Standard Model Measurements at the LHC

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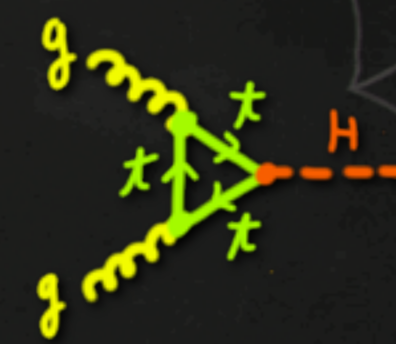
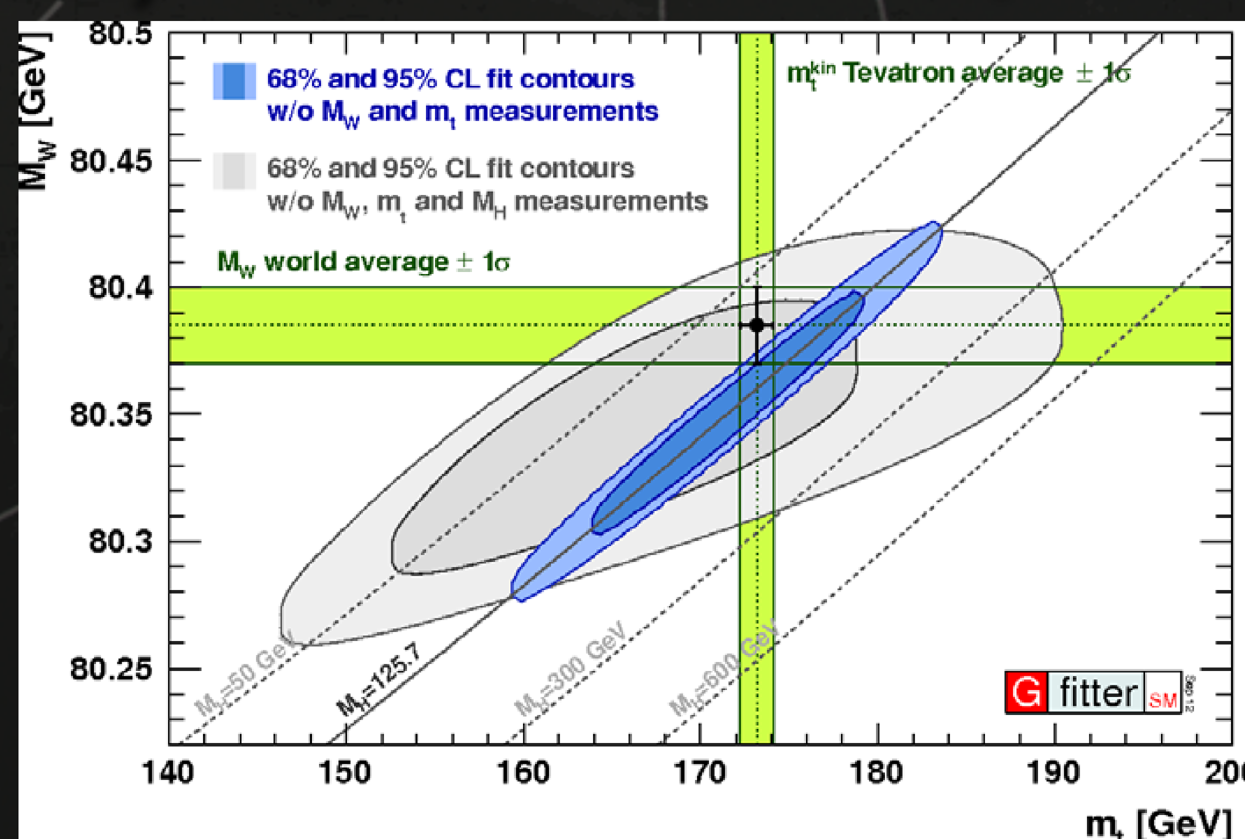
Why Standard Model Physics?

...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
    - E.g.: Drell-yan is a major background for H ➔ WW
  - Improved proton PDFs
- Explore the SM self consistency
  - Measure its parameters



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

Physics

non-perturbative QCD

NLO QCD

NNLO QCD

Proton PDF
Valence, strange quarks
Gluons

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

Hadrons

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

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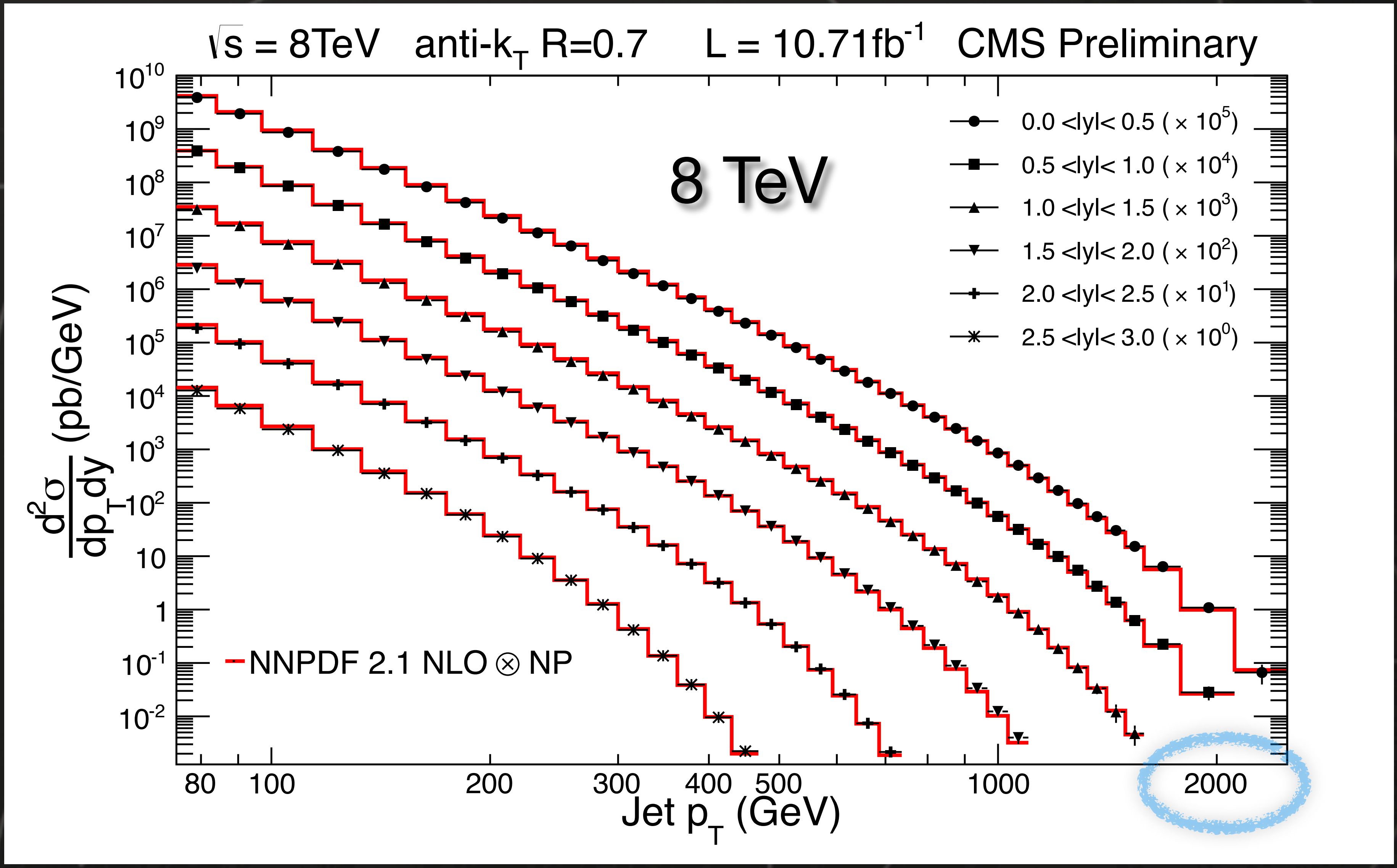
Many topics left out:
- SM Higgs production
- Heavy-flavour physics (B-physics)
- Heavy-ion physics (physics in dense media)

Inclusive Jet Cross Sections

CMS-PAS-SMP-12-01



NLOJET++ prediction with NNPDF 2.1

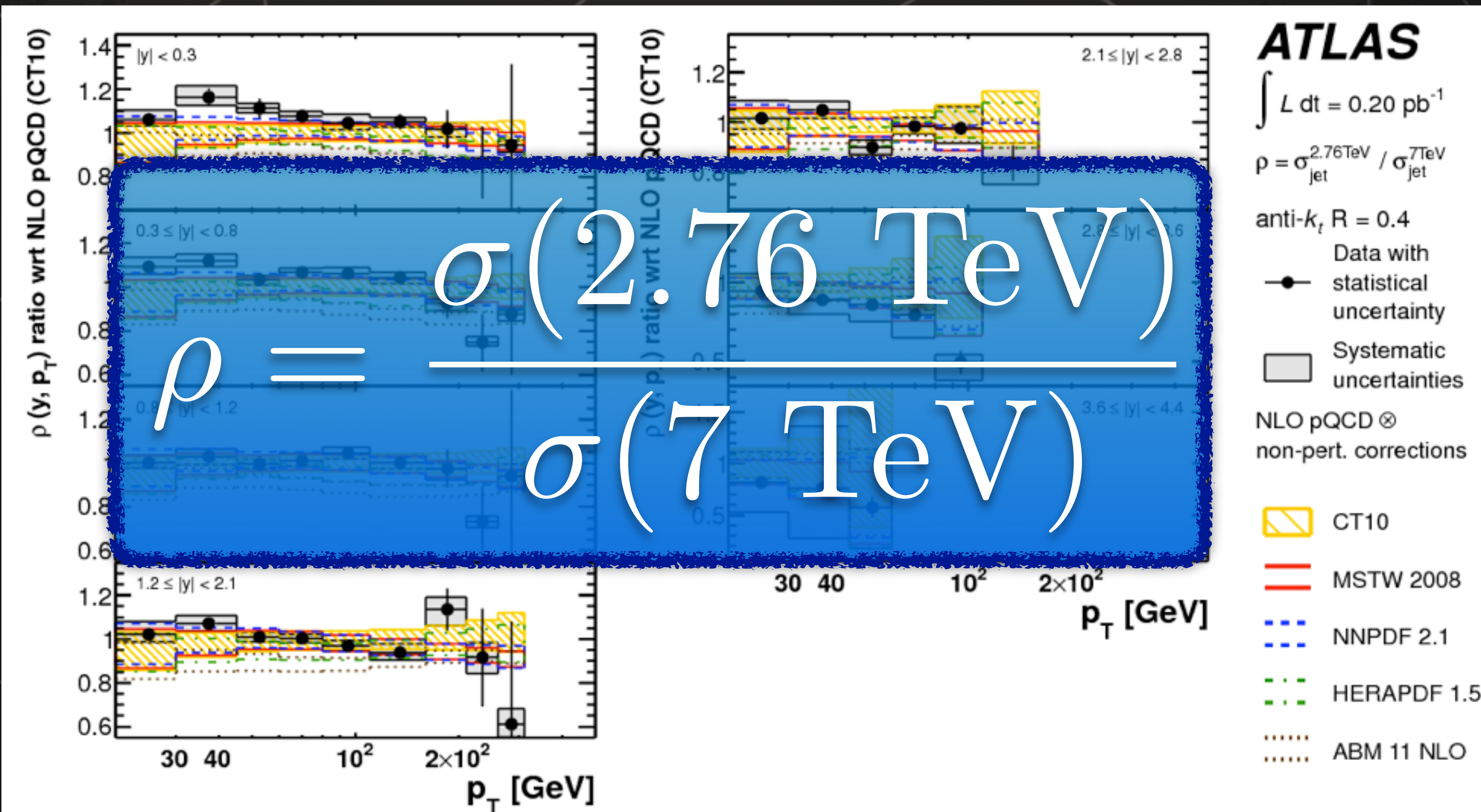
NLO QCD predictions describe data over 10 orders of magnitude!

Jet inclusive data starts to constrain gluon PDFs
(CT10, MSTW2008, NNPDF2.1, HERAPDF1.5, ABM11)

Inclusive cross section ratio 2.76 TeV/7 TeV

- Experimental uncertainties is reduced and generally smaller than theory uncertainty (JES ~ few %)

arXiv:1304.4739



$$\rho = \frac{\sigma(2.76\ \mathrm{TeV})}{\sigma(7\ \mathrm{TeV})}$$

Impact on gluon and sea parton distribution functions

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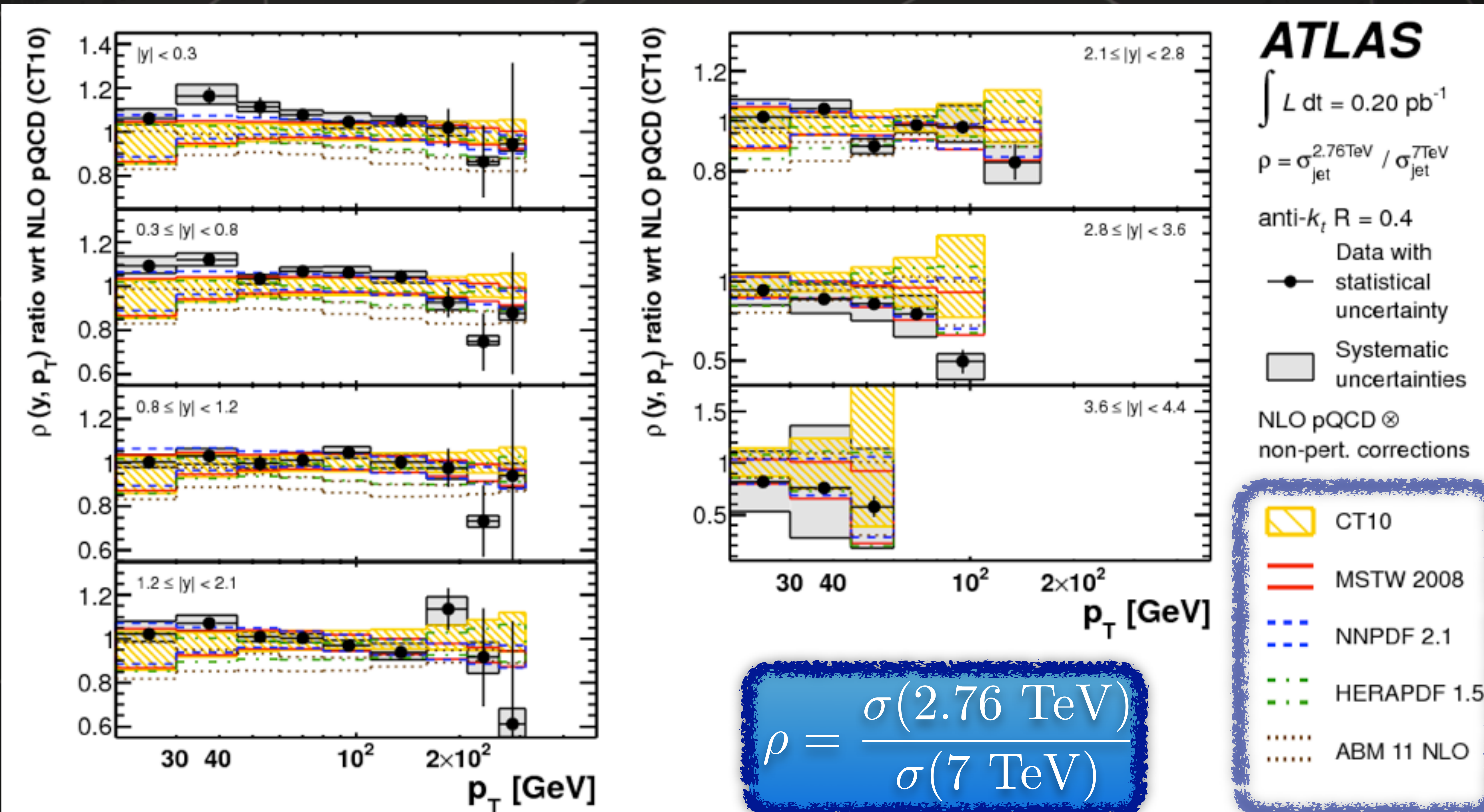

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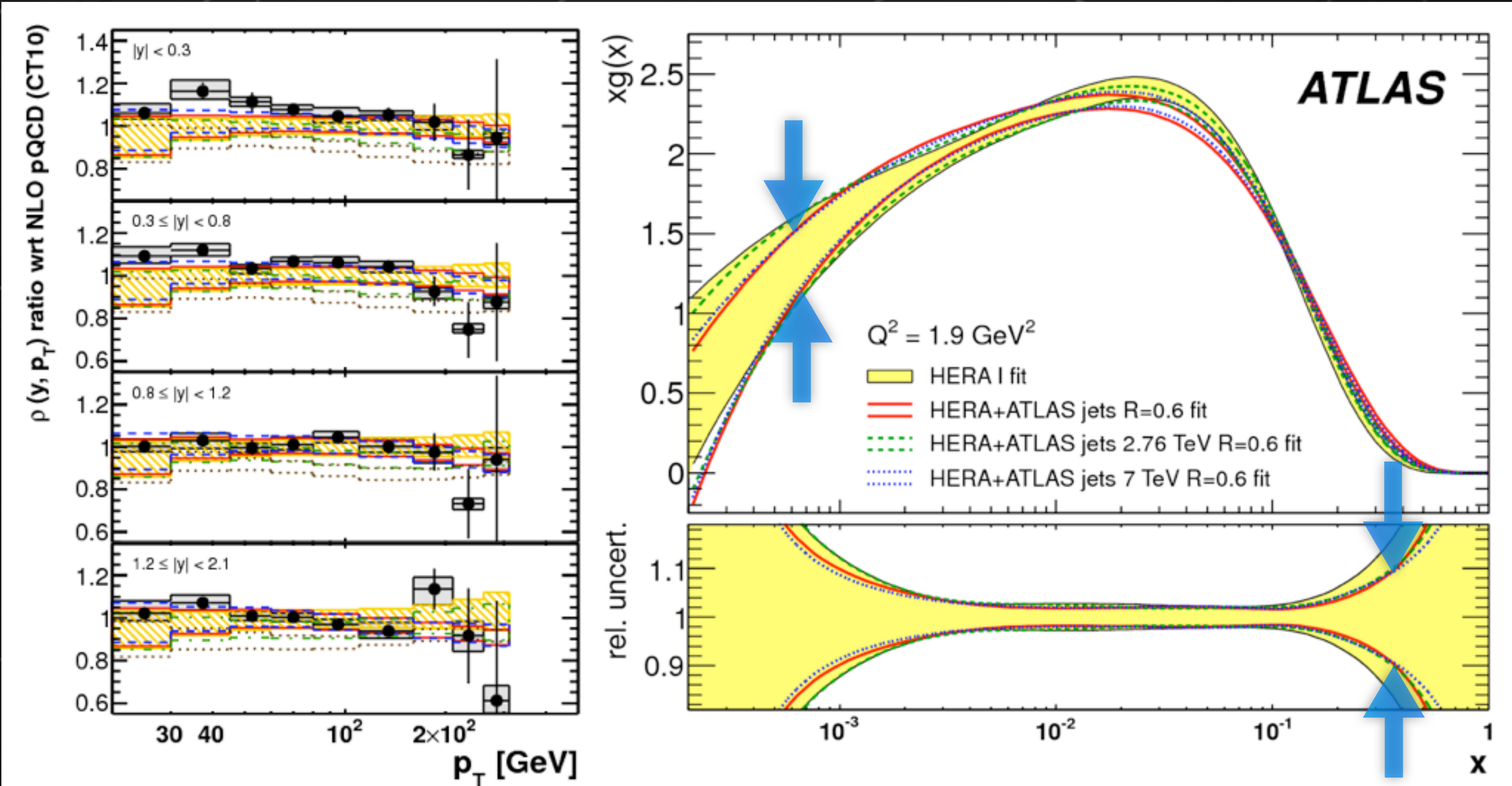
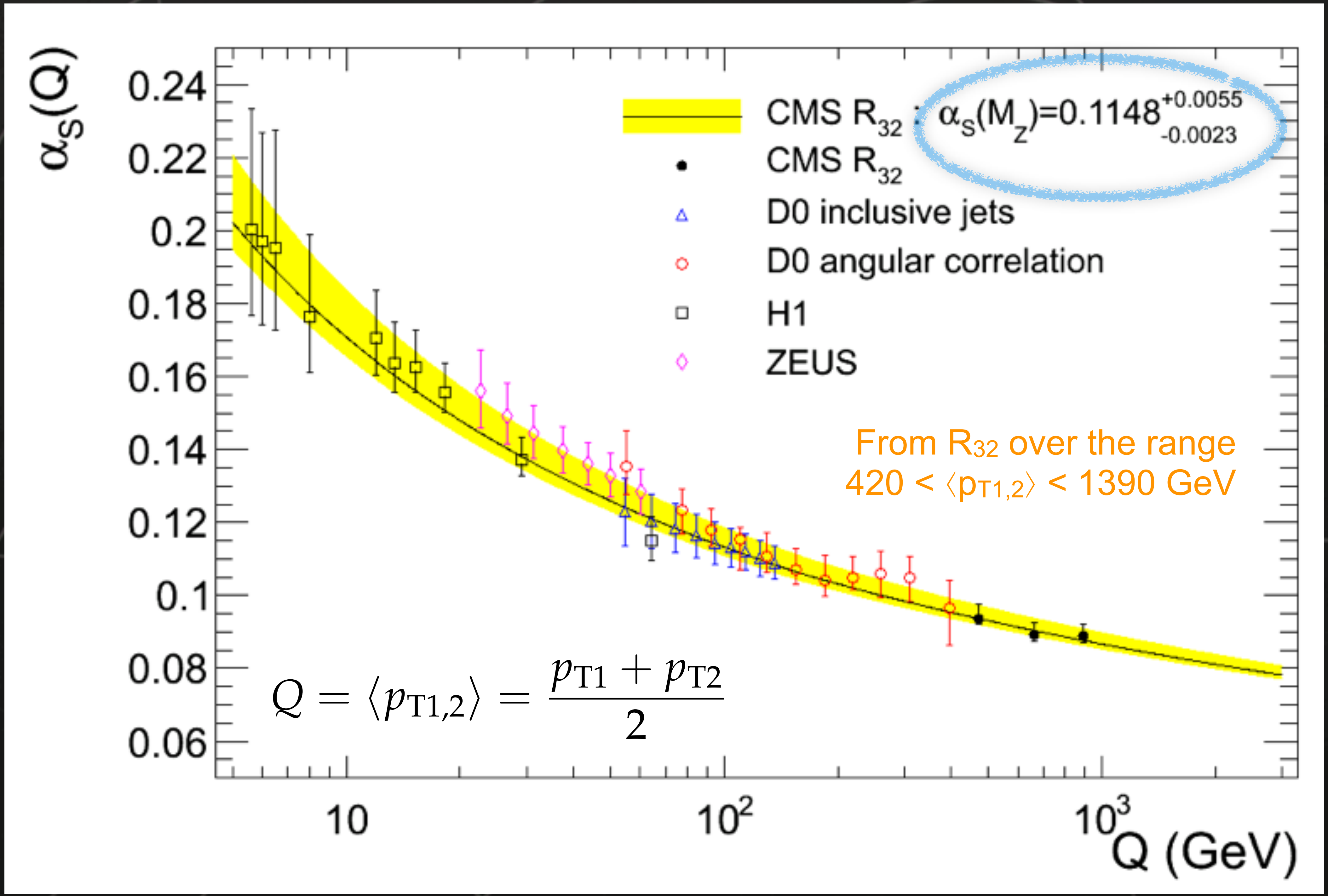


Impact on gluon and sea-quarks distribution functions

Extraction of the Strong Coupling Constant

Ratio of the inclusive 3-jet cross section
to the inclusive 2-jet cross section (R_{32})

arXiv:1304.7498

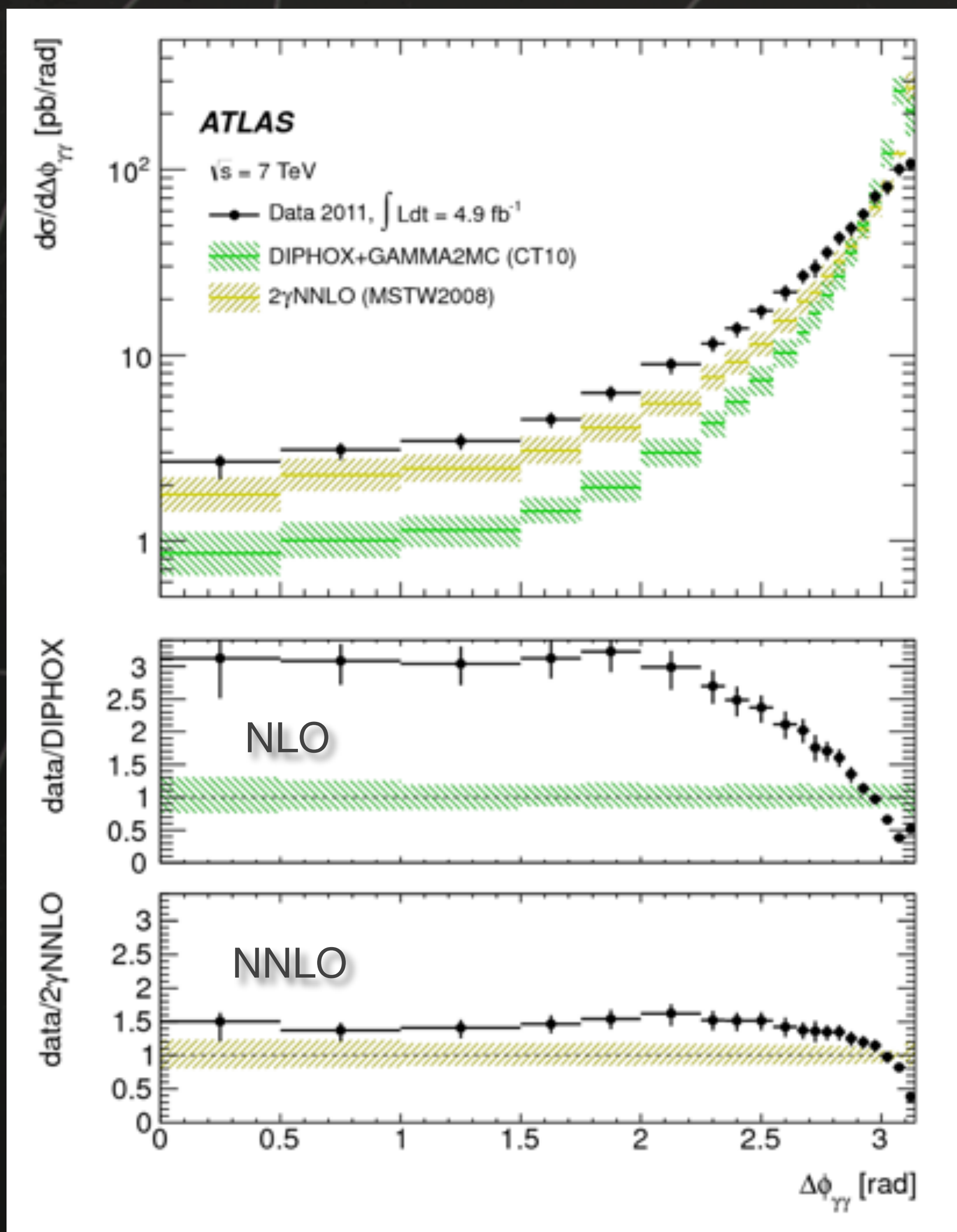


ATLAS: Preliminary result with similar measurement (ATLAS-CONF-2013-041)
CMS: Measurement in top events (CMS-PAS-TOP-12-022)

Photon cross section measurements

γγ

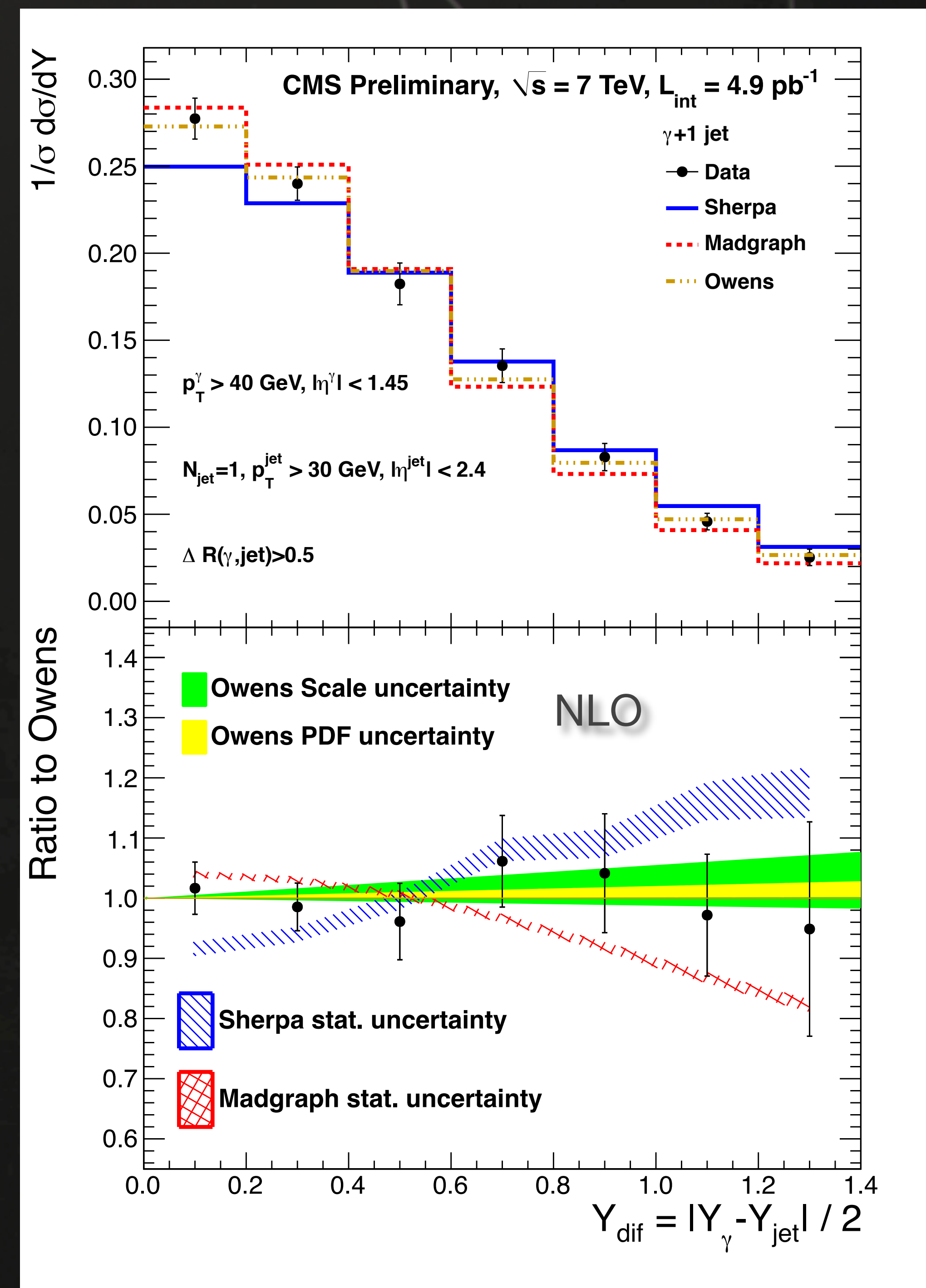
Δ $\phi_{\gamma\gamma}$ distribution



[JHEP 01 (2013) 086]

γ + 1 jet

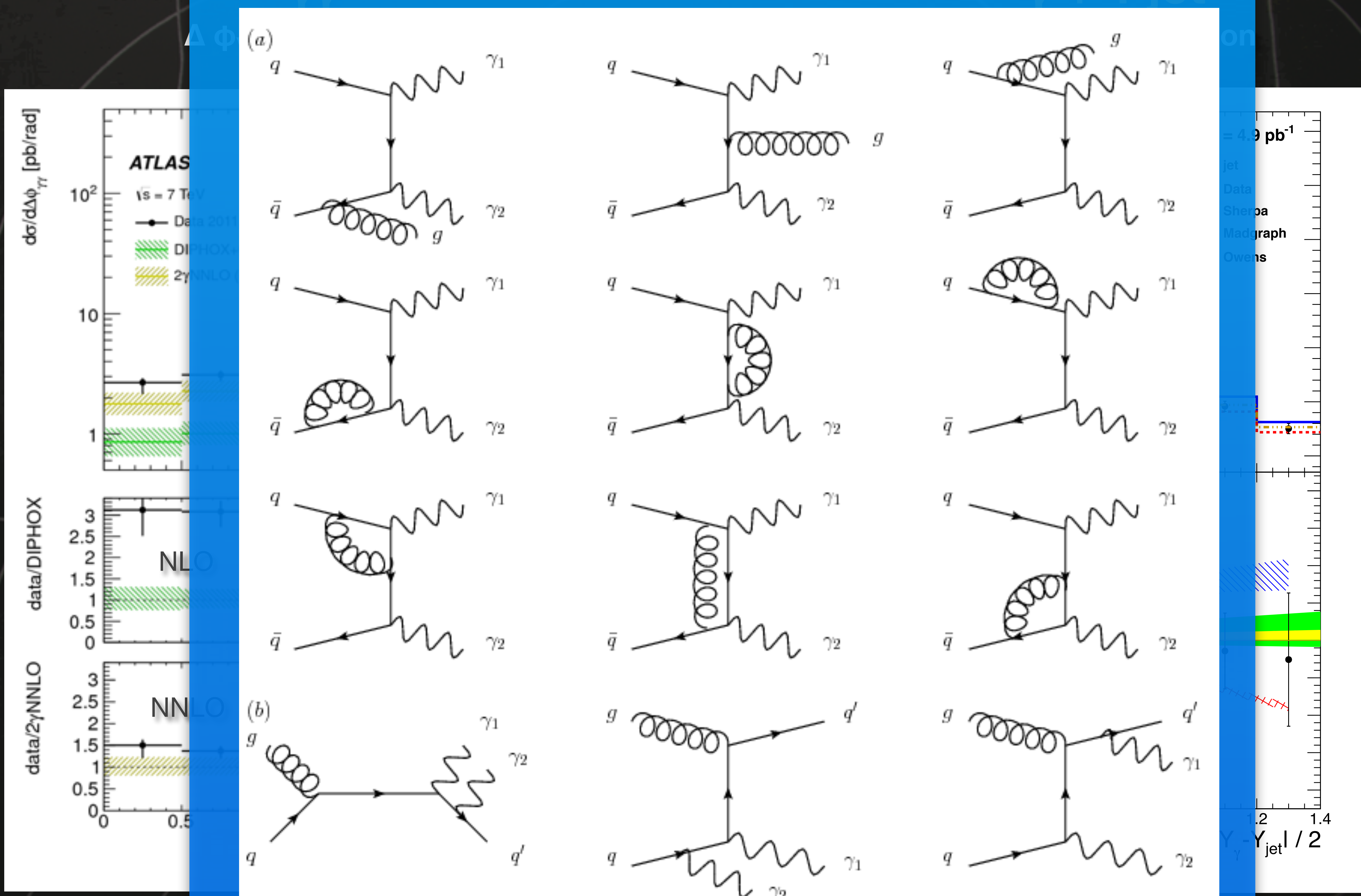
rapidity distribution



CMS-PAS-SMP-12-004

Photon cross section measurements

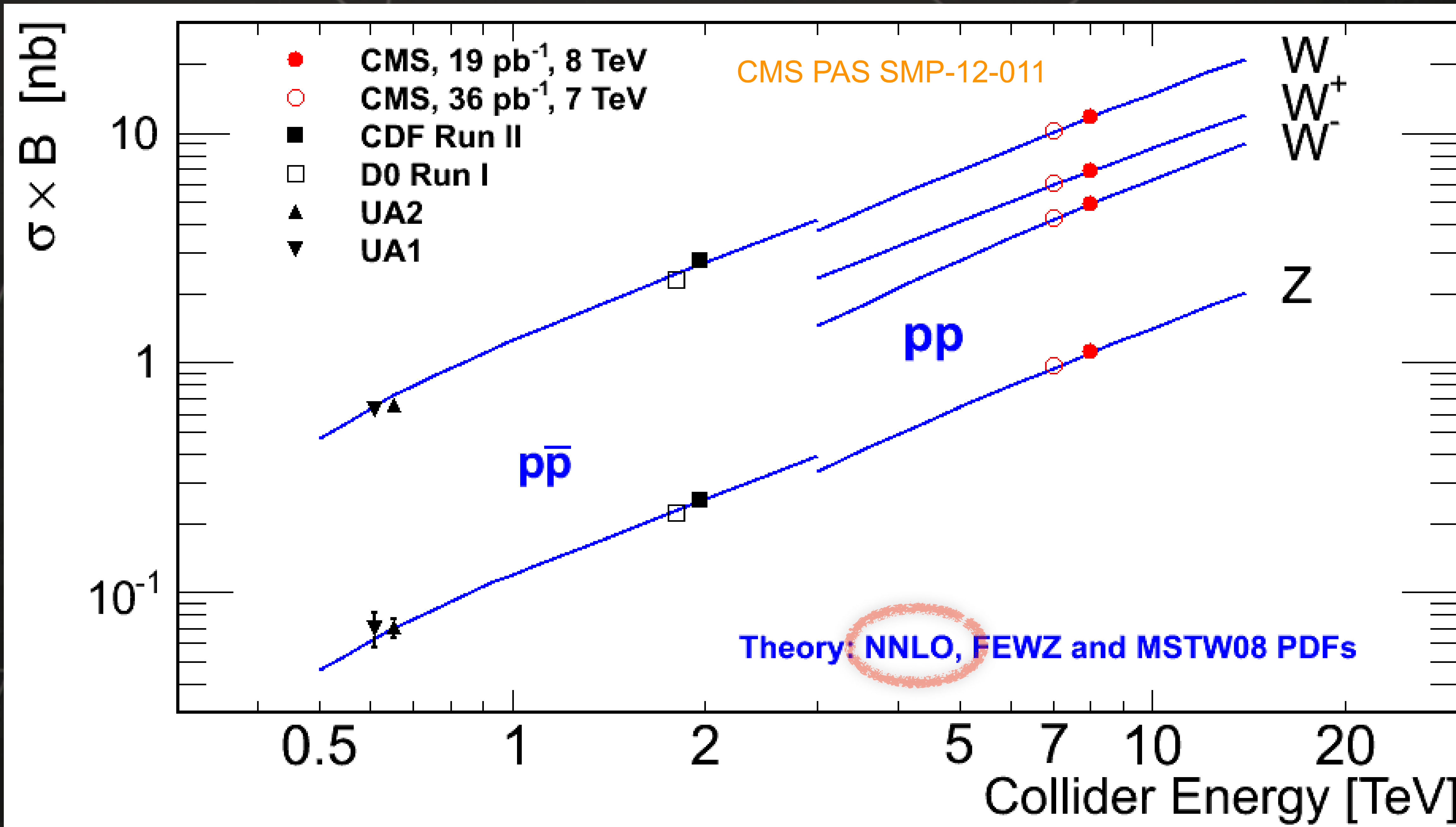
NLO and NNLO essential to describe data



JHEP 01 (2013) 086

CMS-PAS-SMP-12-004

W and Z inclusive production



7 TeV

CMS and ATLAS

Uncertainties: 1-2%

(excluding luminosity)

8 TeV

CMS

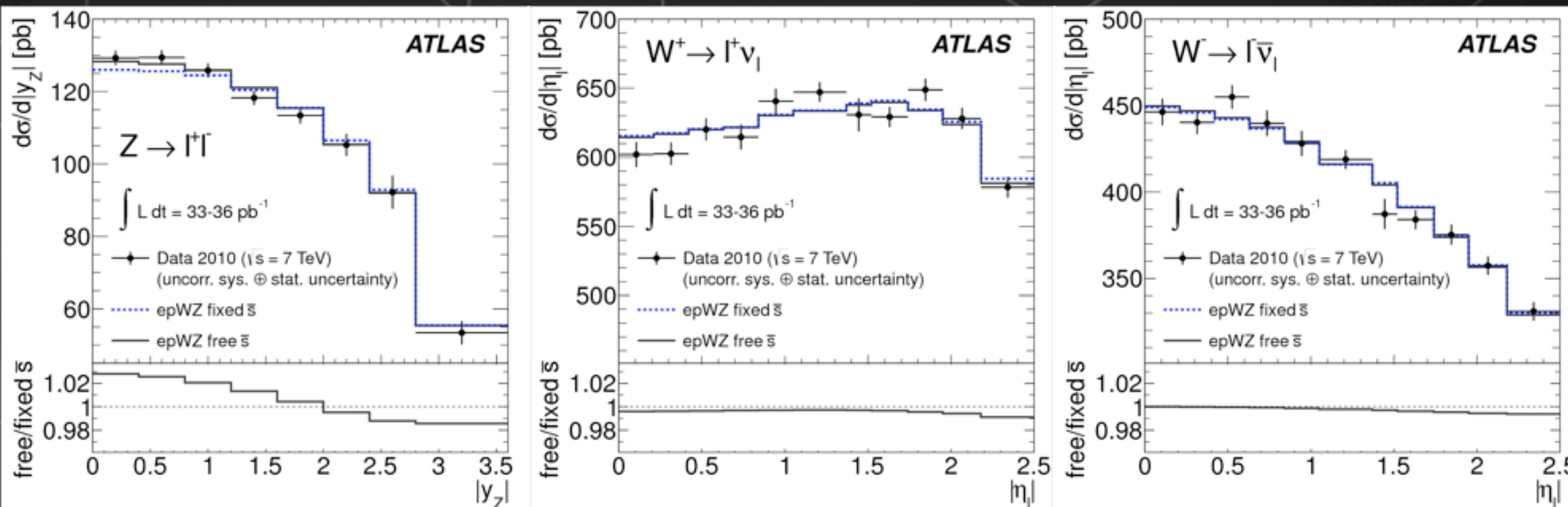
(dedicated low-pileup run)

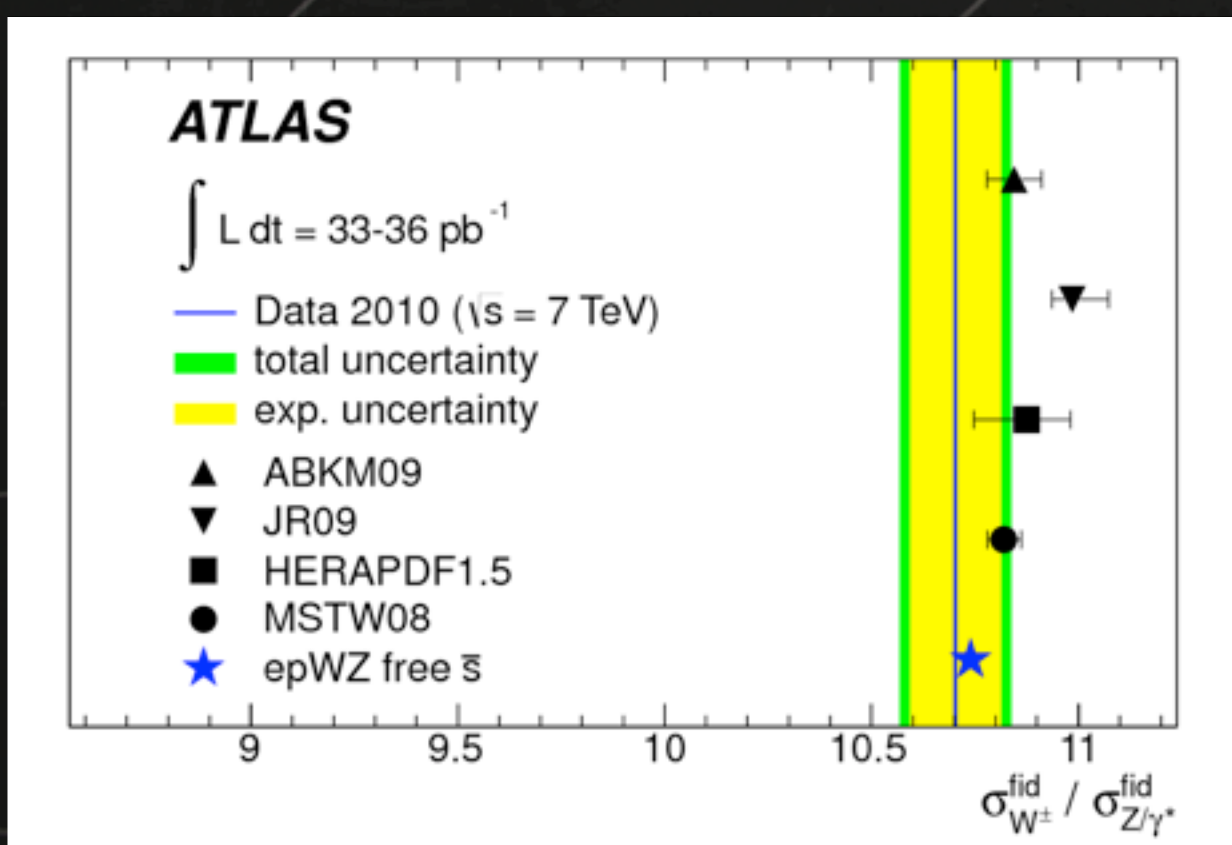
Uncertainties: 2-5%

JHEP 10 (2011) 132; Phys. Rev. D85 (2012) 072004

Strangeness in the Proton (from W and Z data)

Phys.Rev.Lett. 109 (2012) 012001





Fit results:

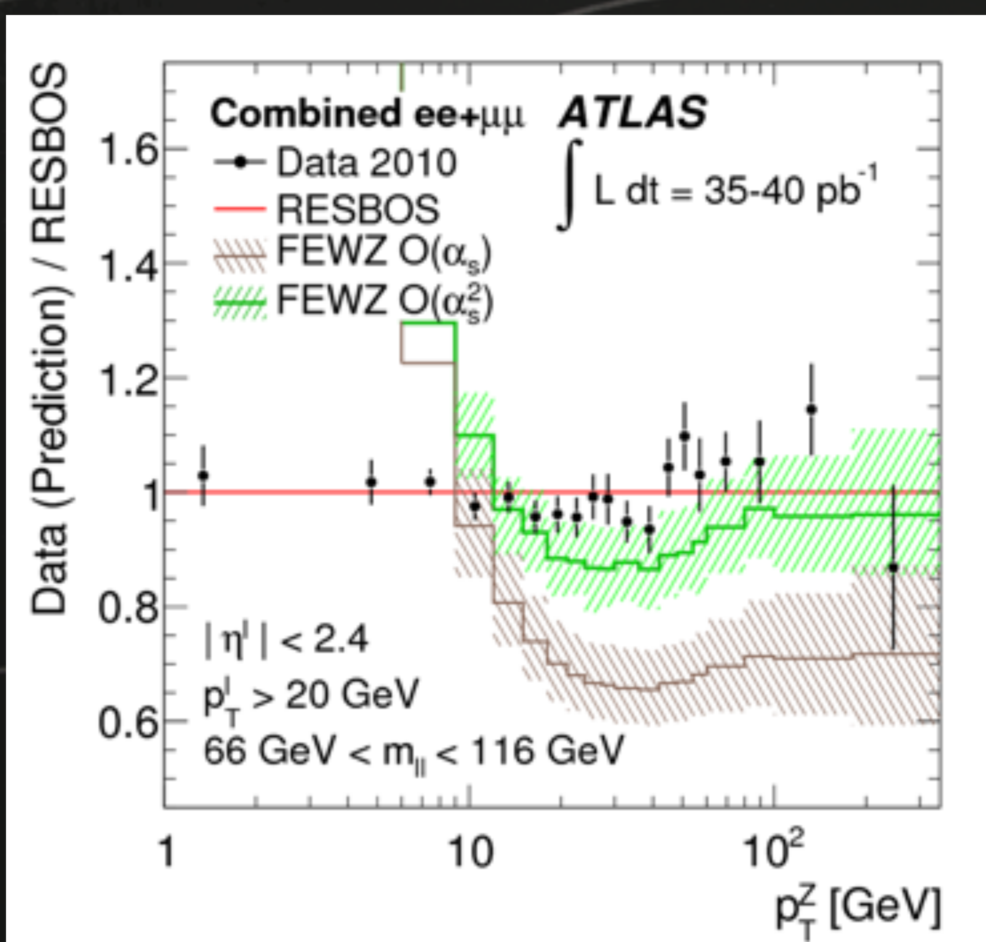
- Light quark sea at low *x* is flavor symmetric (x ~0.023, Q^2 = 1.9 GeV^2)
- Enhancement of strangeness by 50% (2σ)
- Total sea enhancement of 8%

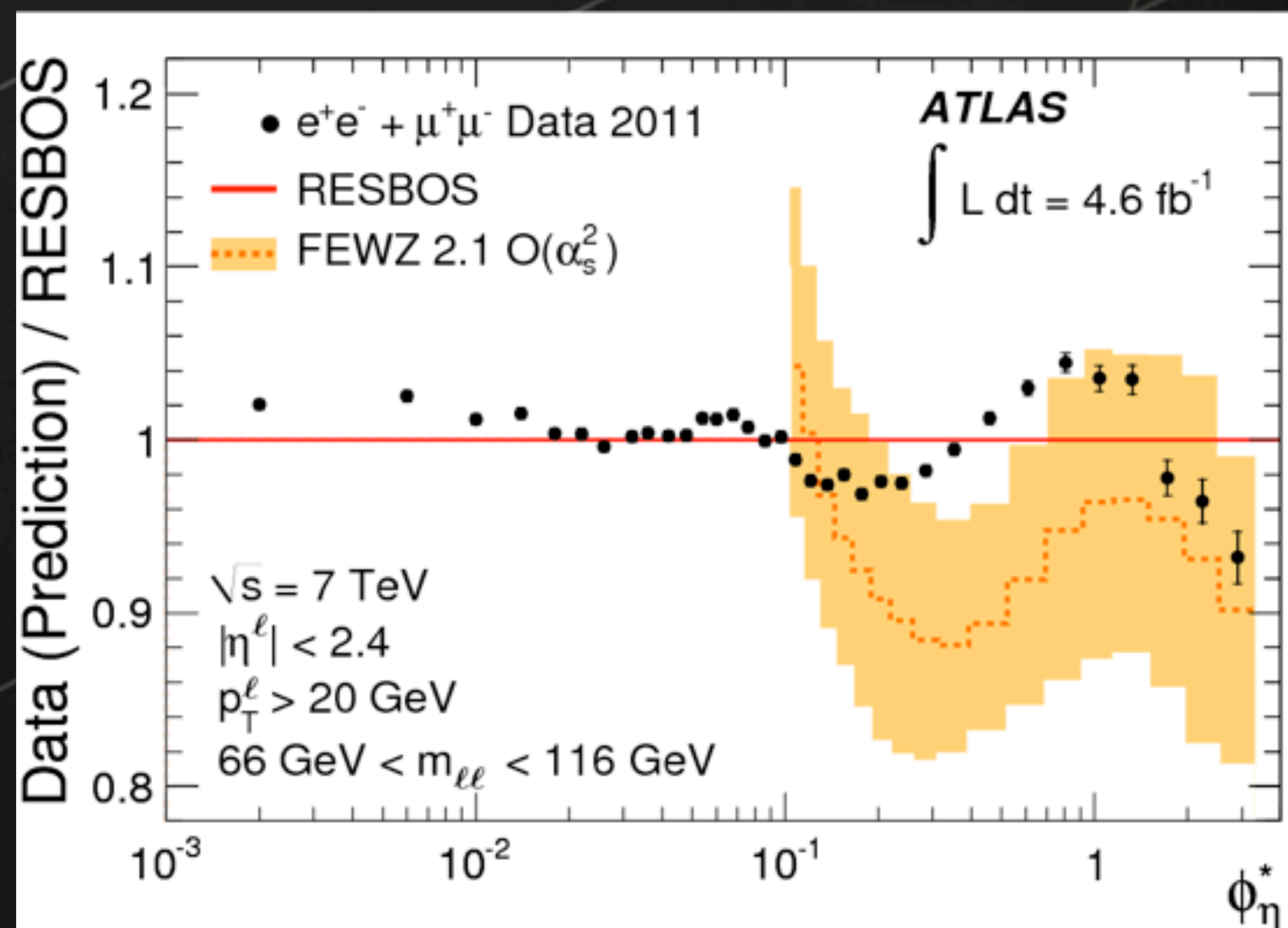
Measurement of the φ_η^* distribution of Z/γ^*

arXiv:1211.6899

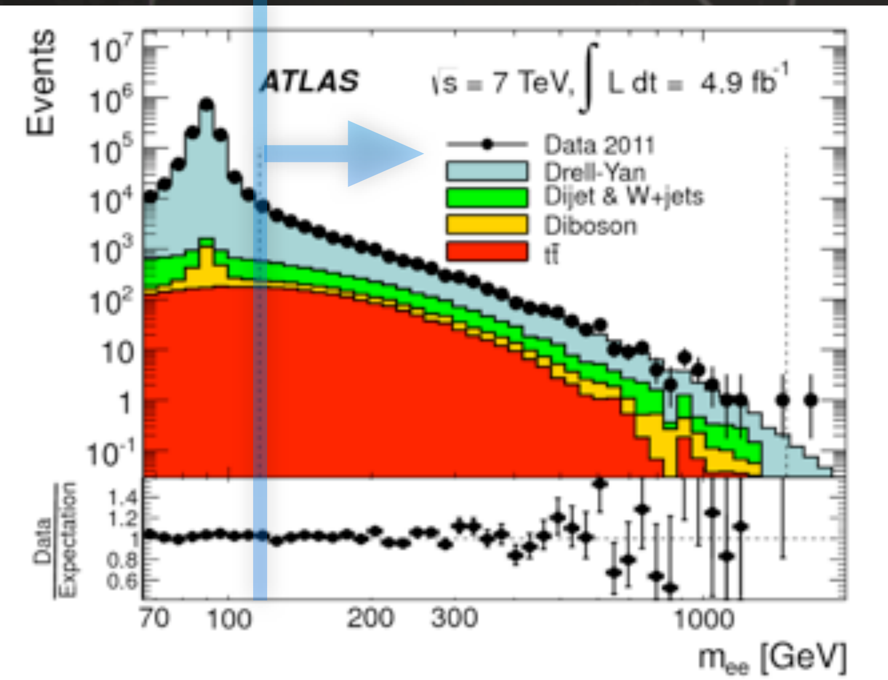
φ_η^* is a measure of scattering angle of leptons relative to beam in Z/γ^* rest frame

- φ_η^* is correlated to $p_T(Z)$ and probes same physics
- φ_η^* depends on lepton angles only, more precisely measured than momenta





High-mass Drell-Yan production



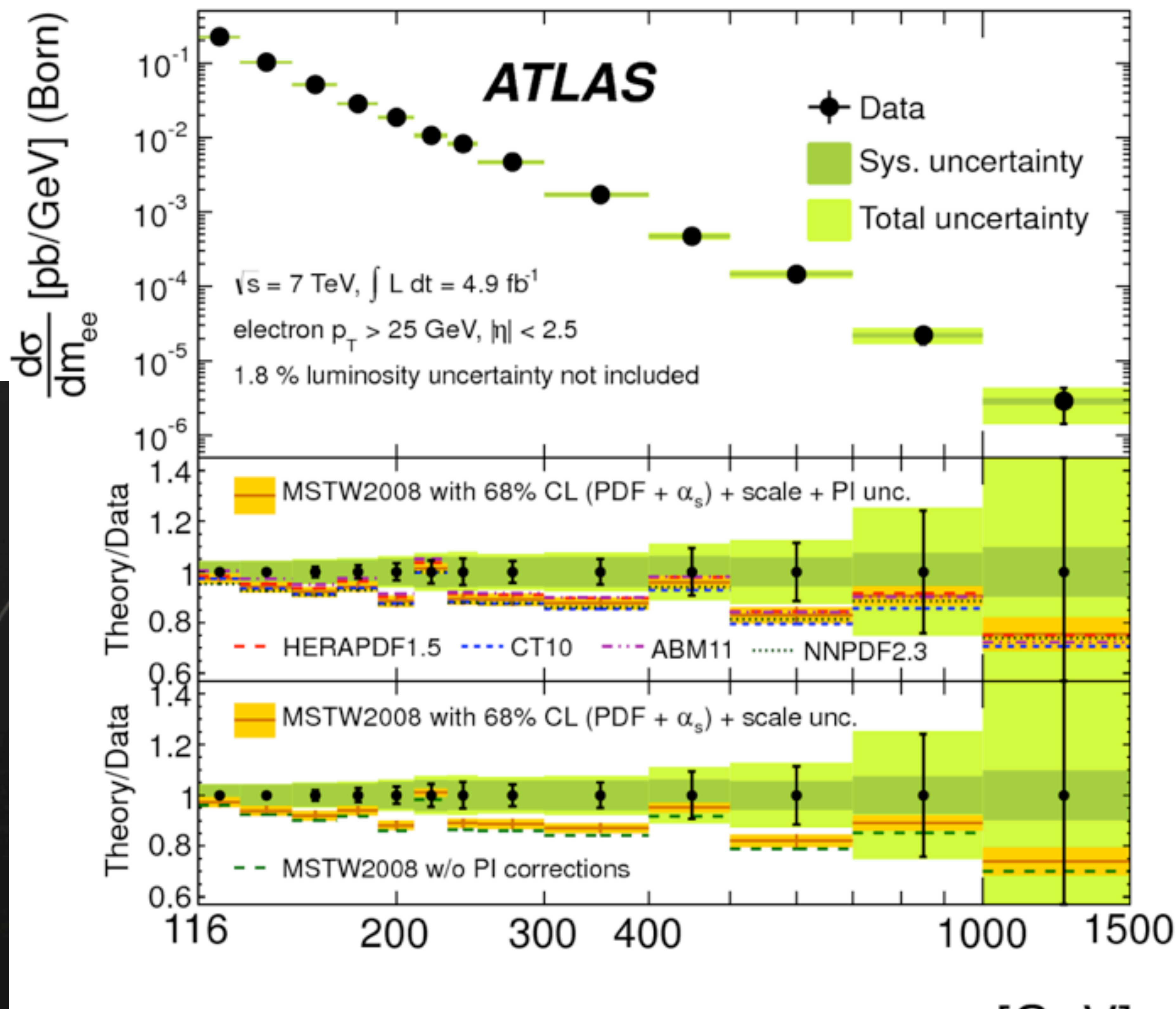
Theory:
NNLO FEWZ 3.1

NNLO QCD calculation
with
NLO electroweak corrections
(G_μ electroweak scheme)

+

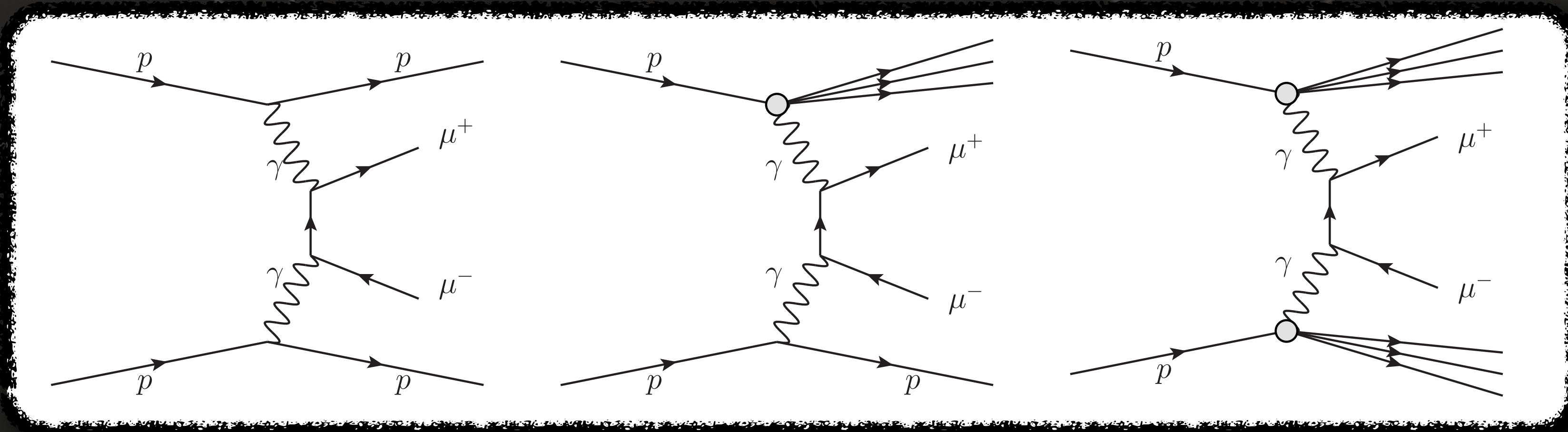
LO photon-induced
correction
$\gamma\gamma \rightarrow e^+e^-$

arXiv:1305.4192

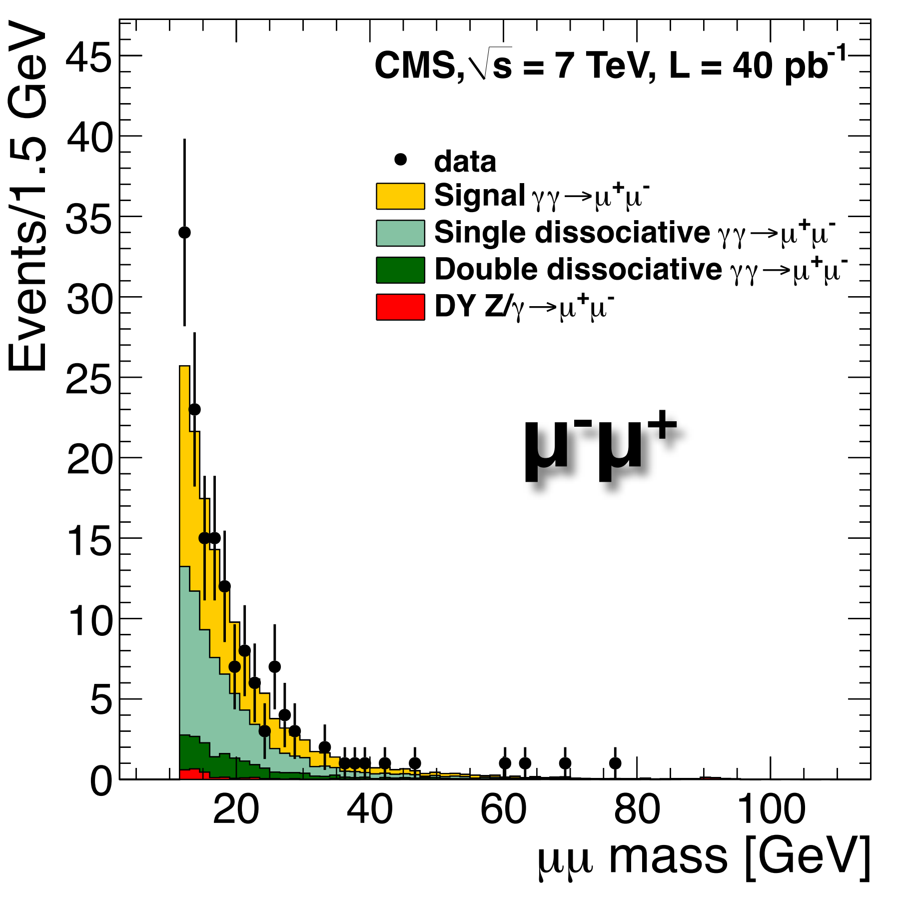


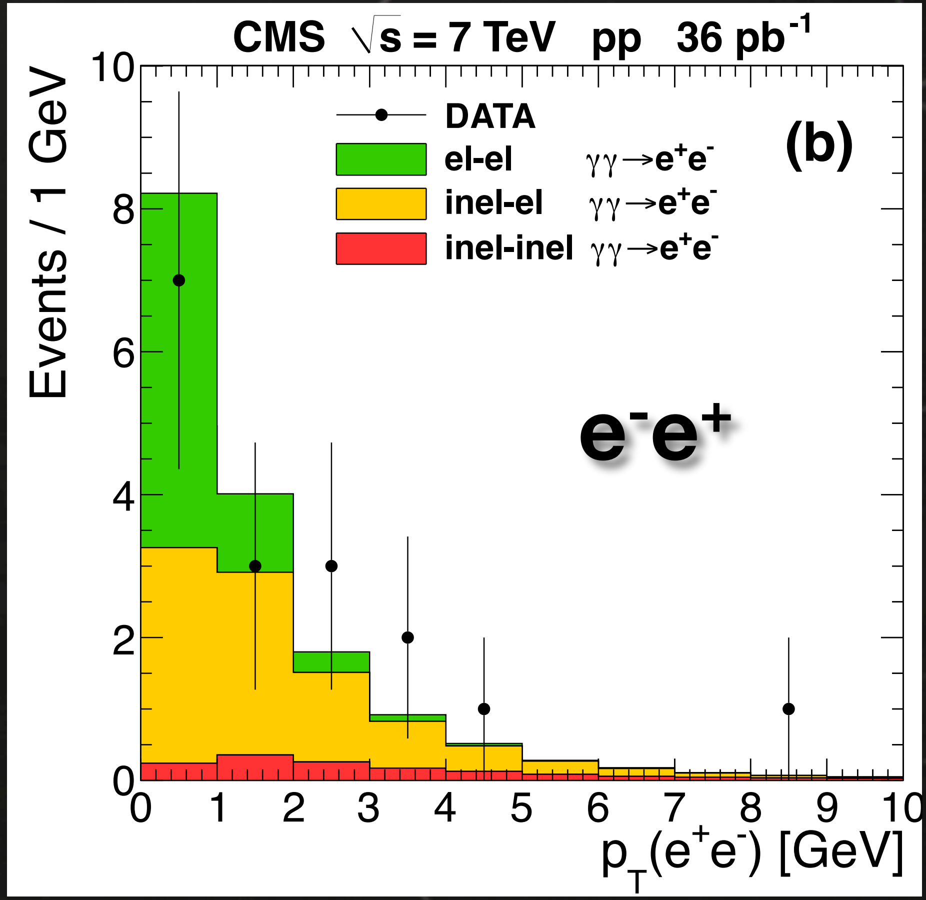
Results are consistent with all PDFs

Exclusive / semi-exclusive l^+l^- production



Main signature: Only two tracks within fiducial region of detector



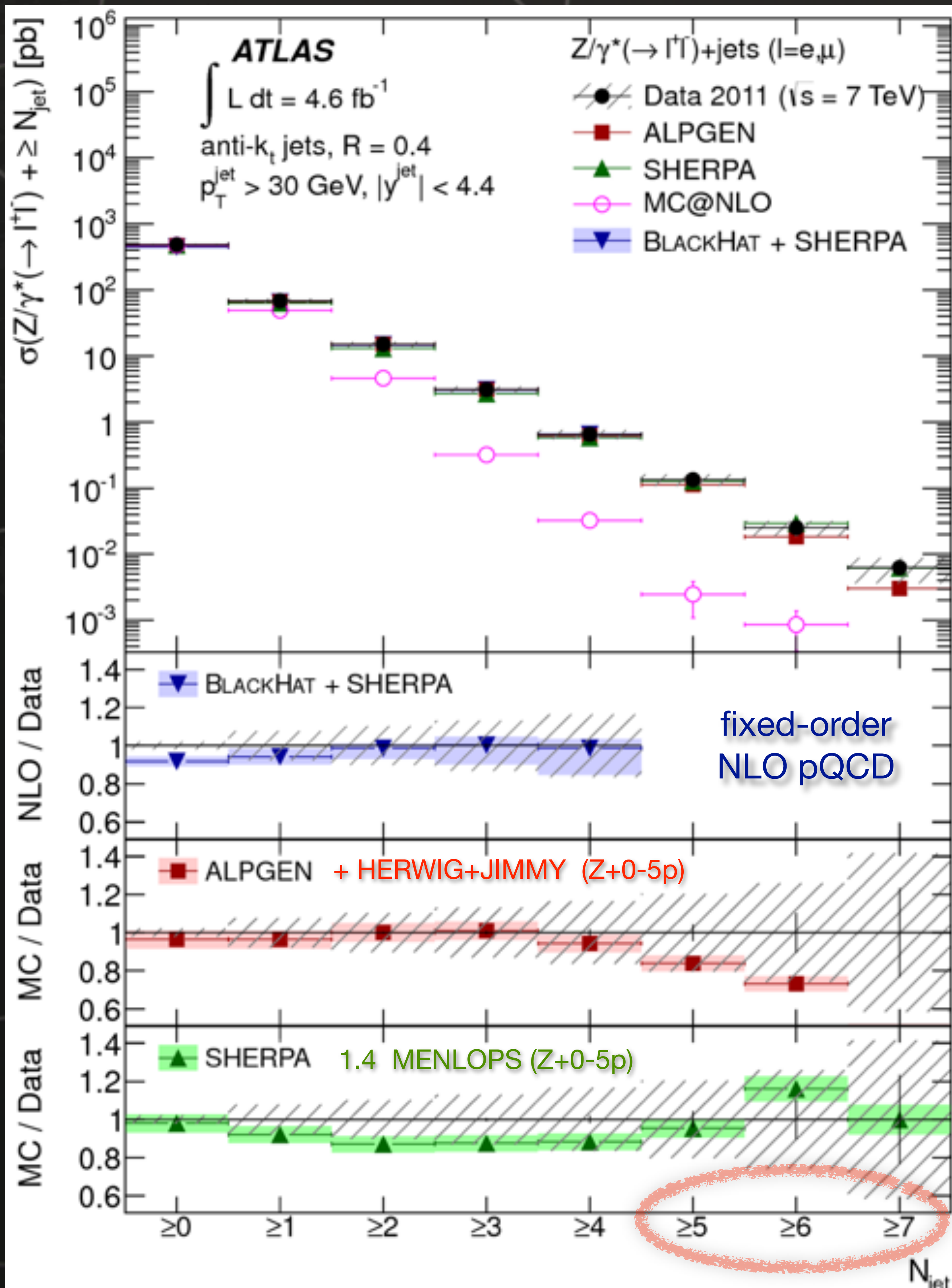


$$\sigma(\mathrm{pp} \to \mathrm{p}\mu^+\mu^-\mathrm{p}) = 3.38^{+0.58}_{-0.55}\,(\mathrm{stat.}) \pm 0.16\,(\mathrm{syst.}) \pm 0.14\,(\mathrm{lumi.})\ \mathrm{pb}$$

Data/prediction = 0.83

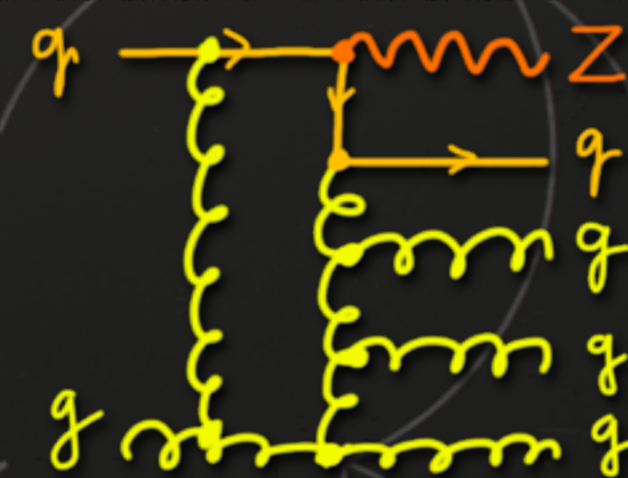
Measurements of Z + jets

arXiv:1304.7098



Explore extreme phase space

(using large dataset at 7 TeV)



Large jet multiplicities

US ATLAS Workshop -- Argonne -- Jul 2013 -- Joao Guimaraes

Measurements of Z + jets

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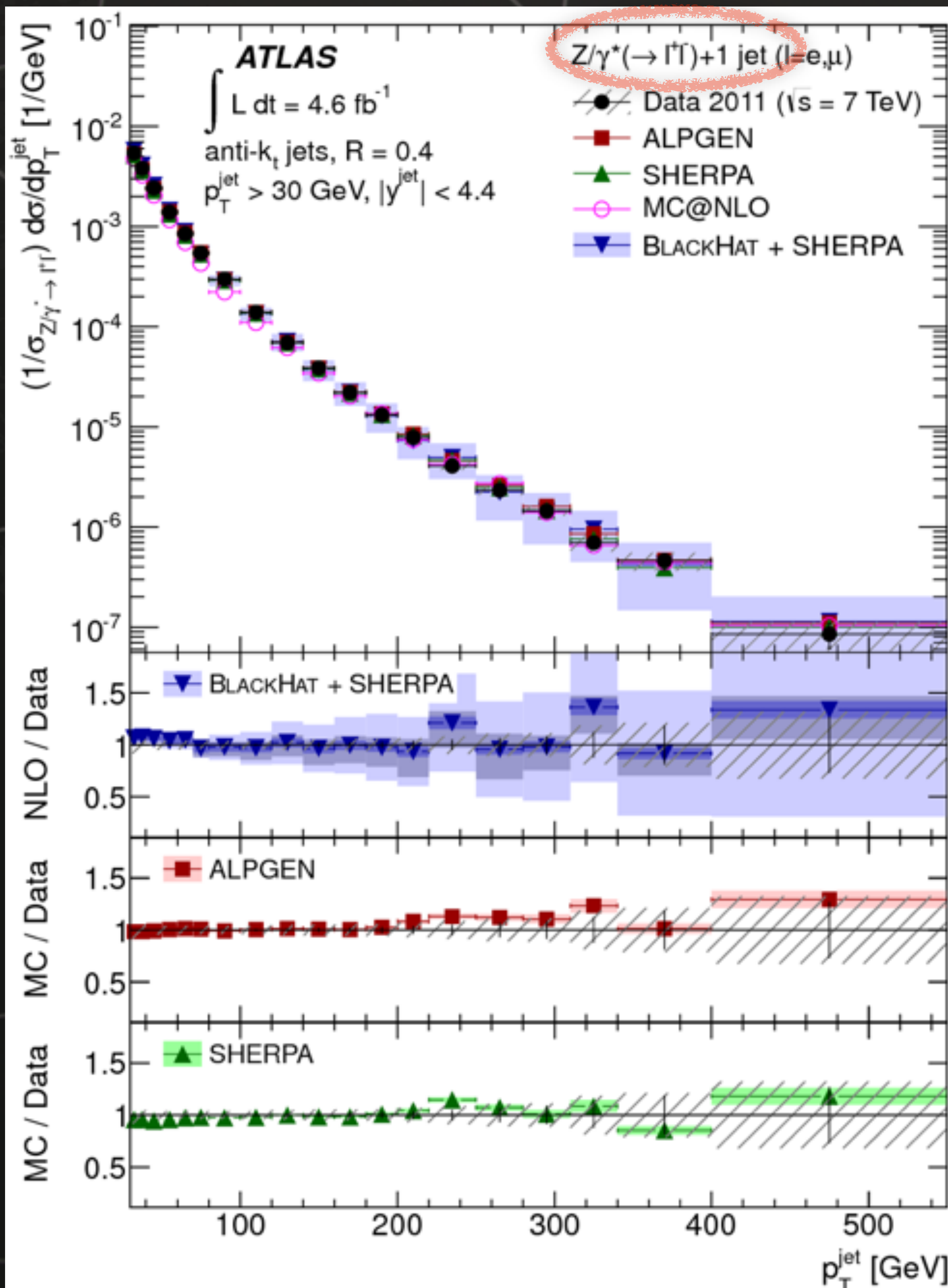

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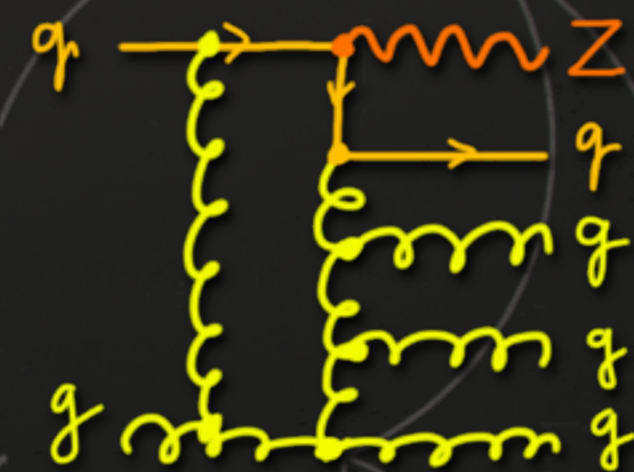


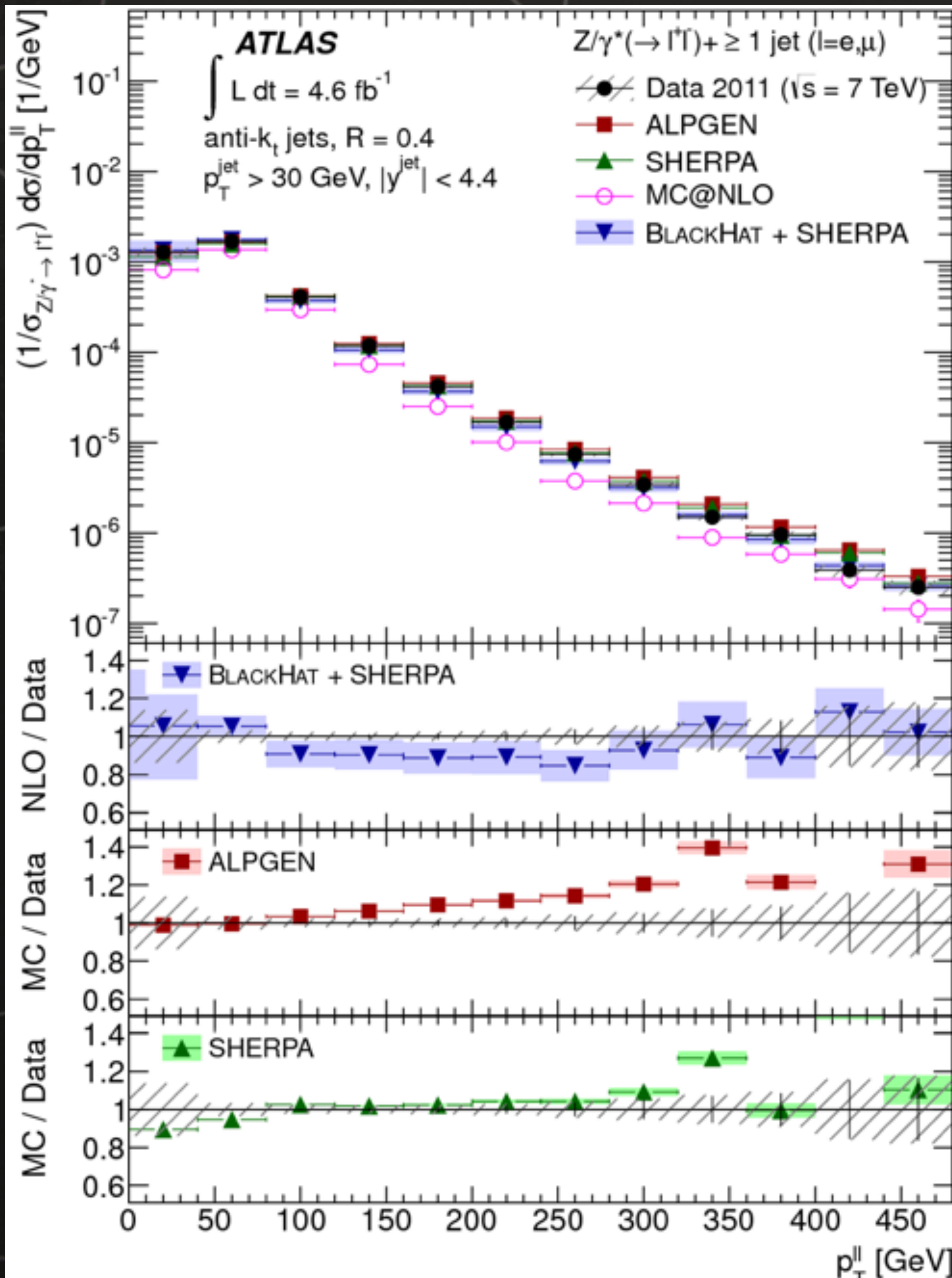
Large jet multiplicities

Large p_T(jet), large H_T

Renormalization, factorization scale uncertainty:
- Naive approach (1/2 , x2)
- Stewart/Tackmann

Measurements of Z + jets

arXiv:1304.7098



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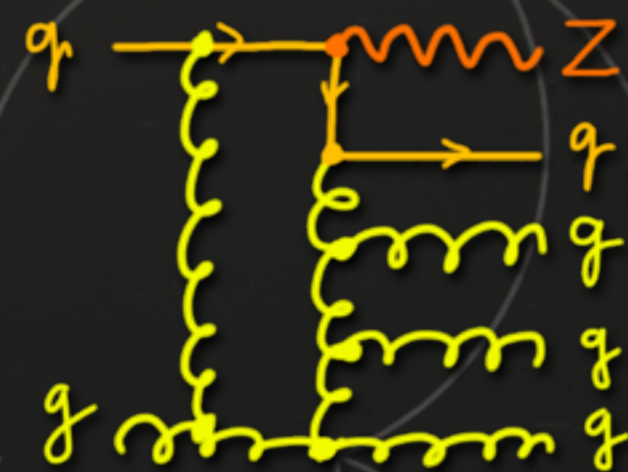

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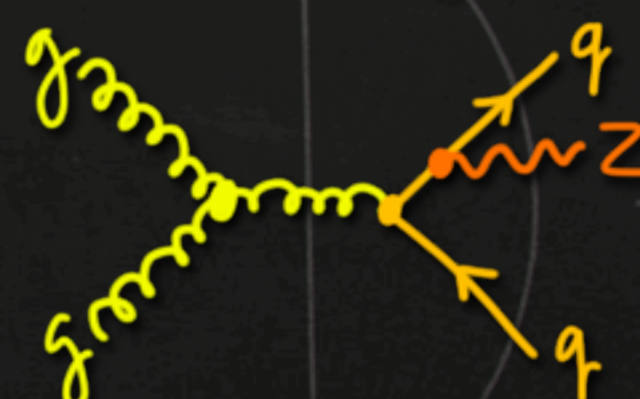
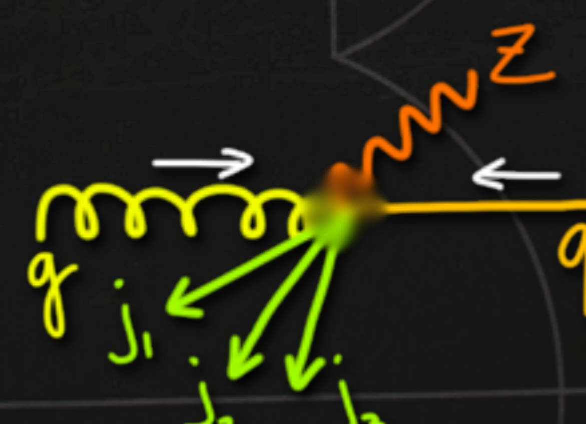


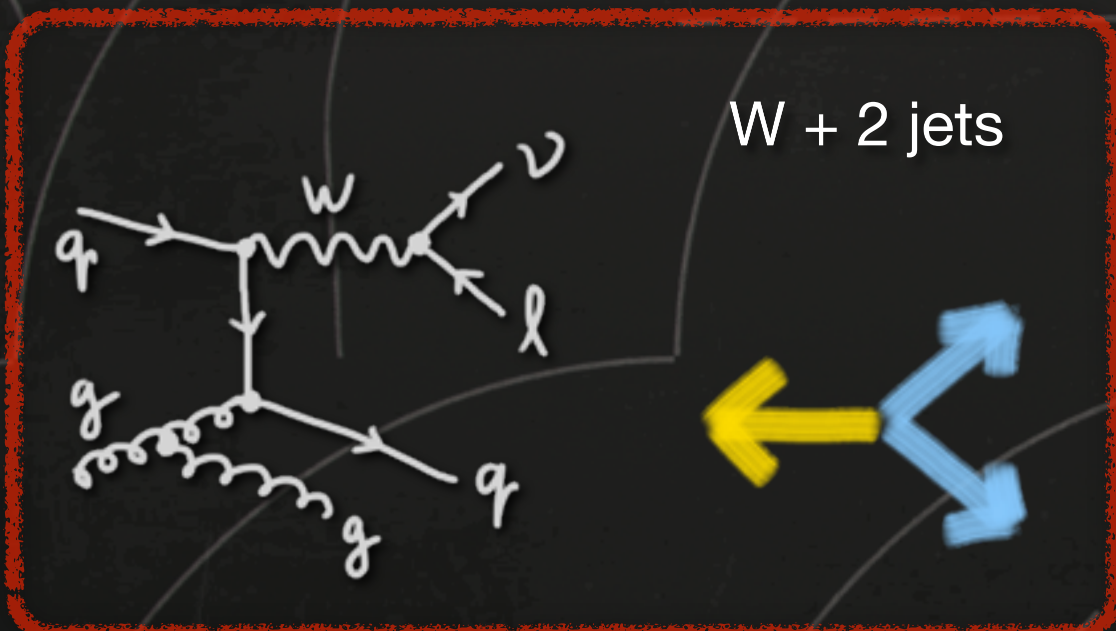
Large p_T(jet), large H_T

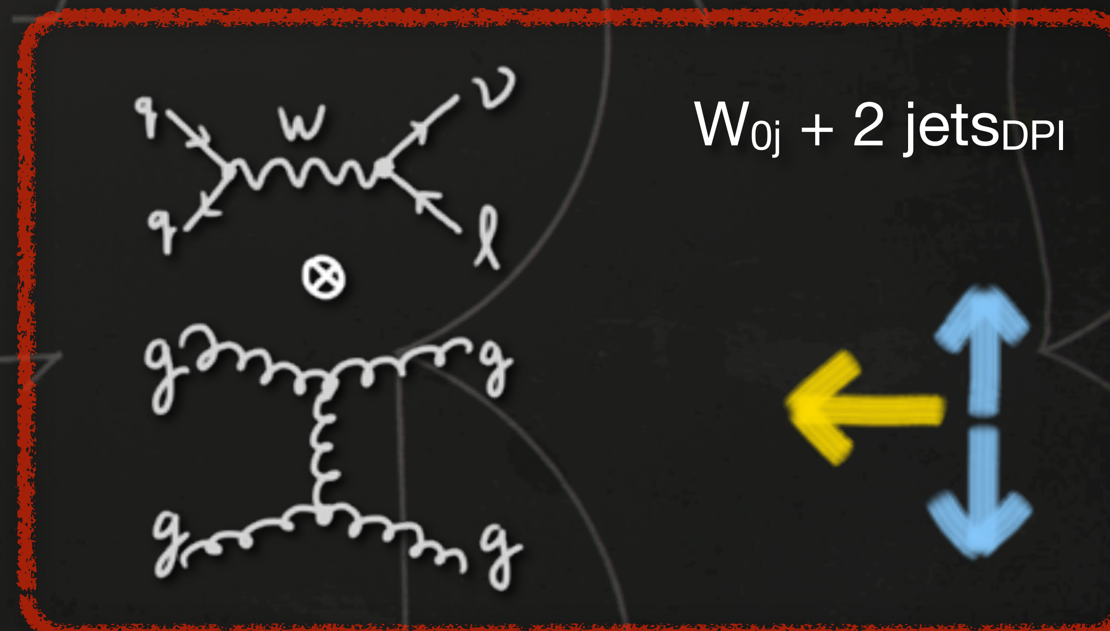


Large p_T(Z)

Hard Double Parton Interactions (in W+2 jets events)

- Irreducible background for SM and New Physics searches
  - How well is this modeled by our MC generators?
  - Example: 25% of Wb cross section





cross section for the double parton interaction (DPI) of a combined Y + Z system

$$\sigma^{(DPI)}_{Y+Z} = \frac{\sigma_Y \cdot \sigma_Z}{\sigma_{eff}}$$

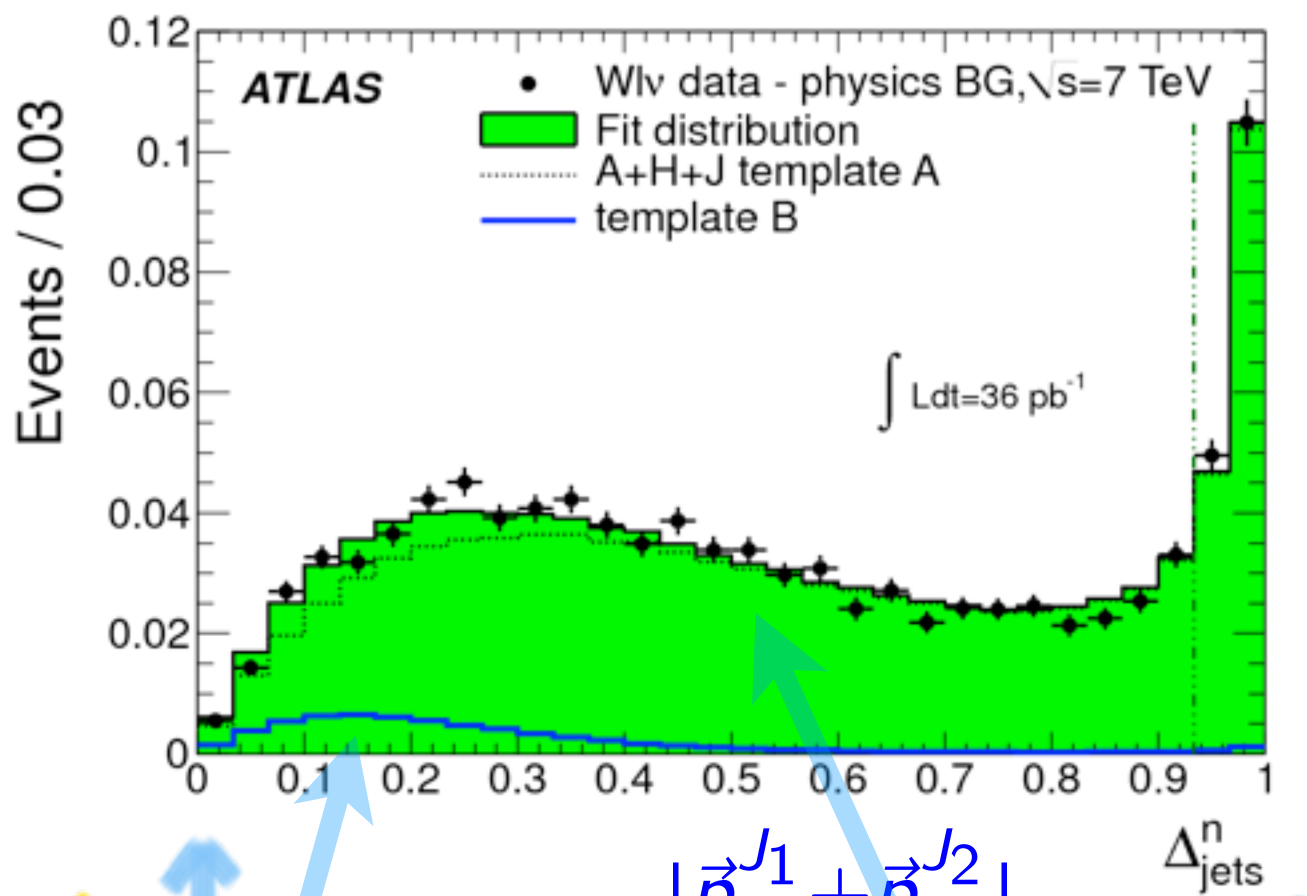
σ_{eff} ~ proton area

$$\sigma_{eff} = \frac{\sigma_{W_{0j}} \cdot \sigma_{2j}}{\sigma_{W_{0j}+2j_{DPI}}}$$

Measure fraction of DPI events

Hard Double Parton Interactions (in W+2 jets events)

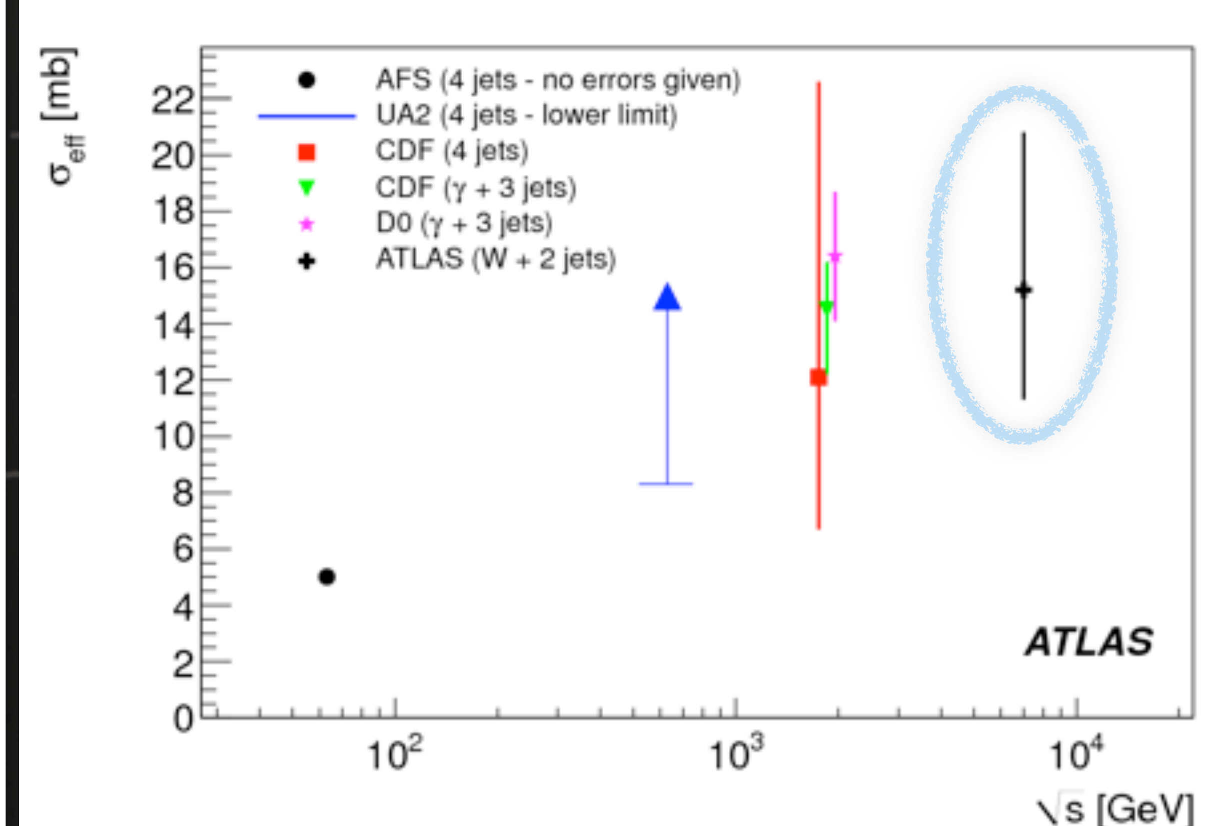
New J. Phys. 15 (2013) 033038



$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$

DPI 2-jet template (data)

W + 2 jets template (MC)



$$\sigma_{\mathrm{eff}}(7\ \mathrm{TeV}) = 15 \pm 3\ (\mathrm{stat.})\ ^{+5}_{-3}\ (\mathrm{sys.})\ \mathrm{mb}$$

$$f^{(D)}_{DP} = 0.08 \pm 0.01\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{sys.})$$

within phase space: e.g. p_T(jet) > 20 GeV

Consistent with prediction from ALPGEN + Jimmy

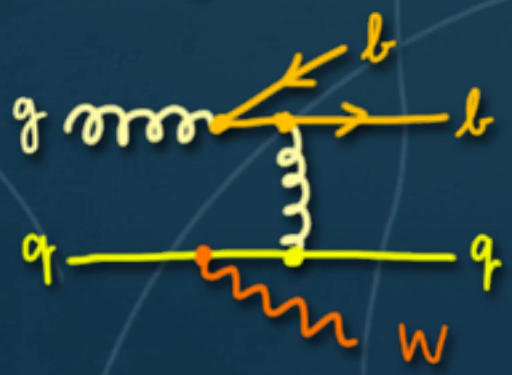
CMS has a recent study of different variables with sensitivity to DPI (but no σ_{eff})

CMS PAS-FSQ-12-028

W + Heavy Flavor (HF) production

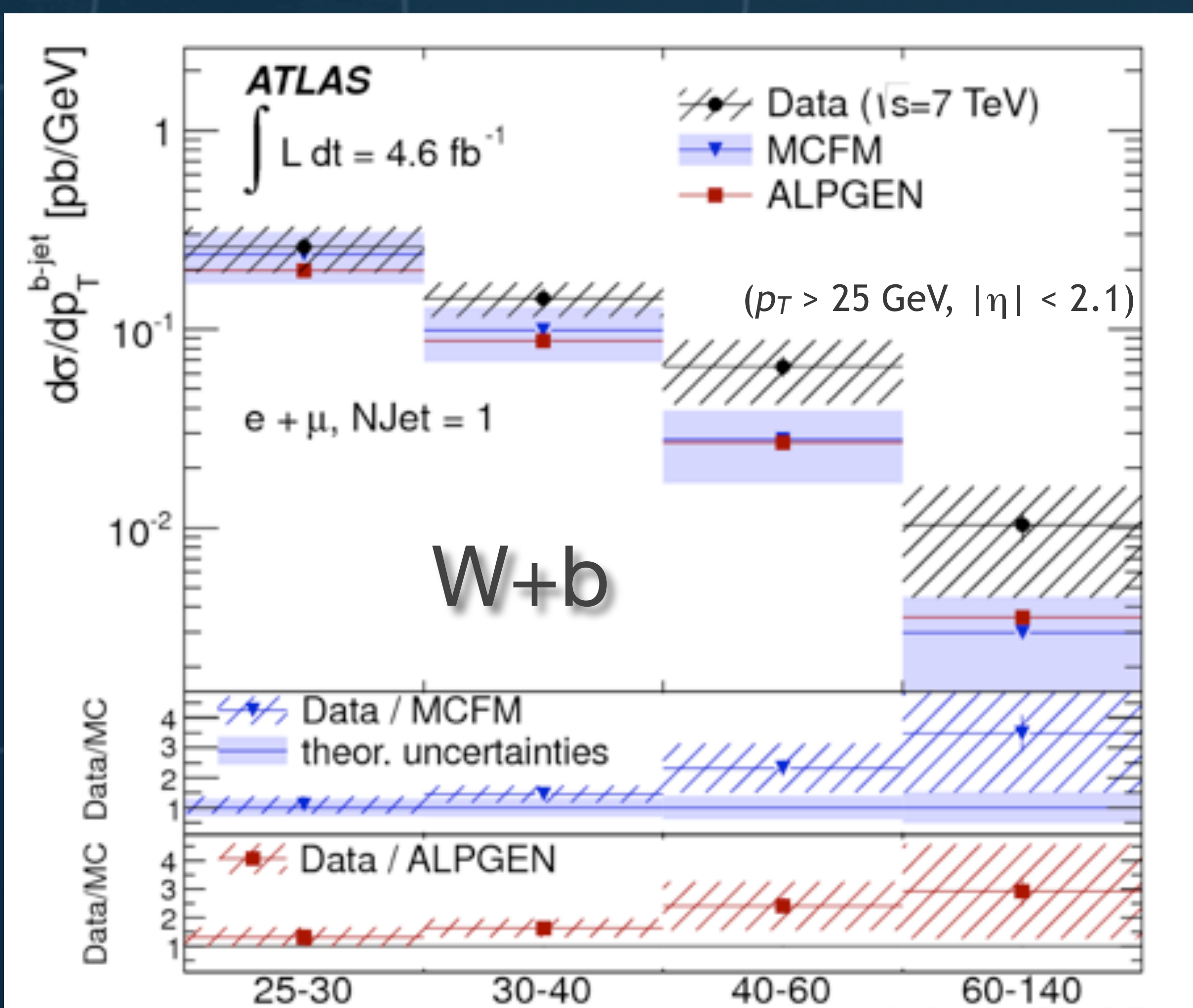
W+b

Background to Higgs and top quark studies



ATLAS: Wb production arXiv:1302.2929

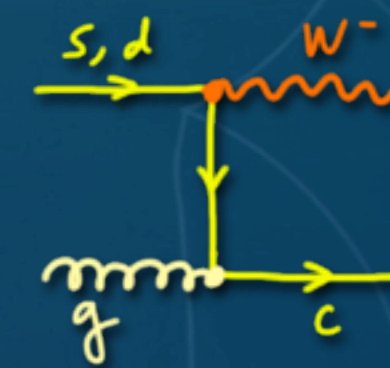
CMS: Wbb production CMS-PAS-SMP-12-026



(includes a 25% effect due to DPI)

Combined Wb + single top cross section also done

W+c

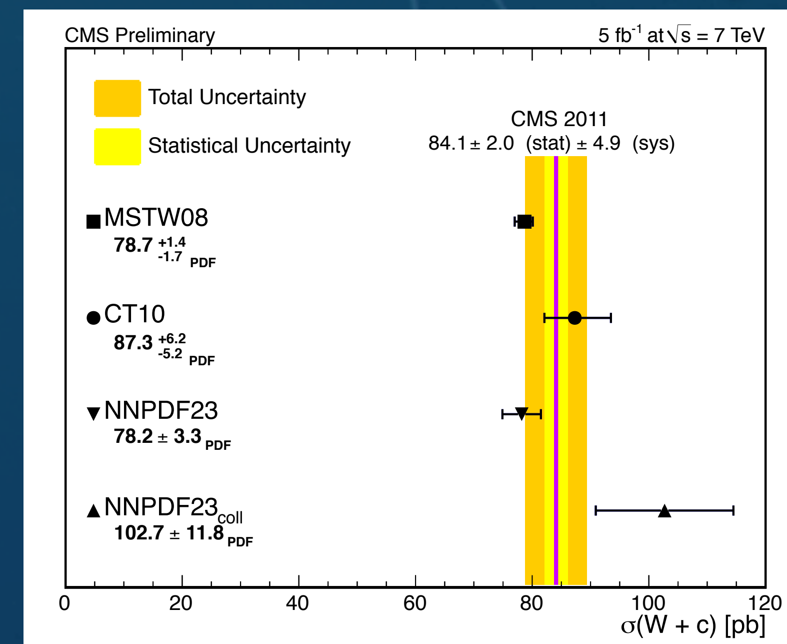


Sensitive to strange quark PDF

at x ~ 0.01

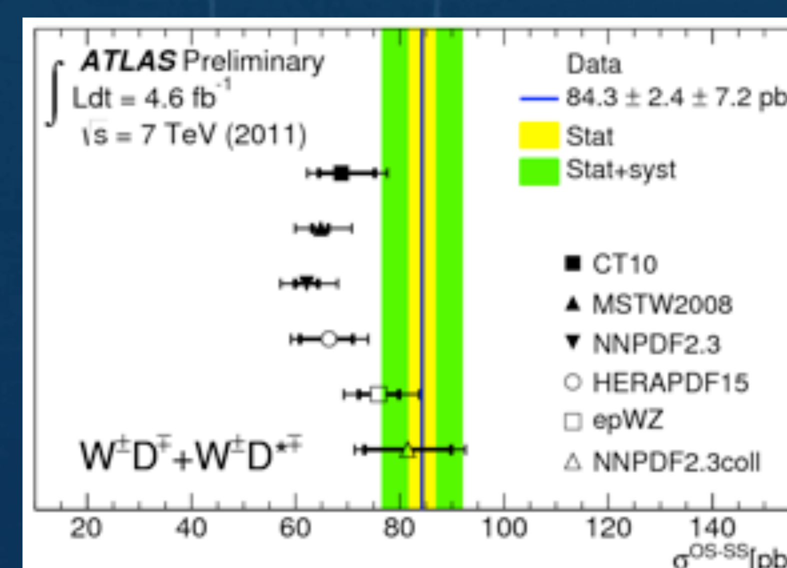
(important for W mass precision measurement)

Both results consistent with each other



CMS-PAS-SMP-12-002

CMS W+c: strangeness suppression

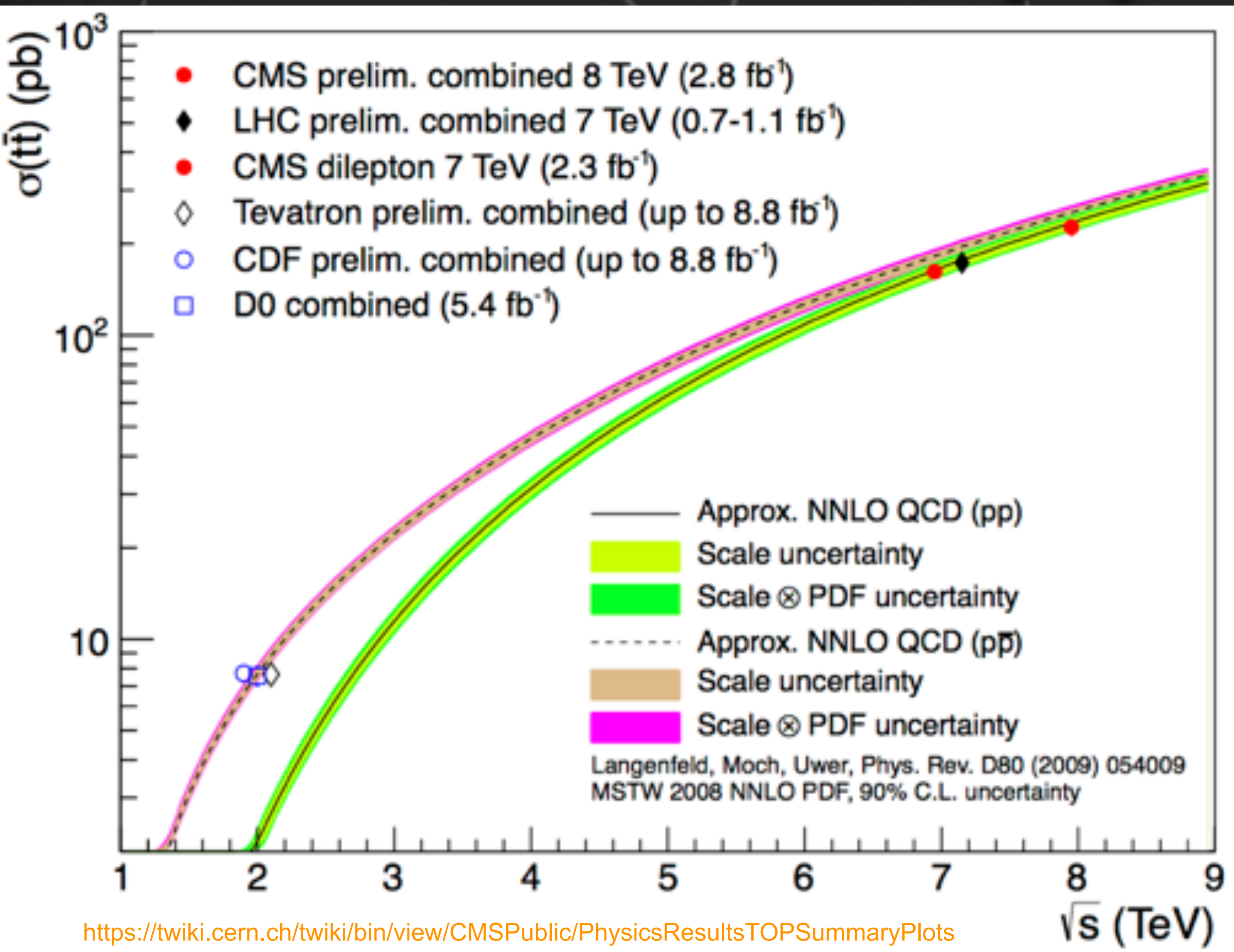


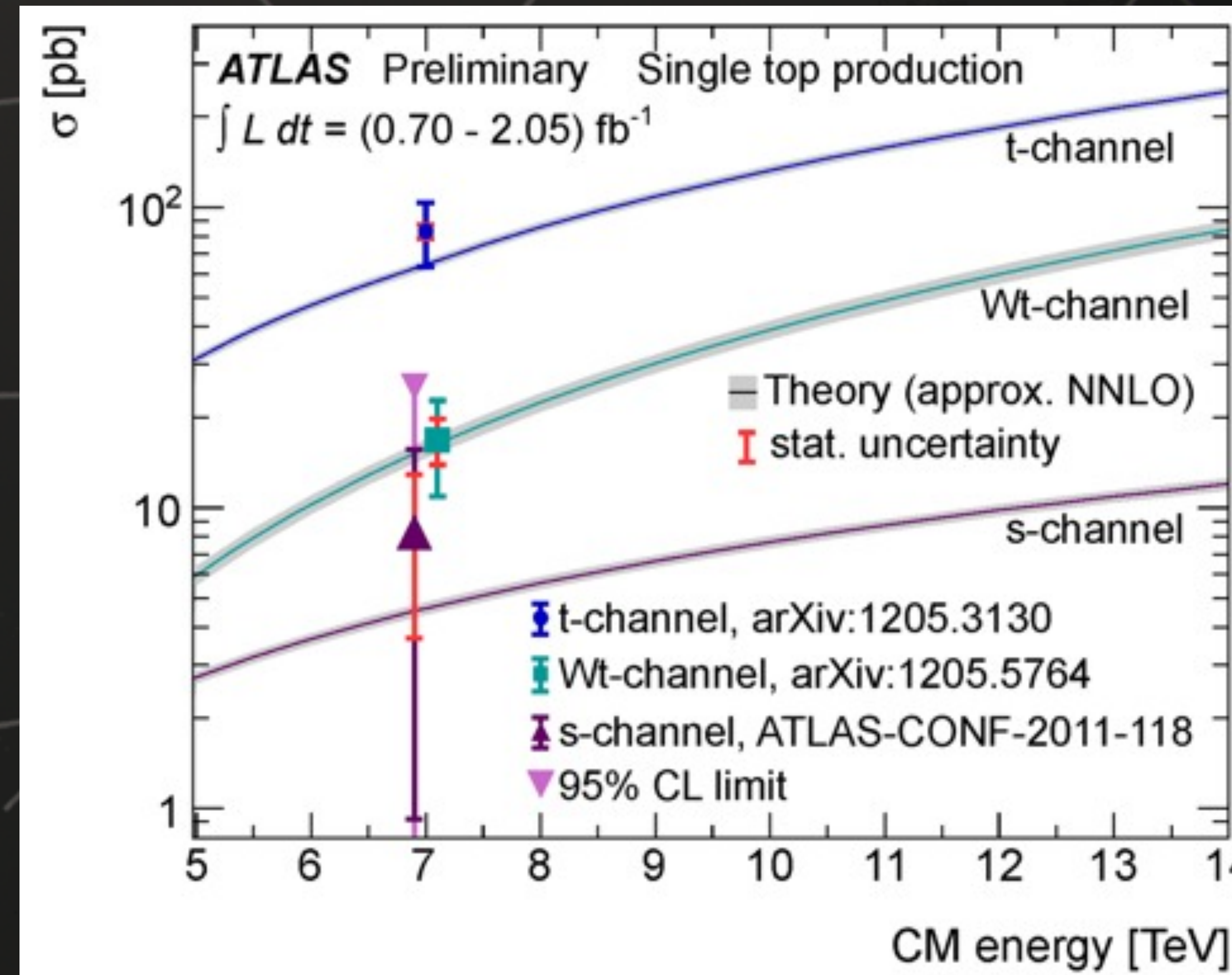
ATLAS-CONF-2013-045

ATLAS W+c: consistent with symmetric light quark sea

(similar to earlier result on W/Z differential cross section)

Top production at 7 and 8 TeV





Top pair production

Consistent across all channels

(Experimental uncertainty: ~ 5-15%)

Approx. NNLO and full NNLO QCD prediction

(Similar theoretical precision)

Start constraining gluon PDFs!

Single top production

New measurements of t-channel production at 8 TeV

(Uncertainty: ~ 13-19%)

ATLAS-CONF-2012-132 CMS-PAS-TOP-12-011

Ratio of top vs anti-top

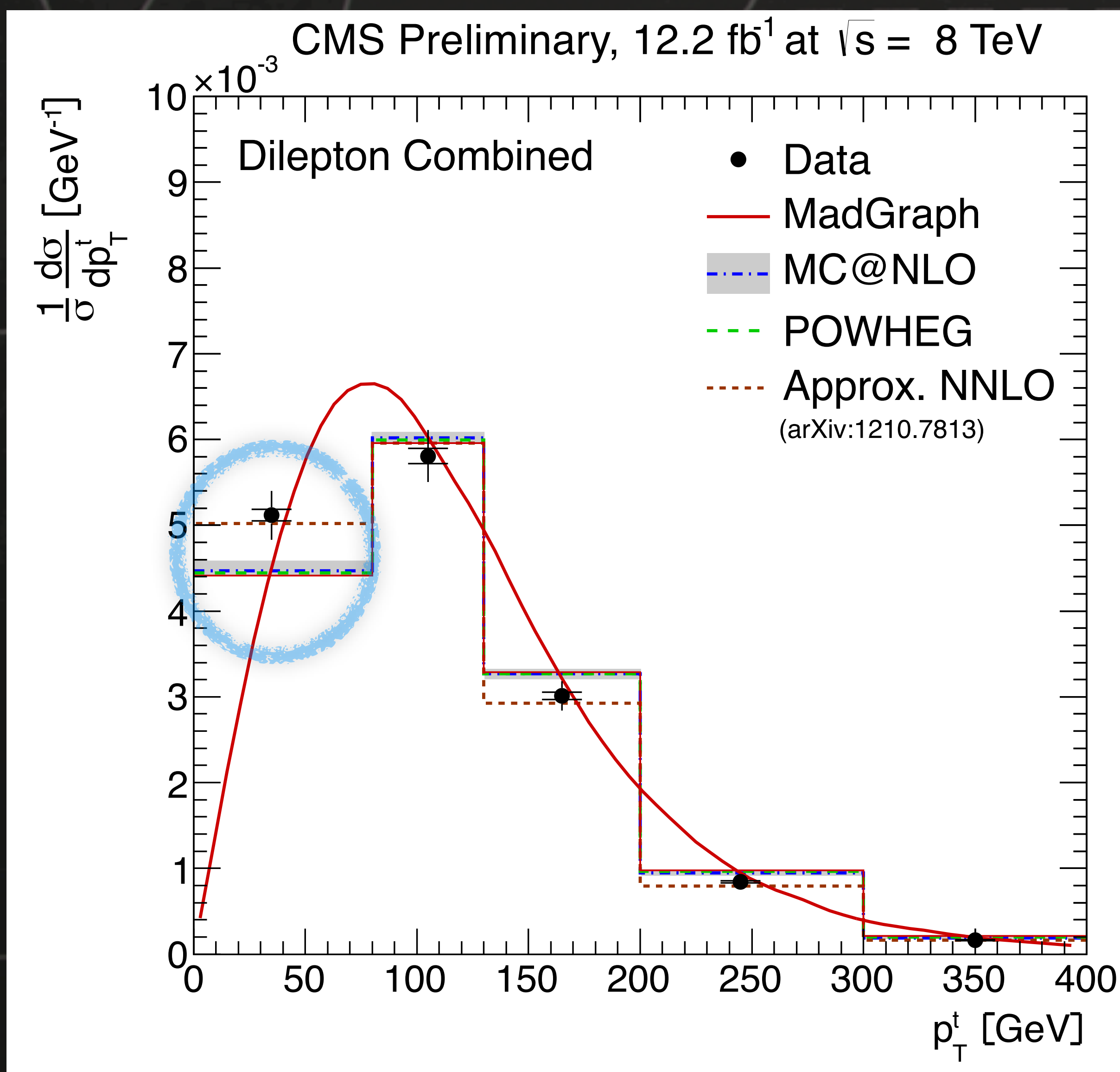
ATLAS-CONF-2012-056 CMS-PAS-TOP-12-038

Probing the top quark: differential cross sections

Many kinematic properties of top events have been measured

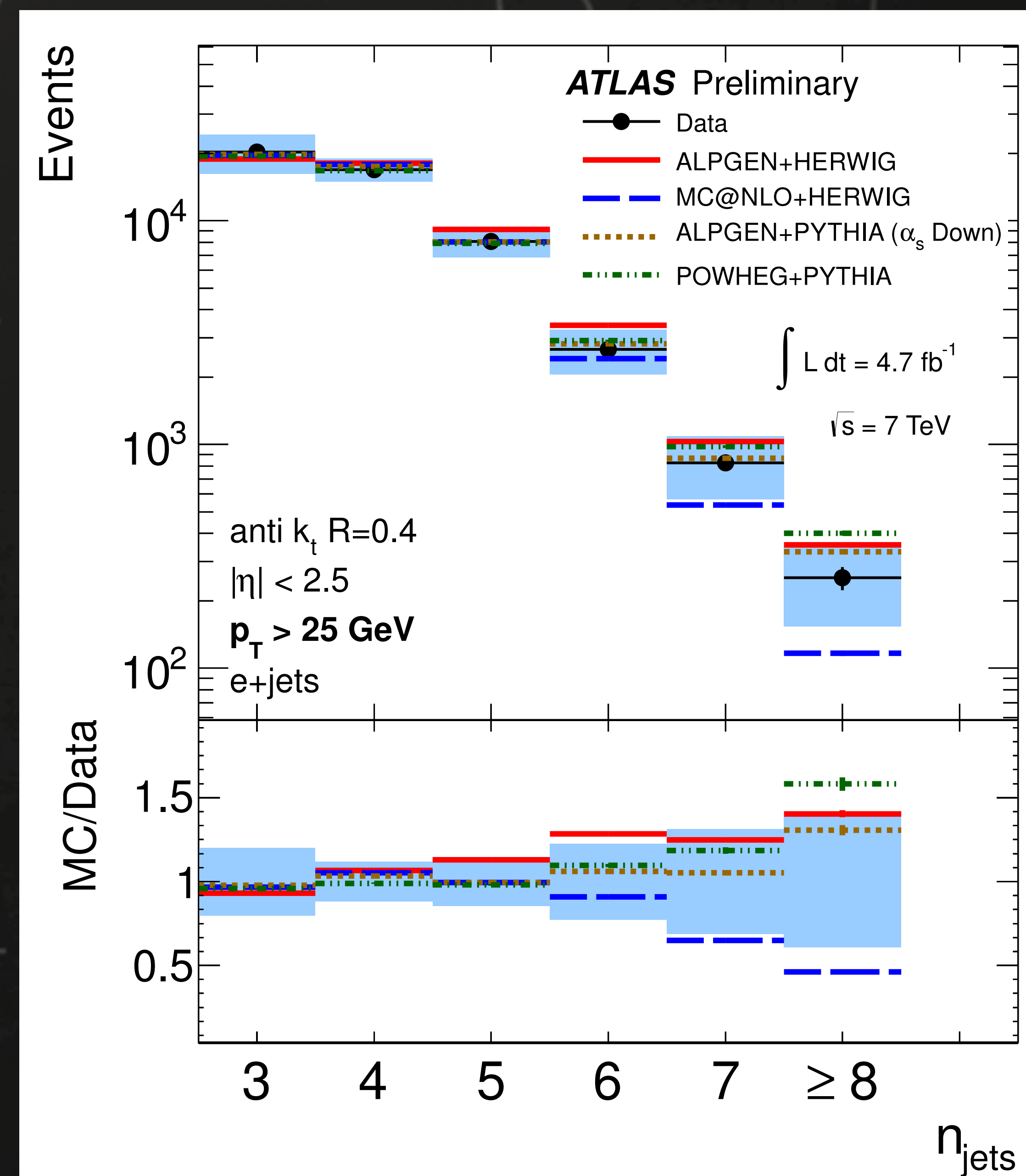
Differential ttbar cross sections

CMS-PAS-TOP-12-028



Jet multiplicity in ttbar events

ATLAS-CONF-2012-155

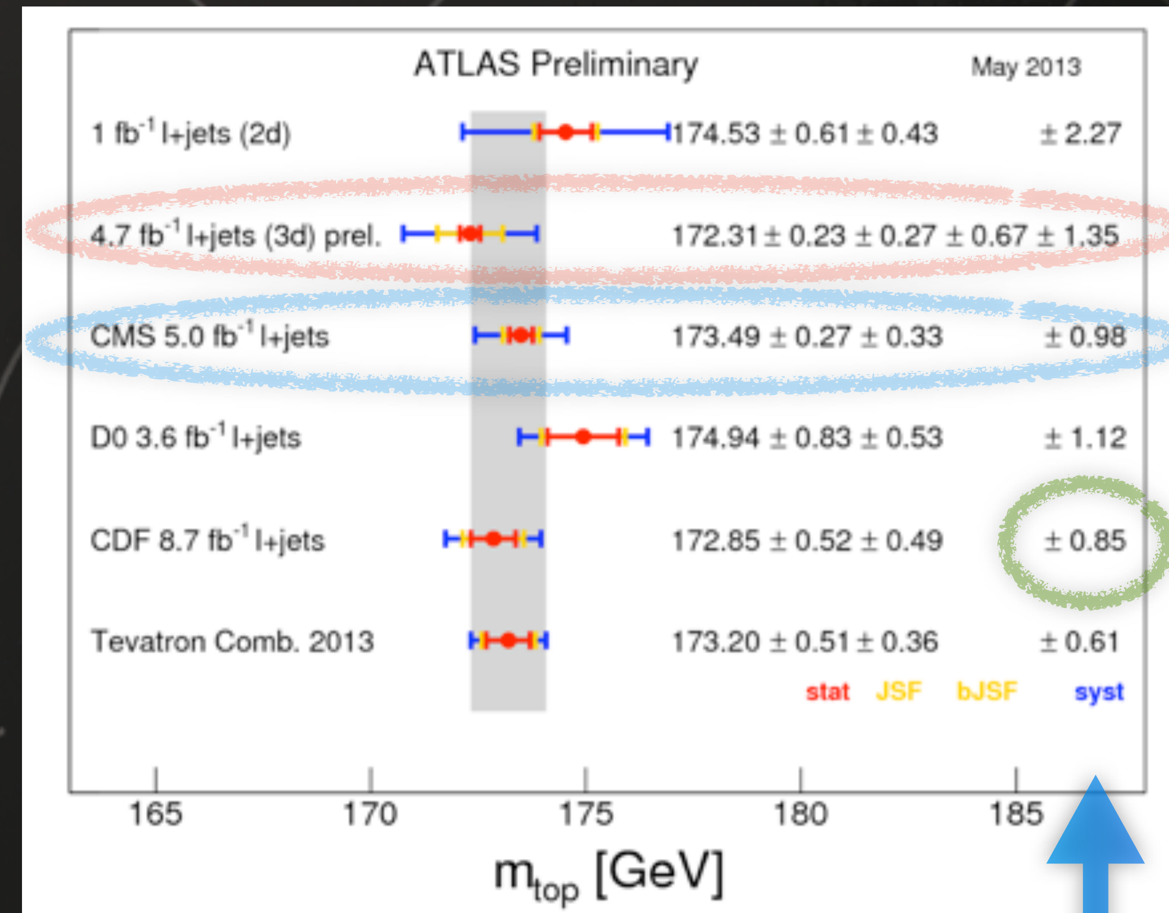


Generally, good agreement with MC and/or approximate NNLO predictions

Top quark mass measurements

Measured in different channels with different techniques

Best measurements are in the lepton+jets channel



Only 7 TeV data used so far

Non-“stat-like” systematics

Dominant systematics:

CMS: arXiv:1209.2319

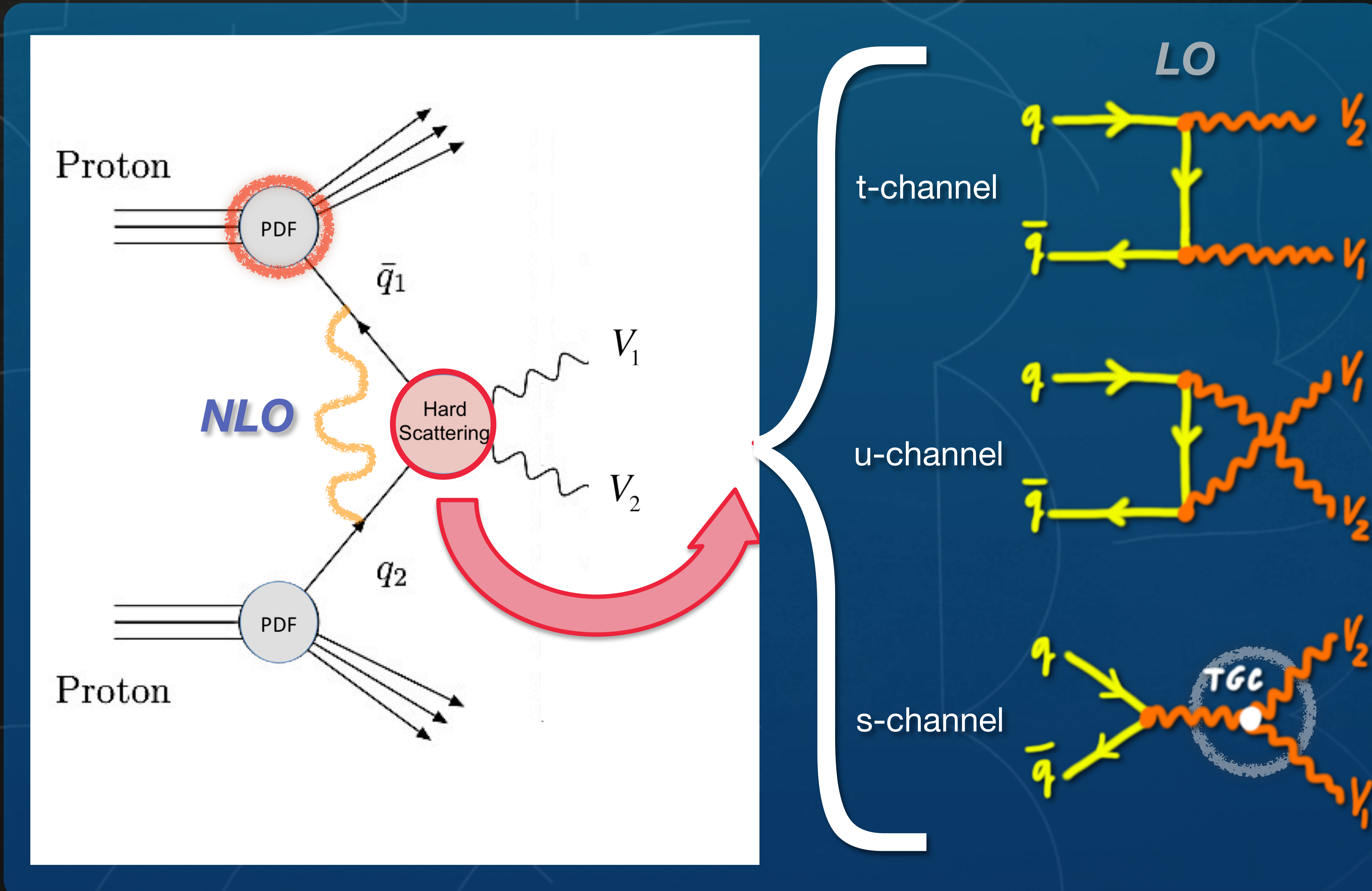
- b-jet energy scale
- Color reconnection
- Total “non-stat” syst.: 0.98 GeV

ATLAS: ATLAS-CONF-2013-046

- Overall jet energy scale
- b-tagging efficiency and mistag
- Total “non-stat” syst.: 1.35 GeV

LHC combination effort on-going: expect 0.5-0.7 GeV

Diboson production at the LHC



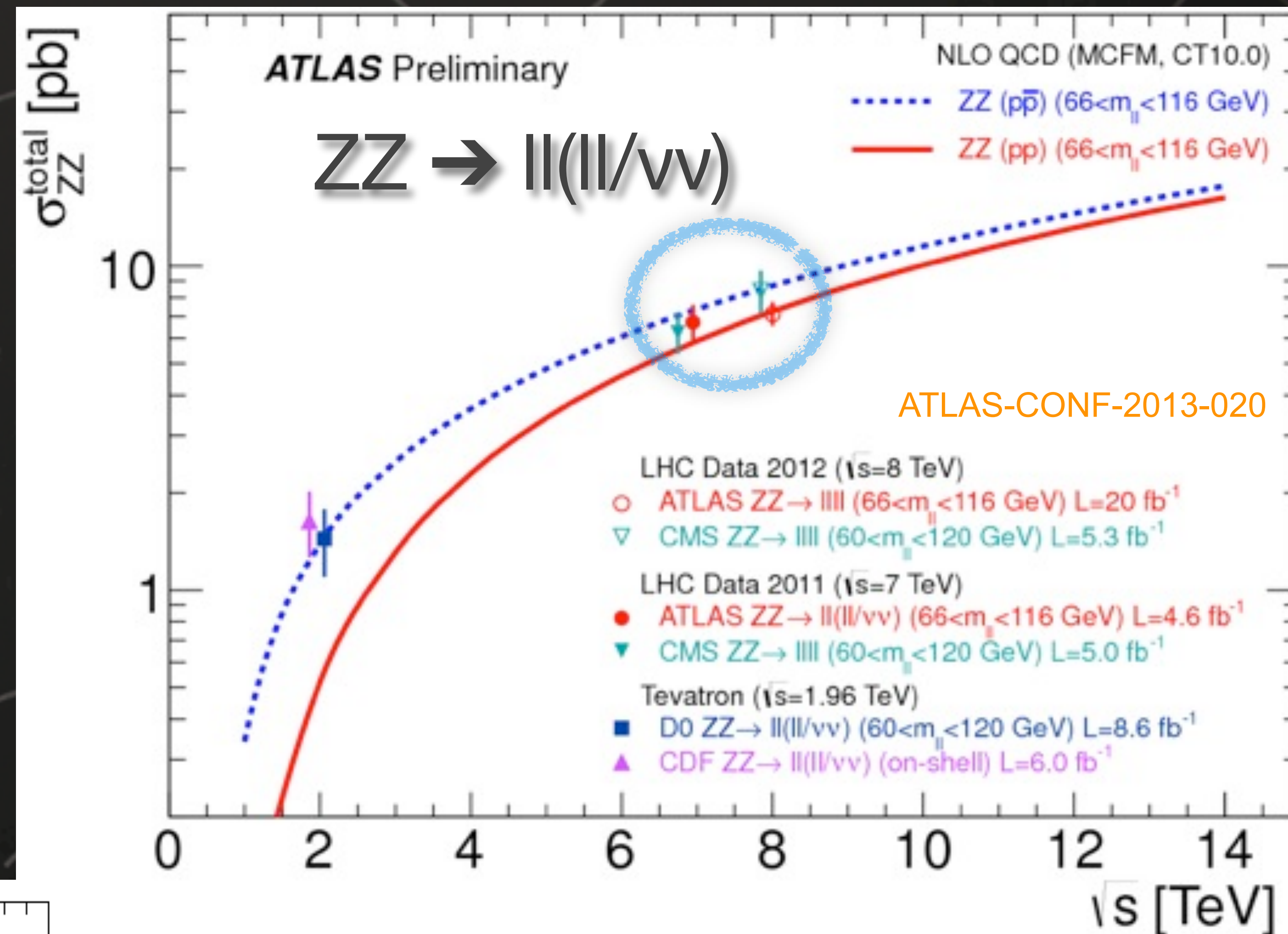
Diboson production cross sections

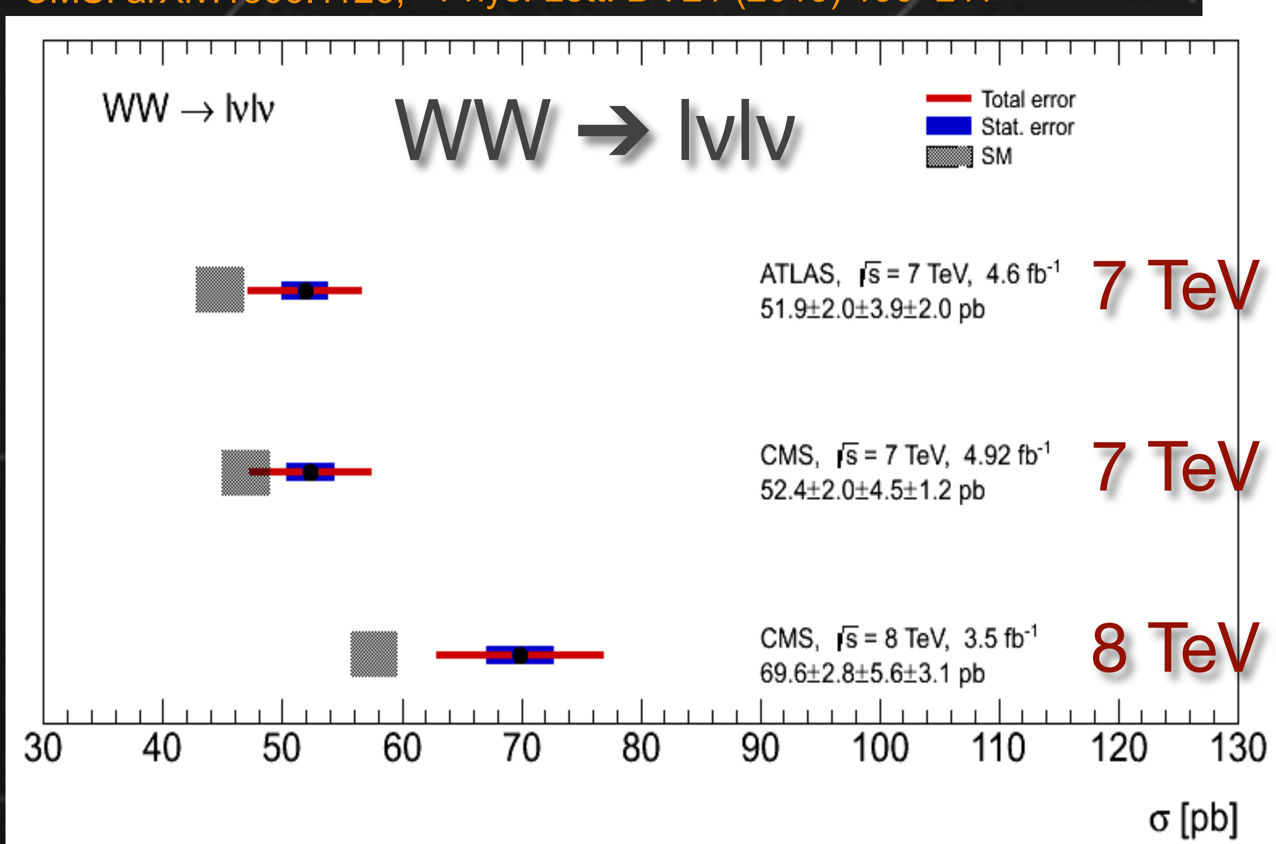
ATLAS and CMS have performed extensive studies of diboson production:

7 TeV: Wγ, Zγ, WW, WZ and ZZ

8 TeV: WW, WZ and ZZ

ATLAS: Phys. Rev. D 87, 112001 (2013)
CMS: arXiv:1306.1126; Phys. Lett. B 721 (2013) 190–211





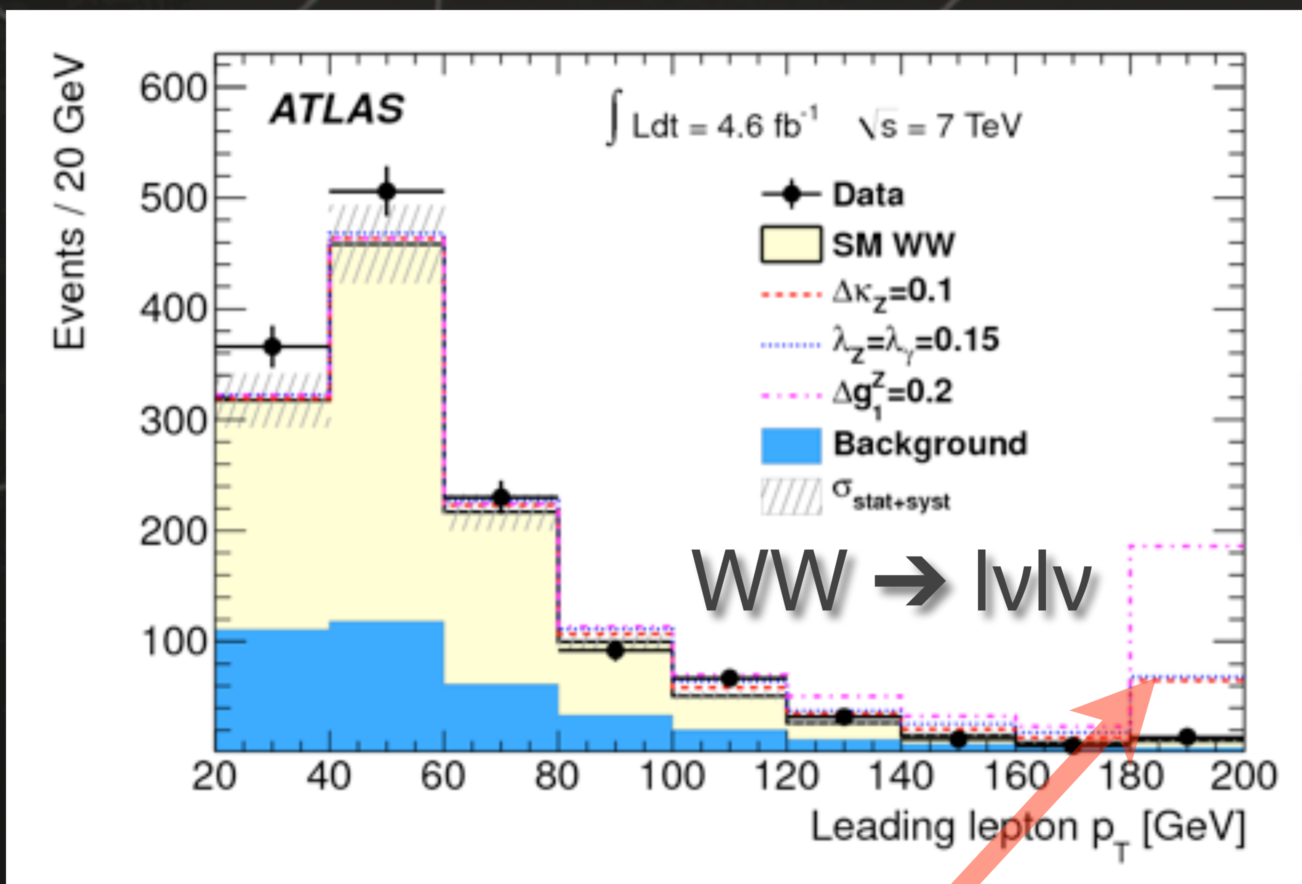
Cross sections a little high (~1 σ) relative to NLO QCD predictions

Largest deviation:
CMS 8 TeV WW (~ 2 σ)

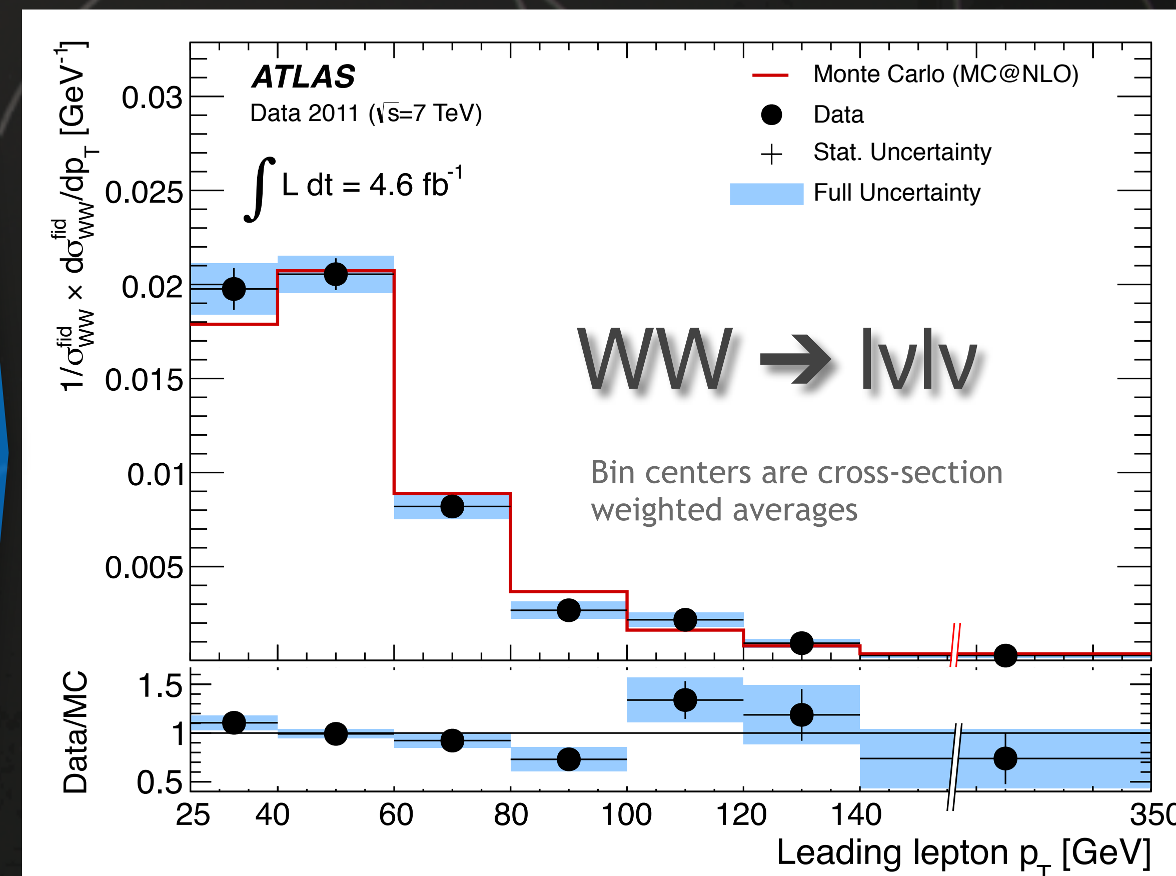
H -->WW contribution ~ 3 (4)% at 7 (8) TeV

Diboson differential cross sections

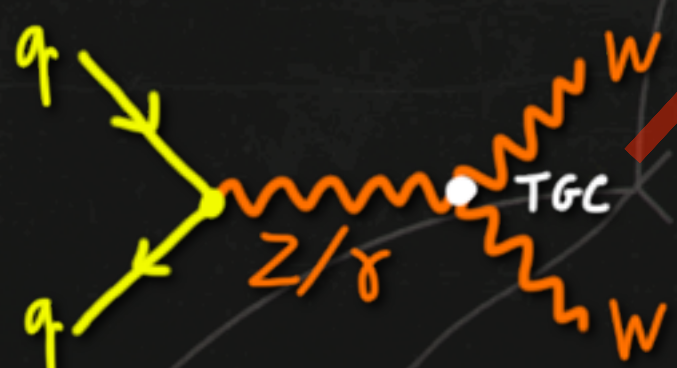
Raw distribution



Unfolded distribution



Normalized cross section



Anomalous TGC (New Physics)

Can be compared with other theoretical predictions

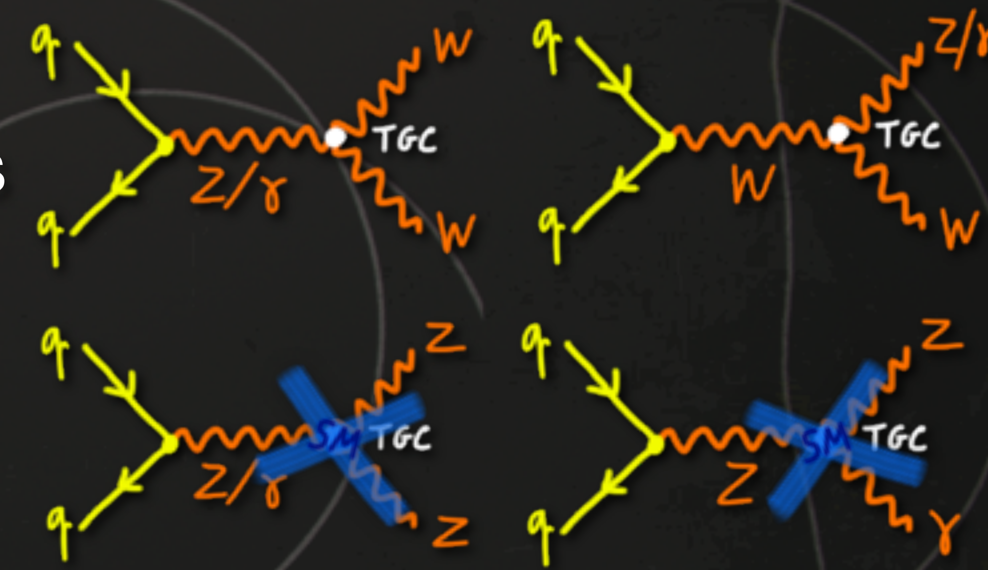
No deviations observed in the differential kinematic distributions for Wγ, Zγ, WW, WZ or ZZ

Phys. Rev. D 87, 112001 (2013)

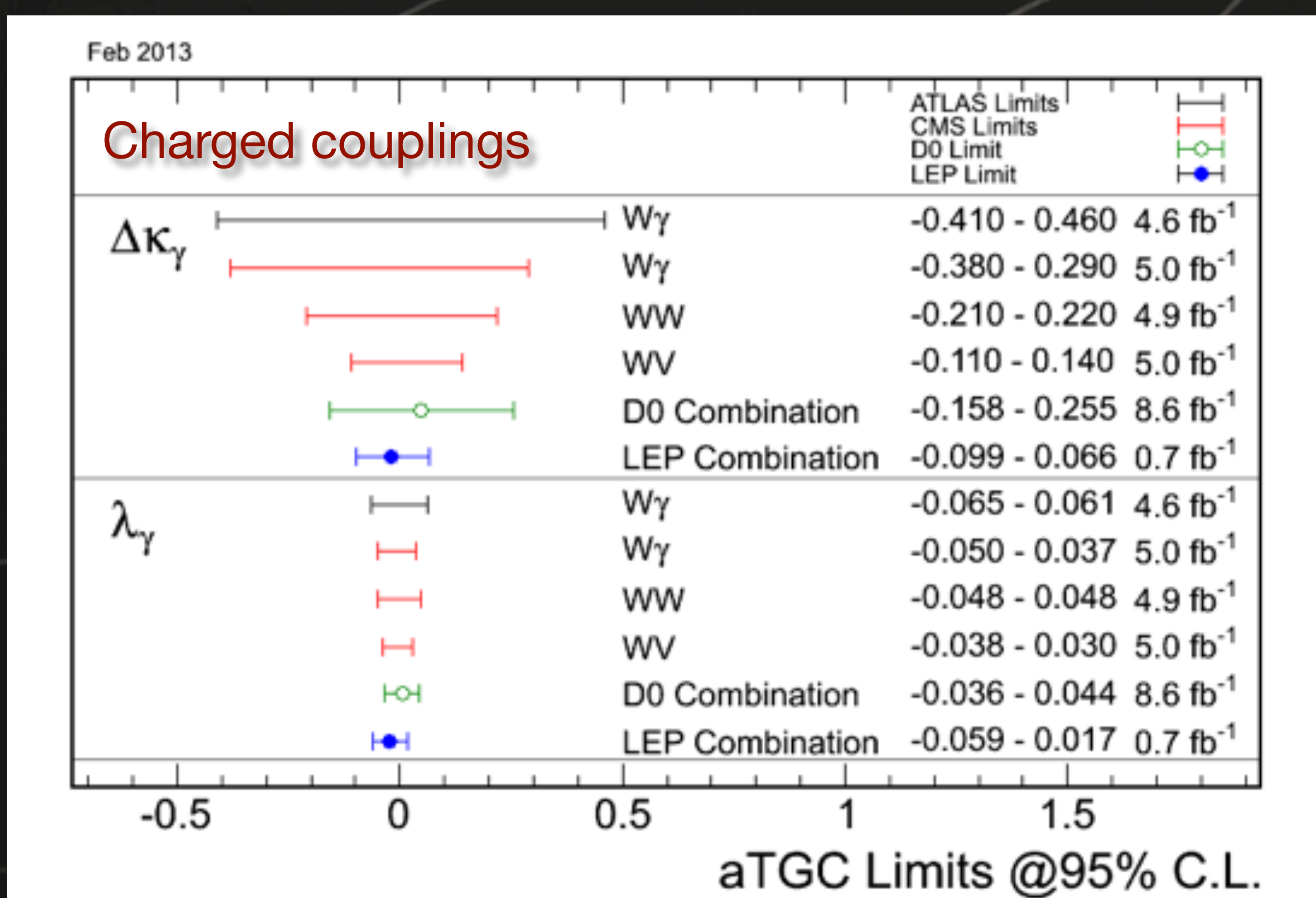
Triple gauge couplings

Channels

- Wγ, WW and WZ → 5 anomalous charged couplings
- Zγ and ZZ → 8 anomalous neutral couplings



No deviations from SM have been observed

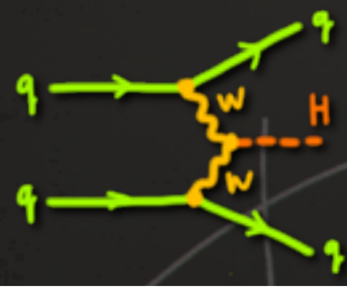


- Charged couplings:
  - LHC limits similar to LEP limits
- Neutral couplings:
  - LHC limits already far stricter than LEP limits

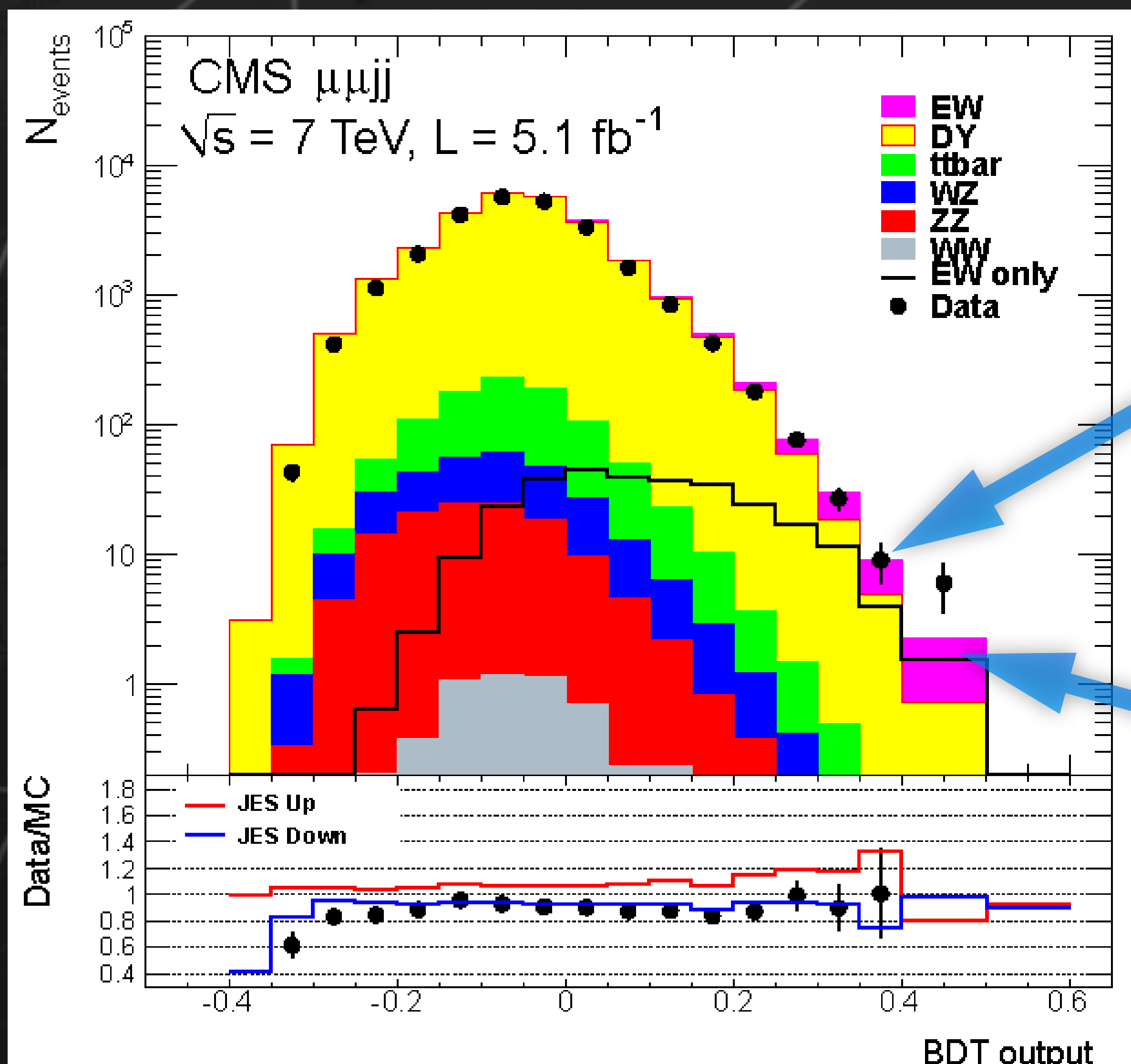
Limits assume no form factor Λ = infinty

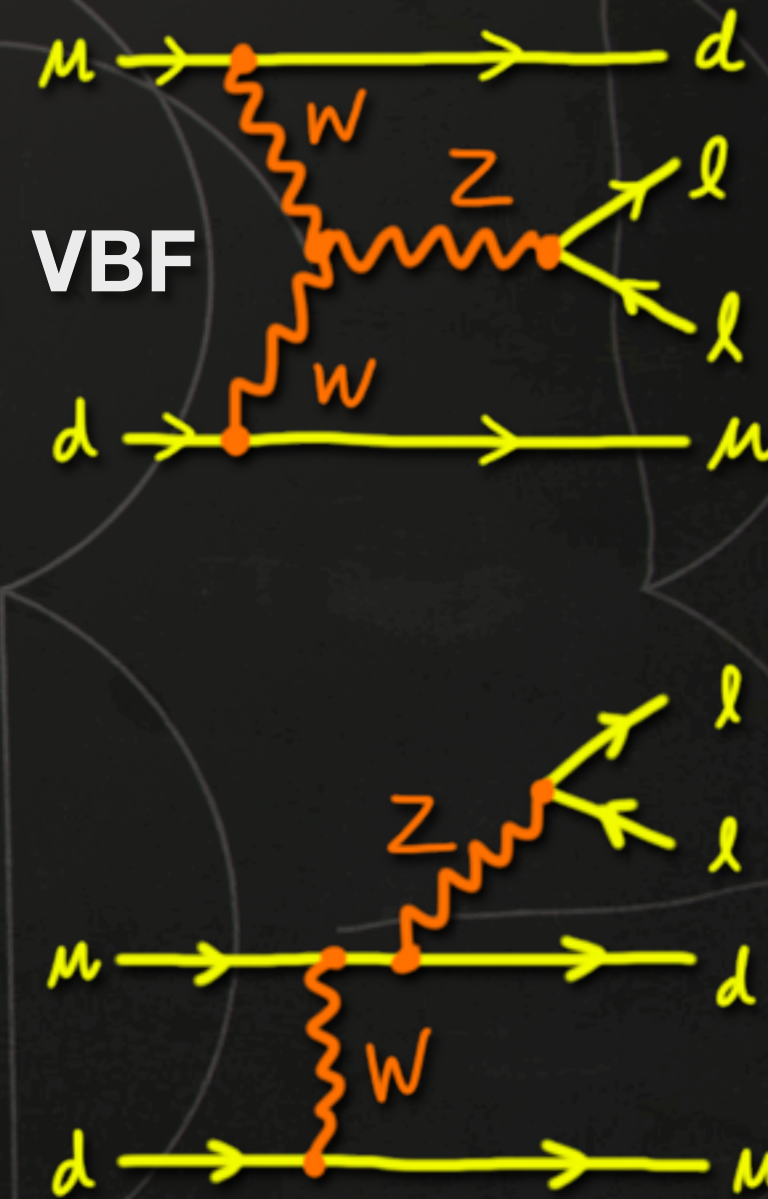
New frontiers in SM physics at LHC

Single Z electroweak production



Similar to VBF Higgs production

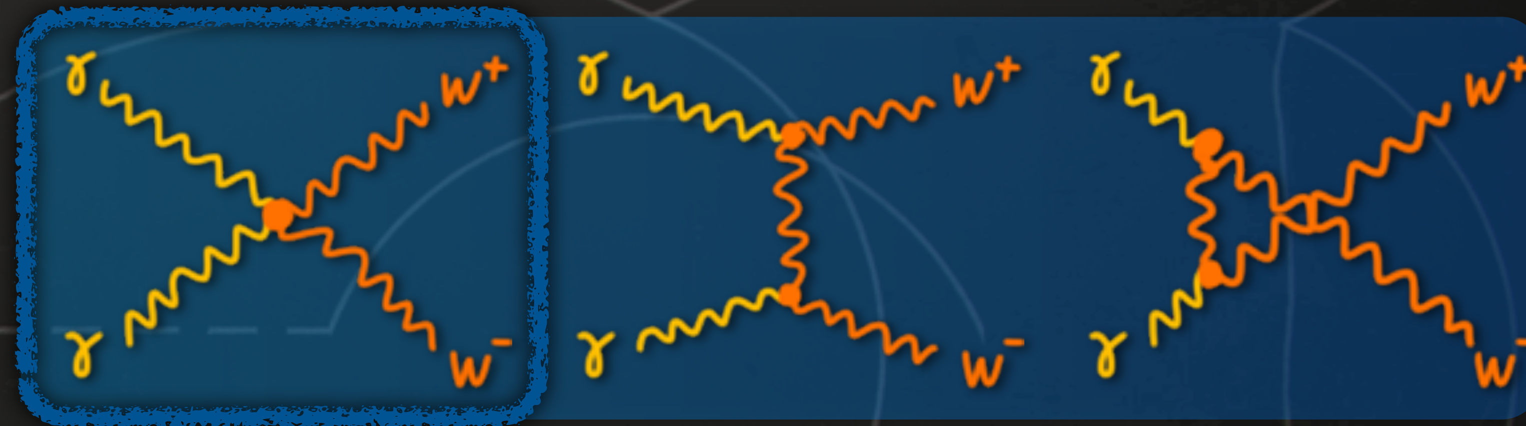




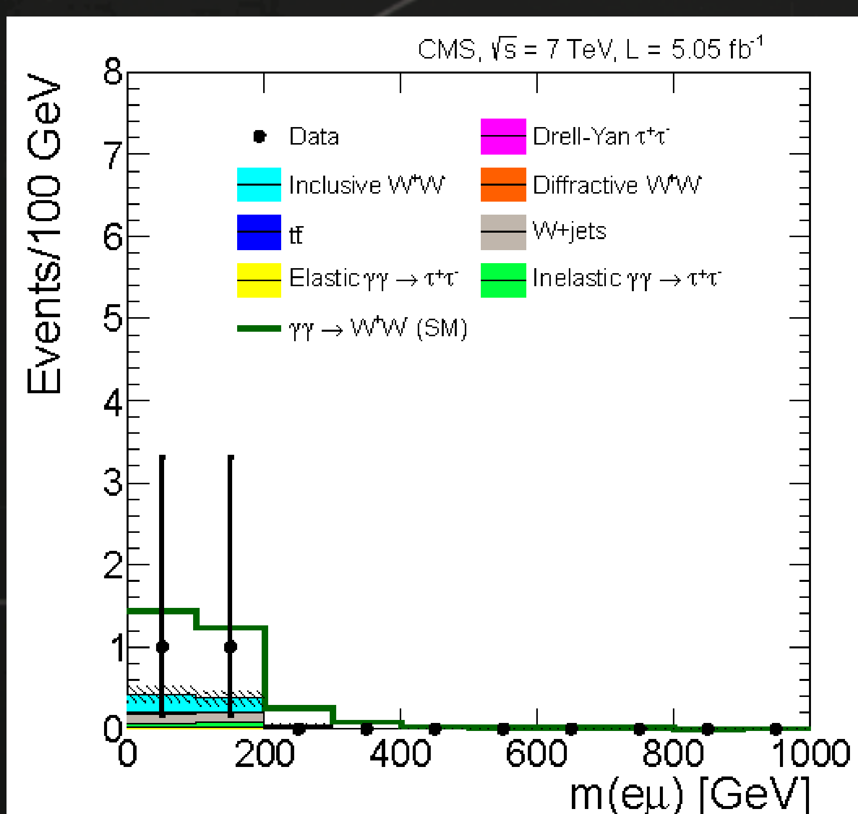
- First evidence for electroweak Z production
  - Uses BDT to separate signal form enormous QCD Z+2 jets background
  - Statistically limited measurement consistent with SM expectations

arXiv:1305.7389

Exclusive production of WW ($\gamma\gamma \rightarrow WW$)



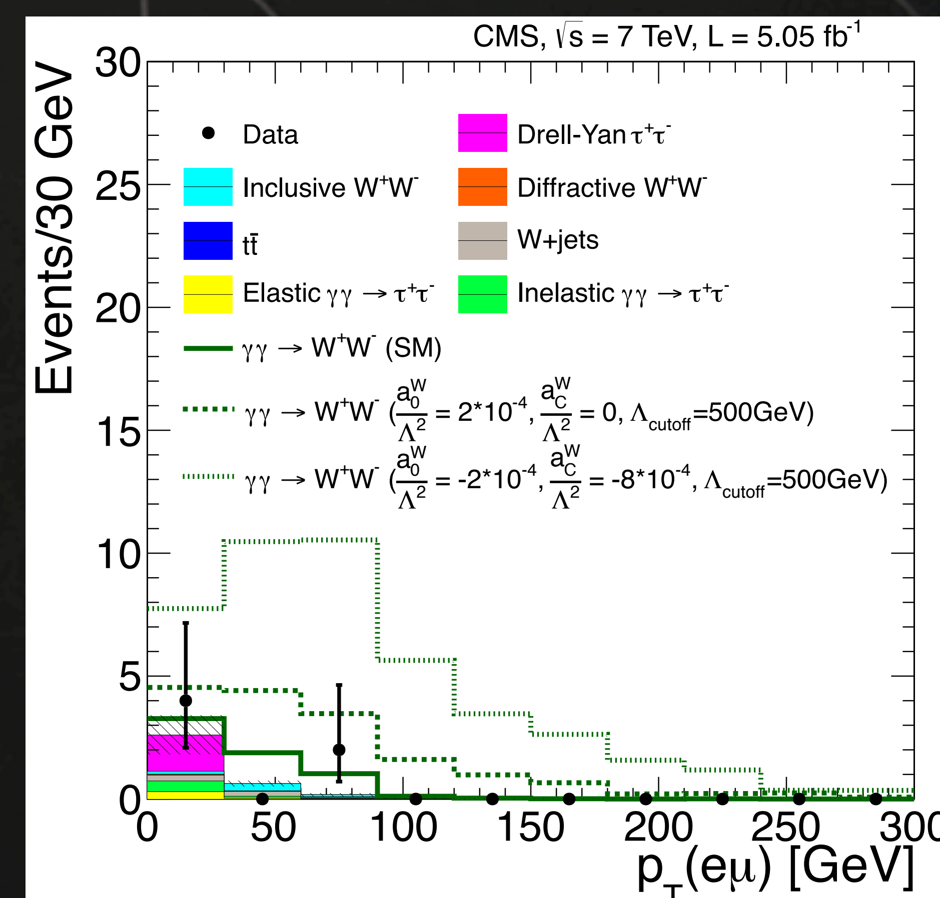
- $pp \rightarrow p^{(*)} W^+W^- p^{(*)} \rightarrow p^{(*)} e\mu\, p^{(*)}$
  - Only two leptons from primary vertex (no other tracks)



$\sigma = 2.2^{+3.3}_{-2.0}$ fb

Set limits on aQGC using events with $P_T(\mu e) > 100$ GeV

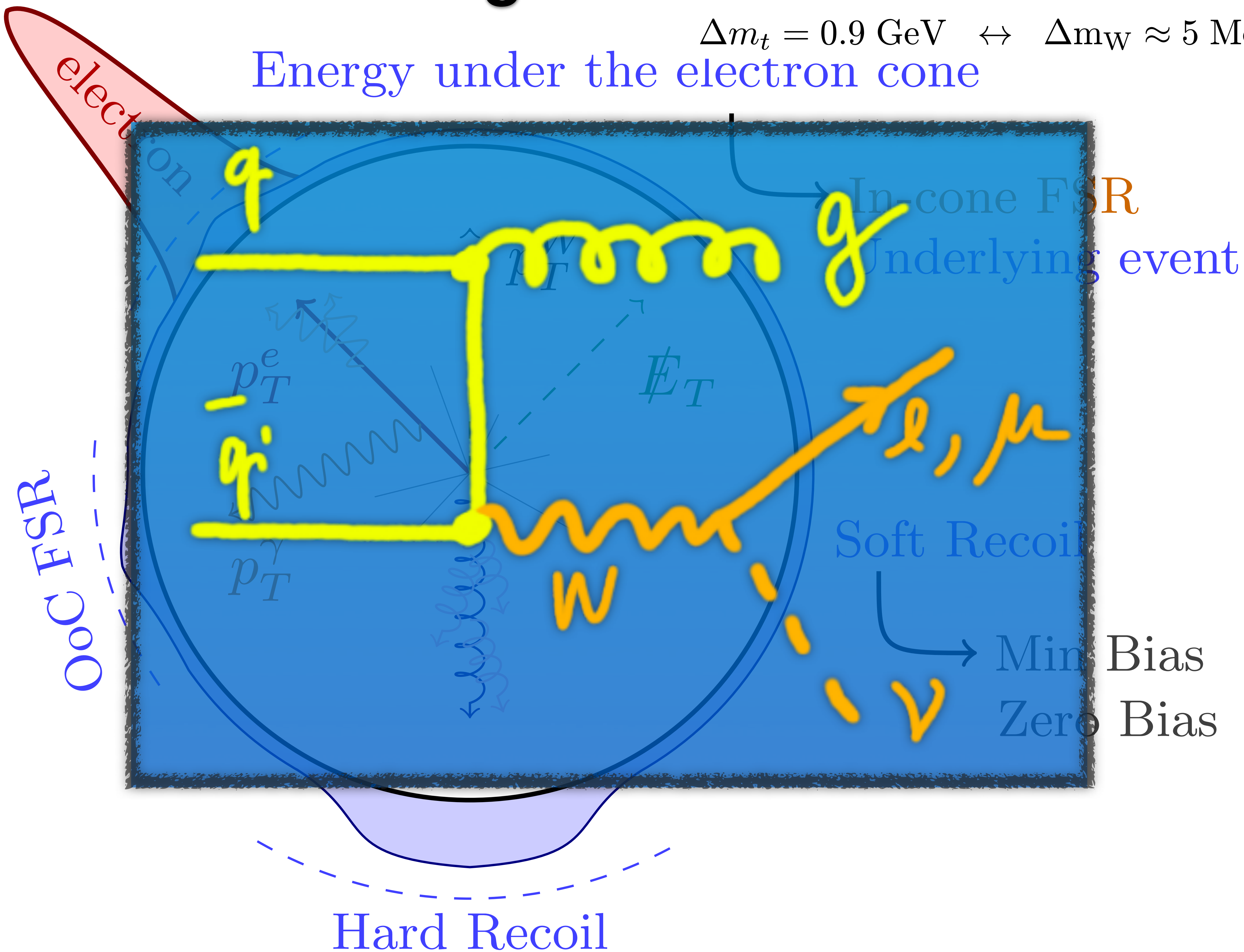
Limit results:
x20 Tevatron
x100 LEP



arXiv:1305.5596

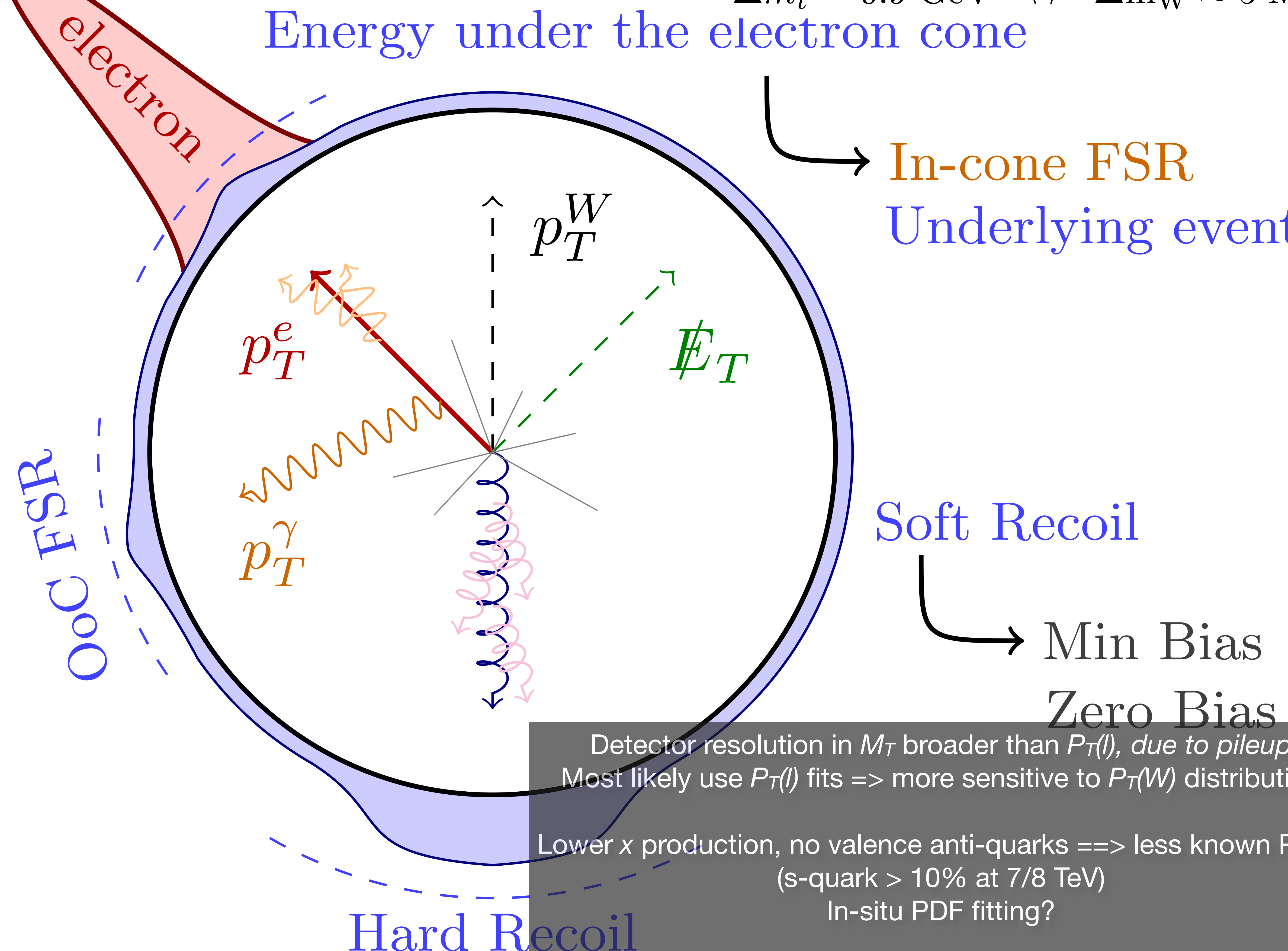
The challenges of the W Boson Mass

$\Delta m_t = 0.9$ GeV $\leftrightarrow$ $\Delta m_W \approx 5$ MeV



The challenges of the W Boson Mass

$\Delta m_t = 0.9$ GeV $\leftrightarrow$ $\Delta m_W \approx 5$ MeV



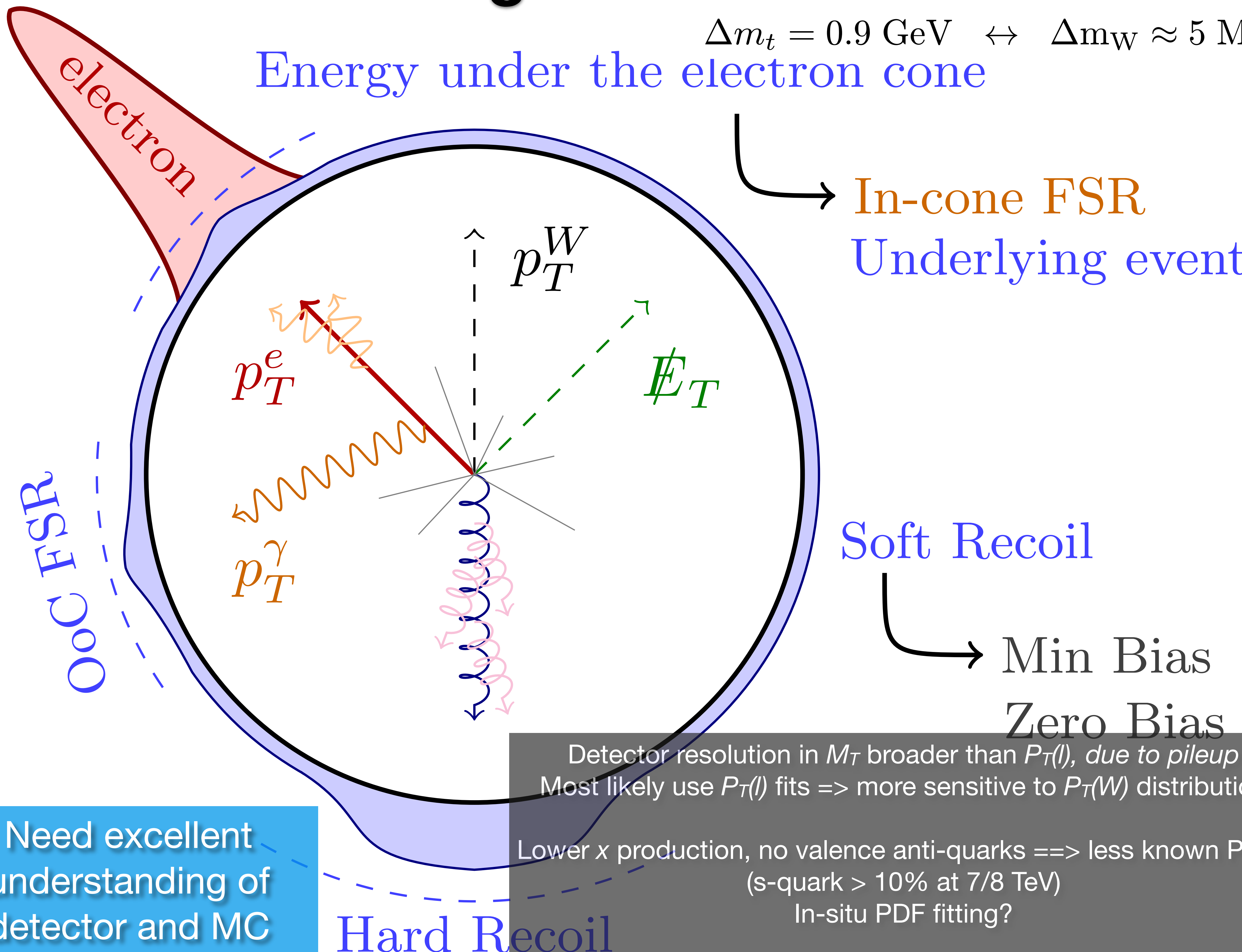
Detector resolution in M_T broader than $P_T(l)$, *due to pileup*
Most likely use $P_T(l)$ fits => more sensitive to $P_T(W)$ distribution

Lower *x* production, no valence anti-quarks ==> less known PDFs
(s-quark > 10% at 7/8 TeV)
In-situ PDF fitting?

W+ and W- have different kinematics

The challenges of the W Boson Mass

$\Delta m_t = 0.9$ GeV $\leftrightarrow$ $\Delta m_W \approx 5$ MeV



Need excellent understanding of detector and MC simulation

Detector resolution in M_T broader than $P_T(l)$, *due to pileup*
Most likely use $P_T(l)$ fits => more sensitive to $P_T(W)$ distribution

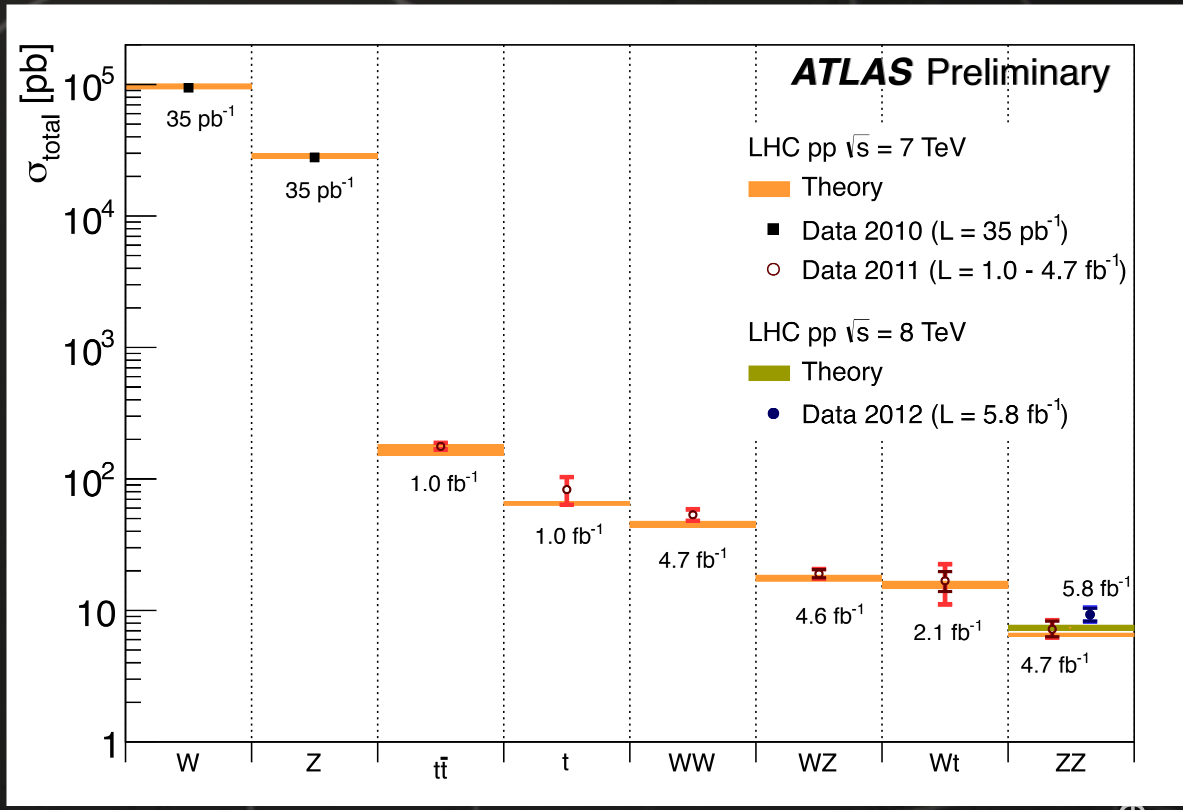
Lower *x* production, no valence anti-quarks ==> less known PDFs
(s-quark > 10% at 7/8 TeV)
In-situ PDF fitting?

W+ and W- have different kinematics

Conclusions

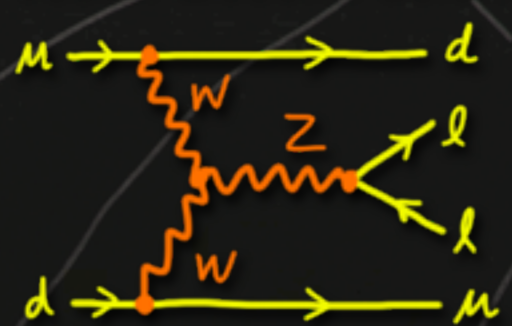
We have re-established the Standard Model at the LHC

- Besides finding the last missing piece of the SM...
- Found impressive agreement with theory across orders of magnitude
  - Continuing to explore ever smaller cross sections
- Established a stable ground for new physics searches
  - Still, deeper understanding is needed:
    - Parton distribution function
    - NNLO QCD calculations and NLO EWK corrections

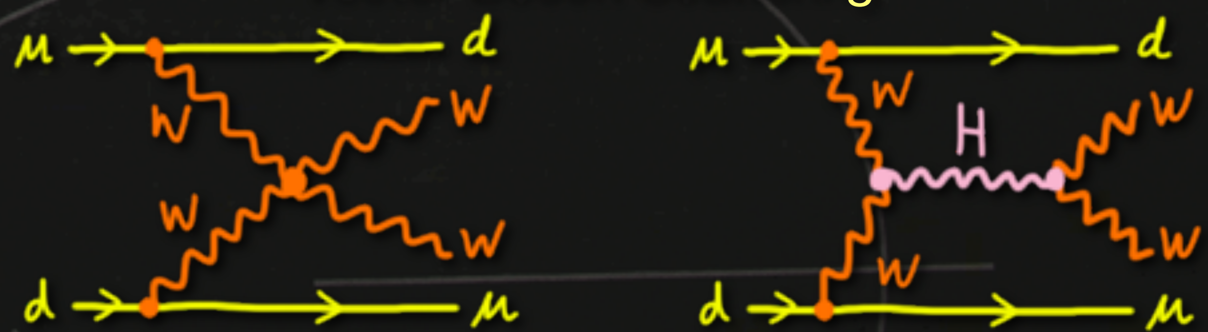


- What's next?
  - Many more results to come in the next few months
    - We are just starting SM physics with the 8 TeV data
  - Later:

Vector Boson Fusion

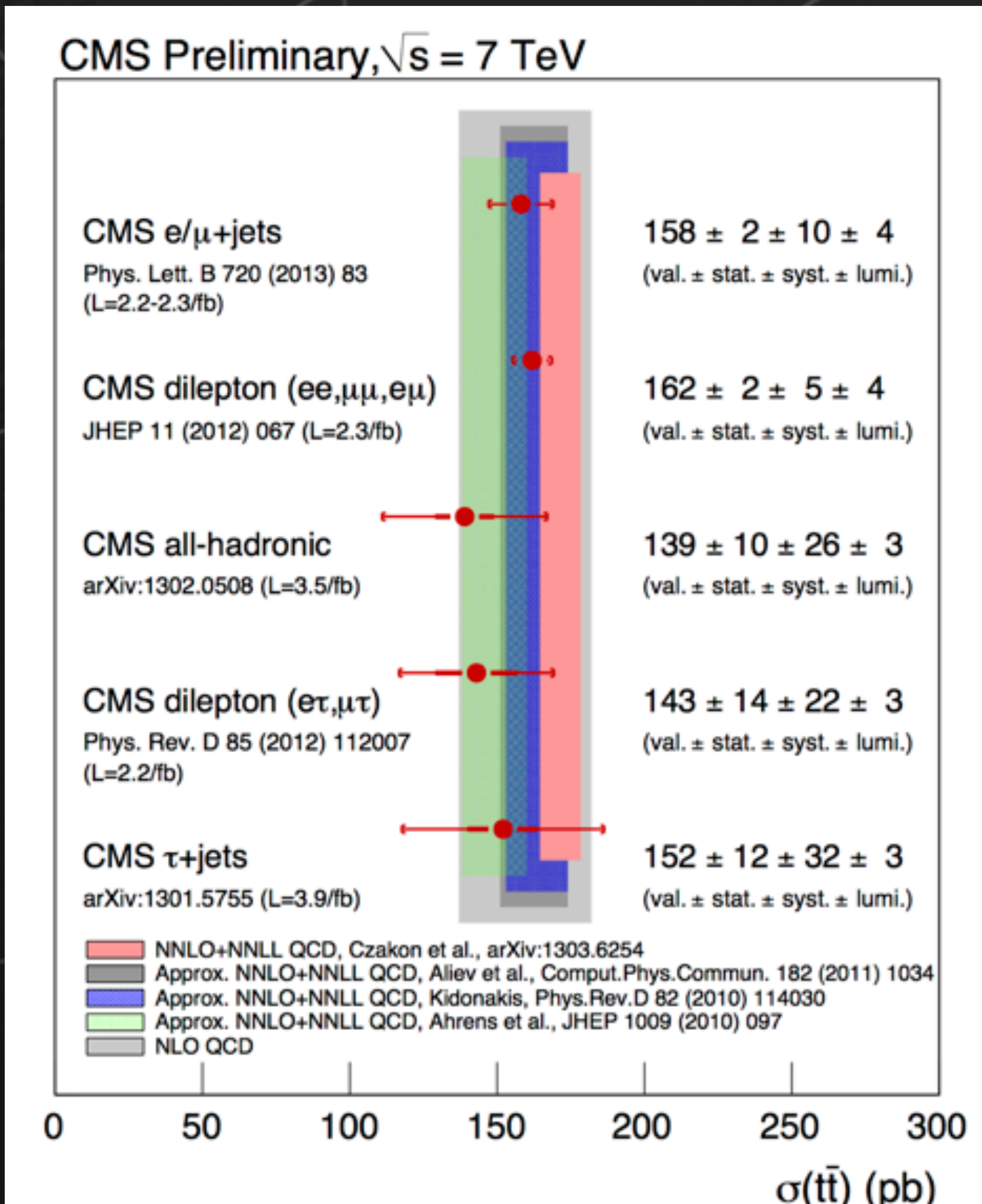


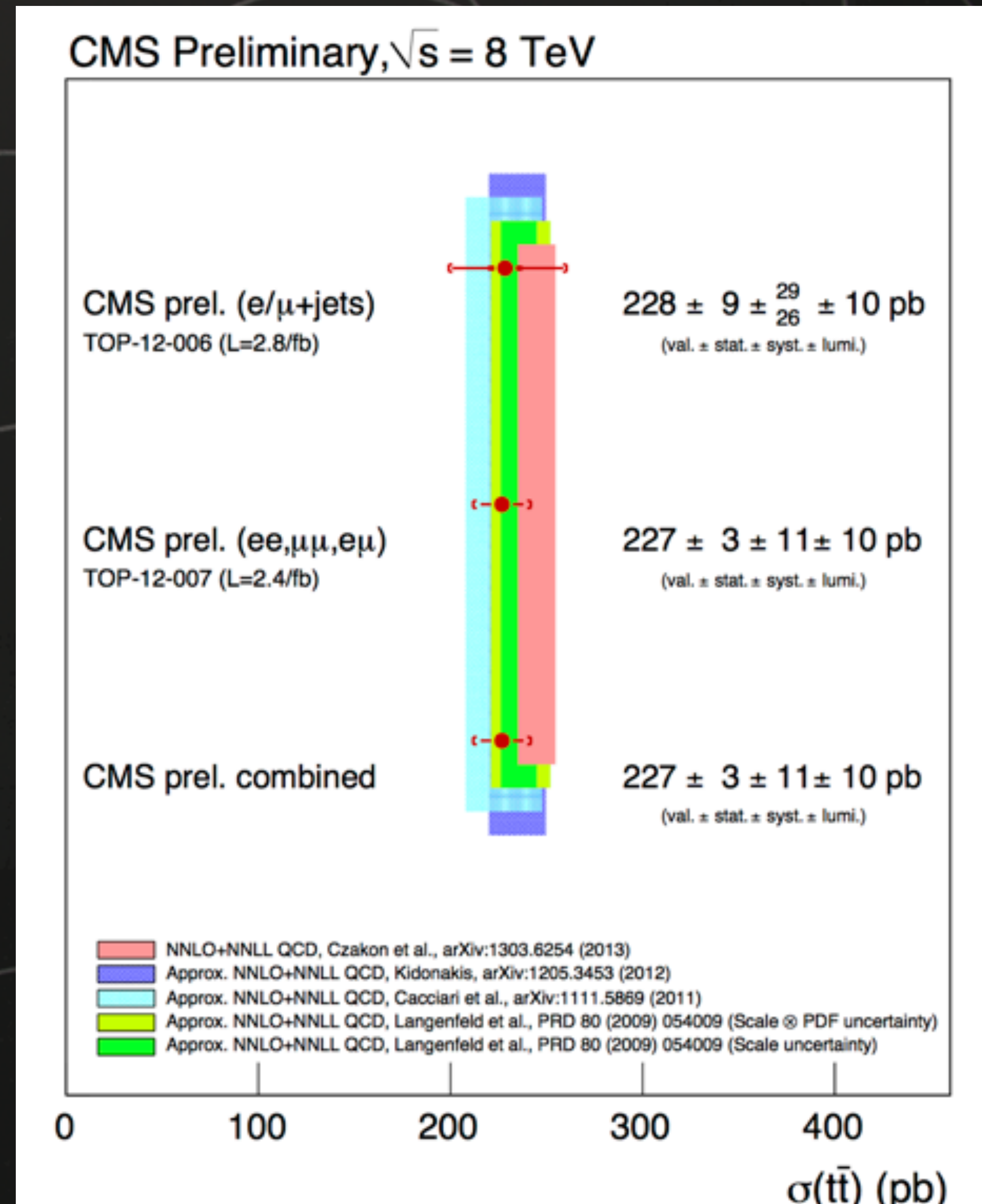
Vector Boson Scattering



Top pair production cross section at 7 and 8 TeV

- Comparisons with new theoretical predictions



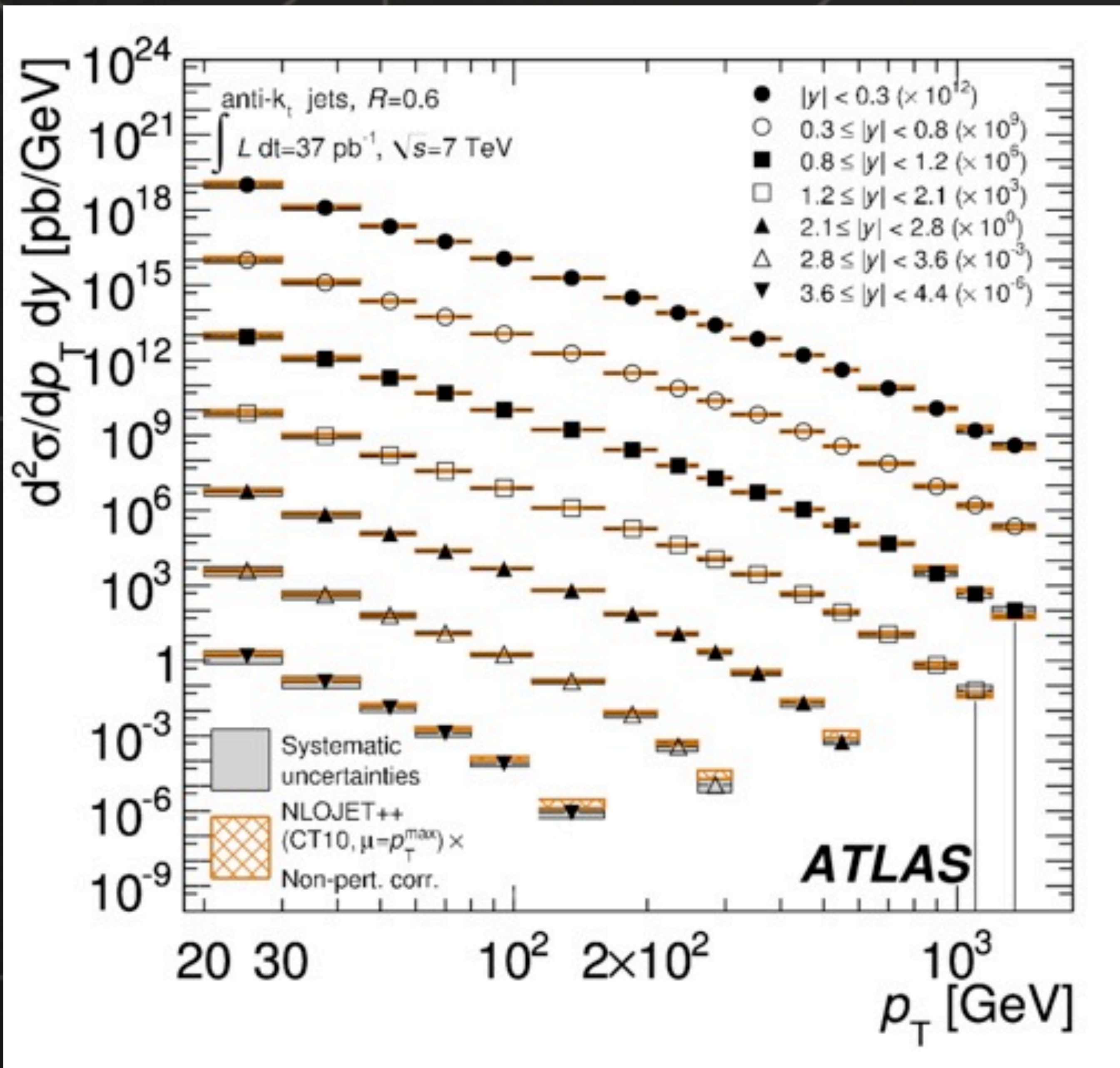


Inclusive Jet and Dijet Cross Sections at 7 TeV

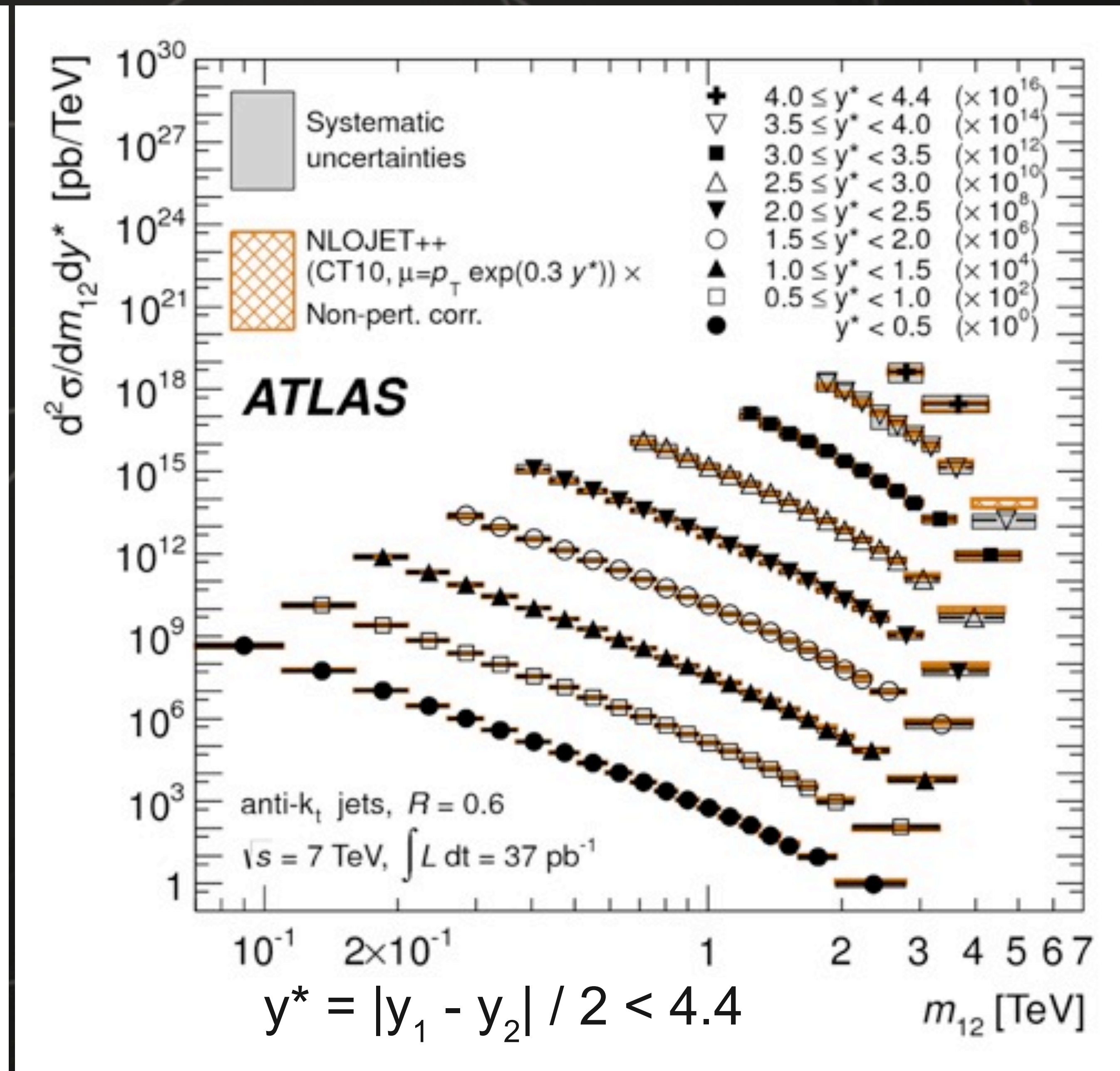
Phys.Rev. D86 (2012) 014022

L = 37 pb^{-1}

Inclusive jet cross section



Dijet cross section

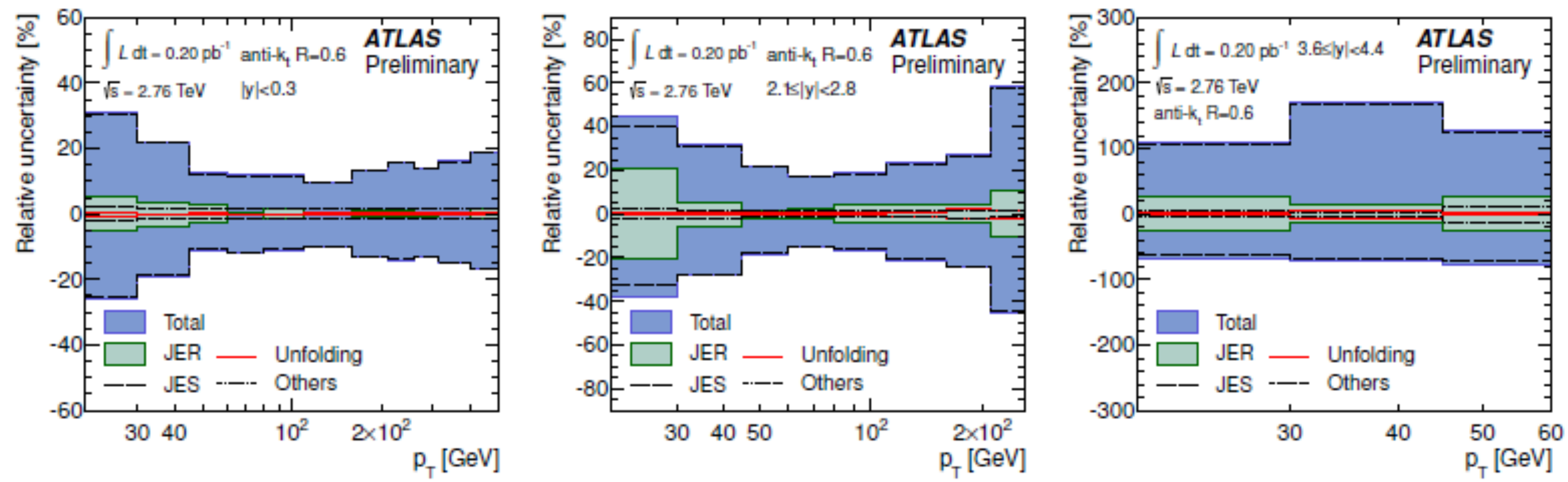


NLOJET++ prediction with CT10

Testing predictions over 9 orders of magnitude!

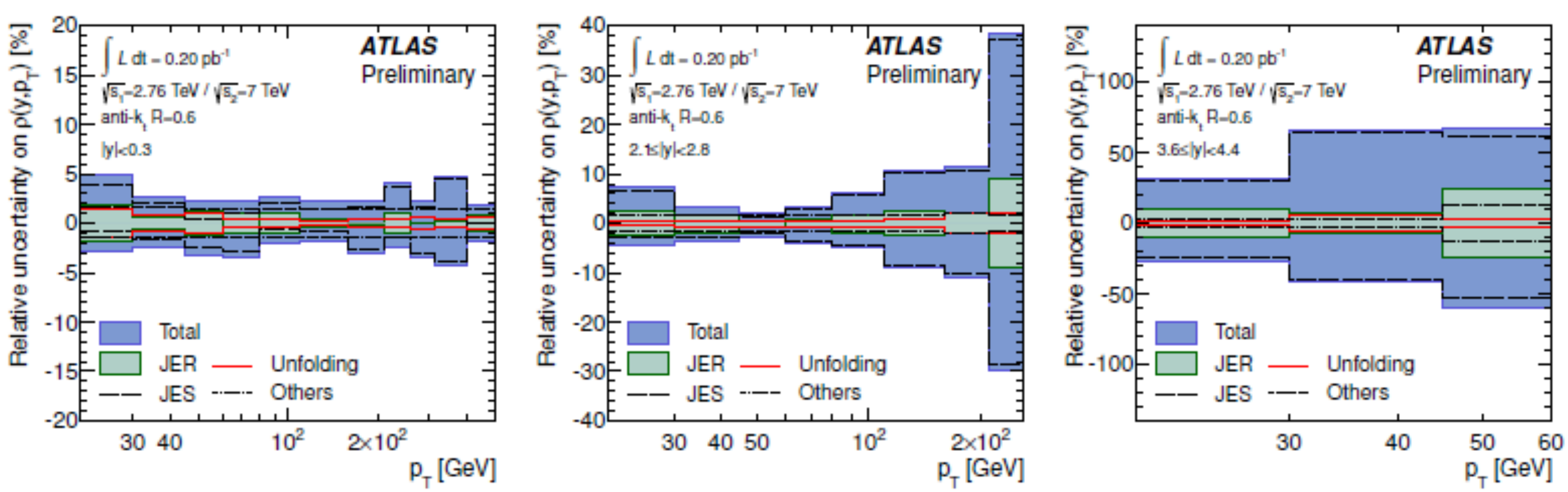
Inclusive jet cross section at 2.76 TeV

Uncertainties on 2.76TeV jet cross section



(a) $|y| < 0.3$ (b) $2.1 \leq |y| < 2.8$ (c) $3.6 \leq |y| < 4.4$

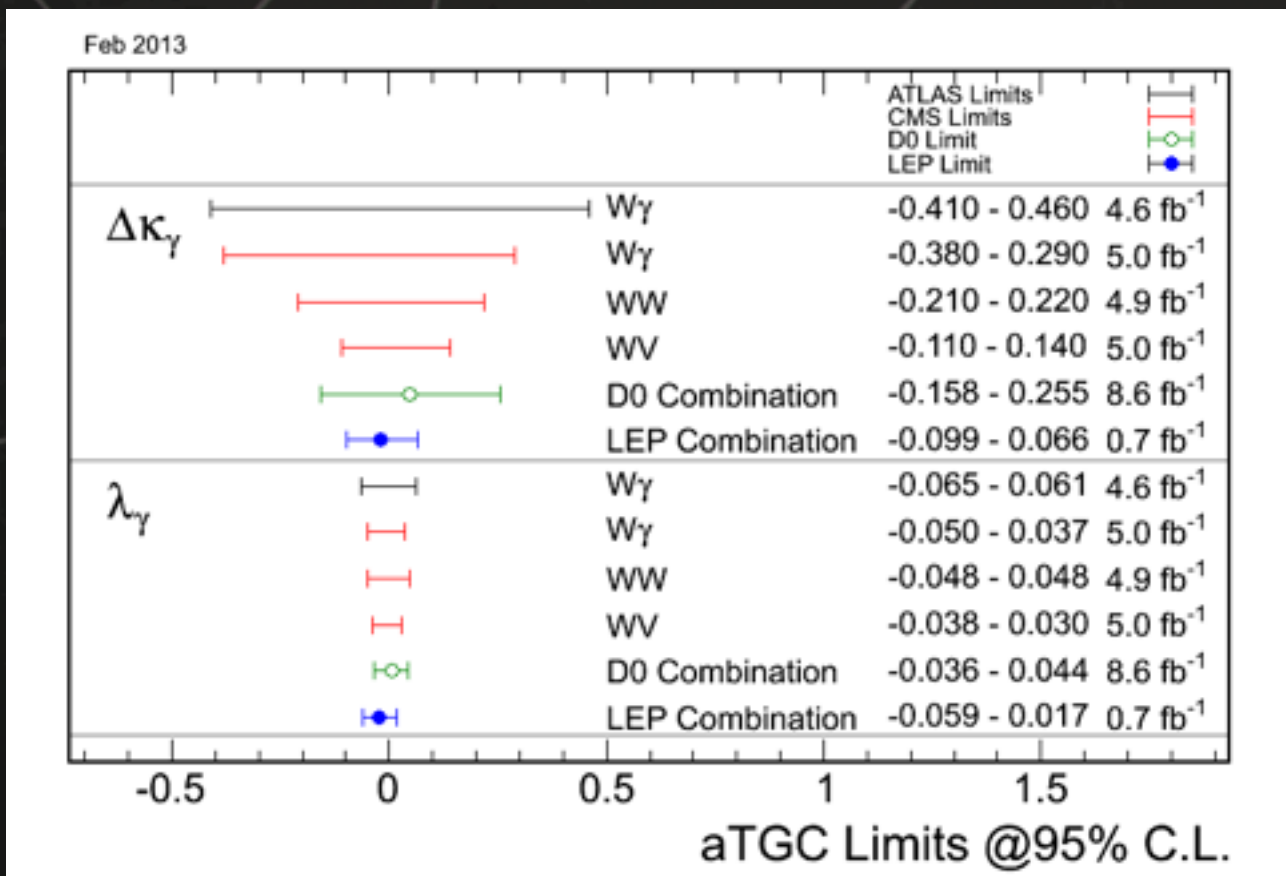
Uncertainties on the ratio 2.76 TeV to 7 TeV jet cross sections

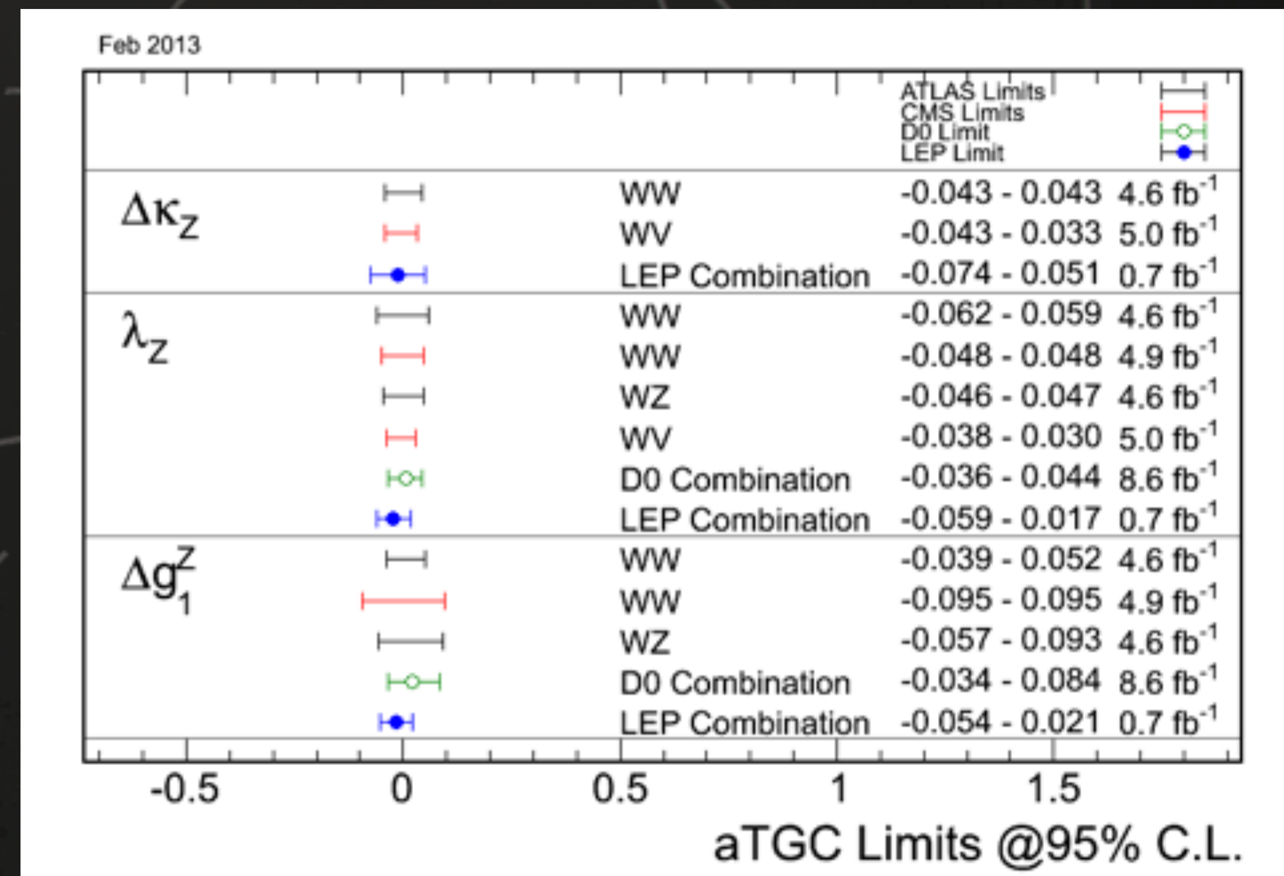


(d) $\rho(y, p_T), |y| < 0.3$ (e) $\rho(y, p_T), 2.1 \leq |y| < 2.8$ (f) $\rho(y, p_T), 3.6 \leq |y| < 4.4$

Anomalous triple gauge couplings

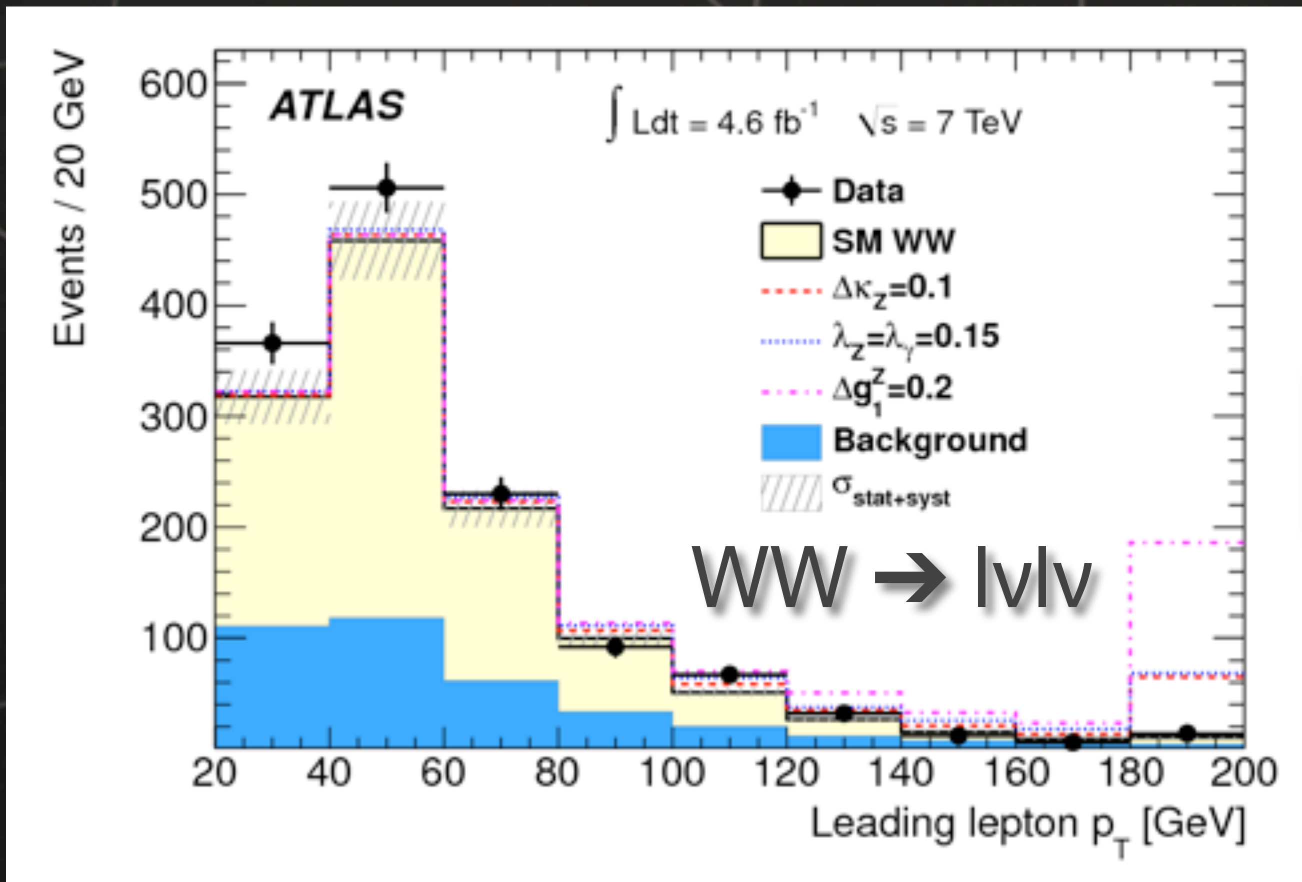
- Limits on 5 anomalous **charged couplings** accessible in Wγ, WW and WZ channels

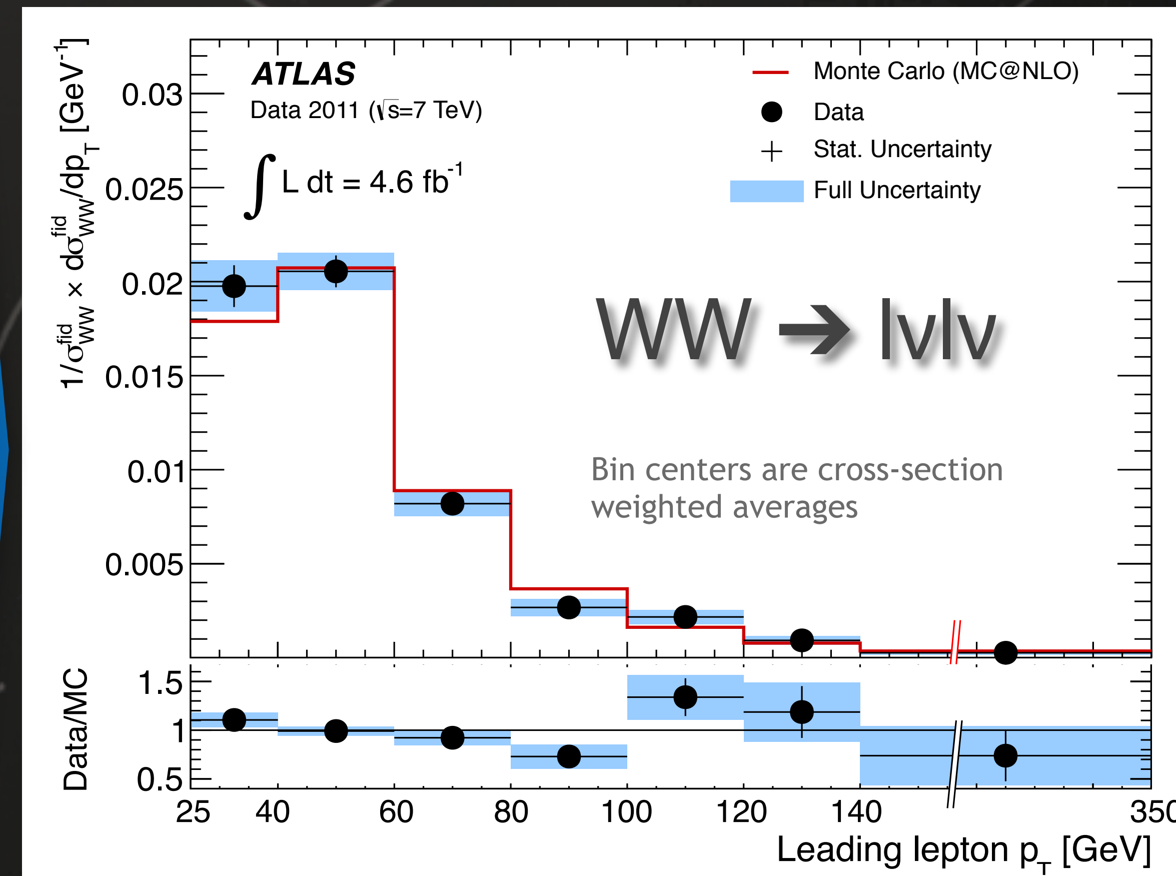


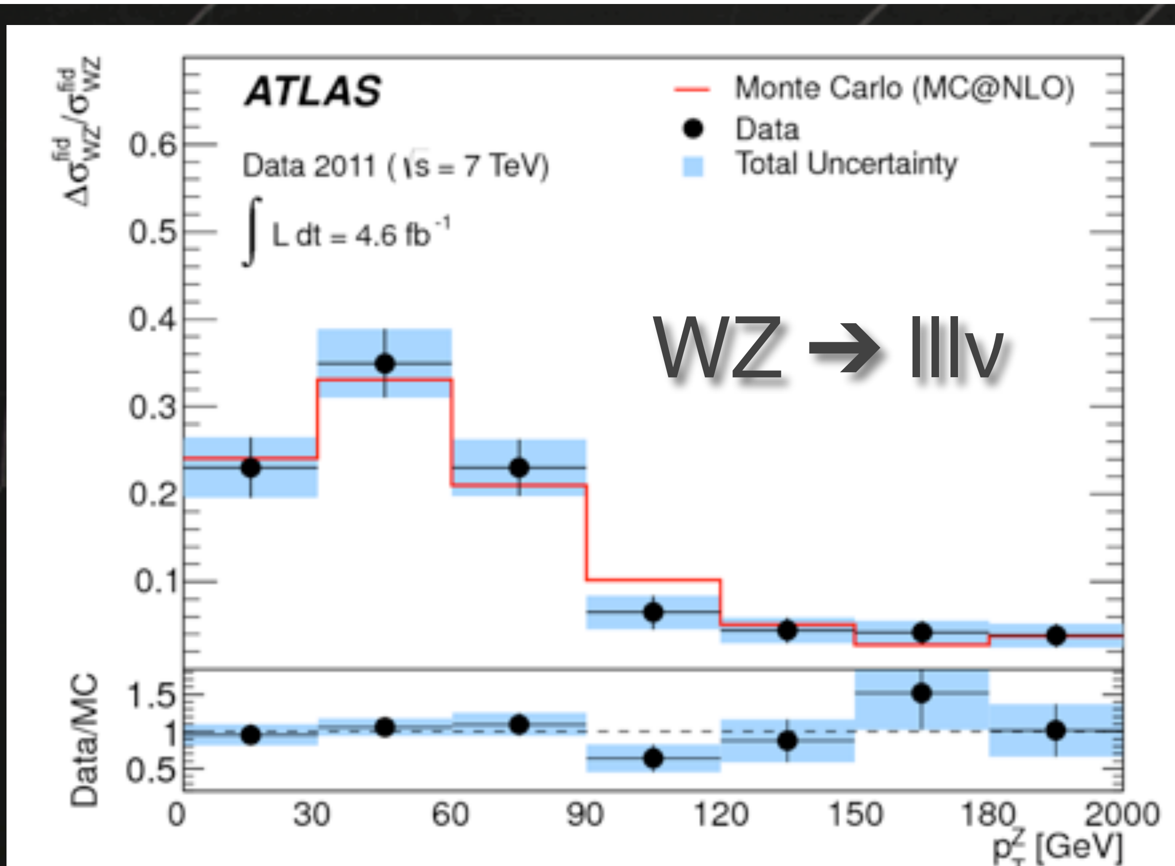


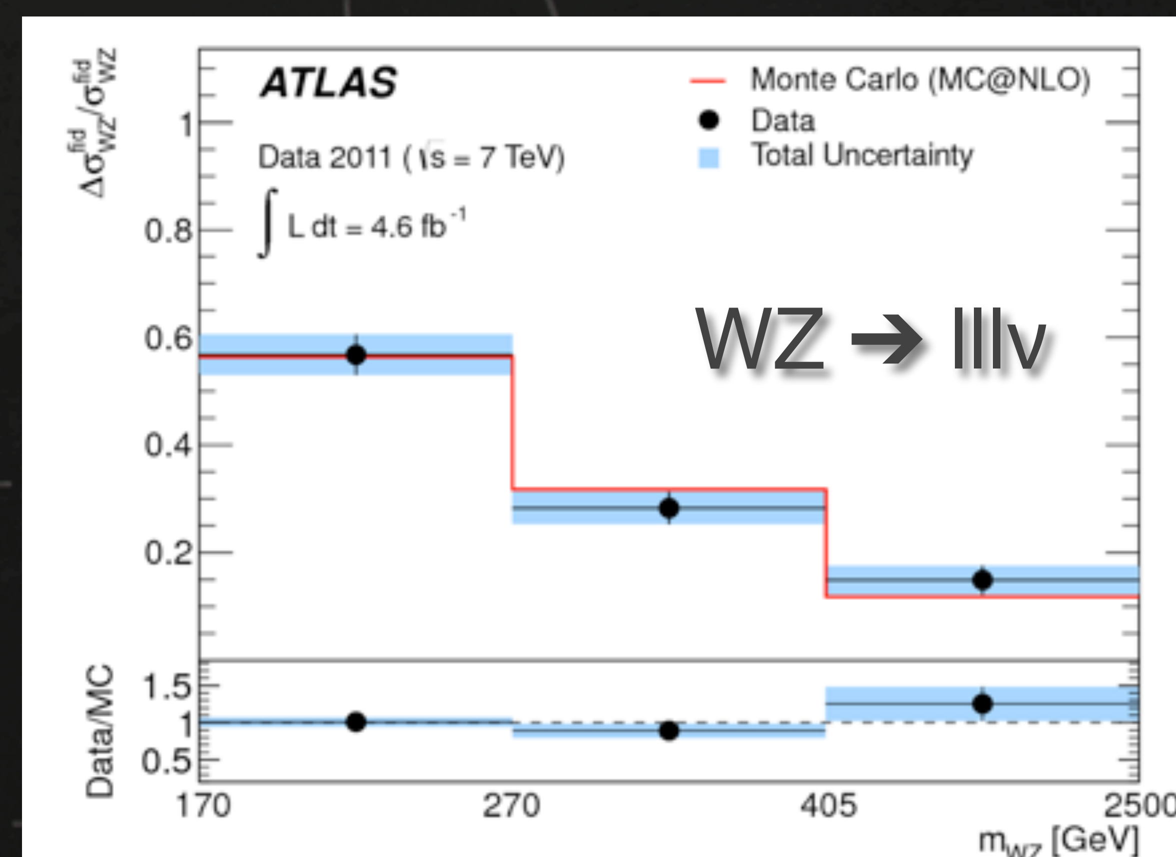
- Stronger limits:
  - CMS WW/WZ ➔ lvjj uses fit to p_T(dijet) distribution
- No deviations from the SM have been been observed
  - LHC limits already at the level of LEP limits

Fiducial differential cross sections

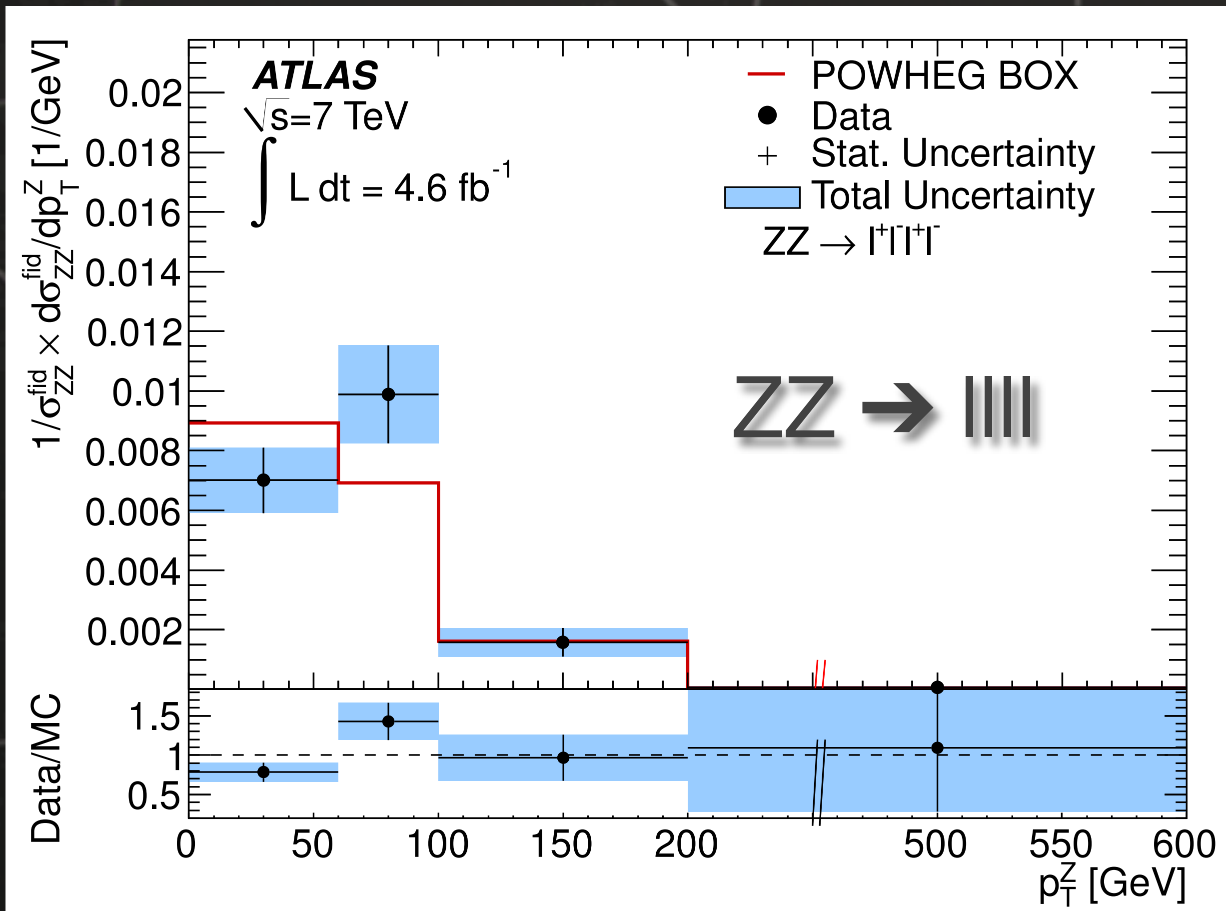


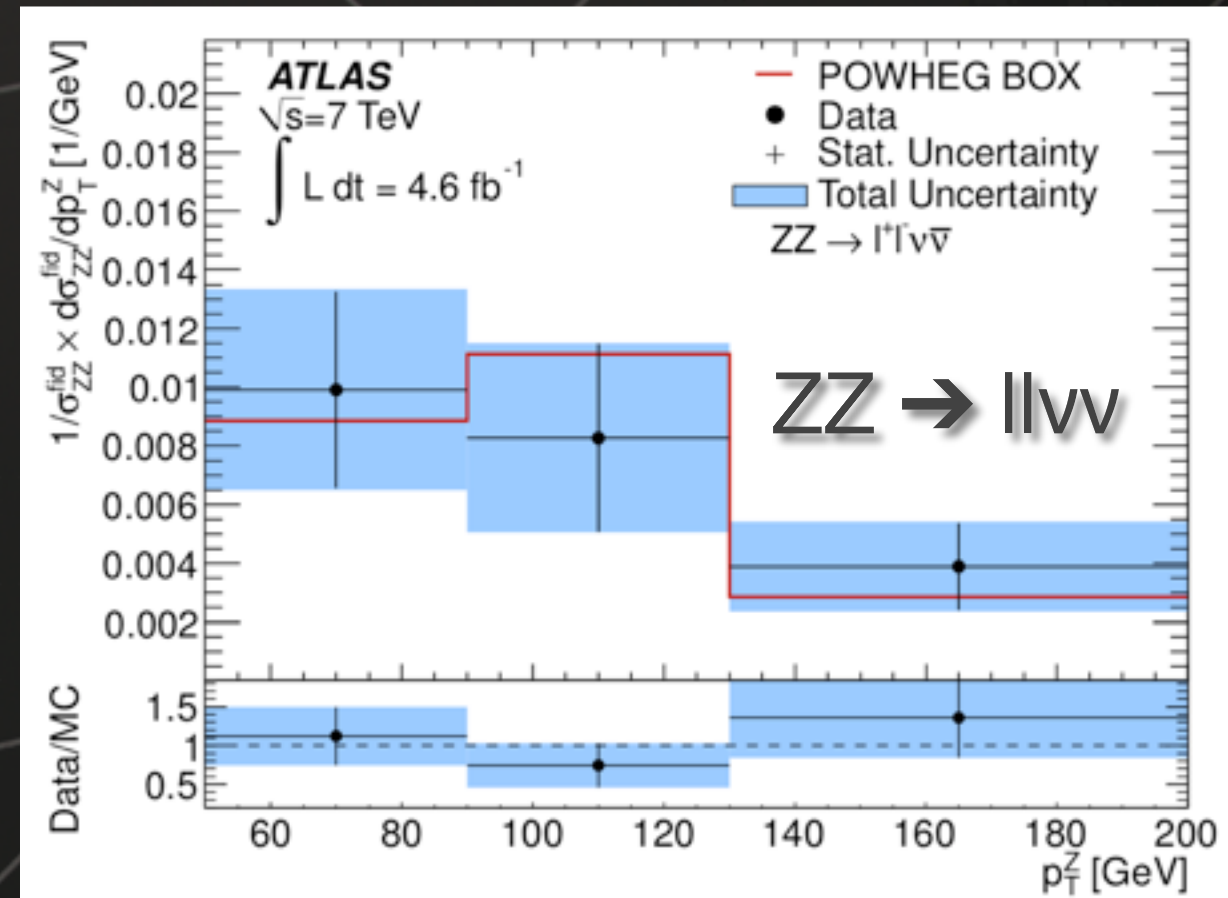


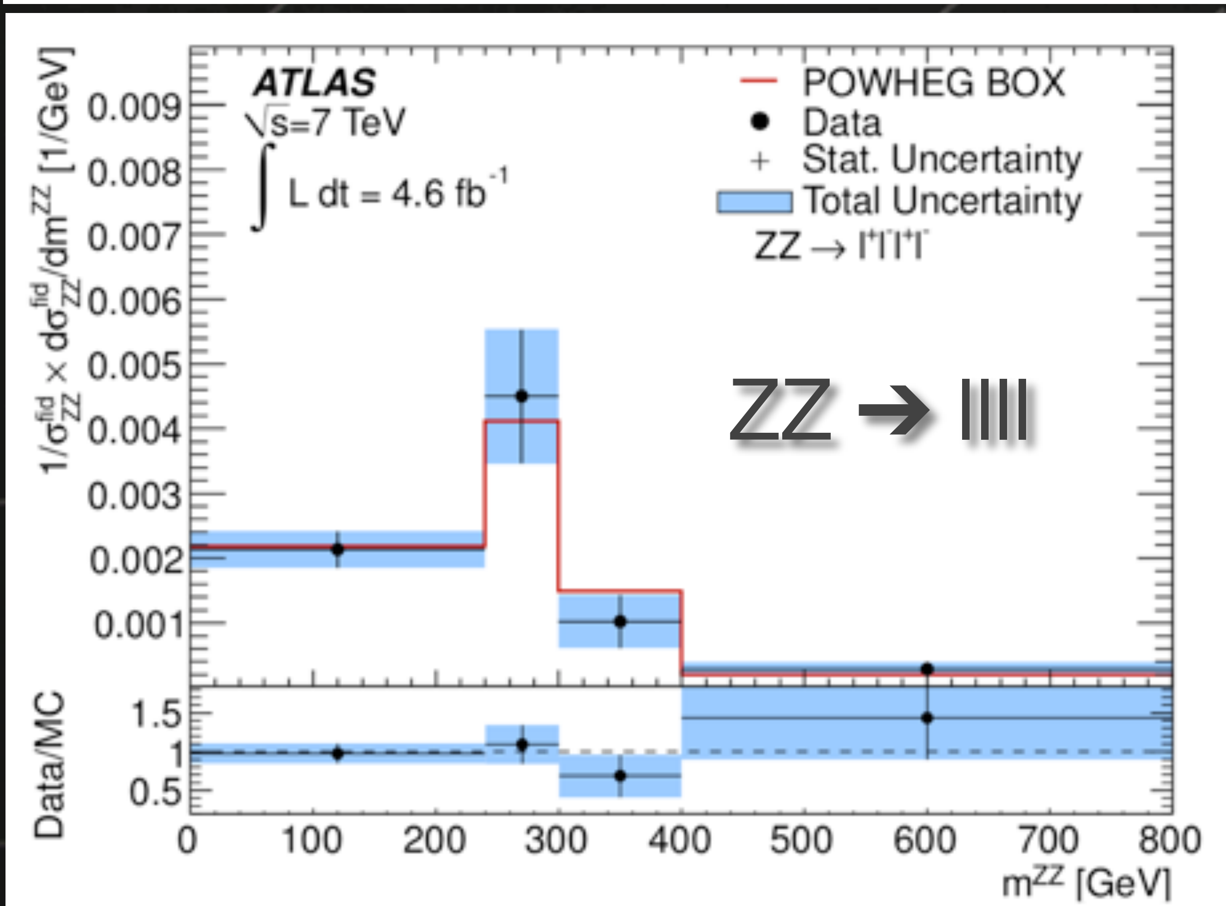


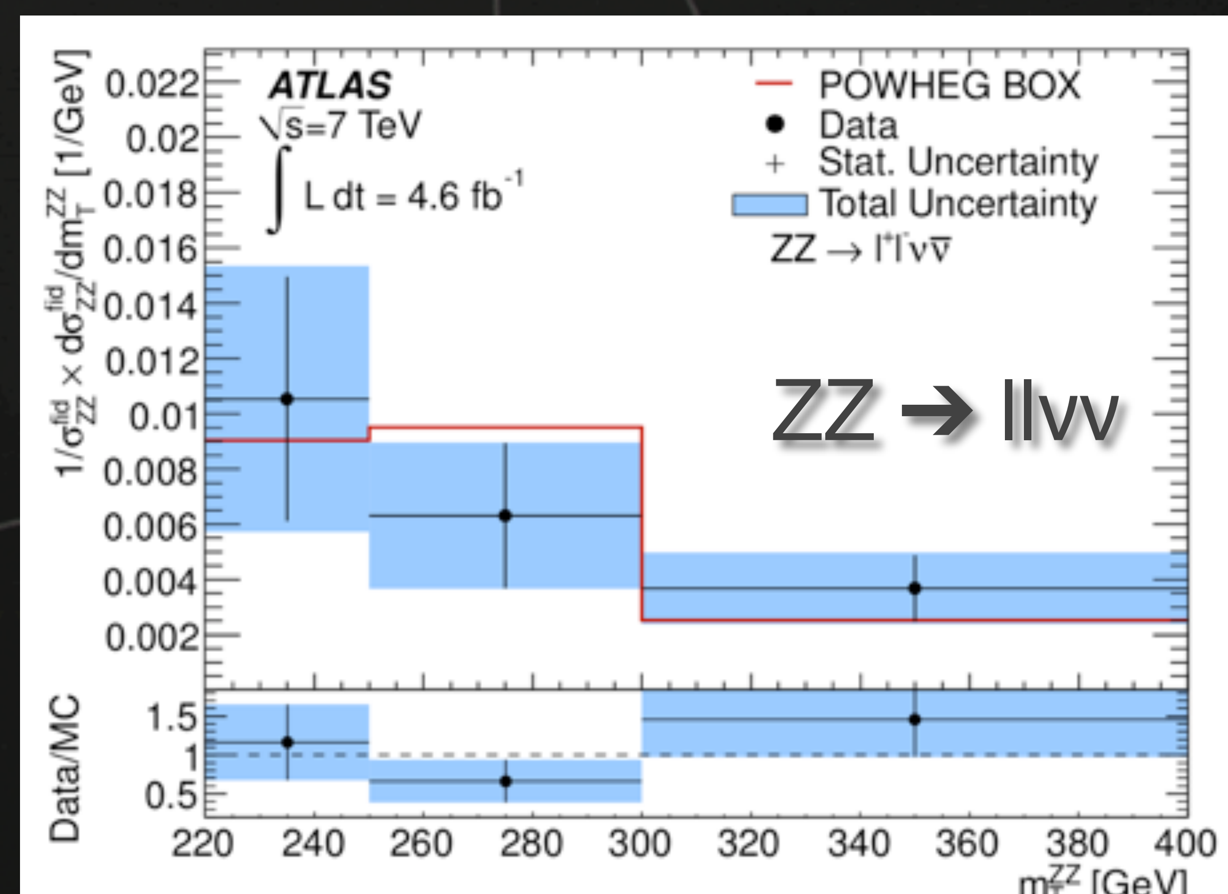


Fiducial differential cross sections









Triple Gauge Couplings (WWZ and WWγ)

The effective Lagrangian for model-independent charged triple gauge couplings can be expressed as:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$

$V = Z$ or γ, $g_{WW\gamma} = -e$, and $g_{WWZ} = -e\cot(\theta_W)$

In the Standard Model: $(g_1^V, k_V, \lambda^V) = (1,1,0)_{SM}$

Set limits on: $\Delta g_1^V = g_1^V - 1$, $\Delta k^V = k_V - 1$, λ^V

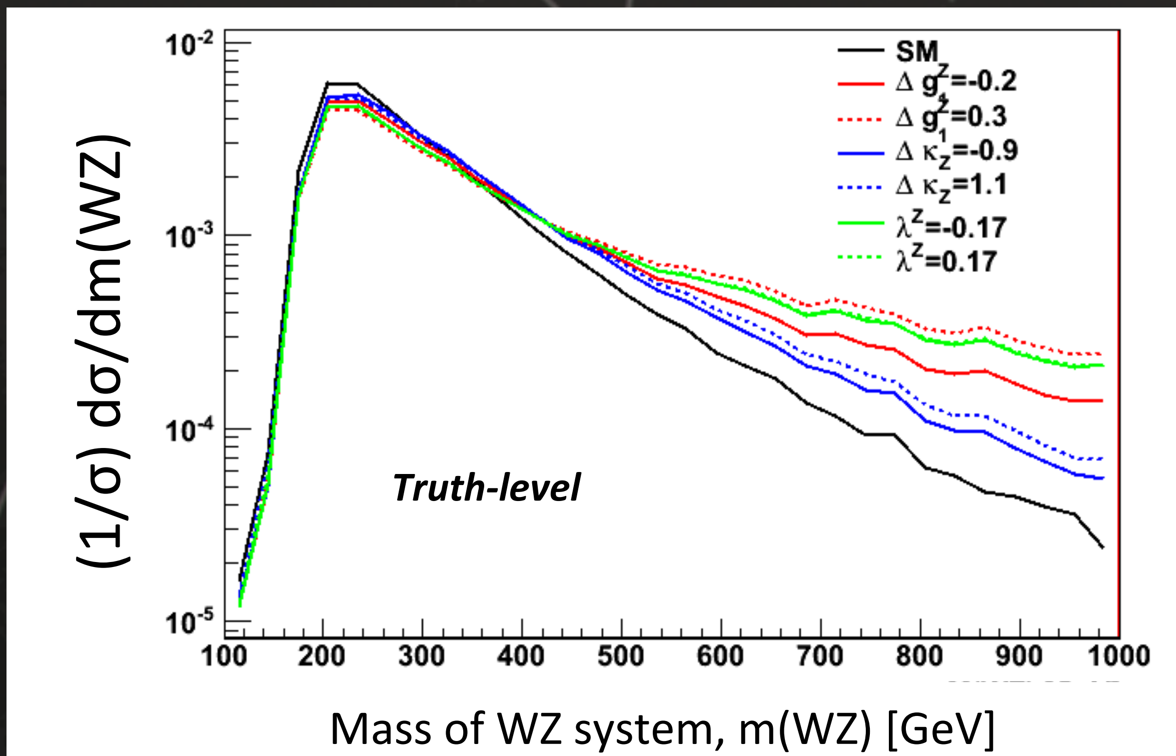
Introduce arbitrary cut-off scale Λ to enforce unitarity

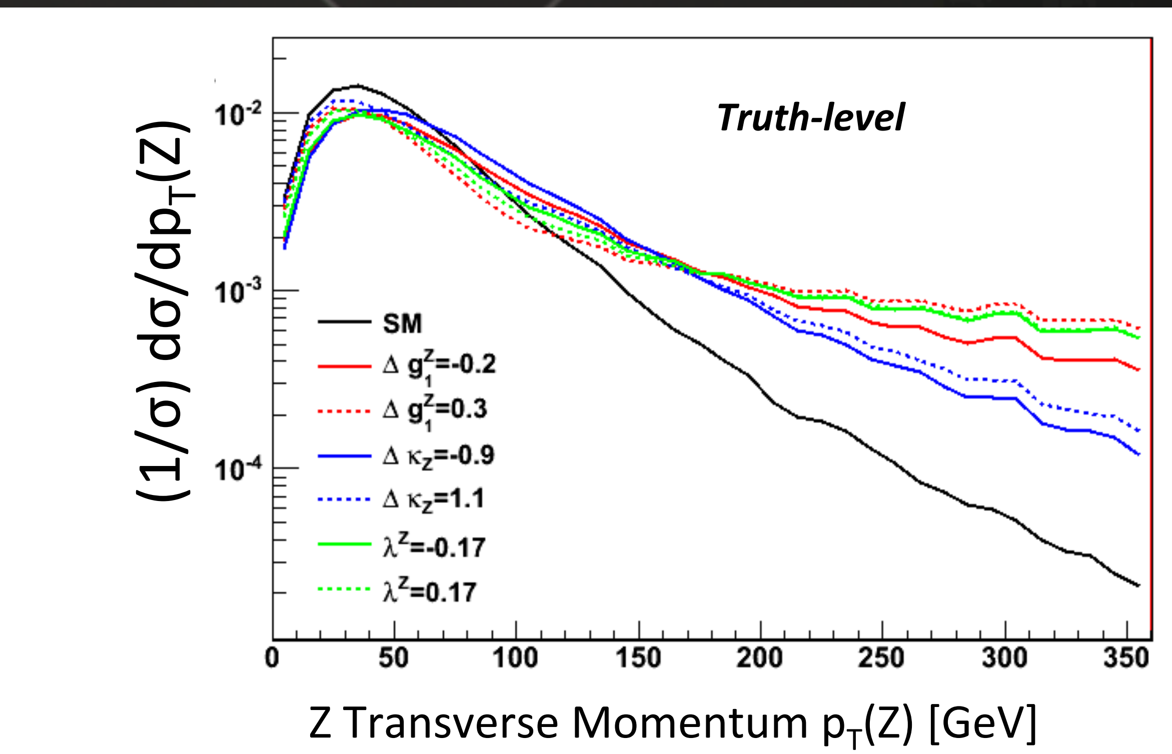
$$\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$$

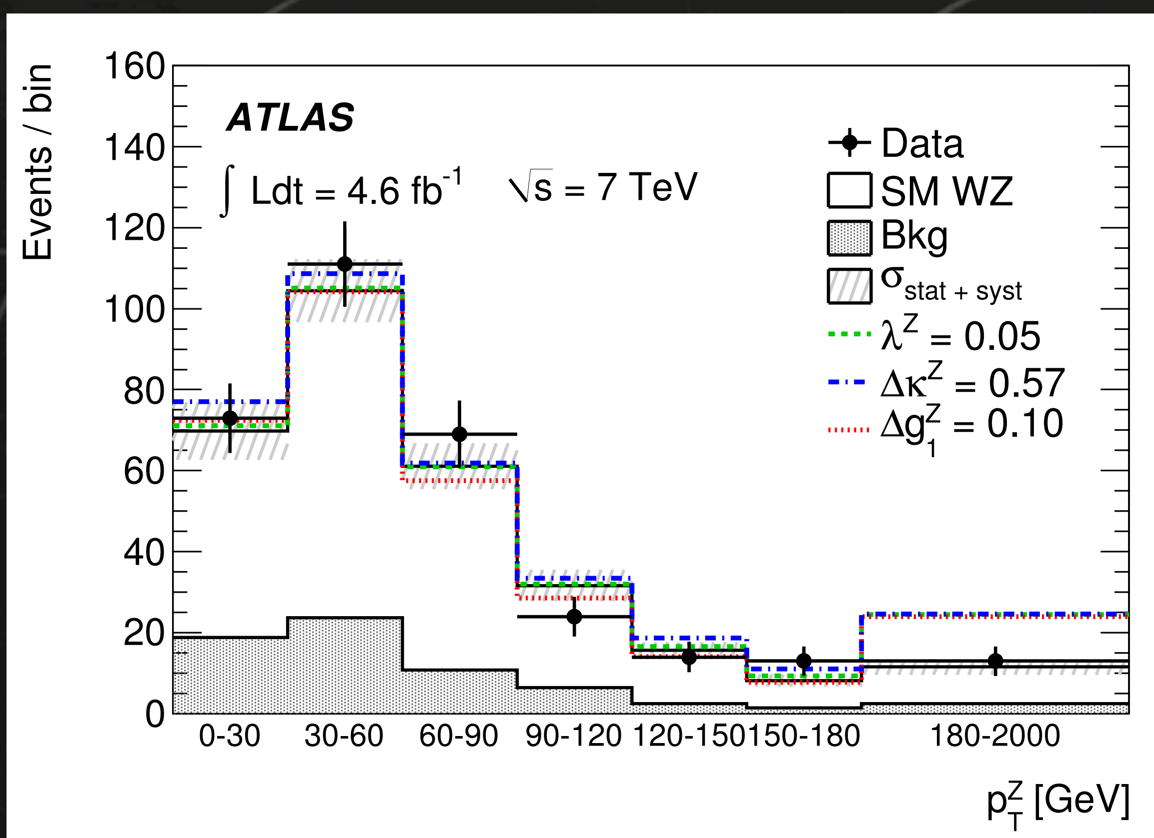
Cross section with aTGCs has strong energy dependence

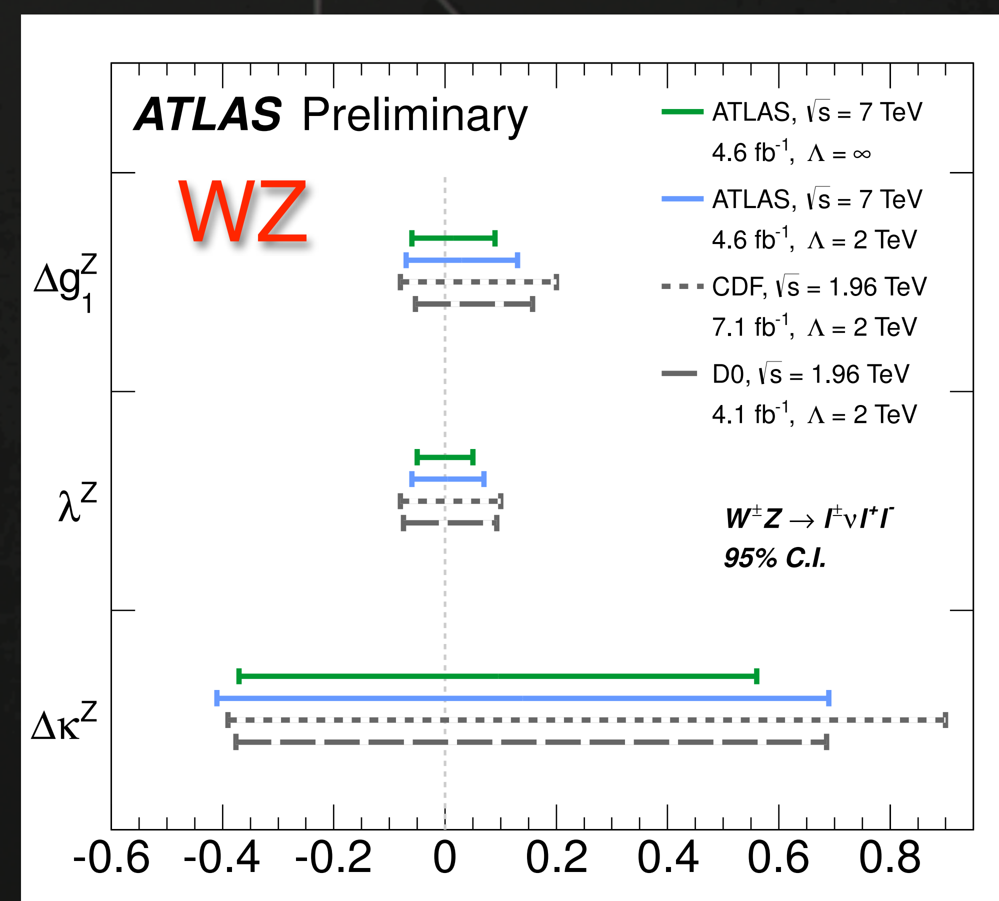
- k_Z proportional to $\sqrt{\hat{s}}$; g_1^Z and $\lambda^Z \sim \hat{s}$
- ➔ measure differential cross-section sensitive to $\sqrt{\hat{s}}$

Anomalous TGC effect in WZ production



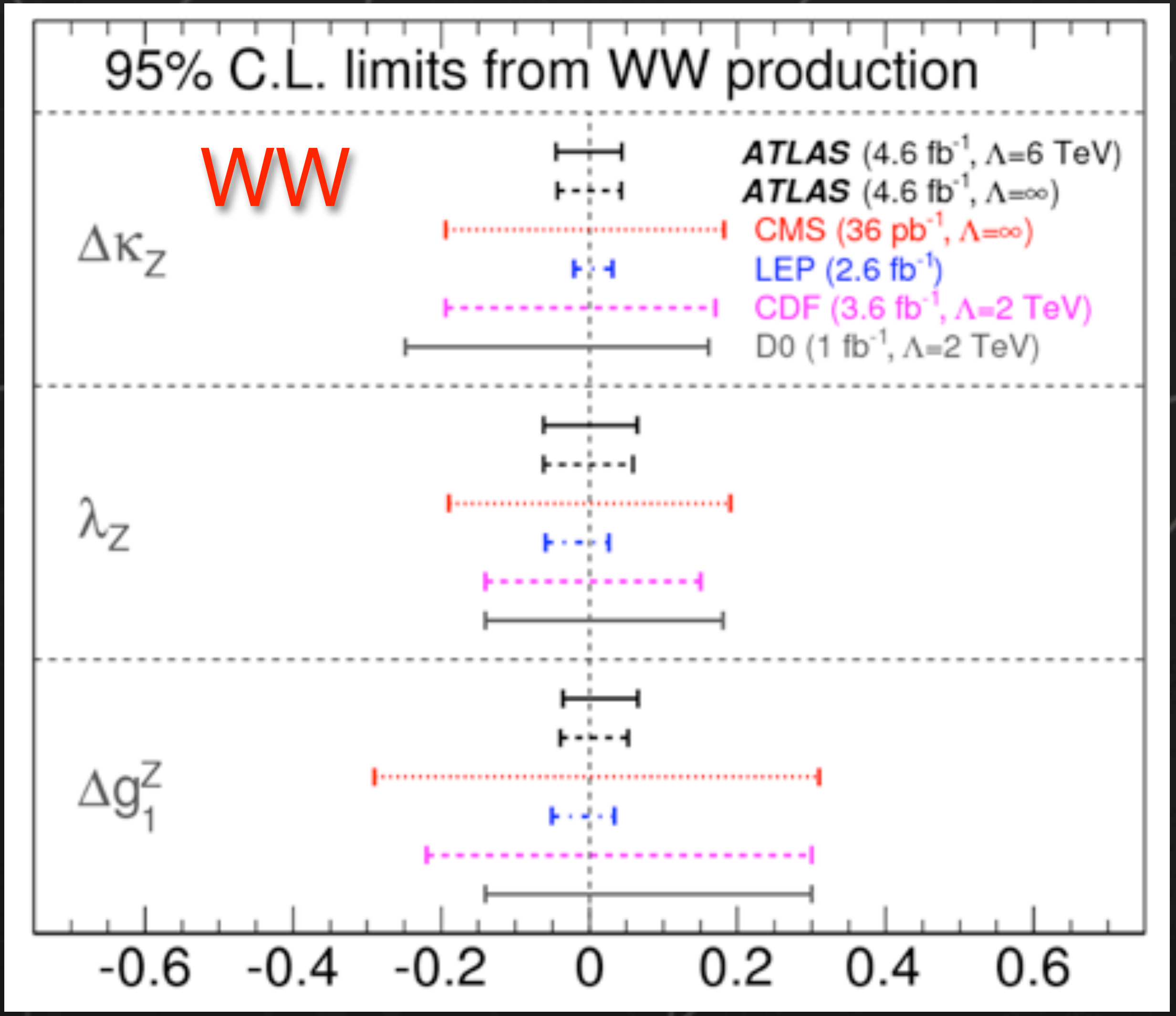




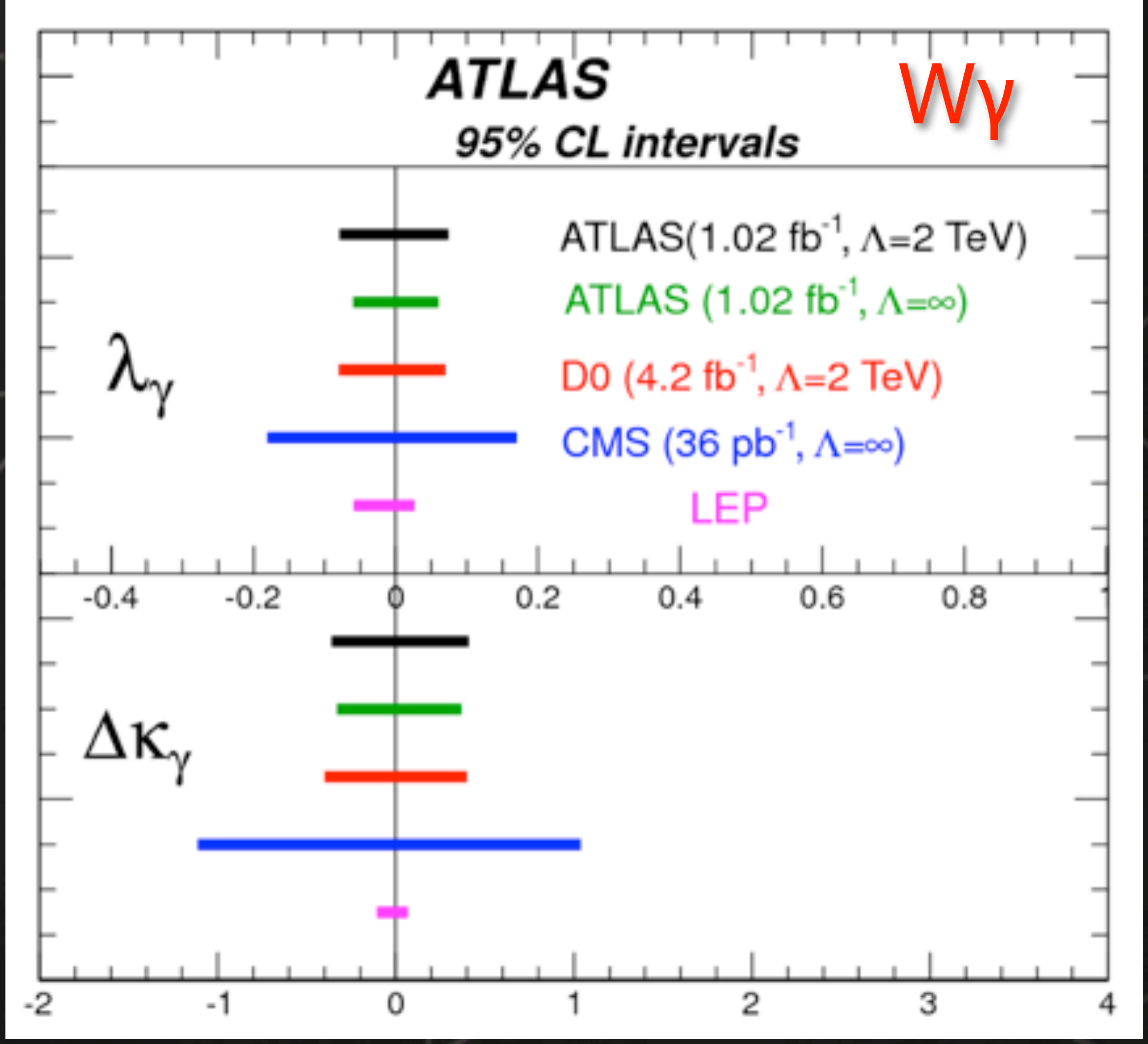


(using $P_T(Z)$ distribution)

Triple Gauge Couplings (WWZ and WWγ)



(using $P_T(l)$ distribution)



(from $P_T(\gamma)$ distribution)

neutral Triple Gauge Couplings (ZZZ and ZZγ)

- Possible vertices using an effective Lagragian

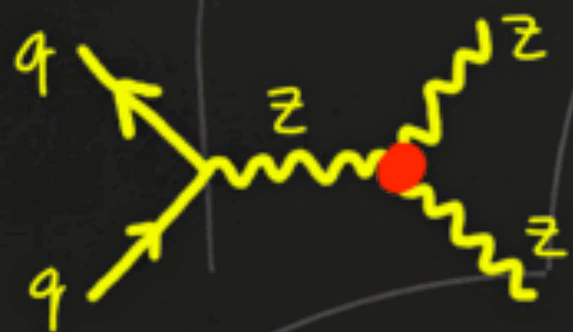
$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left[f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta \right]$$

CP-violating — CP-conserving

Scale dependent form-factors

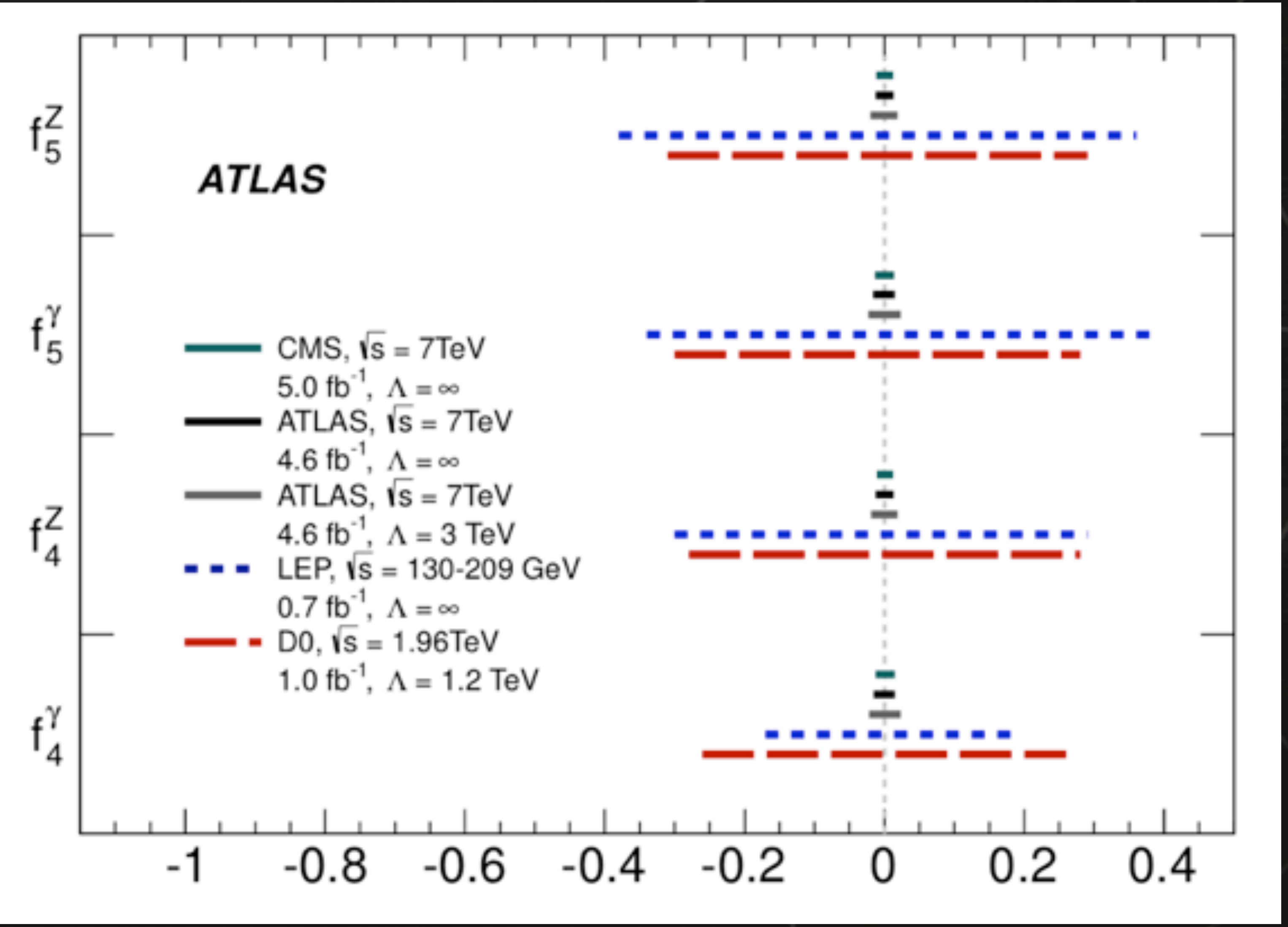
$$\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$$

with cutoff scale Λ



ZZZ, ZZγ

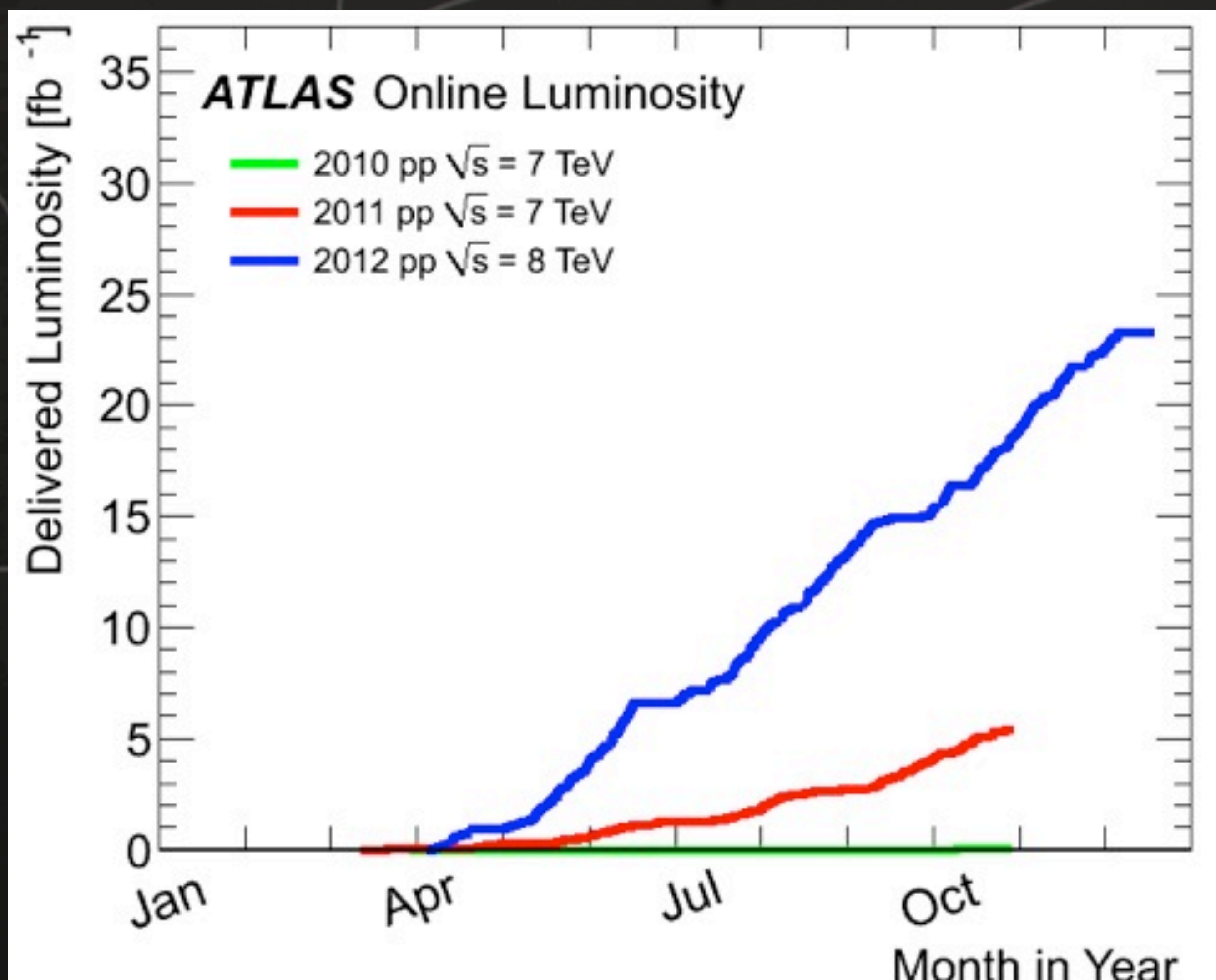
$(f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma) = (0,0,0,0)_{SM}$

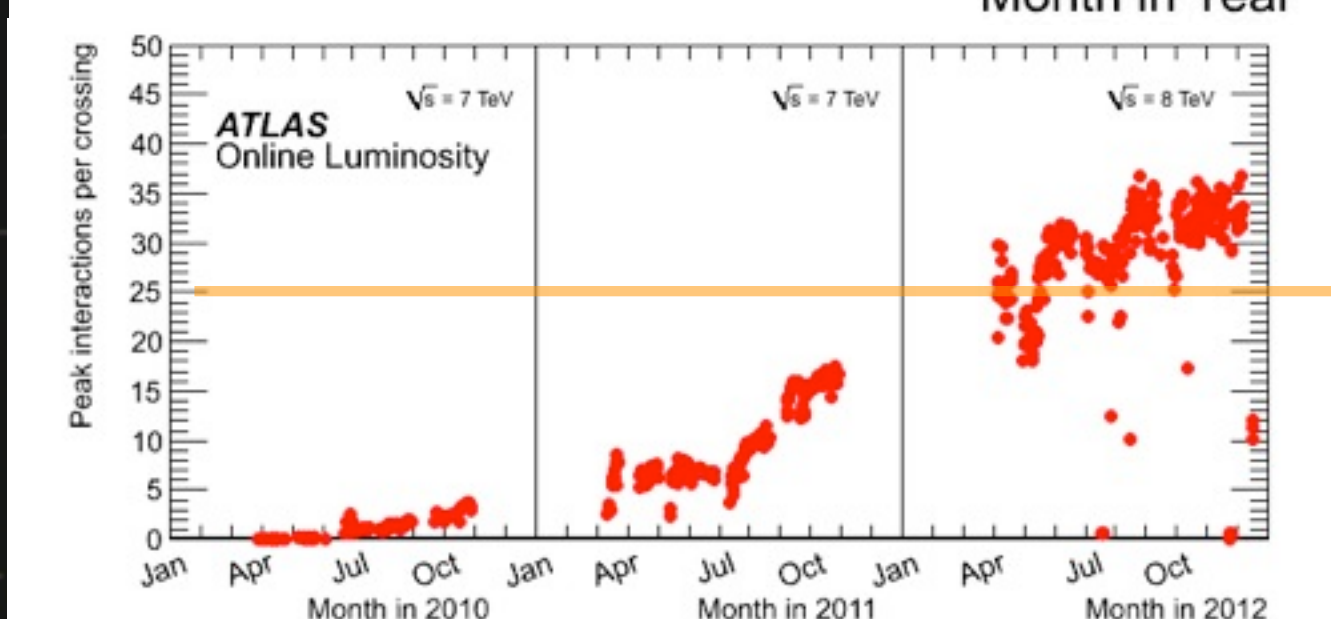


(using $P_T(Z)$ distribution)

Three years at the Energy Frontier

- Remarkable LHC operation….





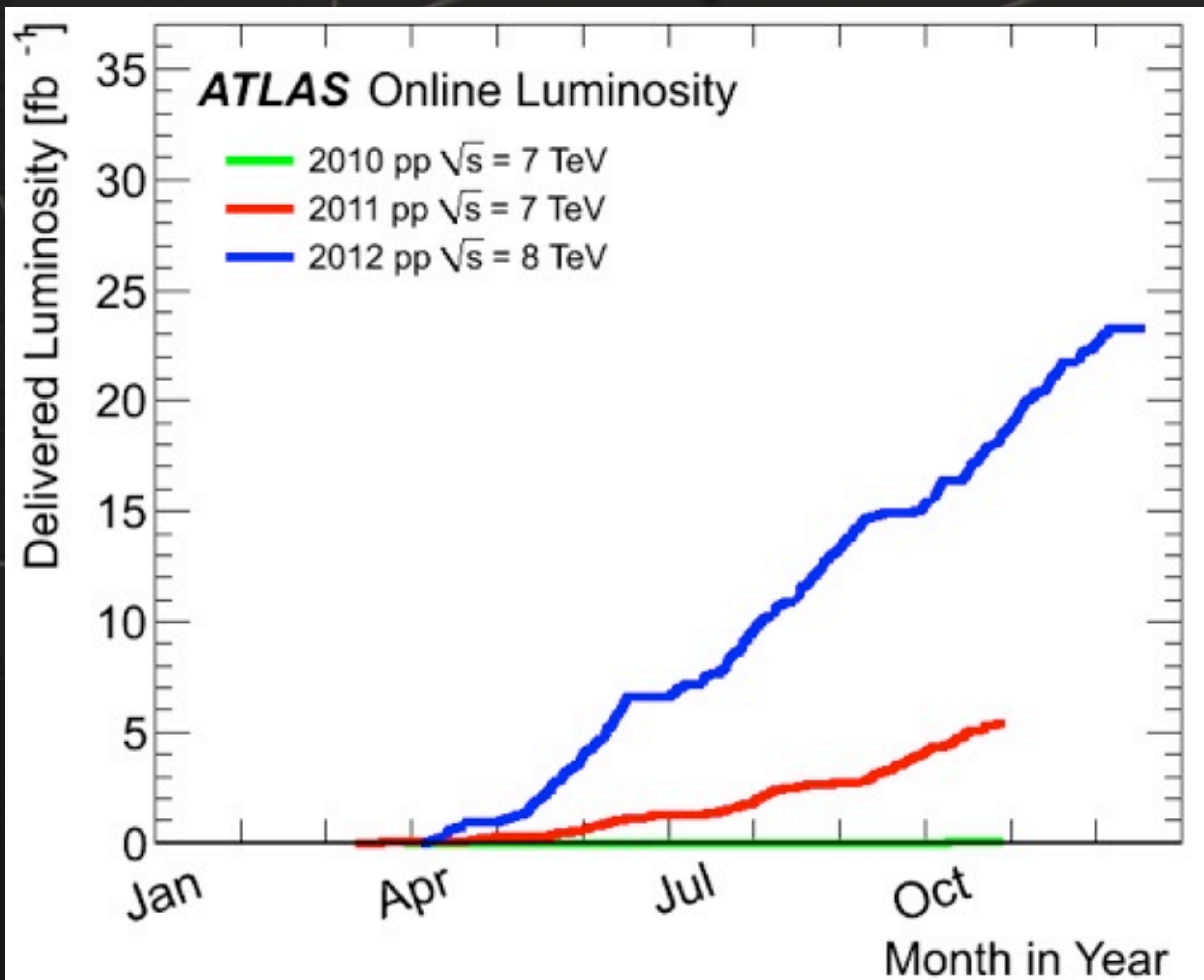
2010
0.05 fb^{-1}
at 7 TeV

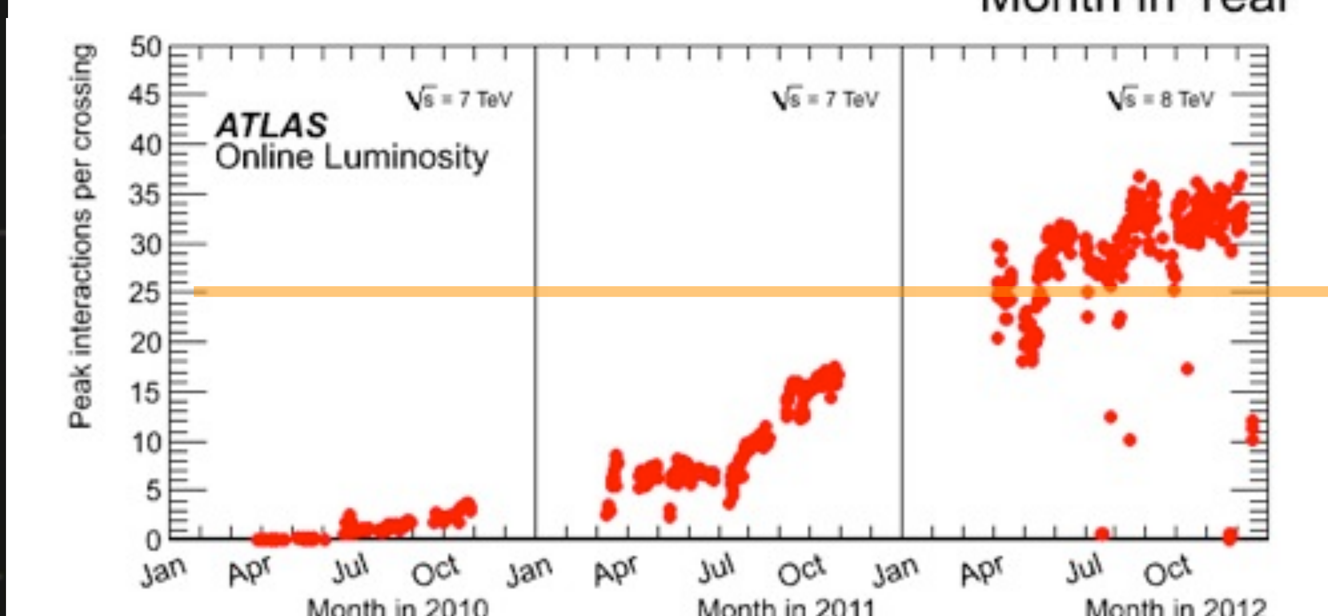
O(2) pile-up events
150 ns bunch spacing

Designed pile-up value
(expected at $L=10^{34}$)

Three years at the Energy Frontier

- Remarkable LHC operation….





2011
5.6 fb^{-1}
at 7 TeV

O(10) pile-up events
50 ns bunch spacing

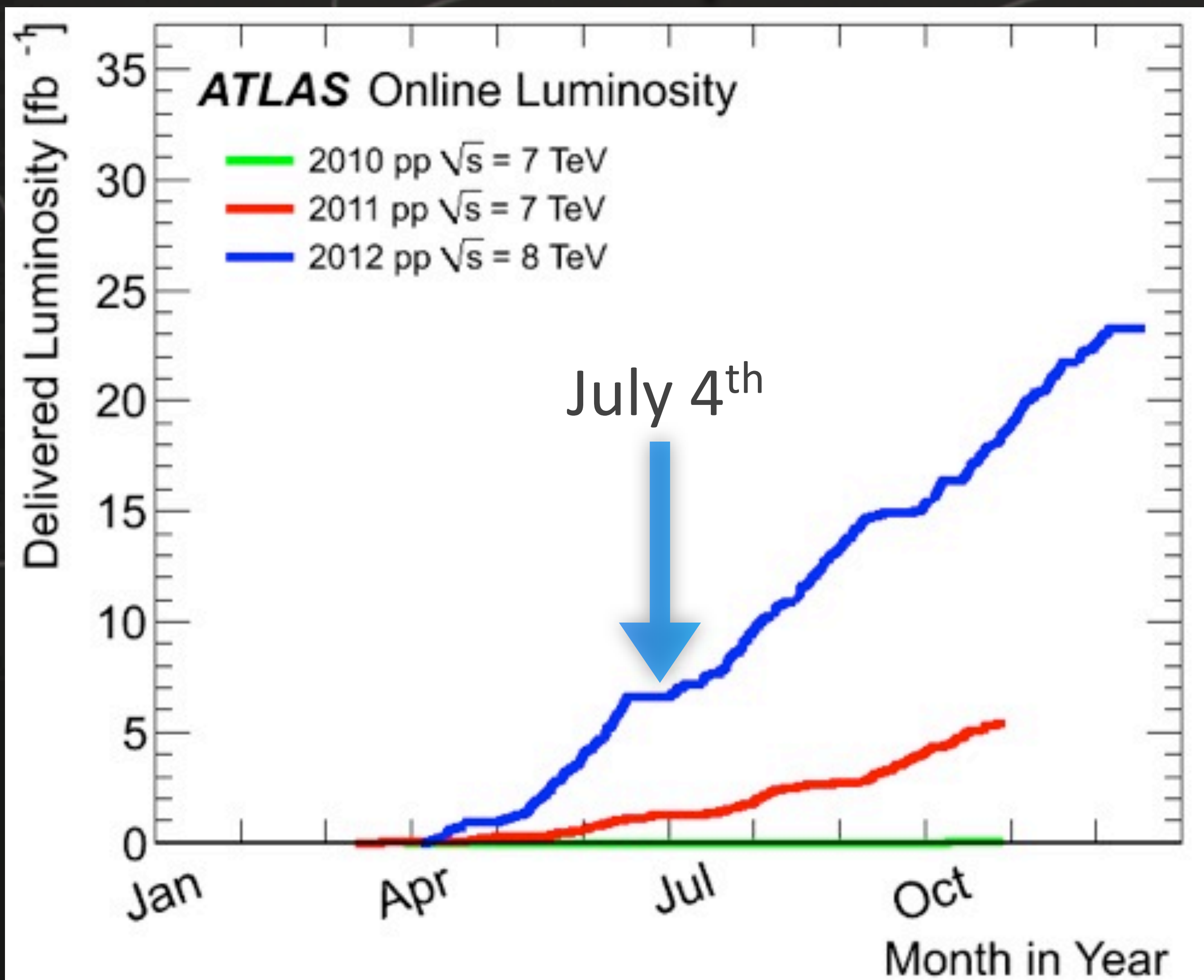
2010
0.05 fb^{-1}
at 7 TeV

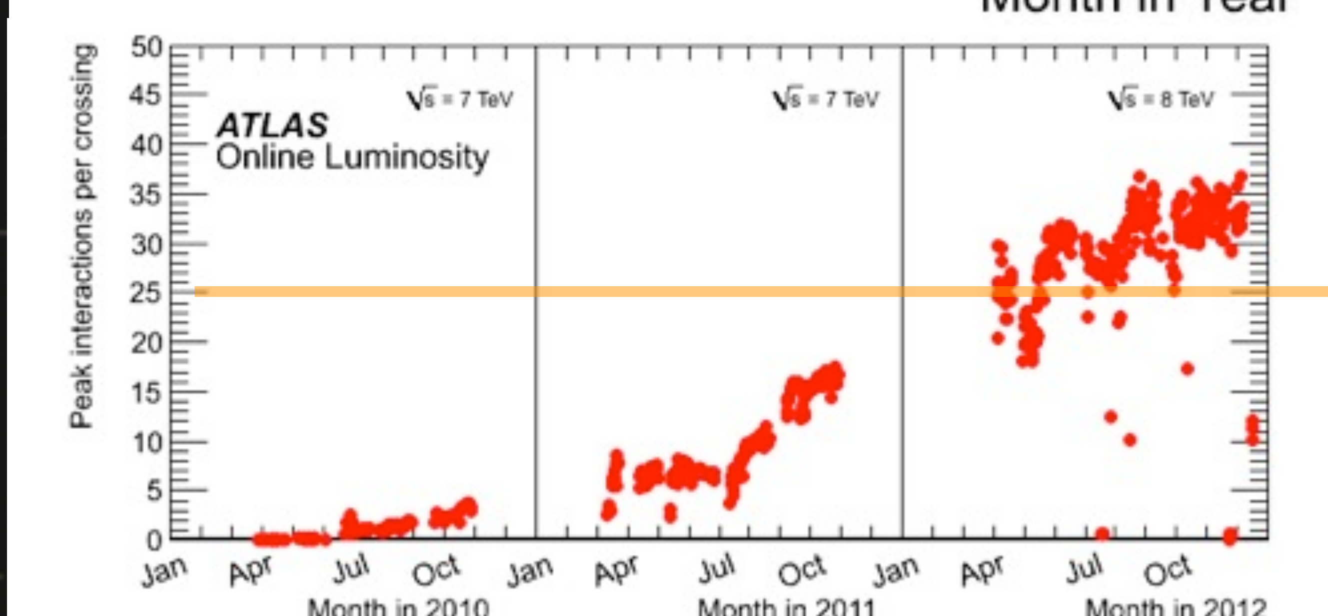
O(2) pile-up events
150 ns bunch spacing

Designed pile-up value
(expected at $L=10^{34}$)

Three years at the Energy Frontier

- Remarkable LHC operation….





2012
23 fb^{-1}
at 8 TeV

O(20) pile-up events
50 ns bunch spacing

2011
5.6 fb^{-1}
at 7 TeV

O(10) pile-up events
50 ns bunch spacing

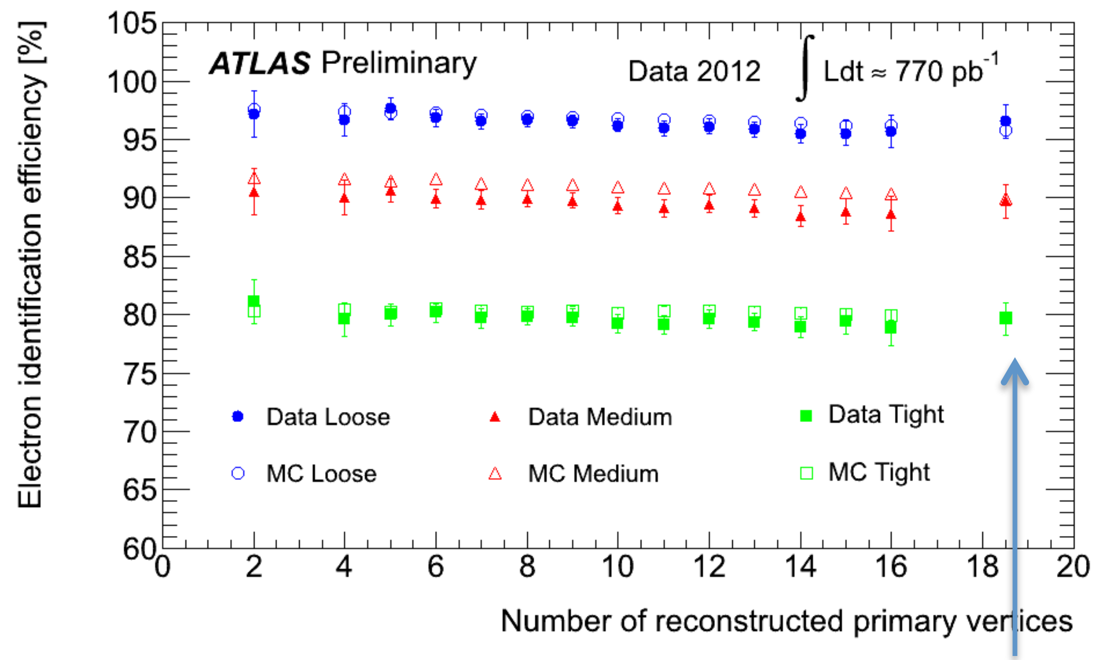
2010
0.05 fb^{-1}
at 7 TeV

O(2) pile-up events
150 ns bunch spacing

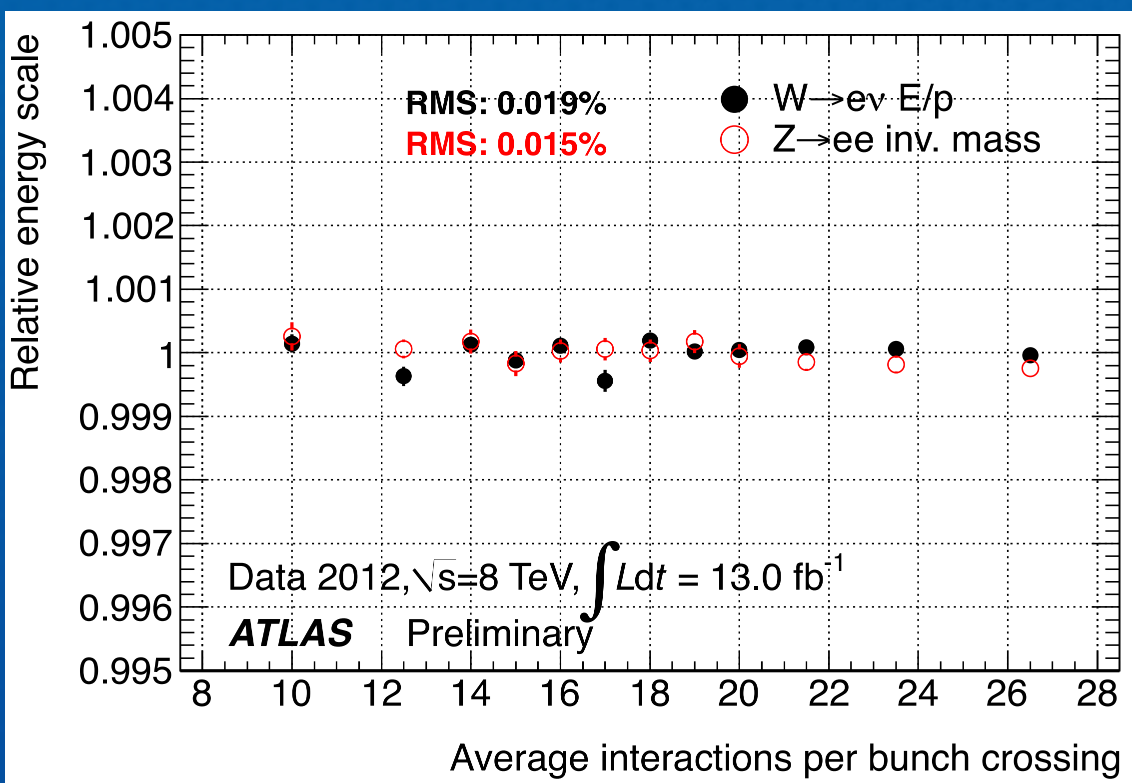
Designed pile-up value
(expected at $L=10^{34}$)

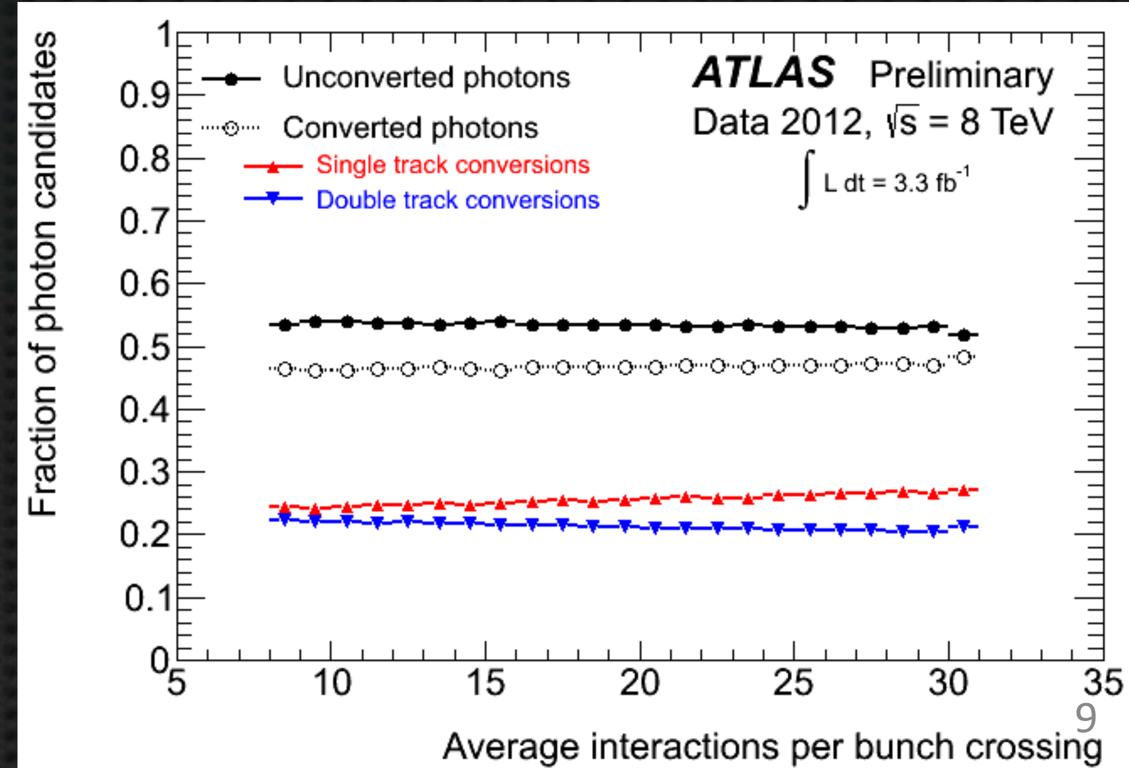
Reconstruction versus pileup

Robust electron reconstruction efficiency

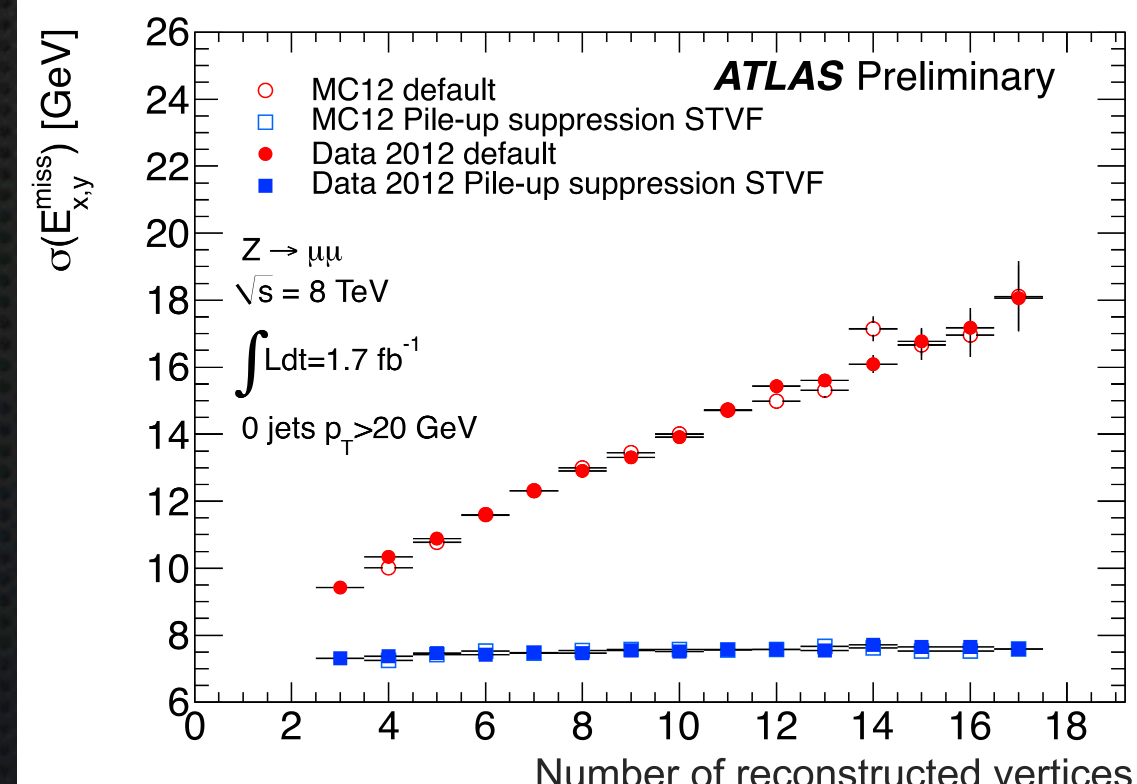


~30 Pile-up events
(60% reconstructed PV)





E_T^{miss} resolution in $Z \to \mu\mu$ events with and without soft-term vertex fraction correction



Re-establishing the SM at LHC

Tevatron timeline

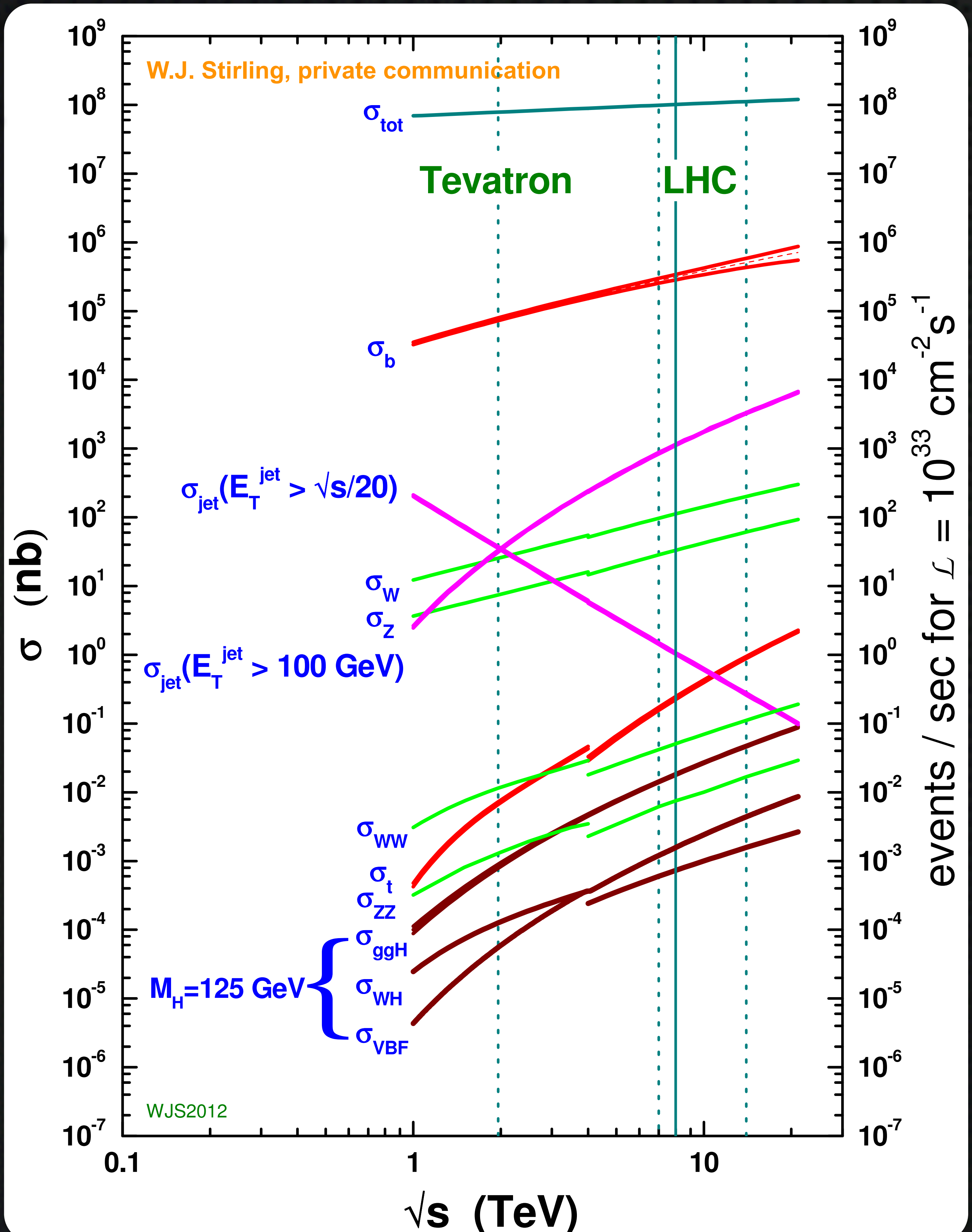
Particles$_{charged}$: 1988

jets$_{inclusive}$: 1989

(*) **W**: 1988
Z: 1988

Top: 1994
WW: 2005
WZ: 2007
ZZ: 2008

(*) Discovered at CERN in 1983 by UA1 and UA2



ATLAS timeline

Apr 2010

jets: Sep 2010

W: May 2010
Z: Jun 2010

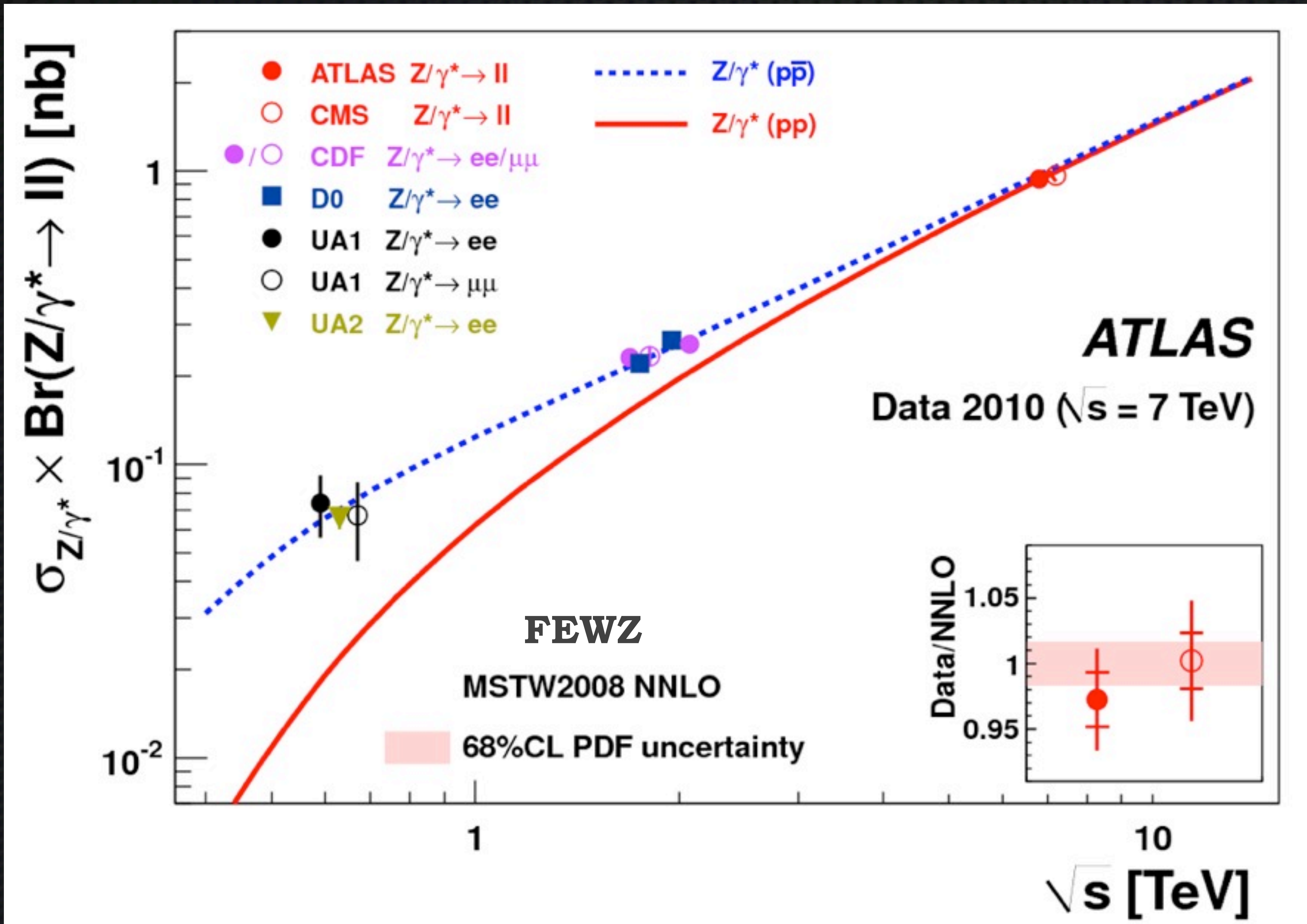
Top: Jul 2010

WW: Dec 2010
WZ: Mar 2011
ZZ: Jul 2011

H: July 4, 2012?

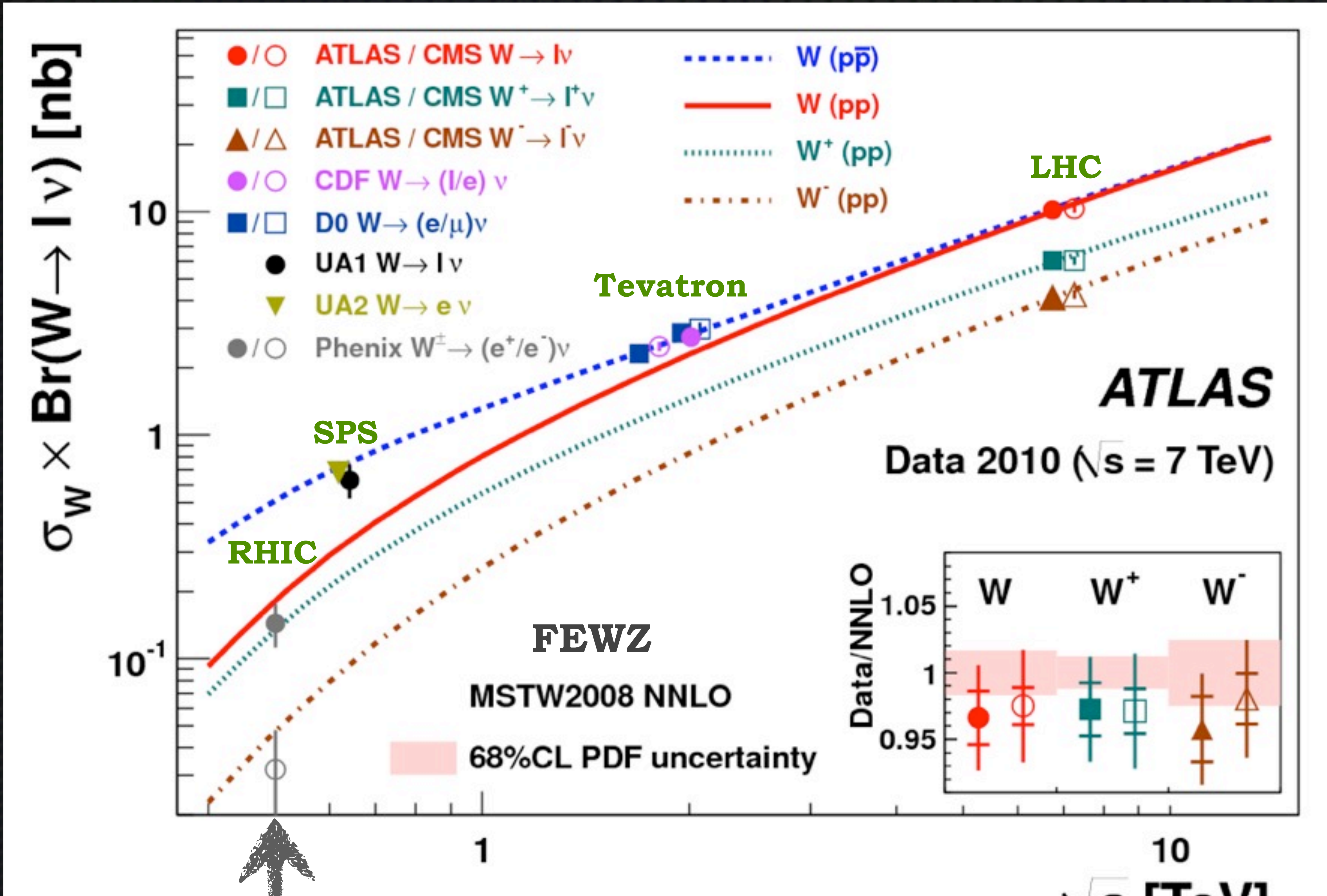
Z inclusive cross section

Phys. Rev. D85 (2012) 072004



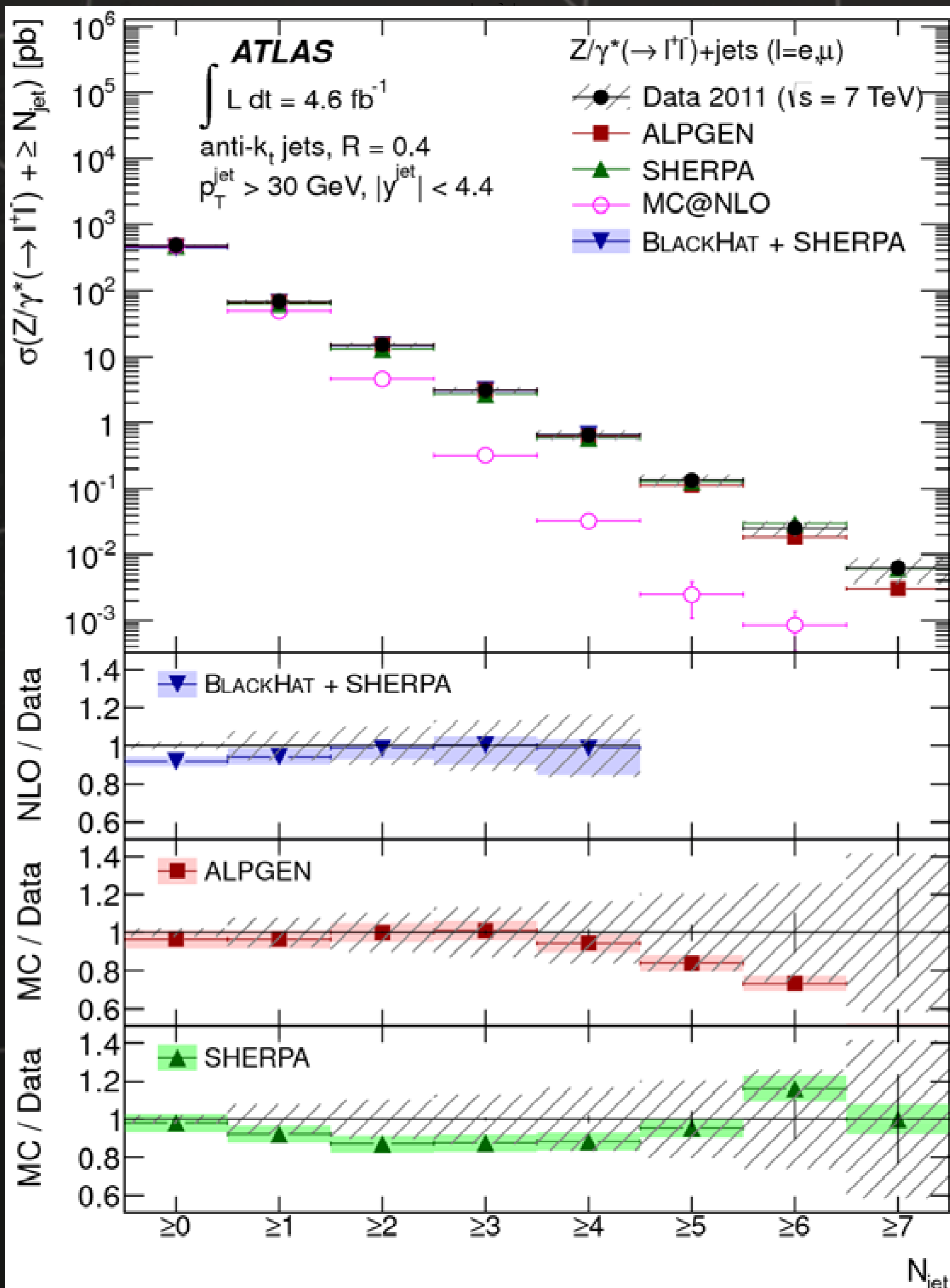
W inclusive cross section

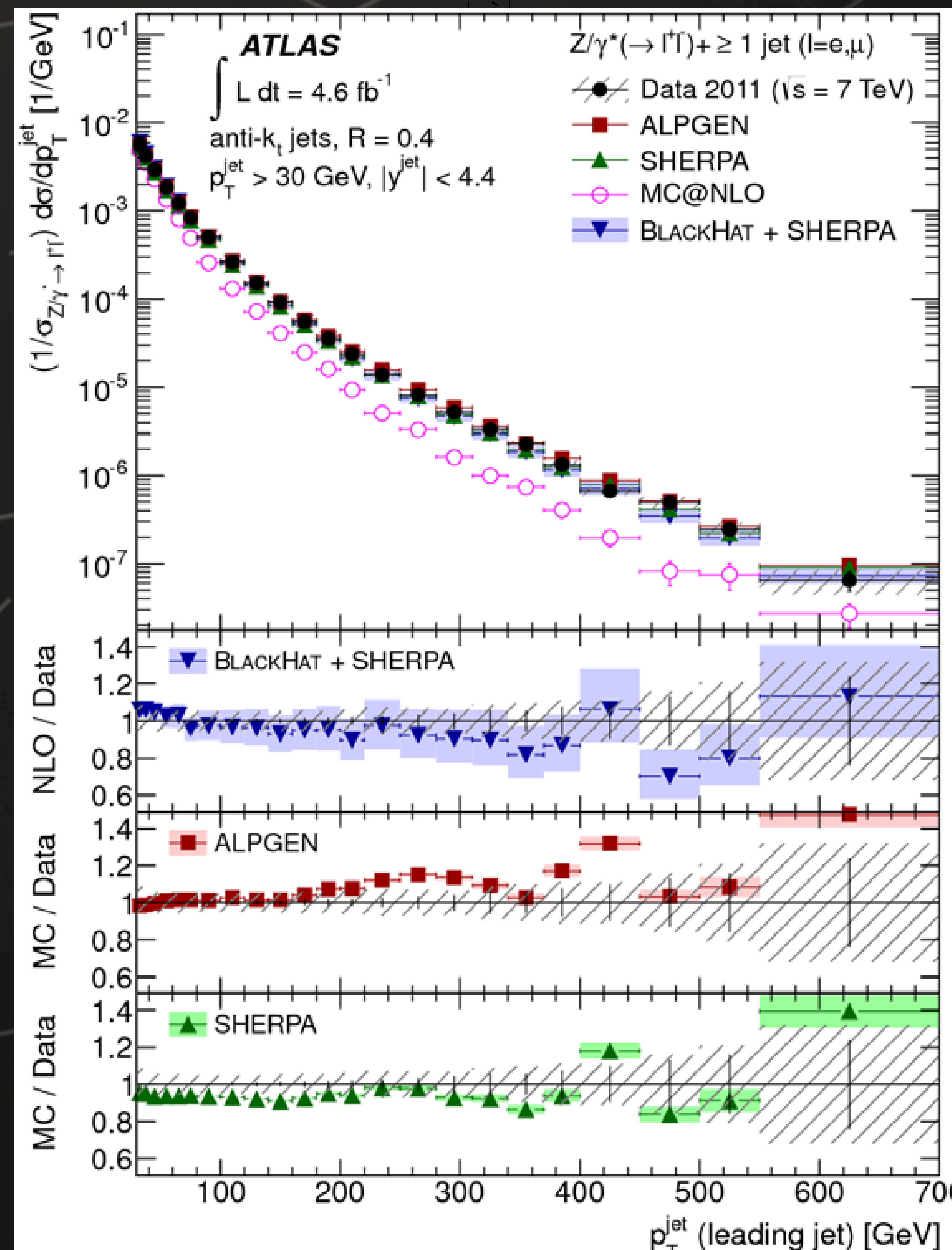
Phys. Rev. D85 (2012) 072004



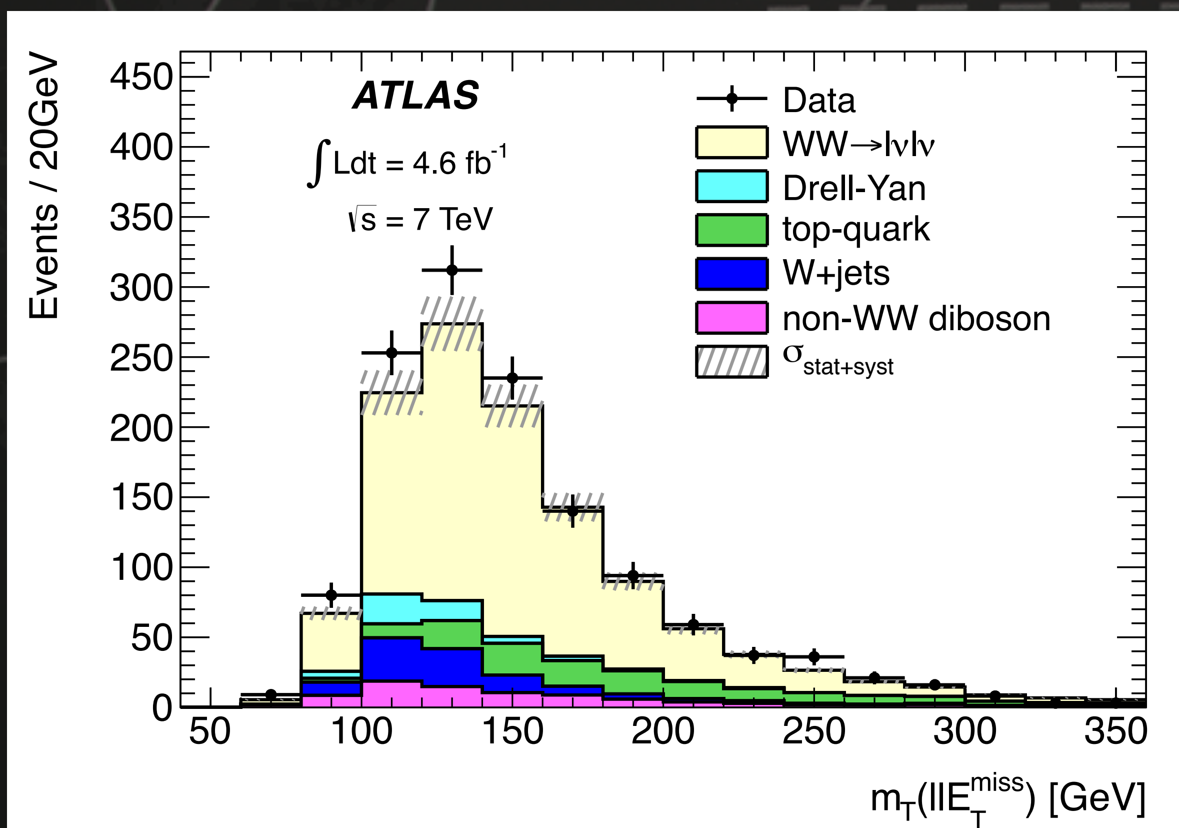
(First measurement in pp collisions)

Measurements of Z + jets

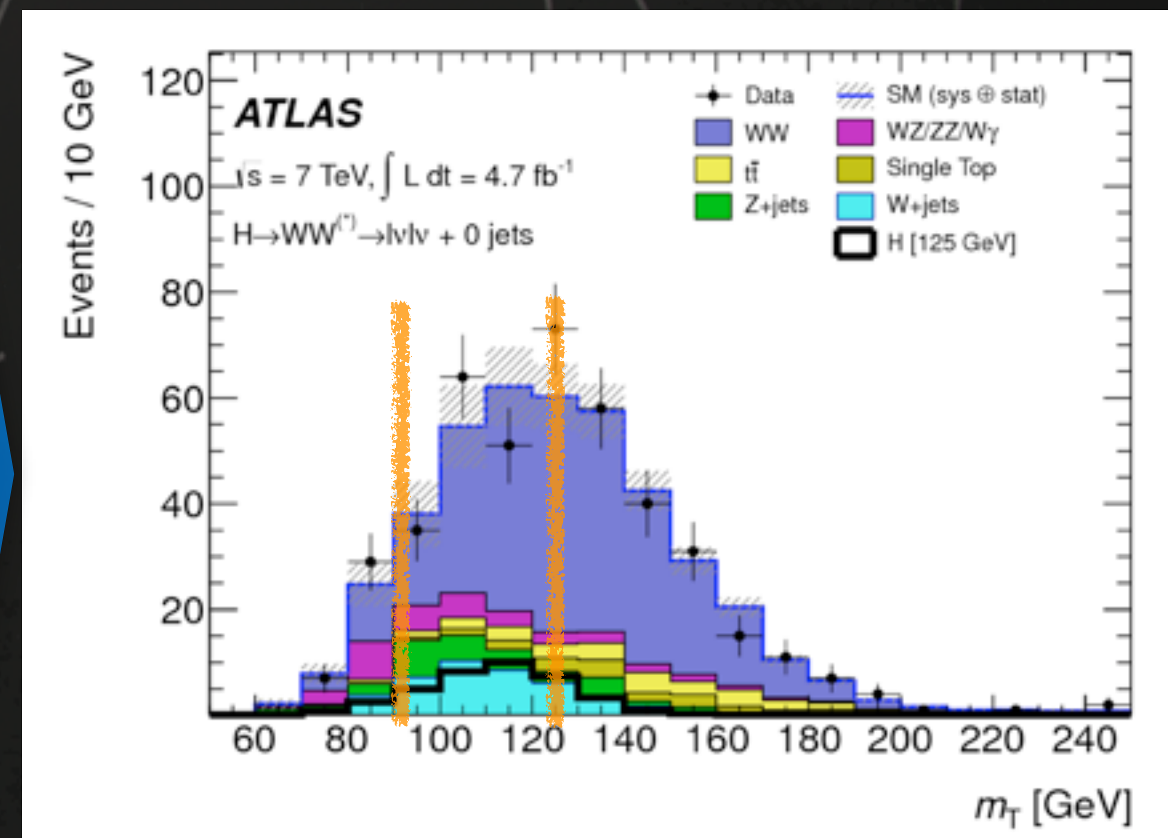




From SM WW to H --> WW



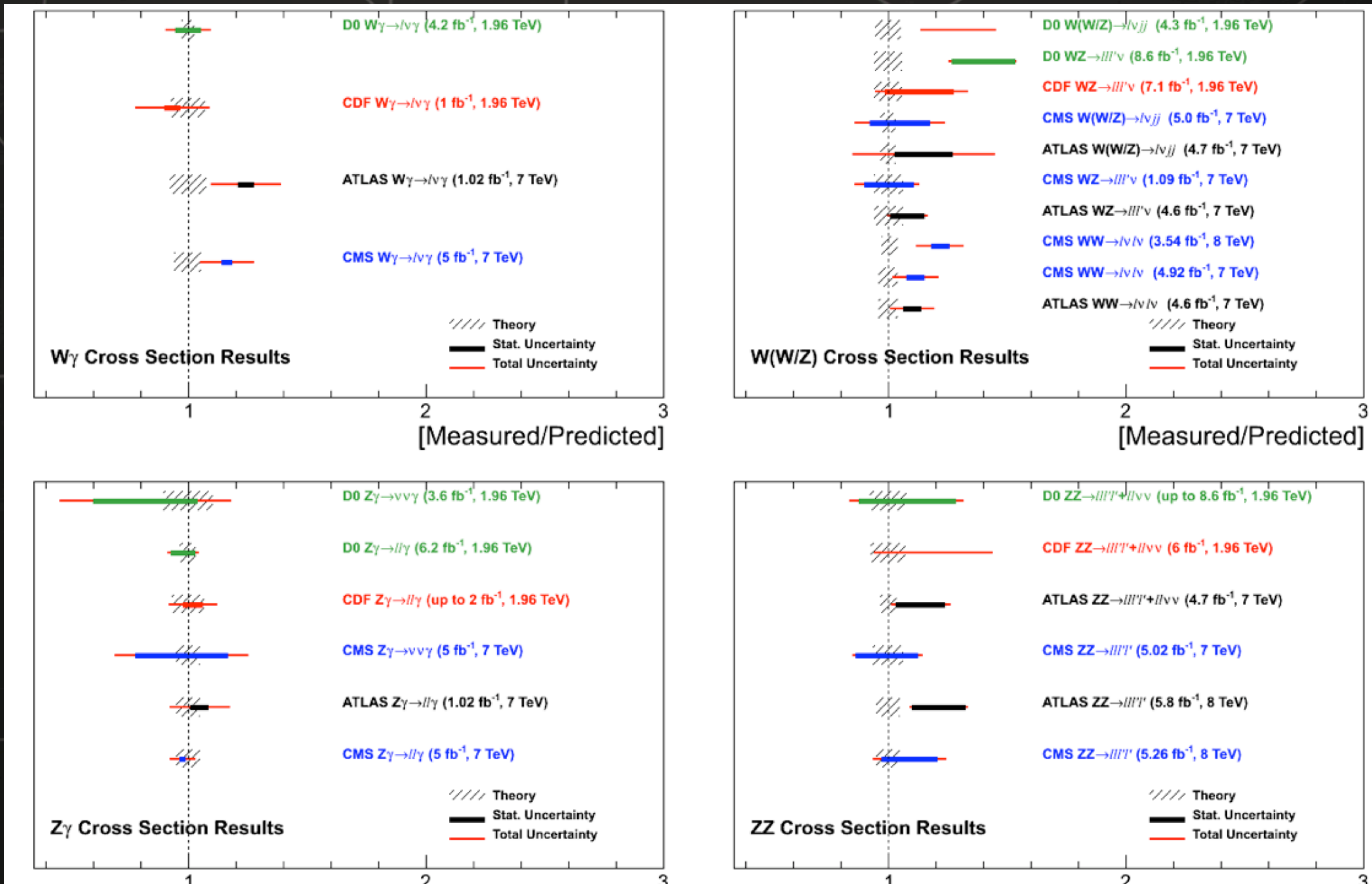
Higgs contribution: 3%



(note: 7 TeV Higgs analysis for proper comparison)

Further kinematic cuts

Summary of diboson cross section measurements

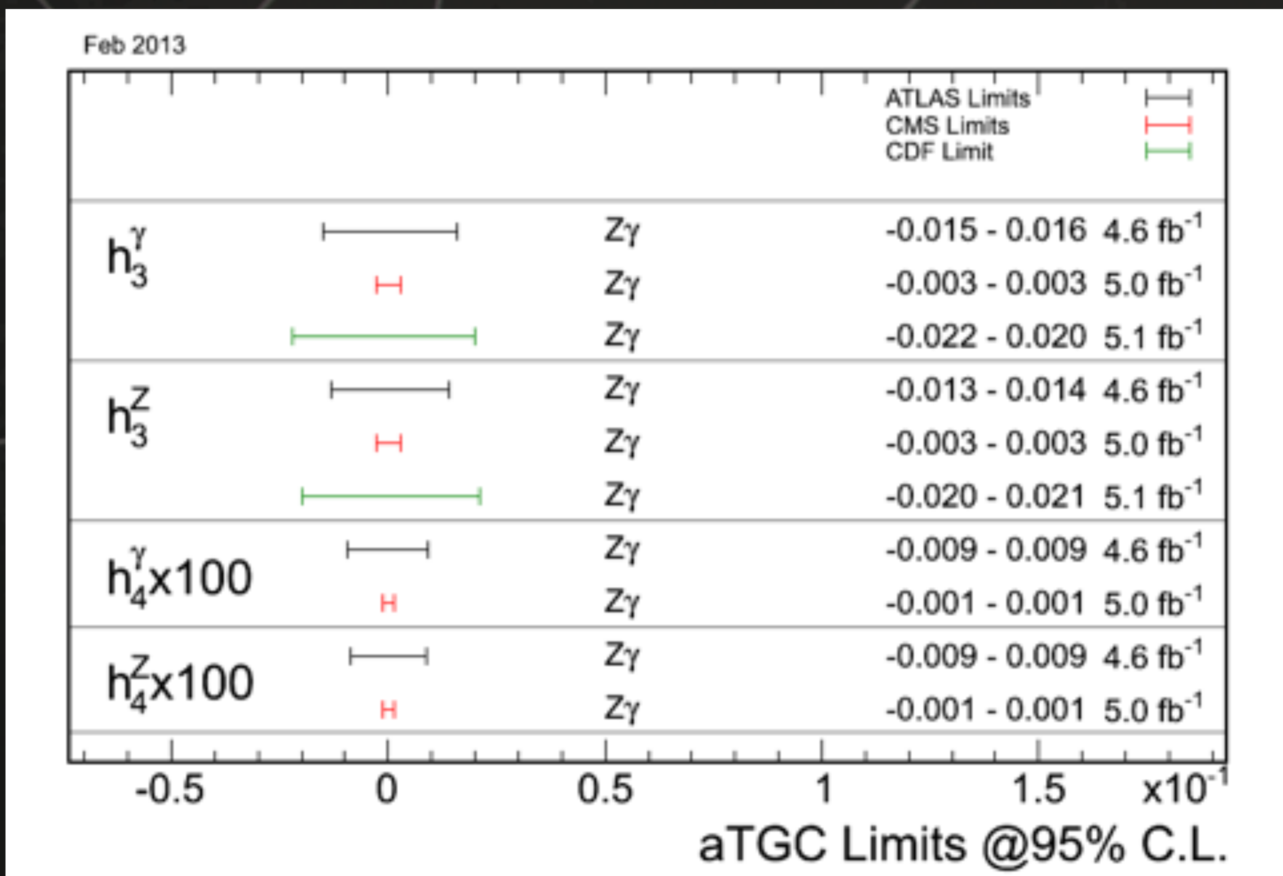


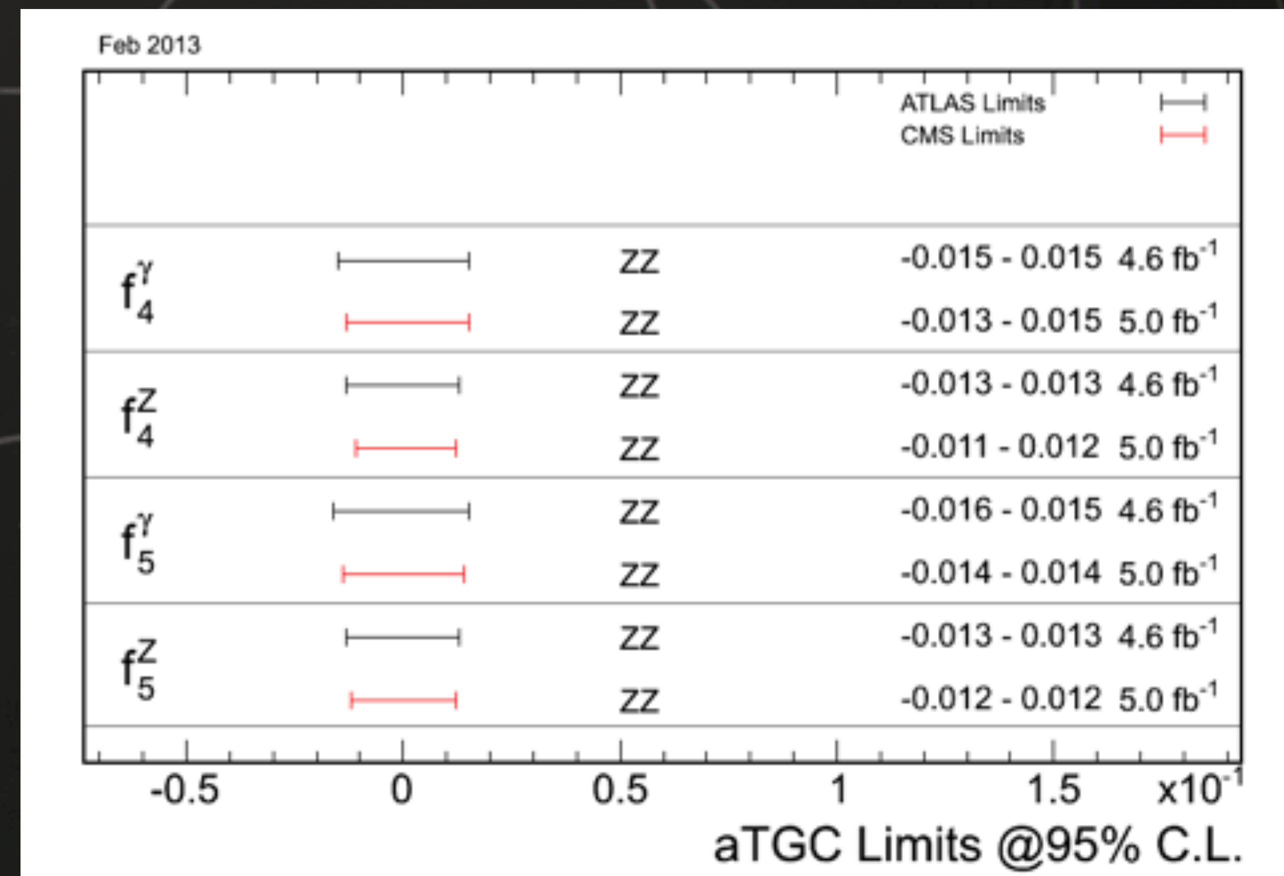
Dave Evans, HCP 2012

16

Anomalous triple gauge couplings

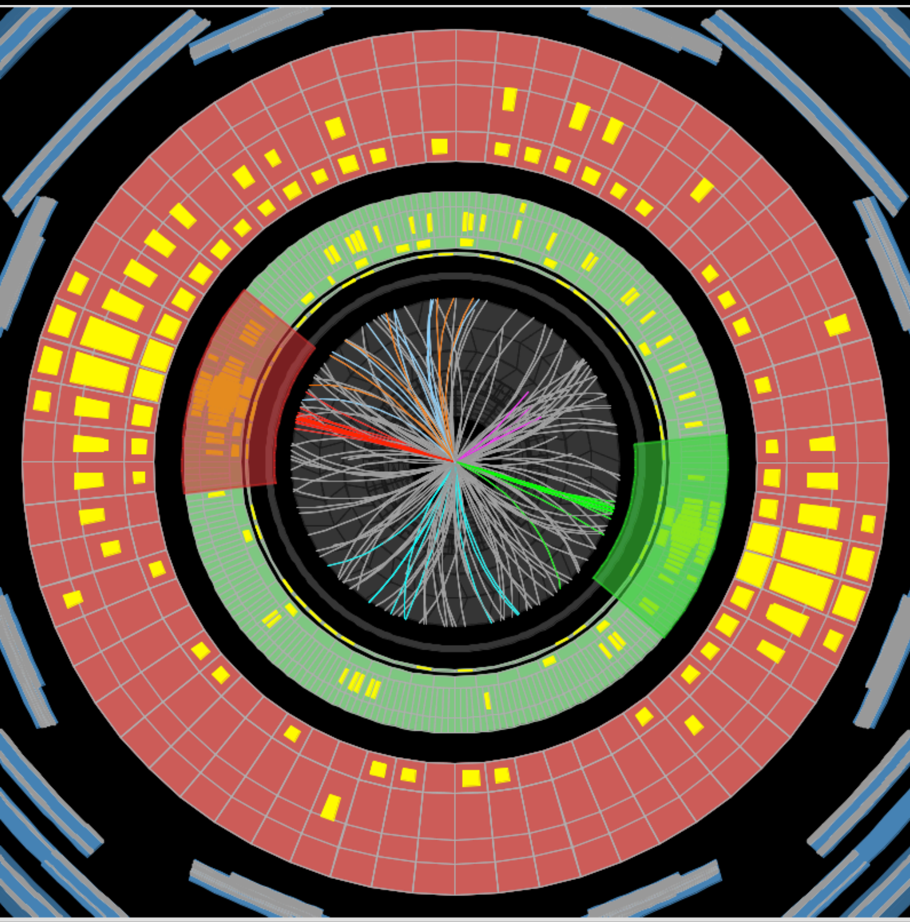
- Limits on 8 anomalous **neutral couplings** accessible in Zγ and ZZ channels

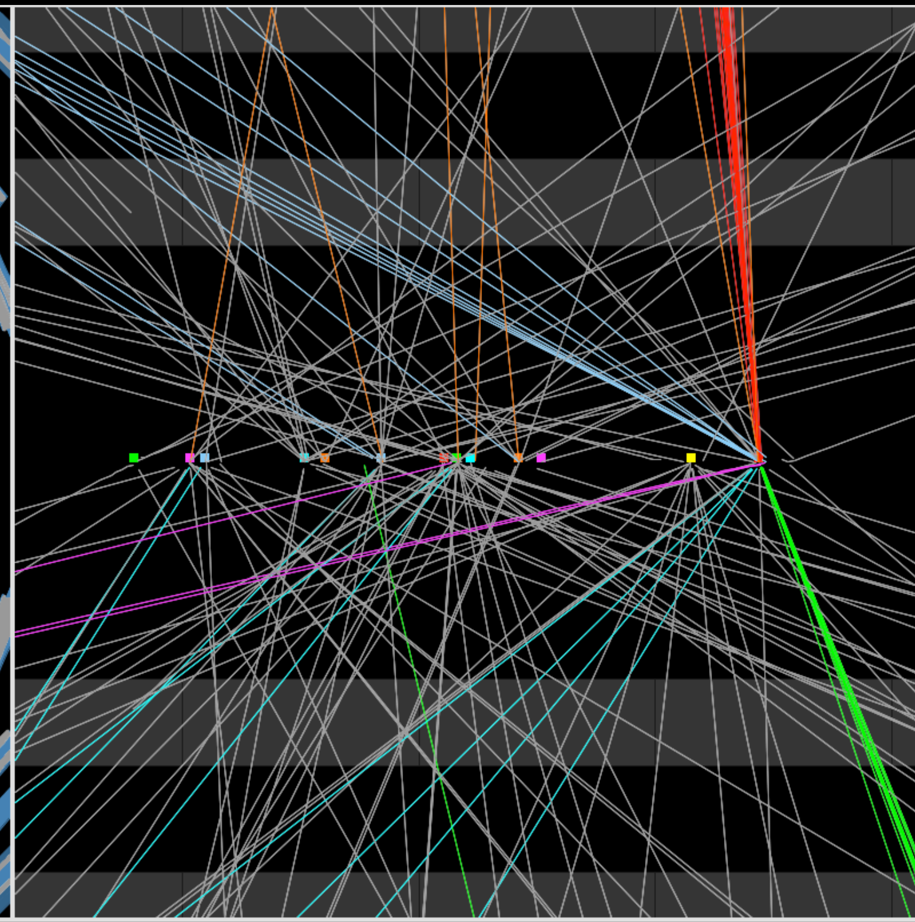




- Zγ limits (Zγ ➔ ννγ):
  - ATLAS fits events with $E_T(\gamma)$ > 100 GeV
  - CMS uses $E_T(\gamma)$ > 400 GeV
- No deviations from the SM have been been observed
  - LHC limits already at the level of LEP limits

The highest-mass central dijet very well measured event. Two central jets with invariant mass of 4.7 TeV

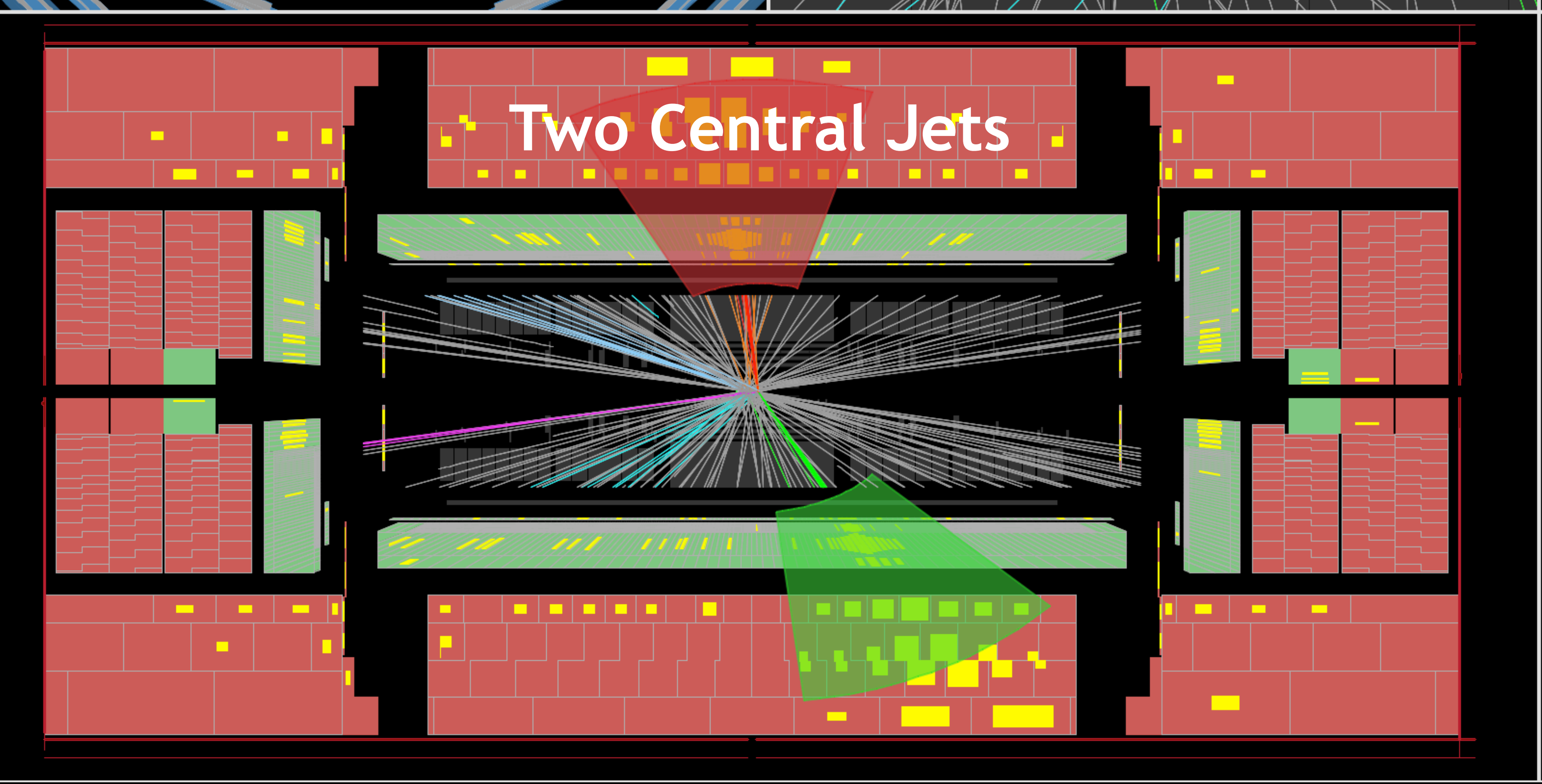


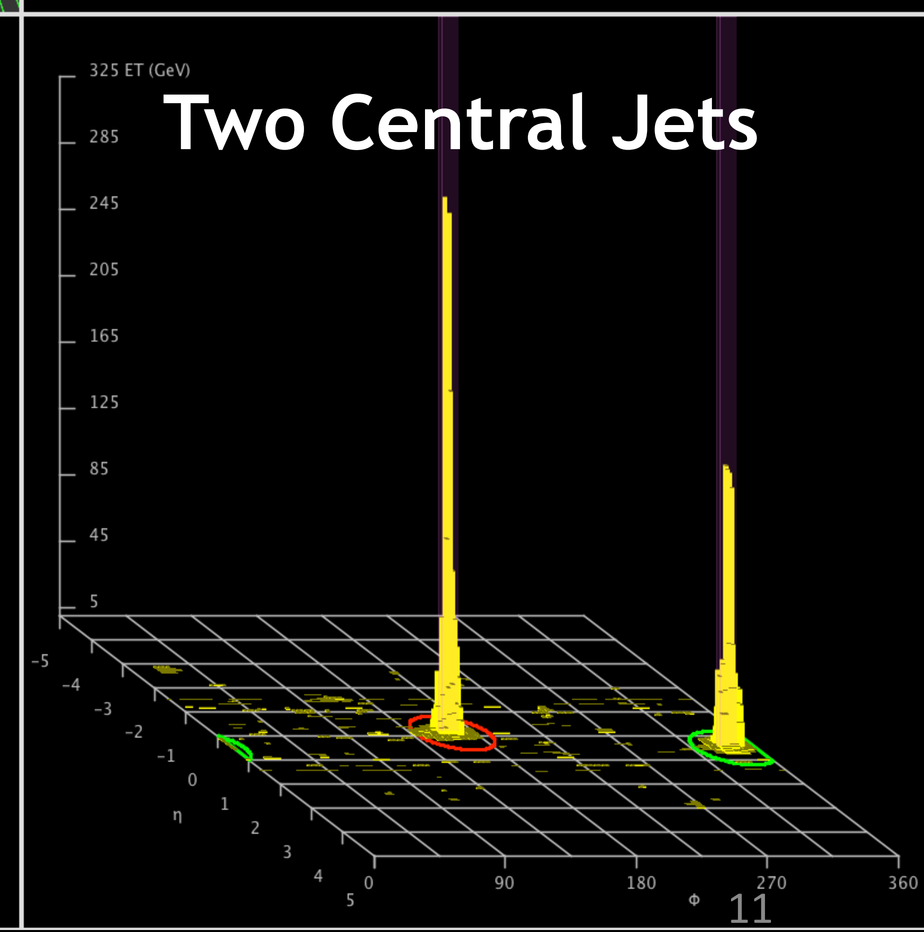


ATLAS EXPERIMENT

m_{jj} = 4.7 TeV
p_T (j_1, j_2) = 2.3-2.2 TeV

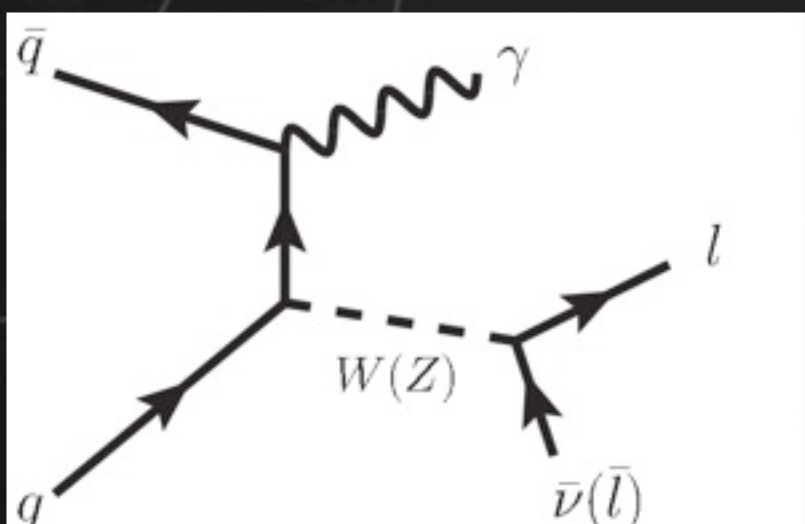
E_T^{miss} = 47 GeV

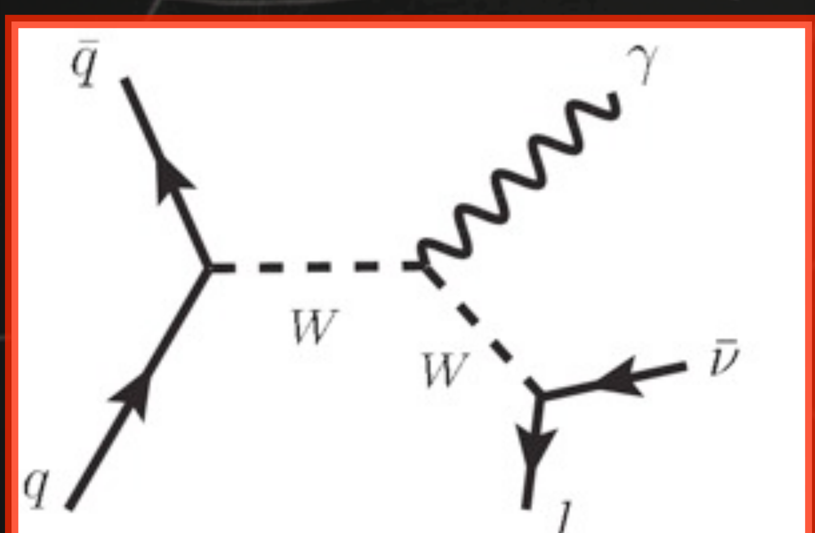




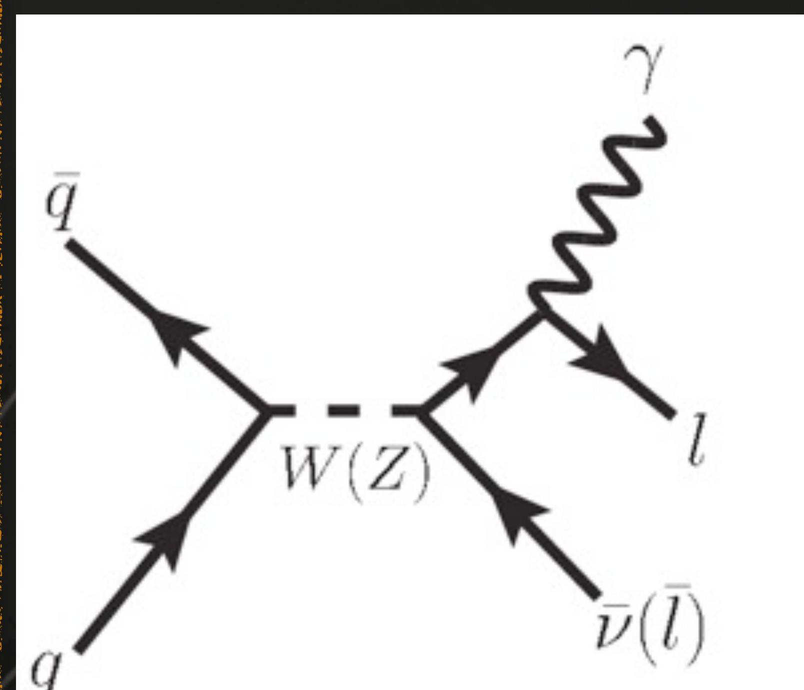
Dibosons: Wγ/Zγ

Initial State Radiation





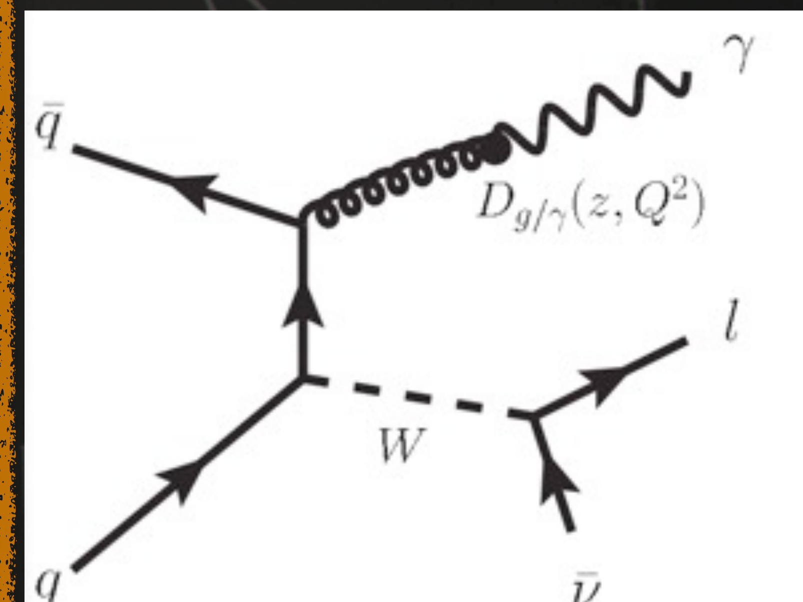
Final State Radiation

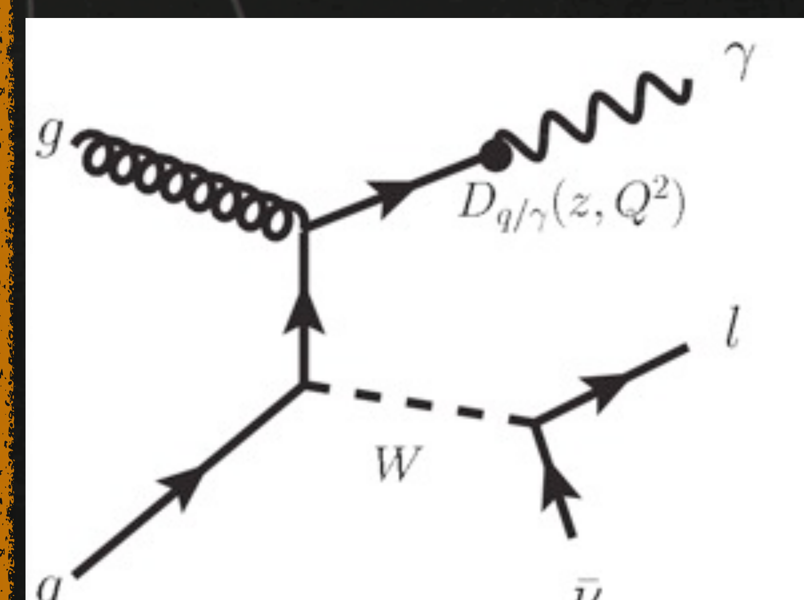


Suppress

ΔR(l, γ) > 0.7

Fragmentation

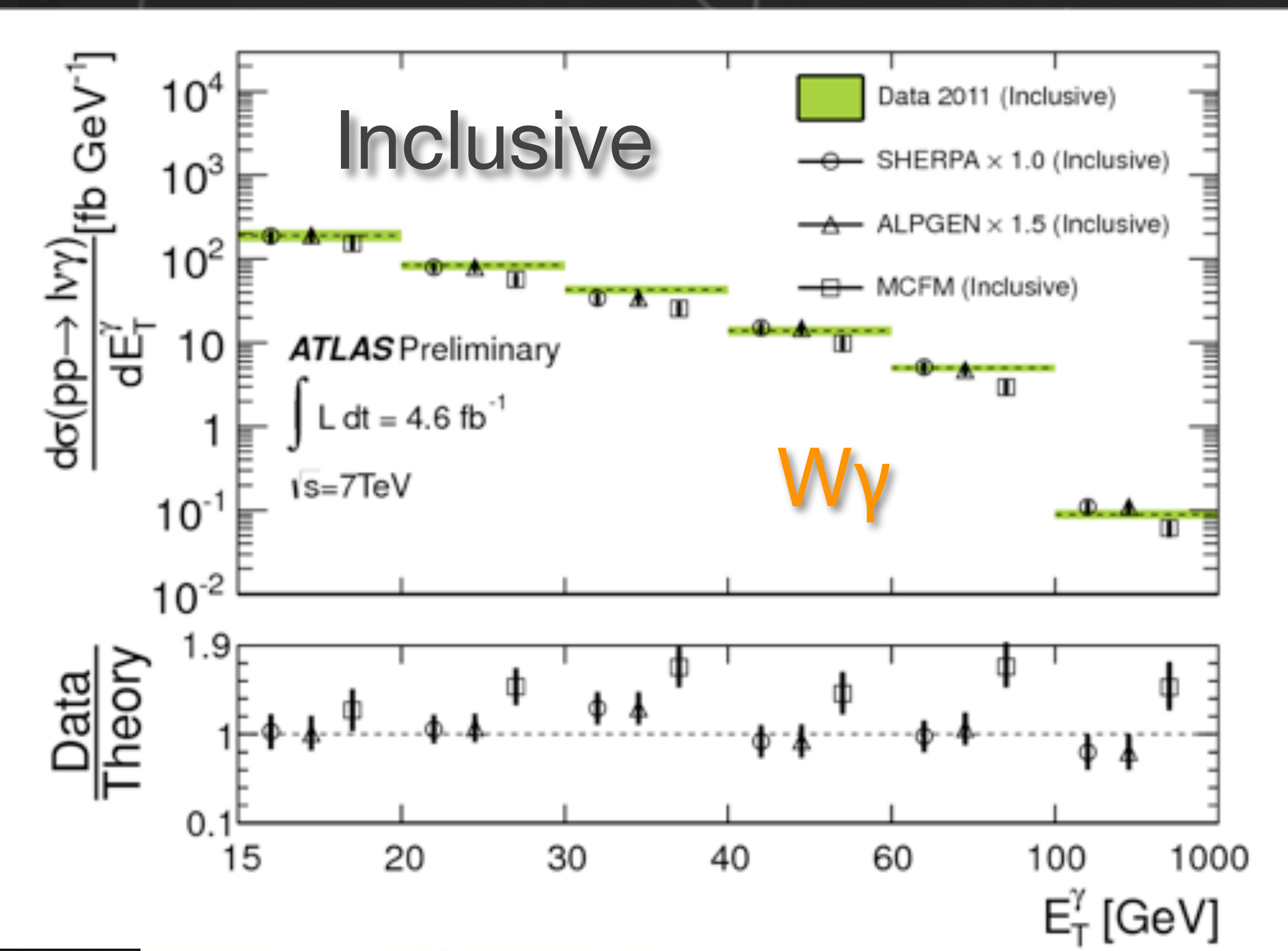


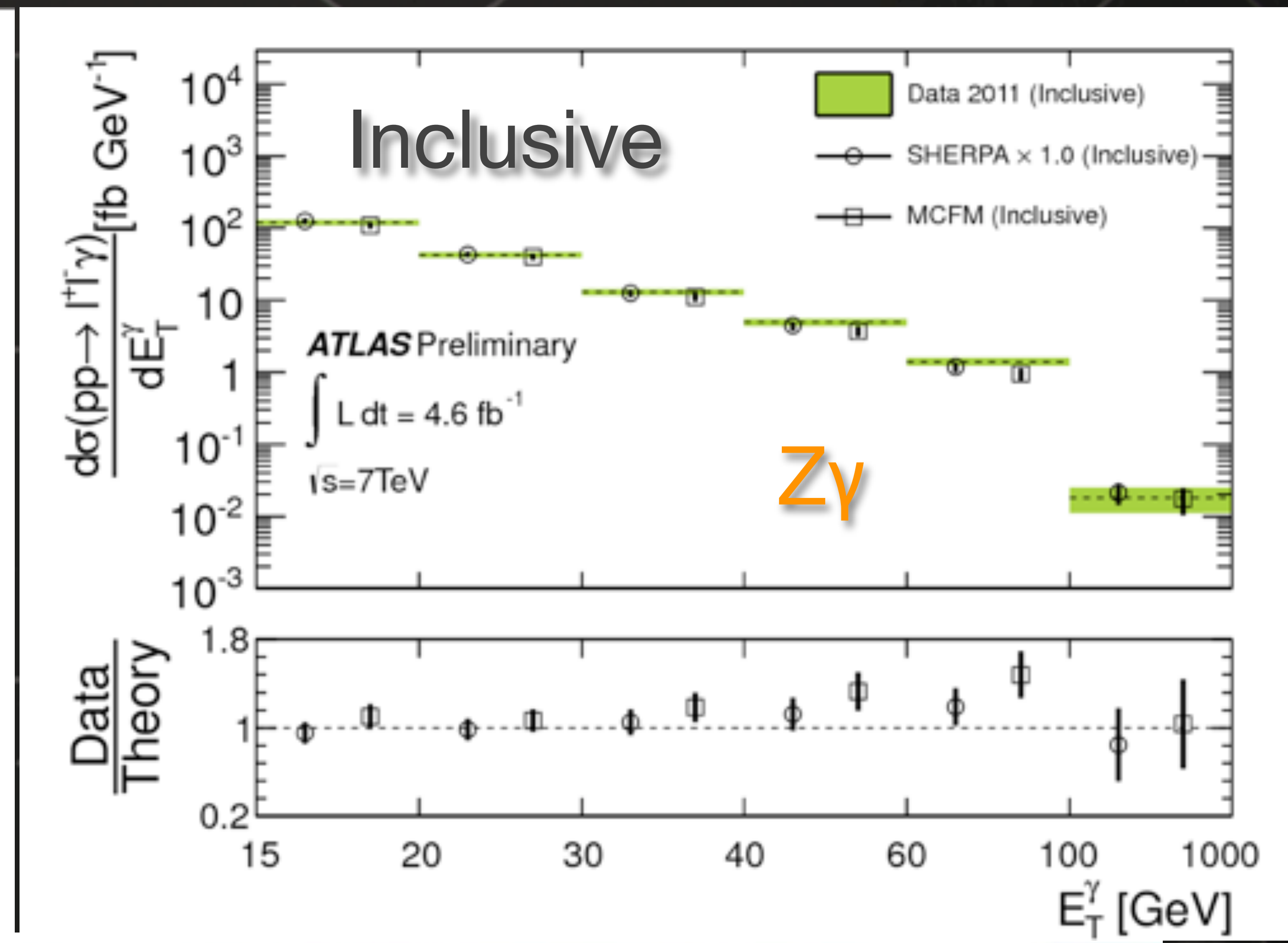


Suppress

Isolation requirement

Dibosons: Wγ and Zγ @ 7 TeV





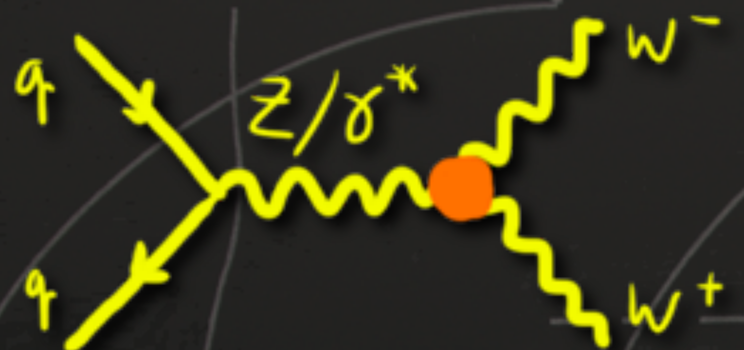
	Measurement pb	NLO (MCFM) pb
lνγ	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
llγ	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
ννγ	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012

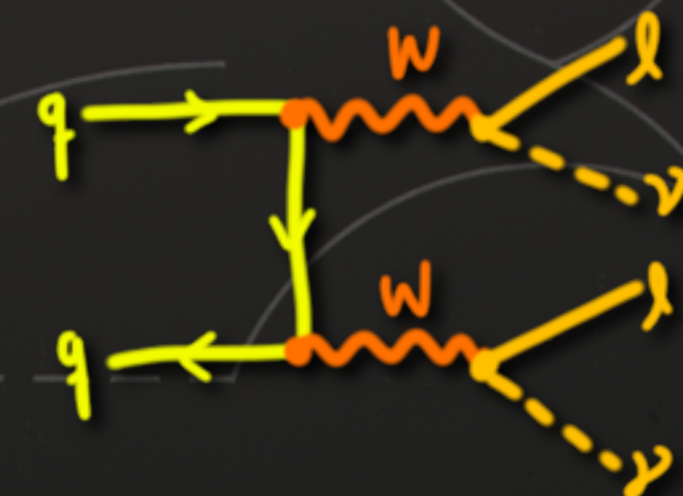
Wγ: Agreement with NLO MCFM calculation is not great
Exclusive calculation (N_{jet} =0) is good

Zγ: Better agreement with NLO MCFM calculation

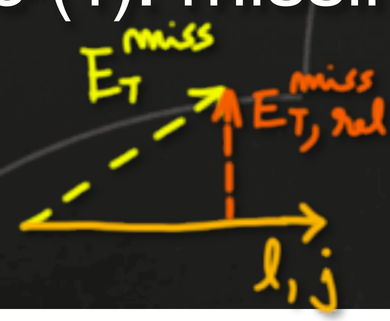
Similar observations at CMS

Dibosons: WW



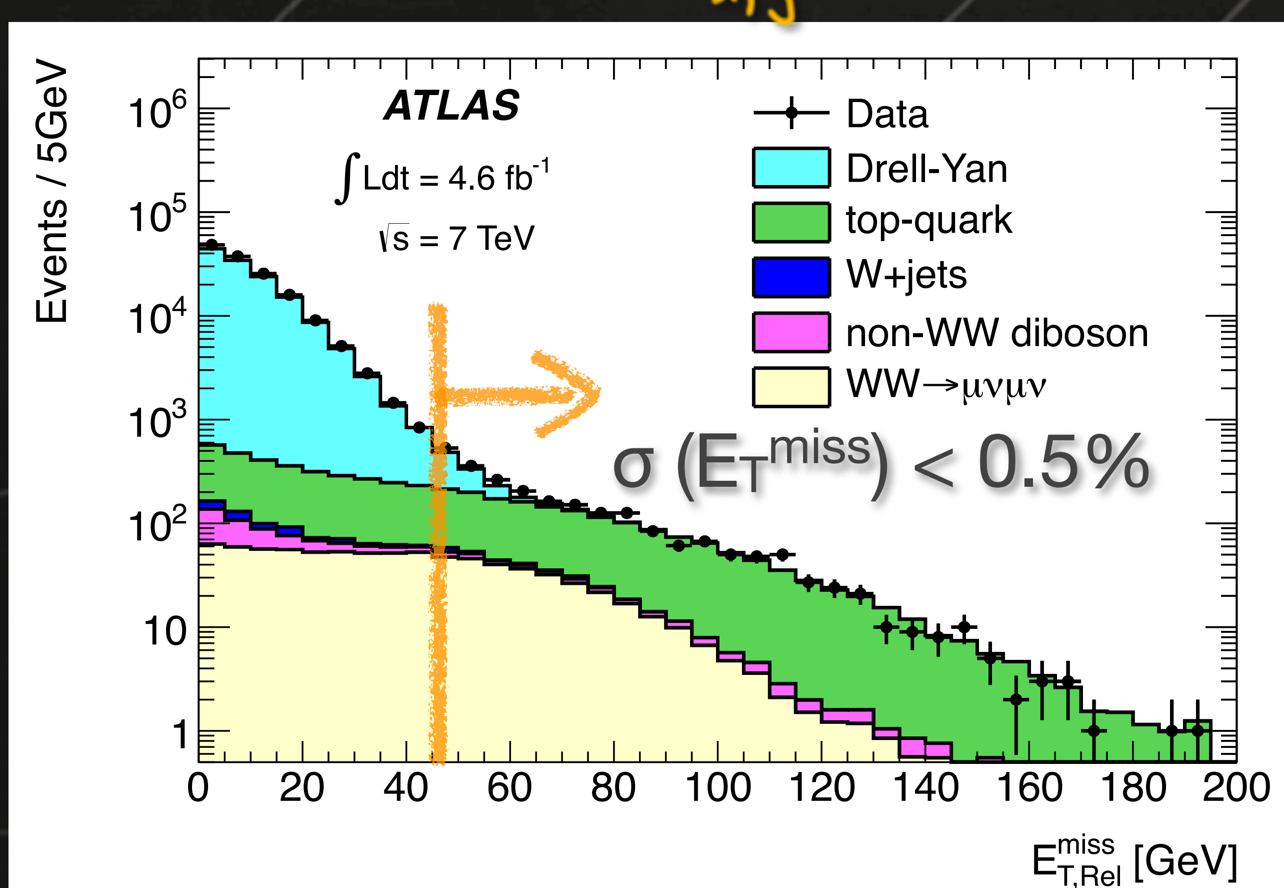


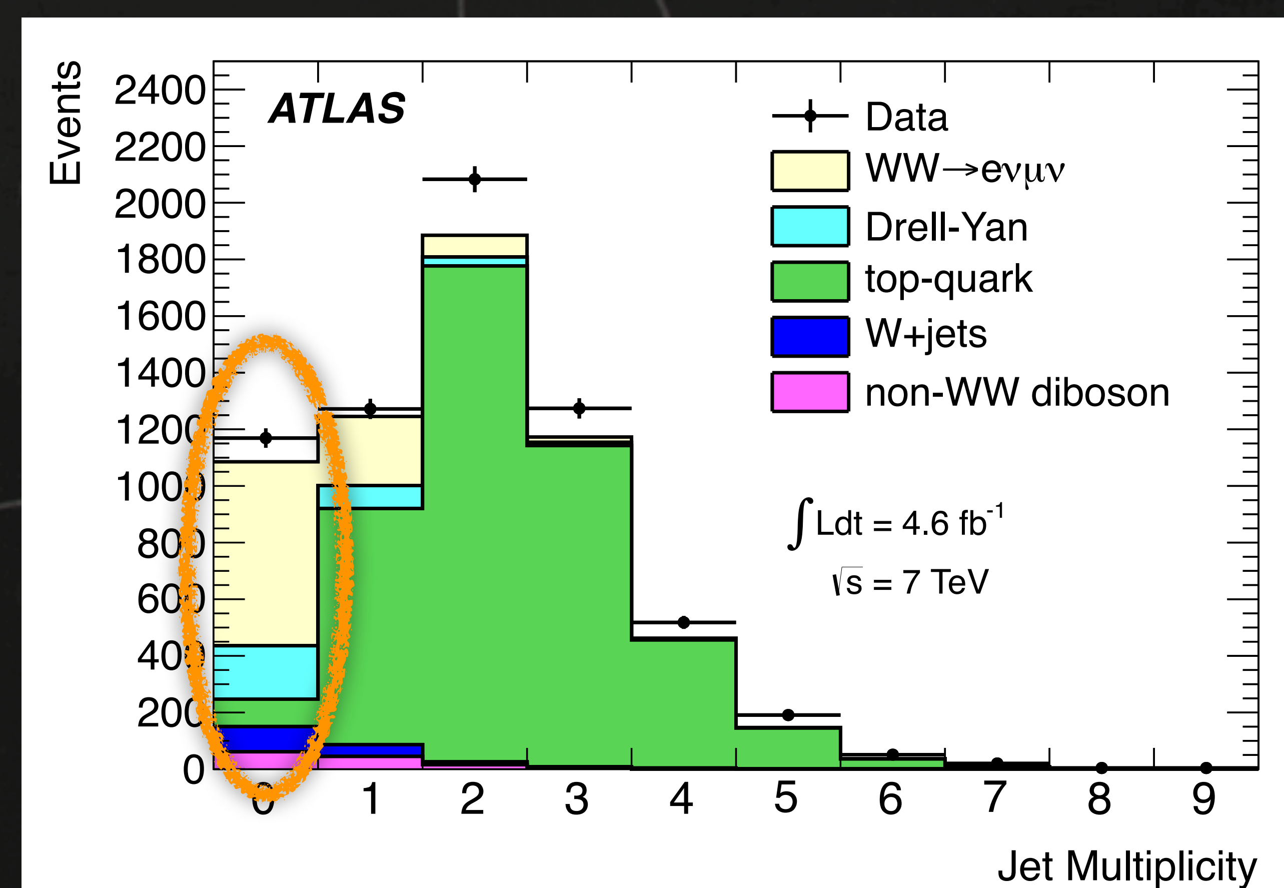
Challenge (1): missing energy



Challenge (2): Jet veto

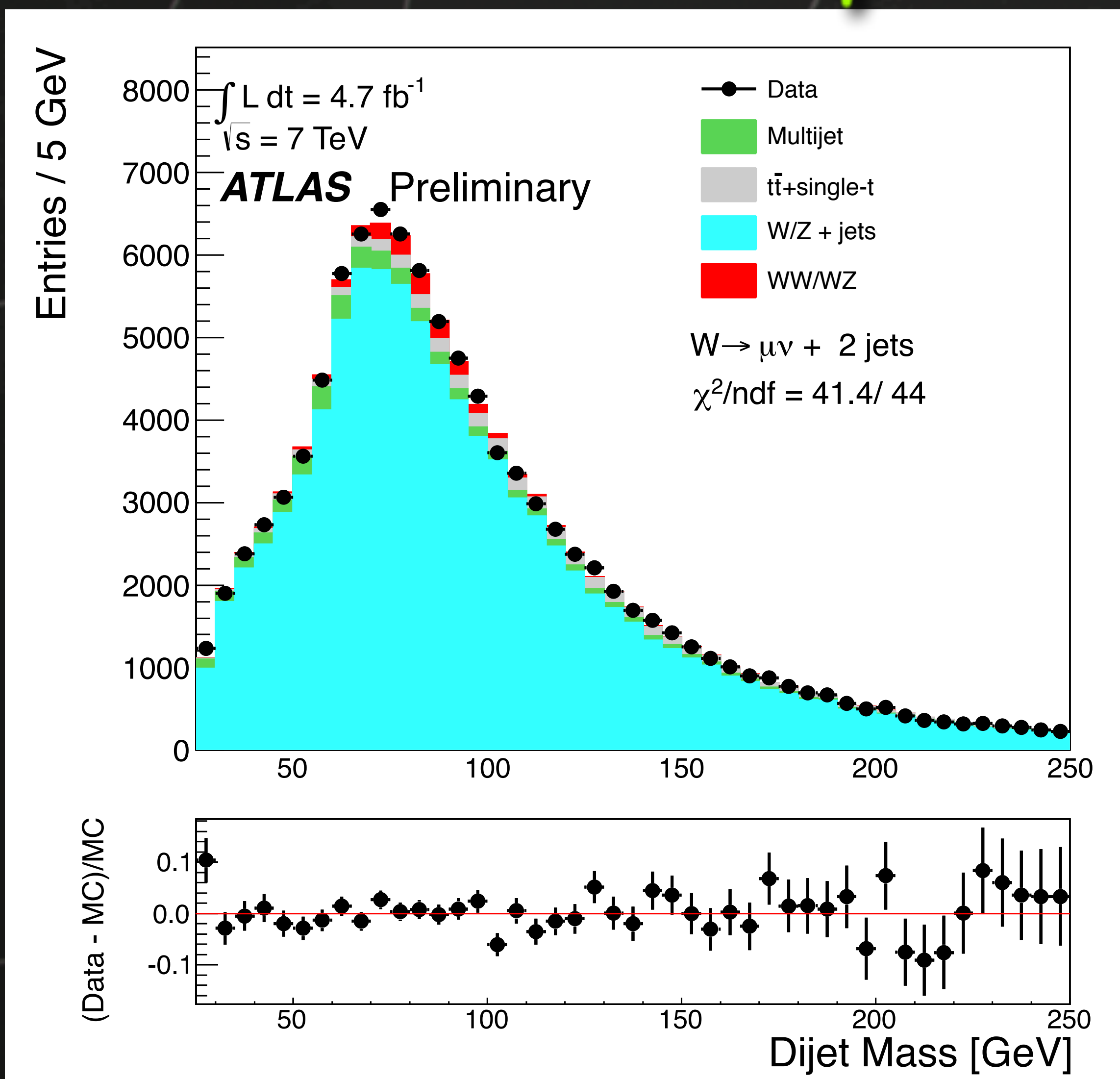
(reduce overwhelming top background)

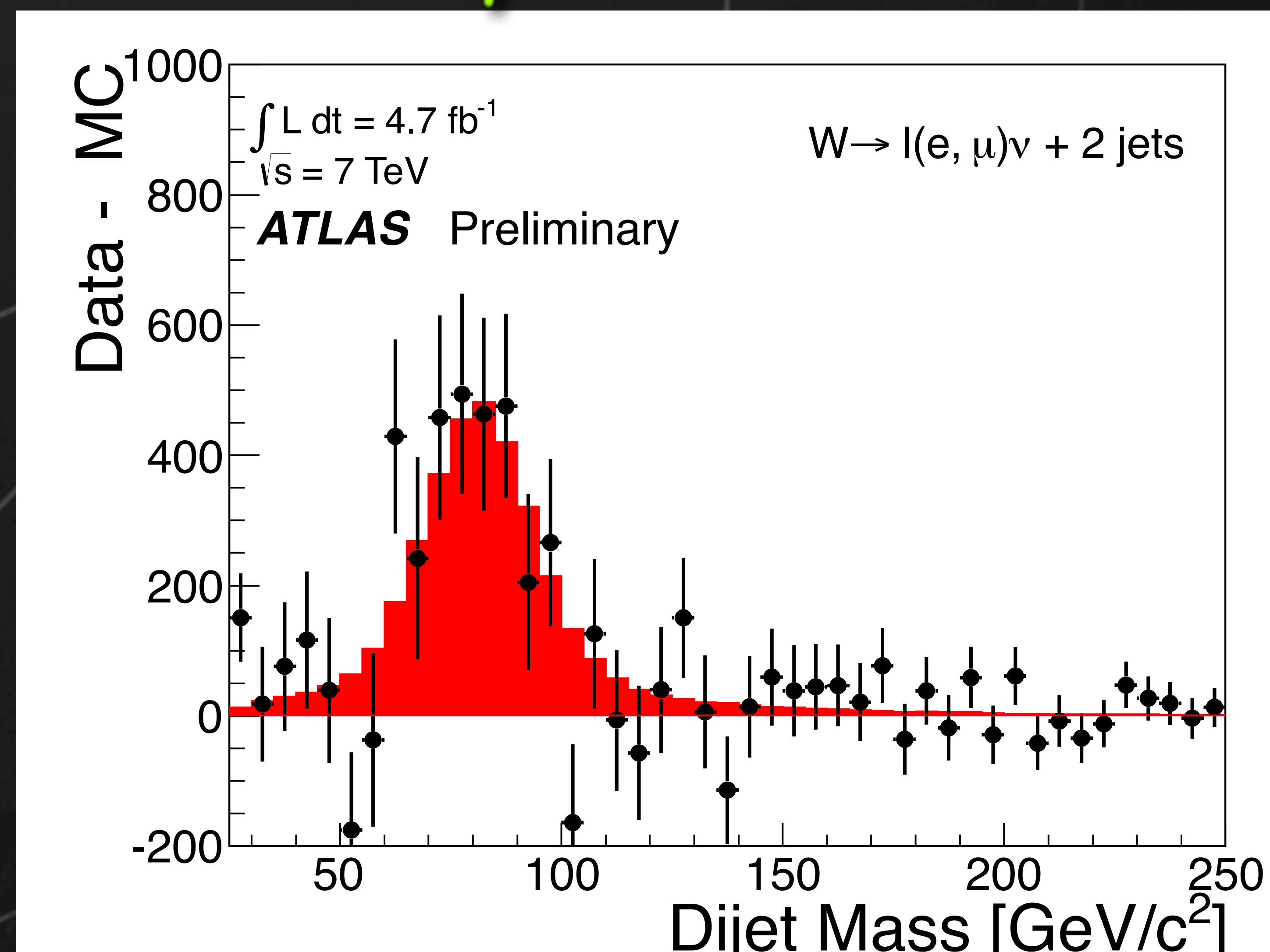




Dibosons: WW+WZ → lν + jj @ 7 TeV

S/B < 1%



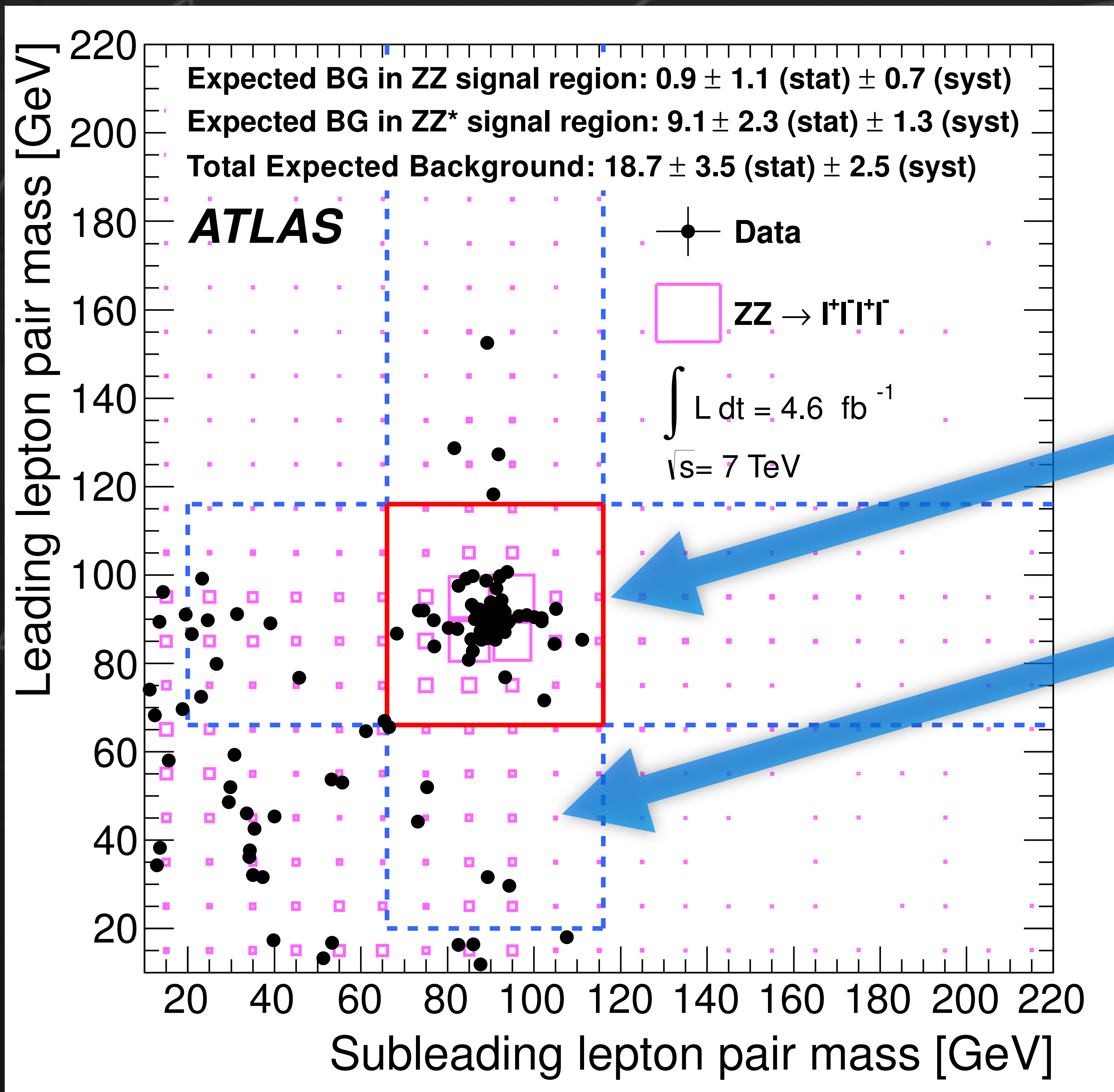


WW+WZ	$\sigma_{measured}$ (pb)	σ_{NLO} (pb)
ATLAS	72 ± 9 ± 15 ± 13 (MC stat)	63.4 ± 2.6

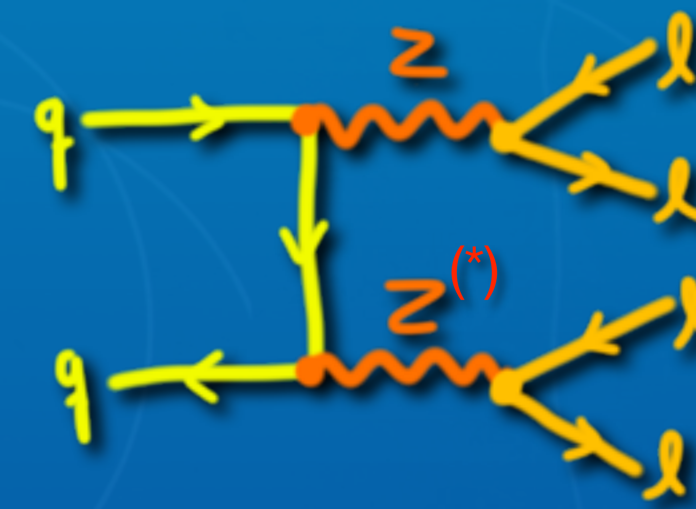
Dibosons: ZZ Production

ZZ ➔ 4 leptons (eeee, μμμμ, eeμμ)

$66 < M_{Z1} < 116$ GeV



$66 < M_{Z2} < 116$ GeV

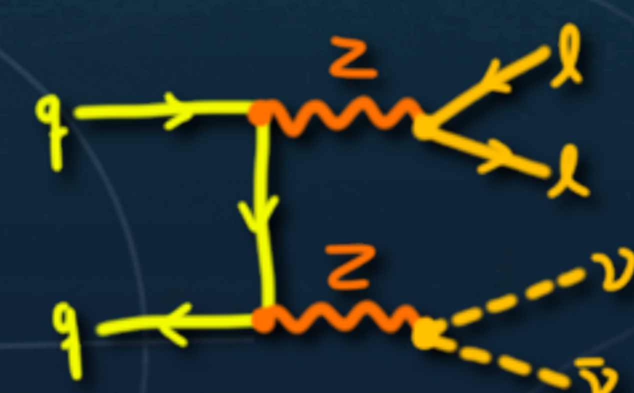


Two Z bosons on-shell

or

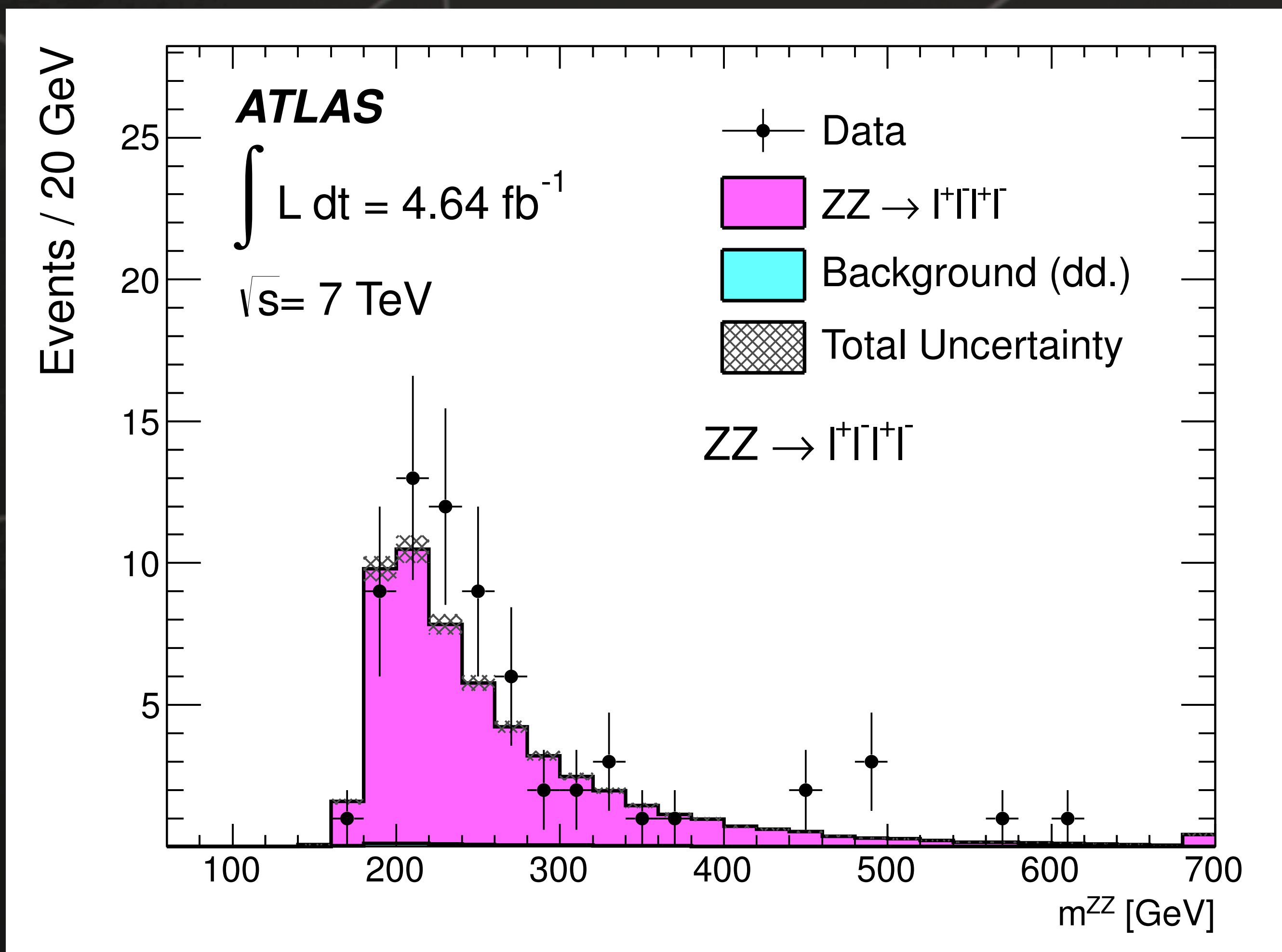
One Z boson on-shell
and the other off-shell

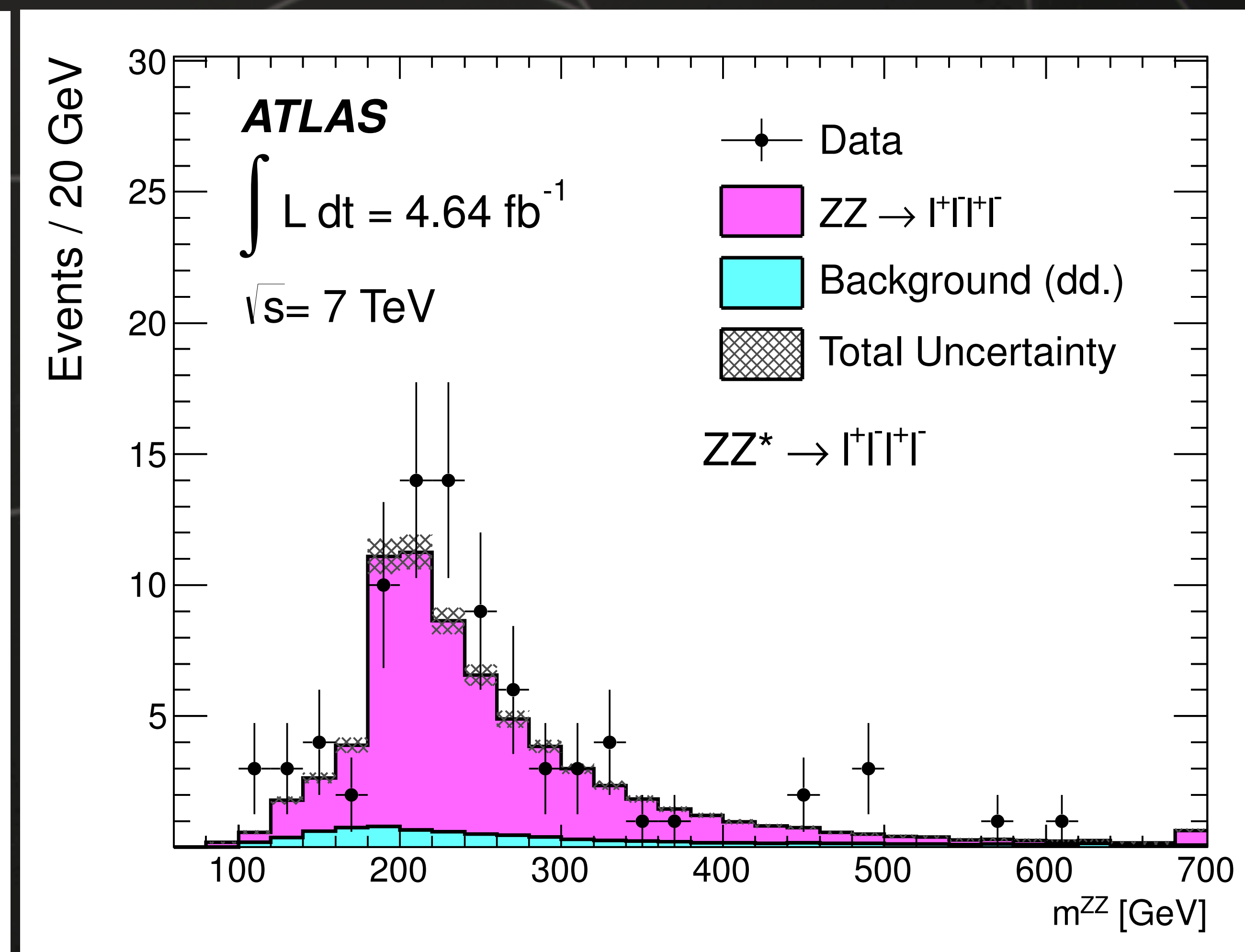
Also used:
Z ➔ νν



Dibosons: ZZ @ 7 TeV

ZZ → 4 leptons (eeee, μμμμ, eeμμ)

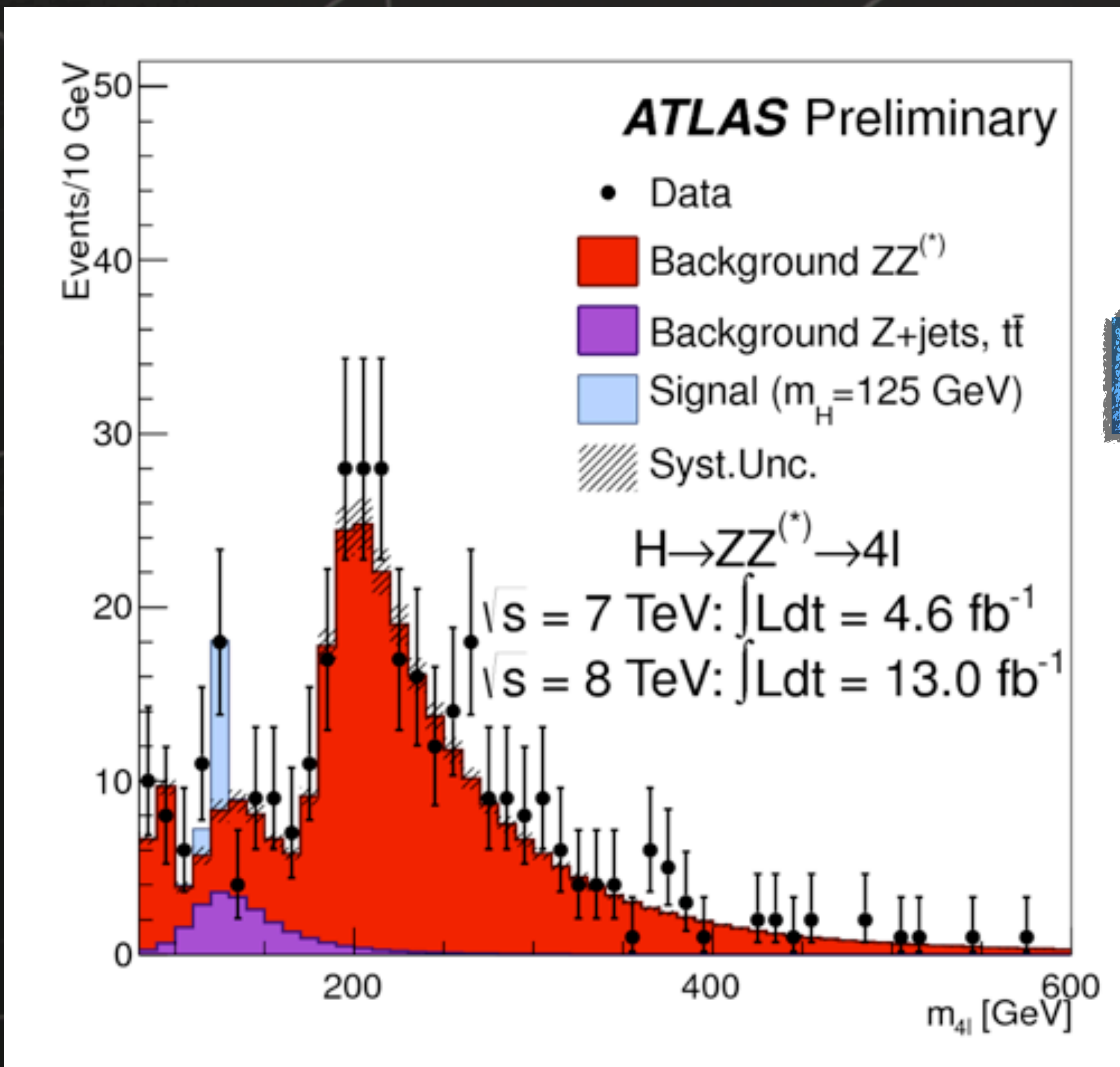


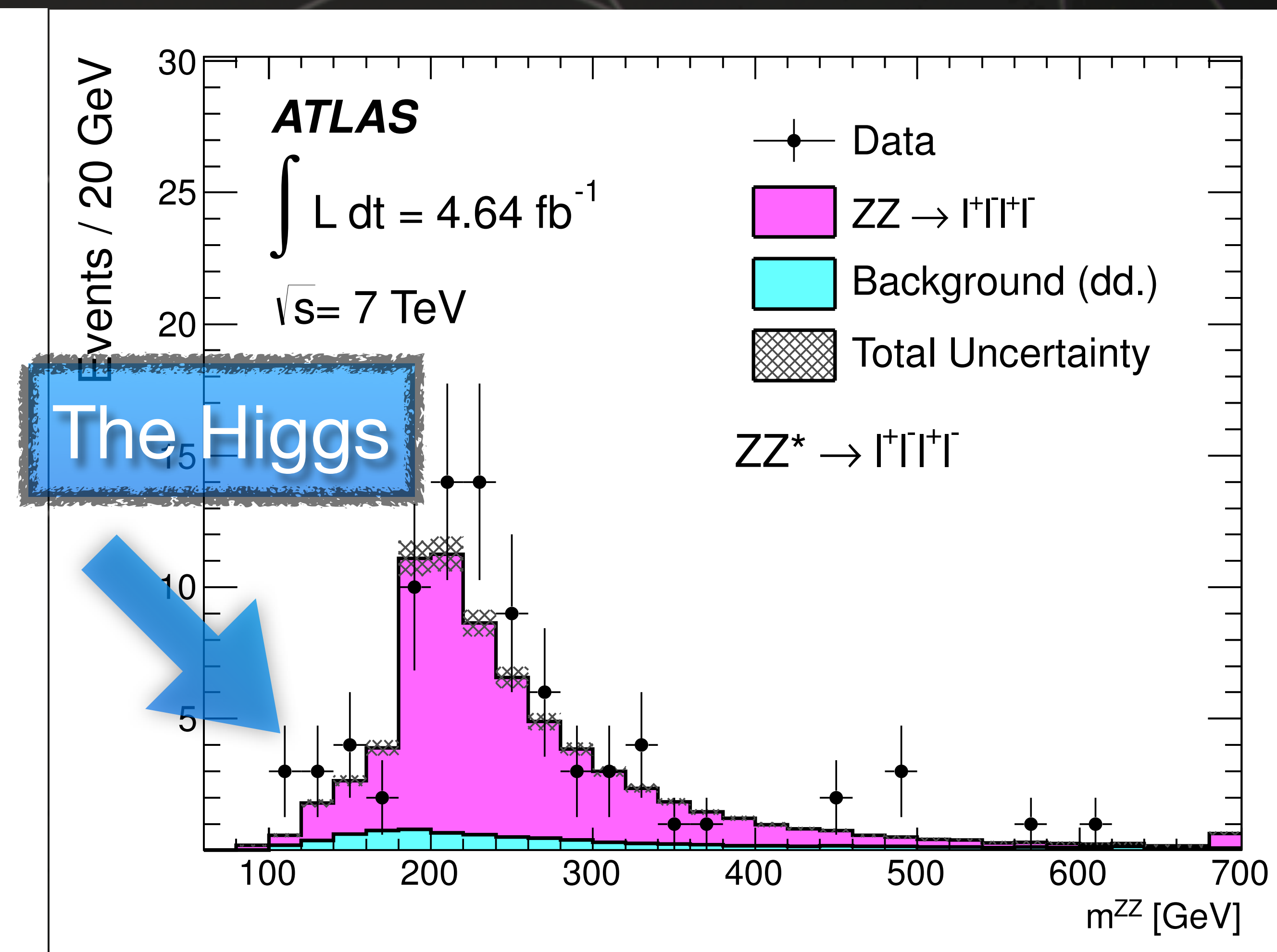


ZZ	$N_{obs(41)}$	$N_{signal(41)}$	$N_{bkg(41)}$	$\sigma_{measured}$ (pb)	σ_{NLO} (pb)
ATLAS	150	117.8	10	$6.7 \pm 0.7 ^{+0.4}_{-0.3} \pm 0.3$	5.9 ± 0.2

Dibosons: ZZ @ 7 TeV

ZZ → 4 leptons (eeee, μμμμ, eeμμ)



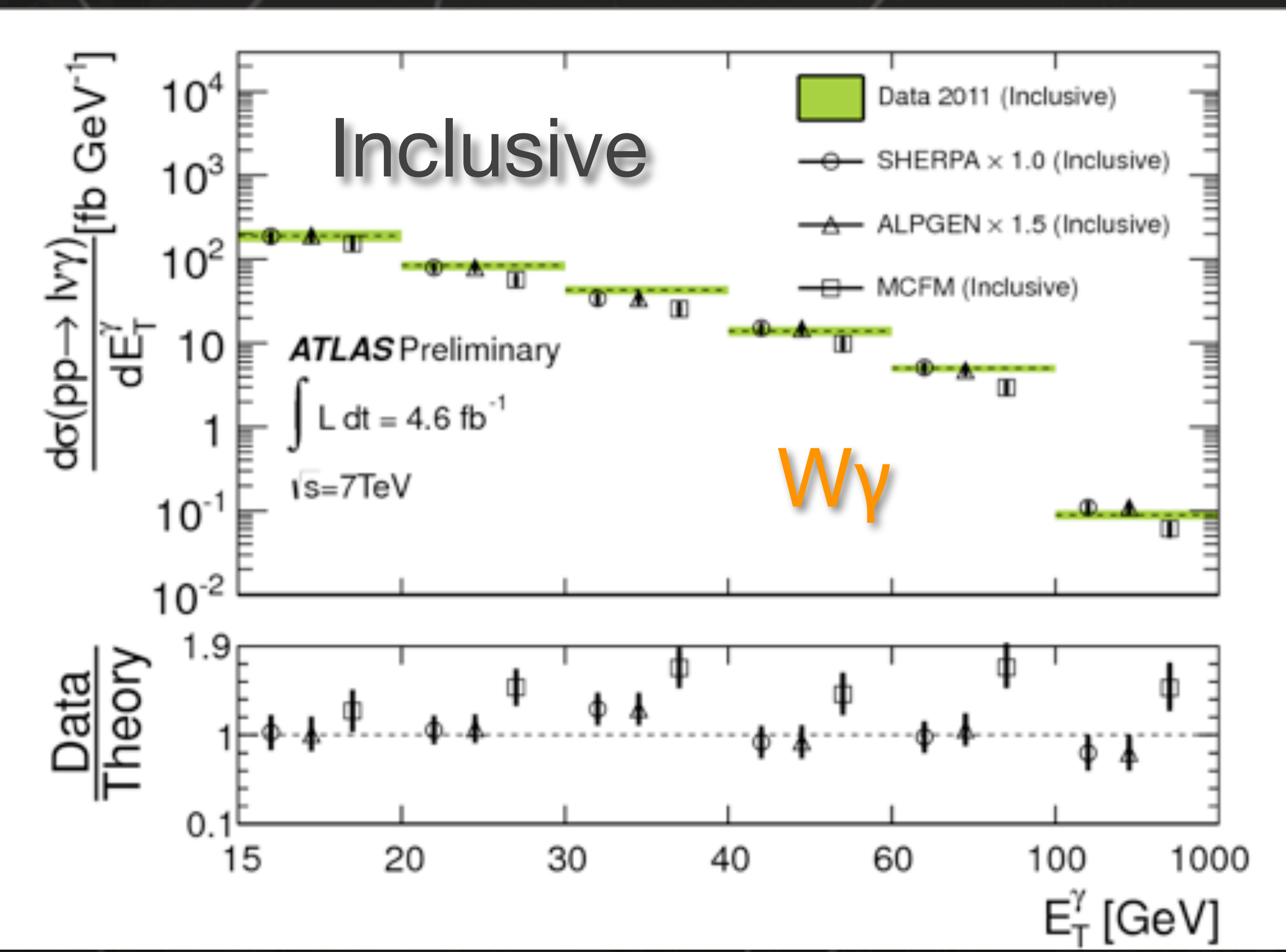


ZZ	$N_{obs(4l)}$	$N_{signal(4l)}$	$N_{bkg(4l)}$	$\sigma_{measured}$ (pb)	σ_{NLO} (pb)
ATLAS	150	117.8	10	$6.7 \pm 0.7 {}^{+0.4}_{-0.3} \pm 0.3$	5.9 ± 0.2

Diboson Physics: WW, WZ, ZZ, Wγ, Zγ,γγ

Examples (7 TeV, 4.6 fb^{-1}):

Wγ: Normalized fiducial differential cross section

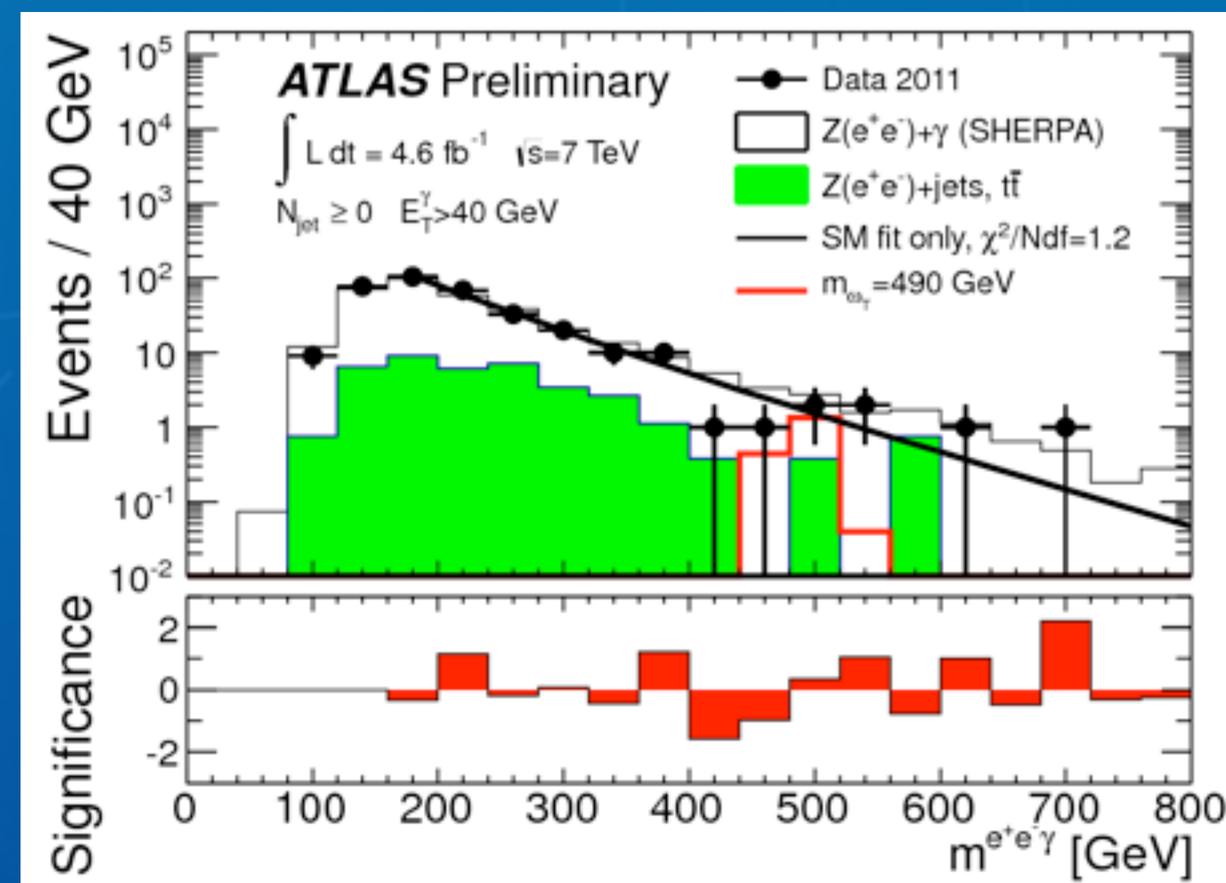


Agreement with NLO MCFM calculation not great

Exclusive calculation (N_{jet} =0) is good

Similar observations at CMS

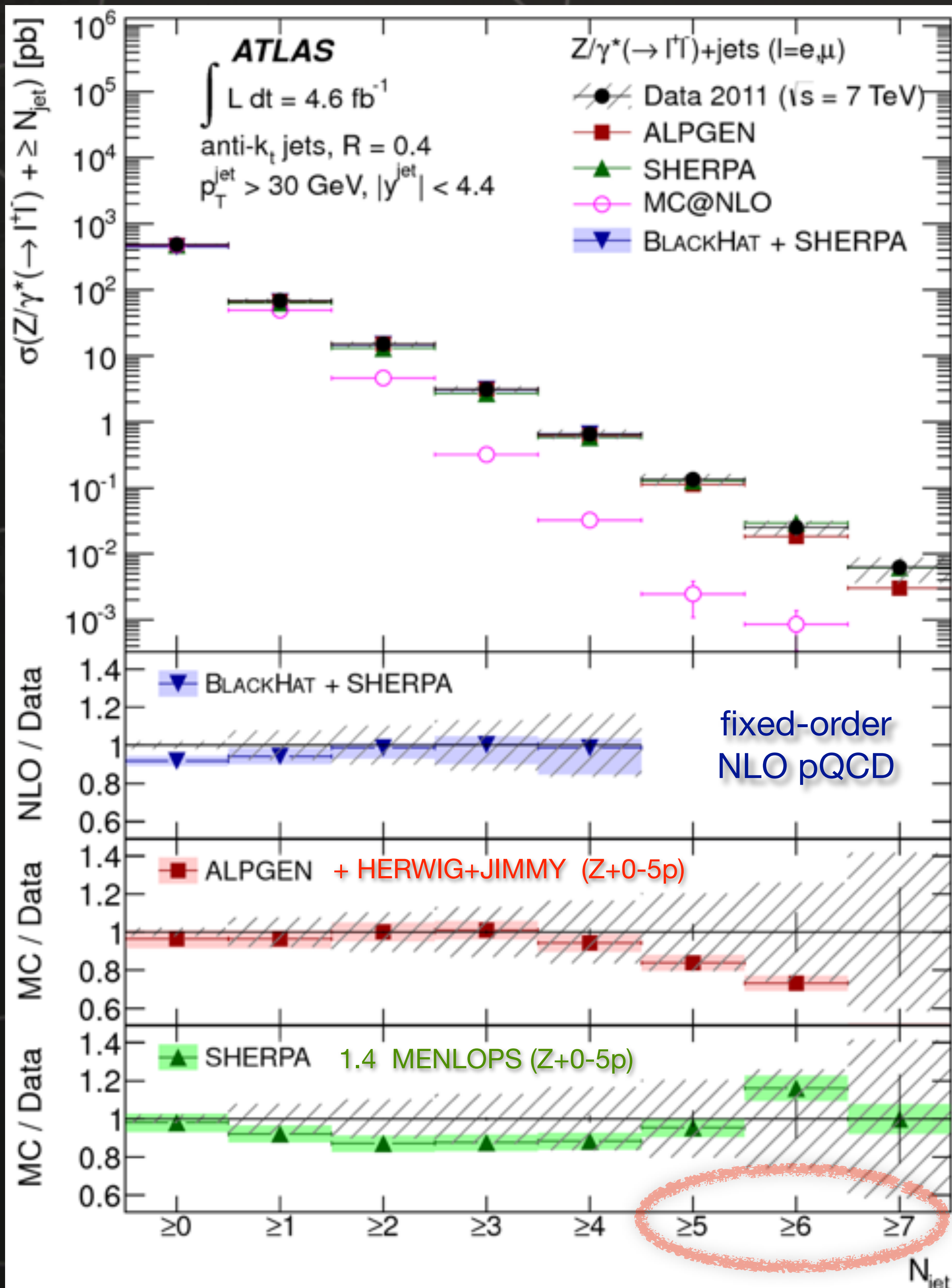
Zγ: Search for narrow resonances (techicolor)



$m_{techni\text{-}meson}$ > ~ 500 GeV

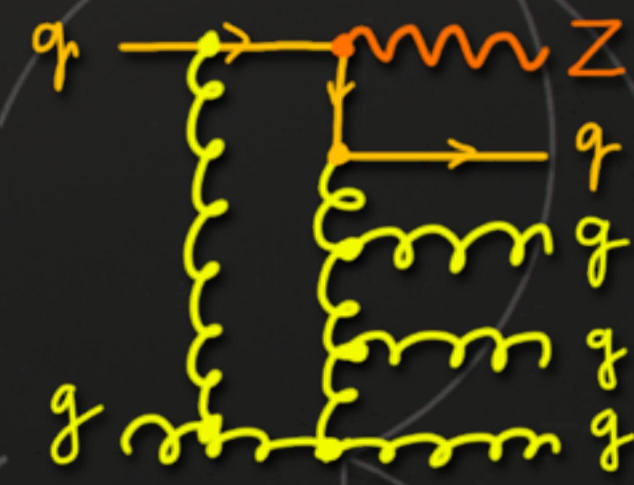
Measurements of Z + jets

arXiv:1304.7098



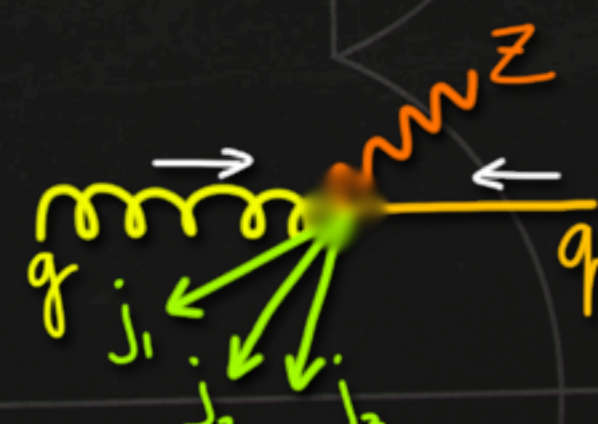
Explore extreme phase space

(using large dataset at 7 TeV)



Large jet multiplicities

Large p_T(jet), large H_T



Large p_T(Z)