Direct photons at CMS

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On behalf of the CMS collaboration

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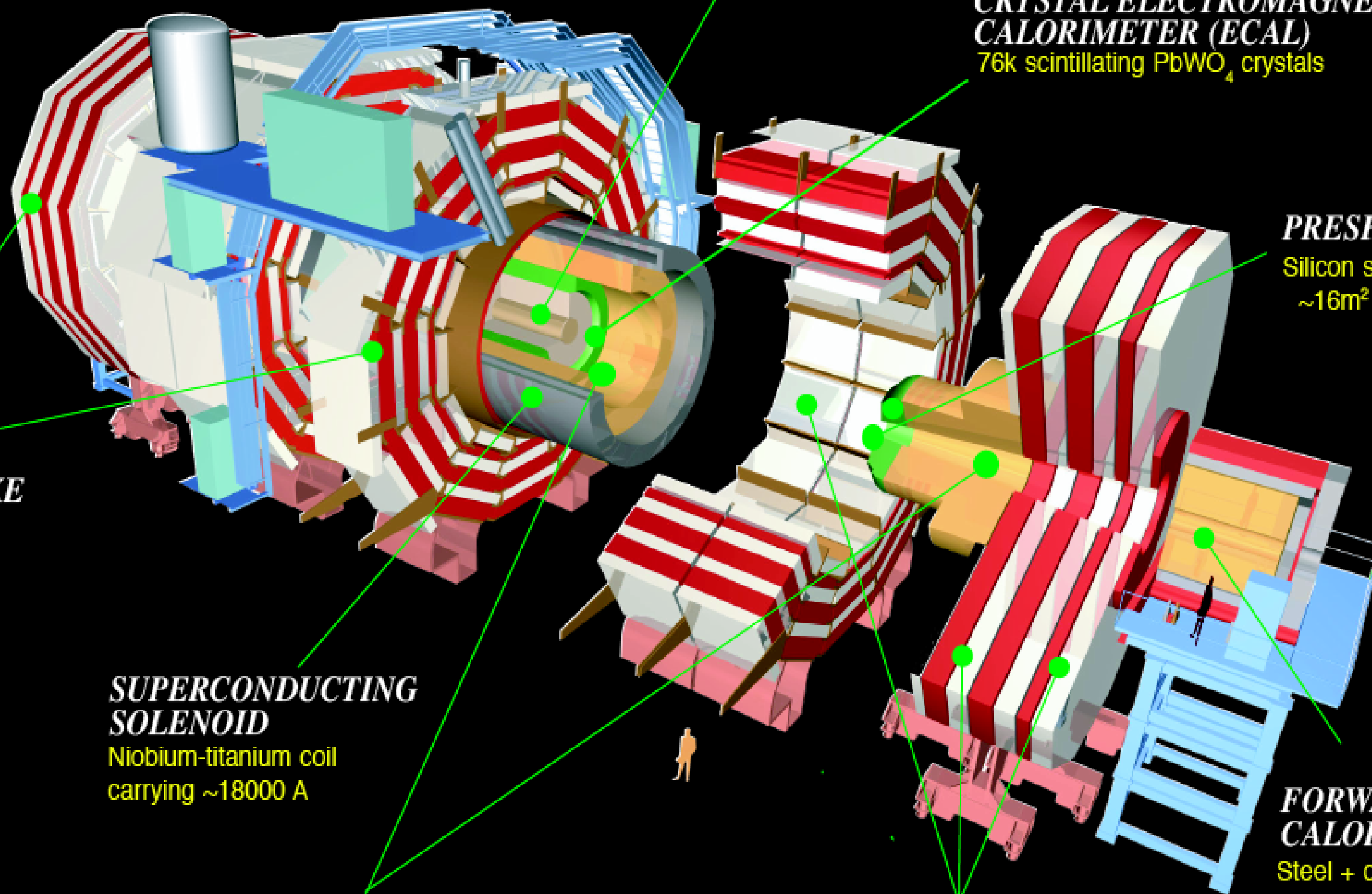
Introduction

- Photon production in p-p collision motivation:
  - Test of pQCD
  - Probing of gluon parton distribution function
  - Background study of Higgs→$\gamma\gamma$
- Outline:
  - CMS detector and photon reconstruction
  - Inclusive direct photon production
  - Direct diphoton production
  - A closure look at the isolation criteria

CMS Detector

HCAL |η| < 5
ECAL |η| < 3.0
Tracker |η| < 2.5
Muons |η| < 2.4

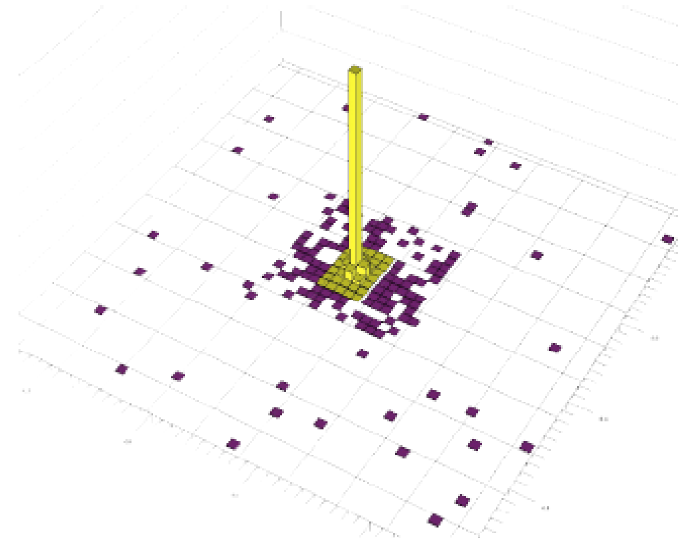
Measurement made within Tracker acceptance |η| < 2.5

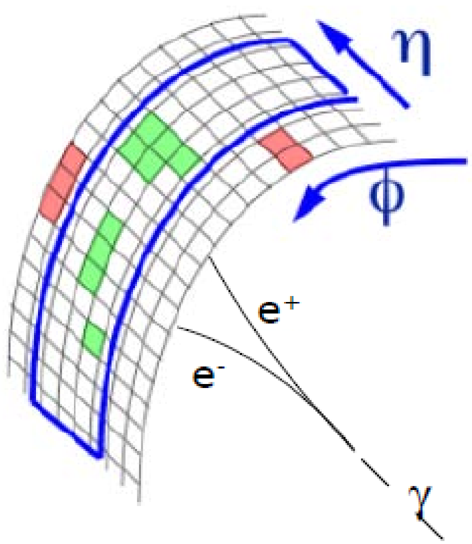


Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Photon reconstruction

- Photons reconstructed through energy deposited in ECAL.
- The presence of material in front of ECAL causes photons to convert in e^+e^- pairs (up to 70 % in region with largest material).
  - ➔ will be exploited for the inclusive direct photon cross-section measurement
- The 3.8 T solenoidal magnetic field leads the energy to be spread along ϕ
  - Energy spread in ϕ direction is clustered.
- Same algorithm used for the trigger





- Prompt electrons rejected by applying a veto with the pixel detector.

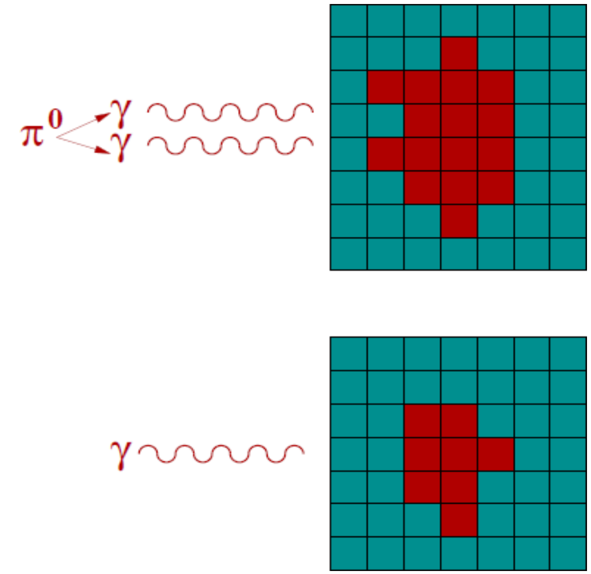
Inclusive direct photon production

Phys. Rev. D84 052011 (2011)

Phys.Rev.Lett. 106 (2011) 082001

Measurement

- Signal:
  - photon with ΣE_T of the particles surrounding it within a cone $R=\sqrt{\Delta\varphi^2+\Delta\eta^2} = 0.4$, smaller than 5 GeV.
- Background
  - Mainly pairs of collinear photons from π^0 and η decays, reconstructed as a single photon
    - rejection based on isolation and on ECAL shower transverse shape.
    - remnant statistically substracted
- Measurement performed in 4 η–bins and 15 E_T bins.



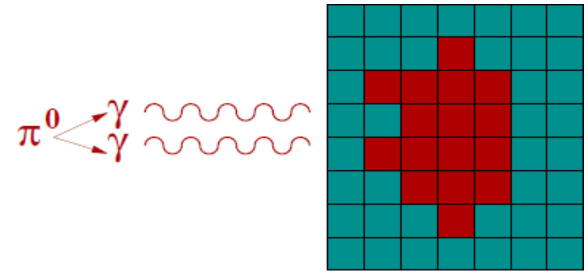
$$\frac{d^2\sigma_{isol}}{d\eta\, d p_T} = \frac{\Delta N_S(p_T,\eta)}{L\cdot\Delta p_T \Delta\eta\cdot U\cdot\epsilon}$$

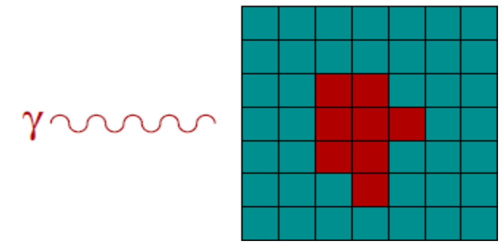
- $\Delta N_S(p_T,\eta)$: Signal event yield
- $U\cdot\epsilon$: Unfolding x efficiency
- $\Delta p_T \Delta\eta$: Bin width
- L: Luminosity

- Combines **two methods**
  - Conversion method, exploiting converted photon, competitive at low E_T range
  - Isolation method, using all photons, competitive at higher E_T range

Event selection

- Trigger requiring one photon candidate with $E_T > E_T^{threshold}$.
  $E_T^{threshold}$ raised with LHC luminosity:
  20, 30, 50, and 70 GeV
  - Trigger efficiency for events selected by the analysis: 99.8 ± 0.1 % in the barrel, 99.0 ± 0.7 % in the endcap
- Photon identification:
  - Spread extension along η of energy deposited in ECAL required to be compatible with a single photon shower.
  - Requiring the energy deposited by the photon candidate in HCAL to be less that 5% than the energy deposited in the ECAL
  - $e^{+/-}$ veto
- Isolation, defined in a cone R < 0.4
  - ΣE_T in ECAL
  - ΣE_T in HCAL
  - Σp_T of charged particles measured in the tracker
  - Combined variable defined as the sum of the 3 above variables

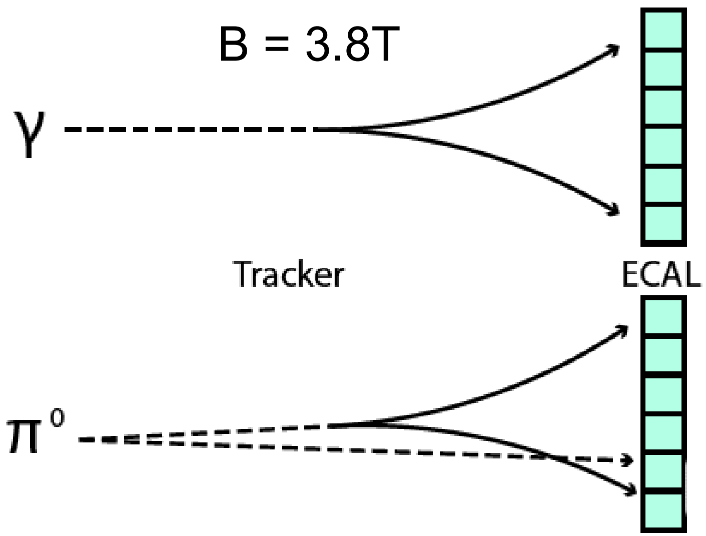




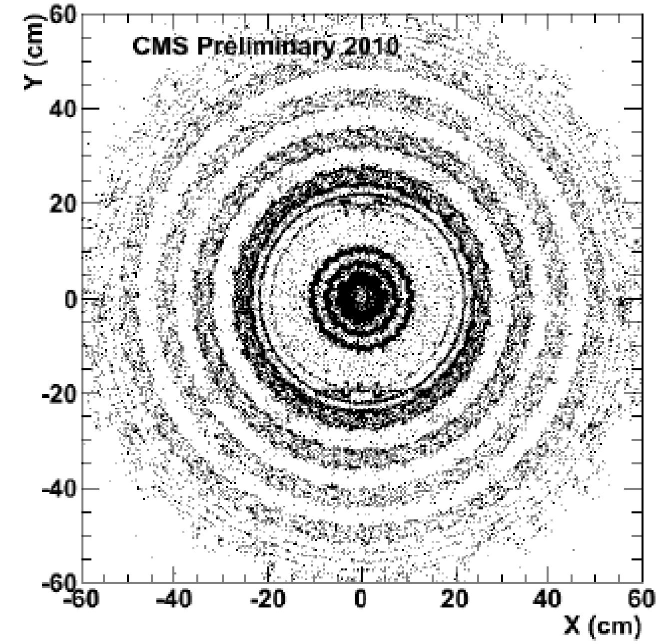
Veto applied on the 3 variables in the conversion method

Used to extract the signal yield in the isolation method

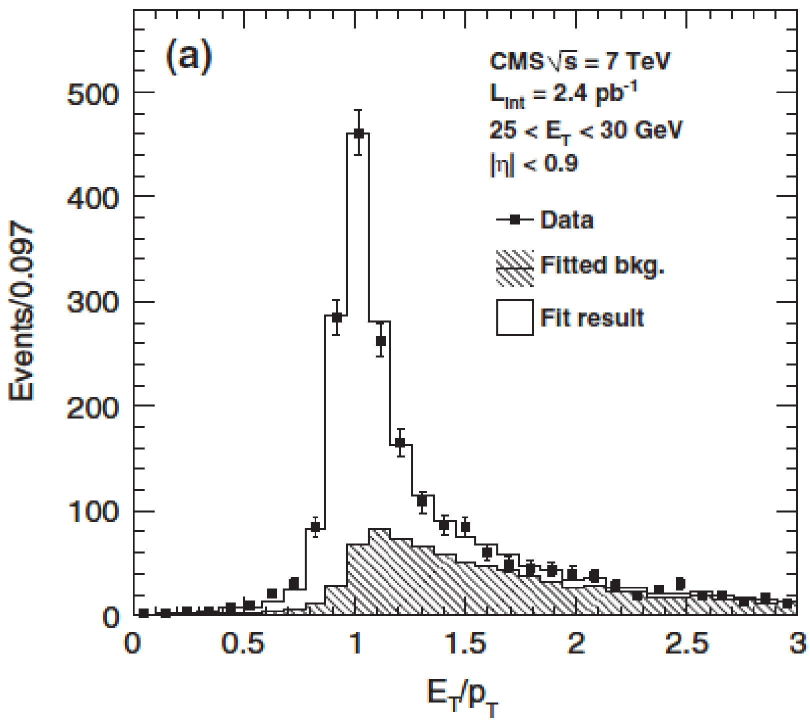
Photon conversion method



- E_T/p_T =1 for photons
- More likely only 1 leg of π^0 converts
  - E_T/p_T > 1



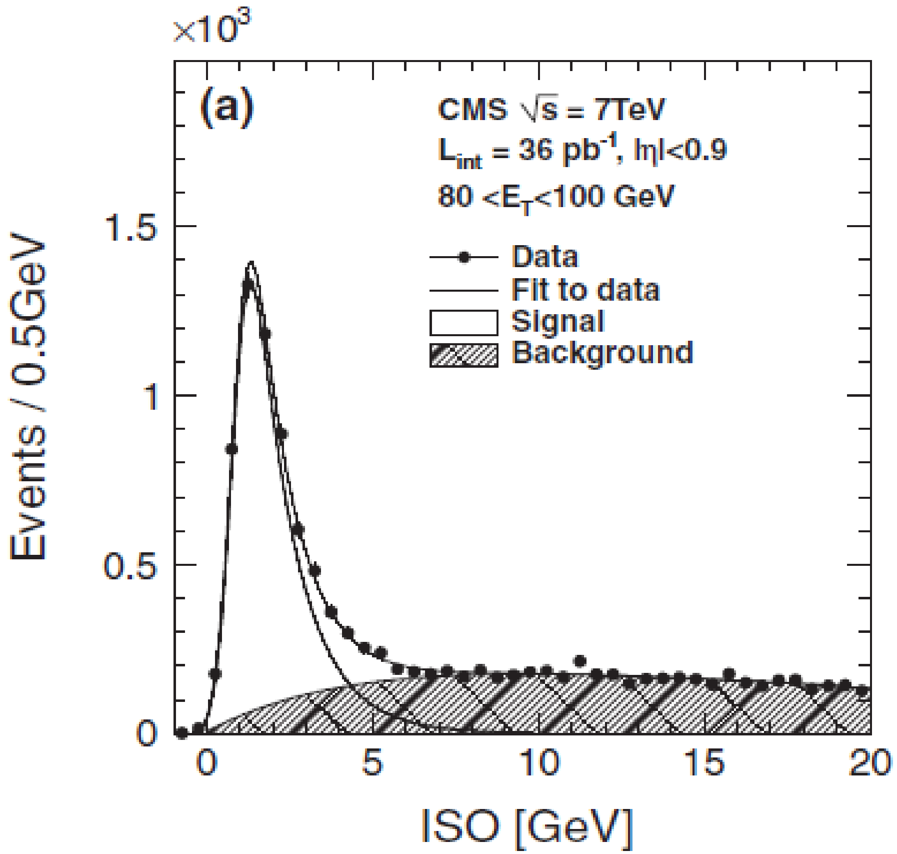
Tracker tomography with converted γ



- Fit of signal and background yield performed on E_T/p_T distribution
- PDF used for the fit obtained from the Monte Carlo simulation.
  - Background PDF uncertainties estimated by comparing with PDF obtained with a side-band control sample.
  - Signal PDF uncertainties estimated by varying the PDF peak position and width

Isolation method

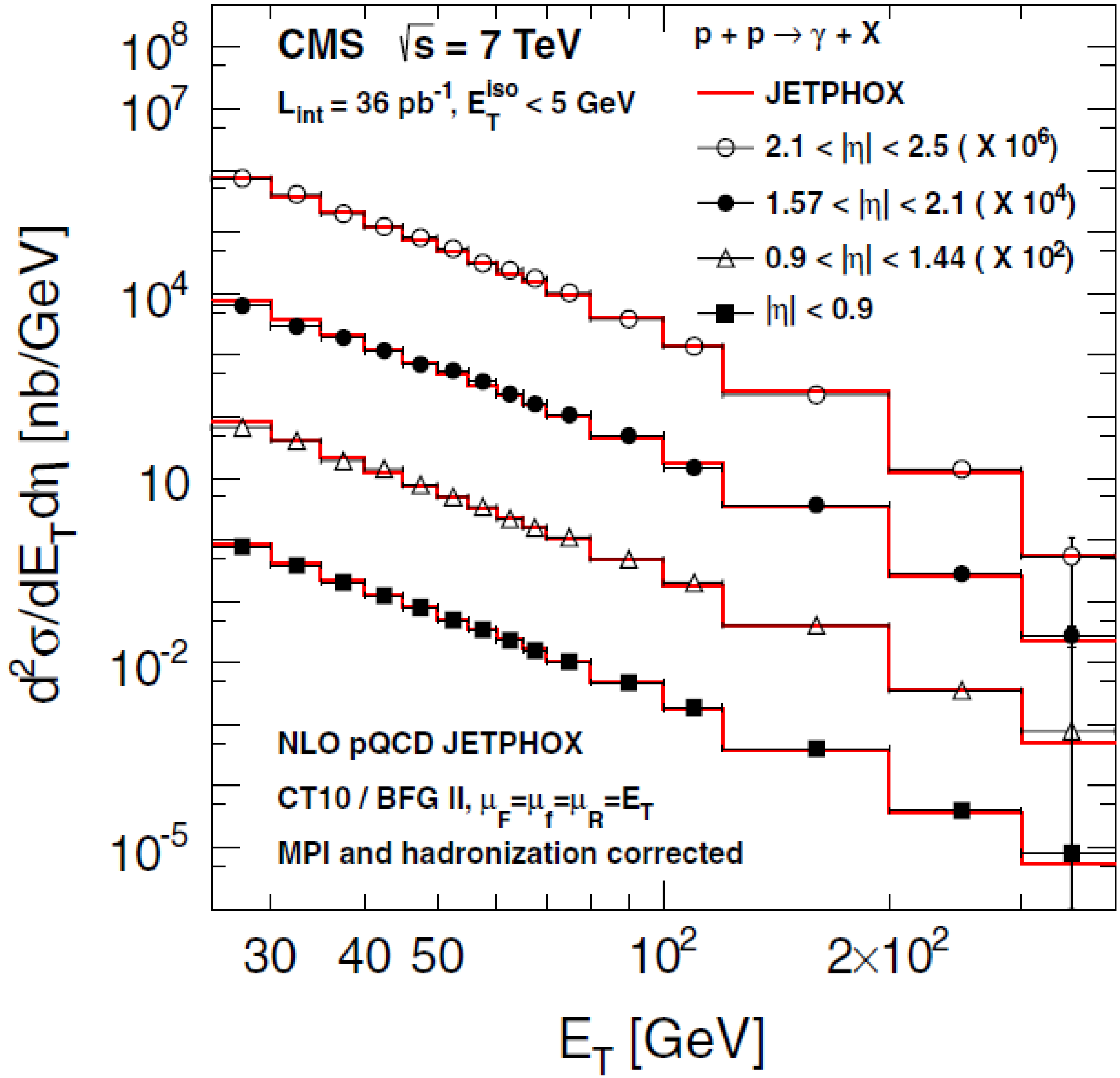
- Uses the sum of the three isolation variable as discriminant observable.
- PDF parametrized with analytic functions
  - Signal: $e^{a x} \otimes \mathrm{Gauss}(\mu,\sigma,x)$
  - Background: $(1-p1(x-p0))^{p2} \times (1-e^{p3(x-p0)})$
  - parameters are either let free in the fit or constrained by corrected MC and control samples:
    - $Z \rightarrow e^{+}e^{-}$ for signal
    - Sample from a side-band region



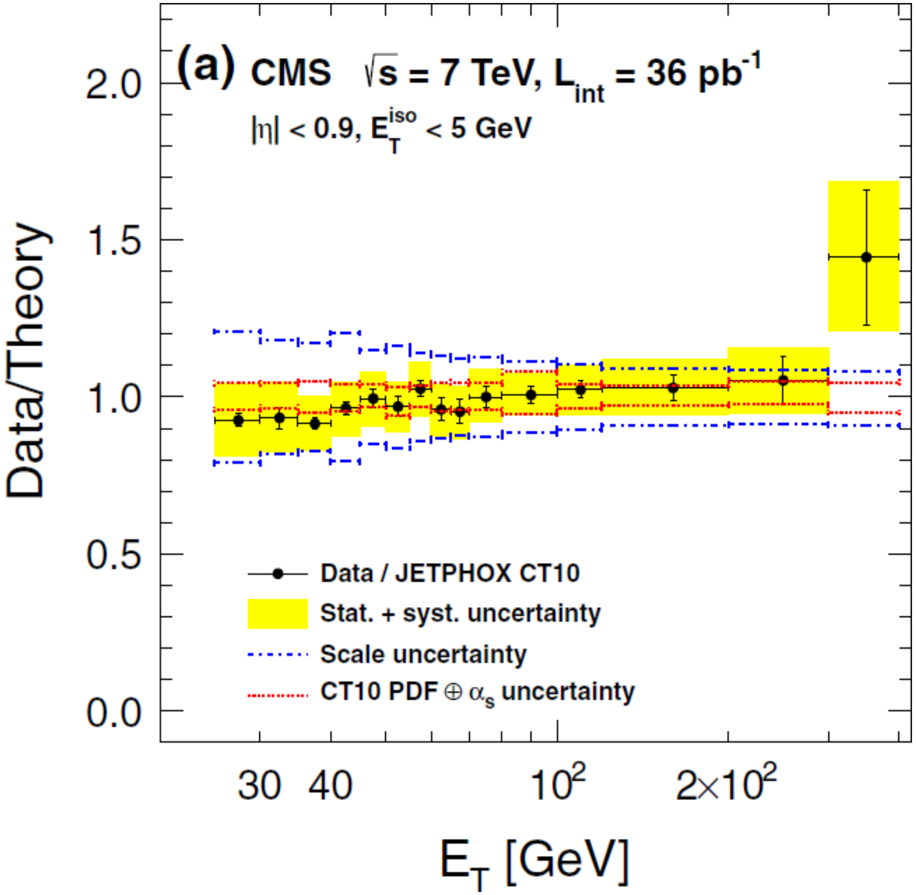
- Systematic errors from PDF limited knowledge estimated from toy MCs by varying the parameters within their respective errors.

Results: isolated prompt photon cross section

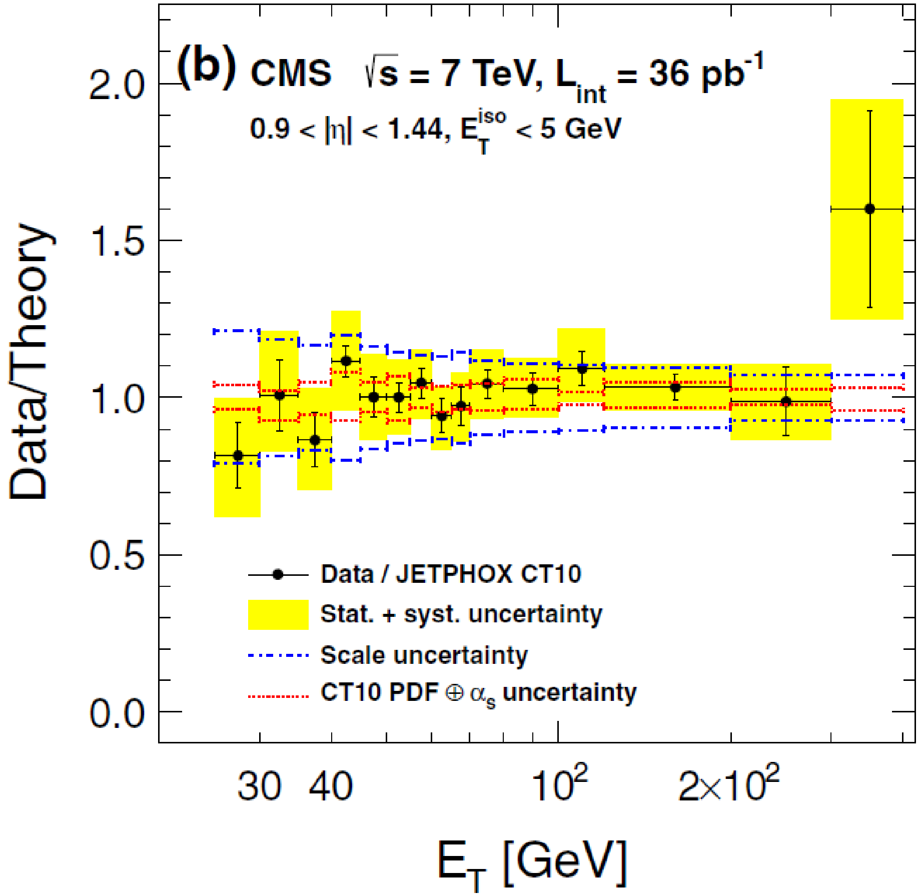
Results of the two methods are combined using the Best Linear Unbiased Estimate method



Comparison with theory

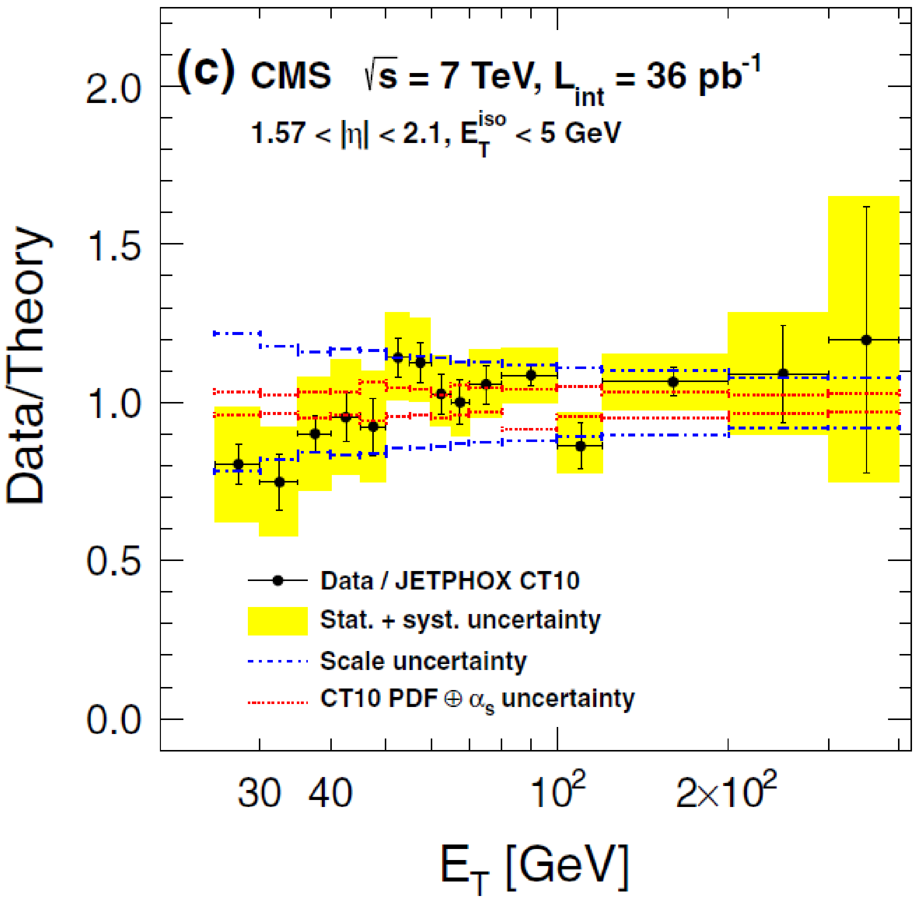


0 < |η| < 0.9

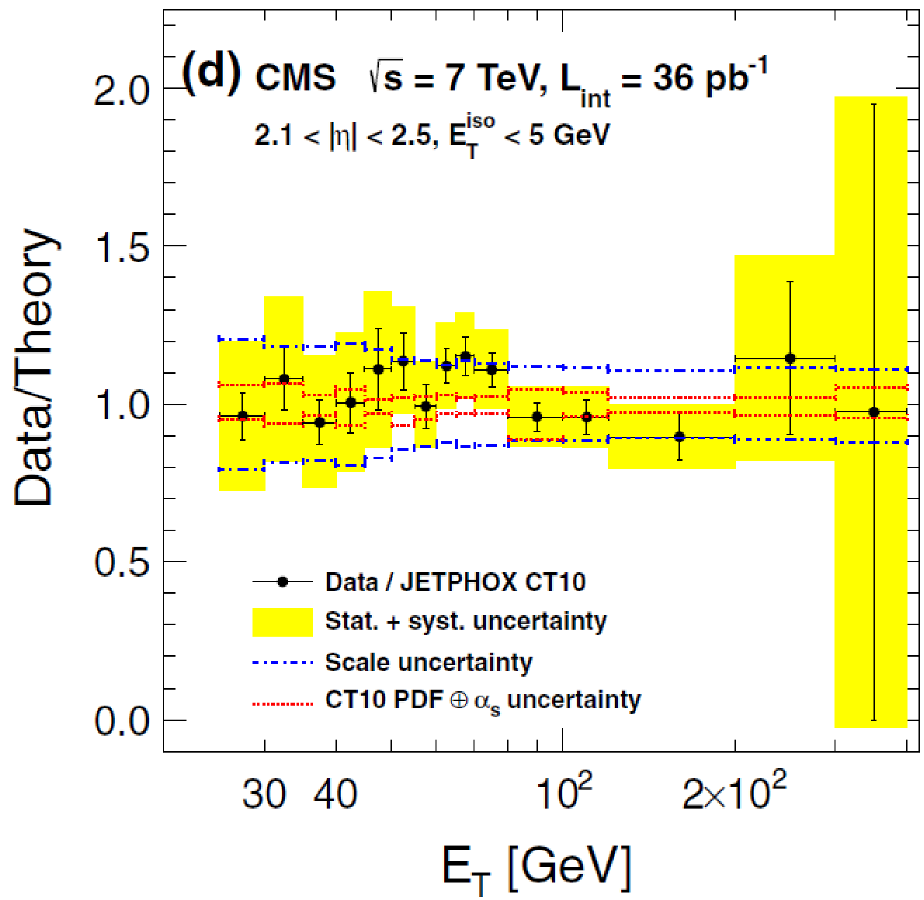


0.9 < |η| < 1.44

Comparison with theory



$1.57 < |\eta| < 2.1$



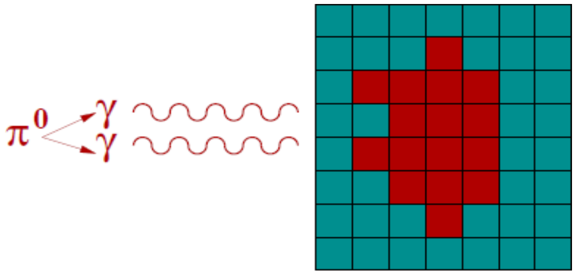
$2.1 < |\eta| < 2.5$

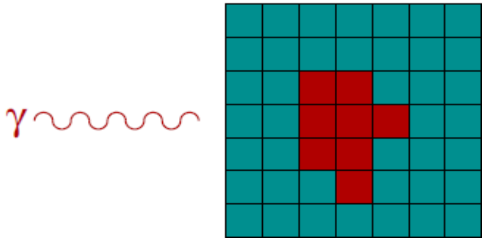
Direct diphoton production

JHEP 1201 (2012) 133

Measurement

- Measurement signal: two *signal photons*
- Measurement background:
  - Two *background photons*, 1 *background* + 1 *signal photon*.
  - Drell-Yan: subtracted (POWHEG NLO + PS + full simulation)
- Signal photon:
  - photon with ΣE_T of the particles surrounding it within a cone $R=\sqrt{\Delta\varphi^2+\Delta\eta^2} = 0.4$, smaller than 5 GeV.
- Background photon:
  - Mainly pairs of collinear photons from π^0 and η decays, reconstructed as a single photon
    - rejection based on isolation and on ECAL shower transverse shape.
    - remnant statistically substracted





- Measurement of differential cross sections as function of $m_{\gamma\gamma}$, $p_{T,\gamma\gamma}$, $\Delta\varphi_{\gamma\gamma}$, $\cos\theta^* = \tanh(\Delta y_{\gamma\gamma}/2)$ in two pseudorapidity regions:

$$|\eta| < 1.44 \quad \text{and} \quad |\eta| \text{ in } [0, 1.44] \cup [1.56, 2.5]$$

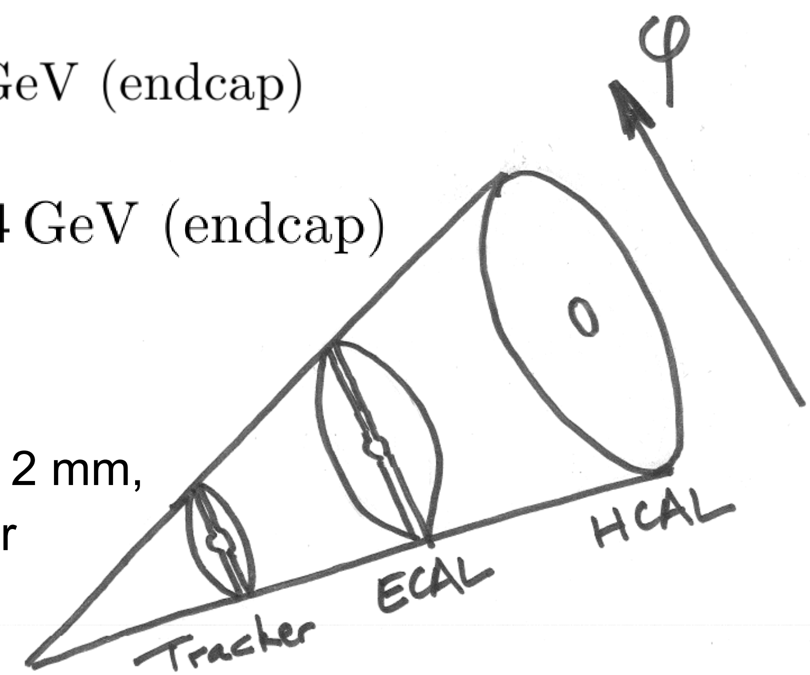
$$\frac{d\sigma}{dX}(X_i) = \frac{N^{U}_{\gamma\gamma}(X_i)}{\mathcal{L}\,\Delta X_i\,\mathcal{C}(X_i)}$$

- $N^{U}_{\gamma\gamma}(X_i)$: Unfolded signal event yield
- $\mathcal{C}(X_i)$: Acceptance x efficiency correction
- ΔX_i: Bin width
- $\mathcal{L}$: Luminosity

Event selection

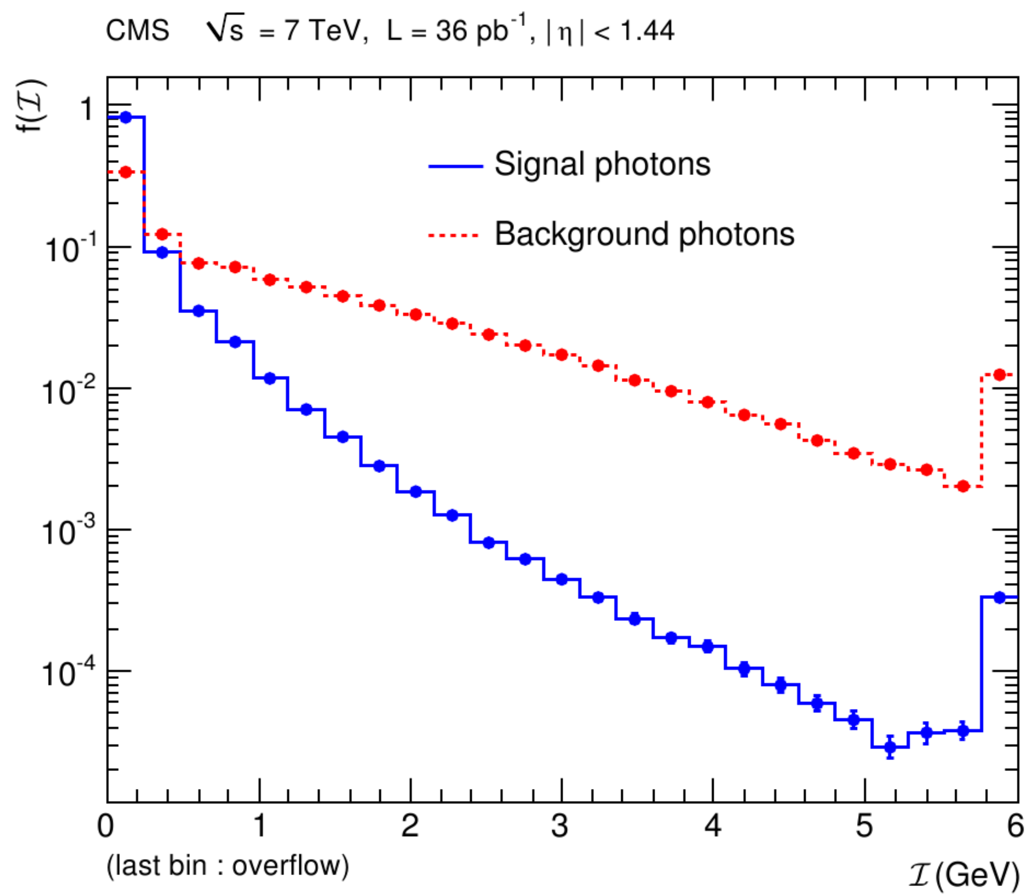
- Two isolated photons with E_T > 23, 20 GeV
- Photon separated by R > 0.45 (mutual isolation exclusion)
- Photon identification:
  - Spread extension along η of energy deposited in ECAL required to be compatible with a single photon shower.
  - HCAL photon deposit < 5% of ECAL photon deposit (in R < 0.15)
- Photon isolation:
  - ECAL: $\sum_{\substack{0.06 \lesssim R < 0.3 \\ \Delta\eta \gtrsim 0.04}} E_T < 0.2\, E_T(\gamma)$ (for trigger)
  - HCAL: $\sum_{0.15 < R < 0.4} E_T < 2\,\mathrm{GeV}\ \mathrm{(barrel)}, 4\,\mathrm{GeV}\ \mathrm{(endcap)}$
  - Tracker: $\sum_{\substack{0.04 < R < 0.4 \\ \Delta\eta > 0.015}} p_T < 2\,\mathrm{GeV}\ \mathrm{(barrel)}, 4\,\mathrm{GeV}\ \mathrm{(endcap)}$

  and no track with: R < 0.4, p_T > 3 GeV,
  impact parameter d_0, d_z < 1, 2 mm,
  with one hit in first pixel layer
  (called *impinging* track)



Signal and background PDFs

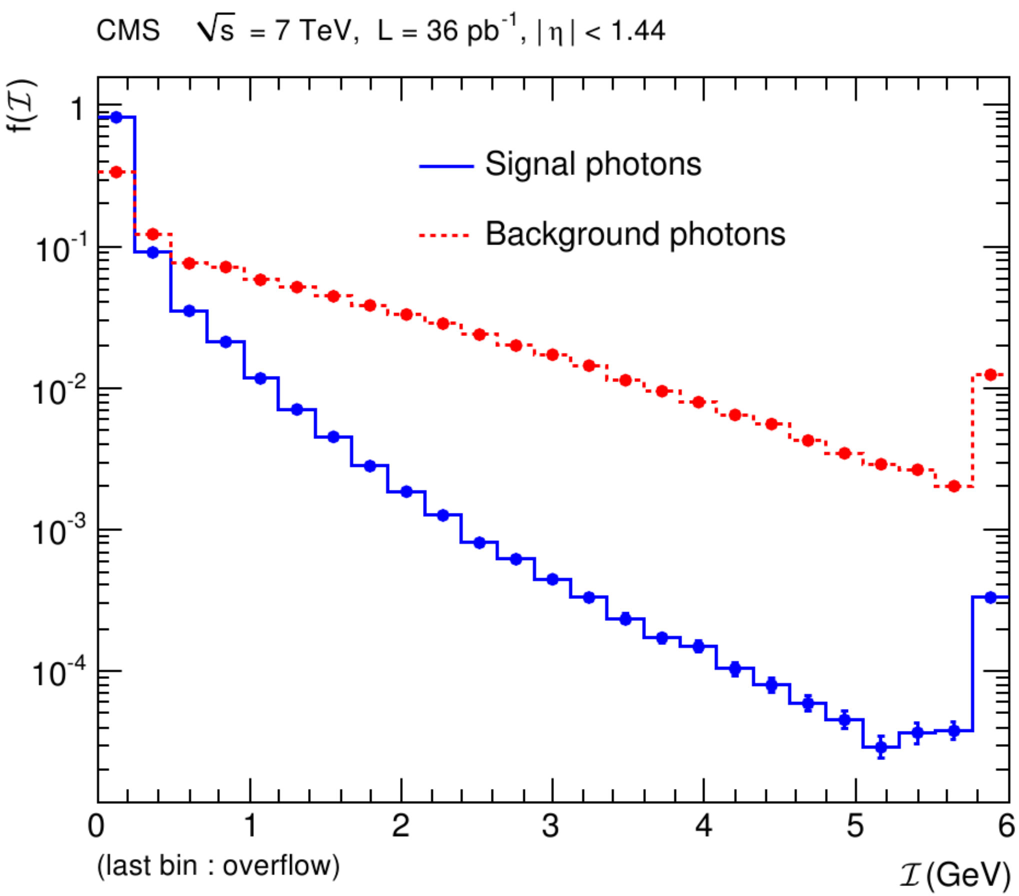
- Background statistically subtracted using an ECAL isolation variable distribution of individual photons.
  - Threshold applied to exclude MIPs from the isolation variable sum
- Probability density function (PDF) extraction:
- **Signal photon**: deposits in isolation area due to pile-up and underlying events
  - Uses ***random cone technique***: isolation calculated from an inclusive photon sample around a "random" direction: at $\pi/2 \pm \pi/4$ from photon in azimuth and at same η



- Systematic uncertainty on the PDF estimated by comparing with the PDFs obtained with three alternative methods: electrons from W, electrons from Z and MC

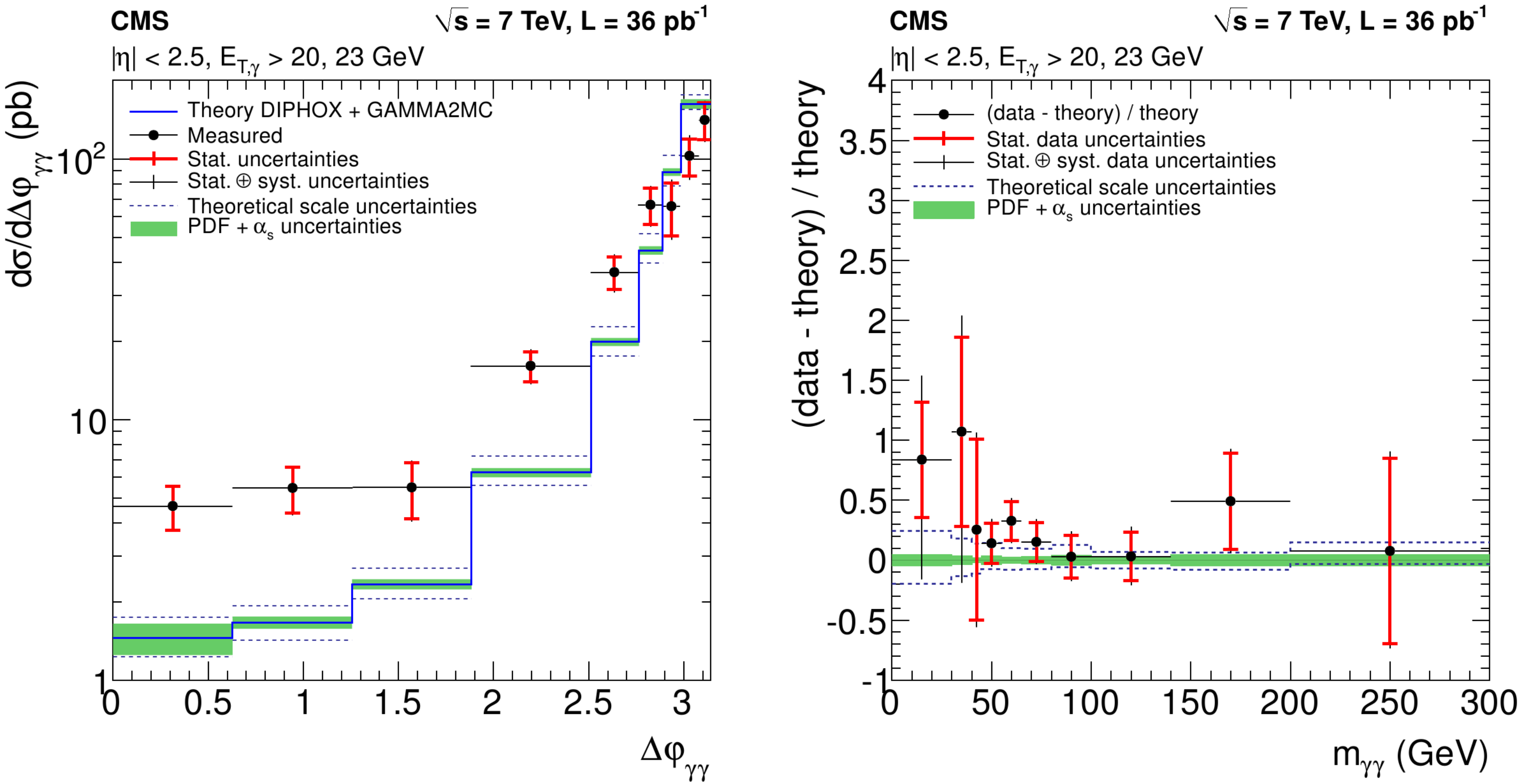
Signal and background PDFs

- Background photon: ***impinging track*** method
- Photon background sample obtained by one charged particle within R < 0.4 around the photon candidate tagged by a reconstructed track issued from the primary vertex
  - measurement sample: no track
  - control sample for background photon PDF extraction: one track
- The ECAL isolation is corrected for the energy deposited by the charge particle (deposited energy not counted in the transverse energy sum)

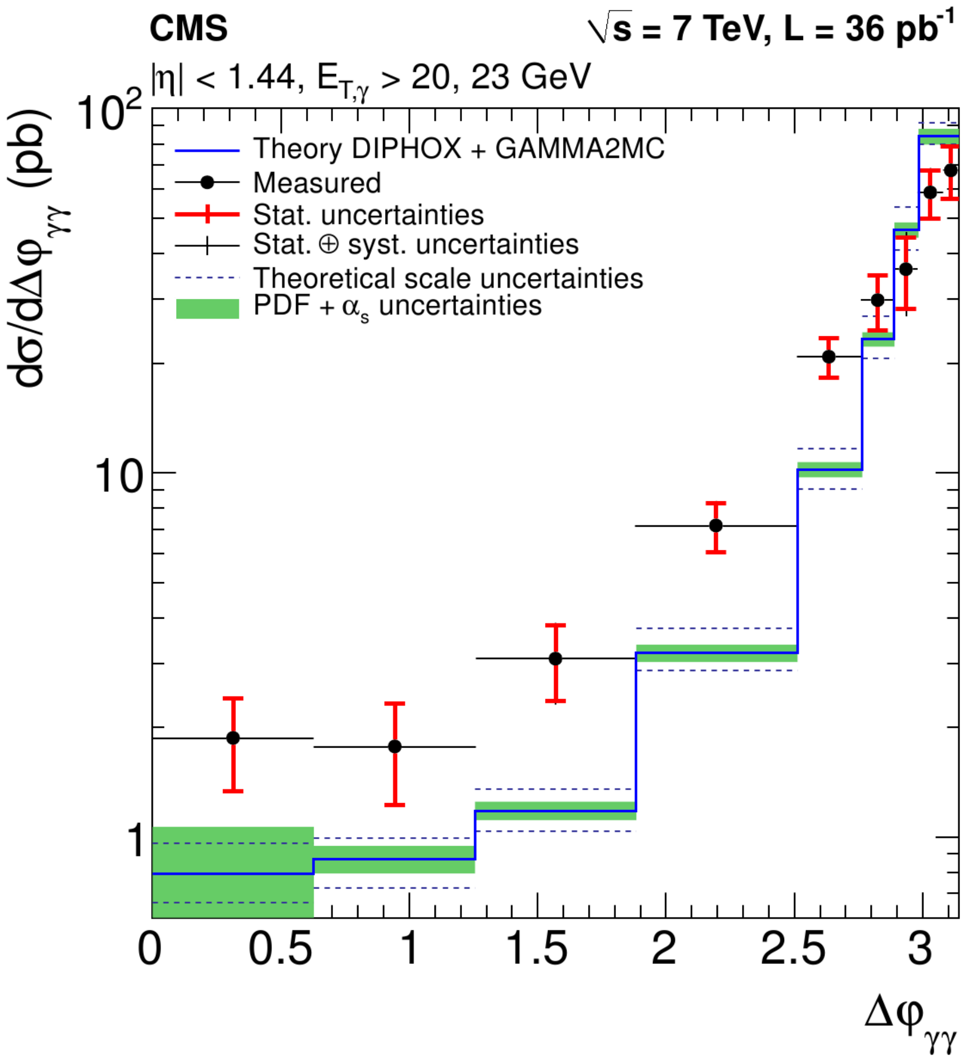


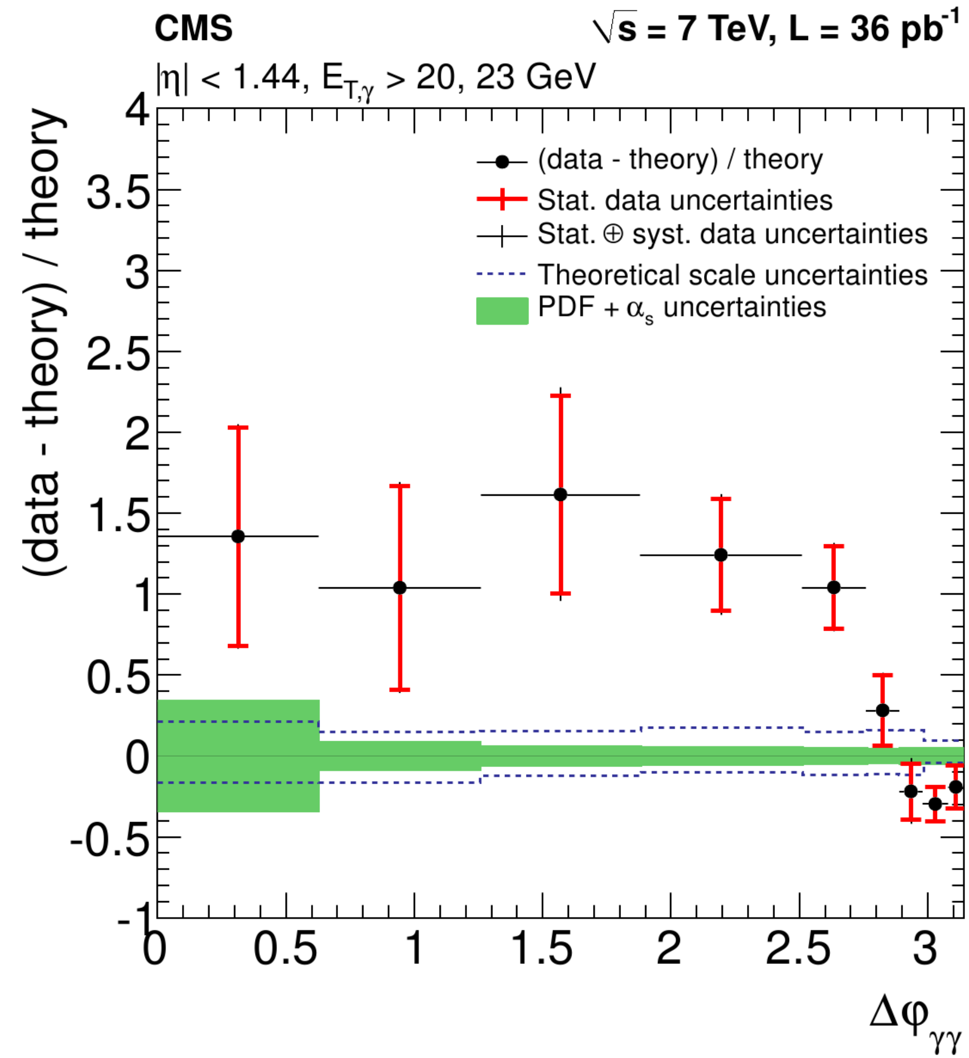
- Systematic uncertainty on the probability density function (PDF):
  - same method applied to extract PDF of one-impinging track events from a two-impinging track sample. Uncertainty estimated by comparing the direct PDF and the one extracted from the two-impinging track method.
  - also estimated from comparison with the simulation

Diphoton: azimuthal angle between the two photons

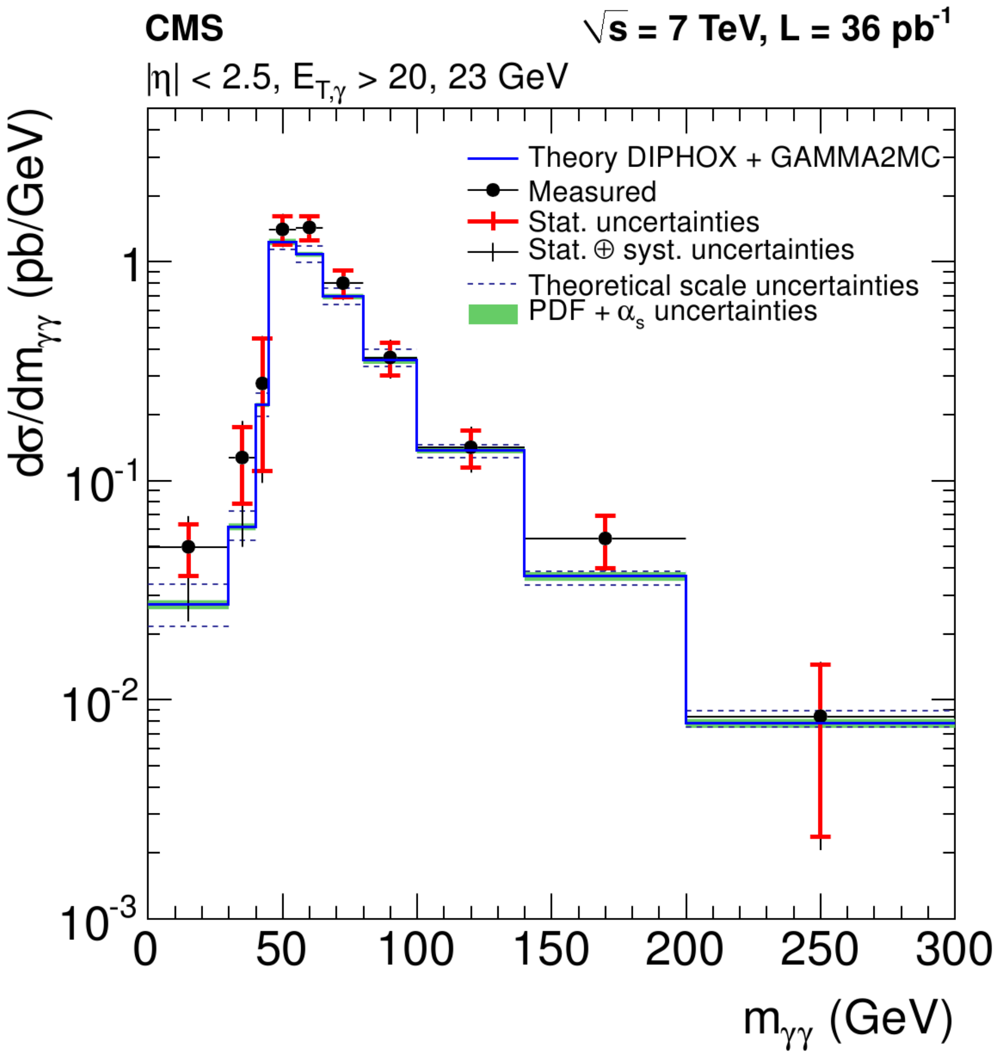


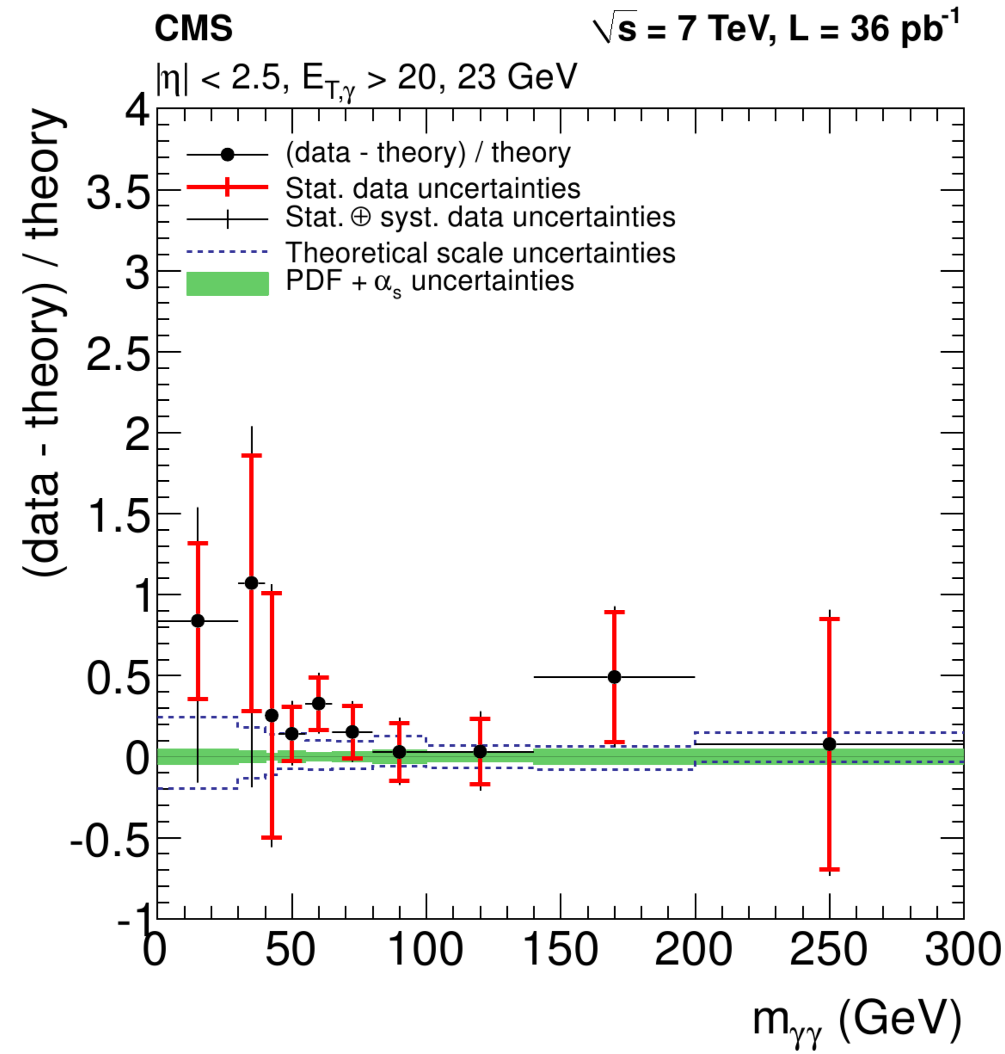
Diphoton: azimuthal angle between the two photons



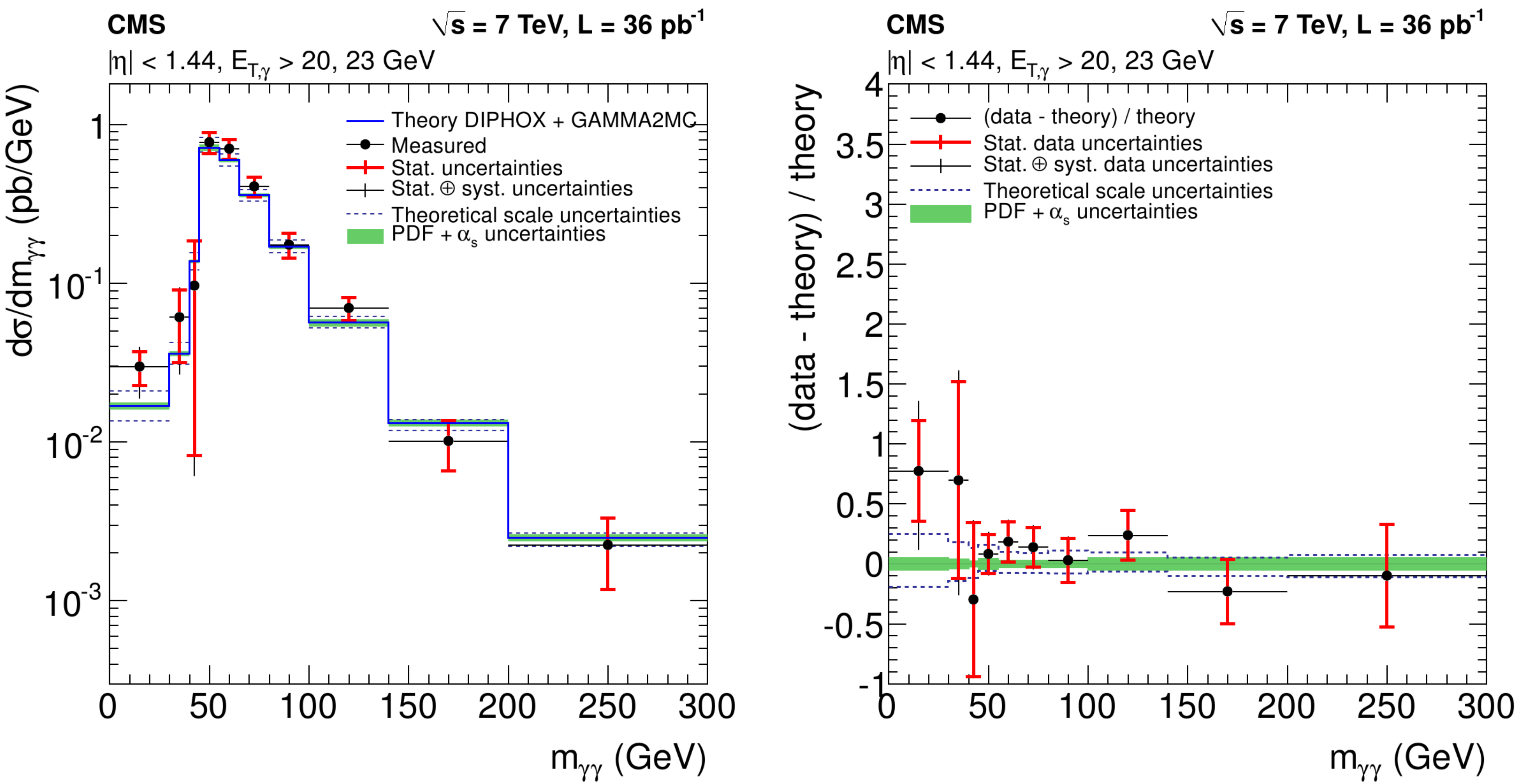


Diphoton: mass

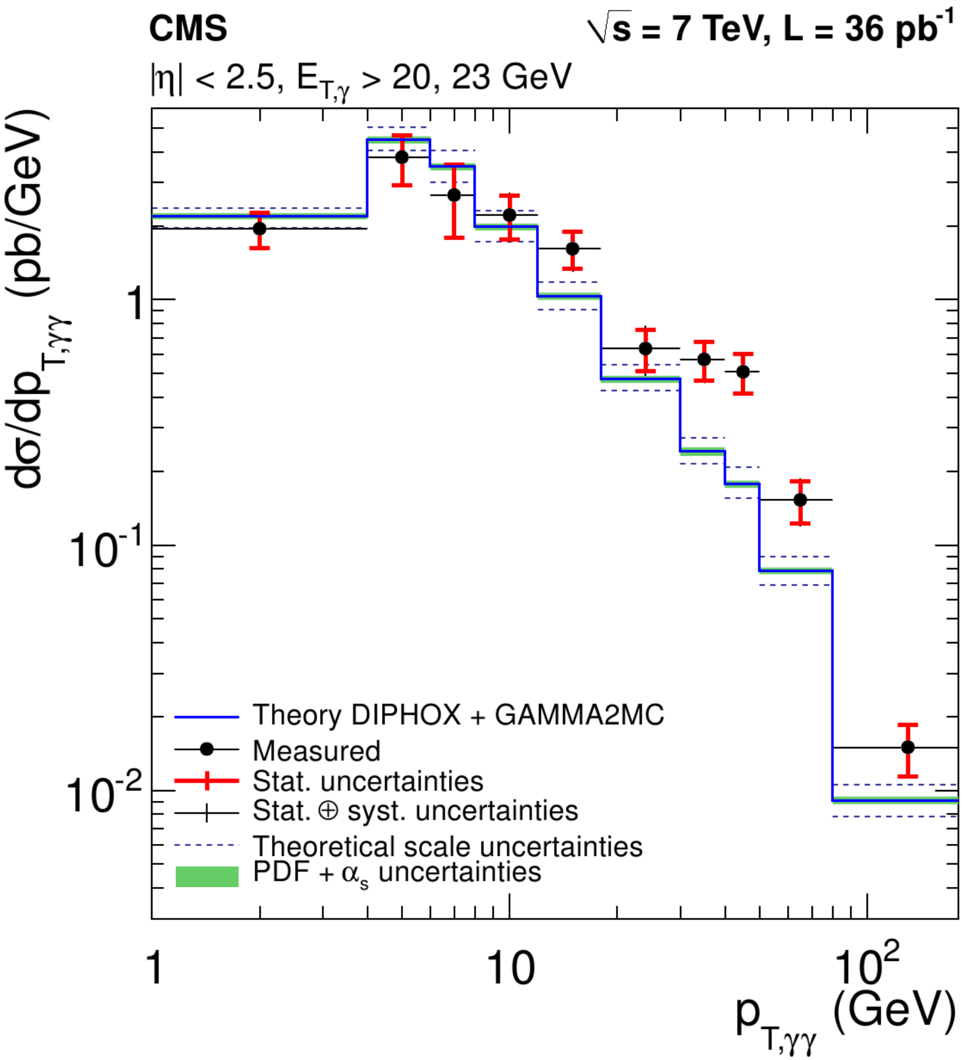


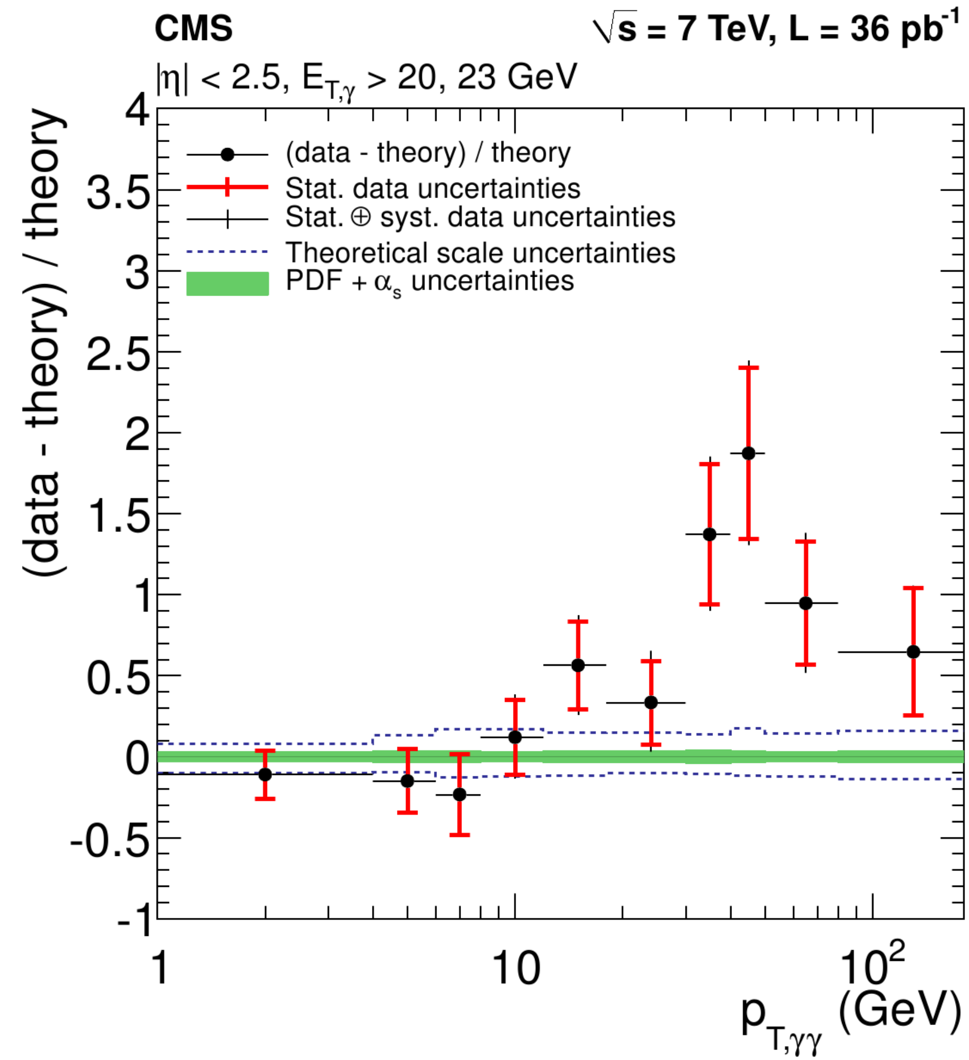


Diphoton: mass

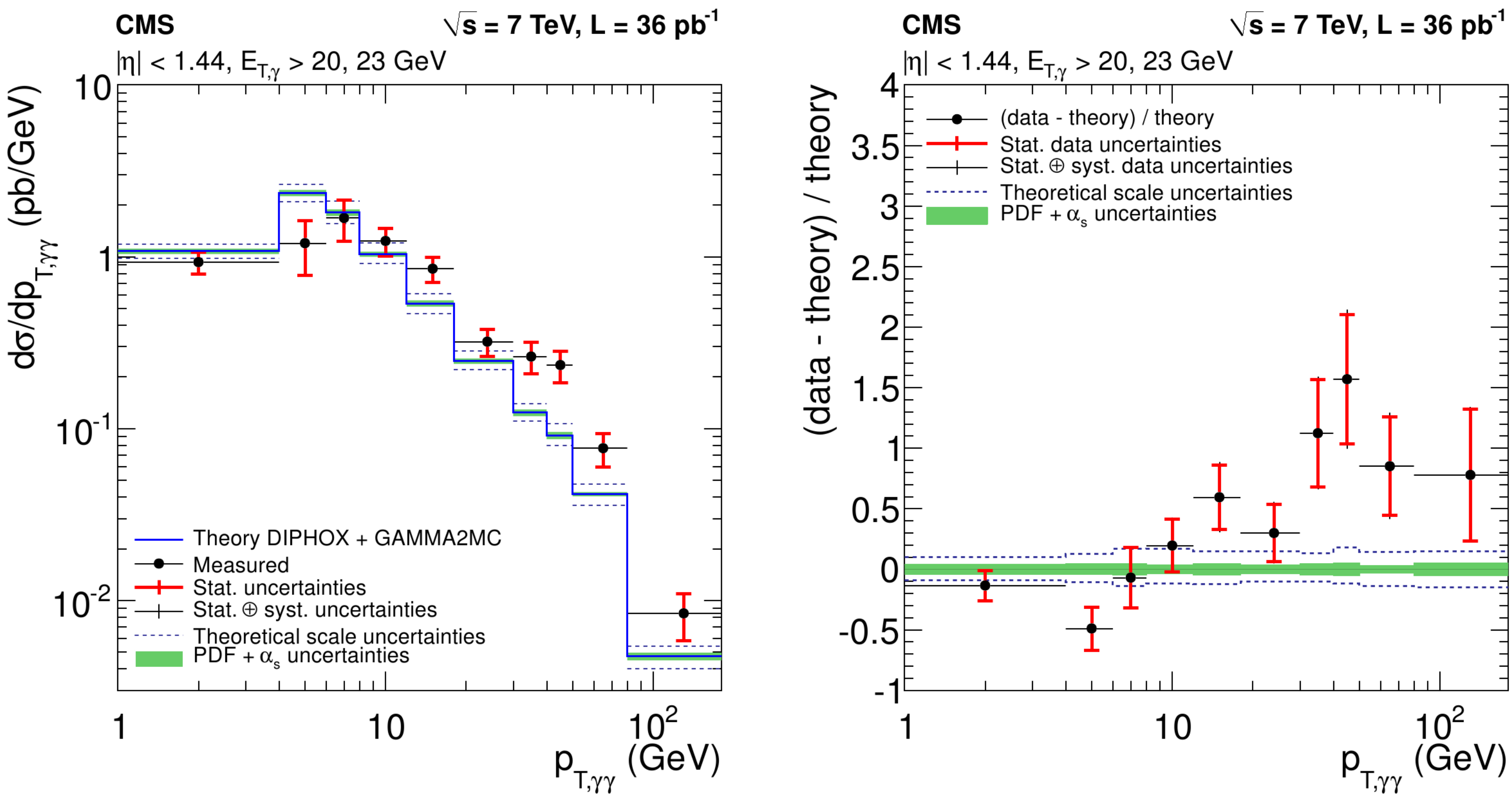


Diphoton: diphoton transverse momentum

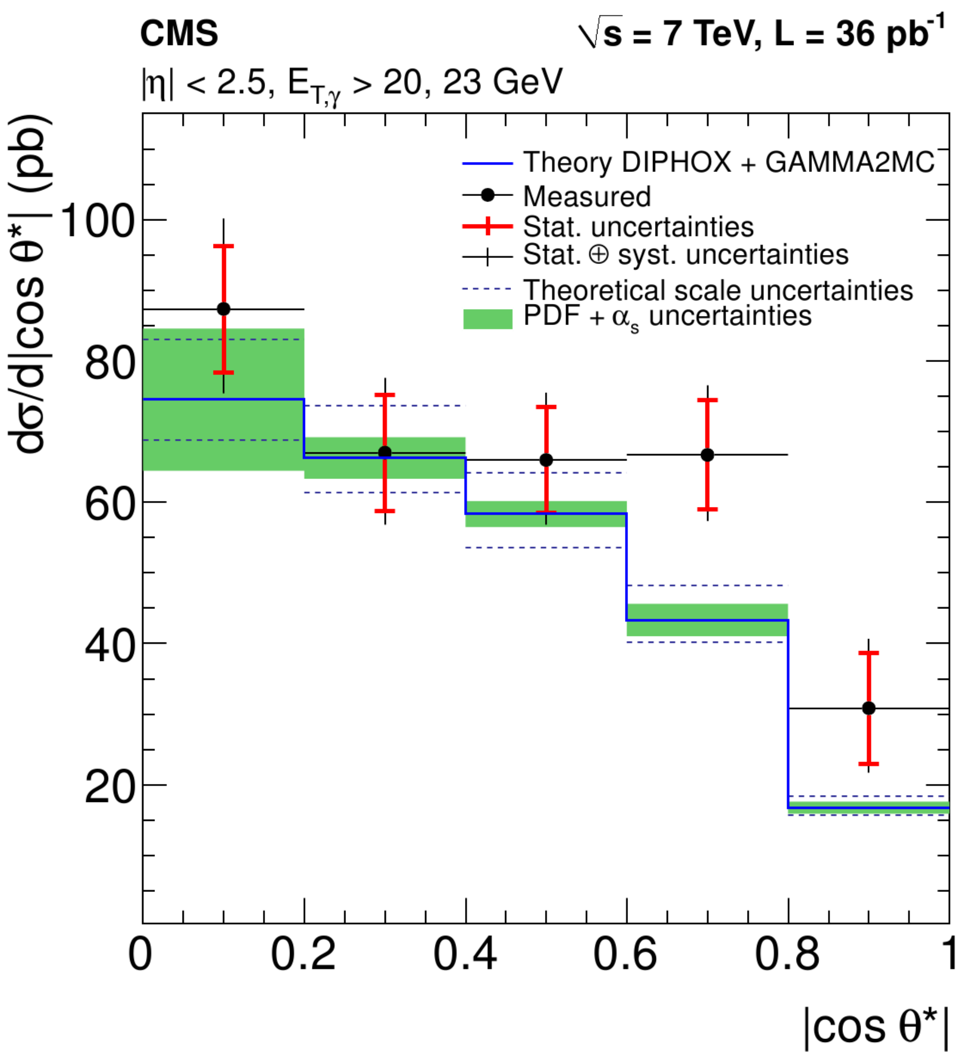


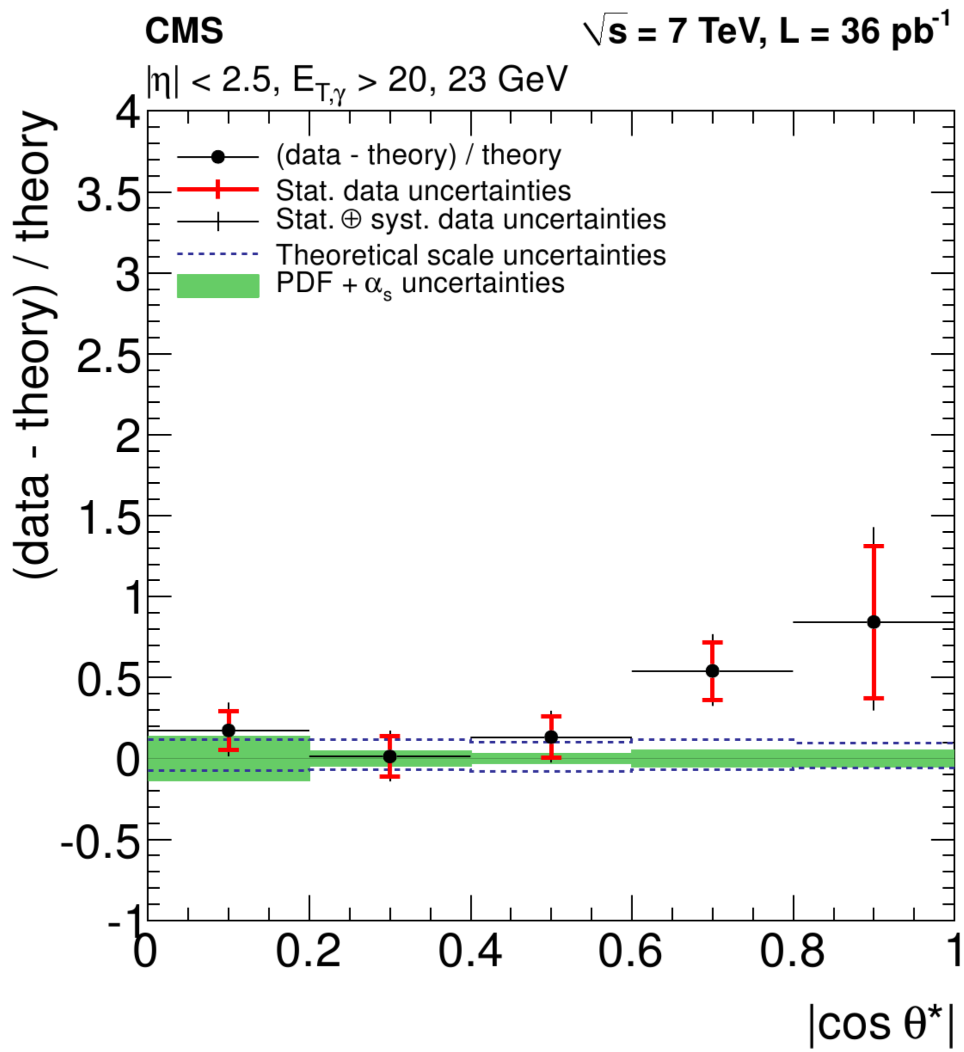


Diphoton: diphoton transverse momentum



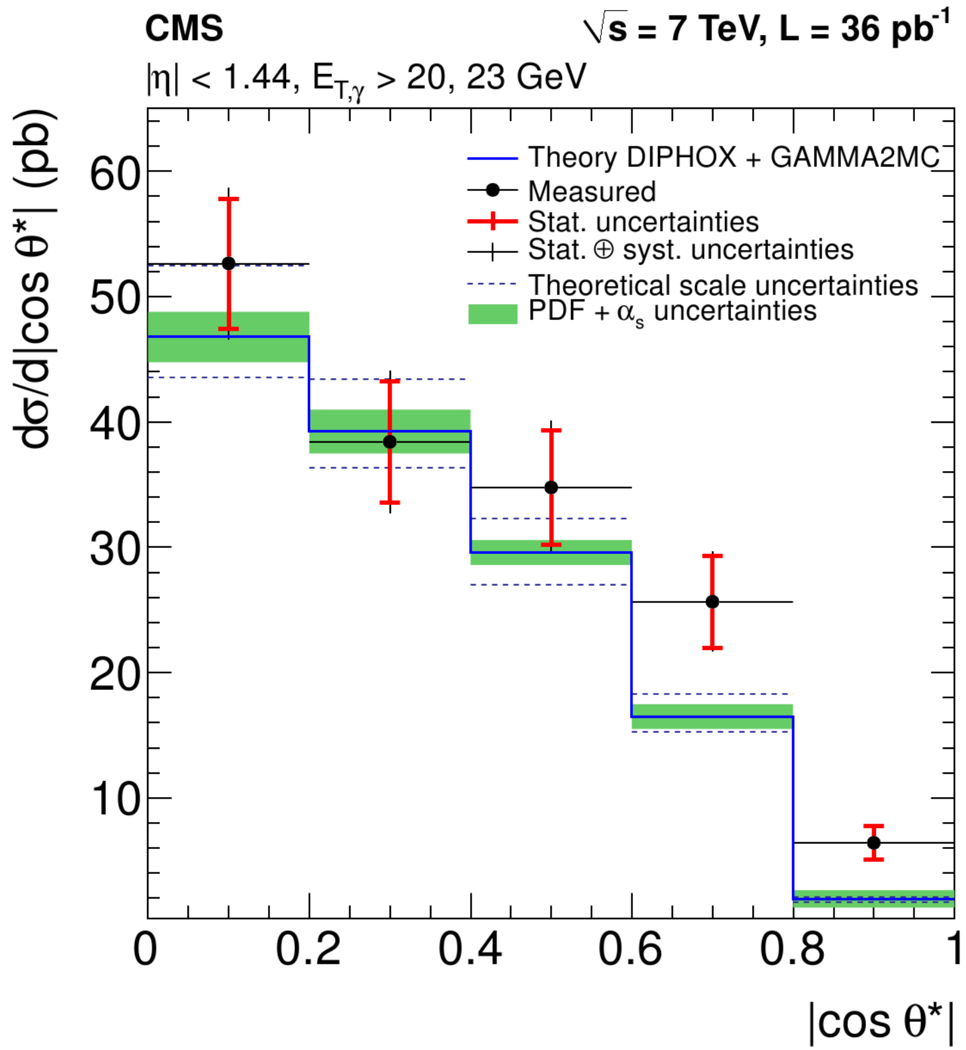
Diphoton: scattering angle

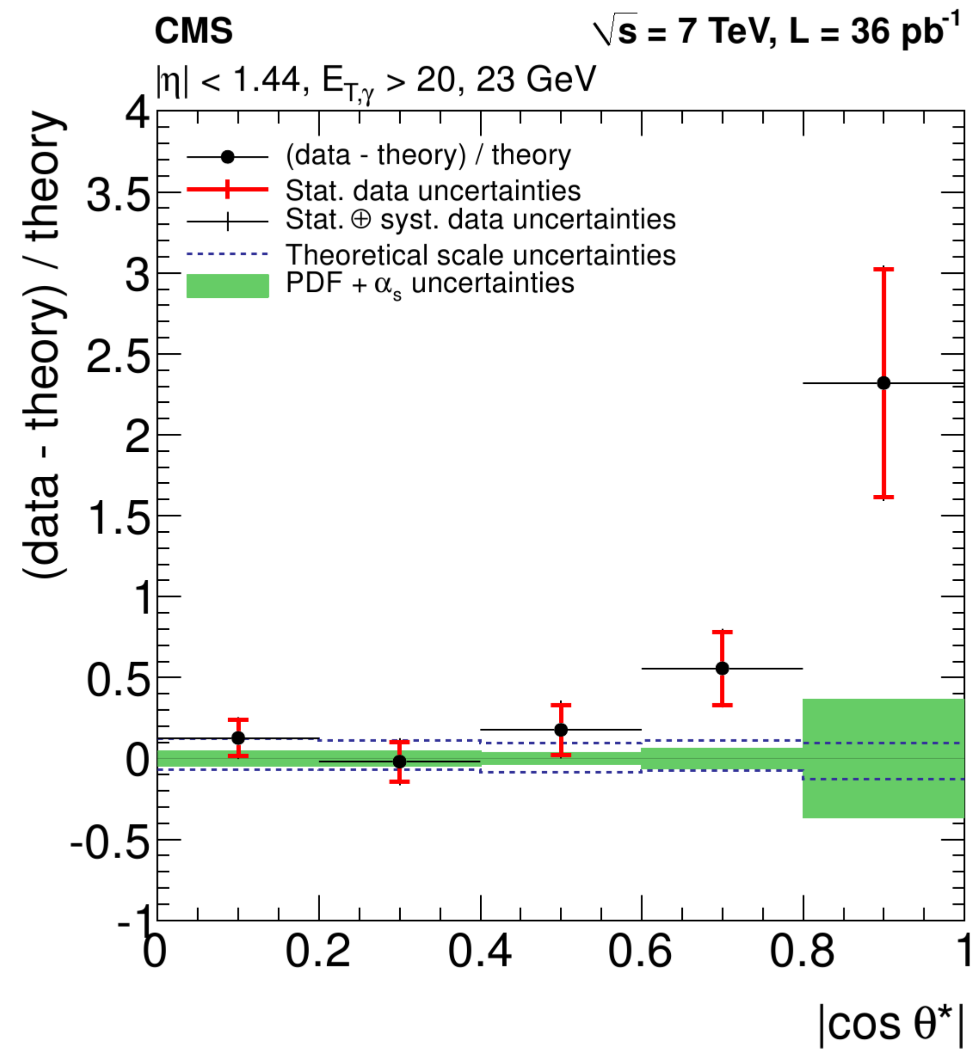




$$|\cos\theta^*| = \left|\tanh\frac{\Delta y_{\gamma\gamma}}{2}\right|$$

Diphoton: scattering angle

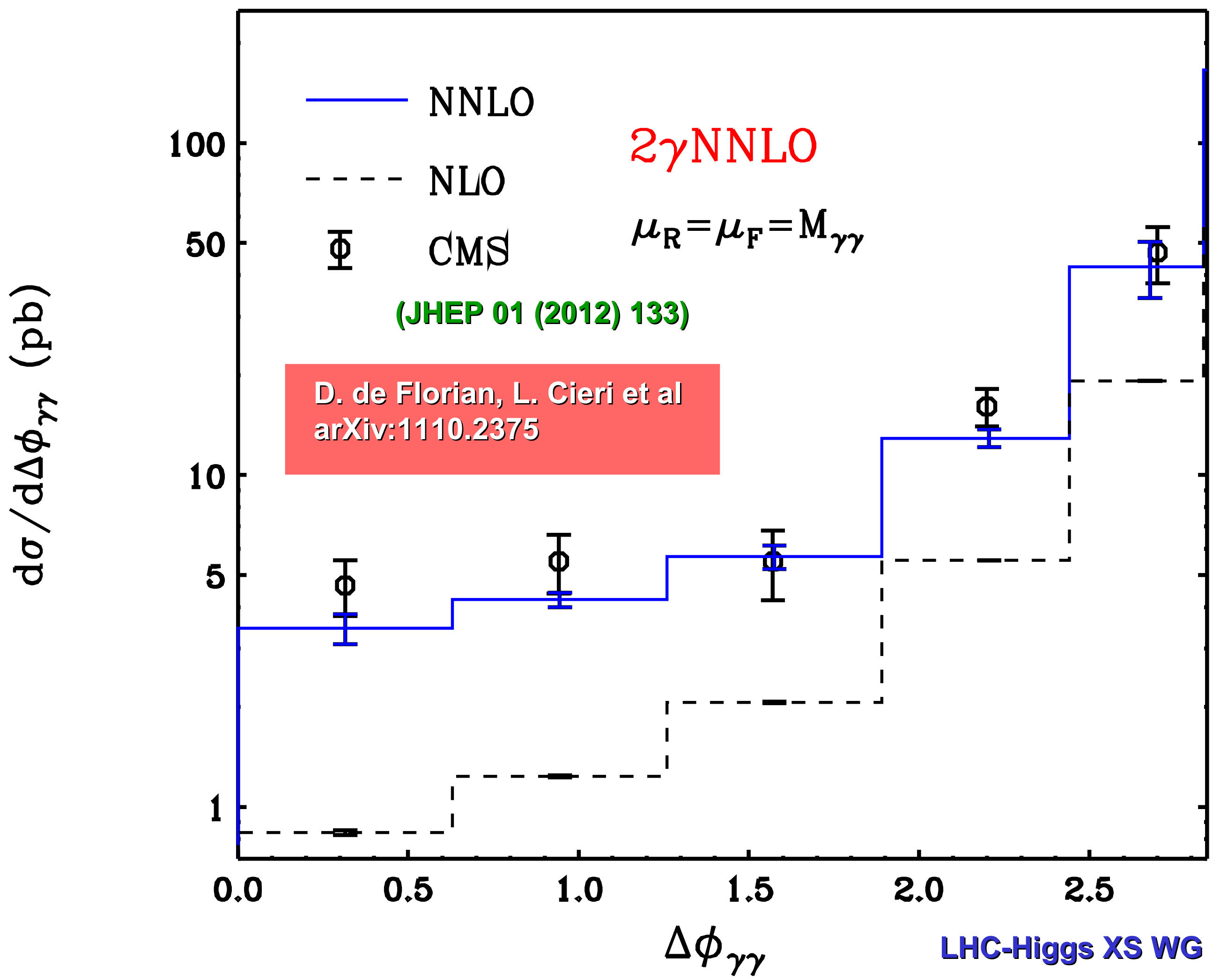




$$|\cos\theta^*| = \left|\tanh\frac{\Delta y_{\gamma\gamma}}{2}\right|$$

NNLO prediction: azimuthal angle between the two photons

- Prediction uses Frixione isolation -> no fragmentation contribution.
- Measurement: cone isolation.



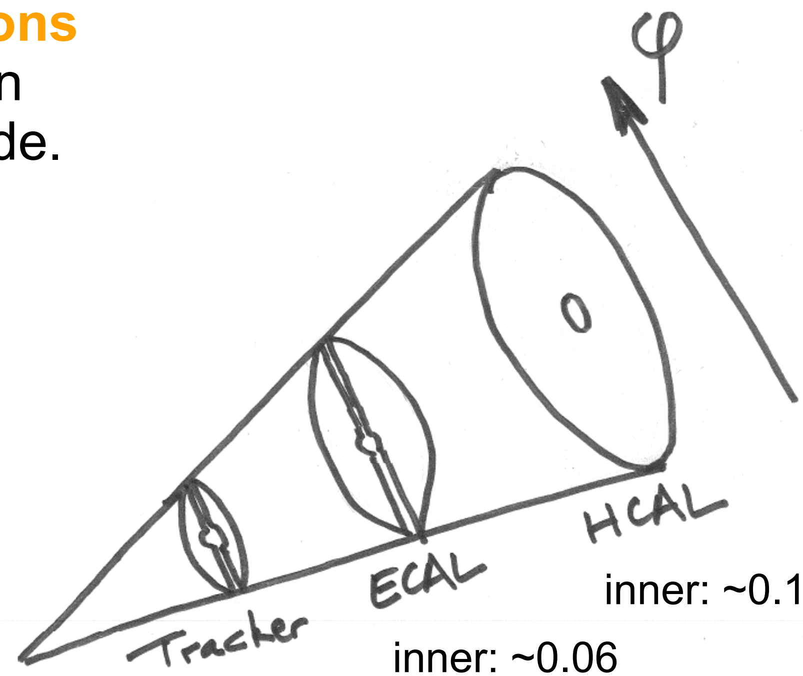
LHC-Higgs XS WG YR2 arXiv 1201.3084v1

A closure look at experimental isolation criteria

Experimental isolation

- Quote from Phys. Rev. D84 052011 (2011): *"In the simulation, a signal photon must have an isolation sum of less than 5 GeV."*
  → used for efficiencies and unfolding
  → a generator level criterion

- But the measurements assumes for signal photons **no energy deposited by hadrons** from the main interaction in their isolation area and apply severe cuts: see next slide.



Experimental isolation

- The measurements assumes for signal photons **no energy deposited by hadrons** in their isolation area
- Conversion method:
  - $H/E_{R<0.15} < 5\%$
  - $I_{track} < 2 + 0.001\ E_T$ (GeV)
  - $I_{ECAL} < 4.2 + 0.003\ E_T$ (GeV)
  - $I_{HCAL} < 2.2 + 0.001\ E_T$ (GeV)

  → Isolation also applied in the photon direction
- Isolation method:
  - $H/E_{R<0.15} < 5\%$
  - No track associated to the photon

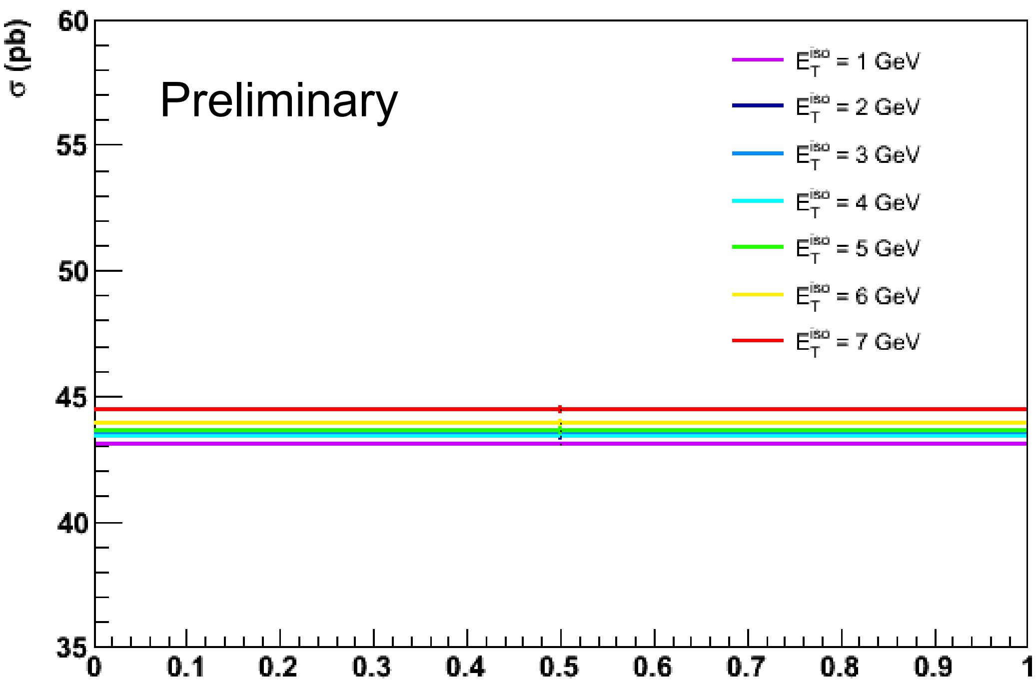
  } → Isolation also applied in the photon direction
  - Isolation compatible with a direct photon. Effect on the isolation variable distribution of photons from ISR/FSR and parton shower evaluated in Pythia and included in the systematic uncertainties
- Impinging track method (diphoton):
  - $H/E_{R<0.15} < 5\%$
  - No track associated to the photon
  - No track from primary vertex with $P_T > 3$GeV within $R < 0.4$

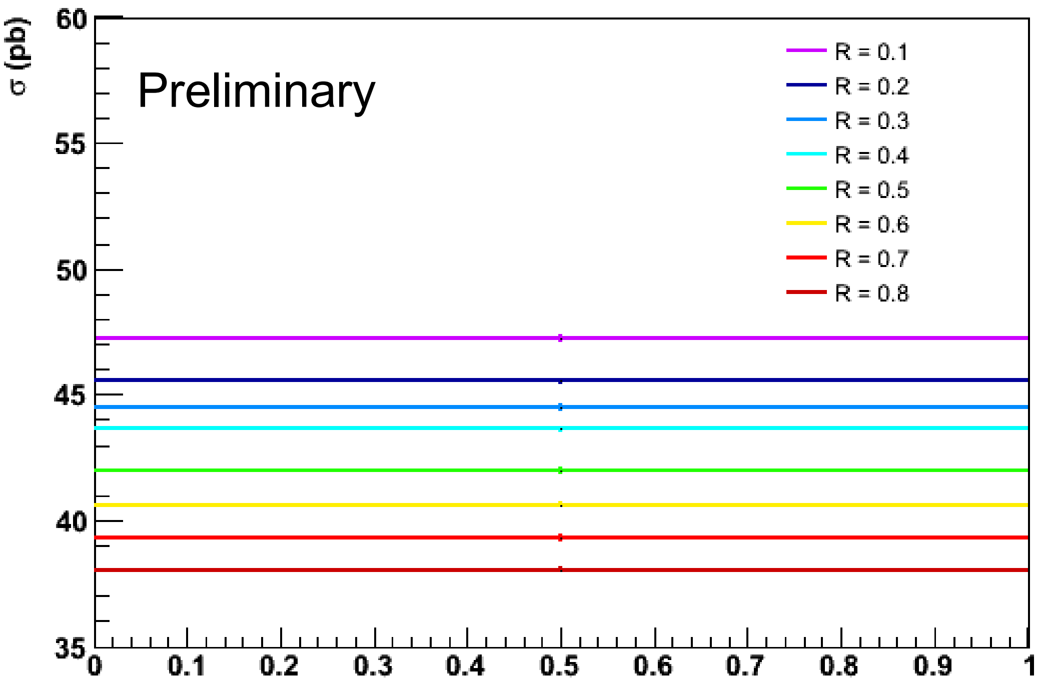
  } → Isolation also applied in the photon direction
  - $I_{track} < 2$ GeV (barrel, $|\eta|<1.44$), 4 GeV (endcap)
  - $I_{HCAL} < 2$ GeV (barrel, $|\eta|<1.44$), 4 GeV (endcap)
  - ECAL isolation compatible with deposits from Pile-up and underlying events

Effect of isolation parameters on prediction

- Effect on total cross section is limited

DIPHOX, Binoth et al.
Parton level study, *Ph .Gras. Not CMS approved.*

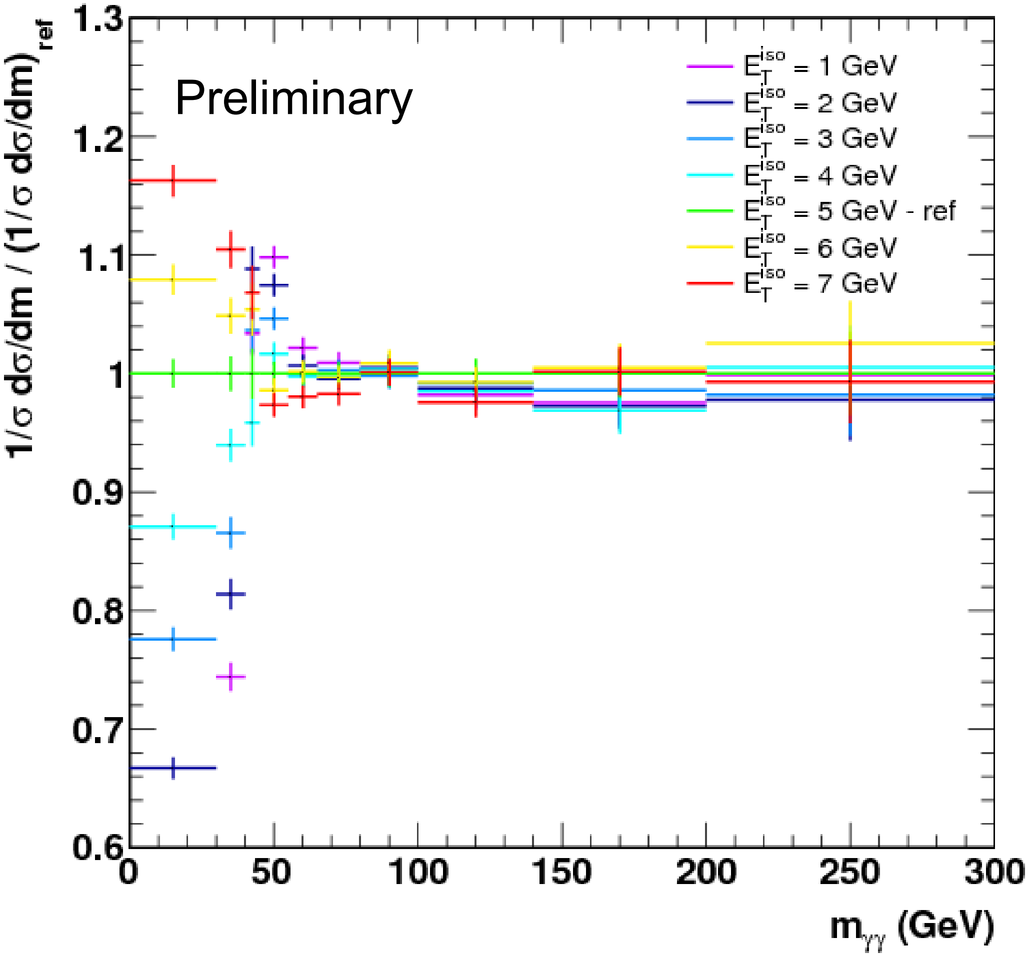


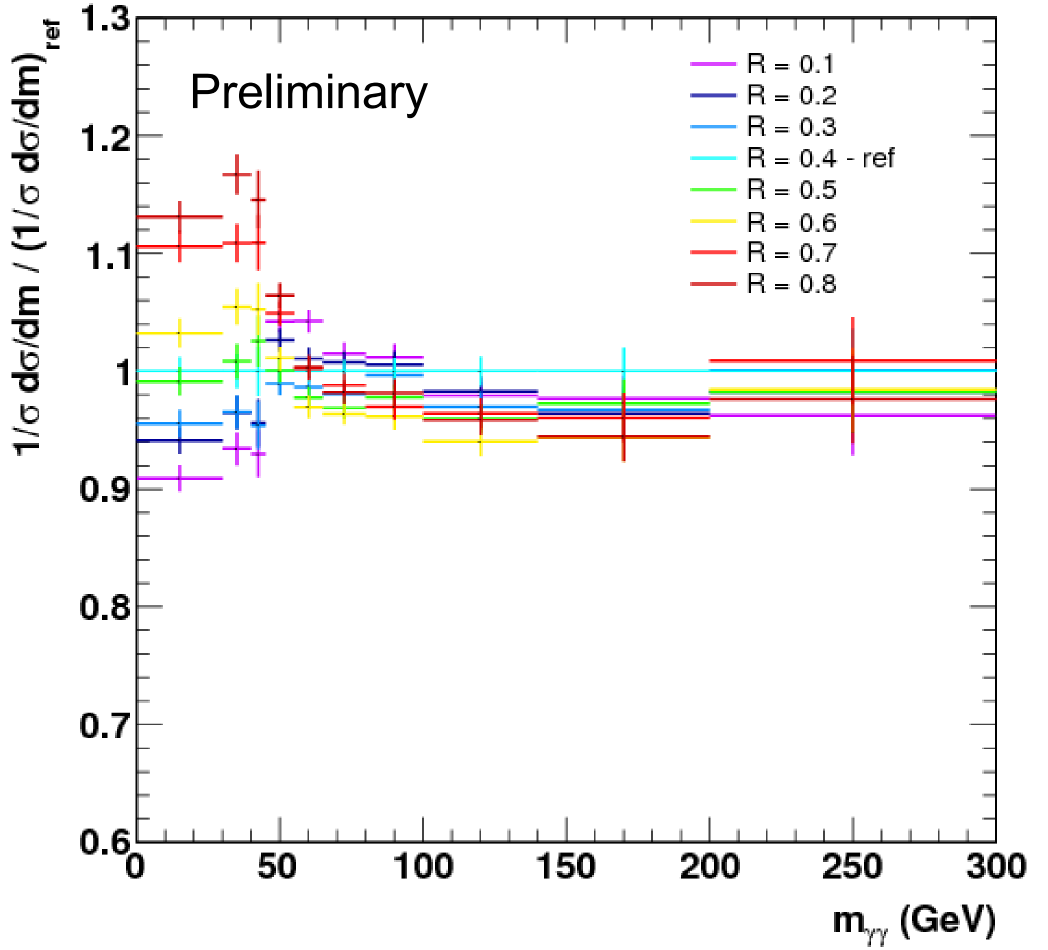


Effect of isolation parameters on prediction

- Effect on mass distribution

DIPHOX, Binoth et al.
Parton level study, *Ph .Gras. Not CMS approved.*

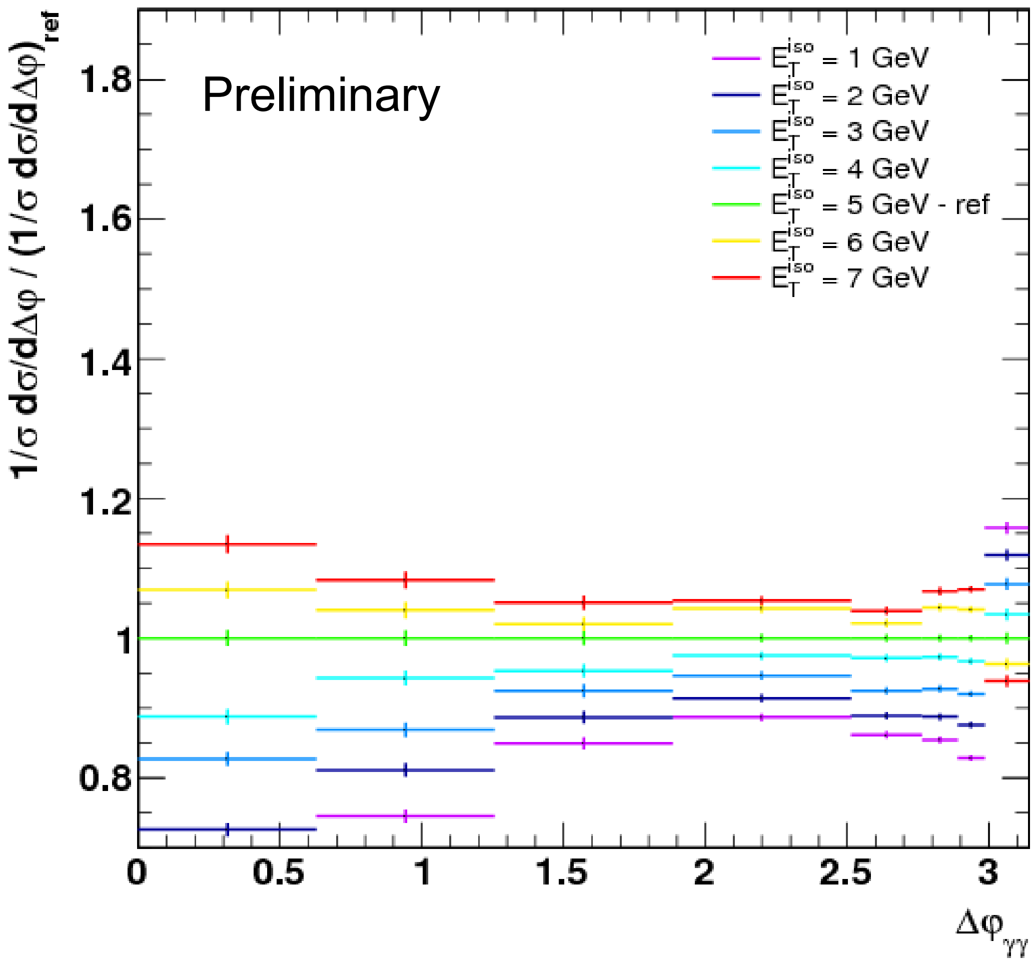


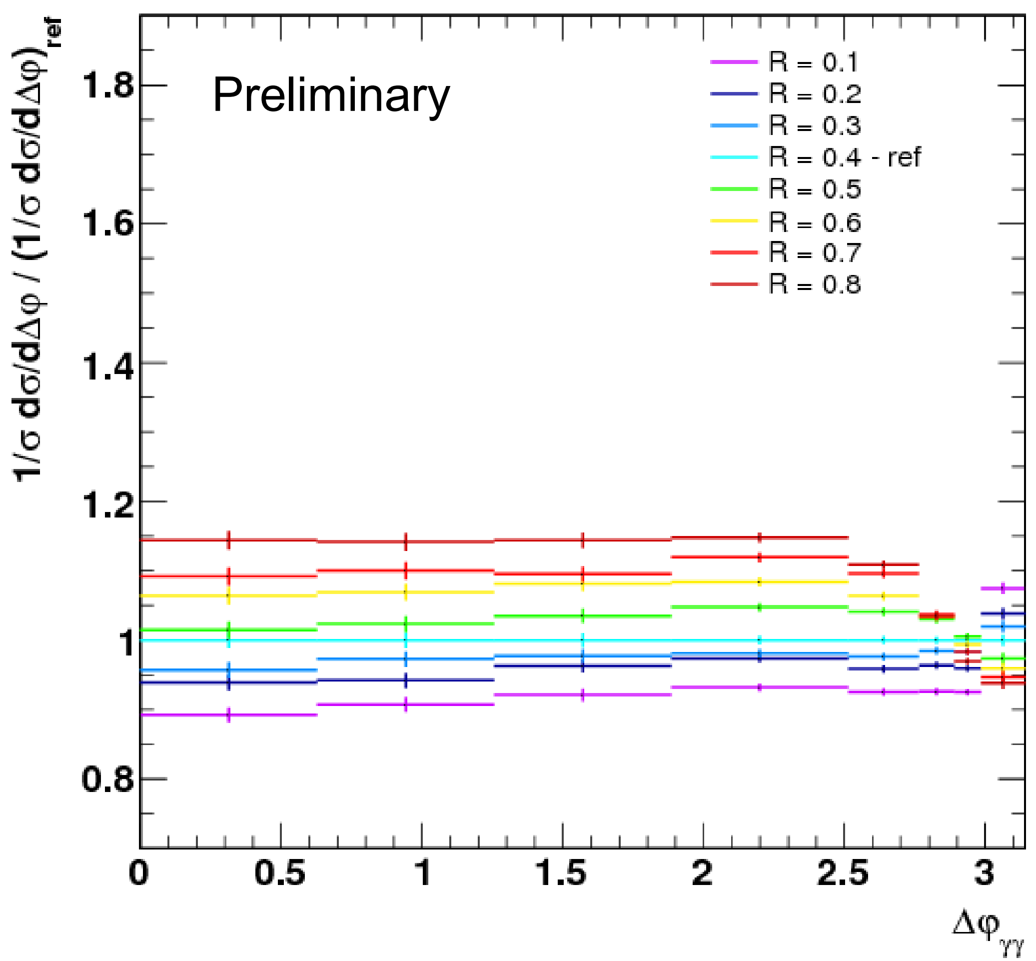


Effect of isolation parameters on prediction

- Effect on the distribution of the azimuthal angle separating the photons

DIPHOX, Binoth et al.
Parton level study, *Ph .Gras. Not CMS approved.*





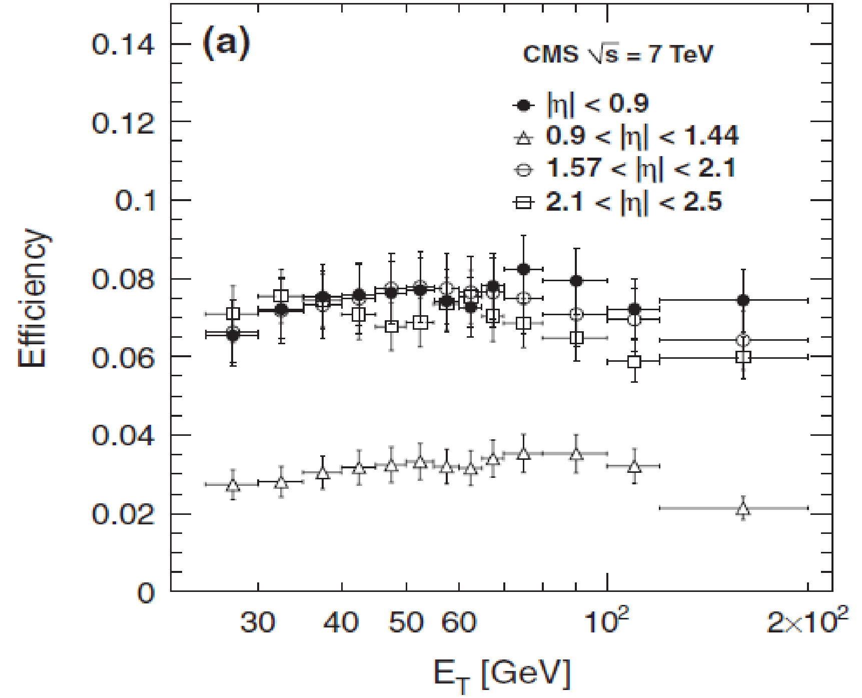
Conclusions

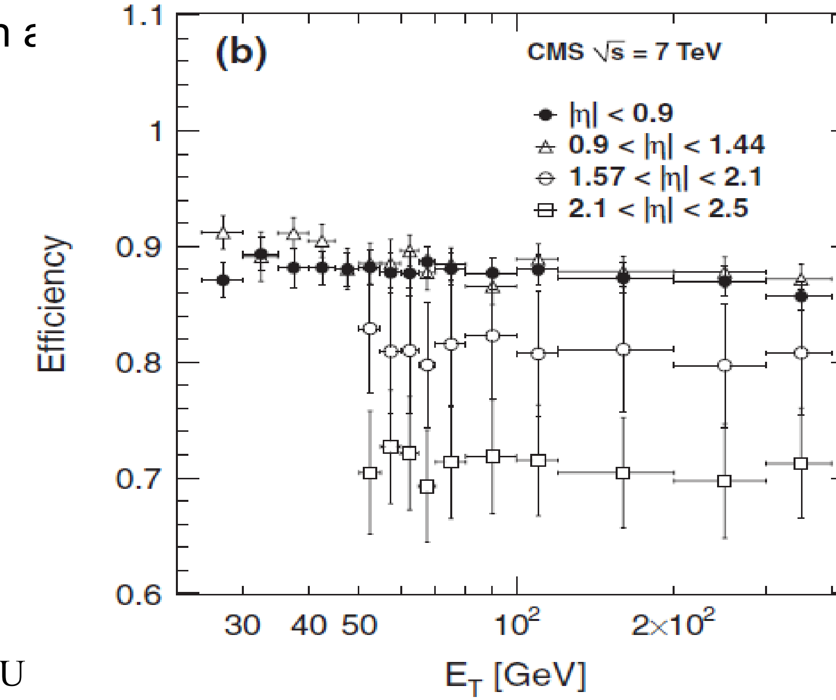
- Inclusive direct photon cross-section measurement: double differential as function of E_T and η. Probed $0.007 < x_T < 0.114$, good agreement with theoretical NLO prediction.
- Direct diphoton cross-section measurement: contribution in region of low $\Delta\varphi_{\gamma\gamma}$ underestimated with NLO + Fragmentation. Good agreement with NNLO w/o fragmentation
- Severe isolation applied on data
  - Far from the simplified cone isolation applied in the prediction
  - Not evident that such a simplified cone isolation describes better the experimental cone isolation than a Frixione isolation would.

Appendices

Inclusive direct photon cross-section measurmen: signal selection efficiency and unfolding

- $\varepsilon_{trig} \times \varepsilon_{reco} \times \varepsilon_{ID1} \times \varepsilon_{ID2}$
  - ε_{trig} ~ 100% (Data Tag & Probe)
  - ε_{reco} ~ 99% (MC)
- ε_{ID1}: Tag and Probe (T&P), $Z \rightarrow e^+e^-$
  - $\mathrm{MC} \times \dfrac{\mathrm{T\&P(data)}}{\mathrm{T\&P(MC)}}$
- ε_{ID2}:
  - Isolation: pixel veto
    - T&P, $Z \rightarrow \mu^+ \mu^- \gamma$
  - Conversion: conversion selection efficiency
    - Exploits isolation method to estimate event yield after and before applying conversion selection on a control sample selected without isolation cuts.





Unfolding

Correction factor is computed from simulation for each η, E_T bin to take into account the finite resolution of the detector:

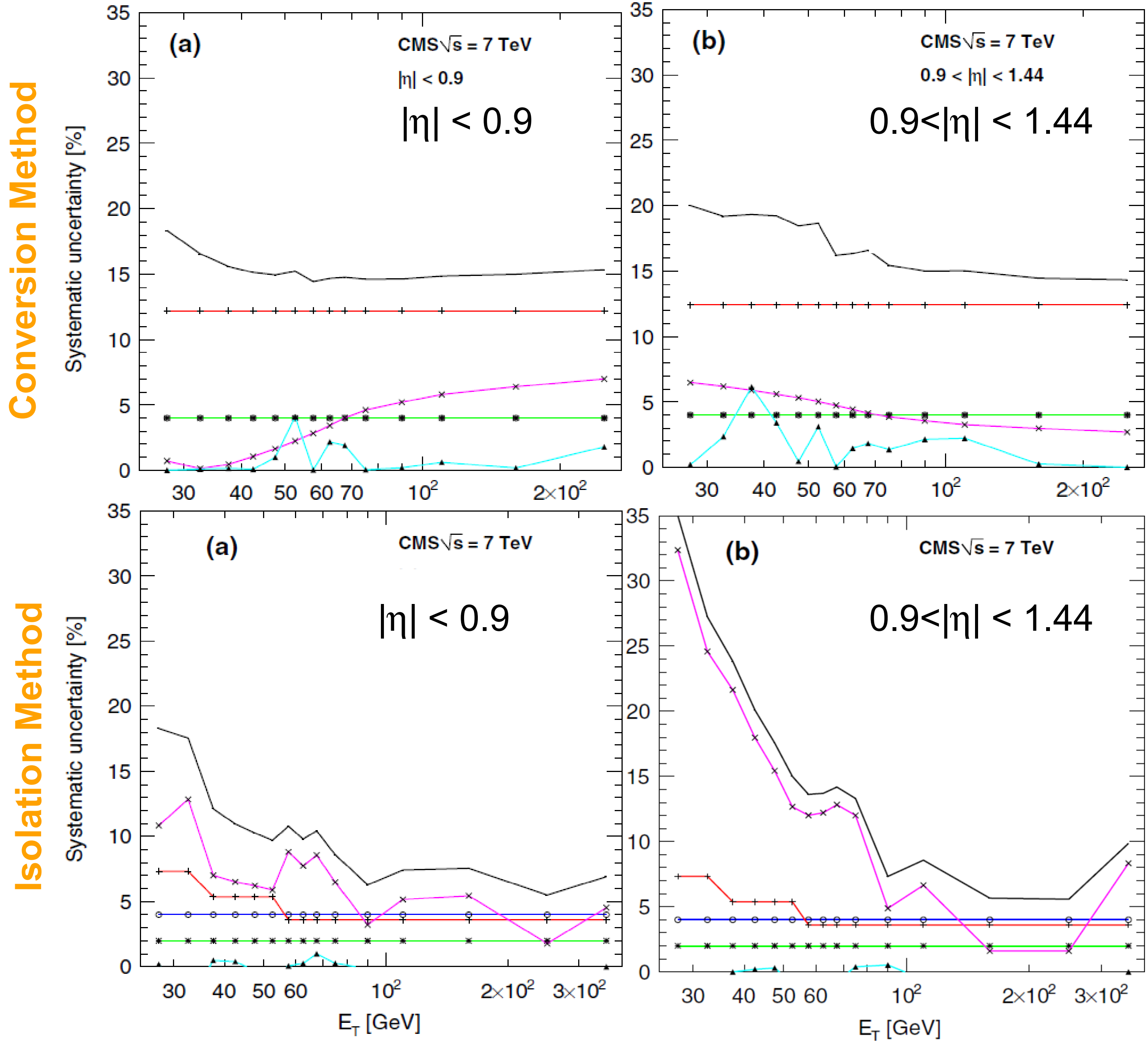
U = 0.90 to 1.03 in the barrel

U = 1.03 to 1.16 in the endcap

Systematic uncertainties

- Source of systematic errors:
  - Fit bias
  - E scale
  - Efficiency
  - Unfolding
  - Sig/bkg shape
  - Total

- The two methods are complementary:
  - conversion competitive in low E_T range
  - Isolation competitive in high E_T range



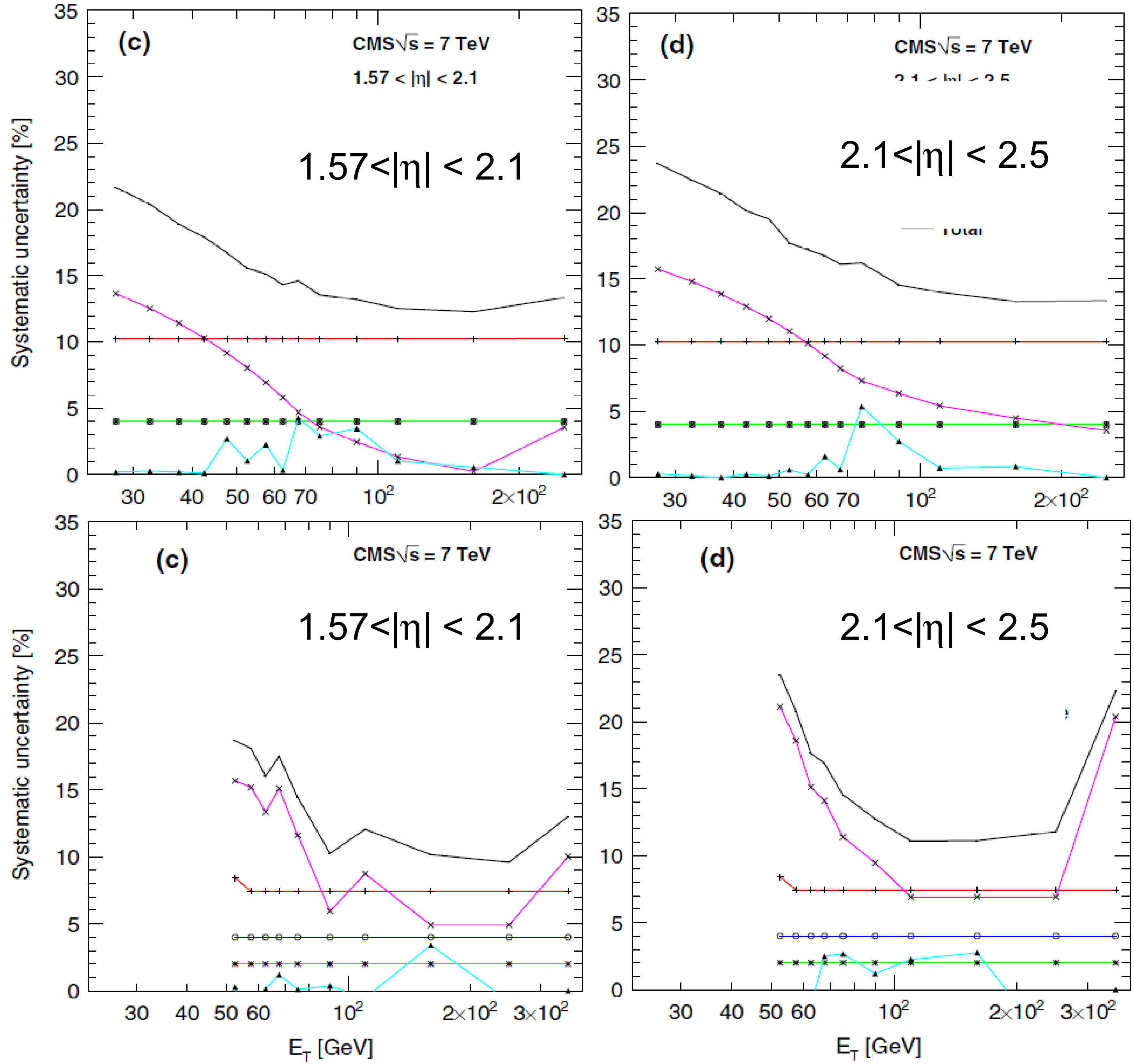
Systematic uncertainties

- Source of systematic errors:
  - Fit bias
  - E scale
  - Efficiency
  - Unfolding
  - Sig/bkg shape
  - Total

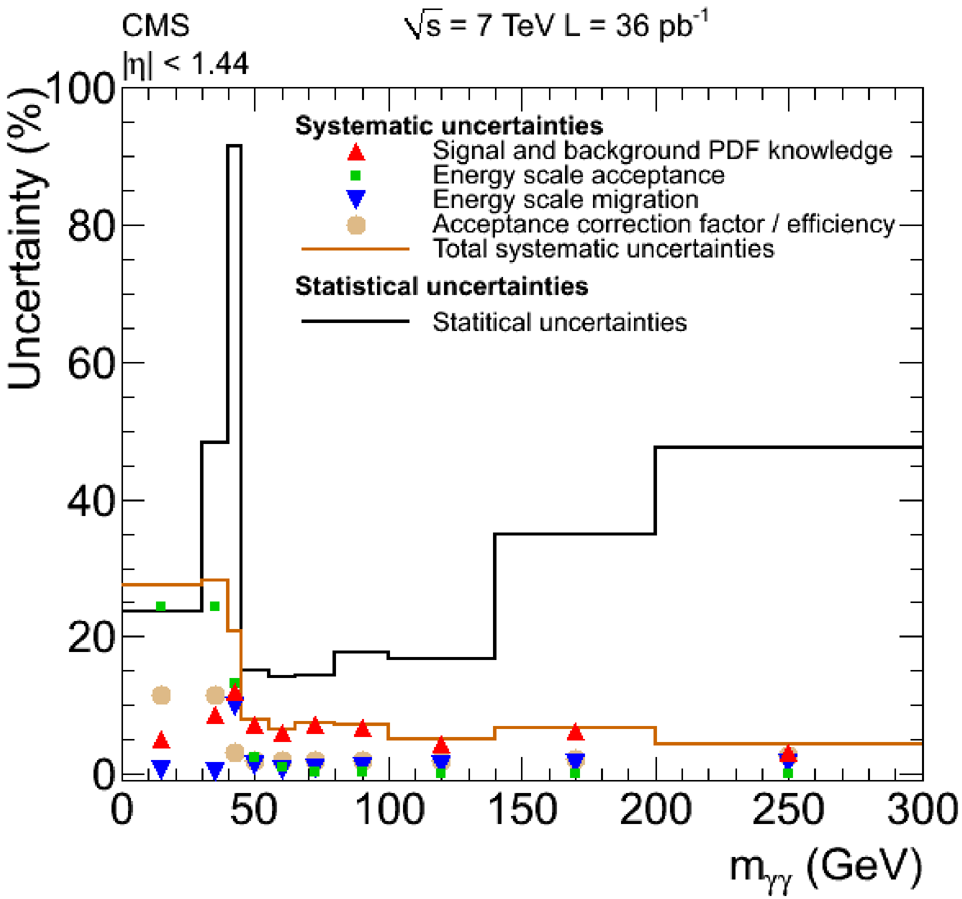
- The two methods are complementary:
  - conversion competitive in low E_T range
  - Isolation competitive in high E_T range

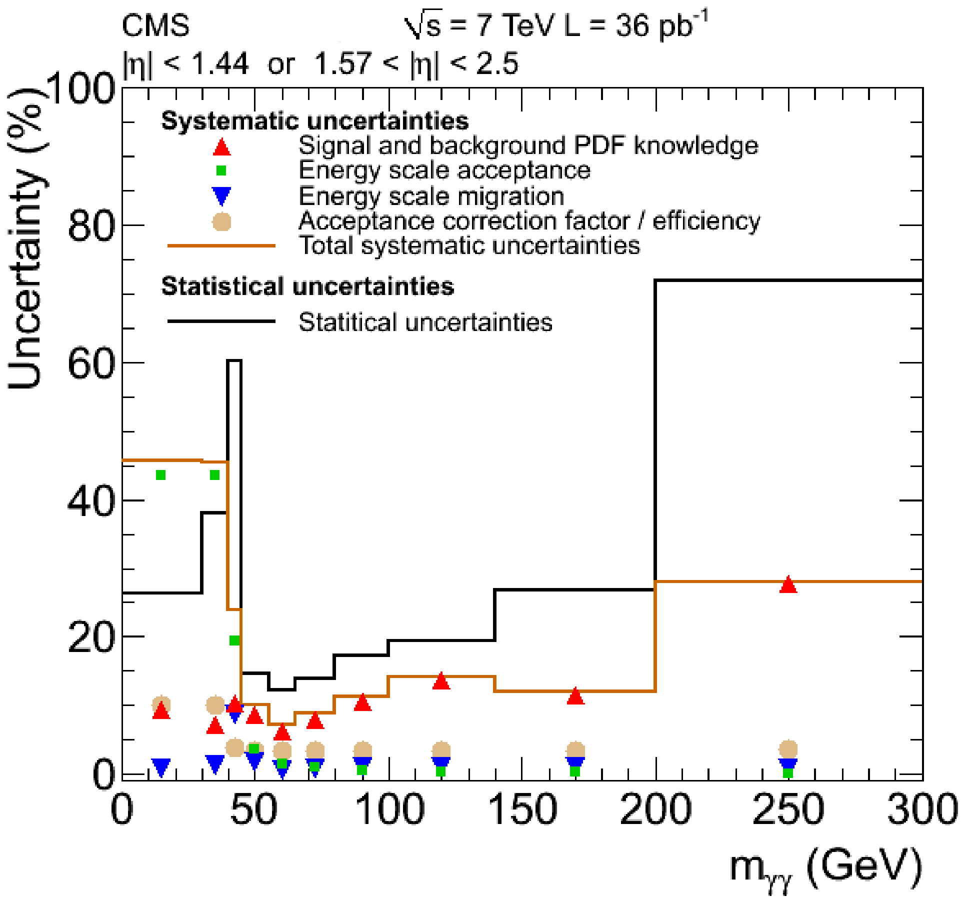
Conversion Method

Isolation Method

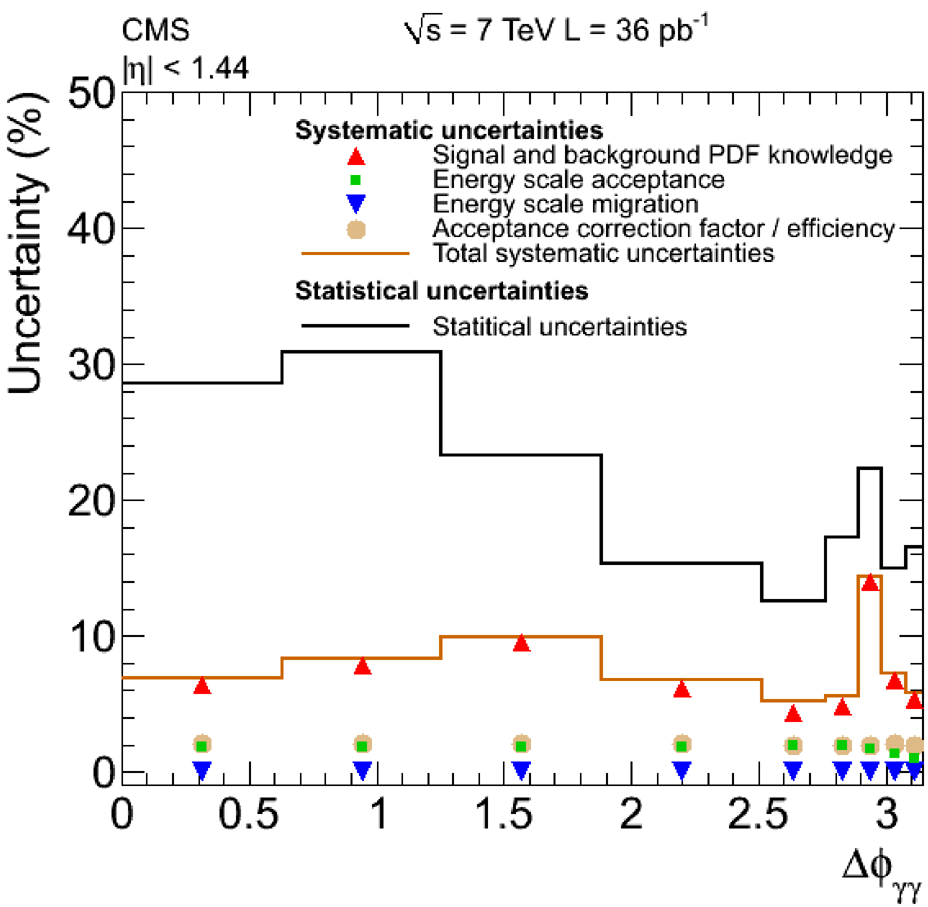


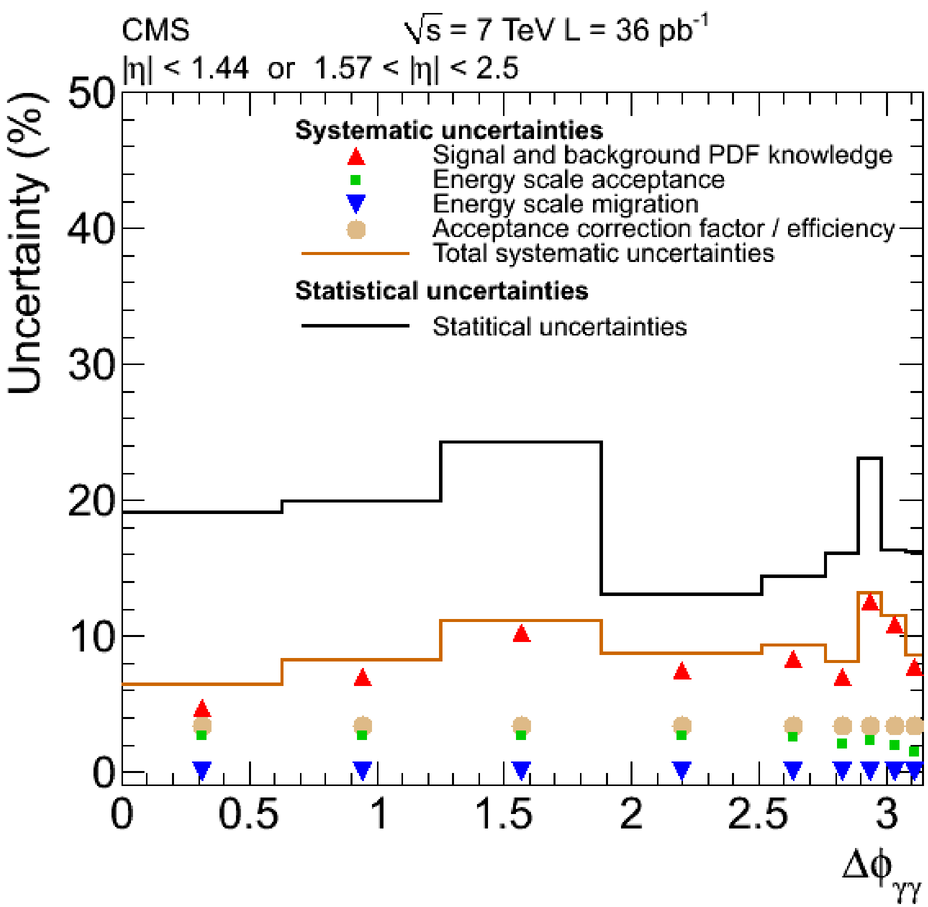
Systematic uncertainties





Systematic uncertainties





Photon deposit shape variable

- Spread extension along η of energy deposited in ECAL required to be compatible with a single photon shower: $\sigma_{\eta\eta} \lesssim 0.010$ (barrel), 0.030 (endcap)

$$\sigma^2_{\eta\eta} = \frac{\sum_i^{5\times 5} w_i(\eta_i - \bar{\eta}_{5\times 5})^2}{\sum_i^{5\times 5} w_i},$$

$$w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E_{5\times 5}}\right),$$