Precision electroweak measurements with the CMS detector

V. Ciulli

University and INFN Florence

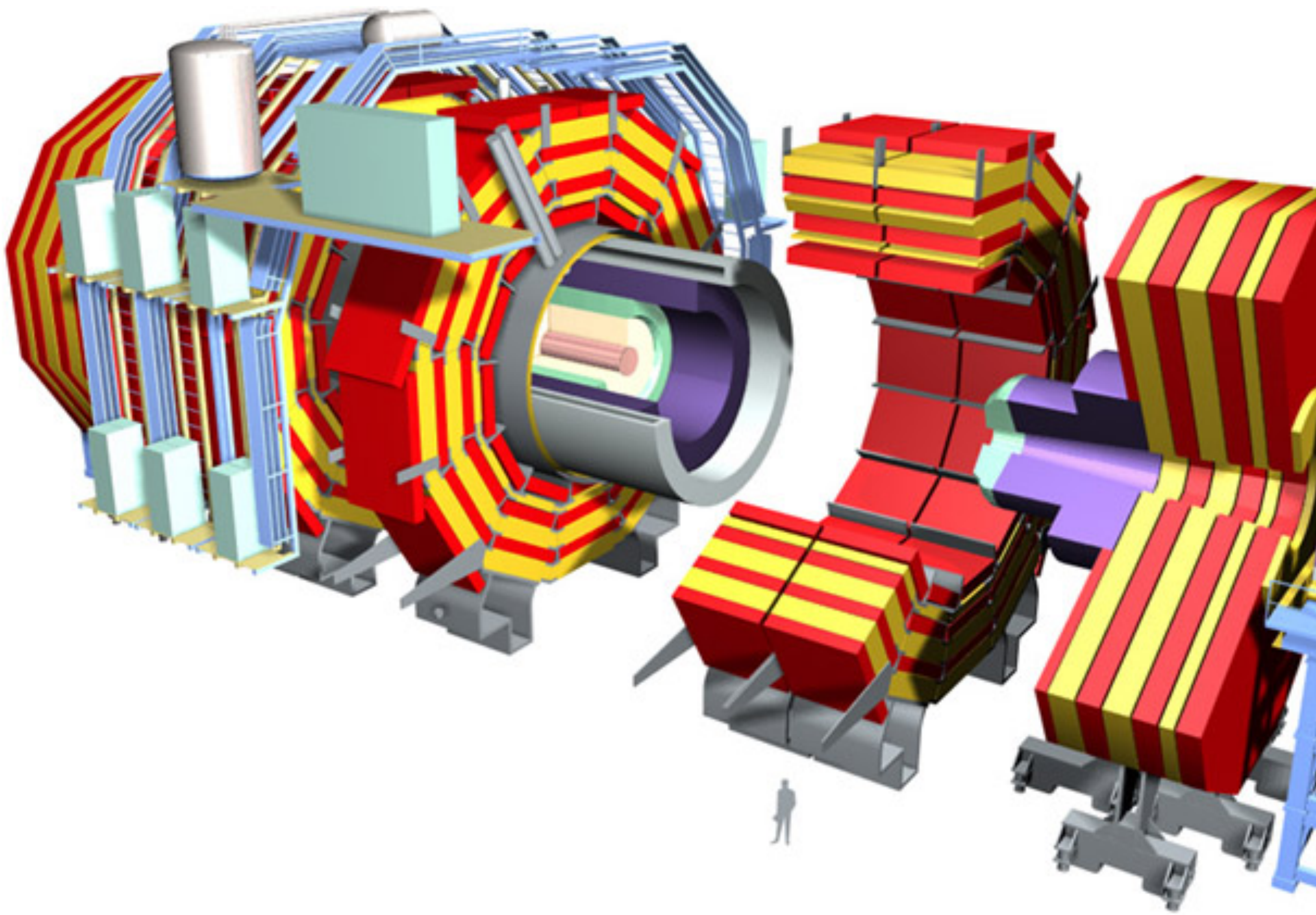
on behalf of CMS

XXVI Cracow EPIPHANY Conference

7-10 January 2020

Outline of the talk

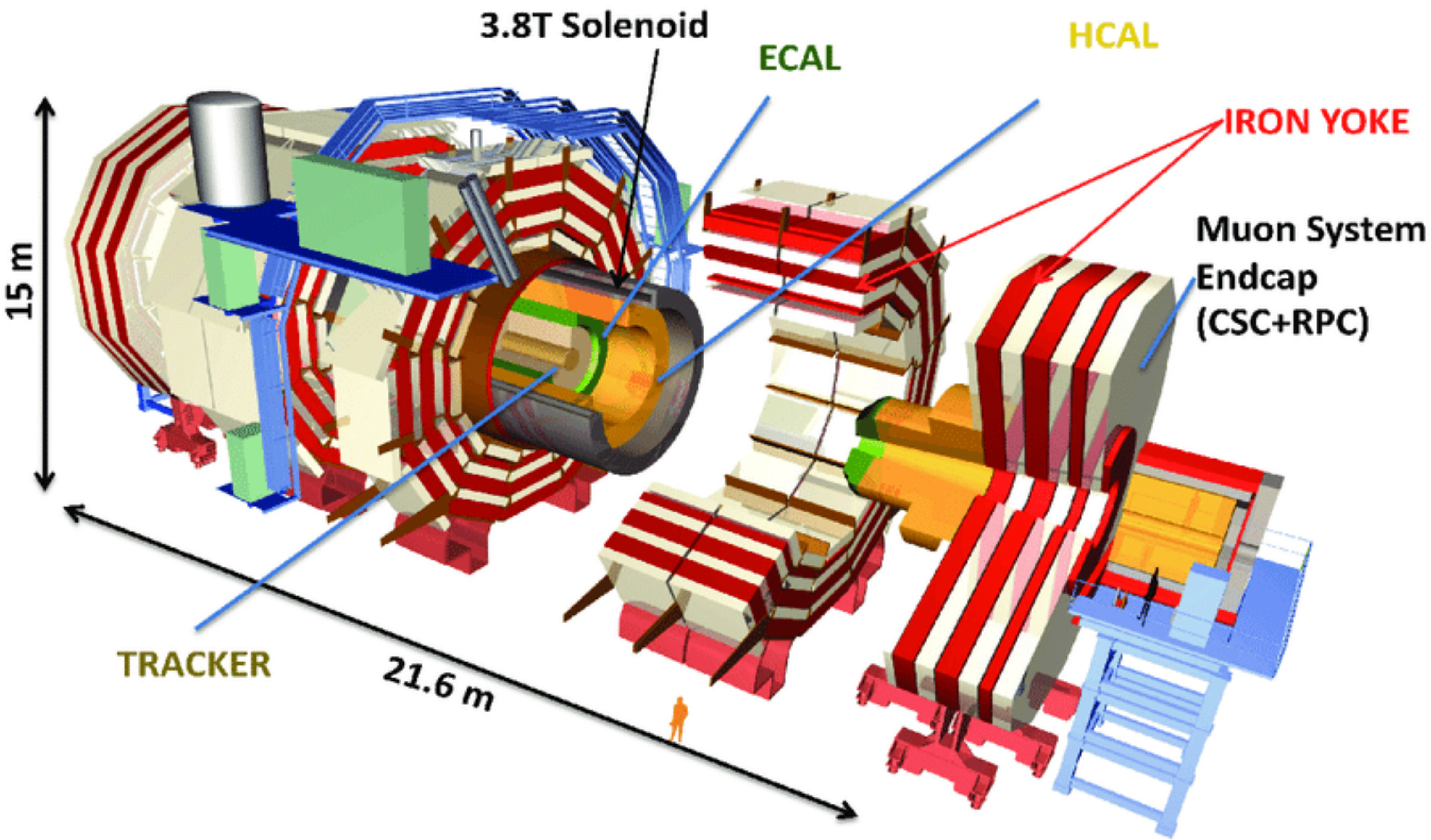
- CMS detector and data taking
- EW processes at the LHC
- Drell-Yan measurements
- EW production of Wjj
- Multiboson production
- Vector Boson Scattering



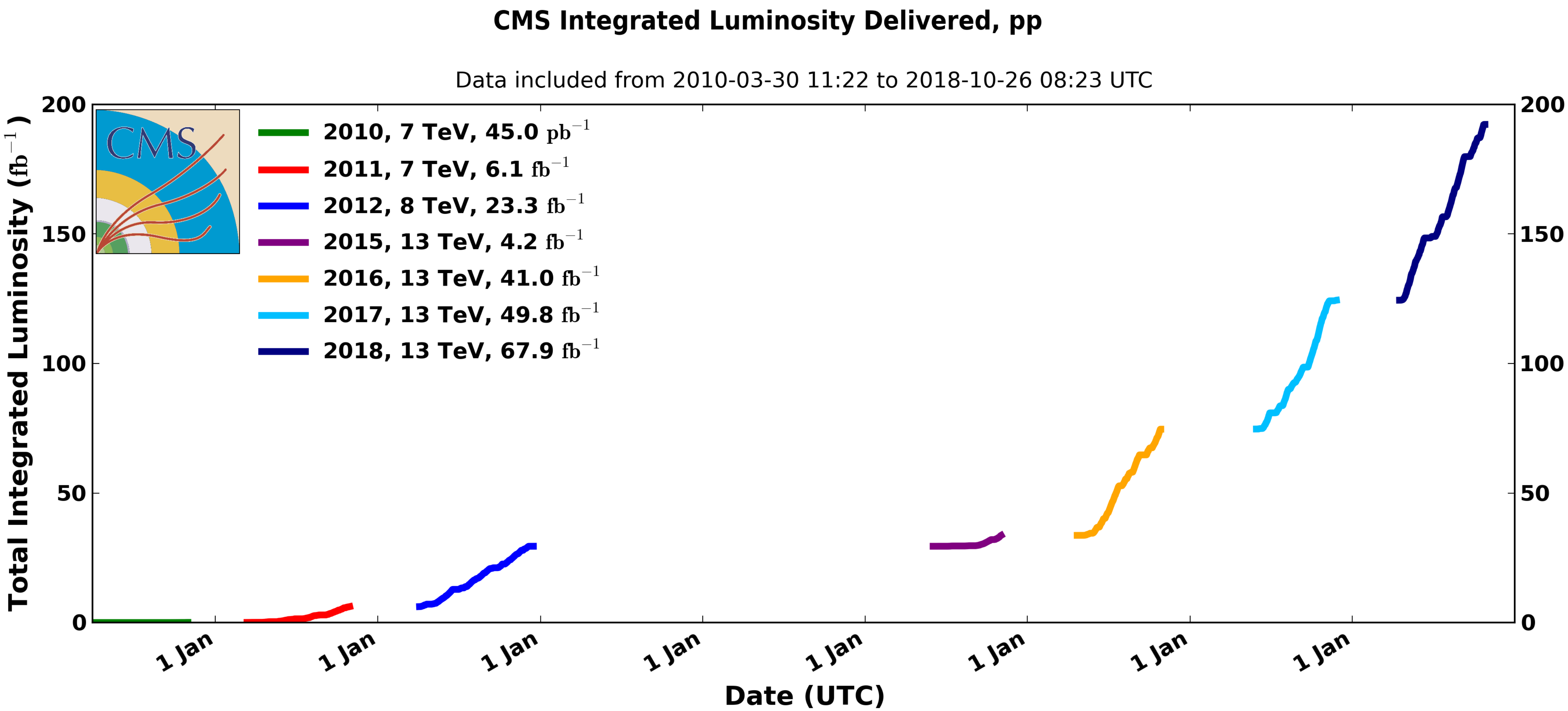
Selection of most recent results: not a comprehensive overview of all EW measurements of CMS

CMS detector and data taking

Compact Muon Solenoid



CMS detector and data taking

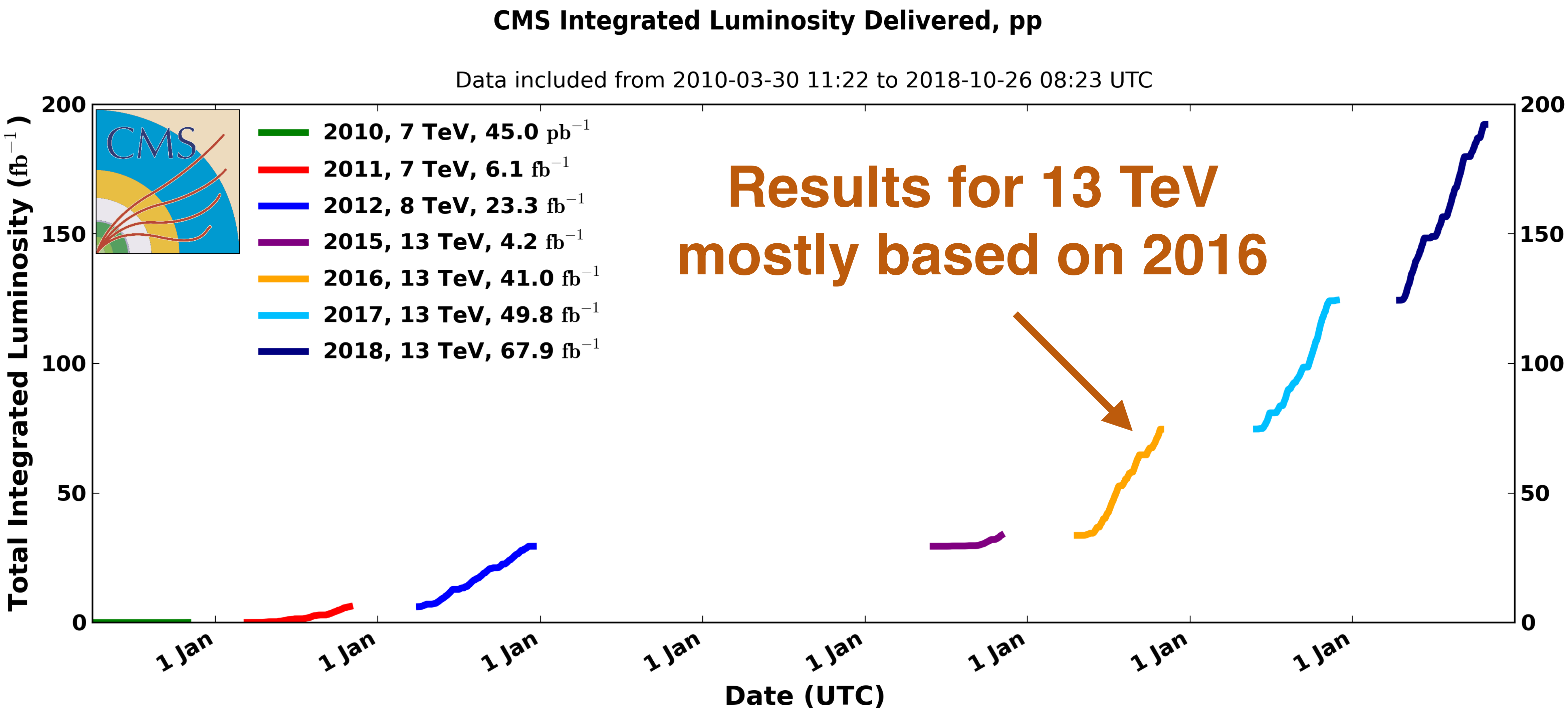


Overall ~200 fb^{-1} of data in Run I and II

of which 160 fb^{-1} at 13 TeV

A total of 300 fb^{-1} expected after Run III (2021-2024)

CMS detector and data taking



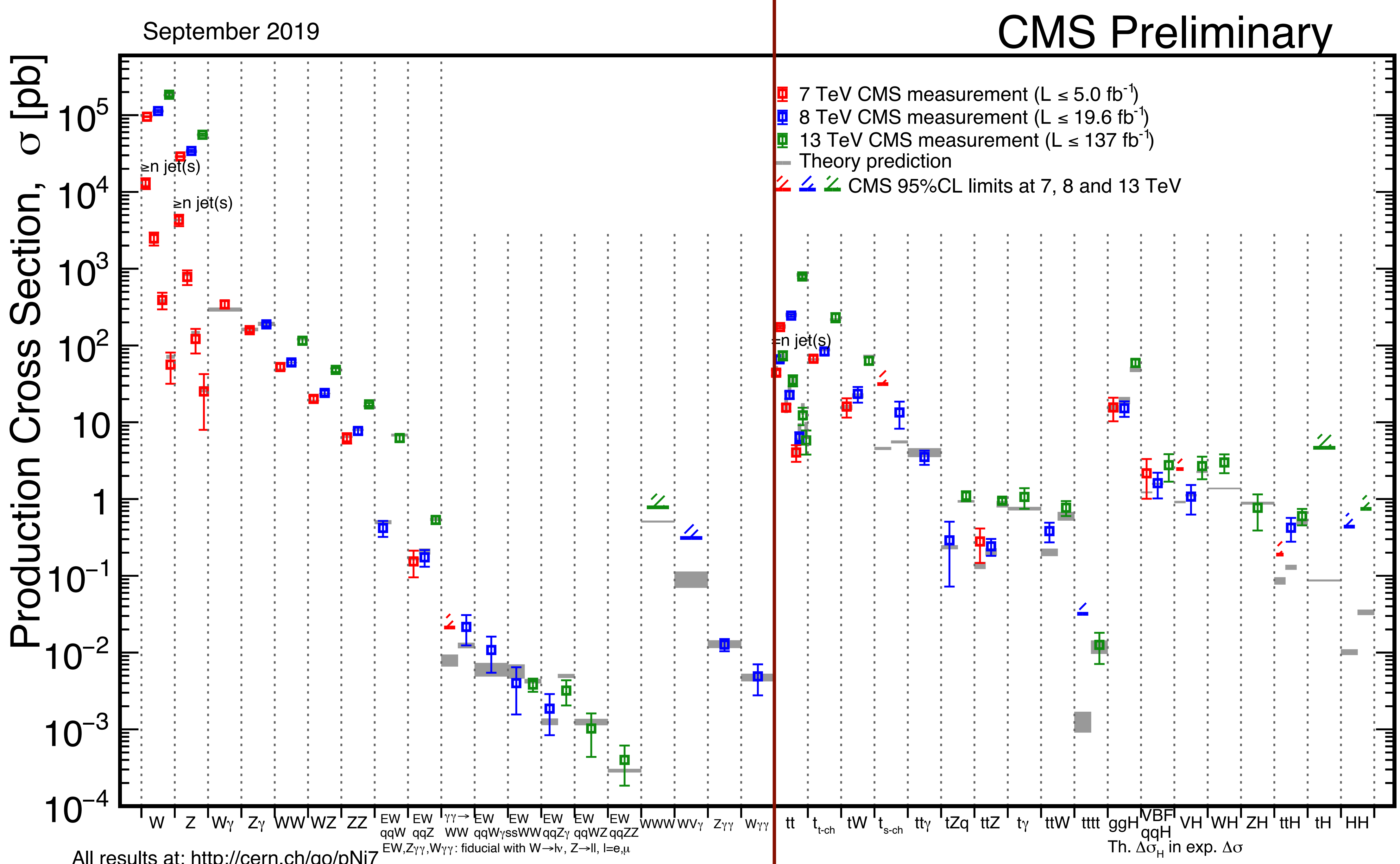
Overall ~200 fb^{-1} of data in Run I and II

of which 160 fb^{-1} at 13 TeV

A total of 300 fb^{-1} expected after Run III (2021-2024)

EW processes at the LHC

At least a weak boson, measurements up to three (including photons)



EW processes at the LHC

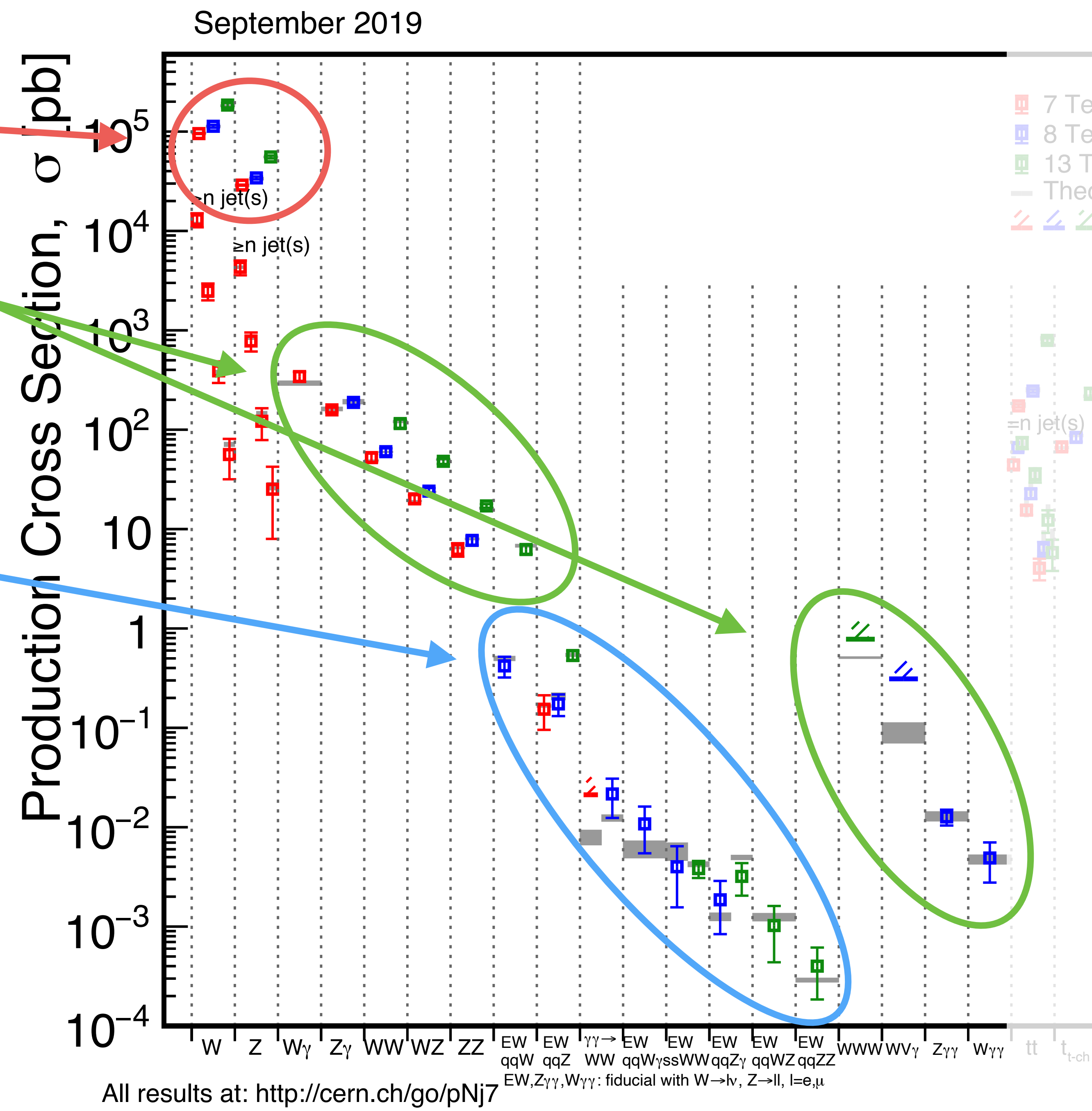
Cross-sections span over 9 orders of magnitude

from single W,Z production

to di-bosons and tri-bosons production

to Vector Boson Fusion

and Vector Boson Scattering

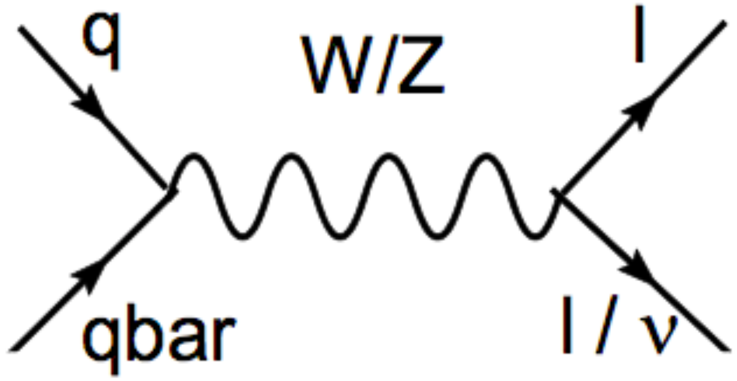


One or more weak bosons decaying to *e* or *μ* leptons is the "golden" signature for EW processes

- ➡ Low background
- ➡ Single bosons are "Standard candles" for SM physics
- ➡ Multibosons are very sensitive to BSM

W/Z production at the LHC

Single W and Z are clean and powerful probes for fundamental processes



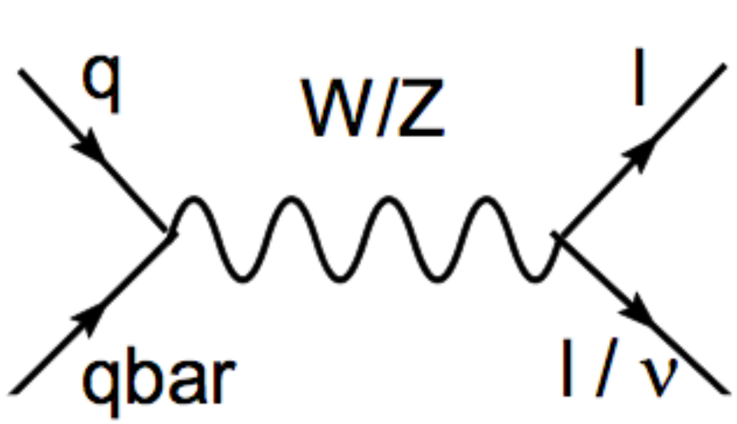
LO

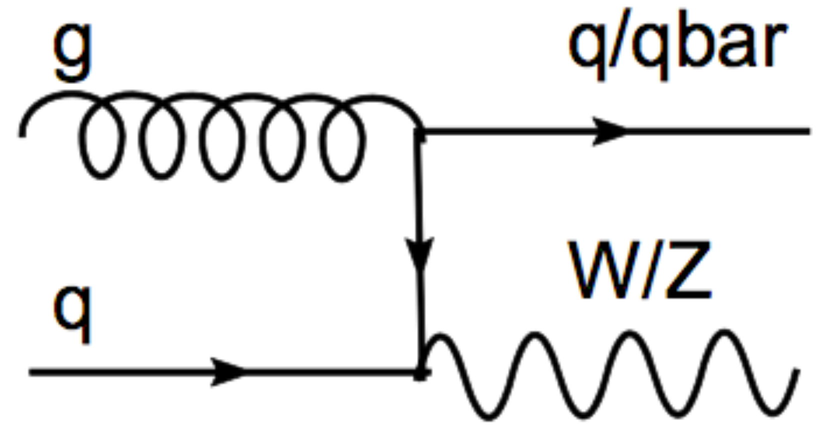
To first order at LHC, W and Z are generated by a valence quark and a sea anti-quark (Q~100 GeV)

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

W/Z production at the LHC

Single W and Z are clean and powerful probes for fundamental processes





LO + NLO

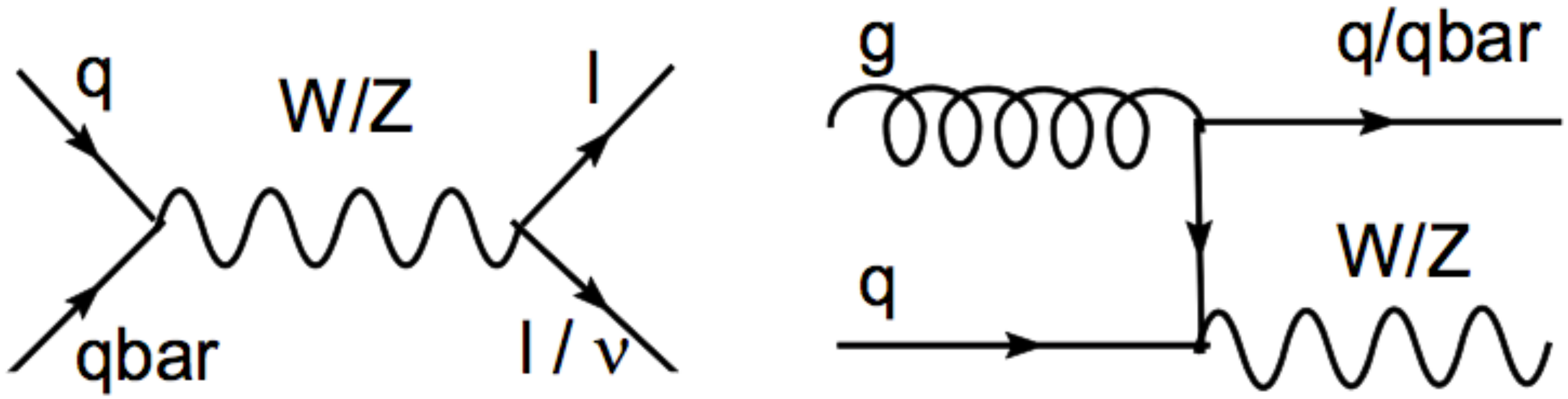
To first order at LHC, W and Z are generated by a valence quark and a sea anti-quark (Q~100 GeV)

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

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

W/Z production at the LHC

Single W and Z are clean and powerful probes for fundamental processes



LO + NLO

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

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

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

EW processes allow precision measurements of fundamental parameters through their couplings, but most measurements will depend on PDFs

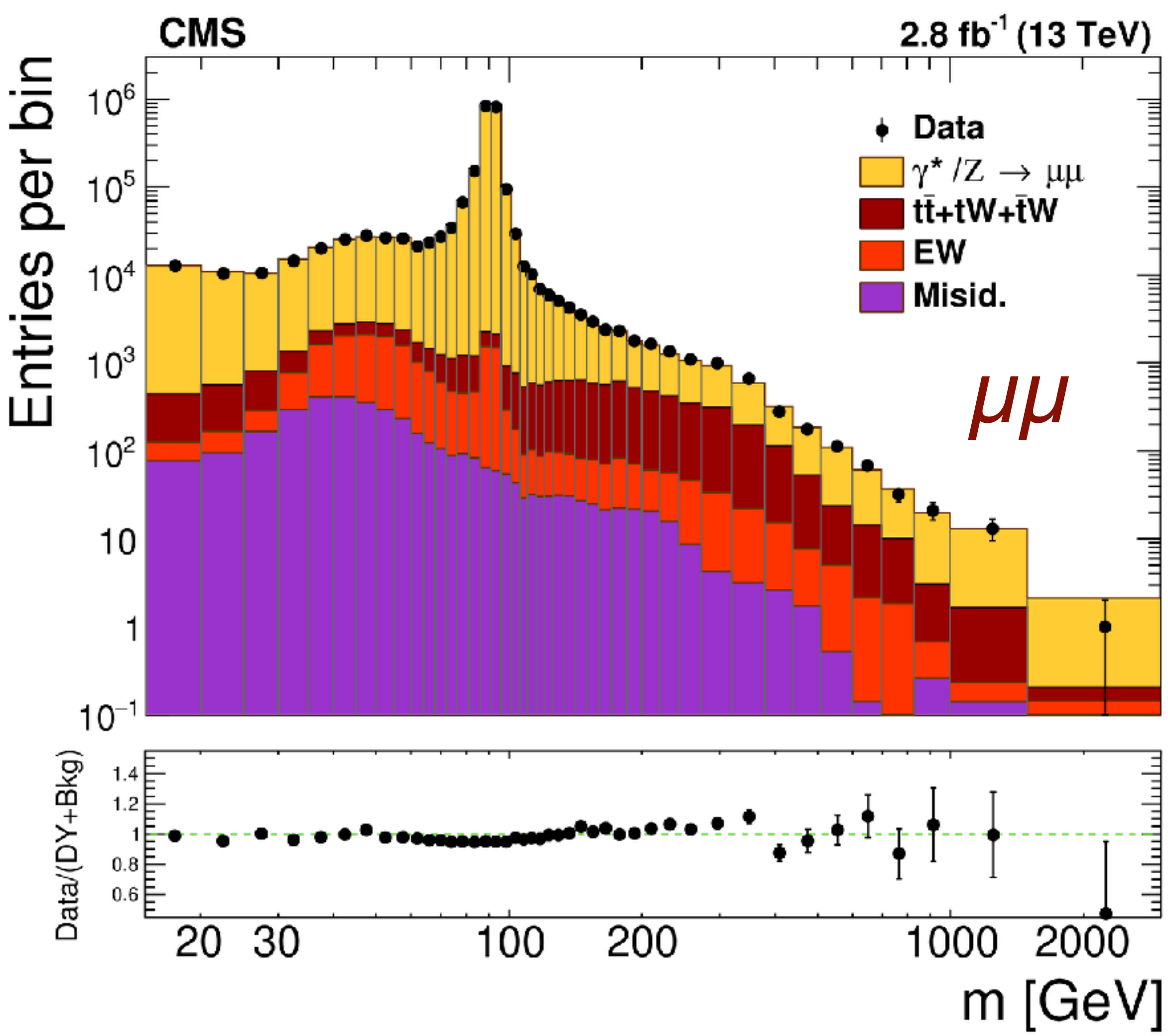
… can not forget QCD!

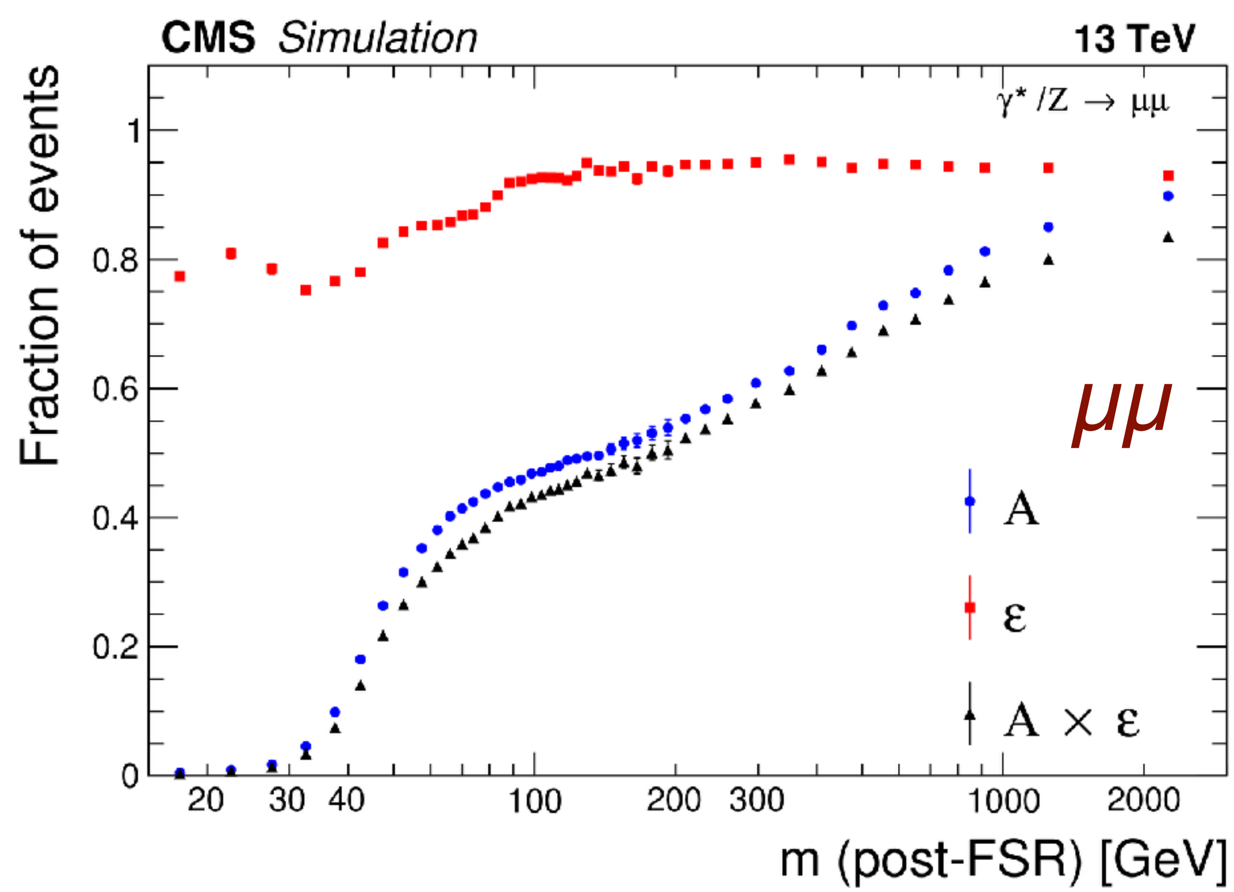
Drell-Yan $m_{\ell\ell}$ differential cross-section

SMP-17-001
JHEP 12 (2019) 059

- 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 QED FSR are unfolded
- Then cross-section is obtained by correcting for acceptance A and efficiency ε

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





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}

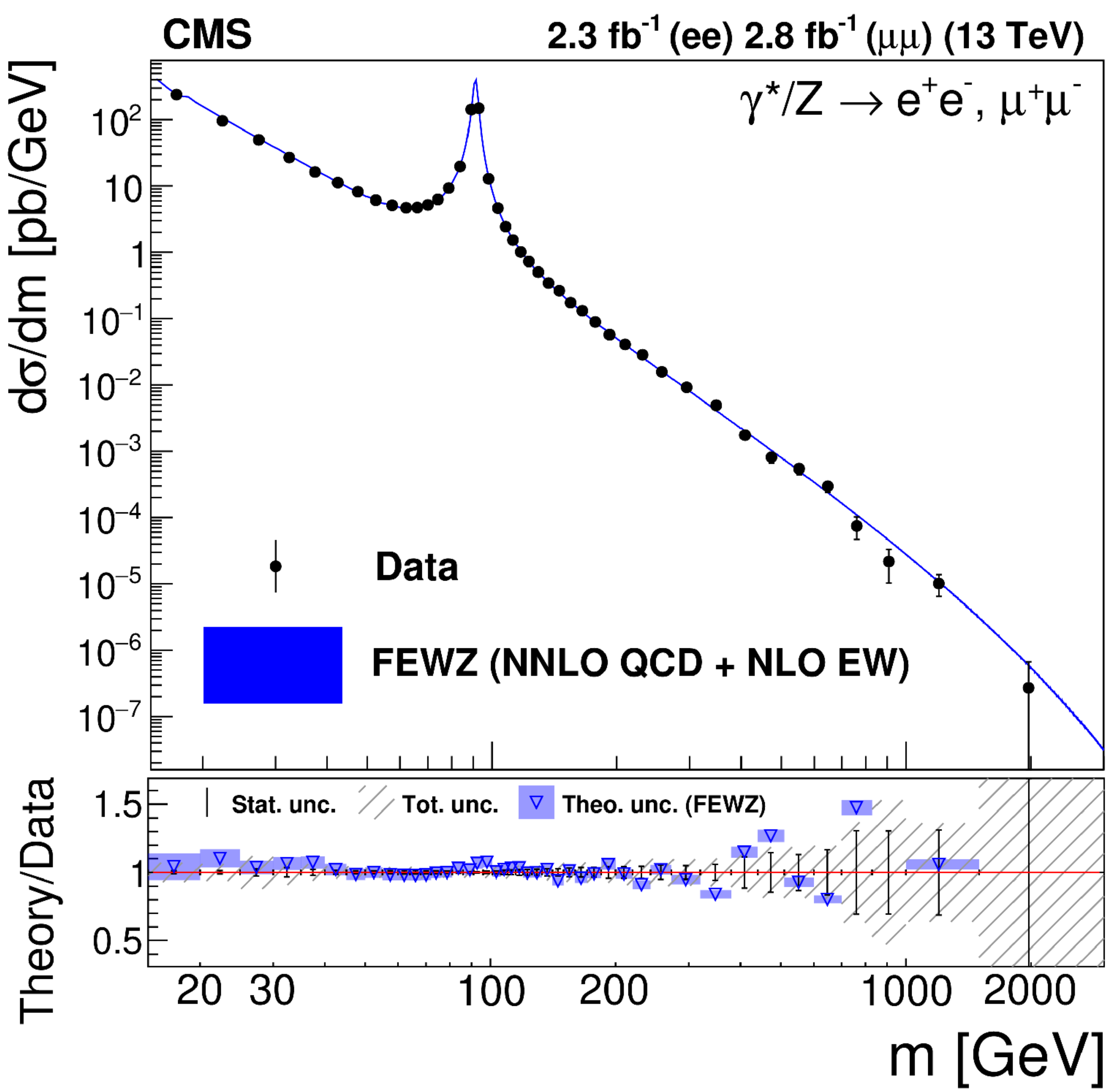
ee and $\mu\mu$ combined after unfolding FSR effects ("dressed leptons")

Acceptance is the largest uncertainty at low mass while statistical ≈ systematics at high mass

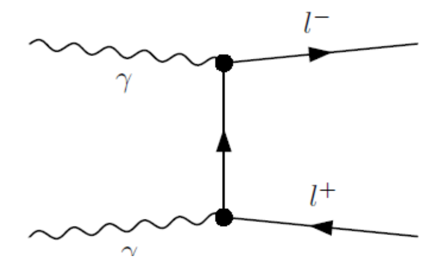
Excellent agreement with predictions from FEWZ (QCD NNLO + EW NLO)

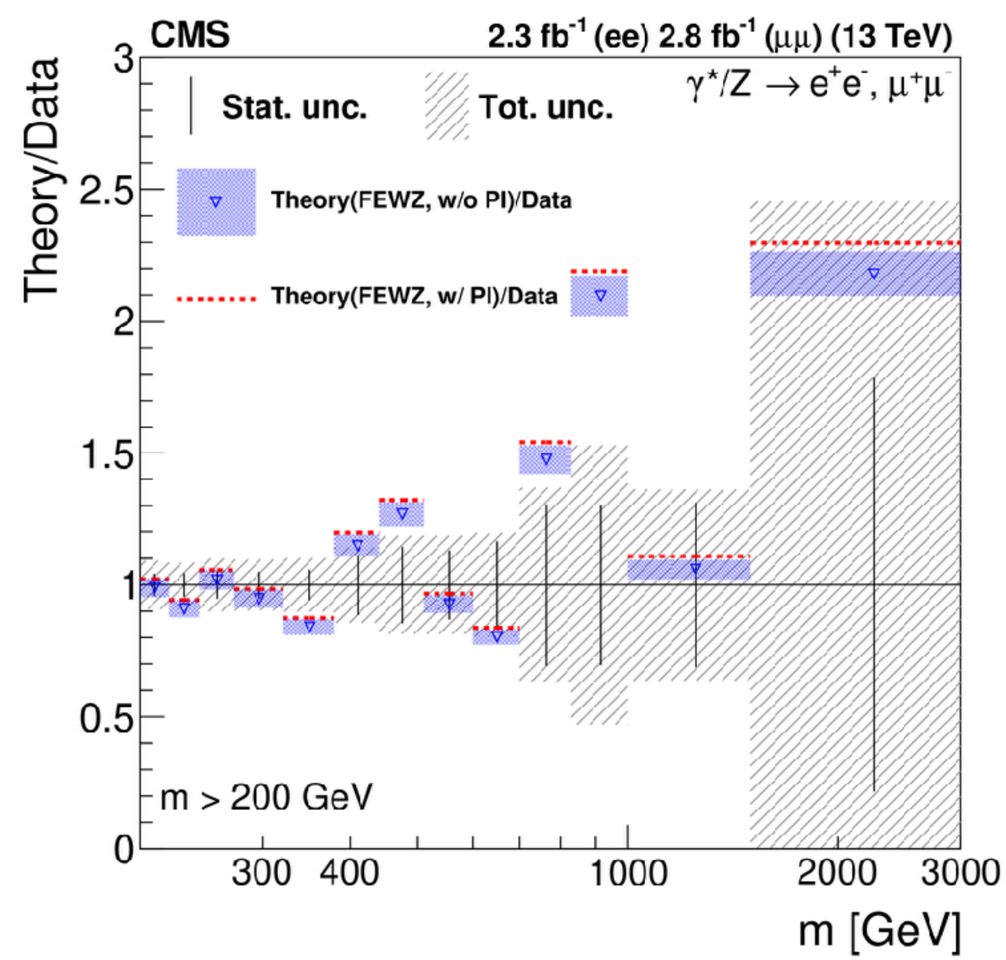
SMP-17-001

JHEP 12 (2019) 059



Photon-initiated negligible except at very high mass





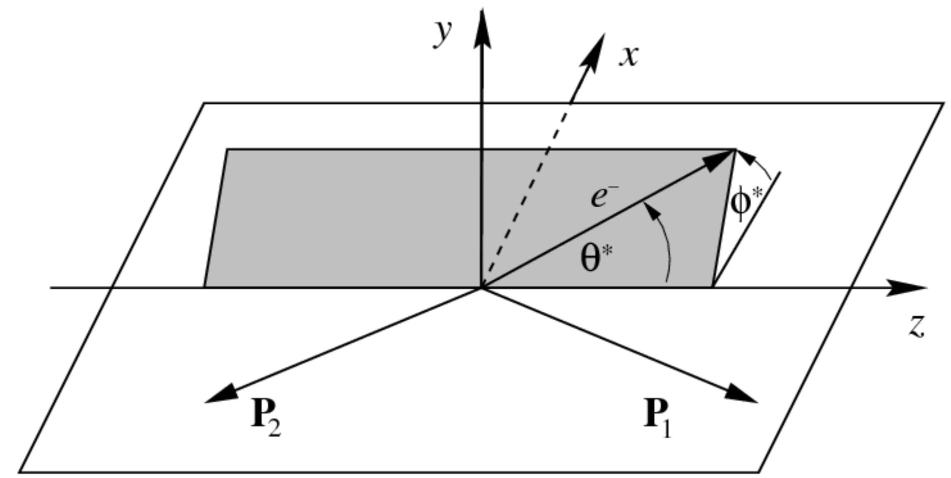
A_{FB} in DY events and $\sin^2\theta_W$

SMP-16-007
EPJC 78 (2018) 701

Angular distribution in qqbar → Z/γ → $\ell^+\ell^-$

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

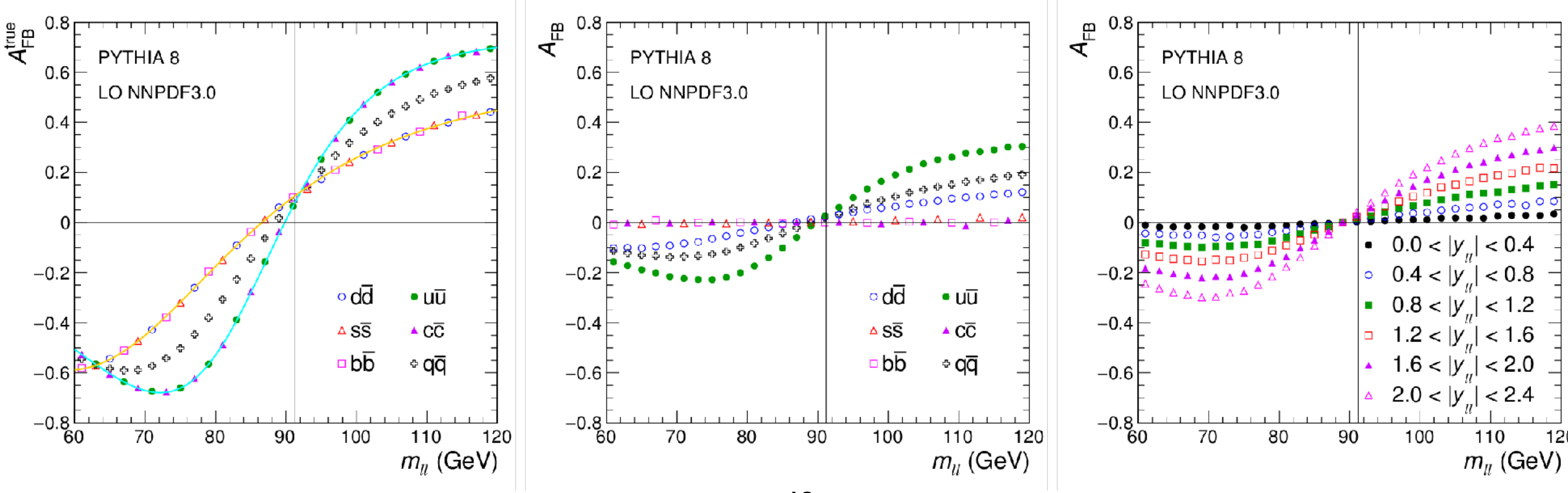
The asymmetry $A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$ is due to the interference of vector and axial currents **⇒ $\sin^2\theta_W$**



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



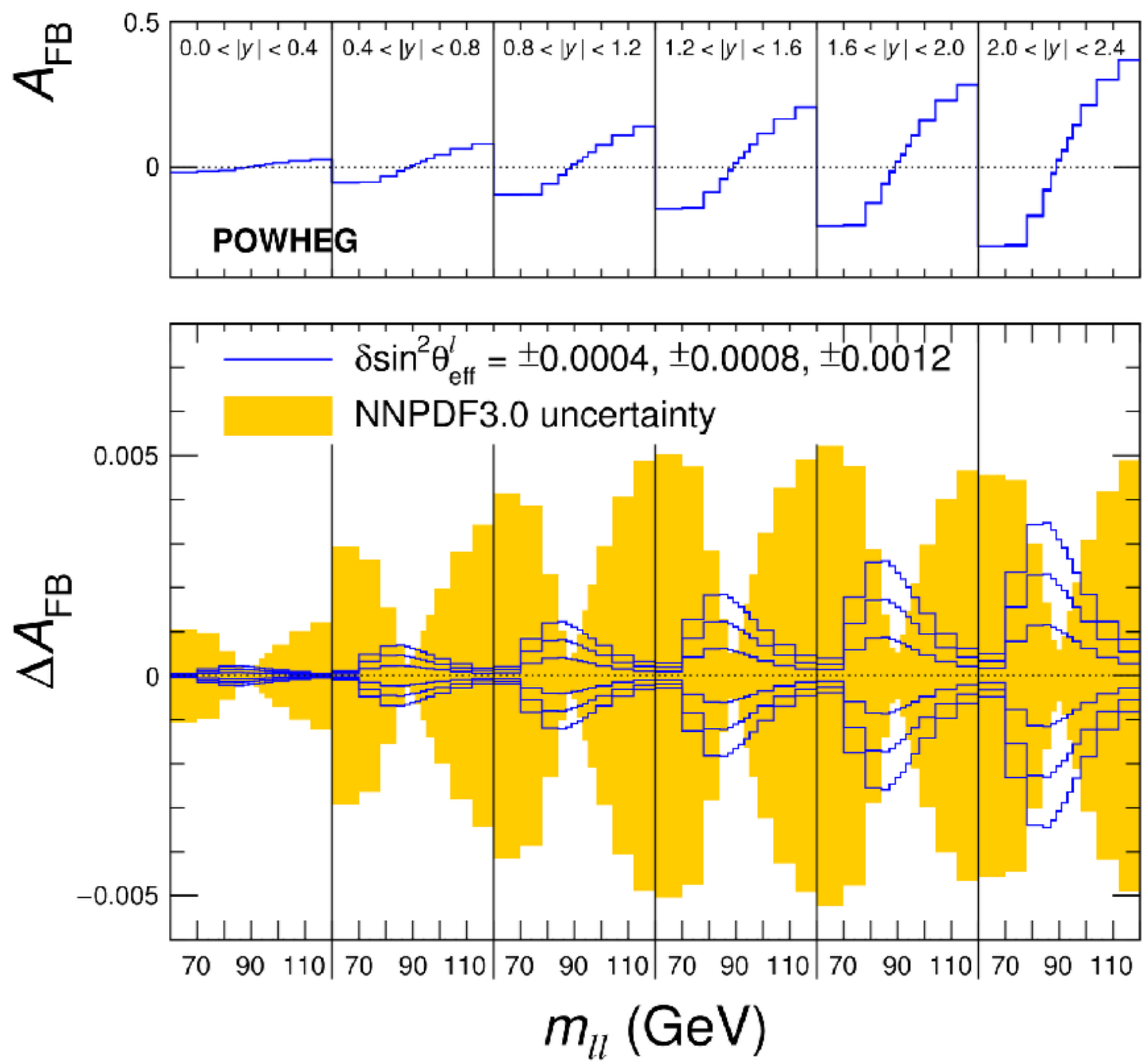
A_{FB} in DY events and $\sin^2\theta_W$

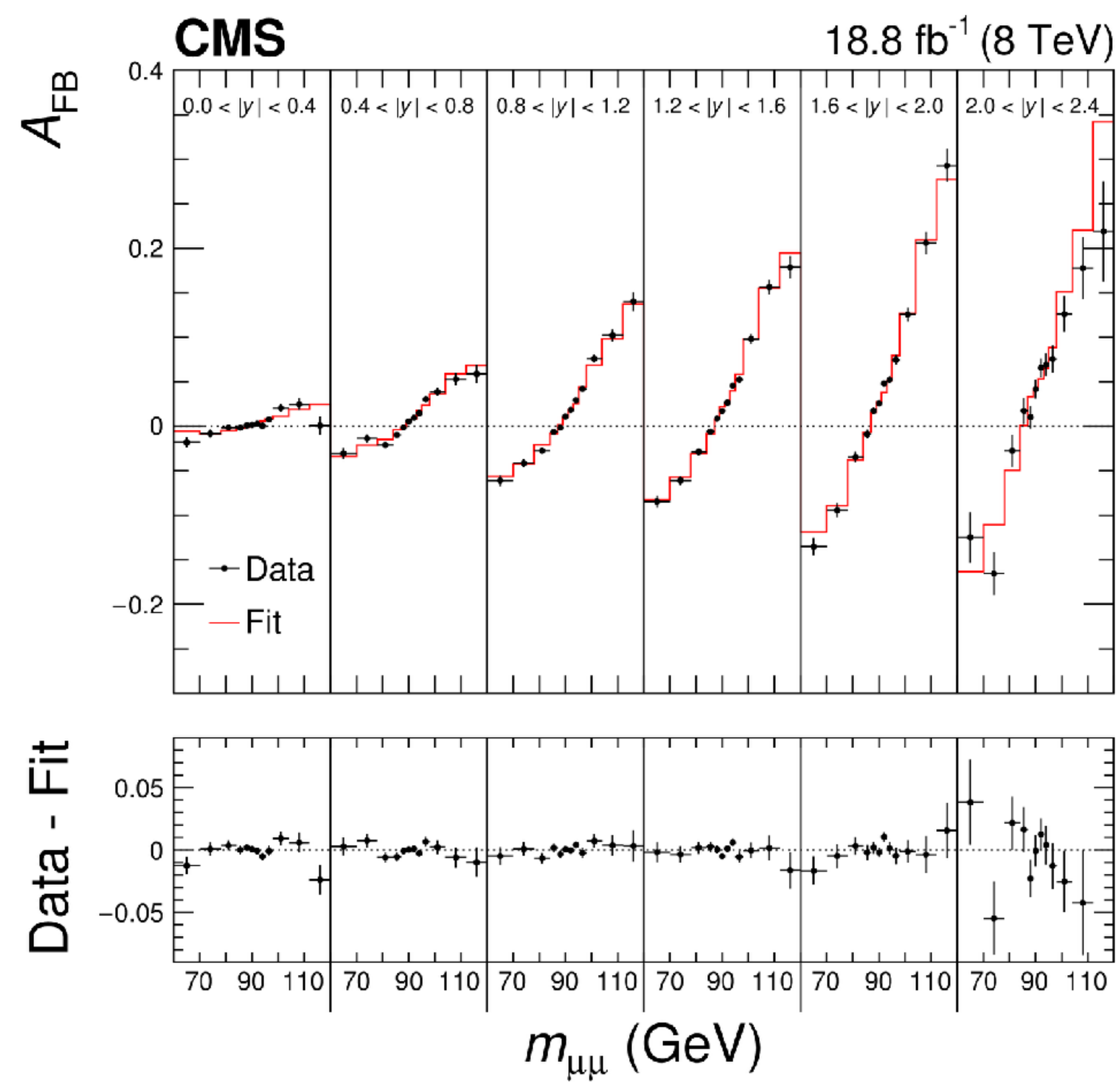
SMP-16-007
EPJC 78 (2018) 701

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}

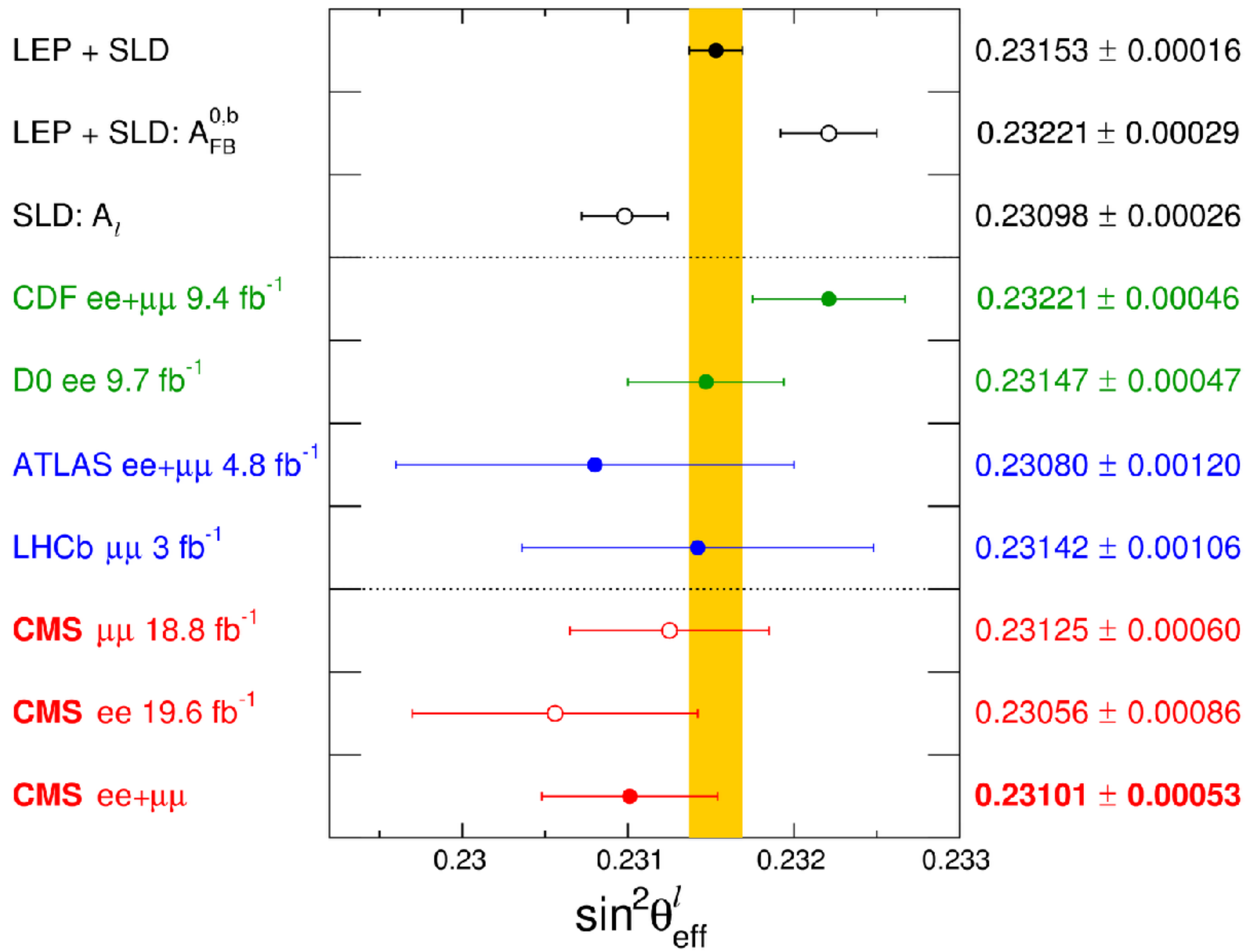




A_{FB} in DY events and $\sin^2\theta_W$

SMP-16-007
EPJC 78 (2018) 701

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF})$$

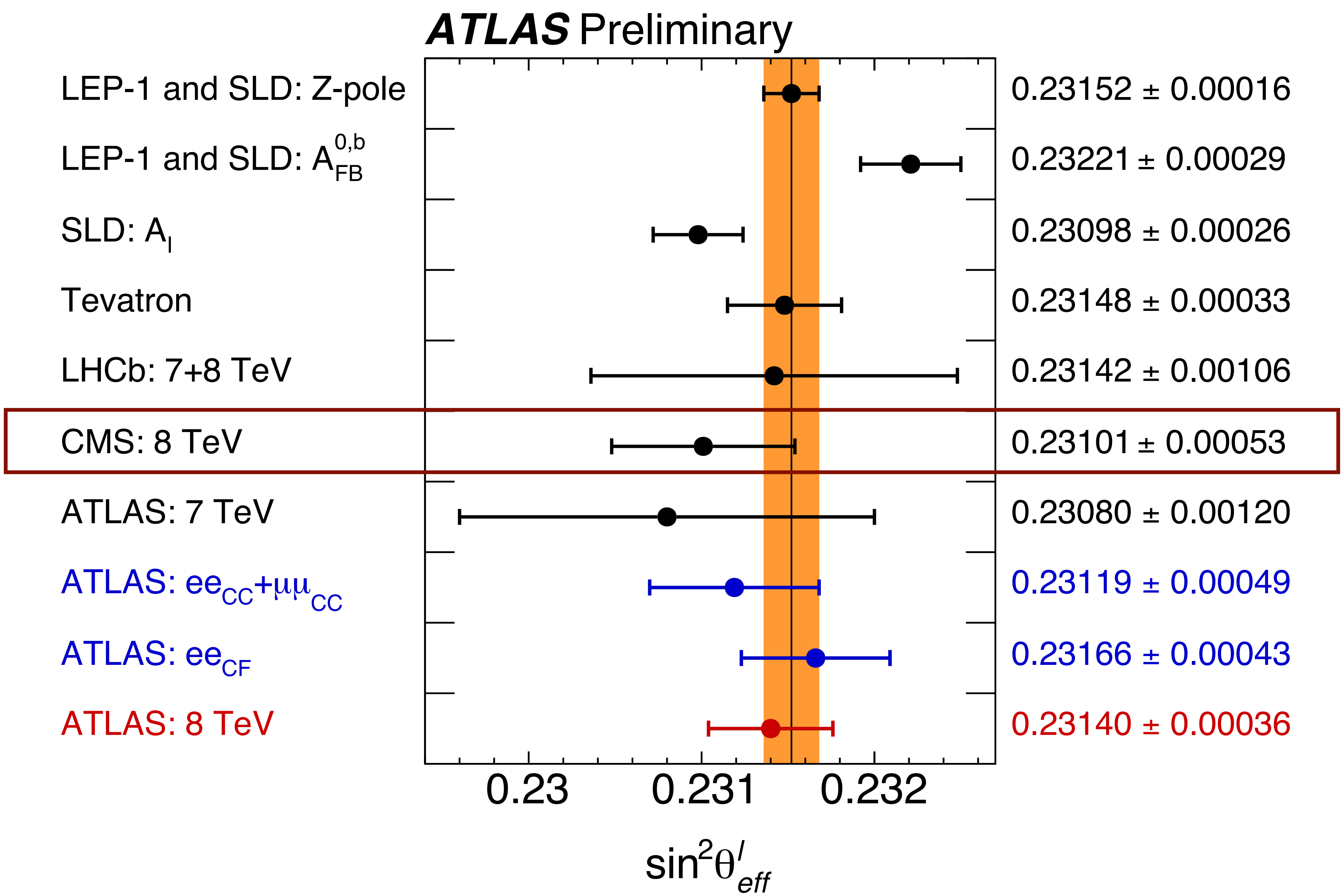


In future can help disentangle LEP/SLD tension!

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

SMP-16-007
EPJC 78 (2018) 701

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



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

Differential Z production cross-section

Results given for fiducial cross-section (2016 data 35.9 fb^{-1}):

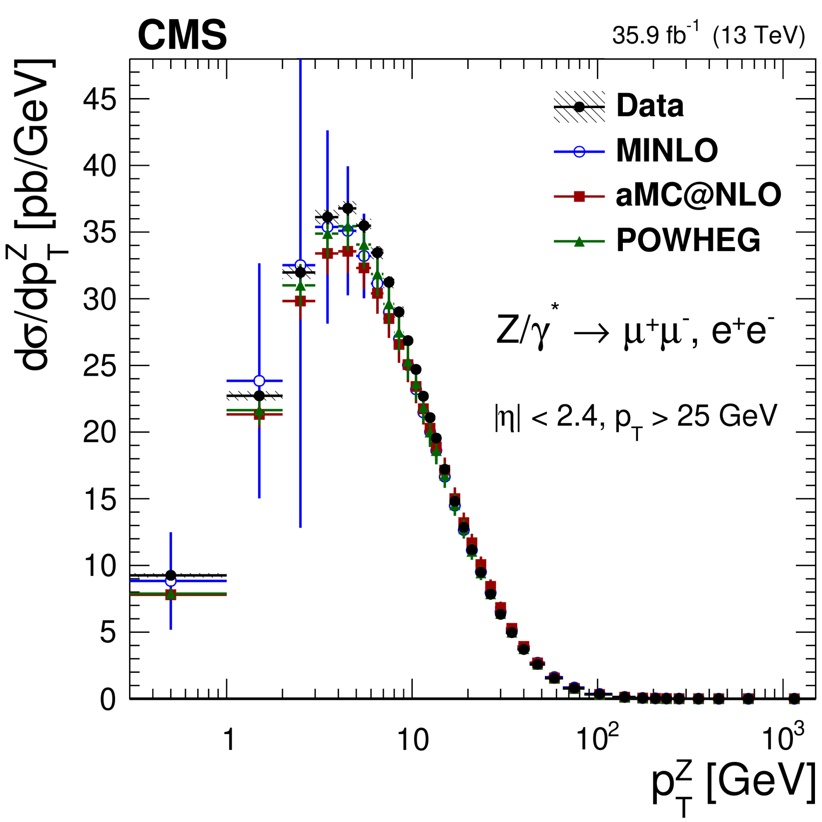
SMP-17-010
JHEP 12 (2019) 061

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

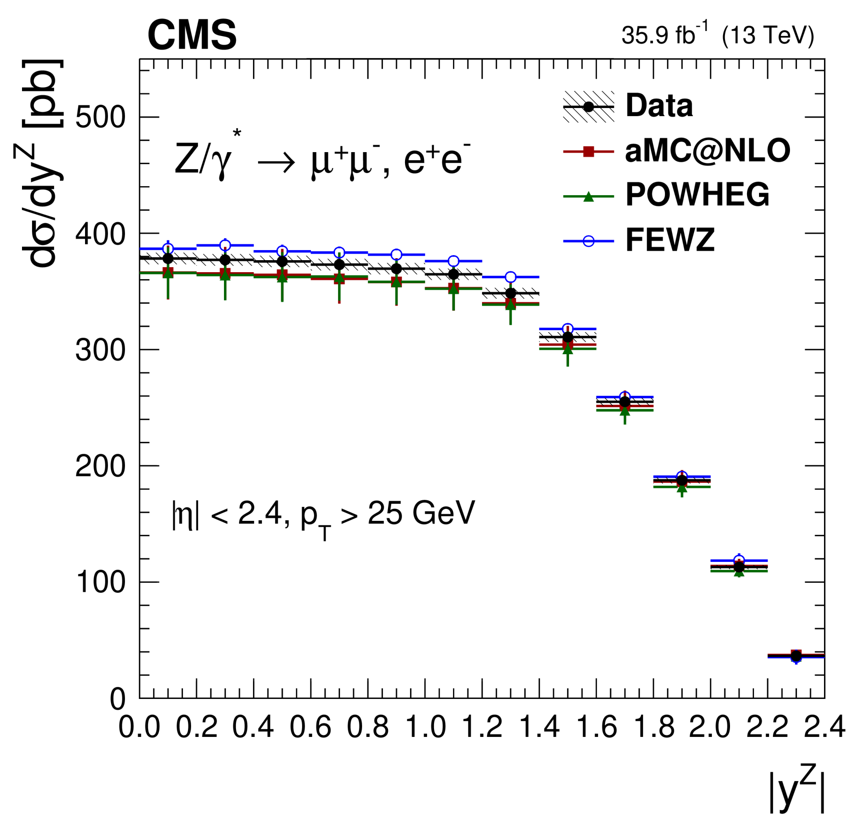
Cross section	$\sigma\,\mathcal{B}$ [pb]
$\sigma_{Z\to\mu\mu}$	$694 \pm 6\,(\text{syst}) \pm 17\,(\text{lumi})$
$\sigma_{Z\to ee}$	$712 \pm 10\,(\text{syst}) \pm 18\,(\text{lumi})$
$\sigma_{Z\to\ell\ell}$	$699 \pm 5\,(\text{syst}) \pm 17\,(\text{lumi})$

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

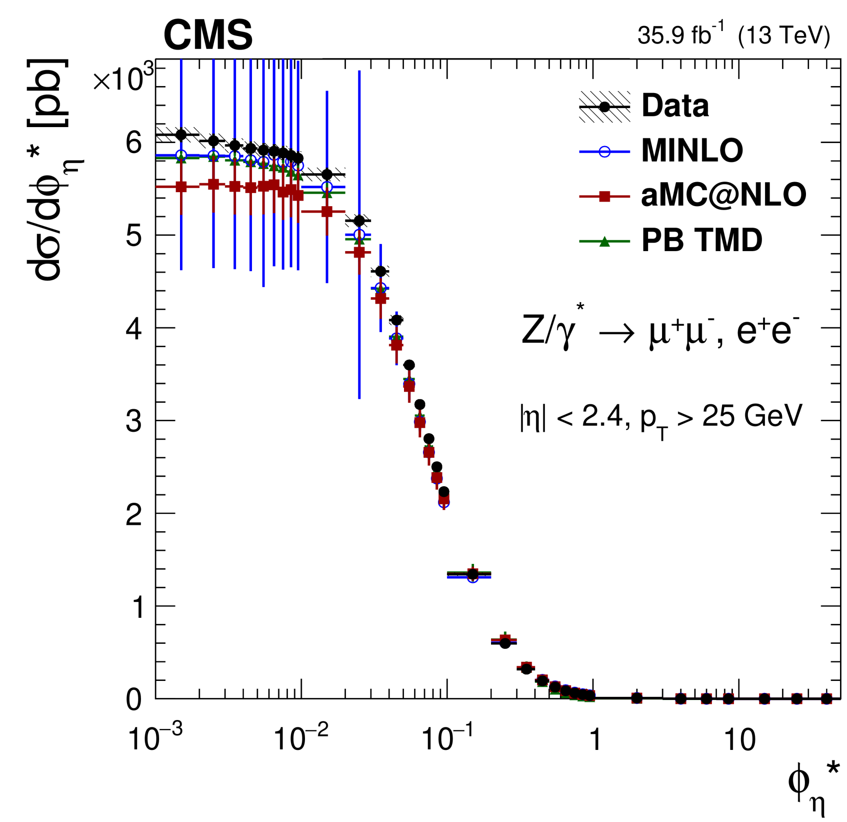
$p_T^{\ell\ell}$



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



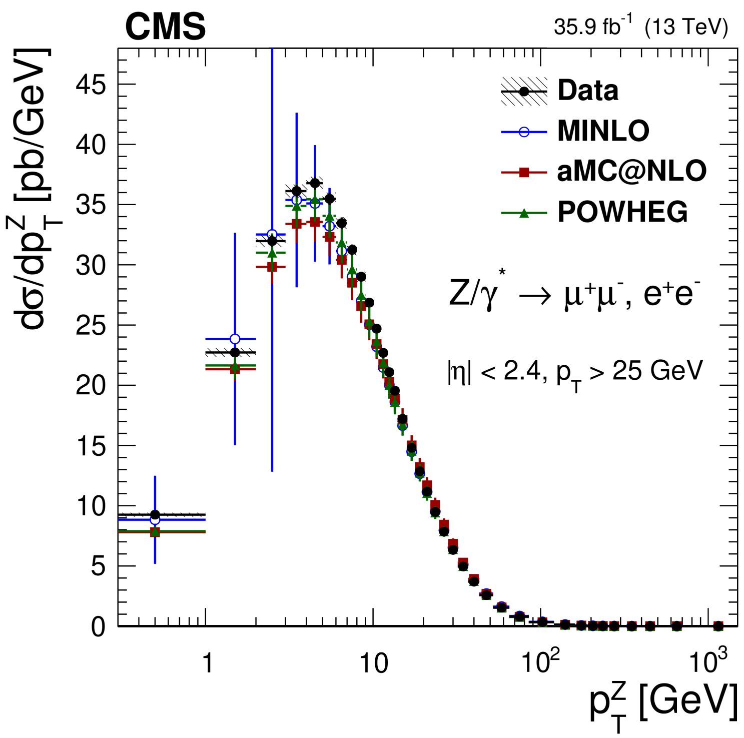
$\phi^*_{\ell\ell} \sim p_T^{\ell\ell}/m_{\ell\ell}$



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

Differential Z production cross-section

SMP-17-010

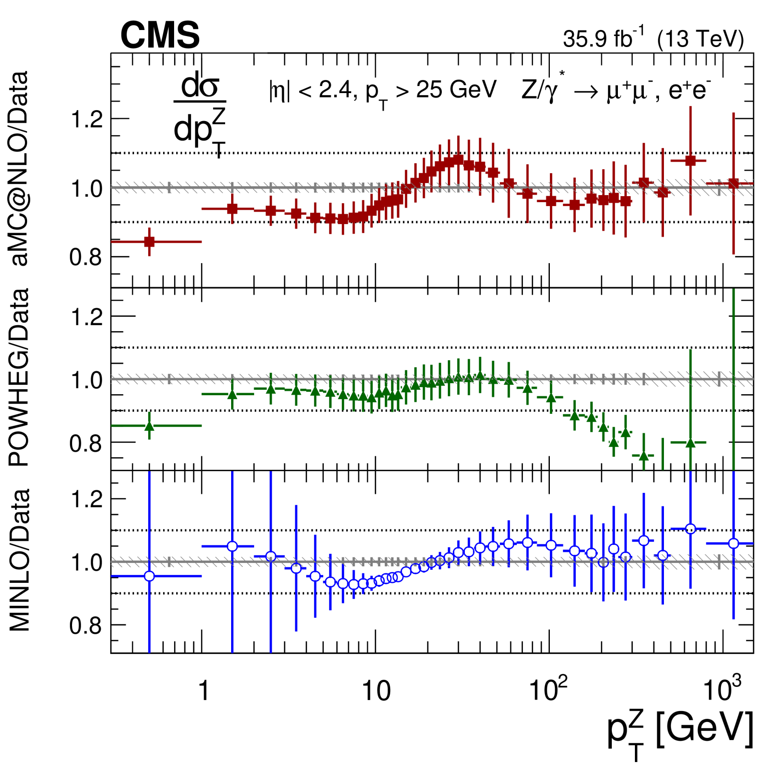


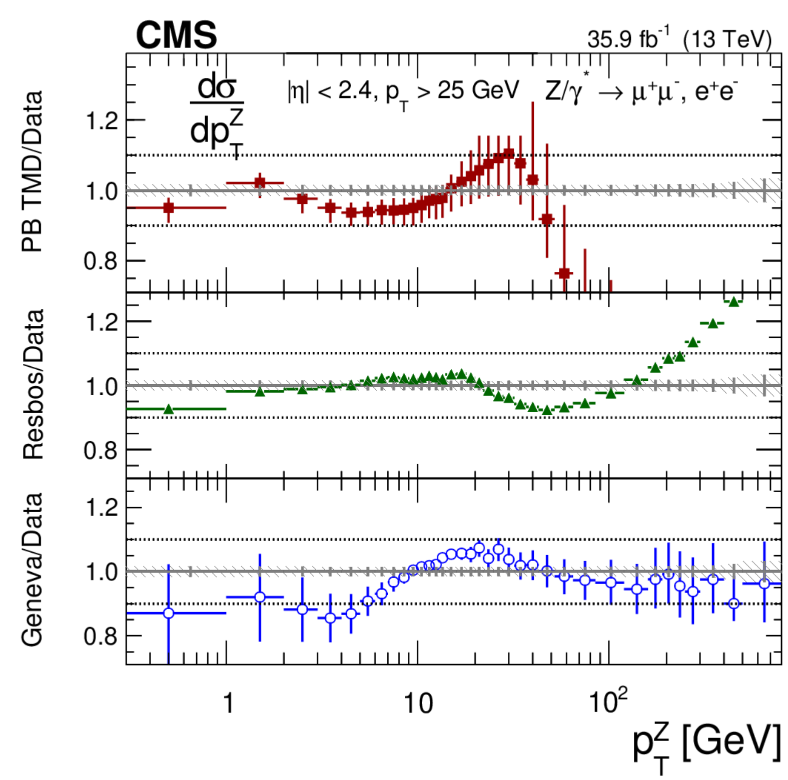
$p_T^{\ell\ell}$ distribution compared with predictions from:

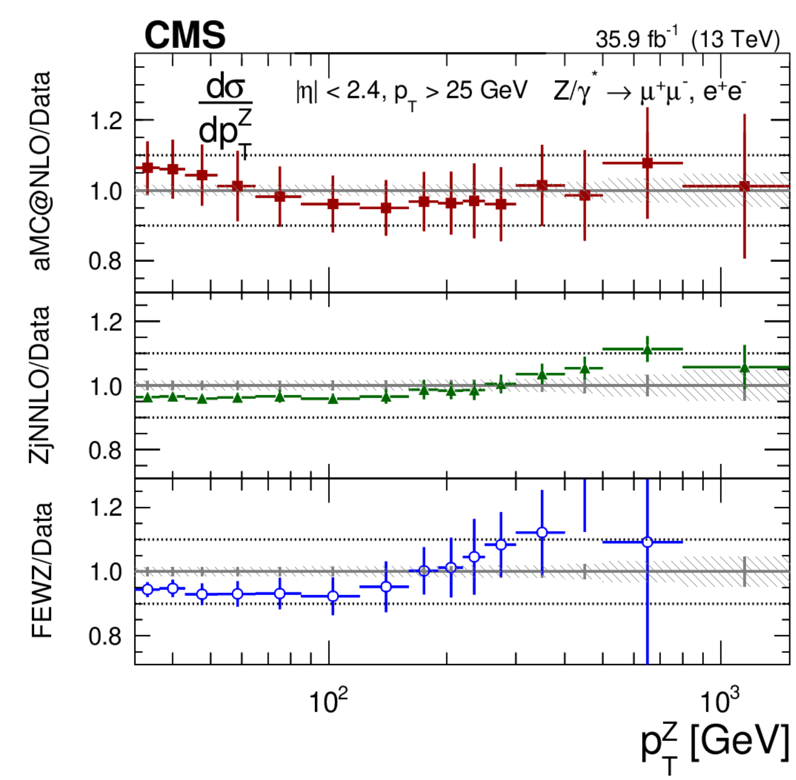
- PS MC: **aMC@NLO (Z+0,1,2 jet NLO)**, **POWHEG**, **MiNLO (Z+0,1 jet NLO)**
- Resummed calculations: **PB TMD (NLL+ NLO), Resbos (NNLL+NLO), Geneva (NNLL+NNLO)**
- NNLO fixed order (for $p_T^{\ell\ell} > 32$ GeV): **ZjNNLO (Z+1 jet)**, **FEWZ**

Overall good agreement with data within the uncertainties:

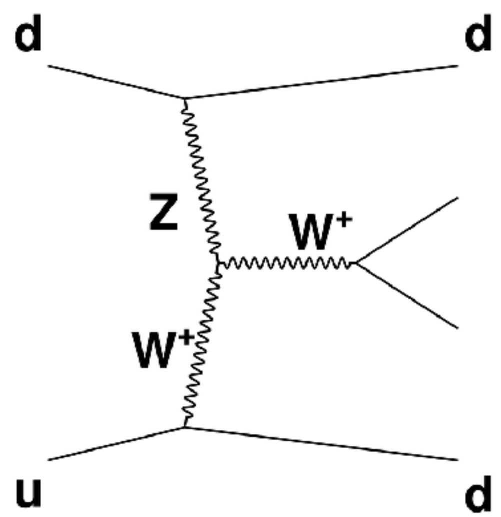
- discrepancies at high p_T for POWHEG, RESBOS, PB TMD (missing higher order Z+jets)
- Z+1 jet NNLO fixed order significantly reduces the scale uncertainties at high $p_T^{\ell\ell}$
- 10%-20% EWK corrections for $p_T^{\ell\ell} > 500$ GeV not included





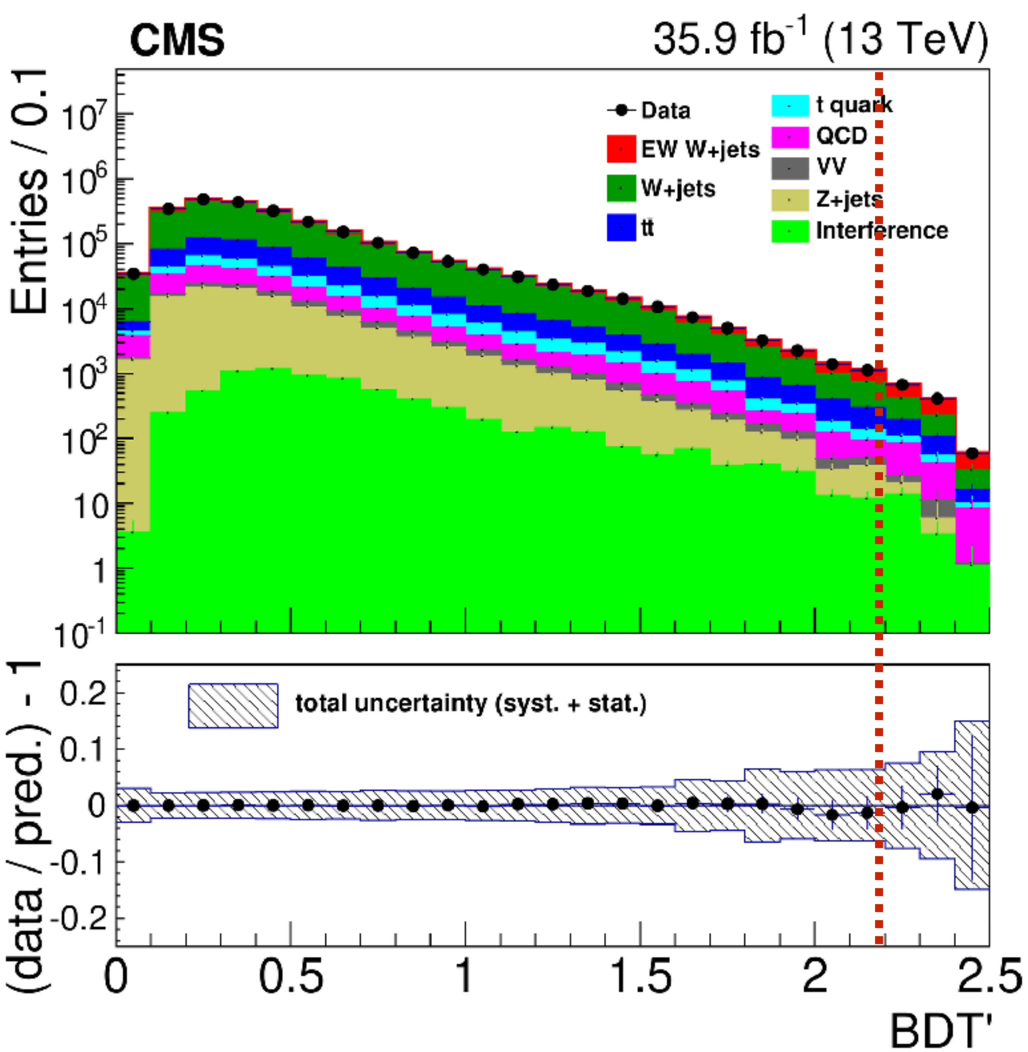


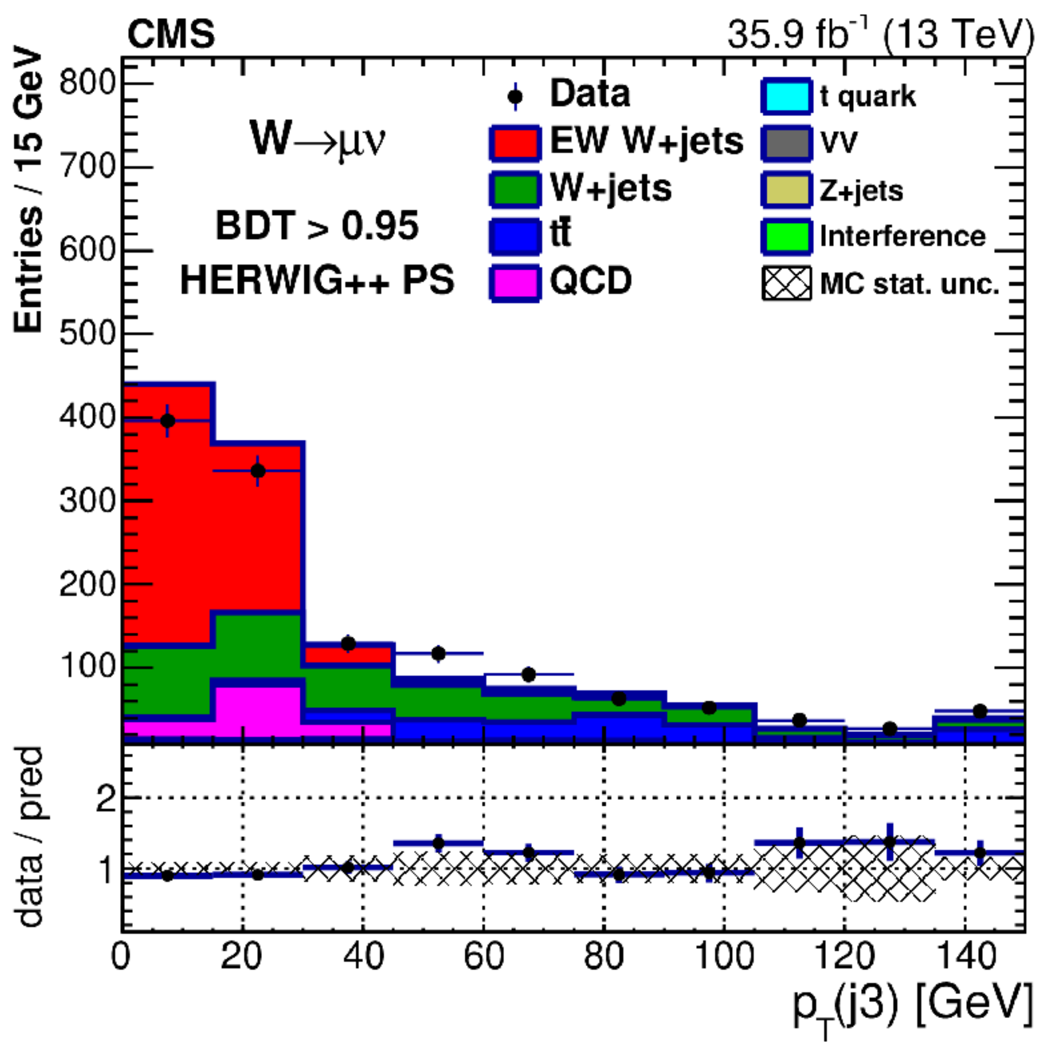
EW production of Wjj



- select μ(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
- fsig = 2 % → 43% for BDT' > 2.185 (BDT>0.95)

σ(EW ℓvjj) = 6.23 ± 0.12(stat) ± 0.61(syst) pb, signal strength μ = 0.91 ± 0.10



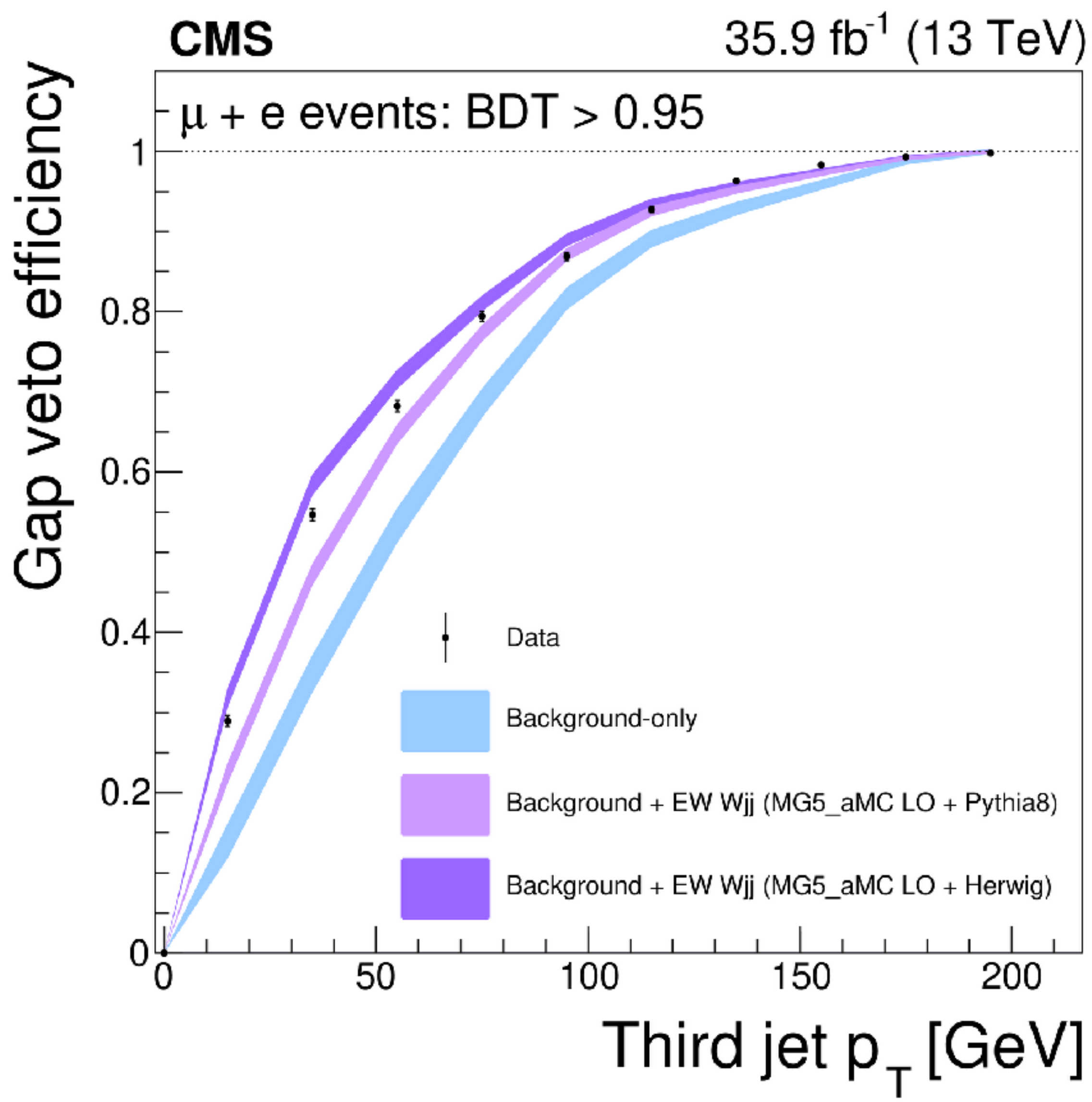


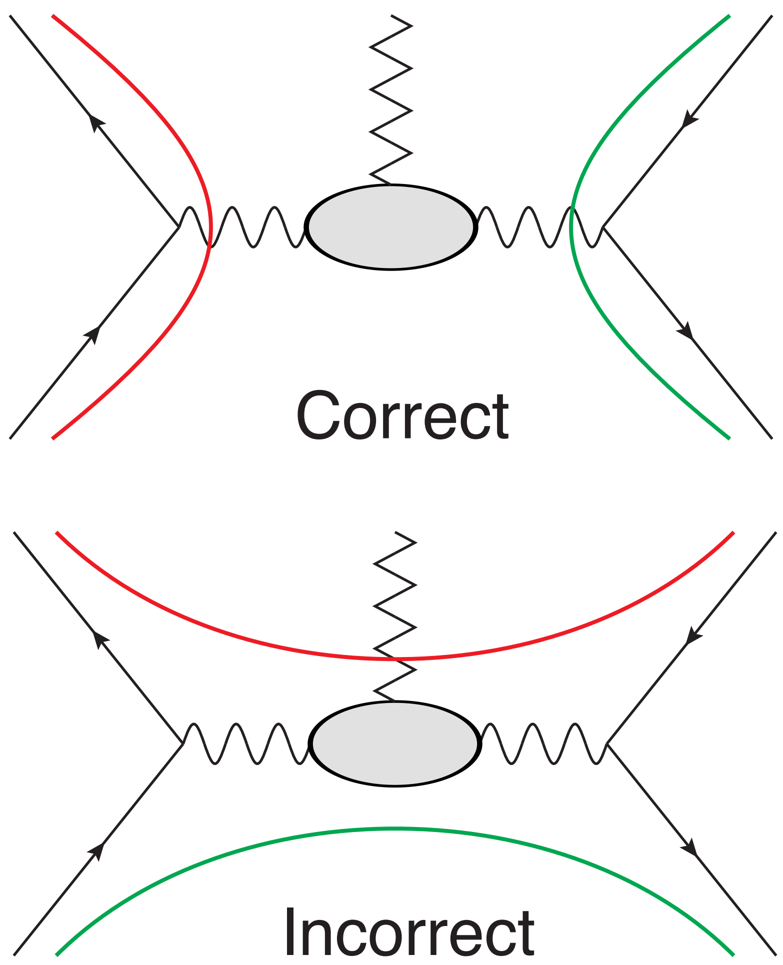
EW production of Wjj

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)

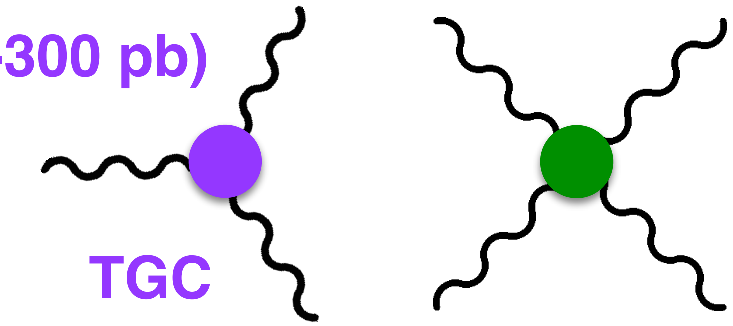




Multiboson production and VBS

Cross-sections are several order of magnitude smaller

diboson production (5-300 pb)



TGC

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

QGC

Measurements provide a powerful 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):

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

dim 6   dim 8

Multiboson production at 13 TeV

Many very recent results!

	Production mode	Final state	Dataset (13 TeV)	Documents
Diboson	WZ	lllν	35.9/fb	JHEP 04 (2019) 122
	ZZ	llll llll + jets	101.2/fb 35.9/fb	CMS PAS SMP-19-001 PLB 789 (2019) 19
	WW/WZ	lνjj	35.9/fb	JHEP 12 (2019) 062
Triboson	WWW	lll, SS ll+jj	35.9/fb	PRD 100 (2019) 012004
VBS	WW	SS ll	35.9/fb	PRL 120 (2018) 081801
	WZ	lllν	35.9/fb	PLB 795 (2019)
	ZZ	llll	35.9/fb	PLB 774 (2017) 682
	WW/WZ/ZZ	lνjj, lljj	35.9/fb	PLB 798 (2019)134985
	Zγ	llγ	35.9/fb	CMS PAS SMP-18-007

Diboson production: $ZZ \to 4\ell$

SMP-19-001

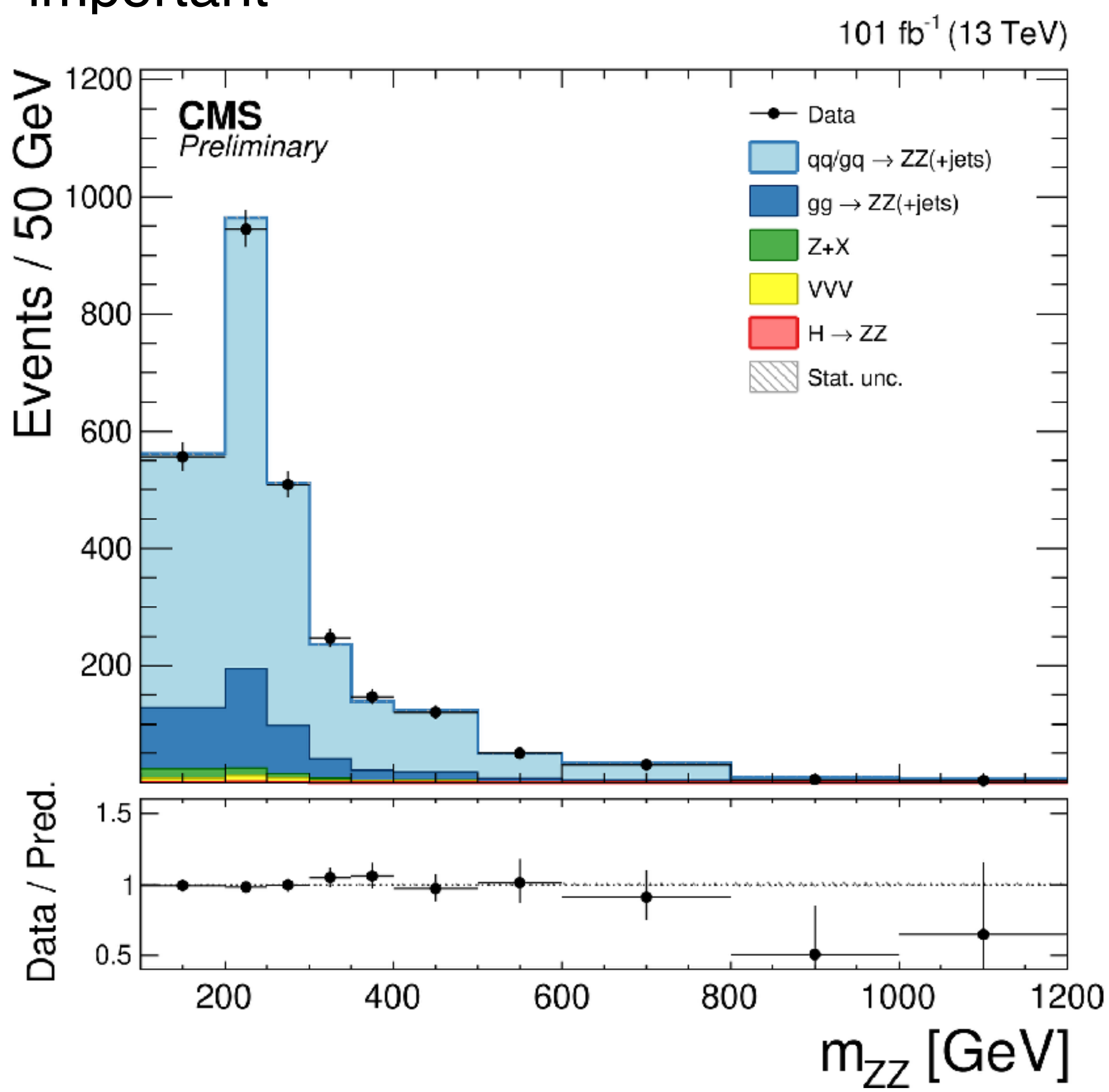
Among first measurements with full Run 2

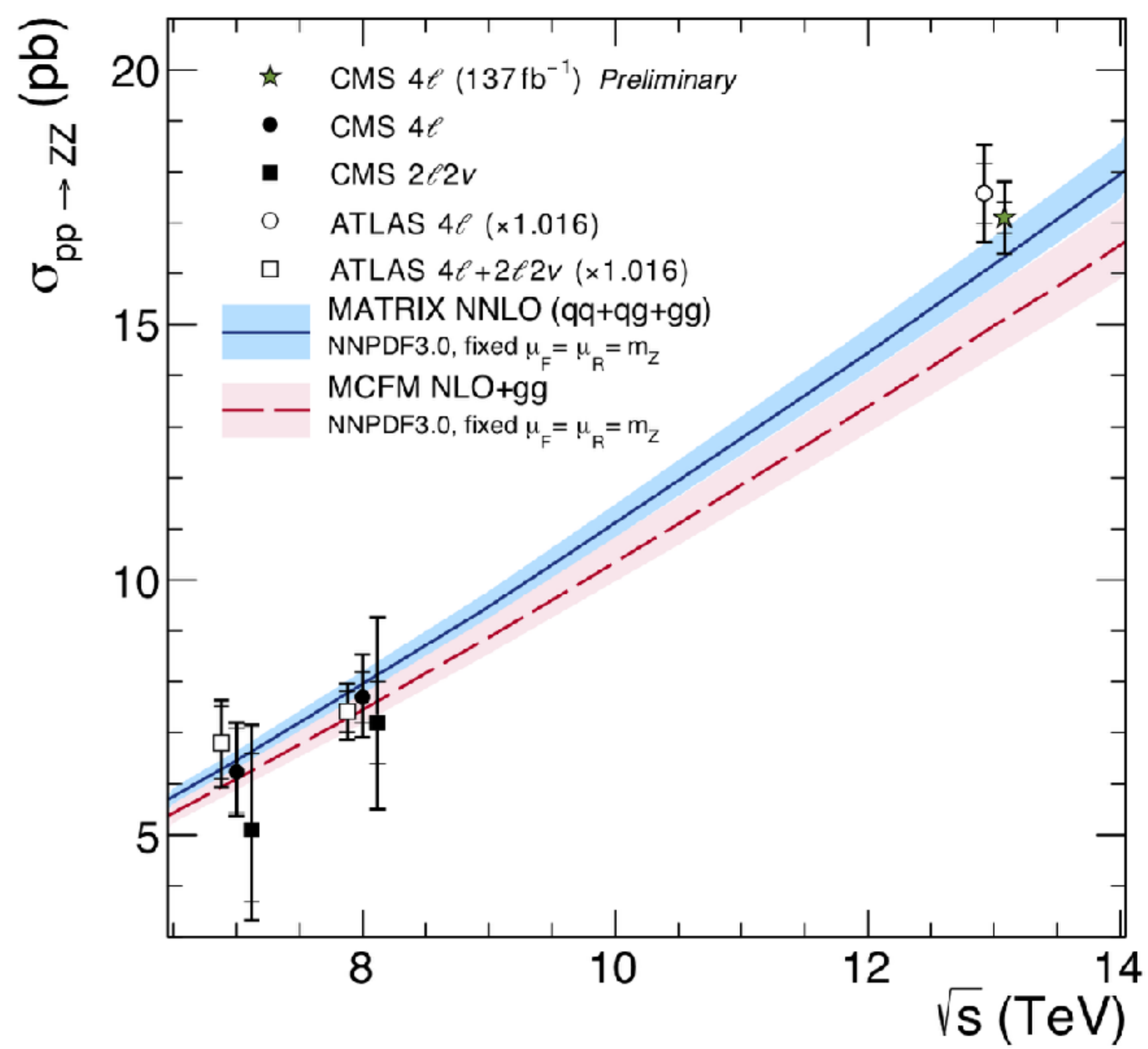
- this measurement 2017+2018: 101.2 fb-1
- combined with 2016: 35.9 fb-1

Systematic uncertainties driven by lepton efficiencies and luminosity

- correlations of the uncertainty across time are important

Year	Fiducial cross section, fb
2016 [5]	$40.9 \pm 1.3\,(\text{stat}) \pm 1.4\,(\text{syst}) \pm 1.0\,(\text{lumi})$
2017	$39.1 \pm 1.2\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 1.0\,(\text{lumi})$
2018	$39.2 \pm 1.0\,(\text{stat}) \pm 1.3\,(\text{syst}) \pm 1.0\,(\text{lumi})$
Combined	$39.9 \pm 0.7\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 0.7\,(\text{lumi})$



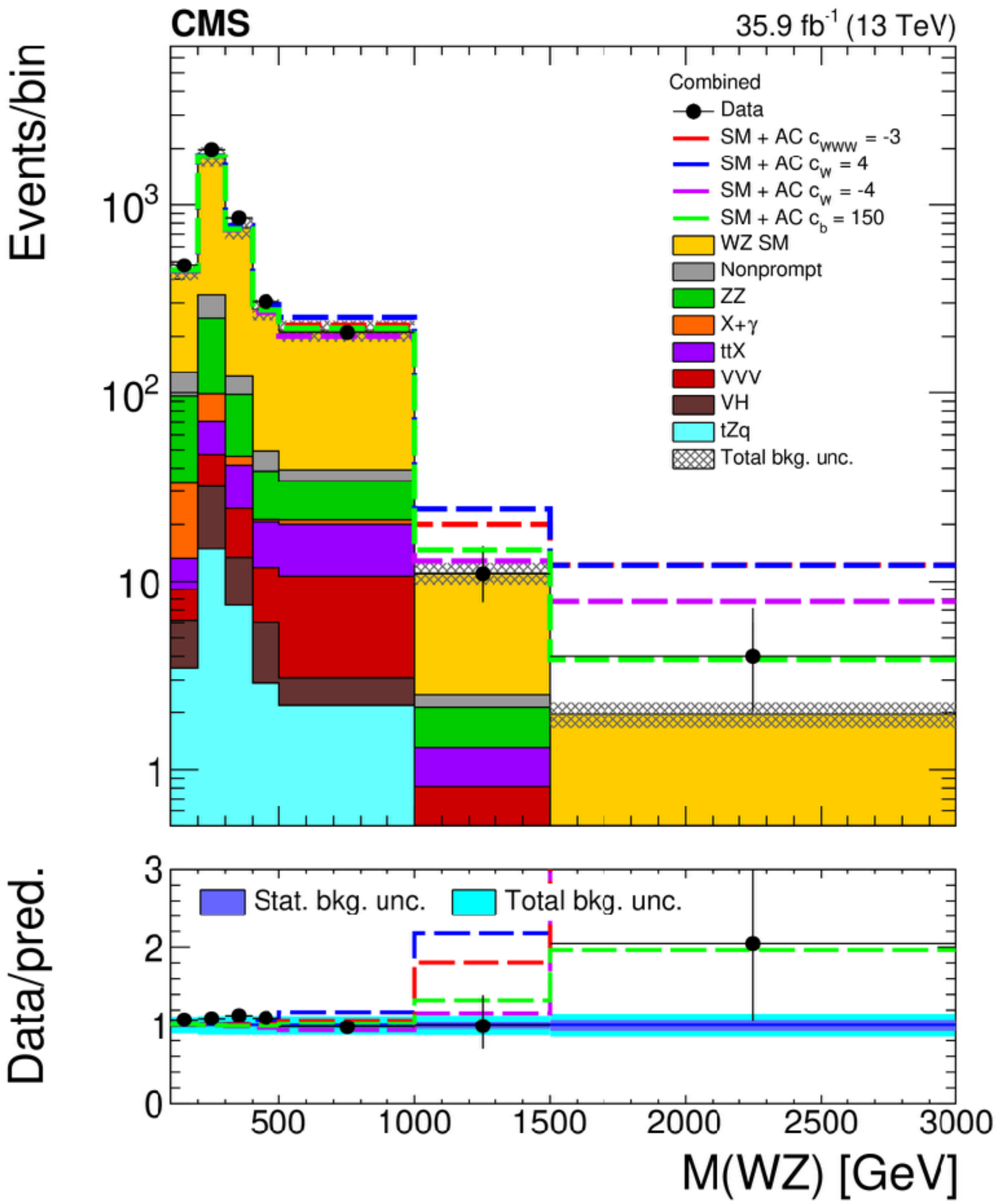


Diboson production: WZ $\rightarrow 3\ell\nu$

SMP-18-002
JHEP 04 (2019) 122

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

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



Parameter	95% CI (expected) $[\mathrm{TeV}^{-2}]$	95% CI (observed) $[\mathrm{TeV}^{-2}]$
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

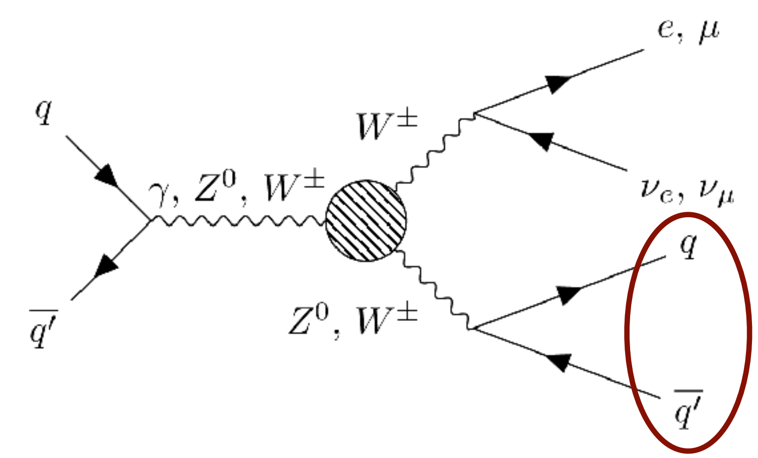
$$\sigma_{tot}(pp \rightarrow WZ) = 48.09^{+2.98}_{-2.78}\ \mathrm{pb}$$

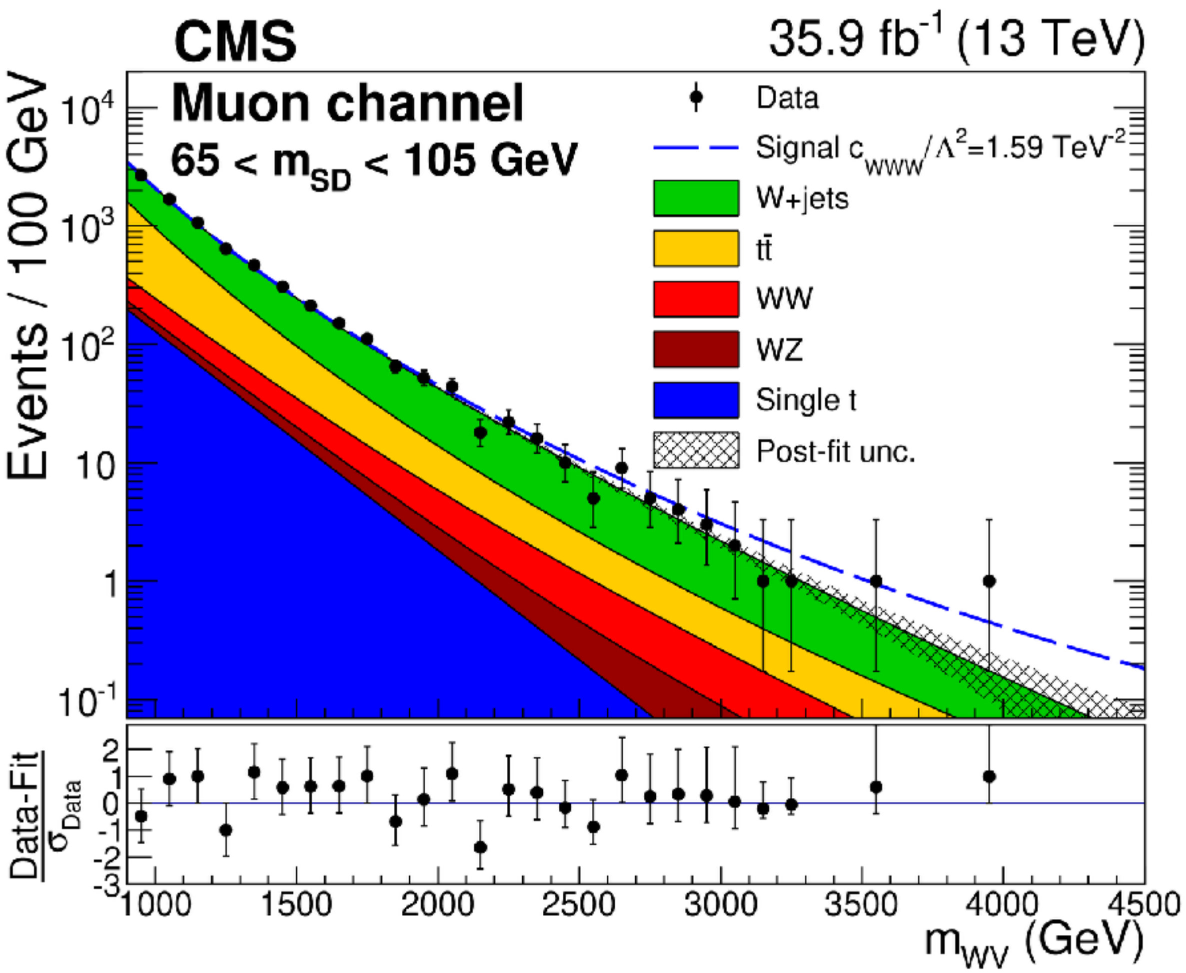
- uncertainty dominated by lepton efficiencies
- result in agreement with MATRIX NNLO predictions

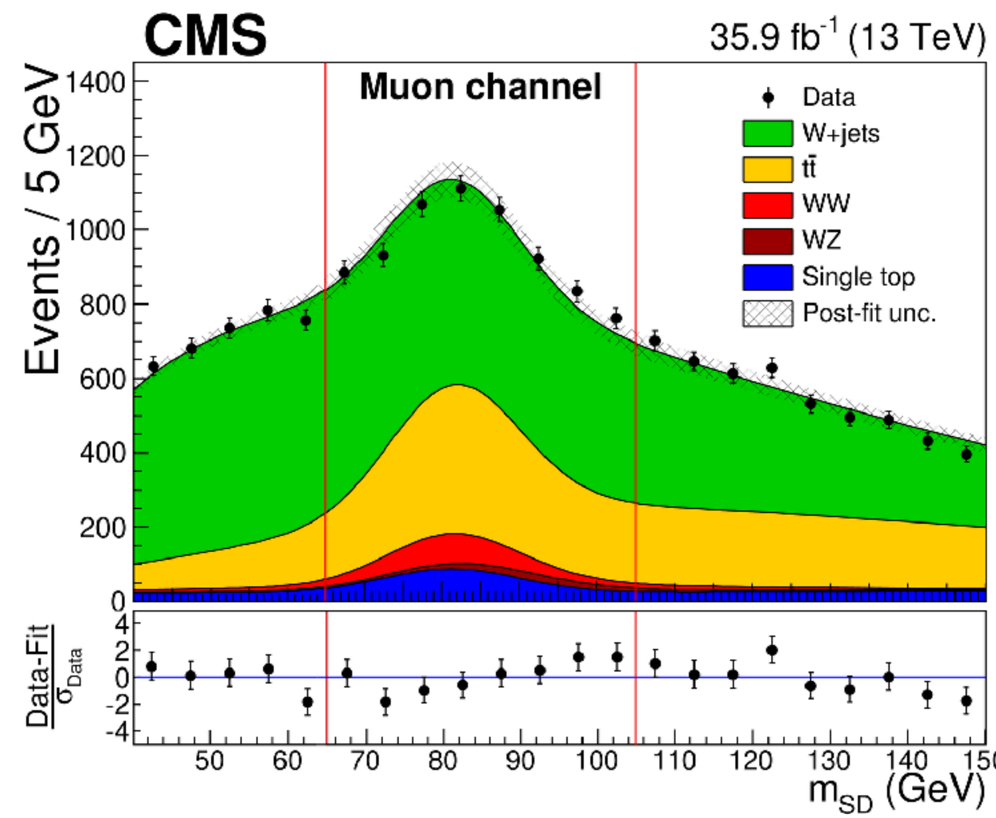
$$\sigma_{NNLO}(pp \rightarrow WZ) = 49.98^{+2.2\%}_{-2.0\%}$$

Diboson production: WW/WZ $\to \ell\nu$ + jet

- "boosted" W/Z → 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}







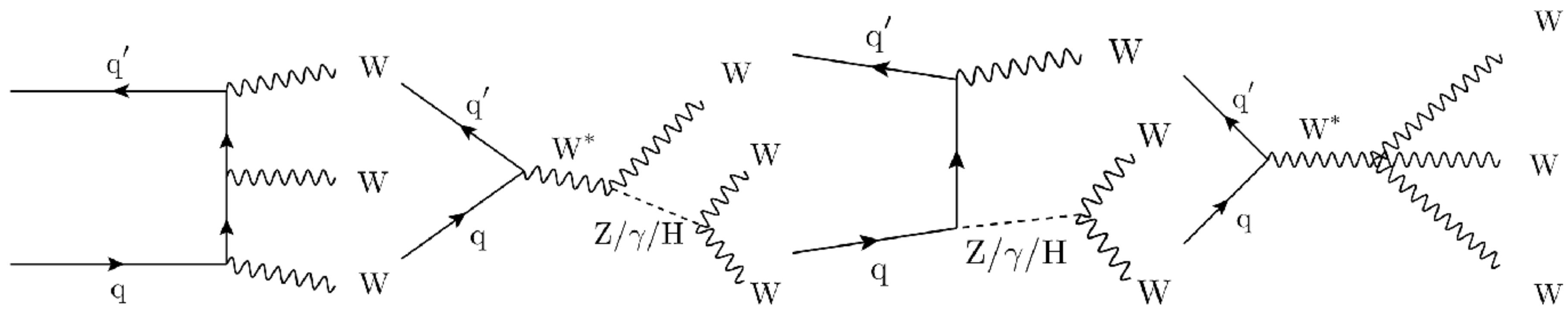
aTGC	Expected limit	Observed limit
c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]
c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]
c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]

- the limit on c_B improves by a factor 10 →

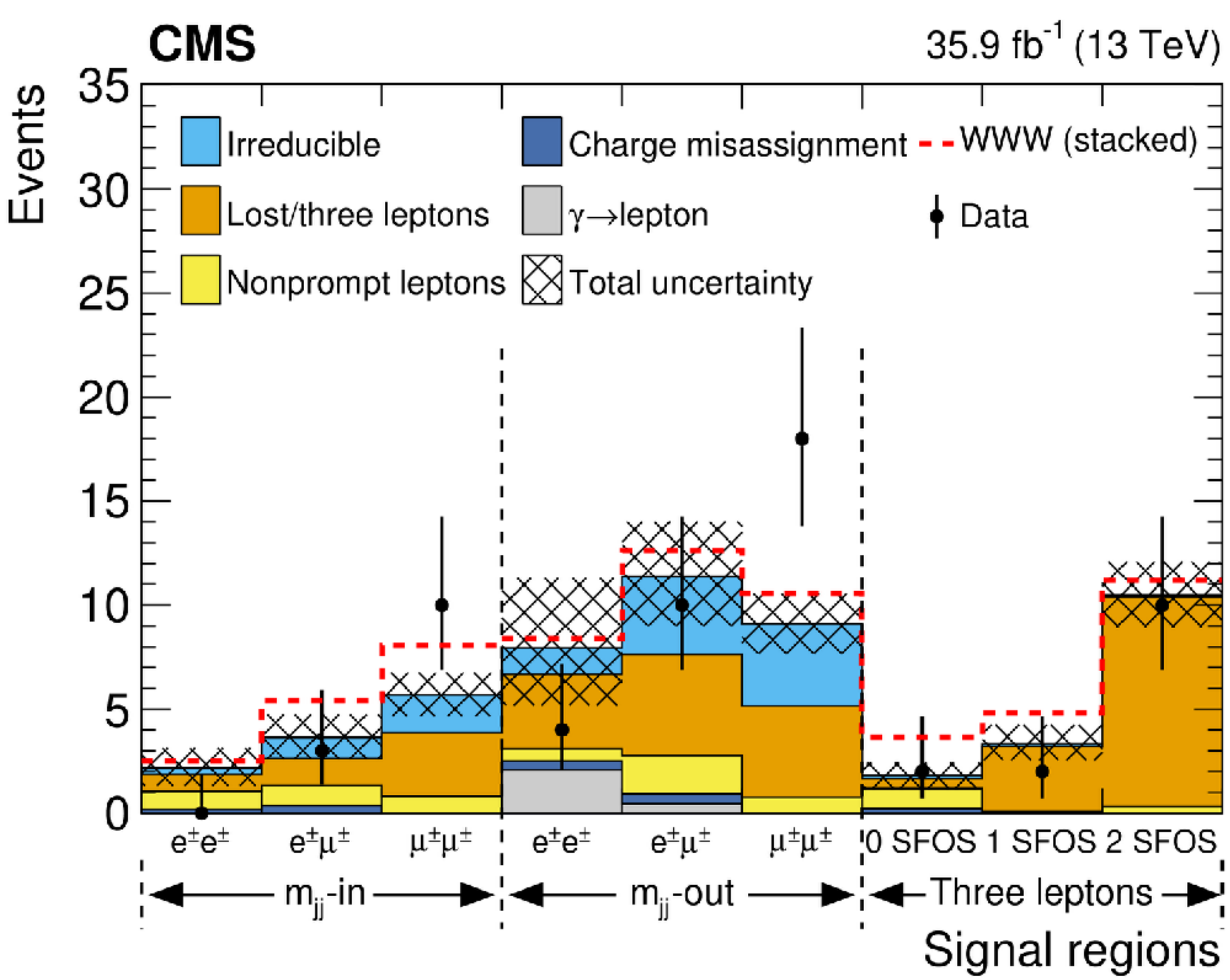
SMP-18-008 JHEP 12 (2019) 062

WWW

SMP-17-013
PRD 100 (2019) 012004



- look for 2SS leptons or 3 leptons



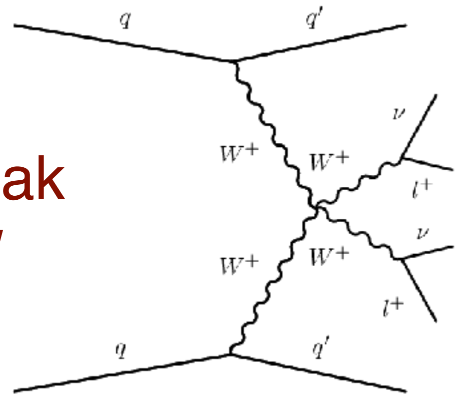
- result:

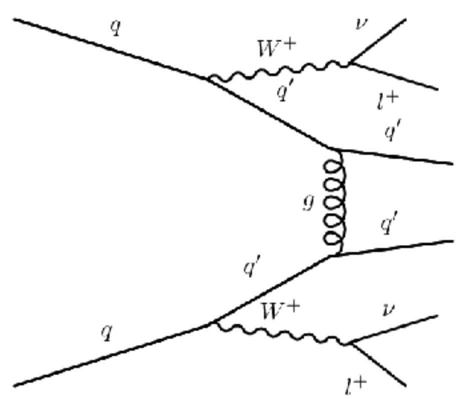
$$\sigma(pp \to W^{\pm}W^{\pm}W^{\mp}) = 0.17^{+0.32}_{-0.17}\,\mathrm{pb}$$

- SM expectation: 0.509 ± 0.013 pb
- signal strenght: $\mu = 0.34^{+0.62}_{-0.34}$
- significance: 0.6(obs) 1.78 (exp)
- upper limit: 0.78 pb (obs) 0.60 pb (exp)

Vector Boson Scattering: same sign W±W±

Electroweak ss WW



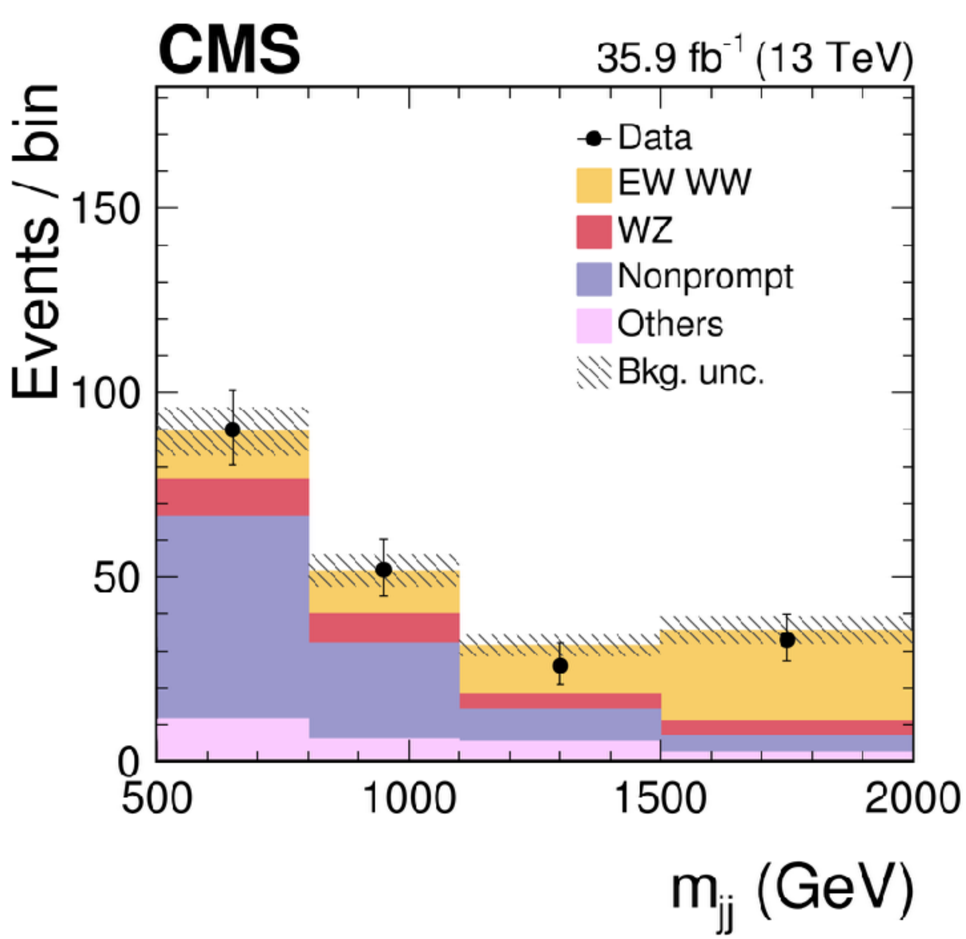


QCD background

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)

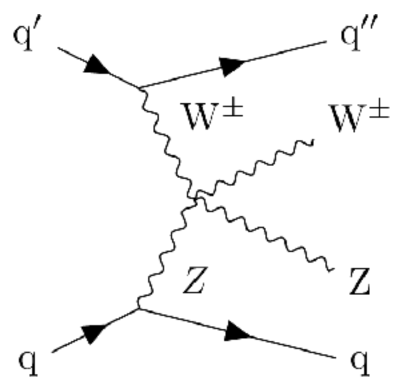


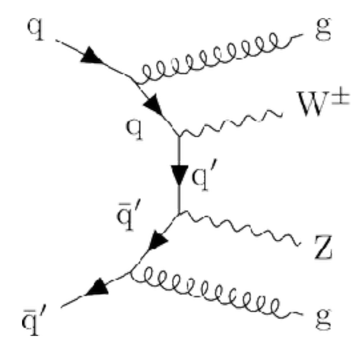
- significance: 5.5σ (obs.) 5.7σ (exp.)
- $\sigma_{fid} = 3.83 \pm 0.66(stat) \pm 0.35(syst)\ fb$
- $\sigma_{pred} = 4.25 \pm 0.27\ (scale + PDF)\ fb$

First observation of VBS!

Vector Boson Scattering: WZ

Electroweak production



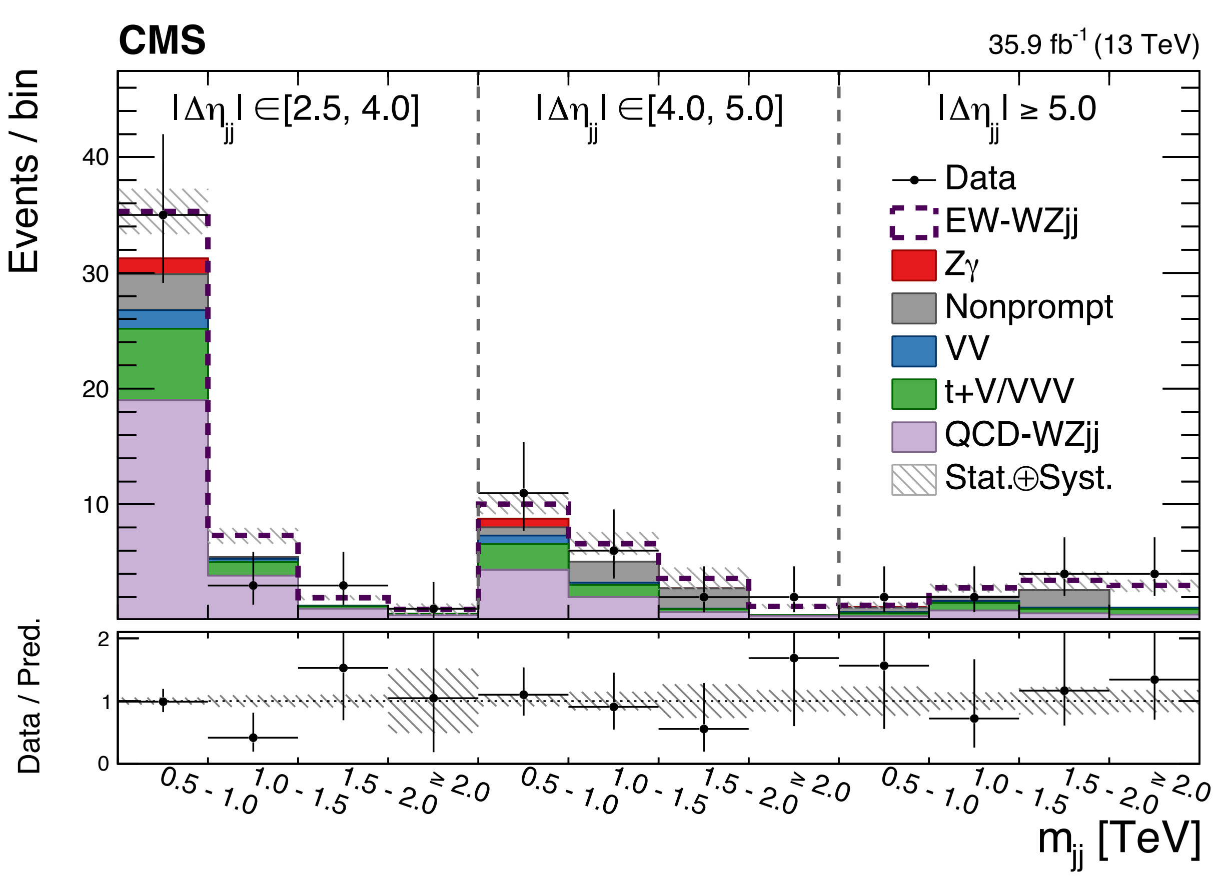


QCD background

SMP-18-001
PLB 795 (2019) 281

Large QCD WZ background

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



- EW+QCD result (tight region):

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

- predicted: $3.27\,^{+0.39}_{-0.32}\,(\text{scale}) \pm 0.15\,(\text{PDF})\,\text{fb}$

  [EW only: $1.25^{+0.11}_{-0.09}\,(\text{scale}) \pm 0.06\,(\text{PDF})\,\text{fb}$]

- 2D fit yields:

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

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

Vector Boson Scattering: WV and ZV

SMP-18-006
PLB 798 (2019)134985

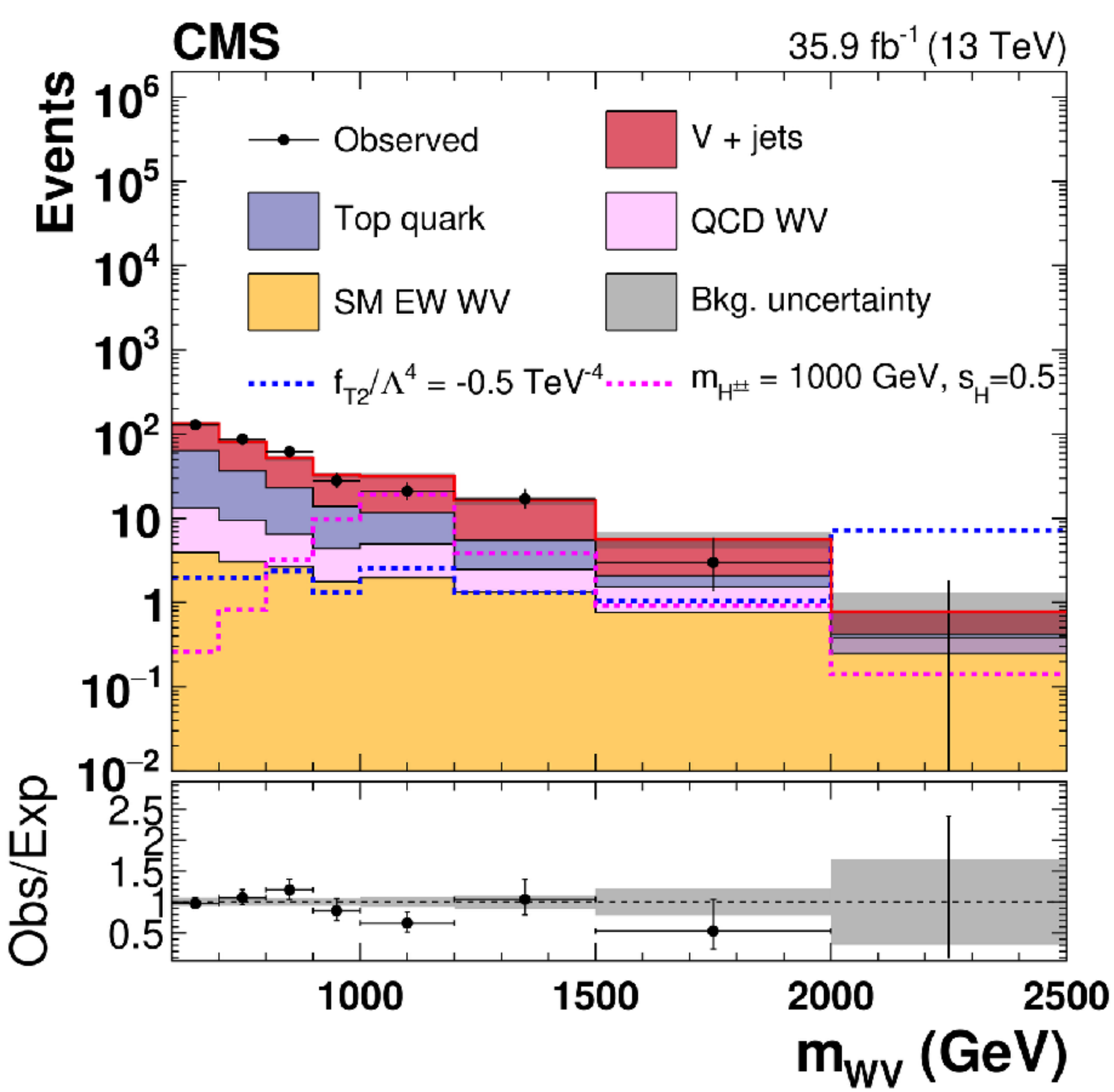
WV → $\ell\nu$ or ZV → $\ell\ell$ + a jet

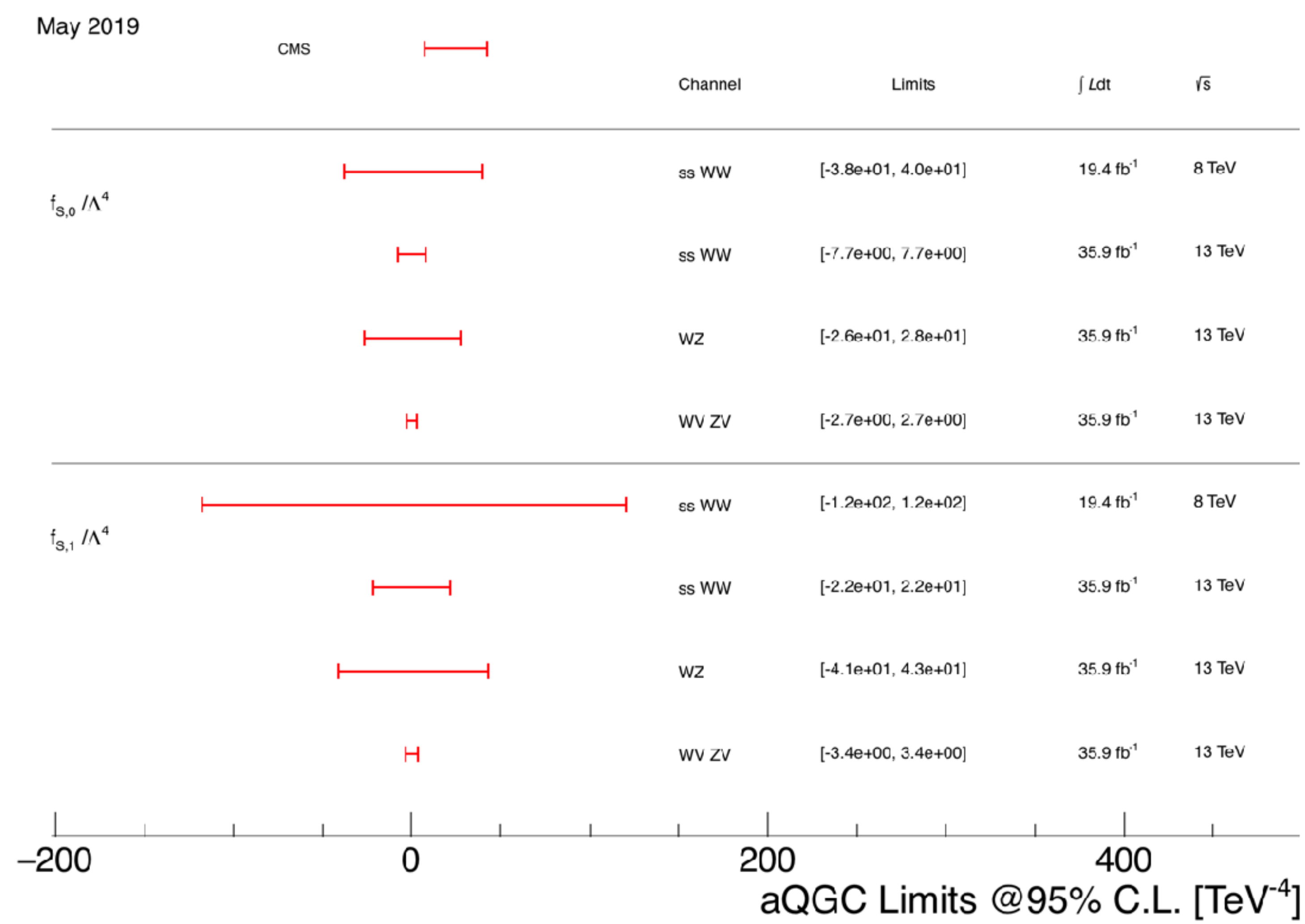
p_T^{jet} > 200 GeV + tight dijet selection and centrality of W/Z

Signal region: 65 GeV < m_V < 105 GeV

Large background from V+jets

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

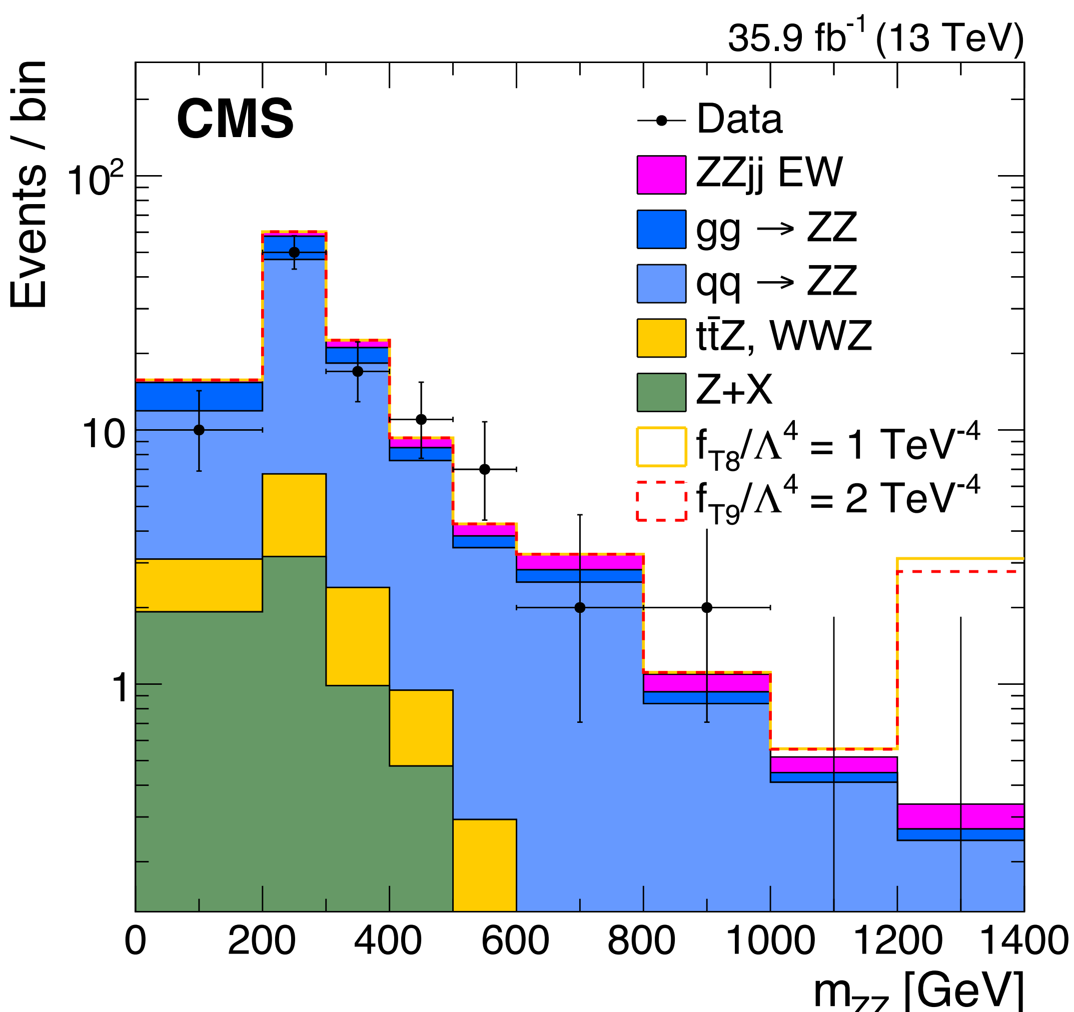




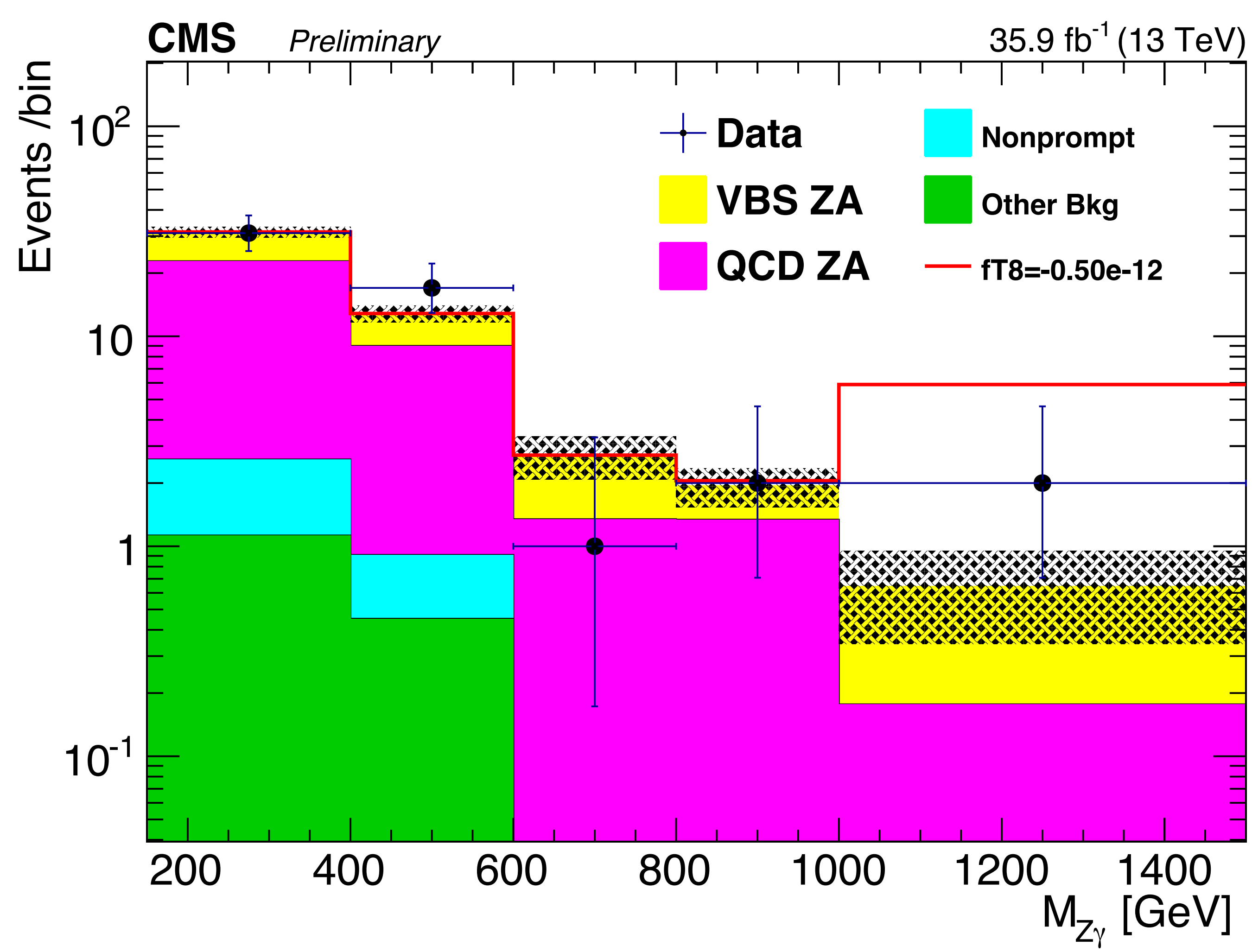
VBS: final states with neutral bosons

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

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



SMP-17-006
PLB 774 (2017) 682

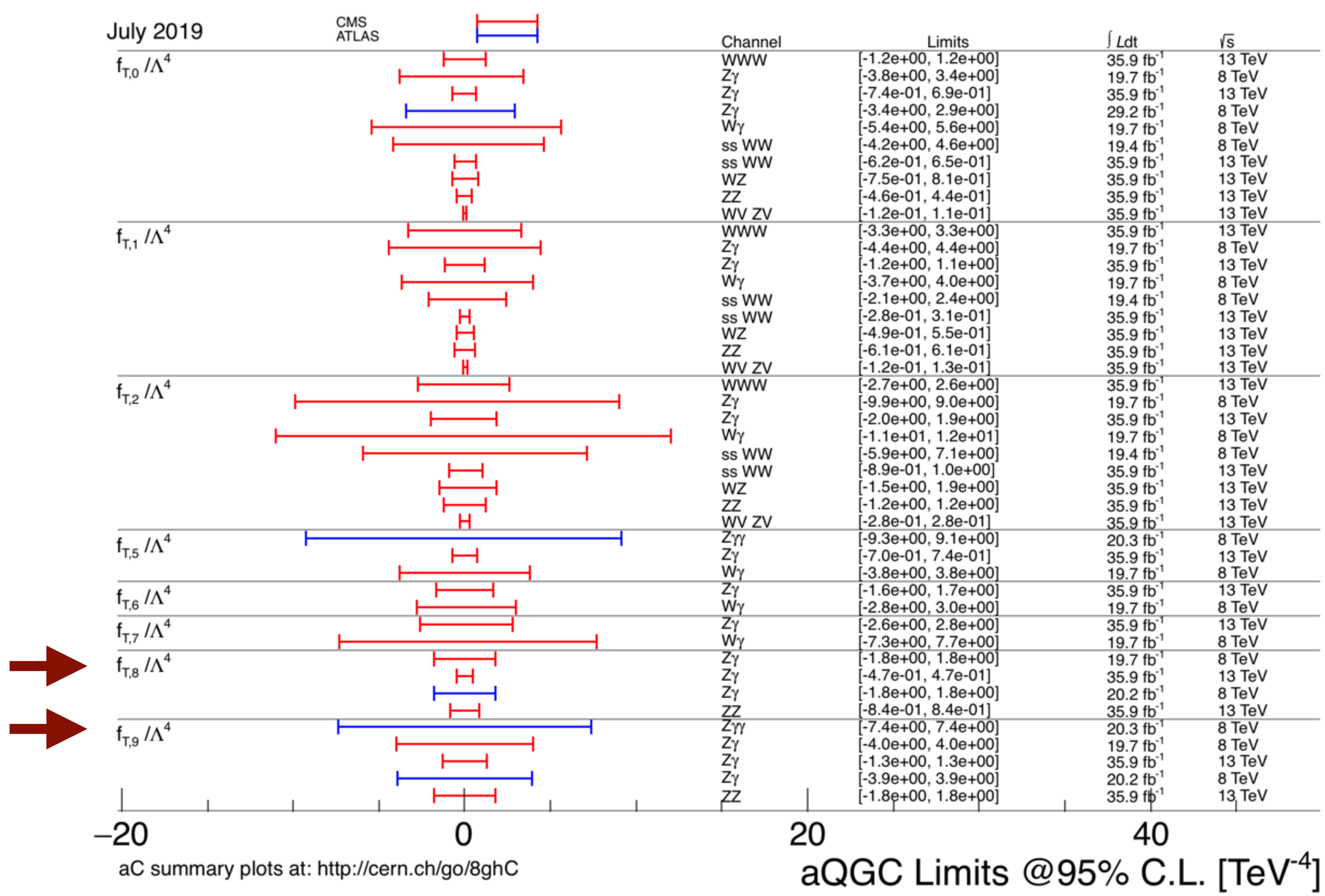


SMP-18-007

VBS: final states with neutral bosons

Some operators only accessible with EW ZZjj and Zγjj

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

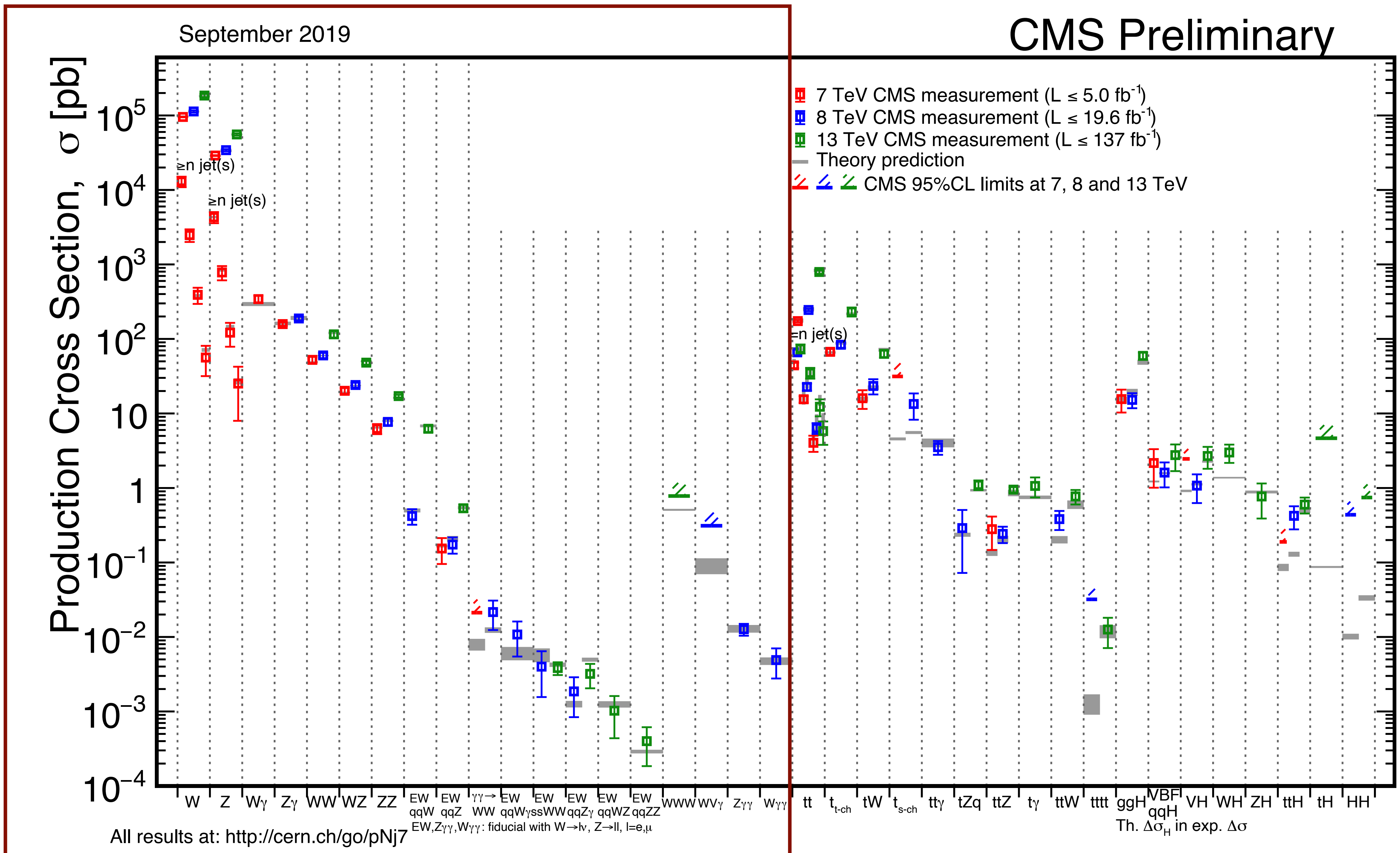


Summary

LHC not only a discovery machine: it can provide precision measurements

So far no disagreement found with theory over 9 order of magnitude

More results to come using full Run2 and (in future) Run3: stay tuned!

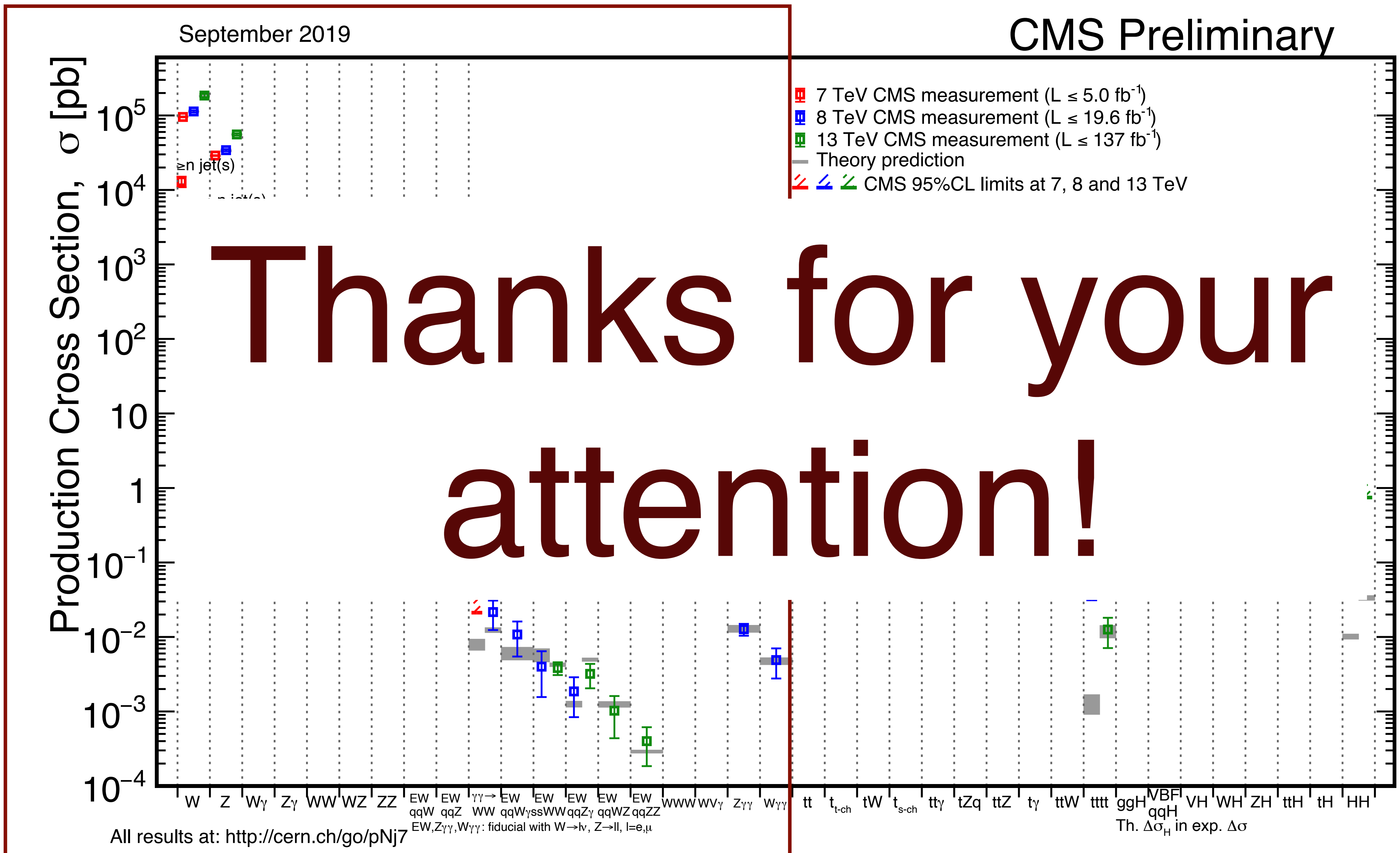


Summary

LHC not only a discovery machine: it can provide precision measurements

So far no disagreement found with theory over 9 order of magnitude

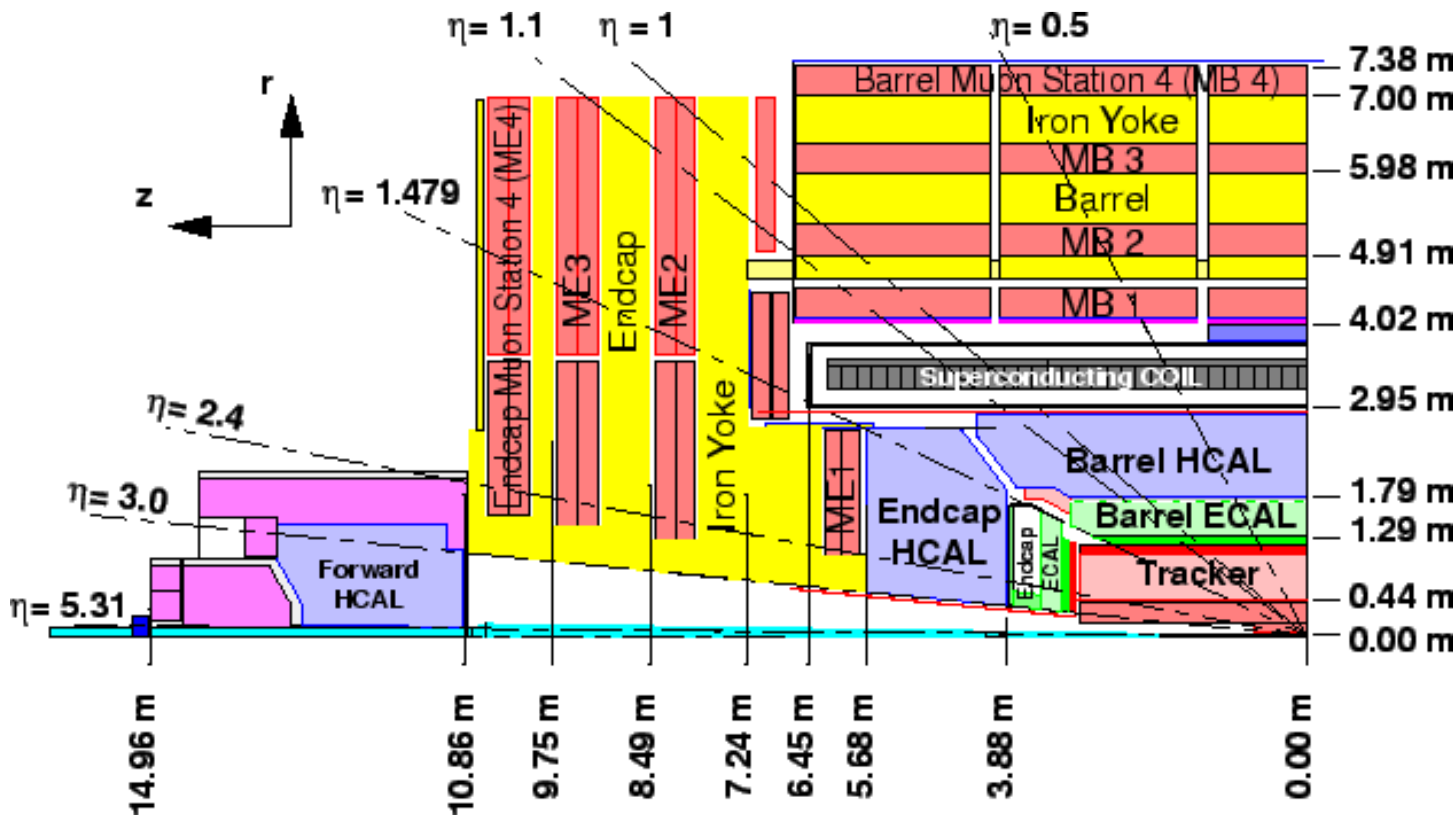
More results to come using full Run2 and (in future) Run3: stay tuned!



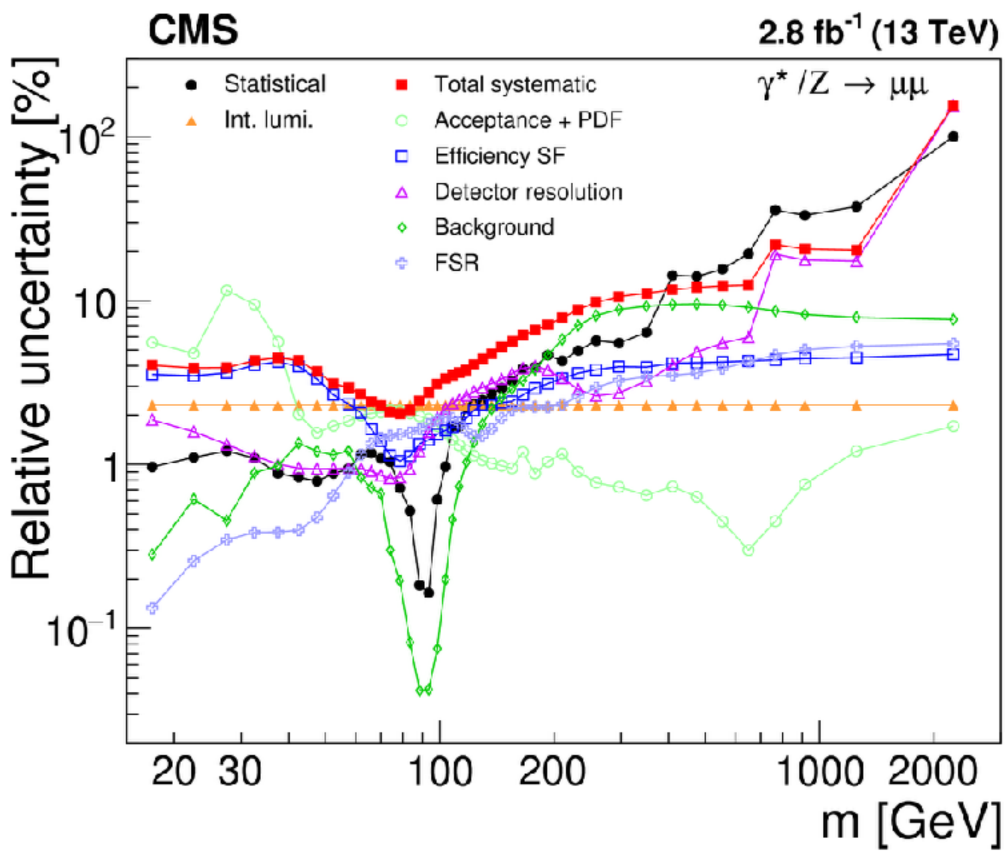
Thanks for your attention!

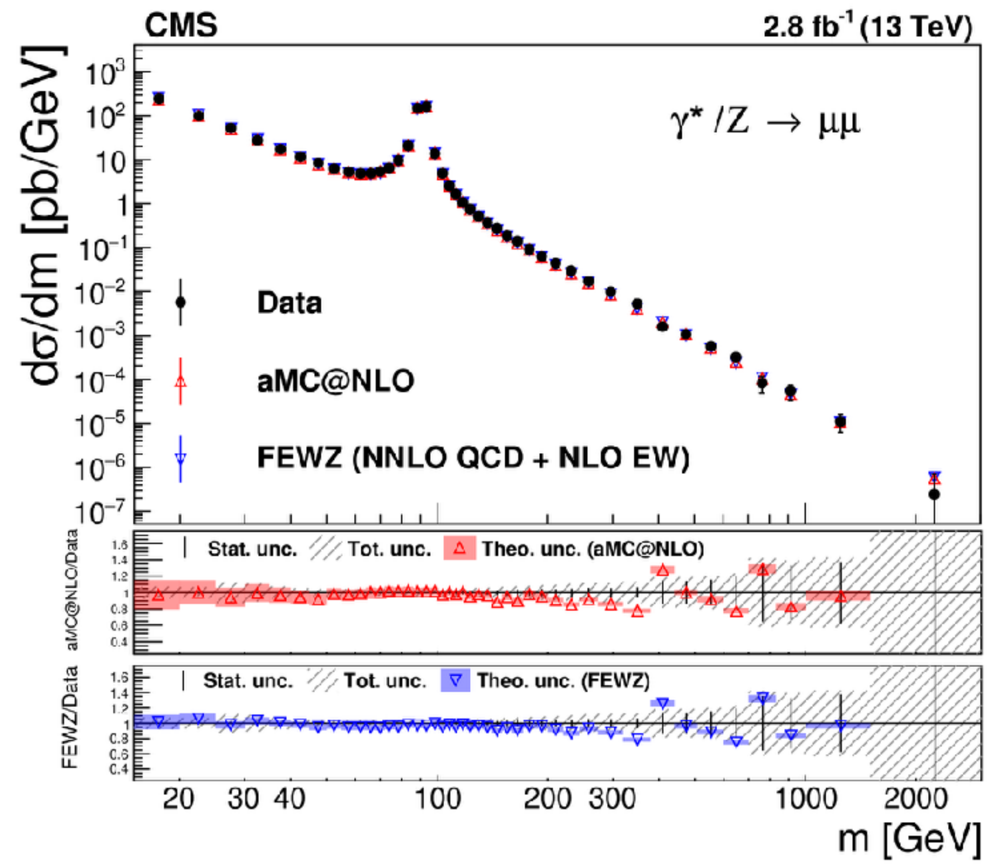
Backup slides

CMS detector reference system



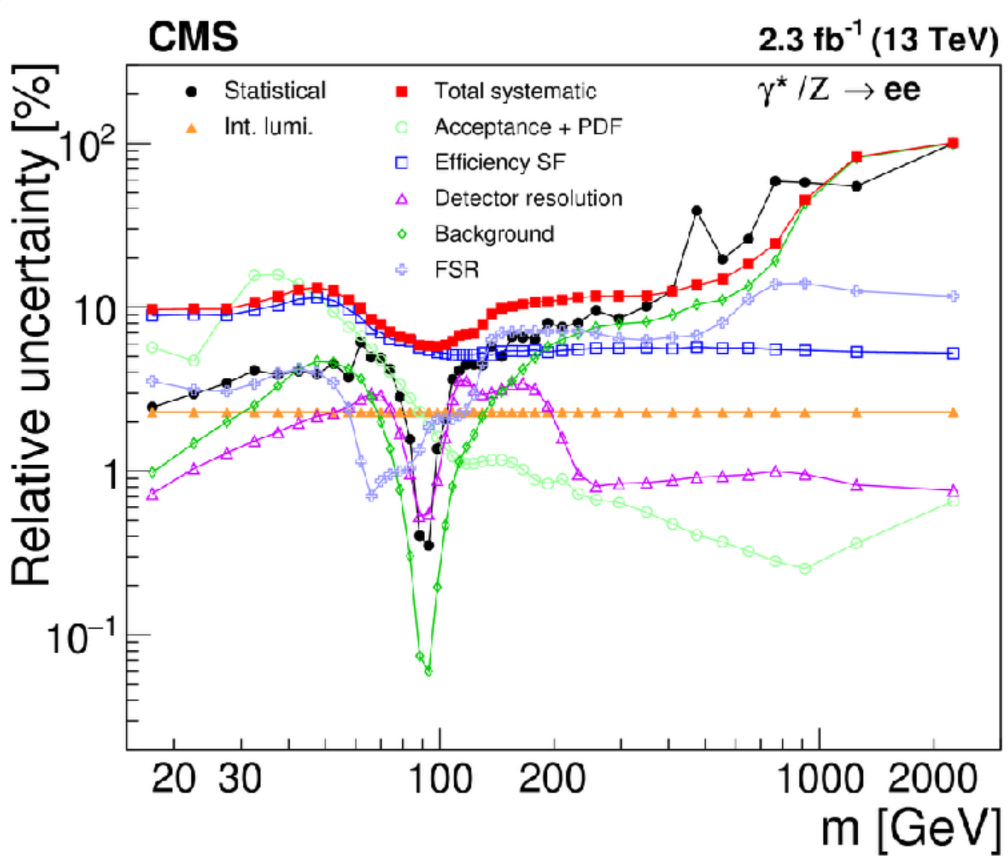
Drell-Yan $m_{\ell\ell}$ differential cross-section

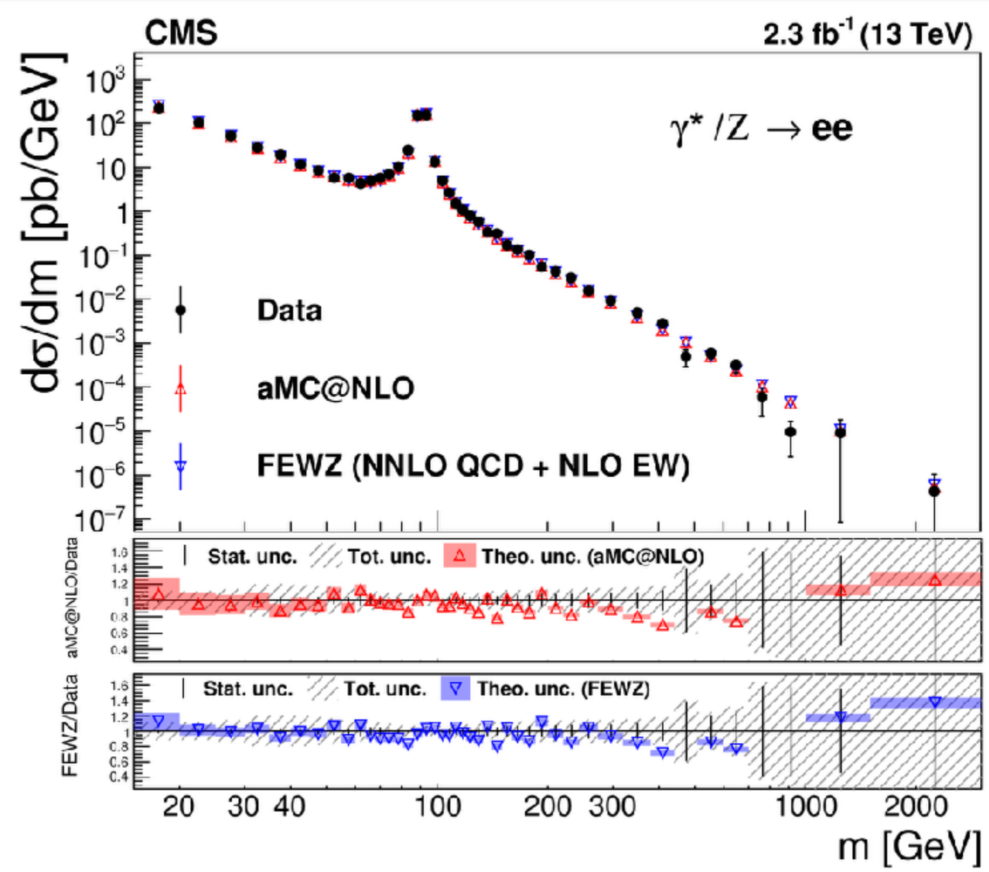




SMP-17-001

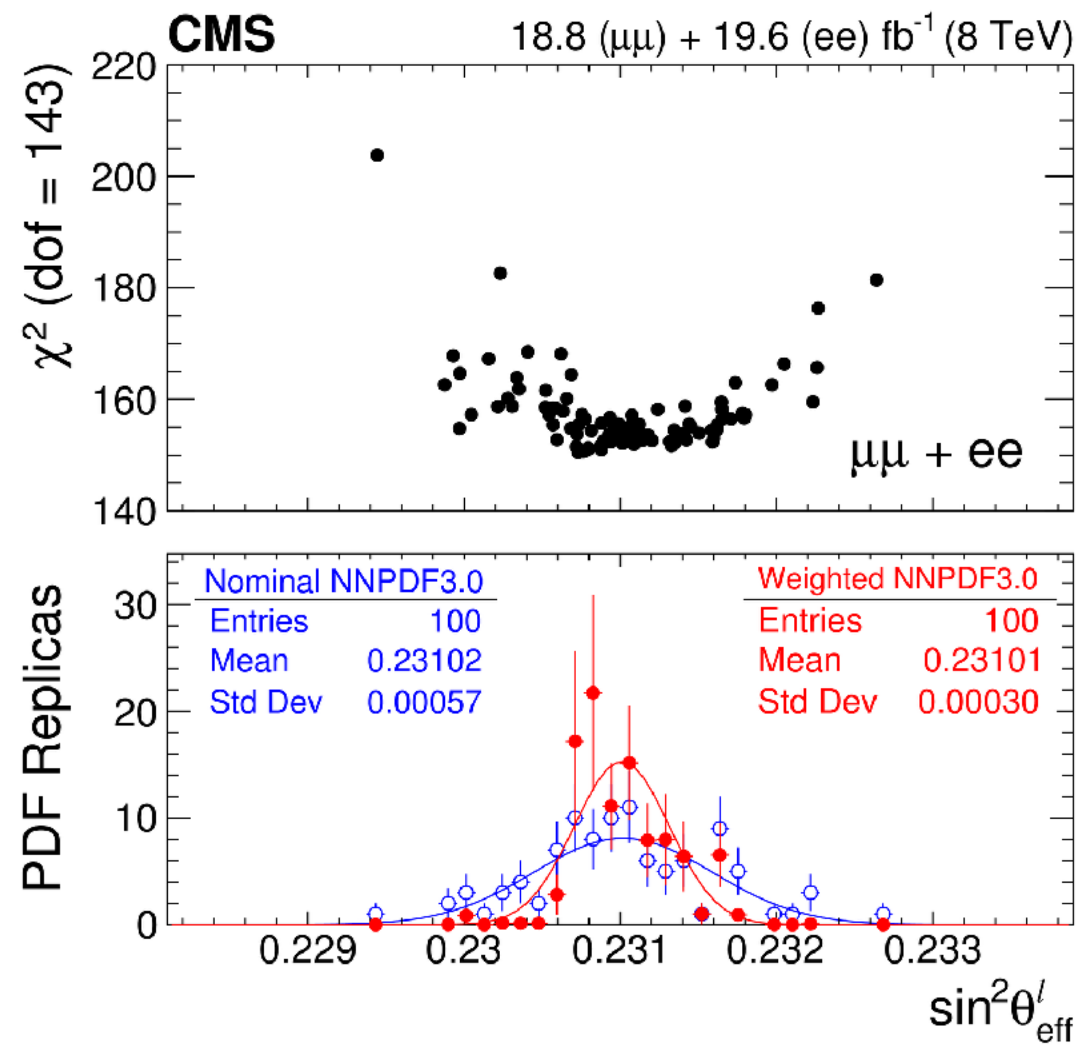
JHEP 12 (2019) 059

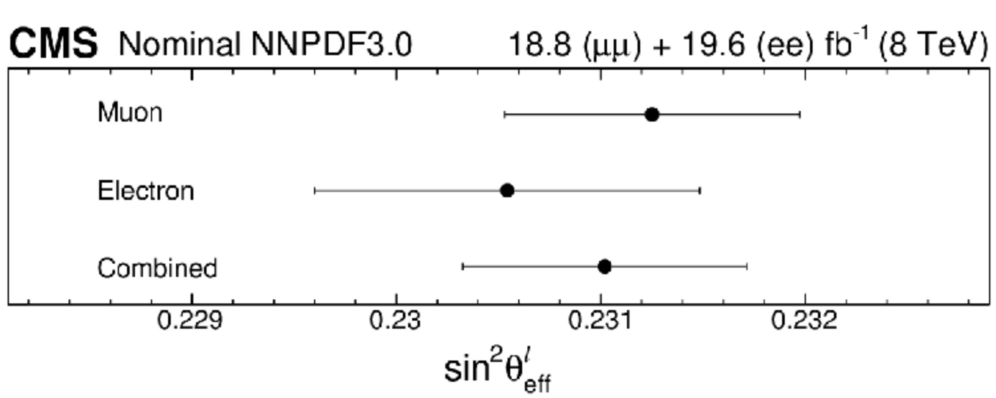


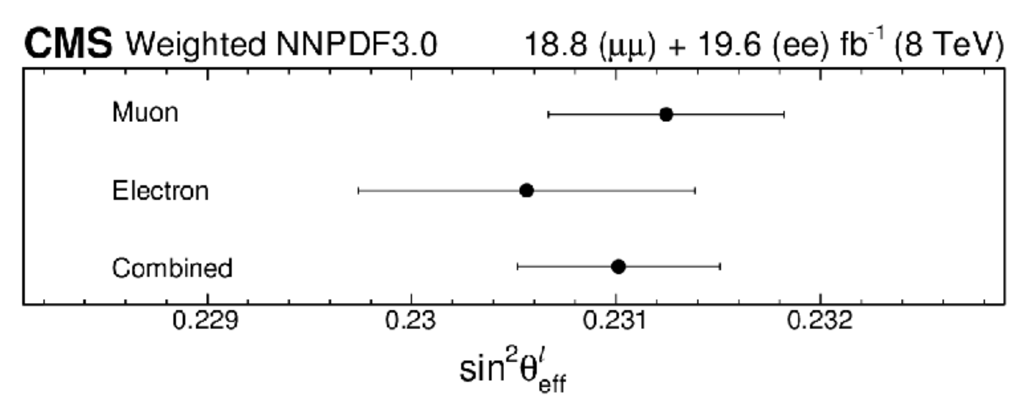


PDF are constrained using Bayesian χ^2 reweighting

$$w_i = \frac{e^{-\frac{\chi^2_{\min,i}}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2_{\min,i}}{2}}}$$



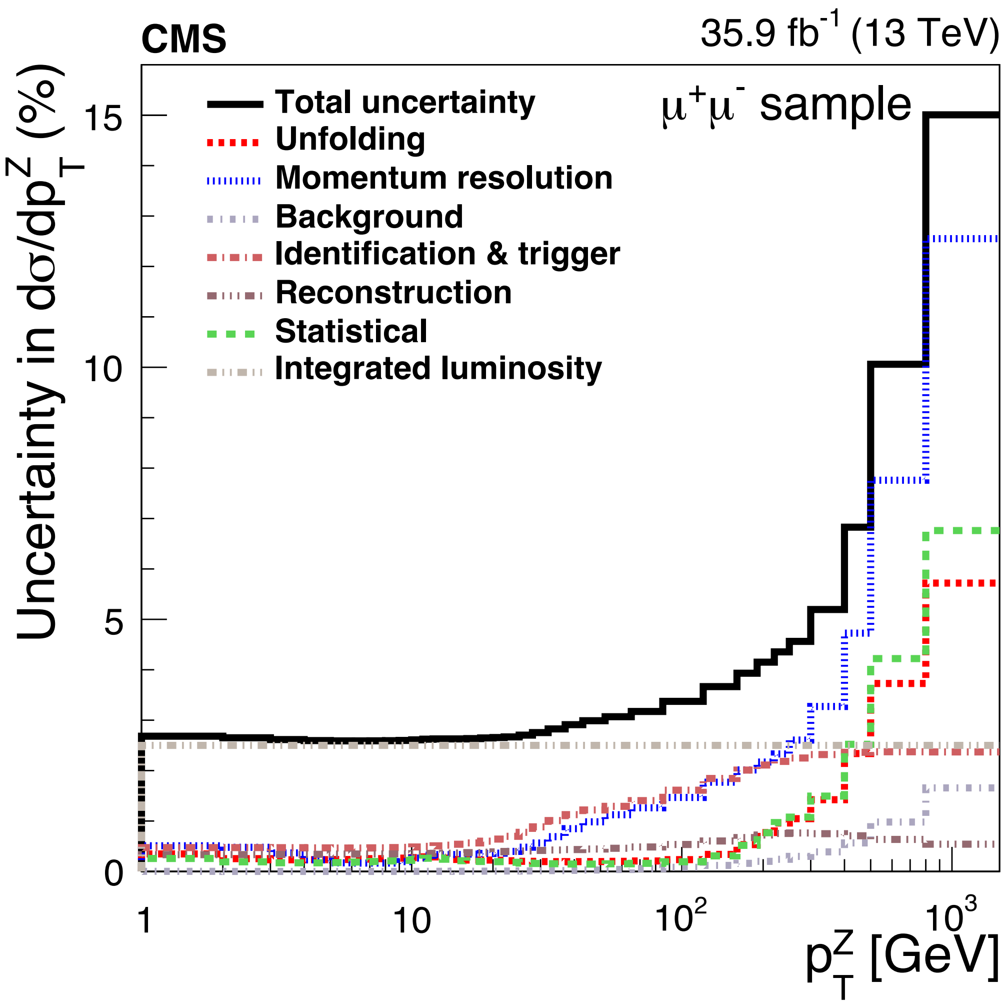


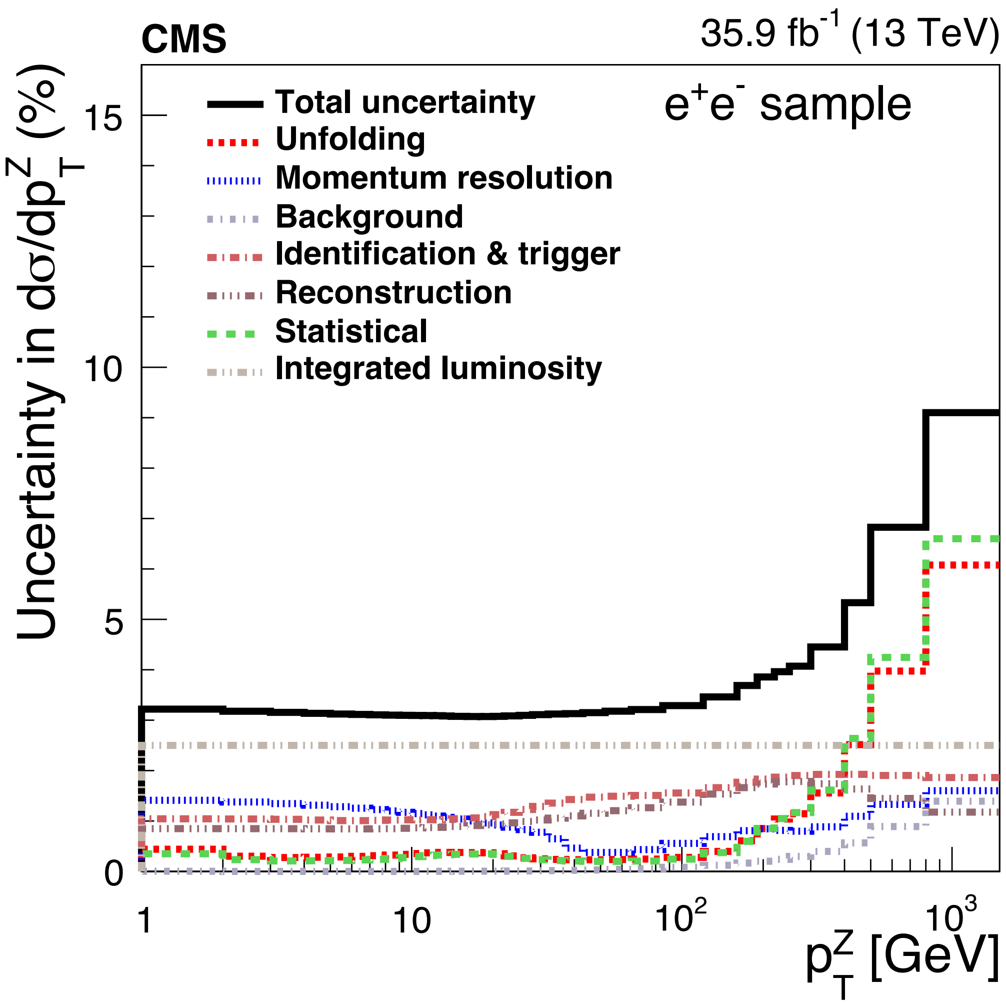


Differential Z production cross-section

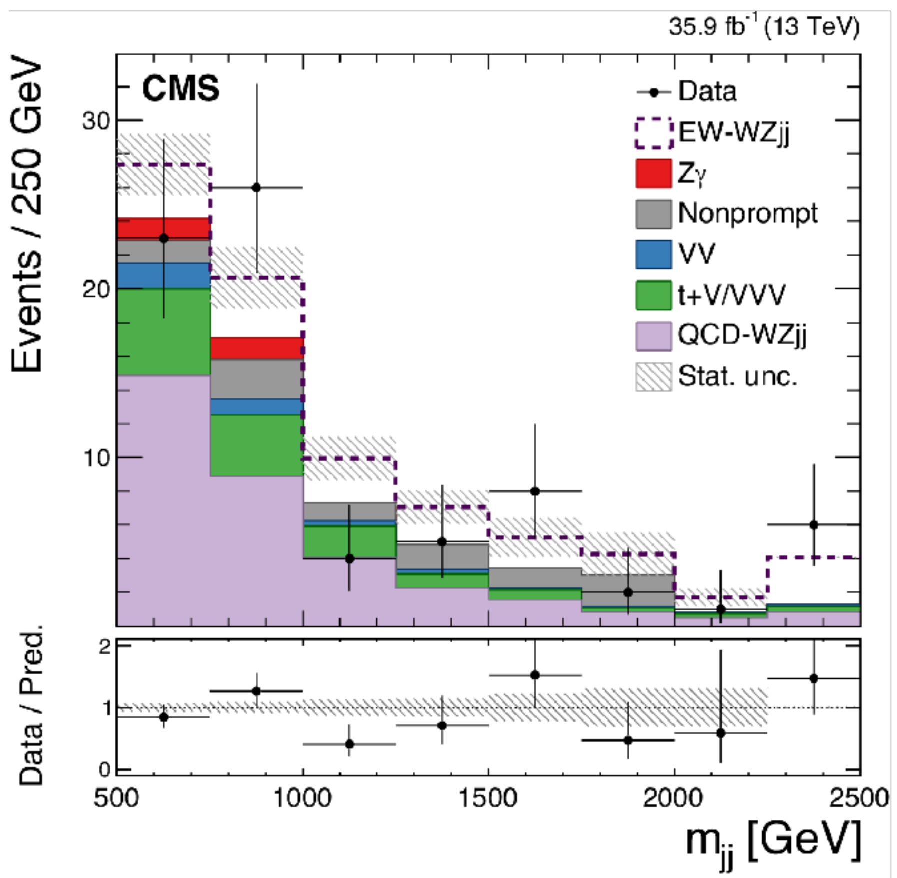
SMP-17-010
JHEP 12 (2019) 061

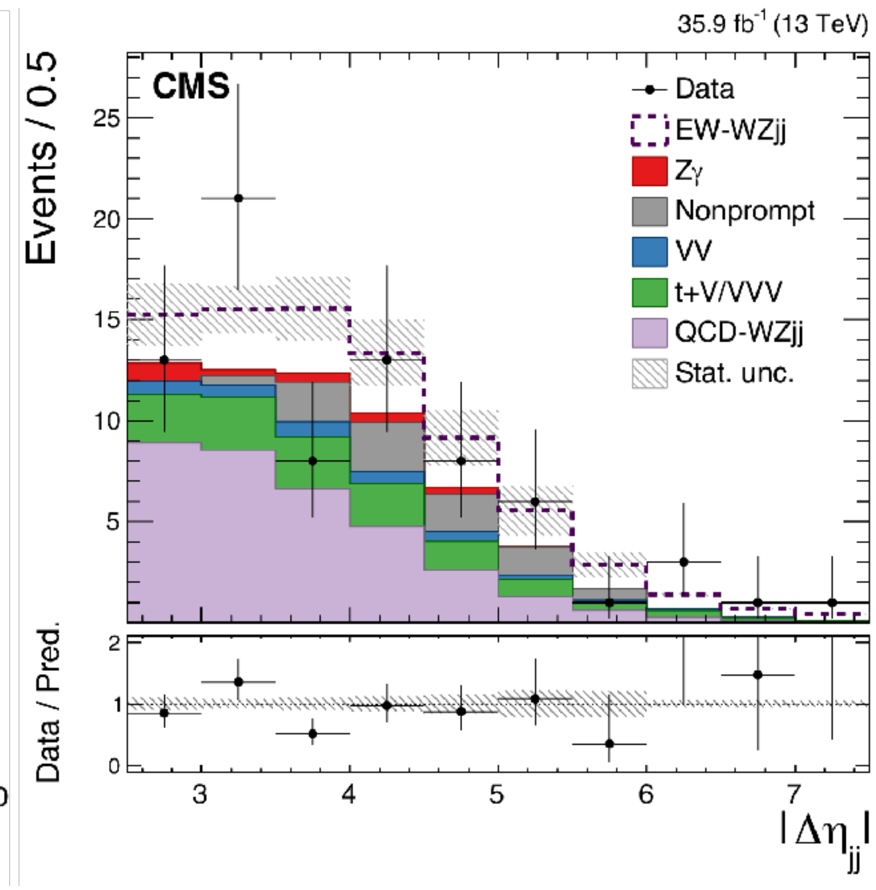
Source	$Z \to \mu\mu$ (%)	$Z \to ee$ (%)
Luminosity	2.5	2.5
Muon reconstruction efficiency	0.4	—
Muon selection efficiency	0.7	—
Muon momentum scale	0.1	—
Electron reconstruction efficiency	—	0.9
Electron selection efficiency	—	1.0
Electron momentum scale	—	0.2
Background estimation	0.1	0.1
Total (excluding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



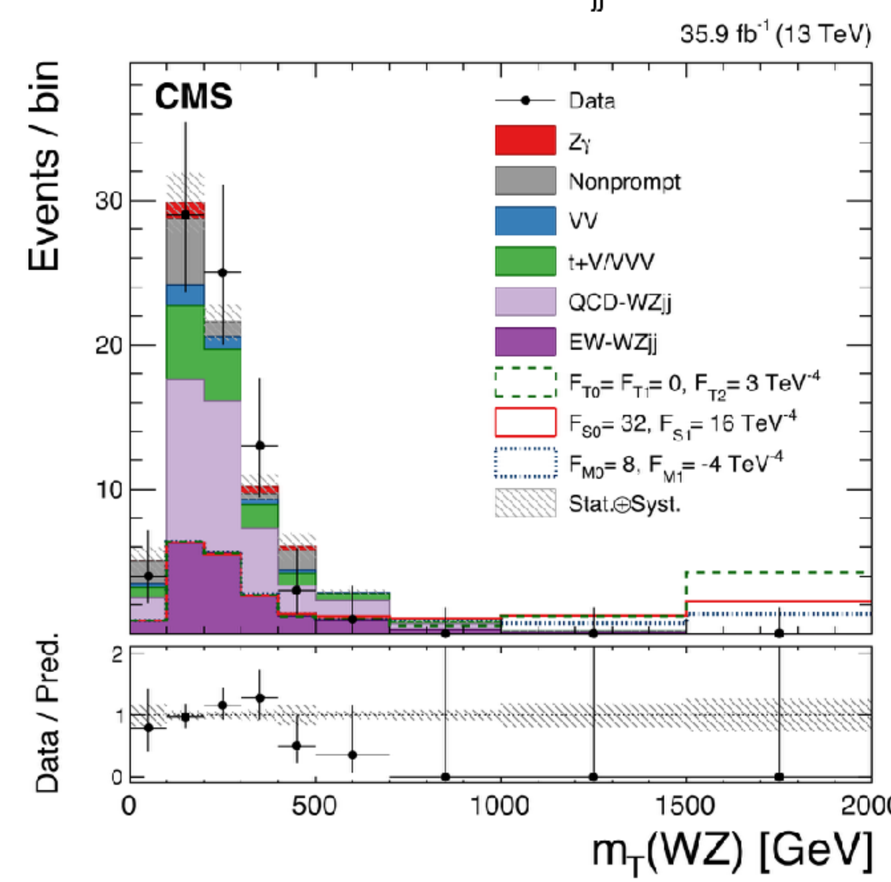


Vector Boson Scattering: WZ



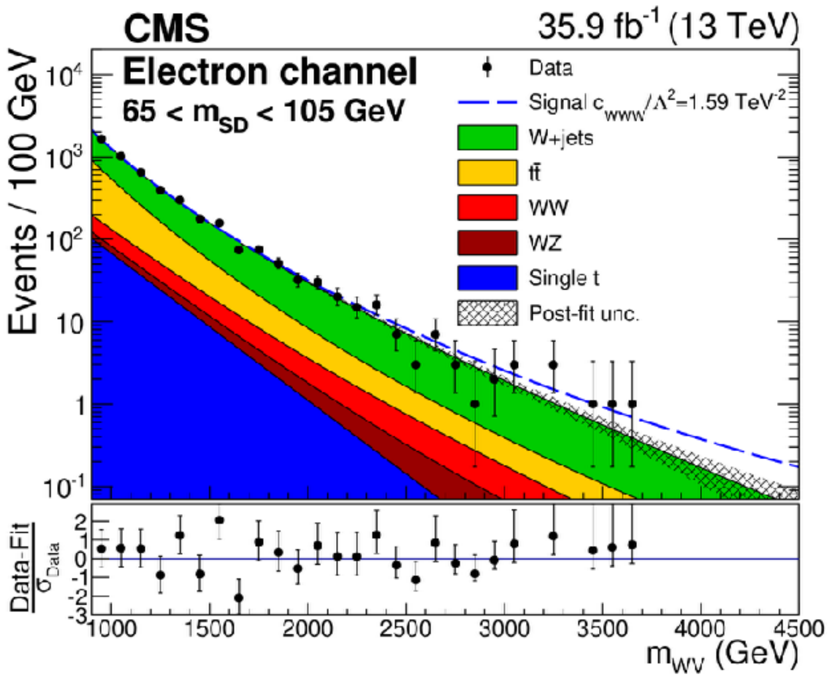


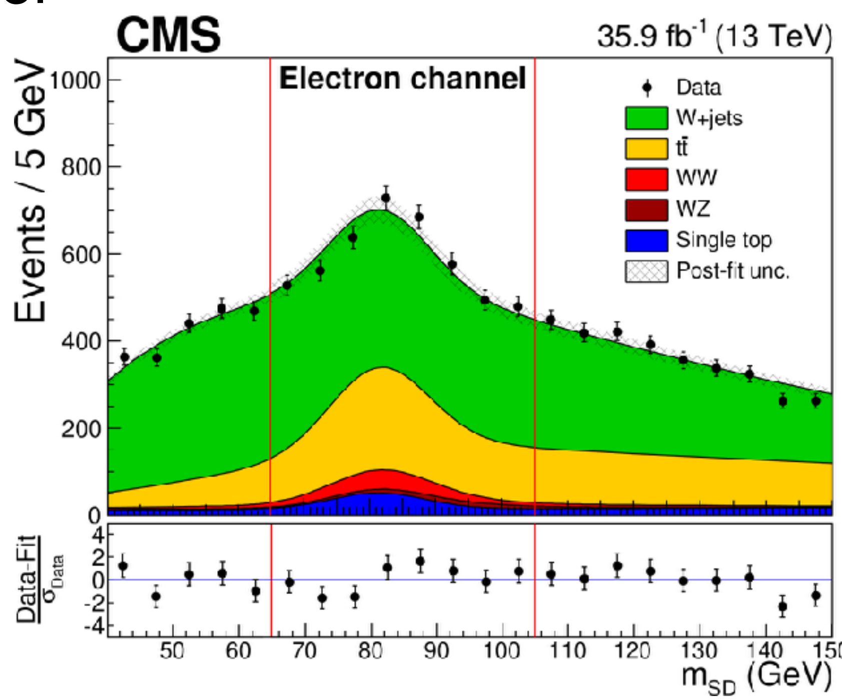
Source of syst. uncertainty	Relative uncertainty [%]	
	σ_{WZjj}	EW WZ sig.
Jet energy scale	+11 / − 8.1	7.0
Jet energy resolution	+1.9 / − 2.1	<0.1
QCD WZ modeling	—	2.2
Other background theory	+2.2 / − 2.2	0.3
Nonprompt normalization	+2.5 / − 2.5	0.3
Nonprompt event count	+6.0 / − 5.8	1.7
Lepton energy 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

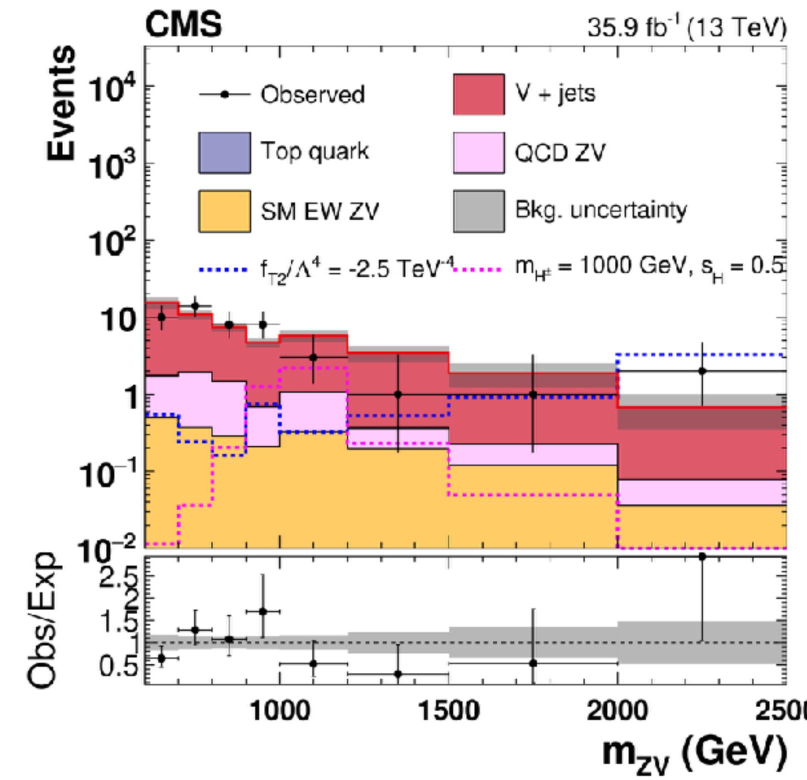


Diboson production: WW/WZ $\to \ell\nu$ + jet

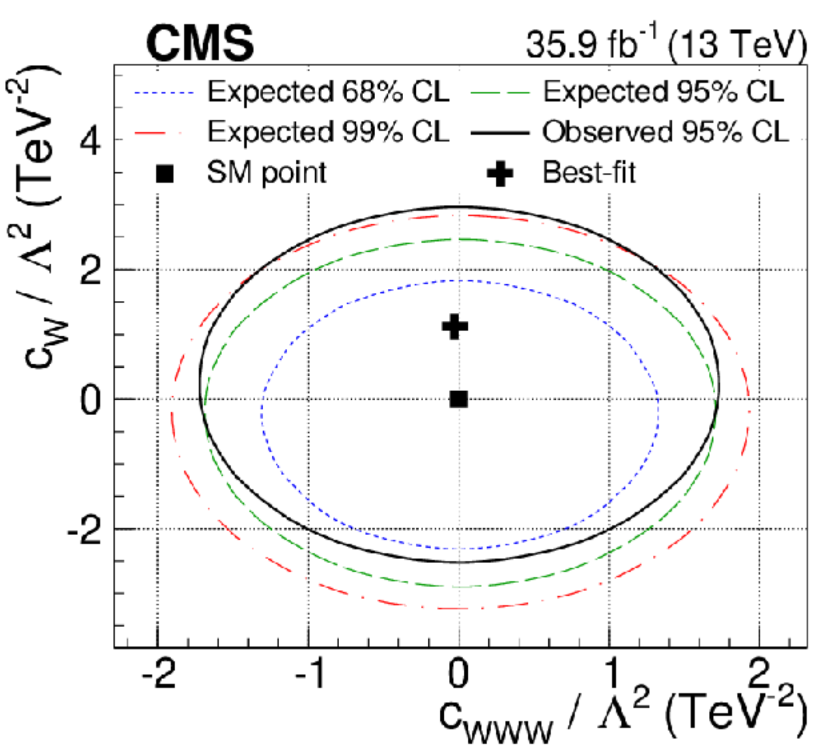
- Plots for the electron channel

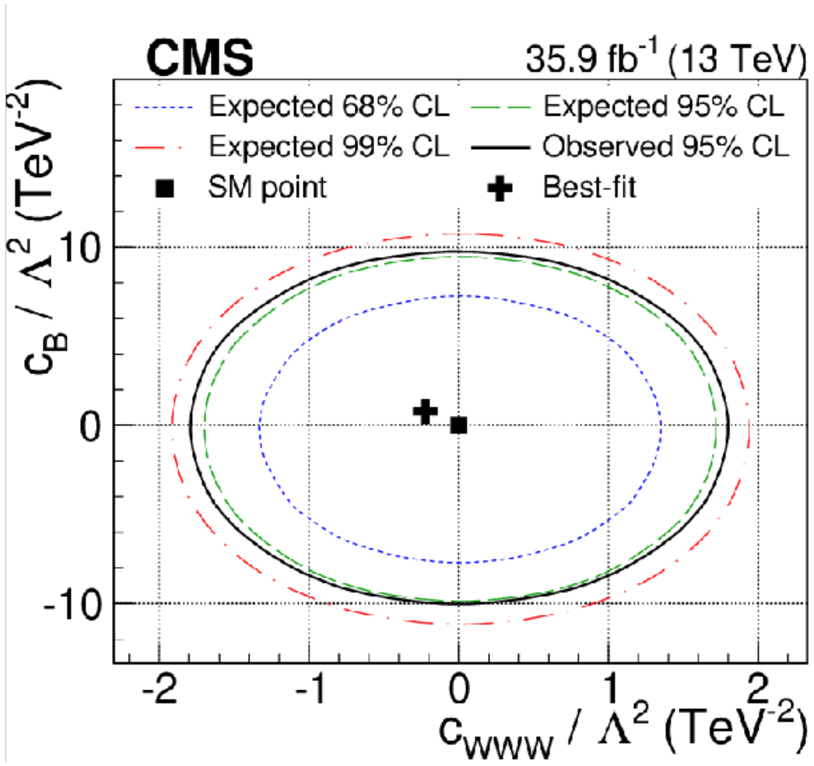


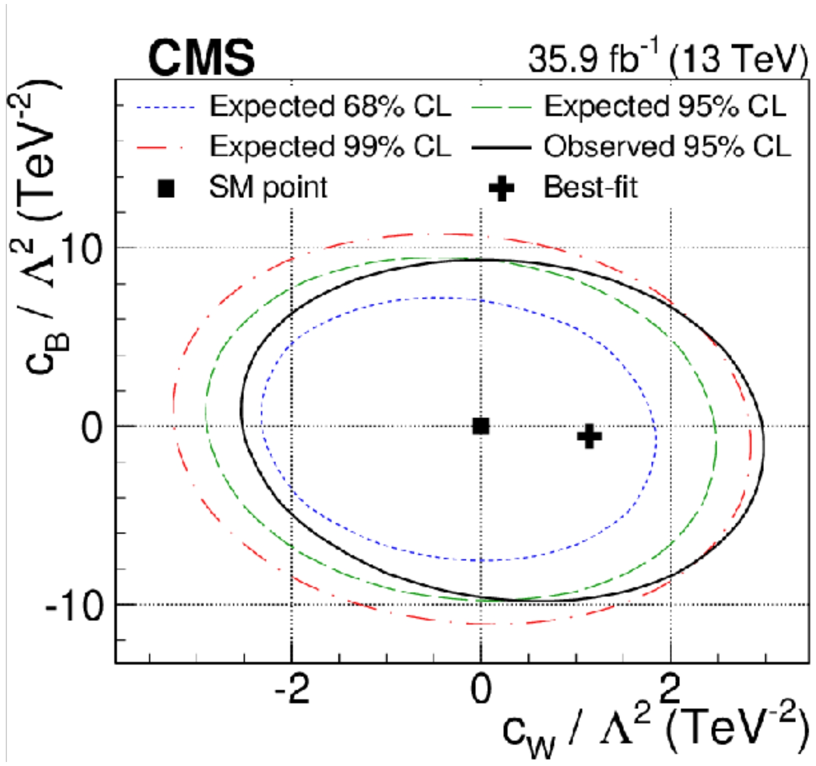




- Contour of EFT parameters

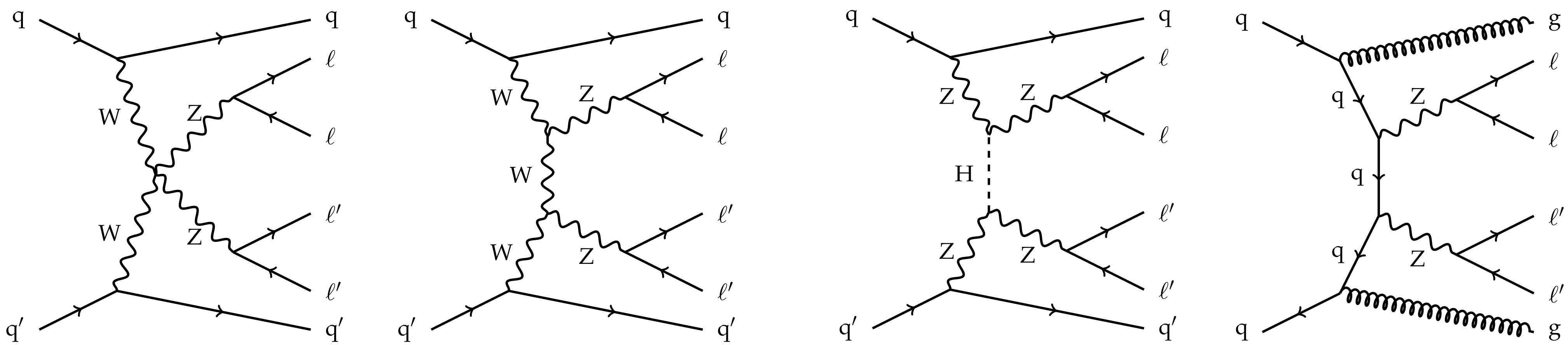


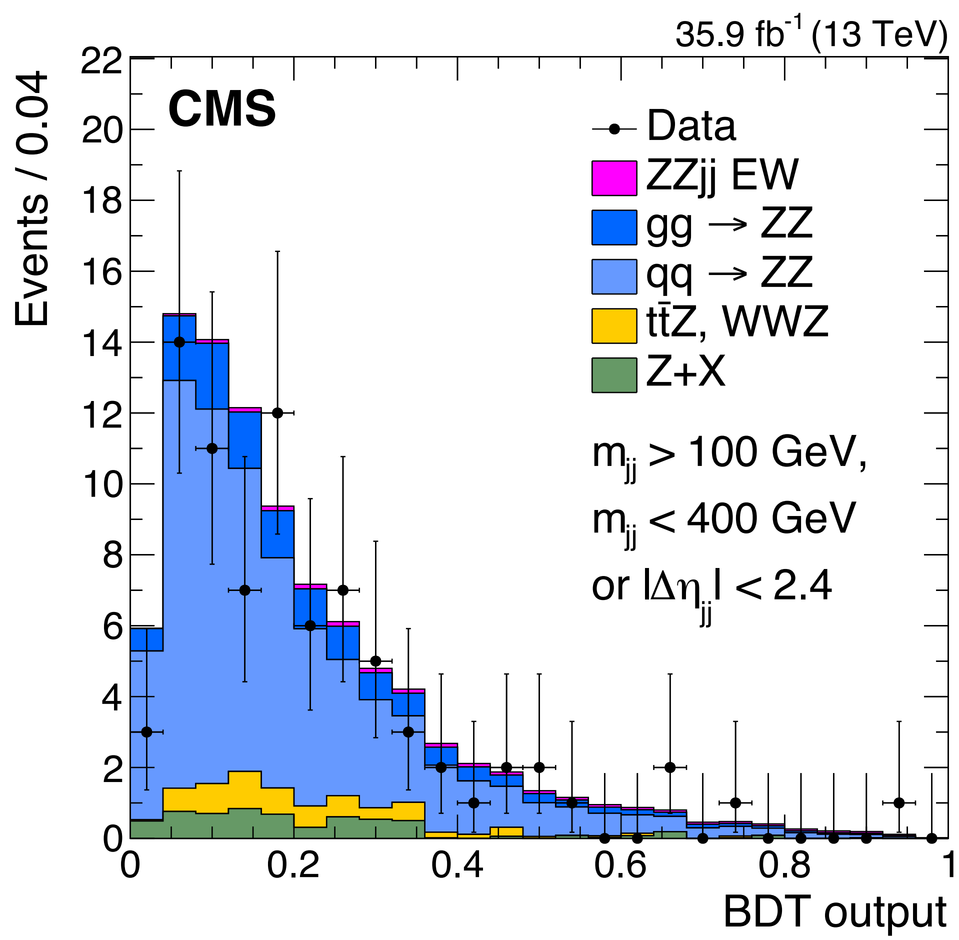


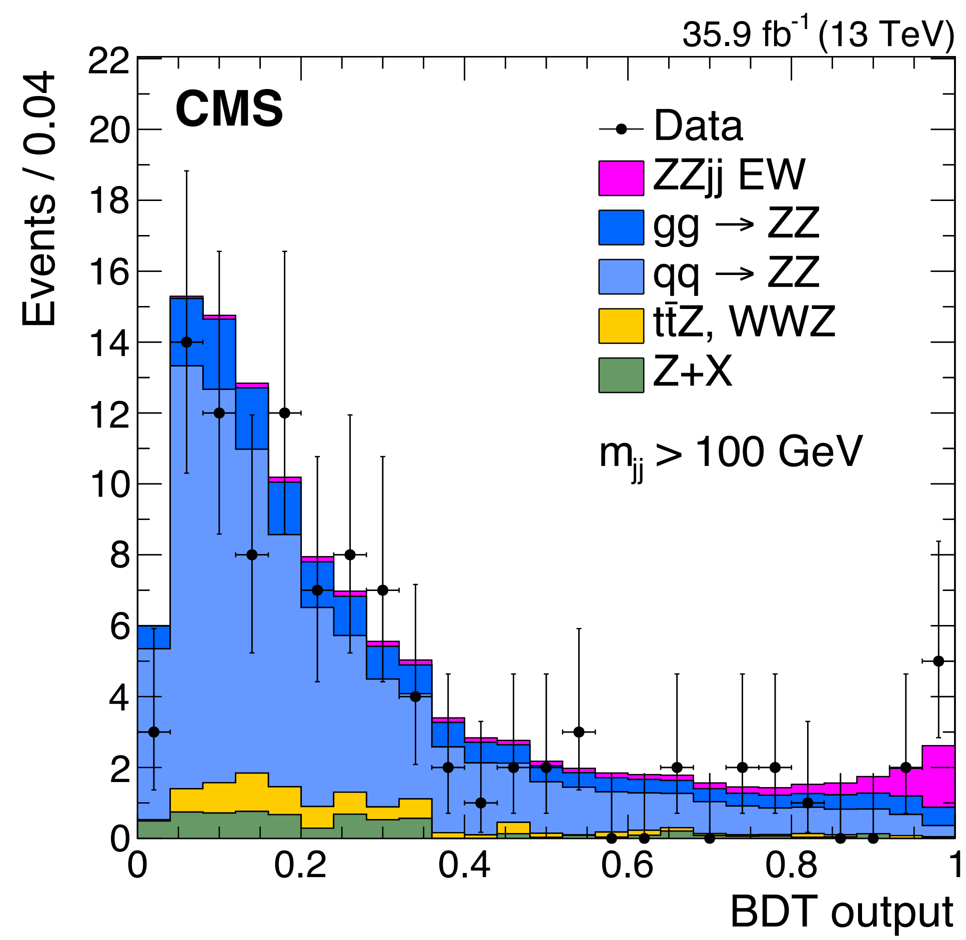


Vector Boson Scattering: ZZ

EW- and QCD-induced production separated using a BDT



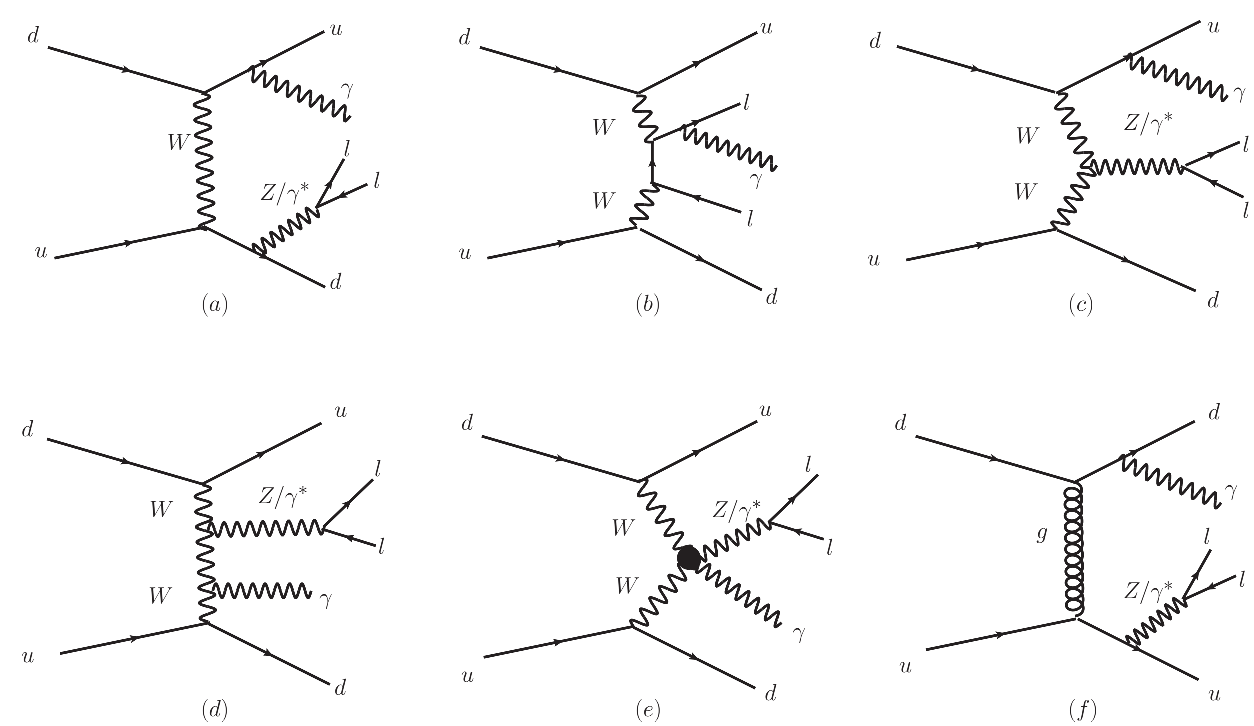


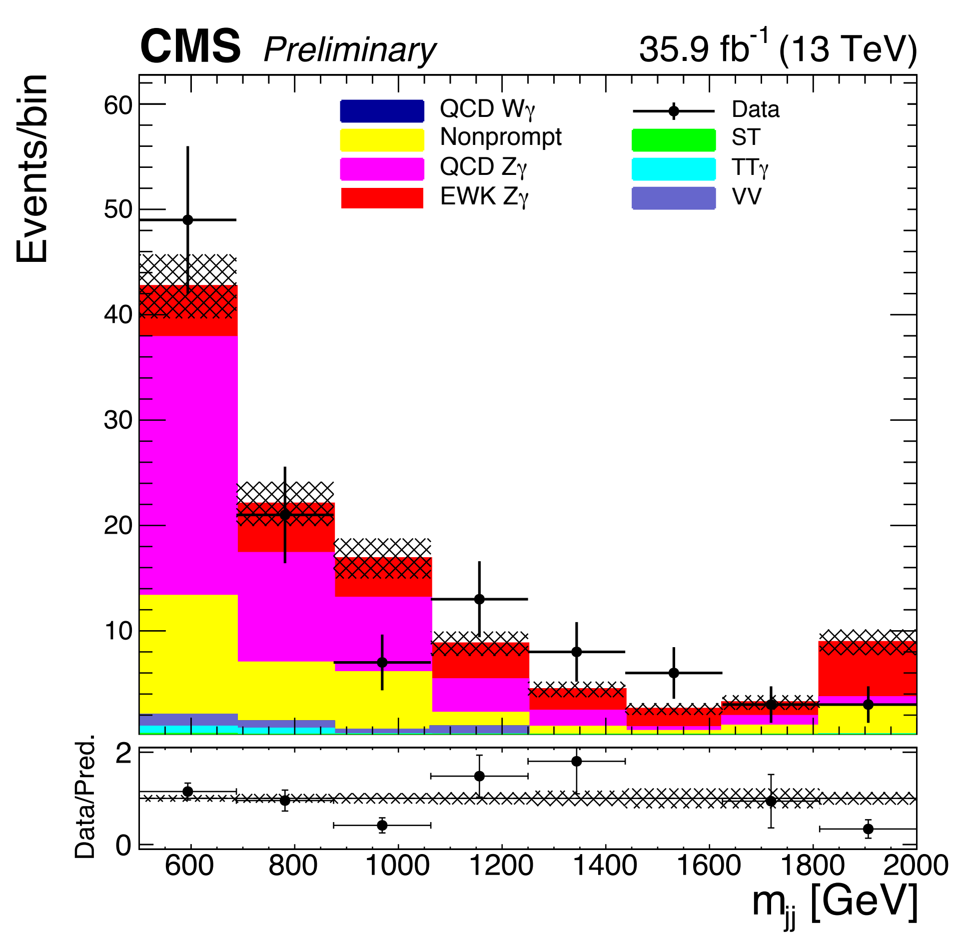


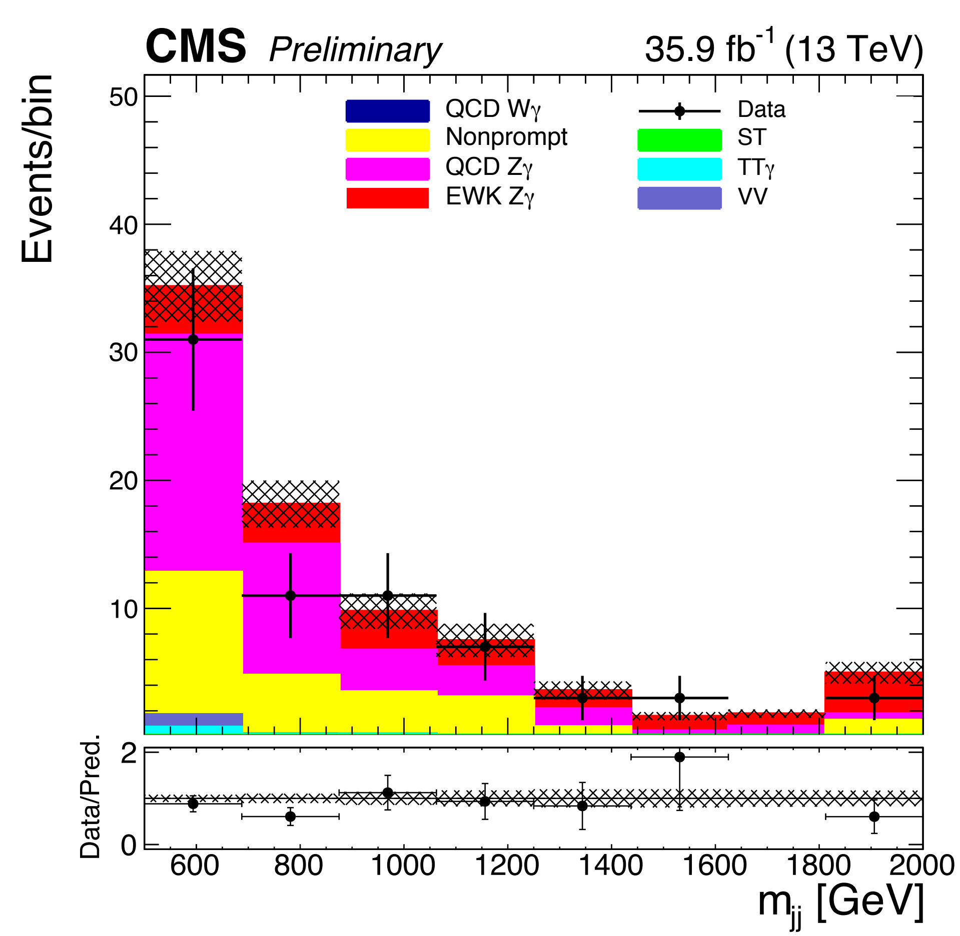
Vector Boson Scattering: Zγ

Fit EW on 2D distribution of mjj and ηjj

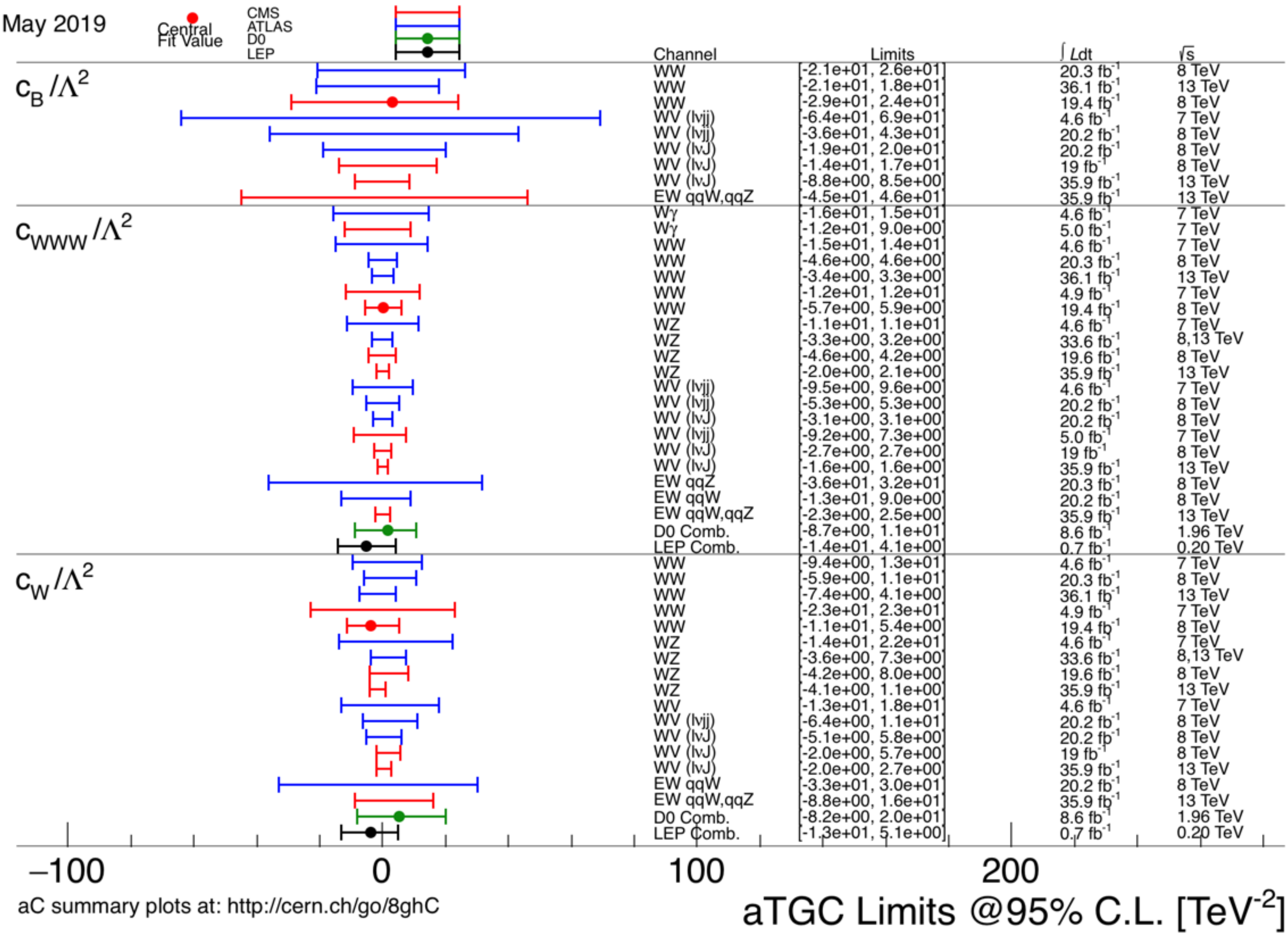
	muon channel	electron channel
Nonprompt photon	47.6 ± 4.5	39.3 ± 4.0
Other background	7.4 ± 1.4	2.7 ± 0.8
QCD Zγjj	62.9 ± 3.1	49.6 ± 2.7
EW Zγjj	36.5 ± 0.7	25.4 ± 0.6
Total background	117.9 ± 5.6	91.6 ± 4.8
Data	172 ± 13	113 ± 11



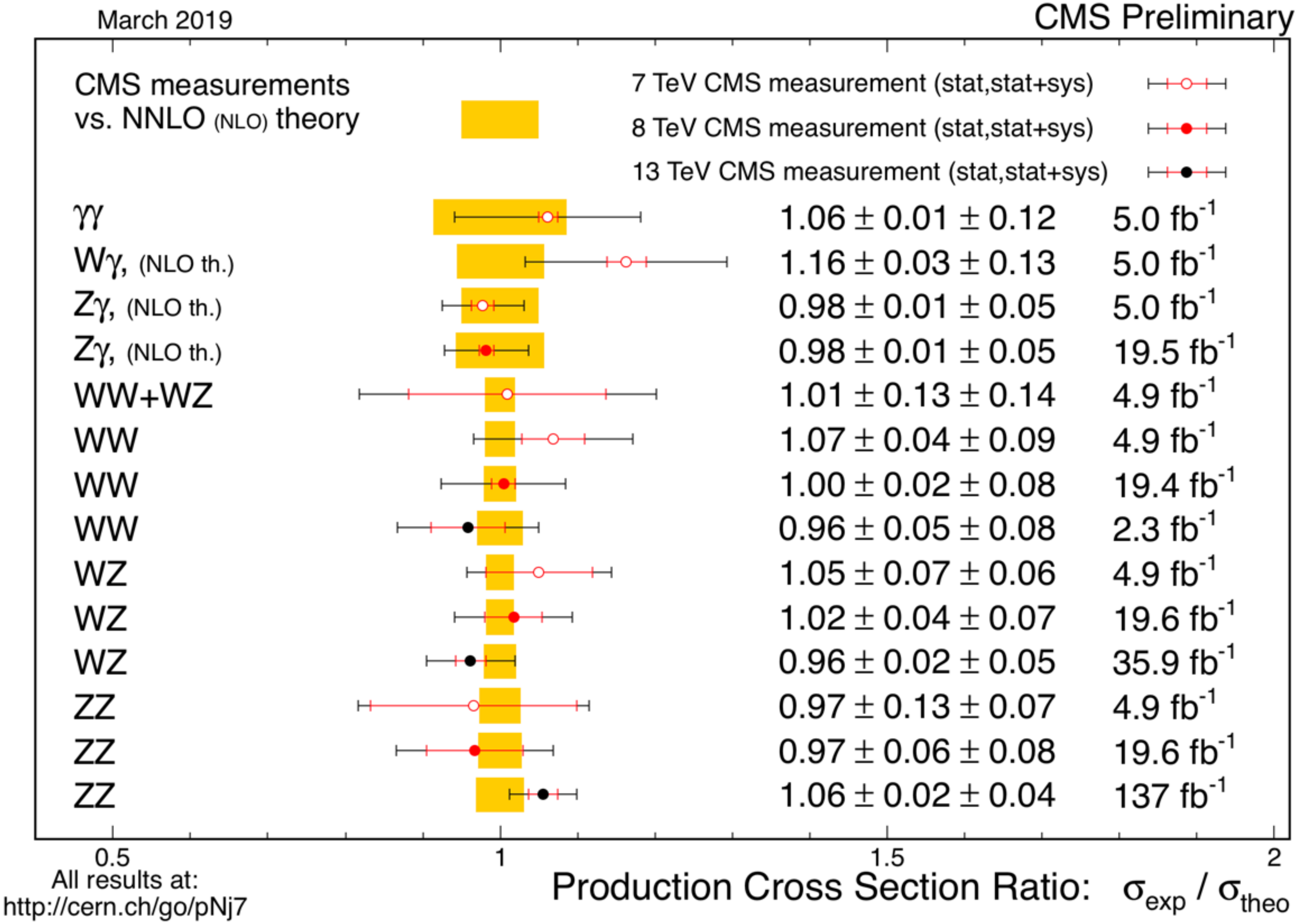




EFT: limits on 6-dim operators



Dibosons cross-sections



VBS cross-sections