# Standard Model Photon Measurements at ATLAS and CMS : $V\gamma(\gamma)$ measurement


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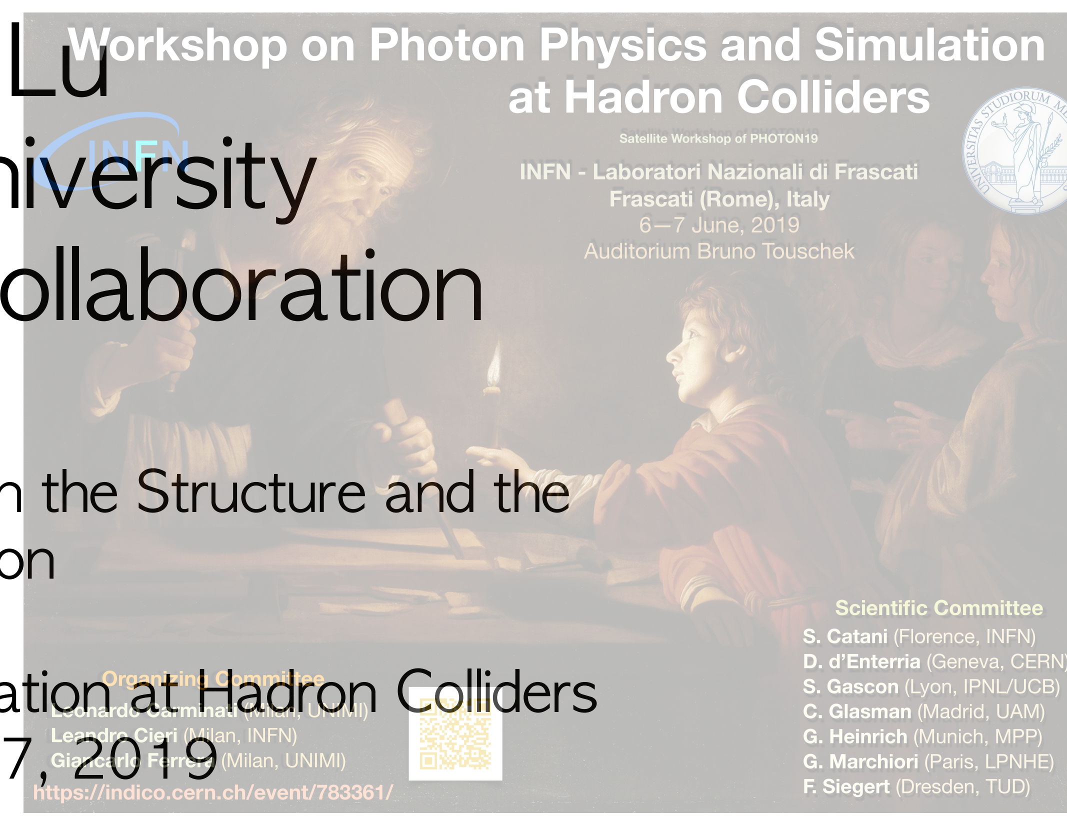



Photon 2019 - International Conference on the Structure and the interaction of the Photon
and
the workshop on Photon Physics and Simulation at Hadron Colliders
INFN-LNF, Frascati, June 3-7, 2019

# Outline

- LHC and CMS/ ATLAS
- Photon selection and signal extraction
- $V\gamma$ measurements and aTGC
- $V\gamma\gamma$ measurements and aQGC
- Summary

# LHC and CMS/ATLAS

# LHC - THE BIG TURN ON

The Large Hadron Collider will accelerate two beams of protons (and later lead ions) in opposite directions and collide them head-on at four locations where huge detectors will analyse the debris


Before the protons or ions enter the main LHC ring, they travel through a series of machines that accelerate them to increasingly higher energies

**THE FIRST STEP**
starts above ground and involves stripping electrons from atoms of hydrogen gas to make protons. These are sped up to 31.4% of the speed of light in a linear accelerator and then enter the accelerator chain

Linac 50MeV

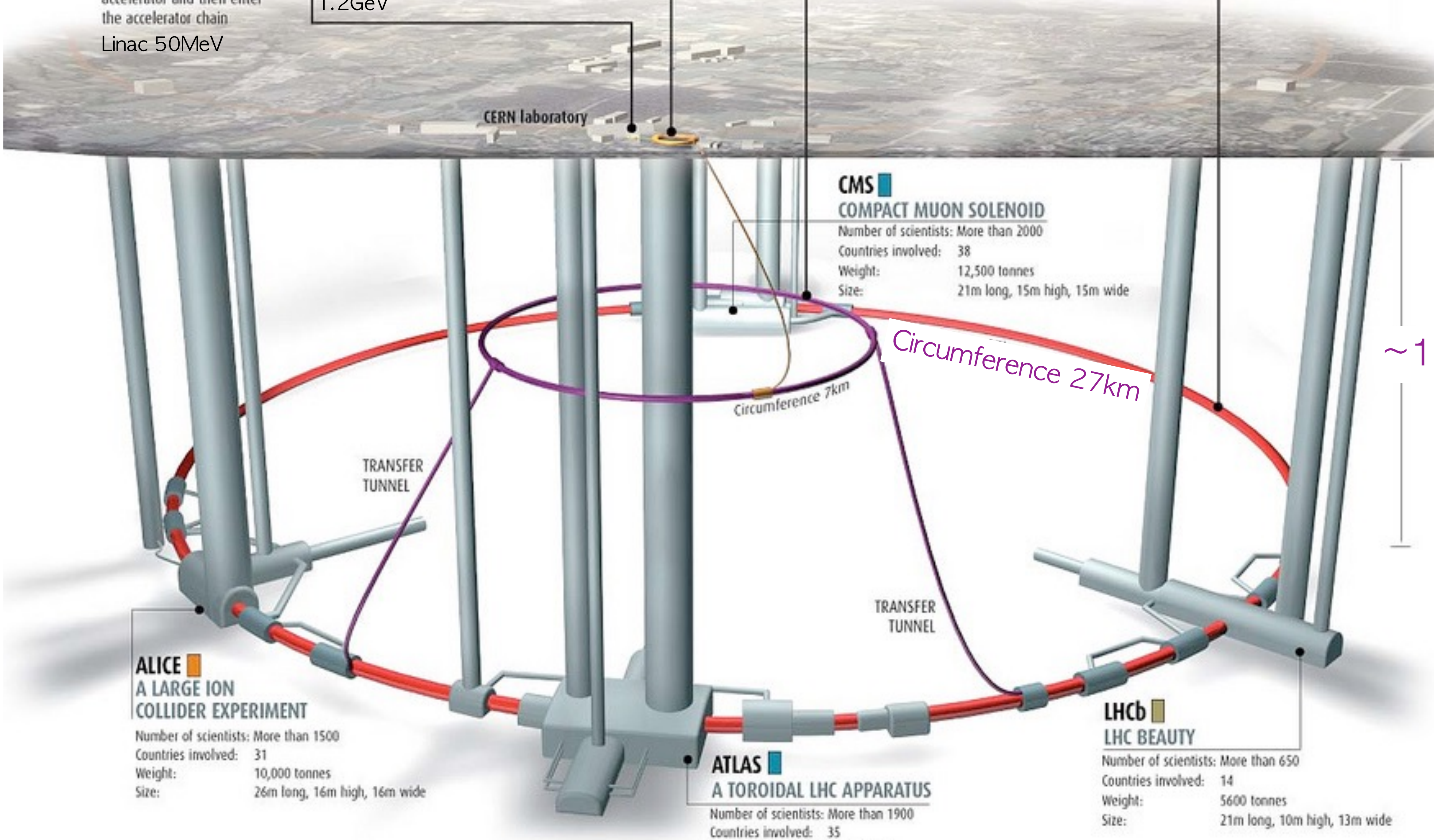
**BOOSTER RING**
Accelerates the protons to 91.6% of the speed of light and feeds them into the 200-metre-diameter Proton Synchrotron machine

1.2GeV

**PROTON SYNCHROTRON**
Almost 50 years old, this machine accelerates protons to 99.93% of the speed of light (25 GeV in energy). For several weeks, starting in late 2009, it will also accelerate lead ions for the ALICE experiment

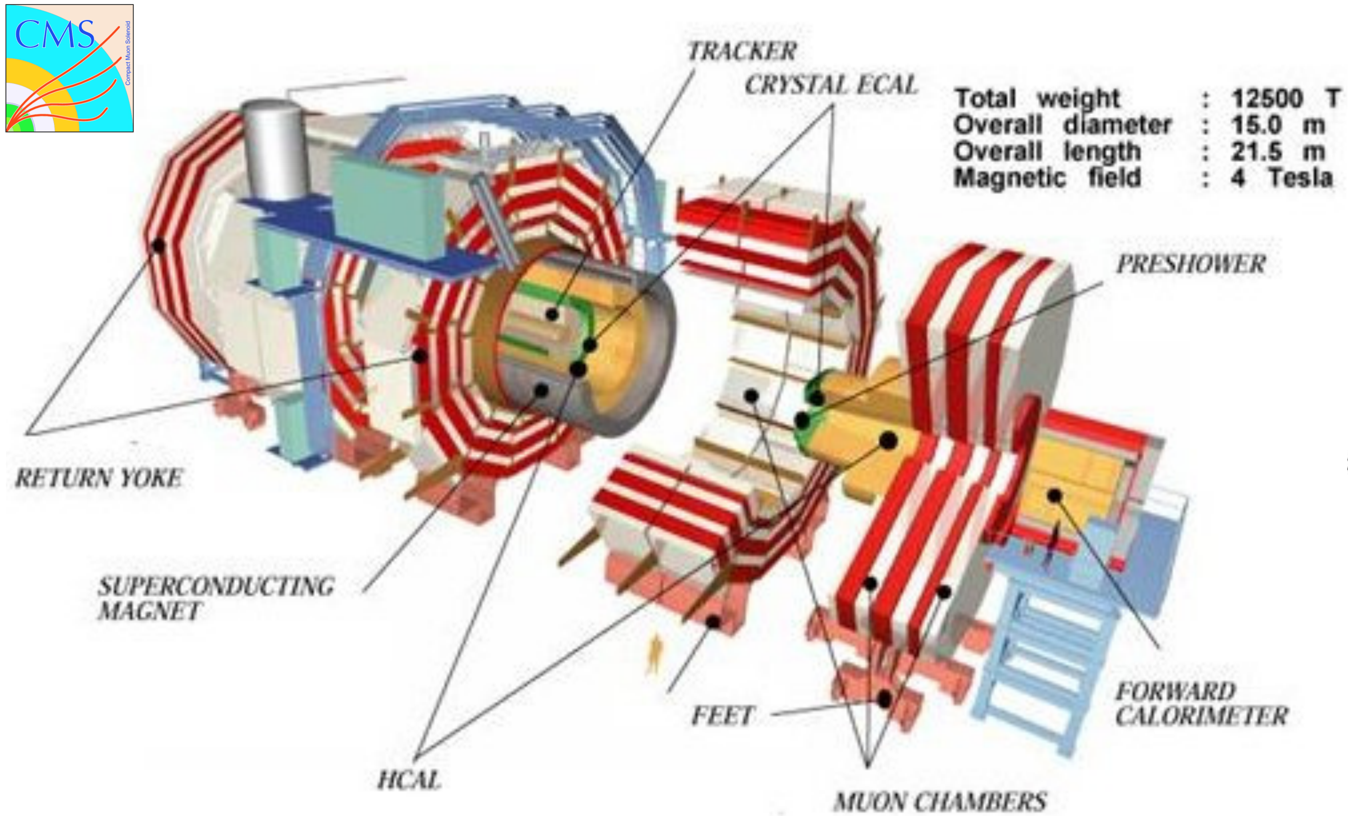
**SUPER PROTON SYNCHROTRON**
Located 40 metres underground, the SPS accelerates protons to 99.9998% of the speed of light (450 GeV in energy). It feeds protons both clockwise and anticlockwise into the LHC

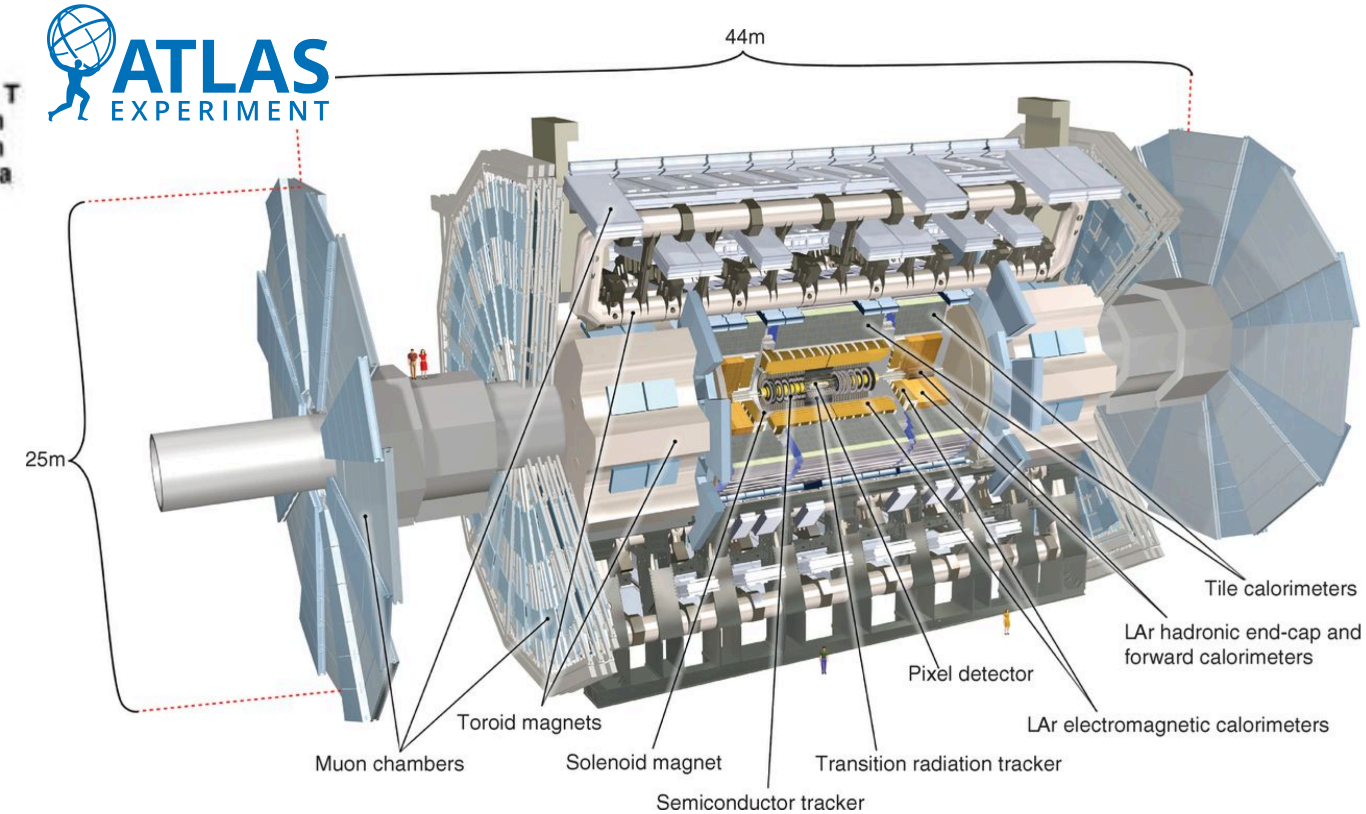
**LARGE HADRON COLLIDER (LHC)**
Designed to accelerate protons to 99.9999991% of the speed of light (7 TeV in energy). The beams will be made to collide in four experimental areas



# CMS and ATLAS

- General purpose design to detect all particles. Wide reaches of physics potential




ECAL 3x3 matrix energy resolution

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{12\%}{E(\mathrm{GeV})} \oplus 0.3\%$$

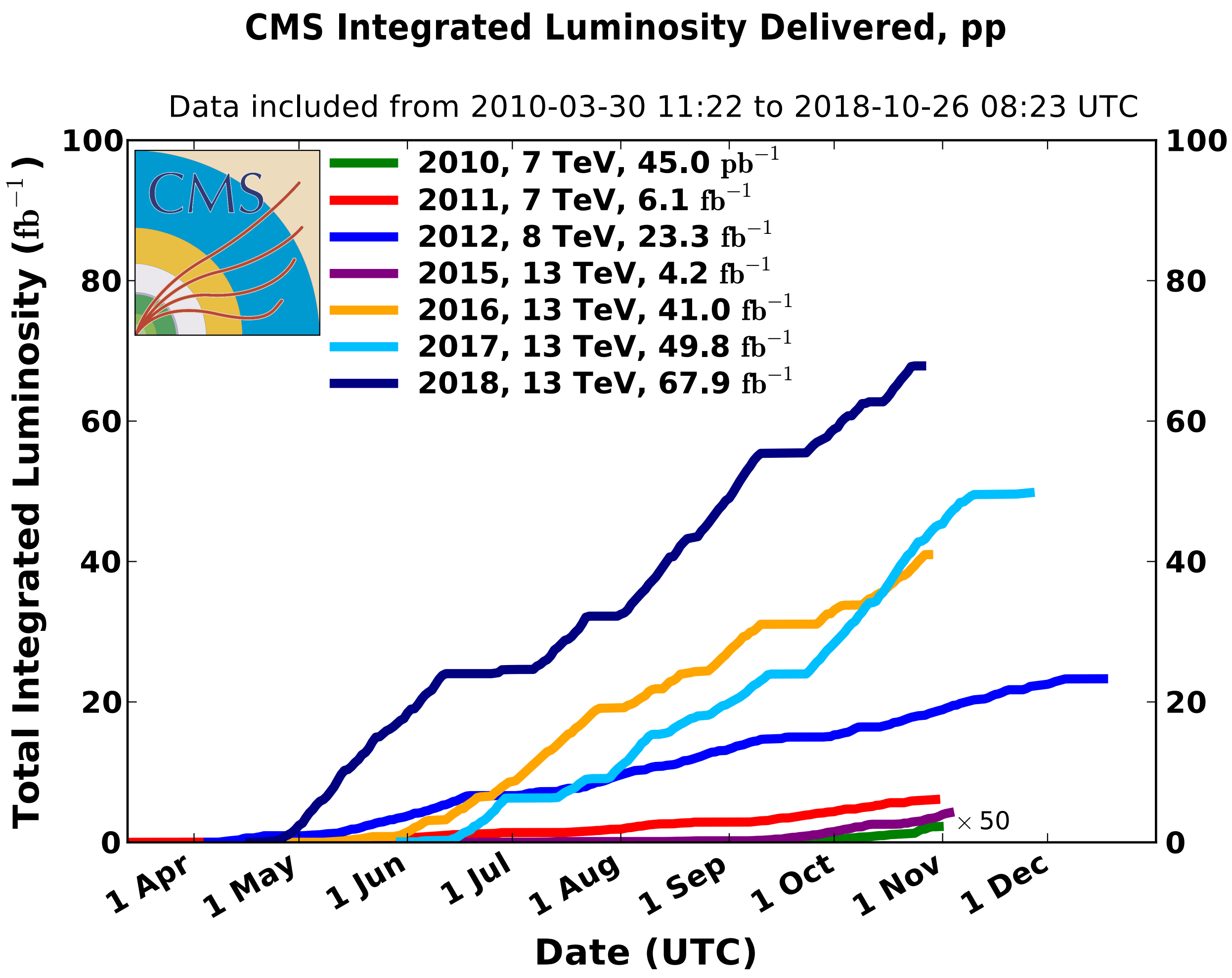
ECAL energy resolution

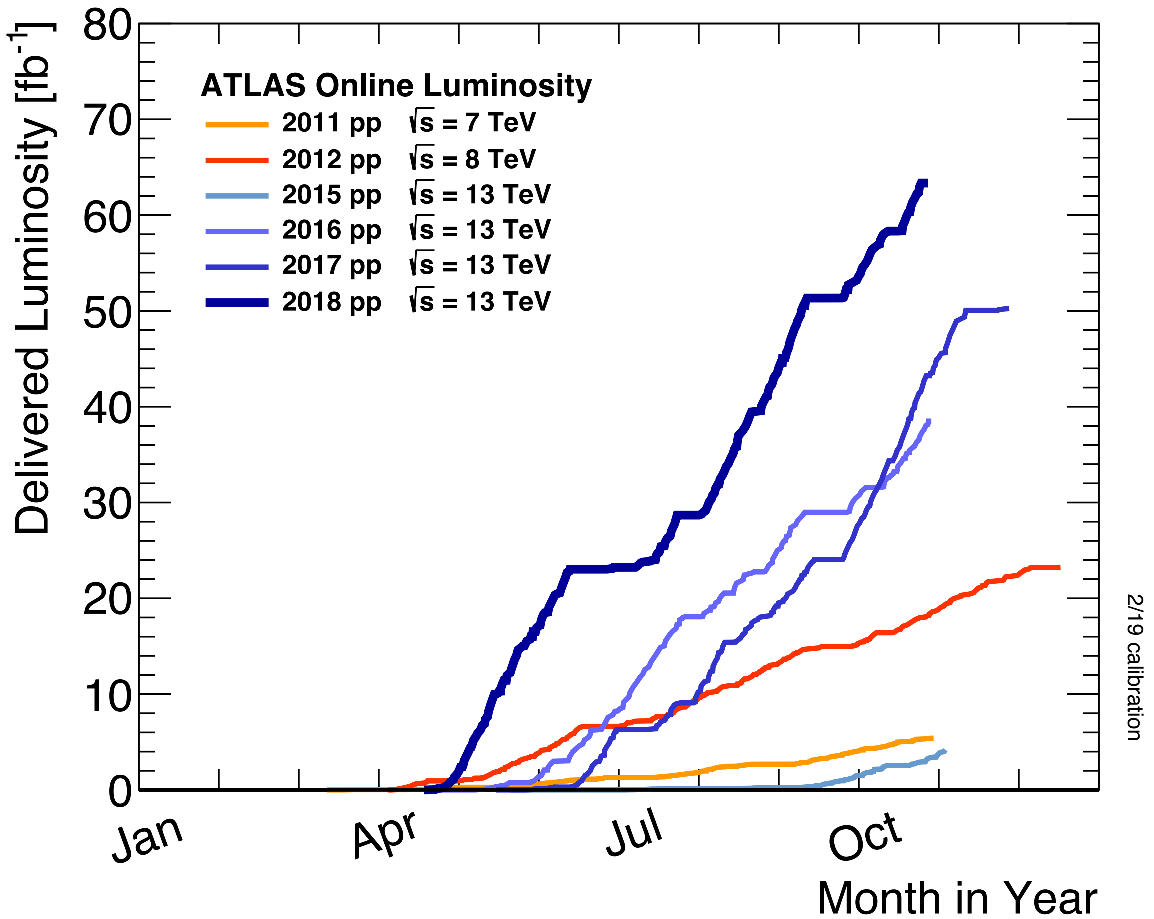
$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{0.2}{E(\mathrm{GeV})} \oplus 0.2\%$$

ATL-LARG-PROC-2013-002

# LHC luminosity

- CMS and ATLAS recorded data @7TeV and 8TeV at Run1 and @13TeV at Run2.

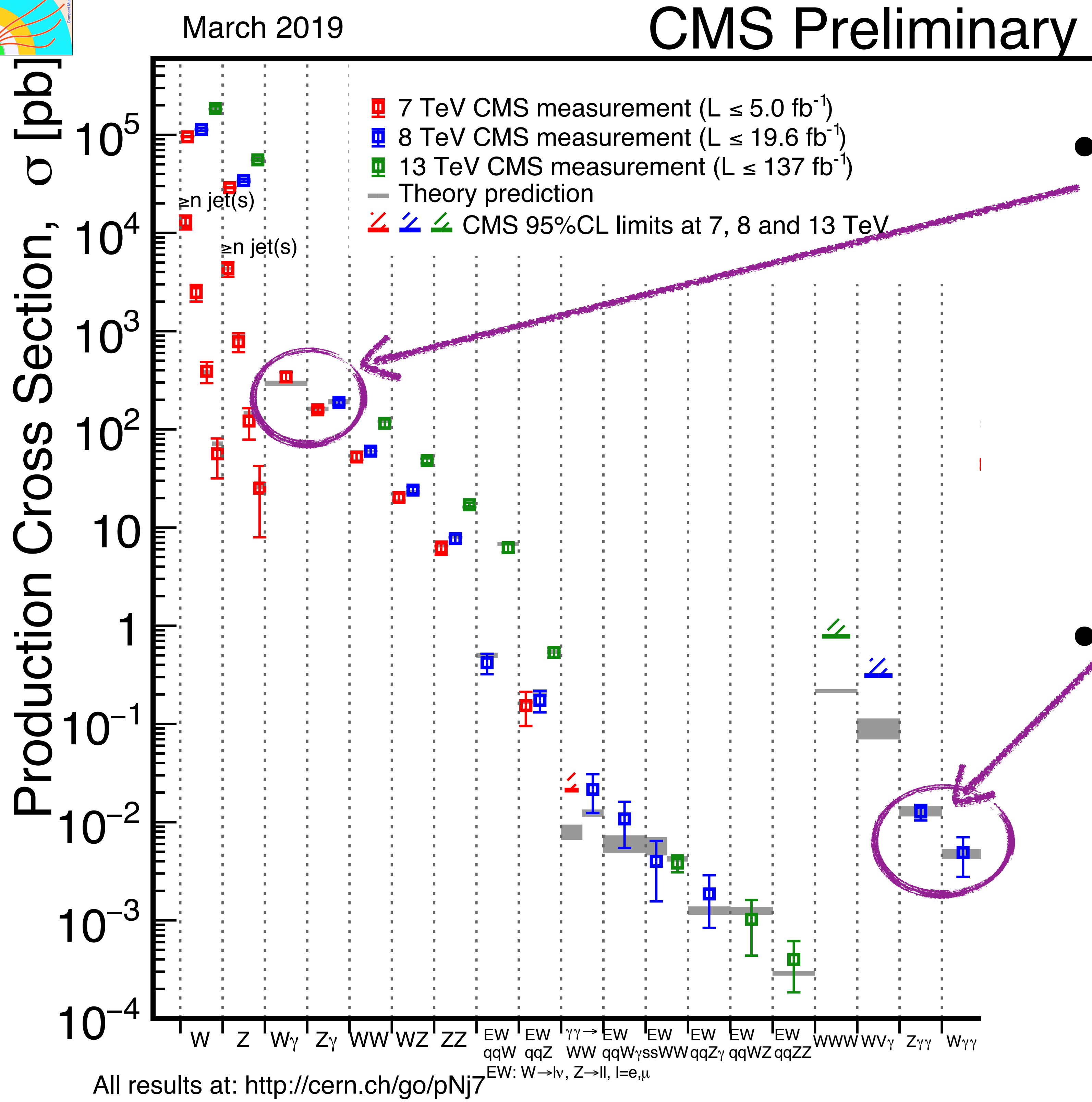



https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

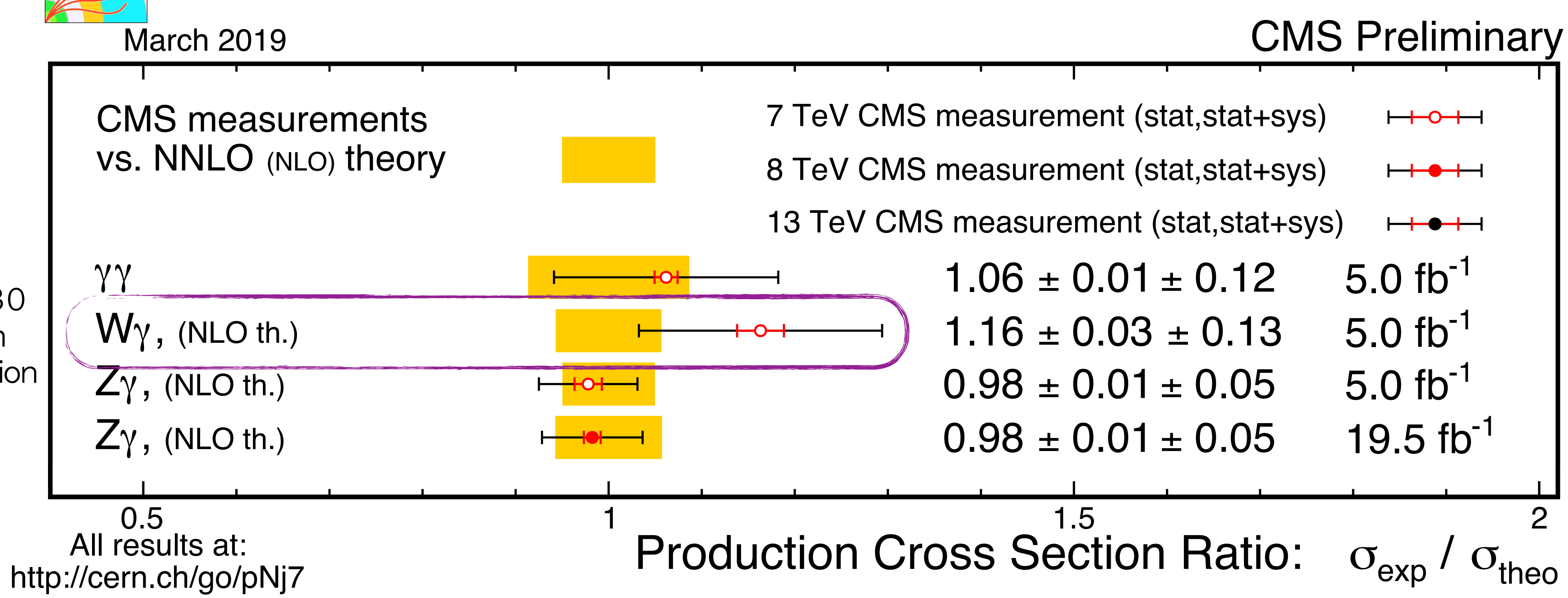
# Summary of CMS cross section Measurements




- ~$10^2$ pb: Inclusive QCD diboson production. Probing:
  - higher order QCD (and QED) perturbative corrections
  - SM gauge structure: triple gauge couplings (TGC)
- ~$10^{-2}$ pb : Inclusive QCD triboson production. Probing:
  - higher order QCD (and QED) perturbative corrections
  - SM gauge structure: quartic gauge couplings (QGC)

# Di-boson cross section ratio comparison to theory

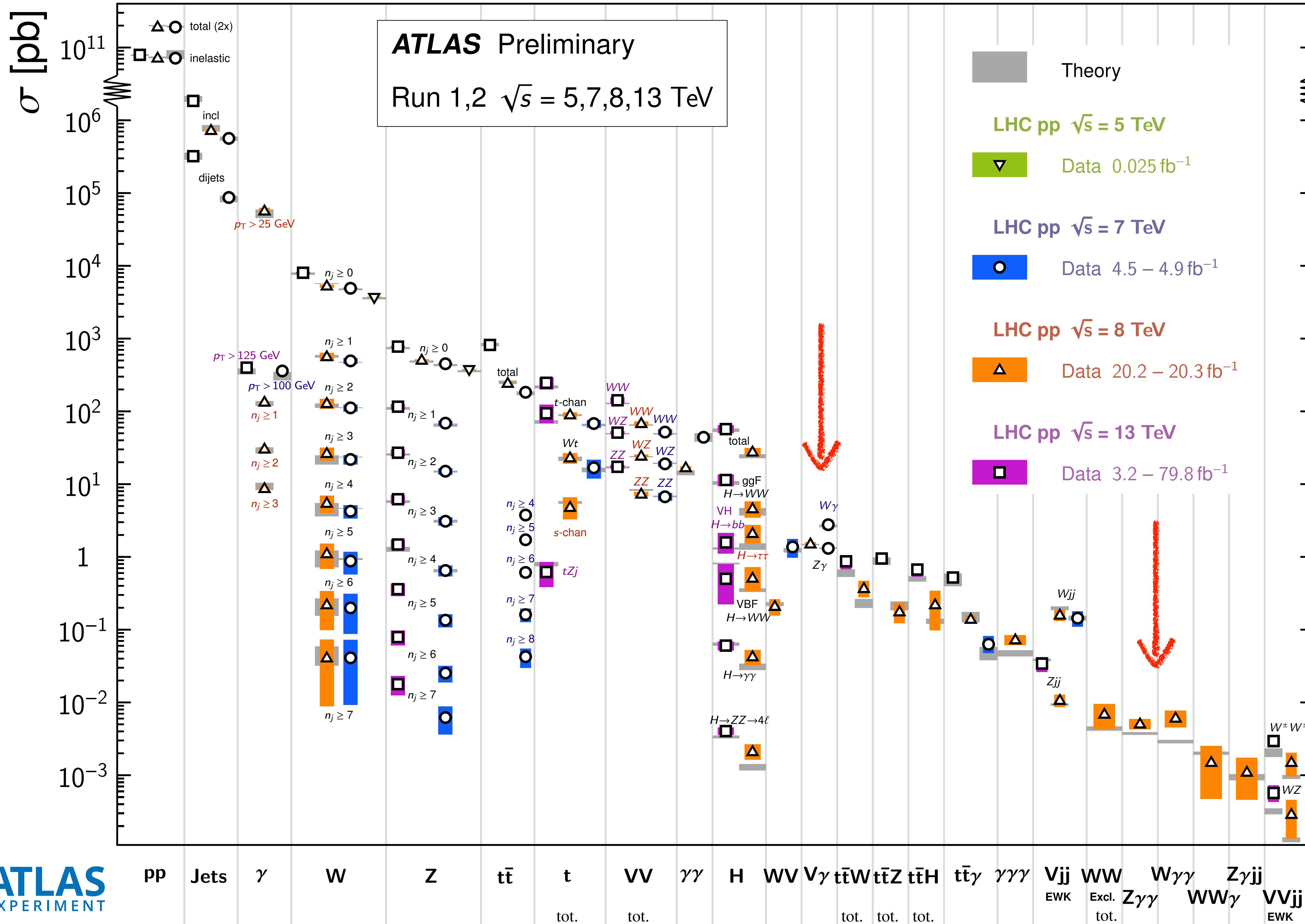
- Theory predictions updated to latest NNLO calculations where available compared to predictions in the CMS papers and preliminary physics analysis summaries.




arXiv.1504.01330
In agreement with
NNLO QCD calculation

## Standard Model Production Cross Section Measurements

Status: March 2019

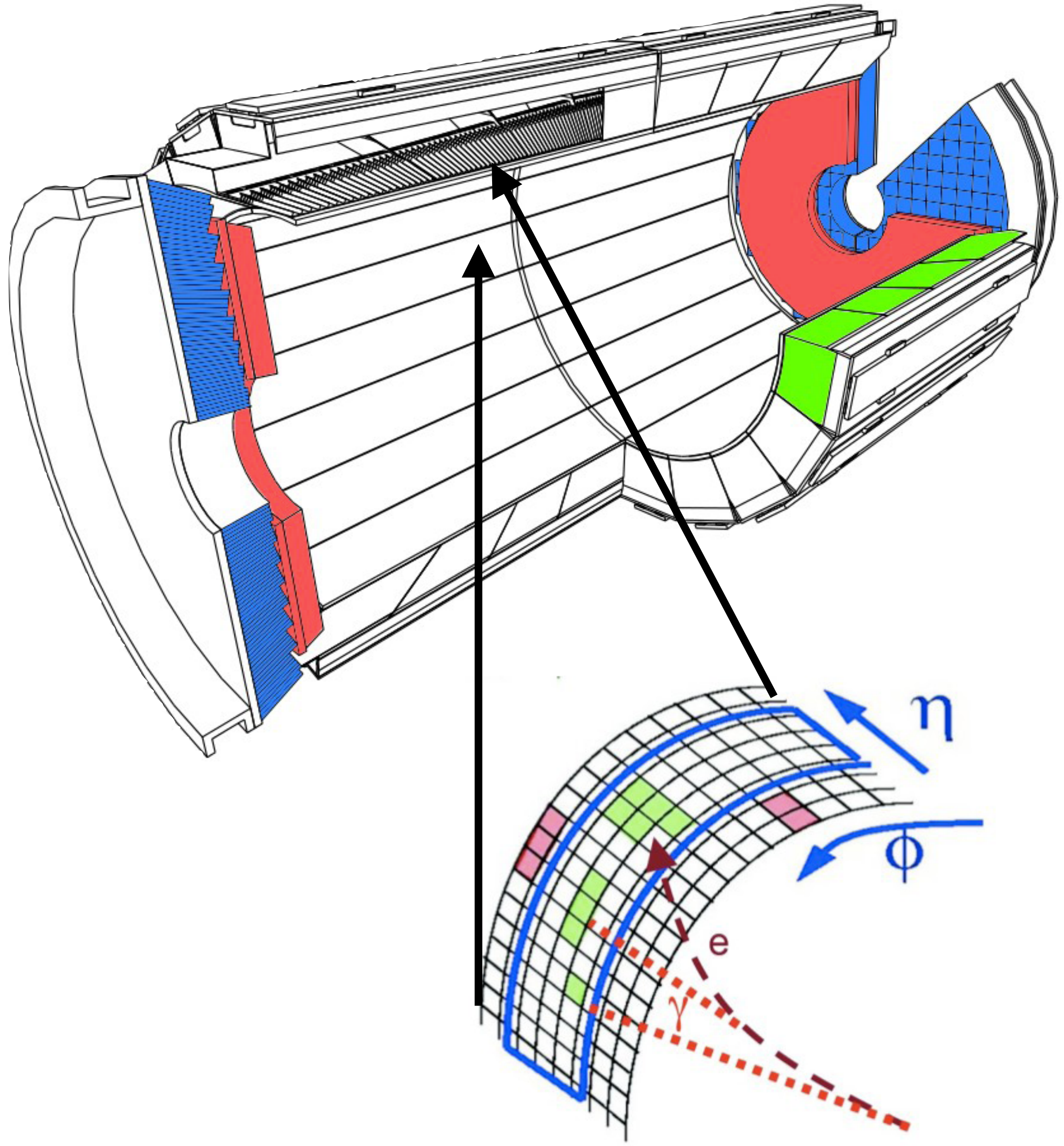


# Photon Selection

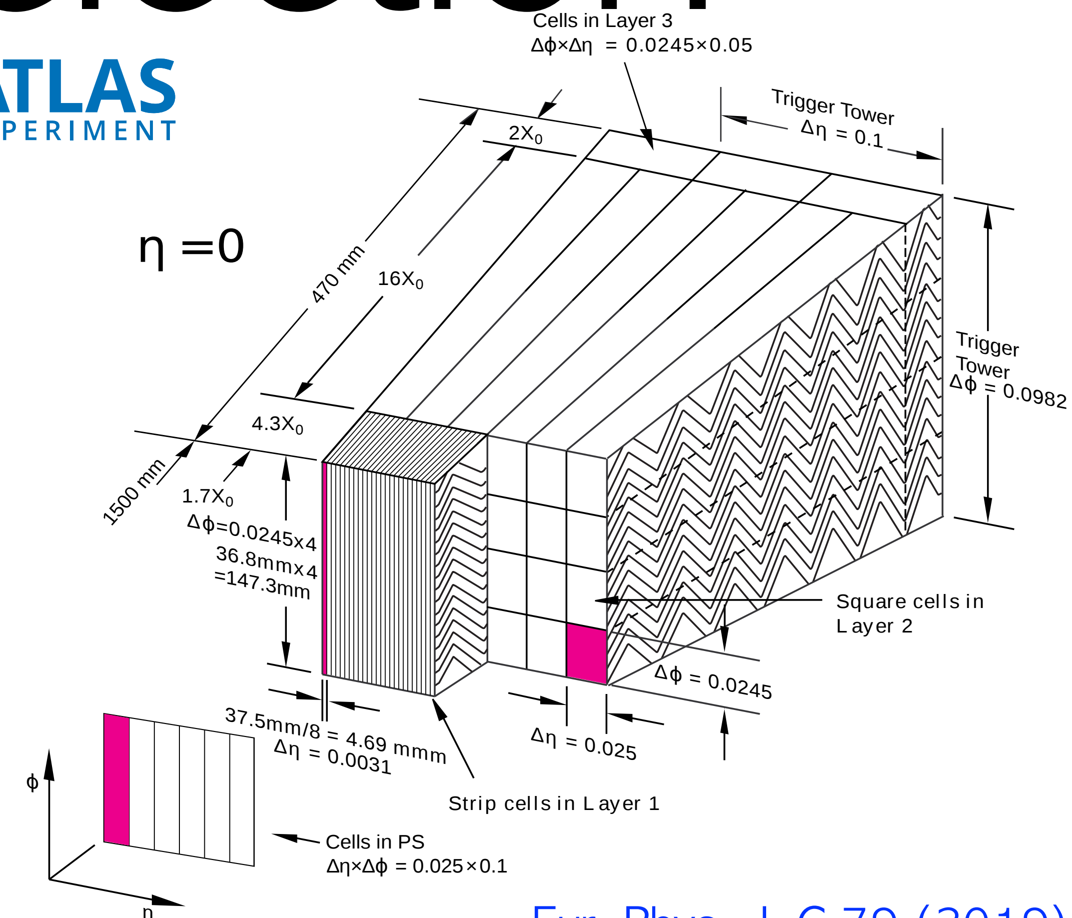
- The $V\gamma(\gamma)$ analyses use simple cut based photon identification, not multivariate methods as the inclusive photon or Higgs analyses
- ID requirements typically include
  - shower shape (longitudinal and/or transverse)
  - isolation energy (track, photon, hadron)
  - energy leakage to the hadronic calorimeter
- It leaves freedom to flip a requirement, e.g. asking for failing an isolation energy cut, to obtain a control sample to study jets fake photons scenario.

# Photon Selection

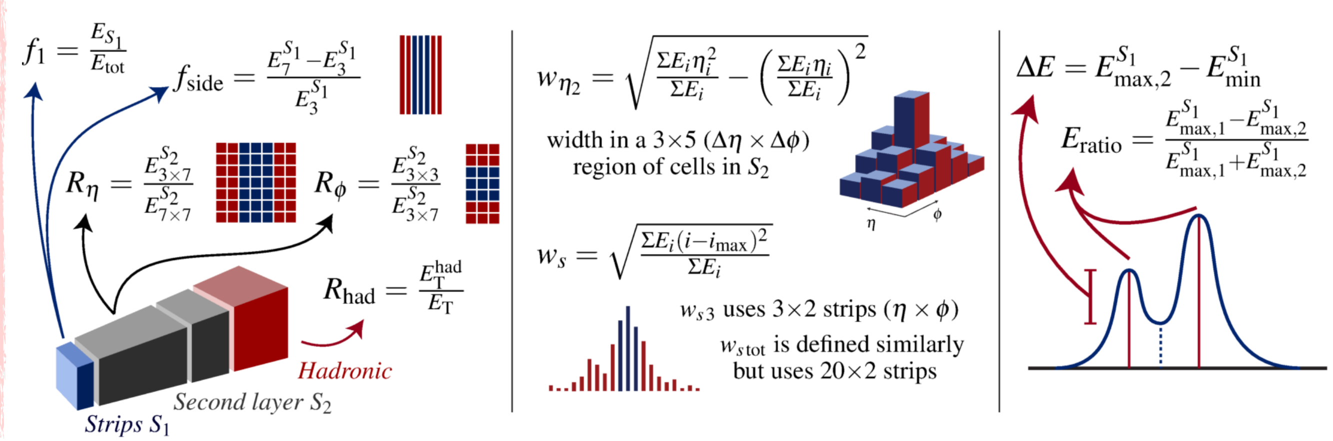
JINST 10 (2015) P08010




- Shower width in η direction $\sigma_{i\eta i\eta}$
- Construct template for a fitting




Eur. Phys. J. C 79 (2019) 205

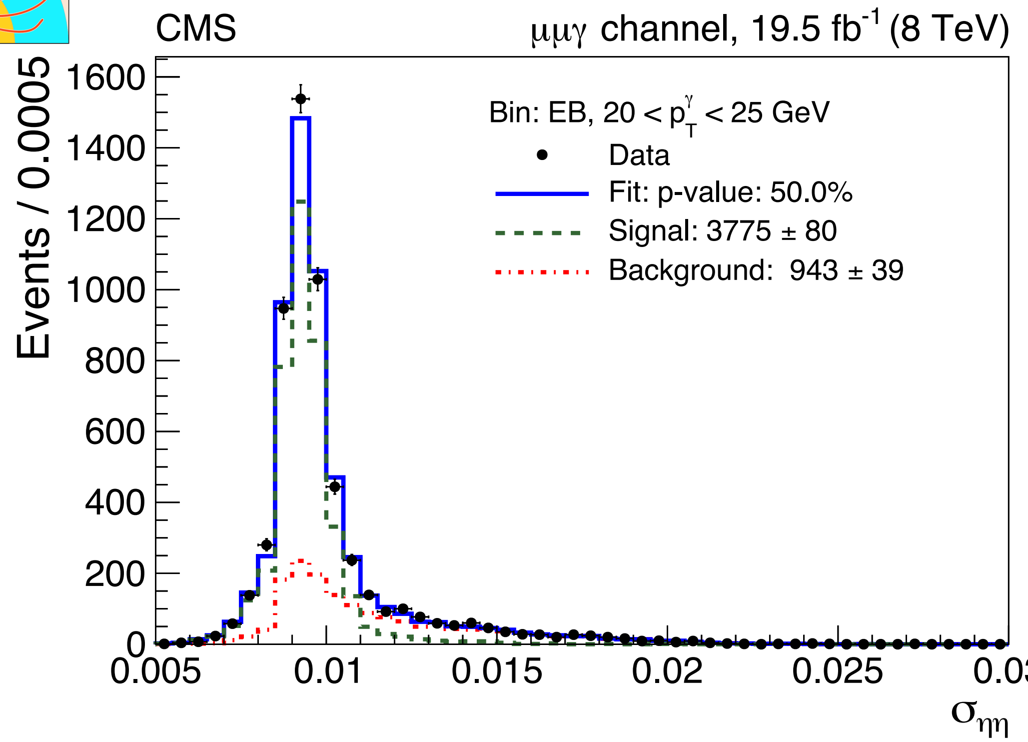


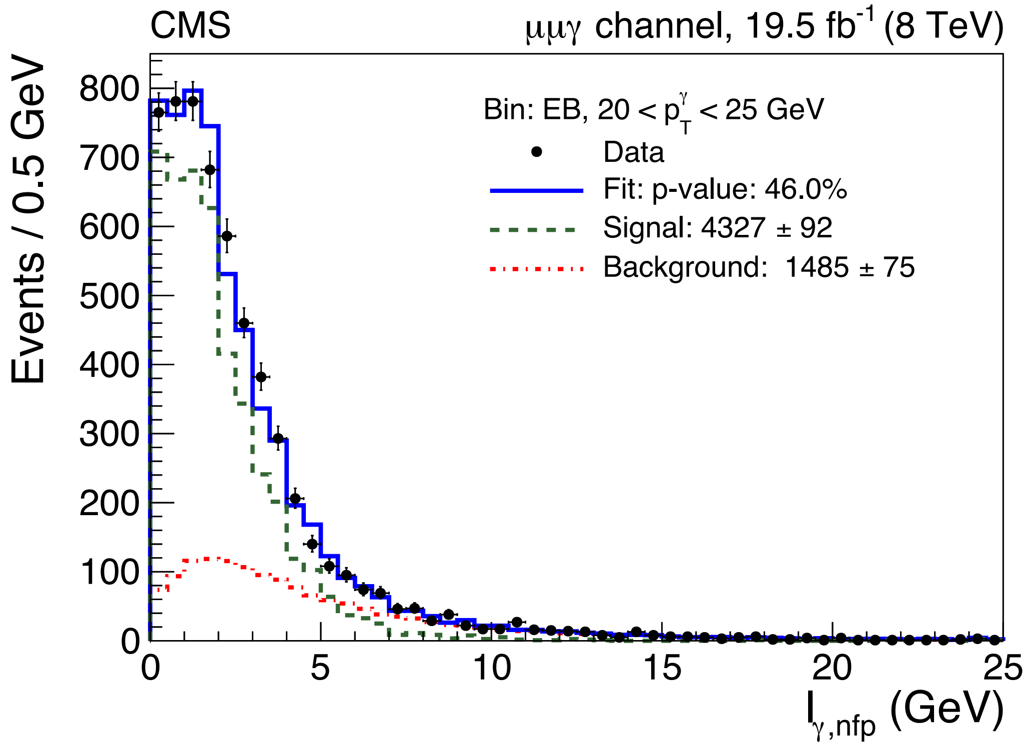

- Longitudinal and transverse energy spread
- Tight and Loose ID

# Background Estimation

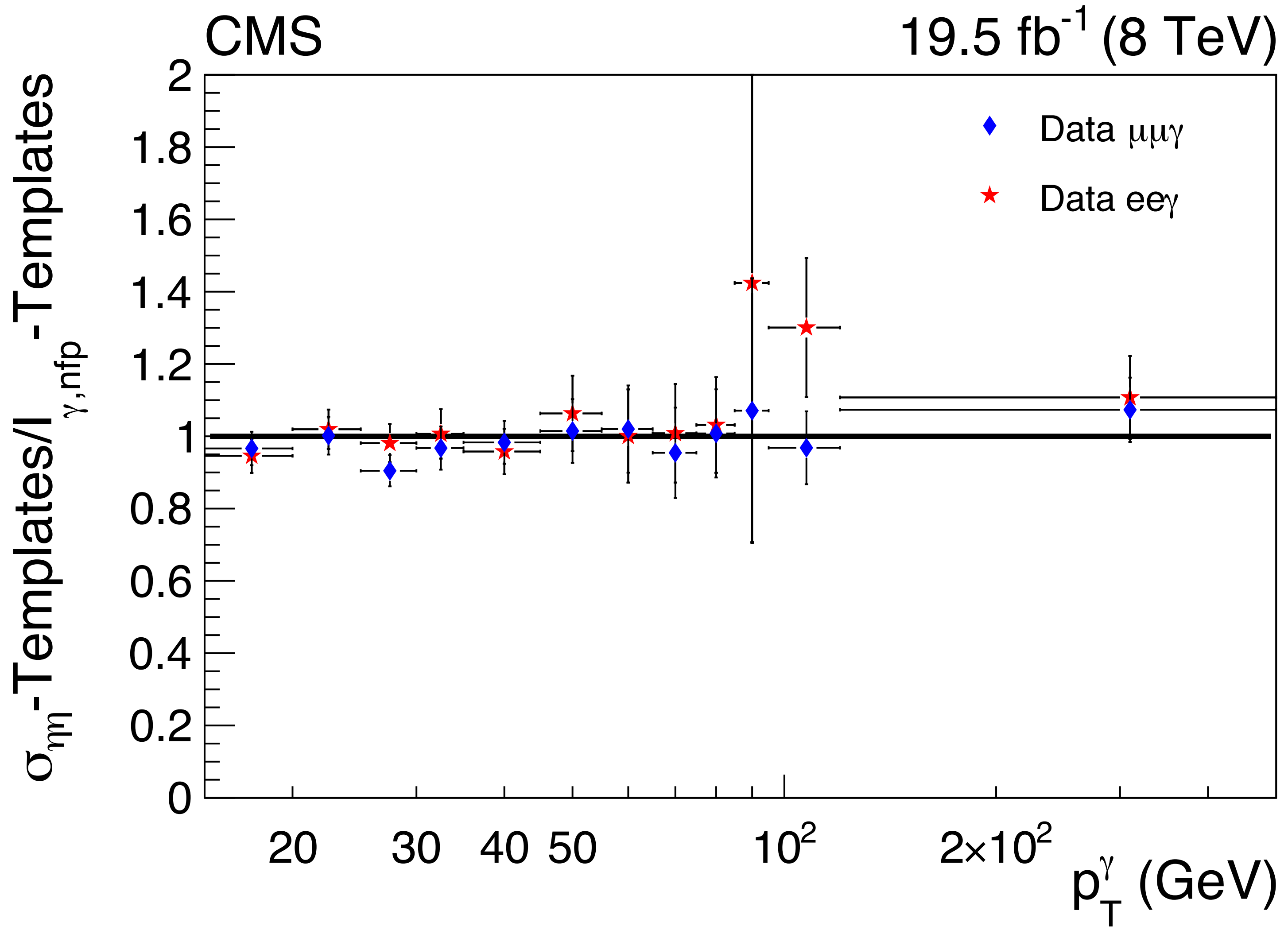
- Most of the photon backgrounds are jets faking photons.
- Analyses estimate this contribution from data directly.
- Template fit with a variable (CMS) or ABCD method (ATLAS) to obtain statistical results on signal and background contribution or purity (S/S+B) for the signal region.

# Signal Extraction (CMS)



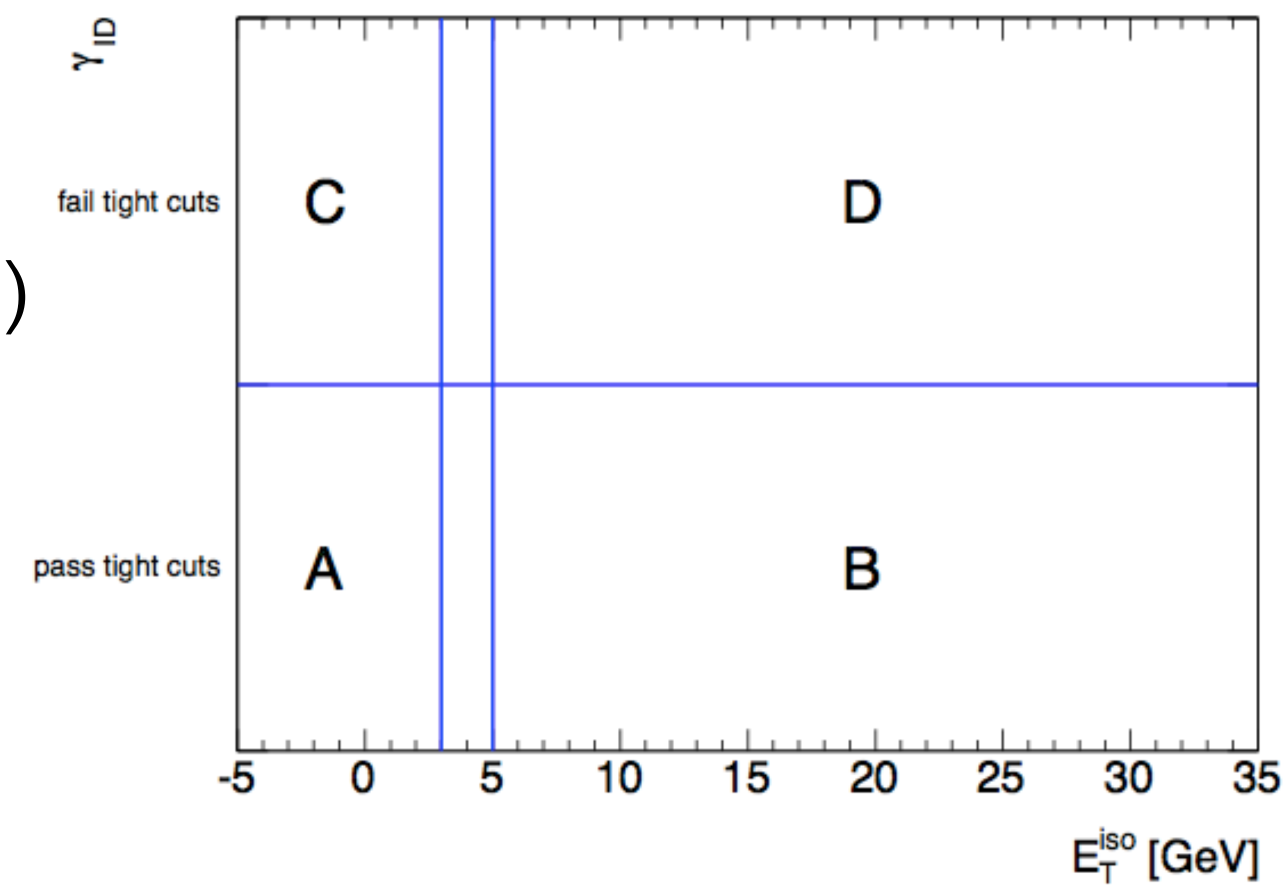




- Signal template from MC
- Bkg template from data sideband.
- Systematics correlate with sideband statistics



# Signal Extraction (ATLAS)

- If ID and Isolation are independent, the ratio of background between (A,B) and (C,D) are the same
- Assume B,C,D to be background only
- Correct this hypothesis with MC



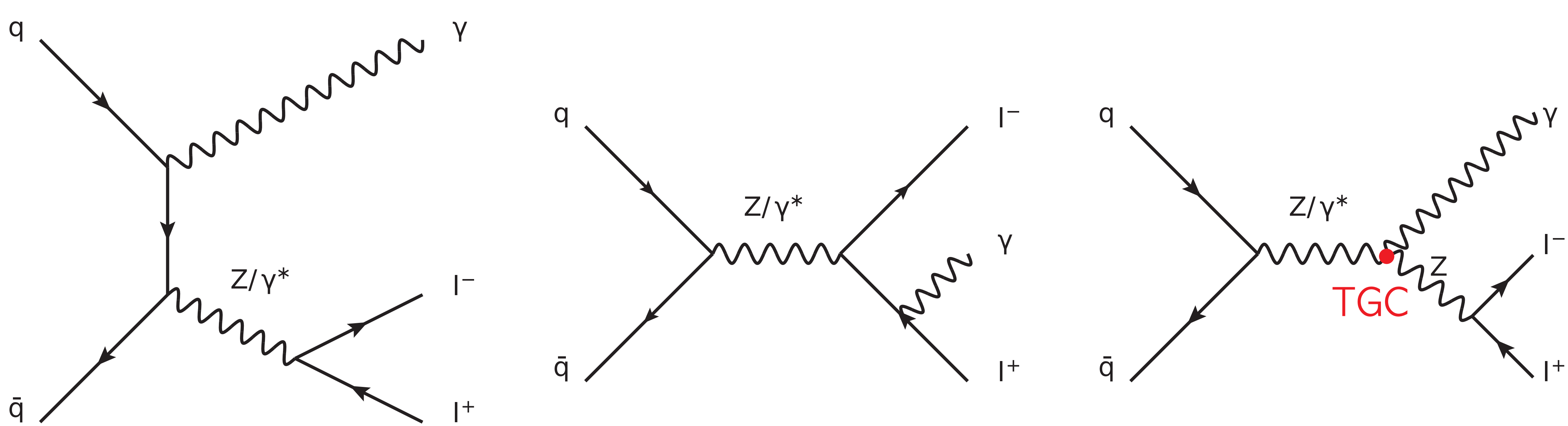

- Systematic uncertainties from: MC inputs; bkg control regions

# Vγ measurements and aTGC

| | CMS | | ATLAS | |
|---|---|---|---|---|
| | 8 TeV | 13 TeV | 8 TeV | 13 TeV |
| $Z\gamma \to \ell\ell\gamma$ | JHEP 04 (2015) 164<br>Cross section and aTGC measurement | | PRD 93, 112002 (2016)<br>Cross section, and aTGC measurement | |
| $Z\gamma \to \nu\nu\gamma$ | PLB 760 (2016) 448<br>Cross section and aTGC measurement | CMS-PAS-SMP-16-004<br>Cross section | | JHEP 12 (2018) 010<br>Cross section and aTGC measurement |
| | 7 TeV | | 7 TeV | |
| $W\gamma \to \ell\nu\gamma$ | Phys. Rev. D 89 (2014) 092005<br>Cross section and aTGC measurement | | Phys. Rev. D 87, 112003 (2013)<br>Cross section and aTGC measurement | |

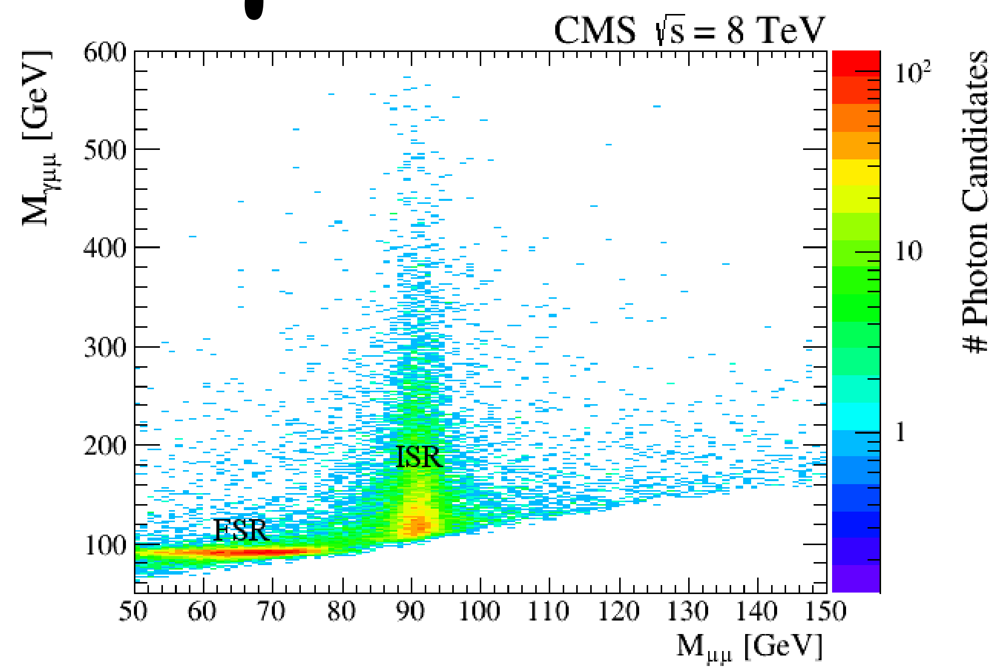
# $Z\gamma \rightarrow \ell\ell\gamma$ Measurements

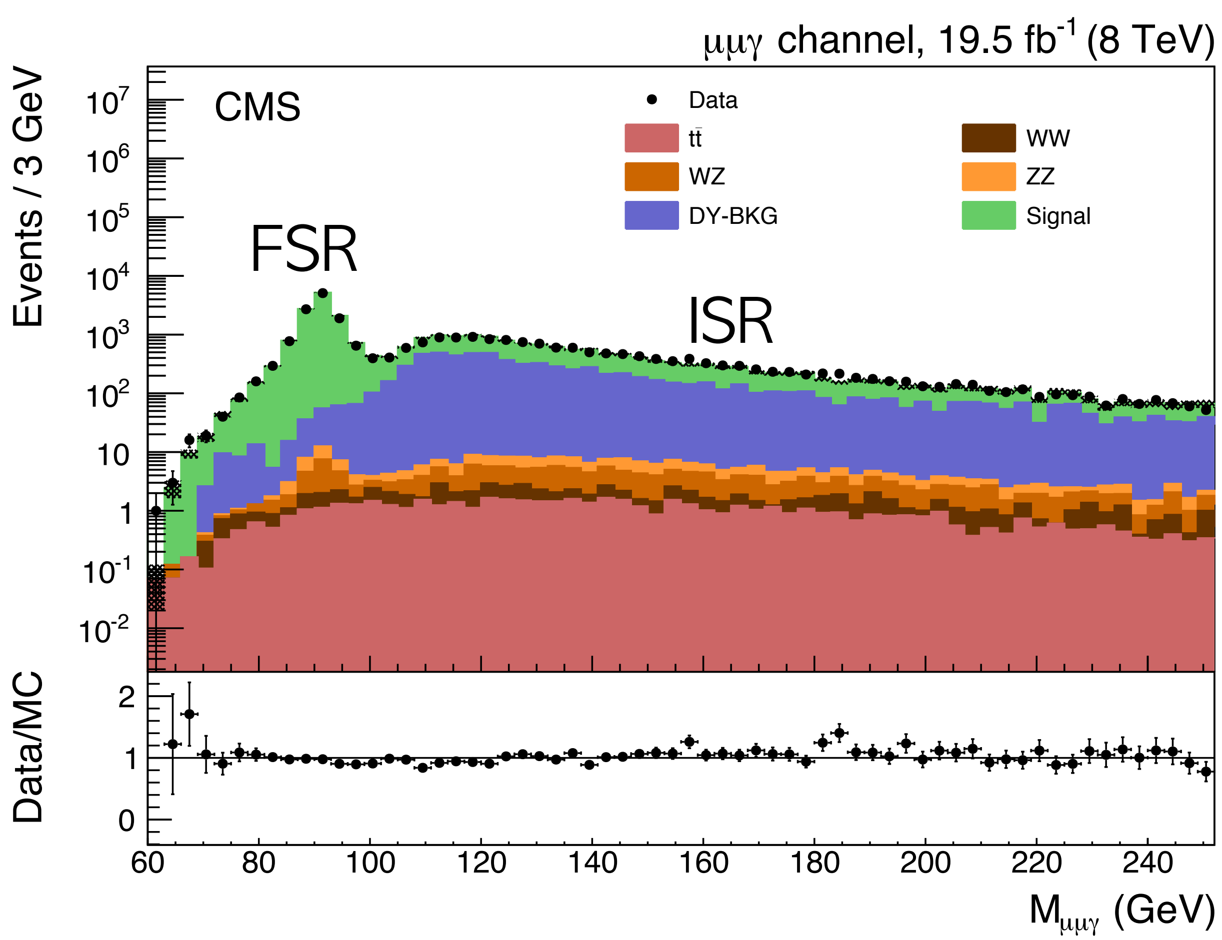
- Standard model (SM) predicts self-interactions of gauge bosons: $U(1)_Y \times SU(2)_L$ gauge group $\rightarrow$ no $ZZ\gamma$ and $Z\gamma\gamma$ coupling.
- Photons couple on charged particles: incoming quarks (ISR) or leptons ($\mu$ or e) in the final state (FSR).
- aTGCs lead to an excess of photons with high transverse momentum($p_T$).

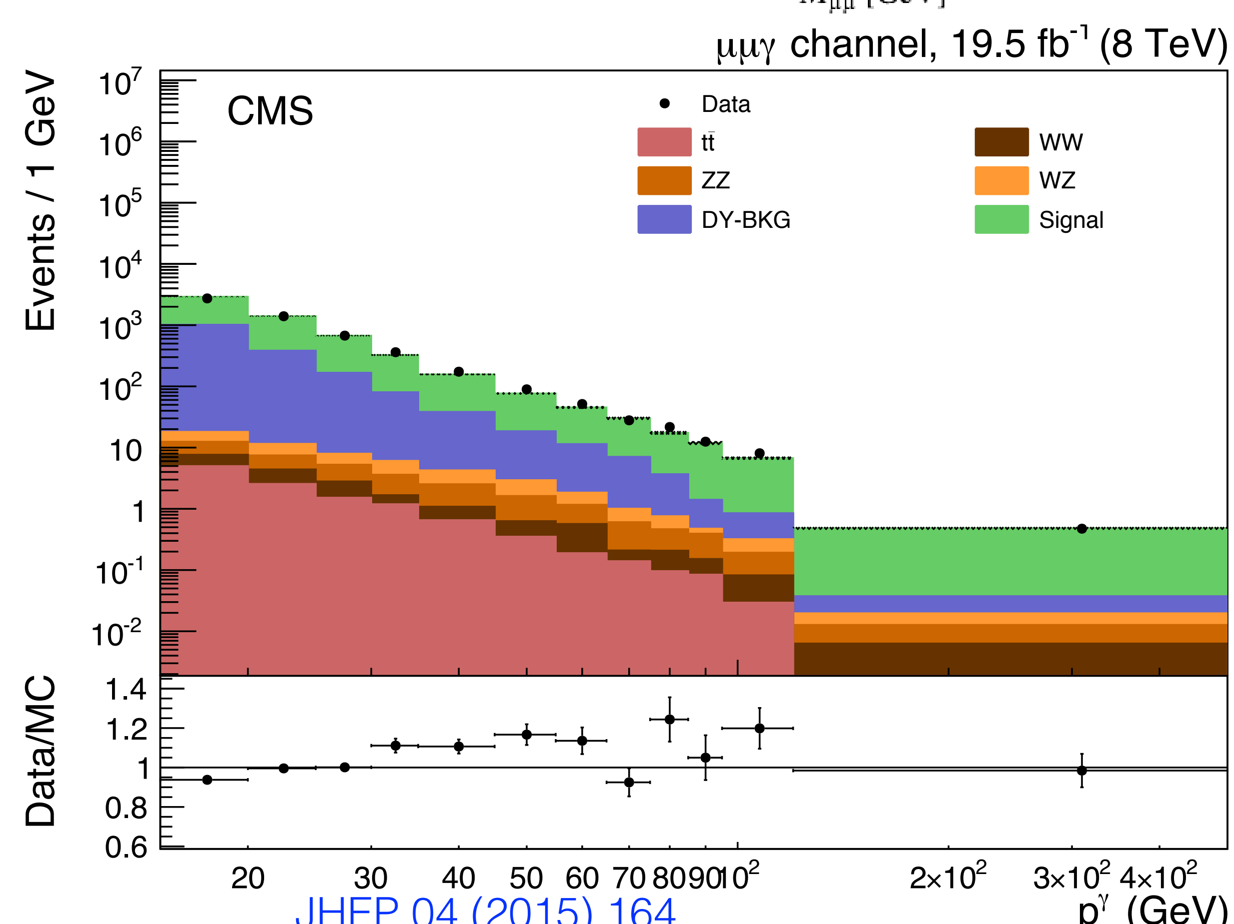


# $Z\gamma \rightarrow \ell\ell\gamma$

- ISR and FSR event signatures



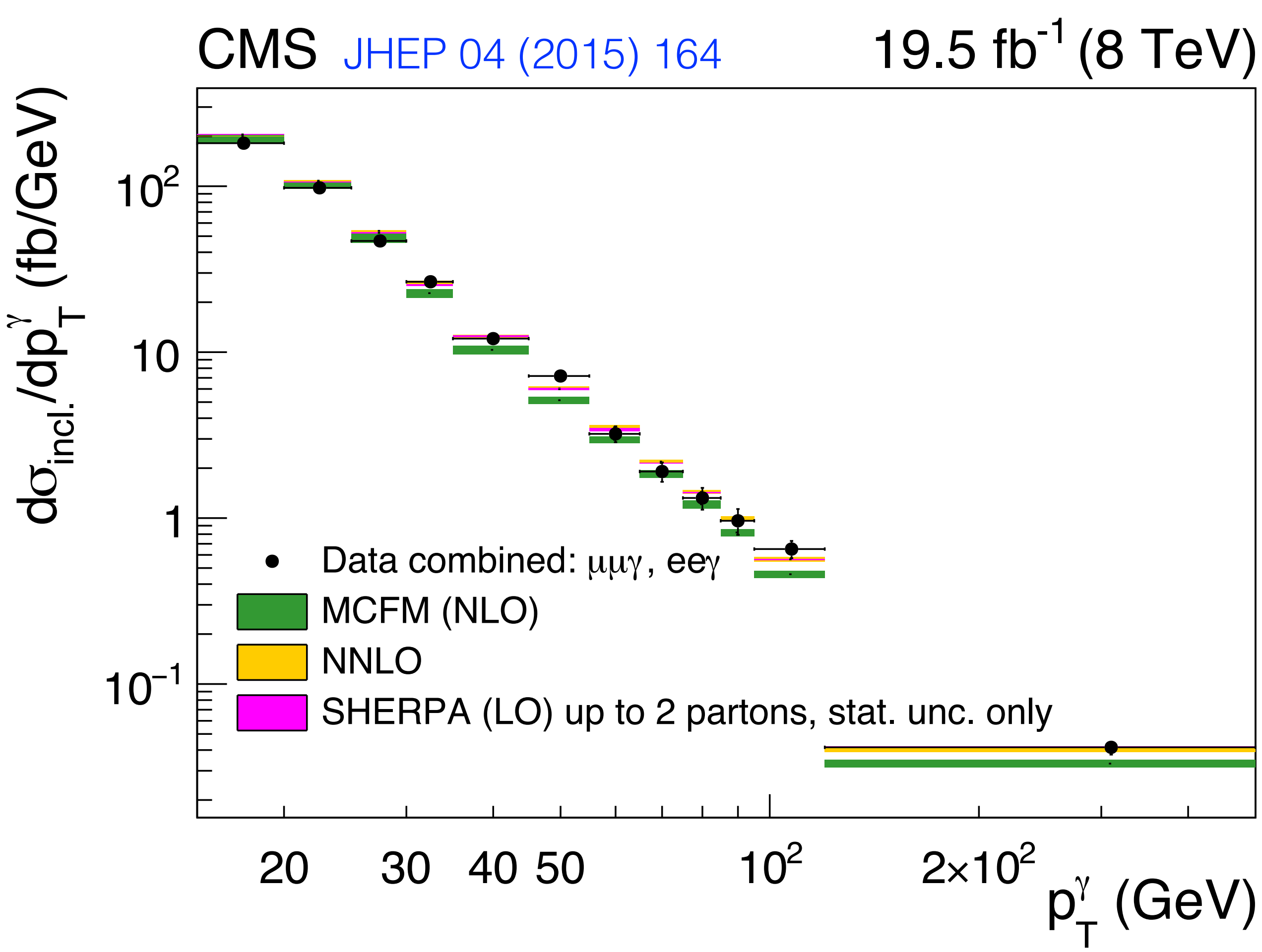



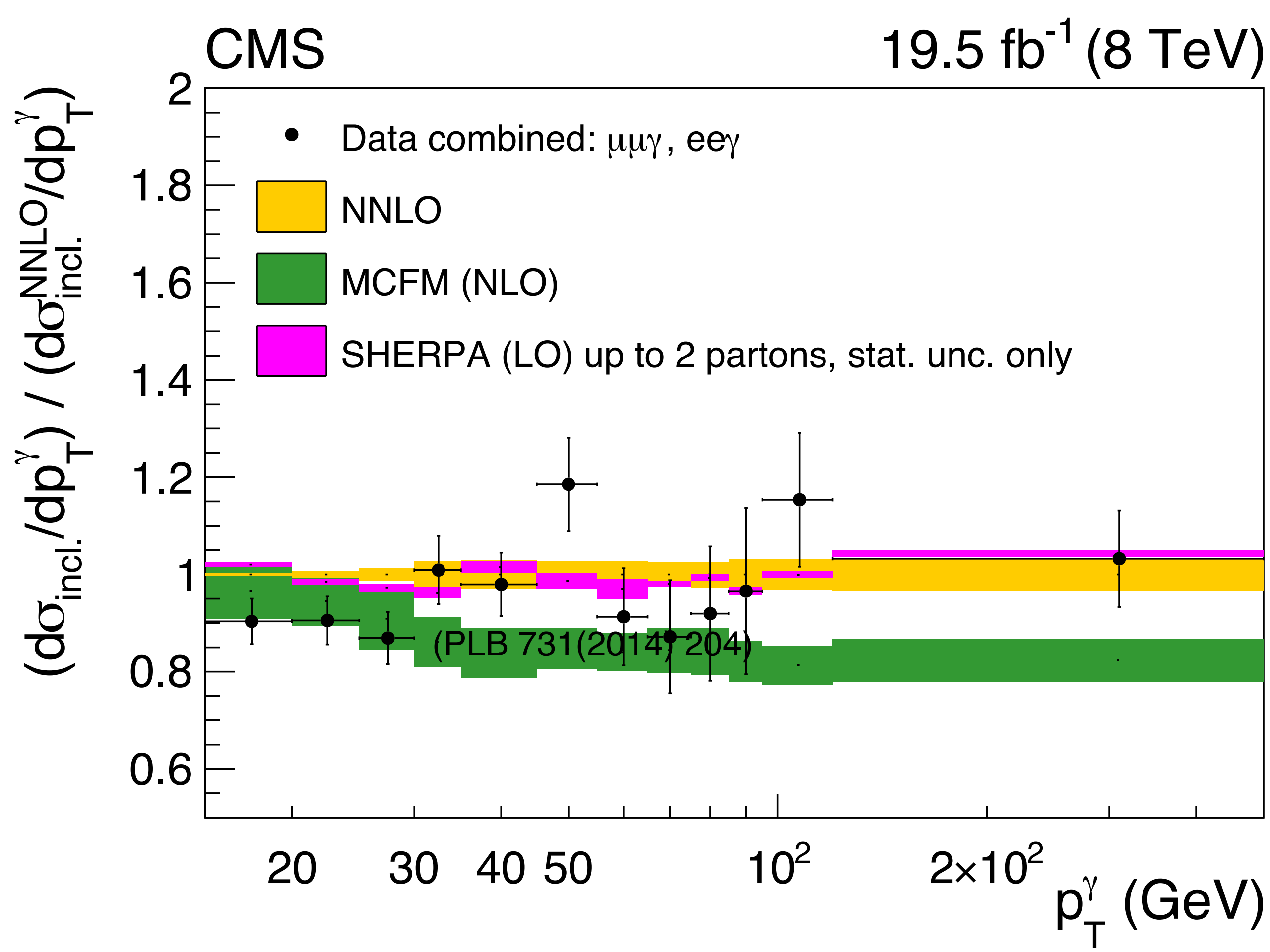




JHEP 04 (2015) 164

# $Z\gamma \to \ell\ell\gamma$ Measurements

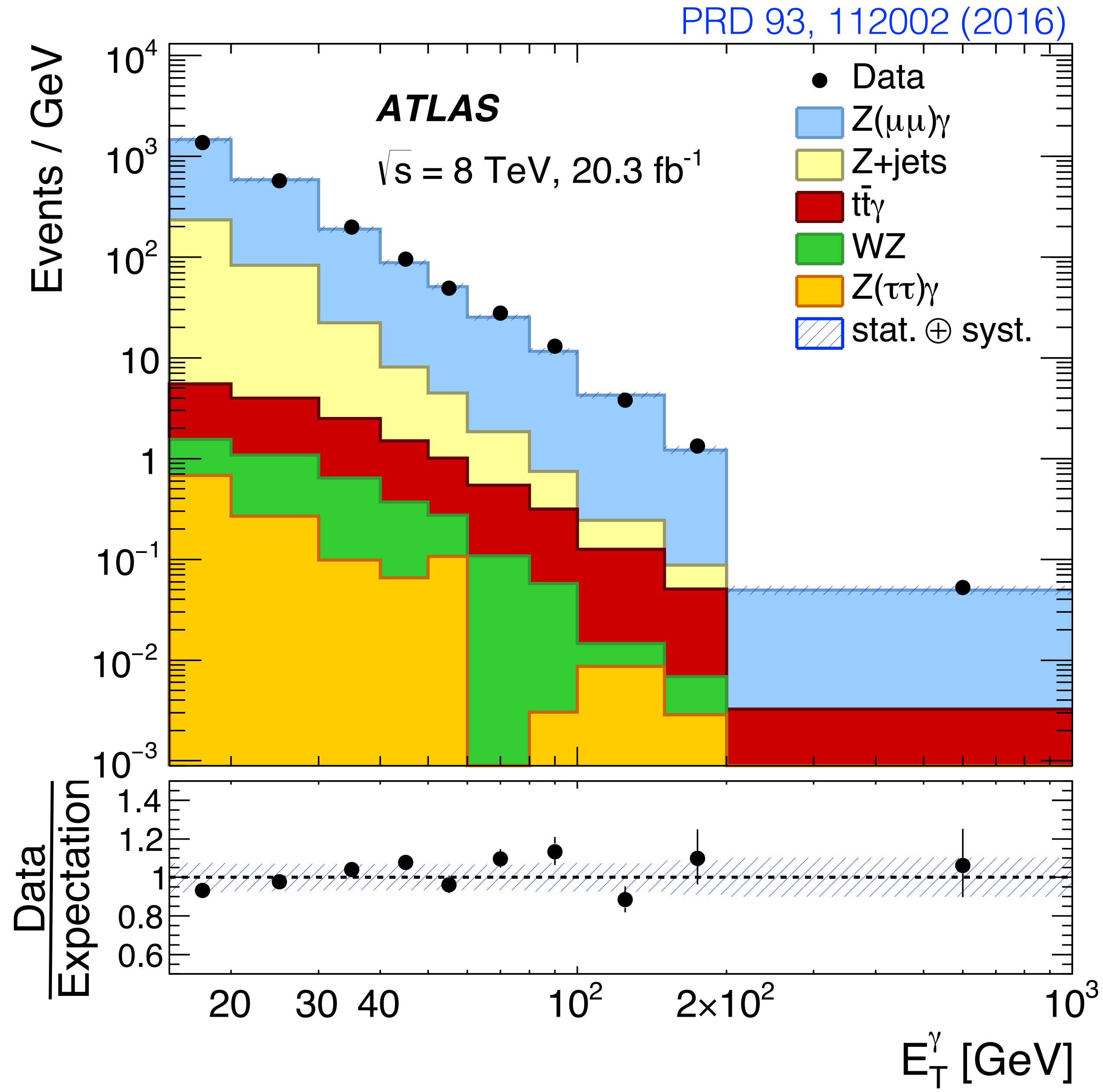
- Cross section phase space: $|\eta(\gamma)| < 2.5$, $|\eta(\ell)| < 2.5$, $p_T(\ell) > 20$ GeV, $\Delta R(\ell, \gamma) > 0.7$, $M_{\ell\ell} > 50$ GeV.
- Additional uncertainties.: di-lepton(2%) and photon(2%) reconstruction, photon energy scale and resolution (2.3%), luminosity (2.6%).
- Consistent with MCFM (NLO) and SHERPA (LO) calculations.

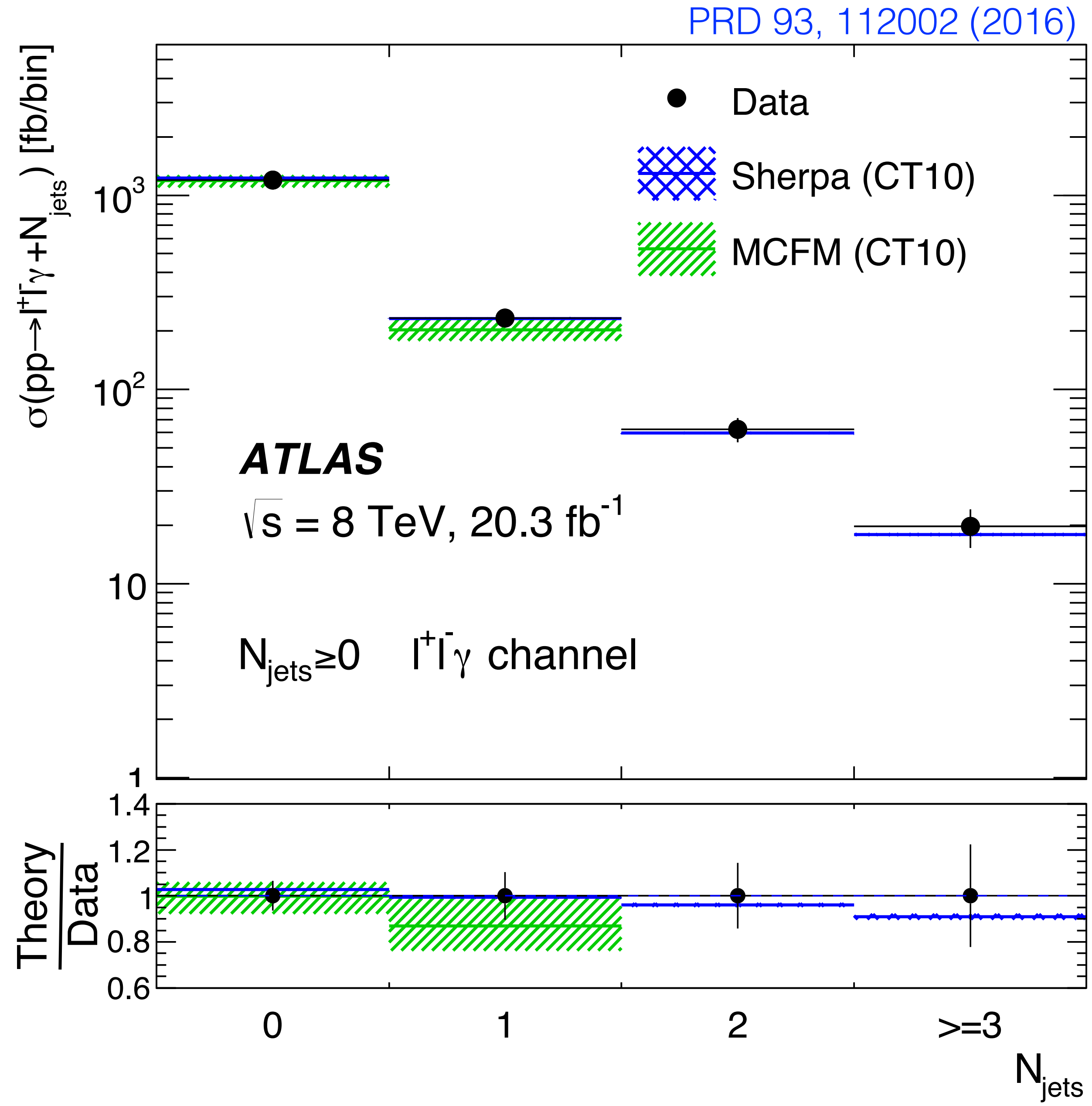


# $Z\gamma \to \ell\ell\gamma$ Measurements

- Overall consistent except for MCFM underestimates the cross section when NJet 〉0



# $Z\gamma \rightarrow \ell\ell\gamma$ aTGC

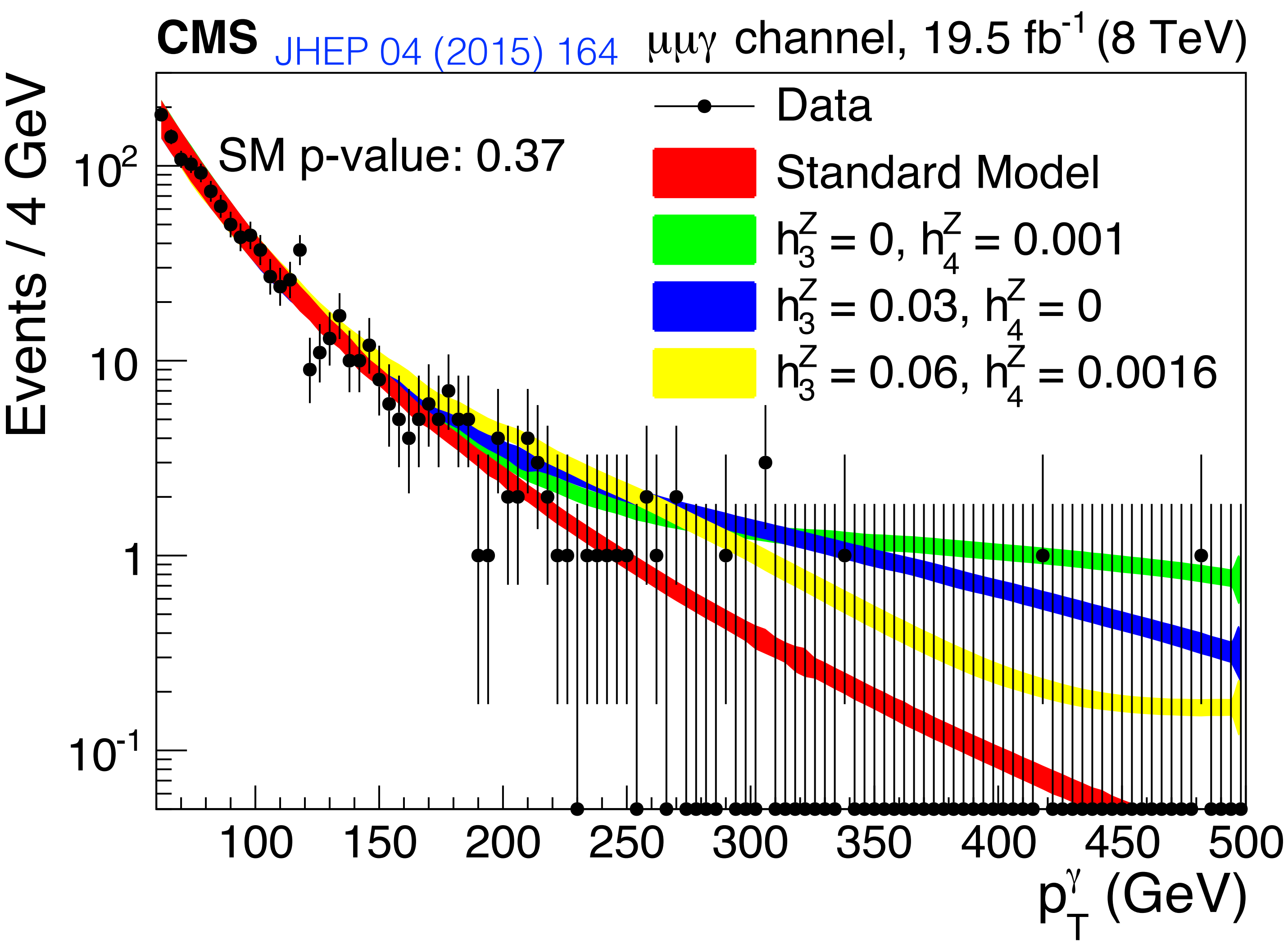
- $ZZ\gamma$ or $Z\gamma\gamma$ aTGC are formulated in the framework of an effective field theory (EFT) considering dimension 6 and 8 operators, fulfilling the requirement of Lorentz invariance and local U(1) gauge symmetry and unitarity.

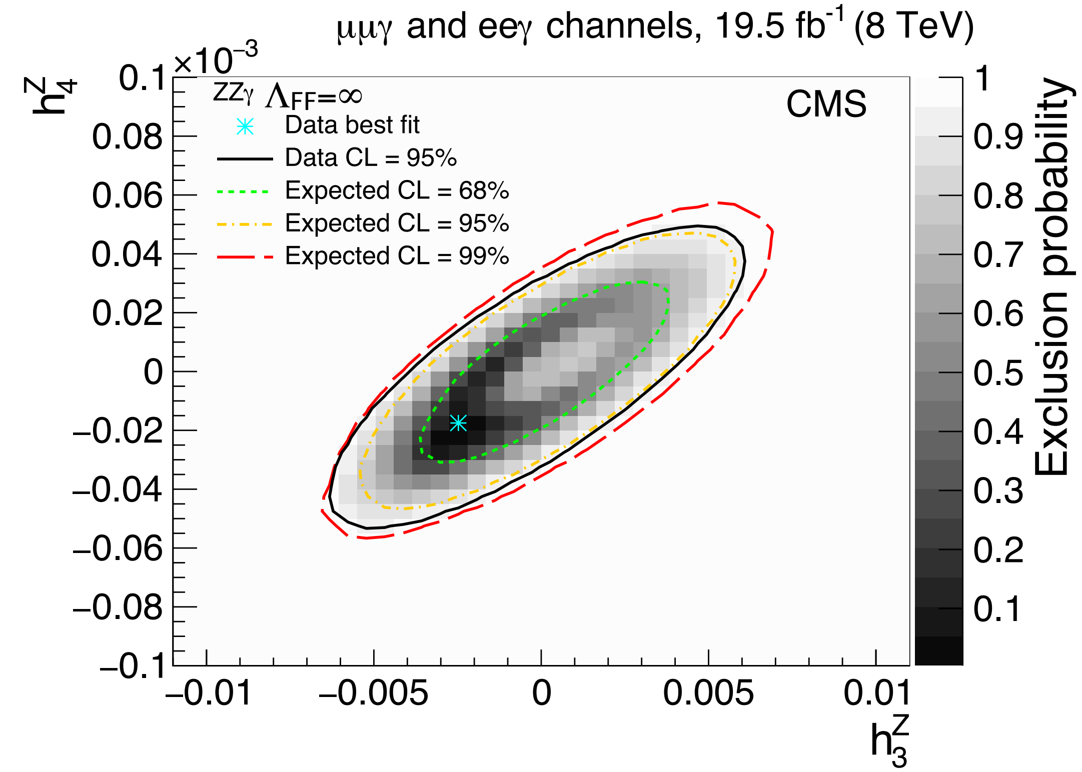
$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots \,.$$

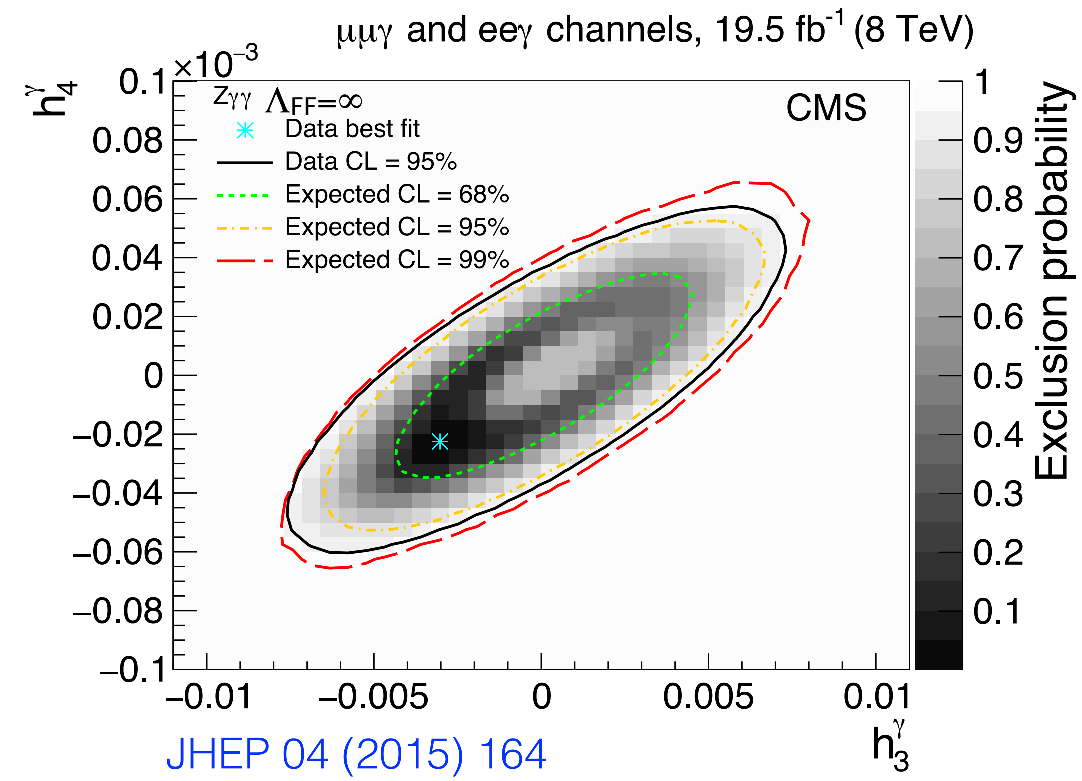
- The aTGC models are parametrized at NLO with MCFM .
- The weighted events are corrected for detector acceptance and efficiency of the leptons and the photon.
- Added a description of the $\pi^0$+fake background
- Theoretical uncertainties of 6~12% from PDF and scale variations. Data with 2% systematics on di-lepton and photon efficiency and depends on photon pT, up to 8% in the background estimation with $\sigma_{\eta\eta}$ method.

# Zγ → ℓℓγ aTGC

- The CP-conserving parameters $h_3^V$ and $h_4^V$ are considered.
- 2-D Limits on aTGC are set



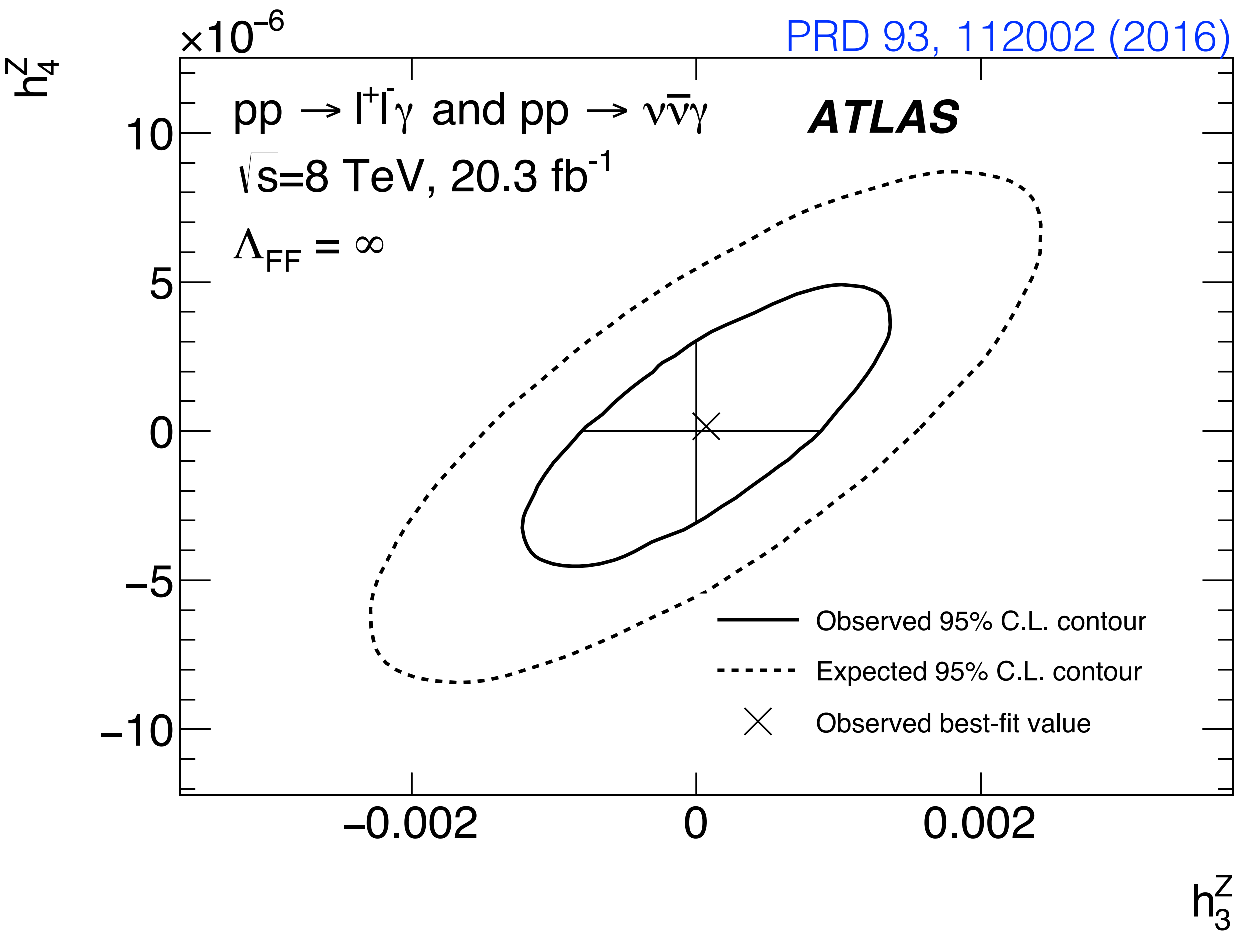



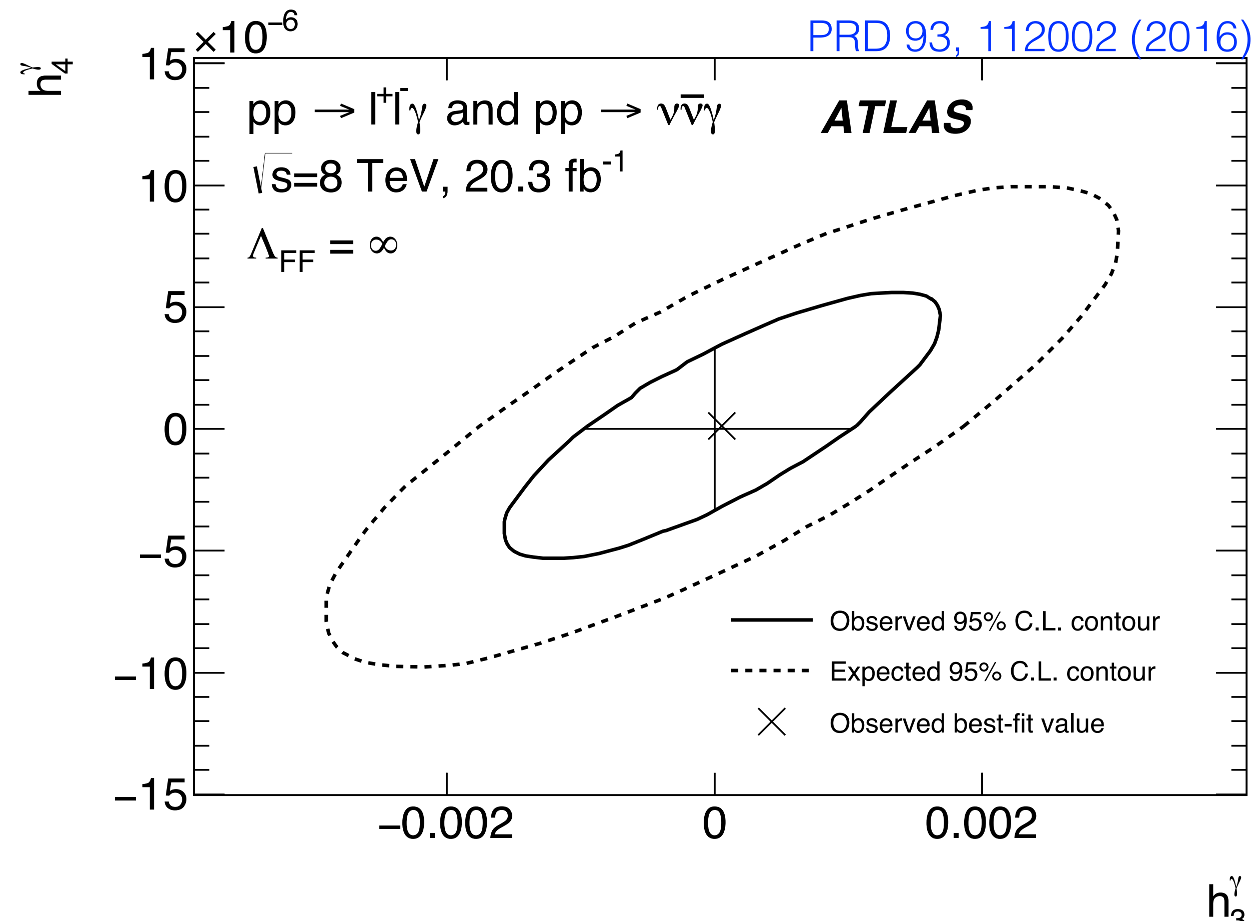



# $Z\gamma \to \ell\ell\gamma$ aTGC

- Uses exclusive 0-jet events which has reduced SM contribution at high $E_T$.

| Channel | Measurement [fb] | Prediction [fb] |
|---|---|---|
| $\ell^+\ell^-\gamma$ ($E_T^\gamma > 250$ GeV) | $0.42^{+0.16}_{-0.13}$(stat.)$^{+0.07}_{-0.04}$(syst.) | $0.660 \pm 0.015$(stat.) $\pm 0.018$(syst.) |
| $\nu\bar{\nu}\gamma$ ($E_T^\gamma > 400$ GeV) | $0.06^{+0.15}_{-0.10}$(stat.)$^{+0.04}_{-0.04}$(syst.) | $0.466 \pm 0.021$(stat.) $\pm 0.020$(syst.) |



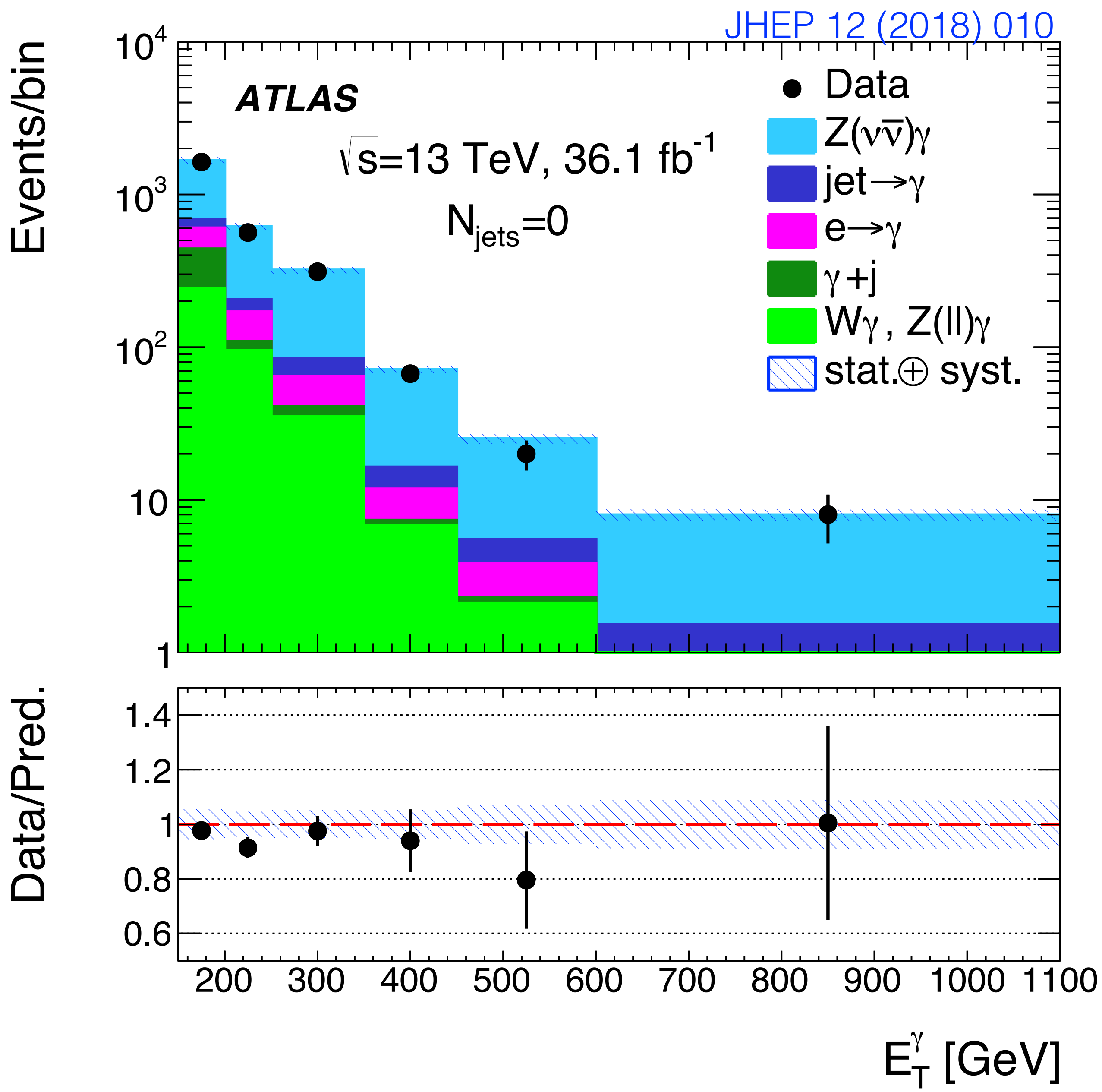



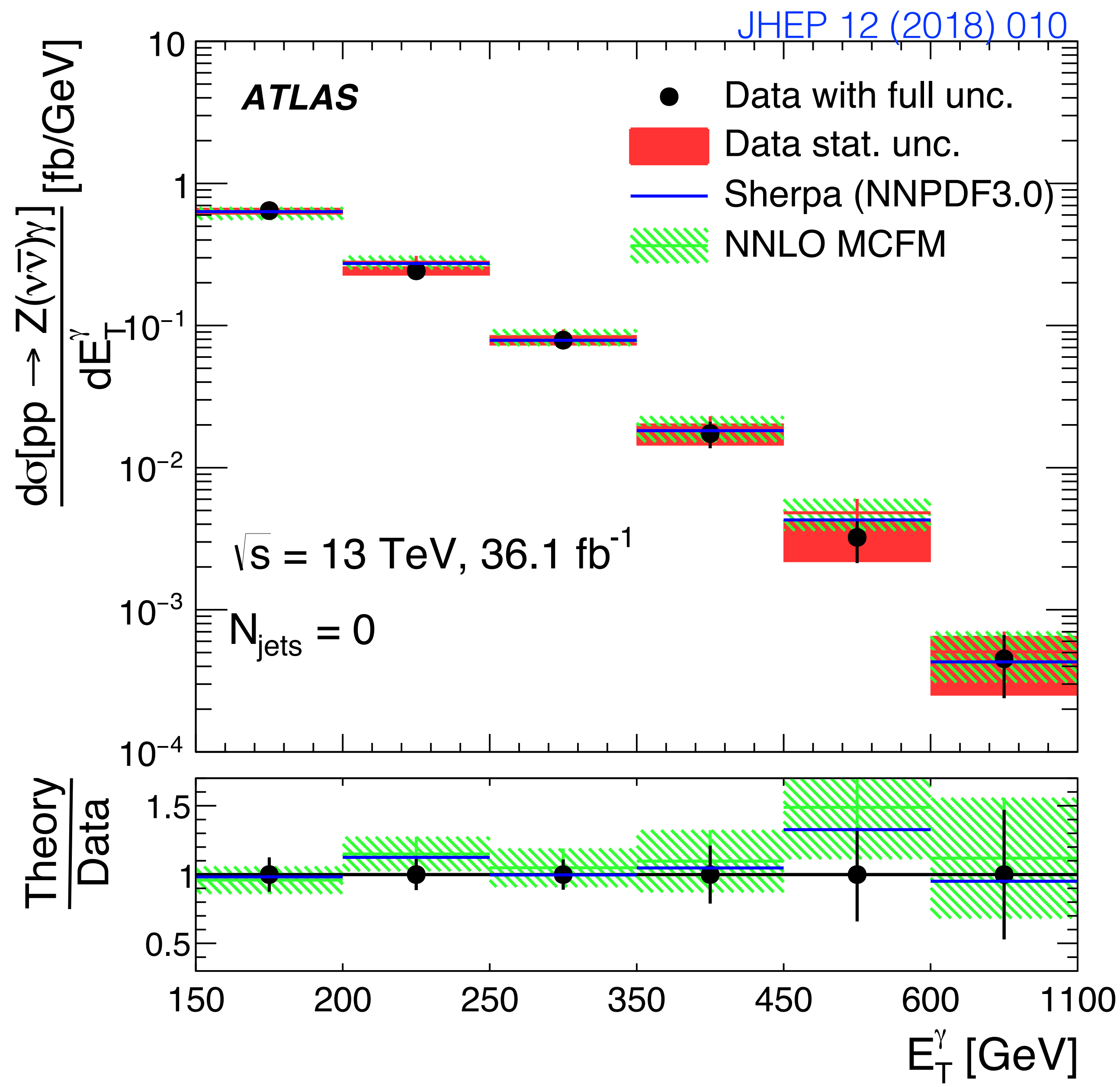
# $Z\gamma \to \nu\nu\gamma$ @13TeV

- $Z\gamma \to \nu\nu\gamma$ channel has an advantage for aTGC measurement than $Z\gamma \to qq\gamma$ (large multijet background) or $Z\gamma \to \ell\ell\gamma$ (FSR and smaller branching ratio).
- The contribution from aTGCs increases with the $E_T$ of the photon and the $Z\gamma$ channel is found to have the highest sensitivity by restricting the search to the fiducial region with $E_T > 600$ GeV.
- Event signature: mono-photon with large MET
- Non-collision background from the beam

# $Z\gamma \rightarrow \nu\nu\gamma$ @13TeV

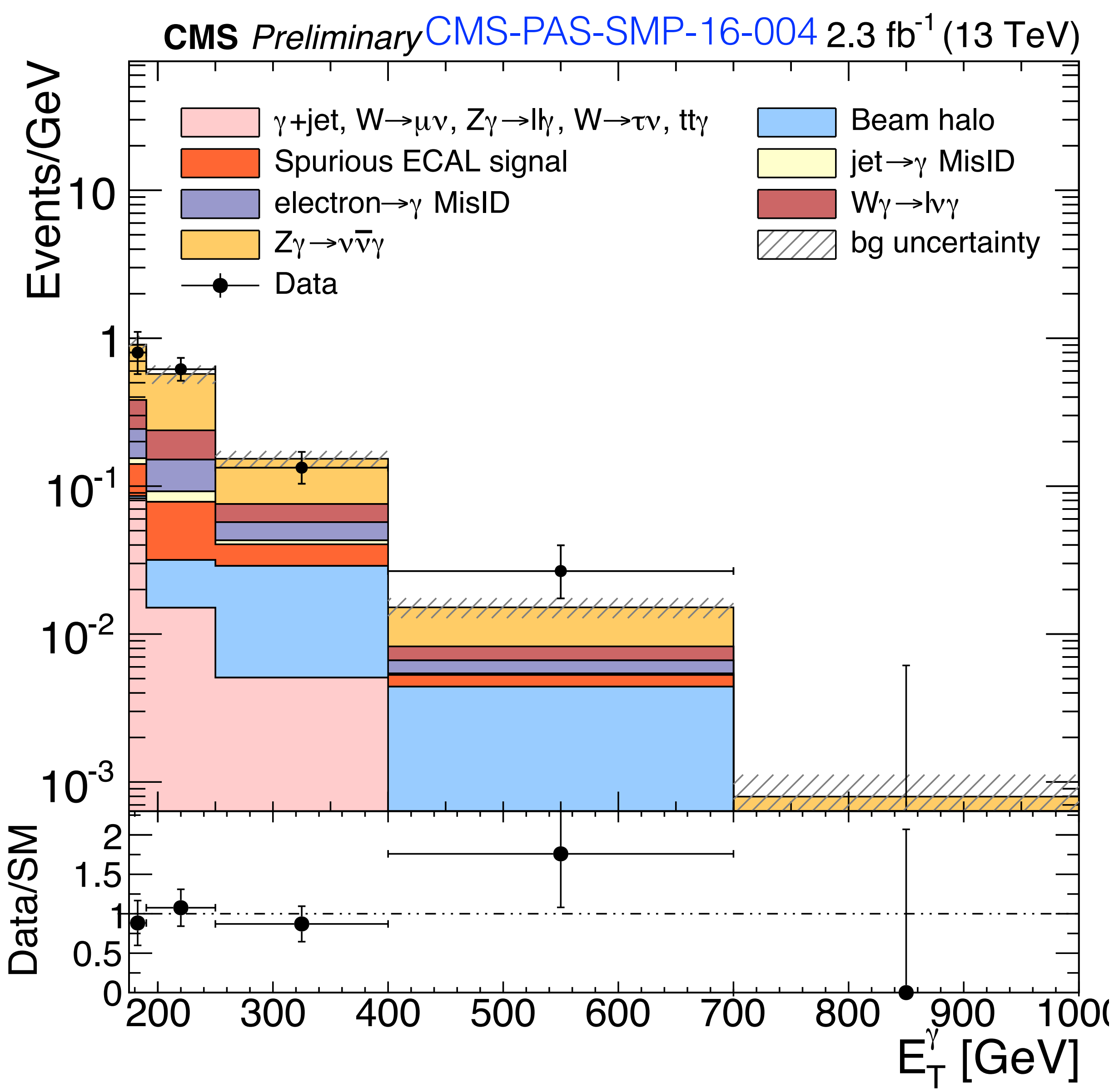
- Again, Njets=0 has good agreement with MCFM, but not Njet〉0
- Needs more statistics exploring $E_T$ 〉 600 GeV bin.

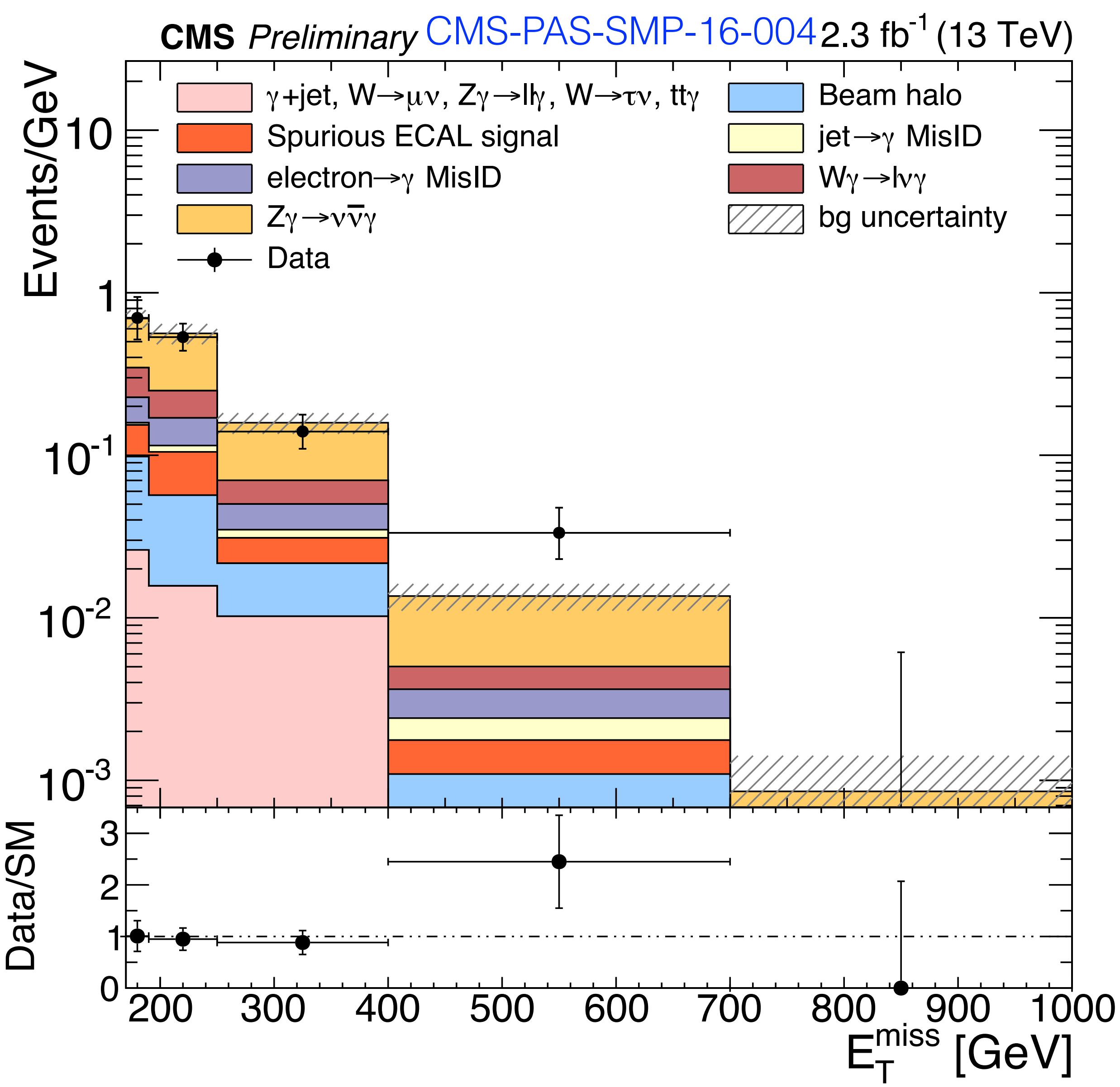


# Zγ → ννγ @13TeV

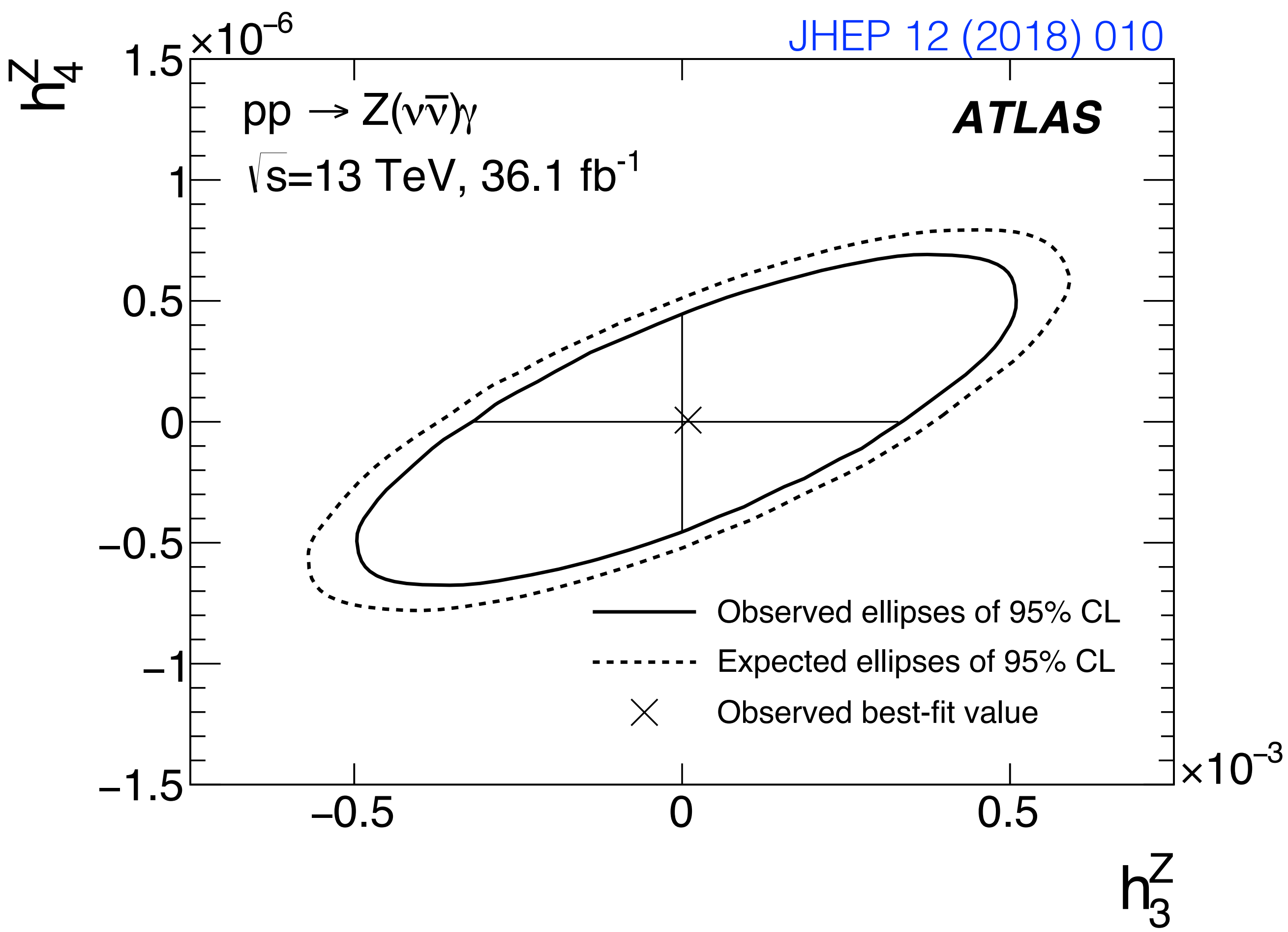
- CMS measured cross section but no aTGC interpretation yet.
- Consistent with SM expectation.

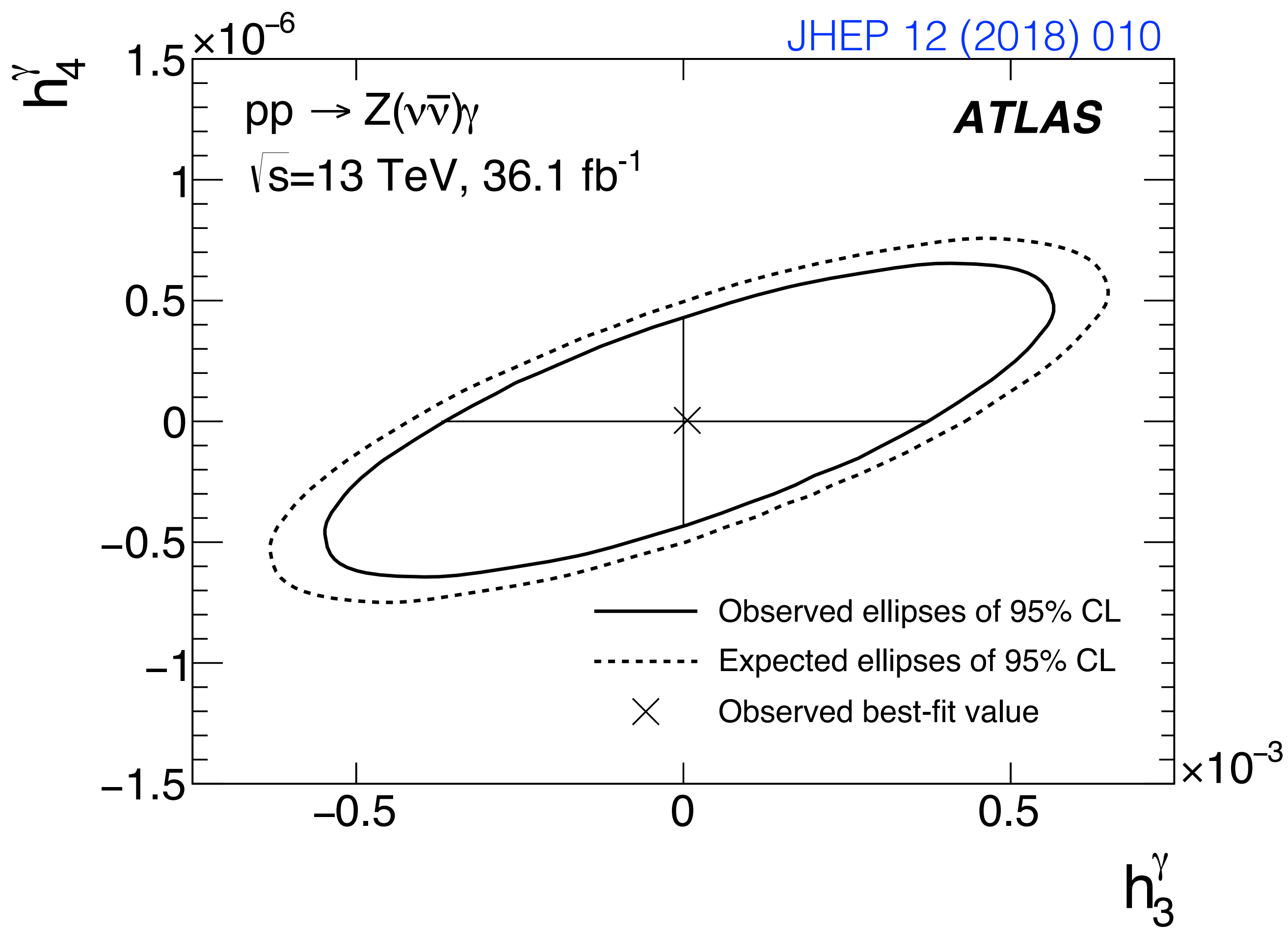


# $Z\gamma \rightarrow \nu\nu\gamma$ aTGC

- No excess is observed relative to the SM expectation.
- Limits on 2d $h_3^V$ and $h_4^V$ of aTGC parameters are evaluated.



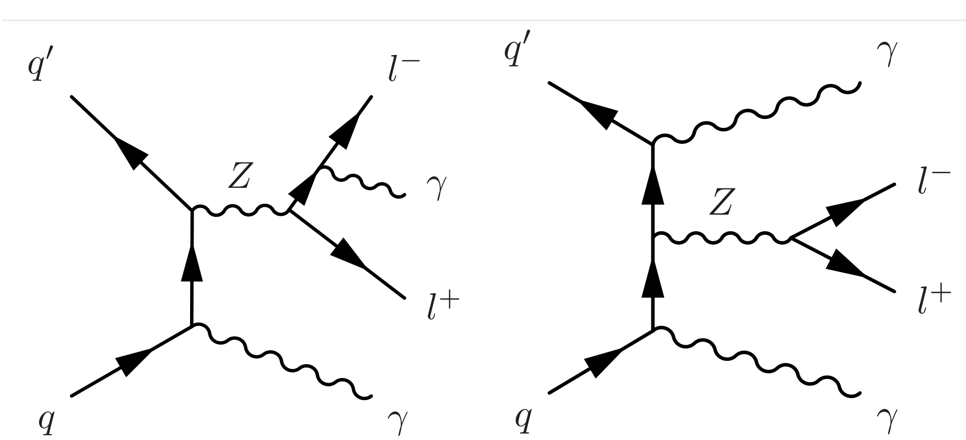



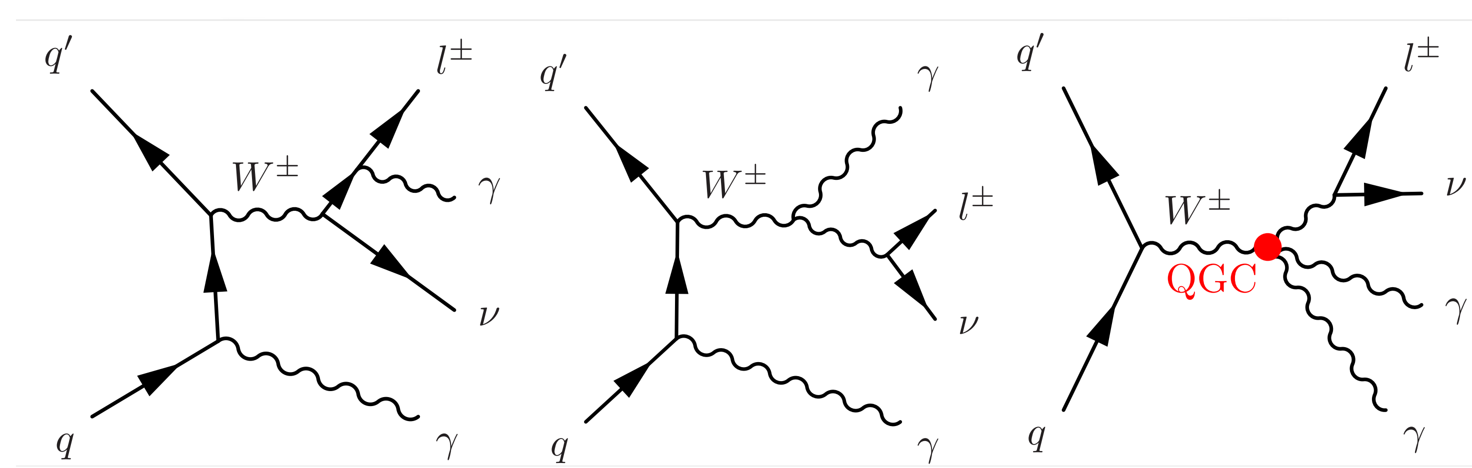
# Vγγ and aQGC

| | CMS | ATLAS |
|---|---|---|
| | 8 TeV | 8 TeV |
| $W\gamma\gamma \rightarrow \ell\nu\gamma\gamma$ | JHEP 10 (2017) 072<br>Cross sections and aTGC measurement | PRL 115, 031802 (2015)<br>Cross section and aQGC measurement |
| $Z\gamma\gamma \rightarrow \ell\ell\gamma\gamma$ | | PRD 93, 112002 (2016)<br>Cross sections and aTGC measurement |
| $Z\gamma\gamma \rightarrow \nu\nu\gamma\gamma$ | PLB 760 (2016) 448<br>Cross section and aTGC measurement | |

# Vγγ measurement

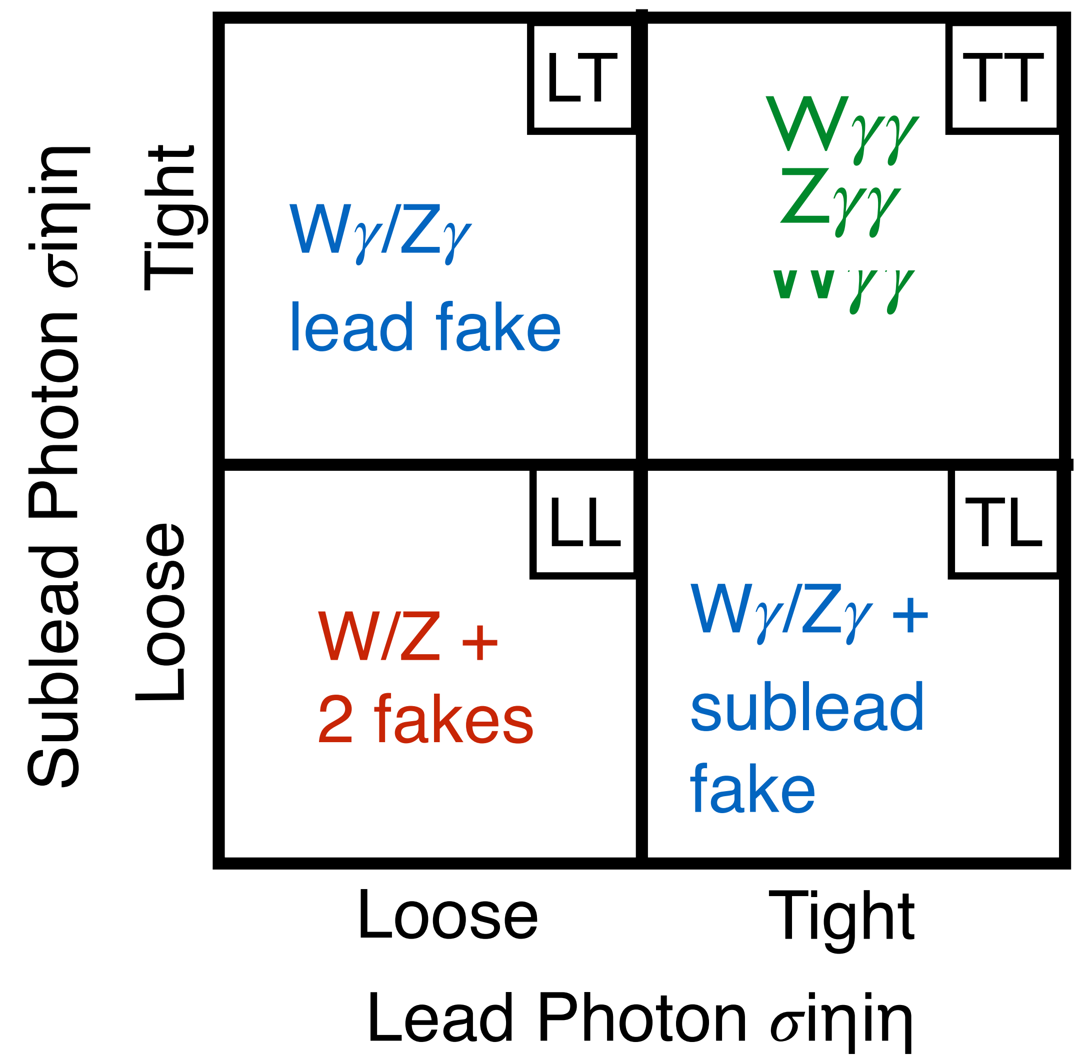
- First time measured in a hadron collider (ATLAS Wγγ @8TeV)
- Theory predicts large NLO/LO k-factors (Wγγ) of cross sections.
- Data is compared with NLO calculation of MadGraph5_aMC@NLO (CMS) or SHERPA (ATLAS)
- Wγγ sensitive to TGC and QGC. QGC most interesting (TGC better studied in higher rate processes). Set limits on aQGC with dimension-8 Effective Field Theory



# Jets fake photons in Vγγ

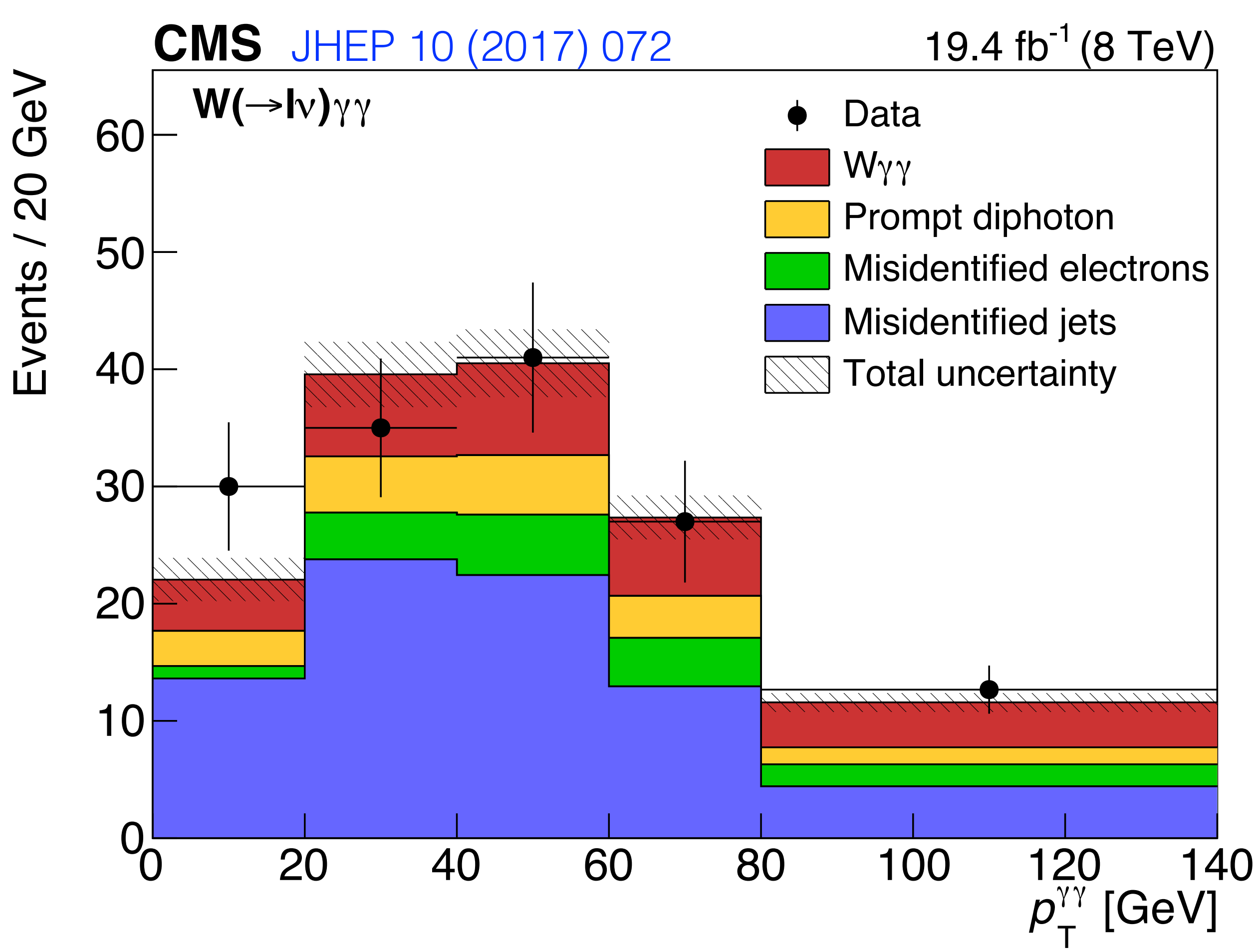
- Define tight/loose ID for photons. Solve the combination of pairs to estimate signal/fake
- CMS has systematics dominated by template method estimating jet faking photon. Fake template obtained in Z+jet sample in data.
  - Zγ subtraction (~15%)
  - Loosening procedure correction factor (~10%)
  - Conservative approach, compatible with Stat. uncertainty
- ATLAS has estimated ~5% syst. on cross section measurement

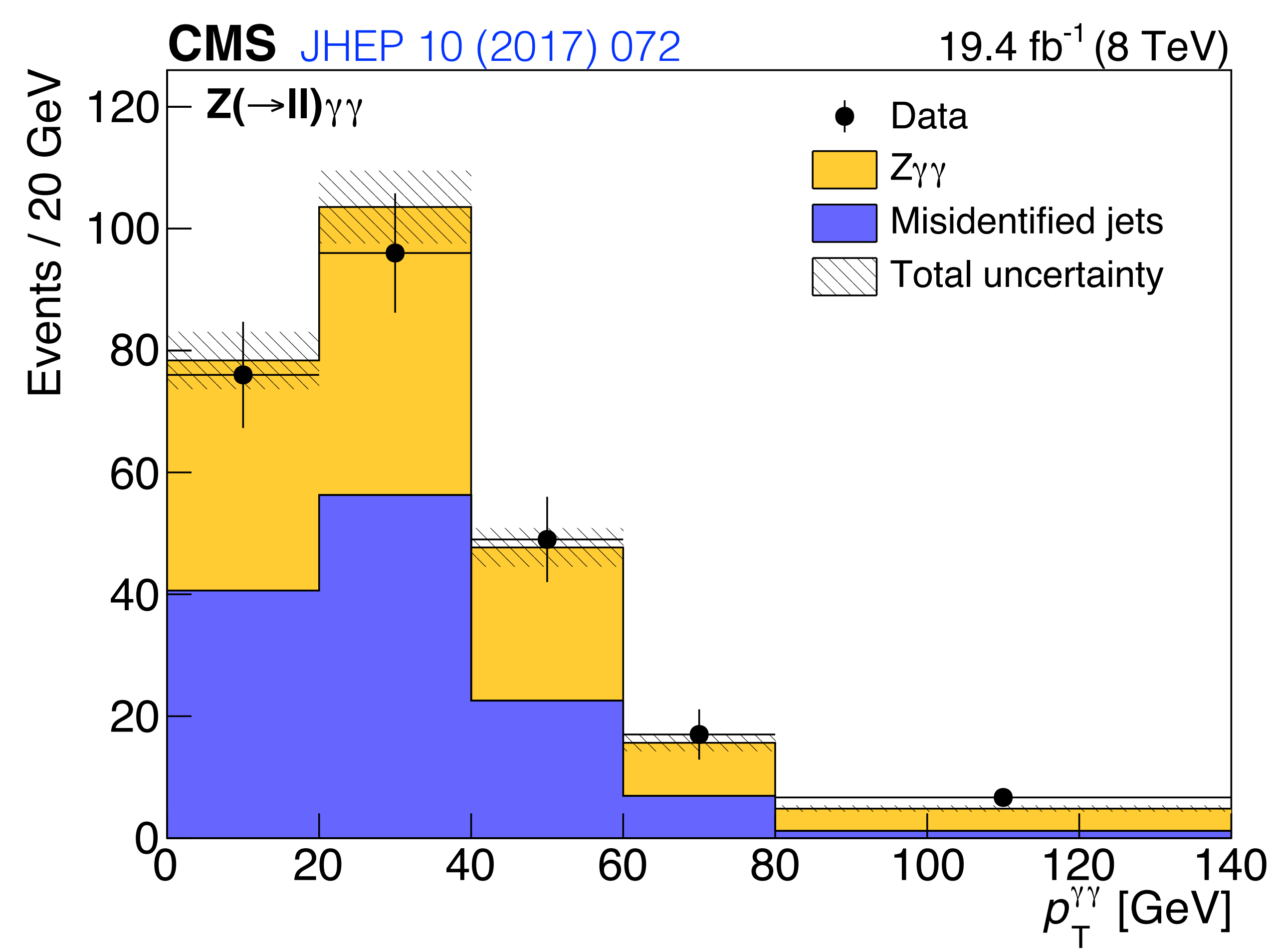



$$\begin{pmatrix} N_{\rm TT} \\ N_{\rm TL} \\ N_{\rm LT} \\ N_{\rm LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N_{\gamma\gamma} \\ N_{\gamma\rm jet} \\ N_{\rm jet\gamma} \\ N_{\rm jetjet} \end{pmatrix}.$$

# Vγγ measurement

- Irreducible background estimated by MC.
- Measured cross section consistent with theoretical expectation.

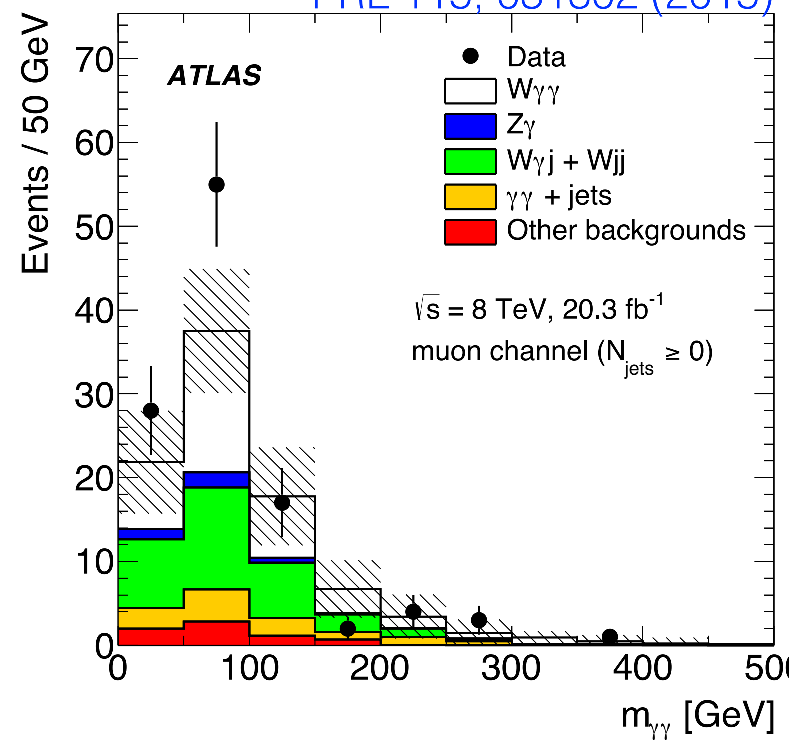


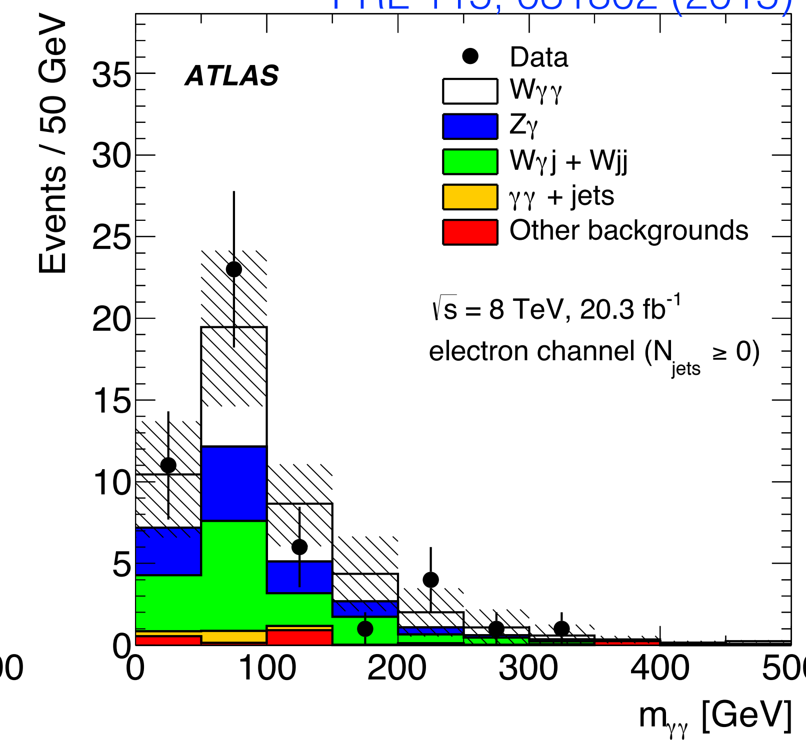
# Vγγ measurement

- Measurements include W(eν, μν)γγ and Z(μμ, ee, νν)γγ
- The measurements were statistically limited. Data and SM prediction agree within the uncertainties.

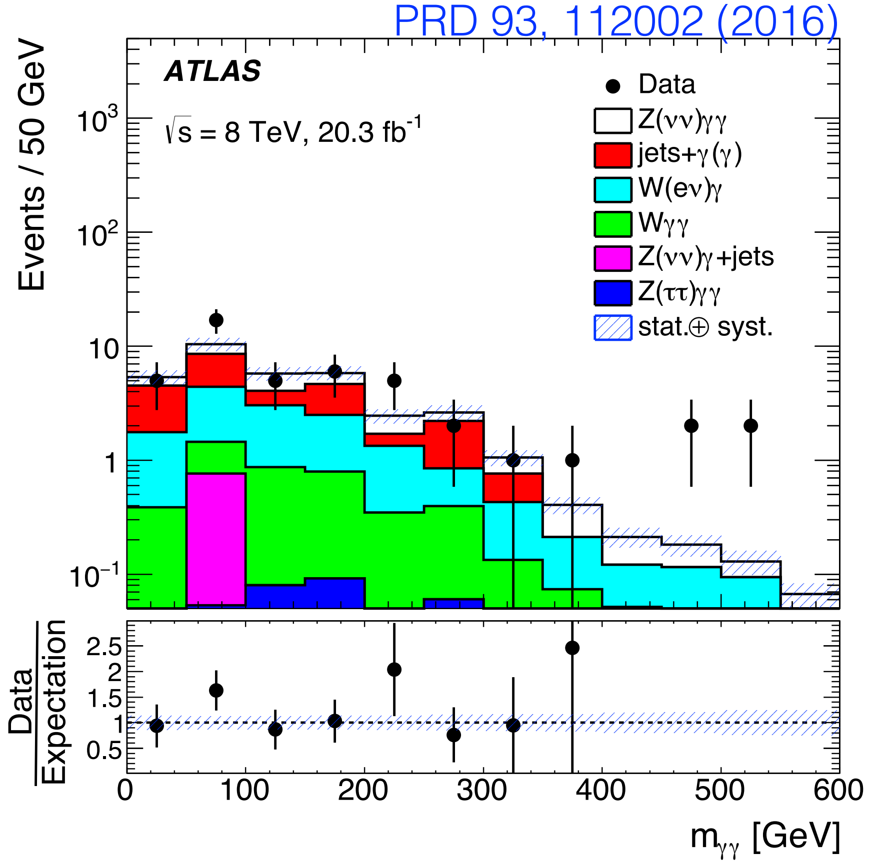
PRL 115, 031802 (2015)




PRL 115, 031802 (2015)




PRD 93, 112002 (2016)

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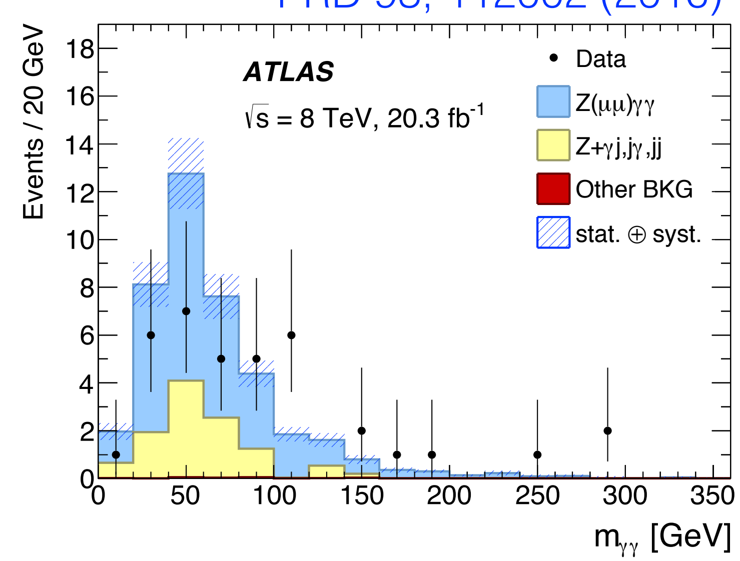
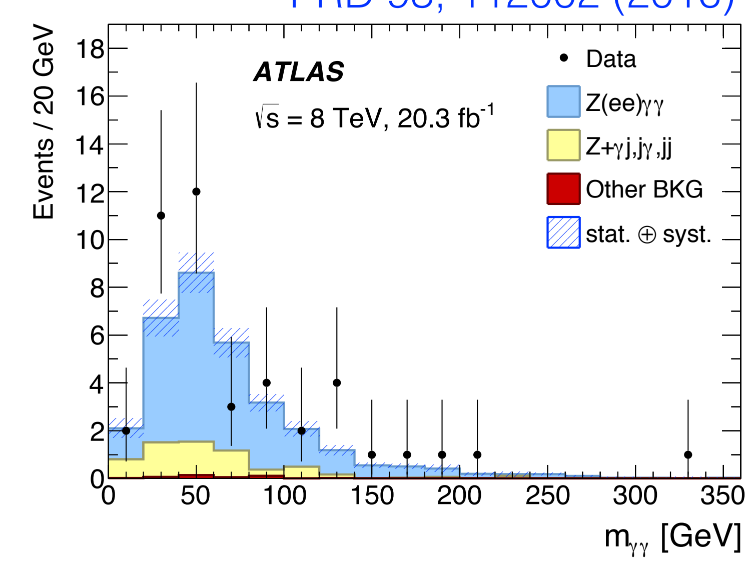
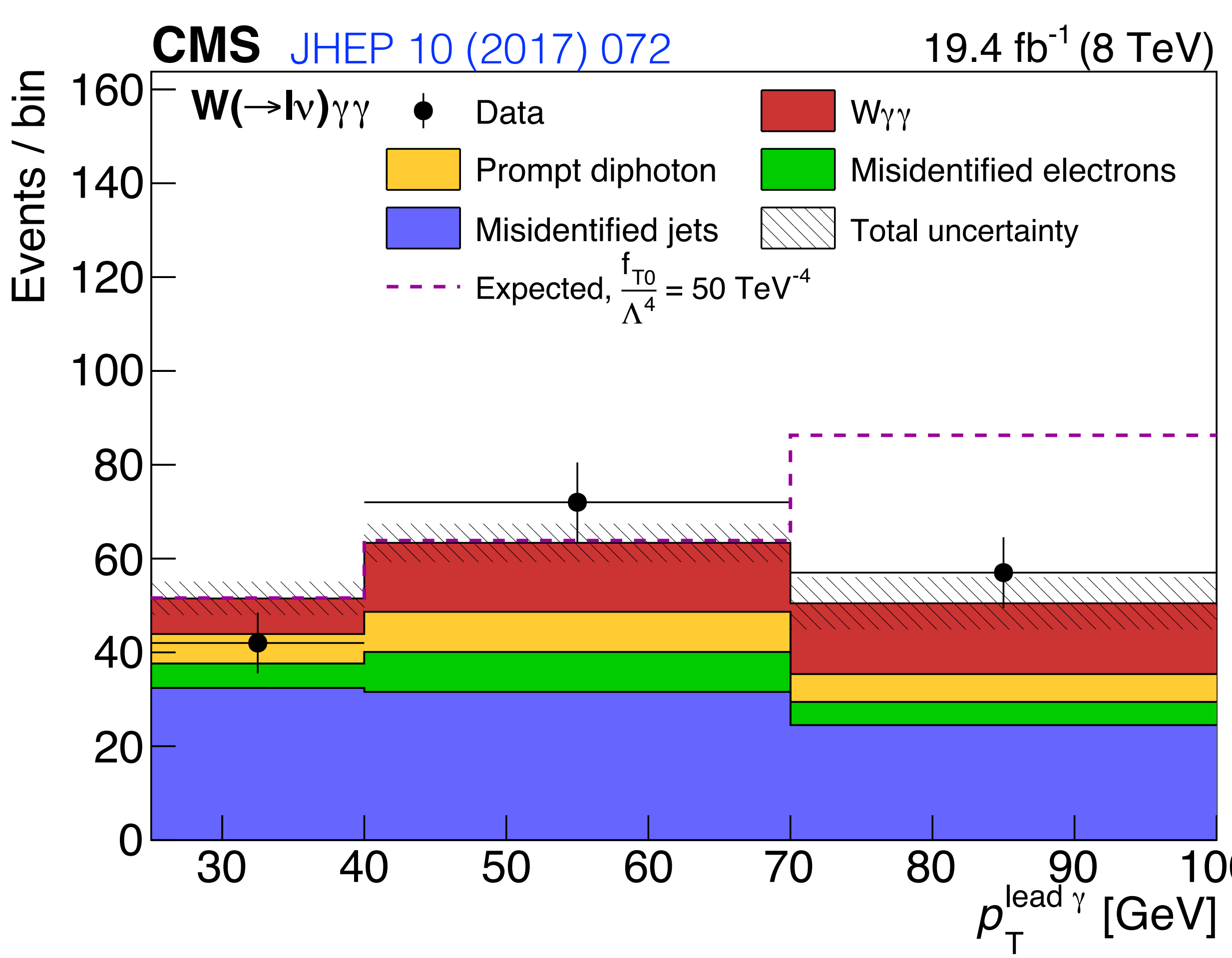


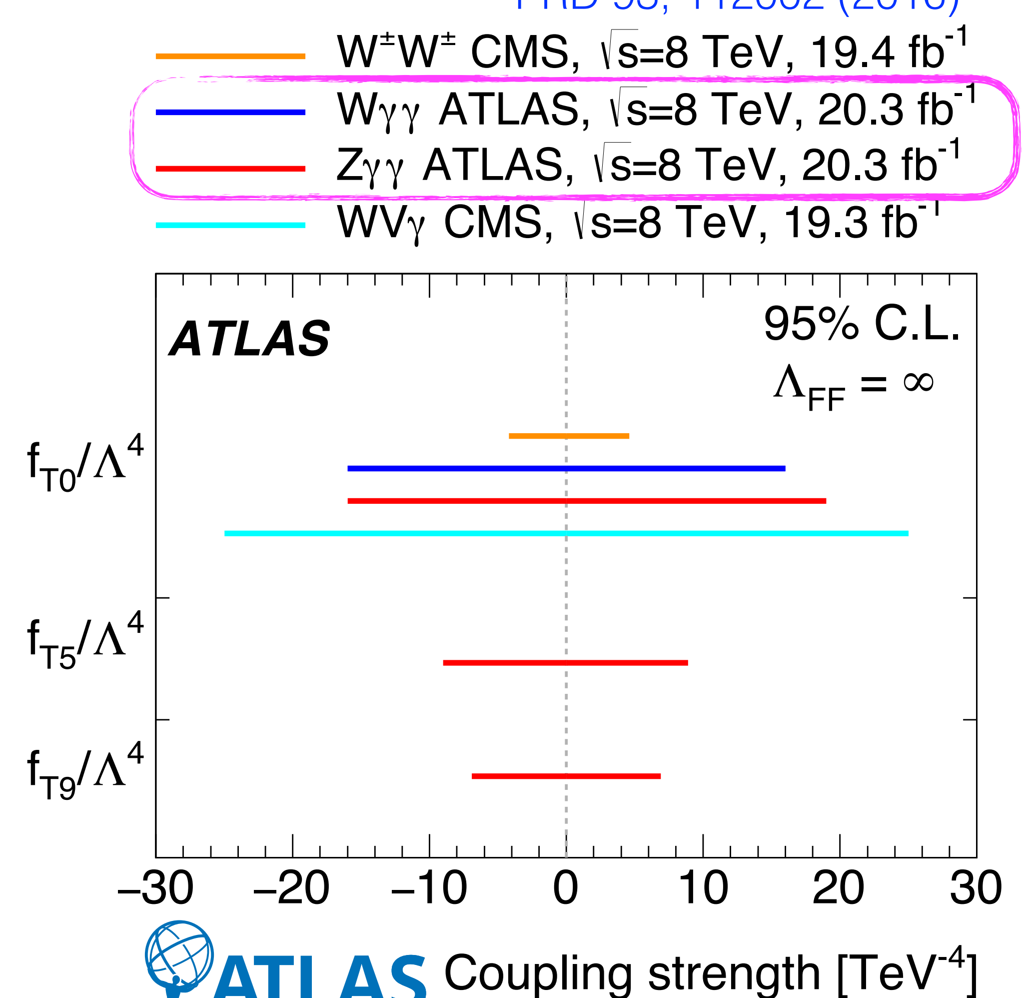

PRD 93, 112002 (2016)



# $V\gamma\gamma$ and aQGC

- No excess in $W\gamma\gamma$ observed in either experiment.
- Set limit on field strength $f_{T0,T5,T9,M2,M3}/\Lambda^4$ of aQGC with lowest-dimension (Dim-8) operators.



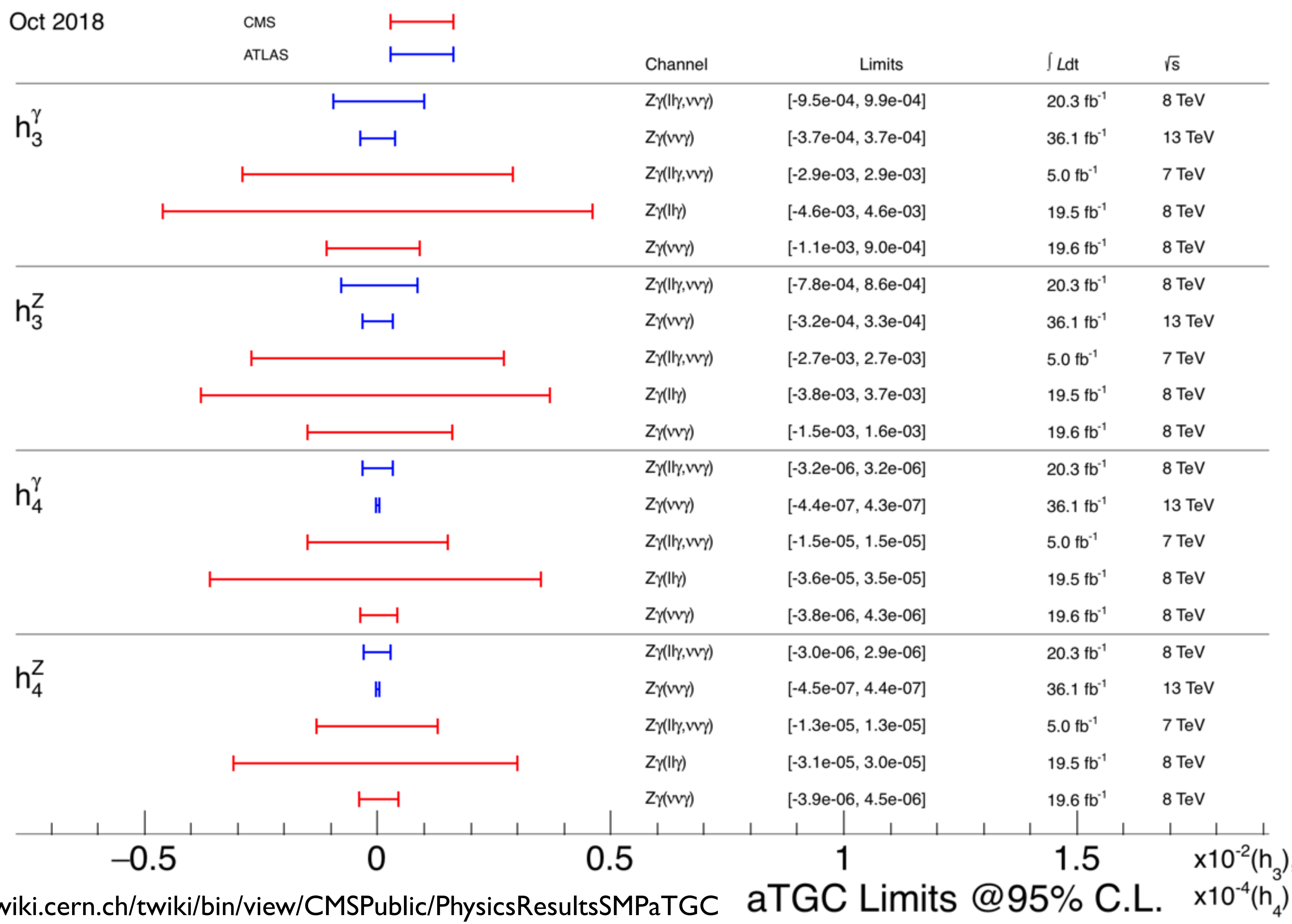
# Summary

- Both CMS and ATLAS have utilized the photon object to measure cross sections of $W\gamma/Z\gamma$ and $W\gamma\gamma/Z\gamma\gamma$ processes with different collision energies. Results are consistent with Standard Model expectation.
- Both experiments use conservative approaches to select photons (ID) and extract signals.
- $V\gamma(\gamma)$ measurements not only provide a test with Standard Model and also searches of anomalous triple/quartic gauge coupling which is expected to be 0 in Standard Model.

- Introduction
- LHC and CMS
- Isolated photon @ 7TeV
- Impact on PDF constraint
- Isolated photon @ 13TeV
- Summary

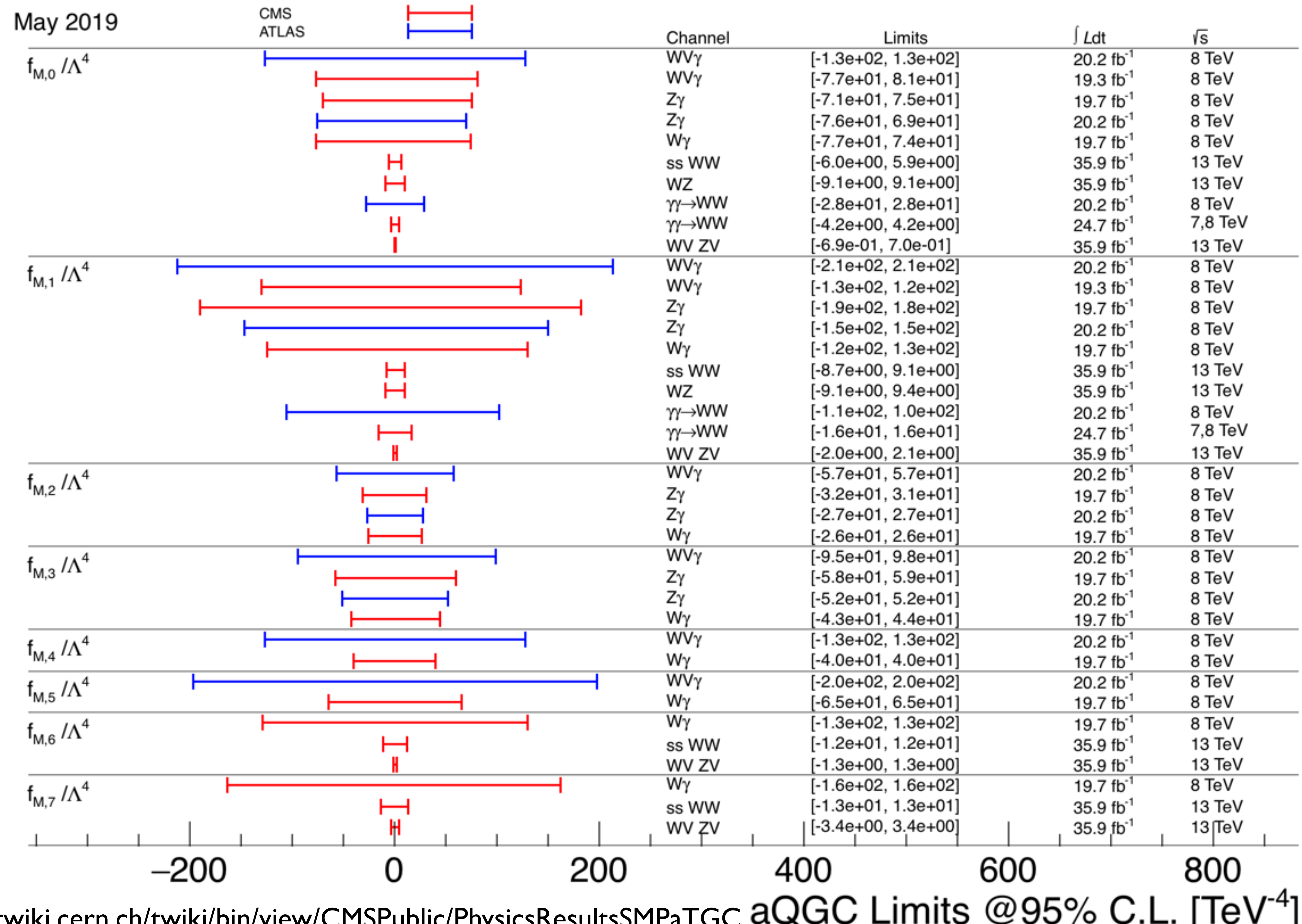
# Backup Slides

# Limits on neutral aTGC Zγγ and ZZγ couplings



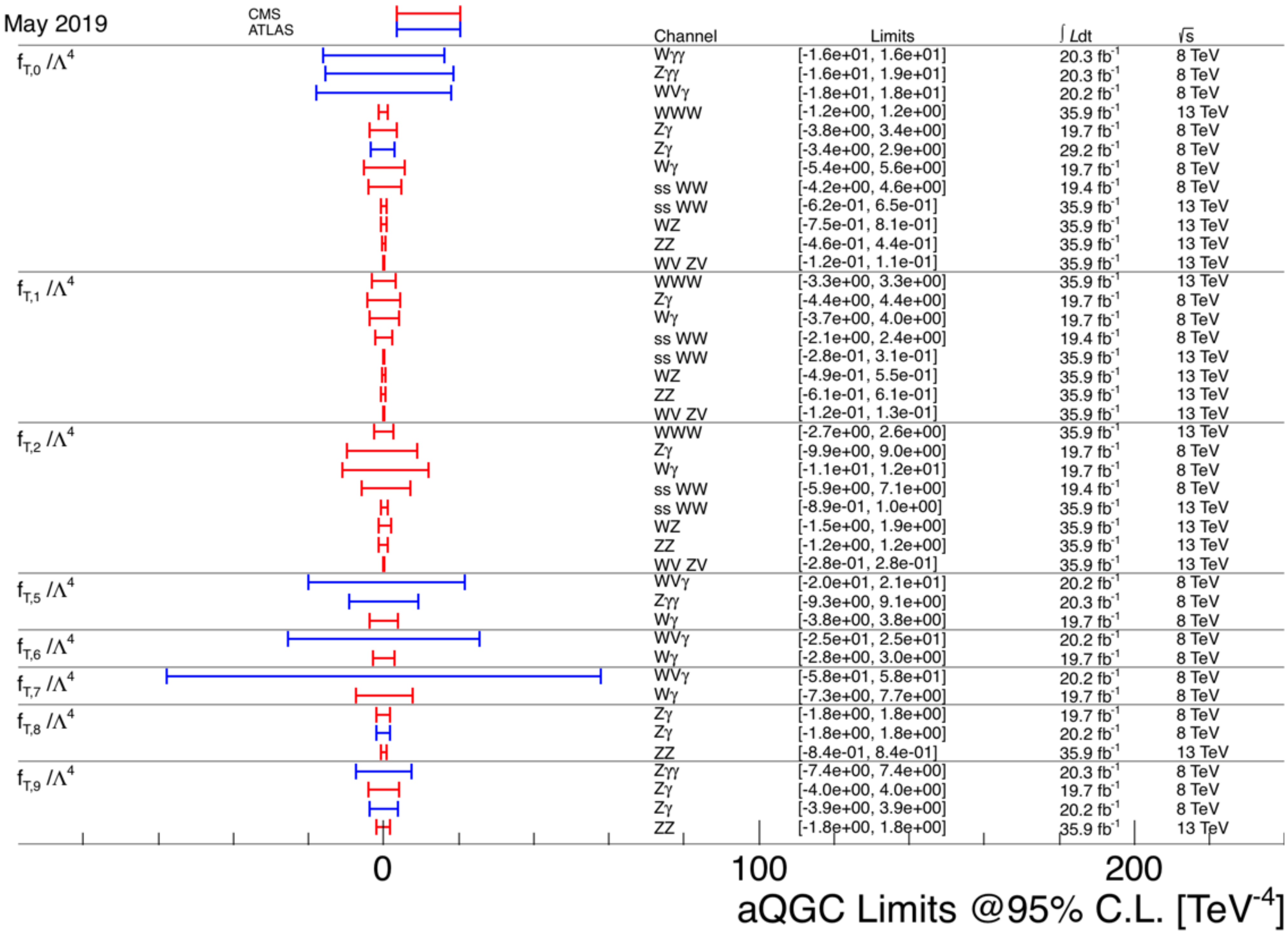

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

# limits on dimension 8 mixed transverse and longitudinal parameters $f_{M,i}$




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

# limits on dimension 8 transverse parameters $f_{T,i}$




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

# ATLAS photon ID

Table 1: Discriminating variables used for *loose* and *tight* photon identification.

| Category | Description | Name | *loose* | *tight* |
|---|---|---|---|---|
| Acceptance | $\lvert\eta\rvert < 2.37$, with $1.37 \le \lvert\eta\rvert < 1.52$ excluded | – | ✓ | ✓ |
| Hadronic leakage | Ratio of $E_T$ in the first sampling layer of the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $\lvert\eta\rvert < 0.8$ or $\lvert\eta\rvert > 1.52$) | $R_{\mathrm{had}_1}$ | ✓ | ✓ |
| | Ratio of $E_T$ in the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $0.8 < \lvert\eta\rvert < 1.37$) | $R_{\mathrm{had}}$ | ✓ | ✓ |
| EM middle layer | Ratio of the energy in $3 \times 7$ $\eta \times \phi$ cells over the energy in $7 \times 7$ cells centered around the photon cluster position | $R_\eta$ | ✓ | ✓ |
| | Lateral shower width, $\sqrt{(\Sigma E_i \eta_i^2)/(\Sigma E_i) - ((\Sigma E_i \eta_i)/(\Sigma E_i))^2}$, where $E_i$ is the energy and $\eta_i$ is the pseudorapidity of cell $i$ and the sum is calculated within a window of $3 \times 5$ cells | $w_{\eta_2}$ | ✓ | ✓ |
| | Ratio of the energy in $3 \times 3$ $\eta \times \phi$ cells over the energy of $3 \times 7$ cells centered around the photon cluster position | $R_\phi$ | | ✓ |
| EM strip layer | Lateral shower width, $\sqrt{(\Sigma E_i (i - i_{\mathrm{max}})^2)/(\Sigma E_i)}$, where $i$ runs over all strips in a window of $3 \times 2$ $\eta \times \phi$ strips, and $i_{\mathrm{max}}$ is the index of the highest-energy strip calculated from three strips around the strip with maximum energy deposit | $w_{s\,3}$ | | ✓ |
| | Total lateral shower width $\sqrt{(\Sigma E_i (i - i_{\mathrm{max}})^2)/(\Sigma E_i)}$, where $i$ runs over all strips in a window of $20 \times 2$ $\eta \times \phi$ strips, and $i_{\mathrm{max}}$ is the index of the highest-energy strip measured in the strip layer | $w_{s\,\mathrm{tot}}$ | | ✓ |
| | Energy outside the core of the three central strips but within seven strips divided by energy within the three central strips | $f_{\mathrm{side}}$ | | ✓ |
| | Difference between the energy associated with the second maximum in the strip layer and the energy reconstructed in the strip with the minimum value found between the first and second maxima | $\Delta E_s$ | | ✓ |
| | Ratio of the energy difference between the maximum energy deposit and the energy deposit in the secondary maximum in the cluster to the sum of these energies | $E_{\mathrm{ratio}}$ | | ✓ |
| | Ratio of the energy in the first layer to the to the total energy of the EM cluster | $f_1$ | | ✓ |

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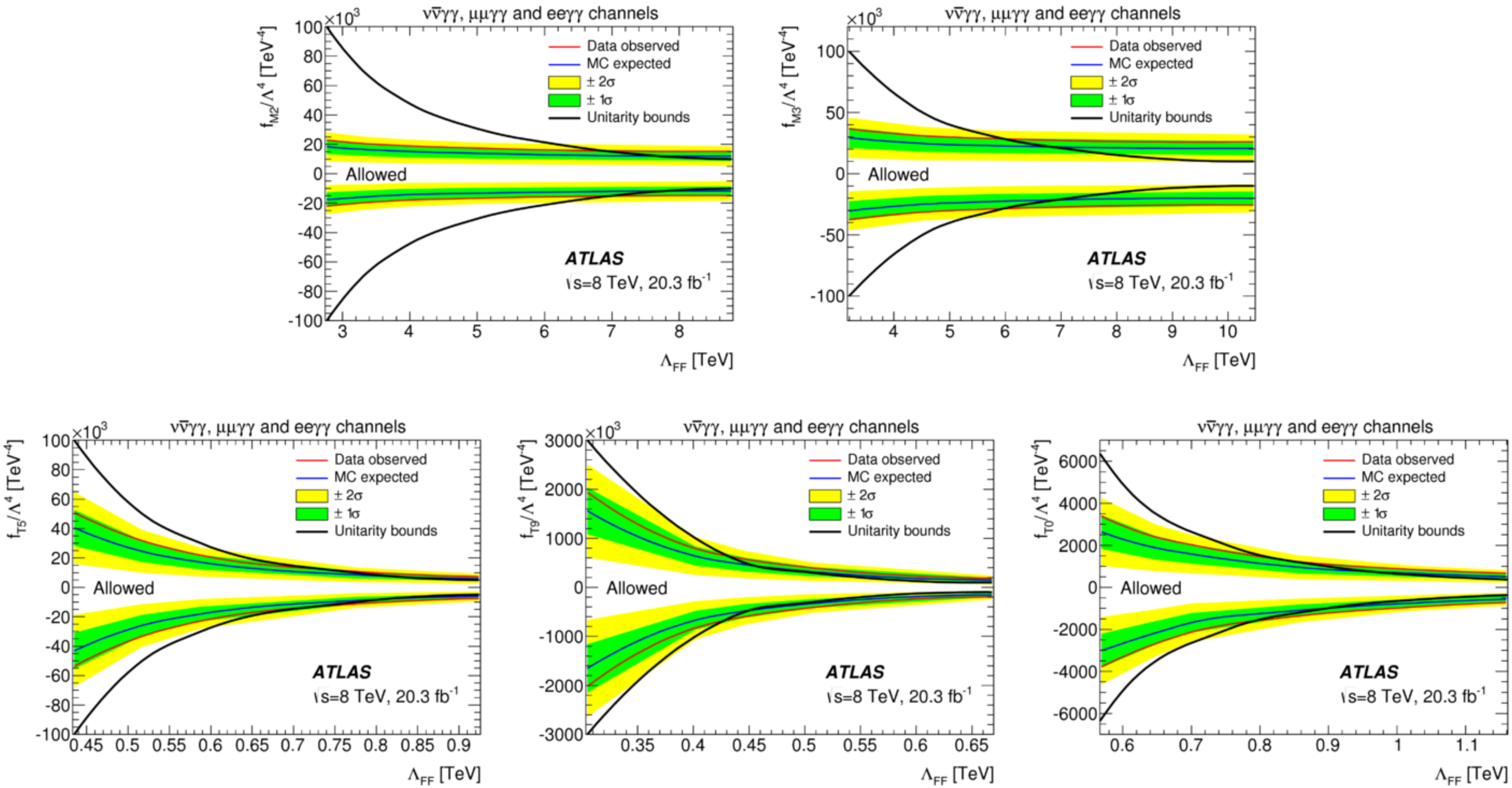
# Zγγ aQGC limit

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# ECAL Energy Resolution

- The energy resolution of a calorimeter is usually parametrized as:
  $\sigma_E / E = a/\sqrt{E} \oplus b/E \oplus c$ (where $\oplus$ denotes a quadratic sum)
- The first term, with coefficient a, is the stochastic term arising from contribution of shower containment, fluctuations in the number of signal generating (gain) processes (and any further limiting process, such as photo-electron statistics in a photodetector)
- The second term, with coefficient b, is the noise term and includes:
  - noise in the readout electronics
  - fluctuations in 'pile-up' (simultaneous energy deposition by uncorrelated particles)
- The third term with coefficient c, is the constant term and includes:
  - imperfections in calorimeter construction (dimensional variations, etc.)
  - non-uniformities in signal collection
  - channel to channel inter-calibration errors
  - fluctuations in longitudinal energy containment
  - fluctuations in energy lost in dead material before or within the calorimeter
- The goal of calorimeter design is to find, for a given application, the best compromise between the contributions from the three terms
- For EM calorimeters, energy resolution at high energy is usually dominated by c