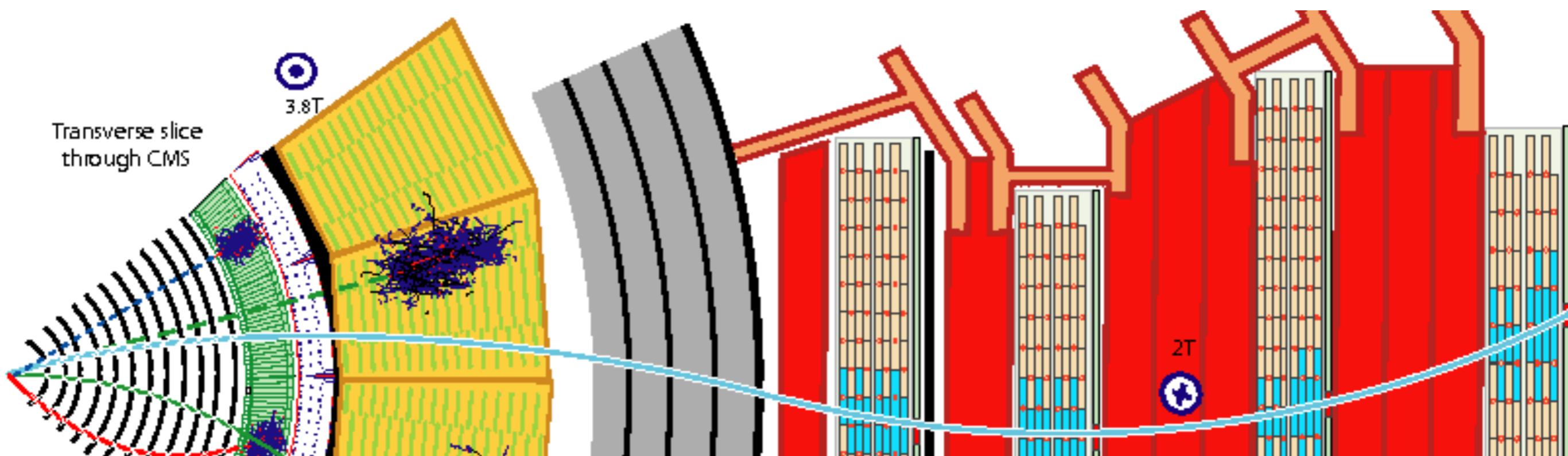




Precision electroweak measurements with the CMS detector

V. Ciulli, University and INFN of Florence

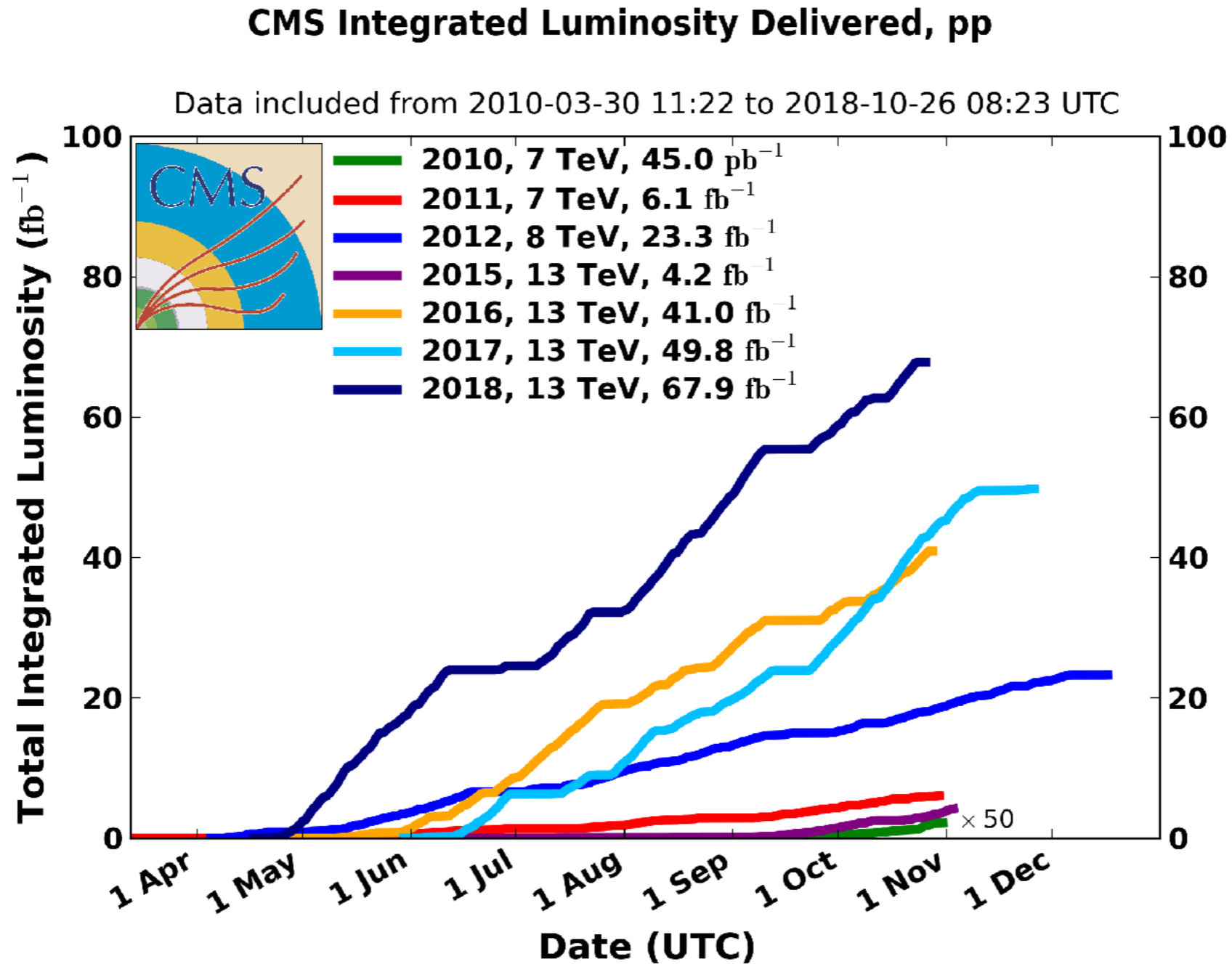
on behalf of CMS Collaboration



Introduction



Overall $\sim 200 \text{ fb}^{-1}$ of data collected



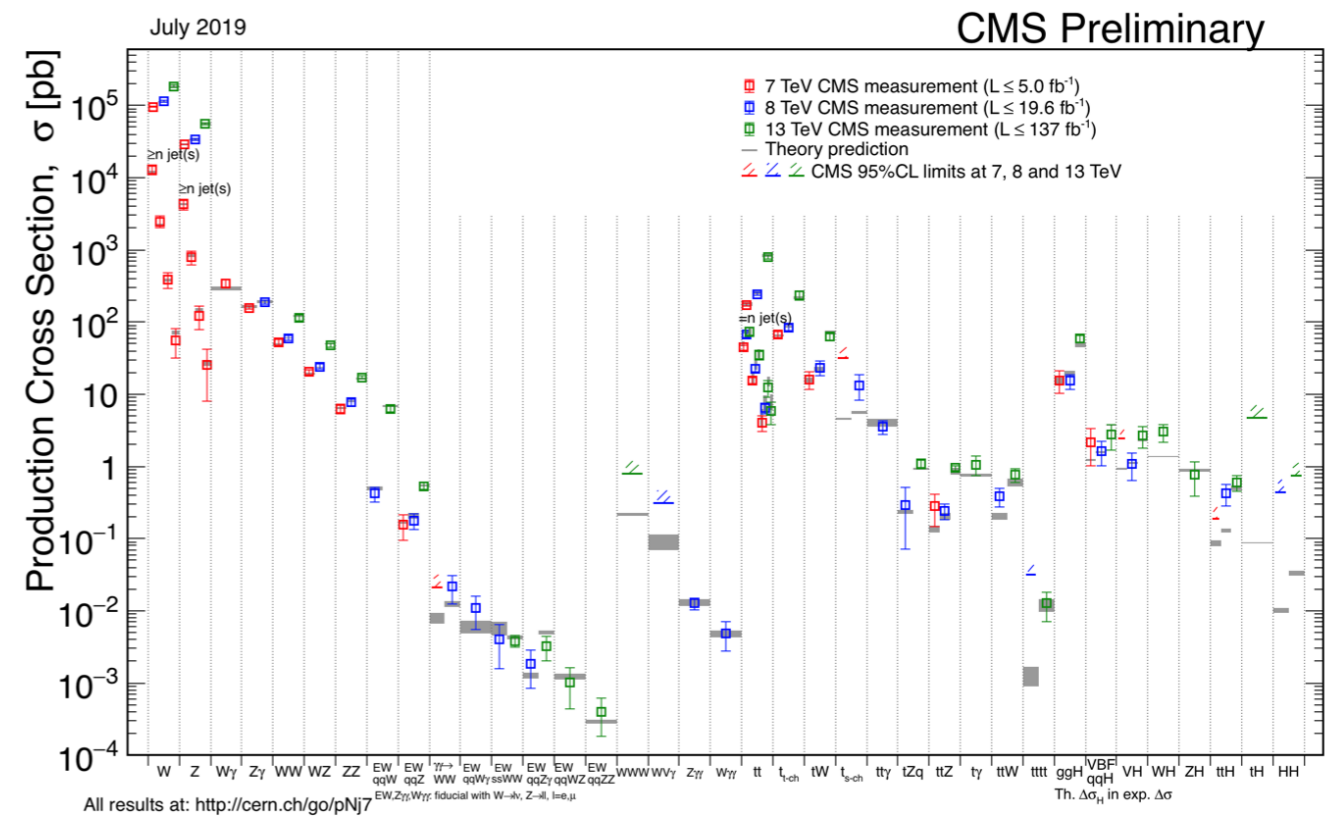
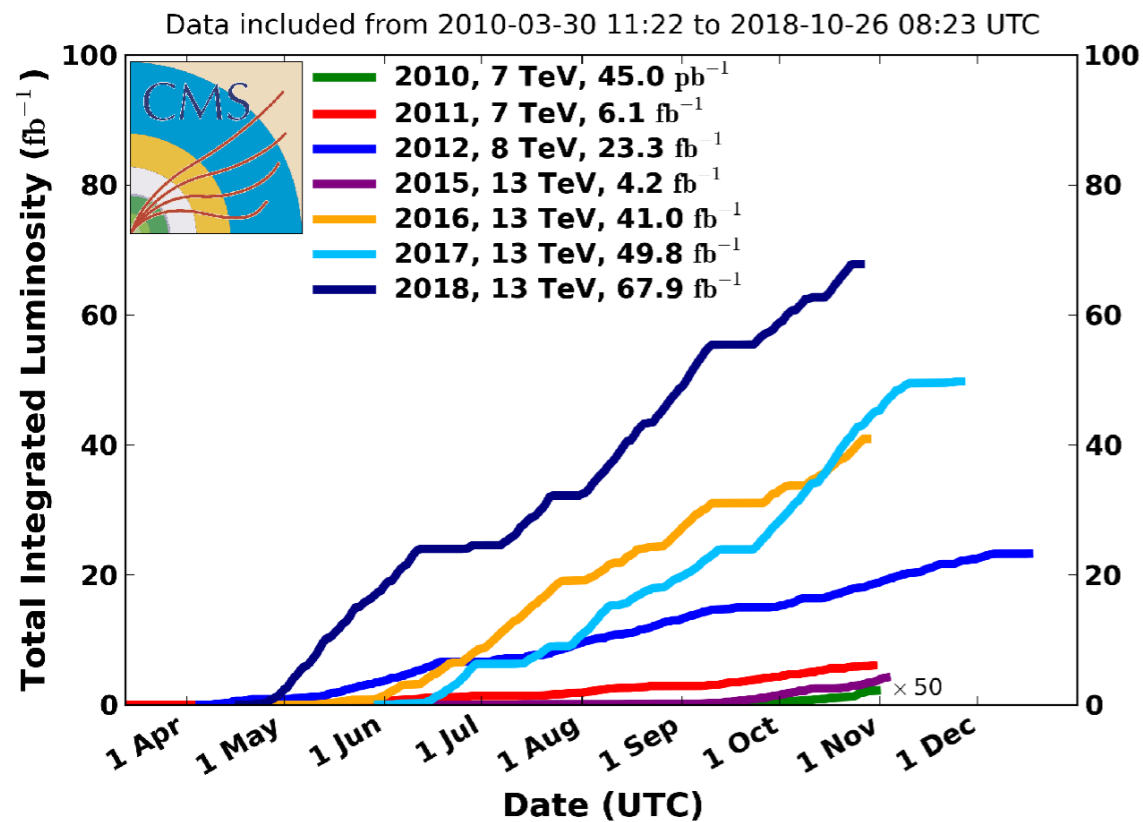
Introduction



Overall $\sim 200 \text{ fb}^{-1}$ of data collected

SM processes measured over 9 orders of magnitude

CMS Integrated Luminosity Delivered, pp



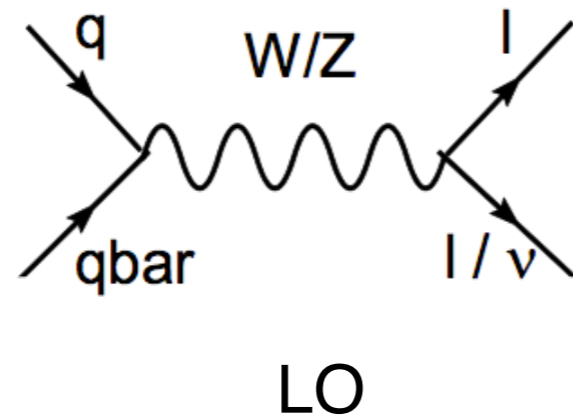
I will show measurements of single and multi-boson production (EW processes)

Most results based on 13 TeV data up to 2016, i.e. $\sim 40 \text{ fb}^{-1}$

W/Z production at the LHC



W and Z are a clean and powerful probe for fundamental processes



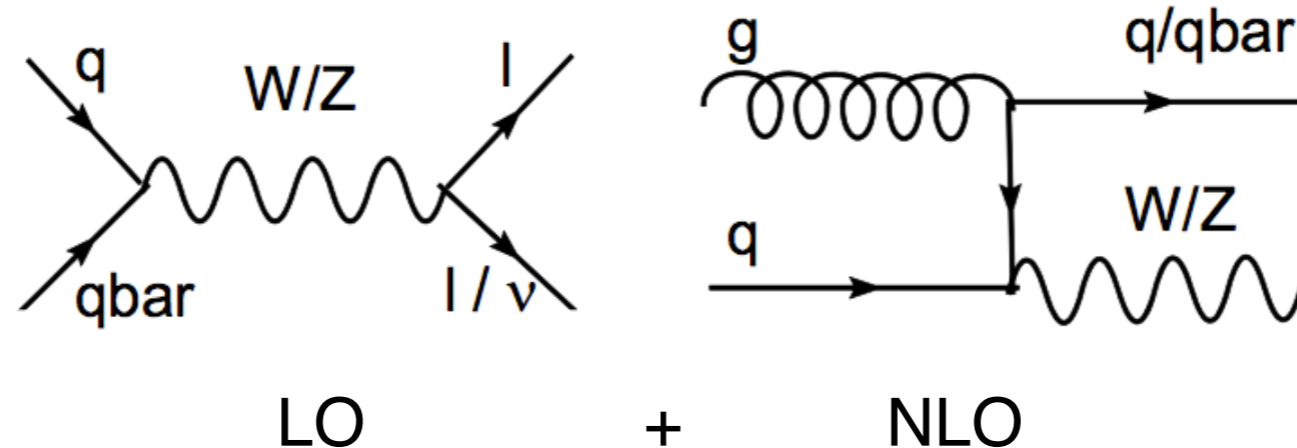
To first order at LHC, W and Z are generated by a valence quark and a sea anti-quark ($Q \sim 100$ GeV)

Parton fractions are $10^{-3} < x < 10^{-1}$, so sea-sea contributions also important

W/Z production at the LHC



W and Z are a clean and powerful probe for fundamental processes



To first order at LHC, W and Z are generated by a valence quark and a sea anti-quark ($Q \sim 100$ GeV)

Parton fractions are $10^{-3} < x < 10^{-1}$, so sea-sea contributions also important

Furthermore NLO (W/Z+jets) depends also on gluon pdf!

EW processes allow precision measurements of fundamental parameters through their couplings, but also provide important PDFs constraints

(conversely PDFs uncertainty is important for the measurements of the couplings)

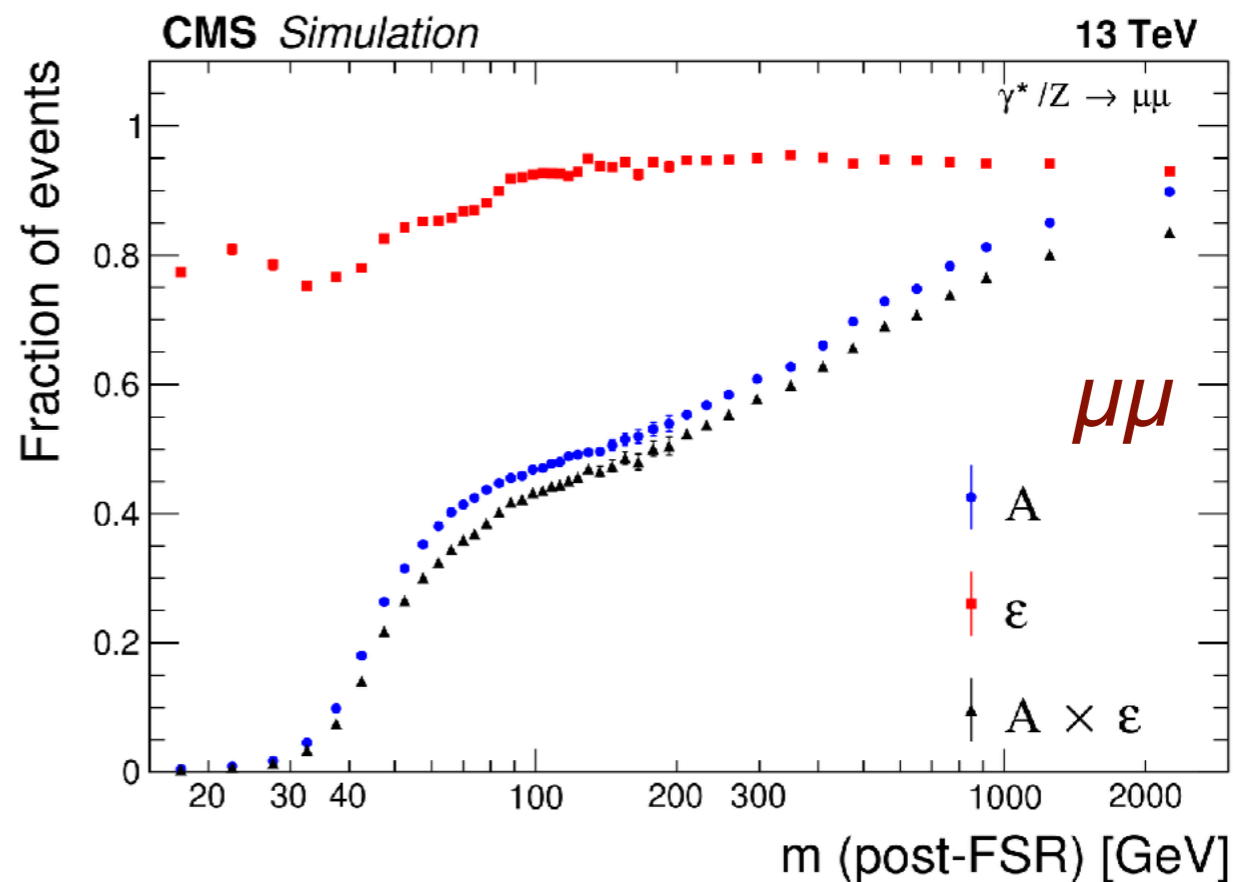
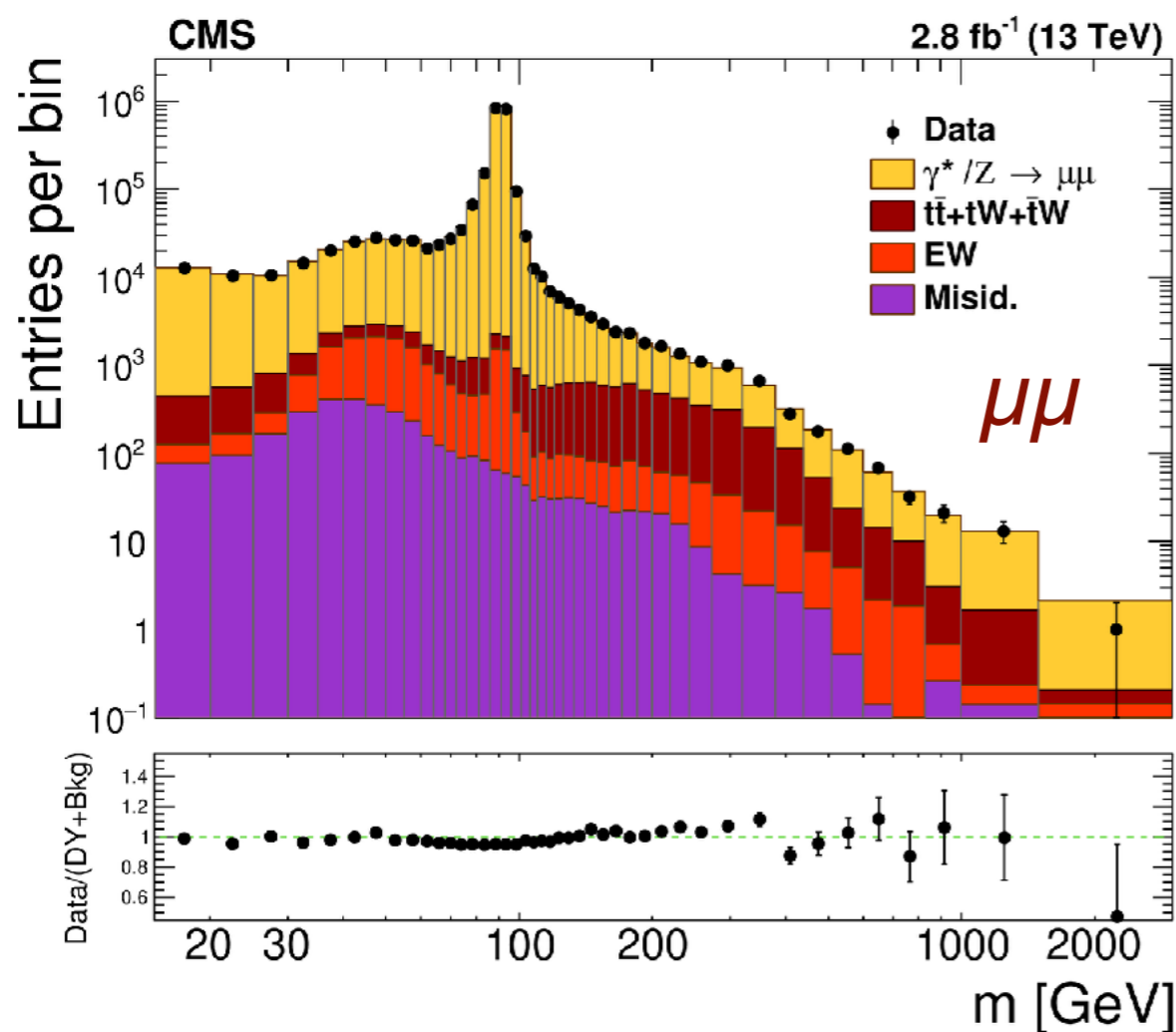
Drell-Yan $m_{\ell\ell}$ differential cross-section



- ▶ Distribution of $m_{\ell\ell}$ measured in the range 15-3000 GeV
- ▶ Leading muon (electron): $p_T > 22$ (30) GeV, $|\eta| < 2.4$ (2.5)
- ▶ Trailing lepton: $p_T > 10$ GeV
- ▶ Resolution effects and FSR are unfolded
- ▶ Then cross-section is obtained by correcting for acceptance A and efficiency ϵ

SMP-17-001
arXiv:1812.10529

$$\Rightarrow \sigma_i = \frac{N_i}{A\epsilon\mathcal{L}}$$



Results also given without A correction:
“fiducial cross-section”

Drell-Yan $m_{\ell\ell}$ differential cross-section



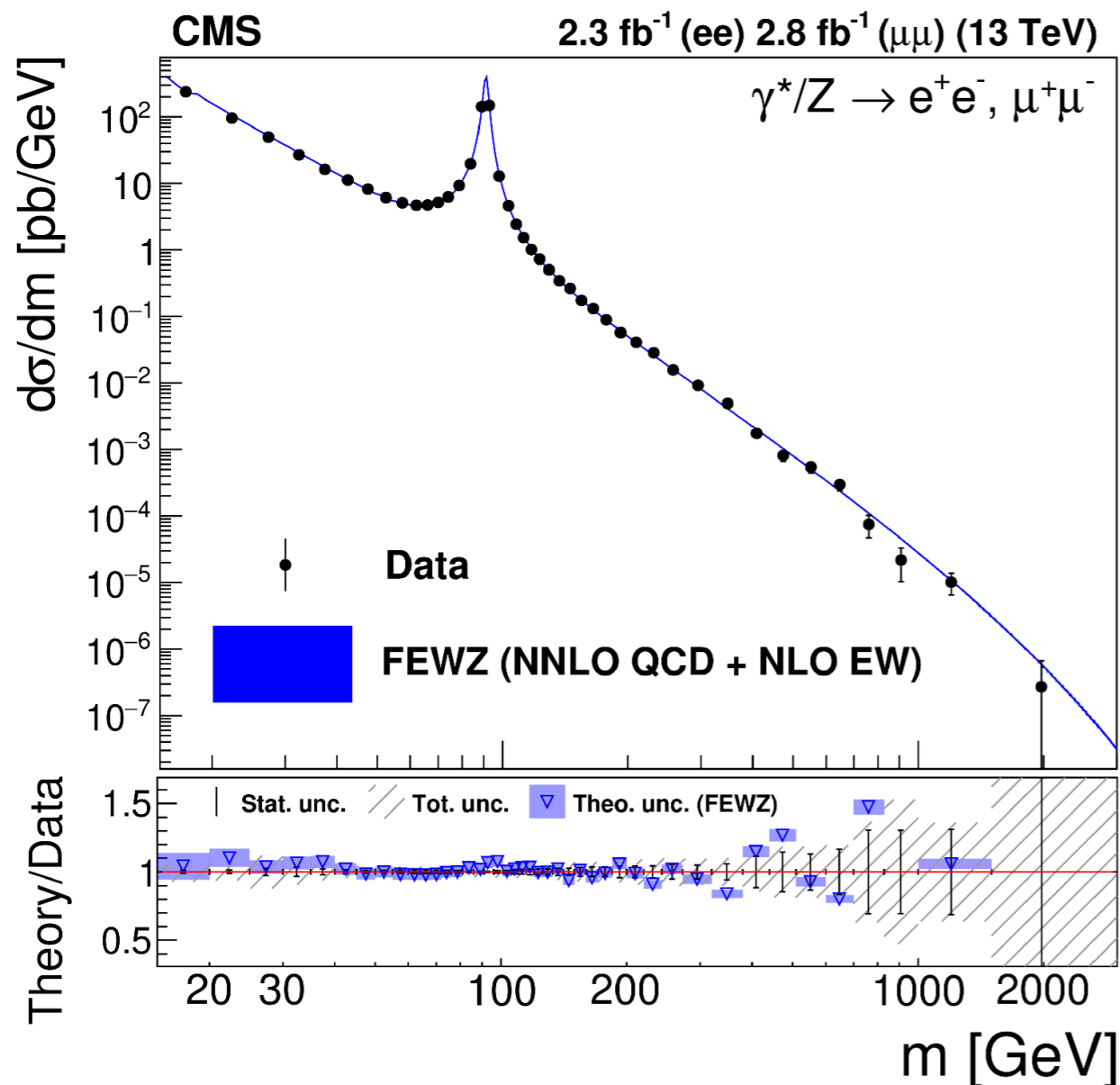
Results for 13 TeV based on 2015 dataset of 2.8 fb⁻¹

ee and $\mu\mu$ combined after unfolding FSR effects (“dressed leptons”)

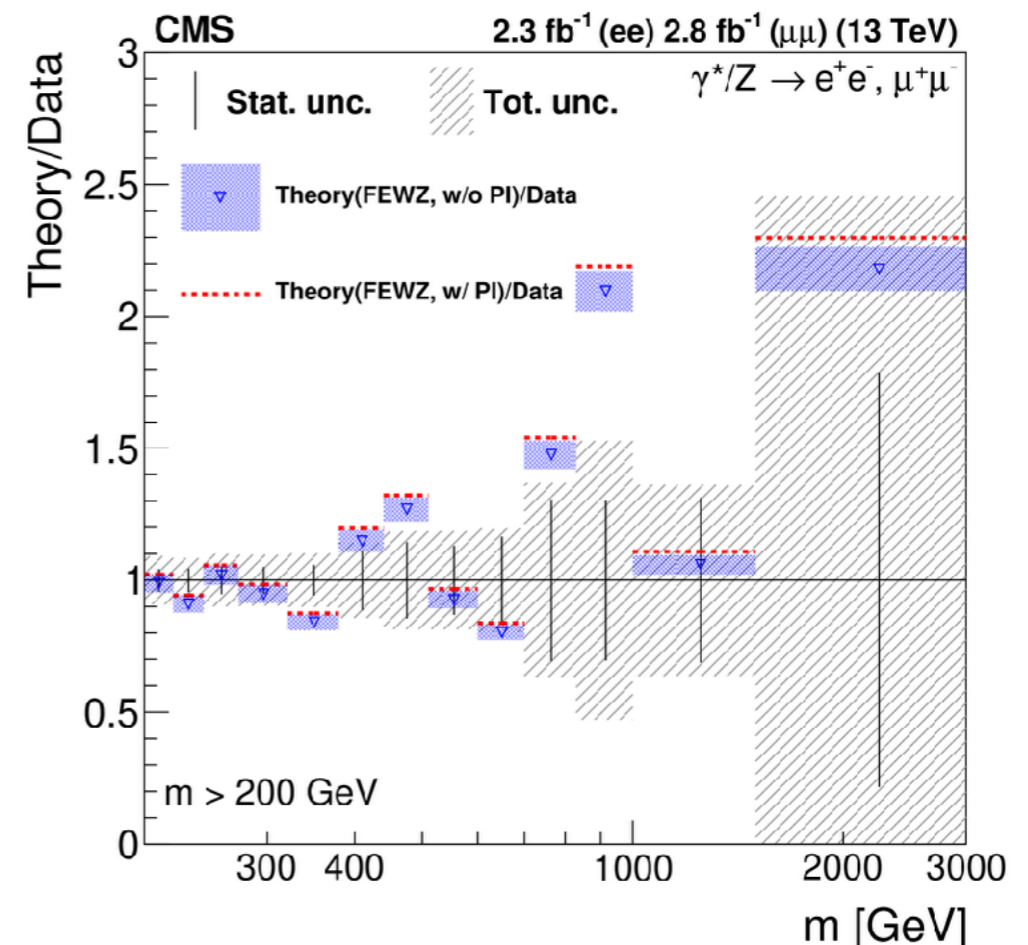
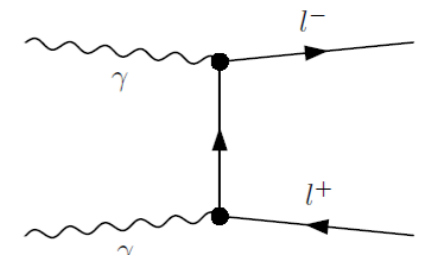
Largest uncertainties: acceptance at low mass and statistical at high mass

Excellent agreement with predictions from FEWZ (QCD NNLO + EW NLO)

SMP-17-001
arXiv:1812.10529



Photon-initiated negligible except at very high mass



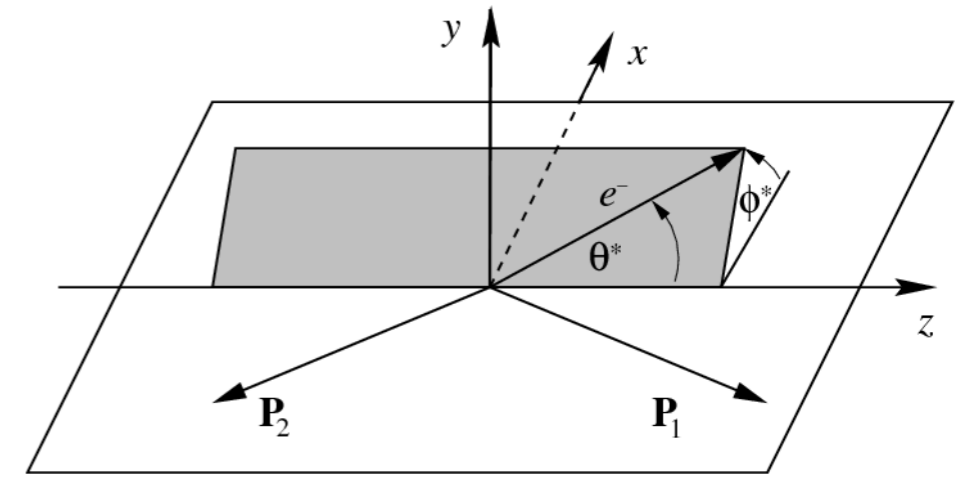
A_{FB} in DY events and $\sin^2\theta_W$



Angular distribution in $qq \rightarrow Z/\gamma \rightarrow \ell^+\ell^-$

$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$$

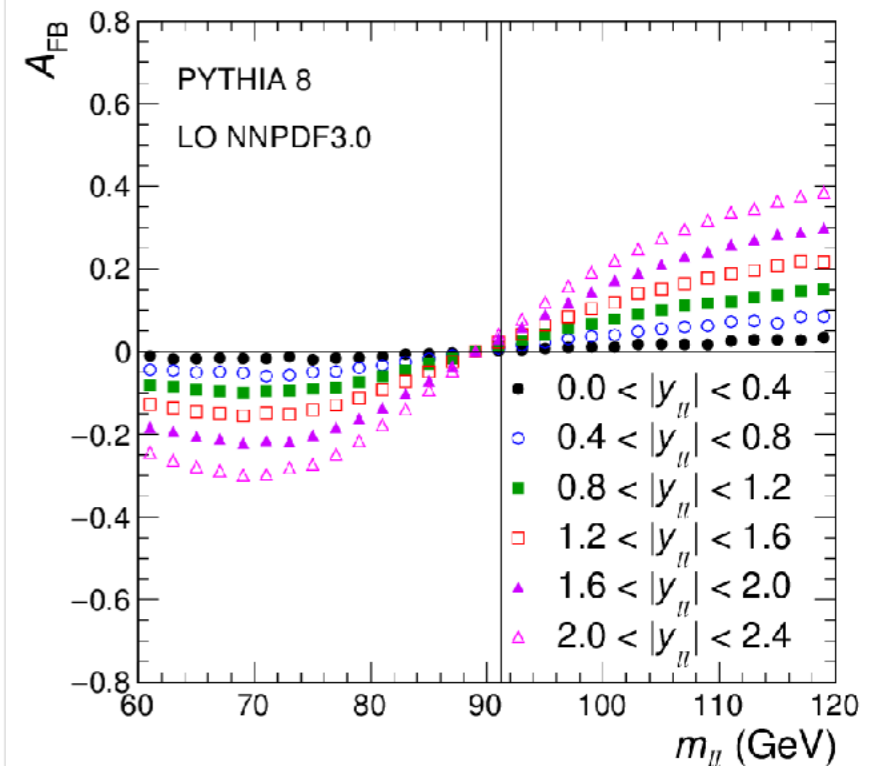
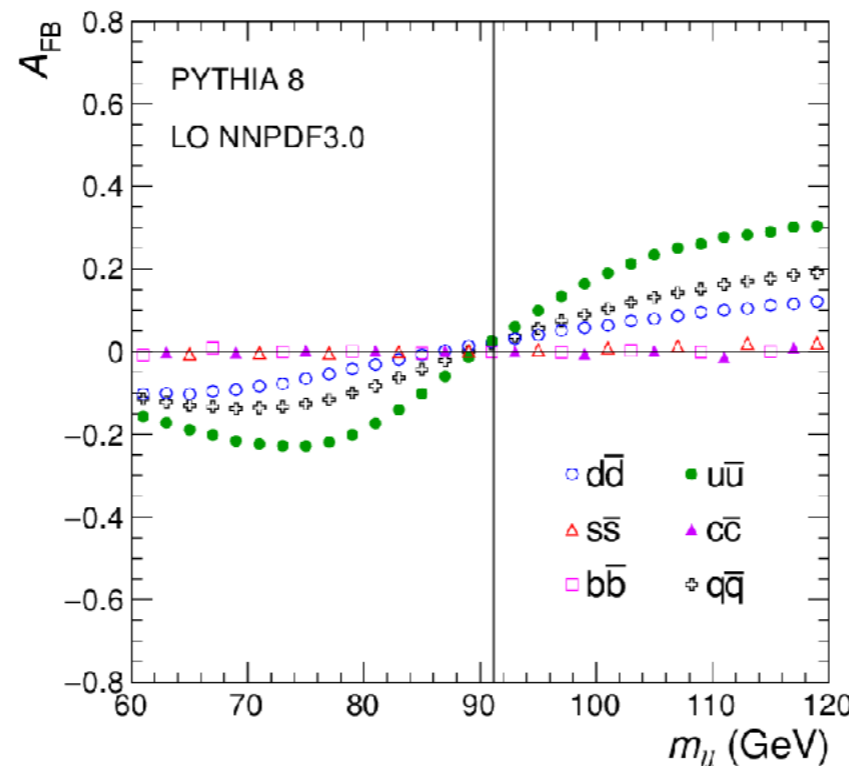
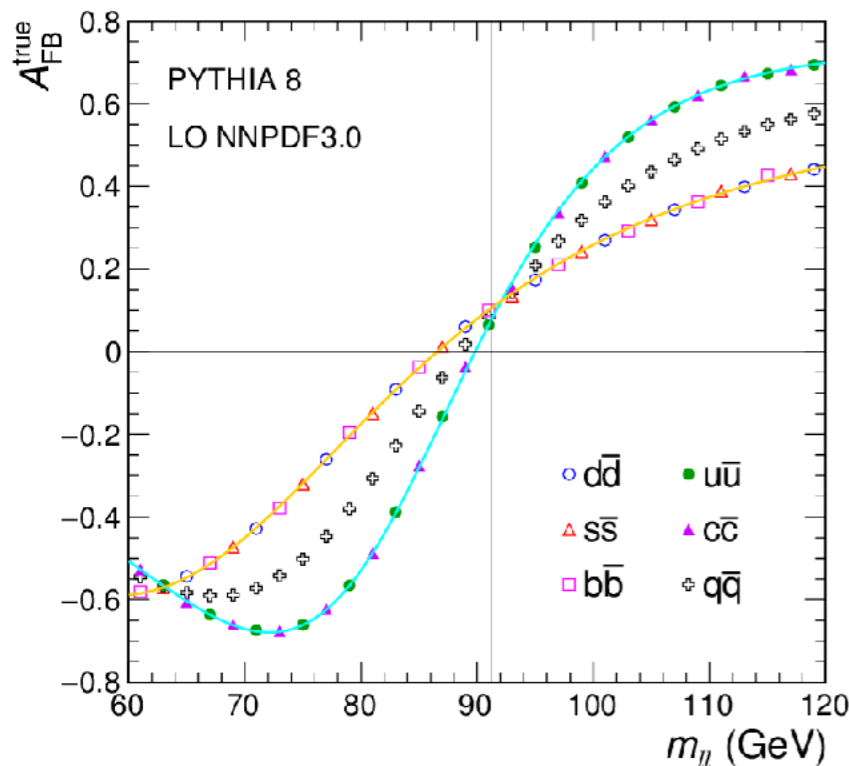
The asymmetry $A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$ is due to the interference of vector and axial currents $\Rightarrow \sin^2\theta_W$



Collins-Soper frame

Direction of incoming quark determined from the boost

- ▶ quarks are mainly originated from valence quarks and tend to have larger x than antiquarks
- ▶ dilution of asymmetry with a strong dependence on the di-lepton rapidity



A_{FB} in DY events and $\sin^2\theta_W$

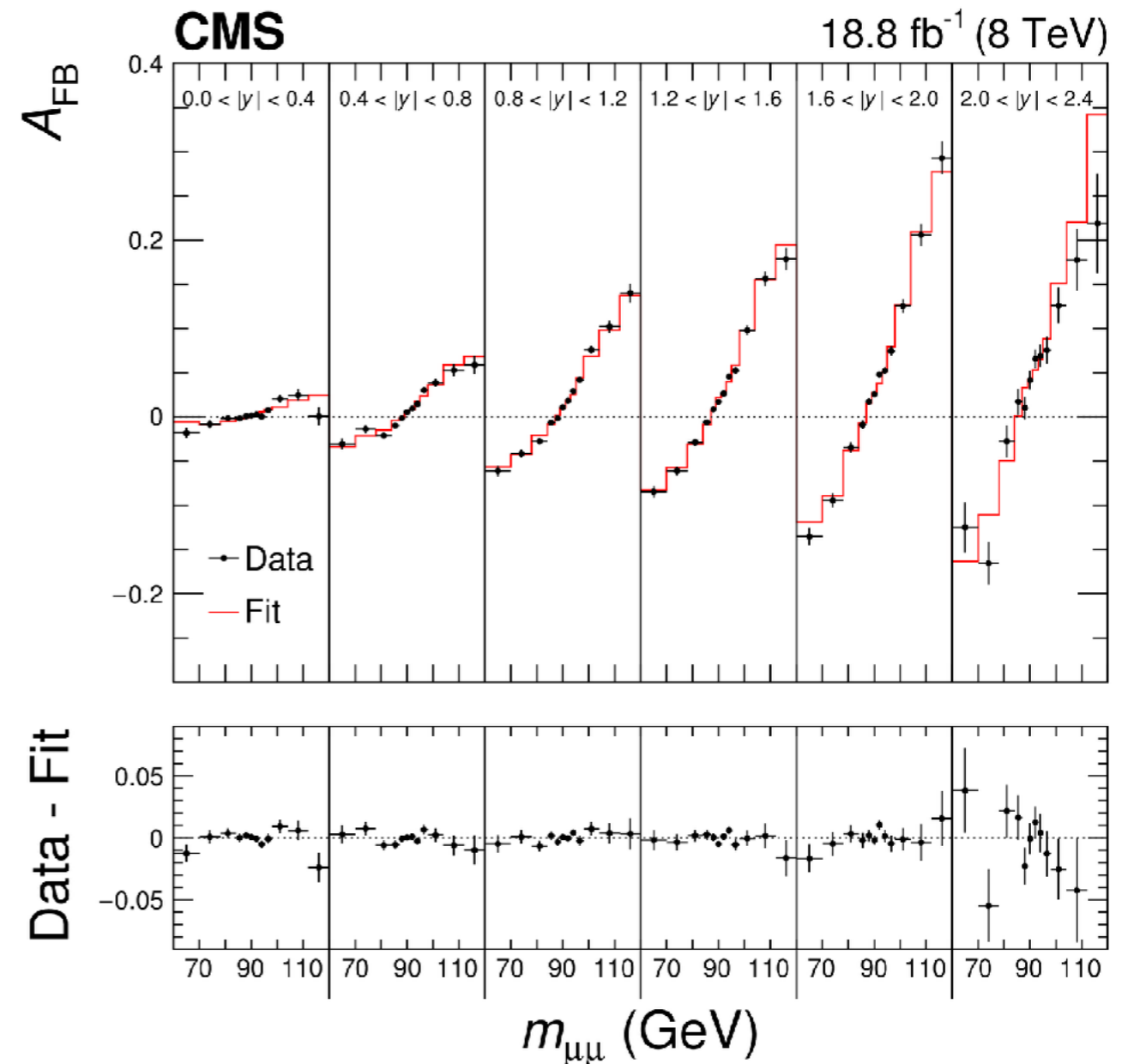
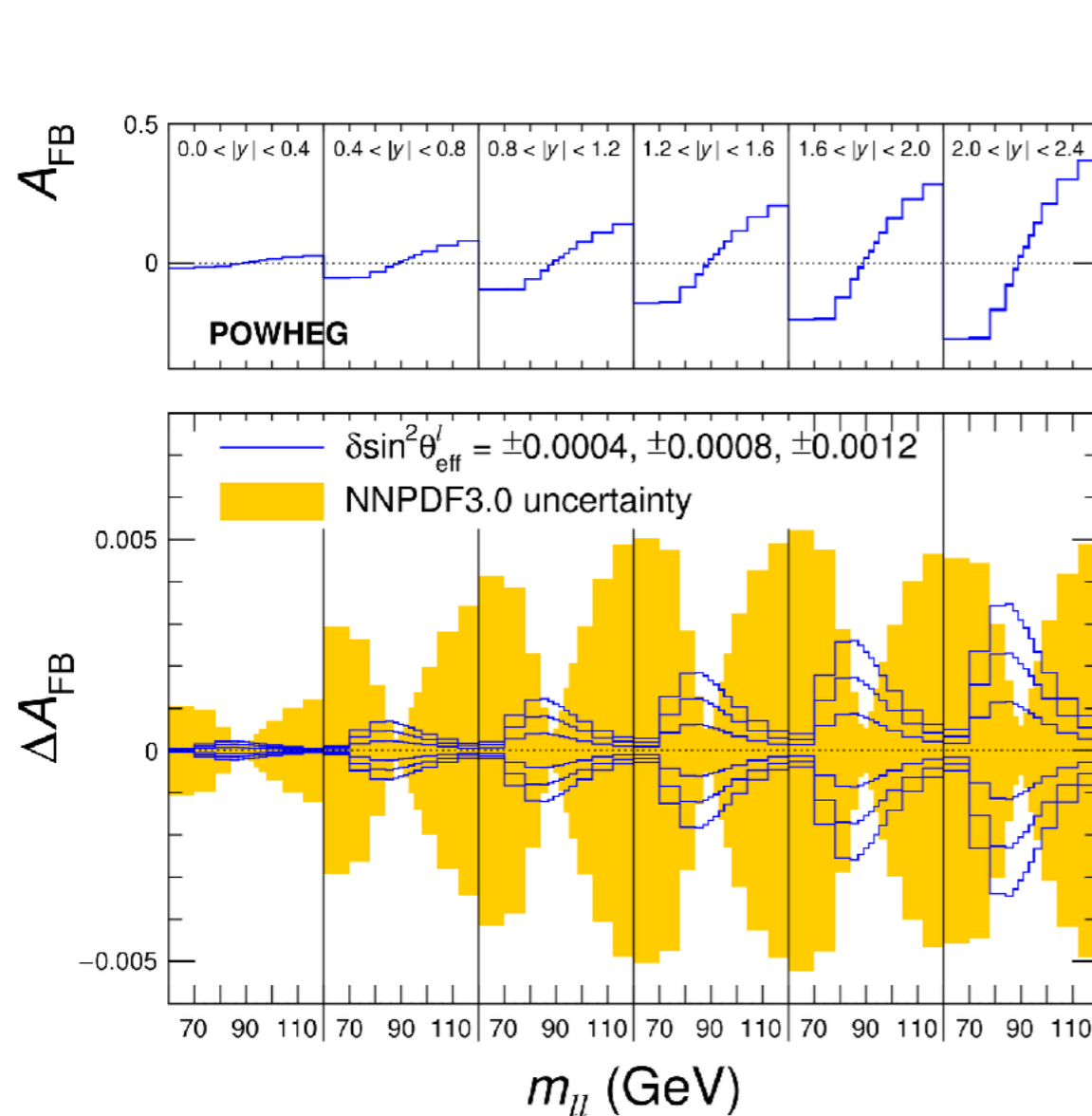
SMP-16-007
EPJC 78 (2018) 701



Measurement done differential in $m_{\ell\ell}$ and $y_{\ell\ell}$

- $\sin^2\theta_W$ sensitivity mainly at Z peak
- PDF constrained from A_{FB} value above/below

Results for full 8 TeV dataset: 18.8 fb⁻¹

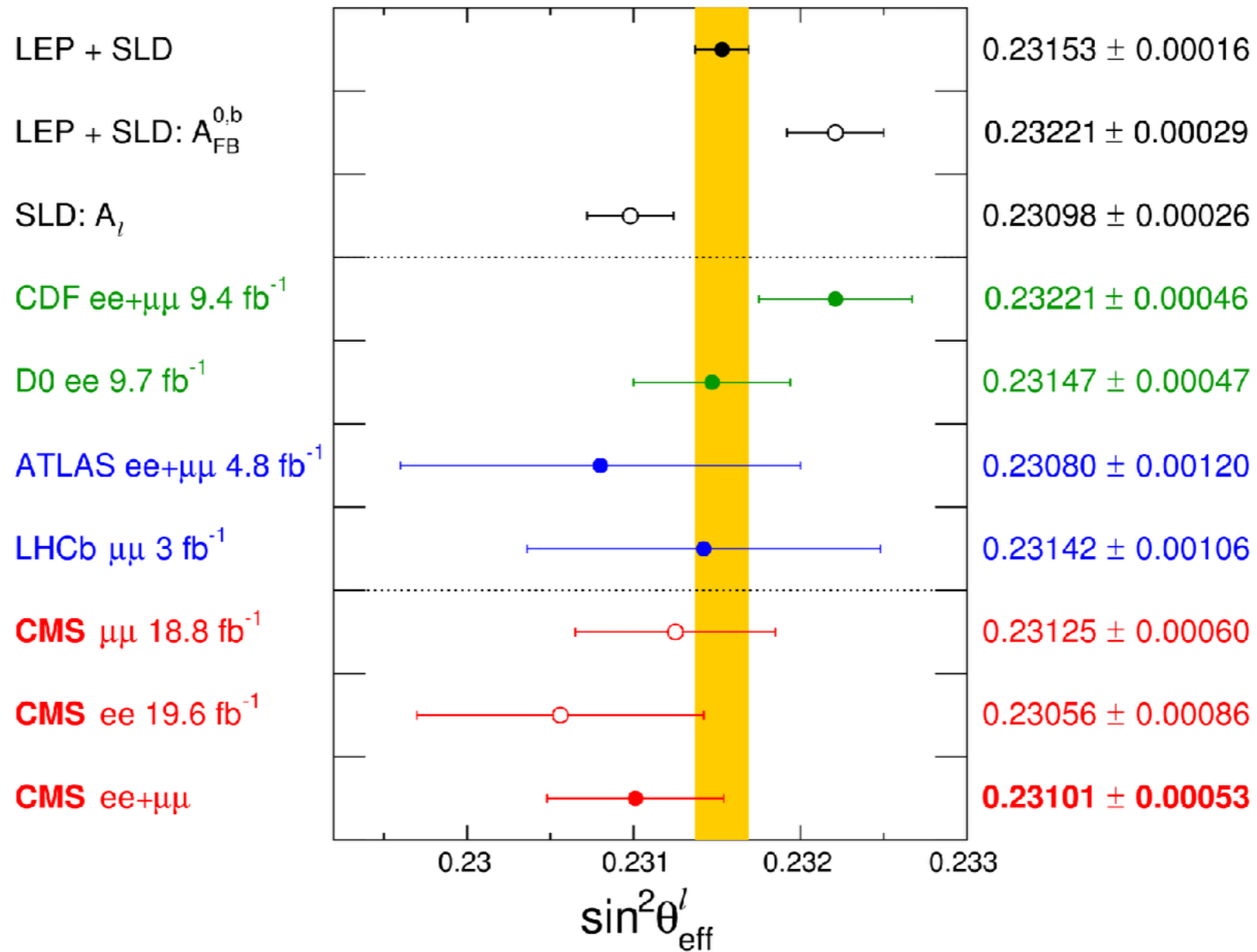


A_{FB} in DY events and $\sin^2\theta_W$

SMP-16-007
EPJC 78 (2018) 701



$$\sin^2 \theta_{\text{eff}}^{\ell} = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (PDF)}$$



In future can help disentangle LEP/SLD tension!

Differential Z production cross-section



Results given for fiducial cross-section (2016 data 35.9 fb⁻¹):

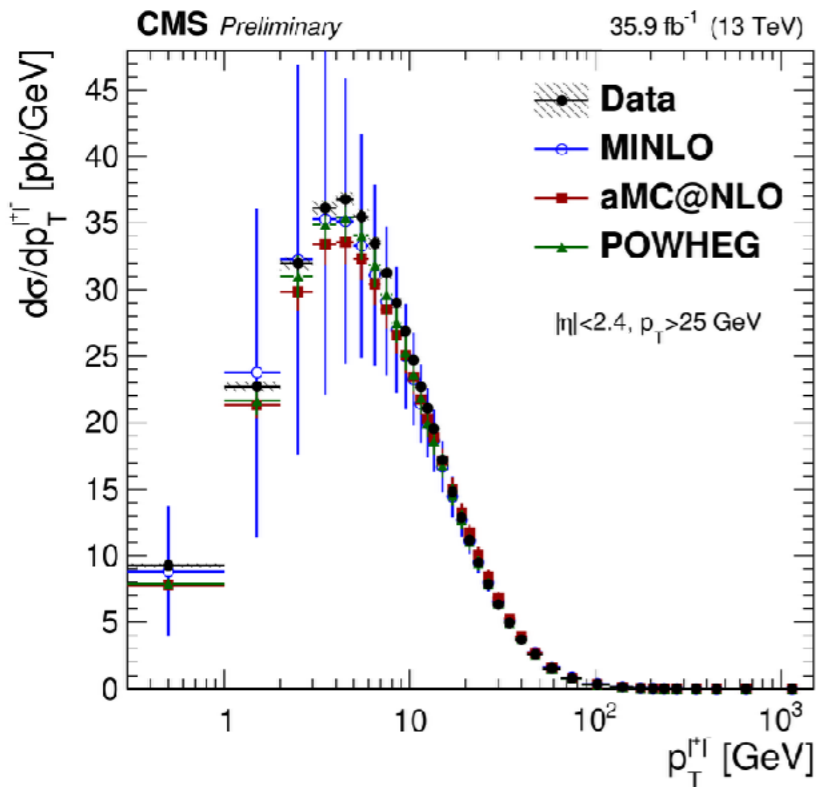
SMP-17-010

- ▶ leptons $p_T > 25$ GeV and $|\eta| < 2.4$
- ▶ $m_{\ell\ell} - 91.2$ GeV < 15 GeV
- ▶ both ee and $\mu\mu$ channel selected
- ▶ background $\sim 1\%$
- ▶ largest syst. from lumi = 2.5%

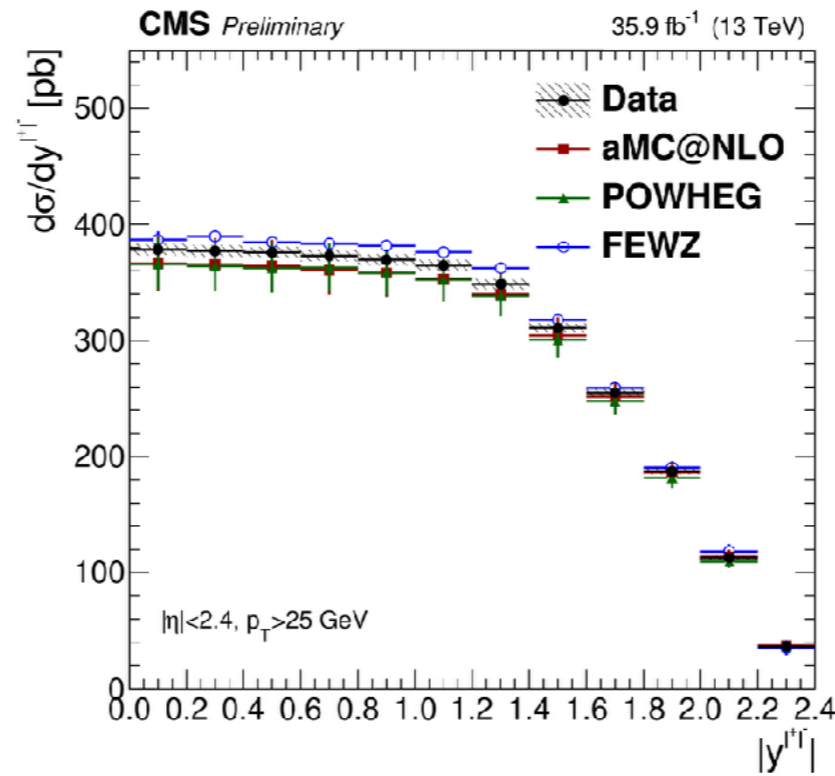
Cross section	$\sigma \mathcal{B}$ [pb]
$\sigma_{Z \rightarrow \mu\mu}$	694 ± 6 (syst) ± 17 (lumi)
$\sigma_{Z \rightarrow ee}$	712 ± 10 (syst) ± 18 (lumi)
$\sigma_{Z \rightarrow \ell\ell}$	699 ± 5 (syst) ± 17 (lumi)

FEWZ predicted (NNLO): $\sigma_{Z \rightarrow \ell\ell} = 719 \pm 8$ pb

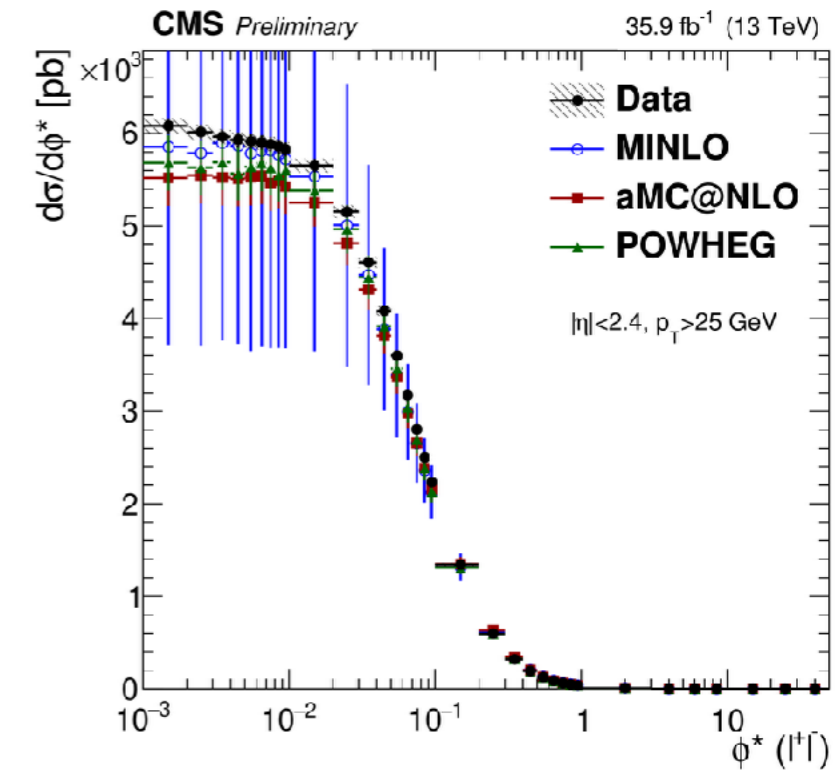
$p_T^{\ell\ell}$



$|y^{\ell\ell}|$



$\phi_{\ell\ell}^* \sim p_T^{\ell\ell}/m_{\ell\ell}$

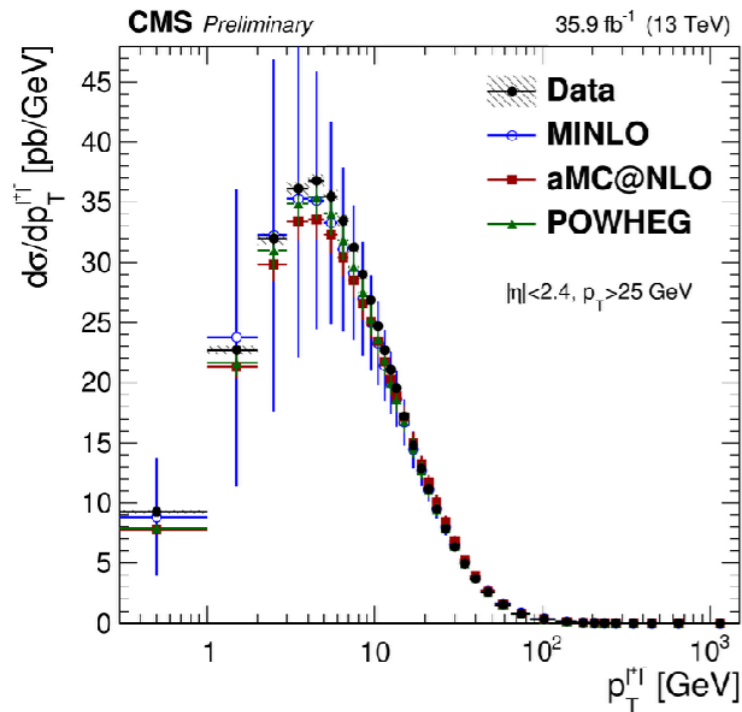


- ▶ for normalized cross-section $< 1\%$ uncertainty in most bins

Differential Z production cross-section



SMP-17-010

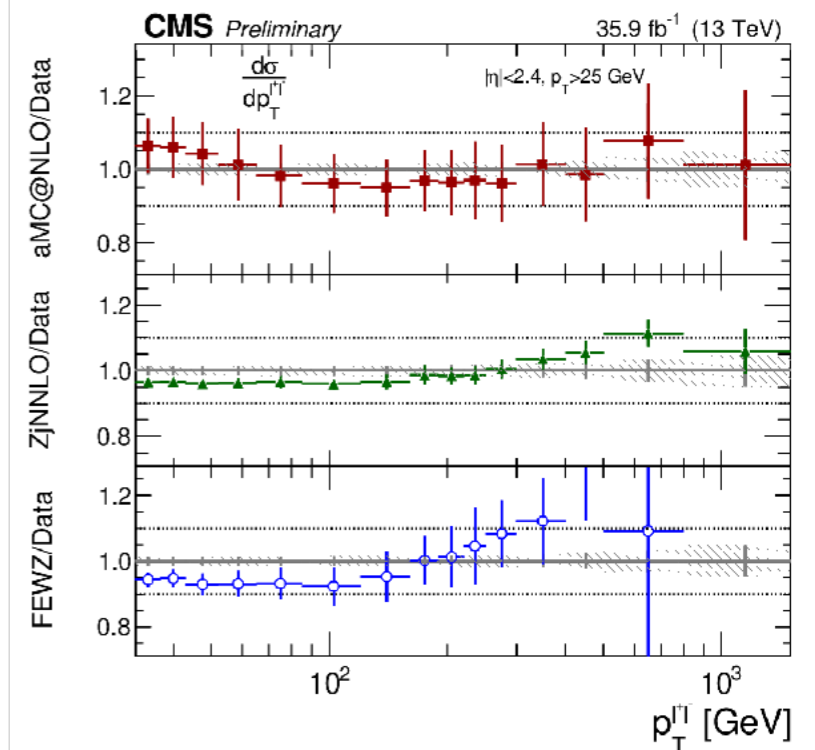
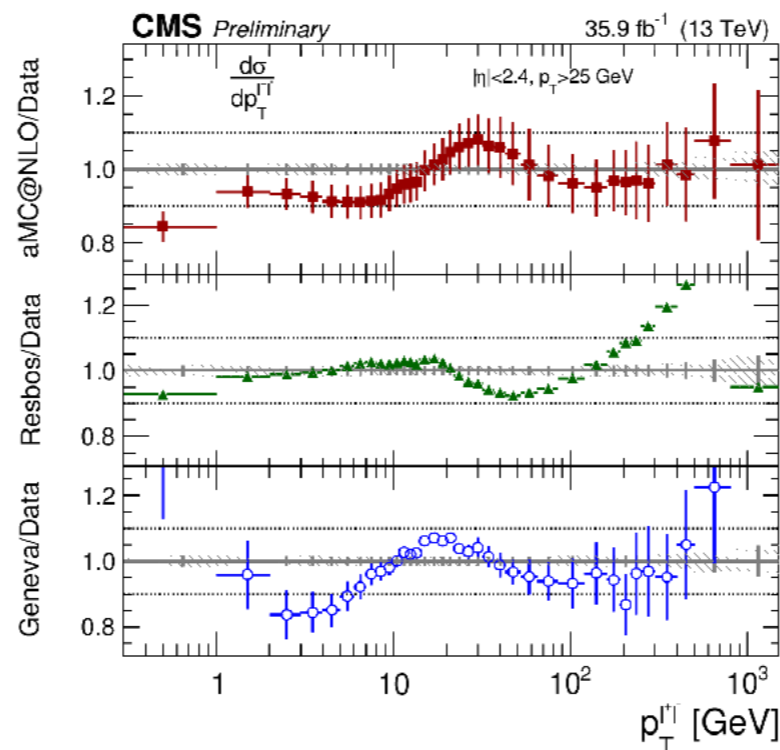
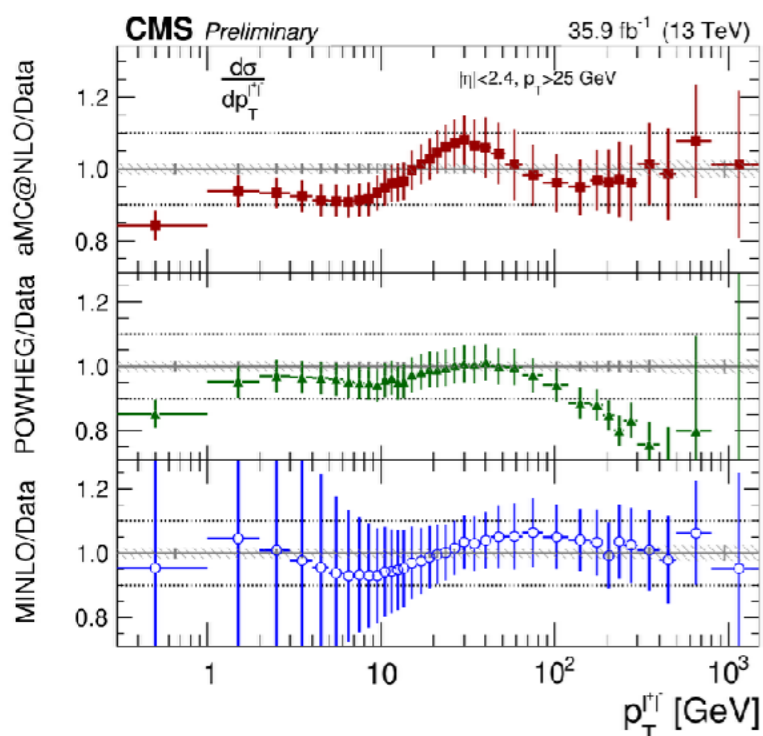


$p_T^{\ell\ell}$ distribution compared with predictions from:

- ▶ PS MC: **aMC@NLO (Z+0,1,2 jet NLO)**, **POWHEG**, **MINLO (Z+0,1 jet NLO)**
- ▶ NNLL resummed calculations: **Resbos (NLO)**, **Geneva (NNLO)**
- ▶ NNLO fixed order (for $p_T^{\ell\ell} > 32$ GeV): **ZjNNLO (Z+1 jet)**, **FEWZ**

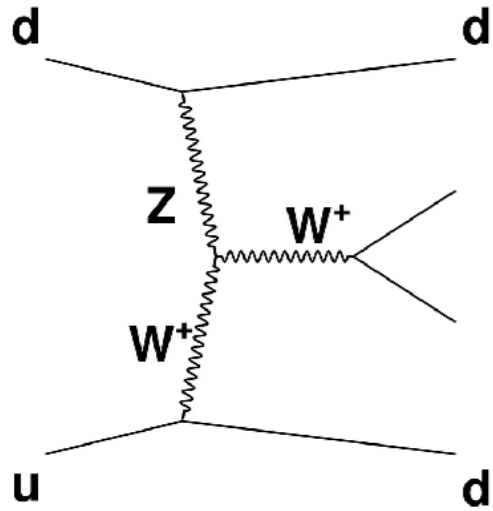
Overall good agreement with data within the uncertainties:

- ▶ discrepancies at high p_T for POWHEG and RESBOS and at low p_T for GENEVA
- ▶ Z+1 jet NNLO fixed order significantly reduces the scale uncertainties at high $p_T^{\ell\ell}$
- ▶ 10%-20% EWK corrections for $p_T^{\ell\ell} > 500$ GeV not included

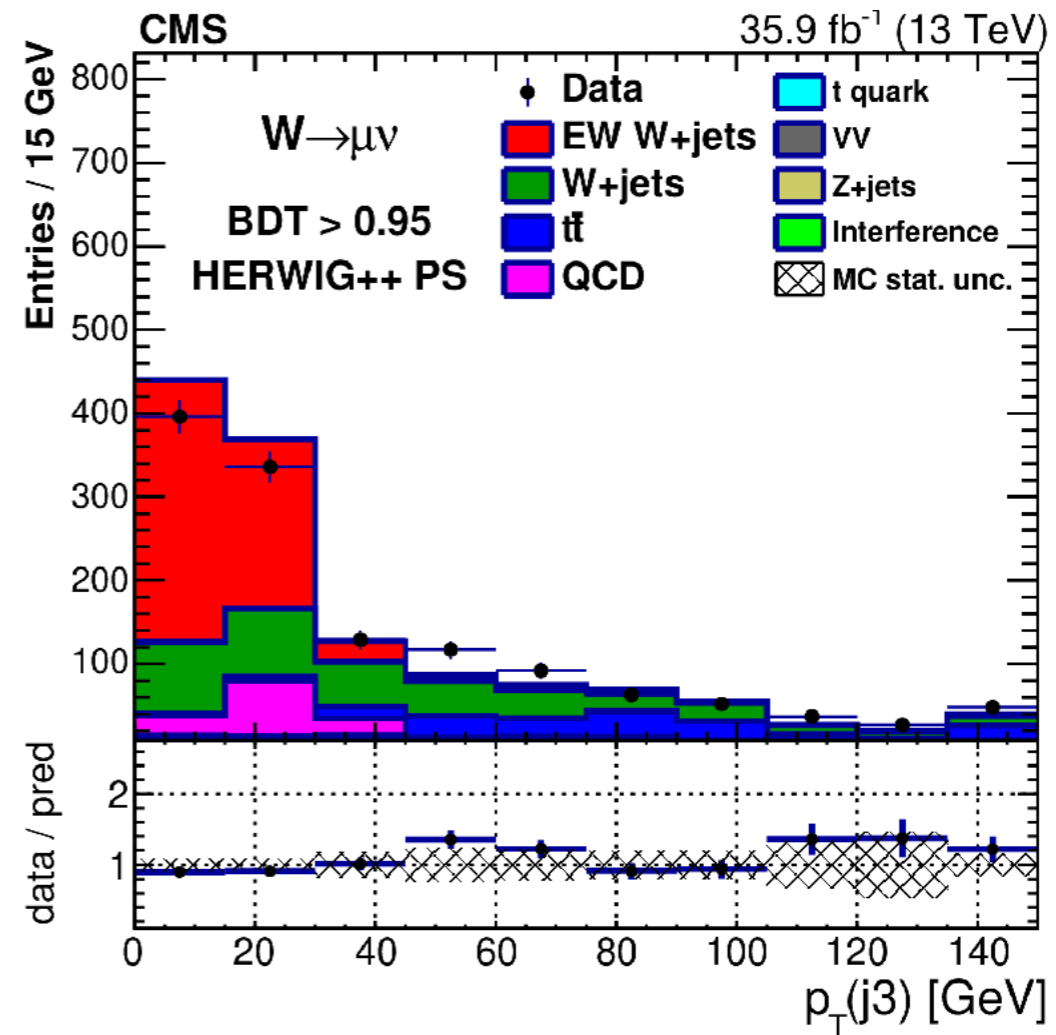
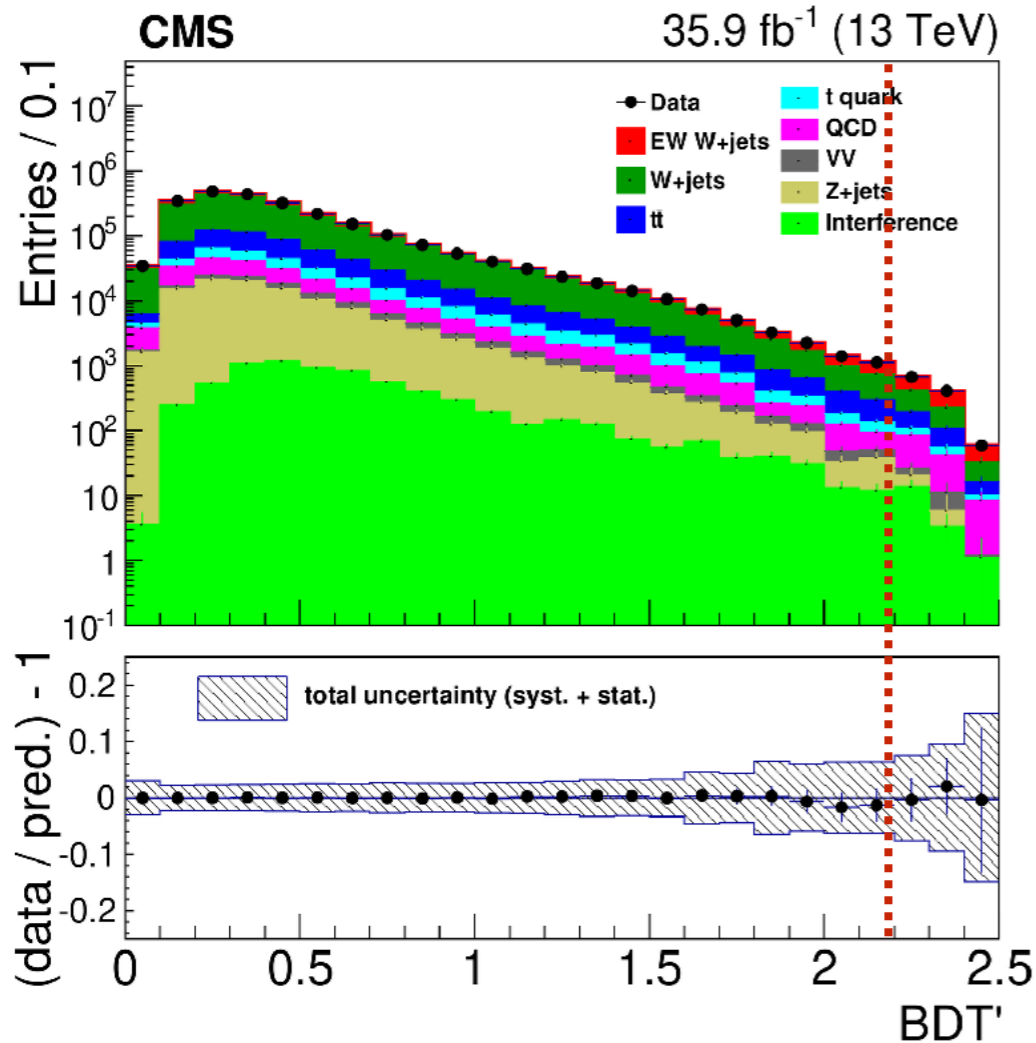


EW production of Wjj

SMP-17-011
arXiv:1903.04040



- ▶ select $\mu(e) +$ missing momentum, 2 jets with $p_T > 50/30$ GeV, $m_{jj} > 200$ GeV and an event p_T balance < 0.2
- ▶ Train BDT using m_{jj} , $\Delta\eta_{jj}$, z^* , quark-gluon likelihood
- ▶ $f_{sig} = 2\% \rightarrow 43\%$ for $BDT' > 2.185$ ($BDT > 0.95$)



$$\sigma(\text{EW } \ell\nu jj) = 6.23 \pm 0.12(\text{stat}) \pm 0.61(\text{syst}) \text{ pb, signal strength } \mu = 0.91 \pm 0.10$$

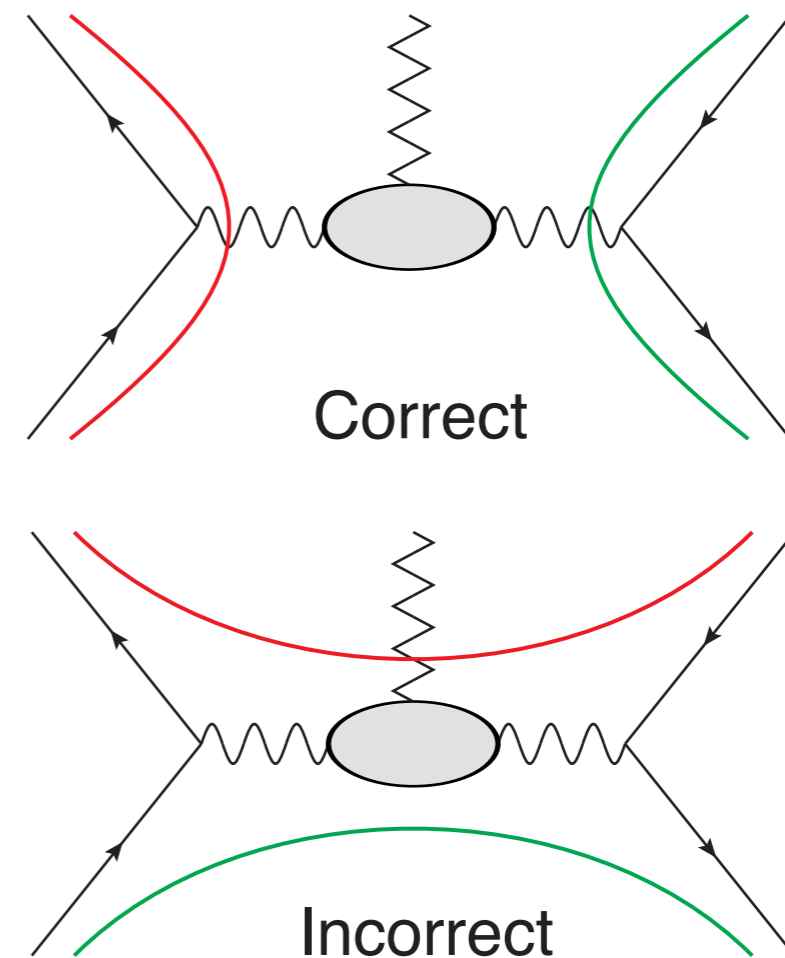
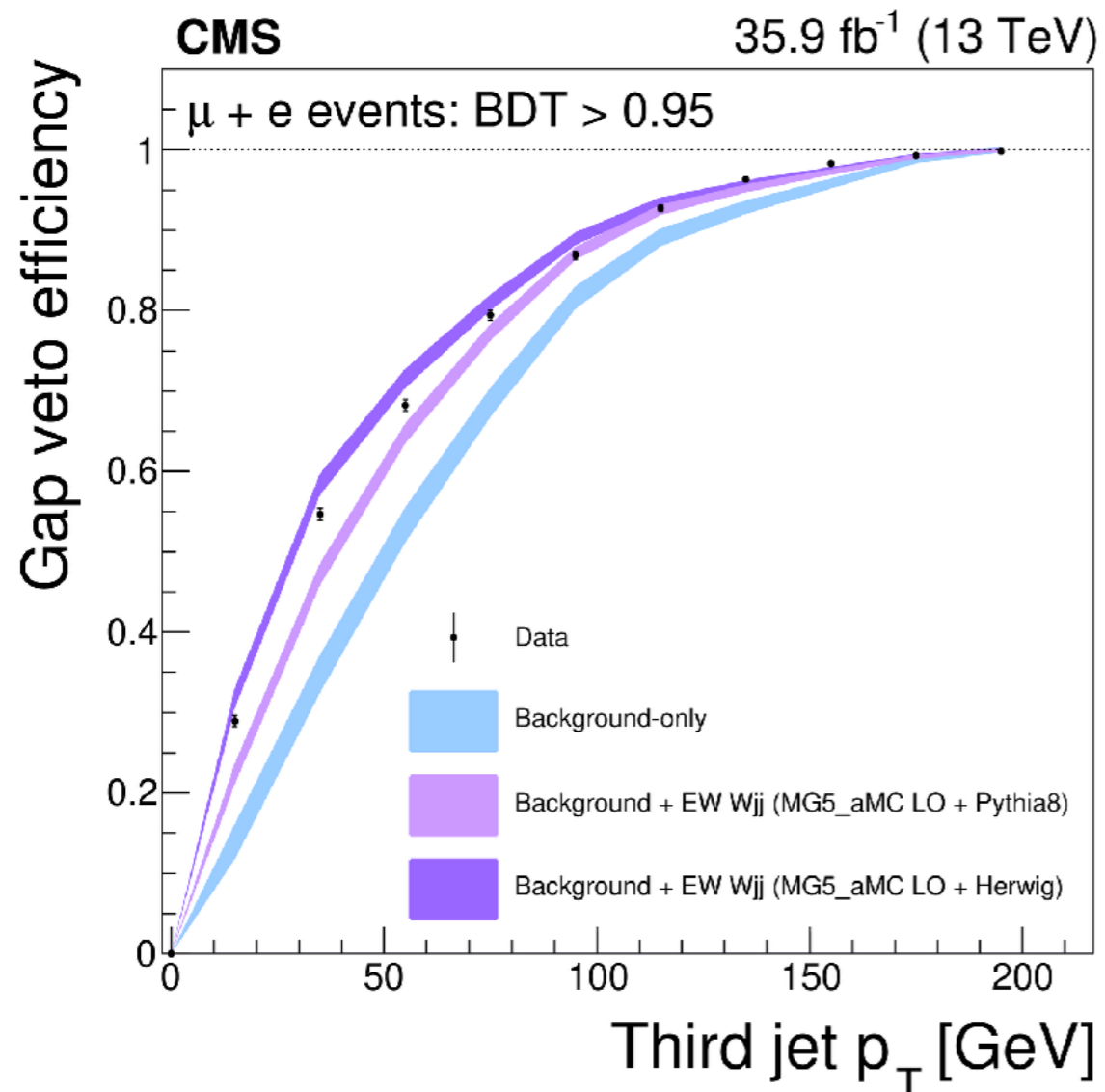
EW production of Wjj

SMP-17-011
arXiv:1903.04040



Hadronic activity in the rapidity gap studied in the signal region $BDT > 0.95$

- ▶ sensitive to the treatment of the colour flow
- ▶ Herwig in good agreement down to jet $p_T \sim 10$ GeV
- ▶ clear disagreement between Pythia and data (now fixed by “dipole recoil” option)

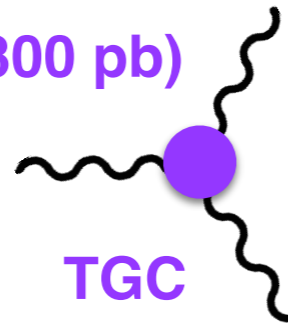


Multiboson production

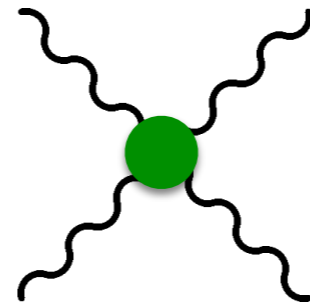


Cross-sections are several order of magnitude smaller

diboson production (5-300 pb)



TGC



QGC

triboson production (0.1-0.005 pb)
vector boson scattering (< 0.01 pb)

Measurements provide a test of SM and an indirect search for new physics

- ▶ new phenomena can induce changes in TGCs/QGC
- ▶ enhanced cross-sections, especially at large boson p_T
- ▶ anomalous couplings usually interpreted in terms of coefficients for dim-6 and dim-8 operators in the framework of effective field theory (EFT):

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j + \dots$$

dim 6 **dim 8**

Multiboson production at 13 TeV



Many very recent results!

	Production mode	Final state	Dataset (13 TeV)	Documents
Diboson	WZ	lllv	35.9/fb	JHEP 04 (2019) 122
	ZZ	llll llll + jets	101.2/fb 35.9/fb	CMS SMP-19-001 PLB 789 (2019) 19
	WW/WZ	lvjj	35.9/fb	CMS SMP-18-008
Triboson	WWW	lll, SS ll+jj	35.9/fb	CMS SMP-17-013 arXiv:1905.04246
VBS	WW	SS ll	35.9/fb	PRL 120 (2018) 081801
	WZ	lllv	35.9/fb	CMS SMP-18-001 arXiv:1901.04060
	ZZ	llll	35.9/fb	PLB 774 (2017) 682
	WW/WZ/ZZ	lvjj, lljj	35.9/fb	CMS SMP-18-006 arXiv:1905.07445
	Z γ	ll γ	35.9/fb	CMS SMP-18-007

Diboson production: $ZZ \rightarrow 4\ell$



Among first measurements with full Run 2

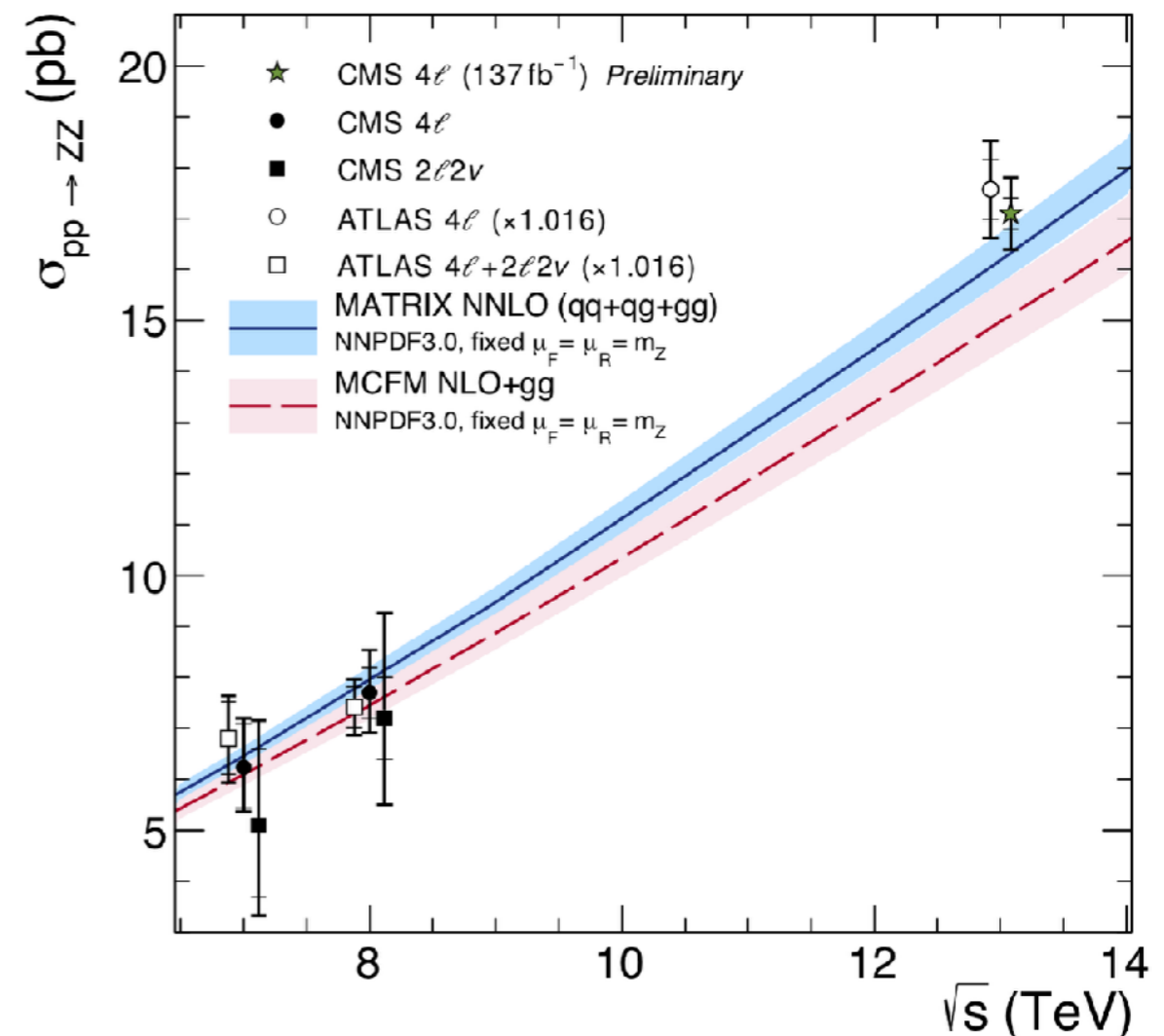
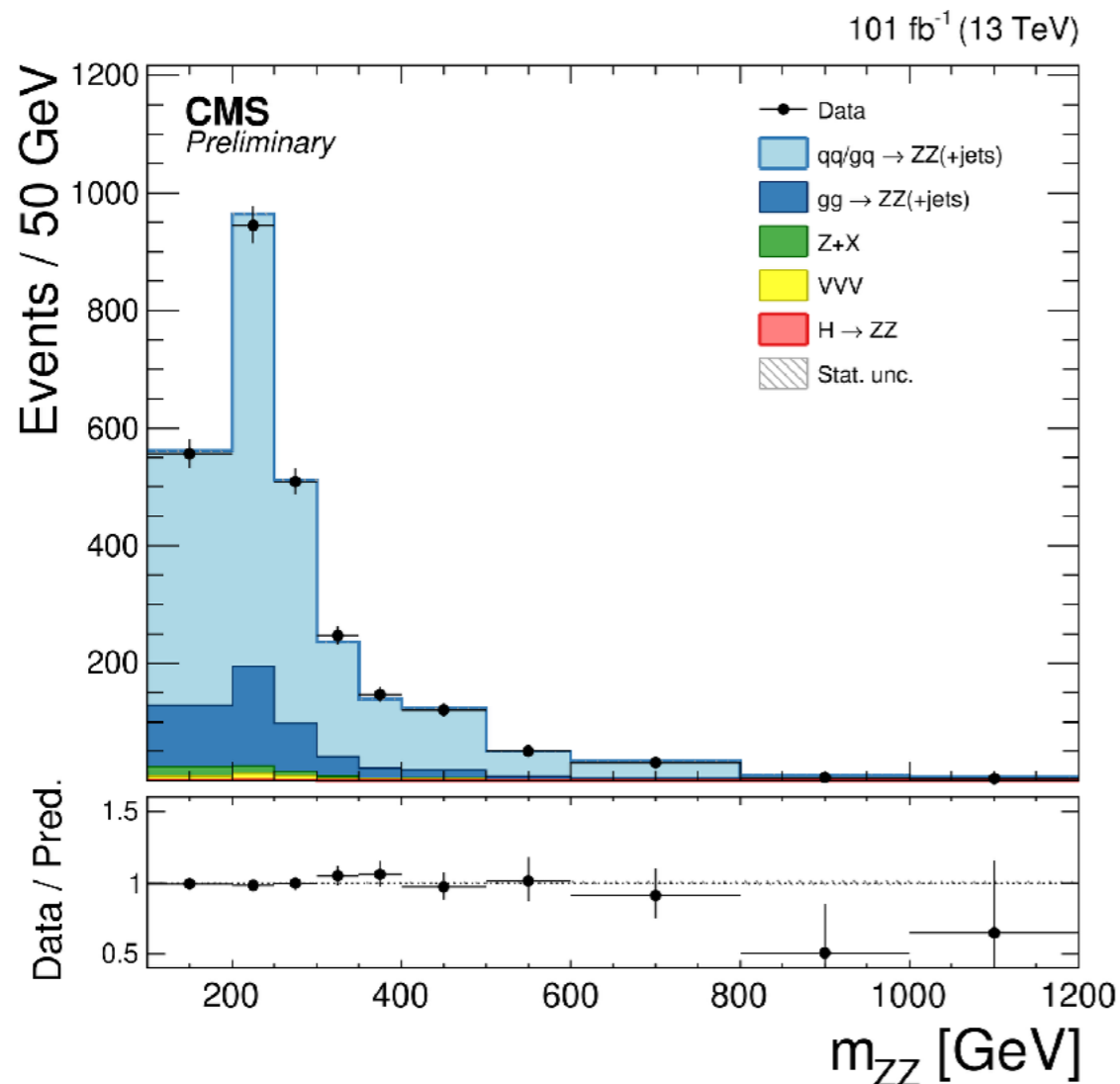
- ▶ this measurement 2017+2018: 101.2 fb⁻¹
- ▶ combined with 2016: 35.9 fb⁻¹

Systematic uncertainties driven by lepton efficiencies and luminosity

- ▶ important correlations across time

SMP-19-001

Year	Fiducial cross section, fb
2016 [5]	40.9 ± 1.3 (stat) ± 1.4 (syst) ± 1.0 (lumi)
2017	39.1 ± 1.2 (stat) ± 1.2 (syst) ± 1.0 (lumi)
2018	39.2 ± 1.0 (stat) ± 1.3 (syst) ± 1.0 (lumi)
Combined	39.9 ± 0.7 (stat) ± 1.0 (syst) ± 0.7 (lumi)



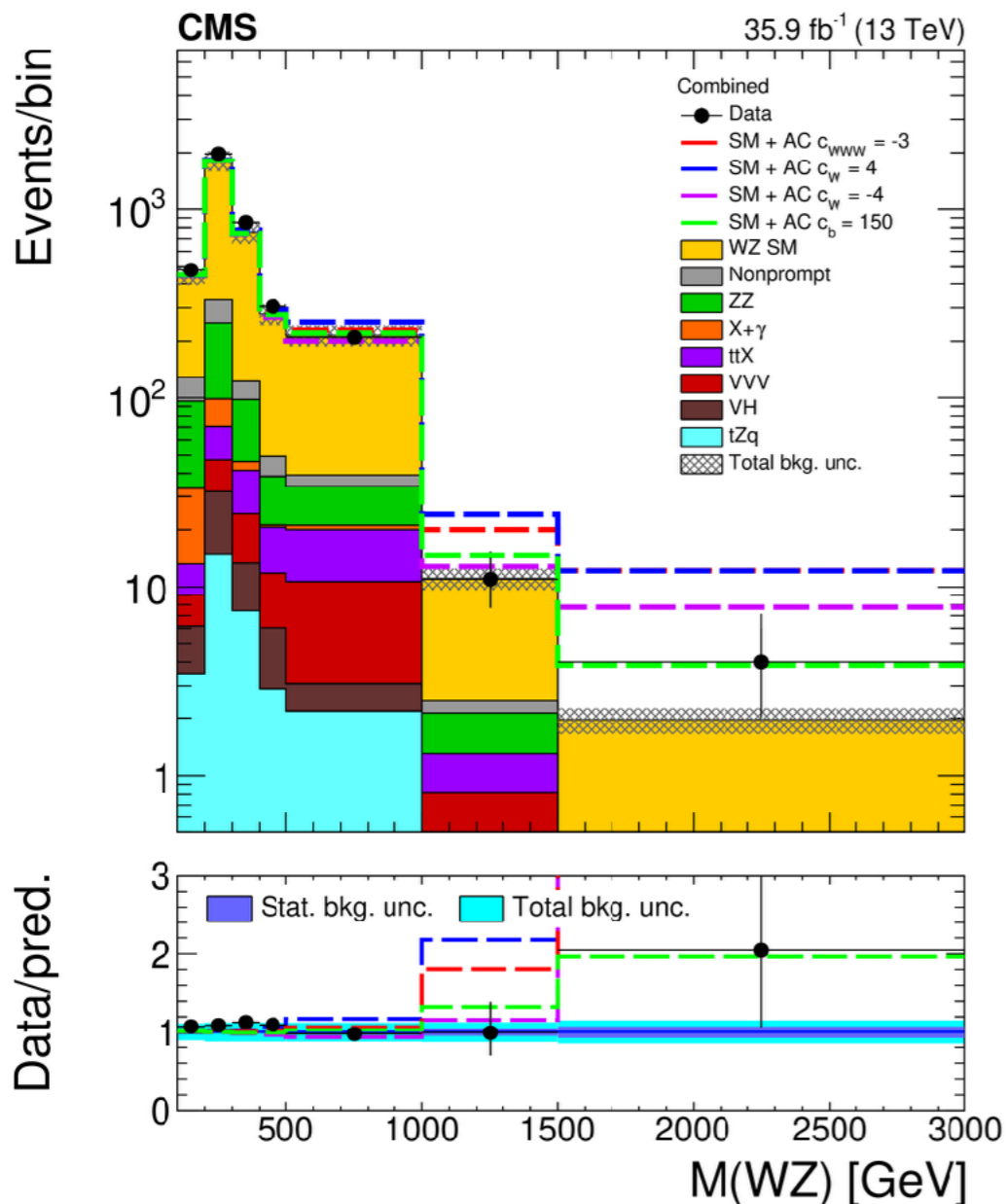
Diboson production: $WZ \rightarrow 3\ell\nu$



- ▶ only multiboson process directly sensitive to WWZ coupling
- ▶ limits on aTGC obtained from $M(WZ)$ distribution

SMP-18-002
JHEP 04 (2019) 122

$$\delta\mathcal{L}_{AC} = \frac{c_{WWW}}{\Lambda^2} \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}] + \frac{c_W}{\Lambda^2} (D_{\mu}H)^{\dagger} W^{\mu\nu} (D_{\nu}H) + \frac{c_b}{\Lambda^2} (D_{\mu}H)^{\dagger} B^{\mu\nu} (D_{\nu}H)$$



Parameter	95% CI (expected) [TeV ⁻²]	95% CI (observed) [TeV ⁻²]
c_W / Λ^2	[-3.3, 2.0]	[-4.1, 1.1]
c_{WWW} / Λ^2	[-1.8, 1.9]	[-2.0, 2.1]
c_b / Λ^2	[-130, 170]	[-100, 160]

- ▶ total cross-section

$$\sigma_{\text{tot}}(pp \rightarrow WZ) = 48.09^{+2.98}_{-2.78} \text{ pb}$$

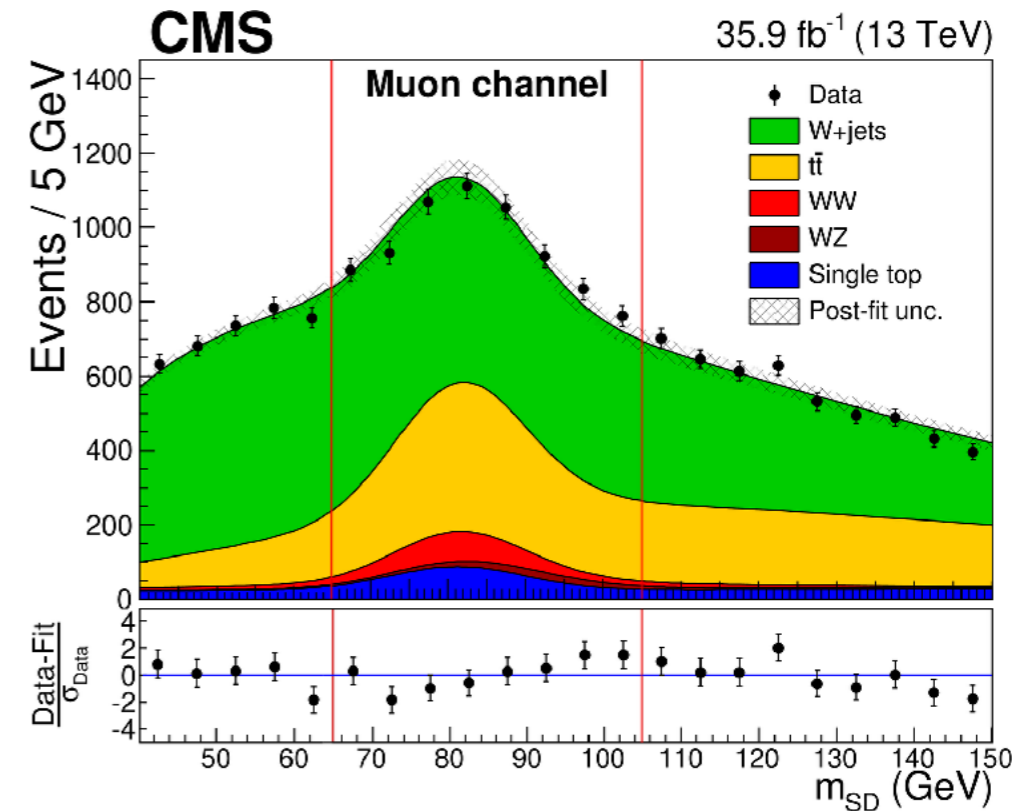
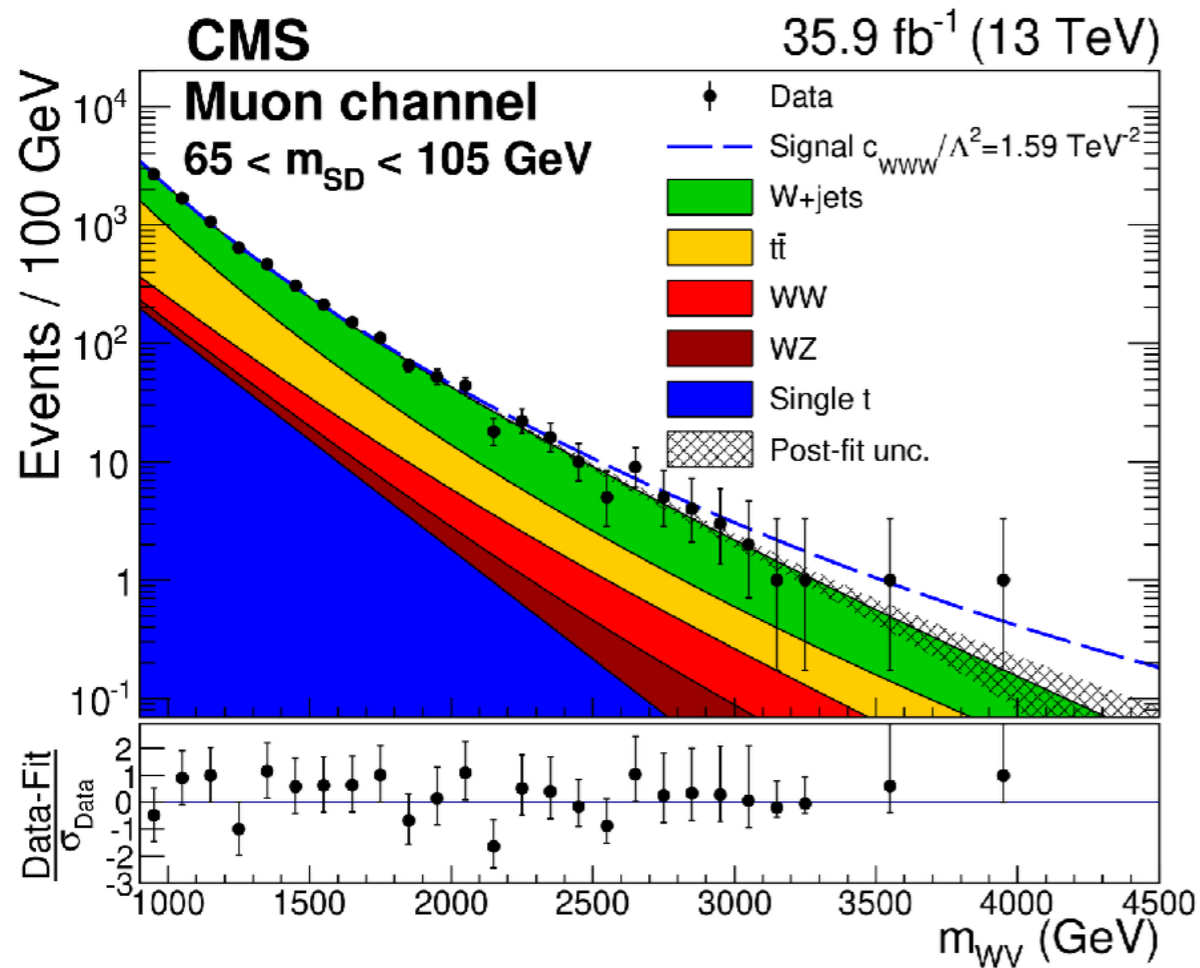
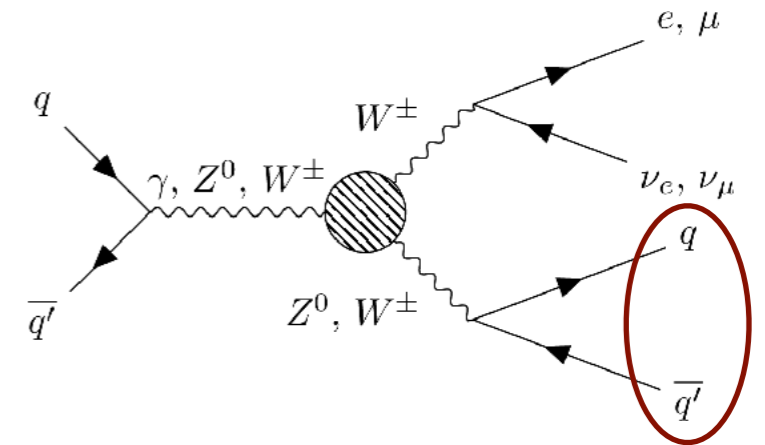
- ▶ uncertainty dominated by lepton efficiencies
- ▶ result in agreement with MATRIX NNLO predictions

$$\sigma_{\text{NNLO}}(pp \rightarrow WZ) = 49.98^{+2.2\%}_{-2.0\%}$$

Diboson production: $WW/WZ \rightarrow \ell\nu + \text{jet}$



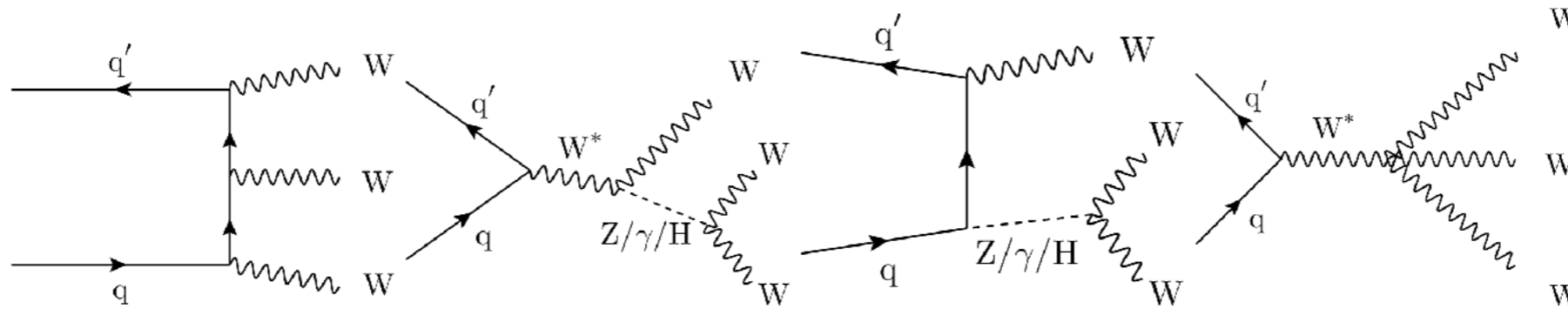
- ▶ “boosted” $W/Z \rightarrow qq$ reconstructed as a single jet
- ▶ mass obtained from sub-jet structure: m_{SD}
- ▶ limits set with a 2-D fit to $M(WV)$ and m_{SD}



▶ the limit on c_B improves by a factor 10



aTGC	Expected limit	Observed limit
c_{WWW} / Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]
c_W / Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]
c_B / Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]



► look for 2SS leptons or 3 leptons

► result:

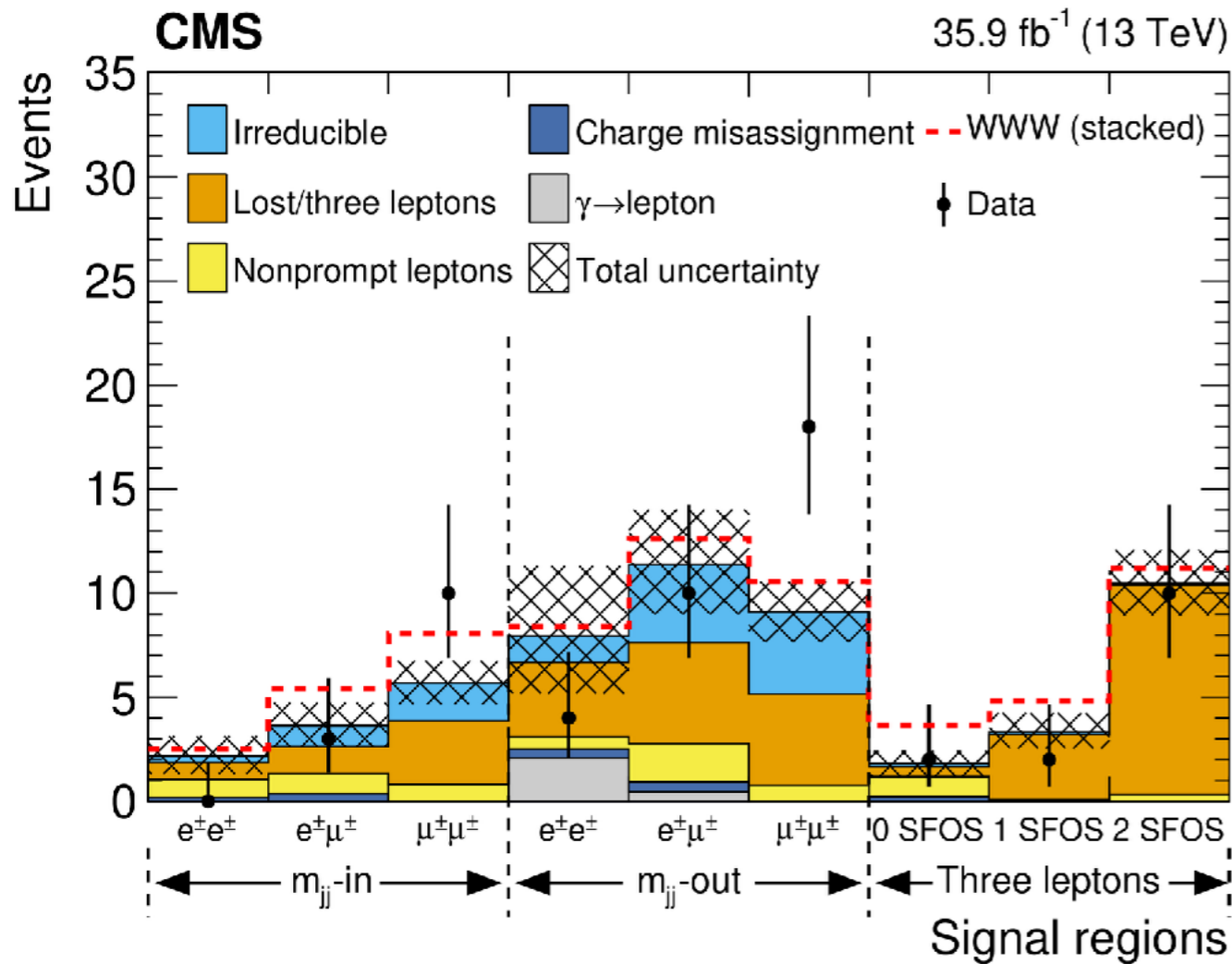
$$\sigma(pp \rightarrow W^\pm W^\pm W^\mp) = 0.17^{+0.32}_{-0.17} \text{ pb.}$$

► SM expectation: $0.509 \pm 0.013 \text{ pb}$

► signal strength: $\mu = 0.34^{+0.62}_{-0.34}$

► significance: 0.6(obs) 1.78 (exp)

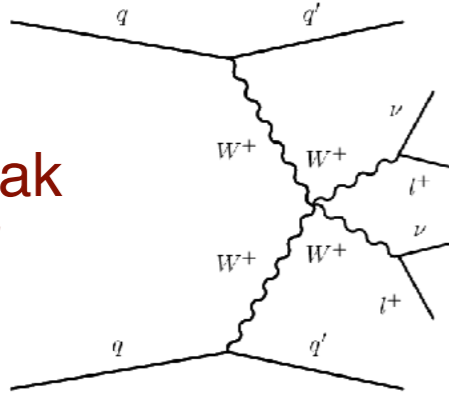
► upper limit: 0.78 pb (obs) 0.60 pb (exp)



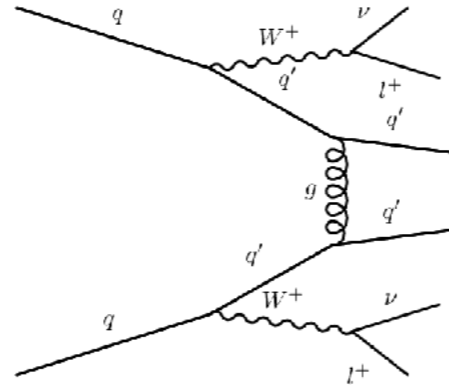
Vector Boson Scattering: same sign $W^\pm W^\pm$



Electroweak
ss WW



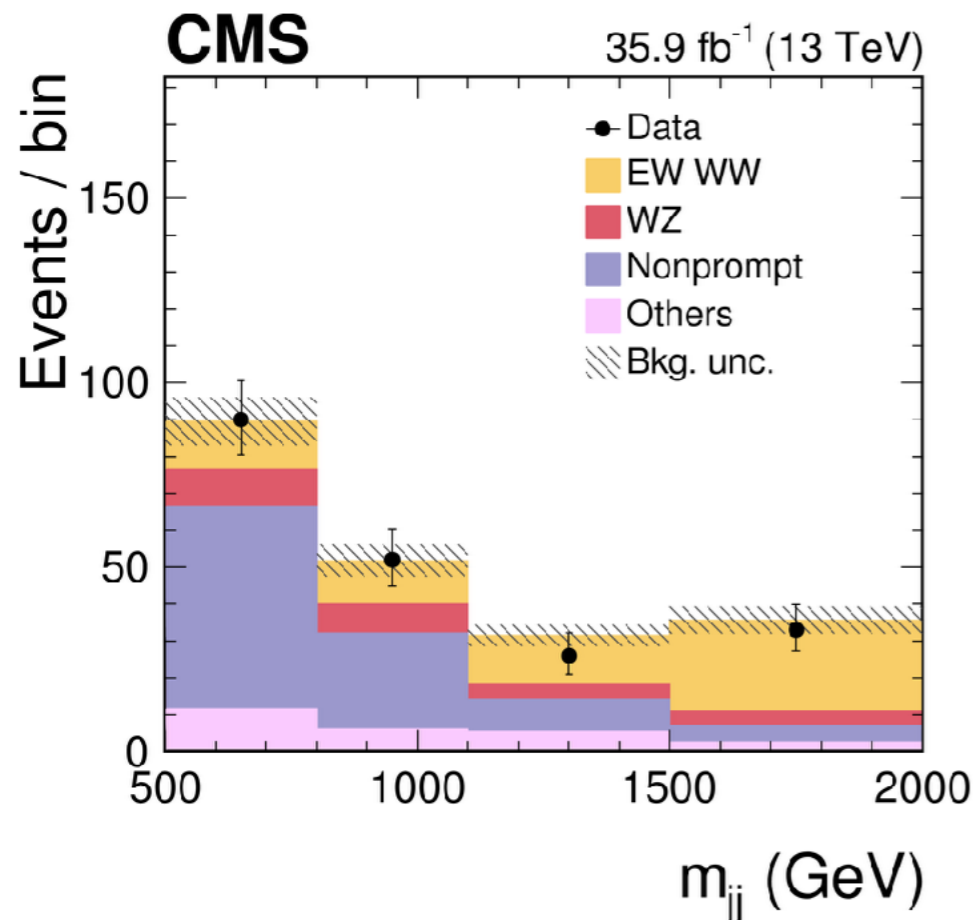
QCD
background



SMP-17-004
PRL 120, 081801 (2018)

Largest ratio of EWK to QCD production compared to other VBS processes

- ▶ small background because of same sign leptons (mainly non prompt and WZ)



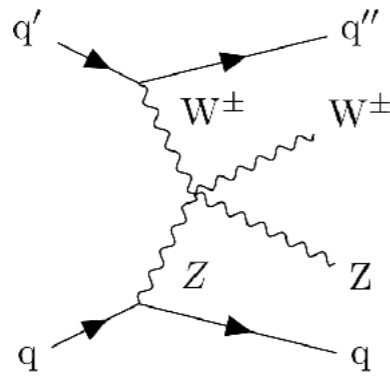
- ▶ significance: 5.5σ (obs.) 5.7σ (exp.)
- ▶ $\sigma_{fid} = 3.83 \pm 0.66(stat) \pm 0.35(syst) fb$
- ▶ $\sigma_{pred} = 4.25 \pm 0.27 (scale + PDF) fb$

First observation of VBS!

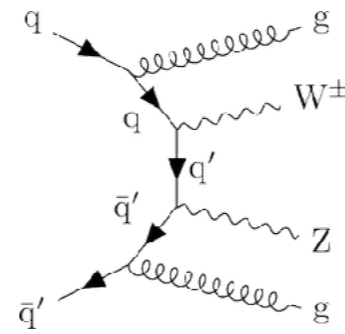
Vector Boson Scattering: WZ



Electroweak production



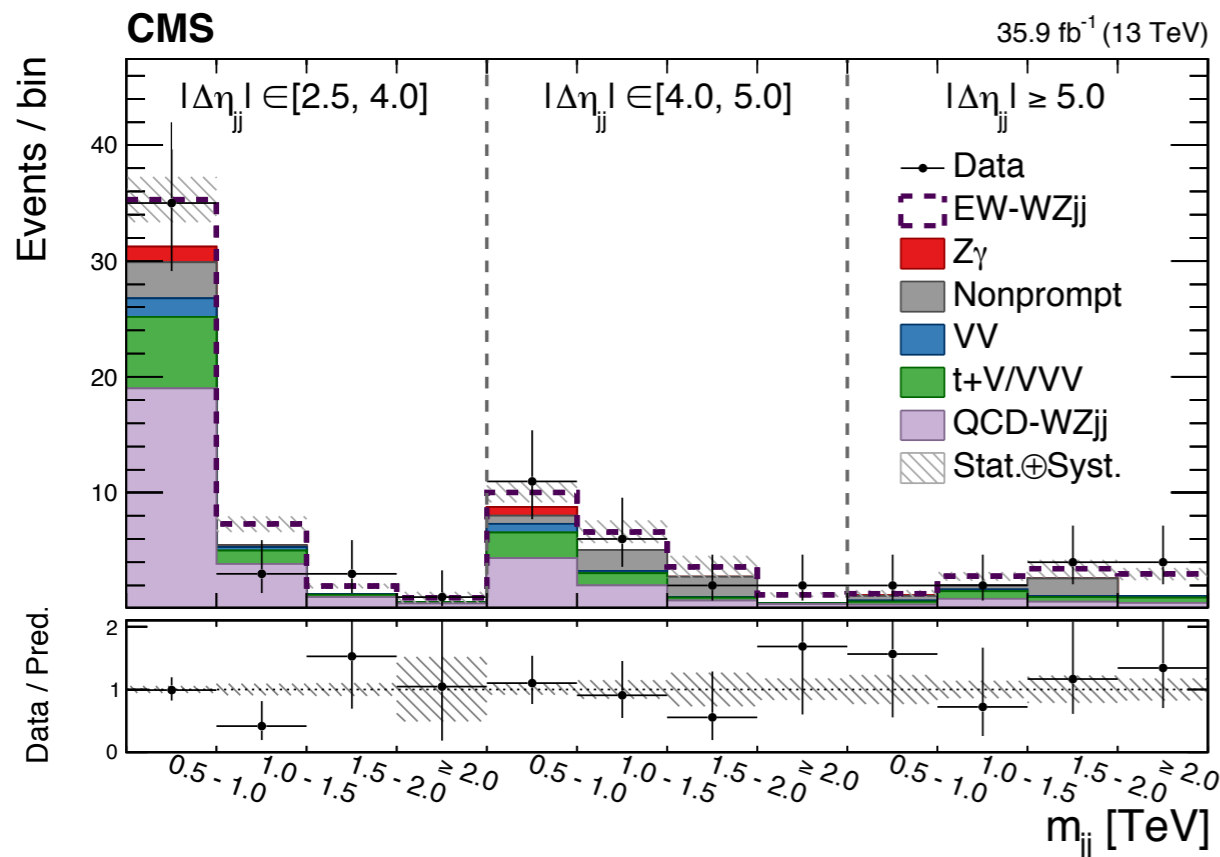
QCD background



SMP-18-001
PLB 795 (2019) 281

Large QCD WZ background

- ▶ EW+QCD cross-section measured in a fiducial region
- ▶ Fit EW on 2D distribution of m_{jj} and $\Delta\eta_{jj}$



- ▶ EW+QCD result:

$$\sigma_{WZjj}^{\text{fid}} = 3.18^{+0.57}_{-0.52} (\text{stat})^{+0.43}_{-0.36} (\text{syst}) \text{ fb}$$

- ▶ predicted: $3.27^{+0.39}_{-0.32} (\text{scale}) \pm 0.15 (\text{PDF}) \text{ fb}$
[EW only: $1.25^{+0.11}_{-0.09} (\text{scale}) \pm 0.06 (\text{PDF}) \text{ fb}$]

$$\mu_{\text{EW}} = 0.82^{+0.51}_{-0.43}$$

- ▶ significance of EW: 2.2σ (obs.) 2.5σ (exp.)

Vector Boson Scattering: WV and ZV



$WV \rightarrow \ell\nu$ or $ZV \rightarrow \ell\ell + \text{a jet}$

$p_{T}^{\text{jet}} > 200 \text{ GeV}$ + tight dijet selection and centrality of W/Z

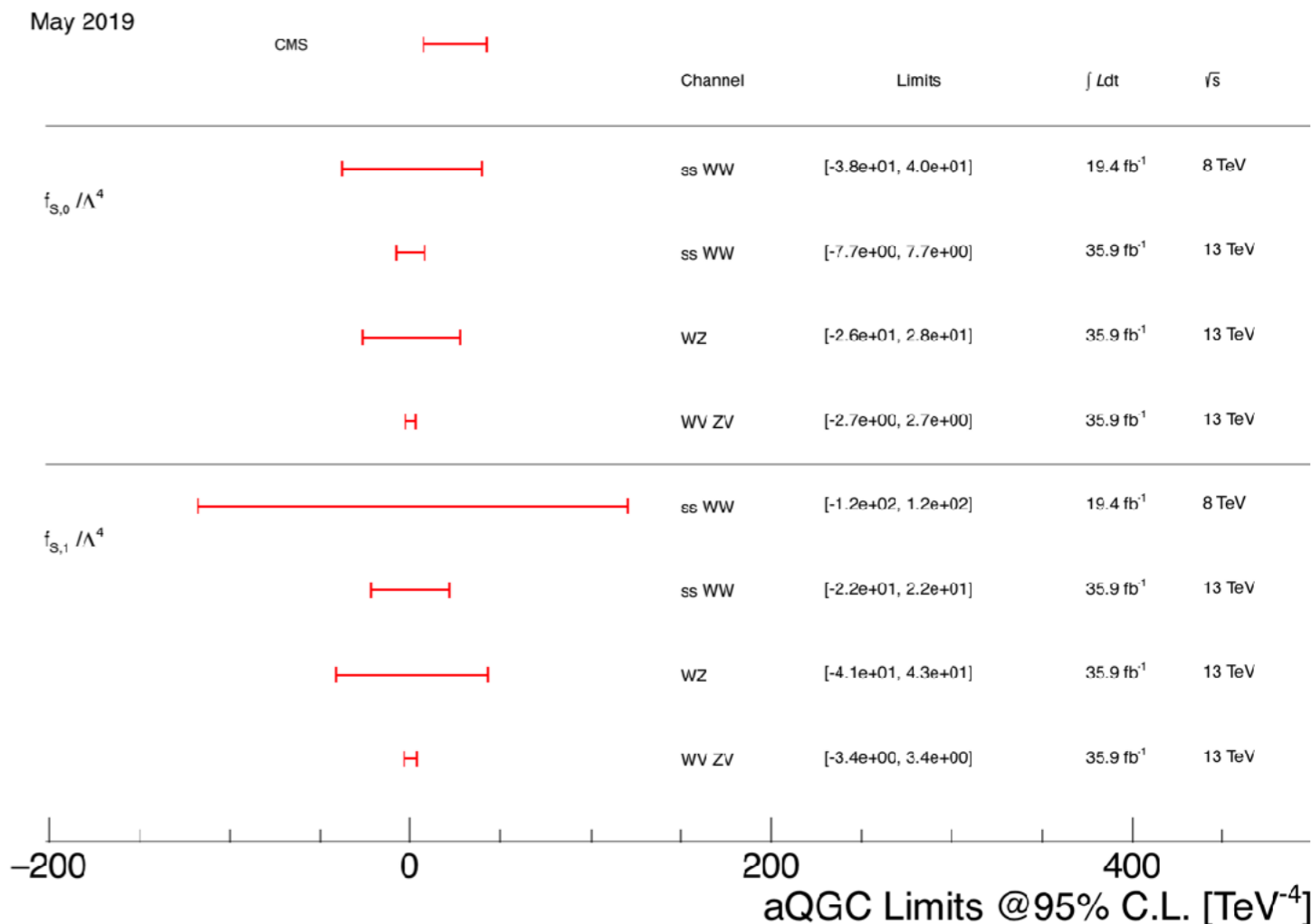
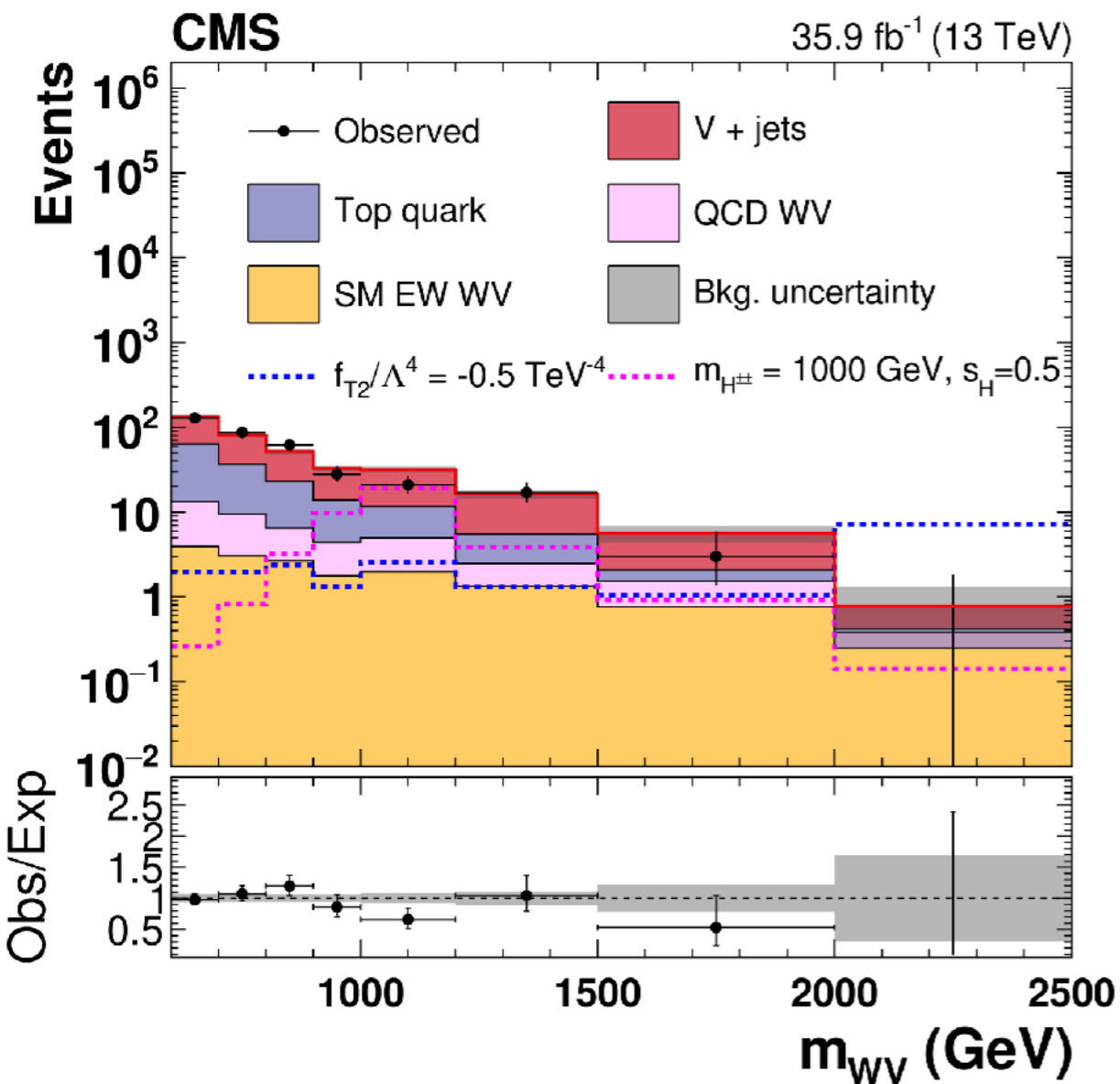
Signal region: $65 \text{ GeV} < m_V < 105 \text{ GeV}$

Large background from V+jets

Not sensitive to SM yet but sets most stringent limits on EFT operators

SMP-18-006

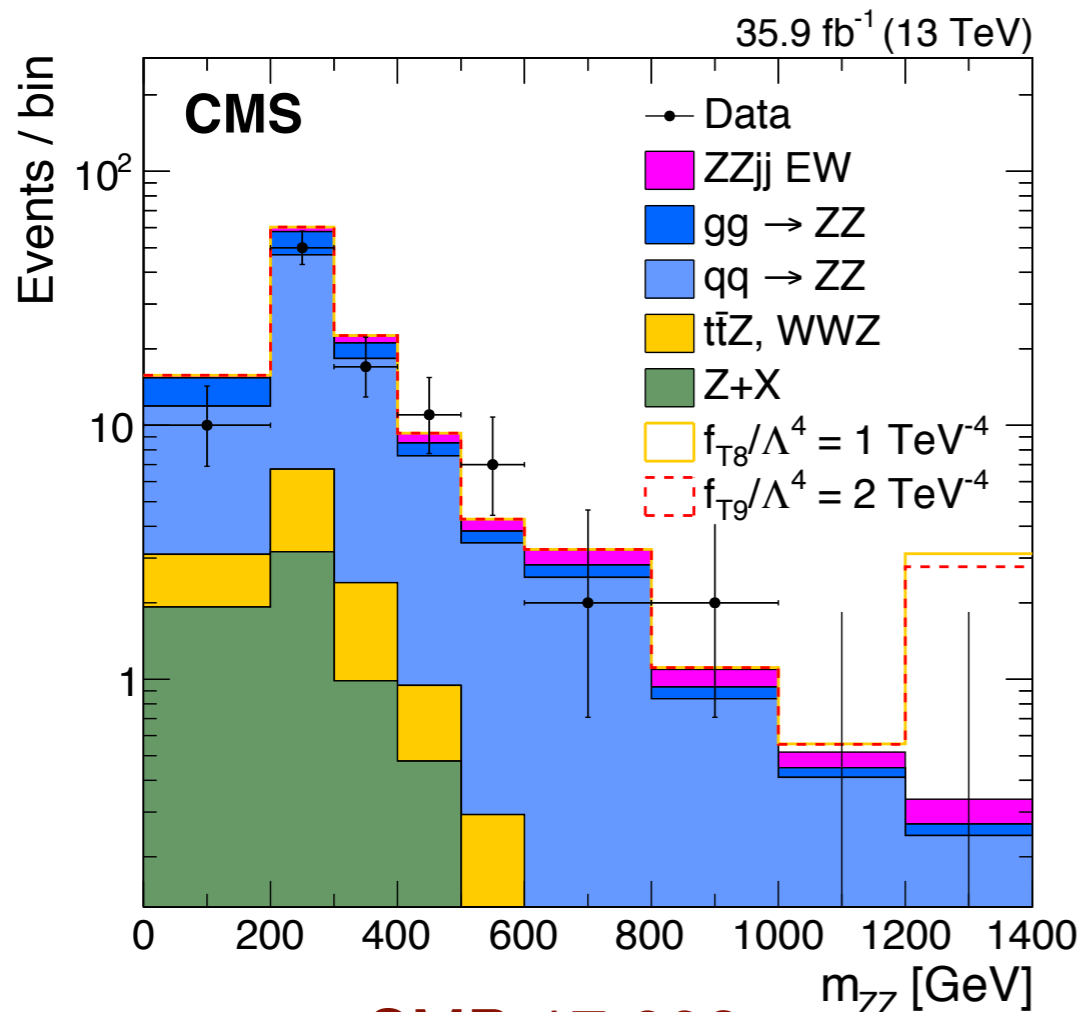
arXiv:1905.07445



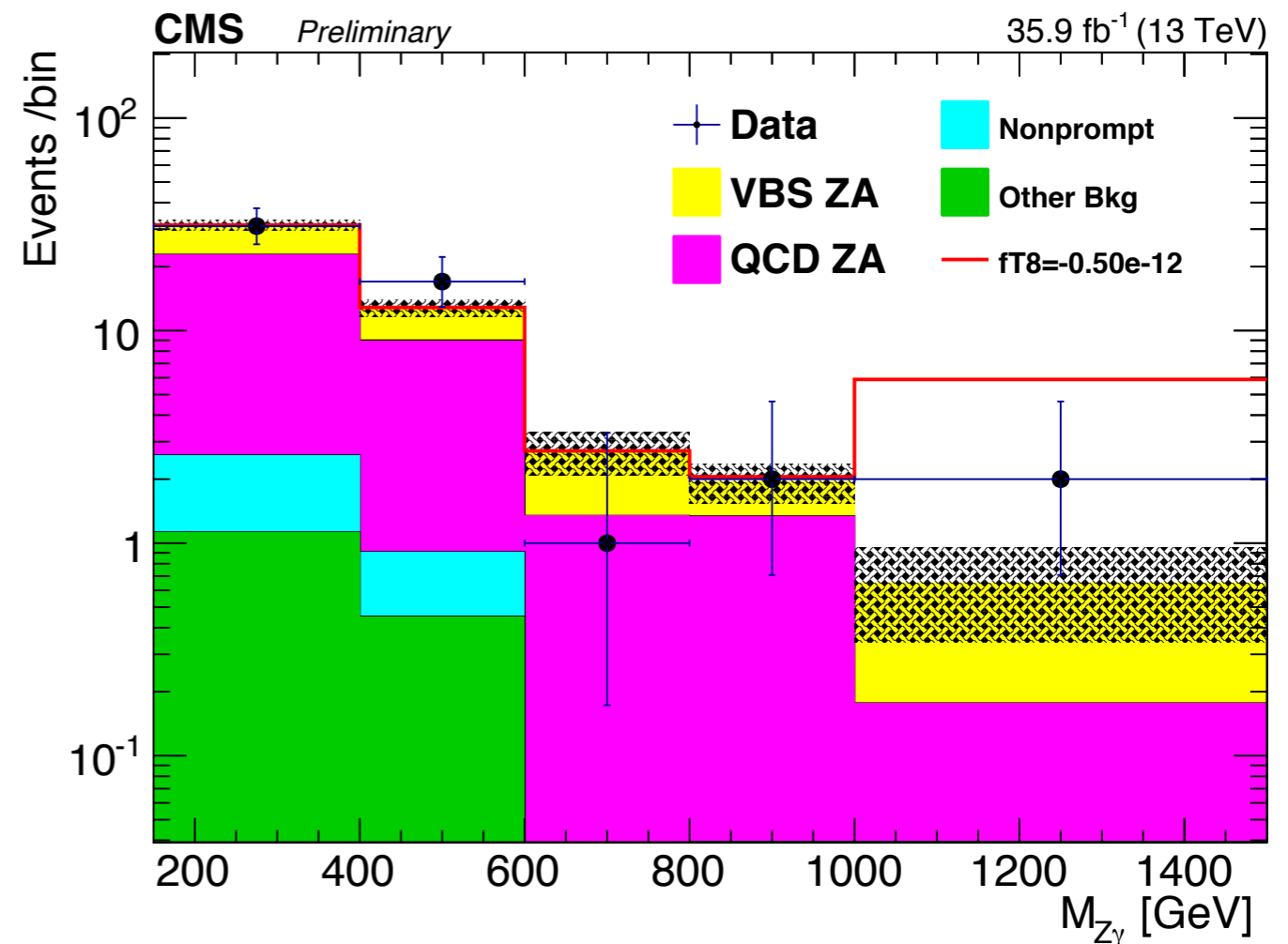
VBS: final states with neutral bosons

Some operators involve U(1) fields only accessible with EW ZZjj and Zγjj

- ▶ ZZjj: $\sigma_{EW}^{fid} = 0.40_{-0.16}^{+0.21}$ (stat) $_{-0.09}^{+0.13}$ (syst) fb $\mu_{EW} = 1.39_{-0.65}^{+0.86}$
 - ▶ significance: 2.7σ (obs.) 1.6σ (exp.)
- ▶ Zγjj : $\sigma_{EW}^{fid} = 3.20 \pm 0.07$ (lumi) ± 1.00 (stat) ± 0.57 (syst) fb $\mu_{EW} = 0.64_{-0.21}^{+0.23}$
 - ▶ significance: 4.7σ (obs.) 5.5σ (exp.) [Run1+2016]



SMP-17-006
PLB 774 (2017) 682



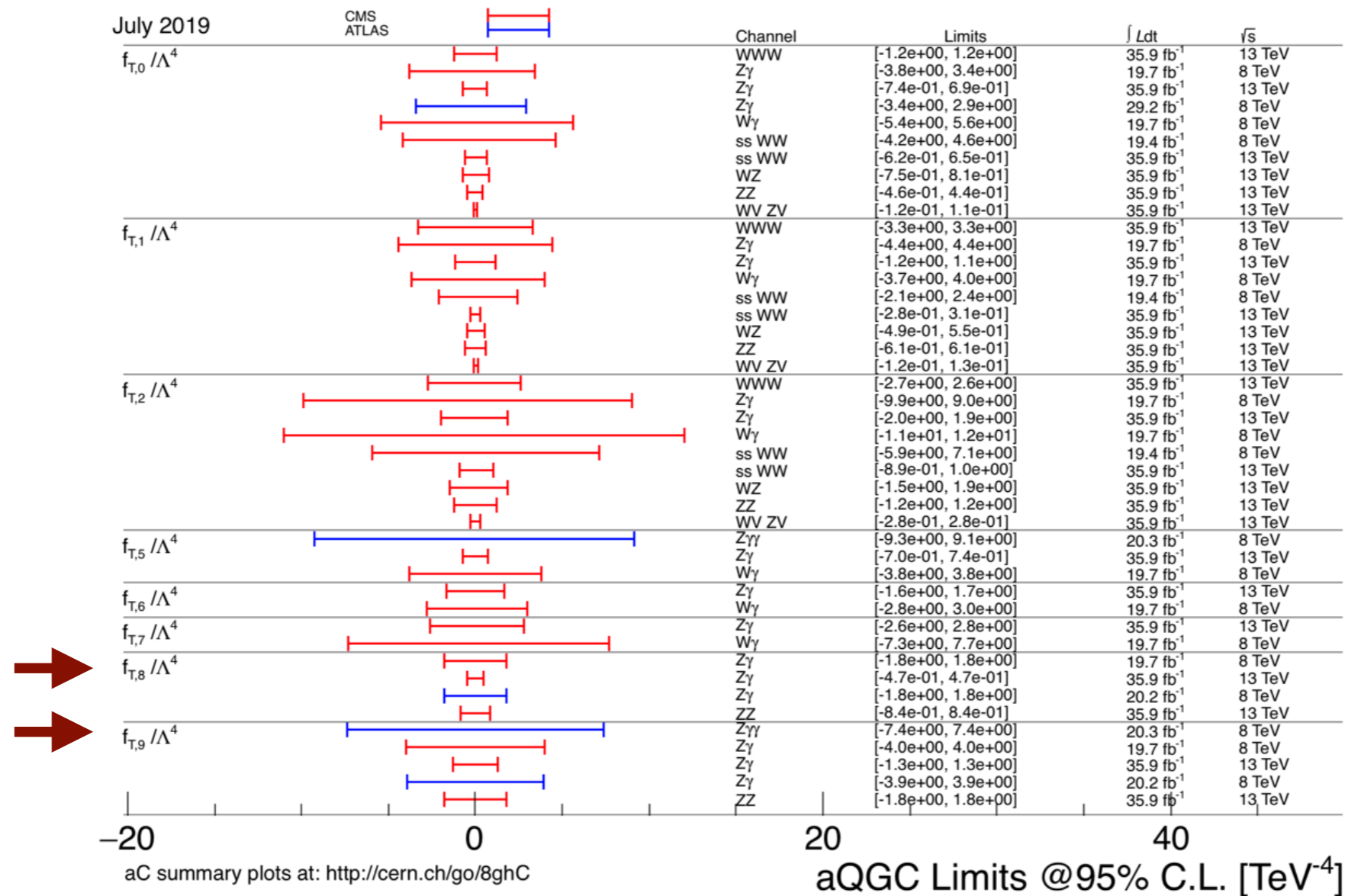
SMP-18-007

VBS: final states with neutral bosons



Some operators involve U(1) fields only accessible with EW ZZjj and Zγjj

- ▶ ZZjj: $\sigma_{EW}^{fid} = 0.40_{-0.16}^{+0.21}$ (stat) $_{-0.09}^{+0.13}$ (syst) fb $\mu_{EW} = 1.39_{-0.65}^{+0.86}$
- ▶ significance: 2.7σ (obs.) 1.6σ (exp.)
- ▶ Zγjj : $\sigma_{EW}^{fid} = 3.20 \pm 0.07$ (lumi) ± 1.00 (stat) ± 0.57 (syst) fb $\mu_{EW} = 0.64_{-0.21}^{+0.23}$
- ▶ significance: 4.7σ (obs.) 5.5σ (exp.) [Run1+2016]



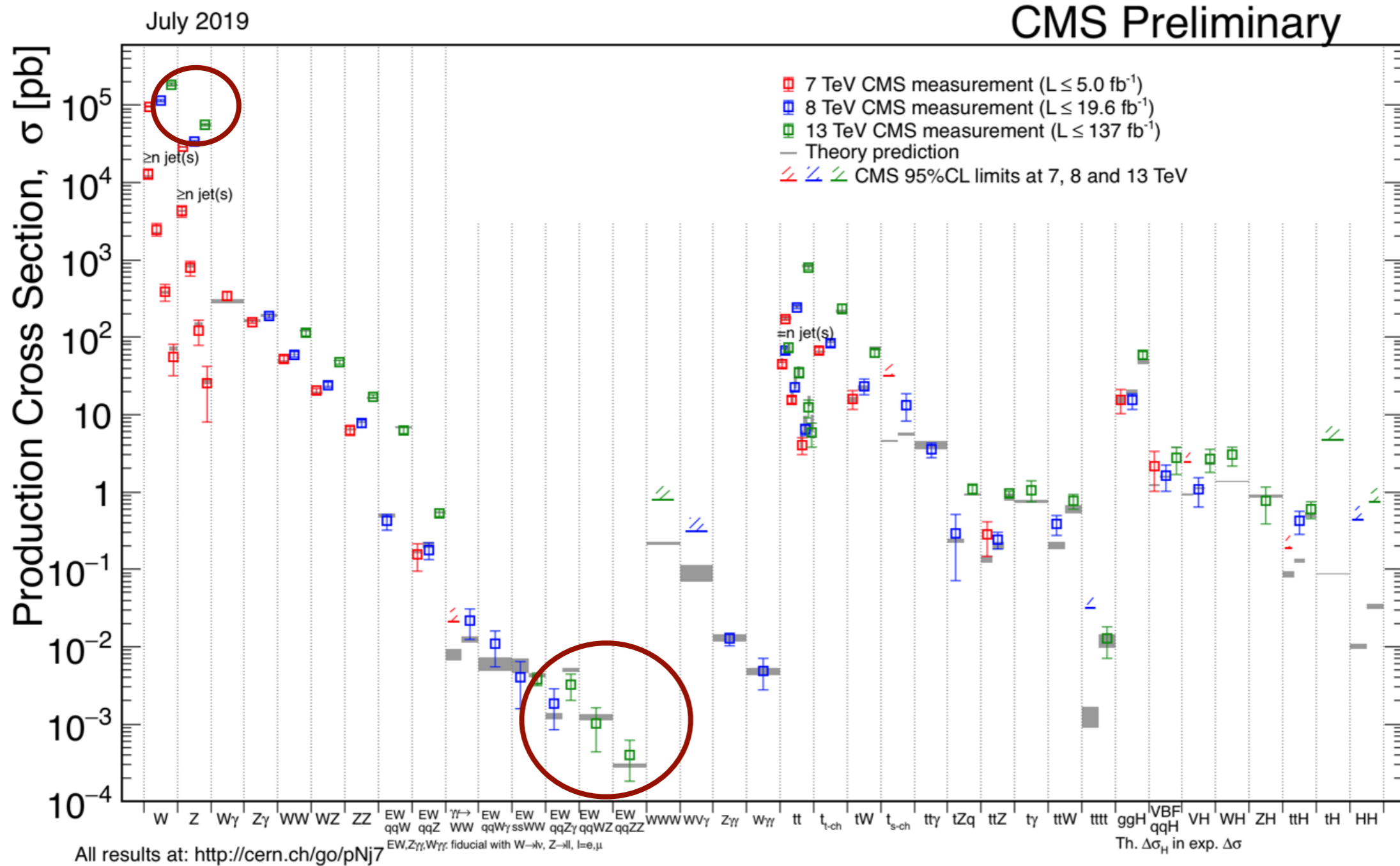
Summary



LHC is not only a discovery machine, but can provide precision measurements

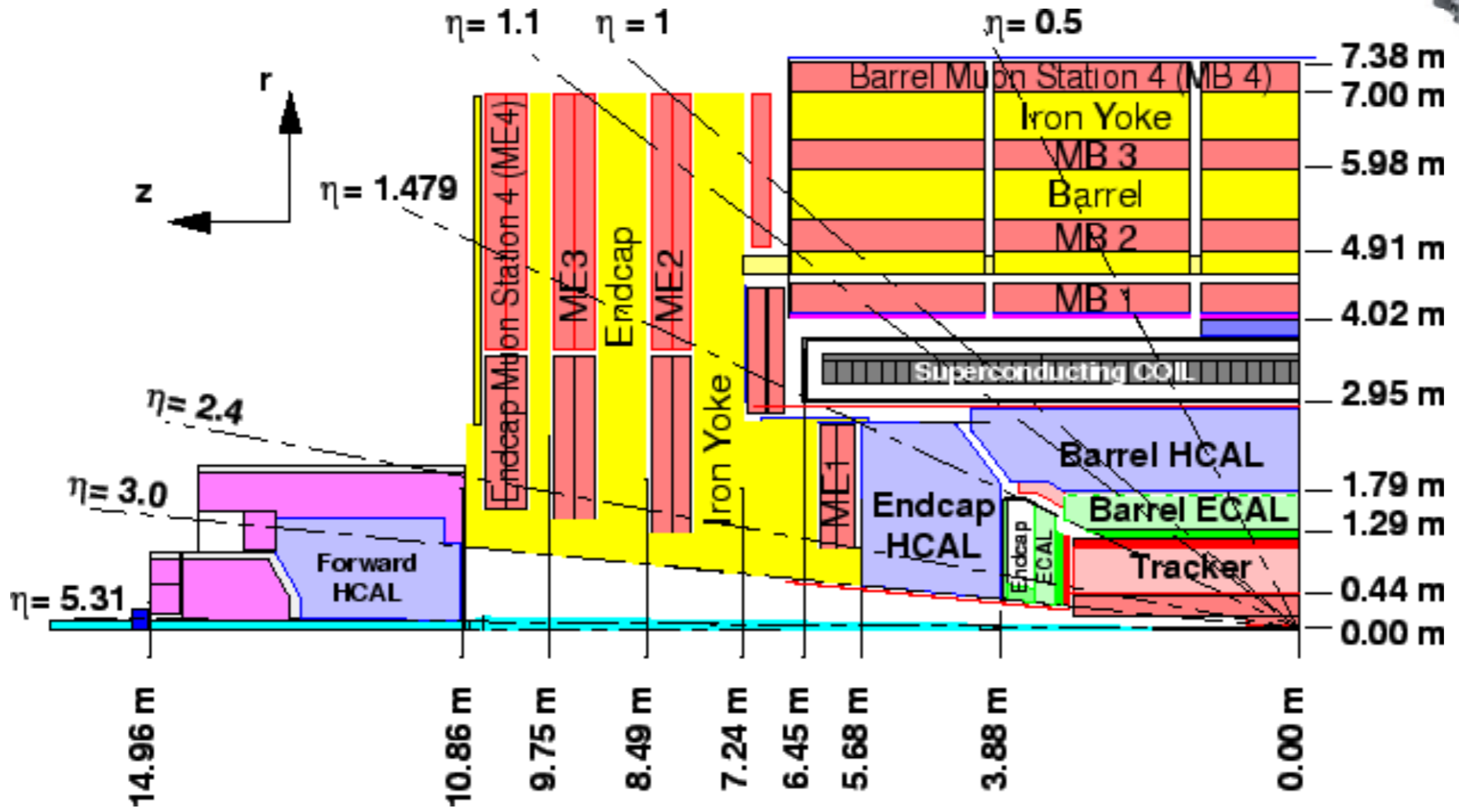
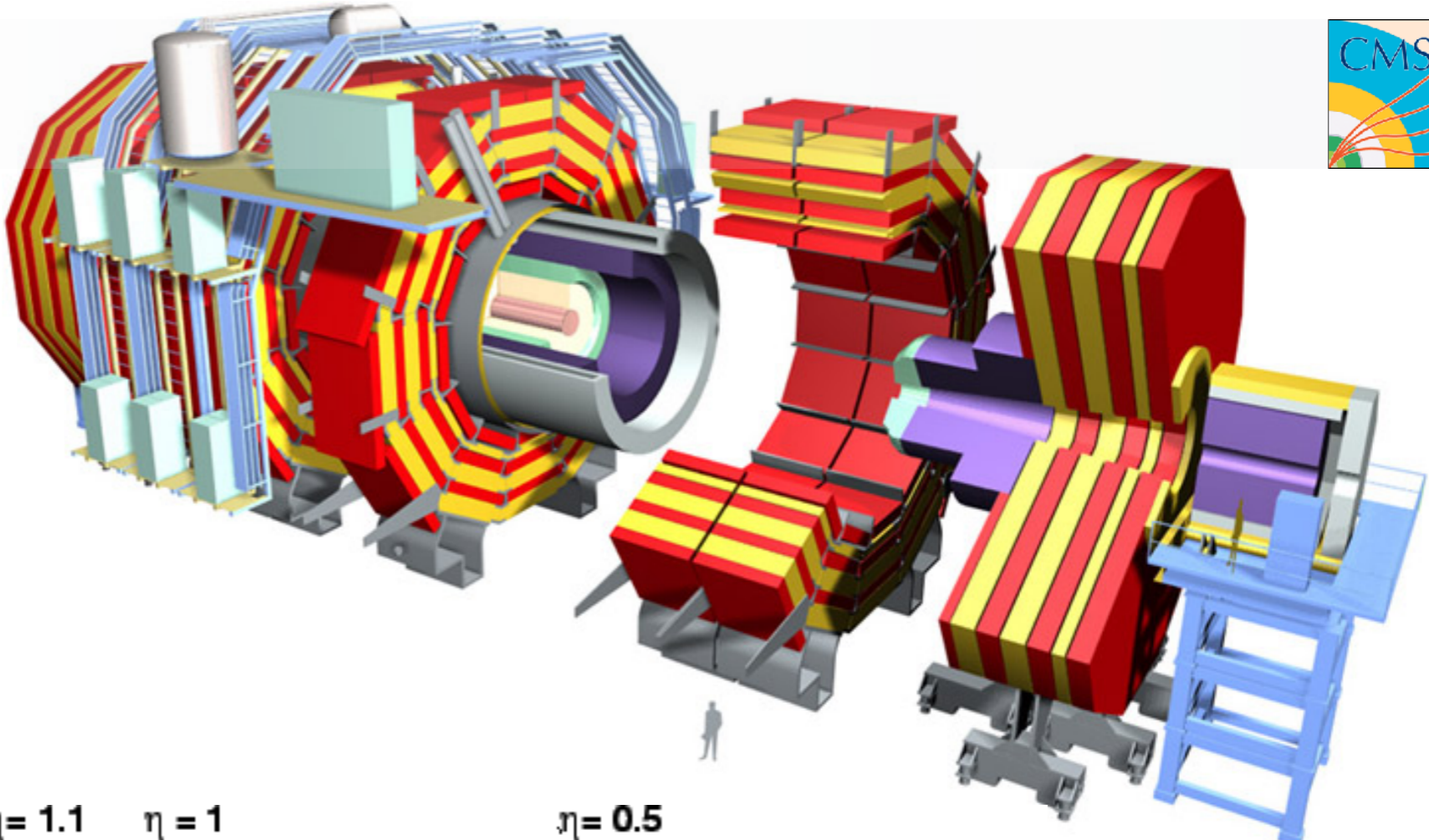
So far no disagreement found between data and theory over 9 order of magnitude

However more results to come using full Run2 statistics: stay tuned!



Backup slides

CMS detector

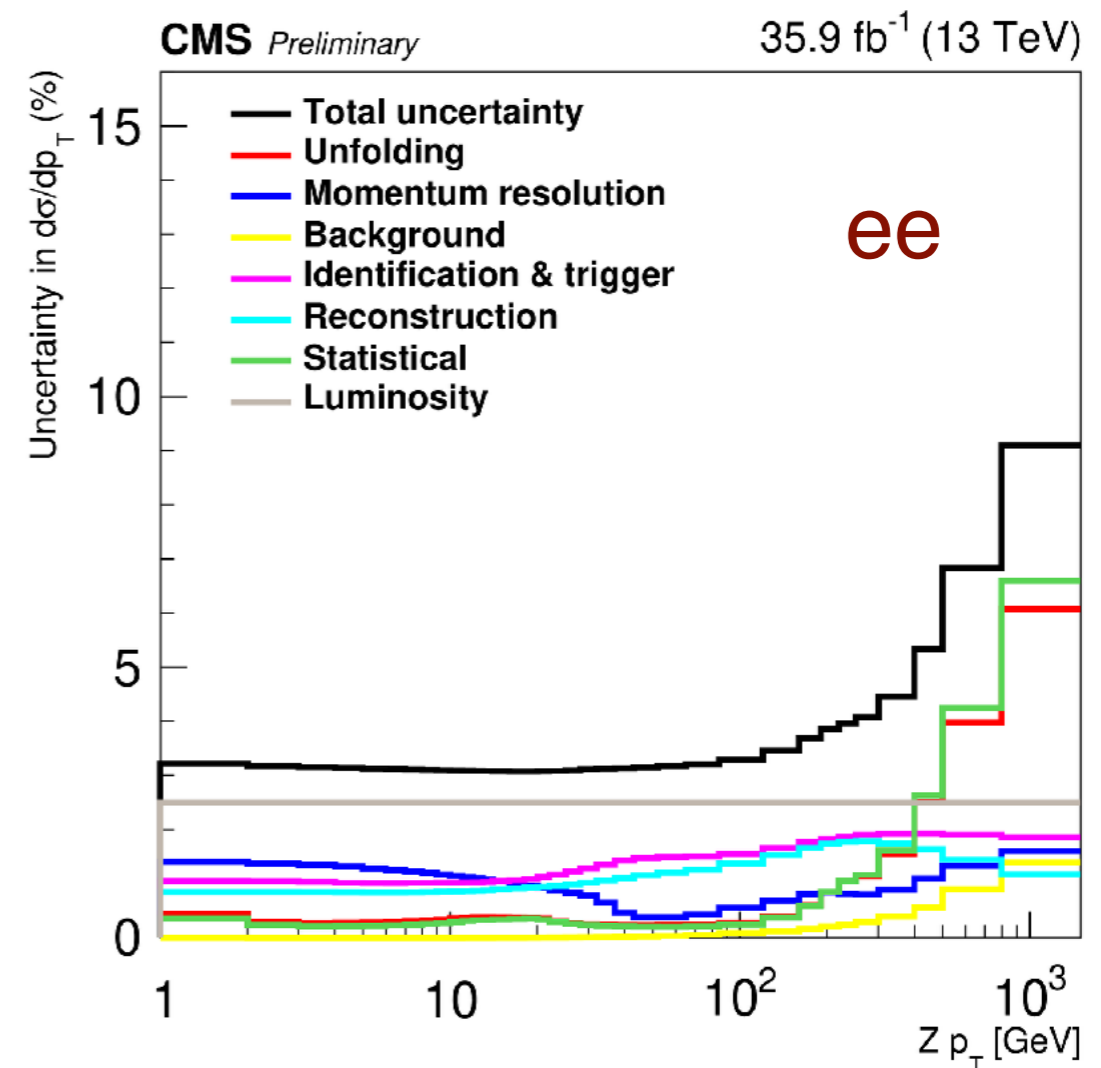
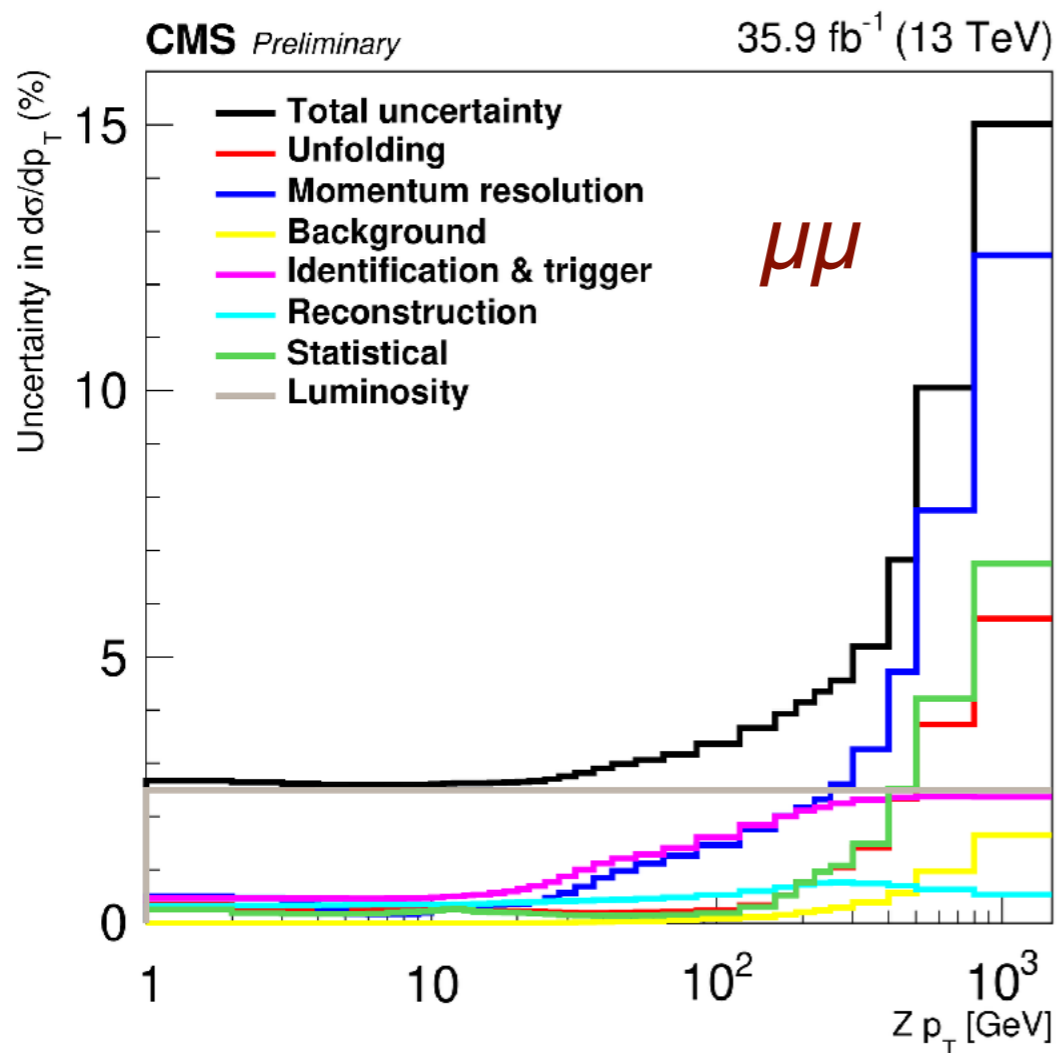


Differential Z production cross-section

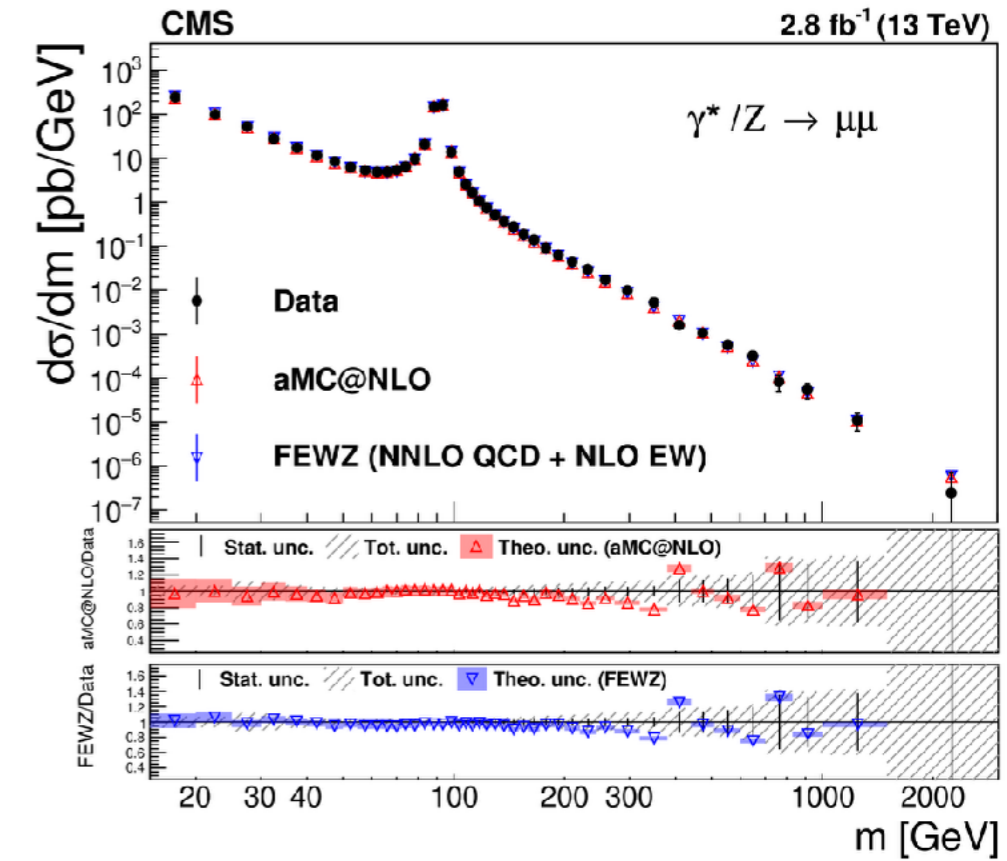
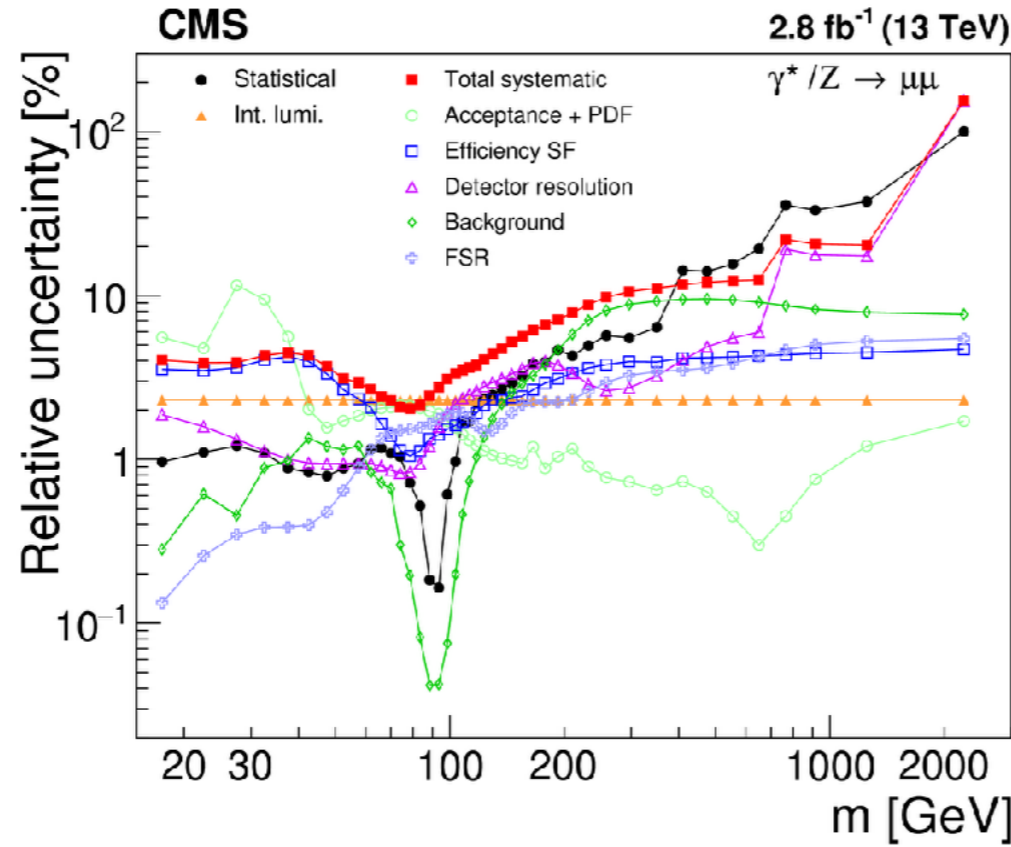


SMP-17-010

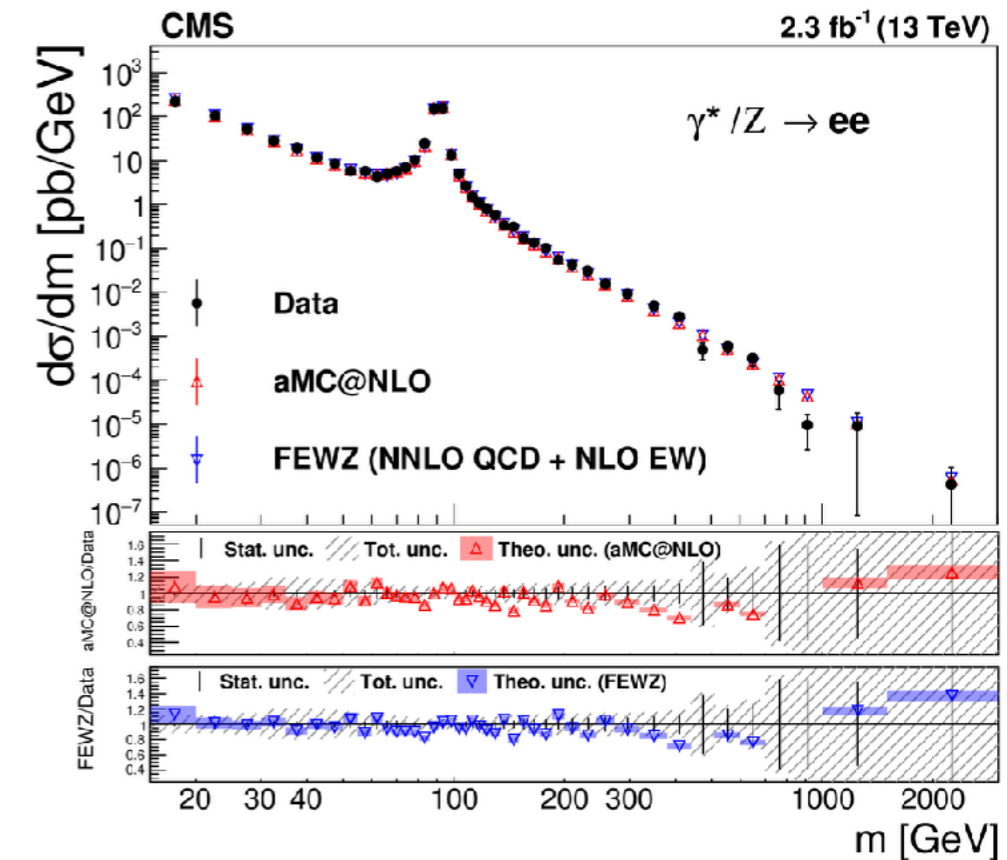
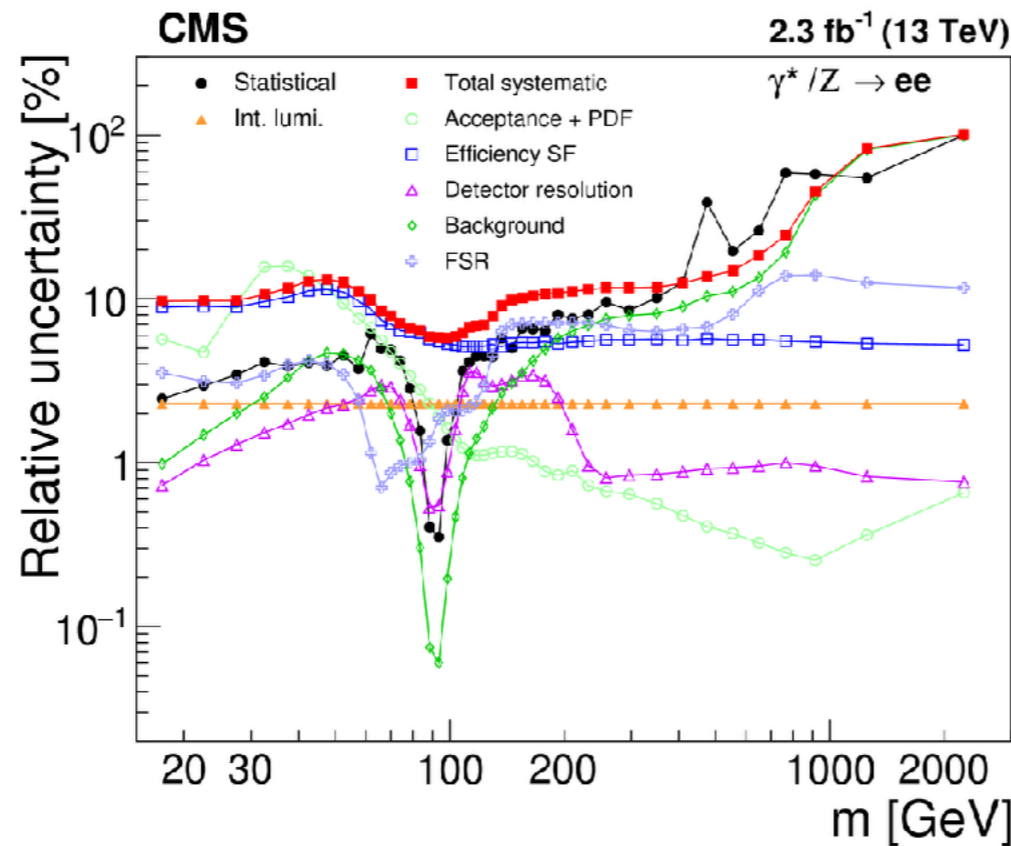
Source	$Z \rightarrow \mu\mu$ (%)	$Z \rightarrow ee$ (%)
Luminosity	2.5	2.5
Muon reconstruction efficiency	0.4	-
Muon selection efficiency	0.7	-
Muon momentum scale	0.1	-
Electron reconstruction efficiency	-	0.9
Electron selection efficiency	-	1.0
Electron momentum scale	-	0.2
Background estimation	< 0.1	< 0.1
Total (excluding luminosity)	0.8	1.4



Drell-Yan $m_{\ell\ell}$ differential cross-section

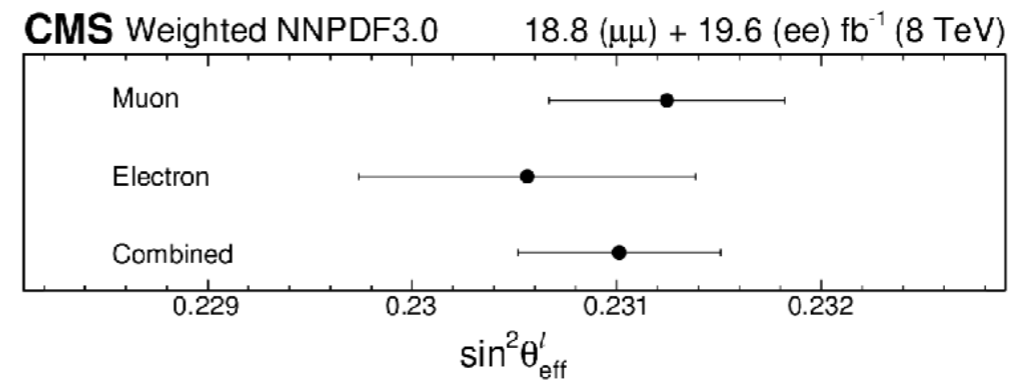
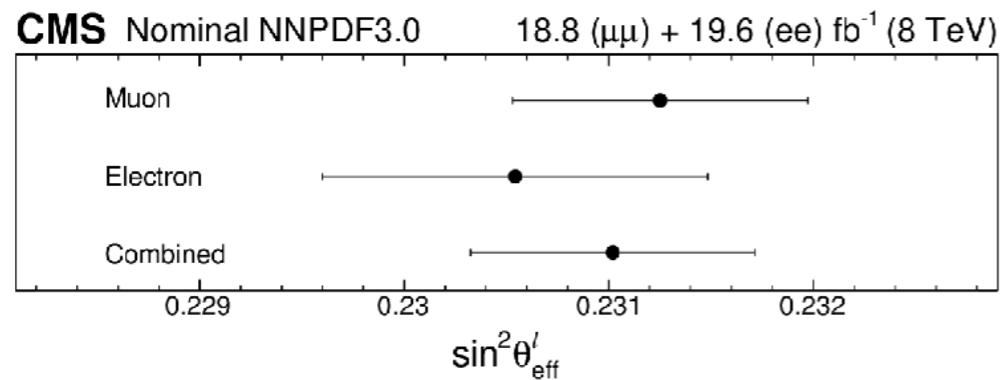
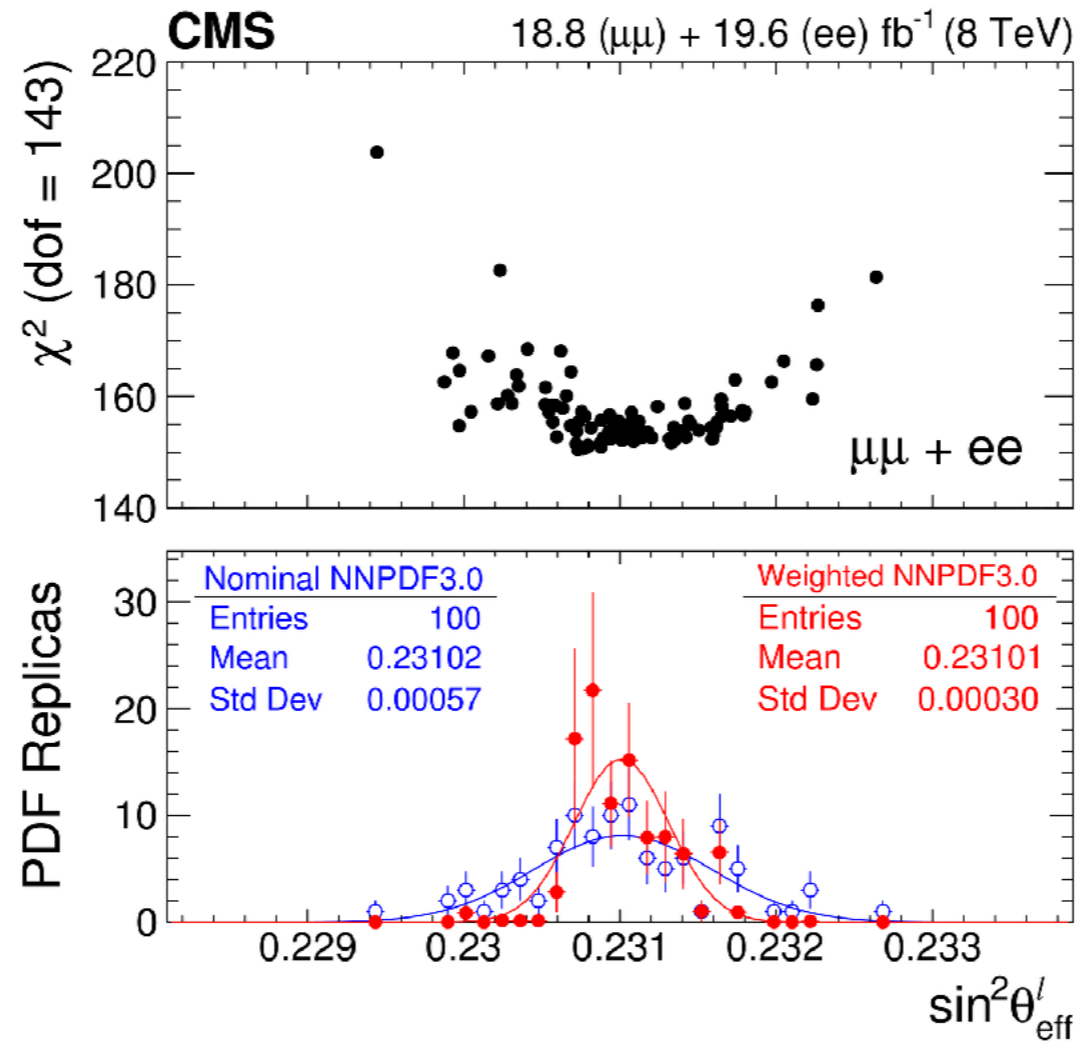


SMP-17-001
arXiv:1812.10529



A_{FB} in DY events and $\sin^2\theta_W$

SMP-16-007
EPJC 78 (2018) 701

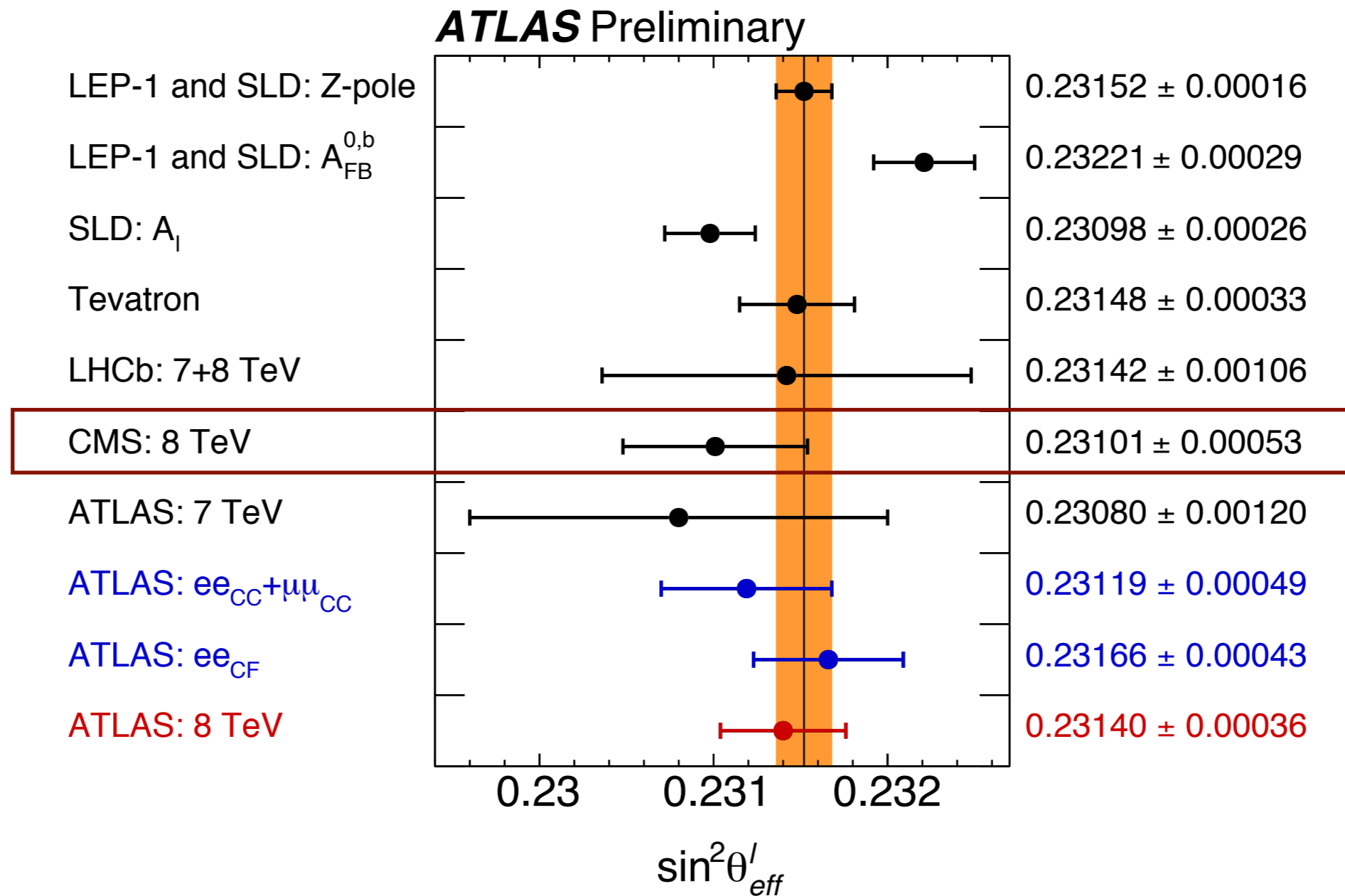


A_{FB} in DY events and $\sin^2\theta_W$

SMP-16-007
EPJC 78 (2018) 701

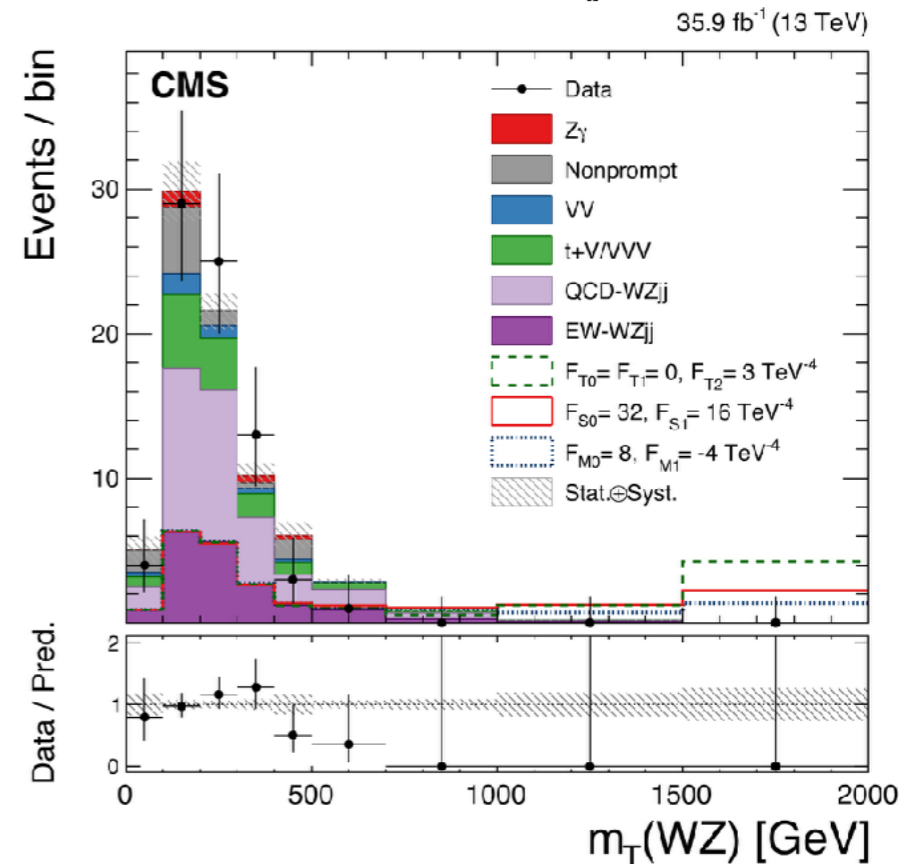
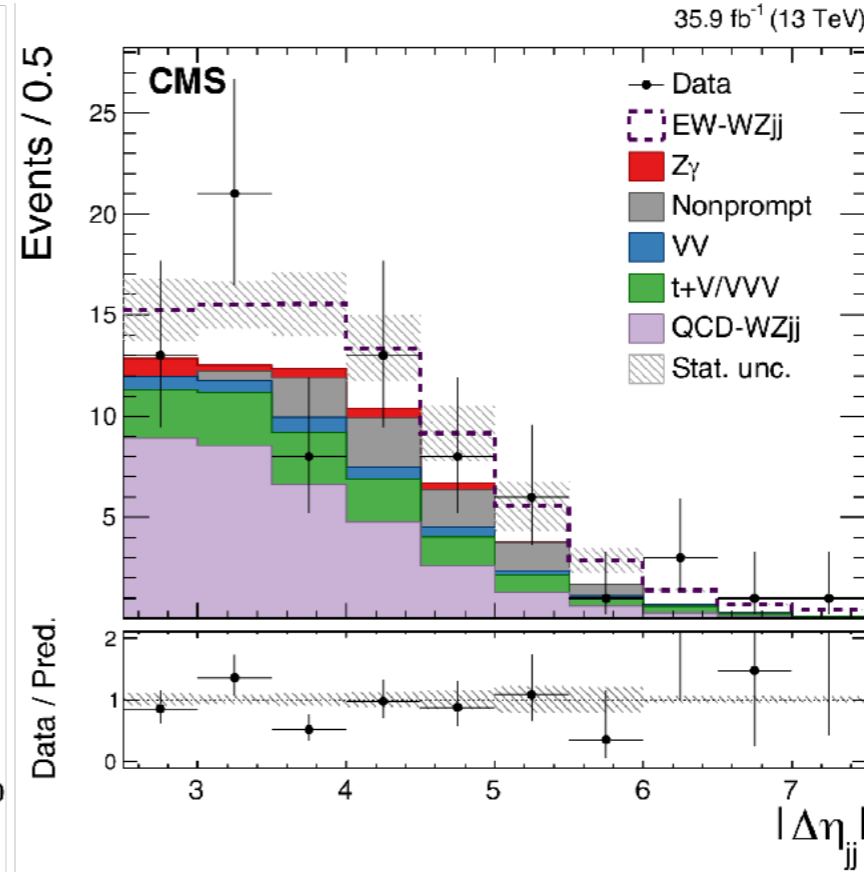
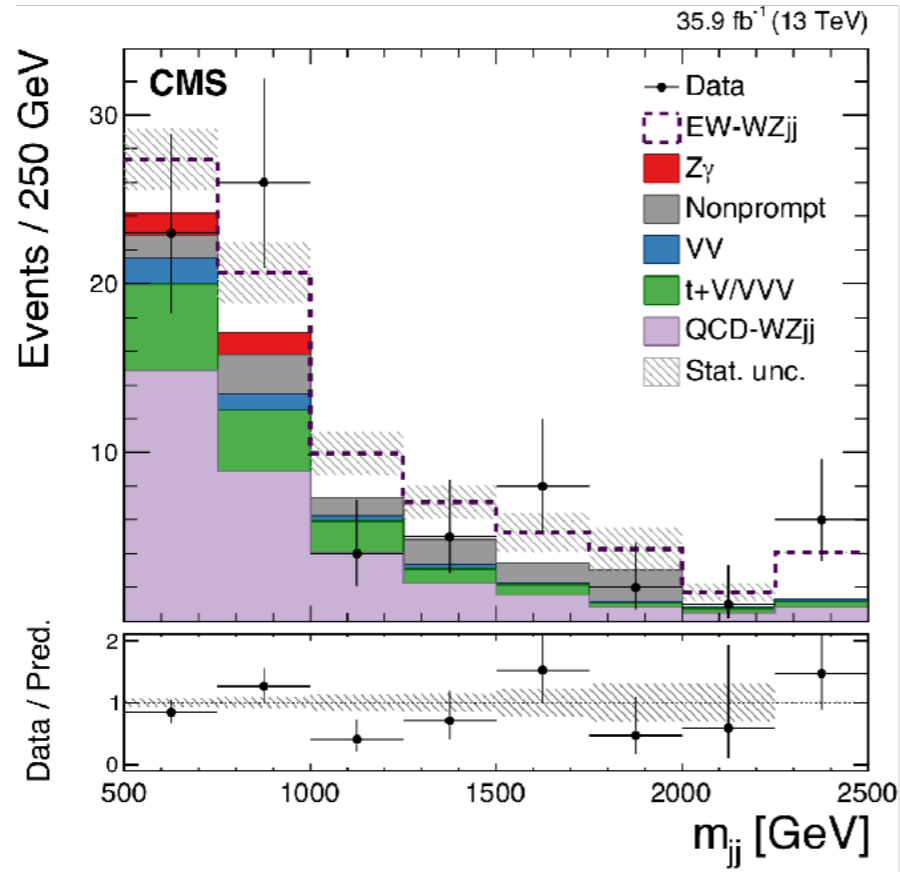


$$\sin^2\theta_{\text{eff}}^{\ell} = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (PDF)}$$



In future can help disentangle LEP/SLD tension!
(including new ATLAS preliminary result)

Vector Boson Scattering: WZ

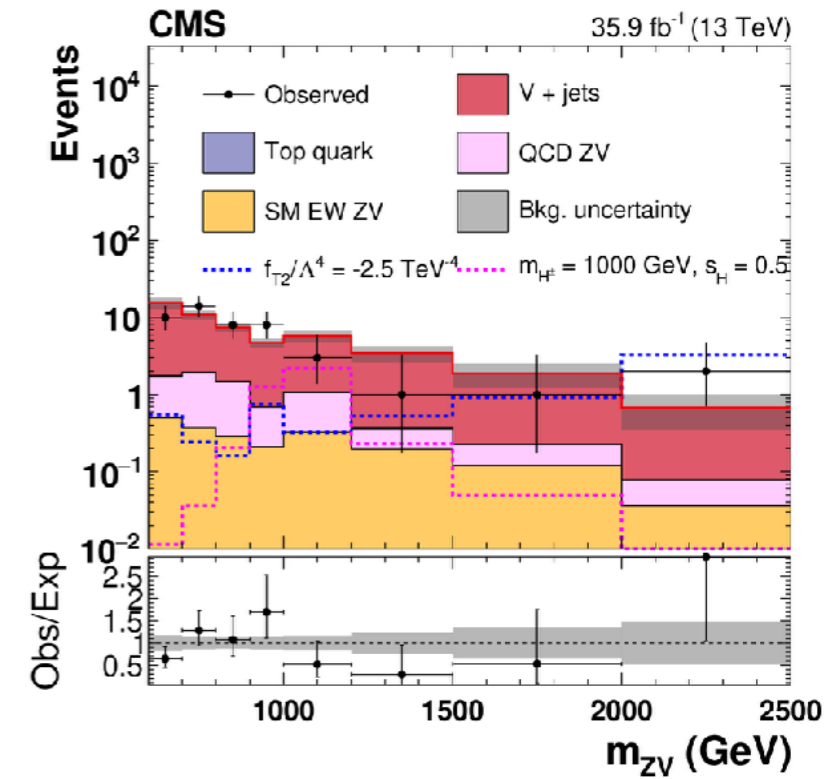
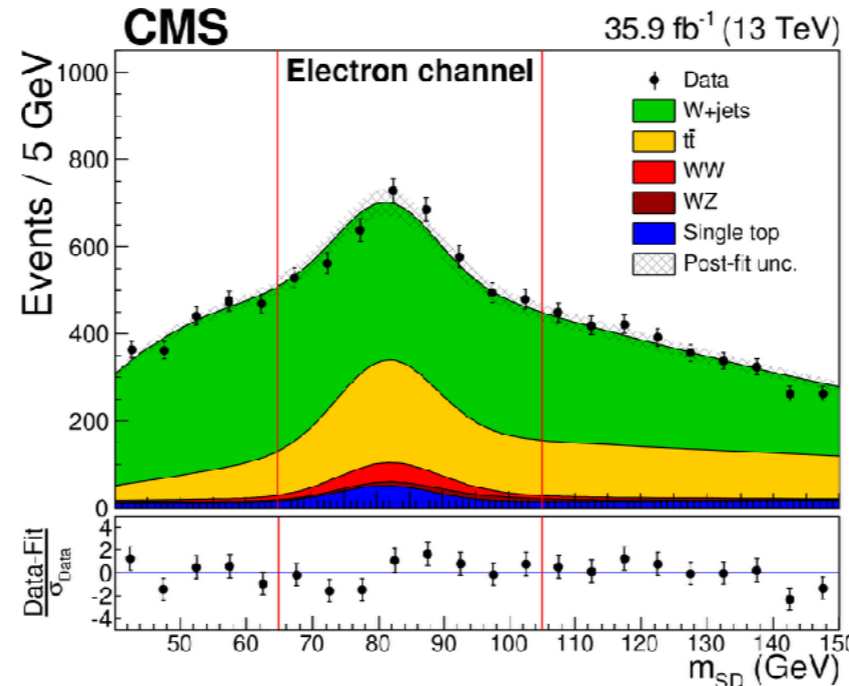
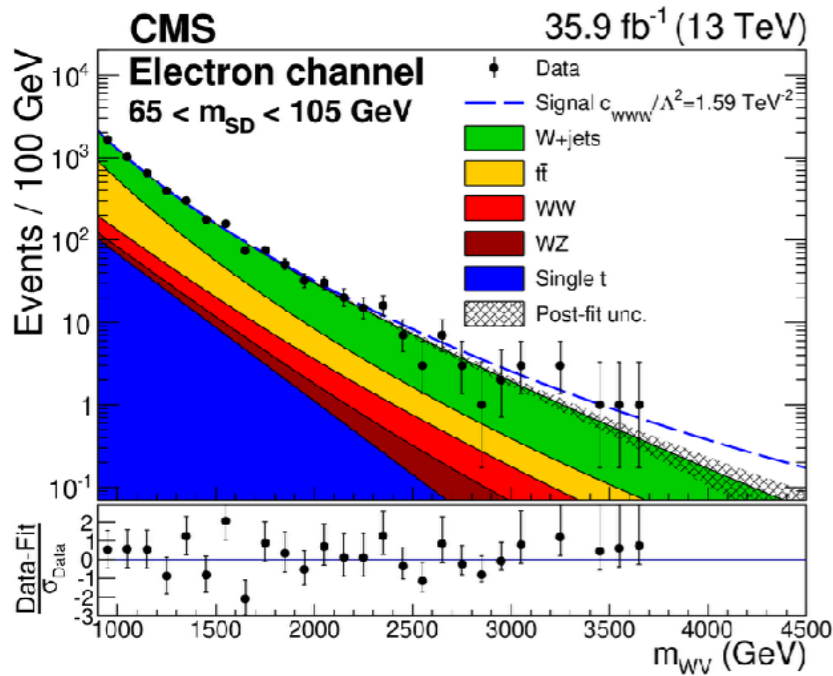


Source of syst. uncertainty	Relative uncertainty [%]	
	σ_{WZjj}	EW WZ sig.
Jet energy scale	+11 / - 8.1	7.0
Jet energy resolution	+1.9 / - 2.1	<0.1
QCD WZ modeling	—	2.2
Other background theory	+2.2 / - 2.2	0.3
Nonprompt normalization	+2.5 / - 2.5	0.3
Nonprompt event count	+6.0 / - 5.8	1.7
Lepton energy scale and eff.	+3.5 / - 2.7	<0.1
b tagging	+2.0 / - 1.7	<0.1
Integrated luminosity	+3.6 / - 3.0	<0.1

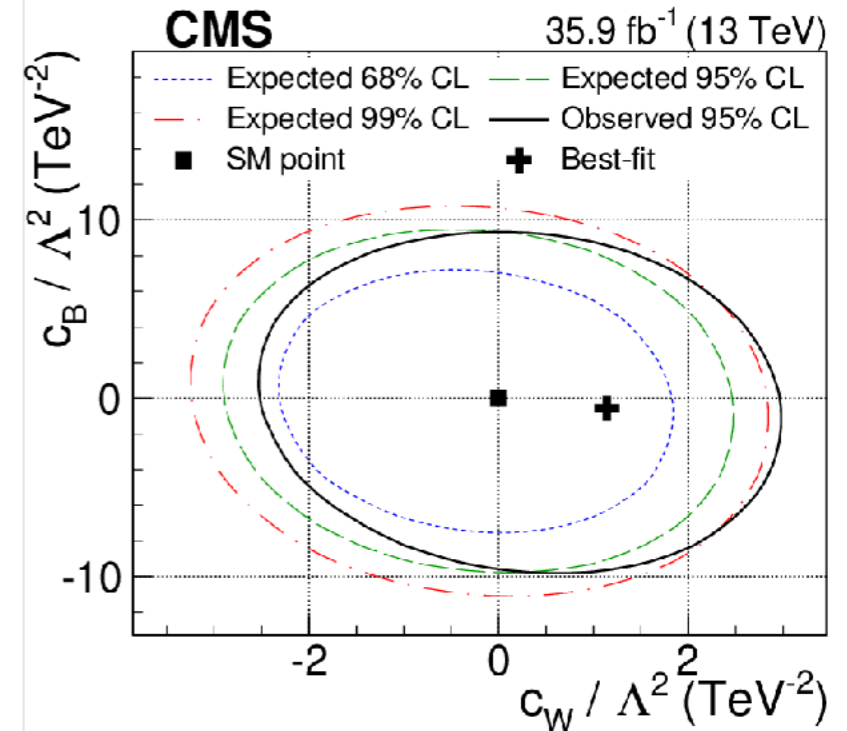
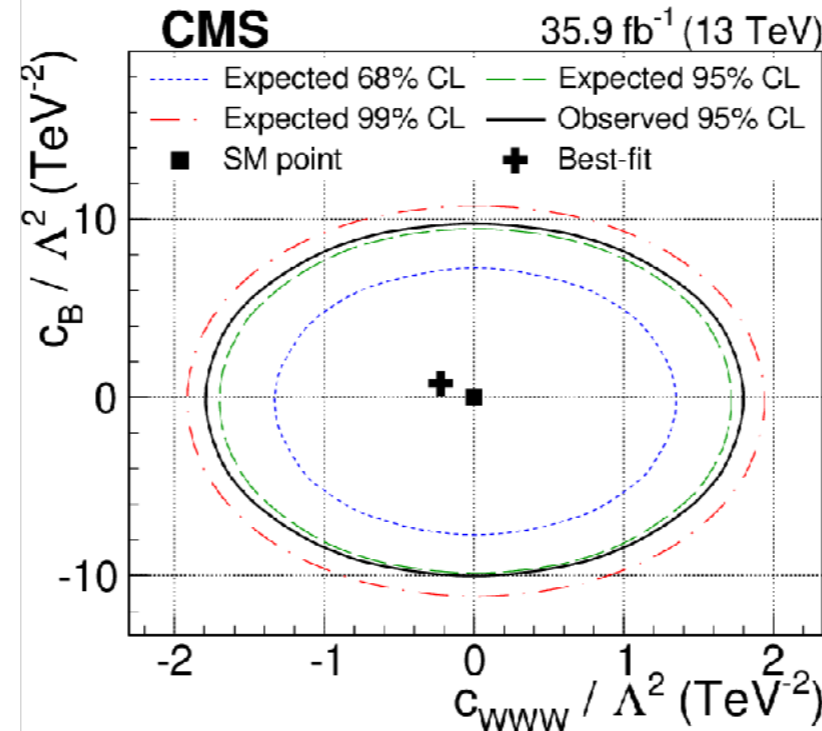
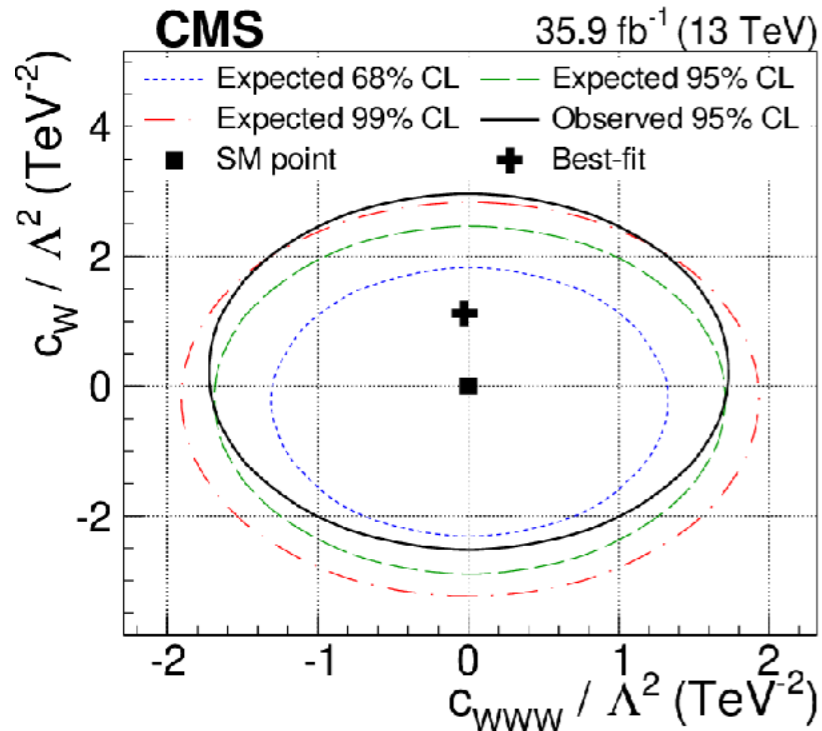
Diboson production: $WW/WZ \rightarrow \ell\nu + \text{jet}$



Plots for the electron channel



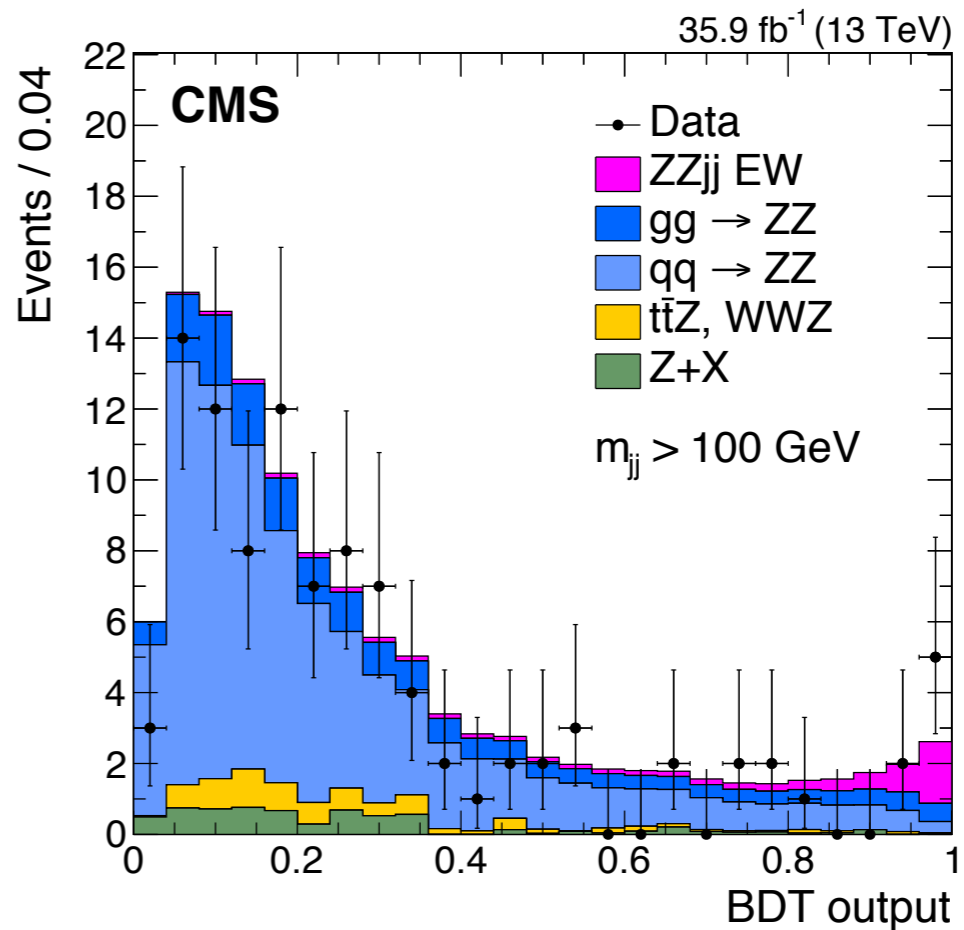
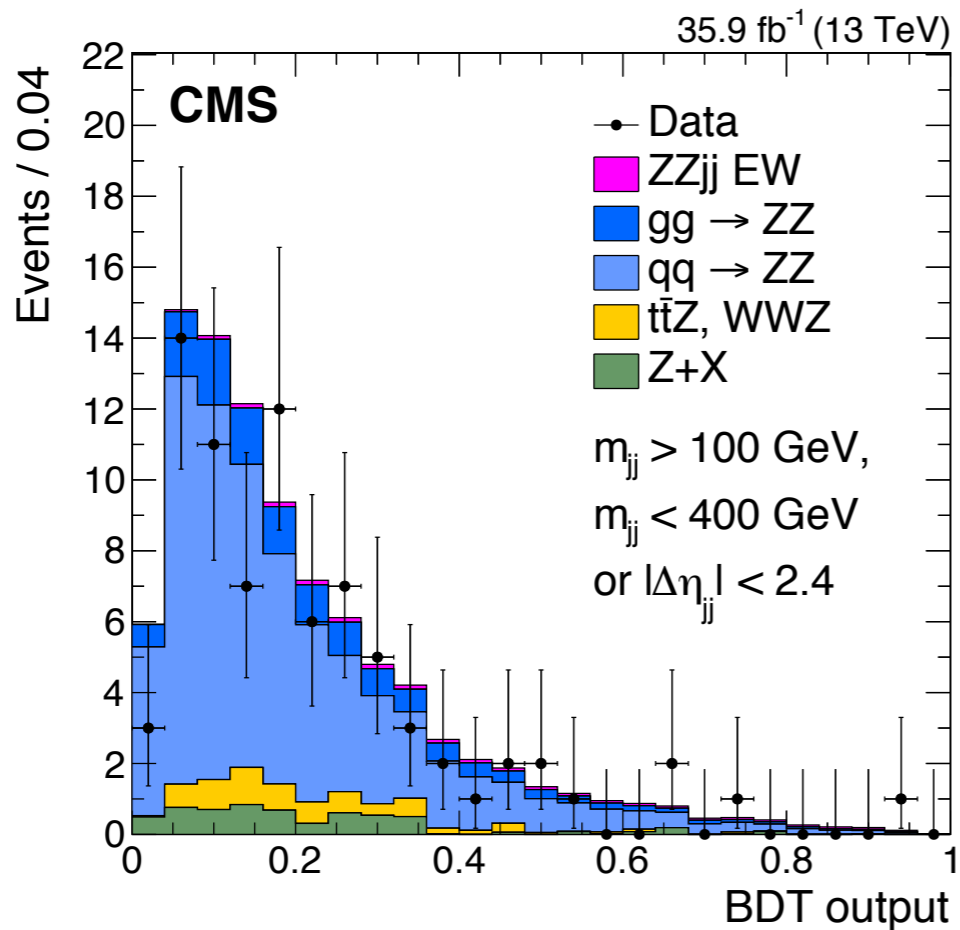
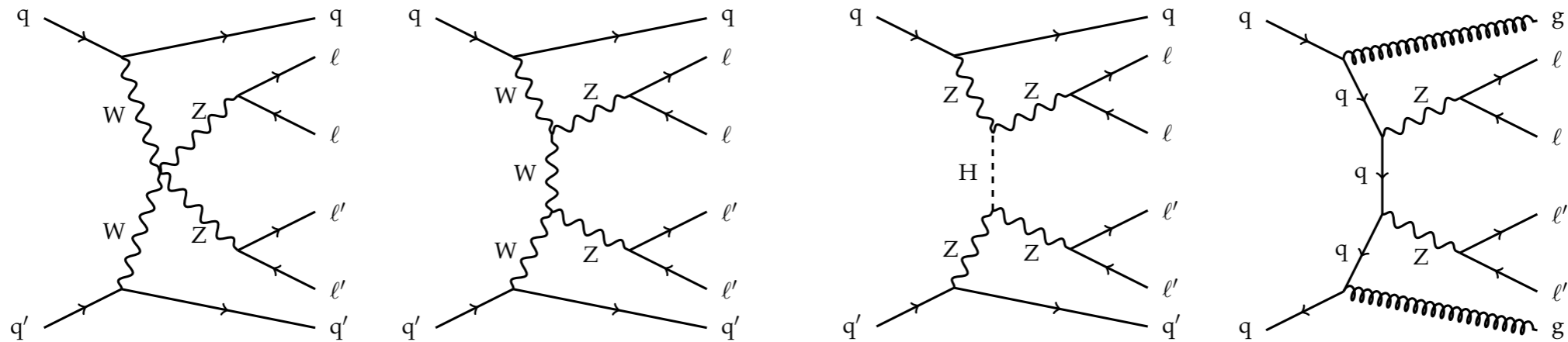
Contour of EFT parameters



Vector Boson Scattering: ZZ



EW- and QCD-induced production separated using a BDT

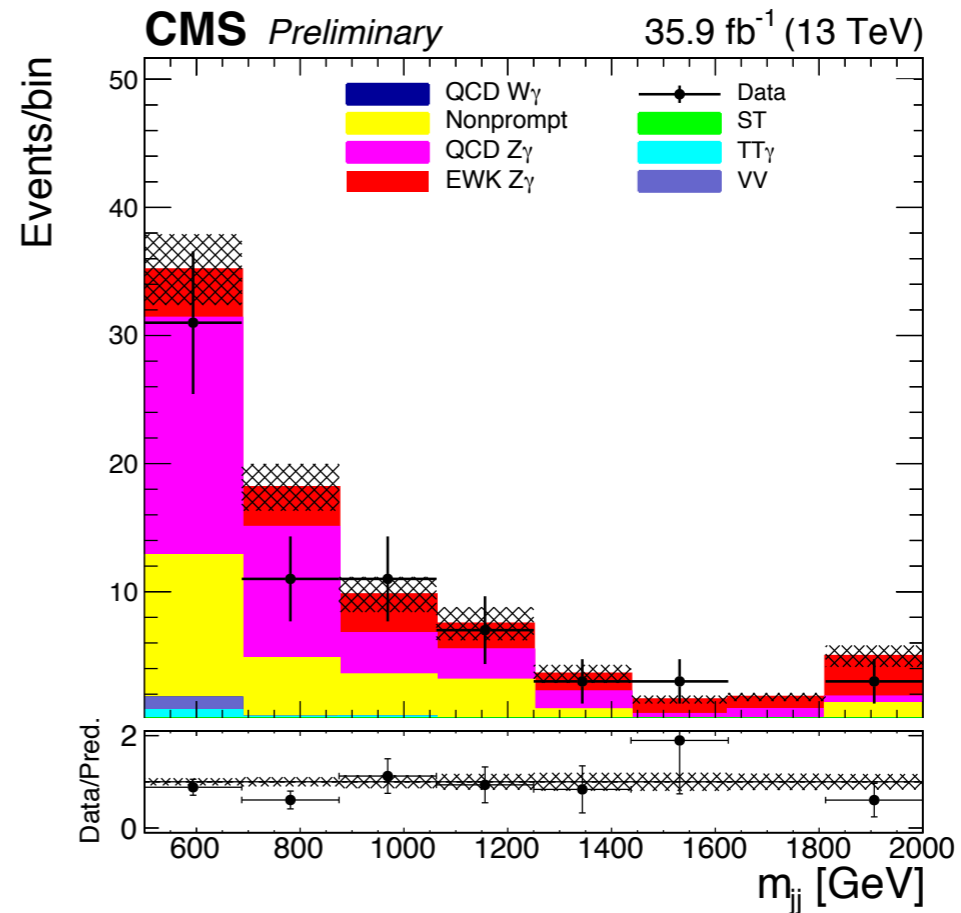
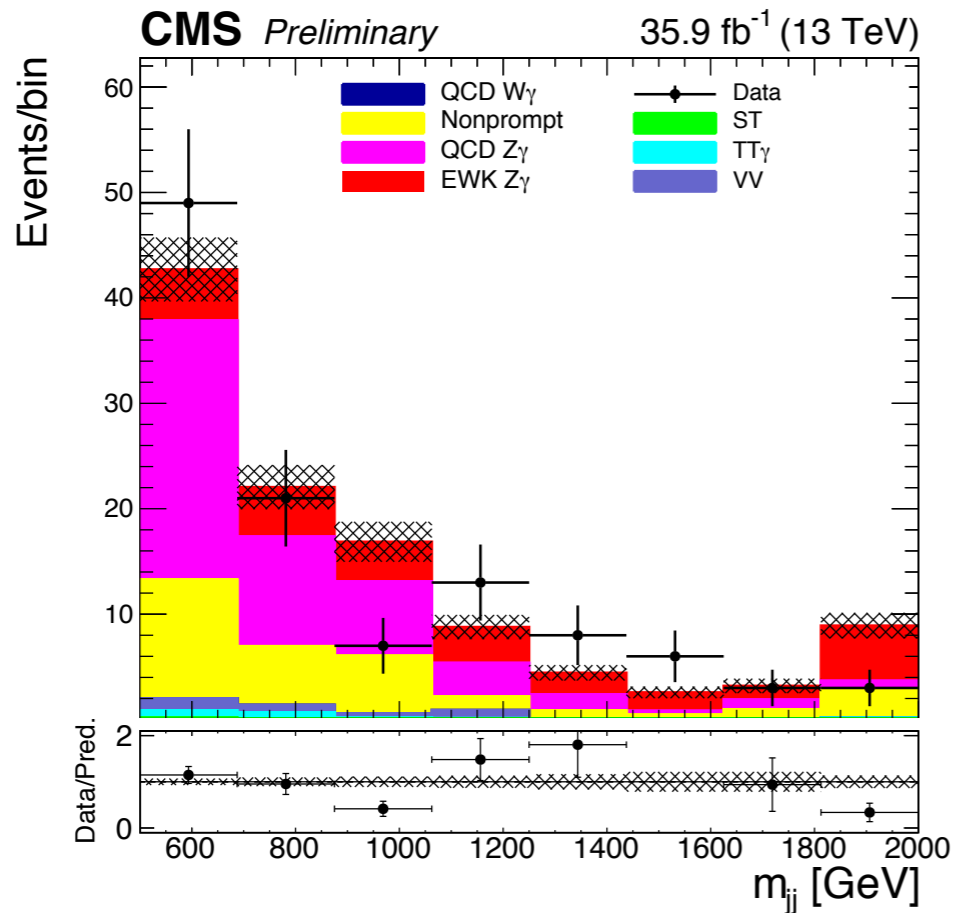
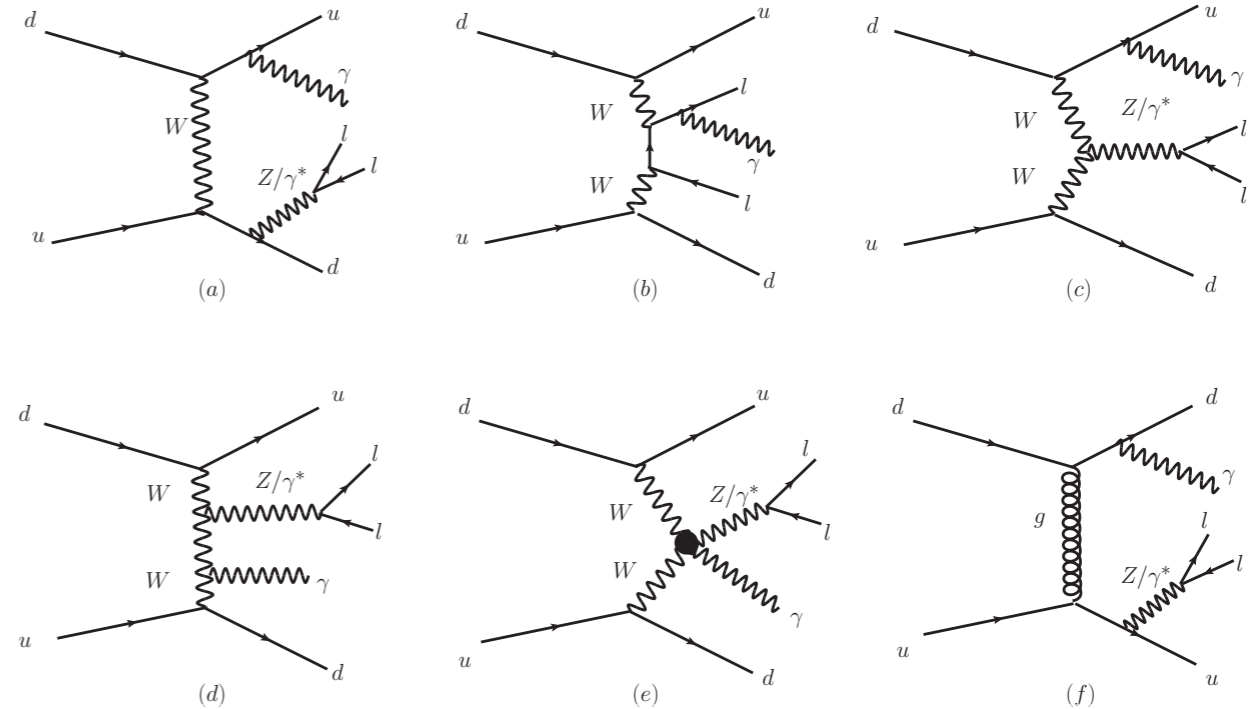


Vector Boson Scattering: $Z\gamma$

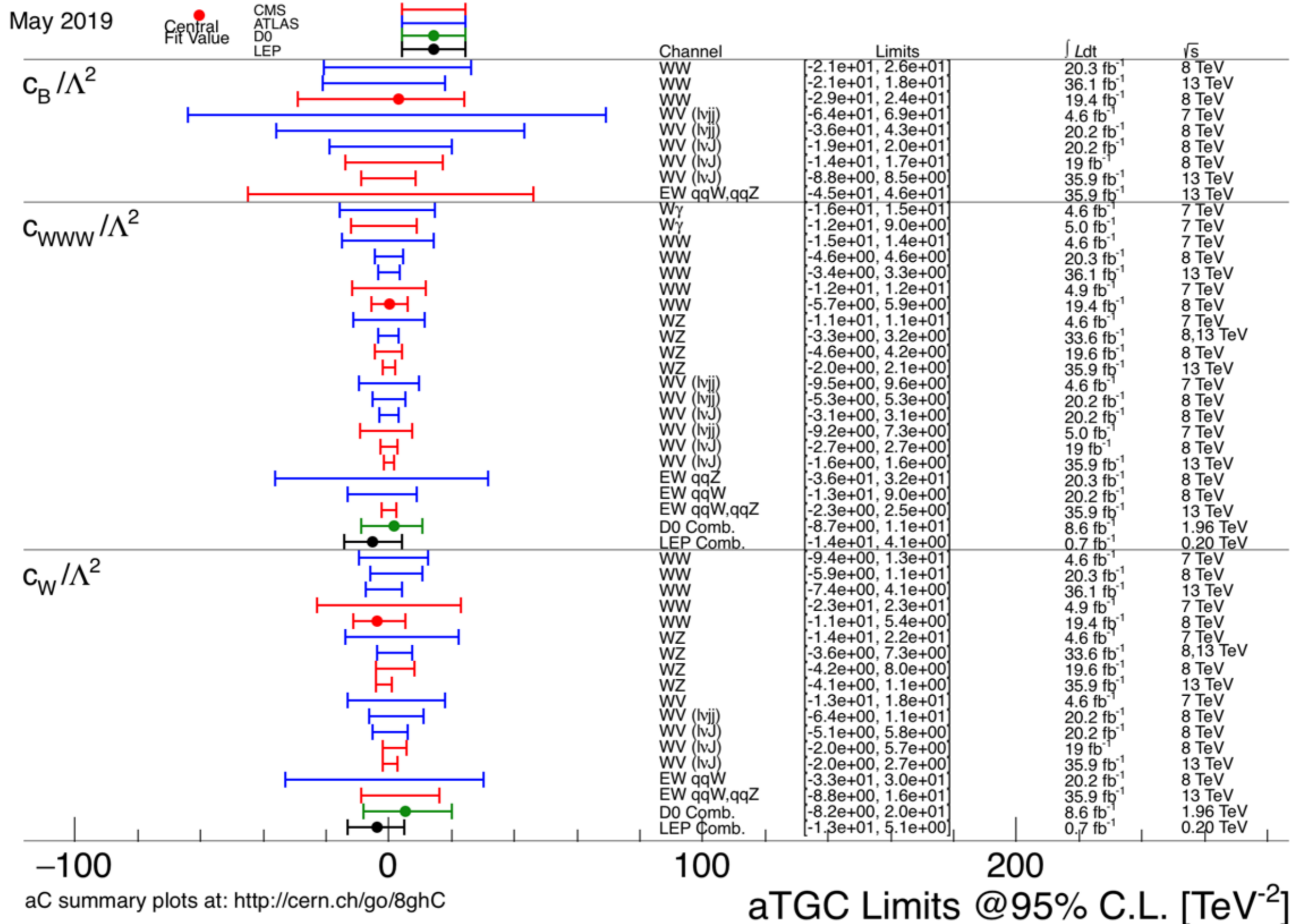


Fit EW on 2D distribution of m_{jj} and η_{jj}

	muon channel	electron channel
Nonprompt photon	47.6 ± 4.5	39.3 ± 4.0
Other background	7.4 ± 1.4	2.7 ± 0.8
QCD $Z\gamma_{jj}$	62.9 ± 3.1	49.6 ± 2.7
EW $Z\gamma_{jj}$	36.5 ± 0.7	25.4 ± 0.6
Total background	117.9 ± 5.6	91.6 ± 4.8
Data	172 ± 13	113 ± 11



EFT: limits on 6-dim operators

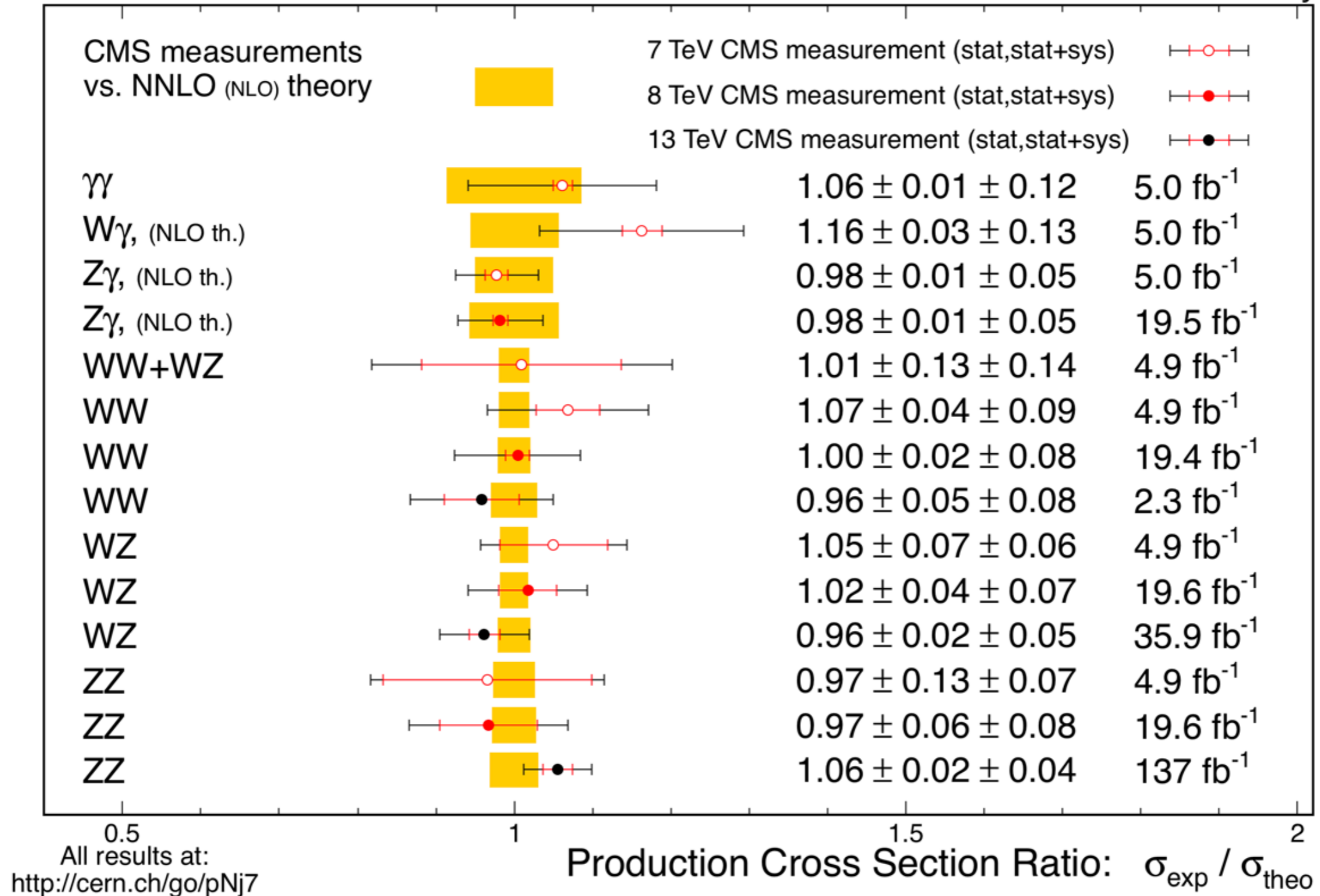


Dibosons cross-sections



March 2019

CMS Preliminary



VBS cross-sections



July 2019

CMS Preliminary

