VBS and VBF results from ATLAS

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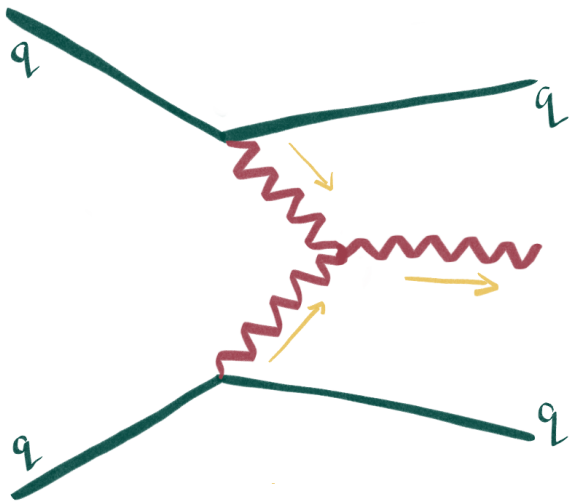
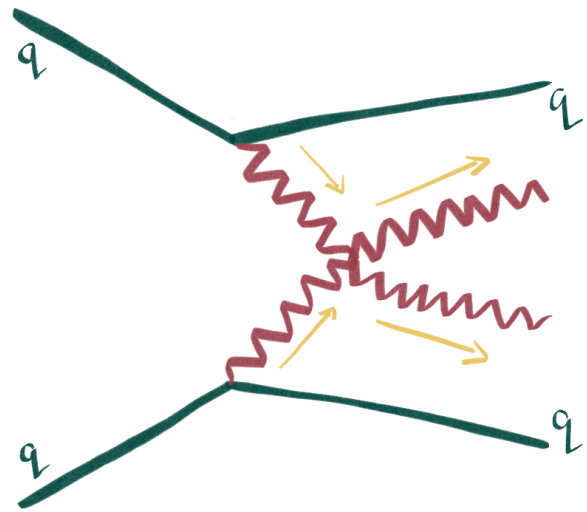
On behalf of the ATLAS Collaboration

LHCP 2020 – 25 – 30 May 2020

Overview



vector boson **fusion**
$\mathcal{O}(\alpha_{\mathrm{EW}}) = 3$



vector boson **scattering**
$\mathcal{O}(\alpha_{\mathrm{EW}}) = 4$

NB: we cannot directly measure VBF or VBS – significant **interference** with other diagrams of the same order in α_{EW} means extracting the VBF/VBS component is not a gauge invariant operation

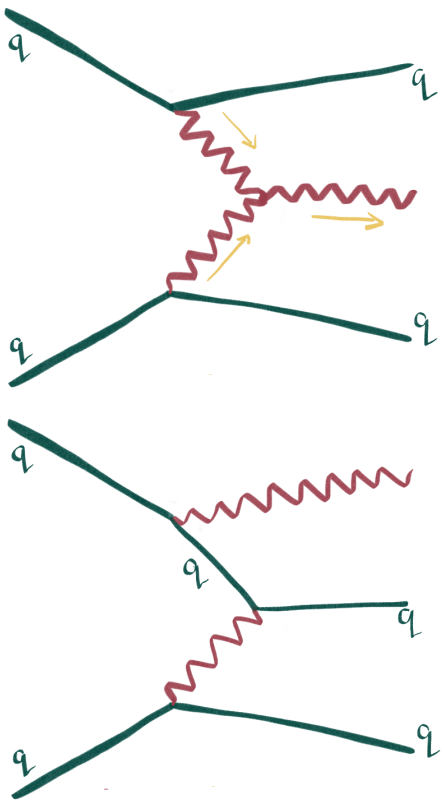
➔ Measure **electroweak production** of Vjj or VVjj

Details in C. Gutschow's talk yesterday: https://indico.cern.ch/event/856696/contributions/3722393/

Overview – QCD background

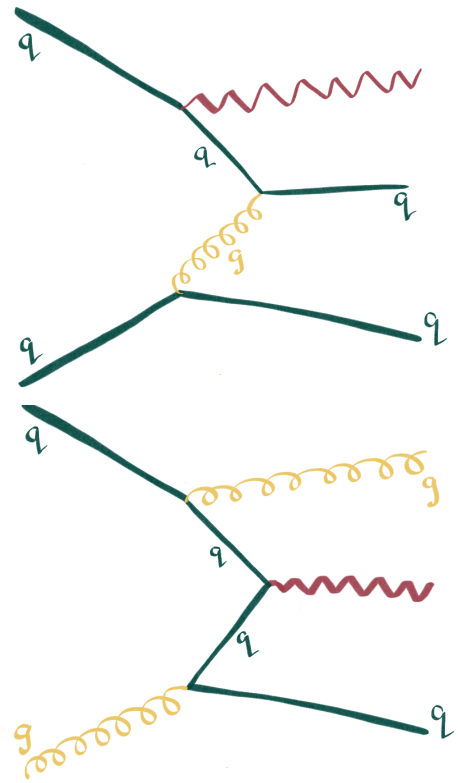
Electroweak Vjj production

$\mathcal{O}(\alpha_{EW}) = 3$

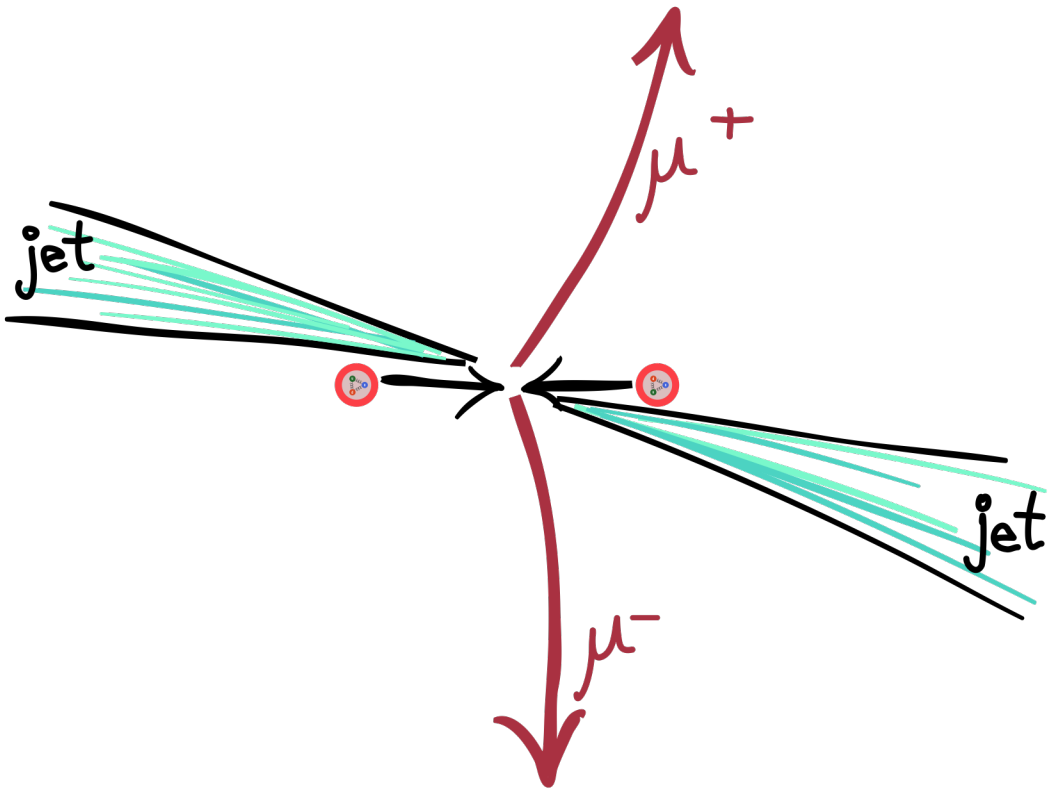


Strong Vjj production

$\mathcal{O}(\alpha_{EW}) = 1,\ \mathcal{O}(\alpha_S) = 2$



Strong production has the same final state and **usually** has a higher cross-section: understanding and reducing this background is crucial to an effective electroweak Vjj (or VVjj!) production measurement



Electroweak *Zjj* production

Z boson decaying leptonically (2e/2μ)

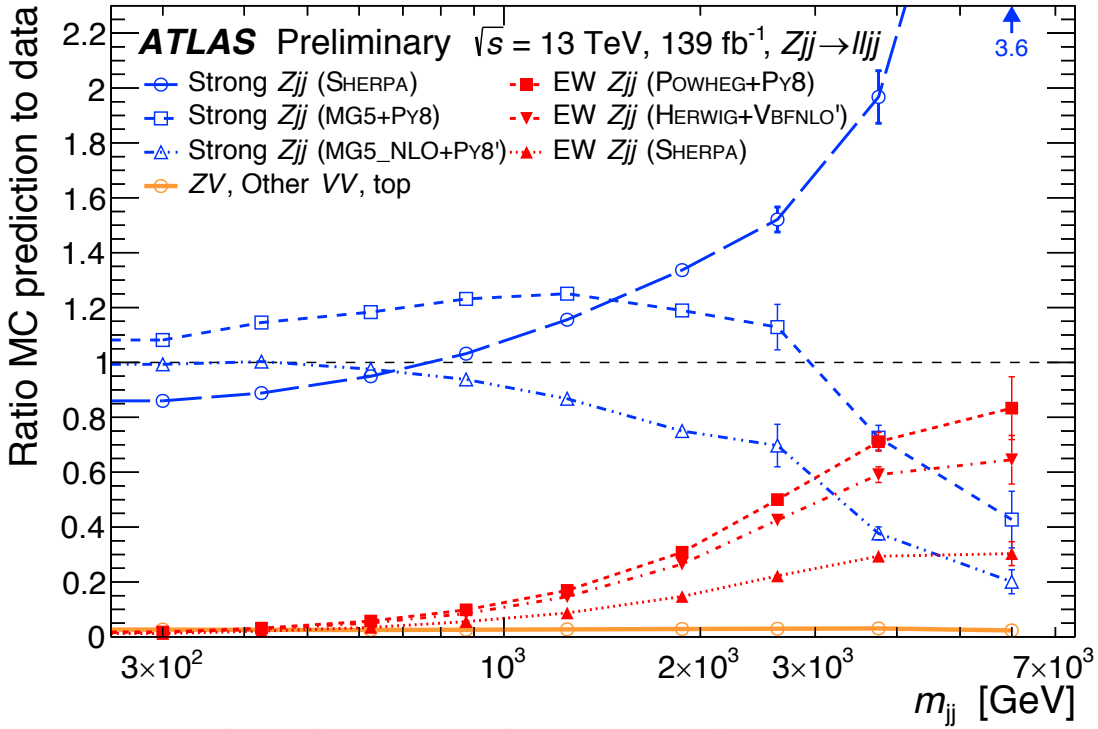
Two jets

- Large rapidity separation
- Large invariant mass

No jets in the gap

Electroweak *Zjj* production

STDM-2017-27

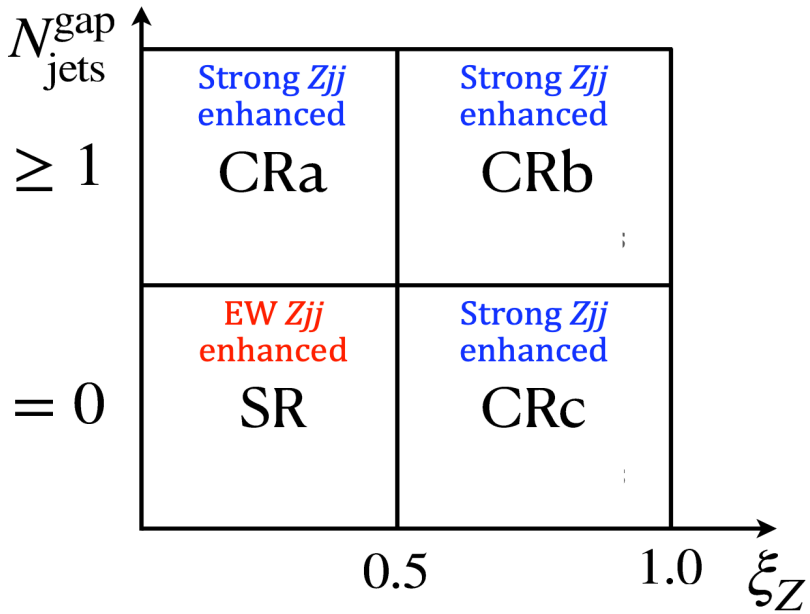


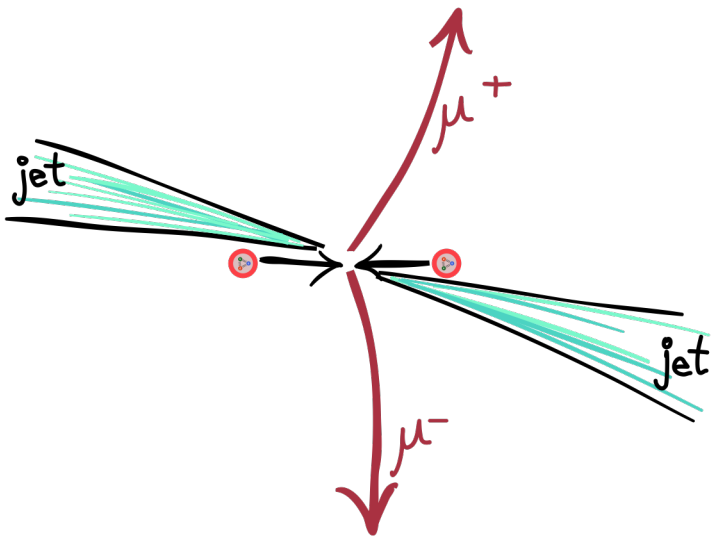
Strong *Zjj* is the largest background across the spectrum

Monte Carlo modelling of both strong electroweak *Zjj* shows discrepancies between generators

Modelling of strong *Zjj* is especially poor, particularly in the high-m_{jj} signal-enriched region

Data-driven background modelling





Analysis is split into four regions with two uncorrelated variables:

number of jets between the leading and subleading jets

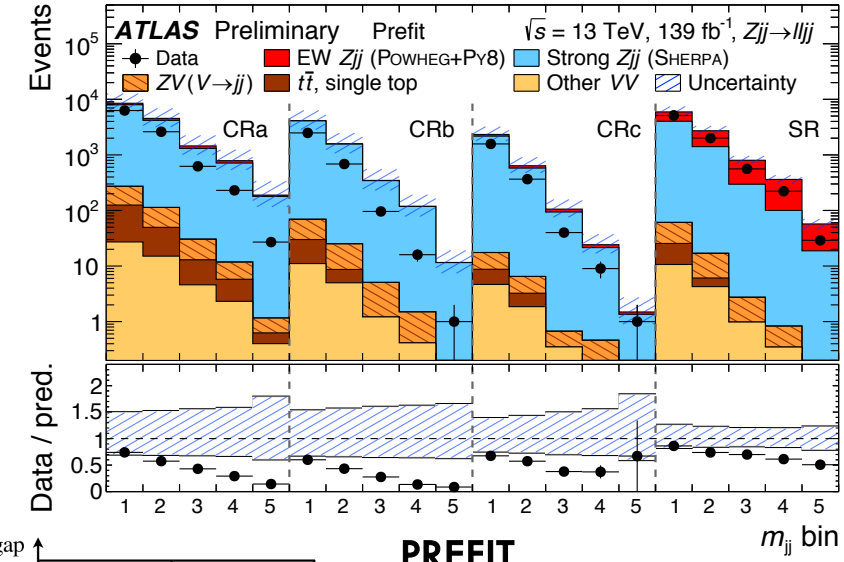
centrality of the reconstructed Z boson:

$$\xi_Z = |y_{\ell\ell} - 0.5(y_{j1} + y_{j2})|/|\Delta y_{jj}|$$

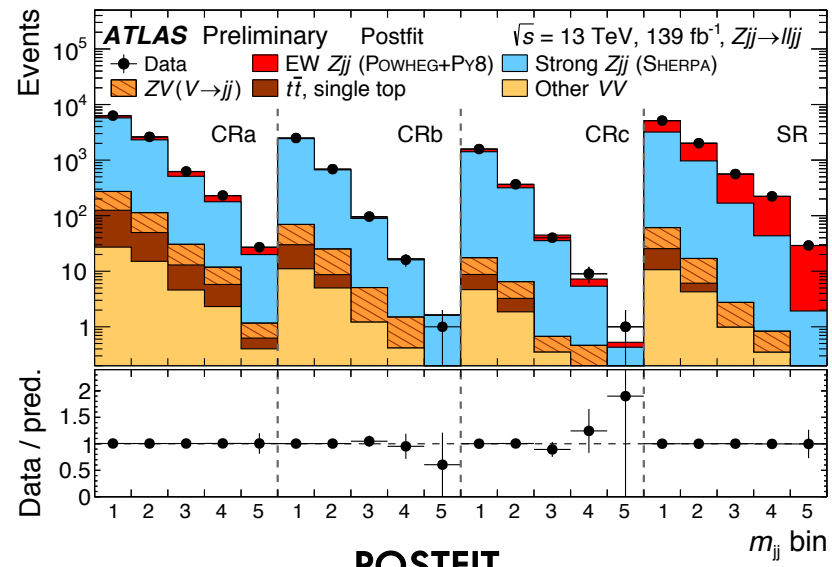
➔ three background-enhanced regions and one signal region

Extracting the EW *Zjj* signal

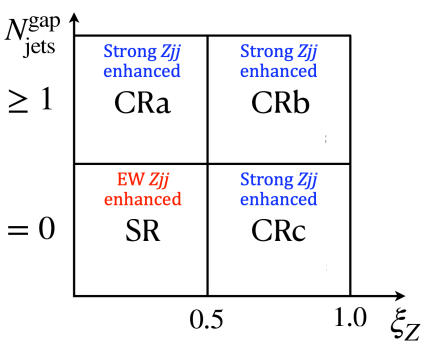
STDM-2017-27



PREFIT



POSTFIT



Binned maximum likelihood fit is performed to reduce dependence on MC mismodelling, with $3 * N_{\text{bins}} + 2$ free parameters:

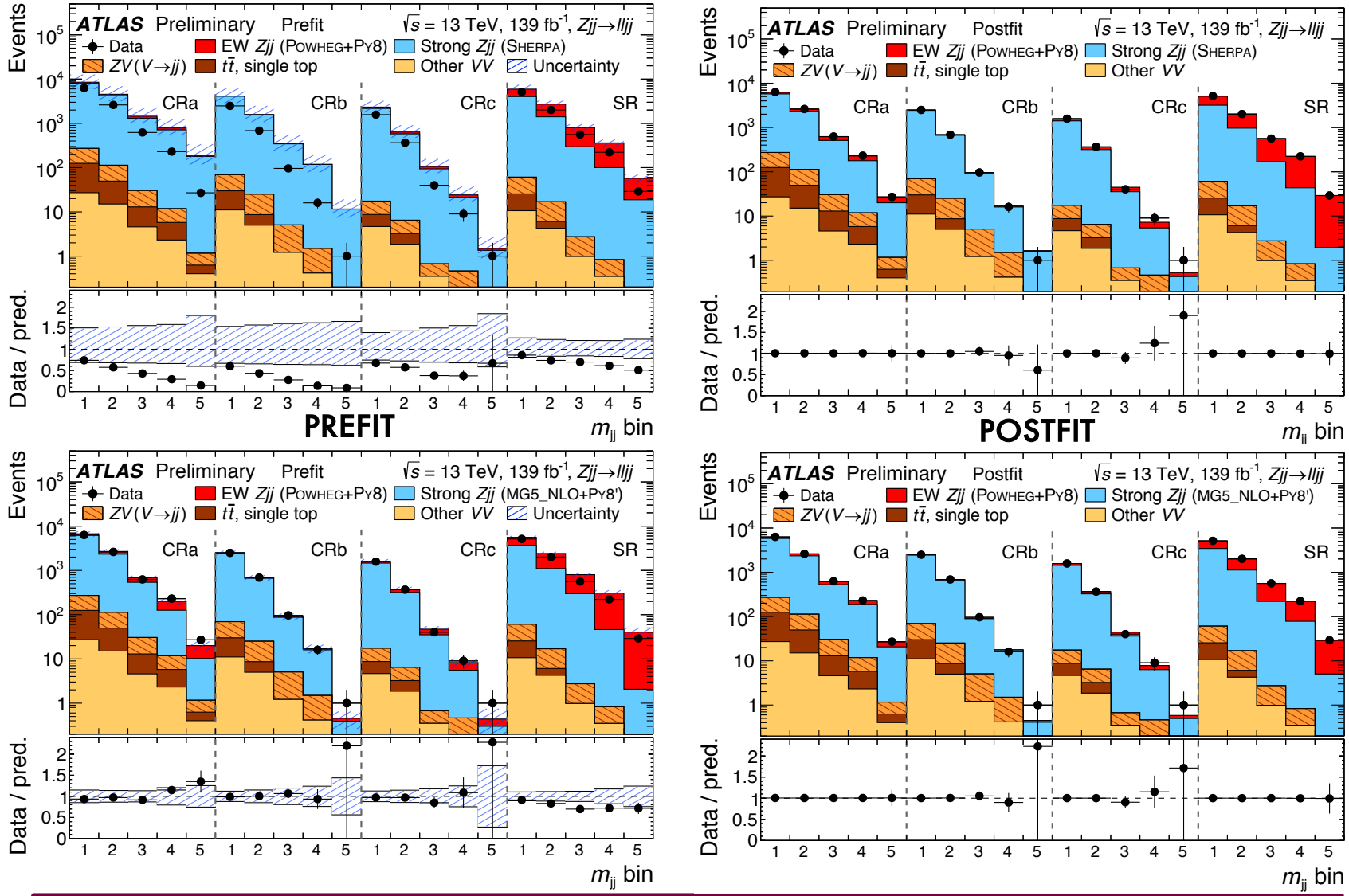
(1) bin-by-bin weights for strong *Zjj*, separate for low and high centrality but linked between $N_{\text{jets}}^{\text{gap}} \geq 1$ and $N_{\text{jets}}^{\text{gap}} = 0$

(2) linear f(x) applied to strong *Zjj* to correct for residual $N_{\text{jets}}^{\text{gap}}$ dependence

(3) bin-by-bin electroweak *Zjj* signal strengths (same in all regions)

Extracting the EW Zjj signal

STDM-2017-27

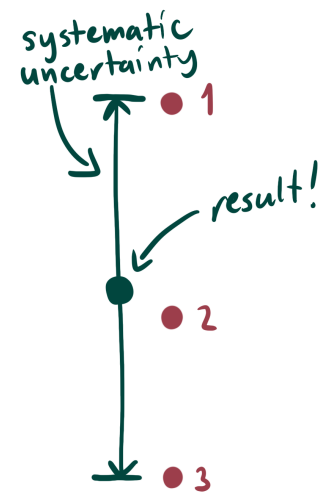


➔ Perform fit again with alternative generators for strong Zjj component

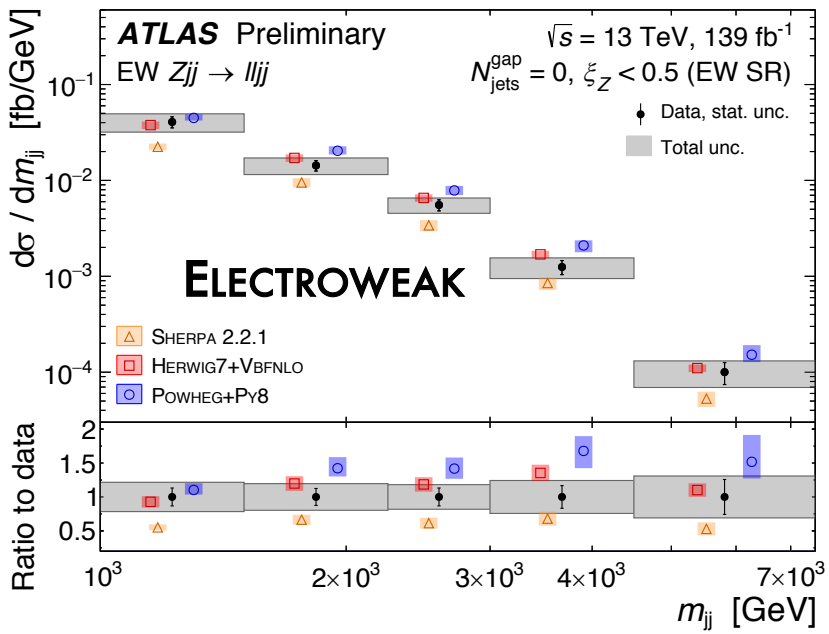
Results

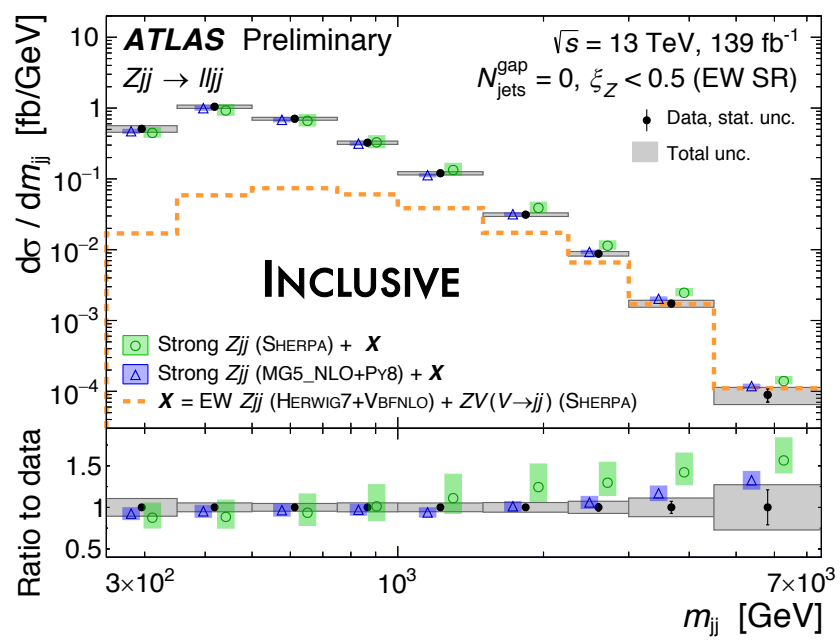
Extract the electroweak Zjj signal once for each of three strong Zjj generators:

result is the midpoint of the envelope



Signal and control regions are unfolded for both electroweak and inclusive *Zjj* yields:

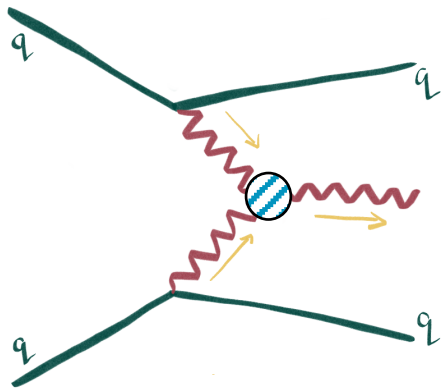




Effective field theory interpretation

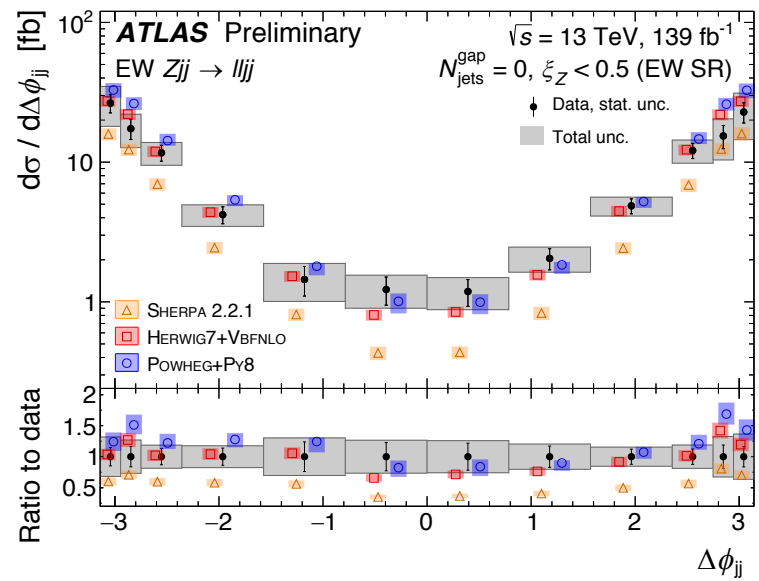
STDM-2017-27

$$\sigma_{EFT} = \sigma_{SM} + \sum_j \frac{c_j}{\Lambda^3}\sigma^{\text{interf.}}_{SM,j} + \sum_j \frac{c_j^2}{\Lambda^6}\sigma^{\text{NP}}_j + \sum_{j\neq k} \frac{c_j c_k}{\Lambda^6}\sigma^{\text{NP - interf.}}_{jk}$$



Wilson coefficient	Linear EFT	95 % confidence limit [TeV^{-2}] Expected (Asimov)	Observed
c_W/Λ^2	yes	[−0.30, 0.30]	[−0.19, 0.41]
	no	[−0.31, 0.29]	[−0.19, 0.41]
$\tilde{c}_W/\Lambda^2$	yes	[−0.12, 0.12]	[−0.11, 0.14]
	no	[−0.12, 0.12]	[−0.11, 0.14]
c_{HWB}/Λ^2	yes	[−2.45, 2.45]	[−3.78, 1.13]
	no	[−3.11, 2.10]	[−6.31, 1.01]
$\tilde{c}_{HWB}/\Lambda^2$	yes	[−1.06, 1.06]	[0.23, 2.34]
	no	[−1.06, 1.06]	[0.23, 2.35]

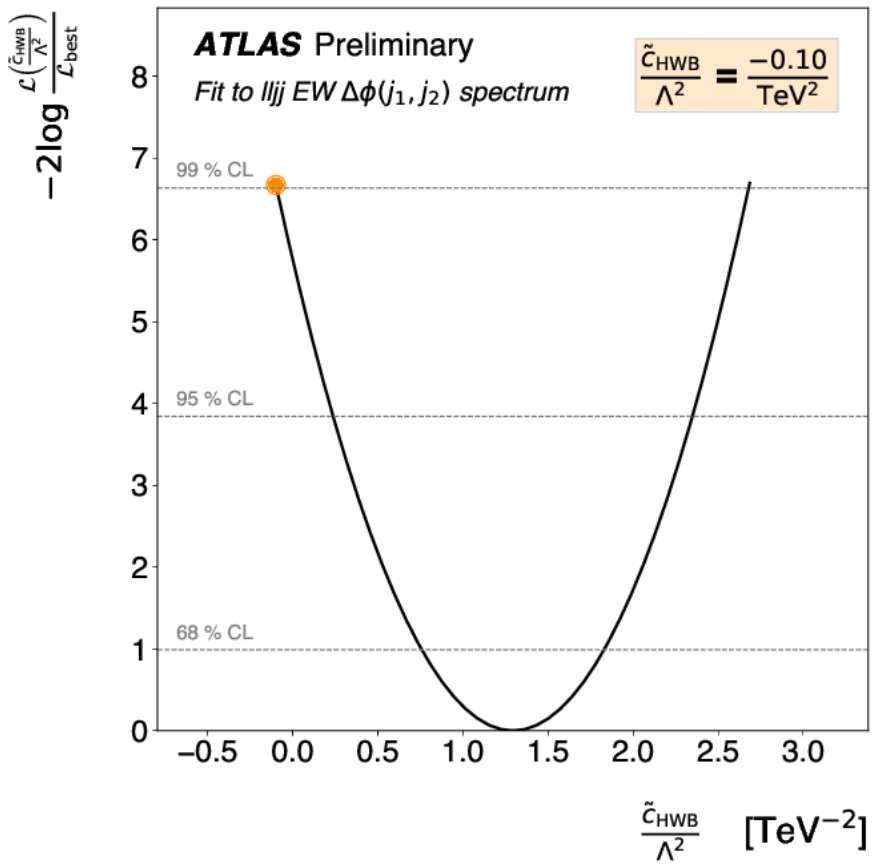
Two CP-even and two CP-odd operators were tested

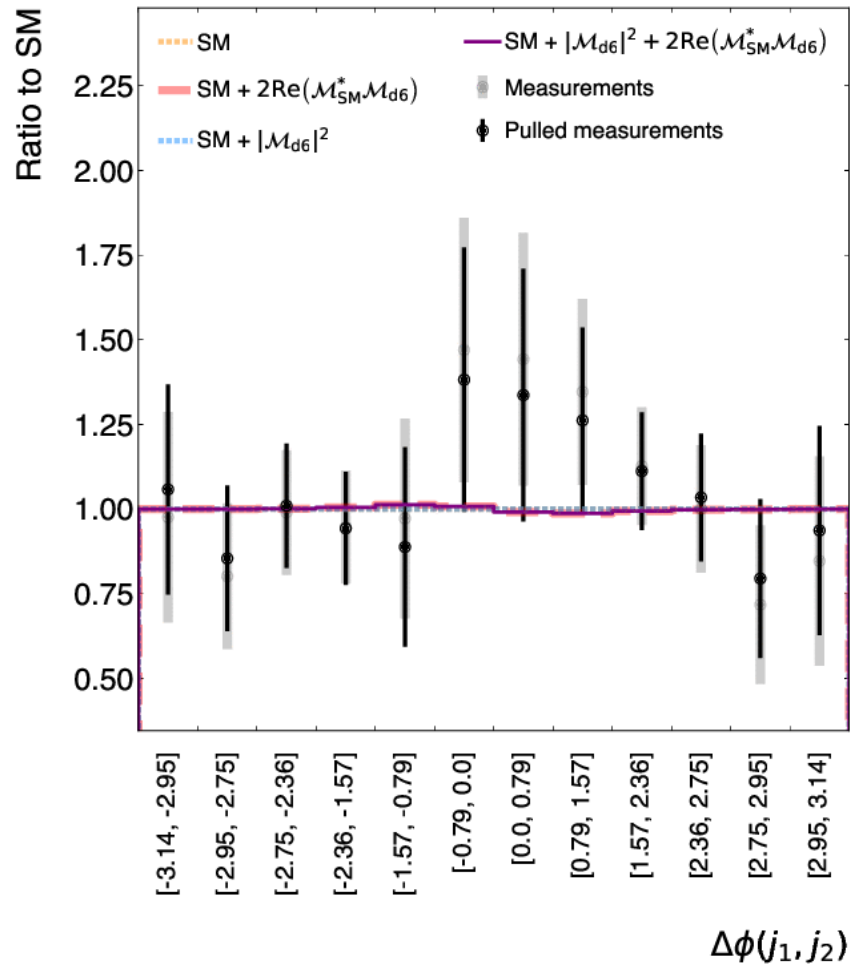


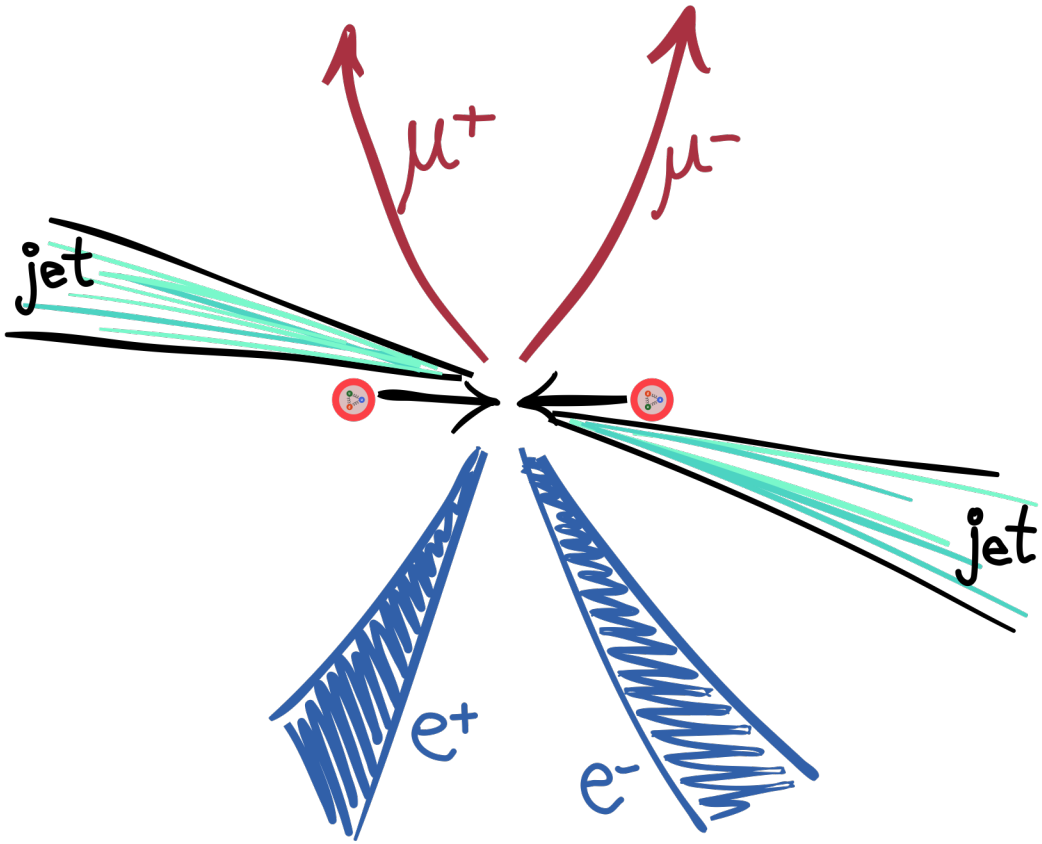
→ sensitivity to CP-odd operators through the parity-odd observable $\Delta\varphi_{jj} = \varphi_{\text{higher rapidity jet}} - \varphi_{\text{lower rapidity jet}}$, where jj = the two leading jets

Effective field theory interpretation

STDM-2017-27







Electroweak *ZZjj* production

Two Z bosons decaying leptonically (4e/ 2e2μ/4μ)

OR

One Z boson decaying leptonically (2e/2μ) and the other invisibly (2ν)

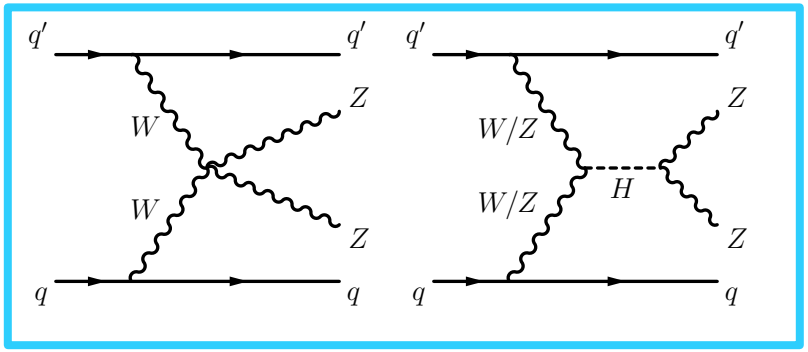
Two jets

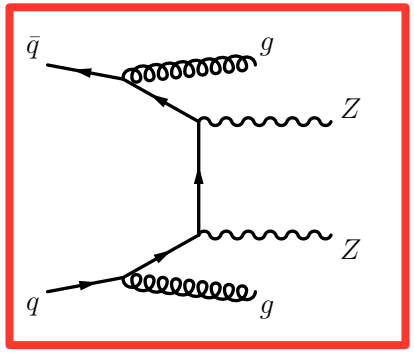
- Different sides of the detector
- Large rapidity separation
- Large invariant mass

arXiv:2004.10612

Electroweak $ZZjj$ production

arXiv:2004.10612





Analysis in two channels with slightly different selection:

Signal region defined by Z-mass and "electroweak" selection:
$y_{j1}{}^{*}y_{j2} < 0$, $m_{jj} > 400$ GeV ($\ell\ell\ell\ell$)/300 GeV ($\ell\ell\nu\nu$), and $\Delta y(jj) > 2$

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	–	21.4 ± 4.8
WZ	–	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114 ± 26	78.4 ± 6.2
Data	127	82

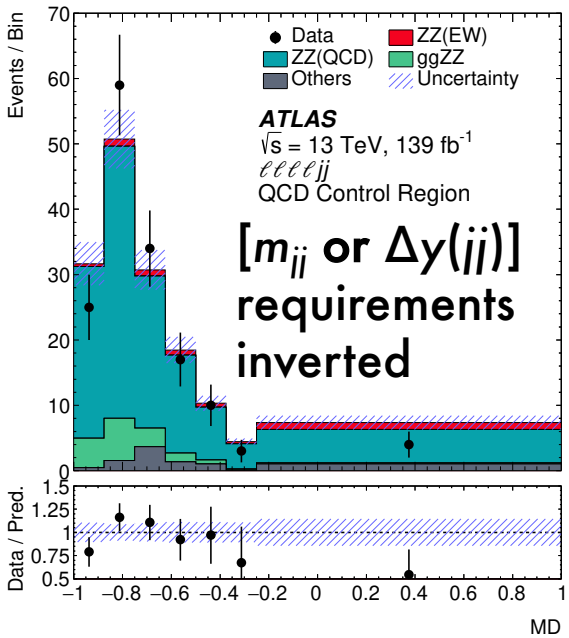
High non-$ZZjj$ background

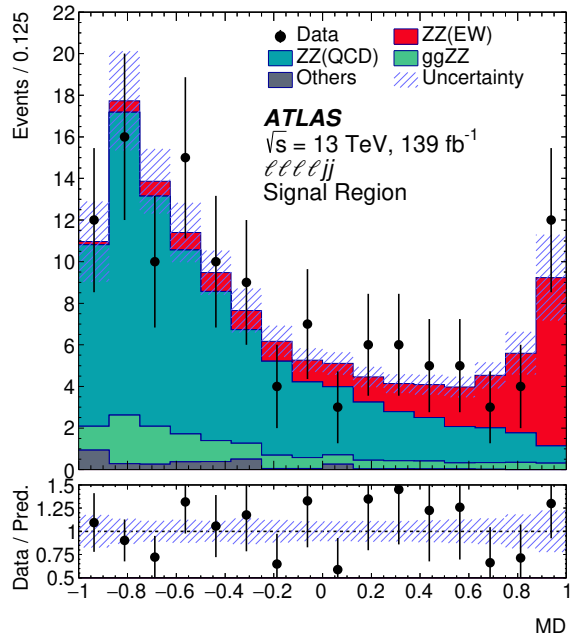
Extract **inclusive cross-section** in the signal region, then use BDTs to separate the electroweak and QCD components

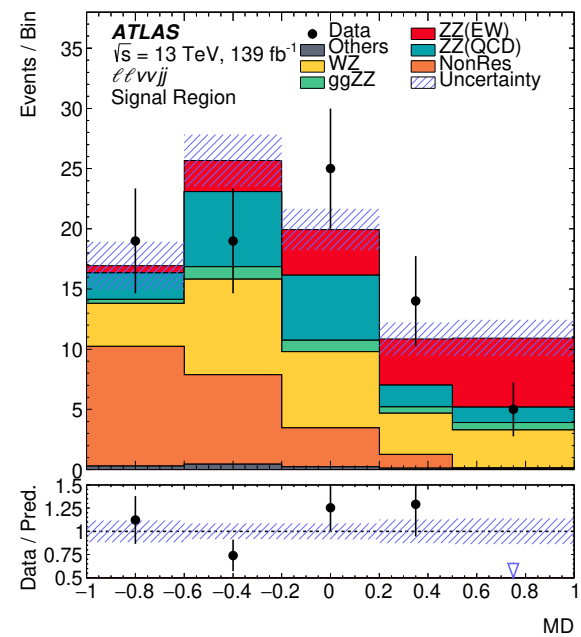
Fit BDT shape for maximum sensitivity

Electroweak $ZZjj$ production

arXiv:2004.10612







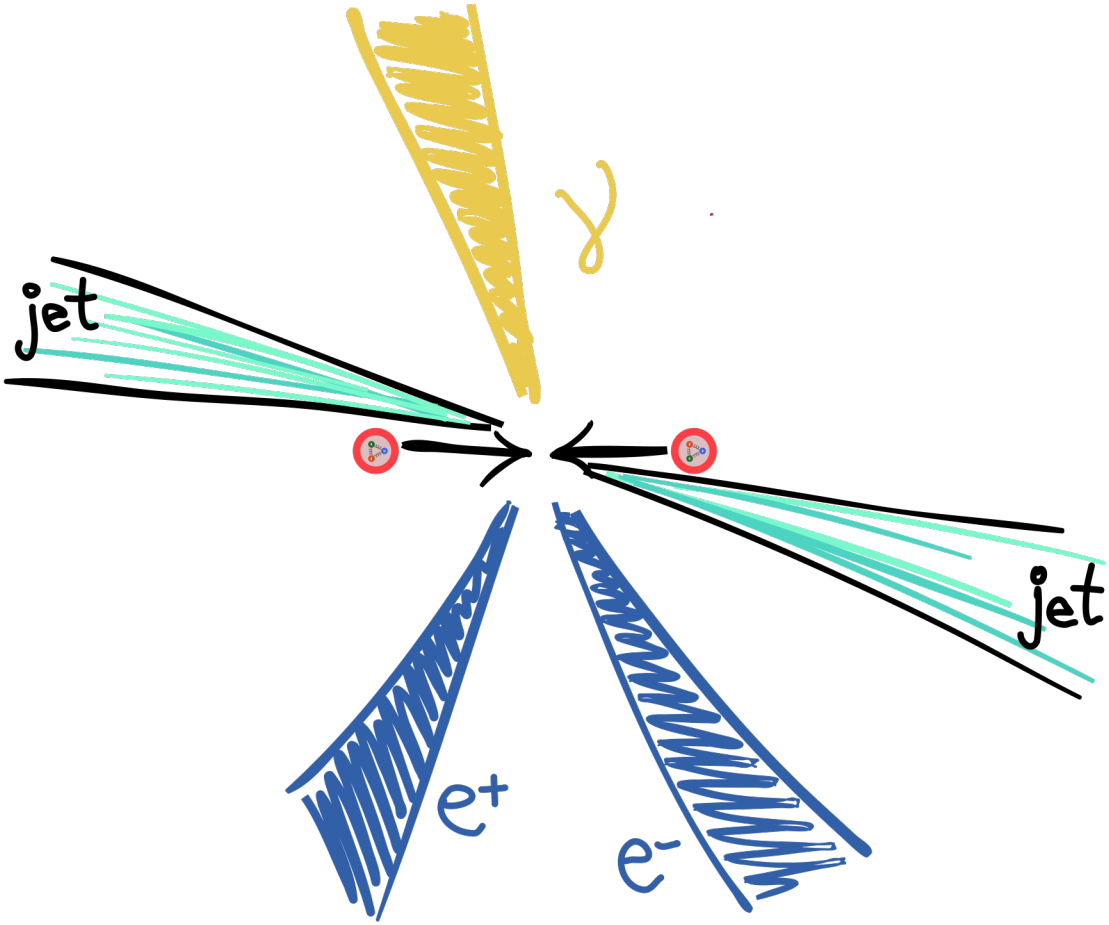
EWK $ZZjj$: LO Madgraph

	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	5.5 (3.9) σ
$\ell\ell\nu\nu jj$	1.2 (1.8) σ
Combined	5.5 (4.3) σ

Observation of electroweak $ZZjj$ production!

$$\sigma_{EW}^{zzjj} = 0.82 \pm 0.21 \text{ fb}$$

➔ One of the smallest measured cross-sections by ATLAS!



Electroweak $Z\gamma jj$ production

One Z boson decaying leptonically (2e/2μ)

One photon not from final state radiation

Central $\{\ell\ell\gamma\}$ system

Two jets

- Large rapidity separation
- Large invariant mass

No *b*-jets

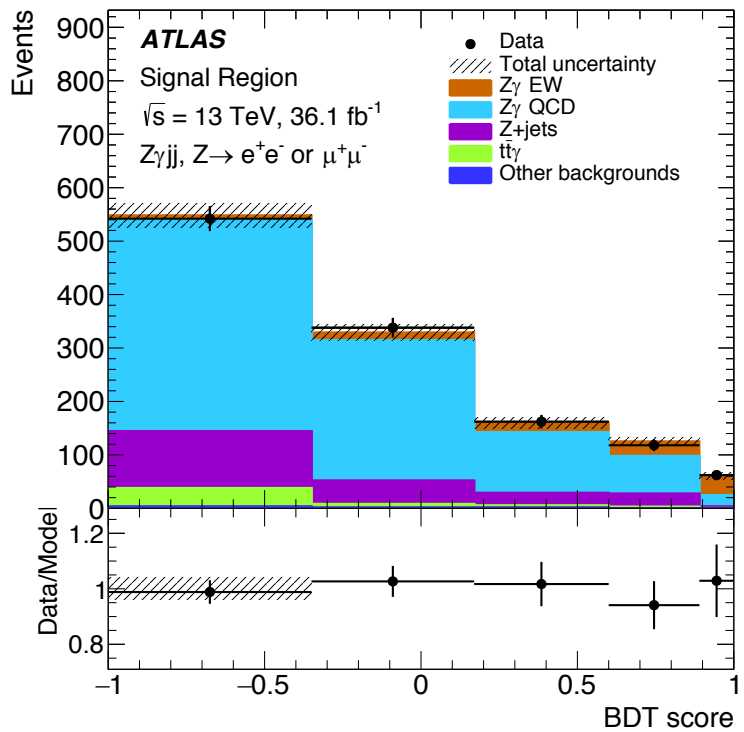
Phys. Lett. B 803 (2020) 135341

Electroweak $Z\gamma jj$ production

Search in **leptonic** $Z \rightarrow \ell\ell$ events, partial Run 2 dataset (36/fb)
sensitive to only $WWZ\gamma$ quartic coupling

Signal region defined by $|\Delta\eta_{jj}| > 1$ && $\zeta(\ell\ell\gamma) = \left|\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{(y_{j_1} - y_{j_2})}\right| < 5$,
and zero *b*-jets

Control region with >= 1 *b*-jet to constrain $t\bar{t}+\gamma$ background



BDT score distribution in SR and N(*b*-jet) distribution in CR used in maximum-likelihood fit to extract signal strength

Results:

Observed and expected significance:
4.1 σ

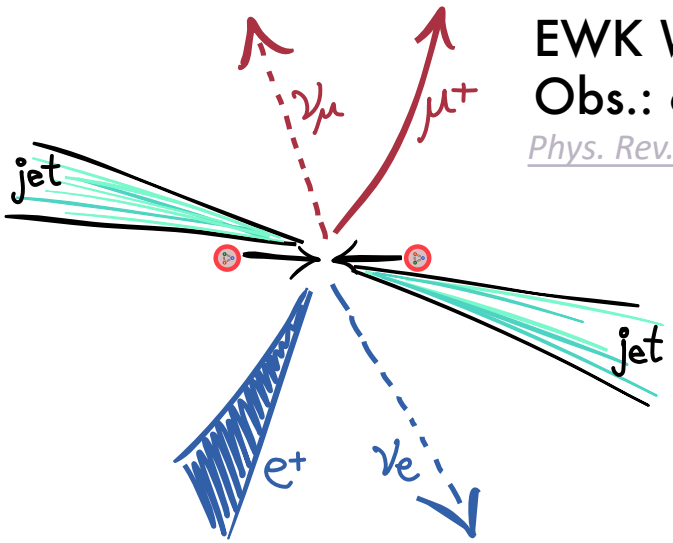
Fiducial cross-section:

$$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})\ \text{fb} = 7.8 \pm 2.0\ \text{fb.}$$

Phys. Lett. B 803 (2020) 135341

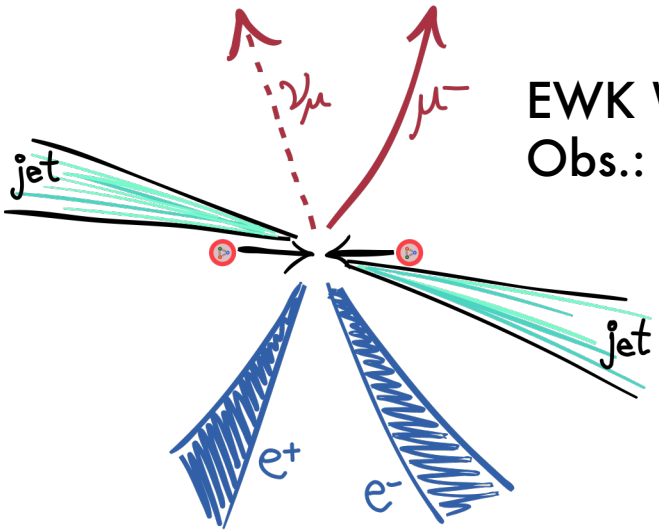
Additional results

Three additional electroweak diboson production results using 36/fb of Run 2 data: details in the backup



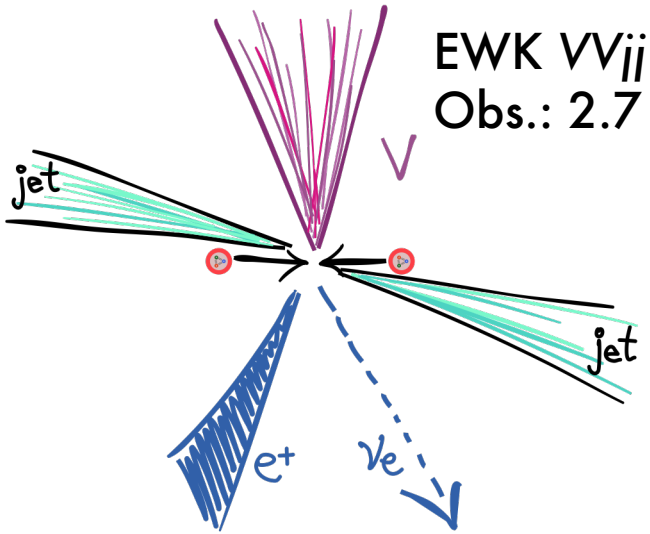
EWK $W^{\pm}W^{\pm}jj$
Obs.: 6.5 σ

Phys. Rev. Lett. 123 (2019) 161801



EWK $WZjj$
Obs.: 5.3 σ

Phys. Lett. B 793 (2019) 469

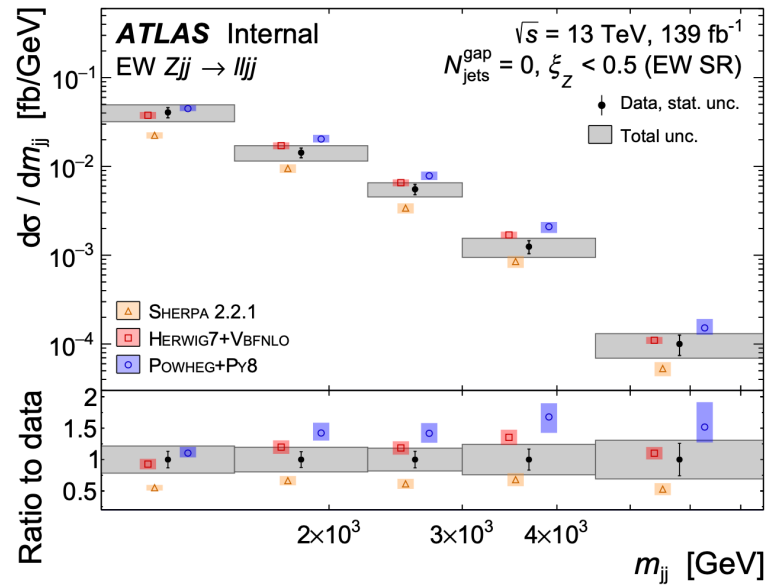


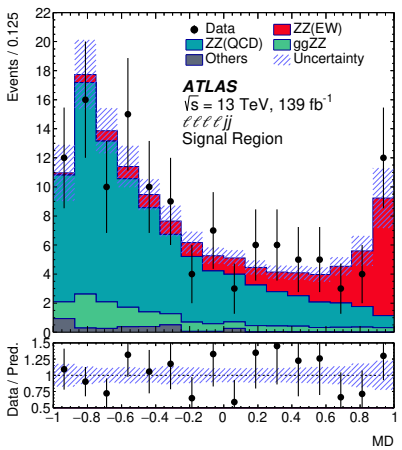
EWK $VVjj$
Obs.: 2.7 σ

Phys. Rev. D 100 (2019) 032007

Summary

New differential cross-section measurement of electroweak Zjj production, with strong limits on new physics through an effective field theory interpretation

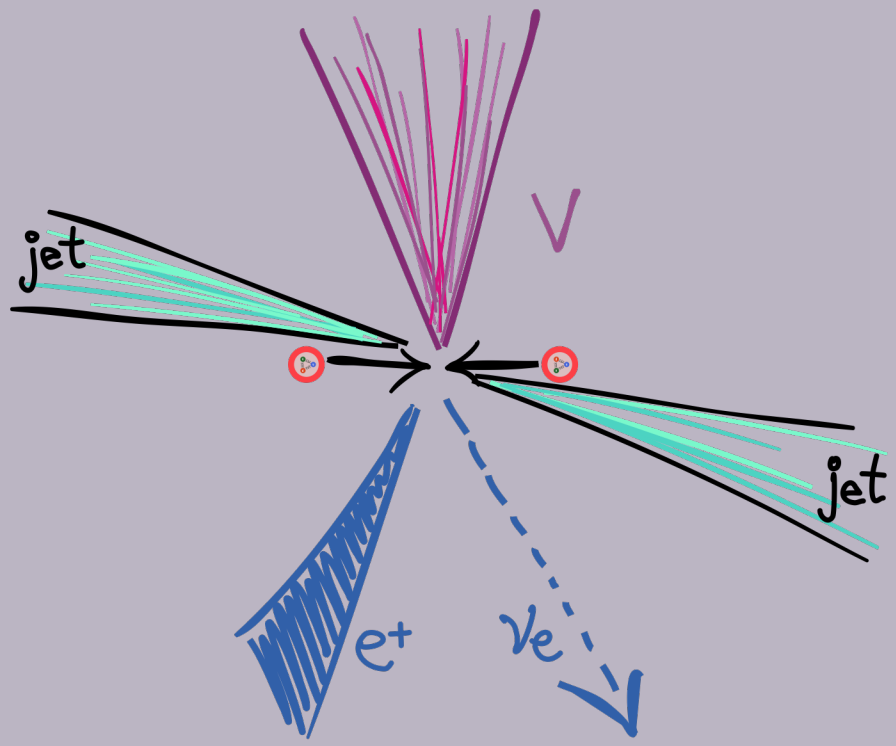




Observation of electroweak ZZjj production

➔ Other recent ATLAS VBS results using 36/fb of the13 TeV dataset: many results with the full Run 2 dataset are still to come!

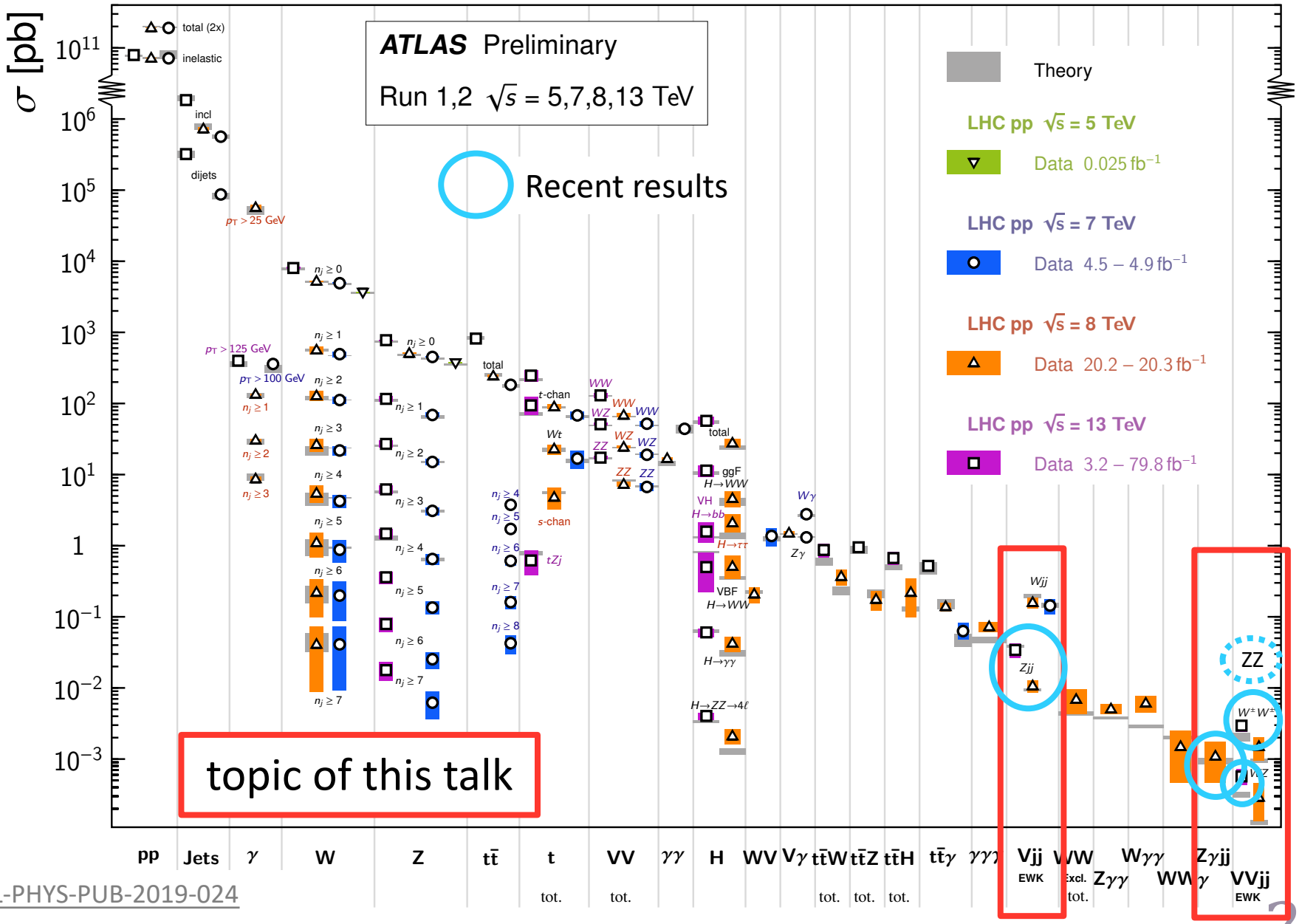
post-session zoom chat: Meeting ID: 963 3146 1387 Password: 373372



Backup

Standard Model Production Cross Section Measurements

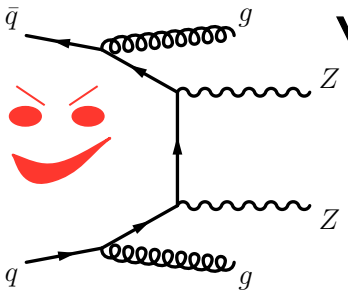
Status: November 2019



ATL-PHYS-PUB-2019-024

Electroweak $ZZjj$ production

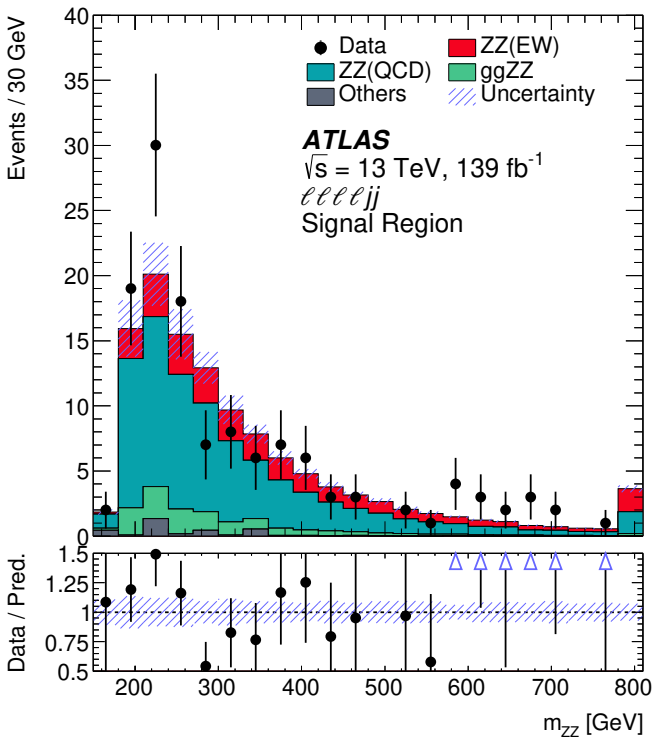
arXiv:2004.10612



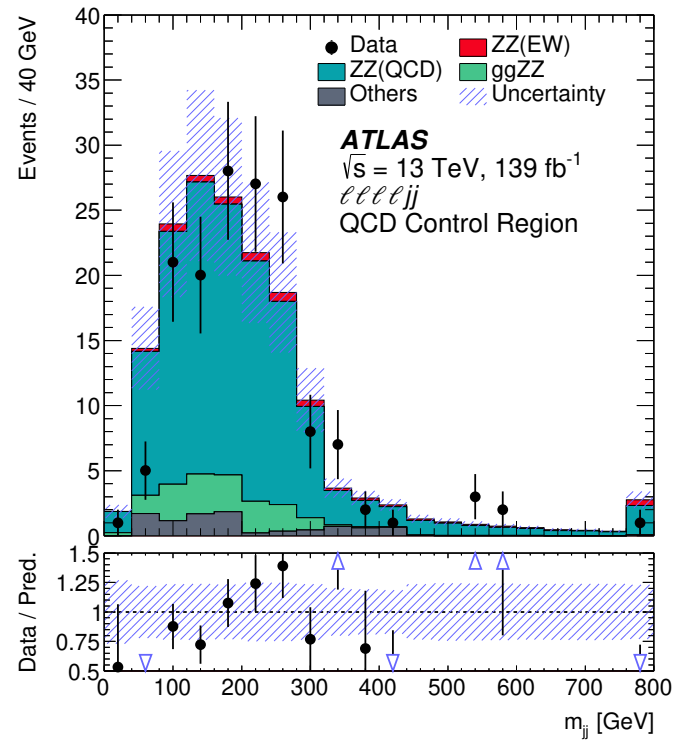
very large QCD background in the signal region

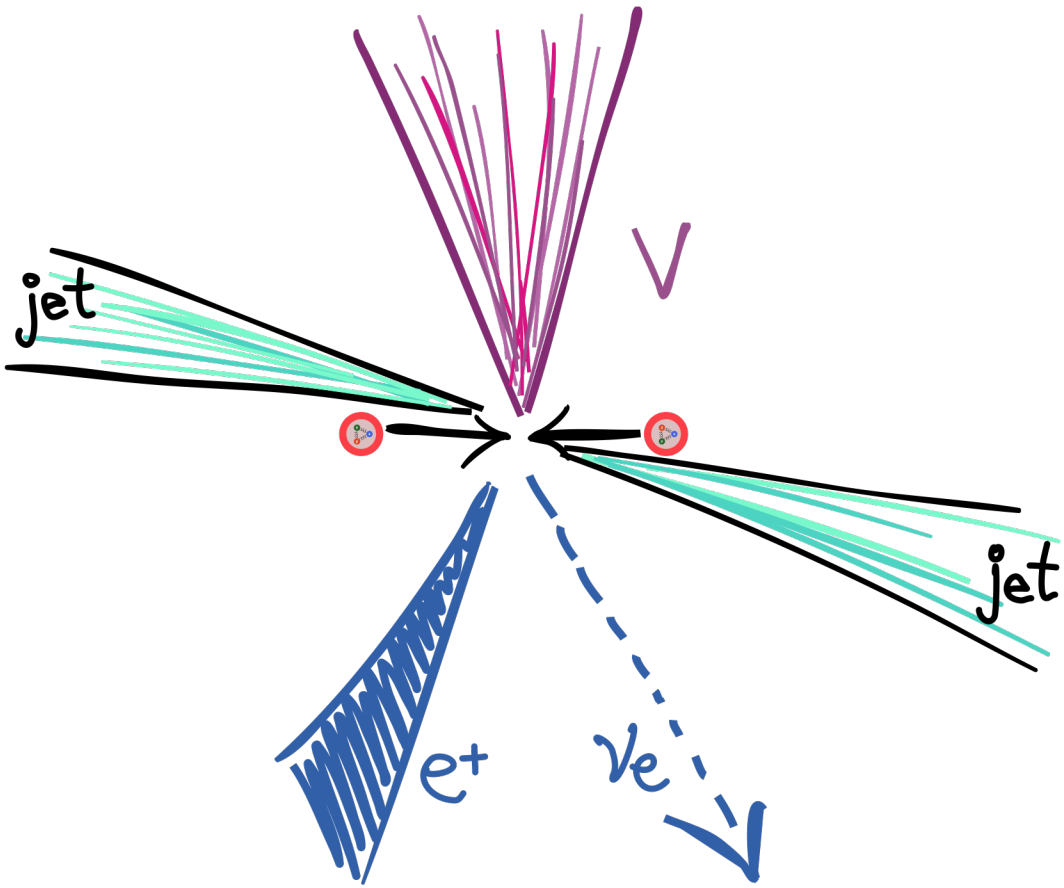
QCD **modelling (shape) uncertainties** are estimated by comparing Sherpa 2.2.2 and MadGraph5_aMC@NLO 2.6.1

EWK-QCD **interference** counted as an uncertainty on the EWK contribution (7% 4ℓ, 2% $\ell\ell\nu\nu$)



QCD background is **constrained** in a dedicated QCD control region, defined by inverting [m_{jj} **or** $\Delta y(jj)$] requirements





Electroweak *VVjj* production

One leptonic (e/μ/ν) W/Z

One hadronic (qq) W/Z, boosted or resolved

Two additional jets

- Different sides of the detector
- Large invariant mass

Phys. Rev. D 100 (2019) 032007

Electroweak *VVjj* production

Search for electroweak VV production in a **semileptonic** final state

Do not distinguish between $W \rightarrow qq'$ and $Z \rightarrow qq$; allow for both boosted (one large-radius jet) and resolved (two small-radius jets) topologies

<u>Analysis performed in three channels</u>, each with three signal regions:

SR: resolved $V \rightarrow jj$ (two jets), $64 < m_{jj} < 106$ GeV

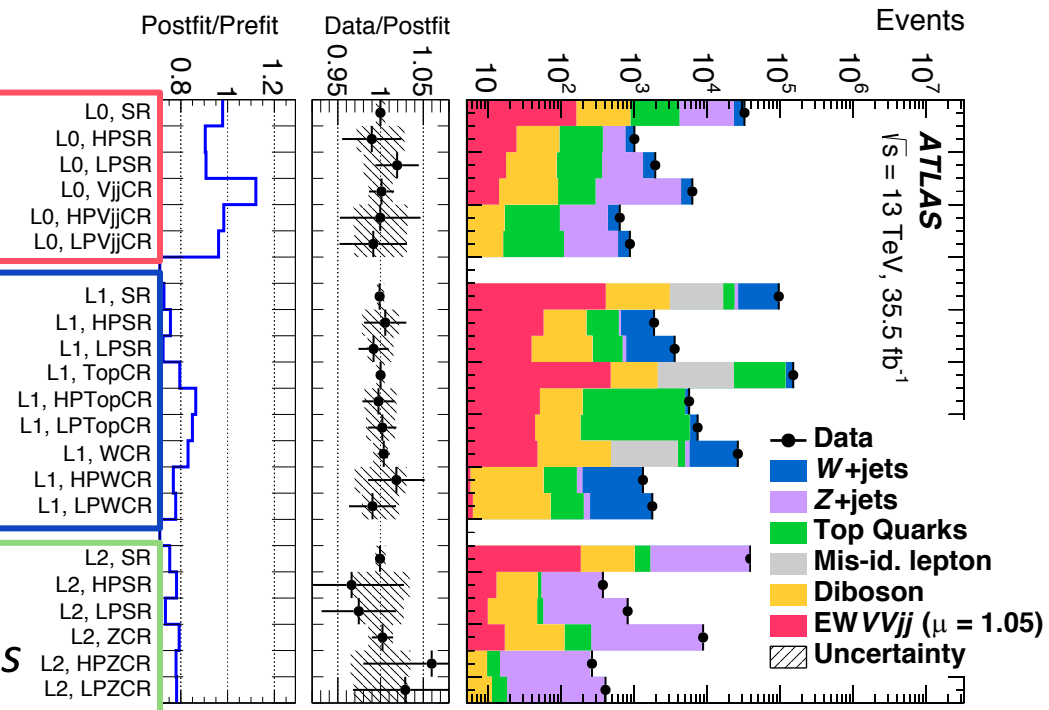
High-purity SR: boosted $V \rightarrow jj$ jet passes 50% signal efficiency working point

Low-purity SR: boosted $V \rightarrow jj$ jet fail 50% WP but passes 80% WP

0-lepton: *vvqq + jj*
missing energy > 200 GeV

1-lepton: *ℓvqq + jj*
exactly 1 lepton > 27 GeV
missing energy > 80 GeV

2-lepton: *ℓℓqq + jj*
2 leptons > 28, 20 GeV w/ Z mass



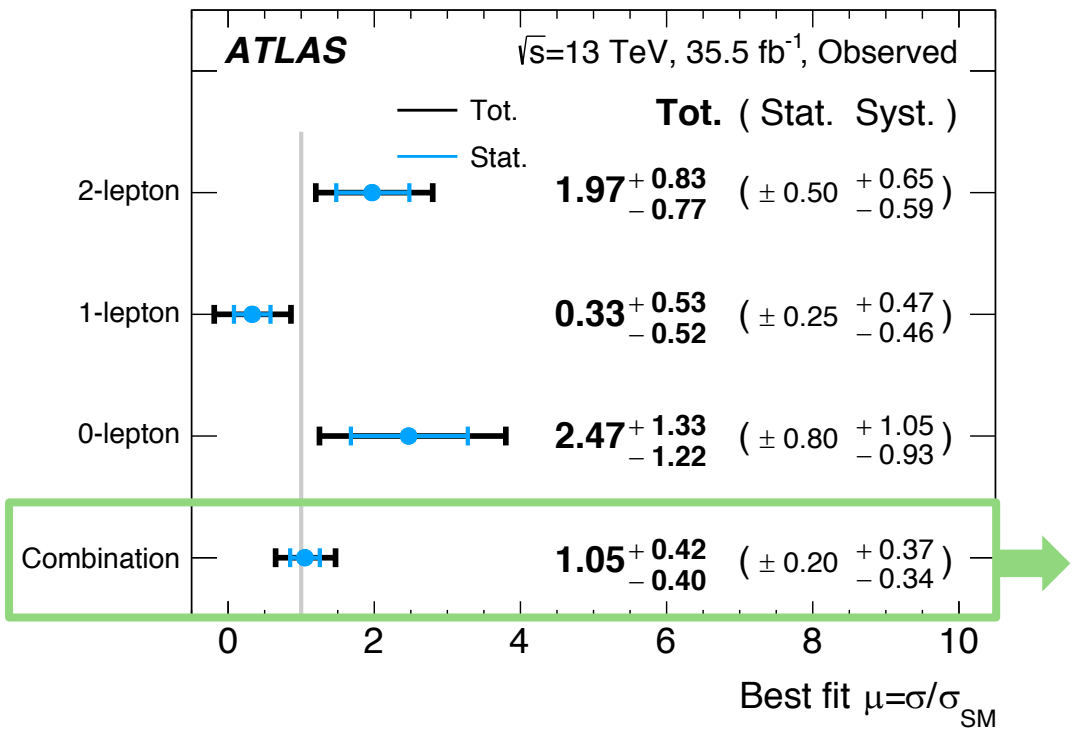
Phys. Rev. D 100 (2019) 032007

Electroweak *VVjj* production

6 separate BDTs are trained for 0/1/2 lepton and boosted and resolved regions

Binned profile likelihood fit in 21 channels shown on previous slide:

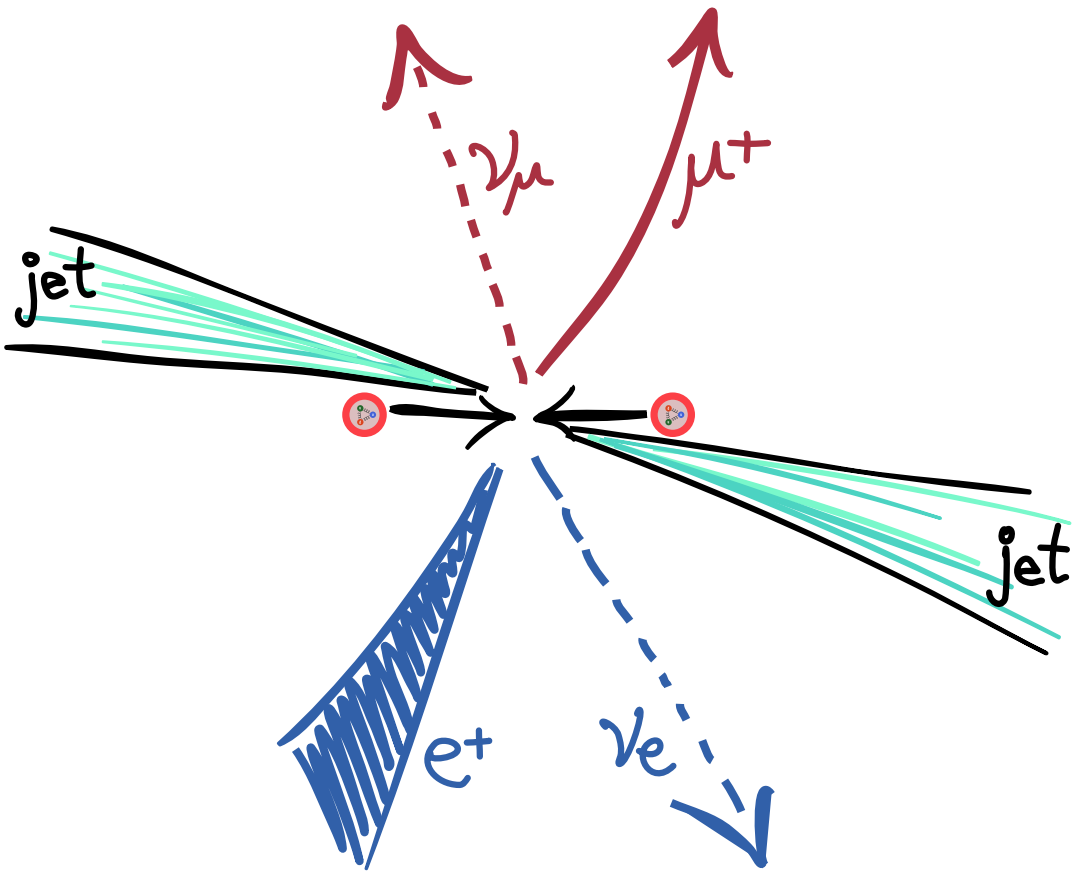
- BDT output in signal regions
- m_{jj}^{tag} in *Z*, *W*, and *Vjj* control regions
- event yield in top control regions



Observed significance:
2.7 σ
Expected significance:
2.5 σ

Fiducial cross-section (combination):

$$\sigma_{EWK\,VVjj}^{\text{fiducial,obs.}} = \mu_{EWK\,VVjj}^{\text{obs.}} \cdot \sigma_{EWK\,VVjj}^{\text{fid, SM}}$$
$$= 45.1 \pm 8.6\ (\text{stat.})\ +15.9\ -14.6\ (\text{syst.})\ \text{fb}$$



Electroweak $W^\pm W^\pm jj$ production

Two leptonic, same charge (e/μ) W bosons

Two additional jets

- Large rapidity separation
- Large invariant mass

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Electroweak $W^{\pm}W^{\pm}jj$ production

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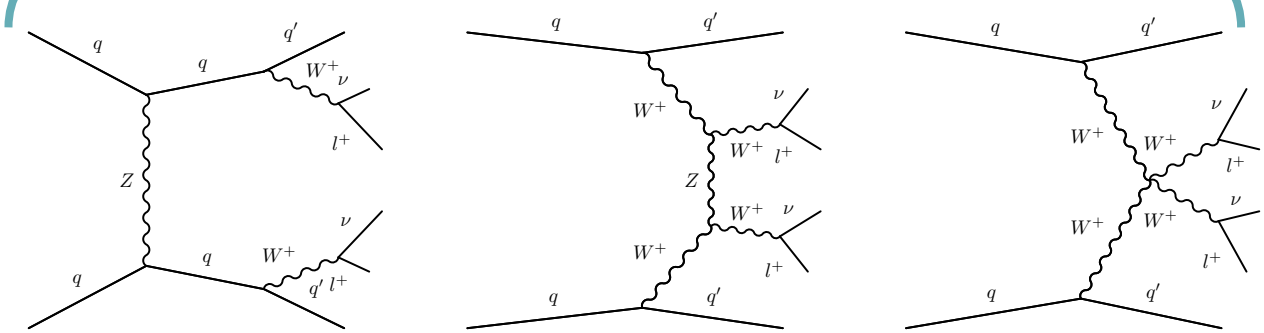
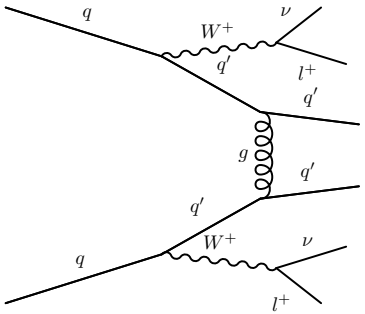
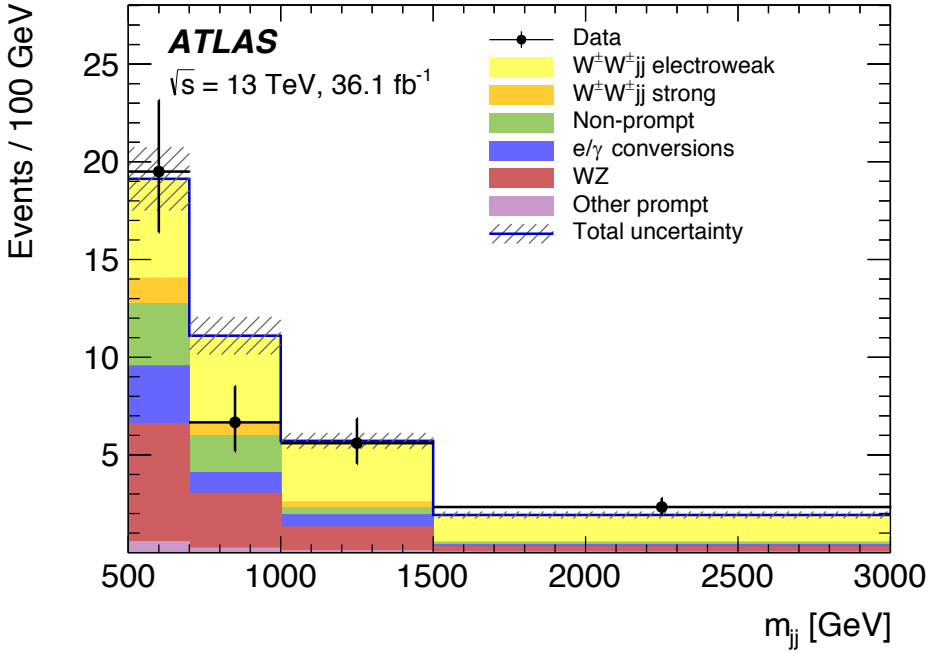
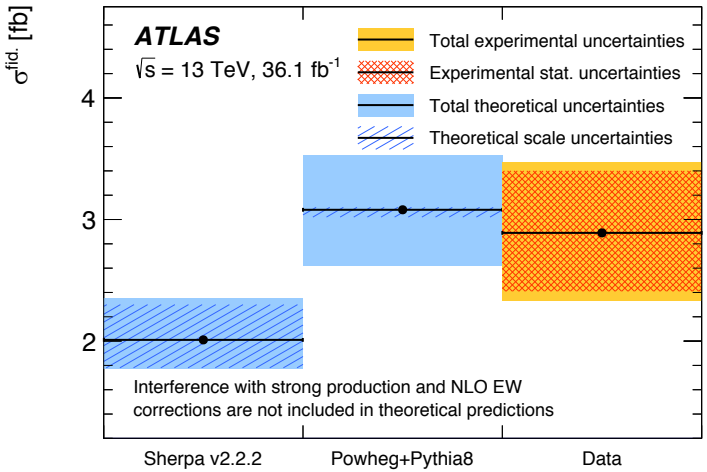
electroweak-induced processes



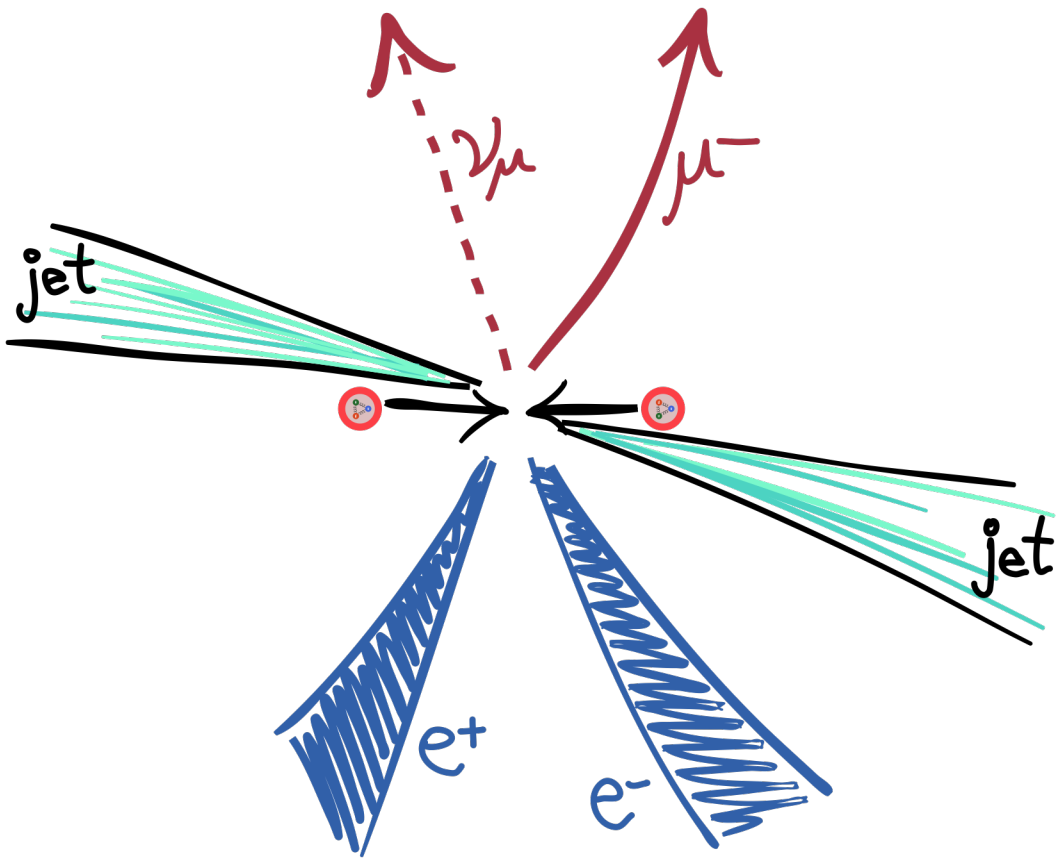
example QCD process







Process observed with the 2015-2016 36/fb dataset



Electroweak *WZjj* production

One leptonic (e/μ) W

One leptonic (e/μ) Z

Two additional jets

- Large invariant mass

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Electroweak WZ*jj* production

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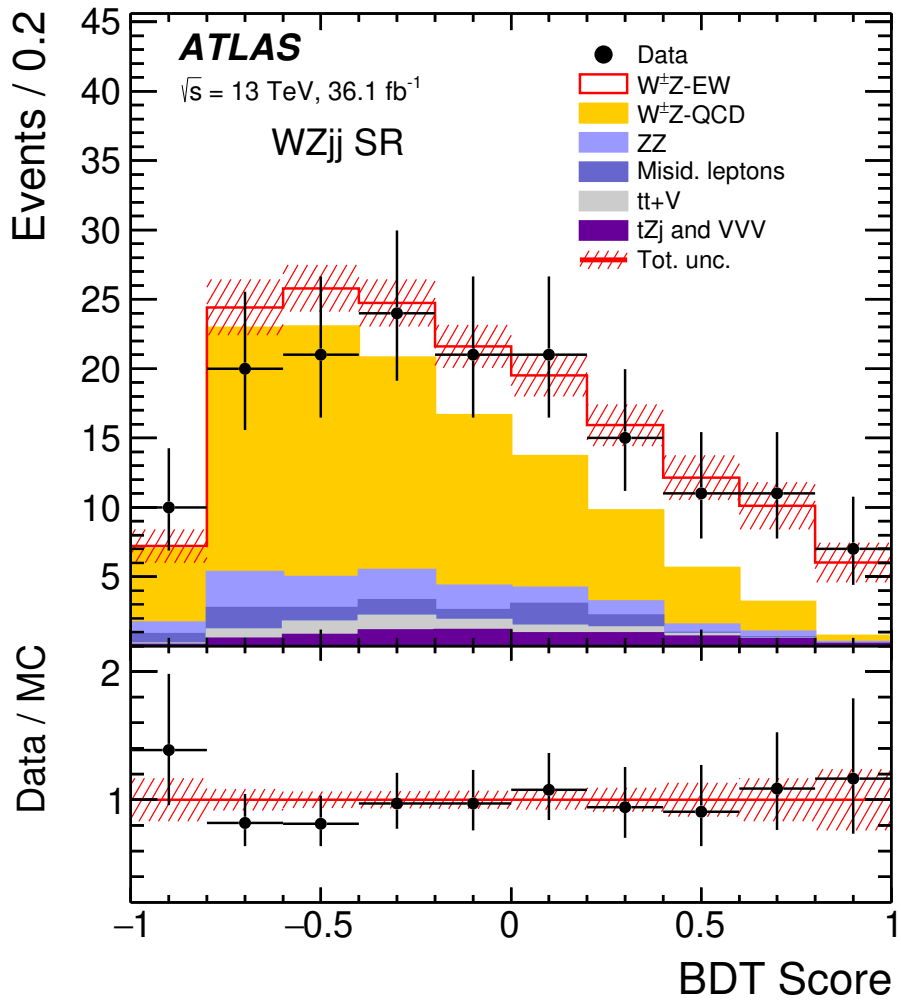

BDT used to discriminate between EW signal and QCD background:

Observed significance: 5.3σ (expected: 3.2σ)