Prompt photons at hadron colliders

Alessandra Lucà
for the **ATLAS and CDF Collaborations**

ICHEP 2016
August 3-10, 2016
CHICAGO

Outline

- **Introduction**

- **The ATLAS and CDF detectors**

- **Measurement of prompt isolated photon production cross sections at 8 TeV with the ATLAS detector**

- **Measurement of the inclusive isolated prompt photon production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the full CDF data sample**

- **Future plans**

- **Summary**

Prompt photon production at hadron colliders

With prompt photons we can

- Test perturbative Quantum Chromodynamics (**pQCD**) with high precision

- Provide information on the parton distribution functions (**PDFs**)
- Constrain models of parton fragmentation (**FFs**)
- Understand backgrounds to important processes (such as H →γγ)
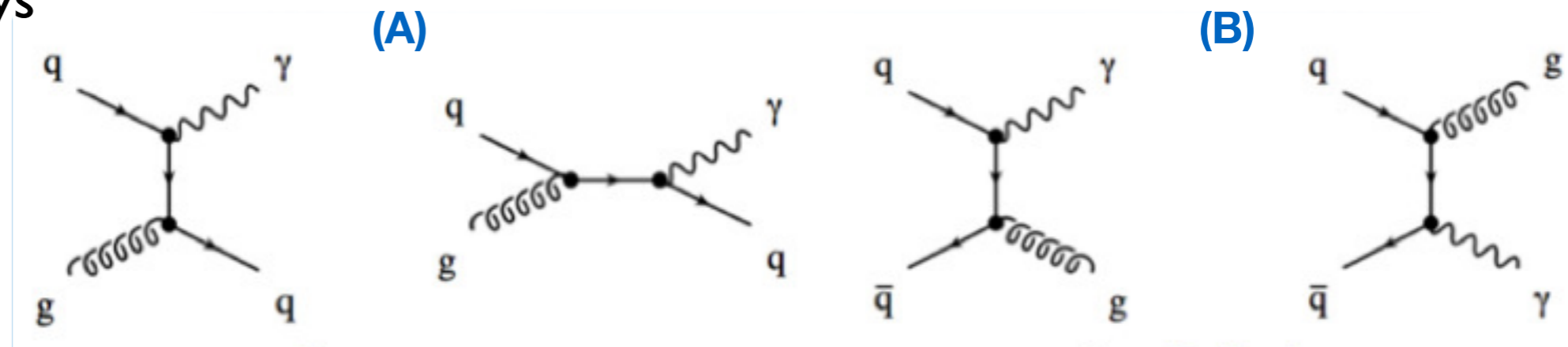
PROMPT PHOTONS:
not from hadron decays
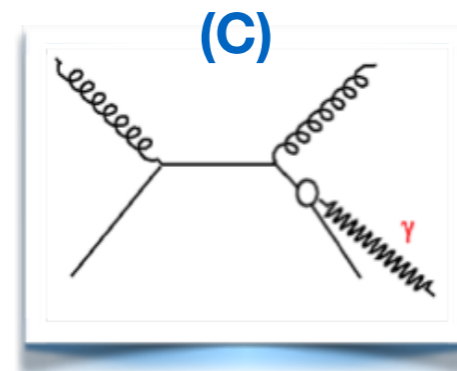
- **Direct photon**
    A. **Compton**
    B. **Annihilation**
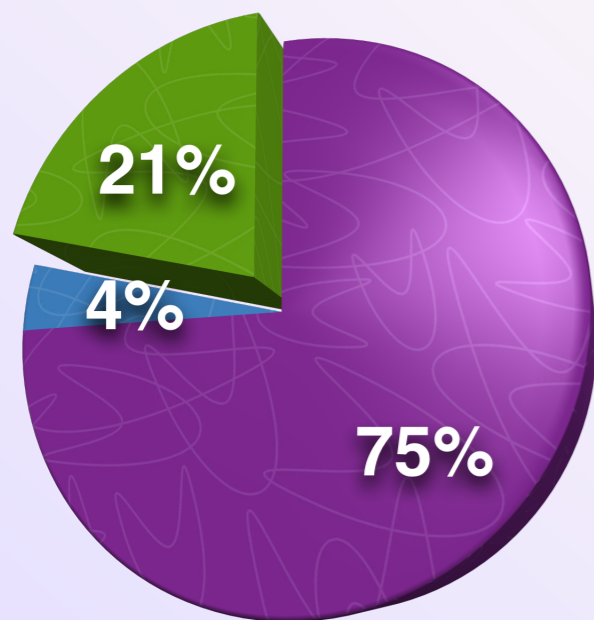

- **Fragmentation photon** (C)
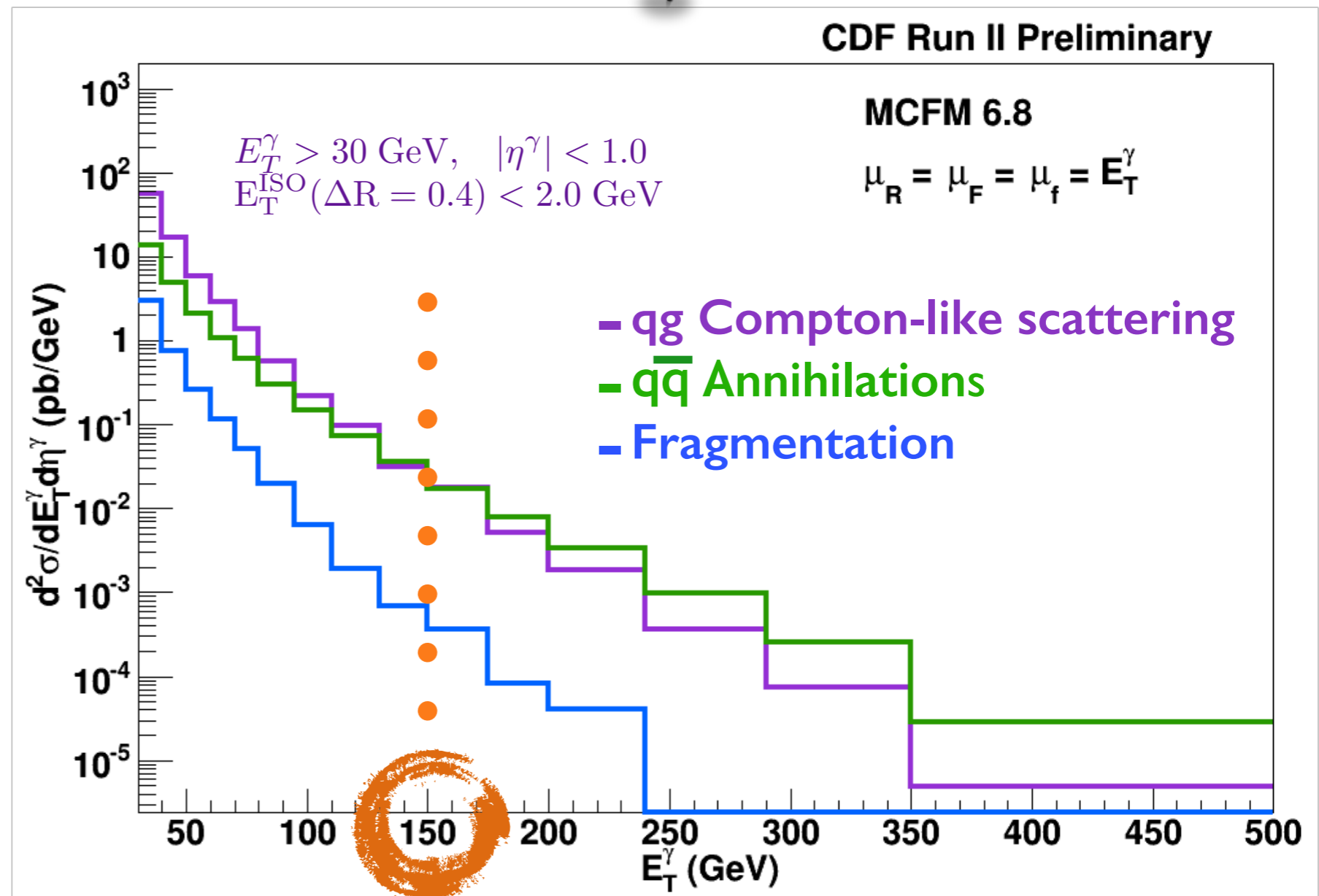   BUT suppressed with isolation

Differential contributions of subprocesses

Predictions for the single subprocesses contribution obtained from the MCFM calculation.
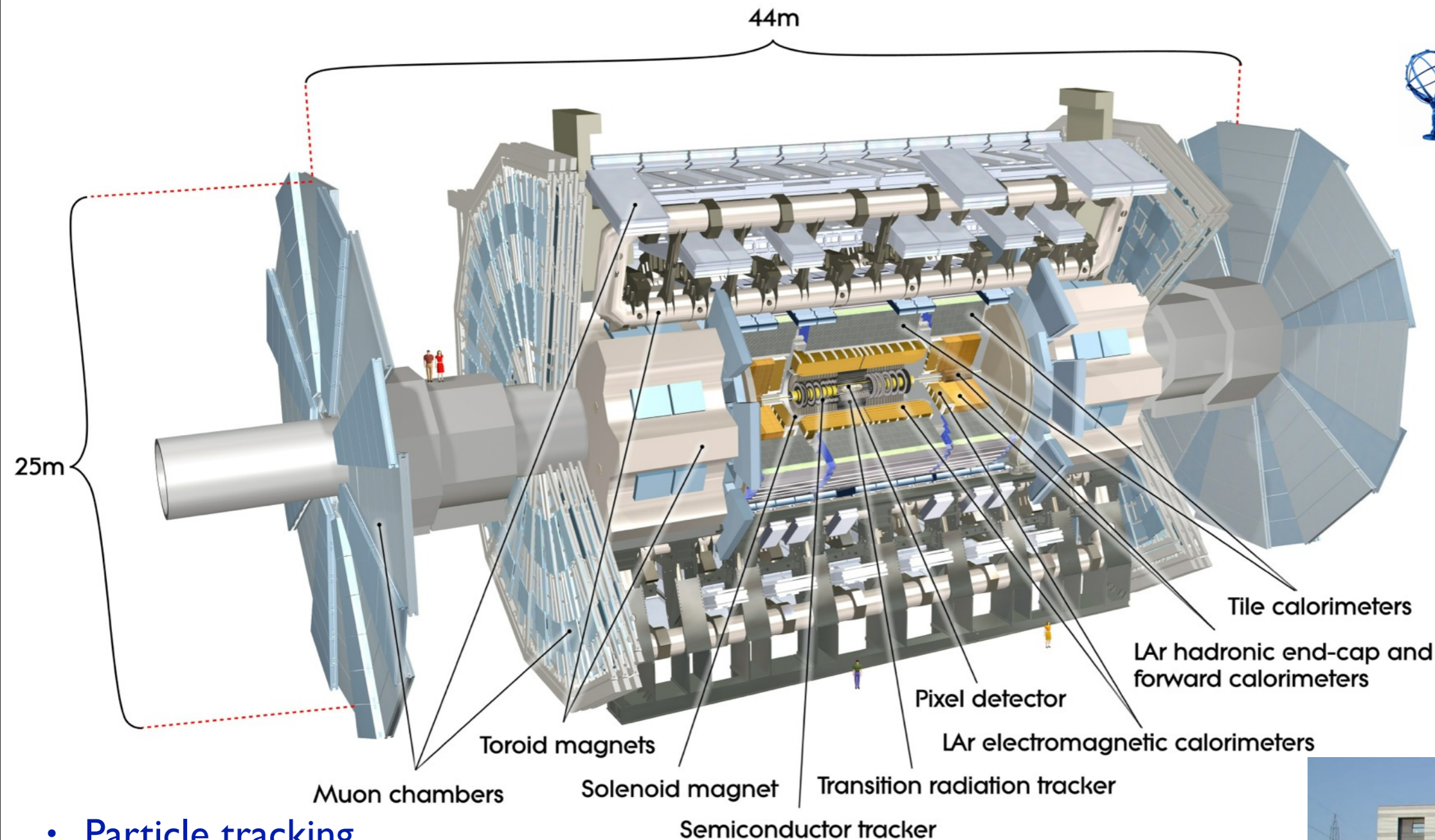(e.g. proton-antiproton collisions @ 2 TeV)

Subprocesses fraction
(Integrated over all spectrum)

21%

4%

75%

- gg: gluon-gluon fusion: negligible (within scale uncertainty)

CDF Run II Preliminary

MCFM 6.8

$E_T^\gamma > 30$ GeV, $\quad |\eta^\gamma| < 1.0$
$E_T^{ISO}(\Delta R = 0.4) < 2.0$ GeV

$\mu_R = \mu_F = \mu_f = E_T^\gamma$

- qg Compton-like scattering
- $q\bar{q}$ Annihilations
- Fragmentation

$d^2\sigma/dE_T^\gamma d\eta^\gamma$ (pb/GeV)

E_T^γ (GeV)

The ATLAS detector at the Large Hadron Collider

44m

25m

Tile calorimeters

LAr hadronic end-cap and
forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Toroid magnets

Solenoid magnet

Transition radiation tracker
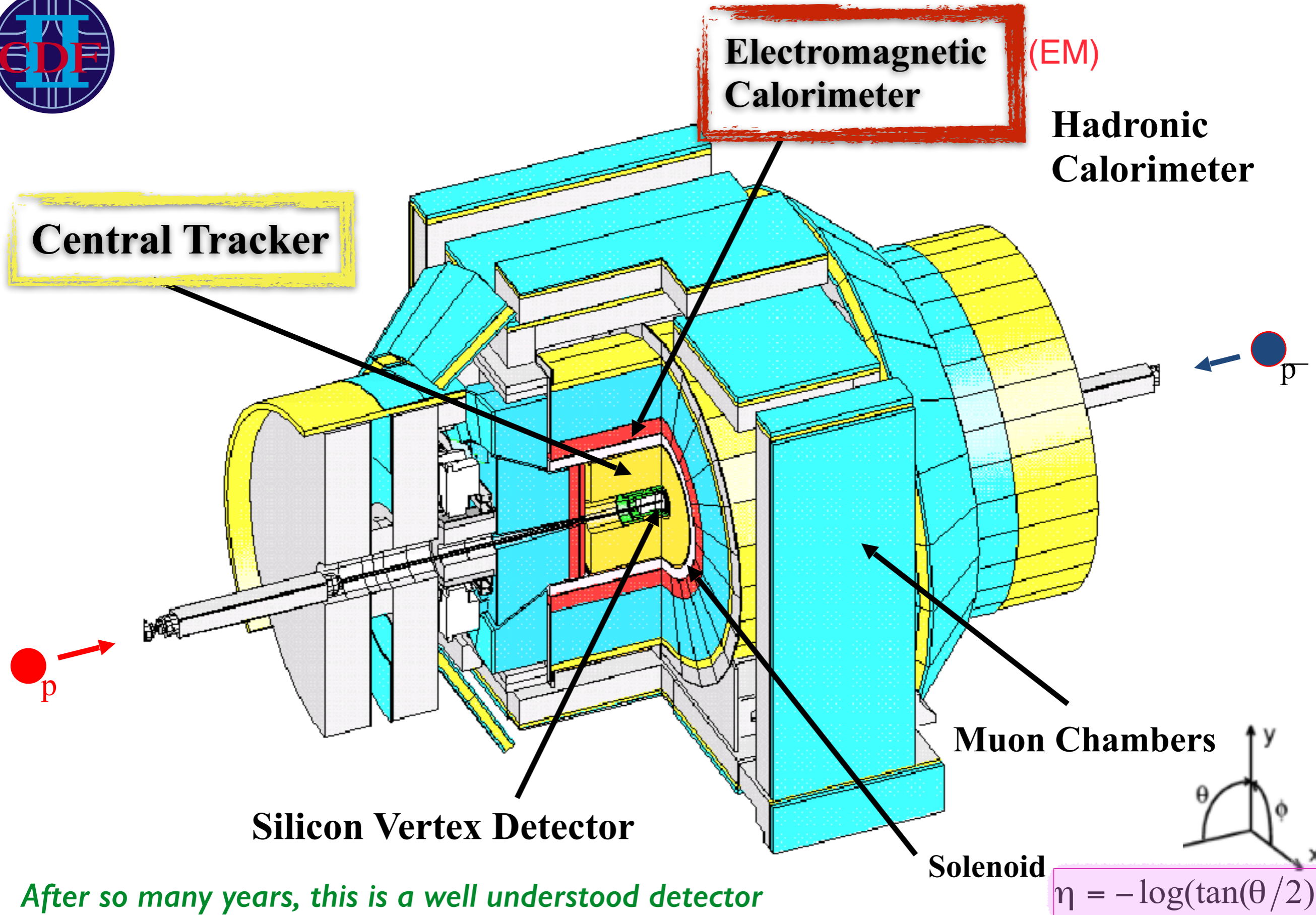
Muon chambers

Semiconductor tracker

- **Particle tracking**
  Pixel+SCT+TRT

- **Calorimetry (EM+Had)**

- **Photon/e- ID**
  Tracking +ECAL

**ATLAS superimposed on the
building 40 at CERN**

The CDF detector at the Tevatron collider

Electromagnetic Calorimeter (EM)

Hadronic Calorimeter

Central Tracker

$$p^-$$

$$p$$

Muon Chambers

Silicon Vertex Detector

Solenoid

$$\eta = -\log(\tan(\theta/2))$$

After so many years, this is a well understood detector

Measurement of prompt isolated photon production cross sections at 8 TeV with the ATLAS detector

arXiv:1605.03495v1 [hep-ex]

Photon selection and identification

★ **Data set**

L = 20.2 fb⁻¹

★ **Kinematic region**

$$E_T^\gamma > 25 \text{ GeV}$$

$$|\eta^\gamma| < 1.37 \text{ and } 1.56 \leq |\eta^\gamma| < 2.37$$

★ **Isolation**

$$E_T^{iso}(\Delta R = 0.4) < 4.8 \text{ GeV} + 4.2 \times 10^{-3} \times E_T^\gamma$$
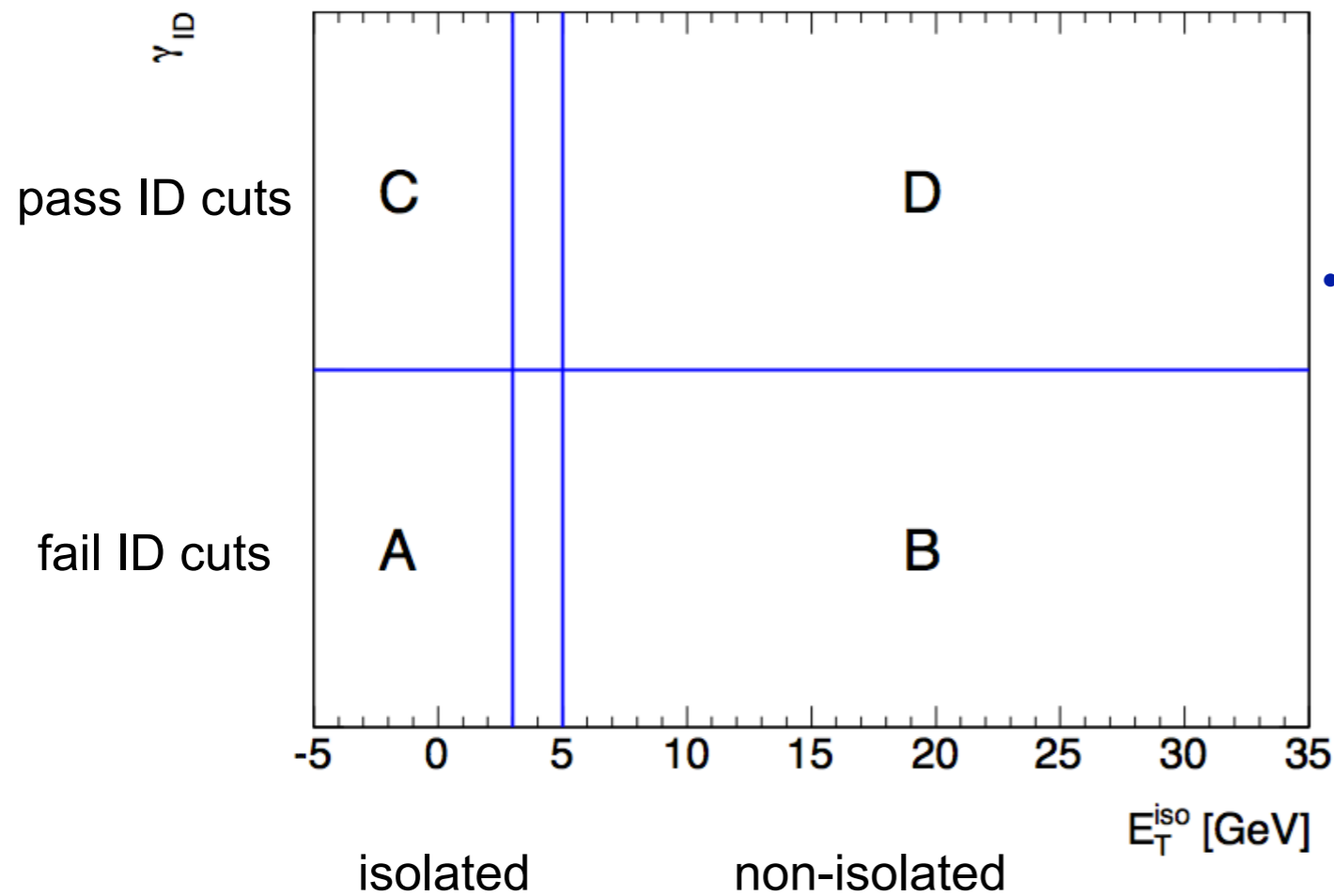
★ **ID criteria**

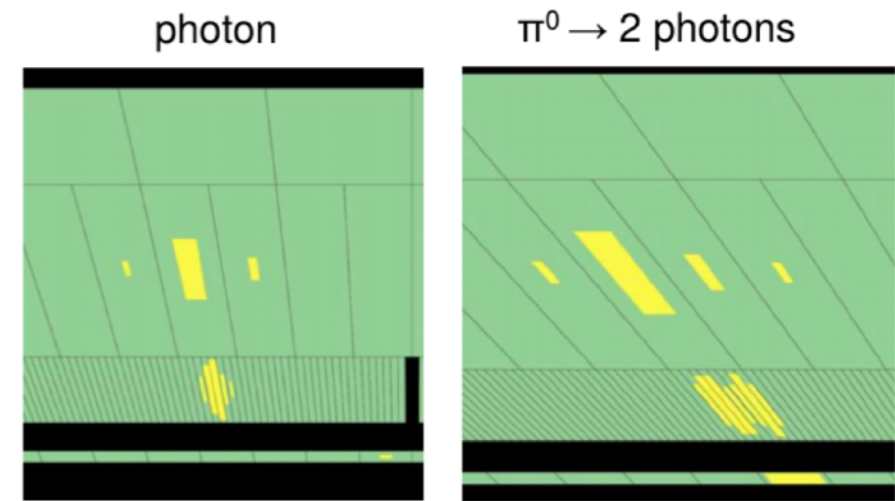**9 shower-shape variables based on calorimeter energy deposition.**

- Id criteria independently tuned for standard and converted photons (when 2 tracks point to the calorimeter cluster).

arXiv:1605.03495v1 [hep-ex]
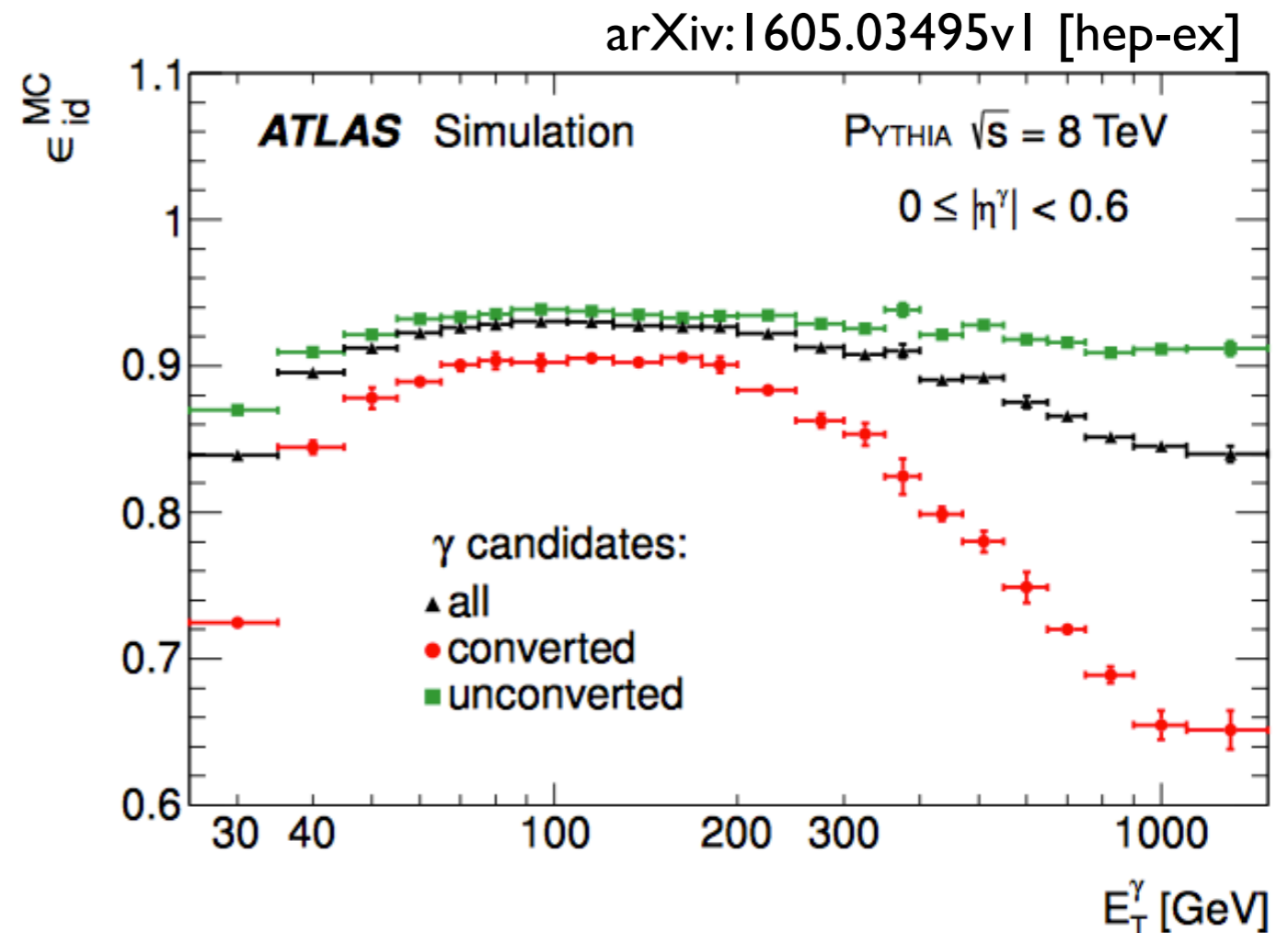
Background subtraction

photon $\pi^0 \to 2$ photons

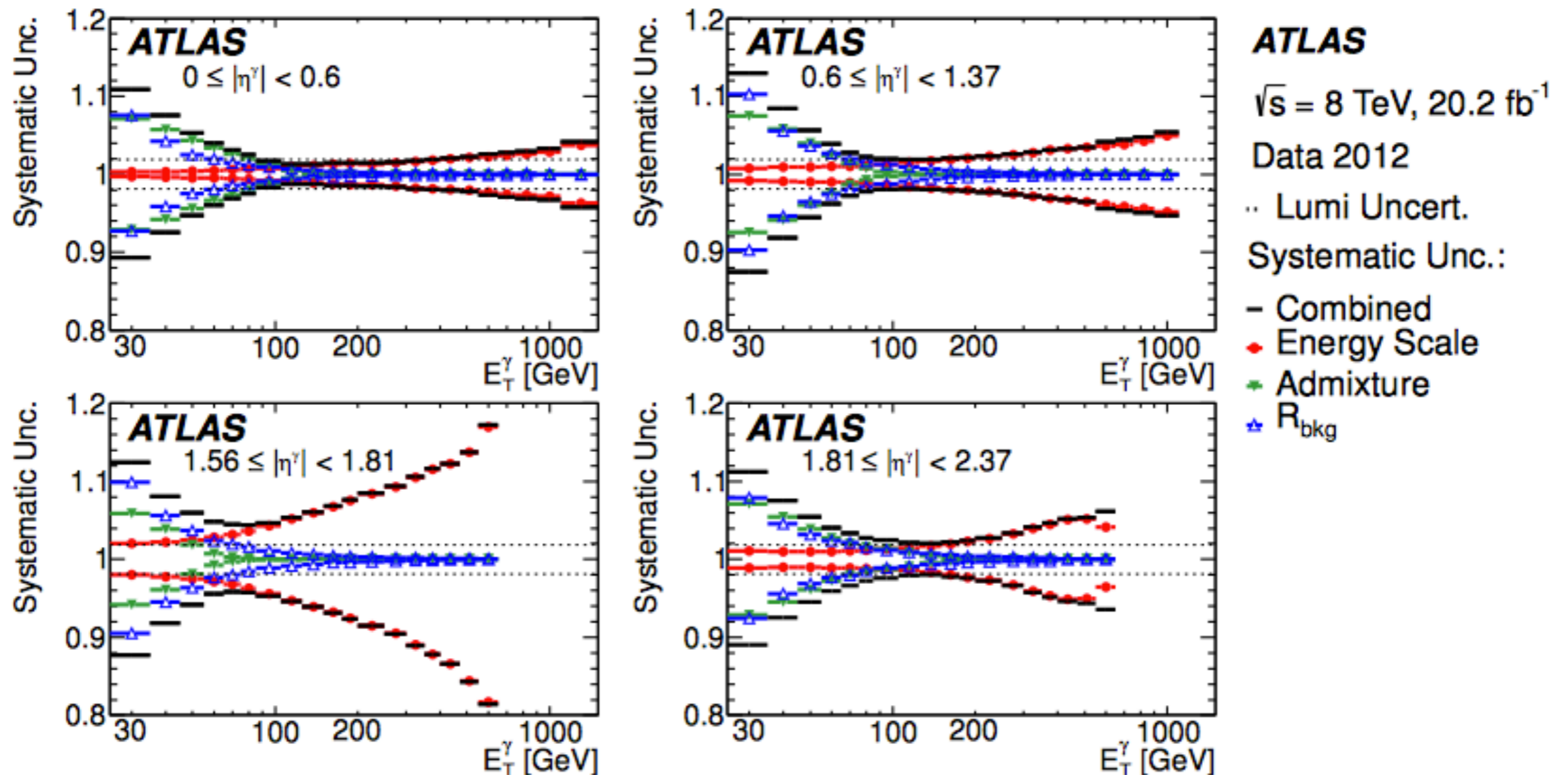- **Main BKG from hadron decays (10^5 jets/γ)**

- **Removed by a data-driven technique**
  - **two-dimensional sidebands method**

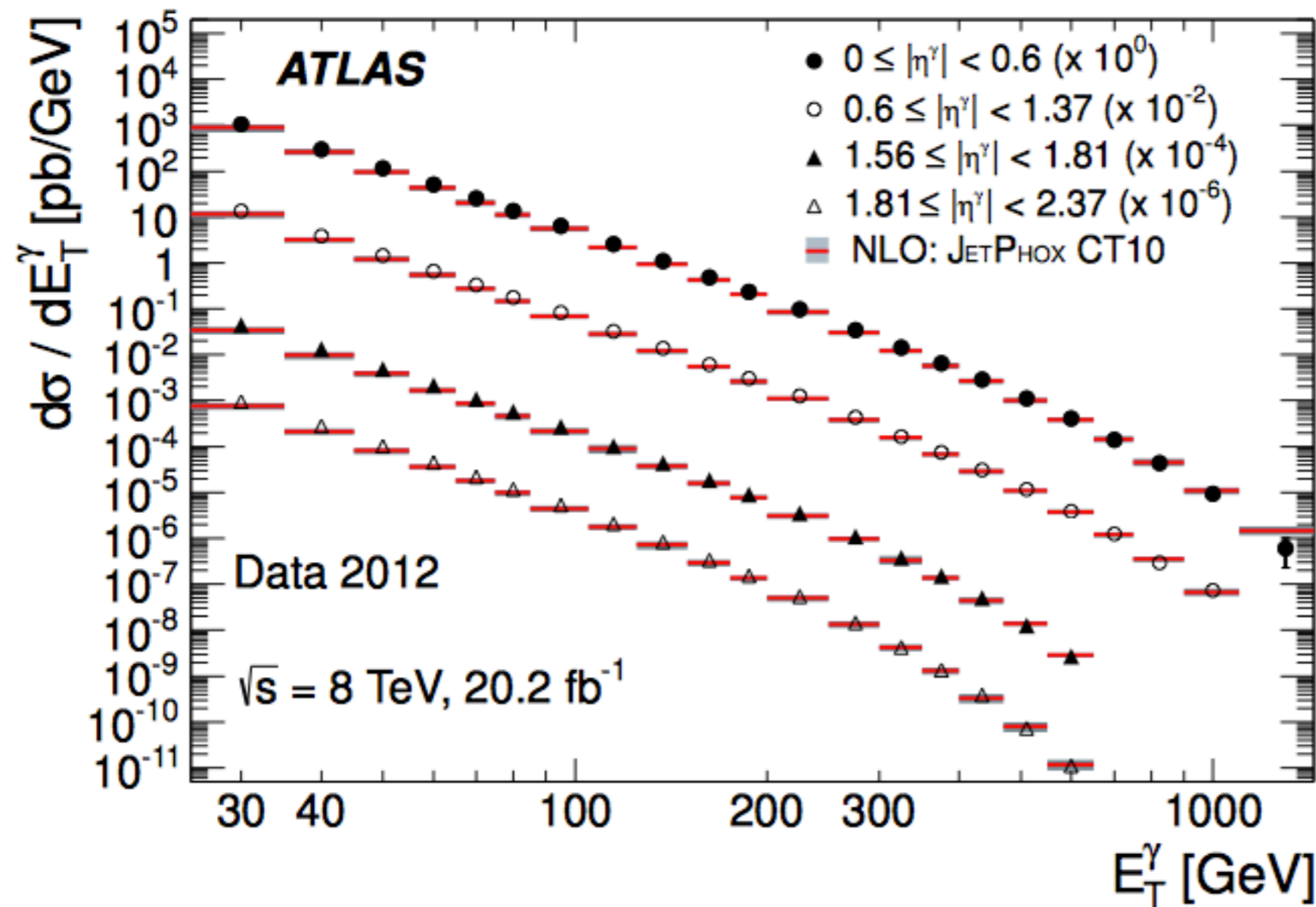Background from electrons subtracted, based on $Z \to ee$.

Main uncertainties

- **Energy scale**
- **Admixture between direct and fragmentation**
- **Correlations between identification and isolation in background**

arXiv:1605.03495v1 [hep-ex]

Prompt isolated photon production cross sections
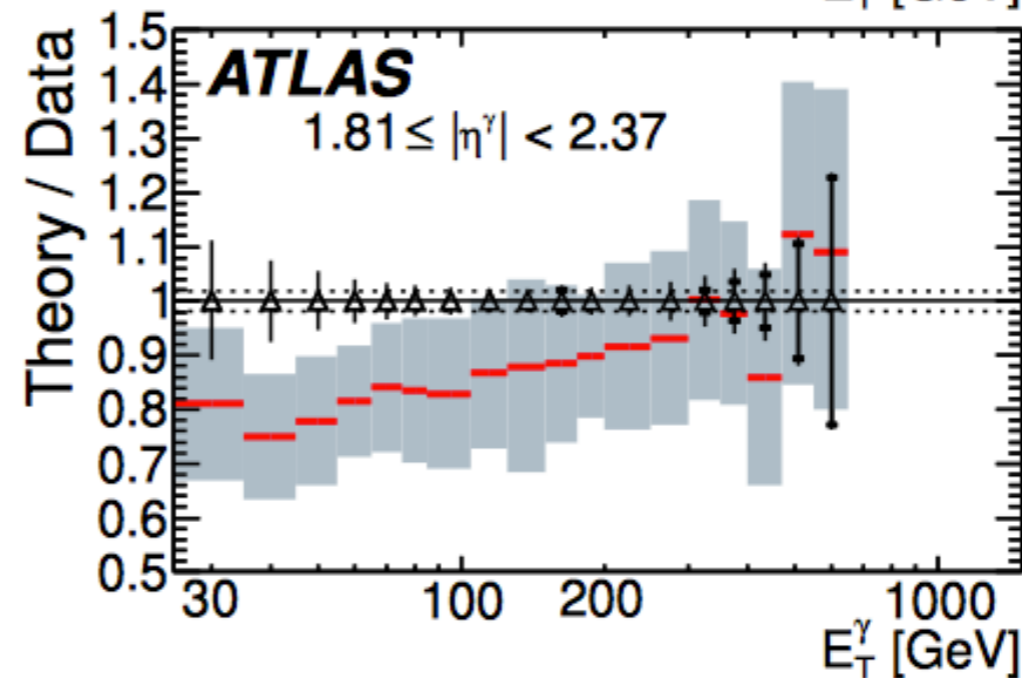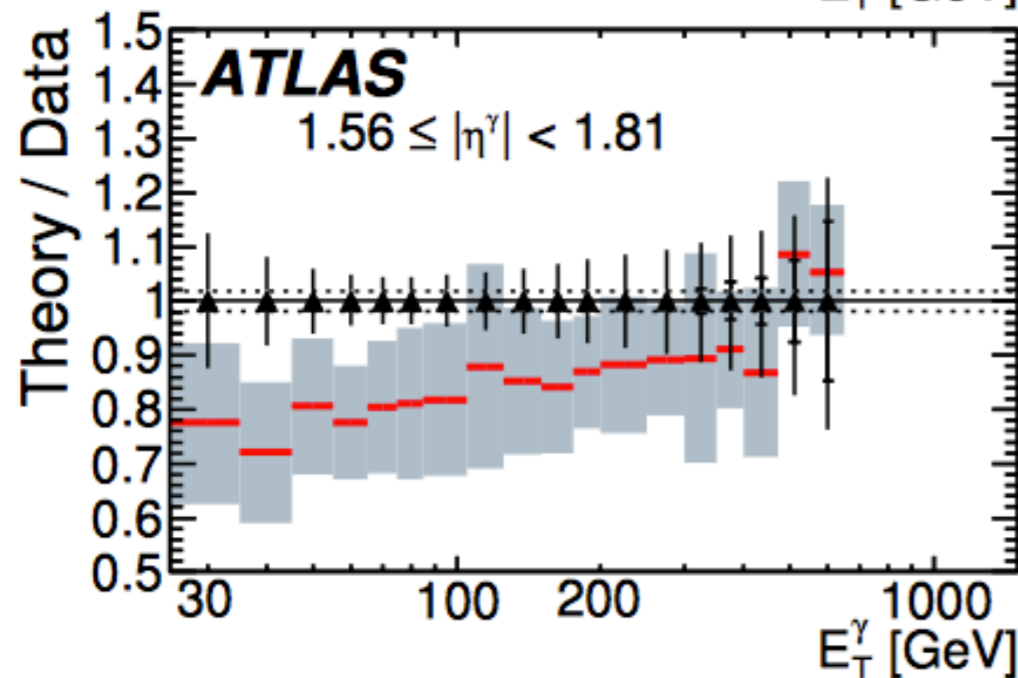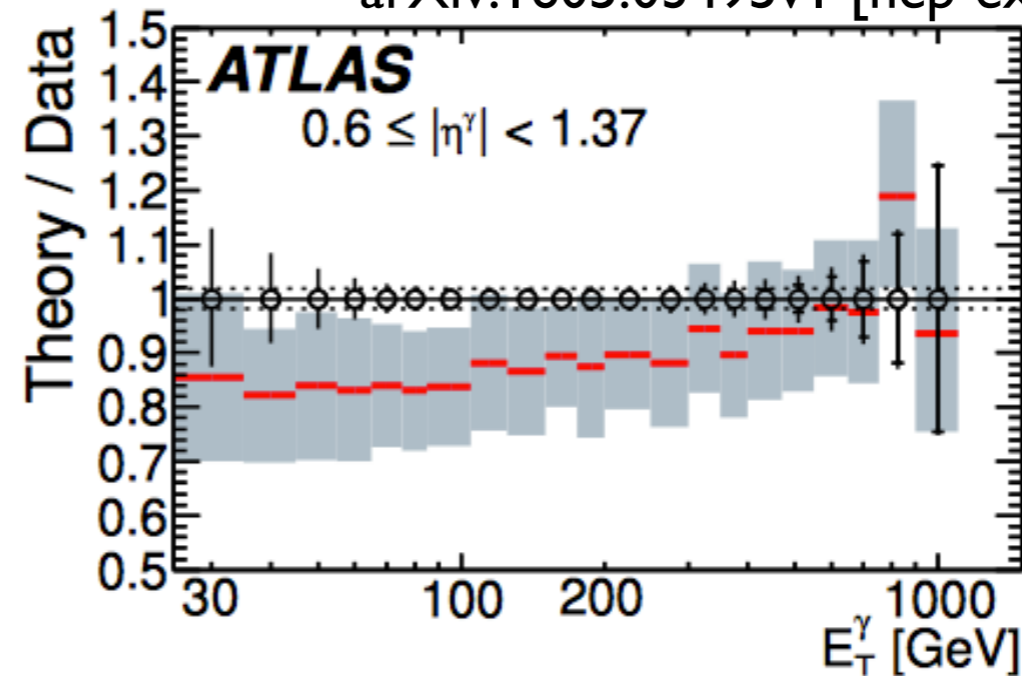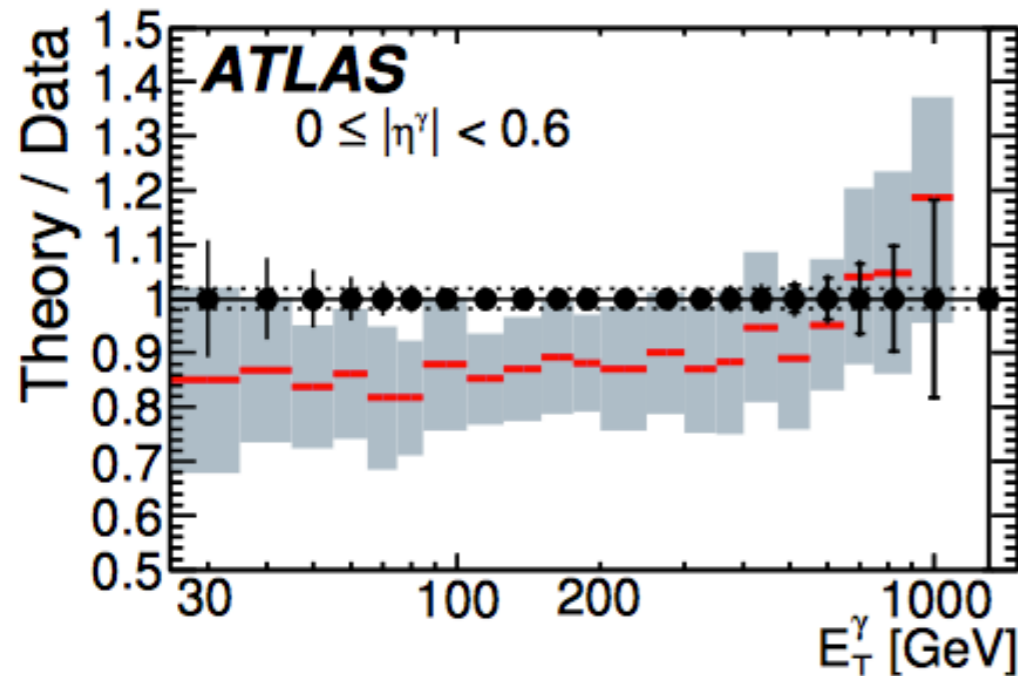
arXiv:1605.03495v1 [hep-ex]

Unfolded with a bin-by-bin method

- using Pythia, (and Sherpa as a cross-check)

Comparison with **JetPhox** , with CT10 PDF's.

E_T^γ - differential cross sections

arXiv:1605.03495v1 [hep-ex]

ATLAS
$\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}

Data 2012
- $\bullet$ $0 \leq |\eta^\gamma| < 0.6$
- $\circ$ $0.6 \leq |\eta^\gamma| < 1.37$
- $\blacktriangle$ $1.56 \leq |\eta^\gamma| < 1.81$
- $\triangle$ $1.81 \leq |\eta^\gamma| < 2.37$
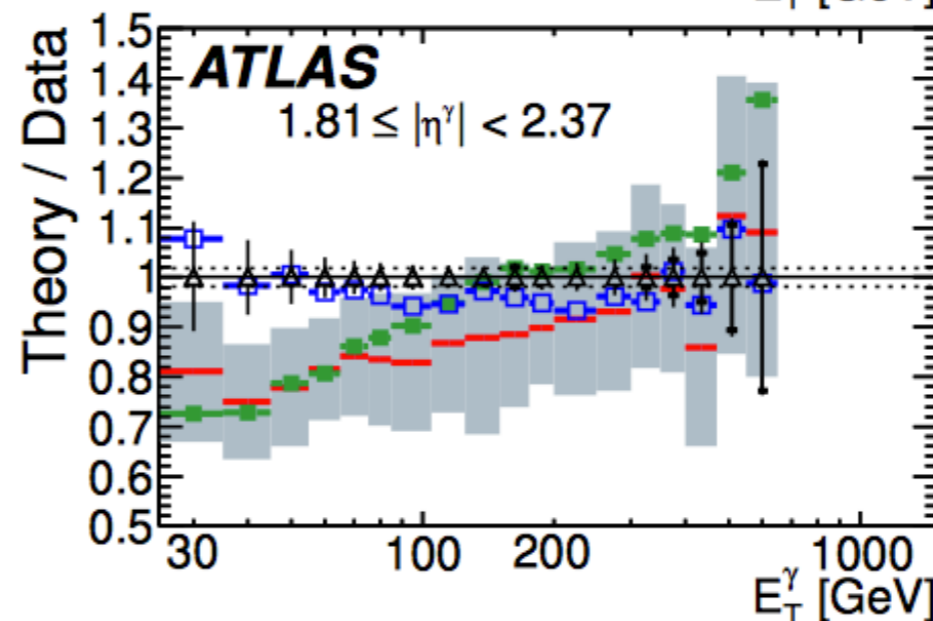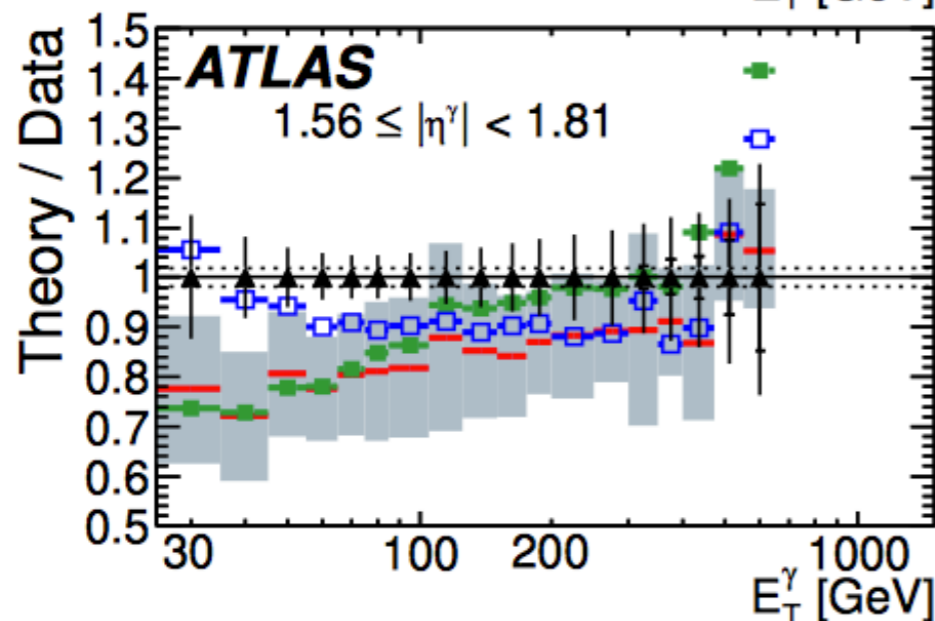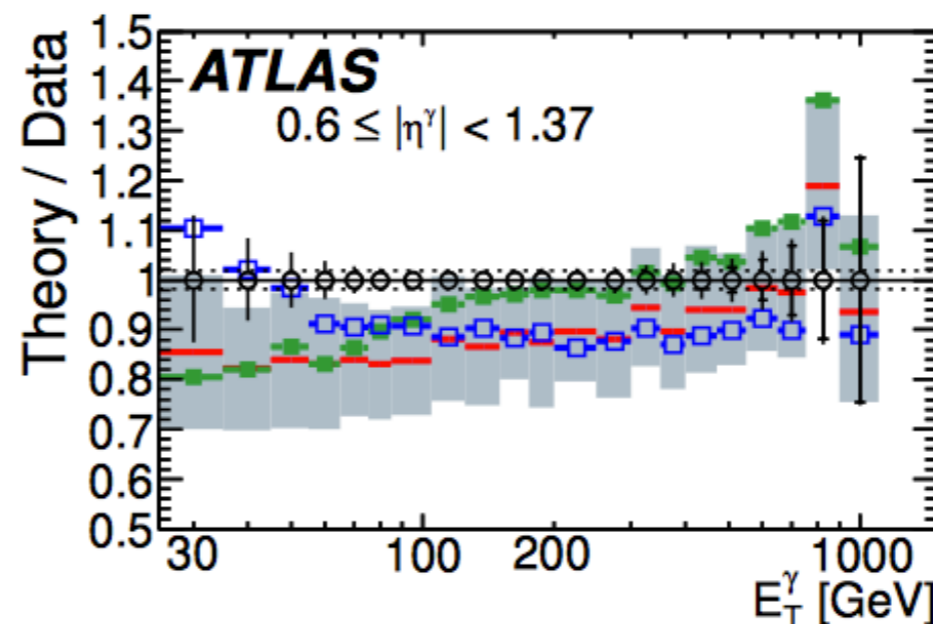- $\cdots$ Lumi Uncert.

NLO:
- JETPHOX CT10

- The NLO JetPhox calculation for most of the E_T range has similar shape but lie below data.

E_T^γ - differential cross sections

- Comparison with **JetPhox** NLO calculation, as well as **Pythia8** (CTEQ6L1) and **SHERPA** (CT10)
- Other PDF sets give almost identical predictions

arXiv:1605.03495v1 [hep-ex]

Measurement of the inclusive isolated prompt photon production cross section using the full CDF data set

cdf-note 11180

Photon selection and identification

☆ **Data set**　　　　L = 9.5 fb^{-1}

☆ **Kinematic region**　$E_T^\gamma > 30 \text{ GeV}$

　　　　　　　　　$|\eta^\gamma| < 1.0$

☆ **Isolation**　　　　$E_T^{iso}(\Delta R = 0.4) < 3.0 \text{ GeV} + 0.2 \times (E_T^\gamma - 20 \text{ GeV})$

☆ **ID criteria**

Variables related to energy deposit in calorimeter and track info

☆ Non-collision backgrounds

suppressed via
- Cosmic Rays veto: photon identification time consistent with the collision time
- Low Missing Transverse Energy: MET/E_T^γ < 0.8
  - with this cut also leptonic W boson decays are suppressed

Signal fraction

Main BKG from hadron decays (10^5 jets/γ)

- **Signal fraction**

  from Max Likelihood fit of data ANN output distribution to a linear combination of signal and background MC ANN templates,
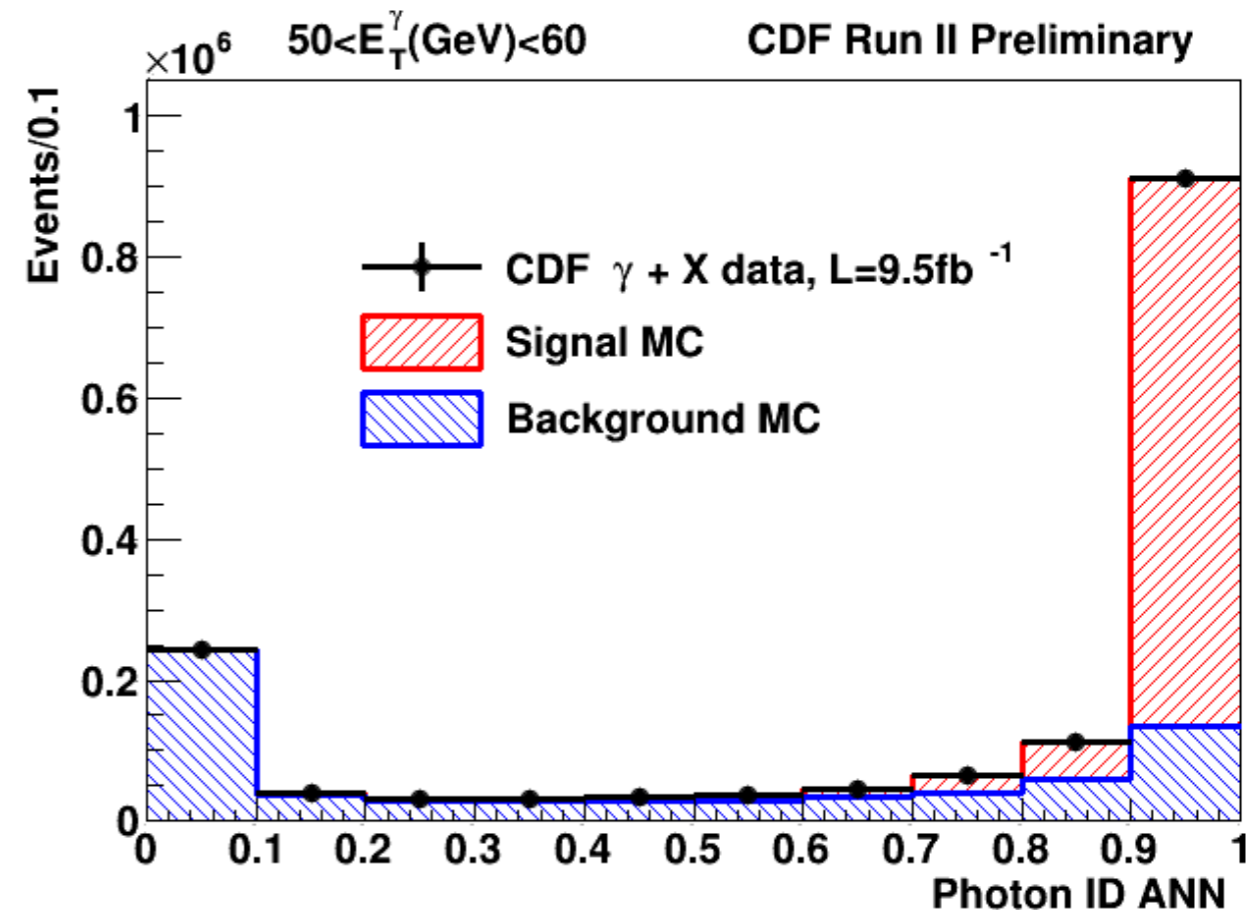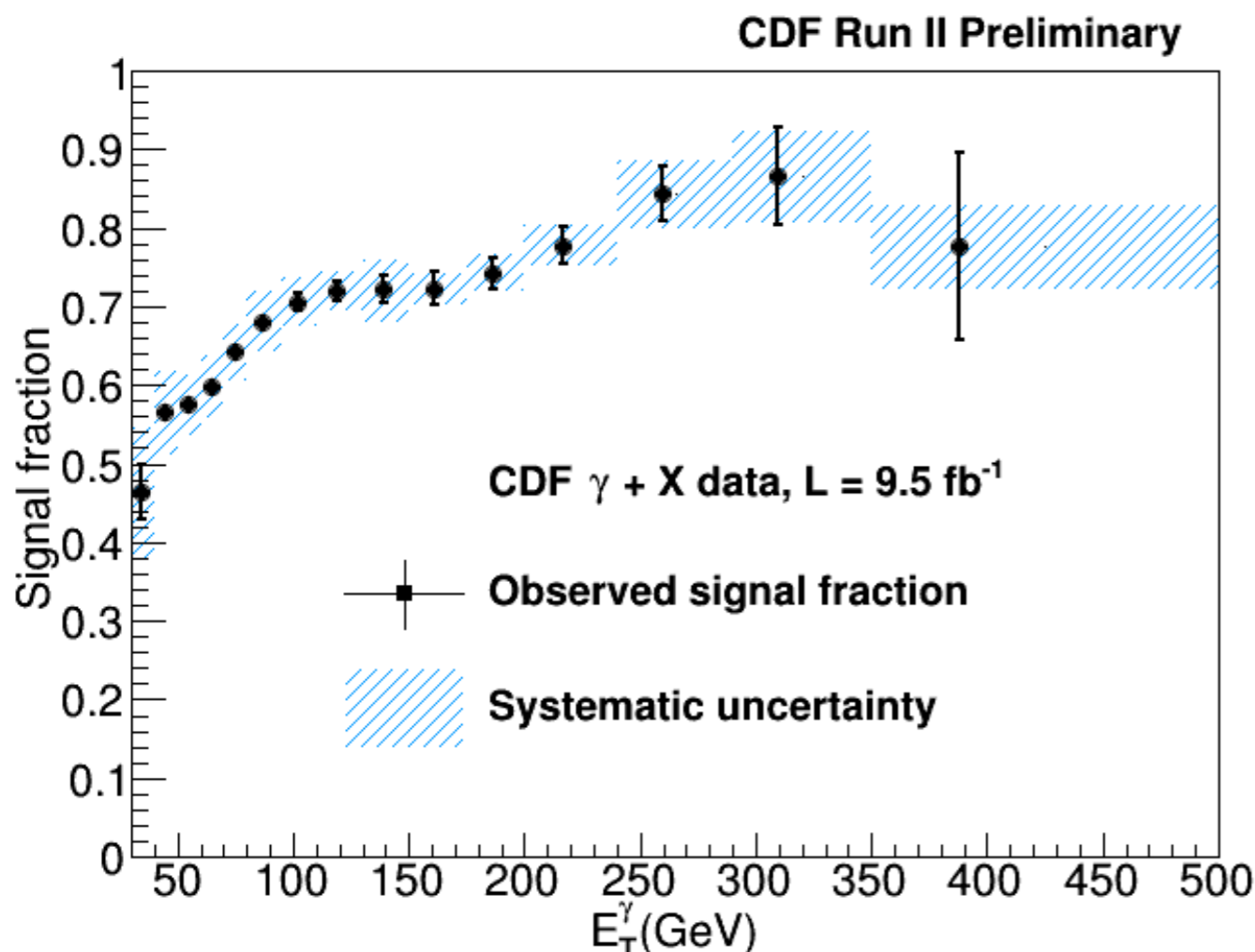
Signal and background normalized to the data according to the fit result in a particular E_T range

Main uncertainties

- **Energy scale**
- **Parton shower generator**
- **Energy isolation**

CDF Run II Preliminary L = 9.5 fb^{-1}

Legend:
- Isolation energy
- Had/Em
- CES/CEM
- Photon energy scale
- PDF
- Pythia-Sherpa
- ANN binning
- Fitting method

Y-axis: $\delta(\text{syst})/\sigma$

X-axis: E_T^γ (GeV)
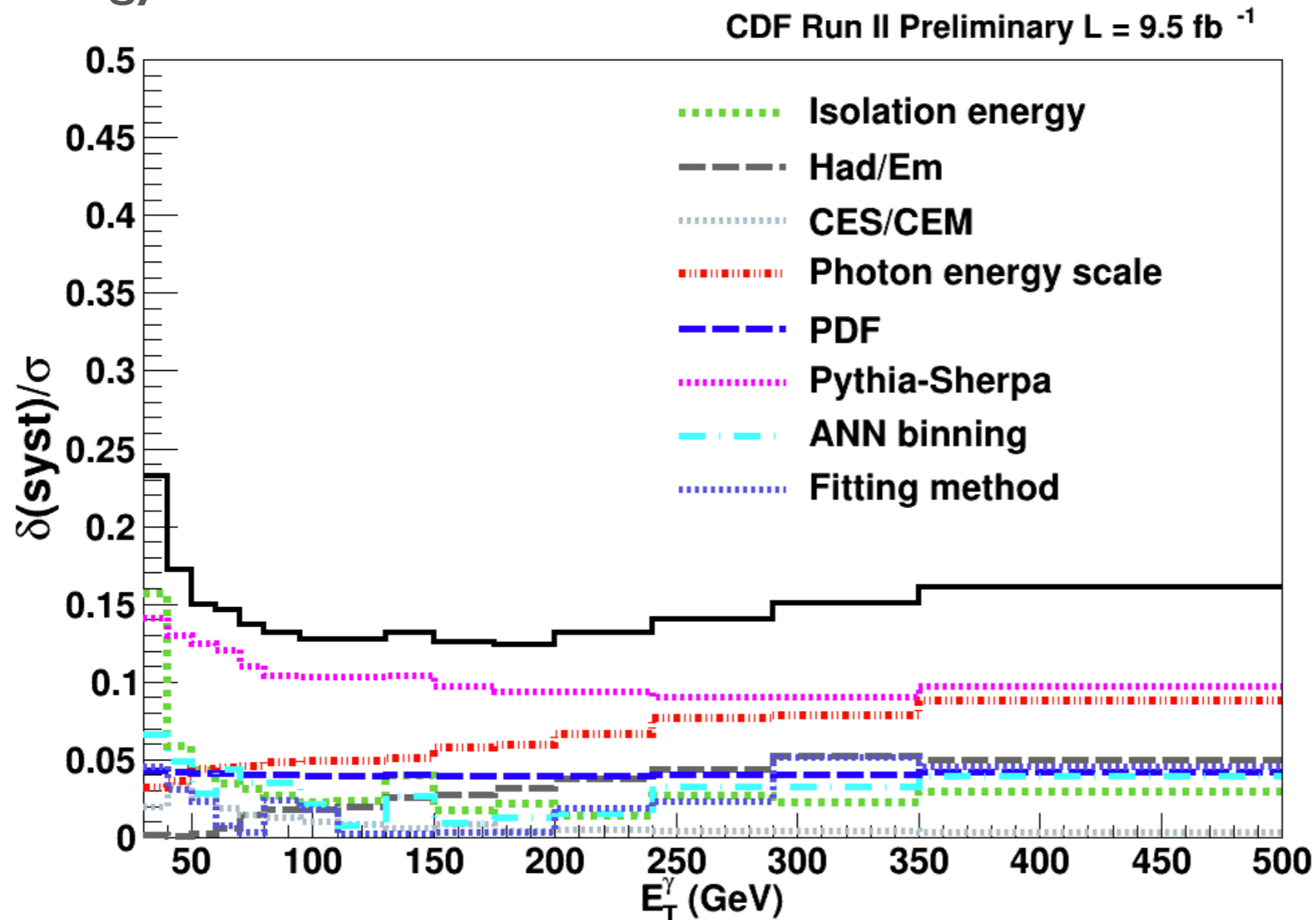
The solid line represents the total systematic uncertainty while the dashed lines correspond to the single contribution.

E_T^γ - differential cross section

CDF Run II Preliminary

- CDF γ+X data, L = 9.5 fb^{-1}
- Systematic uncertainty
- PYTHIA 6.216
- SHERPA 1.4.1
- MCFM 6.8

$\mu_R = \mu_F = \mu_f = E_T^\gamma$
(corrected for UE contributions)

$|\eta^\gamma| < 1.0$ and $E_T^{iso}(R=0.4) < 2$ GeV

vertical axis: $d^2\sigma/dE_T^\gamma d\eta^\gamma$ (pb/GeV)

horizontal axis: E_T^γ (GeV)
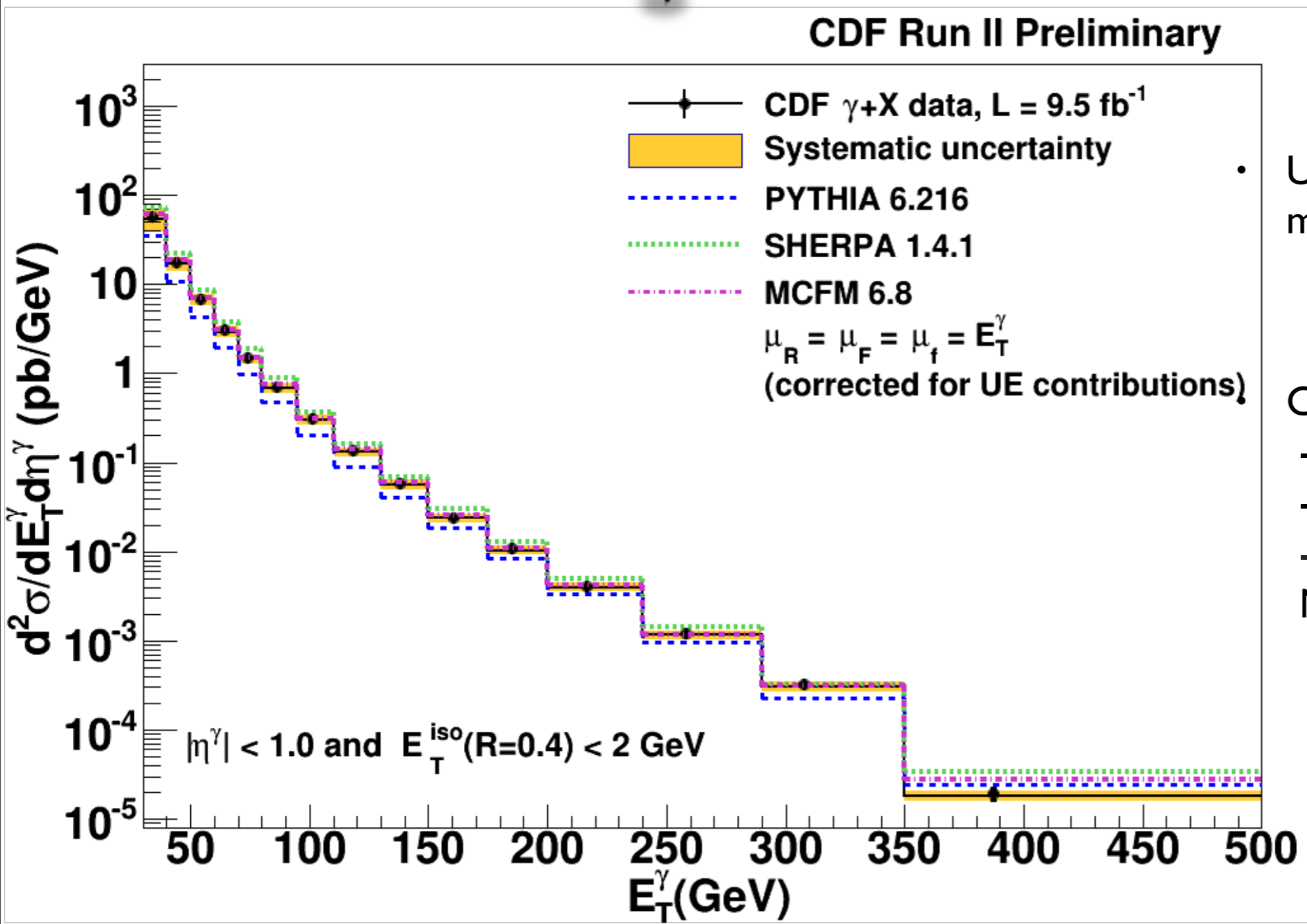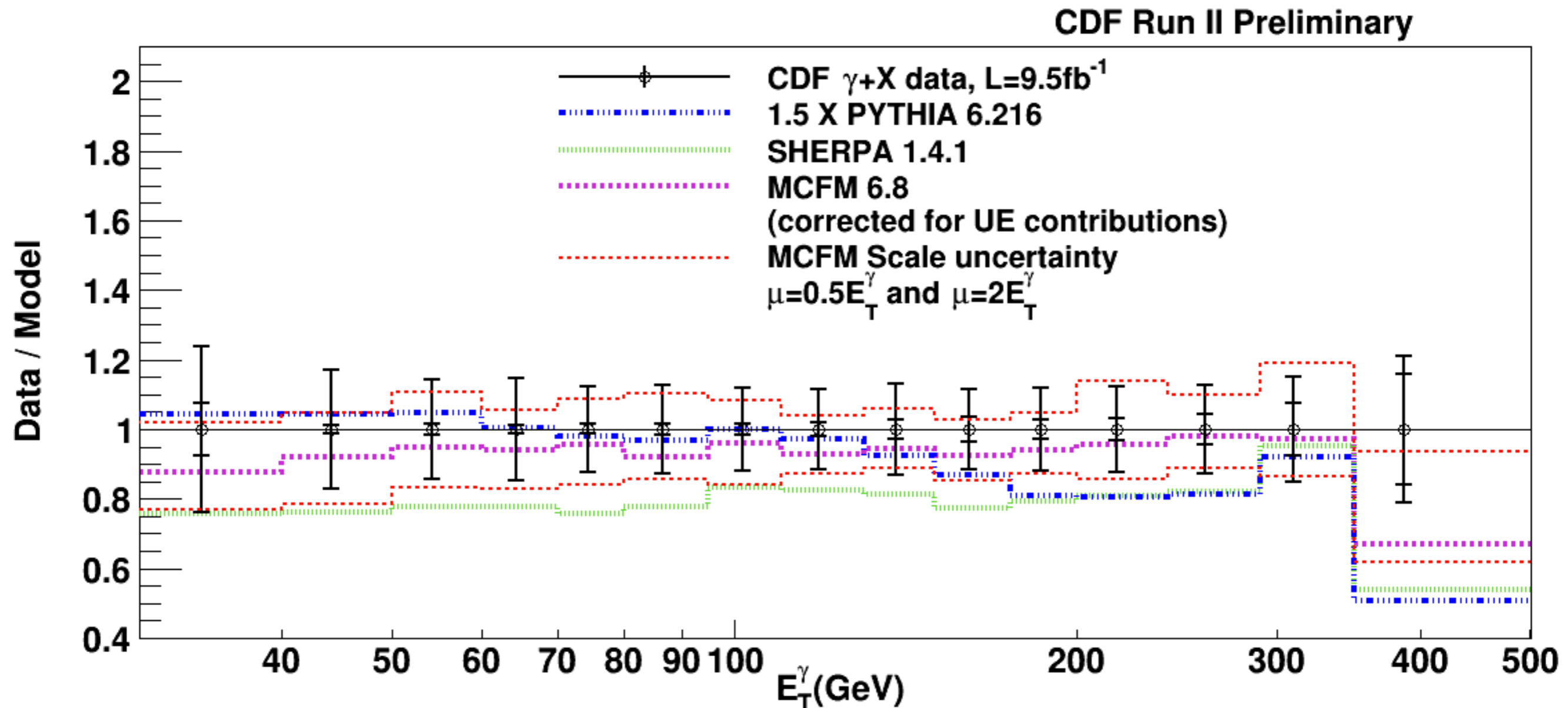
- Unfolded with a bin-by-bin method
  - using Pythia, (and Sherpa as a cross-check)

Compared to
- **PYTHIA (**CTEQ5L PDFs**)**
- **SHERPA (**CT10 PDFs**)**
- **MCFM (**PDFs: MRST2008 NLO, FFs: GdRG LO**)**
  - MCFM (corrected for UE contributions)

E_T^γ - differential cross section

Data points centered at 1 and Data/Model ratio (lines)

- Both **PYTHIA** and **SHERPA** predictions describe the shape of the differential cross section
- **The NLO MCFM calculation provides the best description of data overall.**

Future plans

- **ATLAS**

  ☆ Inclusive photon measurement @ 13 TeV
  ☆ Diphoton measurement @ 13 TeV
  ☆ Photon+jet @ 8 TeV

- **CDF**

  ☆ Photon+jets with the full data set

Summary

☆ **The ATLAS and CDF experiments are performing high precision pQCD tests with prompt photons**

☆ **We have presented the measurements of prompt isolated photon production cross sections**

- at 8 TeV with the **ATLAS** detector
- at 1.96 TeV with the full **CDF** data set

☆ **Results compared to several theoretical predictions.**

- **ATLAS**
  The NLO JetPhox calculation for most of the E_T range has similar shape but lie below data.
- **CDF**
  The NLO MCFM calculation has an overall good agreement

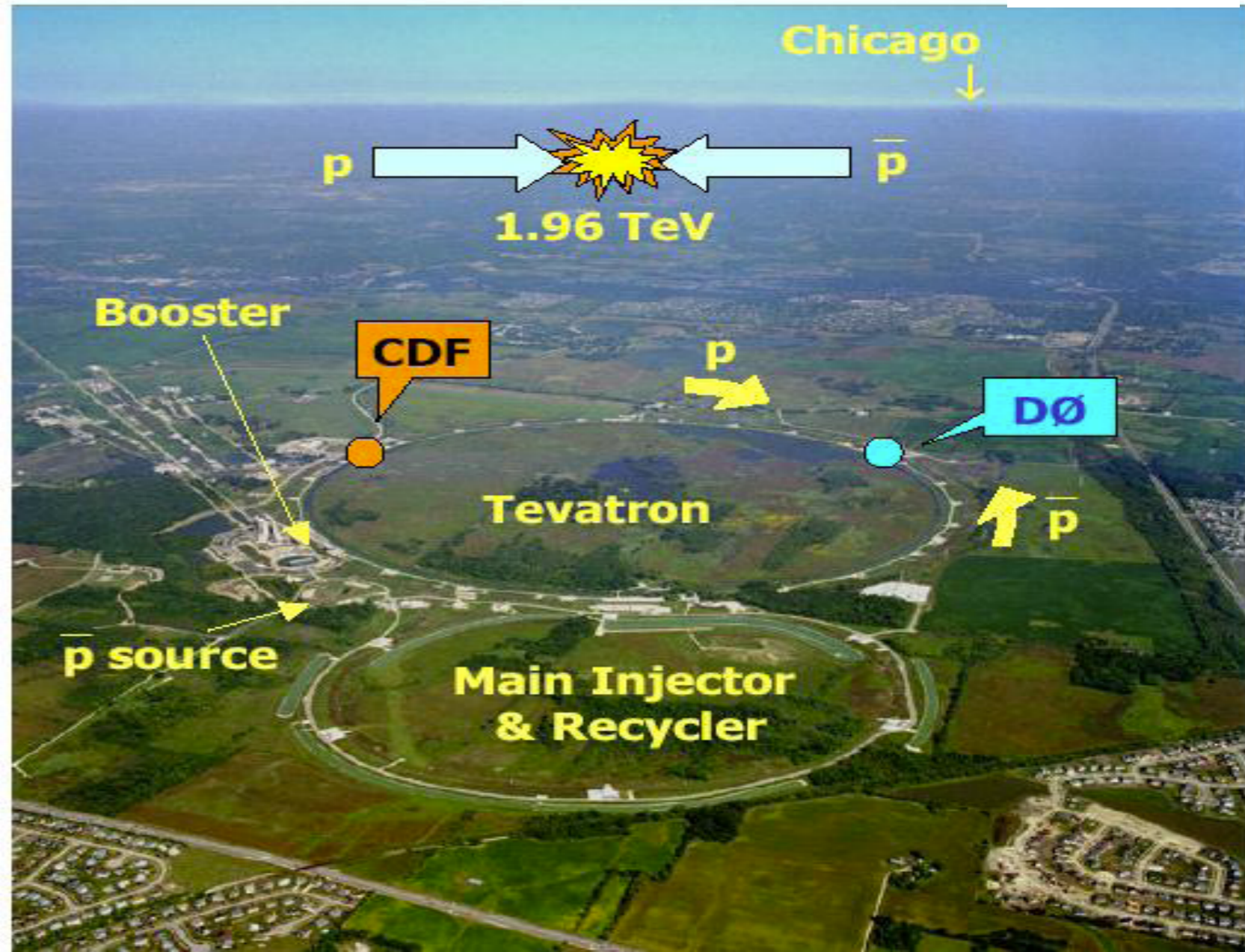☆ **More photon studies are in progress:**

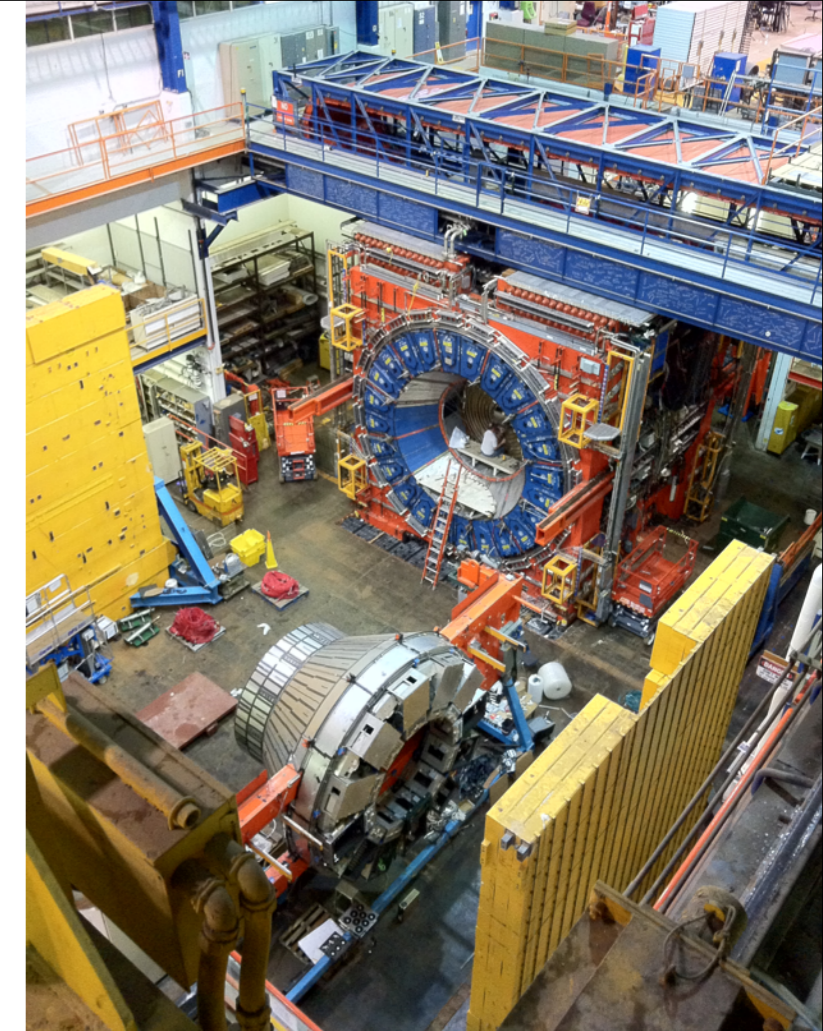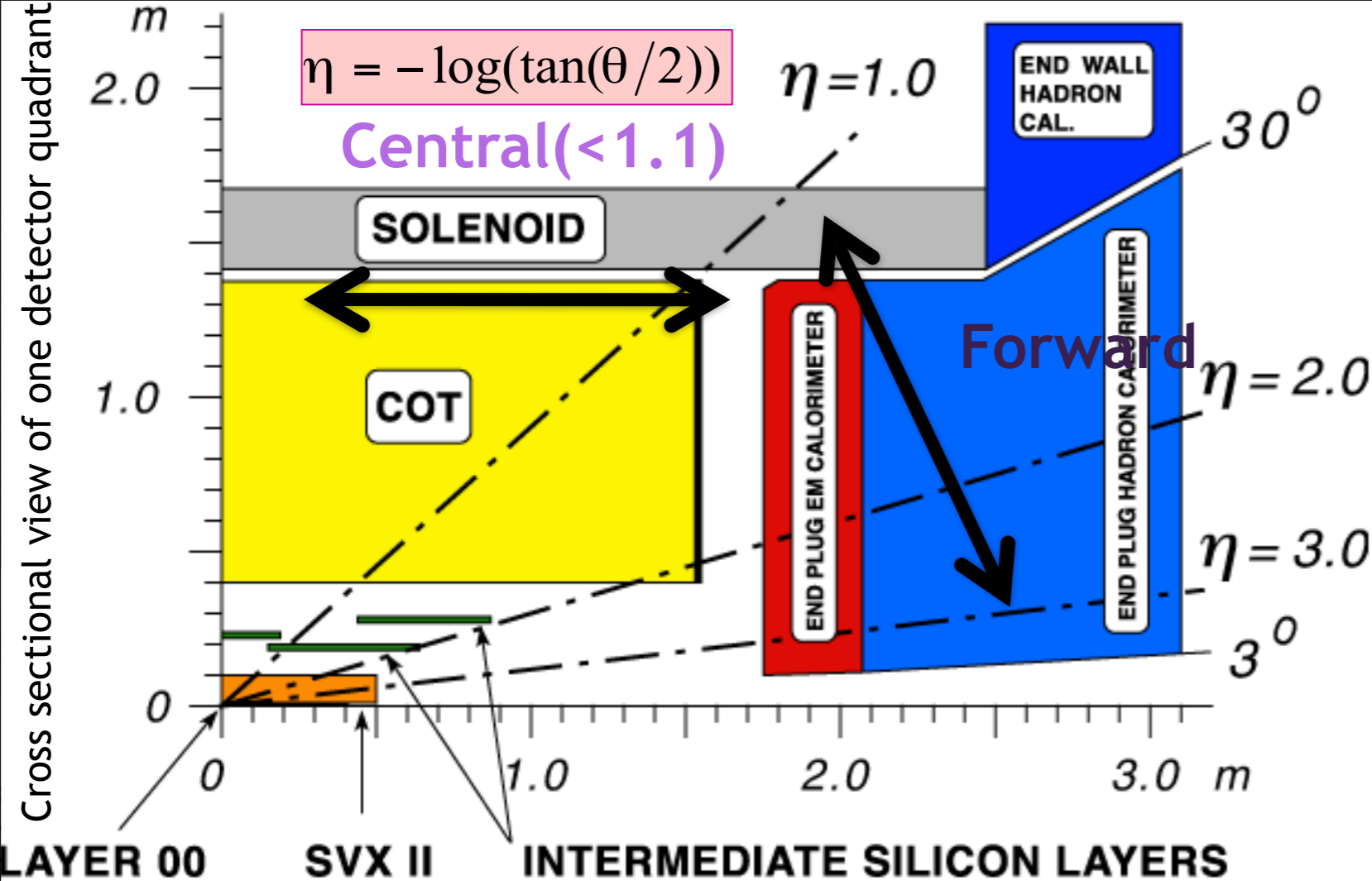- **Stay tuned !**

THANK YOU!

BACKUP

The Tevatron

- proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV

- Two interaction points:
  - **CDF**
    (Collider Detector at Fermilab)
  - **DZero**

- Delivered per experiment roughly 12 fb^{-1} and recorded over **10 fb^{-1},** from 2002–2011 (Run II)

Operated by international collaborations of more than 1000 physicists from ~100 universities and laboratories

Cross sectional view of one detector quadrant

$\eta = -\log(\tan(\theta/2))$

Central(<1.1)

Forward

- **Tracking**:
  → Drift chamber, |η|<1
  → Silicon microstrip tracker, |η|<2 allows also for precise vertex reconstruction
- **Calorimeter**:
  → Split in EM (scintillator – lead) and HAD (scintillator – iron) sampling devices, |η|<1.1 (central), 1.1<|η|<3.6 (plug)
- **Muon system:**
  → Drift chambers outside calorimeter, |η|<1.5
- **Central electromagnetic calorimeter (lηl<1.1):**
  → Tower segmentation: Δη × Δφ ≅ 0.1 × 15º
  → Resolution: σ(E)/E =13.5%/ E(GeV) ⊕1.5%
  → Proportional chambers (CES) at 6 rad. lengths depth (shower max) give location and 2D profile of the EM showers (position resolution ~2 mm for 50 GeV γ)
- **Focus of this analysis on *reconstructed* *photons in the central region* of the detector**

- **"Central"**
  - lηl<1.1
  - Use central calorimeters
- **"Plug"**
  - 1.2<lηl<2.8
  - Use forward calorimeters
  - Tracking efficiency lower than in central region
 - Easier to miss a track and reconstruct fake object as a photon

CDF Detector: EM

- **Focus of this analysis on *reconstructed photons in the central region* of the detector**

- **EM calorimeter (EM)
  segmentation:**
  - $\Delta\eta \times \Delta\phi \sim 0.1 \times 15°$ ($|\eta|<1$)

- **Shower max detector (CES)**
  strip-wire chamber situated at the shower maximum position (~6 radiation lengths) into Central EM

  - Gives resolution to better distinguish $\pi^0/\eta \longrightarrow \gamma\gamma$ from γ at low E_T

  - Symmetric $\pi°$ decay:
    - $\Delta\gamma\gamma \sim 50cm/E_T$, cluster width ~ 2cm
    - Can't resolve 2 EM showers above ~50GeV

Hadronic Calorimeter

Electromagnetic Calorimeter

Shower maximum detector
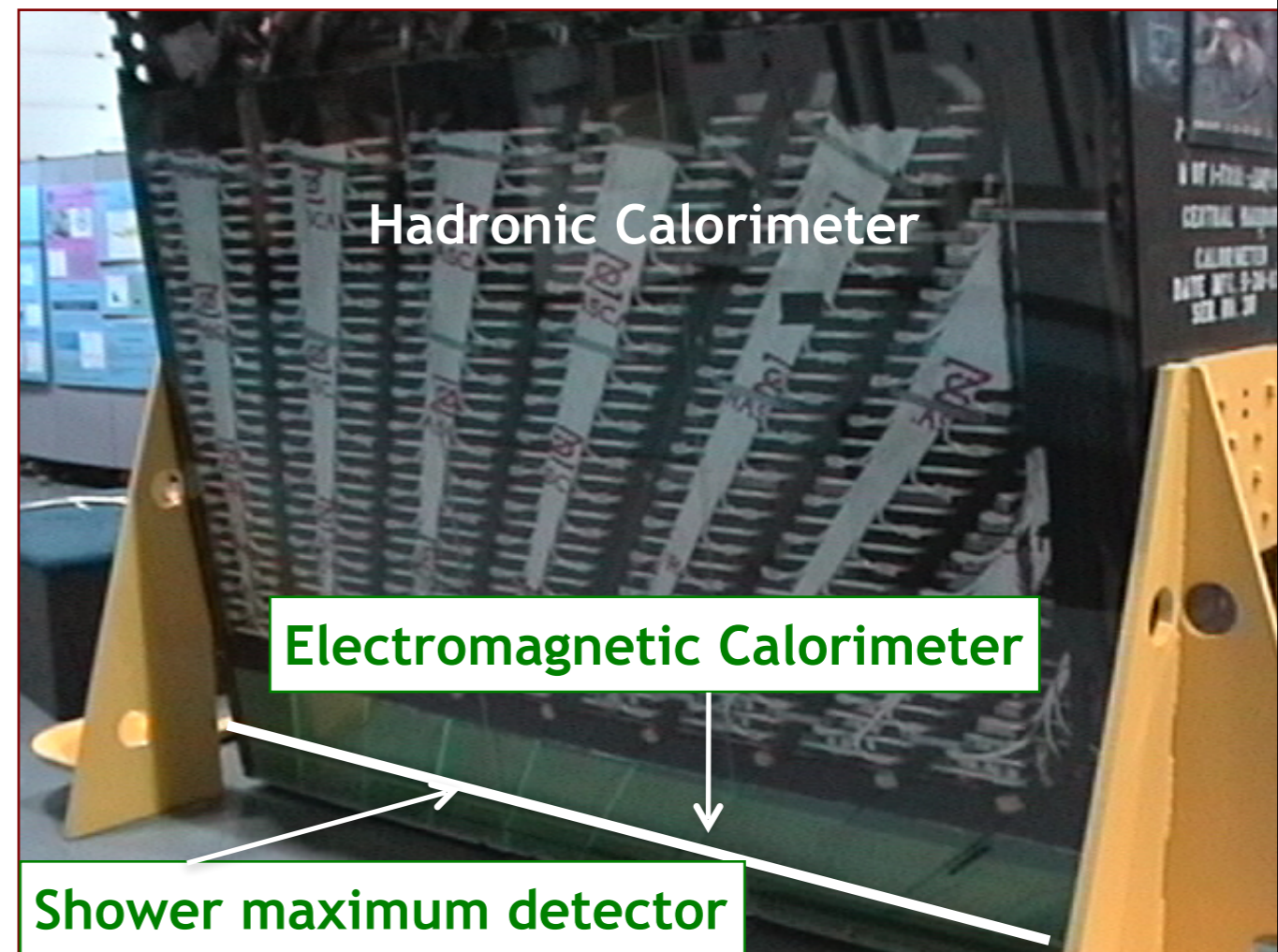
ElectroMagnetic Shower Detection

EM Calorimeter

Preshower

Shower Maximum Profile (CES)
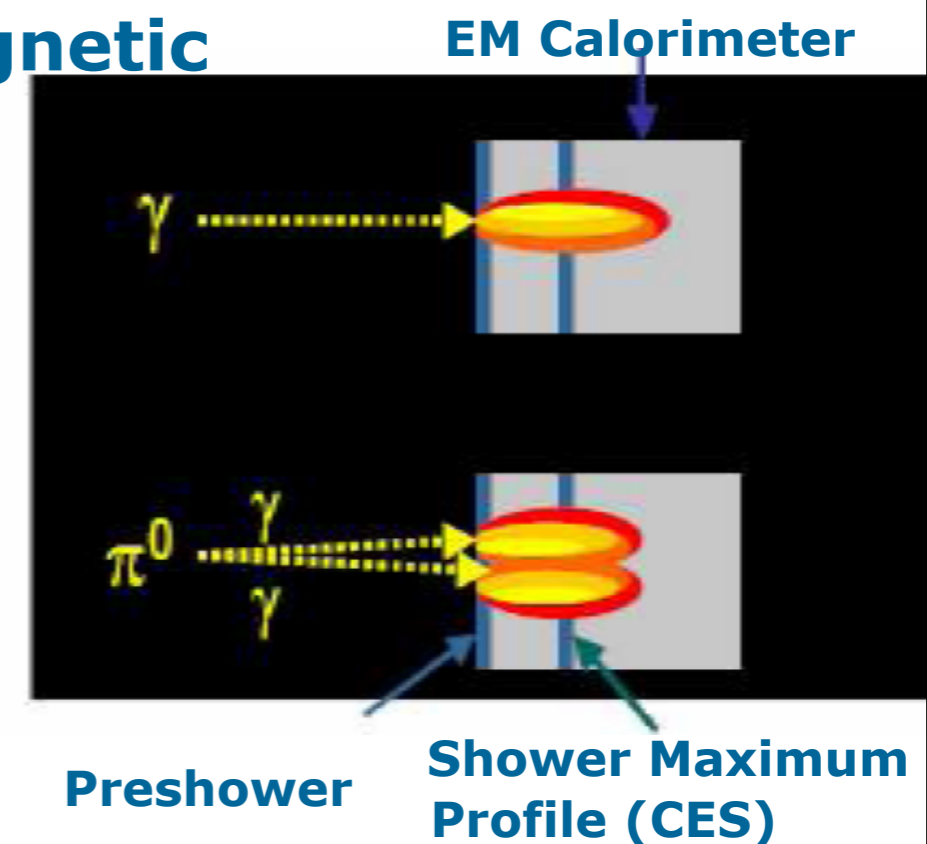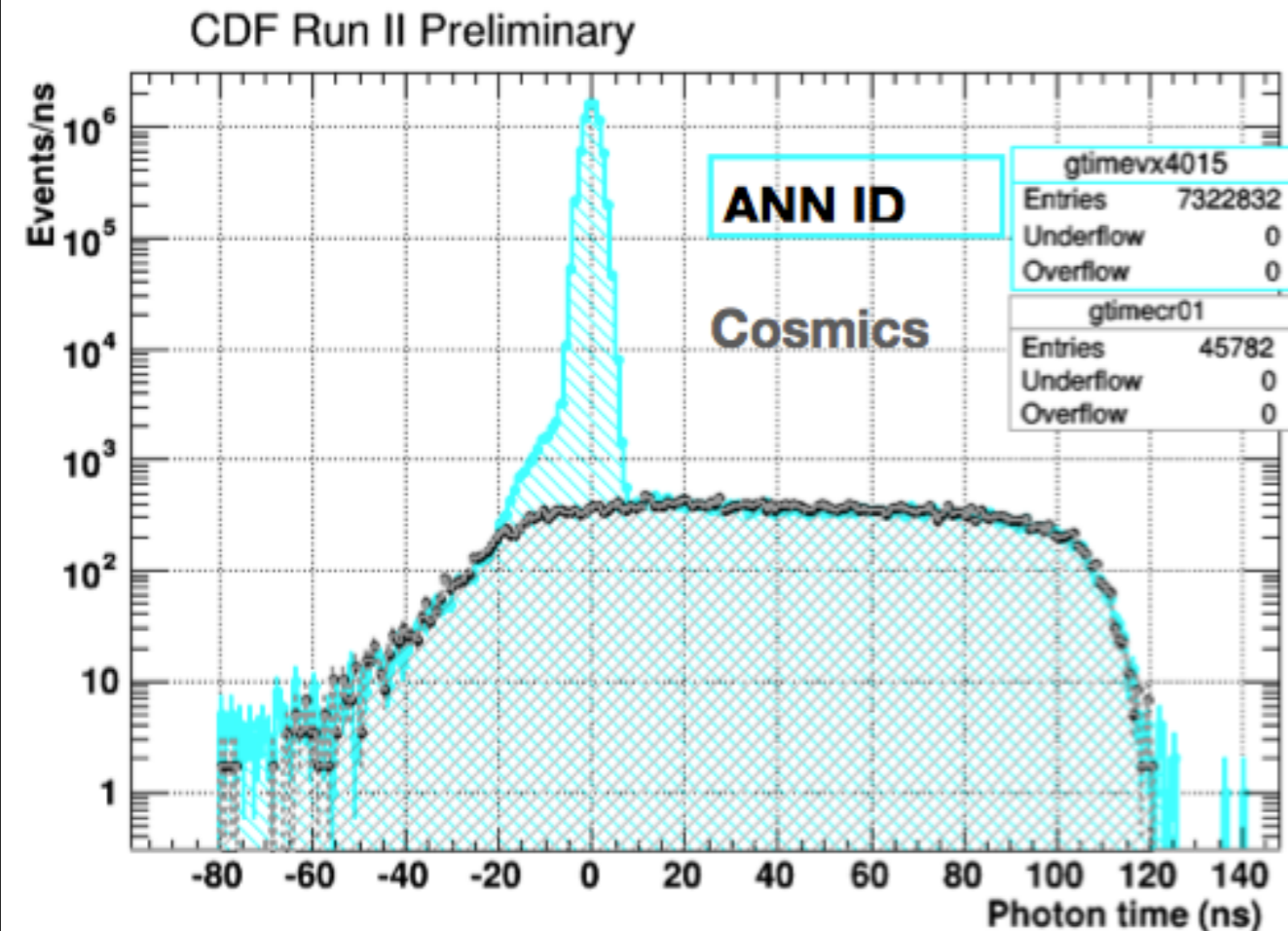
Non collisional background

The non-collision processes include energetic particles from cosmic rays and the beam halo that mimic the signal of a prompt proton. Cosmic muons are the most important source of non collisional background

Non Collision Background

CDF Run II Preliminary

gtimevx4015	
Entries	7322832
Underflow	0
Overflow	0

ANN ID

Cosmics

gtimecr01	
Entries	45782
Underflow	0
Overflow	0

$a = b * c / d = 4\,744$

$b = \#$ ANN in Side Band region
$c = \#$ Cosmics in Signal region
$d = \#$ Cosmics in Side Band region

CDF Run II Preliminary

ANN ID

gtimevx4015	
Entries	7322832
Underflow	0
Overflow	0

Cosmics

gtimecr01	
Entries	45782
Underflow	0
Overflow	0

Signal region
$|t^\gamma| < 6.6$ ns

a

Side Band Region

30ns$< |t^\gamma| < 90$ns

Photon time (ns)

Fraction of cosmic photon remaining in the signal region:
$a / N = 6.5e{-}4$

Negligible!

$N = \#$ ANN in Signal region
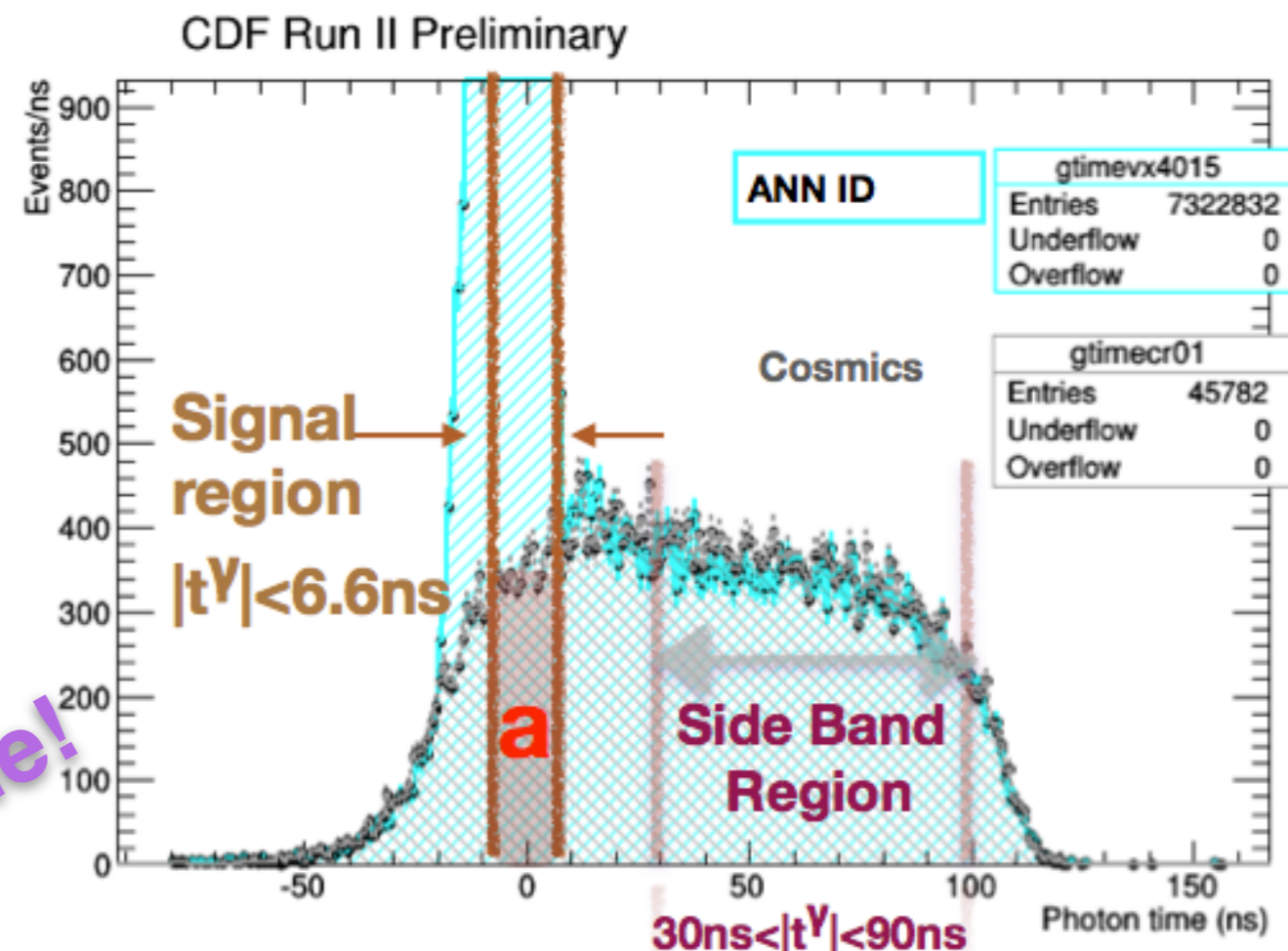
- Use of an Artificial Neural Network (ANN) trained to discriminate between prompt photons and the background from meson decays (π°'s, η's),

> – Signal samples: inclusive photons generated with PYTHIA at a various generated photon pT
> – Background samples: di-jets samples generated with PYTHIA (ISR and FSR removed)
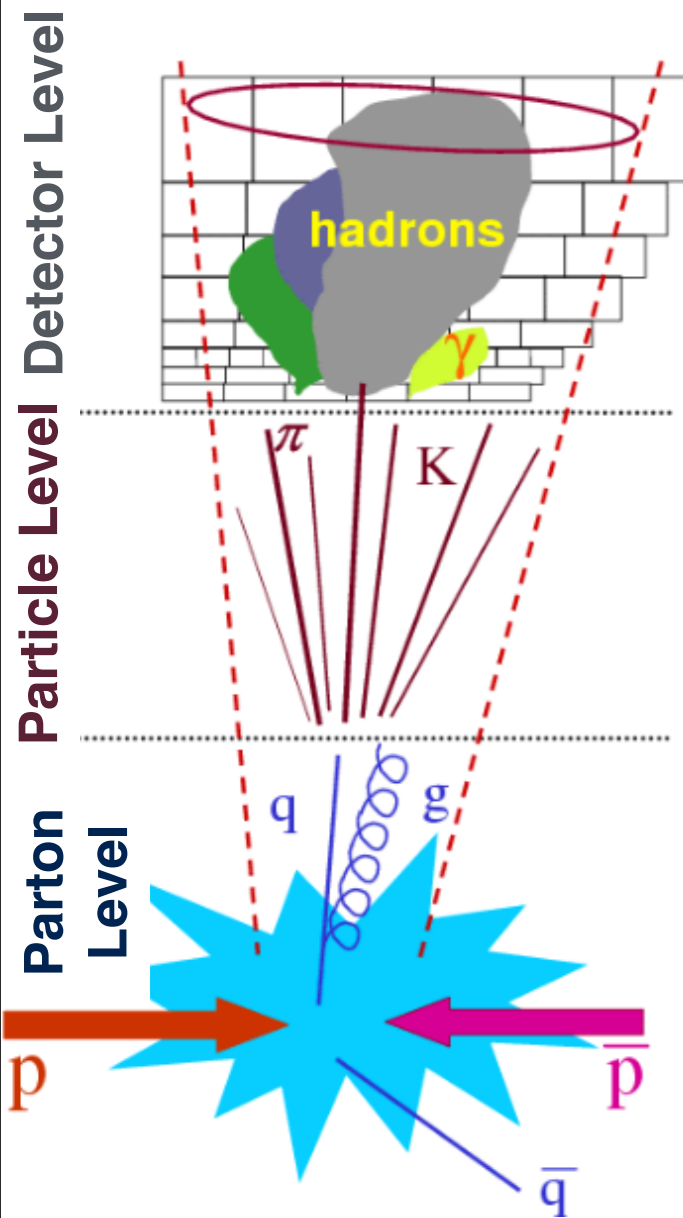
Trained with TMVA (Toolkit for Multivariate Data Analysis)

Photon ID ANN input variables

- Ratio of hadronic to EM transverse energy (HAD/EM)
- Shape in shower max compared to expectation (χ^2 for strips and wires)
- Calorimeter Isolation
- Track isolation
- Ratio of energy at shower max to total EM energy (CES/CEM)
- Lateral sharing of energy between towers compared to expectation
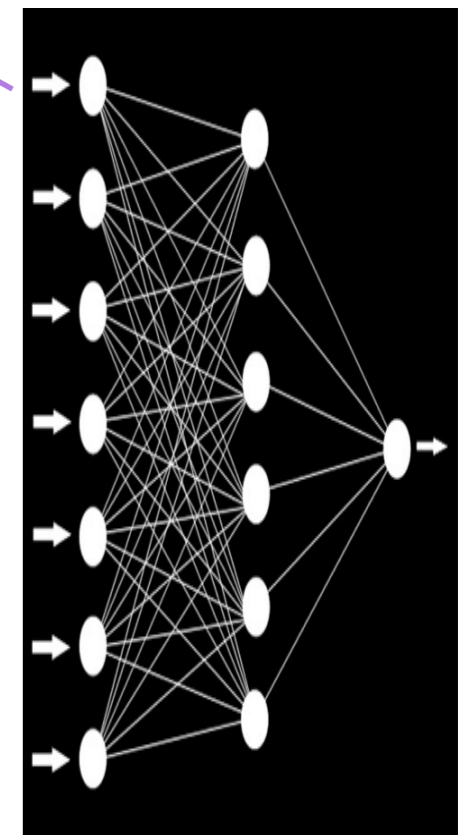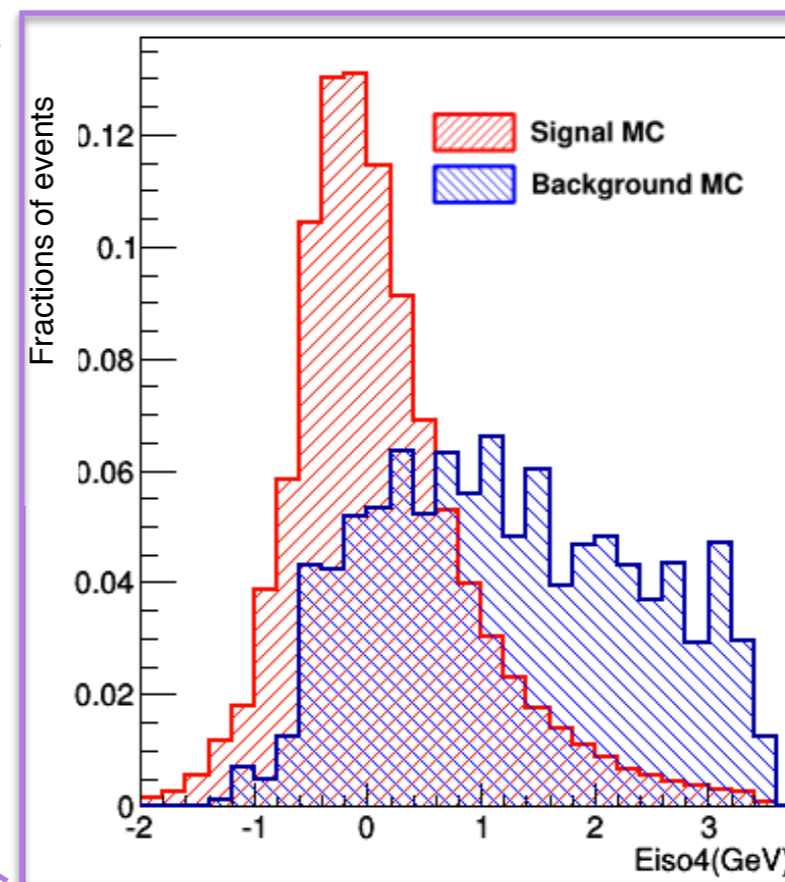
Theoretical Predictions

Particle Level

- **PYTHIA 6.216**
  LO MC generator with CTEQ5L PDFs
  [T. Sjöstrand et al., JHEP **05**, 026 (2006)].

- **SHERPA 1.4.1**
  generator with CT10 PDFs. Tree-level matrix element (**ME**) diagrams with one photon and up to three jets, merged with parton shower (**PS**)
  [T. Gleisberg *et al.*, JHEP **02**, 007 (2009)].

These predictions are done at the particle level, which means that they are are directly comparable to our measurements.

Parton Level

- **MCFM 6.28**
  Fixed-order **NLO calculation** including non-perturbative fragmentation at LO. PDFs: MRST2008 NLO, FFs: GdRG LO
  [J. M. Campbell et al., Phys. Rev. D 60, 113006 (1999)]
  [A. Gehrmann-De Ridder, E. W. N. Glover, Eur. Phys. J. C7, 29-48 (1999)].

For comparisons to data, a correction (C_{UE}) for hadronization and underlying events is applied to this parton-level MC
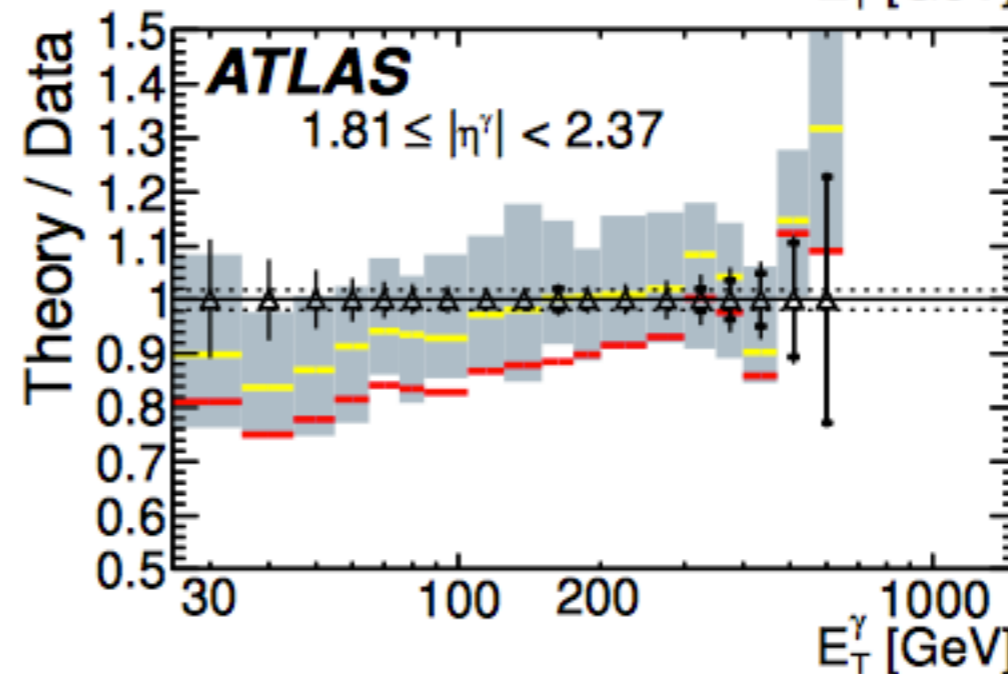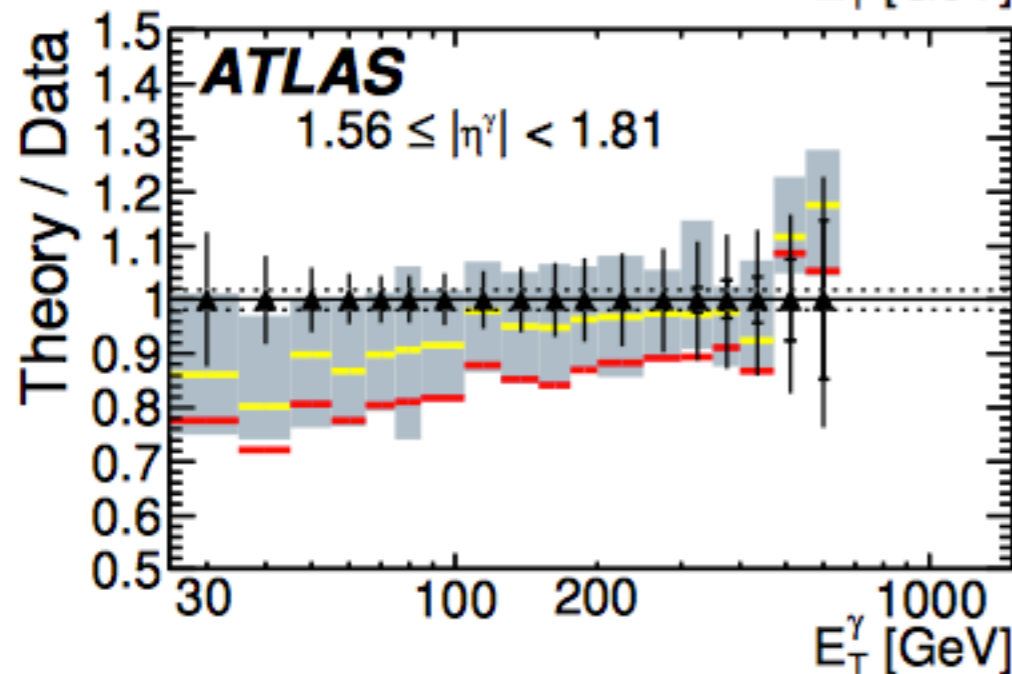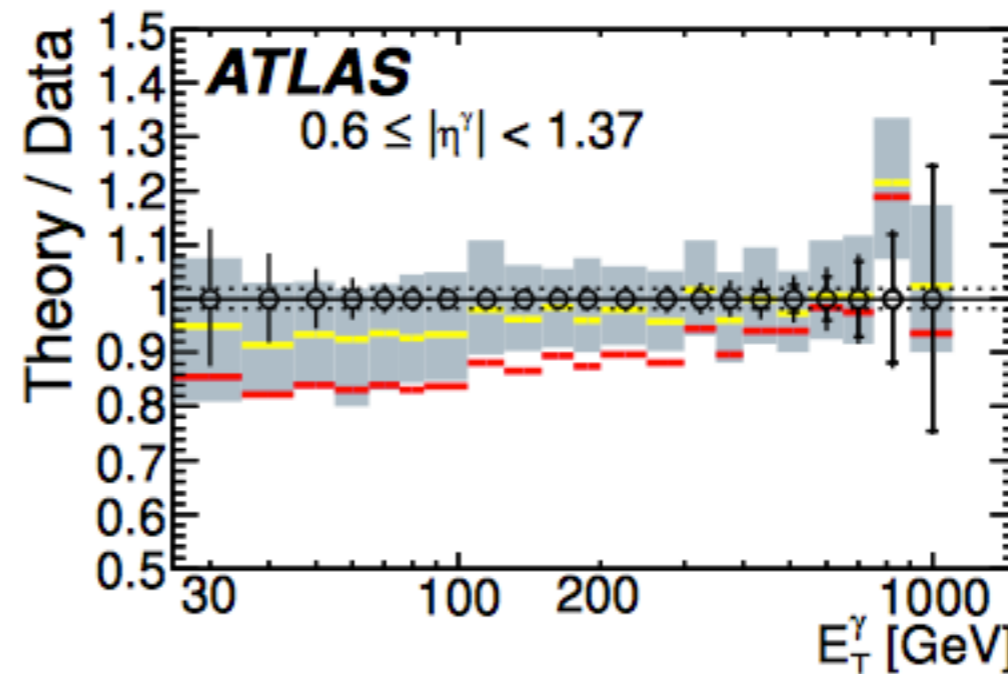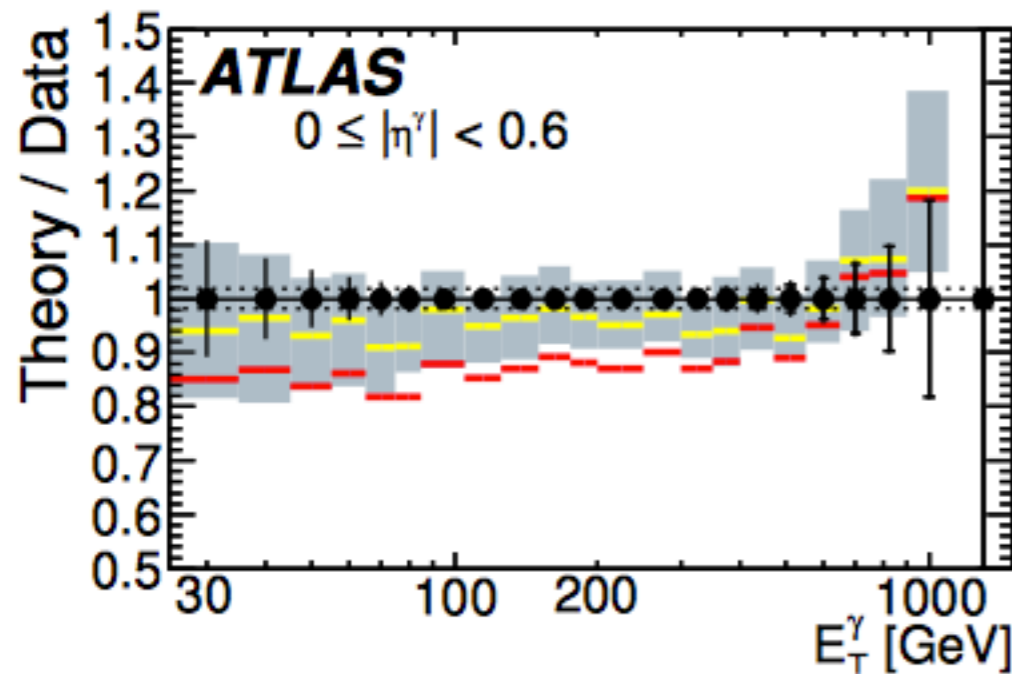- C_{UE} = UE/NO UE,
  where UE/NO UE is the parton level cross section with the underlying events on/off
- C_{UE}, estimated averaging the results in PYTHIA MC generated with the Tune A or DW, is taken from the previous published measurement

Particle Level Detector Level

Particle Level

Parton Level

hadrons

γ

π K

q g

p

$\bar{p}$

$\bar{q}$

E_T^γ - differential cross sections

arXiv:1605.03495v1 [hep-ex]

Comparison with JetPhox and PeTeR calculations, with CT10 PDF's