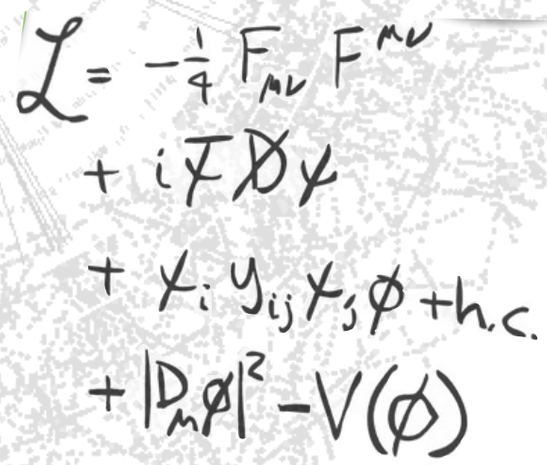
Latest Standard Model results from the LHC

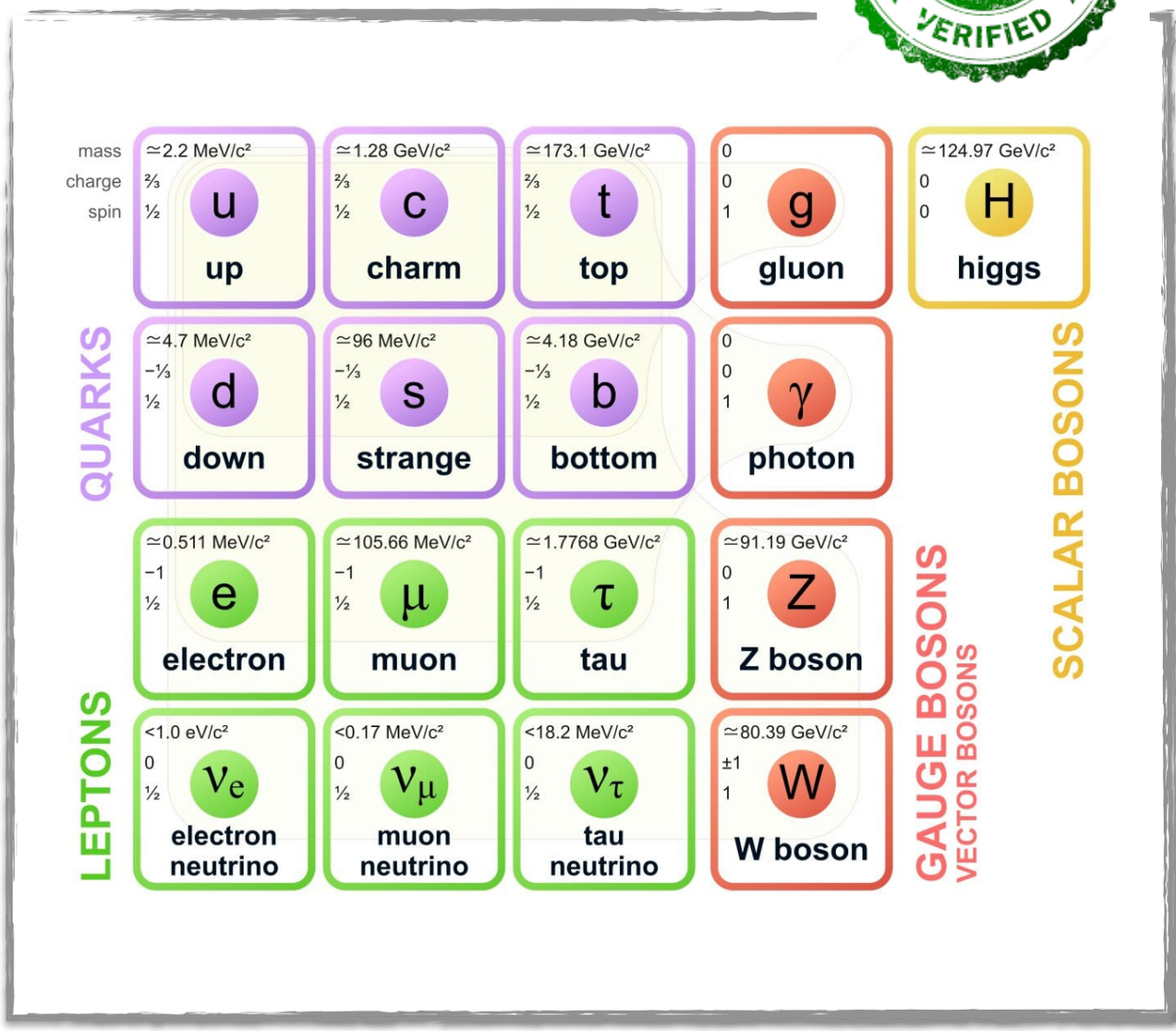
Joany Manjarrés
on behalf of the ATLAS and CMS Collaborations



December 02, 2020

The Standard Model predicts….

A Particle content

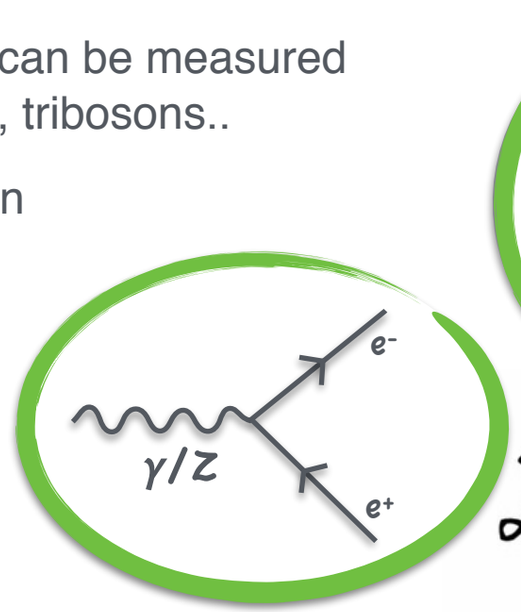


Are we done?

The Standard Model predicts….

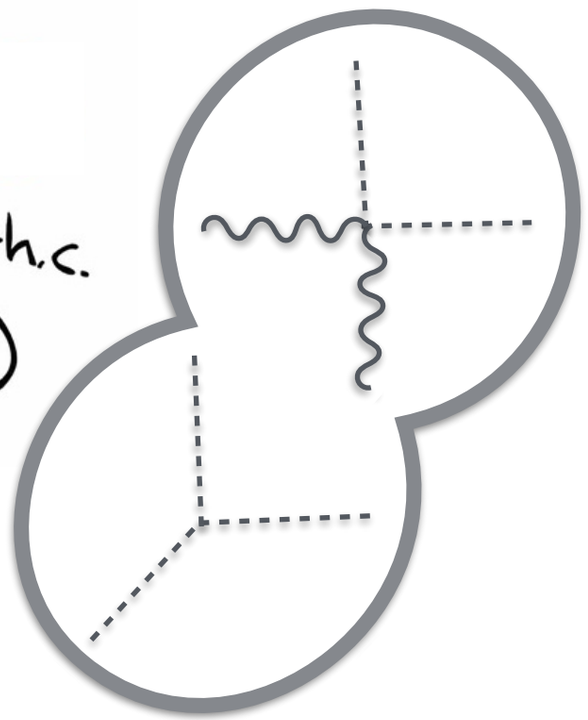
How particles interact with each other

- ✔ γ/Z → ℓℓ, W → ℓν very well understood
- ✔ WWV (V = W, Z, γ) measured at LEP and LHC
- ✔ Higgs coupling to fermions and bosons observed at LHC
- ☐ Coupling of 4 gauge bosons → can be measured through vector boson scattering, tribosons..
- ☐ Higgs self couplings not yet seen



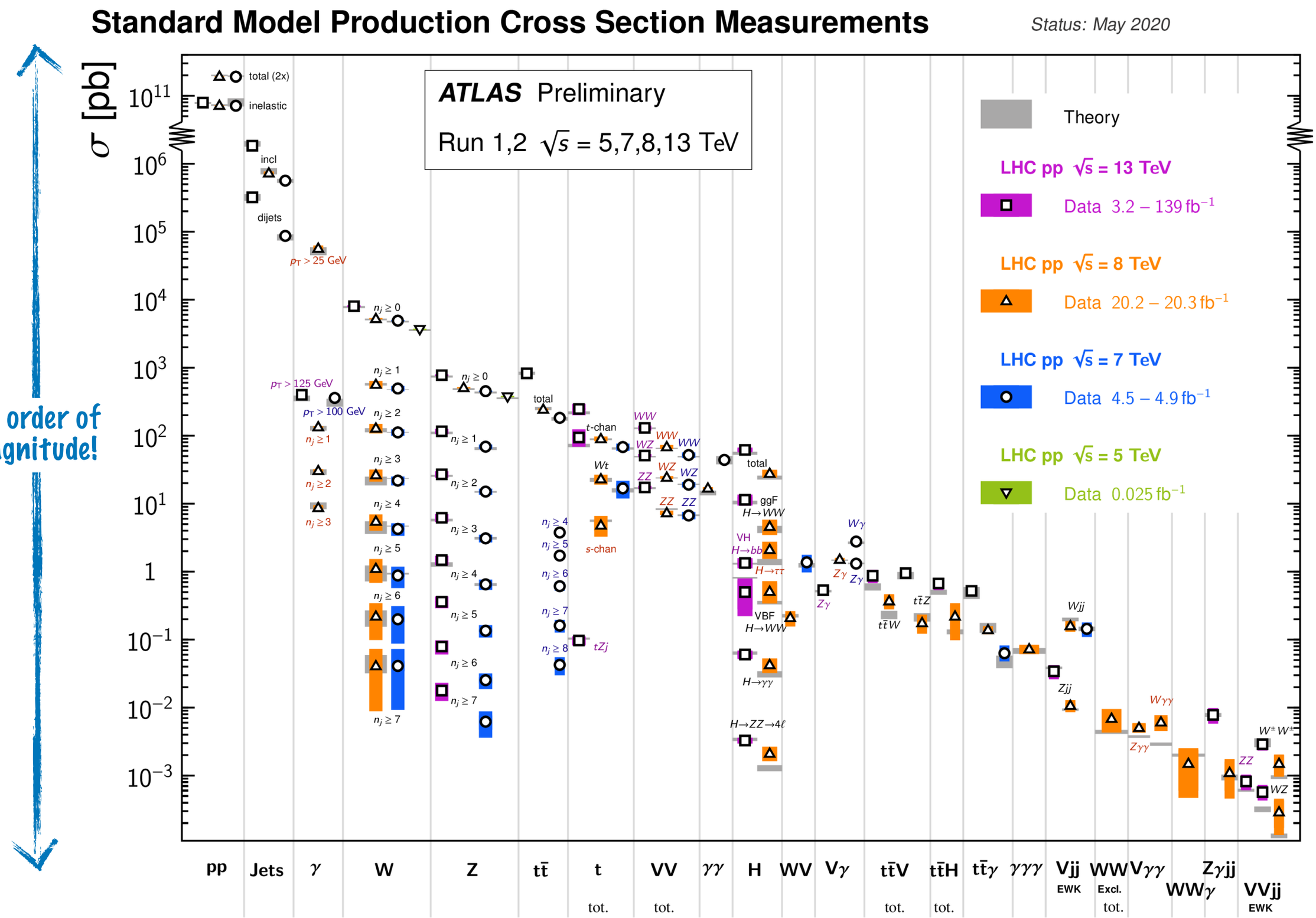
Precision measurements!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \chi_i y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



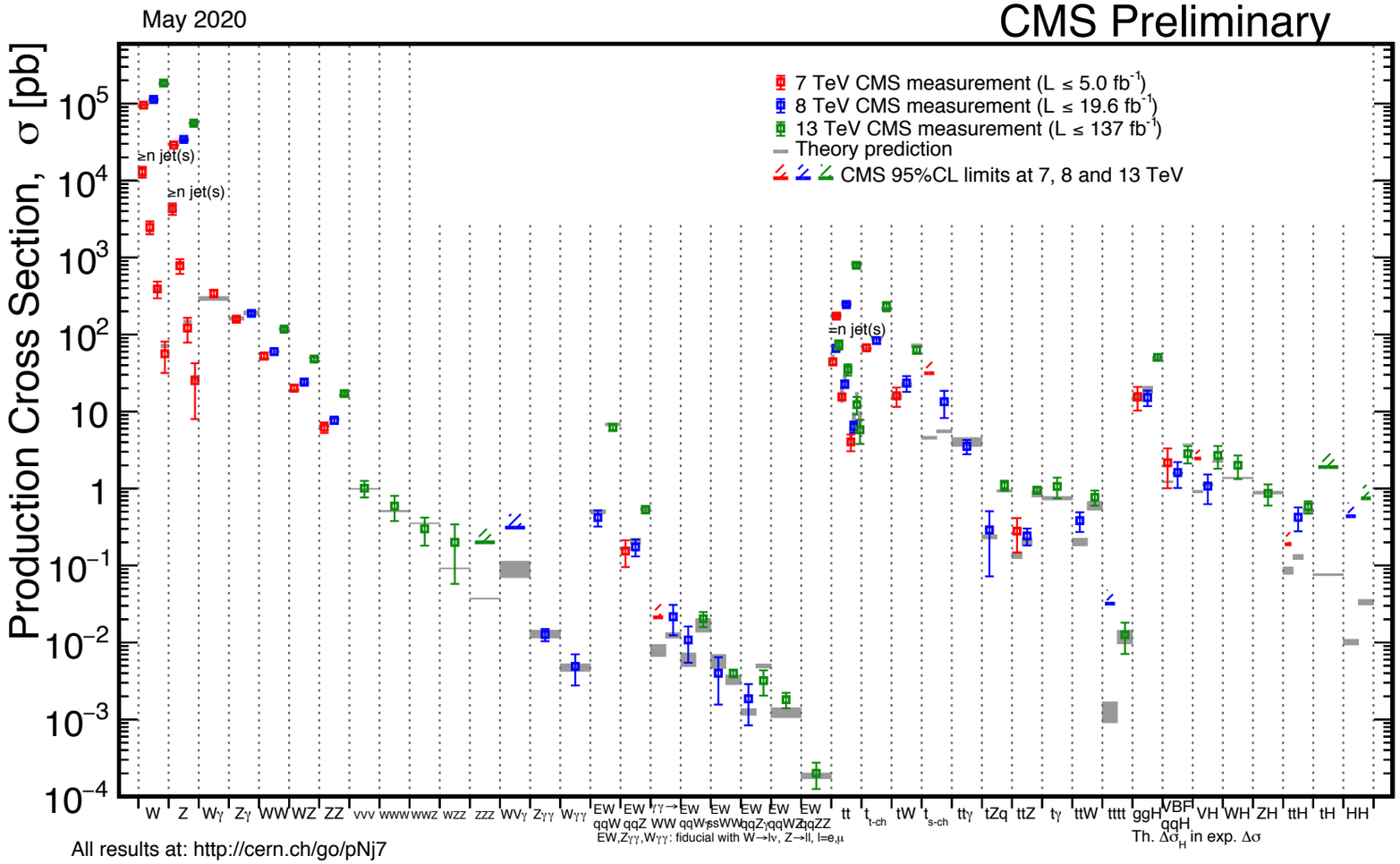
SM searches!

The Standard Model measurements….



The Standard Model measurements this year!

- Many new measurements by the ATLAS and CMS collaborations!
  - Diphoton production
  - Collinear Z boson emission
  - Lepton Flavour Universality test
  - Search for $W \to \pi\gamma$ in $t\bar{t}$ events
  - Inclusive 4l differential cross sections
  - Observation of photon-induced WW and dilepton production
  - Electroweak Zjj differential cross sections
  - Polarization in electroweak WW jj production
  - Observation of electroweak Wγjj, WZjj and ZZjj production
  - Evidence of electroweak Zγjj production
  - Observation of the production of three massive gauge bosons VVV



The W± boson

rare decay?
search for it!

Lepton flavor universality?

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.86 ± 0.09) %	
Γ_2	$e^+\nu$		(10.71 ± 0.16) %	
Γ_3	$\mu^+\nu$		(10.63 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.38 ± 0.21) %	
Γ_5	hadrons		(67.41 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%
Γ_8	cX		(33.3 ± 2.6) %	
Γ_9	$c\bar{s}$		$(31\ ^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p< 200 MeV.

PDG reference

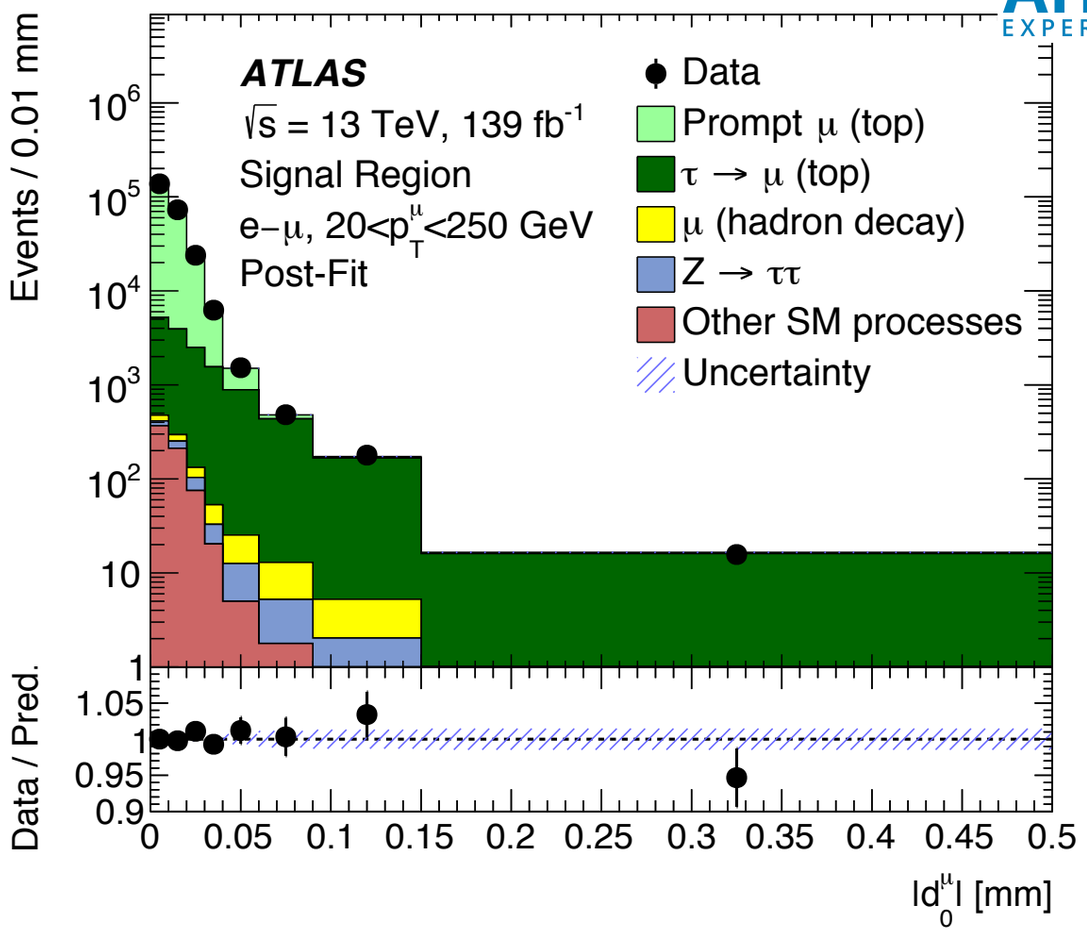
Testing the Lepton-Flavor Universality using *W* decays

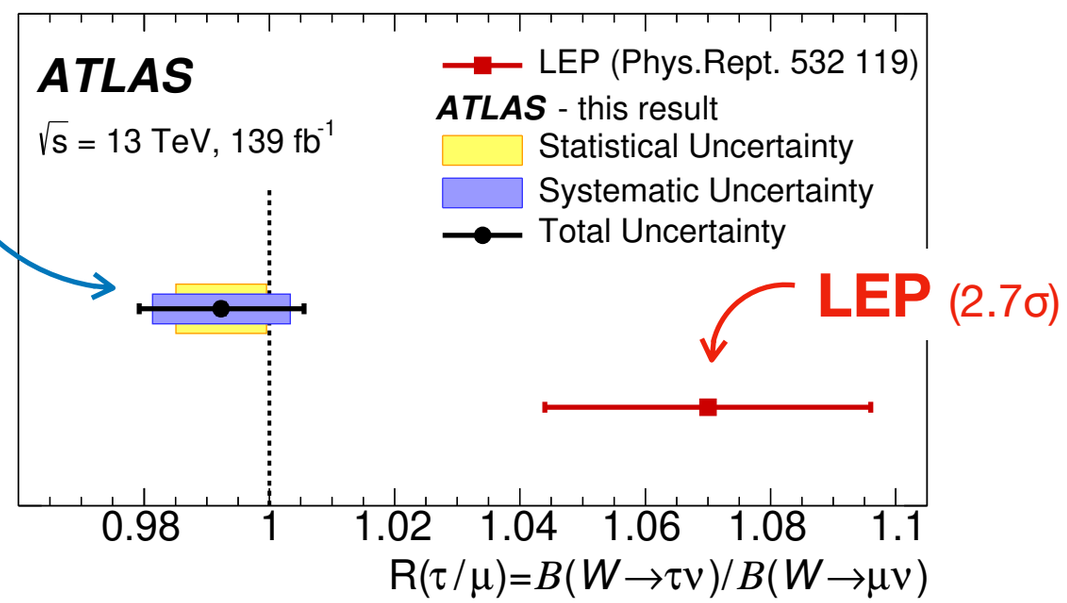
arXiv:2007.14040

- Use a di-leptonic ttbar events to have a clean sample of probe W bosons, tag(e,μ)-and-probe(μ)
- Look at the W coupling to charged leptons and calculate the ratio of the branching fractions
  - $R(\tau/\mu) = BR(W \rightarrow \tau\nu_\tau)/BR(W \rightarrow \mu\nu_\mu)$
- Results in agreement with SM expectation

$$R(\tau/\mu) = 0.992 \pm 0.013$$

- Flavour anomalies observed at LHCb: [JHEP 08 (2017) 055], [PRL 122 (2019) 191801]
- Long-standing 2.7σ deviation from LEP [Phys. Rept. 532 119]
- Factor two in precision compared to LEP, best precision achieved up to now



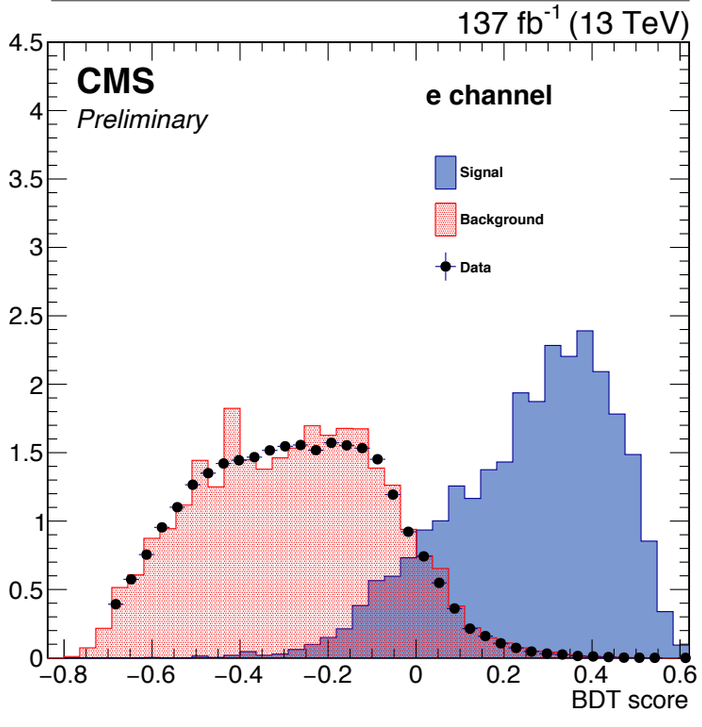


Search for W → πγ in $t\bar{t}$ events

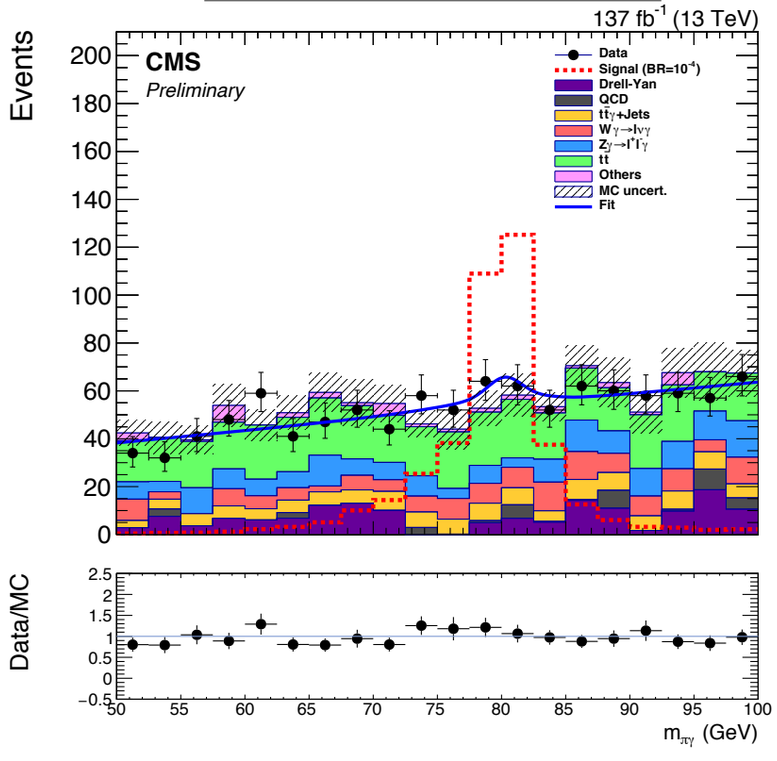
CMS-PAS-SMP-20-008

- First LHC search of the rare exclusive hadronic decay W → πγ: isolated photon plus isolated track compatible with a pion (dedicated variable developed)
- Use ttbar events this time with only one W → lν (l = μ,e), signal discrimination with a Boosted Decision Tree (BDT)
- Upper limits extracted from a fit to the $m_{\pi\gamma}$ distribution:
  B (W → πγ) < 1.51 × 10^{-5} (theoretical calculations in the range 10^{-9} - 10^{-6})

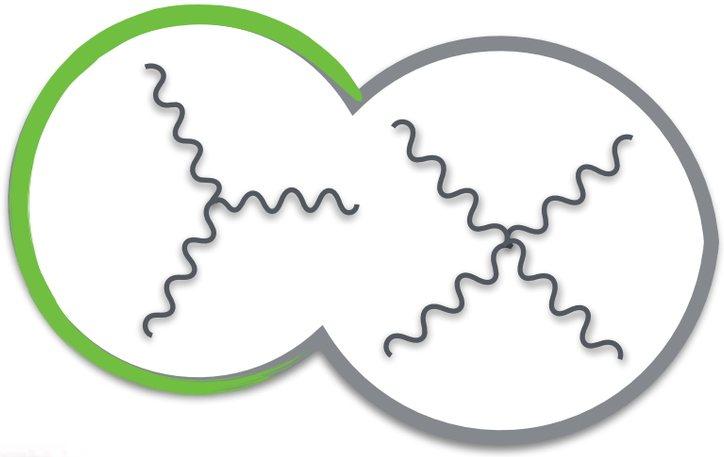
BDT score in electron channel



Fitted $m_{\pi\gamma}$ distribution

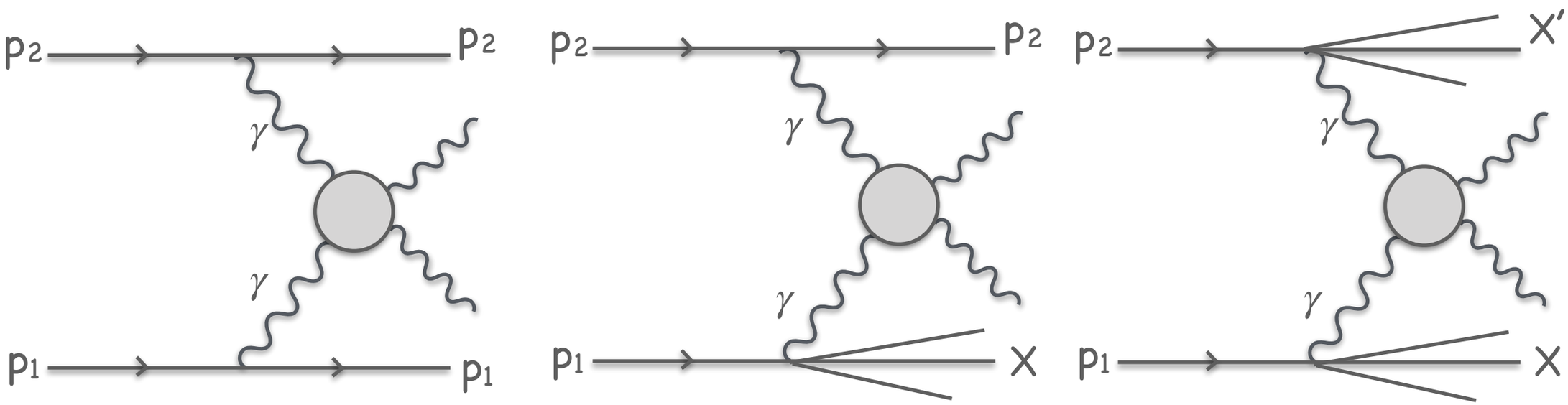


The multiboson interactions



Photon induced processes at the LHC

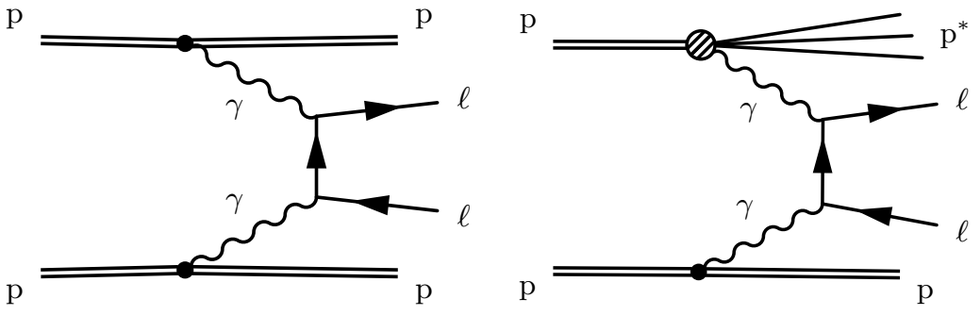
How?

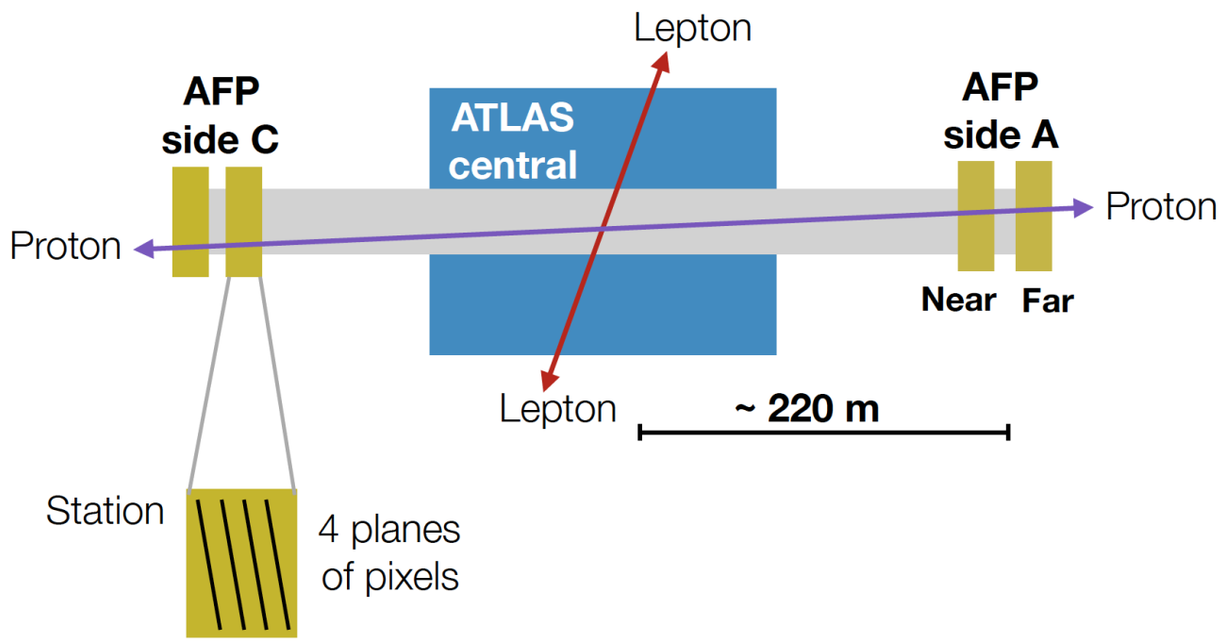


Observation of photon-induced dilepton production

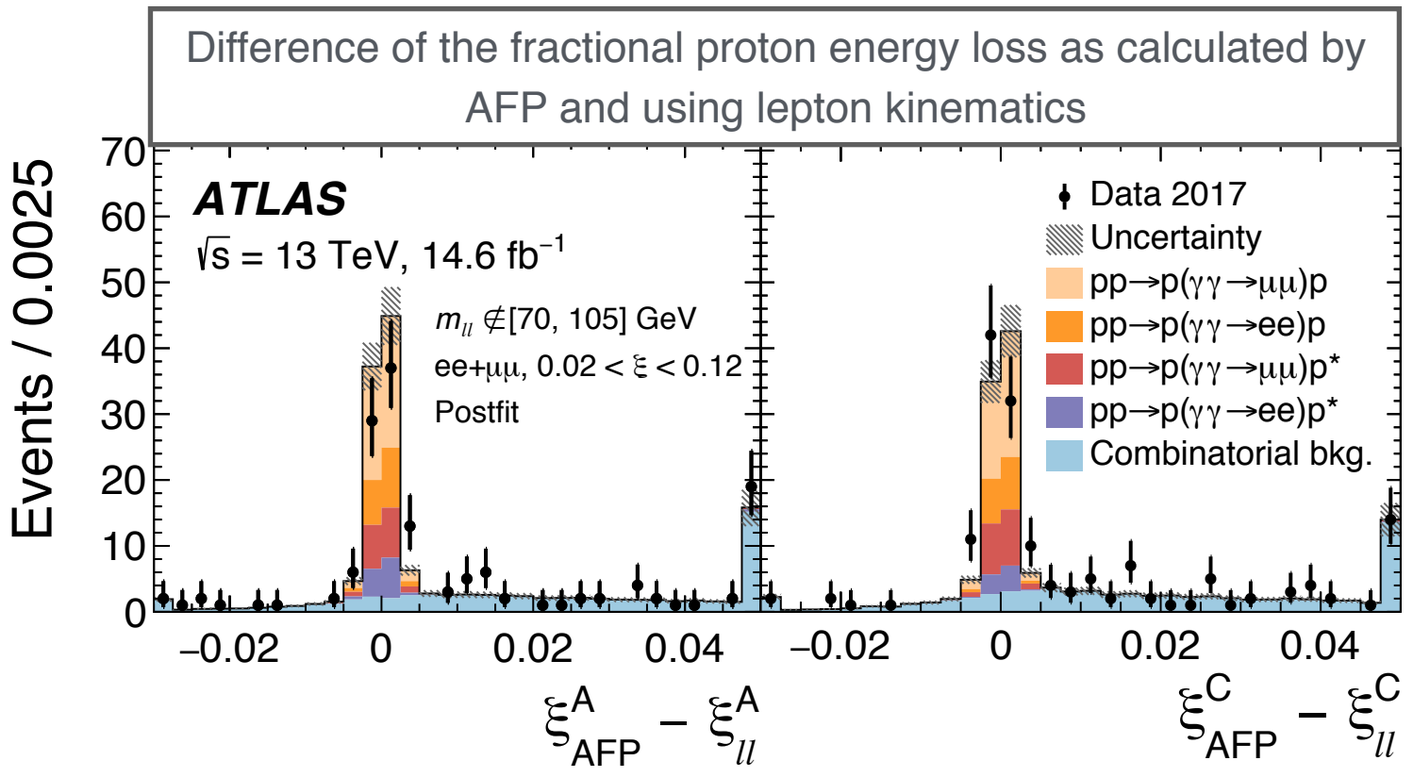
arXiv:2009.14537

- The ATLAS Forward Proton (AFP) detectors are placed 220m away from the interaction point to tag protons that emerge intact from collisions
- Look for photon induced di-lepton pairs in the 2017 dataset (14fb^{-1}) using the AFP to tag protons





Difference of the fractional proton energy loss as calculated by AFP and using lepton kinematics

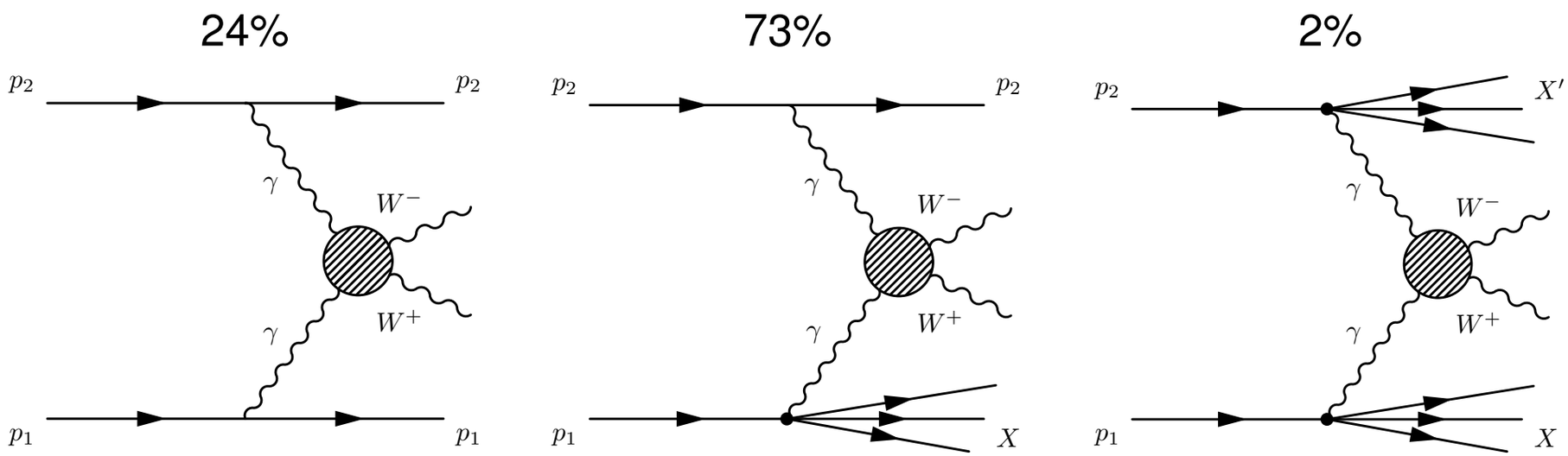


- The first cross section measurement using proton tagging at the LHC!
- **Observation with significances of 9.7σ (13σ) for ee (μμ)!**

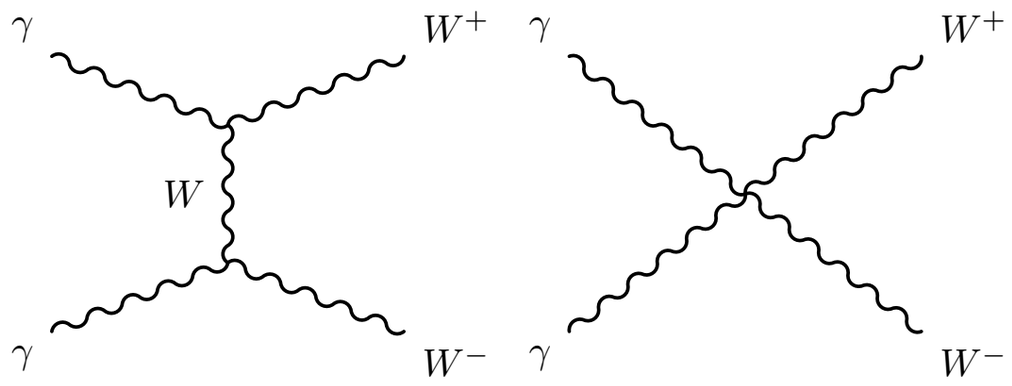
Observation of photon-induced WW production

arXiv:2010.04019

- LHC protons can radiate ISR photons and stay intact or dissociate



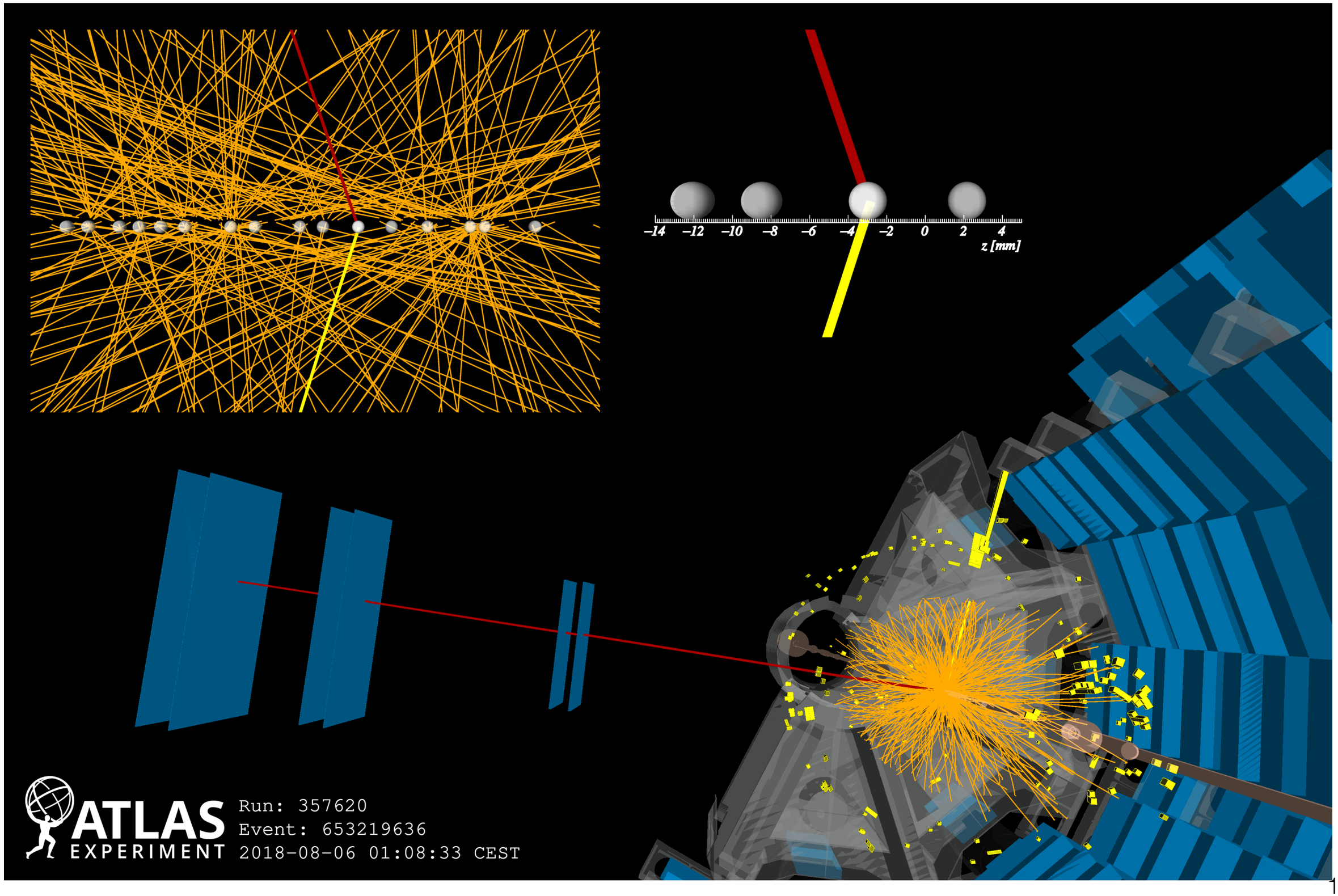
- Direct access to triple γWW and quartic γγWW interactions, $O(\alpha^2_{EM})$



- Observation of this process by ATLAS [Phys. Rev. D 94 (2016) 032011] and CMS [JHEP 08 (2016) 119]

Observation of photon-induced WW production

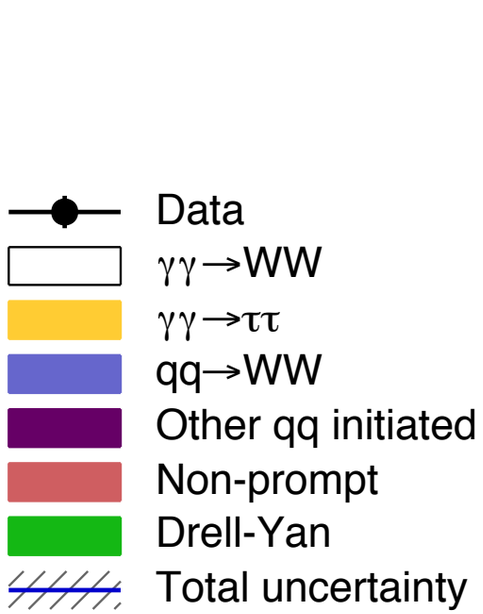
arXiv:2010.04019

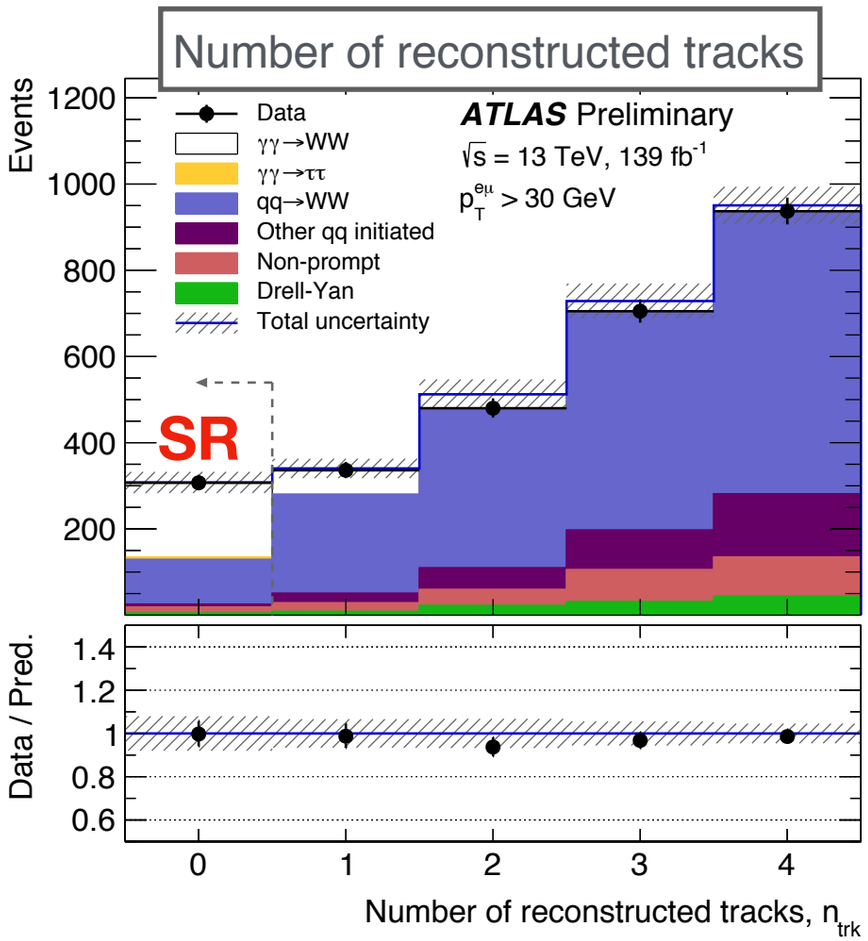


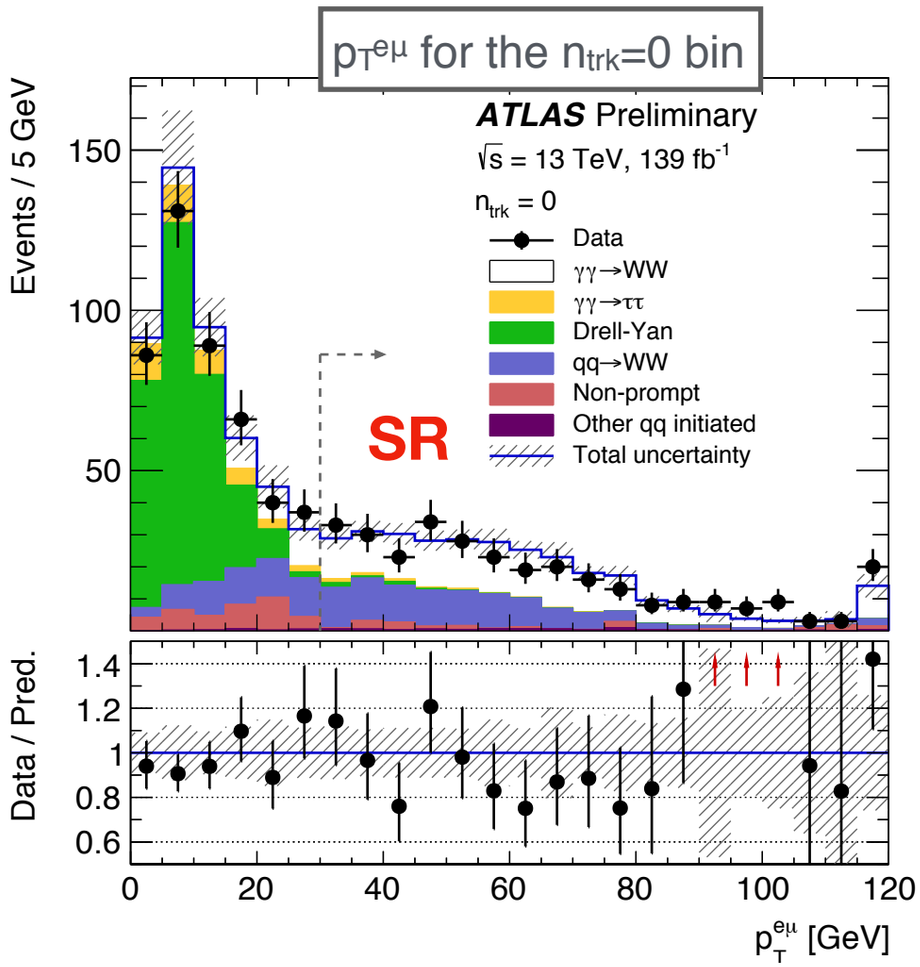
Observation of photon-induced WW production

arXiv:2010.04019

- The number of tracks n_{trk} in a window around the vertex and the momentum of the lepton pairs used to built signal and control regions





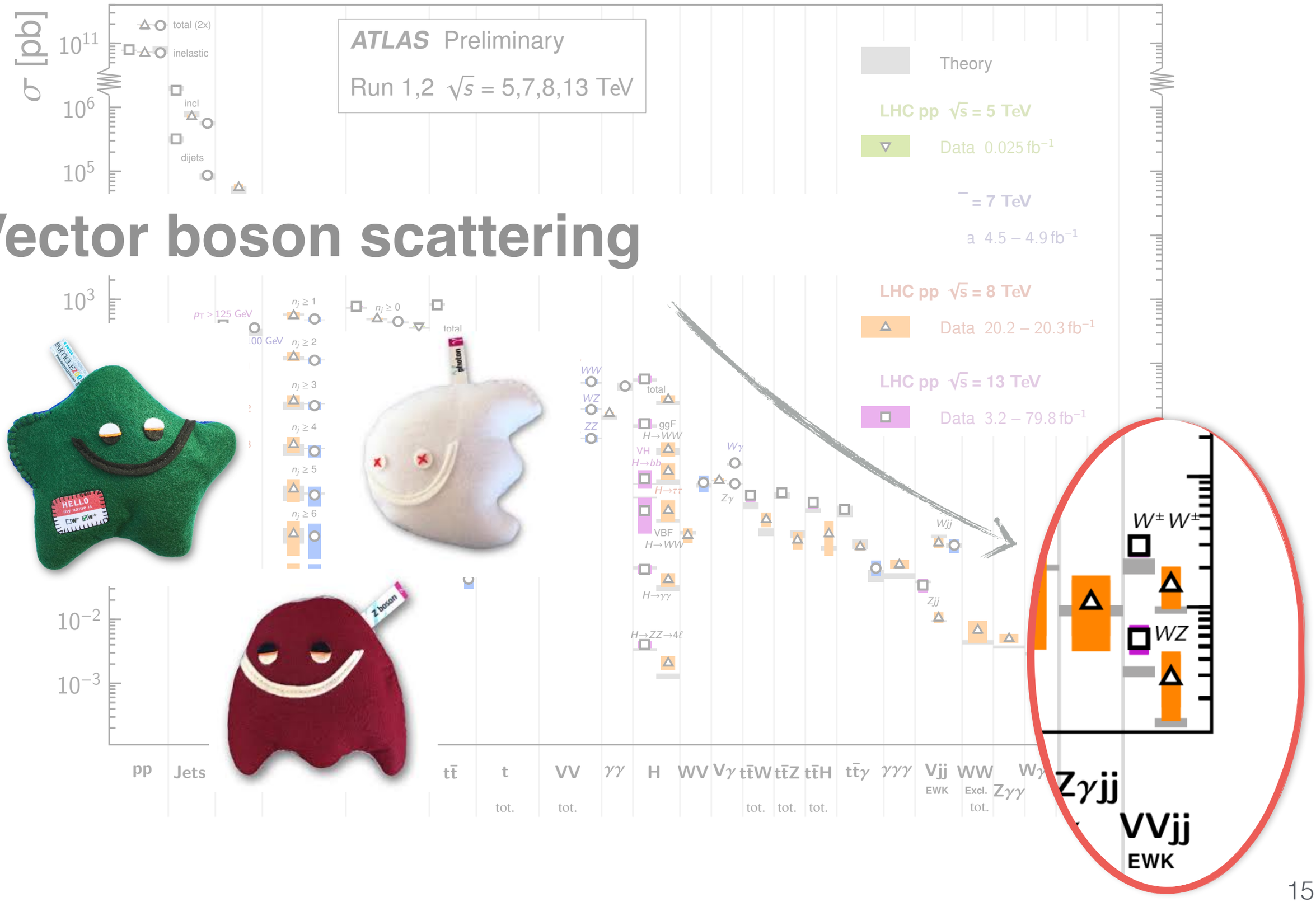


- Very clear signal! **Observation with 8.4σ (6.7σ exp)**
- Measured fiducial cross section $\sigma_{meas} = 3.13 \pm 0.31$ (stat.) ± 0.28 (syst.) fb

  to be compared with predictions from MG5_aMC@NLO+Pythia8 $\sigma_{theo} = 4.3 \pm 1.0$ (scale) ± 0.12 (PDF) fb

  or a scaled Herwig7 $\sigma_{theo} = 2.34 \pm 0.27$ fb

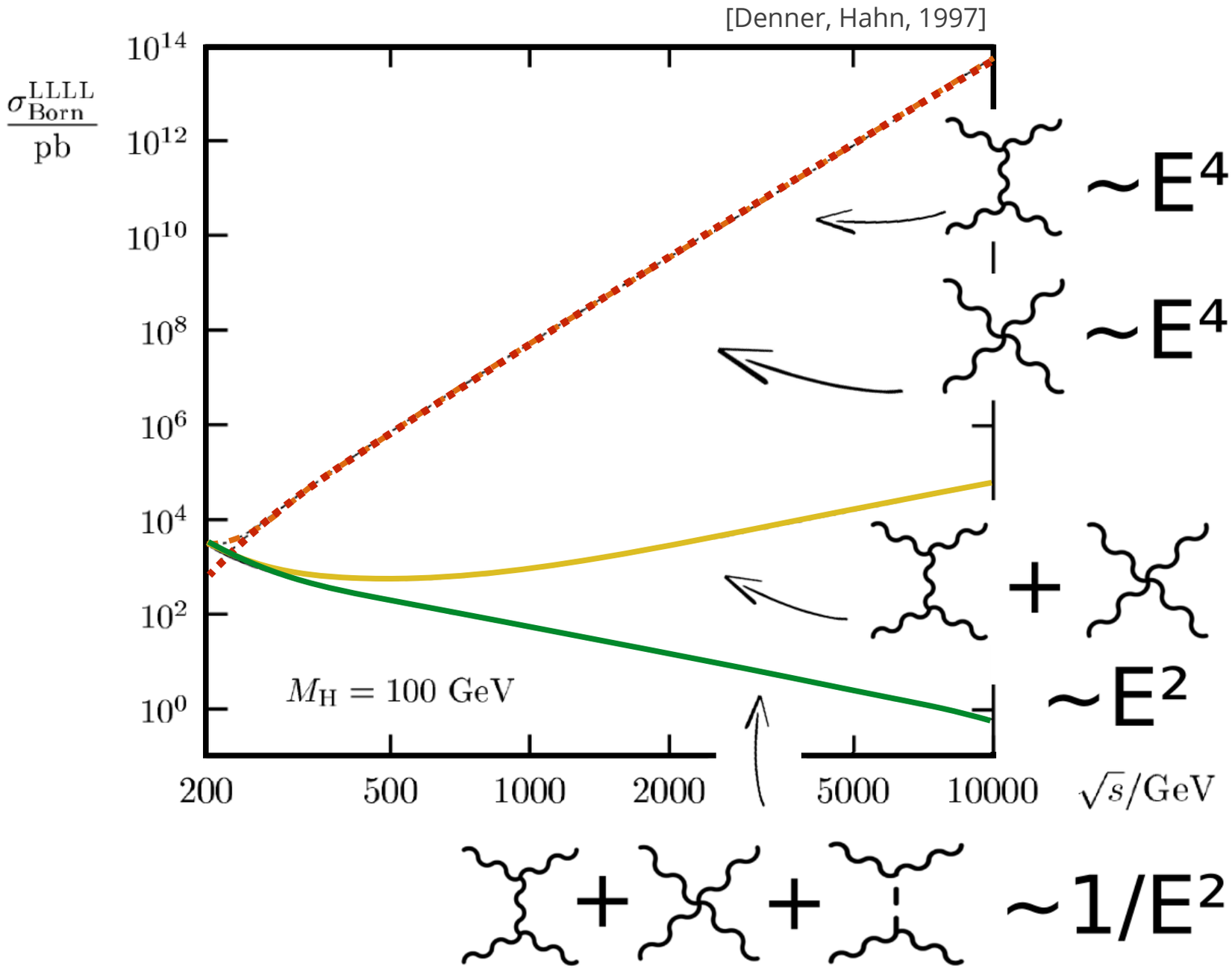
Vector boson scattering



Why Vector Boson scattering is interesting?

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

[Denner, Hahn, 1997]

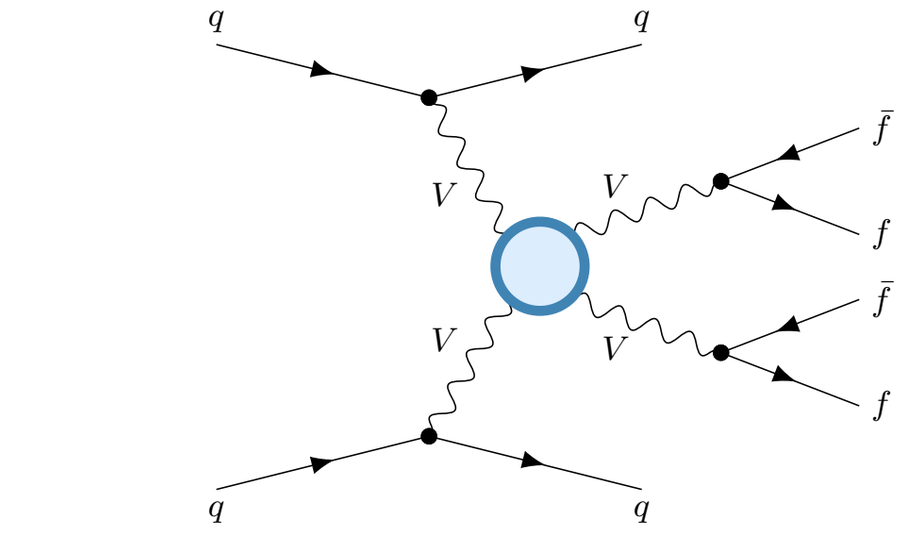


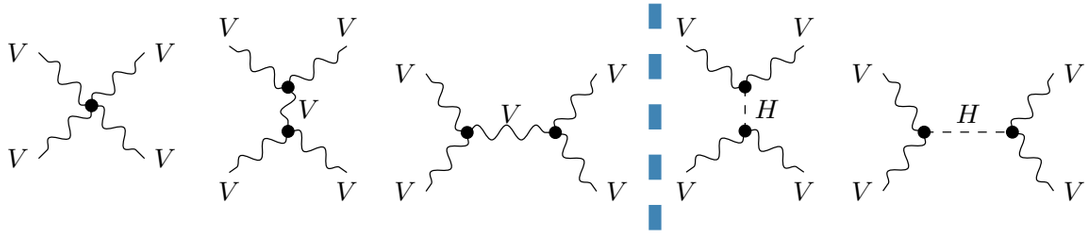
- Test of electroweak sector and EW Symmetry Breaking
- Complementary to “direct” Higgs boson property studies
- Differences in this sector will be indications of new physics

Vector Boson Scattering at the LHC

- Protons in LHC serve as source of vector boson beams.
- As experimentalist we can only access final state VVjj
  - VBS with triple and quartic couplings
  - EW non-VBS (including tribosons)
  - QCD-mediated diboson production

VBS

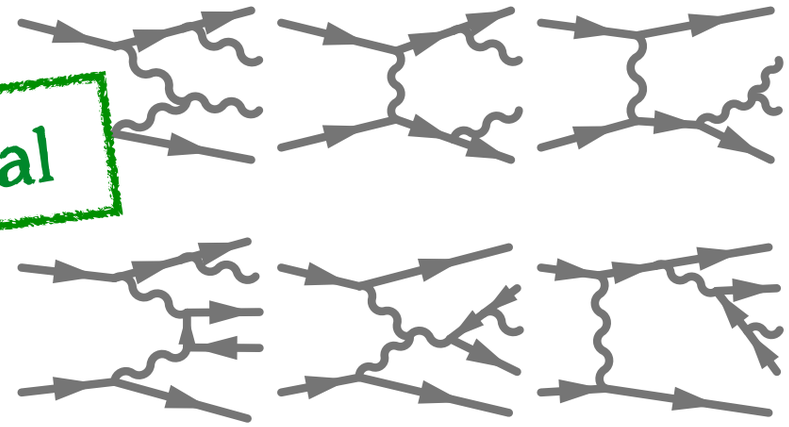




gauge structure of the Standard Model

electroweak symmetry breaking

EWK non-VBS

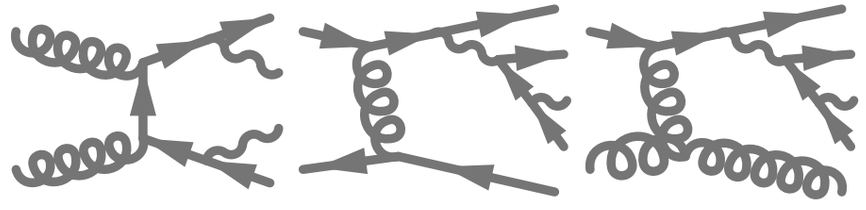


EWK Signal

Interference

QCD Background

QCD



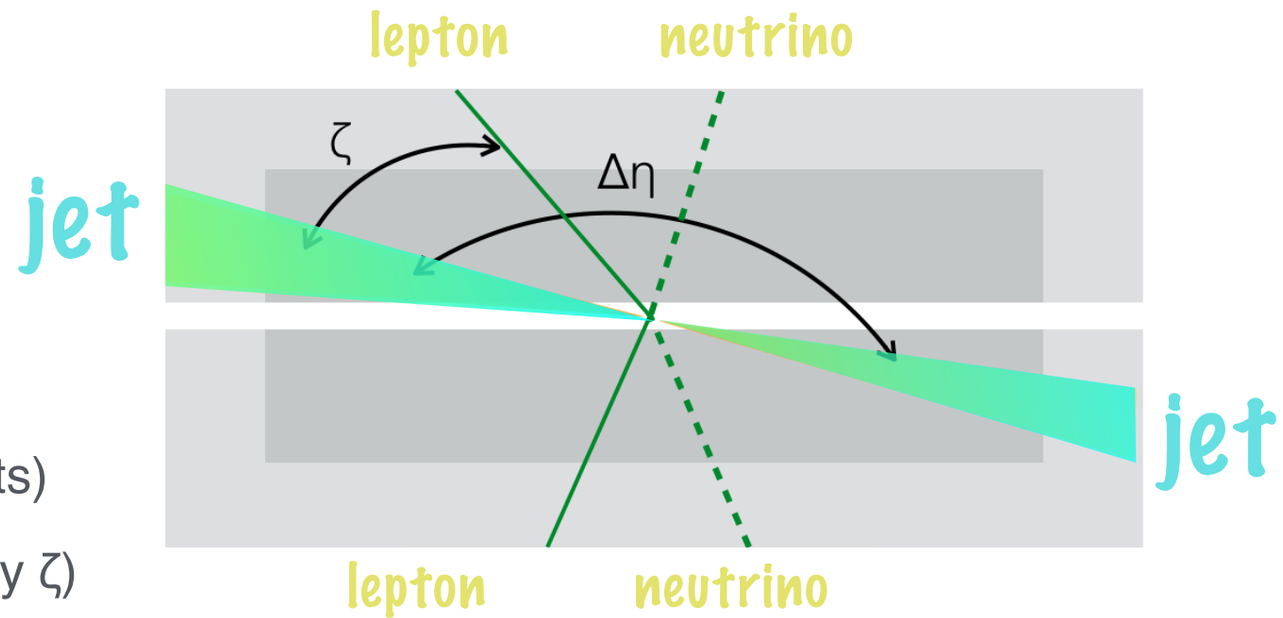
Vector Boson Scattering topology

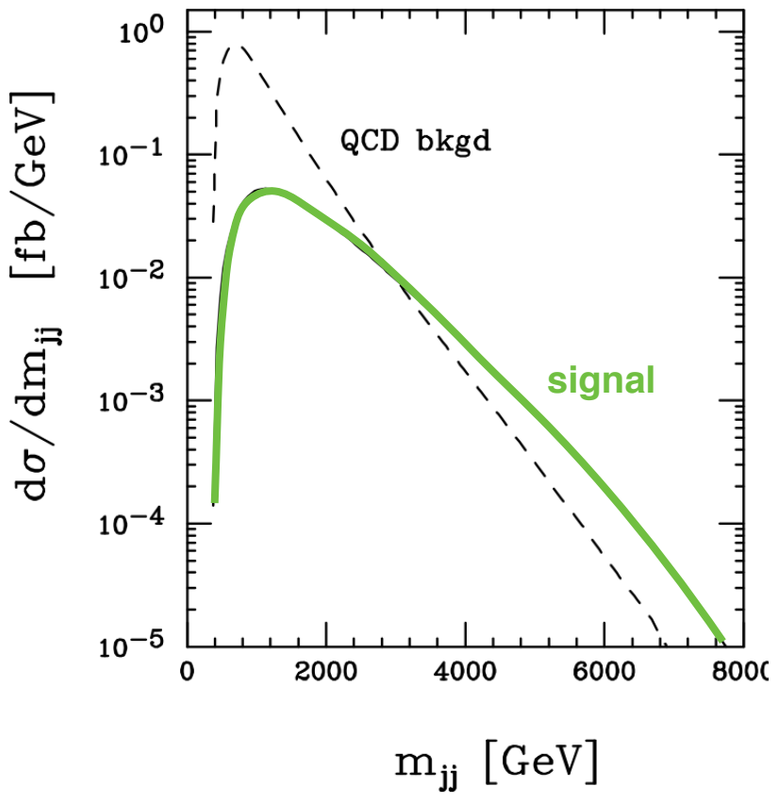
The experimental challenge

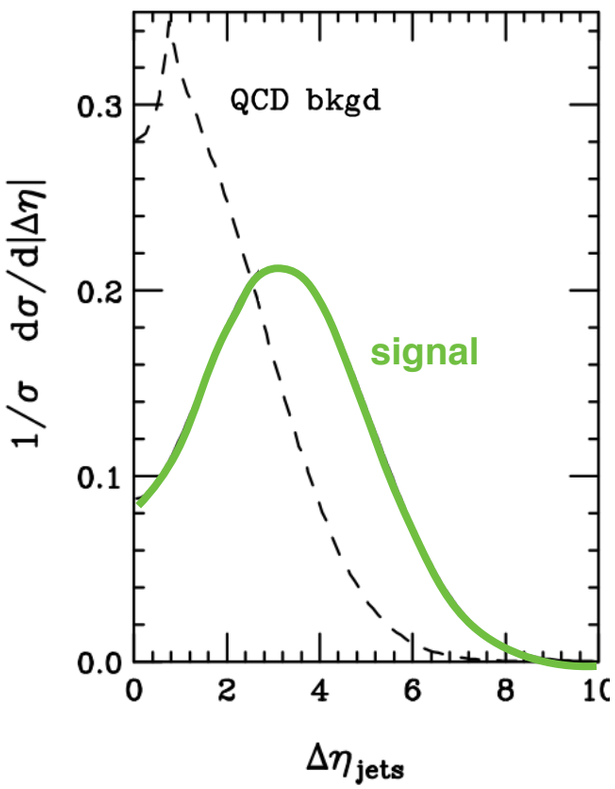
- very low rate (O(fb))
- large background, generally from QCD production of same final state

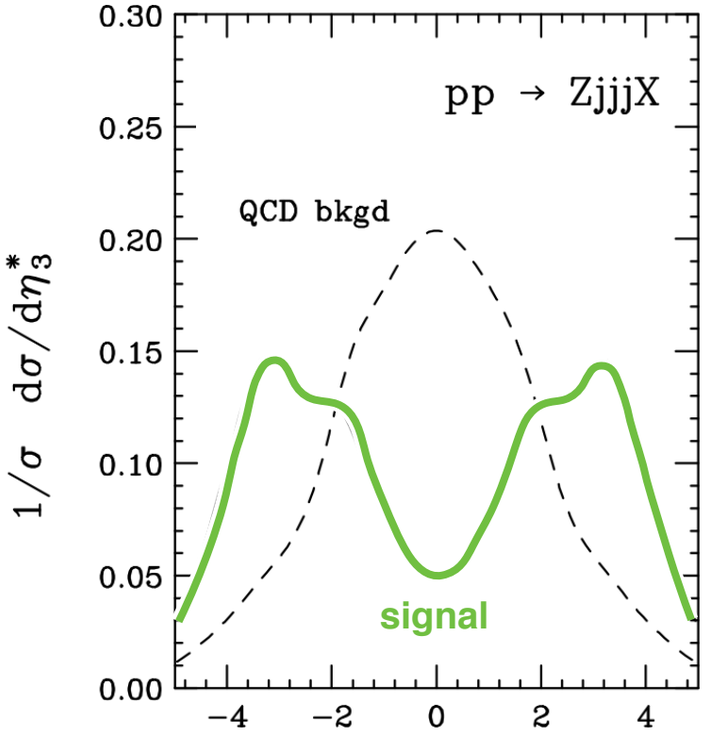
VBS distinctive detector signature

- Two jets in forward and backward regions (tagging jets)
- Two bosons produced ~back-to-back (lepton centrality ζ)
- Hadronic activity suppressed between the two jets





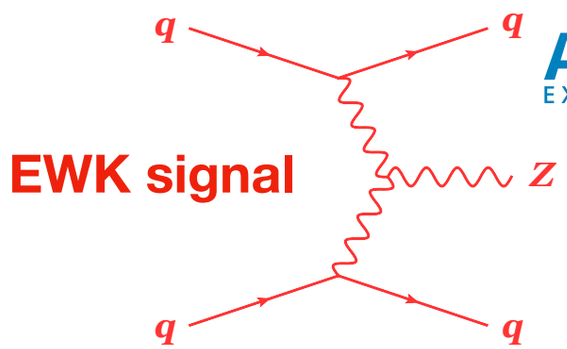


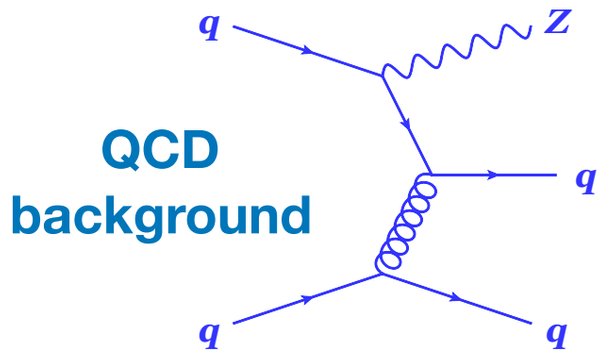


EWK Zjj differential cross sections

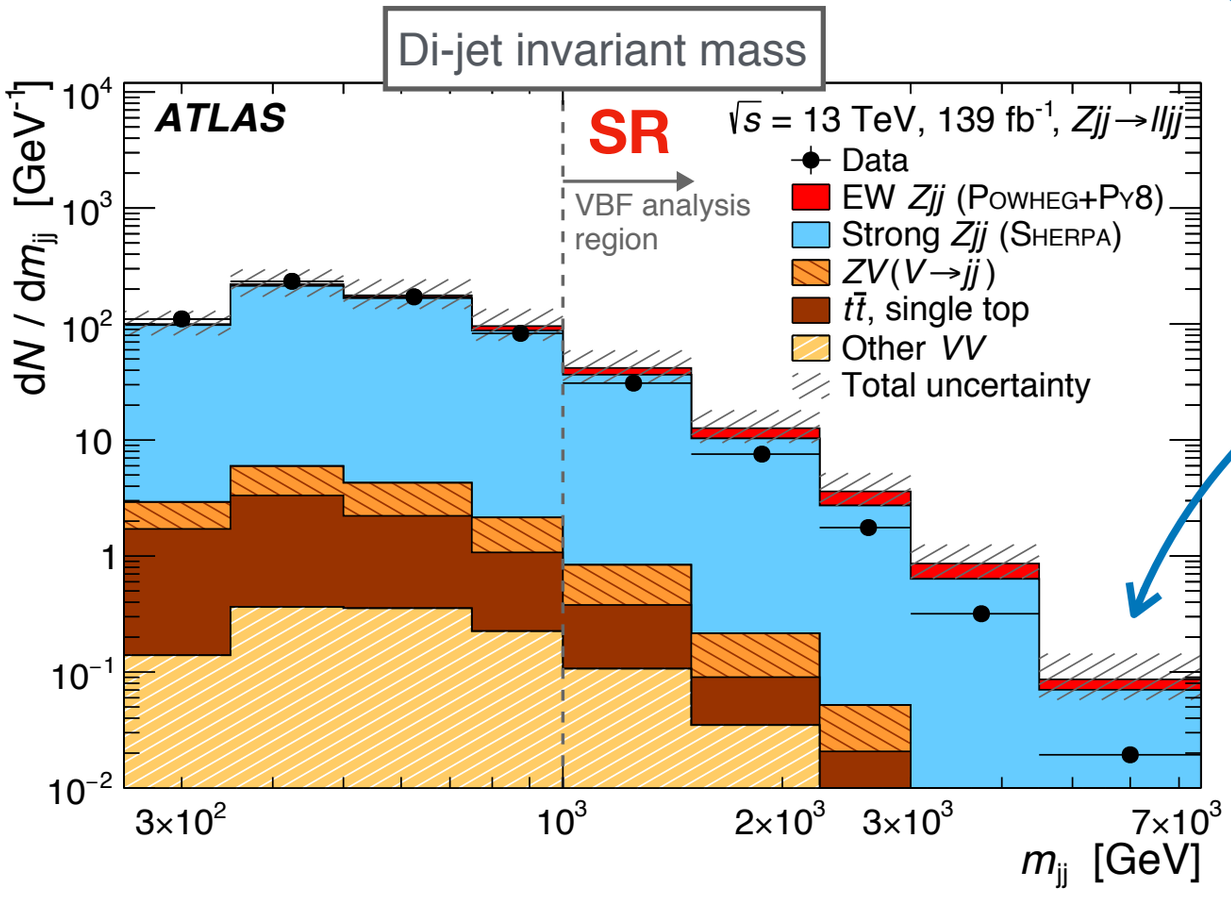
arXiv:2006.15458

- Sensitive to the Vector Boson Fusion (VBF) production mechanism (very close topology to VBS but much larger stat)
- Measured data are sufficiently precise to distinguish between different state-of-the-art theoretical predictions calculated using POWHEG+PYTHIA8, HERWIG7+VBFNLO and Sherpa2.2
- Large QCD background miss-modeling, huge efforts to extract it in a data driven way!

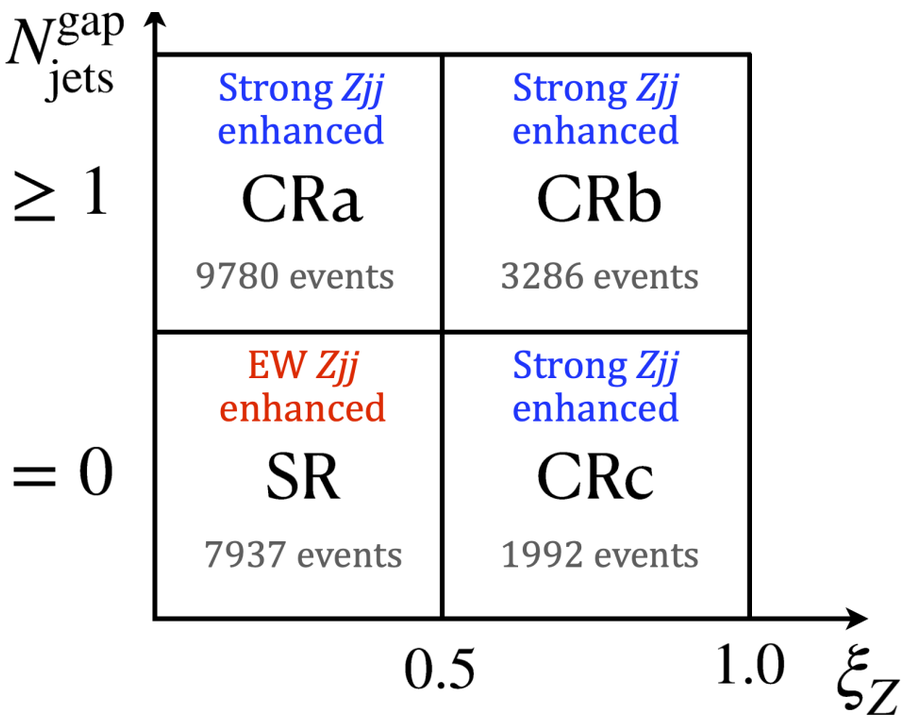




Di-jet invariant mass



Regions to constrain the QCD background

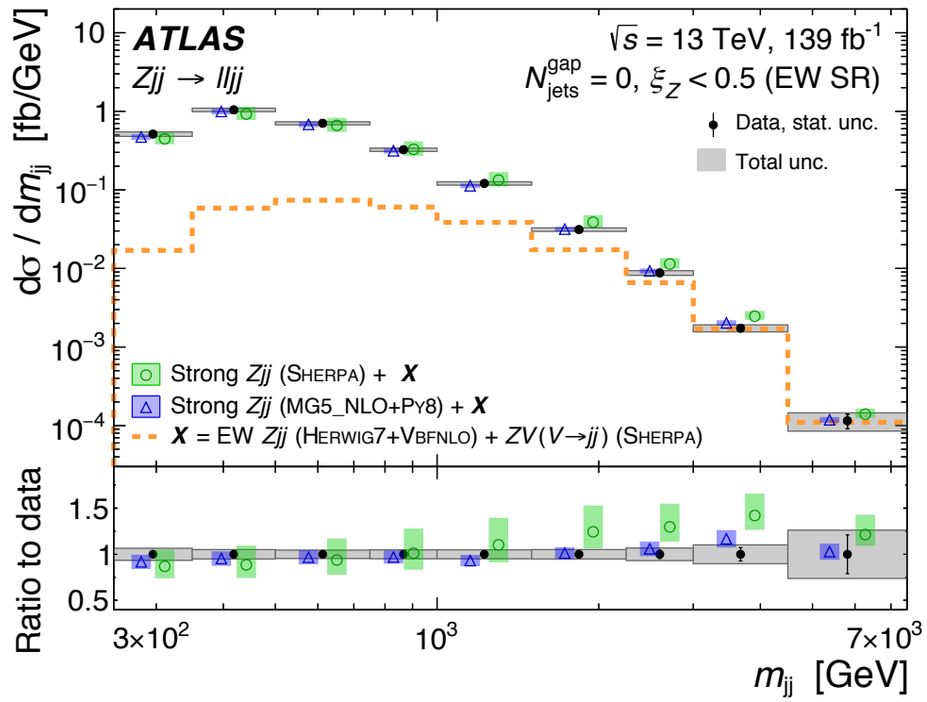


EWK Zjj differential cross sections

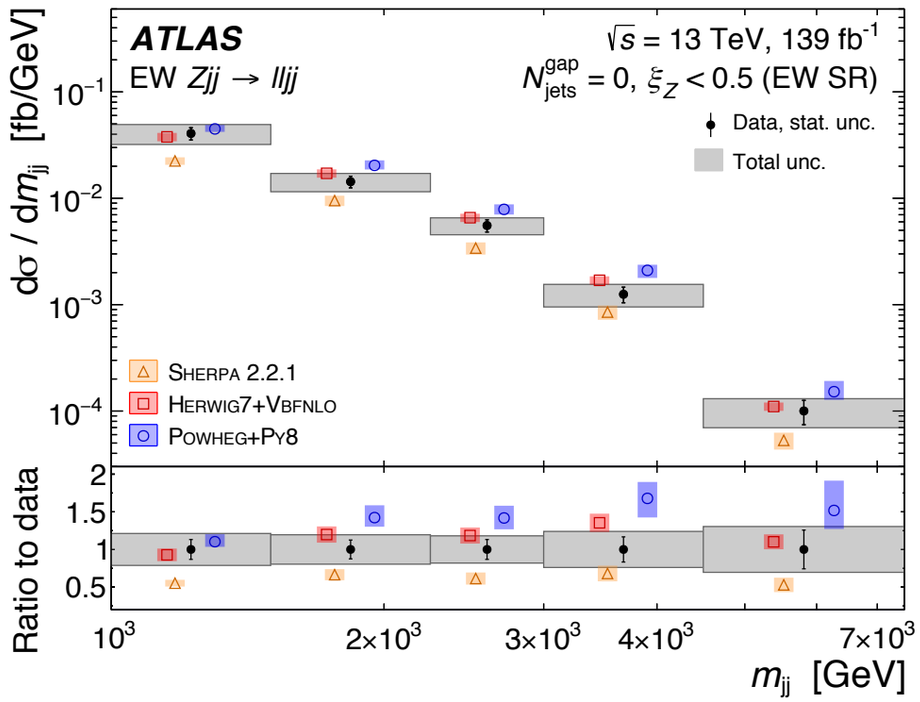
arXiv:2006.15458

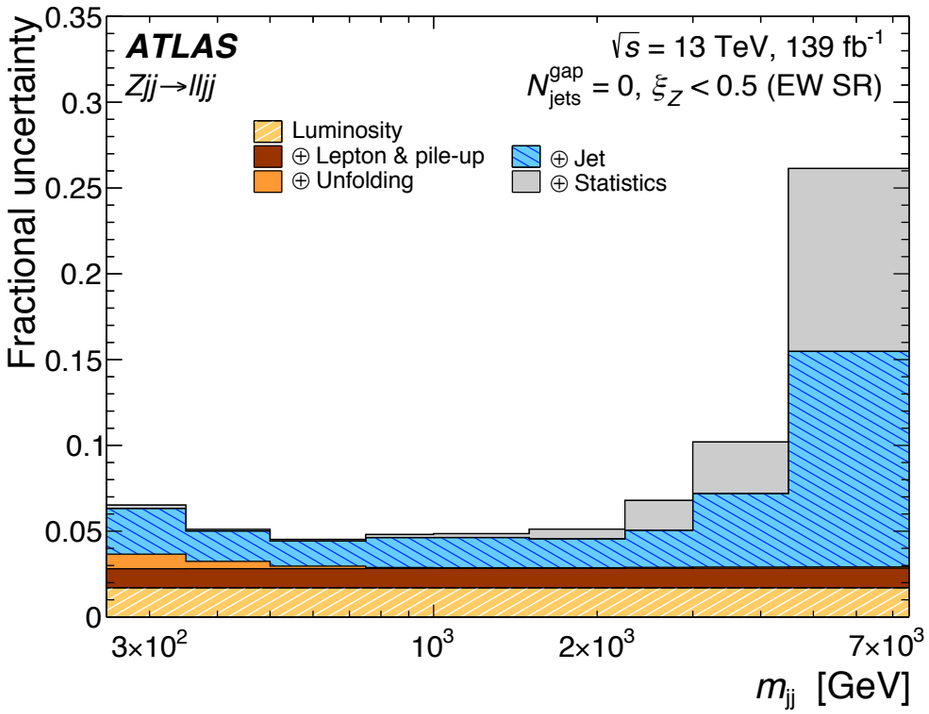
- Differential cross sections as a function of four observables: m_{jj} , $|\Delta y_{jj}|$, $p_{T,ll}$ and $\Delta\phi_{jj}$

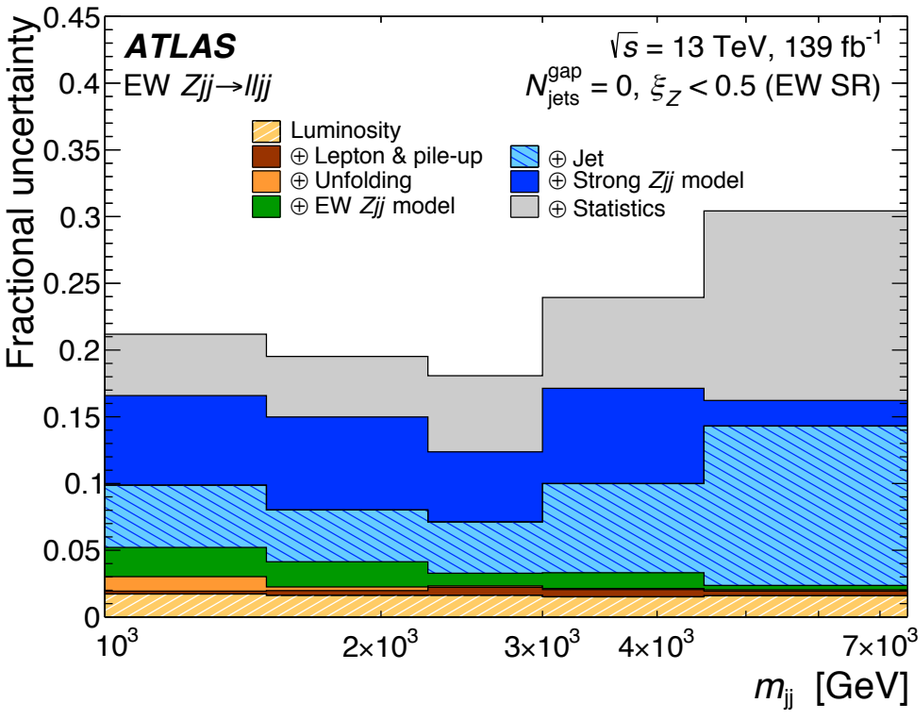
EWK+QCD Zjj production



EWK Zjj production





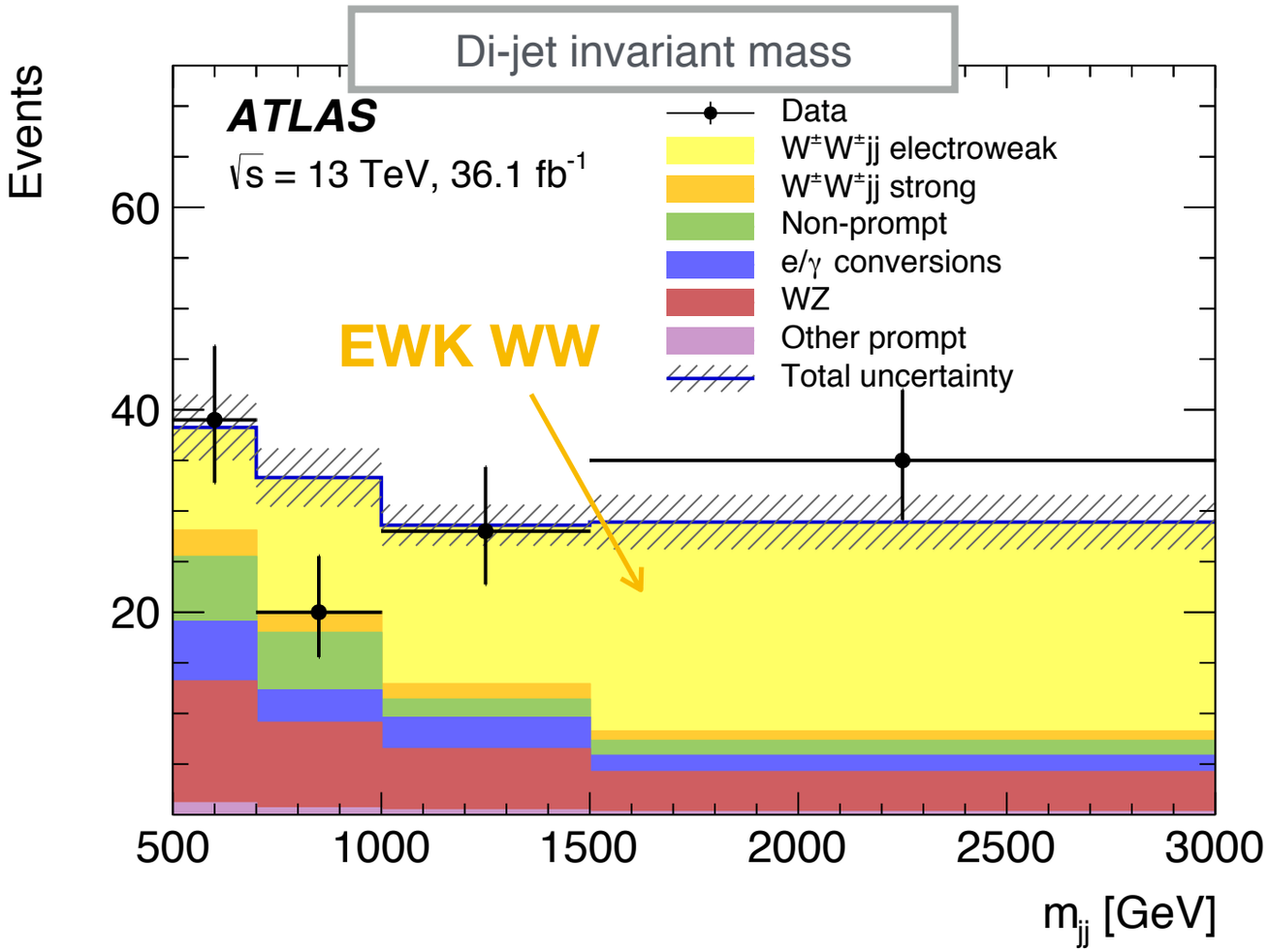


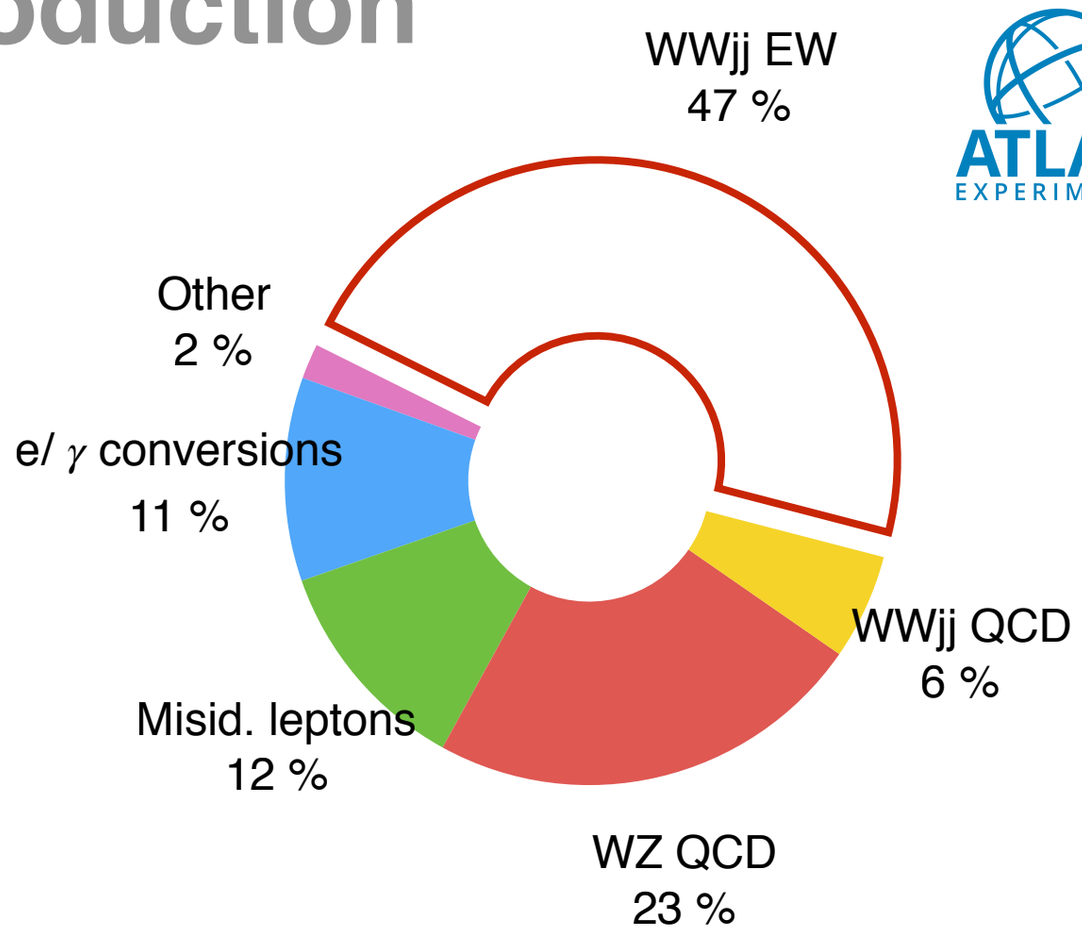
EWK same charge WW production

[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)





Signal extraction strategy → Fitting framework development

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

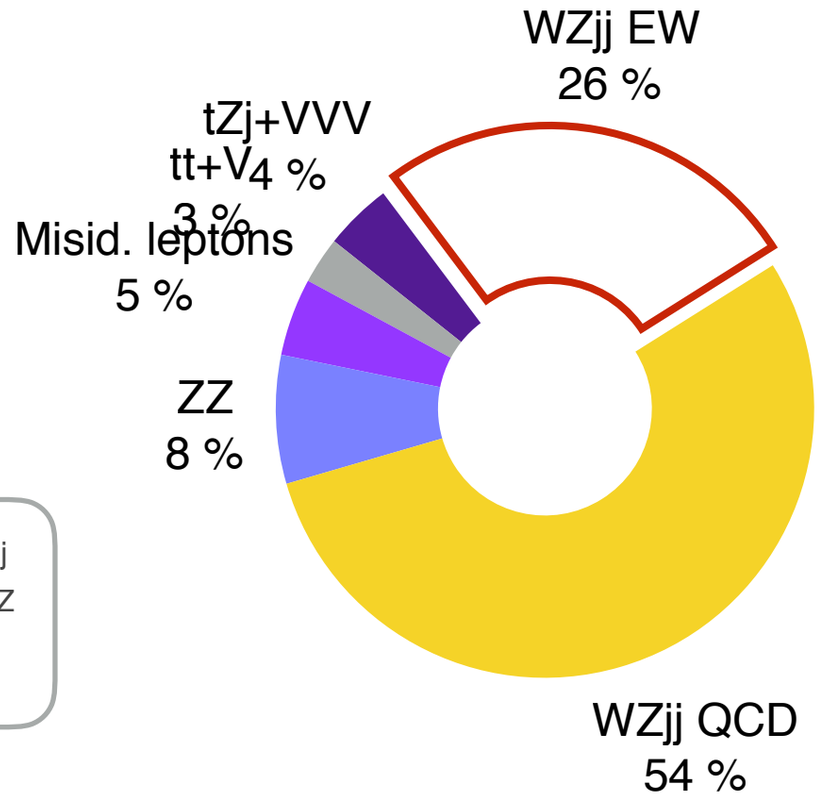
Observation !!

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

EWK WZjj production

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

[arXiv:1812.09740]



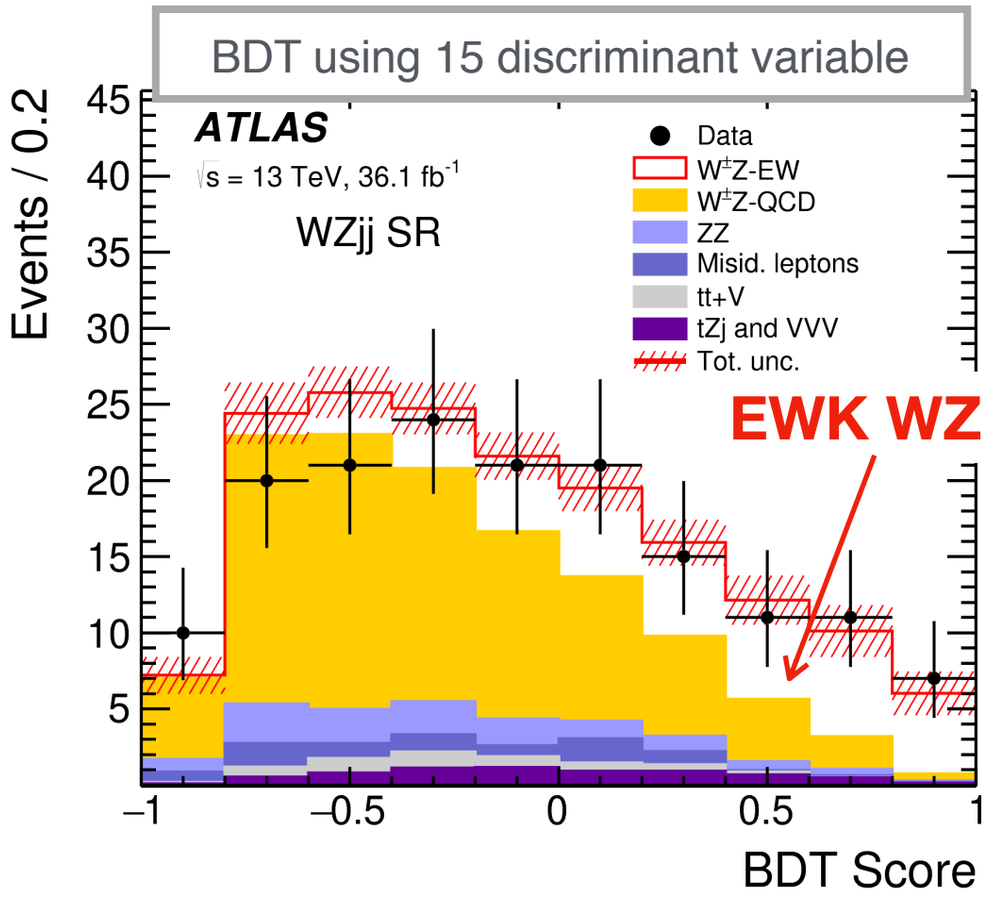
ATLAS EXPERIMENT

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_{pT}^{hard}, ζ_{lep}

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



Observation !!

Results:

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)

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

Electroweak WZjj and W±W±jj production

Phys. Lett. B 809 (2020) 135710

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

Signal extraction strategy

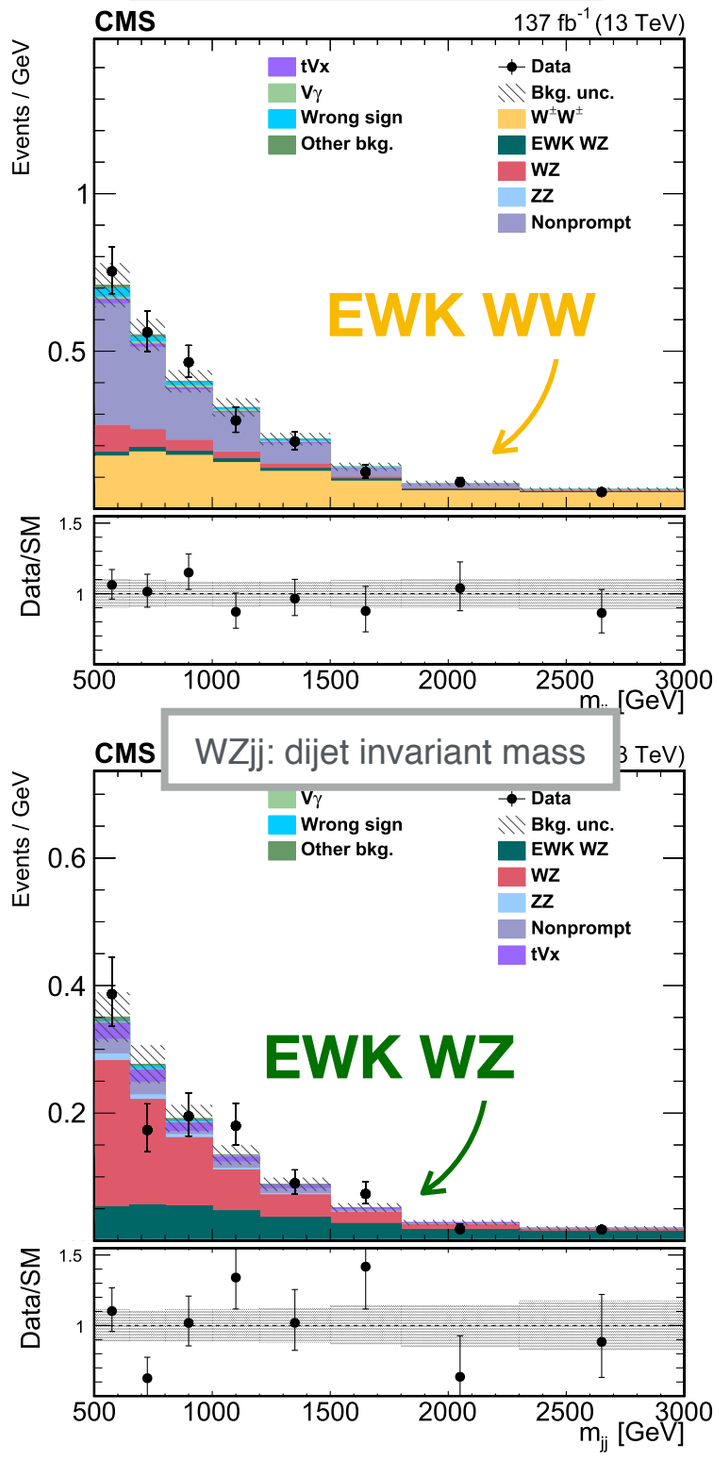
- Fit together ssWWjj and WZjj signal regions ⟶ coherent normalization factors for WZ QCD
- For each signal region 2D distributions were fitted:
  - ssWWjj: Dijet invariant mass (Mjj) and dilepton mass (mll)
  - WZjj: Dijet invariant mass (Mjj) and Boosted Decision Tree trained on simulation

Results:

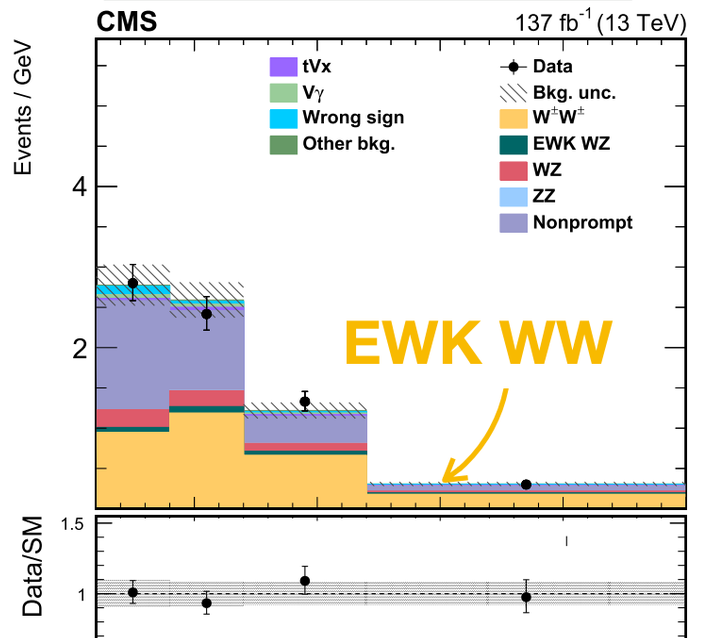
Observation !!

Observation of electroweak production of WZ at **6.8σ** (5.3σ exp) significance and same charge WW

WWjj: dijet invariant mass

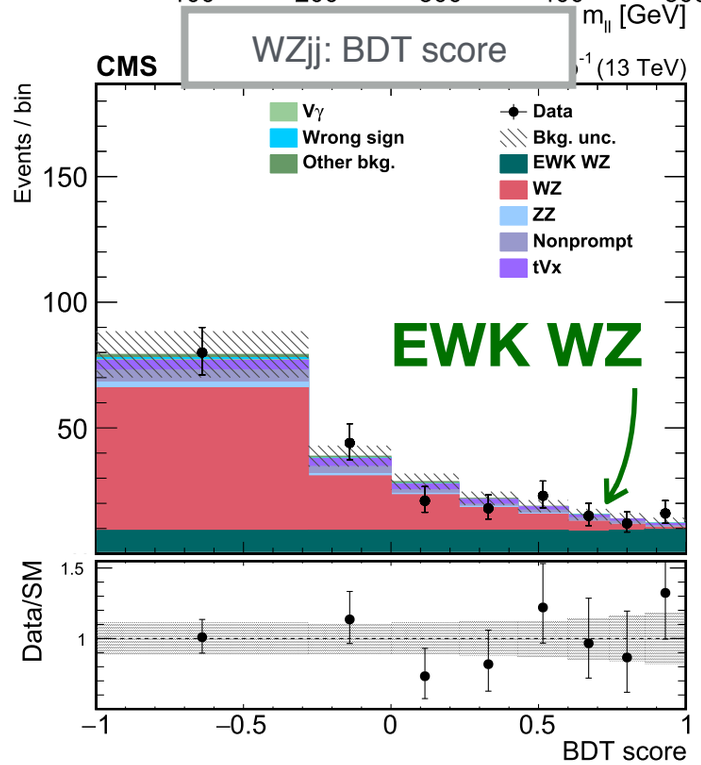


WWjj: dilepton invariant mass



WZjj: dijet invariant mass

WZjj: BDT score



EWK ZZjj production

- ZZjj analysis performed exploiting leptonic decays:
  - ATLAS: lllljj and llvvjj channels
  - CMS: lllljj channel

Signal extraction strategy

- CMS: Matrix element discriminant
- ATLAS: Multivariate discriminants

Results:

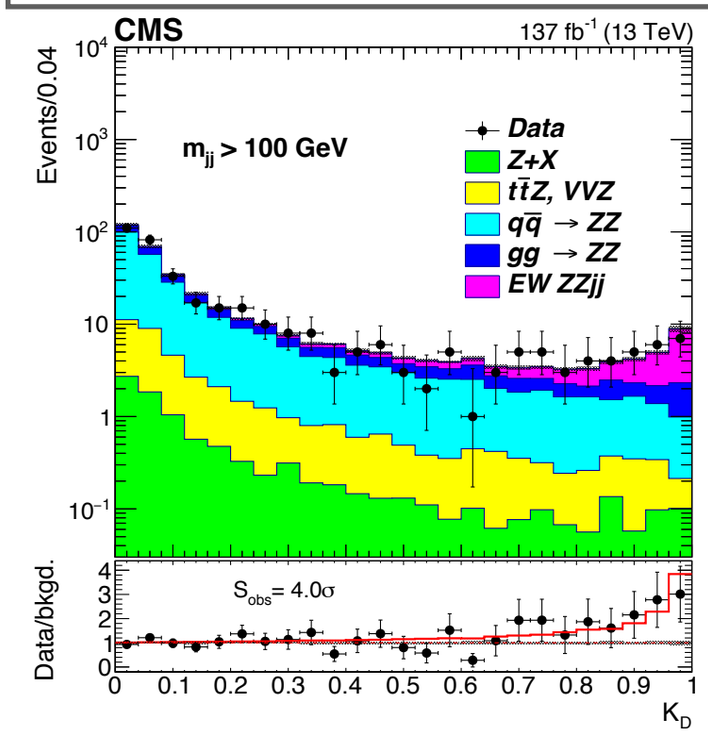
Observation/Evidence !!

ATLAS Observation: **5.5σ** (4.3σ),
CMS Evidence: **4.0σ** (3.5σ)

- Fiducial cross-section in agreement with the SM

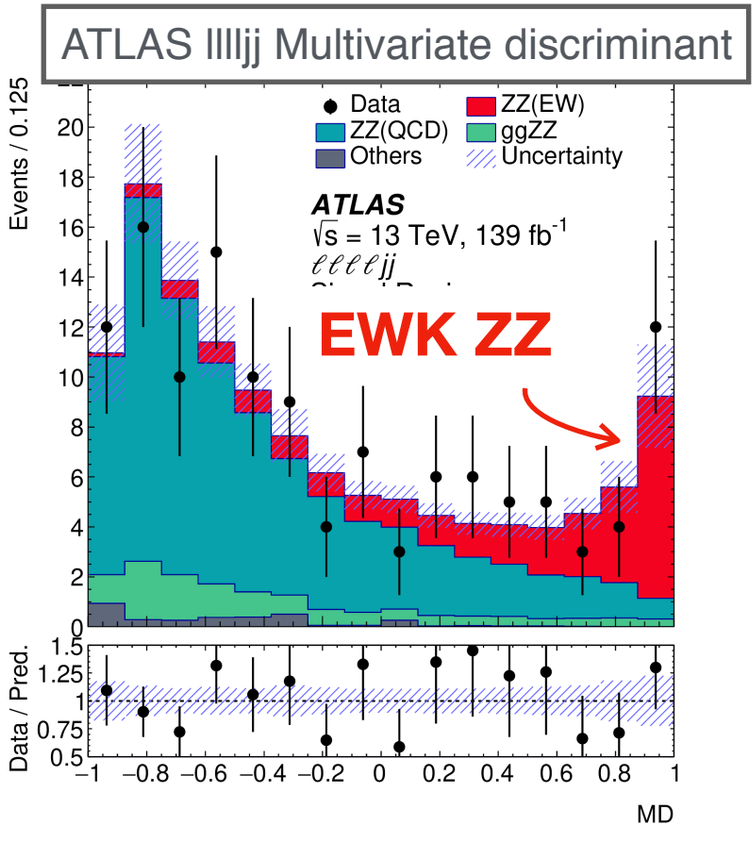
[ATLAS: arXiv:2004.10612](arXiv:2004.10612)
[CMS: arXiv:2008.07013](arXiv:2008.07013)

CMS lllljj Matrix element discriminant

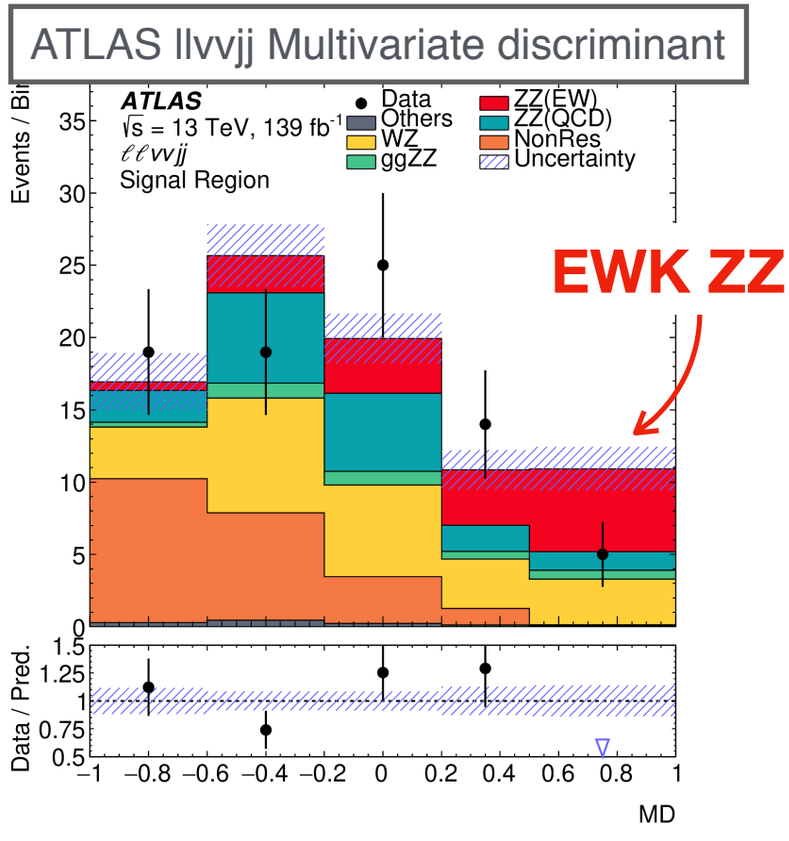


EWK ZZ

ATLAS lllljj Multivariate discriminant



ATLAS llvvjj Multivariate discriminant



EWK Zγjj production

$Z\gamma \rightarrow \ell\ell\gamma$

[Zγ: JHEP 06 (2020) 076](#)
[Wγ: arXiv:2008.10521](#)

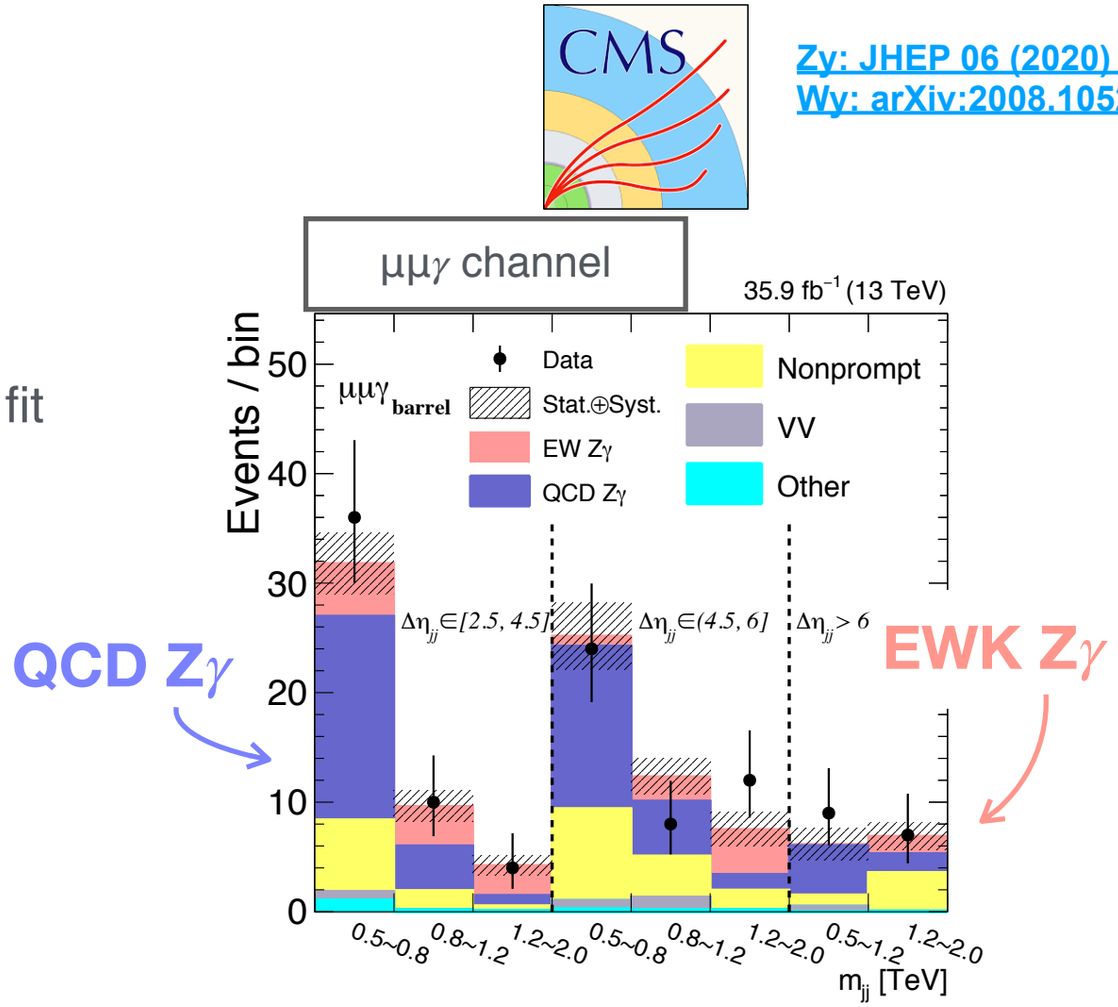
Signal extraction strategy

- Signal extracted from a M_{jj} and $\Delta\eta_{jj}$ two-dimensional fit

Results

Evidence !!

- Evidence **3.9σ** (5.2σ exp) significance (**4.7σ** obtained if combined with 8 TeV data)



EWK Wγjj production

$W\gamma \rightarrow \ell\nu\gamma$

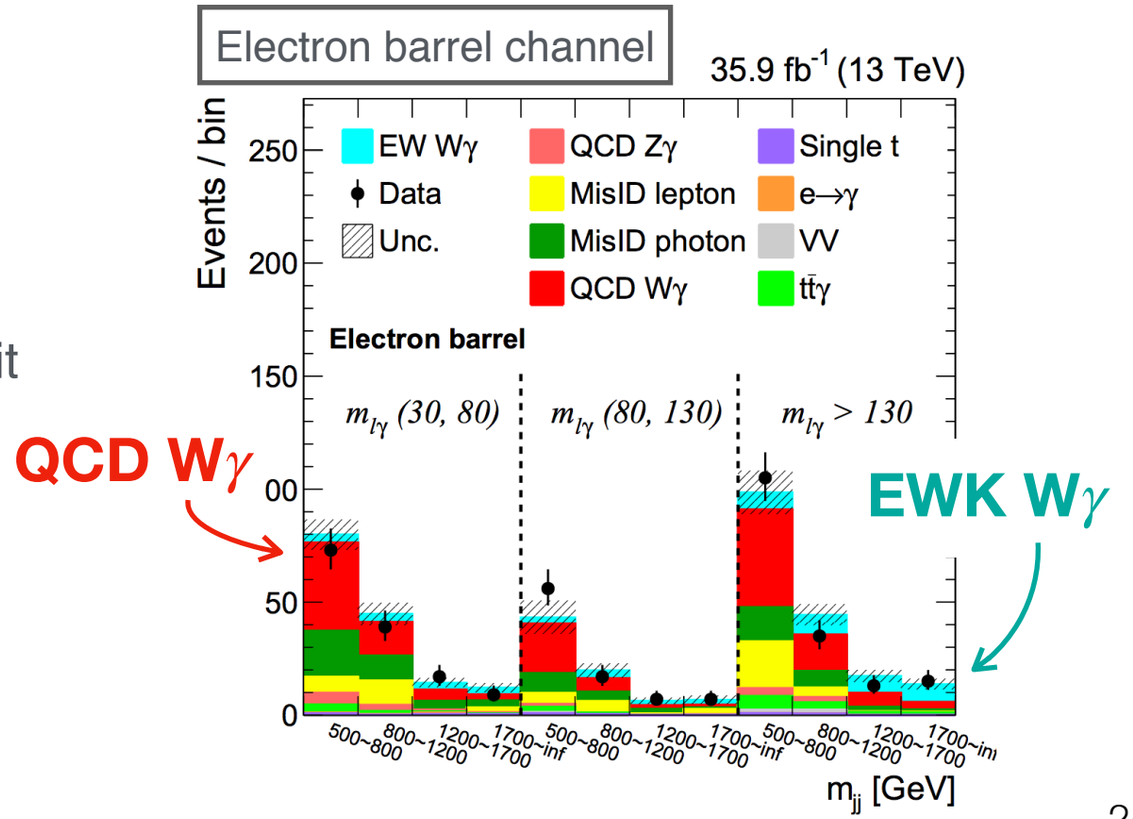
Signal extraction strategy

- Signal extracted from a M_{jj} and $m_{l\gamma}$ two-dimensional fit

Results

Observation !!

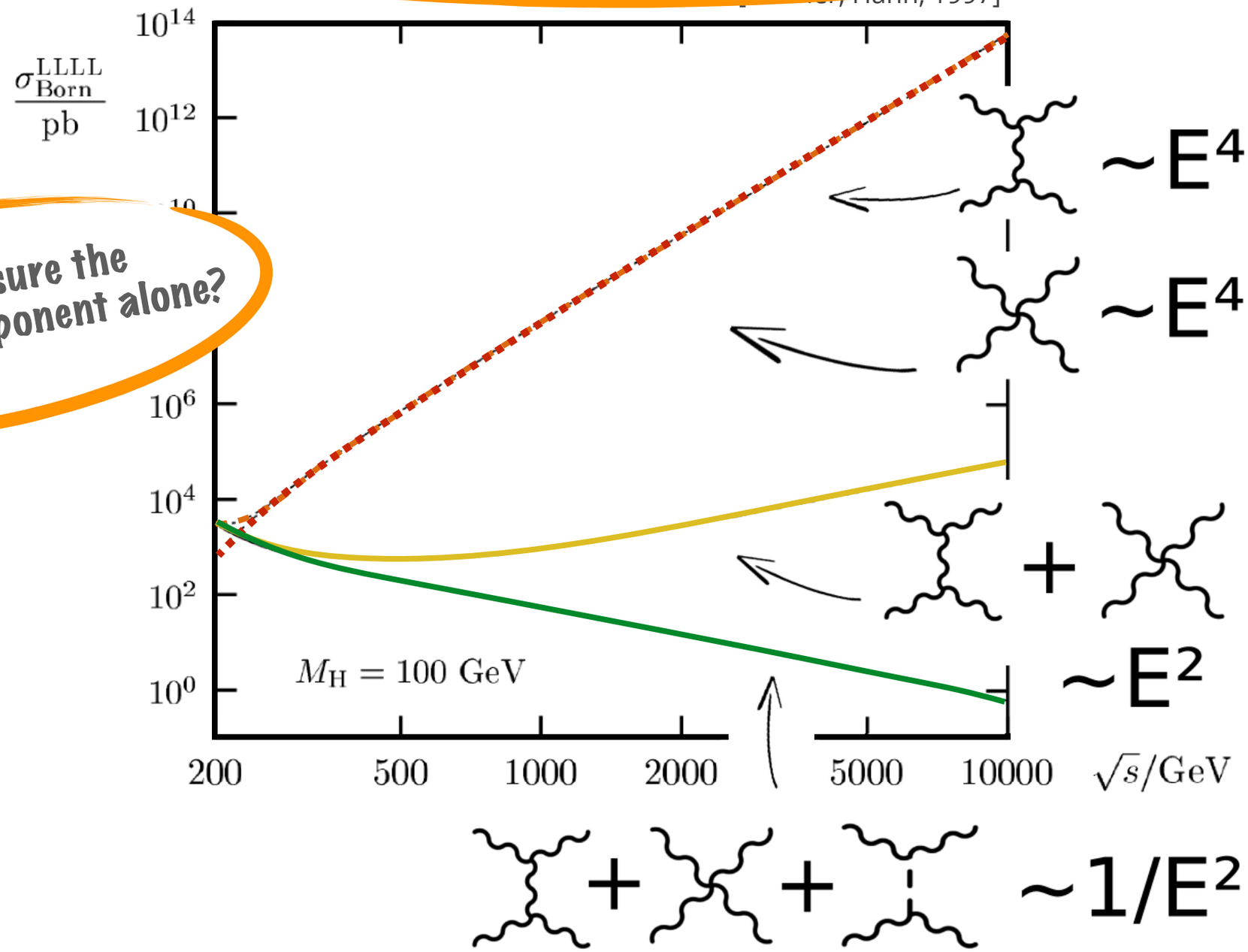
- Significance **4.9σ** (4.6σ), after combining with 8 TeV **5.3σ** (4.8σ)



Why Vector Boson scattering is interesting?

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

[Dobrescu, Hahn, 1997]



Can we measure the longitudinal component alone?

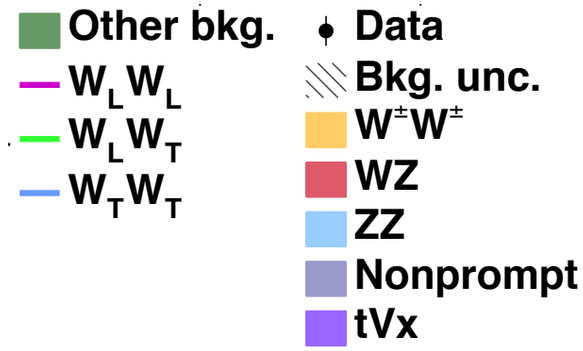
- Test of electroweak sector and EW Symmetry Breaking
- Complementary to “direct” Higgs boson property studies
- Differences in this sector will be indications of new physics

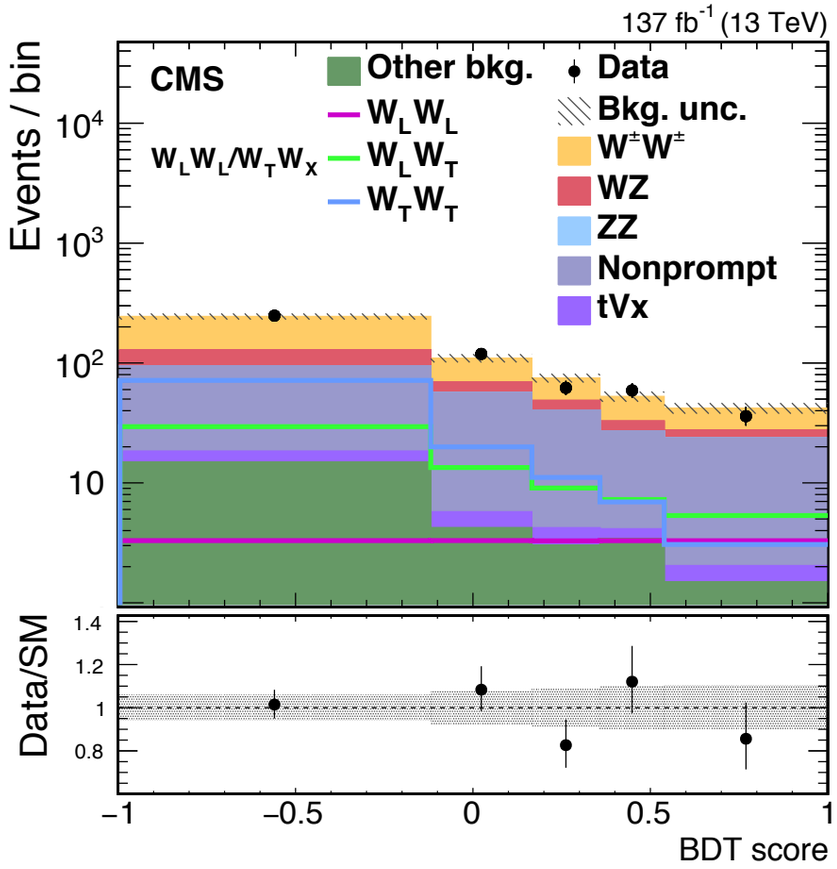
arXiv:2009.09429

Polarization in W±W±jj production

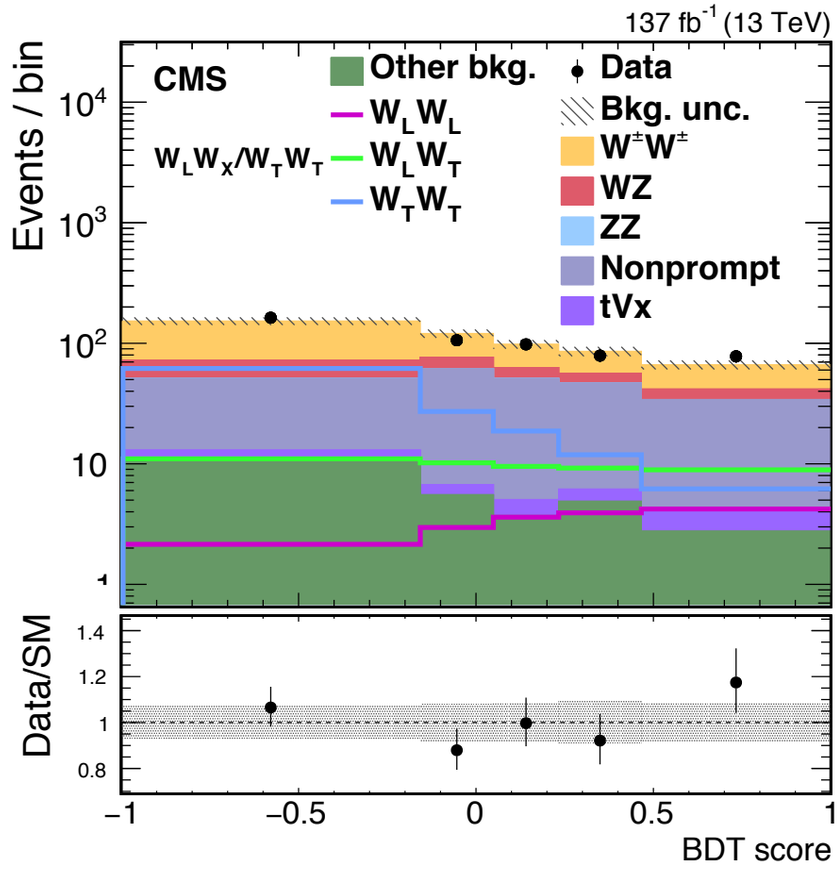
- First try to measure cross sections for polarized same sign W±W± pairs
- Two different BDTs were trained to separate
  - W_LW_L and W_XW_T processes ⟶ not enough statistics to measure double longitudinal polarization
  - W_LW_X and W_TW_T processes
- Measurement of EW W±W± production with at least one longitudinally polarized W boson with a significance of **2.3σ** (3.1σ exp)

BDT for W_LW_L vs W_XW_T discrimination



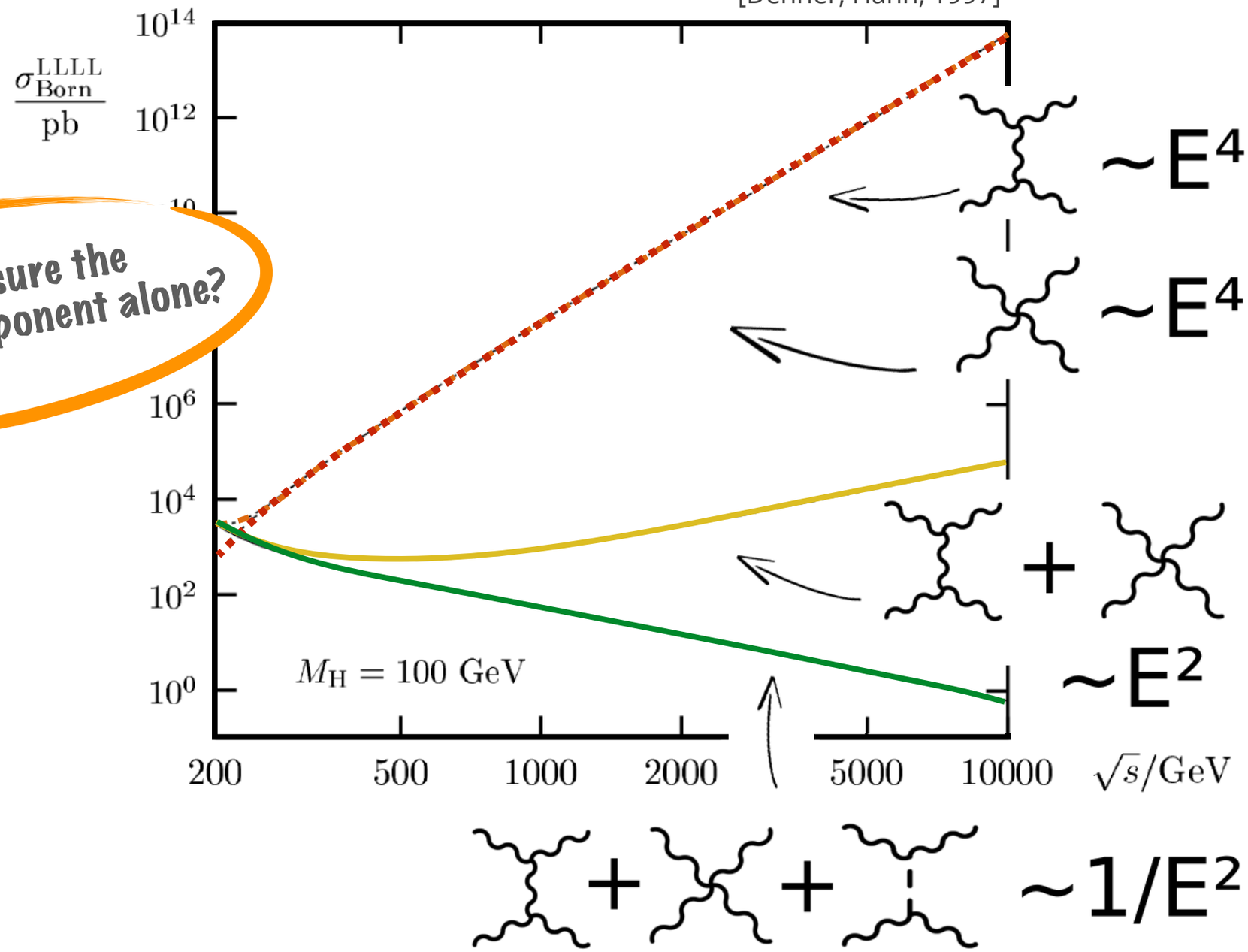


BDT for W_LW_X vs W_TW_T discrimination



Why Vector Boson scattering is interesting?

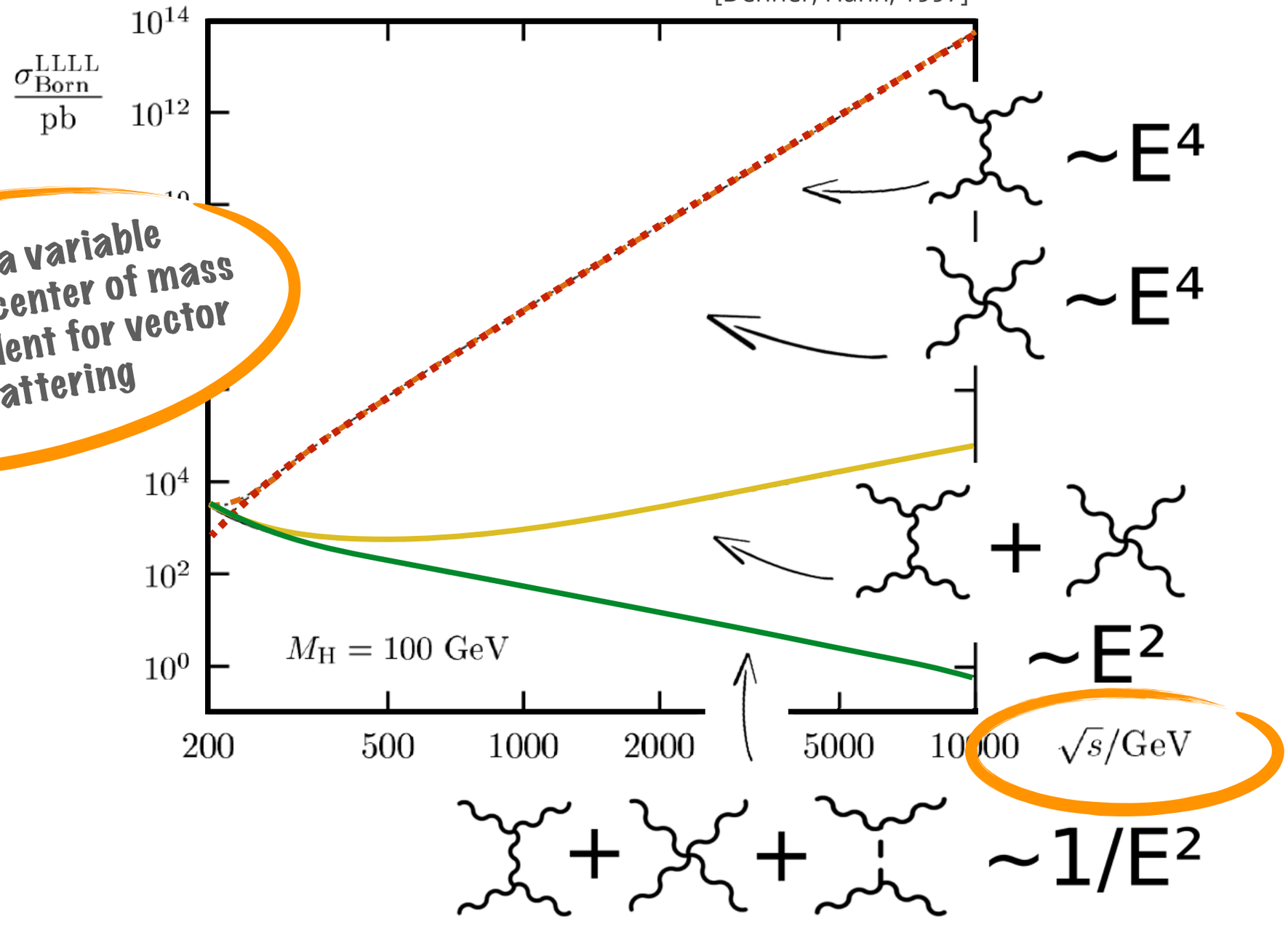
[Denner, Hahn, 1997]



Can we measure the longitudinal component alone?

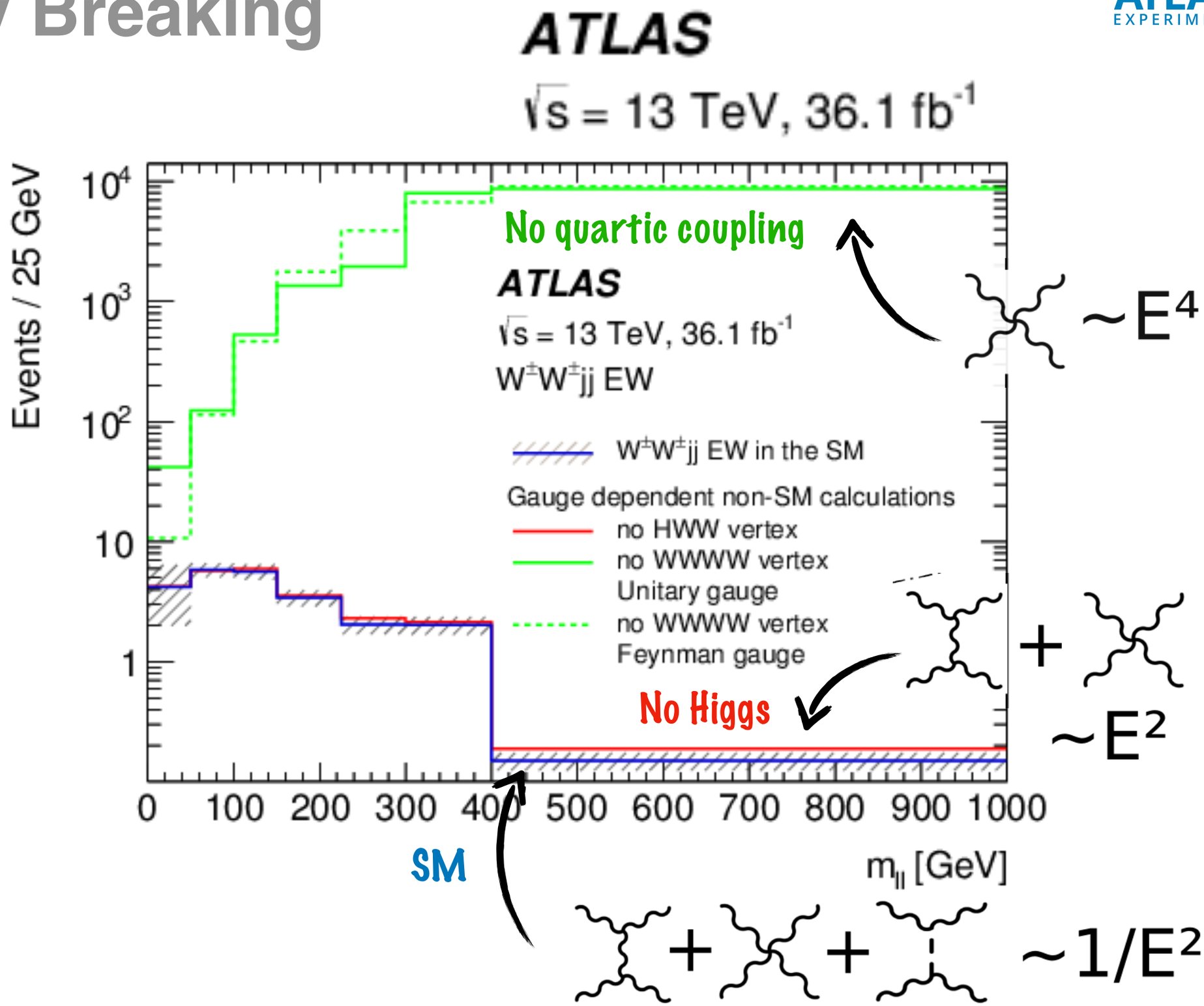
Why Vector Boson scattering is interesting?

[Denner, Hahn, 1997]

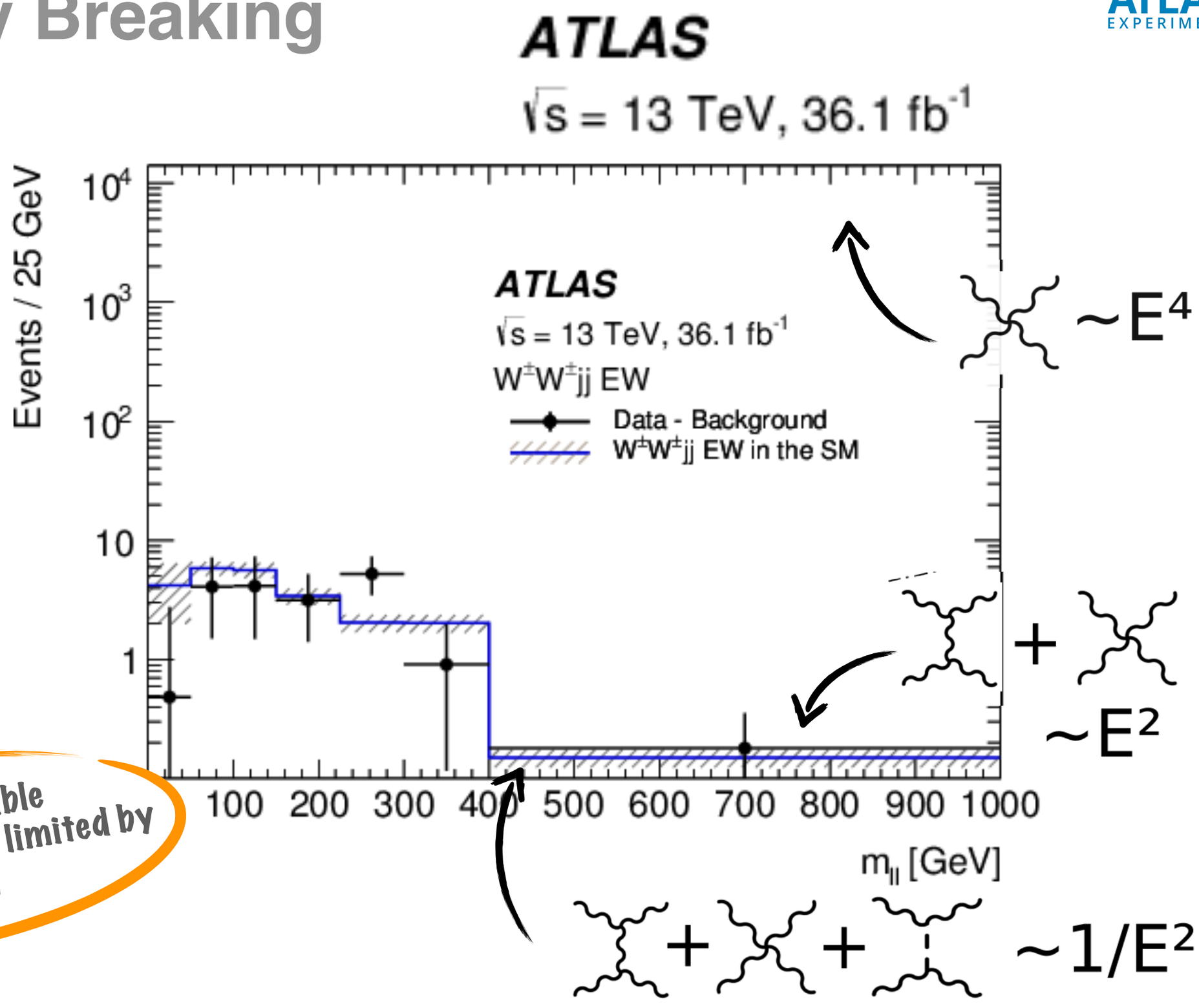


Need to find a variable sensitive to the center of mass energy, not evident for vector boson scattering

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!

Conclusions

- Many new results with the latest and greatest Run 2 dataset by ATLAS and CMS, legacy Run 2 measurements are being published and much more are expected to come!
- Comprehensive tests of the Standard Model over 15 orders of magnitude in cross section and going more differential, results compared to theory predictions from state-of-the-art MC and fixed-order calculations ⟶ The standard model resist the test!
- LFU test in agreement with SM with the best precision achieved up to now
- First LHC search of the rare exclusive hadronic decay $W \to \pi\gamma$
- First measurements of production cross sections for polarized vector bosons in $W^{\pm}W^{\pm}$
- Evidence/Observation of rare processes:
  - Observation of photon-induced processes: $\gamma\gamma \to WW$ and $\gamma\gamma \to ll$
  - Observation of electroweak production of WWjj, Wγjj, WZjj and ZZjj
  - Evidence of electroweak production of Zγjj
  - Observation of production of massive VVV (with V = W , Z)
- More information:
  - ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP