Precision Measurements of Di-boson Differential and Total cross sections from CMS

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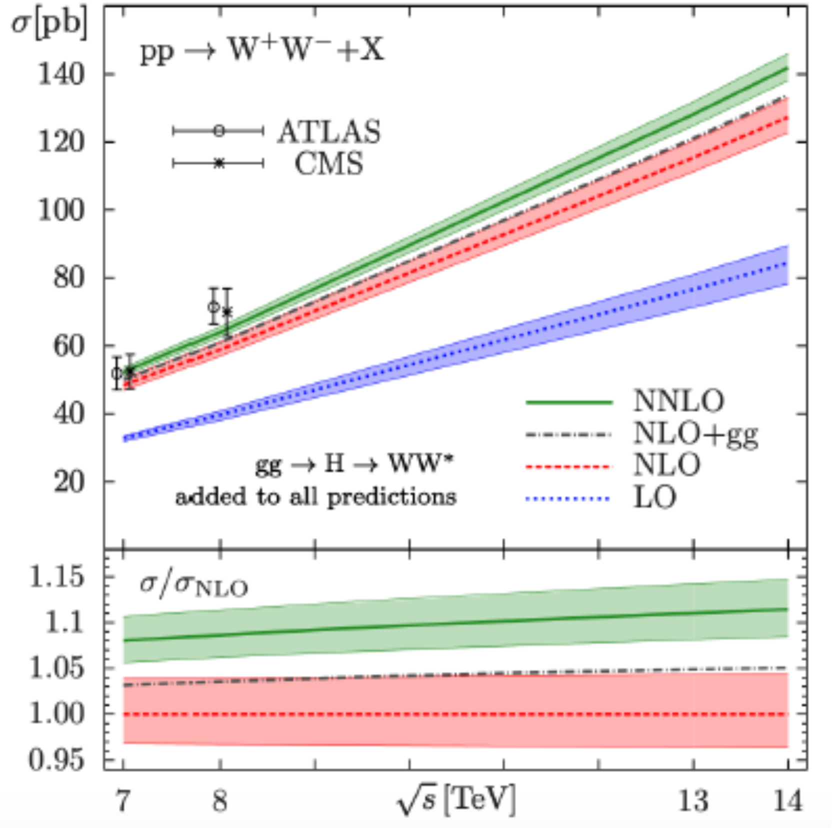
Introduction

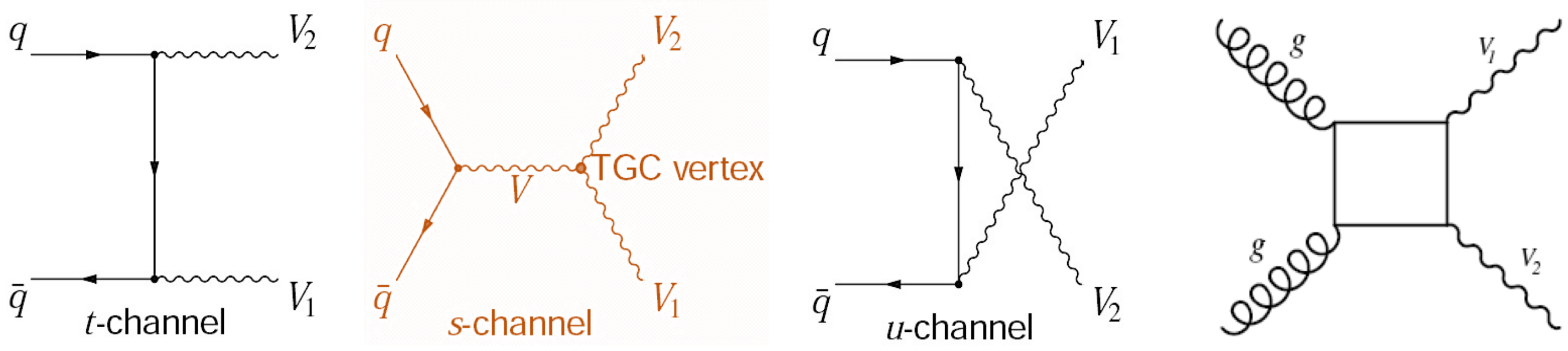
- Why study di-boson processes at the LHC?
  - Stringent test of the standard model (SM) non-abelian character of the $SU(2)_L xU(1)$ gauge group at TeV scale
  - Precision test of:
    - sensitive to higher order QCD / EW corrections at TeV scale
    - New physics (e.g. arXiv:1406.0848 [hep-ph])? Subsequent NNLO calculation agrees much better with measurement.
  - Model-independent means to search for new physics at the TeV scale.
    - allow for the possibility of new physics with mass scales very close to the Electroweak Scale
    - growing interest in indirect searches at LHC
  - Precise measurements help to constrain SM contribution (background) in searches of many new physics models and Higgs analysis.

Phys. Rev. Lett. 113, 212001 (2014)



Introduction

- Di-boson inclusive production

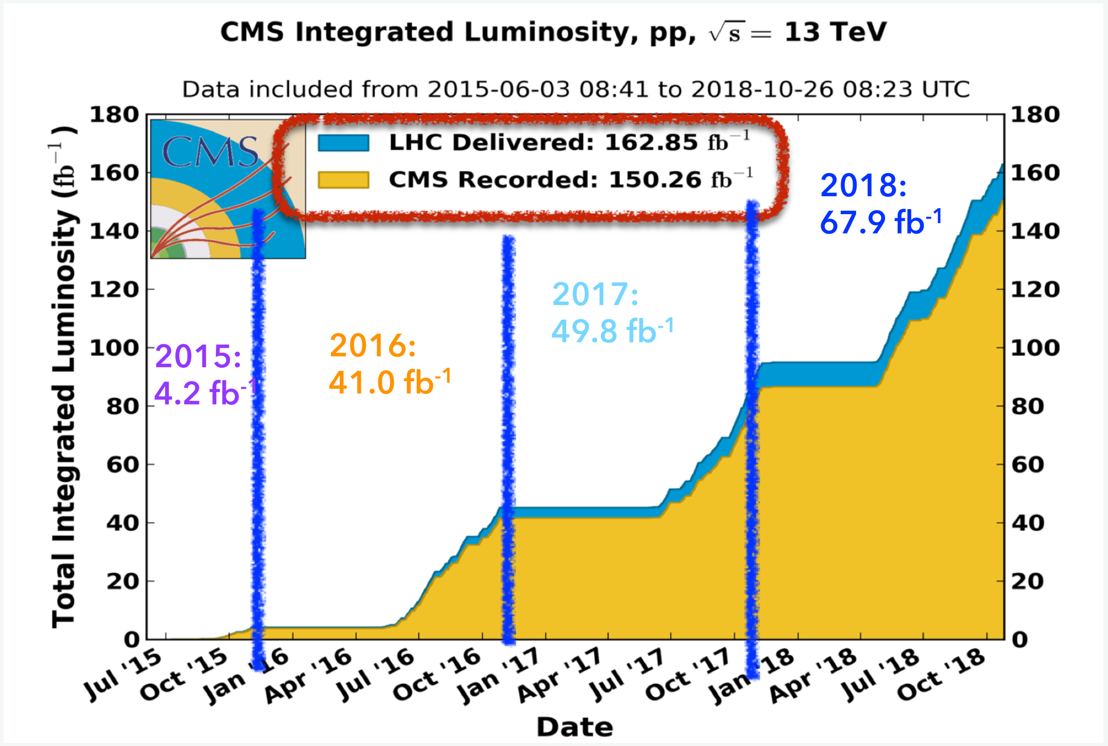


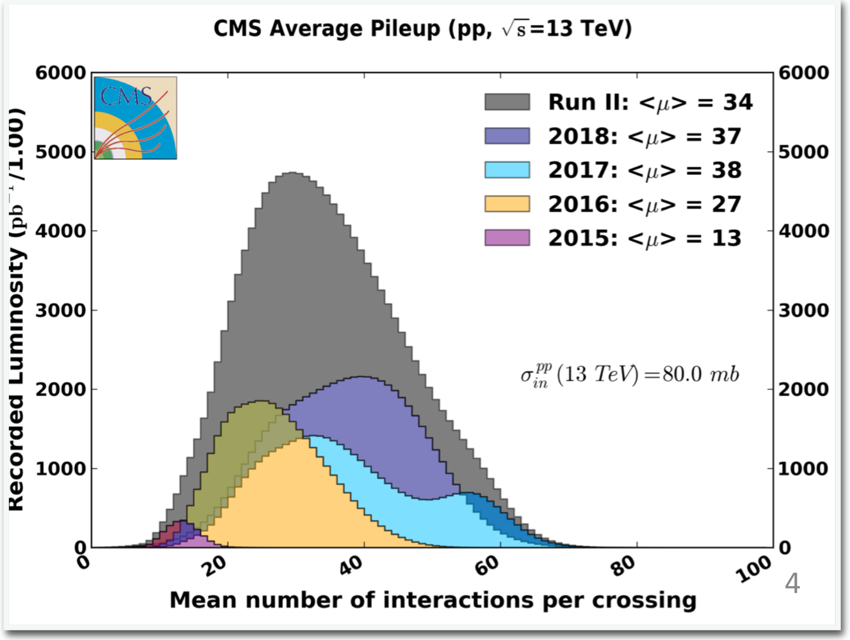
$$\mathcal{L}_{\mathrm{GC}} = \frac{1}{2} g_2 (\partial_\mu W_\nu^i - \partial_\nu W_\mu^i)\varepsilon_{ijk} W^{j\mu} W^{k\nu} - \frac{1}{4} g_2^2 \varepsilon_{ijk}\varepsilon_{imn} W_\mu^j W_\nu^k W^{m\mu} W^{n\nu}$$

- SU(2)xU(1) symmetry leads to several trilinear gauge bosons interactions in the electroweak sector of the SM.
- Only charged couplings allowed in SM (WWZ, WWɣ)
- No neutral couplings in the s-channel (ZZZ, ZZɣ, Zɣɣ)
- New Physics shows up through virtual effects: modification to TGCs wrt to SM (aTGC)
  - Deviations from SM couplings result in large cross section changes

CMS Run 2

- Run 2 pp data taking efficiency 92.3 %
- A total of 137 fb^{-1} in LHC Run 2 collected by CMS.
- 2018: largest dataset collected so far
- Most results shown here use 35.9/fb of data collected in 2015+2016
- Total uncertainty on the integrated luminosity ~ 2 – 2.5%
- Mean number of interactions per bunch crossing in the Run2 of 34



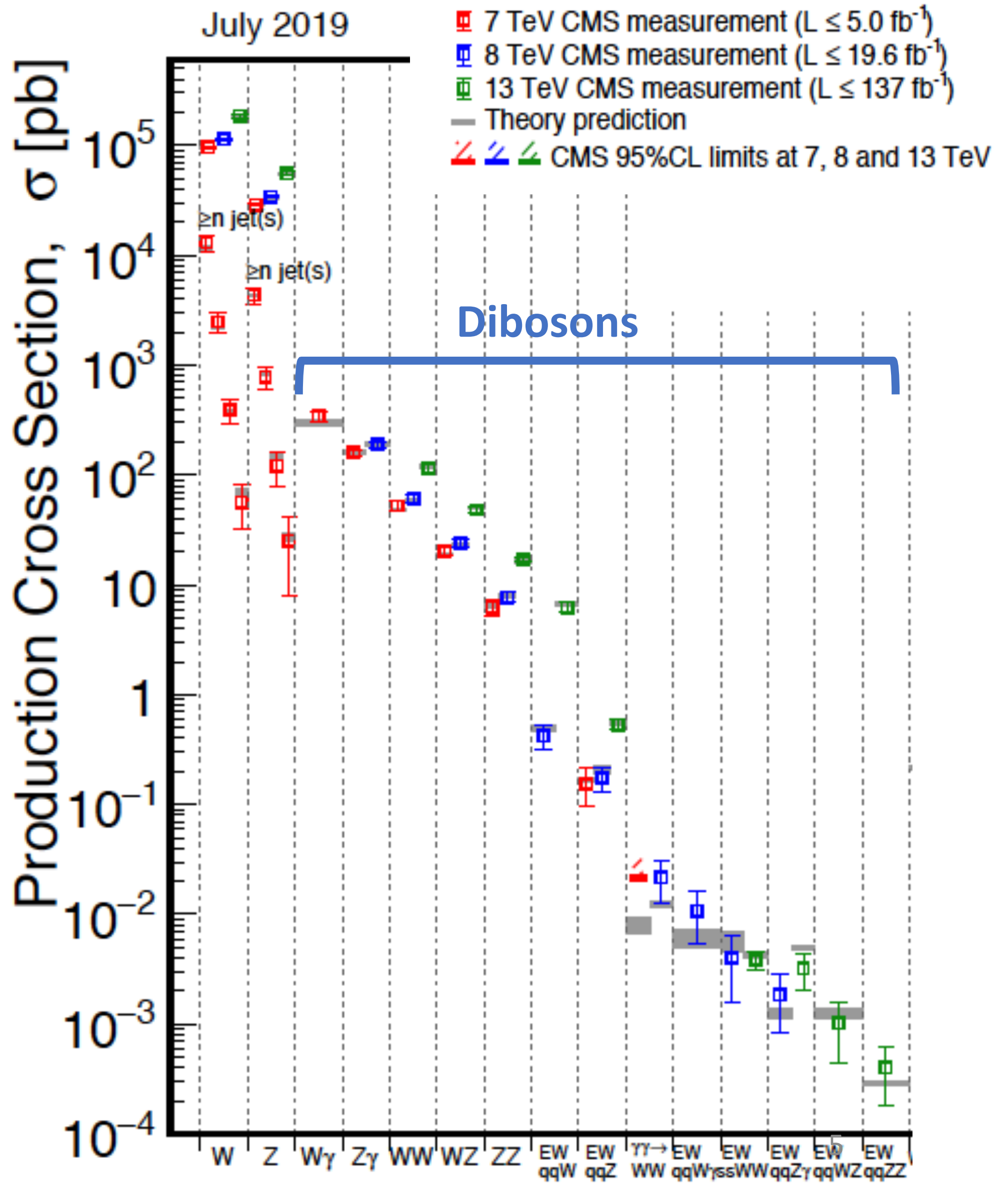


Overview of Run 2 CMS analysis

- Here presenting di-boson measurements performed by CMS in Run2 involving leptonic final states

Process	Final state	Dataset @ 13 TeV	Documents
WZ	lllν	35.9/fb	JHEP 04 (2019) 122
ZZ	llll	137.0/fb	SMP-19-001
ZZ	llll	35.9/fb	Eur. Phys. J.C. (2018) 78
ZZ	llll+jets	35.9/fb	SMP-18-008
WW	lνlν	2.3/fb	PAS-SMP-16-006

NNLO QCD and NLO EWK predictions available for many processes



The measurements

Cut & Count in most cases

Dominant contributions
always data-driven

$$\sigma = \frac{N_{selected} - N_{background}}{A \cdot \epsilon \cdot \int \mathcal{L} dt}$$

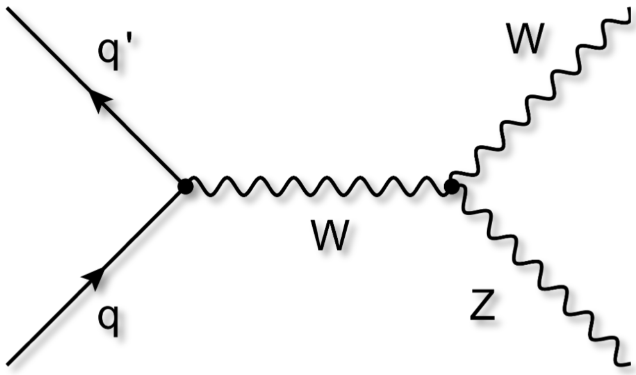
- Total cross section is obtained by correcting for acceptance, efficiency and branching ratio
- Low statistics → inclusive cross sections
- Decent statistics → differential cross sections

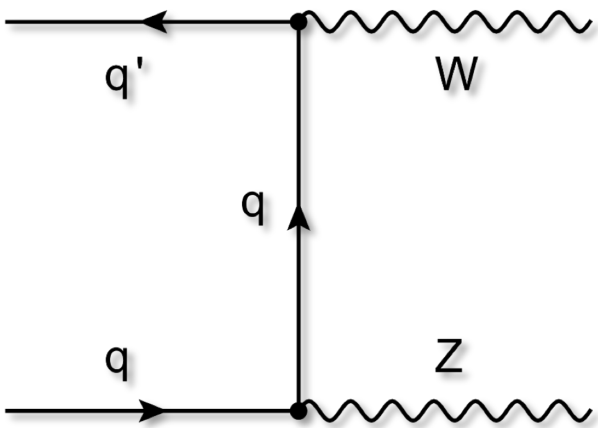
higher order QCD and QED perturbative corrections

probe any deviation from SM prediction more closely (tails)

WZ cross section

POWHEG at NLO in QCD



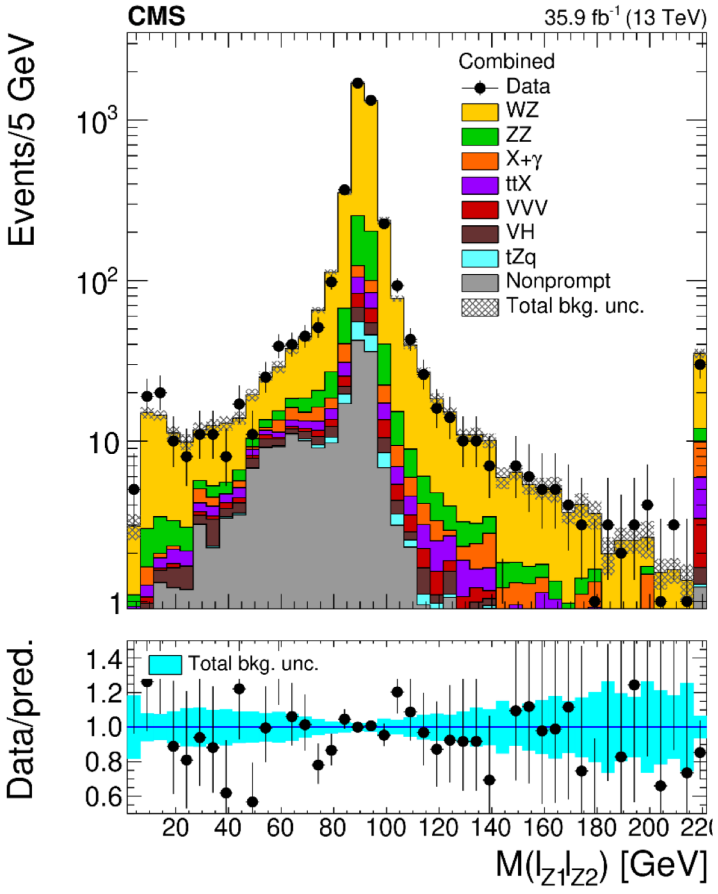


- Sensitive to charged WWZ gauge interaction
- Background to charged resonance searches (e.g. $H^{\pm}$)
- Measure both fiducial and total cross sections
  - with increased precision wrt previous results
- First differential cross-section measurement test of SM prediction at 13TeV
  - Transverse momentum of Z
  - Transverse momentum of WZ system
  - Mass of 3-lepton + pT_{miss} system
- $\sigma(W^+Z)/\sigma(W^-Z)$ is computed as well

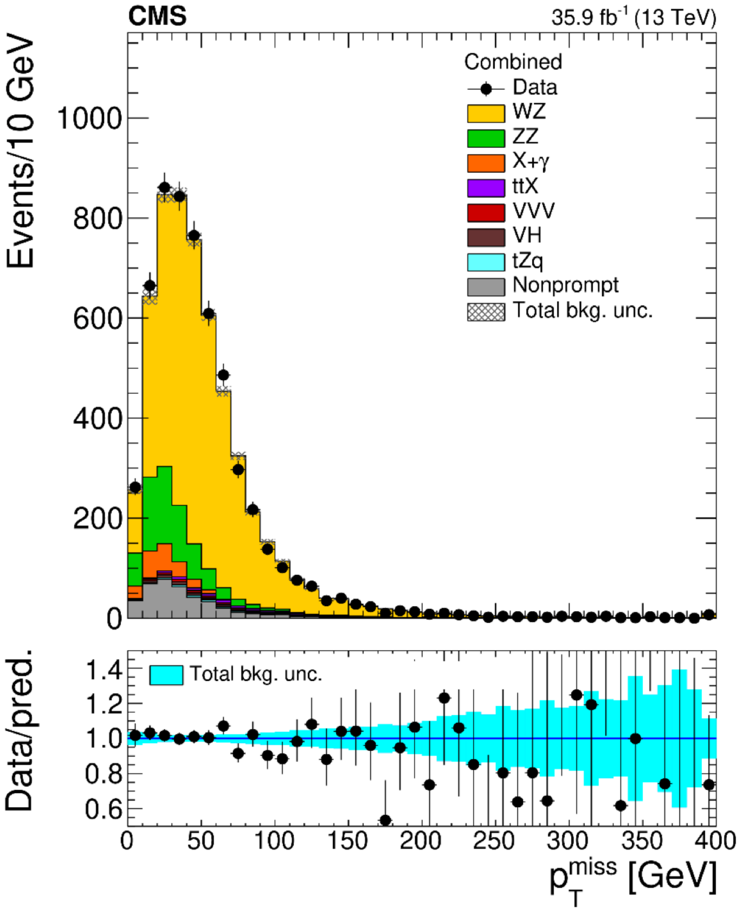
WZ event selection

- Cut & count analysis:
  - Three well-identified leptons, measured with 4 final flavor states: eee, eeμ, eμμ, μμμ
  - $N_{bjets} = 0$
  - Inv. Mass (3l) > 100 GeV
- Main backgrounds Z+jet /top estimated from data (inverting lepton isolation), ZZ (from MC)
- Great agreement between data and simulation

- **Z candidate mass window < 15 GeV**



- **Missing transverse momentum > 30 GeV**



WZ inclusive cross section

- Total phase space: 3 light leptons and 60 GeV < m_Z < 120 GeV at gen level

$$\sigma_{\text{tot}}(\text{pp} \to \text{WZ}) = 48.09^{+1.00}_{-0.96}\,(\text{stat})^{+0.44}_{-0.37}\,(\text{theo})^{+2.39}_{-2.17}\,(\text{syst}) \pm 1.39\,(\text{lumi})\ \text{pb}$$

- Systematic limited: ~ 5% (mainly from b tag and lepton ID)
- Uncertainty on inclusive cross section halved compared to previous results
- Compare to theoretical predictions, enough precision to be able to favor NNLO predictions over the NLO ones

MATRIX [arXiv:1604.08576]

$$\sigma_{\text{NLO}}(\text{pp} \to \text{WZ}) = 45.09^{+4.9\%}_{-3.9\%}\ \text{pb}$$

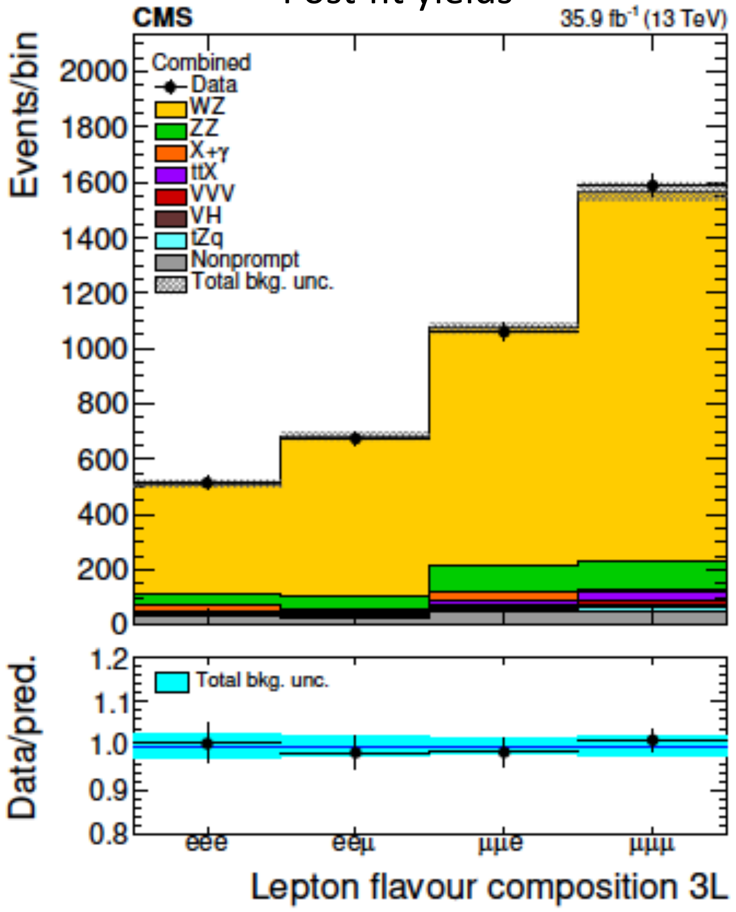
Perturbative QCD from MATRIX [arXiv:1711.06631]

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

POWHEG + PYTHIA

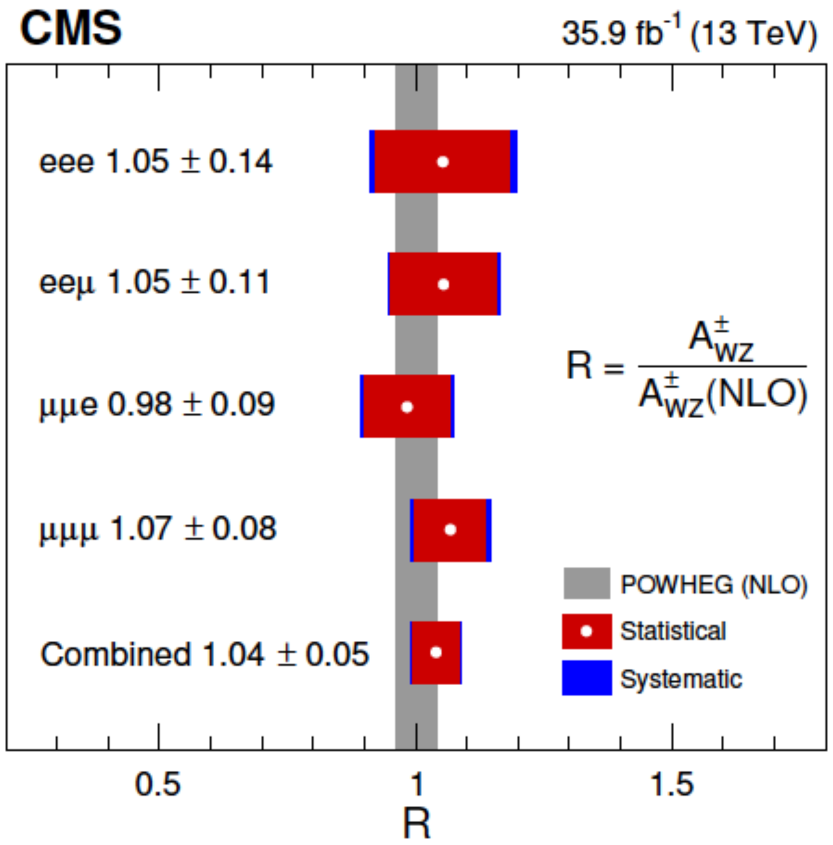
$$\sigma^{\text{NLO}}_{\text{Pow}} = 42.5^{+1.6}_{-1.4}\,(\text{scale}) \pm 0.6\,(\text{PDF})\ \text{pb}.$$

Post-fit yields



Charge-dependent measurements

- Production cross section depending on the W boson charge: W^+Z , W^-Z and the ratio
- Potential observable to constrain the u/d PDF
- Exactly the same procedure as in the inclusive case: most systematics cancelled in the ratio



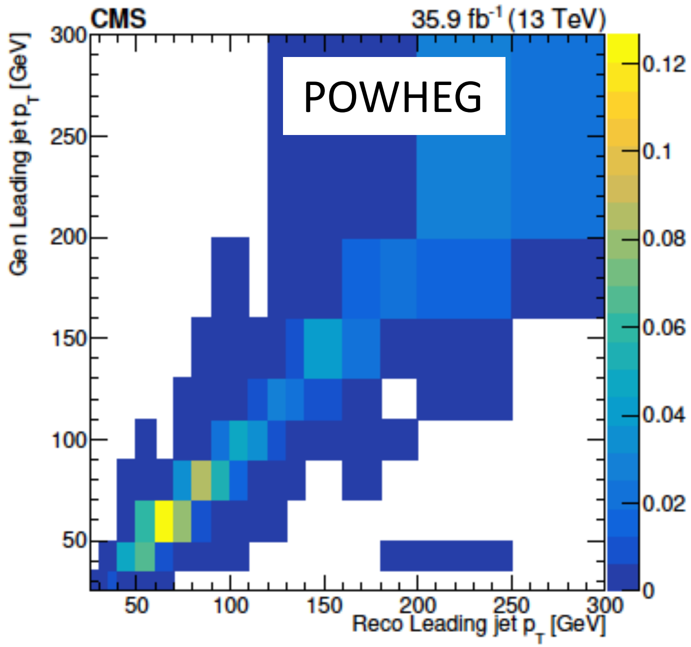
$$\sigma_{tot}(pp \to W^+Z) = 28.91^{+0.63}_{-0.61}\,(stat)^{+0.28}_{-0.25}\,(theo)^{+1.43}_{-1.31}\,(syst) \pm 0.80\,(lumi)\ pb,$$
$$\sigma_{tot}(pp \to W^-Z) = 19.55^{+0.45}_{-0.44}\,(stat)^{+0.17}_{-0.15}\,(theo)^{+0.97}_{-0.88}\,(syst) \pm 0.55\,(lumi)\ pb.$$

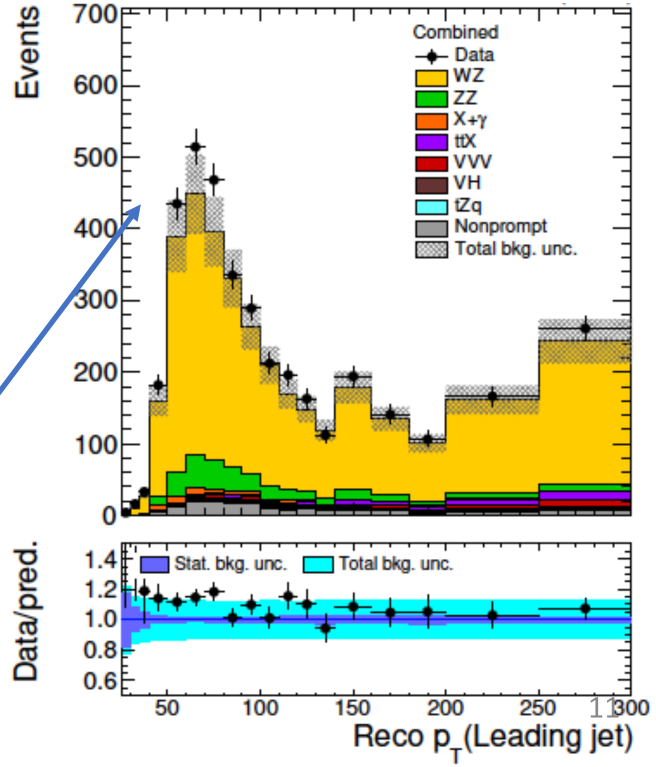
$$A^{+-}_{WZ} = \frac{\sigma_{tot}(pp \to W^+Z)}{\sigma_{tot}(pp \to W^-Z)} = 1.48 \pm 0.06\,(stat) \pm 0.02\,(syst) \pm 0.01\,(theo)$$

Compatible with POWHEG + PYTHIA prediction $A^{+-}_{WZ}(NLO) = 1.43^{+0.06}_{-0.05}$

WZ differential cross section

- Fiducial region at gen level defined by imposing requirements that mimic the lepton kinematic characteristics in the signal region:
  - 3 isolated leptons in the detector acceptance region (including tau decays)
  - Inv. Mass (3l) > 100 GeV
  - Z candidate mass window 60 GeV < m_Z < 120 GeV
- Unfolded (Tikhonov method) data to dressed-lepton level
  - Lepton momentum corrected by adding final-state-radiation photon
- Response Matrix using NLO MC (POWHEG)
  - Alternative MC MADGRAPH5_aMC @NLO
- Differences between generators are included as an additional systematic uncertainty.

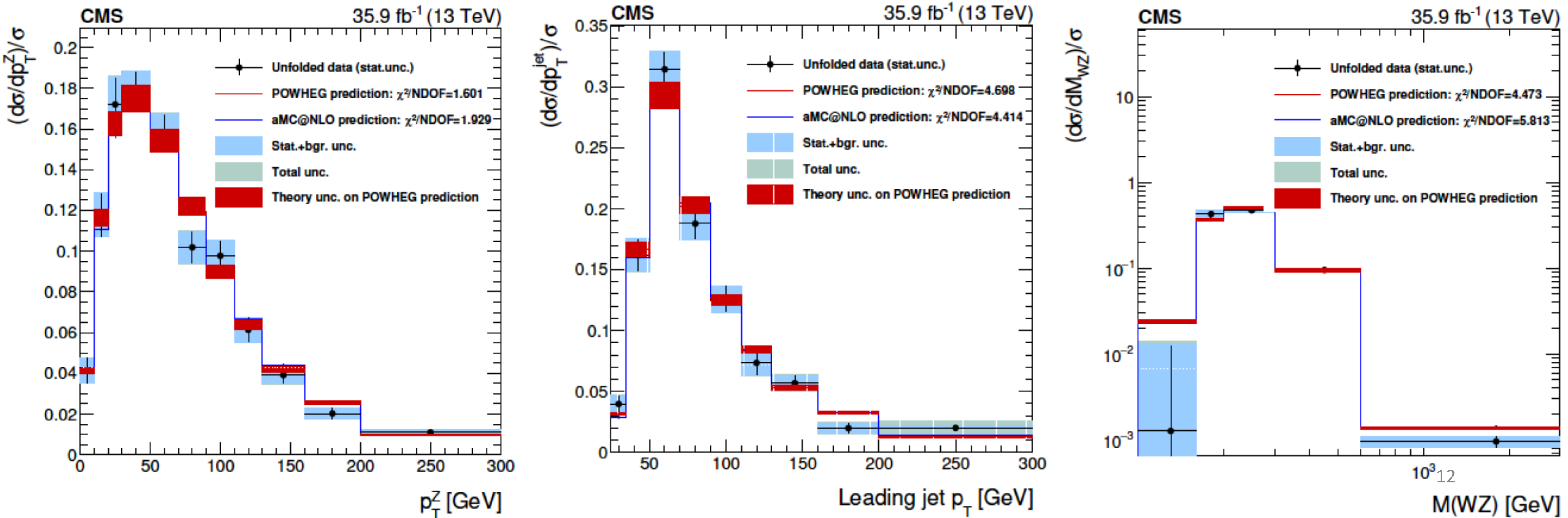




Additional 15% added in the error bar to account for NLO/NNLO

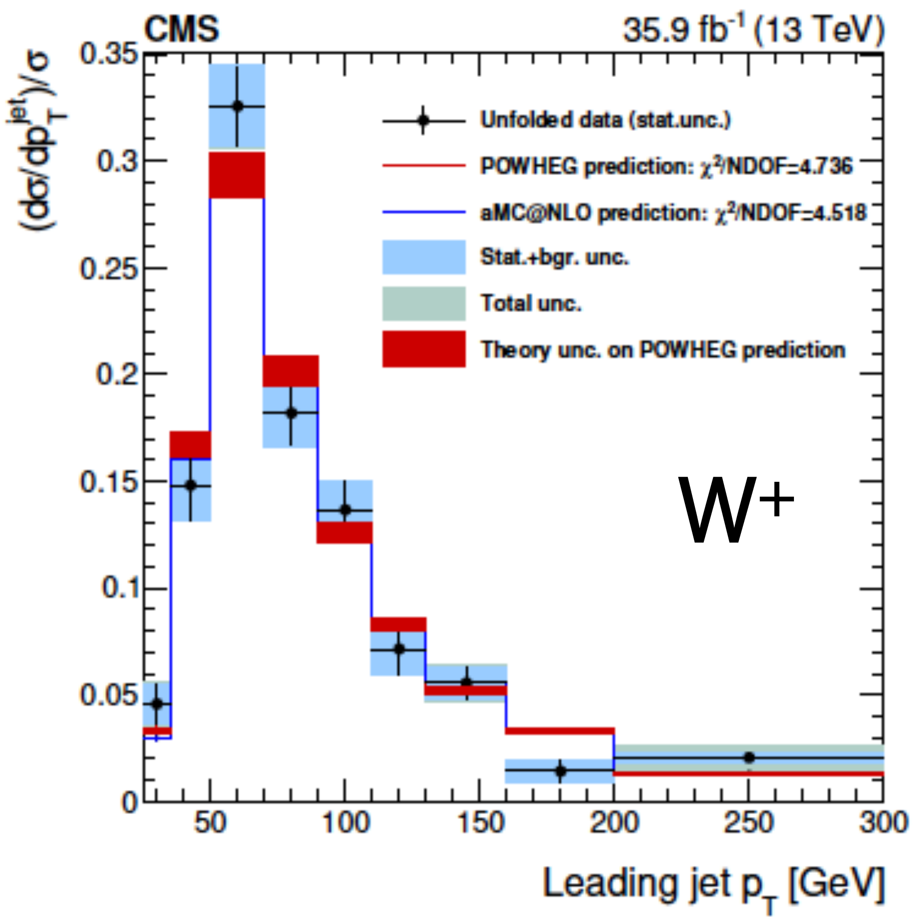
WZ differential cross section

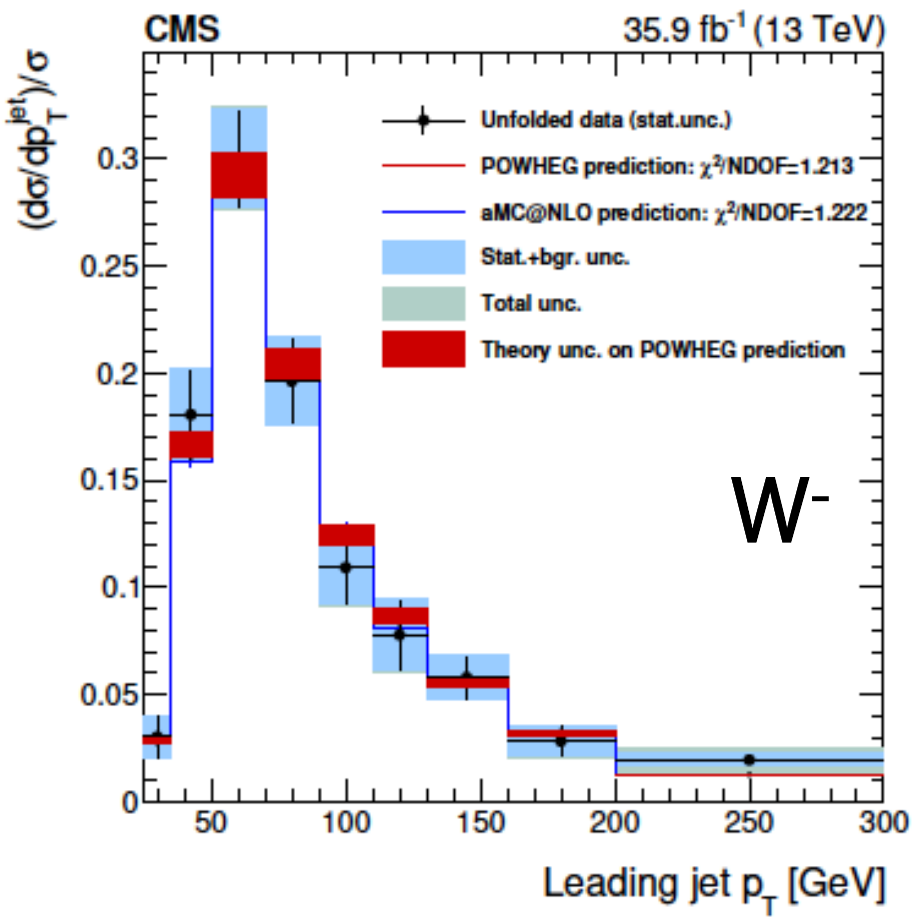
- p_T^Z : typical probe to BSM physics (at high values).
- p_T^{j1} : boost of the WZ system (recoil from ISR).
- M_{WZ}: variable used for the aTGC search (BSM physics sensitivity).
- Measurements and predictions agree well. Statistical uncertainties and background subtraction dominate.



WZ differential cross section

- First look at charge-dependent differential cross sections with thousands of WZ candidate events

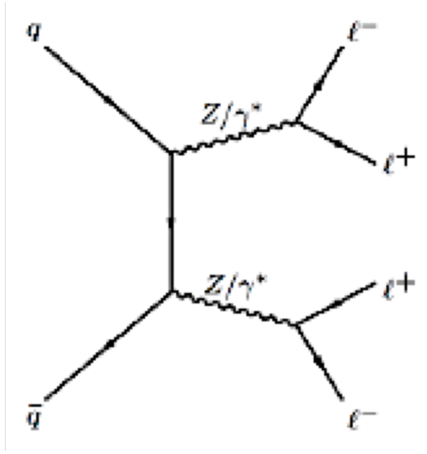




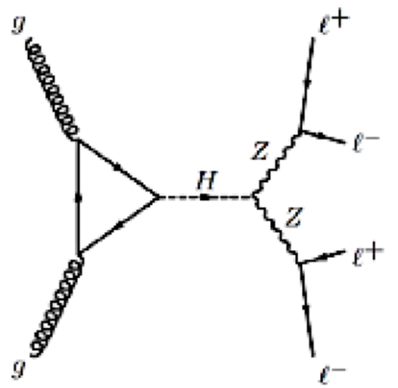
ZZ→4l cross section

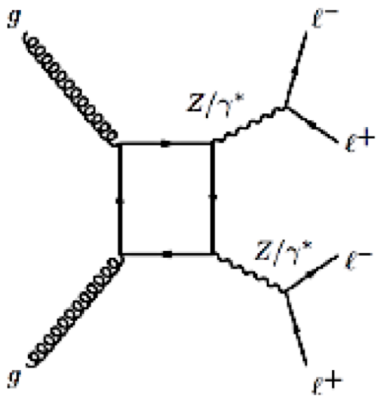
- Smallest diboson cross section but …
    - Clean experimental signature with virtually zero background
    - Main background to standard model Higgs → 4ℓ
- No TGC contribution in the SM
- Dominant process qq→ZZ. Sizeable higher order corrections.
    - NNLO QCD available for qq→ZZ
- gg→ZZ contributes to total rate.
    - NLO QCD available for gg→ZZ.
    - NLO correction for gg→ZZ is large (k=1.7) [*Phys. Rev. D 92, 094028*]
- Measure both fiducial and total cross sections for non resonant ZZ production, and both Z bosons on-shell in the mass range 60 GeV < m_Z < 120 GeV

POWHEG (or MG5 aMC@NLO) at NLO in QCD (NNLO normalization: k= 1.1)



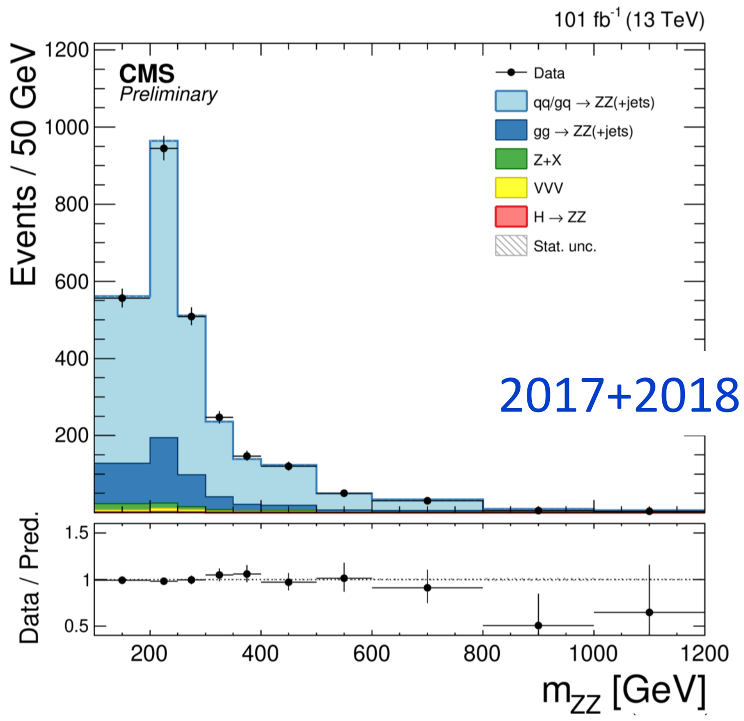
MCFM LO (NLO normalization: k= 1.7)



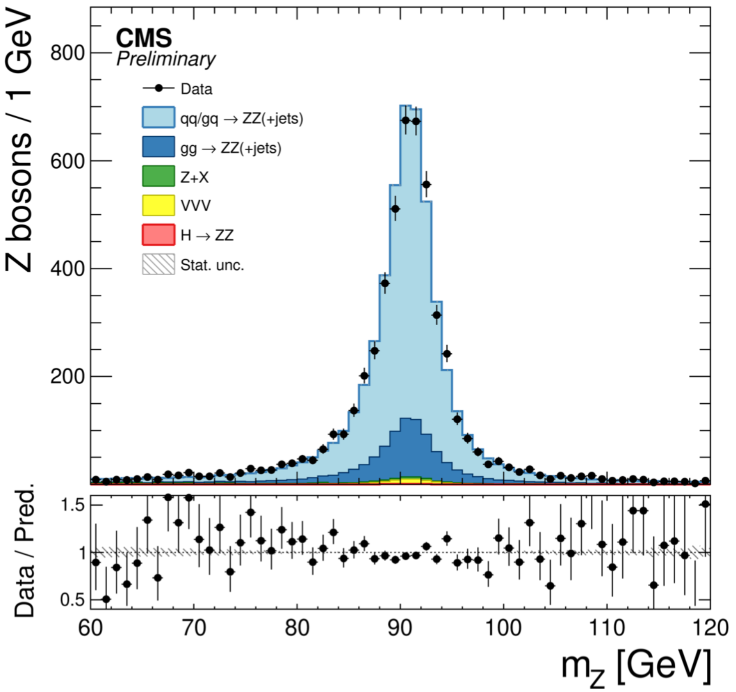


ZZ event selection

- Cut & count analysis:
  - Four well-identified leptons, measured with 3 final flavor states: eeee, eeμμ, μμμμ
  - 60 < Inv. Mass (Z_i) < 120 GeV
- Main backgrounds Z+jets estimated from data (no lepton isolation), VVV ≥ 4 prompt leptons (from MC)
- Great agreement between data and simulation



2017+2018 data



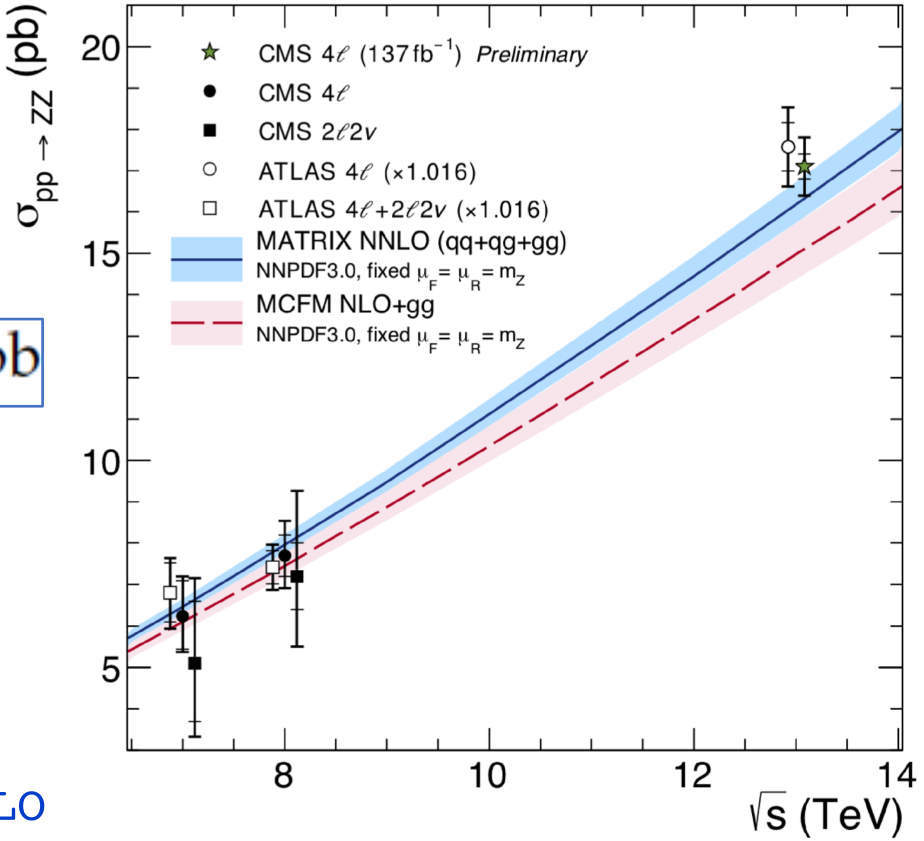
ZZ inclusive cross section

Phys. Rev. D**97**, 032005 (2018)
Eur. Phys. J. C 78 (2018) 165

- Total phase space: 4 final state leptons, each Z candidate within 60 GeV < m_{Zi} < 120 GeV at gen level
- ZZ result with full Run-II data: 137/fb: total cross section measurement using 41.5 fb-1 (2017) and 59.7 fb-1 (2018) data, combined with 2016 result

$$\sigma_{tot} = 17.1 \pm 0.3\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})\ \text{pb}$$

- Systematic + theory ~3% . Dominant uncertainty from lepton Identification
- Good Agreement with NNLO predictions: Including NLO EW and QCD corrections



MATRIX Perturbative QCD [arXiv:1711.06631]

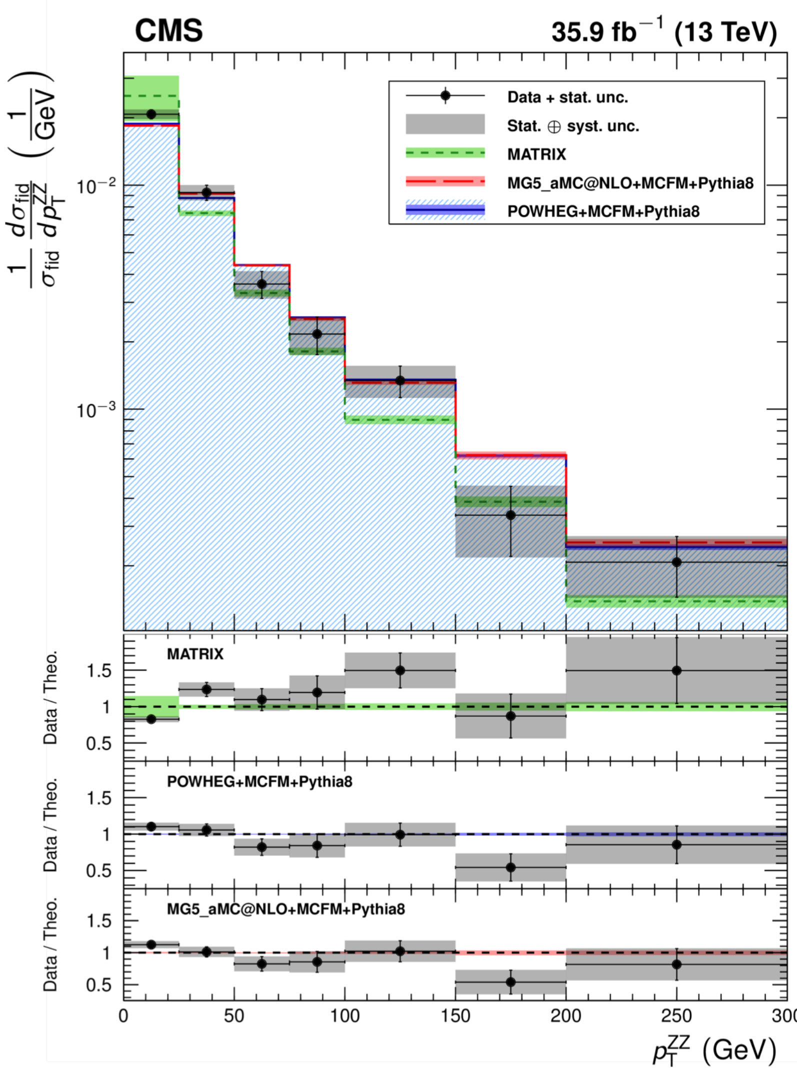
MCFM NLO + gg LO

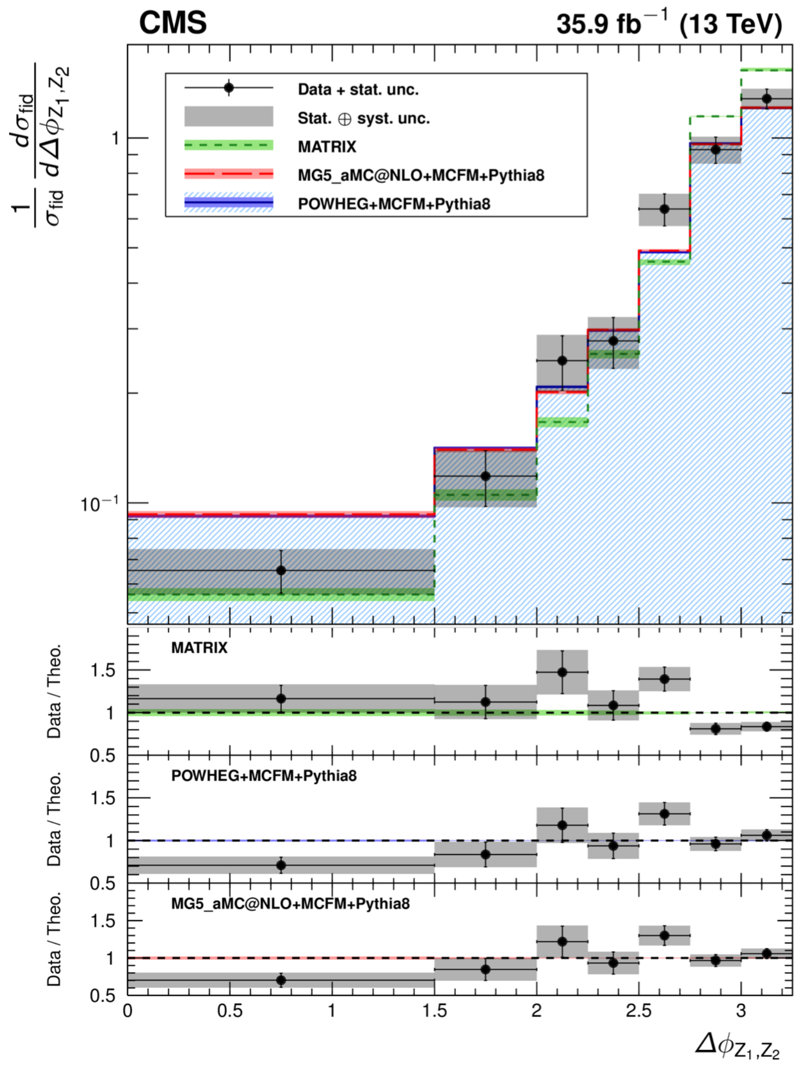
$$\sigma^{NNLO\ QCD} = 16.2^{+0.6}_{-0.4}\ pb$$

$$\sigma^{NLO\ QCD} = 15.0^{+0.7}_{-0.6}(PDF) \pm 0.2(scale)\ pb$$

ZZ differential cross section

- Fiducial region at gen level defined by imposing requirements that mimic the lepton kinematic characteristics in the signal region:
  - 4 isolated leptons in the detector acceptance region (excluding tau decays)
  - Each Z candidate within 60 GeV < m_{Zi} < 120 GeV
- Unfolded (iterative technique) data to dressed-lepton level
- In general good agreements with predictions
  - Slightly softer pt spectrum of the ZZ system





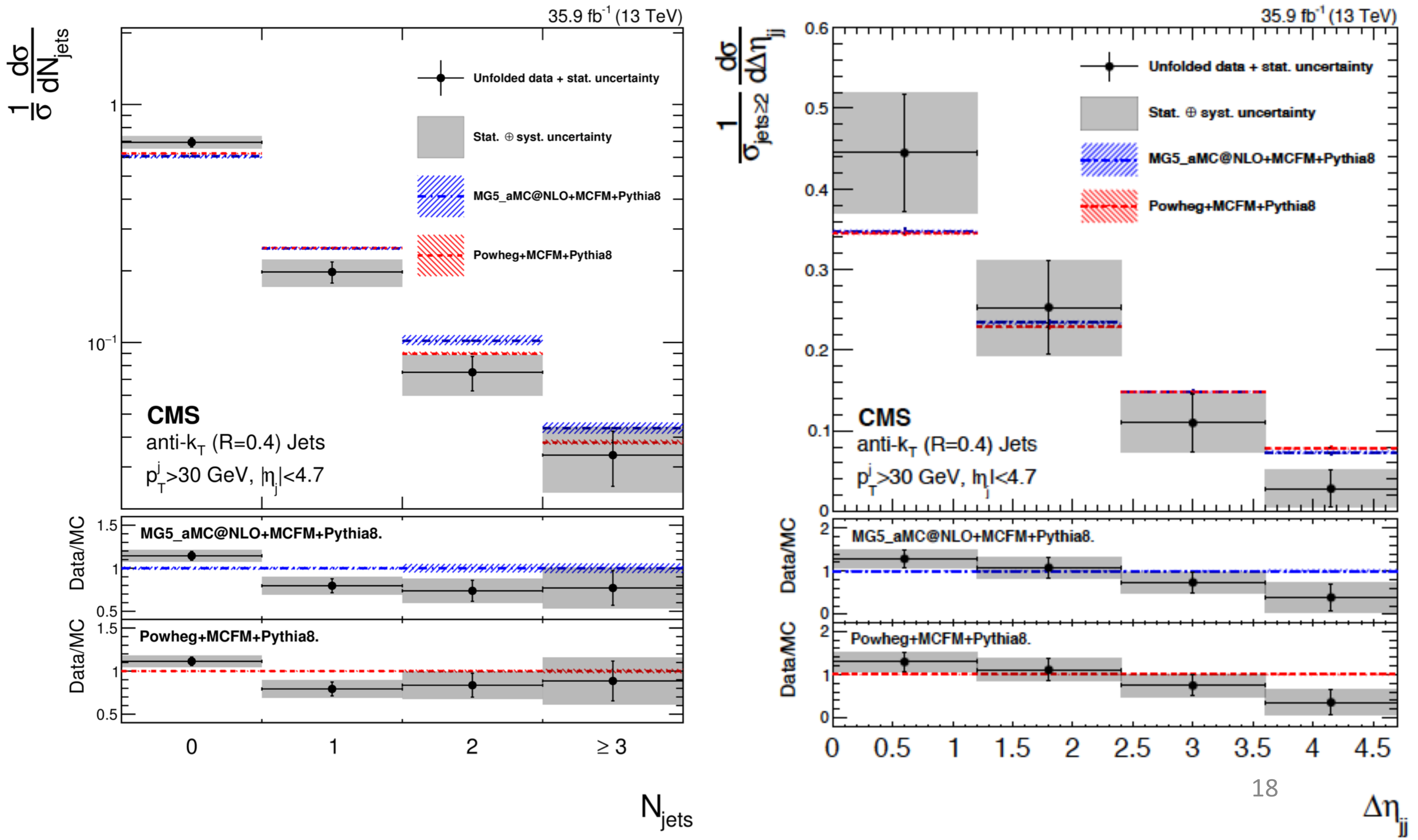
More distributions in the paper Eur. Phys. J. C 78 (2018) 165

ZZ+jets differential cross section

- σ(ZZ→llll) on the jet multiplicity and the kinematic properties of two pT-leading jets
- Provide an important test of the QCD corrections to ZZ production

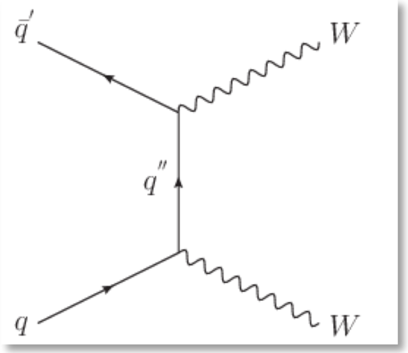
EWK qq → Z + 2jets: PHANTOM (including tribosons ZZV(V→jets) as well as diagrams with quartic vertices)

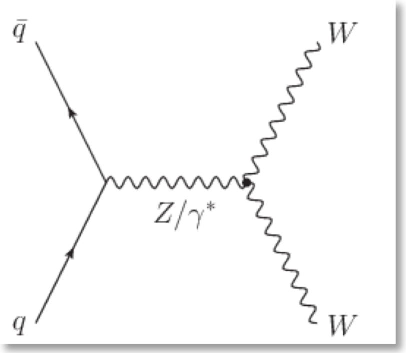
- Overall statistically dominated in the unfolding.
- Njets discrepancies in same direction as the pt of the ZZ system
- Some key VBS variables ($\Delta\eta_{jj}$) are less well modeled



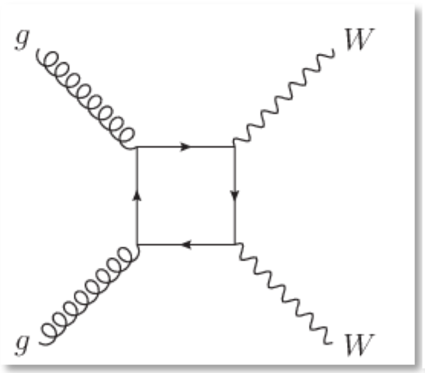
WW cross section

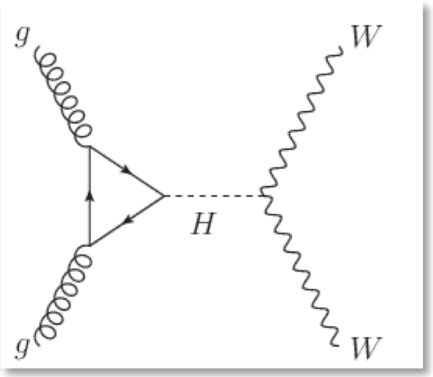
qq → W^+W^-
POWHEG at NLO in QCD (NNLO normalization)



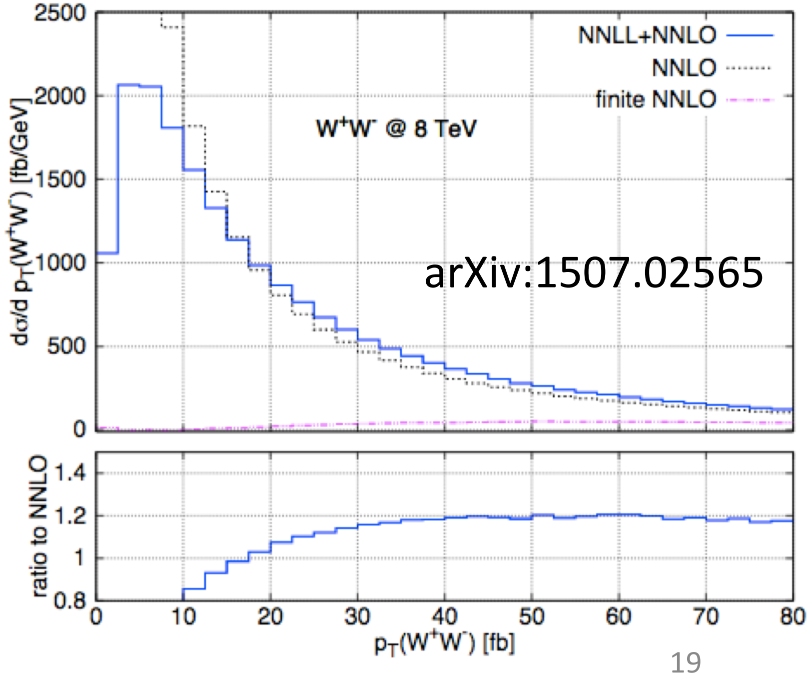


gg→ W^+W^- (~ 5%)
MCFM at LO in QCD (NLO normalization: k=1.4)
Including interference term with gg → H



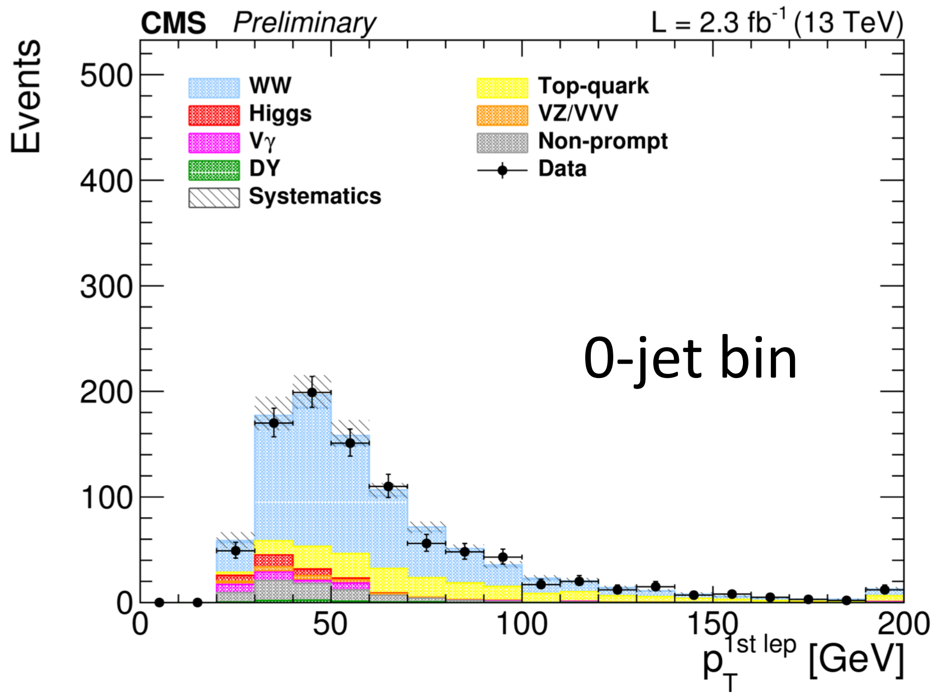


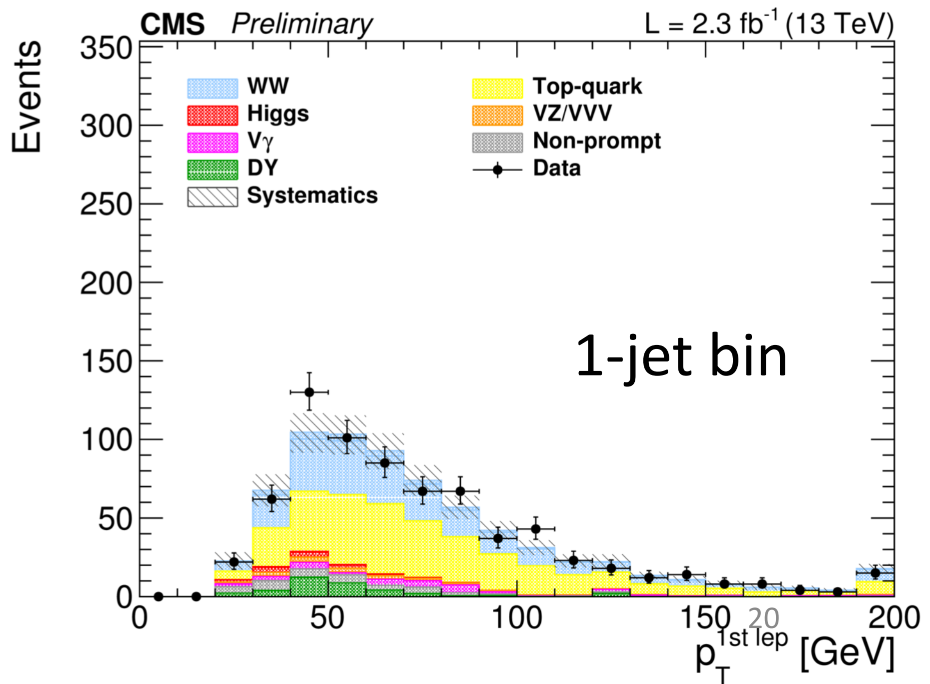
- W^+W^- production cross section larger than $W^\pm Z$ and ZZ production.
- qq→WW known to NNLO [arXiv:1408.5243] and gg→WW NLO [arXiv: 1511.08617].
- Resonant production (gg → H → WW) considered as background in his analysis (only 3% of expected signal yields).
- **The 0-jet (or 1-jet bin) veto applied** in this analysis makes the kinematical distributions particularly sensitive to higher-order QCD corrections.
  - reweight p_T(WW) of the qq → WW MC to a NNLO+NNLL p_T resummation calculation



WW event selection

- Preliminary result from a cut & count analysis (only 2.3/fb)
  - Two well-identified leptons in the **eμ** channel.
  - Missing transverse momentum > 20 GeV
  - min(proj. MET, proj. Track MET) > 20 GeV
  - Separated between events with 0 or 1 reconstructed jet with E_T > 30 GeV and |η| < 4.7
  - N_{bjets}= 0
- Main backgrounds non-promt leptons estimated from data (inverting lepton isolation), $Z \rightarrow \tau\tau$ and top (from MC)
- Great agreement between data and simulation testimony of incredible effort from both theory and experimental communities.





WW inclusive cross section

- Total cross section measured for the independent 0-jet and 1-jet categories and the combined result.
- Combination result with a precisión ~ 5% (stat.) , 10% (syst.)
  - Experimental systematics are the dominant ones

Category	Value ± stat. ± exp. syst. ± theo. syst. ± lumi. [pb]
0-jet	113.6 ± 6.3 ± 5.1 ± 6.5 ± 3.3
1-jet	135.3 ± 15.4 ± 34.0 ± 14.4 ± 6.0
Combination	115.3 ± 5.8 ± 5.7 ± 6.4 ± 3.6

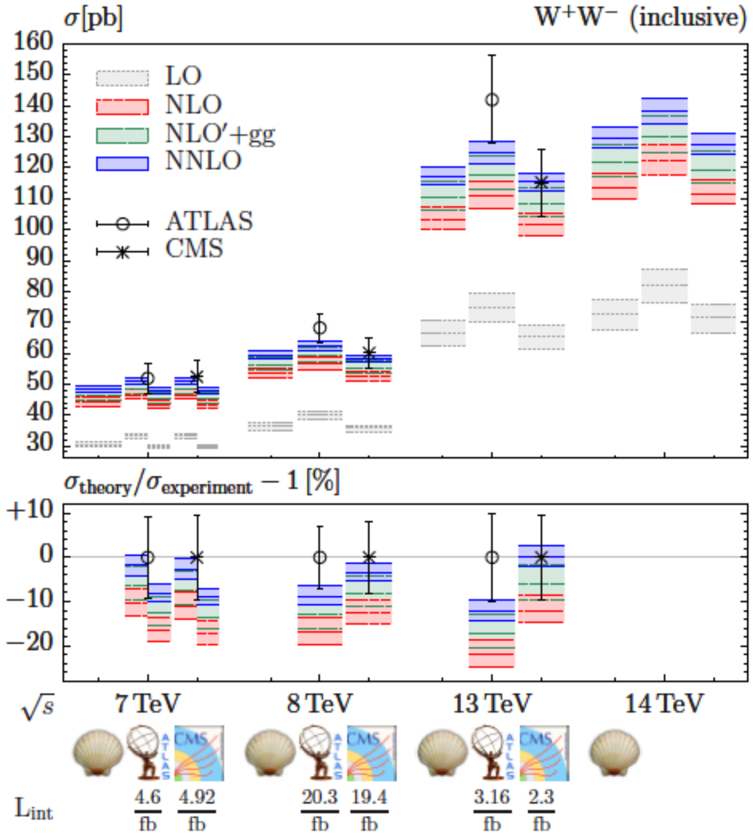
- Compatible with NNLO predictions

qq NNLO Perturbative QCD + gg NLO

$$\sigma^{\rm NNLO}(pp \to W^+W^-) = 120.3 \pm 3.6 \text{ pb}$$

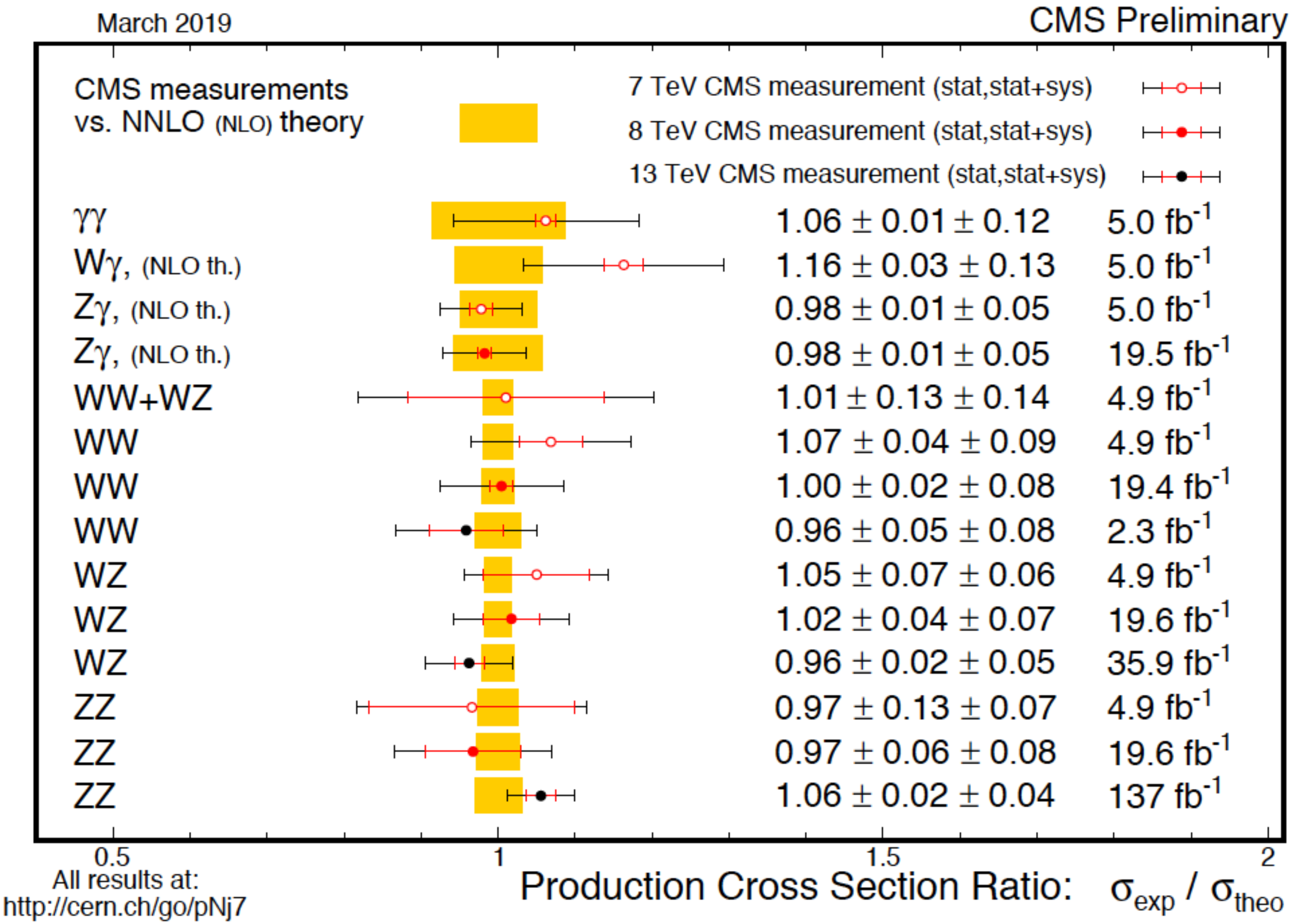
- Working on a final result with more statistic and differential cross section distributions.

MATRIX NNLO



[ATLAS collaboration (2012 – 2017), CMS collaboration (2012 – 2016)]

CMS VV measurements



Conclusions

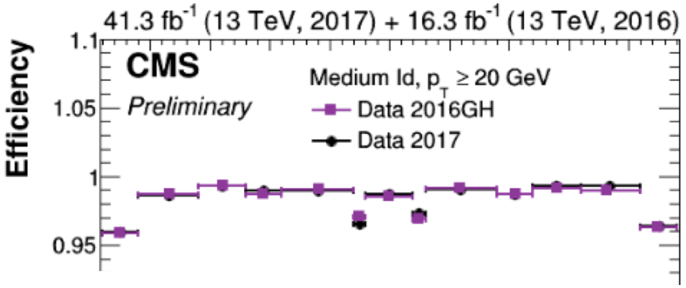
- Most of the results of diboson measurements at 13 TeV in the fully leptonic decay channels are done with partly run 2 data
  - ZZ total cross section already produced with the full Run2 data
  - Reached precision of ~ 5%
  - Good agreement with predictions at NNLO in QCD
- We have entered the era of precision cross section measurements in multiboson physics
  - Inclusive measurement no longer statistically limited
  - We should consciously be mapping out a program to even better precision (2% … 1%?)
- Differential measurements
  - We now have sufficient sensitivity to see differences with state of the art MCs
  - We should move quickly to any better predictions and MCs
- Full results on Run 2 data at 13 TeV on going:
  - Will reduce statistical uncertainty
  - Larger luminosity opens the possibility of more detailed studies in tails
  - EW corrections become more important: especially in the tails of diboson production, etc..

Backup slides

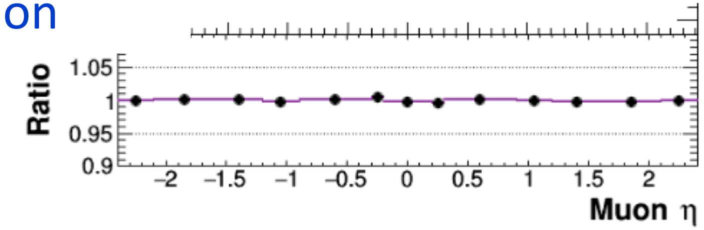
Ingredients for precision measurements

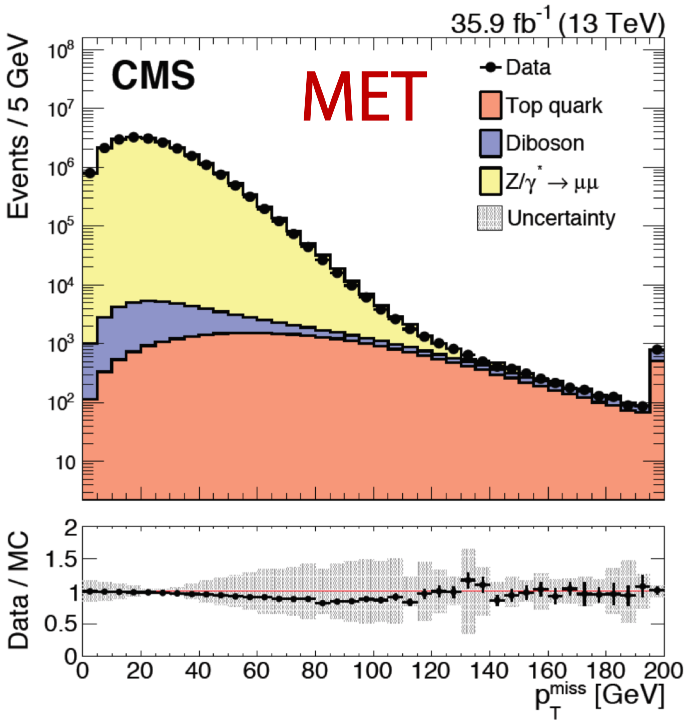
- Object performance is a fundamental key for any precision measurement
  - Stable in the barrel (tracker coverage)
  - Larger variations due to detector transition and acceptance

- High efficiency on lepton reco and identification

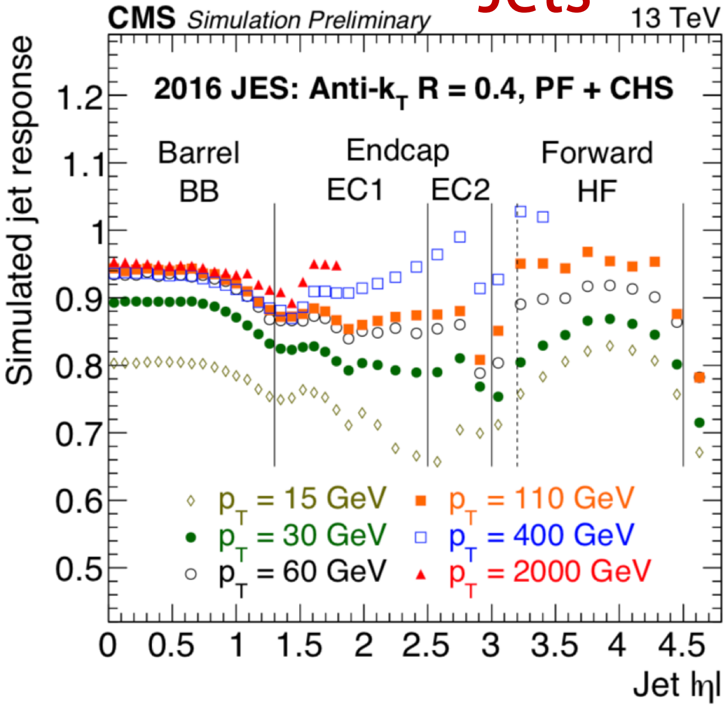


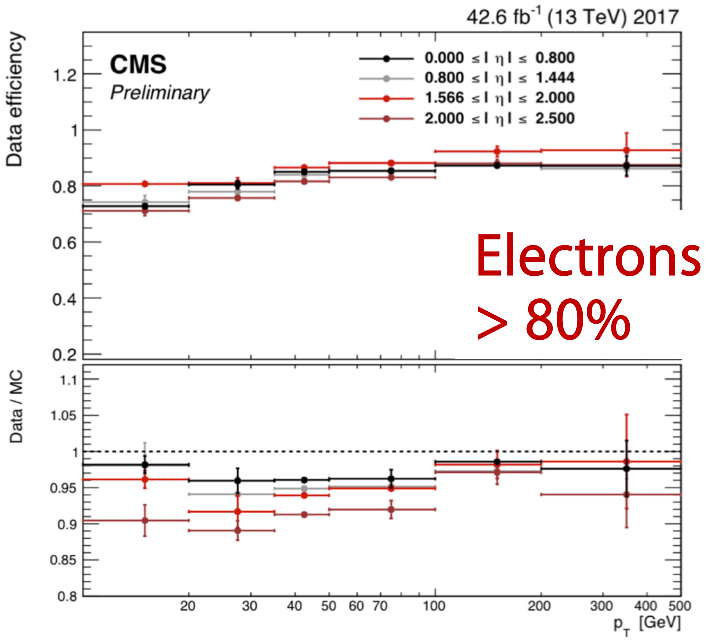
Muons > 95%





Jets





Electrons > 80%

WZ theory predictions

- POWHEG (NLO QCD sample) + Pythia: “nominal” simple.
  - Additional partons at ME using the merging scheme FxFx
- Matrix at NLO in QCD
- Matrix at NNLO
- PDF: NNPDF30NLO
- aTGC: reweighted at LO signal samples generated with Madgraph at NLO or different pt^Z to enrich in the high energy regions.
- At generator level to avoid infrared divergences: veto events with M(ll`) > 4 GeV

WZ selection

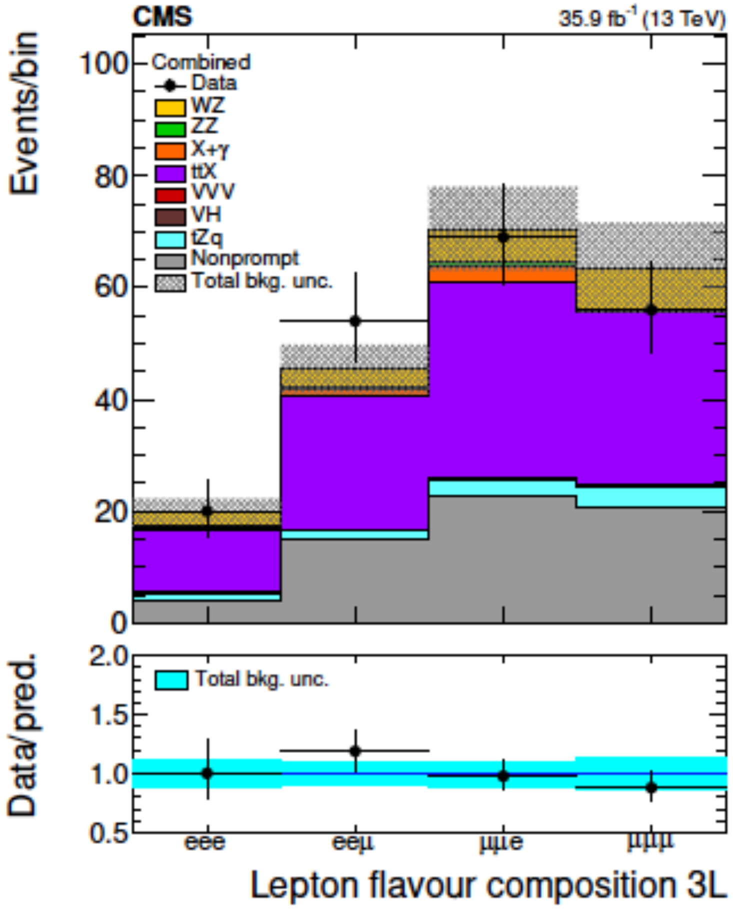
- Non-prompt leptons (Z+jets, tt) from tight to loose method
- ZZ from MC

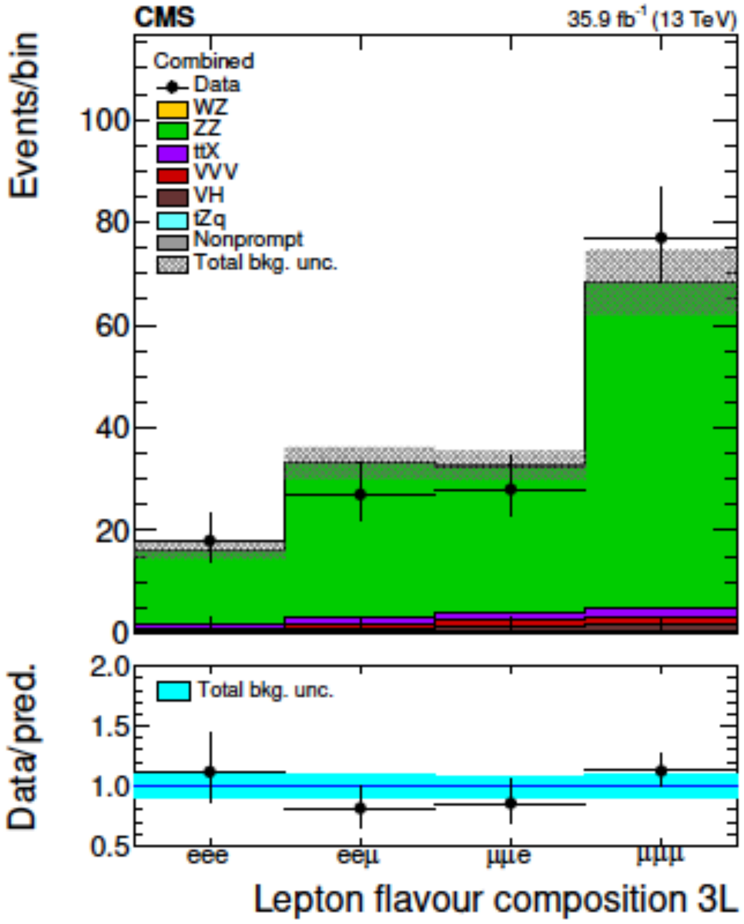
$$q_{ZZ} = 0.99 \pm 0.09.$$

- ttZ and tZq from MC CR

$$q_{t\bar{t}Z+tZq} = 1.09 \pm 0.20.$$

- tt bar background (mainly ttZ and tZq):
  - inv. Mass of Z candidate within 15 GeV the Z mass peak
  - B veto requirement (medium WP for CSV, ~70% efficiency)
- Non prompt (mainly Z+jets):
  - MET > 30 GeV
- ZZZ (tri-leptons): vetoing events with a 4th loose lepton





WZ uncertainties

- B tagging identification ~2.5 %
- Lepton identification and trigger efficiency ~2%
- Non-promp background estimation ~1%

- Theoretical uncertainties: scale factorization and renormalization and PDF+alpha s

Source	Combined	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
Electron efficiency	1.9	5.9	3.9	1.9	—
Electron energy scale	0.3	0.9	0.2	0.6	—
Muon efficiency	1.9	—	0.8	1.8	2.6
Muon momentum scale	0.5	—	0.7	0.3	0.9
Trigger efficiency	1.9	2.0	1.9	1.9	1.8
Jet energy scale	0.9	1.6	1.0	1.7	0.8
b-tagging (id.)	2.6	2.7	2.6	2.6	2.4
b-tagging (mis-id.)	0.9	1.0	0.9	1.0	0.7
Pileup	0.8	0.9	0.3	1.3	1.4
ZZ	0.6	0.7	0.4	0.8	0.5
Nonprompt norm.	1.2	2.0	1.2	1.5	1.0
Nonprompt (EWK subtr.)	1.0	1.5	1.0	1.3	0.8
VVV norm.	0.5	0.6	0.6	0.6	0.5
VH norm.	0.2	0.2	0.3	0.2	0.2
$t\bar{t}$ V norm.	0.5	0.5	0.5	0.5	0.5
tZq norm.	0.1	0.1	0.1	0.1	0.1
X+γ norm.	0.3	0.8	< 0.1	0.7	< 0.1
Total systematic	4.7	7.8	5.8	5.4	4.6
Integrated luminosity	2.8	2.9	2.8	2.9	2.8
Statistical	2.1	6.0	4.8	4.1	3.1
Total experimental	6.0	10.8	8.0	7.5	6.3
Theoretical	0.9	0.9	0.9	0.9	0.9

ZZ theory predictions

- POWHEG (NLO QCD sample) for qq production and LO for quark-gluon.
  - Scaled to NNLO (k=1.1)
- gg simulated with MCFM at LO (including ZZ, Zg*, Z, g*g* and gg→H)
  - Scaled to NLO both ZZ and Higgs (k=1.7=)
- Higgs boson decay is modelled with JHUGEN
- PDF: NNPD31_lo_as_0130 (NNPDF3.0 for ZZ+jets analysis)
- aTGC:
- At generator level to avoid infrared divergences: veto events with M(ll`) > 4 GeV

ZZ uncertainties

- Dominated by lepton identification: ~2-8 %

Uncertainty	Range of values
Lepton efficiency	2–8%
Trigger efficiency	1–2%
Background	0.6–1.3%
Pileup	1%
PDF	1%
μ_R, μ_F	1%
Integrated luminosity	2.3% (2017) 2.5% (2018)

- Theoretical uncertainties: scale factorization and renormalization and PDF+alpha_s
- Additional systematic from NLO to NNLO (or LO to NLO in gg): ~1%

WW selection

Variable	Selection
$q_{\ell_1} \times q_{\ell_2}$	< 0
p_{T}^{ℓ} [GeV]	> 20
$PFE_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20
min(proj. $E_{\mathrm{T}}^{\mathrm{miss}}$, proj. track$E_{\mathrm{T}}^{\mathrm{miss}}$) [GeV]	> 20
$p_{\mathrm{T}}^{\ell\ell}$ [GeV]	> 30
$m_{\ell\ell}$ [GeV]	> 12
Additional leptons ($p_{\mathrm{T}}^{\ell} > 10$ GeV)	veto
Top-tagging veto	applied

- Tight lepton ID/Isolation — **W→lν + jets (jet→fake lepton)**
- min(proj. MET, proj. Track MET) > 20 GeV — **Z→tautau + jets (fake MET)**
- Apply top-veto based on jet b-tagging and soft muon tagging — **tW and ttbar production**
- Reject events with a third lepton passing identification requirements — **WZ backg.**

WW uncertainties

- Experimental uncertainty dominant ~4.9%:
  - Lepton ID, trigger, btag
  - MET and JES, JEC
- Theoretical uncertainties ~5%:
  - NNLL reweithing
  - UE and PS
- Non promp background ~3%

Uncertainty source	Propagation to cross section (%)
Experimental uncertainties	4.9
QCD scales and higher order effects	3.2
PDFs	0.4
Underlying event and parton shower	3.7
Non-prompt normalization	3.0
Top-quark normalization	2.0
$W\gamma^*$ normalization	0.3
Simulation and data control regions sample size	1.4
Total systematic uncertainty	7.4
Total statistical uncertainty	5.0
Luminosity	3.0
Total uncertainty	9.5

Prospects for HL-LHC

- Future LHC upgrades will probe mass scales of a few TeV at 14 TeV with 3 ab^{-1}, or potentially even up to ten TeV at 27 TeV with 15ab^{-1}.
- gg becomes important contribution of the total NNLO cross section at √s = 14 (27) TeV (i.e. gg→ ZZ 8%(11%))
- Significant improvement in sensitivity on aTGC

MATRIX NNLO

W+W−(blue)
W±Z(green)
ZZ(orange)

at14TeV (dashed) and 27TeV (solid).