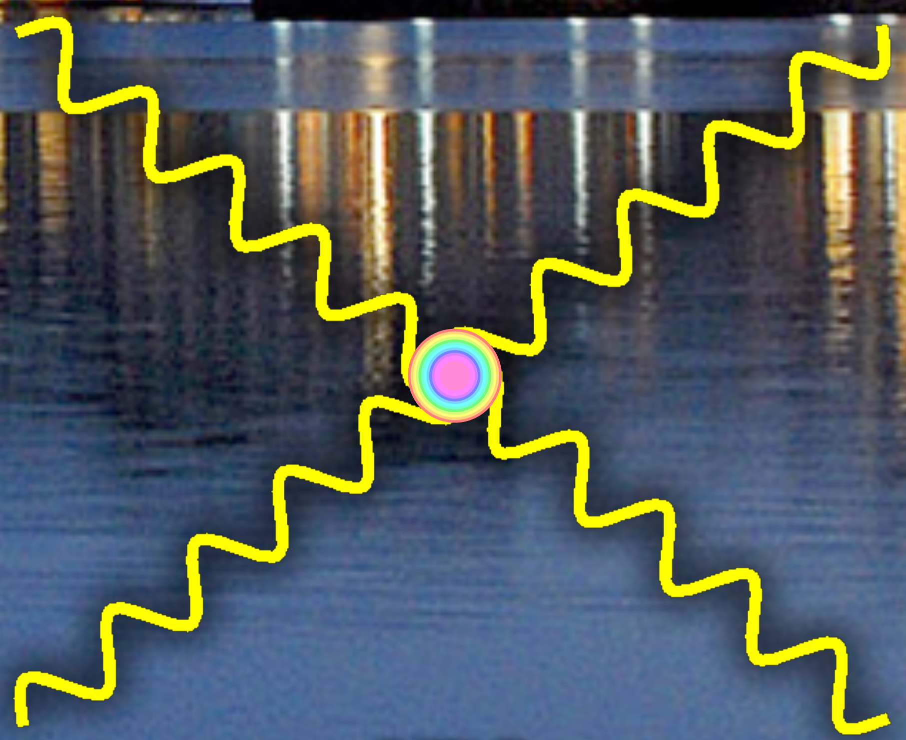
Recent observation and measurements of **vector-boson** fusion and scattering with ATLAS

VBF



VBS

July 26, 2021
Dag Gillberg, Carleton University
On behalf of the ATLAS Collaboration

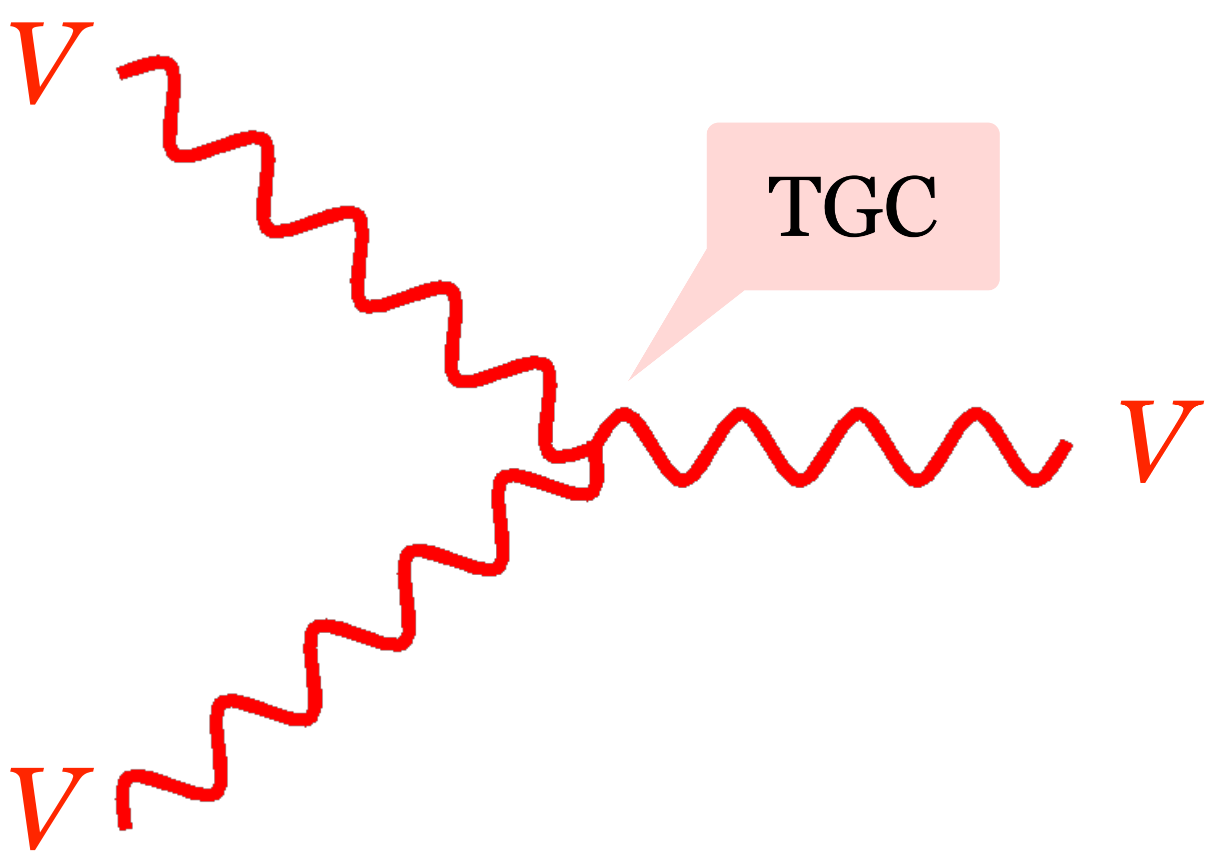
European Physics Society conference on high energy physics, 2021

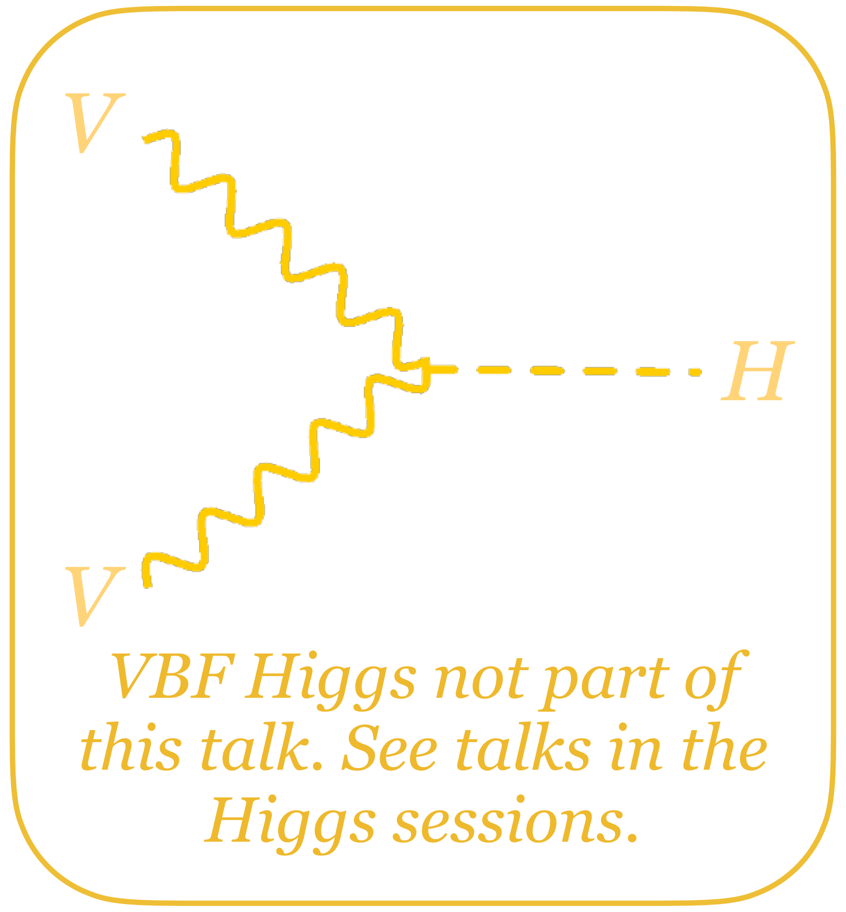
ATLAS EXPERIMENT

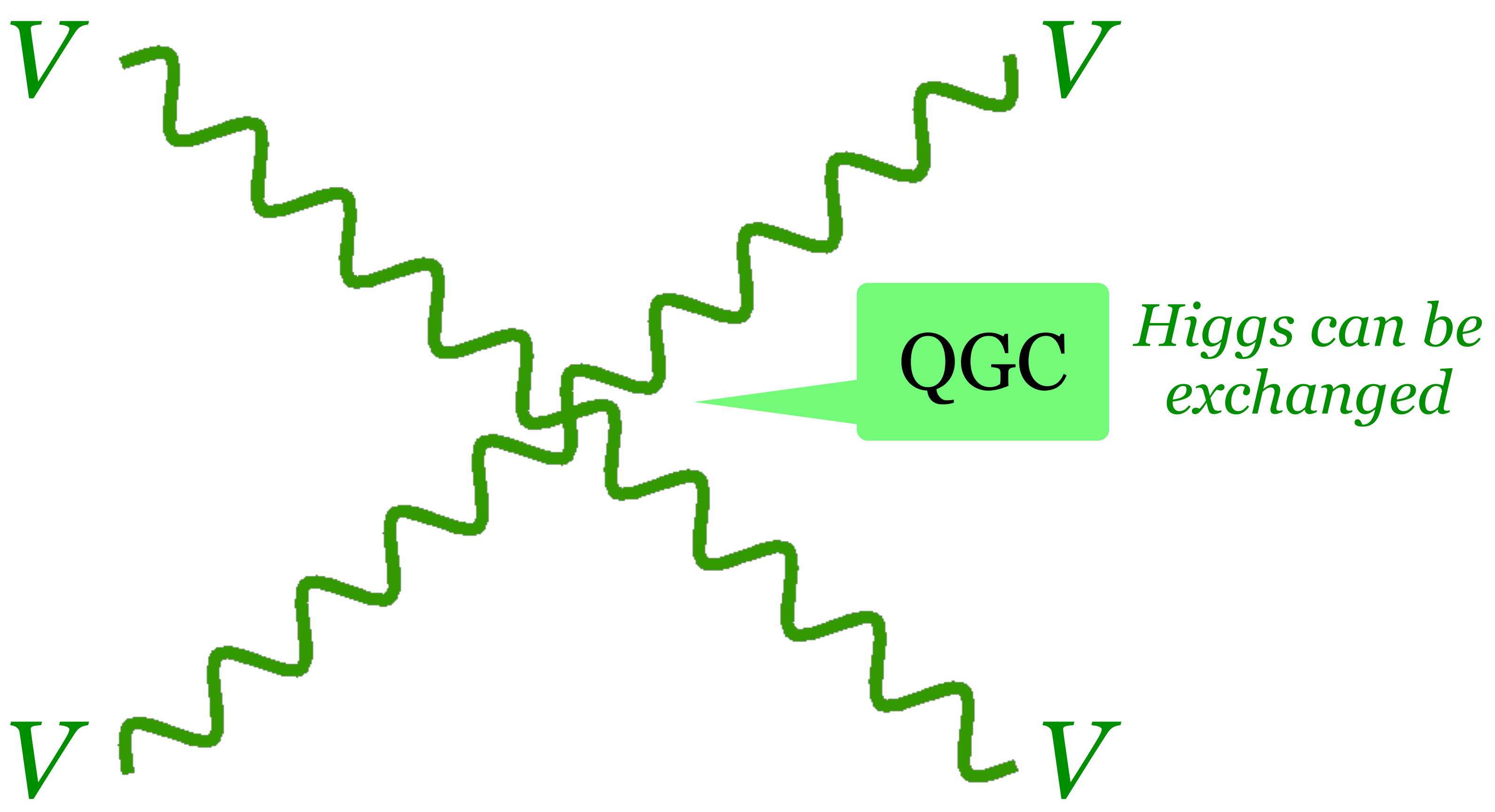
Carleton University

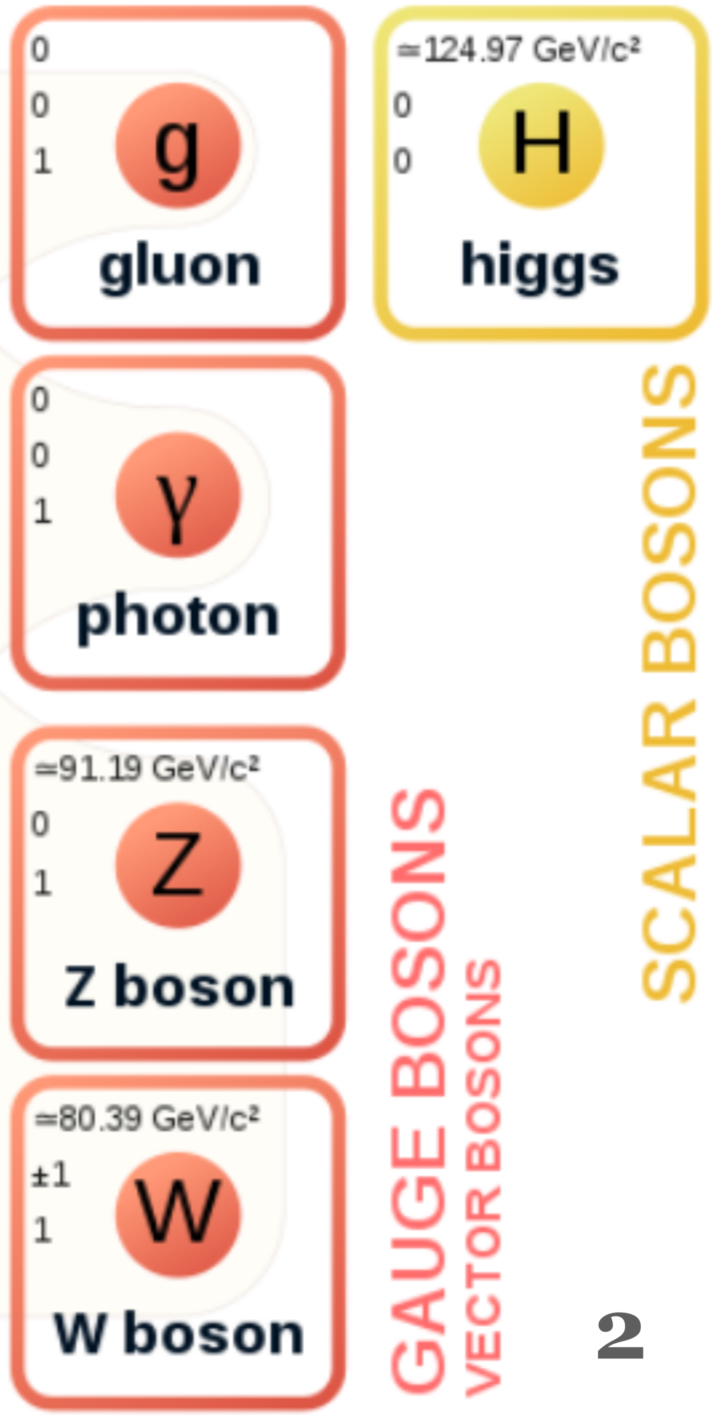
The VBF and VBS processes

- Vector boson fusion and scattering are characterized by a triple or quartic gauge vertex
  - Probes gauge bosons self-interaction and electroweak symmetry breaking
- Although very challenging and vast data required, now benchmark SM measurements
- Sensitive to many new physics scenarios; crucial input to for EFT studies
  - Tests anomalous triple and quartic gauge couplings (aTGC and aQGC)
  - EFT: Probe new physics at scales beyond direct reach of LHC





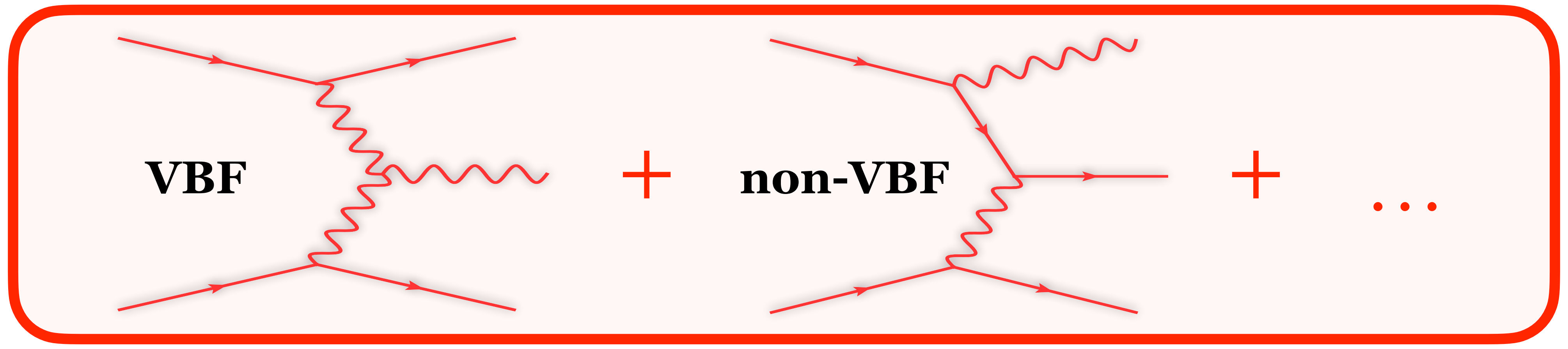




The VBF and VBS signatures

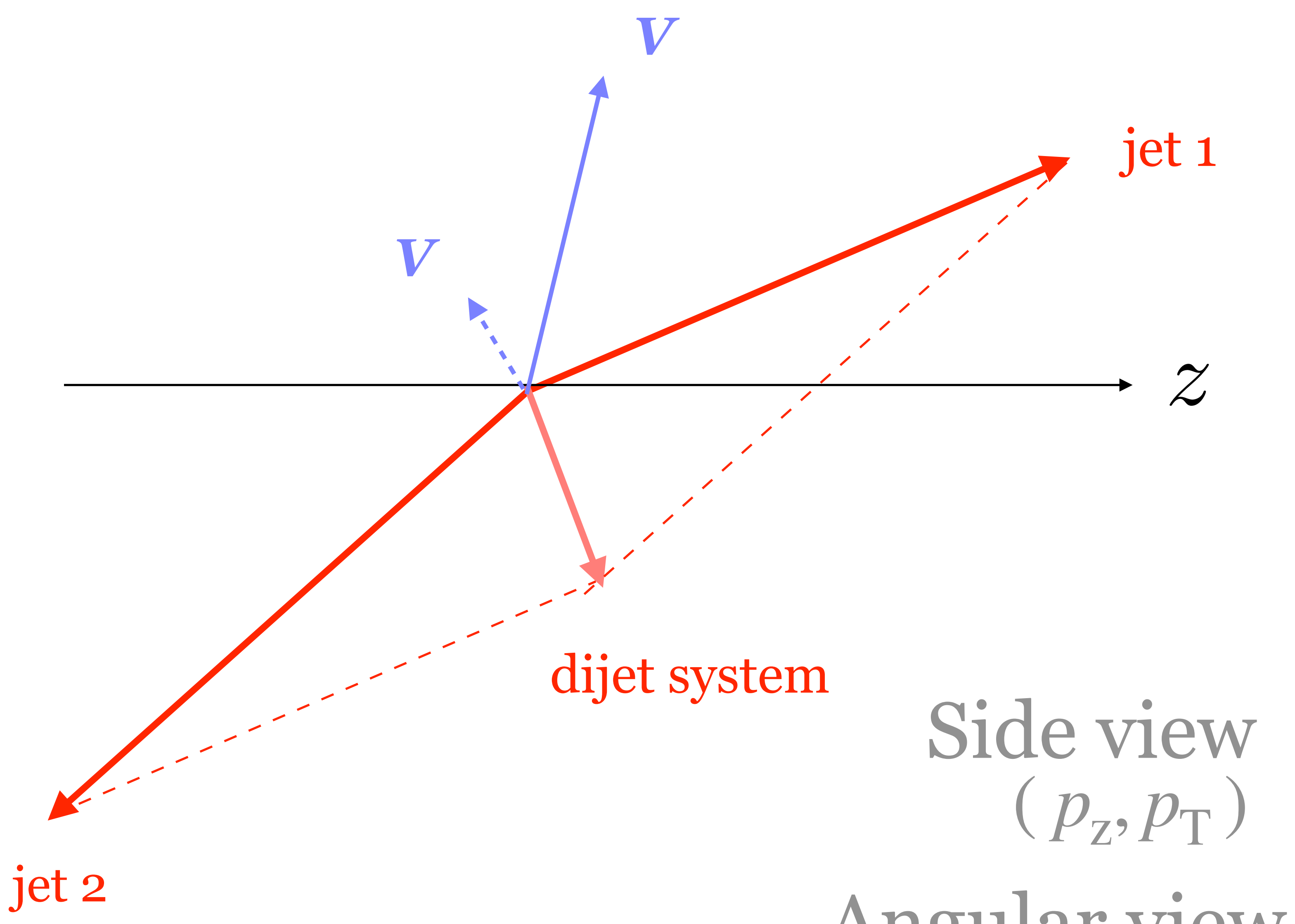
- VBF and VBS cannot be probed in isolation
- The standard approach is to study **EW *Vjj*** and **EW *VVjj*** production, to which the VBF and VBS diagrams contribute

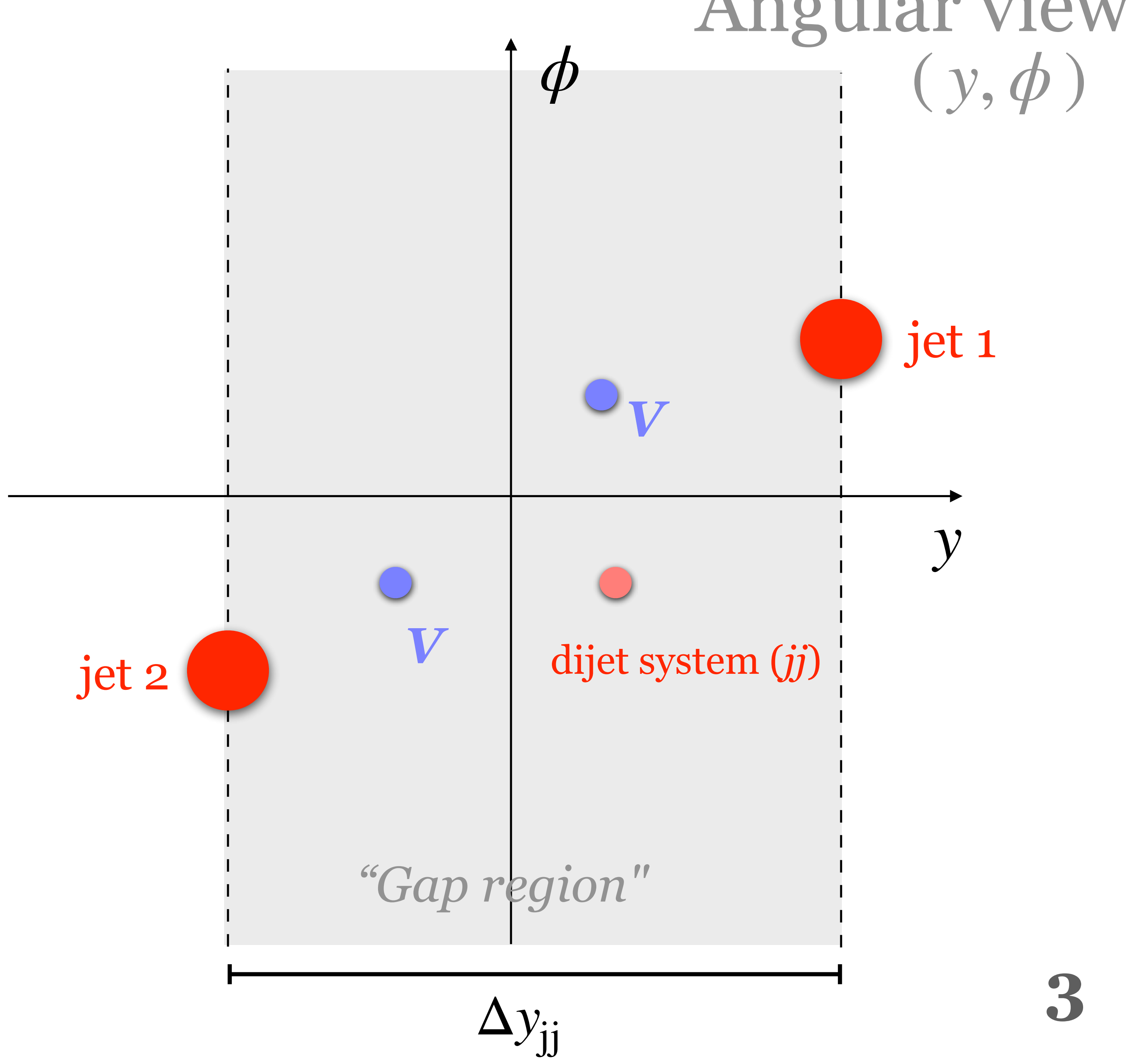
EW *Vjj*



- Rare processes but distinct topology:

1. Large rapidity gap between jets $\boldsymbol{\Delta y_{\mathrm{jj}}}$
2. Large dijet invariant mass $\boldsymbol{m_{\mathrm{jj}}}$
3. **Little hadronic activity** (few extra jets), especially in **rapidity gap** between two leading jets ($N_{\mathrm{jets}}^{\mathrm{gap}}$)
4. Low p_{T} (or lack) of third jet / low p_{T} of $(V)Vjj$ system
5. Boost (rapidity) of (di)boson and dijet system similar *
6. p_{T} of (di)boson and dijet system similar + back-to-back in ϕ





* Centrality: $\xi \approx (y_{V(V)} - y_{jj}) \,/\, \Delta y_{jj}$

The VBF and VBS signatures

- VBF and VBS cannot be probed in isolation
- The standard approach is to study **EW Vjj** an... pro... ...gra...

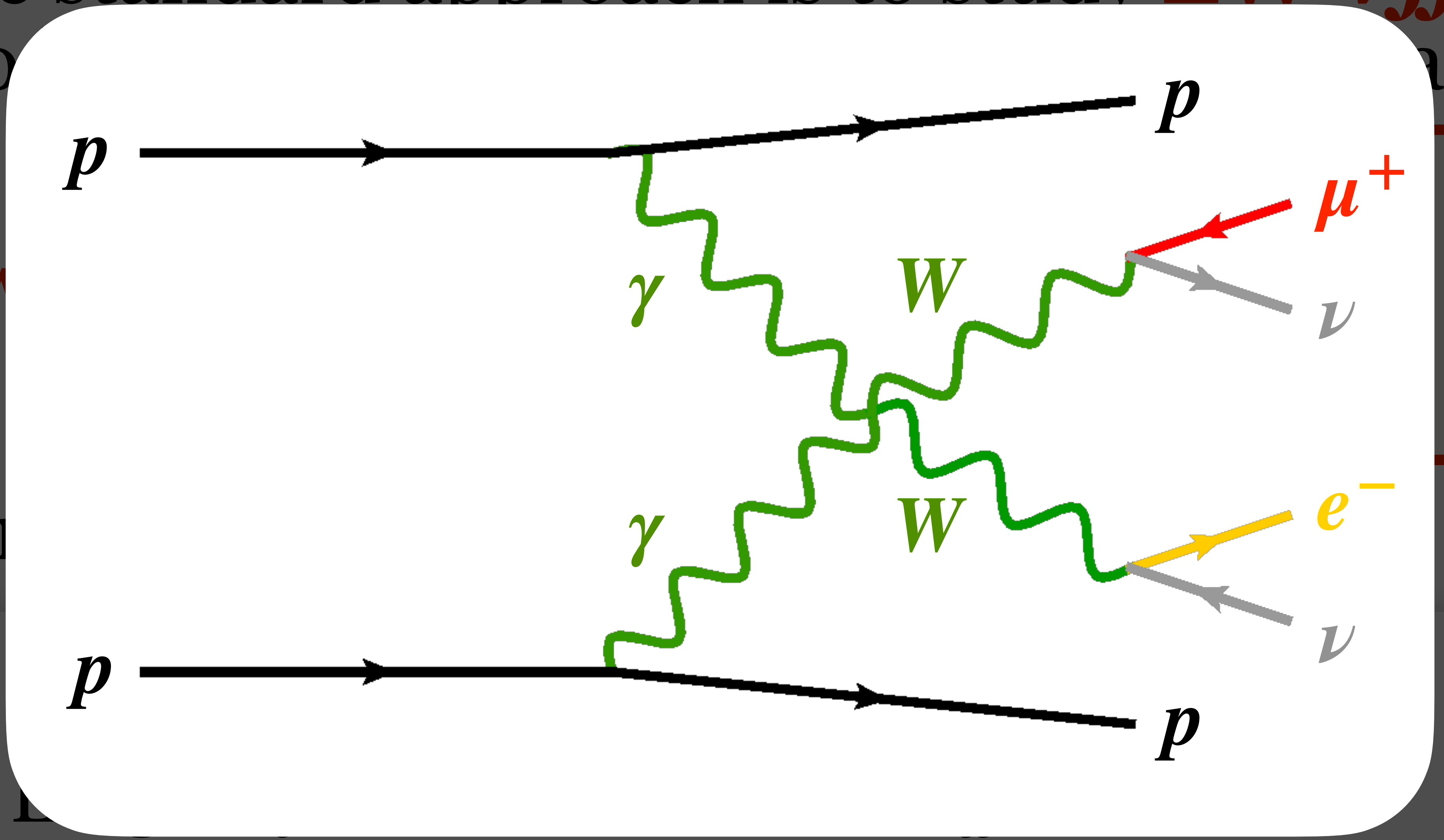
EW... +

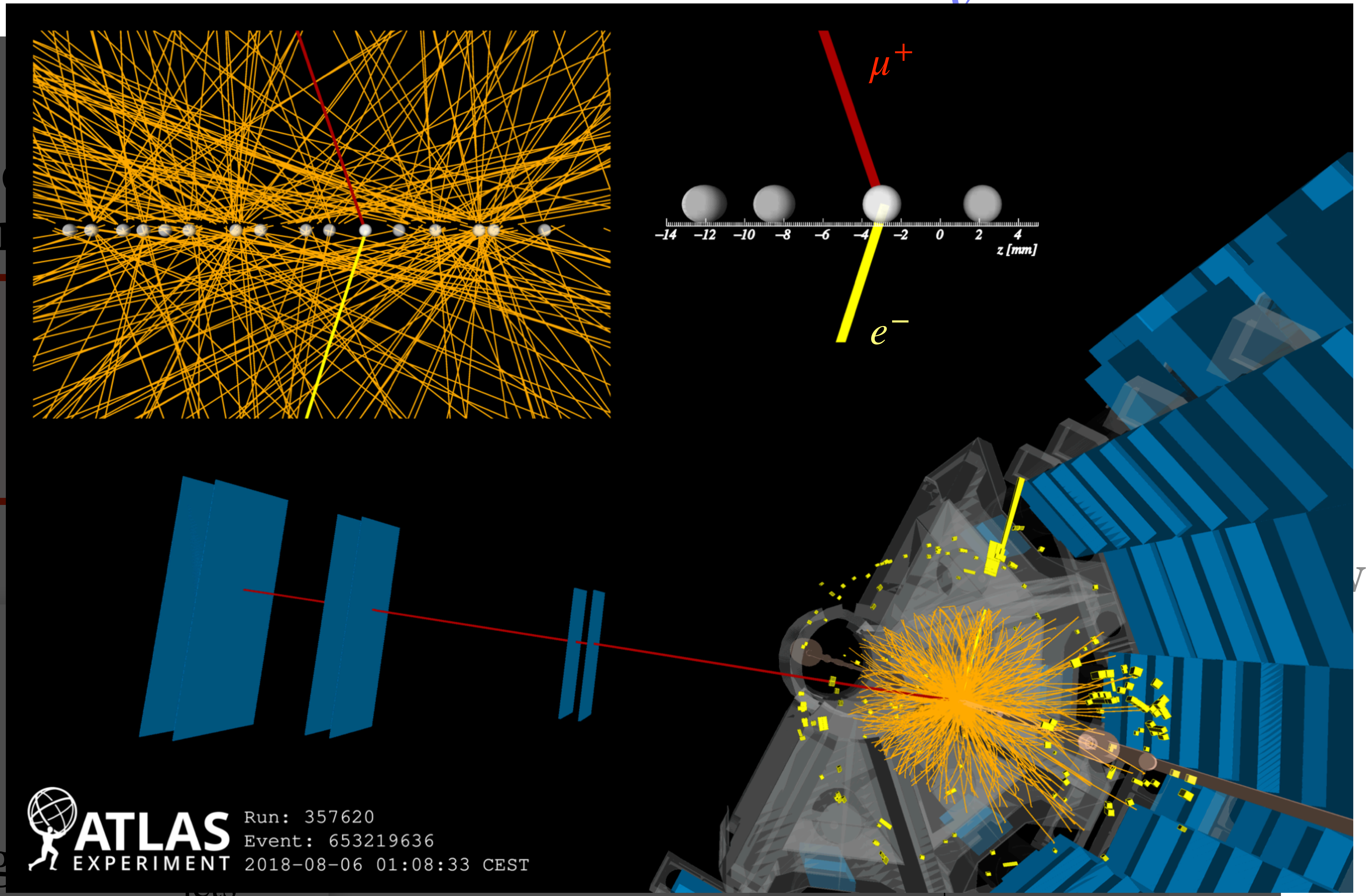
- Ra...

1\.

2\. ...

3\. **Little hadronic activity** (few extra jets), especially in **rapidity gap** between two leading jets





- New way to probe VBS at LHC (2021)
  - Photon induced *VV* production: $\gamma\gamma \to WW$
  - No forward jets; *Very clean, but very rare*

y

jet 2

V

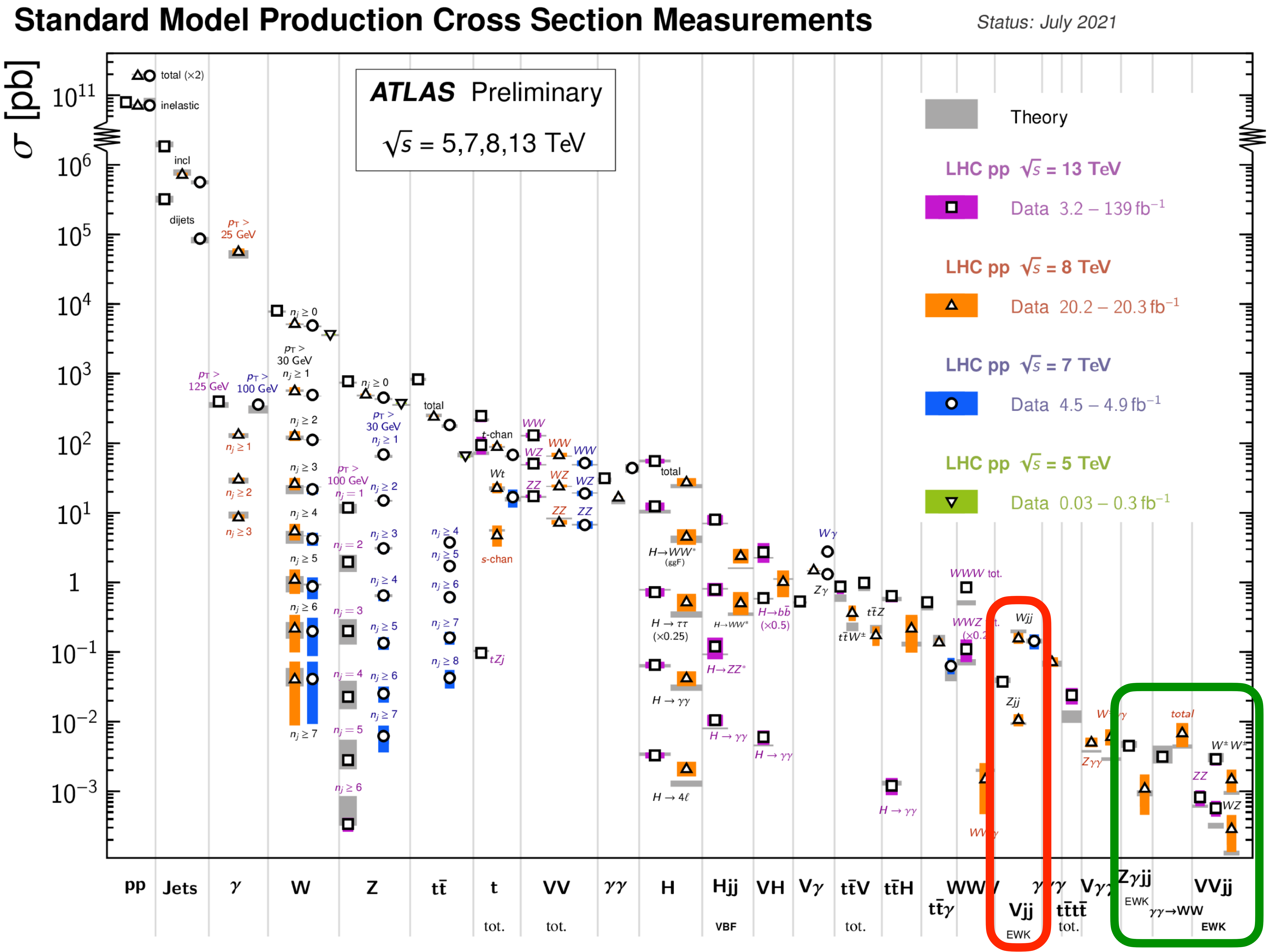
dijet system (jj)

$\ldots - y_{jj}) / \Delta y_{jj}$

Δy_{jj}

Details in Savannah Clawson's talk, Thursday

VBF and VBS measurements at ATLAS

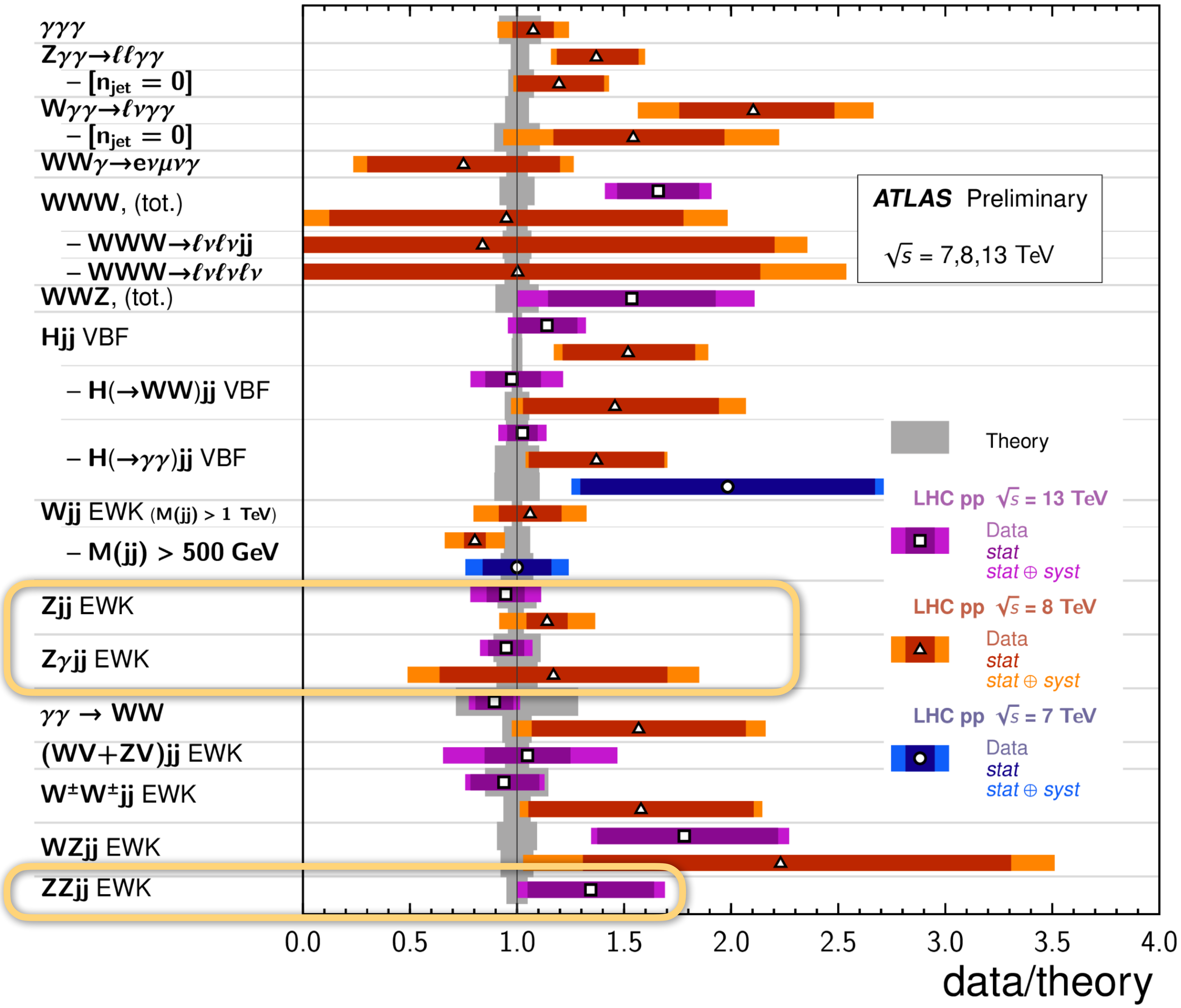


- Electroweak ***Vjj*** and ***VVjj*** and $\gamma\gamma \to WW$ production are all **very rare**
- Rate relative to inel. $pp \to X$

  $\sigma_{Zjj}/\sigma_{\text{inel}} \approx 10^{-12}$

  $\sigma_{ZZjj}/\sigma_{\text{inel}} \approx 10^{-14}$
- Challenging analysis: Small signal swamped by backgrounds; often poorly modelled
- 5σ observation for $WWjj$, $WZjj$, $ZZjj$ etc.

VBF and VBS measurements at ATLAS



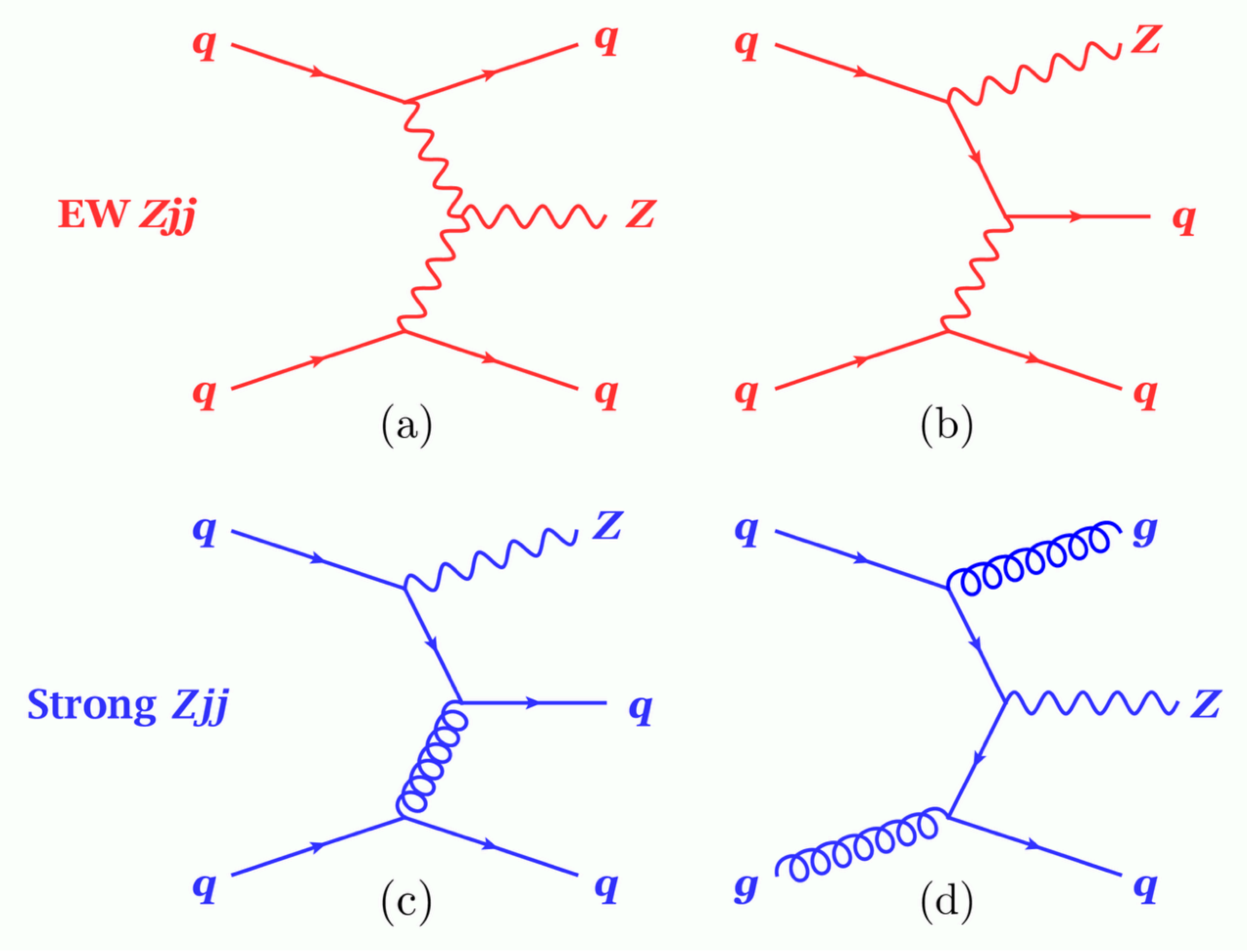
- Summary of ATLAS measurements targeting VBF and VBS
- The following slides presents a selected subset of four recent Run-2 results:
  - EW Zjj — EPJC 81 (2021) 163
  - EW $Z(\to\ell\ell)\gamma jj$ — ATLAS-CONF-2021-038
  - EW $Z(\to\nu\nu)\gamma jj$ — CERN-EP-2021-137
  - EW $ZZjj$ — arXiv:2004.10612

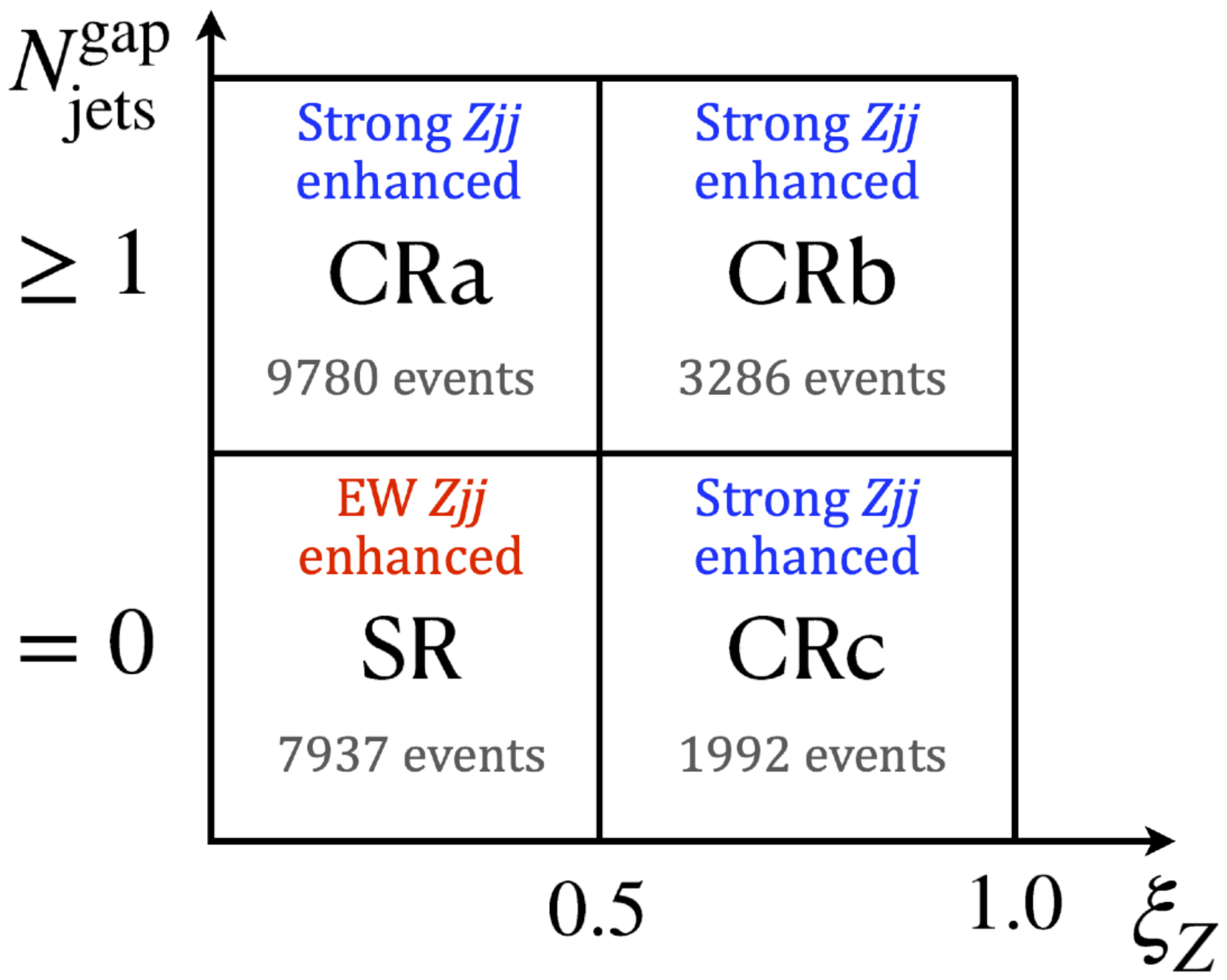
References to all these results can be found in the backup slides + slide on $\gamma\gamma \to WW$ observation, PLB 816 (2021) 136190

CERN-EP-2020-045, arXiv:2006.15458 , EPJC 81 (2021) 163

Measurement of EW *Zjj* (1/3)

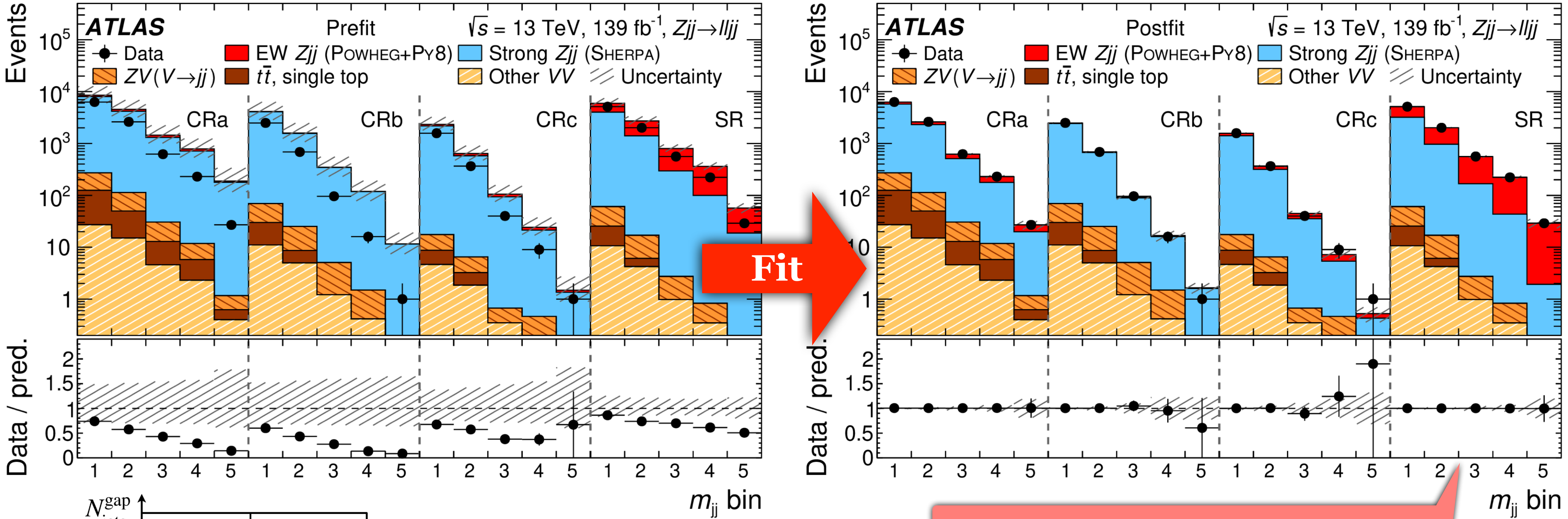
- EW *Zjj* was first observed by ATLAS using Run-1 data
  JHEP 04 (2014) 031
- With the full Run-2 dataset, differential cross sections are measured for four characteristic observables
  - Dijet mass m_{jj} and rapidity separation Δy_{jj}
  - Signed azimuthal dijet separation $\Delta\phi_{jj}$ and $p_{\mathrm{T},\ell\ell}$
- $Z \to ee$ and $Z \to \mu\mu$ data, $p_{\mathrm{T}}^{j1} > 85$ GeV, $m_{jj} > 1000$ GeV
- Main challenge: separate strong *Zjj* and EW *Zjj*
  - Strong *Zjj* poorly modelled in VBF topology region
- EW *Zjj* enhanced signal region using VBF topology cuts
  - Control regions used to constrain strong *Zjj* prediction
  - Likelihood fit measures EW *Zjj* bin-by-bin





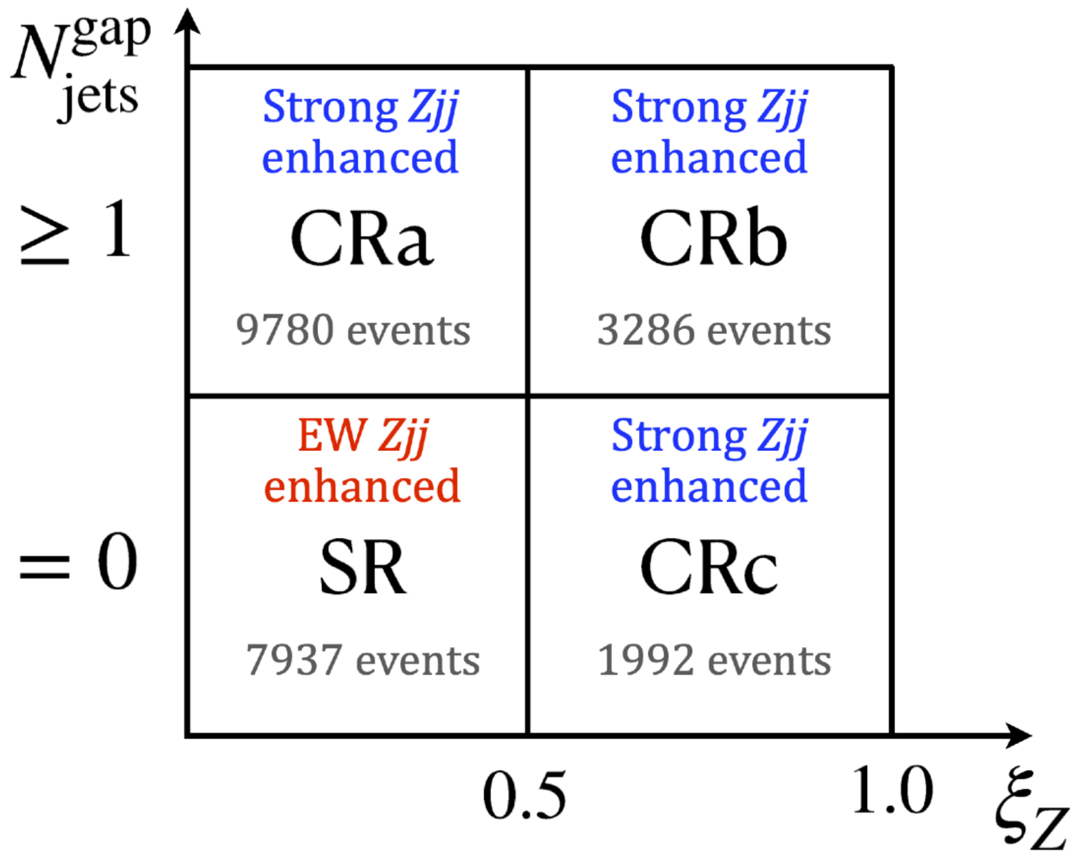
CERN-EP-2020-045, arXiv:2006.15458 , EPJC 81 (2021) 163

Measurement of EW *Zjj* (2/3)



EW *Zjj* measured in 5 m_{jj} bins

Analogously in 9 Δy_{jj}, 10 $p_{\mathrm{T},\ell\ell}$ and 12 $\Delta\phi_{jj}$ bins



Here: 20 bins, 5 POIs (EW *Zjj* bin yields)
12 free parameter that constrain strong *Zjj*

$$\ln \mathcal{L} = -\sum_{r,i} \nu_{ri}(\boldsymbol{\theta}) + \sum_{r,i} N^{\text{data}}_{ri} \ln \nu_{ri}(\boldsymbol{\theta}) - \sum_{s} \frac{\theta_s^2}{2},$$

Main uncertainties:

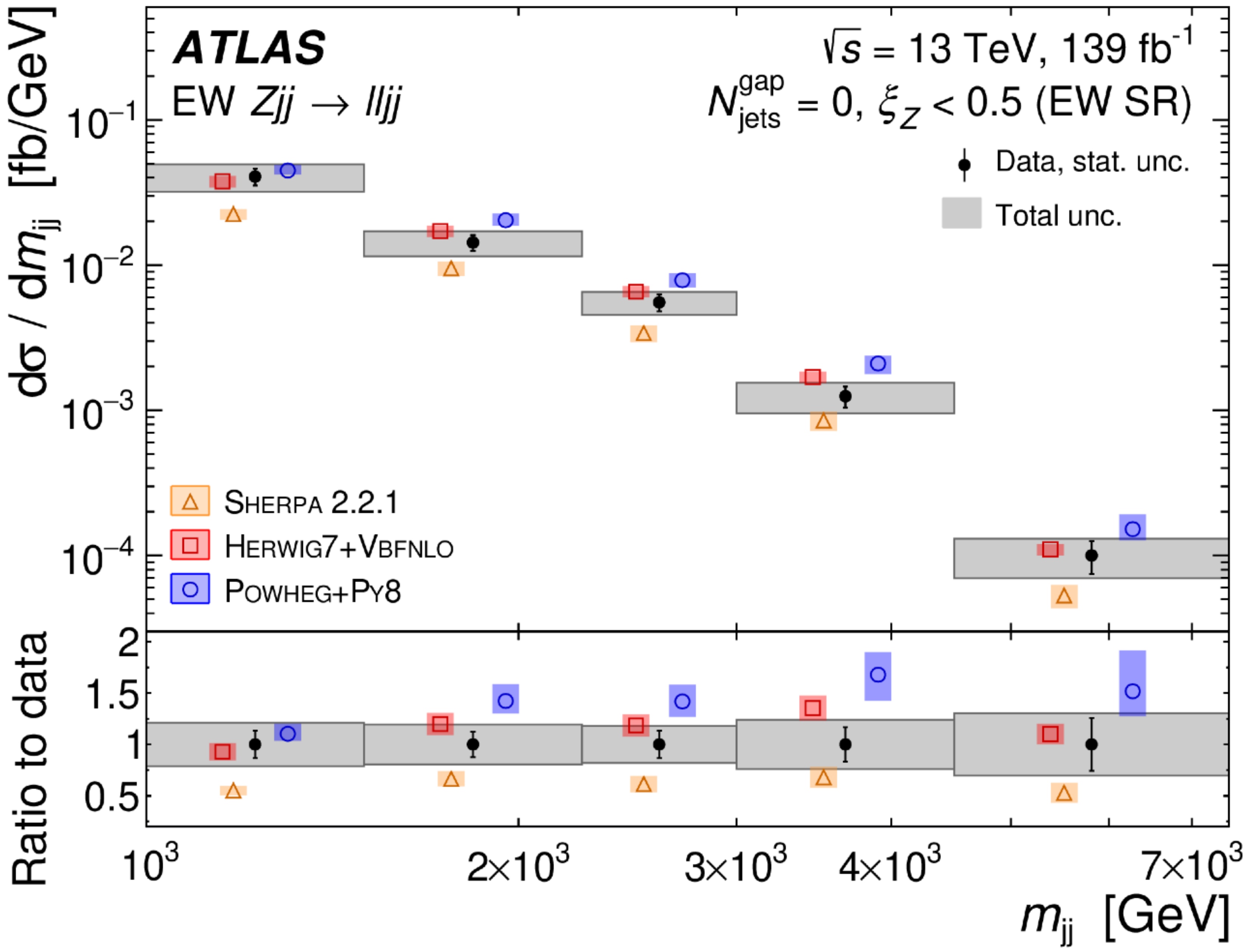
- Data statistics
- Strong generator choice (switching between 3)
- Jet systematics (JES, JER)

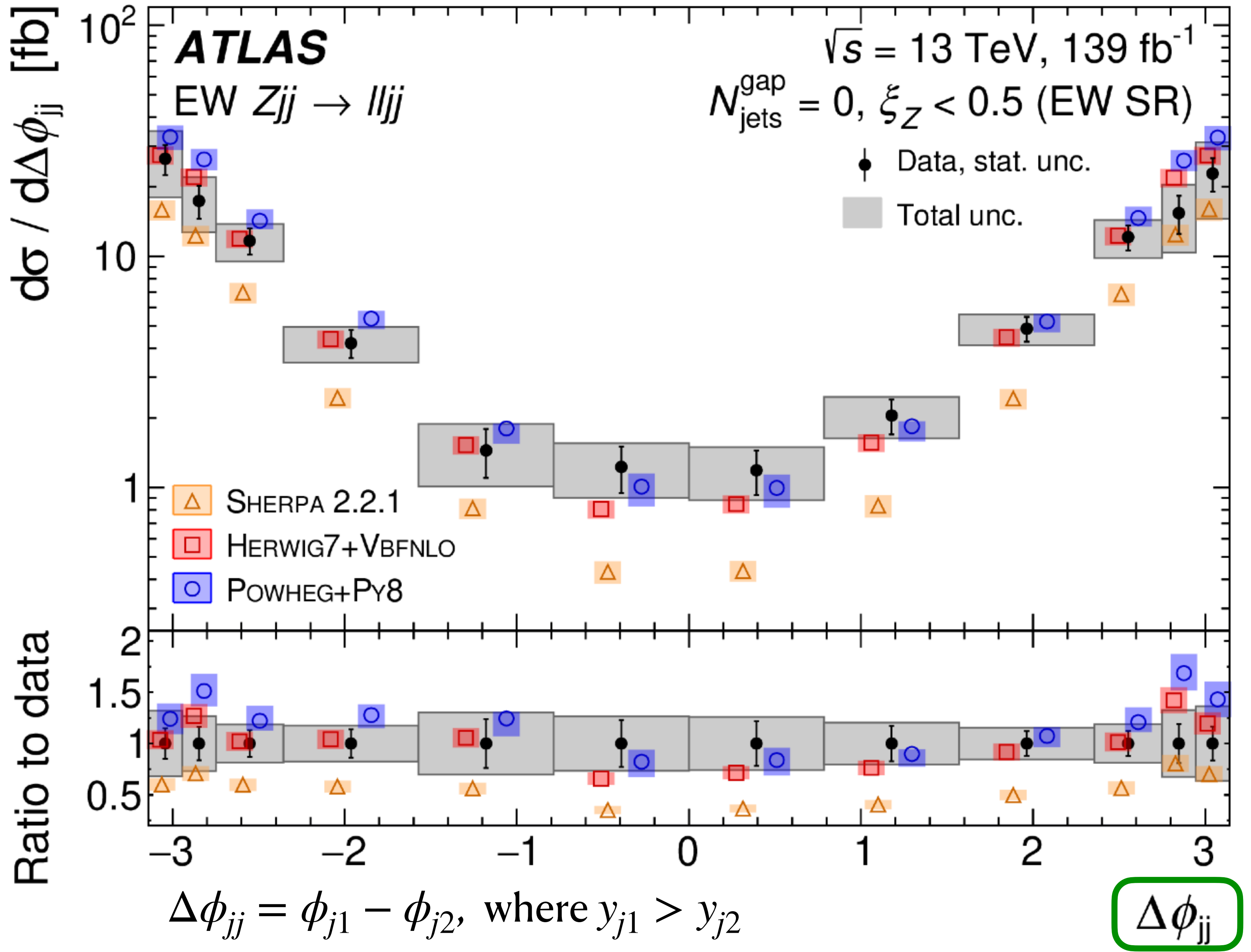
CERN-EP-2020-045, arXiv:2006.15458 , EPJC 81 (2021) 163

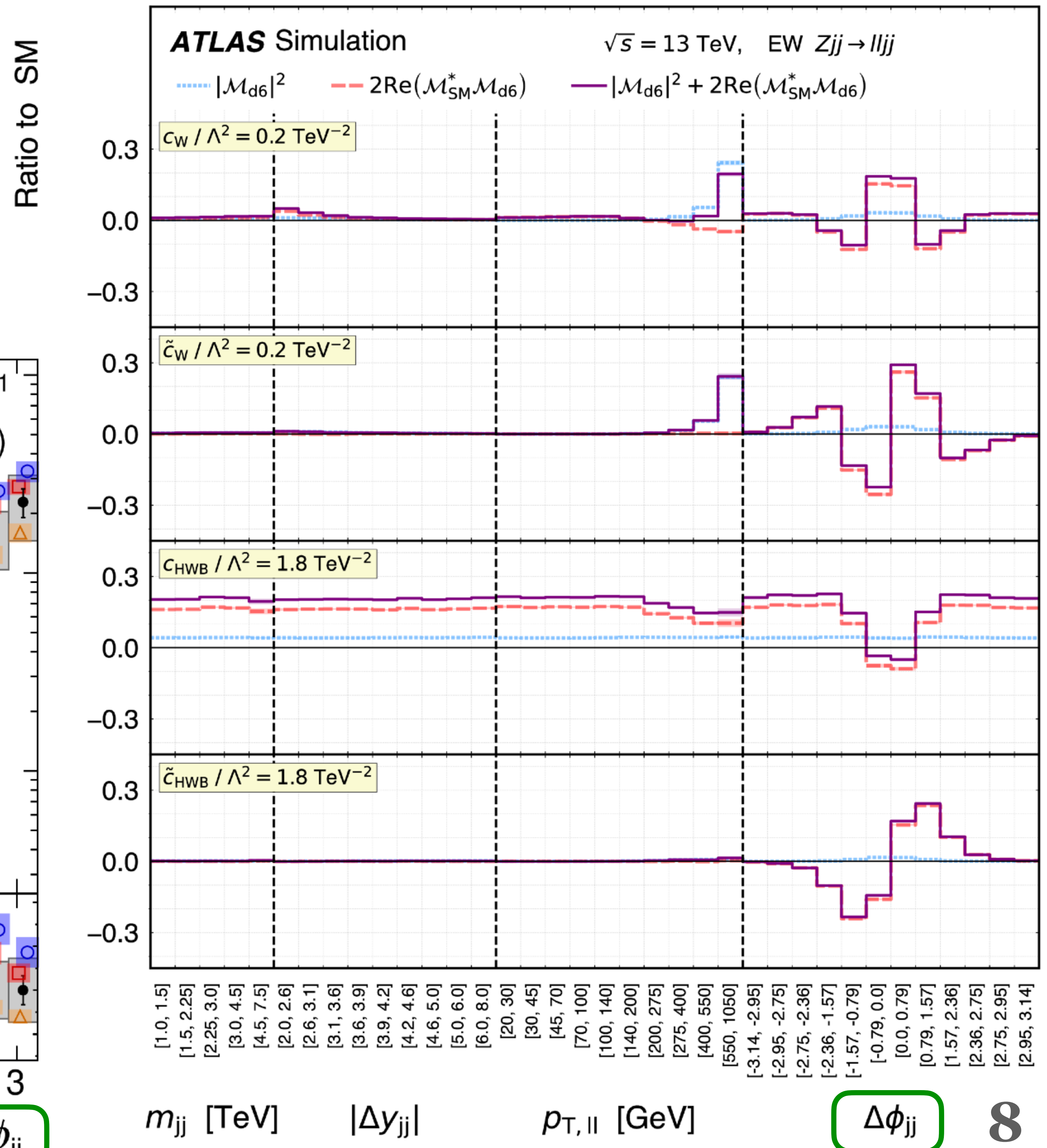
Measurement of EW *Zjj* (3/3)

- Measured event yields are corrected to particle level (Iterative Bayesian unfolding)
- Measurements compared to various MC prediction
  ➡ Guidance on generator choice; refinement of parameter settings
- Differential cross sections are used to set limits on BSM models using an EFT framework
  - $\Delta\phi_{jj}$ is CP-odd and very sensitive to certain Wilson coefficients (c_W)

Impact from BSM modifications on the measured EW Zjj differential cross sections

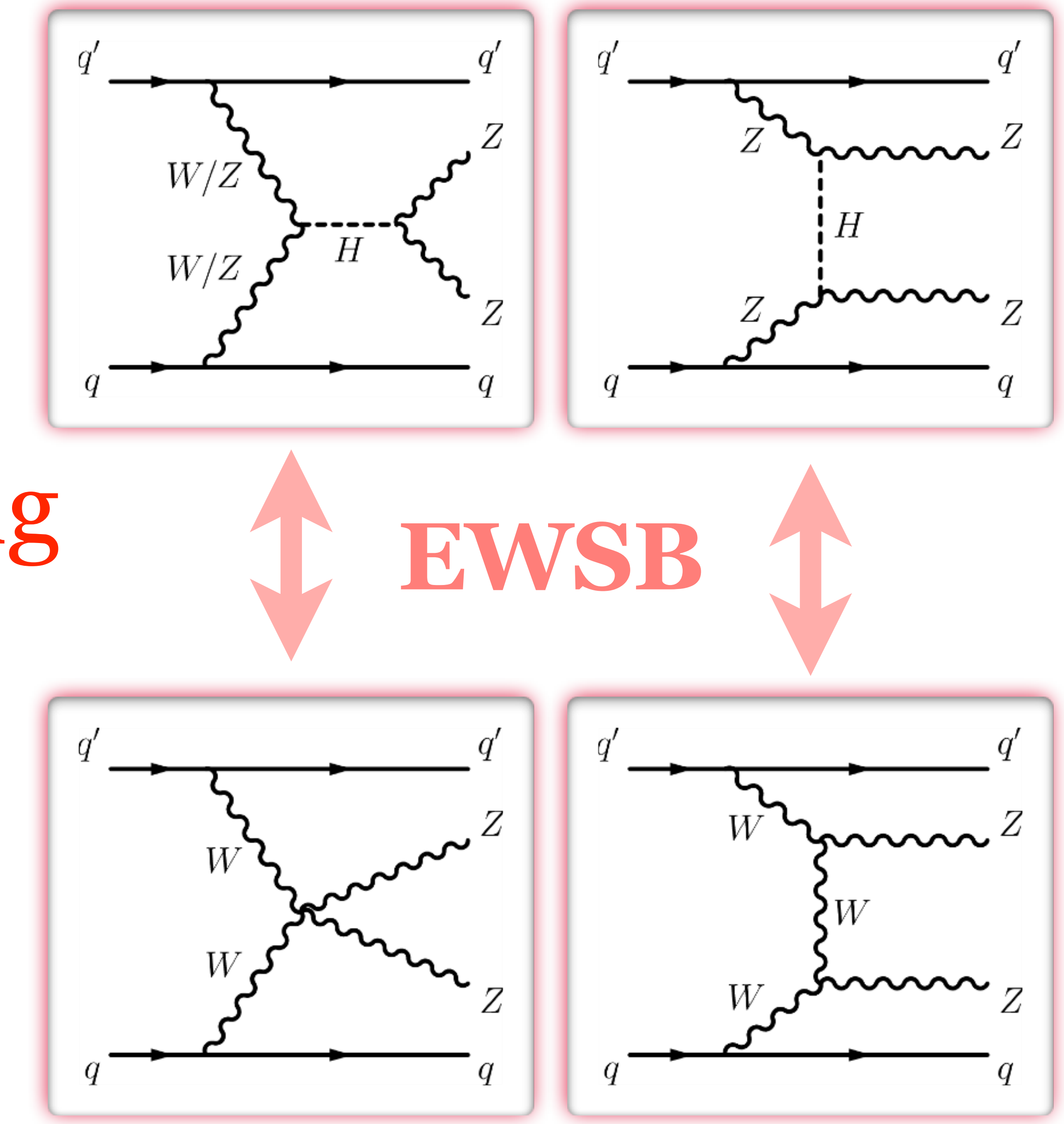




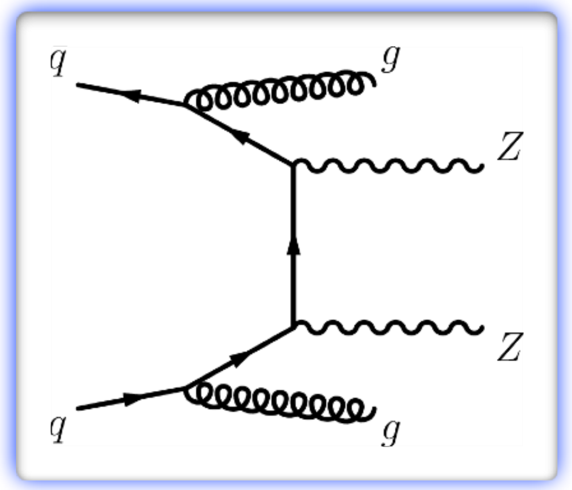


STDM-2017-19, arXiv:2004.10612
Submitted to Nature Physics

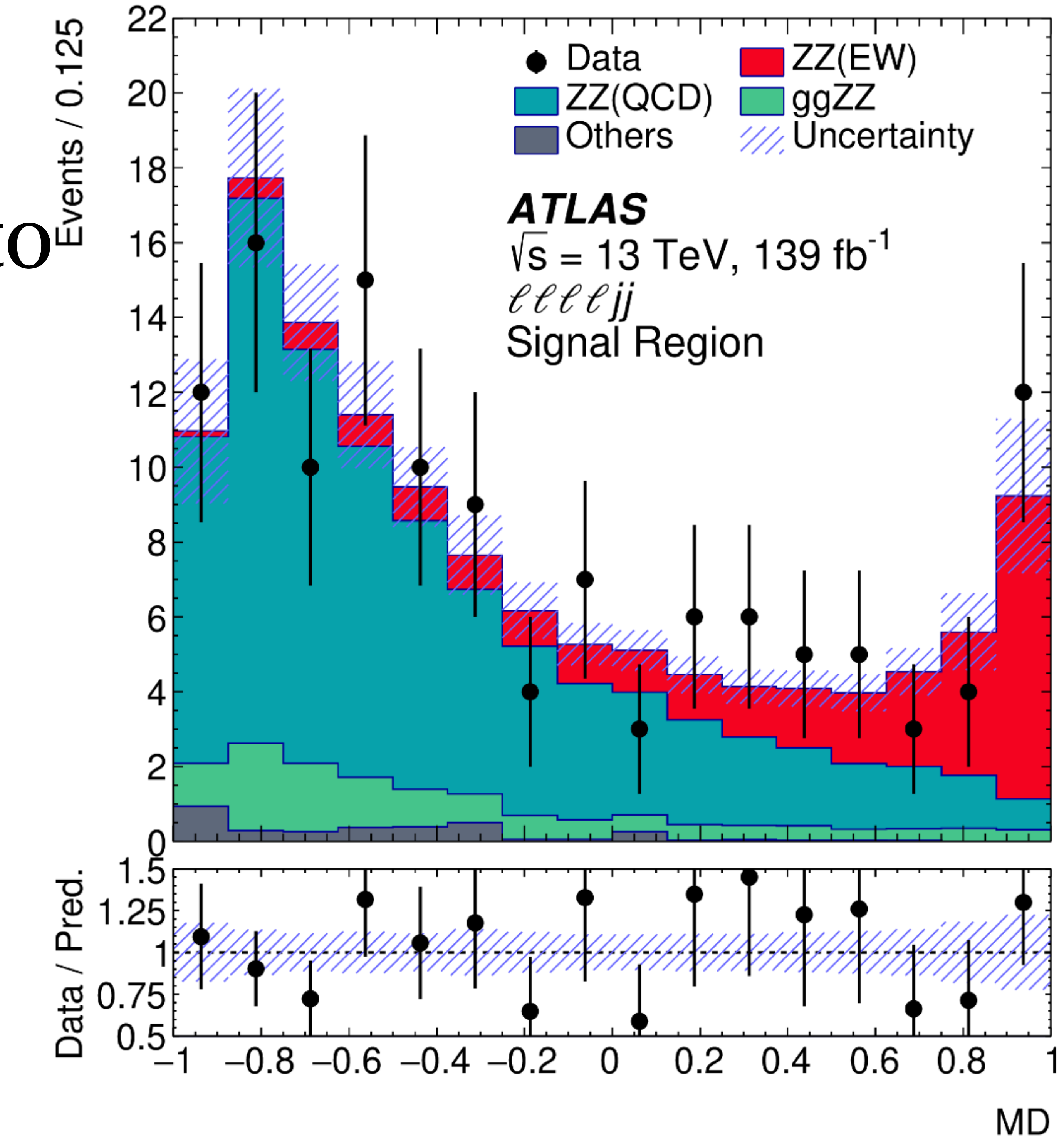
Observation of EW $ZZjj$

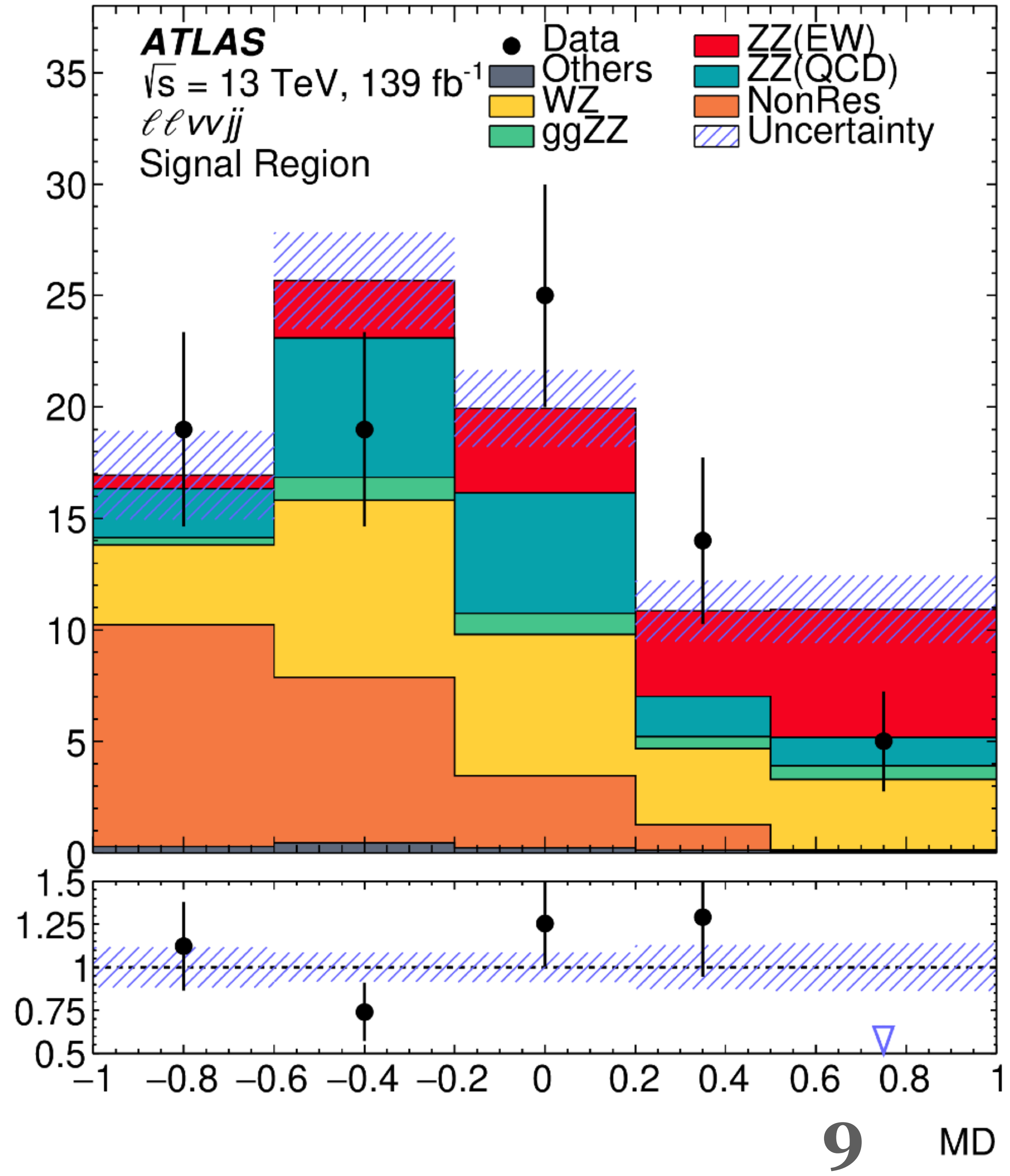


- EW $ZZjj$: very rare; unique sensitivity to non-SM quartic 4-Z coupling
- Main challenge: separate from strong $ZZjj$ production



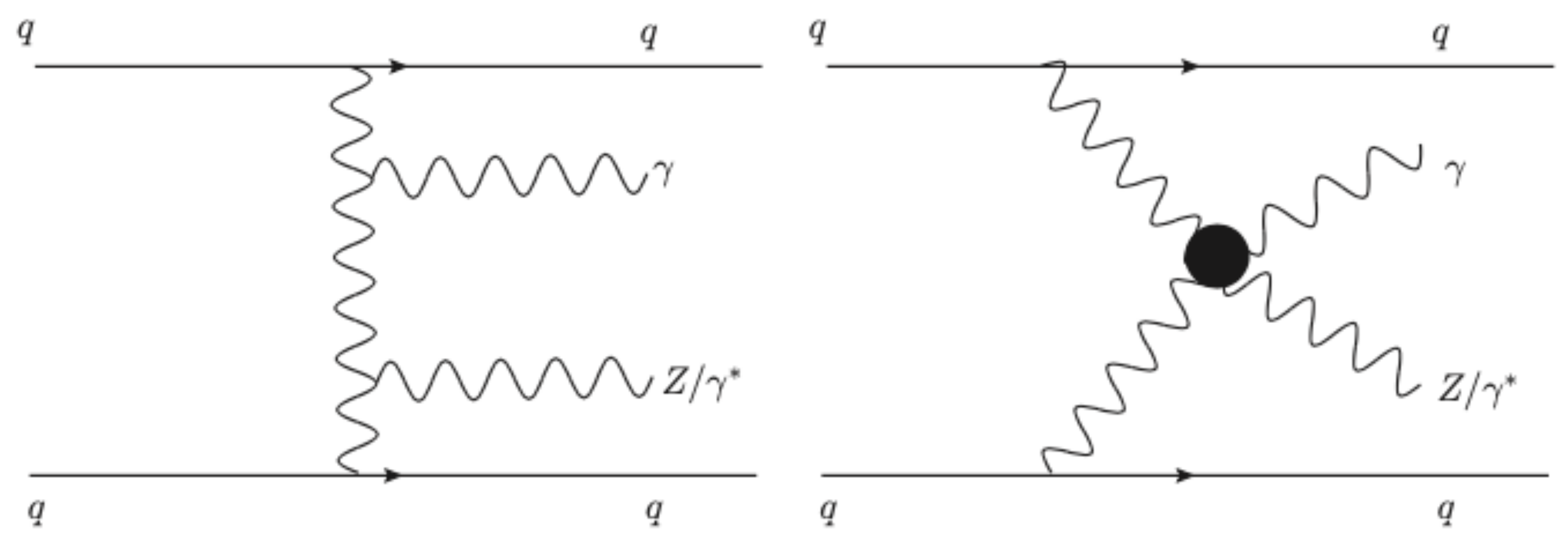
- Analysis:
  - Decay channels: $ZZjj \to 4\ell jj$ and $ZZjj \to \ell\ell\nu\nu jj$
  - Preselection: typical ZZ (4ℓ, $\ell\ell\nu\nu$) topology, b-jet veto (reduce $t\bar{t}$), loose VBF topo. selection (m_{jj}, Δy_{jj})
- Following preselection, BDTs are used to separate EW $ZZjj$ from backgrounds
- EW and strong Zjj measurements:
  - $\mu_{\mathrm{EW}} = 1.35 \pm 0.34$
    $\mu_{\mathrm{strong}} = 0.96 \pm 0.22$
  - EW $ZZjj$ significance: 5.5σ (4.3σ expected)
  - EW+strong fiducial cross sections measured for $4\ell jj$ and $\ell\ell\nu\nu jj$ separately



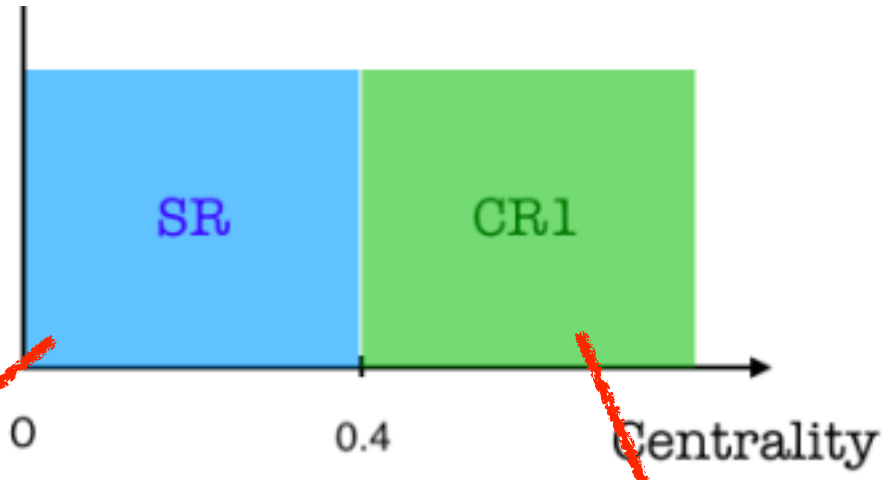


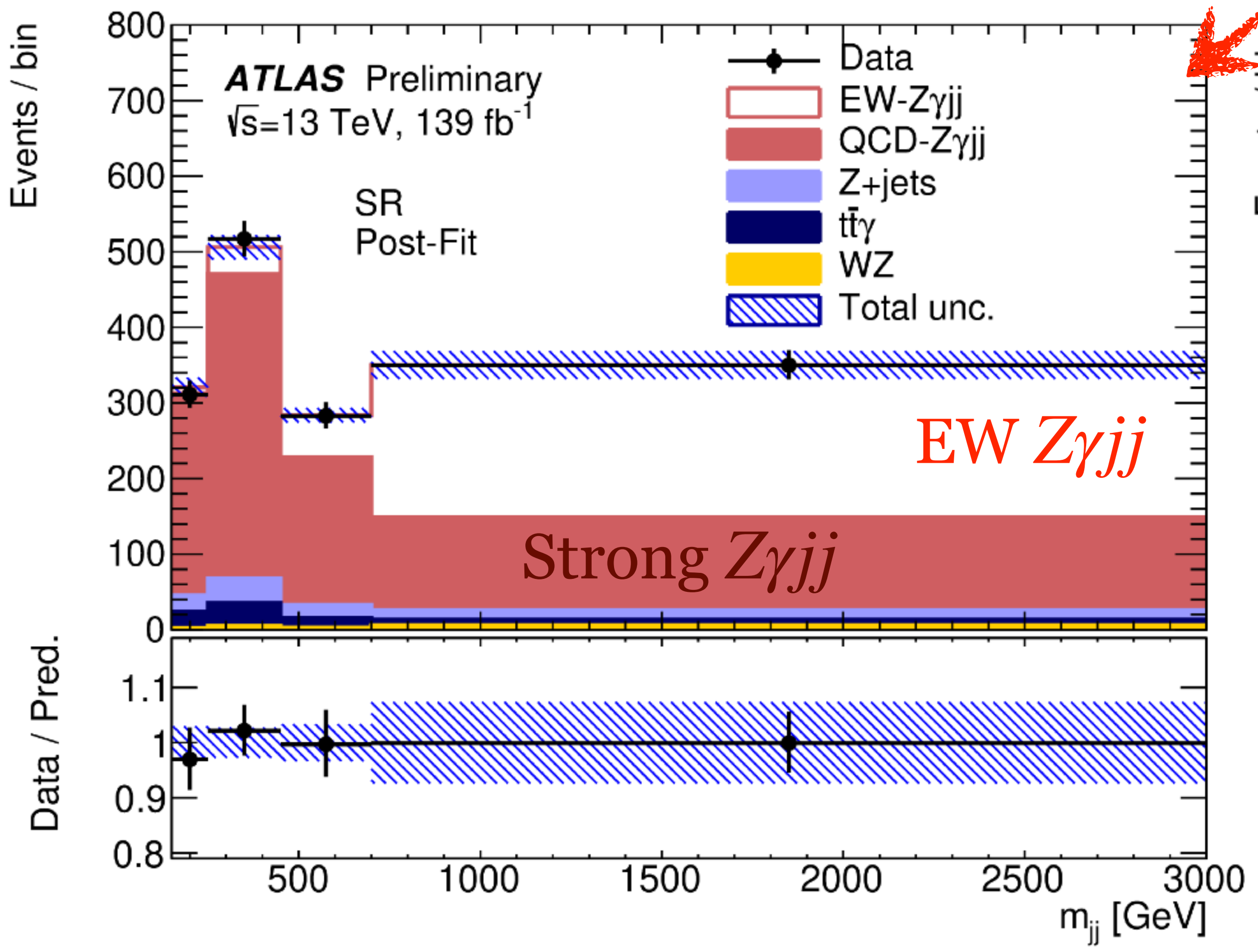
Observation of EW $Z(\ell\ell)\gamma jj$

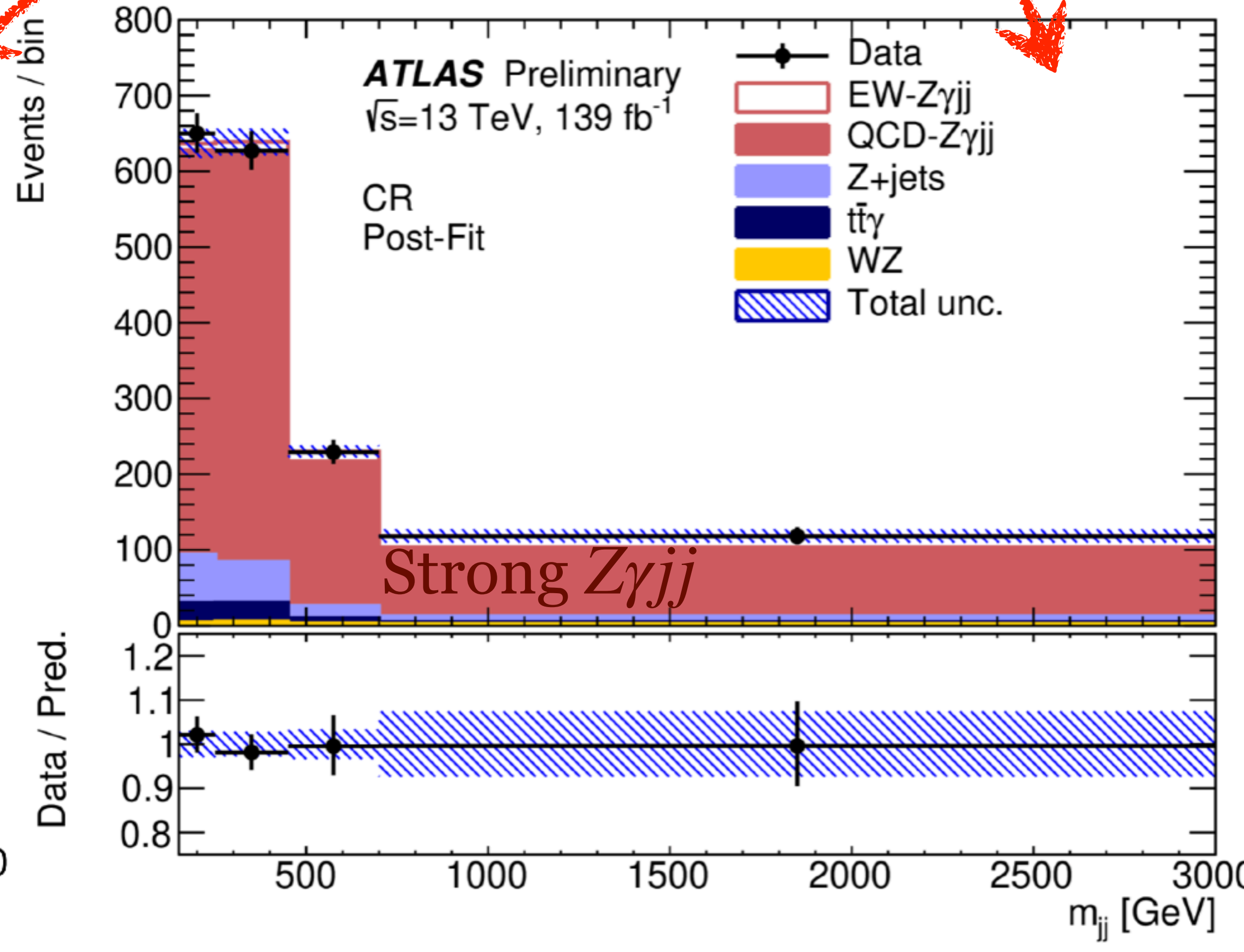
- EW $Z\gamma jj$ is measured in the $ee\gamma jj$ and $\mu\mu\gamma jj$ channels
- Analysis targets VBF topology + $Z \to \ell\ell + \gamma$:
  $p_T^{j1} > 50$ GeV, $p_T^{j2} > 50$ GeV, $p_T^{\gamma} > 25$ GeV, $m_{jj} > 150$ GeV, $\Delta y_{jj} > 1$
  $m_{\ell\ell} > 40$ GeV, and $m_{\gamma\ell\ell} + m_{\ell\ell} > 2\,m_Z$ (veto $Z \to \gamma\ell\ell$)
- Main backgrounds: Strong $Z\gamma jj$, Z+jets with fake γ, $t\bar{t}\gamma$
- Key observable: $Z\gamma$ centrality $\zeta_{\ell\ell\gamma}$; **SR:** $\zeta_{\ell\ell\gamma} < 0.4$
- Fit performed to m_{jj} spectrum
- Observation of EW $Z(\ell\ell)\gamma jj$ with significance well above 5σ ($\sim 10\sigma$)
  - Fiducial cross section is measured:
    $\sigma^{\text{fid}}_{\text{EW}\,Z\gamma} = 4.49 \pm 0.58$ fb, $\sigma^{\text{pred}}_{\text{EW}\,Z\gamma} = 4.73 \pm 0.27$ fb
- The strong+EW $Z\gamma jj$ cross section is measured to be: $20.6^{+1.4}_{-1.2}$ fb (predicted: $20.4^{+2.6}_{-2.0}$ fb)



$$\zeta(\ell\ell\gamma) = \left|\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}}\right|$$



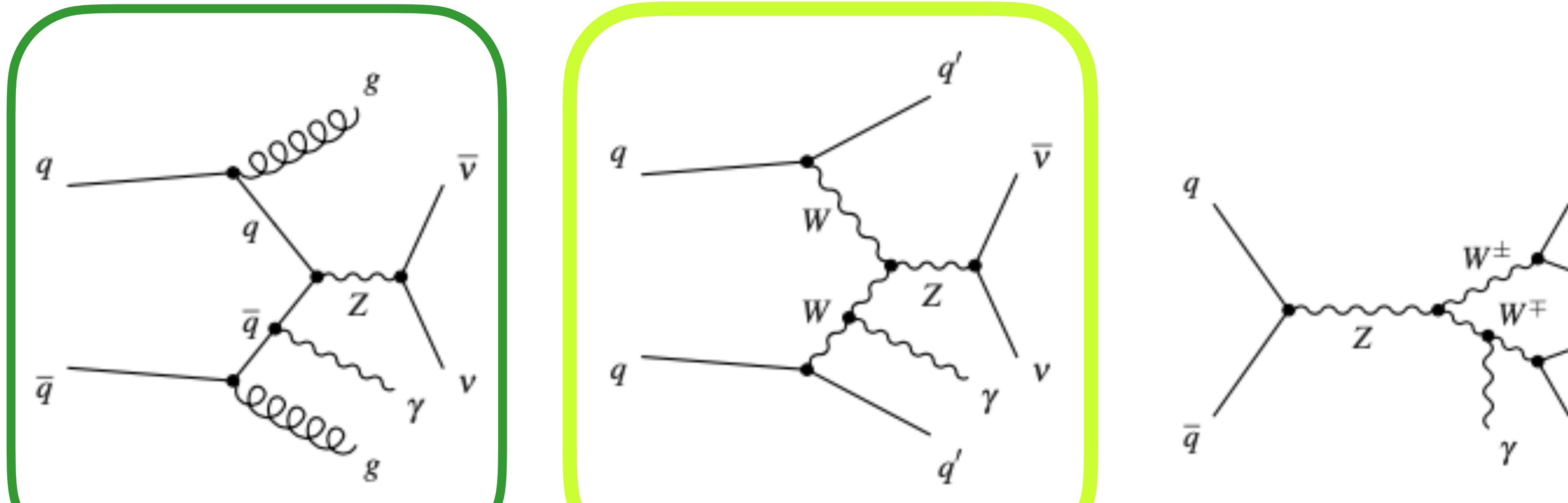




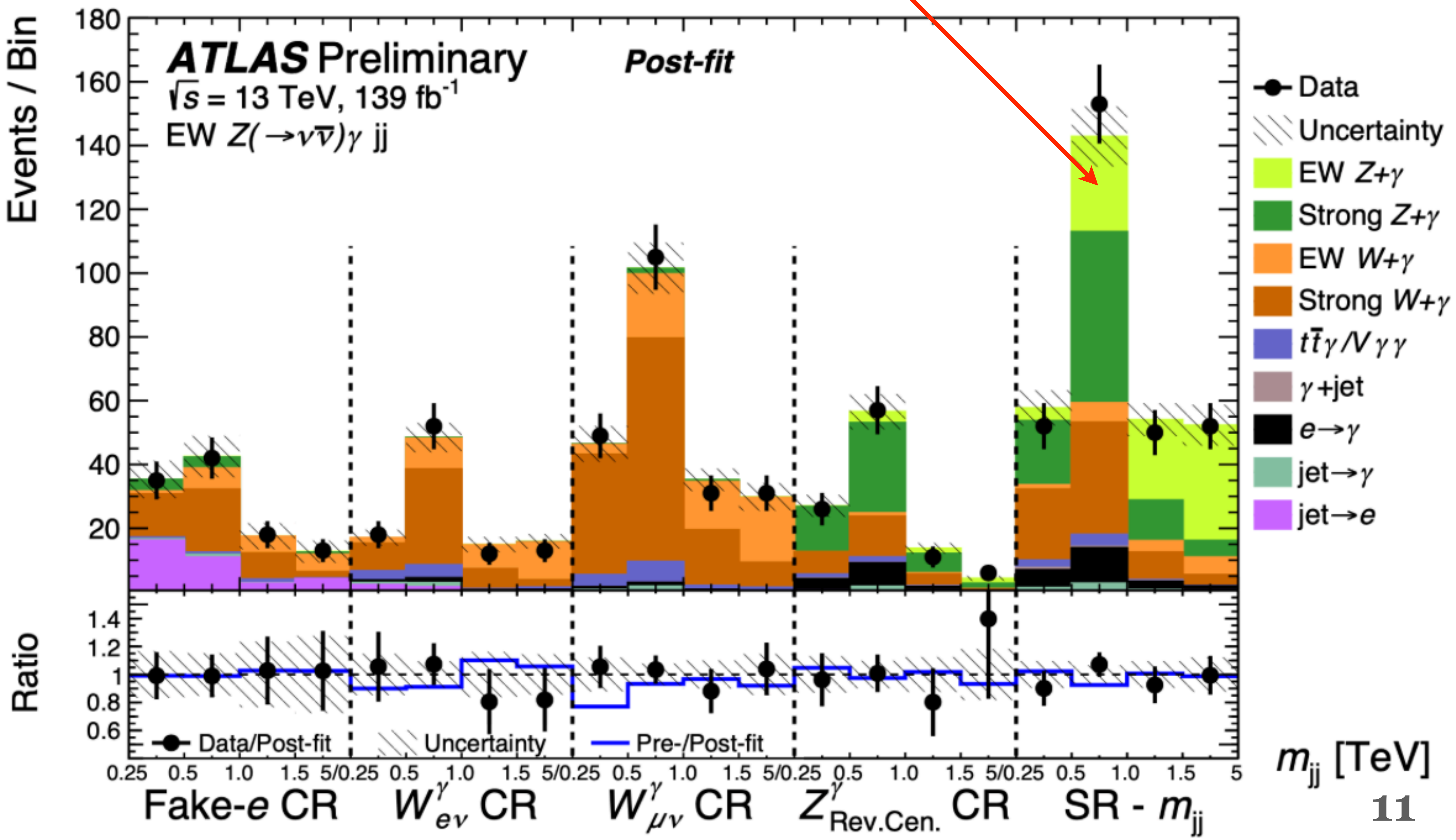
BRAND NEW

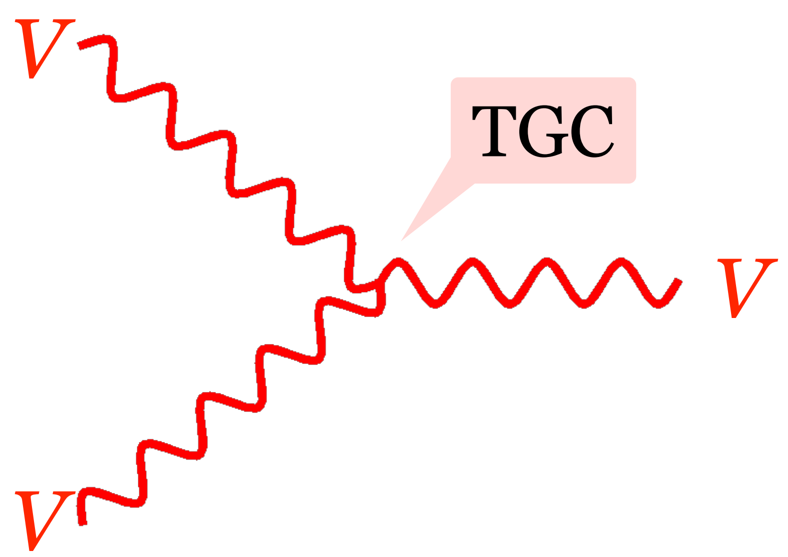
Observation of EW $Z(\nu\nu)\gamma jj$

- First observation of EW $Z(\nu\nu)\gamma jj$
- Strategy: target VBF topology+$E_{\mathrm{T}}^{\mathrm{miss}}$:
  $p_{\mathrm{T}}^{j1} > 60$ GeV, $p_{\mathrm{T}}^{j2} > 50$ GeV, $\Delta\phi_{jj} < 2.5$,
  $N_{\gamma} = 1, N_{\ell} = 0, m_{jj} > 250$ GeV, γ between jets
- Multiple control regions to constrain backgrounds
- EW $Z(\nu\nu)\gamma jj$ signal established with 5.2σ (5.1σ) observed (expected) significance
  - Measurements:
    EW $\mu_{Z\gamma} = 1.03 \pm 0.25$
    $\sigma_{\mathrm{fid}} = 1.31 \pm 0.29$ fb
- In addition to EW $Z\gamma jj$ measurements, also sets limits on invisible / partially inv. decays of a Higgs boson (VBF $H\rightarrow$invisible)

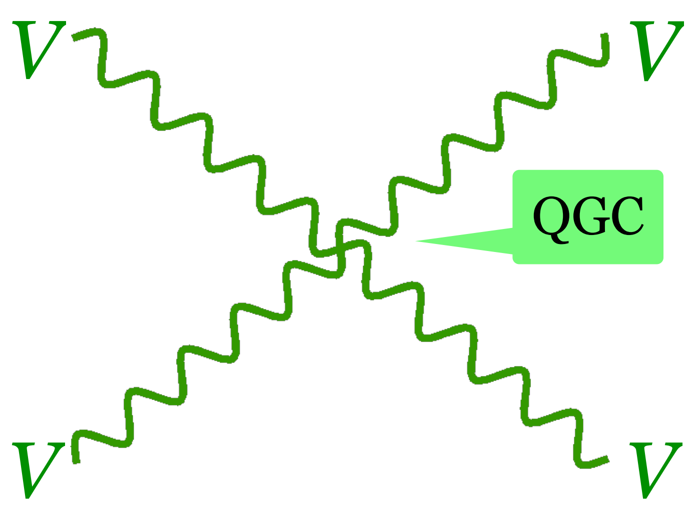


(a) Strong diagram (b) VBF electroweak diagram (c) Triboson diagram





Summary



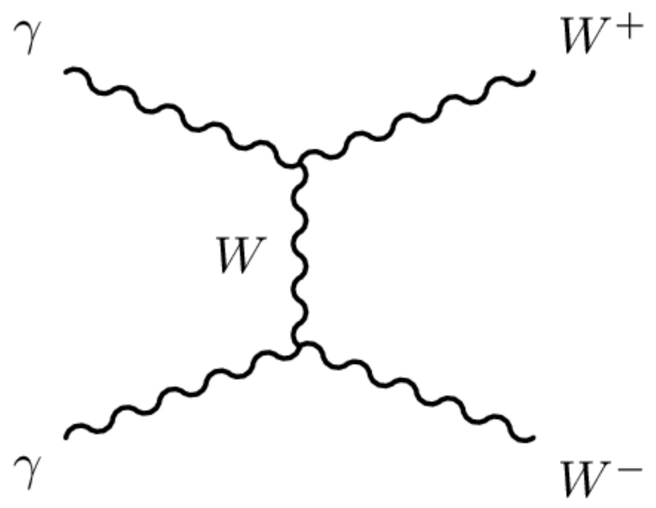
- Precision measurements of processes that probes VBF and VBS provides:
  - Important test of EWSB
  - Sensitivity to searches for new phenomena (BSM)
  - Crucial input to EFT fits
- Typically, the associated cross sections are very small → small signal swamped by large, challenging backgrounds
  - Precision analyses only recently possible due to large dataset required
  - Most measurements are statistics limited
- 5σ observation established for major VBF and VBS sensitive processes & channels
  - Focus shifting to precision differential cross section measurements
- Exciting times ahead with the larger datasets of Run 3 and beyond

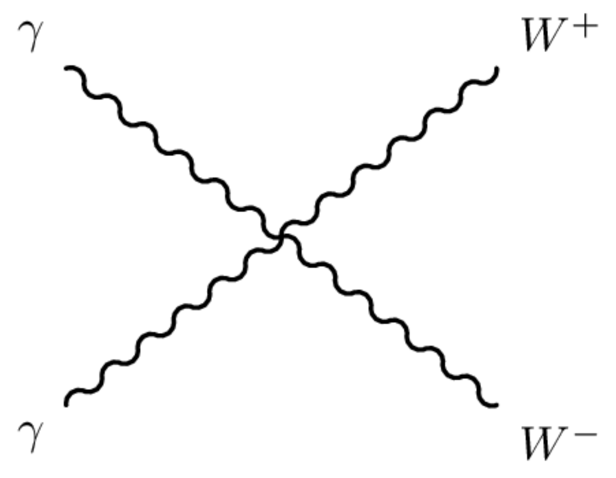
Backup slides

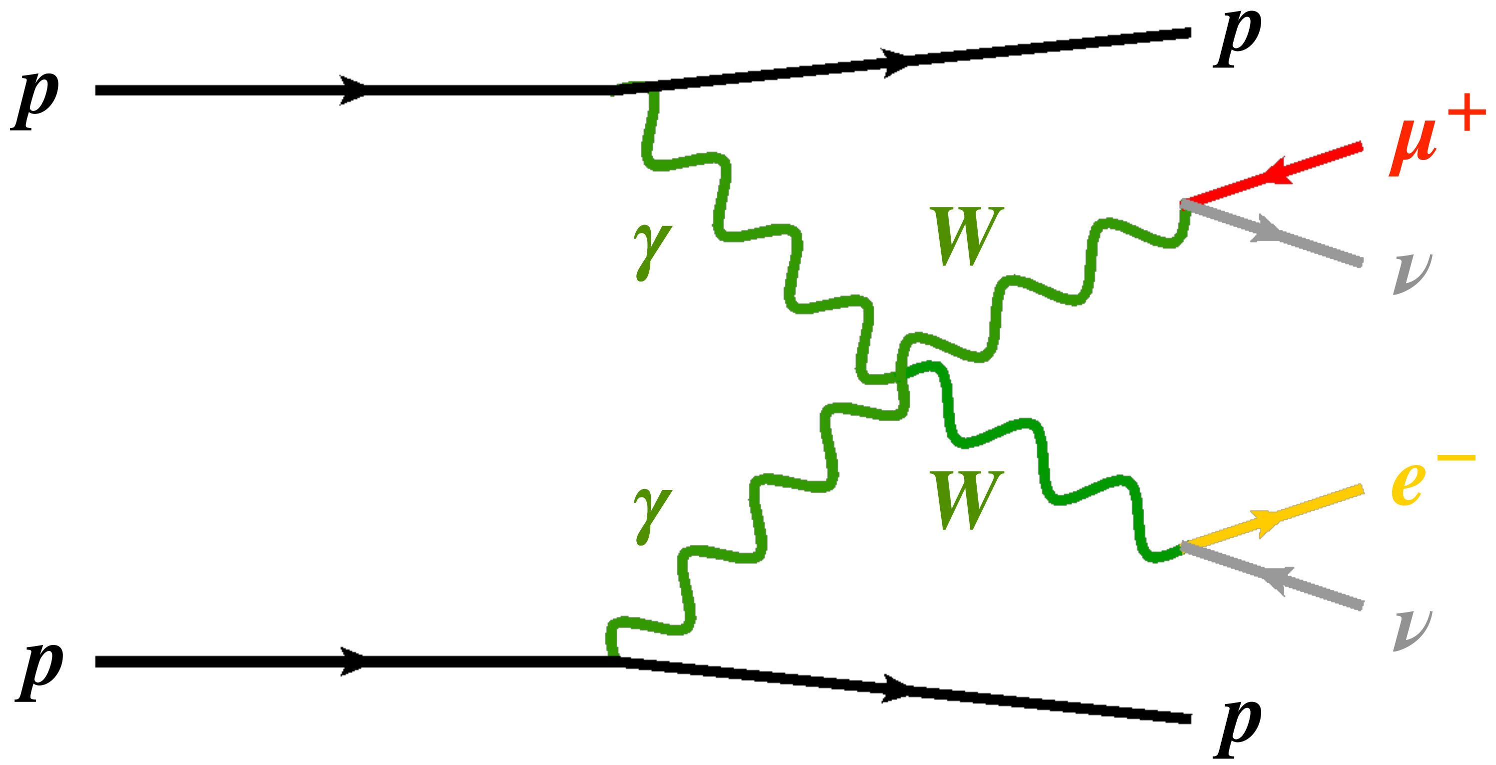
See Savannah Clawson's talk on photon fusion, Thursday

CERN-EP-2020-165, arXiv:2010.04019 , PLB 816 (2021) 136190

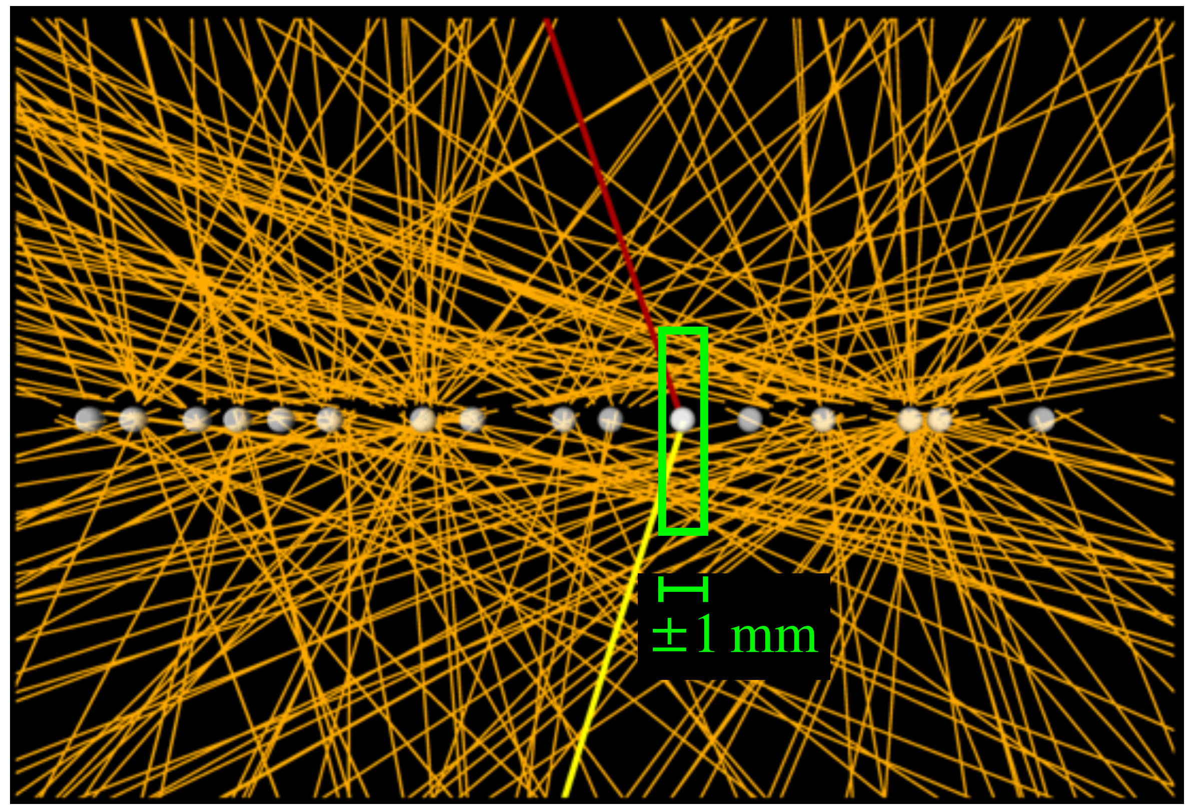
Observation of $\gamma\gamma \to WW$

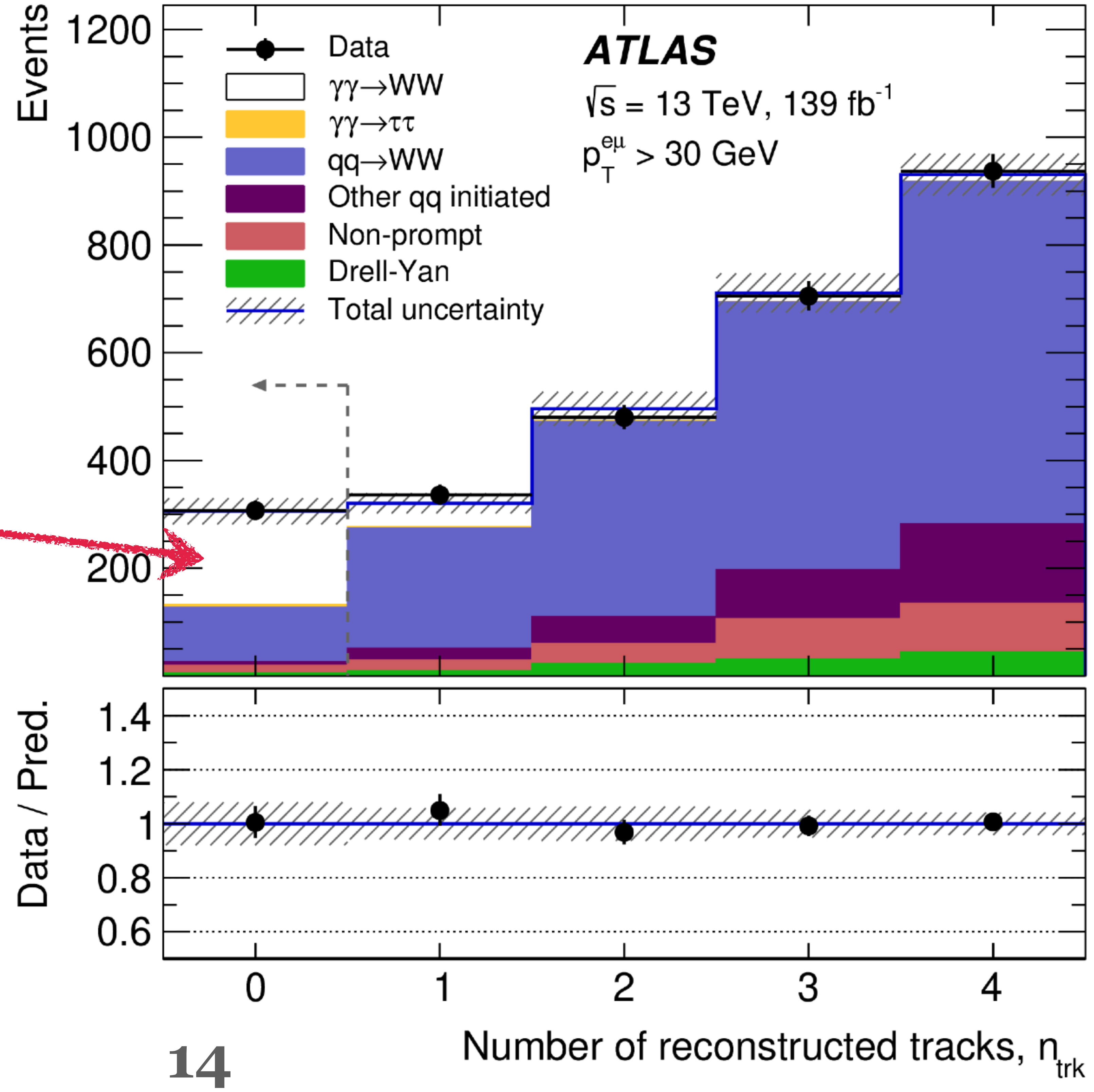






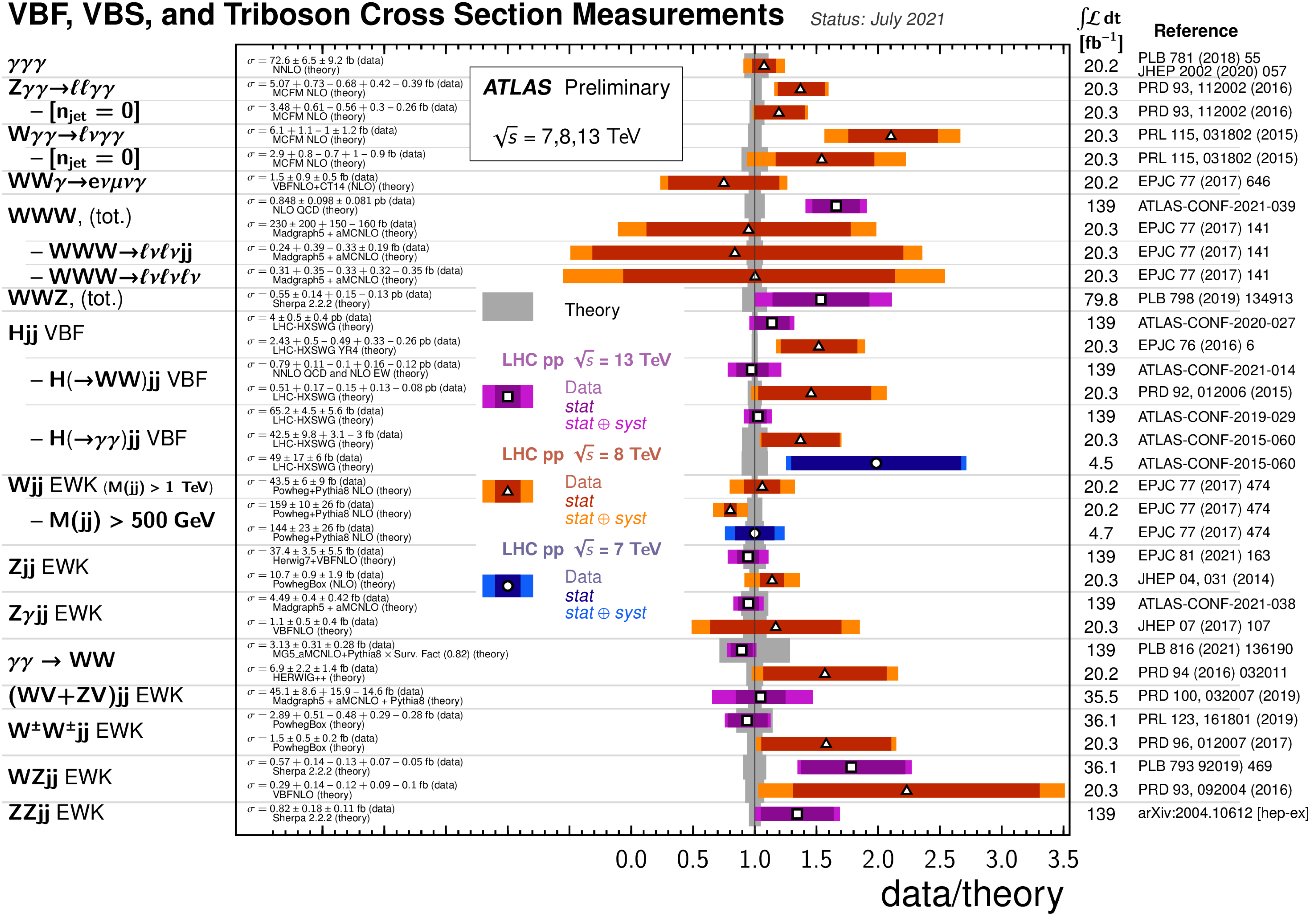
- Photon-photon scattering
  - Incoming protons intact or fragment outside acceptance
  - $WW \to e\nu\mu\nu$ channel **very clean**; opposite charged ℓ, no other tracks
- **Analysis** selects $\ell^{\pm}\ell^{\mp}$ events, fulfilling: $p_T^{\ell 1} > 27$ GeV, $p_T^{\ell 2} > 20$ GeV, $m_{\ell\ell} > 30$ GeV, SR: $p_T^{e\mu} > 30$ GeV
  - Count tracks within 1 mm of $\ell\ell$ primary vertex
  - Expect $n_{\text{trk}} = 0$ additional tracks from $\gamma\gamma \to WW$
  - Backgrounds constrained using CRs: $p_T^{e\mu} < 30$ GeV and $n_{\text{trk}} \geq 1$
- Background-only hypothesis rejected with 8.4σ significance
- $\sigma_{\text{fid}} = 3.13 \pm 0.31\,(\text{stat}) \pm 0.28\,(\text{syst})$



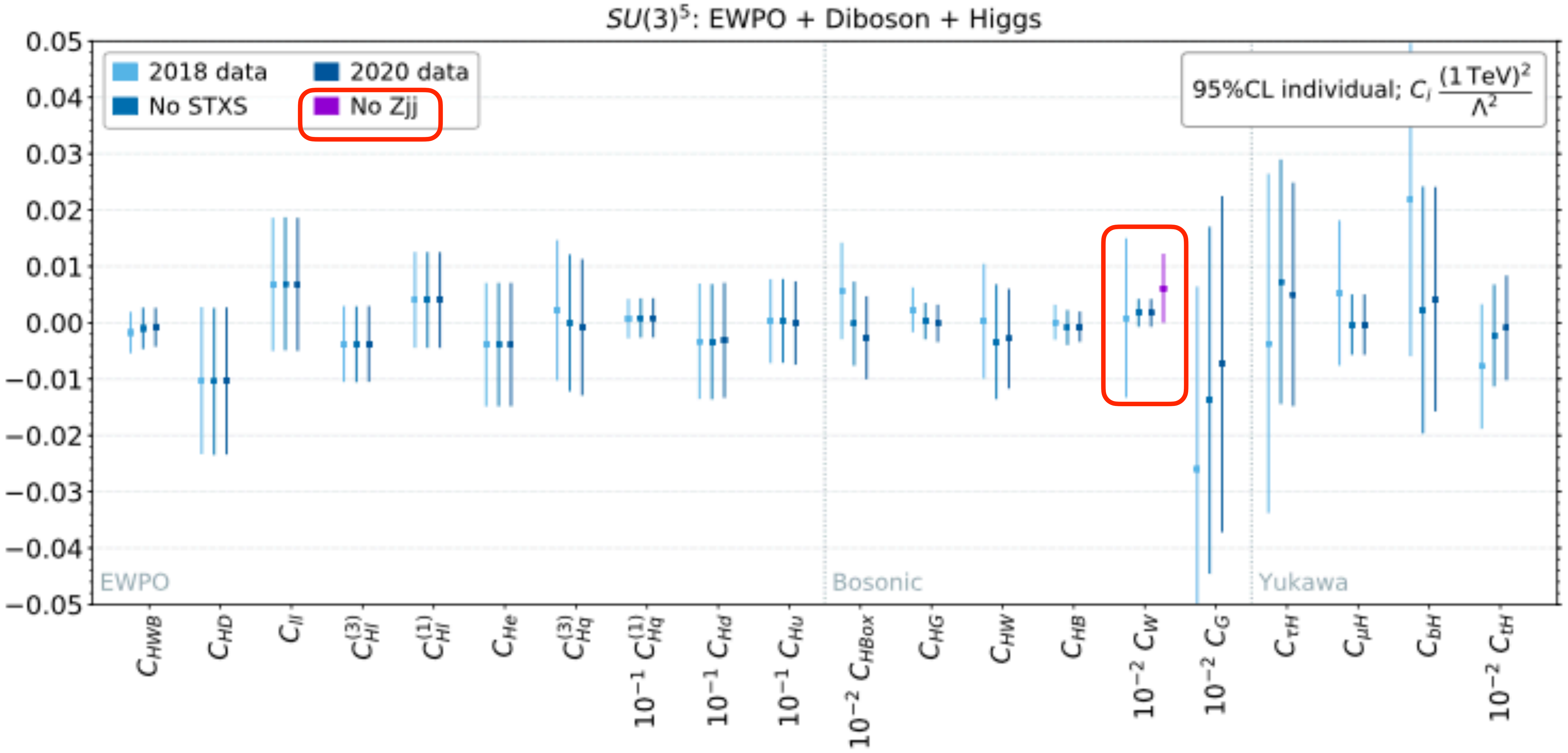


VBF, VBS, and Triboson Cross Section Measurements

Status: July 2021



EW *Zjj/VVjj* measurement in global BSM fits



- The ATLAS EW *Zjj* measurements helps constrain C_W in particular

Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

arXiv:2012.02779, JHEP 04 (2021) 279

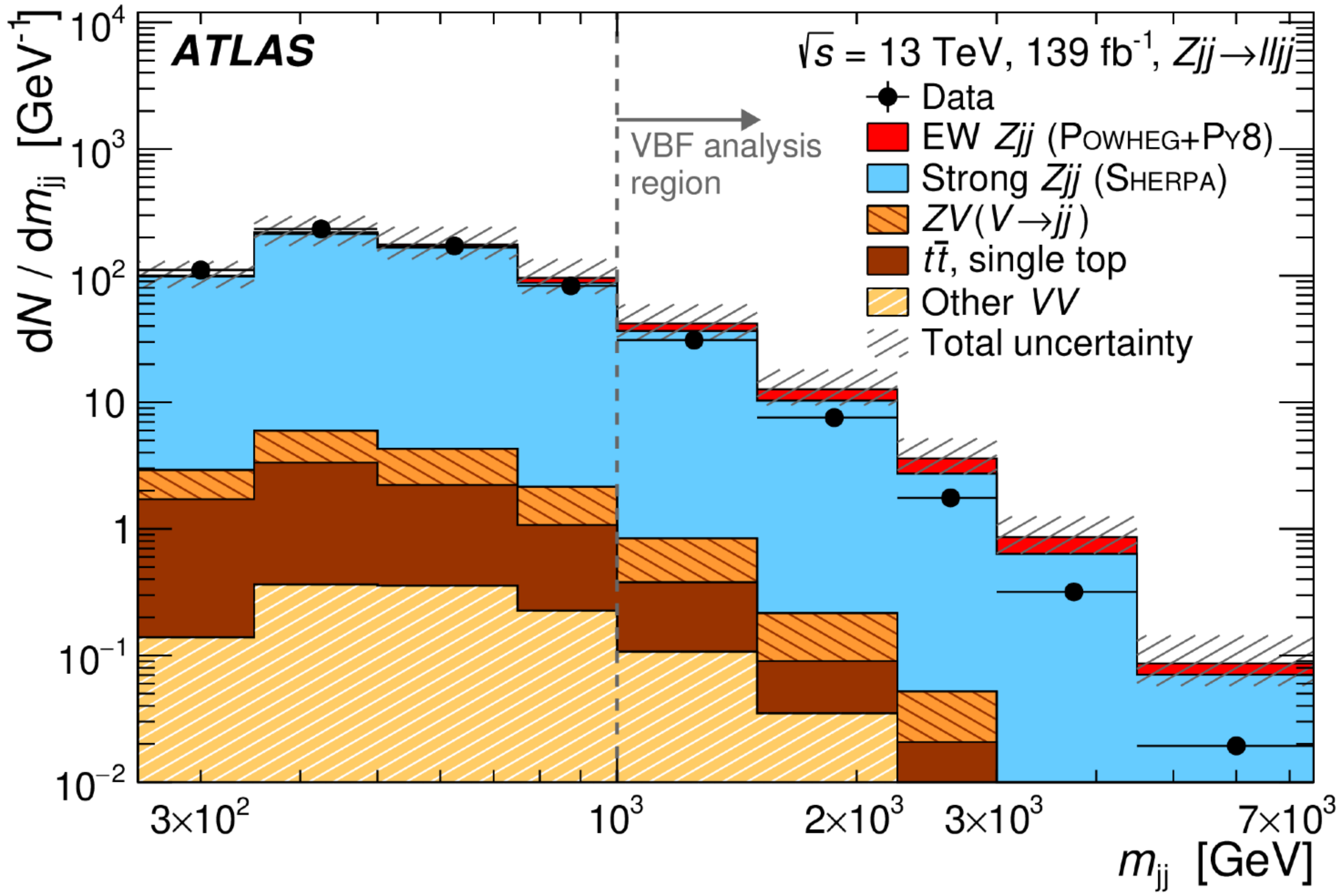
Zjj: Generators, cutflow, fid. def

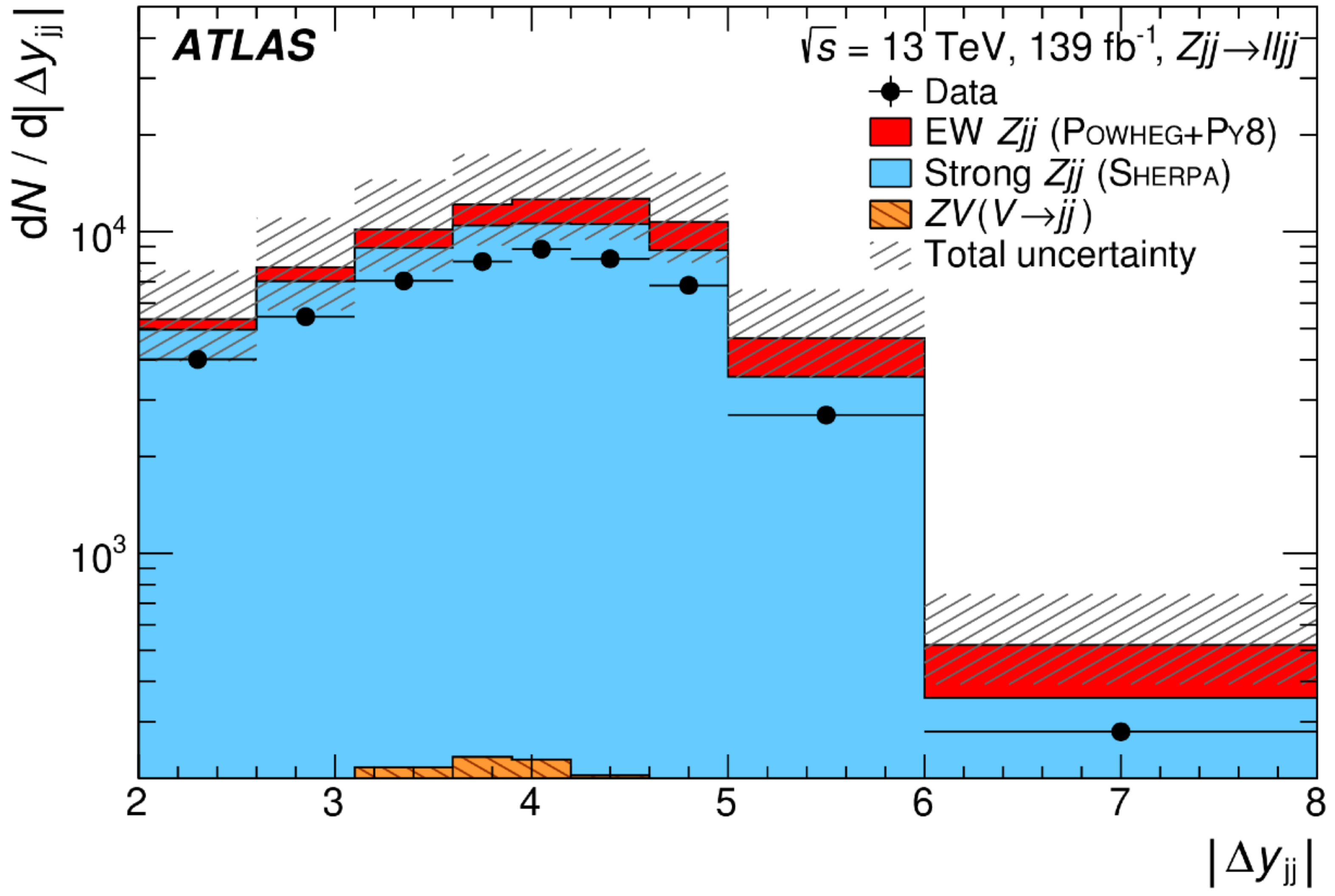
Process	Generator	ME accuracy	PDF	Shower and hadronisation	Parameter set
EW Zjj	Powheg-Box v1	NLO	CT10nlo	Pythia8 + EvtGen	AZNLO
	Herwig7 + Vbfnlo	NLO	MMHT2014lo	Herwig7 + EvtGen	default
	Sherpa 2.2.1	LO (2–4j)	NNPDF3.0nnlo	Sherpa	default
Strong Zjj	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default
	MadGraph5_aMC@NLO	NLO (0–2j), LO (3–4j)	NNPDF2.3nlo	Pythia8 + EvtGen	A14
	MadGraph5	LO (0–4j)	NNPDF3.0lo	Pythia8 + EvtGen	A14
VV	Sherpa	NLO (0–1j), LO (2–3j)	NNPDF3.0nnlo	Sherpa	default
$t\bar{t}$	Powheg-Box v2 hvq	NLO	NNPDF3.0nnlo	Pythia8 + EvtGen	A14
VVV	Sherpa	LO (0–1j)	NNPDF3.0nnlo	Sherpa	default
W+jets	Sherpa	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default

Dressed muons	$p_T > 25$ GeV and $\|\eta\| < 2.4$
Dressed electrons	$p_T > 25$ GeV and $\|\eta\| < 2.37$ (excluding $1.37 < \|\eta\| < 1.52$)
Jets	$p_T > 25$ GeV and $\|y\| < 4.4$
VBF topology	$N_\ell = 2$ (same flavour, opposite charge), $m_{\ell\ell} \in (81, 101)$ GeV
	$\Delta R_{min}(\ell_1, j) > 0.4,\ \Delta R_{min}(\ell_2, j) > 0.4$
	$N_{jets} \geq 2,\ p_T^{j1} > 85$ GeV, $p_T^{j2} > 80$ GeV
	$p_{T,\ell\ell} > 20$ GeV, $p_T^{bal} < 0.15$
	$m_{jj} > 1000$ GeV, $\|\Delta y_{jj}\| > 2,\ \xi_Z < 1$
CRa	VBF topology $\oplus\ N_{jets}^{gap} \geq 1$ and $\xi_Z < 0.5$
CRb	VBF topology $\oplus\ N_{jets}^{gap} \geq 1$ and $\xi_Z > 0.5$
CRc	VBF topology $\oplus\ N_{jets}^{gap} = 0$ and $\xi_Z > 0.5$
SR	VBF topology $\oplus\ N_{jets}^{gap} = 0$ and $\xi_Z < 0.5$

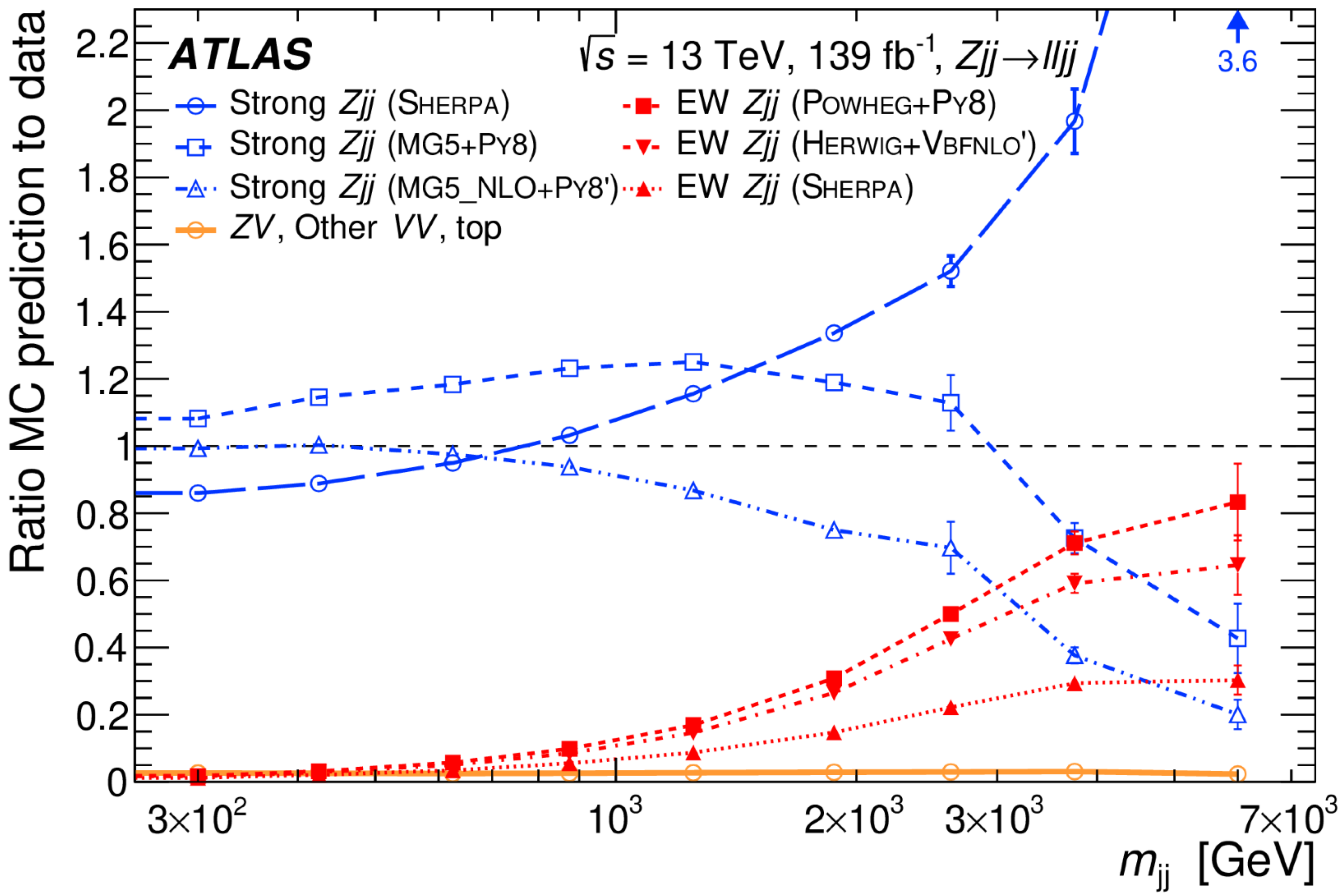
Sample	$Z \to ee$	$Z \to \mu\mu$
Data	10 870	12 125
EW Zjj (Powheg+Py8)	2670 ± 120 ± 280	2740 ± 120 ± 290
EW Zjj (Sherpa)	1280 ± 60 ± 140	1350 ± 60 ± 150
EW Zjj (Herwig7+Vbfnlo′)	2290 ± 100 ± 210	2350 ± 100 ± 220
Strong Zjj (Sherpa)	13 500 ± 600 ± 4500	15 100 ± 600 ± 5000
Strong Zjj (MG5+Py8)	13 140 ± 480 ± N/A	14 810 ± 540 ± N/A
Strong Zjj (MG5_NLO+Py8′)	8800 ± 300 ± 1000	10 000 ± 400 ± 1200
ZV ($V \to jj$)	179 ± 8 ± 6	178 ± 8 ± 6
Other VV	45 ± 2 ± 2	45 ± 2 ± 2
$t\bar{t}$, single top	92 ± 8 ± 6	98 ± 8 ± 6
$W(\to \ell\nu)$+jets, $Z(\to \tau\tau)$+jets	negligible	negligible

Modelling issues for strong backgrounds





Sherpa and (LO) MG5+Py8 over predict the strong *Zjj* contribution after VBF topology selection



Likelihood fit for EW *Zjj* signal extraction

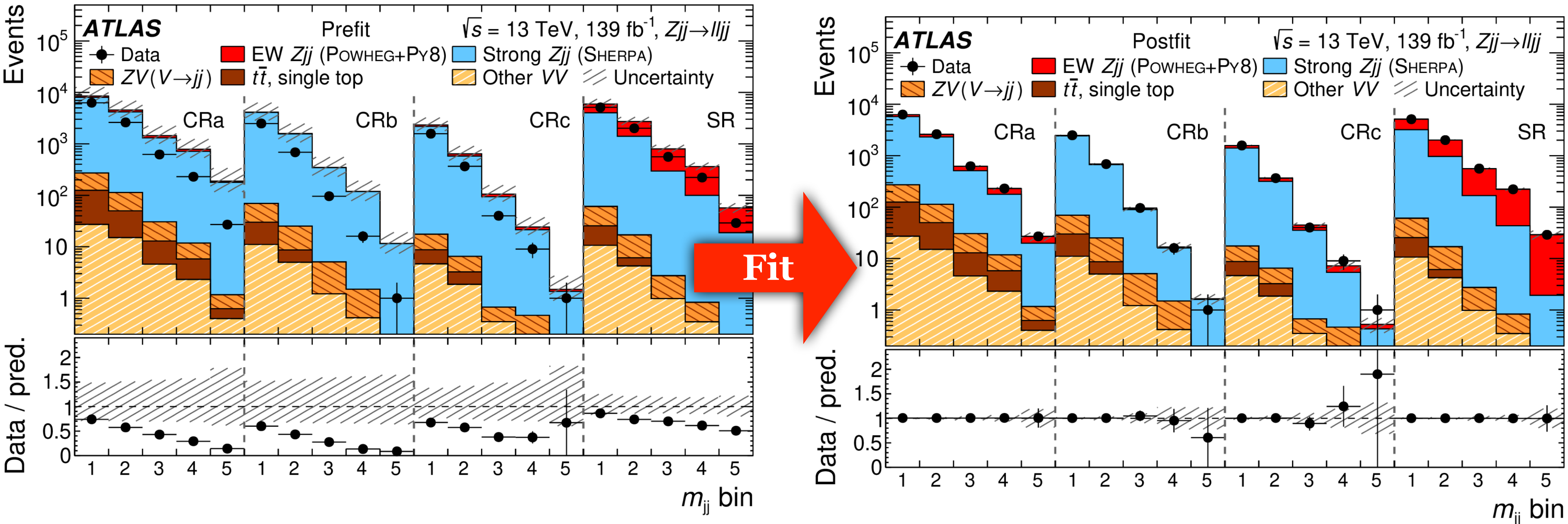
$$\ln \mathcal{L} = -\sum_{r,i} \nu_{ri}(\boldsymbol{\theta}) + \sum_{r,i} N_{ri}^{\text{data}} \ln \nu_{ri}(\boldsymbol{\theta}) - \sum_{s} \frac{\theta_s^2}{2},$$

$$\nu_{ri} = \mu_i \nu_{ri}^{\text{EW,MC}} + \nu_{ri}^{\text{strong}} + \nu_{ri}^{\text{other,MC}},$$

$$\nu_{\text{CRa},i}^{\text{strong}} = b_{\text{L},i}\, \nu_{\text{CRa},i}^{\text{strong,MC}}, \qquad \nu_{\text{CRb},i}^{\text{strong}} = b_{\text{H},i}\, \nu_{\text{CRb},i}^{\text{strong,MC}},$$

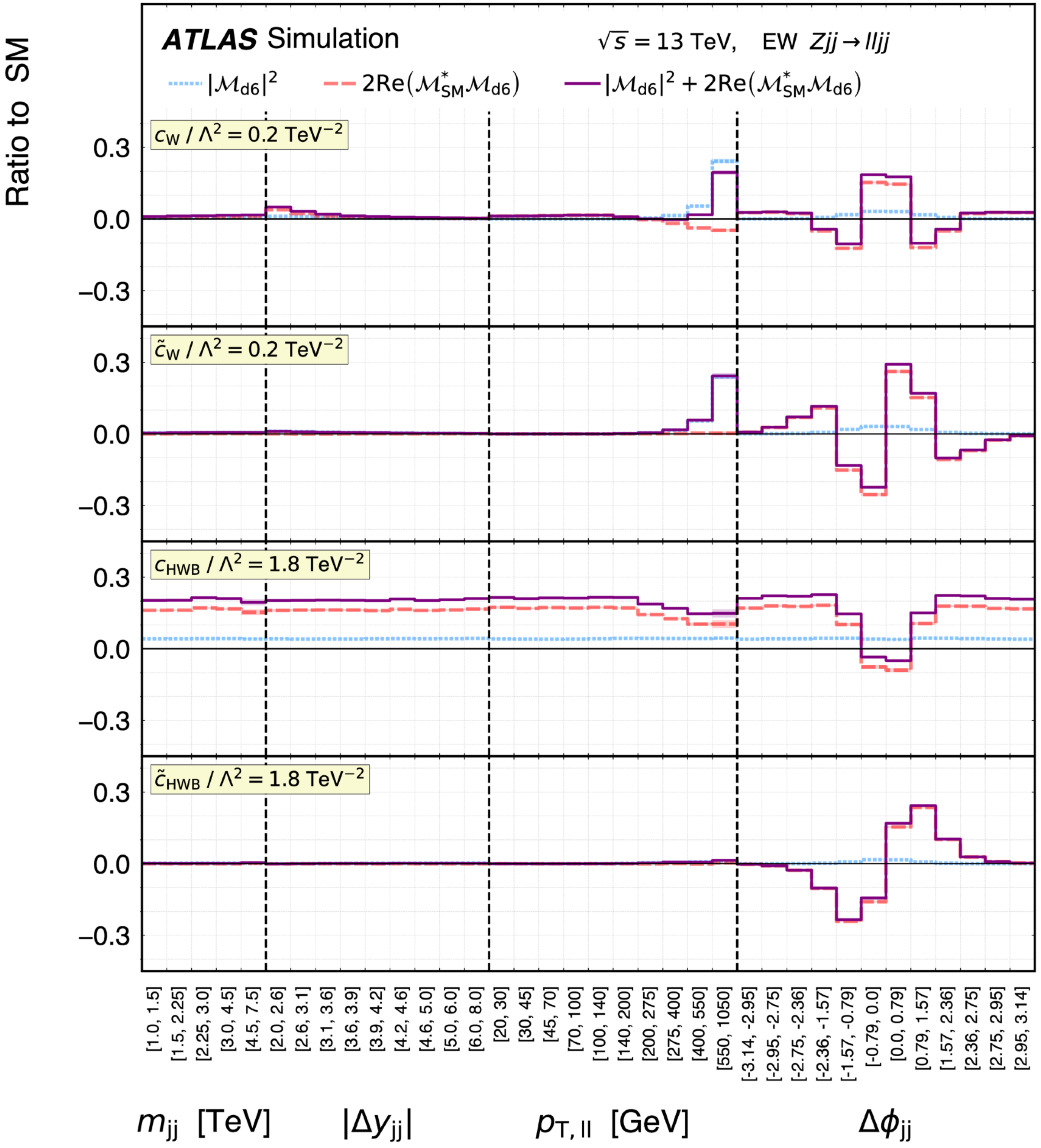
$$\nu_{\text{SR}i}^{\text{strong}} = b_{\text{L},i}\, f(x_i)\, \nu_{\text{SR},i}^{\text{strong,MC}}, \qquad \nu_{\text{CRc},i}^{\text{strong}} = b_{\text{H},i}\, f(x_i)\, \nu_{\text{CRc},i}^{\text{strong,MC}}$$

20 bins, 5 POIs, 12 free parameter that constrain strong *Zjj* (5+5+2)



EW *Zjj* uncertainties

Zjj: EFT fit and HEP-data



Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

EW Zjj SR, m_{jj} cross-section measurements									
$d\sigma / dm_{jj}$ [ab/GeV]	-	-	-	-	41	14	5.5	1.3	0.10
Stat. unc. [%]	-	-	-	-	13	13	13	17	26
Gen. choice [%]	-	-	-	-	11	11	9.4	14	7.6
Theory syst. [%]	-	-	-	-	8.1	6.6	4.3	3.1	1.2
Jet syst. [%]	-	-	-	-	8.4	6.9	6.3	9.4	14
Unfolding syst. [%]	-	-	-	-	2.3	1.1	0.7	0.6	0.6
Other syst. [%]	-	-	-	-	2.0	2.0	2.3	2.2	3.0
Inclusive Zjj SR, m_{jj} cross-section measurements									
$d\sigma / dm_{jj}$ [ab/GeV]	510	1040	700	320	120	31	8.8	1.7	0.12
Stat. unc. [%]	1.6	1.0	0.9	1.3	1.5	2.3	4.5	7.2	21
Jet syst. [%]	5.2	3.8	3.3	3.6	3.6	3.5	4.1	6.6	15
Unfolding syst. [%]	2.3	1.6	0.9	0.6	0.5	0.4	0.5	0.6	0.6
Other syst. [%]	2.8	2.8	2.8	2.8	2.8	2.8	2.9	2.9	3.4
Inclusive Zjj CRa, m_{jj} cross-section measurements									
$d\sigma / dm_{jj}$ [ab/GeV]	250	610	560	320	130	37	8.7	1.6	0.10
Stat. unc. [%]	2.2	1.2	1.0	1.3	1.3	2.1	4.4	7.3	22
Jet syst. [%]	11	11	9.4	8.6	8.6	8.1	9.9	11	14
Unfolding syst. [%]	6.7	5.3	4.1	3.3	2.7	2.6	3.0	3.9	5.3
Other syst. [%]	2.3	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.8
Inclusive Zjj CRb, m_{jj} cross-section measurements									
$d\sigma / dm_{jj}$ [ab/GeV]	190	430	330	150	54	10	1.4	0.11	-
Stat. unc. [%]	2.5	1.4	1.2	1.8	2.2	4.2	11	28	-
Jet syst. [%]	11	9.0	7.6	8.0	7.4	7.9	9.0	8.9	-
Unfolding syst. [%]	2.3	2.4	2.4	2.1	1.8	2.1	3.0	3.8	-
Other syst. [%]	2.3	2.3	2.3	2.4	2.4	2.5	2.6	2.6	-
Inclusive Zjj CRc, m_{jj} cross-section measurements									
$d\sigma / dm_{jj}$ [ab/GeV]	350	690	390	140	37	5.7	0.60	0.07	-
Stat. unc. [%]	1.9	1.2	1.2	2.0	2.7	5.8	18	36	-
Jet syst. [%]	6.7	3.6	3.3	5.0	2.3	4.7	5.5	4.0	-
Unfolding syst. [%]	1.2	1.0	0.8	0.9	1.1	1.6	2.1	2.3	-
Other syst. [%]	2.8	2.8	2.8	2.8	2.8	2.9	2.9	3.1	-
Low bin edge [TeV]	0.25	0.35	0.50	0.75	1.0	1.5	2.2	3.0	4.5
High bin edge [TeV]	0.35	0.50	0.75	1.0	1.5	2.2	3.0	4.5	7.5

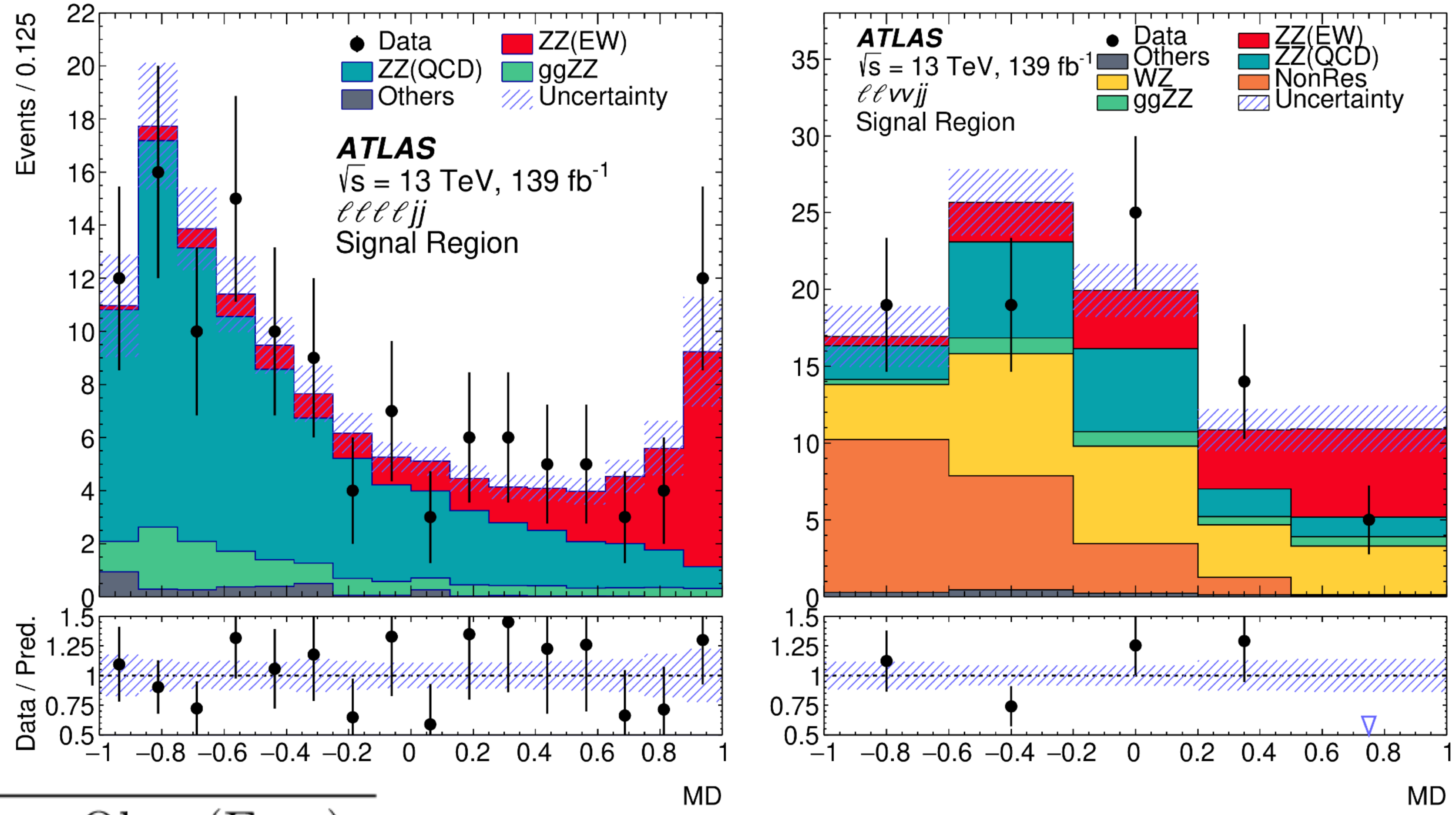
Links to:

HepData entry with all 20 unfolded measurements + statistical cross correlation

Associated **Rivet routine**

EW *ZZjj* measurement details

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

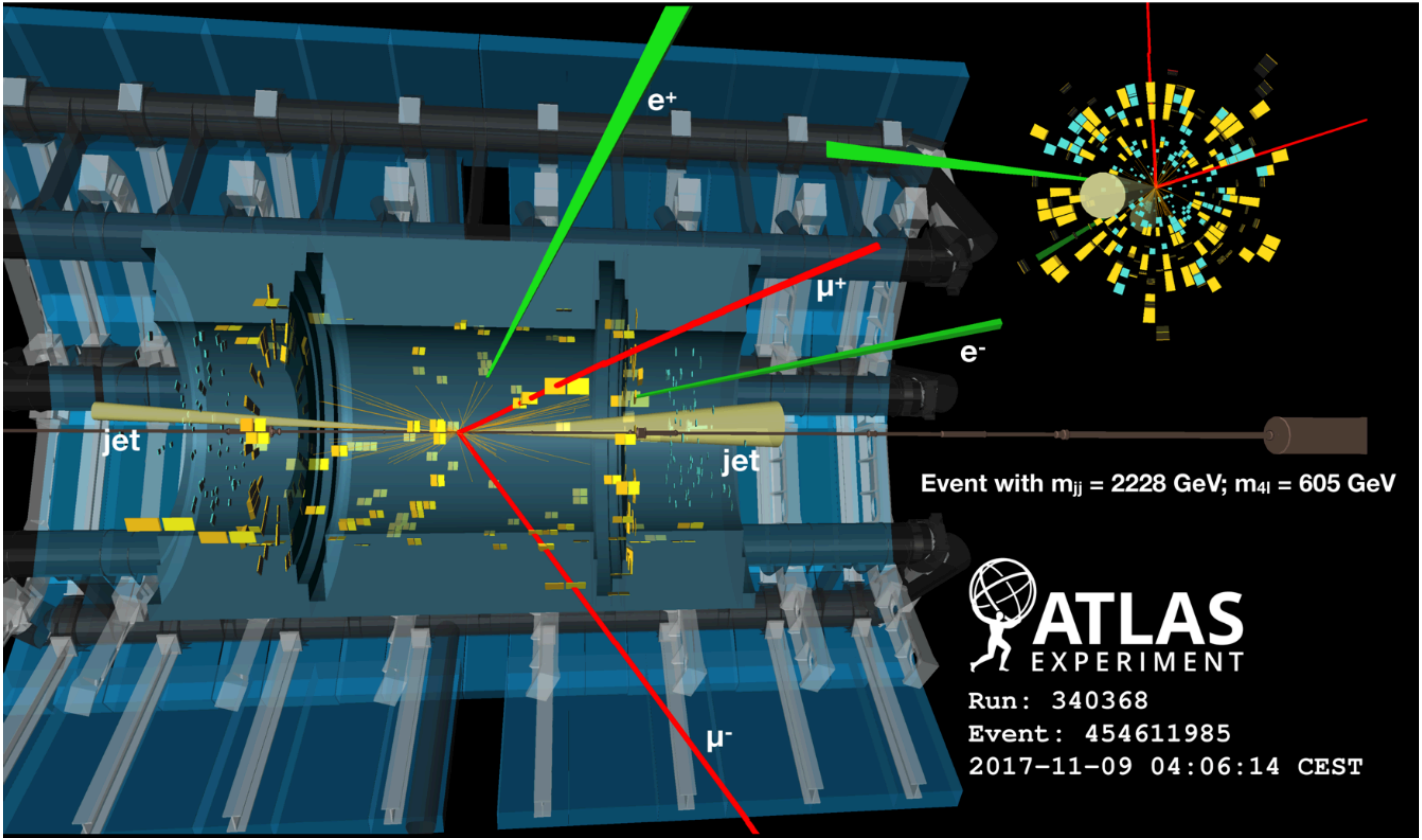


Results:

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	$1.2\ (1.8)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$5.5\ (4.3)\ \sigma$

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

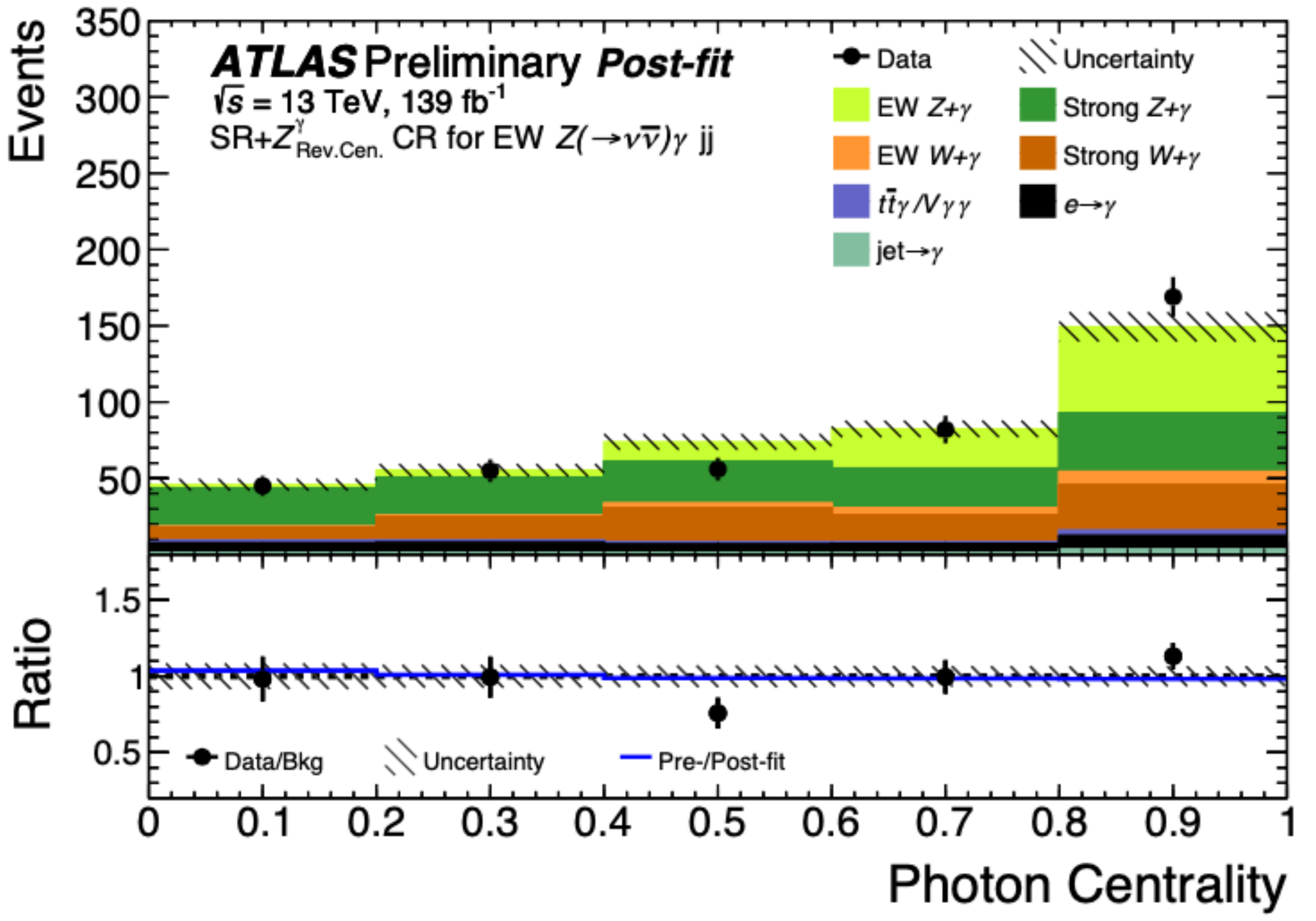
EW *ZZjj* candidate

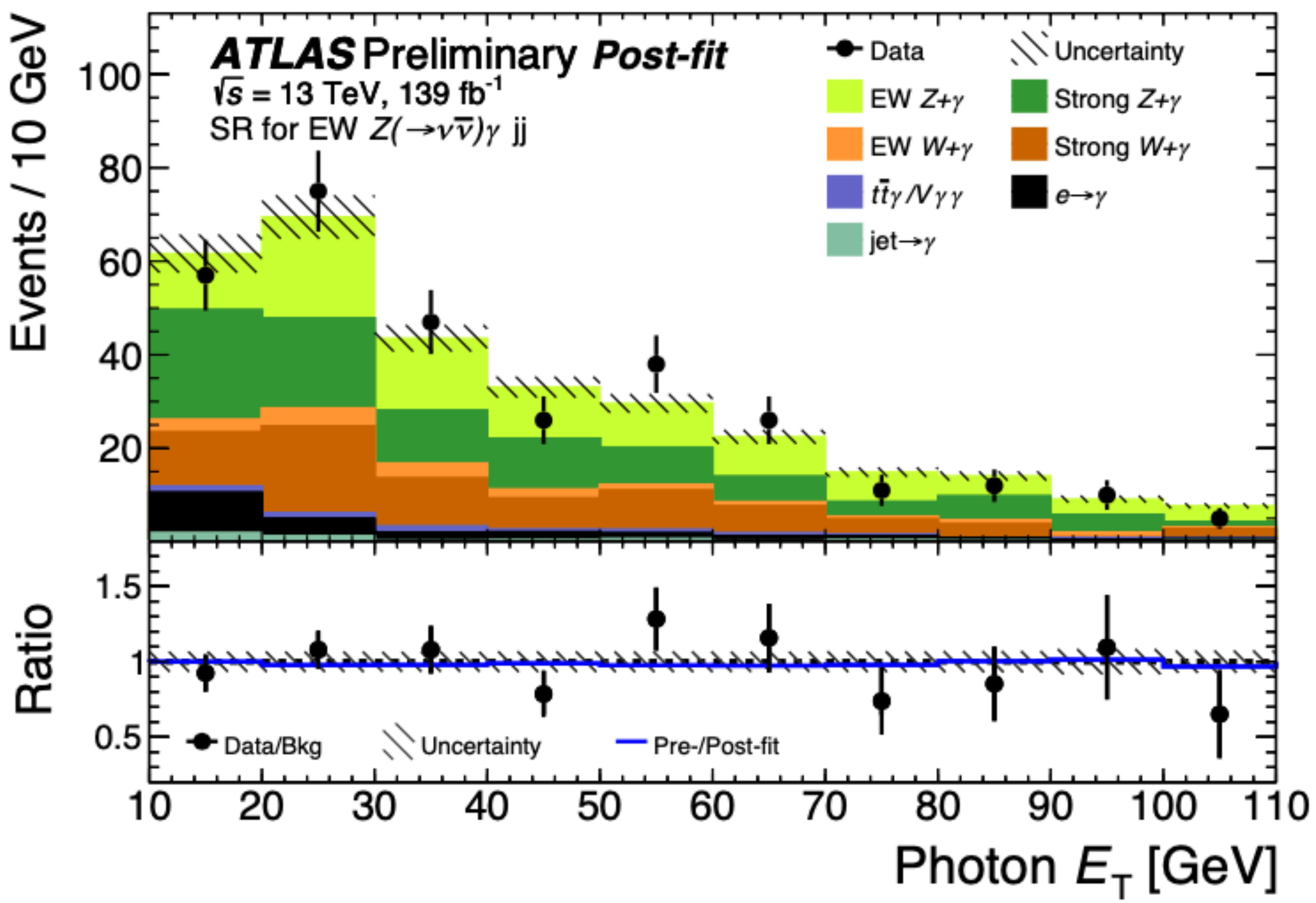


Observation of EW $Z(\nu\nu)\gamma jj$

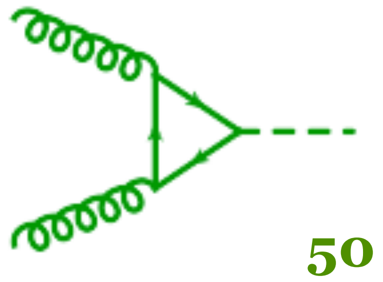
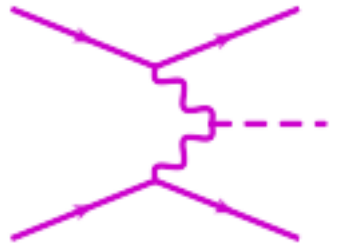
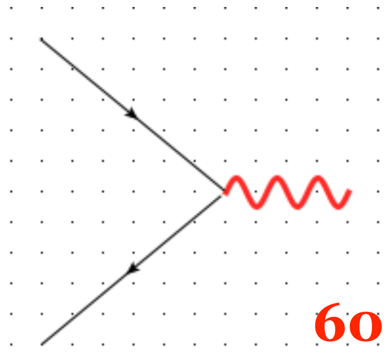
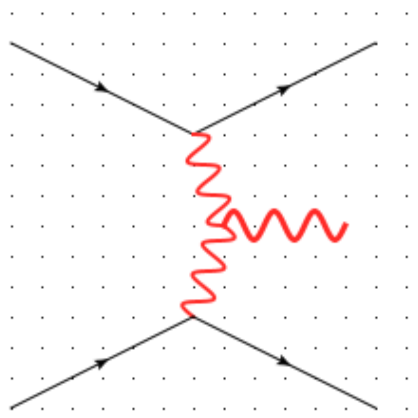
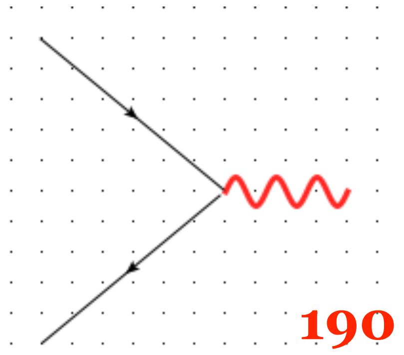
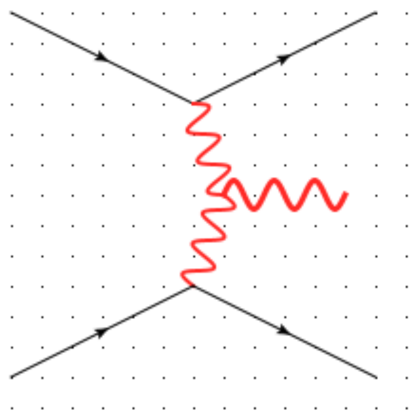
BRAND NEW

Process	Fake-e CR	$W^{\gamma}_{e\nu}$ CR	$W^{\gamma}_{\mu\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	SR - m_{jj} [TeV] 0.25-0.5	0.5-1.0	1.0-1.5	≥ 1.5
Strong $Z\gamma+$jets	8 ± 8	0 ± 1	3 ± 2	50 ± 12	20 ± 6	54 ± 12	13 ± 5	5 ± 2
EW $Z\gamma+$jets	0.6 ± 0.2	0.3 ± 0.2	0.4 ± 0.2	7 ± 2	4 ± 1	30 ± 7	25 ± 5	36 ± 7
Strong $W\gamma+$jets	43 ± 9	47 ± 9	133 ± 21	24 ± 6	22 ± 6	35 ± 10	9 ± 3	3 ± 1
EW $W\gamma+$jets	19 ± 6	31 ± 7	59 ± 13	1.4 ± 0.5	2 ± 1	6 ± 1	4 ± 1	5 ± 1
jet$\to \gamma$	1 ± 1	2 ± 2	3 ± 2	2 ± 2	1 ± 1	2 ± 2	1 ± 1	0.4 ± 0.3
jet$\to e$	34 ± 17	5 ± 3	–	–	–	–	–	–
$e \to \gamma$	–	2.7 ± 0.4	2.9 ± 0.4	13 ± 1	6 ± 1	11 ± 1	2.6 ± 0.4	1.4 ± 0.3
$\gamma+$jet	–	–	–	0.7 ± 0.5	0.7 ± 0.5	0.4 ± 0.3	0.1 ± 0.1	0.1 ± 0.1
$t\bar{t}\gamma/V\gamma\gamma$	3 ± 1	9 ± 2	13 ± 2	3 ± 1	2 ± 1	4 ± 1	0.4 ± 0.2	0.1 ± 0.1
Fitted Yields	108 ± 10	96 ± 8	213 ± 14	102 ± 9	58 ± 6	143 ± 12	54 ± 5	52 ± 6
Data	108	95	216	100	52	153	50	52
Data/Fit	1.00 ± 0.14	0.99 ± 0.12	1.01 ± 0.09	0.98 ± 0.13	0.90 ± 0.15	1.07 ± 0.11	0.93 ± 0.16	0.99 ± 0.18





Single and double boson production

Strong production		Electroweak production (VBF)		Ratio
	*H* 50 pb		*H* 3.8 pb	13 : 1
	*Z* 60 nb		*Z* 23 pb	2700 : 1
	*W* 190 nb		*W* 68 pb	2800 : 1

@ 13 TeV