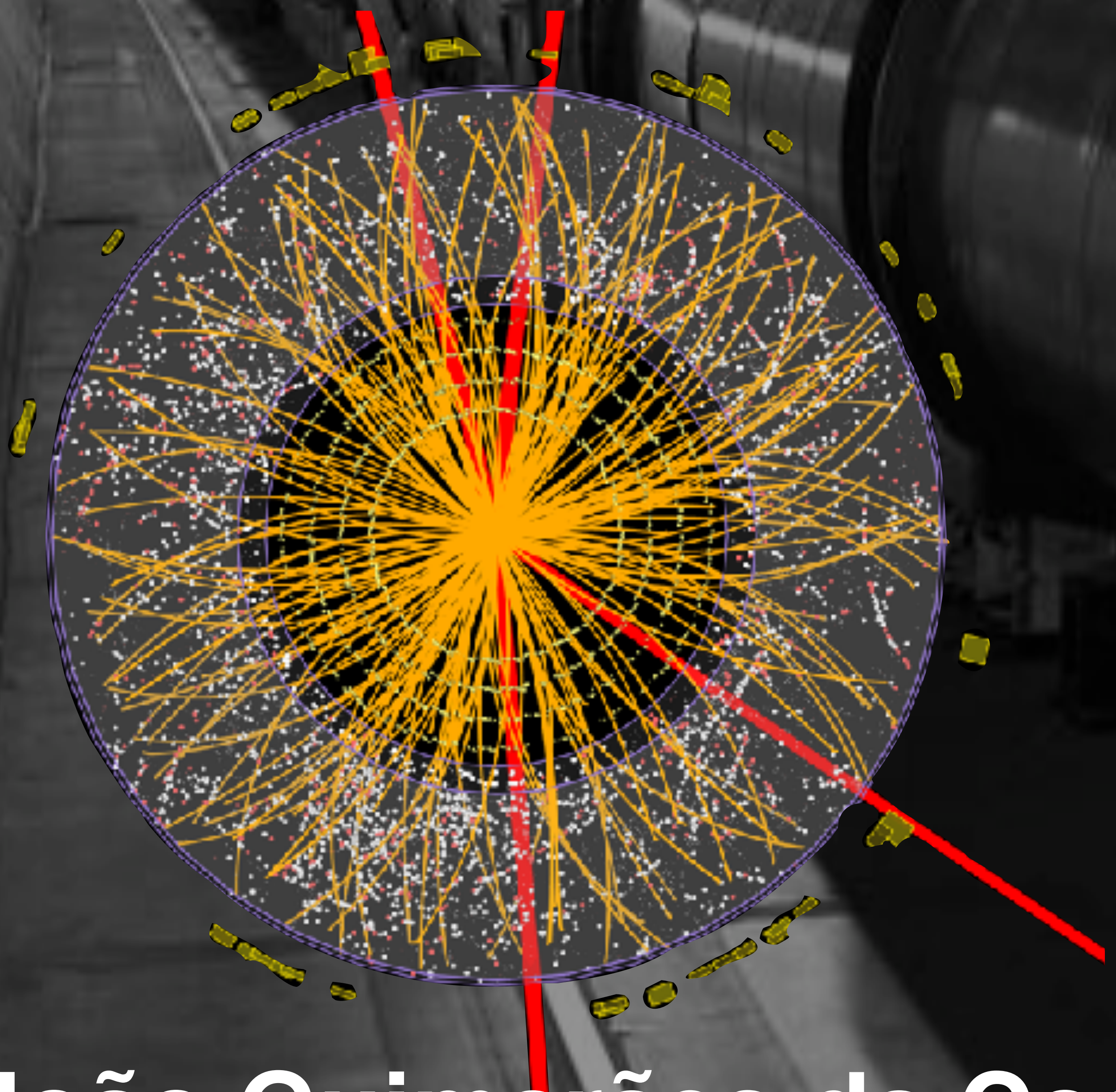
Electroweak and QCD Measurements at the Large Hadron Collider



João Guimarães da Costa
IHEP, Chinese Academy of Sciences

Birmingham, 3 April 2017

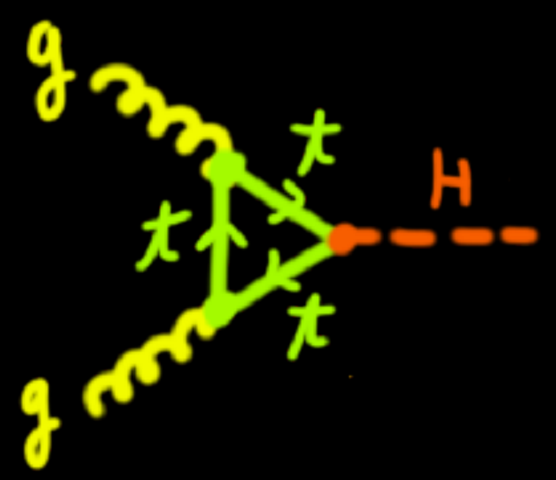
Why Standard Model Physics?

...in the era of the Higgs Boson

Search for deviations from SM:

- Many new physics models reveal deviations from SM similar to the ones from NLO or NNLO QCD

Example: contact interactions versus bump-hunting search



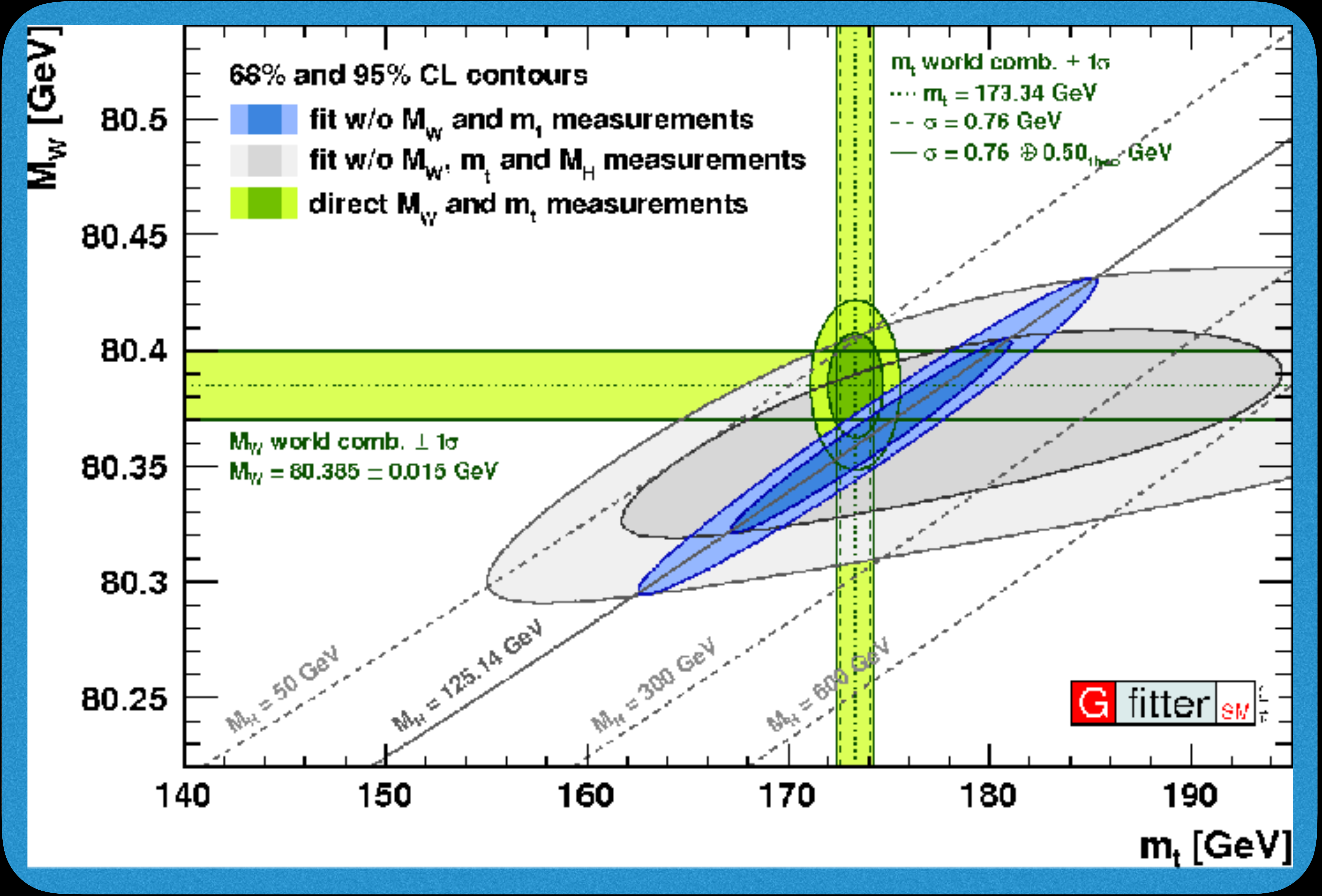
Establish:

- Understanding of backgrounds to new physics searches
- Improved proton PDFs

Explore the SM self consistency:

Measure its parameters with high-precision

Now that the Higgs was found, measuring the top and W mass precise enough will be an enduring challenge



How we do it?

Probes

Jets
inclusive
dijets
multijets
jet sub-structure
HF production

Photons
inclusive
diphotons
γ + jets
γ + HF

Hadrons

Physics

Non-perturbative QCD

Perturbative QCD

Proton PDF
Valence, strange quarks
Gluons

EWK corrections

Electroweak parameters

Probes

W/Z Bosons
inclusive
V+jets
Ratio W/Z + jets
W and Z + HF

Top quark

Dibosons
WW, WZ, ZZ, Wγ, Zγ

Higgs

Combine analyses, *e.g.* to obtain the most information about PDFs

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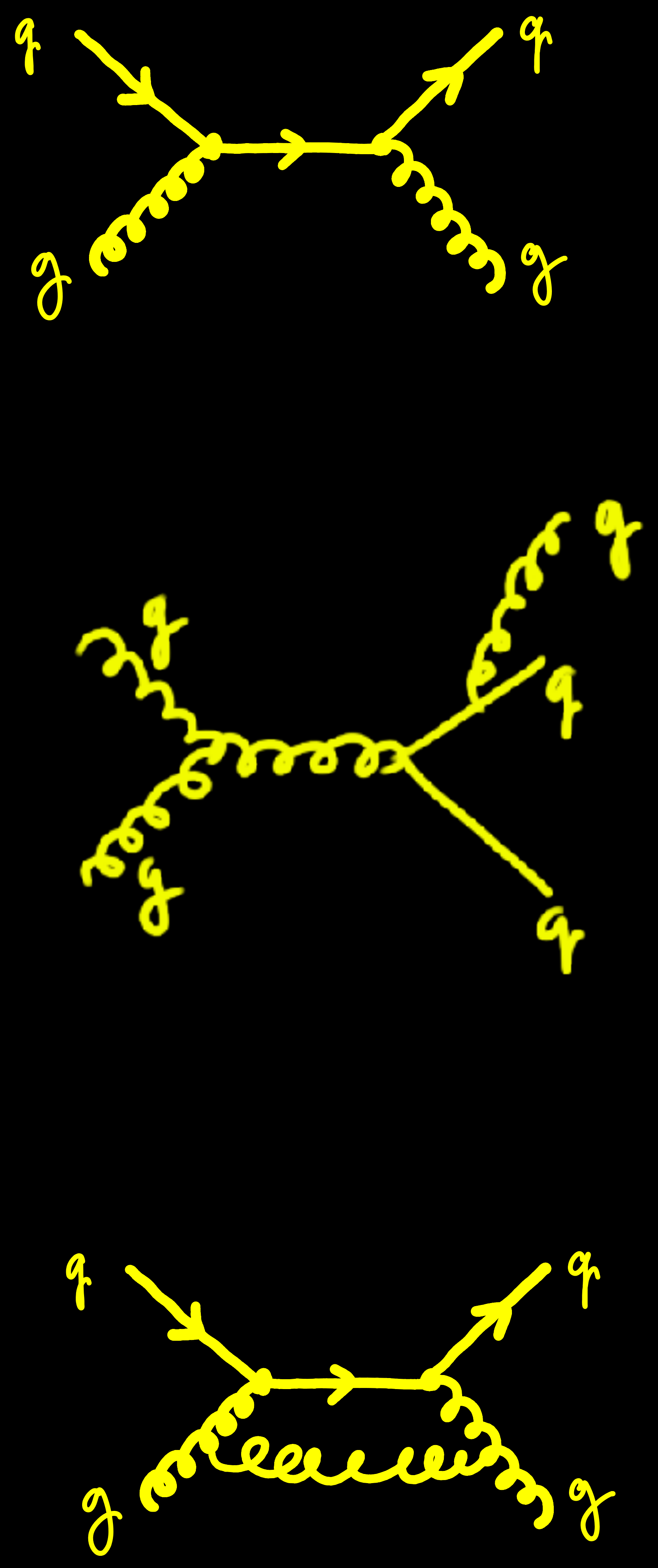
Higgs

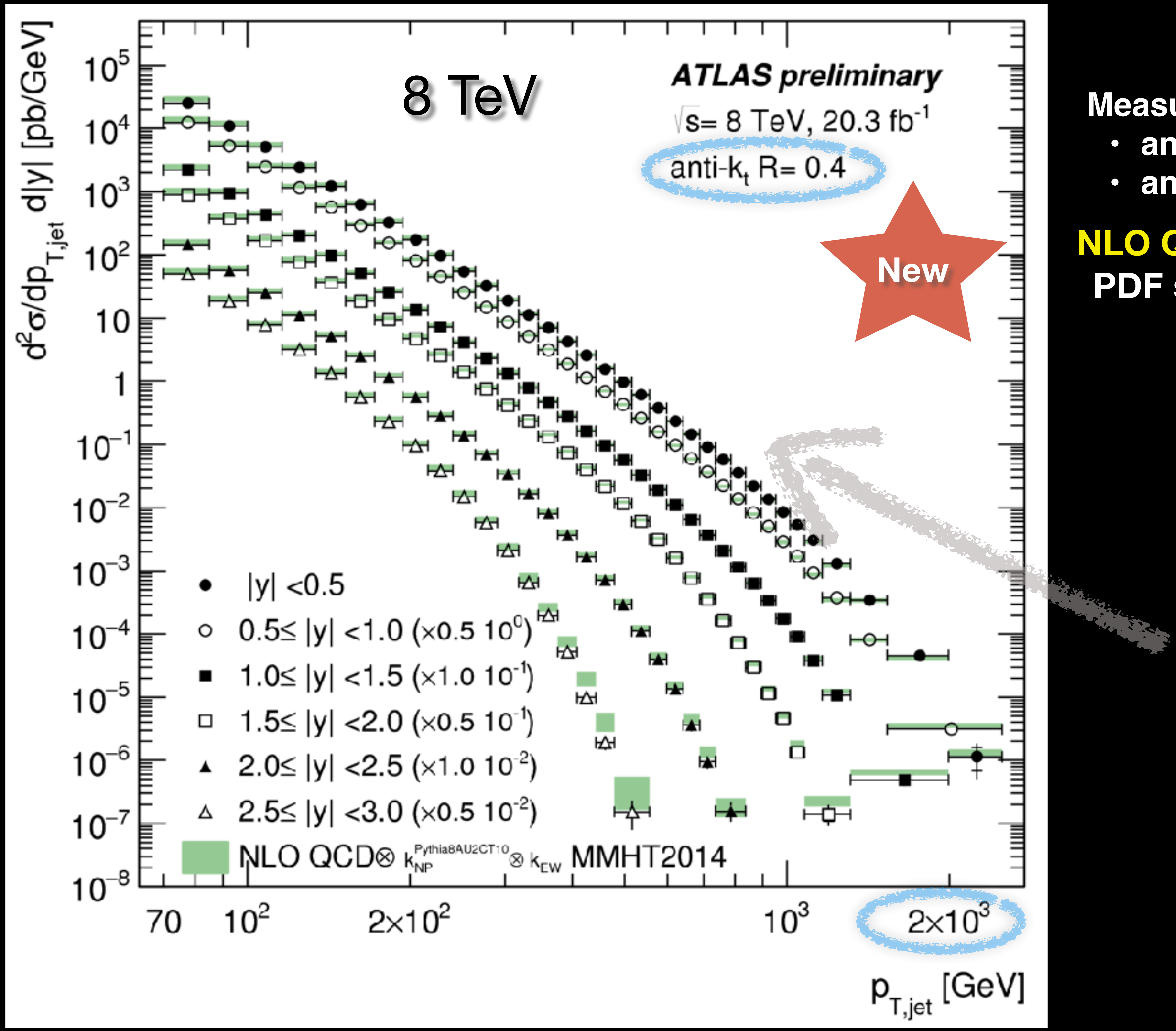
Combine analyses, *e.g.* to obtain the most information about PDFs

Many topics left out:
- SM Higgs production
- Heavy-flavour physics (B-physics)
- Heavy-ion physics (physics in dense media)

Inclusive Jet Cross Sections

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-01/





Measurement done for two jet algorithms:

- anti-k_t R=0.4
- anti-k_t R=0.6

NLO QCD prediction with the **MMHT2014** PDF set corrected for **non-perturbative** and **electroweak** effects

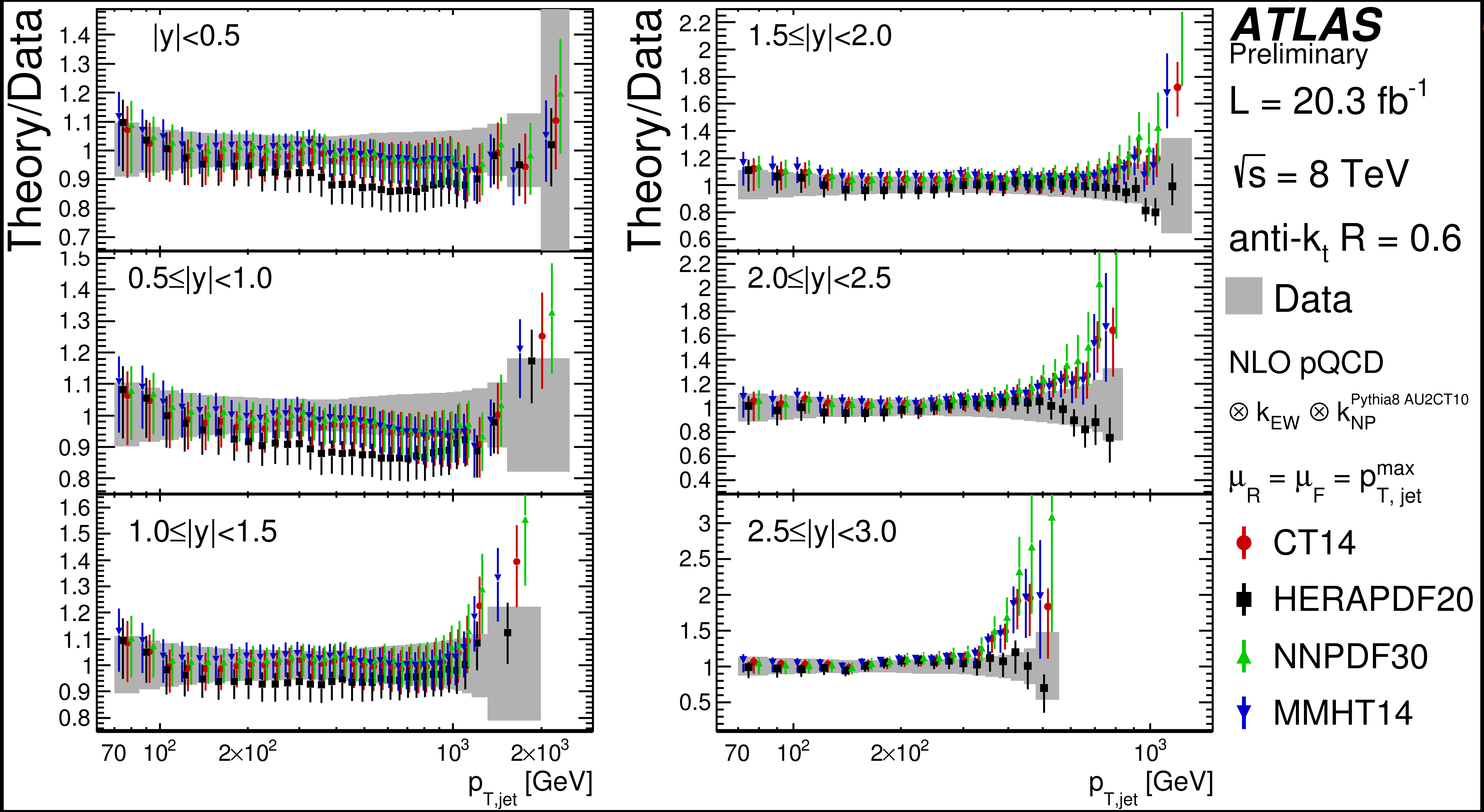
Dominant uncertainty is the jet energy scale

NLO QCD predictions describe data over 9 orders of magnitude!
Jet inclusive data starts to constrain gluon PDFs
(CT14, MMHT14, NNPDF3.0, HERAPDF2.0)

Inclusive jet cross section

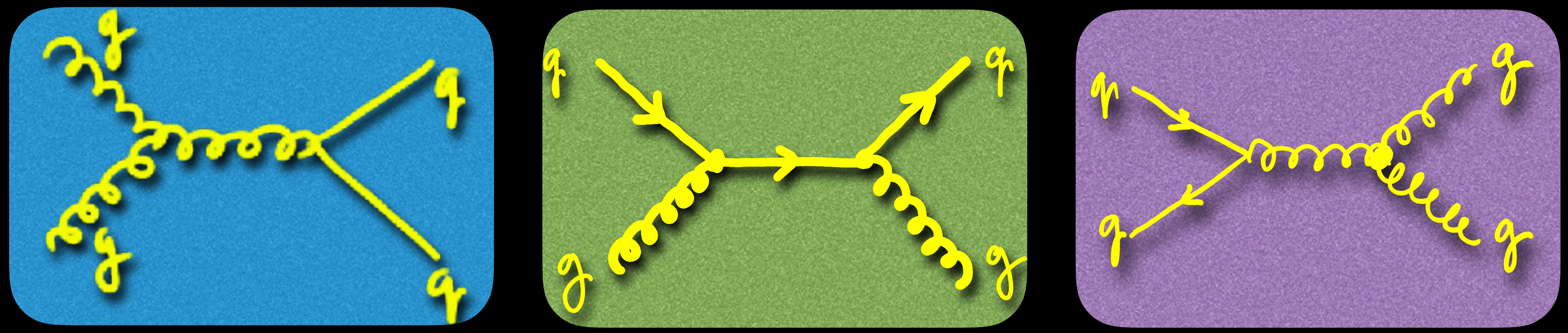
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-01/

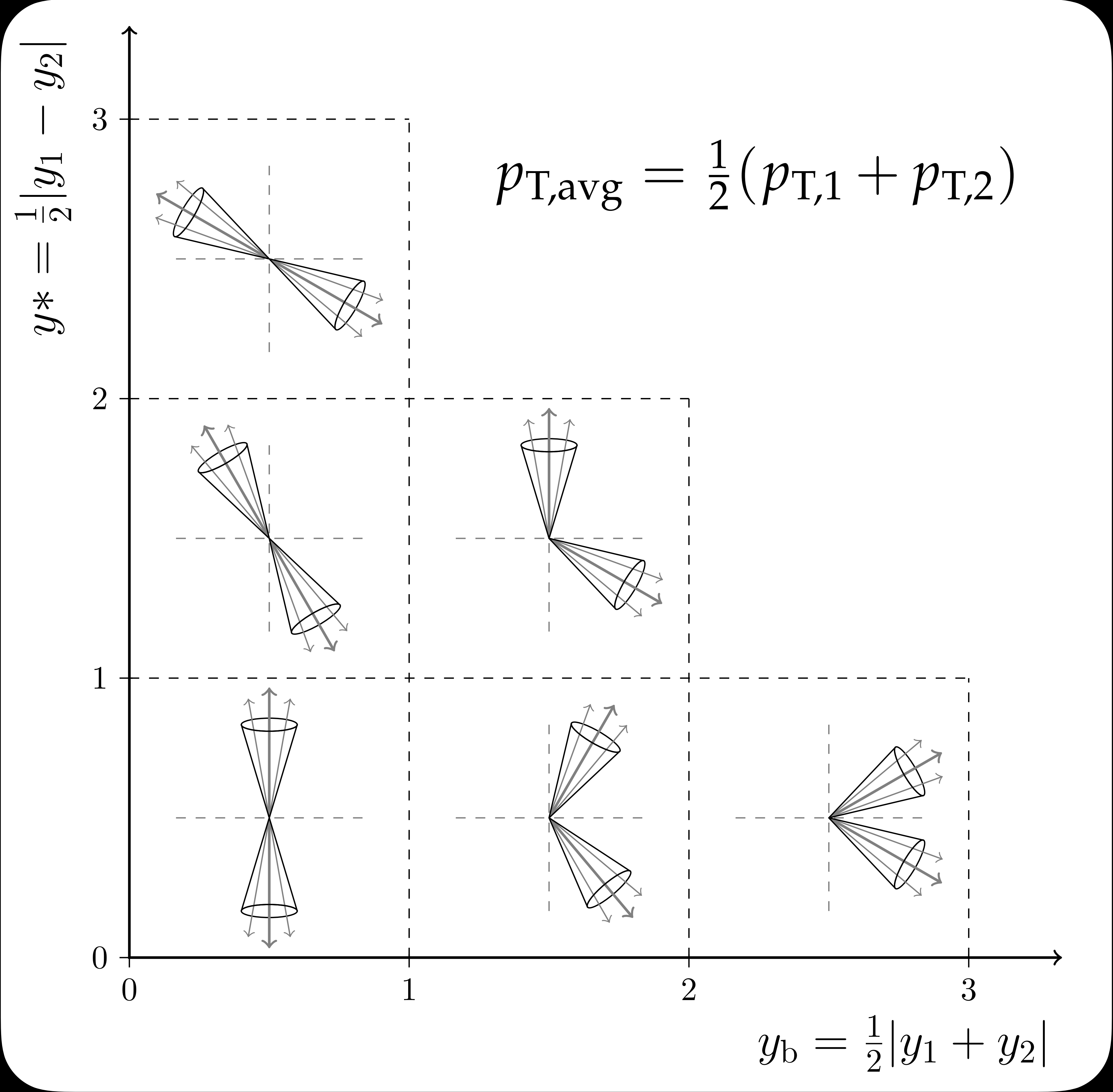
New

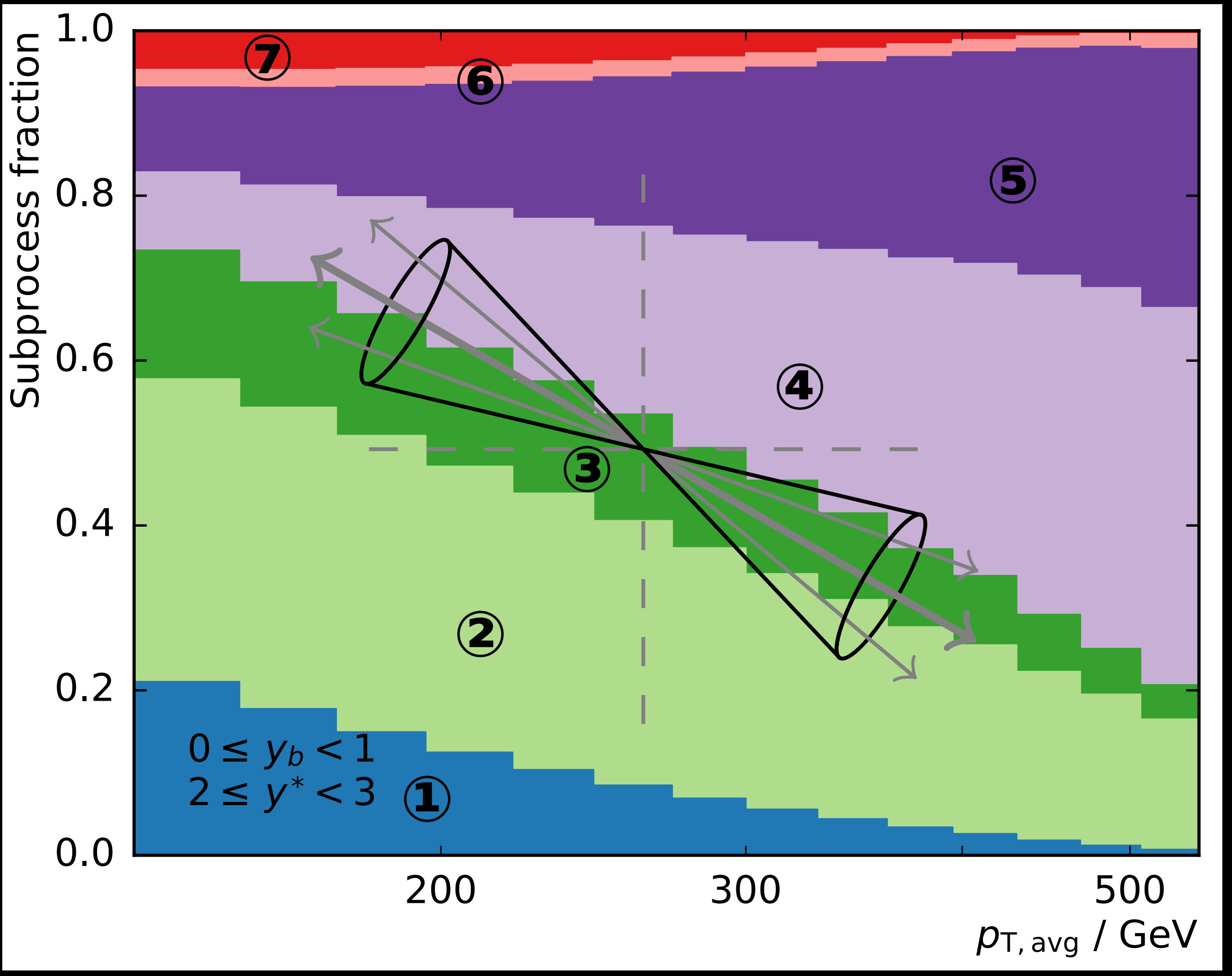


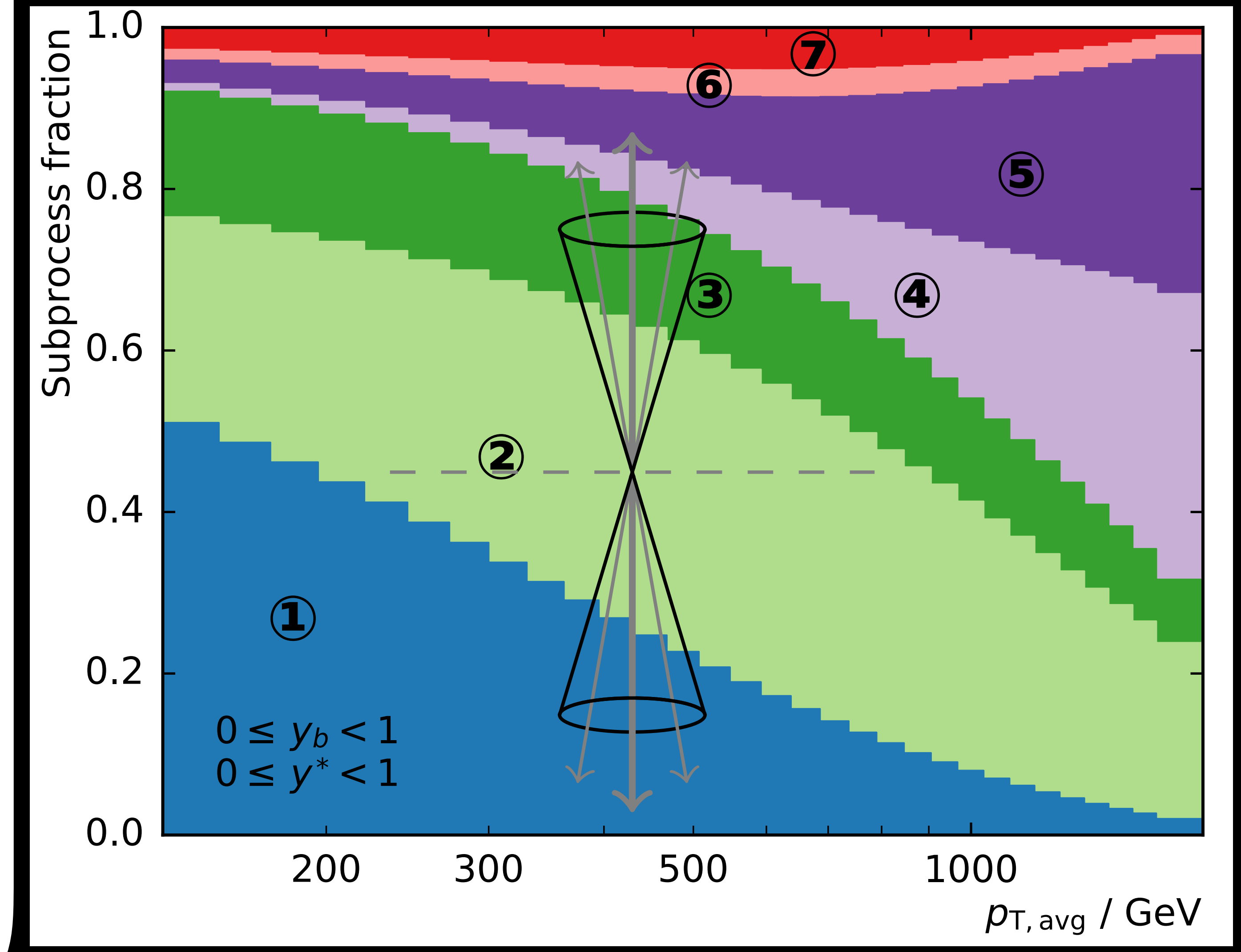
Triple differential dijet cross section

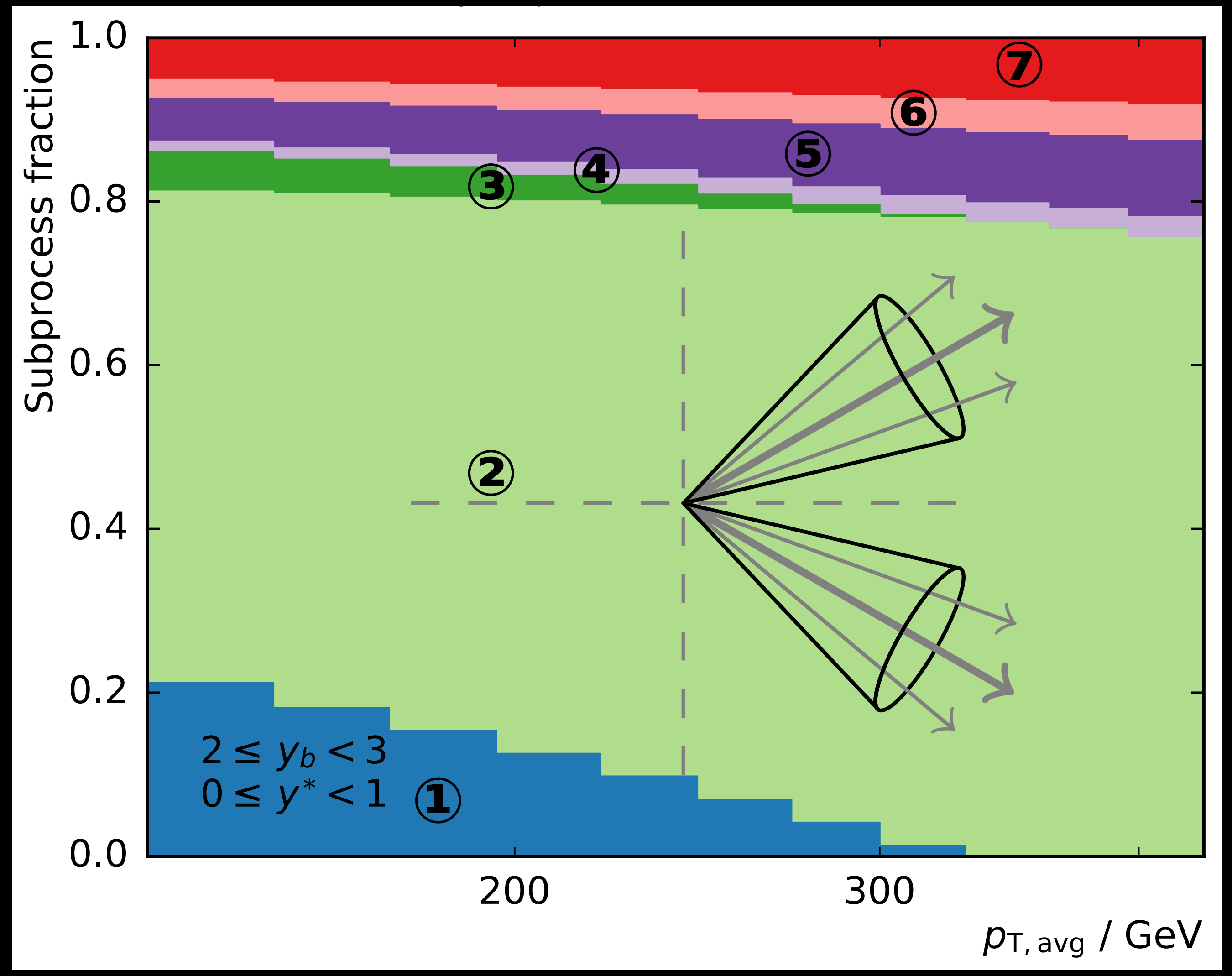
New











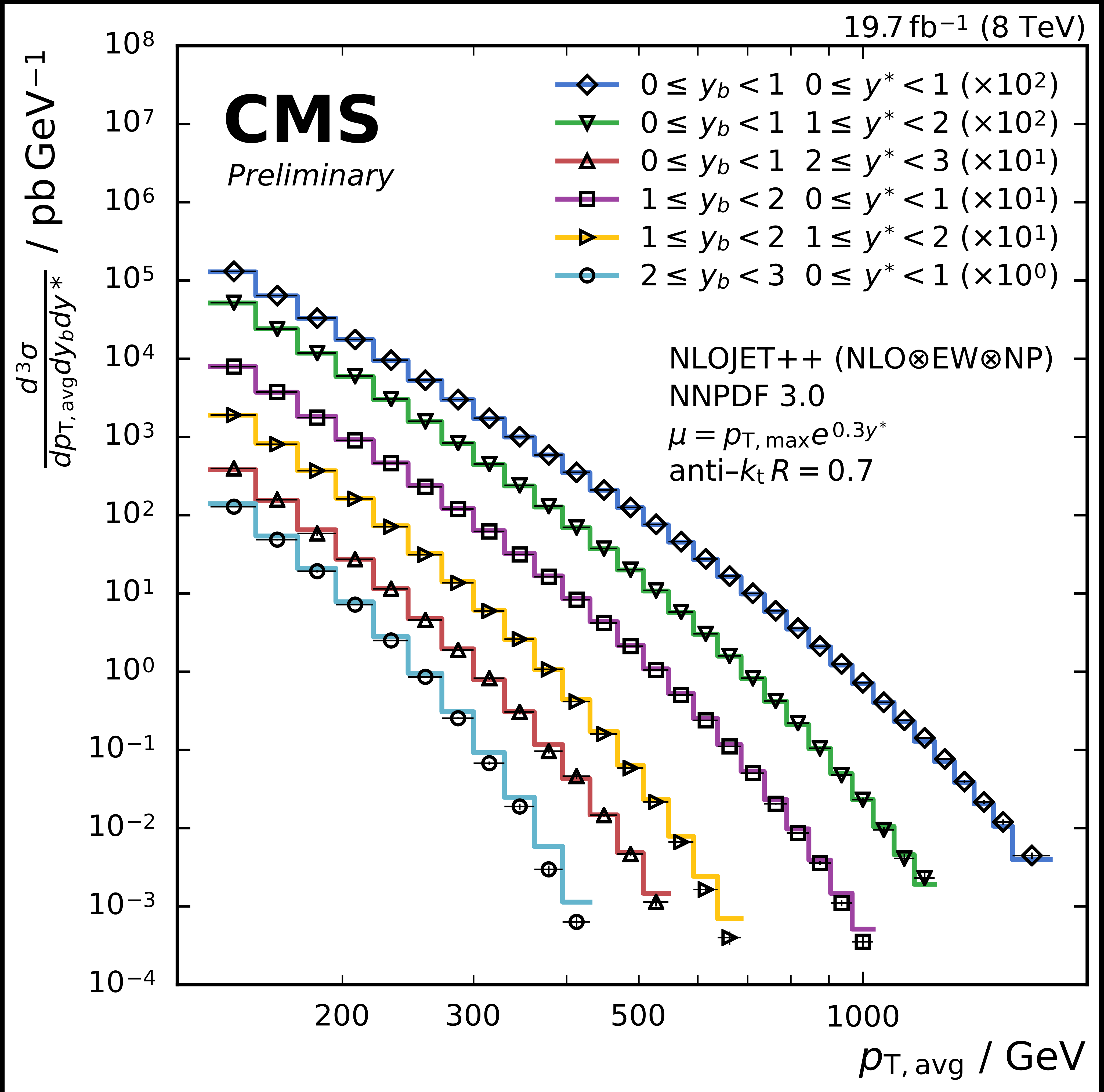
- ① gg → jets
- ② gq → jets ($x_g < x_q$)
- ③ gq → jets ($x_g > x_q$)
- ④ $q_i q_i$ → jets
- ⑤ $q_i q_j$ → jets
- ⑥ $q_i \bar{q}_i$ → jets
- ⑦ $q_i \bar{q}_j$ → jets

Triple differential dijet cross section

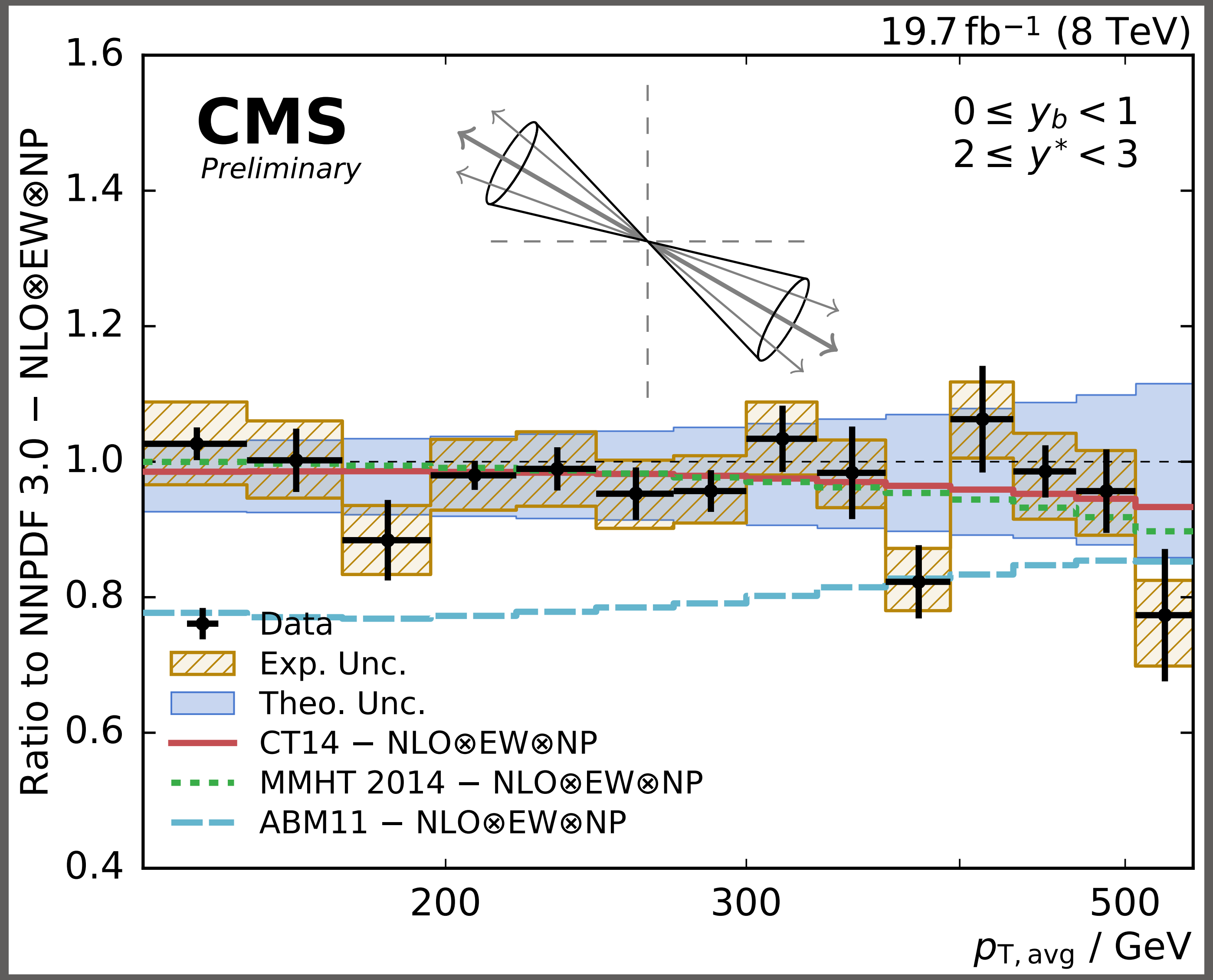
CMS SMP-16-011

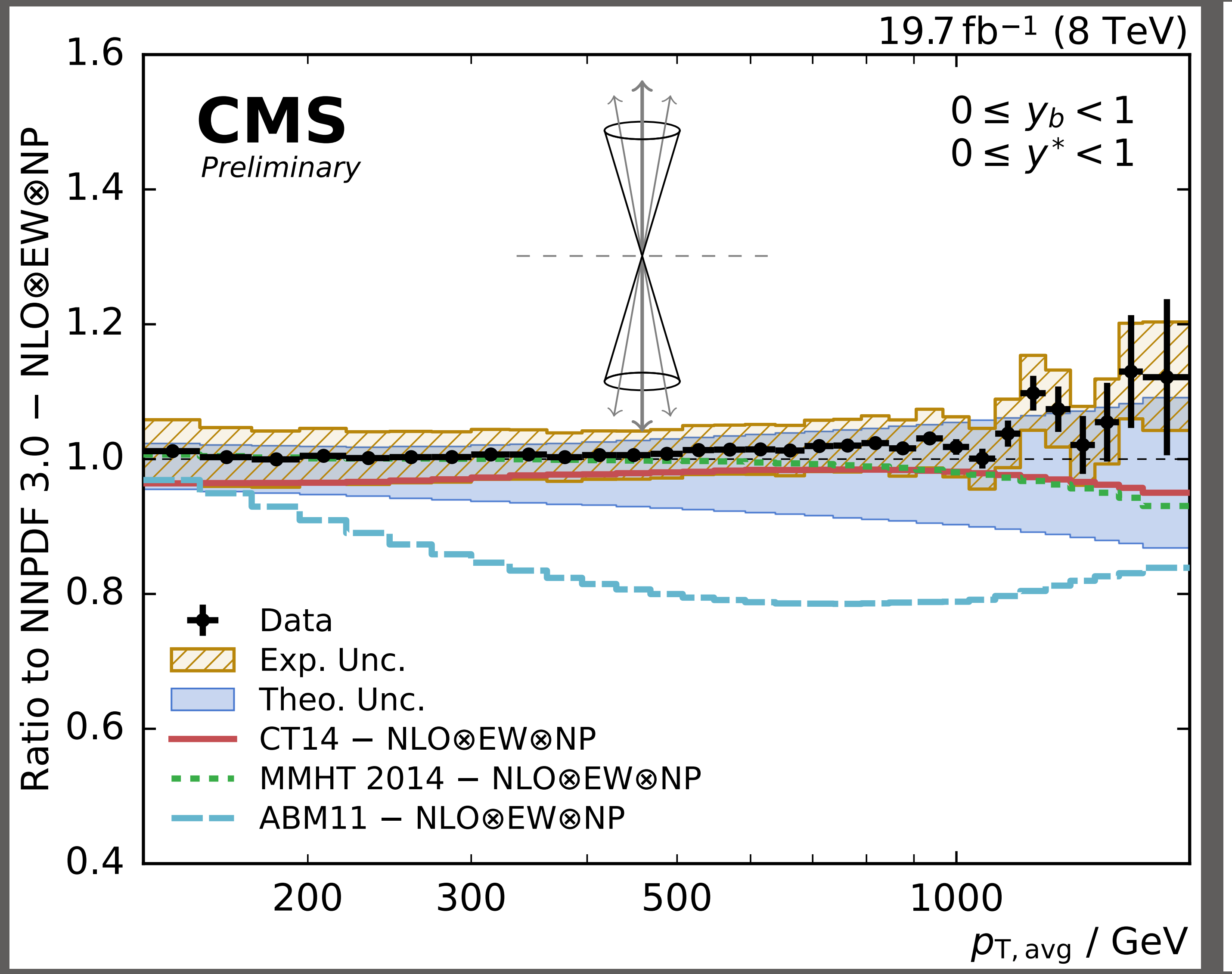
New

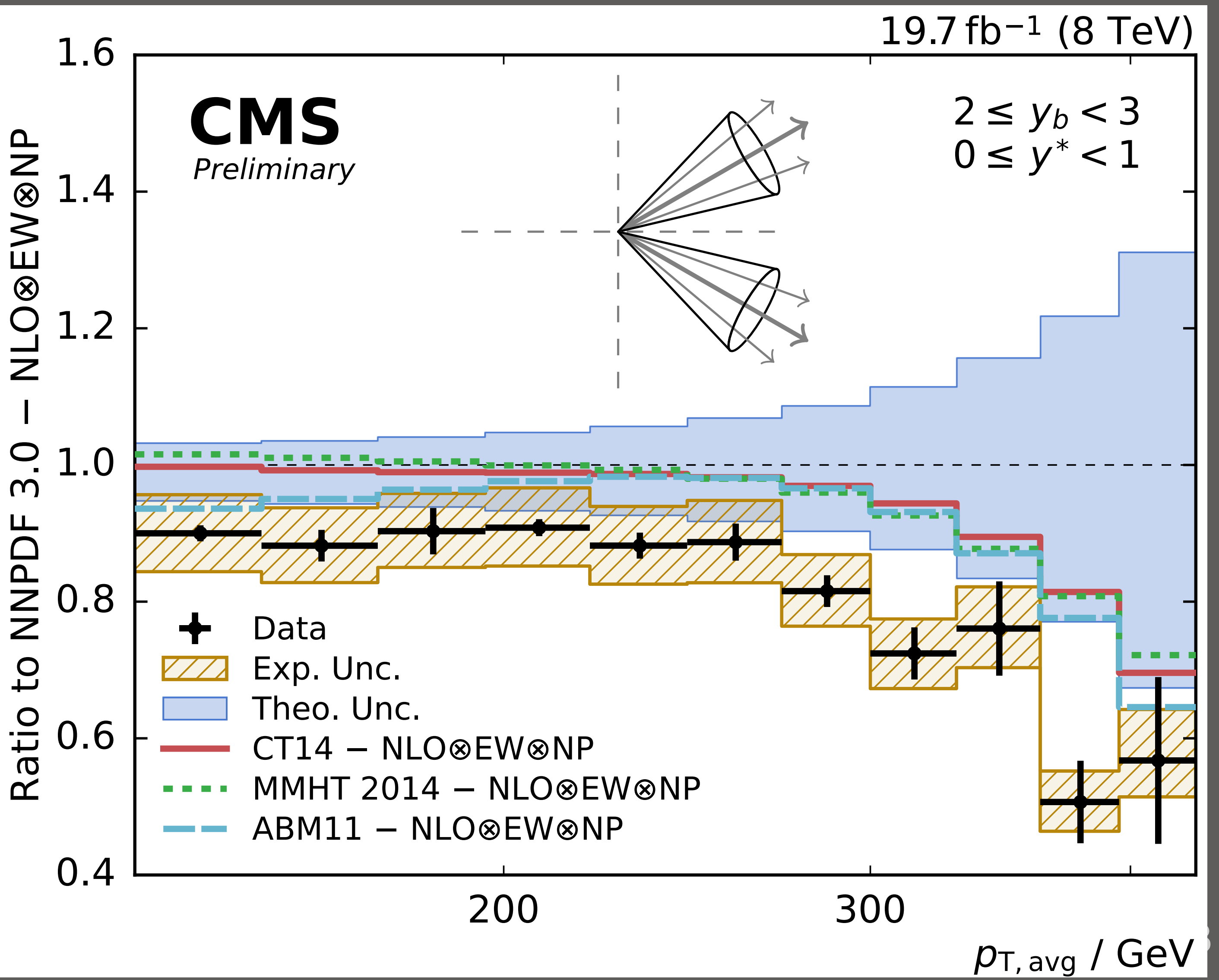
$$\frac{d^3\sigma}{dp_{\mathrm{T,avg}}\,dy^*\,dy_{\mathrm{b}}} = \frac{1}{\epsilon\mathcal{L}_{\mathrm{int}}^{\mathrm{eff}}}\frac{N}{\Delta p_{\mathrm{T,avg}}\,\Delta y^*\,\Delta y_{\mathrm{b}}}$$



PDF constraints



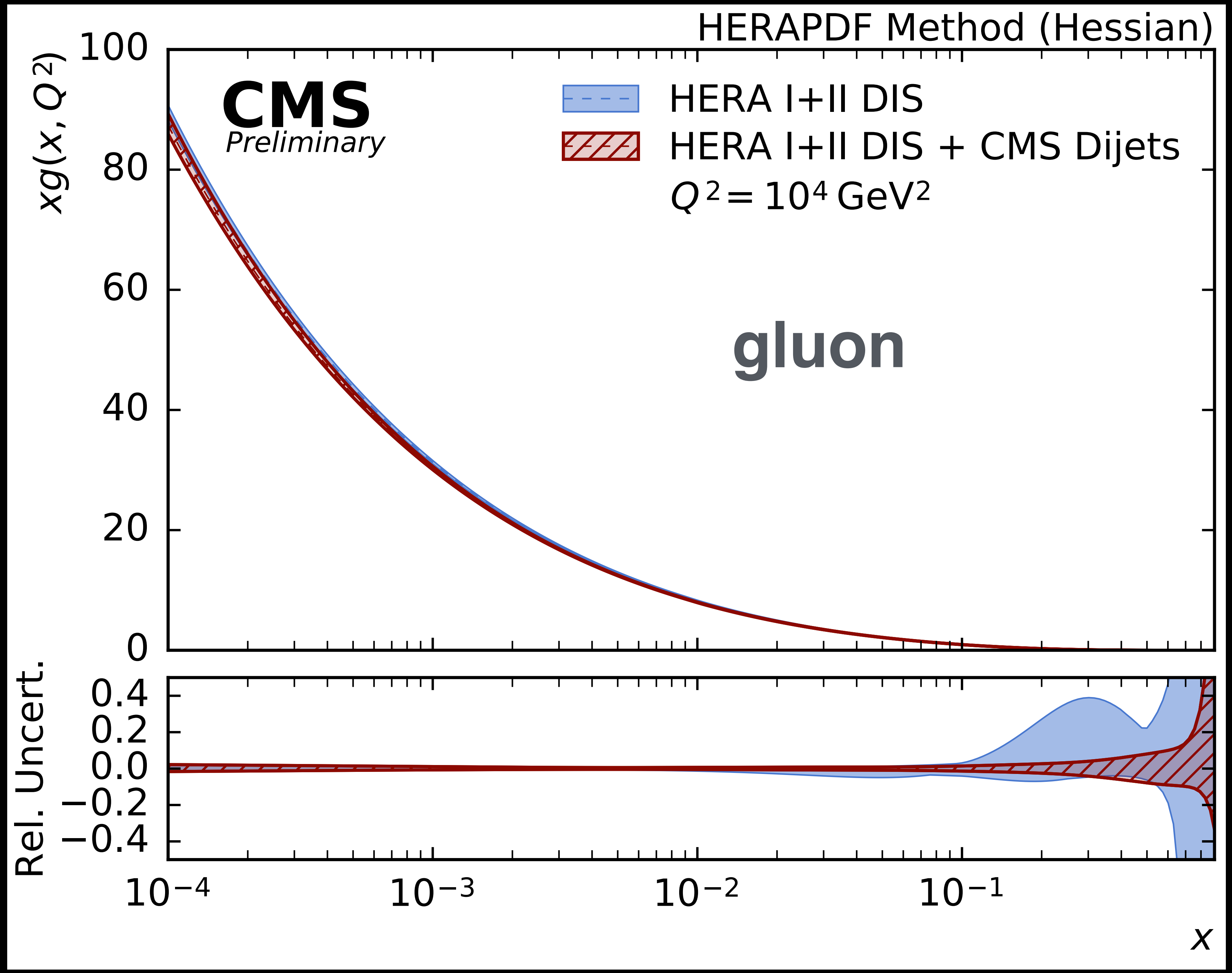


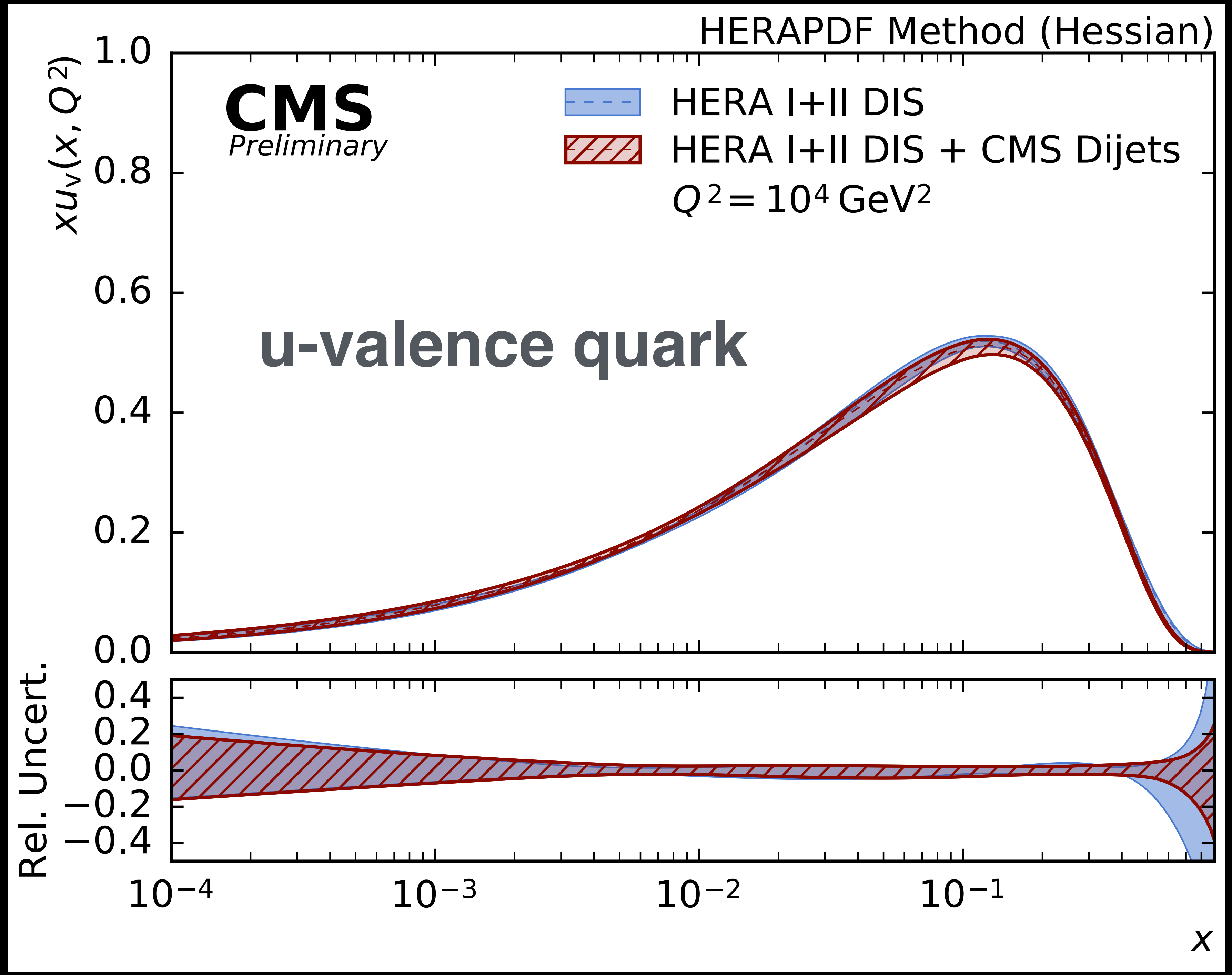


Triple differential dijet cross section

New

Impact of CMS dijet measurement on PDFs: HERA I+II





CMS+HERA:
$\chi^2 / n_{dof} = 1.18$

Extraction of Strong Coupling Constant (α_S)

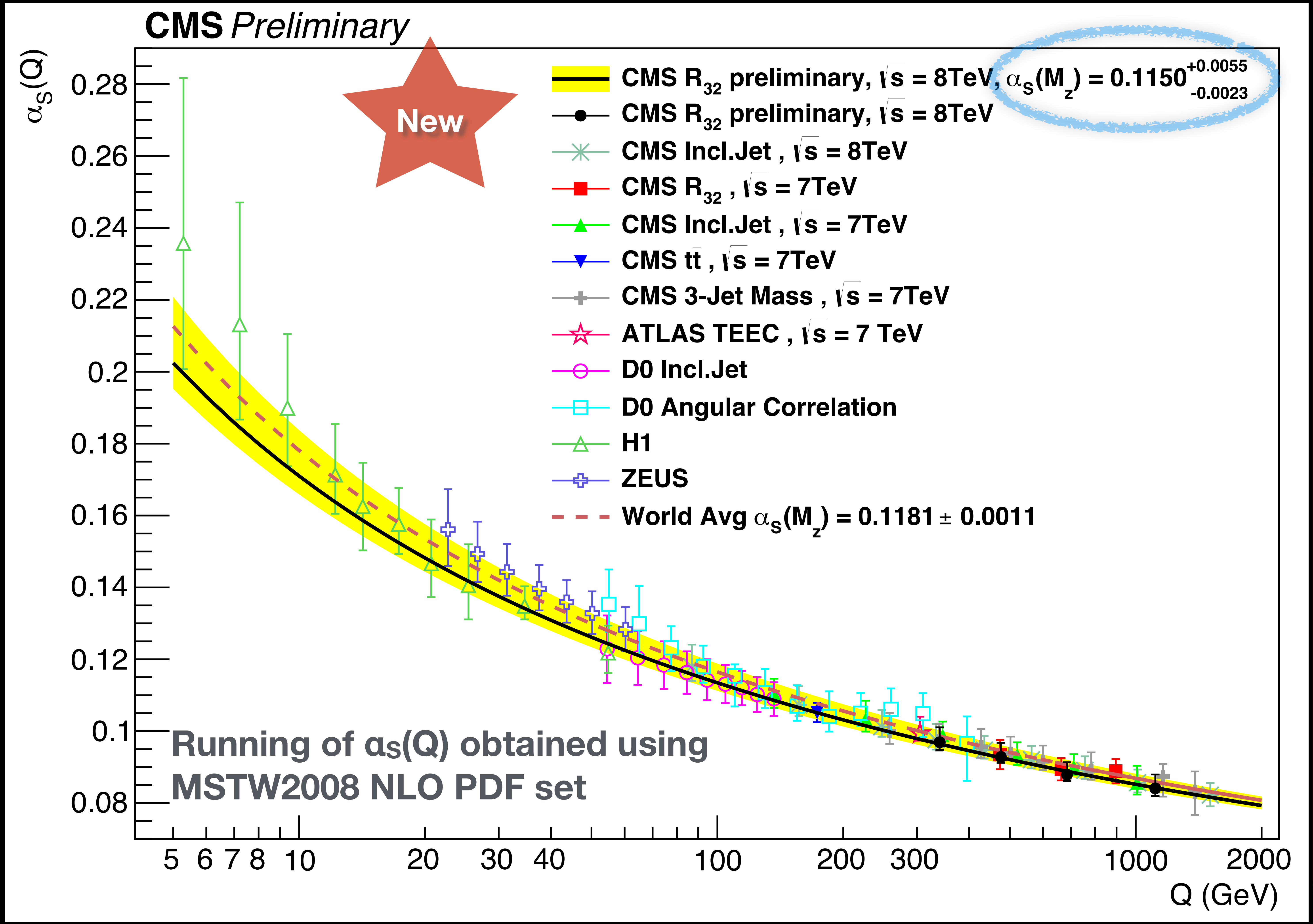
PDF fit repeated with α_S as a free parameter

$$\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp}) \pm 0.0002\,(\text{mod})\,^{+0.0002}_{-0.0004}\,(\text{par})\,^{+0.0031}_{-0.0019}\,(\text{scale})$$

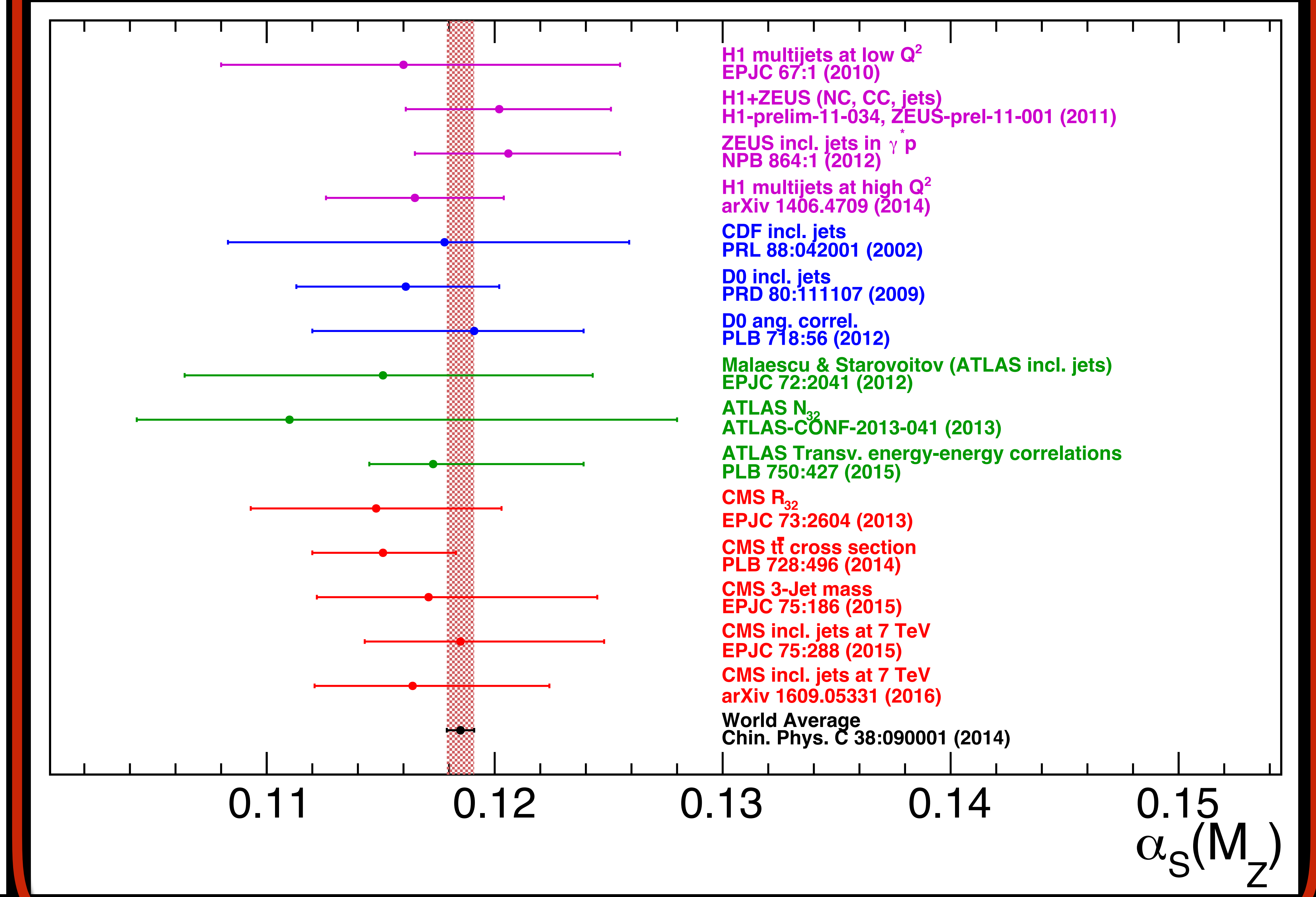
New

Inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in pp collisions at $\sqrt{s}$ = 13 TeV (just out)
CMS-PAS-SMP-16-014

Extraction of the Strong Coupling Constant



Overview of $\alpha_S(M_Z)$ measurements using hadrons



$\alpha_s(M_Z) = 0.1150 \pm 0.0010\ (\text{exp}) \pm 0.0013\ (\text{PDF}) \pm 0.0015\ (\text{NP})\ ^{+0.0050}_{-0.0000}\ (\text{scale})$

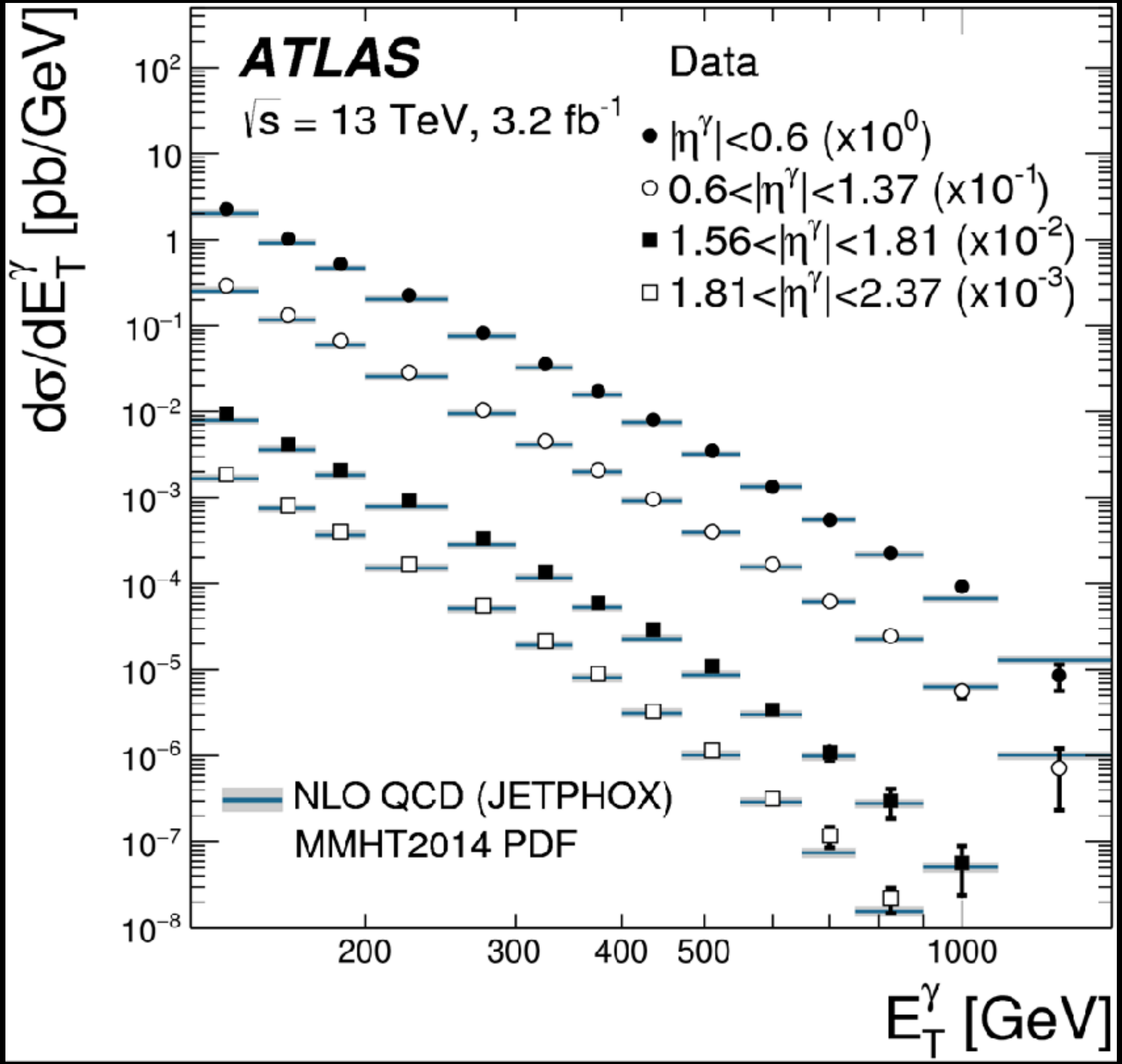
$= 0.1150 \pm 0.0023\ (\text{all except scale})\ ^{+0.0050}_{-0.0000}\ (\text{scale})$

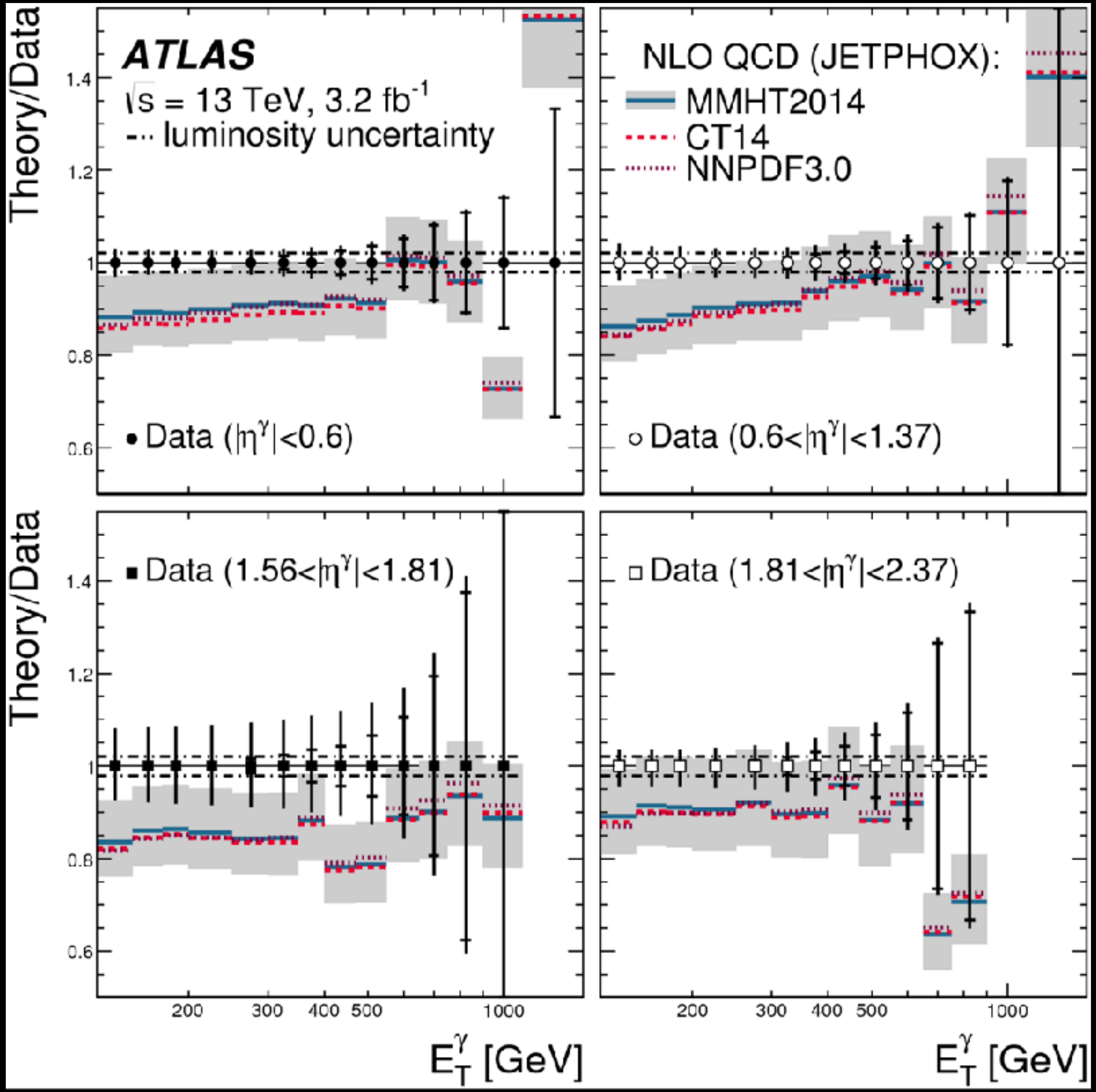
Inclusive isolated–photon cross section

arXiv:1701.06882v1

New

$E_T(\gamma) > 150$ GeV

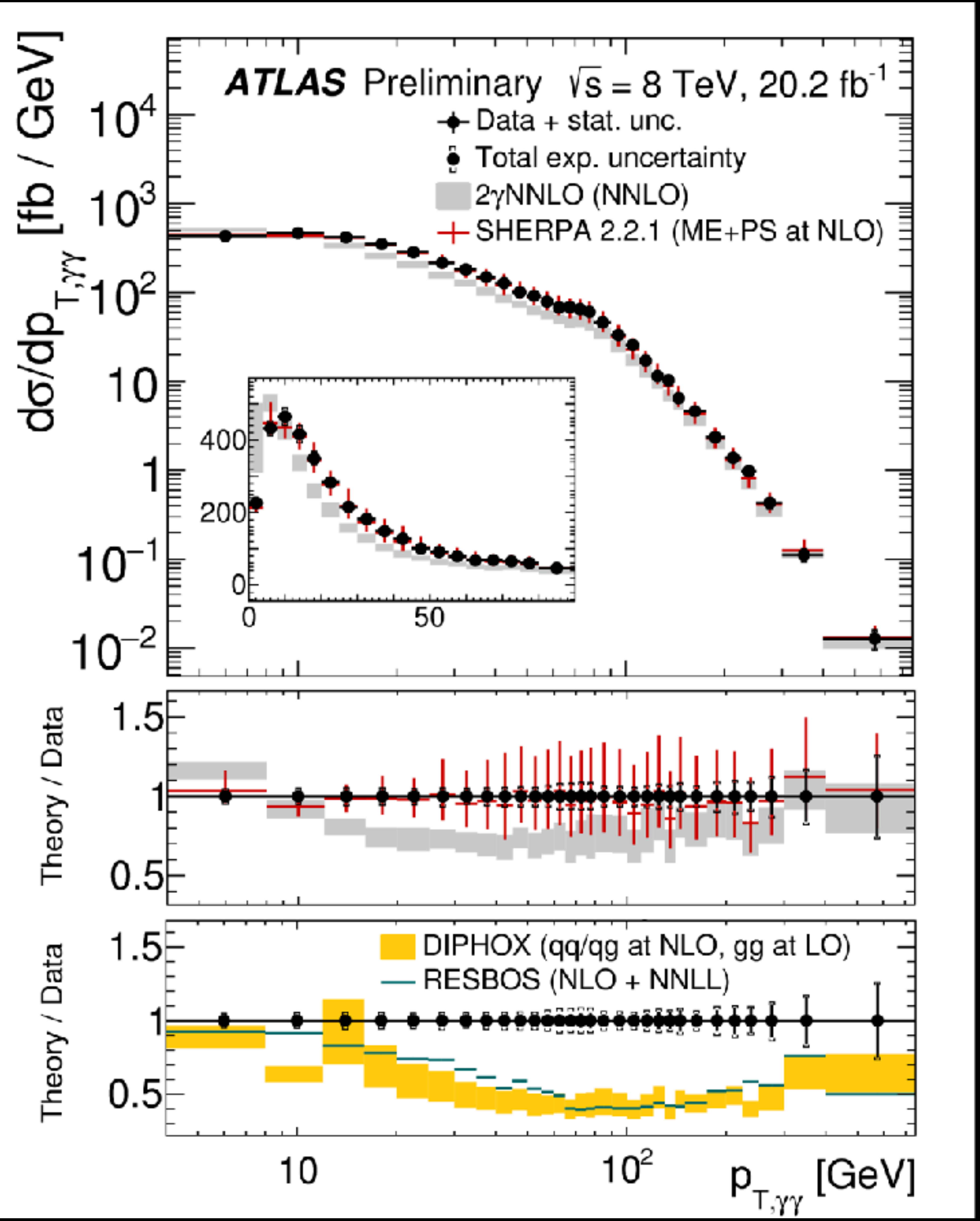


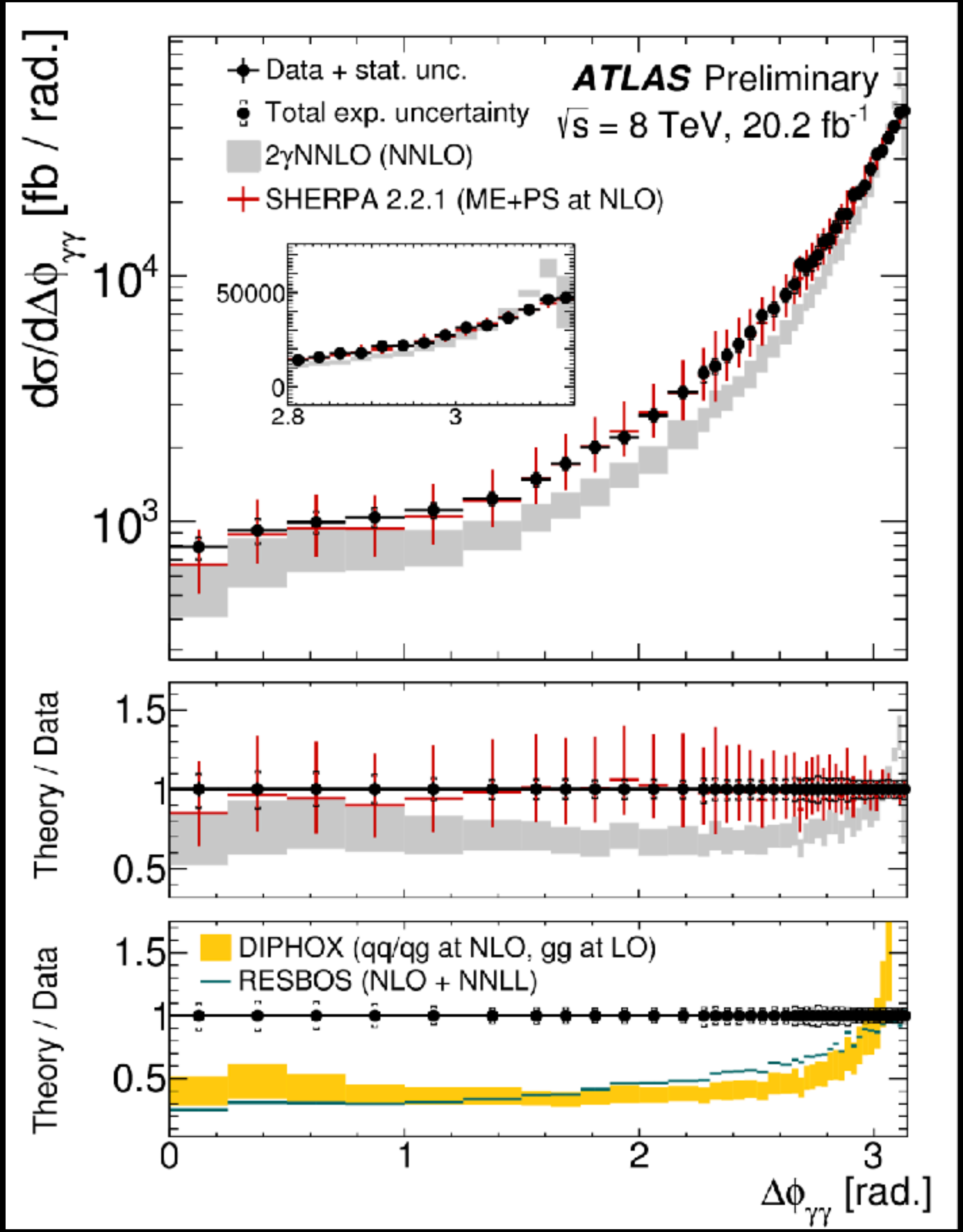


The NLO pQCD predictions(Jetphox) provide an adequate description of the data

Di-photon production cross section

New





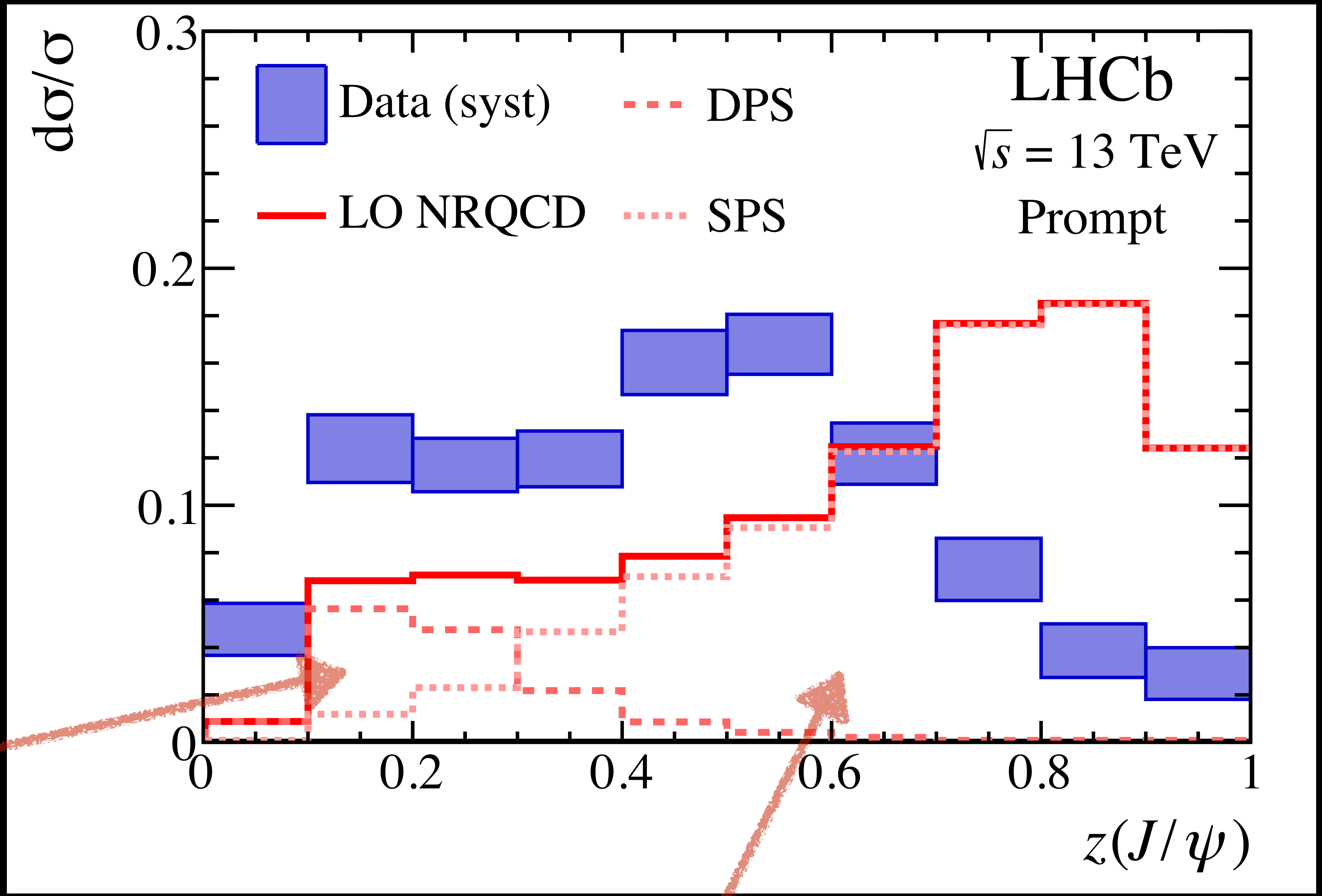
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-15/

J/ψ production in jets

Fraction of jet transverse momentum carried by J/ψ meson: z(J/ψ)

2.5 < η(jet) < 4.0

Prompt J/ψ

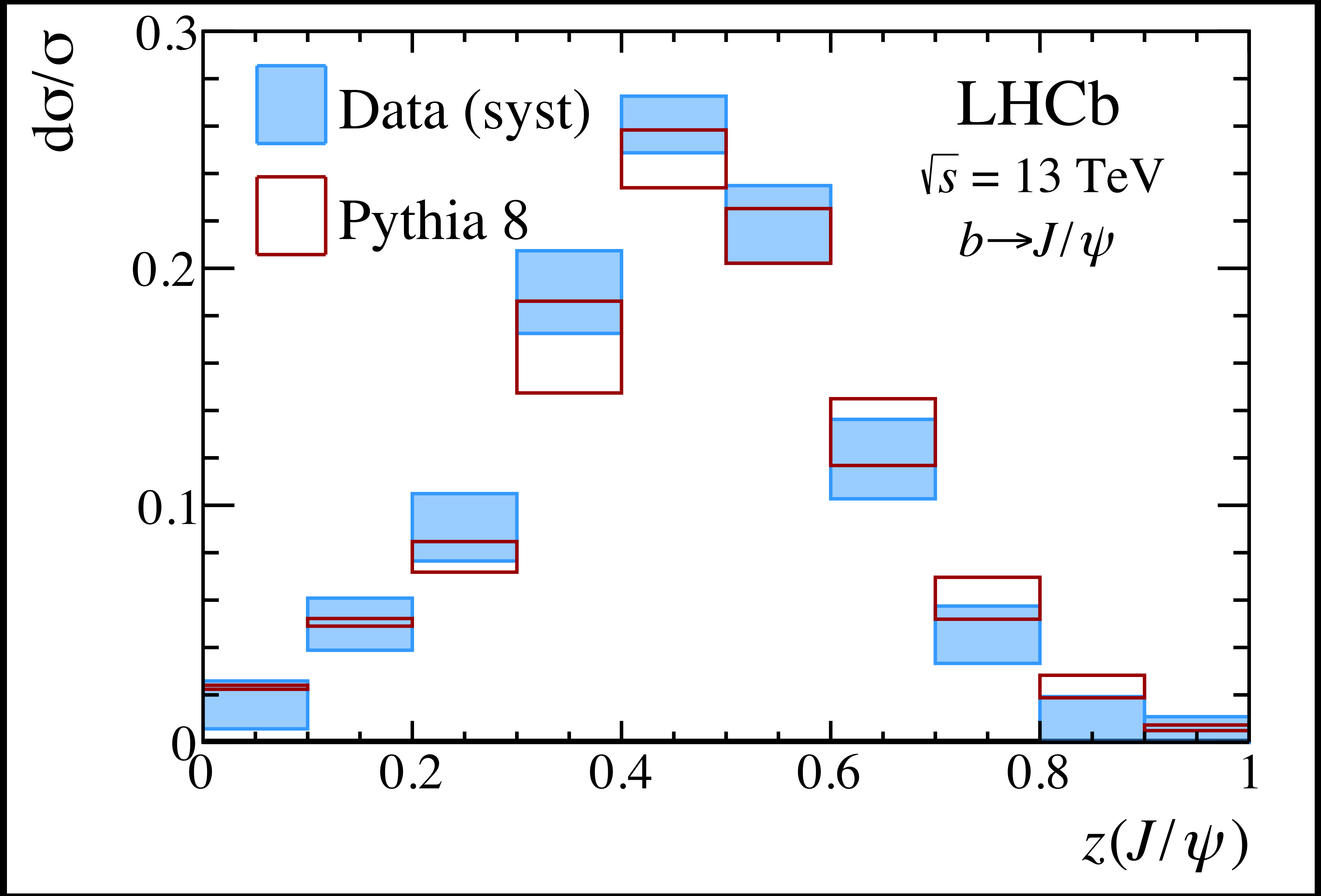


Double parton scattering (DPS)

Single parton scattering (SPS)

Data disagrees with LO non-relativistic QCD from Pythia 8

J/ψ inside b-jets



Good agreement with Pythia 8

See: LHCb parallel talk by Philip Ilten

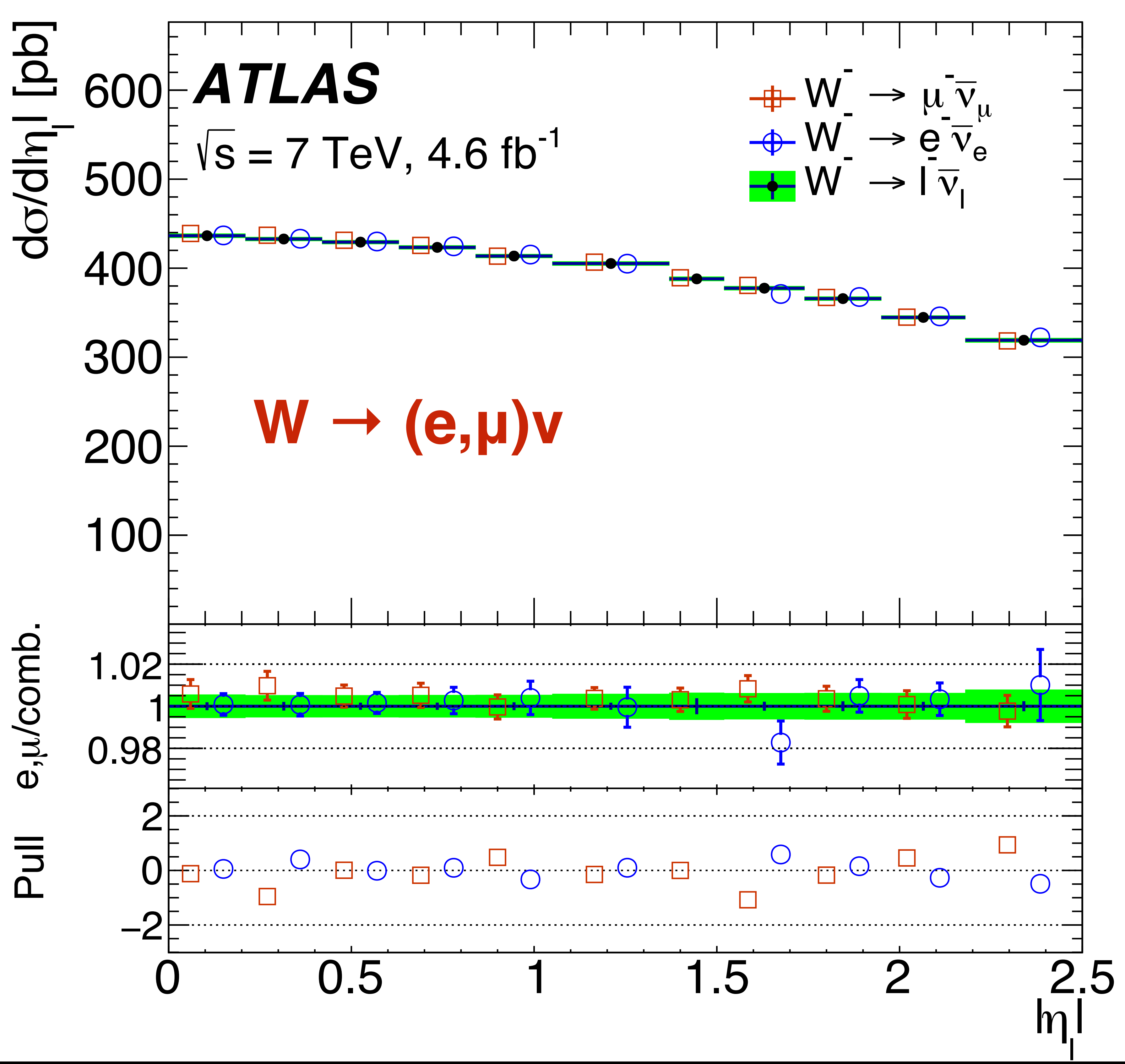
Precision measurement of W and Z cross sections
7 TeV, 4.6 fb^{-1}

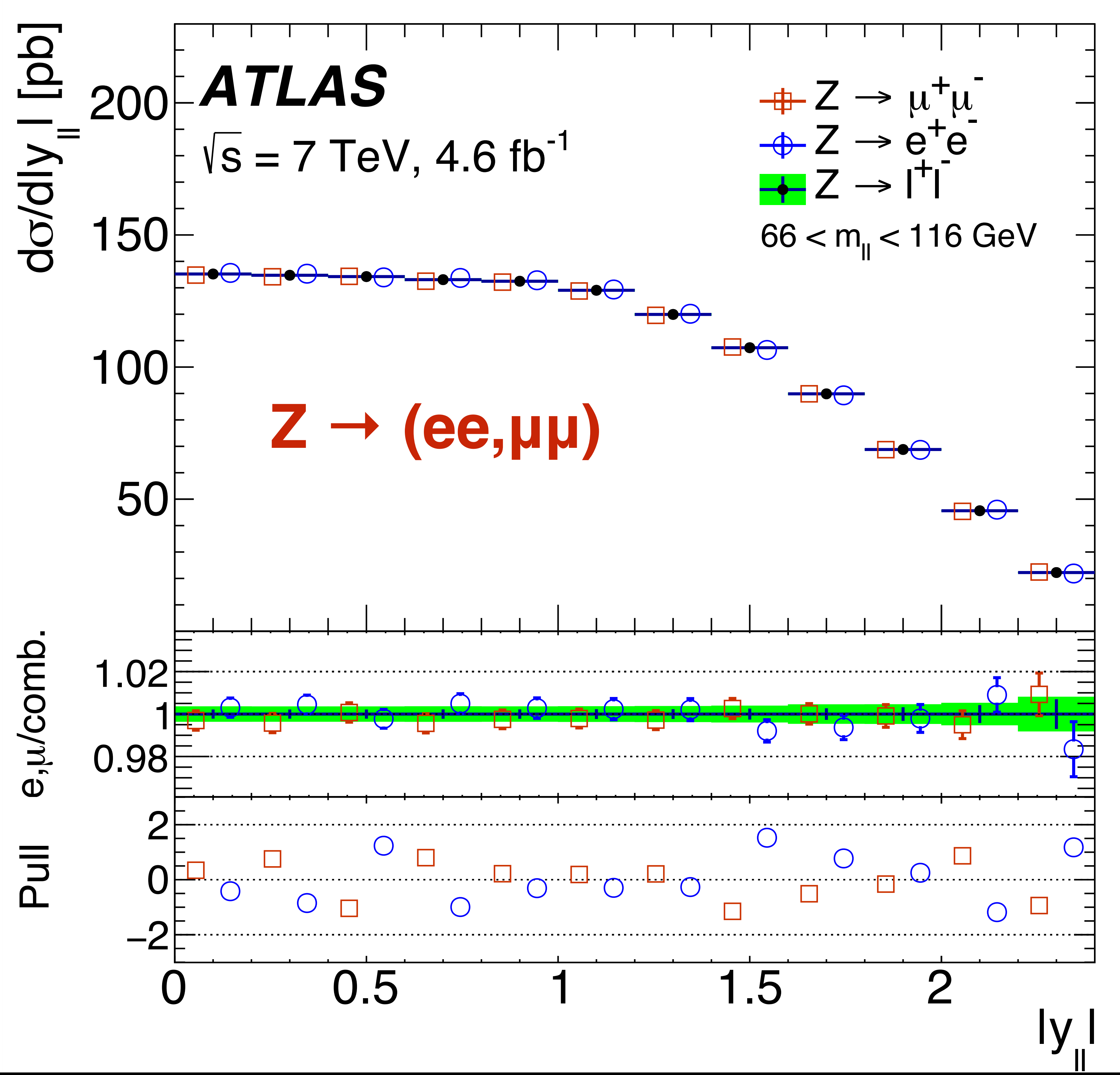
Measurement of differential and integrated cross sections

arXiv:1612.03016

Differential measurements

- $W \to (e,\mu)\nu$: $|\eta_{(ee,\mu\mu)}|$
- $Z \to (ee,\mu\mu)$: $|y_{(ee,\mu\mu)}|$, 3 mass bins





Since 2010:

- 100x statistics
- Luminosity determination 3.4% → 1.8%
- Better understanding of triggers and lepton reconstruction

Main systematics:
- Signal modeling
- Multijet background

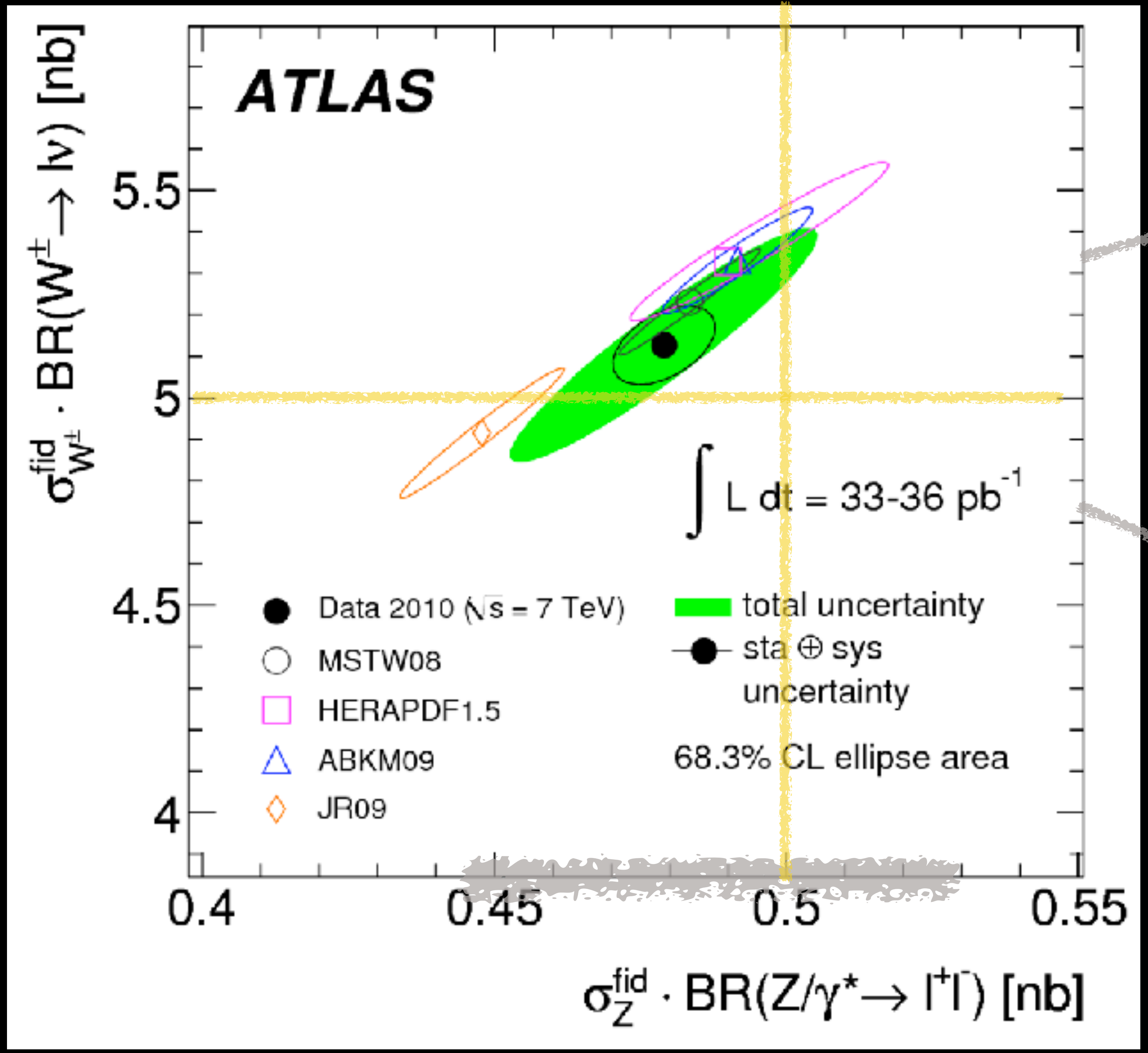
Fiducial W and Z Cross Sections

Fiducial cross sections

No theoretical uncertainty from extrapolation outside experimental acceptance

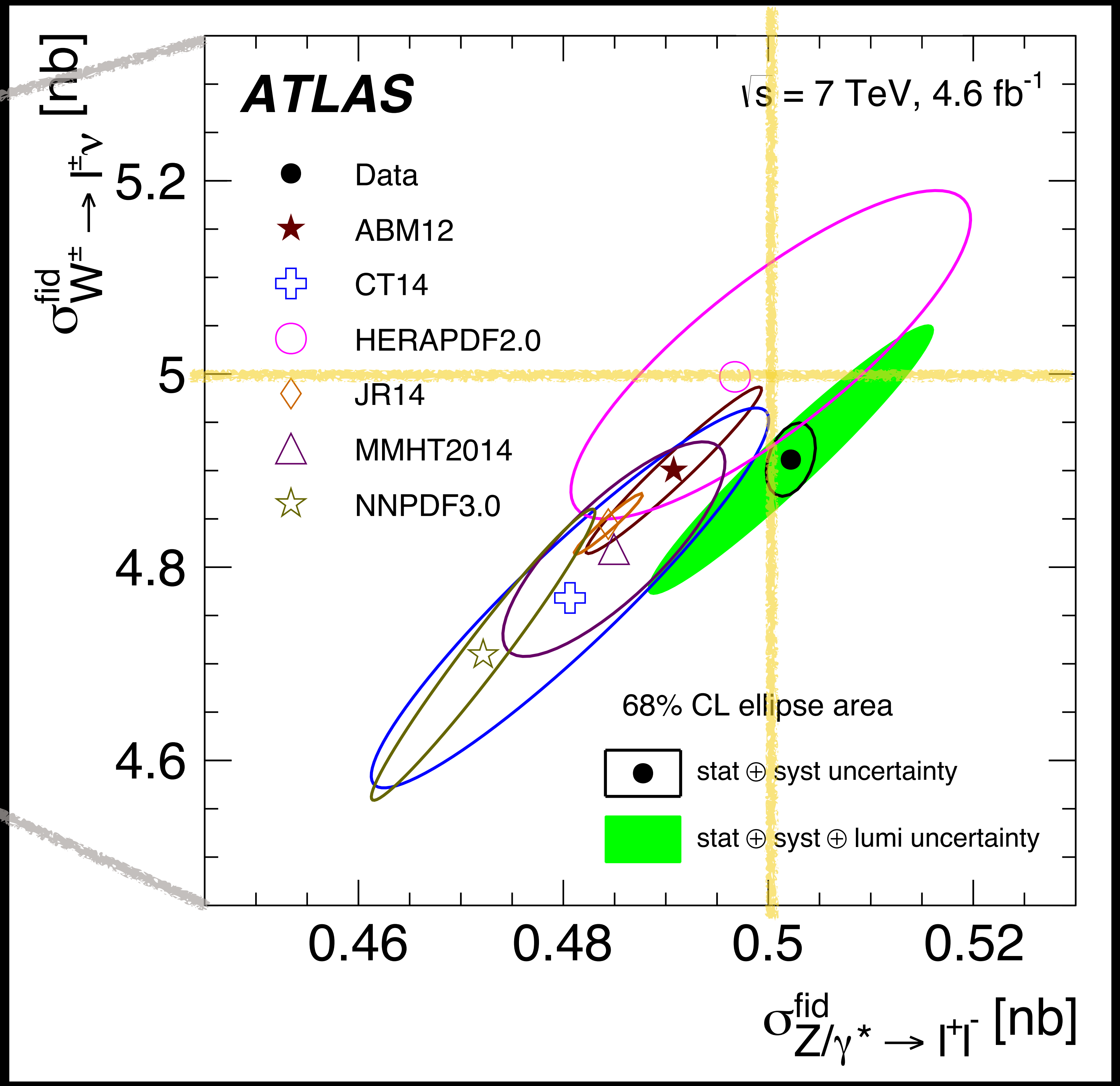
$\sigma_{Fiducial}$: W versus Z

Phys. Rev. D85 (2012) 072004



FEWZ = DYNNLO ~ 1%

arXiv:1612.03016



DYNNLO 1.5

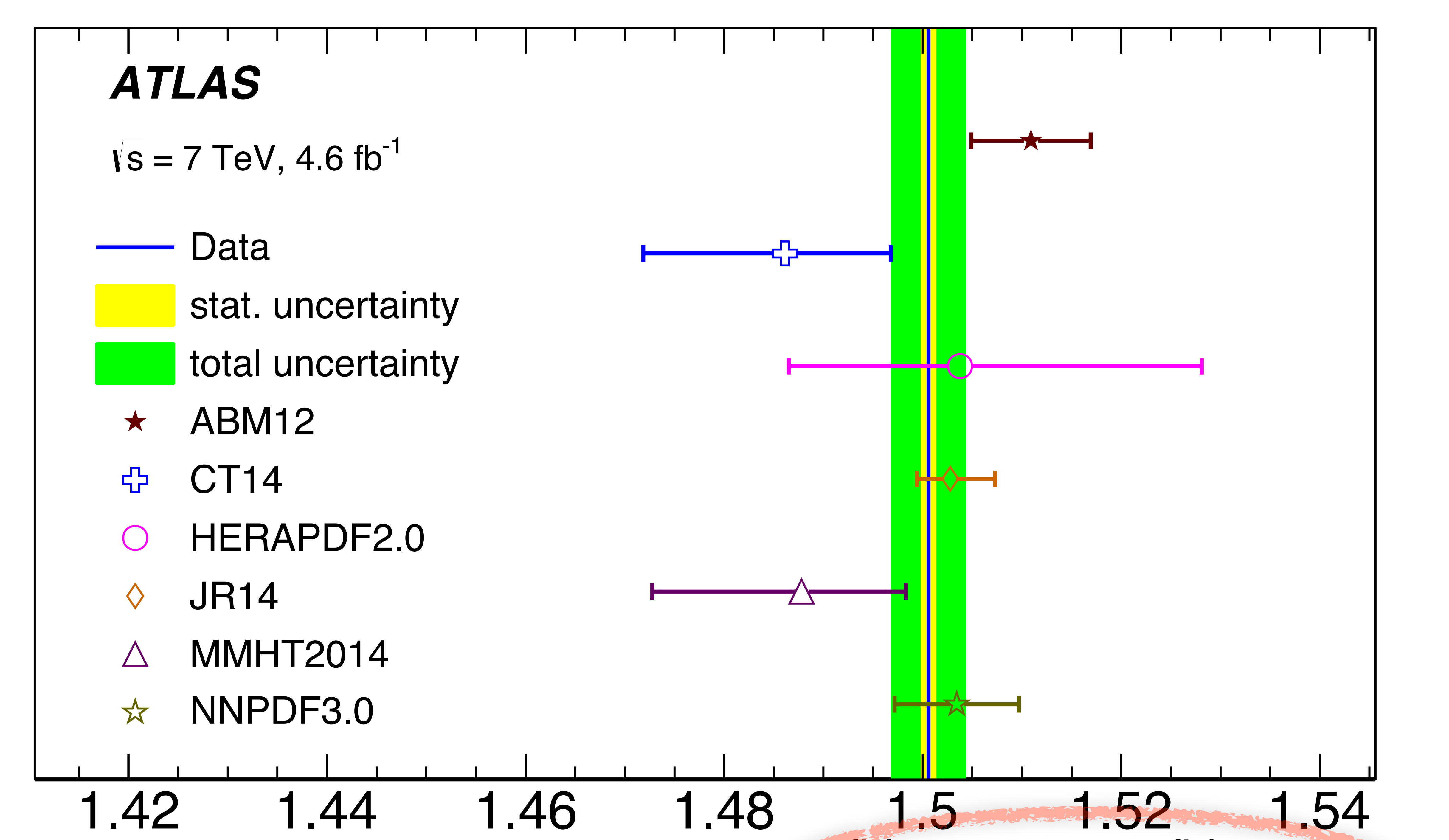
Luminosity 3.4% ==> 1.8%

Some differentiation between PDF sets observed
Experimental uncertainties smaller than individual PDF uncertainties

Ratios of fiducial cross sections

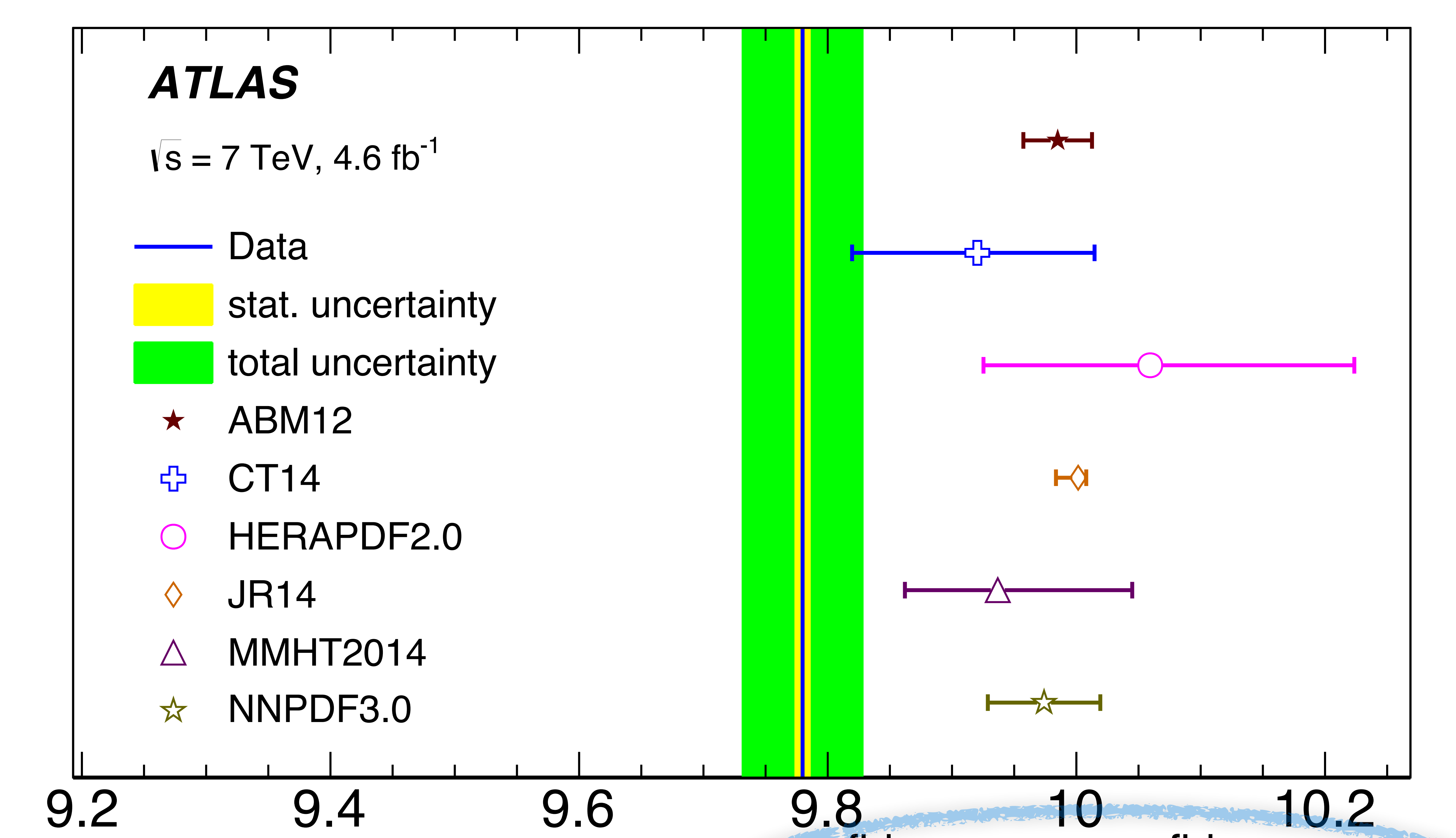
arXiv:1612.03016

W+/W- in good agreement



$\sigma^{fid}_{W^+ \to l^+\nu} / \sigma^{fid}_{W^- \to l^-\bar{\nu}}$

W/Z lower than predictions



$\sigma^{fid}_{W^\pm \to l^\pm\nu} / \sigma^{fid}_{Z/\gamma^* \to l^+l^-}$

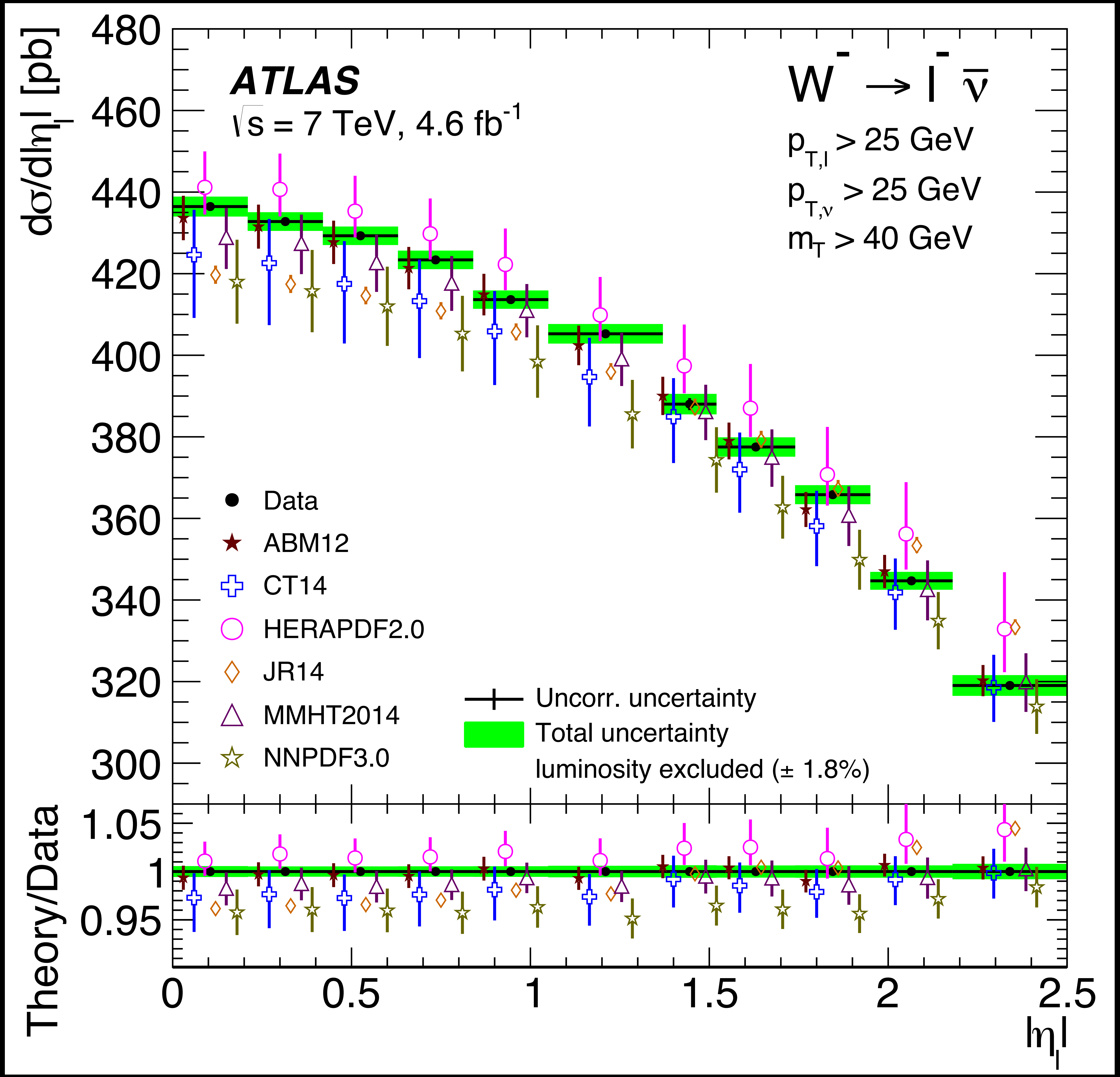
Theoretical calculation uncertainties only from PDF

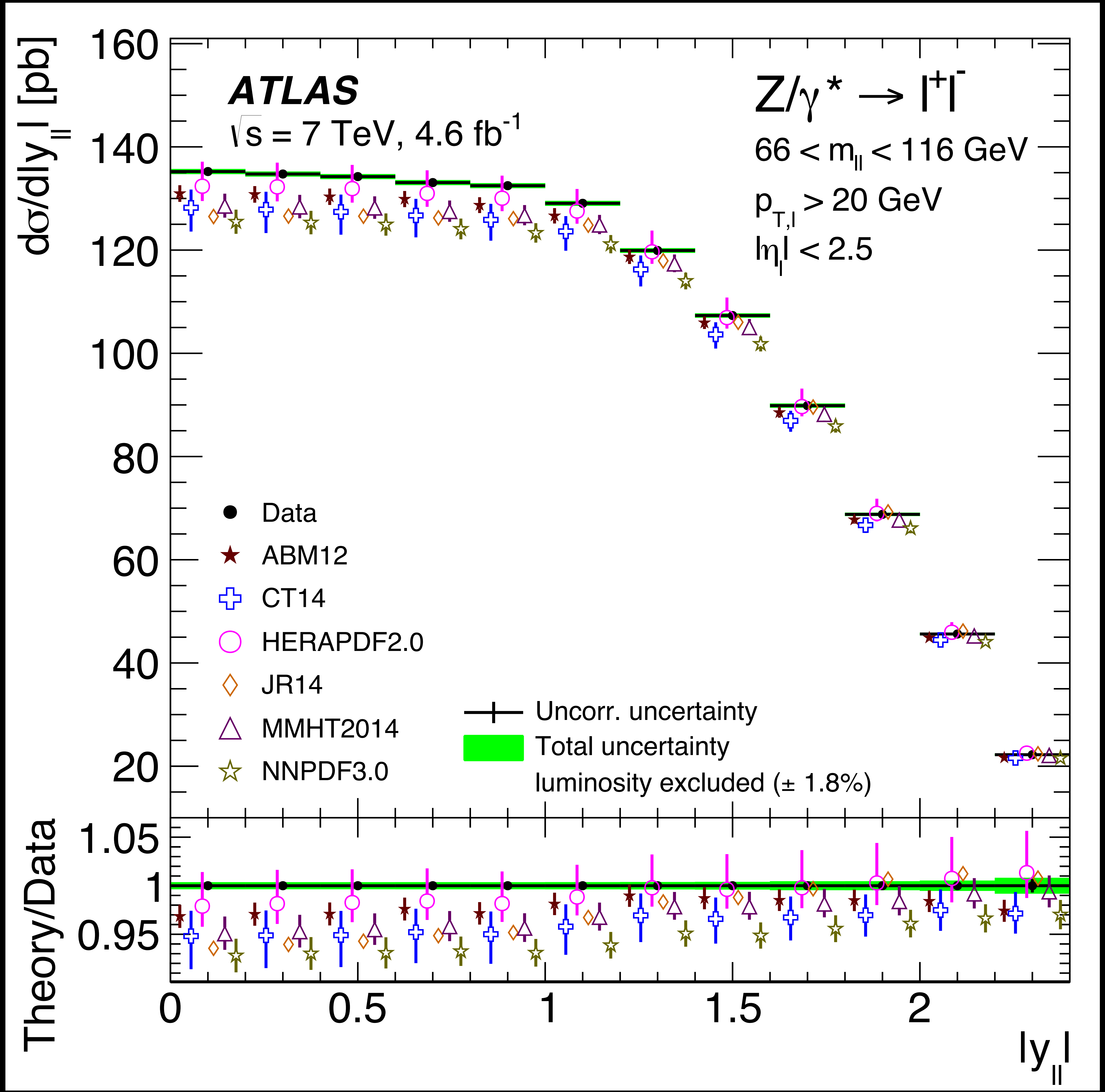
Explore the flavor structure of the proton via electroweak interactions

Differential cross section measurements

Measured with a precision of 0.4-0.6 (exp) ± 1.8 (lumi)%

Higher precision than NNLO predictions



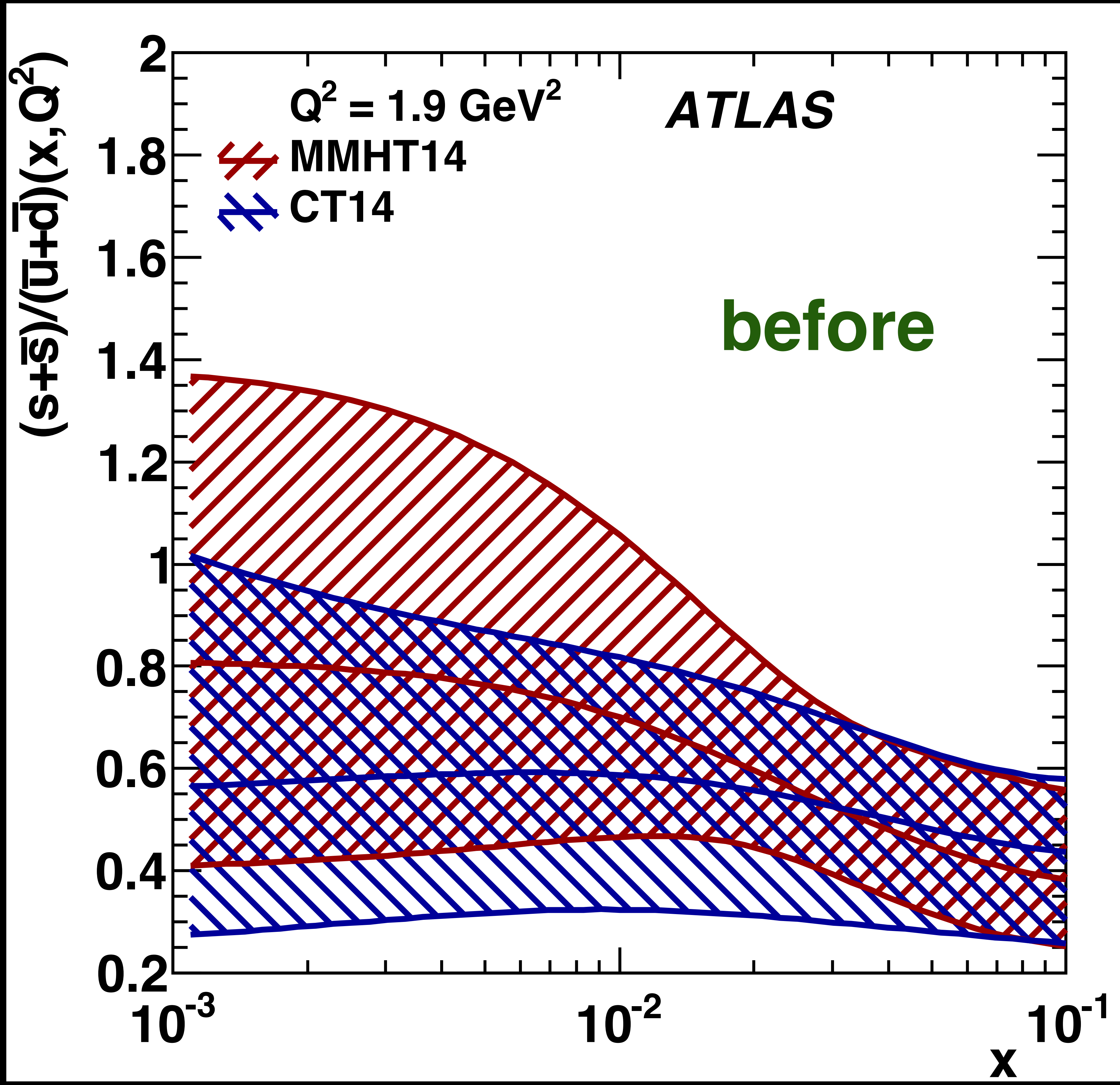


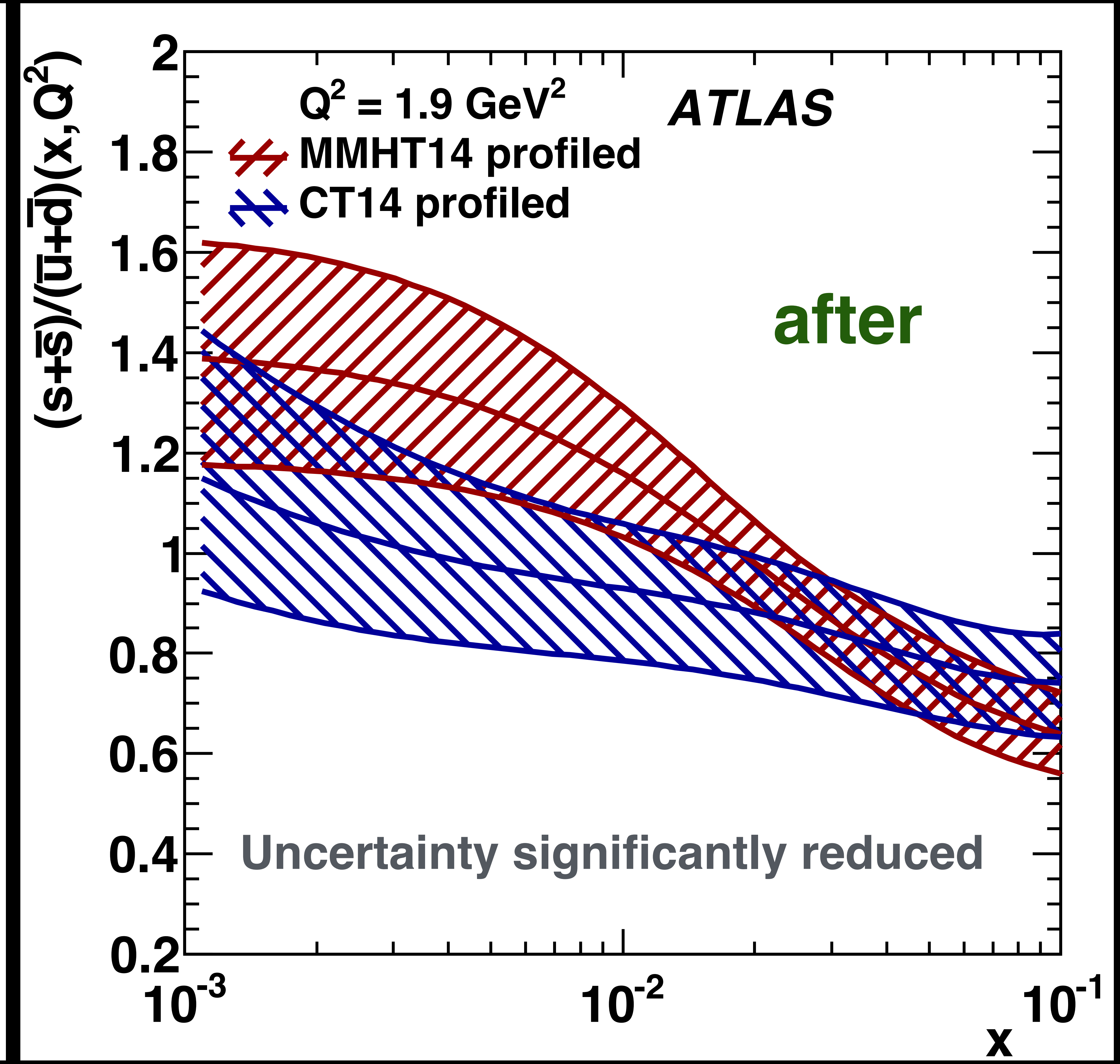
PDF profiling results from W/Z precision measurement

arXiv:1612.03016

Impact of measurement when applied to existing PDF (MMHT14,CT14)

$$R_s(x) = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$$

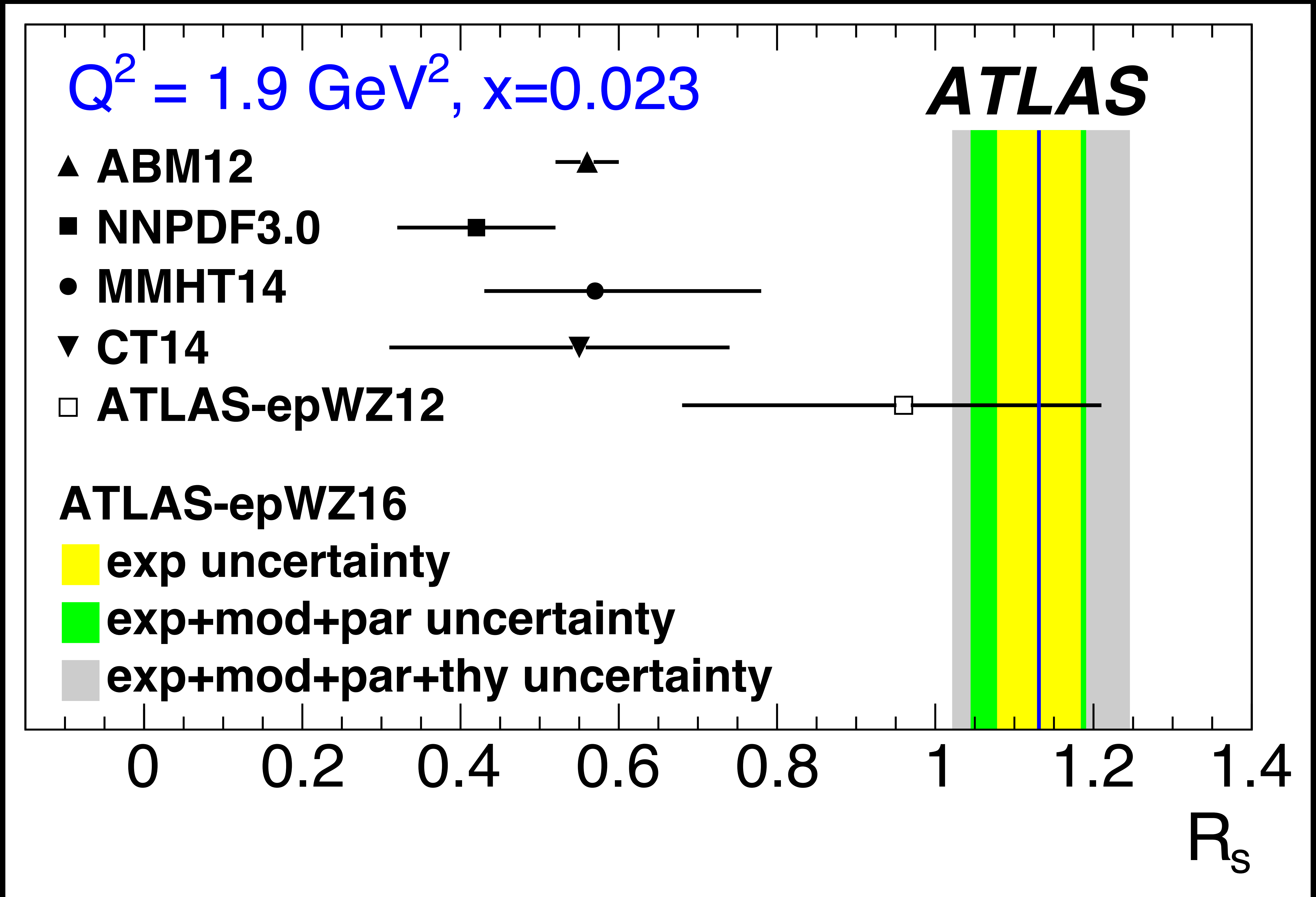




Strange quarks not suppressed w.r.t. up- and down-sea quarks

Strangeness in the Proton

arXiv:1612.03016

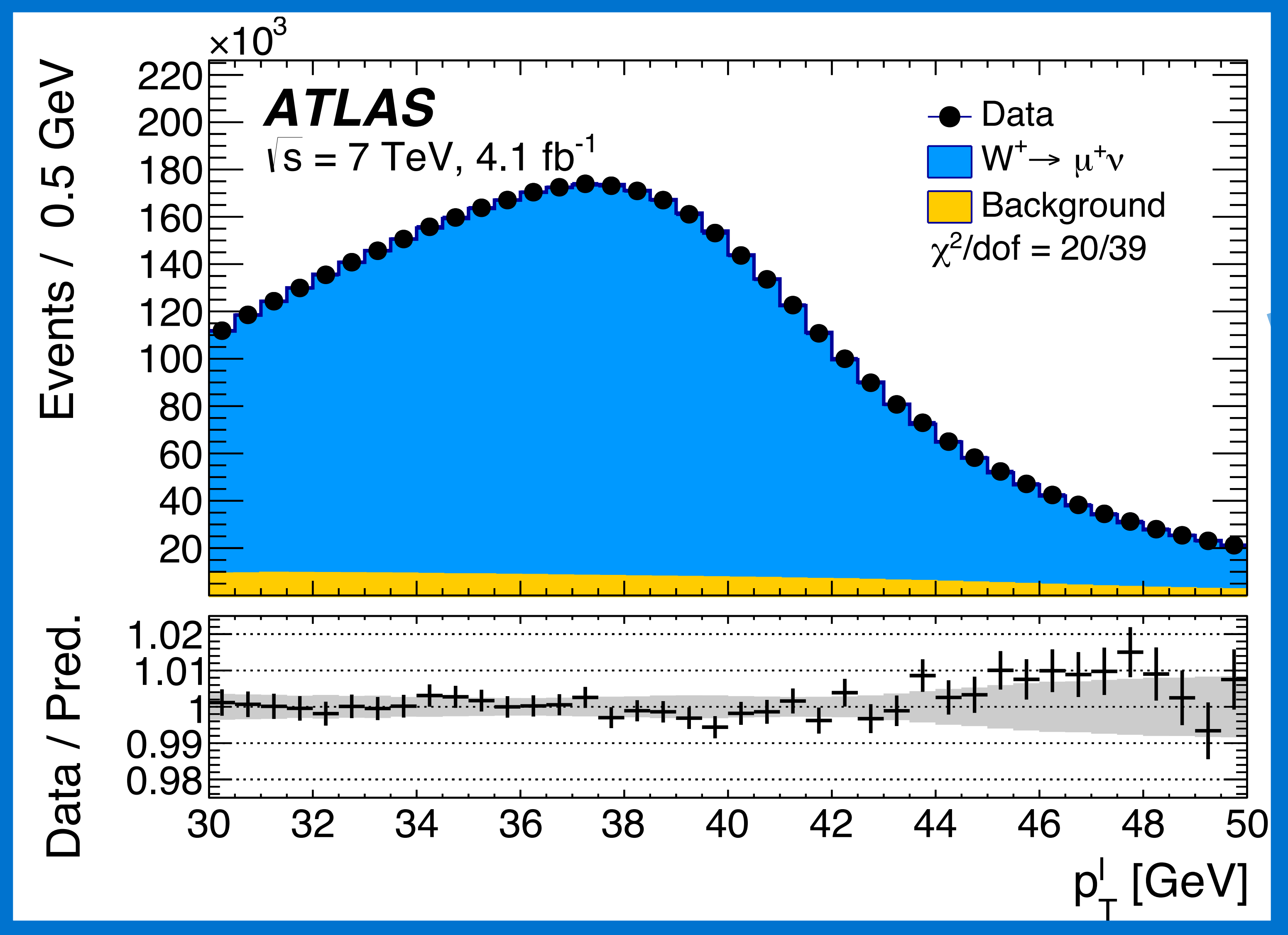


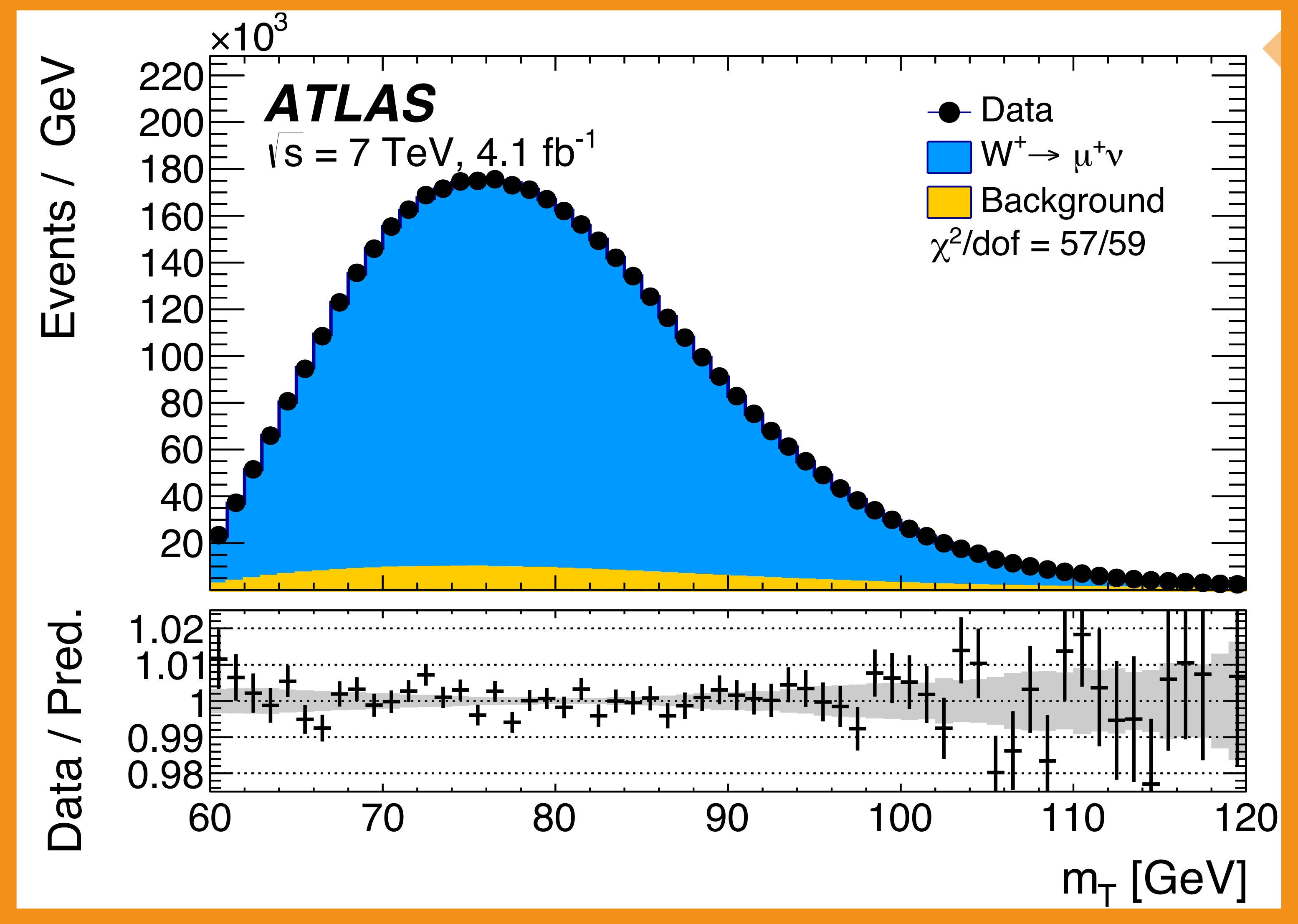
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}} = 1.13 \pm 0.05\,(\mathrm{exp}) \pm 0.02\,(\mathrm{mod})\,{}^{+0.01}_{-0.06}\,(\mathrm{par})$$

W mass measurement

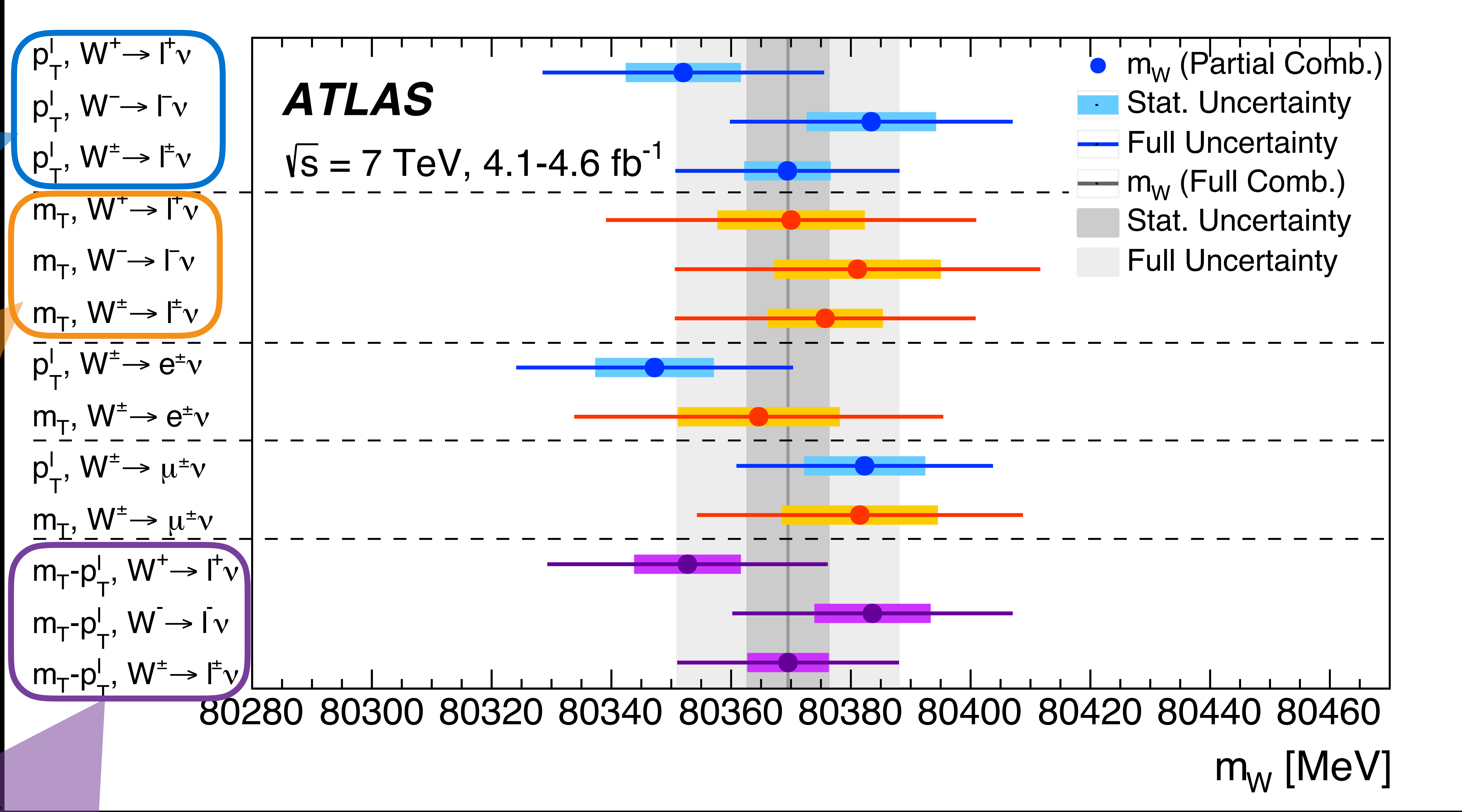
arXiv:1701.07240

Extract mass from Jacobian edges of final-state kinematic distributions





Overview of M_W measurements from ATLAS



Stability across a variety of analysis channels and kinematic distributions

$$
\begin{aligned}
m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\
&= 80370 \pm 19\ \text{MeV},
\end{aligned}
$$

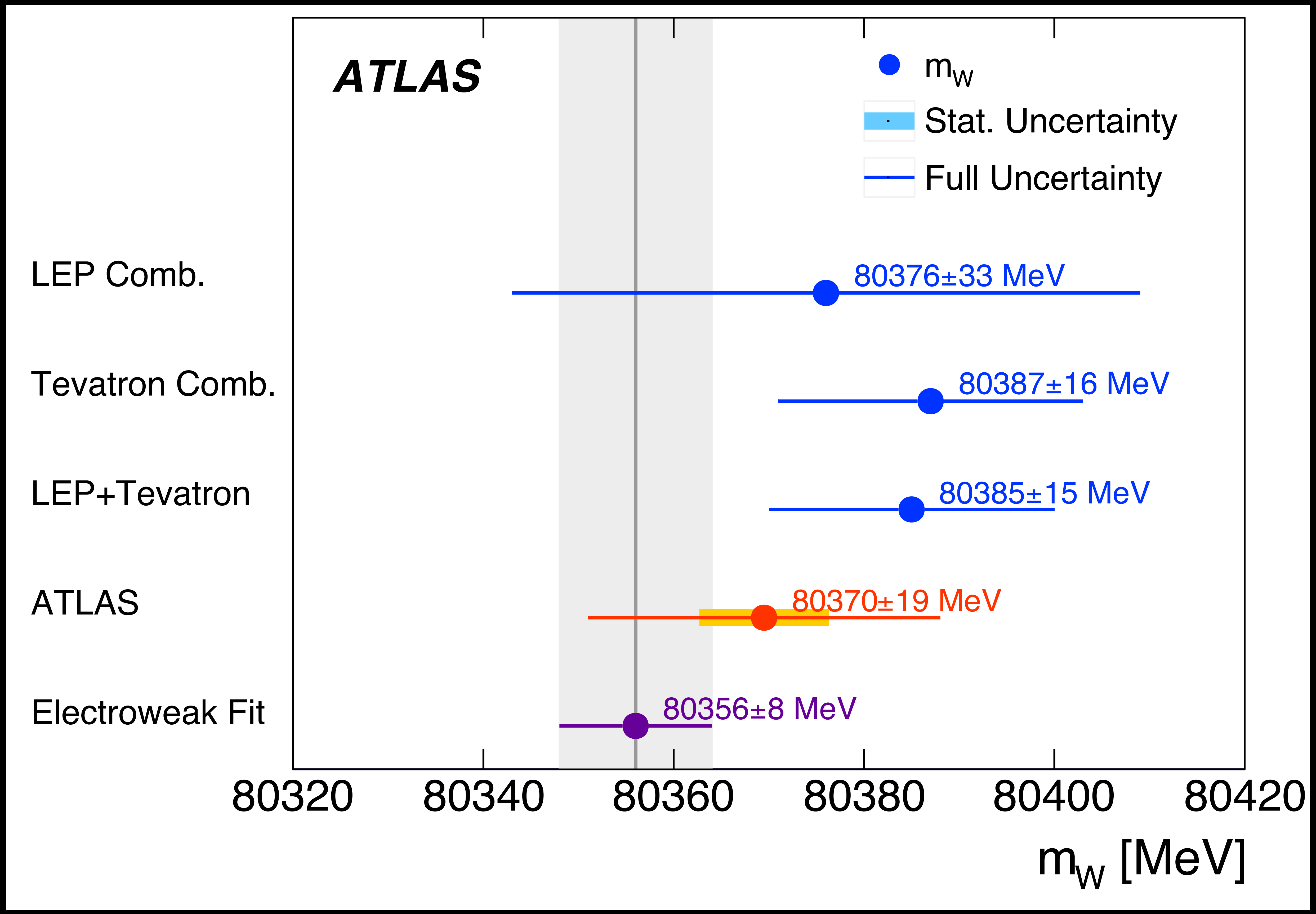
Measurement relies on Z→ll for calibration

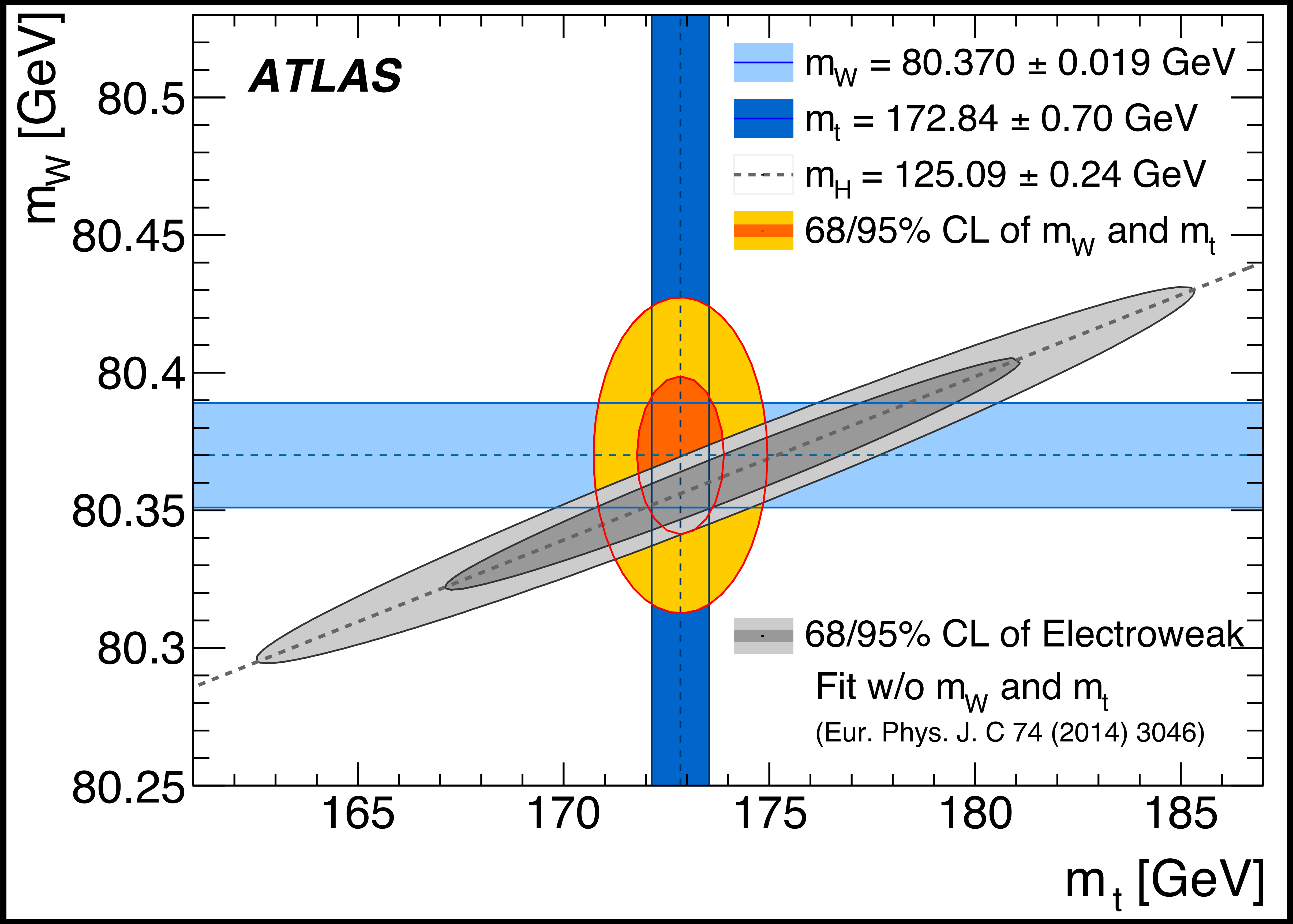
Modeling of $p_T(W)/p_T(Z)$ one of the main sources of uncertainty

W mass measurement results

arXiv:1701.07240

M_W = 80370 ± 19 MeV



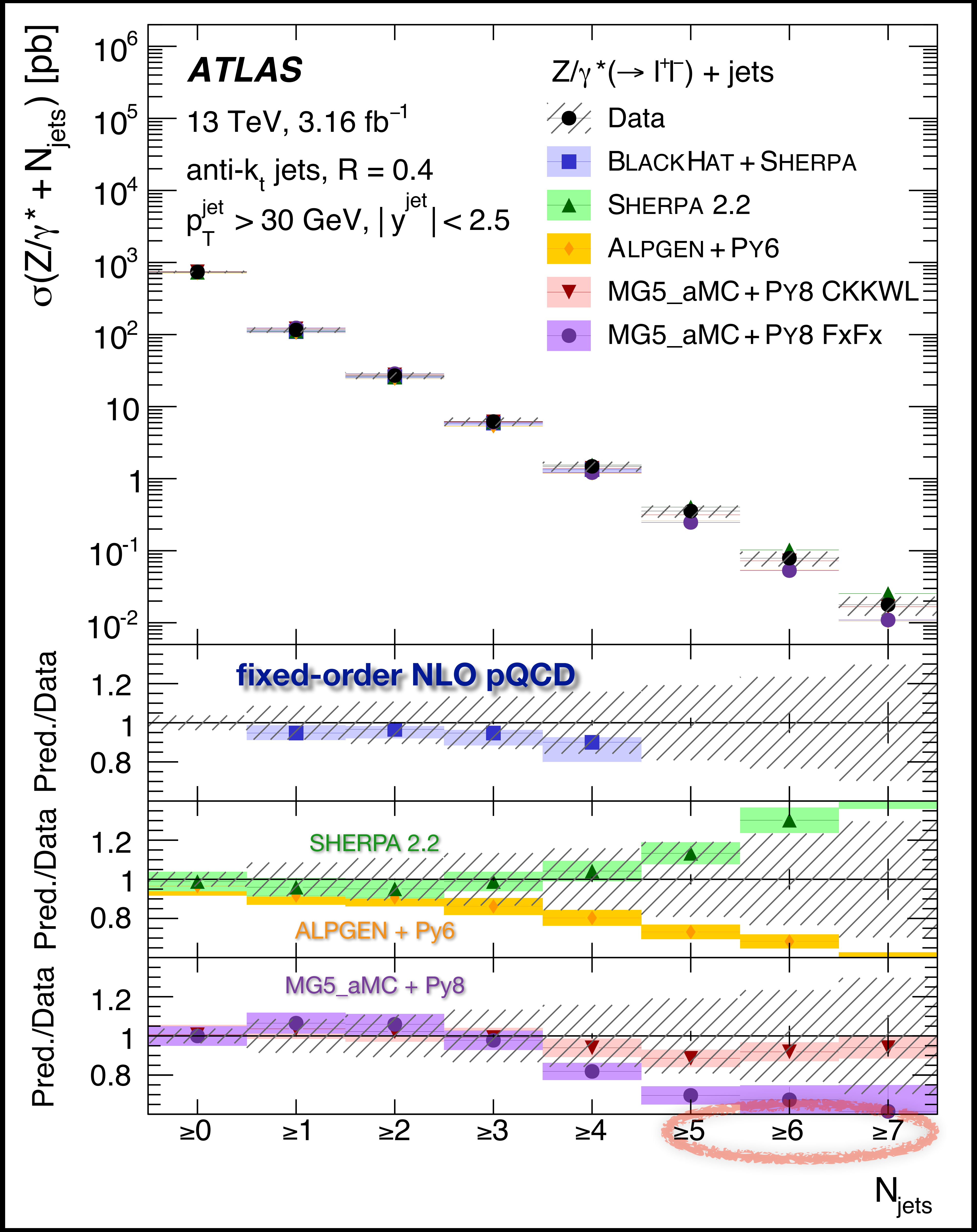


ATLAS measurement precision close to current best measurement

Consistent with other results and SM electroweak fit

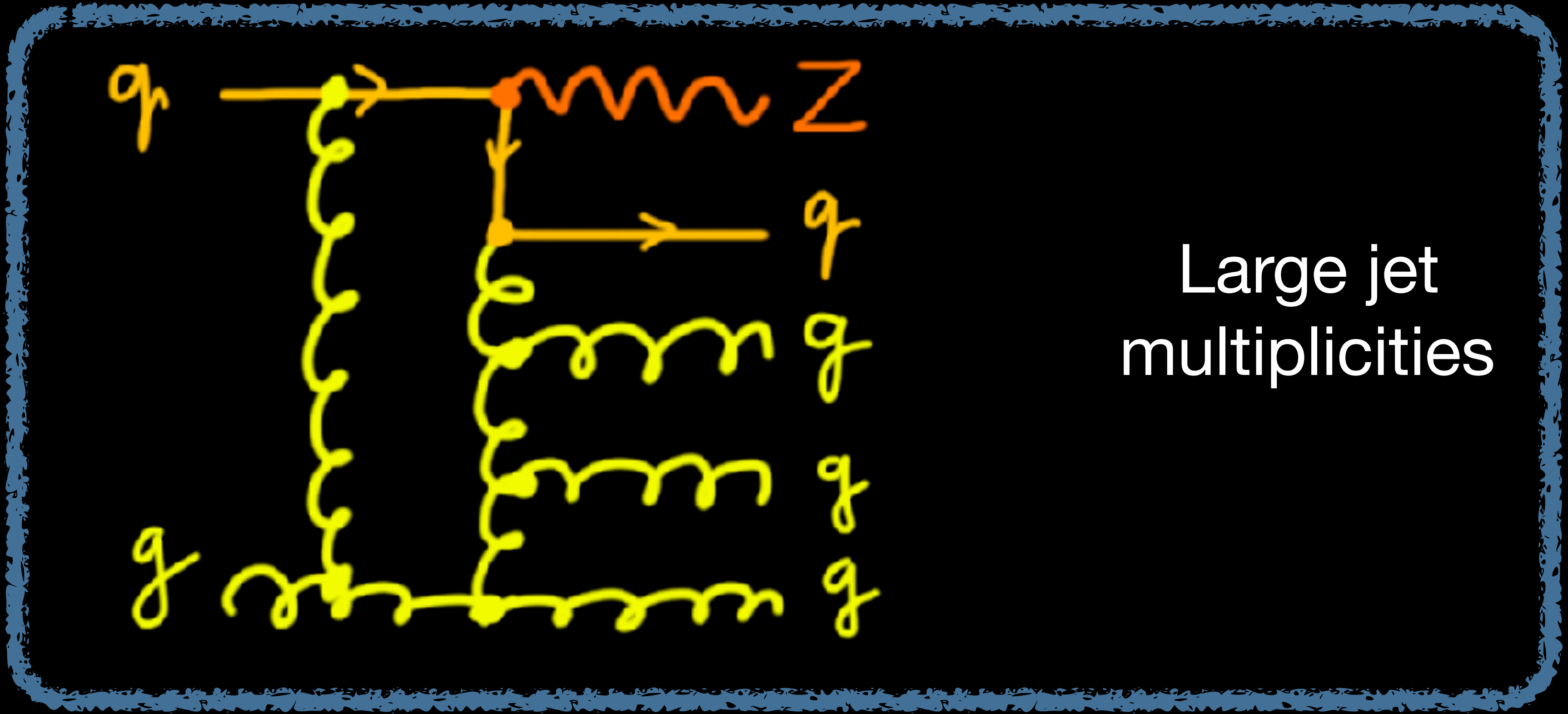
Measurements of Z + jets

arXiv:1702.05725



Explore extreme phase space

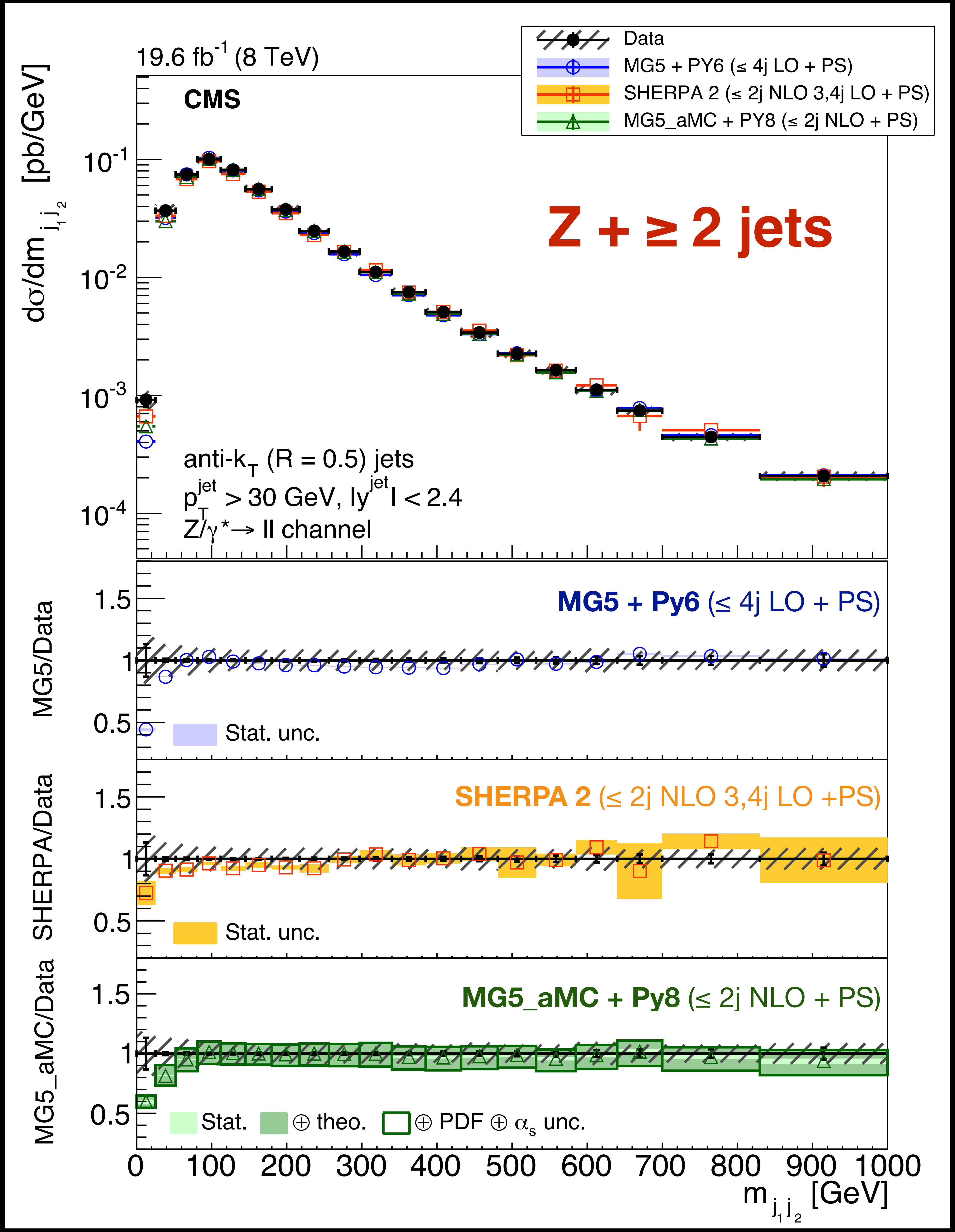
(using 13 TeV dataset)



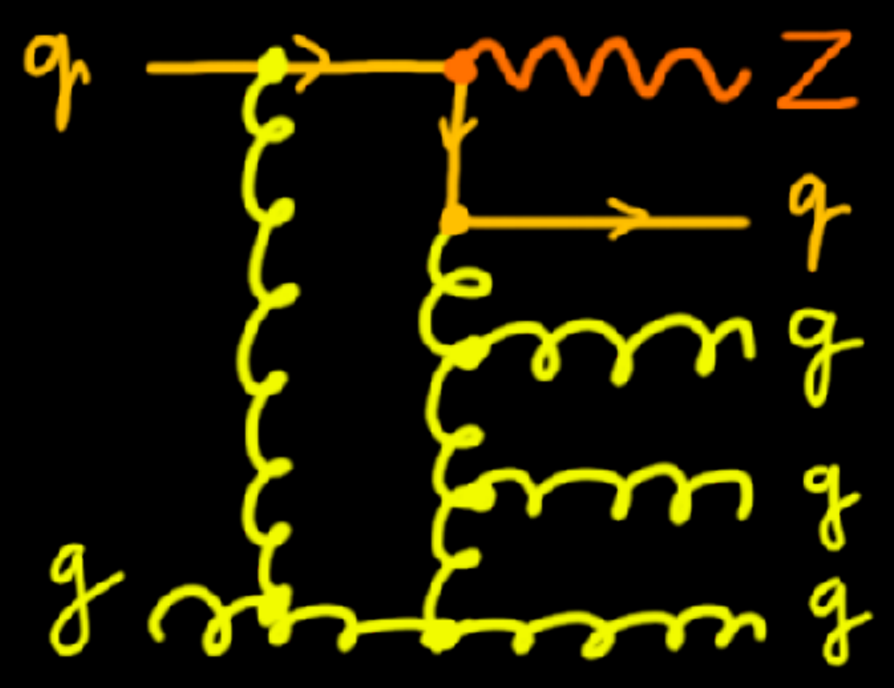
Large jet multiplicities

Measurements of Z + jets

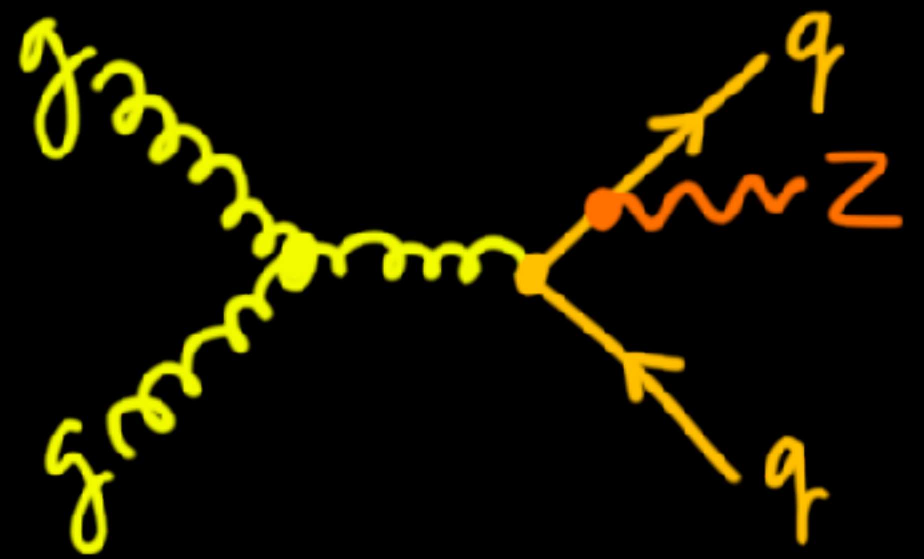
arXiv:1611.03844v1



Explore extreme phase space
(using 13 TeV dataset)



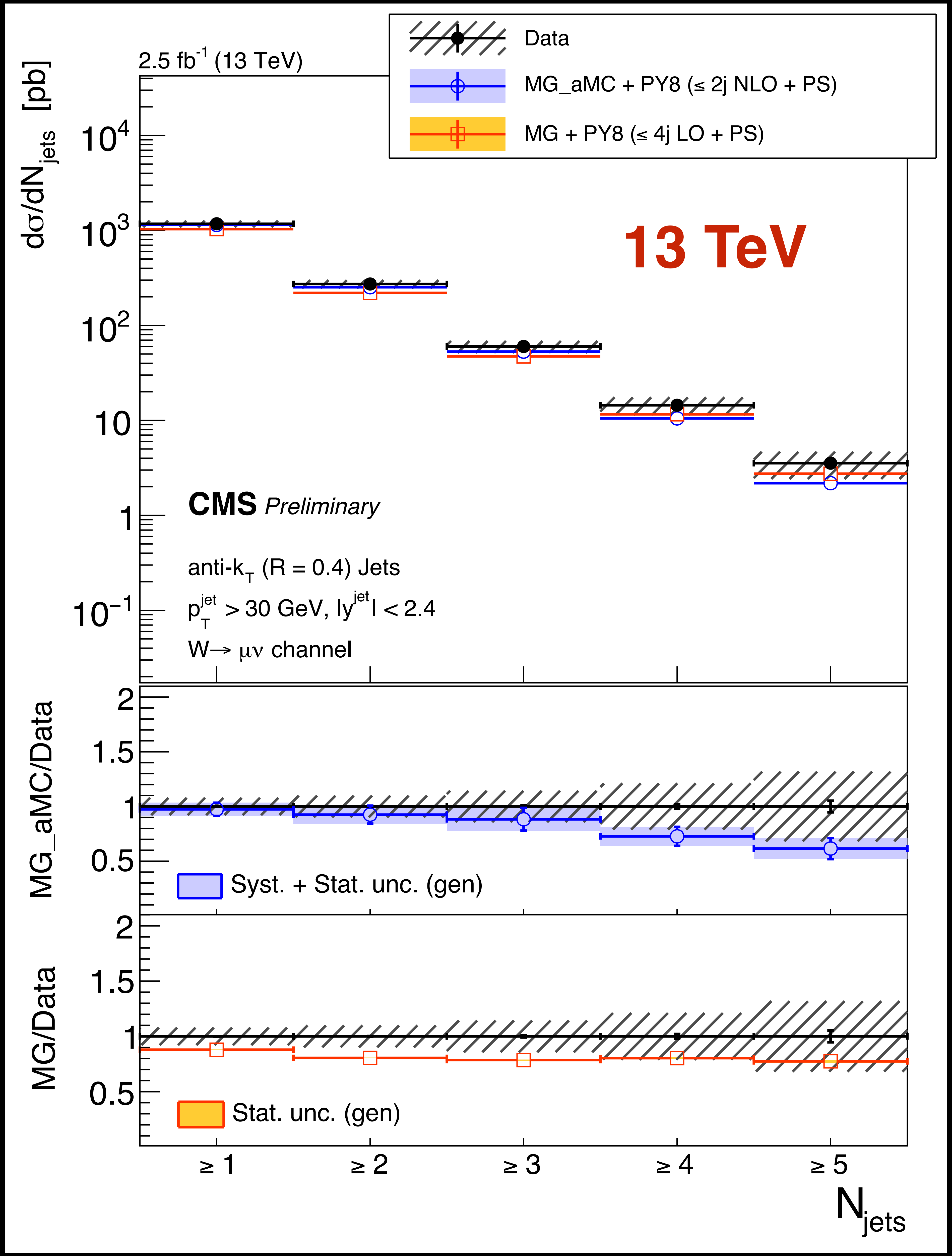
Large jet multiplicities



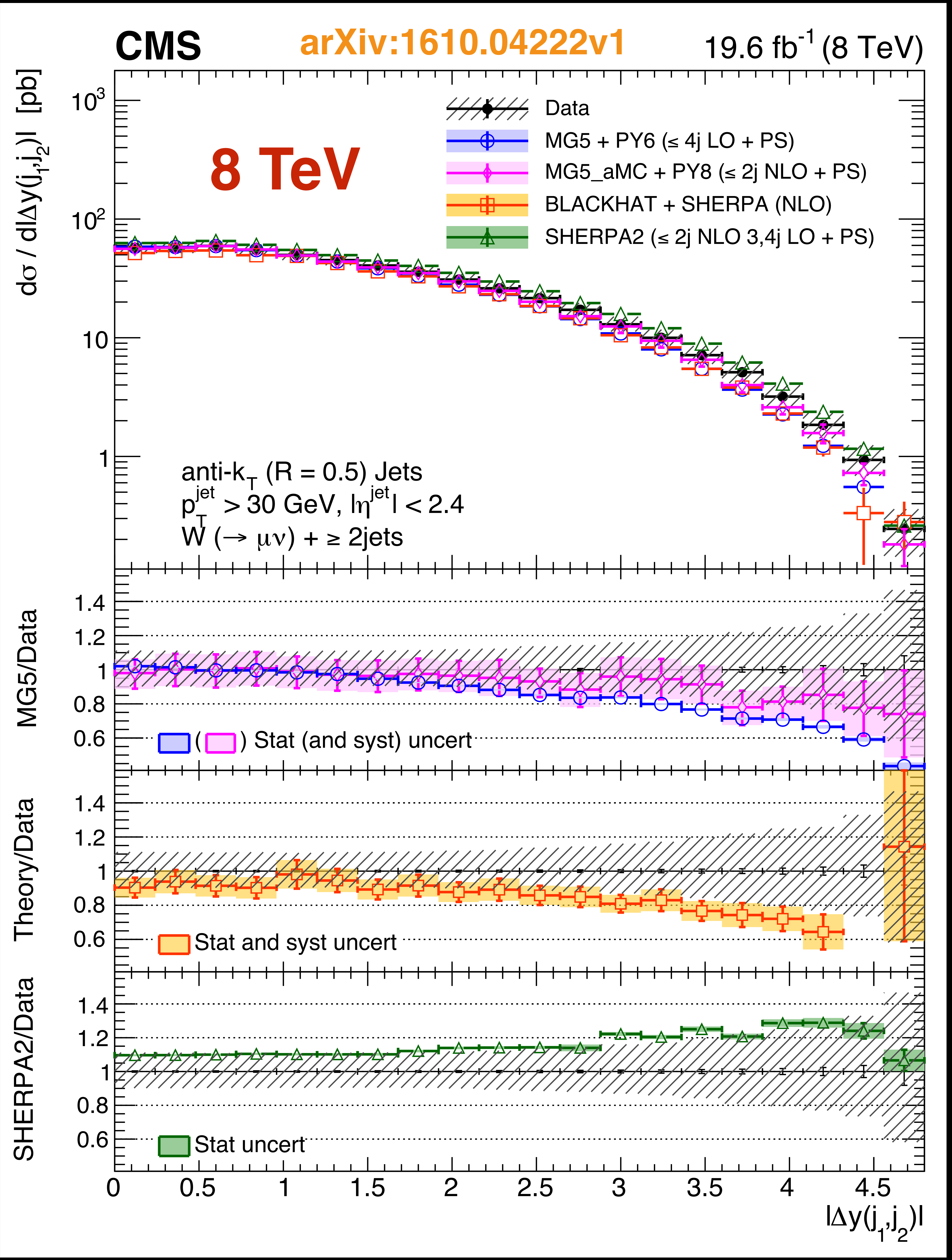
Z + ≥ 2 jets
Large m_{jj}

W+jets production

CMS PAS SMP-16-005

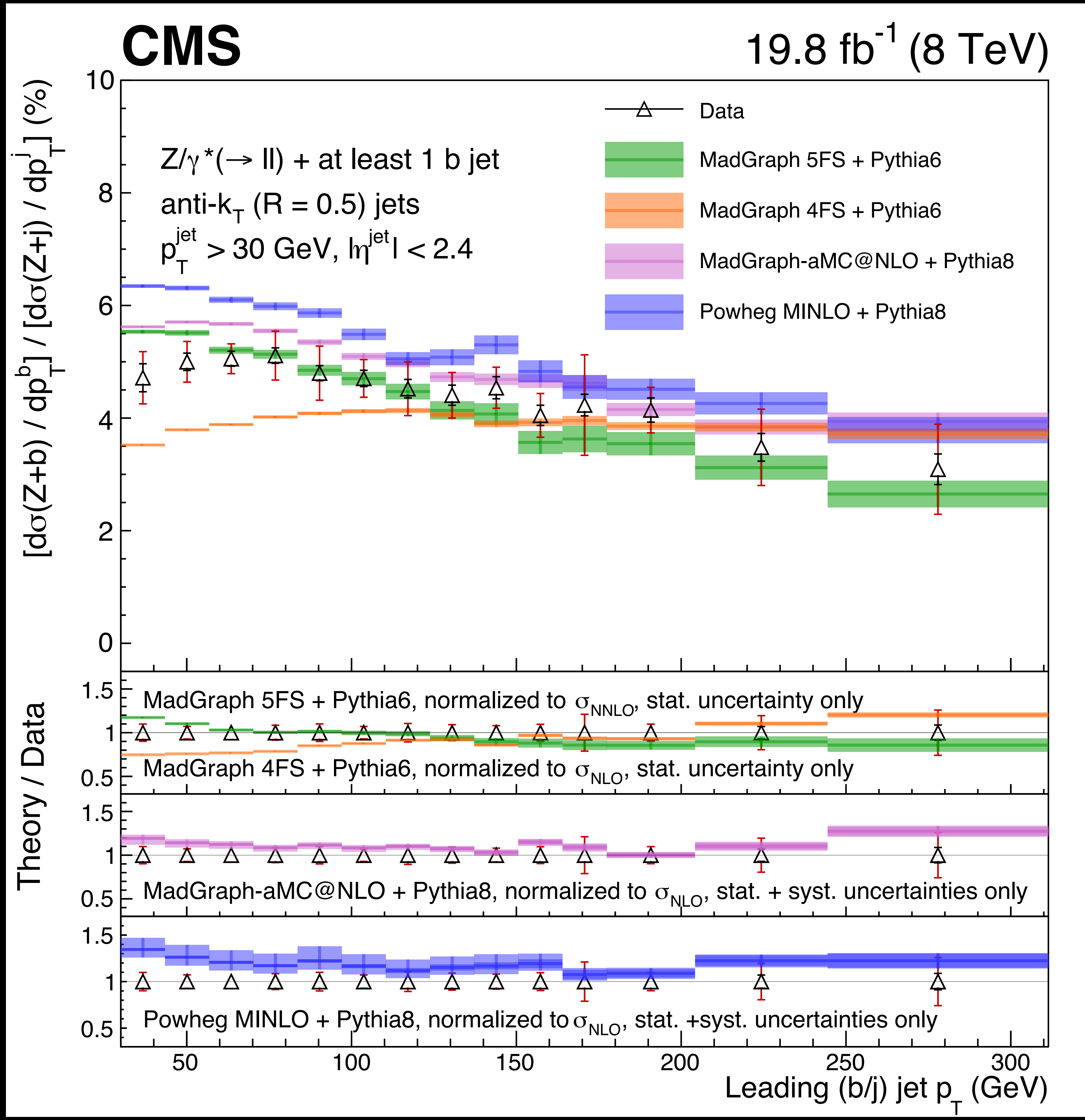


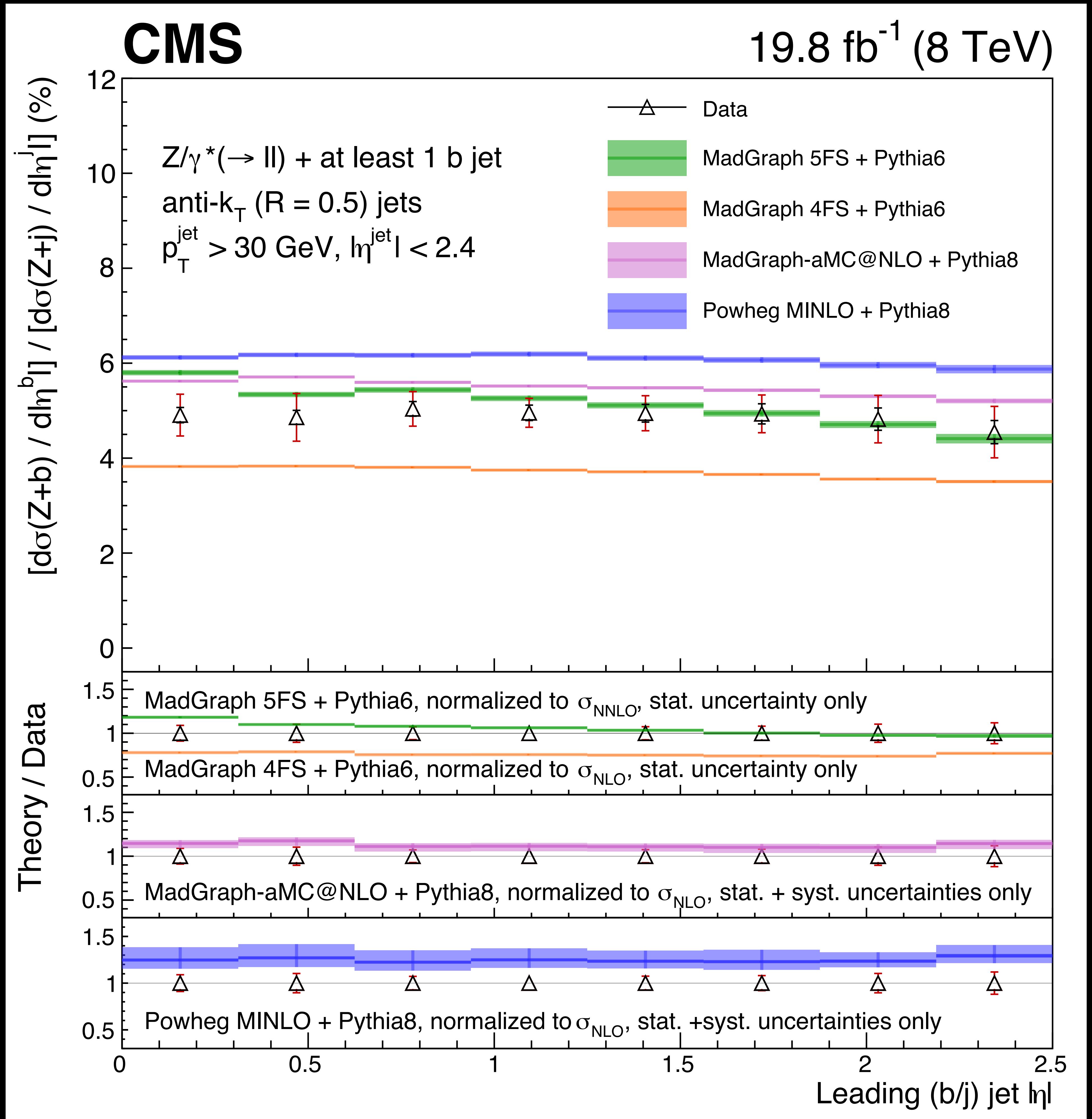
W + ≥ 2 jets



Z+ b-quark production

$$R(x) = \frac{d\sigma(Z+(\geq 1b))/dx}{d\sigma(Z+jets)/dx}$$

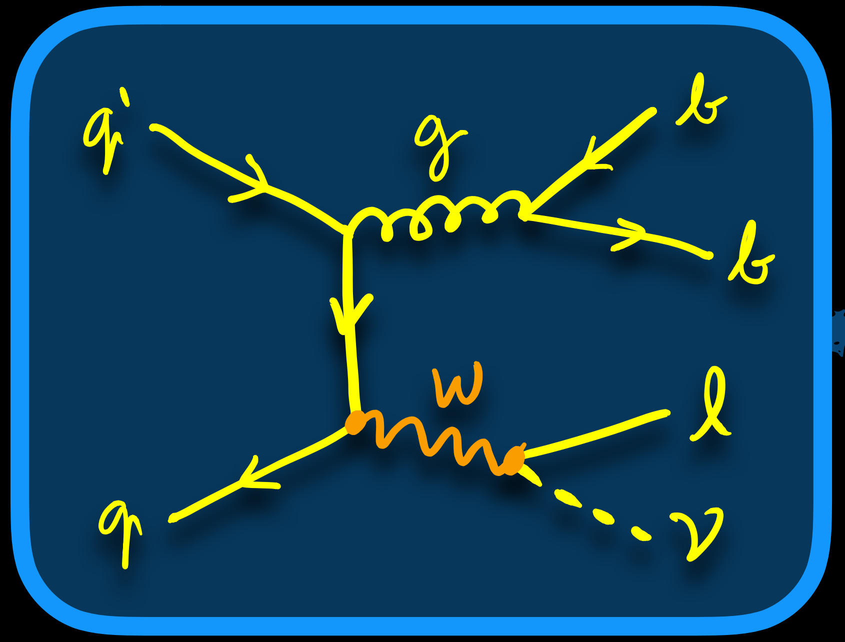


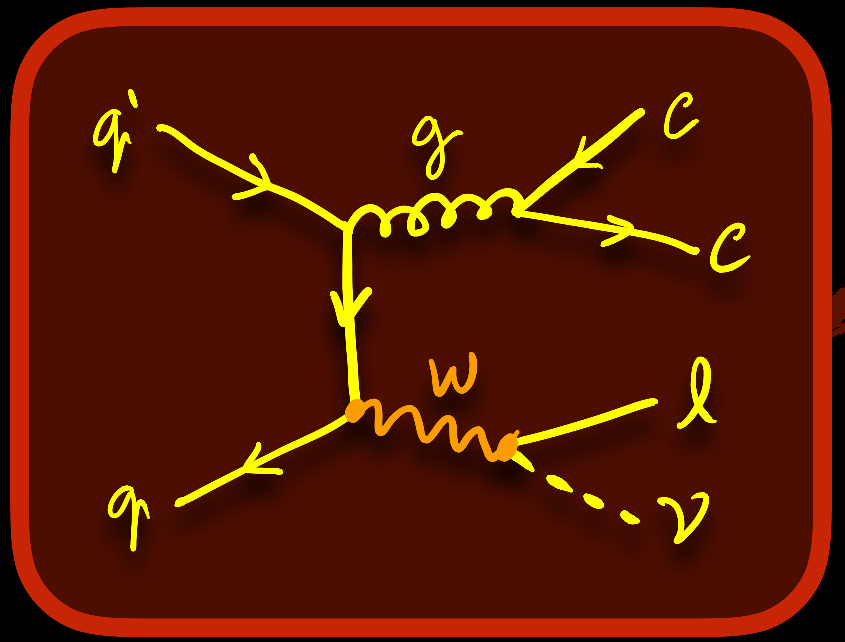


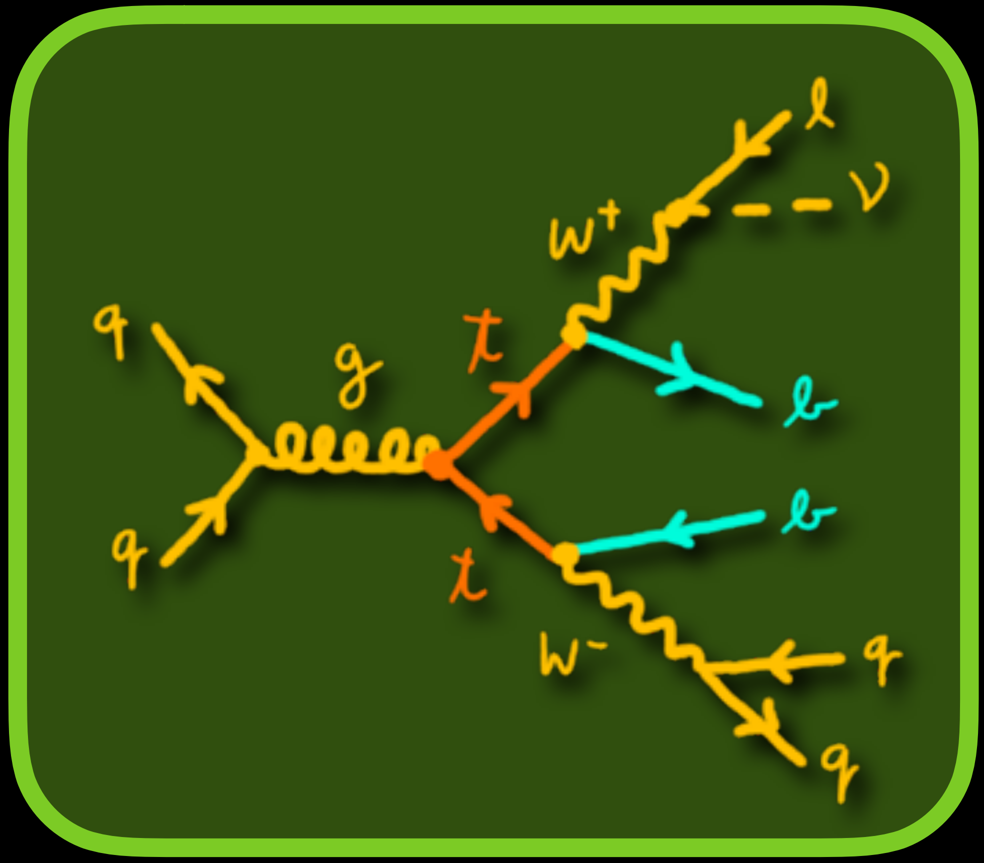
Forward **W+bb**, **W+cc** and **top-quark** production

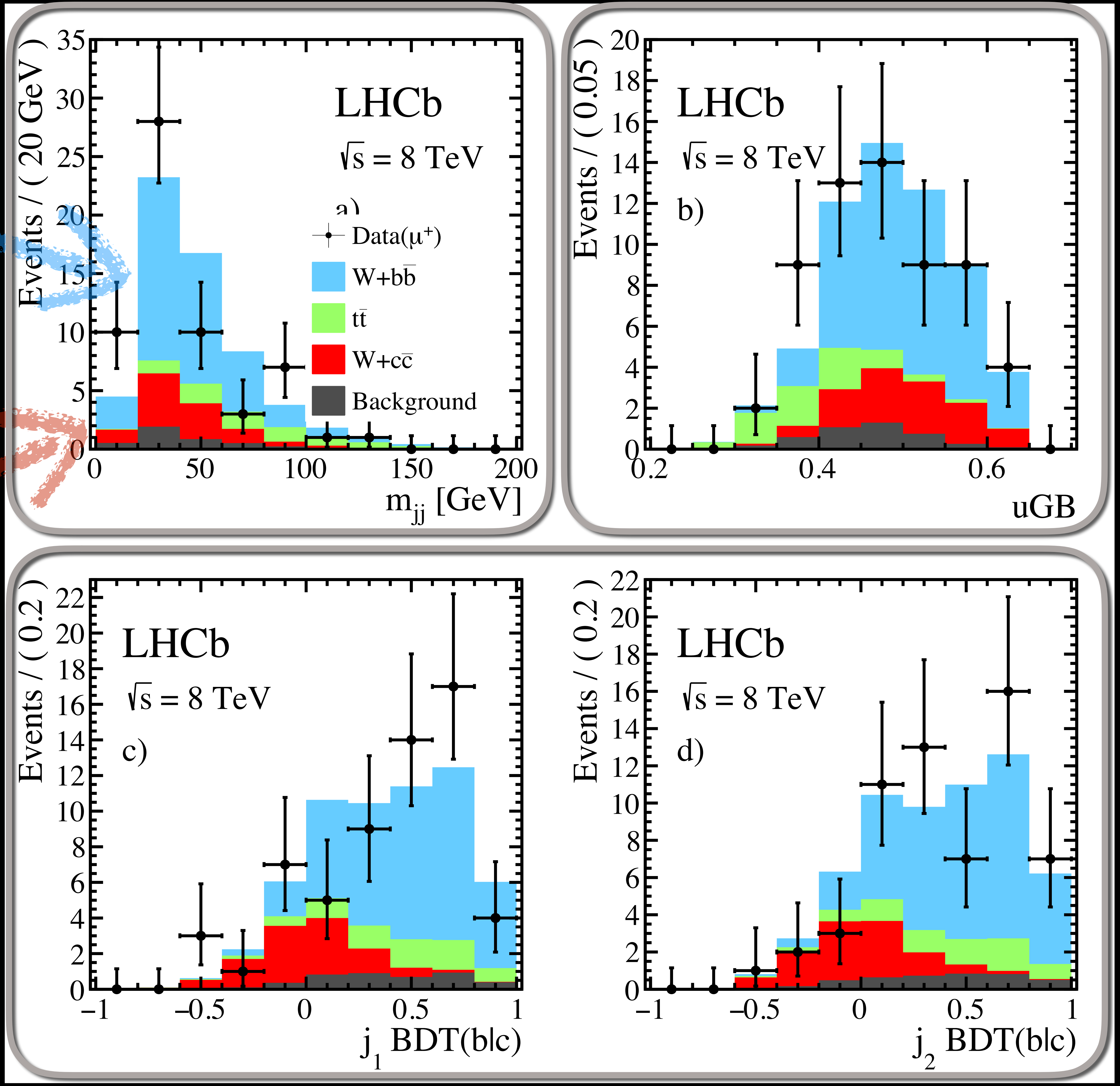
Phys. Lett. B767 (2017) 110

Simultaneous 4D fit to μ^+, μ^-, e^+, e^- samples









Fit projection in the μ^+ sample

Variables

m_{jj}: Dijet mass

uGB: MVA to separate Wbb from top

BDT (blc) for both jets to separate b from c

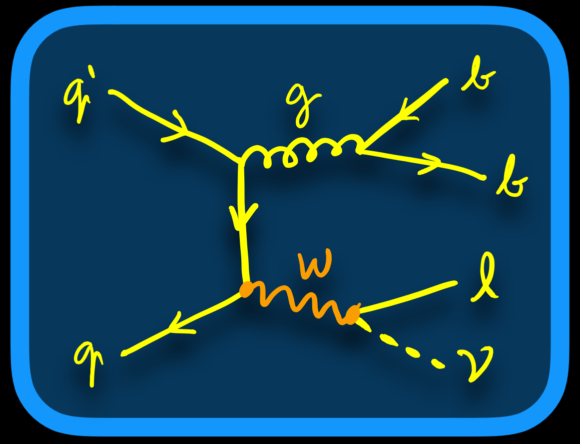
Fit:

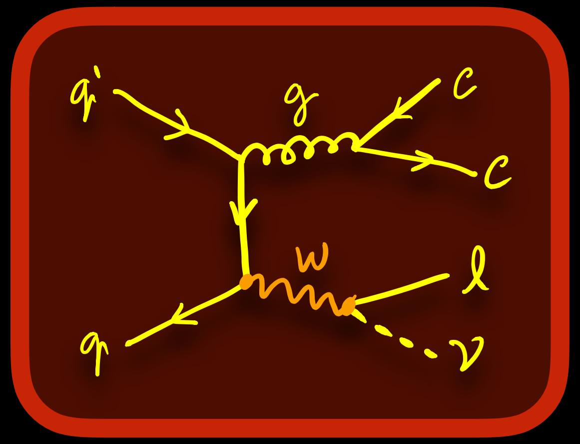
- Wbb, Wcc and tt floating
- Background fixed to theory

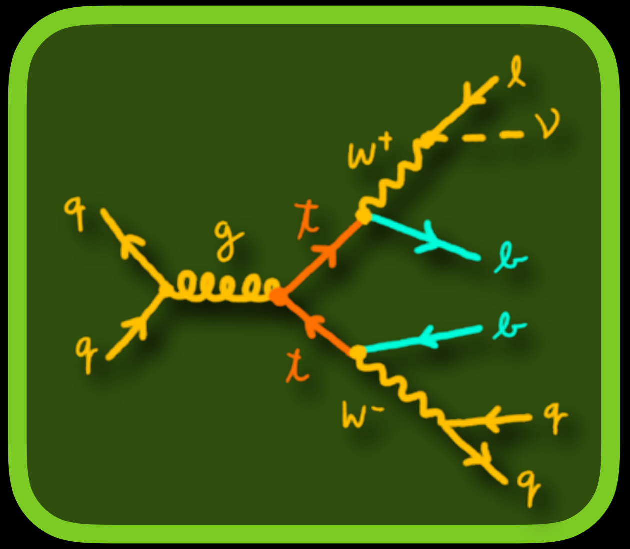
Forward W+bb, W+cc and top-quark production

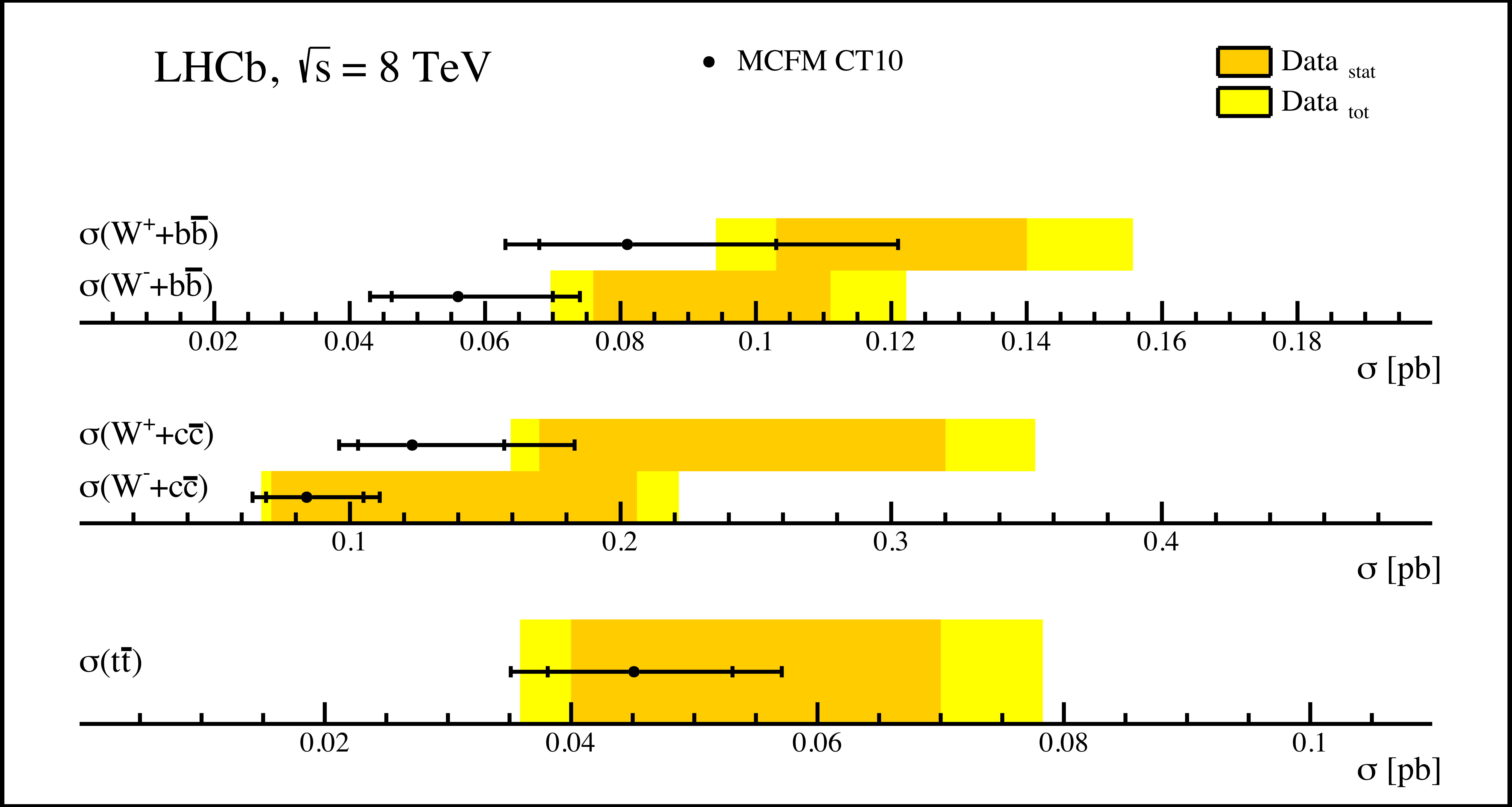
Phys. Lett. B767 (2017) 110

Cross sections and theoretical predictions in the LHCb fiducial region







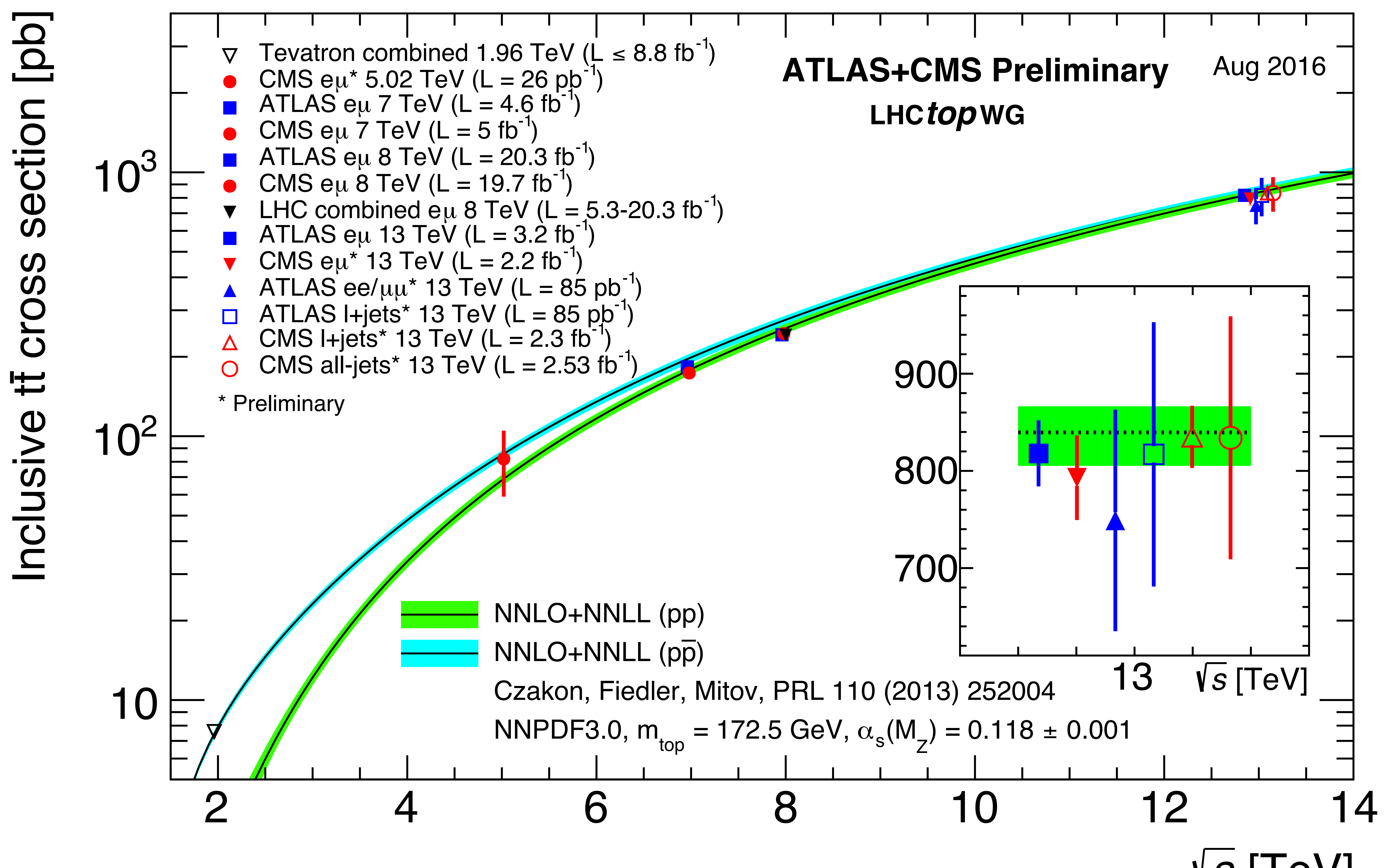


Sample	Significance
$t\bar{t}$	4.9σ
$W^+ + b\bar{b}$	7.1σ
$W^- + b\bar{b}$	5.6σ
$W^+ + c\bar{c}$	4.7σ
$W^- + c\bar{c}$	2.5σ

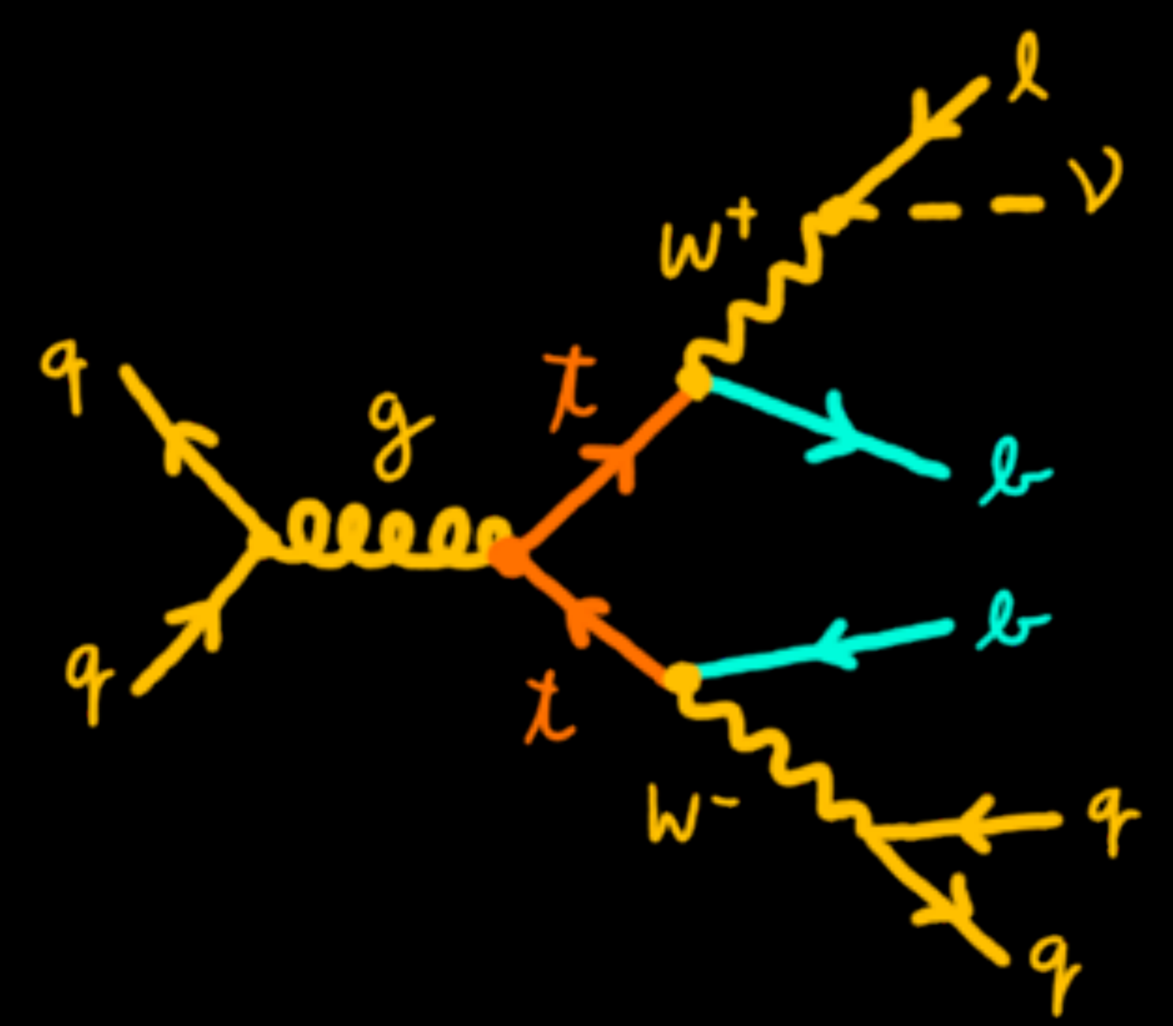
Good agreement with NLO theoretical prediction: MCFM with CT10 + Phytia 8

See: LHCb parallel talk by Marcin Kucharczyk

Top quark pair production



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryPlots



Top pair production

Consistent across all channels

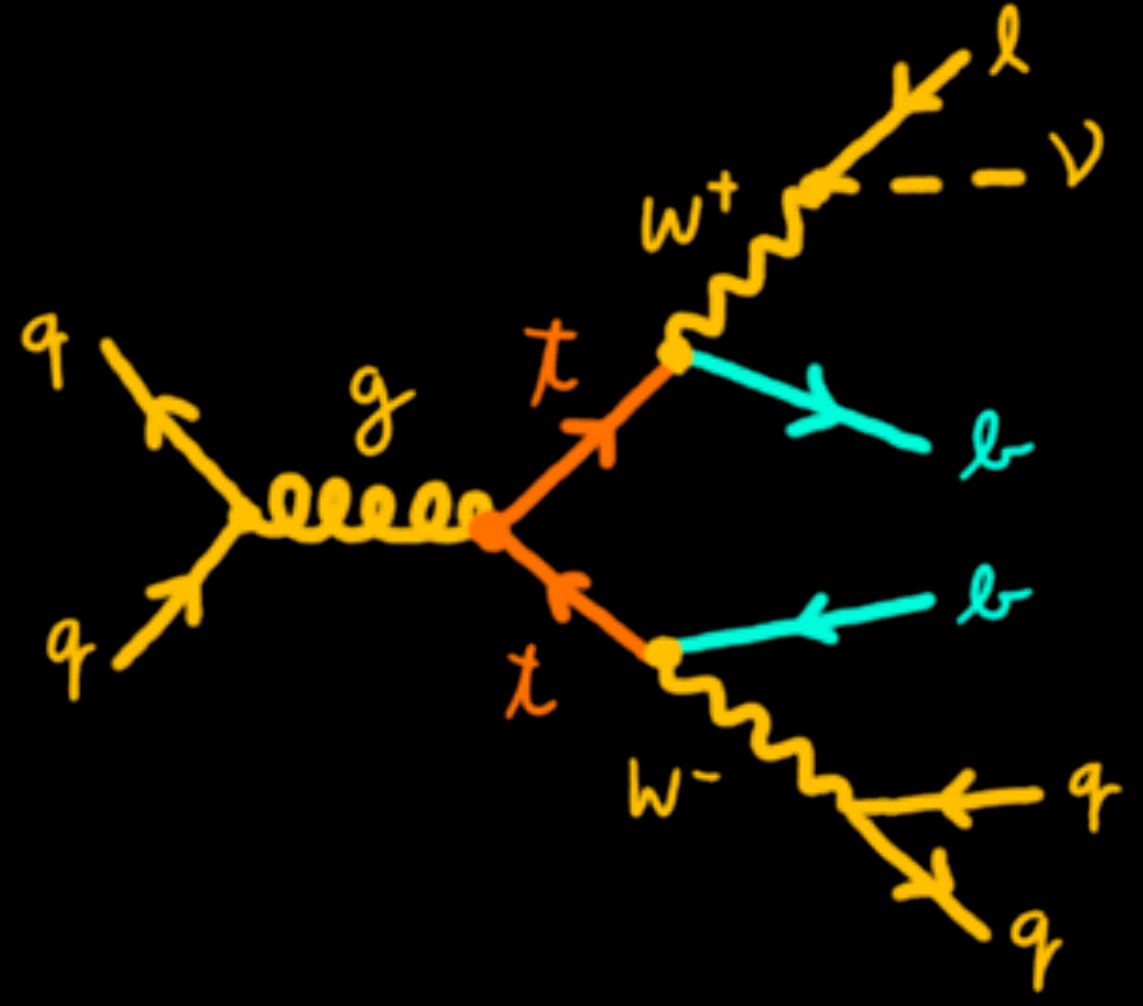
(Experimental uncertainty: ~ 2.5-15%)

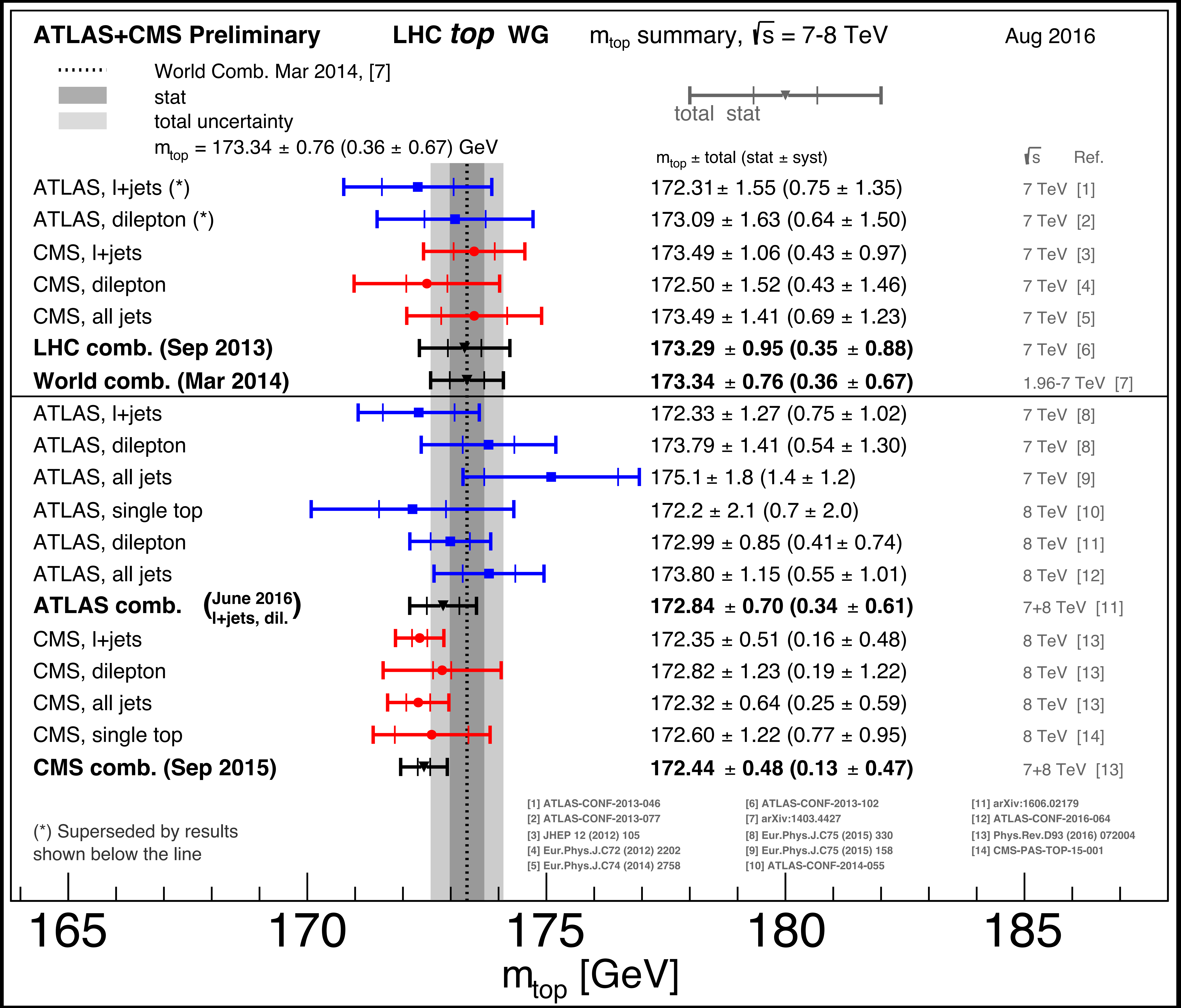
NNLO + NNLL QCD prediction

Start constraining gluon PDFs!

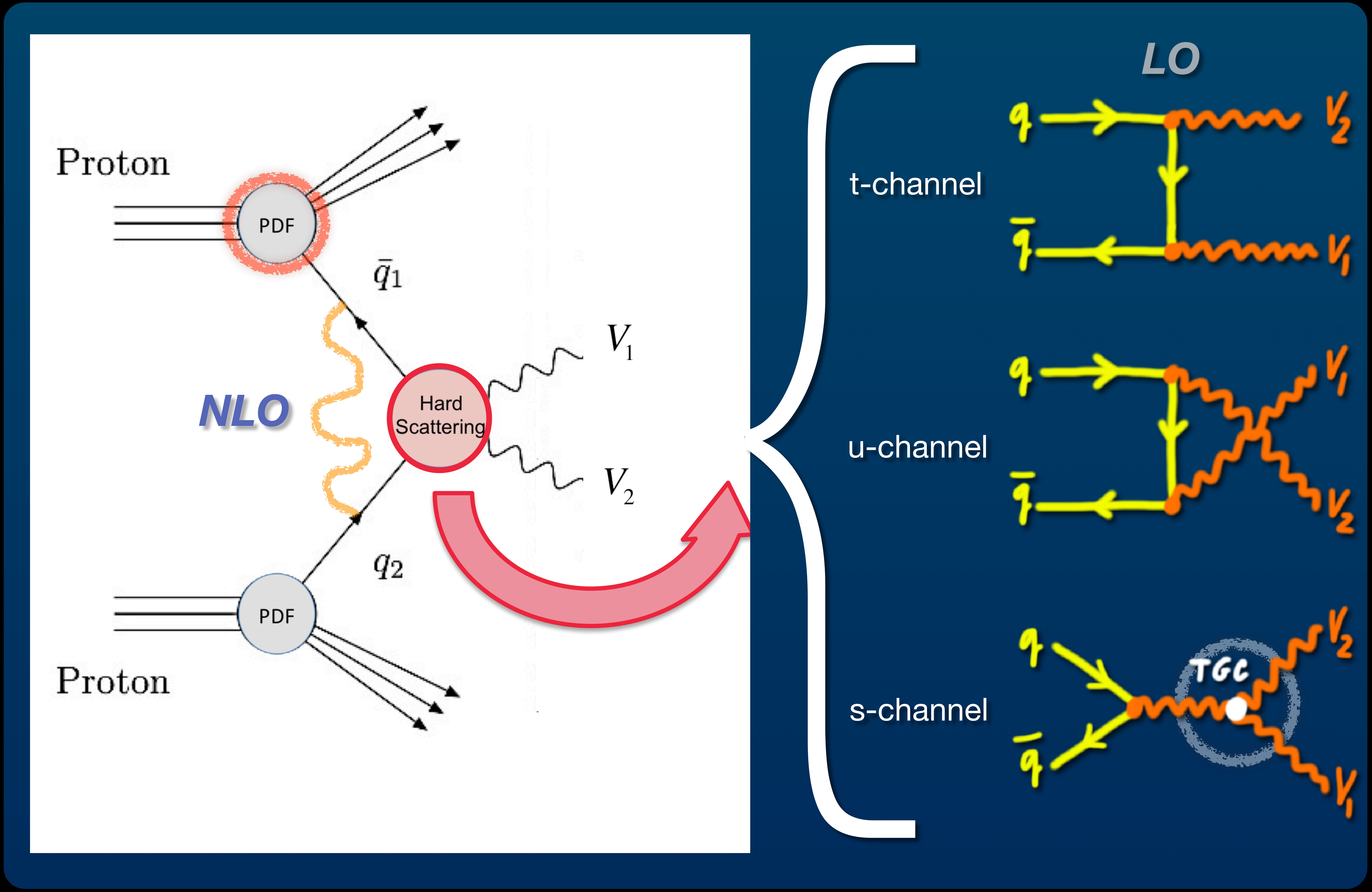
Top quark mass measurements

Measured in different channels with different techniques



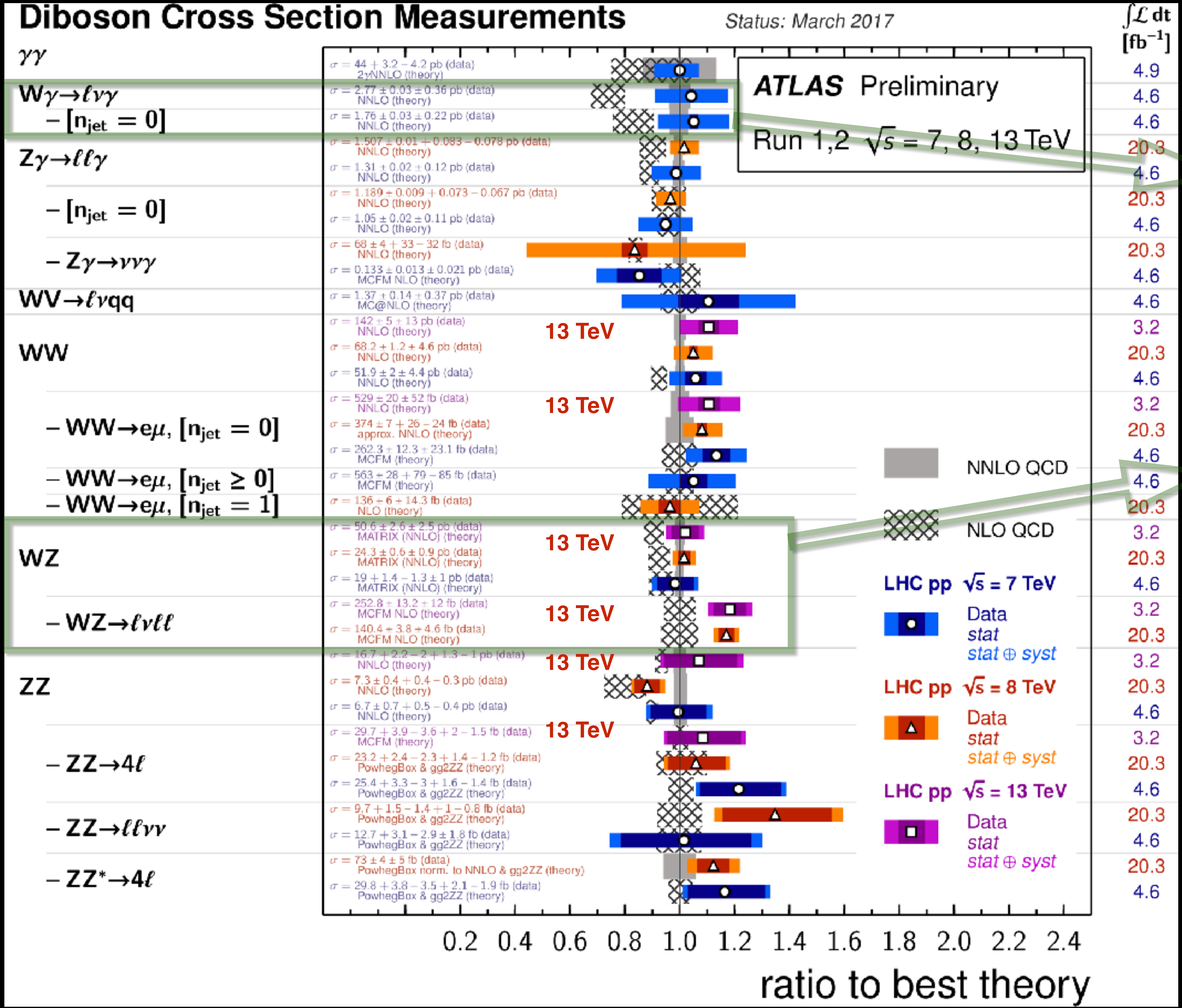


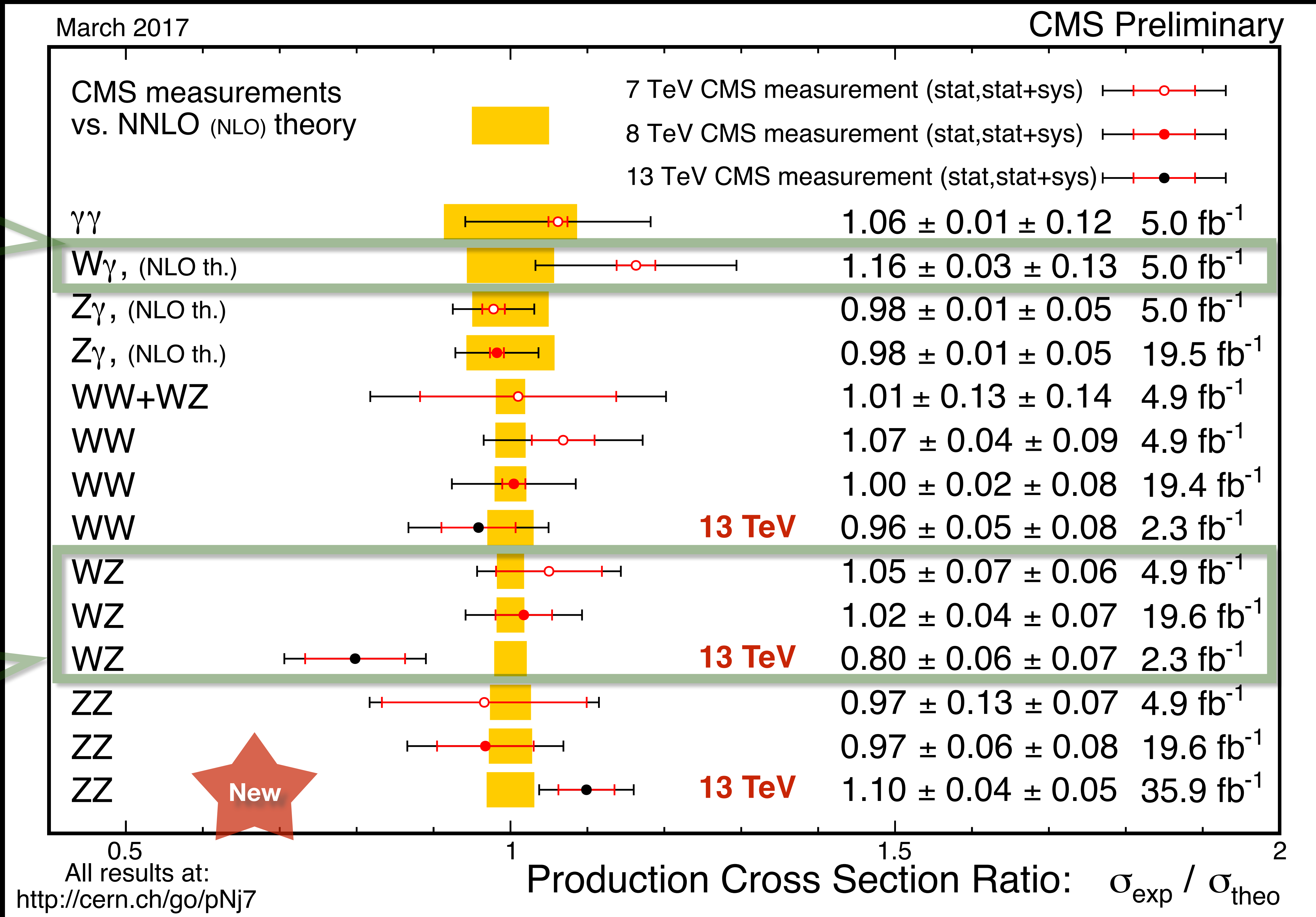
Diboson production at the LHC



Inclusive diboson cross sections summary

ATLAS and CMS have performed extensive studies of diboson production:



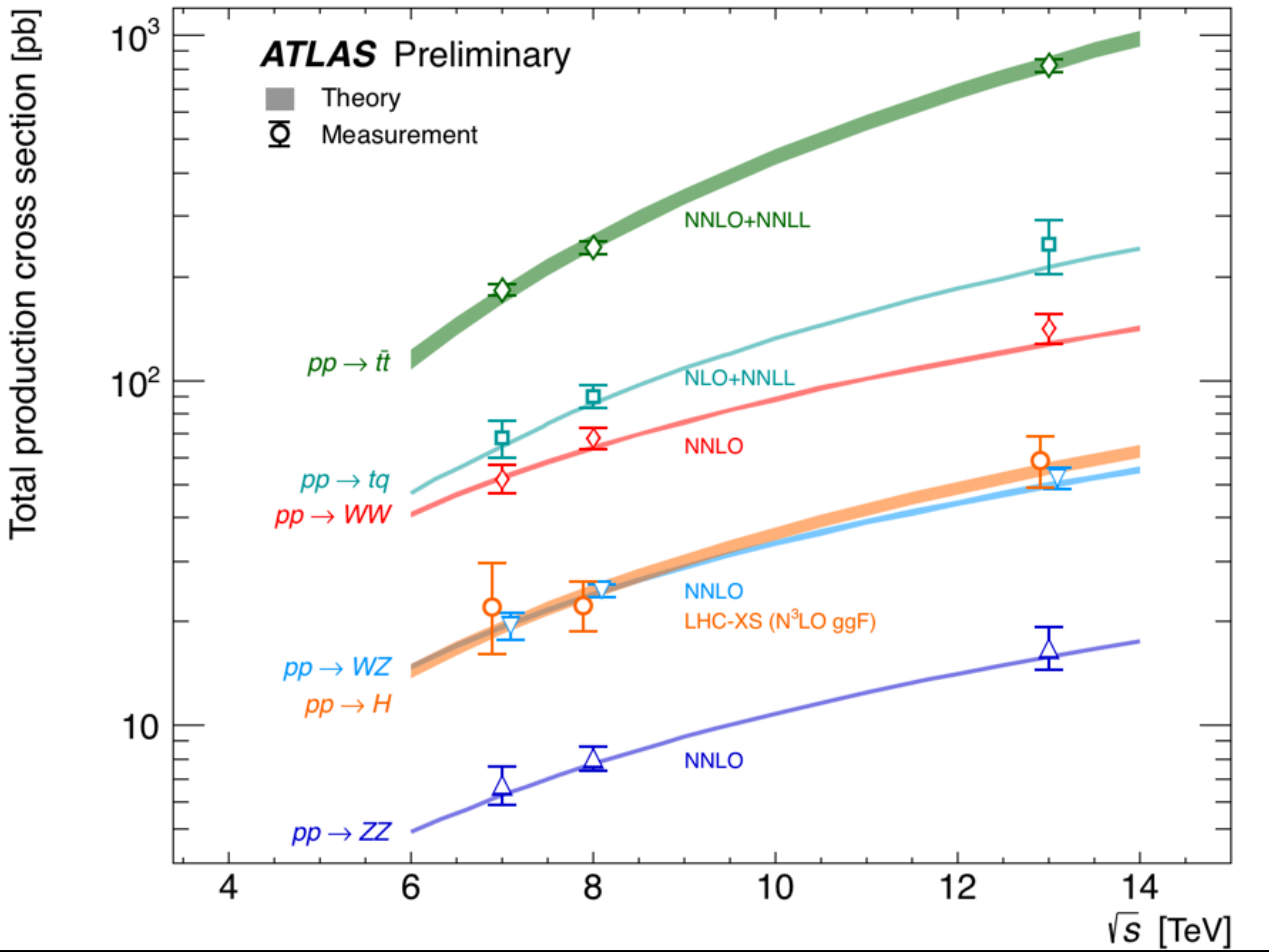


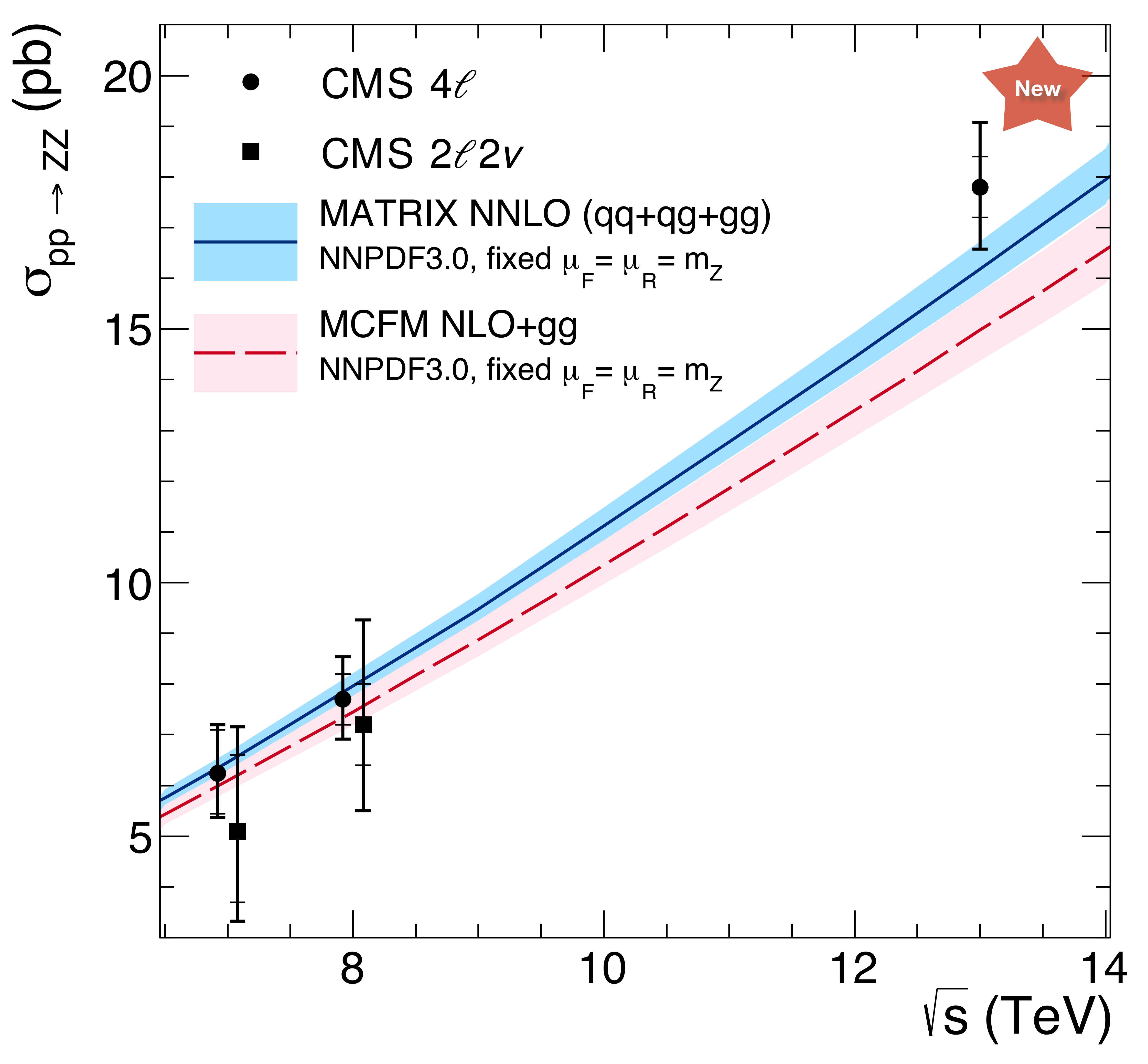
7, 8, 13 TeV: WW, WZ and ZZ
7, 8 TeV: Zγ
7 TeV: Wγ

Good agreement with theory calculations (NNLO or NLO QCD, LO QED)

arXiv.1504.01330
arXiv: 1604.08576

ZZ production cross section



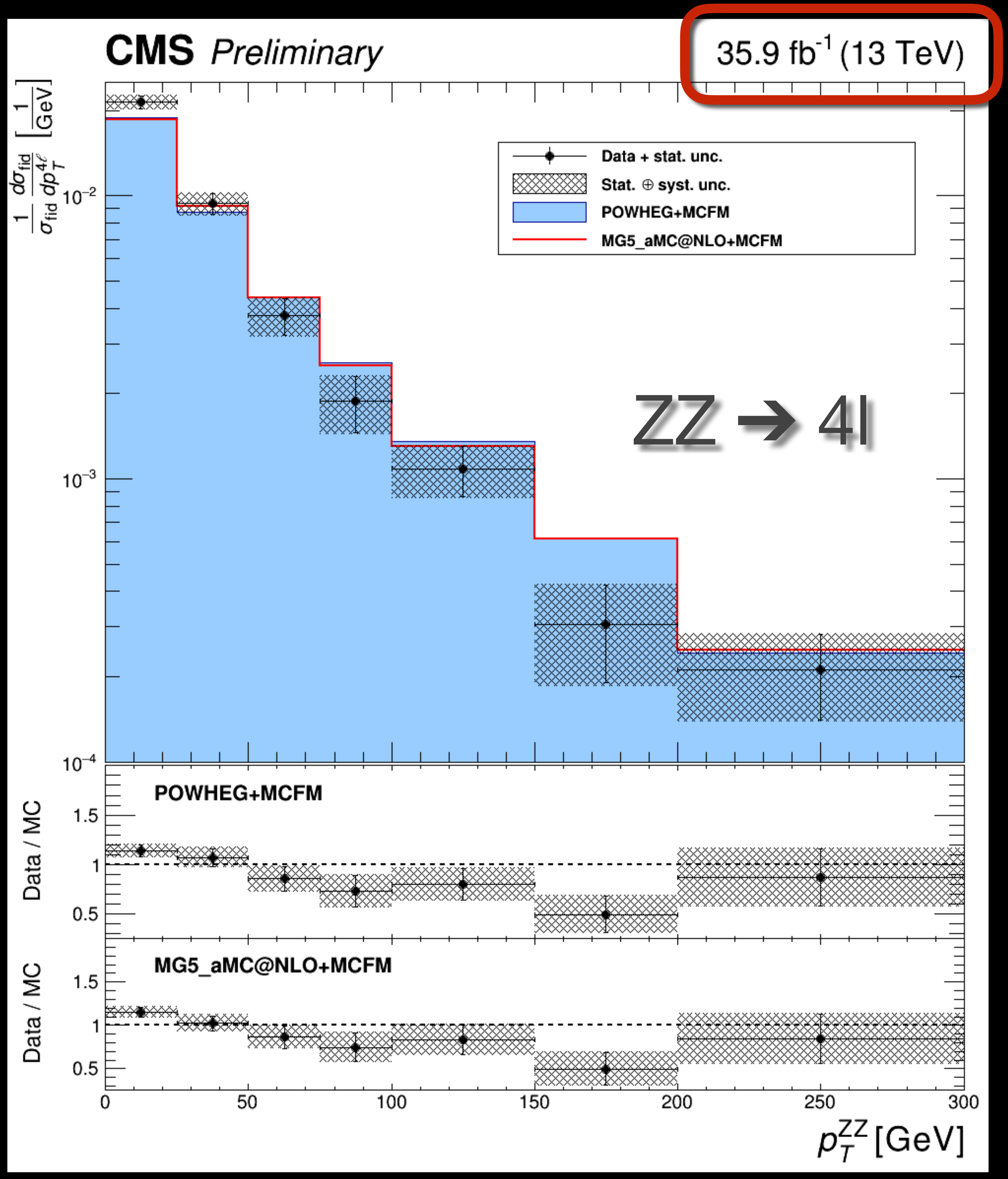


First diboson measurement with full 2016 dataset

Diboson differential cross sections

CMS-PAS-SMP-16-017

New

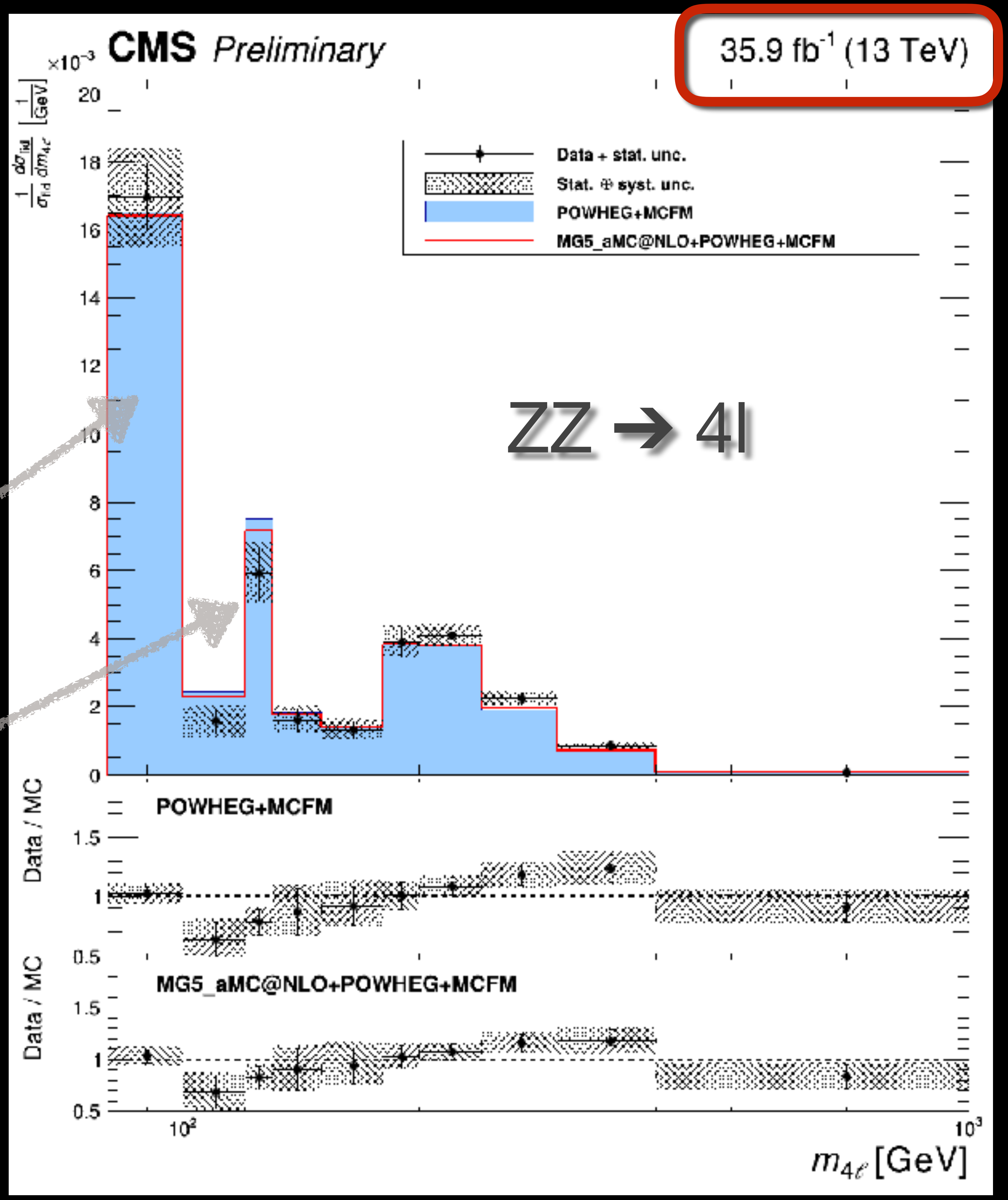


Softer p_T^{ZZ} then predicted by NLO QCD

Normalized differential cross sections

Z boson

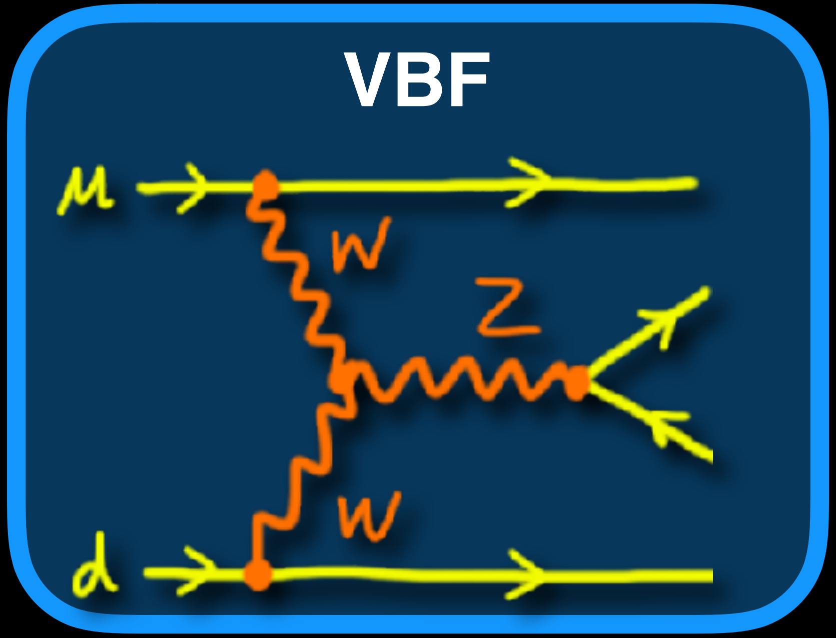
Higgs

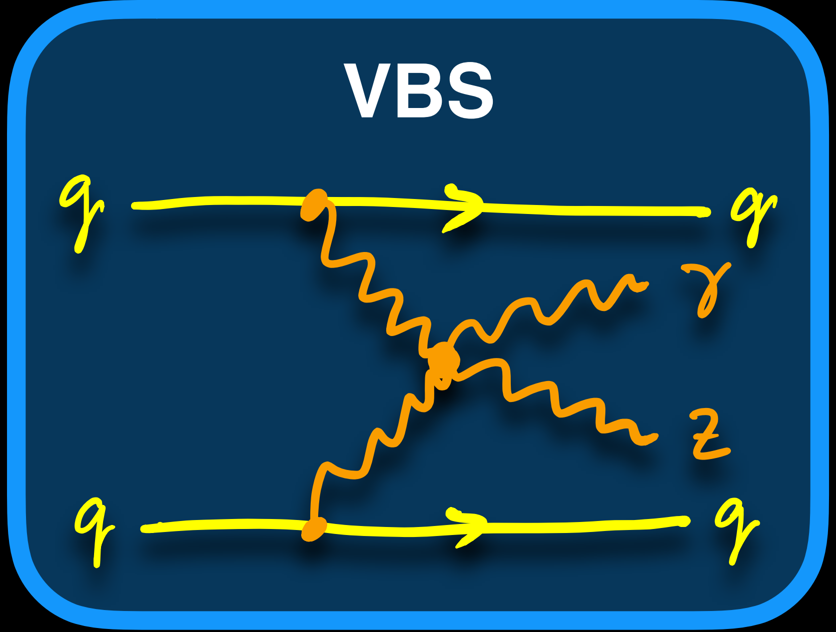


Study different production mechanisms

No deviations observed in the differential kinematic distributions for Wγ, Zγ, WW, WZ or ZZ

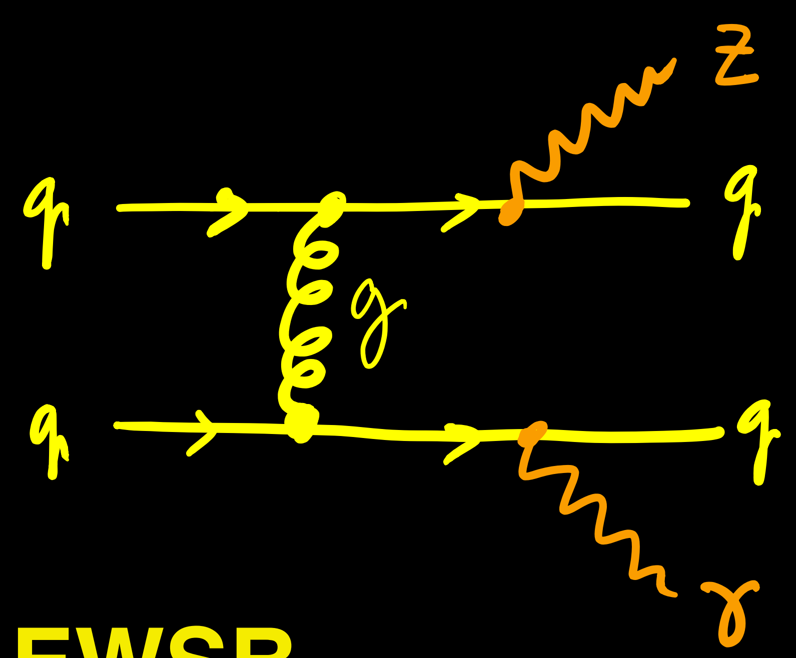
Electroweak production: Vector Boson(s) + 2 jets





V(V) + 2 jets production is dominated by O(α_S^2) QCD processes

- evaluated from data in control region or from simultaneous fit



EWK V(V) + 2 jets production is essential to probe the nature of the EWSB

- characteristic signature: two high-p_T jets in the forward-backward region with:
  - large rapidity separation
  - low hadronic activity in-between

First observation of EWK V+2 jets with 8-TeV data

First evidence for EWK VV+2 jets with 8 TeV data

EWK measurements: V(V)+2jets		ATLAS (8 TeV)	CMS (8 TeV)
Diboson (statistics dominated)	**W±(lν)W±(lν)**	PRL 113, 141803, arxiv:1611.02428 **Evidence:** EWK signal significance 3.6σ (exp	PRL 114 (2015) 051801 EWK signal significance 1.9σ (exp 2.9σ)
	W(lν)γ	-	CMS-PAS-SMP-14-011 EWK signal significance 2.7σ (exp 1.5σ)
	Z(ll)γ	STDM-2015-21 EWK signal significance 2.0σ (exp 1.8σ) New	CMS-PAS-SMP-14-018 **Evidence:** EWK signal significance 3.0σ (exp 2.1σ)
Single boson (systematic dominated)	**Z(ll)**	JHEP 04 (2014) 031 **Observation:** EWK signal significance ~5σ	EPJC 75 (2015) 66 **Observation:** EWK signal significance ~5σ
	W(lν)	arXiv:1703.04362 **Observation:** EWK signal significance >5σ New	JHEP 11 (2016) 147 **Evidence:** EWK signal significance ~4σ

Zγ electroweak production in association with a high-mass dijet system

Vector Boson Scattering

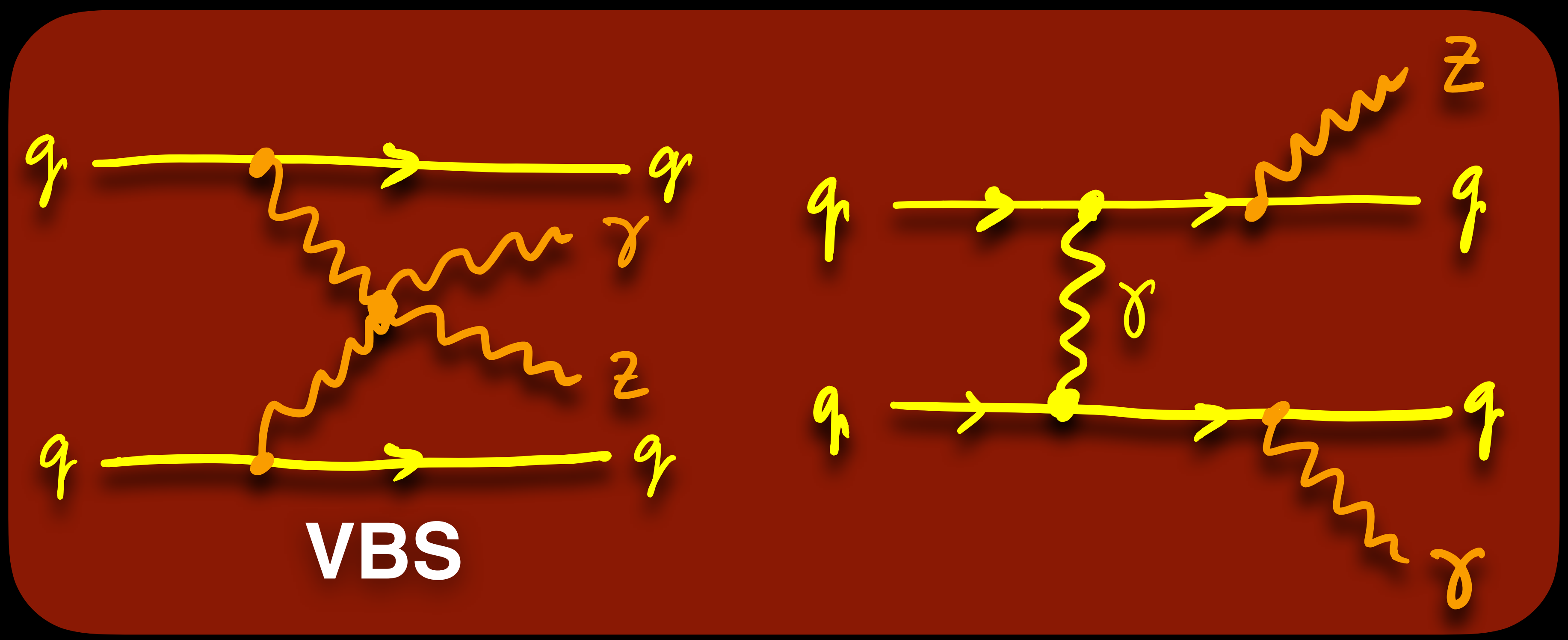
New

$Z \to l^+l^-$ and $Z \to \nu\,\nu$

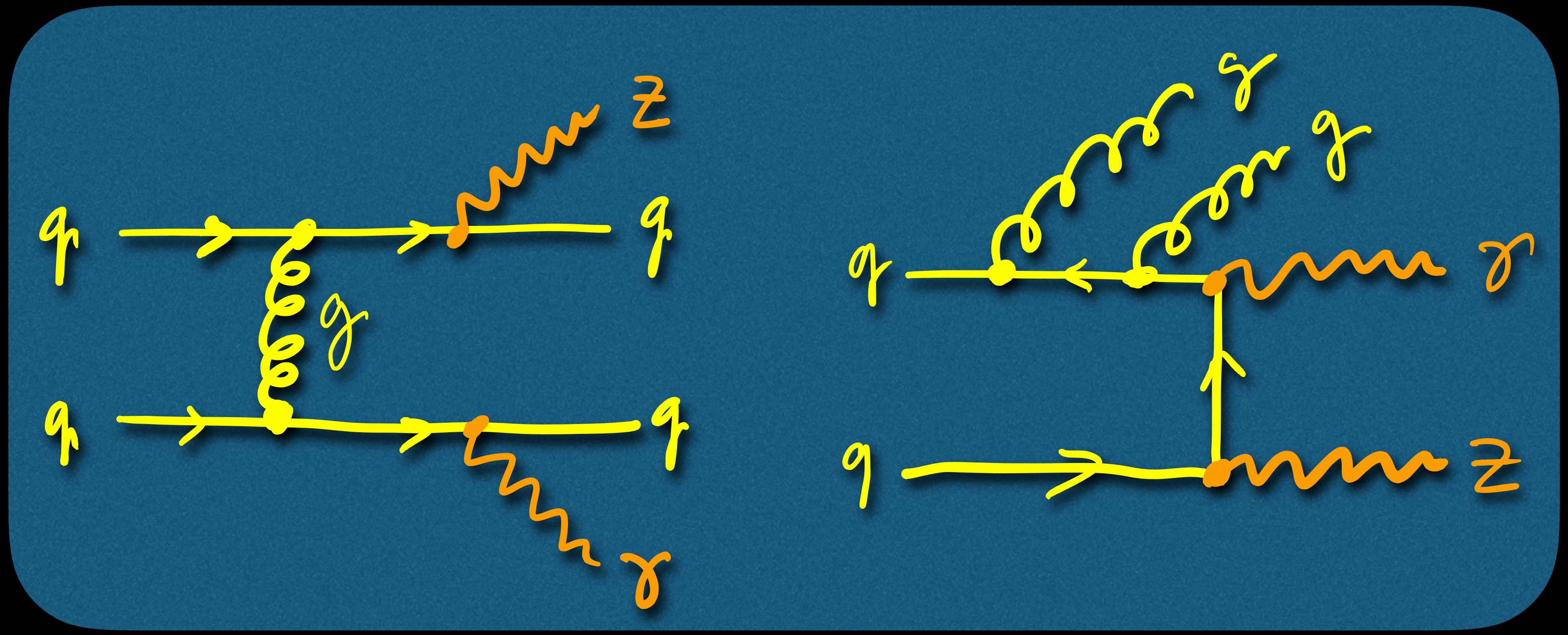
Cross section extracted from likelihood fit on centrality of Zγ

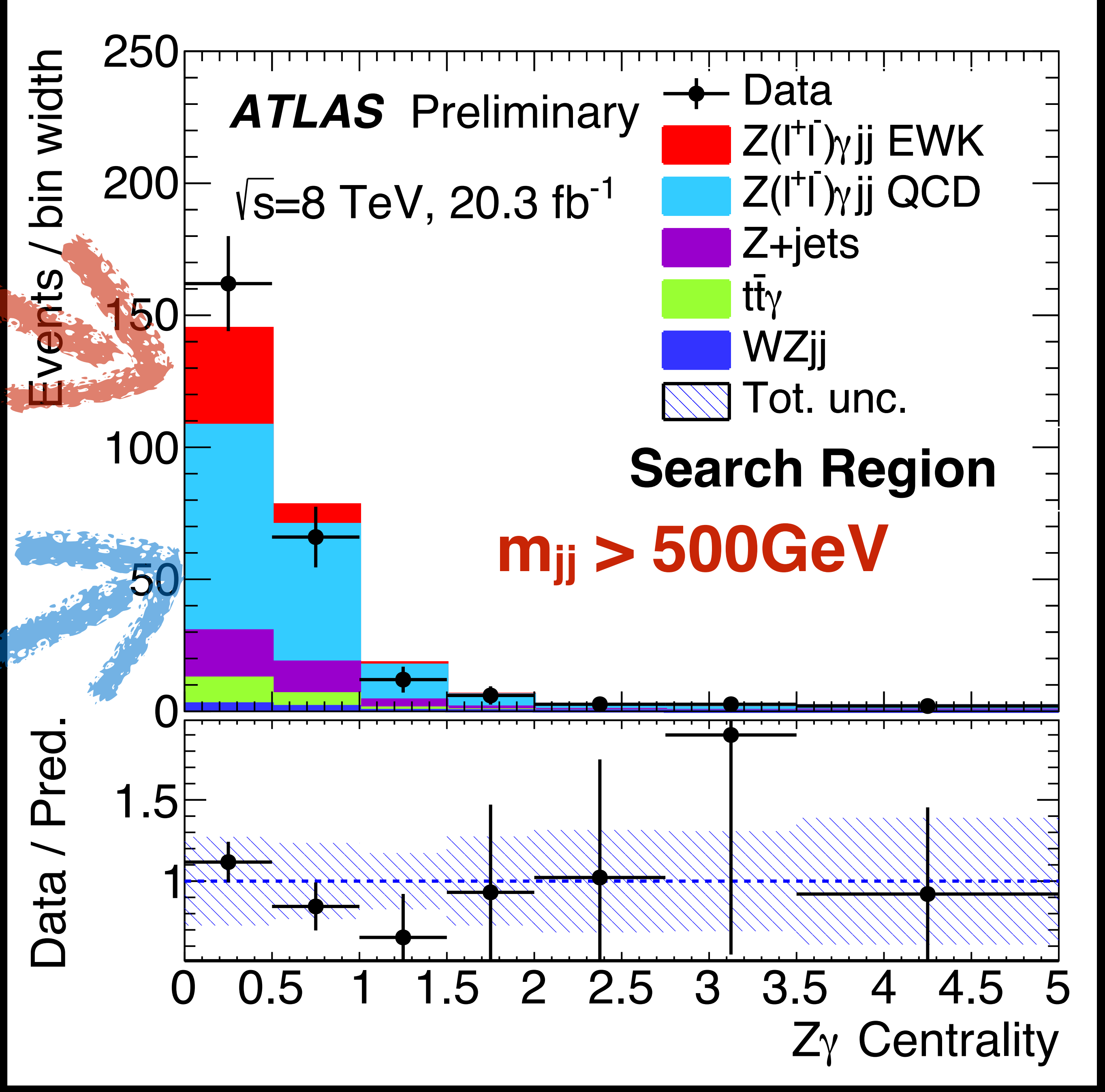
$$\zeta \equiv \left|\frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}}\right| \quad \text{with} \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}$$

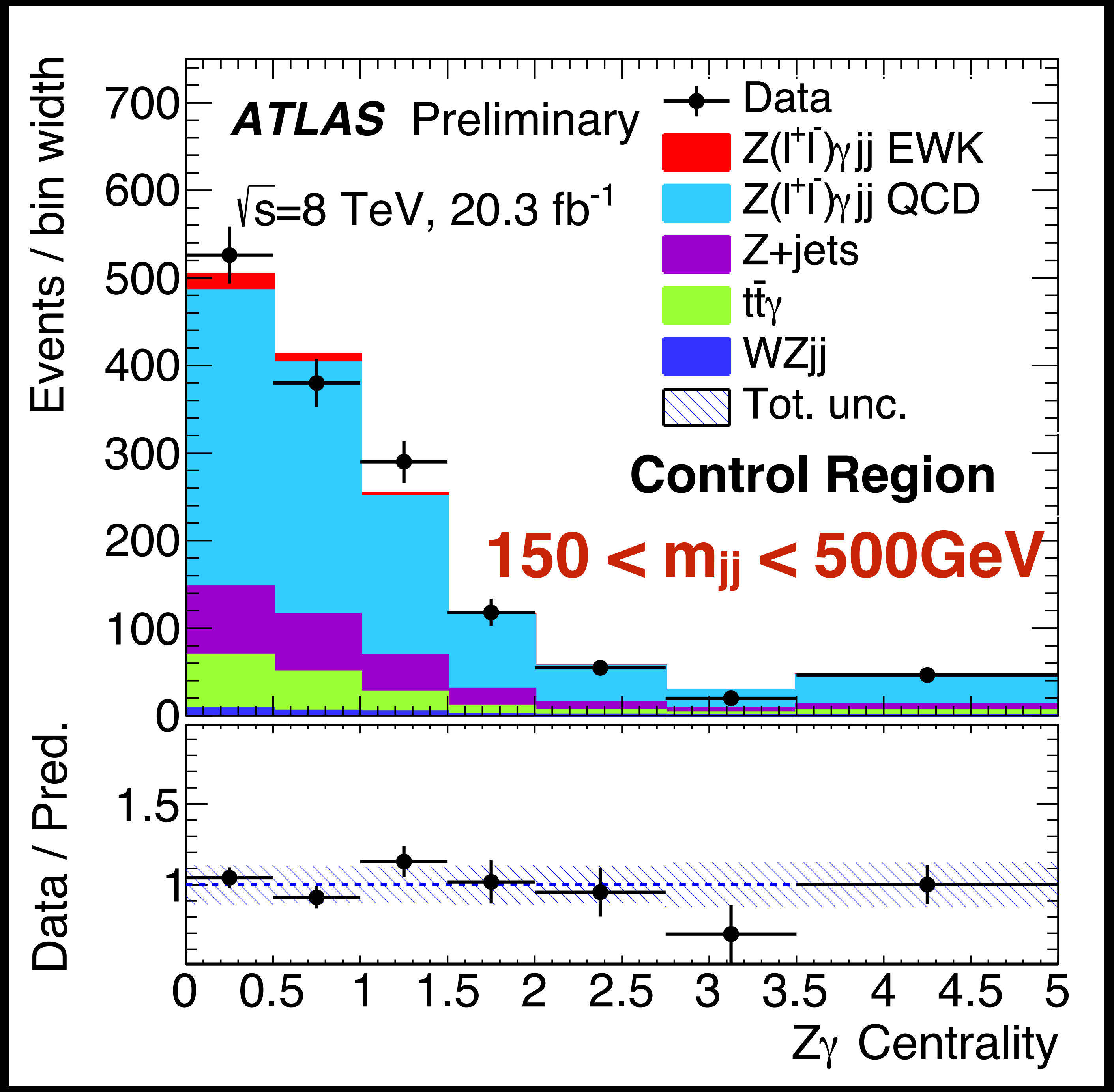
Electroweak processes



QCD processes

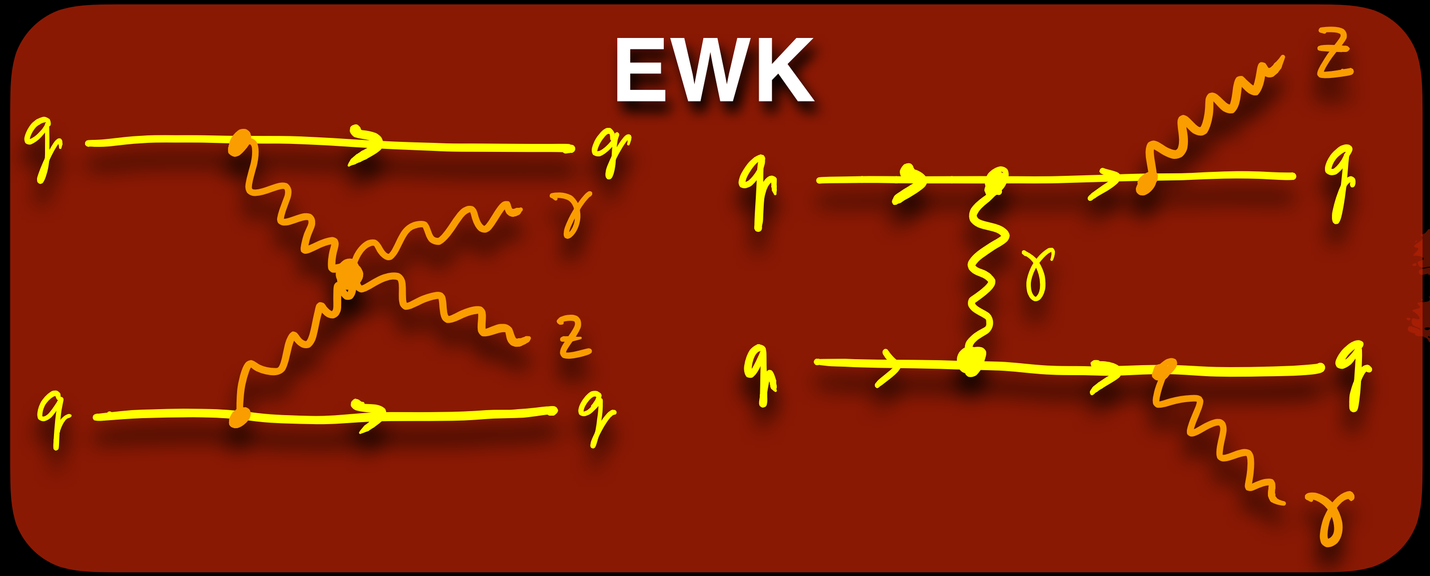


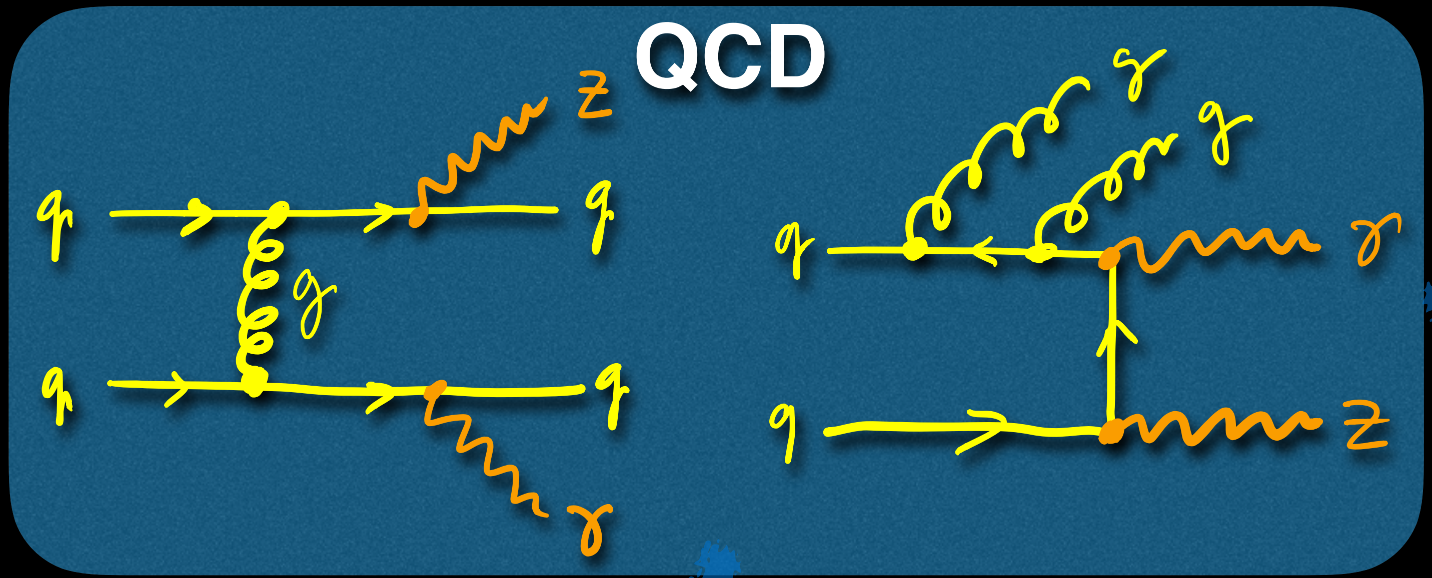


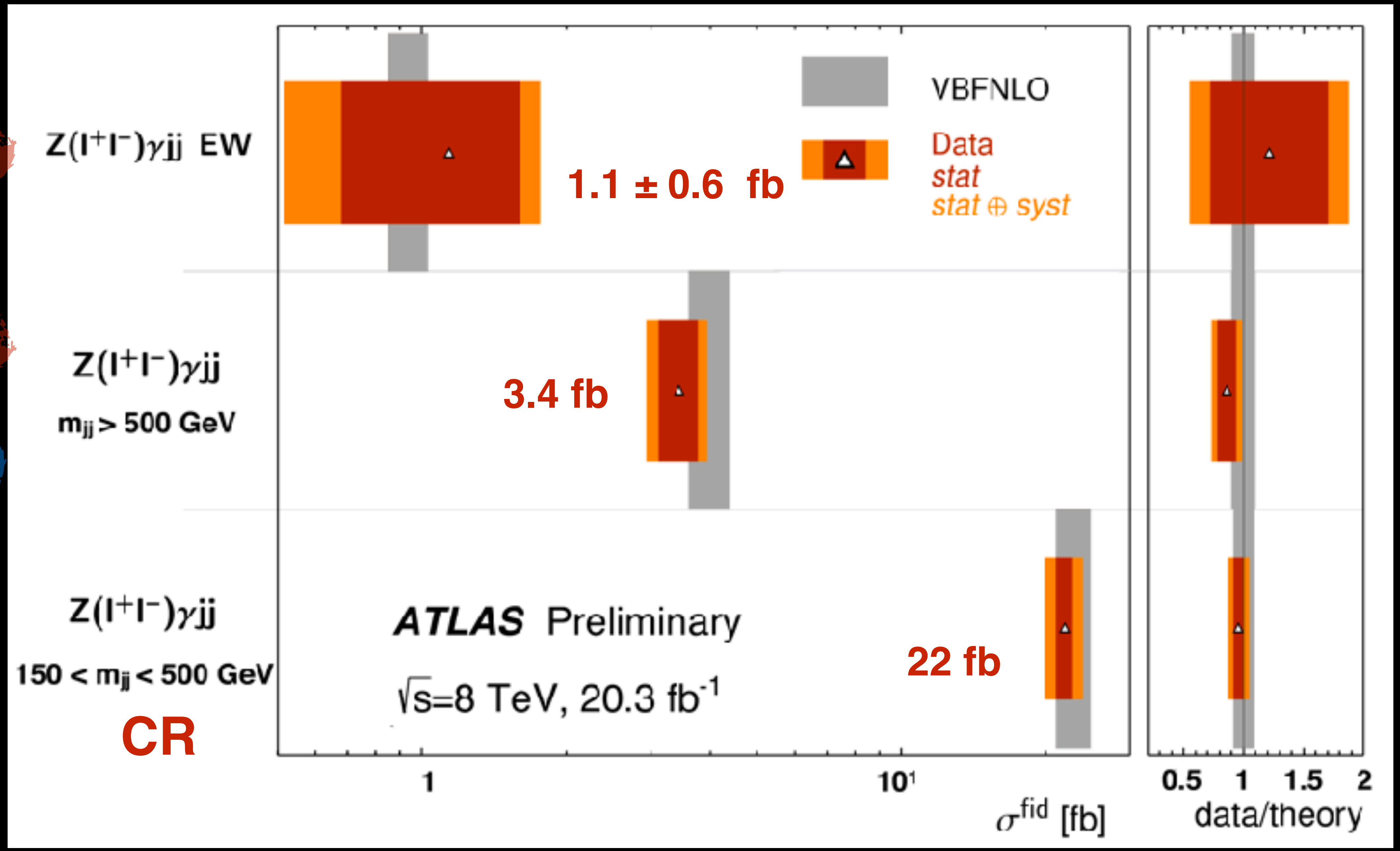


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-21/

Zγ electroweak production in association with a high-mass dijet system

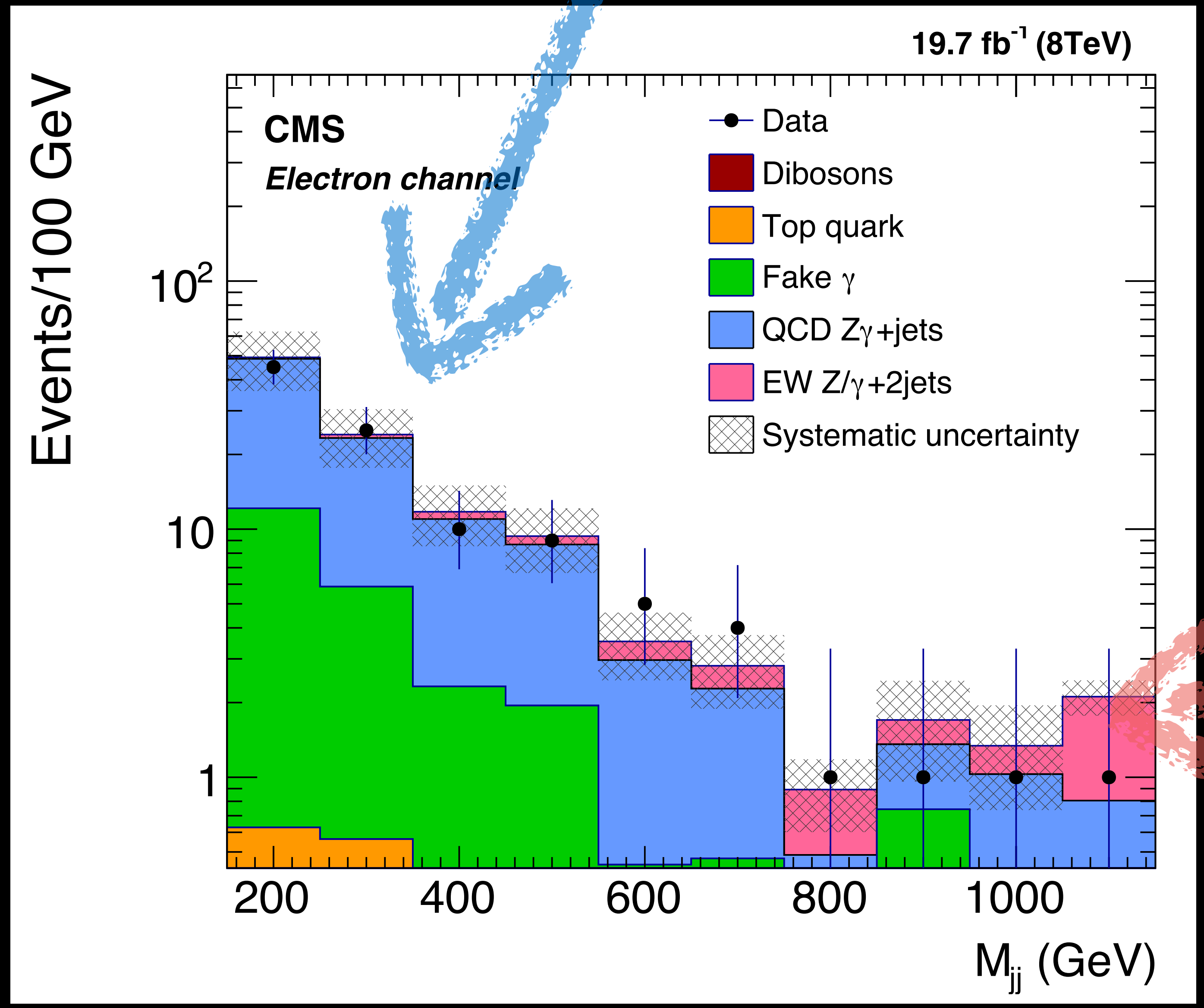






2.0σ (exp 1.8σ)

Measurement is statistics dominated



Similar analysis from CMS

Two bins: 400 < m_{jj} < 400 GeV; m_{jj} > 800 GeV

$$|y_{Z\gamma} - (y_{j1} + y_{j2})/2| < 1.2,\ |\Delta\eta_{jj}| > 1.6, \text{ and } \Delta\phi_{Z\gamma,jj} > 2.0 \text{ radians}$$

Evidence for EWK Zγ jj production

Significance: 3.0 σ (exp 2.1 σ)

$$1.86^{+0.90}_{-0.75}\,(\text{stat})^{+0.34}_{-0.26}\,(\text{syst}) \pm 0.05\,(\text{lumi})\,\text{fb}$$

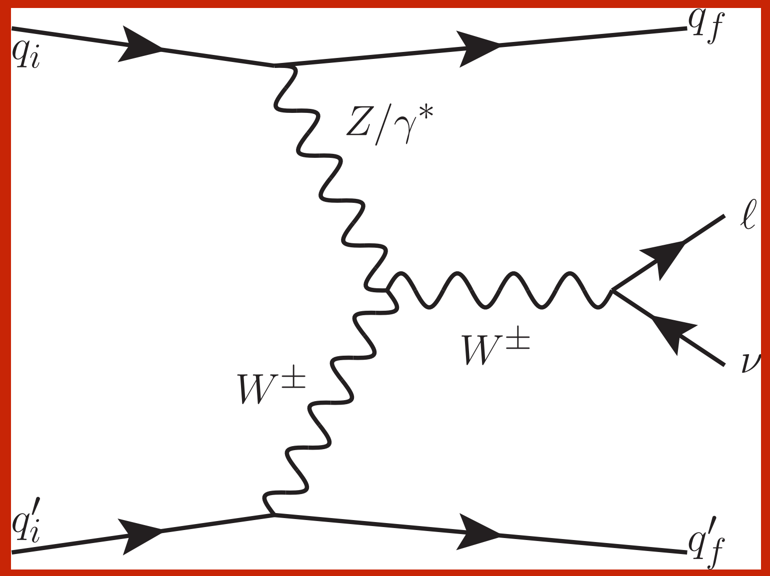
arXiv: 1702.03025v1

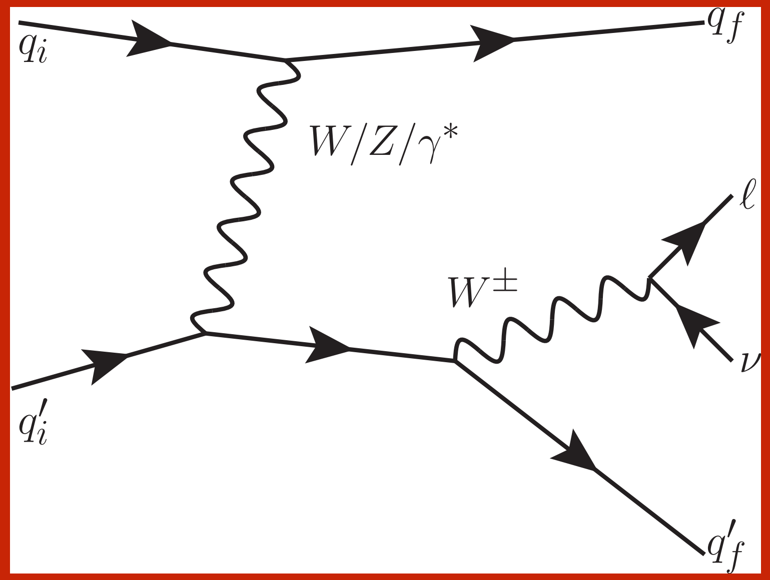
Electroweak W j j production

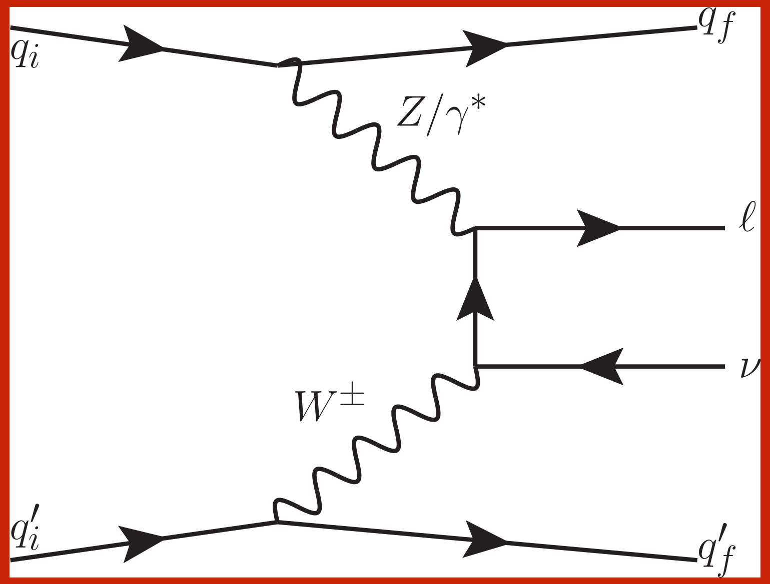
New

arXiv:1703.04362

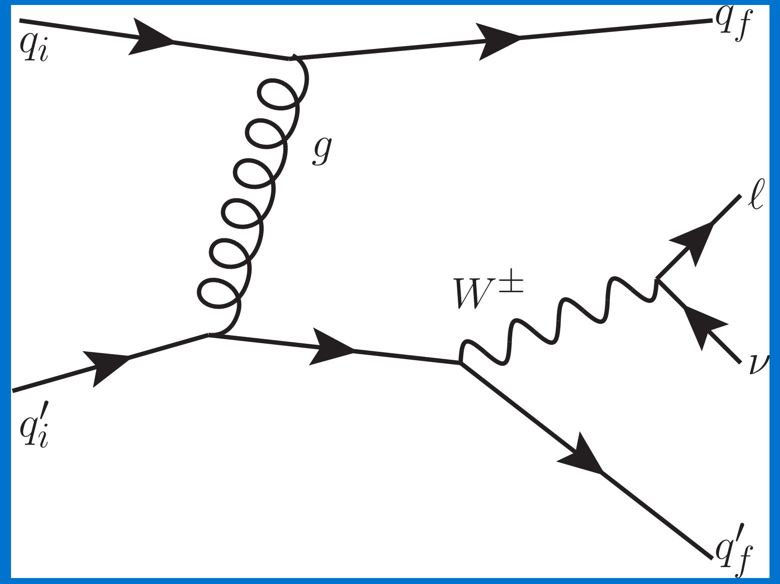
EWK Wjj production

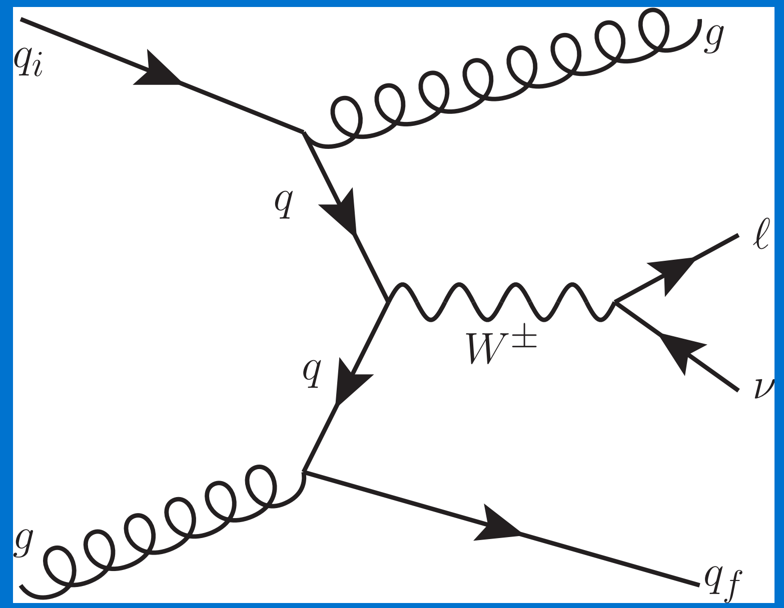


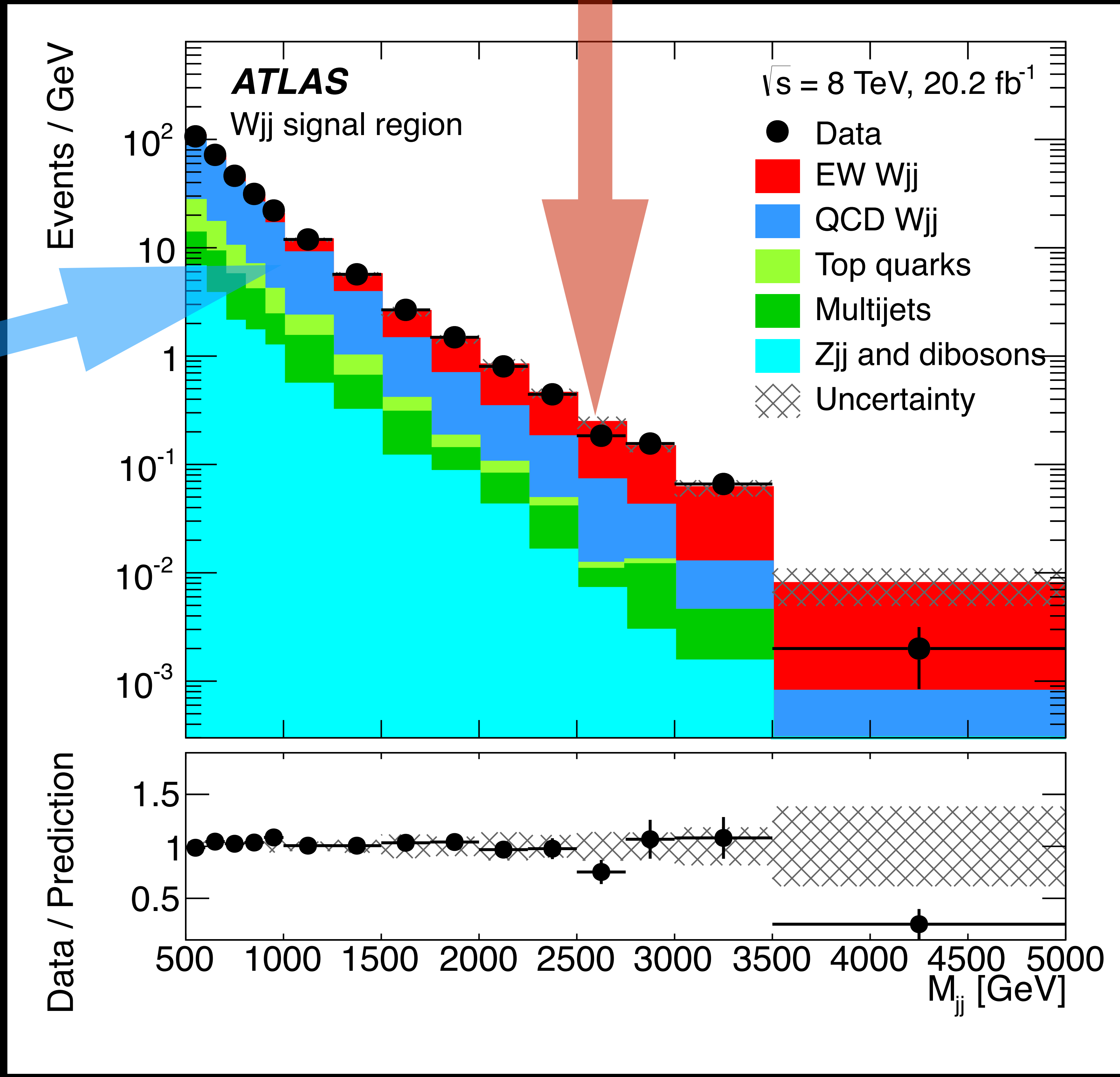




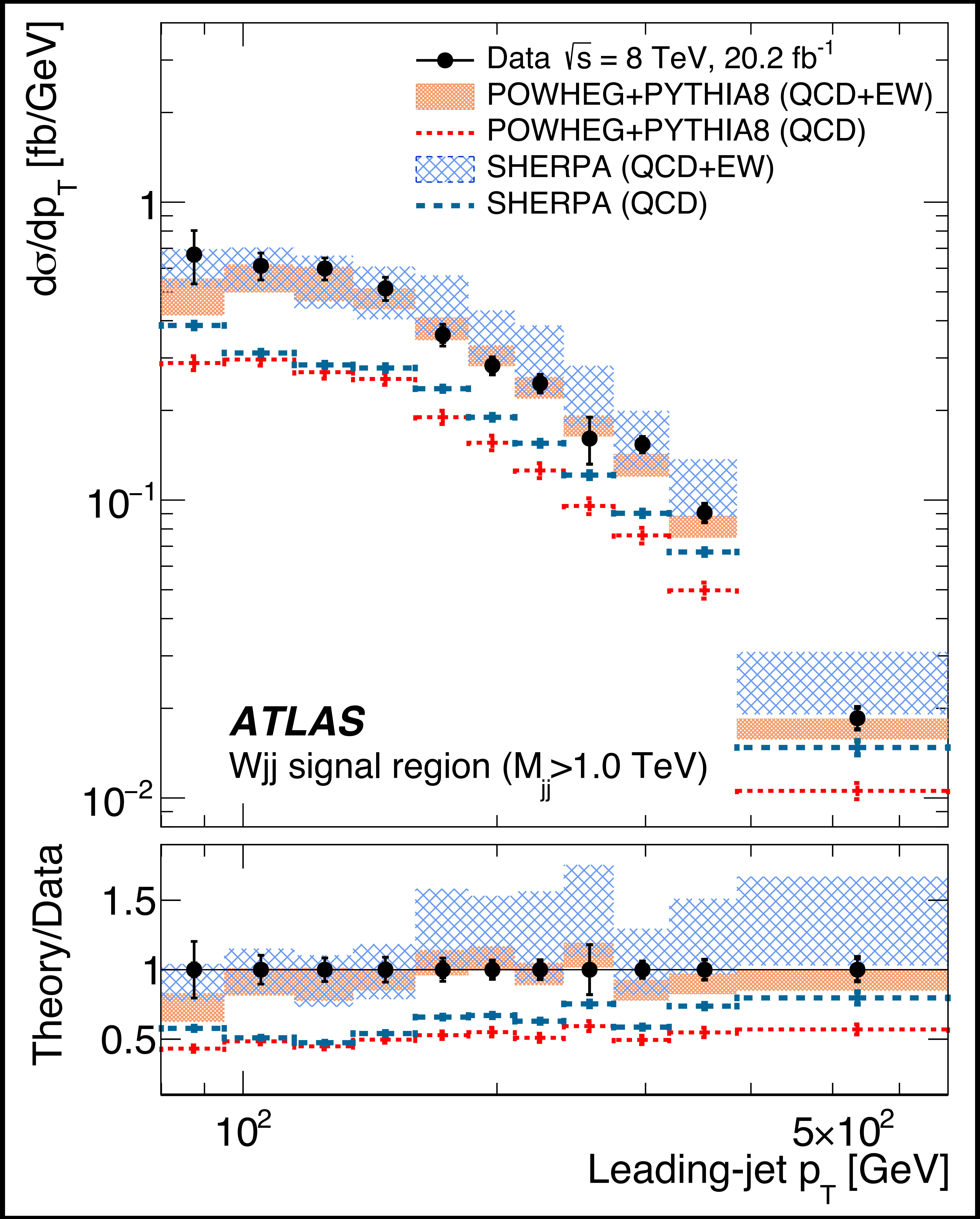
QCD Wjj production







Signal regions with M_{jj} > 0.5 TeV and 1.0 TeV



Predictions with EWK corrections agree with data

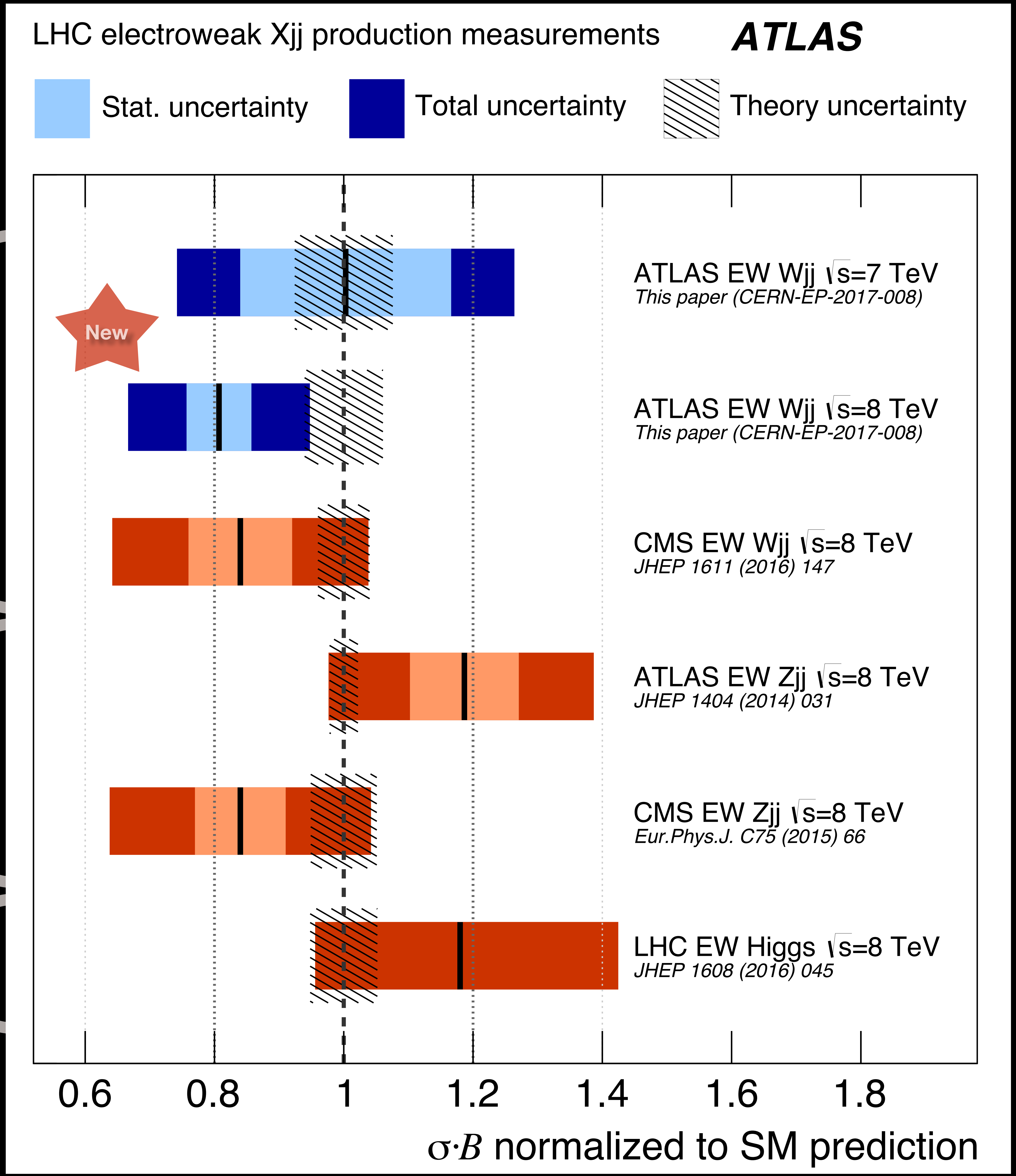
LHC electroweak Xjj production measurements

Summary of electroweak production results

WJJ

ZJJ

HJJ



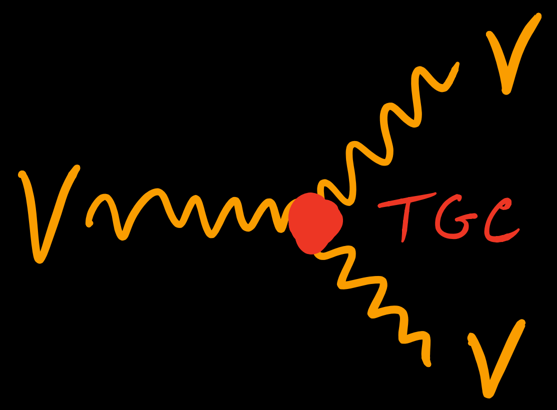
$$\sigma^{\text{fid}}_{\text{EW}\ W(\to\ell\nu)jj}\ (7\ \text{TeV}) = 144 \pm 23\ (\text{stat}) \pm 23\ (\text{exp}) \pm 13\ (\text{th})\ \text{fb}$$

$$\sigma^{\text{fid}}_{\text{EW}\ W(\to\ell\nu)jj}\ (8\ \text{TeV}) = 159 \pm 10\ (\text{stat}) \pm 17\ (\text{exp}) \pm 20\ (\text{th})\ \text{fb}$$

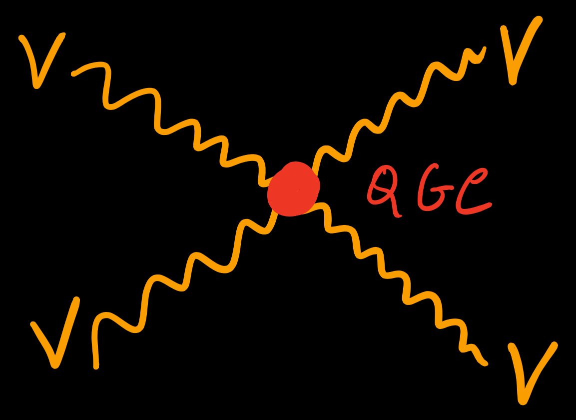
Dominant uncertainty is systematic: jet energy scale and resolution, PDF

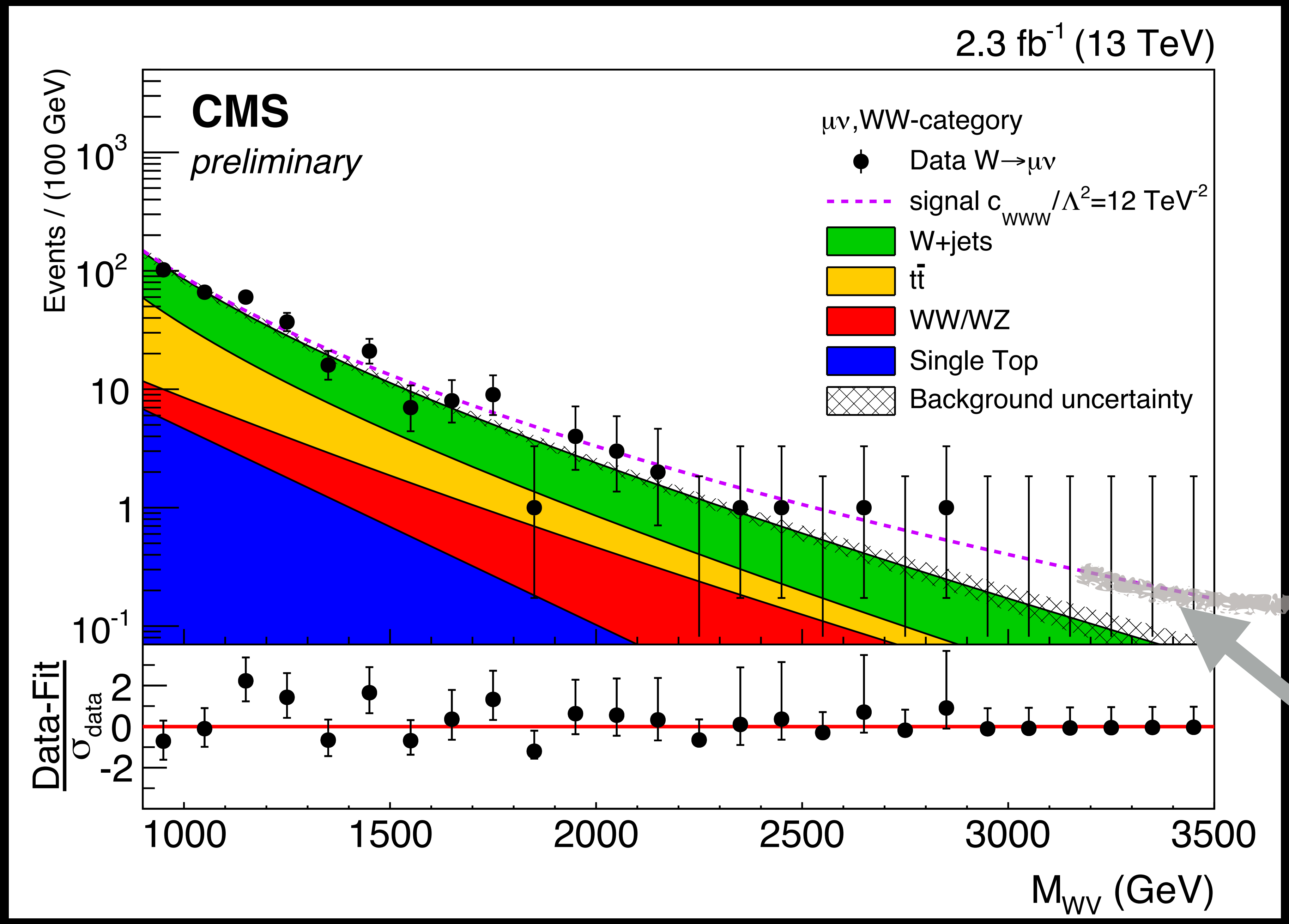
Anomalous Couplings → search for physics beyond Standard Model

anomalous Triple Gauge Couplings (aTGC)

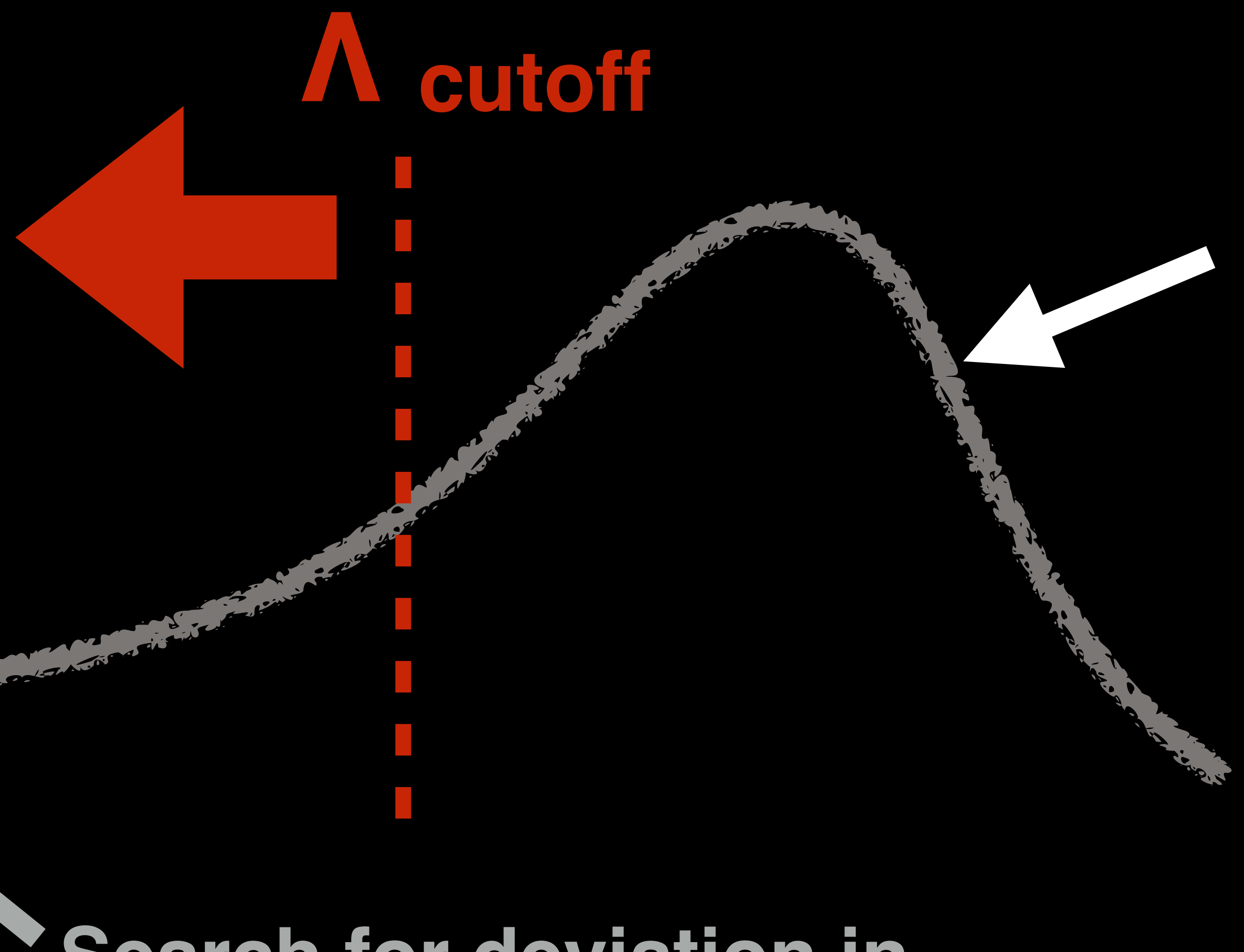


anomalous Quartic Gauge Couplings (aQGC)





Breaking the SM leads to a theory with effective range of validity



New Physics signal at energy beyond direct experimental reach

Probing strongly coupled physics beyond the SM

Search for deviation in the tails

Parametrization: extend SM Lagrangian (effective Lagrangian or effective field theory) with additional operators and anomalous parameters:

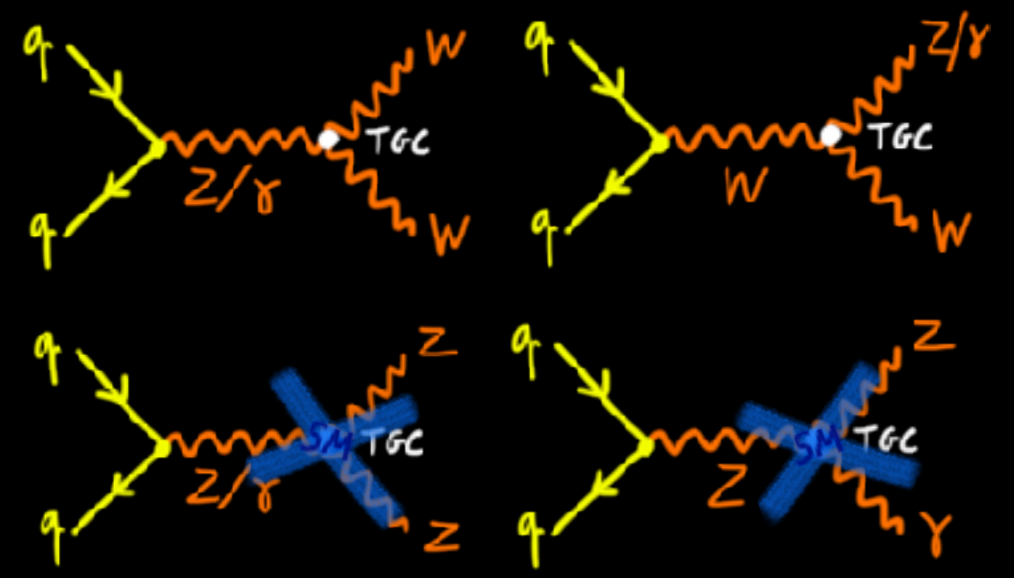
$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

Anomalous Gauge Couplings

Channels

Wγ, WW and WZ
W+jj → anomalous **charged** couplings

Zγ and ZZ
Z+jj → anomalous **neutral** couplings



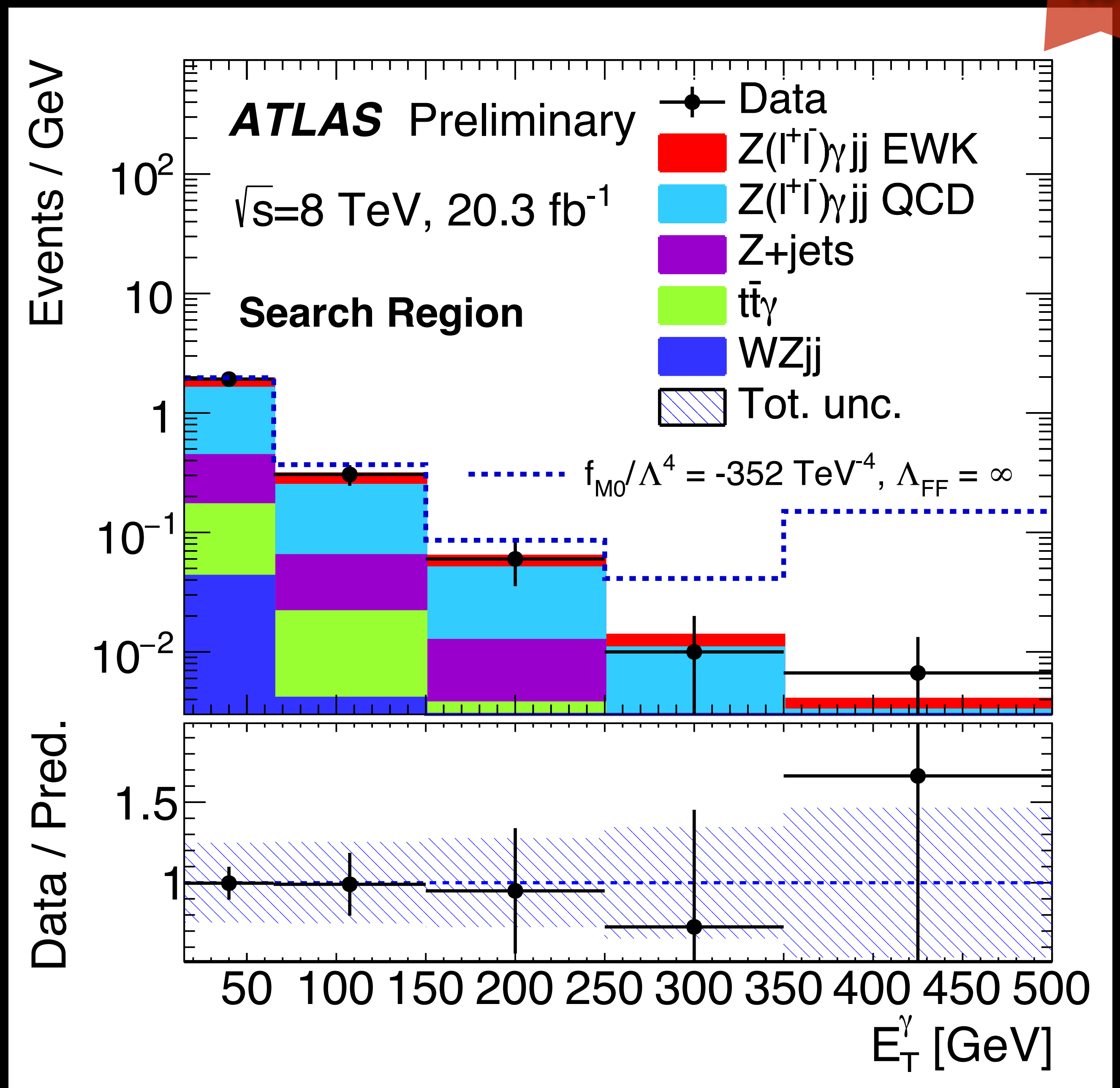
No deviations from SM have been observed

(example)

Anomalous Quartic Gauge Couplings (aQGC)

Zγ + jj

New



Increase of cross section at high energies

Typical probes:

- **invariant mass of the diboson system**
- **boson p_T**

Results are typically limited by:

- **observed statistics in the tail (primary),**
- **systematic and statistical uncertainty on the signal/bkg model**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-21/

Anomalous Gauge Couplings

Charged couplings:

– LHC limits slightly better than LEP limits

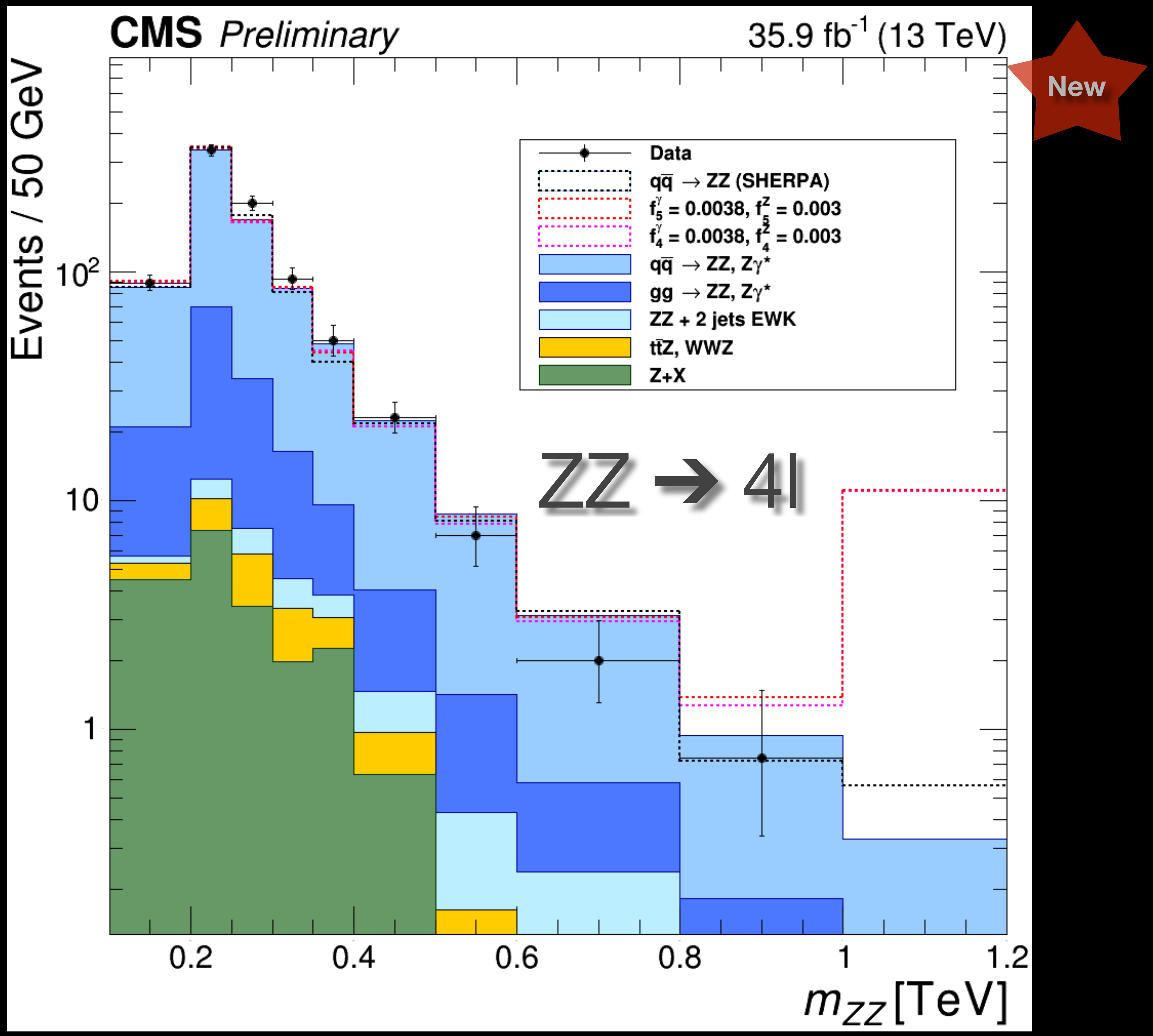
Neutral couplings:

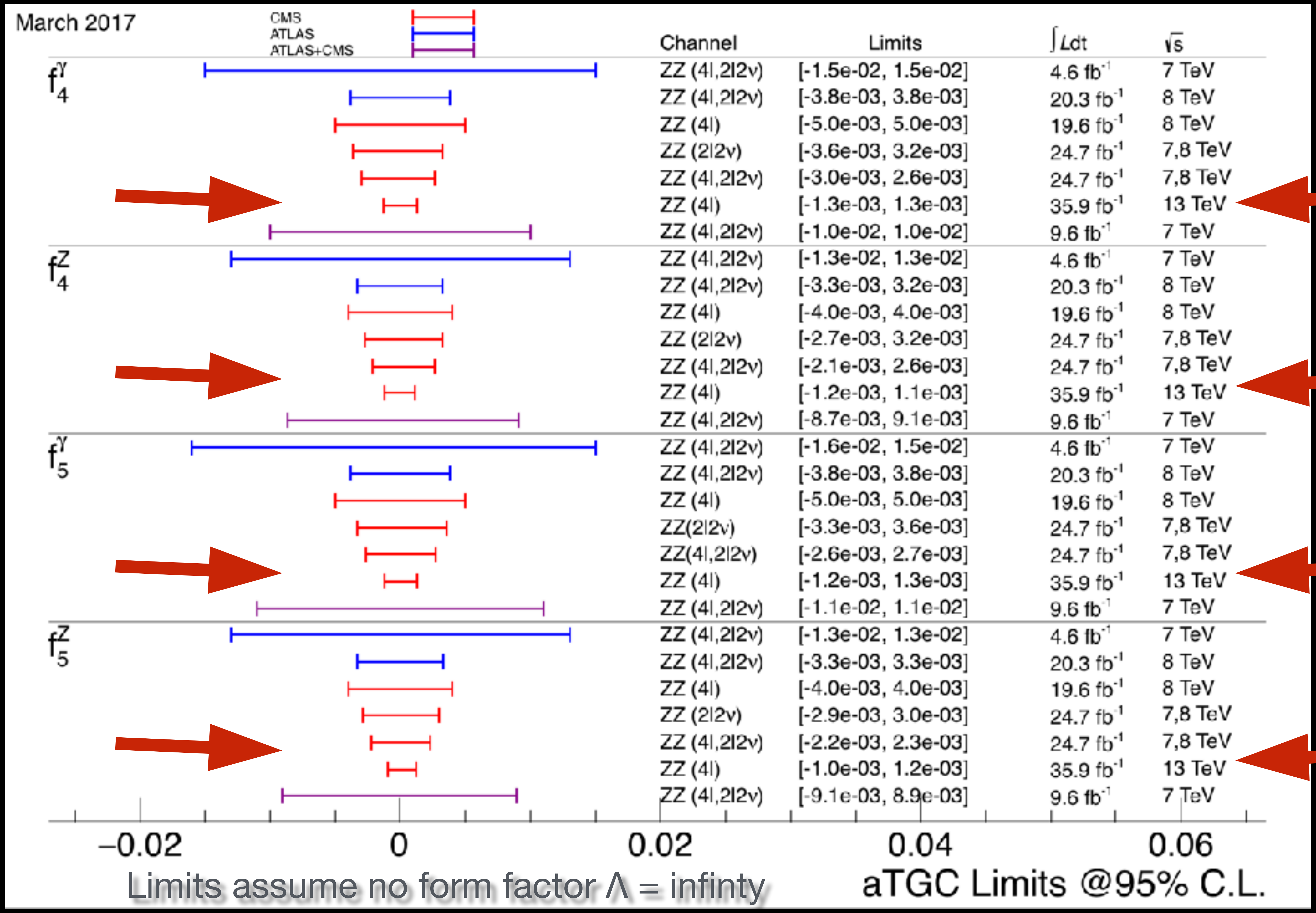
– LHC limits far stricter than LEP limits

Anomalous coupling sensitivity depends on the diboson channel

- Sensitivity set by the reach of the diboson invariant mass
- Best sensitivity from channels with large BR (semileptonic decays in boosted topology)

Large gain in sensitivity with increase of √s





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Closing remarks

The LHC proton-proton runs have produced exceptional Standard Model results at 7, 8 and 13 TeV

Ratification of the Standard Model of Particle Physics

=> Discovery of the Higgs Boson

=> Many precision measurements of ever increasing complexity and exploring smaller and smaller cross sections

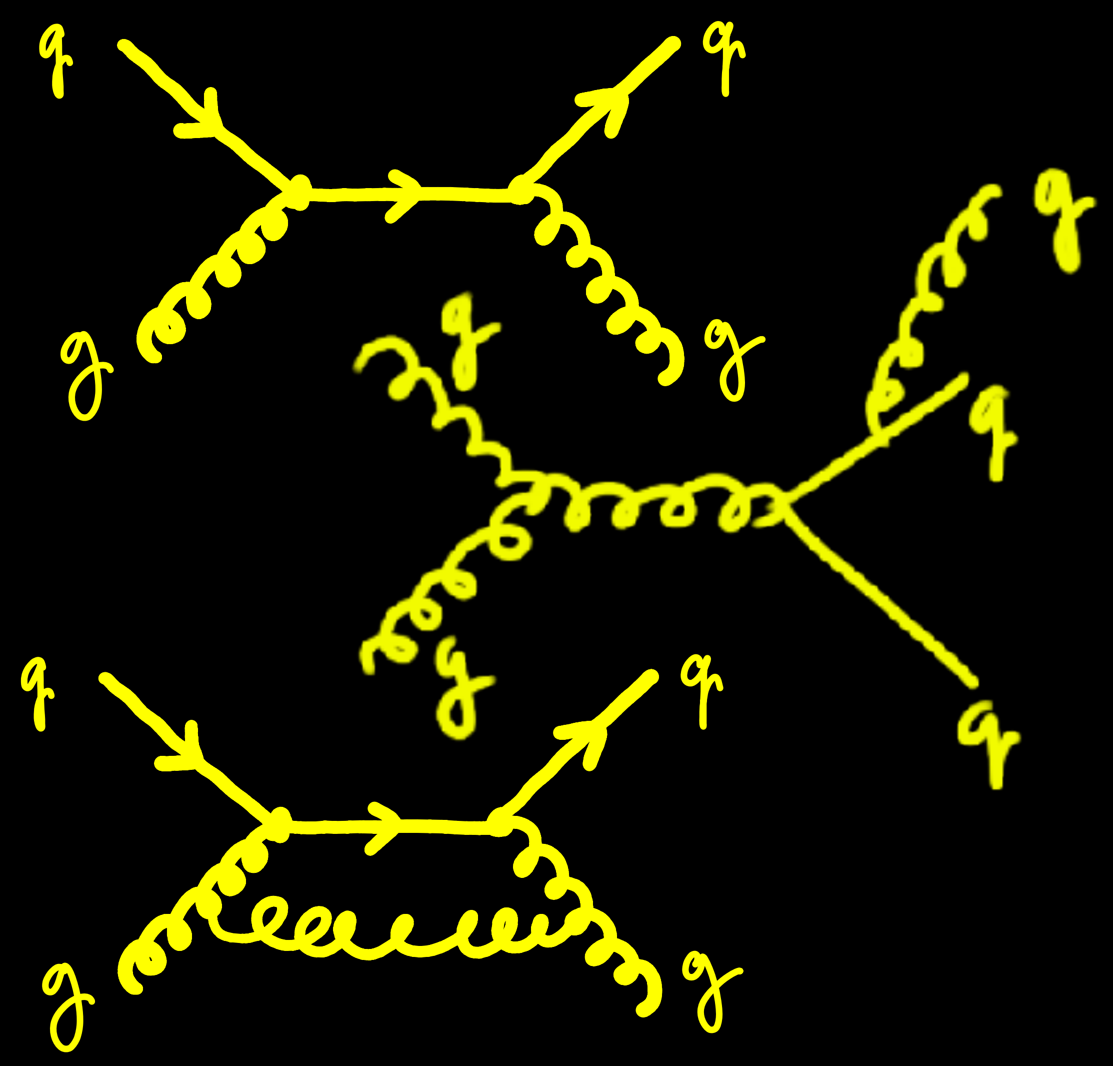
The LHC is getting ready to restart

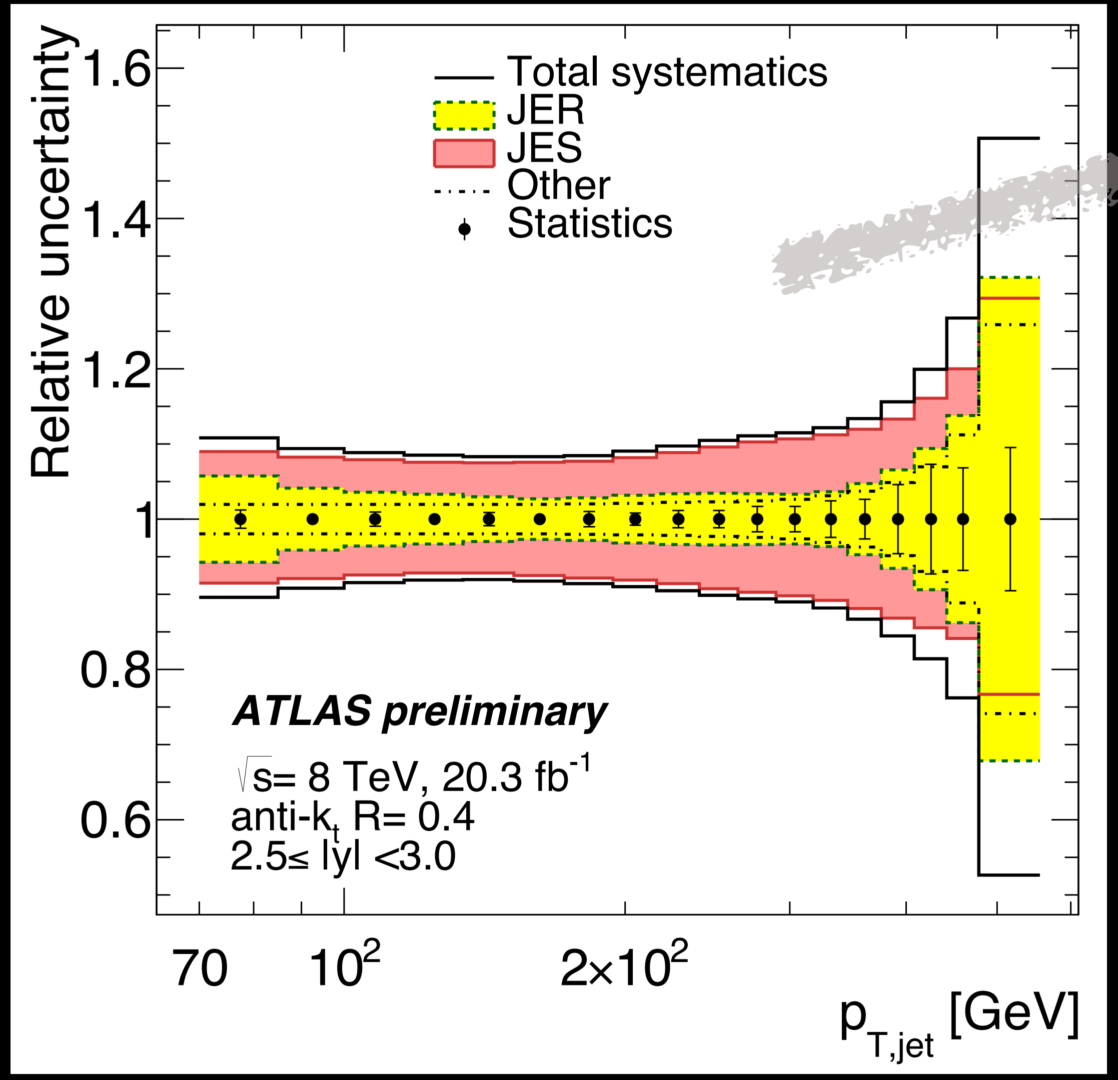
=> Potential for significant discoveries and deeper precision measurements

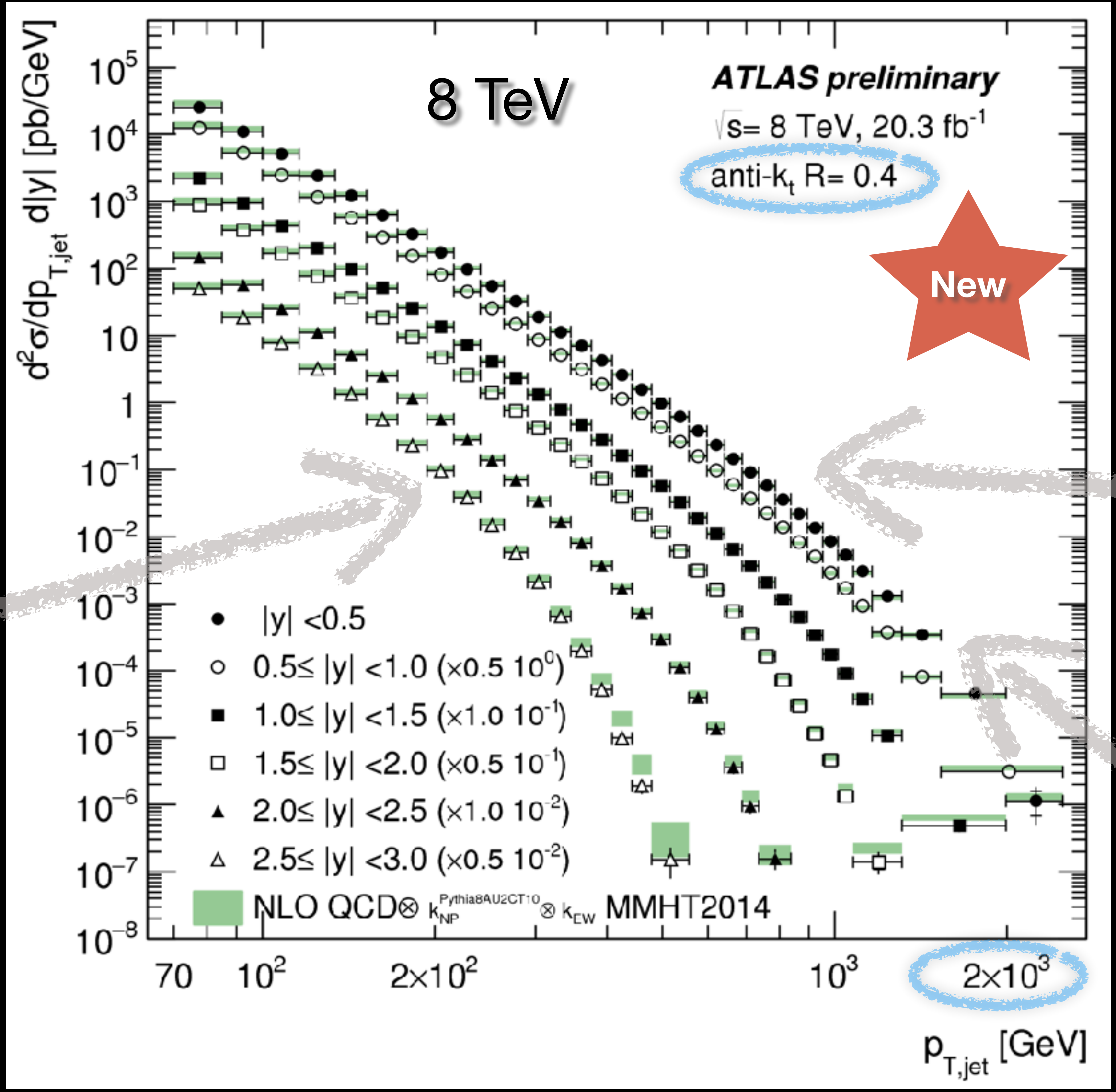
Standard Model measurements and direct searches will play complementary roles in the search for new physics

Inclusive Jet Cross Sections

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-01/



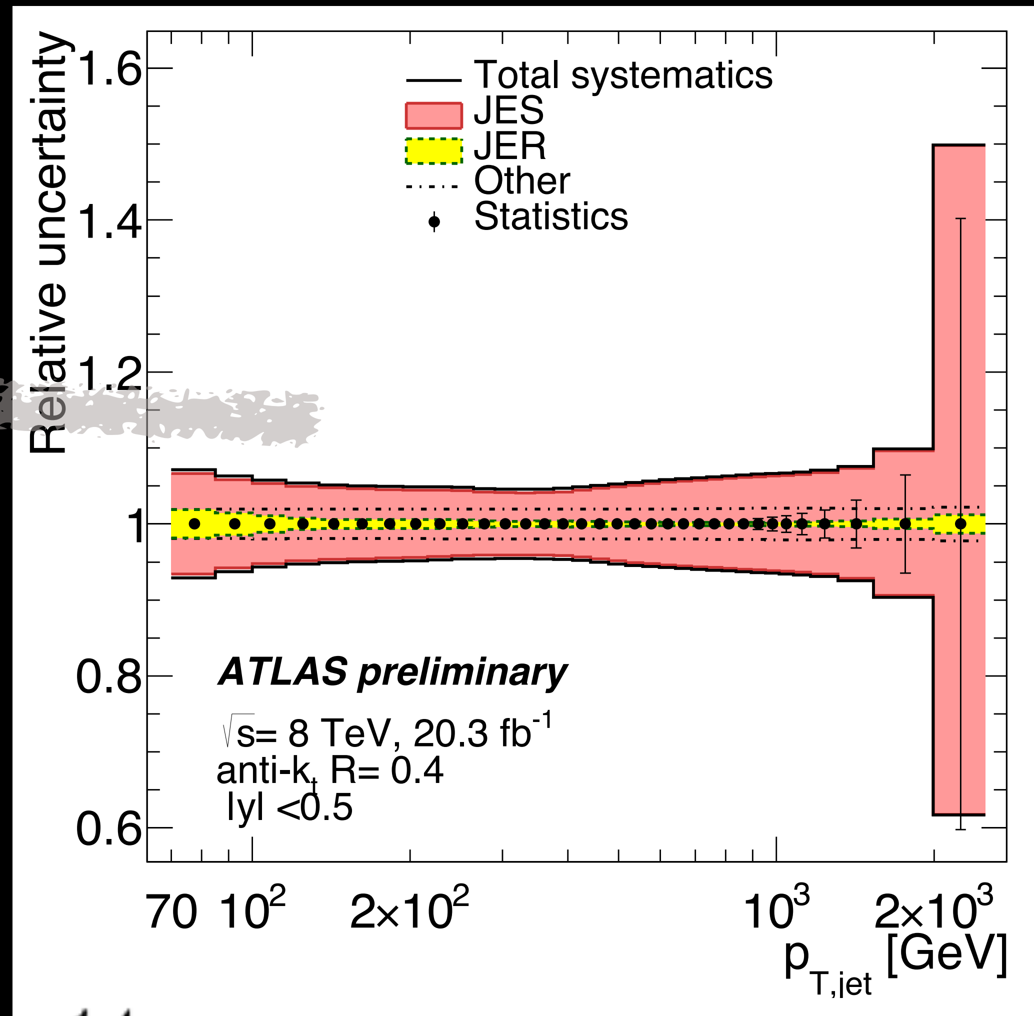


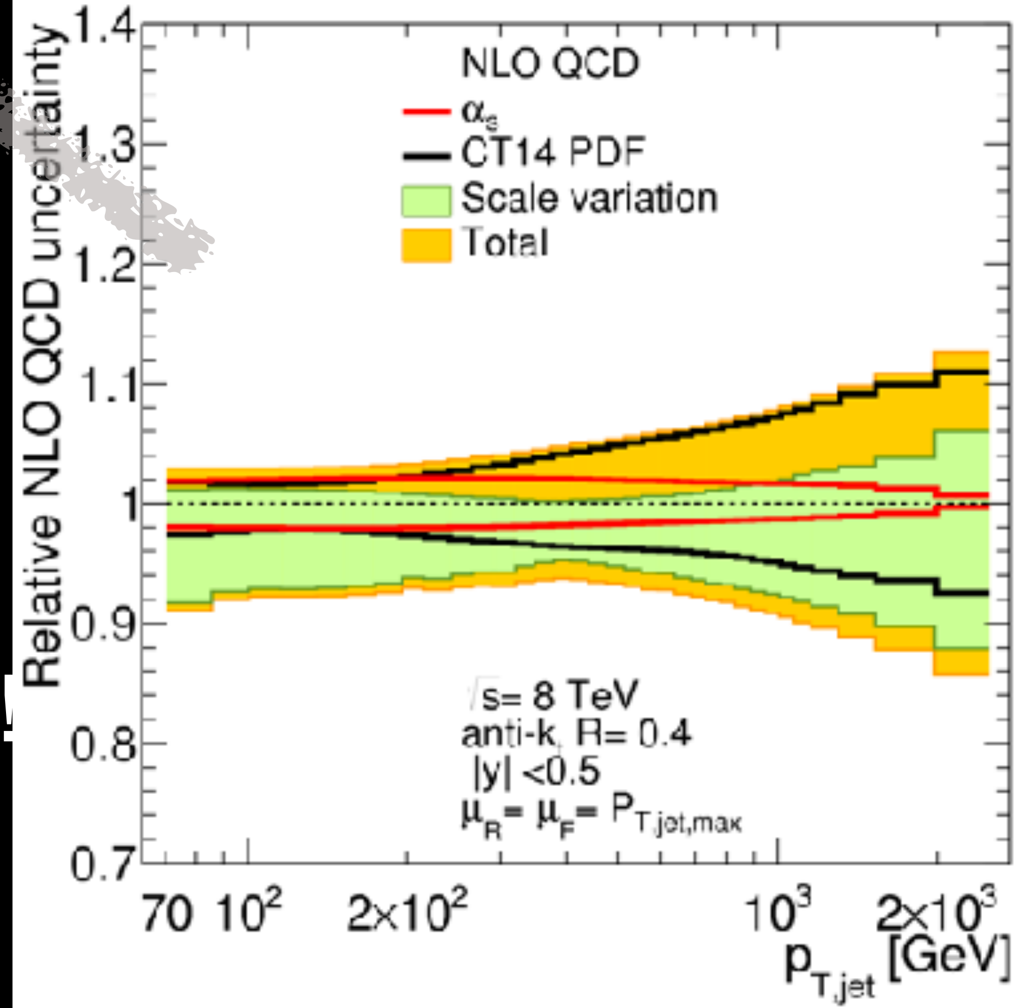


Measurement done for two jet algorithms:

- **anti-k_t R=0.4**
- **anti-k_t R=0.6**

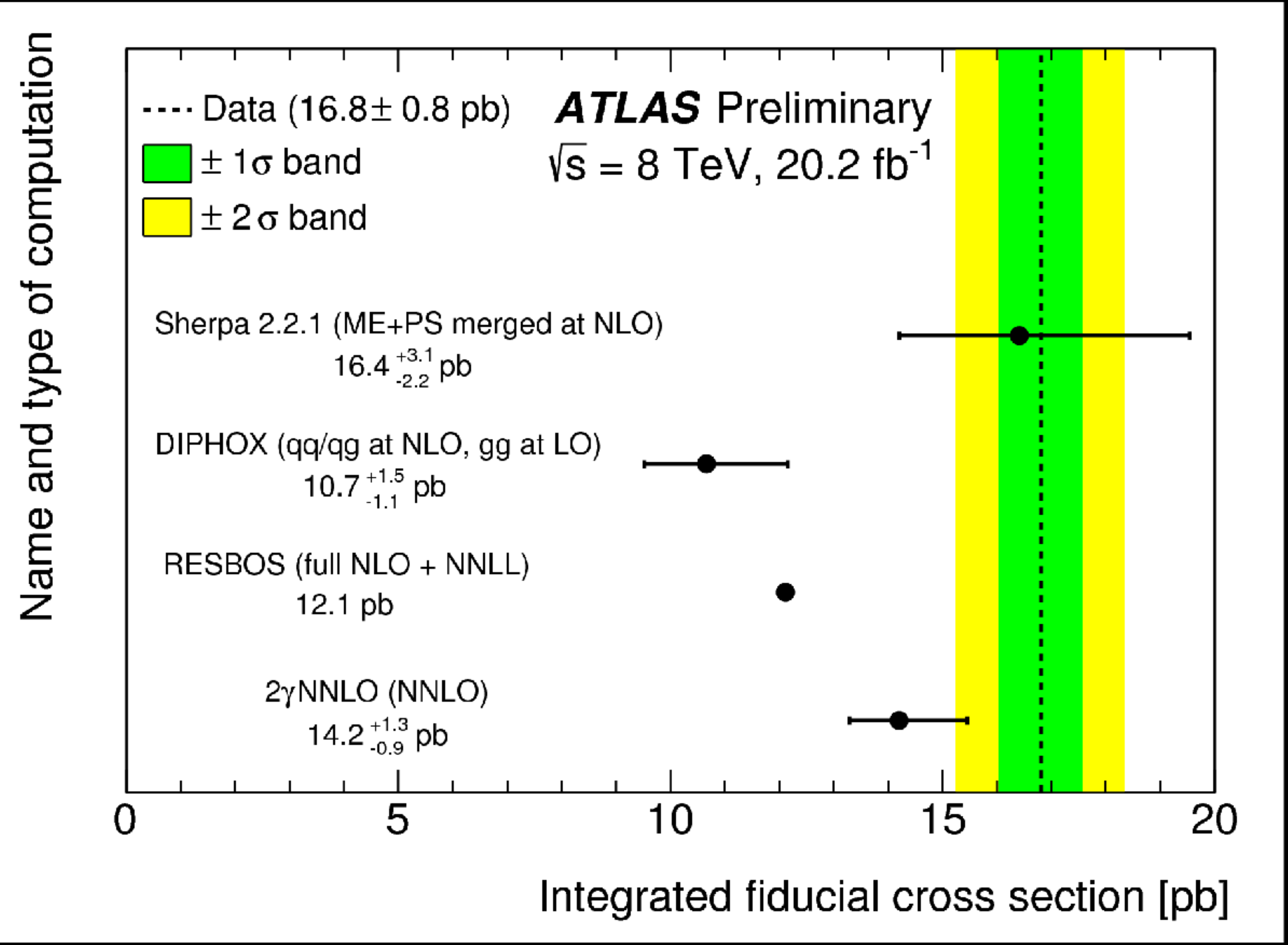
NLO QCD prediction with the MMHT2014 PDF set corrected for non-perturbative and electroweak effects





NLO QCD predictions describe data over 9 orders of magnitude!
Jet inclusive data starts to constrain gluon PDFs
(CT14, MMHT14, NNPDF3.0, HERAPDF2.0)

Di-photon production cross section



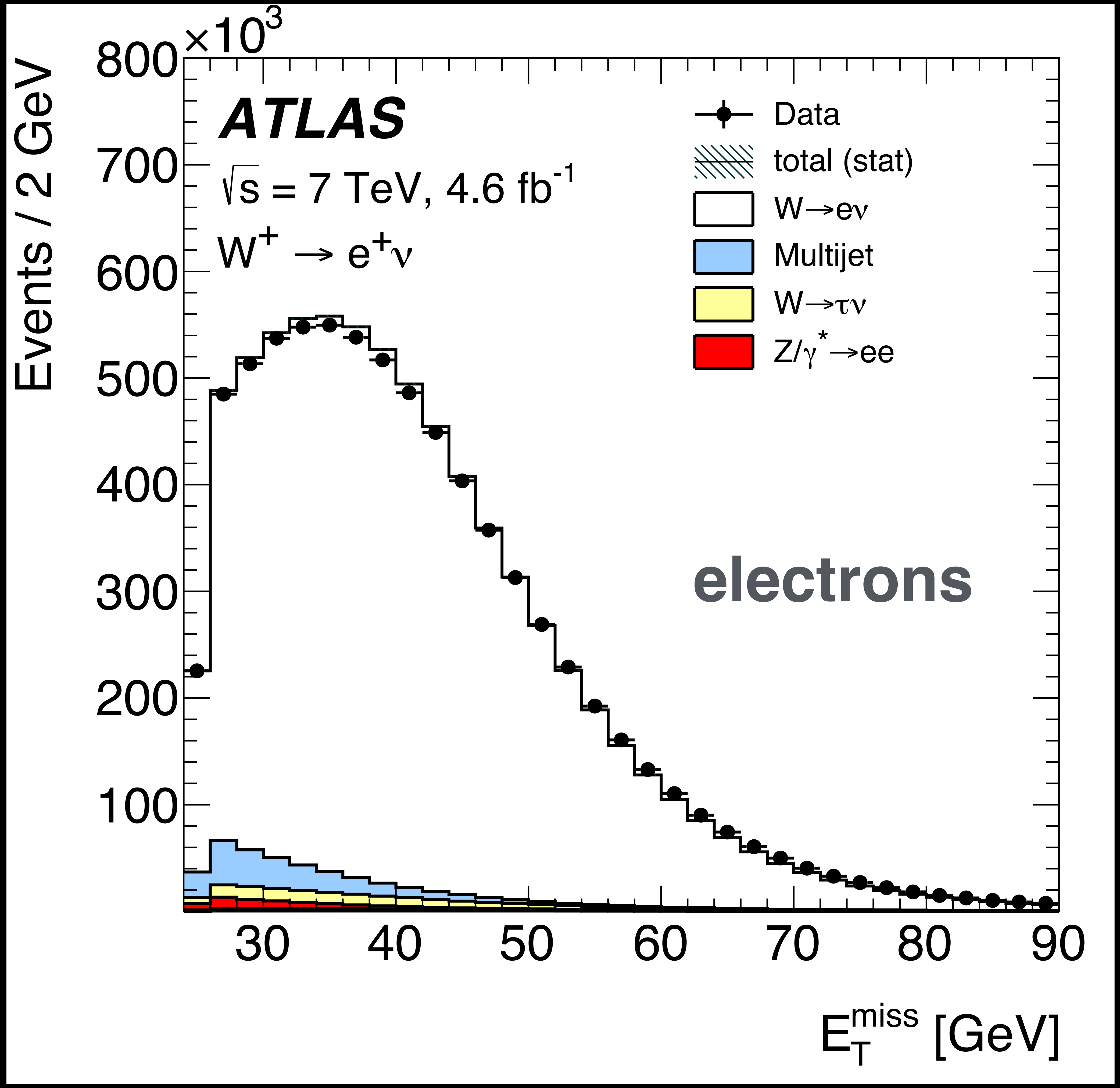
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-15/

Precision measurement of W and Z cross sections

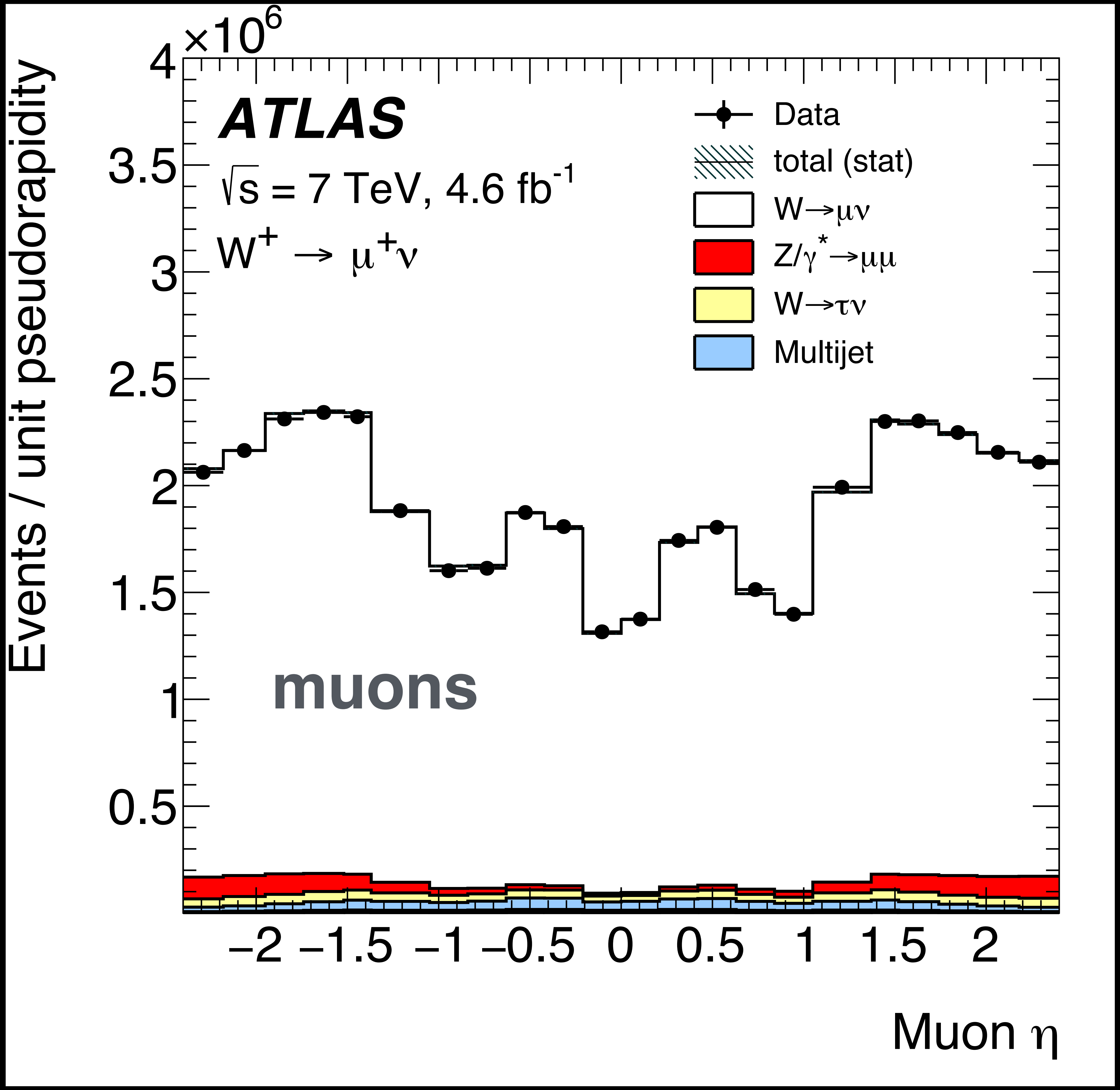
7 TeV dataset - 4.6 fb^{-1}

arXiv:1612.03016

Missing energy modeling



Muon modeling



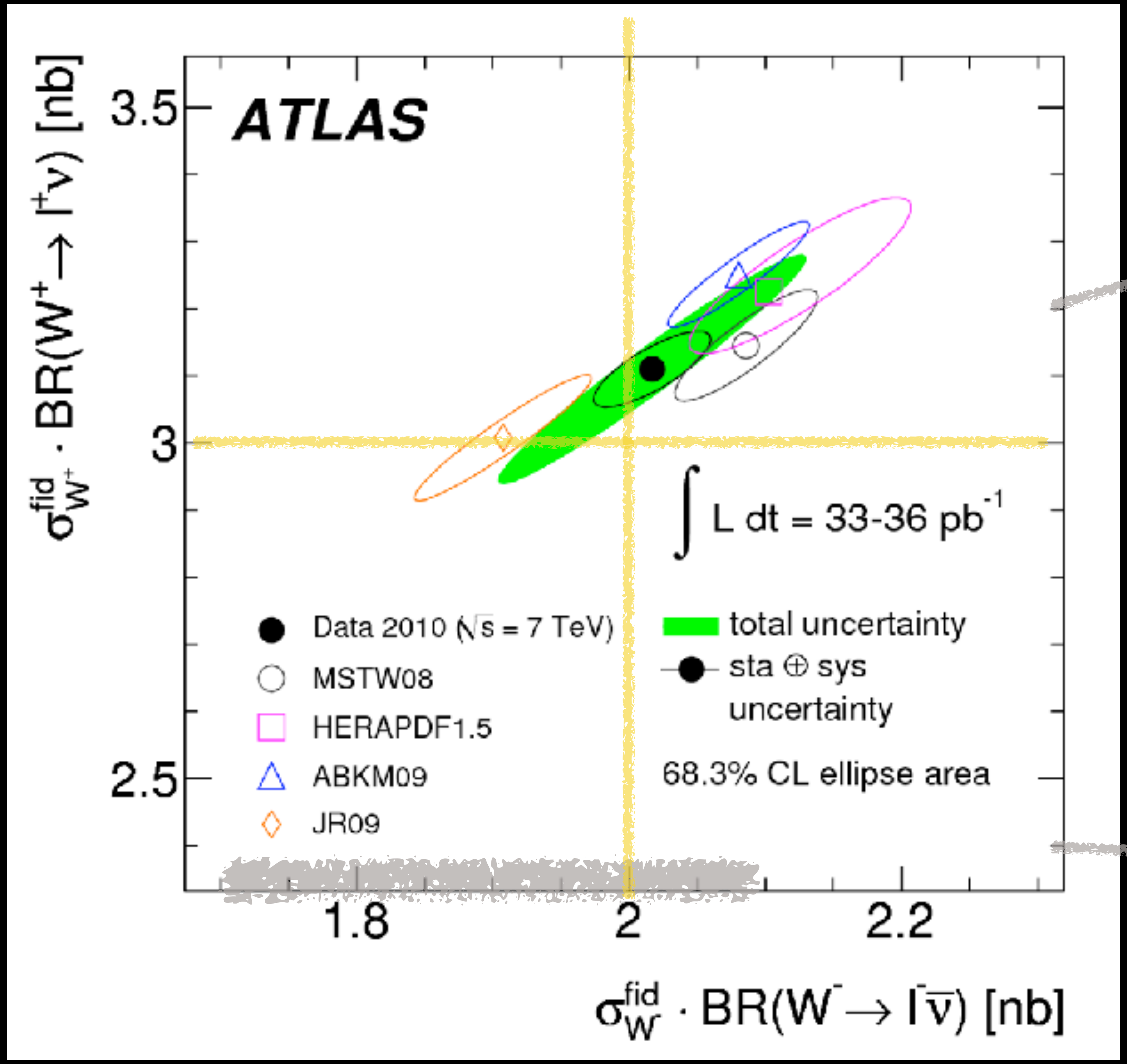
Fiducial W+ and W– Cross Sections

Fiducial cross sections

No theoretical uncertainty from extrapolation outside experimental acceptance

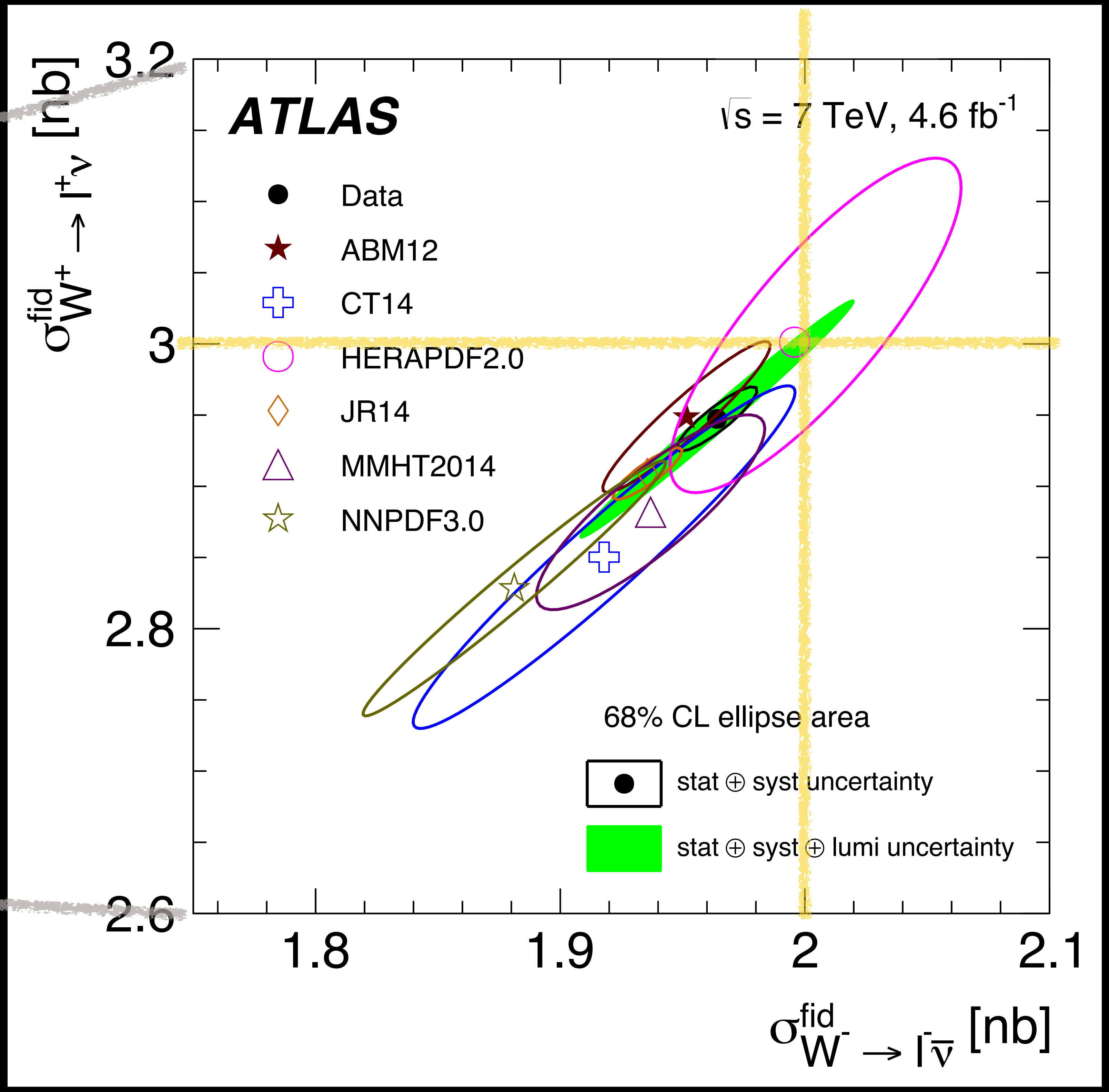
$\sigma_{Fiducial}$: W^+ versus W^-

Phys. Rev. D85 (2012) 072004



FEWZ = DYNNLO ~ 1%

arXiv:1612.03016



DYNNLO 1.5

Luminosity 3.4% ==> 1.8%

Some differentiation between PDF sets observed
Experimental uncertainties smaller than individual PDF uncertainties

Systematic uncertainties

arXiv:1612.03016

Electrons	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]	$\delta\sigma_{\text{forward}\,Z}$ [%]
Trigger efficiency	0.03	0.03	0.05	0.05
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
Forward identification efficiency	–	–	–	1.51
Isolation efficiency	0.03	0.03	–	0.04
Charge misidentification	0.04	0.06	–	–
Electron p_{T} resolution	0.02	0.03	0.01	0.01
Electron p_{T} scale	0.22	0.18	0.08	0.12
Forward electron p_{T} scale + resolution	–	–	–	0.18
$E_{\text{T}}^{\text{miss}}$ soft term scale	0.14	0.13	–	–
$E_{\text{T}}^{\text{miss}}$ soft term resolution	0.06	0.04	–	–
Jet energy scale	0.04	0.02	–	–
Jet energy resolution	0.11	0.15	–	–
Signal modelling (matrix-element generator)	0.57	0.64	0.03	1.12
Signal modelling (parton shower and hadronization)	0.24	0.25	0.18	1.25
PDF	0.10	0.12	0.09	0.06
Boson p_{T}	0.22	0.19	0.01	0.04
Multijet background	0.55	0.72	0.03	0.05
Electroweak+top background	0.17	0.19	0.02	0.14
Background statistical uncertainty	0.02	0.03	<0.01	0.04
Unfolding statistical uncertainty	0.03	0.04	0.04	0.13
Data statistical uncertainty	0.04	0.05	0.10	0.18
Total experimental uncertainty	0.94	1.08	0.35	2.29
Luminosity		1.8		

Muons	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	0.08	0.07	0.05
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_{T} resolution	0.01	0.01	<0.01
Muon p_{T} scale	0.18	0.17	0.03
$E_{\text{T}}^{\text{miss}}$ soft term scale	0.19	0.19	–
$E_{\text{T}}^{\text{miss}}$ soft term resolution	0.10	0.09	–
Jet energy scale	0.09	0.12	–
Jet energy resolution	0.11	0.16	–
Signal modelling (matrix-element generator)	0.12	0.06	0.04
Signal modelling (parton shower and hadronization)	0.14	0.17	0.22
PDF	0.09	0.12	0.07
Boson p_{T}	0.18	0.14	0.04
Multijet background	0.33	0.27	0.07
Electroweak+top background	0.19	0.24	0.02
Background statistical uncertainty	0.03	0.04	0.01
Unfolding statistical uncertainty	0.03	0.03	0.02
Data statistical uncertainty	0.04	0.04	0.08
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	

Electron–Muon Universality

arXiv:1612.03016

$$R_W = \frac{\sigma^{\text{fid},e}_{W\to e\nu}/E^e_W}{\sigma^{\text{fid},\mu}_{W\to\mu\nu}/E^\mu_W} = \frac{\sigma^{\text{fid}}_{W\to e\nu}}{\sigma^{\text{fid}}_{W\to\mu\nu}} = \frac{BR(W\to e\nu)}{BR(W\to\mu\nu)}$$
$$= 0.9967 \pm 0.0004\,(\text{stat}) \pm 0.0101\,(\text{syst})$$
$$= 0.997 \pm 0.010\,.$$

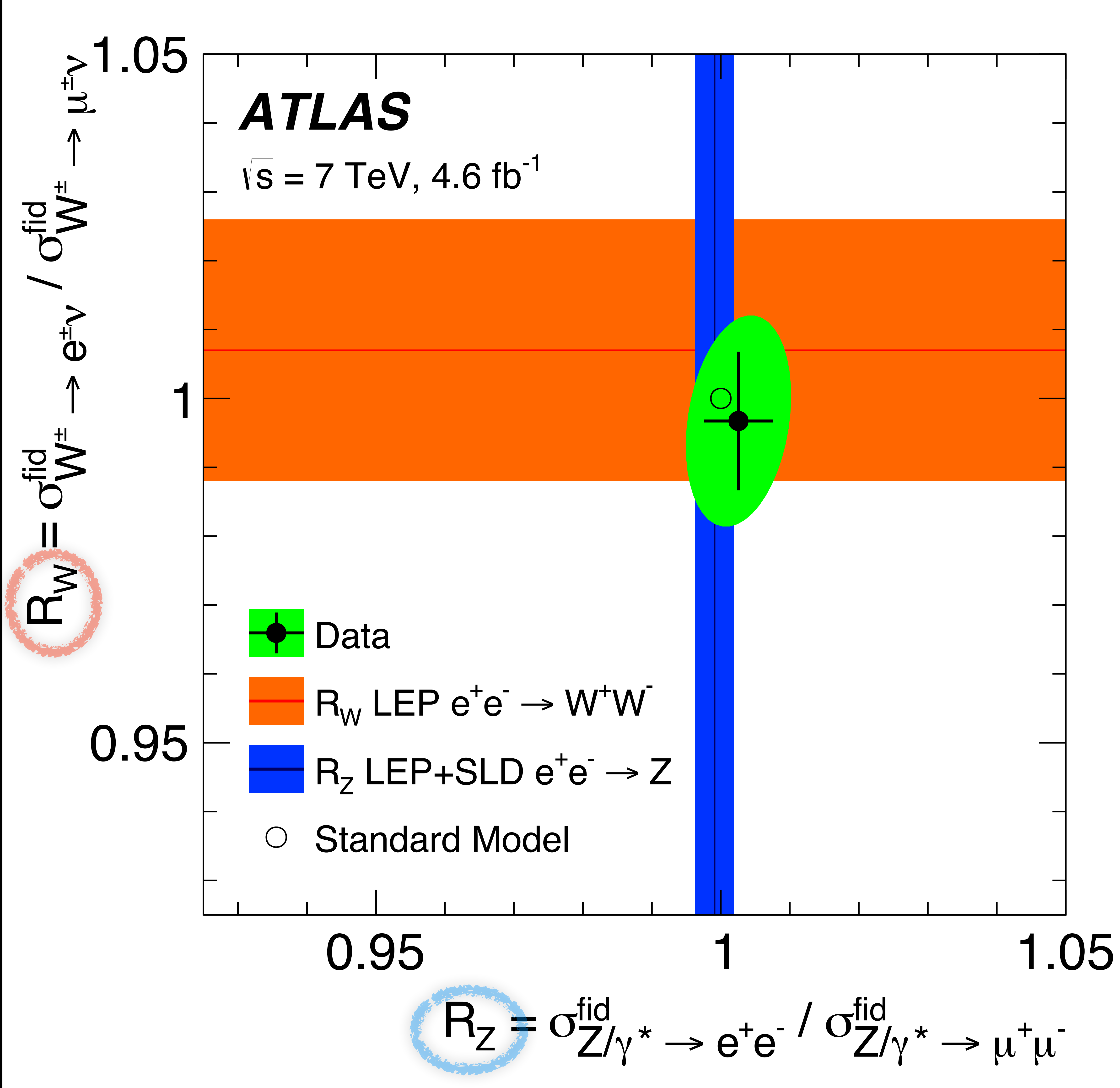
1.0%

LEP
$e^+e^- \to WW$
1.9%

$$R_Z = \frac{\sigma^{\text{fid},e}_{Z\to ee}/E^e_Z}{\sigma^{\text{fid},\mu}_{Z\to\mu\mu}/E^\mu_Z} = \frac{\sigma^{\text{fid}}_{Z\to ee}}{\sigma^{\text{fid}}_{Z\to\mu\mu}} = \frac{BR(Z\to ee)}{BR(Z\to\mu\mu)}$$
$$= 1.0026 \pm 0.0013\,(\text{stat}) \pm 0.0048\,(\text{syst})$$
$$= 1.0026 \pm 0.0050\,.$$

0.50%

LEP+SLC
$e^+e^- \to Z$
0.28%



PDF profiling results from W/Z precision measurement

arXiv:1612.03016

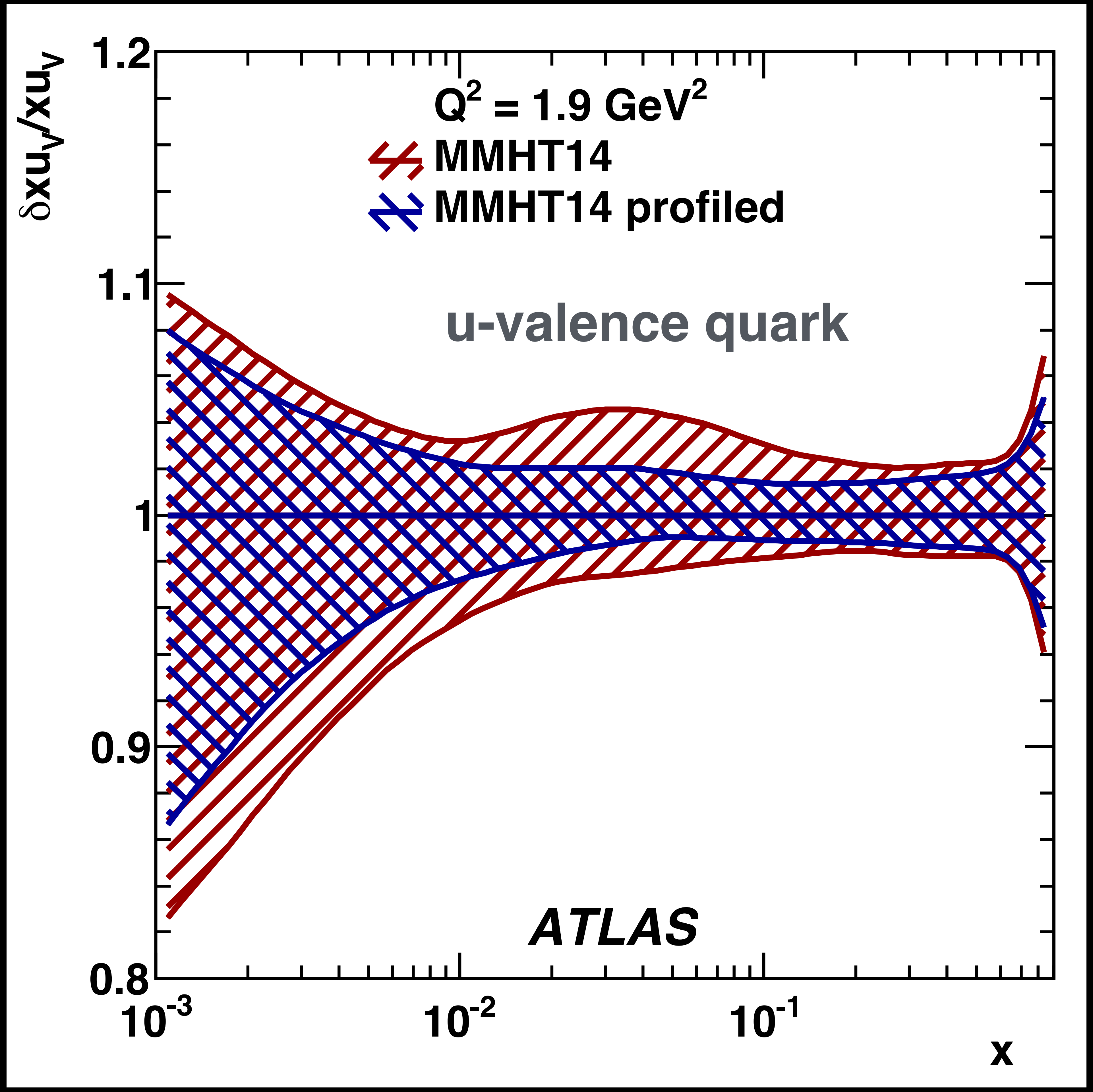
Impact of measurement when applied to existing PDF (MMHT14,CT14)

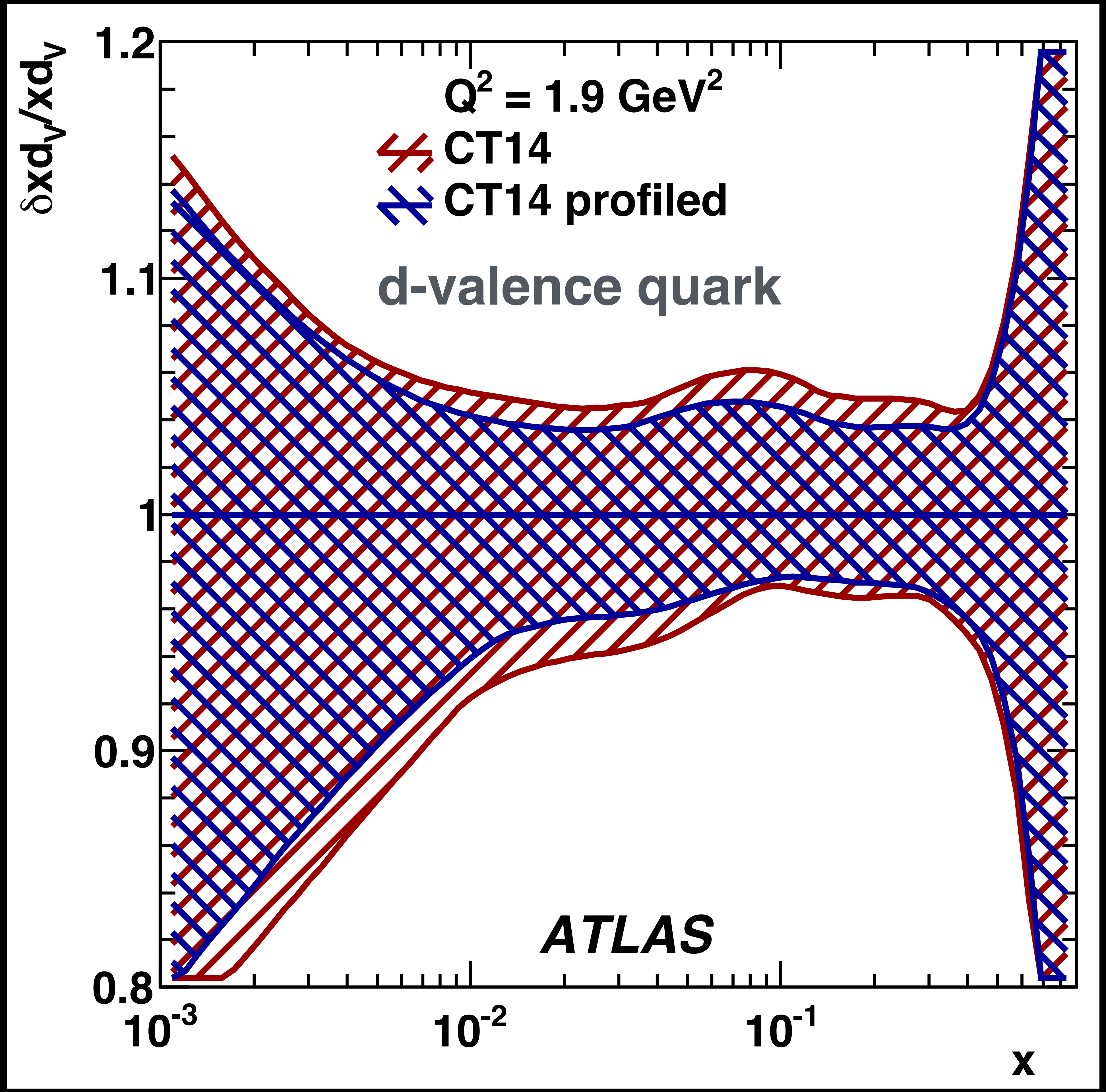
The strange-quark distribution is significantly increased and the uncertainties are reduced

PDF profiling results from W/Z precision measurement

arXiv:1612.03016

Impact of measurement when applied to existing PDF (MMHT14,CT14)

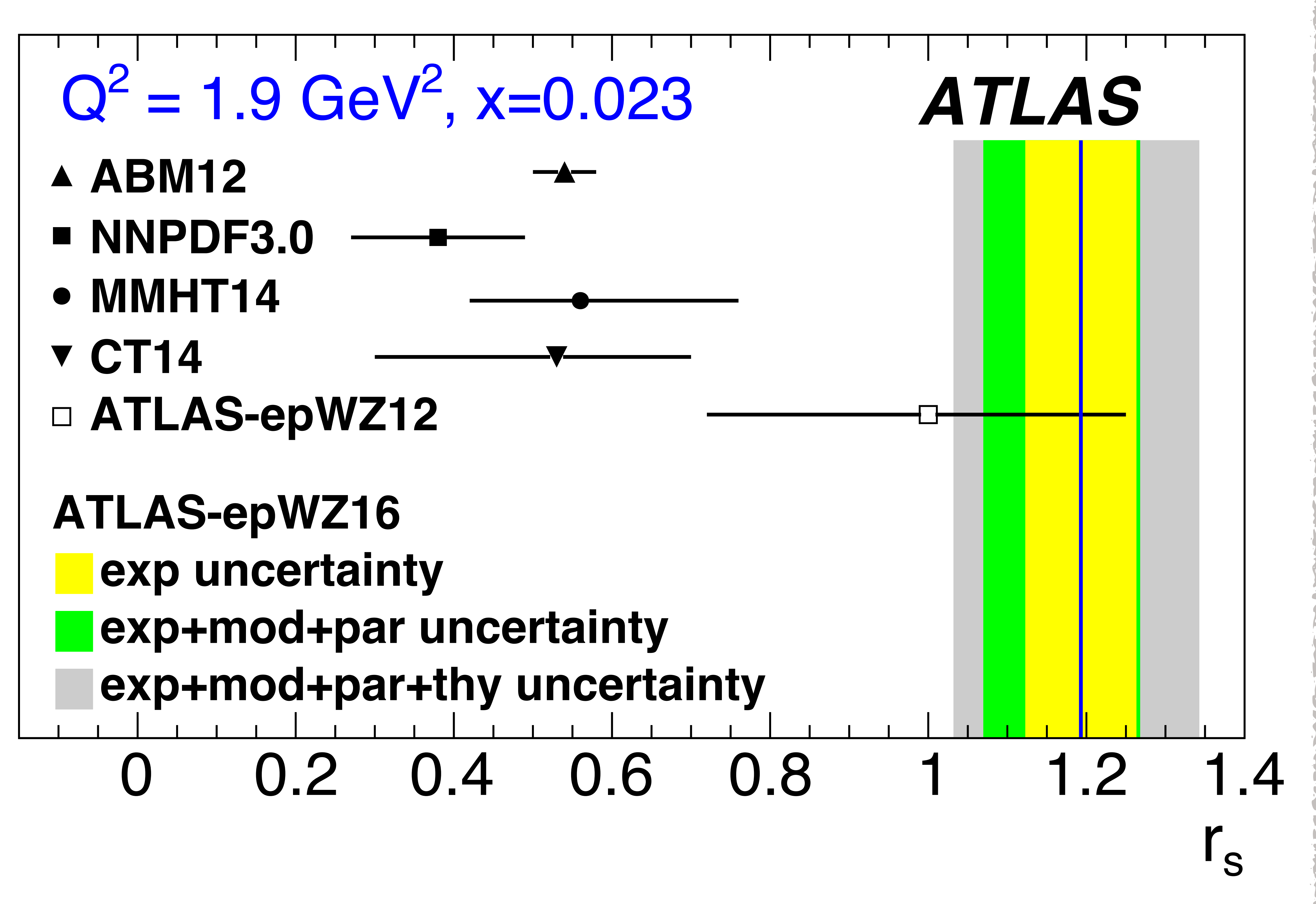


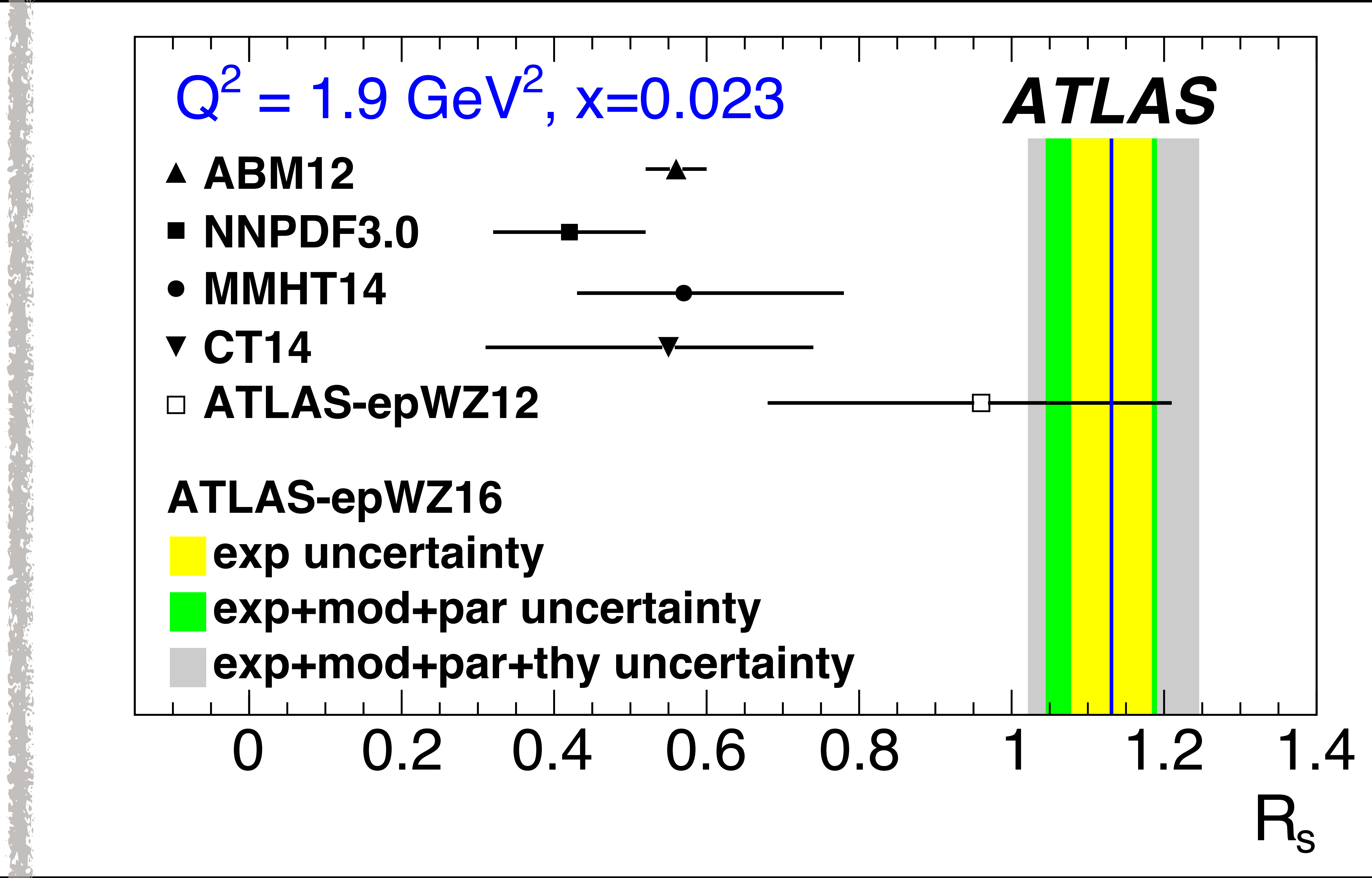


Reduction of uncertainties observed for valence quark PDF distributions

Strangeness in the Proton

arXiv:1612.03016

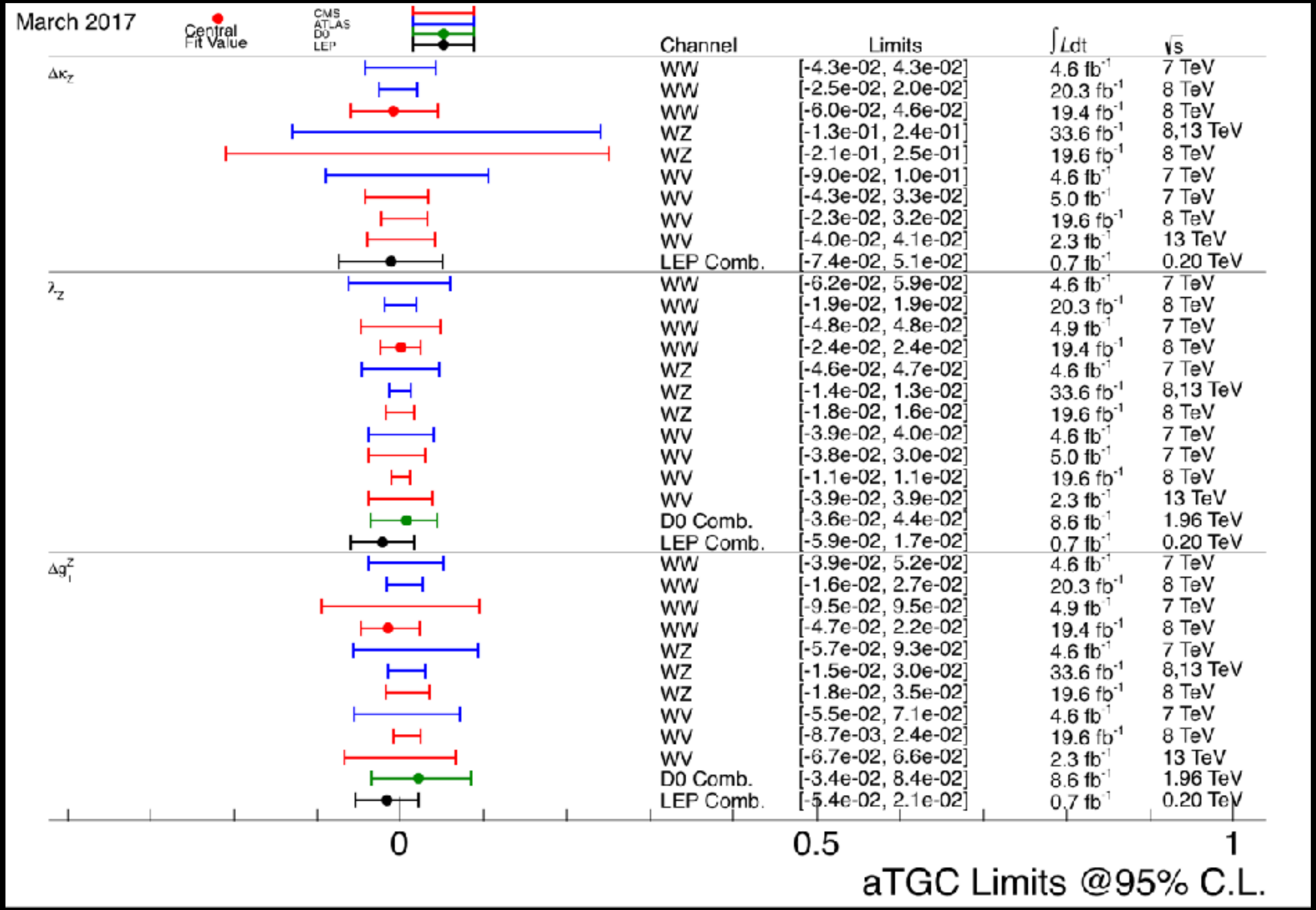


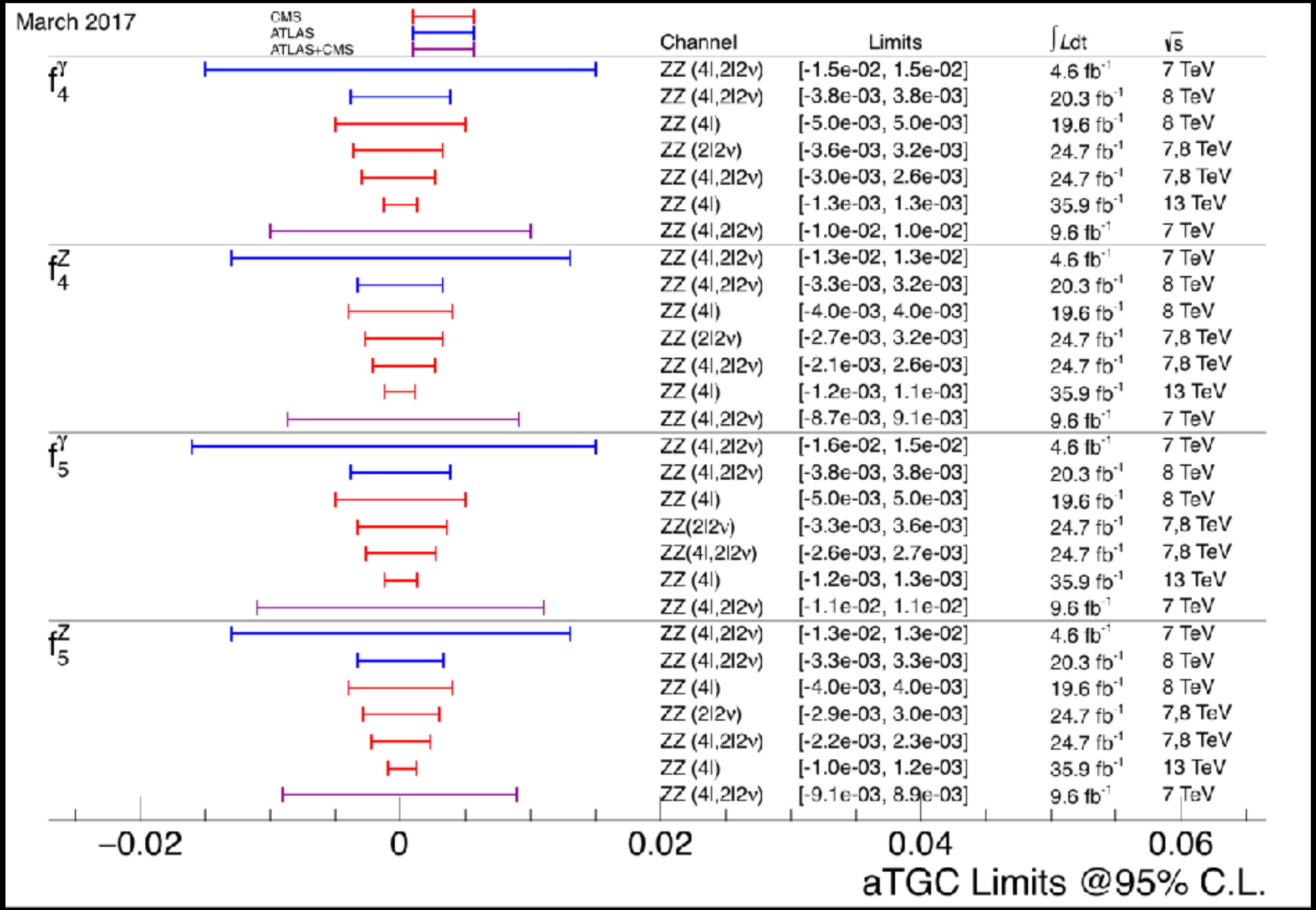


$$r_s = \frac{s+\bar{s}}{2\bar{d}} = 1.19 \pm 0.07\,(\text{exp}) \pm 0.02\,(\text{mod}) \,{}^{+0.02}_{-0.10}\,(\text{par})$$

$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05\,(\text{exp}) \pm 0.02\,(\text{mod}) \,{}^{+0.01}_{-0.06}\,(\text{par})$$

Anomalous Triple Gauge Couplings



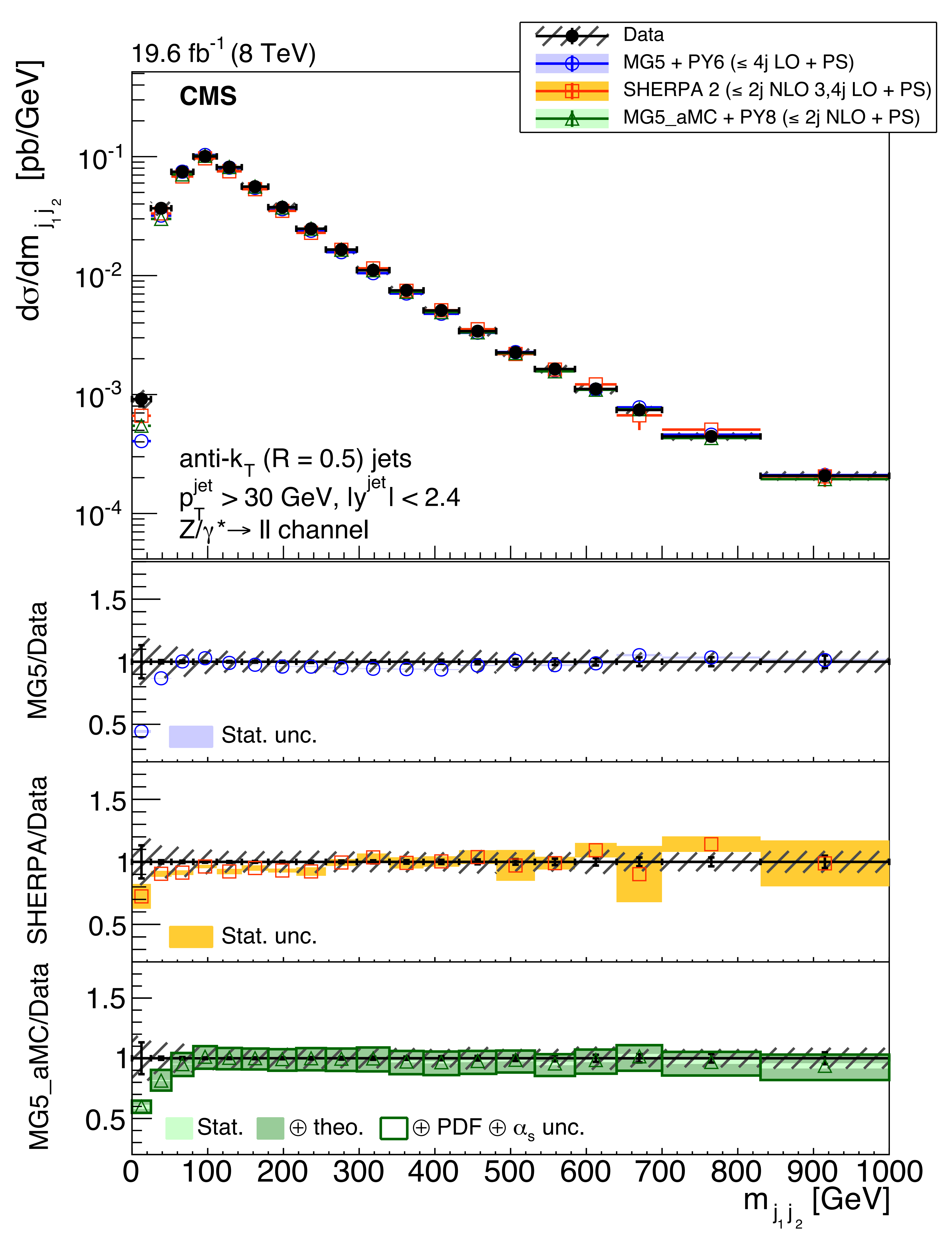


Limits assume no form factor Λ = infinty

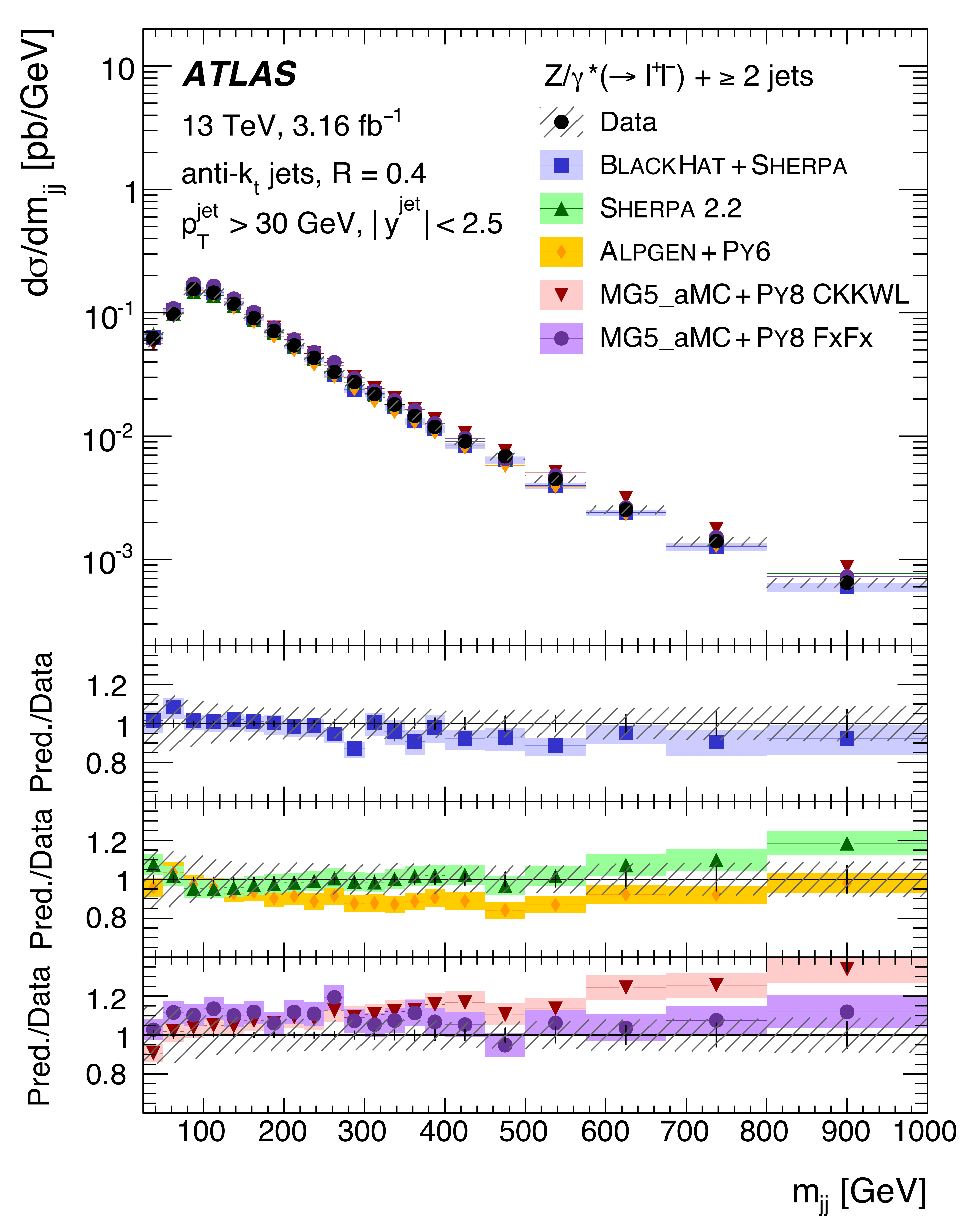
New: CMS ZZ with Z → l^+l^- using 35.9 fb^{-1} of 13 TeV pp collisions, CMS PAS SMP-16-017

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Z+jets: Dijet invariant mass

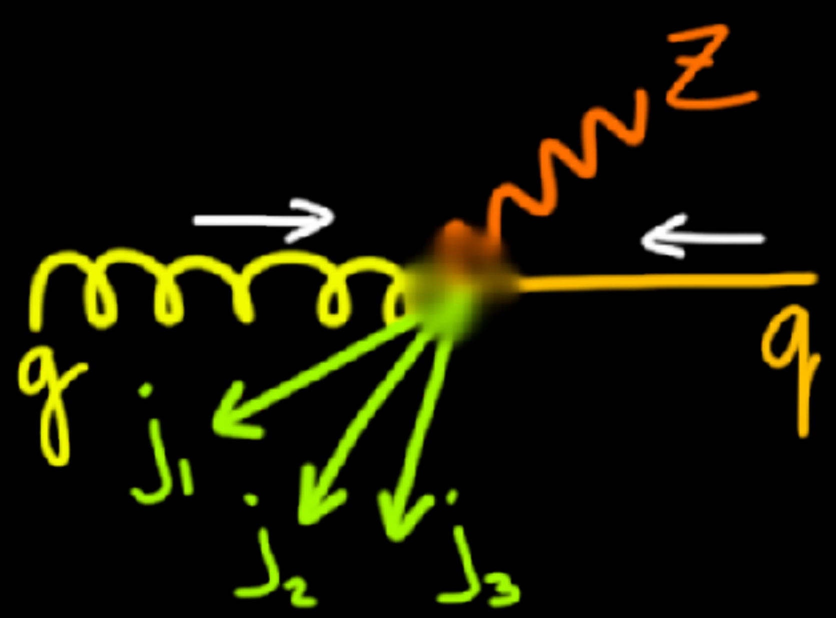


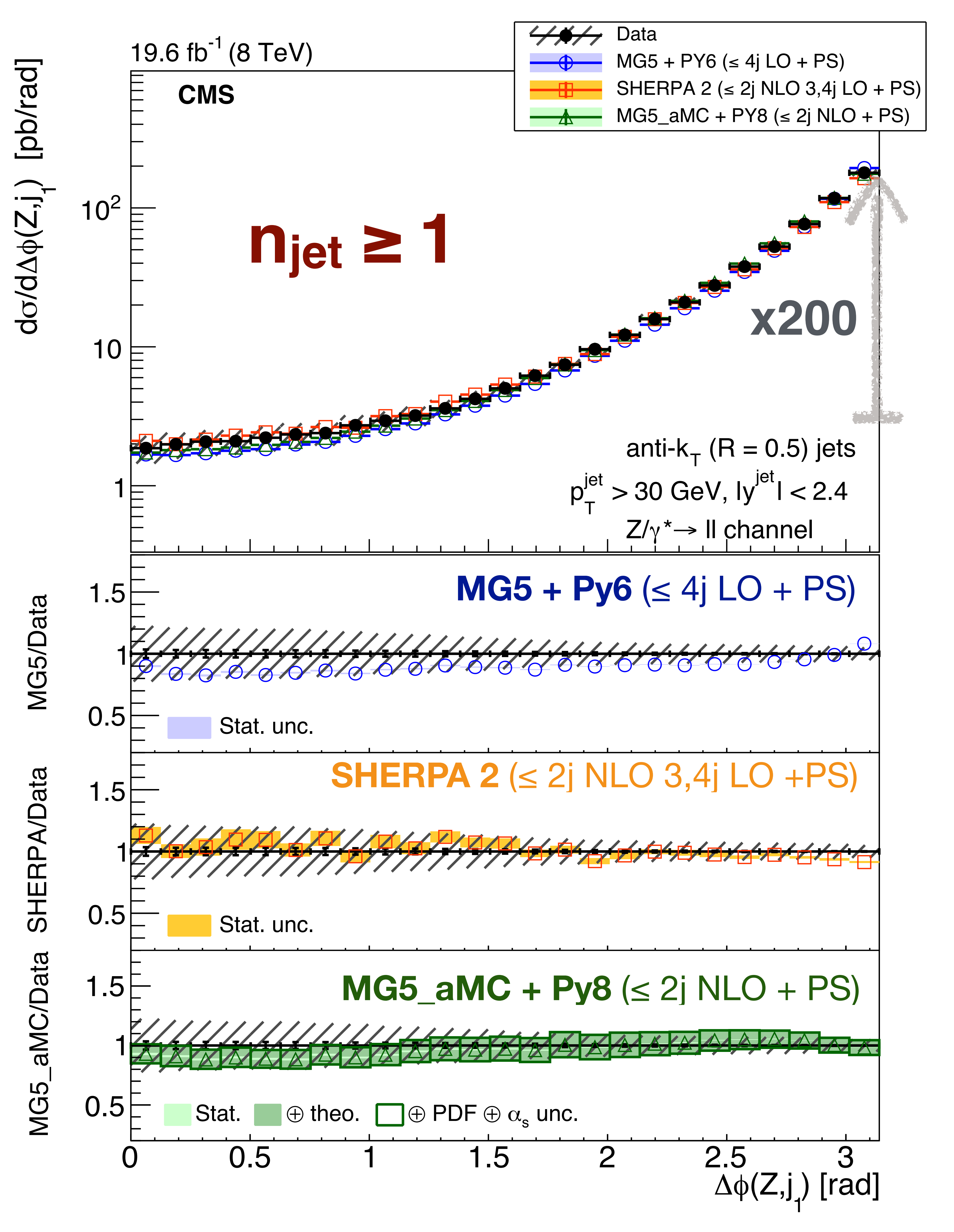
Z+ $n_{jet} \geq 2$

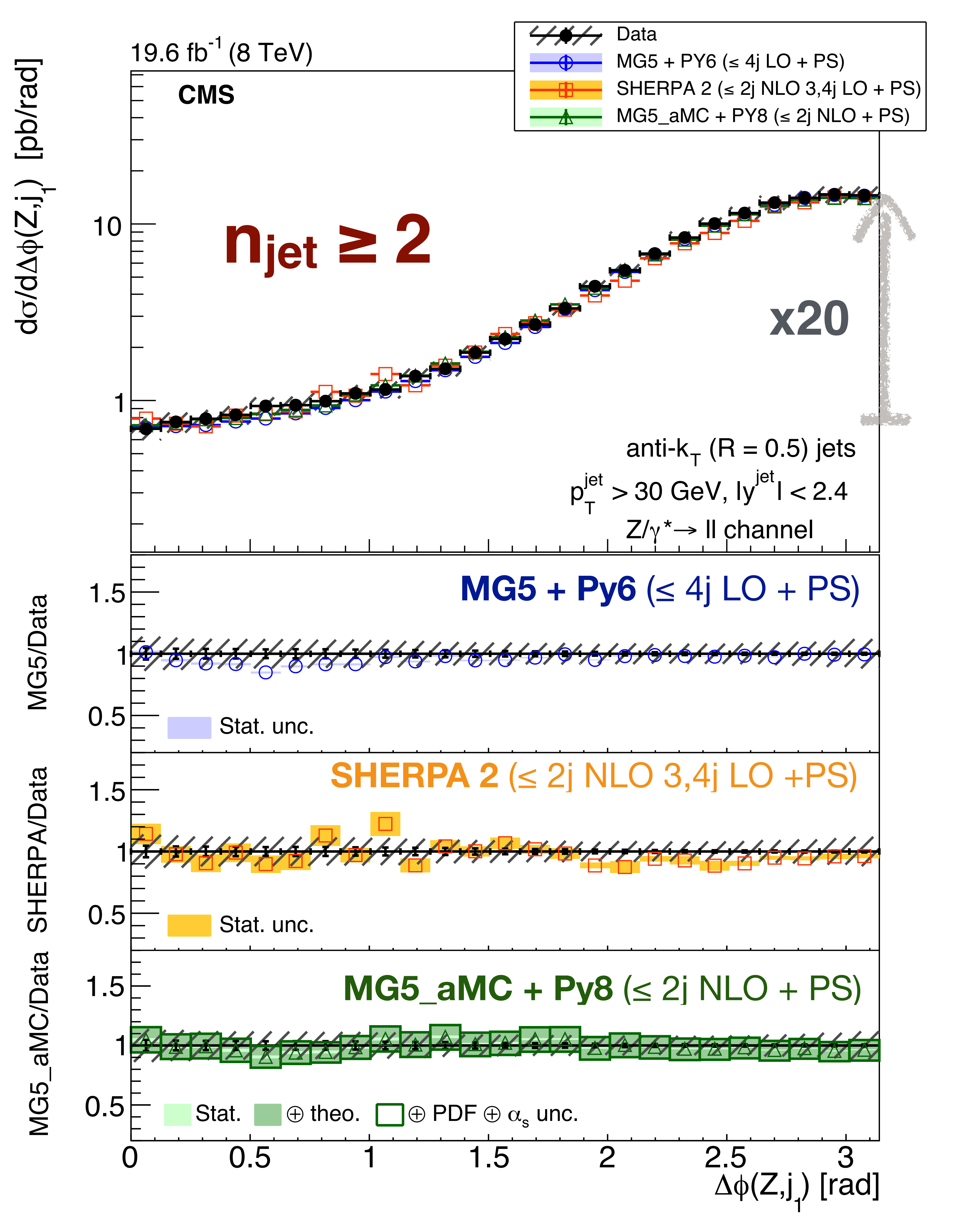


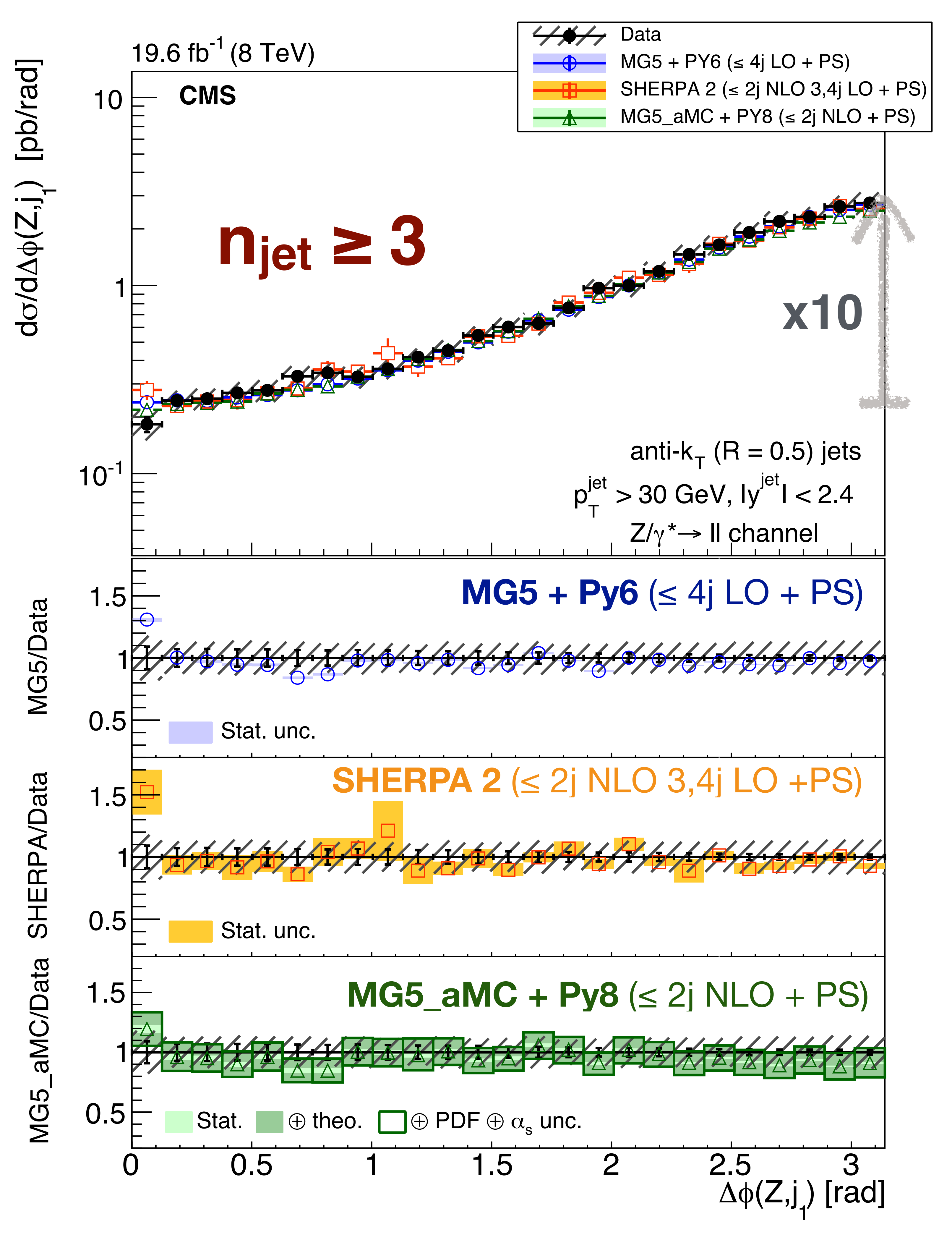
Z+jets: azimuthal angle measurement

arXiv:1611.03844v1

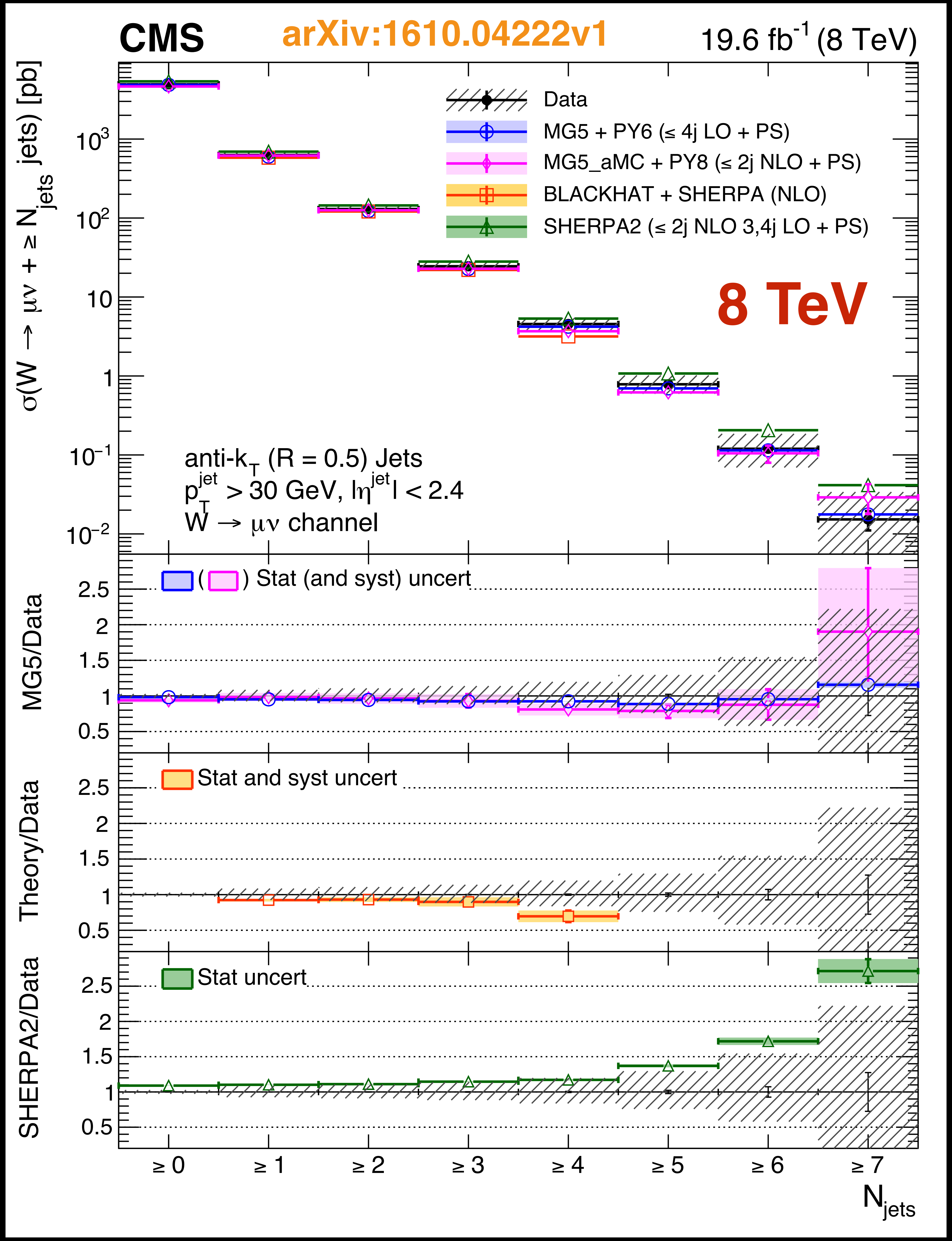




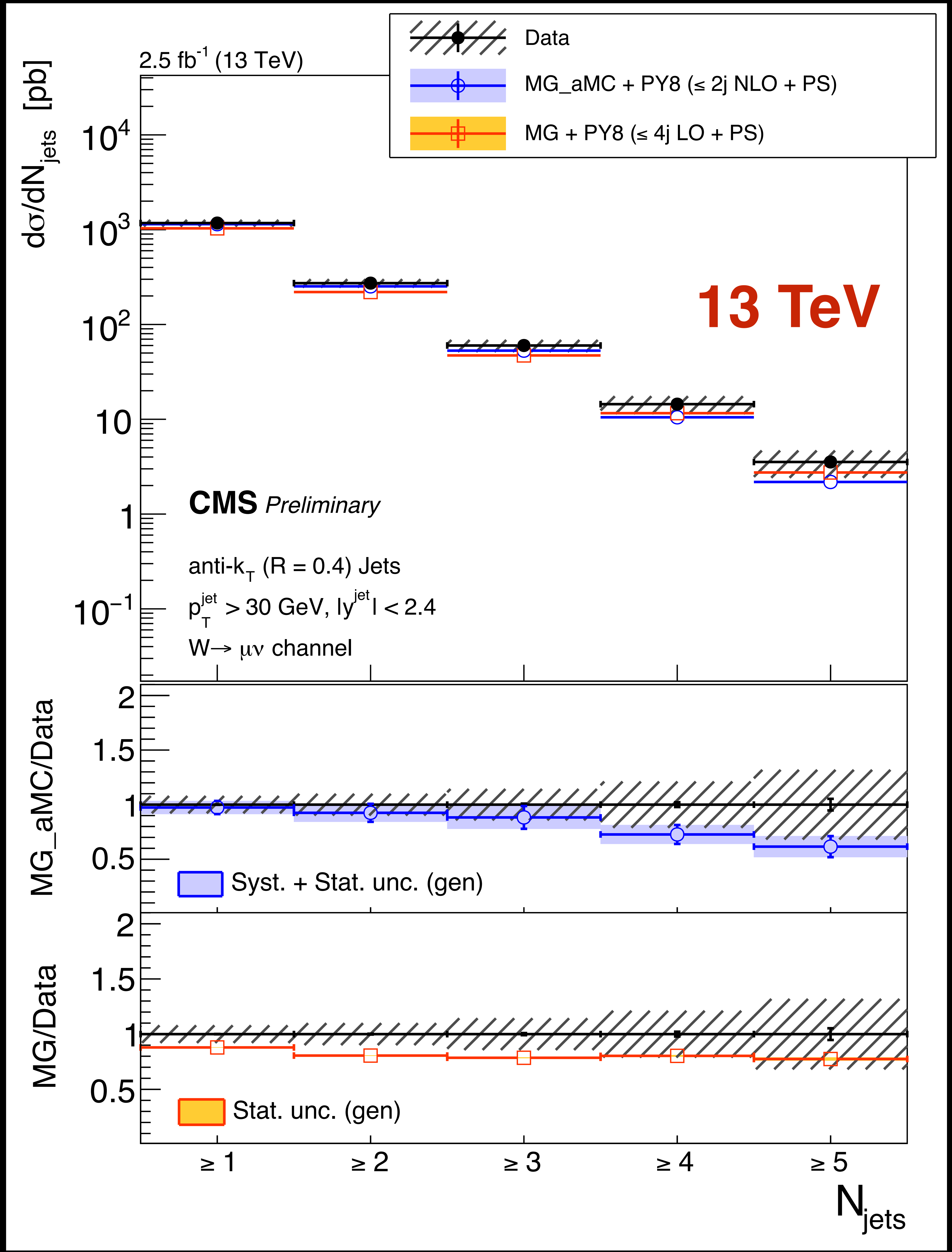




W+jets production

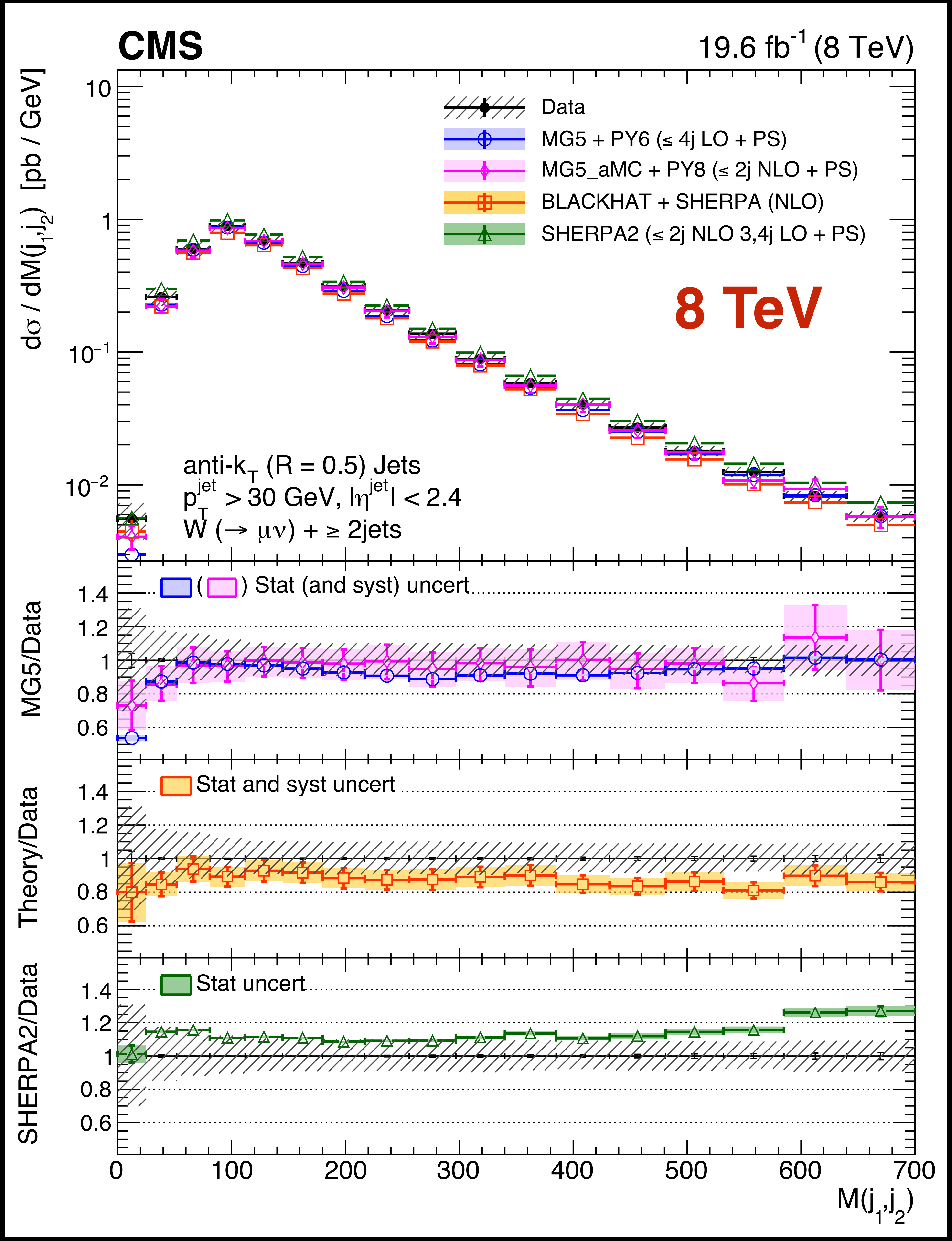


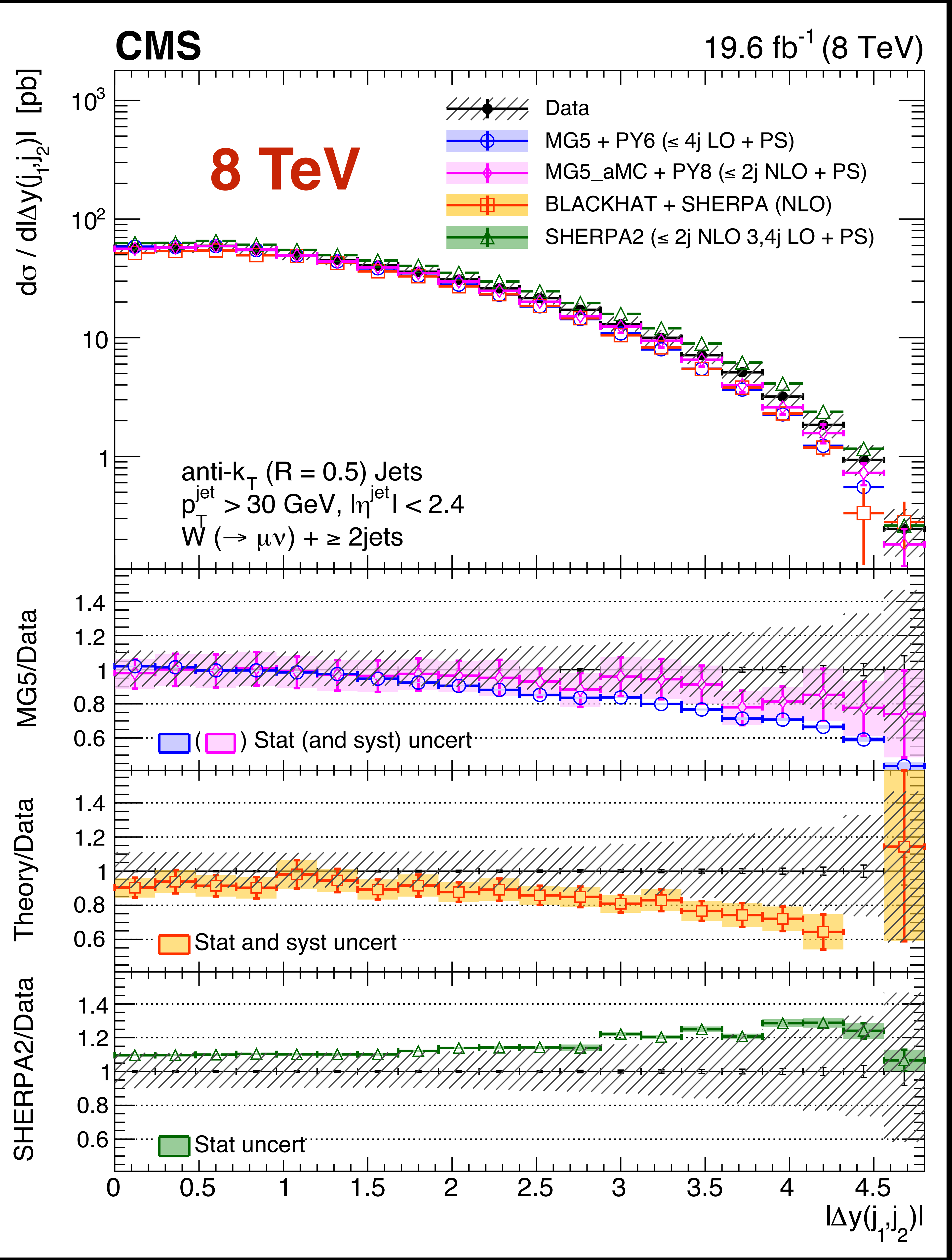
CMS PAS SMP-16-005



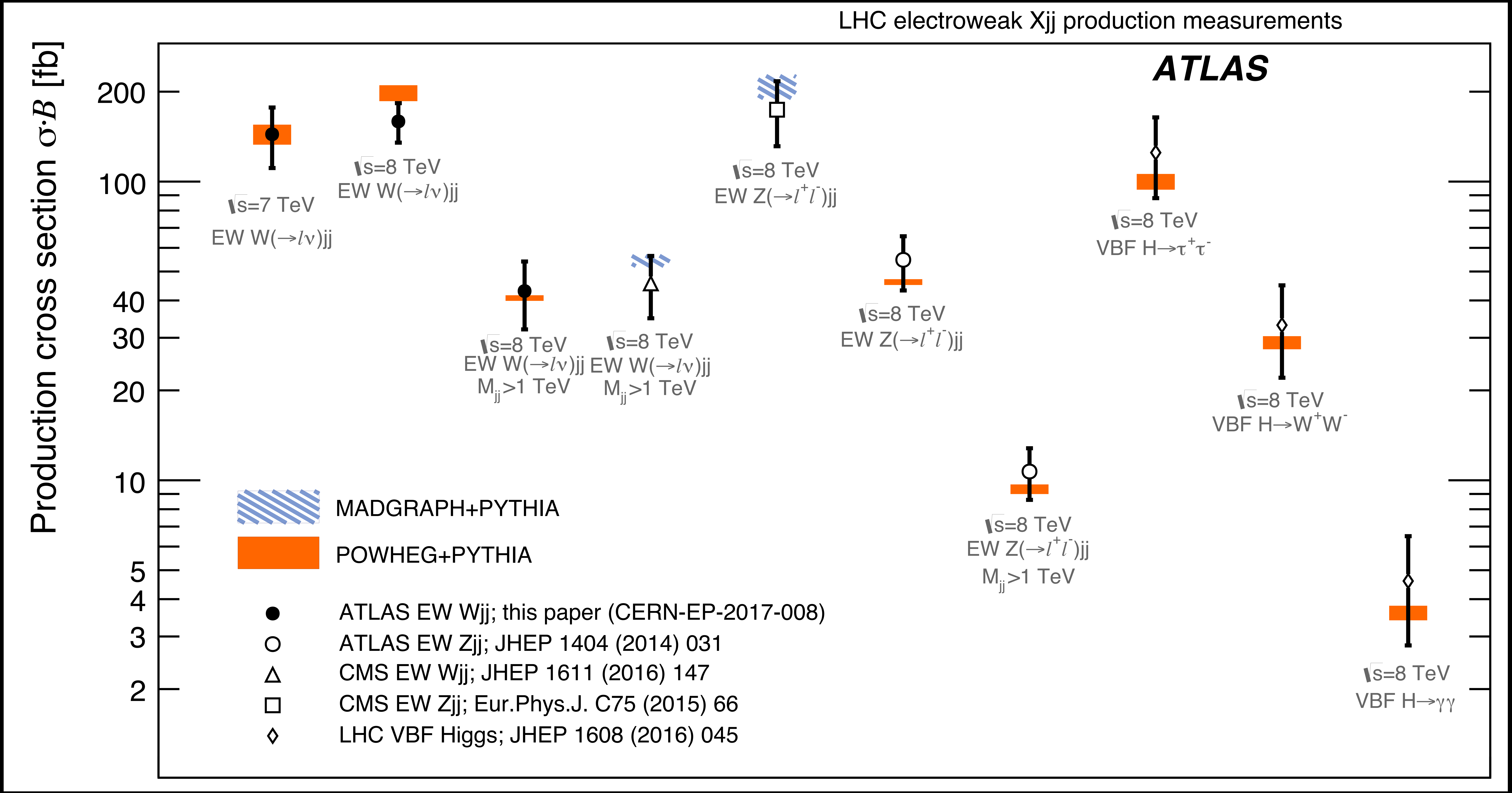
W+jets production: W + ≥ 2 jets

arXiv:1610.04222v1

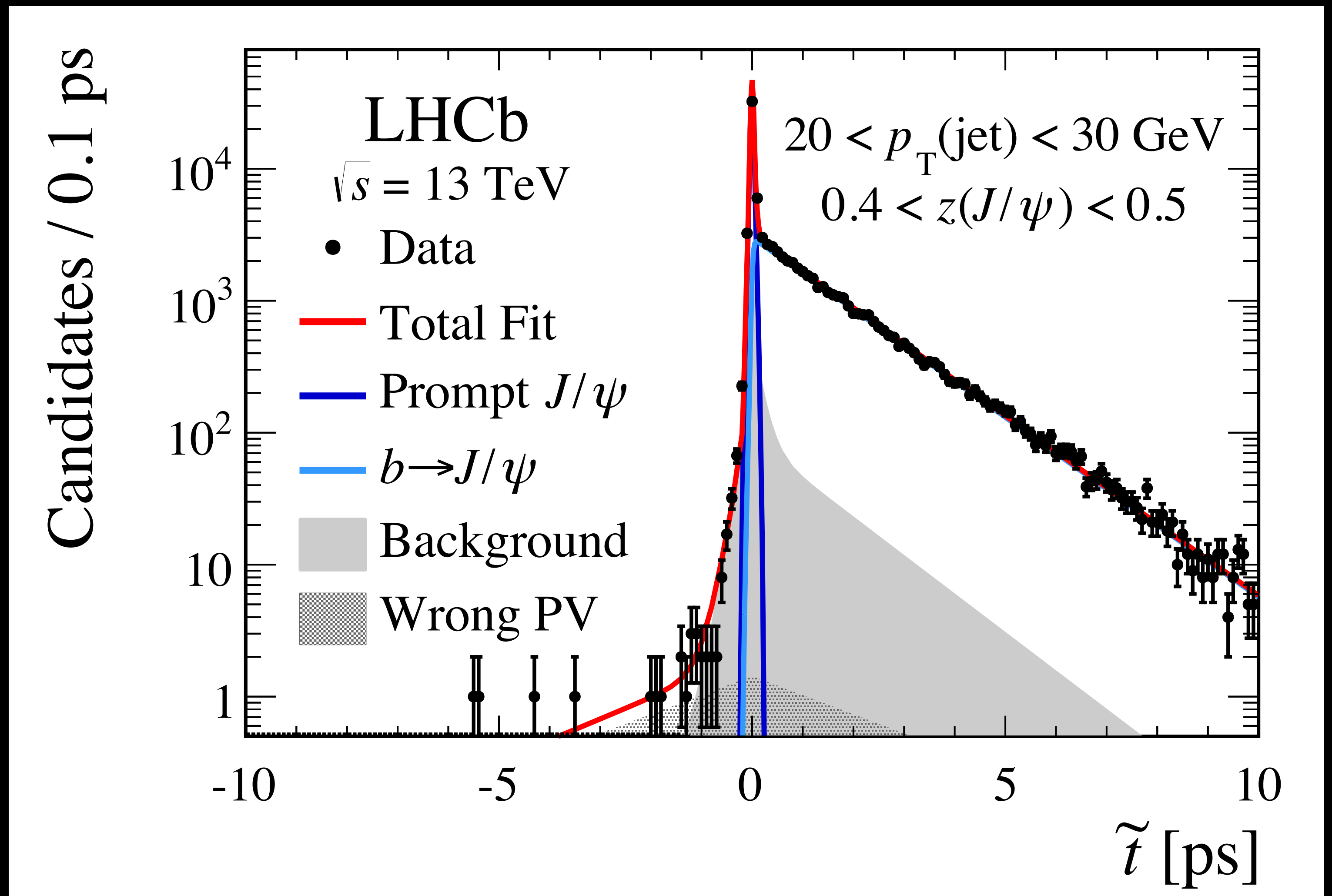


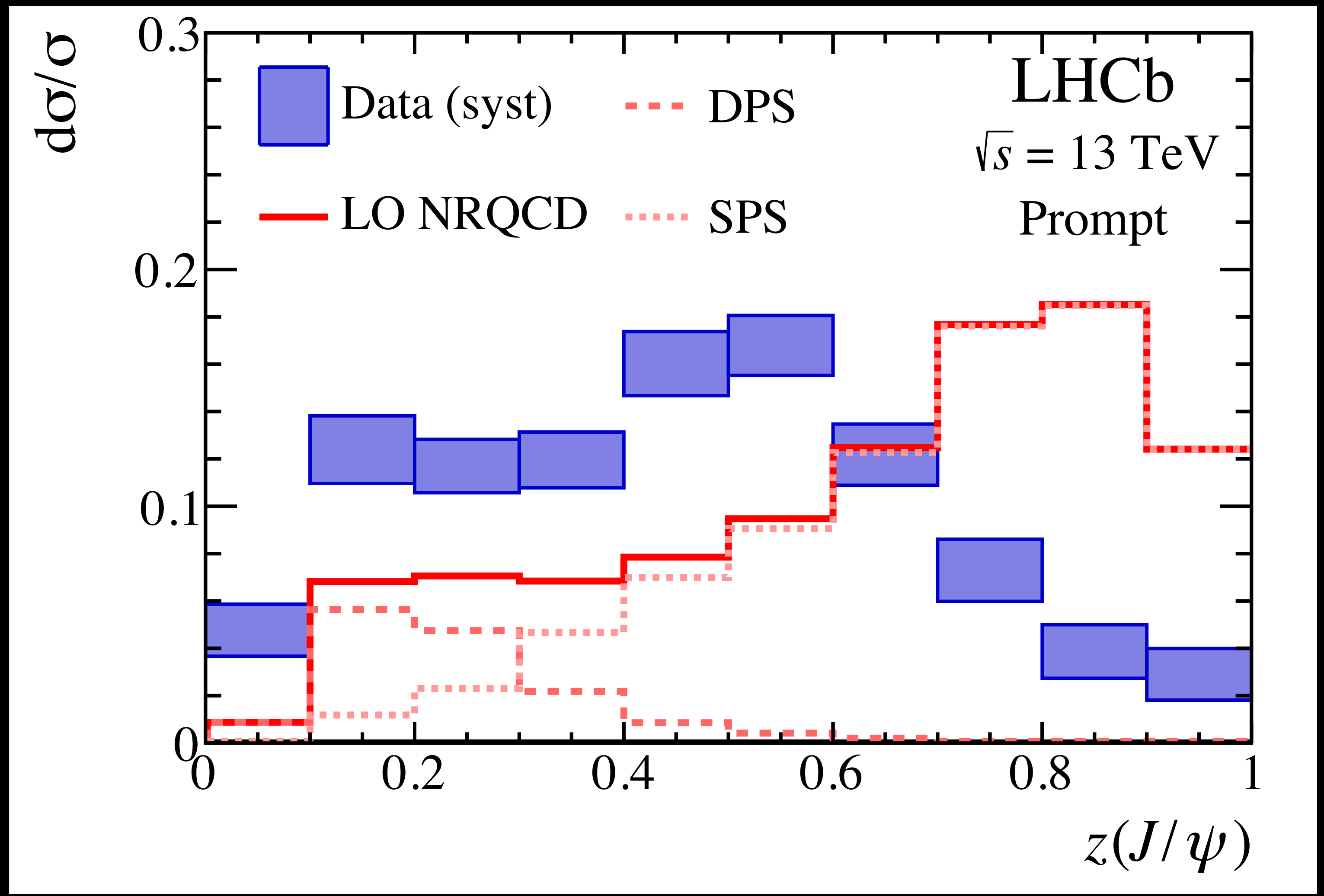


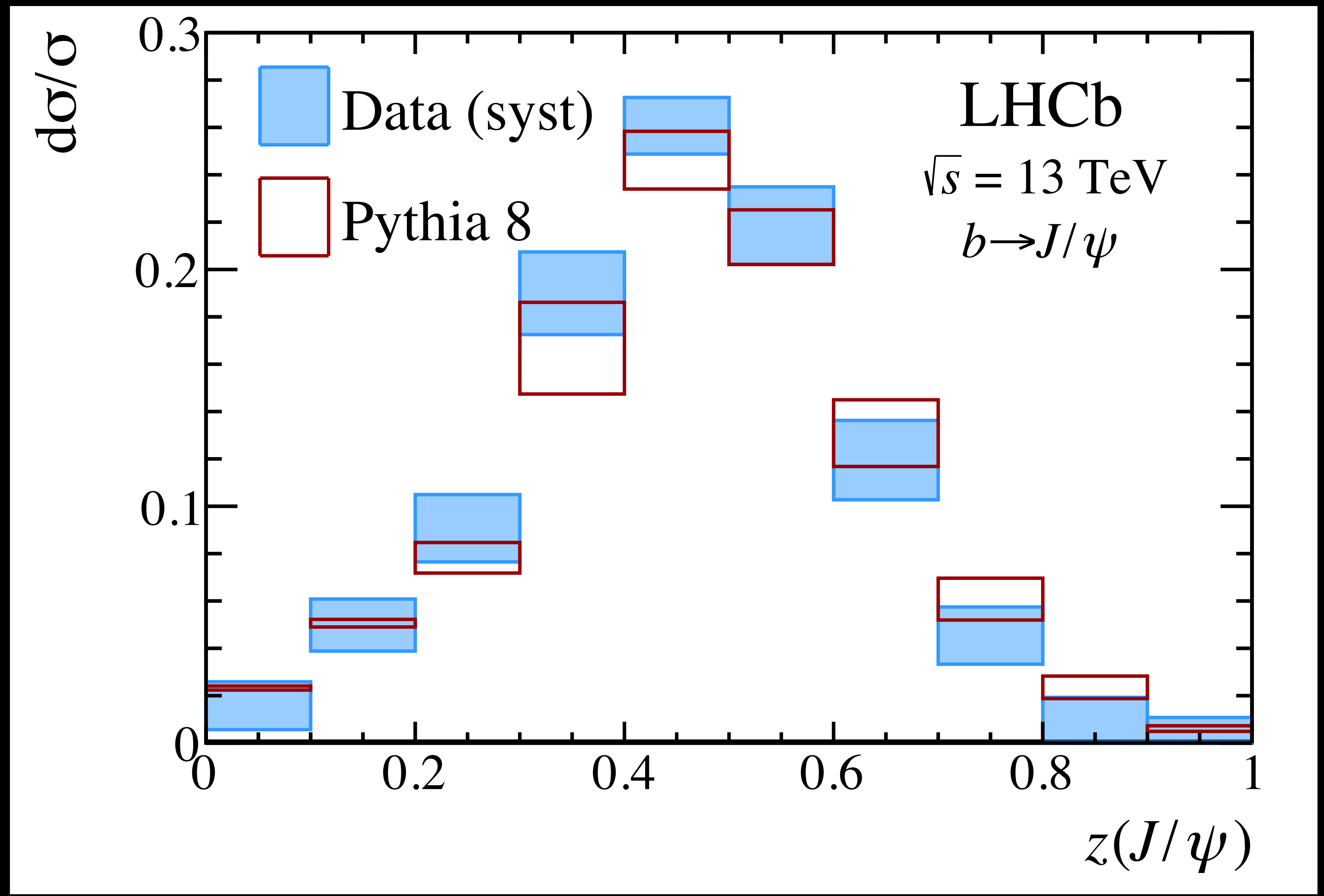
LHC electroweak production of a single W, Z, or Higgs boson



J/ψ production in jets



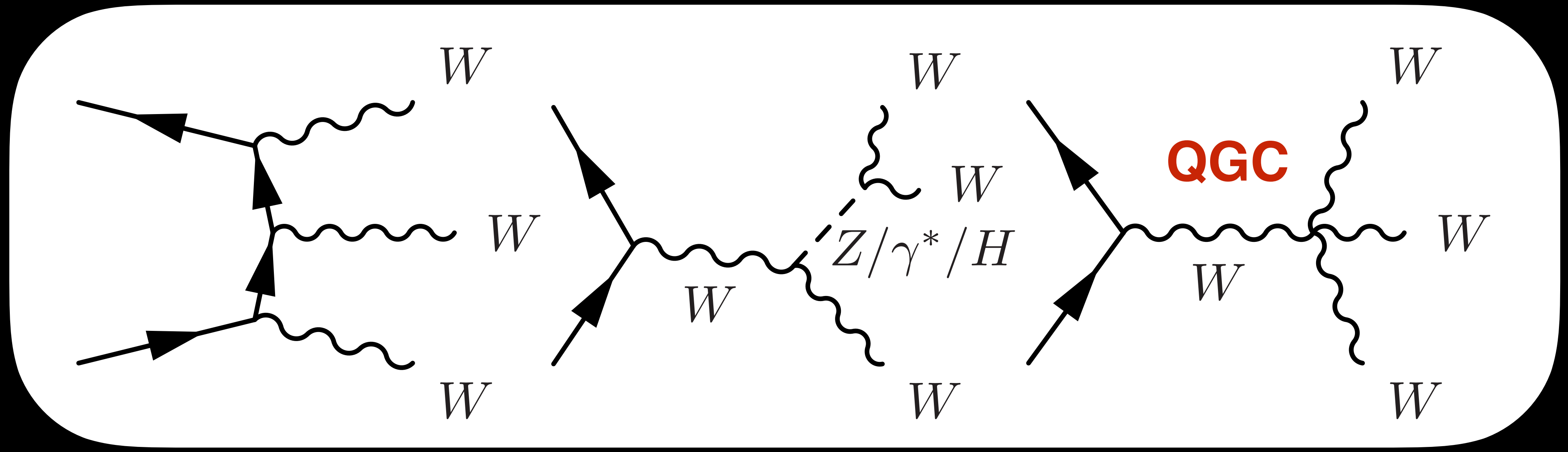




See: LHCb parallel talk by Philip Ilten

Search for triboson W±W±W∓

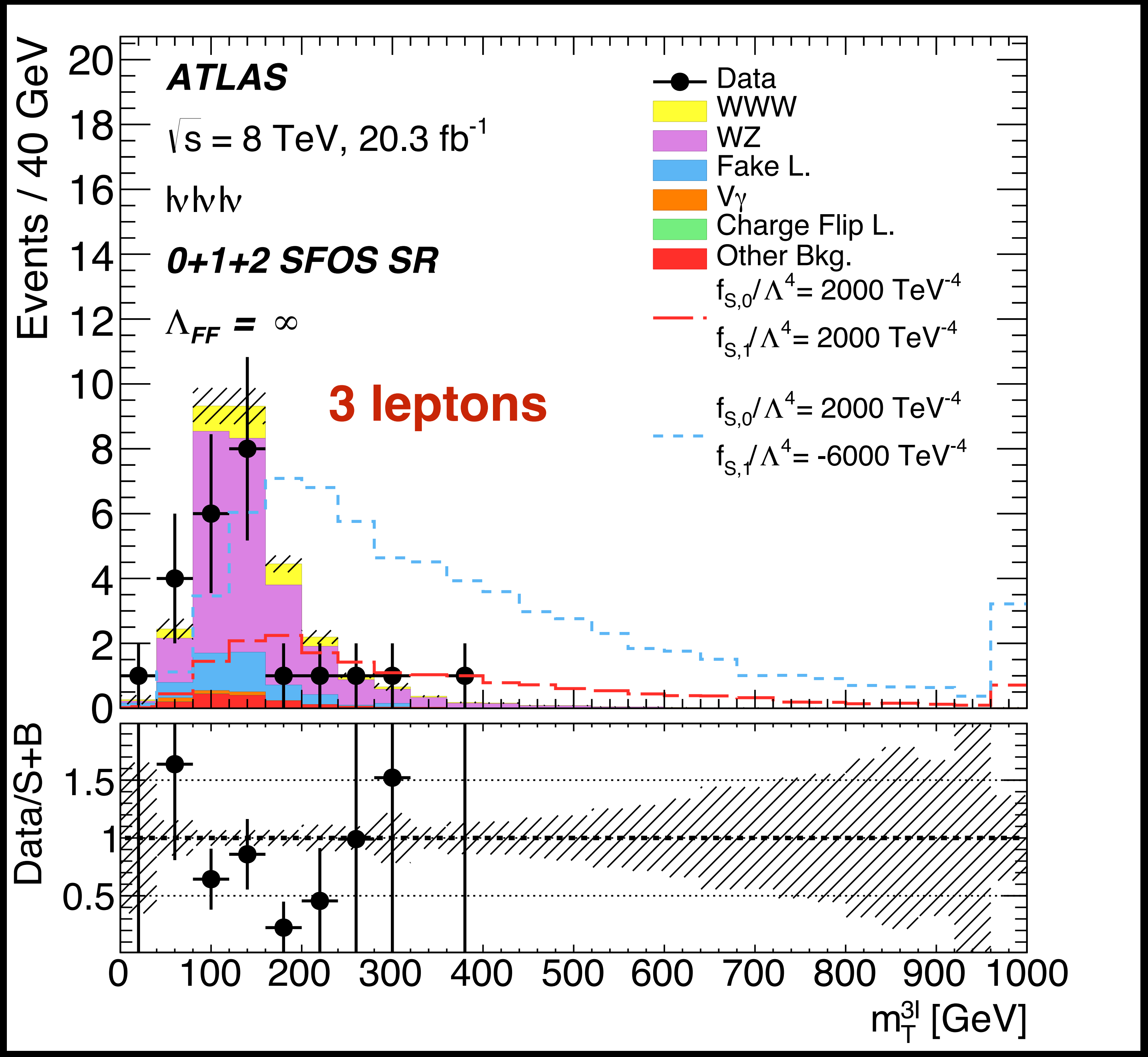
arXiv:1610.05088v2

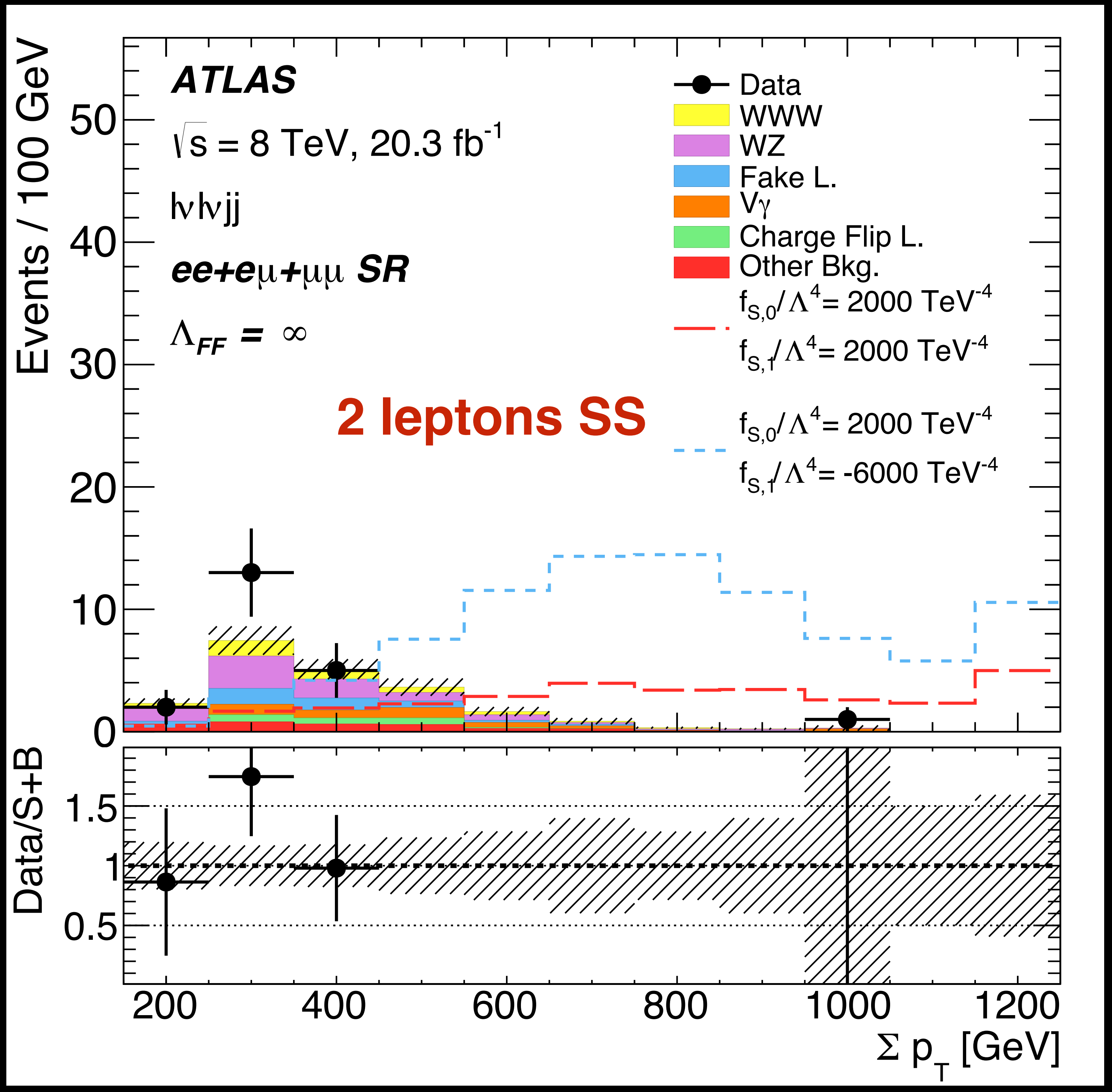


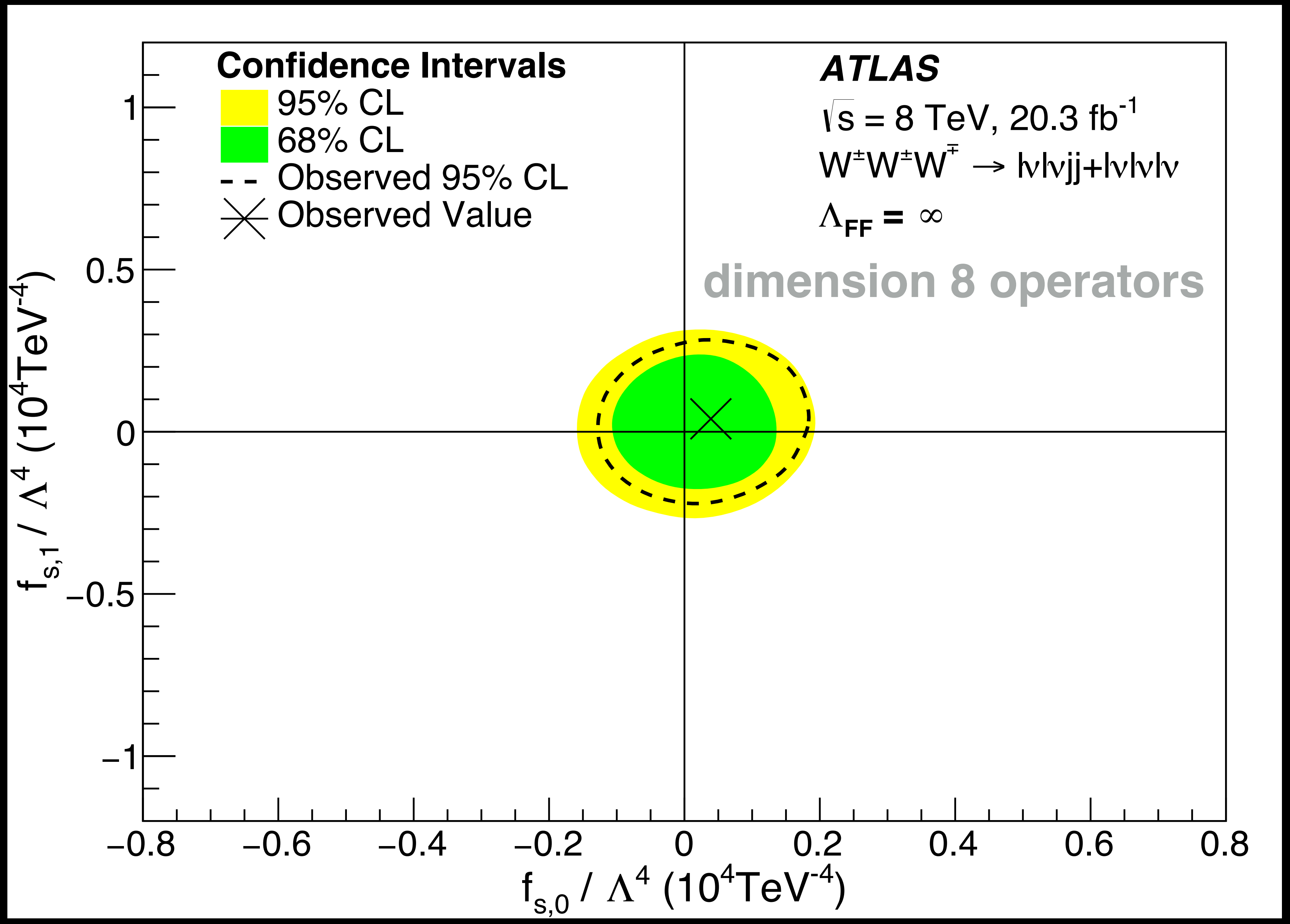
		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.286 ± 0.006 (stat.) ± 0.015 (PDF) ± 0.010 (scale)	$0.24\ ^{+0.39}_{-0.33}$ (stat.) $^{+0.19}_{-0.19}$ (syst.)

sub-fb cross section

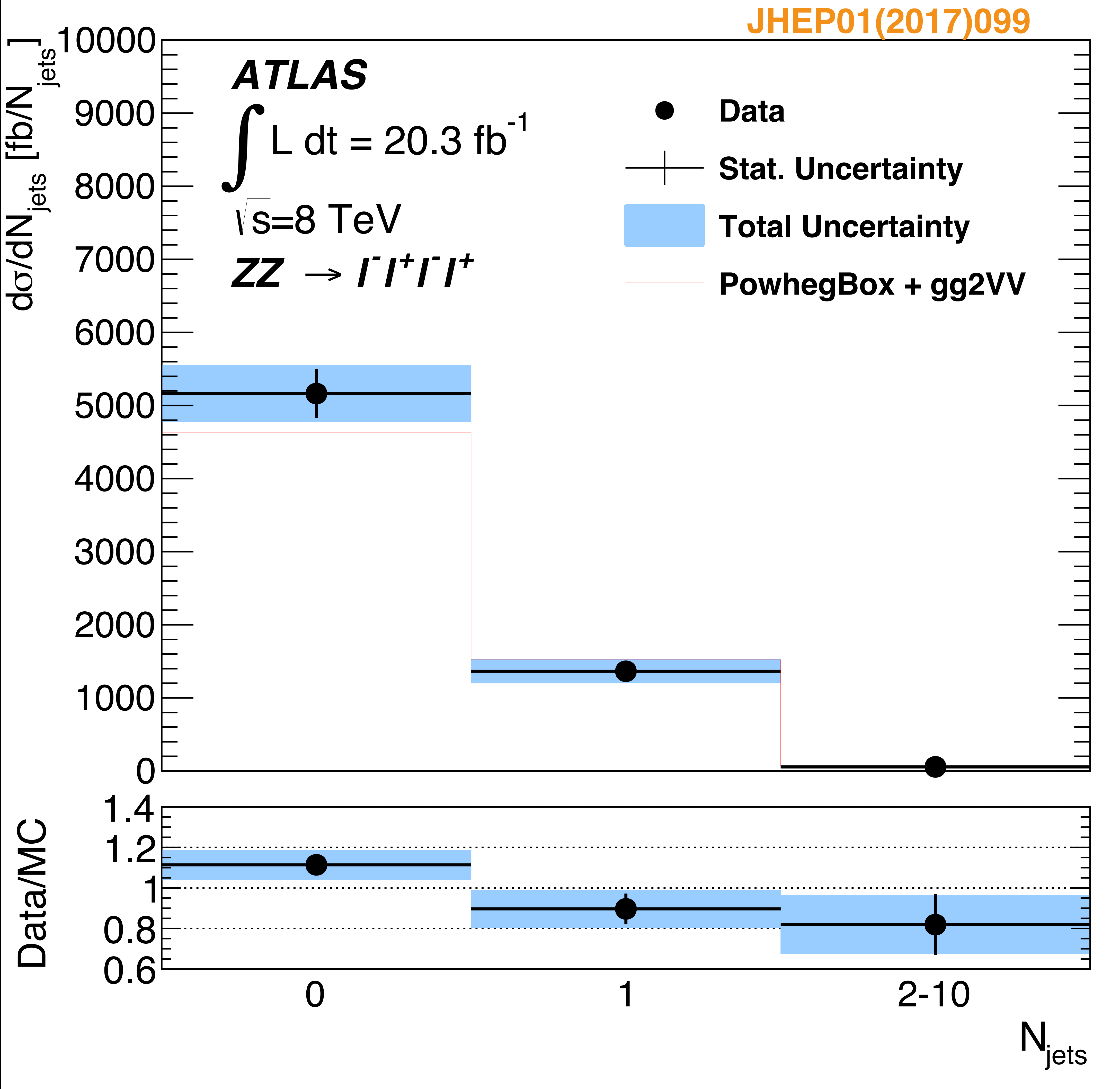
Limits on anomalous quartic gauge couplings

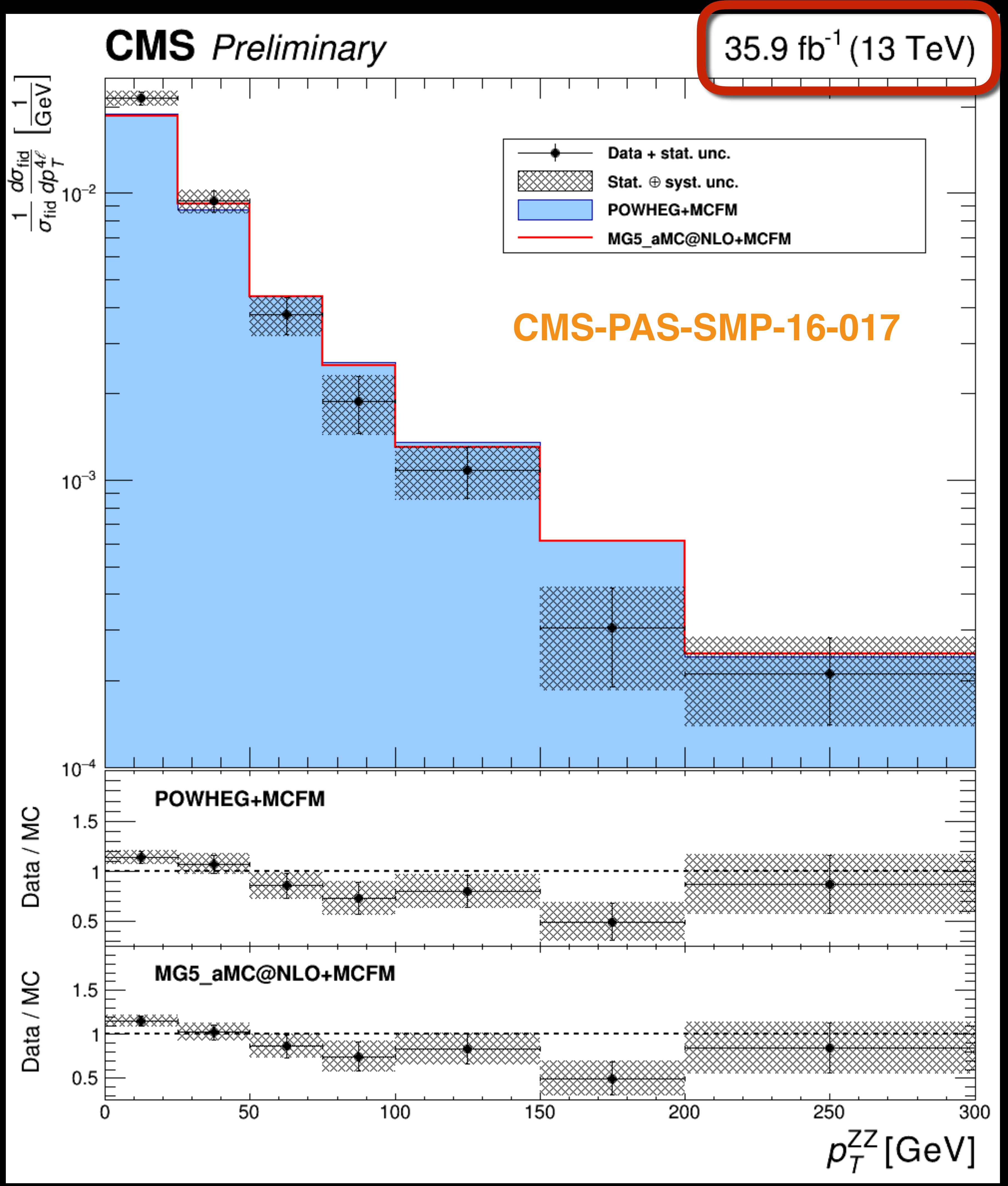






Diboson differential cross sections



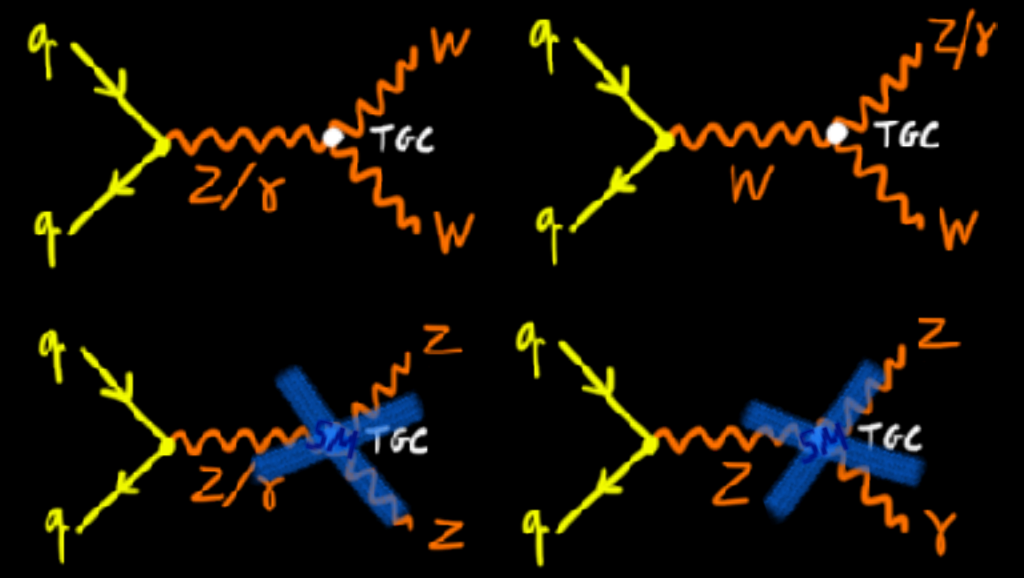


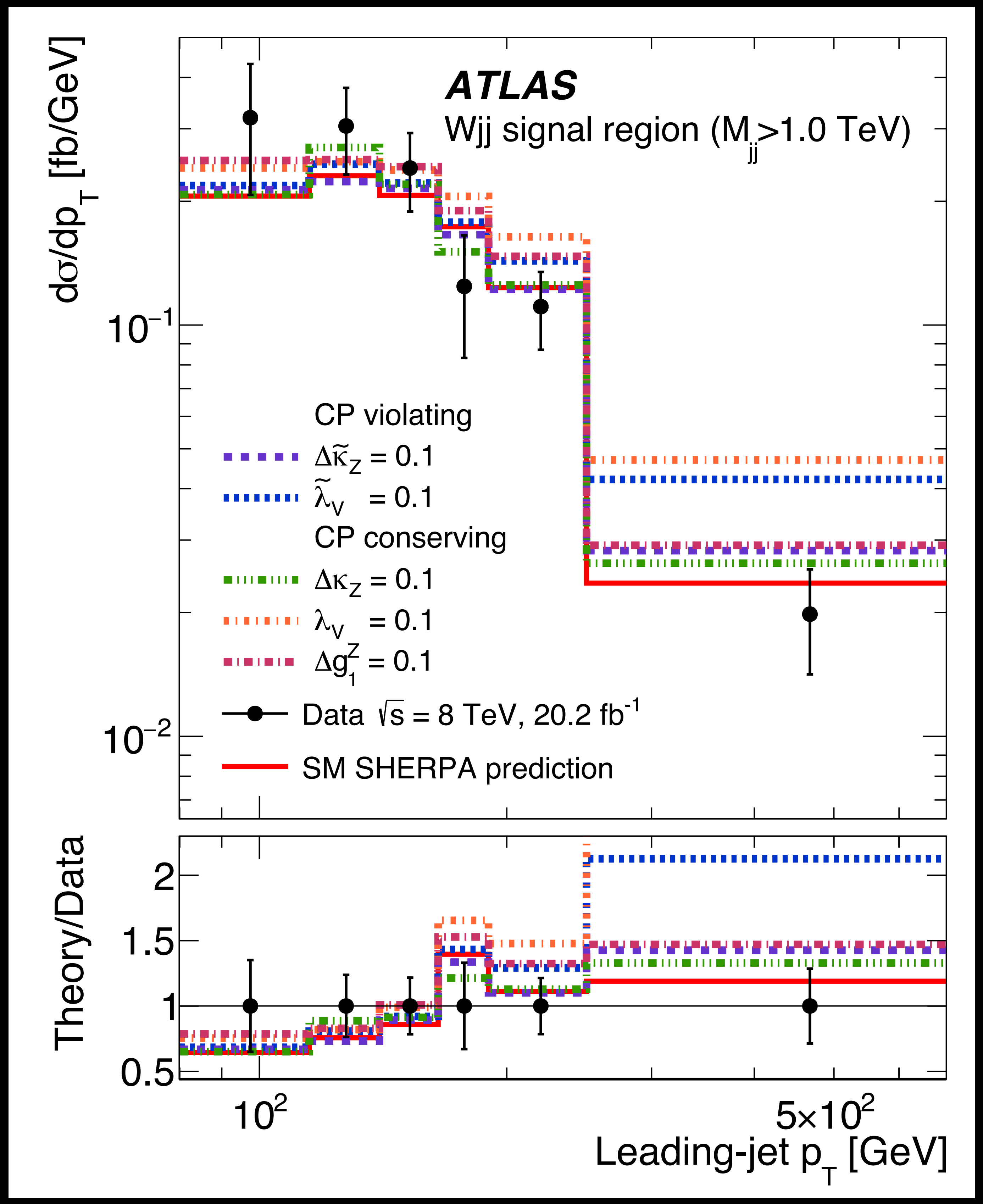
Softer p_T^{ZZ} then predicted by NLO QCD

Anomalous Gauge Couplings

Channels

- Wγ, WW and WZ → anomalous charged couplings
- Zγ and ZZ → anomalous neutral couplings
- Z+2Jets and W+2J





No deviations from SM have been observed

Charged couplings:

- **LHC limits slightly better than LEP limits**

Neutral couplings:

- **LHC limits far stricter than LEP limits**

New: CMS ZZ with Z → l^+l^- using 35.9 fb^{-1} of 13 TeV pp collisions, CMS PAS SMP-16-017

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC