Recent results on SM physics with Vector Bosons in CMS

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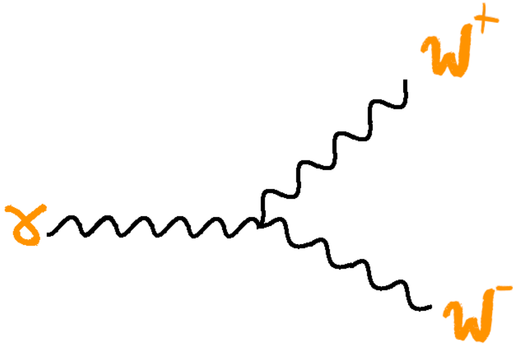
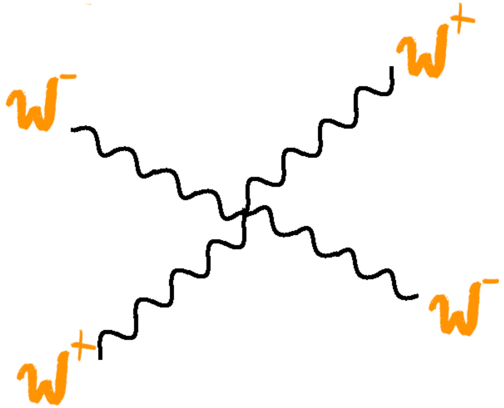
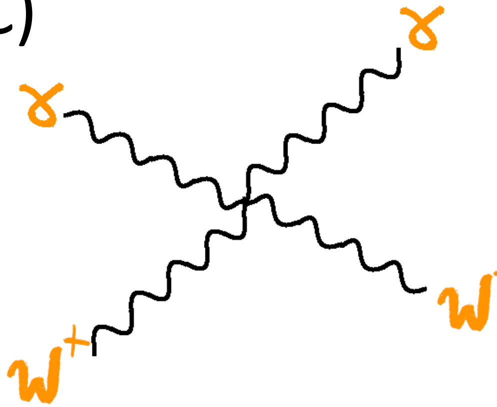
Physic Motivation



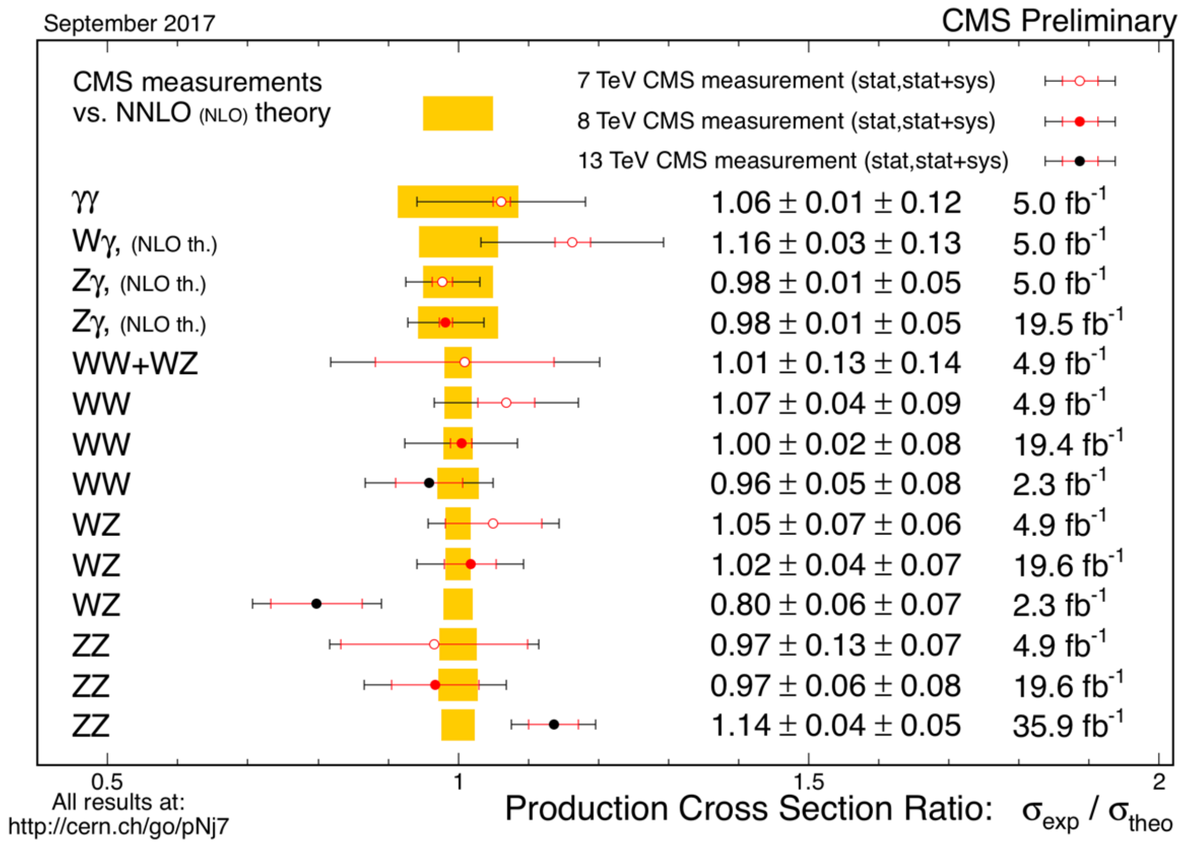


- Test of the perturbative calculations.
  - QCD corrections and hadronization models.
- Test of electroweak sector of SM.
- Sensitive to the interaction between gauge bosons via triple/quartic gauge couplings (TGC,QGC).
- Sensitive to anomalous triple/quartic couplings (aTGC,aQGC)
- Important test of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

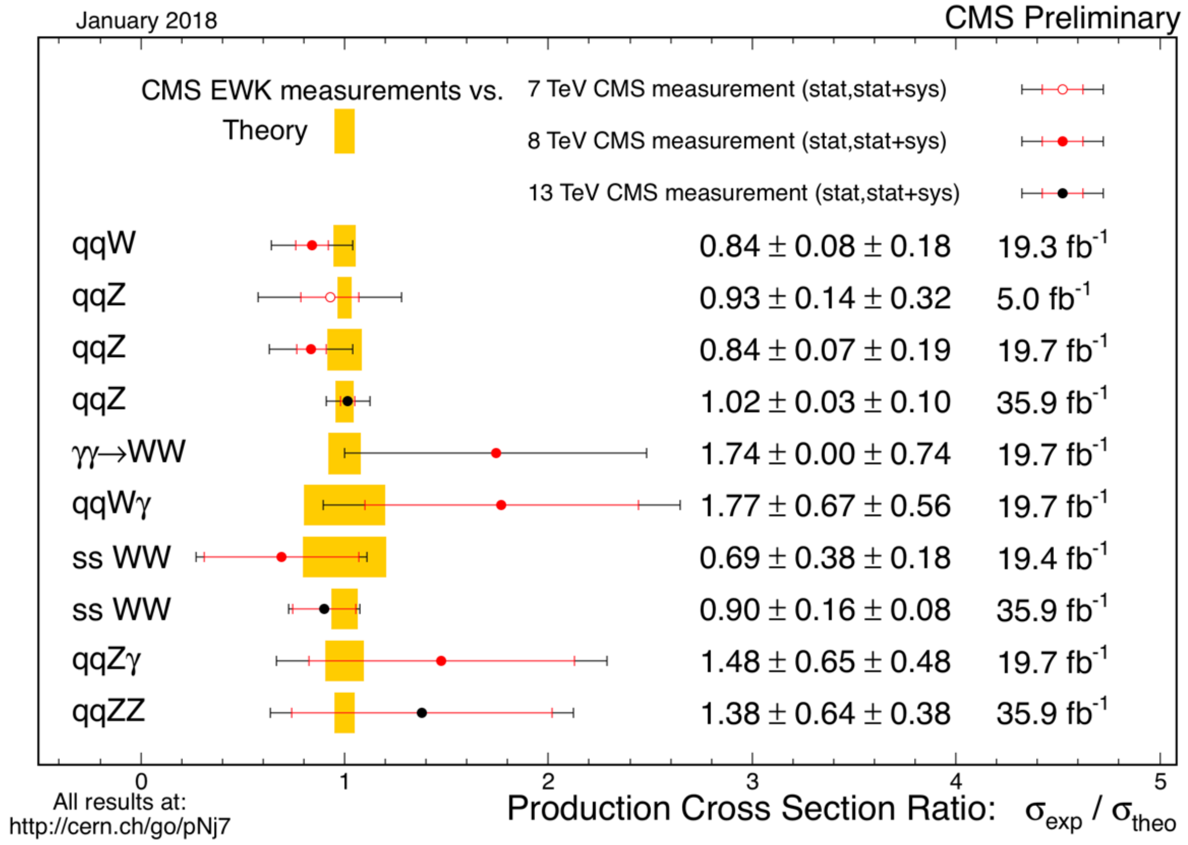


CMS standard model results overview

Multi Boson



Electro Weak



Selection of analysis

- Measurement of differential cross sections in the $\varphi*$ variable for inclusive Z boson production in pp collisions at $\sqrt{s}$ = 8 TeV
  - https://arxiv.org/abs/1607.06943
- Electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  - https://arxiv.org/abs/1712.09814
- Measurements of differential cross sections of the production of two Z bosons in association with jets at $\sqrt{s}$ 13 TeV
  - http://cds.cern.ch/record/2264556?ln=en
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Z and ϕ* variable (Z➔2ℓ)

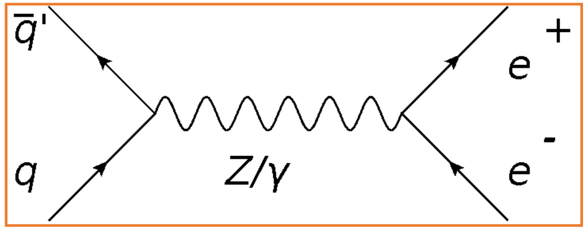
- Transverse momentum of Z (**q_T**) is essential for high-precision measurements at the LHC (W boson mass).
- Low experimental resolution of **q_T**
  - Uncertainties in the magnitude of the transverse momenta of the leptons from the decay of the Z boson.
- Angles are measured more precisely.
- $\phi * = \tan(\frac{\pi - \Delta\phi}{2}) \sin(\theta^*_\eta)$
- $\phi * \sim q_T / m_{\ell\ell}$

> - $\Delta\varphi$ = opening angle of leptons in the transverse plane.
> - $\cos(\theta^*_\eta) = \tanh[\Delta\eta/2]$

Z Selection

Signal

Mainly Drell Yan



Main Background

tt, Z → $\tau^+\tau^-$, WW, WZ, ZZ, single top quarks.

Final state

Z➔2ℓ   ℓ=μ,e

High p_T isolated leptons.

$\sqrt{s}$ = 8 TeV L = 19.7 fb^{-1}

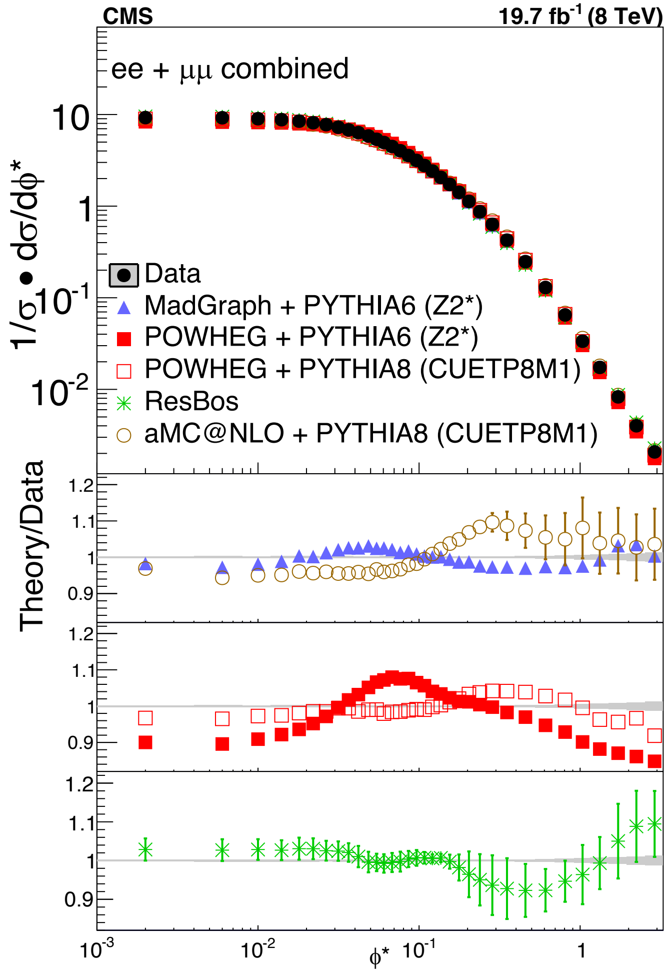
Fiducial Phase space

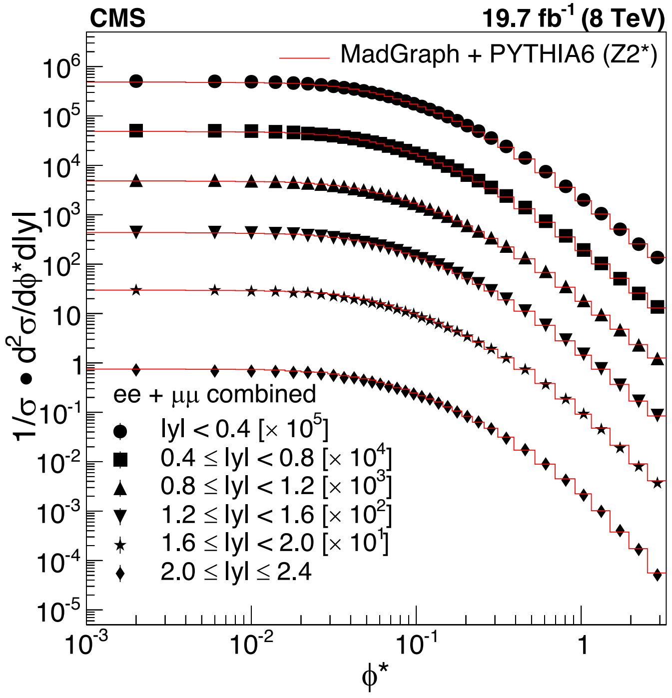
- $p_T^{\ell 1}$>30 GeV
- $|\eta^{\ell 1}| \leq 2.1$
- $p_T^{\ell 2}$>20 GeV
- $|\eta^{\ell 2}| \leq 2.4$
- 60 < $m_{\ell\ell}$ <120 GeV.
- $\varphi^* < 3.227$

- The distributions of the observables need to be corrected back to the stable particle level for efficiencies and for detector resolution effects. (**Unfolding**)
- The model for the detector resolution is derived from **MADGRAPH (LO)** generator interfaced with PYTHIA6.

Z production cross sections

- Normalized and absolute differential cross section presented.
- Different bin of rapidity (y).
- Compared with five theoretical predictions.
- None of the predictions matches perfectly for the entire range.





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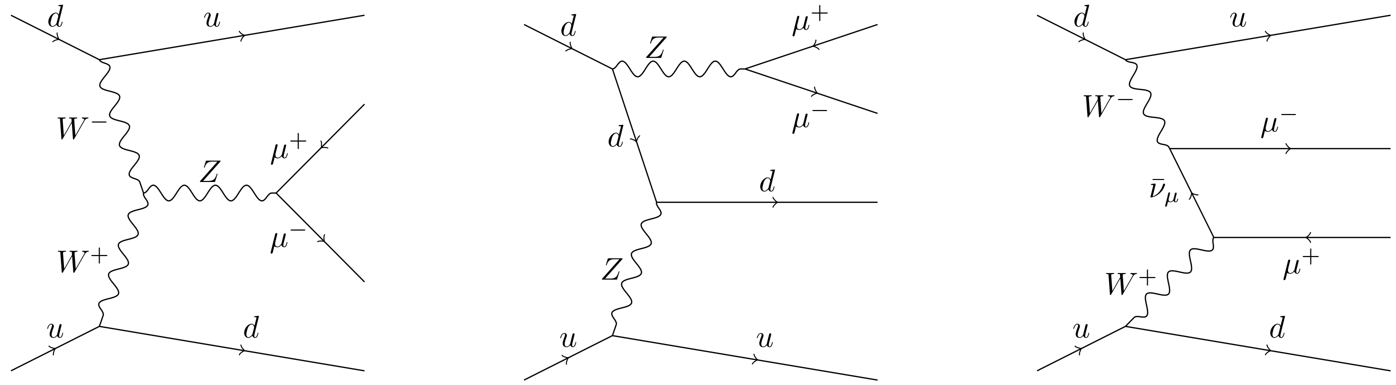
Z+qq Electro-Weak



Event Selection

- $p_T^{\ell 1}$>30 GeV $p_T^{\ell 2}$>20 GeV
- $|\eta^{\ell}| \leq 2.4$
- $|mZ - m^{\ell\ell}| < 15$ GeV,
- $p_T^{jet1} > 50$ GeV $p_T^{jet2} > 30$ GeV
- $m_{jj} > 200$ GeV

sample	$\mu^+\mu^-$	e^+e^-
Data	422 499	163 640
Signal	6665.1	2833.2
WW	116.5	61.8
WZ	2151.3	914.5
ZZ	1323.7	522.6
$t\bar{t}$	12938.1	5362.8
single top	723.2	269.1
DY + jets (AMC)	394 640	152 755
Total MC	418 415	162 059
DY rescaling (AMC)	1.009	1.006

Small interference between signal and the main background. <0.4% in high signal purity phase space.

Final state

Zqq➔2ℓ+2 jets (ℓ=μ,e)

$\sqrt{s}$ = 13 TeV L = 35.9 fb^{-1}

Signal

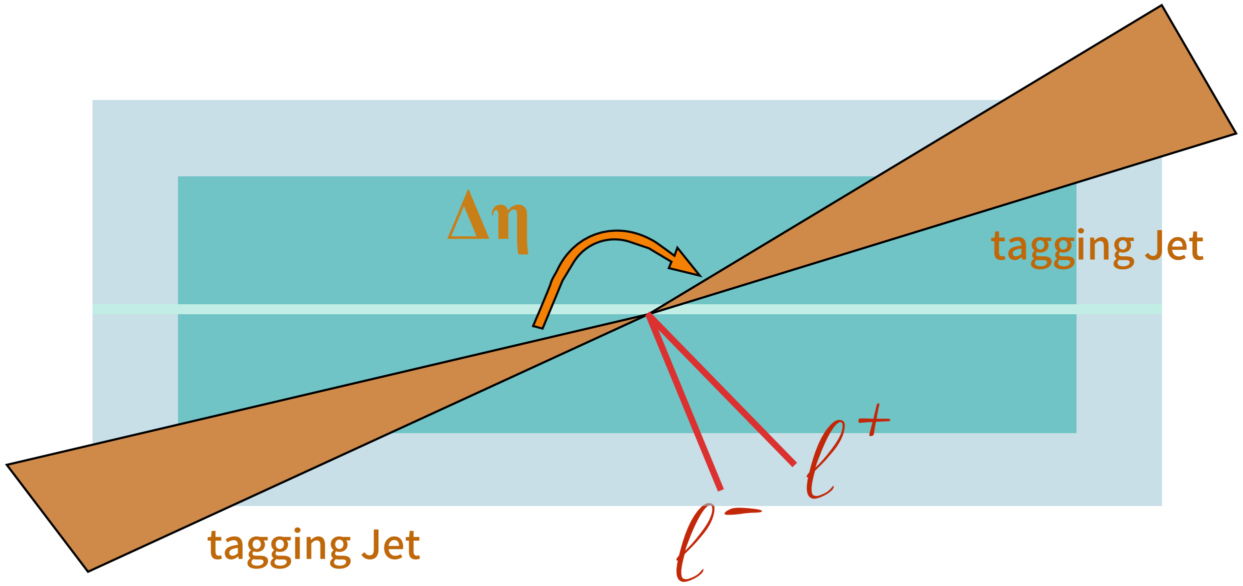
α^4_{EW}

Main Background

$\alpha^2_{EW}\alpha^2_{S}$ (DY+jets)

Z+qq EW topology

- Signal vs. Background discrimination made with a **multi variate analysis**. Boosted Decision Tree (BDT)
- 7 Inputs:
  - m_{jj}
  - $\Delta\eta_{jj}$
  - Quark gluon likelihood discriminant (1st jet and 2nd jet)
  - p_T^{jj}

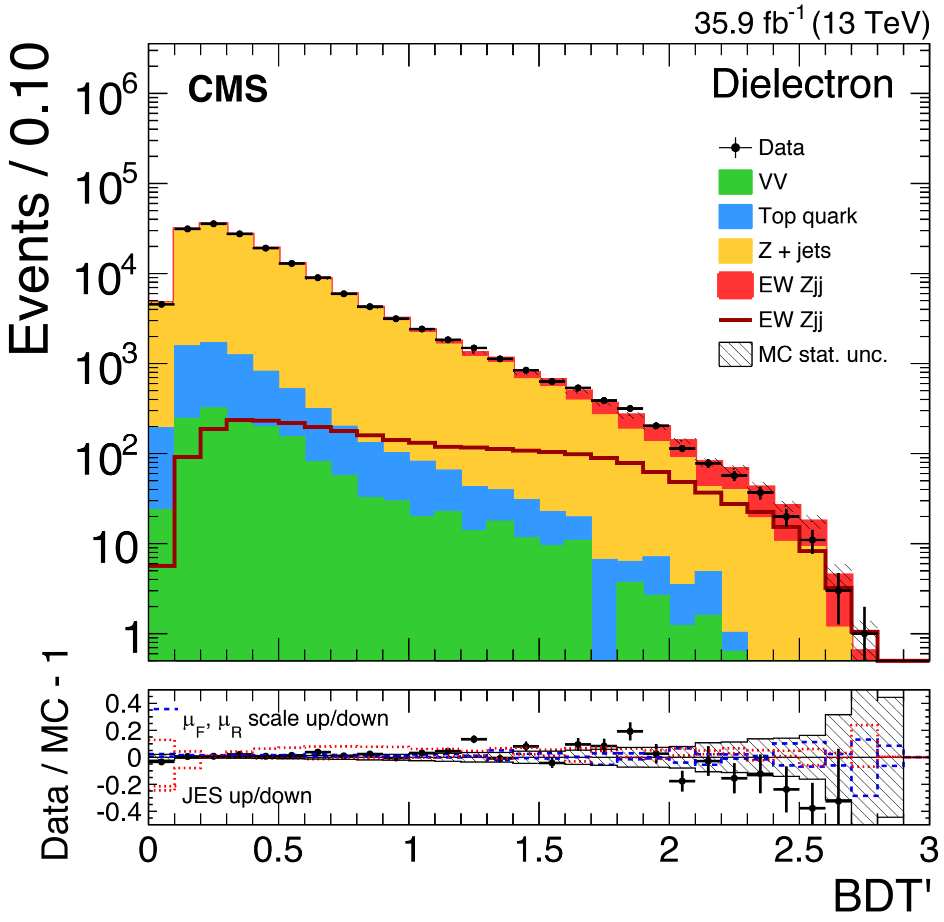


- $$z^* = \left(y_Z - \frac{1}{2}(y_{j1} + y_{j2}) \right) / \Delta y_{jj}$$ (Zeppenfeld variable)

- $$R(p_T^{\mathrm{hard}}) = \frac{|\vec{p_T}_{j1} + \vec{p_T}_{j2} + \vec{p_T}_Z|}{|\vec{p_T}_{j1}| + |\vec{p_T}_{j2}| + |\vec{p_T}_Z|} = \frac{|\vec{p}_T^{\mathrm{hard}}|}{|\vec{p_T}_{j1}| + |\vec{p_T}_{j2}| + |\vec{p_T}_Z|}$$ (event balance variable)

Z+qq EW results

- Good agreement observed in all distributions.
- A binned maximum likelihood is used to fit simultaneously the strength modifiers for the EW Zjj and DY Zjj
  - strength modifiers ($\mu=\sigma/\sigma_{SM}$)
- Main systematics: Jet energy scale and the limited statistics of simulated events



$$\sigma(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 552 \pm 19\,(\mathrm{stat}) \pm 55\,(\mathrm{syst})\,\mathrm{fb} = 552 \pm 58\,(\mathrm{total})\,\mathrm{fb}$$

$$\sigma_{LO}(EW\ell\ell jj) = 543 \pm 24 fb$$

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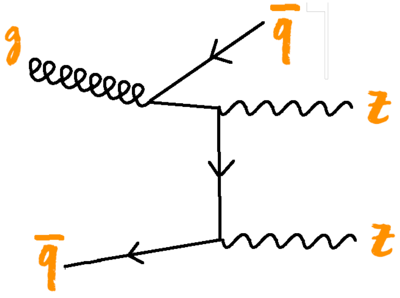
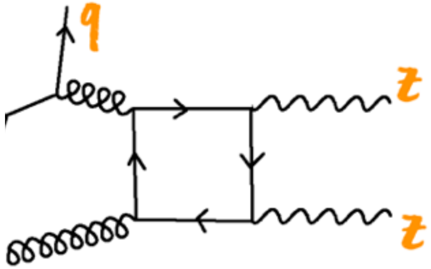
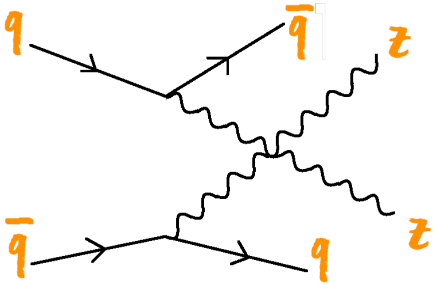
ZZ+jets







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

Signal

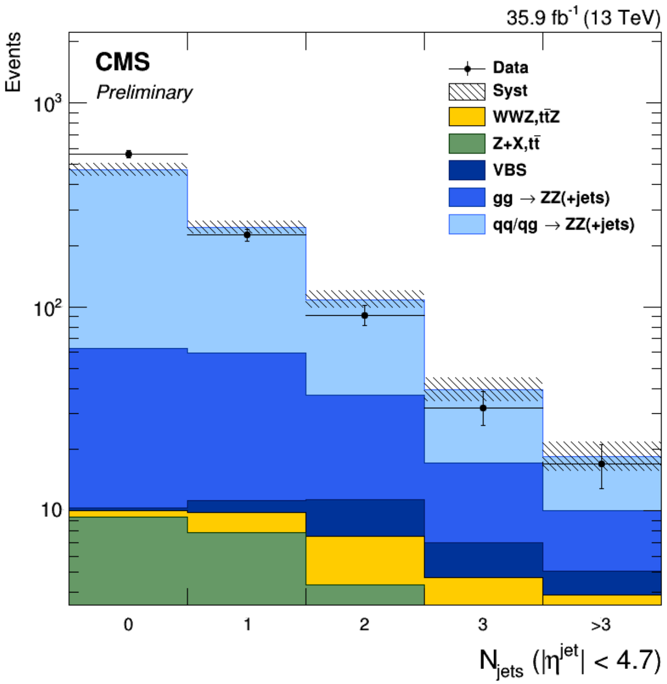
qq->ZZ +jets, gg->ZZ(box) +jets , VBS

Main Background

DY+jets

Not well represented by MC samples.

➡ **data driven method.**



Final state

ZZ+jets➔4ℓ+2 jets

(ℓ=μ,e)

$\sqrt{s}$ = 13 TeV L = 35.9 fb^{-1}

ZZ+jets cross sections

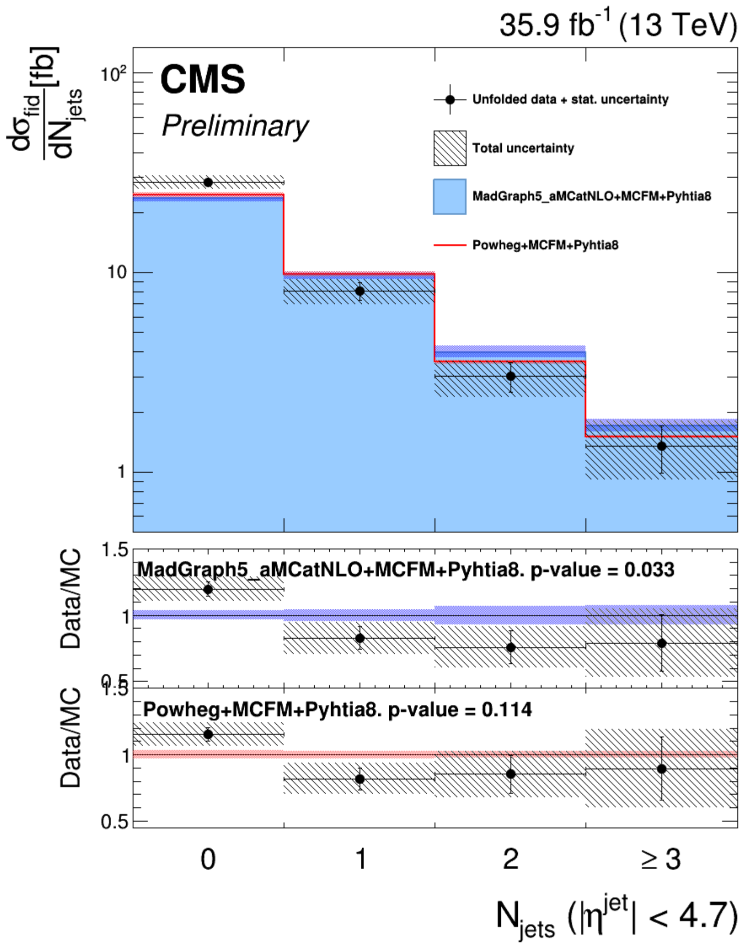
Fiducial Phase space

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

Main systematics:

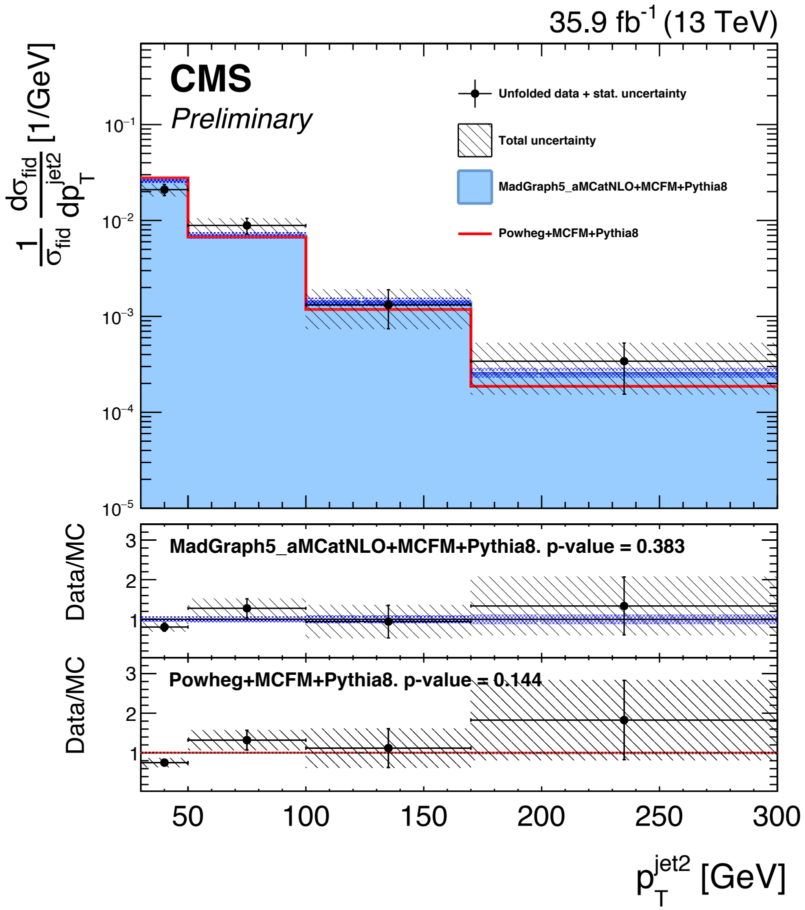
- Jet energy scale
- Unfolding

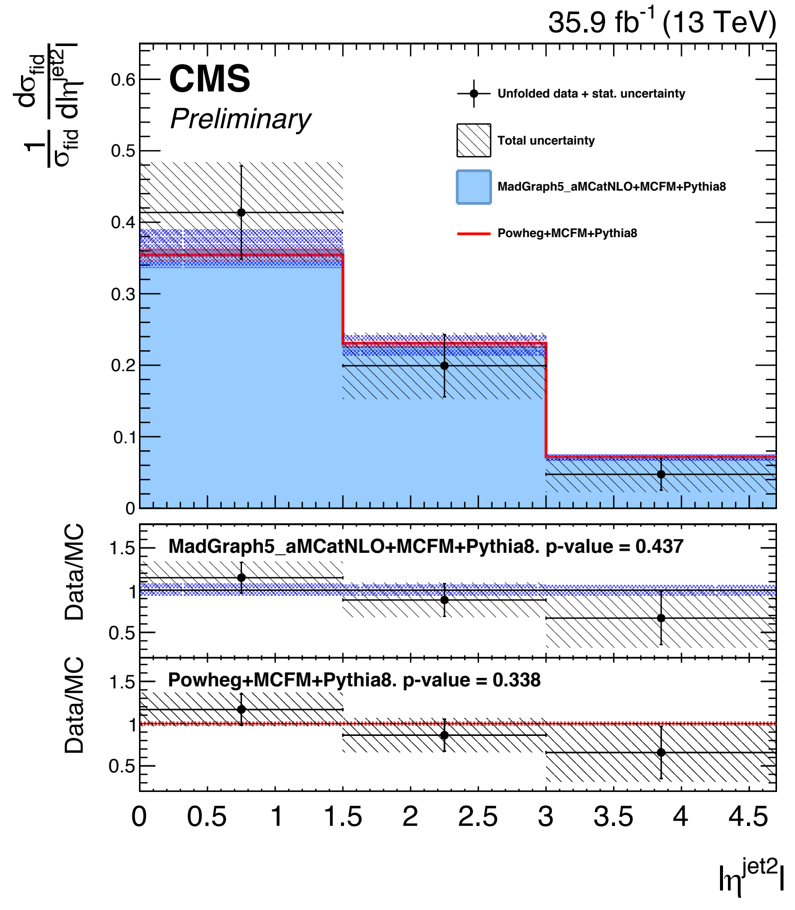
- The distributions is unfolded.
- The model for the detector resolution is derived from **MadGraphAMC@NLO + MCFM** generators interfaced with PYTHIA8.
- Normalized and absolute differential cross section presented.
- Overall good agreement

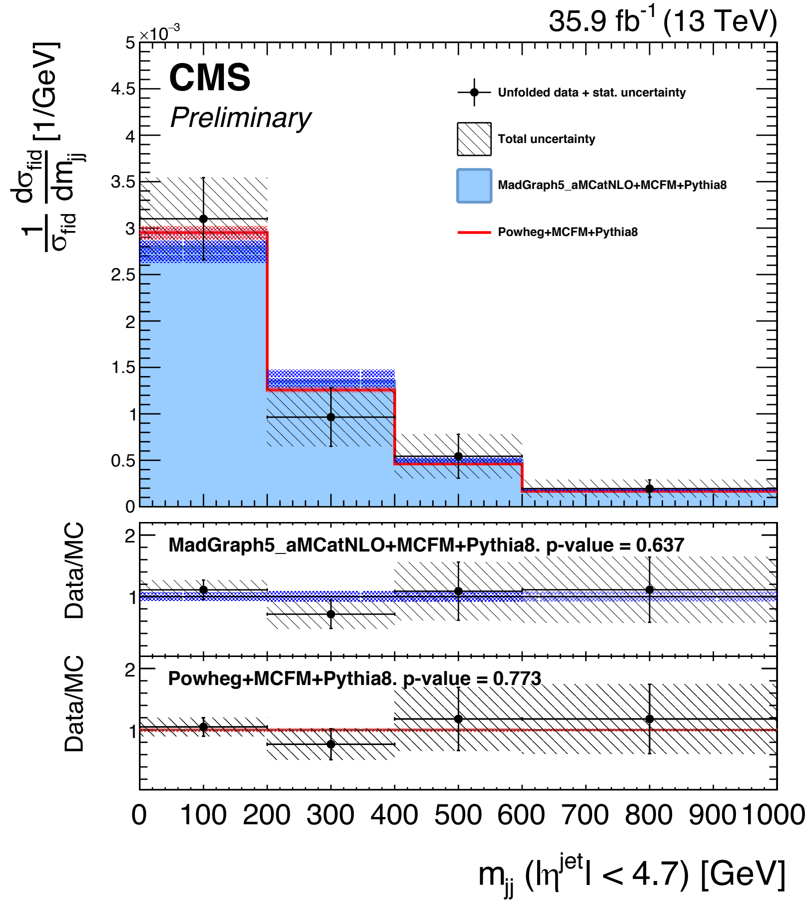


Number of jets ($\|\eta^{jet}\| < 4.7$)	Fiducial cross section [fb]	Theo. cross section [fb]
0	28.3 ± 1.3 (stat)$^{+1.7}_{-1.6}$ (syst) ± 0.7(lumi)	$23.6^{+0.8}_{-0.9}$
1	8.1 ± 0.8 (stat)$^{+0.8}_{-0.8}$ (syst) ± 0.2(lumi)	$9.7^{+0.4}_{-0.4}$
2	3.0 ± 0.5 (stat)$^{+0.3}_{-0.4}$ (syst) ± 0.1(lumi)	$4.0^{+0.3}_{-0.2}$
≥ 3	1.3 ± 0.4 (stat)$^{+0.3}_{-0.2}$ (syst)	$1.7^{+0.1}_{-0.1}$

ZZ+jets cross sections







P_T^{jet2} $|\eta|^{jet2}$ M_{jj}

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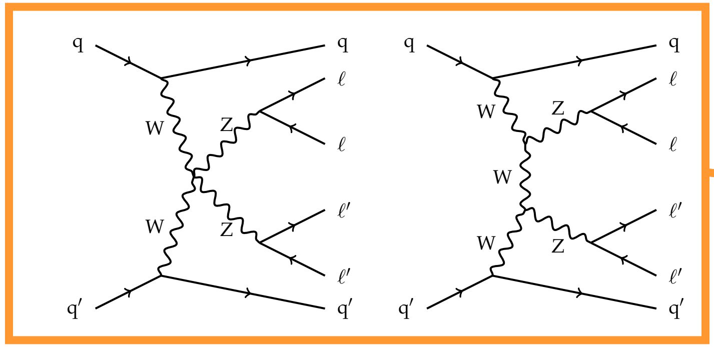
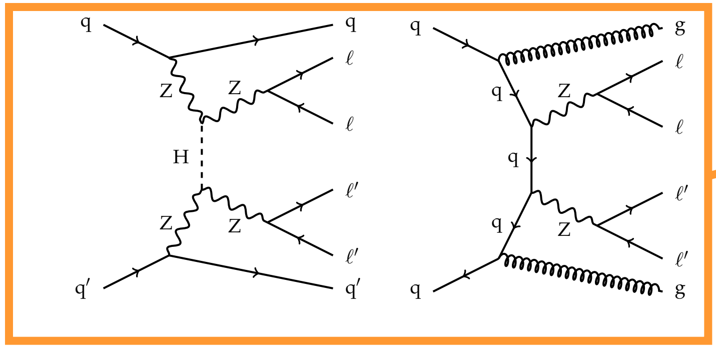
ZZ+jets EWK



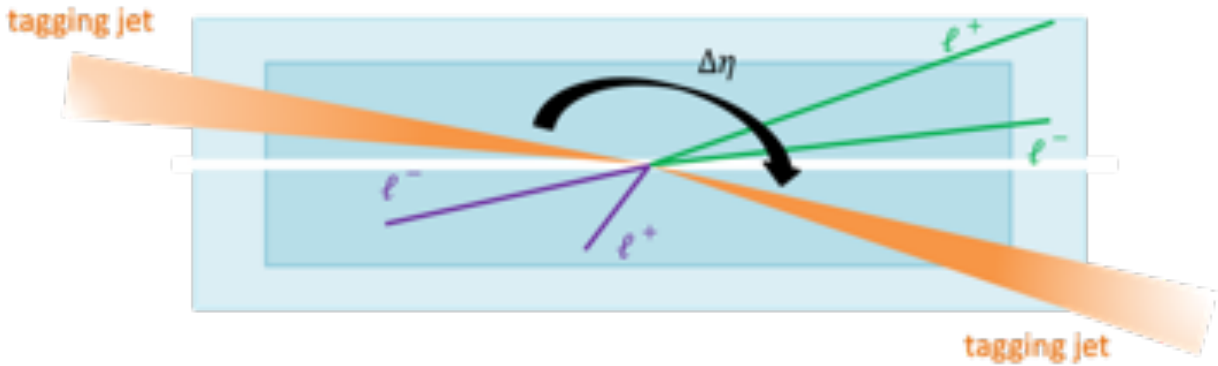


Signal

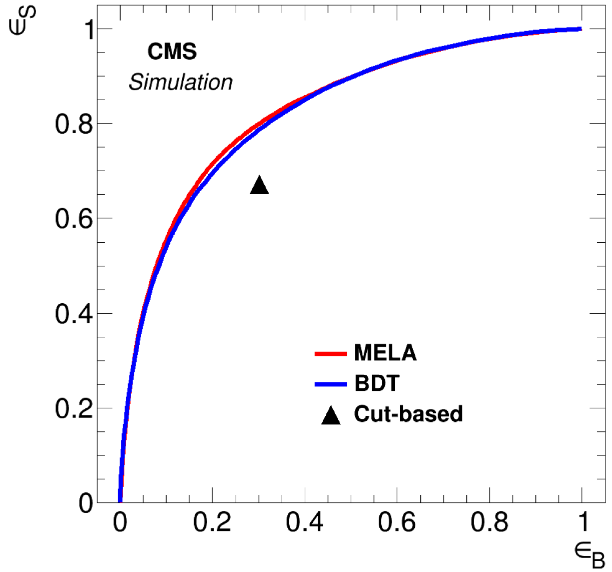
α^6_{EW} (VBS)

Main Background

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



- Base selection identical to ZZ +jets
  - + mJJ > 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)

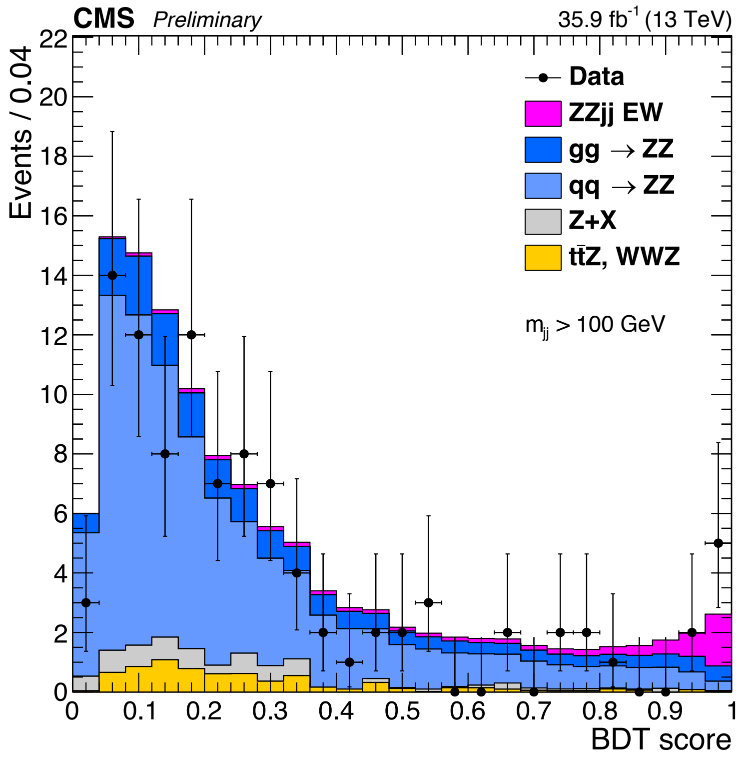


ZZ+jets EWK Multi variate analysis

- 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.
- 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

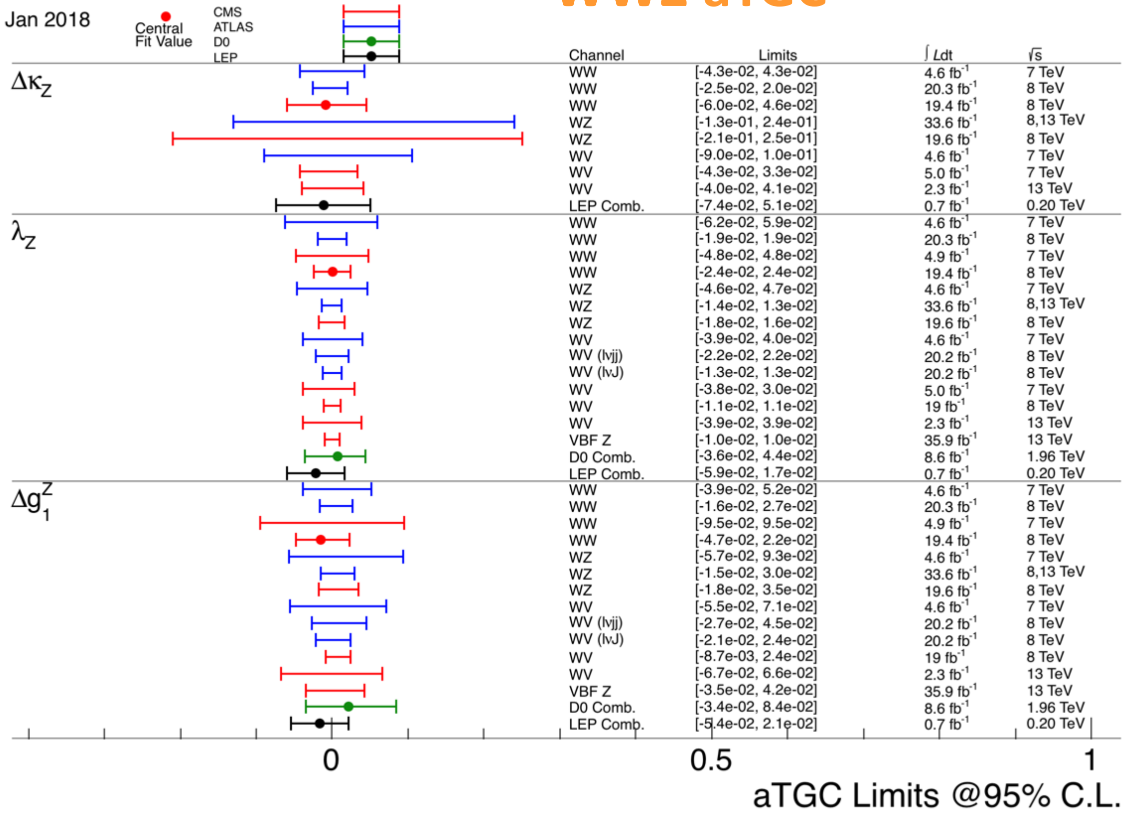


$$\sigma_{\text{fid.}}(\text{EW pp} \to ZZjj \to \ell\ell\ell'\ell'jj) = 0.40^{+0.21}_{-0.16}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})\ \text{fb} \quad \sigma_{theo} = 0.29^{+0.02}_{-0.03}\ \text{fb}$$

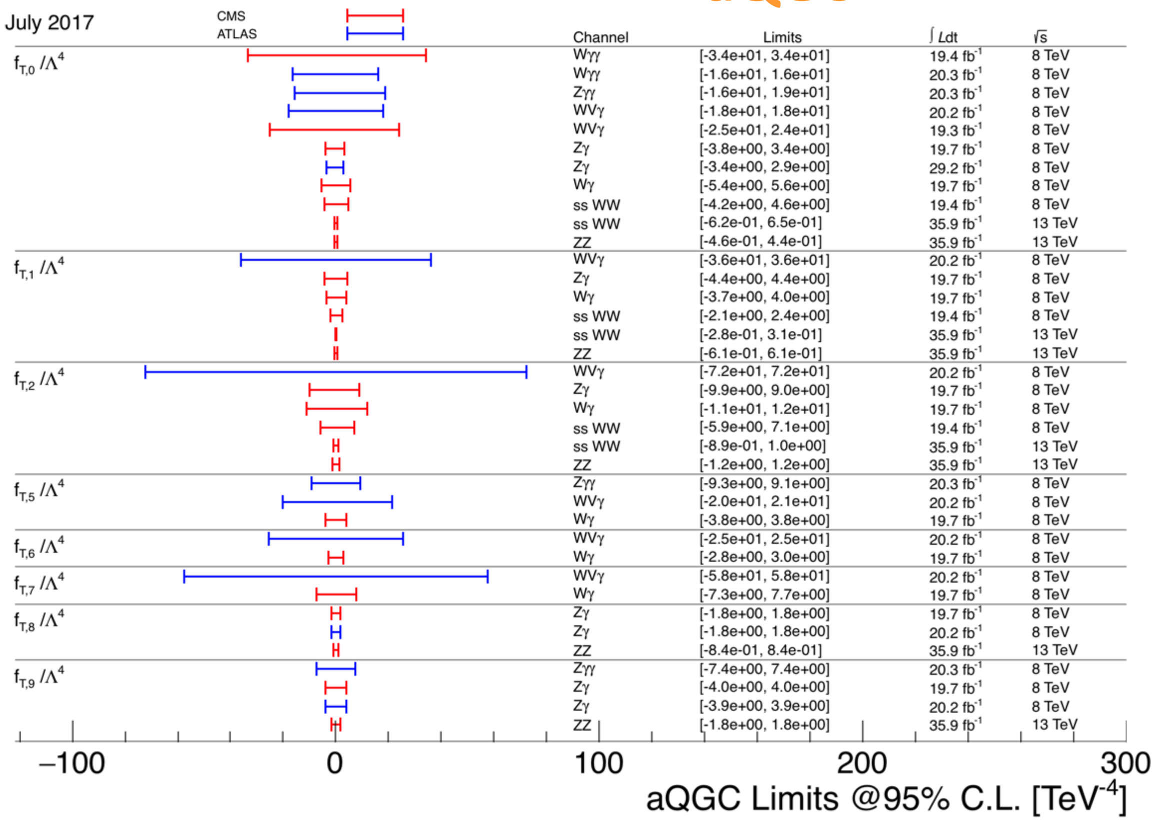
Anomalous Couplings

Almost all analyses include measurement of anomalous vector boson couplings.
2 summary plot as example:

WWZ aTGC



aQGC



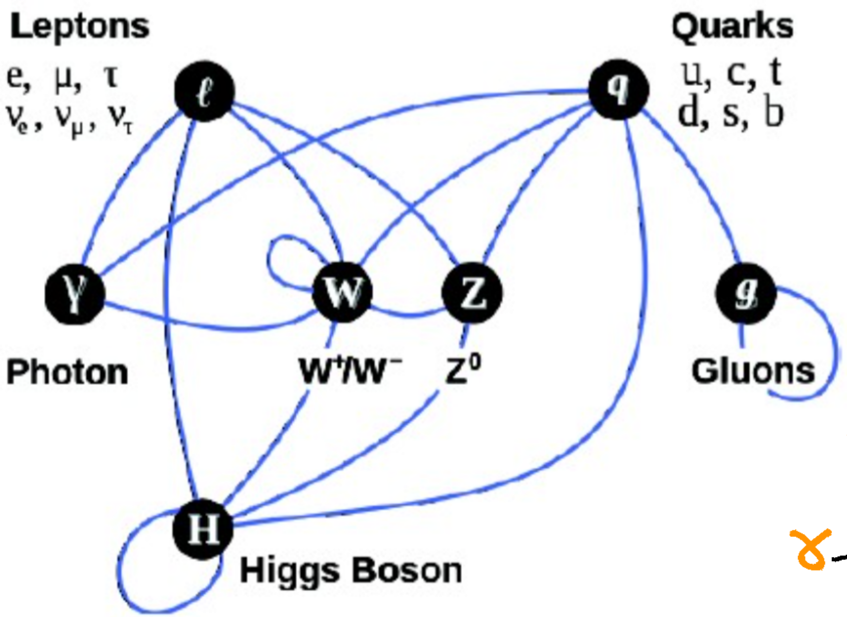
Summary

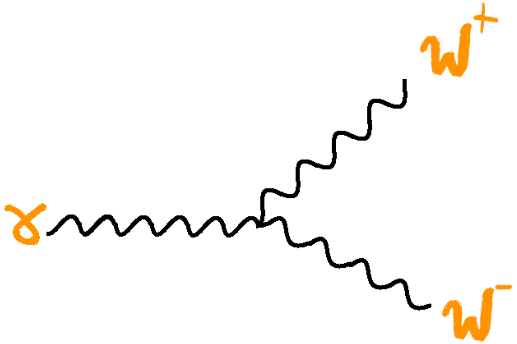
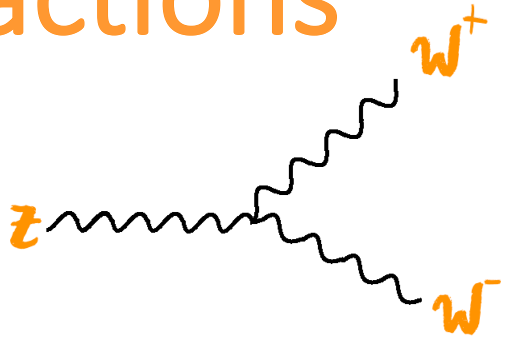
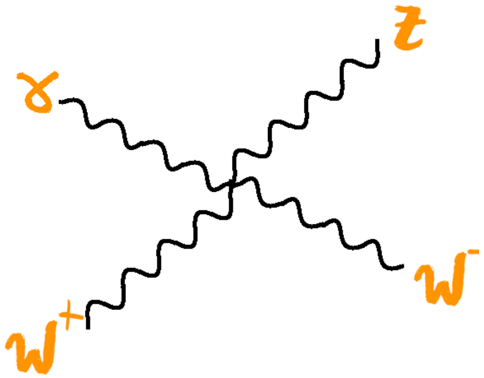
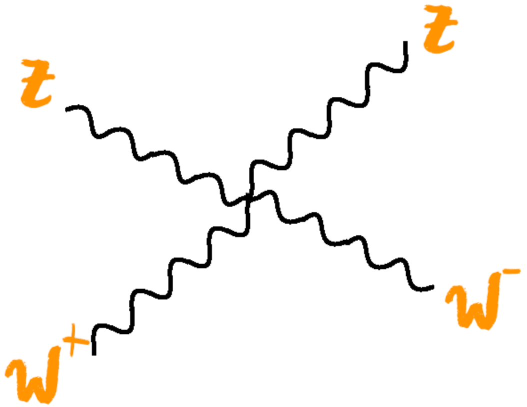
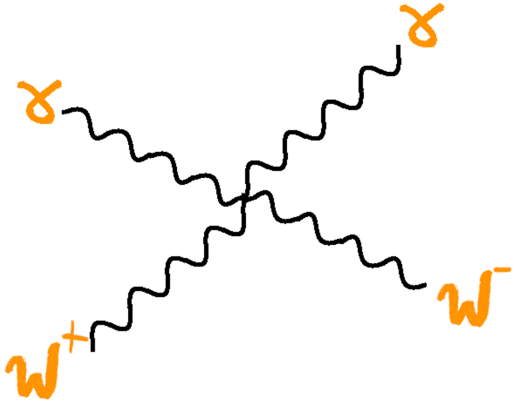
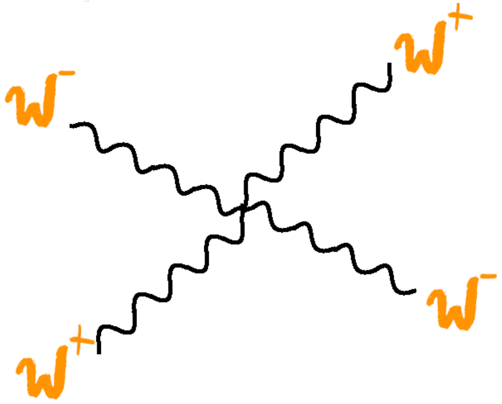
CMS is pursuing a very active scalar program of measurement:

- Many different channels studied with access to unfolded differential measurements and limits on anomalous gauge couplings.
- VBS observed in same sign WW and search is on-going in other channels such ZZ, Wɣ, Zɣ and WZ.
- Precise measurement on weak mixing angle.
- Expect many new interesting results from Run 2 data.

Back Slide

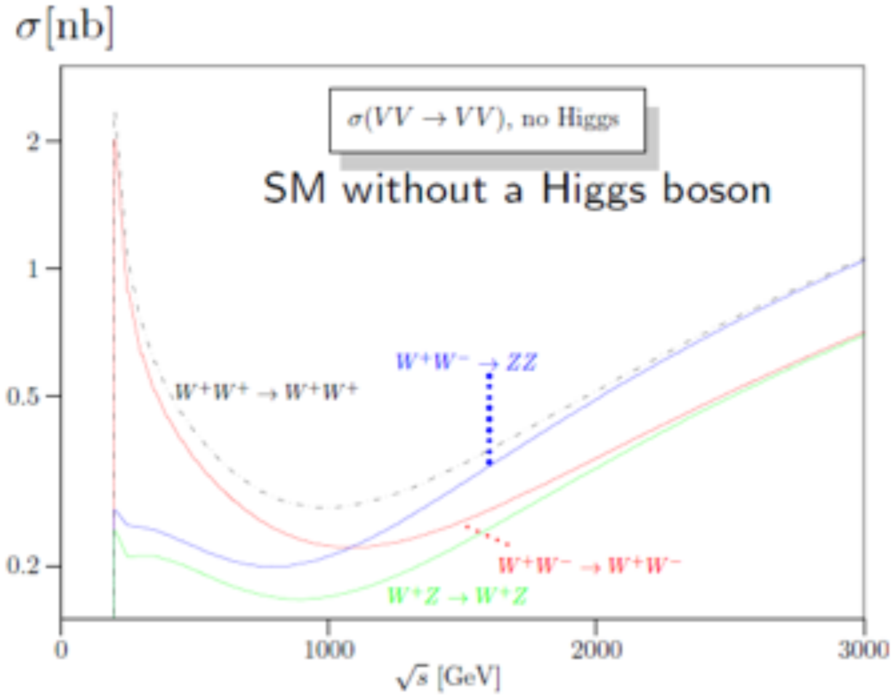
Electroweak gauge boson interactions

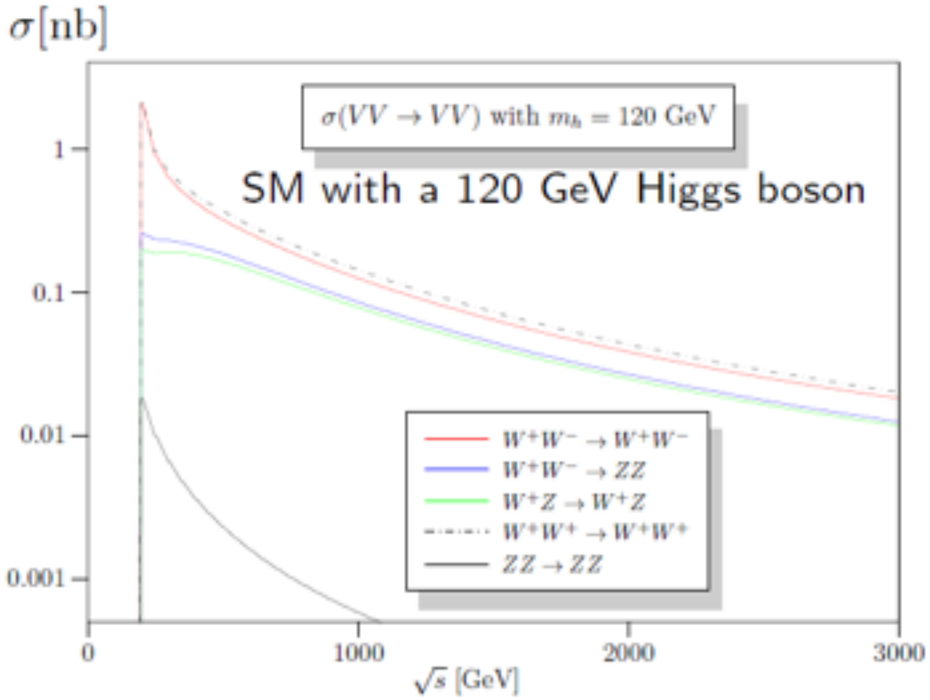


Unitarity violation

- The Vector Boson scattering is deeply connected the nature of EWSB.
  - The Goldstone bosons of the Higgs field become longitudinal, massive modes of the weak gauge bosons.
- If the Higgs boson is only partially responsible for EWSB than $V_L V_L$ cross section will keep growing with center of mass energy up to a new physic scale Λ

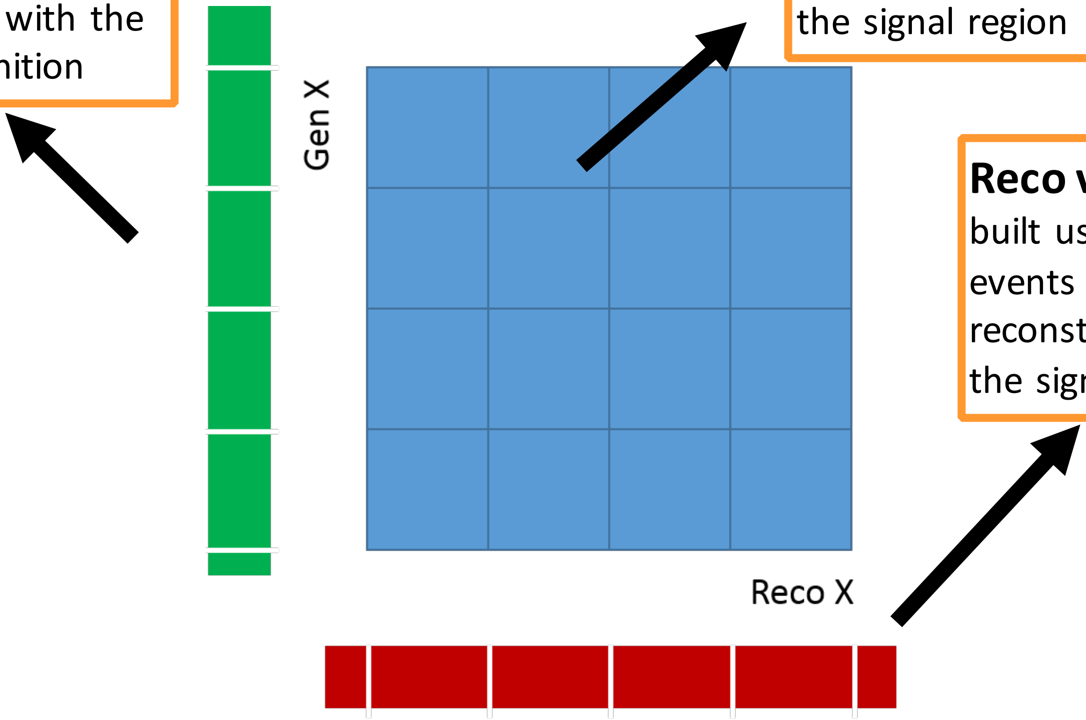




Unfolding Procedure – Ingredients

Gen vectors built using ALL events generated with the signal definition

Response matrices built using events generated with the signal definition AND reconstructed in the signal region



Reco vectors built using ALL events reconstructed in the signal region

Fiducial phase space

$p_T^e > 5$ GeV, $|\eta^e| < 2.5$

$p_T^\mu > 5$ GeV, $|\eta^\mu| < 2.5$

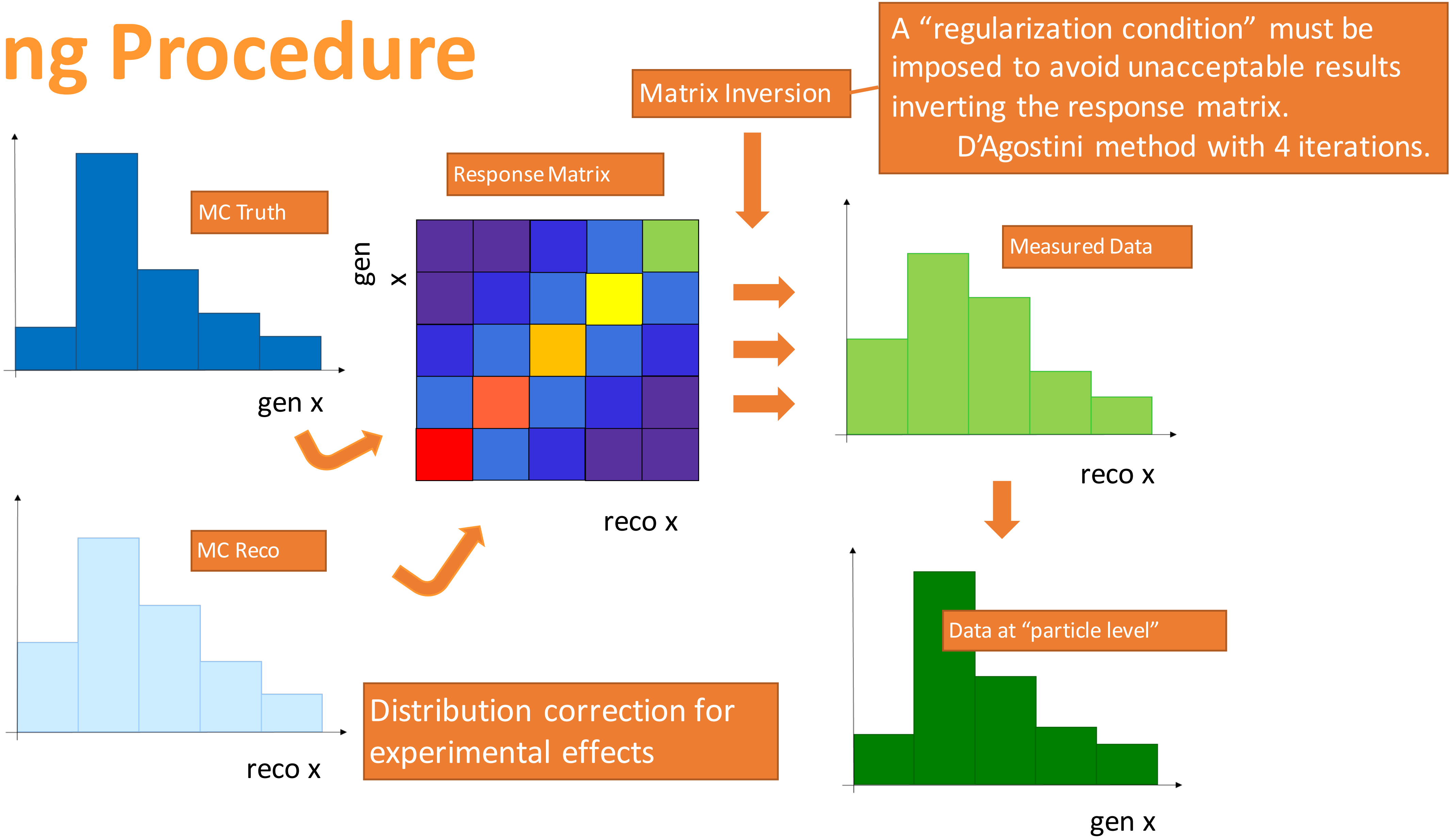
$p_T^{\ell_{3,4}} > 5$ GeV

$p_T^{\ell_1} > 20$ GeV , $p_T^{\ell_2} > 10$ GeV

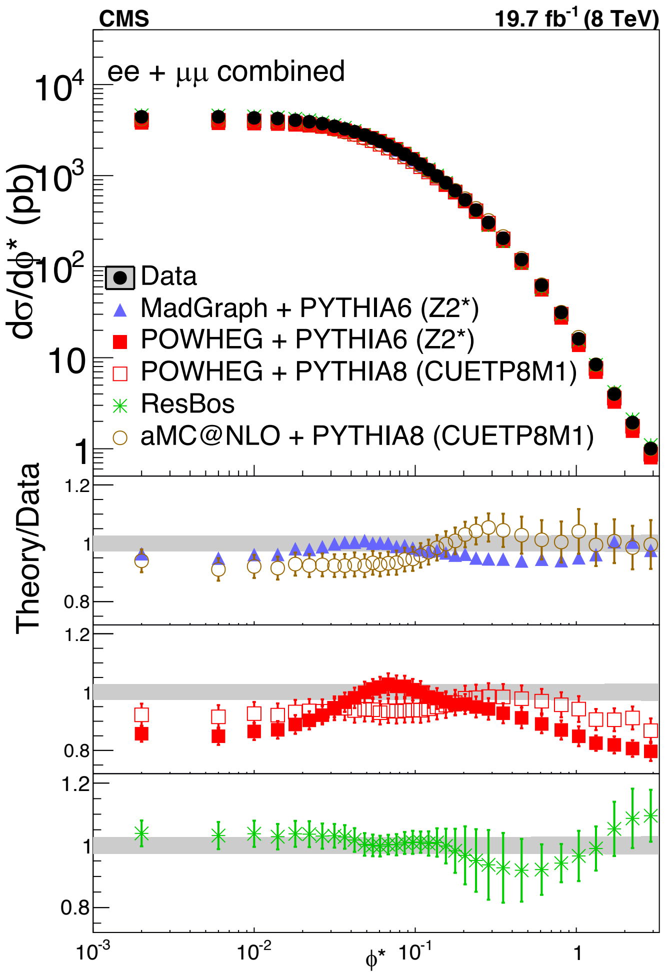
$m_{\ell+\ell-} > 4$ GeV (any OSSF pair)

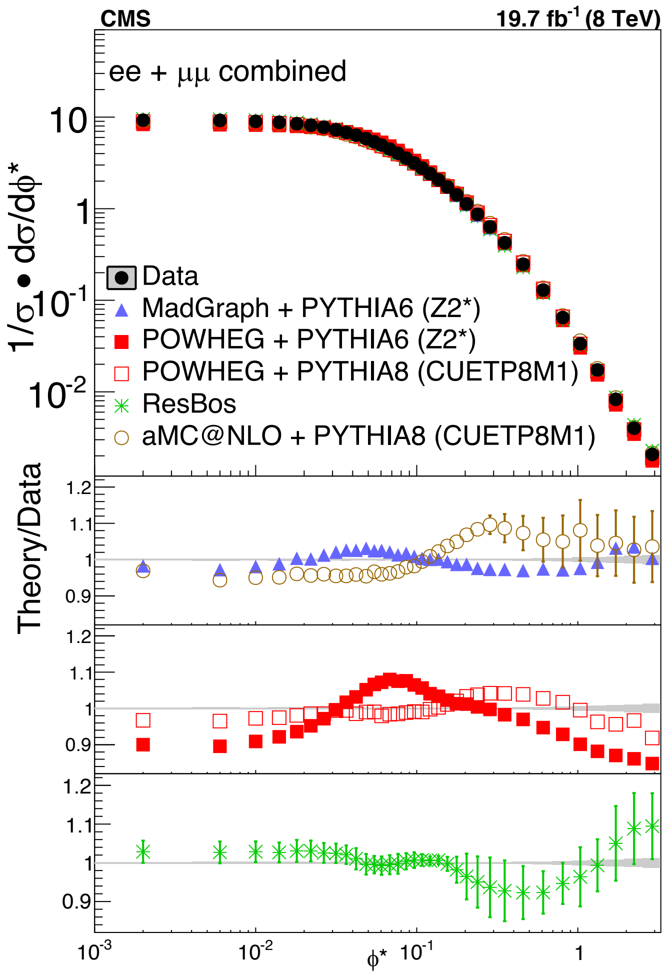
$60 < m_{Z_1}, m_{Z_2} < 120$ GeV

Unfolding Procedure



Z Cross sections





- Normalized and absolute differential cross section presented.
- Compared with five theoretical predictions.
- None of the predictions matches perfectly for the entire range

From integral of absolute differential cross section

$$\sigma(pp \to Z/\gamma* \to \ell^+\ell^-) = 480.7 \pm 0.2\ (\text{stat}) \pm 3.6\ (\text{syst}) \pm 12.5(\text{lumi})\text{pb}$$

BDT Variables

- An event balance variable:

$$R(p_T^{\text{hard}}) = \frac{|\vec{p_{T}}_{j1} + \vec{p_{T}}_{j2} + \vec{p_{T}}_{Z}|}{|\vec{p_{T}}_{j1}| + |\vec{p_{T}}_{j2}| + |\vec{p_{T}}_{Z}|} = \frac{|\vec{p_T^{\text{hard}}}|}{|\vec{p_{T}}_{j1}| + |\vec{p_{T}}_{j2}| + |\vec{p_{T}}_{Z}|}$$

- Zeppenfeld variable:

$$z^* = \left(y_Z - \frac{1}{2}(y_{j1} + y_{j2})\right) / \Delta y_{jj}$$

Quark gluon likelihood

- In case of pure EWK production only jets initiated by final states with quarks are possible
- In case of DY background about half of all jets produced are originated from gluons
- Differences in internal q/g jet composition are structure are exploited in QGL to enhance separation of signal events
- QGL input variables:
  - The jet constituents minor RMS in the $\eta\phi$ plane.
  - The jet particle multiplicity.
  - The jet internal p_T distribution

Z+qq EW anomalous gauge couplings

- Tested 6 dimensional operators
- ATGC signal events are simulated at LO using MADGRAPH5 aMC@NLO
- No significant deviation from the SM expectation is observed.

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

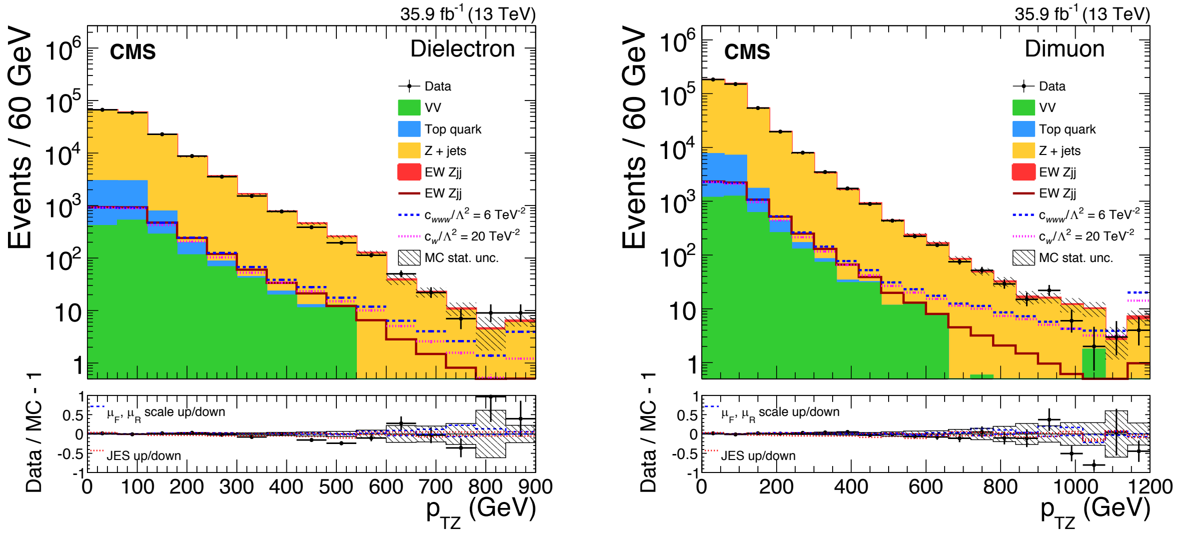
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$

$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi),$$

$$\widetilde{\mathcal{O}}_{WWW} = \frac{\widetilde{c}_{WWW}}{\Lambda^2} \widetilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\cdot\mu},$$

$$\widetilde{\mathcal{O}}_{W} = \frac{\widetilde{c}_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} \widetilde{W}_{\mu\nu} (D^{\nu}\Phi),$$

- Additional hadron activity is also studied and generally good agreement is found between data predictions (PYTHIA or HERWIG++)



Event Selection

4μ 4e 2e2μ Final state

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
- Δβ PU correction

Jets

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

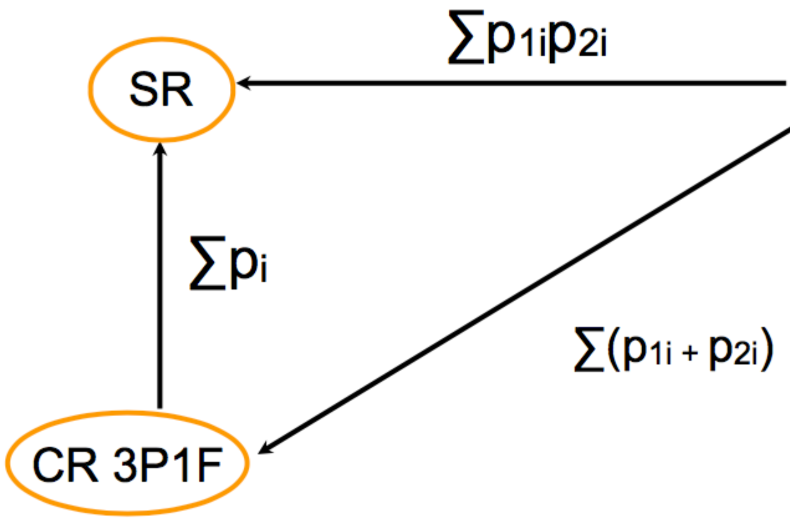
- $60 < m_{Z1} < 120$ GeV
- $60 < m_{Z2} < 120$ GeV (If # Z_2 >1 the pair of leptons with highest scalar sum of p_T is chosen)
- $M_{\ell\ell crossed}$ (OSSF) < 4 GeV
- At least two leptons with $p_T > 10$ GeV and one with $p_T > 20$ GeV

Background

- **Irreducible background**: processes which contain **4 prompt leptons** from non-signal processes (*ttZ* , *WWZ*), **very small**.
    - 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** used from the $H \to ZZ \to 4l$ Analysis based on the **lepton-to-jet fake rate**

Control regions

- We need 3 different control regions to measure the reducible background with data
- ZL ($Z(ll)+l_{loose}$) 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



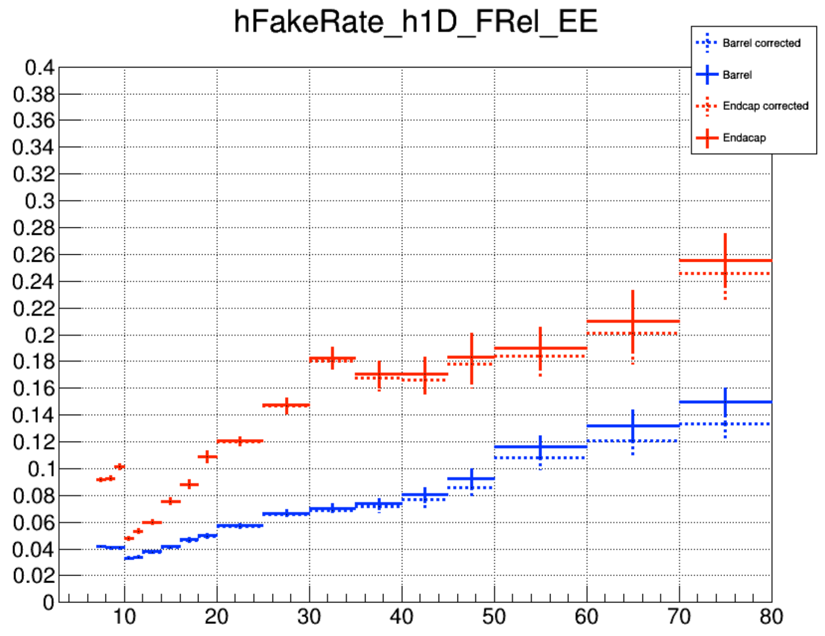
$RB_{SR} = \sum p_i(3P1F) - \sum p_{1i}p_{2i}(2P2F)$

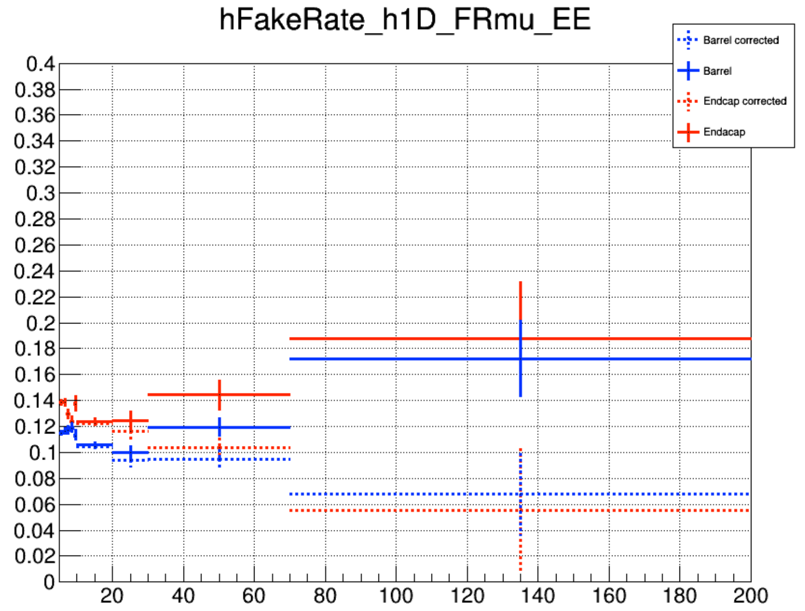
Fake rate

Select a sample of Z(ll)+l_{loose} defined as follow:

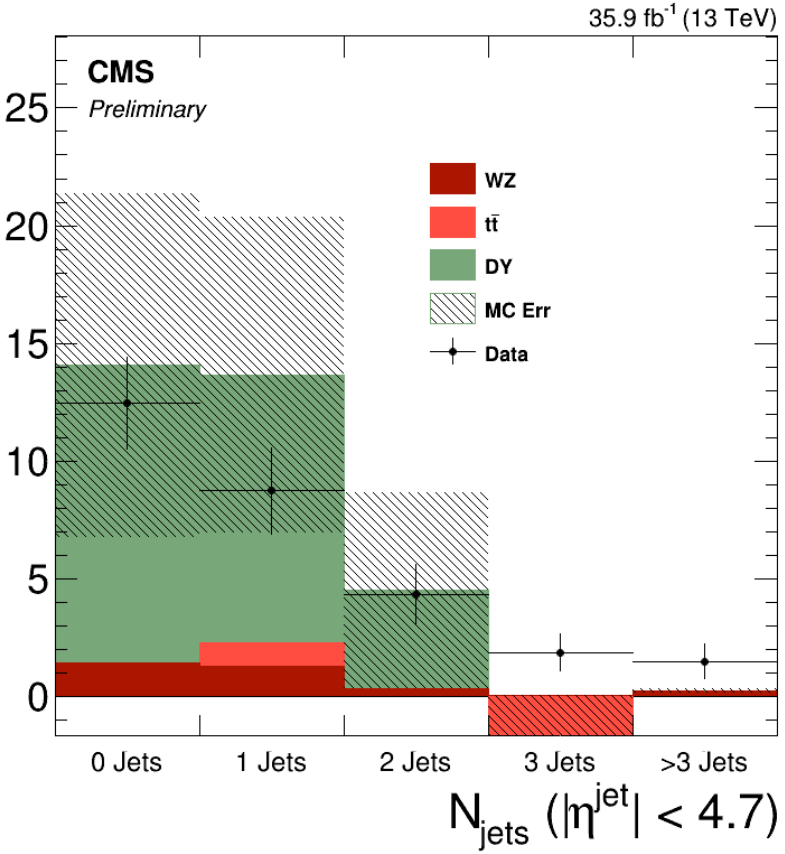
- Z made of 2 tight leptons (as for signal)
- $|m_{ll} - m_Z| < 10$ GeV.
- l_{loose} passing the loose selection criteria. (loose selection criteria details in back slide)
- The invariant mass of l_{loose} and the Z lepton with the opposite sign must be greater than 4 GeV.
- $E_T^{miss} < 25$ GeV.
- $M_T^W < 30$ GeV (3rd leptons and MET).

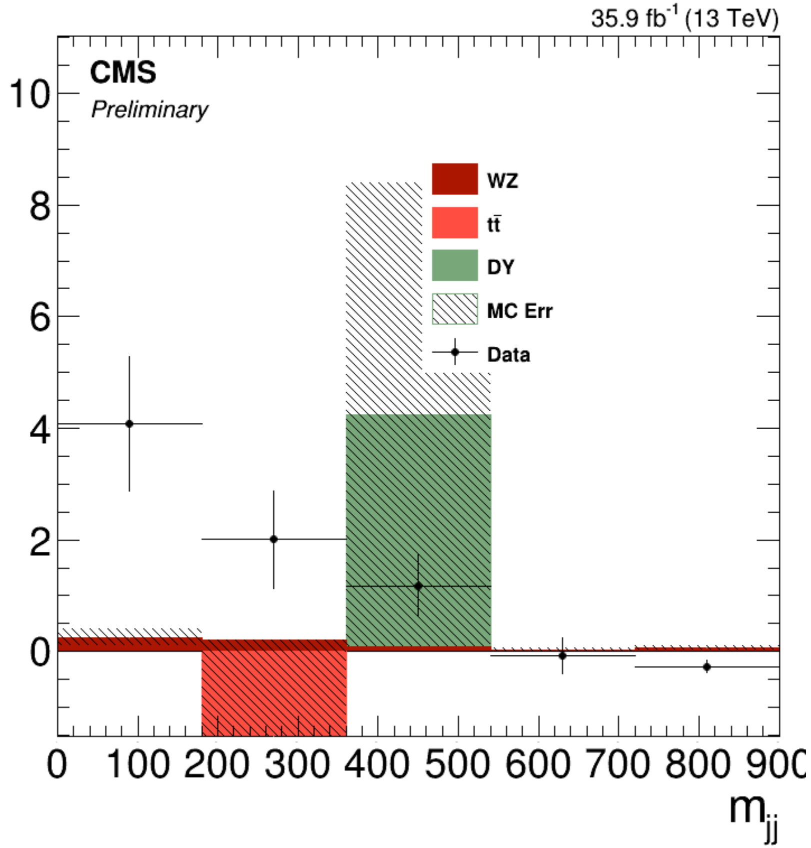
- Fake rate binned as function of eta and pT





Reducible background

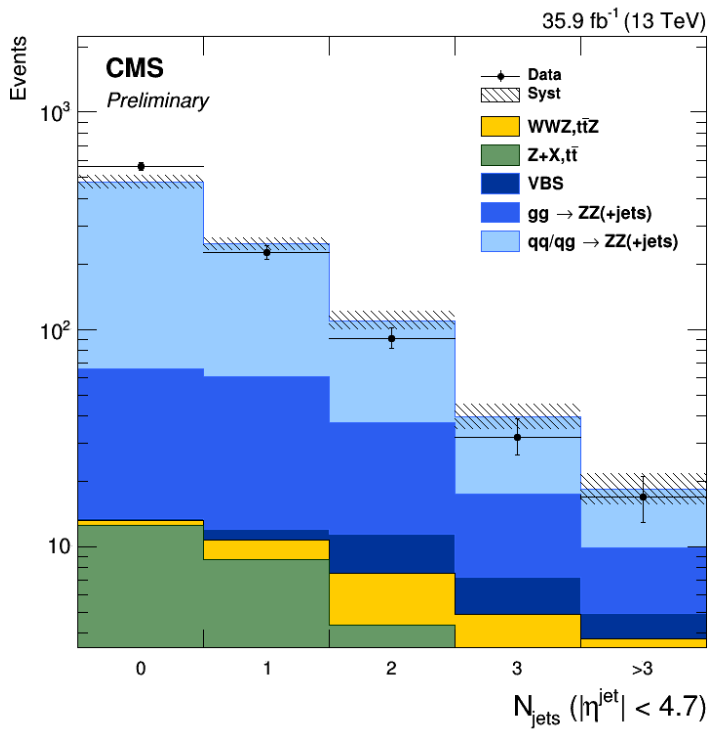


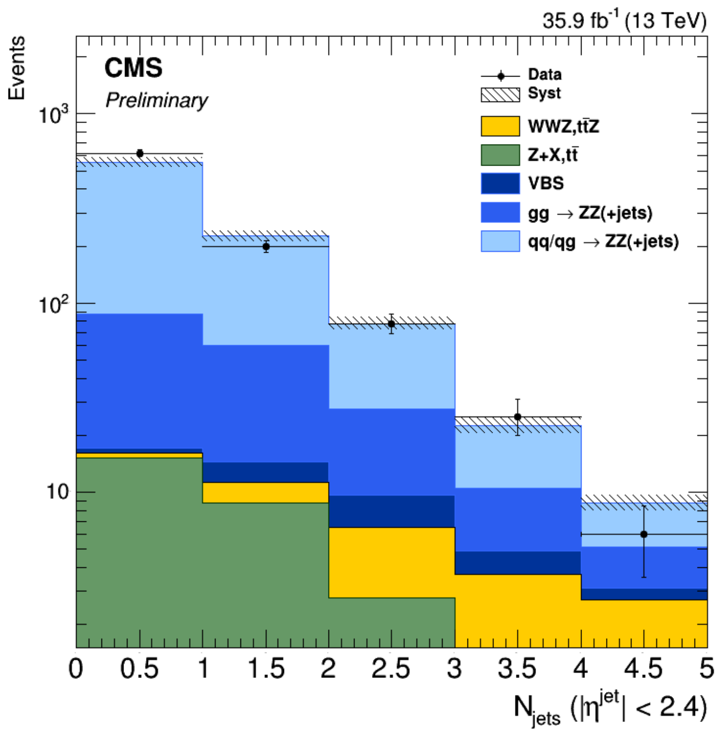


Bad agreement with MC as expected.

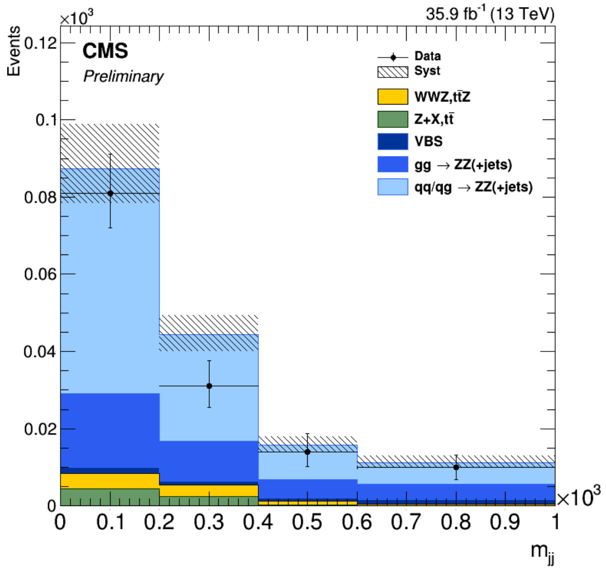
DY has very low statistic. Only 3 events. One is negative because of matching technic

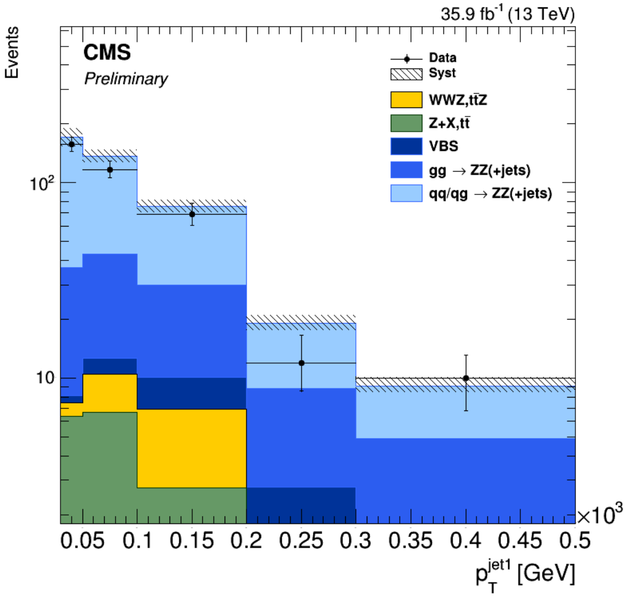
Data MC comparison

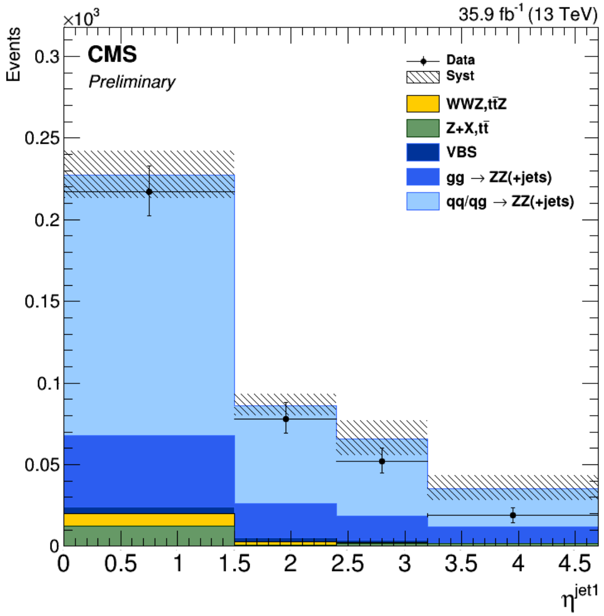


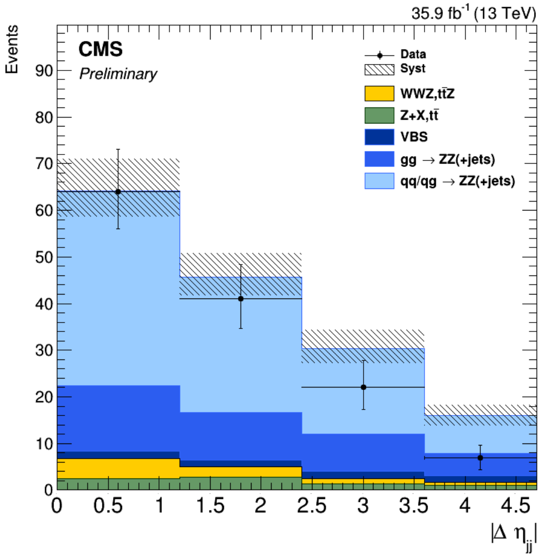


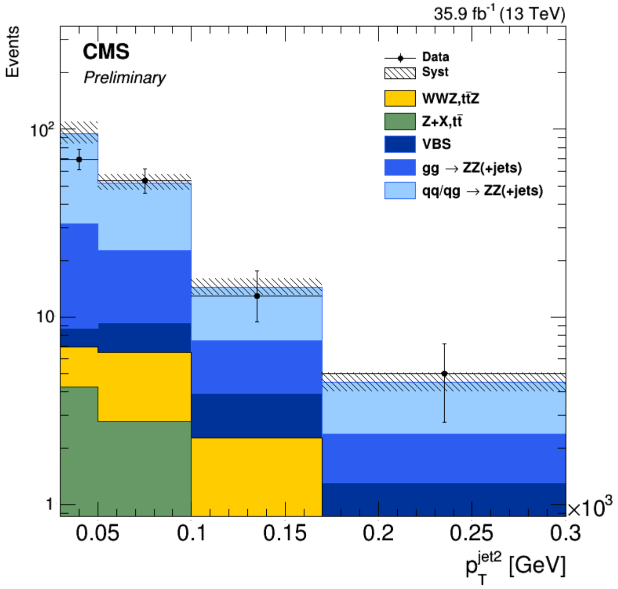
Leading jets

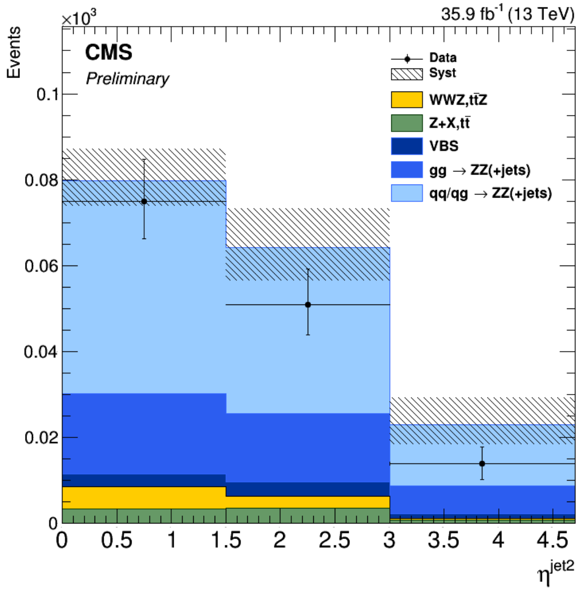












Differential cross-section

- Variables: #Jets, #Jets (η<2.4) , p_T and η of leading jet, p_T and η of sub-leading jet, m_{JJ}, $\Delta\eta_{JJ}$.
- Unfoding with D'Agostini and 4 iteration.
  - ZZ Inclusive
  - 8 TeV analysis
- 2 sets of samples:
- **MadGraph** + MCFM + Phantom (nominal set)
- **Powheg** + MCFM + Phantom (Comparison and systematics)
- Differential cross-section obtained in two configuration:
  - Absolute: Used to extract Cross section per jet multiplicity.
  - Normalized to 1: Compare shape and reduce systematic uncertainties.
  - Jet multiplicity plots presented in both configuration.

Fidcucial phase space

$$
\begin{aligned}
&p_T^e > 5 \text{ GeV}, |\eta^e| < 2.5 \\
&p_T^\mu > 5 \text{ GeV}, |\eta^\mu| < 2.5 \\
&p_T^{\ell_{3,4}} > 5 \text{ GeV} \\
&p_T^{\ell_1} > 20 \text{ GeV} , p_T^{\ell_2} > 10 \text{ GeV} \\
&m_{\ell^+\ell^-} > 4 \text{ GeV (any OSSF pair)} \\
&60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}
\end{aligned}
$$

Systematic uncertainty 1/3

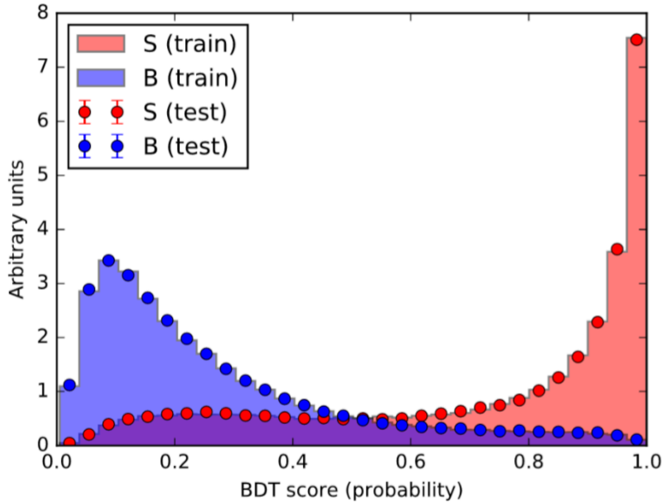
- **Trigger**: Difference between trigger efficiencies in data and in simulated events. Trigger efficiencies are found with a tag-and-probe technique.
- **ID, Isolation, SIP**: Distributions recomputed with the scaling factors varied up and down by the tag-and-probe uncertainties.
- **Reducible background**: Control regions statistics, difference composition of ZL and others CR. 30 % on fake rate.
- **Irreducible background**: MC statistic.
- **Pile-Up**: ± 4.6% variation of the minimum bias cross section for the pile-up re-weighting in the MC .
- **PDF α_S**: Estimated using the last NNPDF3.0 recipe.
- **MC Choice**: Compare data unfolded with response matrices obtained from Madgraph5_aMC@NLO and POWHEG samples

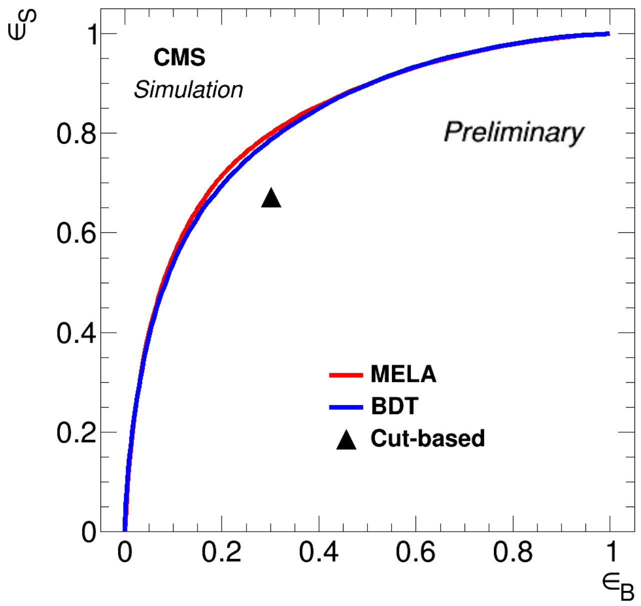
Systematic uncertainty 2/3

- **Jet energy scale**: Variation of p_T of the jets in MC w.r.t. their uncertainties
- **Jet energy resolution**: Variation of p_T of the jets in MC w.r.t. their uncertainties

Development and optimization of the BDT

- Choice of input variables:
  - Explored a total of 36 observables
  - Prune variables that provide a small gain or are expected to be poorly-modelled in MC
  - m_{JJ}, $\Delta\eta_{JJ}$, $m_{4\ell}$, $p_{T,4\ell}$, η^*_{Z1}, η^*_{Z2}, $p_T^{rel,hard}$, $p_T^{rel,jets}$
- Hyper-parameters optimized using grid search
- Cross-check of BDT performance with a Matrix Element Discriminator (MELA)
- **Template analysis**
- VBS Selection efficiency: 65% signal vs 30% background.
- BDT working point with 65% signal efficiency has 19% QCD background efficiency.





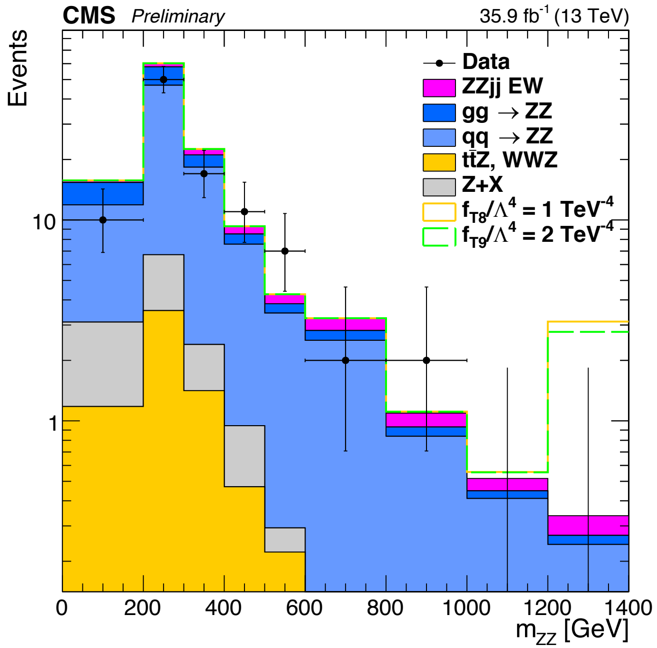
ZZ+jets EWK anomalous quartic gauge couplings

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

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

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

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

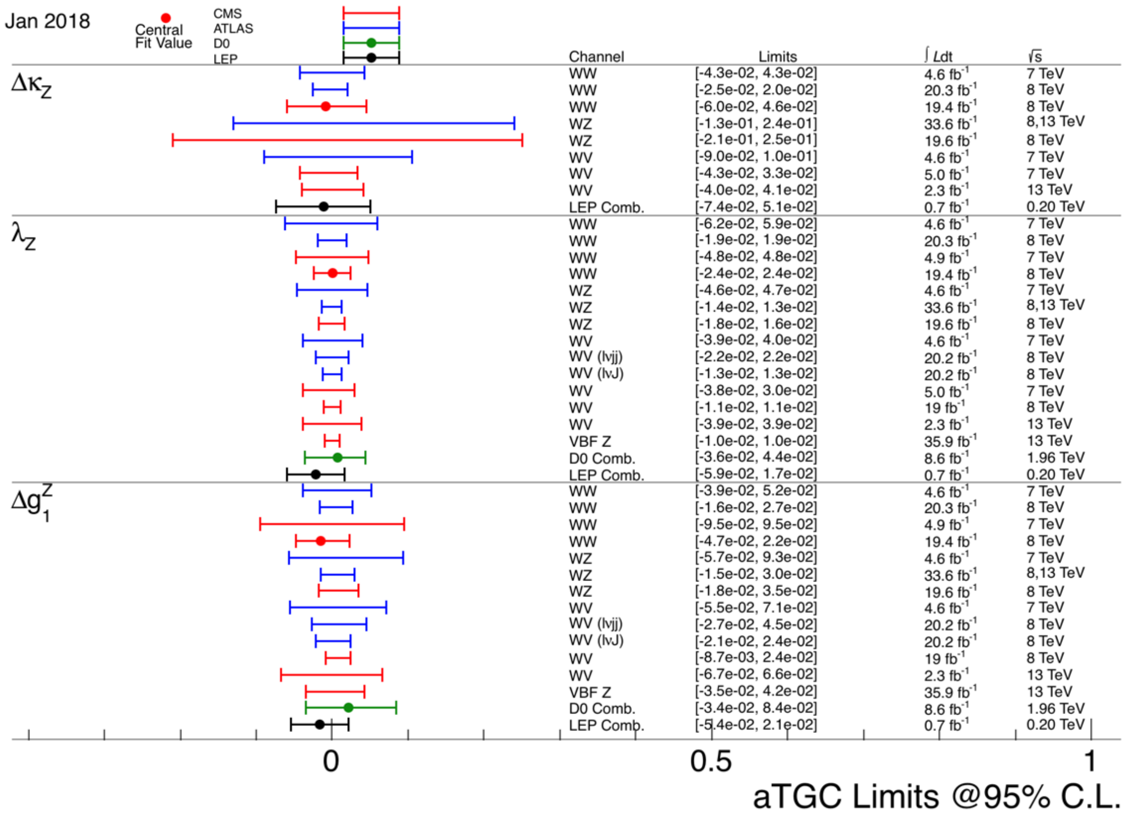


- 1D 95% confidence limits are derived for each operator coupling, setting the other to zero

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

Anomalous Couplings

WWZ aTGC



WWɣ aTGC