Studies on $Z\gamma$ Scattering at 13 TeV with ATLAS Detector

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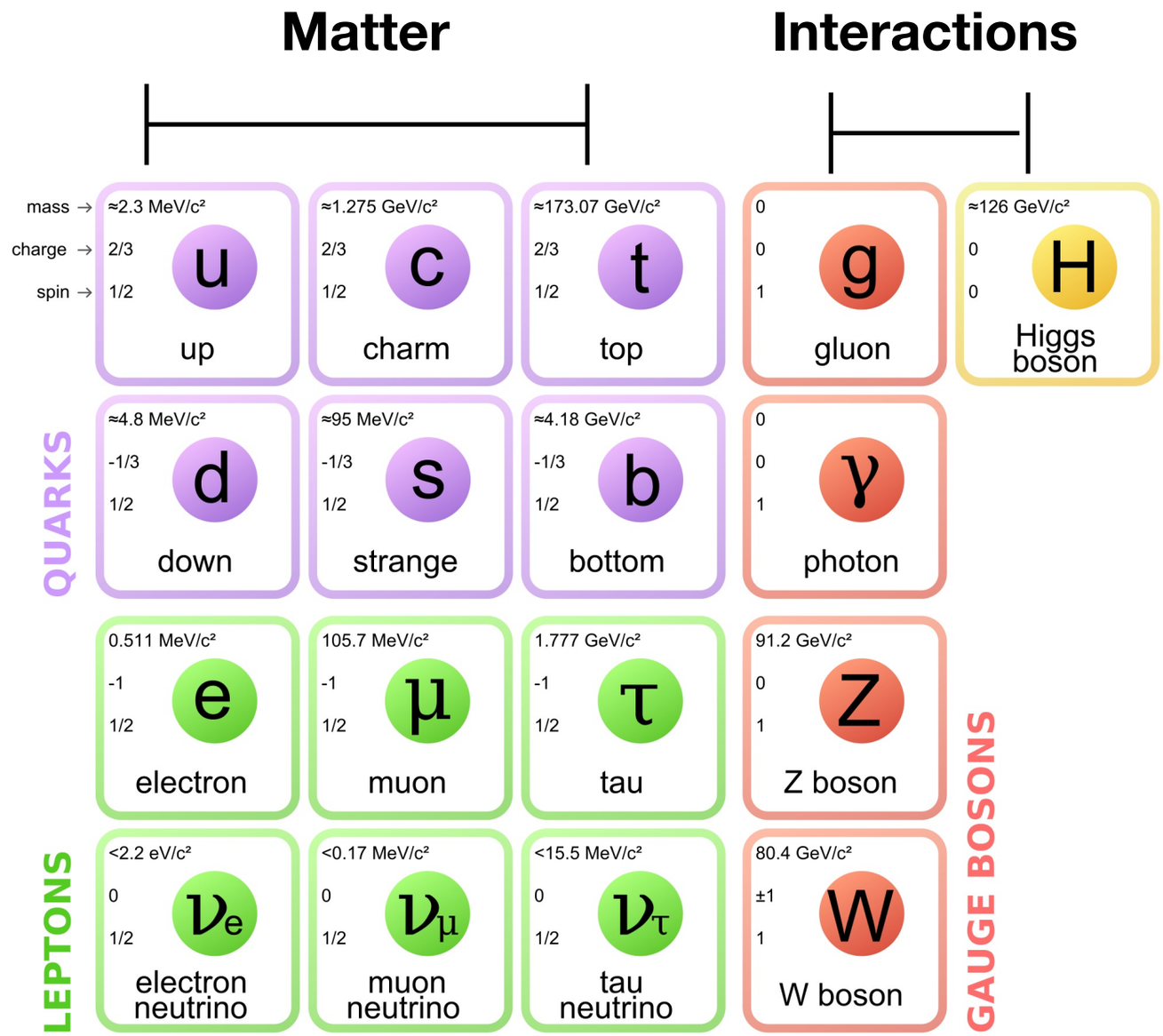
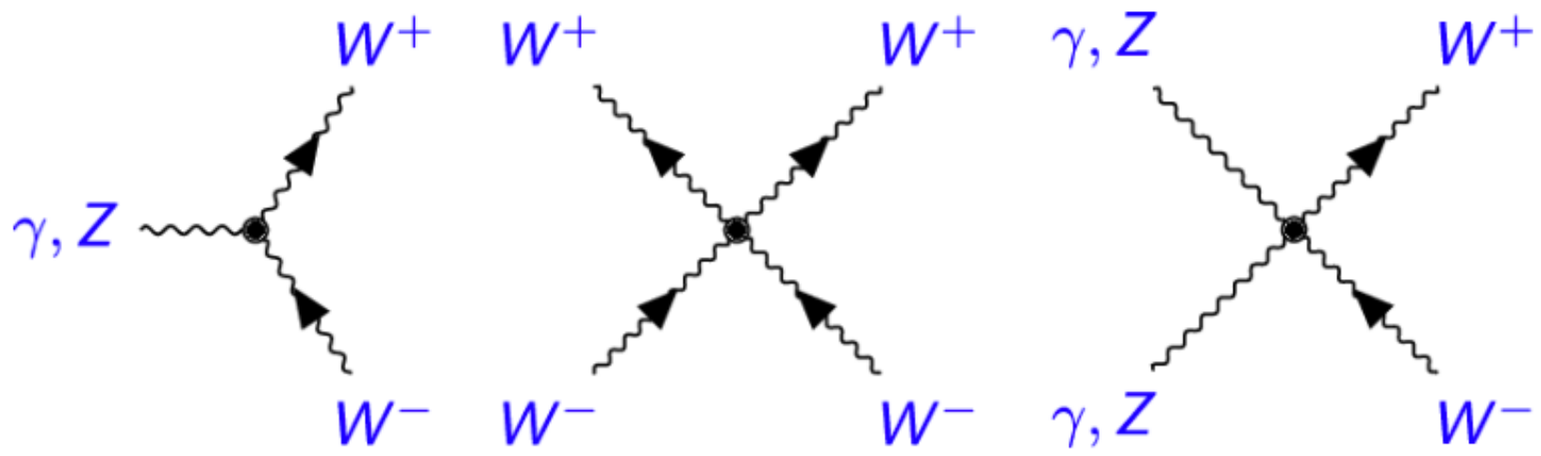
The Standard Model (SM)

- Well-tested theory of fundamental particles and their interactions
  - Complete with Higgs boson discovery in 2012
- However, it has its limitations:
  - Gravity
  - Dark matter and dark energy
  - Masses of neutrinos



New physics? → measure deviations from SM predictions

Vector Boson Scattering: Motivation



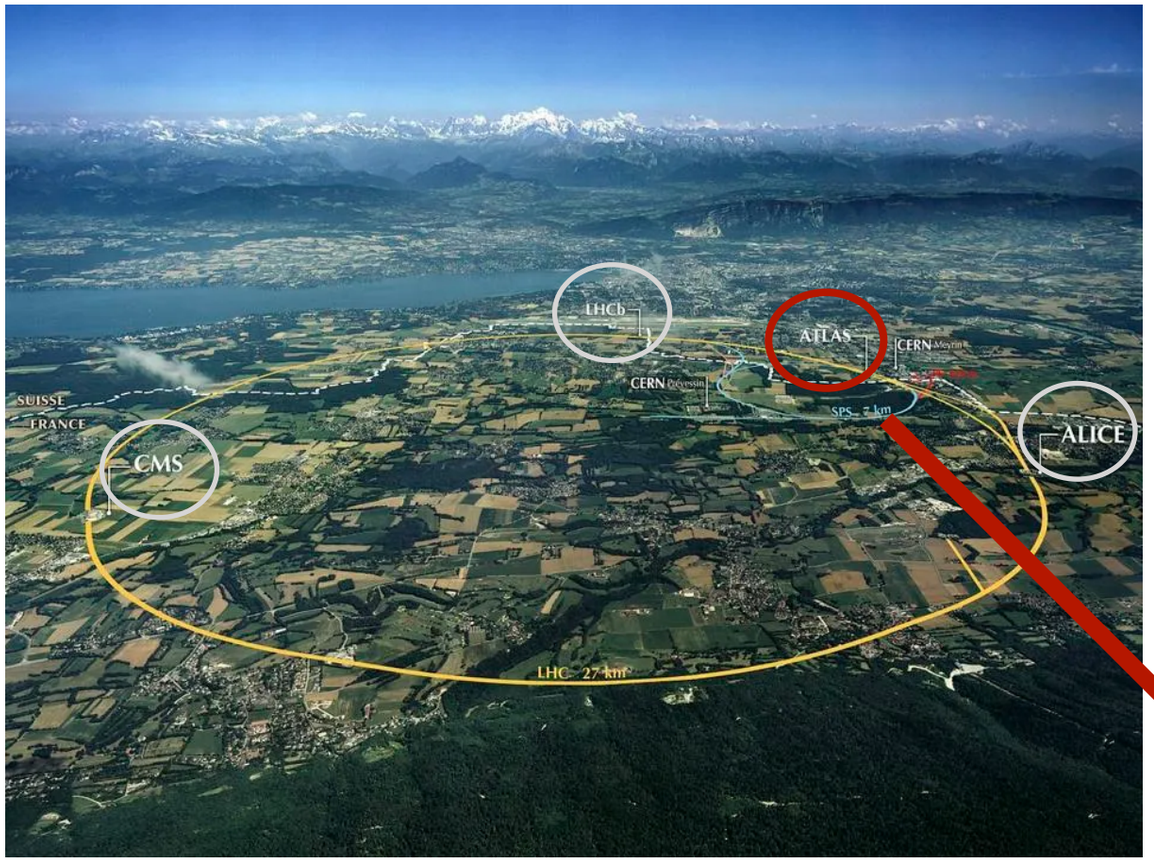
SM self-couplings of electroweak vector boson ($V = W, Z, \gamma$)

- Deviation from self-coupling predicted by SM
- Existence of neutral quartic self-coupling forbidden by SM

→ New physics!

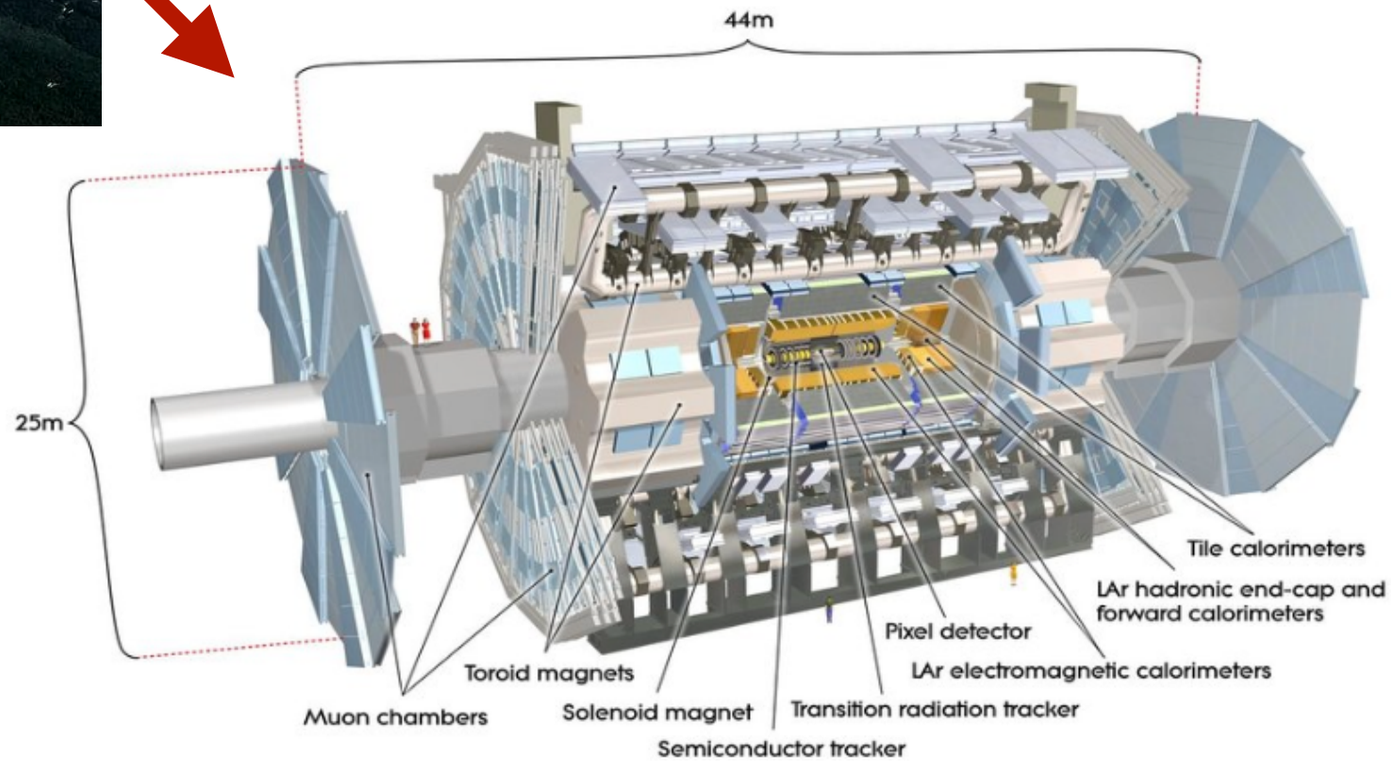
Probe self-couplings → study Vector Boson Scattering ($VV \to VV$)

Large Hadron Collider (LHC)



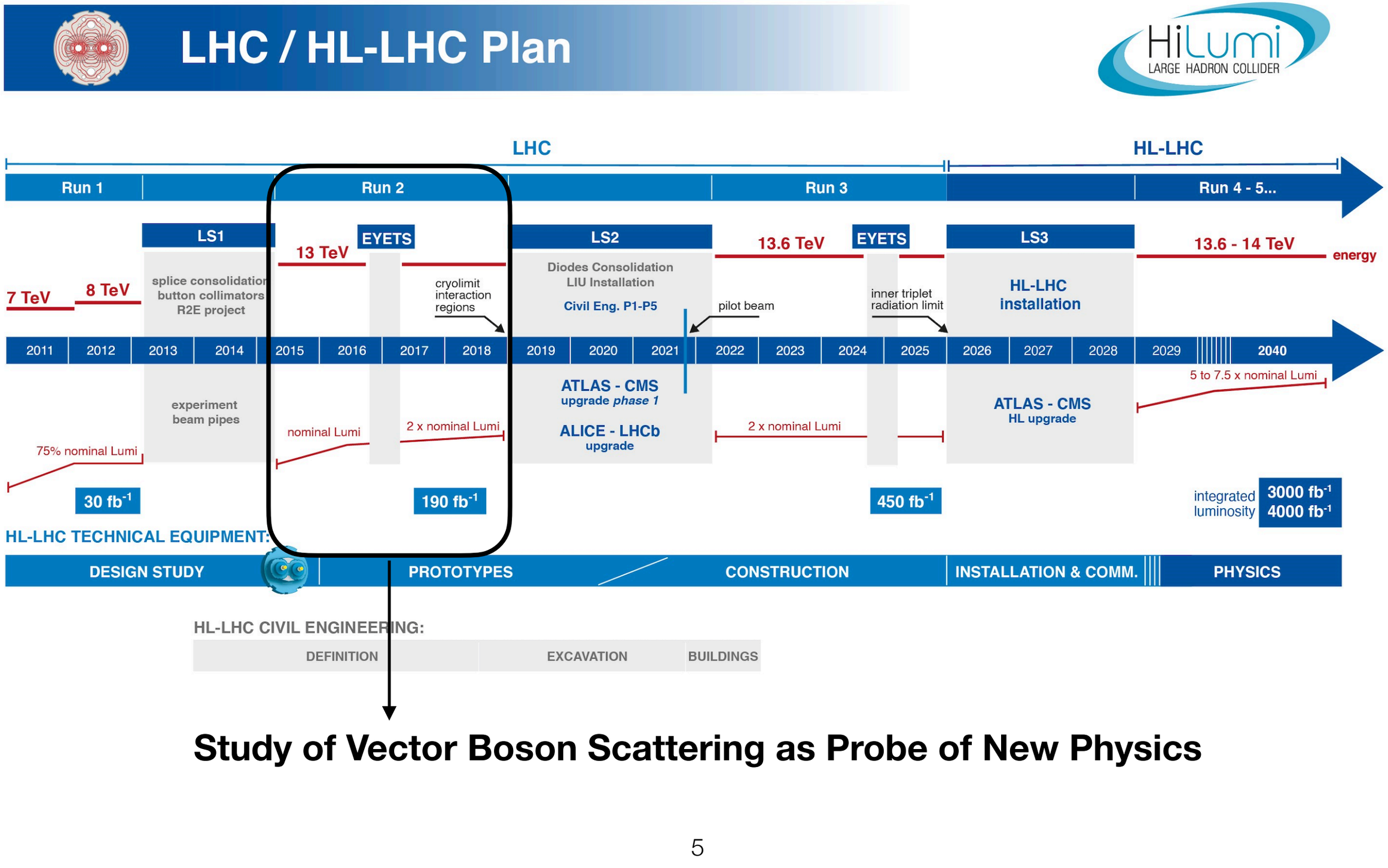
- 27 km ring, 100 m below ground
- Proton-proton* collider
  - 40 million collisions per second

- 4 detectors: ALICE, ATLAS, LHCb, CMS
  - General purpose detector



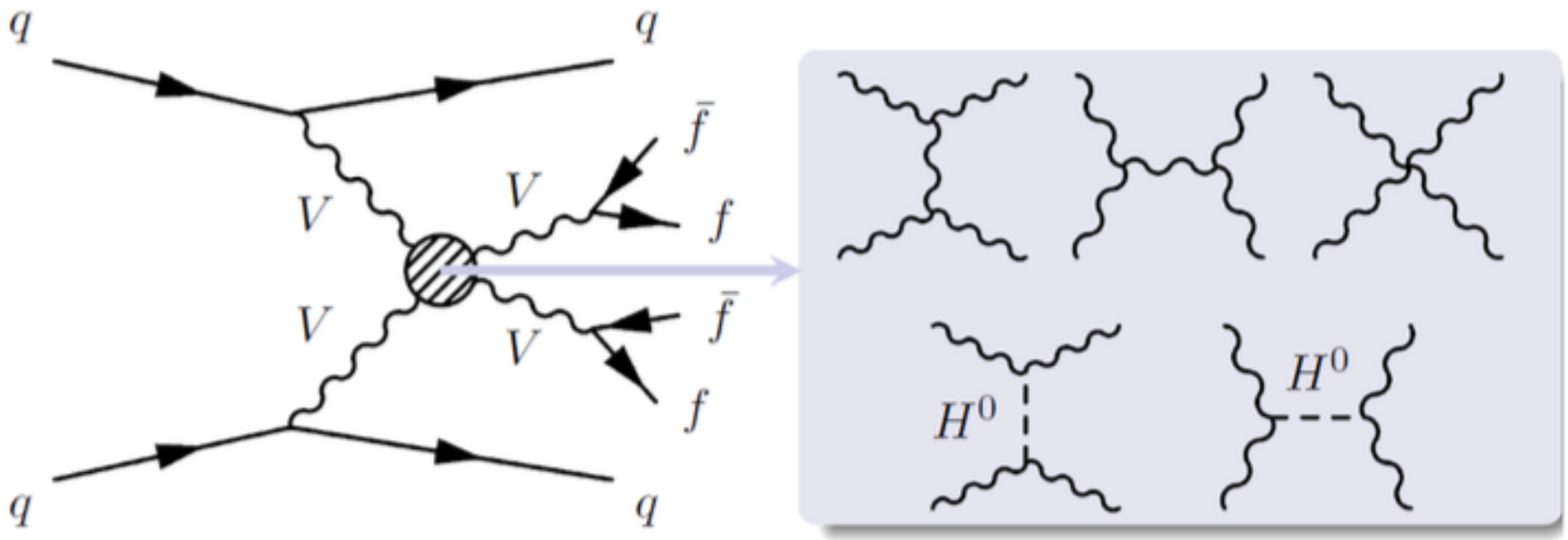
*also collides heavy ions

Operation Timeline



Study of Vector Boson Scattering as Probe of New Physics

Vector Boson Scattering at LHC

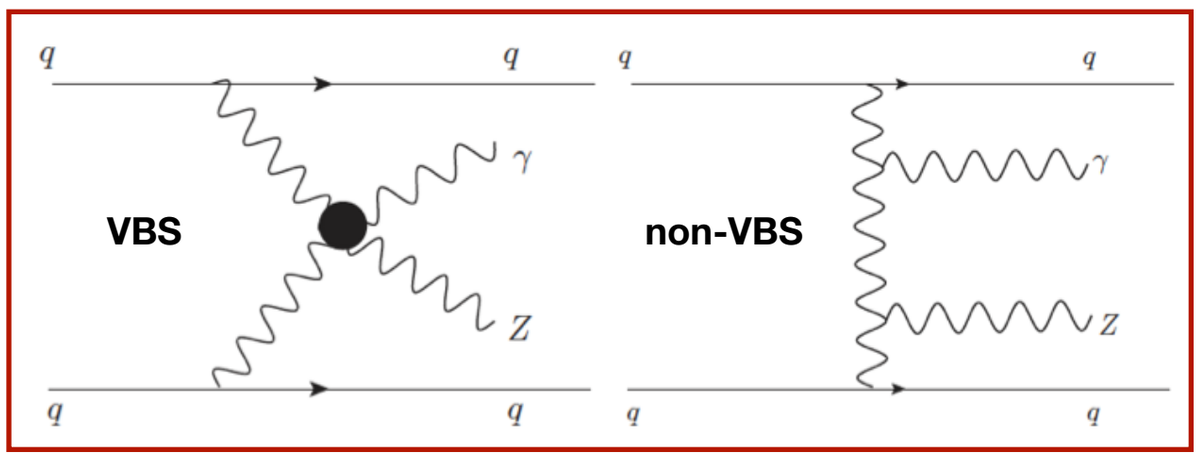


- Characterised by two vector bosons and two jets

- Consists of vector boson self-couplings and coupling of vector boson to Higgs boson

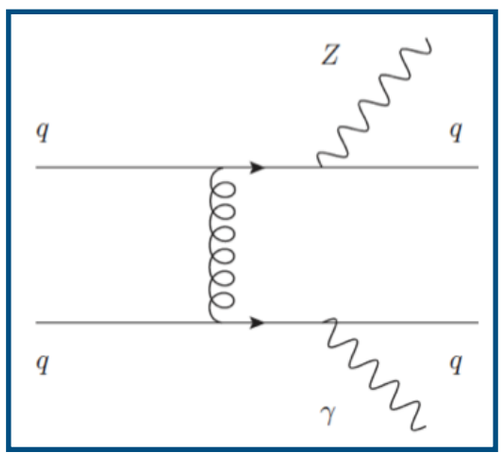
Vector Boson Scattering at LHC (II)

EW-$VVjj$ $O(\alpha_{EW}^4)$



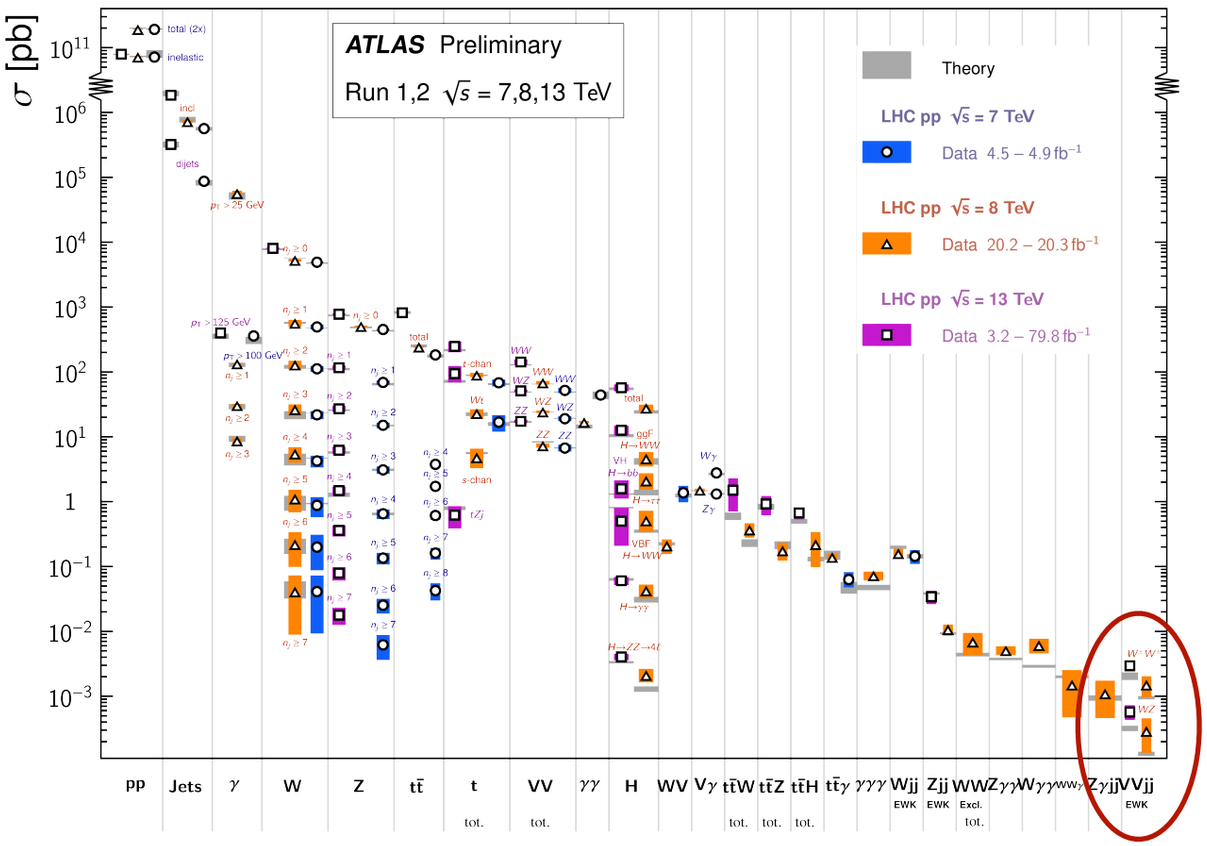
Signal

QCD-$VVjj$ $O(\alpha_S^2\alpha_{EW}^2)$



Background

\+ Small interference $O(\alpha_S\alpha_{EW}^3)$



Very **rare processes** → only accessible in recent years with Run 2 data

Electroweak Production of $Z\gamma jj$

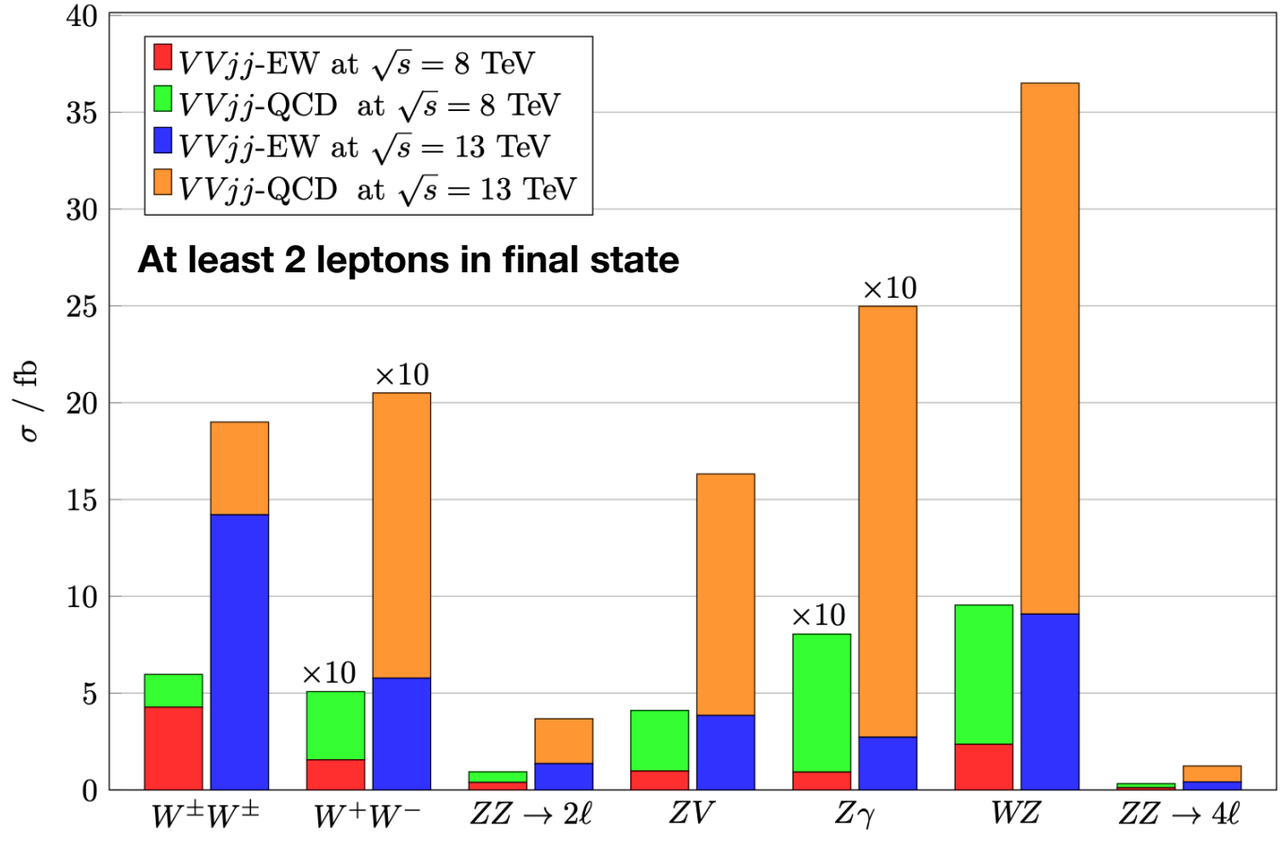
Final state: $l^+l^-\gamma$, where $l = e, \mu$ (τ have negligible contribution)

- $2q\gamma$: large hadronic backgrounds*
- $2\nu\gamma$: neutrinos escape without a detectable signal

https://cds.cern.ch/record/1753849/files/CERN-THESIS-2014-105.pdf

Best channel to probe forbidden **neutral quartic gauge coupling**

- ZZ: low cross section
- $\gamma\gamma$: large background from misidentified photons



*LHC is a QCD factory

Studies on EW-$Z(\rightarrow ll)\gamma jj$ with ATLAS

2017

- 2012 data $\rightarrow$ L = 20.2 fb^{-1}
- No evidence of EW-$Z\gamma jj$ $\rightarrow$ 2σ

2020

- 2015-2016 data $\rightarrow$ L = 36 fb^{-1}
- Evidence of EW-$Z\gamma jj$ $\rightarrow$ 4.1σ

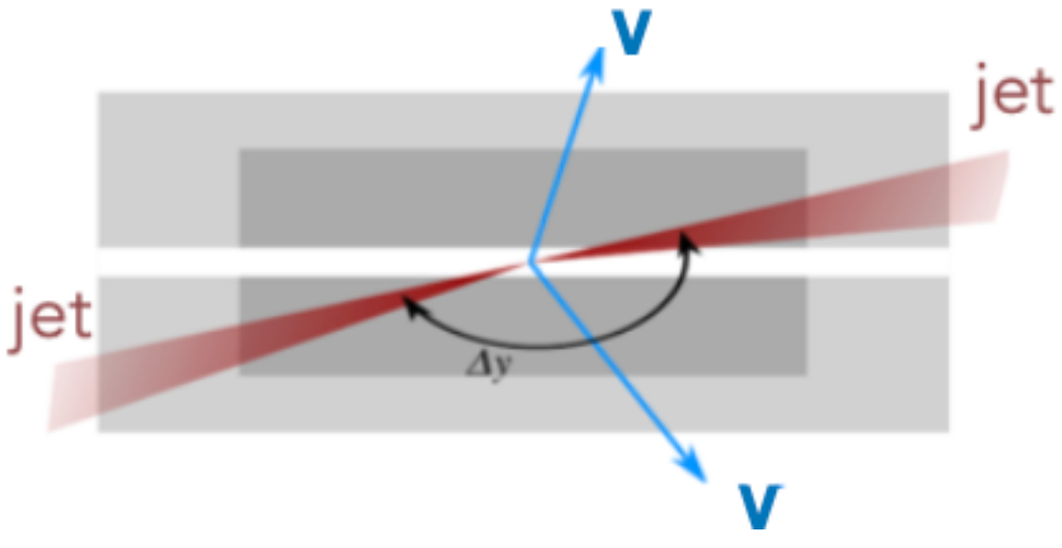
2023 (this analysis)

- 2015-2018 data $\rightarrow$ L = 140 fb^{-1}
- Main goals:
  - Observation of EW-$Z\gamma jj$
  - First differential cross section measurements of EW-$Z\gamma jj$

Event Selection

Based on **typical VBS topology**

- Two high energy forward jets: m_{jj}>500 GeV, $|\Delta y|$>1
- Hadronic activity suppressed between jets: $N_{gap}^{jets} = 0$
- Centrally produced vector bosons: $\zeta(Z\gamma) = |\frac{y_{Z\gamma} - (y_{j1} + y_{j2})/2}{y_{j1} - y_{j2}}| < 0.4$



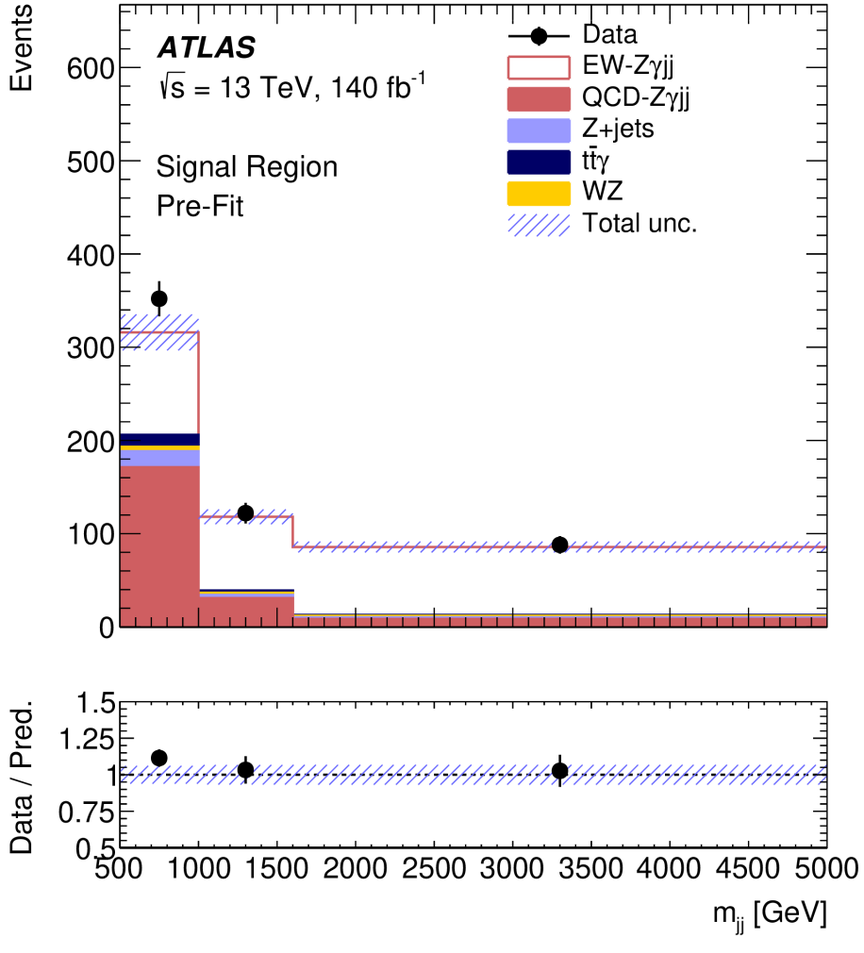
Measurement Strategy

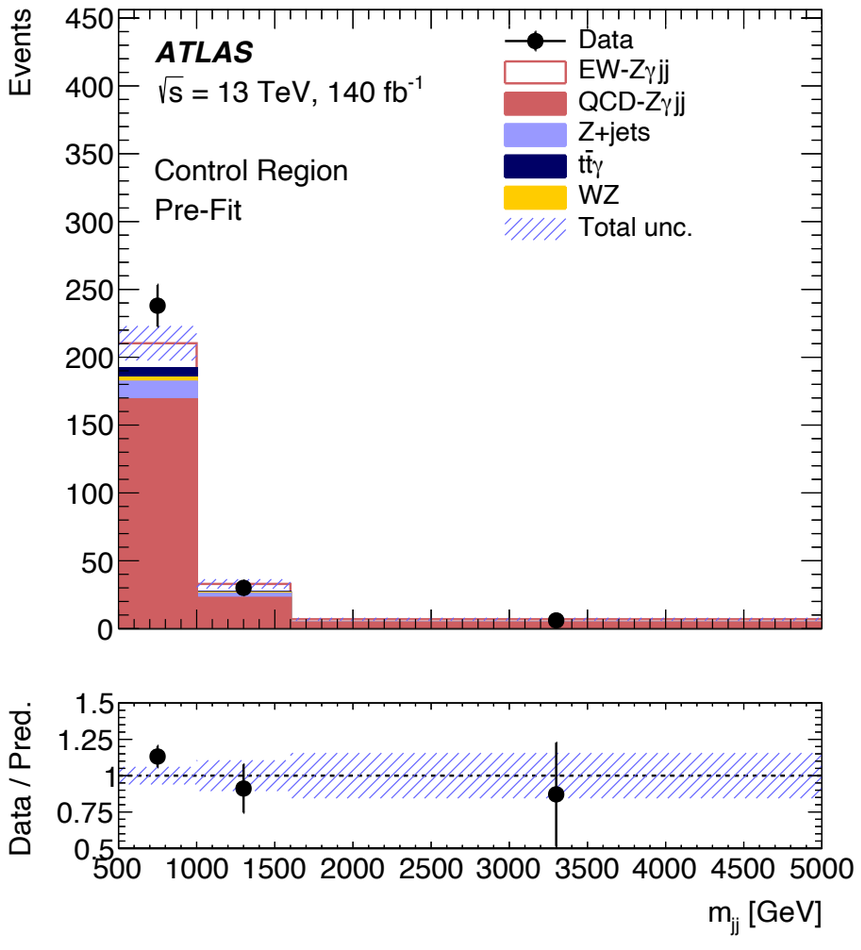
- **Signal Region**: $\zeta(Z\gamma) < 0.4$
- **Control Region**: $\zeta(Z\gamma) > 0.4$

  → To constrain QCD-$Z\gamma jj$ background

Variable: m_{jj}

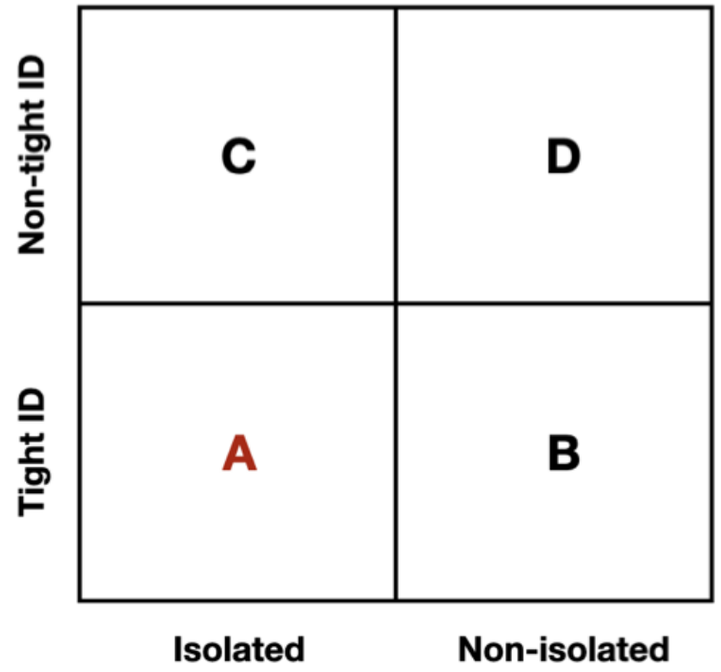
→ uncorrelated with $\zeta(Z\gamma)$

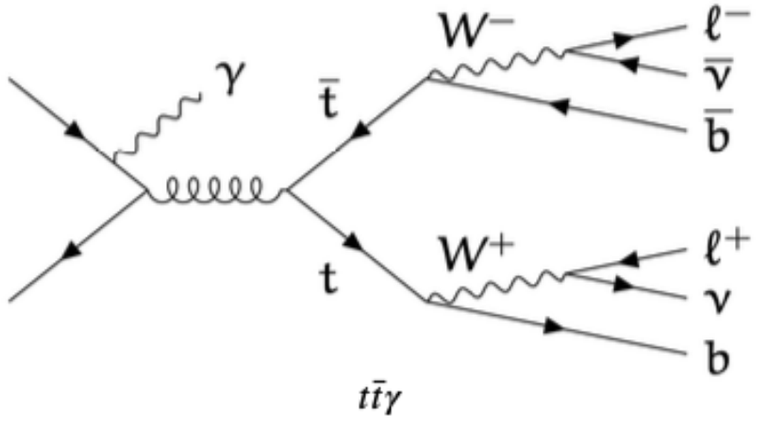




Background

1. QCD-$Z\gamma jj$:
   - Dominant background
   - Constrained in QCD-$Z\gamma jj$ enriched control region
2. Z+jets:
   - Obtained from data-driven *ABCD method* based on photon isolation and identification
3. $t\bar{t}\gamma$:
   - Estimated from simulation, validated in $e\mu\gamma$ control region
4. $WZjj$:
   - Estimated from simulation





$t\bar{t}\gamma$

Systematic Uncertainties

Experimental

- $Z\gamma jj$:
  - Detector reconstruction of photons, leptons and jets
  - Pileup* reweighting
- Estimation of Z+jets, $t\bar{t}\gamma$, $WZjj$
- Luminosity

Theoretical

- EW-$Z\gamma jj$:
  - EW-QCD $Z\gamma jj$ interference
  - Theoretical modelling
- QCD-$Z\gamma jj$:
  - Theoretical modelling

*additional pp collisions

Profile Likelihood Fit

Data

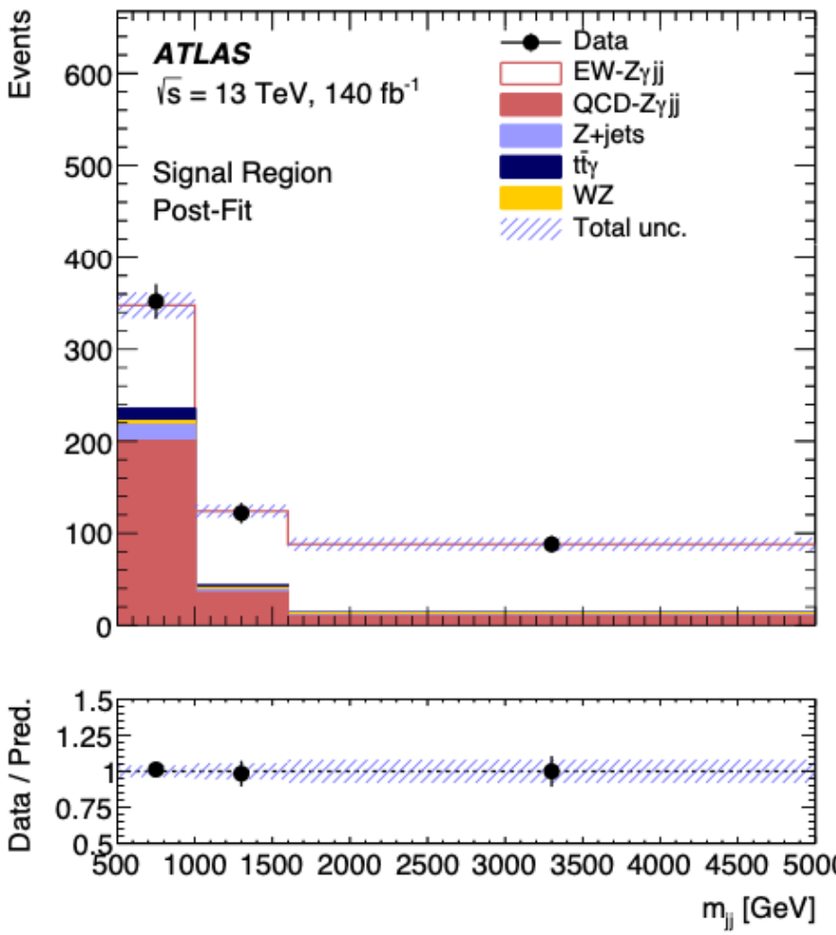
$$L(\mu, \vec{k}, \vec{\theta}, \vec{\gamma}) = \prod_{i \in \text{bins}} \text{Pois}(n_i | (\mu s_i(\vec{\theta}) + k b_i(\vec{\theta}))\gamma_i) \times \prod_{j \in \text{syst}} C(\theta_j | 0, 1) \times \prod_{i \in \text{bins}} C(\gamma_i | 1, \sigma_{\gamma_i})$$

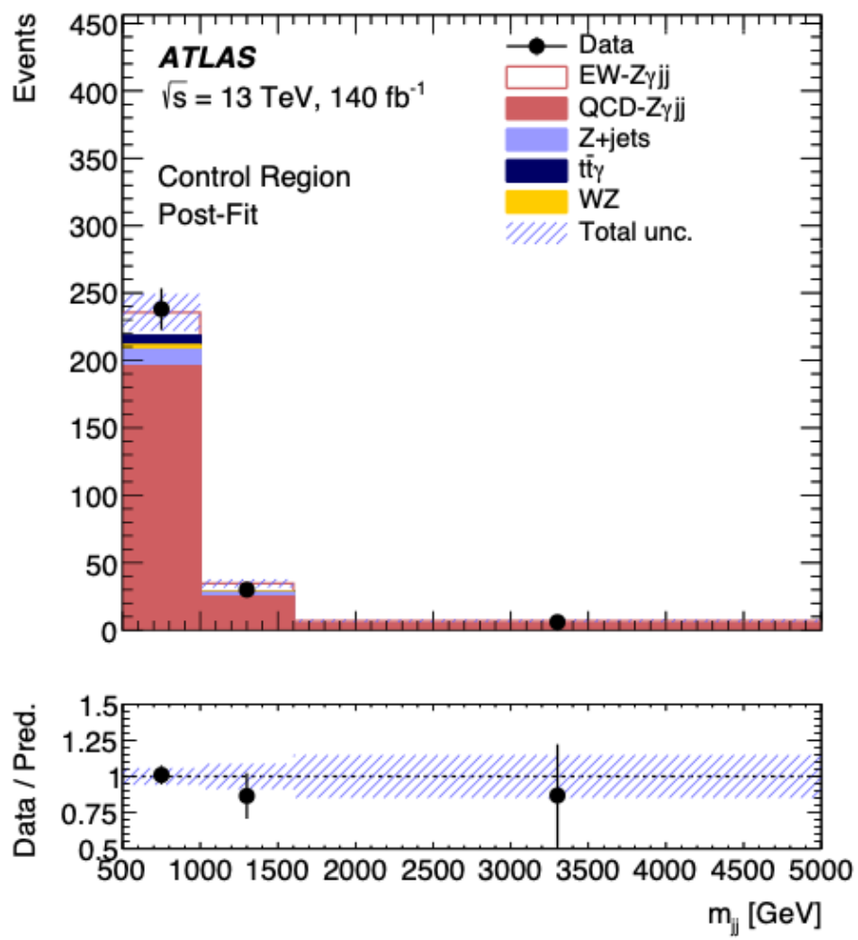
Prediction
(Signal+Background)

Goal: maximise L to estimate its parameters

- **Parameter of Interest**:
  - Unconstrained $\mu_{EW} = \sigma^{EW-Z\gamma jj}_{measured} / \sigma^{EW-Z\gamma jj}_{predicted}$
- **Nuisance Parameters**:
  - Unconstrained k: normalisation of QCD-$Z\gamma jj$
  - Constrained θ: experimental and theoretical systematic uncertainties
  - Constrained γ: systematic uncertainty due to finite size of simulation

Results





$$\mu_{EW} = 1.02^{+0.13}_{-0.12}$$
$$= 1.02 \pm 0.09(stat.) \pm 0.09(syst.)$$

Dominant systematics: EW-$Z\gamma jj$ modelling

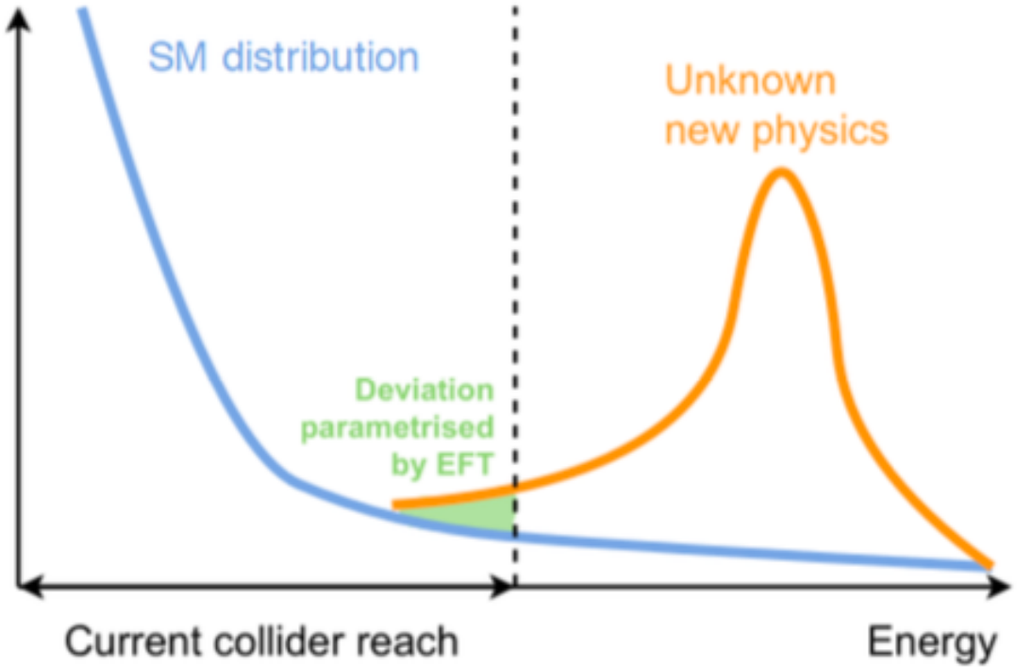
$$\sigma_{EW} = 3.6 \pm 0.5 \text{ fb}$$

$$\sigma_{EW}^{predicted} = 3.5 \pm 0.2 \text{ fb}$$

First observation of EW-$Z\gamma jj$ with ATLAS

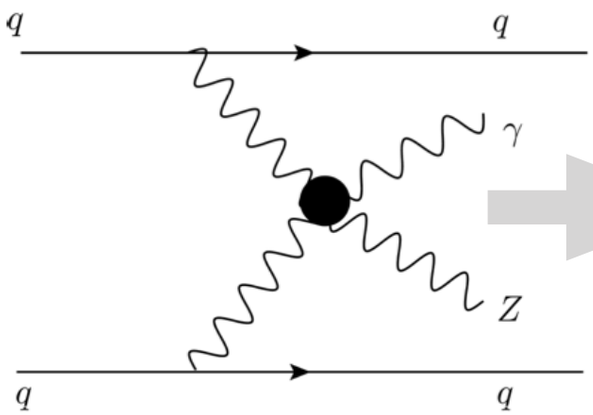
Differential Measurements: Motivation

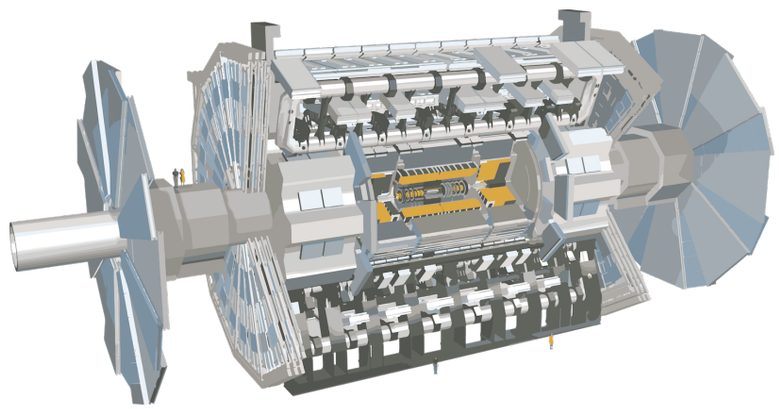
- Improve modelling of EW-$Z\gamma jj$
  - Variables: $m_{jj}, |\Delta y_{jj}|, p_T^l, p_T^j$
- Sensitive to Effective Field Theory studies
  - Variables: $p_T^{Z\gamma}, E_T^{\gamma}, |\Delta\phi(Z\gamma, jj)|$

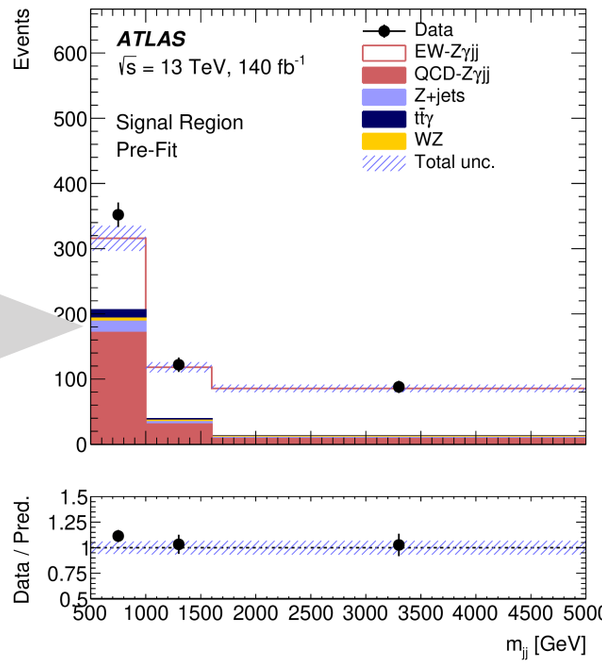


Unfolding

Correcting measured distribution for detector effects



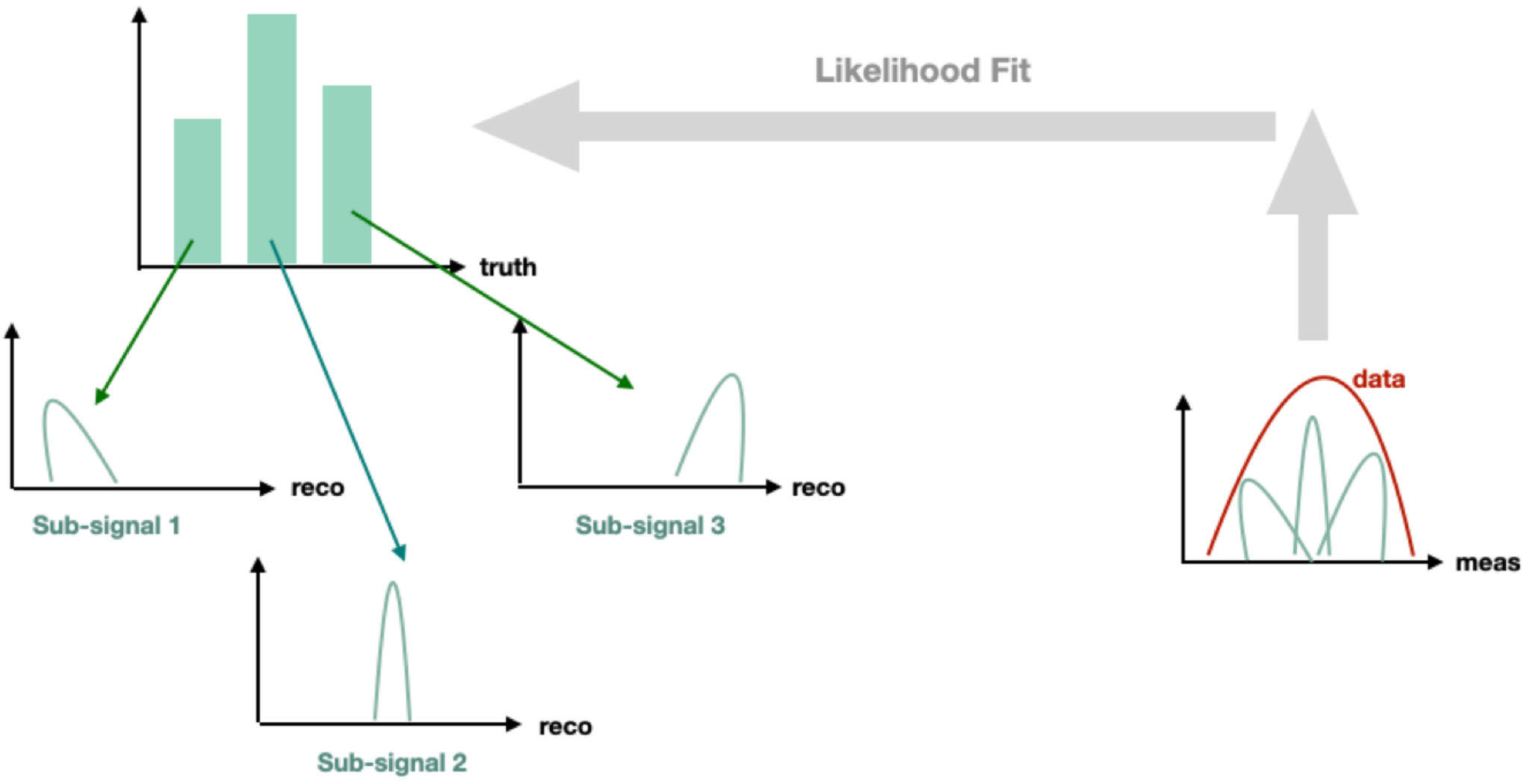




?

Goal: to perform EW-$Z\gamma jj$ unfolding and measure differential cross-sections

Profile Likelihood Unfolding

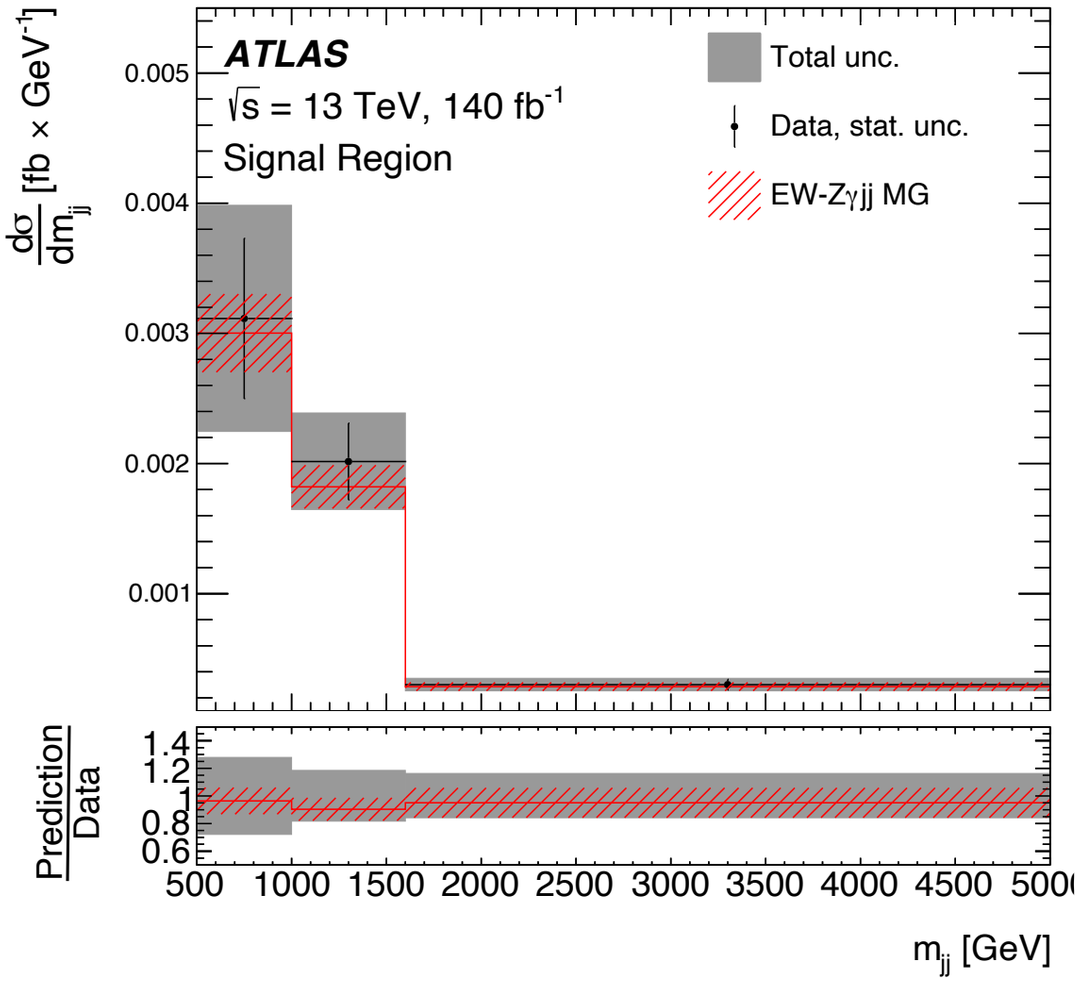


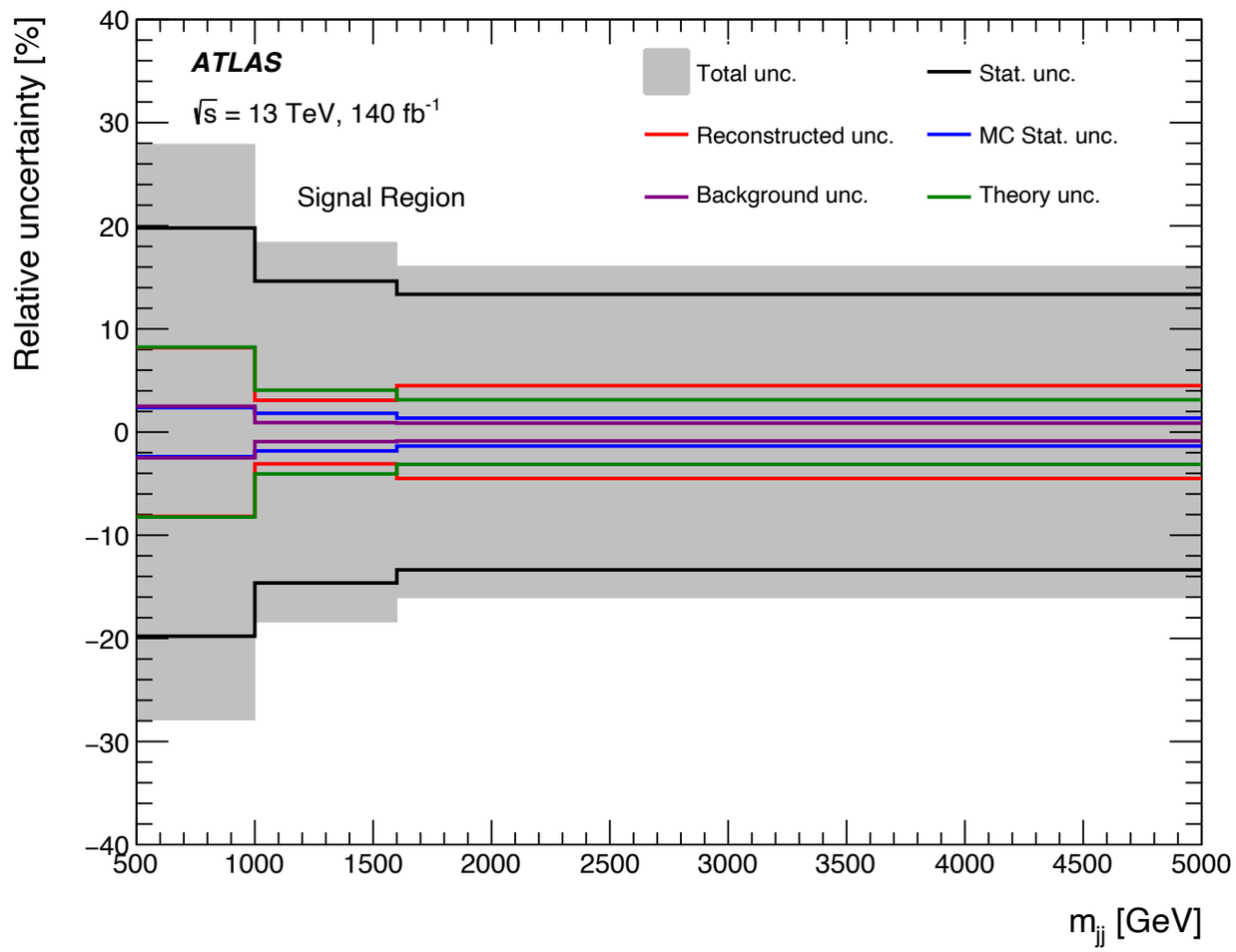
Simultaneously constrain normalisation of QCD-$Z\gamma jj$ bin-by-bin

Truth: simulation of particle level physics model
Reconstructed: simulation of measured data

Results

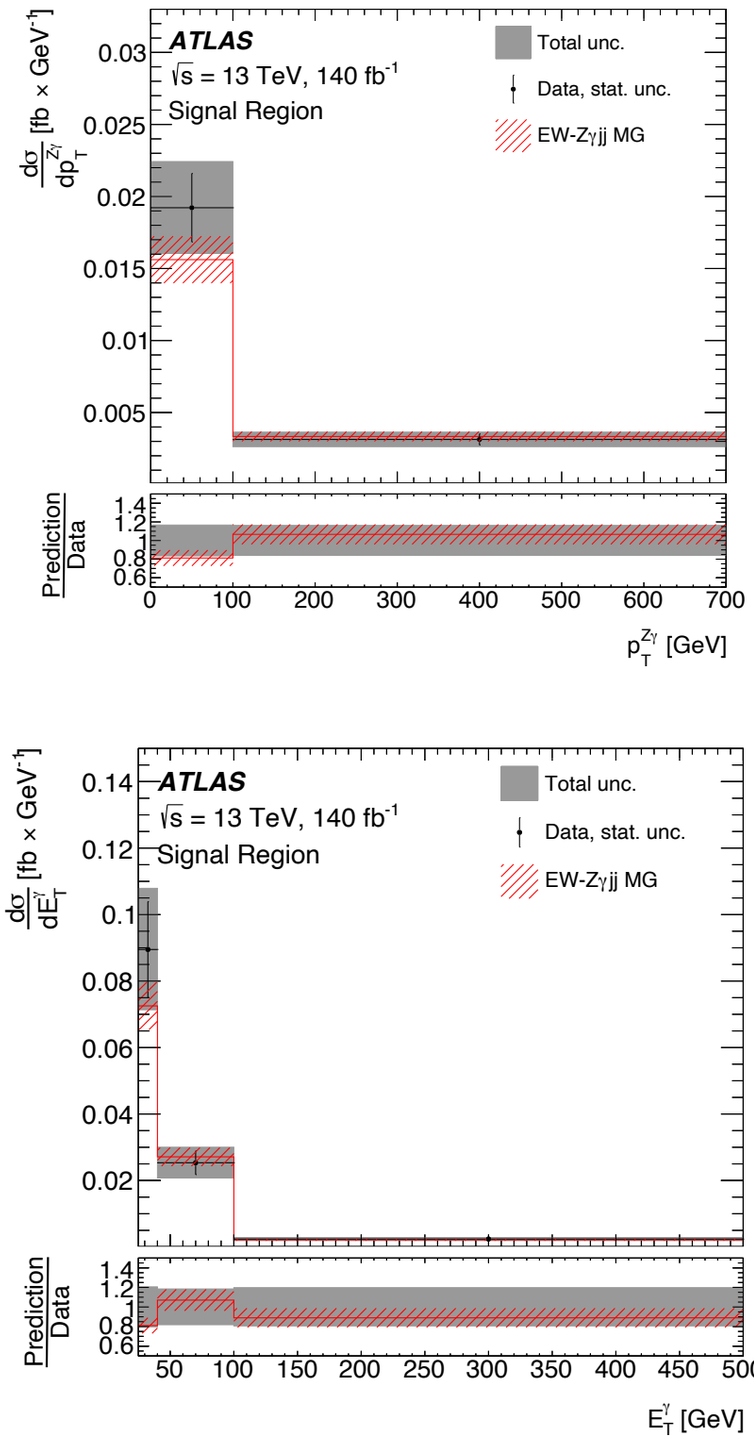
Differential measurements performed **first time for EW-$VVjj$ with ATLAS**

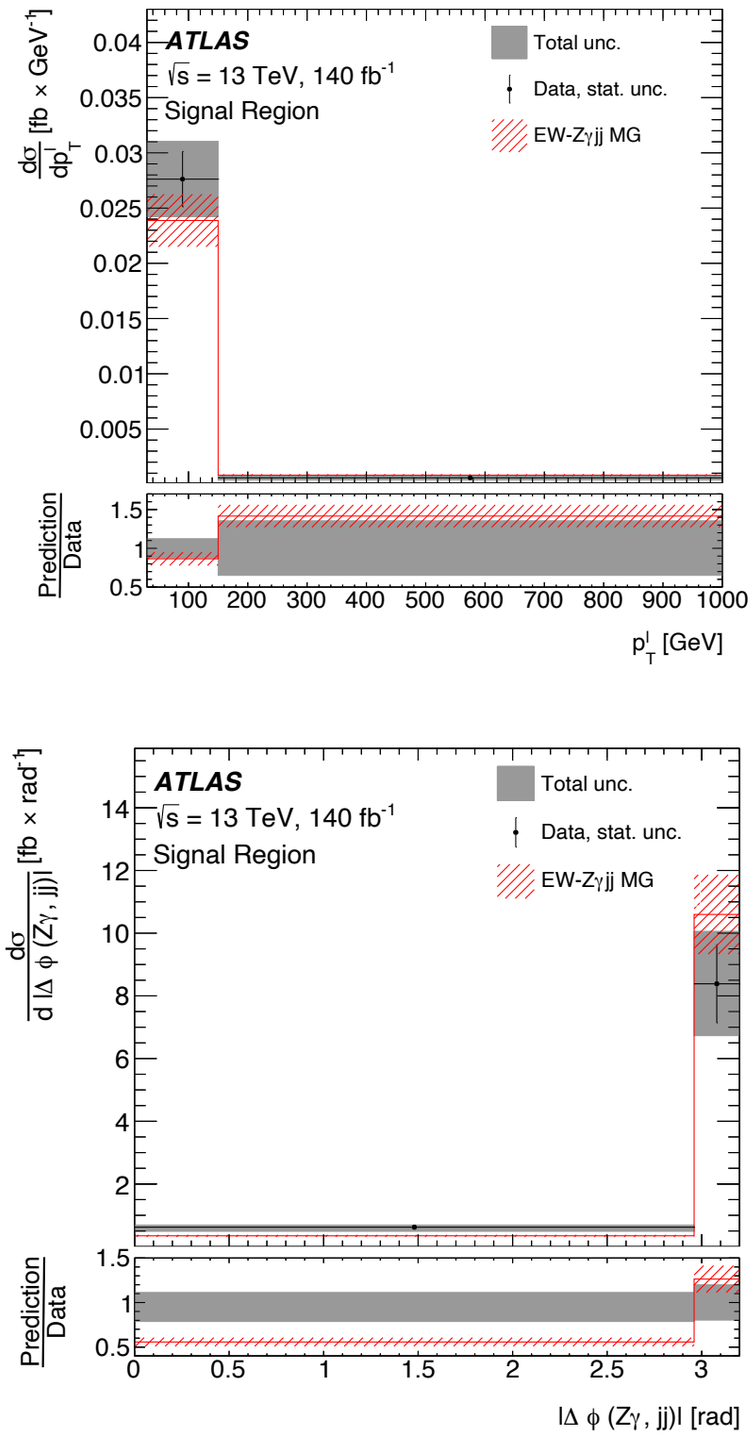


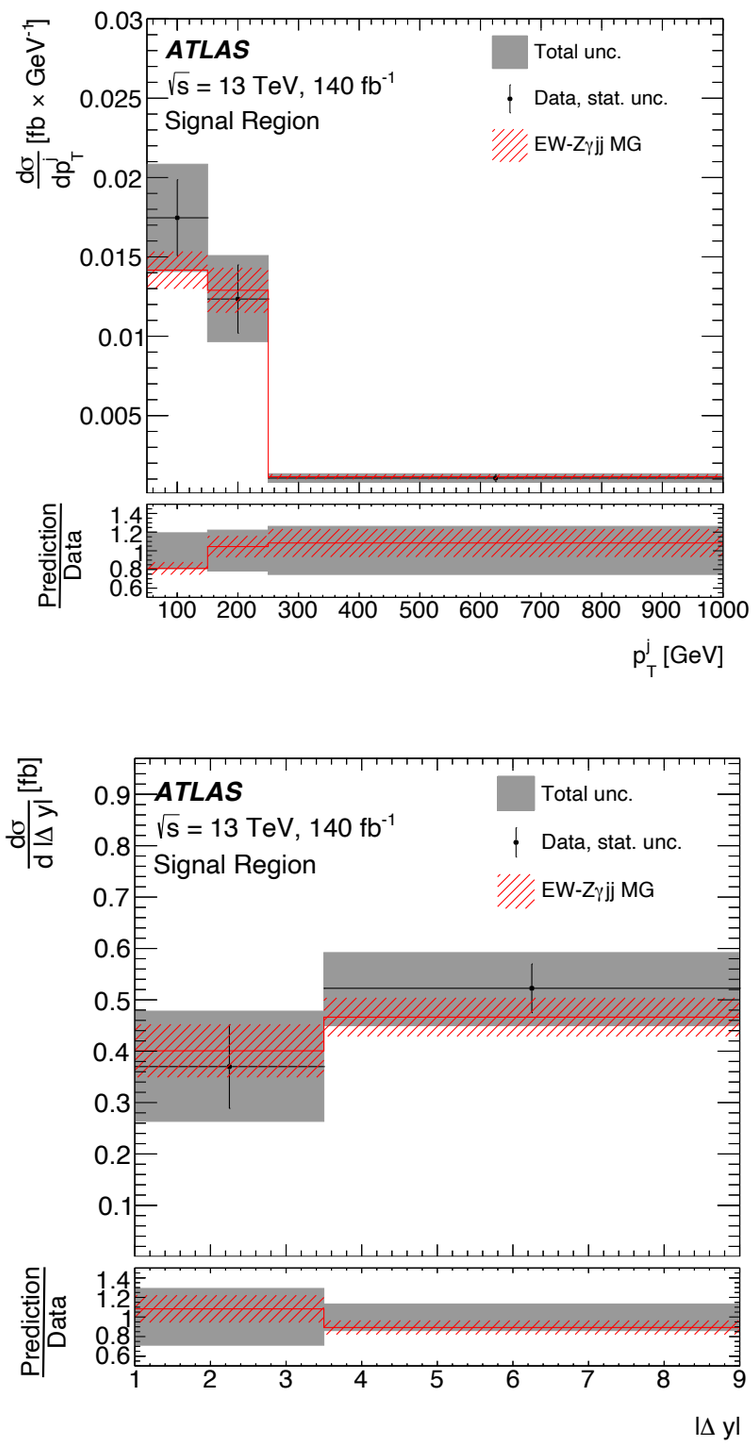


Statistics dominated uncertainty, results are consistent within 1σ of SM

Results (II)


ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
dσ/dp_T^Zγ [fb × GeV-1]
Prediction/Data
p_T^Zγ [GeV]


ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
dσ/dp_T^l [fb × GeV-1]
Prediction/Data
p_T^l [GeV]


ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
dσ/dp_T^j [fb × GeV-1]
Prediction/Data
p_T^j [GeV]

ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
dσ/dE_T^γ [fb × GeV-1]
Prediction/Data
E_T^γ [GeV]

ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
dσ/d|Δφ(Zγ, jj)| [fb × rad-1]
Prediction/Data
|Δφ(Zγ, jj)| [rad]

ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
dσ/d|Δy_jj| [fb]
Prediction/Data
|Δy_jj|

Summary

- First observation of EW-$Z\gamma jj$ with ATLAS
- First differential measurements of EW-$VVjj$ with ATLAS
  - $p_T^{Z\gamma}$ and $|\Delta\phi(Z\gamma, jj)|$ measured differentially for the first time at LHC
- Next: EFT interpretation

Prospectives

Run	Integrated Luminosity	Statistical Uncertainty
Run 2	140	0.09
Run 3	300	0.06
HL-LHC	4000	0.02

- **Run 3**: improved quark/gluon tagger
- **HL-LHC**:
  - Upgraded inner tracker: extending to larger rapidity
  - High granularity timing detector: aid reconstruction of leptons and jets in forward region
- Improved theory modelling and treatment of interference