Measurement of Differential Photon-Jet Cross-Section from 7 TeV p-p Collisions in the CMS Experiment

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on behalf of the CMS collaboration

Introduction

History

- Early measurements of prompt photon production were carried out at the ISR (Intersecting Storage Rings) hadron collider at CERN [1-2]
- Later studies established prompt photons as a powerful probe of the dynamics of hard QCD interactions [3-5]
- More recent prompt photon studies from CMS [6] and ATLAS [7-8]
- More recent photon and associated jet cross-section measurements are from DØ [page 4] and ATLAS [page 5]

Scope

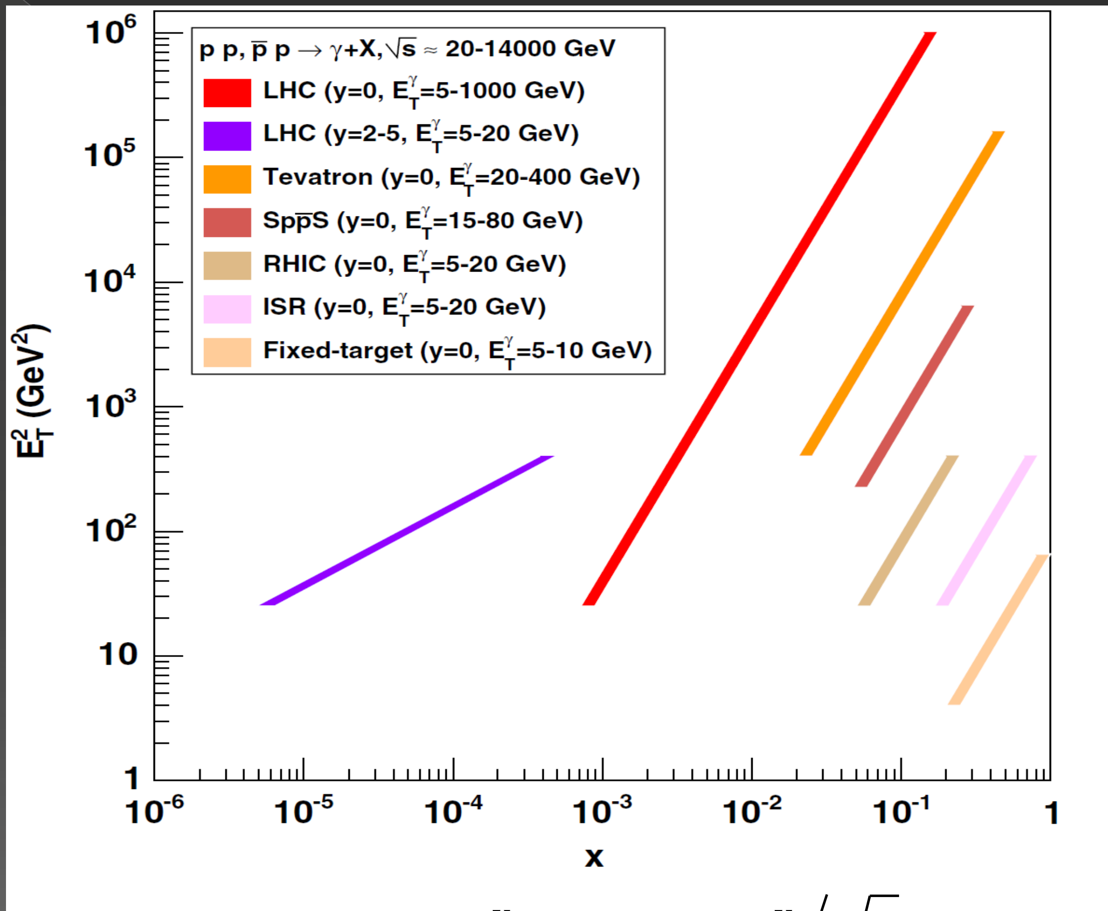
- **Measurement of triple differential cross-section for photon+jet production from 7 TeV proton-proton collisions with 2.14 fb^{-1} data in the CMS experiment at the LHC will be presented here**
- **Public results can be found at: CMS-PAS-QCD-11-005**

Acknowledgement

- Many thanks to CMS collaborators and **CMS photon+jet cross-section measurement team** who marked these results in history.

Photon Physics @ LHC

- Kinematical region probed by existing prompt photon measurements at fixed-target (Fermilab) and collider (ISR, RHIC, SppS, Tevatron) energies, and expected range probed at the LHC at central (y=0) and forward (y=2–5) rapidities.
- More than 30 years of experimental data varying from 20 GeV to 7 TeV energies



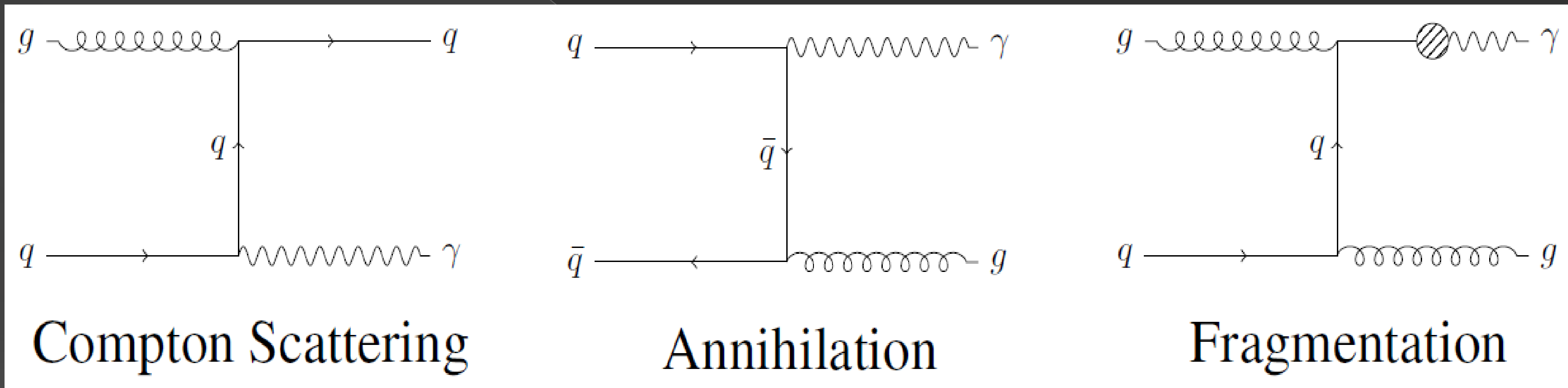
$$x = x_T \times e^{-y} = 2p_T \times e^{-y} / \sqrt{s}$$

- **LHC results probe a couple of orders of magnitude lower x compared to previous measurements** [R. Ichou and D. d'Enterria, Phys. Rev. D 82, 014015 (2010)]

Prompt Photons

Production Mechanisms

- Prompt photons: high-p_T photons from the hard subprocess (direct photons) and from the collinear fragmentation of partons with large p_T (fragmentation photons)
- Prompt photons do not come from hadron (π^0, η, k_s^0, ω, ρ, …) decays
- Direct (or pointlike) photon: most probably separated from hadronic environment
- Fragmentation (or bremsstrahlung) photon: most probably accompanied by hadrons
- Compton-like gluon scattering (dominates at LHC) and quark-antiquark annihilation mechanisms yield direct photon



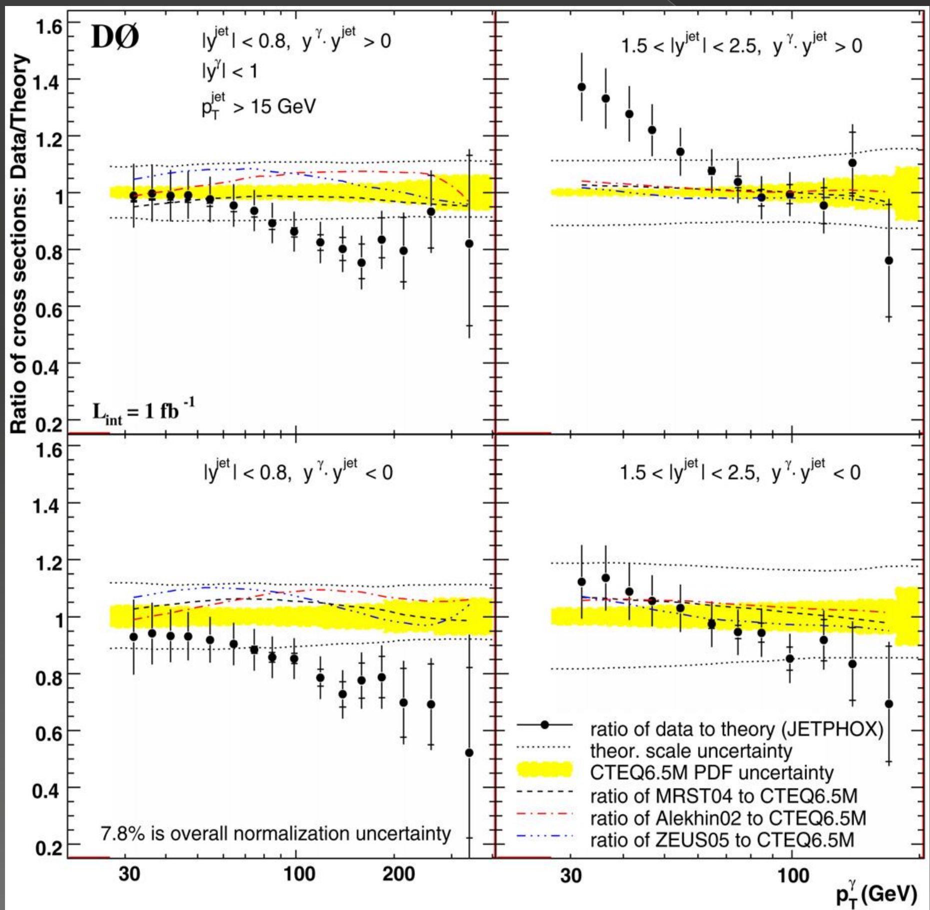
Physics Motivation [9-20]

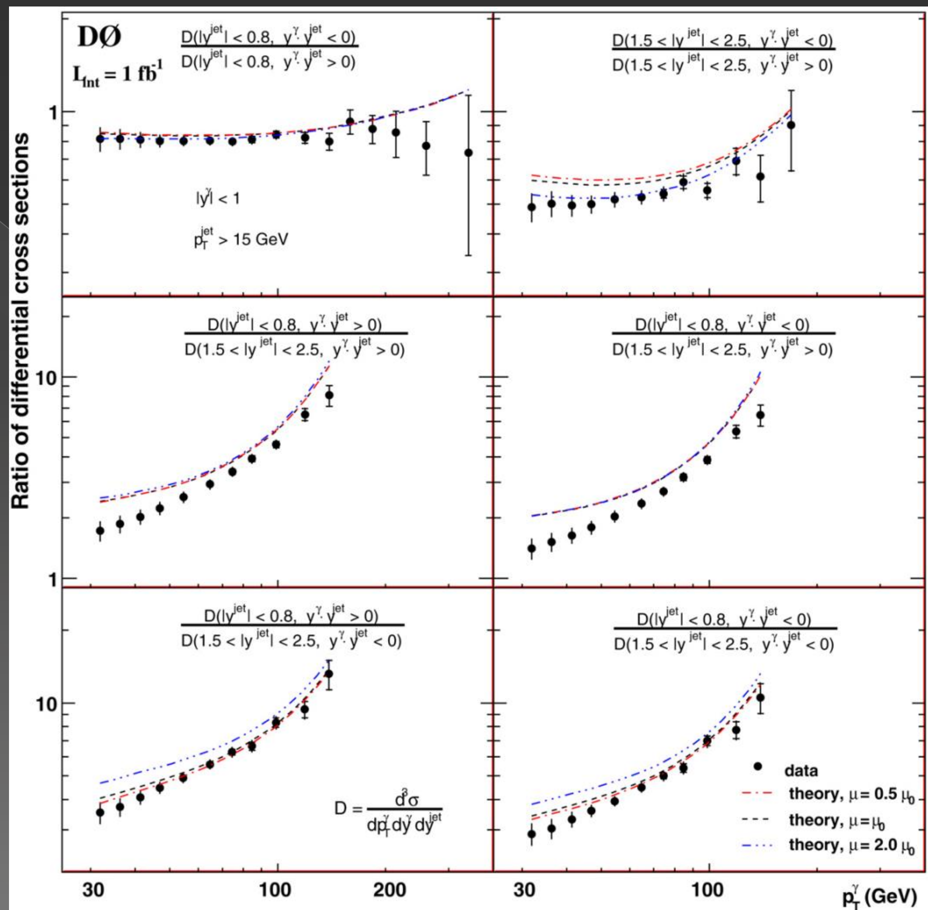
- Provides means for testing pQCD predictions
- Sensitive to gluon PDF in proton
- Background to searches for Higgs boson and new physics signatures ($H\rightarrow\gamma\gamma$, graviton, SUSY, excited fermions)
- Valuable for jet energy calibration and modeling of missing energy
- Reference for similar measurements in heavy ion collisions

More Recent Photon-Jet Results (I)

DØ Measurement [Physics Letters B 666 (2008) 435-445]

- Central photons ($|y^{\gamma}|<1.0$) with p_T^{γ}: 30-400 GeV & central ($|y^{jet}|<0.8$) and forward ($1.5<|y^{jet}|<2.5$) jets with $p_T^{jet}>15$ GeV @ 1 fb^{-1} data
- Comparisons between data-theory and PDF sets in different rapidity orientations
- Theoretical description of photon-jet production needs to be improved in terms of parameterizations of PDFs and theoretical scale variations



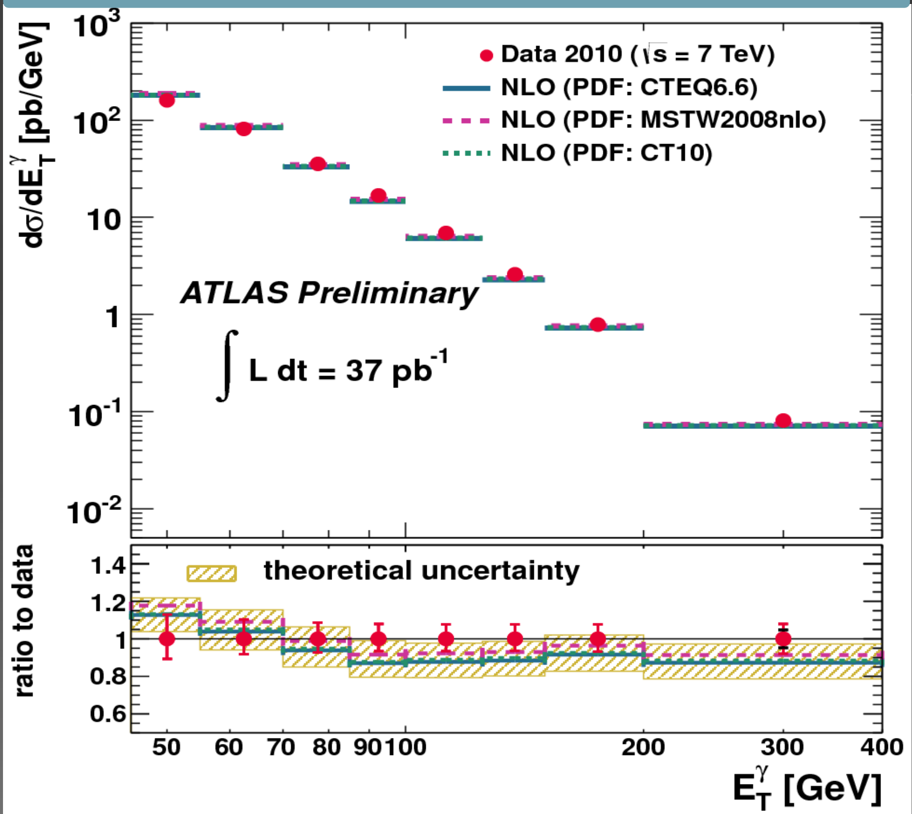


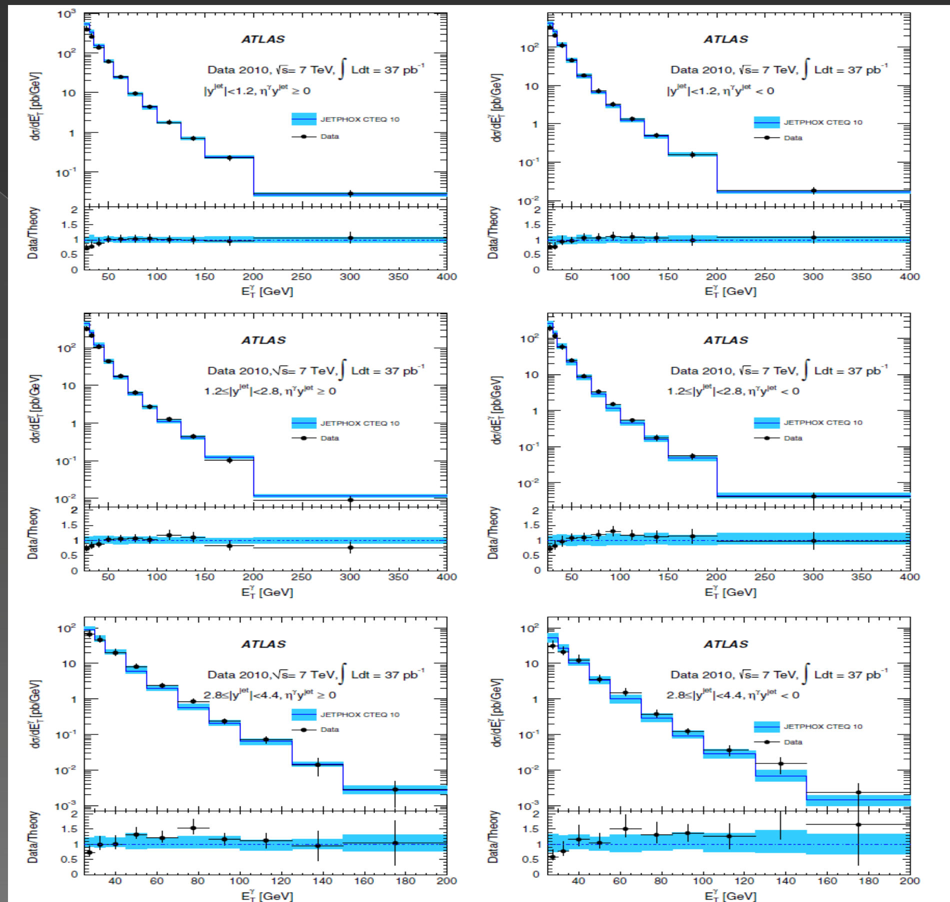
More Recent Photon-Jet Results (II)

ATLAS Measurement [Physical Review D 85, 092014 (2012)]

- Photons ($|\eta^{\gamma}|<1.37$) with p_T^{γ}: 25-400 GeV & jets ($|y^{jet}|<4.4$) with $p_T^{jet}>20$ GeV @ 37 pb^{-1} data
- Cross section vs. photon E_T and data-theory ratios in 3 jet rapidity regions and with 2 photon-jet orientations
- Fair agreement of data-theory, except for $E_T^{\gamma}<45$ GeV where JETPHOX overestimates data

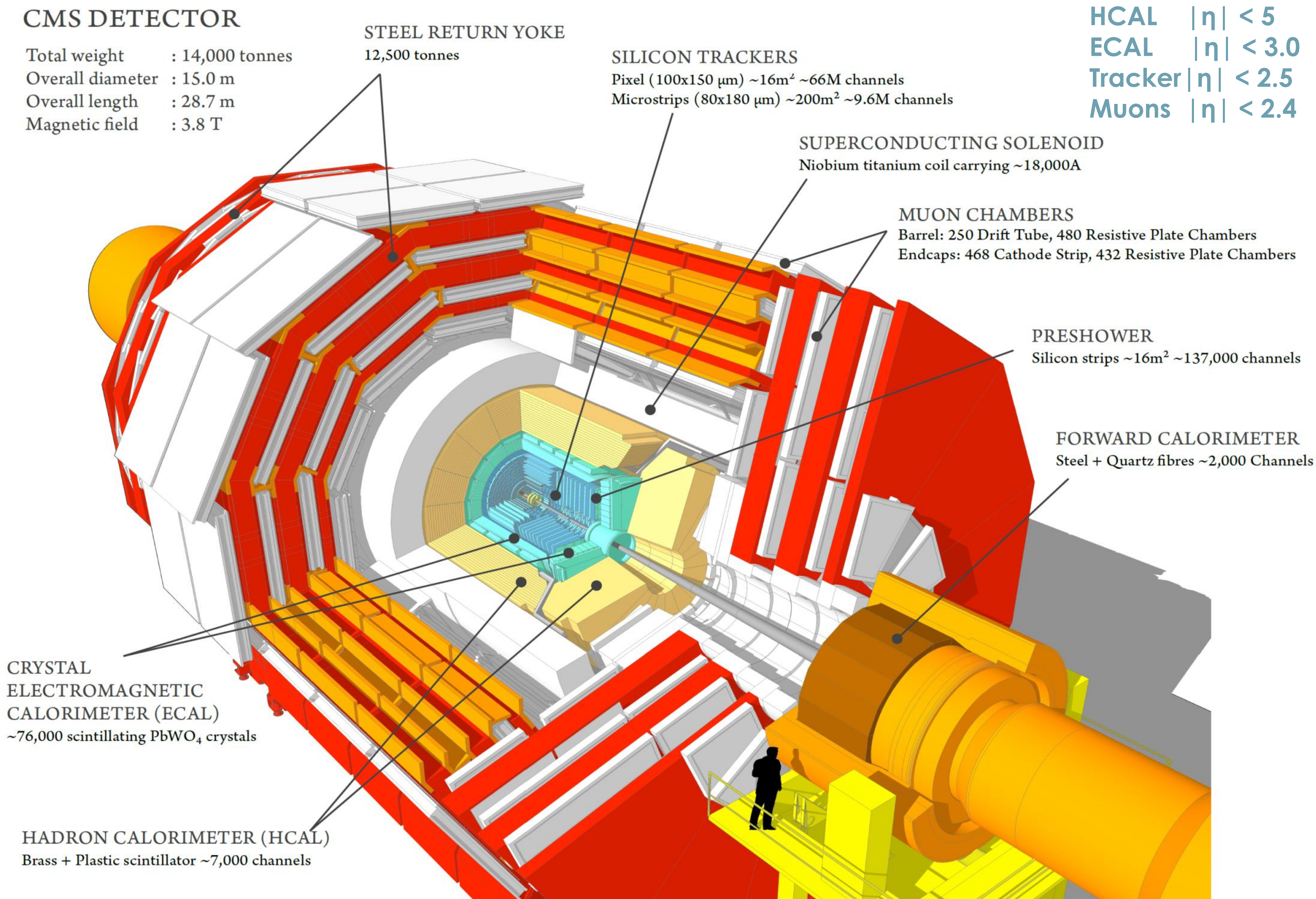
Photon-jet dynamics, [ATLAS-CONF-2013-023]





CMS Detector

Measurement made within Tracker acceptance |η| < 2.5



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

Triple Cross-section Ingredients

$$\frac{d^3\sigma}{dE_T^\gamma d\eta^\gamma d\eta^{jet}} = \frac{1}{\Delta E_T^\gamma \Delta\eta^\gamma \Delta\eta^{jet}} \frac{N_{signal}^\gamma \cdot U}{L \cdot \varepsilon}$$

E_T^γ: Transverse energy of photon

η^γ: Pseudorapidity of photon

η^{jet}: Pseudorapidity of leading jet

N_{signal}^γ: Signal yield of photon

ε: Signal efficiency of photon

U: Unfolding factor

L: Integrated luminosity

Binning of the measurement:

p_T^γ: 40-300 GeV

$|\eta^\gamma|$: 0-0.9, 0.9-1.4442, 1.566-2.1, 2.1-2.5

$|\eta^{jet}|$: 0-1.5, 1.5-2.5

Barrel region: $|\eta| < 1.4442$

Endcap region: $1.566 < |\eta| < 2.5$

Signal Selection Efficiency (I)

- **Total efficiency of photon selection is factorized into four items**

$$\varepsilon_{Total} = \varepsilon_{Trigger} \times \varepsilon_{RECO} \times \varepsilon_{ID} \times \varepsilon_{PMV}$$

- High Level Trigger (HLT) efficiency **($\varepsilon_{Trigger}$)**, from data by Tag&Probe technique * on $Z \rightarrow e^+e^-$
- Reconstruction efficiency **(ε_{RECO})**, from Pythia MC samples
- Identification efficiency **(ε_{ID})**, from Pythia MC samples and also from data T&P technique on $Z \rightarrow e^+e^-$
- Pixel Match Veto (electron rejection) efficiency, **(ε_{PMV})**, from data by T&P on $Z \rightarrow \mu^+\mu^-\gamma$ events **[CMS AN-12-043]**

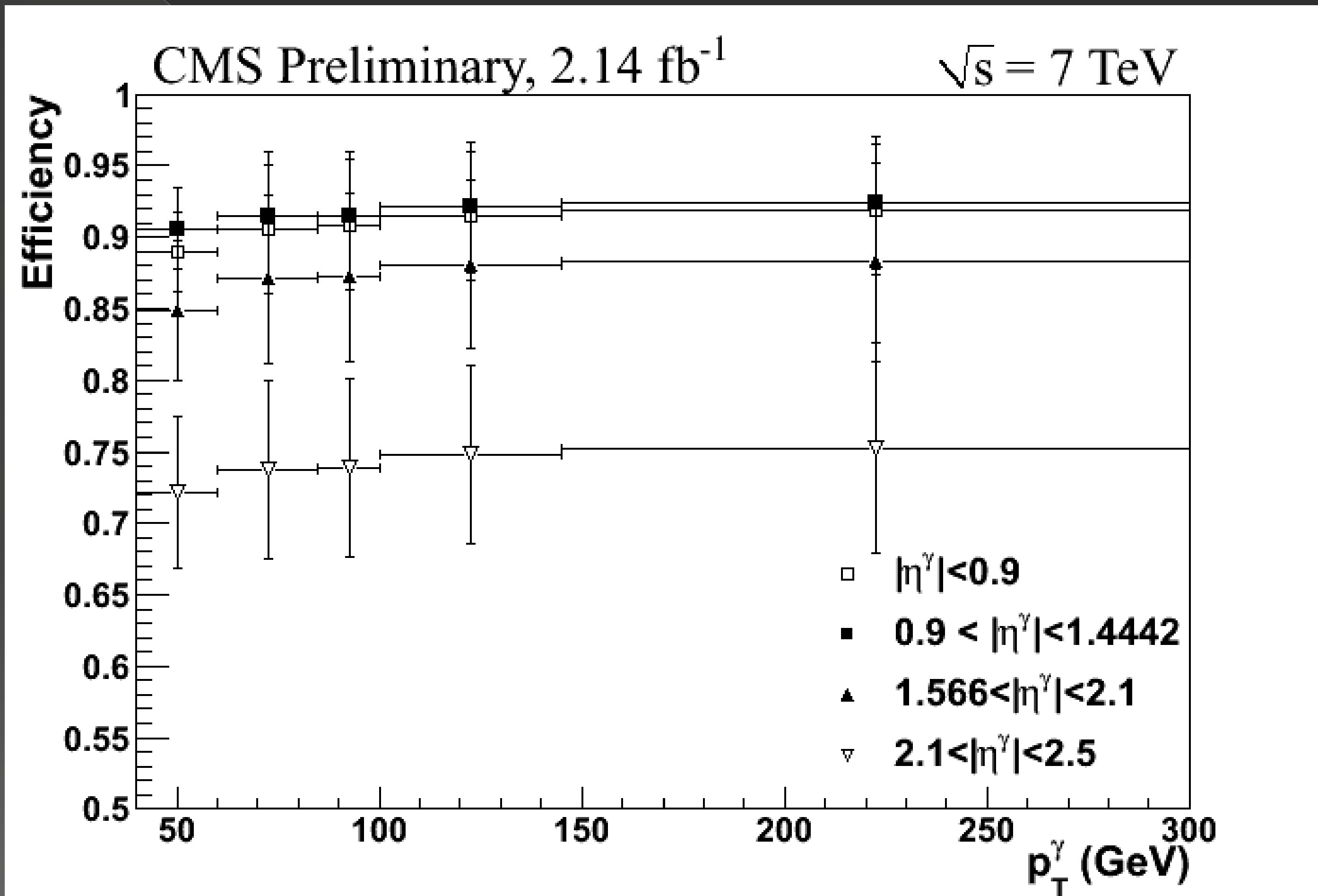
Summary Remarks

- **Photon HLT paths are fully efficient (100%) 10 GeV above their online E_T (such as after 85 GeV for HLT_Photon75_CaloIdVL)**
- **Photon reconstruction is 98-99%, while photon identification is ~93-99% efficient in the acceptance**
- **PMV efficiency changes in the band of 77-97%, decreases from inner to outer pseudorapidity regions of the electromagnetic calorimeter**

* CMS Collaboration, Measuring electron efficiencies at CMS with early data, CMS Note, CMS-NOTE-EGM-07-001 (2007)

Signal Selection Efficiency (II)

- HLT and ID efficiencies are observed not to be strongly affected by pile-up
- Total efficiency of photon selection is ~72-92%, lowest in the outer endcap ECAL



- Errors include both statistical and systematical contributions added in quadrature, systematical uncertainties are dominant

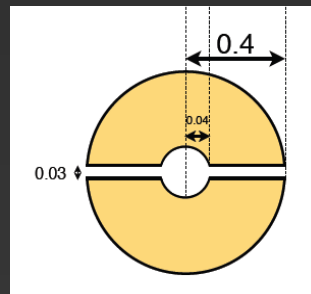
Signal Purity Calculation (I)

Isolation Template

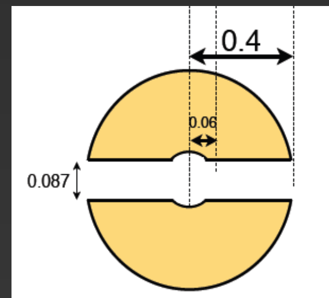
- **Jet background ($\pi^0,\eta \rightarrow \gamma\gamma$) needs to be suppressed by limiting the energy of other particles surrounding photon in different sub-systems.**
- **Isolation = Tracker Iso + HCAL Iso + ECAL Iso**

Photon Offline Selection:

- Trigger: HLT_Photon*_CaloIdVL
- H/E < 0.05
- No pixel match
- **$\sigma_{i\eta i\eta}$ < 0.01 for barrel**
- **$\sigma_{i\eta i\eta}$ < 0.028 for endcap**



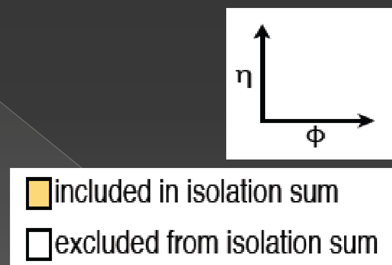
Tracker Iso

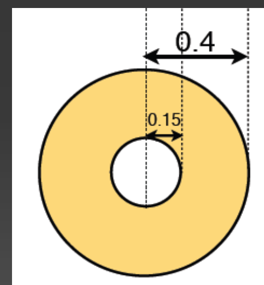


ECAL Iso

Sideband Selection:

- Trigger: HLT_Photon*_CaloIdVL
- H/E < 0.05
- No pixel match
- **0.011 < $\sigma_{i\eta i\eta}$ < 0.015 for barrel**
- **0.035 < $\sigma_{i\eta i\eta}$ < 0.040 for endcap**





HCAL Iso

H/E

H = Σ(HCAL tower energies within ΔR < 0.15 centred on SC)
E = SC energy

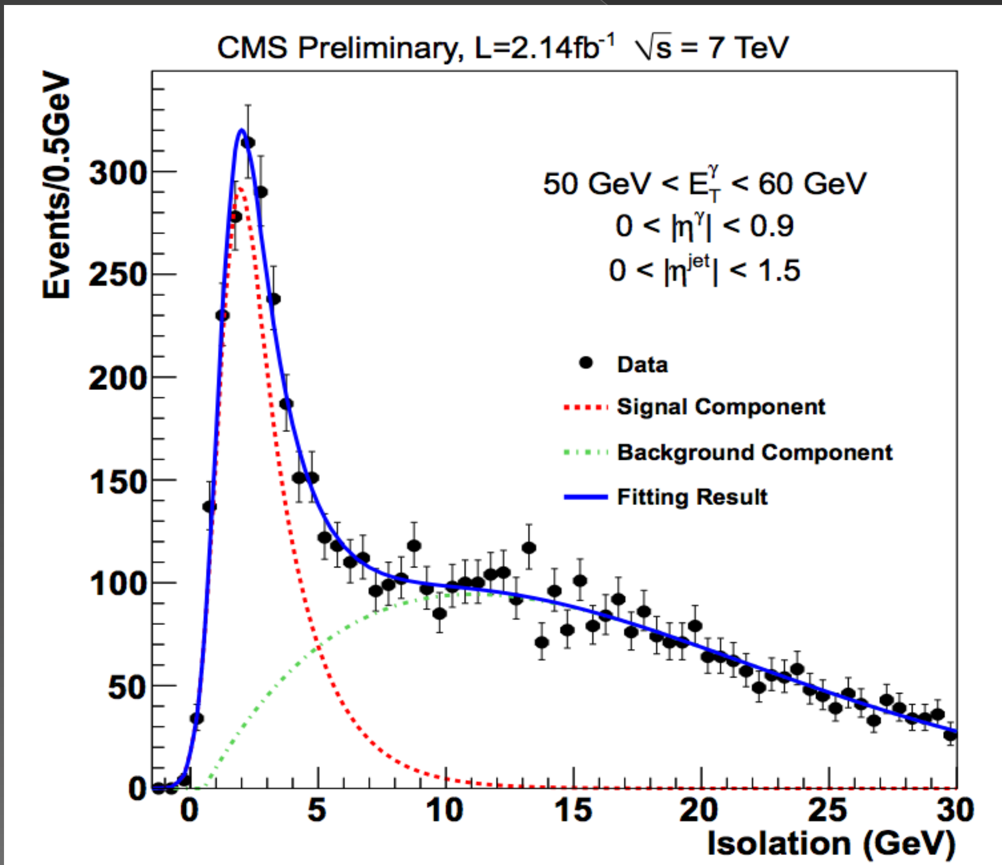
$\sigma_{i\eta i\eta}$

$$\sigma_{i\eta i\eta}^2 = \frac{\sum_i^{5\times5}(\eta_i - \bar{\eta})^2 w_i}{\sum_i^{5\times5} w_i}, \quad w_i = \max\left(0, 4.7 + \log(E_i / E_{5\times5})\right)$$

Signal Purity Calculation (II)

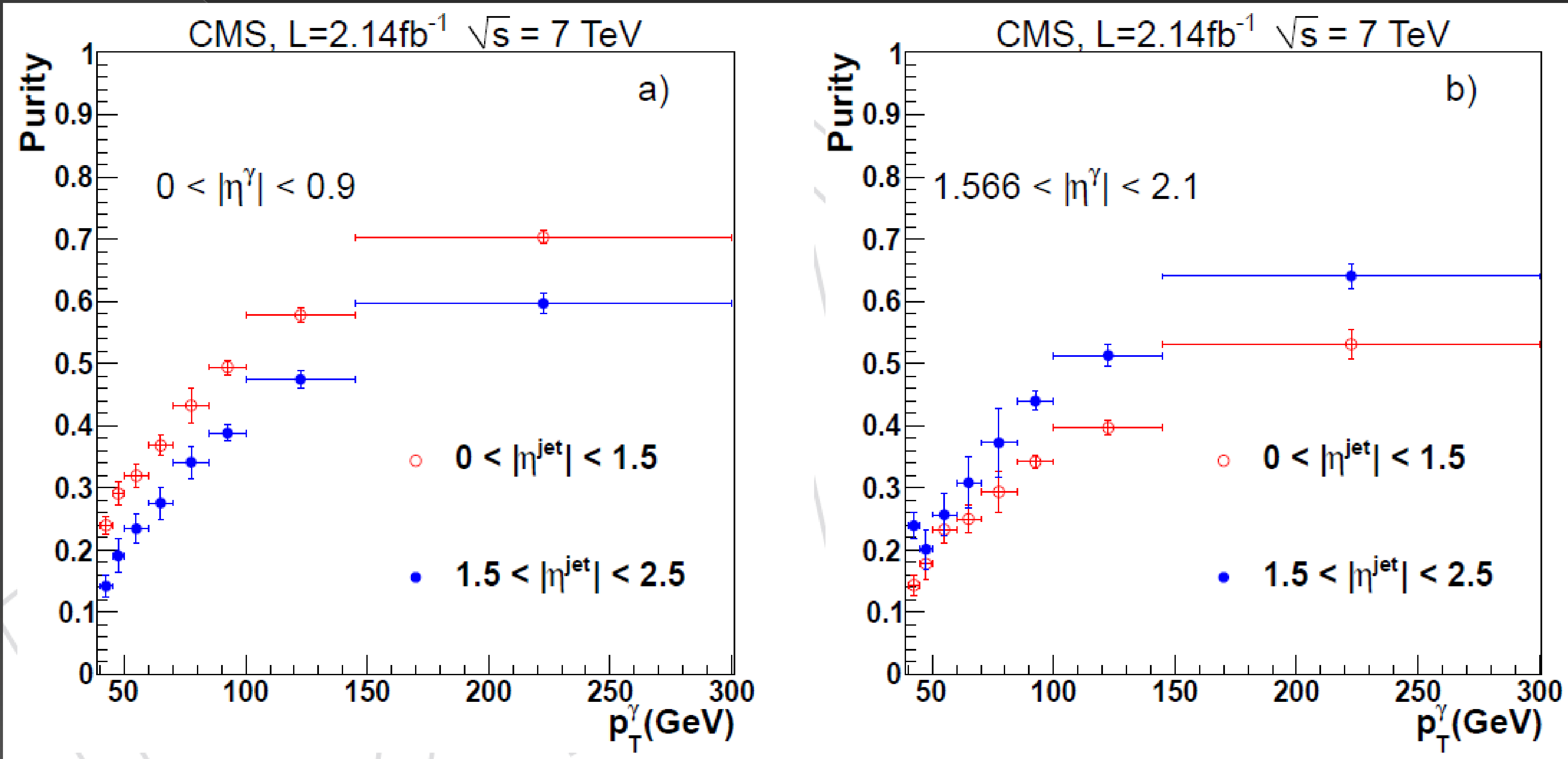
Template Fitting

- Signal template from MC, background template from data with sideband selection
- Both templates are fitted to data to obtain fitting results
- See details in [backup pages]



Example of fitting result from signal and background templates: Background has broader shape as opposed to sharper signal component on isolation variable

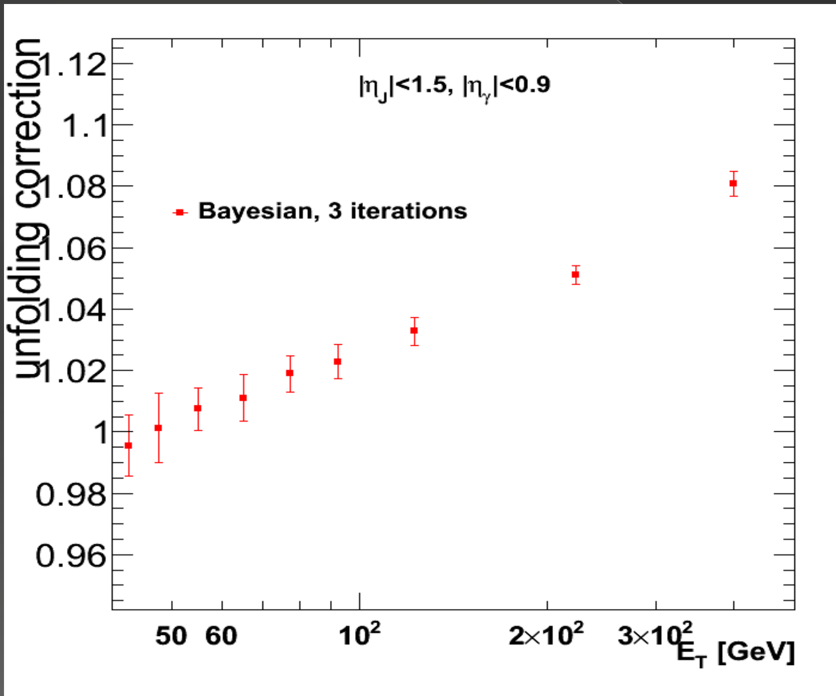
Signal Purity Calculation (III)



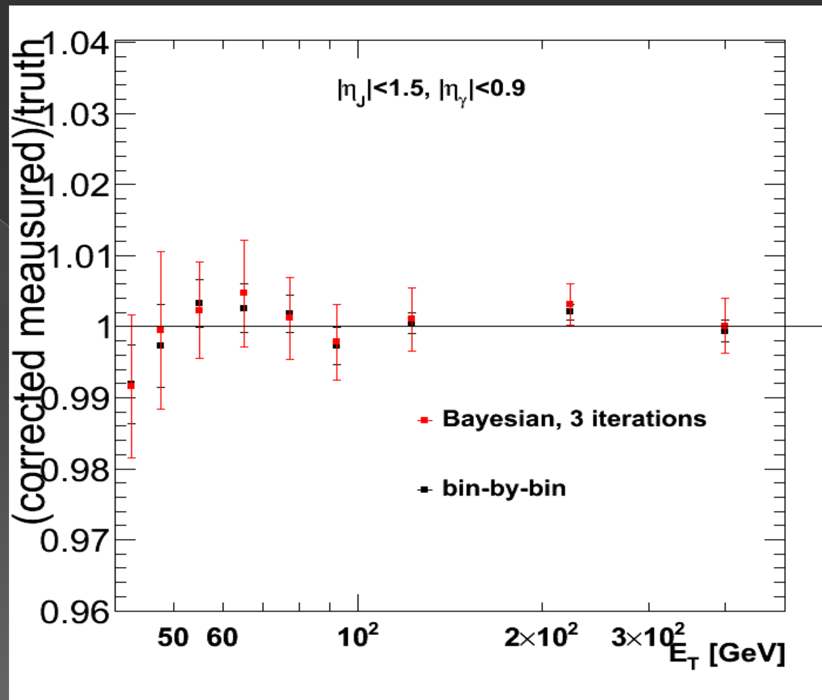
Example purity results for very loosely isolated photons i.e. Isolation < 30 GeV

Unfolding Correction

- Used RooUnfold software package*
- 3D unfolding iterative (Bayesian) approach** and a simple bin-by-bin correction
- In the first (training) part: established relation between train-measured and train-true distributions
- In the second (testing) part: performed closure test of how well corrected test-measured distribution reproduce test-true



Correction Factor from training sample



Closure Test result from testing sample

* http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html

** G. D'Agostini, Nucl. Instr. and Meth. in Phys. Res. A362 (1995) 487

Theory Predictions

JETPHOX

- NLO calculation for the processes: hadron hadron → gamma/hadron + jet+X

Settings

- PDF: CT10 for NLO
- $40 < p_T^\gamma < 300$ GeV, $|\eta^\gamma|<2.5$
- Iso cone size $\Delta R < 0.4$, Iso energy < 5 GeV
- $\mu_R=\mu_F=\mu_f=p_T^\gamma/2$

SHERPA

- Leading order 2→n hard process generator
- Inbuilt matrix-element generator: Comix
- Provides completely unweighted, inclusive and fully hadronized final states
- Better description of multi-jet processes

Settings

- PDF: CTEQ6M
- $40 < p_T^\gamma < 300$ GeV, $|\eta^\gamma|<2.5$
- Iso energy < 5 GeV
- $\mu_R=\mu_F=\mu_f=p_T^\gamma$

* Both JETPHOX and SHERPA includes description of fragmentation photons
** Run on 7 TeV configuration

Systematic Uncertainties

- **Efficiency:** Difference in MC/data photon ID efficiencies
- **Purity:**

  Signal Template: shifting parameter of lifetime function ±5%

  Background Template: difference between signal region and sideband region and shifting parameter of p4 by ±p4_error
- **Unfolding:** Difference in shape between data and MC distributions and energy resolution
- **Theory:**

  PDF Variation: CT10 (CTEQ6M) has 52 (40) variation of PDF

  Scale Variation: By changing factor of 2 for Scale Factor

$\lvert\eta^{\gamma}\rvert < 1.4442$				
P_T^{γ} GeV	efficiency (%)	unfolding (%)	purity (%)	total (%)
40-45	2.5	2.1	4.9 - 9.3	5.9 - 9.9
45-50	1.2	2.5	4.9 - 17.0	5.5 - 17.2
50-60	4.5	2.6	4.2 - 13.4	6.7 - 14.4
60-70	4.5	2.4	3.7 - 11.4	6.3 - 12.5
70-85	4.5	1.2	4.6 - 5.7	6.6 - 7.4
85-100	4.5	1.4	2.2 - 3.1	5.2 - 5.6
100-145	4.5	1.4	1.8 - 2.5	5.0 - 5.4
145-300	4.5	1.2	1.4 - 2.6	4.9 - 5.3
$1.556 < \lvert\eta^{\gamma}\rvert < 2.5$				
P_T^{γ} GeV	efficiency (%)	unfolding (%)	purity (%)	total (%)
40-45	3.0	2.1	6.9 - 9.9	7.8 - 10.5
45-50	3.5	2.5	8.6 - 37.5	9.6 - 37.7
50-60	5.0	2.6	7.2 - 24.5	9.1 - 25.1
60-70	5.0	2.4	7.0 - 12.4	9.0 - 13.5
70-85	5.0	1.2 - 5.0	10.0 - 13.3	11.3 - 15.1
85-100	5.0	1.4 - 5.0	2.8 - 4.6	5.9 - 8.0
100-145	5.0	1.4 - 4.0	2.8 - 6.3	5.9 - 8.2
145-300	5.0	1.2 - 2.1	2.9 - 5.1	6.1 - 7.3

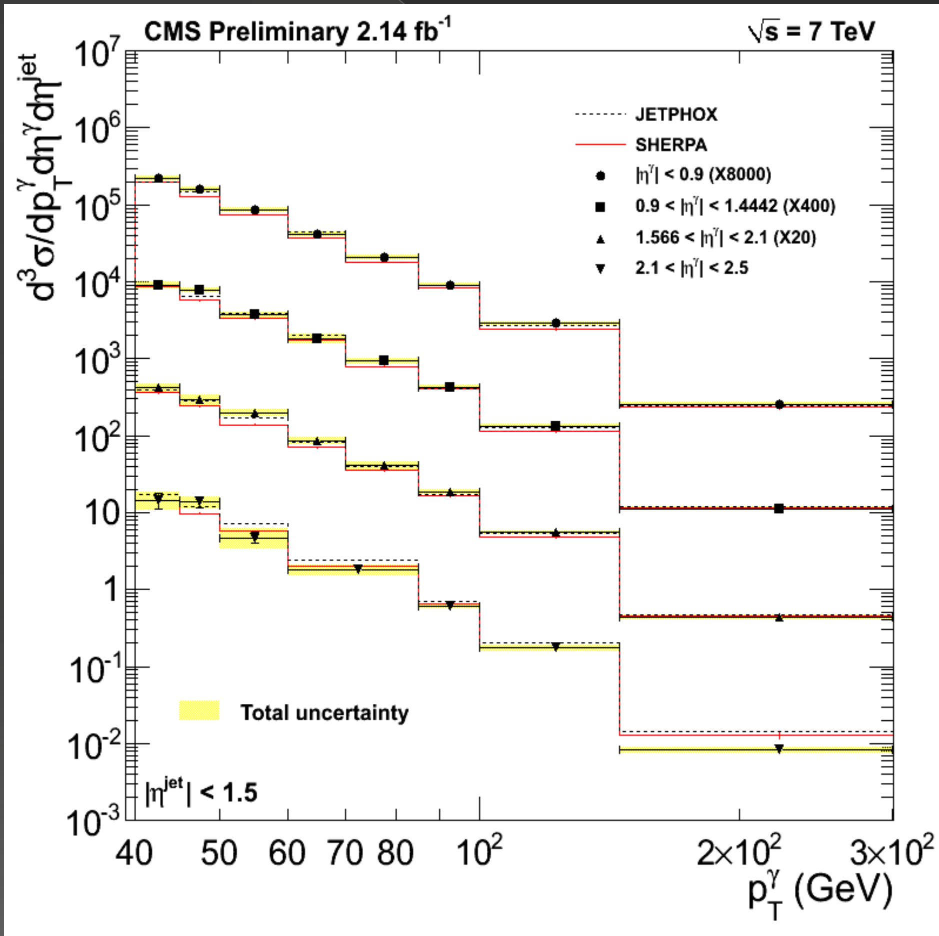
Theoretical Sys.: ~4% (PDFs) and ~10% (scales)

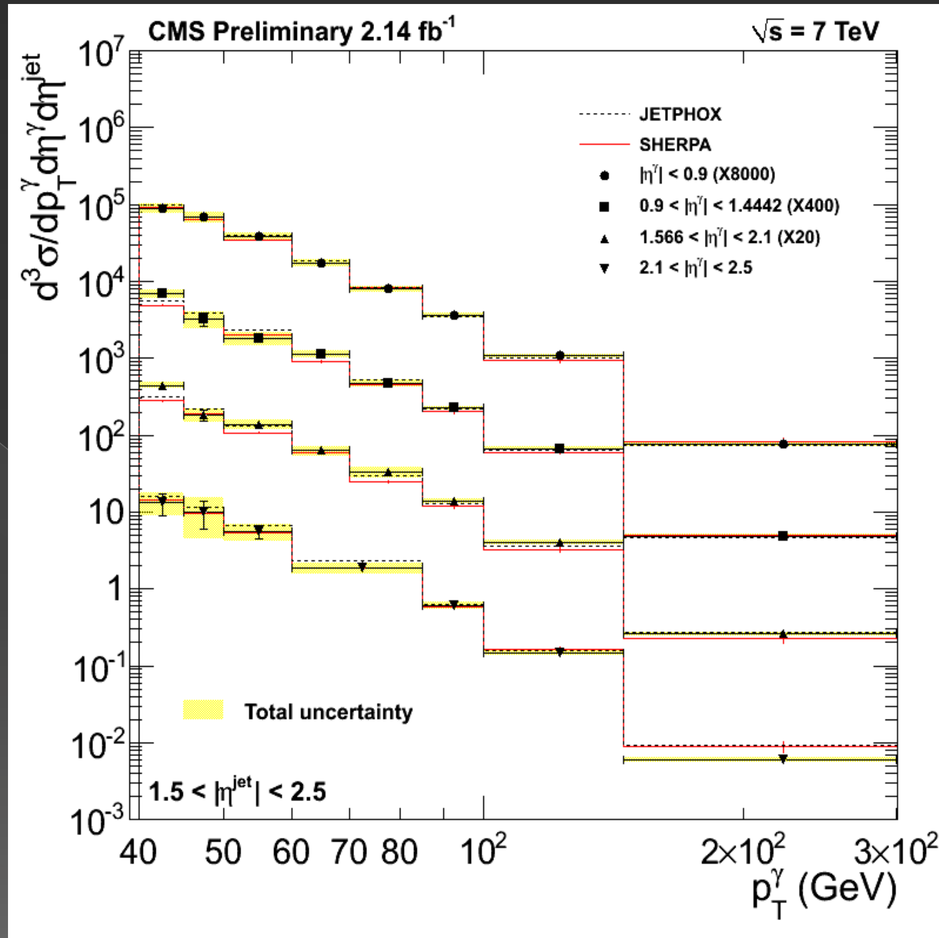
Total sys. uncertainty is obtained by adding all contributions in quadrature

Results (I)

Triple Differential Photon-Jet Cross-Section

Central Jet Region | **Forward Jet Region**

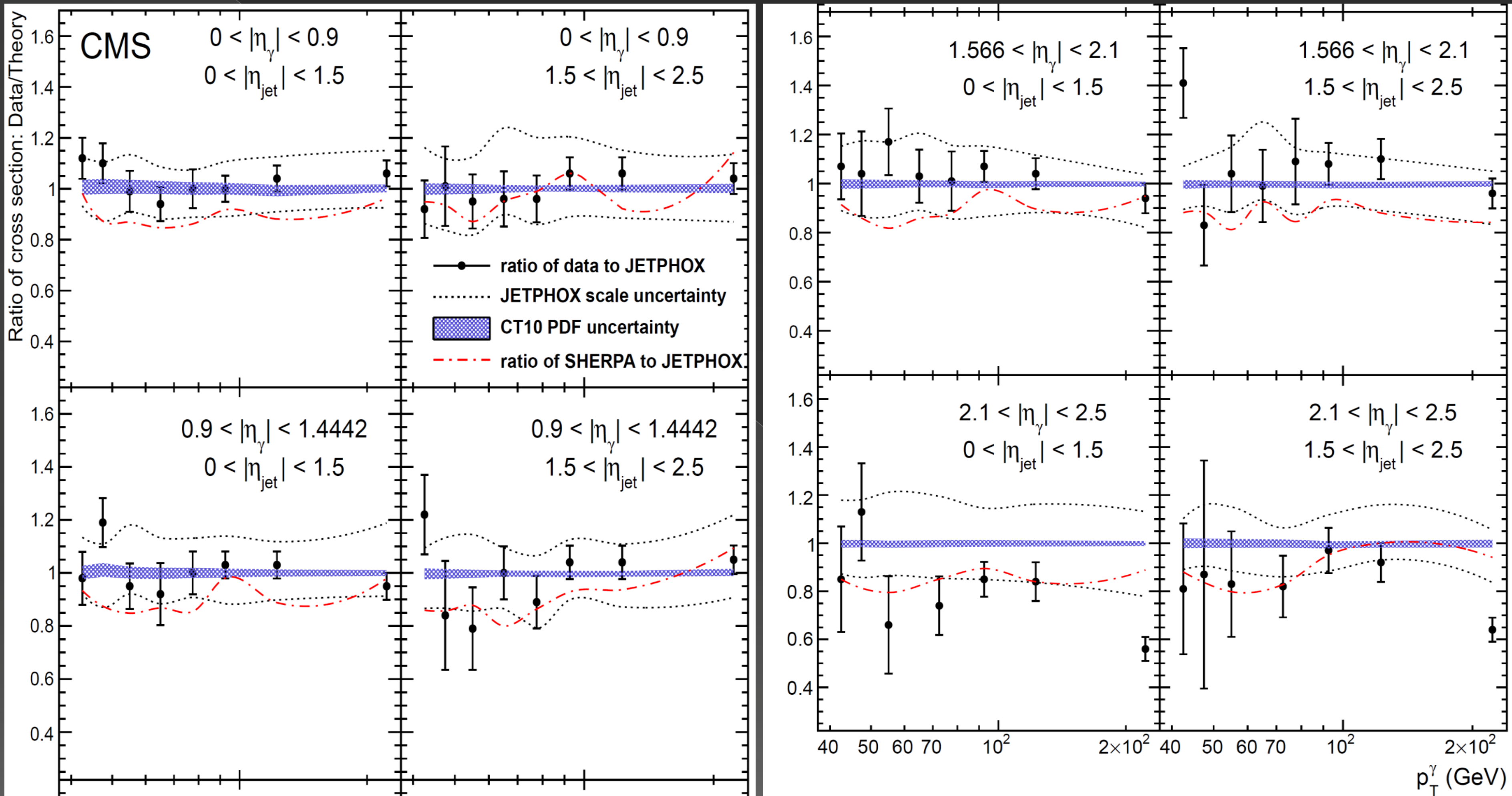




JETPHOX & SHERPA comparisons to data @ 2.14 fb^{-1}
Data/Theory agreement is consistent within total uncertainty

Results (II)

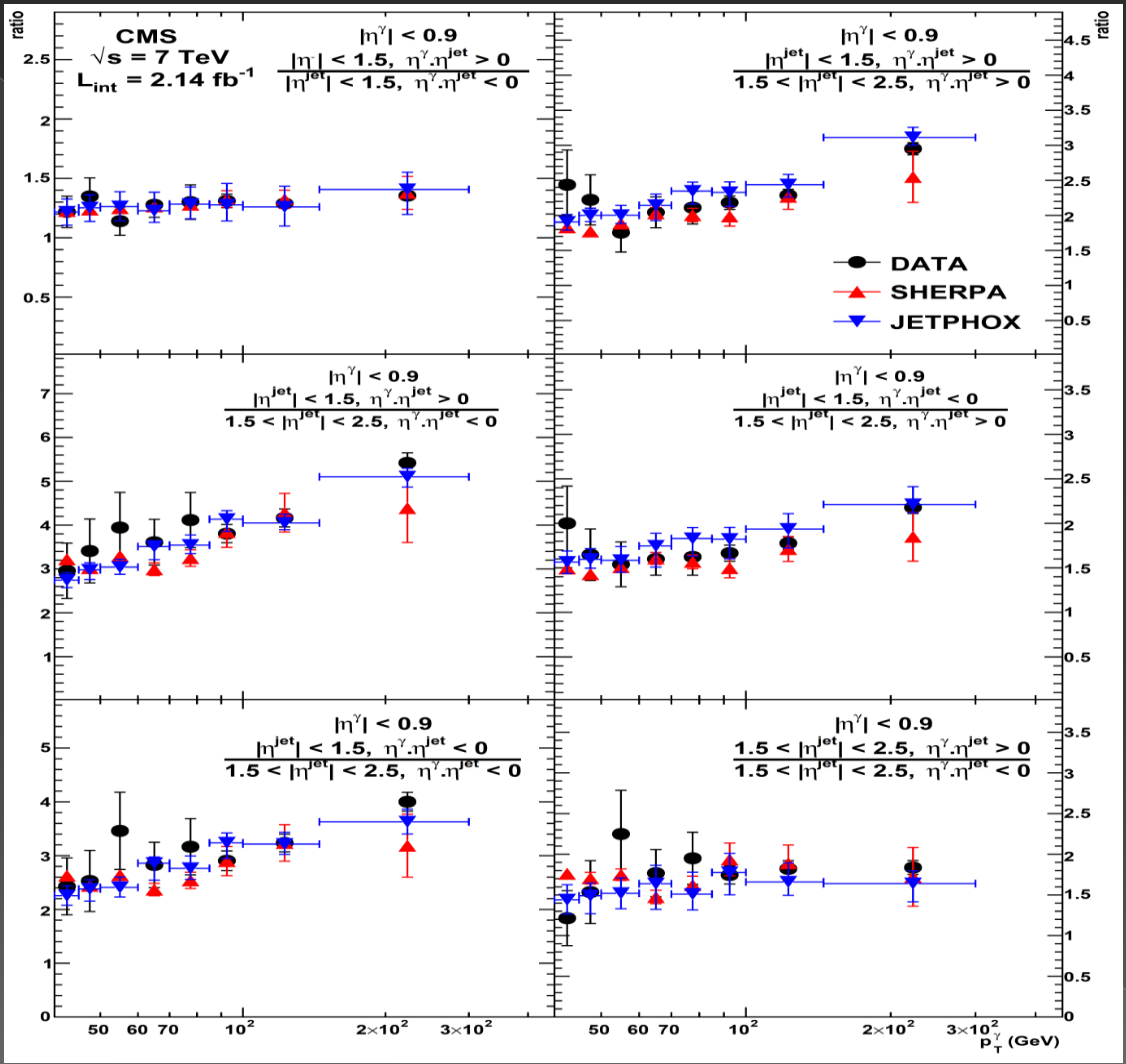
Data/Theory Ratios



Data/JETPHOX/SHERPA comparisions in 8 different leading photon and jet orientations

Results (III)

Data/Theory Ratios



Ratios for different orientations probing a wide range of parton momentum fraction x

Conclusions

- **We have measured triple differential photon-jet cross-section in 7 TeV pp collisions by analyzing 2.14 fb^{-1} data recorded by the CMS detector**
- Photon efficiency measurement is performed with data-driven technique where ever possible
- Photon purity measurement is performed using the isolation template
- Unfolding corrections are determined by using 3D unfolding iterative (Bayesian) approach
- The cross section as a function of p_T^{γ} is measured for 8 different orientations between the leading photon and the leading jet
- We present ratios of the triple differential cross section for the different orientations, which compares results over a wide range of parton momentum fraction x
- Comparison of results from data with theoretical predictions from SHERPA and JETPHOX are presented
- **While JETPHOX is generally in fair agreement with the data, the calculations from SHERPA are found to be systematically underestimating the data within total uncertainty**

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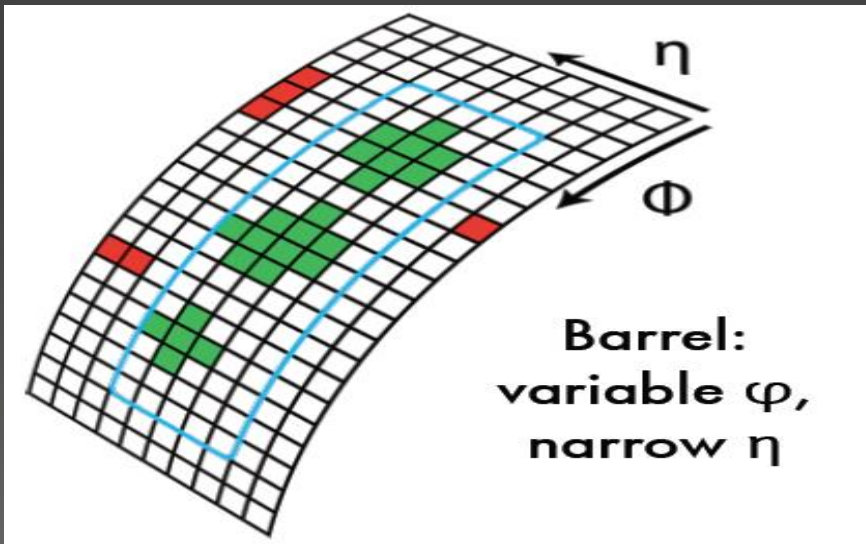
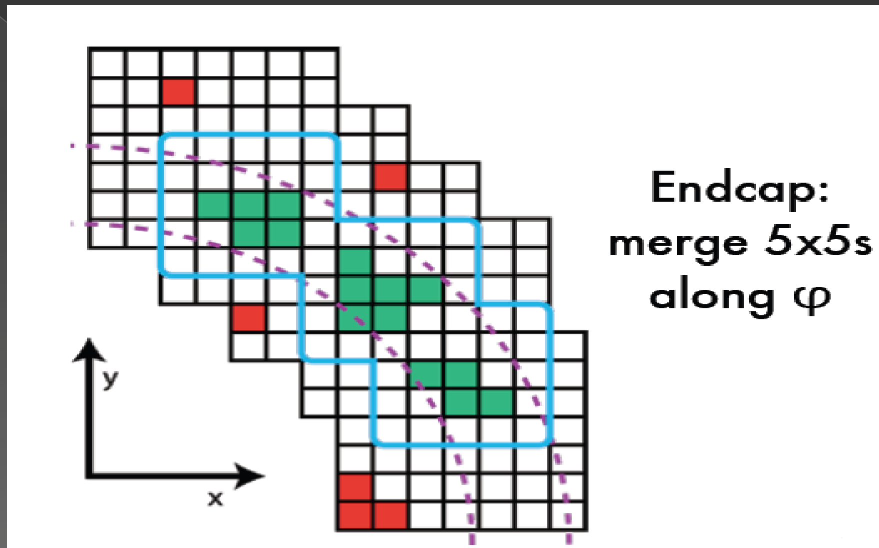
Additional Slides

CMS Photon Reconstruction

- Energy deposits in the ECAL crystals are collected as "superclusters"
- Photons are reconstructed from superclusters:
  - **In the ECAL barrel region ($|\eta| < 1.4442$),** use 5 crystal window in η-direction around the most energetic crystals and a variable window in φ-direction (designed to recover bremsstrahlung photons and photon conversions)
  - **In the ECAL endcap region ($1.566 < |\eta| < 2.5$),** merge contiguous 5×5-crystal matrices around the most energetic crystals. Preshower energy is included.
- Hybrid (in Barrel) and Multi5x5 (in Endcap) clustering algorithms are used
- Energy is corrected for better resolution due to lateral leakage, ET - dependence of bremsstrahlung and conversion processes, material budget in front of the ECAL





- **Prompt electrons are rejected by applying veto on their match with Pixel detector hits**

Object Selection Criteria

Photon selection:

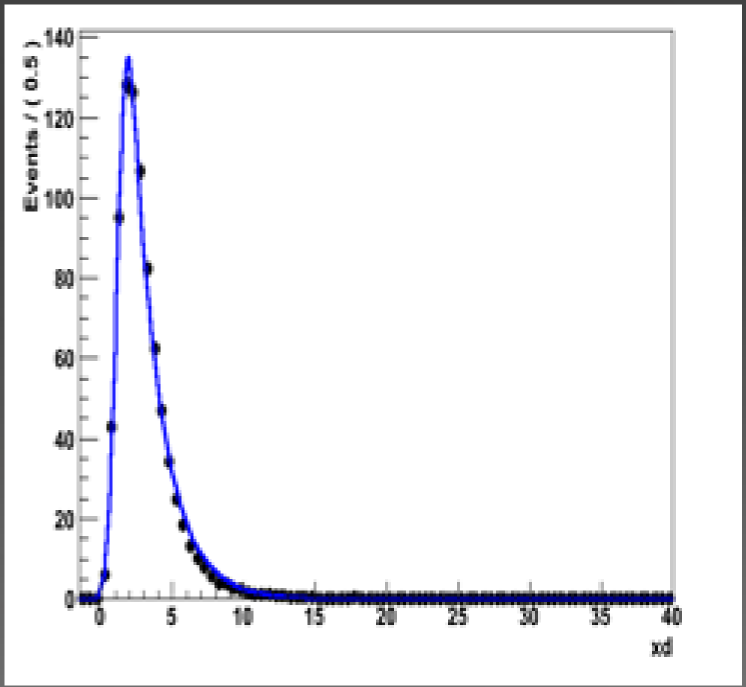
- Reconstructed photons
- $|\eta^{\gamma}|<2.5$ (excluding transition gap $1.4442<|\eta^{\gamma}|<1.566$)
- p_T^{γ}: 40-300 GeV
- Trigger: HLT_Photon*_CaloIdVL
- $H/E < 0.05$
- No pixel match
- $\sigma_{i\eta i\eta} < 0.01$ for barrel
- $\sigma_{i\eta i\eta} < 0.028$ for endcap

Jet selection:

- Particle flow jets
- anti-k_t05 clustering algorithm
- $|\eta^{jet}|<2.5$
- p_T^{jet} >30 GeV
- Residual jet energy corrections applied
- ΔR(photon,jet) > 0.5

Signal Template from MC

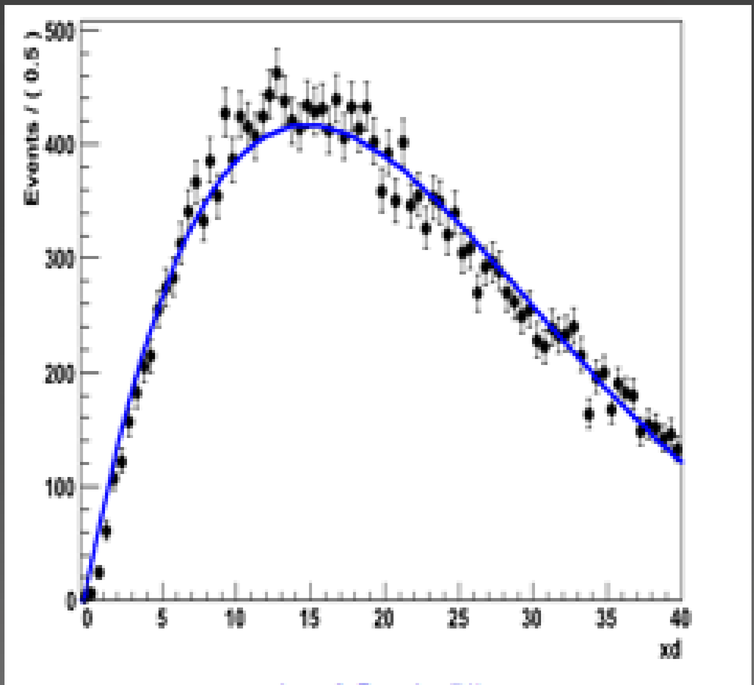
- Gaussian convoluted with exponential function to fit signal template from Gamma + Jet MC (Binned Maximum likelihood)
- Three parameters are used to describe the density function, mean (p1), sigma(p2) , exponent variable (a)
- Mean (p1) and sigma (p2) are used to describe the peak of signal template, allowed to vary in fitting
- Exponent variable (a) is used to describe the right-side tail, fixed in fitting



$$Iso_S^{\gamma}(\vec{p}, \alpha) = \exp(\alpha x) \otimes \text{Gaussian}(x, p_1, p_2)$$

Background Template from Data

- Inverse Argus function used to fit background template from side-band selected data (Binned Extended Maximum likelihood)
- Four parameters are used to describe the density function, p3, p4, p5, p6
- q1 is the function turning-on point, fixed by sideband z mainly influences the background under the signal peak, constrained by sideband fit
- q2 and q3 mainly influence the background pure region, allowed to vary in fitting

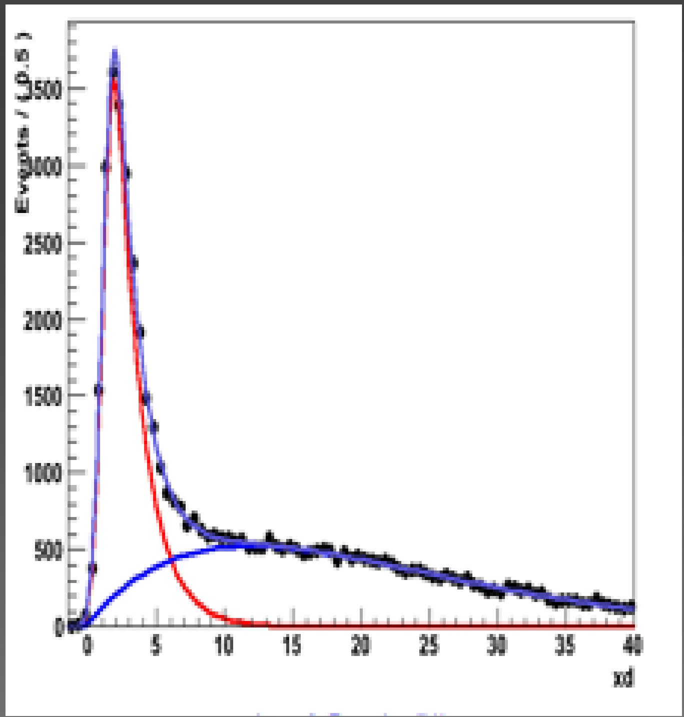


$$Iso_B^{\gamma}(z,\vec{q}) = \left[1 - e^{z(x-q_1)}\right] \cdot \left[1 - q_2(x-q_1)\right]^{q_3}$$

Template Fitting to Data

- The template is the sum of signal template + background template, with seven parameters.
- Mean (p1), sigma (p2), q3, q4 are floating, z are constrained, q1 and a is fixed.
- Fitting utility function is defined by chi-square function + constrained terms for z

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{N_i - (N_S S_i(\vec{p}, \alpha) + N_B B_i(z, \vec{q}))}{\sigma_{N_i}} \right)^2 + \left(\frac{(z - z_{\text{central}})}{\sigma_z} \right)^2$$



Set Y in log scale