# Measurement of the Differential Isolated Prompt Photon and Diphoton Production Cross Sections in pp Collisions at $\sqrt{s}$ = 7 TeV

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**Nicolas Chanon** (ETH Zürich)
on behalf of the CMS collaboration

# Introduction

- **$\gamma$+X and $\gamma\gamma$+X cross-section measurements** probe our knowledge of perturbative QCD
- **Photons** constitute a clear signature for new physics searches : $H \rightarrow \gamma\gamma$, gravitons, supersymmetry, excited fermions. $\gamma$+X and $\gamma\gamma$+X processes are background for those rare processes

## Outline :

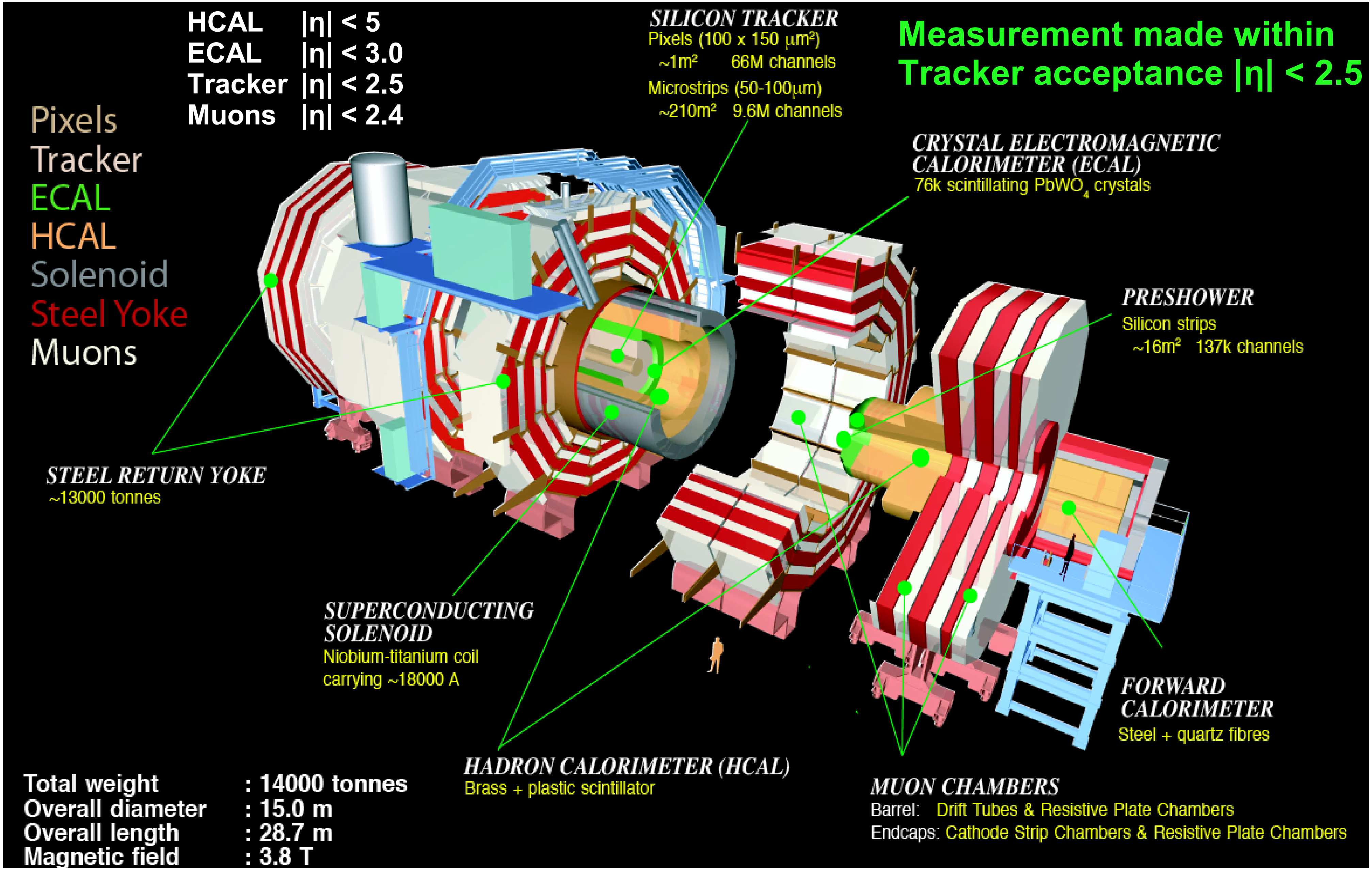
**I - Inclusive photon cross-section measurement**

- Combined isolation method
- Photon conversion method
- Results

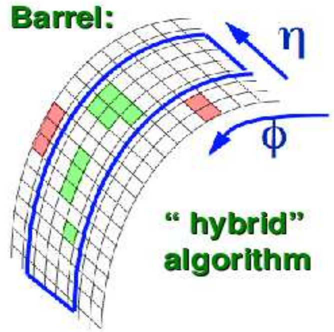
**II - Diphoton cross-section measurement**

- Electromagnetic isolation method
- Results

# CMS detector

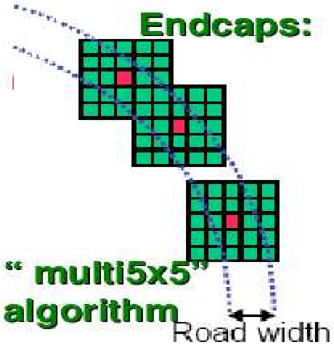


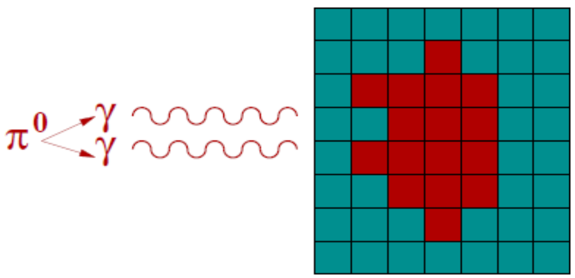
# Photon reconstruction and selection

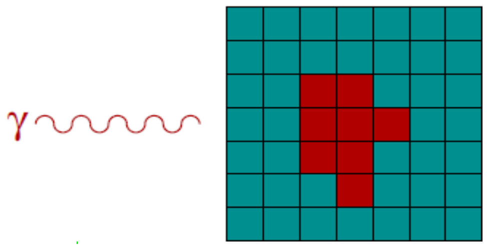



**Photons** are reconstructed with energy deposits in **ECAL** crystals

- **Barrel** : take advantage of the 3.8 T magnetic field which bends the charged particles trajectory (in case of a photon conversion)
- **Endcap** : merge contiguous 5 × 5-crystal matrices around the most energetic crystals



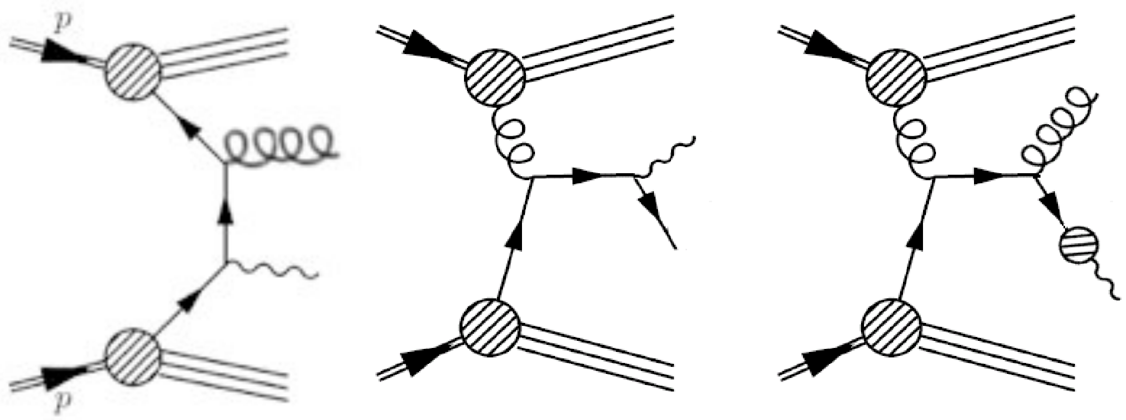

## Photon identification :

- **Electron rejection** : the energy deposit should not be matched to hits in the pixel detector
- The **transverse shape** of the energy deposits in ECAL should be compatible with a single photon shower
- **Isolation** : in a cone **$\Delta R<0.4$** around the photon, use $\sum E_T$ of energy deposits in **ECAL**, **HCAL** and $\sum p_T$ of the charged particles measured in the **tracker**

- **Huge background of boosted neutral mesons** decaying to two photons, reconstructed as a single one
- After identification, **need to statistically subtract the background component**

# Inclusive isolated photon production

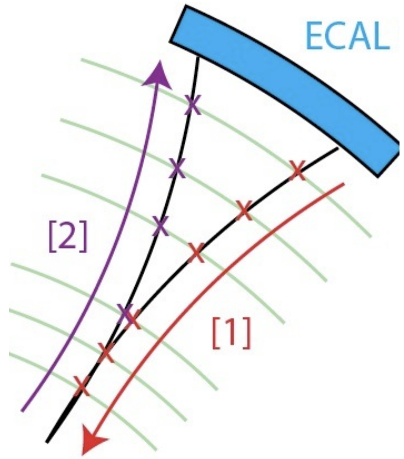
- **Prompt photons** are produced via quark annihilation, quark-gluon compton scattering and via parton to photon fragmentation




## CMS PAPER QCD 10-037

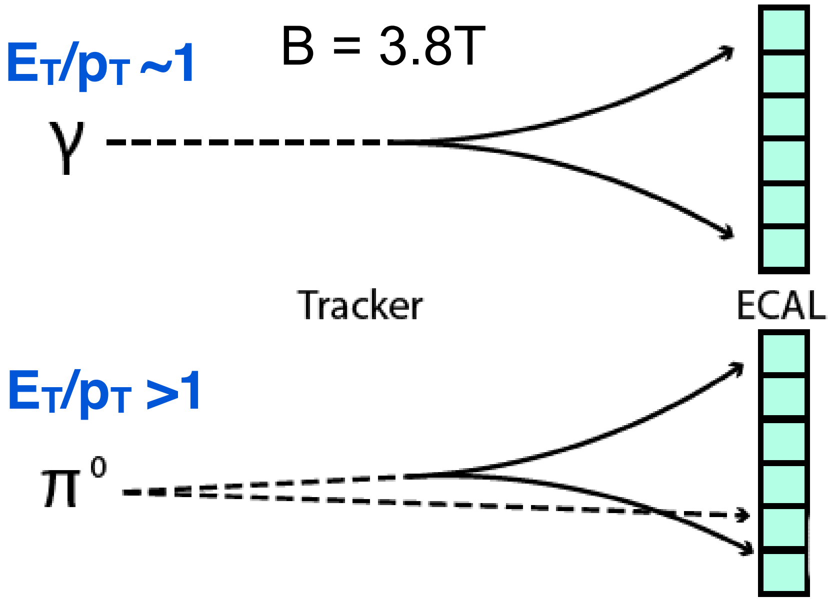
- Update of the first measurement made with 2.9 $pb^{-1}$ in the range $|\eta| < 1.44$ (*Phys. Rev. Lett. 106, 082001, 2011*) with the **full 2010 dataset : 36 $pb^{-1}$**
- Extend the measurement to **forward region** : 4 $\eta$ bins, up to $|\eta|<2.5$
- $E_T$ range extended to **25-400 GeV**
- **Two complementary methods** combined : **photon conversions** and **isolation energy** measured in the calorimeters and tracker, used to extract the signal yield

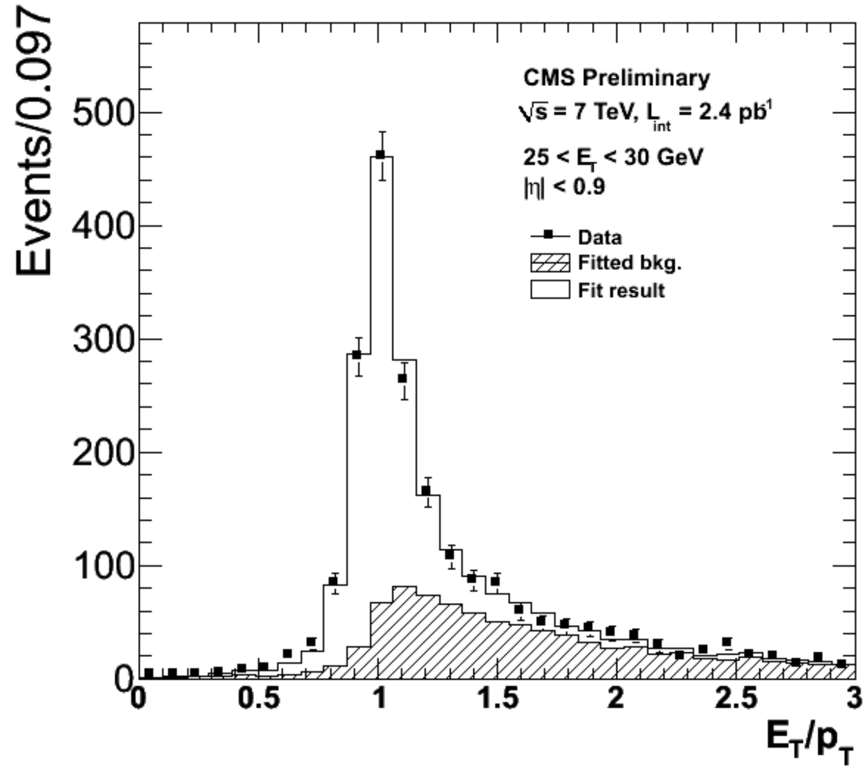
# Photon conversion method : competitive at low $E_T$




**Use the variable $E_T/p_T$ :**

- **$E_T$** transverse energy measured in ECAL,
- **$p_T$** transverse momentum of the $e^+/e^-$ pair measured in tracker.

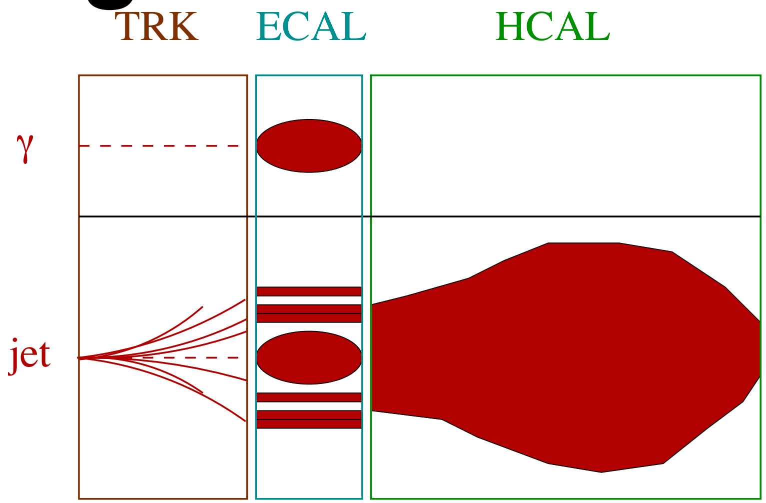


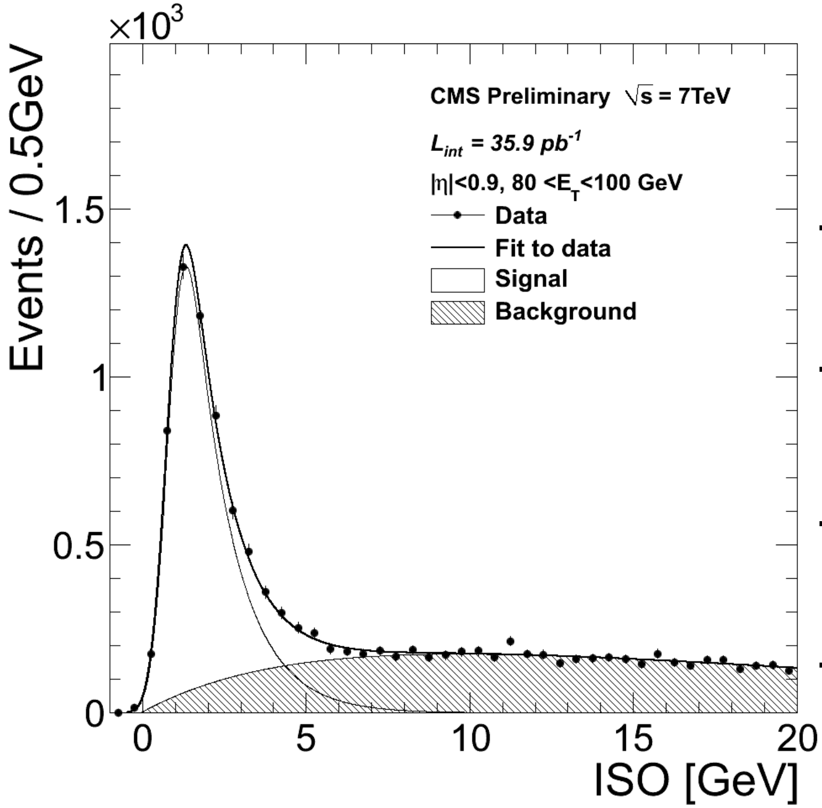

Extract the **signal yield** with a binned **likelihood fit** :

- Signal and background **pdf from Monte-Carlo**
- **Signal shape uncertainties** : vary peak mean and width
- **Background shape uncertainties** : estimated from isolation and cluster shape sidebands in data

# Isolation method : competitive at high $E_T$




- Use **ISO**, the **sum of the isolation energies** measured in the ECAL, HCAL and tracker
- Signal photons have ISO close to 0




Extract the **signal yield** with an unbinned **likelihood fit** :

- Signal and background **pdf estimated from Monte-Carlo and controled with data**
- **Signal shape** corrected for data / Monte-Carlo difference in Z→ee events
- **Background shape** controled with cluster shape sidebands in data
- **Uncertainties** assessed with toy experiments (parameters varied within systematics)

# Signal selection efficiency

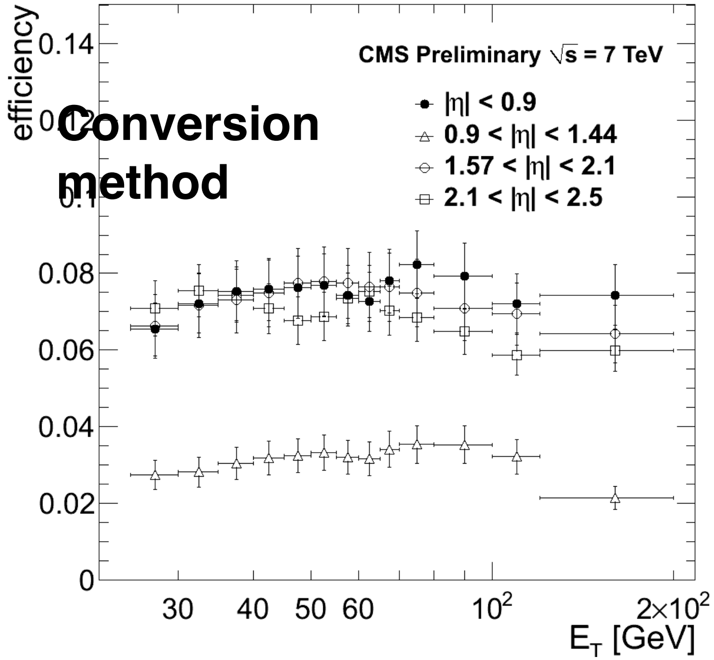
**Selection efficiency :**

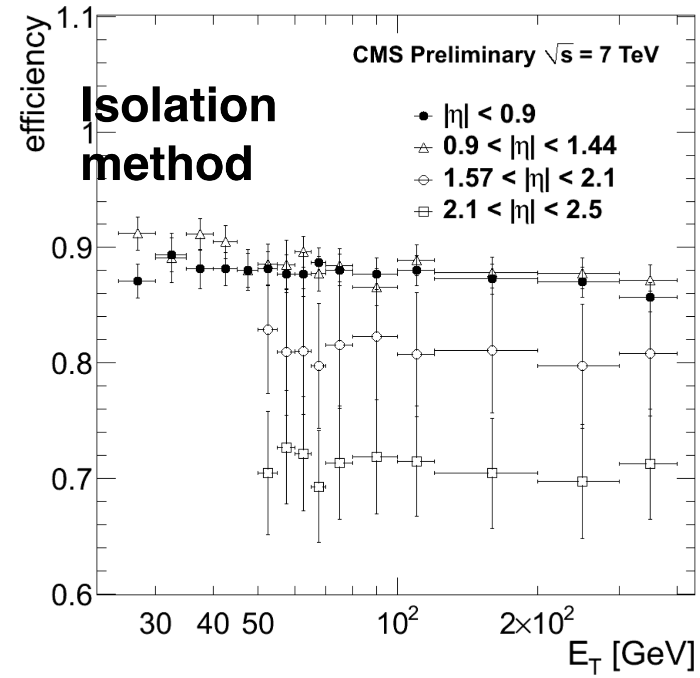
$$\varepsilon_{trig} \times \varepsilon_{reco} \times \varepsilon_{ID}$$

- **Trigger** : one photon candidate with $E_T > E_T^{threshold}$, raising with instantaneous luminosity periods, efficiency > 99% . $\varepsilon_{trig} \sim 100\%$, ($Z \rightarrow ee$ events in data)

- **Reconstruction** : $\varepsilon_{reco} \sim 99\%$ (simulation)

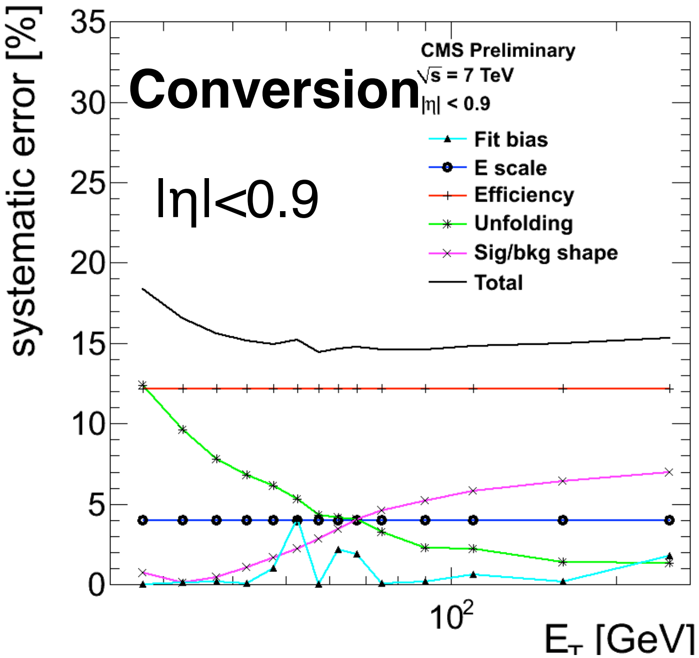
- **Identification** $\varepsilon_{ID}$:
    - **Cluster shape, isolation**: measured with $Z \rightarrow ee$ events in data, corrected for photon/electron difference
    - **Pixel hit veto**: uses $Z \rightarrow \mu\mu\gamma$ events in data
    - **Conversion selection**: uses isolation method applied before and after conversion selection in data

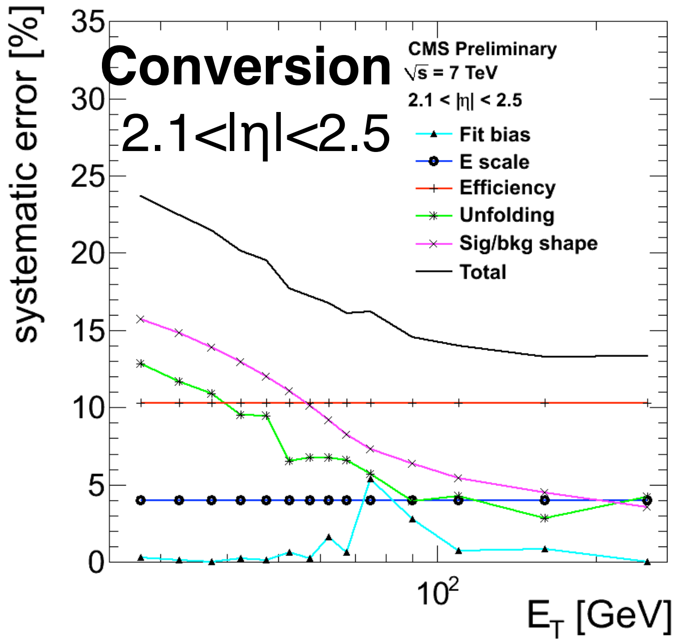


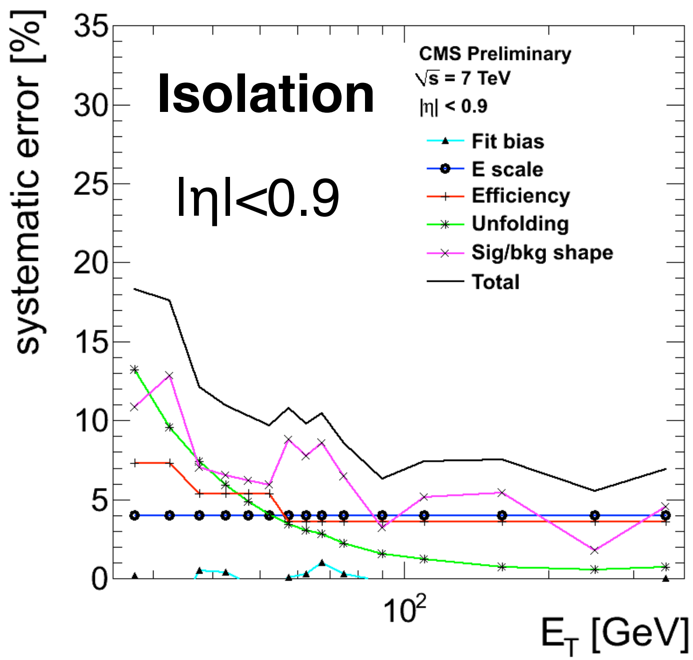
# Systematic uncertainties :

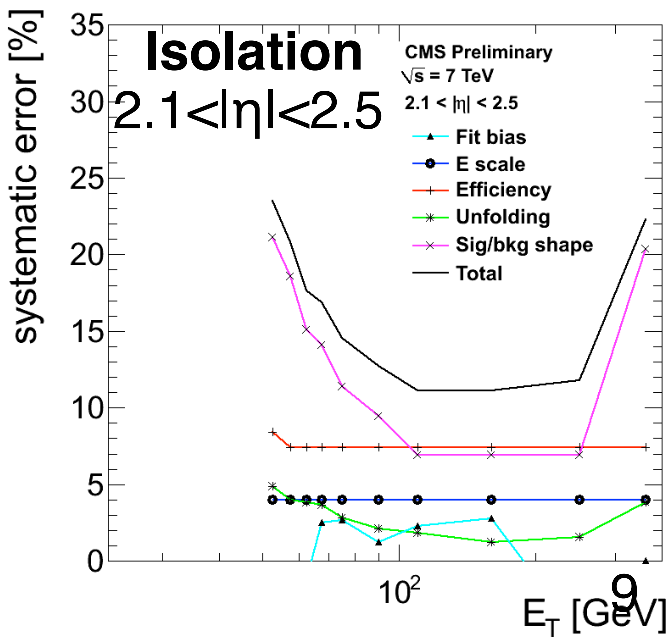
**Conversion method :** biggest uncertainty from conversion efficiency, estimated conservatively




For **isolation method,** the biggest uncertainty comes from the signal and background shapes

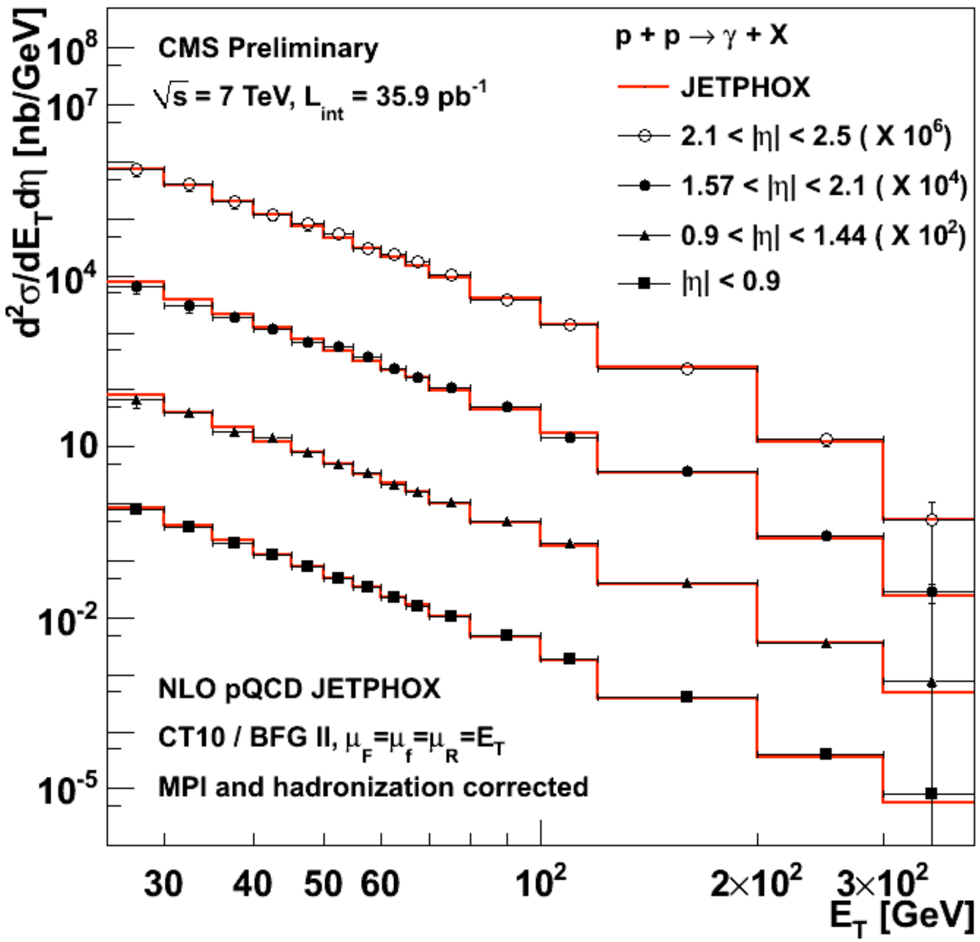


# Isolated prompt photon cross-section

$$d^2\sigma/dE_T d\eta = N^\gamma \cdot \mathcal{U}/(L \cdot \epsilon \cdot \Delta E_T \cdot \Delta\eta),$$

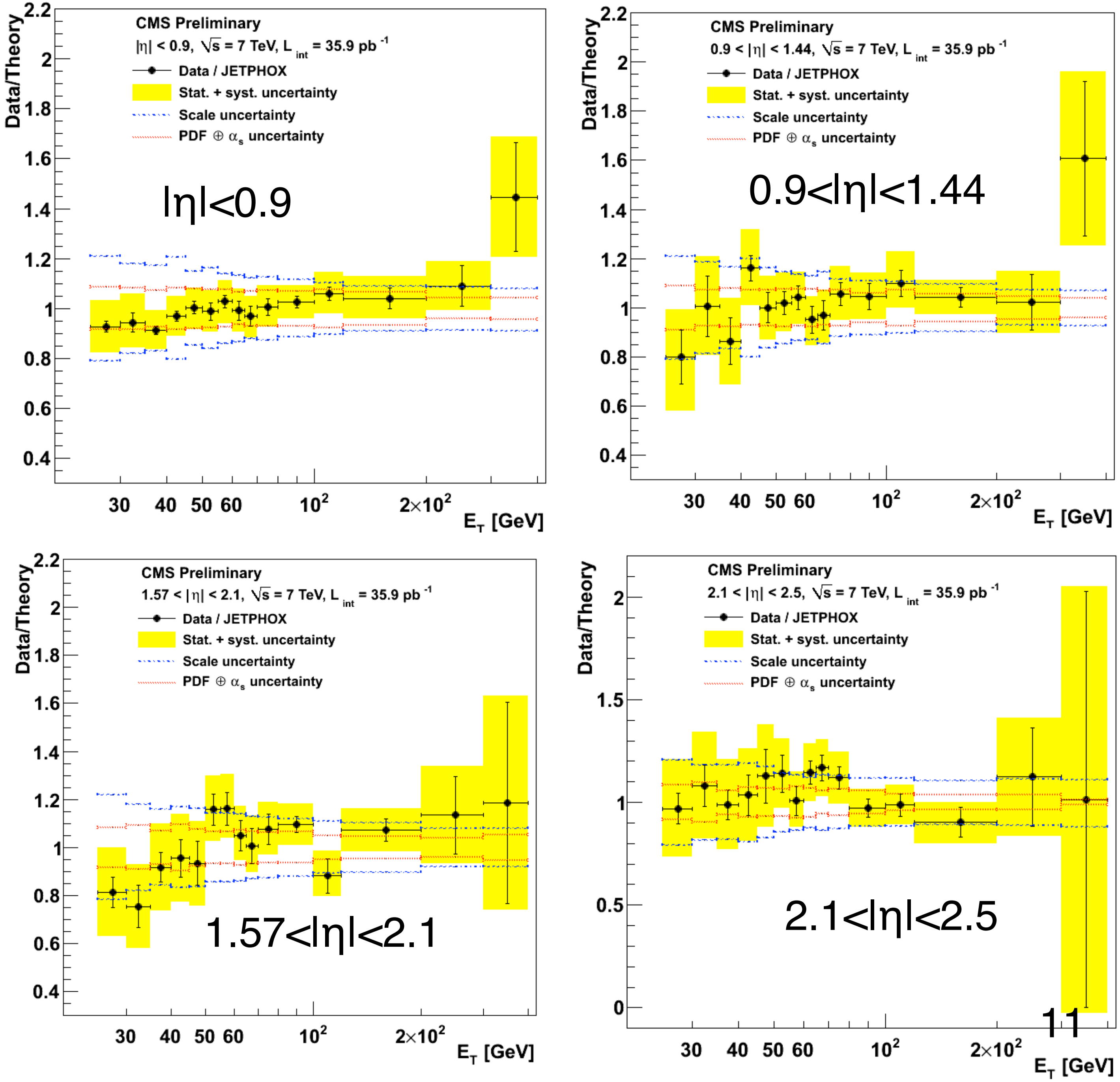
- **Isolation and conversion results** are **statistically combined** with the BLUE method [1] (Best Linear Unbiased Estimate)
- Comparison with **predictions from JetPhox** [2] (NLO), corrected for multiple parton interaction and hadronization effects. Pdf **CT10**, BFG II fragmentation function.




*Agreement between data and theory in the whole η and $E_T$ range considered*

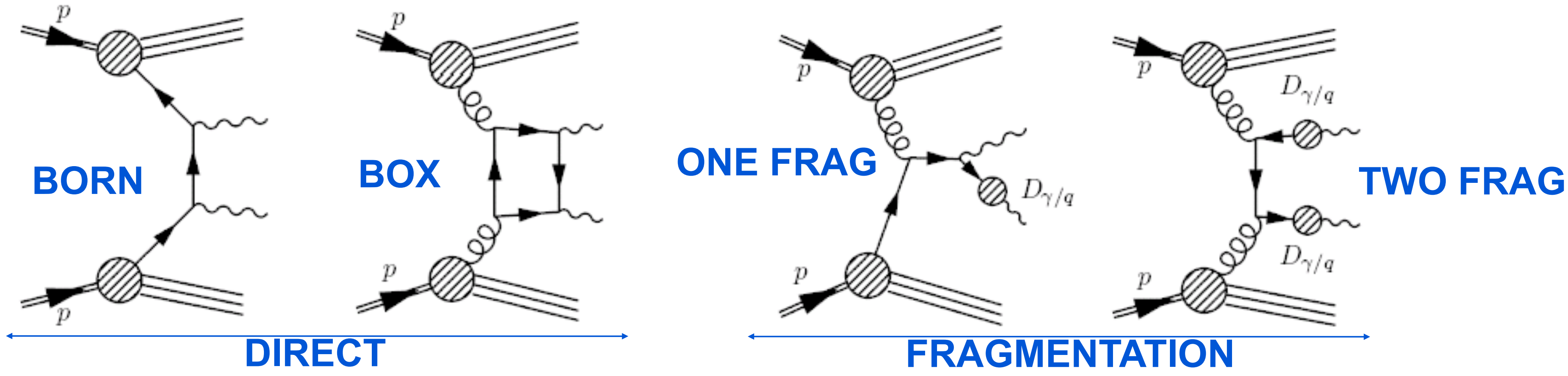
# Data / theory comparison

- **Measurement** **driven by conversion method at low $E_T$ and by isolation method at high $E_T$**
- Data below prediction in the low $E_T$ region, agreeing within uncertainties
- Largest theoretical uncertainty from renormalization / factorization / fragmentation scales



# Production of isolated diphotons

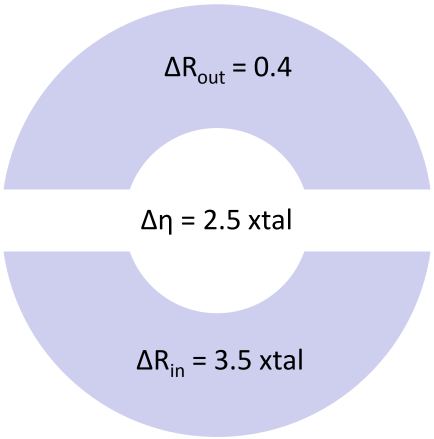
**- Prompt diphoton production** via quark annihilation ('Born'), gluon-gluon fusion ('Box') and via single and double parton to photon fragmentation




**CMS PAPER QCD 10-035**

- First measurement in CMS, with the **2010 dataset** : **36 pb$^{-1}$**, in the kinematical range **$|\eta|<2.5$**, with **$E_{T1}>23$, $E_{T2}>20$ GeV, $\Delta R(\gamma 1,\gamma 2)>0.45$**
- Method using **electromagnetic isolation energy**
- Differential cross-section for 4 variables : $M_{\gamma\gamma}$, $P_{T,\gamma\gamma}$, $\Delta\Phi$, $\cos(\theta^*)$

# ECAL isolation method

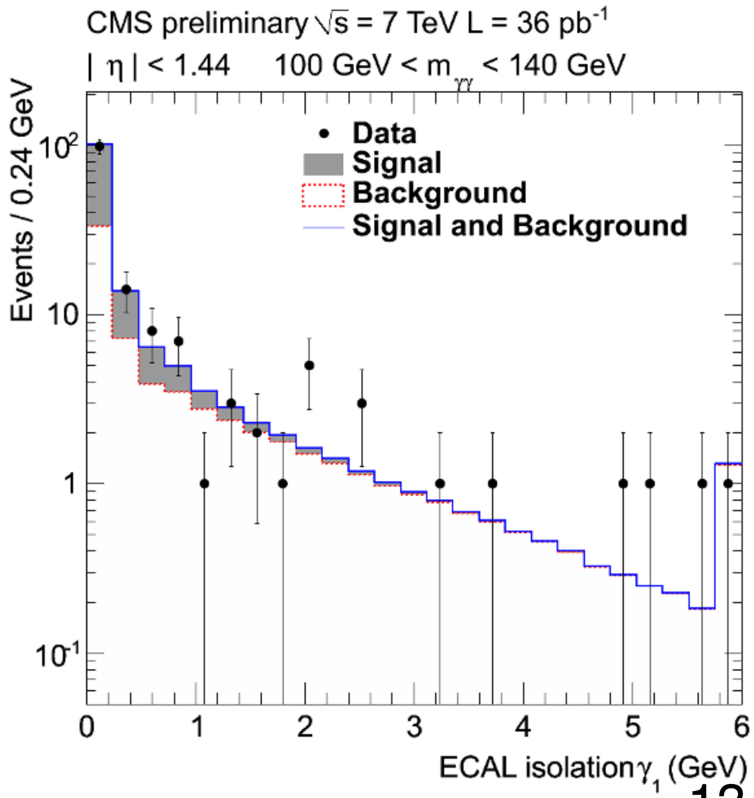



## Use Ecal isolation energy :

- $\sum E_T$ collected with the crystals in a cone $\Delta R<0.4$ around the photon
- Crystal threshold $E_T>300$ MeV, well above the electronic noise and readout threshold, *which allows to use fully data-driven techniques*

**Extract diphoton yield with simultaneous unbinned likelihood fit on the two photons:**

- **Fully data-driven** signal and background pdf
- **Signal pdf** with '***random cone***' technique: measure Ecal isolation energy in a cone randomly thrown. Uncertainties from Z->ee and W->ev comparison.
- **Background pdf** with '***impinging track***' method: require one track in isolation cone. Uncertainties from comparison with two tracks.
- **Systematic uncertainty on signal extraction : ~5%**



# Signal selection efficiency for $\gamma\gamma$+X measurement

- **Selection efficiency :** $\varepsilon_{trig} \times \varepsilon_{reco} \times \varepsilon_{ID} = 76.3\%$
- **Trigger** : Three paths requiring two photon candidates. $\varepsilon_{trig} \sim 100\%$ (simulation)
- **Reconstruction** : Estimated from simulation
- **Identification** :
  - **Isolation and cluster shape selection** : measured with $Z \rightarrow ee$ events in data, corrected for the photon/electron difference
  - **Impinging track veto** : measured from random cones

For a generic variable Ω

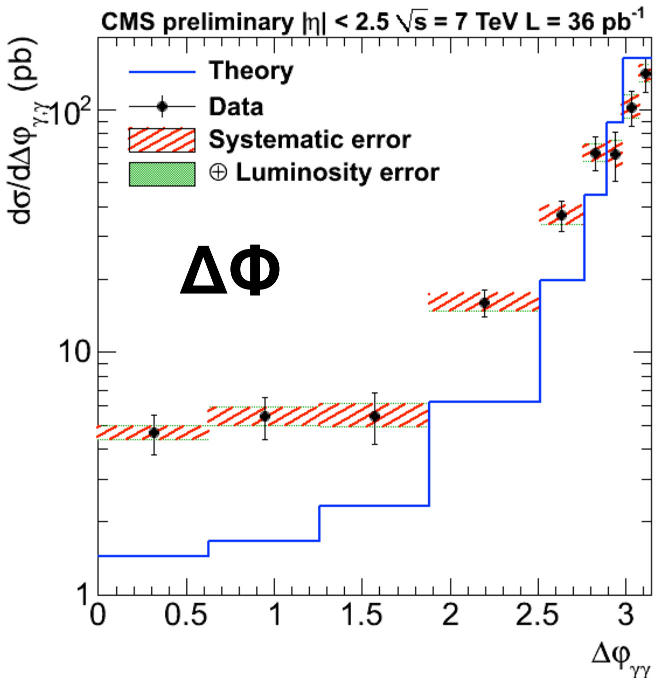
$$\frac{d\sigma}{d\Omega} = \frac{N_{\gamma\gamma}^{\mathrm{unfolded}}}{\mathrm{Efficiency} \times \Delta\Omega \times \mathcal{L}}$$

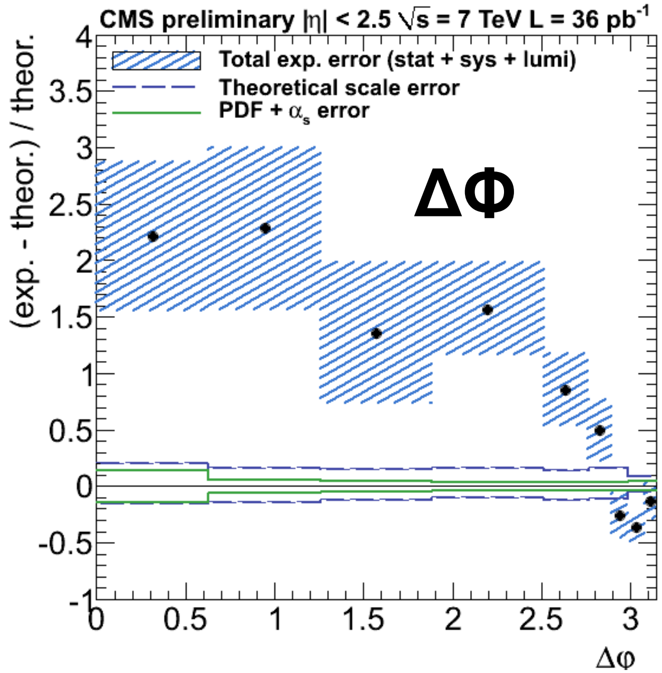
**Comparison of the differential cross-section to theoretical predictions at NLO :**

- Follow **PDF4LHC** prescription [3,4,5,6]
- **Born** and **fragmentation** contributions at **NLO** with **DIPHOX** [7]
- **Box** contribution at **NLO** with **GAMMA2MC** [8]
- **Asymmetric $E_T$>23,20 GeV requirement improves fixed order predictions**

# Diphoton cross-section

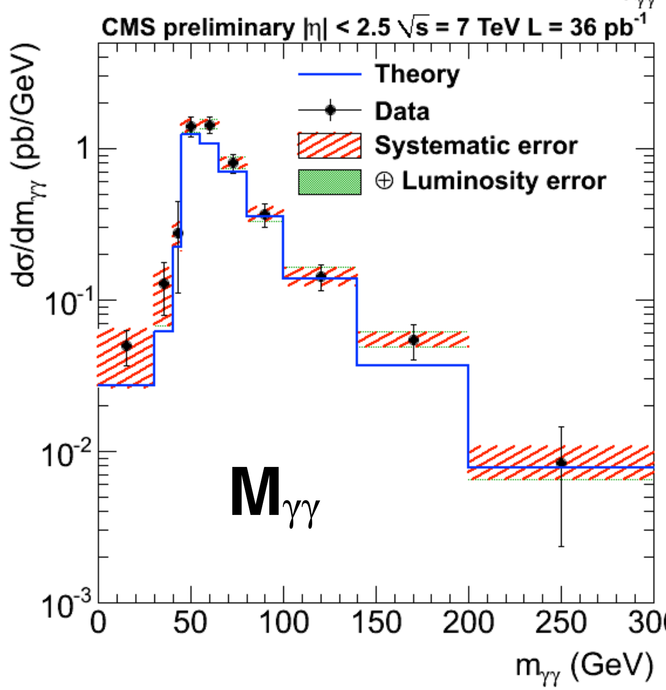
Smaller **azimuthal difference ΔΦ** in data than in theory (missing higher order contributions in the predictions)

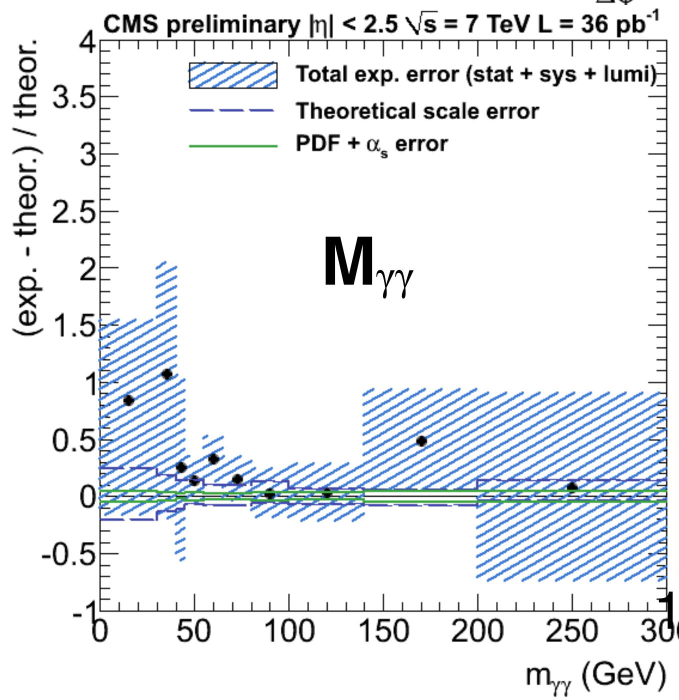



**Diphoton invariant mass $M_{\gamma\gamma}$**

Predictions underestimate data near the kinematical threshold $M_{\gamma\gamma} \sim 2 \times P_{T\gamma\gamma}^{threshold}$ (corresponds to low ΔΦ region)

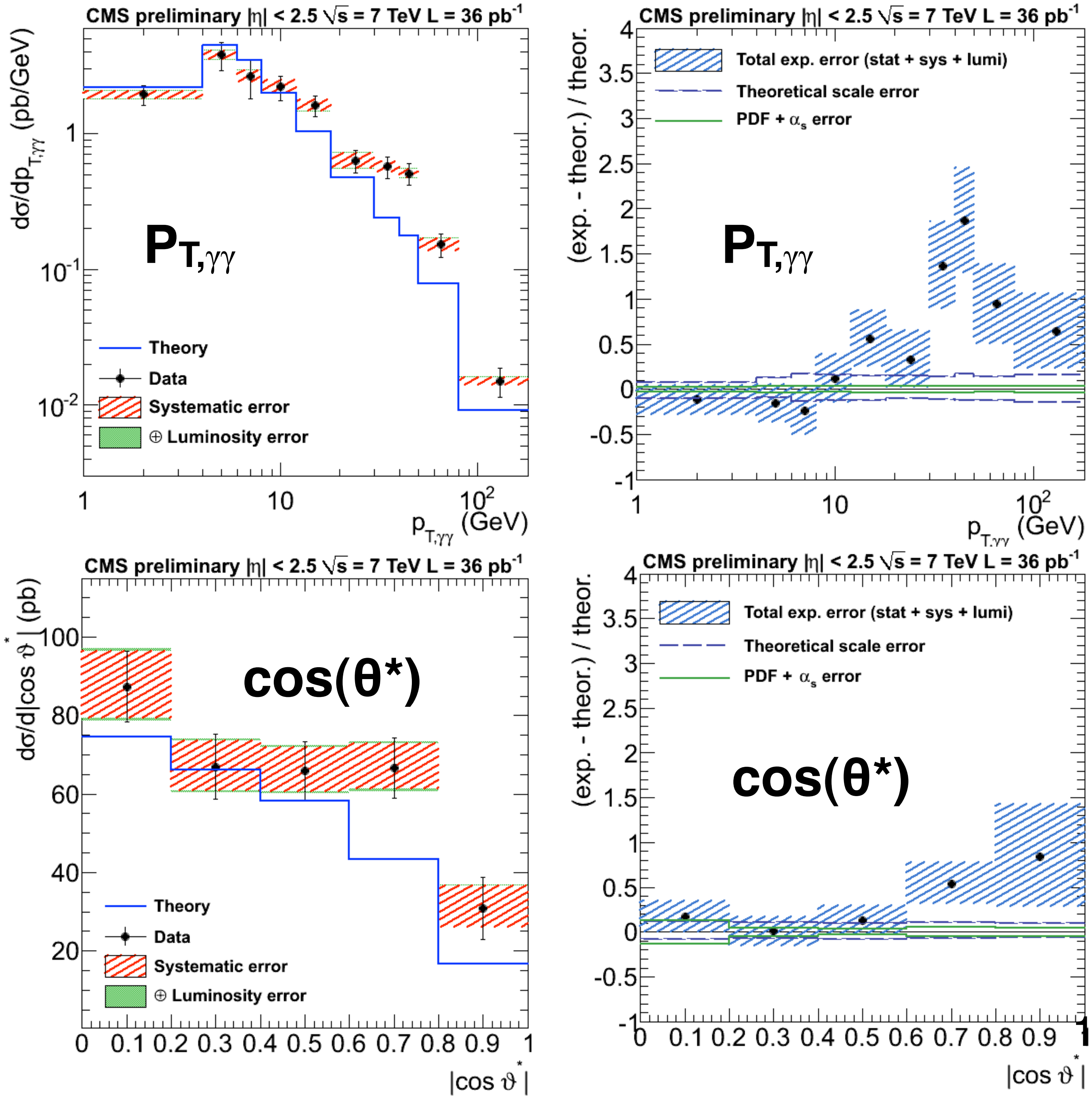


# Diphoton cross-section

**Diphoton transverse momentum $P_{T\gamma\gamma}$**
Known shoulder near $P_{T,\gamma\gamma} \sim 2 \times P_{T\gamma}^{threshold}$ not reproduced in theory (corresponds to low $\Delta\Phi$ region)

**cos(θ*)**, scattering angle in Collins-Soper frame,
**$\cos(\theta^*)=\tanh(\Delta Y_{\gamma\gamma}/2)$**



# Conclusions

## Inclusive isolated prompt photon measurement :

- Extend previous CMS measurement with the 2010 dataset (36 $pb^{-1}$), 25 < $E_T$ < 400 GeV in 4 $\eta$ bins up to $|\eta|<2.5$
- Combines two methods : photon conversions (competitive at low $E_T$) and isolation sum (competitive at high $E_T$)
- Agreement with NLO predictions within the whole range studied

## Isolated prompt diphoton measurement :

- First presentation of this new CMS measurement, with the full 2010 dataset (36 $pb^{-1}$), performed in the kinematic region $E_T$ >23,20 GeV, $\Delta R>0.45$, $|\eta|<2.5$
- Uses an innovative ECAL isolation method
- Overall agreement with NLO predictions, apart from the low $\Delta\Phi$ region, sensitive to higher order perturbative QCD effects

# BACK-UP SLIDES

# References : Theory


[1] L. Lyons, D. Gibaut, and P. Clifford, "How to Combine Correlated Estimates of a Single Physical Quantity", Nucl. Instrum. Meth. A270 (1988) 110.

[2] S. Catani, M. Fontannaz, J.P. Guillet et al., "Cross section of isolated prompt photons in hadron-hadron collisions", JHEP 05 (2002) 528

[3] M. Botje et al., "The PDF4LHC Working Group Interim Recommendations", arXiv: 1101.0538.

[4] H.L. Lai, M. Guzzi, J. Huston et al., "New parton distributions for collider physics", Phys. Rev. D 82 (2010) 070424

[5] A.D. Martin, W.J. Stirling, R.S. Thorne et al., "Parton distribution for the LHC", Eur. Phys. J. C63 (2009) 189

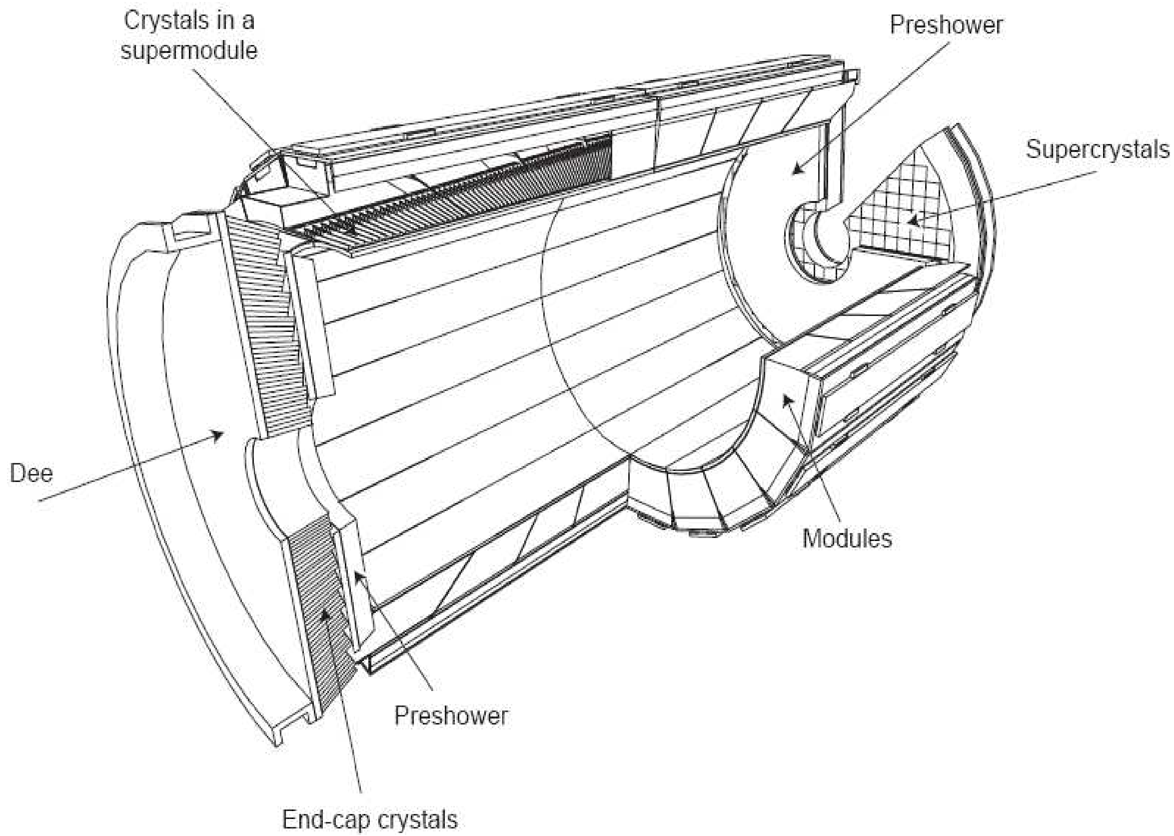
[6] NNPDF Collaboration, "A first unbiased global NLO determination of parton distributions and their uncertainties", Nucl. Phys. B838 (2010) 136

[7] T. Binoth, J. P. Guillet, E. Pilon et al., "A Full next-to-leading order study of direct photon pair production in hadronic collisions", Eur. Phys. J. C16 (2000) 311–330, arXiv:hep-ph/9911340. doi:10.1007/s100520050024.

[8] Z. Bern, L. J. Dixon, and C. Schmidt, "Isolating a light Higgs boson from the di-photon background at the LHC", Phys. Rev. D66 (2002) 074018, arXiv:hep-ph/0206194. doi: 10.1103/PhysRevD.66.074018.

# CMS electromagnetic calorimeter (ECAL)

The **ECAL** is made of scintillating crystals of PbWO4 :
-**Barrel** : 36 “supermodules” with 1700 crystals each (coverage $|\eta|<1.48$)
-**Endcaps** : 268 “supercrystals” with 25 crystals each (coverage $1.48<|\eta|<3.0$)
Furthermore, a **preshower** made of silicon strip sensors is located in front of the endcaps ($1.65<|\eta|<2.6$)

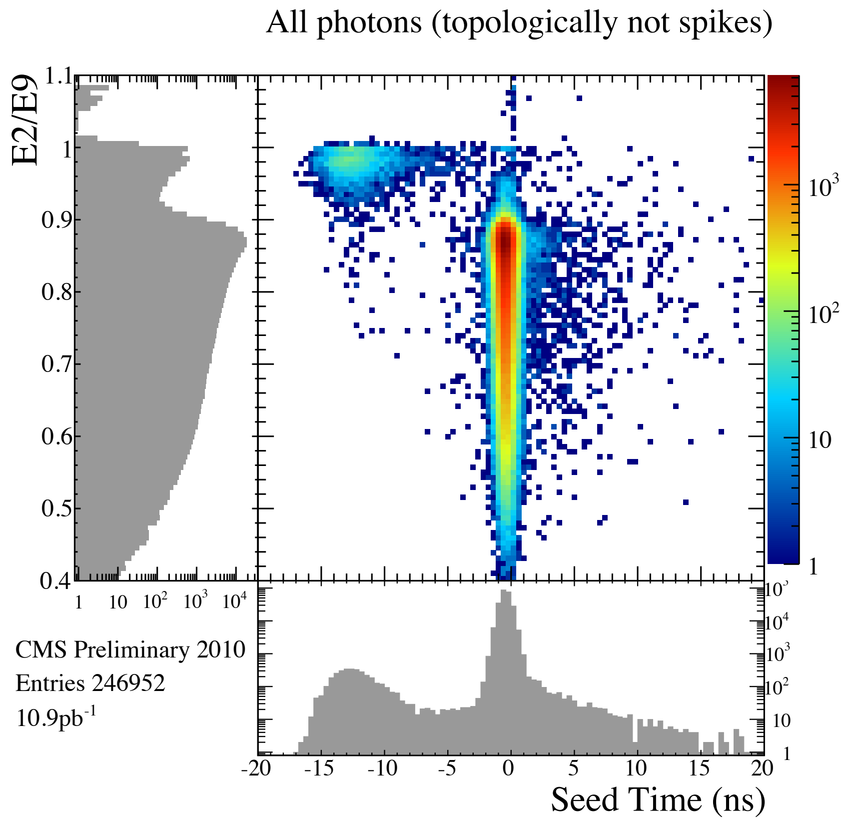


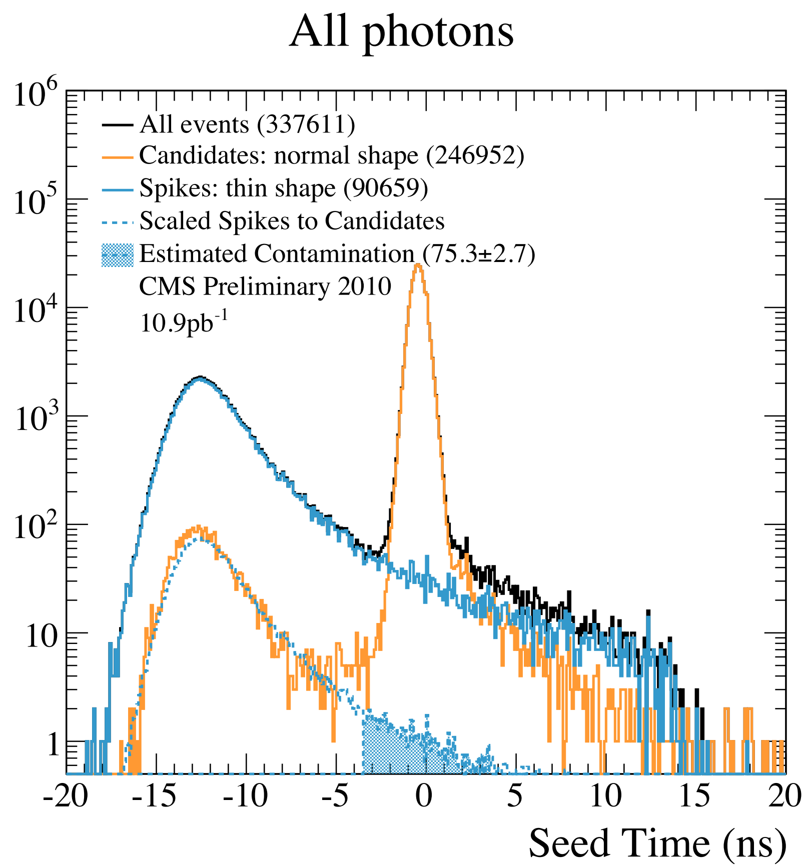

**Energy resolution** (measured in electron test beam) :

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus \frac{b}{E(GeV)} \oplus c$$

a = 2.8% stochastic term
b = 12% noise term
c = 0.3% constant tern

# Anomalous energy deposits in ECAL



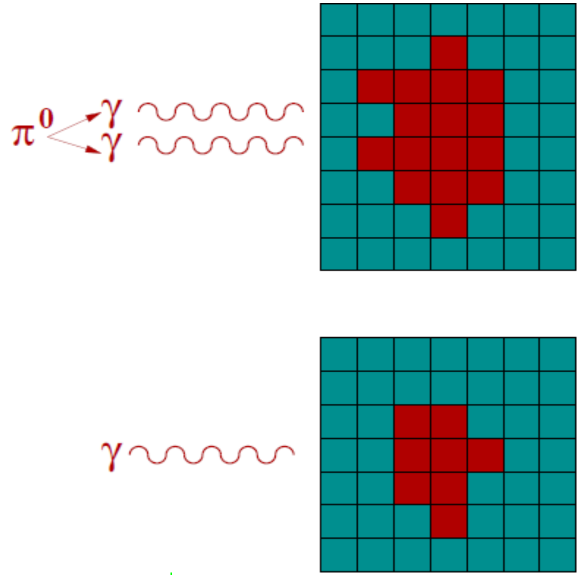



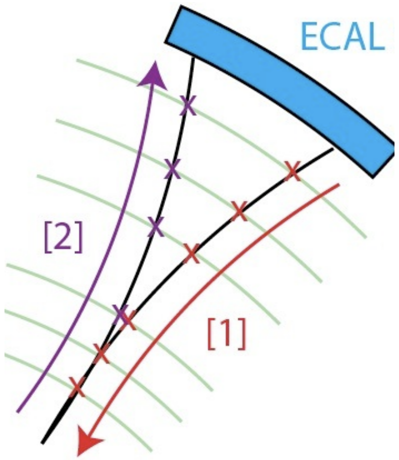

Contamination : <0.2%

# Photon selection

## Photon identification :

- **Electron rejection** : the supercluster should not be matched to hits in the pixel detector (not applied for conversion method)
- Selection on the **transverse shape** of the energy deposit in ECAL, required to be compatible with a single photon shower
- **Isolation** : in a cone $\Delta R<0.4$ around the photon, use $\sum E_T$ of energy deposits in ECAL, HCAL and $\sum p_T$ of the charged particles measured in the tracker



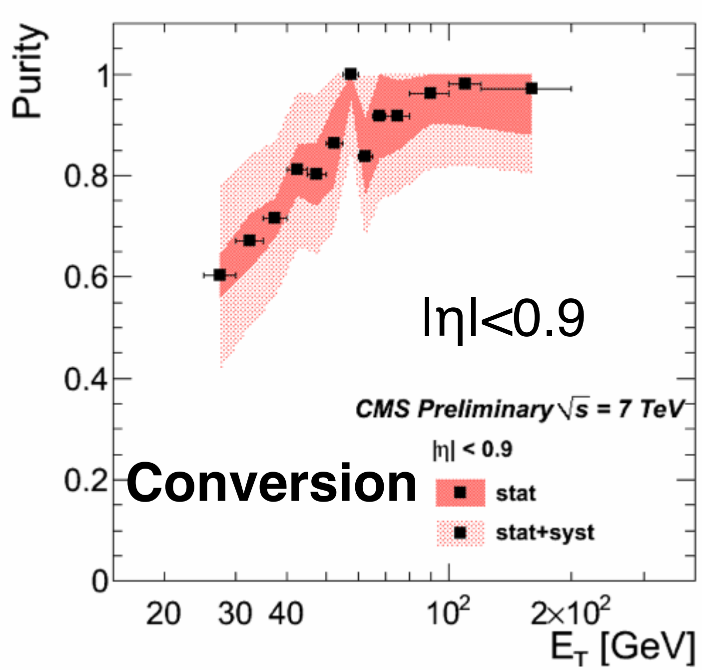

## Converted photons :

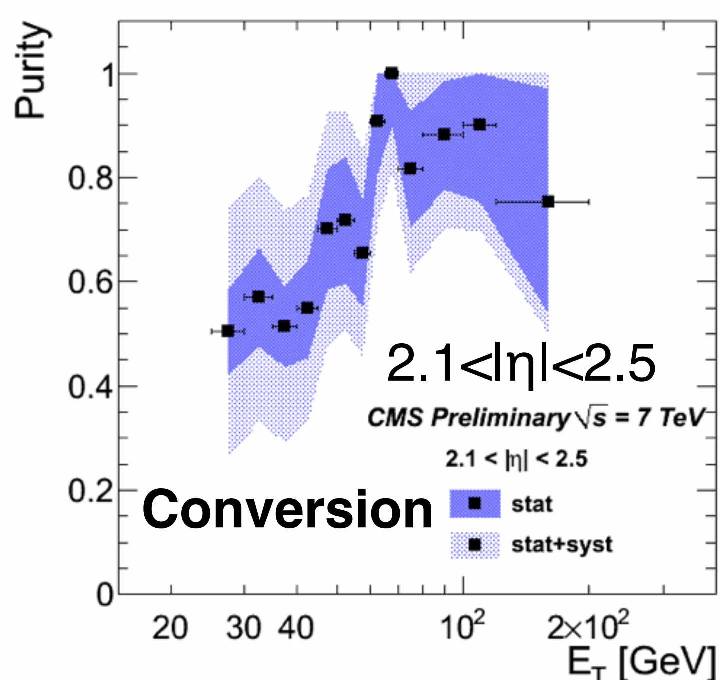
- Start from **energy deposits in ECAL**
- **Track finding** proceeds inward and outwards, taking into account electron energy loss by bremsstrahlung
- Select the $e^+/e^-$ pair with the best vertex fit $\chi^2$

- Huge background of boosted neutral mesons decaying to two photons, reconstructed as a single one
- After identification, **need to statistically subtract the background component**

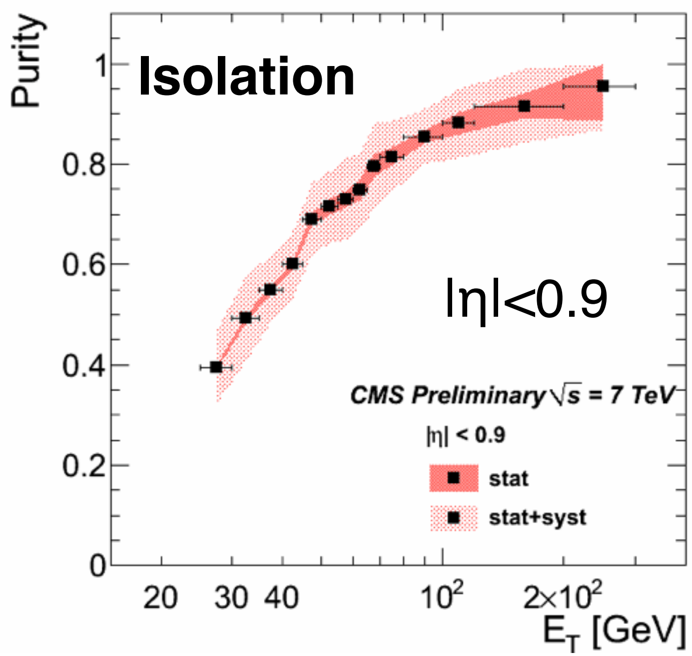
# γ+X : Purity after selection

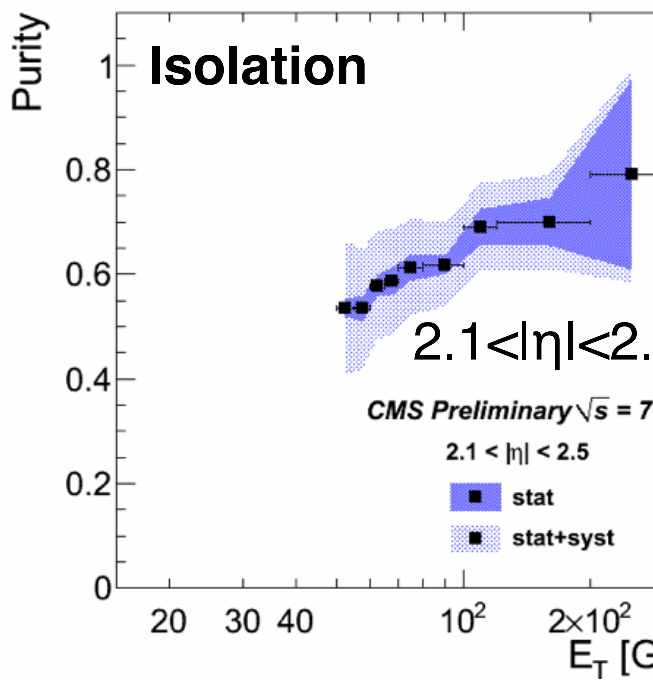
- **Conversion method :**
  **High purity at low $E_T$.**
  Higher than 60% in barrel and 45% in endcap, close to 100% at high $E_T$



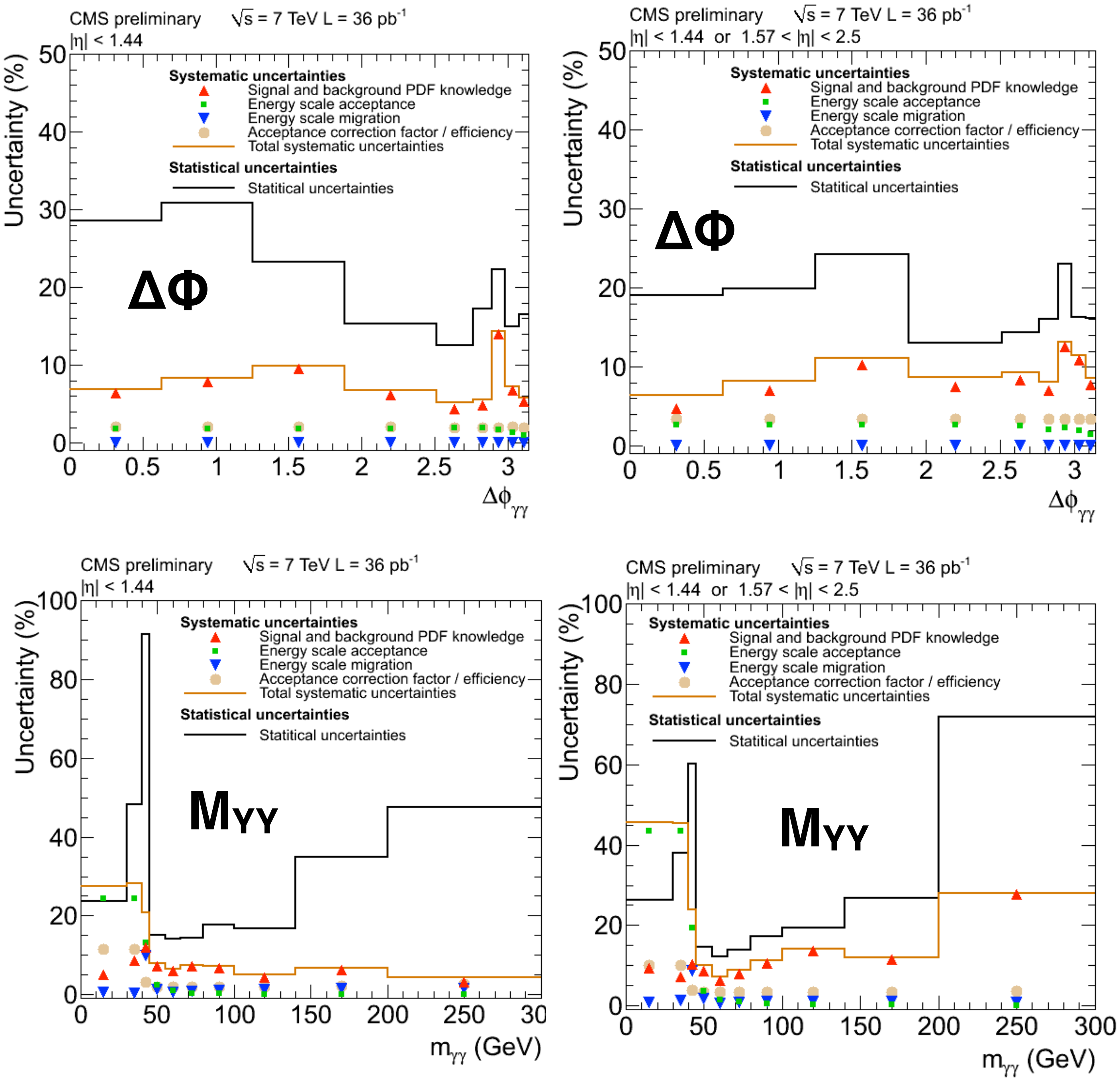

- **Isolation method** :
  Purity higher than 40% in barrel and 55% in endcap




Note : the two methods are using a different selection, thus the difference of purity

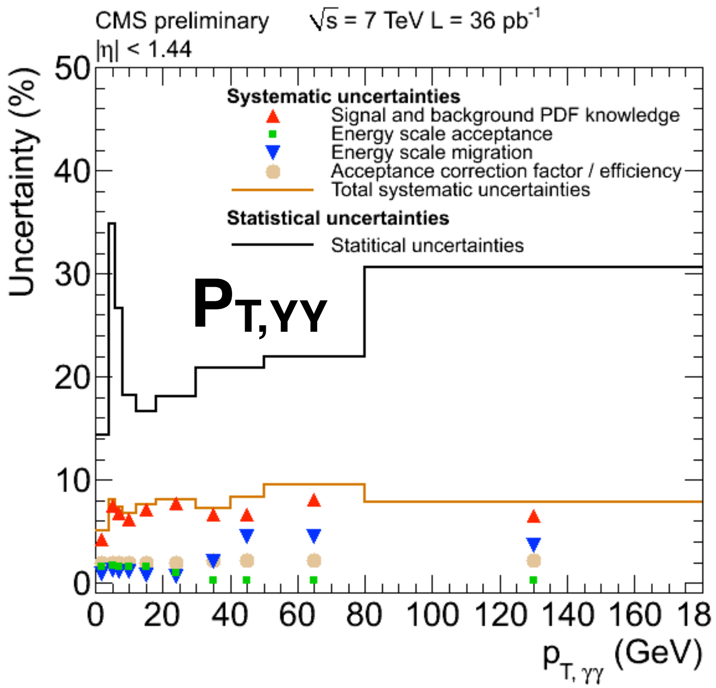
# γγ+X : Systematic uncertainties

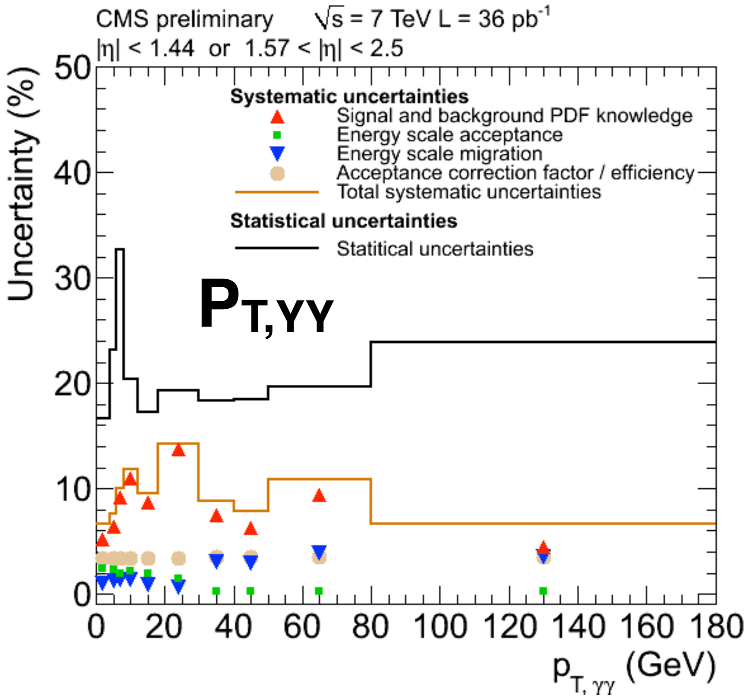



- Measurement statistically dominated

- Systematic uncertainties : ~10%

# γγ+X : Systematic uncertainties

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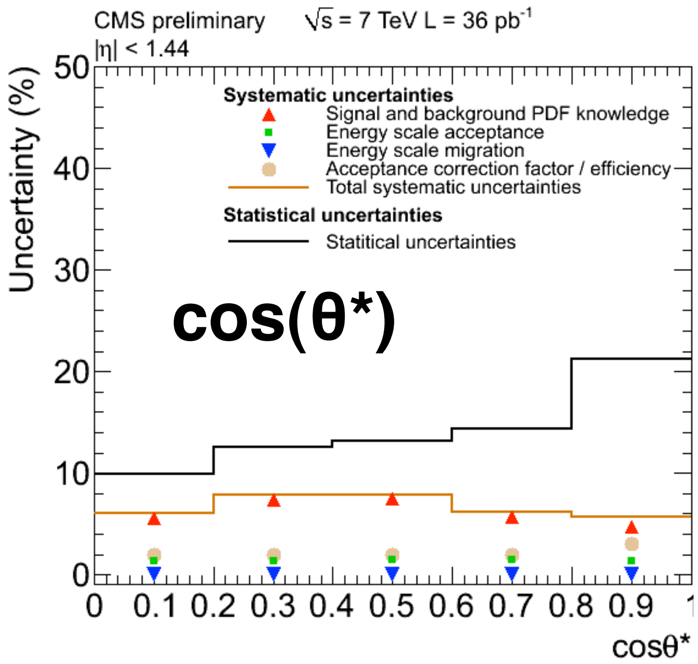
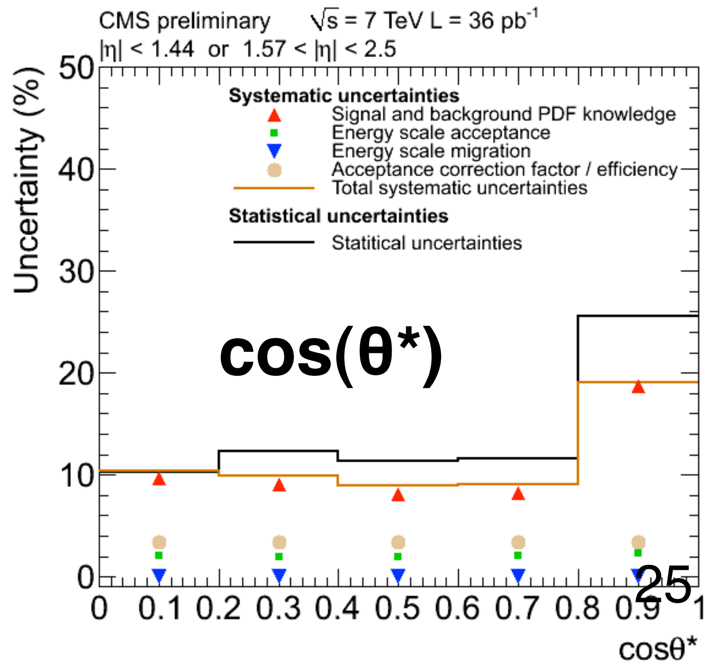
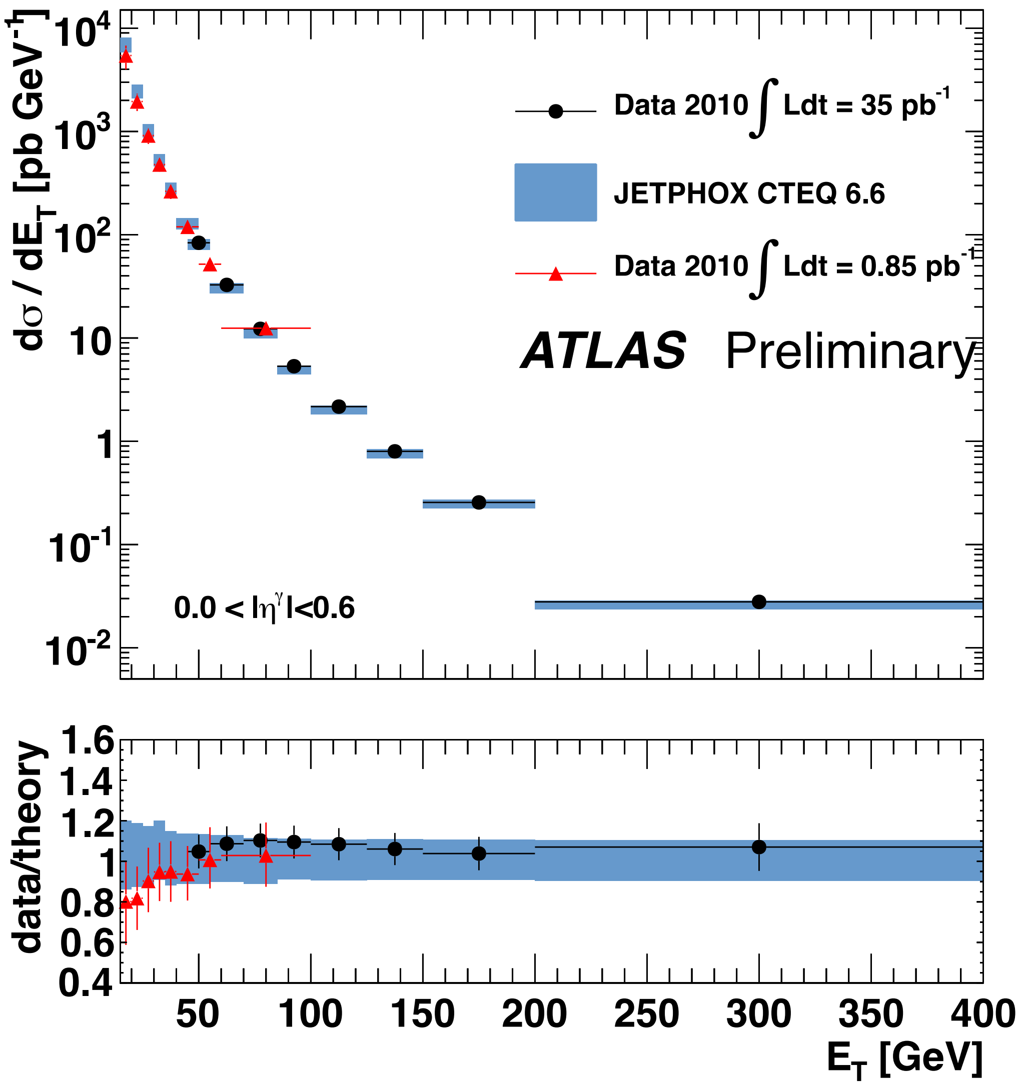


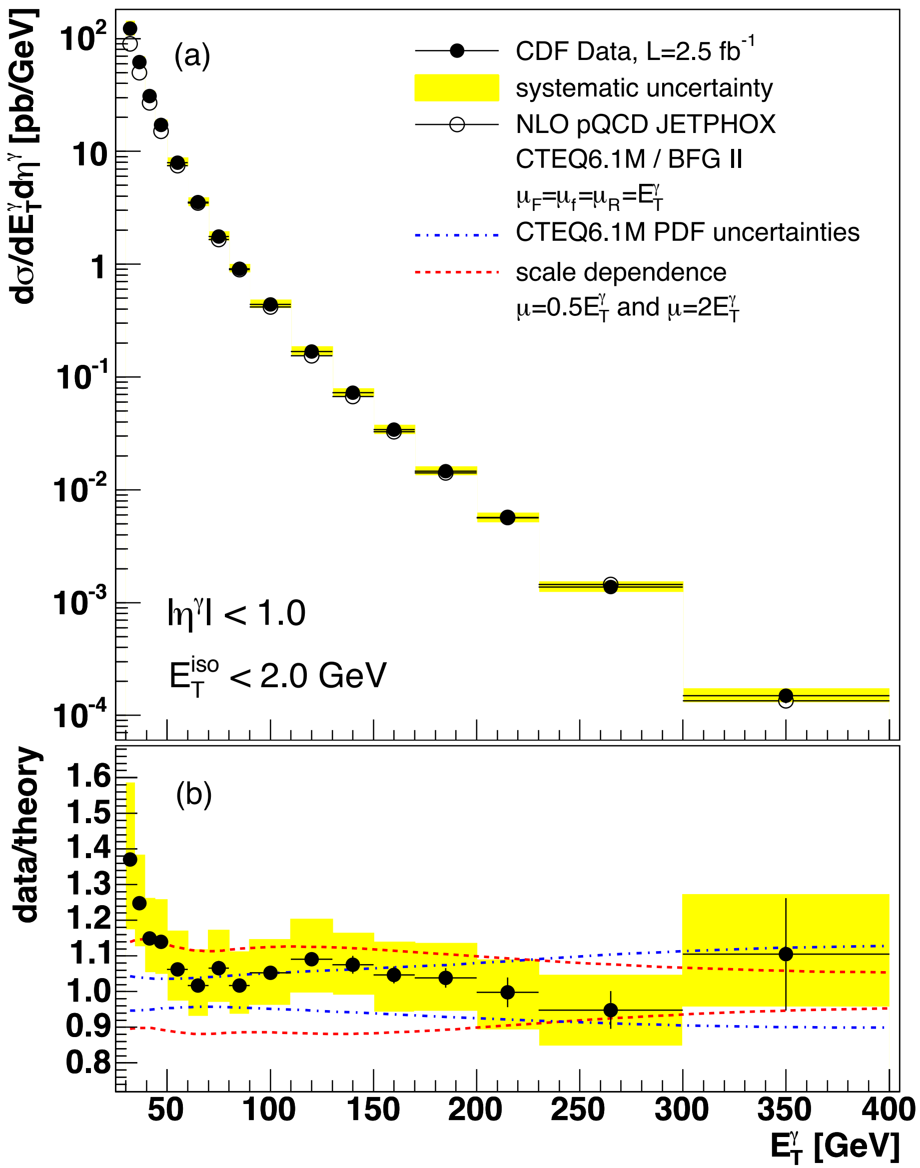



# Low pt trend in inclusive photon cross-section ?

## ATLAS CONF-2011-058

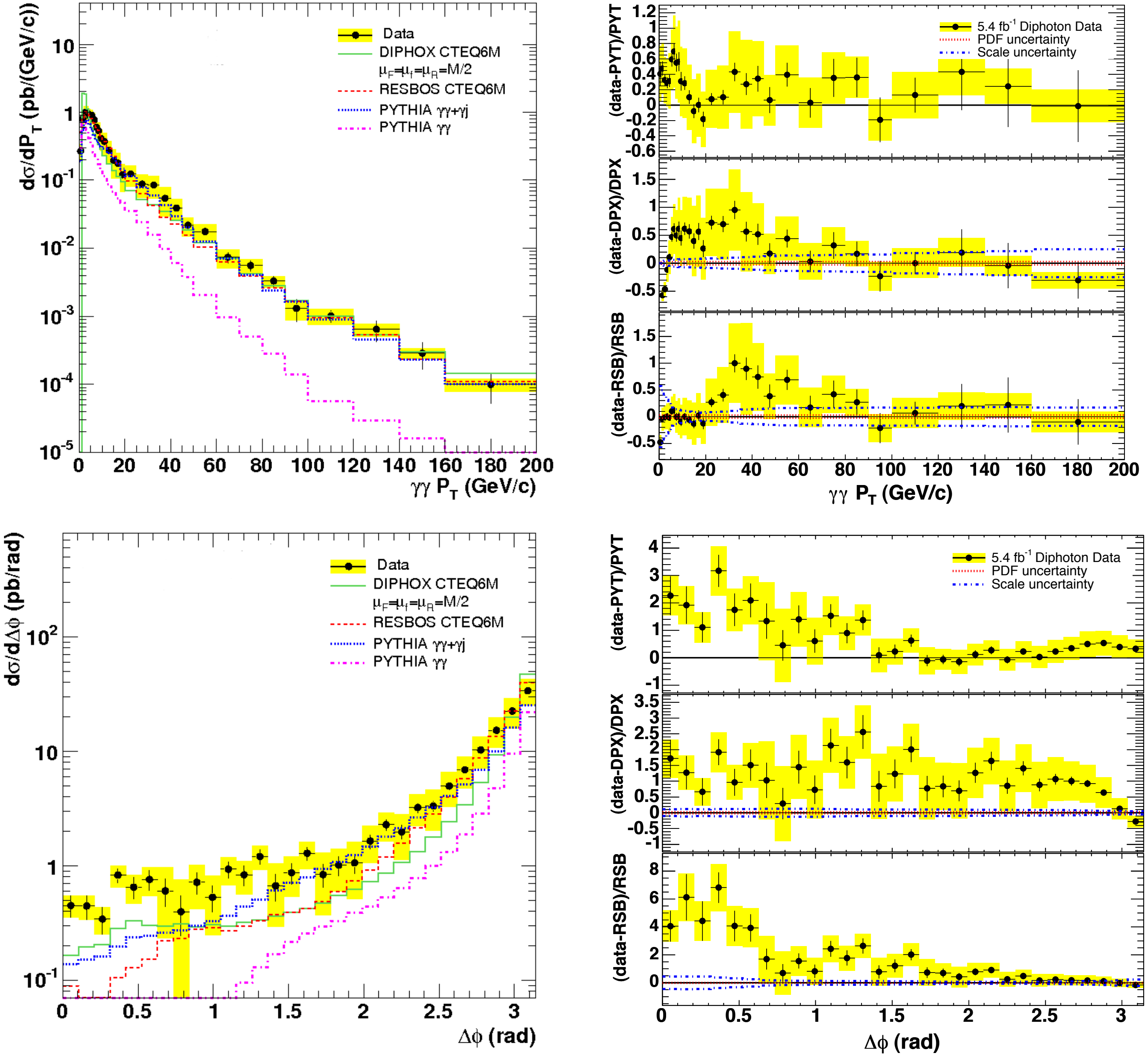



## CDF, Phys.Rev.D80:111106,2009



# CDF Diphoton measurement

**arXiv:1106.5123**



# ATLAS Diphoton measurement

**arxiv:1107:0581**