Measurement of the electroweak production cross section of dijets associated with vector bosons at LHC

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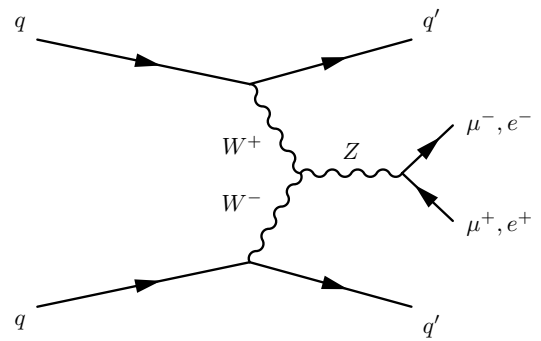
BERGISCHE UNIVERSITÄT WUPPERTAL

Overview

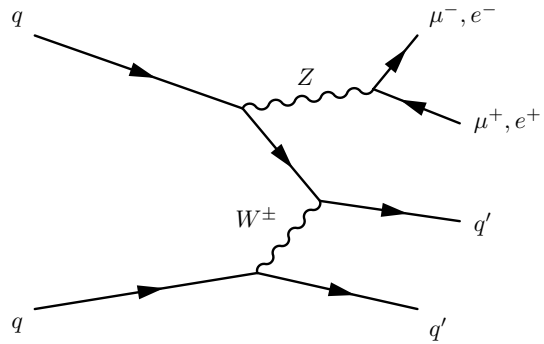
- Introduction to electroweak production of Z bosons in association with two jets: CMS and ATLAS measurements both with $20fb^{-1}$ @ 8TeV
- Vector-Boson-Scattering of WW in ATLAS
- Two-photon production of WW in CMS
- Summary

Introduction to electroweak Z+2jets

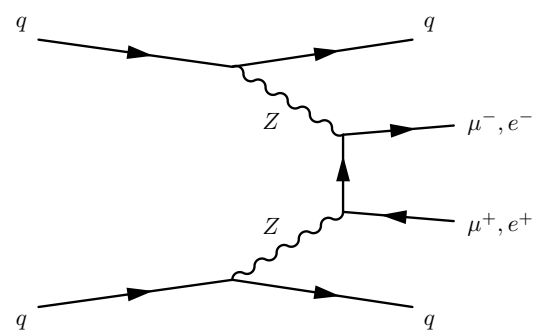
electroweak Z+2jets



Vector Boson Fusion



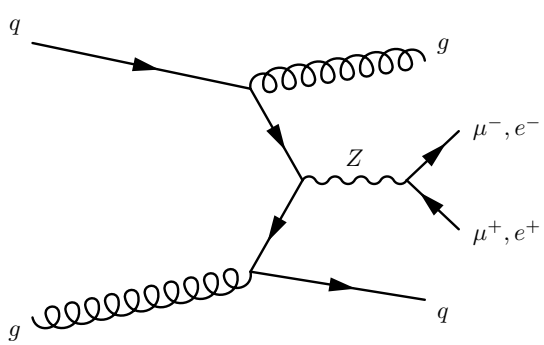
Z bremsstrahlung



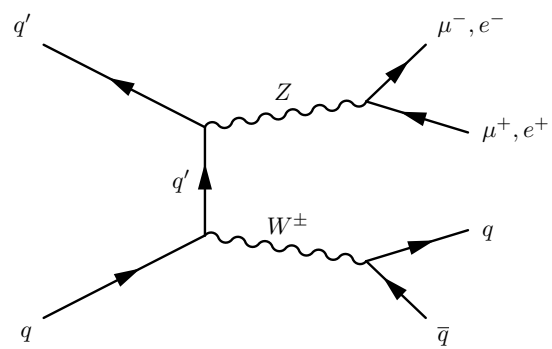
non-resonant

Background: Z+2jets

simulated separately



strong/ QCD Z+2jets



diboson

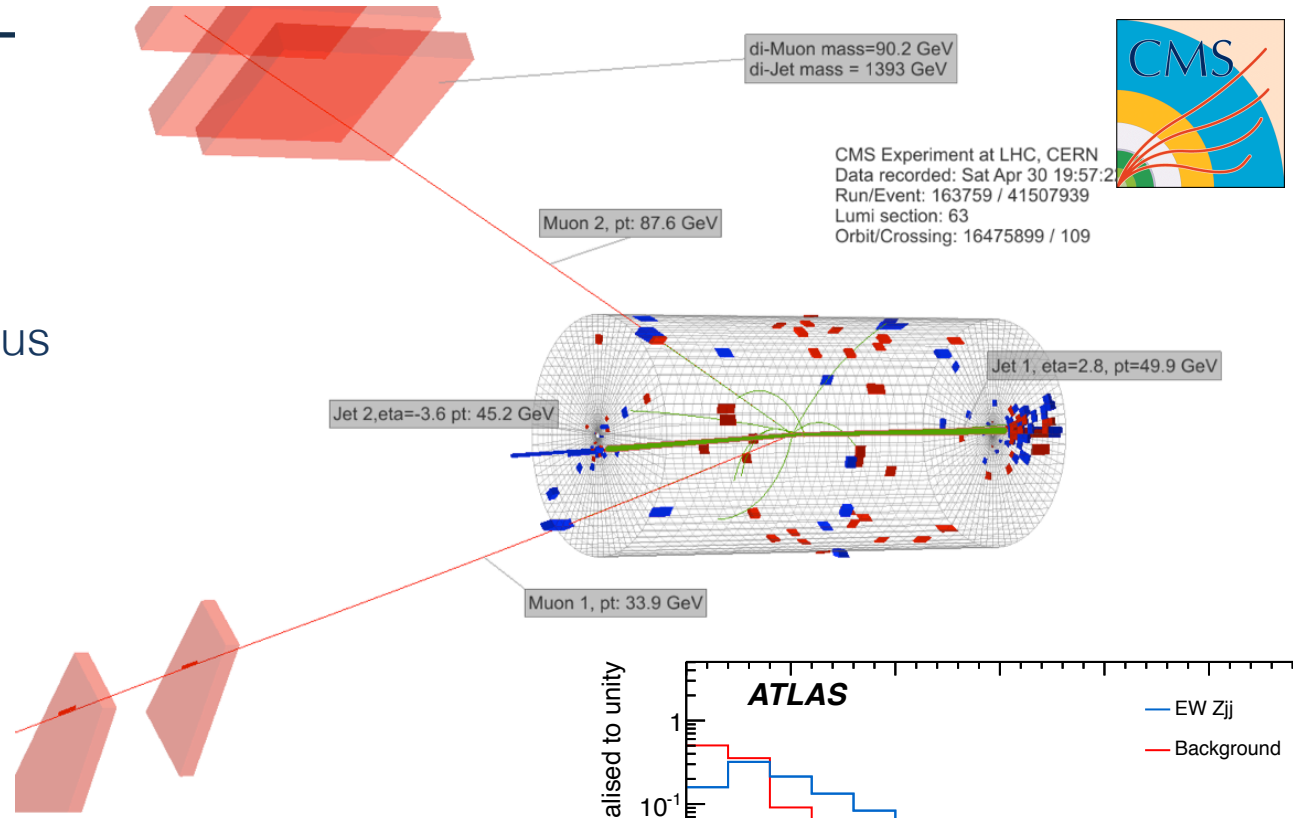
Other backgrounds:

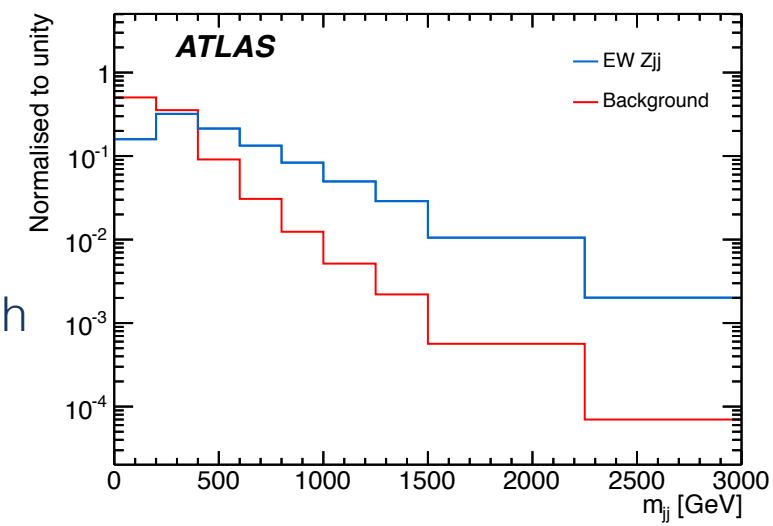
- Top-pair/ single top
- W+jets
- Multi-jet

Motivation

Similar to VBF Higgs process

Sensitive to anomalous triple-gauge-boson couplings



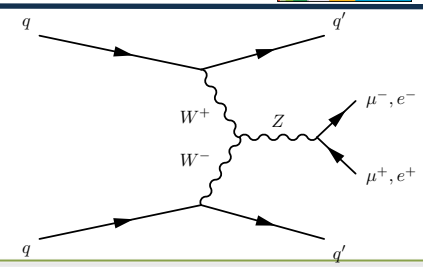


Signature:

Two isolated leptons in the central region of the detector

Two well separated, high p_T forward jets
-> large invariant mass

EWK Z+2jets: CMS@8TeV CMS-PAS-FSQ-12-035



First publication from CMS in 2011

JHEP10(2013)062

Signal selection:

- Two opposite charged, isolated leptons
- Lepton p_T>25 GeV, |η|<2.4
- $|m_{ll} - m_Z|$ <15 GeV
- At least two jets
  - Jet p_T > 30 GeV, |η| < 4.7
  - tag jets: two highest p_T jets (p_T>50 GeV)

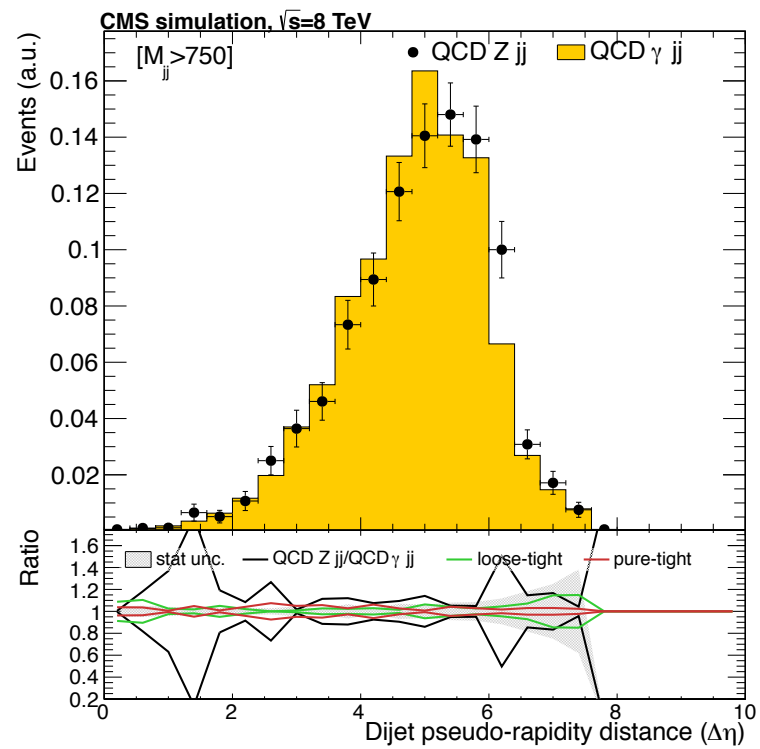
Extraction of the electroweak signal difficult due to large Z+2jets background

- Large theoretical and experimental uncertainties
  - Choice of PDF, Jet energy scale and resolution
  - Only LO accuracy from simulation
- Developed two different ways to improve the background modeling
  - Simulation-based and data-driven

Signal extraction EWK Z+2jets: CMS@8TeV

strong Z+2Jet Background modeling:

- Simulation-based:
  - Introduce scale factor by comparing MADGRAPH with showering to MCFM at parton-level -> Reweight simulation event by event
  - Uncertainty: half the difference between re-weighted and nominal
- Data driven:
  - Select γ+2jets -> mimic the kinematic distributions of the tag jets
  - reweighting the $p_T(\gamma)$ to $p_T(Z)$
  - subtracting the EWK γ+2jet (from simulation)
  - Cut harder: $p_T(Z \text{ or } \gamma) > 50$ GeV and $|y(Z \text{ or } \gamma)| < 1.442$



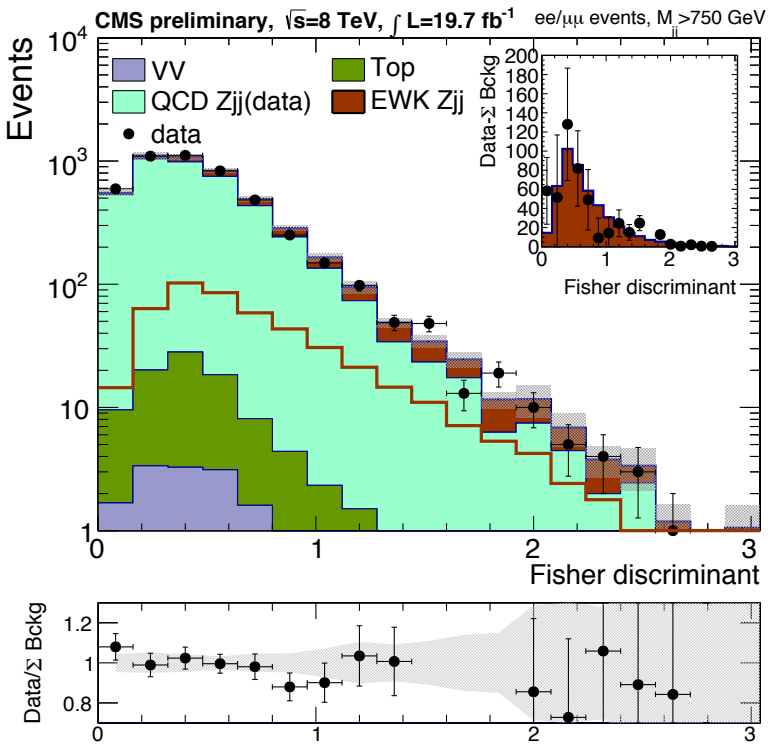
Results EWK Z+2jets: CMS@8TeV

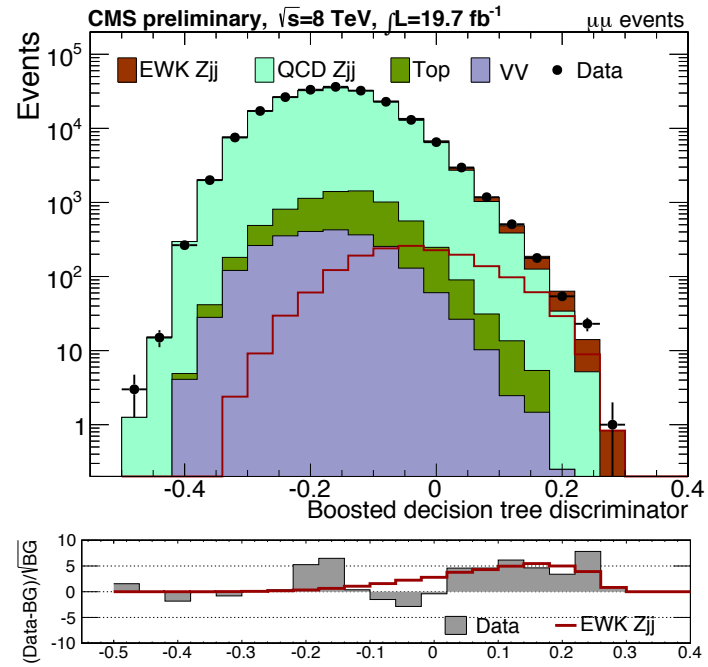
Boosted decision tree (μμ-channel):

$$\sigma(\mathrm{EWK}\ \ell\ell + \mathrm{jj})_{\mathrm{I}} = 191 \pm 29_{\mathrm{stat}} \pm 39_{\mathrm{syst}}\ \mathrm{fb}$$

Fisher discriminant:

$$\sigma(\mathrm{EWK}\ \ell\ell + \mathrm{jj})_{\mathrm{II}} = 303 \pm 29_{\mathrm{stat}} \pm 57_{\mathrm{syst}}\ \mathrm{fb}$$





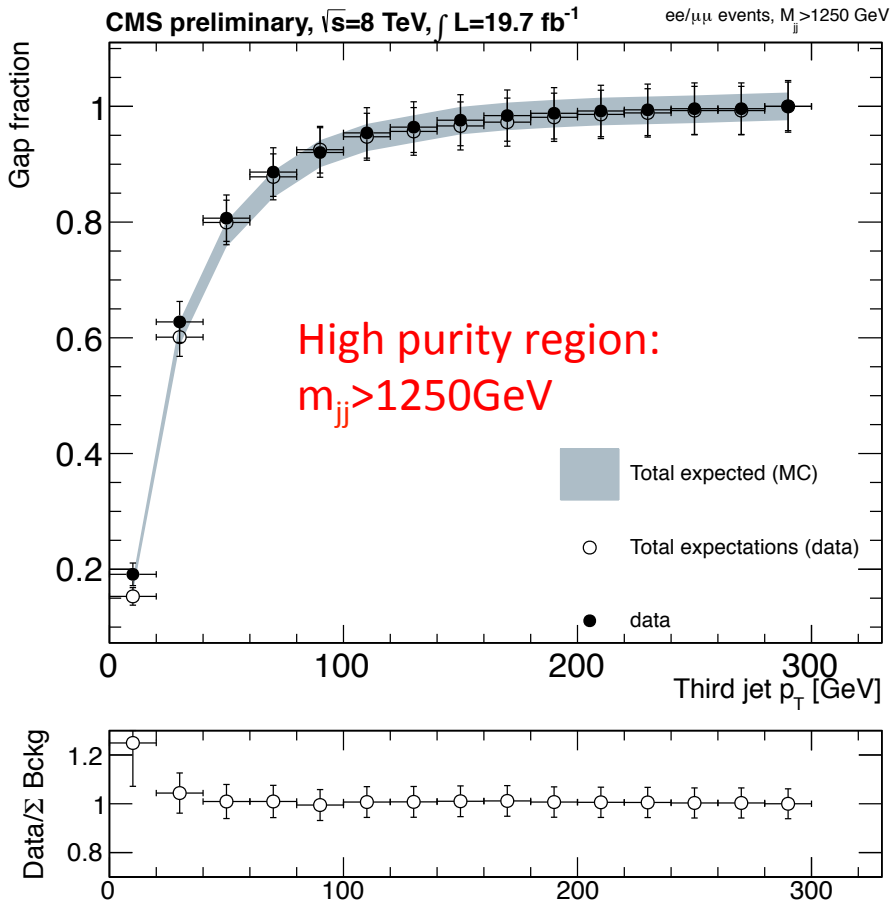
Combined:

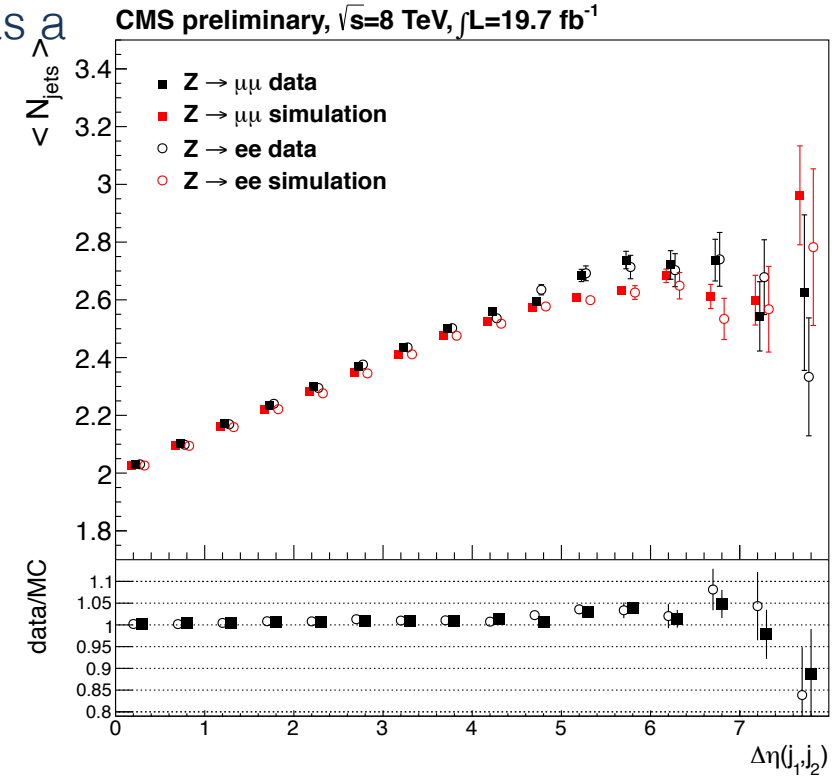
$$\sigma(\mathrm{EWK}\ \ell\ell\mathrm{jj}) = 226 \pm 26_{\mathrm{stat}} \pm 35_{\mathrm{syst}}\ \mathrm{fb}$$

Good agreement with the theoretical cross section at NLO: 239 fb

Hadronic activity CMS@8TeV

Average number of jets with p_T>40GeV as a function of $|\Delta\eta(j_1,j_2)|$
(simulation: MadGraph+Pythia)





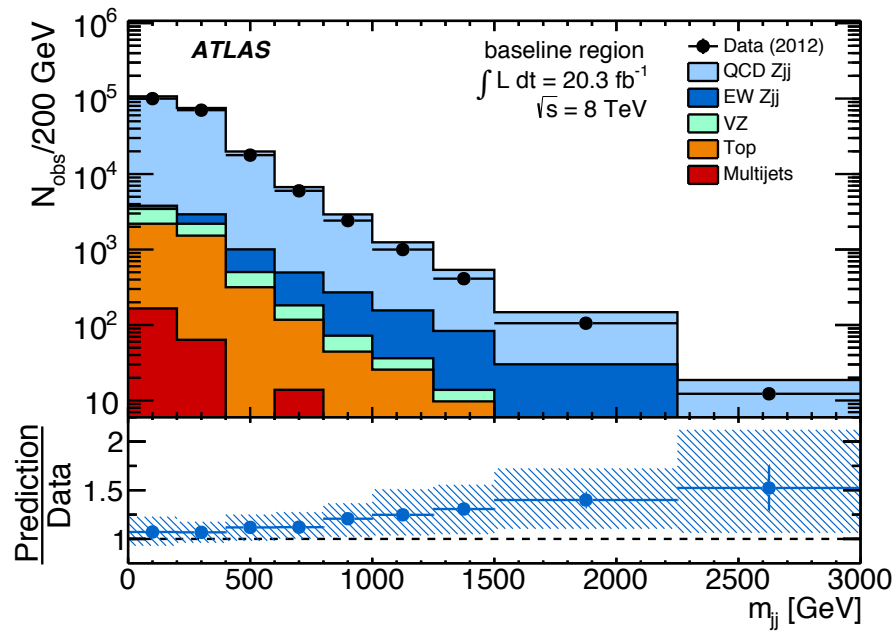
Gap fraction as a function of 3rd jet p_T
(gap fraction: fraction of events which do not have a third jet above a given threshold)

EWK Z+2jets: ATLAS@8TeV

JHEP04(2014)031

- Measure cross section of Z+2jet production in 5 fiducial regions (different sensitivity to electroweak component)
- Unfolding of interesting distributions
- Extraction of the electroweak cross section in a fiducial region
  - Data-driven estimate of the Z+2jet background
- Limits on aTGC

ATLAS: 20fb^{-1}@8TeV



Results: EWK Z+2jets: ATLAS@8TeV

$Jet_1 > 85$ GeV
$Jet_2 > 75$ GeV

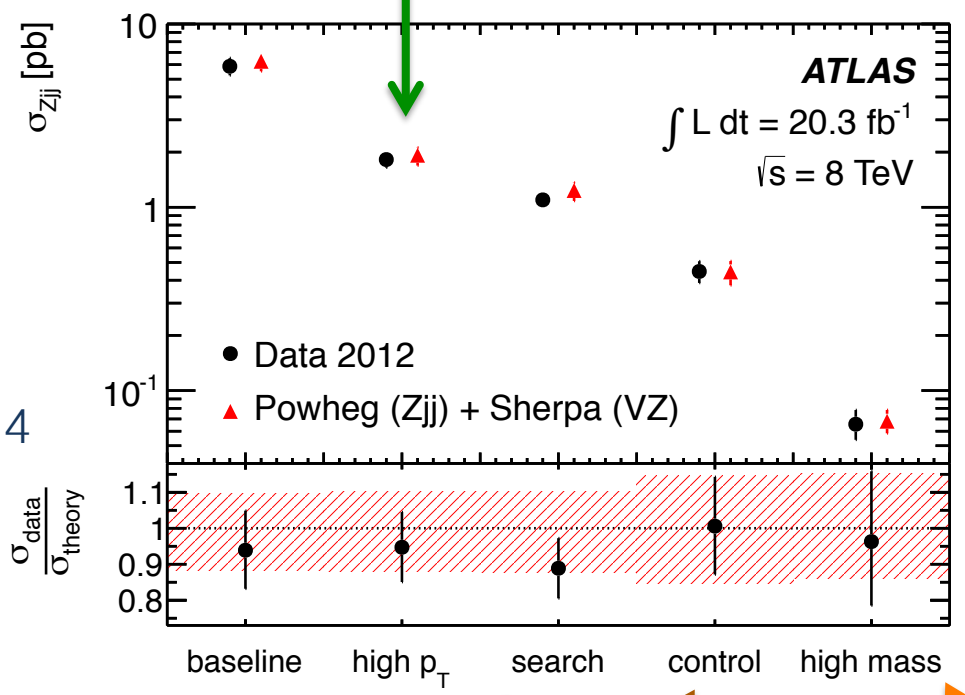
Baseline selection:

- Two opposite charged, isolated leptons
- Lepton $p_T > 25$ GeV, $|\eta| < 2.4$
- $|m_{ll} - m_Z| < 10$ GeV
- $p_T^{ll} > 20$ GeV
- two jets
  - Jet_1/jet_2 $p_T > 55/45$ GeV, $|\eta| < 4.4$
  - tag jets: two highest p_T jets

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\int L\,\mathrm{d}t \cdot \mathcal{C}}$$

C: correction factor for differences at reconstruction and particle level

All cross section are in good agreement with the theoretical prediction.

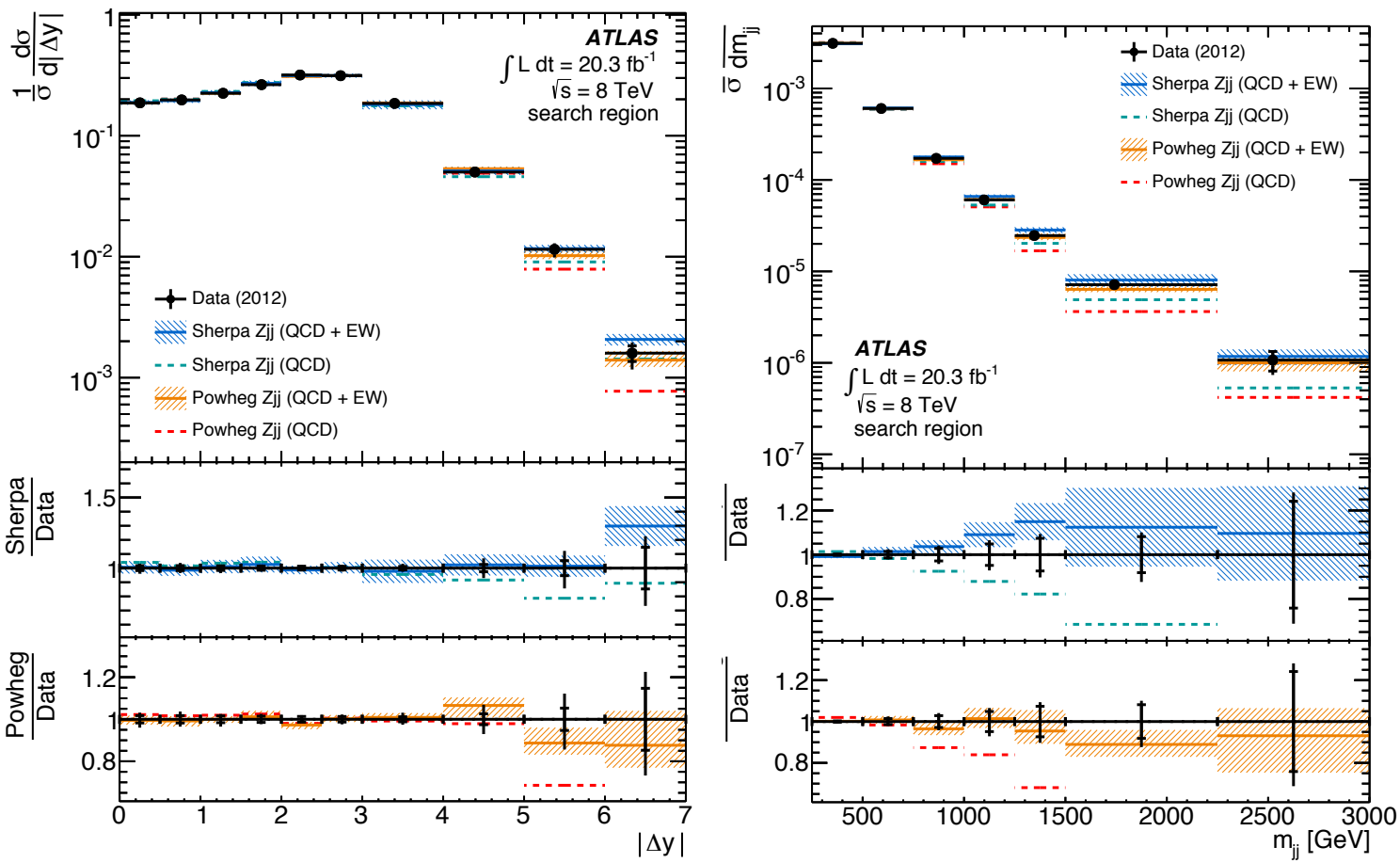


$M_{jj} > 250$ GeV, $p_T^{balance} < 0.15$
No additional jet in rapidity gap

$M_{jj} > 250$ GeV, $p_T^{balance,3} < 0.15$
At least 1 additional jet in rapidity gap

$M_{jj} > 1$TeV

Unfolded jet distributions: ATLAS@8TeV

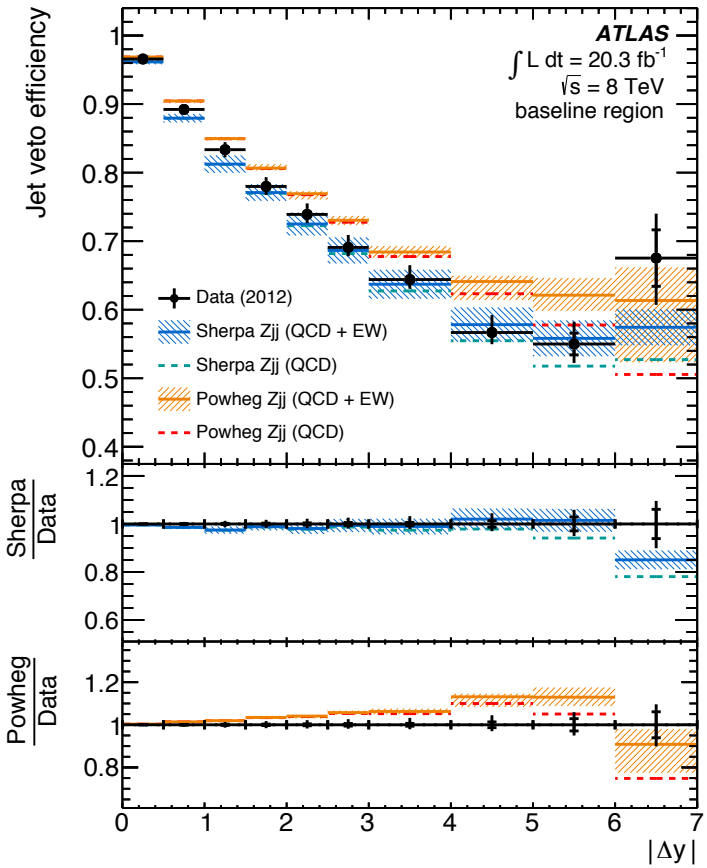


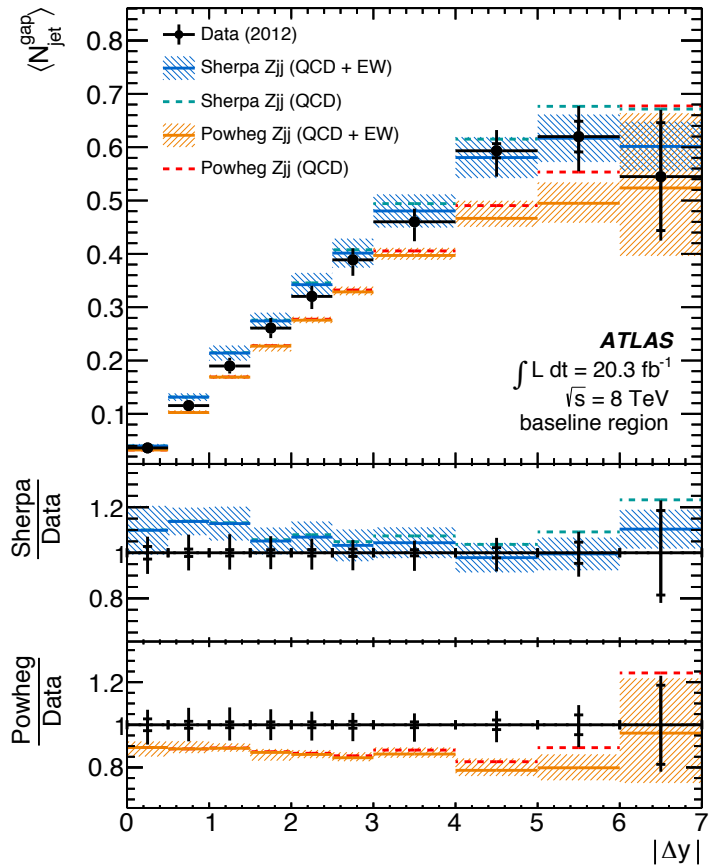
Powheg: NLO in QCD for Z+2j

Sherpa: LO in QCD for Z+2j

Better description of jet distributions from Powheg

Unfolded distributions of gap properties

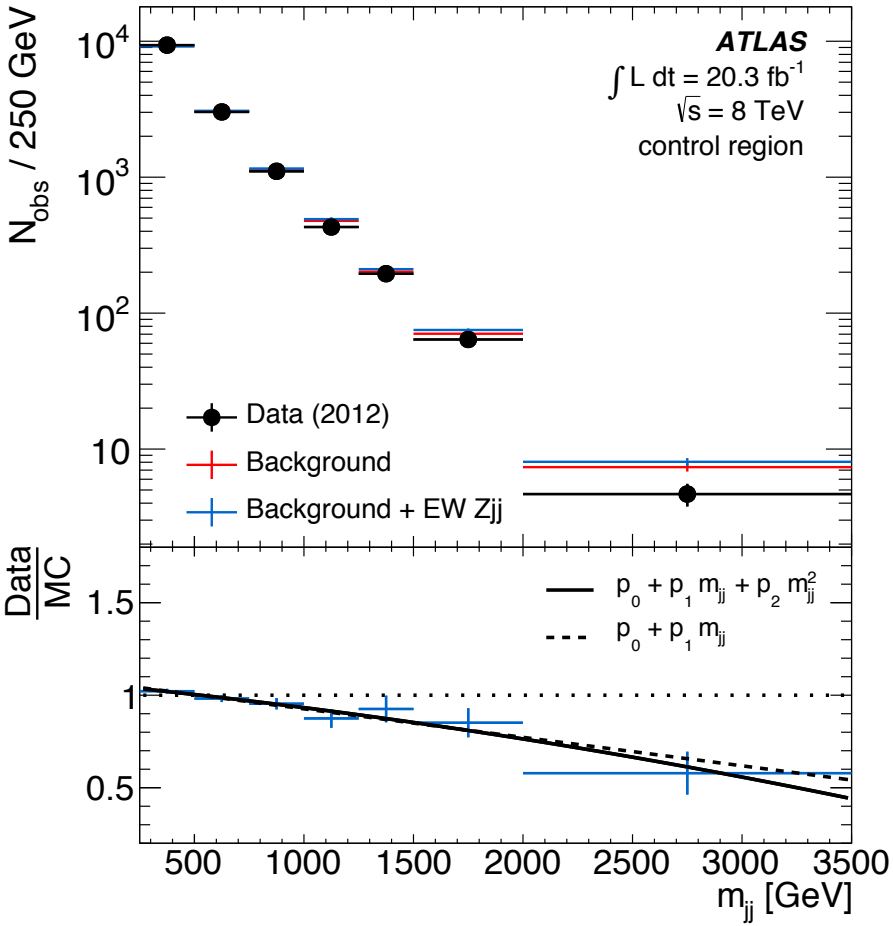




Sherpa: LO in QCD for third and fourth jet emission
Powheg: only accurate to LO in QCD for third jet
Powheg underestimates gap activities

Background modeling in fiducial region

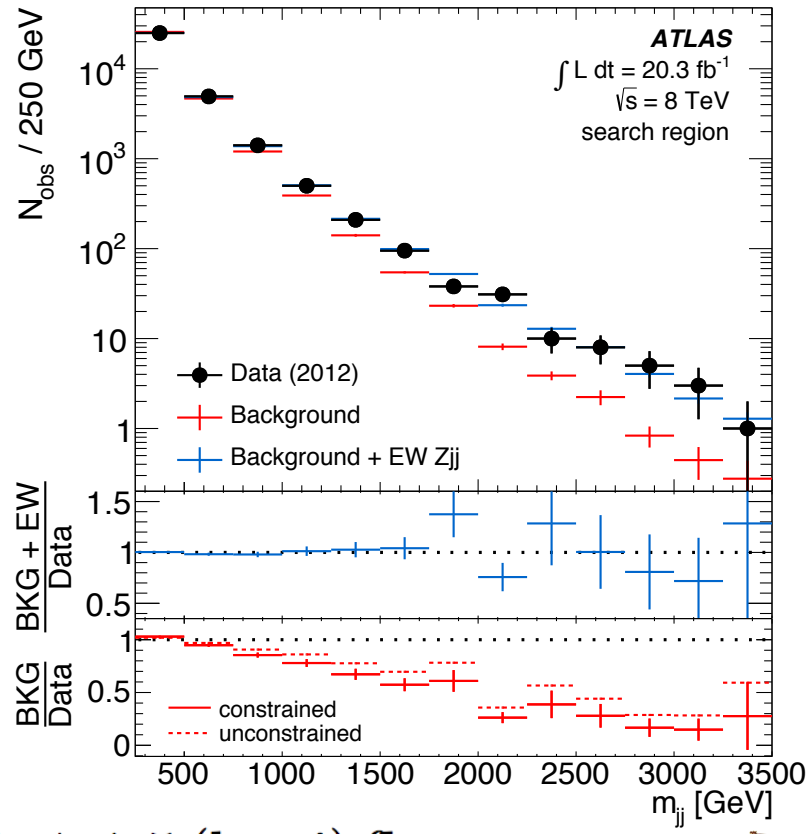
- Large experimental and theoretical uncertainties on strong Z+2jet background
- Control region: invert the jet veto -> require a third jet between the tagging jets
- Determine correction factor from data/MC ratio in control region



Extraction of EW Z+2jets fiducial cross section

Fit electroweak and background template in the dijet invariant mass spectrum in the *search region* to data

- High p_T and high m_{jj} cuts
- Veto events with additional jet in rapidity gap



Allows the background only hypothesis to be rejected by more than 5σ significance (2.6σ without data-driven Z+2jets estimate)

results:

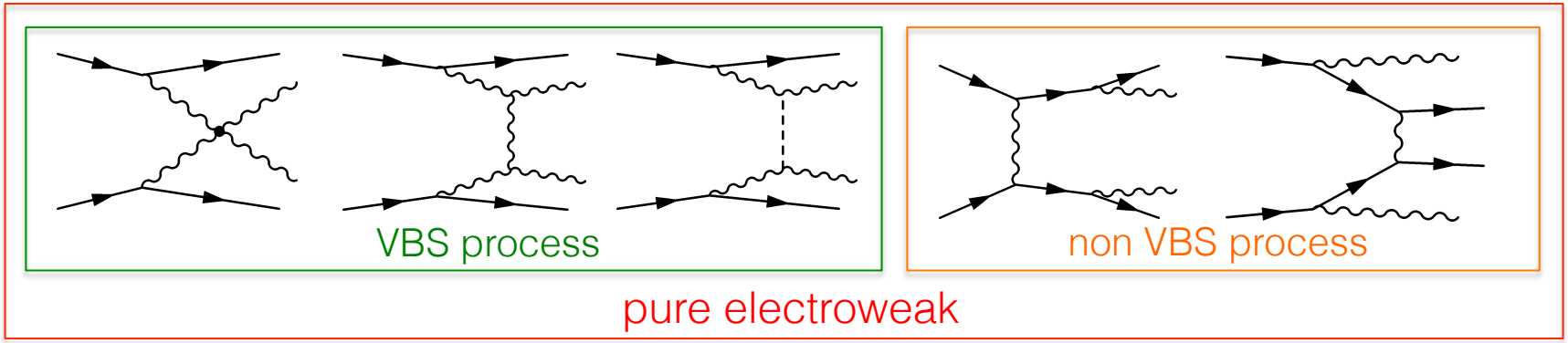
$$\sigma_{\mathrm{EW}} = 54.7 \pm 4.6\,(\mathrm{stat})\,^{+9.8}_{-10.4}\,(\mathrm{syst}) \pm 1.5\,(\mathrm{lumi})\ \mathrm{fb}$$

Compare with theoretical prediction from Powheg

$$46.1 \pm 0.2\,(\mathrm{stat})\,^{+0.3}_{-0.2}\,(\mathrm{scale}) \pm 0.8\,(\mathrm{PDF}) \pm 0.5\,(\mathrm{model})\ \mathrm{fb}$$

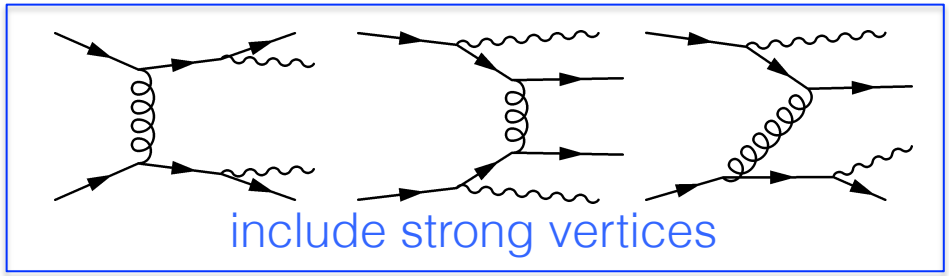
same sign VBS WW: ATLAS@8TeV

- Scattering of two massive vector bosons (VBS) is a key process to probe the nature of electroweak symmetry breaking.
- No process involving a four vector boson vertex has ever been measured



ATLAS-CONF-2014-013

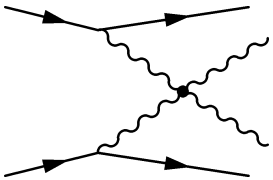
- In same electric charge WW production the strong production cross section does not dominate the electroweak cross section -> ideal choice for initial studies on VBS



Interference between pure electroweak and strong processes increases XS 7-12% (depending on the phase space)

Results: same sign VBS WW ATLAS@8TeV

Cross section is measured in inclusive and VBS region

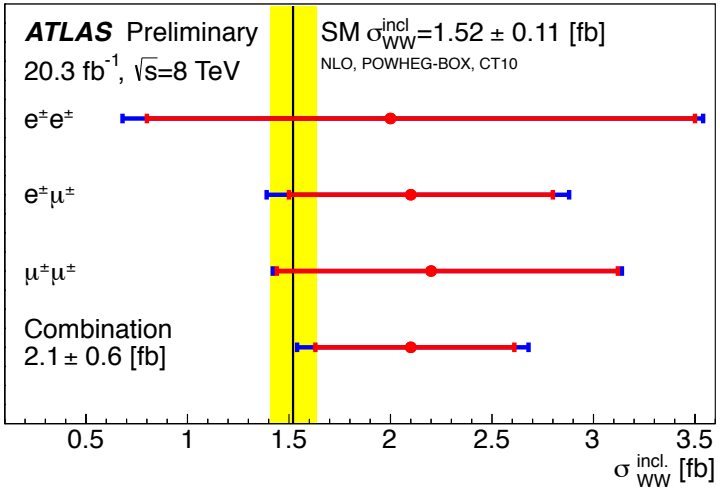


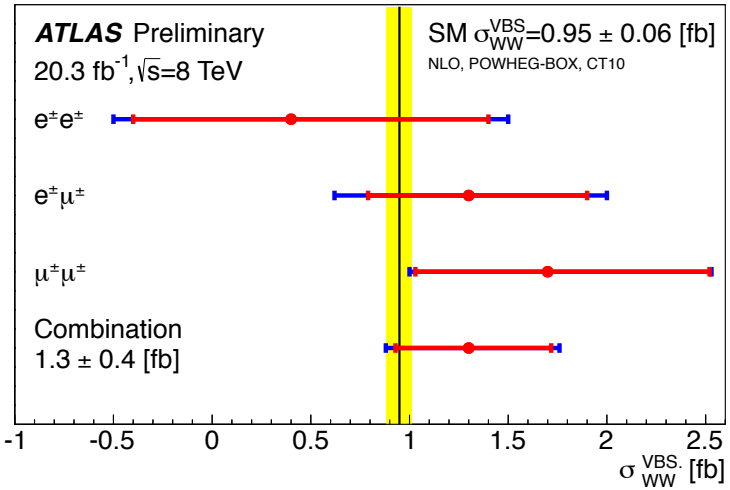
Signal selection:

- Exactly two same charged, isolated leptons (p_T > 25 GeV, $|\eta|$ < 2.4)
- m_{ll} > 20 GeV
- Z-mass veto (for electrons)
- E_t^{miss}> 40 GeV
- At least two jets
  - Jet p_T > 30 GeV, $|\eta|$ < 4.5
  - tag jets: two highest p_T jets
- M_{jj} > 500 GeV

VBS region:

Additional $|\Delta\eta\ jj|$ >2.4



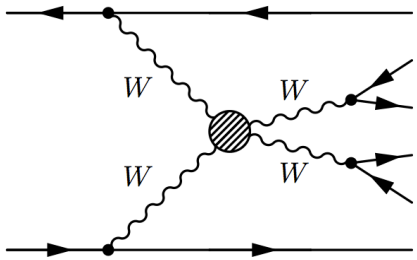


Inclusive region: expected 3.4 σ, observed 4.5σ

VBS region: expected 2.8σ, observed 3.6σ

same sign VBS WW: aQGC

- Measured cross section of the VBS fiducial region is used to set limits on aQGCs with four W bosons
- First exclusion limits on parameters α_4 and α_5 from the chiral Lagrangian with the K-matrix unitarization scheme:



1D 95% confidence intervals with the respective other $\alpha_i = 0$

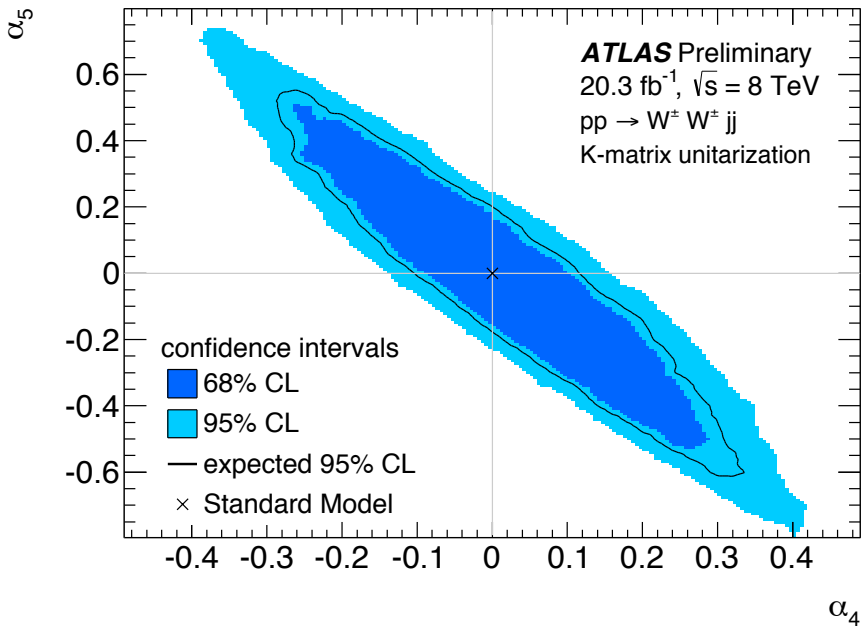
$$-0.14 < \alpha_4 < 0.16$$

$$-0.23 < \alpha_5 < 0.24$$

expected limits on $\alpha_{4,5}$:

$$-0.10 < \alpha_4 < 0.12$$

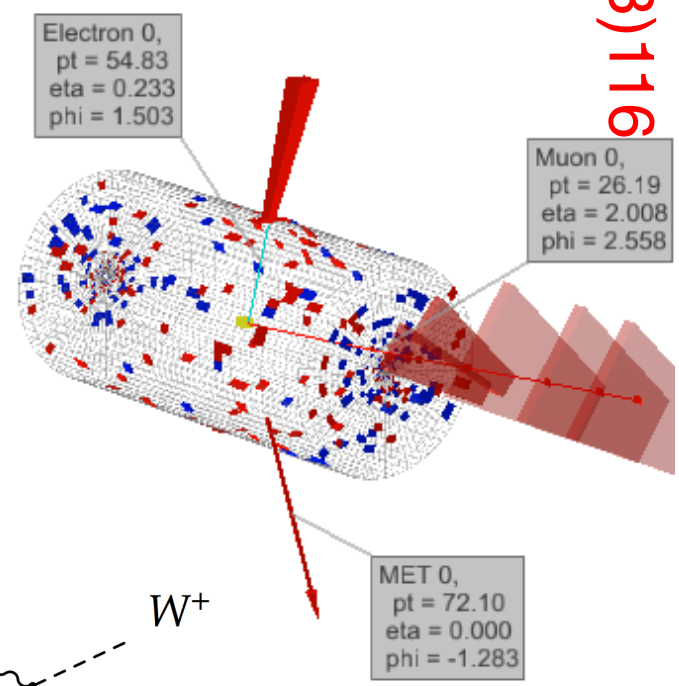
$$-0.18 < \alpha_5 < 0.20$$

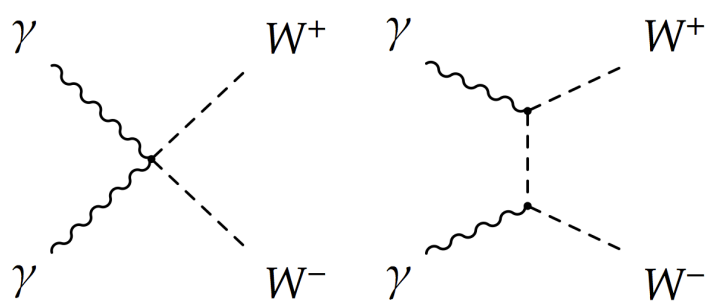


Exclusive two photon production of W+W-

JHEP07(2013)116

- Elastic proton-proton scattering
  - Both very forward-scattered protons escape detection
  - Primary vertex with no extra tracks
  - Large missing transverse energy due to the two neutrinos
  - Large transverse momentum and invariant mass of the lepton pair
- Sensitive to aQGC
- Only eμ final state is used as signal
- Fraction of dissociative production measured with μμ-controll region in different kinematic regions





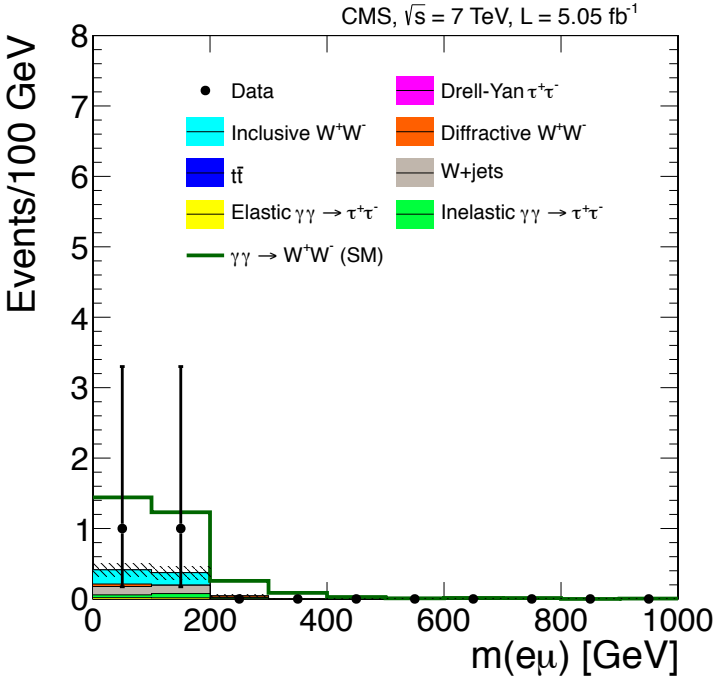
CMS: 5fb^{-1}@7TeV

Exclusive two photon production of W+W-

- Results:
  - Two events passing all selection criteria, expected from the SM: 2.2±0.4 signal and 0.84±0.15 background events

Upper bound on the SM cross section:

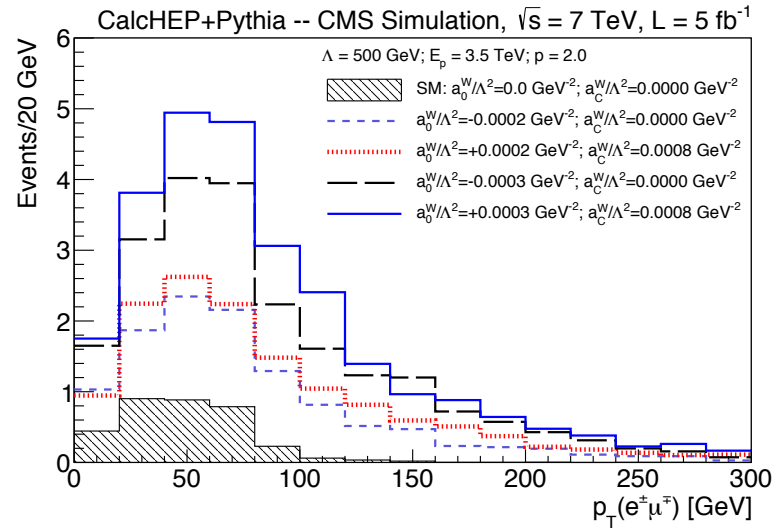
$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) < 10.6\,\mathrm{fb}$$

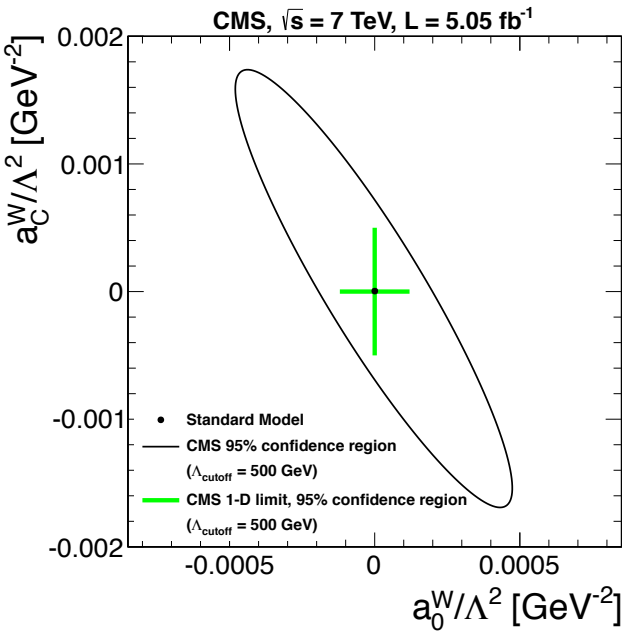


Exclusive two photon production of W+W-

Search region: p_T^{ll}>100GeV

- Sensitive to anomalous coupling of order 10^{-4} with form factor unitarization for Λ_{cutoff}=500GeV





Upper limit on cross section:

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) < 1.9\,\text{fb}$$

Set limit on parameter with form factor:

$$-0.00015 < a_0^W/\Lambda^2 < 0.00015\,\text{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \Lambda_{\text{cutoff}} = 500\,\text{GeV})$$

$$-0.0005 < a_C^W/\Lambda^2 < 0.0005\,\text{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \Lambda_{\text{cutoff}} = 500\,\text{GeV})$$

Set limit on parameter without form factor:

$$-4.0\times10^{-6} < a_0^W/\Lambda^2 < 4.0\times10^{-6}\,\text{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \text{no form factor})$$

$$-1.5\times10^{-5} < a_C^W/\Lambda^2 < 1.5\times10^{-5}\,\text{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \text{no form factor})$$

summary

- The outstanding performance of the LHC in 2011 and 2012 and the large amount of data recorded by the experiments allows measurements of rare processes, which are sensitive to new physics
- Cross section of the electroweak Z+2jet process was measured by CMS and ATLAS and is consistent with the theory prediction
- First evidence of a process containing vector boson scattering [and therewith a VVVV vertex] is observed by ATLAS and first limits on the α_4, α_5 [or WWWW] aQGC parameters set
- Search for two-photon production of WW is performed by CMS and an upper limit on the cross section and limits on the corresponding couplings can be set.

Back up

VBF Z @ CMS 8TeV

- Signal selection:
  - Two lepton triggers (pT= 8 and 17GeV), for electron with isolation, additional isolated single muon trigger pT=24GeV
  - Lepton pT >25GeV
  - Muon (electron) eta < 2.4 (2.5)
  - Impact parameter cut
  - Relative isolation: scalar sum pT in a deltaR =0.4 cone around the lepton smaller 10% (12%) of the electron (muon) pT
  - Take the two opposite charged leptons with the highest transverse momenta, if more than two leptons
  - $|M_Z - M_{ll}| < 15$GeV
  - Either use PF- or JPT jets:
    - pT > 30 GeV
    - |eta| < 4.7
    - Tagging jets: highest pT jets, require pT > 50GeV

VBF Z @ CMS 8TeV

- Signal: MADGRAPH (v5.1.3.30)+Pythia6 and CTEQ6L1 PDF
  - NLO to LO kFactor 1.12 from VBFNLO
- DY background: MADGRAPH, NNLO XS from FEWZ, dynamic scale factor from MCFM to re-weight the simulation to NLO
- Ttbar: MADGRAPH normalized to NNLO+NNLL
- Single Top: POWHEG normalized to NNLO cross section
- Di-Boson: WW,WZ,ZZ generated with Pythia normalized to NLO cross section from MCFM
- Pile up rate: 23 additional interactions

Definition of 5 fiducial regions

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	Z-boson selection $\lvert\eta^\ell\rvert < 2.47,\ p_T^\ell > 25$ GeV				
Dilepton pair	$81 \le m_{\ell\ell} \le 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	baseline jet selection $\lvert y^j\rvert < 4.4,\ \Delta R_{j,\ell} \ge 0.3$				
	$p_T^{j1} > 55$ GeV				$p_T^{j1} > 85$ GeV
	$p_T^{j2} > 45$ GeV				$p_T^{j2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}} = 0$	$N_{\text{jet}} \ge 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance},3} < 0.15$	—

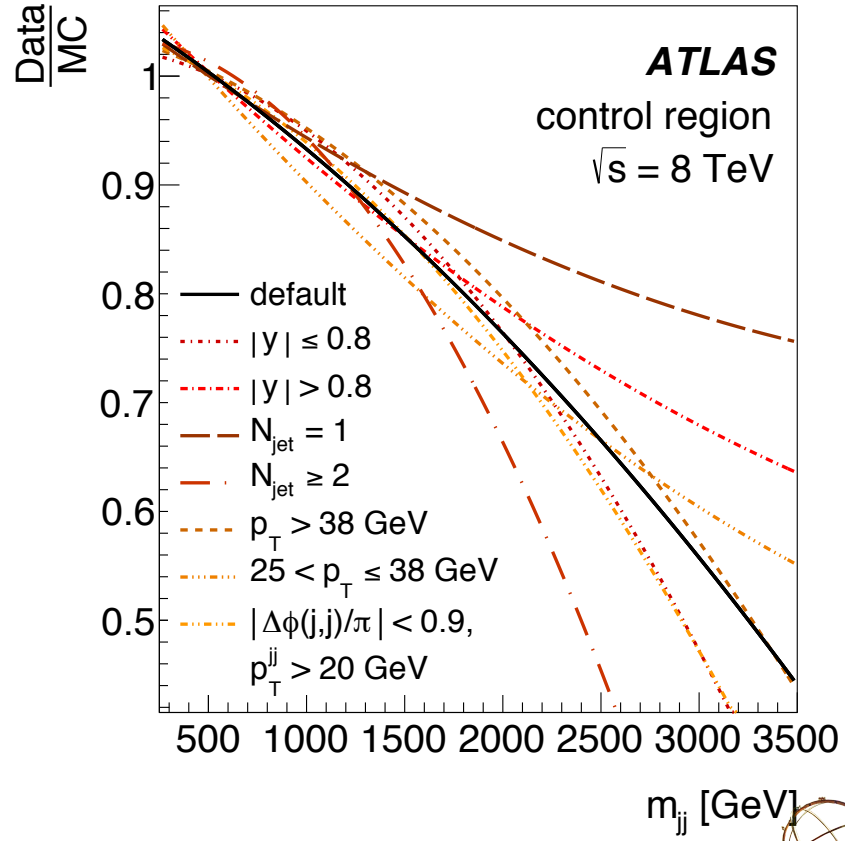
search/control region

probe of high-pT/high mass

Extraction of EW Z+2jets fiducial cross section

Choice of generator checked by using
POWHEG (instead of SHERPA) and
repeating full analysis chain.
–Extracted signal yields agree to 0.8%

Choice of control region validated by
splitting it into seven sub-regions,
– deriving new constraints,
– repeating full analysis chain.
– extracted signal yields agree to within 5%.



VBS WW

- Dominant Uncertainty:
  - JES
- Samples:
  - Signal: Sherpa
  - WZ/gamma (mis-id lepton) Sherpa (XS from VBFNLO at NLO)
  - ZZ+jets (Sherpa),ttbar+W/Z (MADGRAPH +Pythia8) and tZj
  - Backgrounds from charge flip (negligible for muons), data driven (mainly ttbar and DY)
  - Non-promt backgrounds (like W+jets, ttbar) data driven

Exclusive two photon production of W+W-

- Selection:
  - Electron-muon-trigger (17/8GeV threshold)
  - Lepton pT >20GeV, $|\eta|<2.4$
  - $M_{ll}>20$GeV
  - No extra tracks from the primary vertex
  - $pT_{ll}>30$GeV

VBS WW

- Selection (inclusive region):
  - Exactly two same charged, isolated electrons/muons with pT >25GeV, |eta|<2.47/2.4
  - M_{ll} >20GeV
  - Delta R_{ll} >0.3
  - At least two Jets with pT>30GeV and |eta|<4.5
  - Tagging jets: two highest pT jets
  - m_{jj}>500GeV
  - MET>40GeV
  - Veto events with additional (looser isolated) leptons
  - Z-mass window for electron channel (mis-identified charge)
- VBS region:
  - Additional |delta eta jj| >2.4

Exclusive two photon production of W+W-

- Samples:
  - $\gamma\gamma$->WW signal: CALCHEP∞2.5.4, with Pythia6 fpr the WW decay
  - WW+jets, W+jets, ttbar: MADGRAPH5
  - $\tau\tau$ (produced by Drell Yan): POWHEG
  - All taus are handled by TAUOLA
  - VBS WW studied with VBFNLO