Latest ATLAS VBF/VBS results

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on behalf of the ATLAS collaboration

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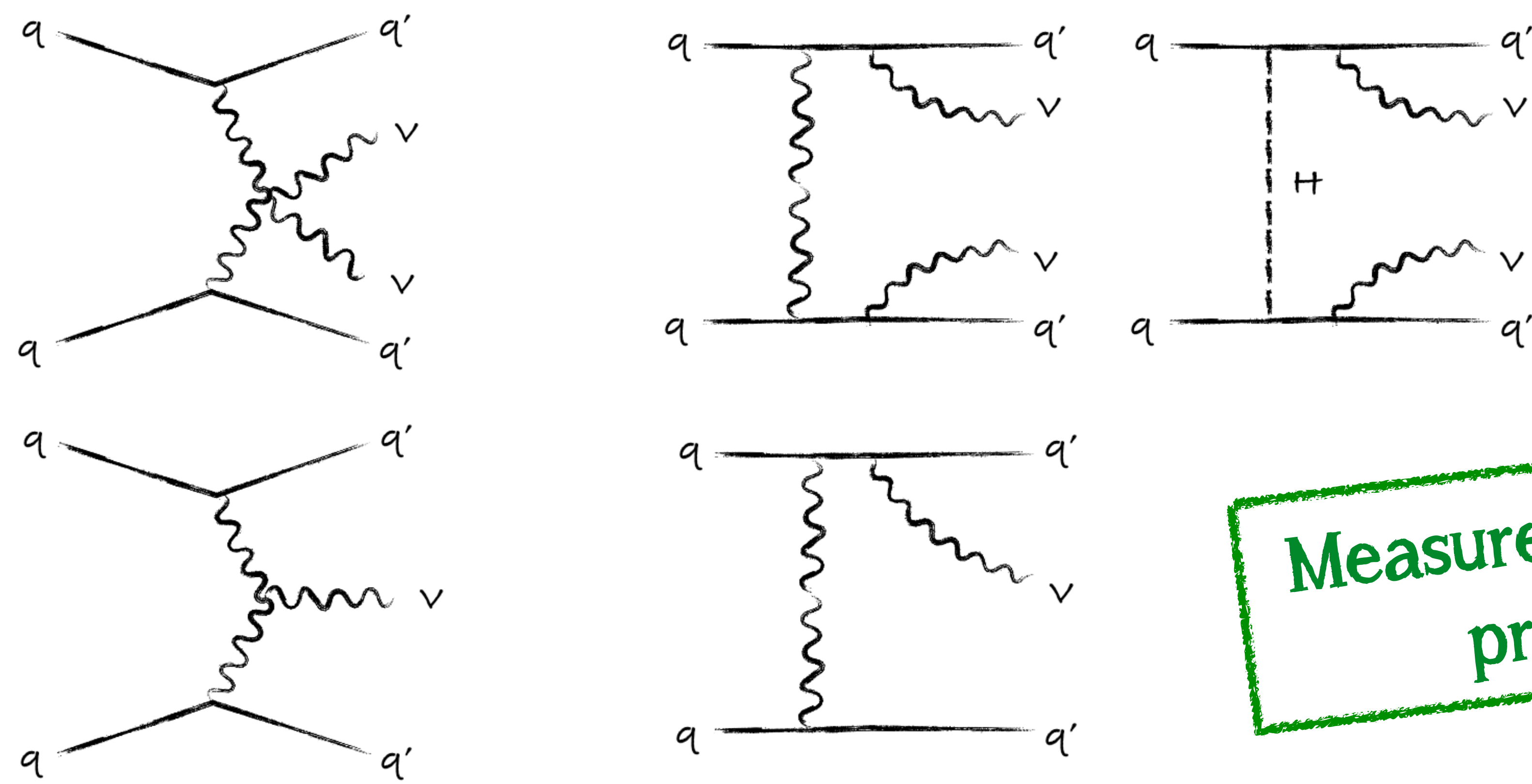
VBS and VBF: measurable, but not measurable

- Protons in LHC serve as source of vector boson beams
- Not possible to separate VBS (or VBF) in a gauge invariant way → Measure EWK V(V)jj production

Vector Boson Scattering/Fusion | **Vector Boson bremsstrahlung**

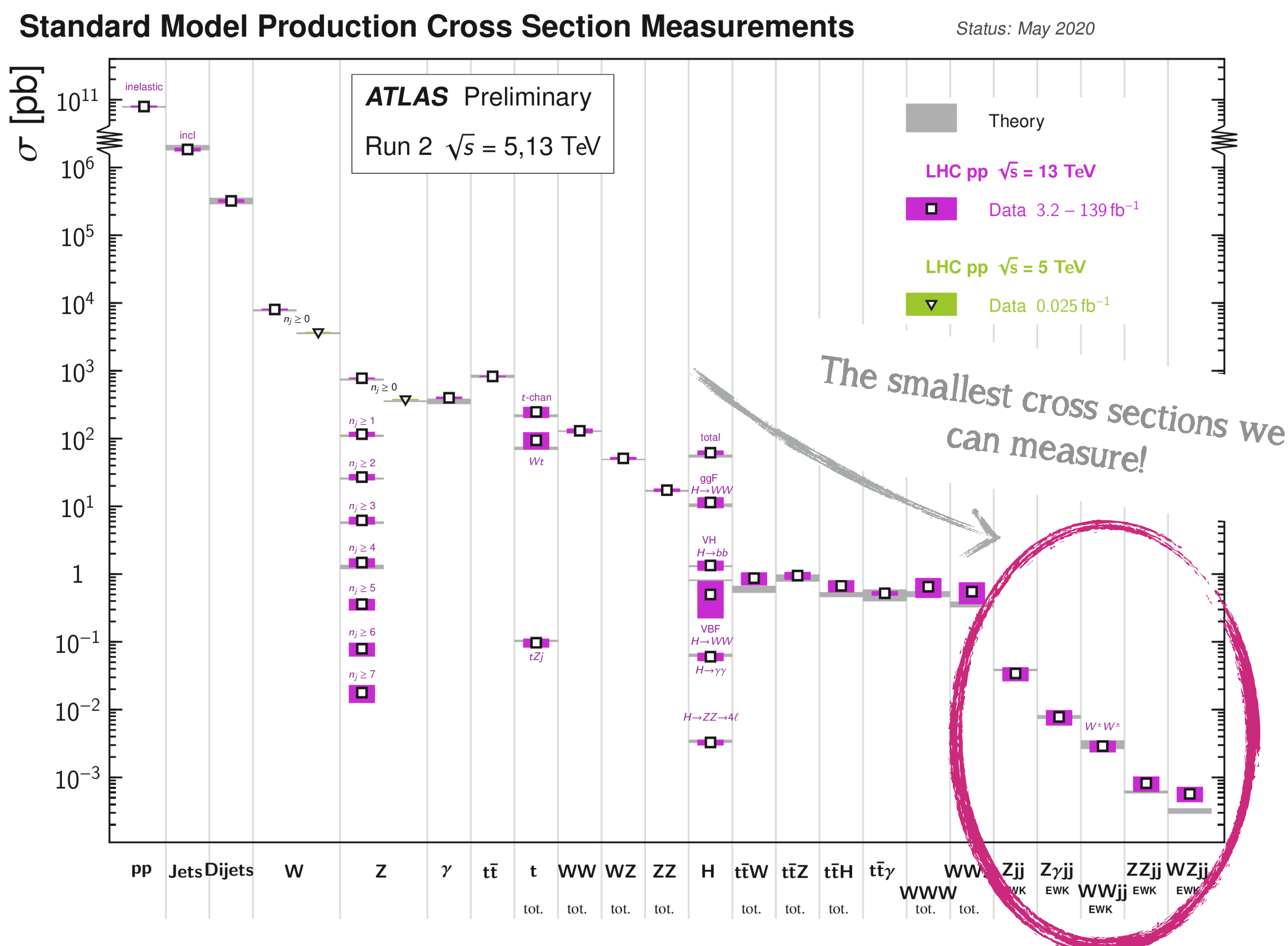


Measure EWK V(V)jj production

- Usually QCD mediated production of V(V)jj at the LHC has larger cross sections than the EWK production → ***crucial for a precise measurement to understand and reduce the QCD background!***

Published measurements

- What has been done so far, and what will be covered in this talk ?



Published measurements

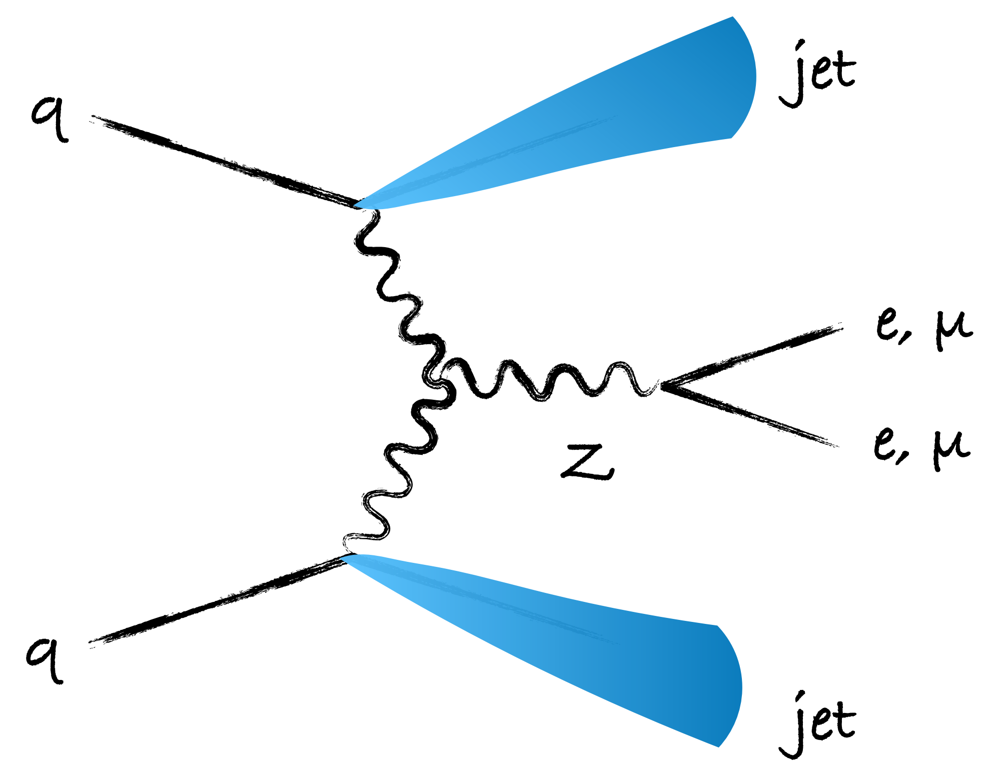
- What has been done so far, and what will be covered in this talk ?

	Channel		Energy (Luminosity)	Observed (Expected) σ
VBF	$W^{\pm}$ jj	Eur. Phys. J. C 77 (2017) 474	7, 8 TeV (5, 20 fb^{-1})	> 5σ
	Z jj	2006.15458	13 TeV (139 fb^{-1})	> 5σ
VBS	$W^{\pm}W^{\pm}$ jj	Phys. Rev. Lett. 123 (2019) 161801	13 TeV (36 fb^{-1})	6.5σ (4.4)
	$W^{\pm}Z$ jj	Phys. Lett. B 793 (2019) 469	13 TeV (36 fb^{-1})	5.3σ (3.2)
	$W^{\pm}\gamma$ jj	-	-	-
	$Z\gamma$ jj	Phys. Lett. B 803 (2020) 135341	13 TeV (36 fb^{-1})	4.1σ (4.1)
	ZZ jj	2004.10612	13 TeV (139 fb^{-1})	5.5σ (4.3)
	$W^{\pm}V$ semi-lept jj	Phys. Rev. D 100 (2019) 032007	13 TeV (36 fb^{-1})	< 3σ

Covered in this talk! (VBF $W^{\pm}$ jj, Z jj)

Covered in this talk! (VBS $Z\gamma$ jj, ZZ jj)

Electroweak Zjj production

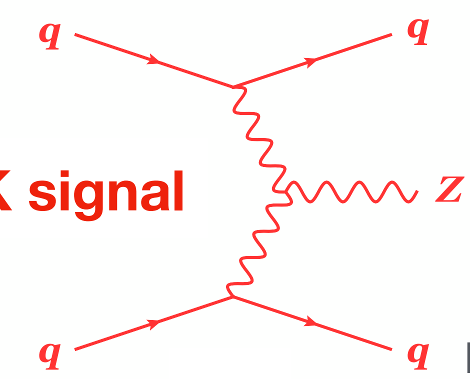


arXiv:2006.15458

EWK Zjj differential cross sections

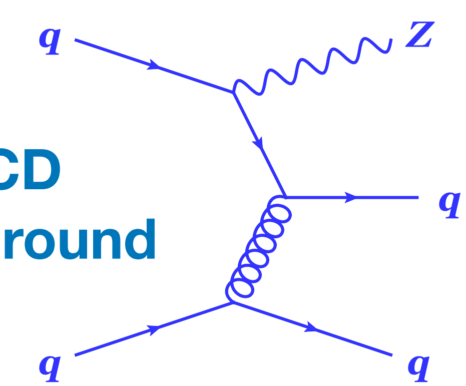
- Signal region built requiring high di-jet invariant mass, no hadronic activity in between the tagging jets and Z boson centrality
- QCD background (strong) has the largest contribution over the spectra
- Large QCD background miss-modeling, huge efforts to extract it in a data driven way!

EWK signal



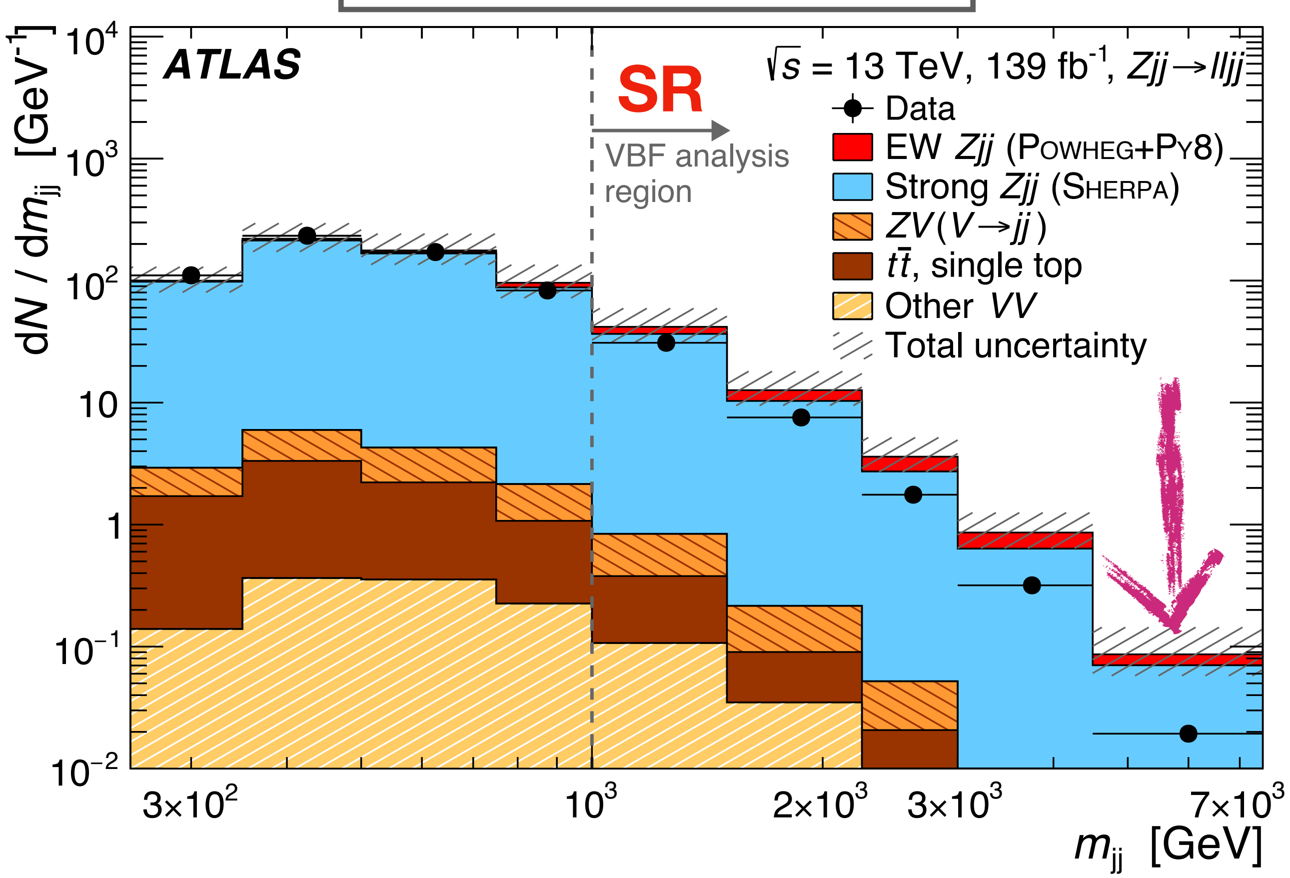
Ratio
2700 : 1

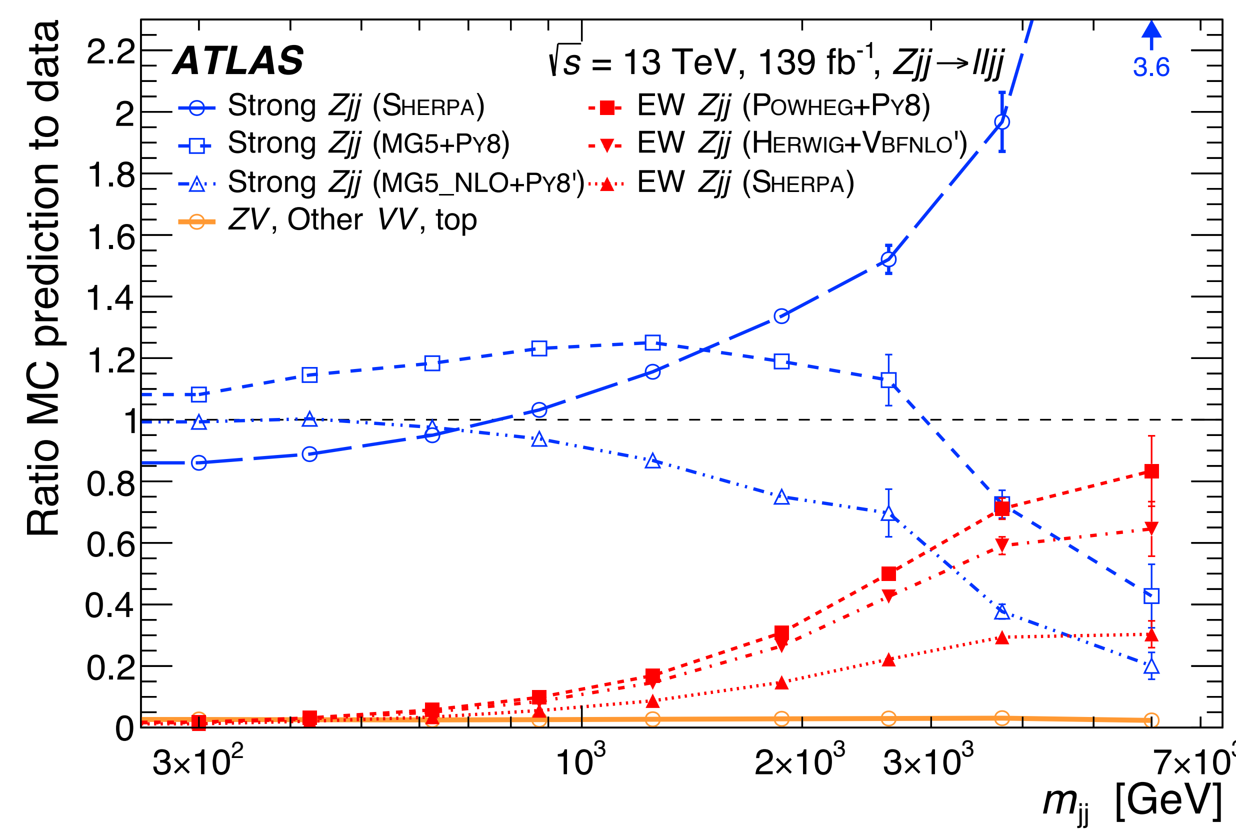
QCD background



	QCD production			EWK production	
	Generator	ME accuracy		Generator	ME accuracy
-○-	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	-■-	Powheg+Py8	NLO
-□-	MG5+Py8	LO (0–4j)	-▼-	Herwig7+VBFNLO	NLO
-△-	MG5_NLO+Py8	NLO (0–2j), LO (3–4j)	··▲··	Sherpa 2.2.1	LO (2–4j)

Di-jet invariant mass (pre-fit)





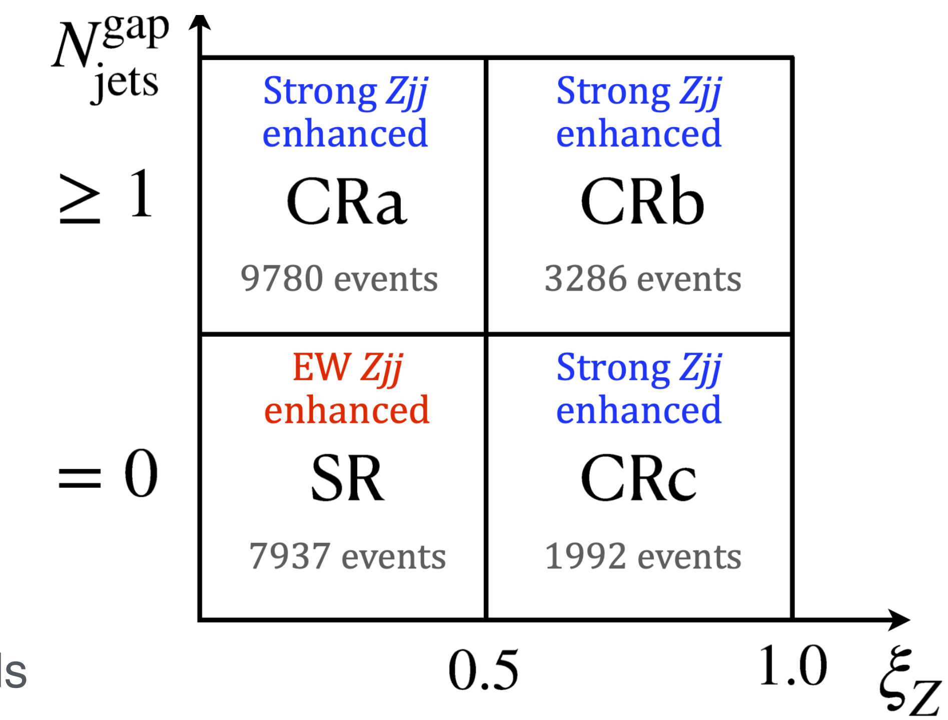
[arXiv:2006.15458]

Signal extraction steps

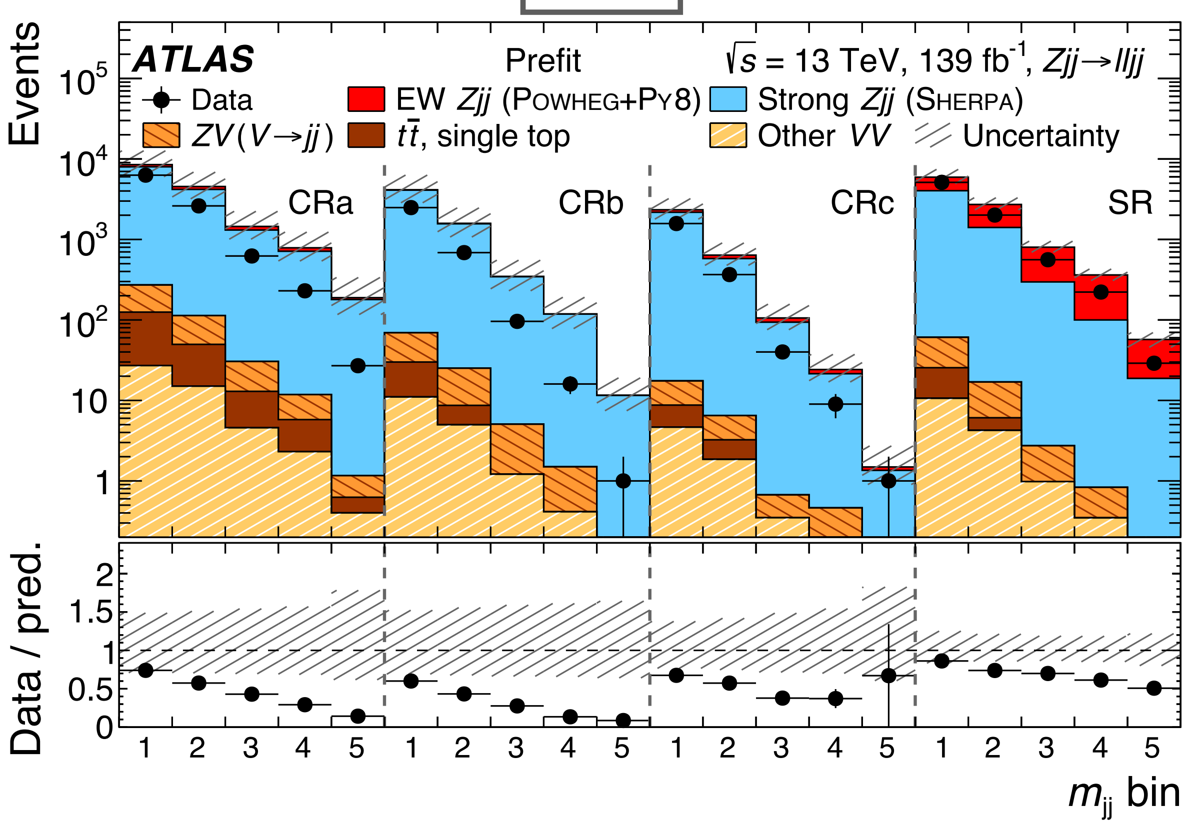
Binned maximum likelihood fit performed to reduce dependence on MC mis-modeling. In the fit:

1. QCD background is estimated → 4 different regions using two uncorrelated variables:
   - Bin-by-bin weights for strong Zjj, separate for low and high centrality and linked within the gap jets bins
   - Linear correction applied to strong Zjj to correct for residual dependence on the N gap jets
2. Bin-by-bin electroweak Zjj signal strengths (same in all regions)
3. Procedure repeated for different MC generators
4. The final EWK signal is taken to be the midpoint of the envelope of yields obtained using the three different QCD Zjj event generators

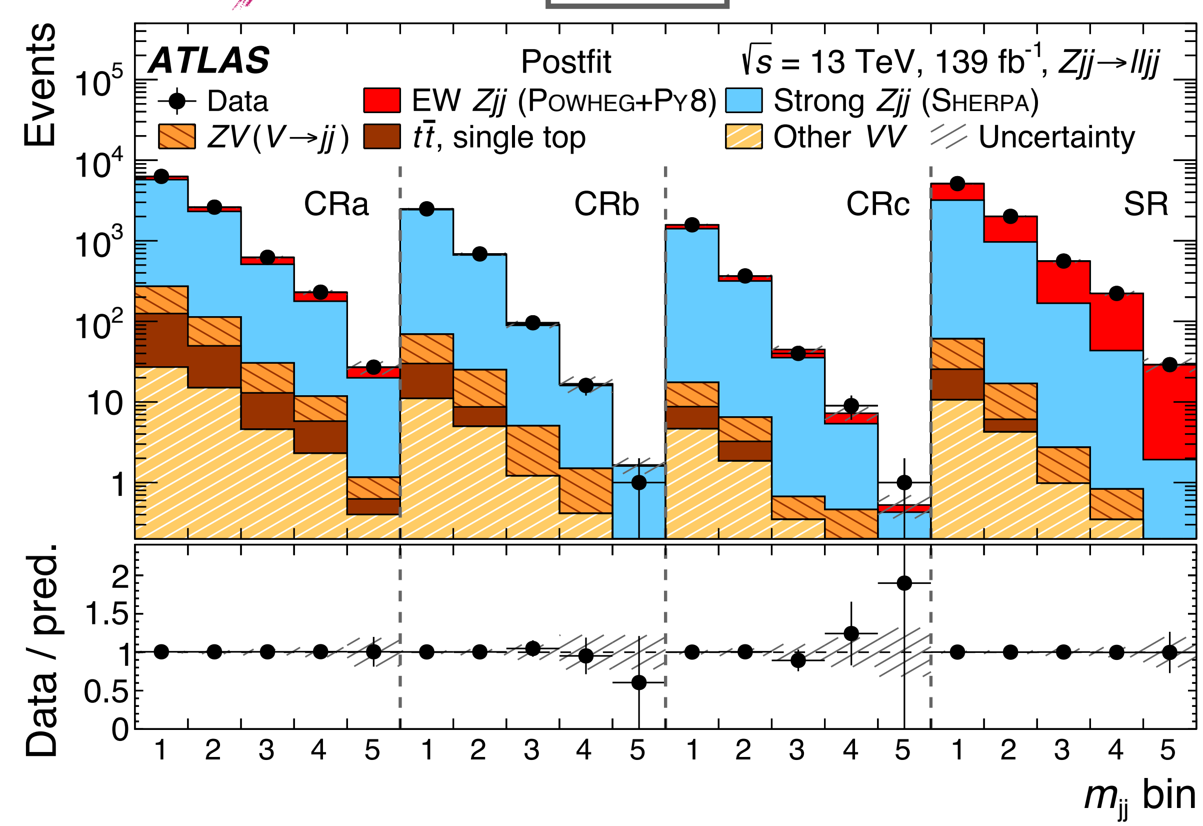
Regions for data-driven background



Pre-fit



Post-fit

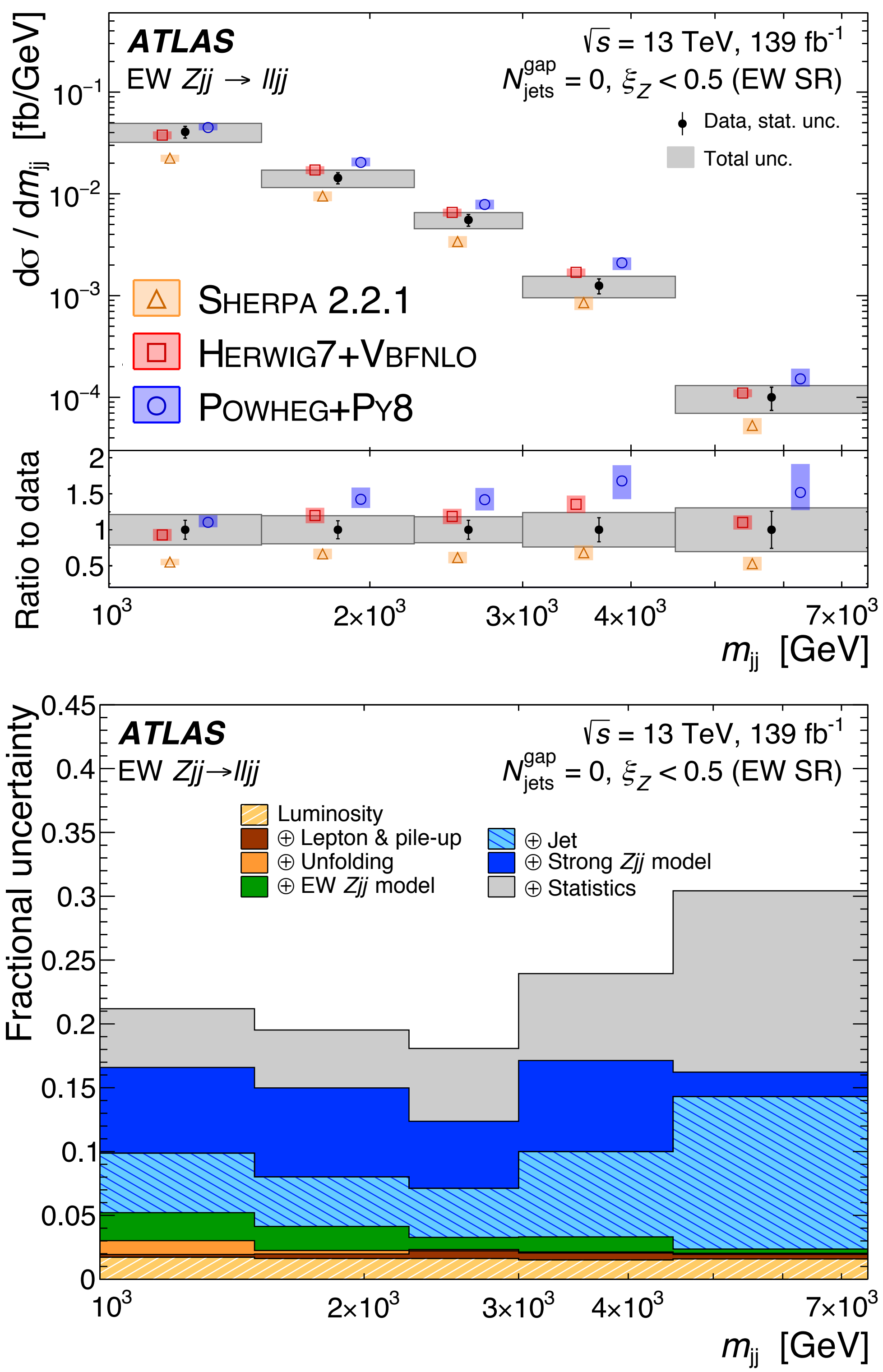


[arXiv:2006.15458](https://arxiv.org/abs/2006.15458)

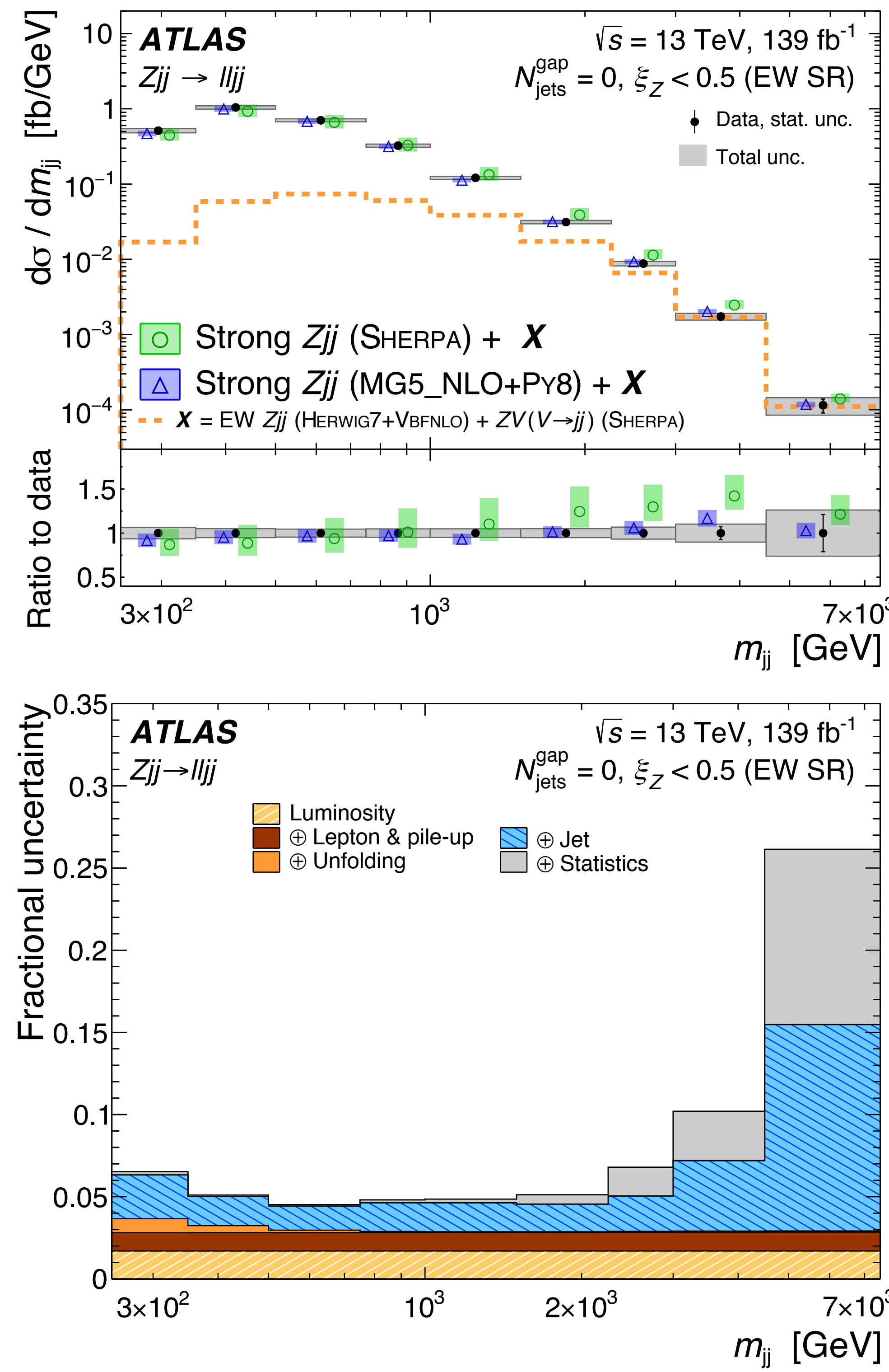
Zjj differential cross sections results

- Differential cross sections extracted for EWK only and EWK+QCD production as a function of four observables: m_{jj} , $|\Delta y_{jj}|$, $p_{T,ll}$ and $\Delta\phi_{jj}$

EWK Zjj production



EWK+QCD Zjj production



arXiv:2006.15458

Effective Field Theory interpretation

- To capture the EFT effects cross sections can be written as :

$$\sigma = \sigma_{SM} + \sum_i \frac{c_i}{\Lambda^2}\sigma^{interf}_{SM,i} + \sum_i \frac{c_i^2}{\Lambda^4}\sigma^{NP}_i + \sum_{ij,\, i\neq j} \frac{c_i c_j}{\Lambda^4}\sigma^{NP\text{-}interf}_{ij}$$

SM | EFT-SM interference (linear in $c_i \propto 1/\Lambda^2$) | Pure EFT terms (quadratic in $c_i \propto 1/\Lambda^4$)

Quadratic: $|\mathcal{M}_{d6}|^2$

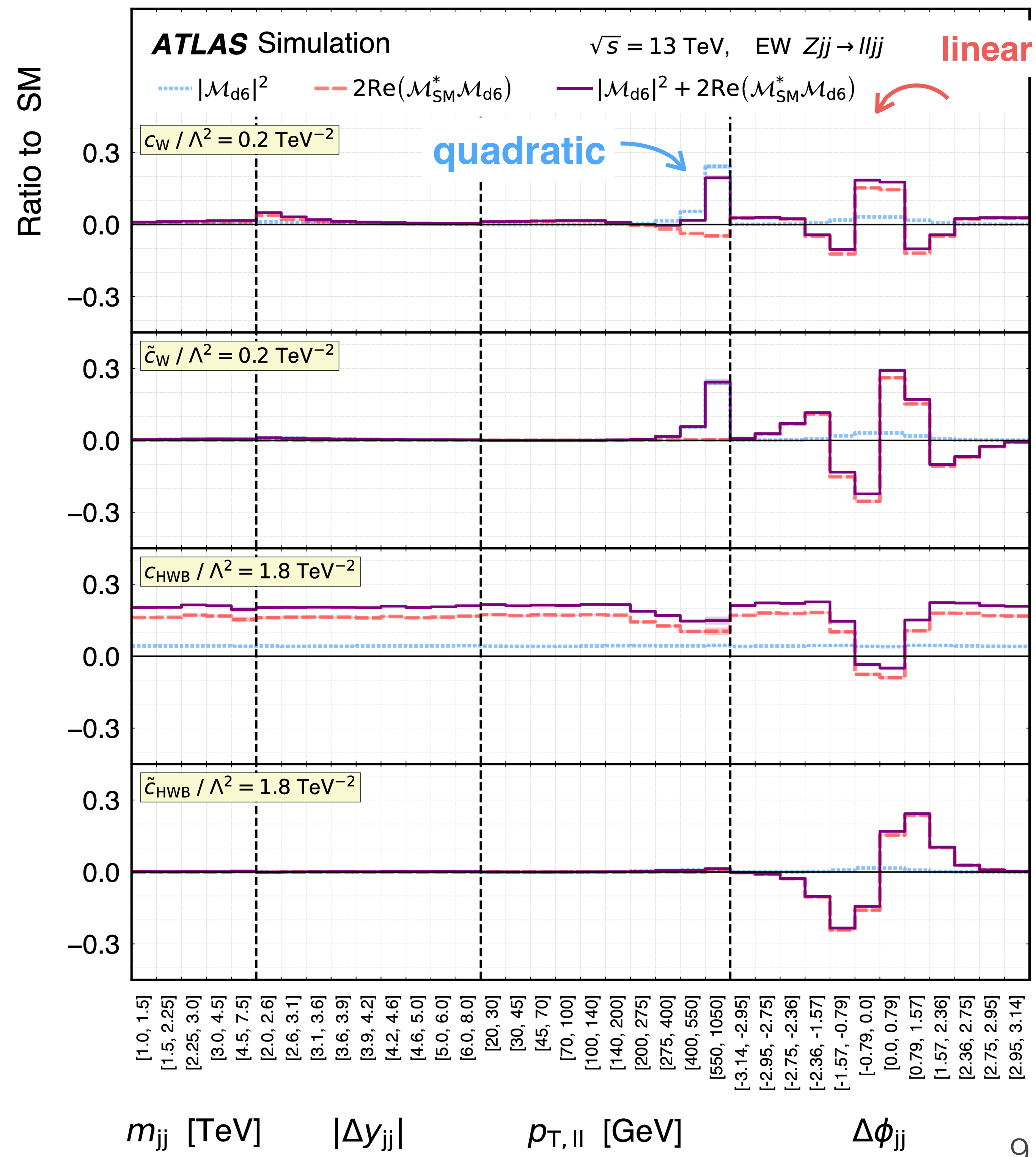
EFT-SM linear: $2\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{d6})$

full EFT: $|\mathcal{M}_{d6}|^2 + 2\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{d6})$

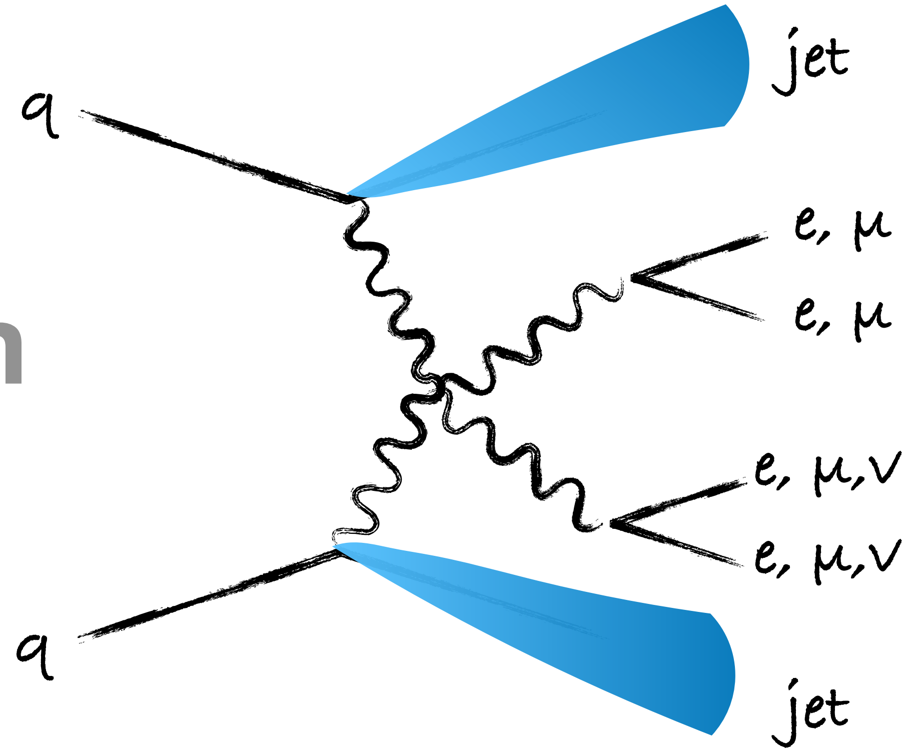
- Expectation: EFT-SM interference (linear) leading contribution
- Different distributions show different sensitivities to the linear and quadratic terms (Madgraph SMEFT at LO)
- Limits extracted using the measured EW Zjj differential cross-section as a function of the parity-odd $\Delta\phi_{jj}$

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%

- Strongest limits when pure dim-6 are excluded from the theoretical prediction!



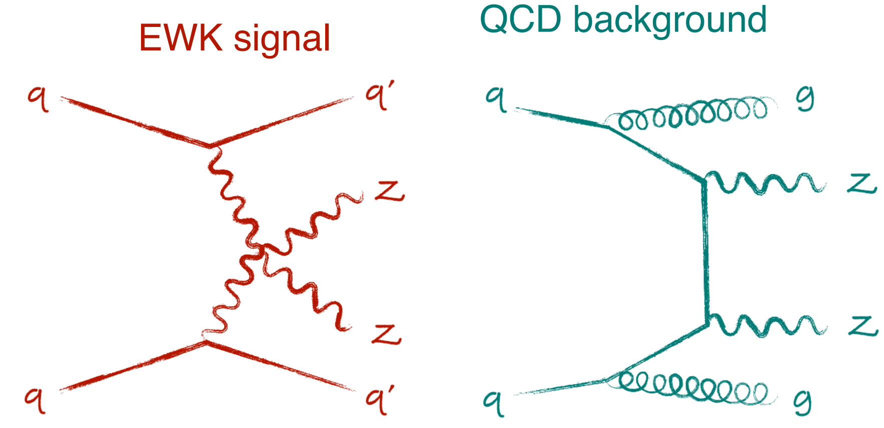
Electroweak ZZjj production



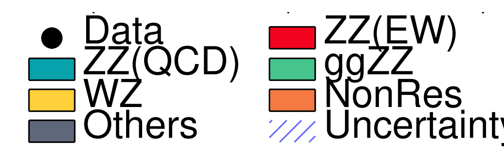
arXiv:2004.10612

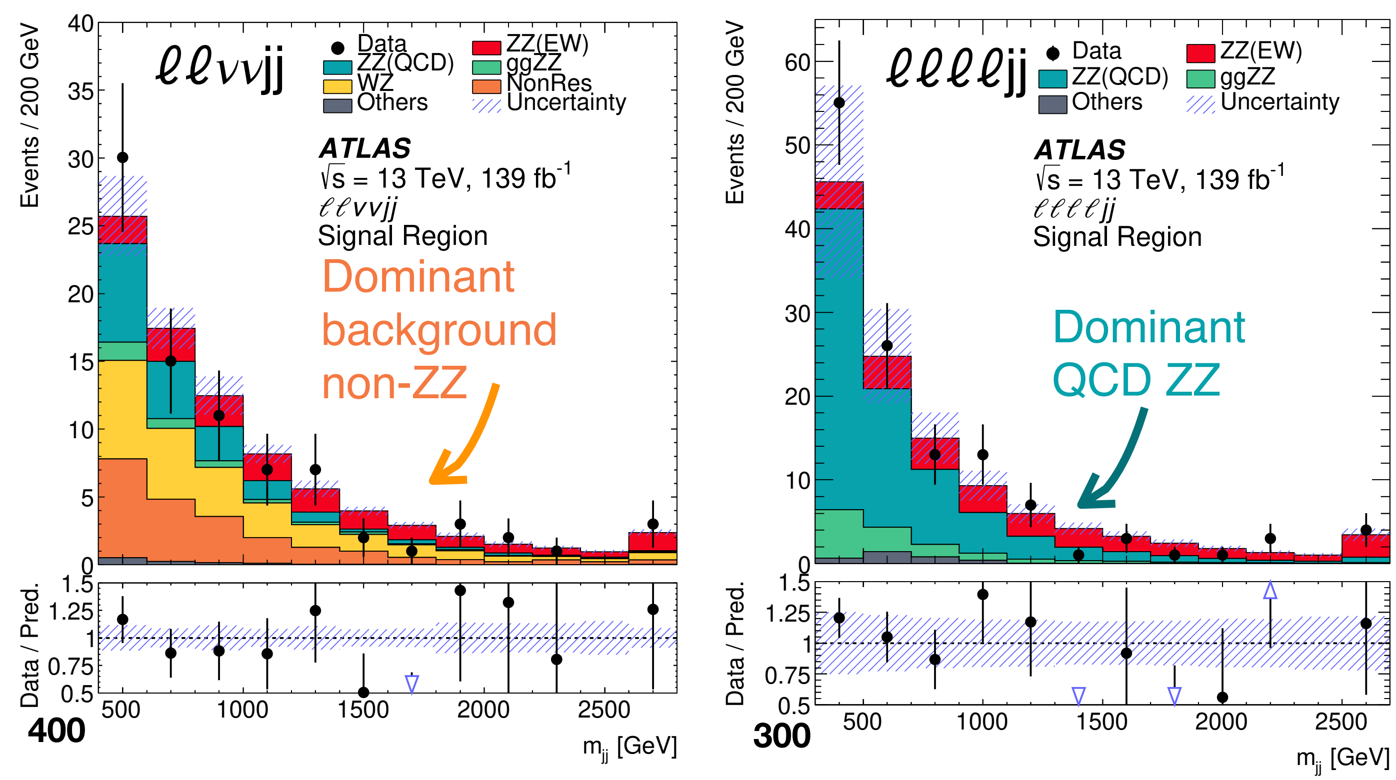
EWK ZZjj production

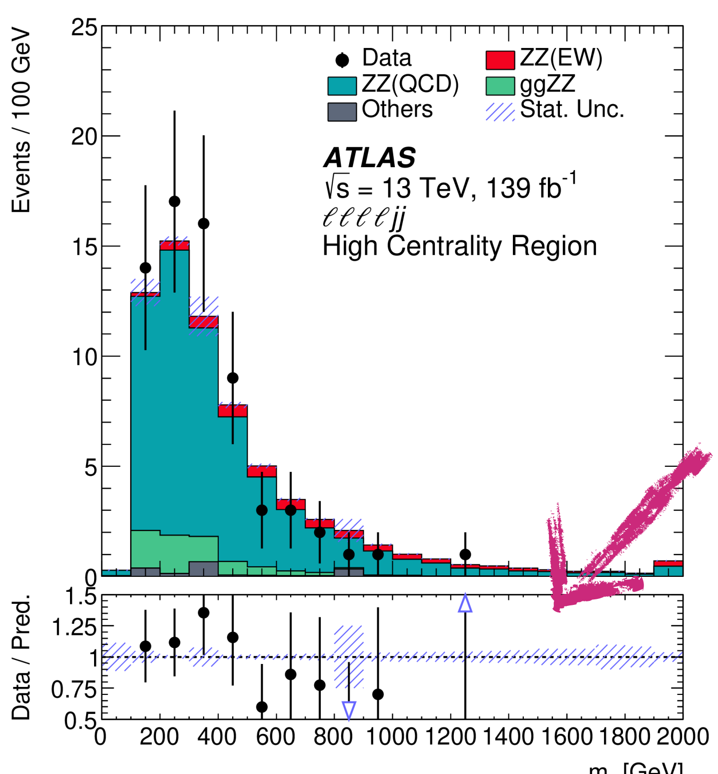
- ZZjj analysis performed in two channels $\ell\ell\ell\ell$jj and $\ell\ell\nu\nu$jj
- Interesting channel to probe neutral aQGCs
- Different background composition, data driven estimation for the main components
  - $\ell\ell\nu\nu$jj signal region:
    - WZ estimated in 3-lepton control region
    - Non-resonant (ttbar and WW) estimated in e$\mu\nu\nu$ control region
  - $\ell\ell\ell\ell$jj signal region:
    - QCD ZZjj control region with low m_{jj} or $\Delta y(jj)$ included in the fit



Di-jet invariant mass in the signal regions







High centrality region to verify m_{jj} modeling

	Process	Generator	ME accuracy
(red)	ZZ EWK	MG5_NLO+Py8	LO
(teal)	ZZ QCD	Sherpa 2.2.2	NLO (0j), LO (1-3j)
(yellow)	WZ	Sherpa 2.2.2	NLO (0j), LO (1-3j)

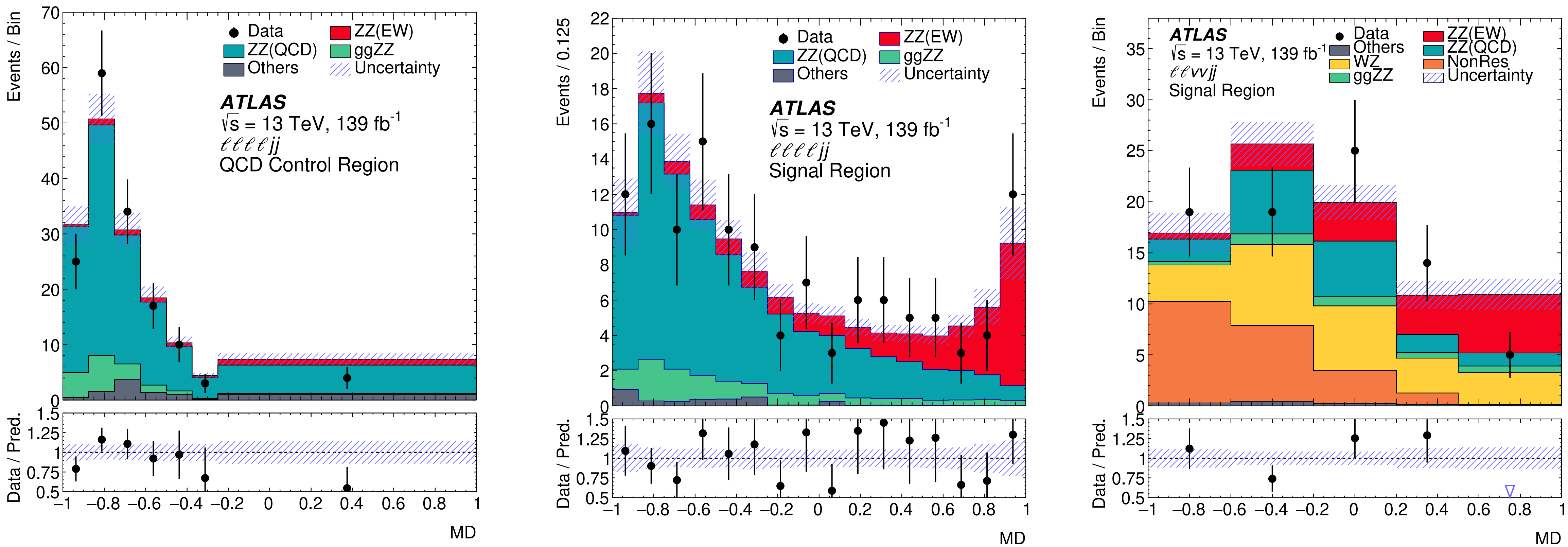
arXiv:2004.10612

EWK ZZjj results

- Extract inclusive cross-section EWK+QCD in the signal region

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

- Then use Multivariate Discriminants (MD) to separate the EWK component. Three MD fitted together

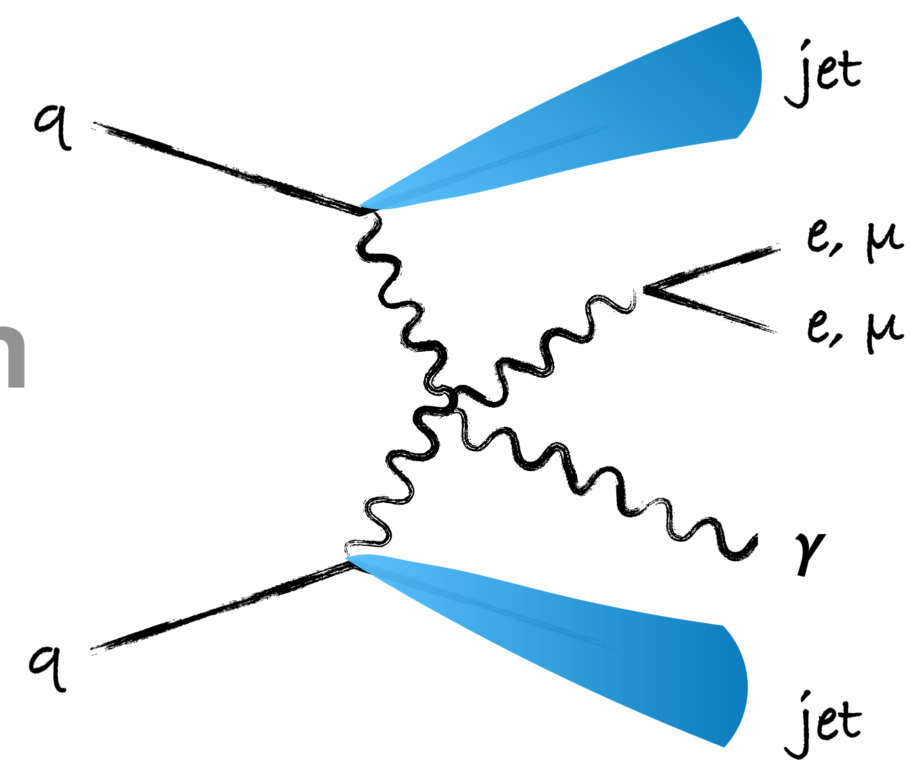


Observation!!

	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	$5.5\ (4.3)\ \sigma$

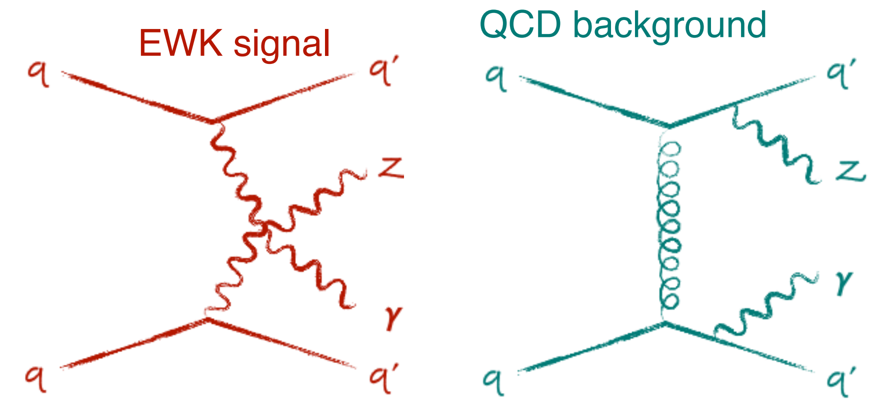
Fiducial cross-section in agreement with the SM

Electroweak $Z\gamma jj$ production



EWK Zγjj production

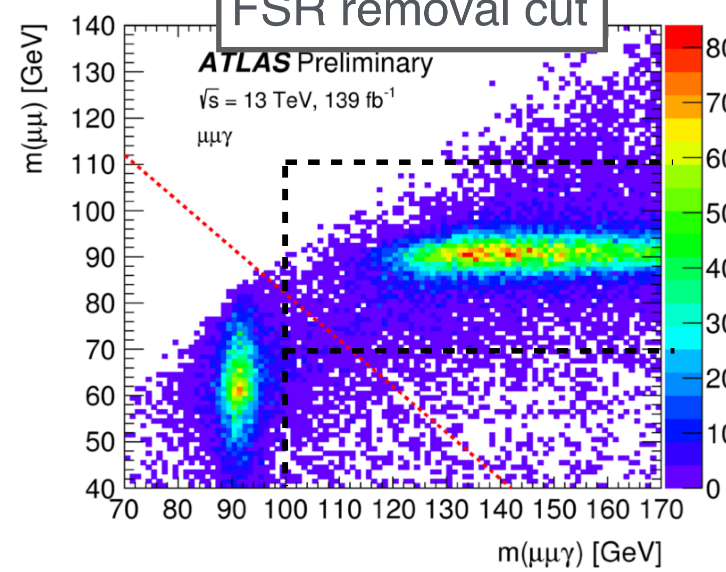
Phys. Lett. B 803 (2020) 135341

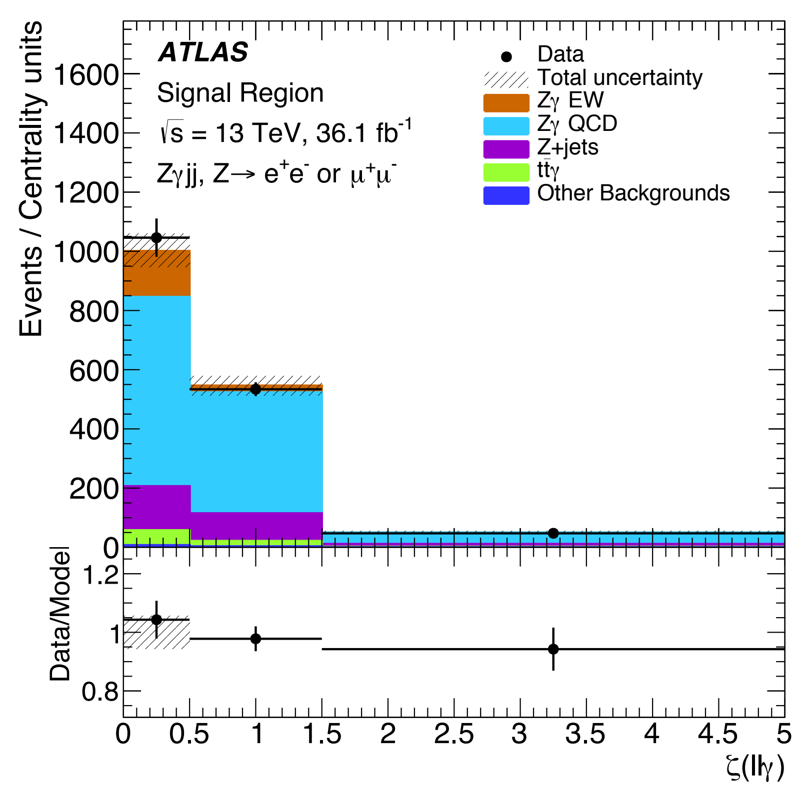


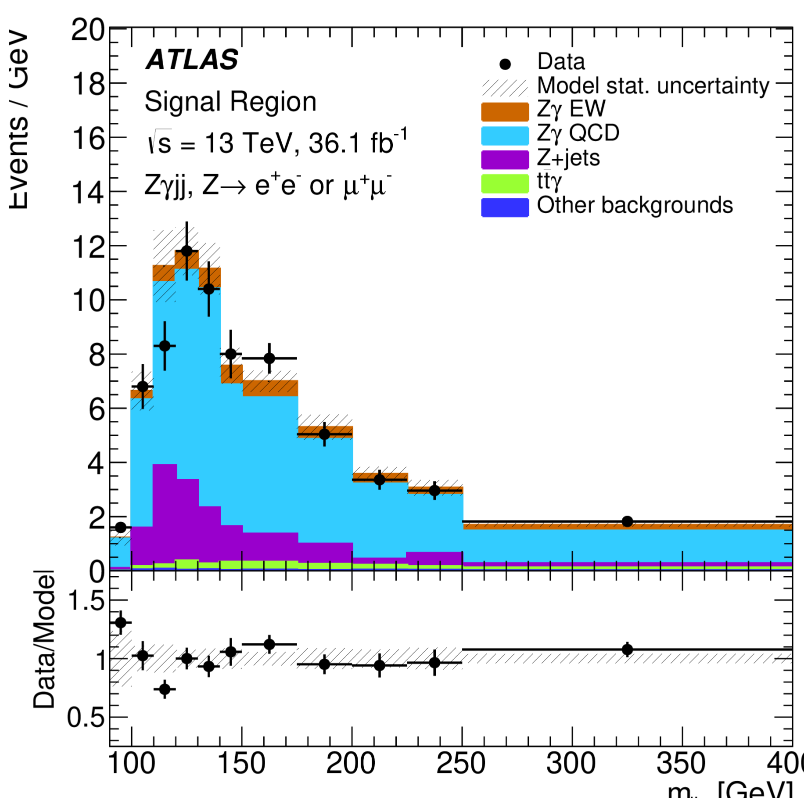
- Electroweak Zγ+2j production not yet observed.
  - Strong evidence reported by both ATLAS and CMS with 13 TeV data
  - Latest ATLAS result using 2015+2016 data ($36fb^{-1}$)
- Interesting channel to probe neutral aQGCs (larger cross section than ZZ), sensitive to WWZγ vertex
- Analysis selection:
  - Uses an mll+mllγ cut to reduce FSR contributions
  - Veto b-jets
  - $\Delta\eta_{jj}>1$, centrality ($Z\gamma$)<5 and $m_{jj}>150$GeV → *Looser than the usual VBS selections used*
- Simulation

Process	Generator	ME accuracy
Zγ EWK	MG5_NLO+Py8	LO
Zγ QCD	Sherpa 2.2.2	NLO (0-1j), LO (3j)
Z+jets	Sherpa 2.2.2	NLO (0-2j), LO (3-4j)

FSR removal cut

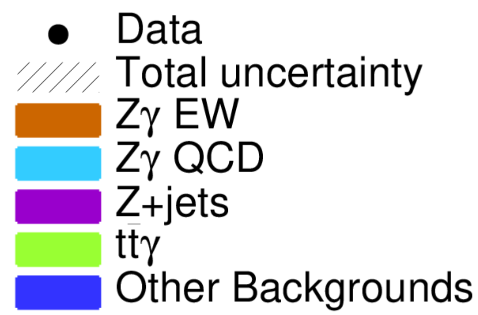






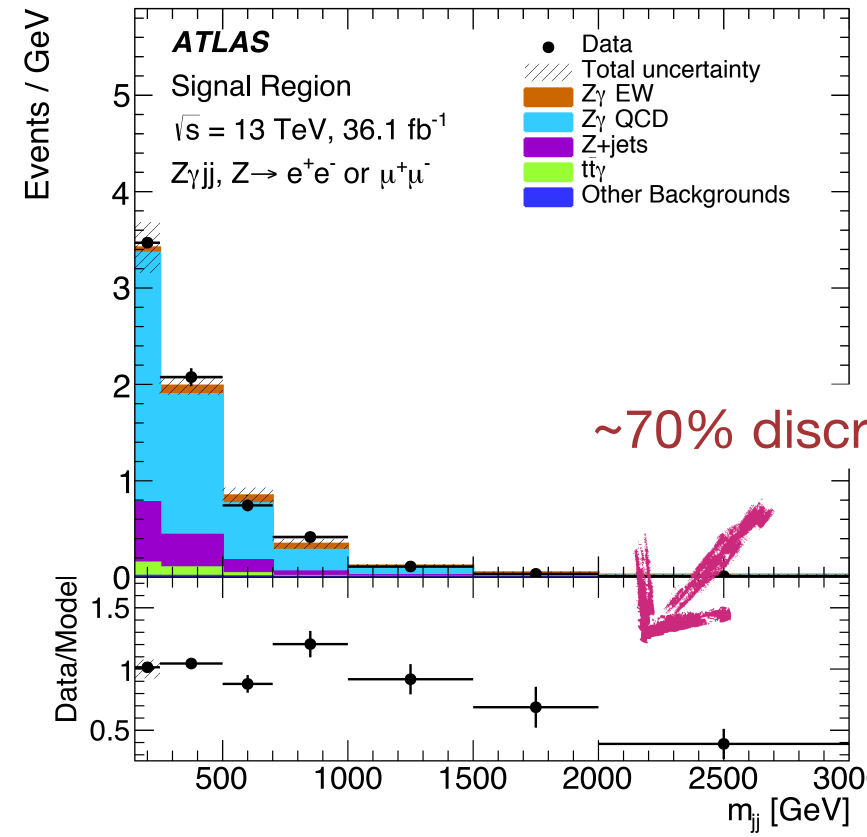
Phys. Lett. B 803 (2020) 135341

Background estimation



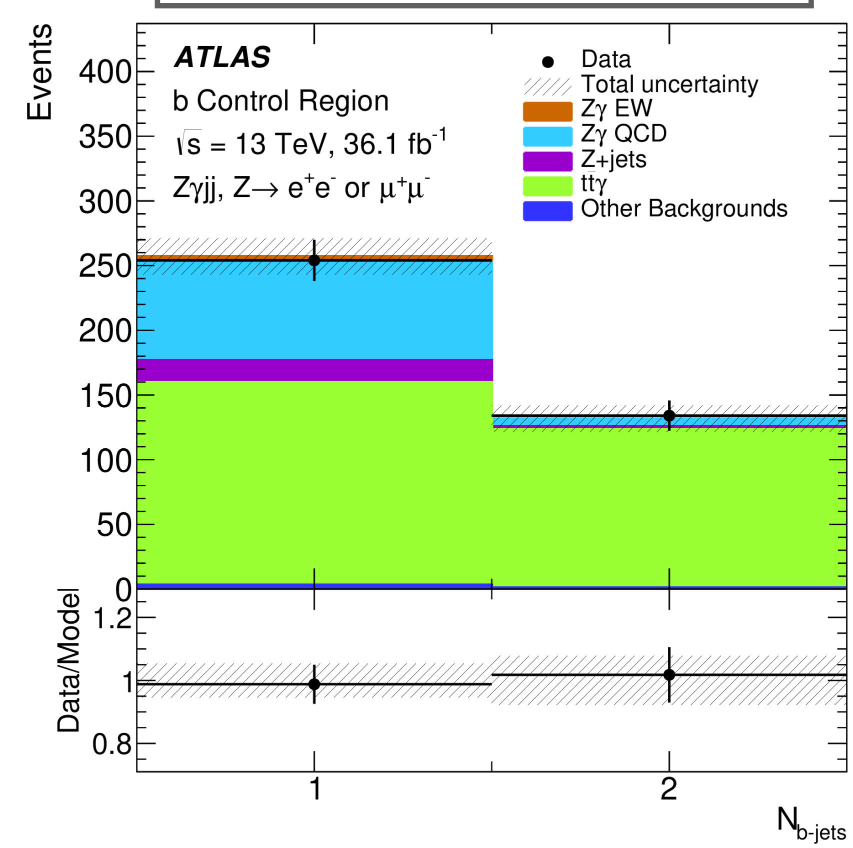
- **QCD Zγ+2j**
  - Normalization estimated from data (pre-correction 0.91), and then fitted in the signal region
- **Z+jet**: DD estimate of shape and normalization
  - 2D sideband method (photon ID, isolation), in region close to SR except: jet pT 30 GeV, mjj<150 GeV
  - Extrapolation to SR using ratio Z+jet/Zγ
- **ttbar γ**:
  - Pre-correction factor from data: 1.41 + fit in a CR
  - Dedicated CR (b-CR): >=1 b-jet -> ~70% purity, 25% Zγ QCD.
- **Smaller backgrounds: WZ, Wt**
  - From MC (less than 0.5% in SR)

Signal Region - dijet invariant mass



~70% discrepancy

b-jet enriched Control Region



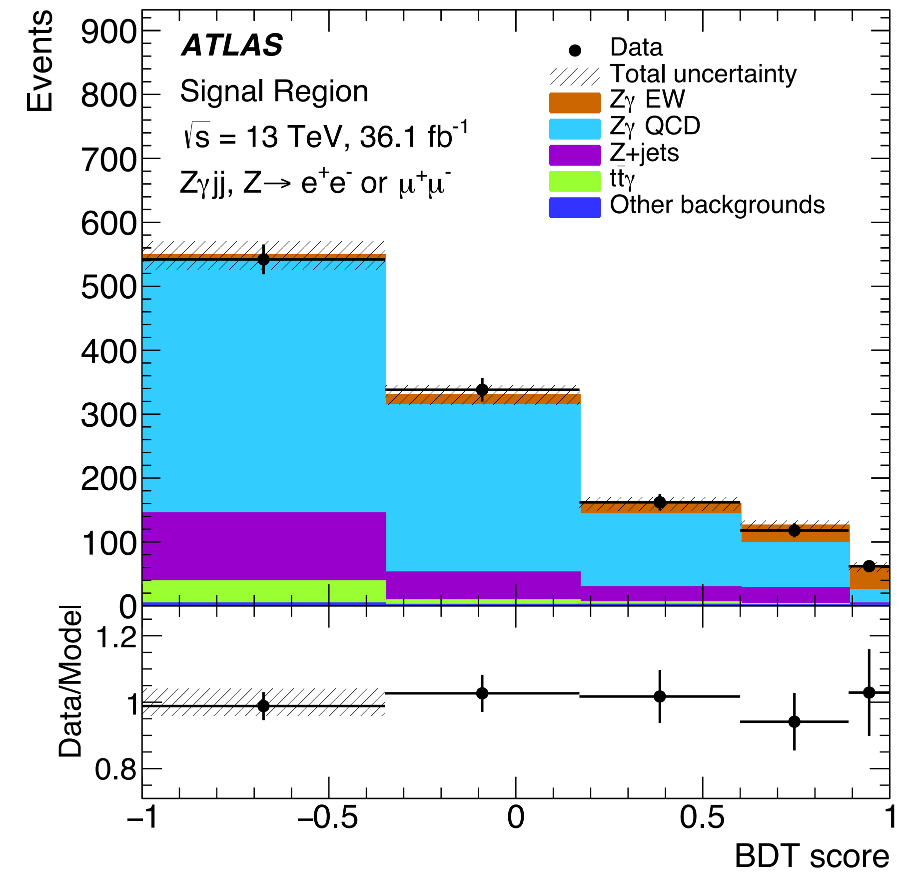
Phys. Lett. B 803 (2020) 135341

Zγjj results

- EWK Zγjj signal extraction:
  - Fitted BDT distribution trained to separate EW signal from background (13 variables)
  - Simultaneous fit of signal region and b-CR

Variable used in the BDT
m_{jj}
$\Delta\eta_{jj}$
$\zeta(\ell\ell\gamma)$
$m_{\ell\ell\gamma}$
$p_T^{\ell\ell\gamma}$
$m_{\ell\ell}$
$p_T^{\ell\ell}$
$p_T^{\text{lead lep}}$
$p_T^{\text{lead jet}}$
$\eta^{\text{lead jet}}$
$\min\Delta R(\gamma, j)$
$\Delta\phi(\ell\ell\gamma, jj)$
$\Delta R(\ell\ell\gamma, jj)$

BDT score in the signal region



Evidence !!

4.1σ expected and observed significance

- Measured cross sections:

$$\sigma^{\text{fid.}}_{Z\gamma jj\text{-EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})\text{ fb}$$
$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj\text{-EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\text{ fb}$$
$$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj\text{-EW}} = 8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.50\,(\text{scale})\text{ fb}$$

- Combined EW+QCD Zγjj cross-section also measured: same method and phase spaces, except for CRs which are excluded

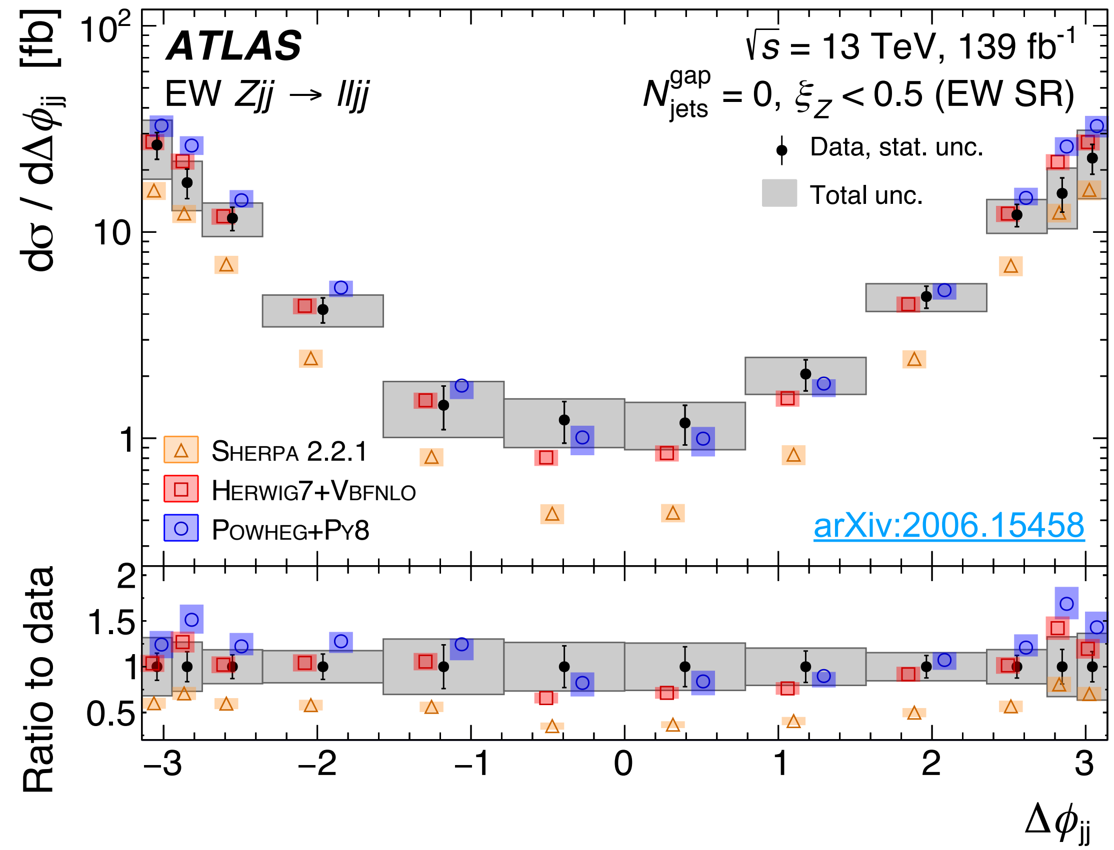
$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\,^{+9}_{-7}\,(\text{syst.})\,^{+21}_{-17}\,(\text{mod.})\text{ fb}$$
$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\text{ fb.}$$

In agreement with the expectation. Large uncertainties from theory modeling!

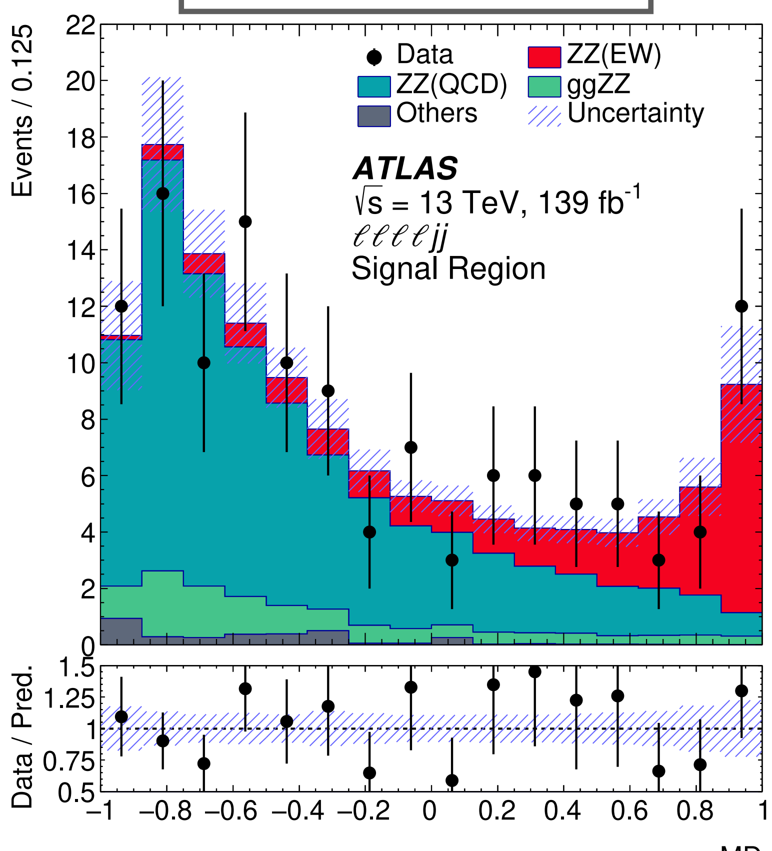
Summary

- New differential cross-section measurement of electroweak Zjj production, with strong limits on new physics through an effective field theory interpretation
- Measurements of inclusive Vjj and VVjj production in VBF/VBS topologies are providing a stress test of perturbative QCD
  - Crucial to understanding the background modeling and to make public the relevant information! What do theorist need?

EWK Zjj production



EWK ZZjj production



arXiv:2004.10612

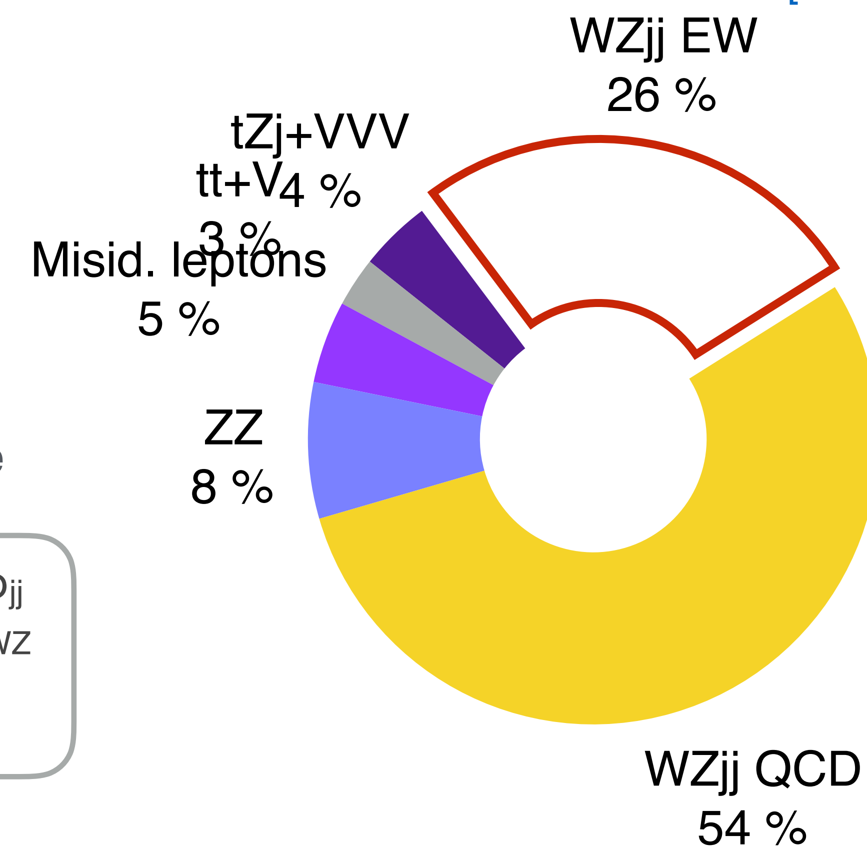
- VBS measurements are still in their infancy!
  - Lots of new results in preparation with full run-2 data
  - For “precision” measurement, need to improve signal and background modeling uncertainties

Backup

[arXiv:1812.09740]

EWK WZjj production

$W^{\pm}Z \rightarrow \ell\nu\ell\ell$



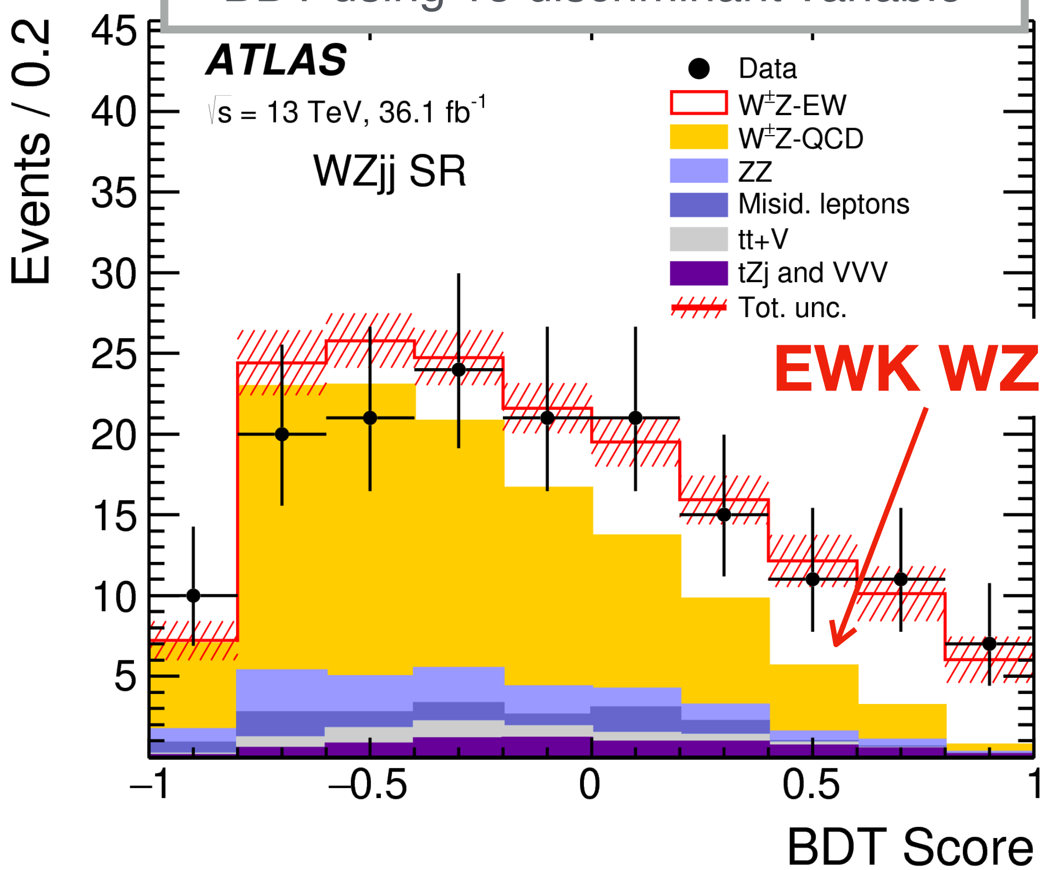
Signal extraction strategy

- Boosted Decision Tree trained on simulation events, to separate WZjj-EW from backgrounds
- 15 discriminant variables used

m_{jj}, N_{jets}, p_T^{j1}, p_T^{j2}, η^{j1}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$
$|y_{l,W} - y_Z|$, p_T^W, p_T^W, η^W, m_T^{WZ}
$\Delta R(j1, Z)$, $R_{p_T}^{hard}$, ζ_{lep}

- Simultaneous fit of BDT in signal region with 3 Control region regions (WZ QCD, ZZ and tZj)

BDT using 15 discriminant variable



Results:

Observation !!

Observed (expected with Sherpa) significance is **5.3σ** (3.2σ)

- Fiducial cross section measurement

$$\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57\,^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp. syst.})\,^{+0.05}_{-0.04}\,(\text{mod. syst.})\,^{+0.01}_{-0.01}\,(\text{lumi.})\text{ fb}$$

- LO Sherpa cross-section (No EW/QCD interference)

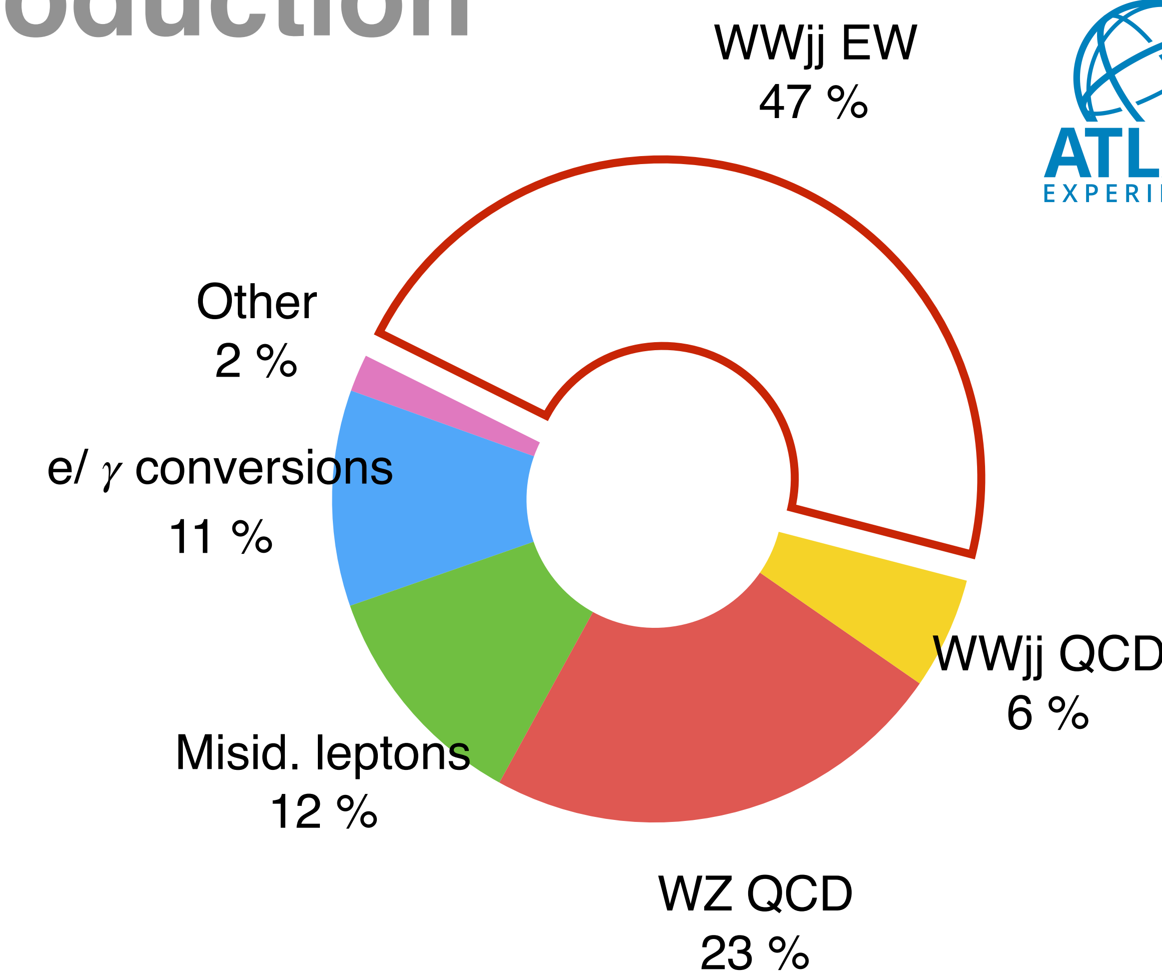
$$\sigma^{\text{fid., Sherpa}}_{WZjj-\text{EW}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\text{ fb},$$

EWK same charge WW production

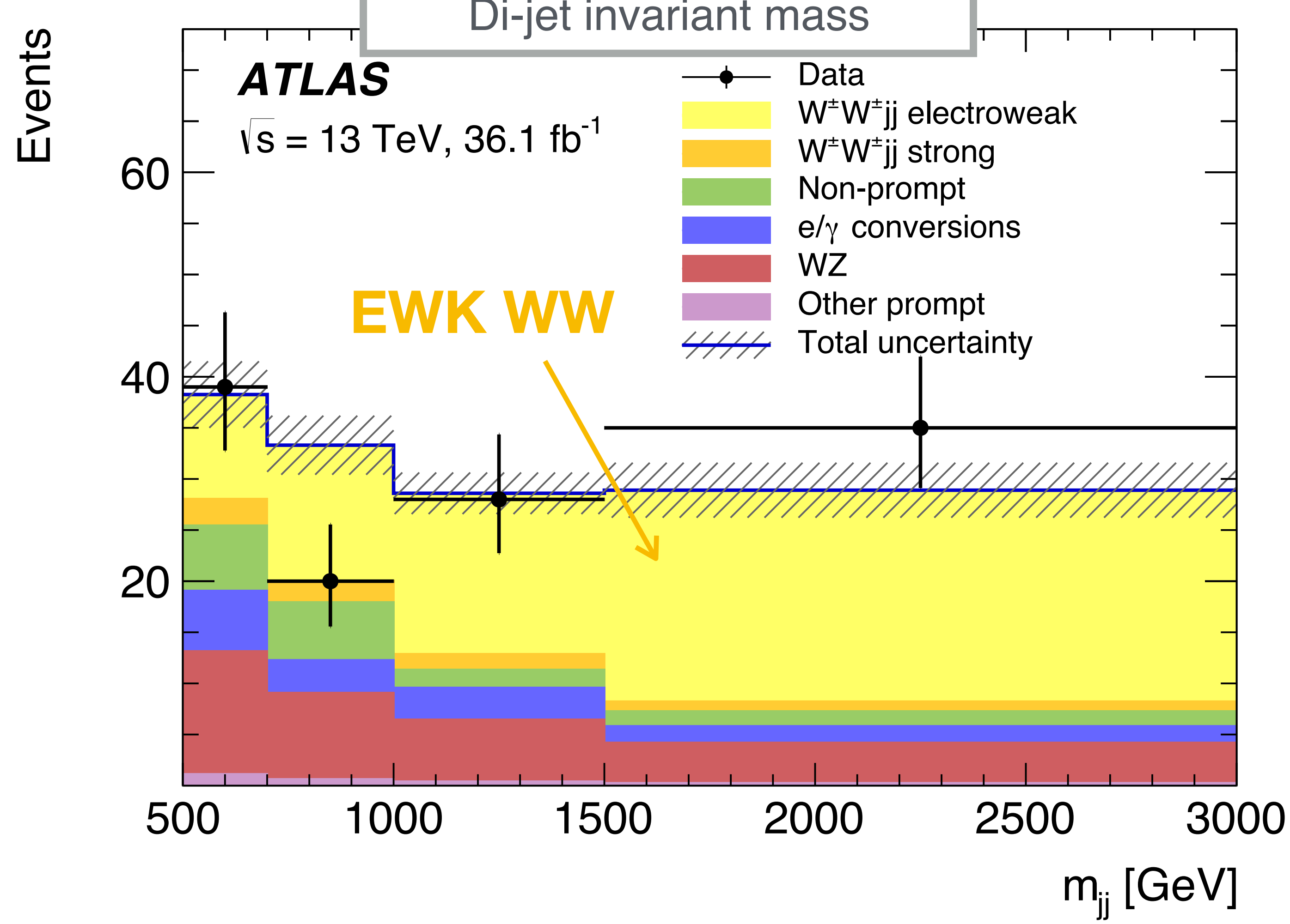
[Phys. Rev. Lett. 123 (2019) 161801]

$W^\pm W^\pm \rightarrow \ell\nu\ell\nu$

- Best EWK/QCD over background ratio!
- Main background WZ QCD mediated production:
  - Normalization taken from data
  - Shape taken from simulation
    - Theory uncertainties applied (PDF, scale, shower)



Di-jet invariant mass



Signal extraction strategy → Fitting framework development

- Simultaneous fit of dijet invariant mass (M_{jj}>200GeV) and WZ control region

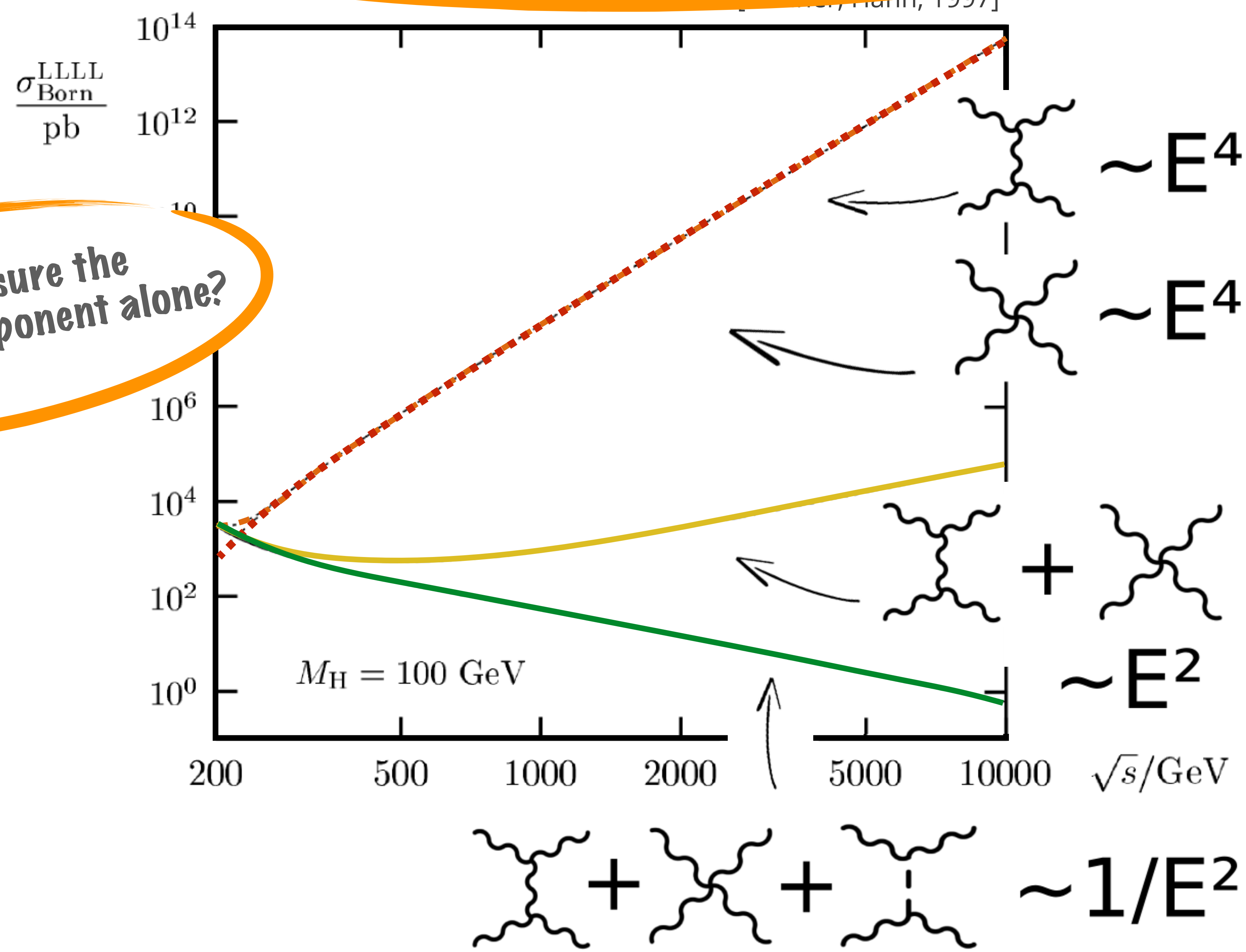
Observation !!

Observed (expected with Sherpa) significance is **6.5σ** (4.4σ)

Why Vector Boson scattering is interesting?

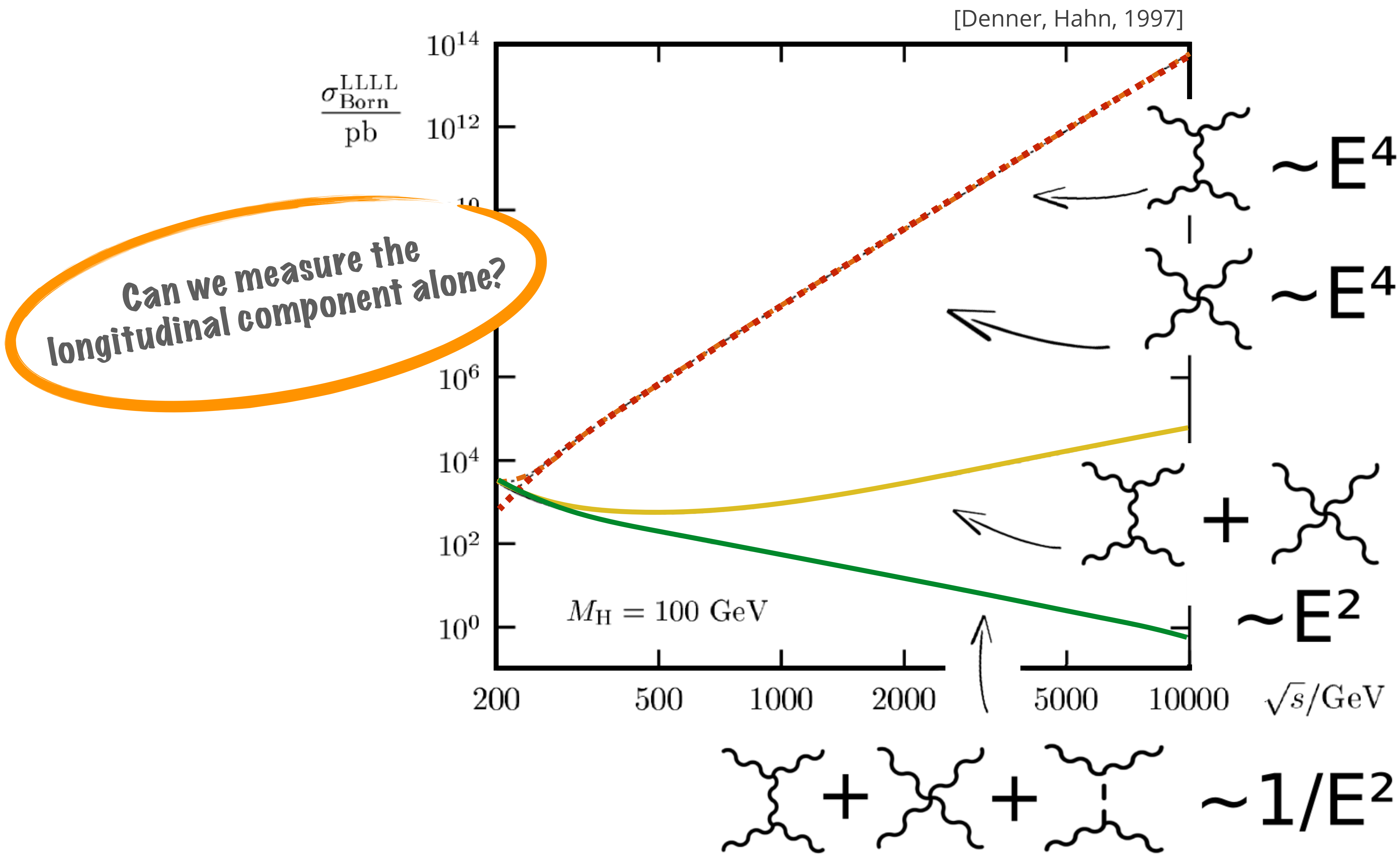
- Example: Cross-section for longitudinal $W_L^+W_L^- \to W_L^+W_L^-$ scattering

Can we measure the longitudinal component alone?

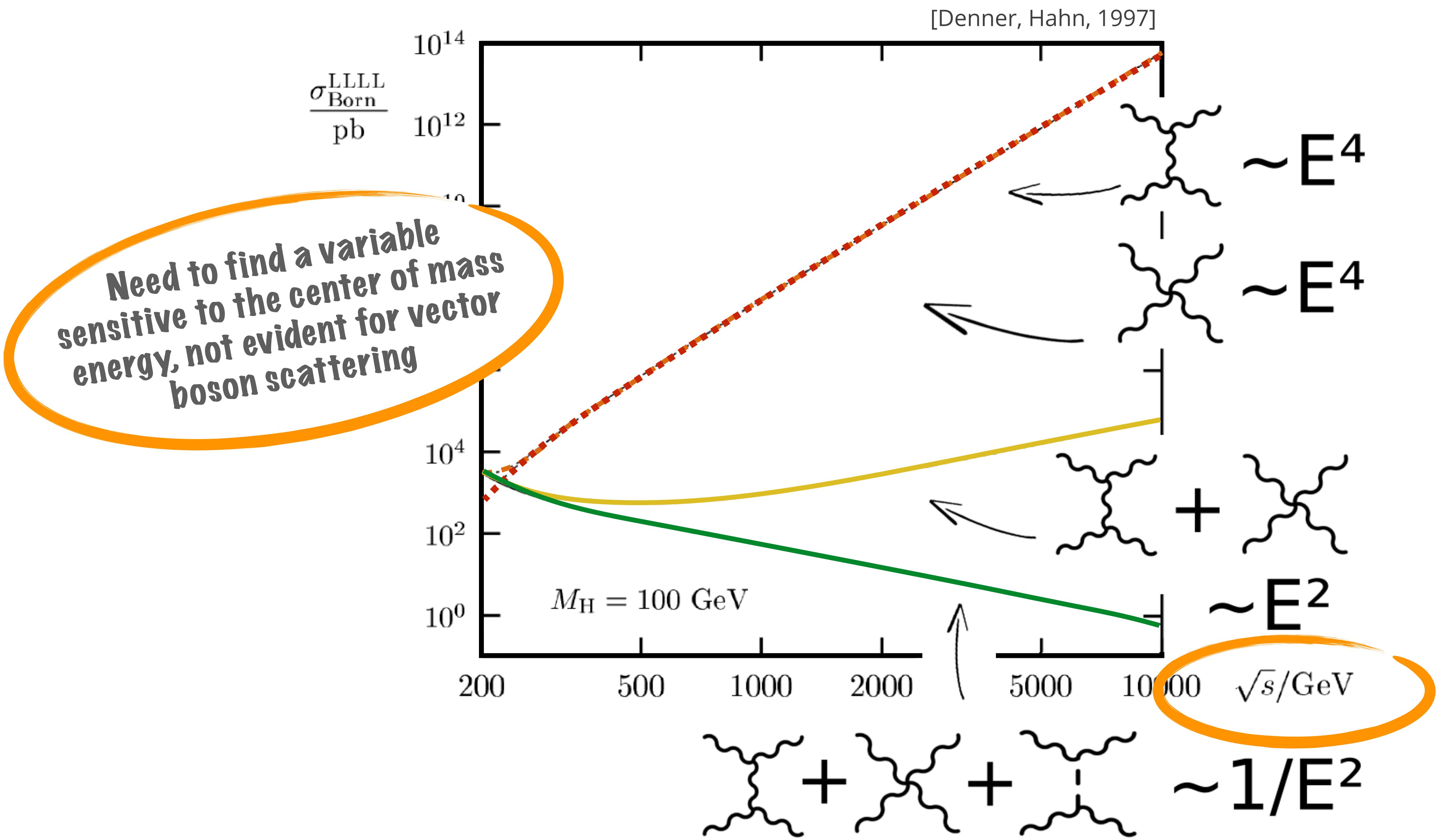


- Test of electroweak sector and EW Symmetry Breaking
- Complementary to "direct" Higgs boson property studies
- Differences in this sector will be indications of new physics

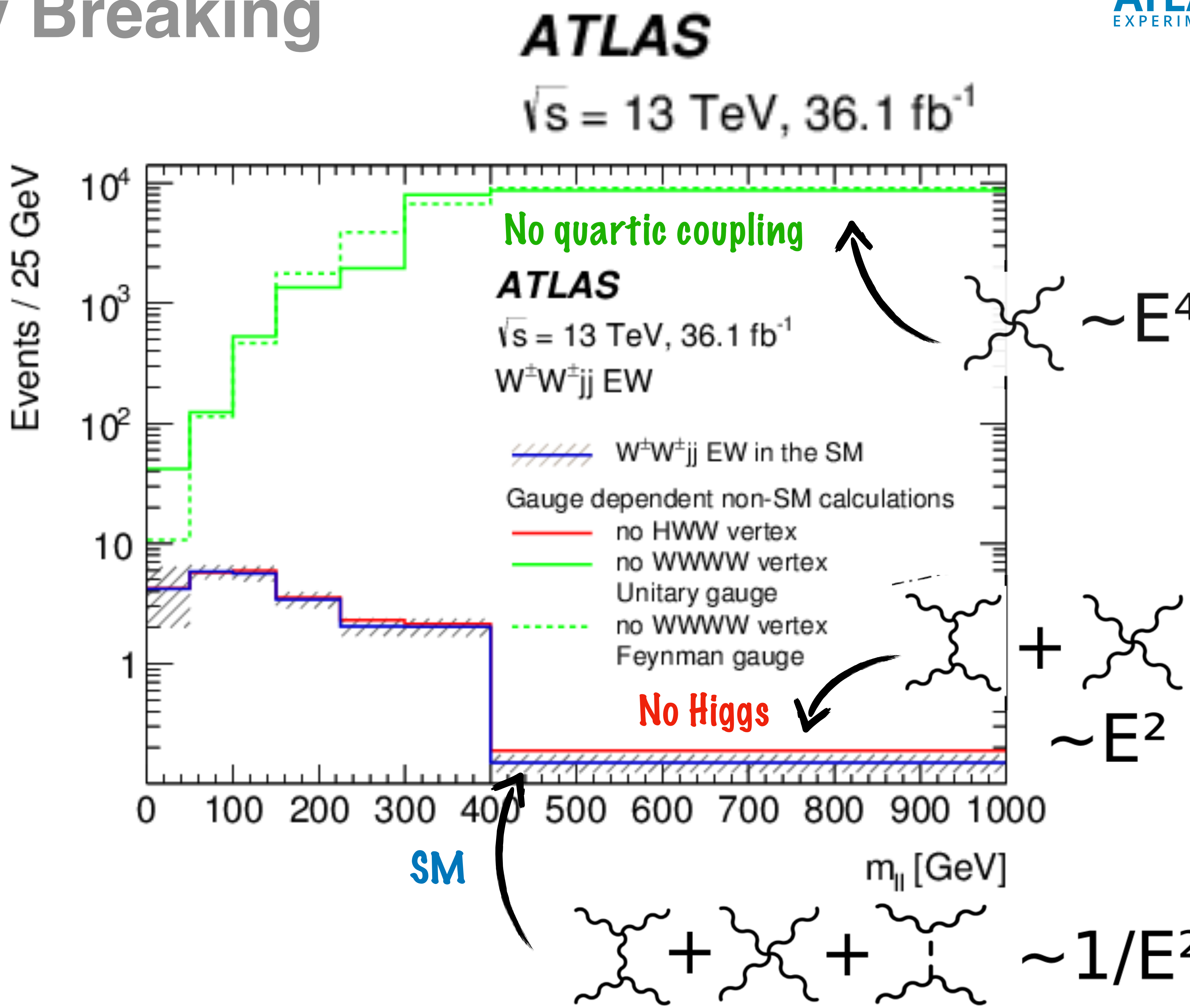
Why Vector Boson scattering is interesting?



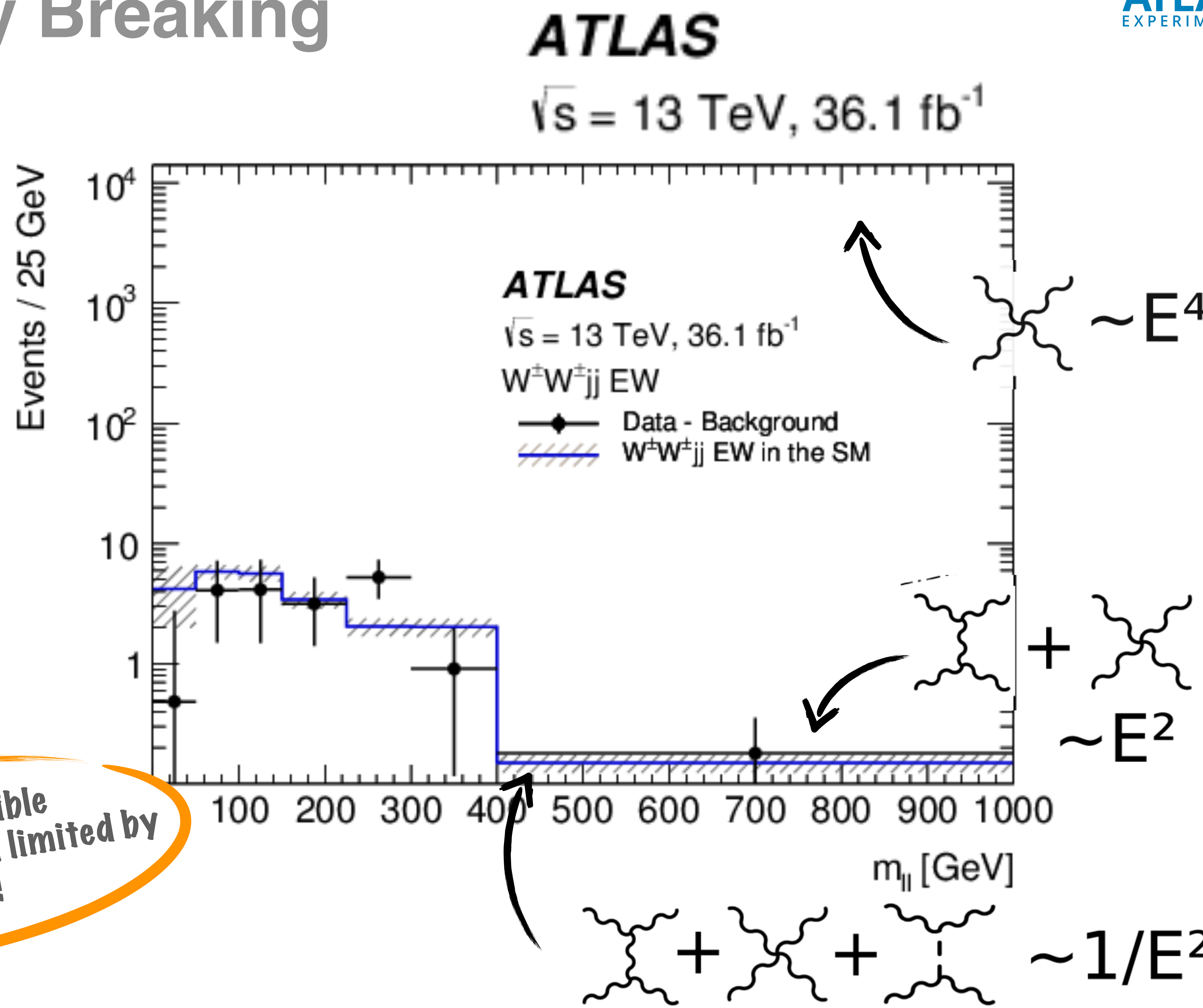
Why Vector Boson scattering is interesting?



Testing the electroweak sector and EW Symmetry Breaking



Testing the electroweak sector and EW Symmetry Breaking



So far compatible with the SM, but still limited by statistics!