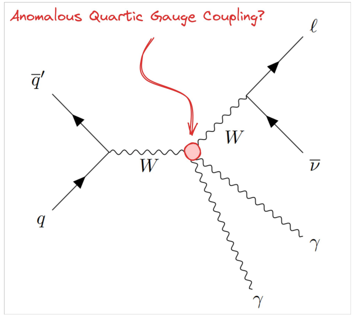
# First Observation of the Production of a *W* Boson in Association with Two Photons in Proton-Proton Collisions at the Large Hadron Collider with the ATLAS Detector

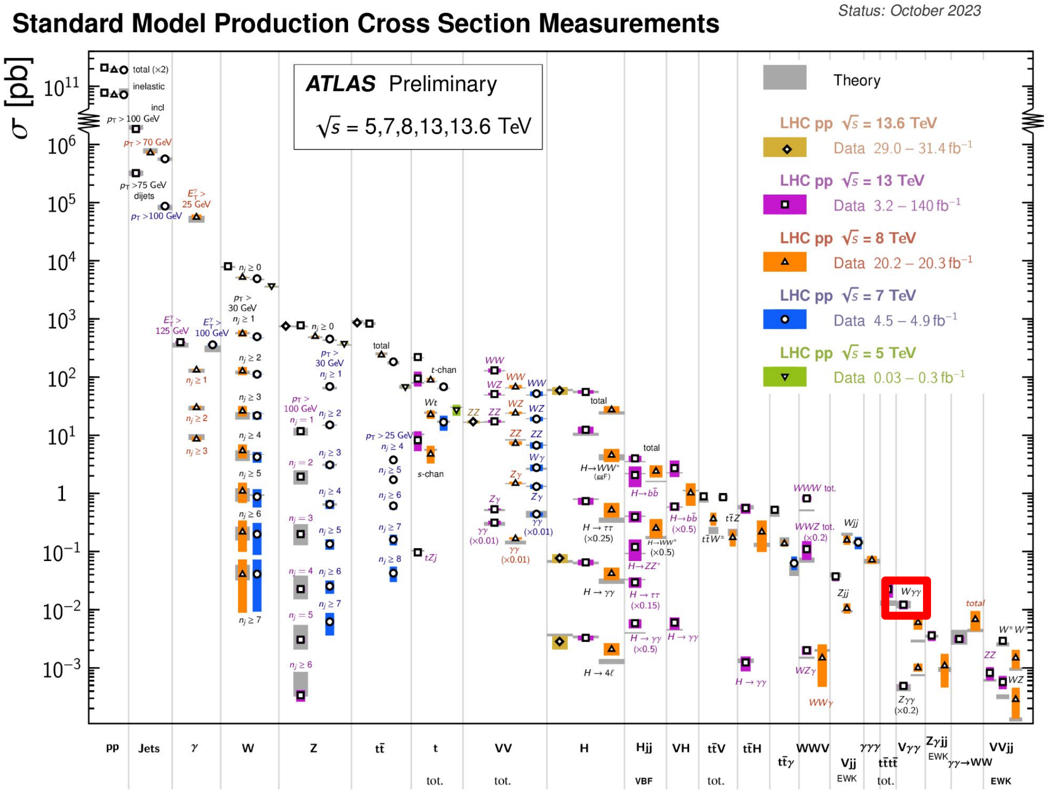
Alessandro Ambler

Supervisor : Professor Brigitte Vachon

# Motivation

- Probe of non-Abelian **self couplings of the electroweak gauge bosons** in the Standard Model (SM)
  - Sensitive to anomalous Quartic Gauge Couplings (aQGC)
  - Can set limits within Effective Field Theories (EFT)
  - 

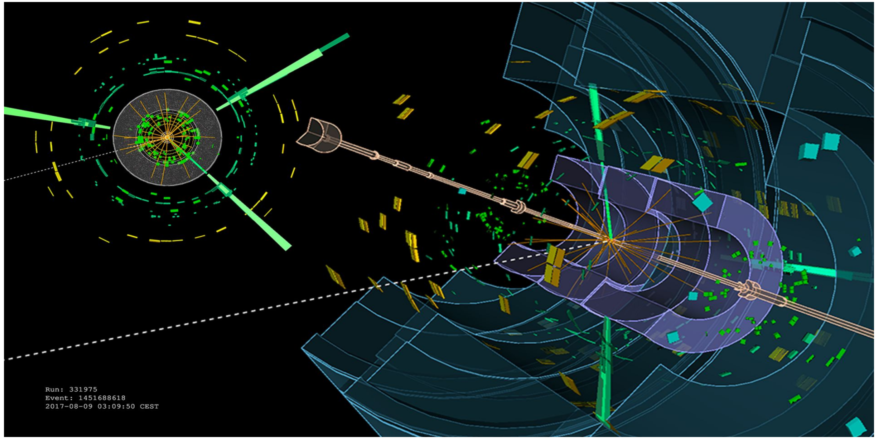
- **Triboson final states are rare** and some are only now becoming accessible at the LHC
  - Many first observations of triboson processes with previous round of data-taking
  - ***Wγγ***, *WZγ*,and *WWγ*
  - *Wγγ* is 4000× rarer that the Higgs!
- Backgrounds to SM processes like *WH(→γγ)* that will become accessible during next data-taking period and beyond

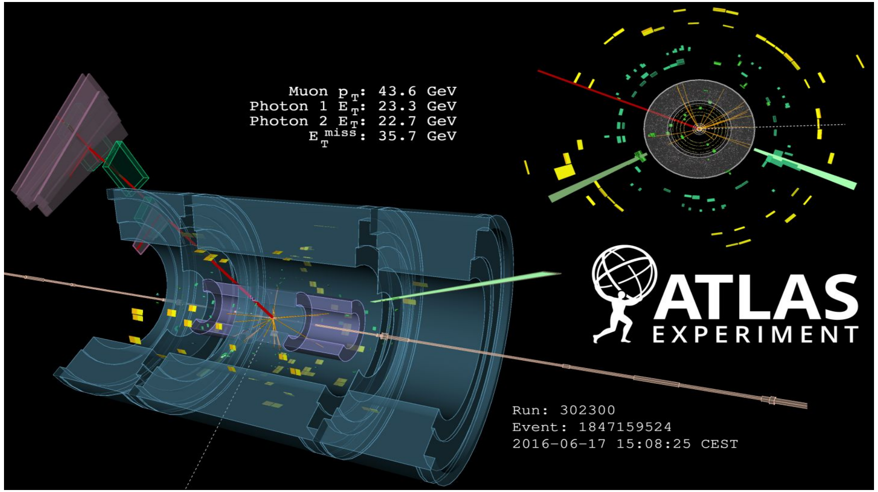



Ref. : ATL-PHYS-PUB-2023-039

# Event Selection

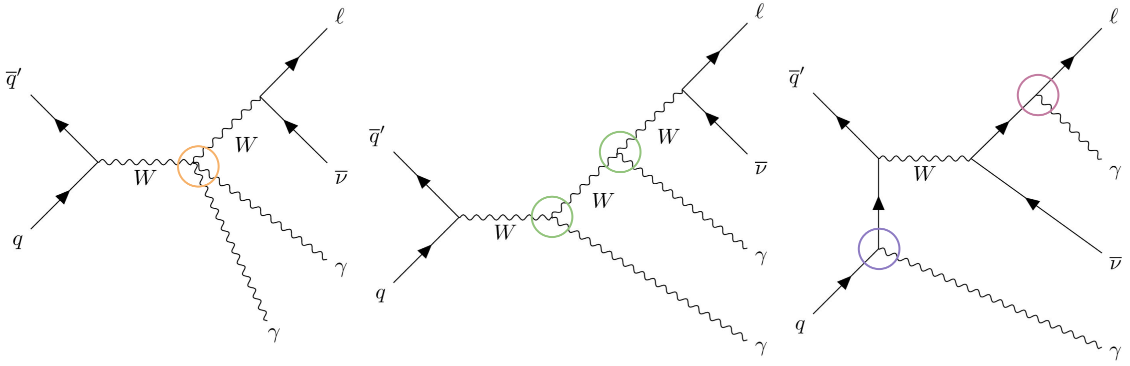
- *pp→Wγγ* **event selection** :
- **Electron and muon** decay channels
- **Two photons**
- **Missing transverse energy**
    - From momentum carried off by the non-interacting neutrino
- Veto on jets containing *b*-hadrons
    - To reduce top quark background
- Cuts to reduce *Zγ* background
    - $m(l\gamma)$, $m(l\gamma\gamma)$, and $p_T(l\gamma\gamma)$




Aux. fig. 6 and 7 in: Phys. Lett. B 848 (2024) 138400

# Signal and Backgrounds



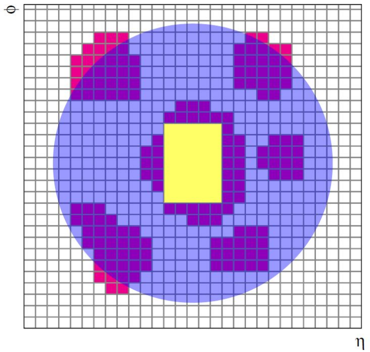

- Several types of $W\gamma\gamma$ signal
- Photons can be produced via :
  - Quartic $WW\gamma\gamma$ couplings
  - Triple $WW\gamma$ couplings
  - Initial and final state radiation
- **Backgrounds**
  - Most crucial part of analysis
- **Irreducible** backgrounds - **simulation**
- **Reducible** backgrounds - **data-driven**

| Source | SR |
|---|---|
| $W\gamma\gamma$ | $410 \pm 60$ |
| Non-prompt $j \to \gamma$ | $420 \pm 50$ |
| Misidentified $e \to \gamma$ | $155 \pm 11$ |
| Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$) | $76 \pm 13$ |
| Non-prompt $j \to \ell$ | $35 \pm 10$ |
| Top ($tt\gamma$, $tW\gamma$, $tq\gamma$) | $30 \pm 7$ |
| Pileup | $10 \pm 5$ |
| Total | $1\,136 \pm 34$ |

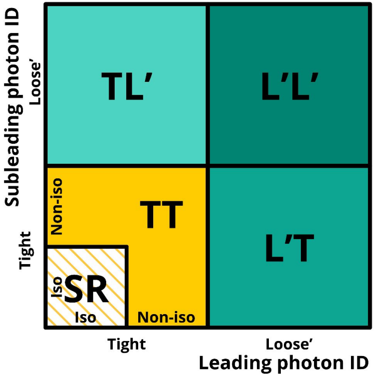
Table 1 in Phys. Lett. B 848 (2024) 138400

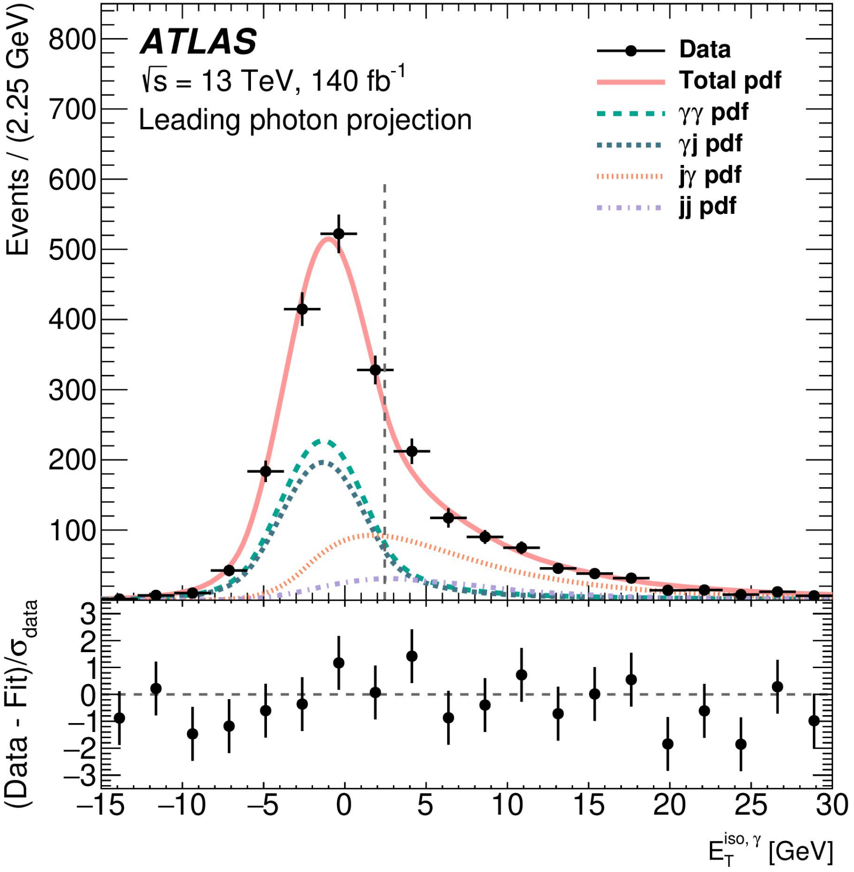
# Hadronic Fake Photons

- ***j→γ* fakes** : 37% background
  - Jets misidentified as photons
  - Non-prompt photon from neutral hadron decays
- Difficult to simulate :
  - Complex interactions in electromagnetic calorimeter
  - Very low fake rate
- Data-driven estimate :
  - **Shapes of *j→γ* photon isolation energy** :
    - Control regions enhance in fakes
    - Obtained by inverting **identification cuts**
  - **Shapes for prompt photon isolation energy**
    - taken from simulation
  - **Normalization of shapes** fit in signal region to extract yield




Ref. : Eur. Phys. J. C 79 (2019) 639

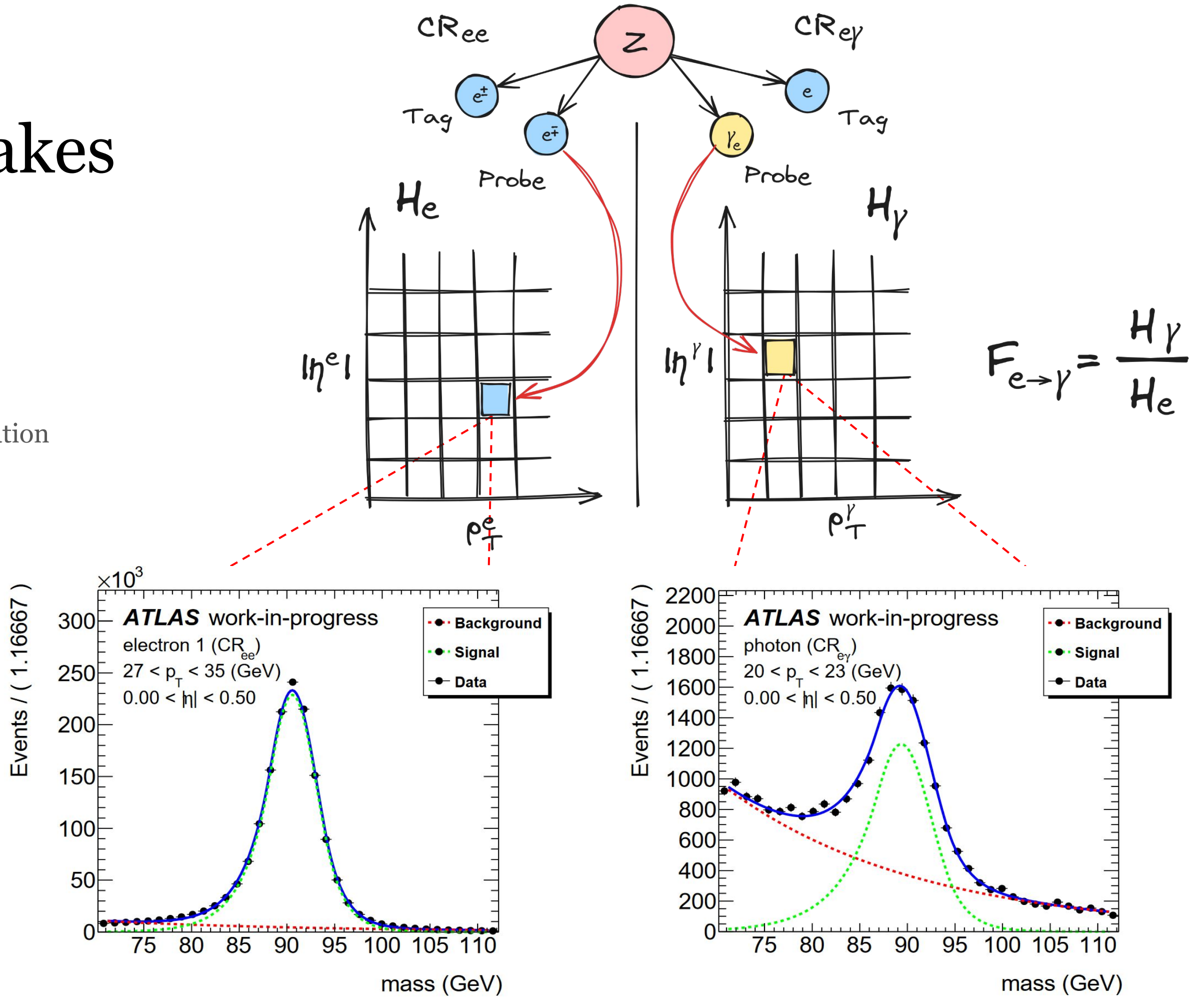



Aux. fig. 1a in Phys. Lett. B 848 (2024) 138400

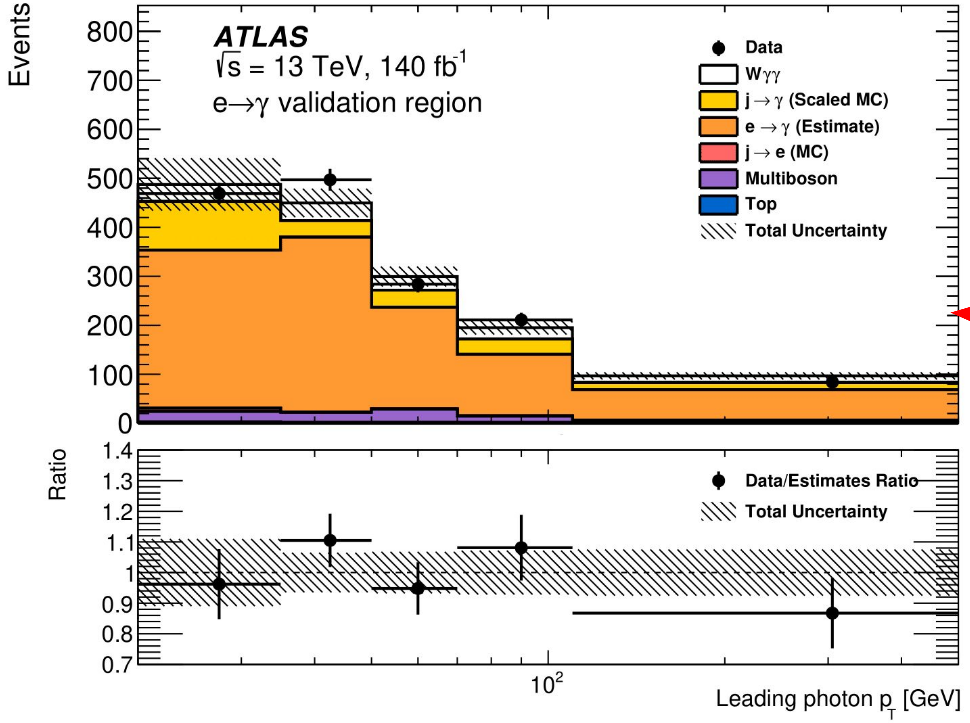
# Electron to Photon Fakes

- ***e→γ* fakes** : 14% background
  - Inefficiencies in the tracking detectors
  - Mismatched tracks to energy clusters
- Difficult to simulate :
  - Large disagreements between data and simulation
  - Large theoretical uncertainties
- Data-driven estimate :
  - Using $Z \rightarrow e^+e^-$ events
  - ***ee*** and ***eγ*** pairs reconstructed close to $m_Z$
  - ***e→γ* fake rate = # *eγ* / # *ee***
  - Fits done to extract signal / background



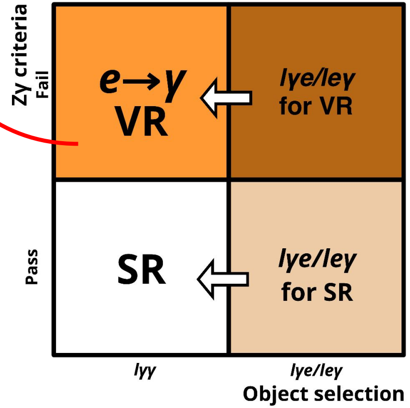
# Electron to Photon Fakes

$$N_{W\gamma\gamma} = F_{e\to\gamma}\, N_{We\gamma}$$



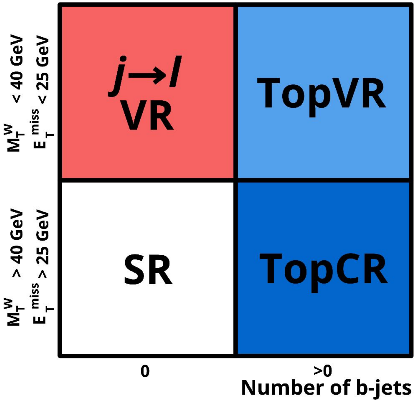

Aux. fig. 4 in Phys. Lett. B 848 (2024) 138400

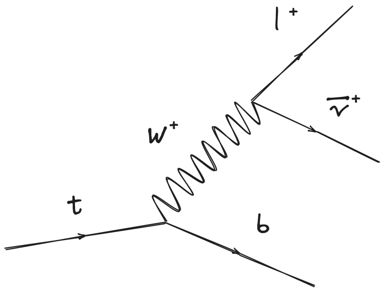
- *# Wγγ e→γ fakes* =
  - ***e→γ fake rate × # Weγ events***
  - *# Weγ* events : *γ ⇔e* selection
- **Validation region** :
  - Invert *Zγ* veto cuts on *m(lγ)*, *m(lγγ) (and pT(lγγ))*
  - Region enhanced in *e→γ* fakes
- Validates well!

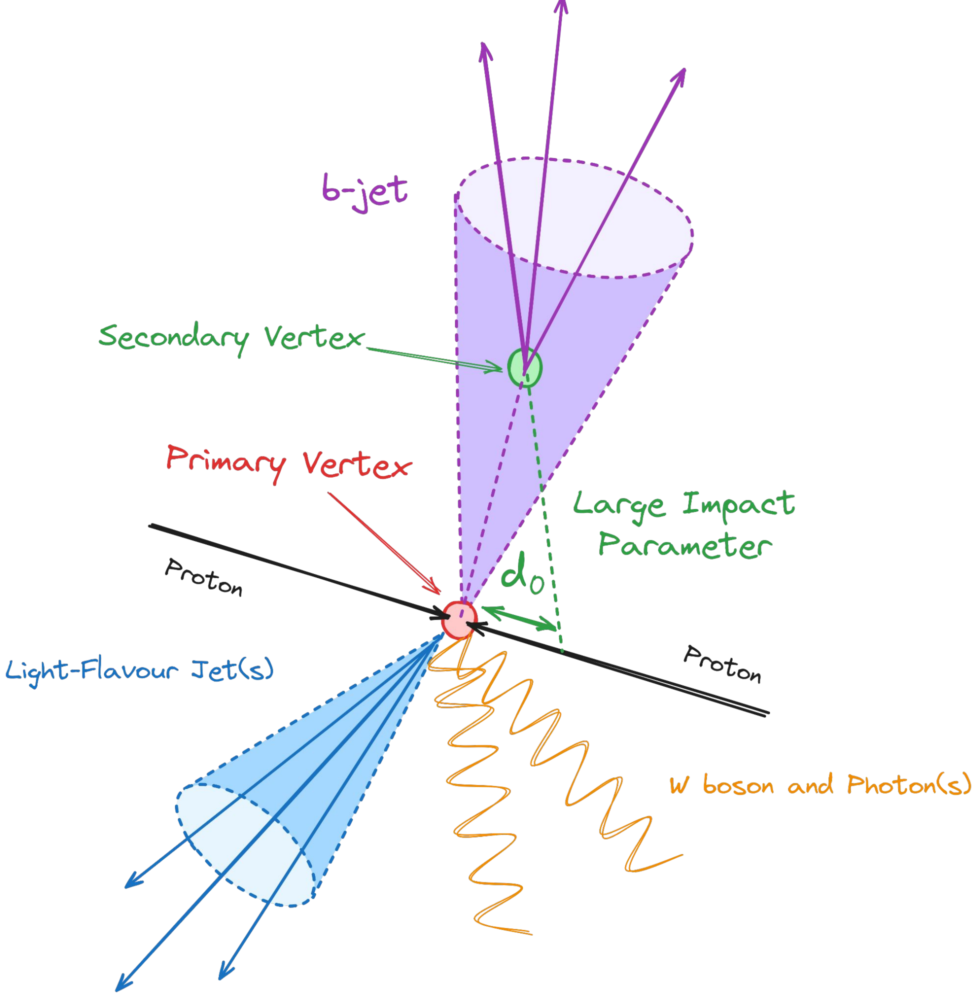


# Top-quark background

- **Top-quark processes** : 3% background
    - $t\bar{t}\gamma$, $tW\gamma$ and $tq\gamma$ events
    - $\boldsymbol{t \rightarrow W + b}$ branching ratio > 95%
- Reduced by vetoing on b-jets
    - Multivariate algorithms based on shower shape and impact parameter properties
- **Normalized in b-jet control region**
    - Requiring at least 1 b-jet



# Uncertainties

- **Systematic** Uncertainties :
  - Uncertainties on data-driven estimates
    - *j*→*γ* uncertainty leading systematic
  - Experimental uncertainties
    - Object trigger, reconstruction, identification, and isolation efficiencies
    - Energy calibration and resolution
    - Integrated luminosity measurement
  - Theoretical uncertainties
  - Top normalization uncertainties
  - *b*-jet tagging efficiency
- **Statistical** uncertainties on data and simulation
- Analysis is Systematically limited
  - More data in data-driven control regions would drive the overall uncertainty down

| Source of uncertainty | Impact [%] |
|---|---|
| $j \to \gamma$ data-driven background estimate | 12 |
| Photon efficiency | 4.5 |
| Other data-driven background estimates | 3.5 |
| Background MC theoretical modeling | 3.0 |
| Monte Carlo statistics | 2.7 |
| Signal MC theoretical modeling | 2.6 |
| Jet efficiency and calibration | 2.4 |
| Top normalization | 2.3 |
| Pileup reweighting | 1.6 |
| Muon efficiency and calibration | 1.4 |
| $E_T^{miss}$ calibration | 1.3 |
| Luminosity | 1.0 |
| Electron and photon calibration | 0.7 |
| Flavor tagging efficiency | 0.6 |
| Systematic | 15 |
| Statistical | 8.3 |
| Total | 17 |

Table 2 in Phys. Lett. B 848 (2024) 138400

# Significance Extraction

- Final **fit** done simultaneously in signal region and top control region to constrain top normalization
  - **Maximum Likelihood Estimate**
  - Parameter of interest : signal strength
  - Systematic uncertainties implemented as nuisance parameters and constrained in final fit

- Expected and observed **significance** of signal over background of **5.6 σ**
  - <0.00003% probability excess events are due to statistical fluctuation
  - Passes 5σ threshold for **first observation**

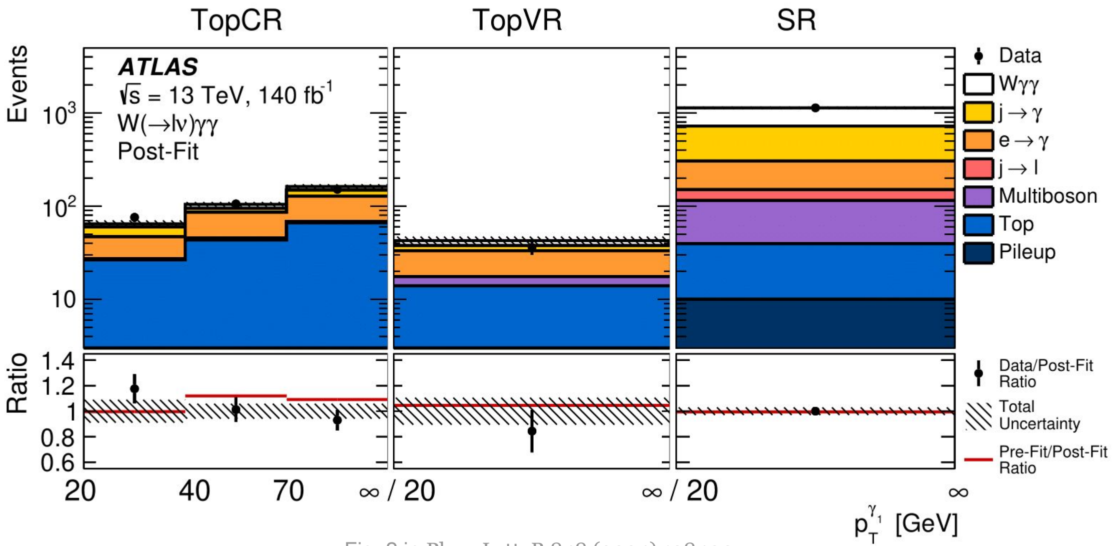



Fig. 2 in Phys. Lett. B 848 (2024) 138400

- TopCR : Top Control Region
- TopVR : Top Validation Region
- SR : Signal Region

# Cross Section Measurement

- Deconvolve the detector acceptance and efficiency from the reconstructed signal :
  - Process is called **unfolding**
- **Cross section** in agreement with **Standard Model predictions**
  - Obtained using most accurate simulations currently available

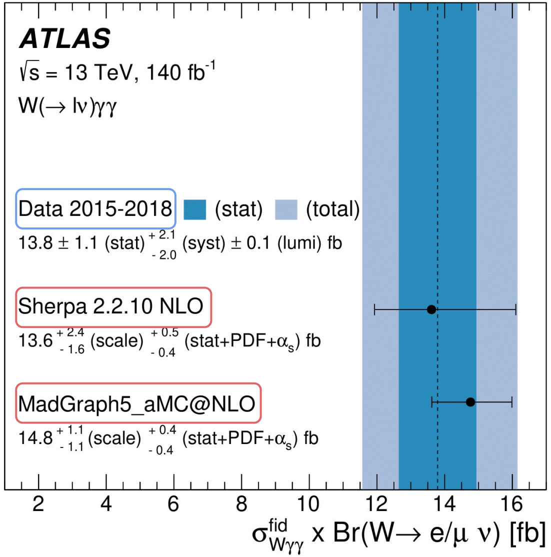
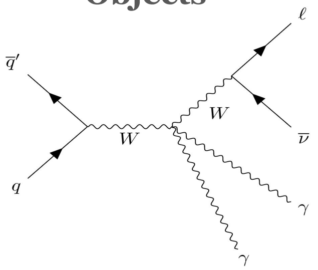


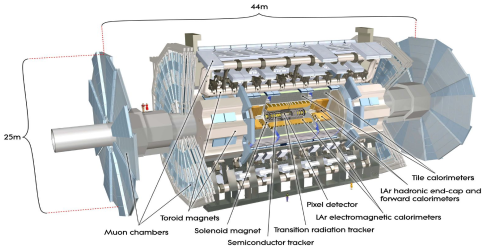

Fig. 3 in Phys. Lett. B 848 (2024) 138400

**Particle Level Objects**




x

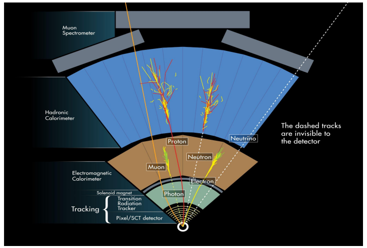
**Detector Acceptance and Efficiency**




Ref. : 2008 *JINST* 3 S08003

=

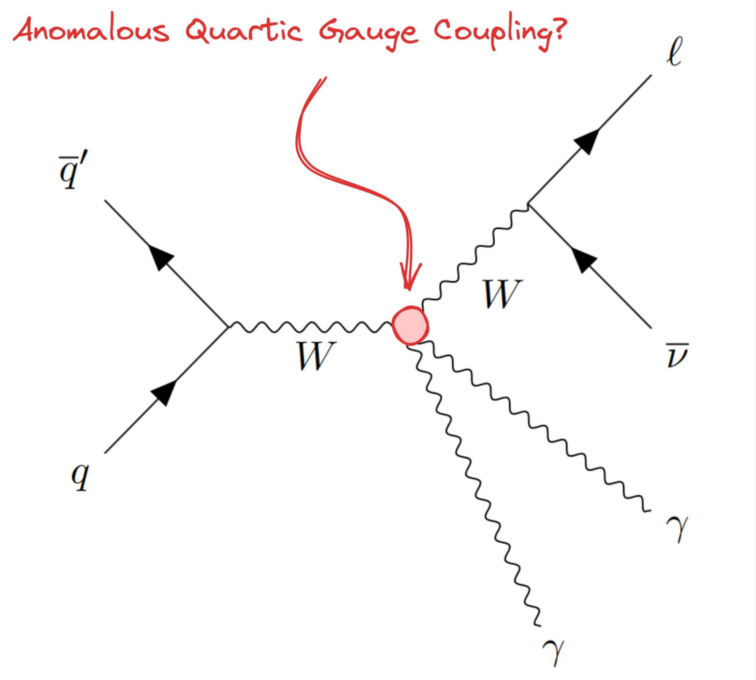
**Detector Level Objects**




Ref. : Morisbak, Vanja & Ould-Saada, Farid.

# Conclusion

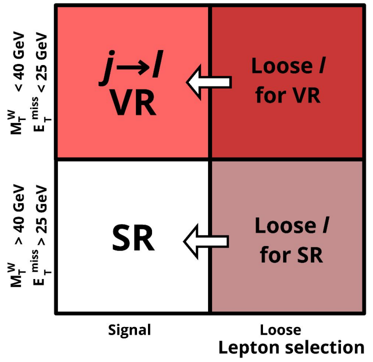
- Exciting new first observation of a Standard Model process!
  - $W\gamma\gamma$ observed for the first time with 5.6σ significance
  - Paper has been published : Phys. Lett. B 848 (2024) 138400
- Next steps :
  - **Differential** cross section measurement
  - Set limits on **beyond the Standard Model** physics
- Thank you for your attention!
  - Are there any questions?

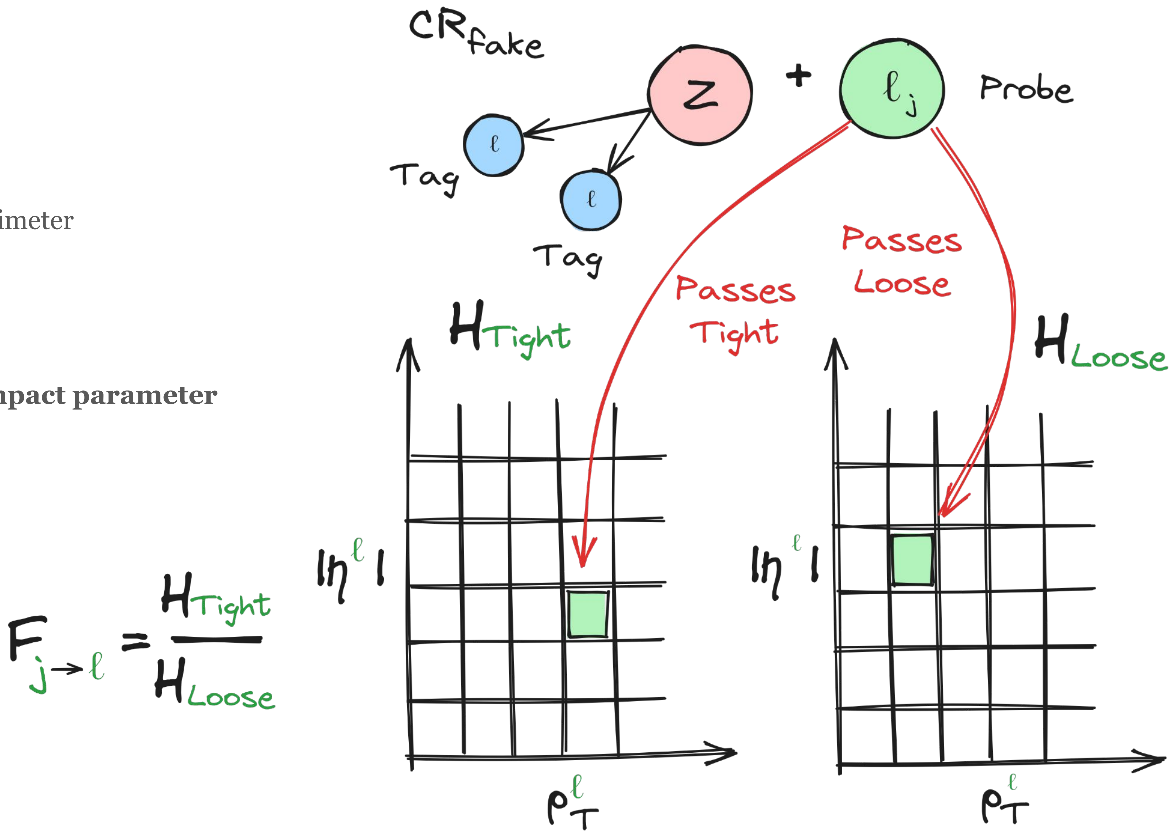


# Backup

# Fake Leptons

- ***j→l* fakes** : 3% background
  - Jets misidentified as leptons
  - Non-prompt leptons from hadron decays
- Difficult to simulate :
  - Complex interactions in electromagnetic calorimeter
  - Very low fake rate
- Data-driven estimate :
  - Using ***Z(→l⁺l⁻)+j→l' fake*** events
  - ***j→l fake rate* = *# Tight / Loose probes***
    - **Loose : inverted isolation and impact parameter**
  - Background from *WZ* events subtracted



# Pileup Backgrounds

- **Pileup** : 1% background
  - From events in which one or both photons come from a different proton-proton interaction
- Estimated using **converted photons**
  - Photons that convert to $e^+e^-$ **pair** leaving well defined **tracks**
  - Good measurement of their **impact parameter**