Standard Model Electroweak in Run 2

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pp@LHC 2016 – Pisa, 16-18 May 2016

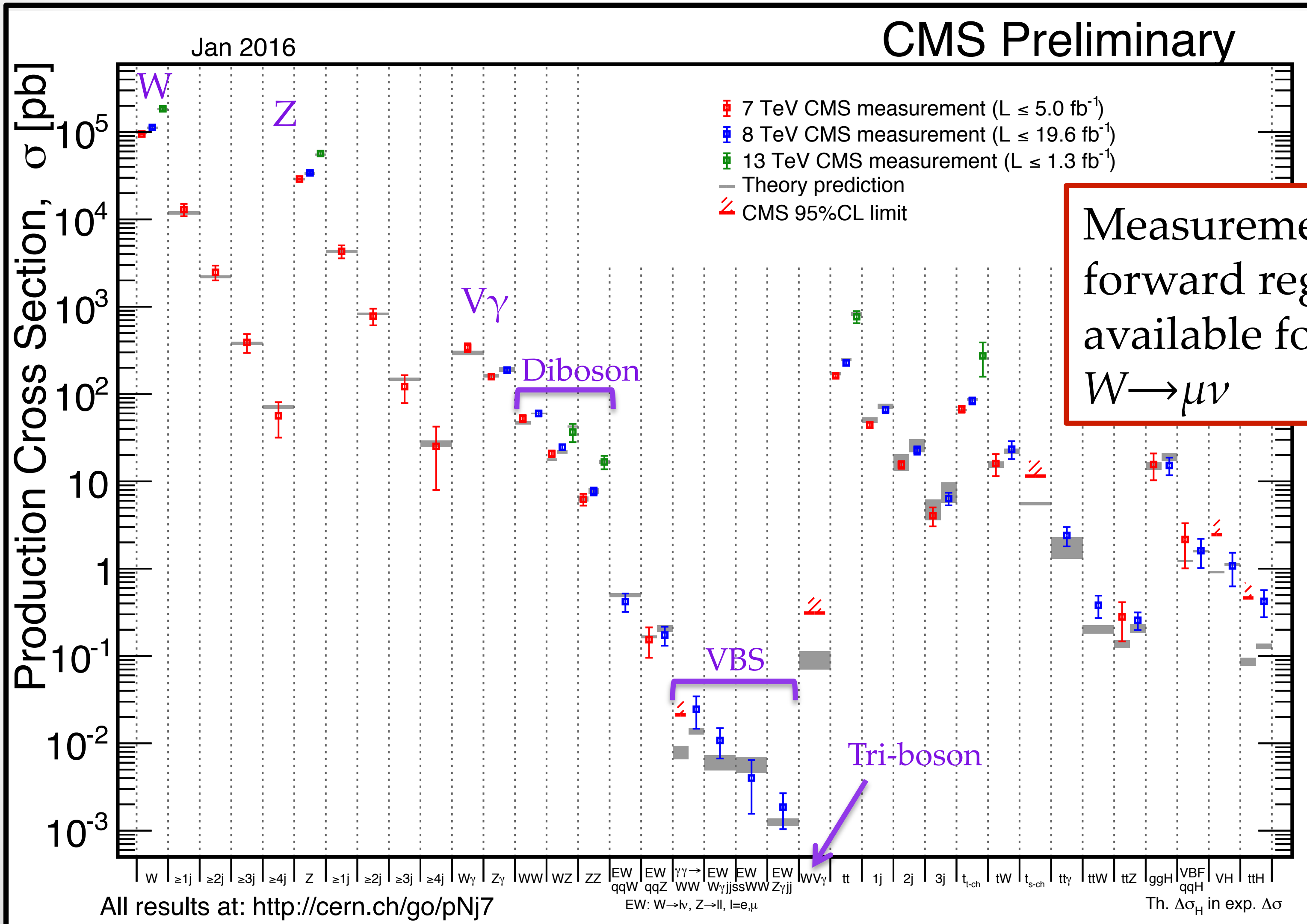
Overview

- Current status at LHC
  - Focus on most recent results
- What can we do with Run 2 data
- Electroweak physics in Run 2
  - Single boson physics: W, Z
  - Precision measurements
  - Multi-bosons physics

For any missing reference, public results can be found here:
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
LHCb: http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php

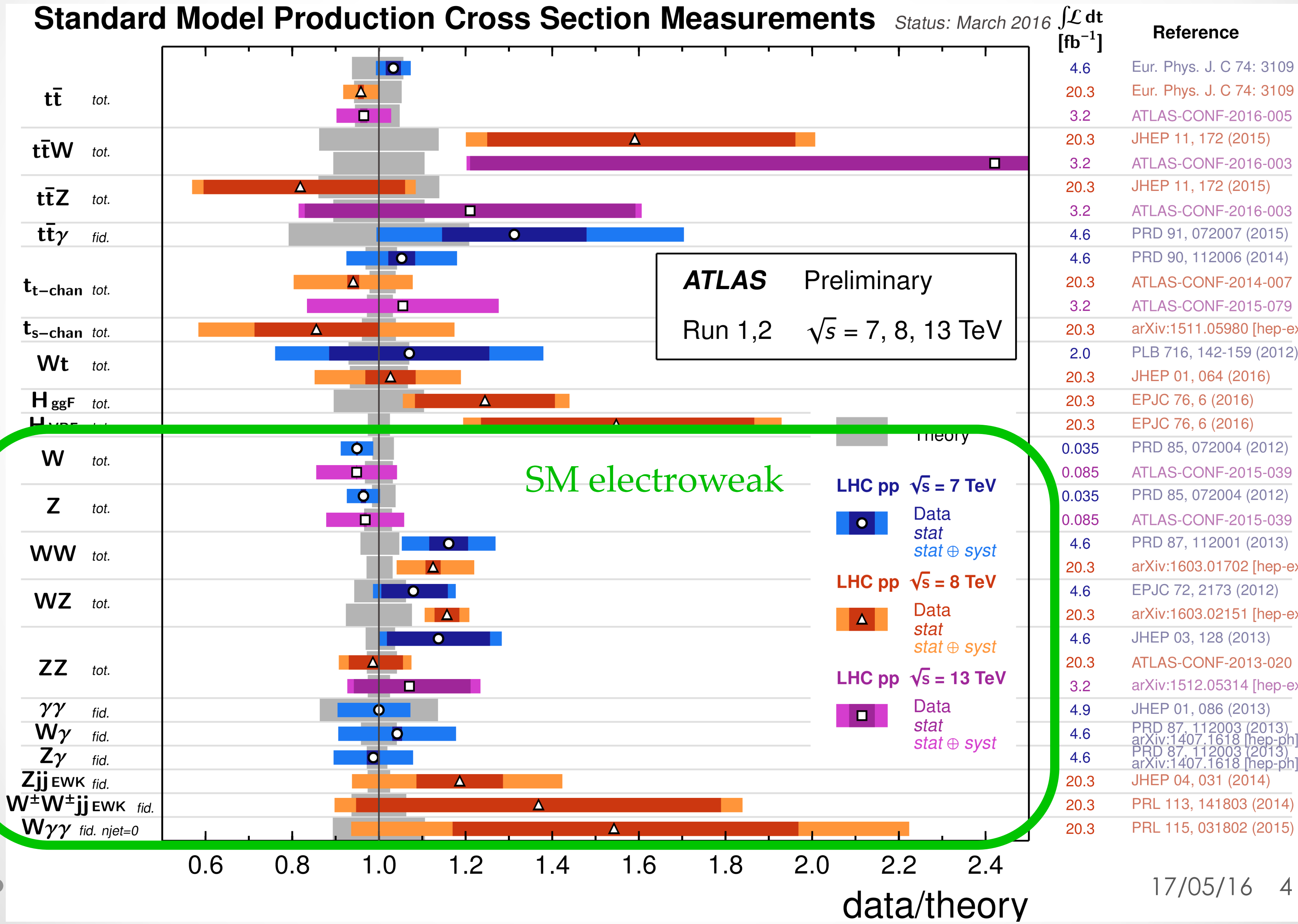
Standard Model electroweak results

- A wide range of measurements.

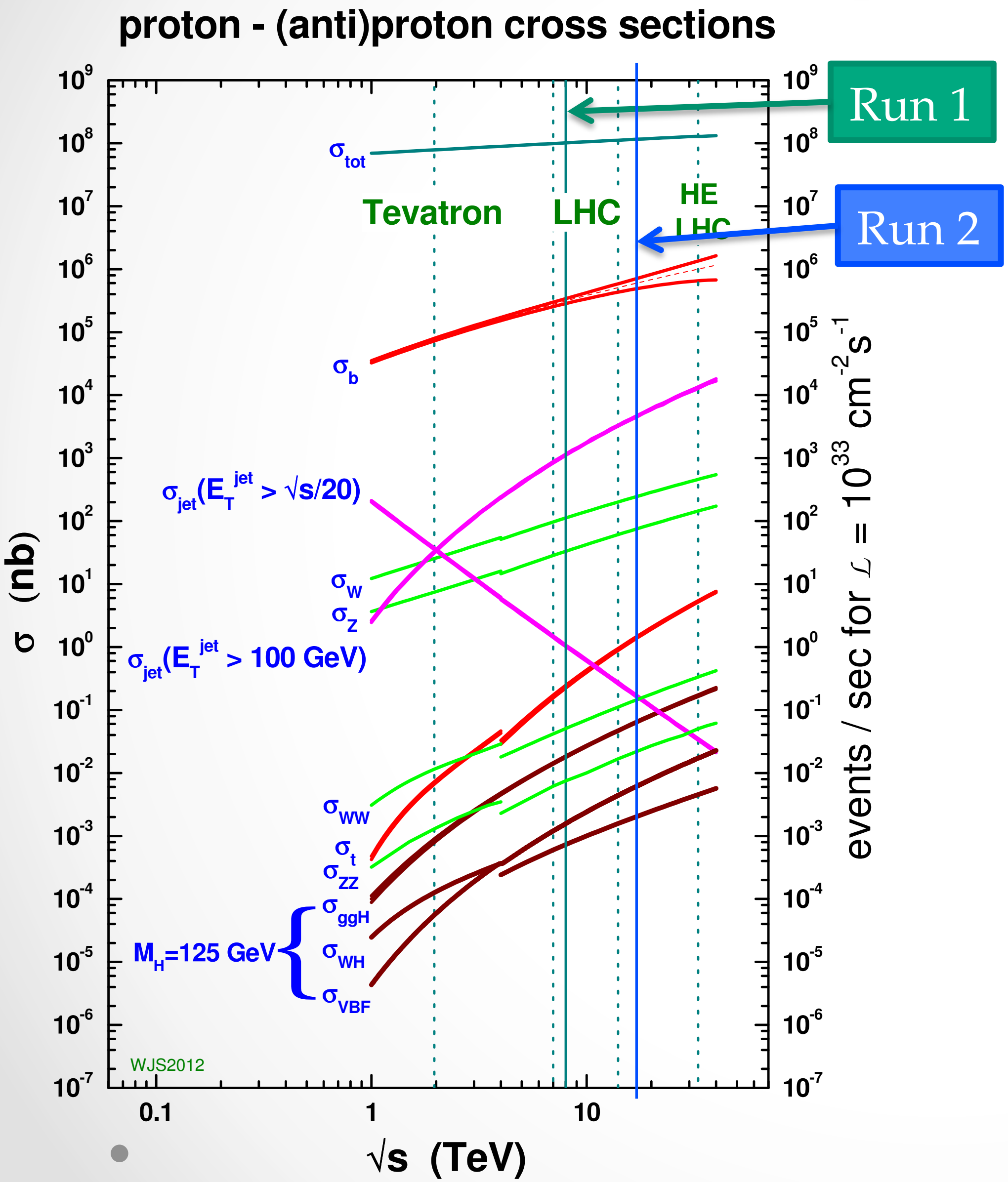


Measurements in forward region (LHCb) available for $Z \longrightarrow ll$ and $W \longrightarrow \mu\nu$

Standard Model electroweak results: data/predictions agreement



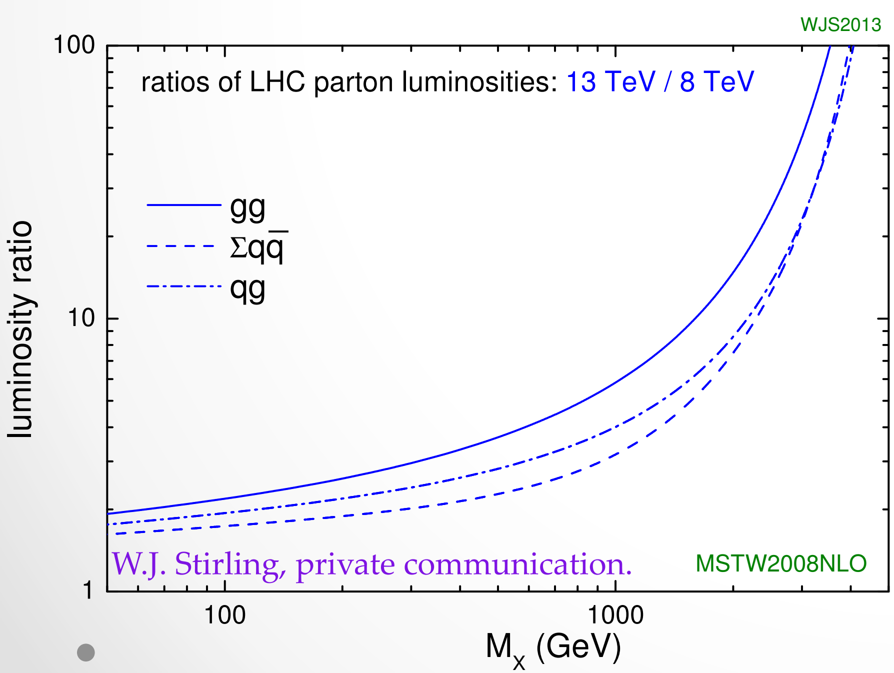
What changes with Run 2

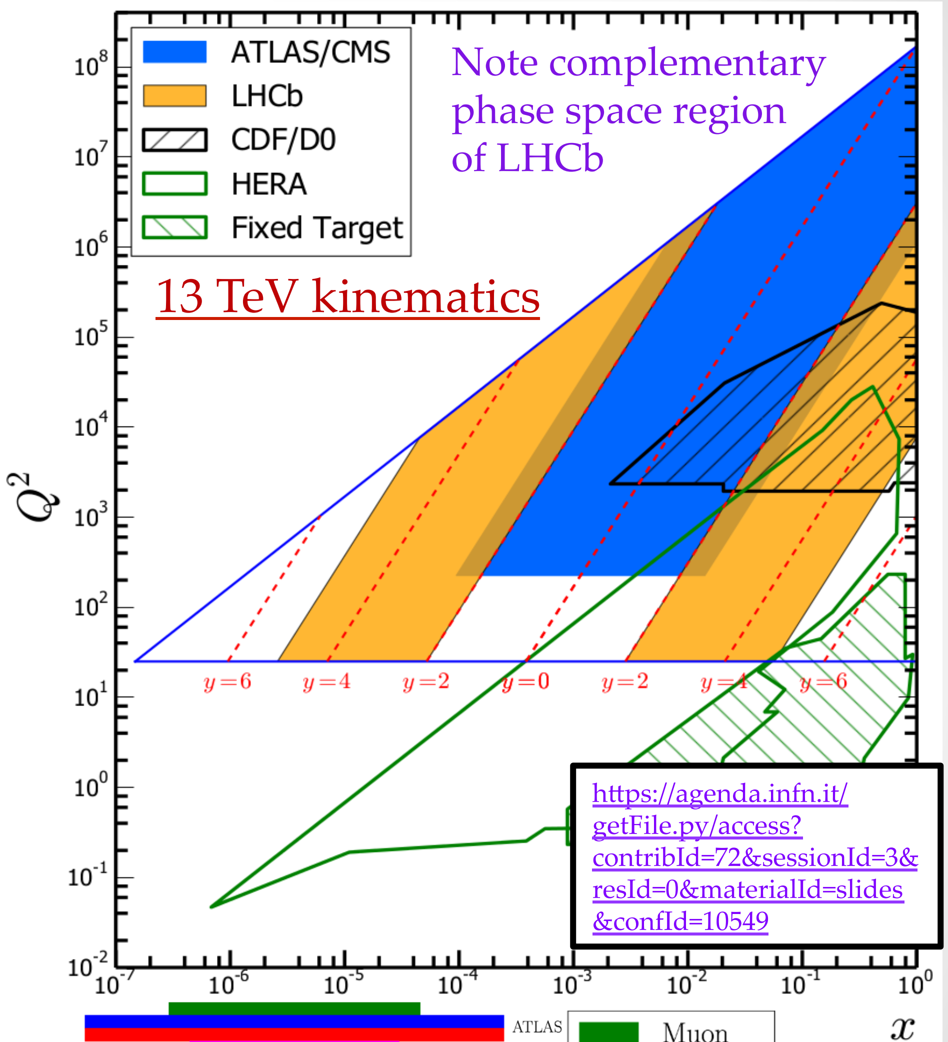


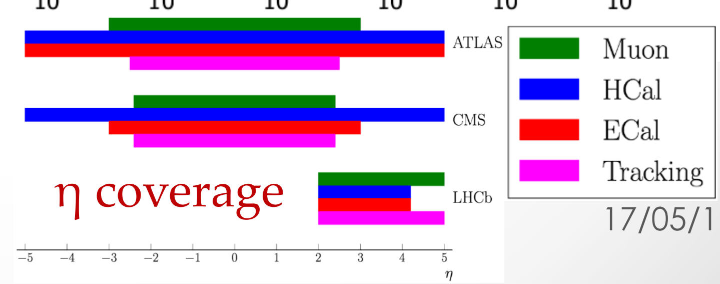
- Most electroweak cross sections increase by roughly a factor 2.
- Expected luminosity at the end of 2016: roughly 30 fb^{-1}
- To effectively increase sensitivity in SM processes, we need at least 2016 data

What changes with Run 2

- Phase space and parton luminosities
  - Larger contributions from quark-gluon and gluon-gluon
  - Low x region particularly interesting for PDF.

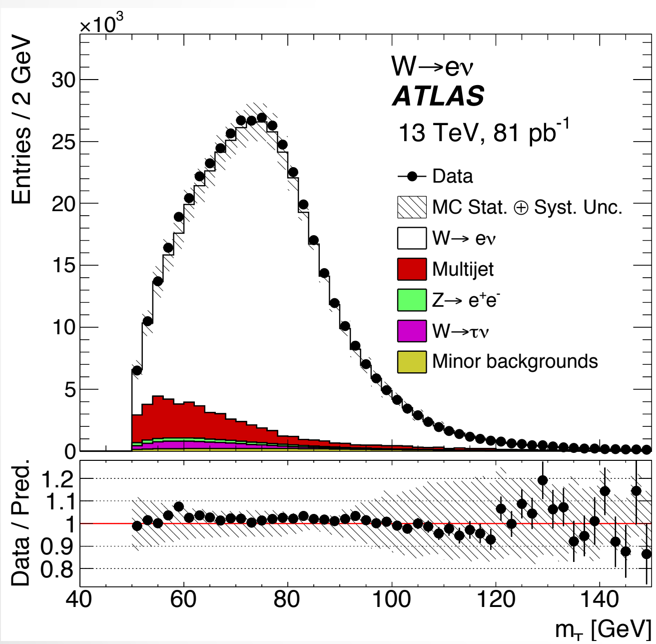


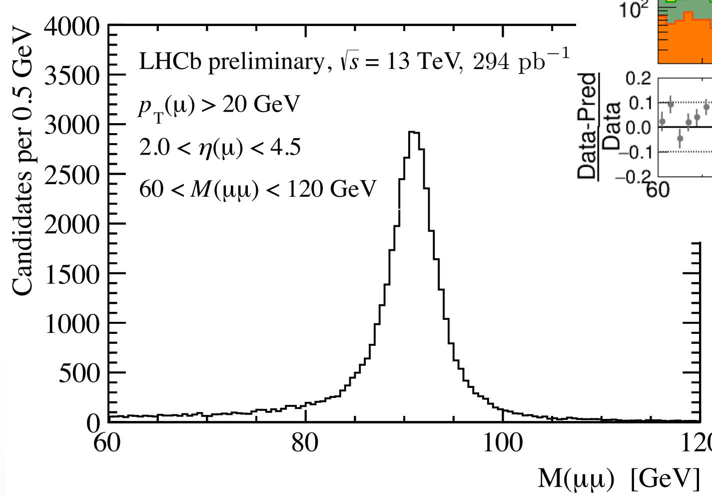


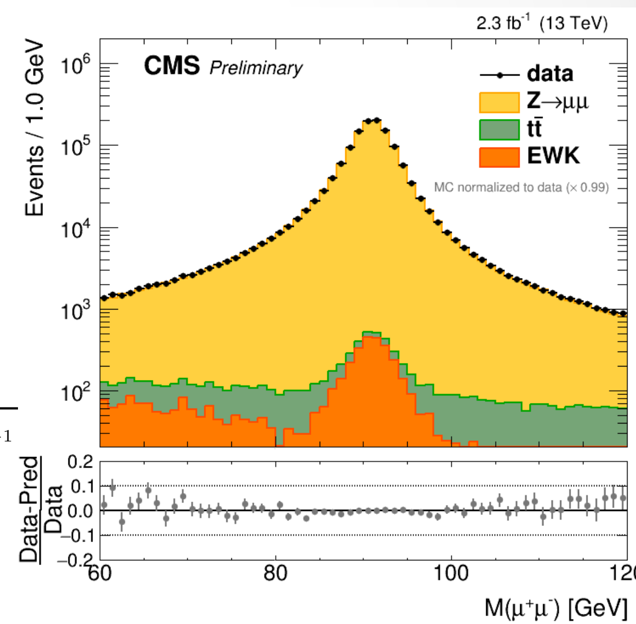


W and Z at 13 TeV

- First 13 TeV results recently published:
  - W and Z cross section from CMS (SMP-15-004, SMP-15-011) and ATLAS (arXiv:1603.09222)
  - $Z \longrightarrow \mu\,\mu$ from LHCb (LHCb-CONF-2016-002)

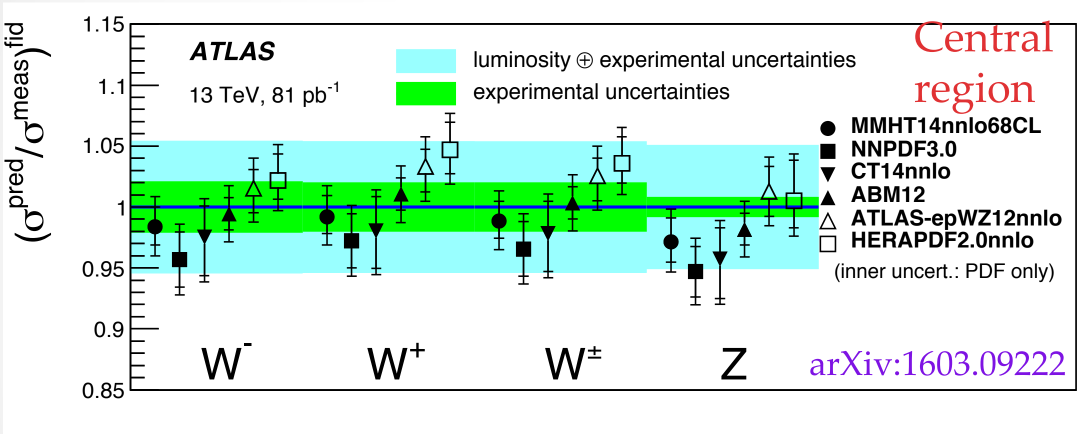


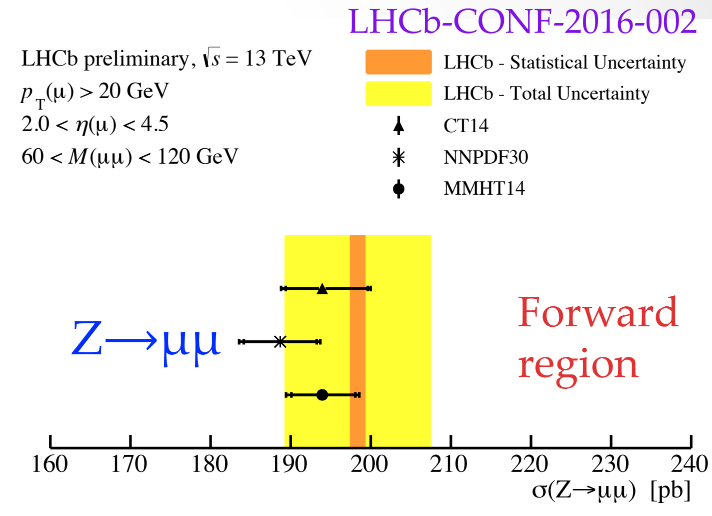


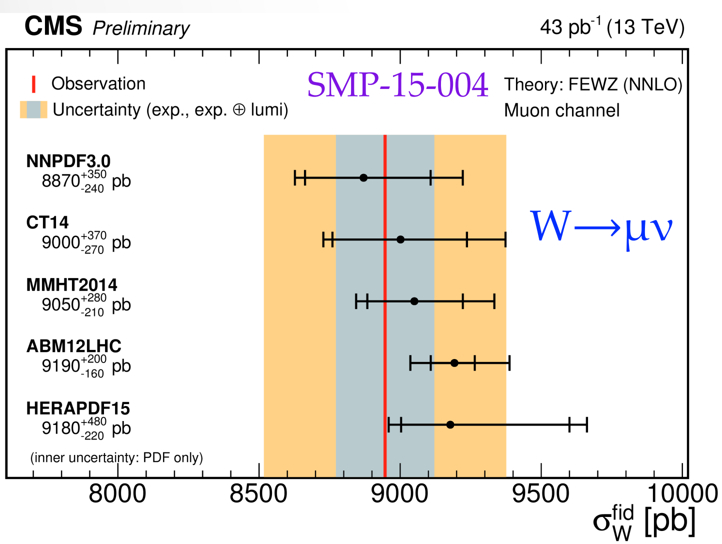


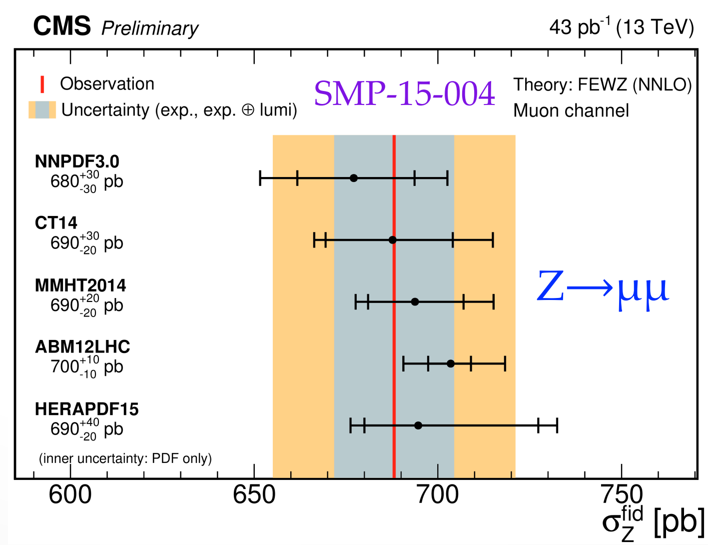
W and Z at 13 TeV: results

- Measured cross sections provides a test of different PDF sets in orthogonal phase spaces.





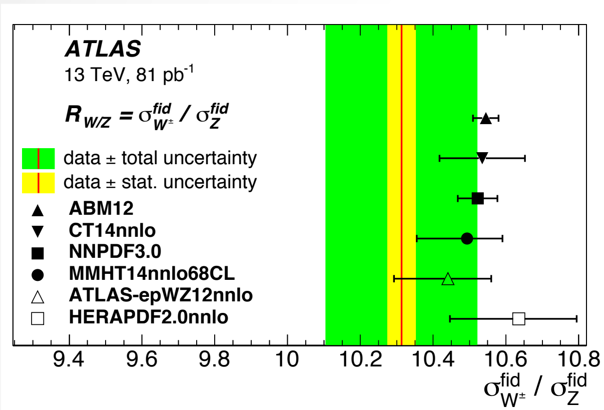


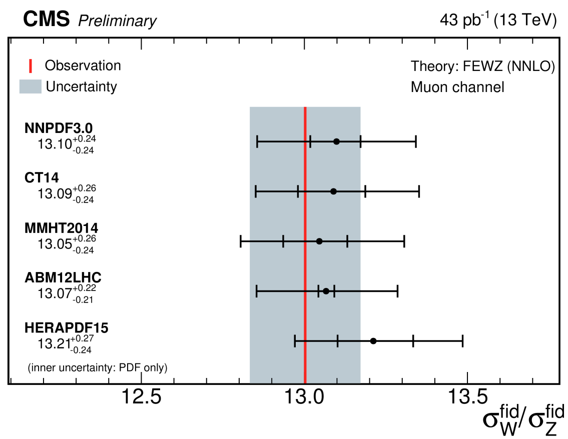


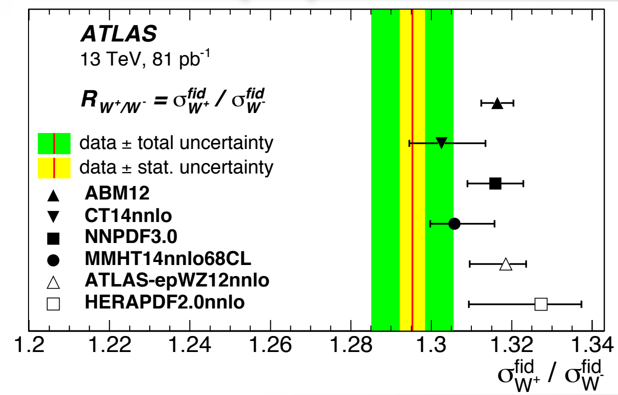
Central region

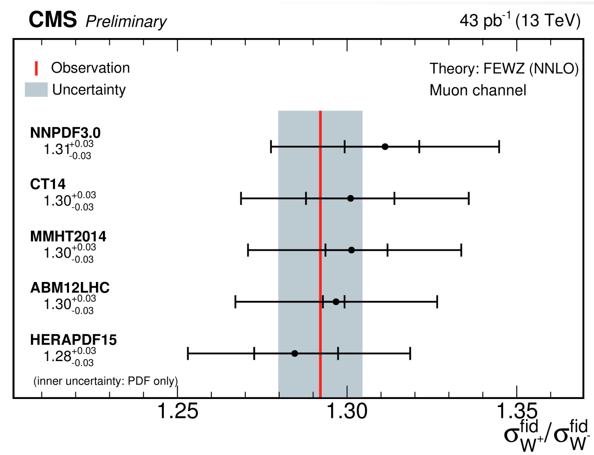
W and Z at 13 TeV: results (2)

- Cross sections ratio provides lower uncertainties.









➤ How much can we improve PDFs?

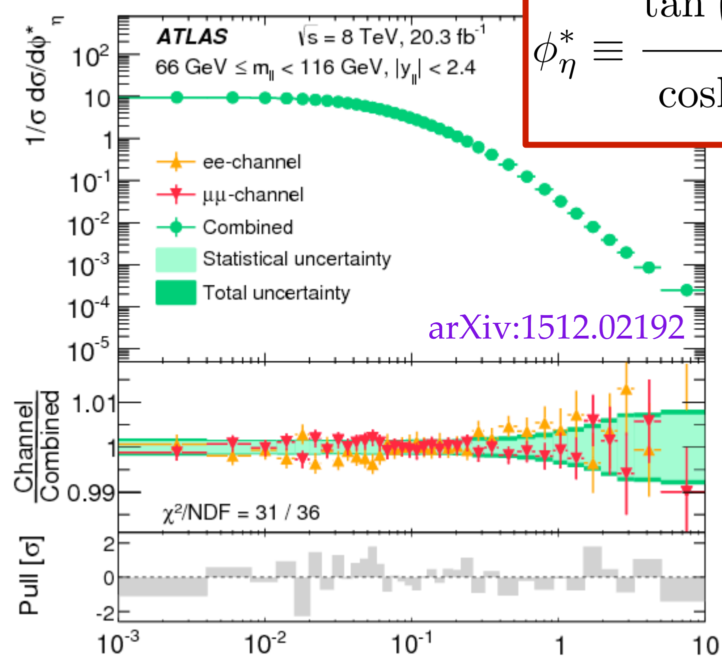
- Expected PDF improvements
  - W charge asymmetry
    - Studied as a function of η in Run 1 (ATLAS: CERN-PH-EP-2011-143; CMS: CERN-EP/2016-043; LHCb: CERN-PH-EP-2015-301)
  - Forward-backward asymmetry in Drell-Yan
    - V+jets: more in QCD session

Differential cross sections

- Channel: $Z/\gamma^* \longrightarrow l^+l^-$
  - CMS and LHCb provided first 13 TeV results (CMS-PAS-SMP-15-011, LHCb-CONF-2016-002)
  - ATLAS: detailed study on 8 TeV data (arXiv:1512.02192)

- <u>P_T and ϕ_η* spectrum</u>
  - p_T is very sensitive to QCD corrections and PDF
  - ϕ_η*: reflects p_T angular component
    - introduced to remove uncertainties from energy measurement.

$$\phi^*_\eta \equiv \frac{\tan\left(\frac{\pi-\Delta\phi}{2}\right)}{\cosh\left(\frac{\Delta\eta}{2}\right)}$$

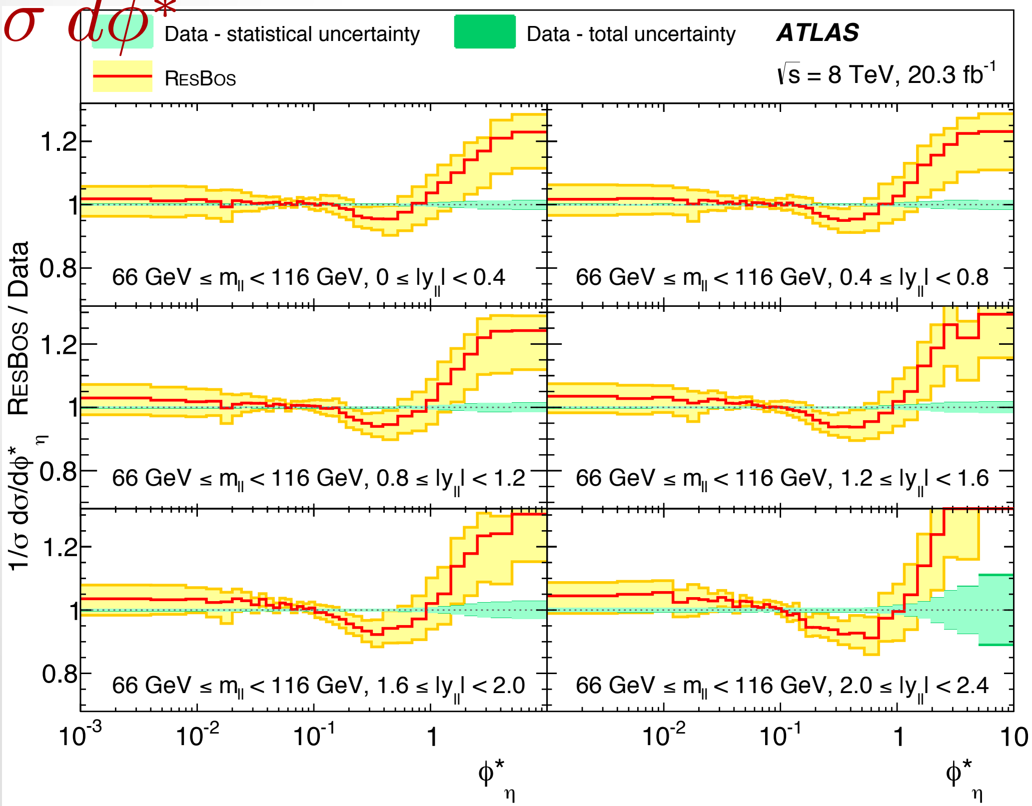


Example of ϕ_η* distribution

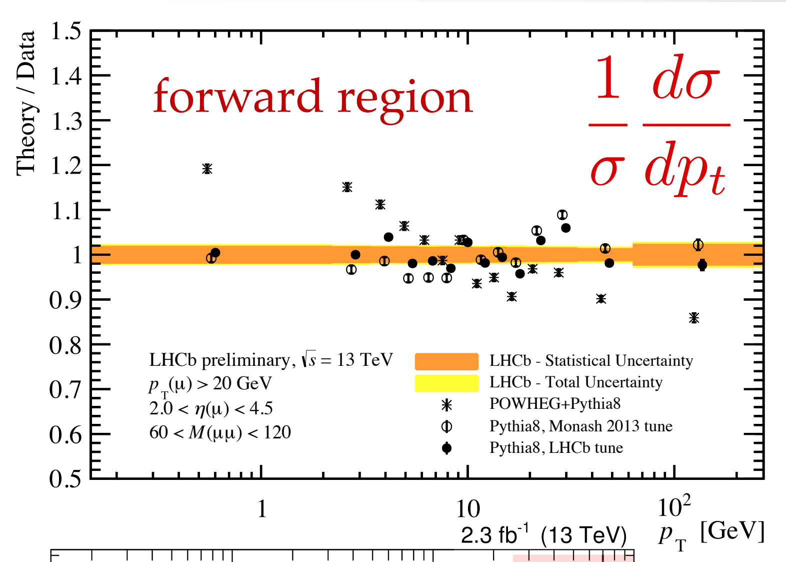
Differential cross sections

- $Z/\gamma^* \longrightarrow l^+l^-$, at 8 TeV
- All studied generators are unable to describes data through all the kinematic range

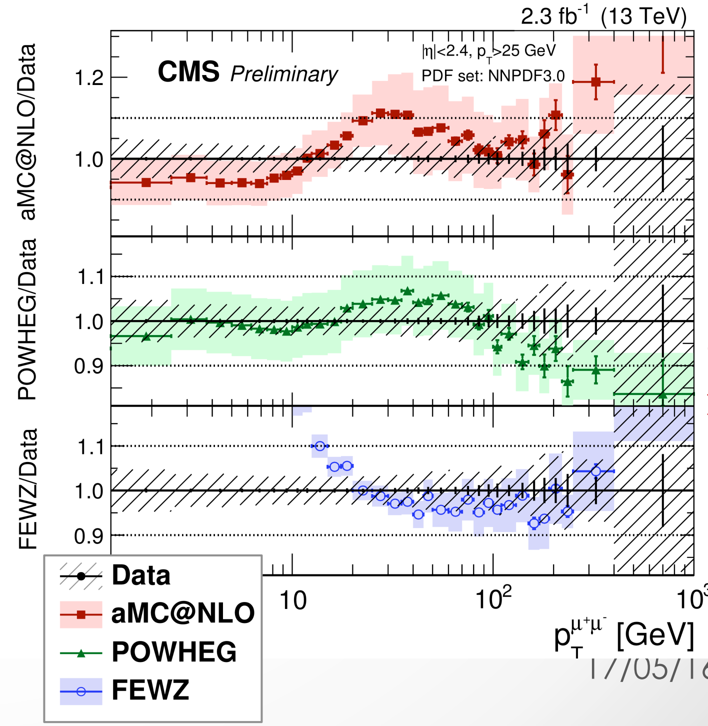
$\frac{1}{\sigma}\frac{d\sigma}{d\phi^*}$ varying y_{ll} region



forward region $\frac{1}{\sigma}\frac{d\sigma}{dp_t}$



$\frac{d\sigma}{dp_t}$ central region



Single boson in Run 2

- Replicate a full study at 13 TeV

- Will provide higher statistics in high pt tails
  - Sensitive to EWK corrections
  - Useful for searches

- Differential cross sections are fundamental inputs to precision measurements (next slides)
  - 13 TeV statistics will allow finer binning in soft region: systematic constraints for W mass measurement.

Precision measurements

- Test of the Standard Model (SM) through precision measurements of fundamental parameters.

- Of particular interest for electroweak physics at LHC:
  - W mass, M_W
    - SM consistency check: simultaneous indirect determination of top quark, Higgs boson and W mass.
  - $\sin^2(\vartheta_W)$
    - LEP/SLD precision measurement legacy: inconsistent results, discriminate between them.

W mass

- High precision needed

$$M_W(\text{global EW fit}) = 80.358 \pm 0.008\ \text{GeV}$$ [arxiv:1407.3792]

$$M_W(\text{exp.}) = 80.385 \pm 0.015\ \text{GeV}$$ [pdg.lbl.gov]

- M_W extracted fitting the Jacobian peak of $W \longrightarrow l\nu$ spectrum
  - Used variables: $m_T(l\nu)$, $p_T(l)$, E_T^{miss}
  - To achieve ~10 MeV precision on M_W we need permille precision on $p_T(l)$ spectrum [arXiv:1501.05587v2]
- Sensitive to PDF and higher orders corrections

W mass at LHC

- Analysis in progress in ATLAS/CMS (no public result)
- Proof of principle from CMS: $Z \longrightarrow \mu\ \mu$ mass removing one muon (CMS PAS SMP-14-007).
  - 20 MeV precision on calibrations is at hand
  - Concentrate on theoretical systematics

Sources of uncertainty [MeV]	$M_Z^{\mathrm{W like}+}$ p_T	$M_Z^{\mathrm{W like}+}$ m_T	$M_Z^{\mathrm{W like}+}$ $\not{E}_T$	$M_Z^{\mathrm{W like}-}$ p_T	$M_Z^{\mathrm{W like}-}$ m_T	$M_Z^{\mathrm{W like}-}$ $\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

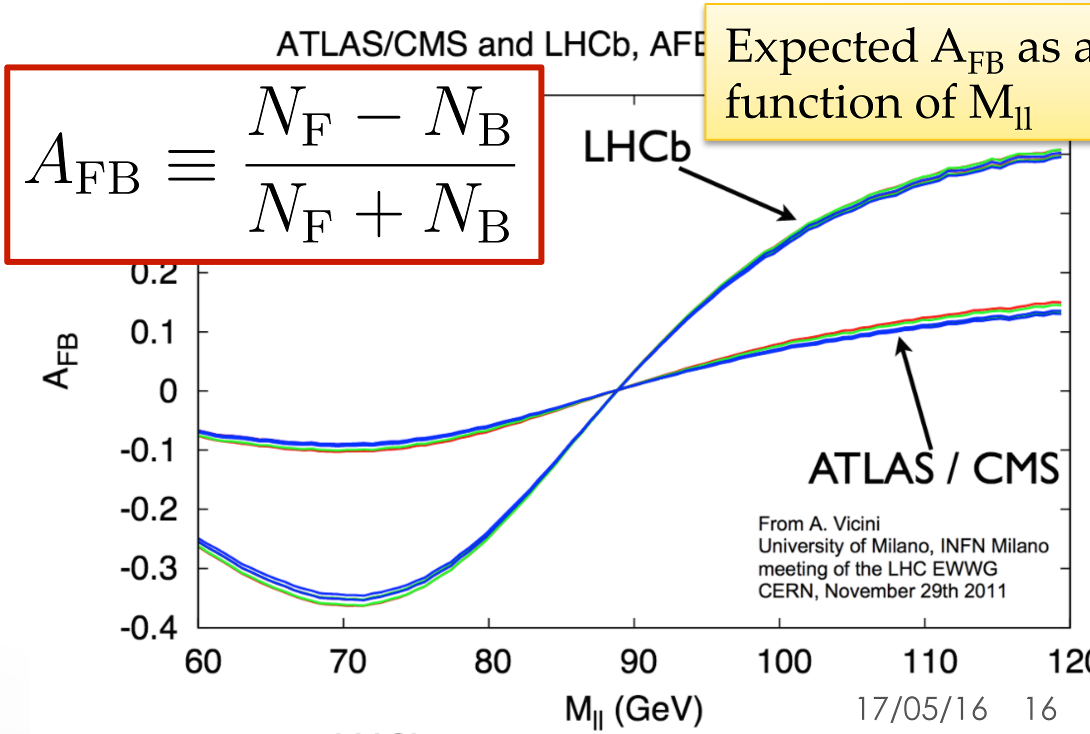
- Improvement expected from LHCb
  - adding information from forward region could increase the precision of roughly 30% [arXiv:1508.06954v2]

$\sin^2(\vartheta_W)$ in $Z/\gamma^* \to l^+l^-$ events

- ATLAS / LHCb: 7/8 TeV results (arXiv:1503.03709v2/arXiv:1509.07645v2), older (2011) result from CMS (arXiv:1110.2682v2).
- We measure $\sin^2(\vartheta_{eff})$:
  - proportional to $\sin^2(\vartheta_W)$, includes radiation corrections.
- Extracted fitting A_{FB} as a function of di-lepton invariant mass.
  - Quark direction assumed to correspond with that of the Z
    - $u\bar{u}, d\bar{d} \to Z$
    - Valence quark: more likely to have the largest momentum.
    - Better sensitivity in the forward region

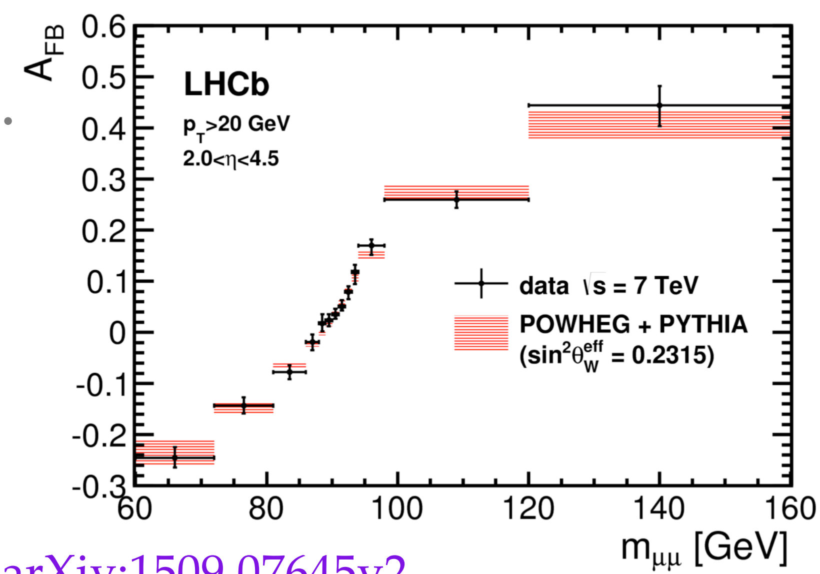
$$A_{\mathrm{FB}} \equiv \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}$$

Expected A_{FB} as a function of M_{ll}

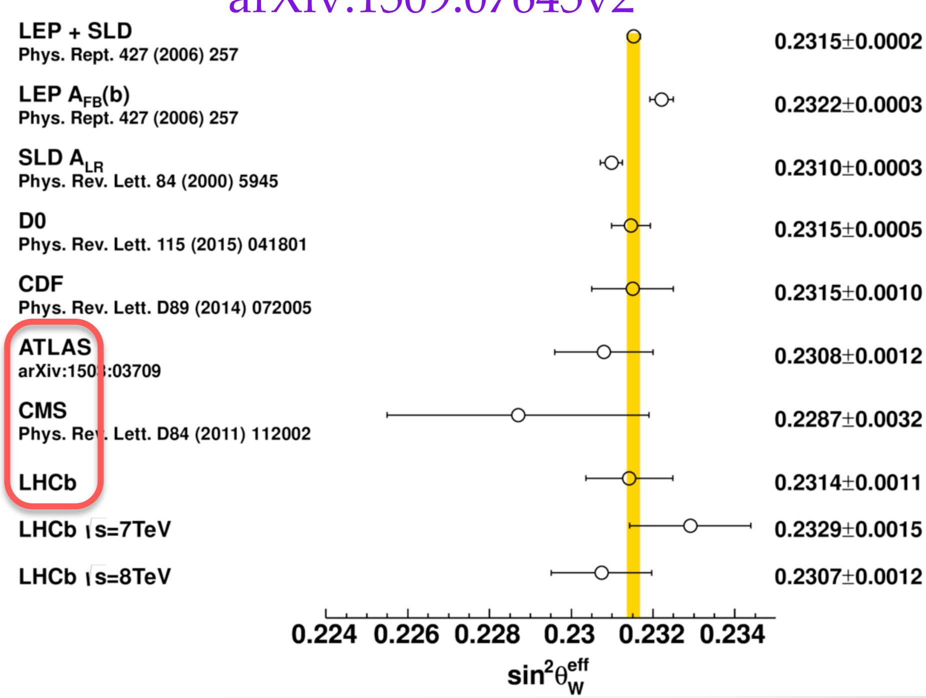


$\sin^2(\vartheta_W)$ latest results

- LHCb has the highest sensitivity.
  - statistically dominated.
  - ATLAS has similar precision, but dominated by PDF uncertainty



arXiv:1509.07645v2

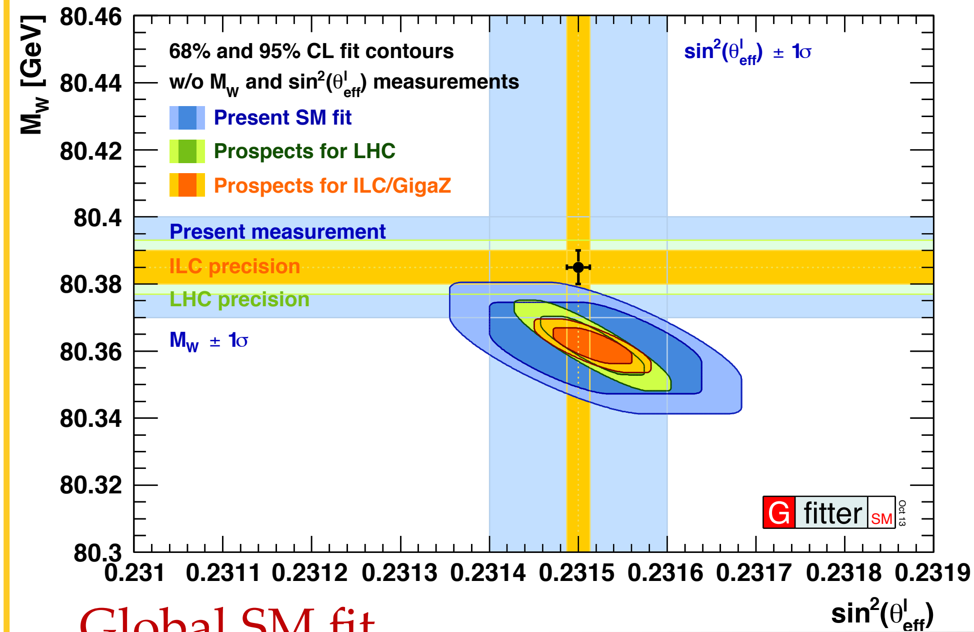


- CDF approach may help (arXiv:0911.2850v4, arXiv:1512.08256v1)
  - corrects for A_{FB} diluition, reweight dependent on polar angle ϑ
- PDFs can be improved by in situ measurements

Future prospects for precision measurements

- Improving precision in next year(s) results rely on
  - Theoretical calculation
  - PDF constraint
    - New data available
    - Larger contribution from sea quarks: constraints at low x needed
  - Detector calibration
    - Larger PileUp to handle (especially ATLAS/CMS)
  - Statistics
    - Allow more sensitive approaches as A_{FB} in bins of η_Z
    - Energy region of interest quite low for ATLAS/CMS trigger thresholds: trigger optimization could be needed.

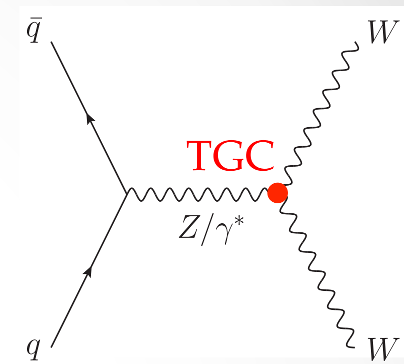
- Expected improvements from future colliders.

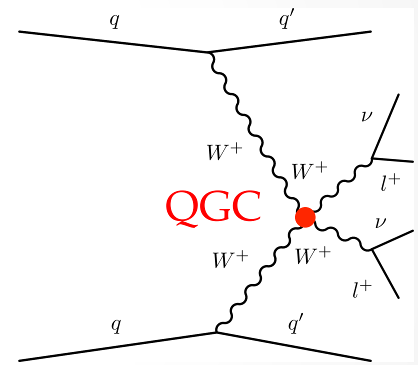


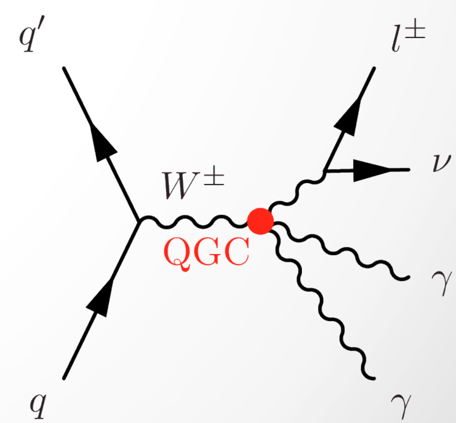
Global SM fit
From 'Snowmass' (arXiv:1310.6708v1)

Multibosons

- Associated production of two (diboson) or more gauge bosons.
  - In this talk:
    - Diboson
    - Vector Boson Fusion (VBF)
    - Vector Boson Scattering (VBS)
    - Tri-bosons
- Fundamental test of gauge bosons self interactions
  - Eventual deviations from expected couplings may be induced by new physics.
  - Anomalous Triple (Quartic) Gauge Coupling or aTGC (aQGC)
- Major backgrounds to Higgs physics and exotic searches.

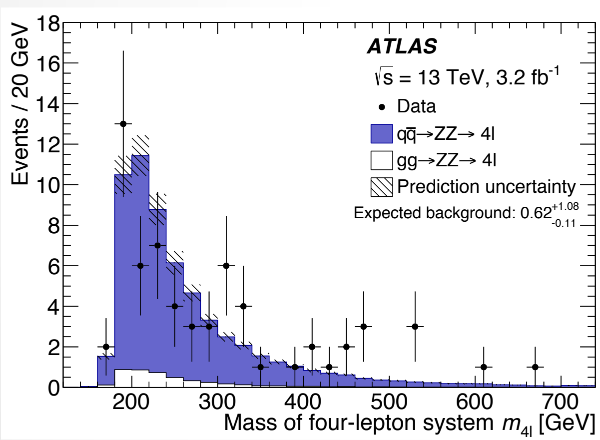




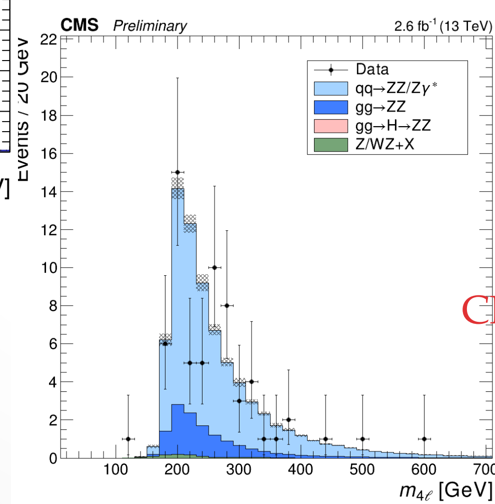


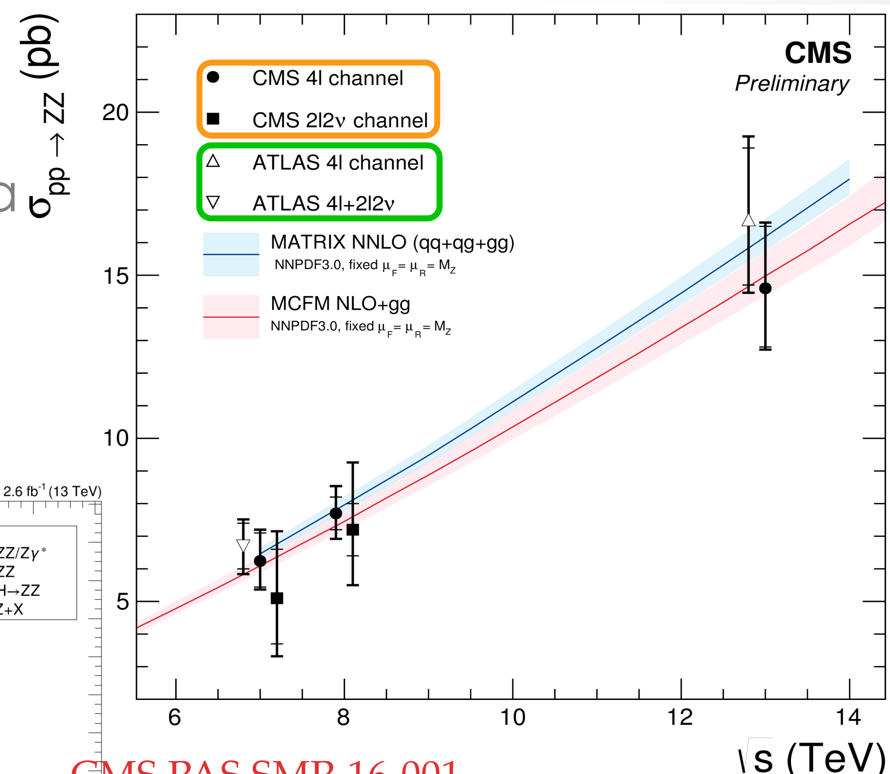
Diboson: ZZ

- Multiple studies by ATLAS and CMS
  - ZZ⟶4l
    - Also studies of inclusive 4-lepton cross section (ATLAS, CERN-PH-EP-2015-220).
  - ZZ⟶2l2 ν
- Still statistic dominated at 8 TeV
- First results at 13 TeV with 2015 data



CERN-PH-EP-2015-318



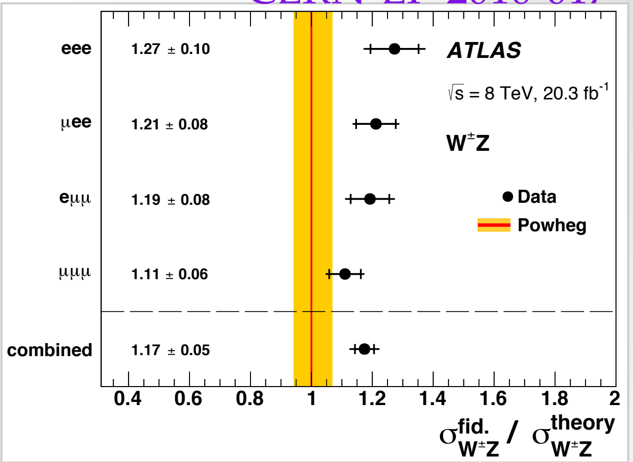


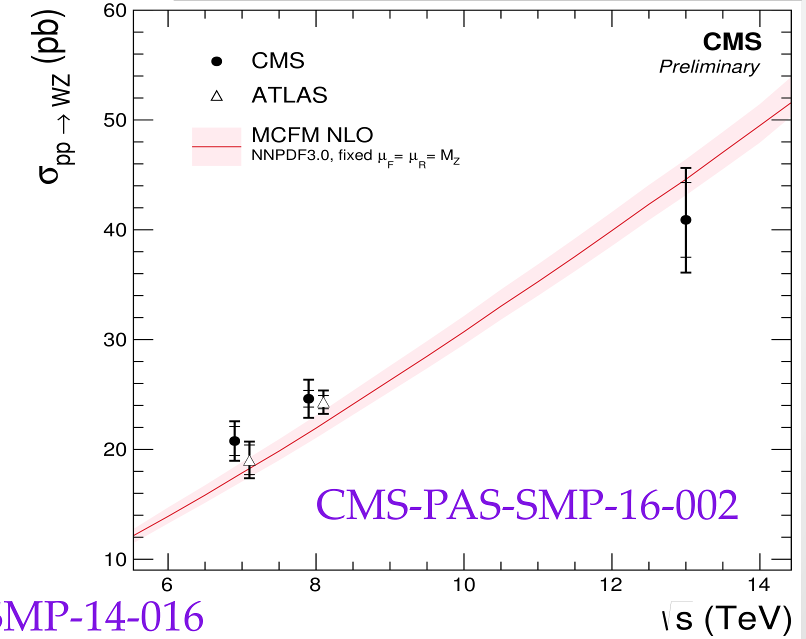
CMS PAS SMP-16-001

Diboson: WW / WZ

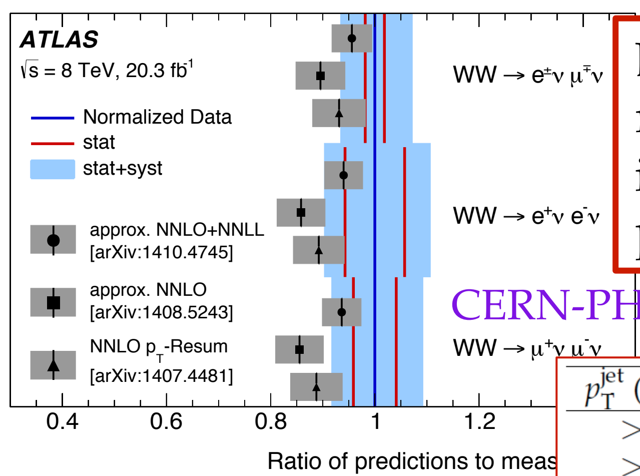
- Analysis from ATLAS and CMS
  - Fully leptonic at 7 and 8 TeV, 13 TeV (only CMS)
- WZ data exceed MC of roughly 2 σ at 8 TeV.
  - Not confirmed by first result at 13 TeV.
- Similar effect observed by ATLAS in WW(+0jets)
  - Jet veto enhances contributions beyond fixed-oreder calculation
  - CMS reweights MC to p_T-resummed calculation.

CERN-EP-2016-017





CMS-PAS-SMP-16-002



Disagreement reduces with increasing MC precision

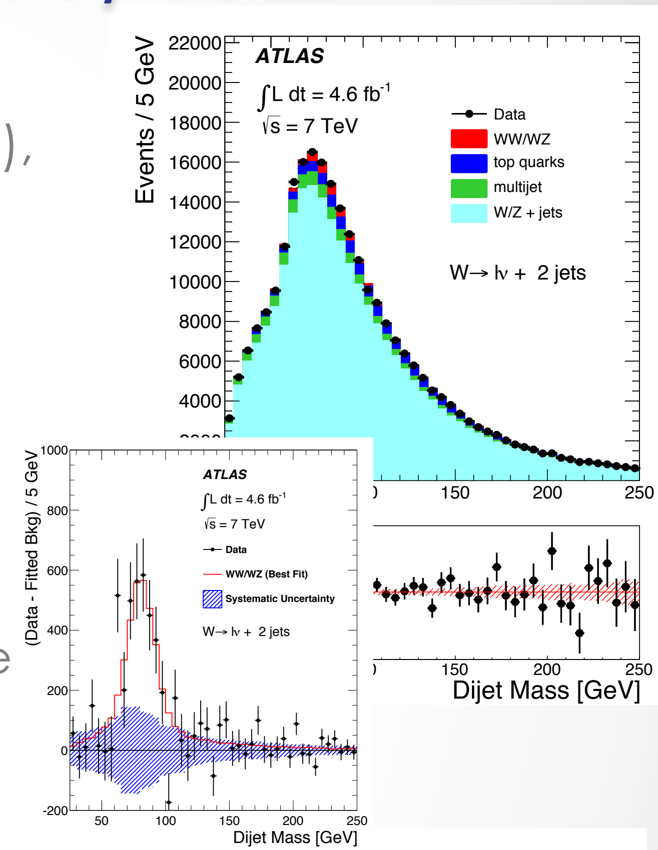
CERN-PH-EP-2015-323

CMS-SMP-14-016

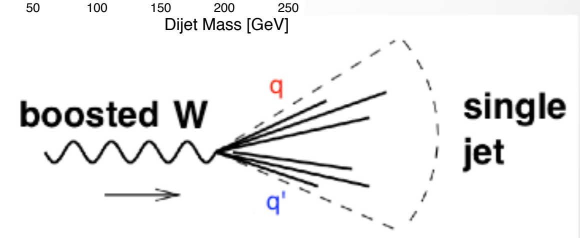
p_T^{jet} (GeV)	$\sigma_{zero\text{-}jet}$ measured (pb)	$\sigma_{zero\text{-}jet}$ predicted (pb)
>20	36.2 ± 0.6 (stat) ± 2.1 (exp) ± 1.1 (theo) ± 0.9 (lumi)	36.7 ± 0.1 (stat)
>25	40.8 ± 0.7 (stat) ± 2.3 (exp) ± 1.3 (theo) ± 1.1 (lumi)	40.9 ± 0.1 (stat)
>30	44.0 ± 0.7 (stat) ± 2.5 (exp) ± 1.4 (theo) ± 1.1 (lumi)	43.9 ± 0.1 (stat)

Semi-leptonic WW/WZ

- W⟶lν , W/Z⟶jj
  - Run 1 results: ATLAS (CERN-PH-EP-2014-244), CMS (CERN-PH-EP-2012-311)
  - Larger background and systematics than fully leptonic
  - No 8 TeV results: stay tuned for more!



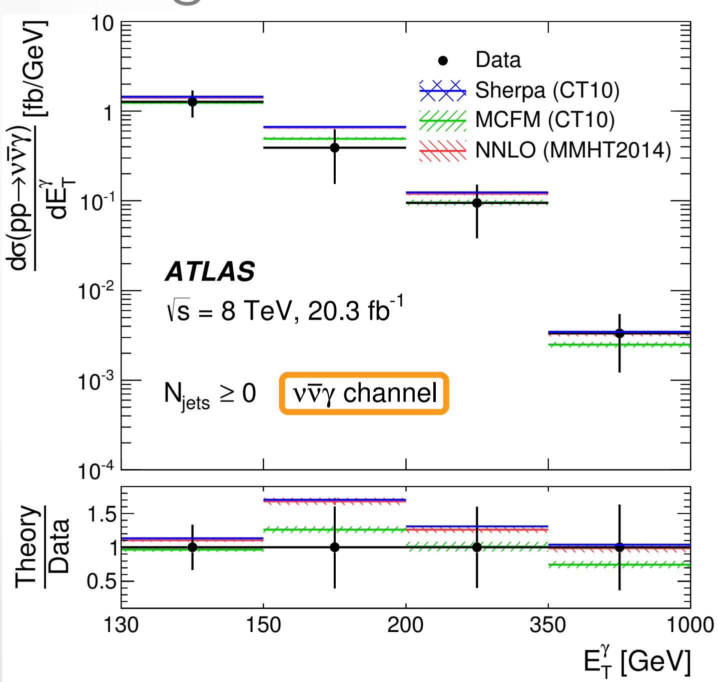
- Many developing 'W-taggers' for Run 2
  - Hadronically decaying W/Z in boosted regime
    - the quarks from W/Z decay collimated due to W/Z boost
    - detected as single large jet
  - Used for exotic searches (more in dedicated talk)
  - For reference: CERN-PH-EP-2015-204, CMS-JME-13-006.

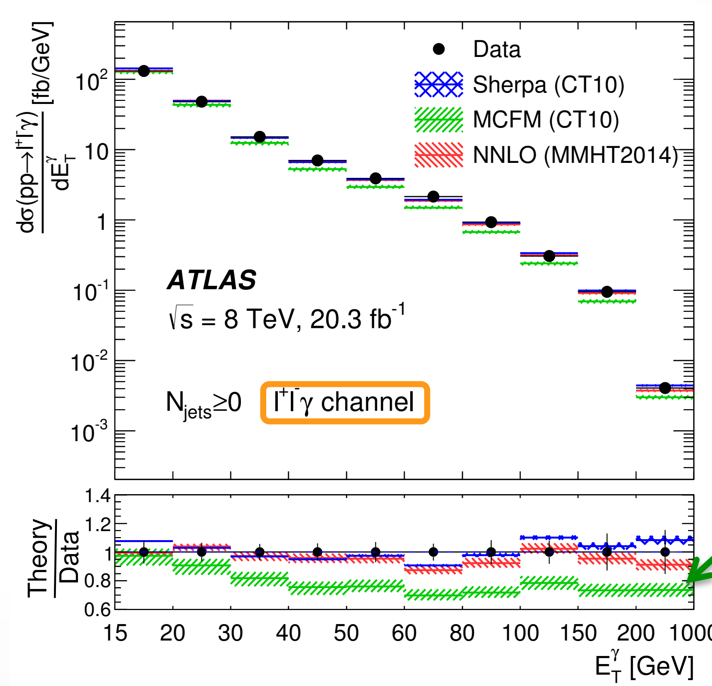


- Standard model WW/WZ: important to test these methods on real known resonances.

Diboson: W/Z and photons

- $W\gamma$ and $Z\gamma$ measured at 7 TeV by ATLAS and CMS
- New studies on $Z\gamma$ with 8 TeV statistics
  - CMS (SMP-14-019): $Z\gamma \to \nu\bar{\nu}\gamma$
  - ATLAS (CERN-EP-2016-049): $Z\gamma \to l^+l^-\gamma$ $Z\gamma \to \nu\bar{\nu}\gamma$
- ATLAS: differential cross section in observables sensitive to higher-order QCD corrections





NLO,
no parton
shower

Anomalous Triple Gauge coupling (aTGC)

- Deviations from SM expectations due to new physics.

- Model-independent description of new physics
  - Effective Field Theory (EFT)
    - Operators of mass dimension >4 added to the SM Lagrangian.
  - Anomalous couplings: equivalent (older) scenario
    - Linear relation between the two:

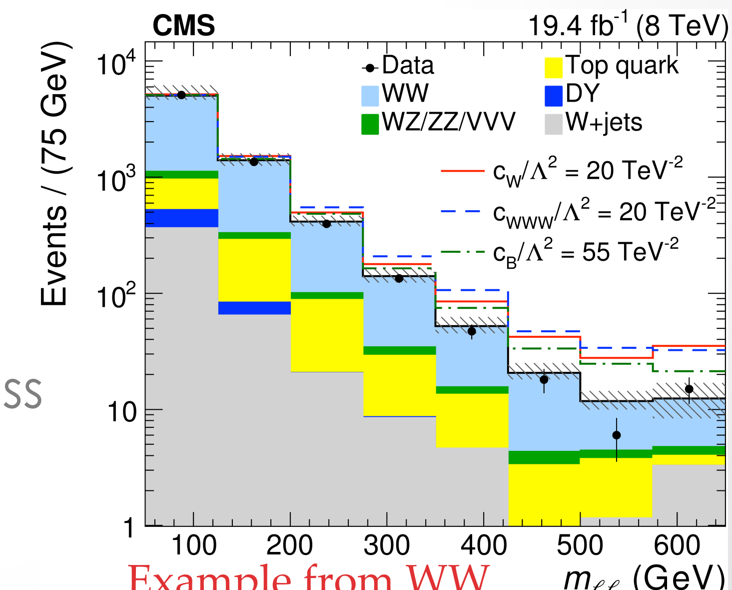
Example: dimension 6 operators

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}],$$

$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2}\left(D_\mu\Phi\right)^\dagger W^{\mu\nu}\left(D_\nu\Phi\right)$$

$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2}\left(D_\mu\Phi\right) B^{\mu\nu}\left(D_\nu\Phi\right),$$

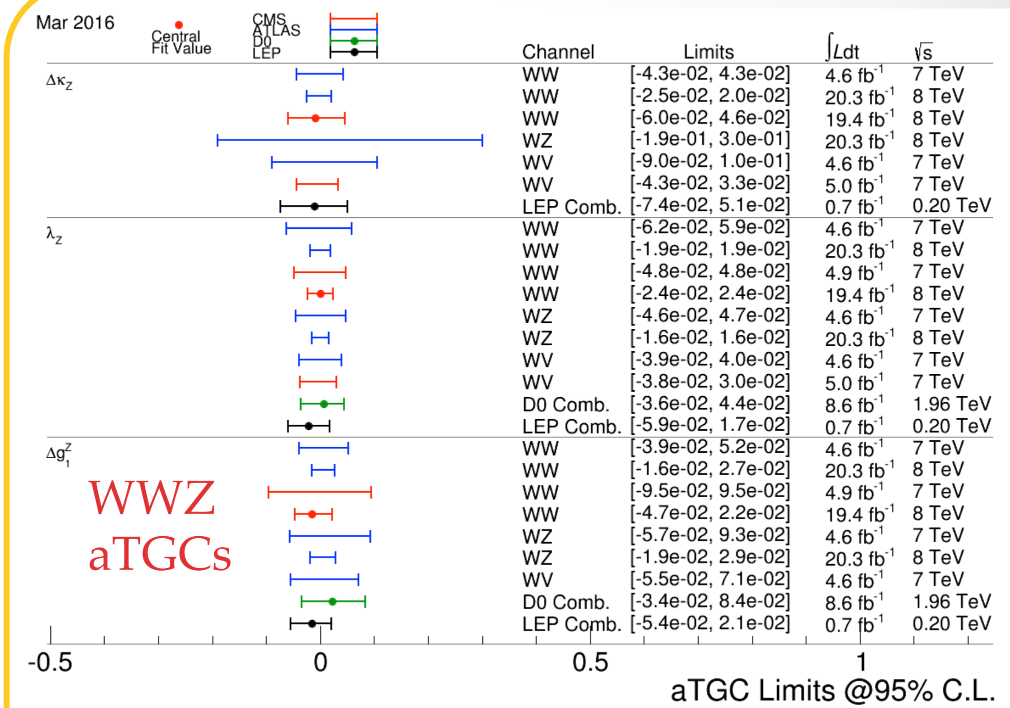
- New physics parameters estimated fitting data
  - Expected larger effect at larger mass
  - The invariant mass is used
    - or related quantities as boson p_T



Example from WW (CMS-SMP-14-016)

aTGC summary

- No evidence of anomalous coupling from available analysis
- ATLAS/CMS provide competitive limits.
- Larger statistics at high mass needed
  - precision will improve with Run 2



<u>Anomalous couplings</u>

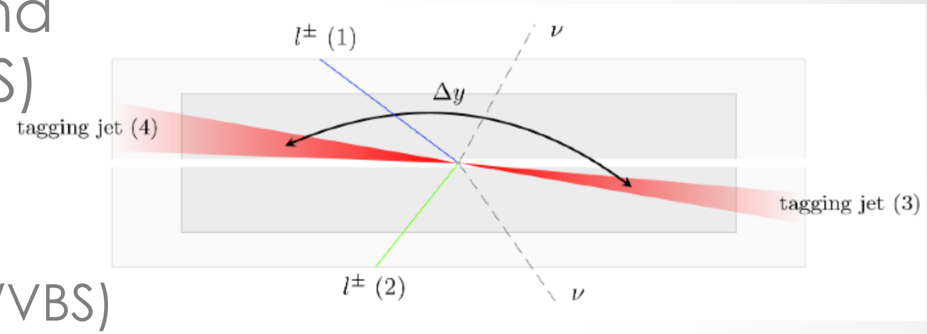
- Charged couplings:
  - WWZ, WW γ
- Neutral couplings:
  - $Z\gamma\gamma/ZZ\gamma$, $ZZ\gamma/ZZZ$

Diboson prospects for run 2 (and beyond)

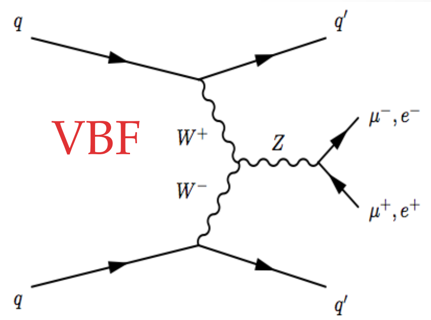
- ATLAS/CMS: precision diboson measurements
  - Improve cross sections using full 13 TeV statistics.
  - Understand differential cross sections and kinematic spectra.
- LHCb: up to now, statistics not sufficient
  - In run 2, diboson measurements in forward region will be possible.
  - Key cross-check of ATLAS/CMS results in complementary phase space region.
- aTGCs, possible sensitivity improvements:
  - Larger statistics on high-mass tails in Run 2
  - Combination between aTGC and Higgs measurements (arXiv:1604.03105)
  - Larger precision with future e^+e^- colliders.

Vector bosons + forward-backward jets

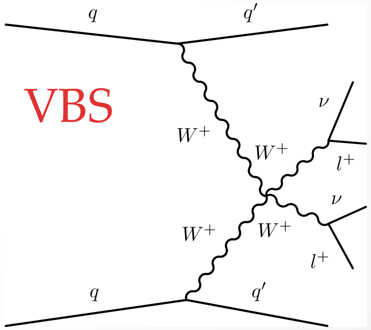
- Vector Boson Fusion (VBF) and Vector Boson Scattering (VBS)



- Common signature
  - One/two vector bosons (VBF/VBS)
  - Two jets of large |Δy|
    - Low activity in Δy gap



- Common issue
  - Interference with QCD diagrams
  - Electroweak contribution is extracted treating the QCD component as background
    - Systematic associated to interference term
  - Methods
    - Fit of m_{jj}
    - Multivariate analysis
    - Cut&count for very rare processes

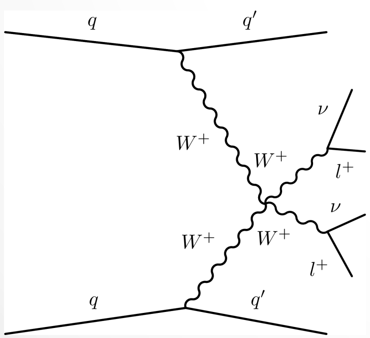


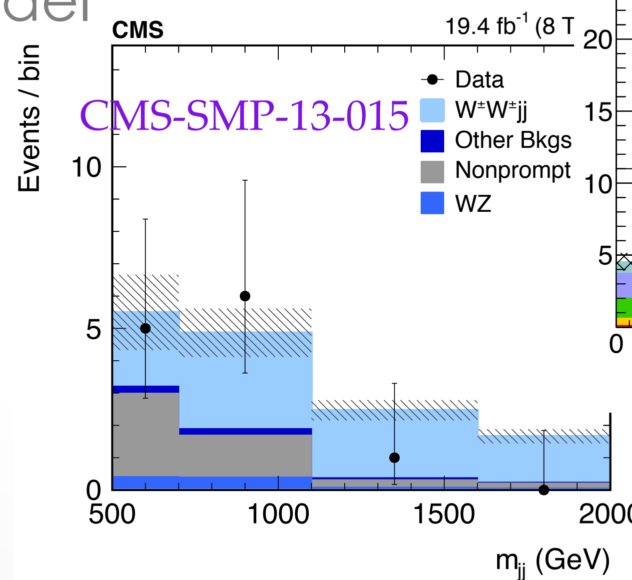
Vector Boson Scattering (WW⟶WW)

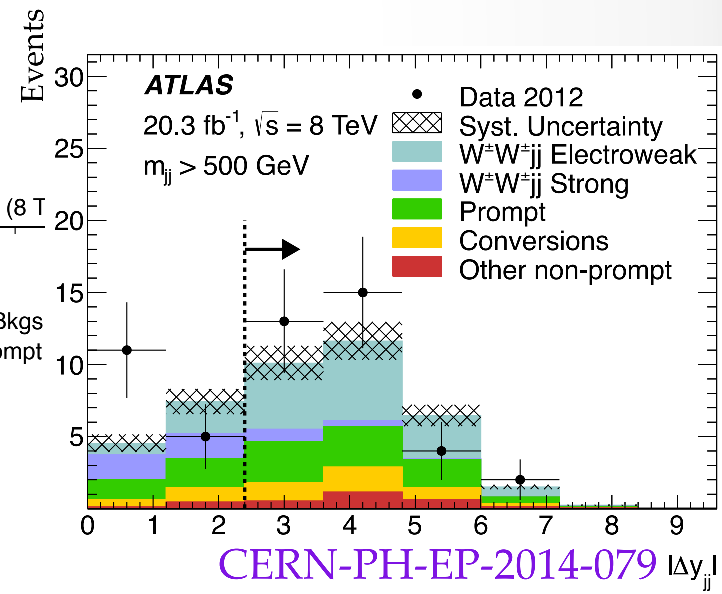
- Without a Higgs boson, VBS amplitude increase with √s and ultimately violate unitarity
  - to be proved that unitarization is due to Higgs boson
  - possible VBS enhancements due to additional resonances

- Key search strategy: same sign W±W±jj
  - Electroweak W±W±jj observed by ATLAS and CMS (SMP-13-015, CERN-PH-EP-2014-079)
  - Consistent results between the two

- No evidence of physics beyond the Standard Model

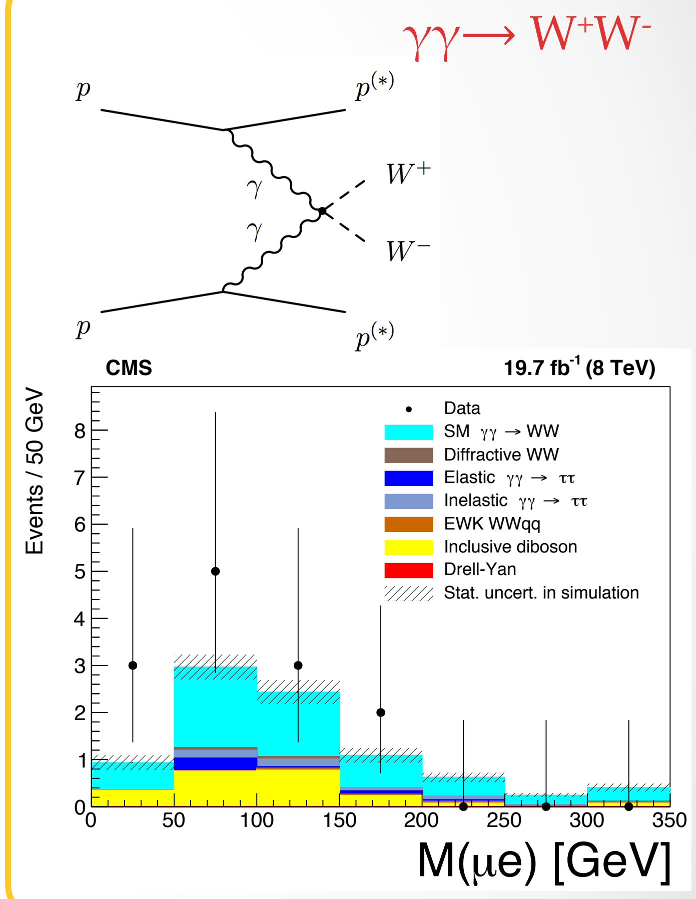






Other VBS channels

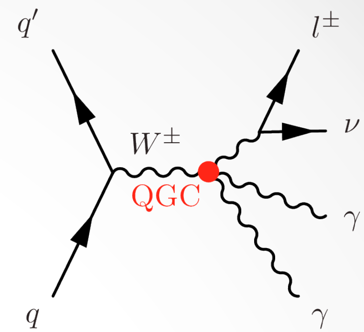
- Electroweak component of opposite-sign WWjj: $\gamma\gamma \longrightarrow W^+W^- \longrightarrow e\nu\mu\nu$ (CMS: CMS-FSQ-13-008)
  - $e\mu$ final state chosen to reduce Drell-Yan background
  - 3.4σ observed significance
  - stringent limits on aQGC



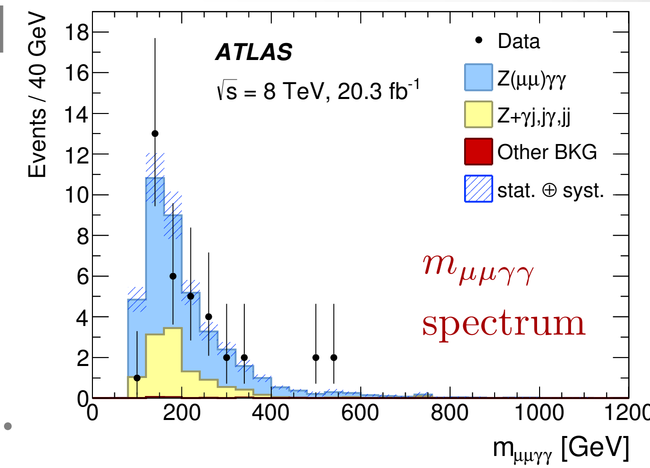
- WZjj (CMS: CMS-SMP-13-015. ATLAS: CERN-EP-2016-017)
  - CMS: require one additional lepton in same-sign WWjj
  - ATLAS: require two jets in WZ analysis

- $W\gamma$jj / $Z\gamma$jj (CMS: SMP-14-011, SMP-14-018)
  - Cut and count approach.
  - Evidence of electroweak contribution.

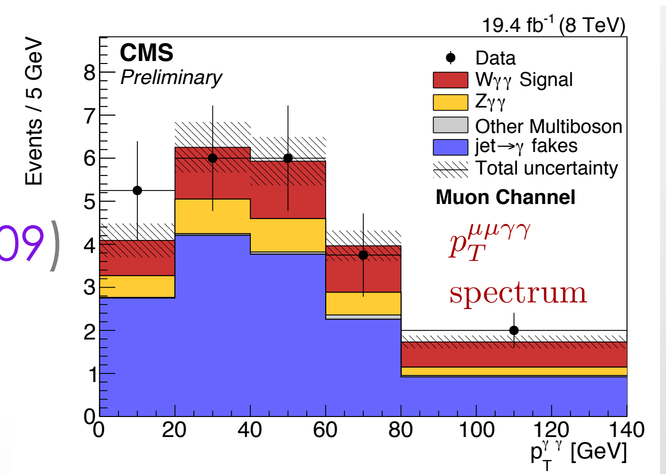
Tri-bosons



- Probe of QGC complementary to VBS
- Three out of four bosons are identified
  - Precise knowledge of the involved vertex



- First measurements of three gauge bosons production are now available.
- V γ γ
  - W γ γ
    - CMS: W⟶ μ ν (SMP-15-008).
    - ATLAS: W⟶ μ ν /e ν (CERN-PH-EP-2015-009)
  - Z γ γ
    - CMS: Z⟶l^+l^- (SMP-15-008).
    - ATLAS: Z⟶l^+l^-/ ν ν , (CERN-EP-2016-049)



Summary and future prospects

- VBS/Tri-boson physics starts being exploited with full 8 TeV data
- All aQGC limits are consistent with zero.
- More complete measurements will be possible with next years statistics
- To get precision measurements, we will have to wait for 300 fb^{-1} or even HL-LHC.
  - High precision to detect small effects in high mass tails.
  - Full hardware upgrade necessary
  - See for instance
    - 'Snowmass' report arXiv:1310.6708v1
    - ATL-PHYS-PUB-2013-006
    - CMS-TDR-15-02

Conclusions

- We can now test full consistency of Standard Model parameters as experimentally determined.
  - From LHC:
    - M_W not yet measured
    - sen(ϑ_W) to be improved

- Precision studies on electroweak processes with large cross section
  - Single bosons and (starting) dibosons
  - Hints on how well we understand and model Standard Model processes
    - Our description still has to be improved
    - Dibosons: detailed test of emerging frontier calculations.

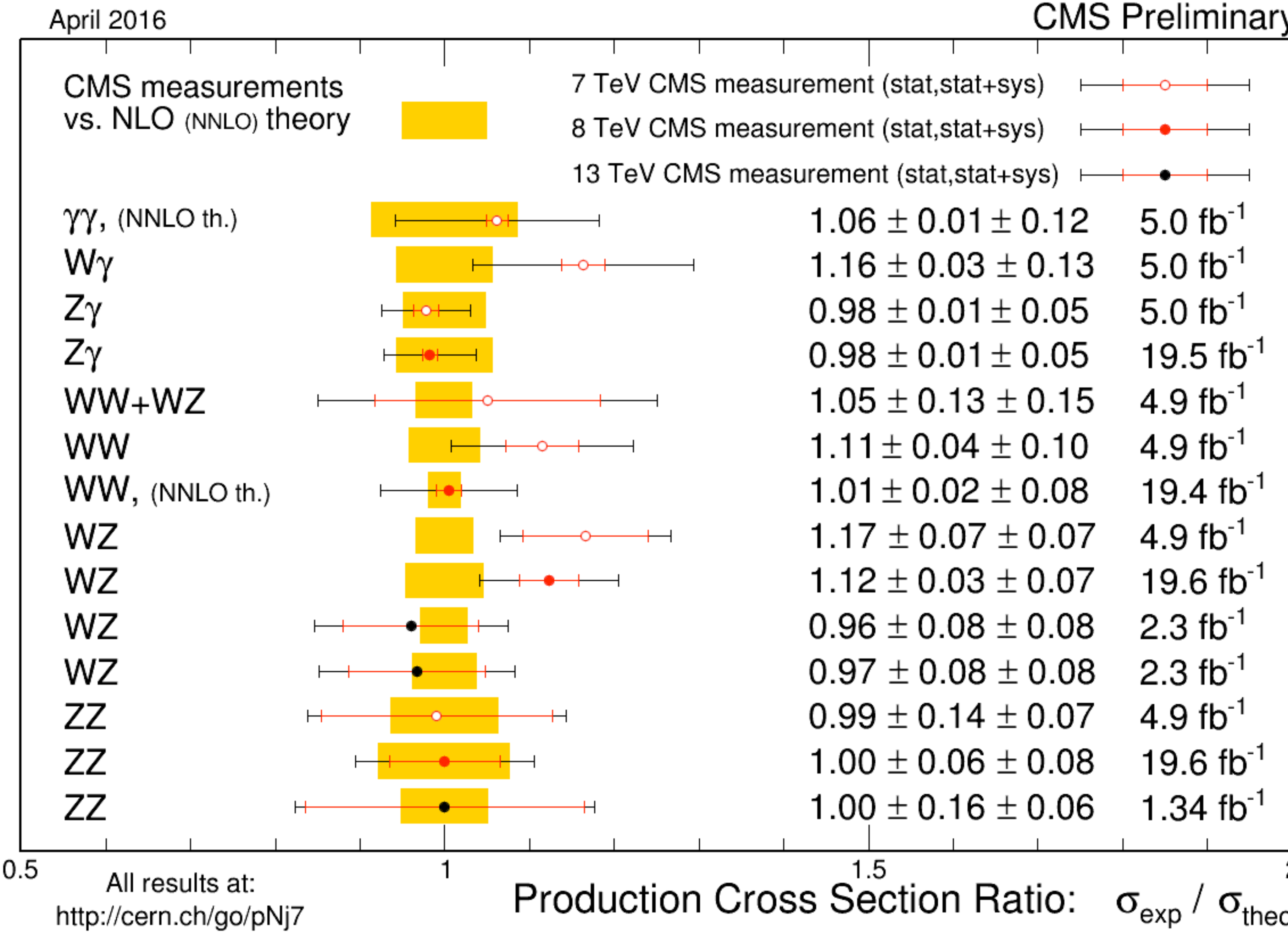
- Rare electroweak processes
  - VBS and tri-bosons
  - Expect full exploiting with $L \geq 30\ fb^{-1}$

- Drell-Yan ϕ^* : quanto è interessante/usabile dal punto di vista teorico?
- La prossima frontiera del confronto: NNLO+PS, NNLO+risommazione, entrambi... quanto agevolmente possiamo usarle dal punto di vista sperimentale?
- Stiamo andando sempre a ordine successivo, ma qual'è il benchmark in precisione che ci serve? La misura dei parametri fondamentali? Altri?
- Quanto possiamo imparare dai rapporti tra diverse energie?

- $\sin^2(\vartheta_W)$ possiamo imparare dagli ultimi risultati del Tevatron?
  - Riduzione della dipendenza dalle PDF...
- M_W: a che punto siamo con le sistematiche teoriche? Come estrapoliamo le misure dalla Z al W?
  - A 13 TeV avremo più pileup, ci aiuta il run 2?
- Combinazione della frontiera delle correzioni QCD e EWK?

- aTGC: come possiamo andare oltre il Run1?
  - combinazione dei risultati a 7 TeV ATLAS/CMS, possiamo evolverla?
  - proposte di analisi combinate di accoppiamenti VV/Higgs
- VBF/VBS
  - Interferenze EW/QCD: esiste un approccio migliore che separare i contributi dei vari diagrammi?

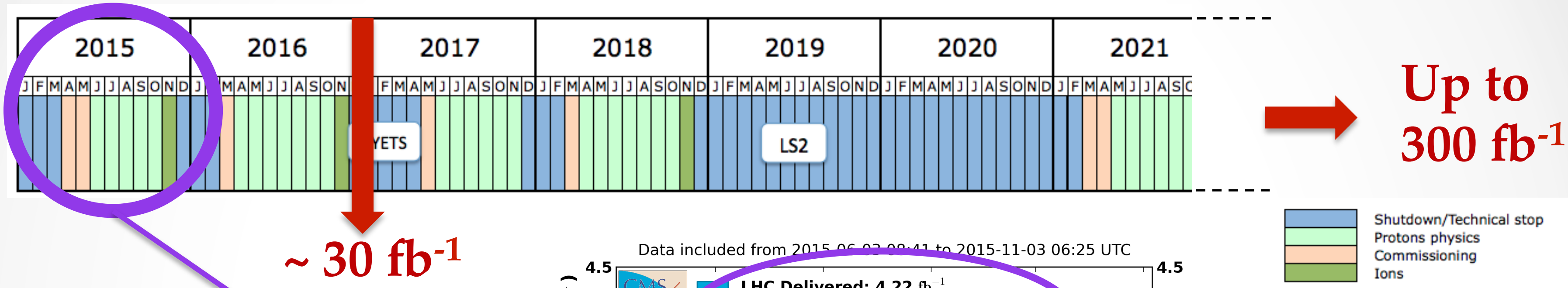
Backup



April 2016
CMS Preliminary
CMS measurements
vs. NLO (NNLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ, (NNLO th.)
Wγ
Zγ
Zγ
WW+WZ
WW
WW, (NNLO th.)
WZ
WZ
WZ
WZ
ZZ
ZZ
ZZ
1.06 ± 0.01 ± 0.12 5.0 fb-1
1.16 ± 0.03 ± 0.13 5.0 fb-1
0.98 ± 0.01 ± 0.05 5.0 fb-1
0.98 ± 0.01 ± 0.05 19.5 fb-1
1.05 ± 0.13 ± 0.15 4.9 fb-1
1.11 ± 0.04 ± 0.10 4.9 fb-1
1.01 ± 0.02 ± 0.08 19.4 fb-1
1.17 ± 0.07 ± 0.07 4.9 fb-1
1.12 ± 0.03 ± 0.07 19.6 fb-1
0.96 ± 0.08 ± 0.08 2.3 fb-1
0.97 ± 0.08 ± 0.08 2.3 fb-1
0.99 ± 0.14 ± 0.07 4.9 fb-1
1.00 ± 0.06 ± 0.08 19.6 fb-1
1.00 ± 0.16 ± 0.06 1.34 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

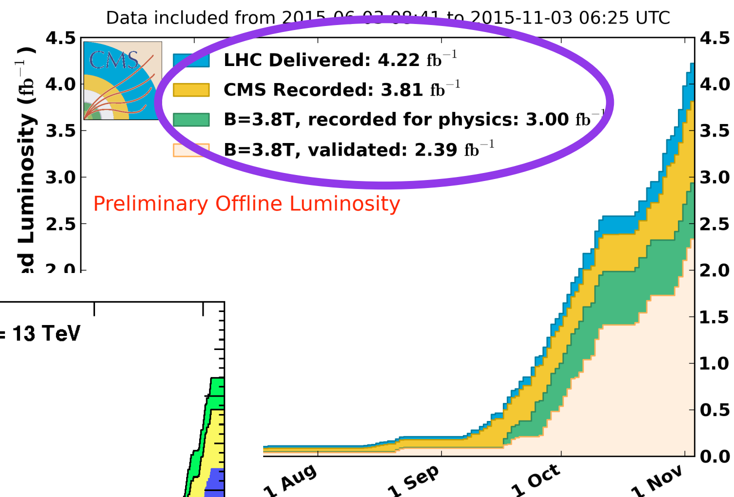
From run 1 to run 2

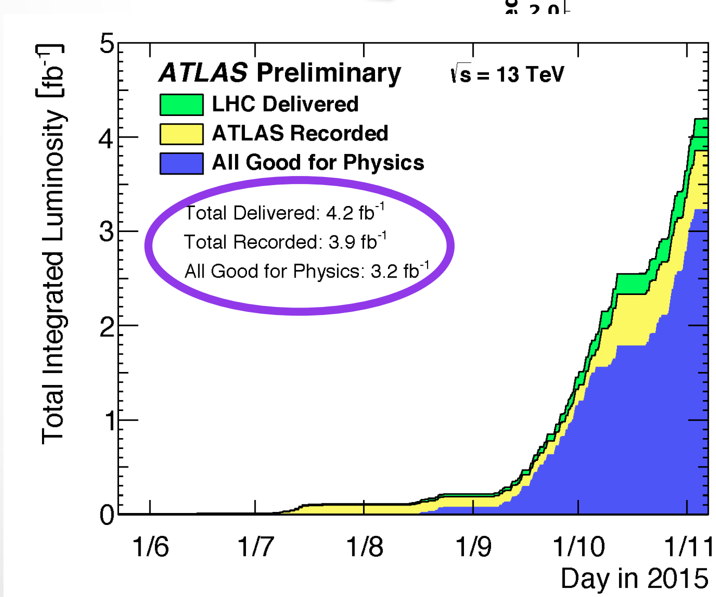
- Run I: $\sqrt{s}$ = 7 TeV / 8 TeV. ATLAS/CMS: ~25 fb^{-1}, LHCb: ~3 fb^{-1}

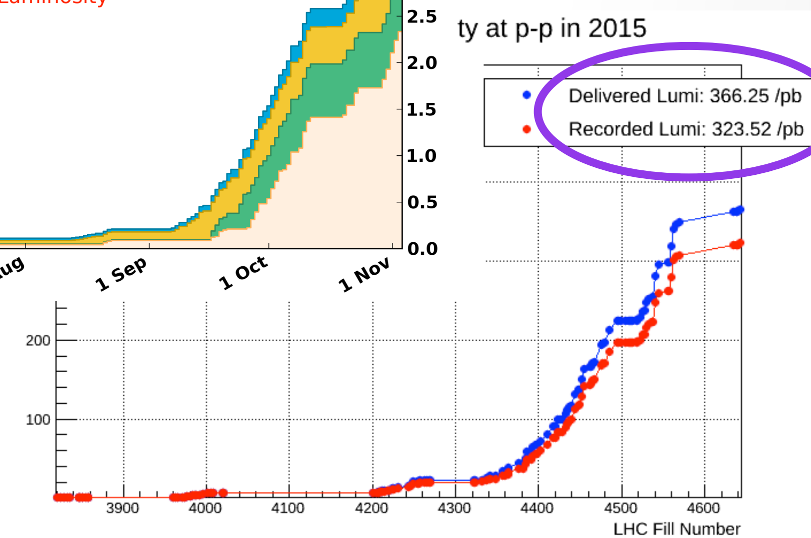


~ 30 fb^{-1}

Up to 300 fb^{-1}

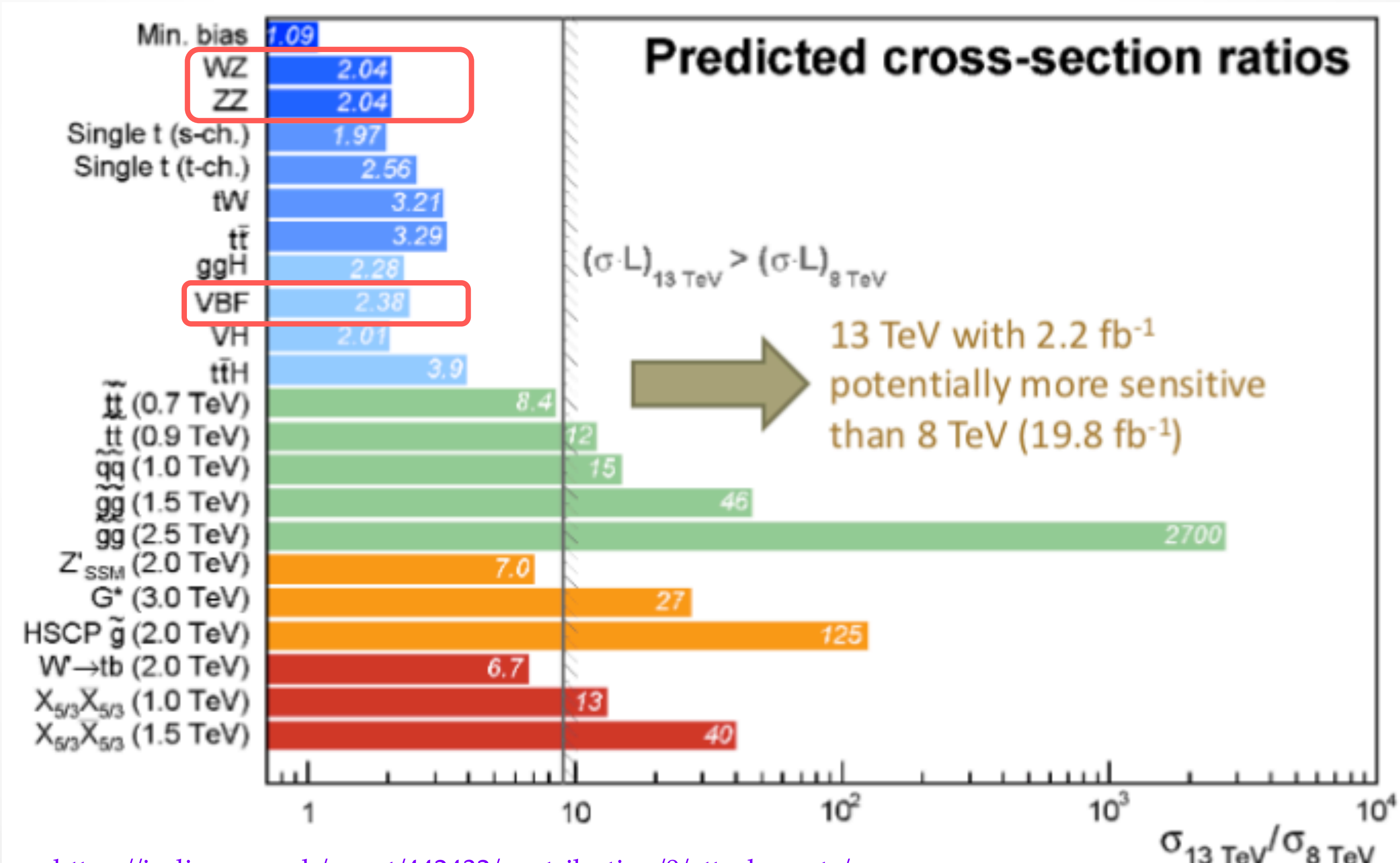






What changes with Run 2

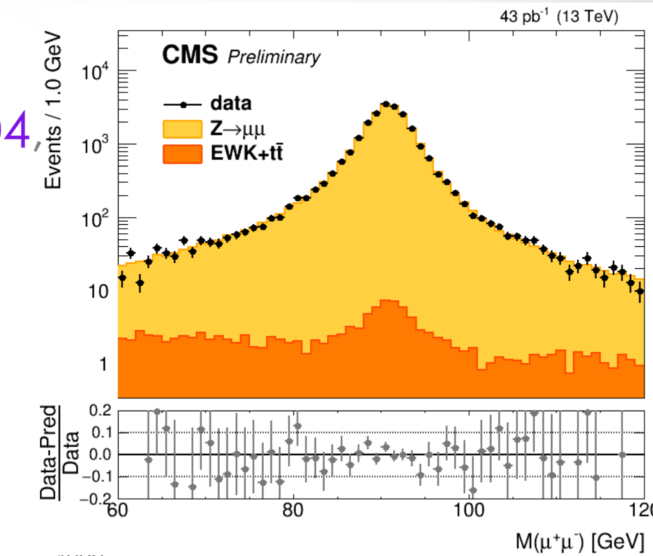
- To effectively increase sensitivity in SM processes, we need at least 2016 data



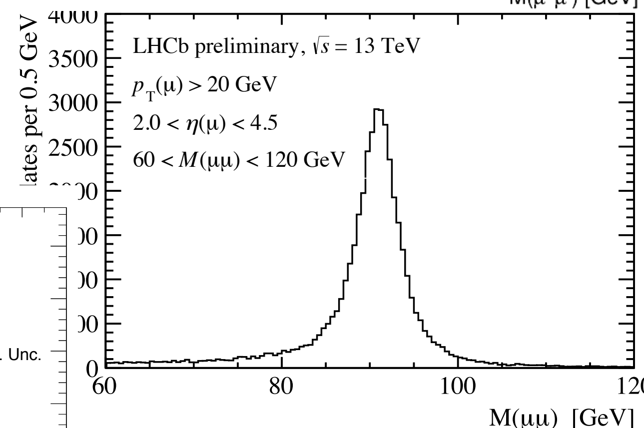
https://indico.cern.ch/event/442432/contribution/0/attachments/1205563/1756687/CMS_13_TeV_results_public.pdf

W and Z at 13 TeV

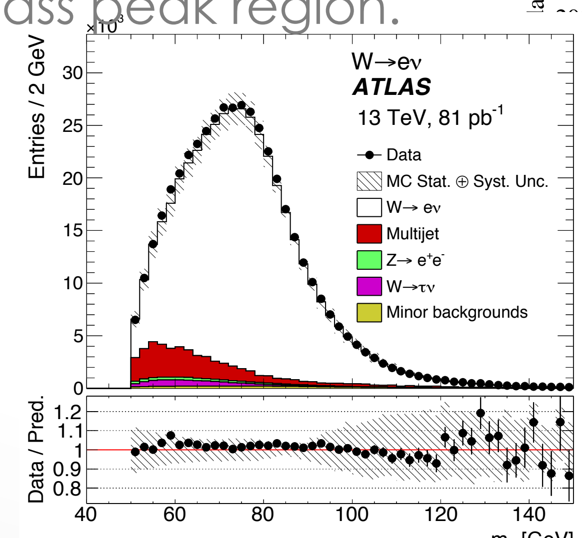
- First 13 TeV results recently published:
  - W and Z cross section from CMS (SMP-15-004, SMP-15-011) and ATLAS (arXiv:1603.09222)
  - $Z \longrightarrow \mu\ \mu$ from LHCb (LHCb-CONF-2016-002)



- Event selection:
  - Similar cuts in the three analysis.
  - Single-lepton or di-lepton trigger
  - One (two) high p_t isolated lepton for W(Z)
  - E_T^{miss} (for W)
  - Analysis restricted to mass peak region.

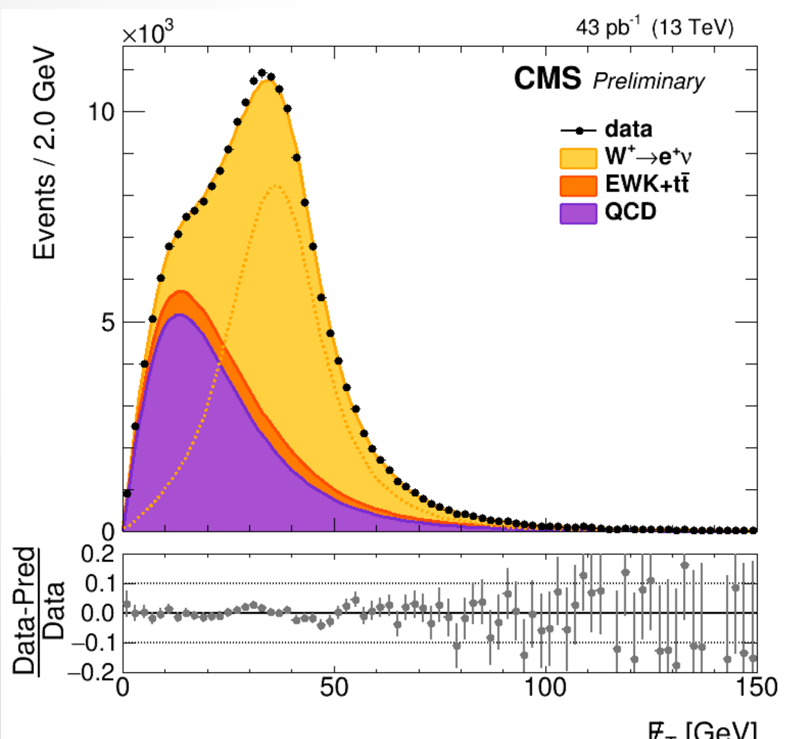


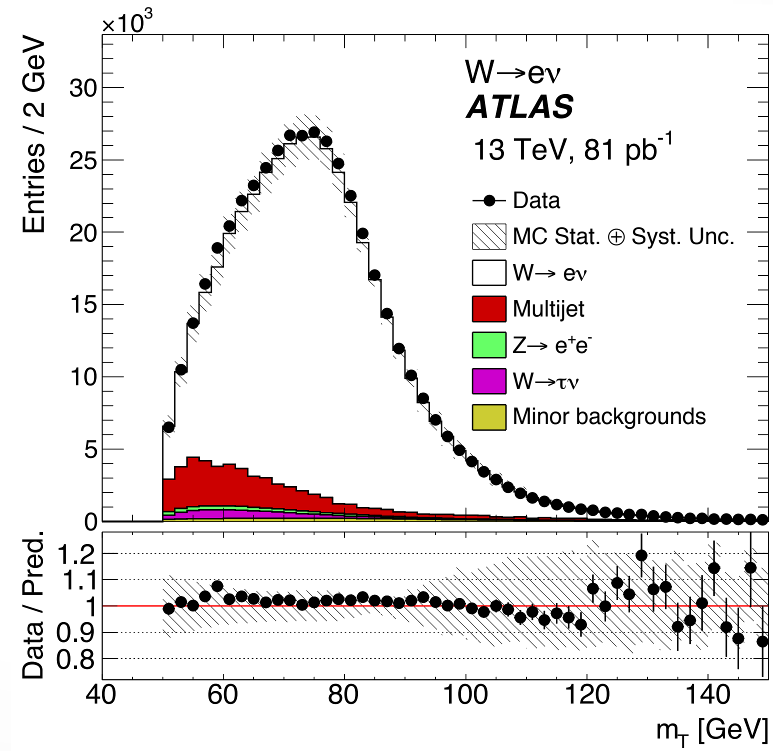
- Main backgrounds:
  - Top production
  - Multijet
  - Electroweak:
    - W/Z decaying to τ
    - diboson production



W at 13 TeV: signal extraction

- CMS extracts both the signal and multijet background normalisation from likelyhood fit of missing E_T.
- ATLAS cuts on missing E_T and evaluate the number of multijet events from control regions.



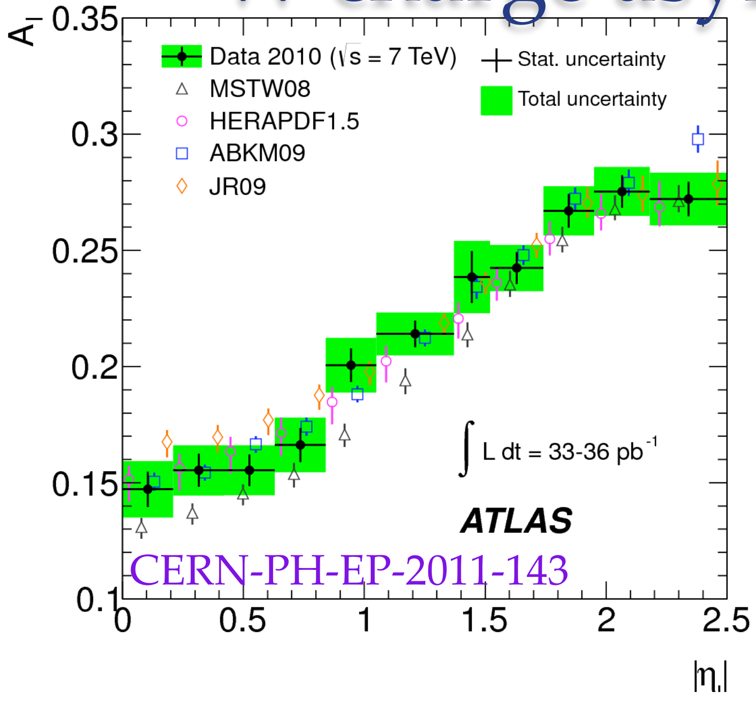


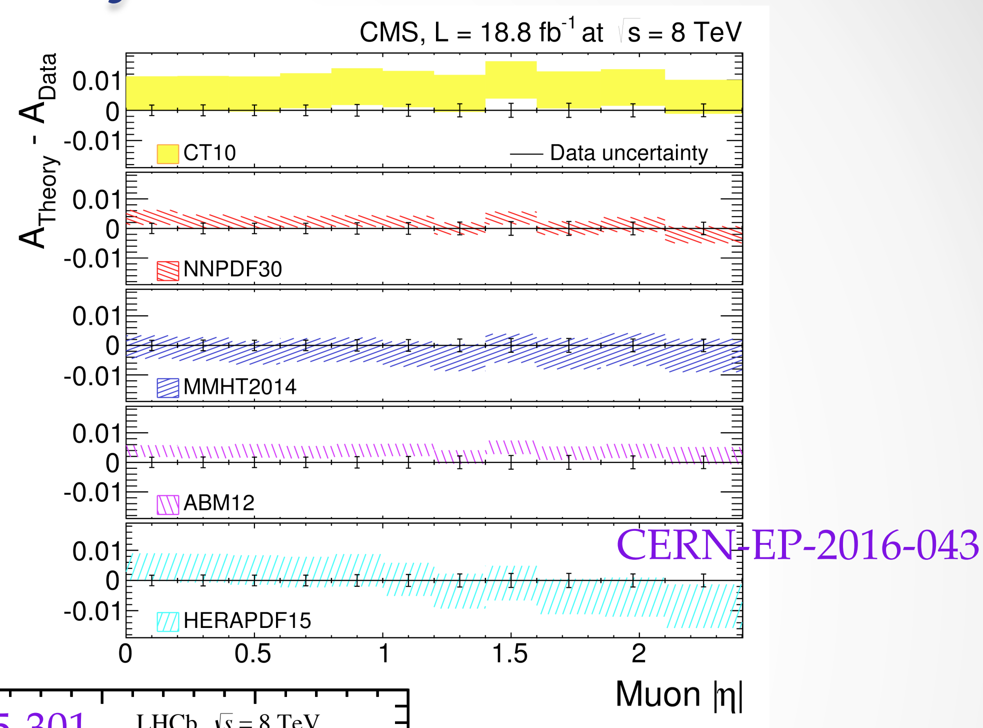
Total 13 TeV W and Z cross sections

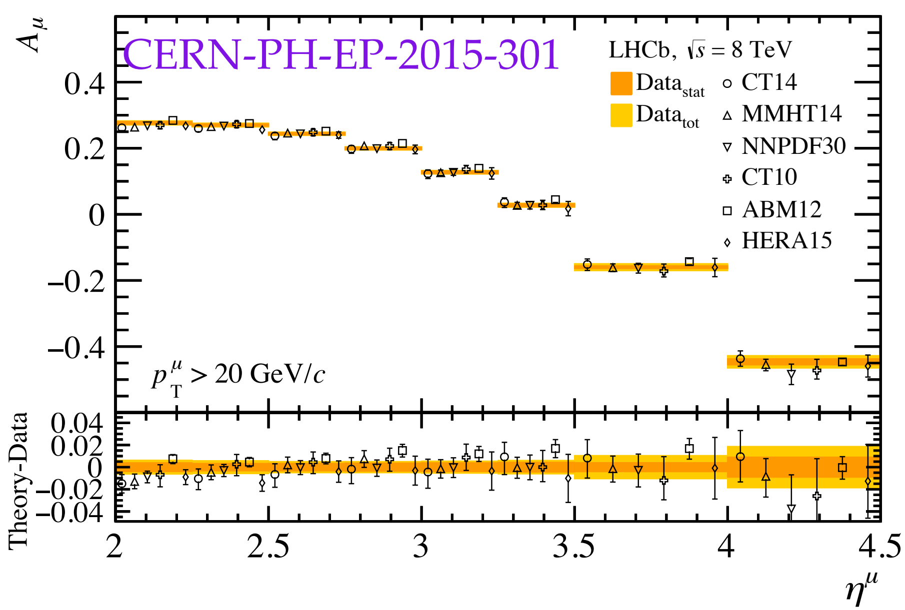
CMS: SMP-15-004, SMP-15-011
ATLAS: arXiv:1603.09222

TOTAL CROSS SECTIONS [pb]		CMS [value ± stat ± syst ± lumi]	ATLAS [value ± stat ± syst ± lumi]
W^+	$e^+\nu$	11390 ± 90 ± 340 ± 550	12180 ± 30 ± 410 ± 630
	$\mu^+\nu$	11350 ± 60 ± 320 ± 550	11700 ± 20 ± 320 ± 630
W^-	$e^-\nu$	8680 ± 80 ± 250 ± 420	8960 ± 20 ± 380 ± 470
	$\mu^-\nu$	8510 ± 60 ± 210 ± 410	8710 ± 20 ± 250 ± 480
Z	e^+e^-	1920 ± 20 ± 60 ± 90	1980 ± 10 ± 40 ± 100
	$\mu^+\mu^-$	1870 ± 2 ± 35 ± 51	1970 ± 10 ± 40 ± 100

W charge asymmetry: studies in run 1

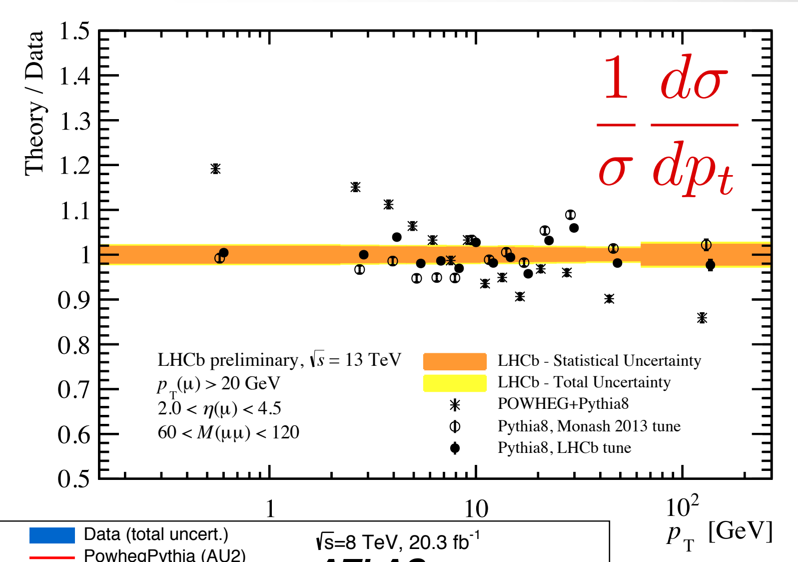


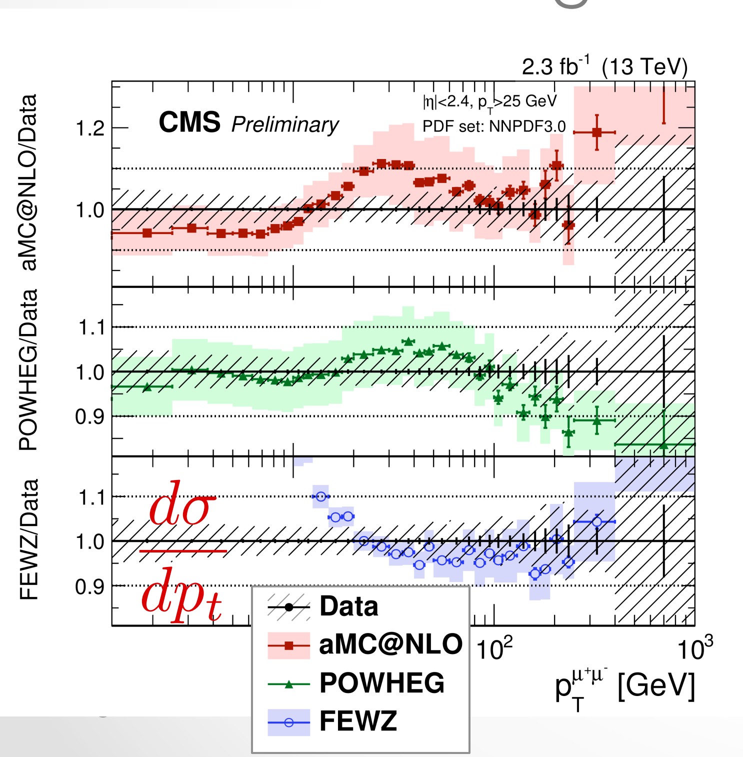


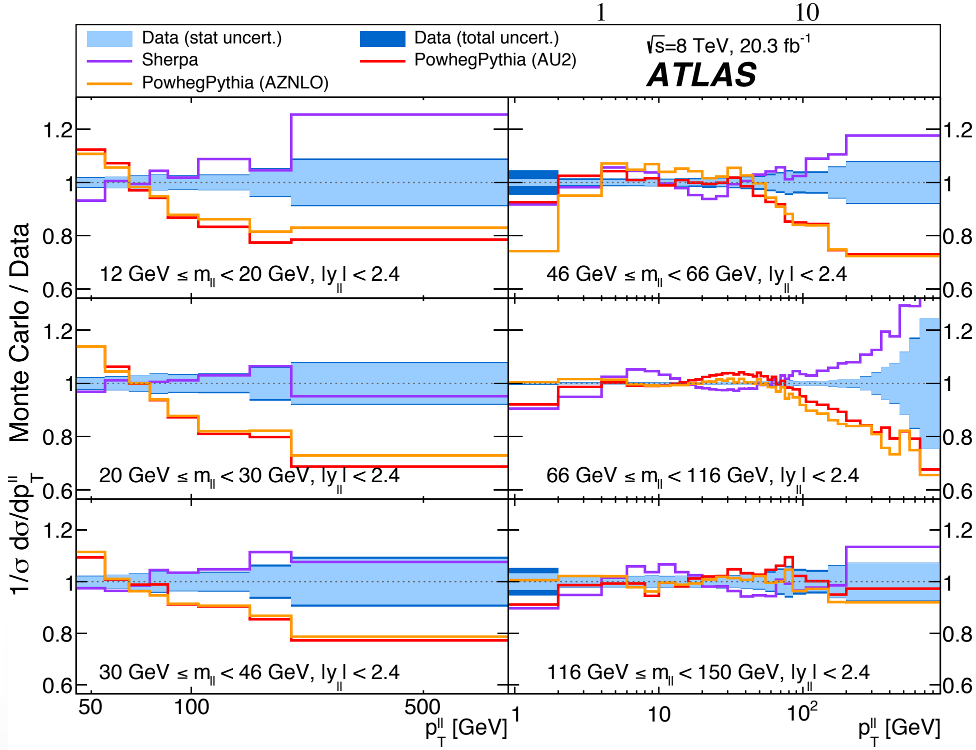


Vector boson transverse momentum

- P_t spectrum
- ATLAS: distributions in different mass bins
- No studied generator describes data through all the kinematic range

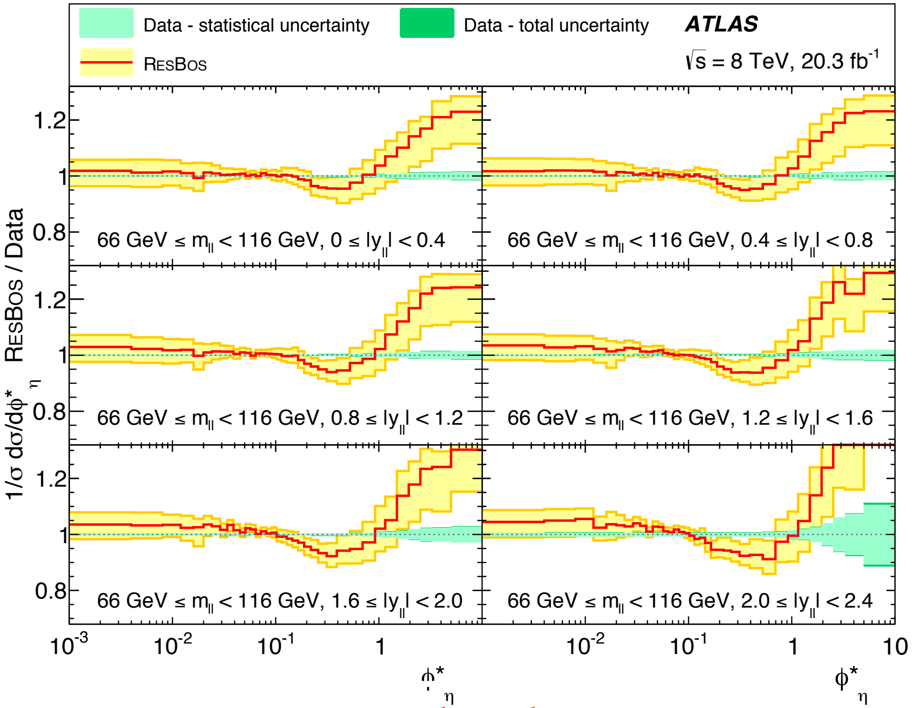




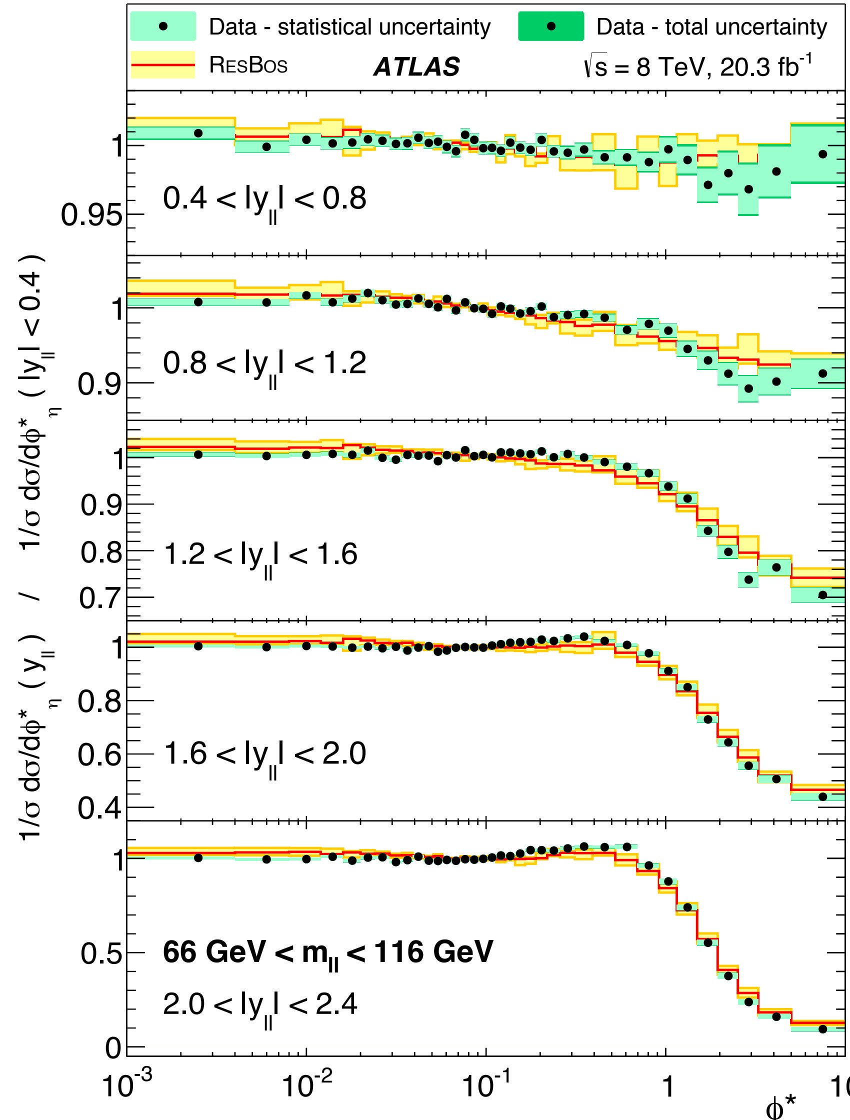


Differential cross sections vs ϕ_η^*

- Example from ATLAS 8 TeV paper: normalized spectrum at low ϕ_η^* in different rapidity regions.



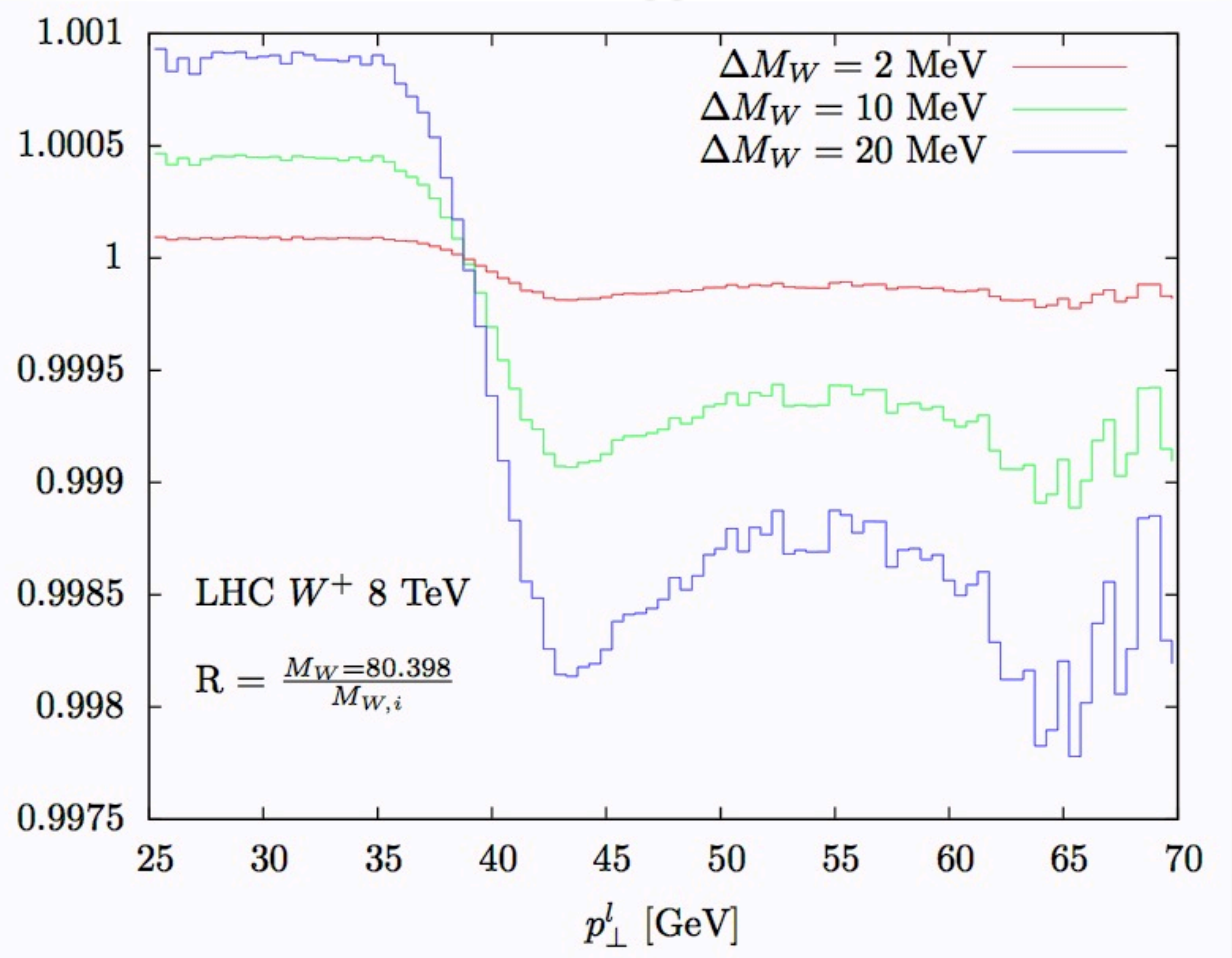
Normalized spectrum in different y_{ll} regions.



Ratios w.r.t. central y_{ll} region

Ratio of $p_T(l)$ distributions with varied M_W

arXiv:1501.05587v2

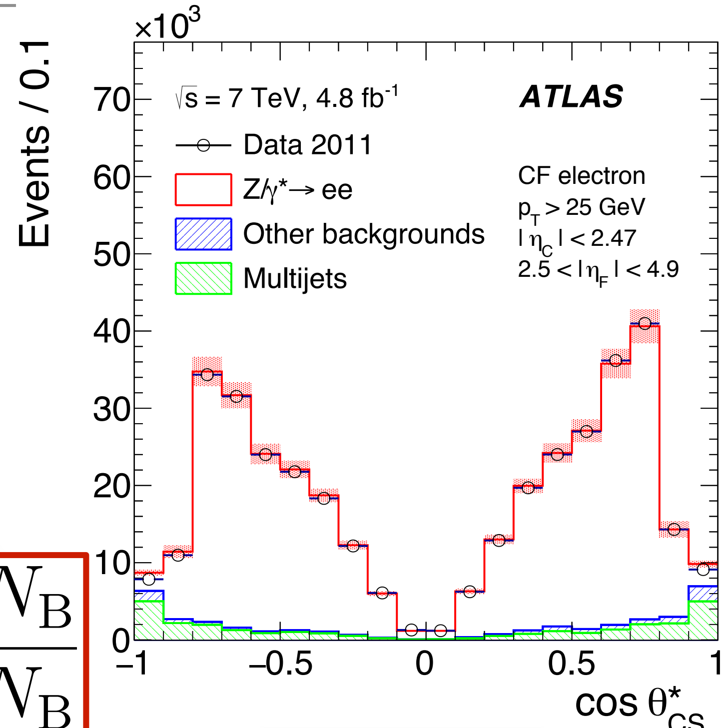


$\sin^2(\vartheta_W)$ in $Z/\gamma^*\longrightarrow l^+l^-$ events

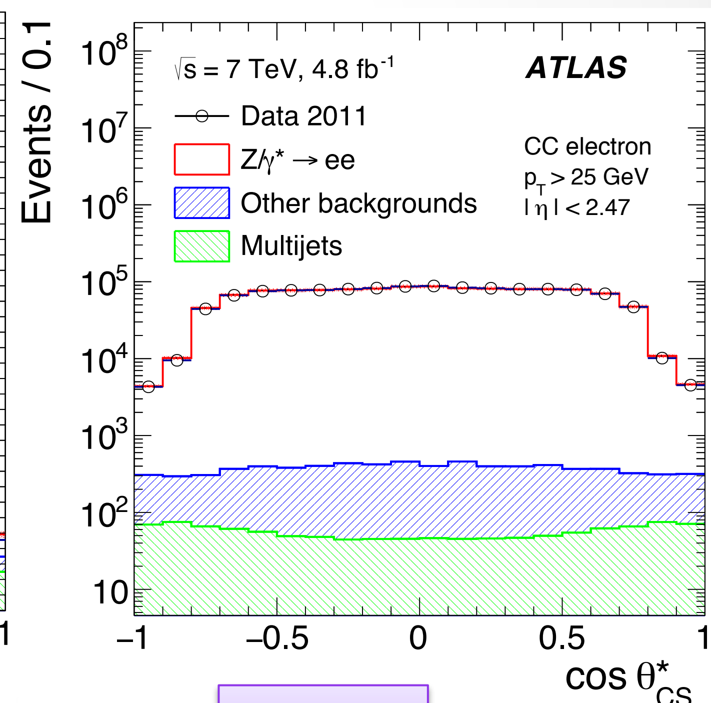
- Extracted fitting A_{FB} as a function of di-lepton invariant mass.
  - Quark direction assumed to correspond with that of the Z
    - Valence quark: more likely to have the largest momentum.
    - Better sensitivity in the forward region

$$u\bar{u}, d\bar{d} \rightarrow Z$$

$$\boxed{A_{\mathrm{FB}} \equiv \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}}$$

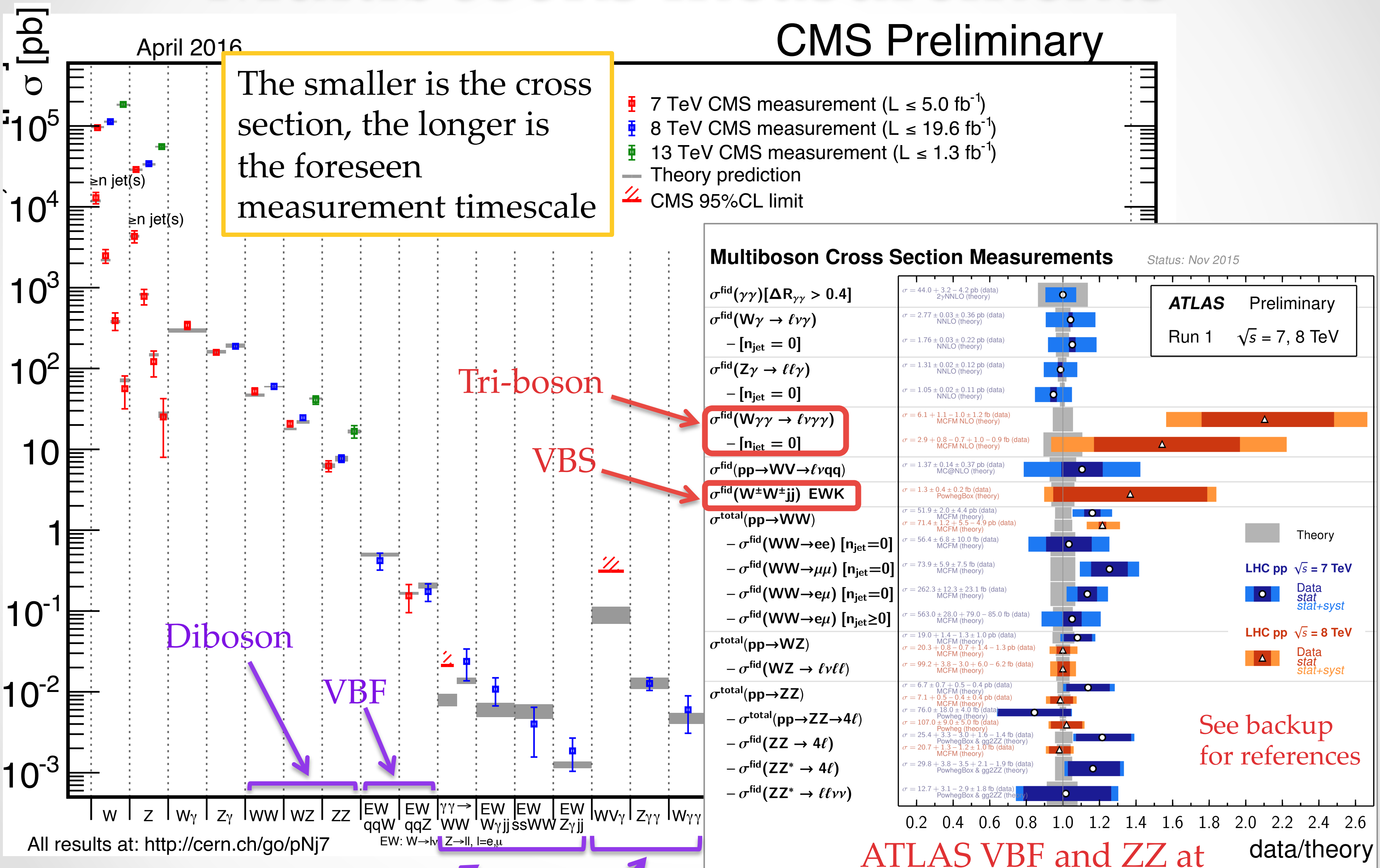


One electron is at high η



Central electrons

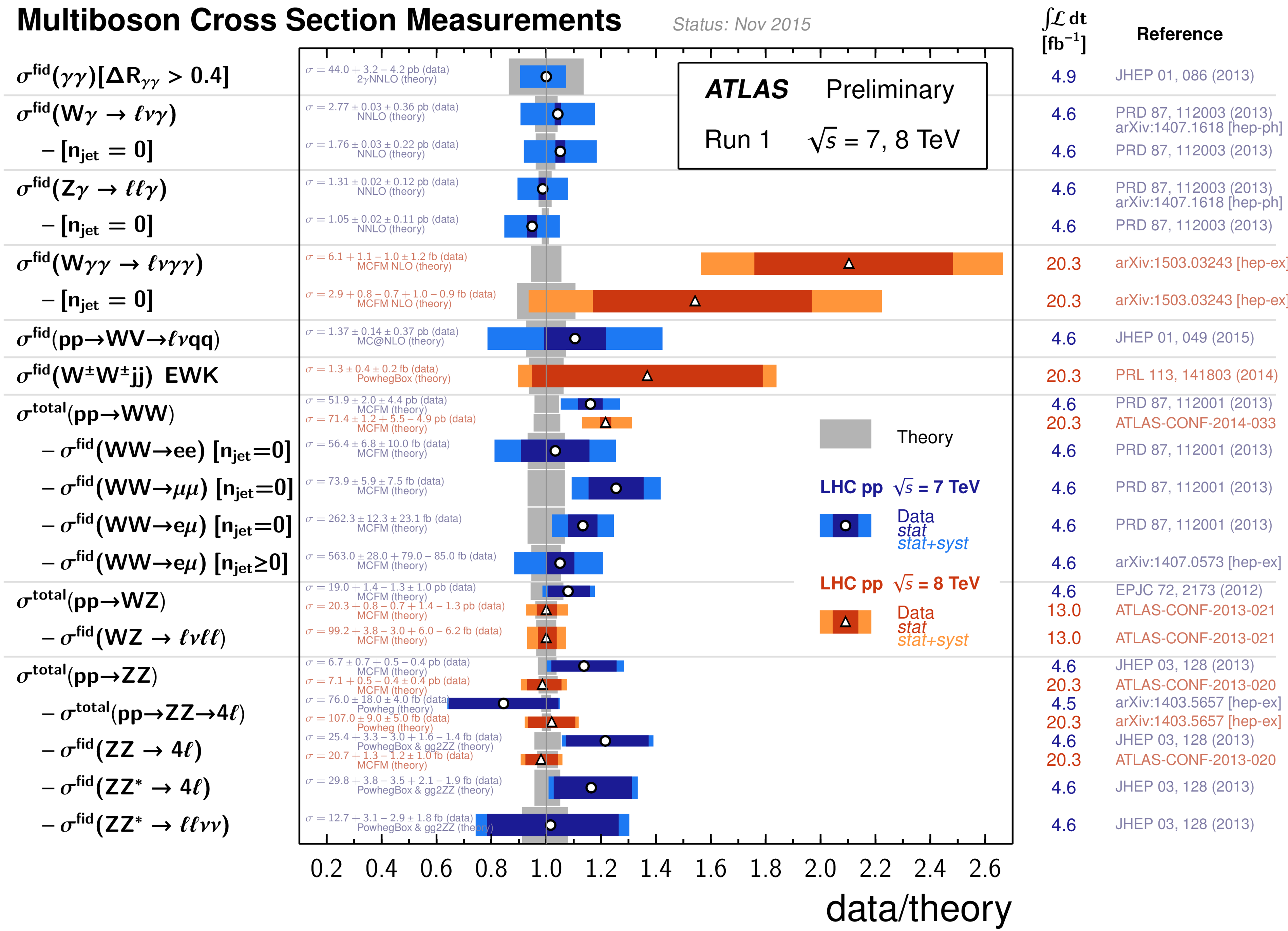
Multibosons measurements



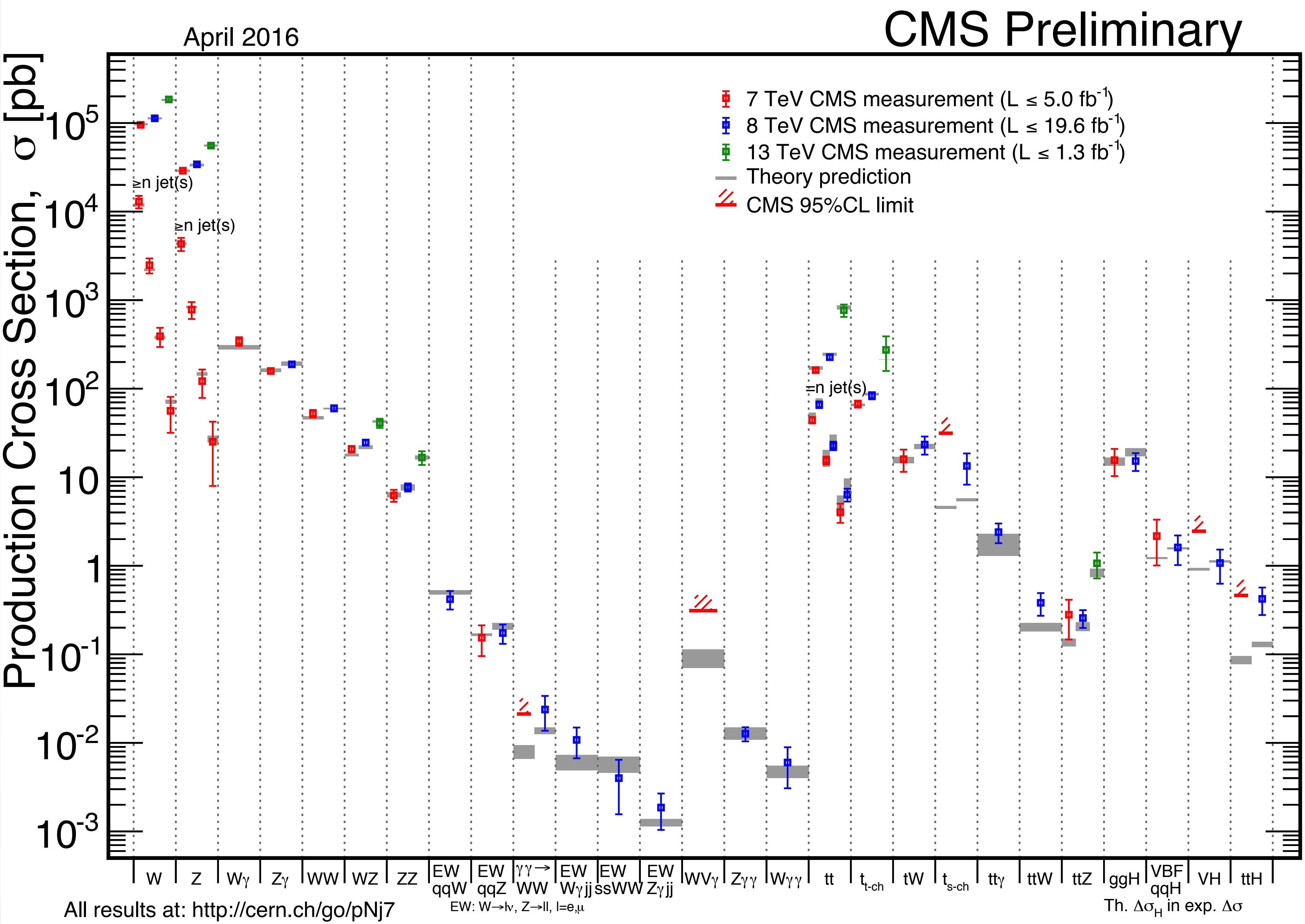
VBS

Tri-boson

ATLAS VBF and ZZ at 13 TeV are missing



Multiboson Cross Section Measurements
Status: Nov 2015
∫ℒ dt [fb⁻¹]
Reference
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
σ^fid(γγ)[ΔR_γγ > 0.4]
σ = 44.0 + 3.2 − 4.2 pb (data) 2γNNLO (theory)
4.9 JHEP 01, 086 (2013)
σ^fid(Wγ → ℓνγ)
σ = 2.77 ± 0.03 ± 0.36 pb (data) NNLO (theory)
4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
− [n_jet = 0]
σ = 1.76 ± 0.03 ± 0.22 pb (data) NNLO (theory)
4.6 PRD 87, 112003 (2013)
σ^fid(Zγ → ℓℓγ)
σ = 1.31 ± 0.02 ± 0.12 pb (data) NNLO (theory)
4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
− [n_jet = 0]
σ = 1.05 ± 0.02 ± 0.11 pb (data) NNLO (theory)
4.6 PRD 87, 112003 (2013)
σ^fid(Wγγ → ℓνγγ)
σ = 6.1 + 1.1 − 1.0 ± 1.2 fb (data) MCFM NLO (theory)
20.3 arXiv:1503.03243 [hep-ex]
− [n_jet = 0]
σ = 2.9 + 0.8 − 0.7 + 1.0 − 0.9 fb (data) MCFM NLO (theory)
20.3 arXiv:1503.03243 [hep-ex]
σ^fid(pp→WV→ℓνqq)
σ = 1.37 ± 0.14 ± 0.37 pb (data) MC@NLO (theory)
4.6 JHEP 01, 049 (2015)
σ^fid(W±W±jj) EWK
σ = 1.3 ± 0.4 ± 0.2 fb (data) PowhegBox (theory)
20.3 PRL 113, 141803 (2014)
σ^total(pp→WW)
σ = 51.9 ± 2.0 ± 4.4 pb (data) MCFM (theory)
4.6 PRD 87, 112001 (2013)
σ = 71.4 ± 1.2 + 5.5 − 4.9 pb (data) MCFM (theory)
20.3 ATLAS-CONF-2014-033
− σ^fid(WW→ee) [n_jet=0]
σ = 56.4 ± 6.8 ± 10.0 fb (data) MCFM (theory)
4.6 PRD 87, 112001 (2013)
− σ^fid(WW→μμ) [n_jet=0]
σ = 73.9 ± 5.9 ± 7.5 fb (data) MCFM (theory)
4.6 PRD 87, 112001 (2013)
− σ^fid(WW→eμ) [n_jet=0]
σ = 262.3 ± 12.3 ± 23.1 fb (data) MCFM (theory)
4.6 PRD 87, 112001 (2013)
− σ^fid(WW→eμ) [n_jet≥0]
σ = 563.0 ± 28.0 + 79.0 − 85.0 fb (data) MCFM (theory)
4.6 arXiv:1407.0573 [hep-ex]
σ^total(pp→WZ)
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data) MCFM (theory)
4.6 EPJC 72, 2173 (2012)
σ = 20.3 + 0.8 − 0.7 + 1.4 − 1.3 pb (data) MCFM (theory)
13.0 ATLAS-CONF-2013-021
− σ^fid(WZ → ℓνℓℓ)
σ = 99.2 + 3.8 − 3.0 + 6.0 − 6.2 fb (data) MCFM (theory)
13.0 ATLAS-CONF-2013-021
σ^total(pp→ZZ)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) MCFM (theory)
4.6 JHEP 03, 128 (2013)
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data) MCFM (theory)
20.3 ATLAS-CONF-2013-020
− σ^total(pp→ZZ→4ℓ)
σ = 76.0 ± 18.0 ± 4.0 fb (data) Powheg (theory)
4.5 arXiv:1403.5657 [hep-ex]
σ = 107.0 ± 9.0 ± 5.0 fb (data) Powheg (theory)
20.3 arXiv:1403.5657 [hep-ex]
− σ^fid(ZZ → 4ℓ)
σ = 25.4 + 3.3 − 3.0 + 1.6 − 1.4 fb (data) PowhegBox & gg2ZZ (theory)
4.6 JHEP 03, 128 (2013)
σ = 20.7 + 1.3 − 1.2 ± 1.0 fb (data) MCFM (theory)
20.3 ATLAS-CONF-2013-020
− σ^fid(ZZ* → 4ℓ)
σ = 29.8 + 3.8 − 3.5 + 2.1 − 1.9 fb (data) PowhegBox & gg2ZZ (theory)
4.6 JHEP 03, 128 (2013)
− σ^fid(ZZ* → ℓℓνν)
σ = 12.7 + 3.1 − 2.9 ± 1.8 fb (data) PowhegBox & gg2ZZ (theory)
4.6 JHEP 03, 128 (2013)
Theory
LHC pp √s = 7 TeV
Data
stat
stat+syst
LHC pp √s = 8 TeV
Data
stat
stat+syst
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
data/theory


CMS Preliminary
April 2016
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 1.3 fb^{-1})
Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW Wγjj
EW ssWW
EW Zγjj
WVγ
Zγγ
Wγγ
tt
t$_{t\text{-ch}}$
tW
t$_{s\text{-ch}}$
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
EW: W→lν, Z→ll, l=e,μ
Th. Δσ$_H$ in exp. Δσ
All results at: http://cern.ch/go/pNj7

Leptonic WW cross section

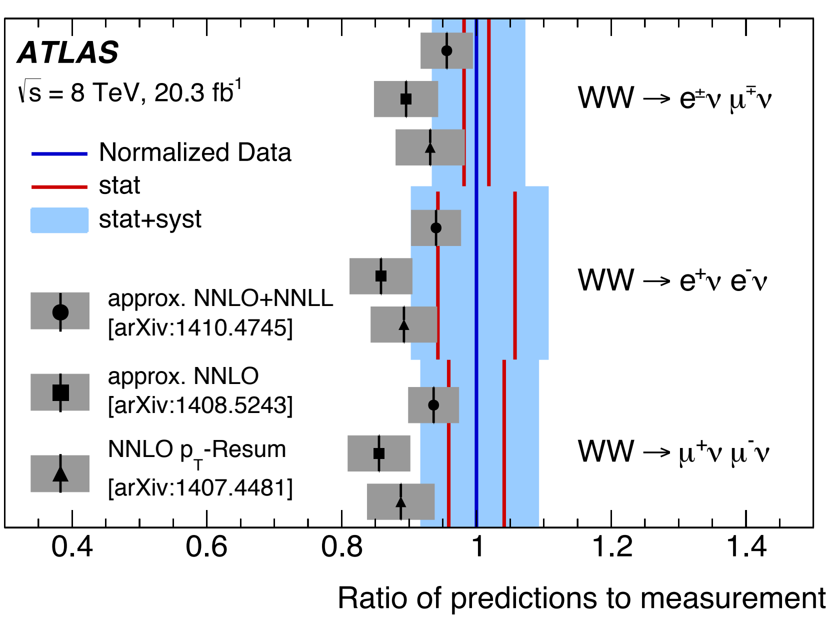
CMS-SMP-14-016

Fiducial cross sections. Varying minimum p_T of veto jets.

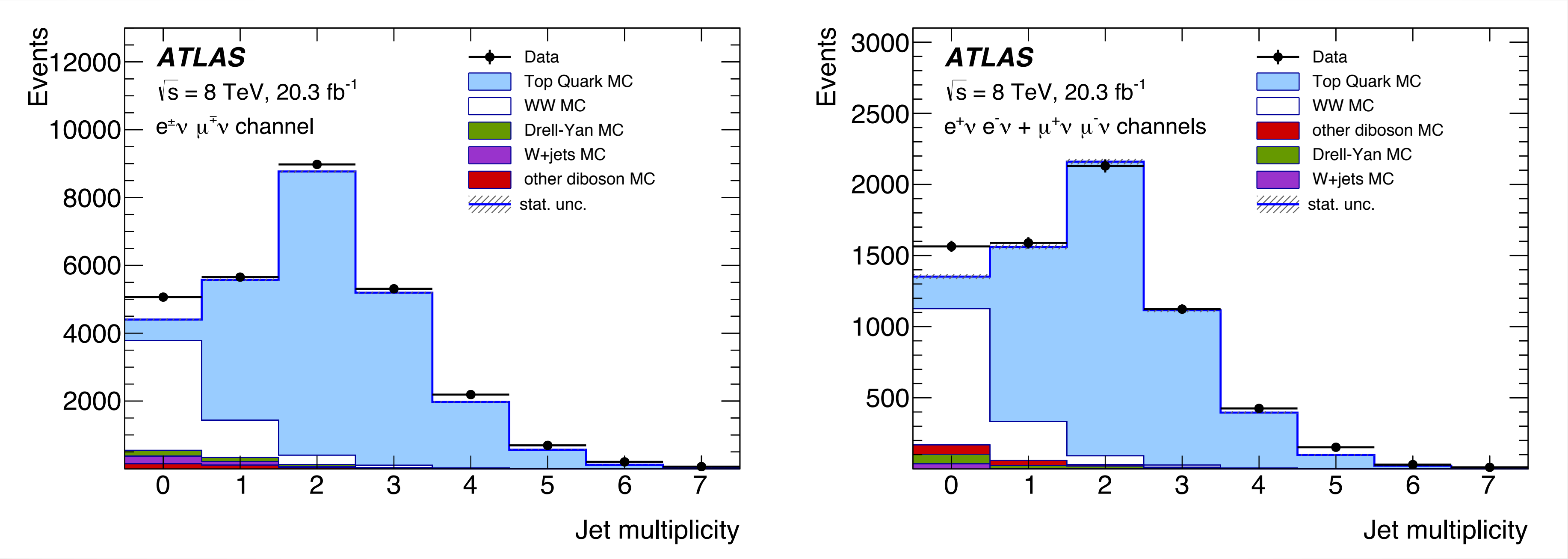
p_T^{jet} (GeV)	$\sigma_{\text{zero-jet}}$ measured (pb)	$\sigma_{\text{zero-jet}}$ predicted (pb)
>20	36.2 ± 0.6 (stat) ± 2.1 (exp) ± 1.1 (theo) ± 0.9 (lumi)	36.7 ± 0.1 (stat)
>25	40.8 ± 0.7 (stat) ± 2.3 (exp) ± 1.3 (theo) ± 1.1 (lumi)	40.9 ± 0.1 (stat)
>30	44.0 ± 0.7 (stat) ± 2.5 (exp) ± 1.4 (theo) ± 1.1 (lumi)	43.9 ± 0.1 (stat)

Prediction	Fiducial cross section $pp \to WW \to \ell\ell\nu\nu$ [fb]
Measured $\sigma_{\text{fid}}^{e\mu}(WW)$	374 ± 7(stat) $^{+25}_{-23}$(syst) $^{+8}_{-7}$(lumi)
$\sigma(\text{nNLO}_{\text{fid},e\mu})$	311 ± 15
$\sigma(\text{approx. NNLO}_{\text{fid},e\mu})$	335 ± 18
$\sigma(\text{approx. (NNLO + NNLL)}_{\text{fid},e\mu})$	358 ± 14
$\sigma(\text{NNLO } p_T\text{-Resum}_{\text{fid},e\mu})$	349 ± 19
Measured $\sigma_{\text{fid}}^{ee}(WW)$	$73.4^{+4.2}_{-4.1}$(stat) $^{+6.5}_{-5.6}$(syst) ± 1.5(lumi)
$\sigma(\text{nNLO}_{\text{fid},ee})$	58.5 ± 2.8
$\sigma(\text{approx. NNLO}_{\text{fid},ee})$	63.0 ± 3.4
$\sigma(\text{approx. (NNLO + NNLL)}_{\text{fid},ee})$	69.0 ± 2.7
$\sigma(\text{NNLO } p_T\text{-Resum}_{\text{fid},ee})$	65.5 ± 3.6
Measured $\sigma_{\text{fid}}^{\mu\mu}(WW)$	$80.2^{+3.3}_{-3.2}$(stat) $^{+6.4}_{-5.5}$(syst) ± 1.6(lumi)
$\sigma(\text{nNLO}_{\text{fid},\mu\mu})$	63.7 ± 3.1
$\sigma(\text{approx. NNLO}_{\text{fid},\mu\mu})$	68.6 ± 3.7
$\sigma(\text{approx. (NNLO + NNLL)}_{\text{fid},\mu\mu})$	75.1 ± 3.0
$\sigma(\text{NNLO } p_T\text{-Resum}_{\text{fid},\mu\mu})$	71.2 ± 4.0

ATLAS: CERN-PH-EP-2015-323



Leptonic WW cross section: Jet multiplicity mismodelling



CMS reweights MC to p_t-resummed calculation.

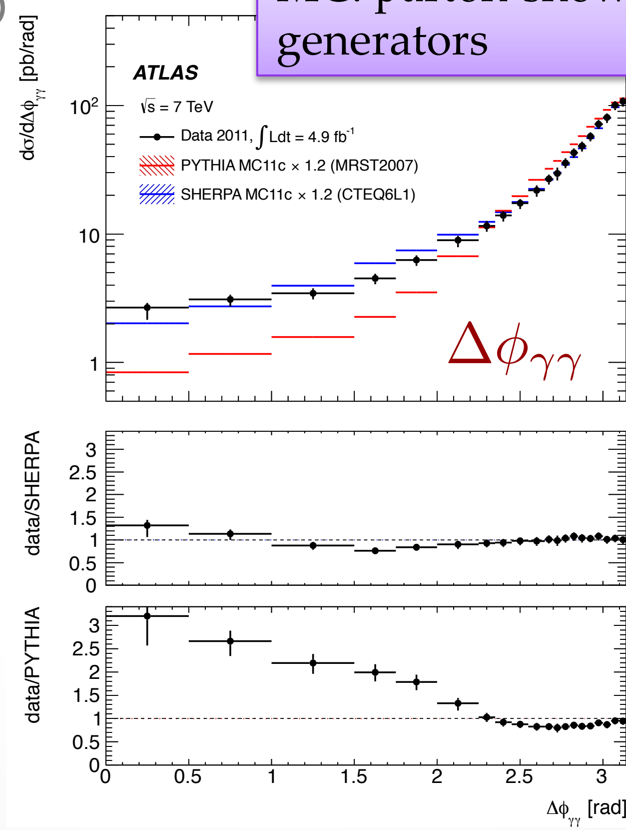
Other differential distributions: $\gamma\gamma$

- Differential cross section studied as a function of:

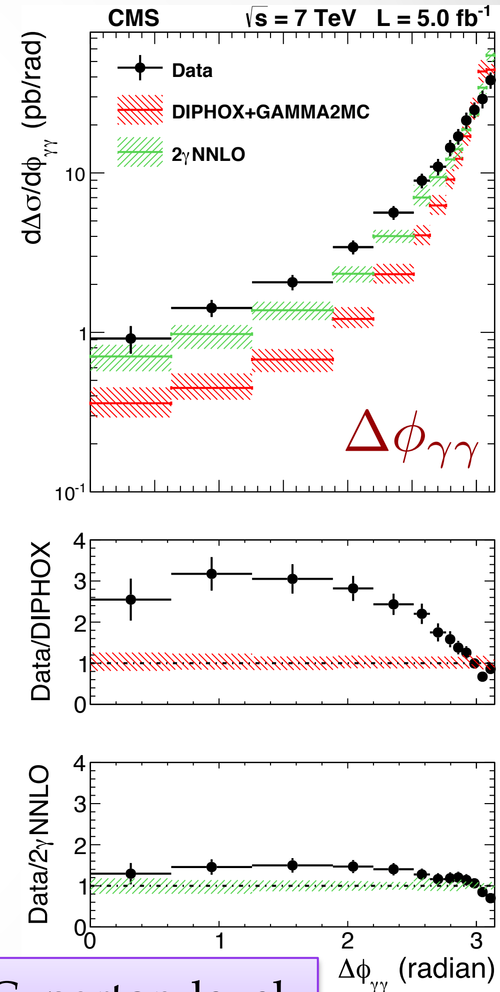
$$m_{\gamma\gamma},\ p_{T,\gamma\gamma},\ \Delta\phi_{\gamma\gamma},\ \cos\theta^{*}_{\gamma\gamma}$$

  - High sensitivity to prove perturbative QCD predictions

- Very similar results between ATLAS (CERN-PH-EP-2012-300) and CMS (CMS-SMP-13-001)



MC: parton-shower generators



MC: parton-level calculation

Anomalous Triple Gauge coupling (aTGC)

- Deviations from SM expectations due to new physics.
- Model-independent description of new physics
  - Effective Field Theory (EFT)
    - Operators of mass dimension >4 added to the SM Lagrangian.
  - Anomalous couplings: equivalent (older) scenario
    - Linear relation between the two:

$$c_W,\ c_B,\ c_{WWW} \Longleftrightarrow \lambda,\ \Delta k_\gamma,\ \Delta g_1^Z$$

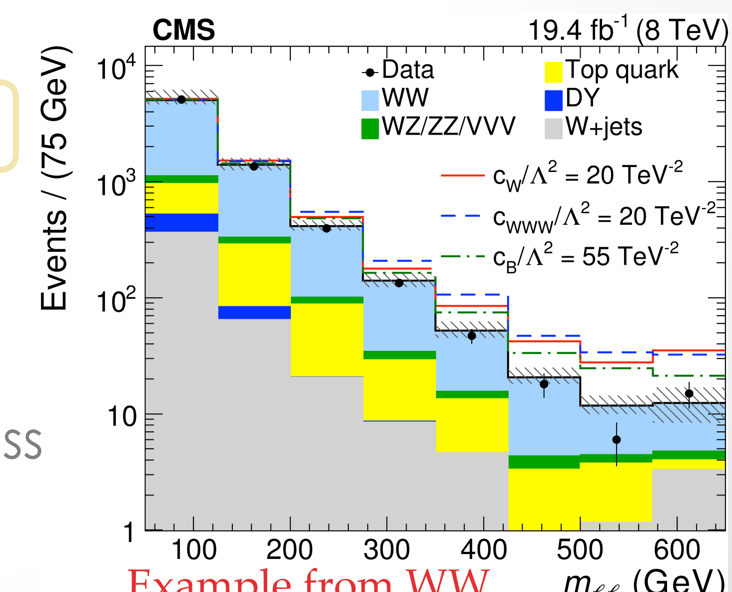
Example: dimension 6 operators

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu],$$

$$\mathcal{O}_W = \frac{c_W}{\Lambda^2}\left(D_\mu\Phi\right)^\dagger W^{\mu\nu}\left(D_\nu\Phi\right)$$

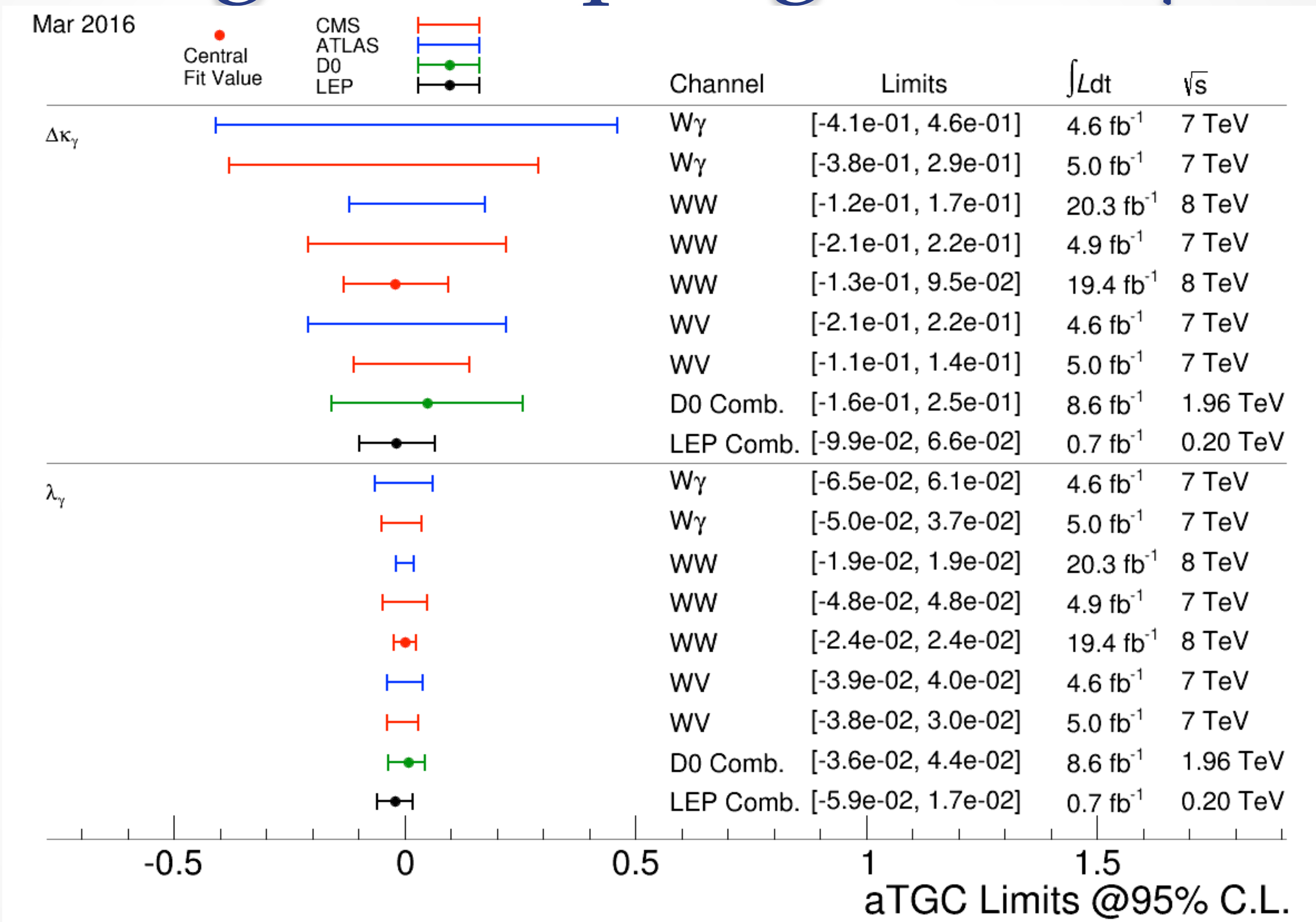
$$\mathcal{O}_B = \frac{c_B}{\Lambda^2}\left(D_\mu\Phi\right) B^{\mu\nu}\left(D_\nu\Phi\right),$$

- New physics parameters estimated fitting data
  - Expected larger effect at larger mass
  - The invariant mass is used
    - or related quantities as boson p_T



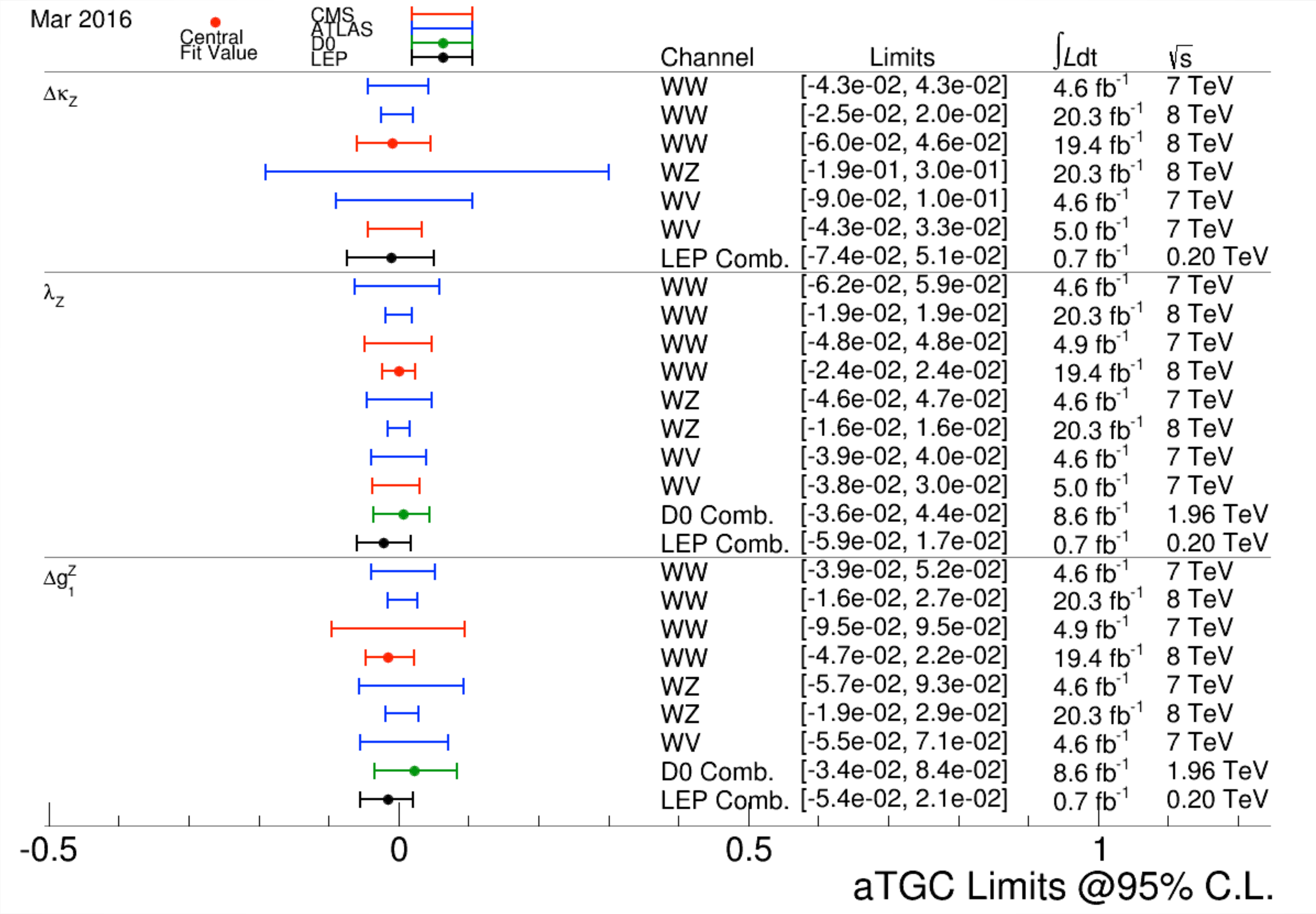
Example from WW (CMS-SMP-14-016)

Charged couplings: WWγ



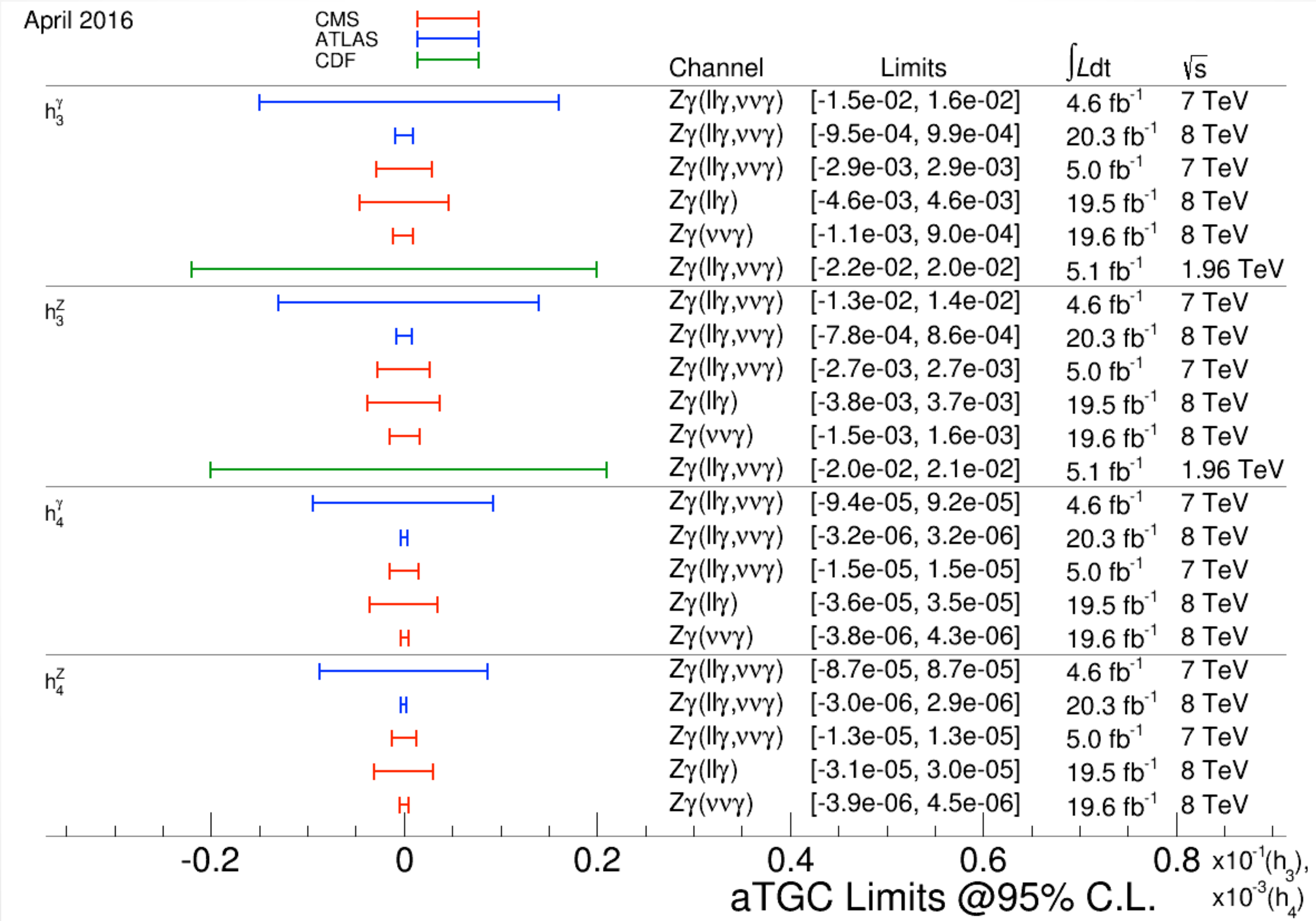
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Charged couplings: WWZ



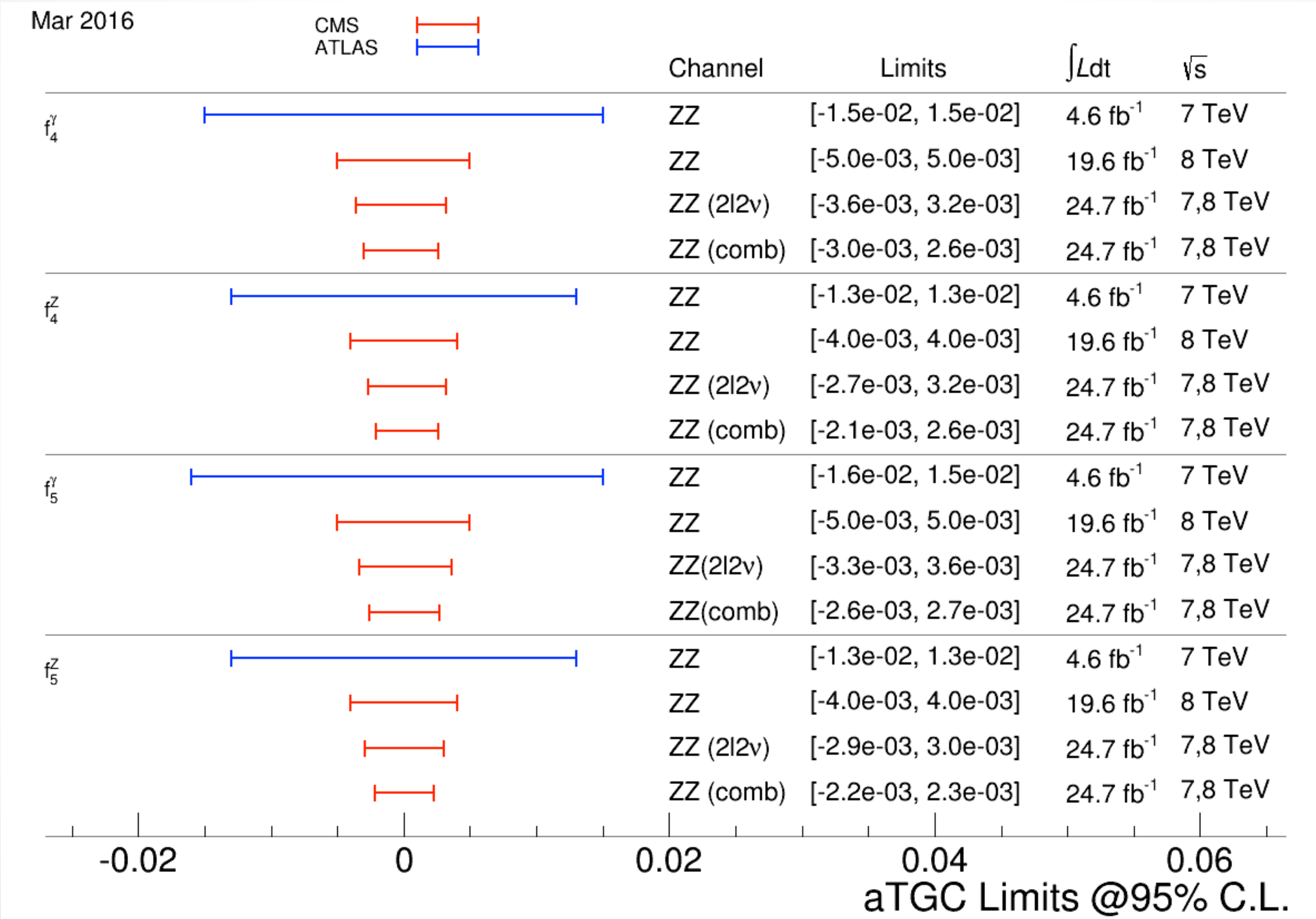
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Neutral coupling: ZZγ /Zγγ



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

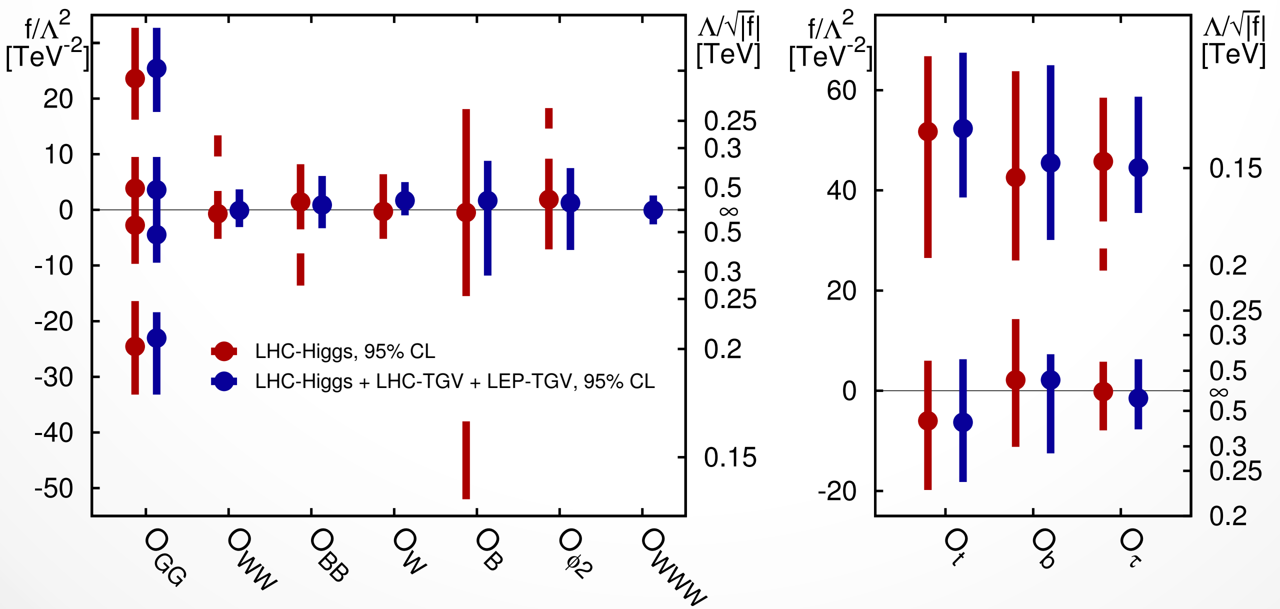
Neutral couplings: ZZγ/ZZZ



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

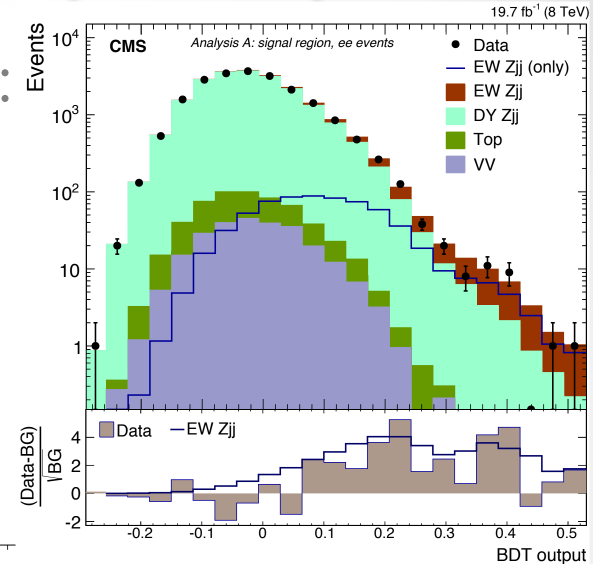
Combining aTGC and Higgs measurements

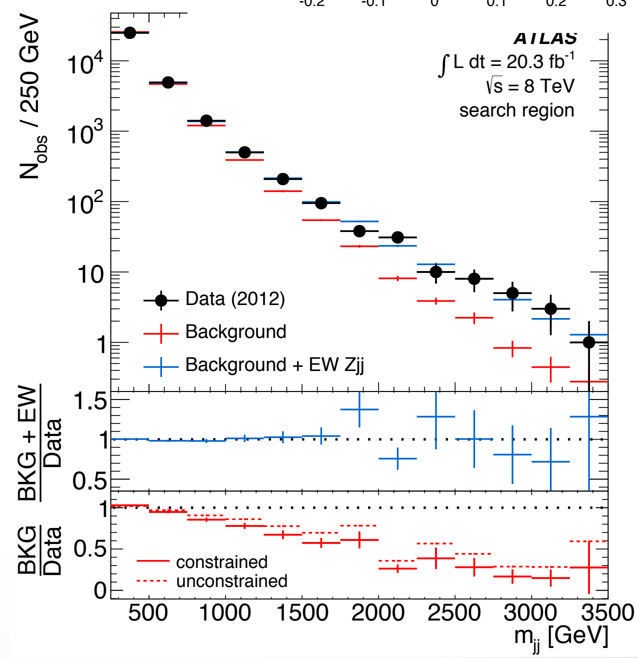
- Some EFT dimension-6 operators contribute to anomalous Higgs interactions and aTGCs at the same time
- Increase sensitivity combining the LHC results on TGVs and Higgs couplings
- Ref: arXiv:1604.03105, combination of Run 1 results.



Vector Boson Fusion (VBF)

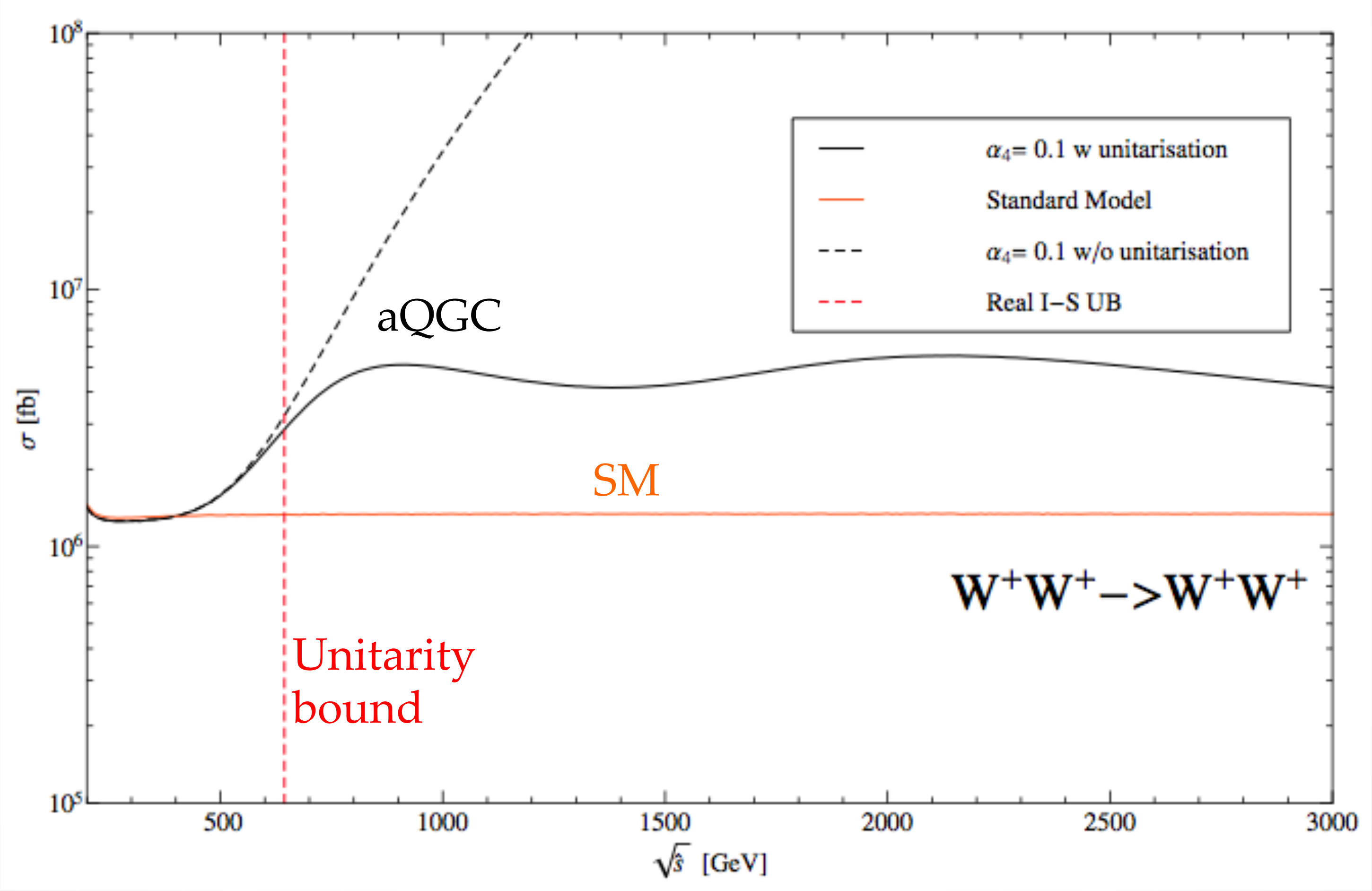
- ATLAS: Z+2j (CERN-PH-EP-2013-227). CMS: Z+2j (CMS-FSQ-12-035), W+2j (SMP-13-012)
  - CMS: fit BDT output
    - Interference term added in the fit (not modelled by MC)
  - ATLAS: fit m_{jj}
    - interference considered as background
    - background normalized to control region
  - ATLAS also measure inclusive cross section.





- Evidence of SM signal with more than 5 σ significance from both experiments

VBS unitarization



Other VBS channels

- WZjj (CMS: CMS-SMP-13-015. ATLAS: CERN-EP-2016-017)
  - CMS: require one additional lepton in same-sign WWjj
  - ATLAS: require two jets in WZ analysis
- W γ jj / Z γ jj (CMS: SMP-14-011, SMP-14-018)
  - Cut and count approach.
  - Evidence of electroweak contribution.

WZjj: ATLAS

95% CL upper limit on $\sigma^{\text{fid.}}_{W^{\pm}Zjj\text{-EW}\to\ell'\nu\ell\ell}$ [fb]		
	VBS only	VBS + tZj
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]

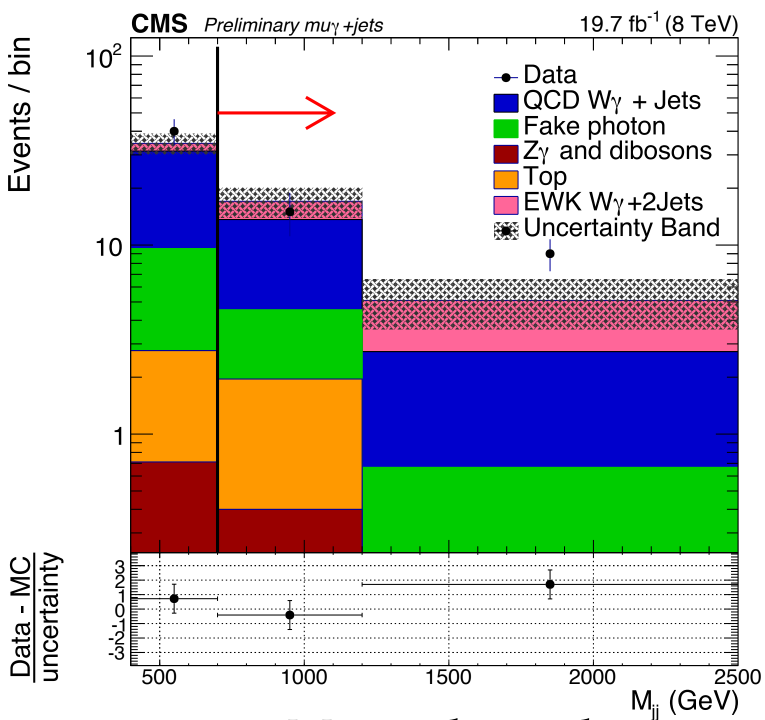
WZjj: CMS

$$\sigma_{fid}(WZjj) = 10.8 \pm 4.0(\text{stat }) \pm 1.3(\text{syst.})\ \text{fb}$$

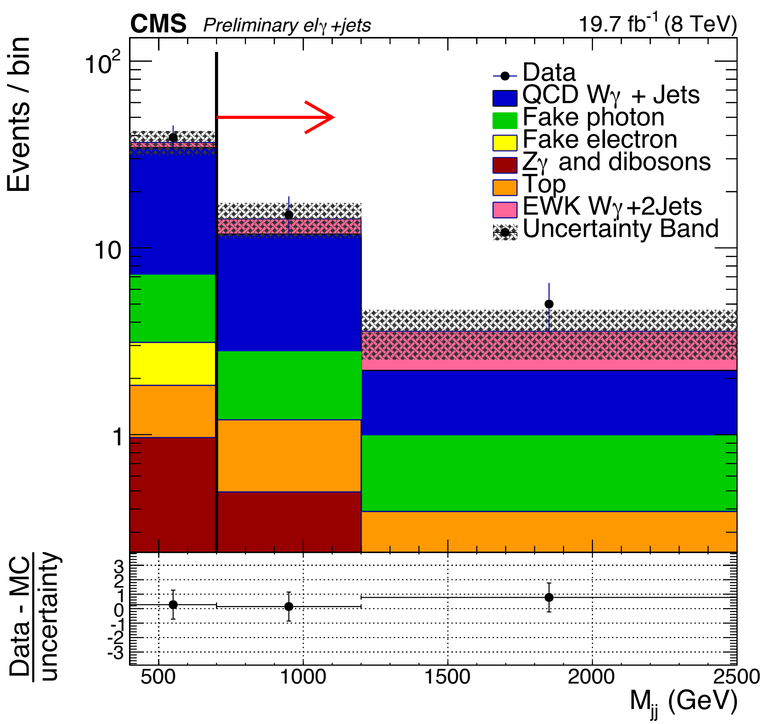
$$\sigma^{MC}_{fid}(WZjj) = 14.4 \pm 4.0\text{fb}$$

CMS Wγjj⟶lνγjj

SMP-14-011



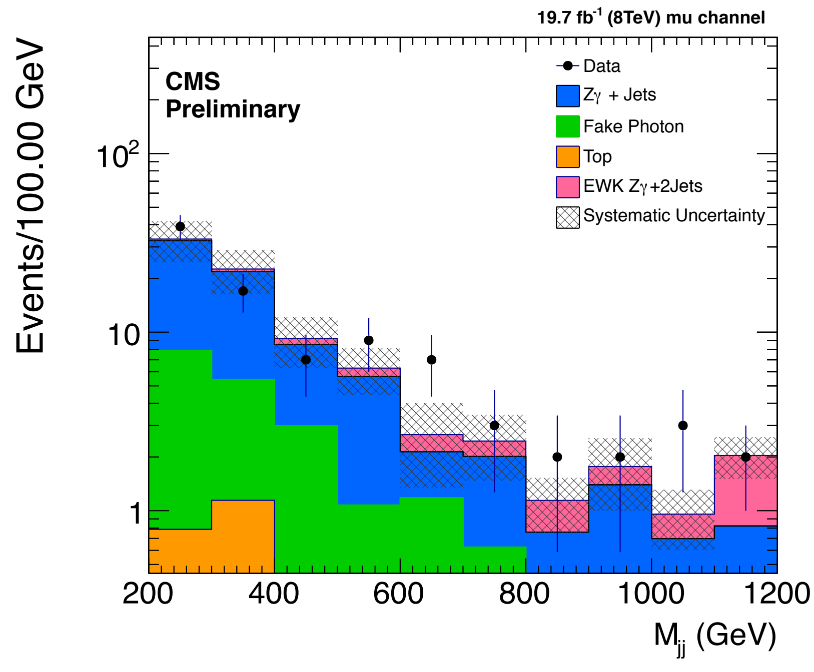
Muon channel



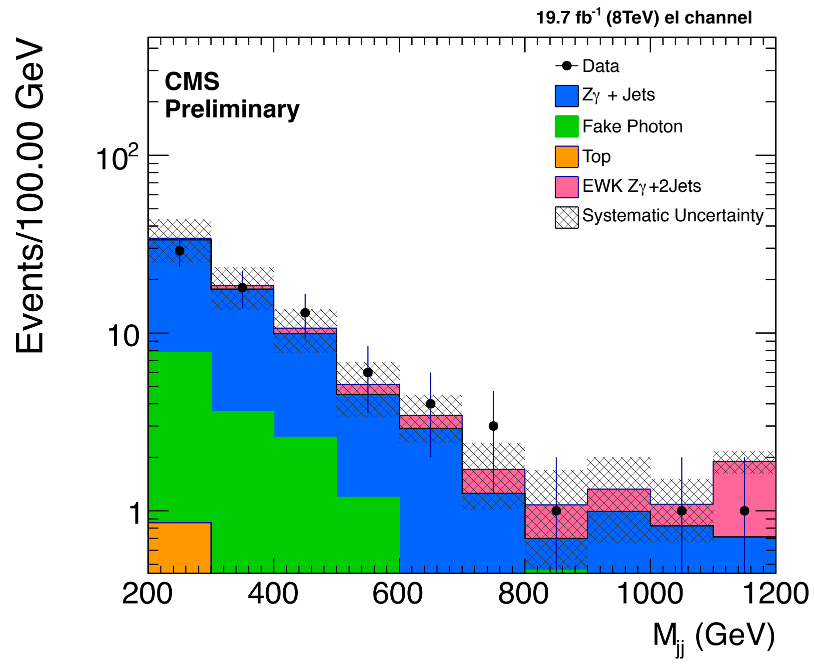
Electron channel

CMS Zγjj⟶llγjj

SMP-14-018



Muon channel



Electron channel

$W\gamma\gamma$ and $Z\gamma\gamma$

Main background: jets misidentified as photons. Data driven methods used

$Z\gamma\gamma$

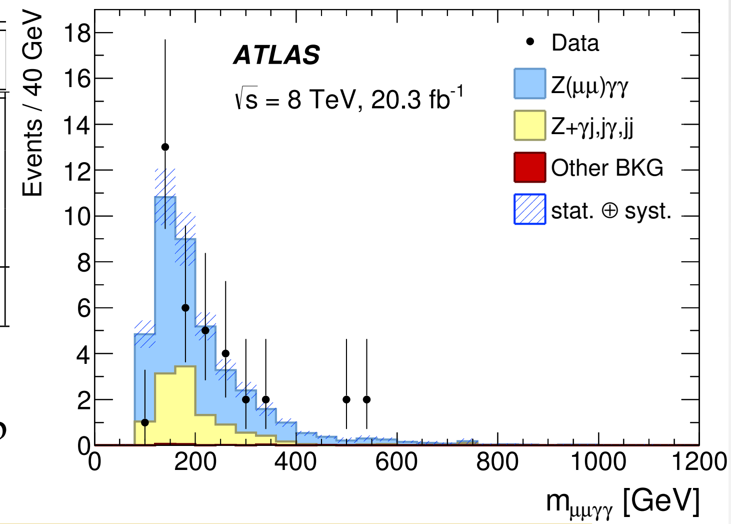
ATLAS: CERN-EP-2016-049

Channel	Measurement [fb]	MCFM Prediction [fb]
$e^+e^-\gamma\gamma$	$6.2\ ^{+1.2}_{-1.1}(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	$3.70^{+0.21}_{-0.11}$
$\mu^+\mu^-\gamma\gamma$	$3.83\ ^{+0.95}_{-0.85}(\text{stat.})^{+0.48}_{-0.47}(\text{syst.}) \pm 0.07(\text{lumi.})$	
$\ell^+\ell^-\gamma\gamma$	$5.07\ ^{+0.73}_{-0.68}(\text{stat.})^{+0.41}_{-0.38}(\text{syst.}) \pm 0.10(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$2.5\ ^{+1.0}_{-0.9}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.1(\text{lumi.})$	$0.737^{+0.039}_{-0.032}$

CMS: SMP-15-008

$$\sigma^{\text{fid}}_{Z\gamma\gamma} \cdot \text{BR}\,(Z \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\ \text{fb}$$

$$\sigma^{\text{NLO}}_{Z\gamma\gamma} \cdot \text{BR}\,(Z \to \ell\ell) = 12.95 \pm 1.47\ \text{fb}$$



$W\gamma\gamma$

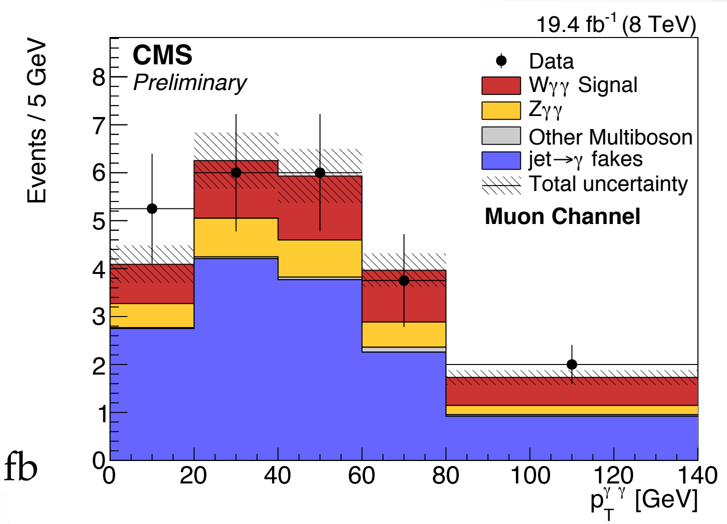
ATLAS: CERN-PH-EP-2015-009

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}\ (\text{stat.}) \pm 1.5\ (\text{syst.}) \pm 0.2\ (\text{lumi.})$	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}\ (\text{stat.})\ ^{+1.9}_{-1.8}\ (\text{syst.}) \pm 0.2\ (\text{lumi.})$	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}\ (\text{stat.}) \pm 1.2\ (\text{syst.}) \pm 0.2\ (\text{lumi.})$	

CMS: SMP-15-008

$$\sigma^{\text{fid}}_{W^\pm\gamma\gamma} \cdot \text{BR}\,(W \to \ell\nu) = 6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})\ \text{fb}$$

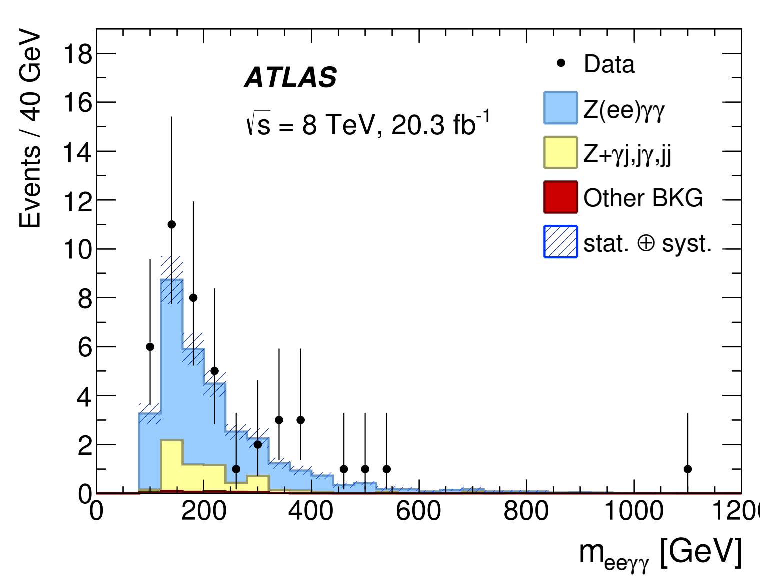
$$\sigma^{\text{NLO}}_{W^\pm\gamma\gamma} \cdot \text{BR}\,(W \to \ell\nu) = 4.76 \pm 0.53\ \text{fb}$$

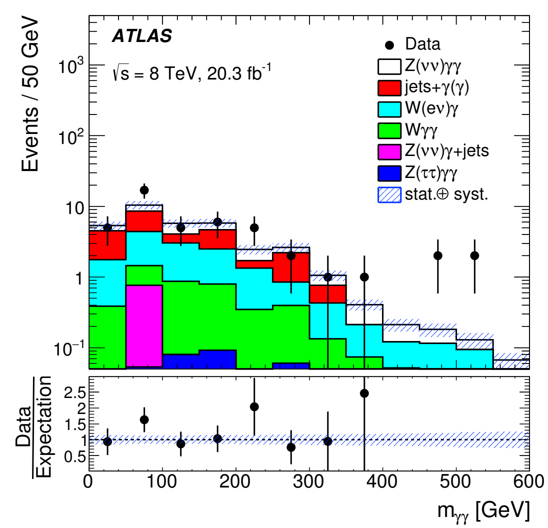


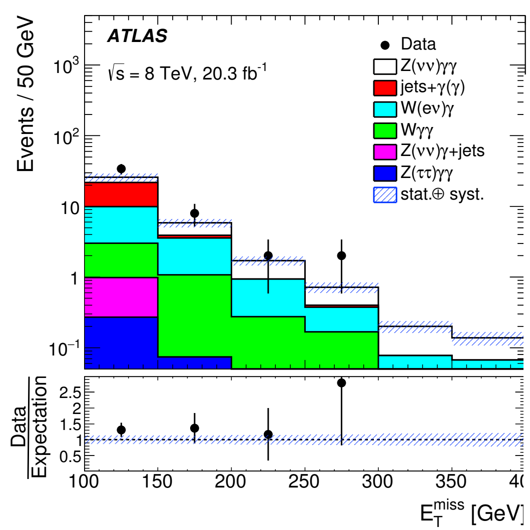
ATLAS $Z\gamma\gamma$

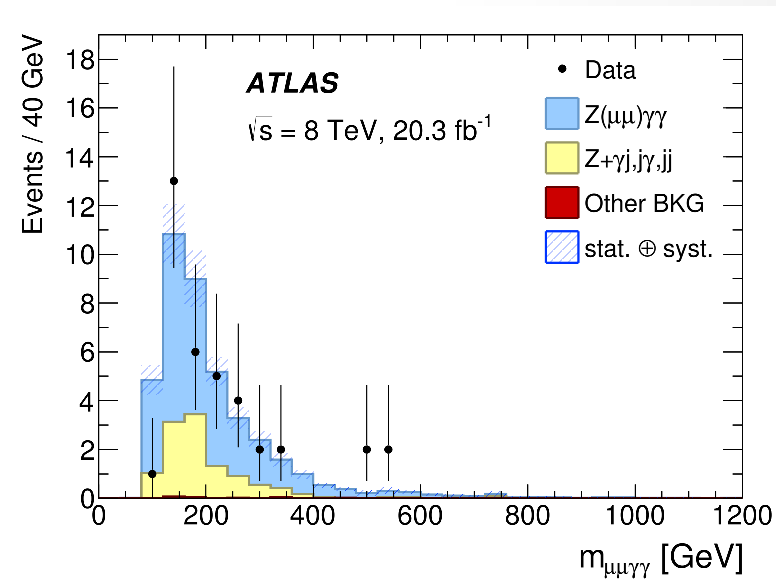
CERN-EP-2016-049

Channel	Measurement [fb]	MCFM Prediction [fb]
	$N_{\text{jets}} \geq 0$	
$e^+e^-\gamma\gamma$	$6.2\ ^{+1.2}_{-1.1}(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	$3.70^{+0.21}_{-0.11}$
$\mu^+\mu^-\gamma\gamma$	$3.83\ ^{+0.95}_{-0.85}(\text{stat.})^{+0.48}_{-0.47}(\text{syst.}) \pm 0.07(\text{lumi.})$	
$\ell^+\ell^-\gamma\gamma$	$5.07\ ^{+0.73}_{-0.68}(\text{stat.})^{+0.41}_{-0.38}(\text{syst.}) \pm 0.10(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$2.5\ ^{+1.0}_{-0.9}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.1(\text{lumi.})$	$0.737^{+0.039}_{-0.032}$







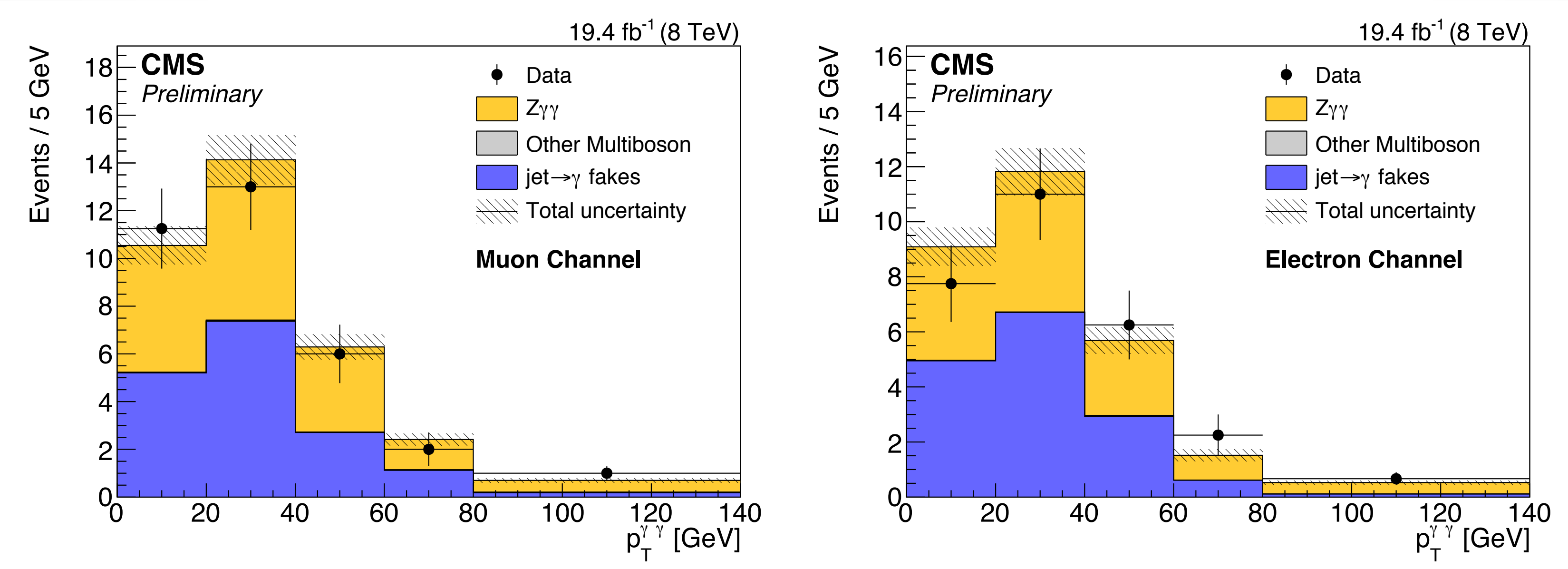


CMS Zγγ

SMP-15-008

$$\sigma^{\text{fid}}_{Z\gamma\gamma} \cdot \text{BR}\left(Z \to \ell\ell\right) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\ \text{fb}$$

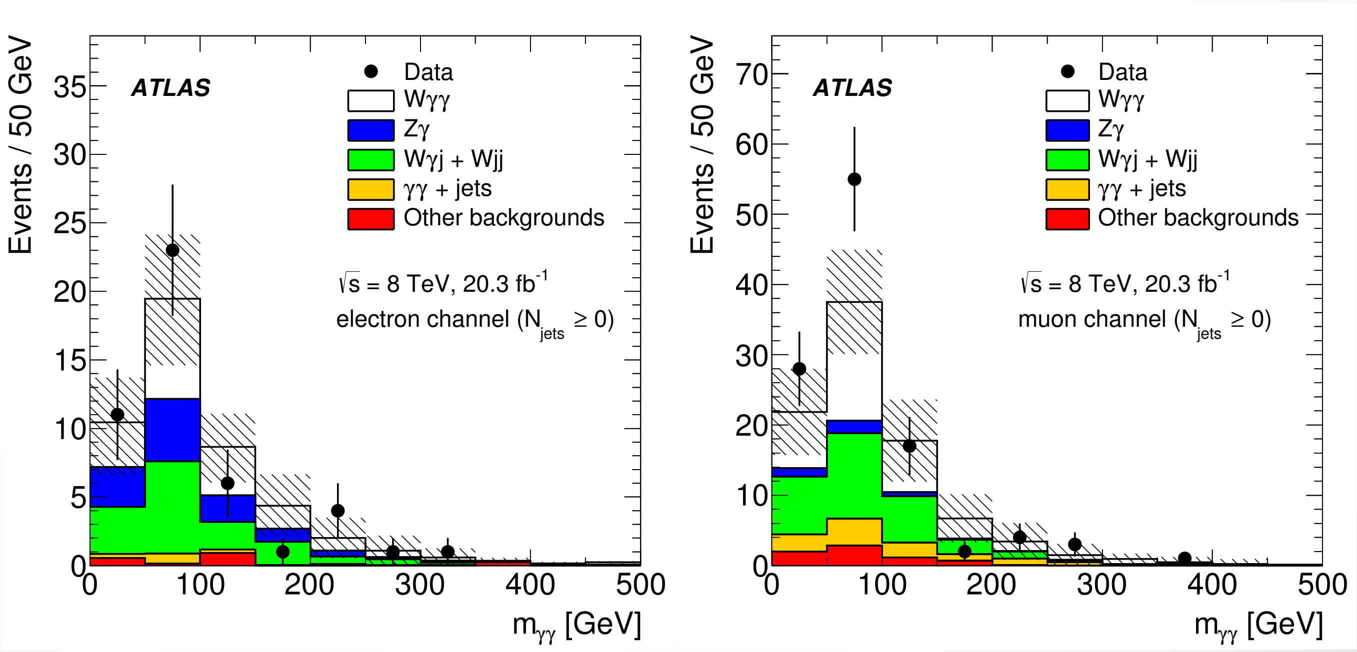
$$\sigma^{\text{NLO}}_{Z\gamma\gamma} \cdot \text{BR}\left(Z \to \ell\ell\right) = 12.95 \pm 1.47\ \text{fb}$$



ATLAS W$\gamma\gamma$

CERN-PH-EP-2015-009

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	

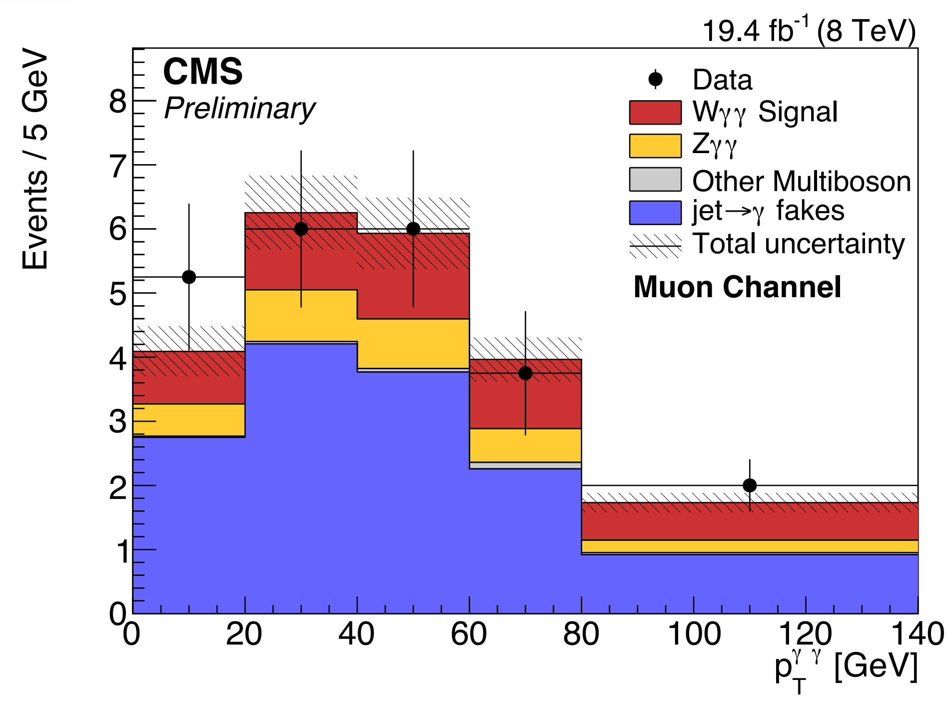


SMP-15-008

CMS Wγγ

$$\sigma^{\mathrm{NLO}}_{\mathrm{W}^{\pm}\gamma\gamma} \cdot \mathrm{BR}\left(\mathrm{W} \to \ell\nu\right) = 4.76 \pm 0.53\,\mathrm{fb}$$

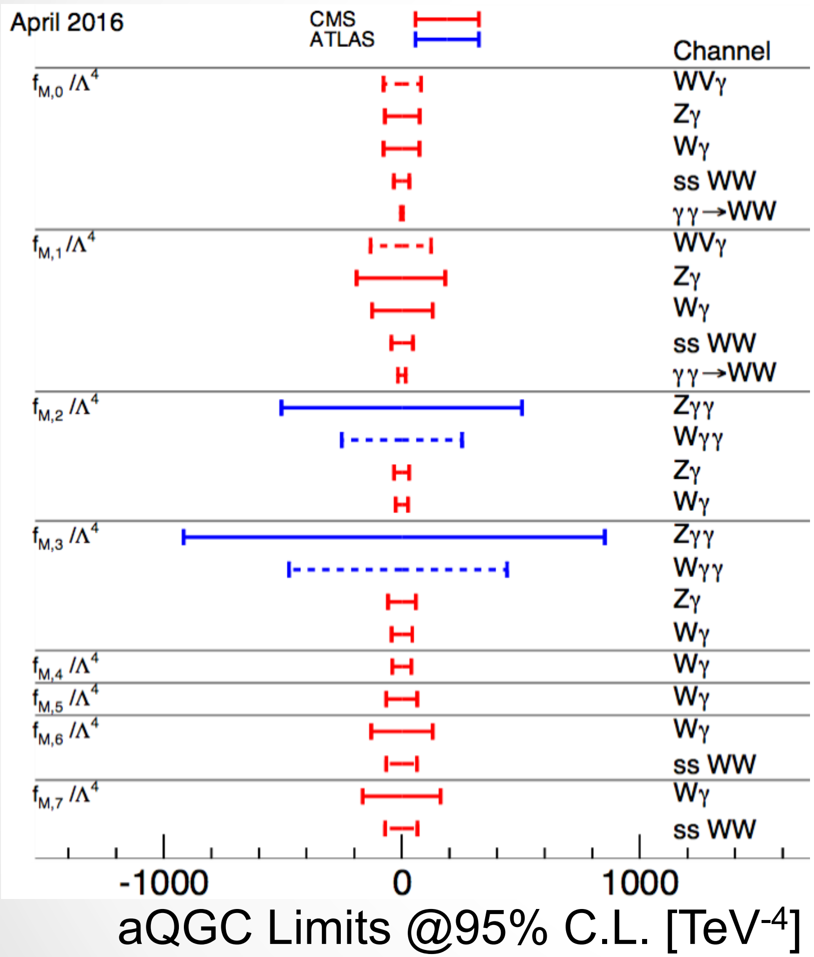
$$\sigma^{\mathrm{fid}}_{\mathrm{W}^{\pm}\gamma\gamma} \cdot \mathrm{BR}\left(\mathrm{W} \to \ell\nu\right) = 6.0 \pm 1.8\,(\mathrm{stat}) \pm 2.3\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\,\mathrm{fb}$$

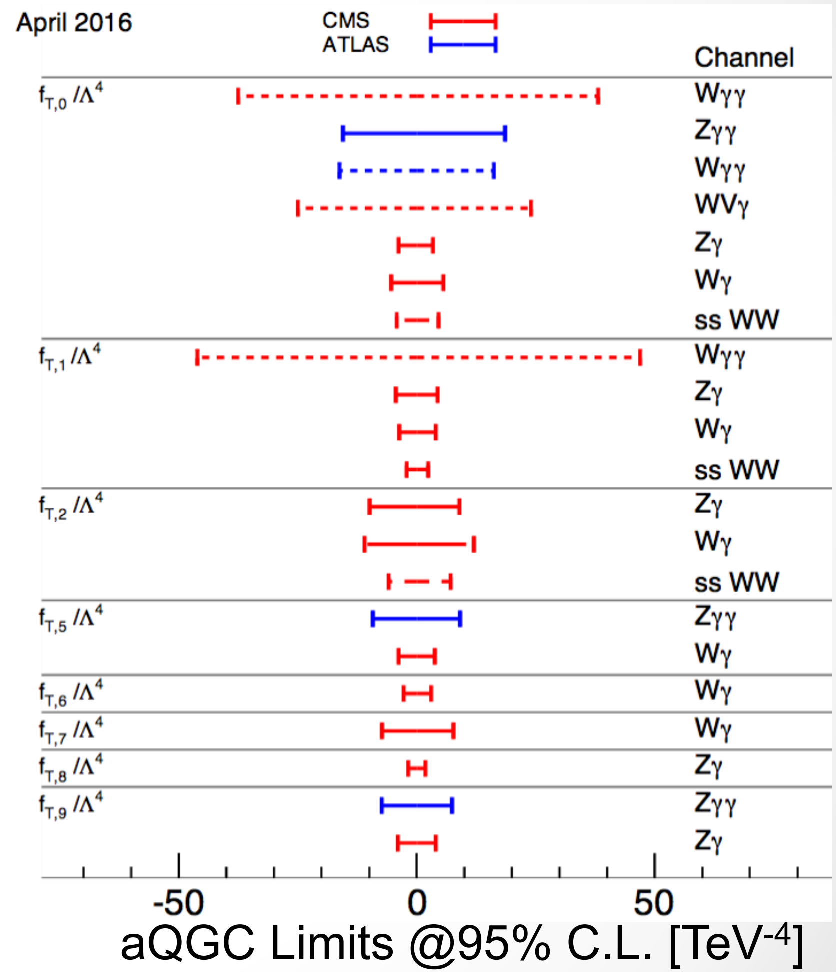


Tri-bosons results: first aQGC limits

- All results compatible with zero

All 8 TeV measurements





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

Future prospects

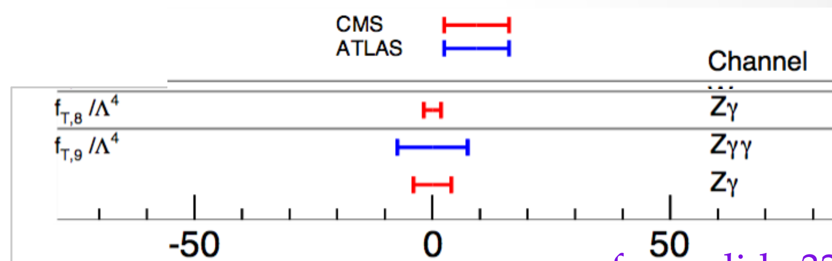
- To get precision measurements, we will have to wait for 300 fb^{-1} or even HL-LHC.
  - High precision to detect small effects in high mass tails.
  - Full hardware upgrade necessary
- New forward proton spectrometer (AFP and PPS) will increase sensitivity in photon induced channels (10.1103/PhysRevD.89.114004).

Example: non-unitarization in VBS

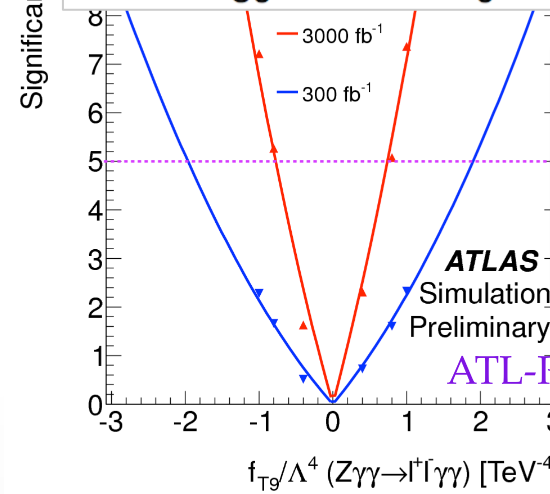
3000 fb^{-1}, 14 TeV	Phase-II	Phase-I aged
Higgsless 95% CL μ exclusion	0.14	0.20
$V_L V_L$ scattering significance	2.75	2.14

CMS-TDR-15-02

Sensitive to scenarios in which Higgs boson has ~80%-85% contribution to VBS unitarization



from slide 32



Example of expected improvement in aQGC

ATL-PHYS-PUB-2013-006