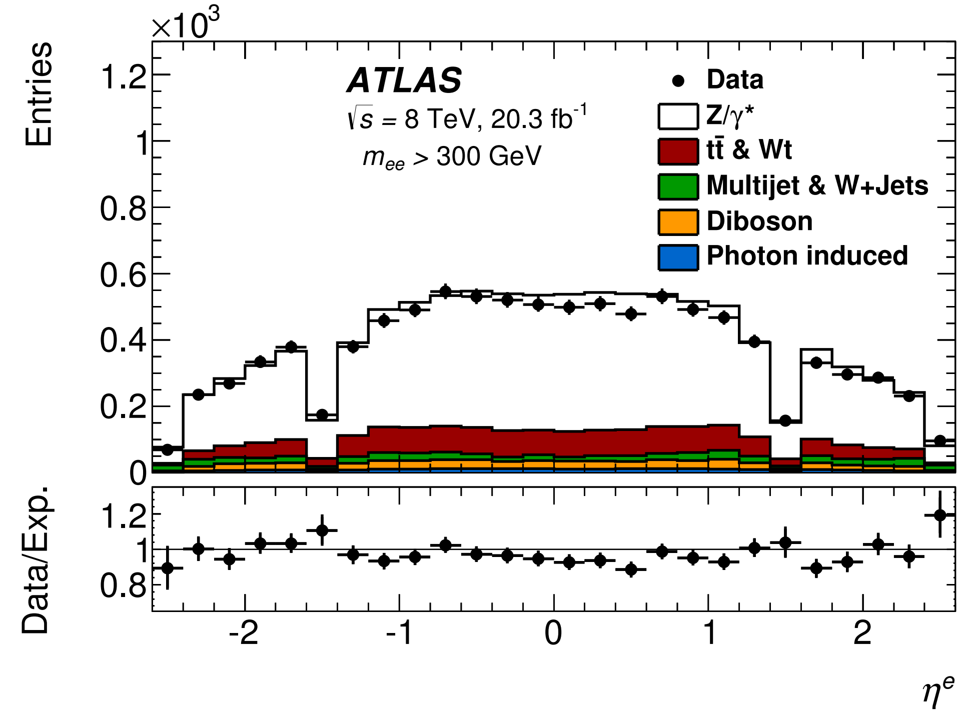
Electron Channel Control Plots

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

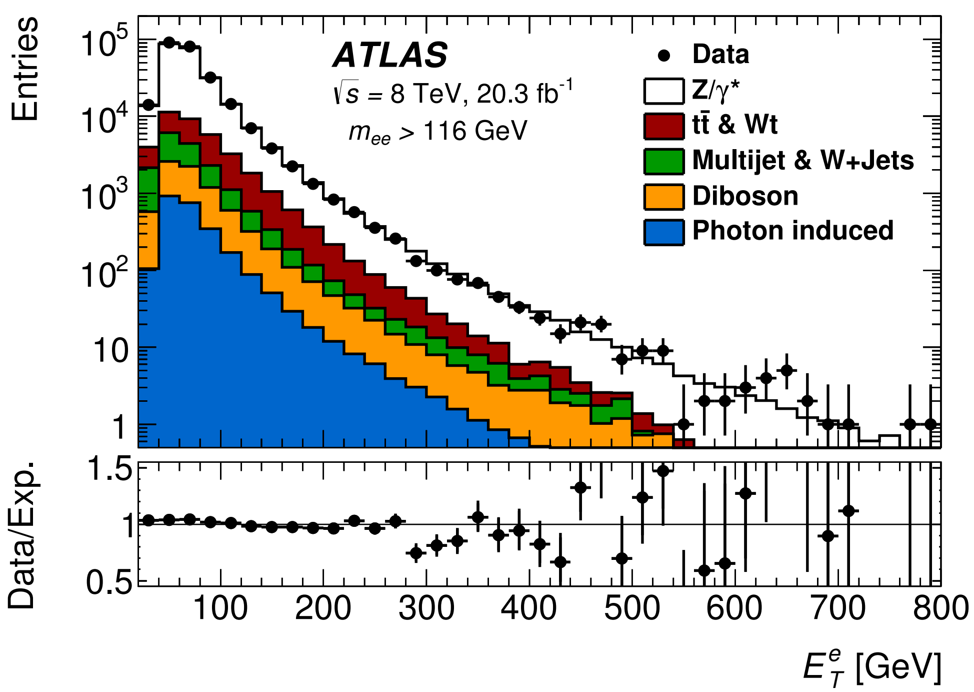
m > 116 GeV | **m > 300 GeV**

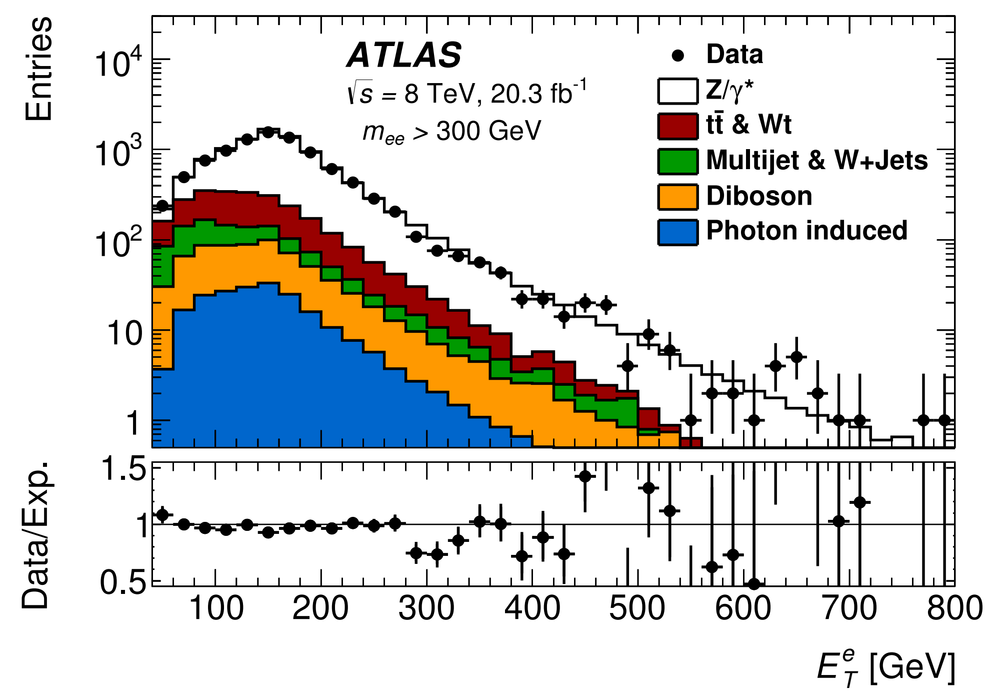
η_e





$p_{T,e}$



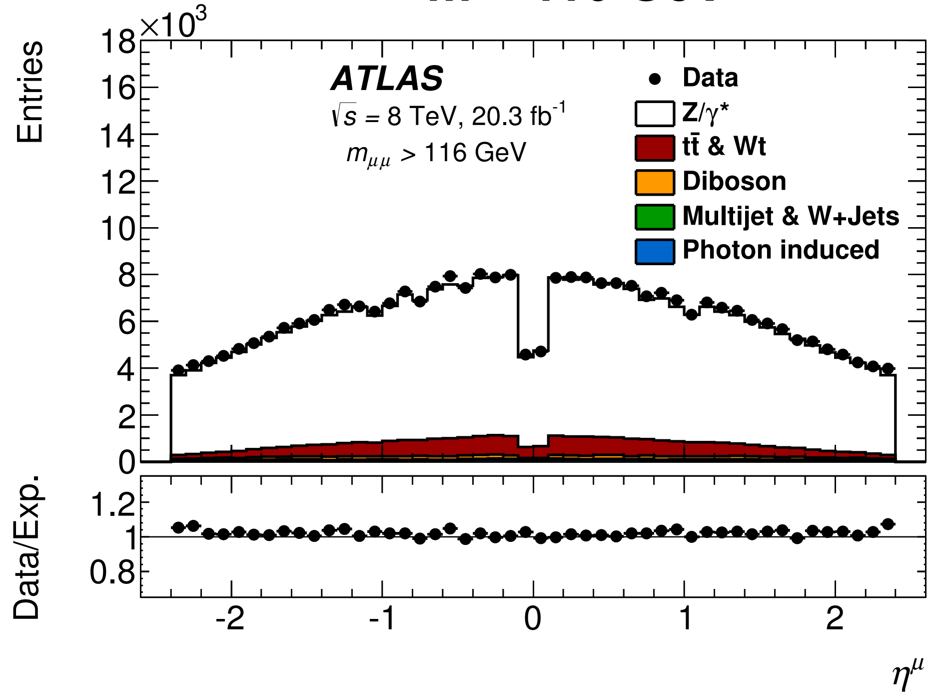


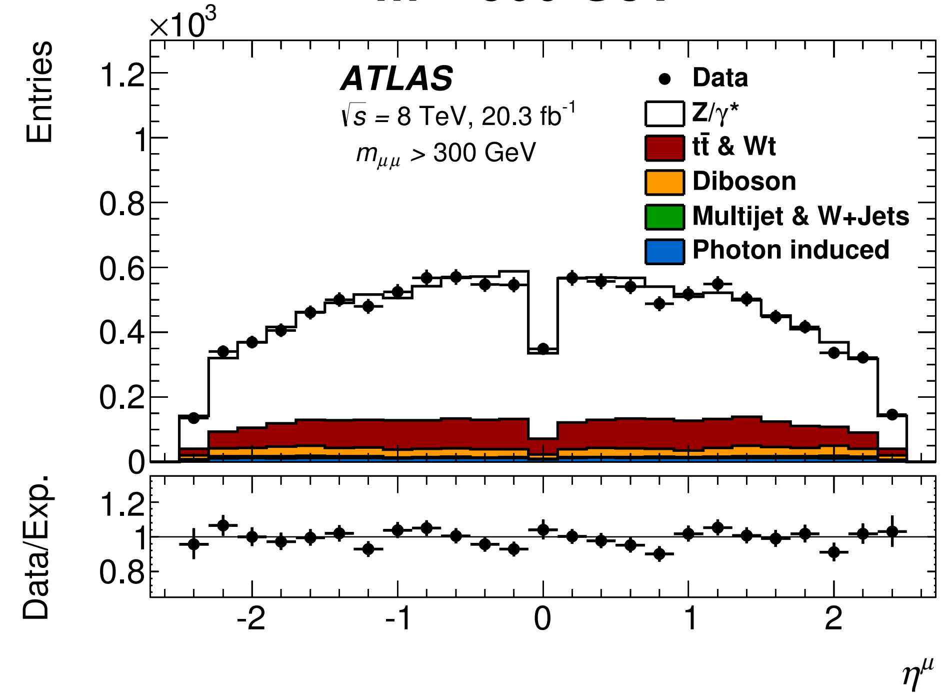
Muon Channel Control Plots

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

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

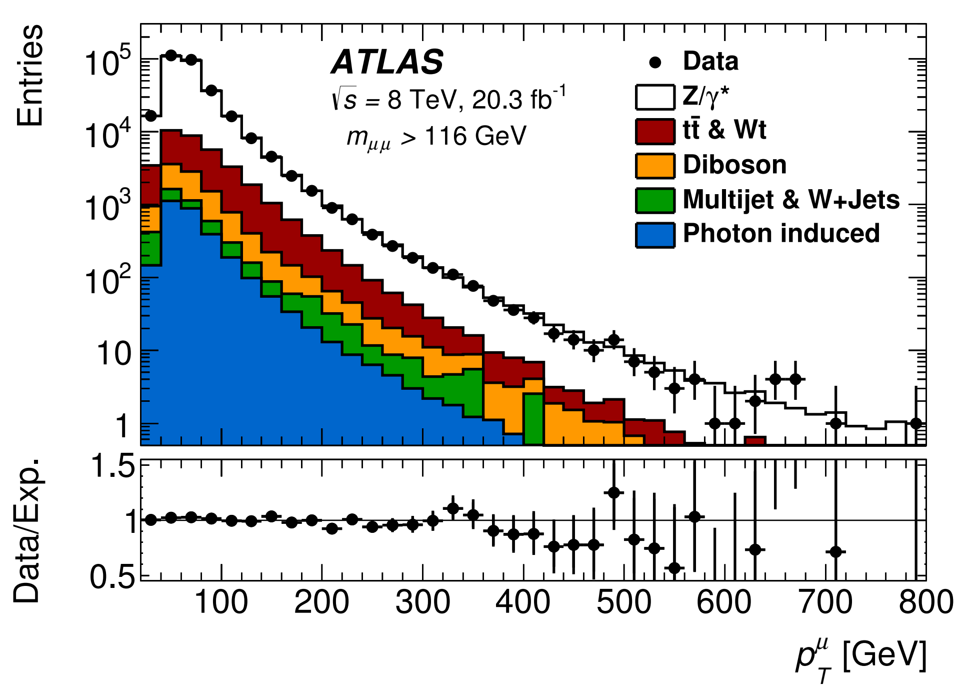
η_μ

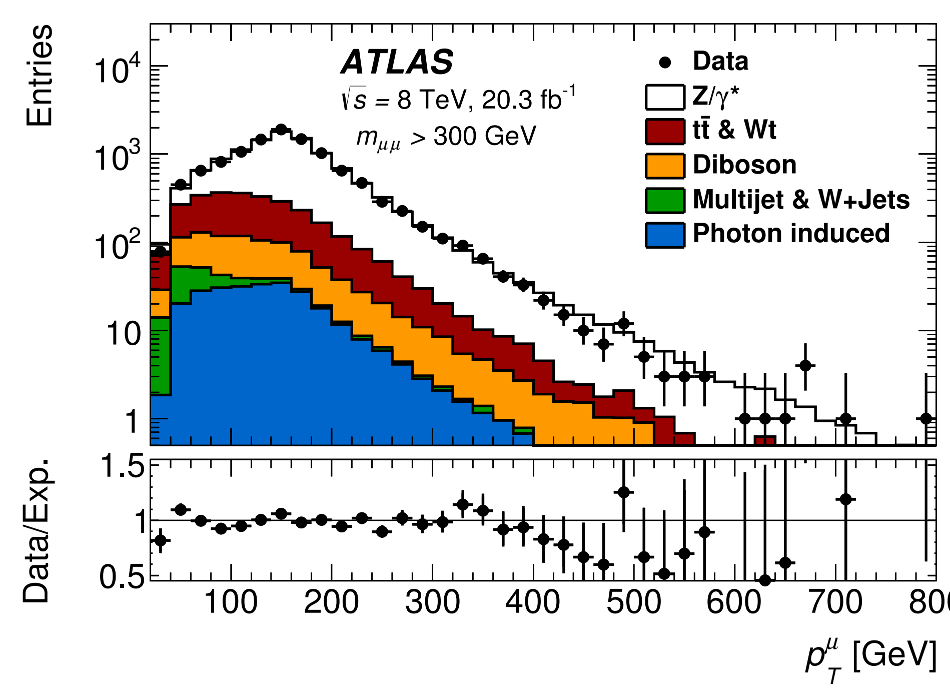




η_μ

$p_{T,\mu}$





$p_{T,\mu}$

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

Electron & Muon Cross Sections and Combination

Cross Section

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

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

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

Combination

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

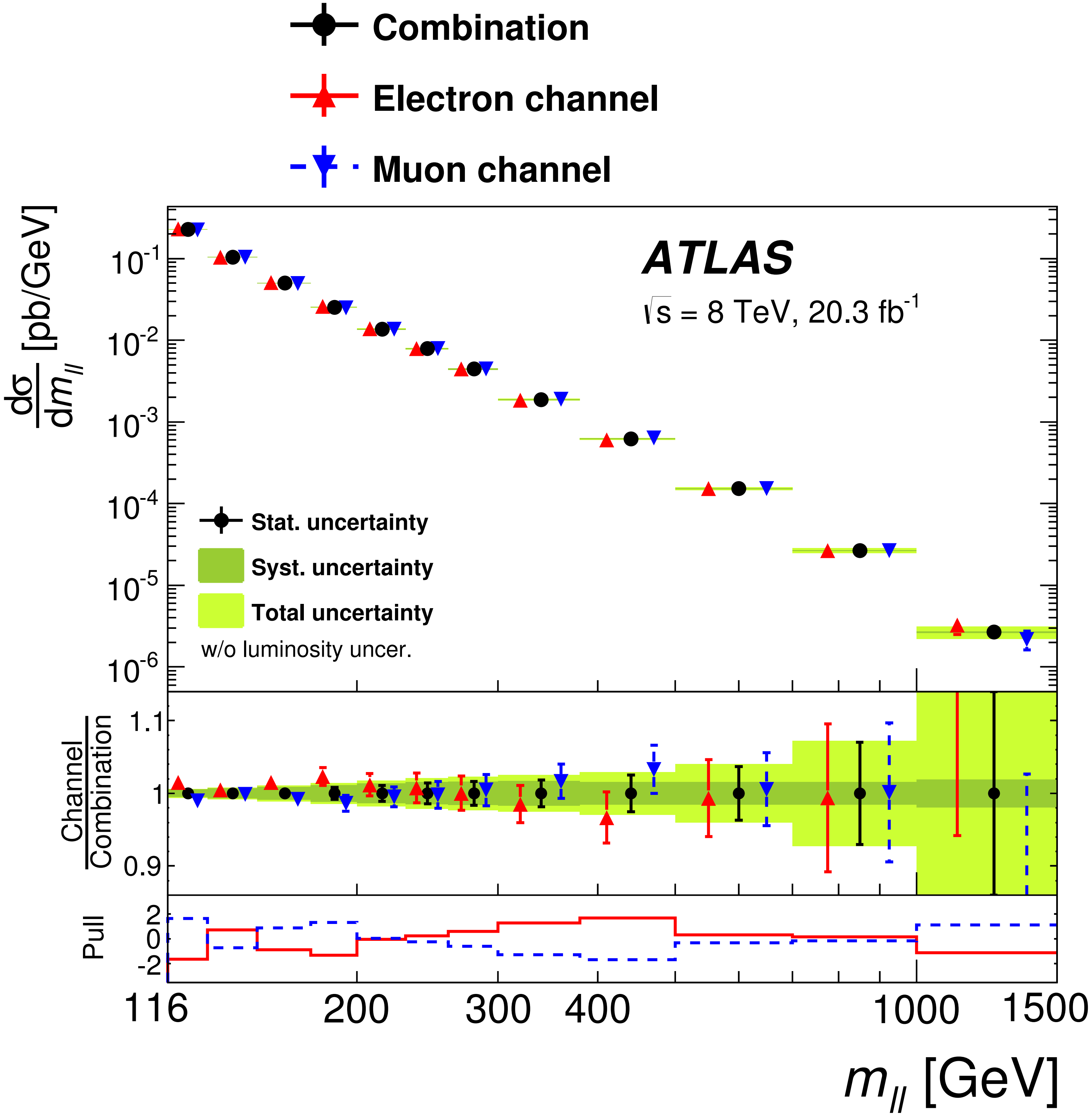
i data points
j systematic error sources

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

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

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

Combination of Electron & Muon Channels



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

Measurement accuracy systematically limited for m < 400 GeV

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

For larger m combination reduces √N statistical error

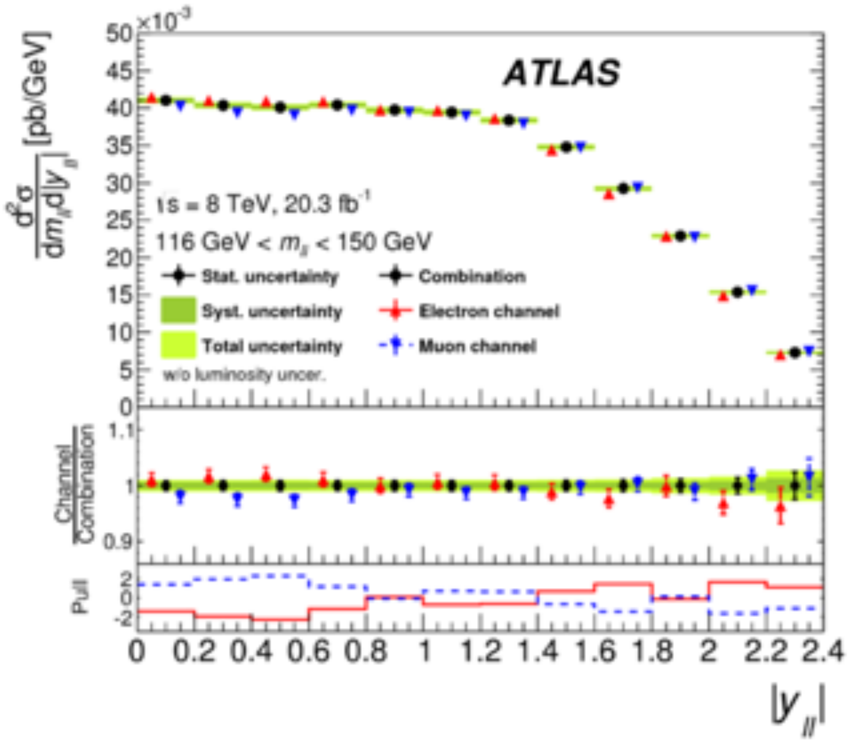
Stat error dominates at large m reaching ~20%

Excellent agreement between channels over full range

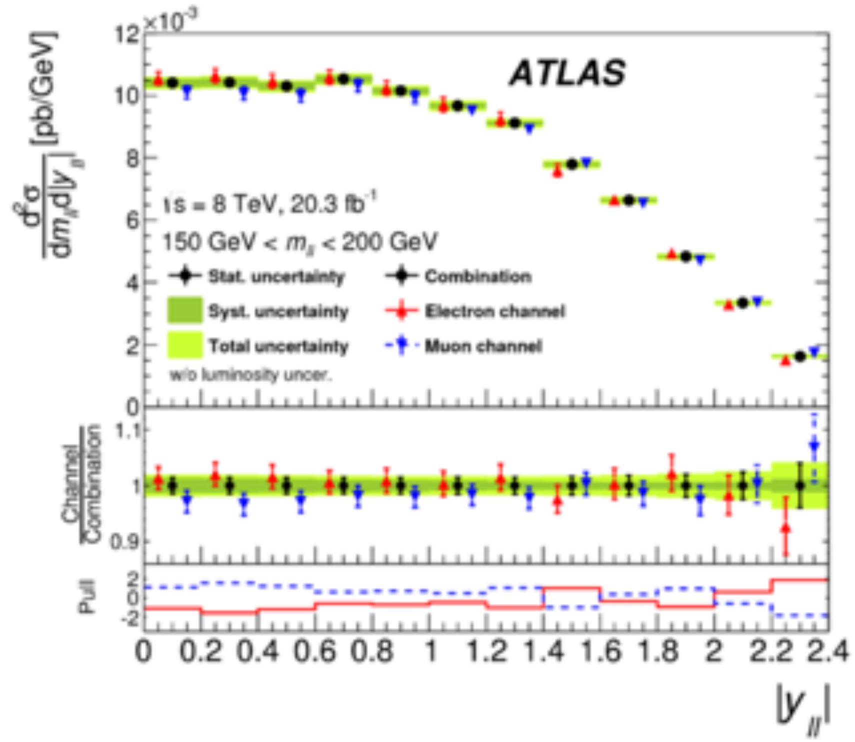
χ^2/ndf = 14.2 / 12 = 1.19

all nuisance parameters < 1 standard deviation

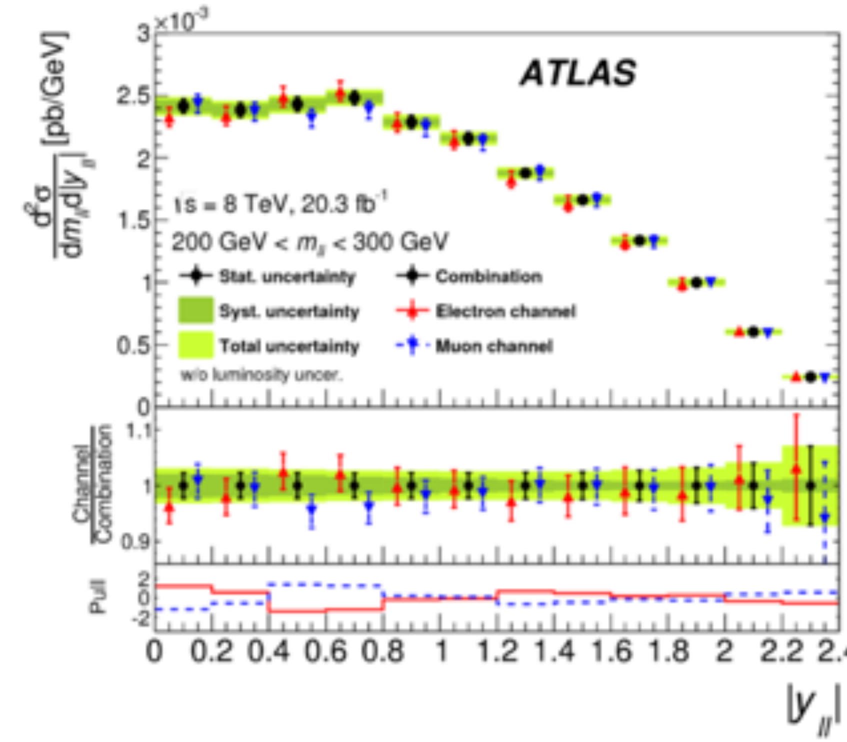
116 GeV < m < 150 GeV



150 GeV < m < 200 GeV

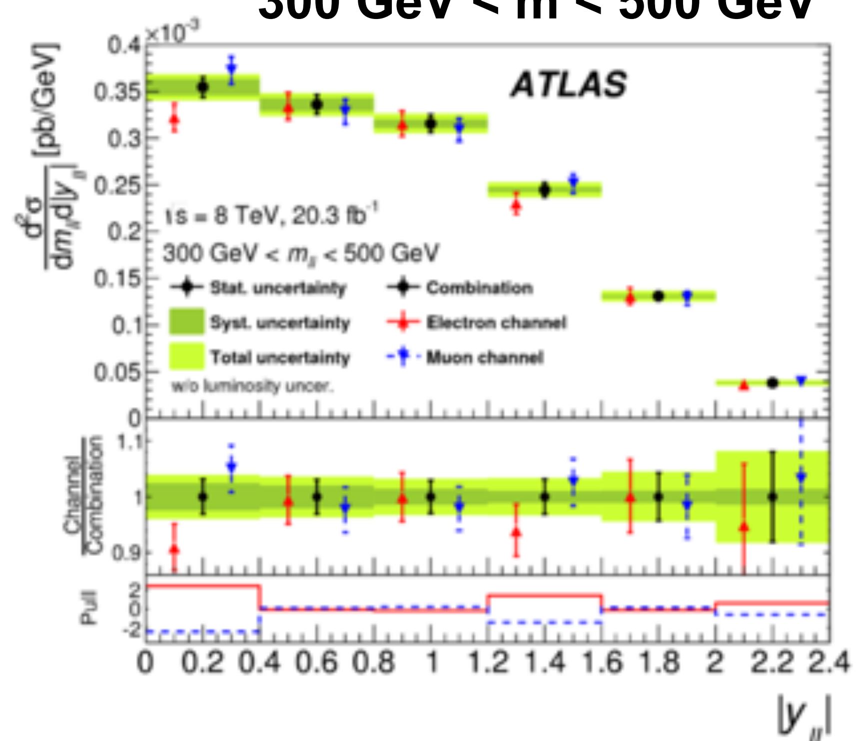


200 GeV < m < 300 GeV

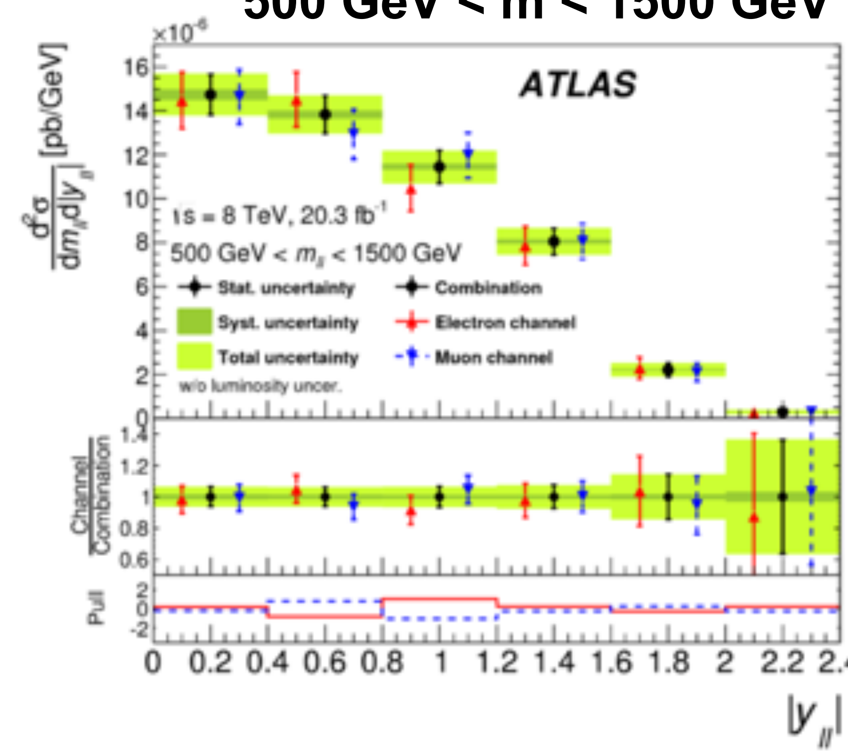


$$\frac{d^2\sigma}{dm_{ll}\,d|y_{ll}|}$$

300 GeV < m < 500 GeV



500 GeV < m < 1500 GeV

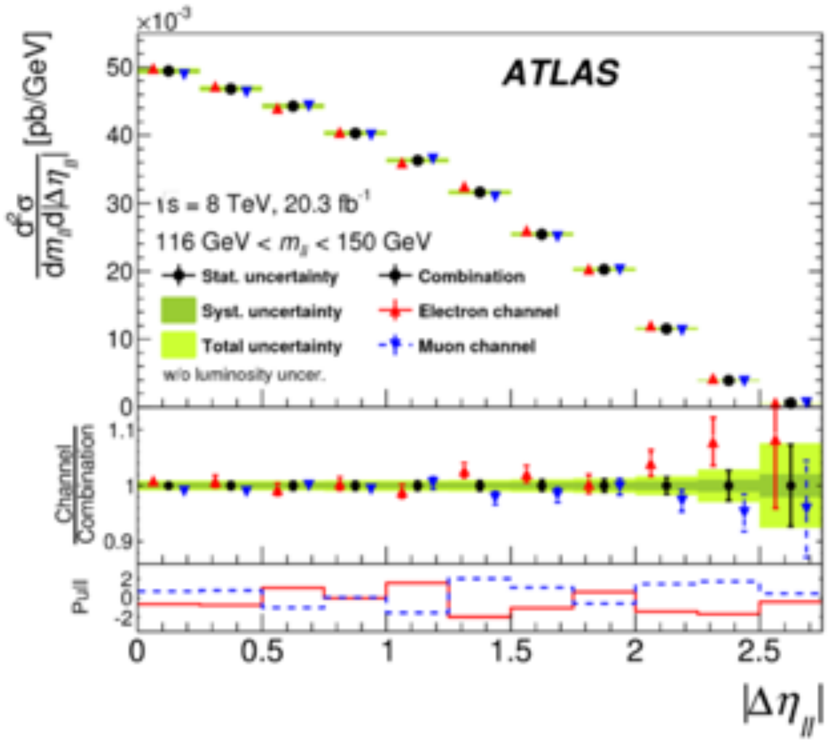


No large pulls between the measurement channels

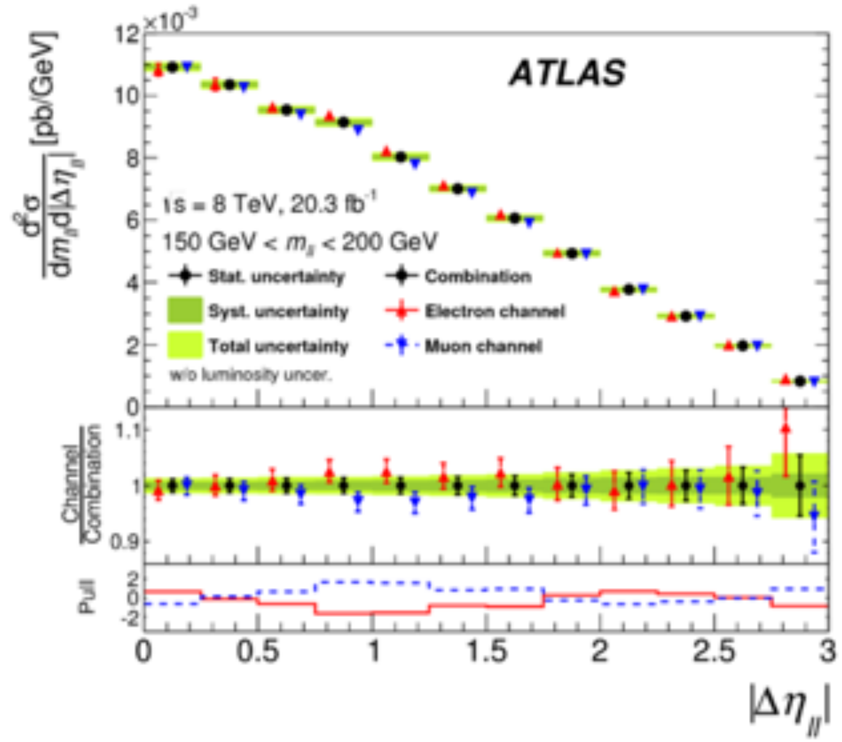
combination χ^2/ndf = 53.1 / 48 = 1.11

Combination of Electron & Muon Channels

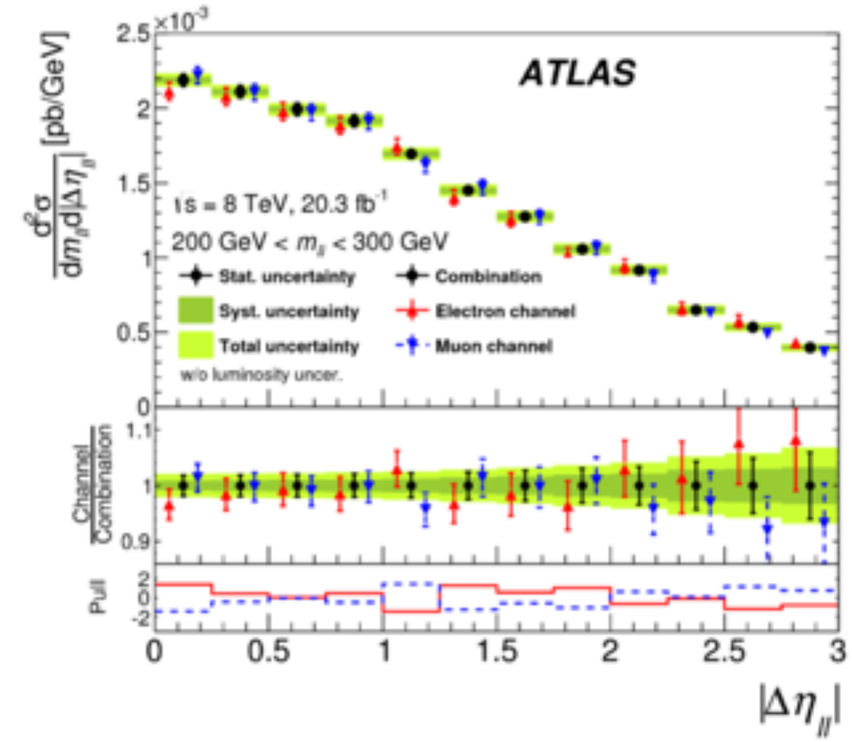
116 GeV < m < 150 GeV



150 GeV < m < 200 GeV

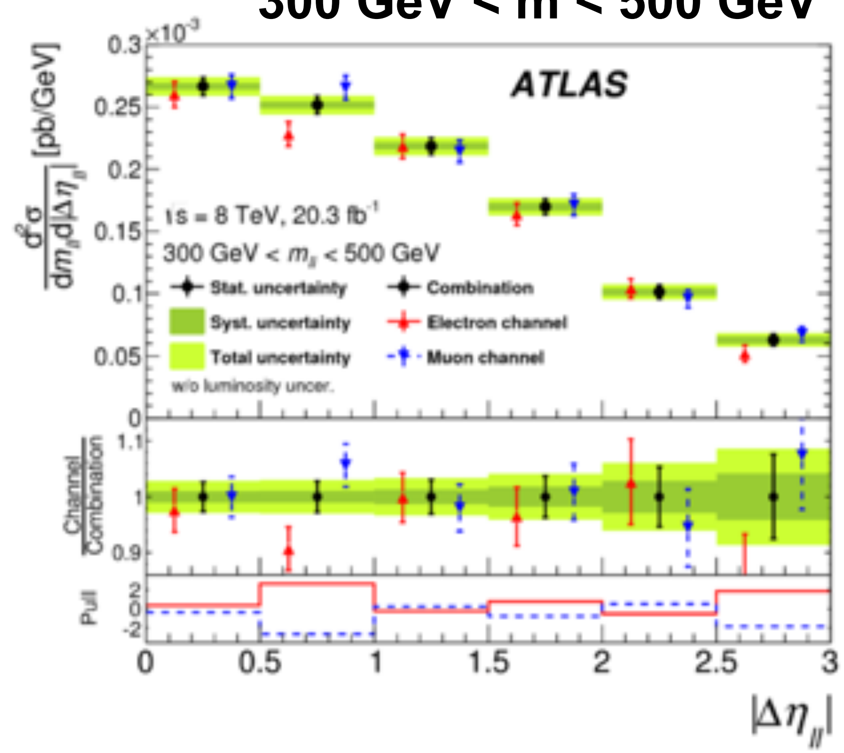


200 GeV < m < 300 GeV

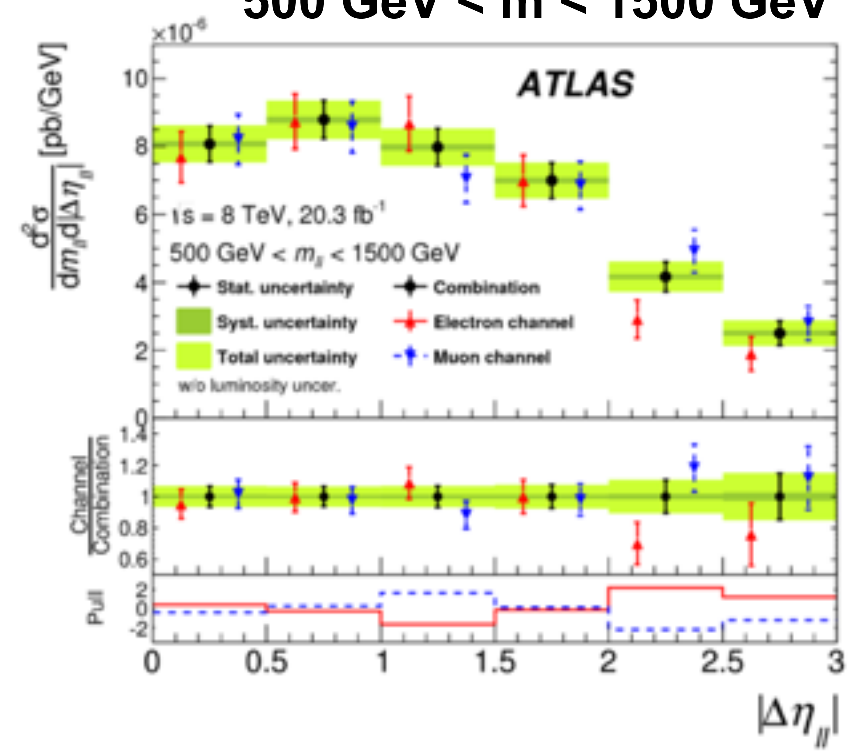


$$\frac{d^2\sigma}{dm_{ll}d|\Delta\eta_{ll}|}$$

300 GeV < m < 500 GeV



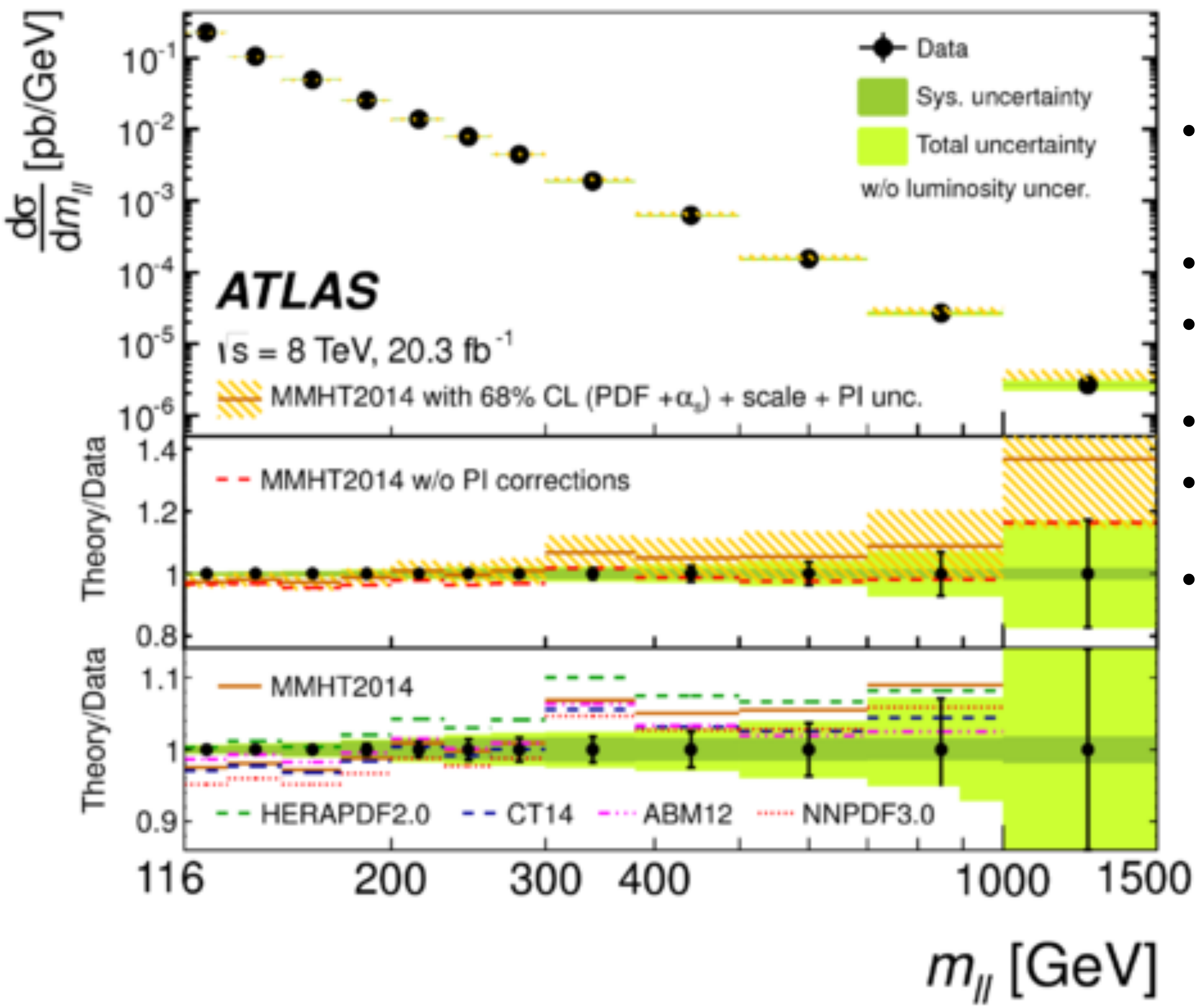
500 GeV < m < 1500 GeV



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

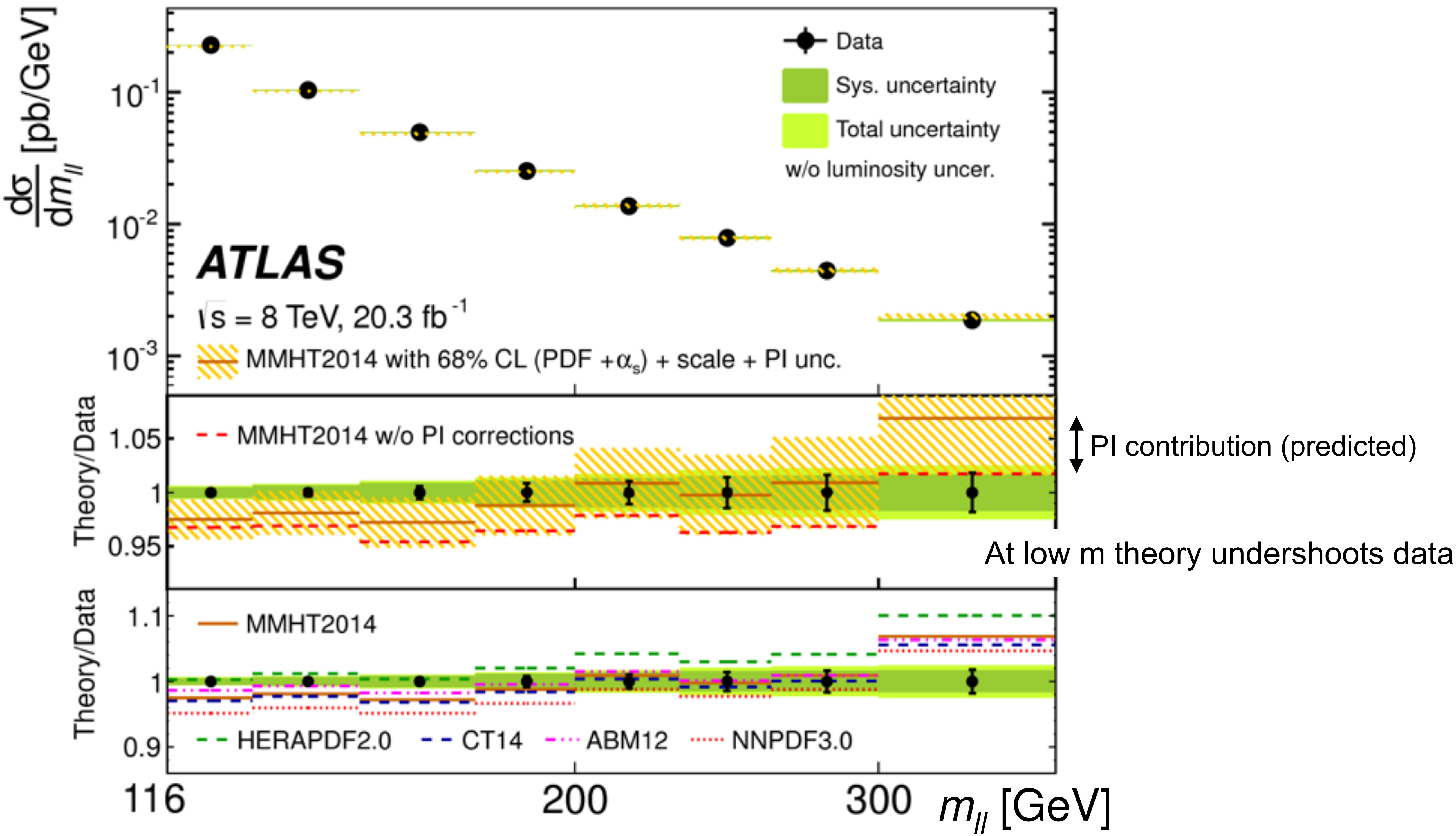
Combined Differential Cross Sections

- Theory = NNLO pQCD ⊗ NLO EW + PI
- pQCD uses MMHT14 NNLO PDF set
- PI uses NNPDF2.3qed for photon PDF ± 68% of replicas
- $\alpha_S = 0.118 \pm 0.001$
- scale error = envelope of μ_F and μ_R varied by factors of 2



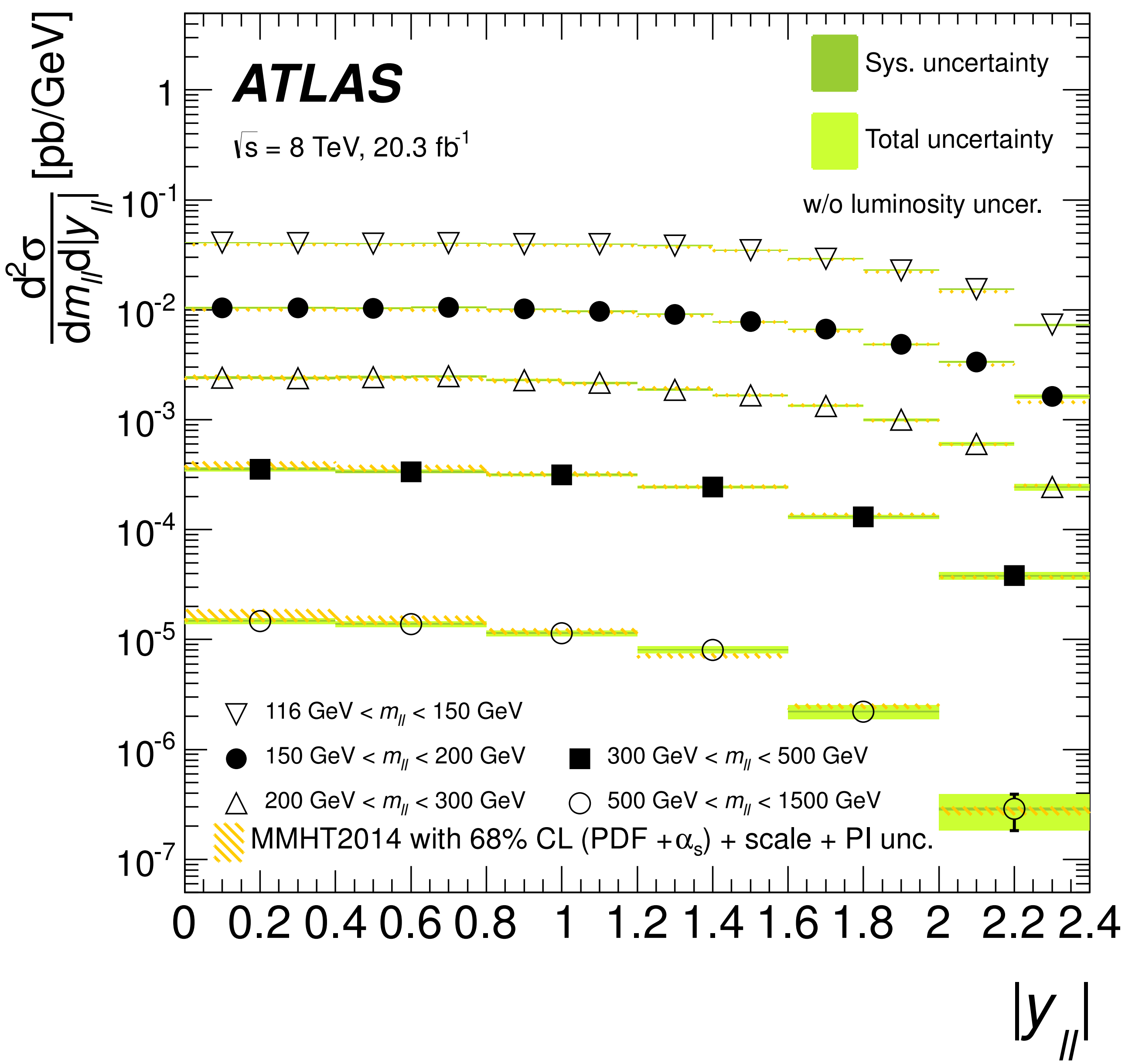
- data precision better than theory uncertainty over most of the phase space → measurements can constrain theory
- theory generally in agreement with data
- comparisons shown with other NNLO PDF sets HERAPDF2.0, CT14, ABM12, NNPDF3.0
- PI predicted to be 15% contribution at large m
- Where PI contribution is large theory uncertainty dominated by PI piece
- Else PDF uncertainty dominates theory precision

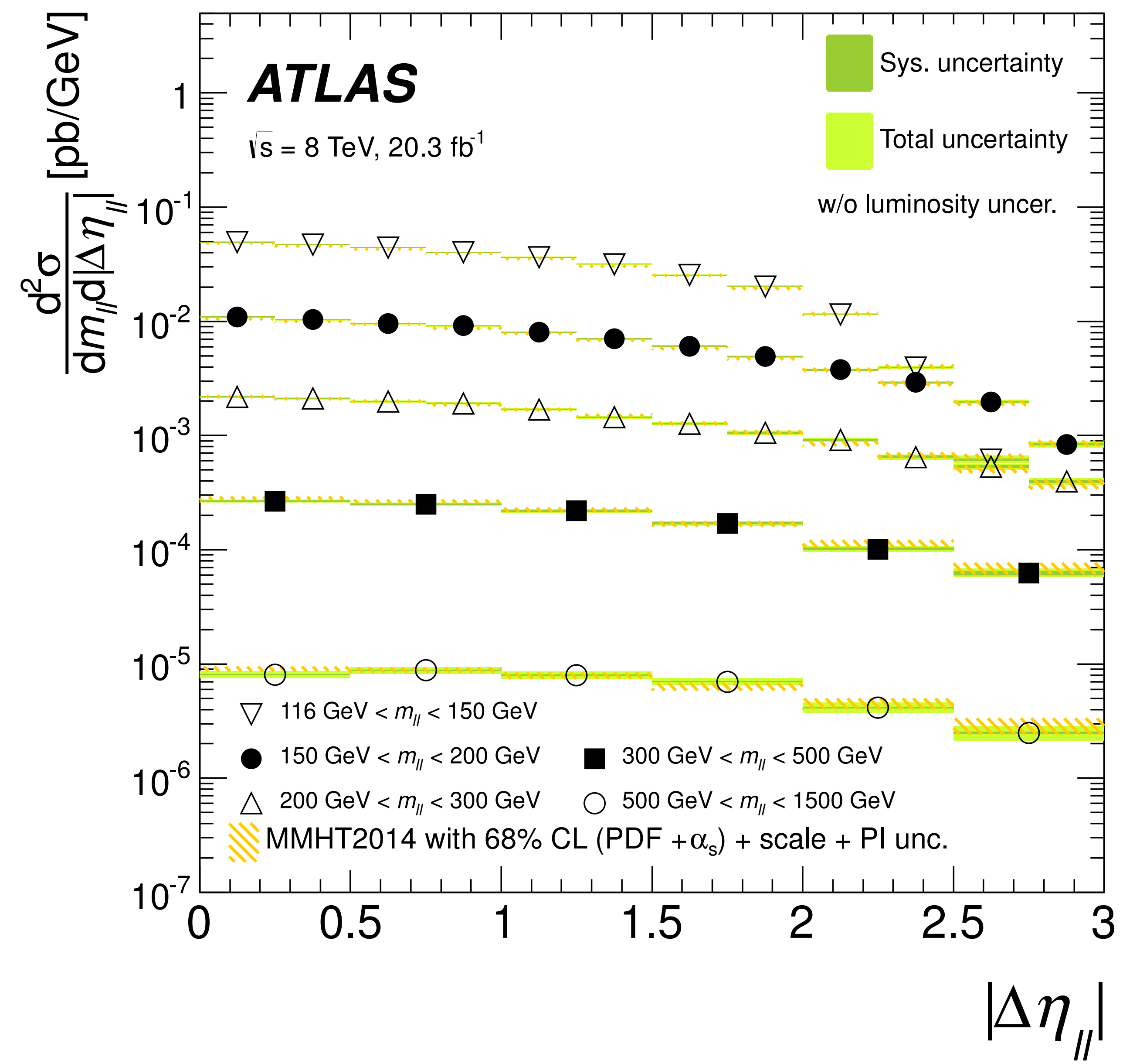
Combined Differential Cross Sections



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

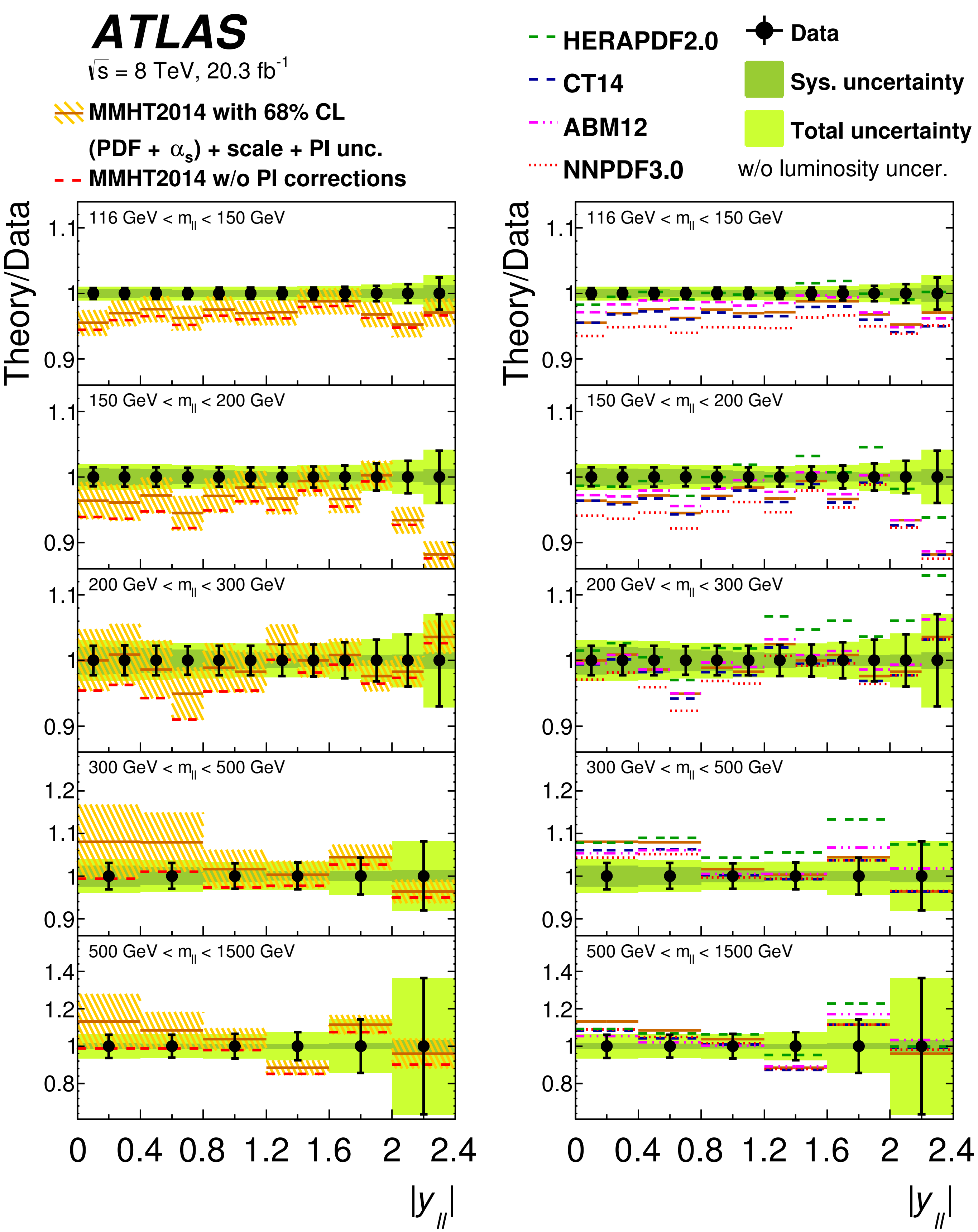
Combined Differential Cross Sections





Both double differential measurements well described by predictions over complete phase space

More detail shown in theory/data ratio…



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

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

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

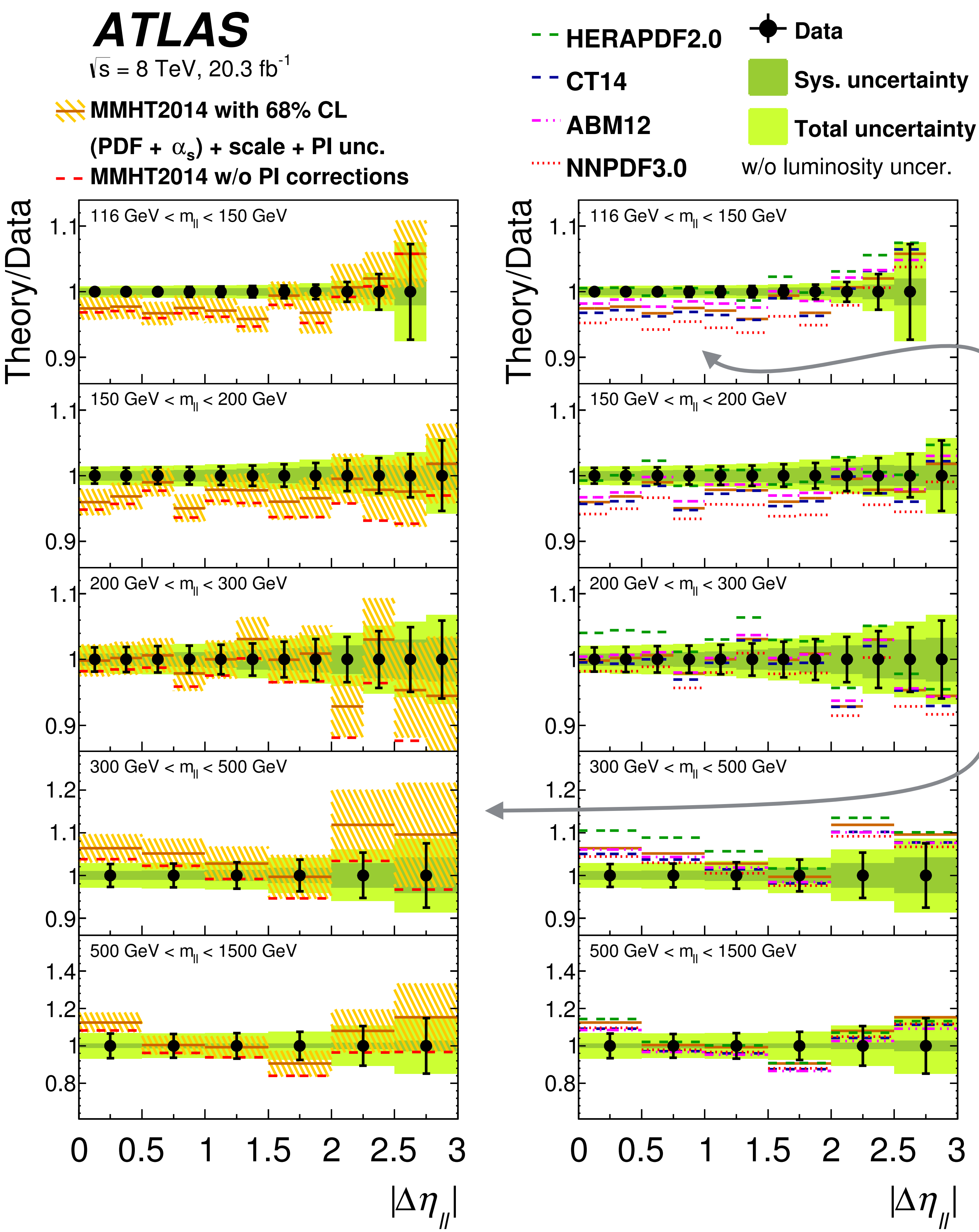
Compatibility of data to predictions with other PDFs tested with χ^2 function

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

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

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

Combined Differential Cross Sections



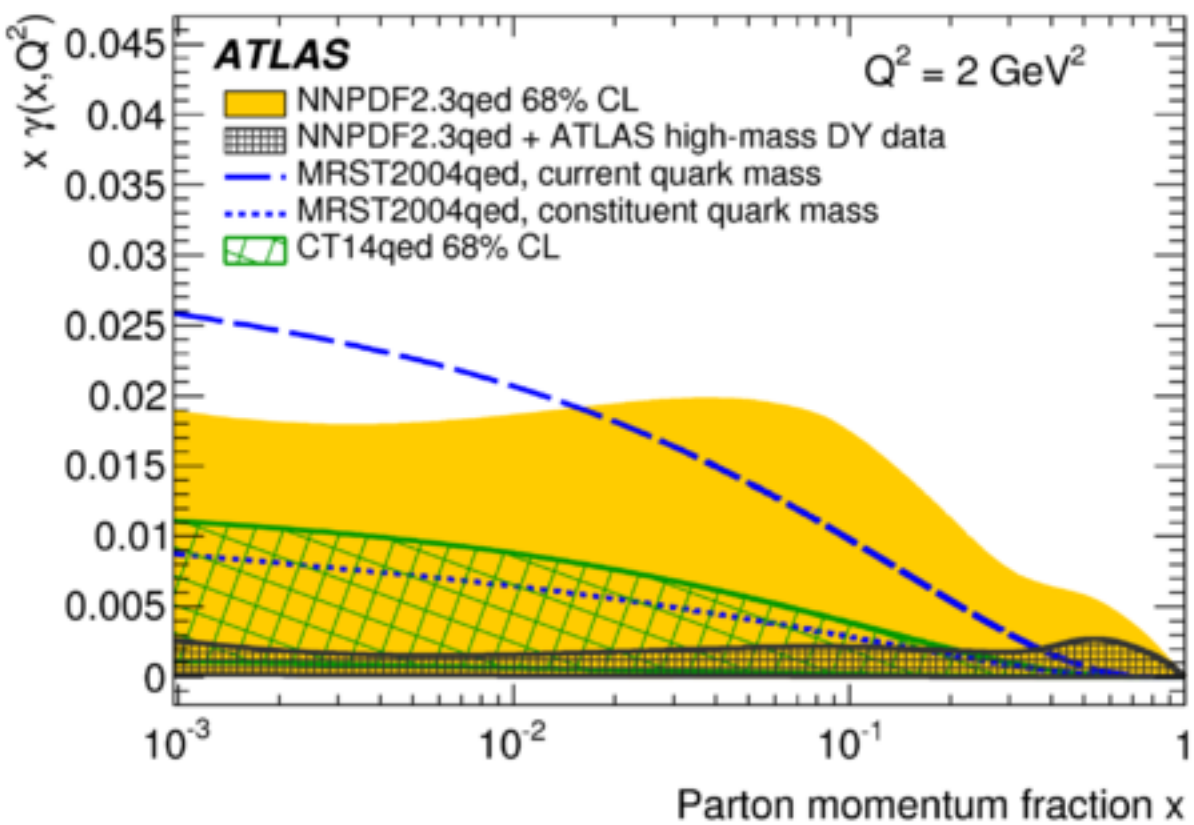
$$\frac{d^2\sigma}{dm_{ll}d|\Delta\eta_{ll}|}$$ **data/theory ratio**

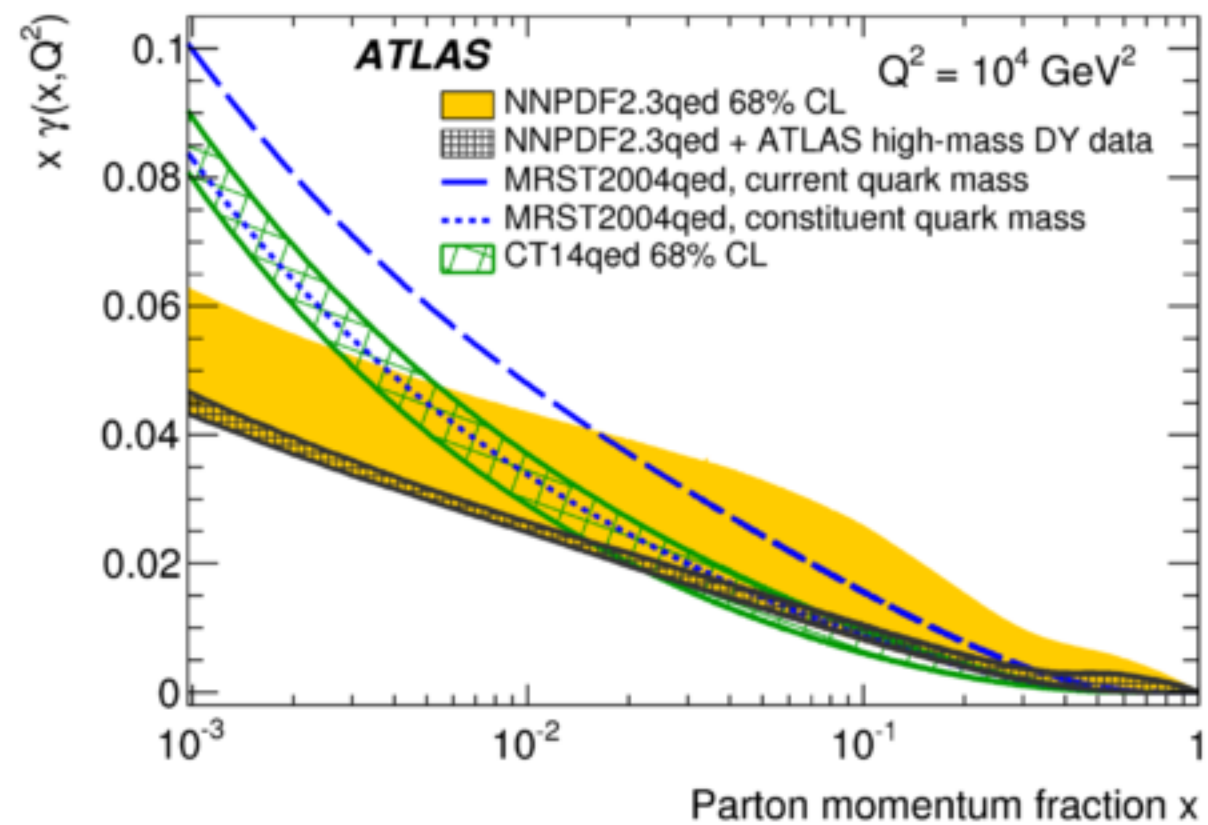
PI contribution increases with m and $|\Delta\eta_{ll}|$

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

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

Photon PDF

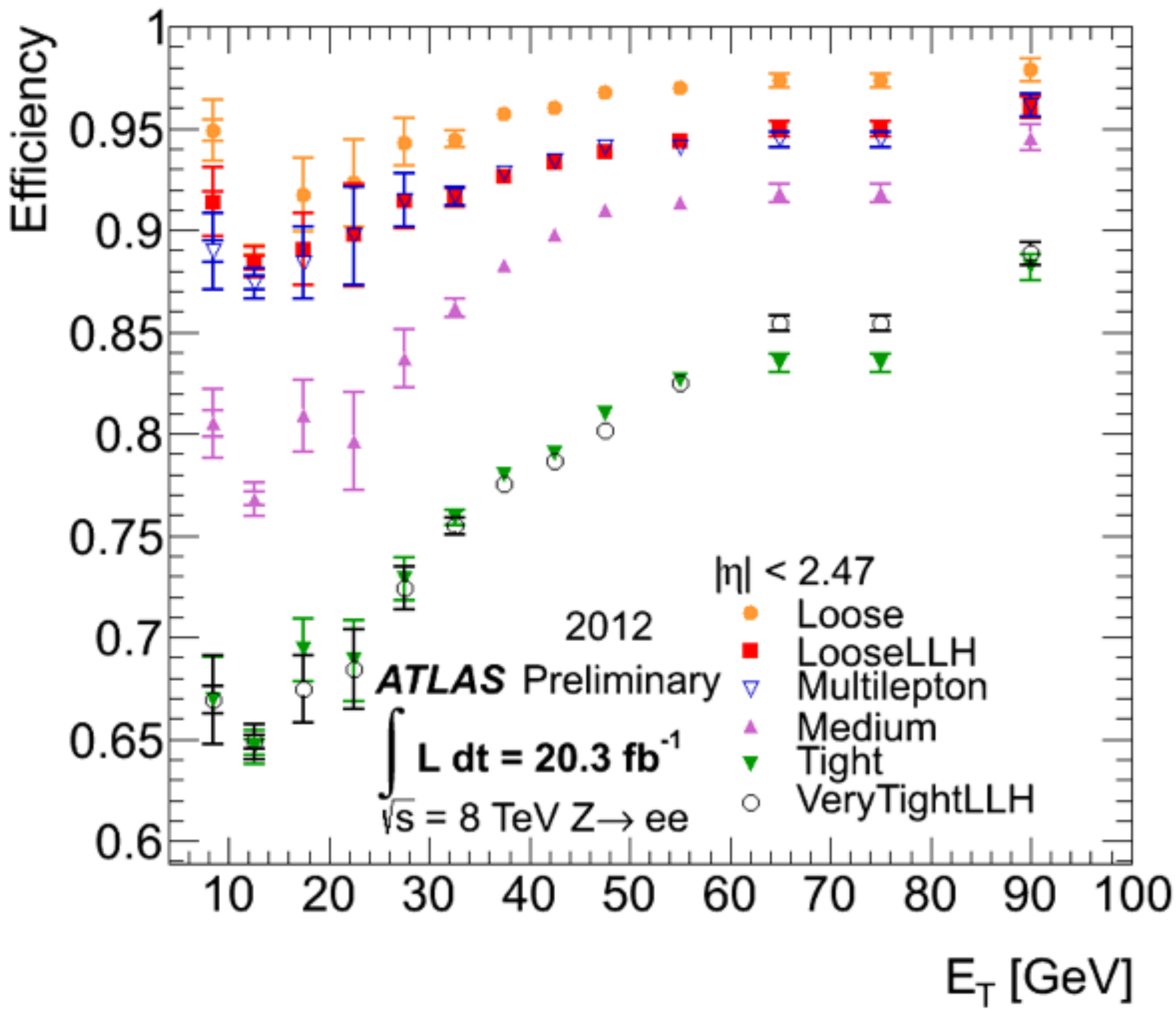




Assess impact of new data on photon PDF → use Bayesian reweighting of NNPDF replicas
Each replica receives a weight according to χ^2 function
Poorly fitting replicas receive a small weight
Replicas describing the data well receive a large weight
New PDF central value is estimated from mean of weighted replicas
New PDF uncertainty determined from 68% CL
Original NNPDF uncertainty dramatically reduced in reweighting

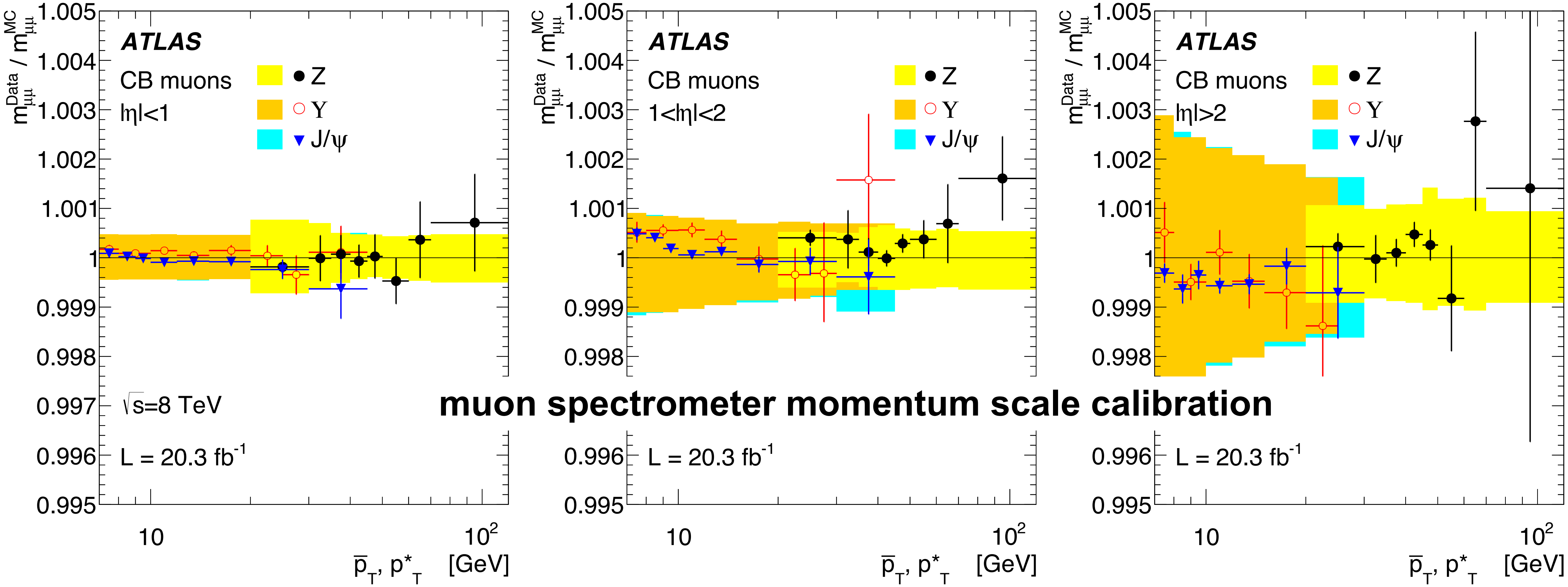
Summary & Conclusions

- New measurement of DY + PI cross section at $\sqrt{s}$ = 8 TeV presented
- Data covers phase space 116 < m < 1500 GeV
- First measurement differential in m and $|\Delta\eta_{ll}|$
- Precision of 1% attained at low m
- Data compatible with NNLO pQCD $\otimes$ NLO EW + PI predictions
- Measurements are sensitive to PDFs
- Constraining power of the data on the photon PDF is demonstrated

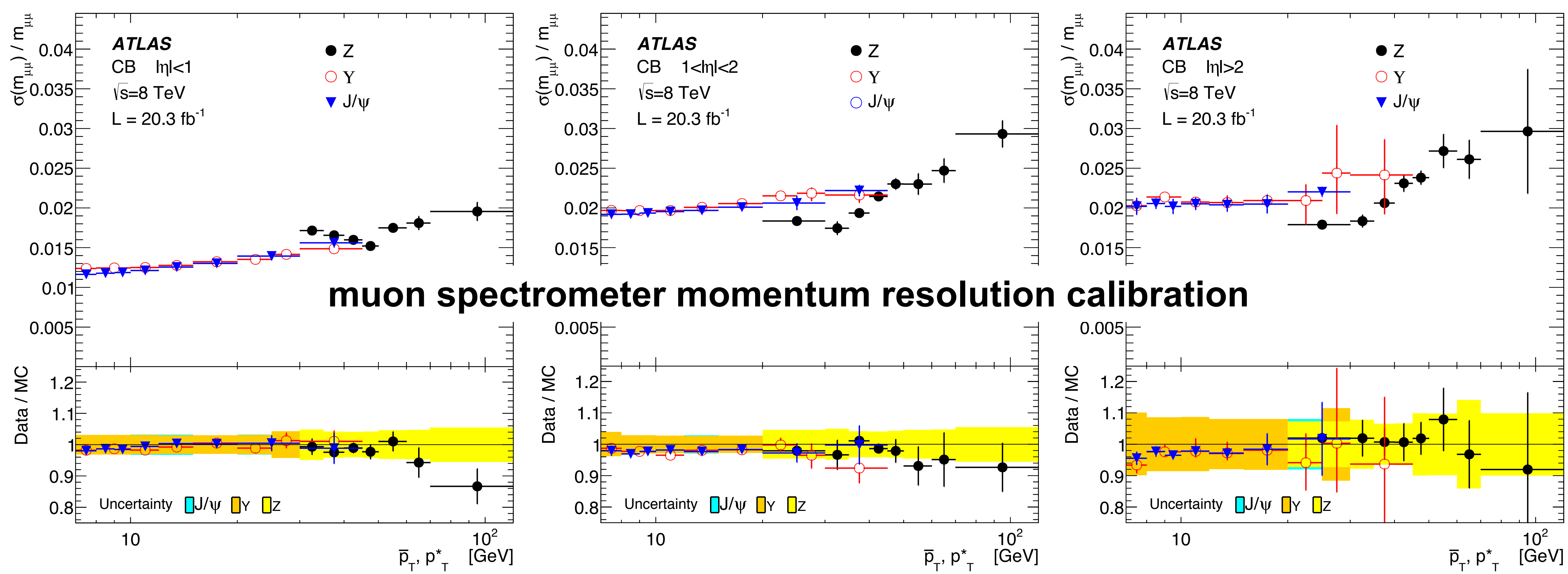


Efficiency
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
10
20
30
40
50
60
70
80
90
100
E_T [GeV]
|η| < 2.47
Loose
LooseLLH
Multilepton
Medium
Tight
VeryTightLLH
2012
ATLAS Preliminary
∫ L dt = 20.3 fb^-1
√s = 8 TeV Z→ ee

ATLAS: Muon Performance



muon spectrometer momentum scale calibration



muon spectrometer momentum resolution calibration