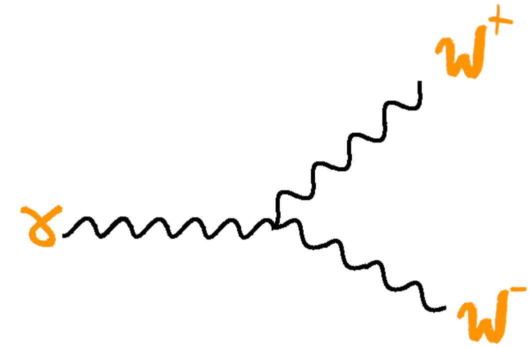
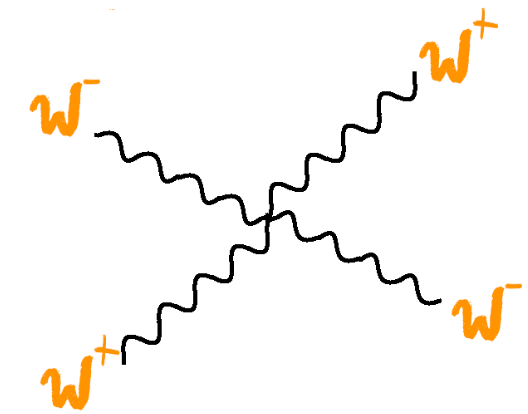
Electroweak physics in multiboson final states at CMS

Gian Luca Pinna Angioni

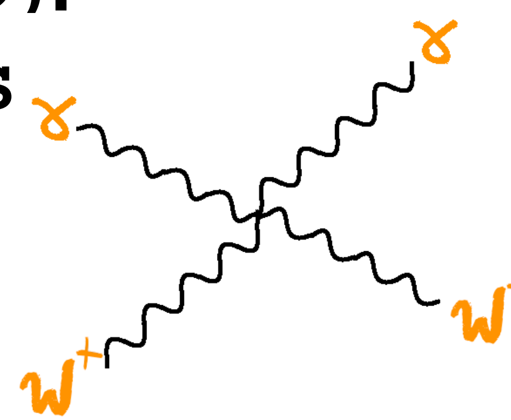
INFN Torino

Physic Motivation

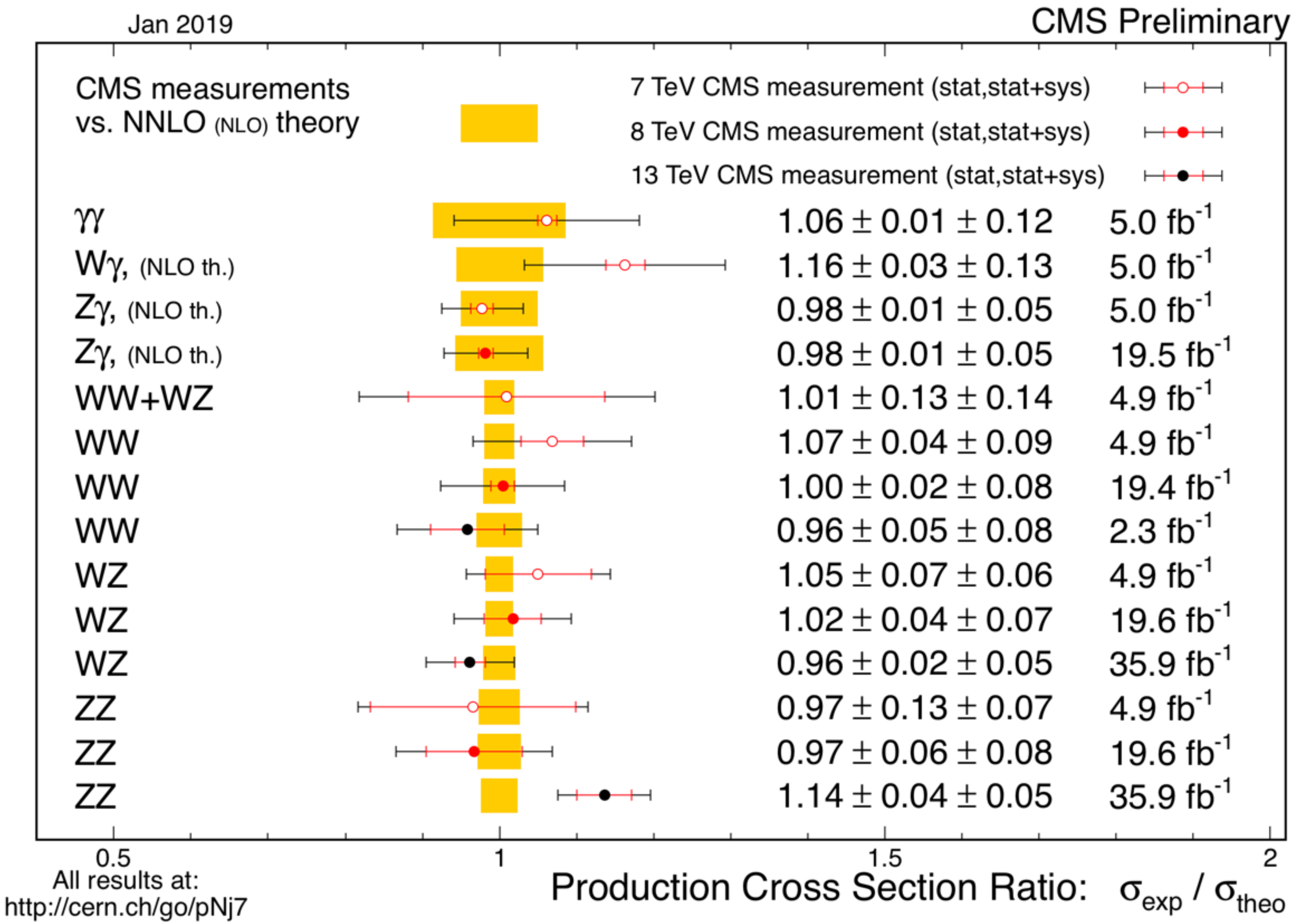




- Test of the perturbative calculations.
  - QCD corrections and hadronization models.
- Test of electroweak sector of SM.
- Sensitive to the interaction between gauge bosons via triple/quartic gauge couplings (TGC,QGC).
- Sensitive to anomalous triple/quartic couplings (aTGC,aQGC)
- Important test of the electroweak symmetry breaking
  - E.g. Higgs boson and unitarity of the VV scattering amplitude at all energies.



CMS multi boson standard model results overview



Selection of analysis

- Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s}$ = 8 and 13 TeV
  - https://doi.org/10.1016/j.physletb.2018.11.007
- Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s}$ = 13 TeV
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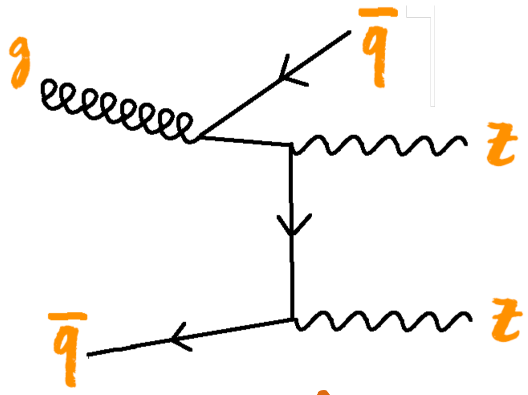
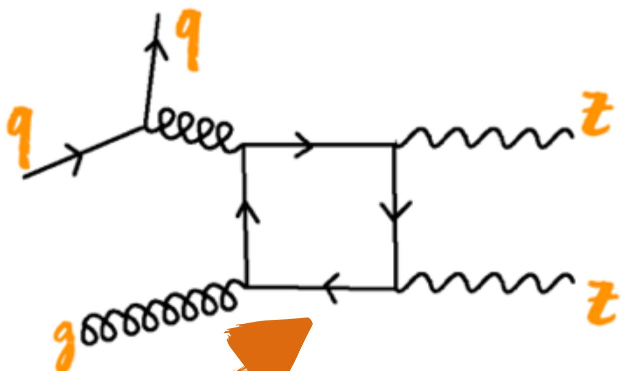
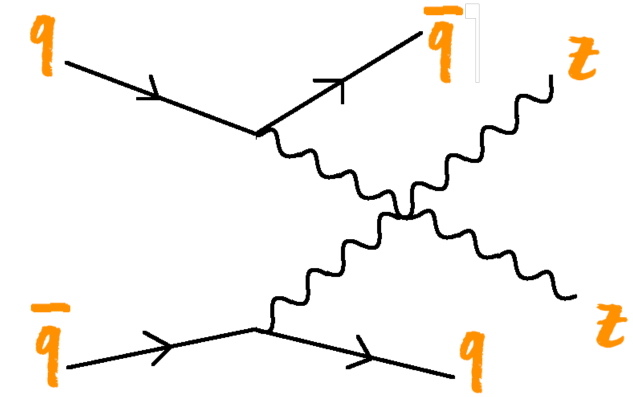
ZZ+jets







Signal

qq->ZZ +jets, gg->ZZ(box) +jets , VBS

Main Background

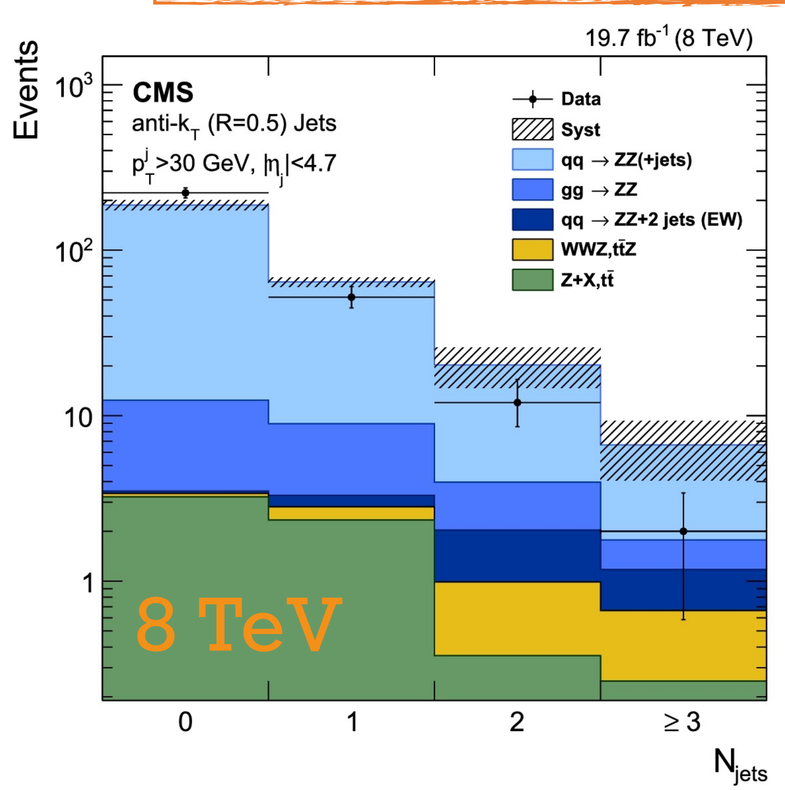
DY+jets

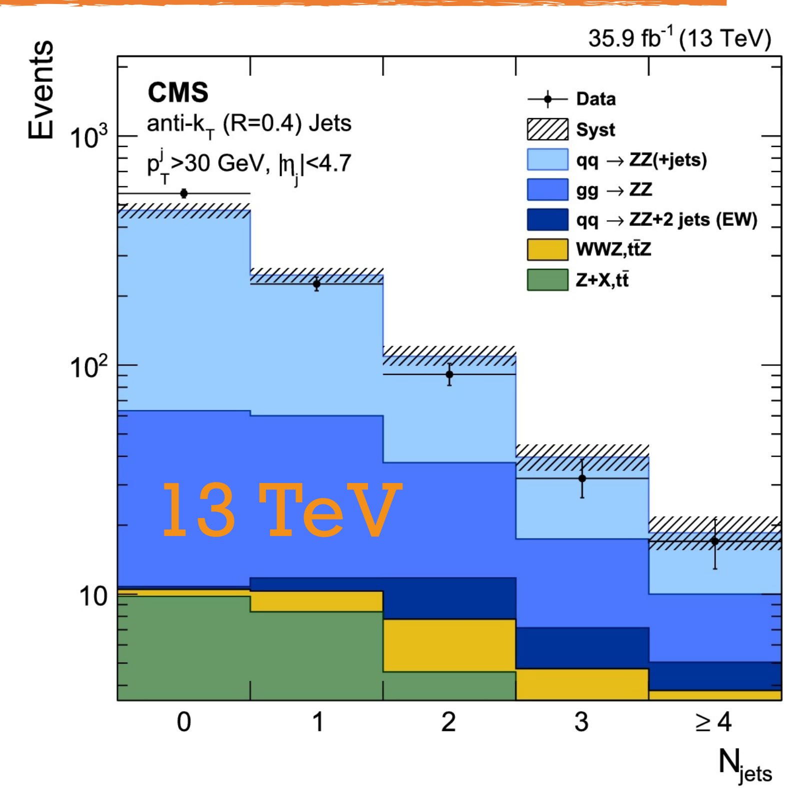
Final state

ZZ+jets→4ℓ+2 jets (ℓ=μ,e)

$\sqrt{s}$ = 13 TeV L = 35.9 fb−1

$\sqrt{s}$ = 8 TeV L = 19.7 fb−1





Differential cross section:

#Jets,

#Jets (η<2.4) ,

p_T and η of leading jet,

p_T and η of sub-leading jet,

m_{JJ}, $\Delta\eta_{JJ}$.

ZZ+jets cross sections

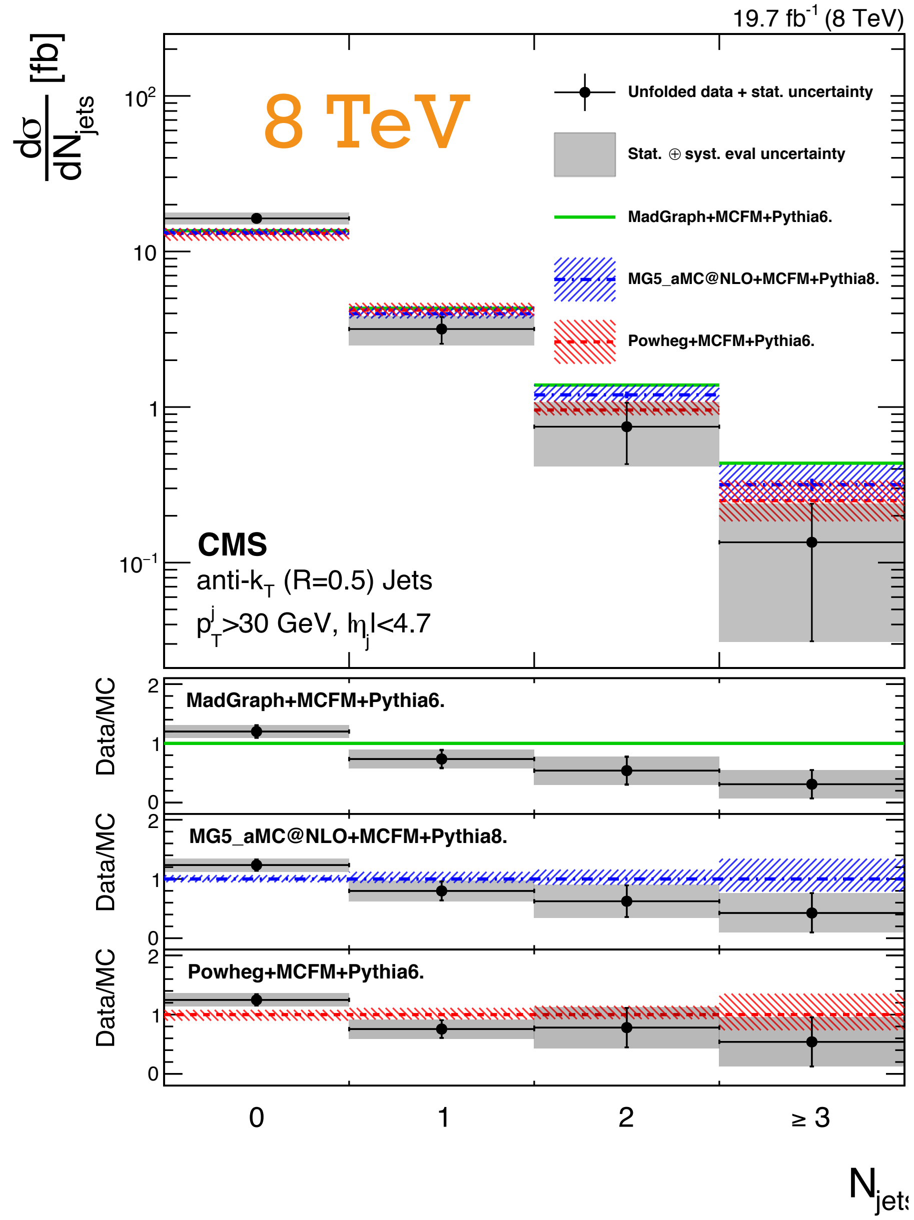
- The distributions is unfolded with Bayesian (D'Agostini) regularisation algorithm.
- The model for the detector resolution is derived from MadGraphAMC@NLO + MCFM generators interfaced with PYTHIA8. (MadGraph +MCFM +PYTHIA6 for 8 TeV)
- Normalized and absolute differential cross section presented.
- Overall good agreement

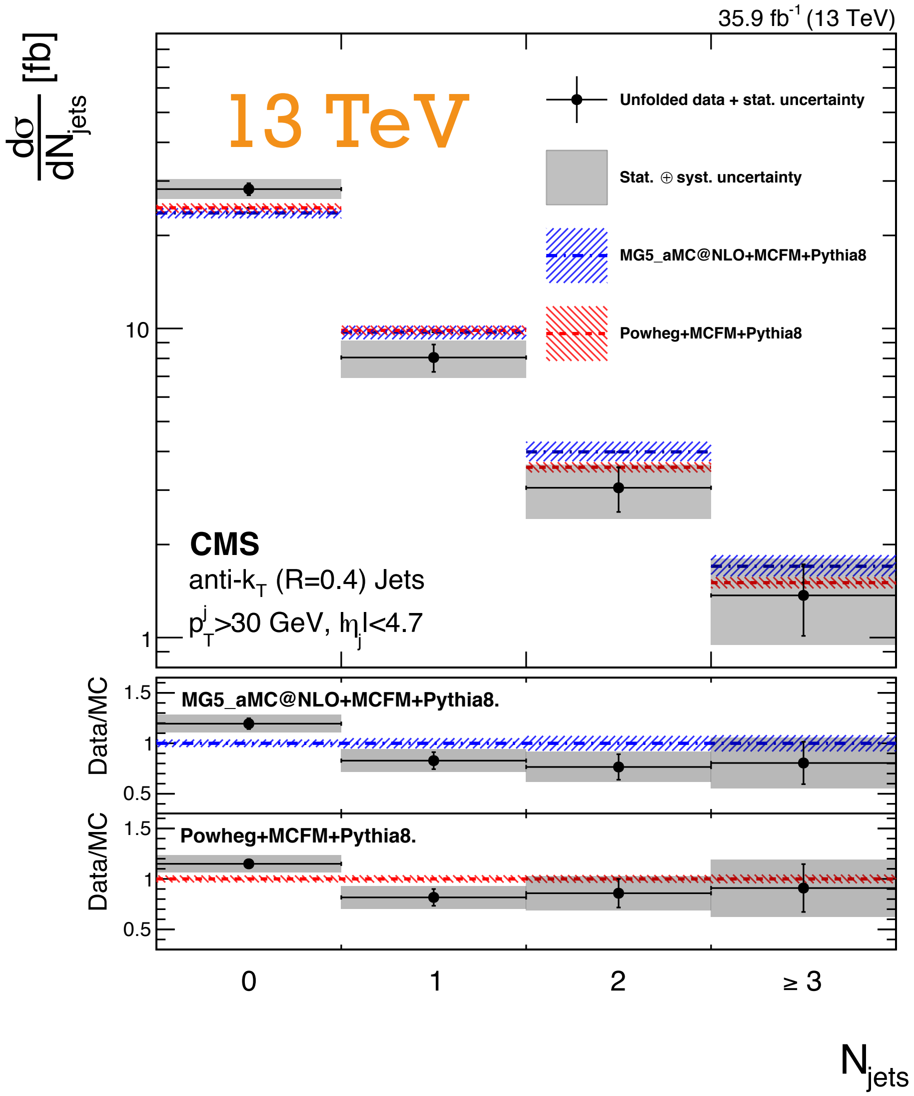
13 TeV Fiducial Phase space

- $p_T^{\ell} > 5$ GeV
- $|\eta^{\ell 1}| \leq 2.4$
- $60 < m_Z < 120$ GeV.
- $p_T^{jet} > 30$ GeV

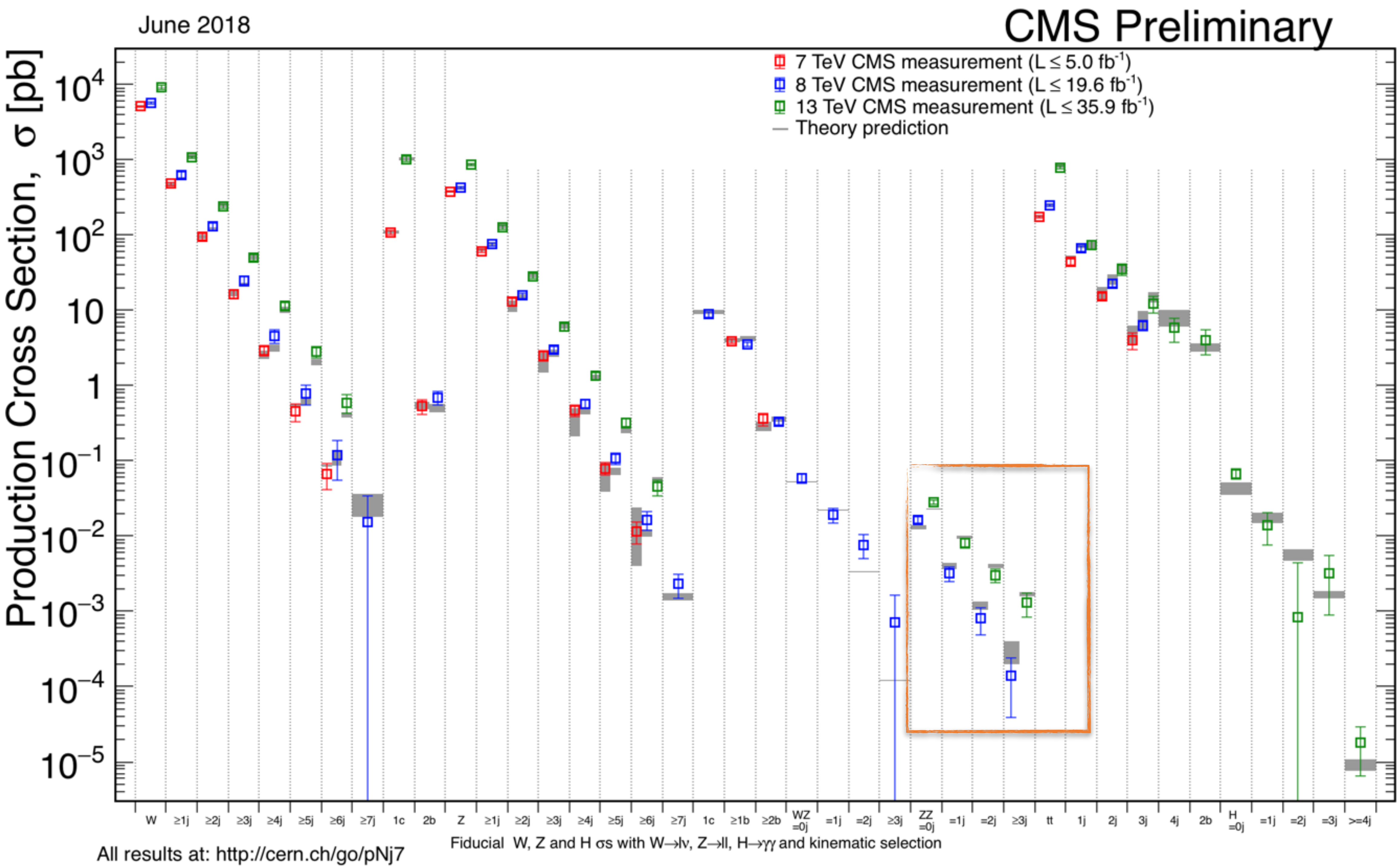
Main systematics:

- Jet energy scale
- Unfolding

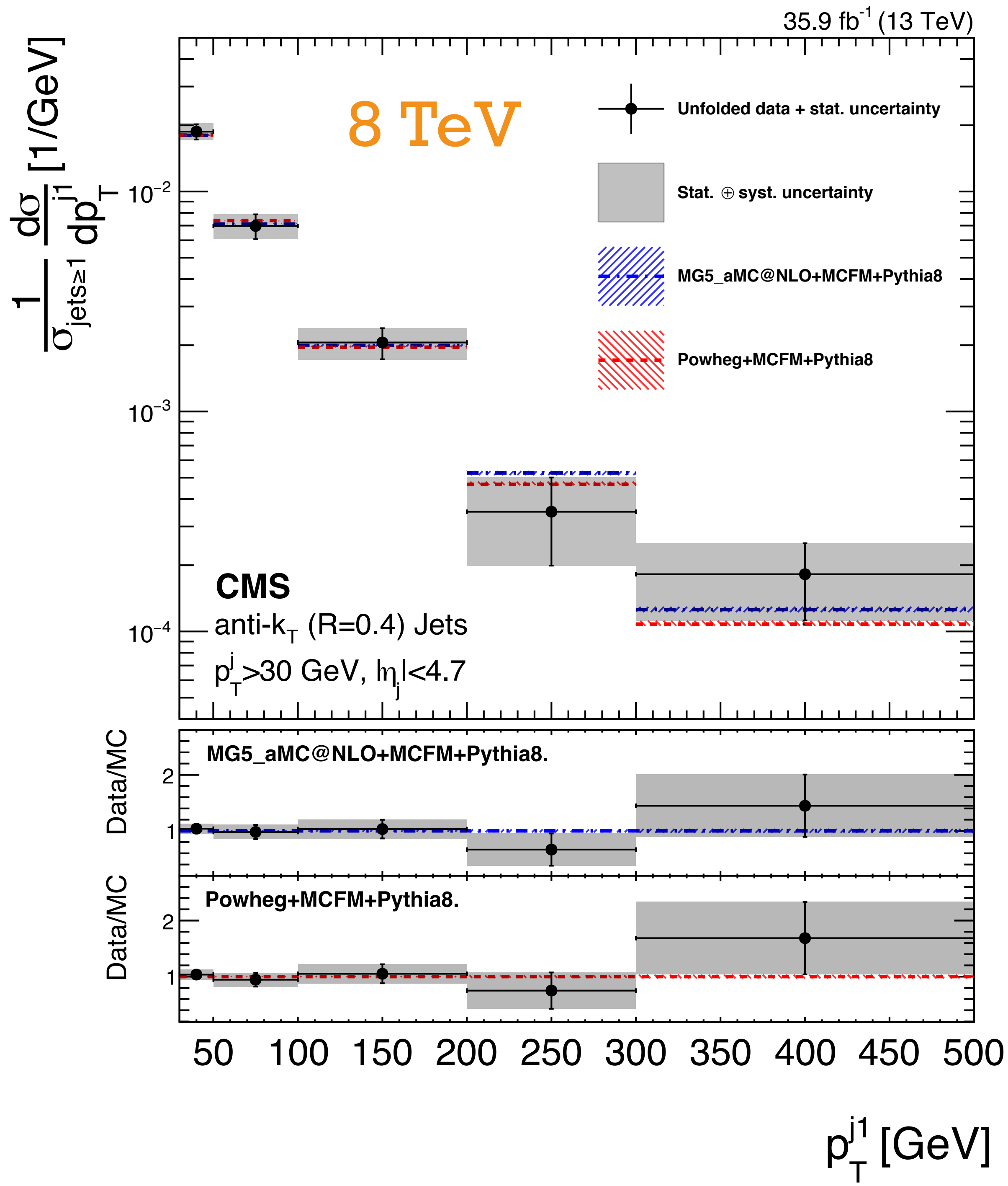


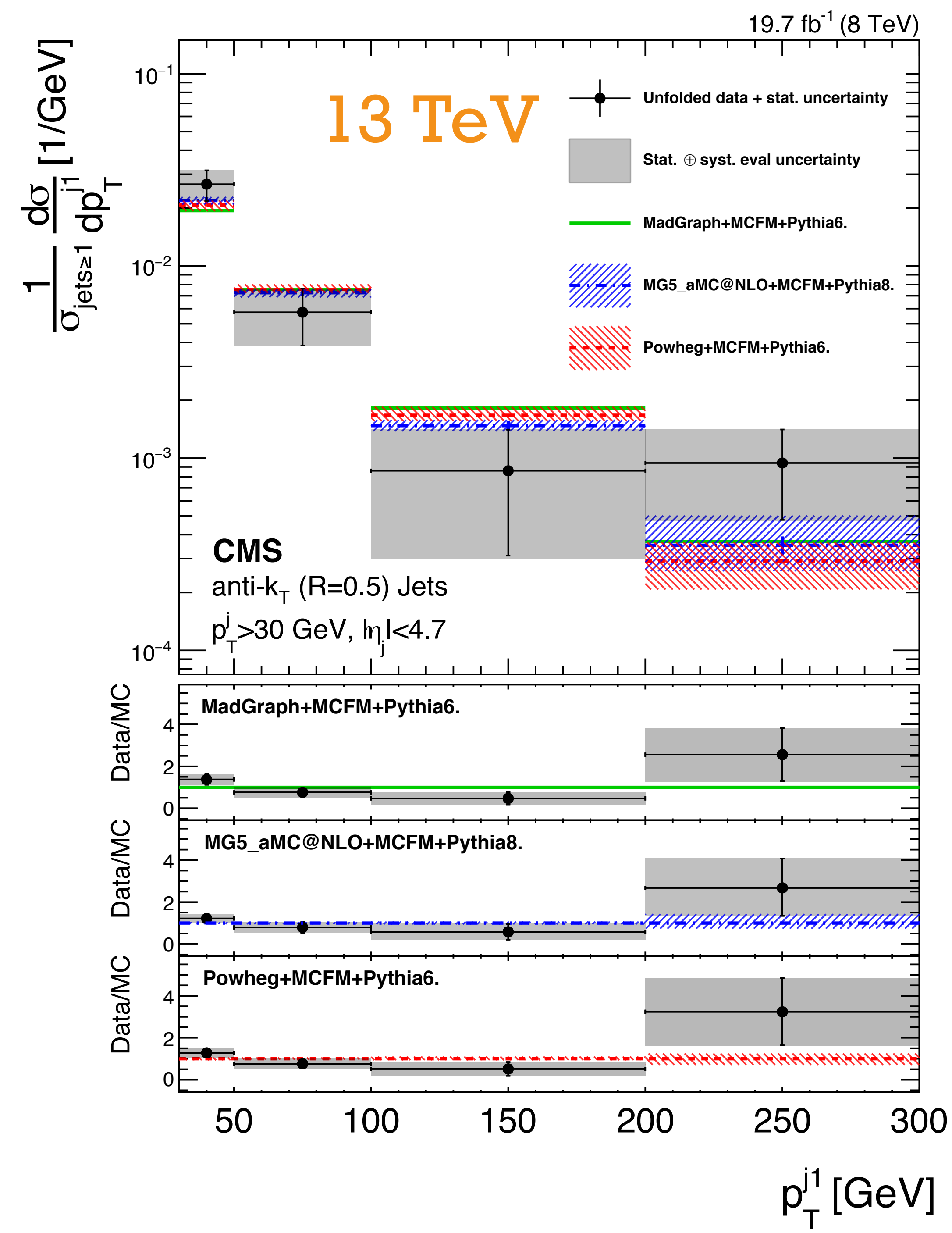


Comparison

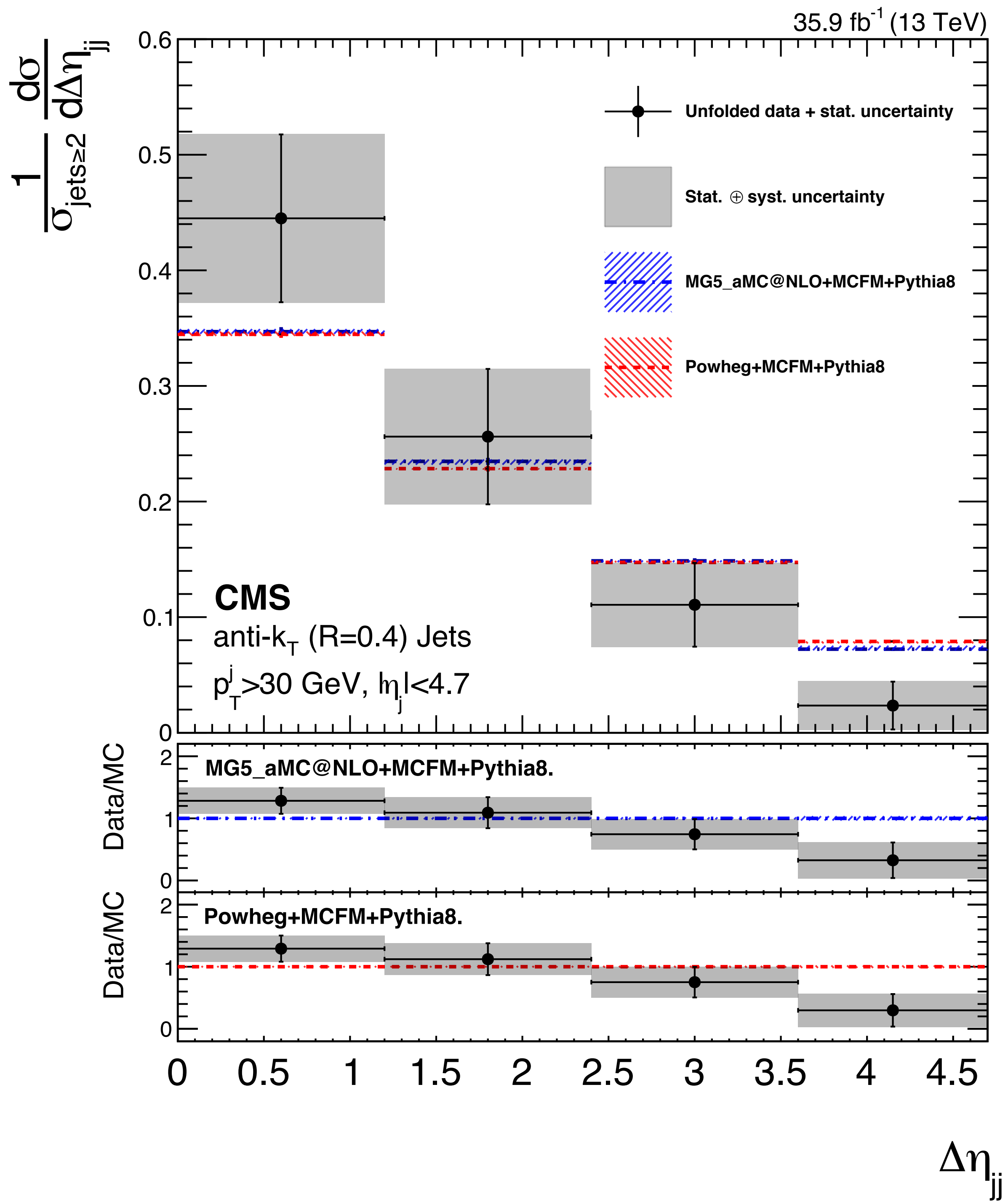

June 2018
CMS Preliminary
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
Production Cross Section, σ [pb]
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
W ≥1j ≥2j ≥3j ≥4j ≥5j ≥6j ≥7j 1c 2b Z ≥1j ≥2j ≥3j ≥4j ≥5j ≥6j ≥7j 1c ≥1b ≥2b WZ =0j =1j =2j ≥3j ZZ =0j =1j =2j ≥3j tt 1j 2j 3j 4j 2b H =0j =1j =2j =3j >=4j
Fiducial W, Z and H σs with W→lν, Z→ll, H→γγ and kinematic selection
All results at: http://cern.ch/go/pNj7

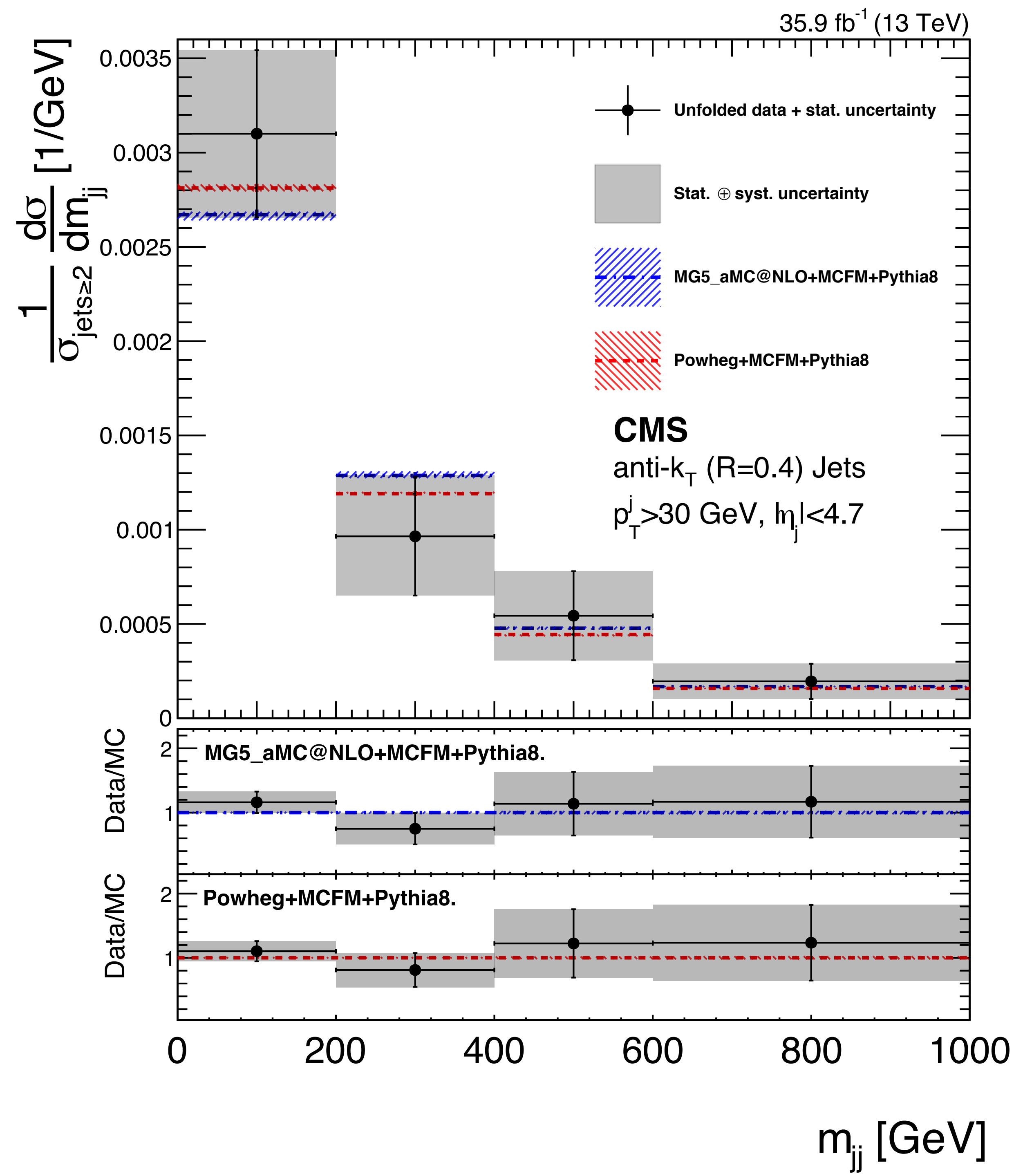
Leading jet p_T normalized differential cross-sections





Normalized differential cross-sections





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  - https://doi.org/10.1016/j.physletb.2017.10.020
- Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at 13 TeV
  - https://doi.org/10.1103/PhysRevLett.120.081801
- Measurement of electroweak WZ production and search for new physics in pp collisions at $\sqrt{s}$ = 13 TeV
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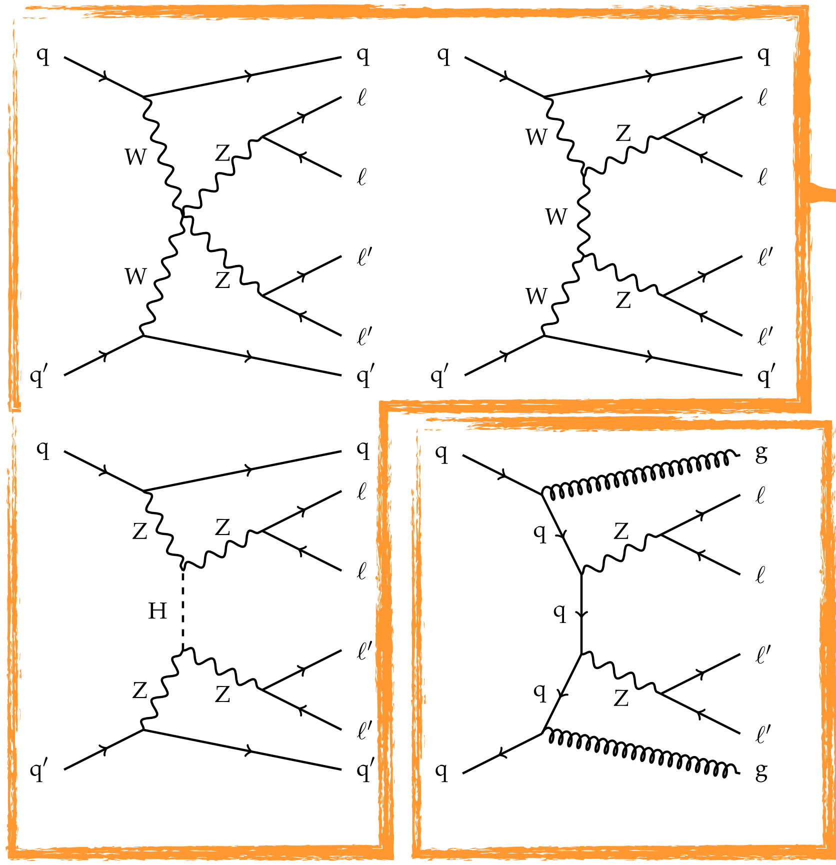
ZZ+jets EWK



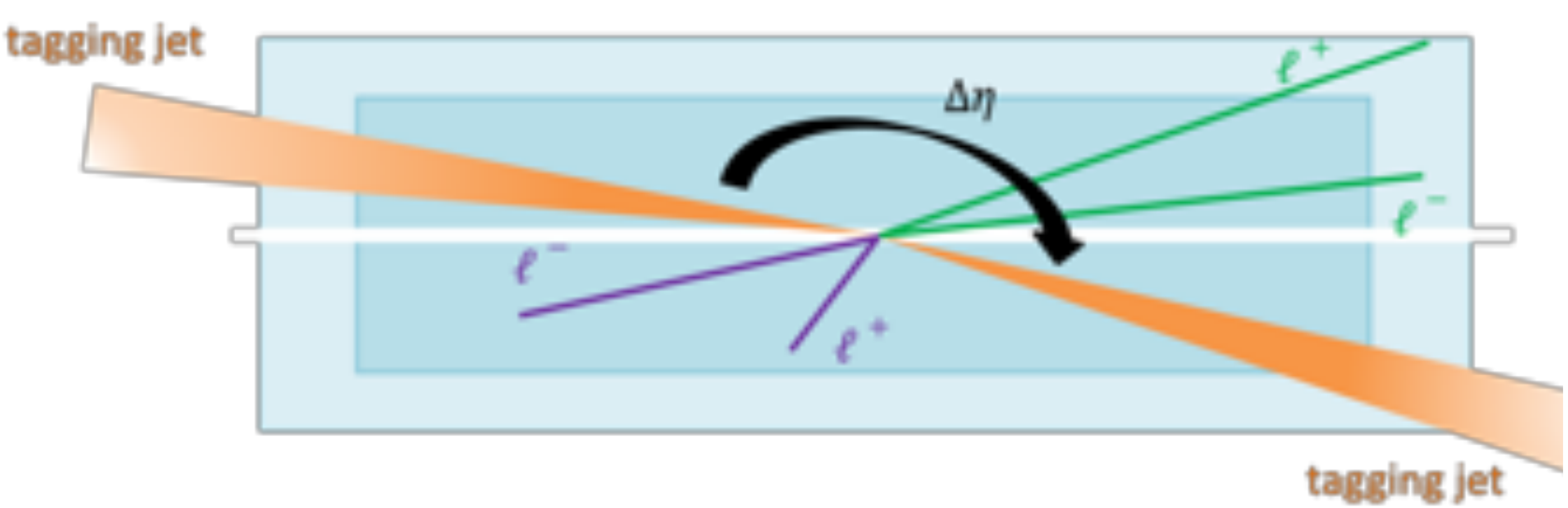
Signal

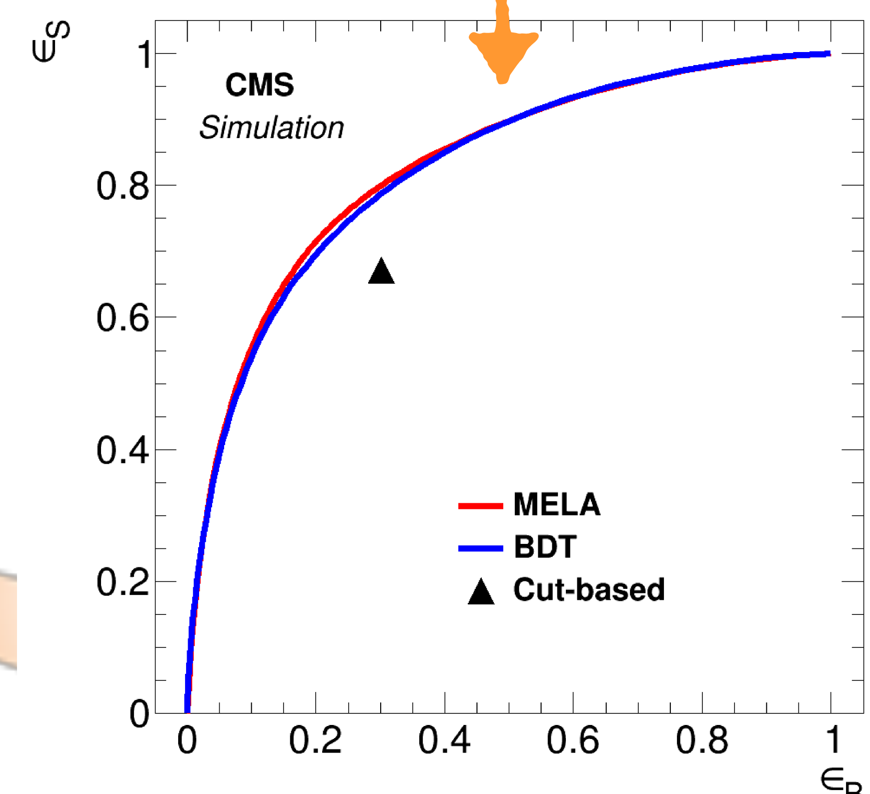
α^6_{EW} (VBS)

Main Background

$\alpha^4_{EW}\alpha^2_{S}$ (QCD-induced production)

- Base selection identical to ZZ +jets
  - + m_{JJ} > 100 GeV
- Multi variate analysis (BDT) using:
  - m_{JJ} ,$\Delta\eta_{JJ}$,
  - $m_{4\ell}$, $p_{T,4\ell}$,
  - z^*_{Z1} , z^*_{Z2} (Zeppenfeld)
  - $R(p_T^{\,hard})$, $R(p_T^{\,rel,jets})$
- Cross-check with a Matrix Element Discriminator (MELA)



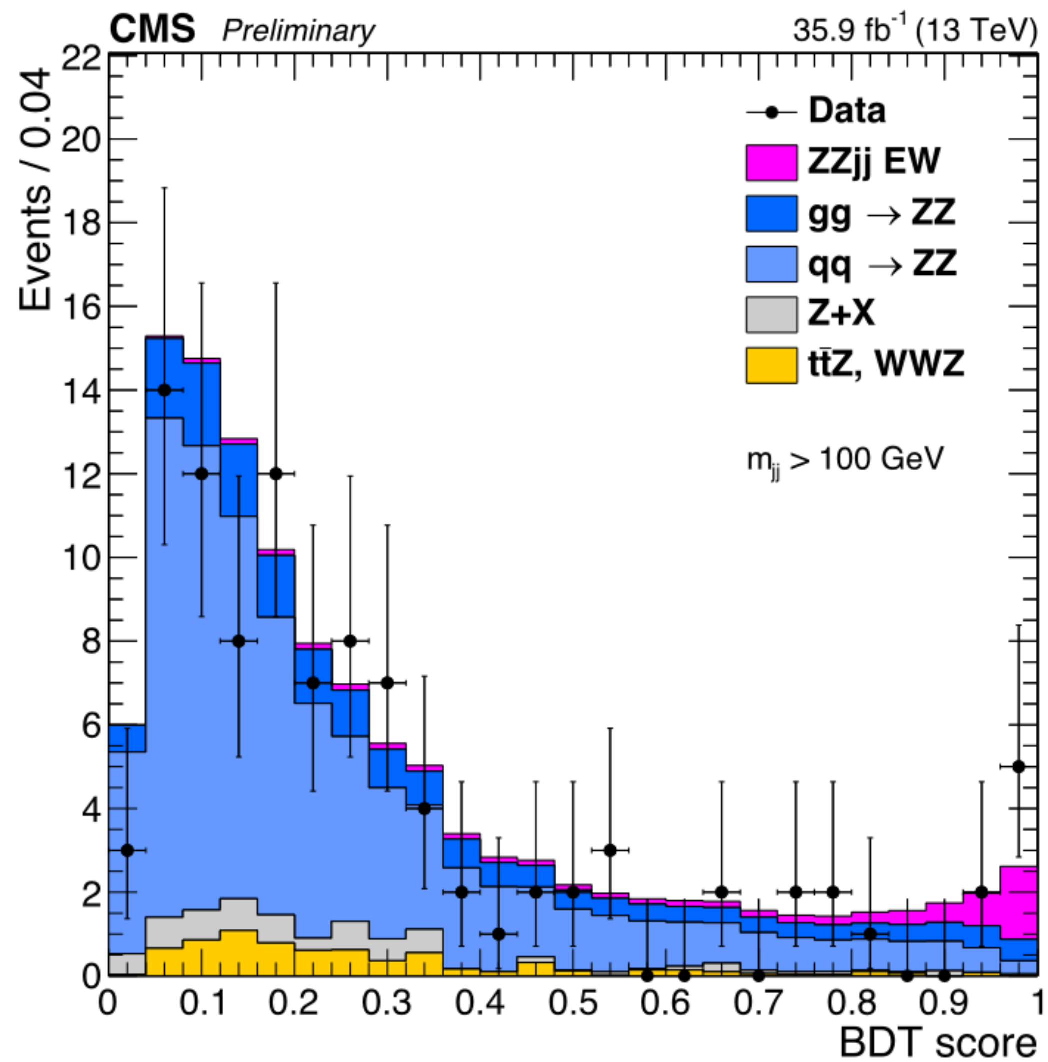


ZZ+jets EWK Multi variate analysis

- The full BDT spectrum from the events in the ZZjj selection is used to extract the significance of the EW signal via a maximum-likelihood template fit on the signal strength $\mu = \sigma/\sigma_{SM}$.
- background-only hypothesis is excluded with a significance of **2.7** standard deviations (1.6 standard deviations expected).

$$\mu = 1.39^{+0.72}_{-0.57}(\text{stat.})^{+0.46}_{-0.31}(\text{syst.}) = 1.39^{+0.86}_{-0.65}$$

- Cross section measured in same fiducial phase space used in ZZ+jets + M_{jj}>100 GeV



$$\sigma_{\text{fid.}}(\text{EW pp} \rightarrow ZZjj \rightarrow \ell\ell\ell'\ell' jj) = 0.40^{+0.21}_{-0.16}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})\ \text{fb}$$

$$\sigma_{theo} = 0.29^{+0.02}_{-0.03}\ \text{fb}$$

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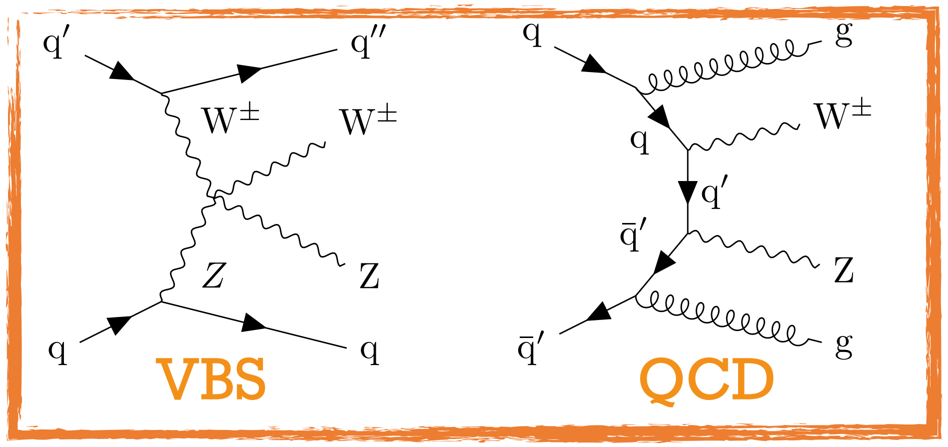
WZ + 2 jets

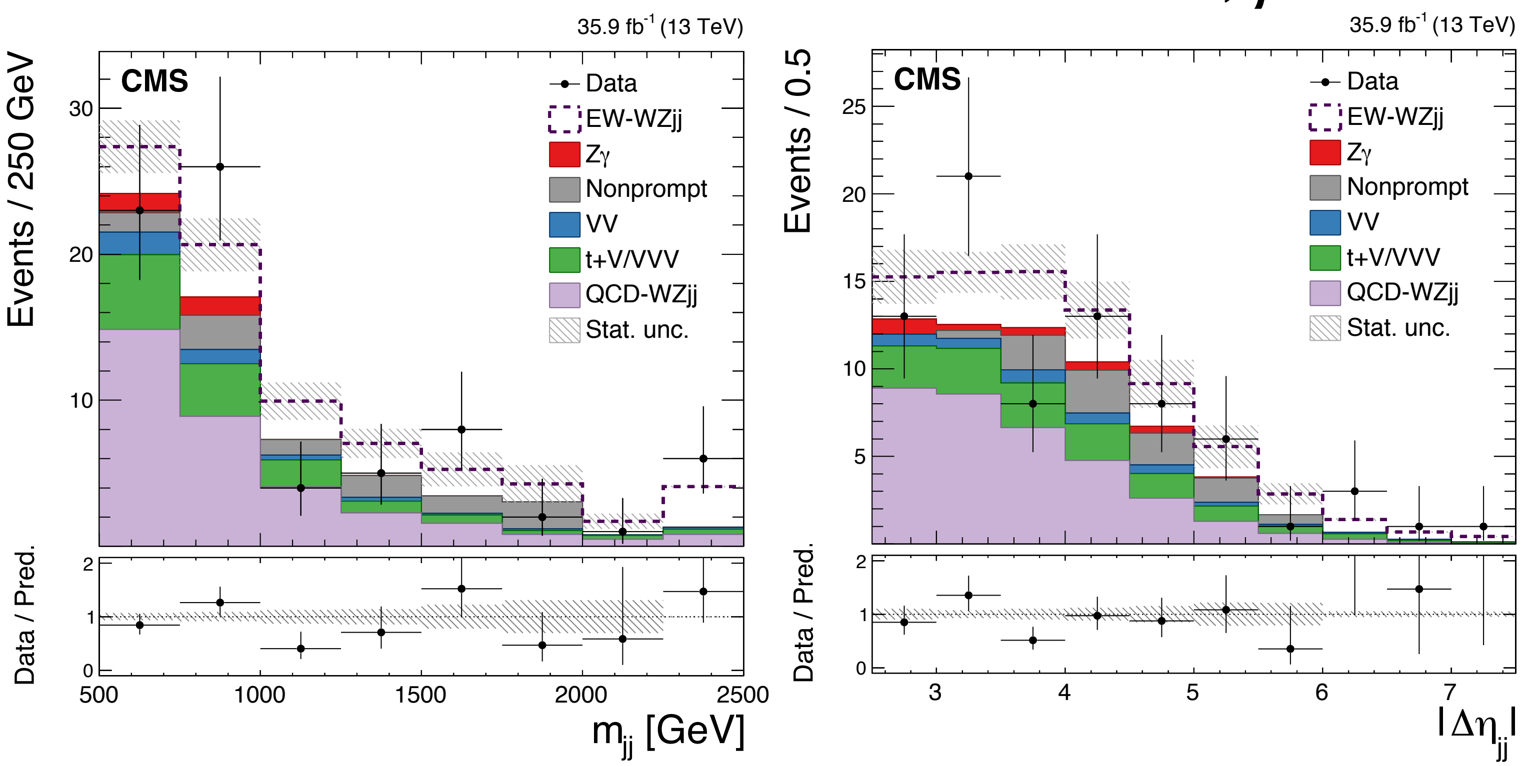


Main event selection:

- High p_T lepton and missing energy.
- $m_{jj} > 500$ GeV
- $\Delta\eta_{jj} > 2.5$
- p_T jet > 50 GeV

$\sqrt{s}$ = 13 TeV L = 35.9 fb−1

- Decay channel: $WZ \to \ell\nu\ell'\ell'$
  $\ell = e, \mu$

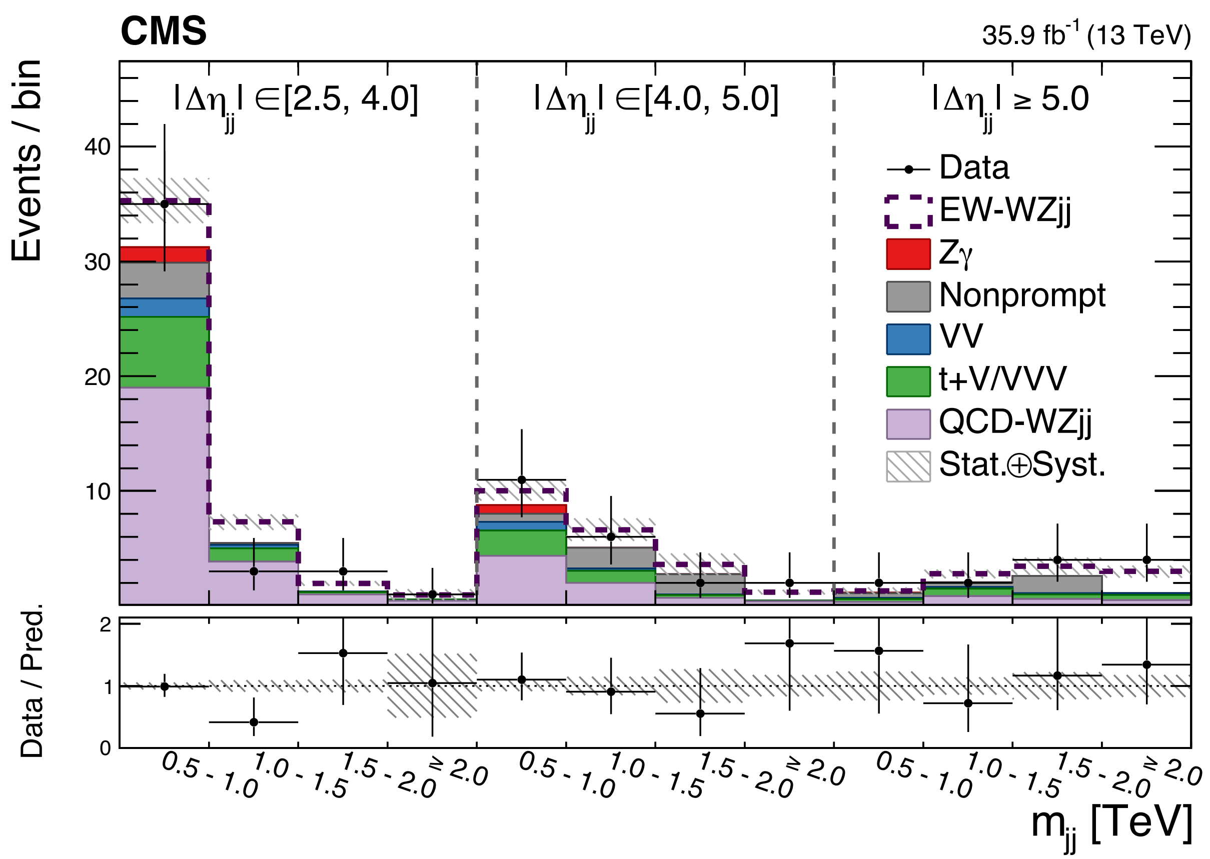


- Inclusive (QCD+EWK) cross-section measured with a combined maximum likelihood fit in two fiducial region:
  - Tight. Close to the selection.
  - Loose: To simplify comparisons with theoretical calculations.

$$\sigma^{fid}_{WZjj} = 3.18^{+0.57}_{-0.52}\ (stat)\ ^{+0.43}_{-0.36}\ (syst) \qquad \sigma^{theo}_{WZjj} = 3.27^{+0.39}_{-0.32}(scale) \pm 0.15\ (PDF)\ \text{fb}$$

$$\sigma^{fid,loose}_{WZjj} = 4.39^{+0.78}_{-0.72}(stat)^{+0.60}_{-0.50}(syst) \qquad \sigma^{theo}_{WZjj} = 4.51^{+0.59}_{-0.45}(scale) \pm 0.18\ (PDF)\ \text{fb}$$

EWK WZjj



- Simultaneous maximum likelihood fit on 2D distribution (m_{jj},$\Delta\eta_{jj}$) and side band region on the signal strength μ.

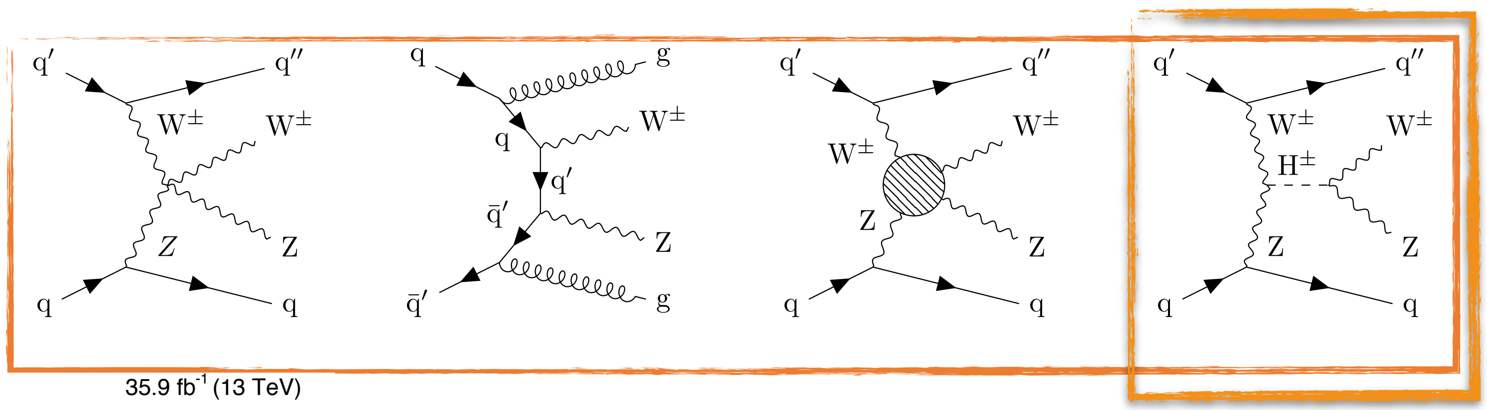
$$\mu_{EW} = 0.82^{+0.51}_{-0.43}$$

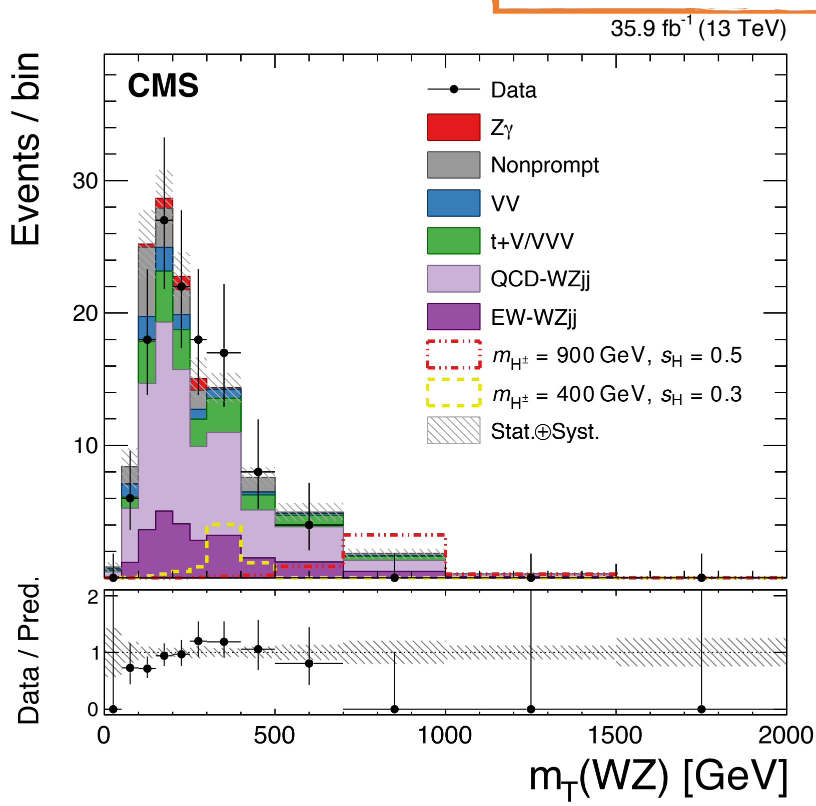
- The observed (expected) statistical significance for EW WZ production is 2.2 (2.5) standard deviations.

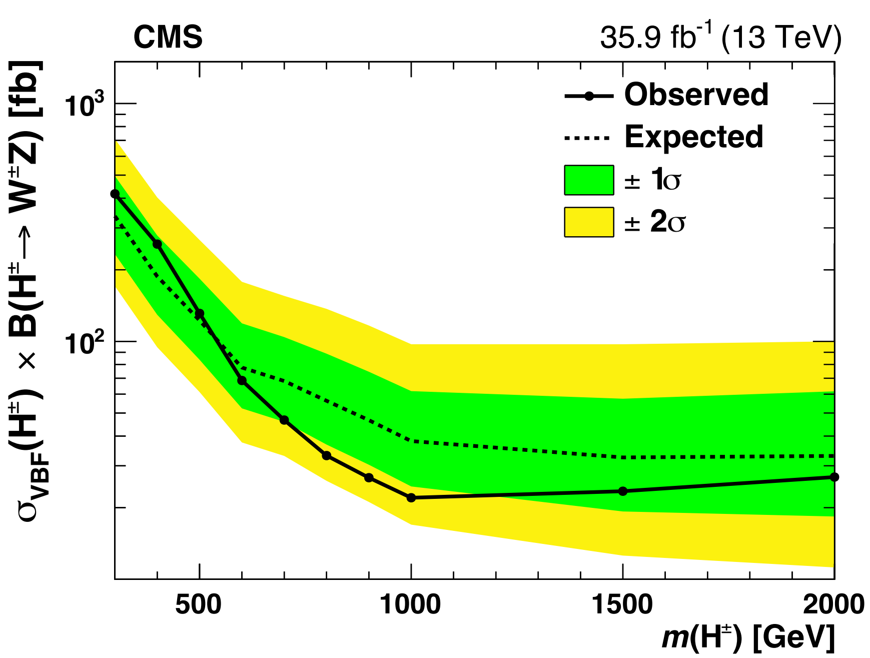
Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	Total yield
QCD WZ	13.5 ± 0.8	9.1 ± 0.5	6.8 ± 0.4	4.6 ± 0.3	34.1 ± 1.1
t+V/VVV	5.6 ± 0.4	3.1 ± 0.2	2.5 ± 0.2	1.7 ± 0.1	12.9 ± 0.5
Nonprompt	5.2 ± 2.0	2.4 ± 0.9	1.5 ± 0.6	0.7 ± 0.3	9.9 ± 2.3
VV	0.8 ± 0.1	1.6 ± 0.2	0.4 ± 0.0	0.7 ± 0.1	3.5 ± 0.2
$Z\gamma$	<0.1	2.1 ± 0.8	<0.1	<0.1	2.1 ± 0.8
Pred. background	25.2 ± 2.1	18.3 ± 1.6	11.2 ± 0.8	7.7 ± 0.5	62.4 ± 2.8
EW WZ signal	6.0 ± 1.2	4.2 ± 0.8	2.9 ± 0.6	2.1 ± 0.4	15.1 ± 1.6
Data	38	15	12	10	75

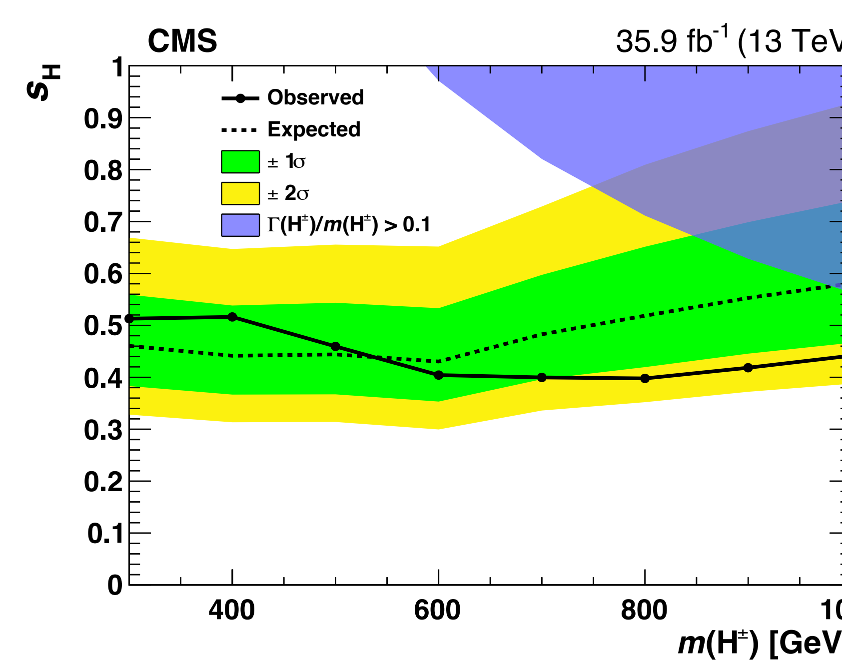
Constraints on charged Higgs production

- Higgs sector is extended by one real and one complex SU(2) triplet (Georgi-Machacek model).
- In this model, the couplings depend on $m(\mathrm{H}^{\pm})$ and $sin\theta_H$ (s_{H}), where s_{H} represents the mixing angle of the vacuum expectation values in the model.
- A combined fit of the predicted signal and background yields to the data is performed in bins of $m_{\mathrm{T}}(\mathrm{WZ})$ to derive model-independent expected and observed exclusion limits on $\sigma_{\mathrm{VBF}}(\mathrm{H}^{\pm})\ \mathrm{B}(\mathrm{H}^{\pm} \rightarrow \mathrm{WZ})$ at 95% confidence level using the $\mathrm{CL_S}$ method.





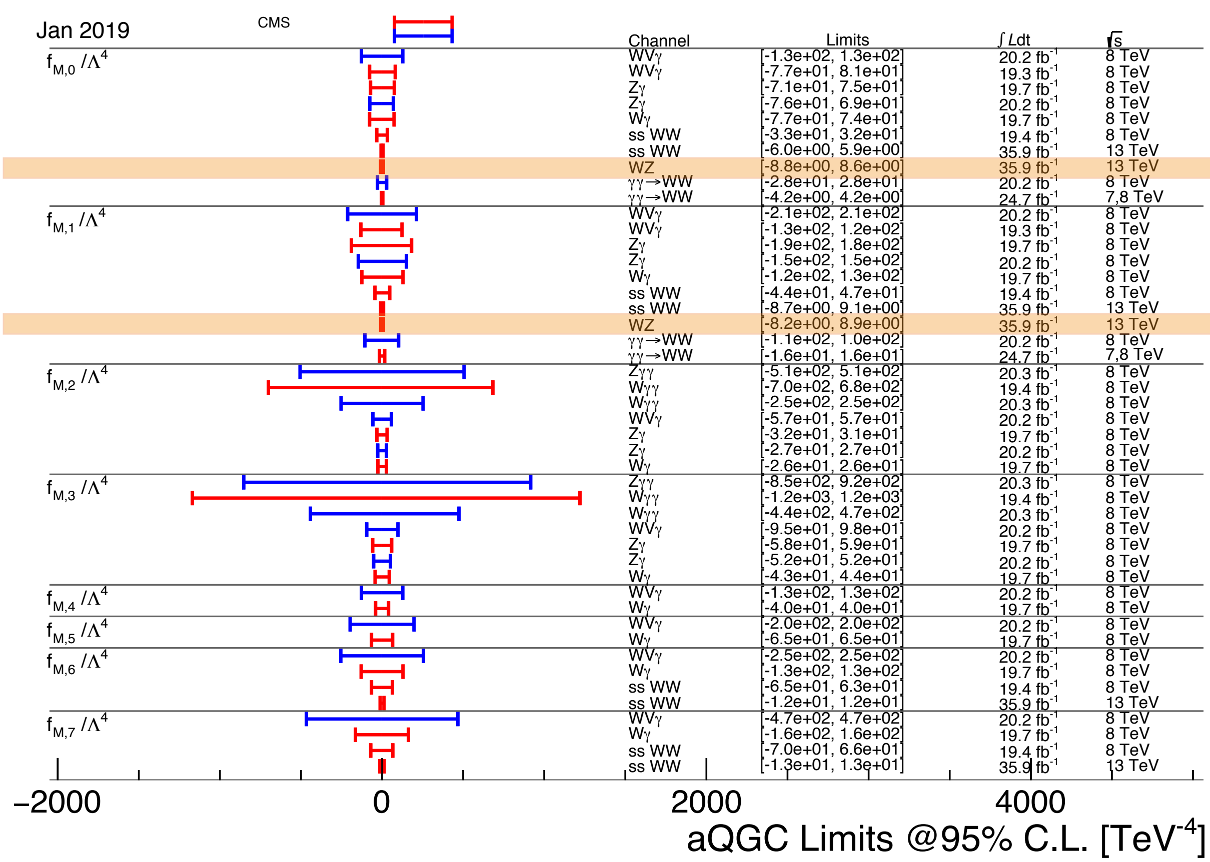


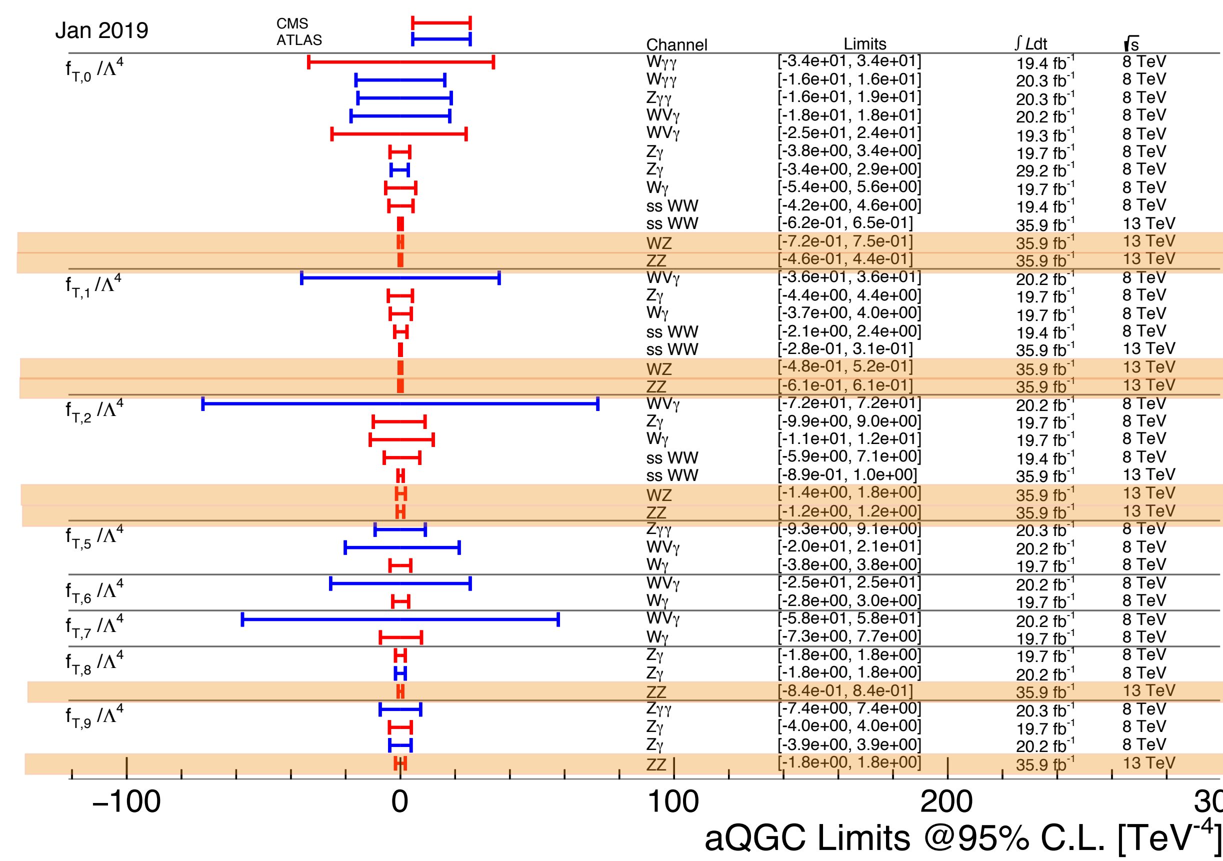


Excluded model independent $\sigma(\mathrm{H}^{\pm}) \times \mathrm{B}(H^{+} \rightarrow \mathrm{WZ})$ and s_{H} values as a function of $m(\mathrm{H}^{\pm})$

Anomalous Couplings

Almost all analyses include measurements of anomalous vector boson couplings using the Effective field theory (EFT) approach.
2 summary plot as example:





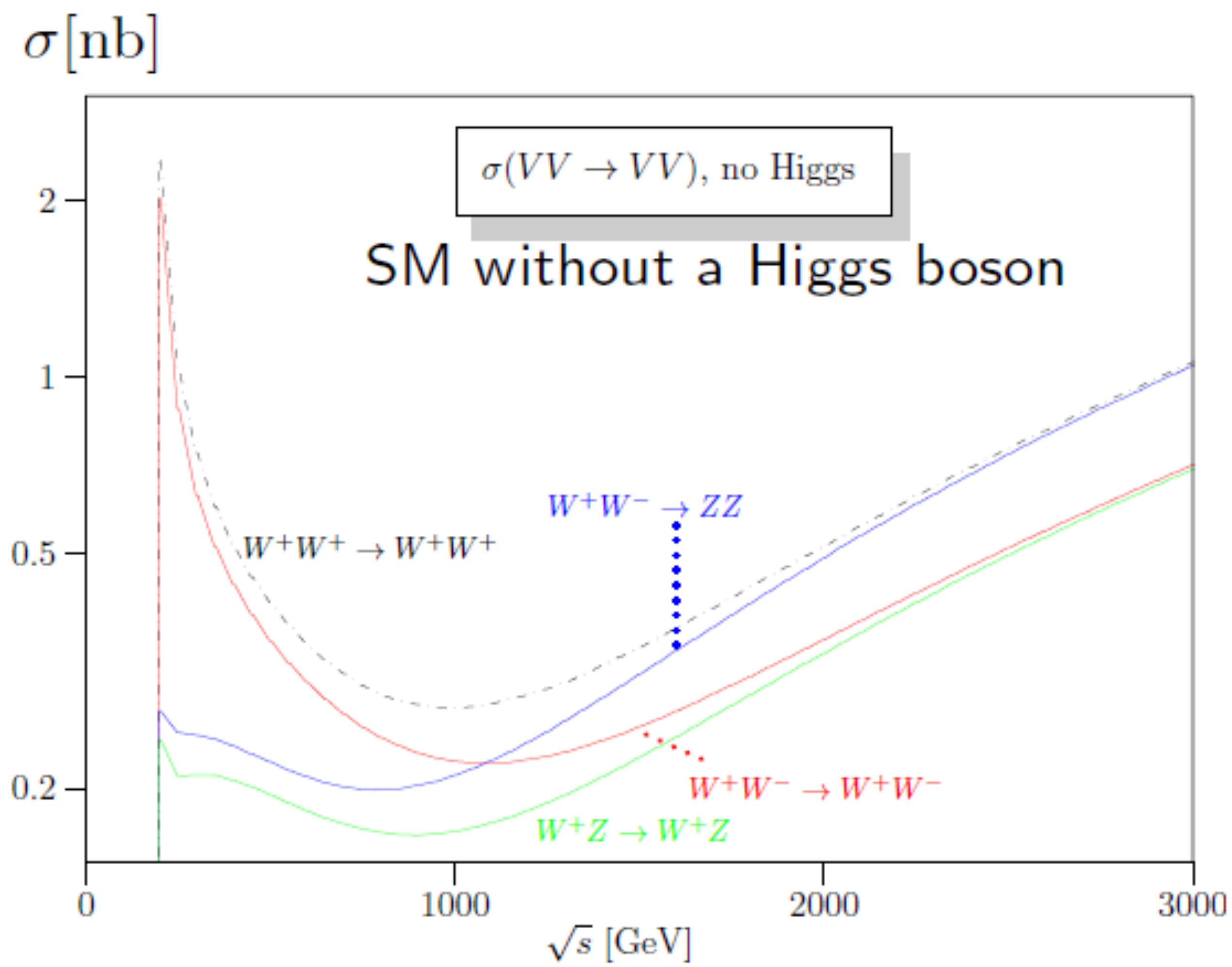
Limits obtained with the analyses presented in this talk

No deviation from SM prediction is observed

Thanks for your attention

Back Slides

The Vector Boson Scattering



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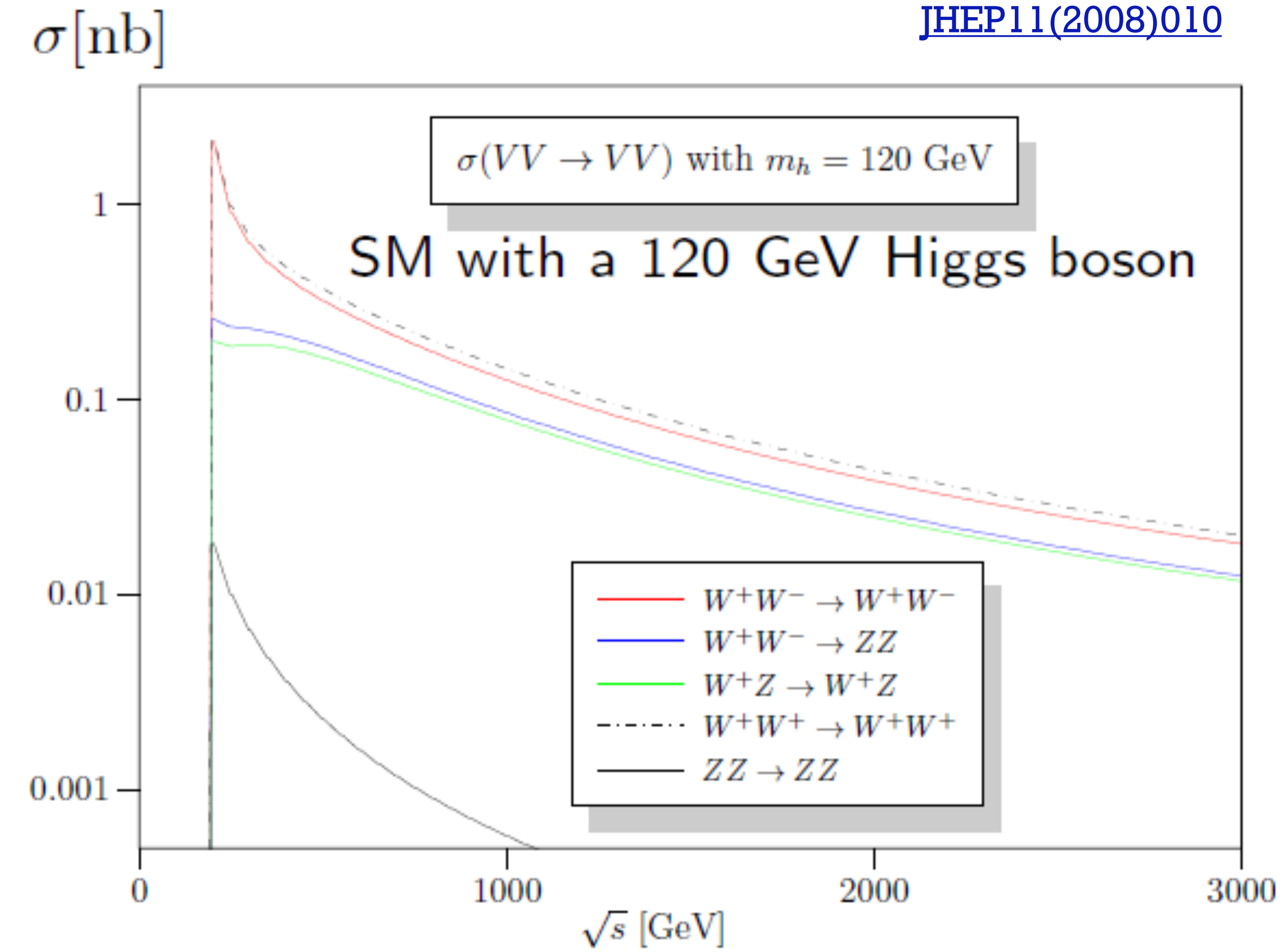

High energy vector boson scattering plays to understand if this Higgs boson only partial responsible for EWSB:

- If the 125 GeV higgs boson is only partially responsabile, then VL VL cross section will keep growing with s, up to the new physic scale Λ

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Monte Carlo

SIGNAL

- ZZTo4L_13TeV-amcatnloFXFX-pythia8 (NLO up to 1 jet in ME)
- ZZTo4L_13TeV_powheg_pythia8 (NLO) Reference
- GluGluToContinToZZTo4e_13TeV_MCFM701_pythia8 (LO)
- GluGluToContinToZZTo4mu_13TeV_MCFM701_pythia8 (LO)
- GluGluToContinToZZTo2e2mu_13TeV_MCFM701_pythia8 (LO)

Add k-factors:

- gg NNLO/LO 2.0-2.6
- qq QCD NNLO/NLO ~ 1.1
- qq EWK NLO ~ 0.9

BACKGROUND

- DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8
- TTJets_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8
- TTTo2L2Nu_13TeV-powheg
- WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8

Event Selection

Particle selection

Both leptons

- PF isolation in cone $\Delta R = 0.3$
  - $R_{iso} < 0.35$
- $SIP = |IP/\sigma_{IP}| < 4$

Electrons

- BDT multivariate technique
- $|\eta^e| < 2.5$
- $p_T{}^e > 7$ GeV
- Effective area PU correction

Muons

- BDT multivariate technique
- $|\eta^\mu| < 2.4$
- $p_T{}^\mu > 5$ GeV
- $\Delta\beta$ PU correction

Jets

- PF jet AK4, Loose ID
- $|\eta^{jet}| < 4.7$
- $p_T{}^{jet} > 30$ GeV

baseline selection

- $60 < m_{Z1} < 120$ GeV
- $60 < m_{Z2} < 120$ GeV (If # Z_2 >1 the pair of leptons with highest scalar sum of p_T is chosen)
- ($|m_{Za}-m_Z| < |m_{Z1}-m_Z|$ && $m_{Zb}<12$), where Za and Zb are the mass-sorted alternative pairing Z candidates (Za one closest to the nominal Z mass)
- $m_{ZZ} > 100$ GeV
- $m_{llcrossed} < 4$ GeV
- At least two leptons with $p_T > 10$ GeV and one with $p_T > 20$ GeV

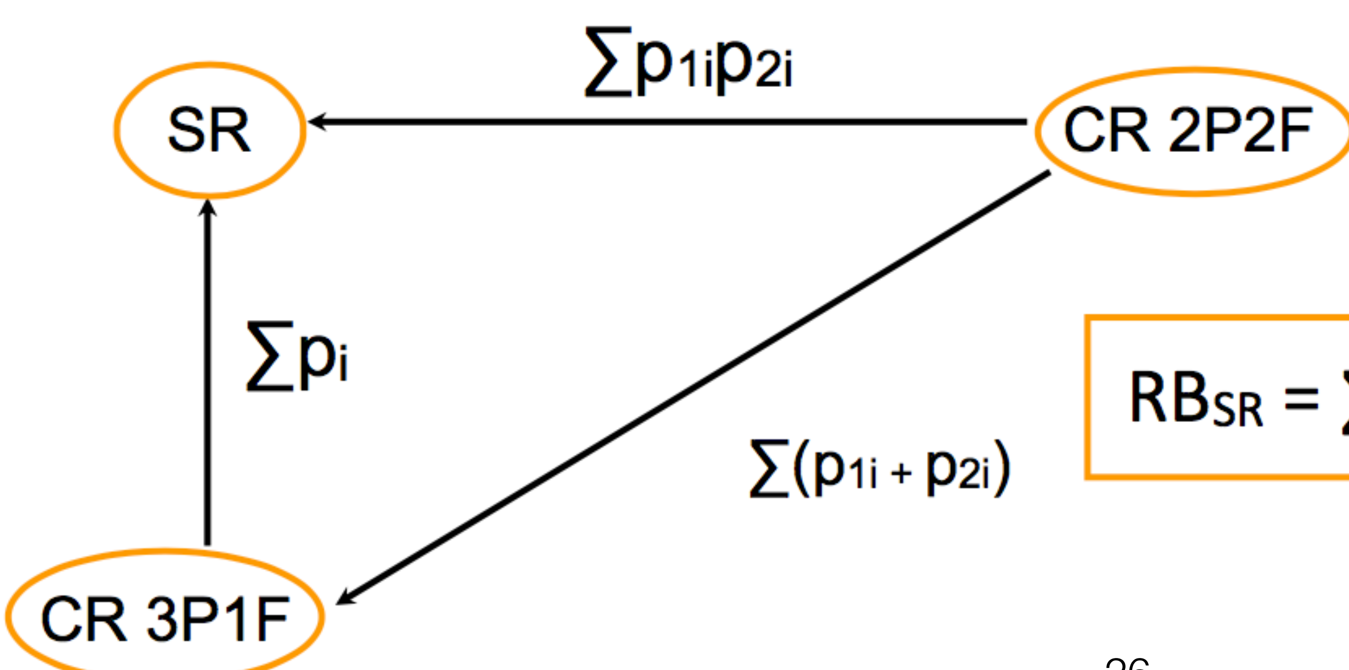
Background

Irreducible background: processes which contain **4 prompt leptons** from non-signal processes (*ttZ* , *WWZ*, *ttWW*), **very small.**

- Will be estimated **from** MC samples.
- **Reducible background: processes which contain one or more non-prompt leptons in the four-lepton final state (*DY*, *tt*, *WZ*, *WWW*)**
- Not well represented by MC samples.
  - Low statistics.
- Estimated using a **data driven method** based on the **lepton-to-jet fake rate.**

Control Regions

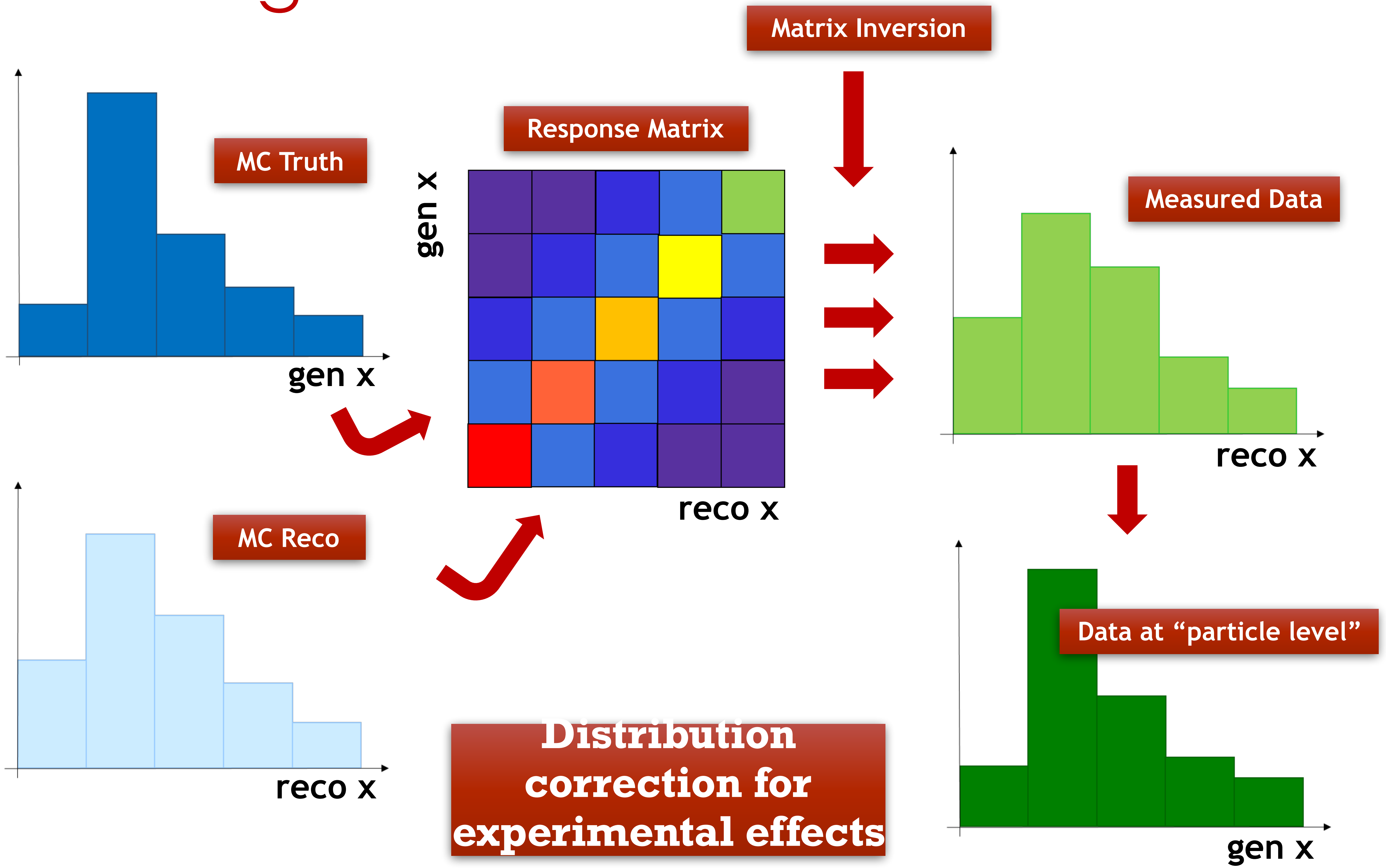
- We need 3 different control regions to measure the reducible background with data
- ZL ($Z(\ell\ell)+\ell_{loose}$) to measure the lepton fake rate f_i
- 2P2F and 3P1F
  - P = lepton passing the final selection criteria (Z1)
  - F = lepton not passing the final ID and ISO criteria



$$p_i = f_i / (1 - f_i)$$

$$RB_{SR} = \sum p_i(3P1F) - \sum p_{1i}p_{2i}(2P2F)$$

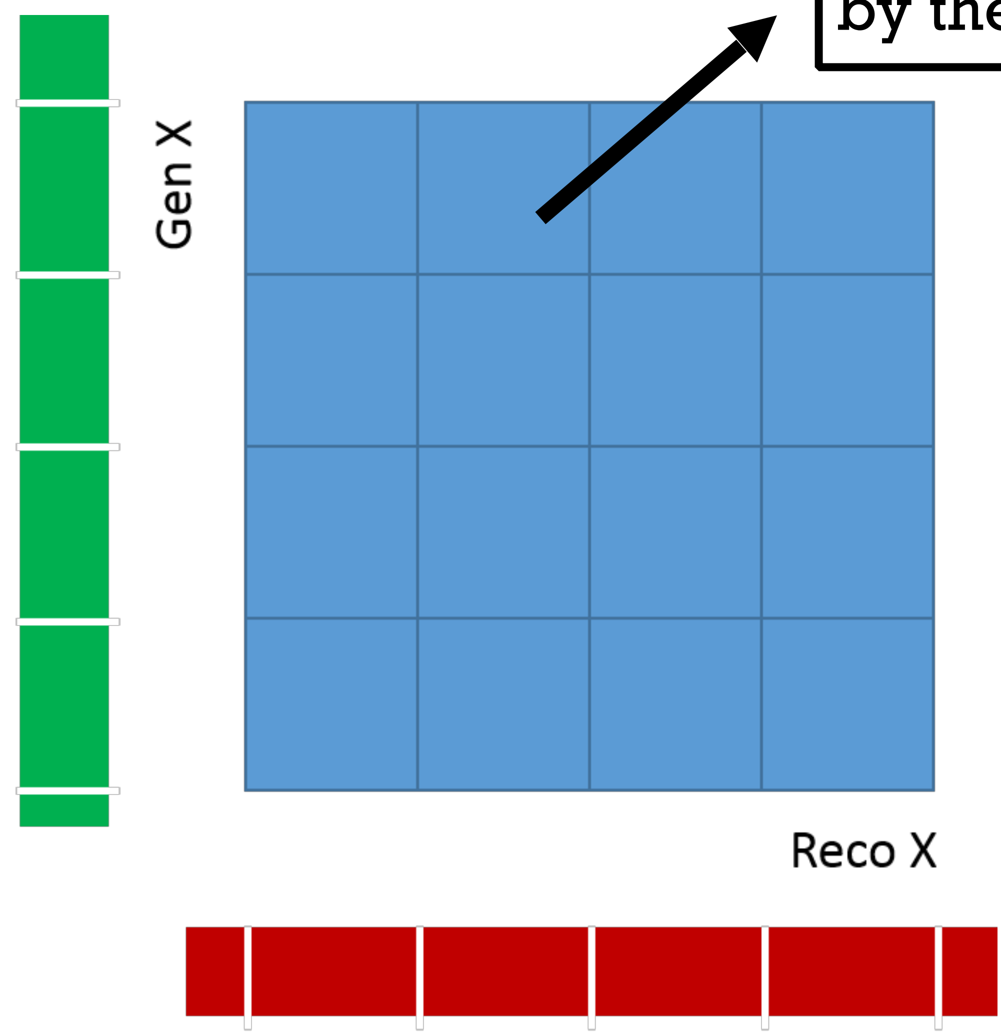
Unfolding Procedure



Unfolding Procedure

Response matrix built using events generated in the fiducial region AND selected by the analysis

Gen vector built using ALL events generated in the fiducial region



Reco vector built using ALL events reconstructed in the signal region

2 sets of samples:

- MadGraph + MCFM + Phantom (reference)
- Powheg + MCFM + Phantom (validation)

Fiducial phase spaces

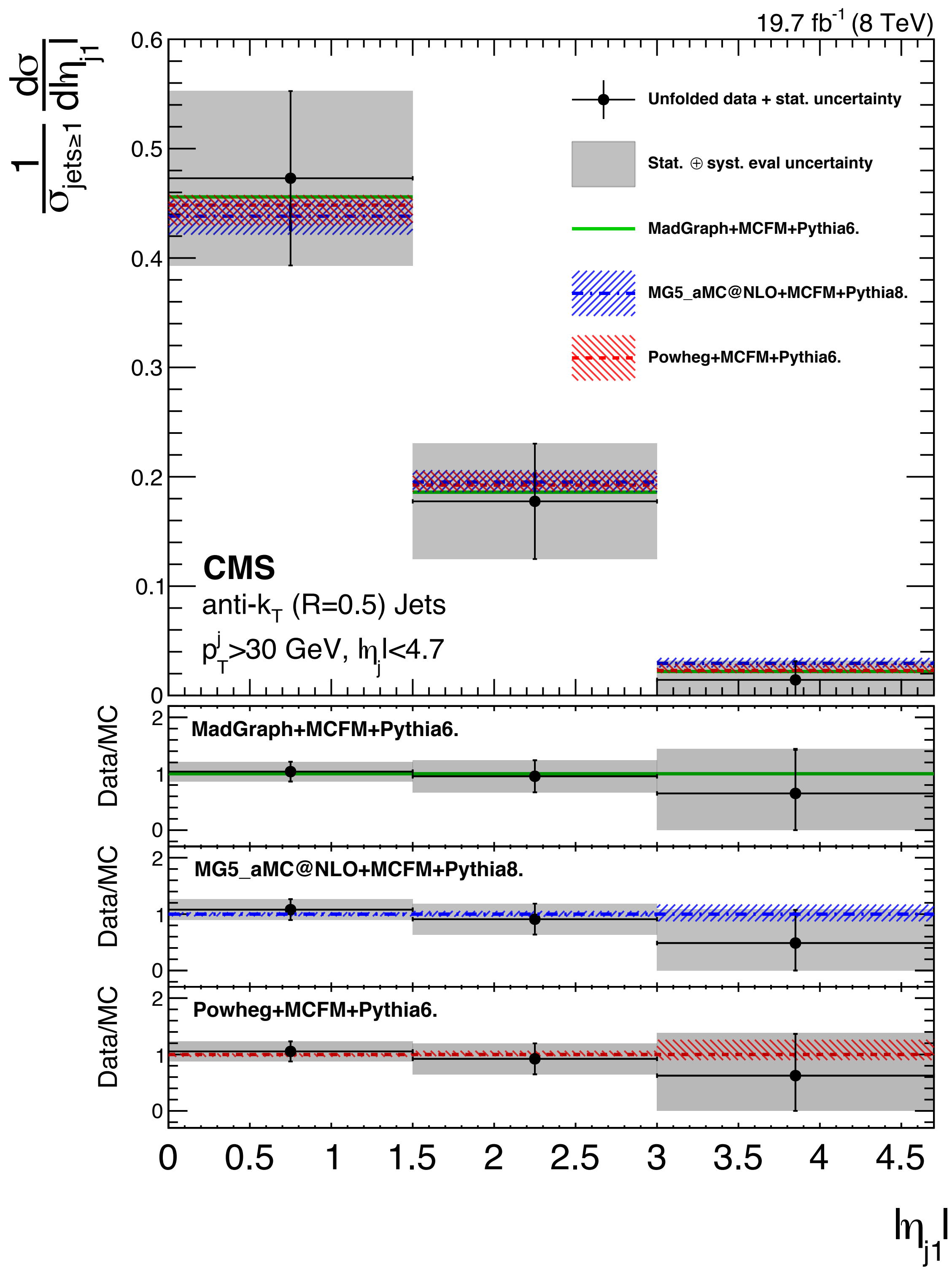
8 TeV	13 TeV
$p_T^e > 7\,GeV, \lvert\eta^e\rvert < 2.5$	$p_T^e > 5\,GeV, \lvert\eta^e\rvert < 2.5$
$p_T^\mu > 5\,GeV, \lvert\eta^\mu\rvert < 2.4$	$p_T^\mu > 5\,GeV, \lvert\eta^\mu\rvert < 2.5$
common definitions	
$p_T^{\ell_1} > 20\,GeV$, $p_T^{\ell_2} > 10\,GeV$	
$m_{\ell^+\ell^-} > 4\,GeV$ (any opposite-sign same-flavor pair)	
$60 < (m_{Z_1}, m_{Z_2}) < 120\,GeV$	

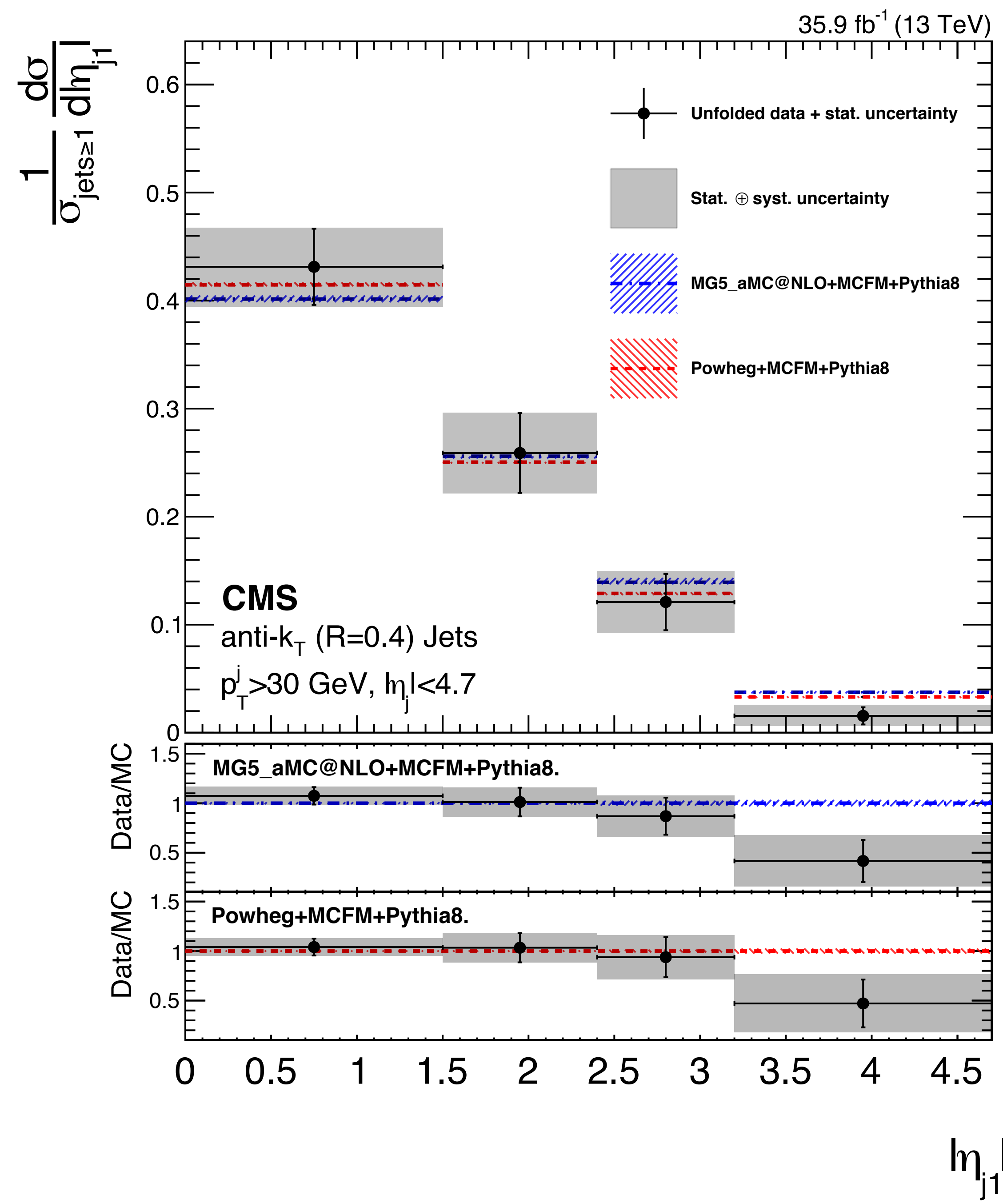
systematics

	8 TeV data		13 TeV data	
Systematic source	Absolute (%)	Normalized (%)	Absolute (%)	Normalized (%)
Trigger	1.5	—	2.0	—
Lepton reconstruction and selection	0.9–4.4	≤0.1	3.7–4.5	0.1–0.8
Jet energy scale	1.5–9.2	1.5–9.1	4.6–17.6	4.6–17.6
Jet energy resolution	0.2–1.7	0.2–1.7	2.1–8.4	2.1–8.4
Background yields	0.7–7.2	0.7–5.4	0.5–2.9	0.4–2.1
Pileup	1.8	1.8	0.3–1.9	0.6–1.8
Luminosity	2.6	—	2.5	—
Choice of Monte Carlo generators	0.2–3.7	0.2–3.7	0.5–5.1	0.8–4.8
qq/gg cross section	0.1–0.8	0.1–0.8	< 0.1–0.3	0.1–0.2
PDF	1.0	—	< 0.1–0.2	< 0.1–0.2
α_S	<0.1	<0.1	≤0.1	≤0.1

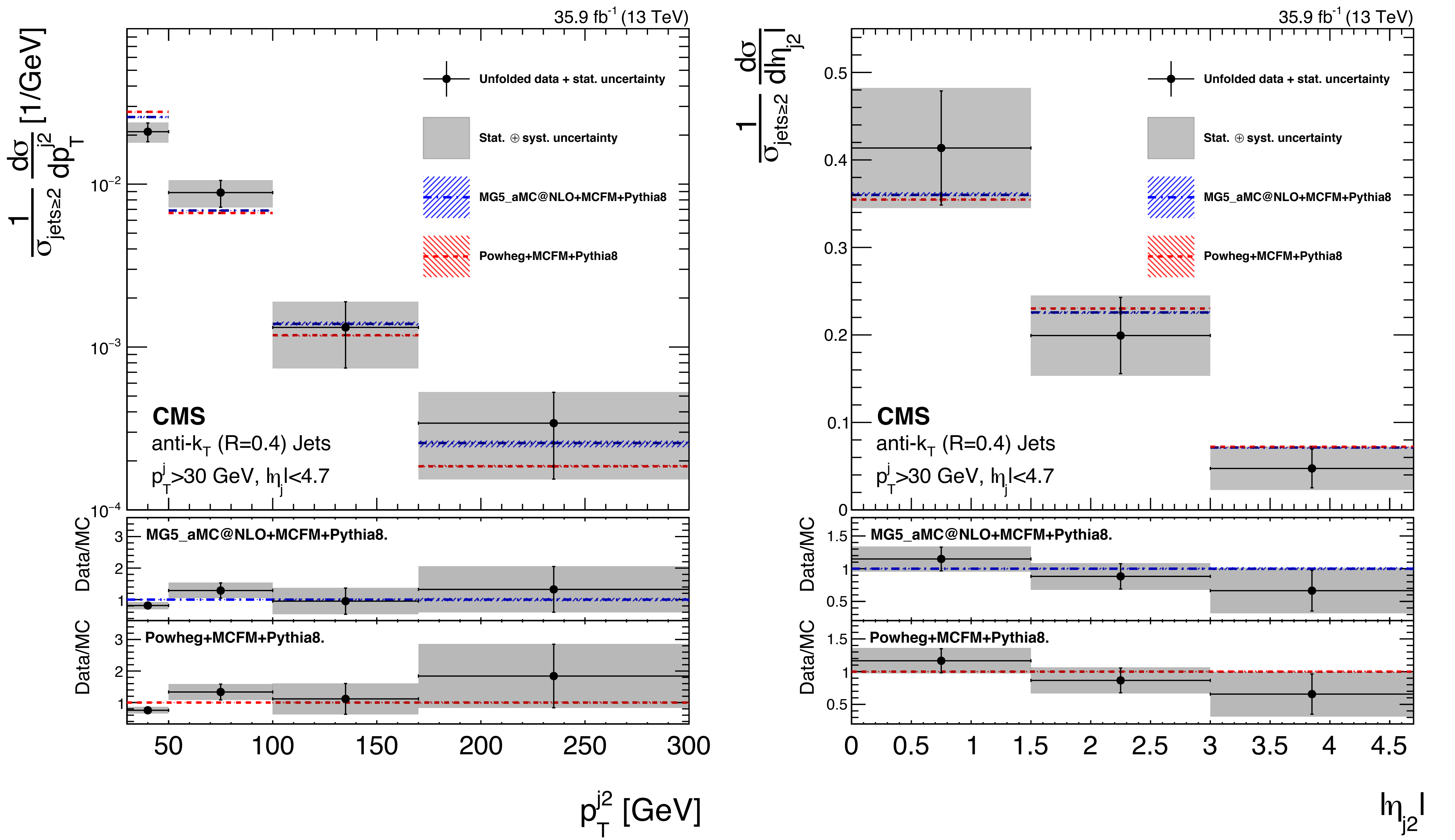
The contributions to the uncertainty in the absolute and normalized differential cross section measurements. Uncertainties that depend on jet multiplicity are listed as a range.

|η| leading jet

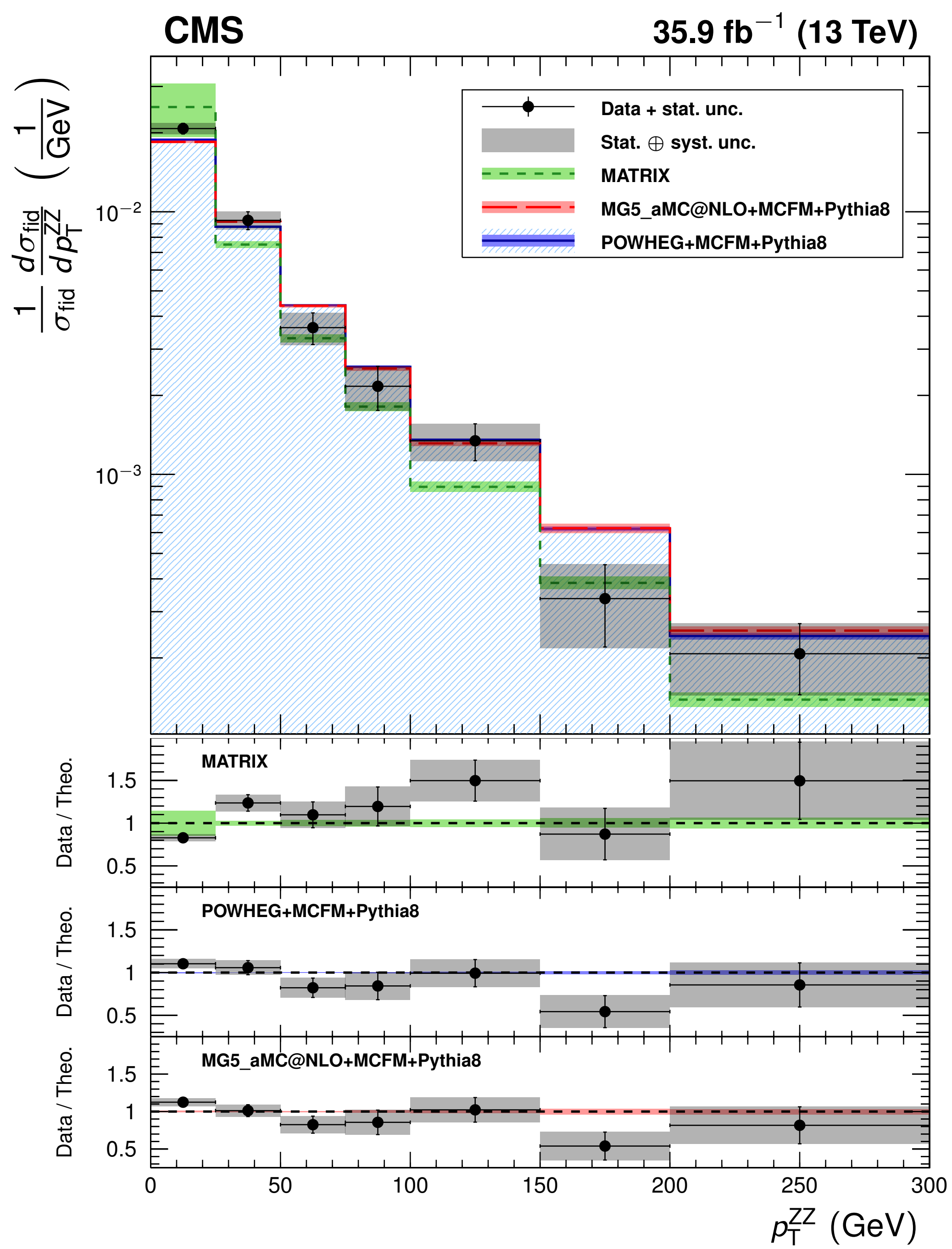




sub-leading jet



ZZ p_T



[Eur. Phys. J. C 78 (2018) 165]

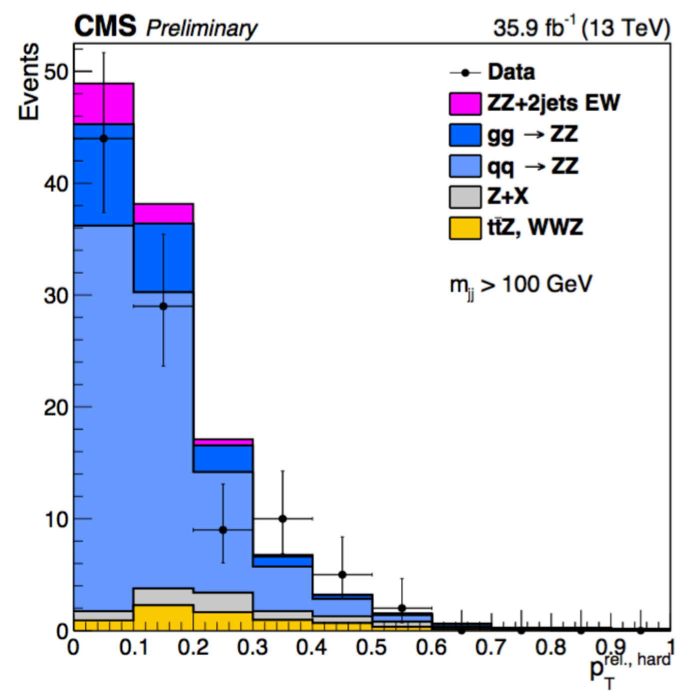
- Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s}$ = 8 and 13 TeV
  - https://doi.org/10.1016/j.physletb.2018.11.007
- Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s}$ = 13 TeV
  - https://doi.org/10.1016/j.physletb.2017.10.020
- Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at 13 TeV
  - https://doi.org/10.1103/PhysRevLett.120.081801
- Measurement of electroweak WZ production and search for new physics in pp collisions at $\sqrt{s}$ = 13 TeV
  - https://arxiv.org/abs/1901.04060

BDT

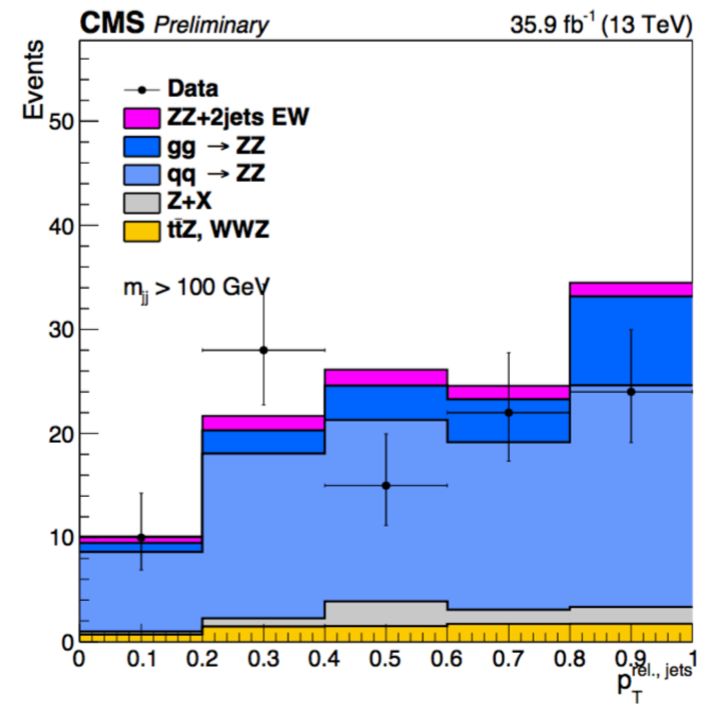
- Choice of input variables:
  - Explored a total of 36 observables
  - Evaluated gain per group of observables
  - Prune variables that provide a small gain or are expected to be poorly-modelled in MC
- Hyper-parameters optimized using grid search
- Cross-check of BDT performance with a Matrix Element Discriminator (MELA)
- Transformation and binning optimized for **template analysis**
  - Ensure sufficient MC statistics in signal and background, while exploiting the stratification
- Choice of input variables:

Observable	Definition
m_{jj}	invariant mass of the tagging jets
$\Delta\eta_{jj}$	separation of the tagging jets in the η plane
m_{4l}	invariant mass of the diboson system; $m_{4l} = \sqrt{s}$ of the vector boson interaction
$\eta^{\star}_{Z_1}$	η Zeppenfeld variable;direction of the Z_1 boson relative to the tagging jets;
$\eta^{\star}_{Z_2}$	η Zeppenfeld variable;direction of the Z_2 boson relative to the tagging jets;
$p_T^{rel.hard}$	$\sum_{Z_{1,2},j_{1,2}} \vec{p}^i\|_{transverse} / \sum_{Z_{1,2},j_{1,2}} p_T^i$
$p_T^{rel.jets}$	$\sum_{j_{1,2}} \vec{p}^i\|_{transverse} / \sum_{j_{1,2}} p_T^i$

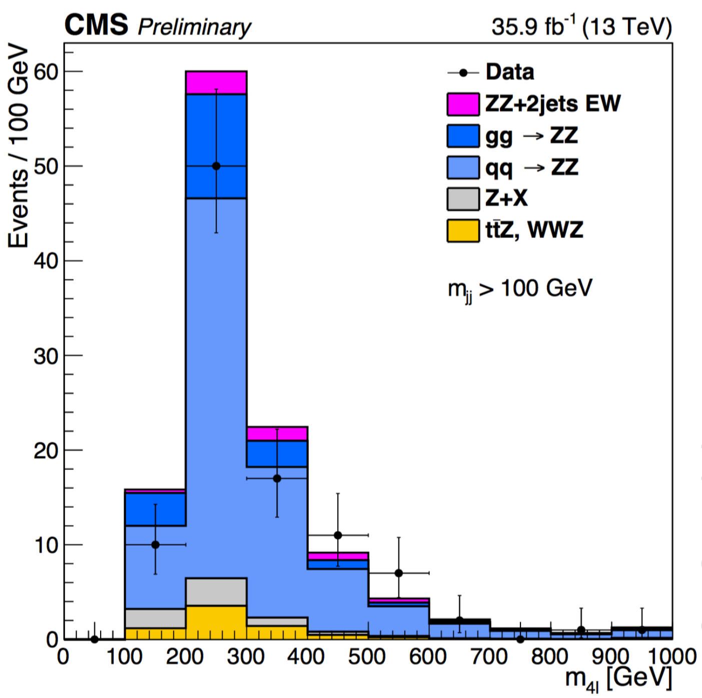
BDT 2



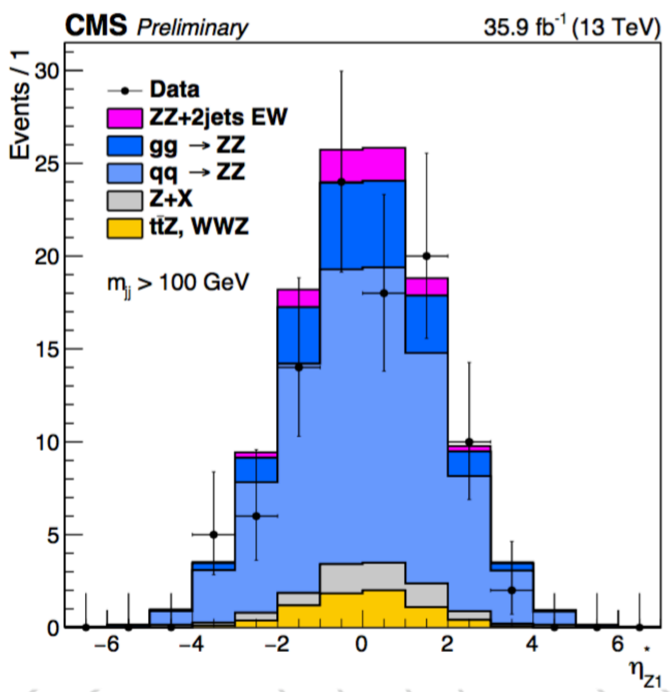
CMS Preliminary
35.9 fb-1 (13 TeV)
Events
Data
ZZ+2jets EW
gg → ZZ
qq → ZZ
Z+X
tt̄Z, WWZ
mjj > 100 GeV
pT rel., hard



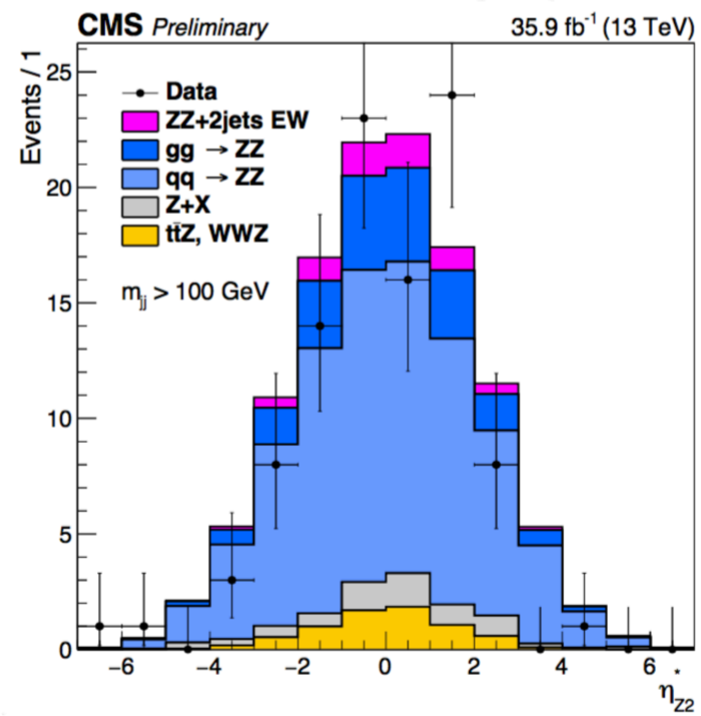
CMS Preliminary
35.9 fb-1 (13 TeV)
Events
Data
ZZ+2jets EW
gg → ZZ
qq → ZZ
Z+X
tt̄Z, WWZ
mjj > 100 GeV
pT rel., jets



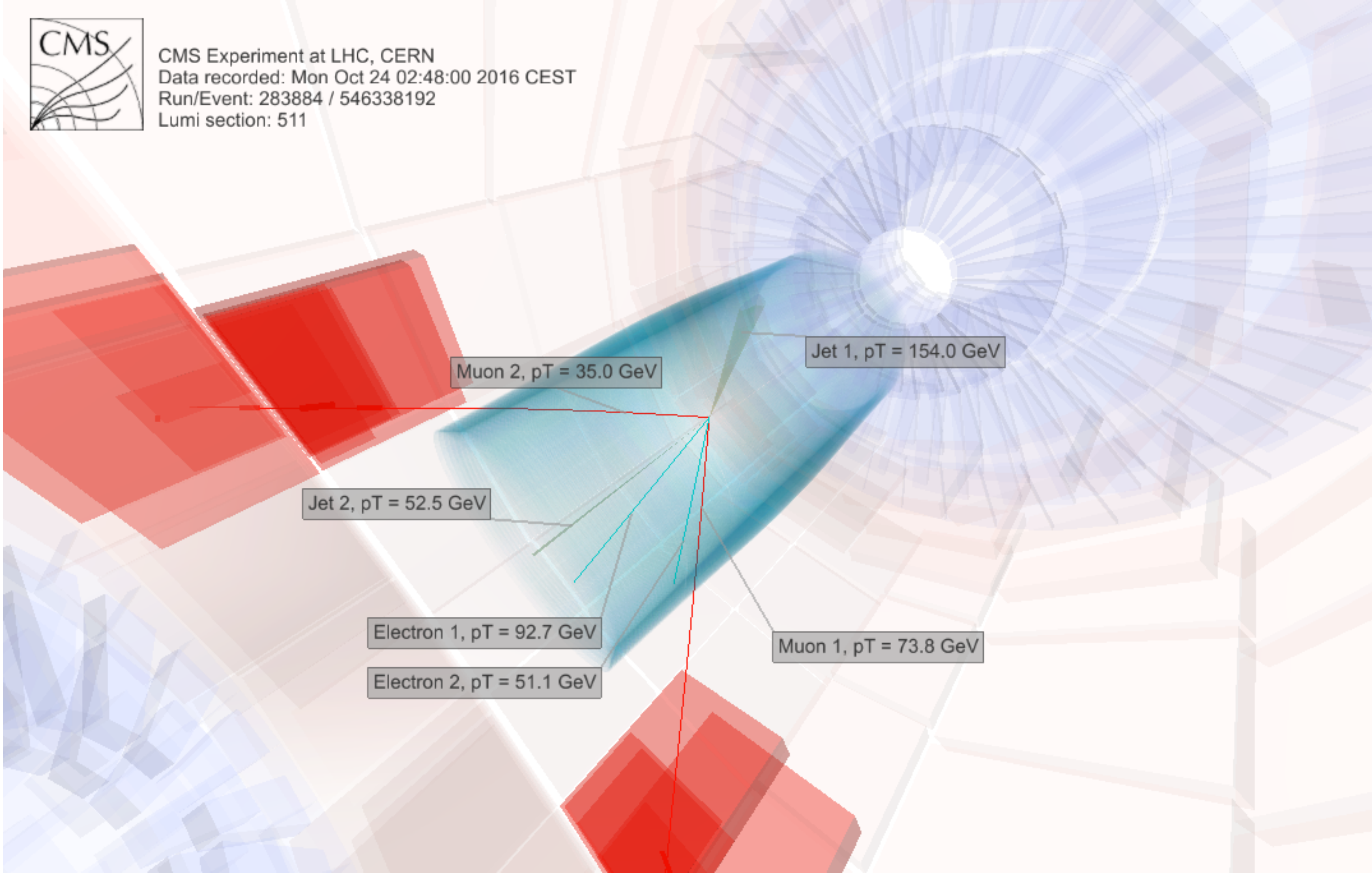
CMS Preliminary
35.9 fb-1 (13 TeV)
Events / 100 GeV
Data
ZZ+2jets EW
gg → ZZ
qq → ZZ
Z+X
tt̄Z, WWZ
mjj > 100 GeV
m4l [GeV]



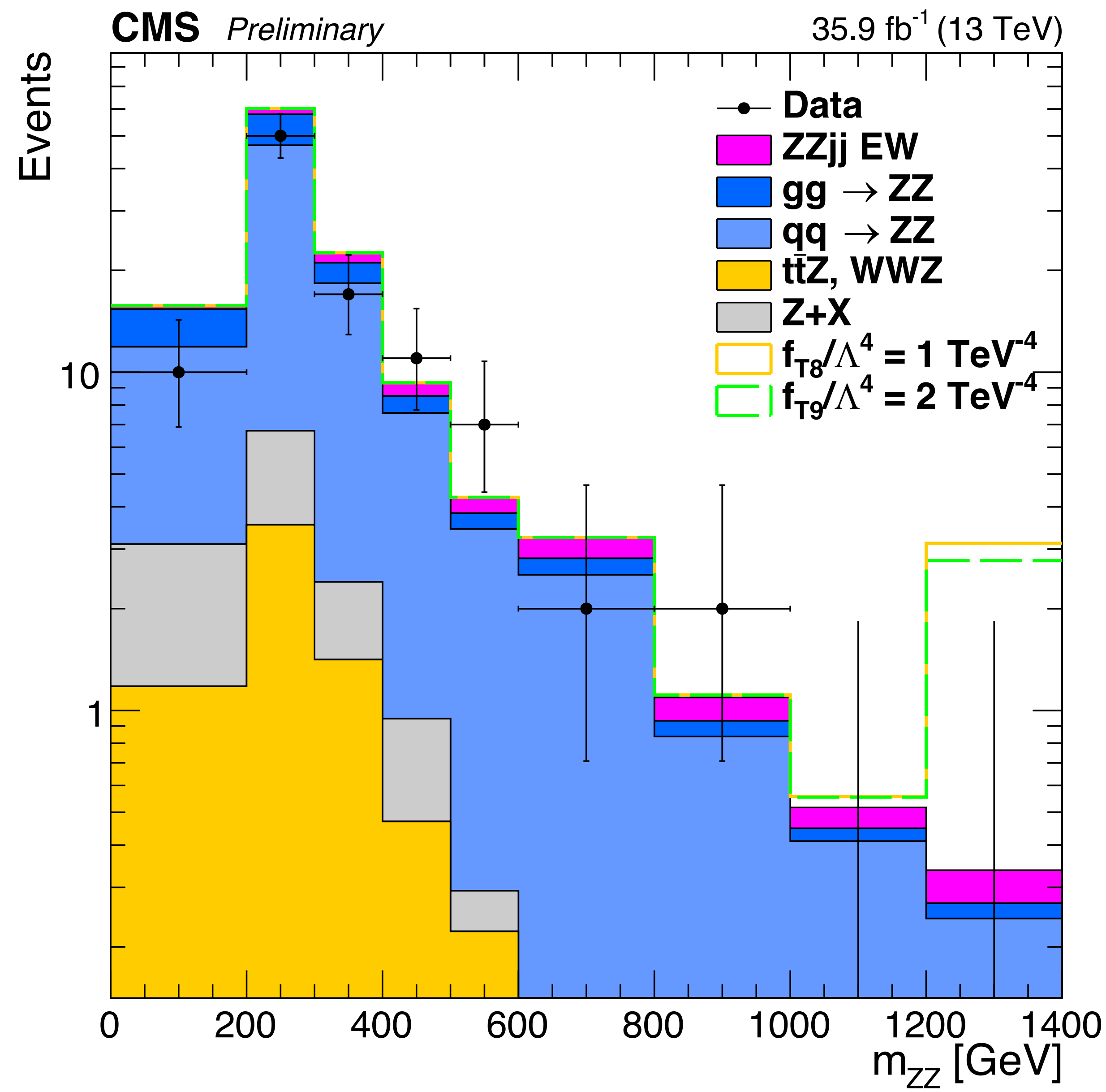
CMS Preliminary
35.9 fb-1 (13 TeV)
Events / 1
Data
ZZ+2jets EW
gg → ZZ
qq → ZZ
Z+X
tt̄Z, WWZ
mjj > 100 GeV
η*Z1



CMS Preliminary
35.9 fb-1 (13 TeV)
Events / 1
Data
ZZ+2jets EW
gg → ZZ
qq → ZZ
Z+X
tt̄Z, WWZ
mjj > 100 GeV
η*Z2


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Oct 24 02:48:00 2016 CEST
Run/Event: 283884 / 546338192
Lumi section: 511
Jet 1, pT = 154.0 GeV
Muon 2, pT = 35.0 GeV
Jet 2, pT = 52.5 GeV
Electron 1, pT = 92.7 GeV
Electron 2, pT = 51.1 GeV
Muon 1, pT = 73.8 GeV

- 1D 95% confidence limits are derived for each operator coupling, setting the other to zero



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T_0}/Λ^4	-0.53	0.51	-0.46	0.44	0.6
f_{T_1}/Λ^4	-0.72	0.71	-0.61	0.61	0.6
f_{T_2}/Λ^4	-1.4	1.4	-1.2	1.2	0.6
f_{T_8}/Λ^4	-0.99	0.99	-0.84	0.84	2.8
f_{T_9}/Λ^4	-2.1	2.1	-1.8	1.8	2.9

Limits on anomalous quartic gauge couplings

ZZjj sensitive to neutral T8 and T9 and T0, T1,T2 operators:

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

MadGraph sample and reweighting used to create grid in the couplings fi
Effect of aQGC greatest for large scattering energies ⇒ Limits based on $m_{4\ell}$

Systematic uncertainties are propagated to $m_{4\ell}$ distribution and profiled in fit.
Limits setting uses the same tool as for aTGC in ZZ inclusive.

$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},\ \mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,0} = \frac{f_{T0}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \mathrm{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}],\ \mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

$$\mathcal{L}_{T,2} = \frac{f_{T2}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}]$$

Selection of analysis

- Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s}$ = 8 and 13 TeV
  - https://doi.org/10.1016/j.physletb.2018.11.007
- Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s}$ = 13 TeV
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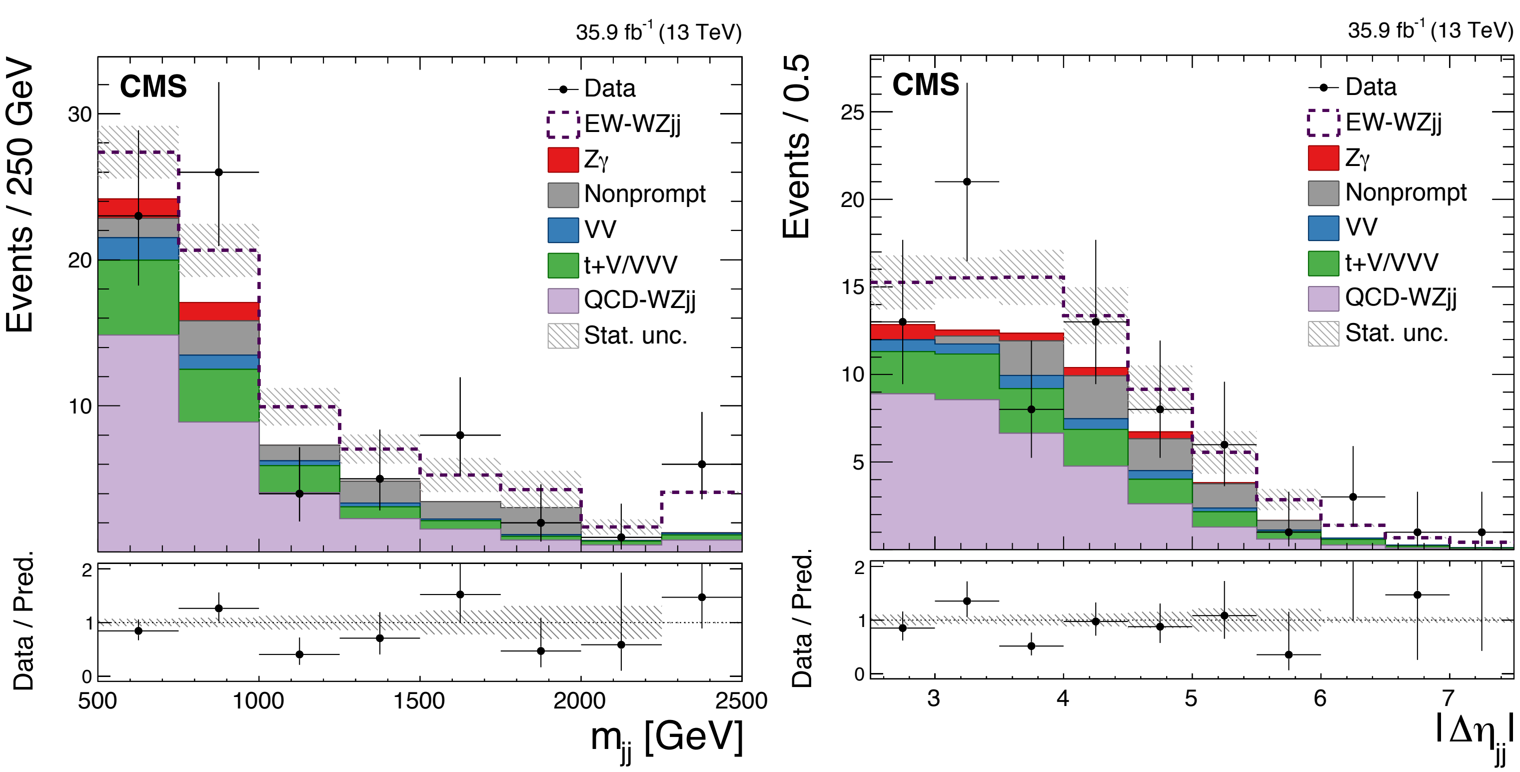
- Measurement of electroweak WZ production and search for new physics in pp collisions at $\sqrt{s}$ = 13 TeV
  - https://arxiv.org/abs/1901.04060

WZ + 2 jets

Event Selection

- $p_T^{\ell Z1}$>25 GeV $p_T^{\ell Z2}$>15 GeV
- $p_T^{\ell W1}$>20 GeV
- $|\eta^{\ell}| \leq 2.4$
- p^{miss}_T > 30 GeV
- $|mZ - m^{\ell\ell}|$ < 15 GeV,
- p_T^{jet} > 50 GeV $|\eta^{jet}|$ < 4.7
- m_{jj} > 500 GeV
- $\Delta\eta_{jj}$>2.5



- Inclusive (QCD+EWK) cross-section measured with a combined maximum likelihood fit in two fiducial region:
  - Tight. Close to the selection.
  - Loose: To simplify comparisons with theoretical calculations.
  - The acceptance from the tight to loose is 72.4 ± 0.8 %

Cross-section measurement

- Selection and fiducial phase spaces

	Electroweak Signal	Higgs Signal	Tight Fiducial	Loose Fiducial
$p_T(\ell_{Z,1})$ [GeV]	> 25	> 25	> 25	> 20
$p_T(\ell_{Z,2})$ [GeV]	> 15	> 15	> 15	> 20
$p_T(\ell_W)$ [GeV]	> 20	> 20	> 20	> 20
$\|\eta(\mu)\|$	< 2.4	< 2.4	< 2.5	< 2.5
$\|\eta(e)\|$	< 2.5	< 2.5	< 2.5	< 2.5
$\|m_Z - m_Z^{PDG}\|$ [GeV]	< 15	< 15	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4	> 4	> 4
p_T^{miss} [GeV]	> 30	> 30	-	-
$\|\eta(j)\|$	< 4.7	< 4.7	< 4.7	< 4.7
$p_T(j)$ [GeV]	> 50	> 30	> 50	> 30
$\|\Delta R(j, \ell)\|$	> 0.4	> 0.4	> 0.4	> 0.4
n_j	≥ 2	≥ 2	≥ 2	≥ 2
$p_T(b)$ [GeV]	> 30	> 30	-	-
n_{b-jet}	$= 0$	$= 0$	-	-
m_{jj}	> 500	> 500	> 500	> 500
$\|\Delta\eta(j_1, j_2)\|$	> 2.5	> 2.5	> 2.5	> 2.5
$\|\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\|$	< 2.5	-	< 2.5	-

Systematic uncertainties

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

- Nuisance parameters
  - log-normal probability density functions are assumed systematic uncertainties affecting the event yields of the various background contributions
  - Continuing perturbation of the spectrum is assumed for systematic uncertainties that affect the shape of the distributions

WZ EWK

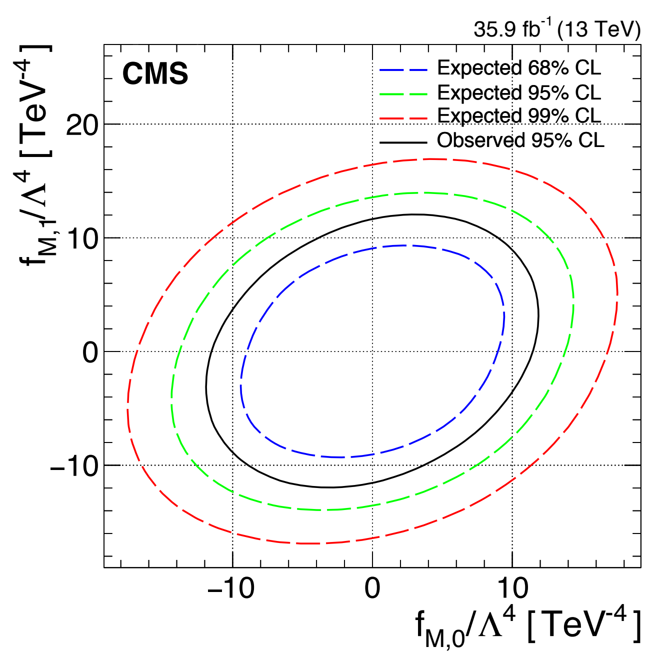
- Electro weak cross section

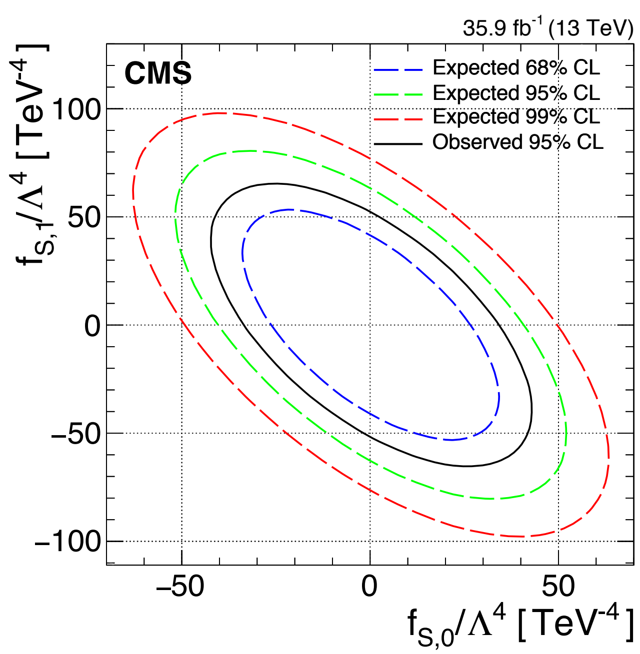
$$\sigma^{loose} = 1.48^{+0.12}_{-0.11}\ (scale) \pm 0.07(PDF)\ \text{fb}$$

Anomalous quartic gauge couplings

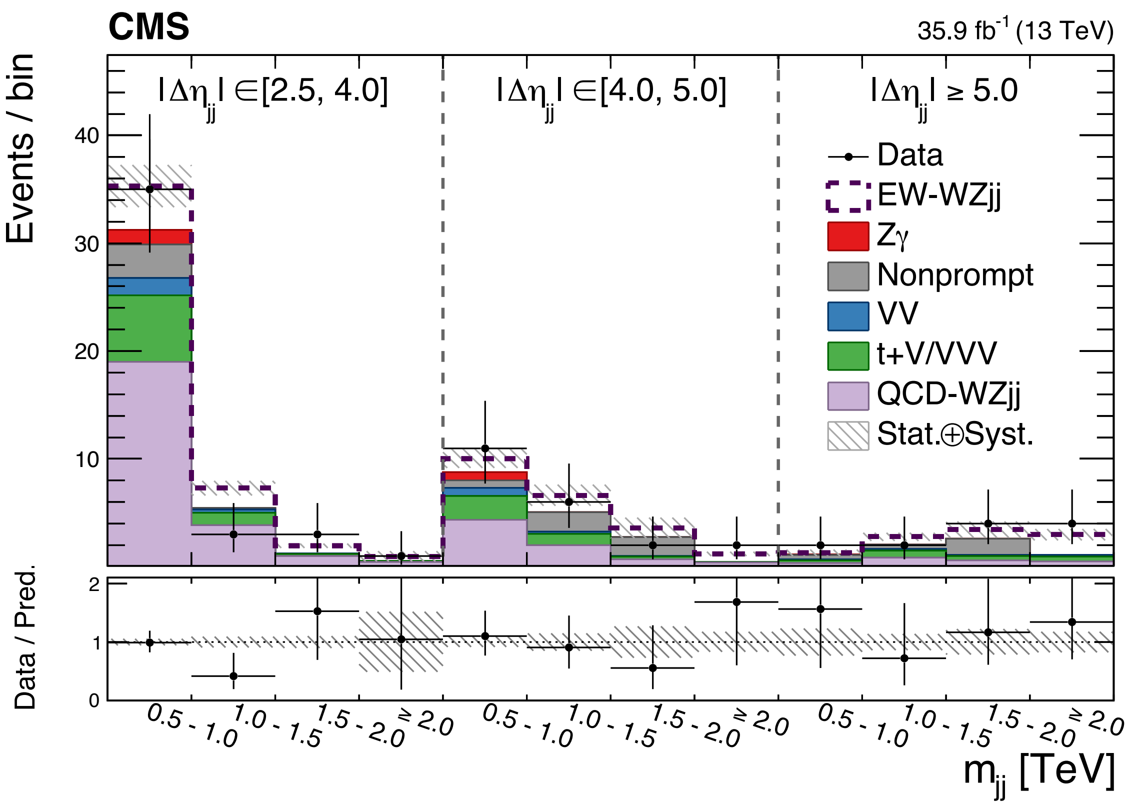
- All operators are charge conjugate and parity-conserving.
- The WZ_{jj} channel is most sensitive to:
  - T0, T1, and T2 operators, which are constructed purely from the SU(2) gauge fields.
  - S0 and S1 operators, which involve interactions with the Higgs field.
  - M0 and M1 operators, which involve a mixture of gauge and Higgs interactions.

Parameters	Exp. limit	Obs. limit
f_{M0}/Λ^4	$[-11.2, 11.6]$	$[-9.15, 9.15]$
f_{M1}/Λ^4	$[-10.9, 11.6]$	$[-9.15, 9.45]$
f_{S0}/Λ^4	$[-32.5, 34.5]$	$[-26.5, 27.5]$
f_{S1}/Λ^4	$[-50.2, 53.2]$	$[-41.2, 42.8]$
f_{T0}/Λ^4	$[-0.87, 0.89]$	$[-0.75, 0.81]$
f_{T1}/Λ^4	$[-0.56, 0.60]$	$[-0.49, 0.55]$
f_{T2}/Λ^4	$[-1.78, 2.00]$	$[-1.49, 1.85]$





EWK WZjj

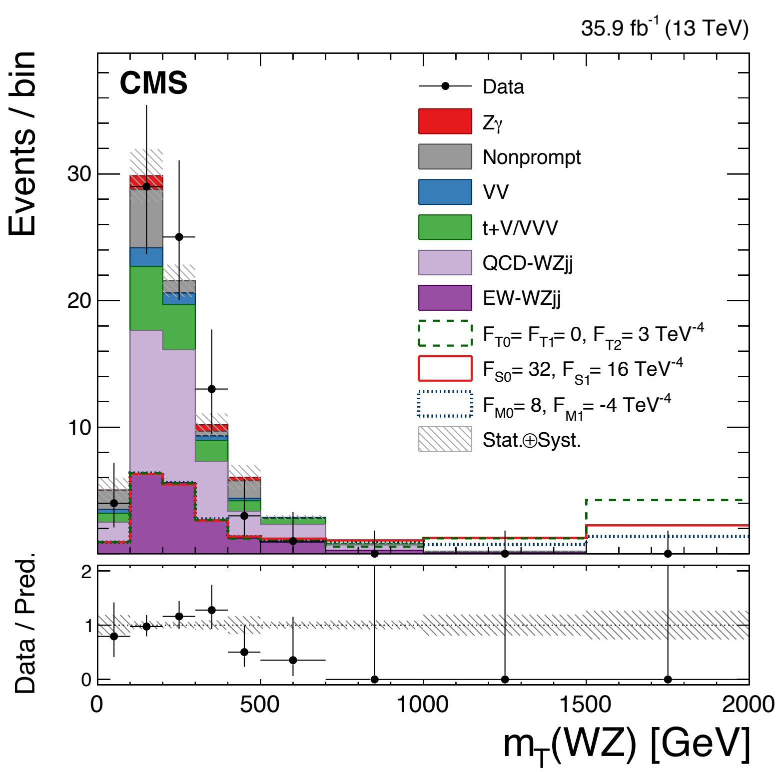


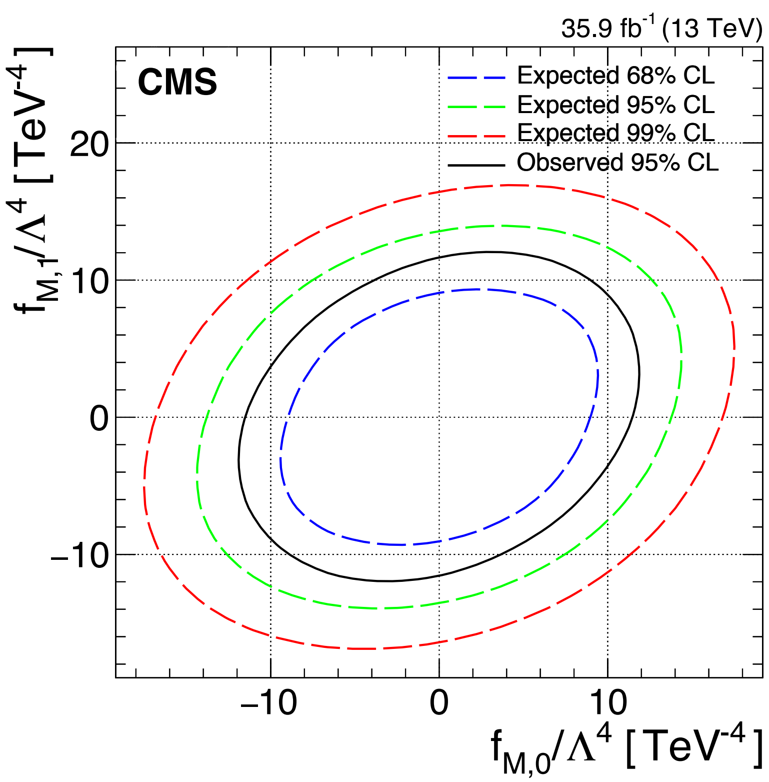
- Simultaneous maximum likelihood fit on 2D distribution (m_{jj},$\Delta\eta_{jj}$) on the signal strength μ.

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

- The observed (expected) statistical significance for EW WZ production is 2.2 (2.5) standard deviations.

Anomalous quartic gauge couplings





- Effective field theory (EFT) approach
- 9 independent dimension-eight operators
- A nonzero aQGC would enhance the production of events with high WZ mass → m_T(WZ)
- One-dimensional 95% confidence level (CL) limits extracted from a maximum likelihood fit using the CL_S method.

Constraints on charged Higgs production

- Higgs sector is extended by one real and one complex SU(2) triplet (Georgi-Machacek model).
- In this model, the couplings depend on $m(H^{\pm})$ and s_H, where s_H represents the fraction of the contribution from the triplets to the W bosons.
- A combined fit of the predicted signal and background yields to the data is performed in bins of $m_T(WZ)$ to derive model-independent expected and observed exclusion limits on $\sigma_{VBF}(H^{\pm})\,B(H^{\pm} \rightarrow WZ)$ at 95% confidence level using the CL_s method.
- For the probed parameter space and $m_T(WZ)$ distribution used for signal extraction, the varying width as a function of s_H is assumed to have negligible impact on the result.
- The value of the branching fraction $B(H^{\pm} \rightarrow WZ)$ is assumed to be one.
- Blue shaded region shows the parameter space for which the $H^{\pm}$ total width exceeds 10% of $m(H^{\pm})$, where the model is not applicable due to perturbativity and vacuum stability requirements.