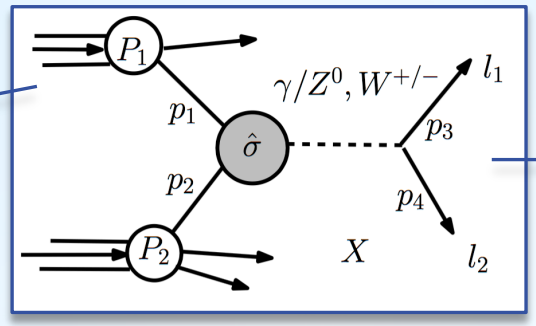
Differential measurements of the Drell-Yan cross-sections

Ulla Blumenschein, QMUL London, on behalf of ATLAS

Drell-Yan production

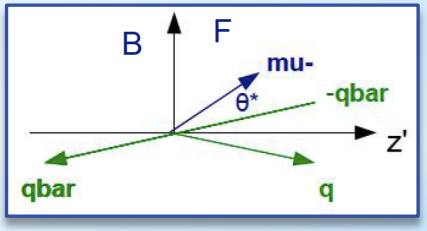
valence & sea PDF sensitivity through Z, W^+ and W^- dσ/dη



Weinberg angle: Z,γ mixing
Z/γ* interference <-> M(ll)
Different coupling to f_R, f_L

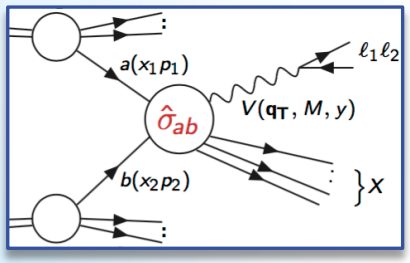
$$u\bar{d},\ c\bar{s} \quad (u\bar{s},\ c\bar{d}) \to W^+ ,$$
$$d\bar{u},\ s\bar{c} \quad (s\bar{u},\ d\bar{c}) \to W^- ,$$
$$q\bar{q} \to Z/\gamma^* ,$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

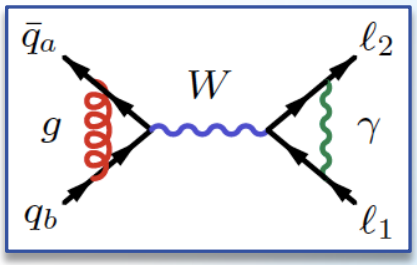


CS frame: θ* (l-q)
-> from y(ll) -> dilution

hadronic activity:
NNLO (-> N^3NLO) QCD

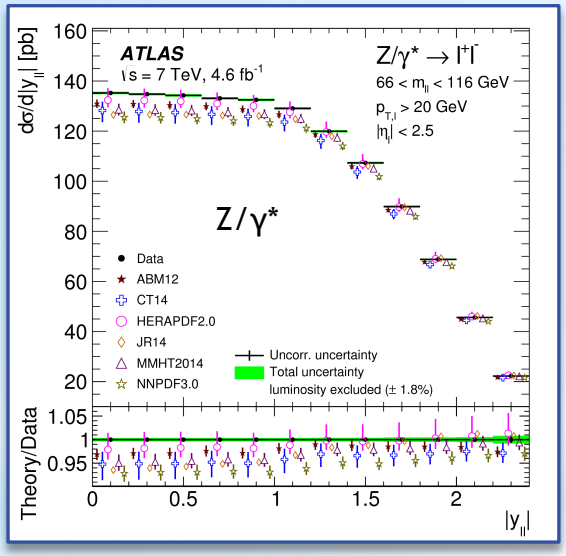


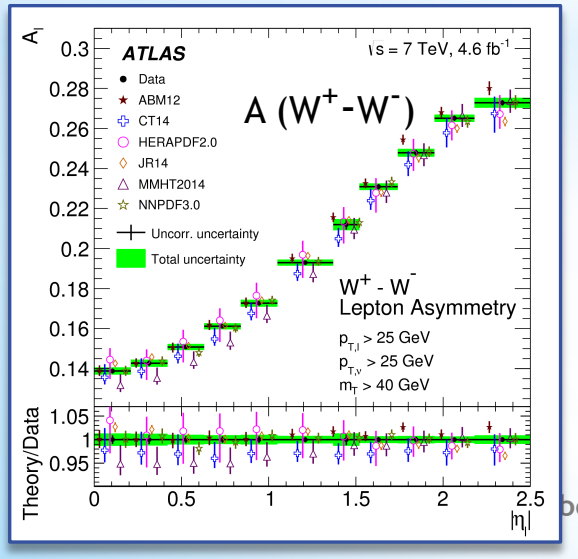
EWK & QCD corrections: mostly factorisable,
up to NNLO QCD + nNLO EWK, partly automated



7TeV precise Z/W cross sections

Eur. Phys. J. C 77 (2017) 367





Z/W inclusive and
η differential cross sect.

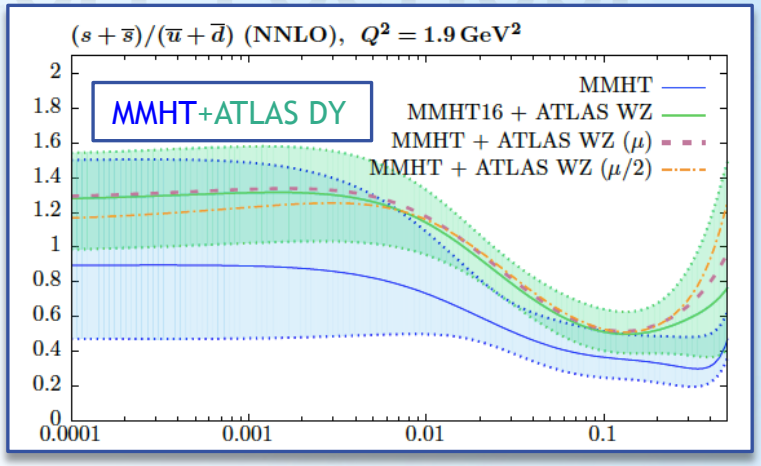
LHC 7-TeV data

syst. uncertainty ≈ 0.5%

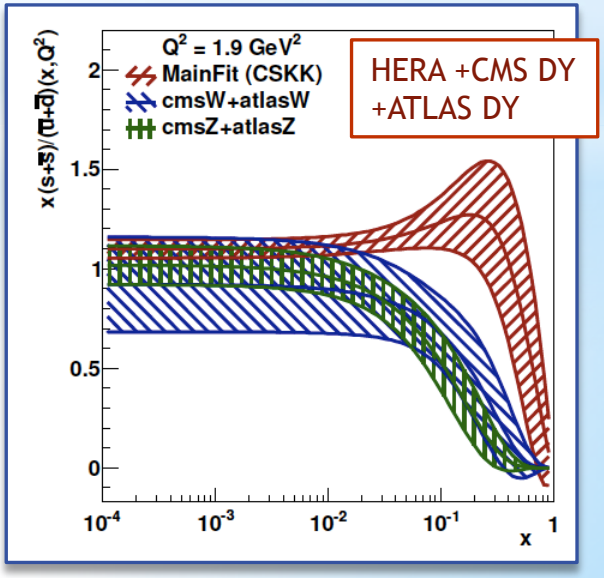
ATLAS data prefers
unsuppressed strange sea.

Meanwhile included in
Global fitters.

- Globally consistent but pulls in different direction from vs->lc DIS
- Prefers lower QCD scale
- Compatible with CMS DY dominates due to precision

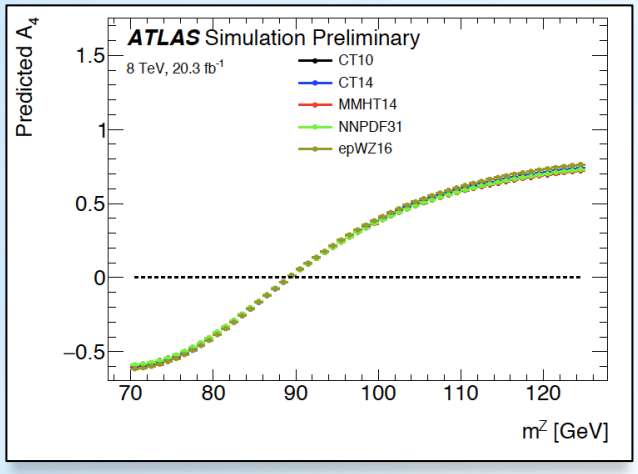


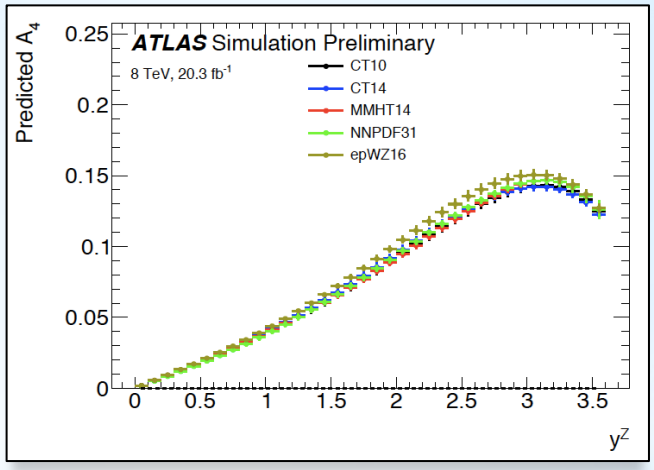
R.S. Thorne et al. arXiv:1708.00047

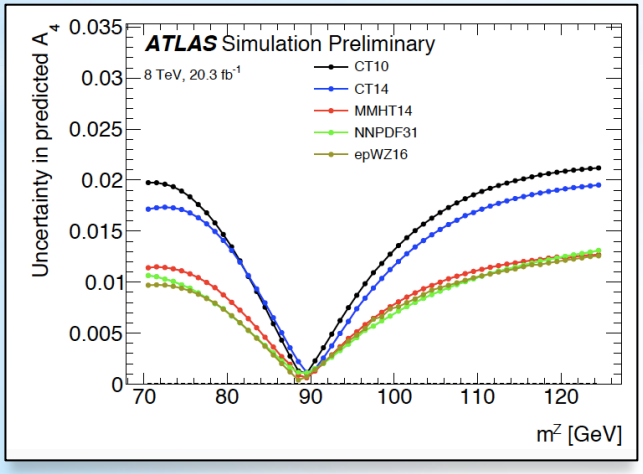


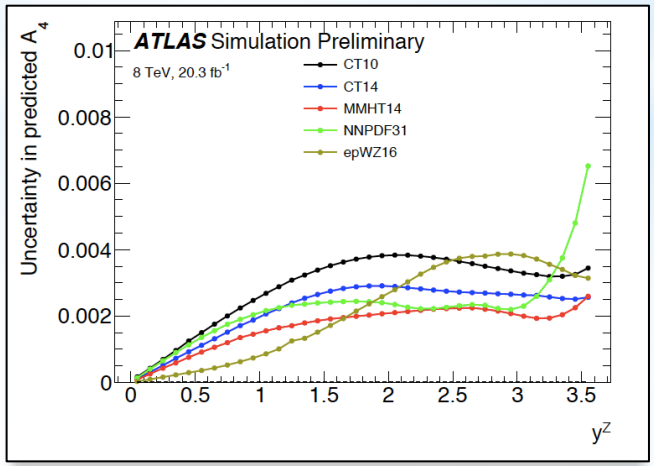
A. Cooper-Sakar et al, arXiv:1803.00968

PDF uncertainties on A_{FB}









$A_{FB} \propto A_4$

PDF sensitivity
- offpeak
- medium y

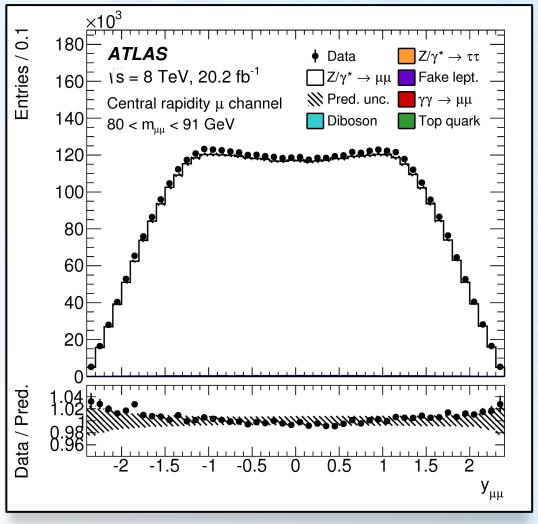
$\sin^2\theta_W$ sensitivity:
- slope at peak
- large y

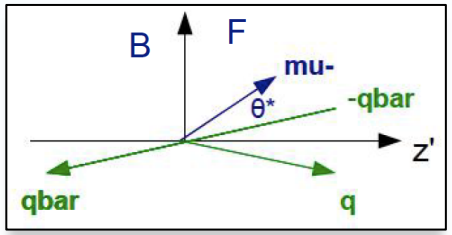
-> reduce PDF uncertainty by combined fit of $\sin^2\theta_W$ and PDF

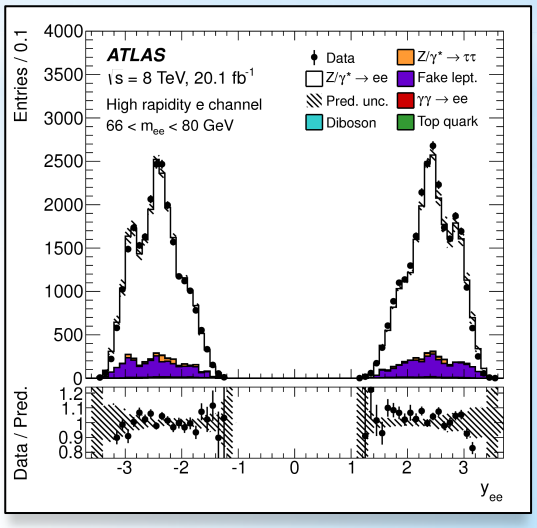
ATL-PHYS-PUB-2018-004

Unfolded 3D DY cross sect.

- ATLAS, 8TeV data (2012)
- 3D cross section:
  - m(ll), y(ll), cosθ*
  - Central electrons and muons (η<2.5) & Forward electrons (2.5 < η<3.5)
  - 505 bins Central+Central
  - 150 bins Central+Forward
- Precision
  - Stat: 0.5% at peak
  - Exp: 0.5% at peak
  - Lumi: 1.9%
- ➔ Plan simultaneous constraint on $\sin^2\theta_W$ & PDF







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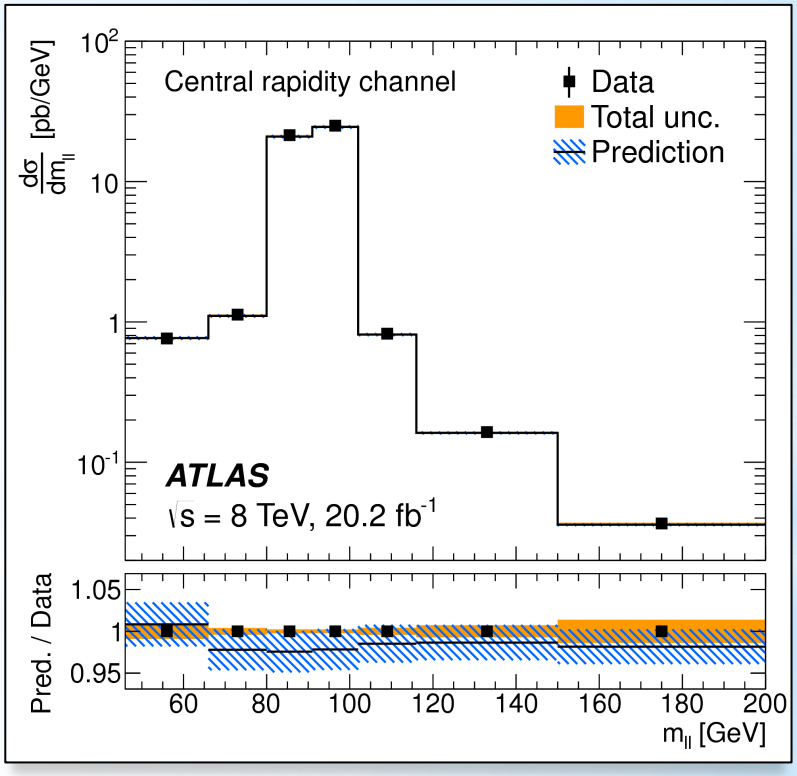

Good agreement with Powheg+Py8 with CT10, m(ll) dependent NNLO QCD + NLO EWK k-factor (FEWZ) and pT(ll) and y(ll) dependent angular coefficient corrections at NNLO (DYNNLO)

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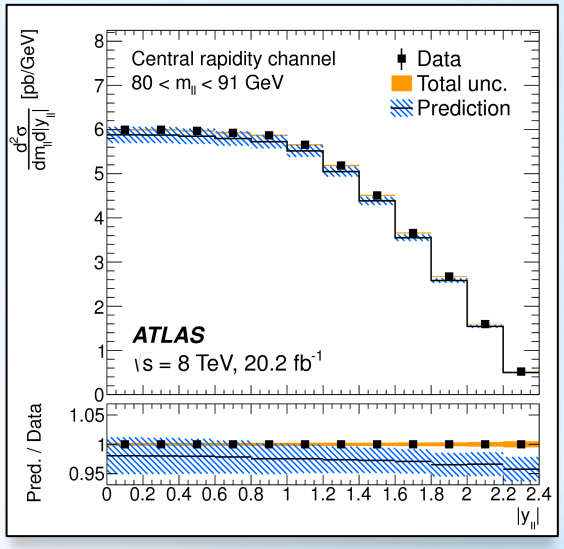

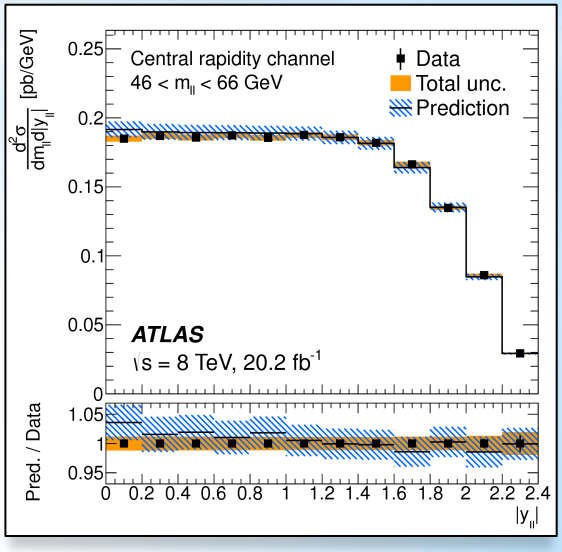

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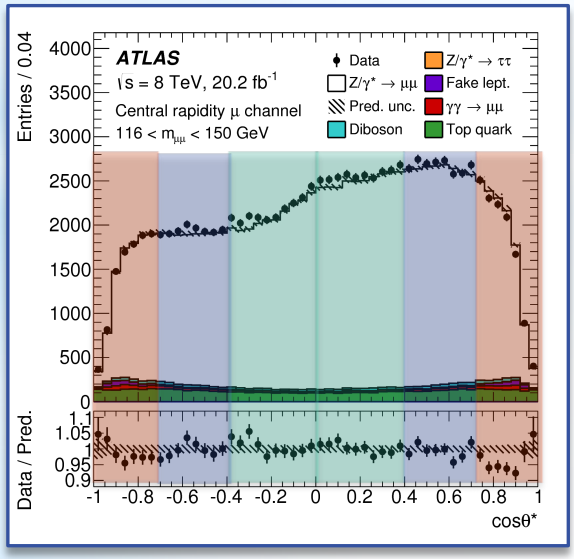
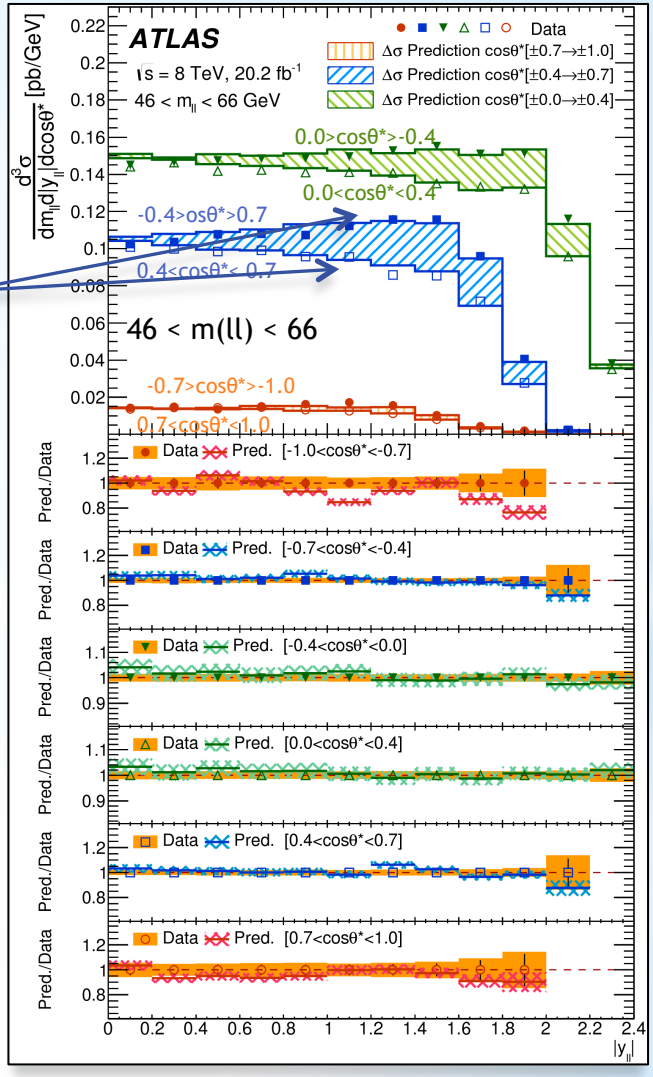
Unfolded 3D DY cross sect.

Central+Central

FBA large
for small m(ll)

Forward-backward
asymmetry





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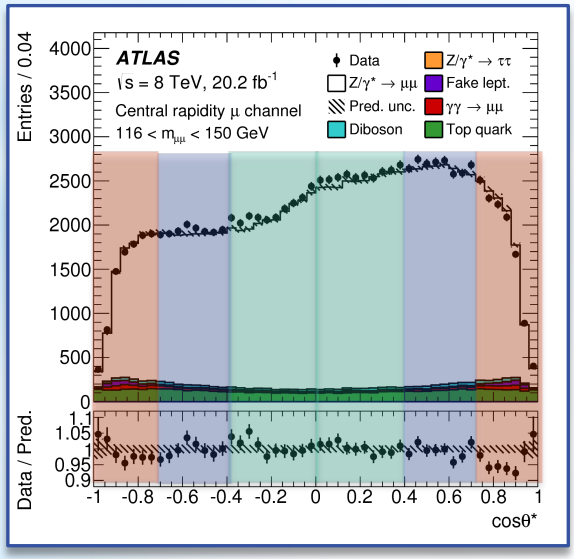
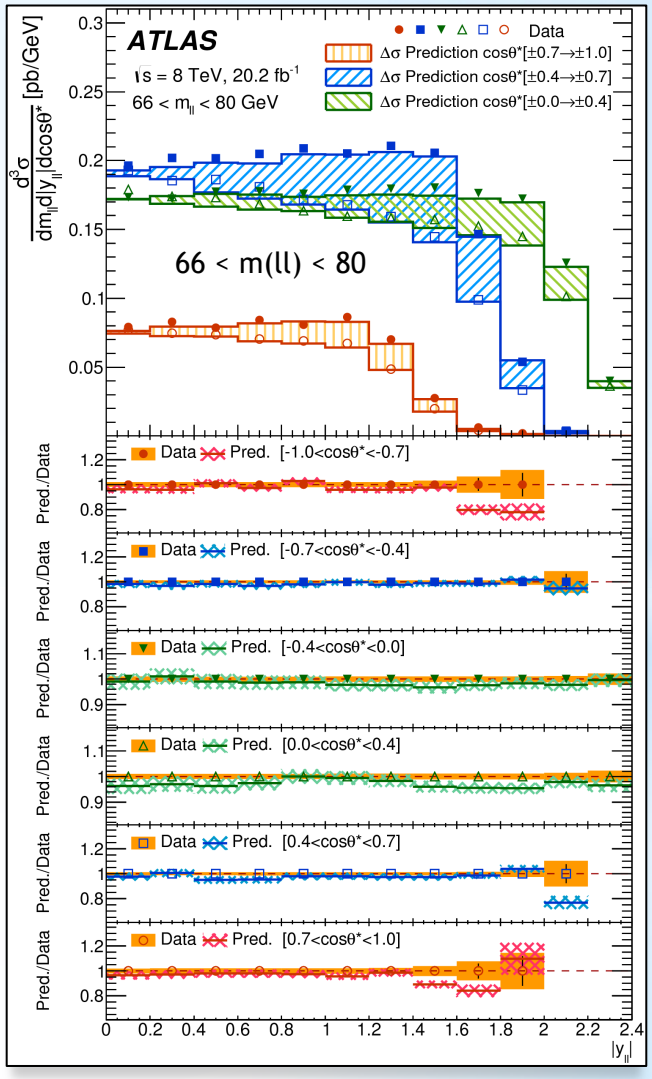
for small m(ll)

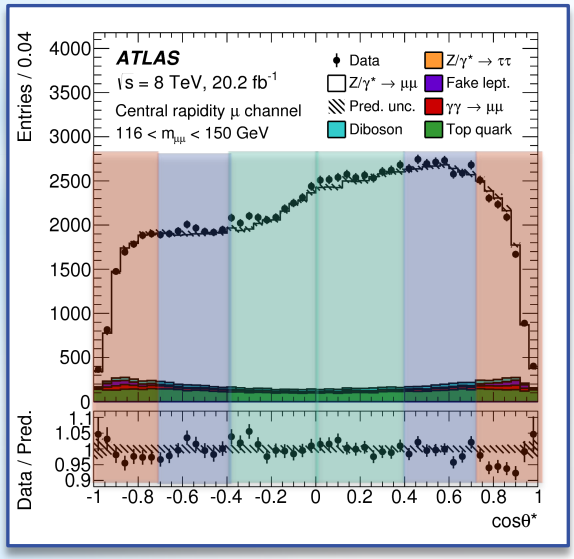


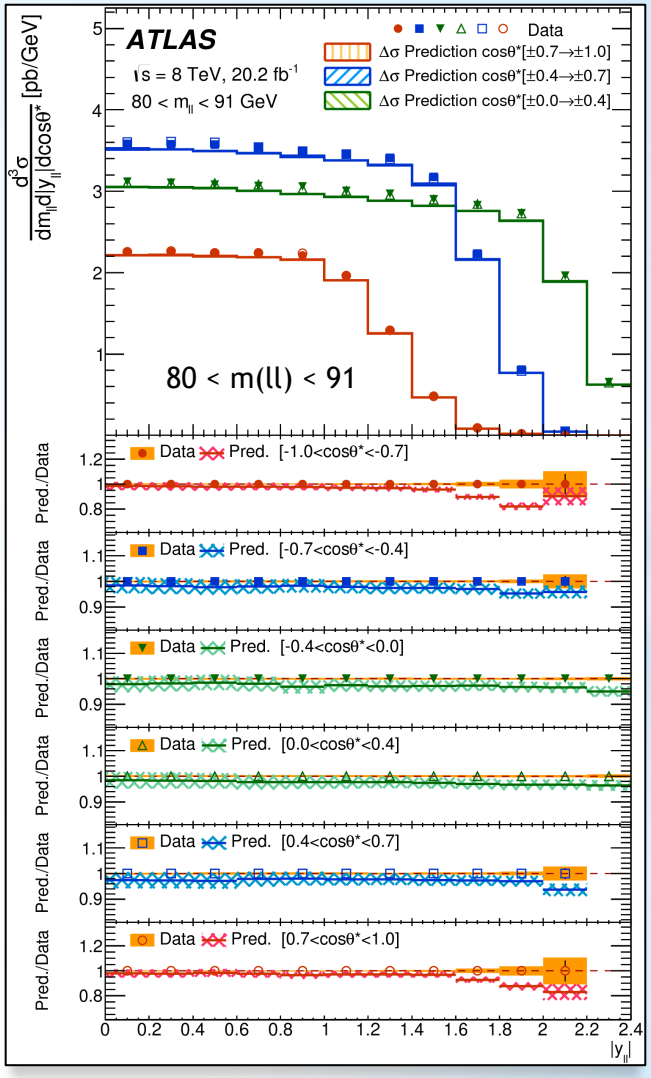


Unfolded 3D DY cross sect.

Central+Central

FBA vanishes
at peak
-> sign flip





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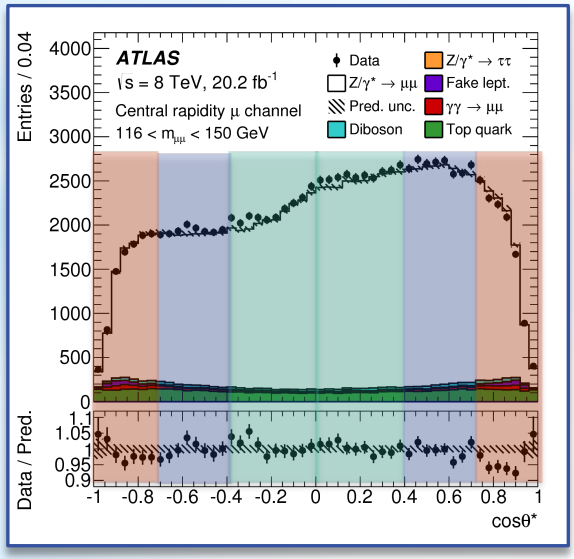
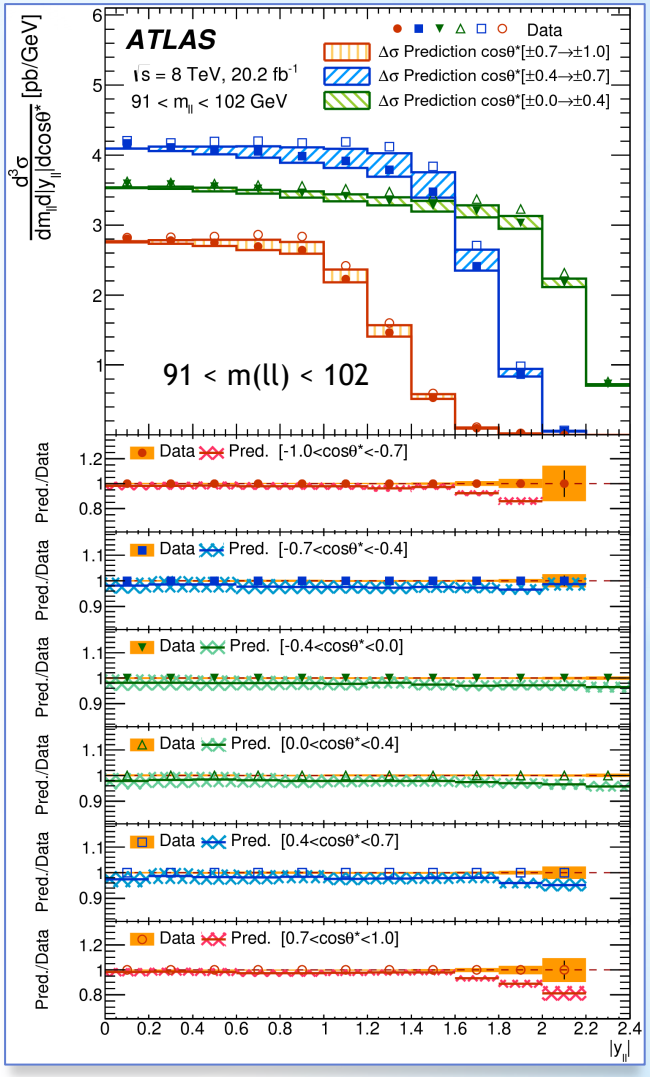
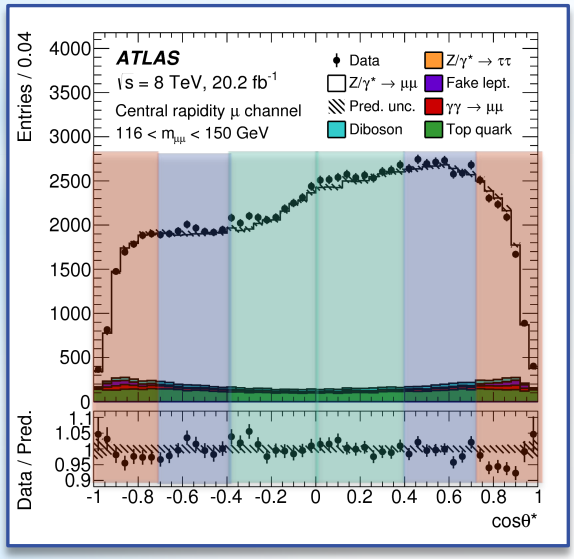


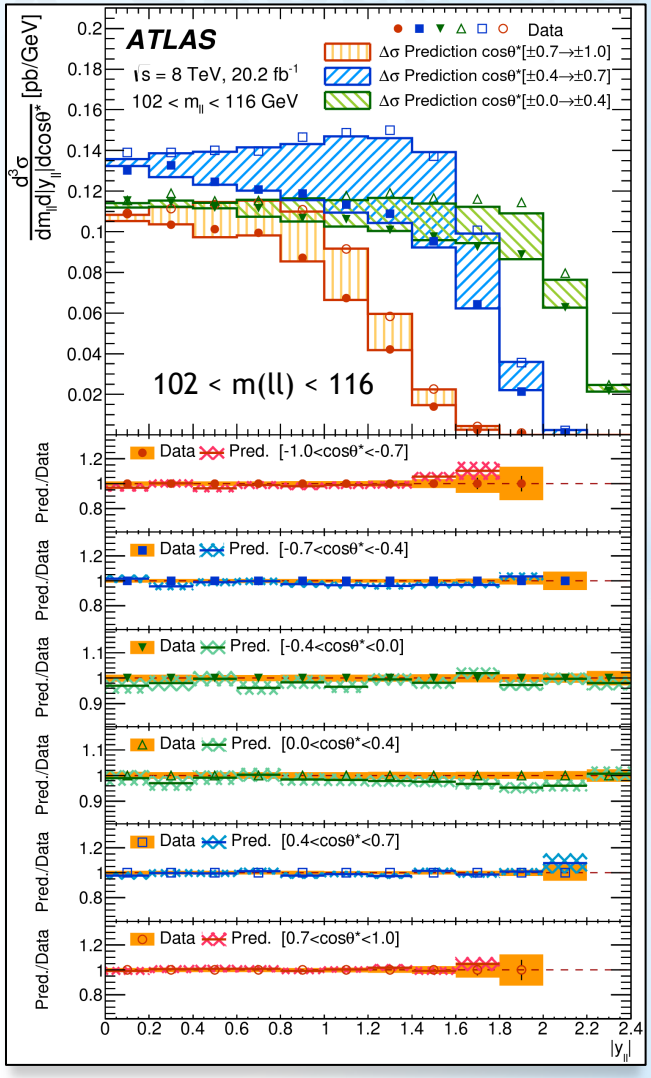


Unfolded 3D DY cross sect.

Central+Central

FBA large
for large m(ll)





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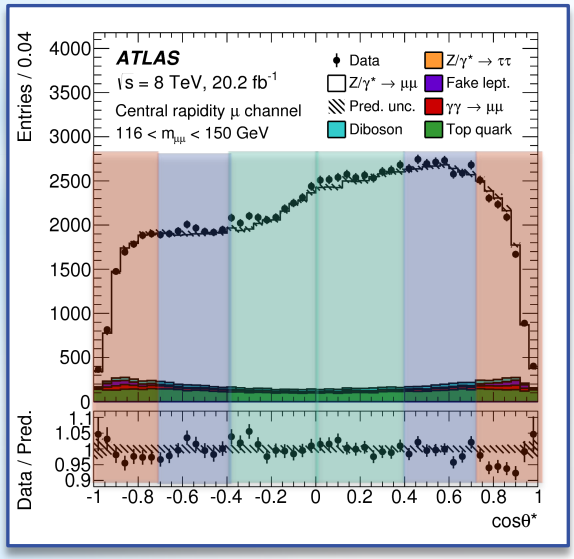
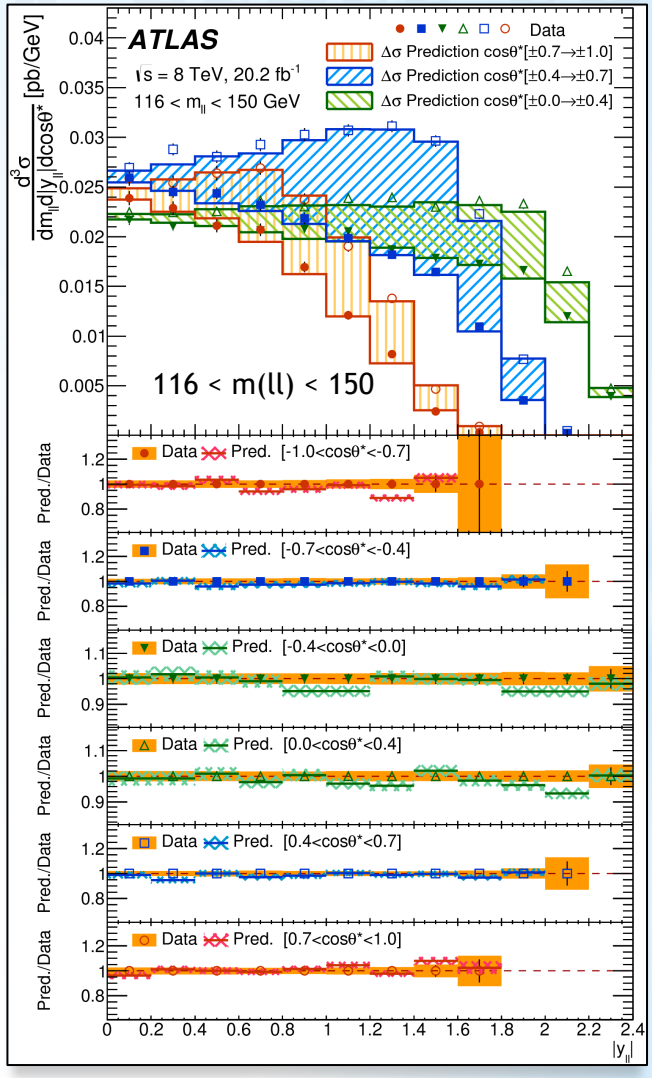
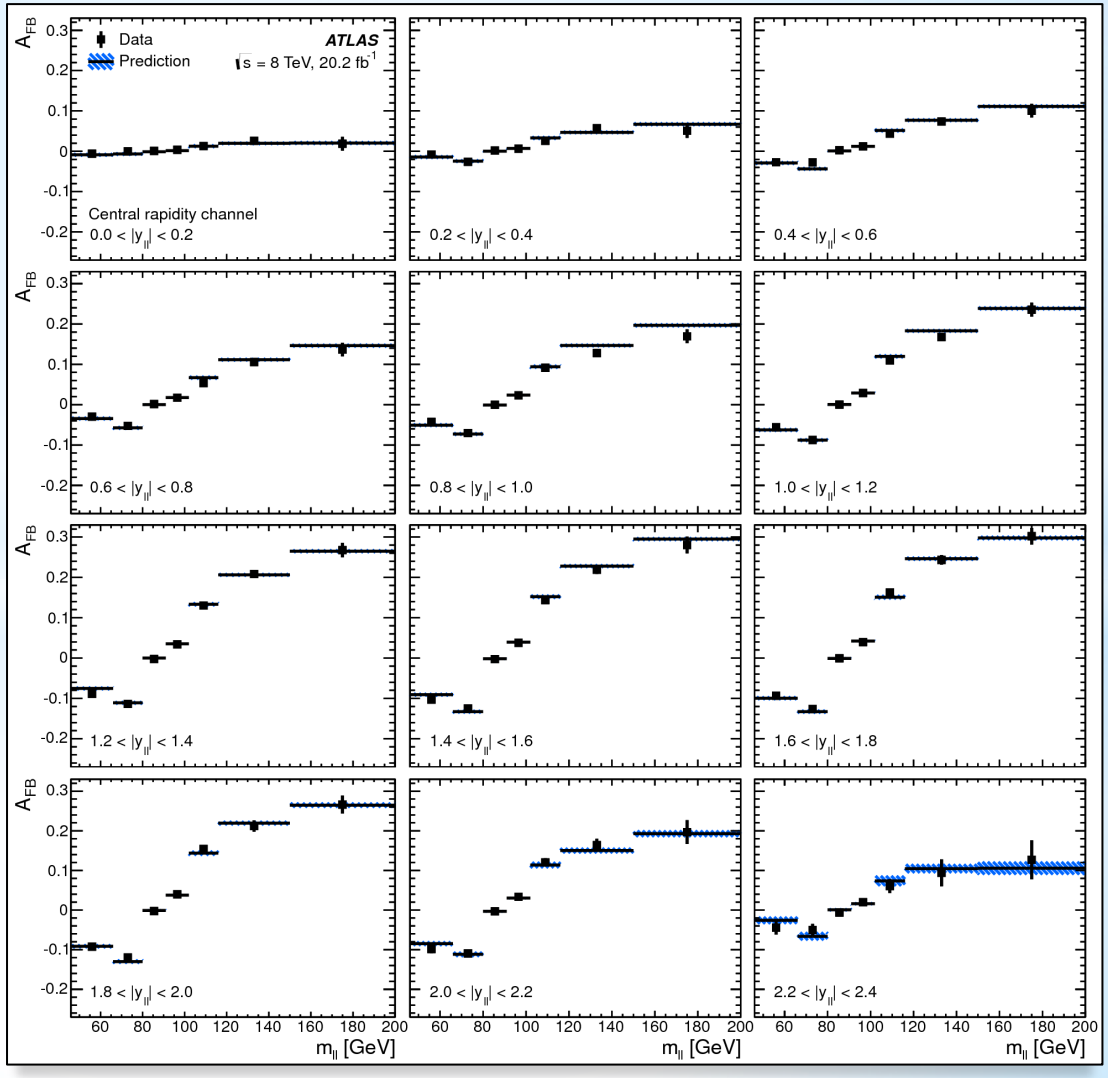




Unfolded 3D DY cross sect.

Central+Central

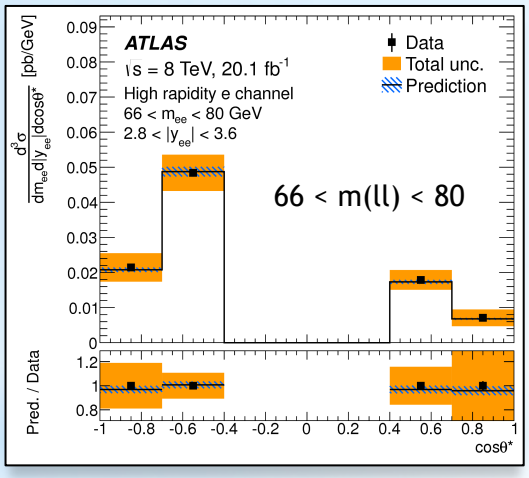
$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

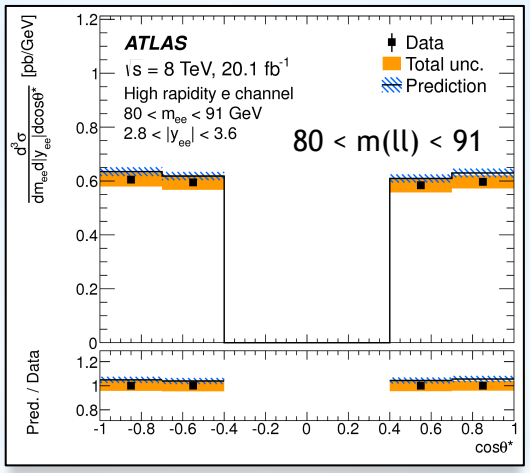


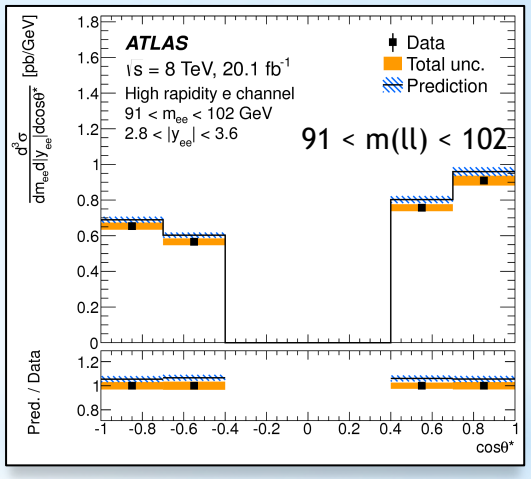
Unfolded 3D DY cross sect.

Central+Forward

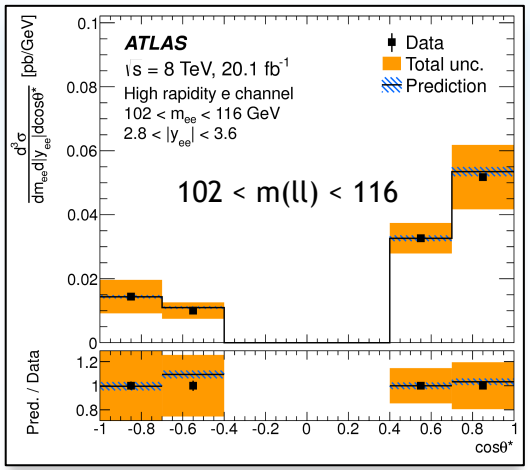
Example: 2.8 < y(ll) < 3.6

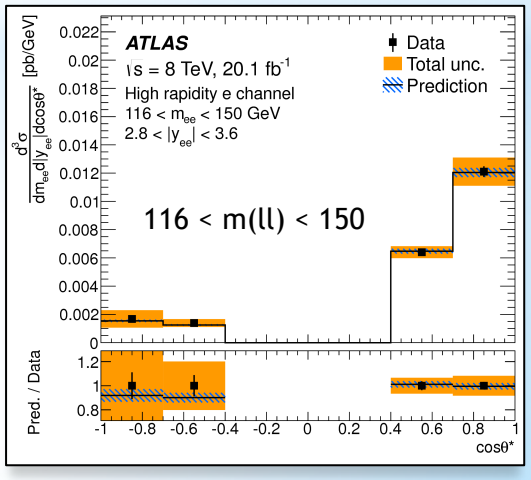






In electron channel up to y(ee) =3.6:
Most sensitive to θ_W (small dilution)





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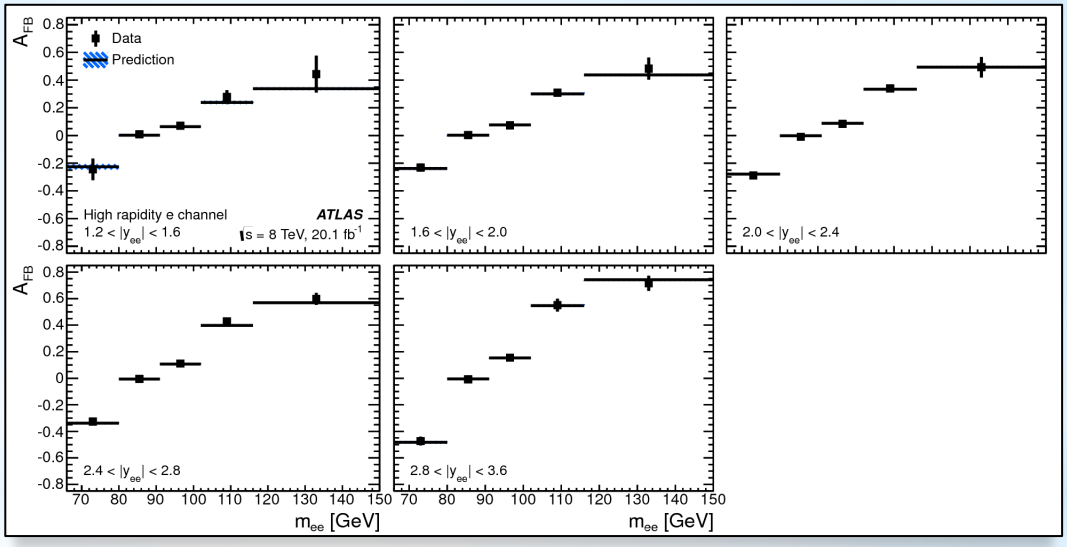


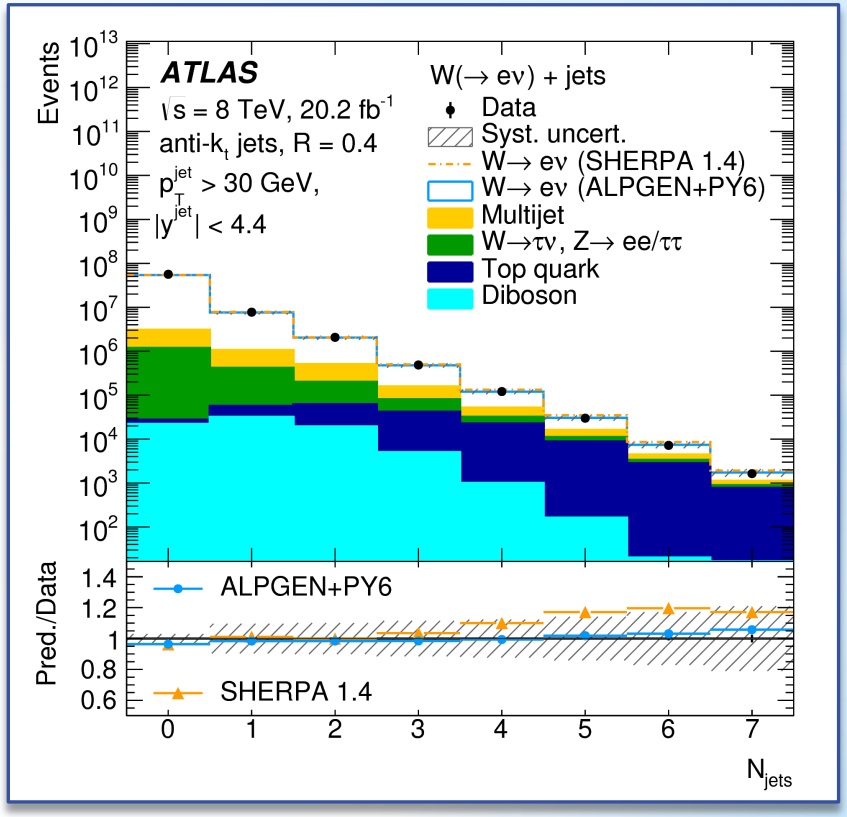
Measurements available in hepdata:
https://www.hepdata.net/record/77492

W+/W- +jets cross sections

$$R_{\pm} = \frac{d\sigma(W^+)/dy_W}{d\sigma(W^-)/dy_W} = \frac{u(x_1)\bar{d}(x_2) + c(x_1)\bar{s}(x_2) + 1 \leftrightarrow 2}{d(x_1)\bar{u}(x_2) + s(x_1)\bar{c}(x_2) + 1 \leftrightarrow 2}$$

- ATLAS, 8TeV data (2012)
- W: pT(e), MET>25GeV, mT> 40GeV
- Jets: pT> 30GeV, |y|<4.4
- **Top bkg small due to b-veto**
- **Jet bkg 3-15% for W+0/1/2 jets**
- Precision: 5-16% for W+0/1/2 jets
  - JES, JER
  - Unfolding
- Precision, ratio: 0.7-4% for 0/1/2 jets
  - Jet background
  - MET
  - JER

➔ Publish unfolded cross section
➔ Ratios W+/W-
➔ Sensitivity to PDF, in particular u/d



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➔ **Compare with selected predictions**
➔ Ratios W+/W-
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Program	Order in α_S	$N_{\text{partons}}^{\max}$ at highest order	PDF set
N_{jetti}	NNLO	1	CT14
BlackHat+Sherpa	NLO	1, 2 or 3	CT10
MCFM 6.8	NLO	1	CT10 + 3 more
Powheg+Pythia 8	NLO	1	CT14
Sherpa 2.2.1	NLO	2	CT10
Sherpa 2.2.1	LO	2 (3)	NNPDF 3.0
Alpgen+Pythia 6	LO	5	CTEQ6L1 (LO)
Alpgen+Herwig	LO	5	CTEQ6L1 (LO)
Sherpa 1.4.1	LO	4	CT10

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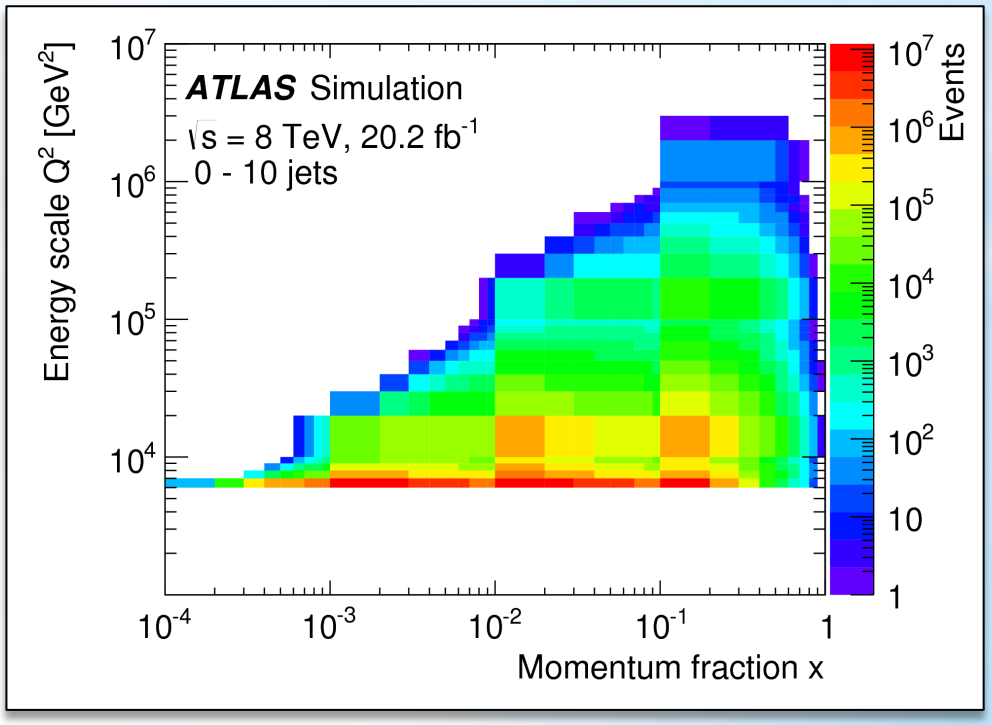
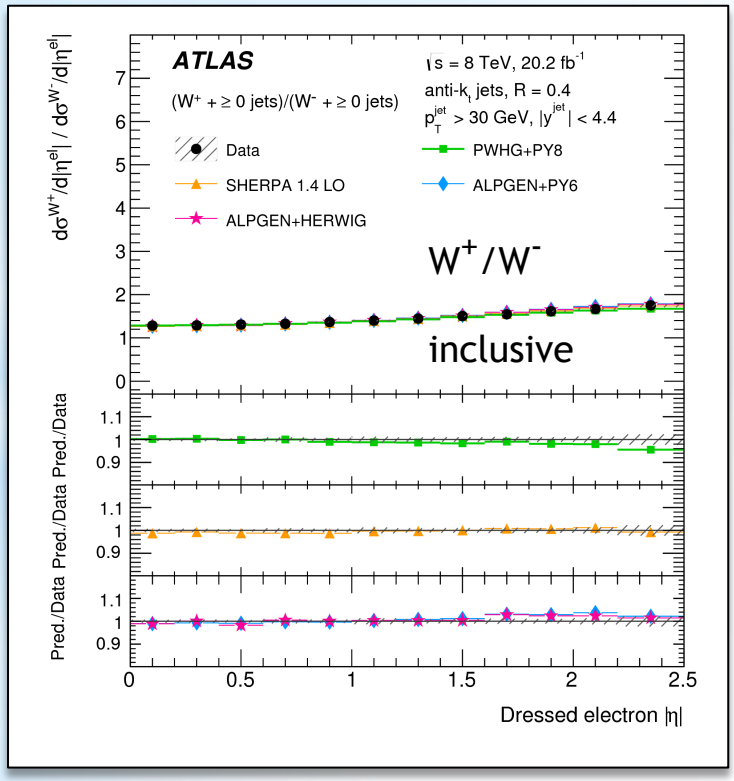
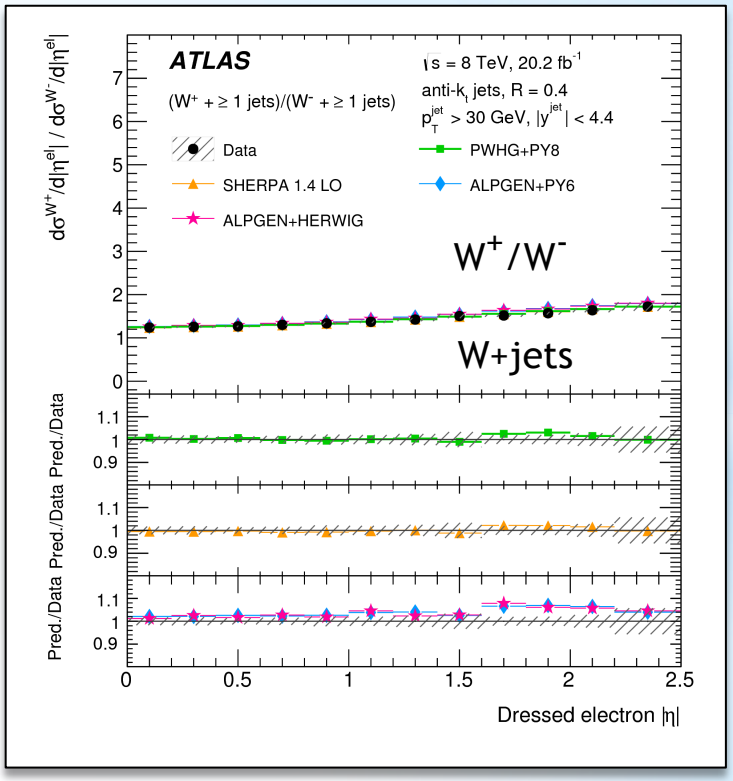


W+/W- +jets cross sections

Analysis not optimized for inclusive W precision
0.7% unc. on W+/W- ratio

lepton |η|

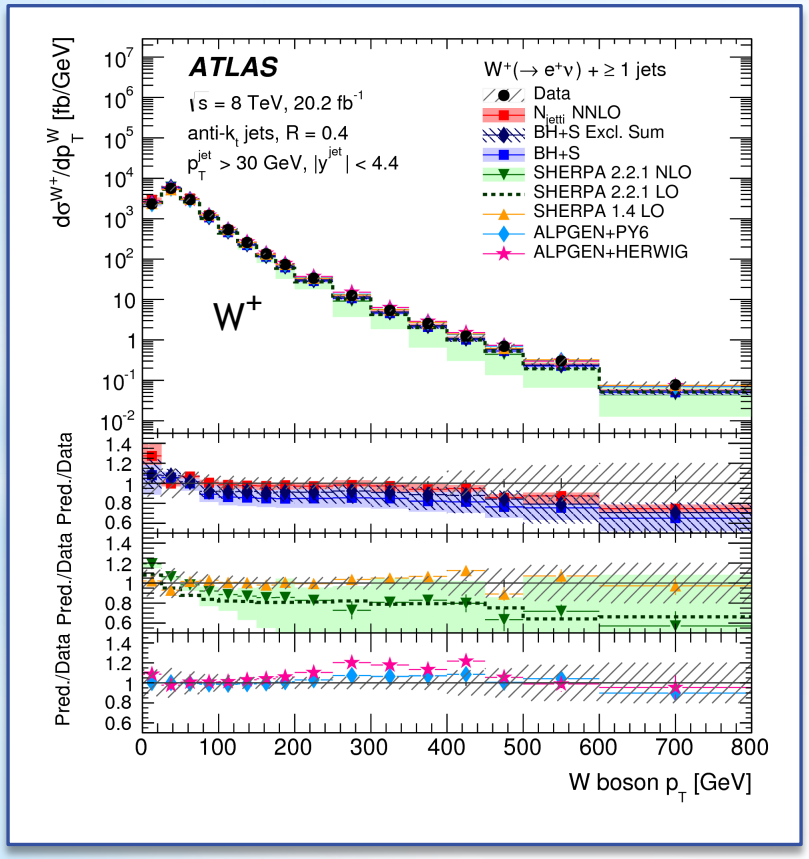


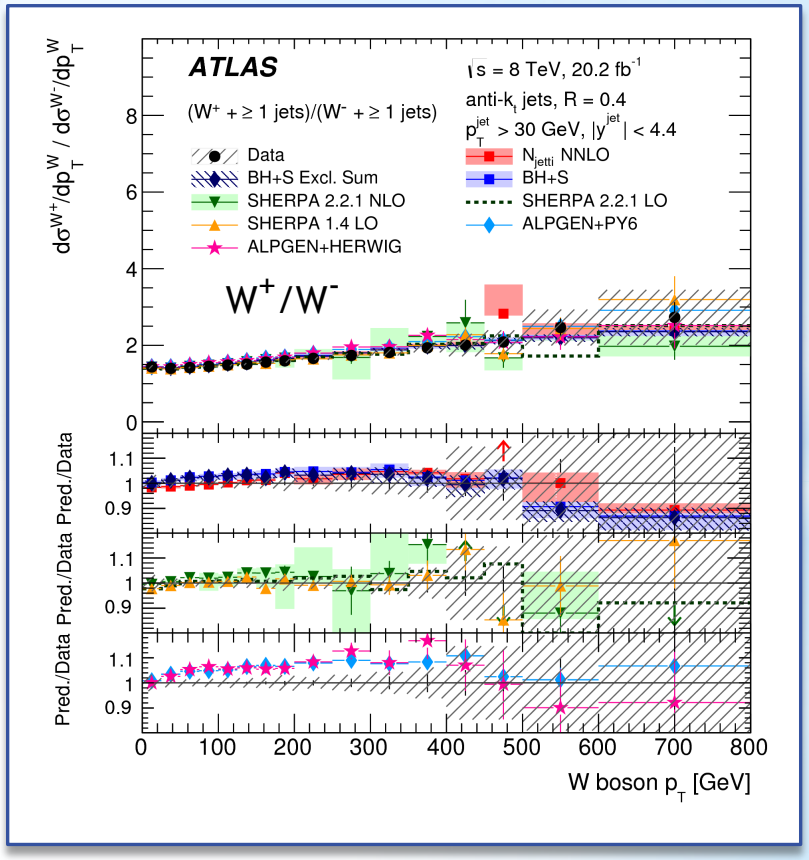


Good modeling by generators, asymmetry potentially sensitive to PDF

W+/W- +jets cross sections

W+jets, pT(W)





NNLO/NLO fixed order and LO ME+PS consistent with data, some trends

Summary

- Measurements of the Drell-Yan production of W and Z/gamma* provide a benchmark of our understanding of perturbative QCD and probe the proton structure in a unique way.
- Most precise measurement at 7TeV now included in global fitters. Globally consistent, pulls strange sea in opposite direction to vs->lc data towards unsuppressed strange sea.
- New set of high precision measurements at 8 TeV:
  - Precise triple differential cross-section measurement as a function of Mll, dilepton rapidity and cosθ* -> sensitivity to the PDFs and the Z forward-backward asymmetry, AFB
  - W+/W- ratios now as well in W+jets, as a function of several observables

Appendix

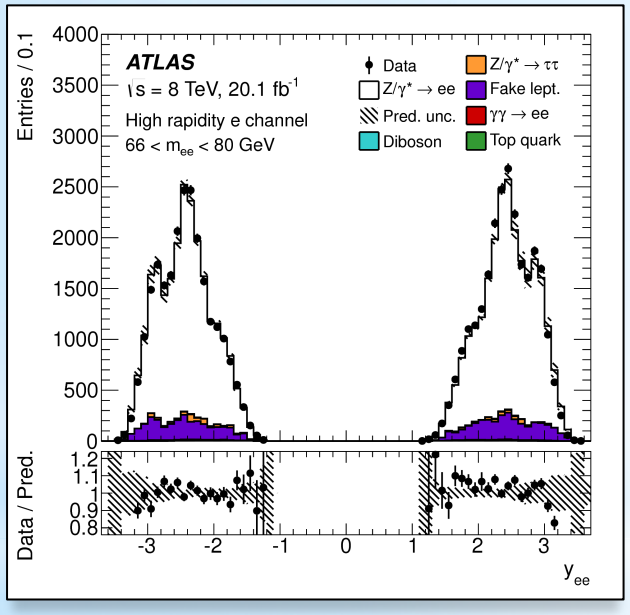
Appendix

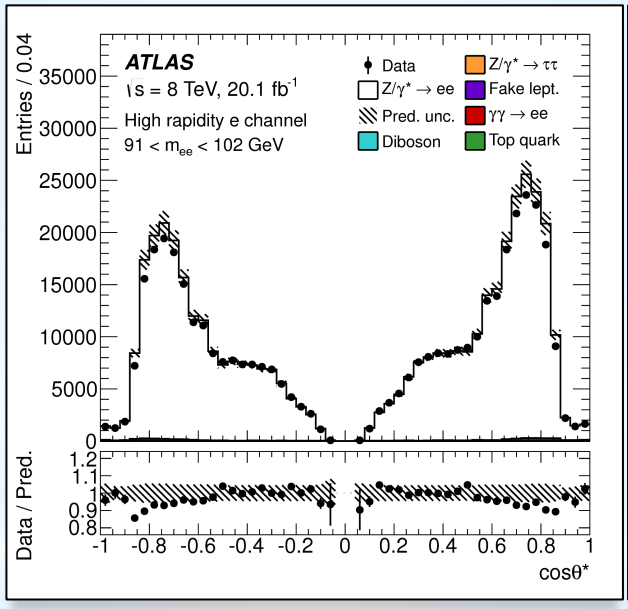
$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q P_q\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q \leftrightarrow \bar{q})\right]$$

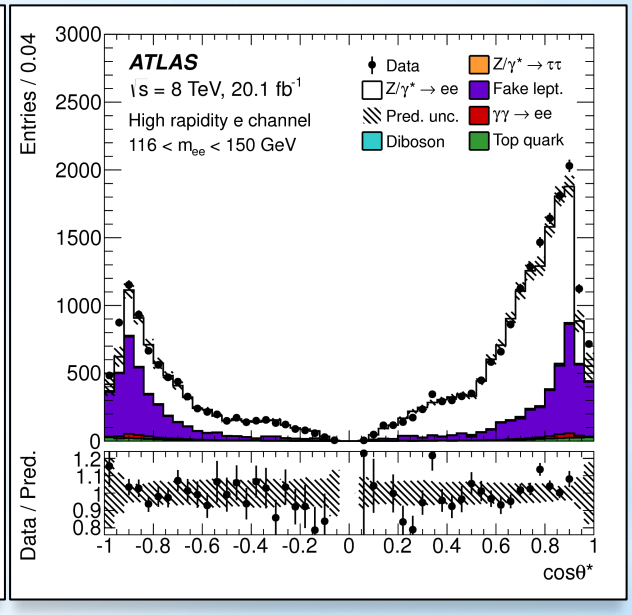
$$\begin{aligned} P_q = {} & e_\ell^2 e_q^2(1+\cos^2\theta^*) \\ & + e_\ell e_q \frac{2m_{\ell\ell}^2(m_{\ell\ell}^2 - m_Z^2)}{\sin^2\theta_W\cos^2\theta_W[(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2]}[v_\ell v_q(1+\cos^2\theta^*) + 2a_\ell a_q\cos\theta^*] \\ & + \frac{m_{\ell\ell}^4}{\sin^4\theta_W\cos^4\theta_W[(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2]}[(a_\ell^2 + v_\ell^2)(a_q^2 + v_q^2)(1+\cos^2\theta^*) + 8a_\ell v_\ell a_q v_q\cos\theta^*]. \end{aligned}$$

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

Appendix


ATLAS
√s = 8 TeV, 20.1 fb-1
High rapidity e channel
66 < mee < 80 GeV
Data
Z/γ* → ττ
Z/γ* → ee
Fake lept.
Pred. unc.
γγ → ee
Diboson
Top quark
Entries / 0.1
Data / Pred.
yee


ATLAS
√s = 8 TeV, 20.1 fb-1
High rapidity e channel
91 < mee < 102 GeV
Data
Z/γ* → ττ
Z/γ* → ee
Fake lept.
Pred. unc.
γγ → ee
Diboson
Top quark
Entries / 0.04
Data / Pred.
cosθ*


ATLAS
√s = 8 TeV, 20.1 fb-1
High rapidity e channel
116 < mee < 150 GeV
Data
Z/γ* → ττ
Z/γ* → ee
Fake lept.
Pred. unc.
γγ → ee
Diboson
Top quark
Entries / 0.04
Data / Pred.
cosθ*

Appendix

Process	Generator	Parton shower & underlying event	Generator PDF	Model parameters ("Tune")
$Z/\gamma^* \to \ell\ell$	Powheg v1(r1556)	Pythia 8.162	CT10	AU2 [62]
$Z/\gamma^* \to \tau\tau$	Powheg v1(r1556)	Pythia 8.162	CT10	AU2
$\gamma\gamma \to \ell\ell$	Pythia 8.170	Pythia 8.170	MRST2004qed	4C [63]
$t\bar{t}$	Powheg v1(r1556)	Pythia 6.427.2	CT10	AUET2 [64]
Wt	Powheg v1(r1556)	Pythia 6.427.2	CT10	AUET2
Diboson	Herwig 6.520	Herwig 6.520	CTEQ6L1	AUET2
$W \to \ell\nu$	Powheg v1(r1556)	Pythia 8.162	CT10	AU2

Bin	m_{ee} [GeV]	$\lvert y_{ee}\rvert$	$\cos\theta^*$	$\delta^{\rm stat}_{\rm unc}$ [%]	$\delta^{\rm sig}_{\rm unc}$ [%]	$\delta^{\rm bkg}_{\rm unc}$ [%]	$\delta^{\rm mj}_{\rm unc}$ [%]	$\delta^{\rm bkg}_{\rm cor}$ [%]	$\delta^{\rm mj}_{\rm cor}$ [%]	$\delta^{\rm scl}_{\rm cor}$ [%]	$\delta^{\rm res}_{\rm cor}$ [%]	$\delta^{\rm rec}_{\rm cor}$ [%]	$\delta^{\rm id}_{\rm cor}$ [%]	$\delta^{\rm trig}_{\rm cor}$ [%]	$\delta^{\rm qmid}_{\rm cor}$ [%]	$\delta^{\rm kfac}_{\rm cor}$ [%]	$\delta^{\rm zpt}_{\rm cor}$ [%]	$\delta^{\rm pdf}_{\rm cor}$ [%]	$\delta^{\rm tot}$ [%]
1	46, 66	0.0, 0.2	−1.0, −0.7	6.7	2.4	3.4	3.1	1.9	5.2	0.5	0.7	0.5	2.5	0.7	0.2	0.0	0.9	0.2	10.6
2	46, 66	0.0, 0.2	−0.7, −0.4	2.3	0.8	1.2	0.9	1.1	2.0	0.2	0.2	0.5	2.7	0.9	0.0	0.0	0.0	0.1	4.7
3	46, 66	0.0, 0.2	−0.4, 0.0	1.4	0.5	0.9	0.4	0.9	0.9	0.3	0.1	0.3	1.9	0.3	0.0	0.0	0.0	0.0	2.9
4	46, 66	0.0, 0.2	0.0, +0.4	1.4	0.5	0.8	0.5	0.9	0.9	0.3	0.1	0.3	1.9	0.3	0.0	0.0	0.0	0.1	3.0
5	46, 66	0.0, 0.2	+0.4, +0.7	2.2	0.8	0.9	0.9	1.1	2.0	0.2	0.1	0.5	2.6	0.8	0.0	0.0	0.0	0.1	4.5
6	46, 66	0.0, 0.2	+0.7, +1.0	6.7	2.3	4.8	3.1	1.8	4.9	0.9	0.5	0.5	2.6	0.7	0.1	0.0	0.9	0.2	10.9
79	66, 80	0.2, 0.4	−1.0, −0.7	2.7	1.3	0.5	0.7	0.5	1.6	1.5	1.1	0.6	3.7	1.2	0.1	0.0	0.3	0.2	5.6
80	66, 80	0.2, 0.4	−0.7, −0.4	1.3	0.6	0.4	0.3	0.3	0.3	0.4	0.4	0.3	1.7	0.4	0.1	0.0	0.0	0.0	2.5
81	66, 80	0.2, 0.4	−0.4, 0.0	1.3	0.4	0.4	0.3	0.3	0.1	0.3	0.1	0.1	0.7	0.2	0.0	0.0	0.0	0.0	1.6
82	66, 80	0.2, 0.4	0.0, +0.4	1.2	0.5	0.3	0.4	0.3	0.1	0.3	0.1	0.1	0.7	0.2	0.1	0.0	0.0	0.0	1.7
83	66, 80	0.2, 0.4	+0.4, +0.7	1.4	0.6	0.3	0.3	0.3	0.3	0.6	0.2	0.3	1.7	0.4	0.1	0.0	0.1	0.0	2.6
84	66, 80	0.2, 0.4	+0.7, +1.0	2.7	1.4	0.4	0.7	0.4	1.6	2.8	1.0	0.6	3.8	1.2	0.2	0.0	0.3	0.1	6.1
157	80, 91	0.4, 0.6	−1.0, −0.7	0.6	0.3	0.0	0.1	0.0	0.1	1.4	0.3	0.3	3.2	0.4	0.1	0.0	0.0	0.1	3.6
158	80, 91	0.4, 0.6	−0.7, −0.4	0.4	0.2	0.0	0.0	0.0	0.0	1.0	0.1	0.1	0.5	0.2	0.1	0.0	0.1	0.0	1.2
159	80, 91	0.4, 0.6	−0.4, 0.0	0.4	0.1	0.0	0.0	0.0	0.0	1.0	0.1	0.0	0.3	0.1	0.1	0.0	0.0	0.0	1.1
160	80, 91	0.4, 0.6	0.0, +0.4	0.4	0.1	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.3	0.1	0.1	0.0	0.0	0.0	1.2
161	80, 91	0.4, 0.6	+0.4, +0.7	0.4	0.2	0.0	0.0	0.0	0.0	1.0	0.1	0.1	0.5	0.2	0.1	0.0	0.1	0.0	1.2
162	80, 91	0.4, 0.6	+0.7, +1.0	0.6	0.3	0.0	0.0	0.0	0.1	1.6	0.2	0.3	3.2	0.4	0.1	0.0	0.0	0.1	3.7
235	91, 102	0.6, 0.8	−1.0, −0.7	0.5	0.2	0.0	0.1	0.0	0.0	2.1	0.2	0.3	2.6	0.5	0.0	0.0	0.2	0.0	3.5
236	91, 102	0.6, 0.8	−0.7, −0.4	0.4	0.2	0.0	0.0	0.0	0.0	1.3	0.0	0.1	0.5	0.2	0.0	0.0	0.1	0.0	1.5
237	91, 102	0.6, 0.8	−0.4, 0.0	0.4	0.1	0.0	0.0	0.0	0.0	1.0	0.1	0.0	0.2	0.1	0.0	0.0	0.0	0.0	1.1
238	91, 102	0.6, 0.8	0.0, +0.4	0.3	0.1	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	1.1
239	91, 102	0.6, 0.8	+0.4, +0.7	0.4	0.2	0.0	0.0	0.0	0.0	1.2	0.0	0.1	0.5	0.2	0.0	0.0	0.1	0.0	1.4
240	91, 102	0.6, 0.8	+0.7, +1.0	0.5	0.2	0.0	0.1	0.0	0.1	2.1	0.1	0.3	2.6	0.5	0.0	0.0	0.2	0.0	3.4
313	102, 116	0.8, 1.0	−1.0, −0.7	2.8	1.2	0.6	0.8	0.5	0.7	2.1	0.9	0.2	1.4	0.3	0.1	0.0	0.1	0.0	4.3
314	102, 116	0.8, 1.0	−0.7, −0.4	2.6	1.2	0.2	0.5	0.2	0.9	2.3	1.0	0.0	0.4	0.2	0.0	0.0	0.1	0.1	4.0
315	102, 116	0.8, 1.0	−0.4, 0.0	2.0	0.8	1.6	0.3	0.2	0.2	1.0	0.3	0.1	0.3	0.1	0.1	0.0	0.0	0.0	2.9
316	102, 116	0.8, 1.0	0.0, +0.4	1.8	0.7	0.1	0.2	0.2	0.1	0.9	0.5	0.1	0.3	0.1	0.0	0.0	0.1	0.1	2.2
317	102, 116	0.8, 1.0	+0.4, +0.7	2.3	1.0	0.5	0.4	0.2	0.7	1.7	1.3	0.0	0.4	0.2	0.1	0.0	0.0	0.1	3.5
318	102, 116	0.8, 1.0	+0.7, +1.0	2.3	1.0	0.2	0.6	0.3	0.6	2.1	0.6	0.2	1.4	0.3	0.0	0.0	0.0	0.1	3.8
391	116, 150	1.0, 1.2	−1.0, −0.7	4.8	1.0	2.8	1.8	1.3	5.1	0.2	0.4	0.1	0.4	0.2	0.1	0.0	0.0	0.1	8.0
392	116, 150	1.0, 1.2	−0.7, −0.4	3.5	0.9	0.4	0.7	0.7	0.6	0.6	0.1	0.1	0.3	0.2	0.1	0.0	0.2	0.1	3.9
393	116, 150	1.0, 1.2	−0.4, 0.0	3.1	0.8	1.3	0.4	0.5	0.8	0.6	0.1	0.1	0.4	0.2	0.1	0.0	0.0	0.2	3.7
394	116, 150	1.0, 1.2	0.0, +0.4	3.0	0.8	0.6	0.5	0.4	0.9	0.6	0.2	0.1	0.4	0.2	0.1	0.0	0.1	0.0	3.5
395	116, 150	1.0, 1.2	+0.4, +0.7	2.8	0.7	0.5	0.5	0.5	0.4	0.6	0.4	0.1	0.3	0.2	0.1	0.0	0.1	0.1	3.2
396	116, 150	1.0, 1.2	+0.7, +1.0	3.7	0.8	2.2	1.1	0.8	3.4	0.4	0.2	0.1	0.4	0.2	0.1	0.0	0.0	0.1	5.7
469	150, 200	1.2, 1.4	−1.0, −0.7	11.9	1.4	2.0	3.6	2.2	1.5	0.4	0.3	0.1	0.5	0.3	0.1	0.0	0.0	0.2	12.9
470	150, 200	1.2, 1.4	−0.7, −0.4	6.6	0.8	1.0	5.9	1.6	0.9	0.9	0.2	0.1	0.5	0.3	0.1	0.0	0.0	0.1	9.2
471	150, 200	1.2, 1.4	−0.4, 0.0	6.6	1.0	3.1	1.9	1.0	0.4	1.0	0.1	0.2	0.6	0.3	0.2	0.0	0.0	0.1	7.8
472	150, 200	1.2, 1.4	0.0, +0.4	5.3	0.9	0.8	0.9	0.6	0.2	0.6	0.2	0.2	0.6	0.3	0.2	0.0	0.1	0.0	5.6
473	150, 200	1.2, 1.4	+0.4, +0.7	4.4	0.6	0.5	1.9	0.7	0.4	0.9	0.2	0.1	0.5	0.3	0.1	0.0	0.0	0.0	5.0
474	150, 200	1.2, 1.4	+0.7, +1.0	7.6	0.9	1.1	2.3	1.1	0.7	0.3	0.2	0.1	0.5	0.3	0.2	0.0	0.0	0.1	8.3

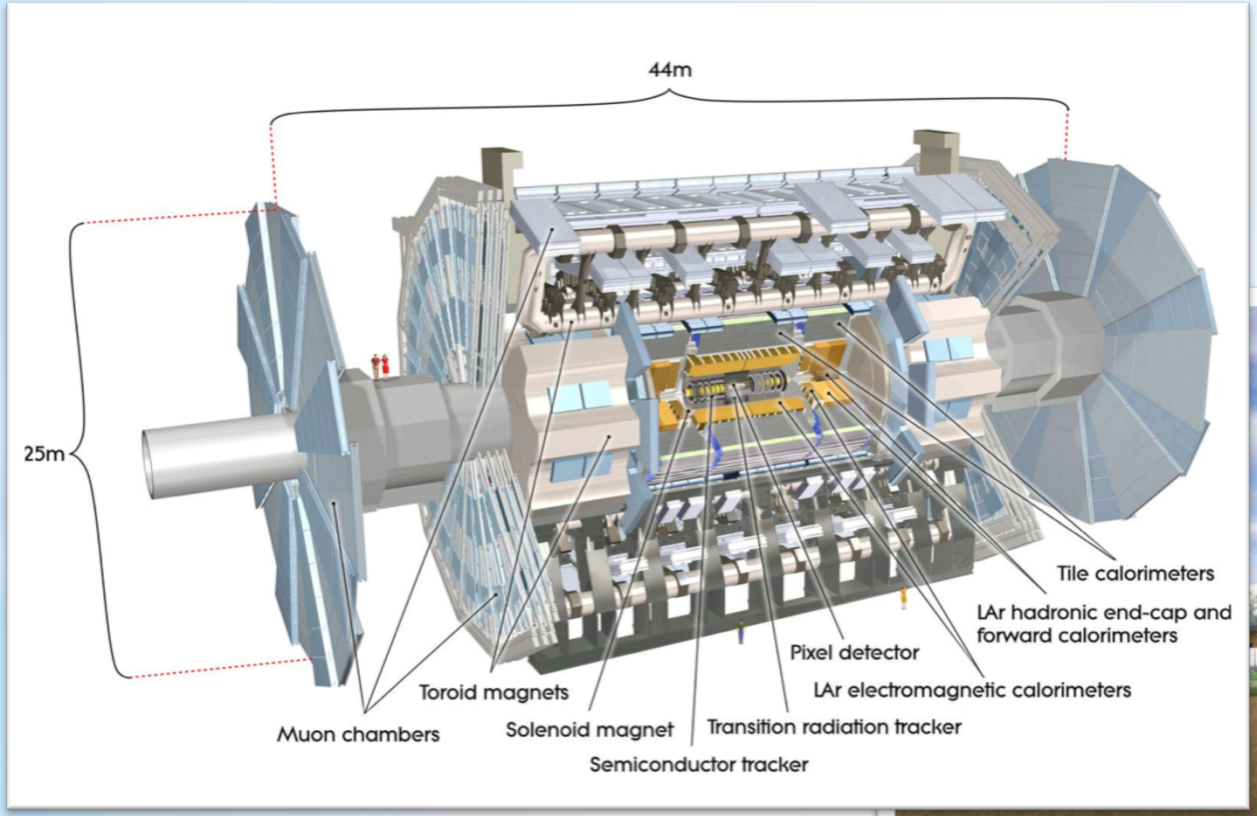
Bin	m_{ee} [GeV]	$\lvert y_{ee}\rvert$	$\cos\theta^*$	$\delta^{\rm stat}_{\rm unc}$ [%]	$\delta^{\rm sig}_{\rm unc}$ [%]	$\delta^{\rm bkg}_{\rm unc}$ [%]	$\delta^{\rm mj}_{\rm unc}$ [%]	$\delta^{\rm bkg}_{\rm cor}$ [%]	$\delta^{\rm mj}_{\rm cor}$ [%]	$\delta^{\rm scl}_{\rm cor}$ [%]	$\delta^{\rm res}_{\rm cor}$ [%]	$\delta^{\rm fscl}_{\rm cor}$ [%]	$\delta^{\rm fres}_{\rm cor}$ [%]	$\delta^{\rm rec}_{\rm cor}$ [%]	$\delta^{\rm id}_{\rm cor}$ [%]	$\delta^{\rm trig}_{\rm cor}$ [%]	$\delta^{\rm iso}_{\rm cor}$ [%]	$\delta^{\rm fid}_{\rm cor}$ [%]	$\delta^{\rm qmid}_{\rm cor}$ [%]	$\delta^{\rm kfac}_{\rm cor}$ [%]	$\delta^{\rm zpt}_{\rm cor}$ [%]	$\delta^{\rm pdf}_{\rm cor}$ [%]	$\delta^{\rm tot}$ [%]
1	66, 80	1.2, 1.6	−1.0, −0.7	6.4	3.0	6.0	4.5	0.9	11.5	0.4	0.6	3.1	2.1	0.2	0.8	0.3	0.0	0.7	0.0	0.0	0.8	0.6	16.0
2	66, 80	1.2, 1.6	−0.7, −0.4	16.4	8.7	8.0	9.9	0.5	11.4	0.5	1.2	5.8	2.5	0.1	0.2	0.1	0.0	0.8	0.0	0.0	0.8	0.3	26.0
3	66, 80	1.2, 1.6	−0.4, 0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
4	66, 80	1.2, 1.6	0.0, +0.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
5	66, 80	1.2, 1.6	+0.4, +0.7	15.7	8.0	6.7	7.9	0.5	10.7	0.9	0.8	3.8	5.5	0.1	0.1	0.1	0.0	0.8	0.0	0.0	1.6	1.4	24.1
6	66, 80	1.2, 1.6	+0.7, +1.0	7.9	3.3	8.8	5.8	1.6	15.3	0.7	0.7	2.3	2.9	0.2	0.8	0.3	0.0	0.7	0.0	0.0	0.9	0.3	20.9
19	66, 80	2.4, 2.8	−1.0, −0.7	3.4	2.2	1.4	2.8	0.3	3.4	2.5	0.7	4.3	5.2	0.2	1.6	0.4	0.1	1.4	0.0	0.0	2.4	0.2	10.1
20	66, 80	2.4, 2.8	−0.7, −0.4	2.2	1.3	0.8	1.6	0.3	1.1	1.2	0.6	3.1	3.9	0.1	0.8	0.2	0.0	1.3	0.0	0.0	0.5	0.1	6.4
21	66, 80	2.4, 2.8	−0.4, 0.0	2.3	1.0	0.8	1.4	0.2	1.5	0.4	0.2	0.9	0.3	0.1	0.5	0.2	0.0	0.8	0.0	0.0	0.1	0.0	3.6
22	66, 80	2.4, 2.8	0.0, +0.4	2.8	1.2	1.5	1.9	0.4	2.0	0.4	0.5	1.3	0.3	0.1	0.5	0.2	0.0	0.7	0.0	0.0	0.3	0.1	4.7
23	66, 80	2.4, 2.8	+0.4, +0.7	2.7	1.6	1.3	2.3	0.4	1.7	1.6	0.2	4.0	6.0	0.1	0.8	0.2	0.0	1.4	0.1	0.0	1.1	0.2	8.8
24	66, 80	2.4, 2.8	+0.7, +1.0	4.2	2.7	3.4	3.7	0.7	5.5	2.8	0.9	4.9	6.5	0.2	1.6	0.4	0.1	1.4	0.0	0.0	3.6	0.3	13.2
73	91, 102	2.0, 2.4	−1.0, −0.7	0.9	0.6	0.2	0.3	0.0	0.8	0.8	0.1	1.9	0.1	0.2	0.8	0.2	0.0	1.2	0.0	0.0	0.8	0.1	2.9
74	91, 102	2.0, 2.4	−0.7, −0.4	0.5	0.3	0.0	0.2	0.0	0.7	0.9	0.1	1.5	0.2	0.0	0.4	0.1	0.0	0.8	0.0	0.0	0.1	0.1	2.1
75	91, 102	2.0, 2.4	−0.4, 0.0	0.7	0.3	0.1	0.4	0.0	0.6	0.6	0.1	1.7	0.1	0.0	0.2	0.1	0.0	0.7	0.0	0.0	0.1	0.0	2.2
76	91, 102	2.0, 2.4	0.0, +0.4	0.6	0.3	0.1	0.4	0.0	0.5	0.5	0.1	1.5	0.1	0.0	0.2	0.1	0.0	0.7	0.0	0.0	0.1	0.1	2.0
77	91, 102	2.0, 2.4	+0.4, +0.7	0.5	0.3	0.1	0.1	0.0	0.5	0.9	0.2	1.3	0.3	0.0	0.4	0.1	0.0	0.8	0.0	0.0	0.2	0.1	2.0
78	91, 102	2.0, 2.4	+0.7, +1.0	0.9	0.5	0.2	0.3	0.0	0.3	0.7	0.2	1.6	0.2	0.2	0.7	0.2	0.0	1.2	0.0	0.0	0.8	0.0	2.6
97	102, 116	1.6, 2.0	−1.0, −0.7	3.8	1.8	2.0	2.9	0.7	4.2	0.6	0.3	2.4	2.2	0.1	0.3	0.1	0.0	0.8	0.0	0.0	1.5	0.1	7.9
98	102, 116	1.6, 2.0	−0.7, −0.4	4.4	2.1	2.0	3.4	0.3	3.6	1.2	0.6	2.1	1.2	0.0	0.2	0.0	0.0	0.7	0.0	0.0	1.5	0.2	8.0
99	102, 116	1.6, 2.0	−0.4, 0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
100	102, 116	1.6, 2.0	0.0, +0.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
101	102, 116	1.6, 2.0	+0.4, +0.7	3.3	1.5	1.6	2.1	0.2	2.2	1.0	0.7	1.7	1.0	0.0	0.2	0.0	0.0	0.7	0.0	0.0	1.1	0.1	5.6
102	102, 116	1.6, 2.0	+0.7, +1.0	2.6	1.4	1.3	1.5	0.3	1.9	0.3	0.1	2.1	1.0	0.1	0.3	0.1	0.0	0.8	0.0	0.0	0.9	0.2	4.9
109	102, 116	2.4, 2.8	−1.0, −0.7	3.7	2.2	2.3	3.4	0.8	6.2	3.3	1.2	6.7	6.6	0.1	0.6	0.1	0.0	1.4	0.0	0.0	3.3	0.3	13.7
110	102, 116	2.4, 2.8	−0.7, −0.4	4.2	2.3	1.0	3.7	0.3	3.3	1.4	1.2	5.5	4.2	0.0	0.2	0.1	0.0	1.2	0.0	0.0	2.0	0.2	10.2
111	102, 116	2.4, 2.8	−0.4, 0.0	3.9	1.9	1.5	4.5	0.2	4.6	0.7	0.9	2.3	1.2	0.1	0.3	0.2	0.0	0.7	0.0	0.0	0.9	0.2	8.5
112	102, 116	2.4, 2.8	0.0, +0.4	3.1	1.5	0.7	2.9	0.1	3.2	0.6	0.4	2.3	1.3	0.1	0.3	0.1	0.0	0.8	0.0	0.0	0.9	0.1	6.3
113	102, 116	2.4, 2.8	+0.4, +0.7	2.7	1.6	1.1	1.7	0.2	1.6	1.2	0.8	4.0	2.1	0.0	0.2	0.1	0.0	1.2	0.0	0.0	1.4	0.2	6.5
114	102, 116	2.4, 2.8	+0.7, +1.0	2.2	1.4	1.3	1.5	0.3	2.4	2.0	0.8	3.3	3.2	0.1	0.6	0.1	0.0	1.3	0.0	0.0	2.2	0.1	7.0
127	116, 150	1.6, 2.0	−1.0, −0.7	8.4	1.7	8.7	7.1	2.9	29.0	0.2	0.4	1.8	1.2	0.0	0.1	0.0	0.0	0.6	0.0	0.0	0.7	0.2	32.5
128	116, 150	1.6, 2.0	−0.7, −0.4	7.6	2.0	4.2	9.0	1.3	8.6	0.6	0.2	0.3	0.5	0.0	0.1	0.0	0.0	0.6	0.0	0.0	0.5	0.2	15.4
129	116, 150	1.6, 2.0	−0.4, 0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
130	116, 150	1.6, 2.0	0.0, +0.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
131	116, 150	1.6, 2.0	+0.4, +0.7	4.4	1.2	3.1	3.8	0.5	3.1	0.2	0.1	0.3	0.2	0.0	0.1	0.0	0.0	0.6	0.0	0.0	0.3	0.1	7.4
132	116, 150	1.6, 2.0	+0.7, +1.0	3.9	0.9	5.5	2.5	1.2	9.8	0.2	0.1	0.9	0.2	0.0	0.1	0.0	0.0	0.7	0.0	0.0	0.5	0.1	12.3
139	116, 150	2.4, 2.8	−1.0, −0.7	16.3	2.9	11.4	14.0	5.4	29.3	1.3	0.5	5.4	1.7	0.1	0.3	0.1	0.0	1.1	0.1	0.0	1.3	0.3	39.1
140	116, 150	2.4, 2.8	−0.7, −0.4	7.5	3.0	7.5	7.3	1.2	10.7	0.2	0.2	1.2	1.4	0.0	0.2	0.1	0.0	0.9	0.0	0.0	1.6	0.3	17.2
141	116, 150	2.4, 2.8	−0.4, 0.0	6.0	1.7	3.8	5.6	0.5	6.8	0.2	0.1	1.8	0.5	0.1	0.4	0.1	0.0	0.6	0.1	0.0	0.9	0.1	11.6
142	116, 150	2.4, 2.8	0.0, +0.4	4.5	1.4	3.1	3.2	0.5	3.4	0.1	0.5	0.8	0.2	0.1	0.4	0.1	0.0	0.6	0.0	0.0	0.5	0.1	7.4
143	116, 150	2.4, 2.8	+0.4, +0.7	3.8	1.4	2.4	2.4	0.4	3.3	0.3	0.3	0.9	0.7	0.0	0.2	0.1	0.0	1.0	0.0	0.0	0.9	0.1	6.5
144	116, 150	2.4, 2.8	+0.7, +1.0	3.3	1.0	1.7	2.0	0.7	3.8	0.7	0.2	1.8	0.6	0.1	0.3	0.1	0.0	1.1	0.0	0.0	0.2	0.1	6.3

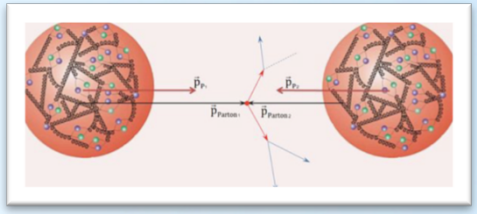
Bin	$m_{\mu\mu}$ [GeV]	$\lvert y_{\mu\mu}\rvert$	$\cos\theta^*$	$\delta^{\rm stat}_{\rm unc}$ [%]	$\delta^{\rm sig}_{\rm unc}$ [%]	$\delta^{\rm bkg}_{\rm unc}$ [%]	$\delta^{\rm bkg}_{\rm cor}$ [%]	$\delta^{\rm mj}_{\rm cor}$ [%]	$\delta^{\rm scl}_{\rm cor}$ [%]	$\delta^{\rm sag}_{\rm cor}$ [%]	$\delta^{\rm res}_{\rm cor}$ [%]	$\delta^{\rm rec}_{\rm cor}$ [%]	$\delta^{\rm id}_{\rm cor}$ [%]	$\delta^{\rm trig}_{\rm cor}$ [%]	$\delta^{\rm kfac}_{\rm cor}$ [%]	$\delta^{\rm zpt}_{\rm cor}$ [%]	$\delta^{\rm pdf}_{\rm cor}$ [%]	$\delta^{\rm tot}$ [%]
1	46, 66	0.0, 0.2	−1.0, −0.7	5.4	2.0	2.1	1.5	0.5	0.2	0.5	0.6	0.3	0.3	0.7	0.0	0.5	0.3	6.6
2	46, 66	0.0, 0.2	−0.7, −0.4	1.8	0.7	1.1	1.2	0.0	0.0	0.1	0.1	0.2	0.2	0.5	0.2	0.3	0.2	2.7
3	46, 66	0.0, 0.2	−0.4, 0.0	1.5	0.6	0.8	0.9	0.5	0.0	0.1	0.0	0.5	0.4	0.0	0.2	0.4	0.2	2.3
4	46, 66	0.0, 0.2	0.0, +0.4	1.5	0.6	0.9	0.9	0.5	0.0	0.1	0.1	0.5	0.4	0.0	0.2	0.5	0.2	2.3
5	46, 66	0.0, 0.2	+0.4, +0.7	1.9	0.6	1.2	1.2	0.0	0.1	0.1	0.4	0.2	0.2	0.5	0.2	0.3	0.2	2.8
6	46, 66	0.0, 0.2	+0.7, +1.0	5.7	2.0	3.6	1.8	0.5	0.1	1.0	0.1	0.3	0.3	0.8	0.2	0.6	0.8	7.7
79	66, 80	0.2, 0.4	−1.0, −0.7	2.3	1.1	0.5	0.6	0.7	0.1	0.7	0.4	0.2	0.2	0.3	0.0	0.0	0.1	3.0
80	66, 80	0.2, 0.4	−0.7, −0.4	1.3	0.7	0.3	0.4	0.1	0.1	0.2	0.1	0.3	0.3	0.0	0.0	0.0	0.1	1.7
81	66, 80	0.2, 0.4	−0.4, 0.0	1.4	0.7	0.4	0.3	0.2	0.1	0.2	0.2	0.4	0.4	0.0	0.1	0.1	0.3	1.8
82	66, 80	0.2, 0.4	0.0, +0.4	1.4	0.7	0.3	0.3	0.2	0.1	0.1	0.2	0.4	0.4	0.1	0.1	0.1	0.2	1.8
83	66, 80	0.2, 0.4	+0.4, +0.7	1.4	0.7	0.4	0.4	0.1	0.1	0.2	0.2	0.3	0.3	0.0	0.1	0.1	0.1	1.8
84	66, 80	0.2, 0.4	+0.7, +1.0	2.2	1.1	0.4	0.6	0.8	0.2	0.7	0.1	0.2	0.2	0.3	0.0	0.0	0.3	3.0
157	80, 91	0.4, 0.6	−1.0, −0.7	0.4	0.2	0.0	0.0	0.0	0.1	1.0	0.1	0.3	0.3	0.0	0.0	0.0	0.1	1.4
158	80, 91	0.4, 0.6	−0.7, −0.4	0.4	0.2	0.0	0.0	0.0	0.2	0.6	0.1	0.4	0.4	0.1	0.0	0.0	0.0	1.1
159	80, 91	0.4, 0.6	−0.4, 0.0	0.3	0.1	0.0	0.0	0.0	0.2	0.3	0.1	0.3	0.3	0.0	0.0	0.0	0.0	0.9
160	80, 91	0.4, 0.6	0.0, +0.4	0.3	0.1	0.0	0.0	0.0	0.2	0.3	0.1	0.3	0.3	0.0	0.0	0.0	0.0	0.9
161	80, 91	0.4, 0.6	+0.4, +0.7	0.4	0.2	0.0	0.0	0.0	0.2	0.6	0.0	0.4	0.4	0.1	0.0	0.0	0.0	1.1
162	80, 91	0.4, 0.6	+0.7, +1.0	0.4	0.2	0.0	0.0	0.0	0.2	1.1	0.1	0.3	0.3	0.1	0.0	0.1	0.0	1.4
235	91, 102	0.6, 0.8	−1.0, −0.7	0.4	0.2	0.0	0.0	0.0	0.1	0.5	0.0	0.3	0.3	0.1	0.0	0.1	0.0	1.0
236	91, 102	0.6, 0.8	−0.7, −0.4	0.3	0.2	0.0	0.0	0.0	0.1	1.0	0.0	0.4	0.4	0.2	0.0	0.0	0.0	1.3
237	91, 102	0.6, 0.8	−0.4, 0.0	0.3	0.1	0.0	0.0	0.0	0.1	0.3	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.8
238	91, 102	0.6, 0.8	0.0, +0.4	0.3	0.1	0.0	0.0	0.0	0.2	0.3	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.8
239	91, 102	0.6, 0.8	+0.4, +0.7	0.3	0.2	0.0	0.0	0.0	0.2	1.0	0.0	0.4	0.4	0.1	0.0	0.0	0.0	1.3
240	91, 102	0.6, 0.8	+0.7, +1.0	0.4	0.2	0.0	0.0	0.0	0.1	0.5	0.0	0.3	0.3	0.1	0.0	0.1	0.1	1.0
313	102, 116	0.8, 1.0	−1.0, −0.7	2.1	1.0	0.1	0.4	0.0	0.2	0.9	1.4	0.4	0.4	0.2	0.0	0.0	0.1	3.0
314	102, 116	0.8, 1.0	−0.7, −0.4	1.8	0.8	0.0	0.2	0.1	0.2	1.8	0.3	0.3	0.3	0.2	0.0	0.0	0.0	2.8
315	102, 116	0.8, 1.0	−0.4, 0.0	1.7	0.7	0.0	0.1	0.0	0.1	0.4	0.6	0.3	0.3	0.1	0.0	0.0	0.0	2.0
316	102, 116	0.8, 1.0	0.0, +0.4	1.6	0.6	0.0	0.1	0.0	0.2	0.4	0.5	0.3	0.3	0.0	0.0	0.0	0.0	2.0
317	102, 116	0.8, 1.0	+0.4, +0.7	1.6	0.7	0.0	0.2	0.1	0.2	2.0	0.8	0.4	0.3	0.1	0.0	0.0	0.1	2.8
318	102, 116	0.8, 1.0	+0.7, +1.0	2.0	0.9	0.1	0.3	0.0	0.2	0.8	1.5	0.4	0.4	0.0	0.0	0.0	0.0	2.7
391	116, 150	1.0, 1.2	−1.0, −0.7	4.1	1.2	0.3	1.3	0.	0.1	0.5	0.3	0.5	0.5	0.2	0.1	0.0	0.1	4.8
392	116, 150	1.0, 1.2	−0.7, −0.4	2.9	0.7	0.2	0.7	0.1	0.1	0.7	0.4	0.4	0.3	0.2	0.0	0.1	0.1	3.4
393	116, 150	1.0, 1.2	−0.4, 0.0	2.5	0.6	0.1	0.5	0.1	0.1	0.5	0.1	0.3	0.3	0.2	0.0	0.1	0.1	2.8
394	116, 150	1.0, 1.2	0.0, +0.4	2.2	0.6	0.1	0.4	0.0	0.0	0.5	0.0	0.3	0.3	0.1	0.0	0.1	0.1	2.5
395	116, 150	1.0, 1.2	+0.4, +0.7	2.3	0.6	0.2	0.5	0.0	0.0	0.4	0.3	0.3	0.3	0.0	0.0	0.1	0.0	2.6
396	116, 150	1.0, 1.2	+0.7, +1.0	3.2	0.9	0.3	0.7	0.1	0.1	0.8	0.1	0.5	0.5	0.0	0.0	0.0	0.1	3.8
469	150, 200	1.2, 1.4	−1.0, −0.7	11.1	1.5	1.2	2.9	0.1	0.3	2.7	0.5	0.7	0.5	0.2	0.1	0.0	0.1	13.6
470	150, 200	1.2, 1.4	−0.7, −0.4	5.6	0.8	0.5	1.4	0.0	0.1	1.3	0.1	0.5	0.4	0.2	0.0	0.0	0.1	6.2
471	150, 200	1.2, 1.4	−0.4, 0.0	4.6	0.6	0.3	0.9	0.1	0.0	1.0	0.2	0.4	0.4	0.2	0.0	0.0	0.1	5.1
472	150, 200	1.2, 1.4	0.0, +0.4	4.1	0.5	0.2	0.7	0.1	0.0	1.1	0.0	0.4	0.4	0.1	0.0	0.0	0.0	4.5
473	150, 200	1.2, 1.4	+0.4, +0.7	4.0	0.5	0.2	0.8	0.0	0.1	0.8	0.2	0.4	0.4	0.0	0.0	0.0	0.1	4.3
474	150, 200	1.2, 1.4	+0.7, +1.0	6.6	0.9	0.5	1.2	0.1	0.0	1.7	0.0	0.6	0.5	0.0	0.0	0.1	0.1	8.0

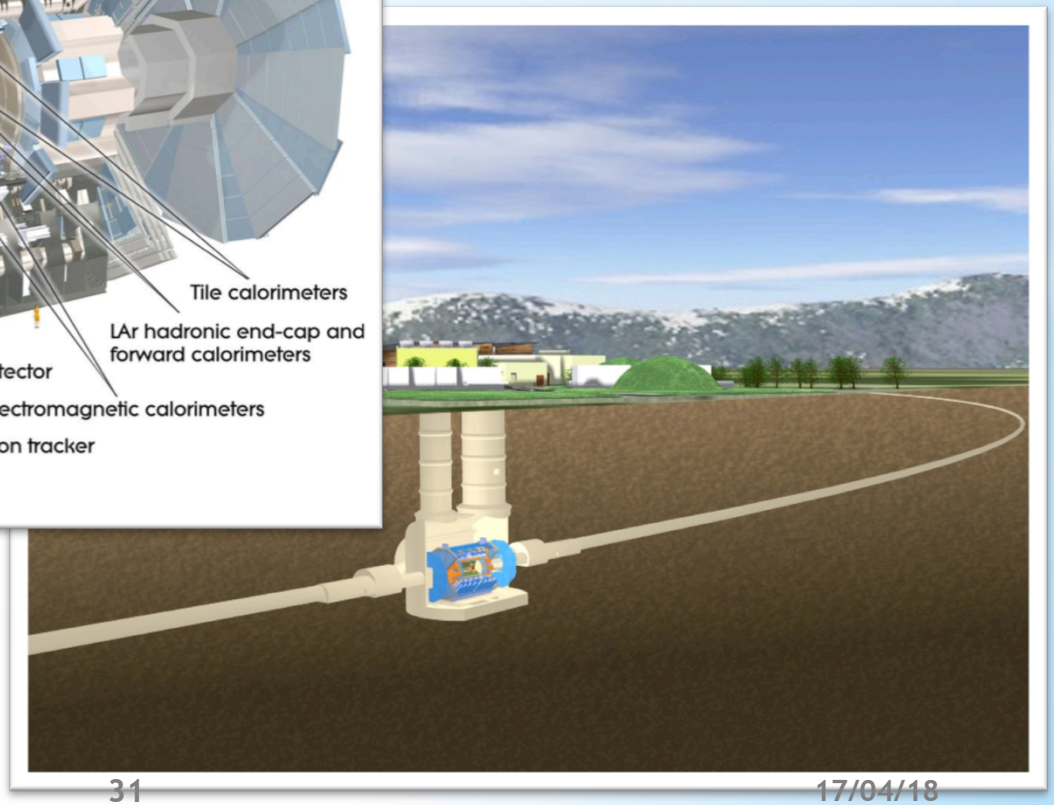
Appendix

$m_{\ell\ell}$ [GeV]	$d\sigma/dm_{\ell\ell}$ [pb/GeV]	δ^{stat} [%]	δ^{syst}_{unc} [%]	δ^{syst}_{cor} [%]	δ^{total} [%]
46, 66	7.61×10^{-1}	0.2	0.1	0.9	0.9
66, 80	1.13	0.1	0.1	0.4	0.4
80, 91	21.4	0.0	0.0	0.2	0.2
91, 102	25.0	0.0	0.0	0.2	0.2
102, 116	8.25×10^{-1}	0.2	0.1	0.4	0.4
116, 150	1.64×10^{-1}	0.3	0.1	0.7	0.7
150, 200	3.66×10^{-2}	0.5	0.2	1.3	1.4

The ATLAS experiment







LHC: proton synchrotron
Circumference: 27km
Center-of-mass energy: 13 TeV
40 MHz collisions (1 kHz recorded)