Electroweak production of dijets in association with a Z boson in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

Stephen Weber

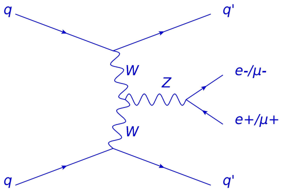
Carleton University

February 17, 2018

ATLAS EXPERIMENT

Signal: Electroweak Zjj

EW Zjj includes all processes where there is a t-channel exchange of a W/Z boson and a l^+l^-jj final state

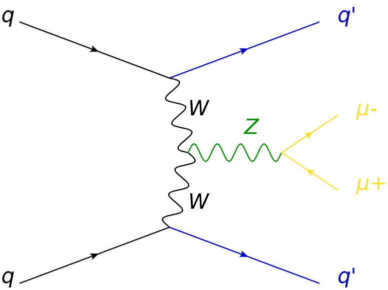


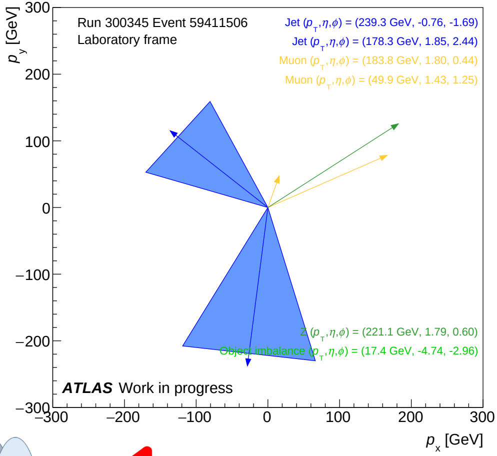
Vector Boson Fusion (VBF)

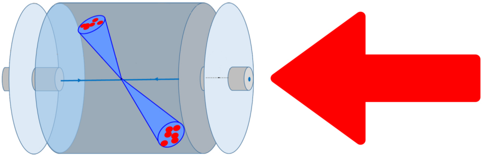
$$\text{cross section} : \sigma_{EW} \approx 1.5\,\text{pb} = 1.5 \times 10^{-12}\,\text{b}$$

- VBF Z is also a probe for new physics via higher order corrections to the WWZ vertex, the triple gauge coupling
- The VBF component of EW production is of interest because of the similarity to VBF higgs production

Signal: What we see with the ATLAS detector







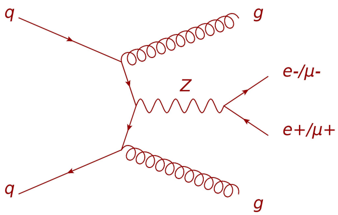
Background: Strongly produced *Zjj*

- *Zjj* events at the LHC are predominantly produced via a **strong interaction**
- Same l^+l^-jj final state as our EW signal but ∼3000 times more likely

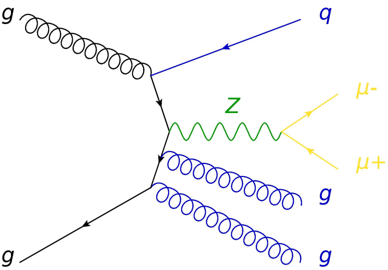
$$\sigma_{Strong} \approx 4.3\,\mathrm{nb} = 4.3 \times 10^{-9}\,\mathrm{b}$$

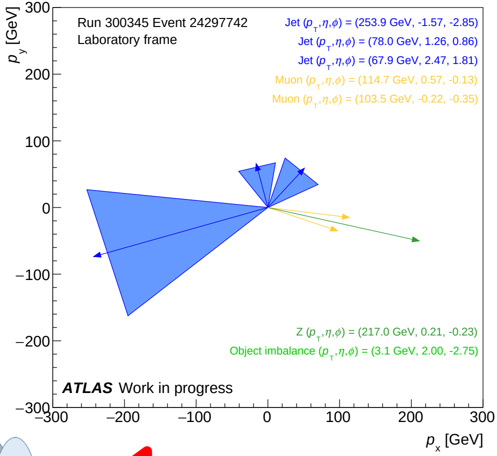
$$\sigma_{EW} \approx 1.5\,\mathrm{pb} = 1.5 \times 10^{-12}\,\mathrm{b}$$

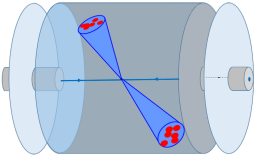
- Strong *Zjj* events are more likely to have additional jets **between** the 2 main jets



Background: What we see with the ATLAS detector







Measurement: Differential cross section

Strong *Zjj* prediction
~99% of total bkg

ttbar, dibosons …
~1% of total bkg

Fiducial EW *Zjj* cross section of bin *i*

$$\sigma_{\text{fid},i} = \frac{N^{\text{data}}_{\text{SR},i} - N^{\text{strong}}_{\text{SR},i} - N^{\text{non-}Z}_{\text{SR},i}}{C_i\,\mathcal{L}}$$

Bin-by-bin correction factor
$C_i = N_{\text{reco},i} / N_{\text{truth},i}$ for signal

Integrated luminosity 33 fb^{-1}

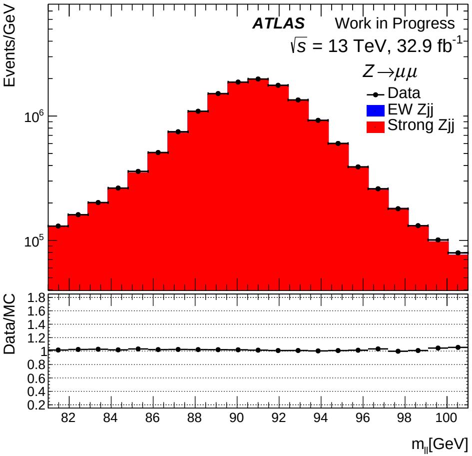
- The Strong Zjj accounts for the vast majority of events
- Crucial to understand this process to measure the EW Zjj signal

Event selection: **Signal** region

Event requirements for the EW Zjj enhanced region

- **1) Z Candidate**:
  - 2 opposite sign, same flavour leptons
  - $p_T^{lep} > 25$ GeV
  - $81 \leq m_{ll} \leq 101$ GeV

$$\frac{N_{EW}}{N_{Strong} + N_{EW}} = 5.0 \times 10^{-4}$$

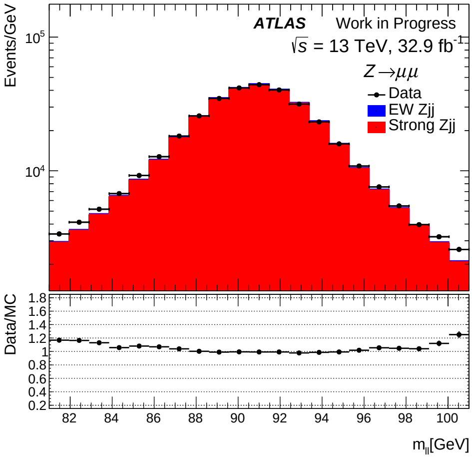


Event selection: **Signal** region

Event requirements for the EW Zjj enhanced region

- **2) 2 Jets**:
  - Jet 1: $p_T > 55$ GeV
  - Jet 2: $p_T > 45$ GeV

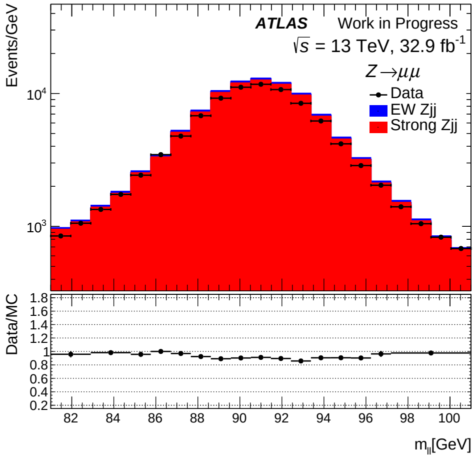
$$\frac{N_{EW}}{N_{Strong} + N_{EW}} = 0.014$$



Event requirements for the EW Zjj enhanced region

- **3) Dijet invariant mass**:
  - $m_{jj} > 250$ GeV
- **4) Dijet Rapidity Gap**:
  - $\Delta Y(j1, j2) > 2.0$

$$\frac{N_{EW}}{N_{Strong} + N_{EW}} = 0.032$$



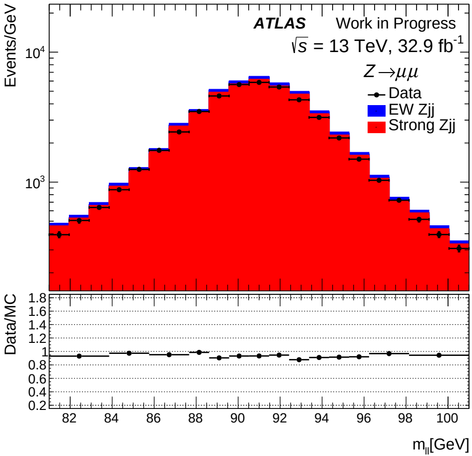
Event selection: **Signal** region

Event requirements for the EW Zjj enhanced region

- **5) Dilepton pT**:
  - $p_T^{ll} > 20$ GeV
- **6) pT balance**:
  - $p_T^{\mathrm{balance}} < 0.15$

$$p_T^{\mathrm{balance}} = \frac{|\vec{p}_T^{\,l1}+\vec{p}_T^{\,l2}+\vec{p}_T^{\,j1}+\vec{p}_T^{\,j2}|}{|\vec{p}_T^{\,l1}|+|\vec{p}_T^{\,l2}|+|\vec{p}_T^{\,j1}|+|\vec{p}_T^{\,j2}|}$$

$$\frac{N_{EW}}{N_{Strong}+N_{EW}} = 0.051$$



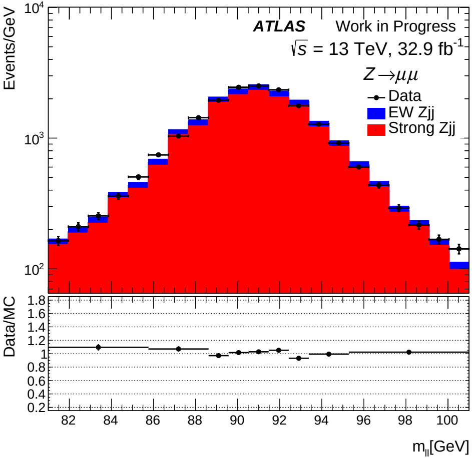
Event selection: **Signal** region

Event requirements for the EW Zjj enhanced region

- **7) No gap jets**:
  - no jets in the rapidity gap between the leading 2 jets
- **8) Z centrality**:
  - $\xi_Z < 0.5$

$$\xi_Z = \frac{y_Z - \frac{1}{2}(y_{j1}+y_{j2})}{|y_{j1}-y_{j2}|}$$

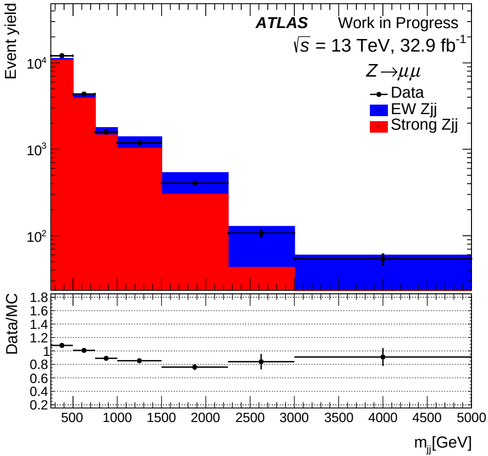
$$\frac{N_{EW}}{N_{Strong} + N_{EW}} = 0.097$$



M_{jj} in the **Signal** region

MC simulation doesn't model the Strong Zjj component well

- Observe a mis-modeling of the Strong Zjj background
- Solution:
  - Define a **Control** region orthogonal to the **Signal** region
  - **Control** region suppresses EW Zjj component
  - Constrain the Strong Zjj background to the match the **Control** region



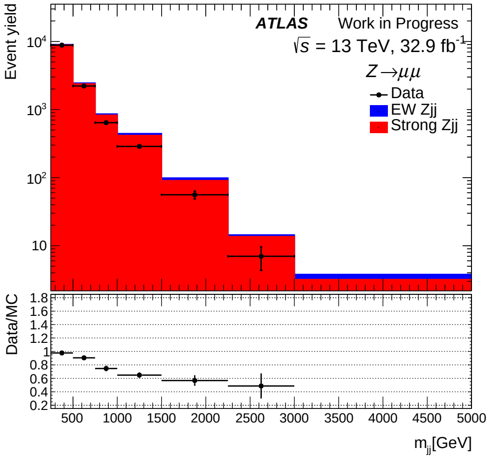
M_{jj} in the **Control** region

MC simulation doesn't model the Strong Zjj component well

- Invert the Z centrality cut:
  - $\xi_Z < 0.5$

$$\xi_Z = \frac{y_Z - \frac{1}{2}(y_{j1} + y_{j2})}{|y_{j1} - y_{j2}|}$$

$$\frac{N_{EW}}{N_{Strong} + N_{EW}} = 0.020$$



Summary: Differential cross section measurement

- Looking at the full 2015-16 dataset ($\sim$36 fb^{-1})
- Goal is to measure the differential cross sections for the EW Zjj as a function of characteristic variables:
  - Invariant mass of the dijet system $\rightarrow M_{jj}$
  - Jet multiplicity in the rapidity gap $\rightarrow N_{\text{jet}}^{\text{gap}}$
  - Z boson centrality $\rightarrow \xi_Z$
- General procedure for differential measurement
  - Fit Strong Zjj template in the control region
  - Extrapolate Strong Zjj template to the signal region
  - Fit the EW signal template by subtracting the Strong Zjj from the data in the signal region
- **Systematic variations** and **Monte Carlo modeling uncertainties** need to be well understood to extrapolate from Control to Signal regions.

Acknowledgements

University of Manchester
J. Crane, A. Pilkington
Carleton
A. Bellerive, C. Chhiv Chau, D. Gillberg

Carleton UNIVERSITY

ATLAS EXPERIMENT

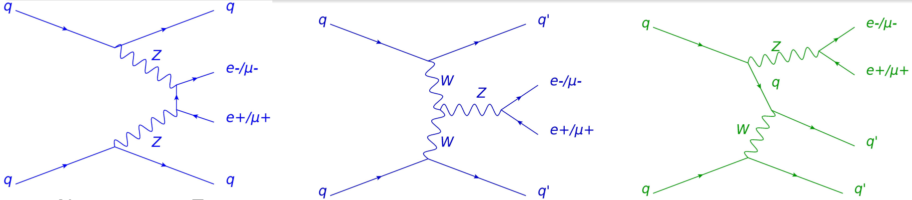
NSERC CRSNG

Questions?

BACKUP

Signal: Electroweak *Zjj* other diagrams

EW *Zjj* includes all processes where there is a *t*-channel exchange of a W/Z boson and a l^+l^-jj final state



Non-resonant Zjj   Vector Boson Fusion (VBF)   Z-bremsstrahlung

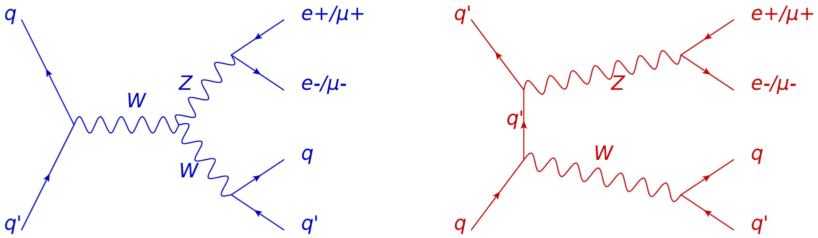
$$\text{cross section} : \sigma_{EW} \approx 1.5\,\text{pb} = 1.5 \times 10^{-12}\,\text{b}$$

- The VBF component of EW production is of interest because of the similarity to VBF higgs production
- VBF Z is also a probe for new physics via higher order corrections to the WWZ vertex, the triple gauge coupling

Background processes (1)

Other backgrounds include:

- Semi-leptonic diboson decays (ZZ, WZ)

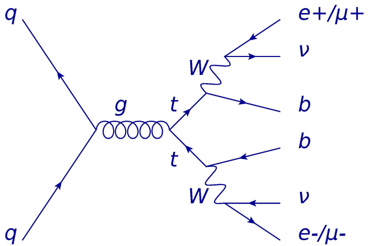


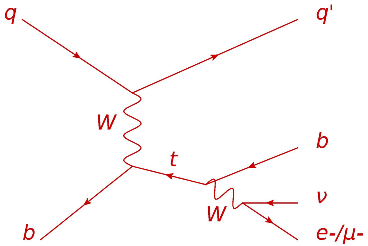
Have a Z boson but the leading jets come from a vector boson

Background processes (2)

Other backgrounds include:

- $t\bar{t}$, single top, multijet, WW and W+jets





These background have no Z boson, a lepton pair is misidentified as a Z

Dataset and MC samples

Data included in current studies

2016 Periods A-L (STDM3 Derivation) $\mathcal{L} = 33\,fb^{-1}$

EW Zjj (Signal)

mc15_13TeV.344265.PhPy8EG_CT10nloME_AZNLOC6L1_VBFZee.DAOD_STDM3.e5208_s2726_r7772_r7676_p2882
mc15_13TeV.344266.PhPy8EG_CT10nloME_AZNLOC6L1_VBFZmumu.DAOD_STDM3.e5208_s2726_r7772_r7676_p2882

Z+jets (Dominant background, ~99%)

Sherpa (NLO for Z+0,1,2 partons, LO for 3,4)

- mc15_13TeV.3641*.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV*.merge.
  DAOD_STDM3.e5299_s2726_r7772_r7676_p2949

Madgraph (LO for Z+0,1,2,3,4 partons)

- mc15_13TeV.3631*.MGPy8EG_N30NLO_Zee_Ht*.DAOD_STDM3.e4866_s2726_r7772_r7676_p2669

Madgraph MG5 aMC@NLO FxFx (VBF filter)

- Samples have been submitted (EVTGEN only)
- https://its.cern.ch/jira/browse/ATLMCPROD-5368

MC samples (cont.)

Other background samples ($\sim$1%)

Semi-leptonic diboson decays (ZZ, WZ)

- mc15_13TeV.3610*.Sherpa_CT10*.DAOD_STDM4*

$t\bar{t}$

- mc15_13TeV.410000.PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5_nonallhad.merge.DAOD_STDM3.e3698_s2608_s2183_r7725_r7676_p2666

single top

- mc15_13TeV.4100*.PowhegPythiaEvtGen_P2012*.DAOD_STDM3*

W+jets

- mc15_13TeV.36110*.PowhegPythia8EvtGen_AZNLOCTEQ6L1*.DAOD_STDM3*

Z$\rightarrow \tau\tau$

- mc15_13TeV.361108.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Ztautau.merge.DAOD_STDM3.e3601_s2726_r7725_r7676_p2666

Object and Event Selection

Object	Electron Channel	Muon Channel
Leptons	$p_T > 25$ GeV $\|\eta\|< 1.37 \mid\mid 1.52 < \|\eta\| < 2.47$ Medium likelihood Gradient Isolation	$p_T > 25$ GeV $\|\eta\|<2.4$ Medium WP Gradient Isolation
Jets	anti-k_t $R = 0.4$, EM+JES Jet Cleaning: *LooseBad* $p_T > 25$ GeV $\|y_j\|<4.4$ JVT > 0.59 for $p_T < 60$ GeV and $\|\eta\|<2.4$	

Event Selection: VBF topology

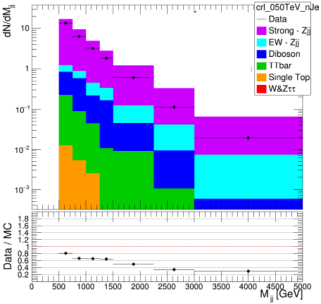
Dilepton pair	$81 < M_{ll} < 101$ GeV, $p_t^{ll} > 20$ GeV
Dijet system	$p_T^{j1} > 55$ GeV $p_T^{j2} > 45$ GeV $M_{jj} > 500$ GeV $\Delta Y(j1, j2) > 2.0$
System	$p_T^{\mathrm{balance}} < 0.15$

A gap-jet (gj) has rapidity between the leading two jets

$$p_T^{\mathrm{balance}} = \frac{\vec{p}_T^{\,l1} + \vec{p}_T^{\,l2} + \vec{p}_T^{\,j1} + \vec{p}_T^{\,j2} + \vec{p}_T^{\,gj}}{|\vec{p}_T^{\,l1}| + |\vec{p}_T^{\,l2}| + |\vec{p}_T^{\,j1}| + |\vec{p}_T^{\,j2}| + |\vec{p}_T^{\,gj}|}$$

Strong Z+jets miss modeling

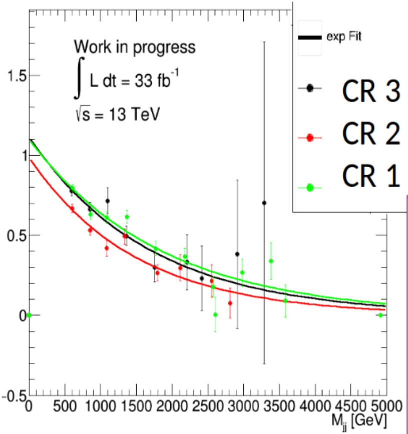
- Analysis challenge: Strong Z+jets samples significantly overestimate the cross section at high m_{jj}
  - The MG5 aMC@NLO FxFx samples (being submitted) have a large fraction of negative events
  - Virtual corrections are significant, how will this sample compare to data?
- To account for this affect we:
  - 1) Derive a data-driven reweighing function in control regions $\rightarrow r_{\mathrm{CR}}$
  - 2) Apply the reweighing function to improve the strong Z modeling in the signal region

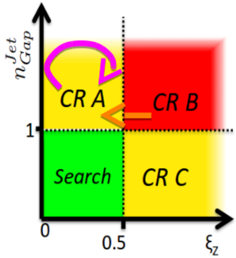


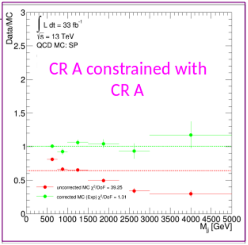
Applying the data driven constraint

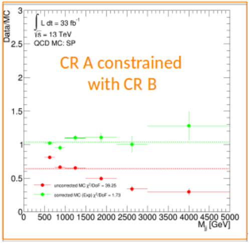
$$r_{\mathrm{CR},i} = \frac{N^{\mathrm{data}}_{\mathrm{CR},i} - N^{\mathrm{non-}Z}_{\mathrm{CR},i}}{N^{\mathrm{strong-MC}}_{\mathrm{CR,i}}}$$

- Fit constraint in given CR
- Validate by applying to other CRs



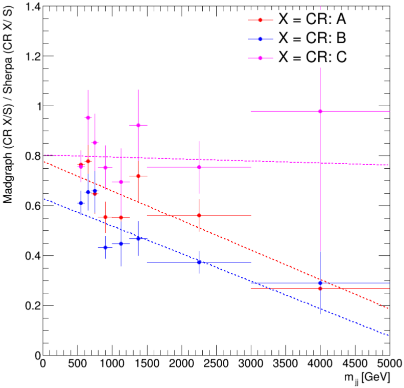


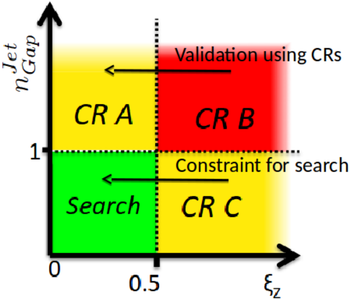




Using constraint on Search region

- Looking at the ratio N_{CR}/N_{SR} for different strong Zjj generators
- This is flat for **CR C** $\rightarrow$ implies consistent modeling
- We can constrain across Z centrality "boundary"





Cross section measurement challenges

Recall the fiducial cross section in bin i:

$$\sigma_{\mathrm{fid},i} = \frac{N^{\mathrm{data}}_{\mathrm{SR},i} - N^{\mathrm{strong}}_{\mathrm{SR,i}} - N^{\mathrm{non}-Z}_{\mathrm{SR},i}}{C_i\,\mathcal{L}}$$

The term in red is the strong Zjj component:

$$N^{\mathrm{strong}}_{\mathrm{SR,i}} = k \cdot r_{\mathrm{CR},i} \cdot N^{\mathrm{strong-MC}}_{\mathrm{SR,i}}$$

where our constraining function is:

$$r_{\mathrm{CR},i} = \frac{N^{\mathrm{data}}_{\mathrm{CR},i} - N^{\mathrm{non}-Z}_{\mathrm{CR},i}}{N^{\mathrm{strong-MC}}_{\mathrm{CR,i}}}$$

so the predicted yield in a signal region bin i is:

$$N^{\mathrm{strong}}_{\mathrm{SR,i}} = k\left(N^{\mathrm{data}}_{\mathrm{CR},i} - N^{\mathrm{non}-Z}_{\mathrm{CR},i}\right)\frac{N^{\mathrm{strong-MC}}_{\mathrm{SR},i}}{N^{\mathrm{strong-MC}}_{\mathrm{CR},i}}$$

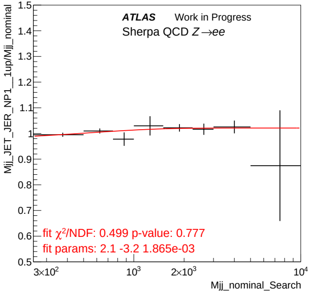
Control to signal ratio

We study the ratio term N_{CR}/N_{SR} for MC modeling and systematic variations

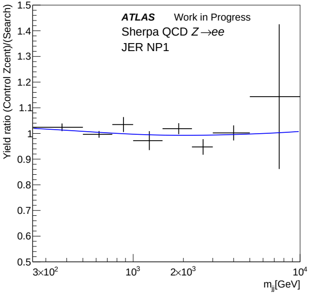
Systematic variations: JES and JER

Procedure:

- Perform analysis selection with nominal and systematically varied jets
- Fit varied/nominal distributions as a function of characteristic variables (M_{jj}, ΔY_{jj}, $N_{\text{jet}}^{\text{gap}}$ and ξ_Z) in a particular region of phase space
- Construct a ratio of two such distributions



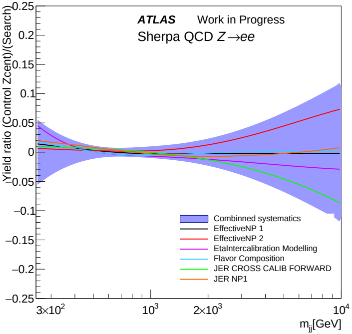
Search region: Varied/Nominal
JER NP1 systematic

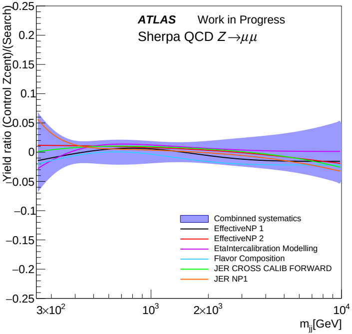


Double ratio: (CR C)/(Search region)
JER NP1 systematic

Systematic variations: JES and JER (continued)

Combined plots of dominant jet systematics, ratio of CR C to Search region





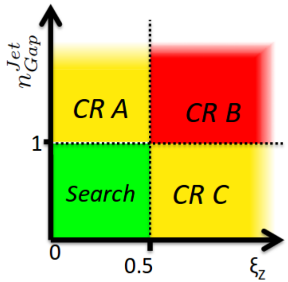
If this so-called **double ratio** of control regions is flat the background template can be safely extrapolated from one region to another without a systematic shift

Systematic variations: JES and JER (continued)

Table summarizing the 6 dominant JES/JER systematics contribution as a function of M_{jj}

CR C / Search region

Bin Low-Edge [GeV]	250.0	500.0	750.0	1000.0	1500.0	2250.0	3000.0	5000.0
JES effNP1	1.22%	-0.21%	-0.80%	-0.81%	-0.61%	-0.38%	-0.30%	-0.26%
JES effNP2	1.40%	-0.19%	0.09%	0.64%	1.53%	2.54%	3.63%	5.17%
JES etaModelling	2.77%	-1.02%	-1.45%	-1.49%	-1.49%	-1.49%	-1.49%	-1.49%
JES FlavourComp	3.00%	-1.16%	-1.84%	-1.47%	-0.92%	-0.53%	-0.39%	-0.31%
JER xcalib	2.14%	0.00%	-0.24%	-0.26%	-0.26%	-0.26%	-0.26%	-0.26%
JER effNP1	3.36%	0.18%	-0.18%	-0.21%	-0.21%	-0.21%	-0.21%	-0.21%
(Total JES+JER)	6.00%	1.58%	2.50%	2.36%	2.43%	3.03%	3.97%	5.41%



- The double ratio is relatively flat
- We can extrapolate the background template from this control region to the search region