Experimental Methods and Physics at the LHC

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First Measurements with Run 1 CMS Data

Questions

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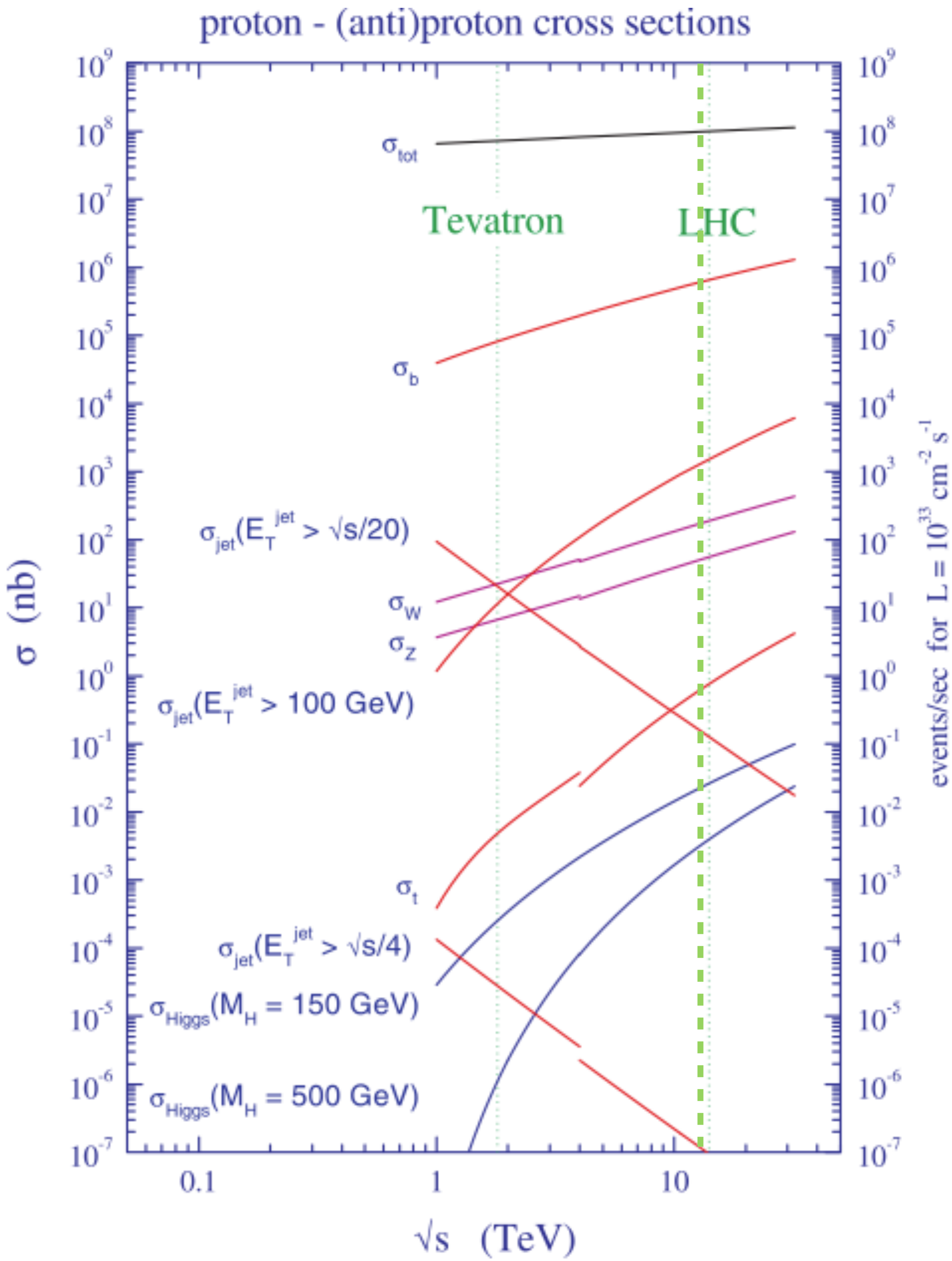
- What measurements can be performed with minimum amount of data?
  - Physics processes with large cross sections
  - Physics processes that have clean signatures
- What measurements can be performed with minimum number of working sub-detectors?
  - Provided that the magnet is working
- Before we explore the new territory, we need to make sure we understand our old friends

Number of Produced Events per Second



- 10^8/sec Total number of pp interactions, ~60% inelastic
- 200/sec W boson
- 60/sec Z boson
- 0.8/sec top quark
- 0.045/sec Higgs

Current instantaneous luminosity is 20 times higher!

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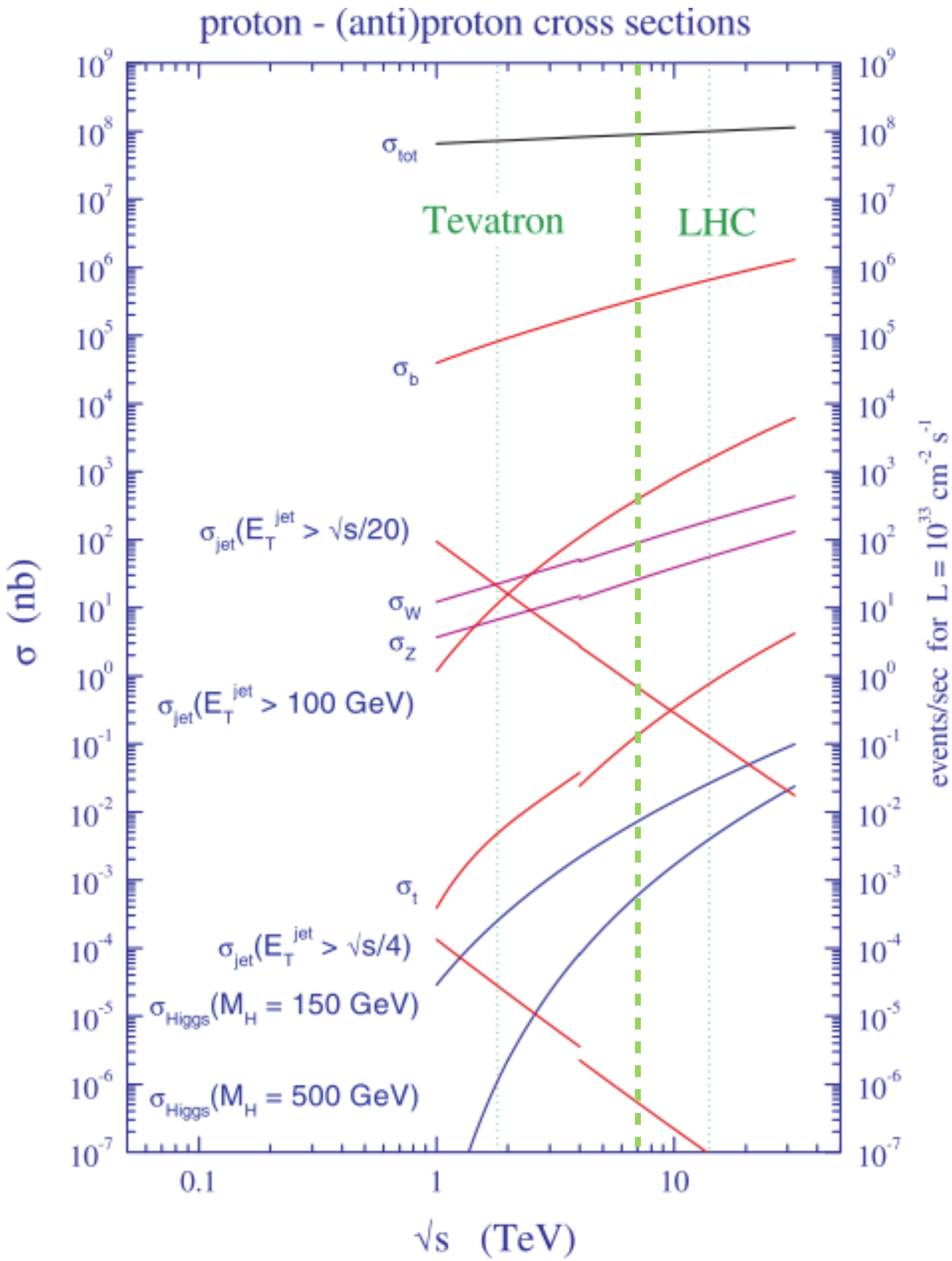

- 10^8/sec Total number of pp interactions, ~60% inelastic
- 100/sec W boson
- 30/sec Z boson
- 0.2/sec top quark
- 0.001/sec Higgs

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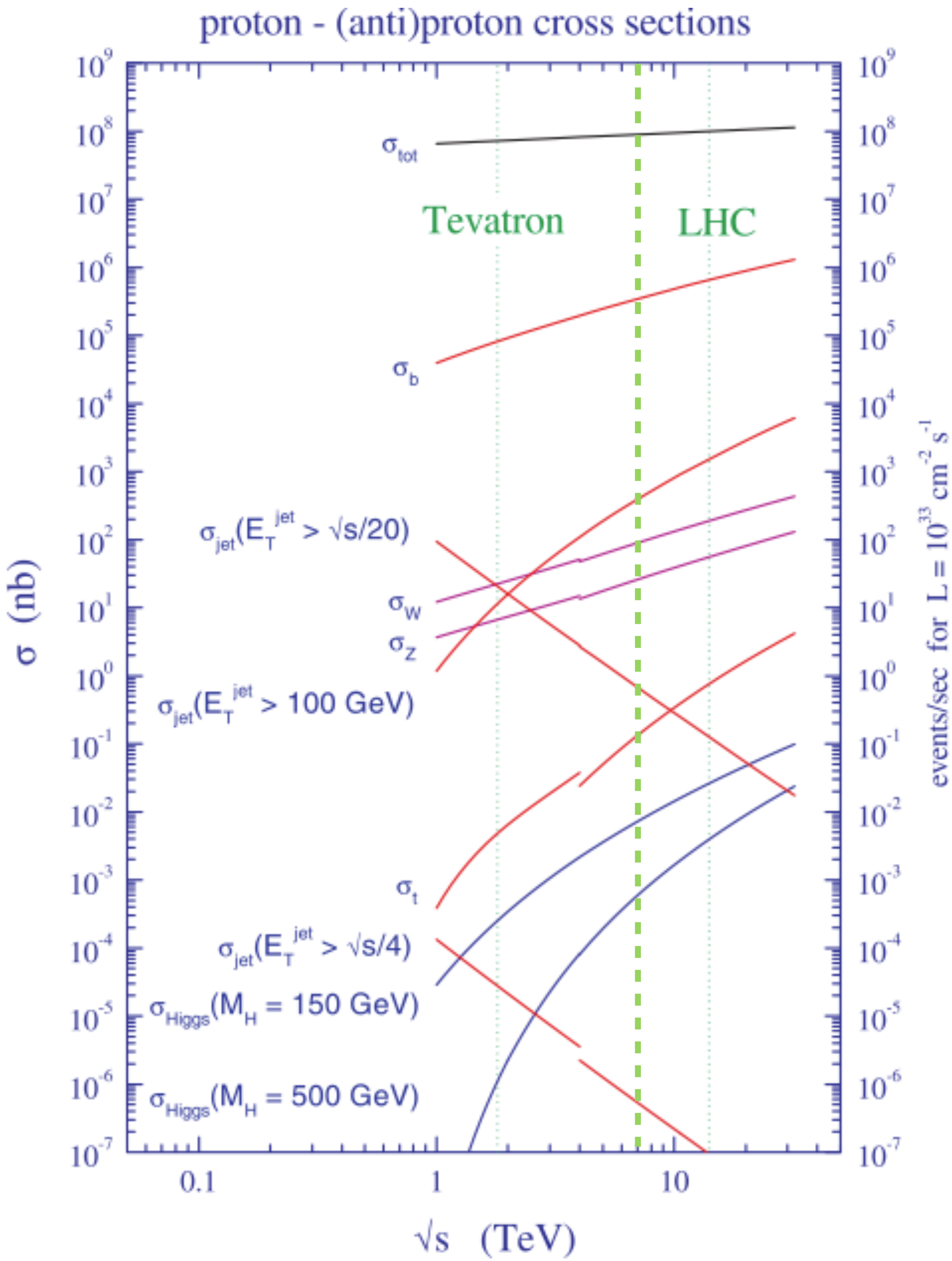

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- 30/sec Z boson
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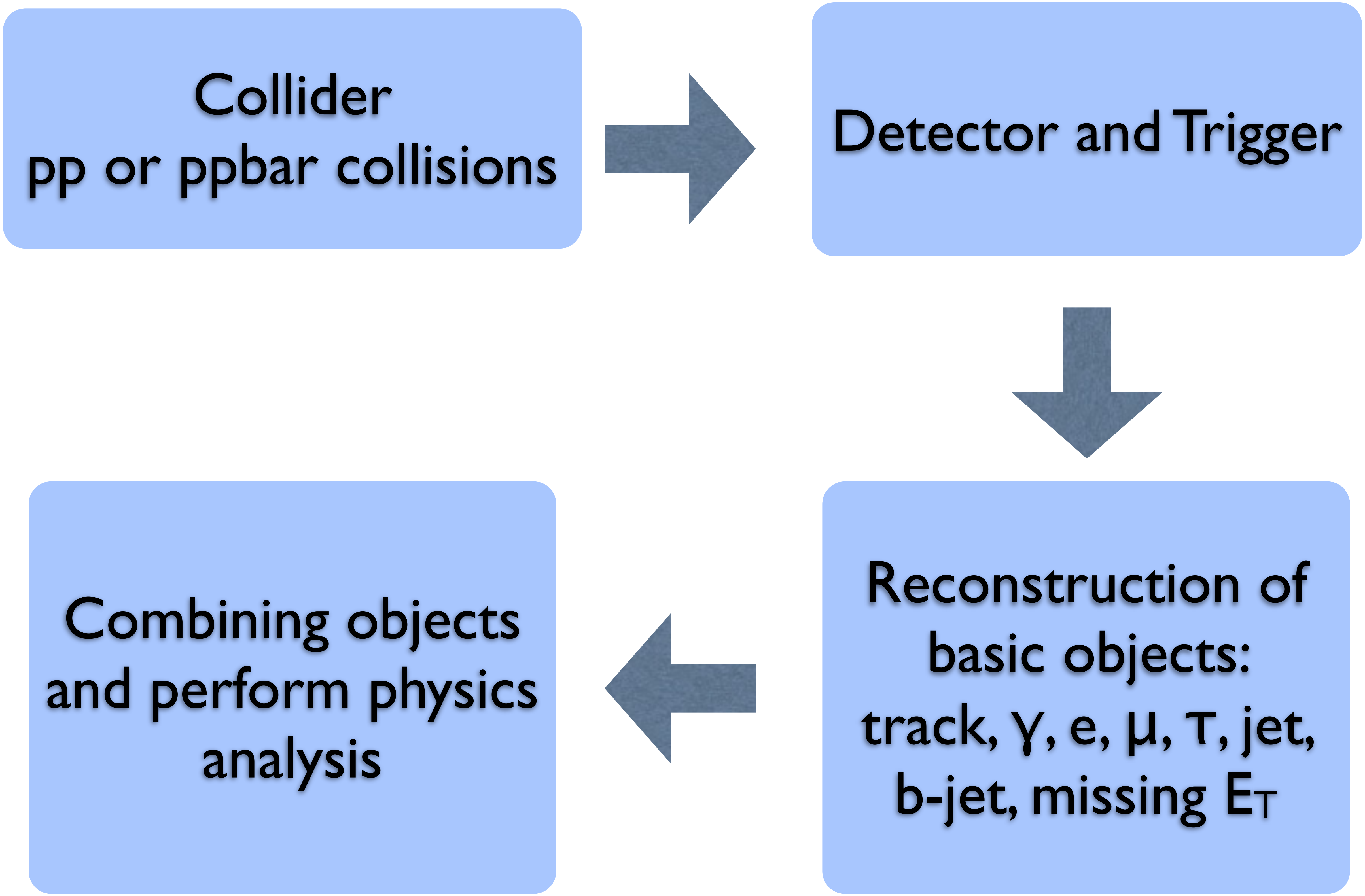
Initial instantaneous luminosity was 10 times lower!

What Does History Tell Us?

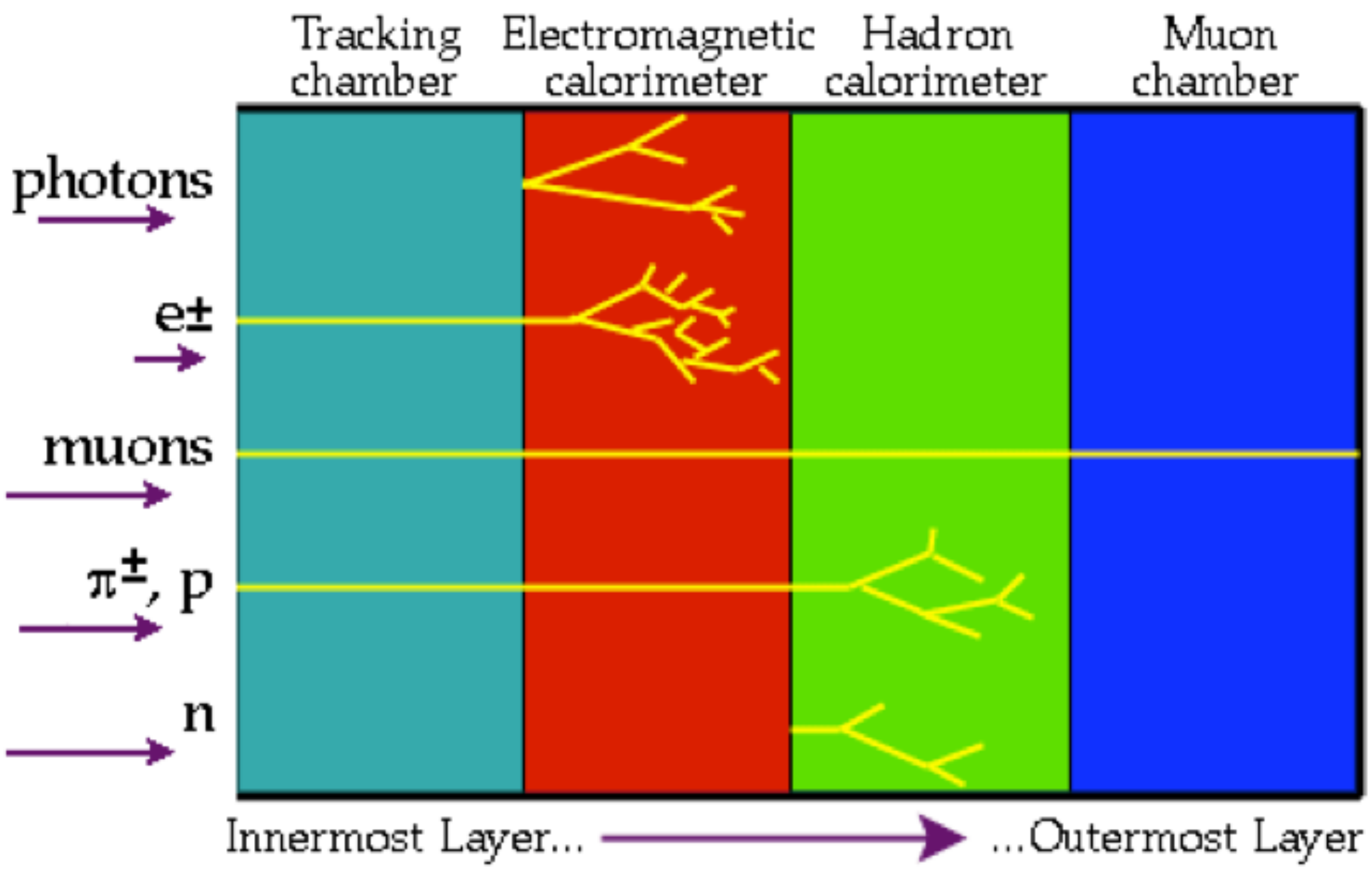
To look for a needle in a haystack, we need to understand the haystack as well!

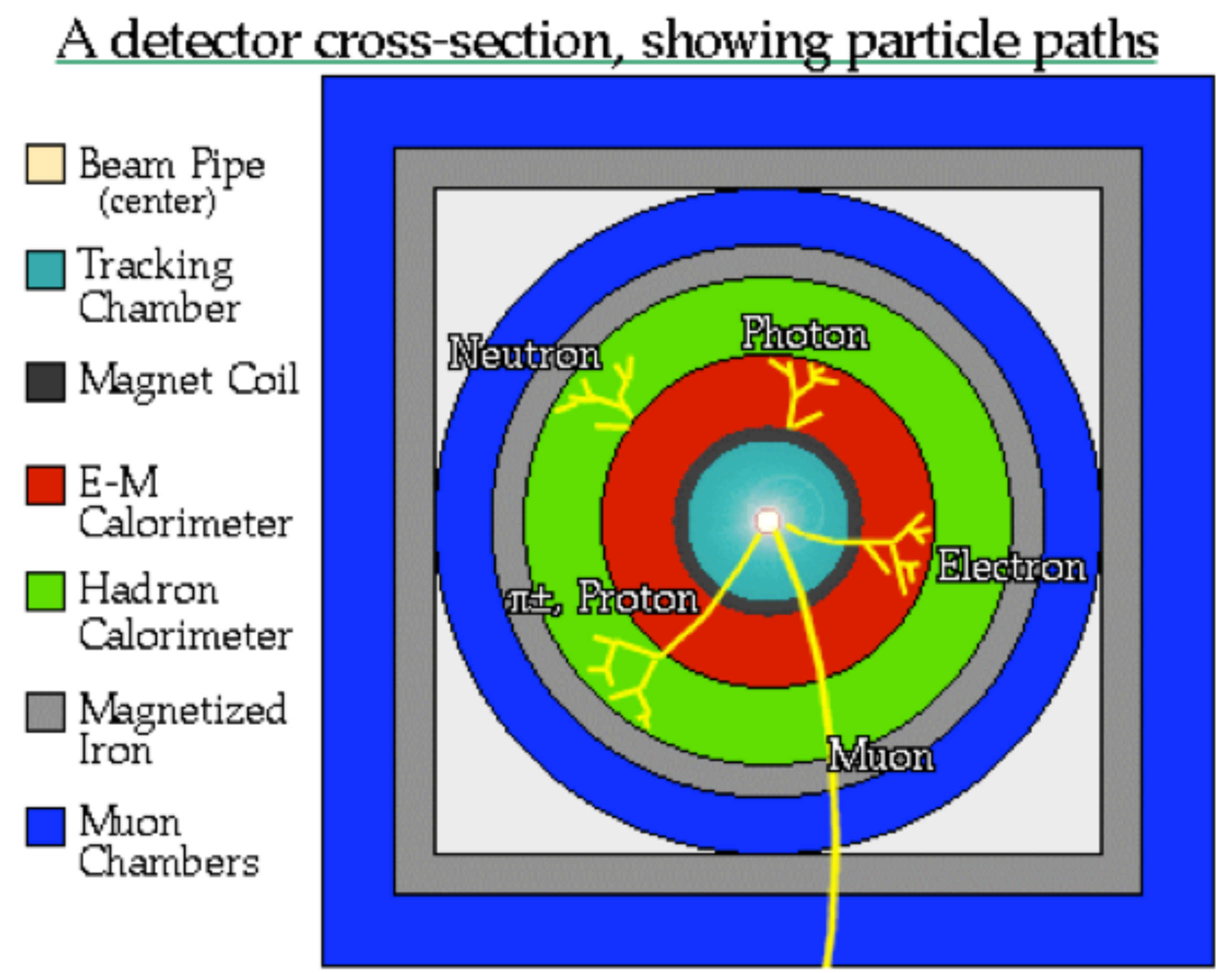
Otherwise ...

From the Beginning to the End



Signatures of Physics Objects





The First 15 CMS Physics Papers

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Measurement of Charge Hadron Distributions

Charge Hadron Multiplicity vs. p_T and η

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- 2.36 TeV results were the highest-energy measurements
  - Tevatron ppbar collisions $\sqrt{s}$ = 1.96 TeV
- 7 TeV results came from 1.1 μb^{-1} of data taken on 30 March 2010 in the first hour of LHC 7 TeV operation
  - Inelastic pp collision rate: 50 Hz
  - Results without magnetic field consistent within 1.5%

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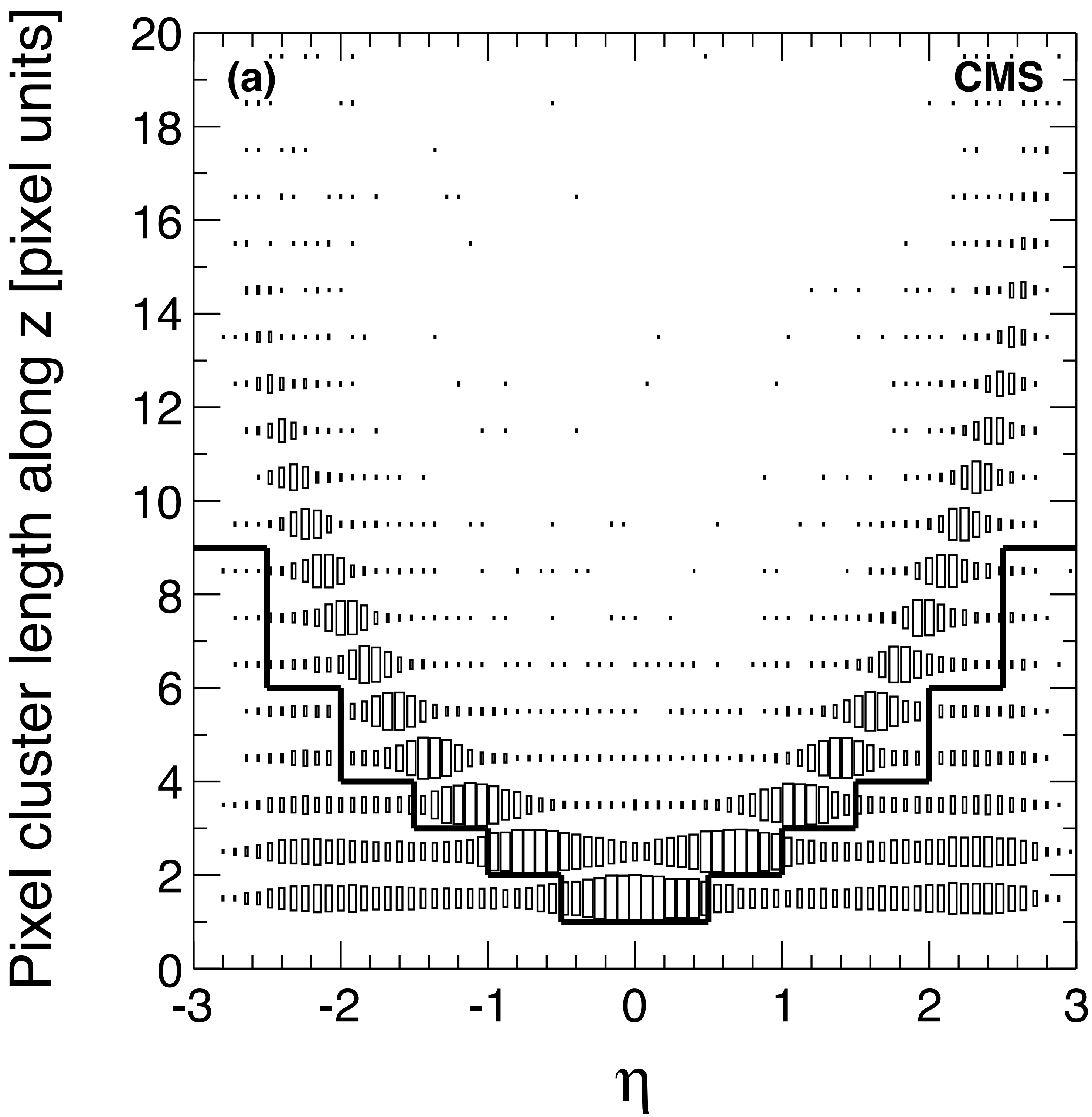

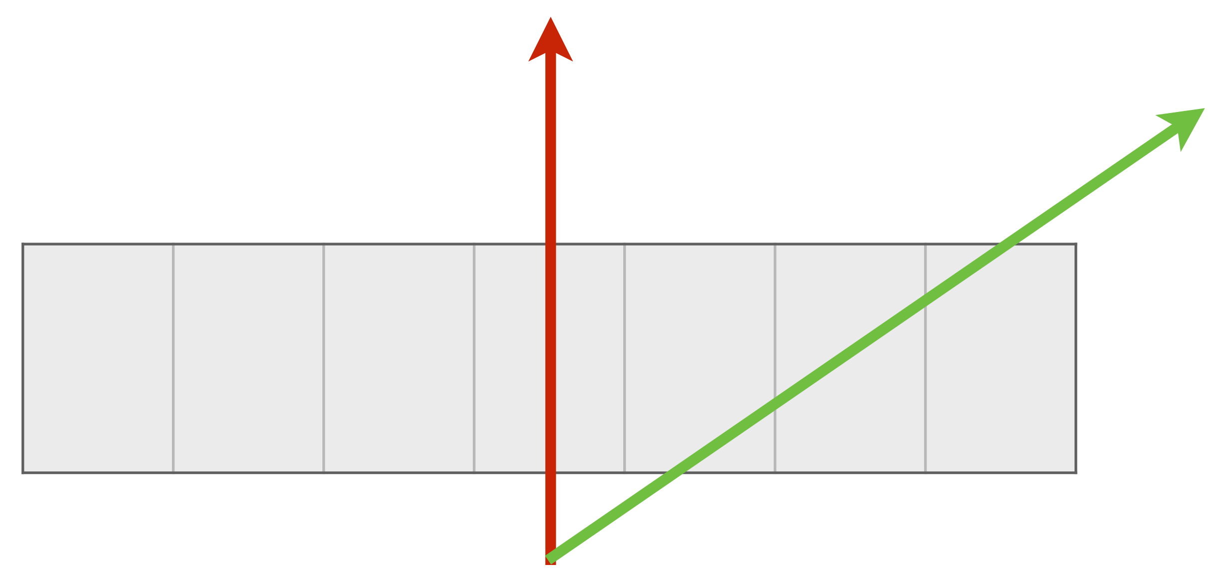

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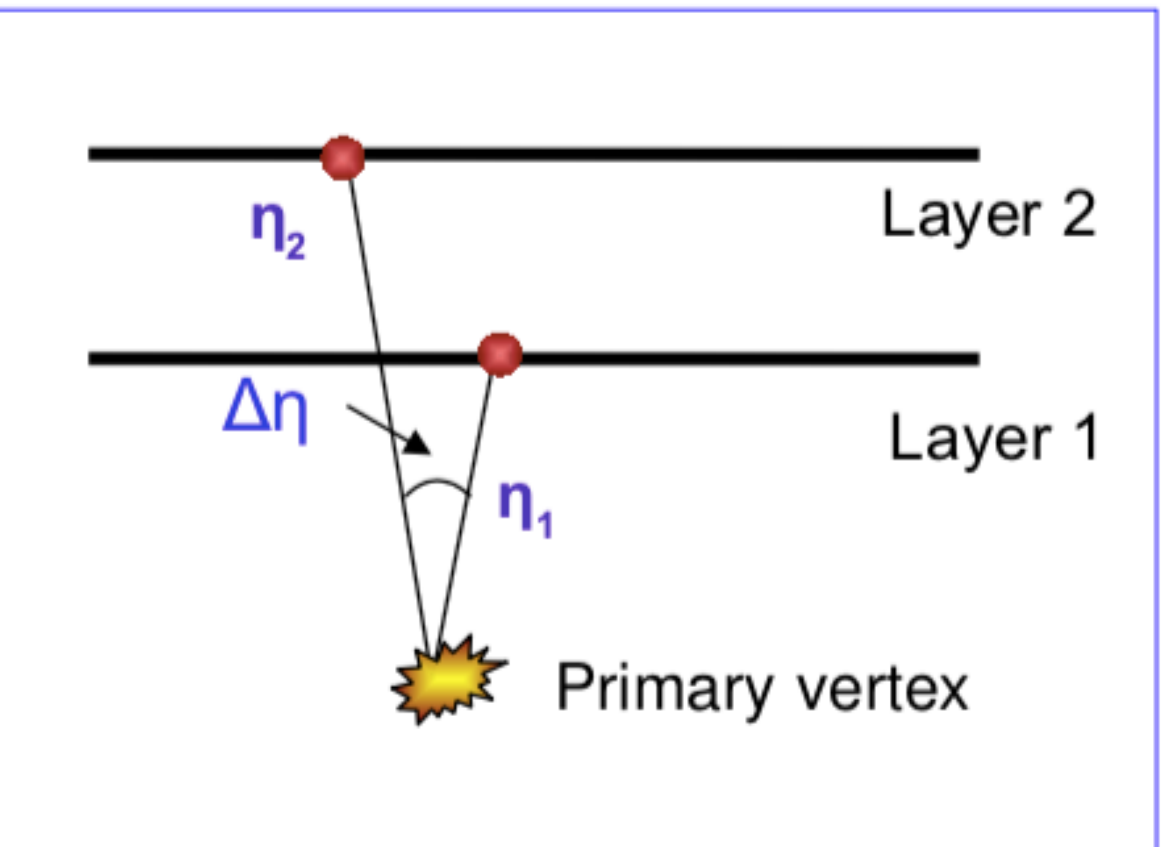

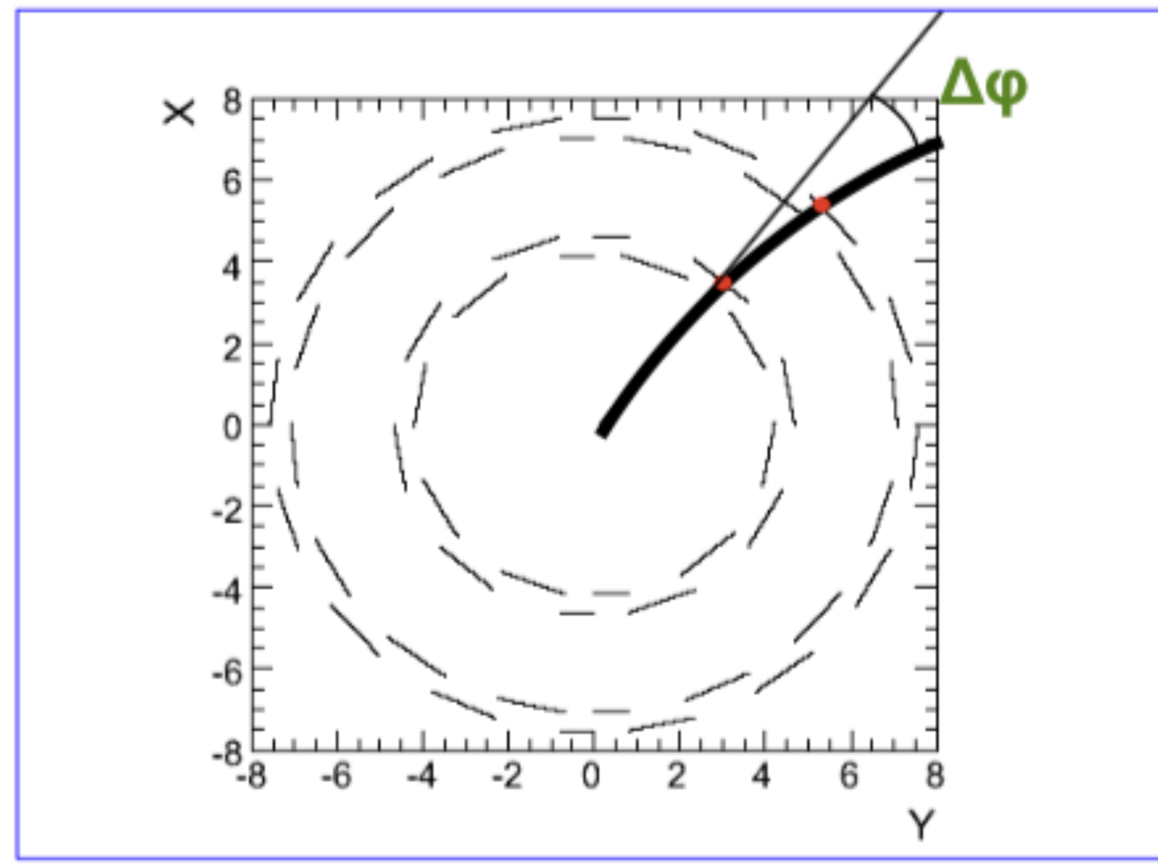

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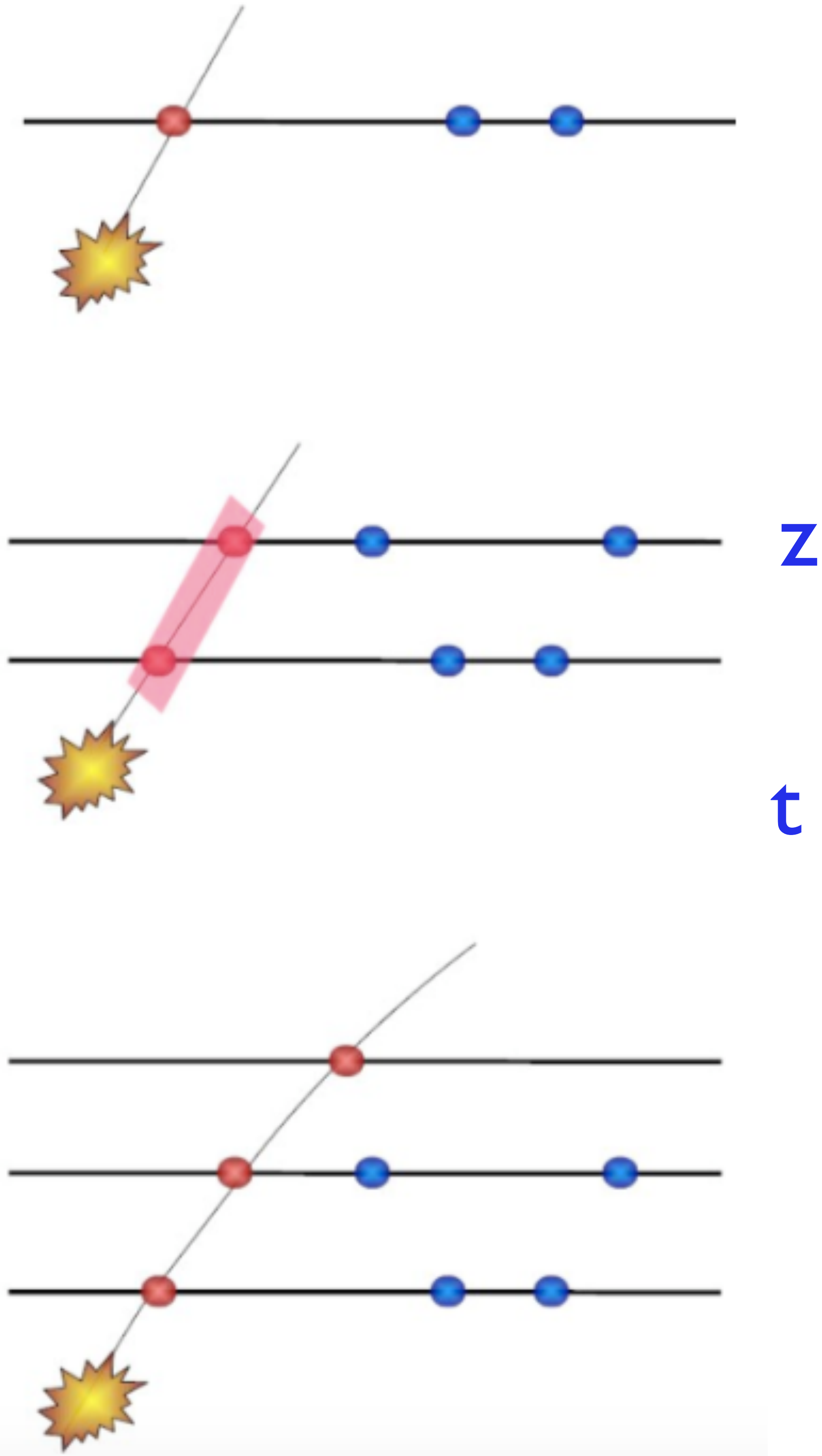
- Three different methods for $dN/d\eta$
  - cluster size of barrel pixel layer along the z direction
  - trackless from pairs of clusters in different layers of barrel pixel
  - tracks reconstructed with both pixel and strip → used to measure p_T as well

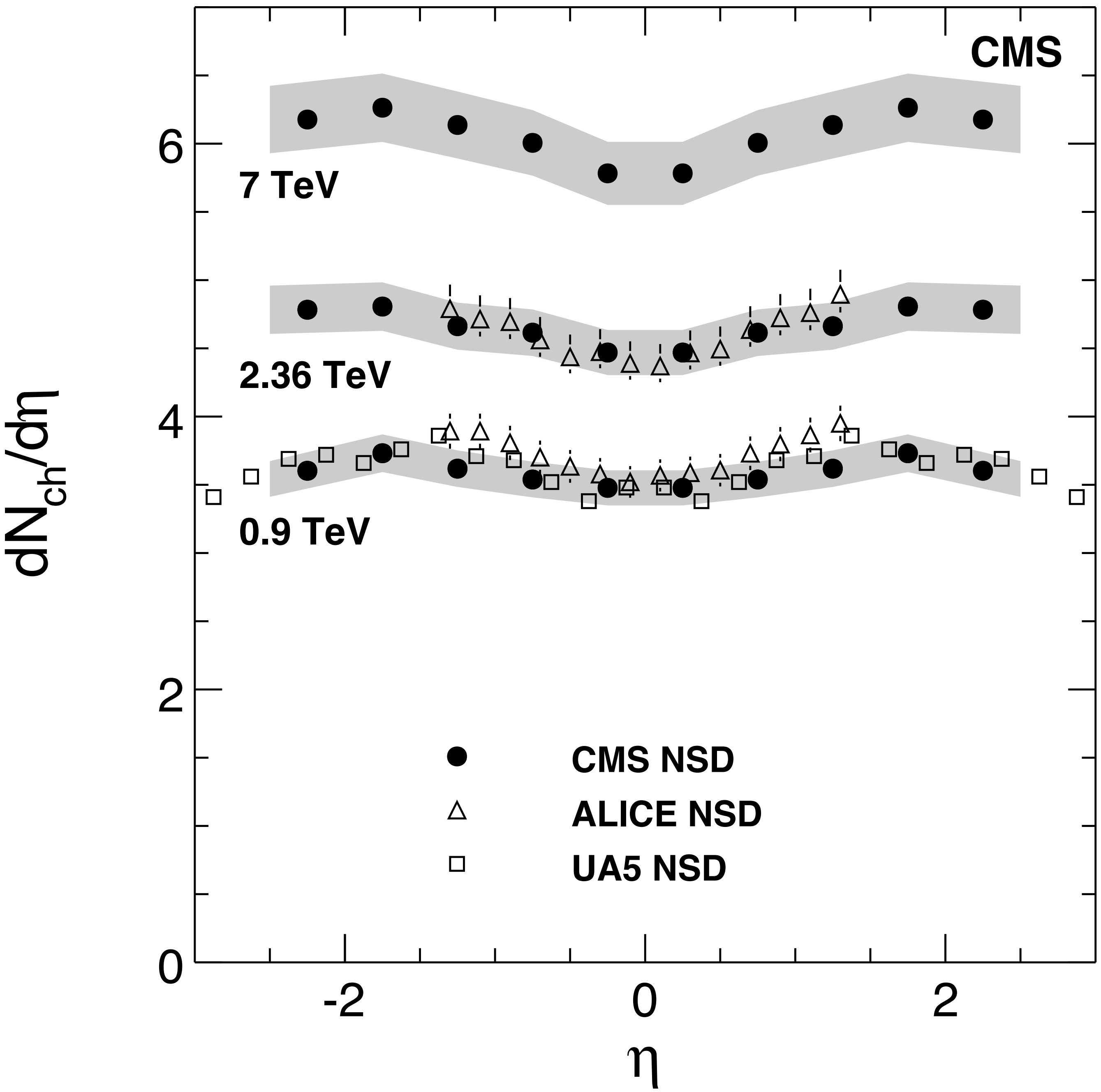
Charge Hadron Multiplicity vs. p_T and η

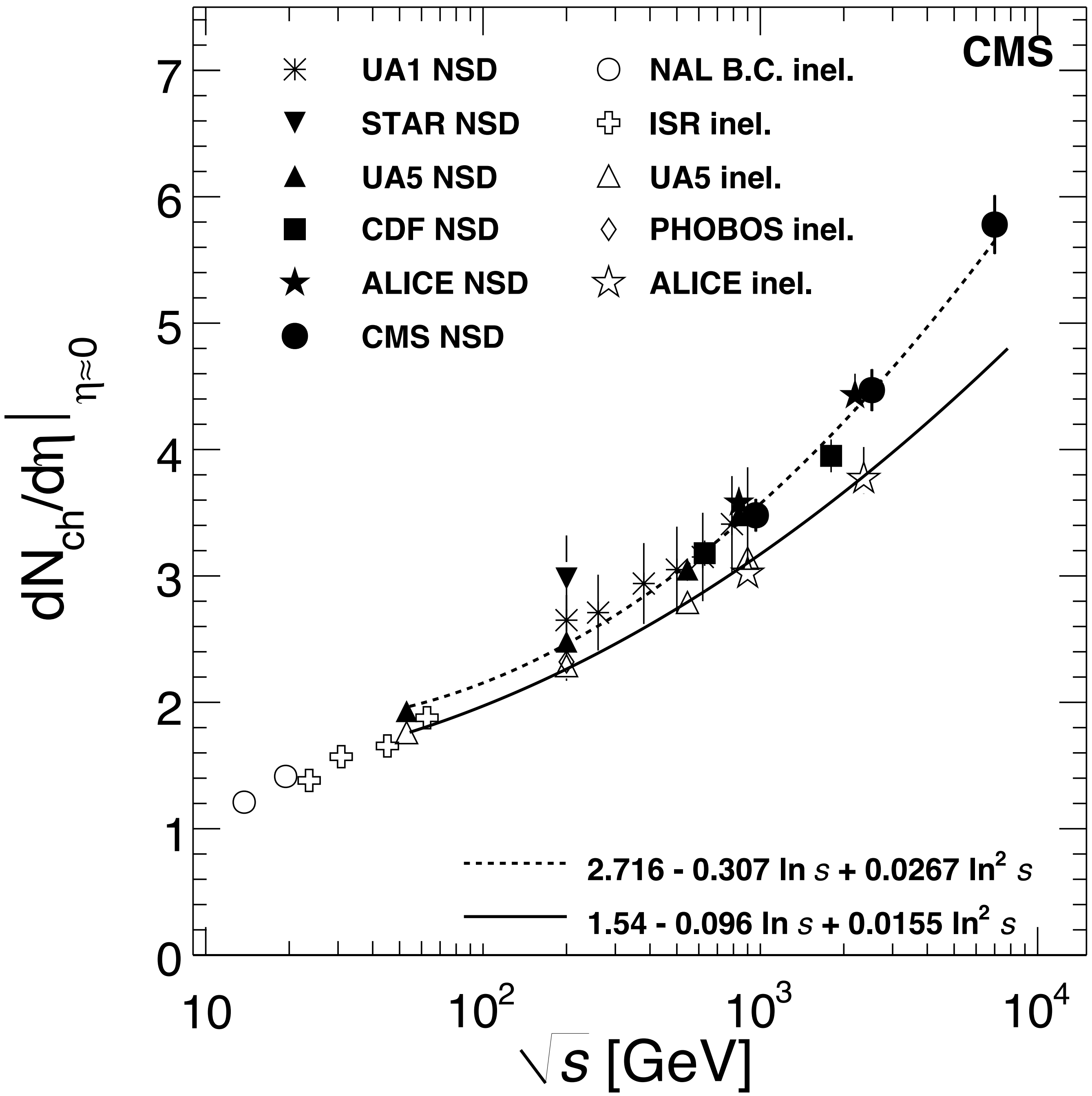
- Pixel-counting
- Tracklet reconstruction

Track reconstruction



Charge Hadron Multiplicity vs. η





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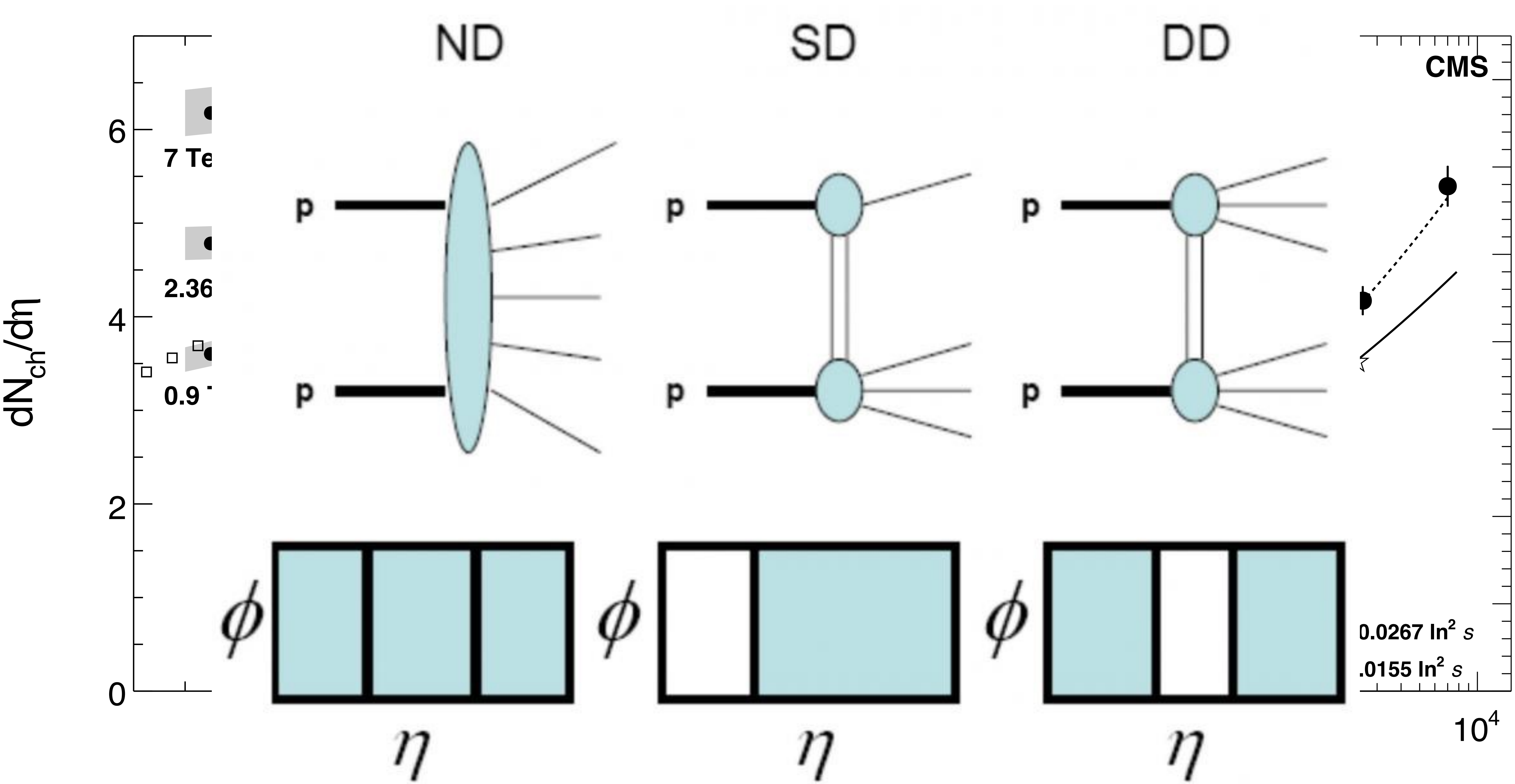

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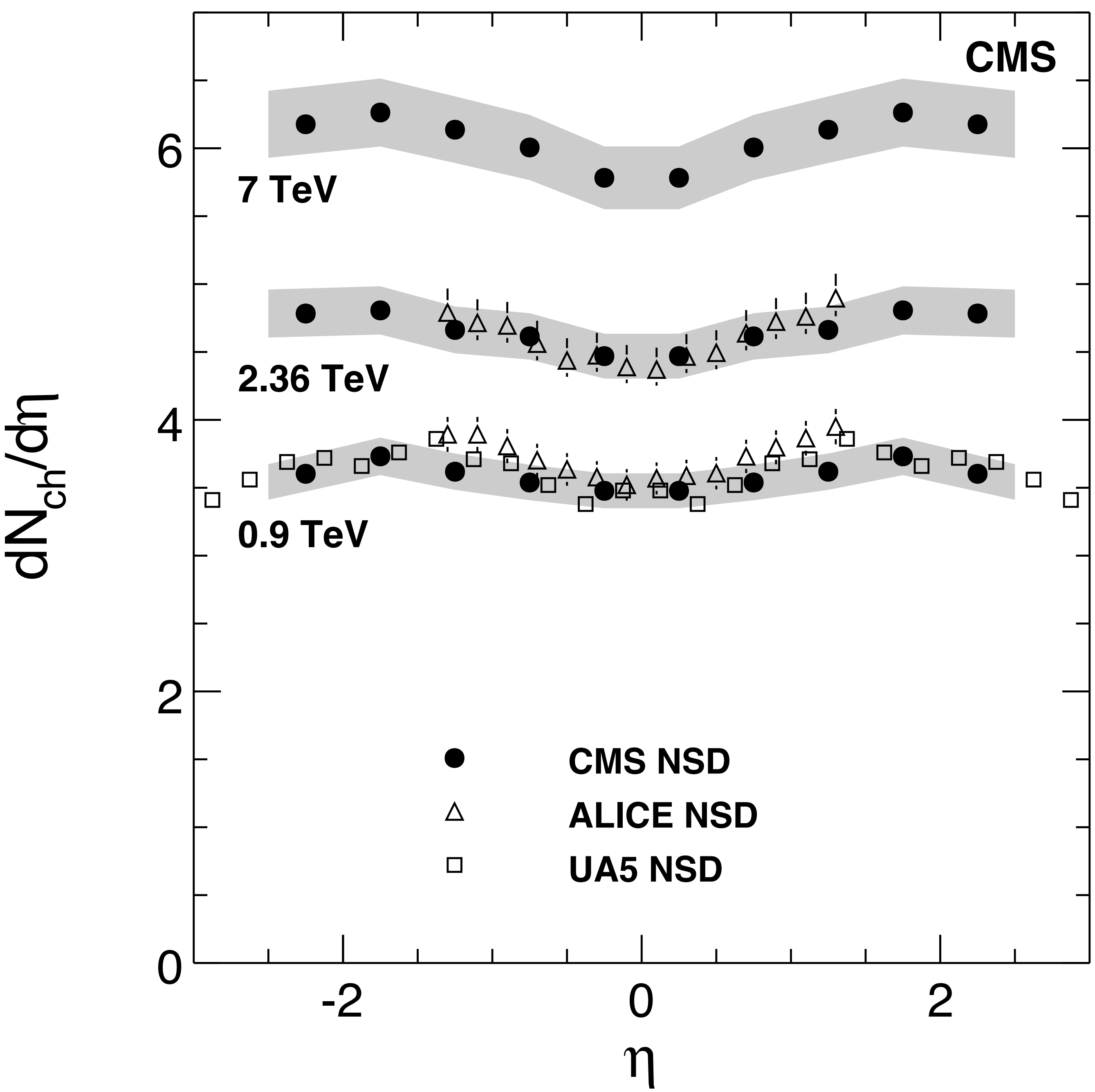
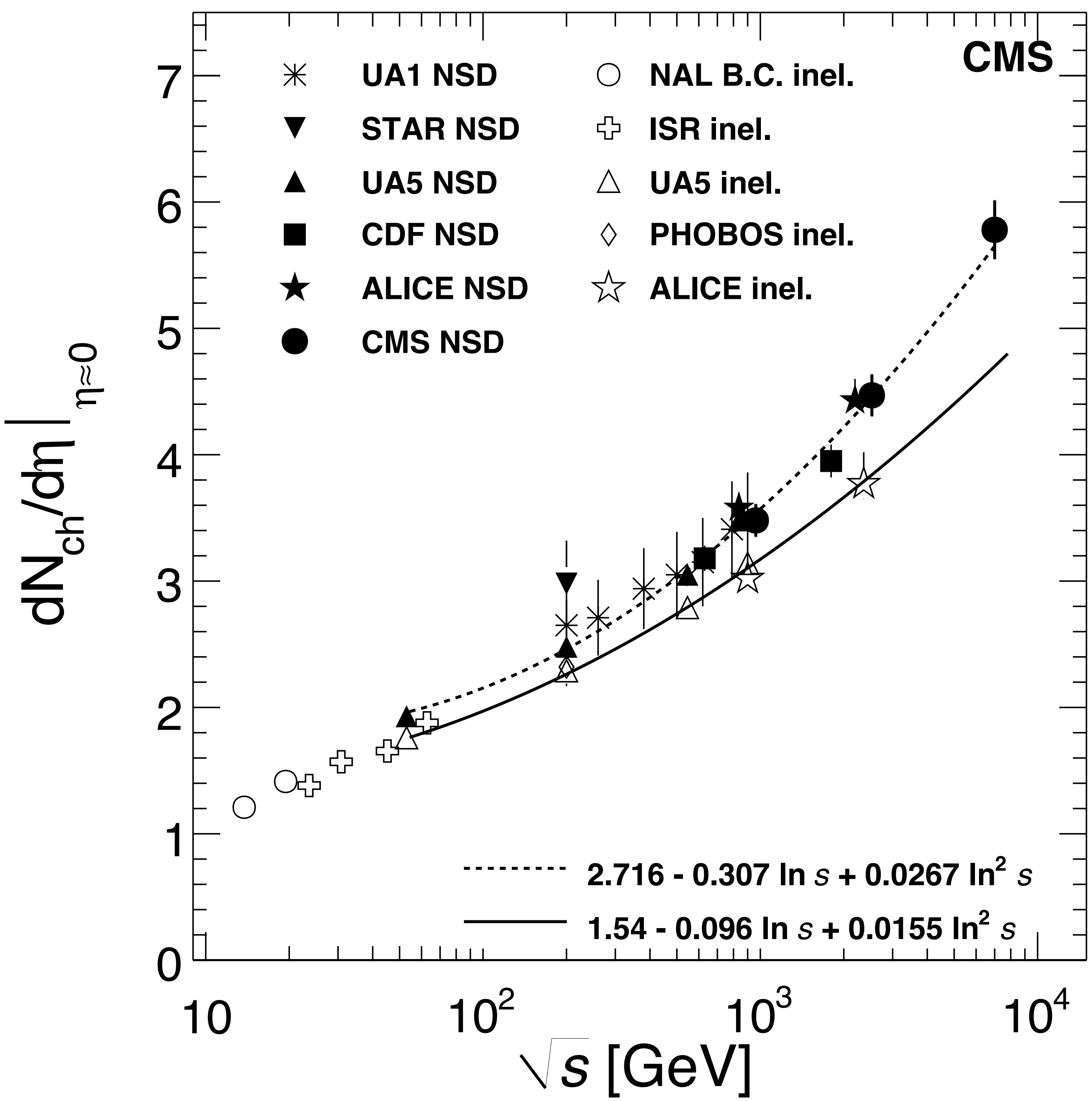
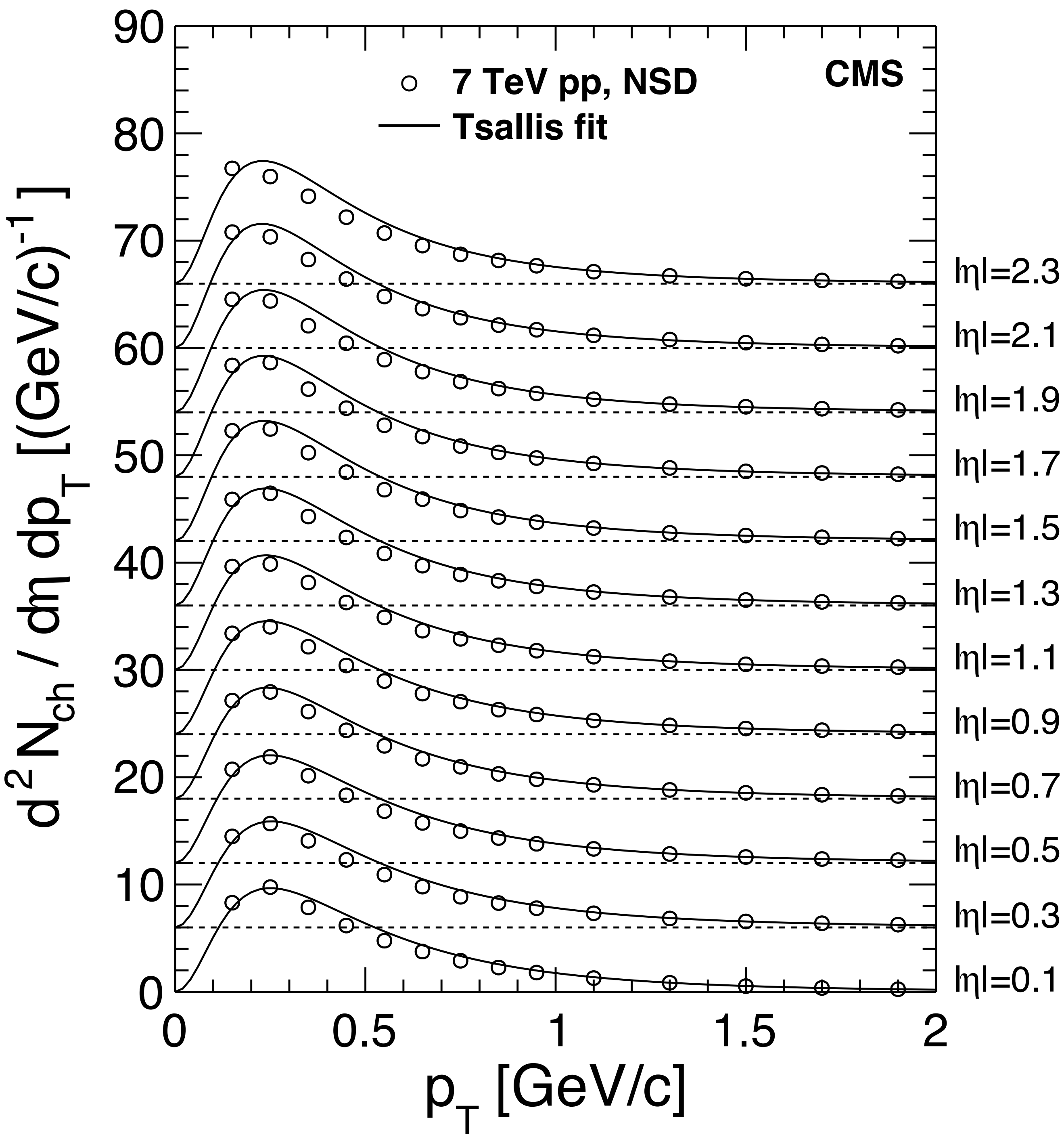
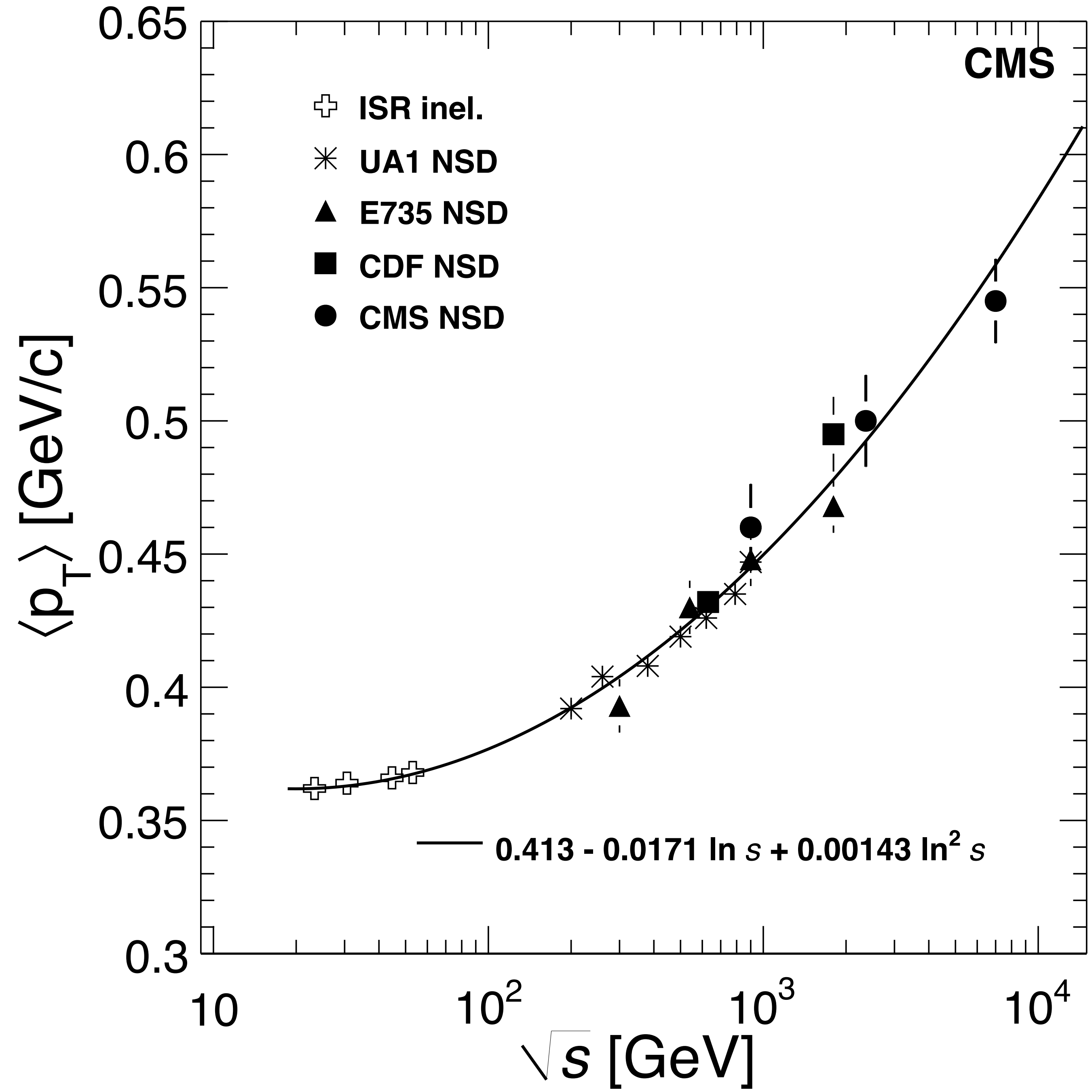




Charge Hadron Multiplicity vs. p_T





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Measurement of Isolated Prompt Photon Cross Section

Why Photons?

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- Test perturbative QCD in a wide range of photon E_T and pseudo-rapidity η and potentially provide constraint to gluon PDF

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- Energy well measured by EM calorimeters (better energy resolution and less uncertainty on energy scale), could be used to calibrate jet energy scale

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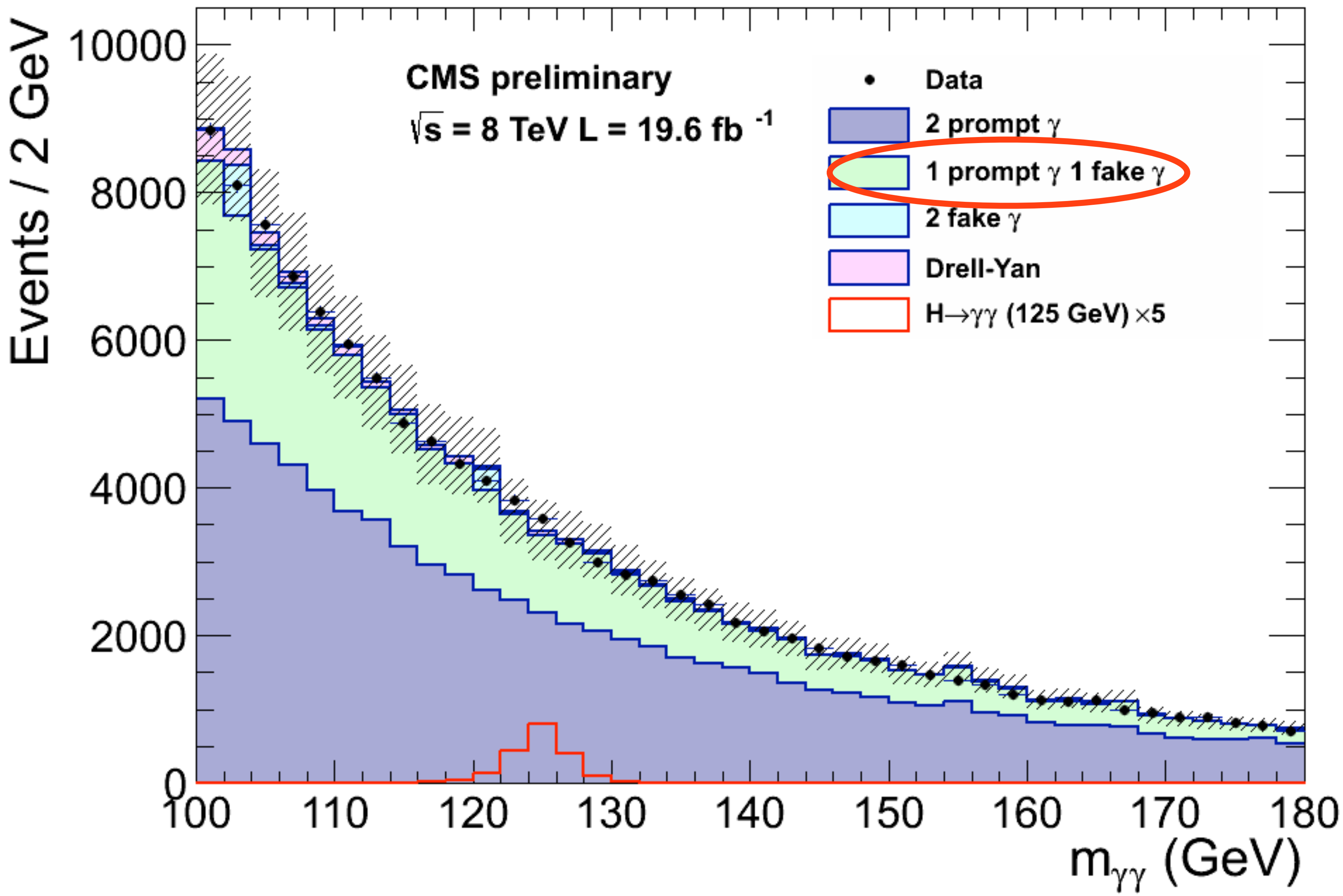
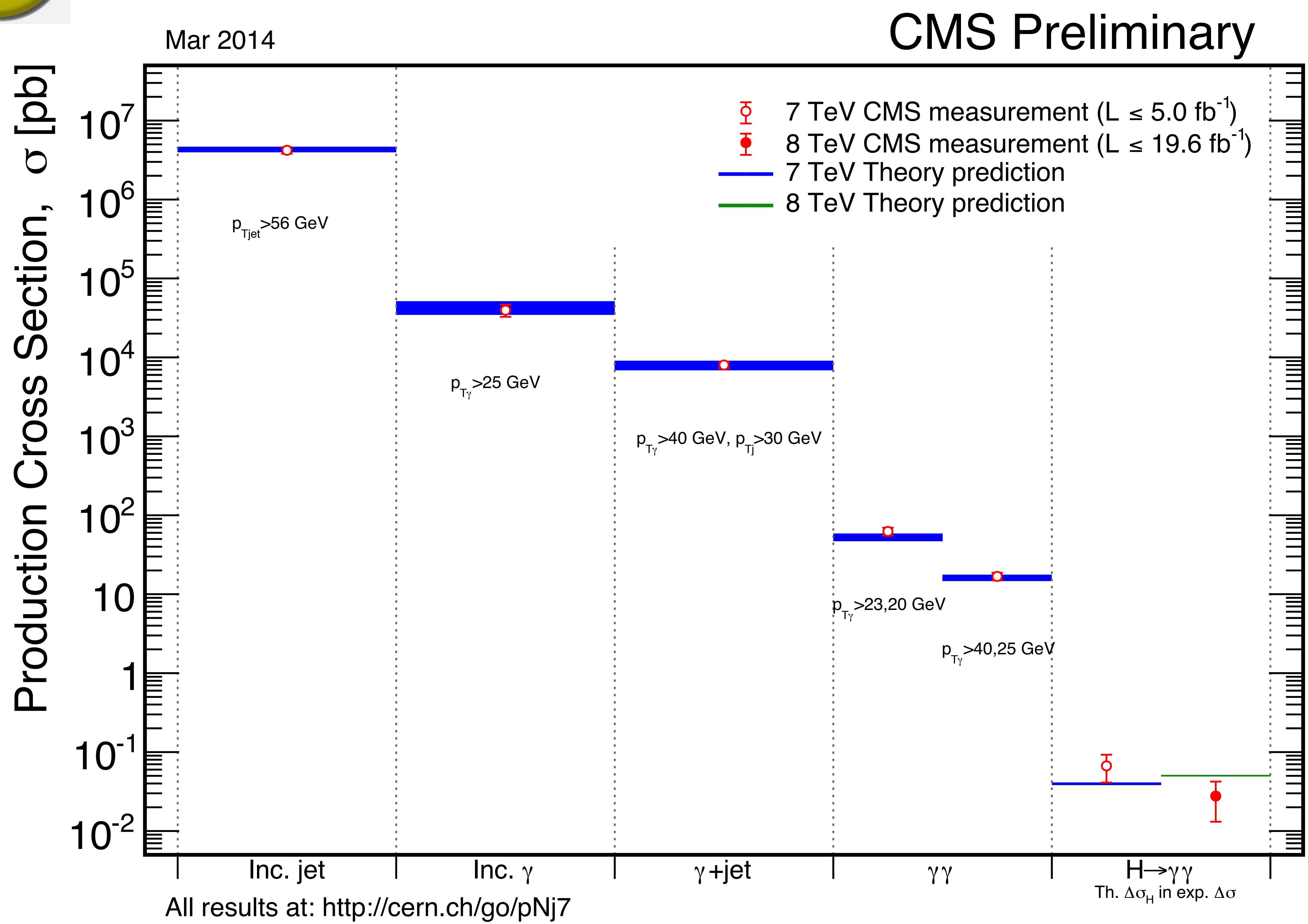
  - QCD photons are background to search for new physics
  - Establish benchmark for photon ID and background estimate

Background to Searches



Search for Higgs→γγ

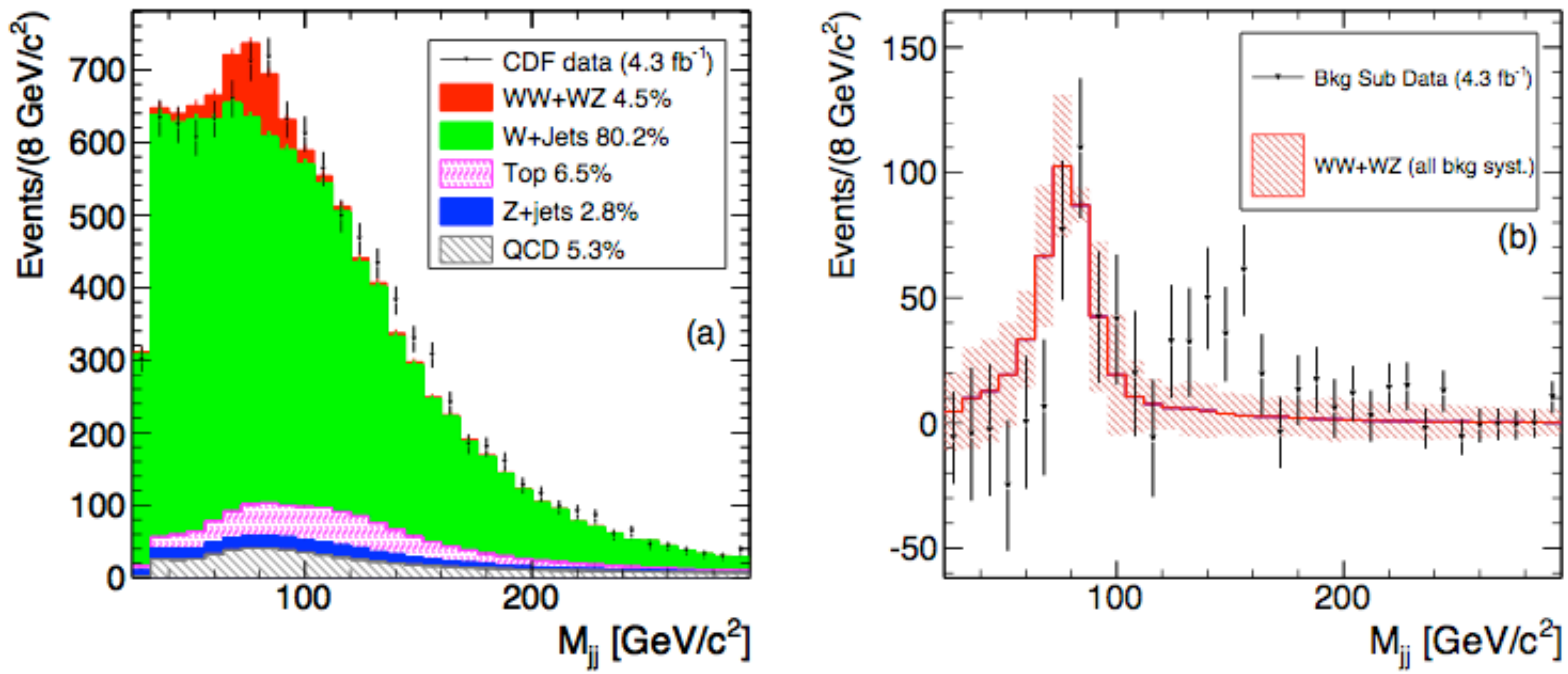
Why Photons?



CMS Preliminary
Mar 2014
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
pTjet>56 GeV
pTγ>25 GeV
pTγ>40 GeV, pTj>30 GeV
pTγ>23,20 GeV
pTγ>40,25 GeV
Inc. jet
Inc. γ
γ+jet
γγ
H→γγ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

Discovery of x ?

Phys. Rev. Lett.
106, 171801 (2011)



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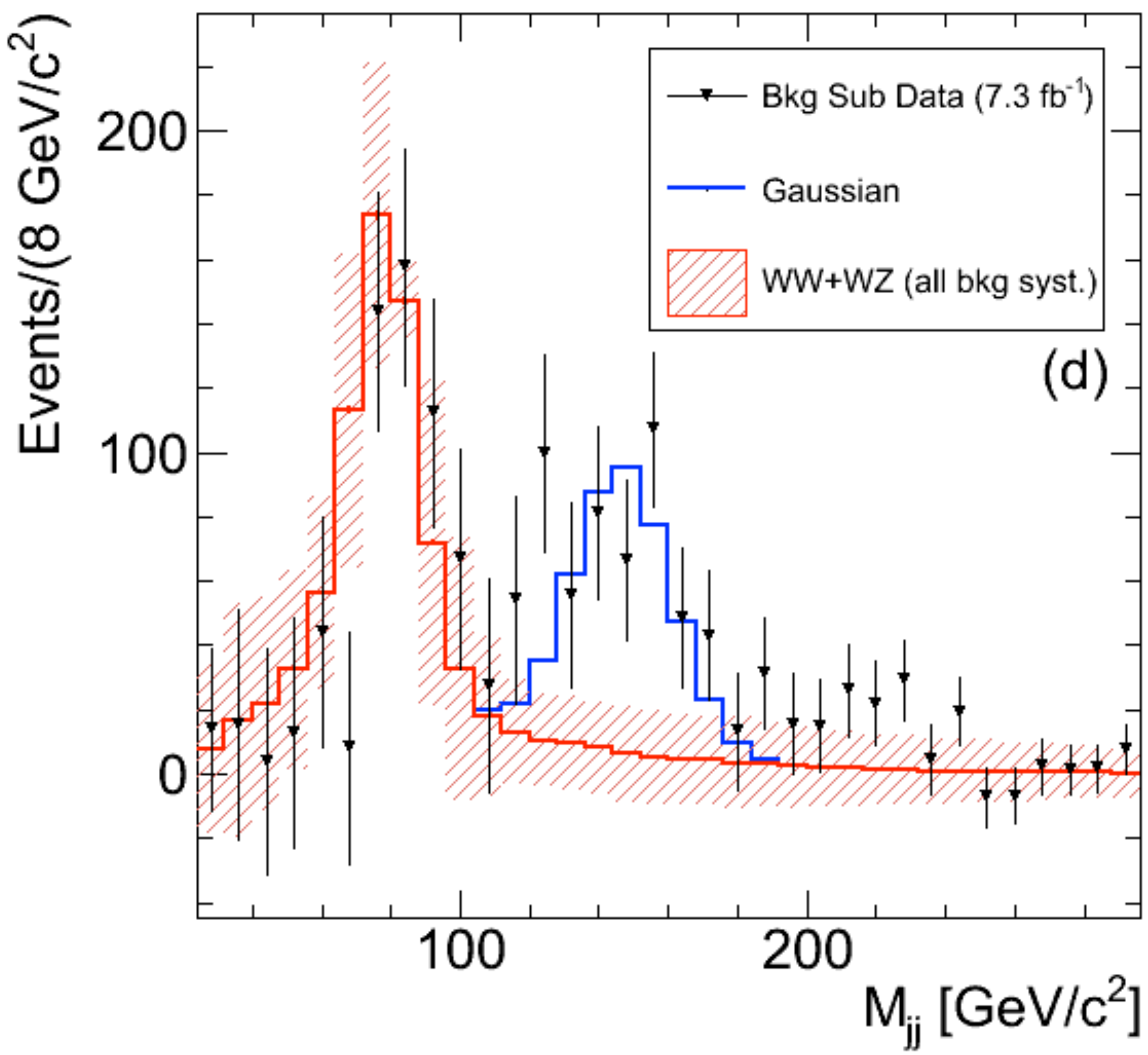
Phys. Rev. Lett. 106, 171801 (2011)



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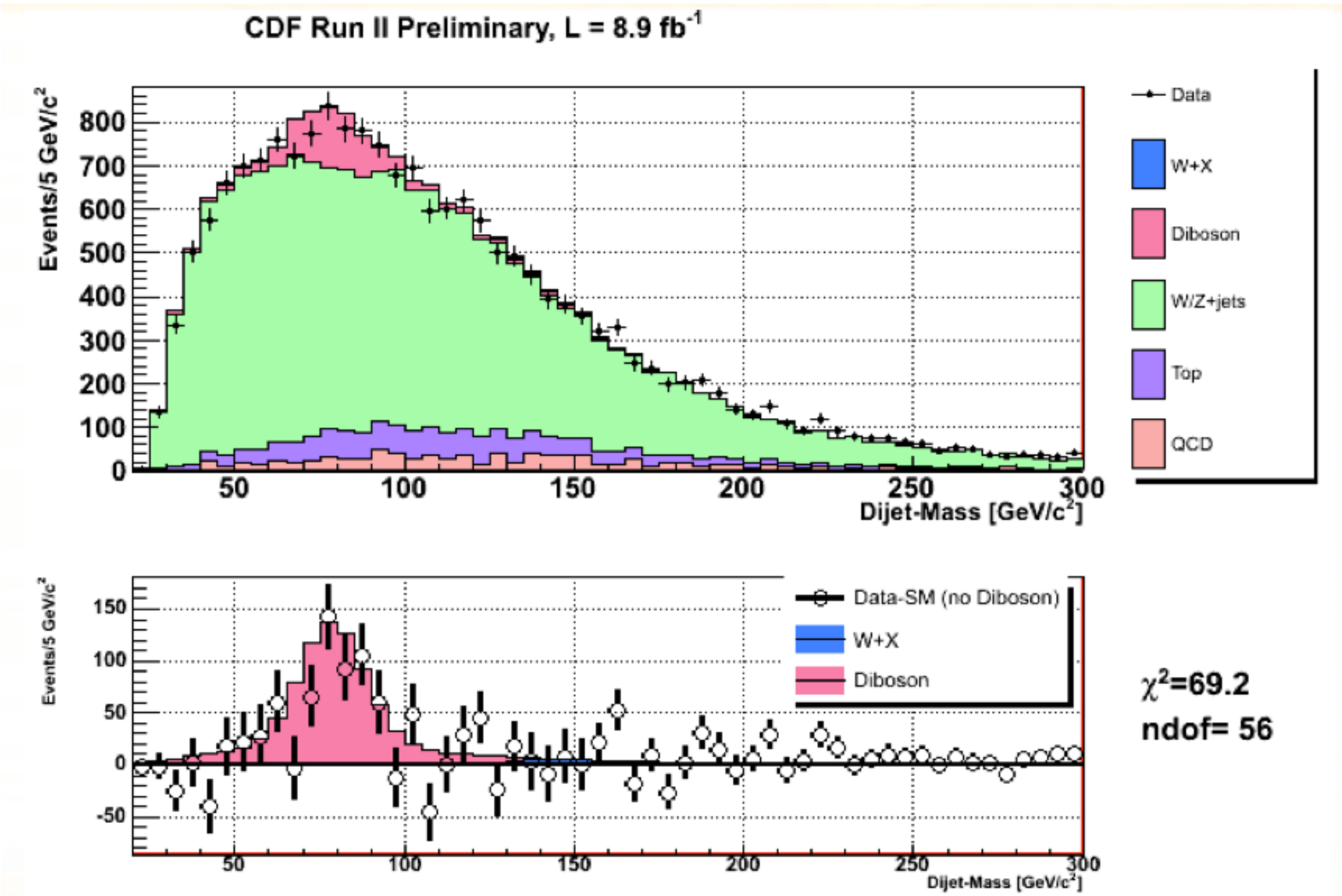
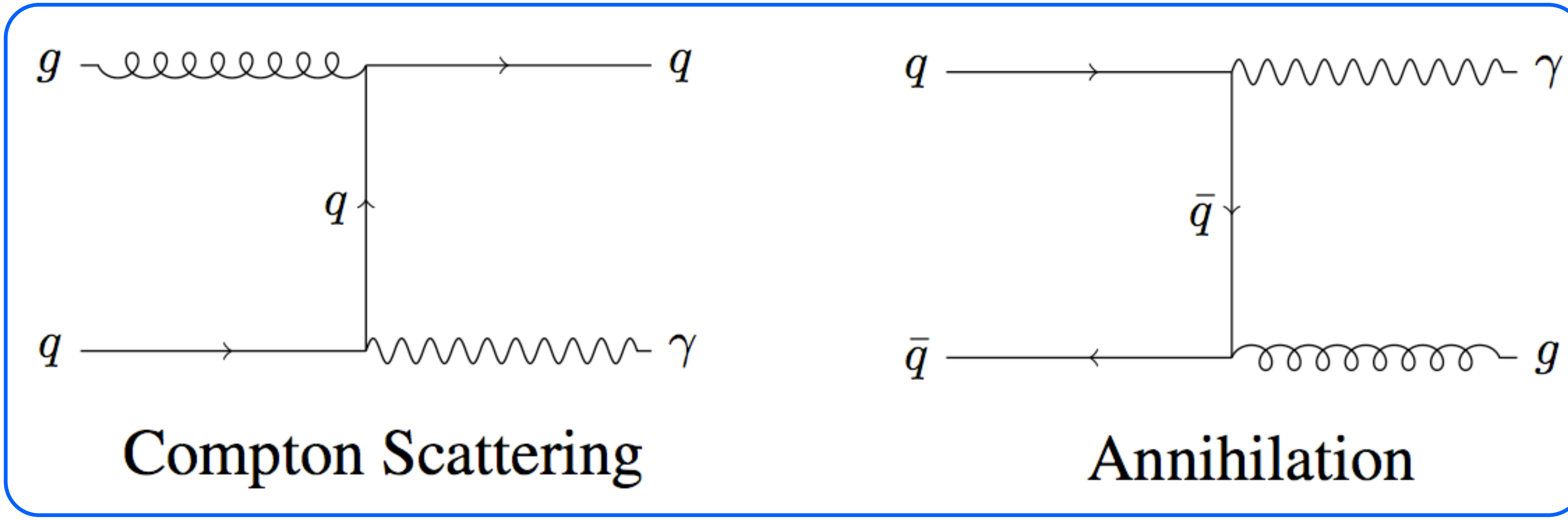


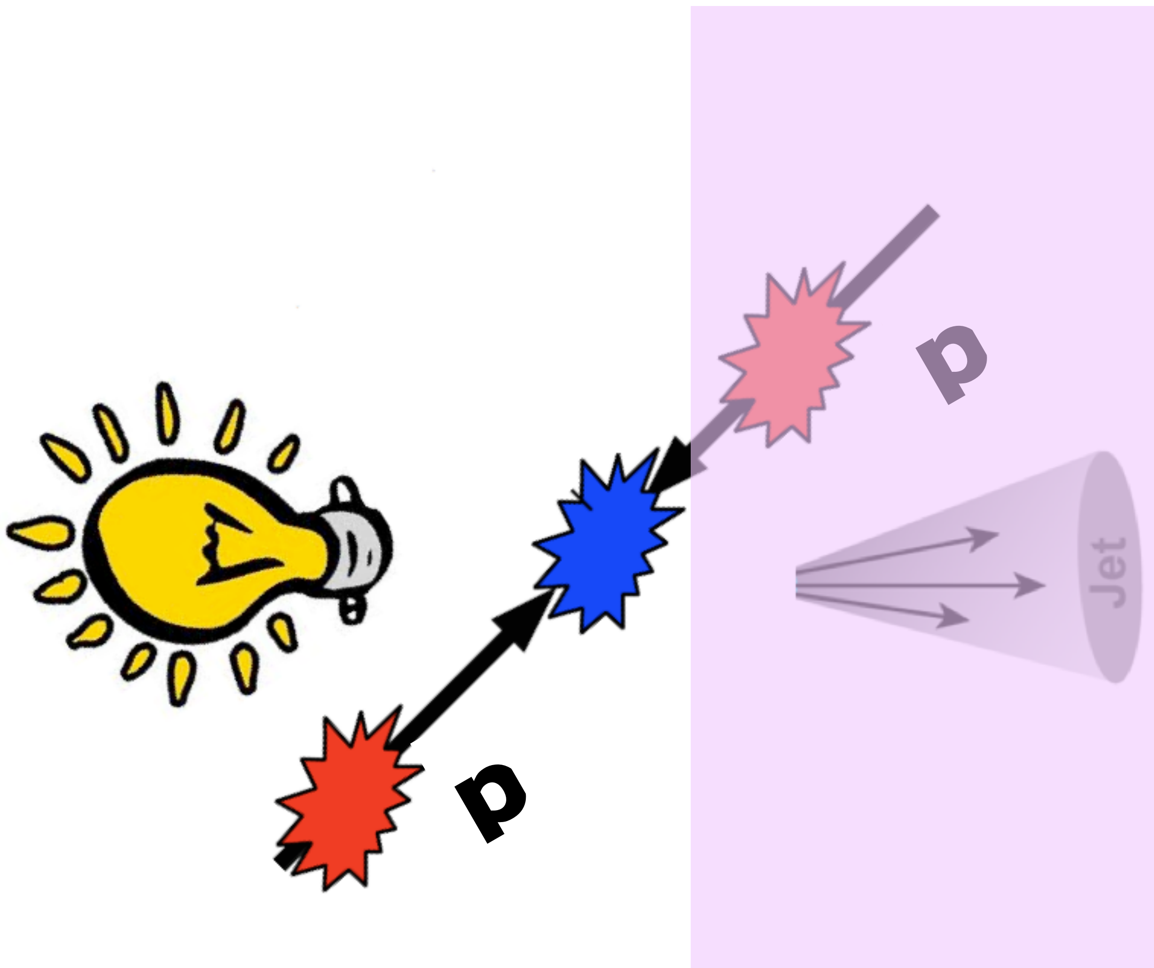
- The fake signal was due to two mis-modelings of background distributions
  - Fake electrons, energy of quark vs gluon jet

What Are Prompt Photons?



- Prompt photons are high-p_T photons that take part directly in the hard process
- Prompt photons do not come from decays of hadrons (π^0, η).

Inclusive Photon Cross Section



- For early measurements, we study only the photon side
  - Minimize the selection requirement
  - Calibration of jet energy needs some time
  - No signal reduction due to the acceptance of jets

What You Observe in the Data

$$\boxed{N_{\text{observed}} = \sigma \cdot L \cdot \varepsilon}$$

Cross Section Definition

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

- N^γ: number of signal photons
- U: correction of energy resolution and loss of energy in the reconstruction (reconstructed → true)
- ε: efficiency of reconstruction, identification, and trigger selections

- Inclusive, isolated, prompt photon cross section
  - no explicit requirement on the other objects in the same event

Photon Reconstruction

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- Naively, one would think that photon is like electron without track.
  - Photon interacts with ECAL material, convert into electron and positron pair, electron and positron bremsstrahlung, and so on and so forth→shower in ECAL
  - Just sum up (cluster) the energy in calorimeter cells?

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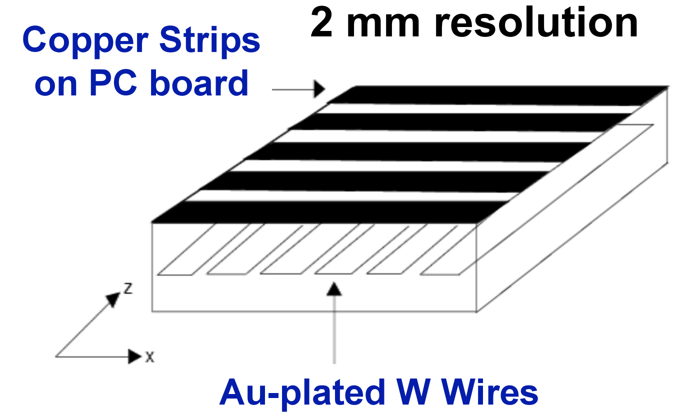
    - Just sum up (cluster) the energy in calorimeter cells?
- But the large tracker material budget makes photon convert frequently.
    - In CMS ECAL, 97% of non-converted photon energy is contained in 5x5 crystals.

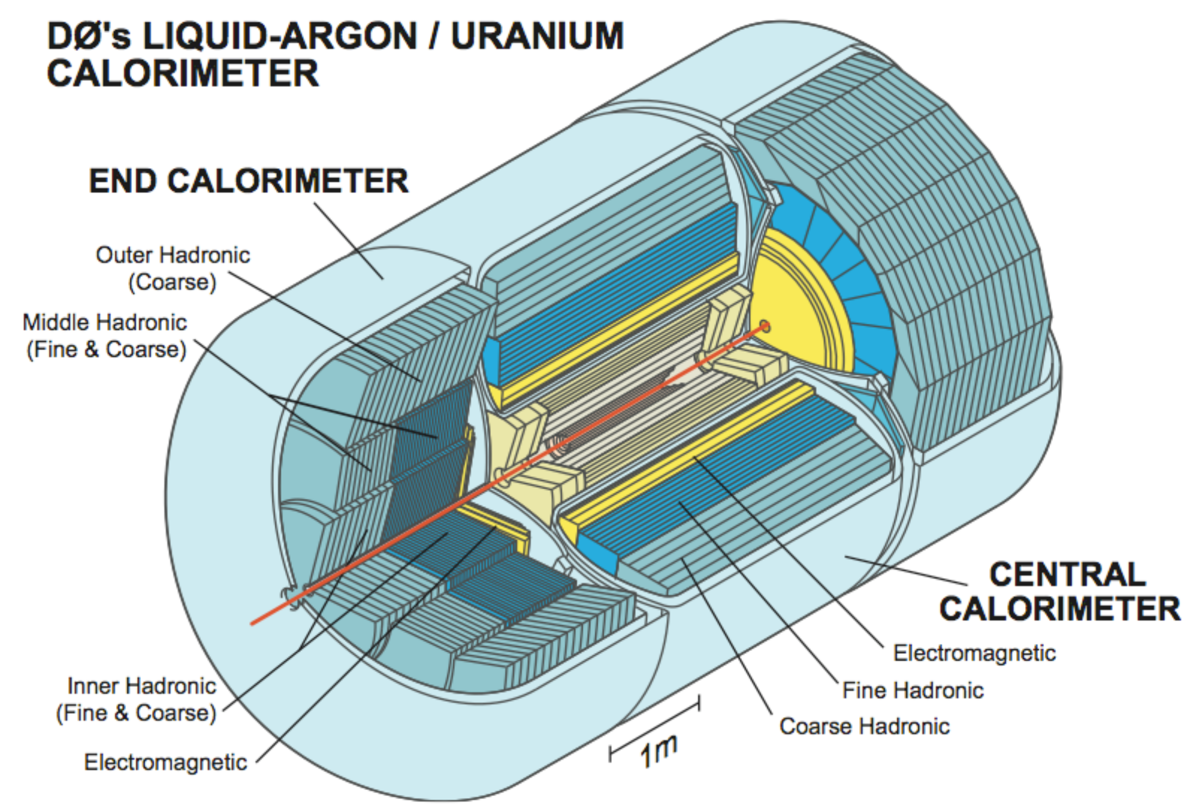
Tevatron Detectors

- **CDF central ECAL (lead+scintillator), |η| < 1.1**
  - **shower profile detector at 6 X_0**
  - **18 X_0, $\Delta\eta\times\Delta\varphi$=0.1×0.26**
  - **tracker 0.2 X_0, B=1.4 Tesla**
  - **~3% energy resolution at 50 GeV**



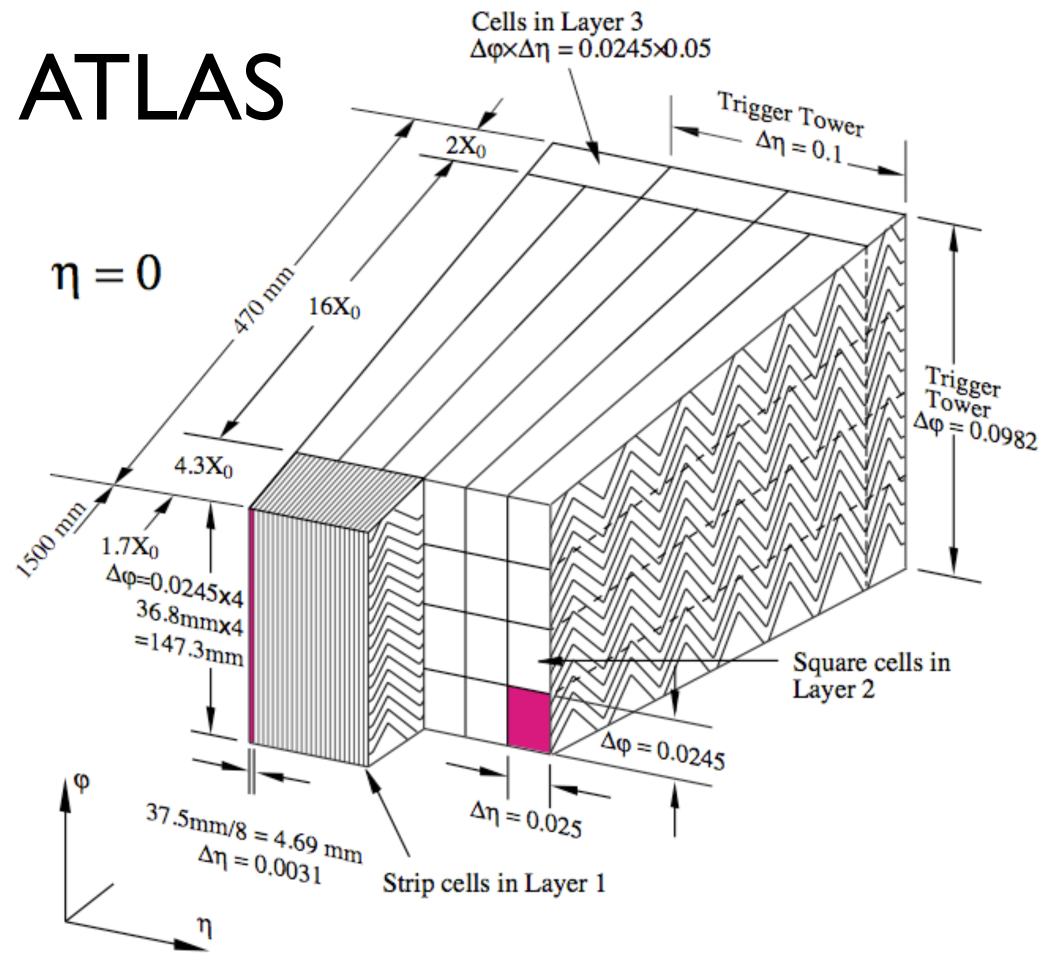
$\Delta\eta\times\Delta\varphi$
=0.01×0.01

- **D0 central ECAL (uranium + liquid argon), |η| < 1.1**
  - **four longitudinal readouts (2, 2, 7, 10 X_0)**
  - **$\Delta\eta\times\Delta\varphi$=0.1×0.1 (0.05 × 0.05 for EM3)**
  - **tracker 0.3 X_0, B= 2.0 Tesla**
  - **~3.6% energy resolution at 50 GeV**



LHC Detectors

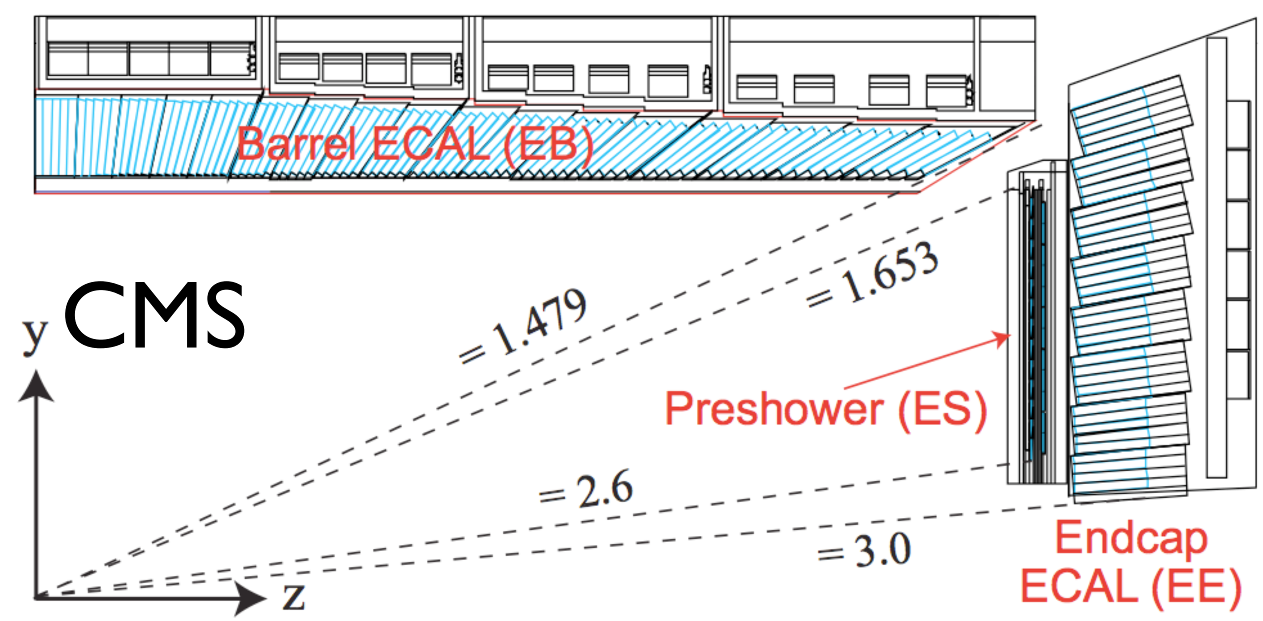
ATLAS



ATLAS ECAL (lead+liquid argon), |η| < 3.2

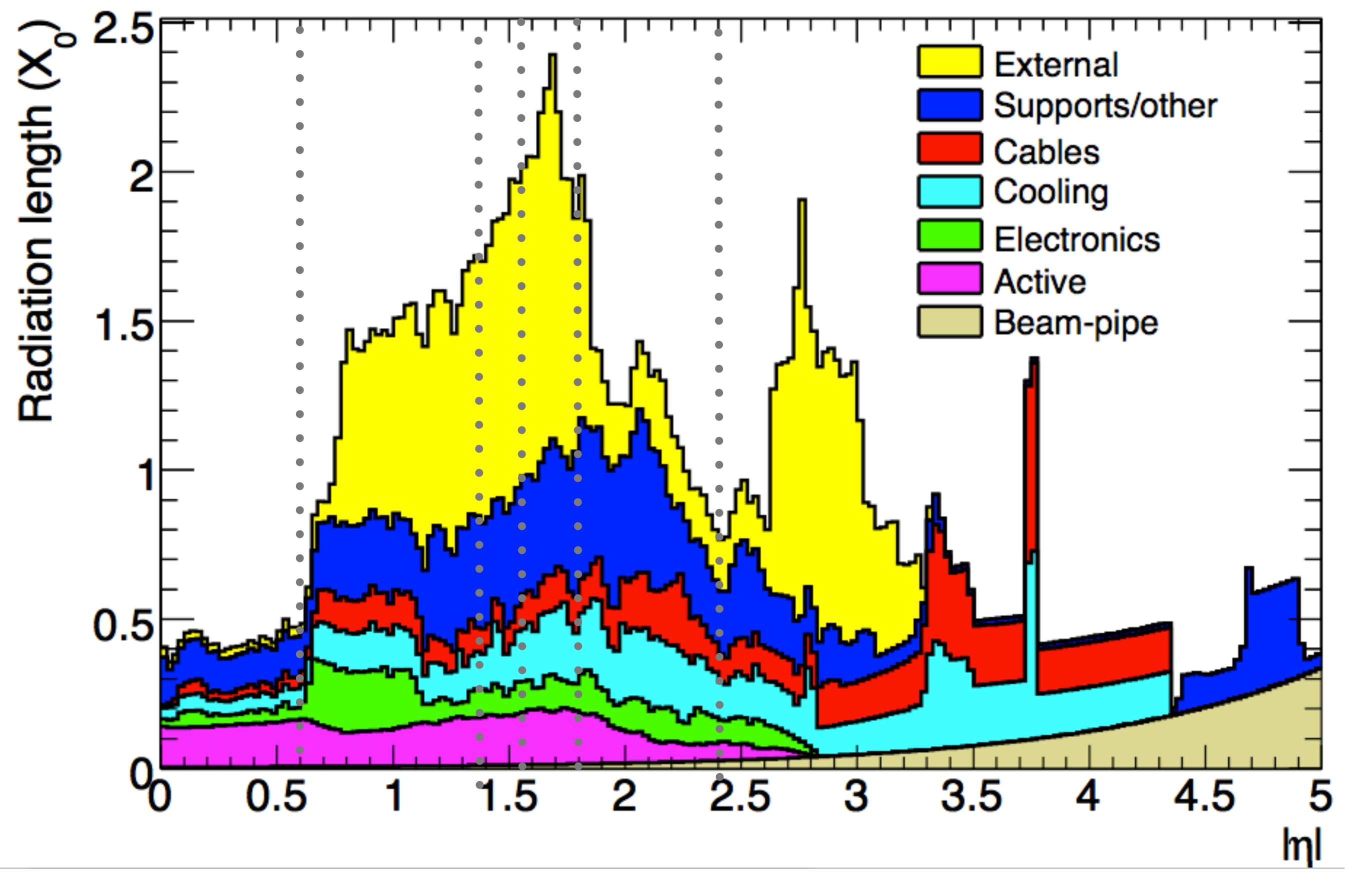
- **three longitudinal readouts (3-5, 17, 4-15 X_0)**
- **$\Delta\eta\times\Delta\varphi$= 0.003-0.006× 0.098, 0.025×0.0245, 0.05×0.0245**
- **tracker: 0.5-2.5 X_0, B=2.0 Tesla**
- **1.6-2.5% energy resolution at 50 GeV**

- **CMS ECAL ($PbWO_4$ crystals), |η| < 3.0**
  - **~25 X_0, $\Delta\eta\times\Delta\varphi$=0.0174×0.0174**
  - **tracker: 0.5-2 X_0, B=3.8 Tesla**
  - **< 1% energy resolution for unconverted barrel photons above 20 GeV**

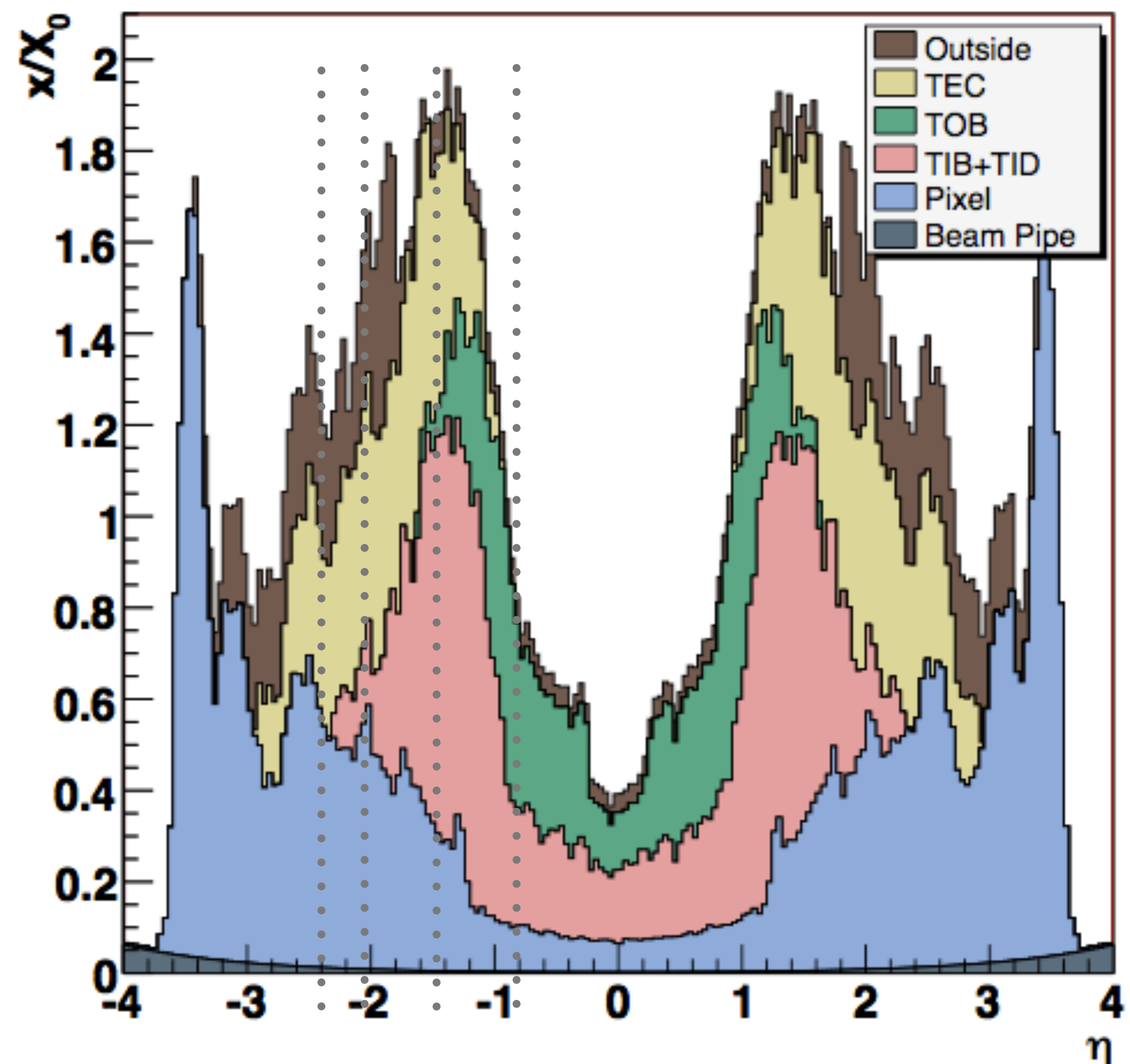


Amount of Material in LHC Trackers

ATLAS



CMS

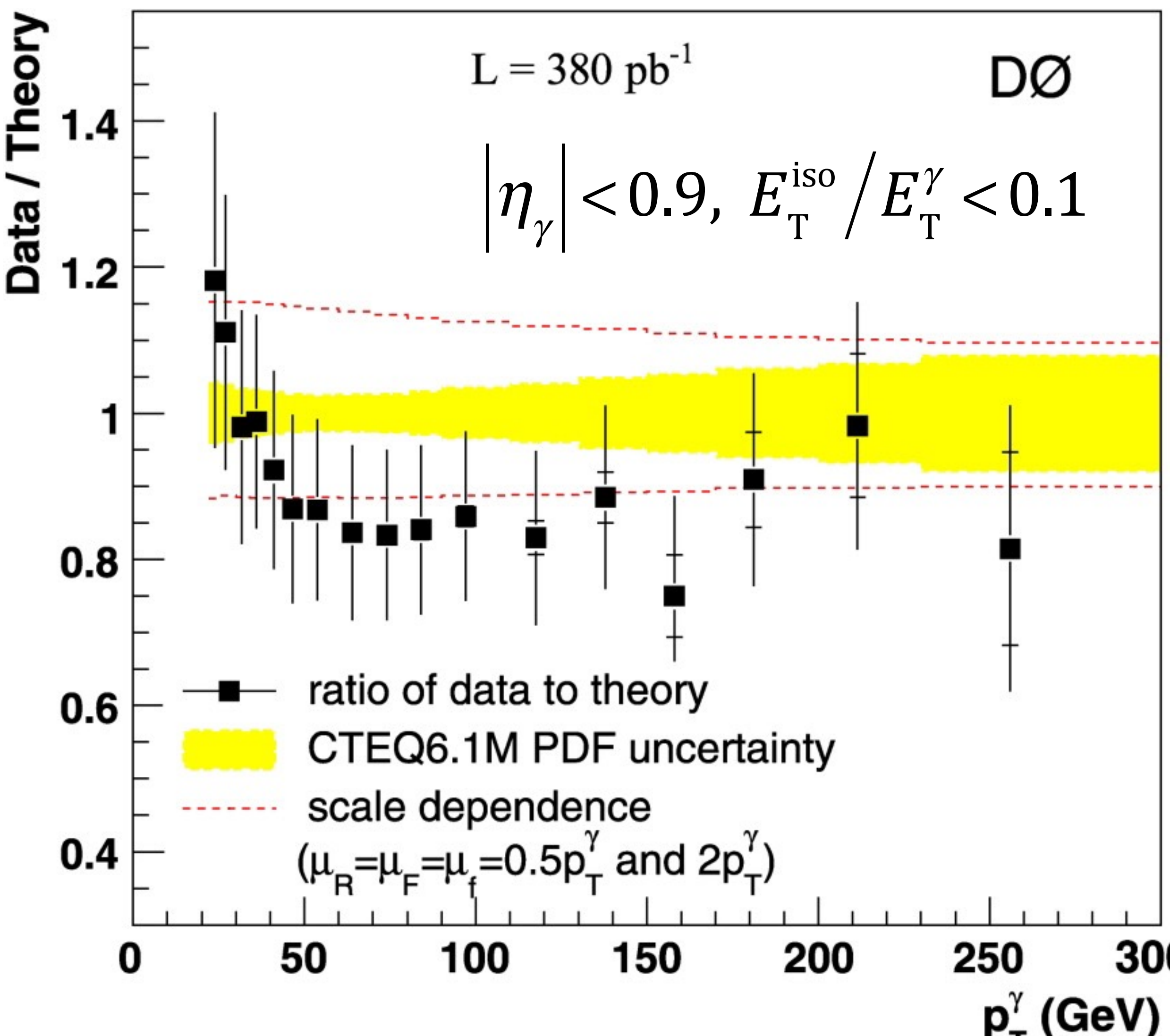


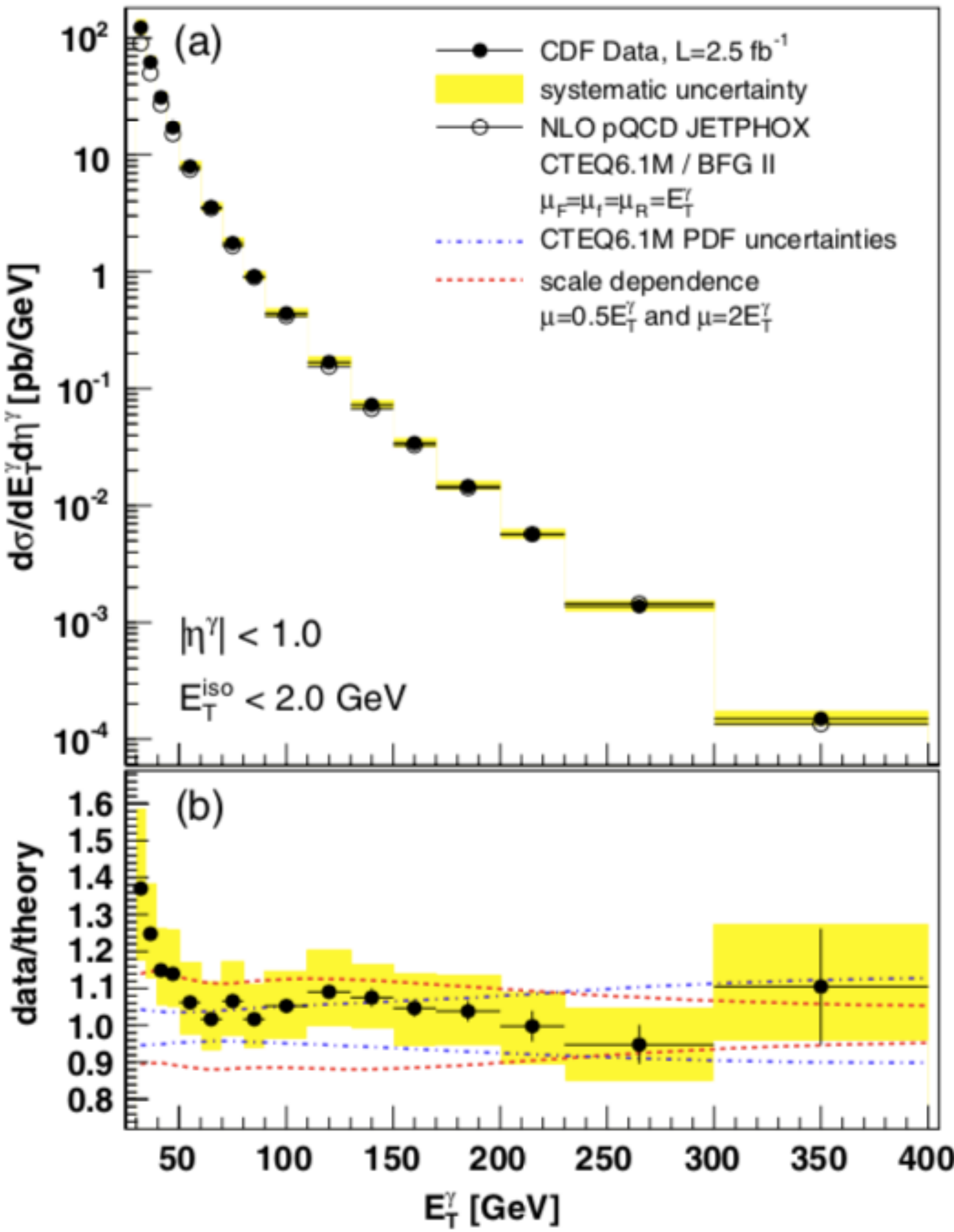
On average, about 1 X_0 in $|\eta| < 1.45$ before photons reach ECAL and photons convert ~65% of the time.

Compared to CDF where photons convert in front of preshower+ECAL ~15% of the time.

Previous Measurements at Tevatron

- Barrel photons only
- Use shower shape and isolation





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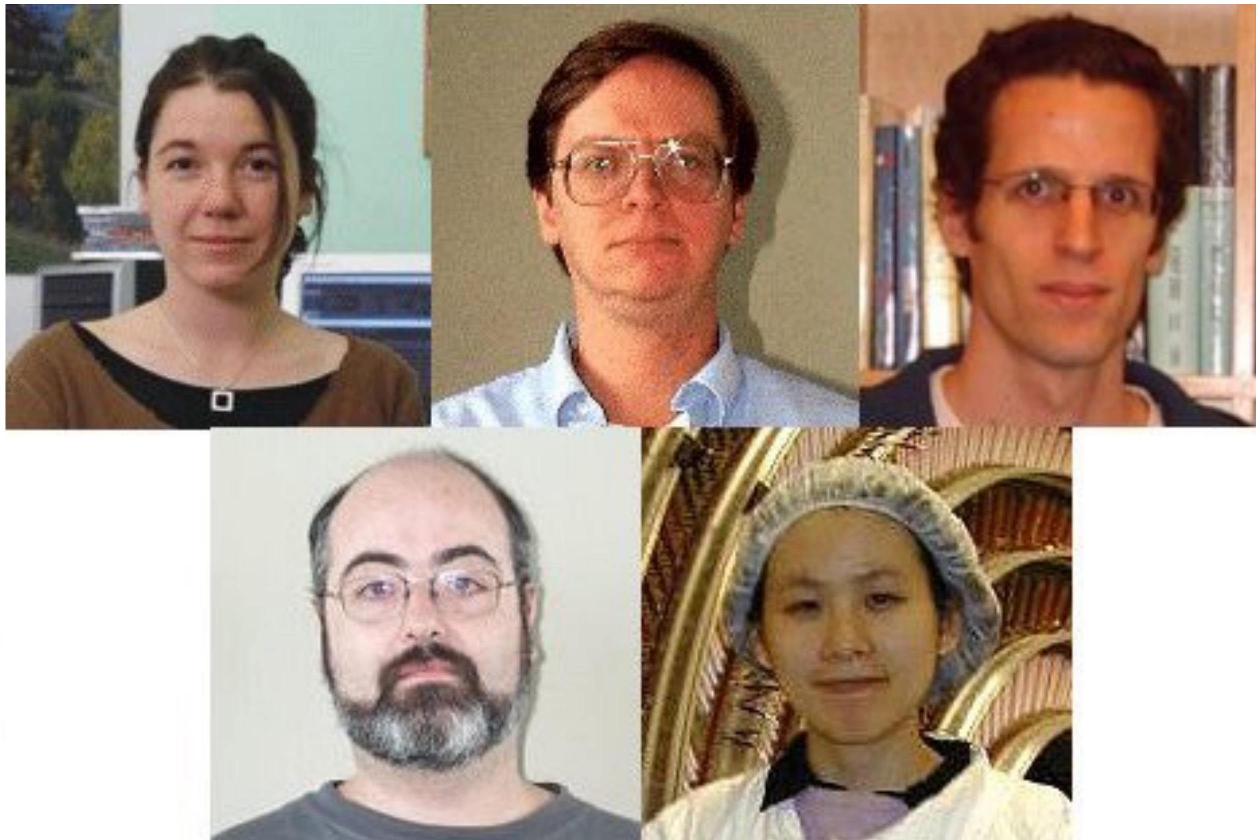
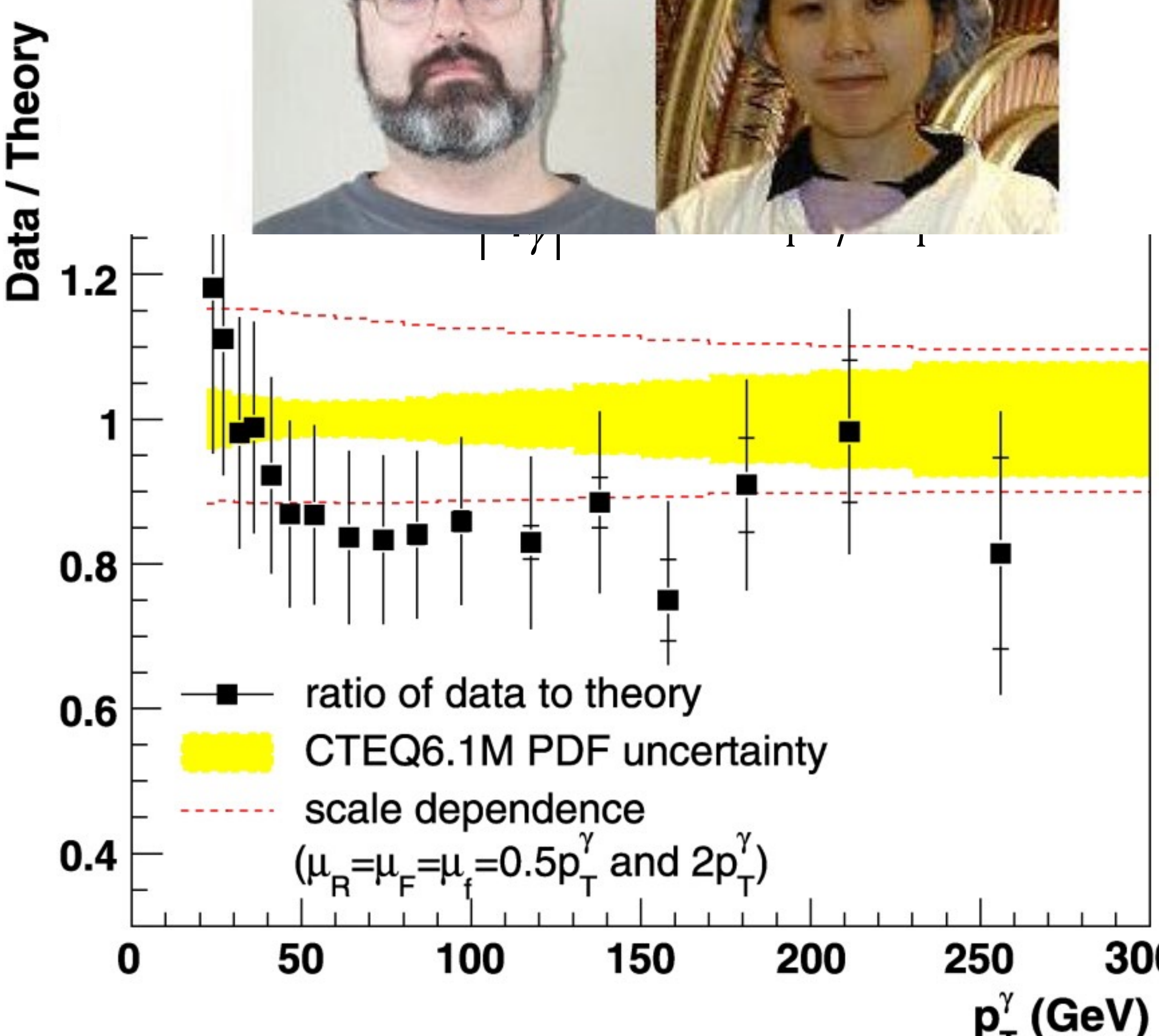
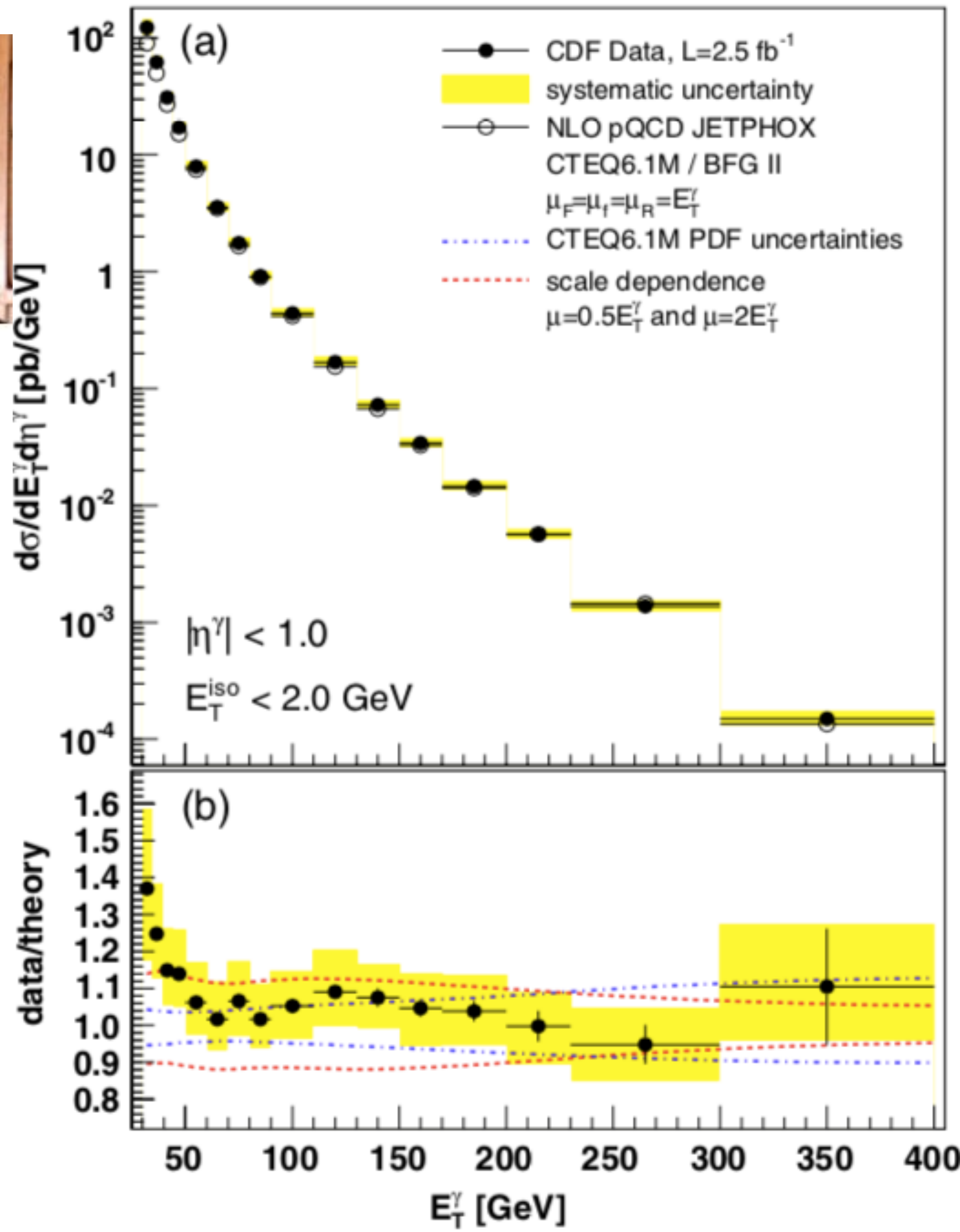






Overall Comparison

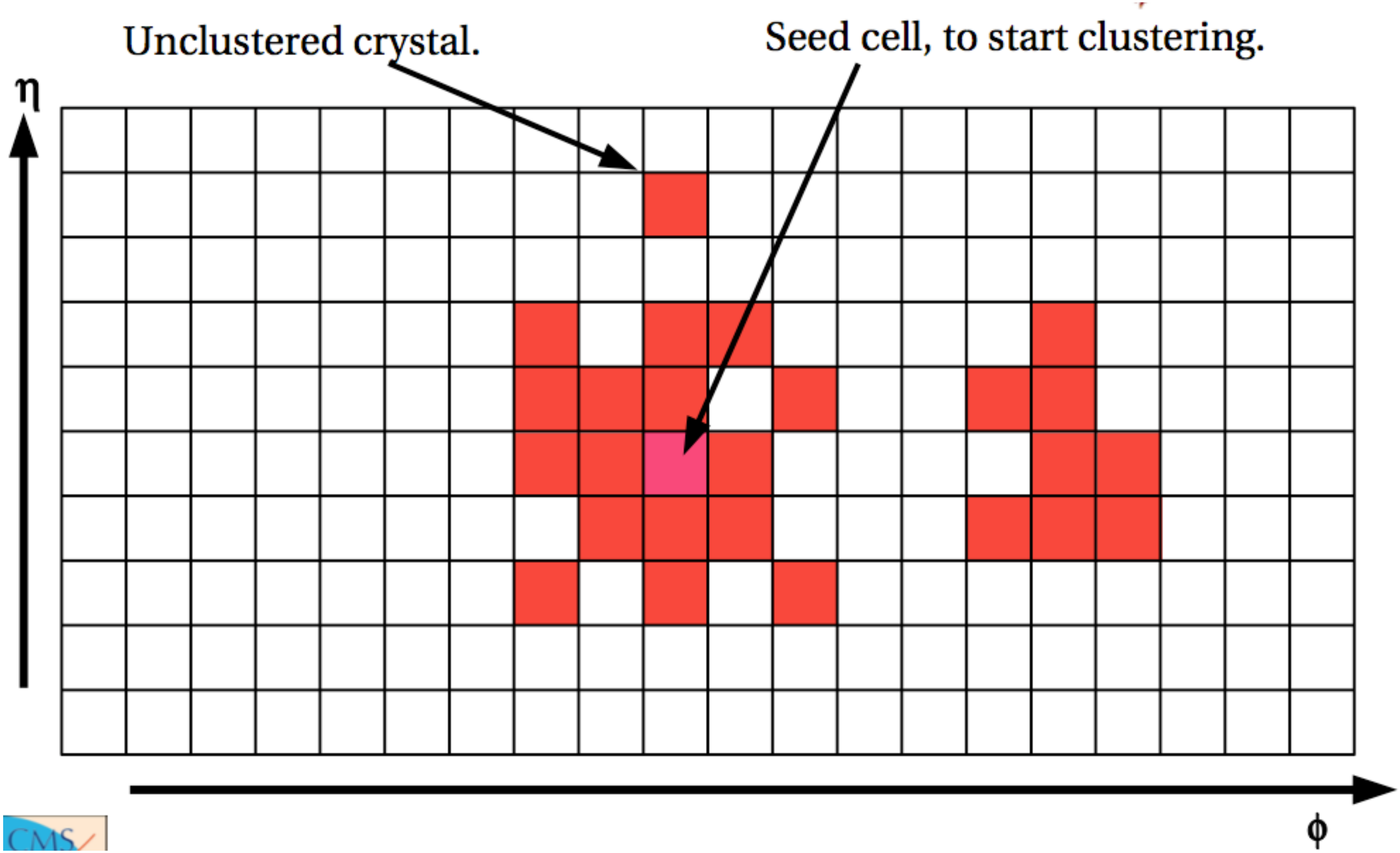
- Tevatron measurements
  - worse energy and angular resolution
  - loss of converted photons < 15%
- LHC measurements
  - a factor of 2 better energy resolution
  - need to recover converted photons (could be as large as 70%)

CDF, D0	$|\eta| < 1.0$
ATLAS, CMS	$|\eta| < 2.5$

A Way to Resolve the Problem at LHC

- Build superclusters of small clusters
  - Small clusters that are close-by are likely to come from photon conversion or electron bremsstrahlung.
- Again, take CMS photon reconstruction algorithm in ECAL barrel as an example.

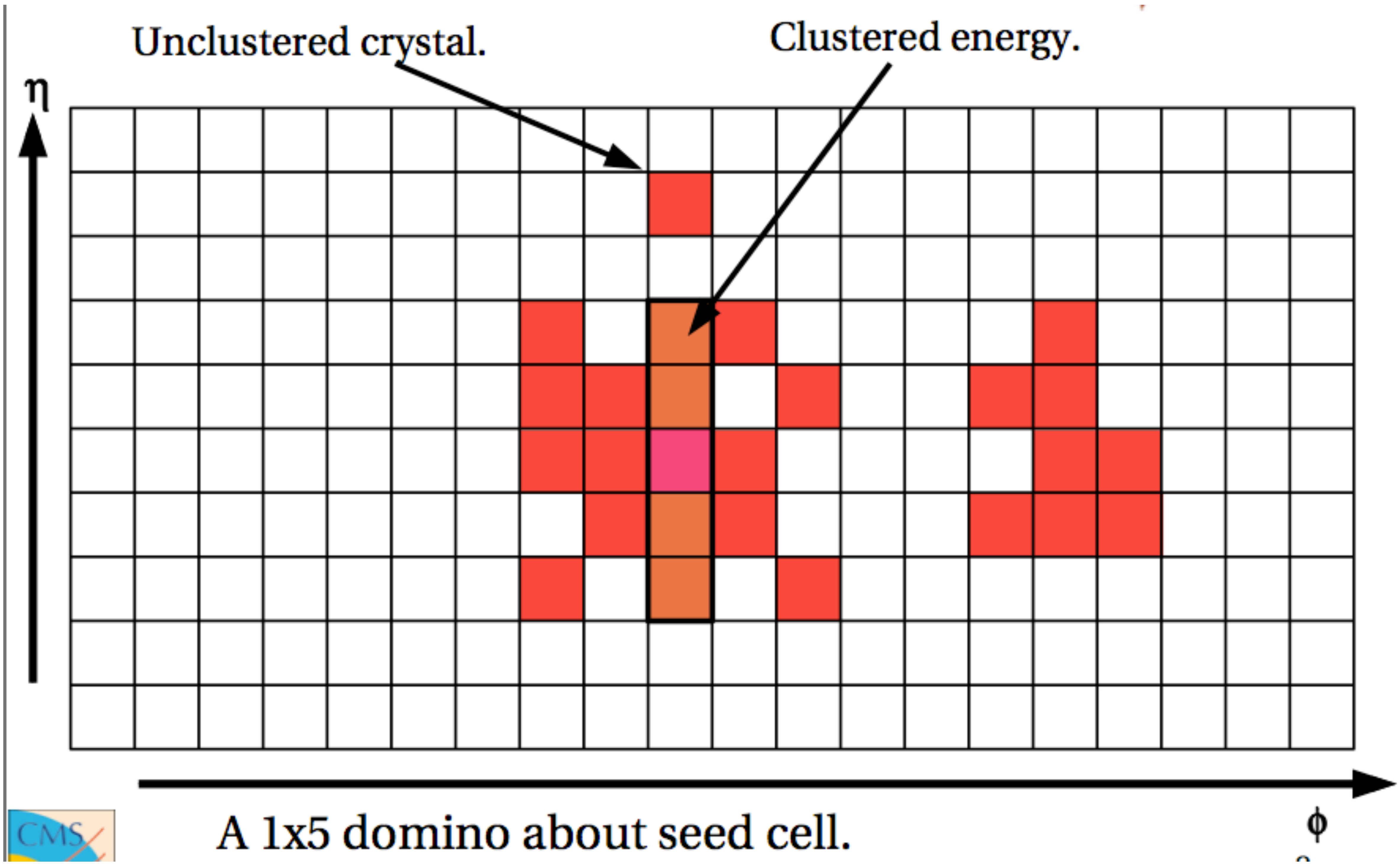
Algorithm Step 1



$\Delta\eta \times \Delta\Phi = 0.0175 \times 0.0175$

Slide from A. Askew

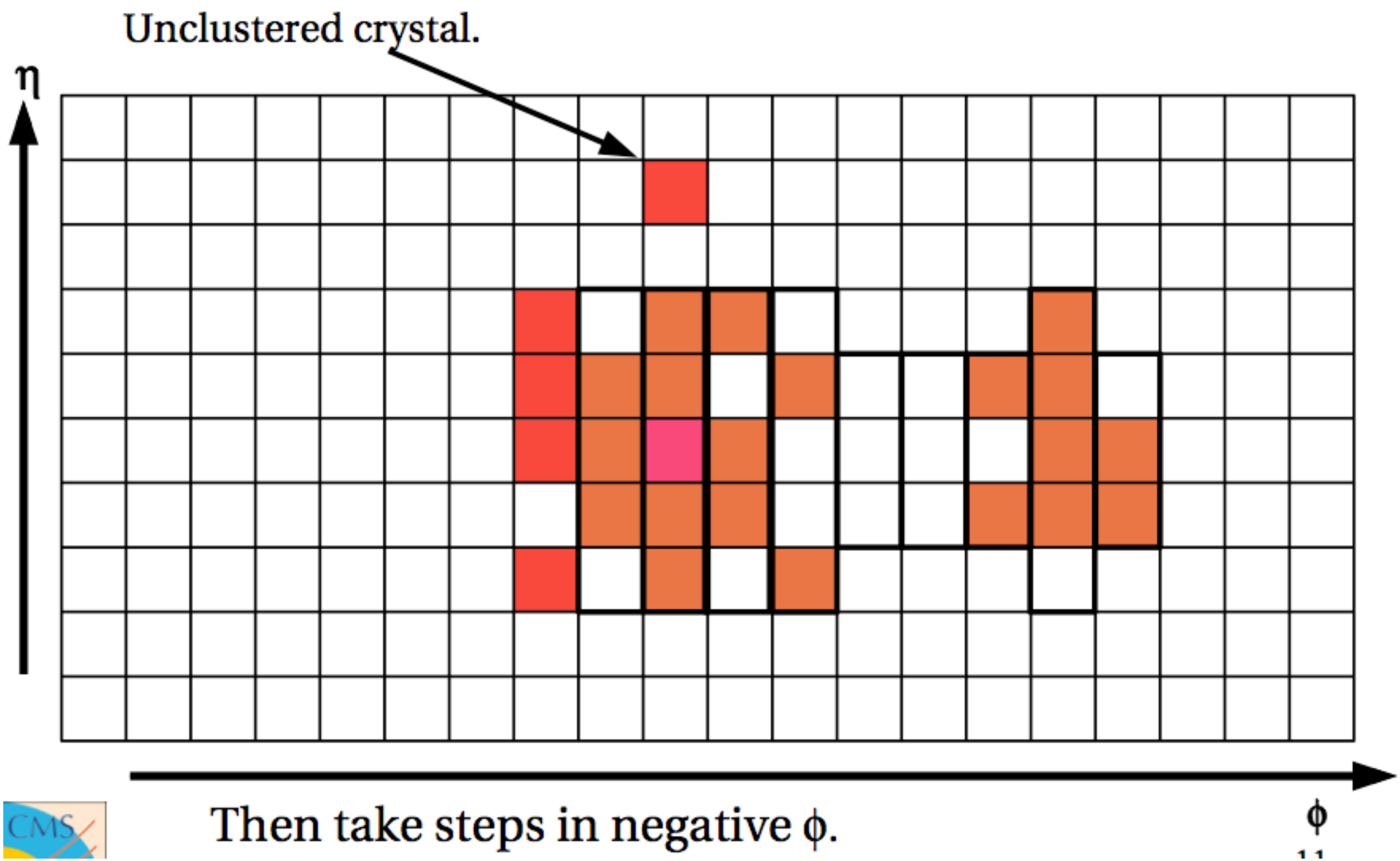
Algorithm Step 2



$\Delta\eta \times \Delta\Phi = 0.0175 \times 0.0175$

Slide from A. Askew

Algorithm Step 3



The magnetic field is along the z axis.

Slide from A. Askew

More on Algorithm

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- These steps form superclusters.

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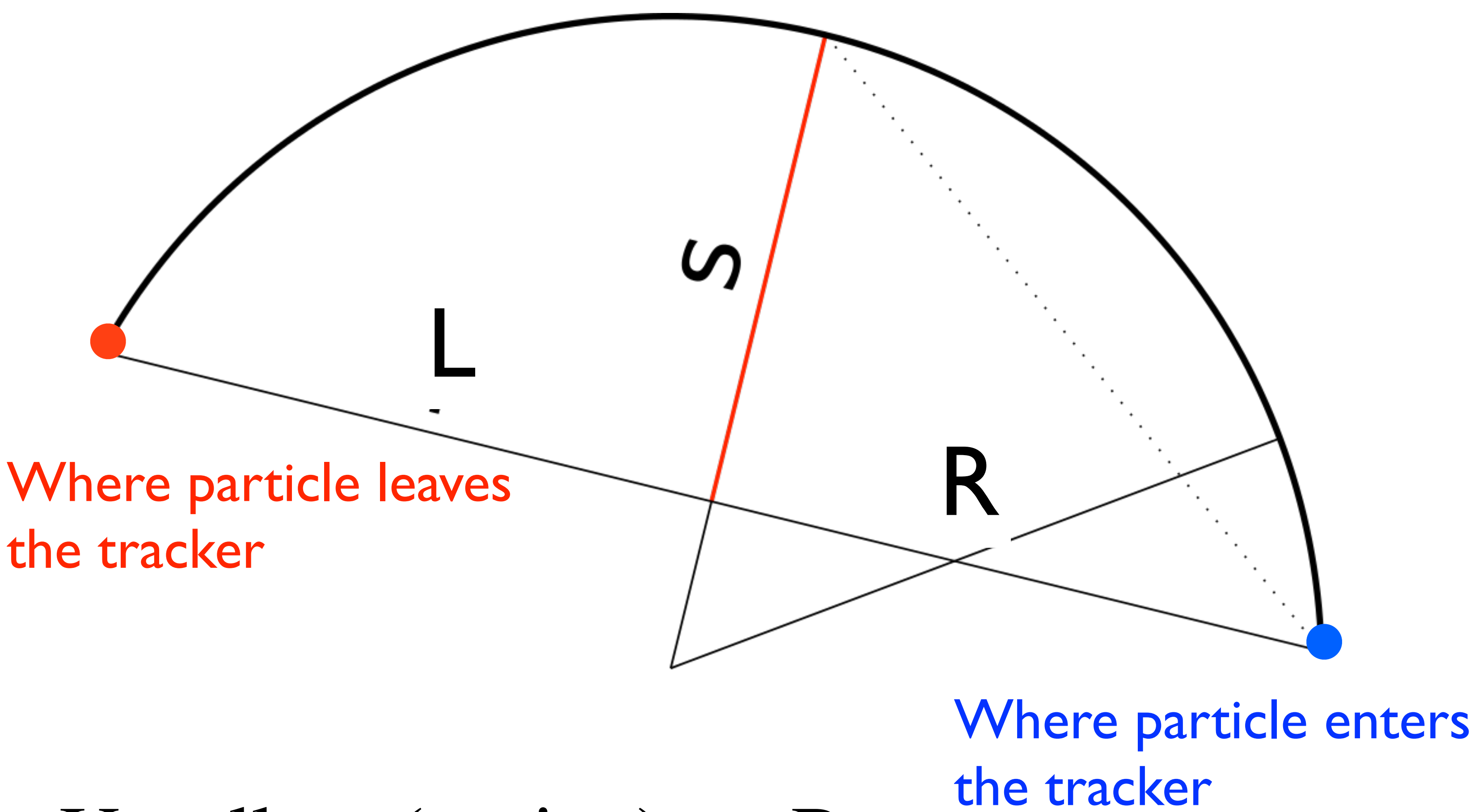
  - ± 17 steps in Φ direction (limit photon energy to 10 GeV and above)
- If the ratio of energy deposited in 3x3 crystals to the energy of supercluster is very close to 1, take the energy deposited in 5x5 crystals as photon energy.
- Photon momentum is defined from the primary vertex to the energy-weighted cluster position.

Sagitta and Bending Distance

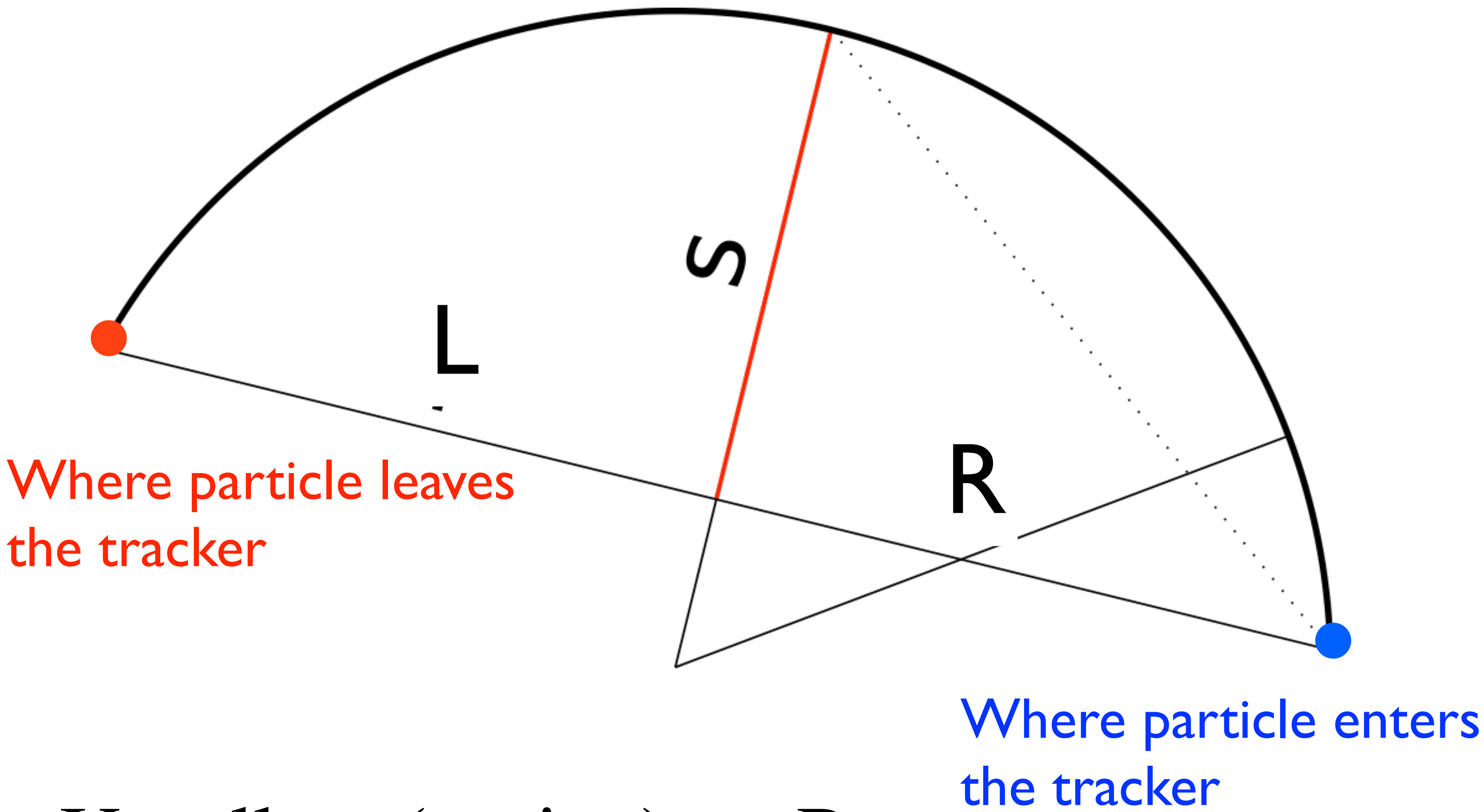
D. Stuart

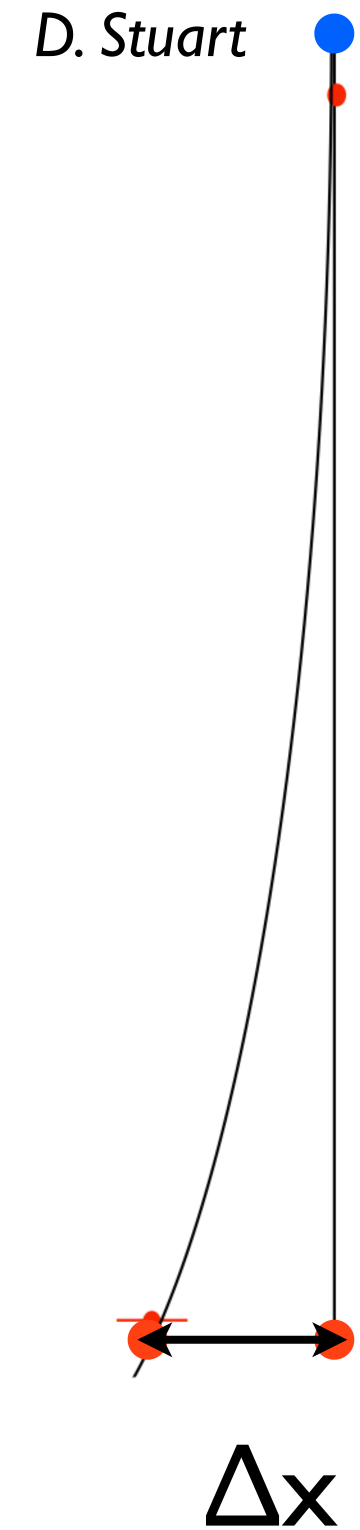


Usually s (sagitta) $\ll$ R

$$\Rightarrow R \cong \frac{L^2}{8s} \text{ or } s \cong \frac{L^2}{8R} = \frac{0.3\,BL^2}{8\,p_T}$$

Sagitta and Bending Distance





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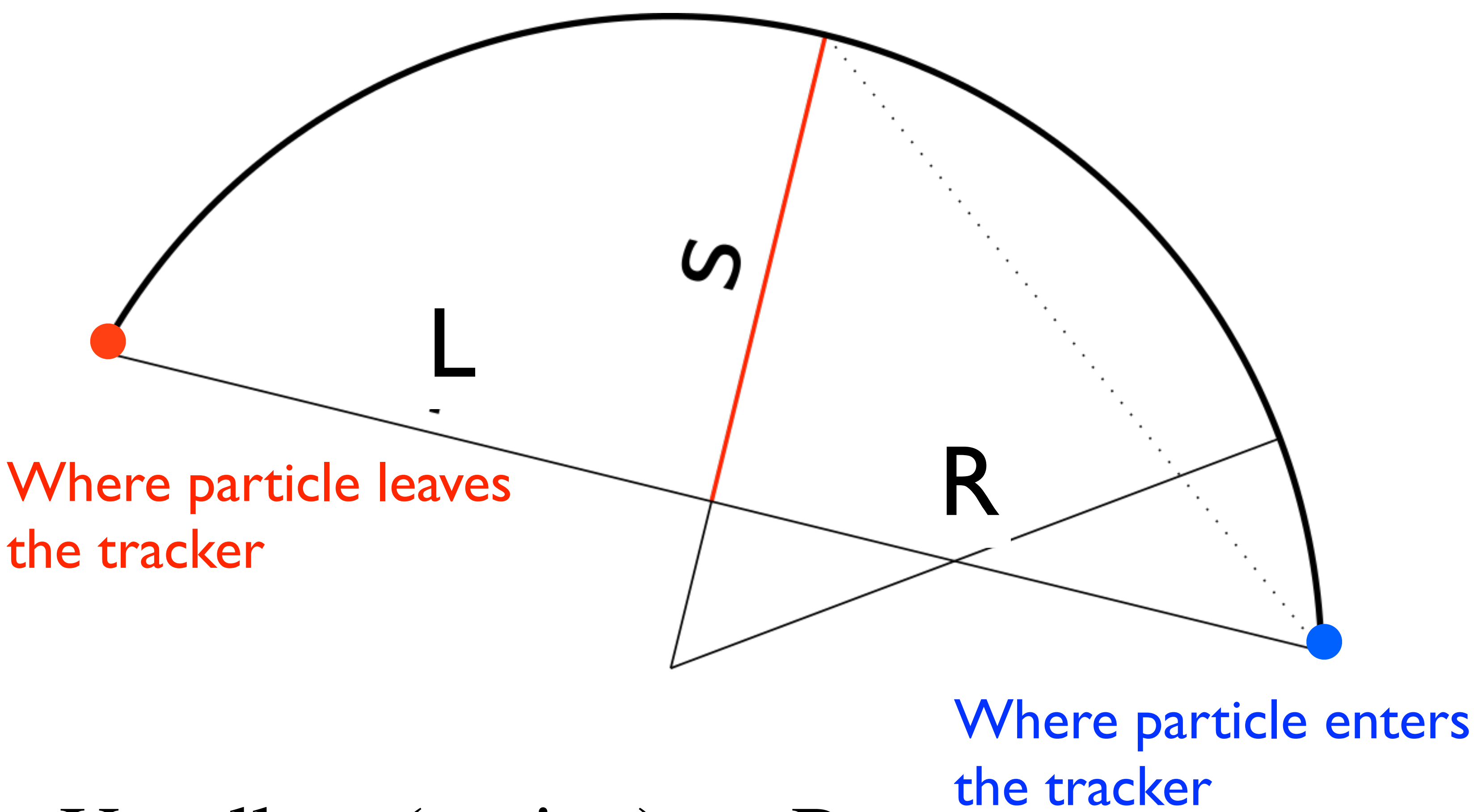

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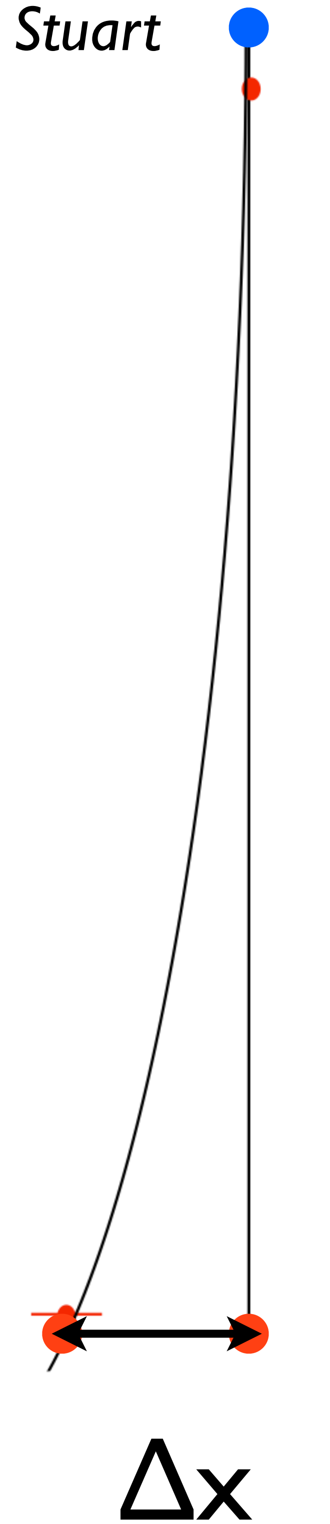
Homework

$$\boxed{\Delta x \cong 4s \cong \frac{0.3\,BL^2}{2\,p_T}}$$

D. Stuart

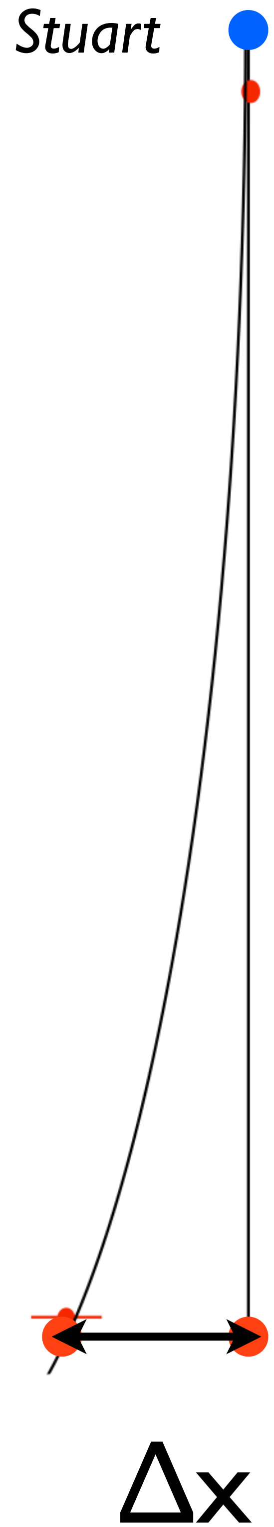


Sagitta and Bending Distance

D. Stuart

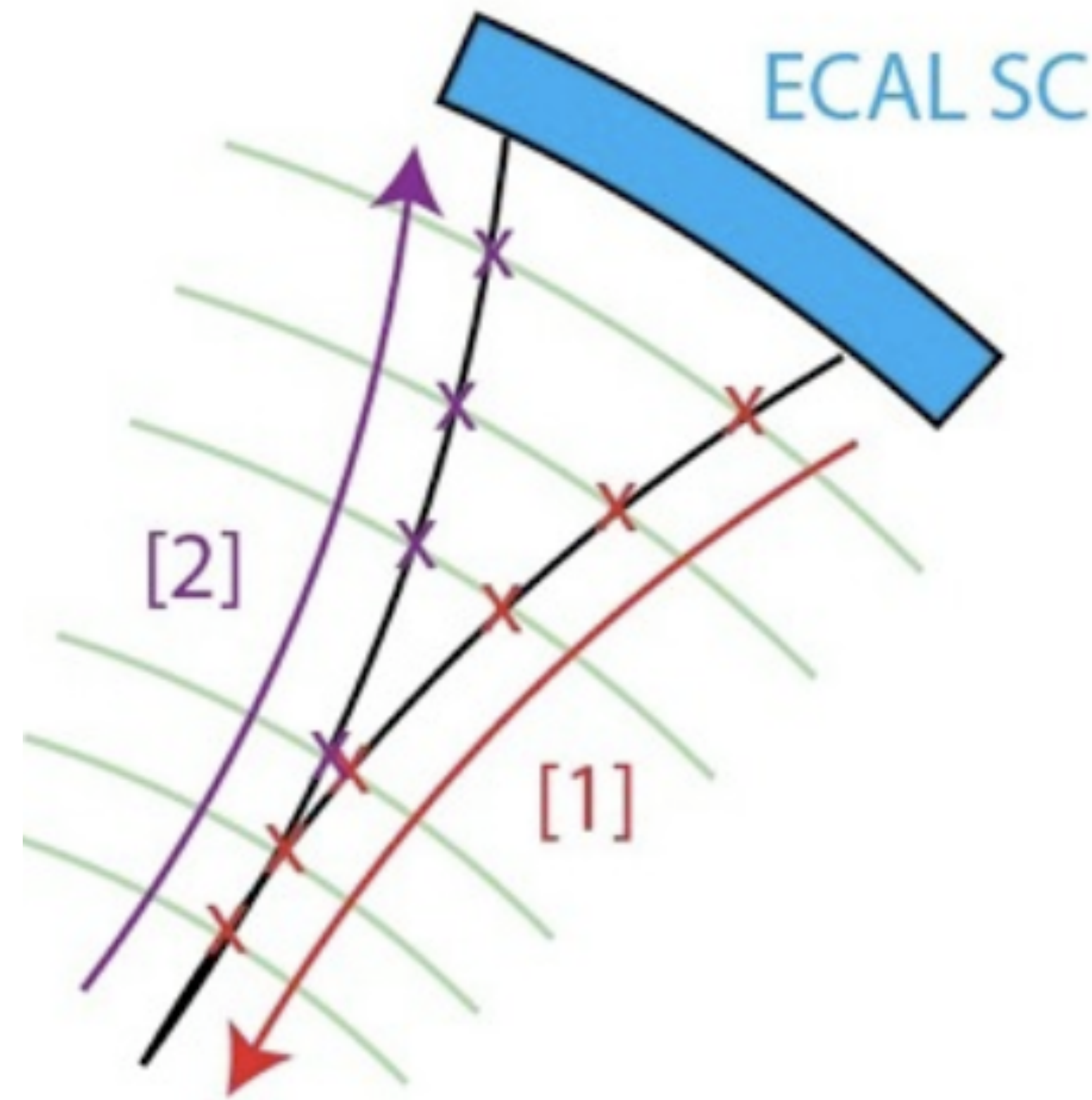
Important for estimating separation between electrons and photons due to bremsstrahlung and conversion, also separation between neutral and charged particles in the particle flow algorithm.

$$\boxed{\begin{aligned}\Delta x &\cong 4s \\ &\cong \frac{0.3\,BL^2}{2\,p_T}\end{aligned}}$$



Explicitly Reconstruct Converted Photons

- Start from ECAL cluster, going inwards to find hits in the tracker
  - the search road depends on energy measured in ECAL
- From the inner most layer where the track ends, going outwards to find the second track
- Alternative method by starting from tracker



Background to Photons of Interest

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- Signal photons are:
  - Produced directly from hard scattering
  - Decays of exotic particle (such as Higgs)

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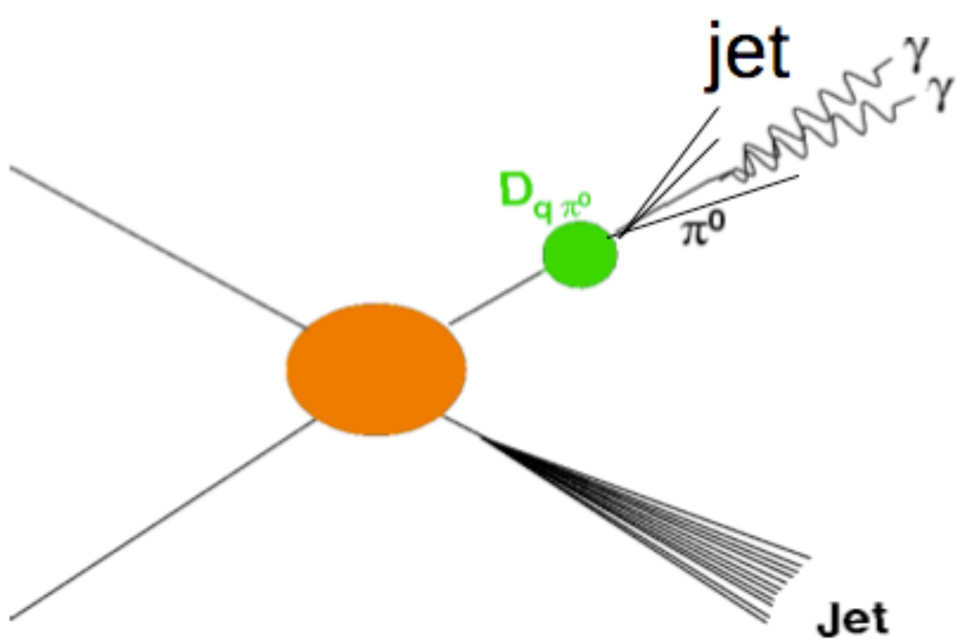
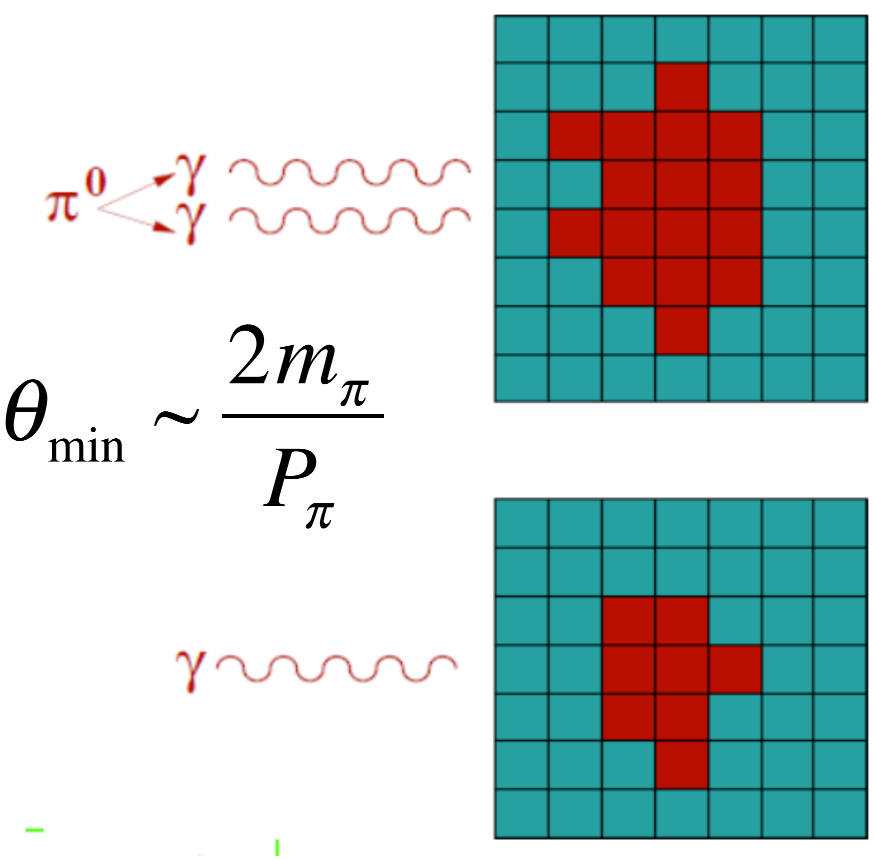
- Signal photons are:
  - Produced directly from hard scattering
  - Decays of exotic particle (such as Higgs)
- Background photons are:
  - Electrons due to loss of track or hard BREM
  - Photons from decays of neutral hadrons (such as π^0, η^0, K_s^0)
  - Non-collision photons due to BREM of beam halo, cosmic muons
  - Hadron-induced electronic noise (spikes)

Background Photons

- When the two photons are close by, a jet could be mis-identified as a single photon



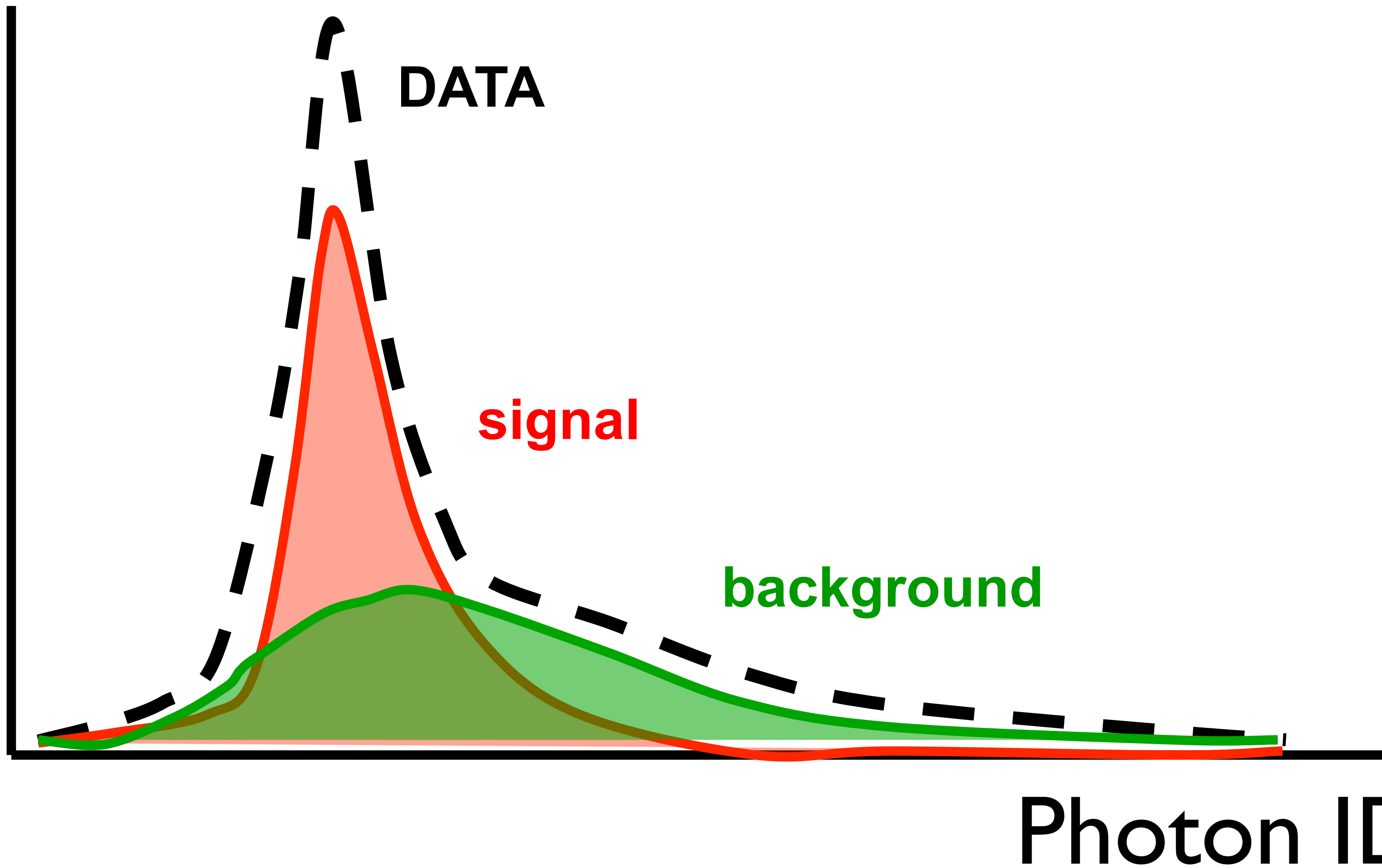


$$\Delta\theta_{\min} \sim \frac{2m_\pi}{P_\pi}$$

How to “Separate” Signal and Background

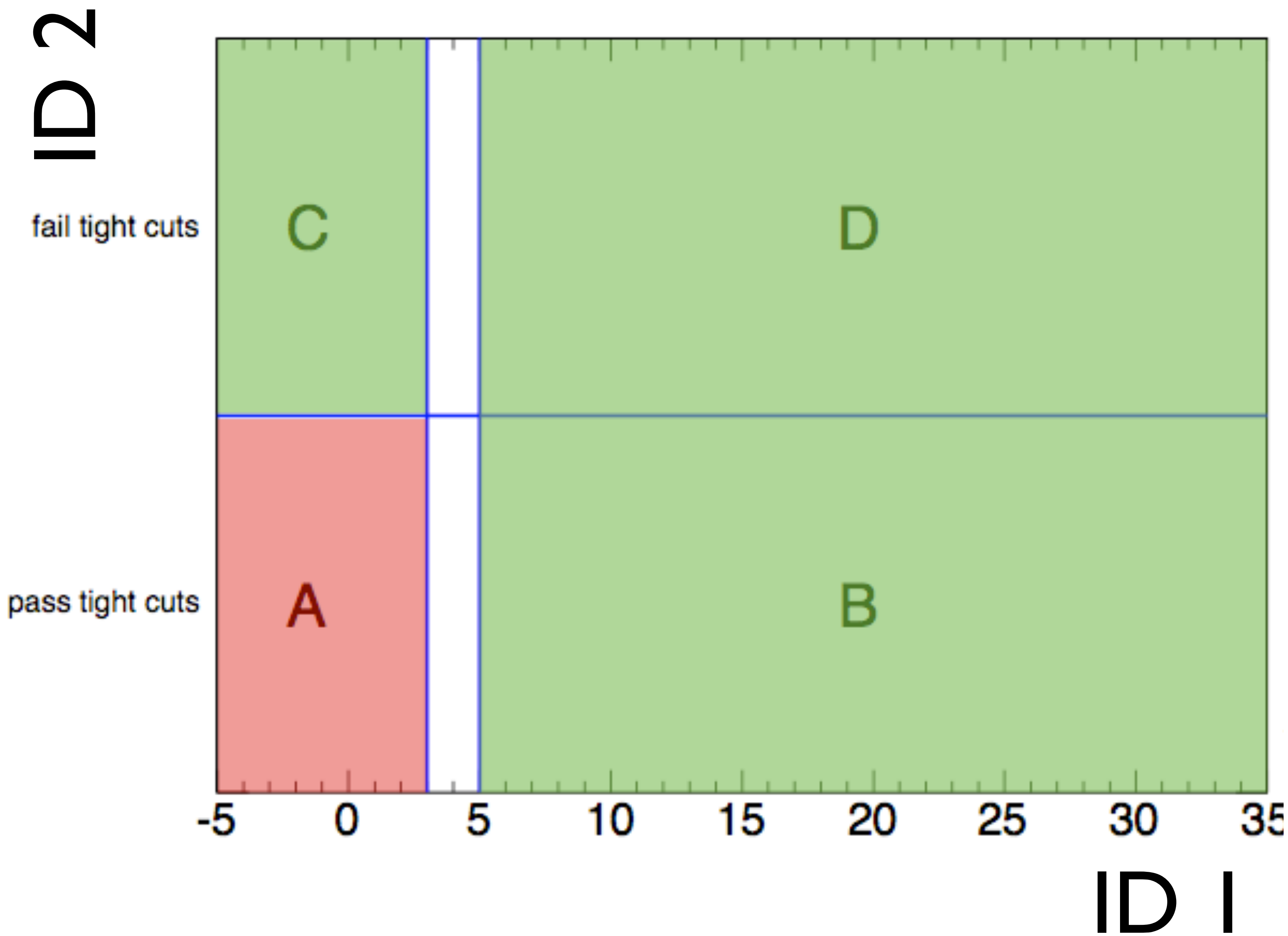
- Event-by-event separation couldn’t be achieved, need to estimate background on a statistical basis.
- Some variables are used to apply preselections, others are used to estimate remaining background.

Strategy



- Obtain signal and background templates from the control samples
- Fit data to $N_{\text{data}}\mathcal{P}_{\text{data}} = N_{\text{sig}}\mathcal{P}_{\text{sig}} + N_{\text{bkg}}\mathcal{P}_{\text{bkg}}$

Background Templates



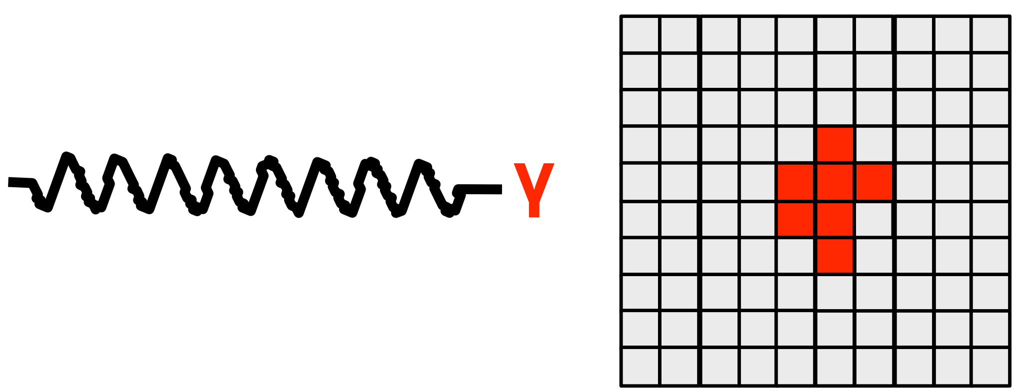
A: photon candidates that satisfy our selection, could contain our signal

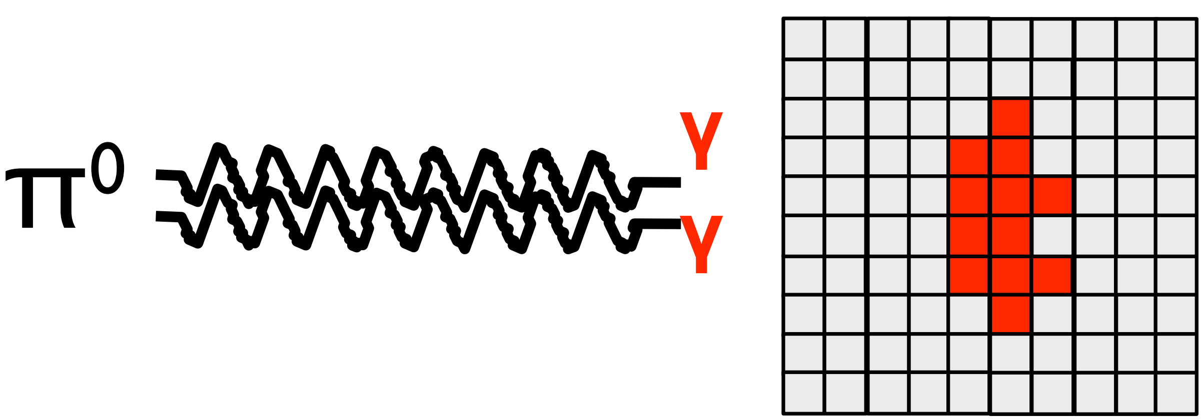
- ID1 and ID2 are not correlated
- If we use ID1 to be our fitting variable, we could use events in regions C and D to model the background in regions A and B

The Usual Photon ID Variables

Shower Shape:

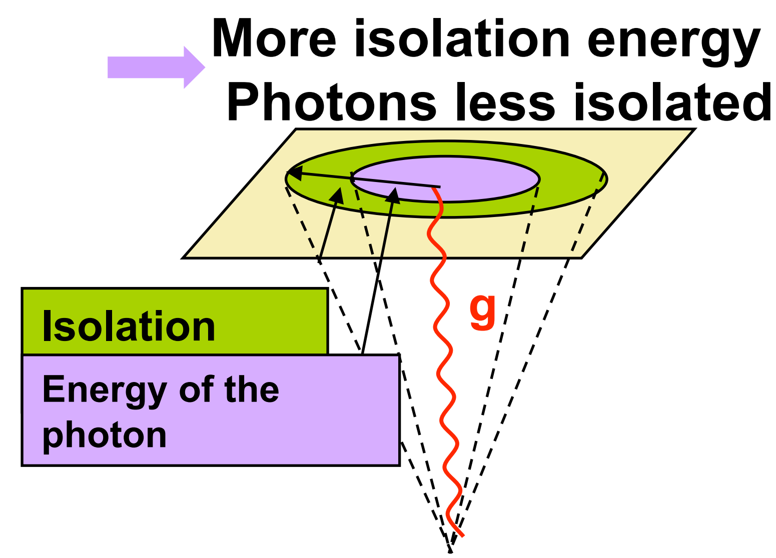
shape of energy distribution in ECAL

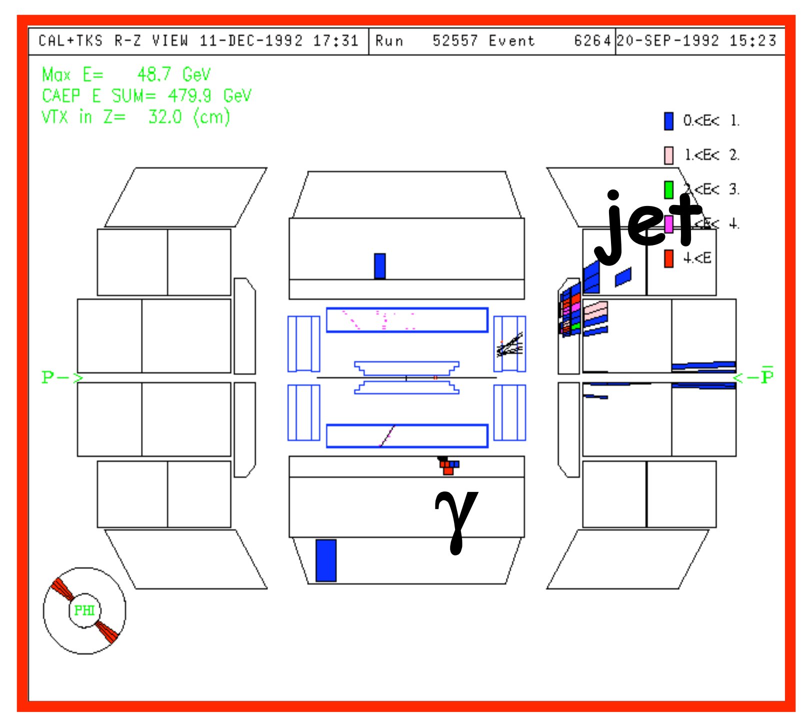




Isolation:

activity near candidate





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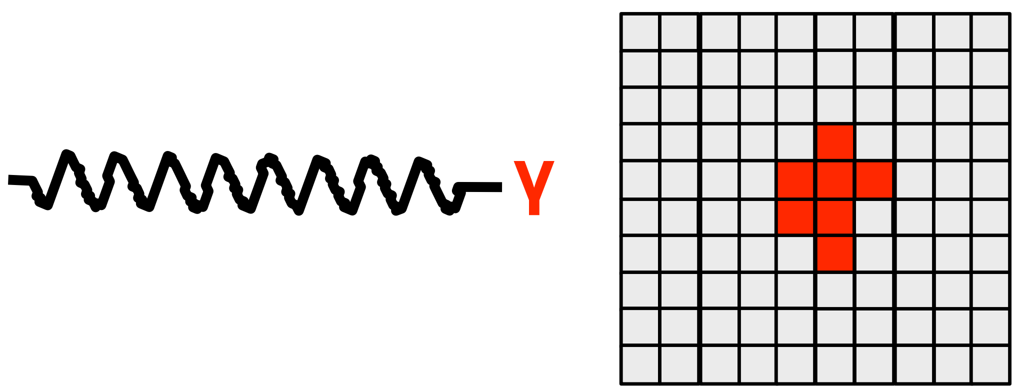

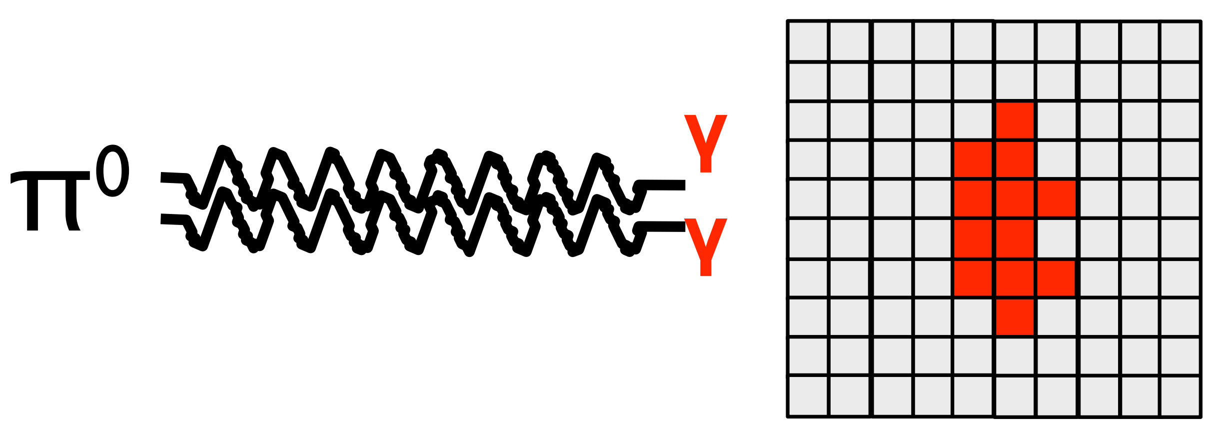

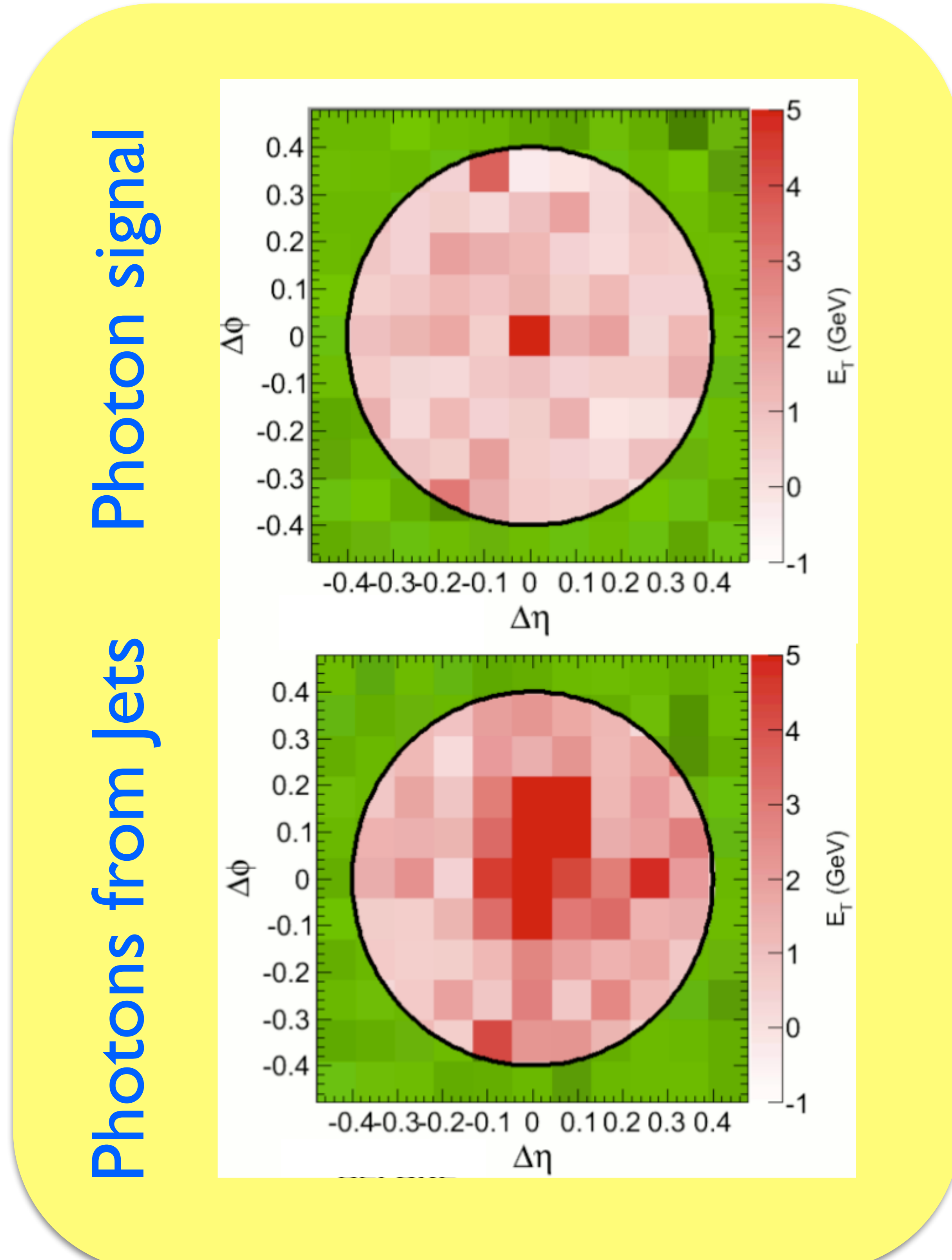

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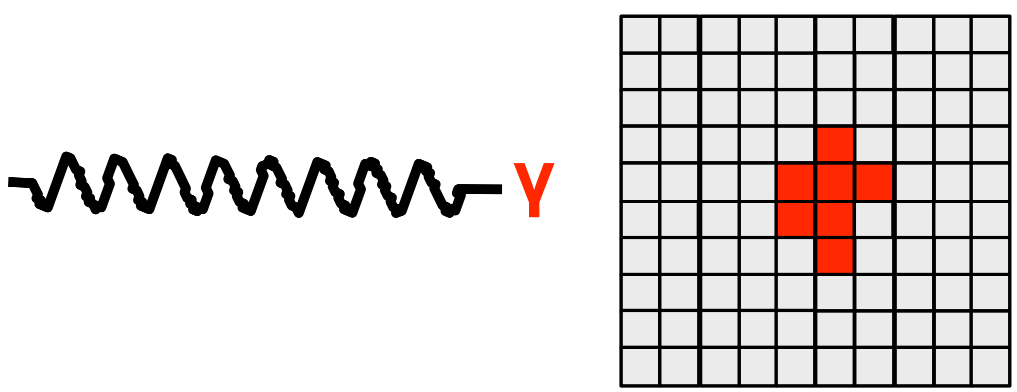

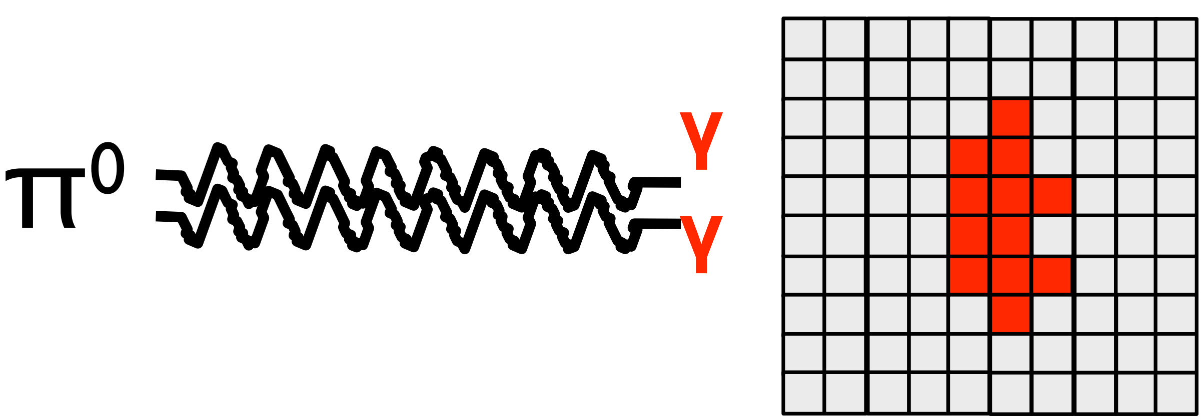

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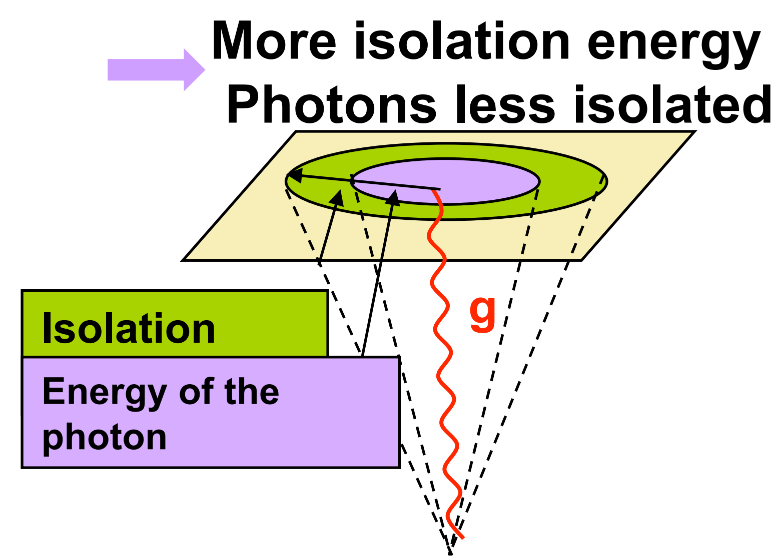

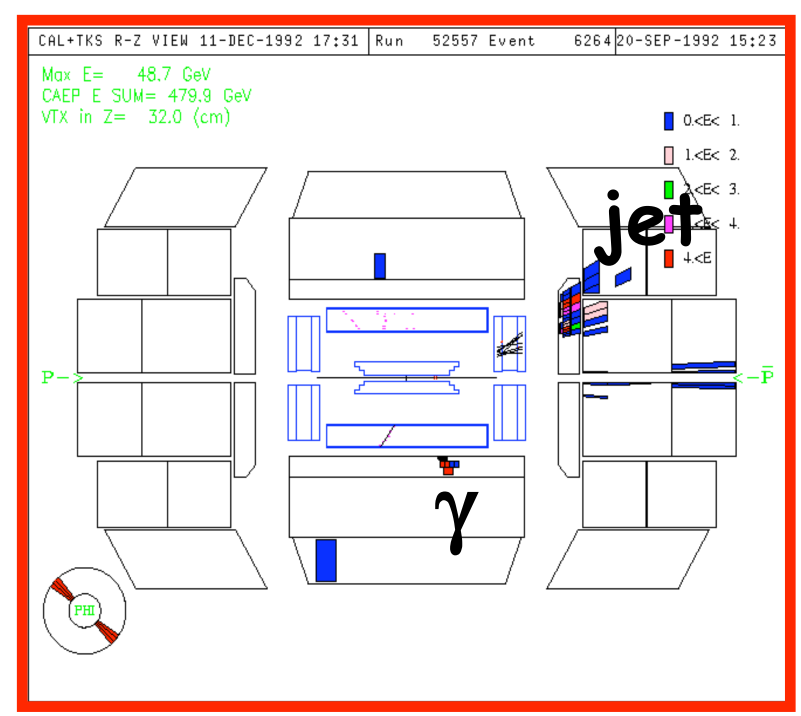

In the Photon Analysis

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- Balance between efficiency and purity

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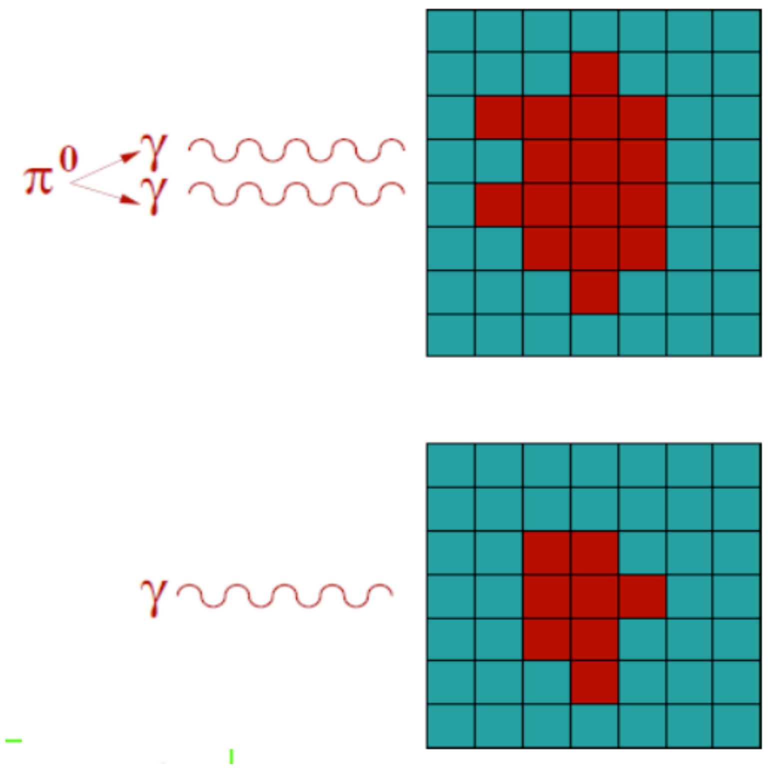
- Want high purity to reduce uncertainty from background

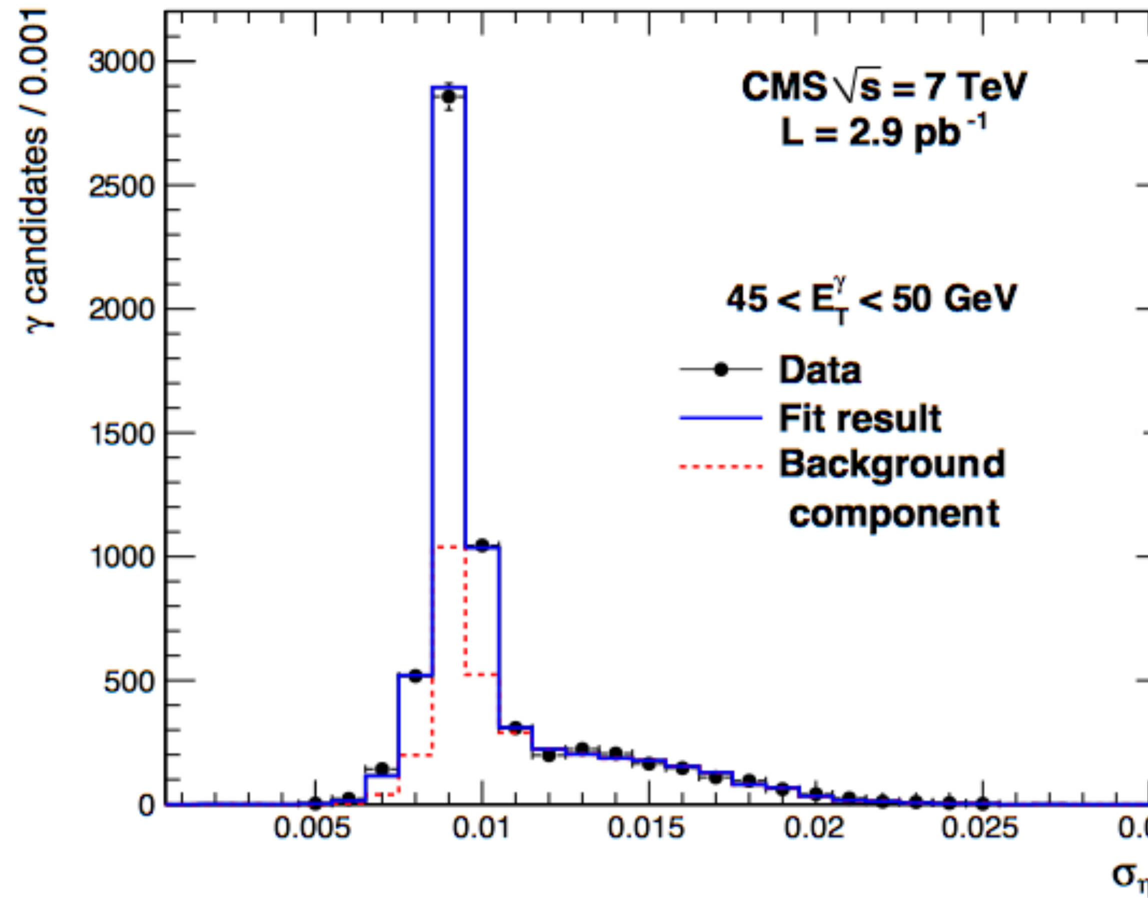
In the Photon Analysis

- Balance between efficiency and purity
- Want high purity to reduce uncertainty from background
- Want to calibrate efficiency with electrons
  - Before we get enough real photons from final state radiation of W or Z leptonic decays

Estimation of Photon Purity



EM shower shape



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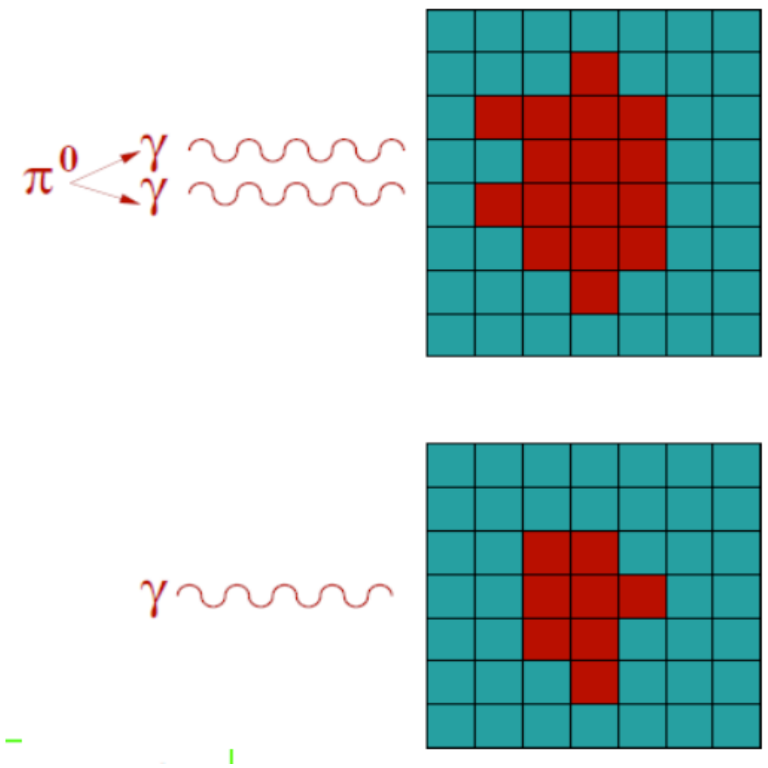

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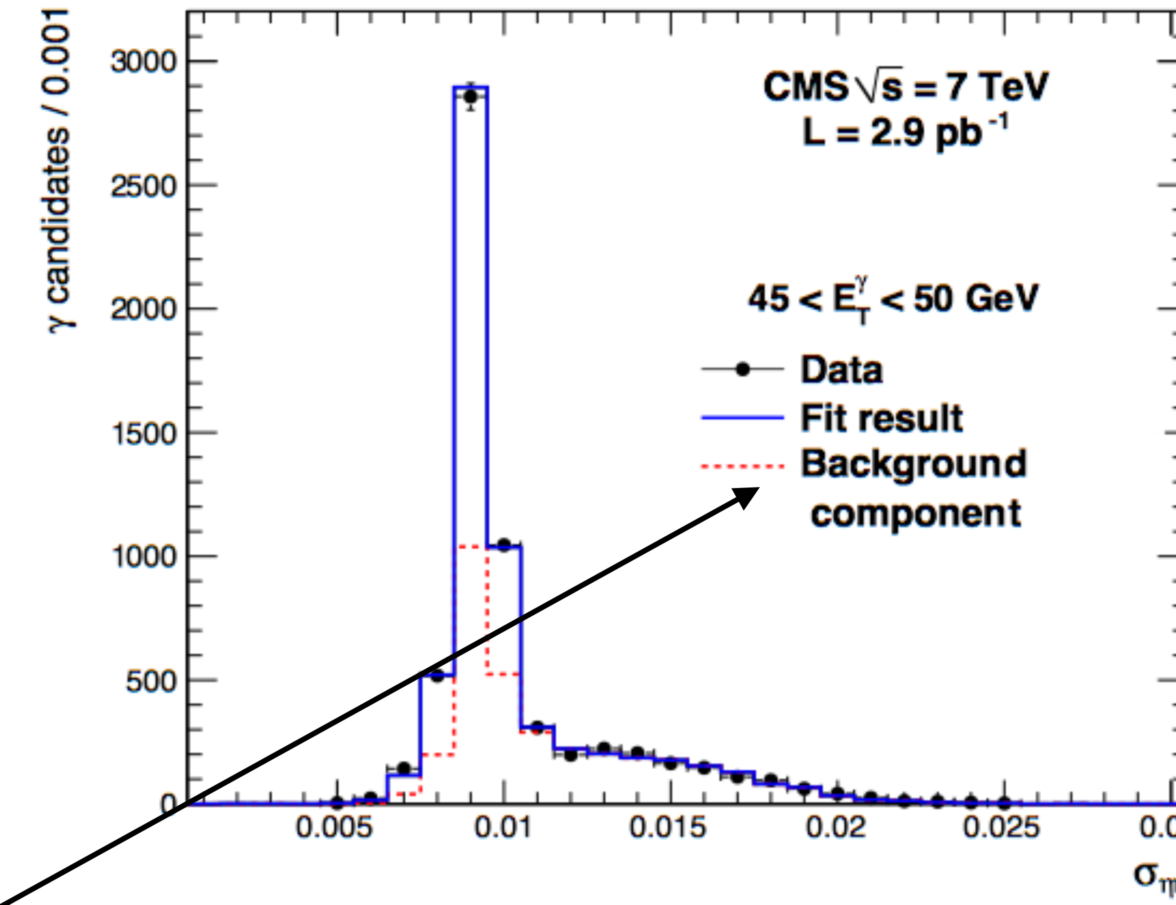
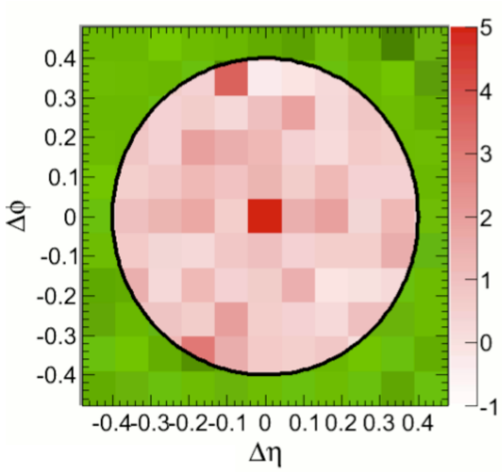
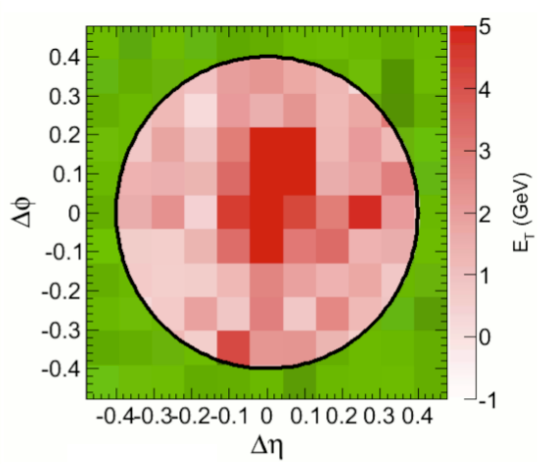




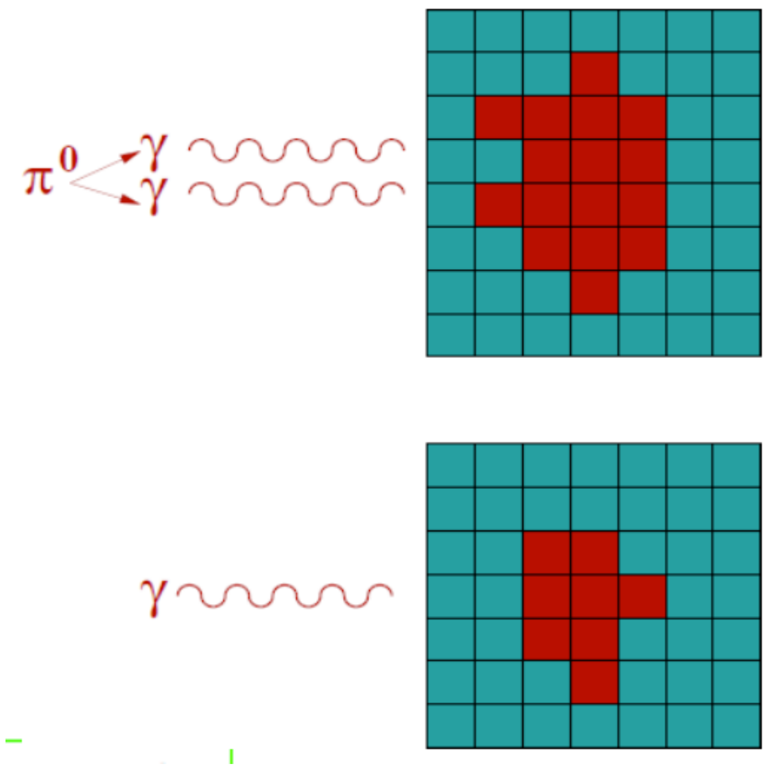
Signal



Jet

Control sample from data with photon candidates failing track isolation requirements

Estimation of Photon Purity



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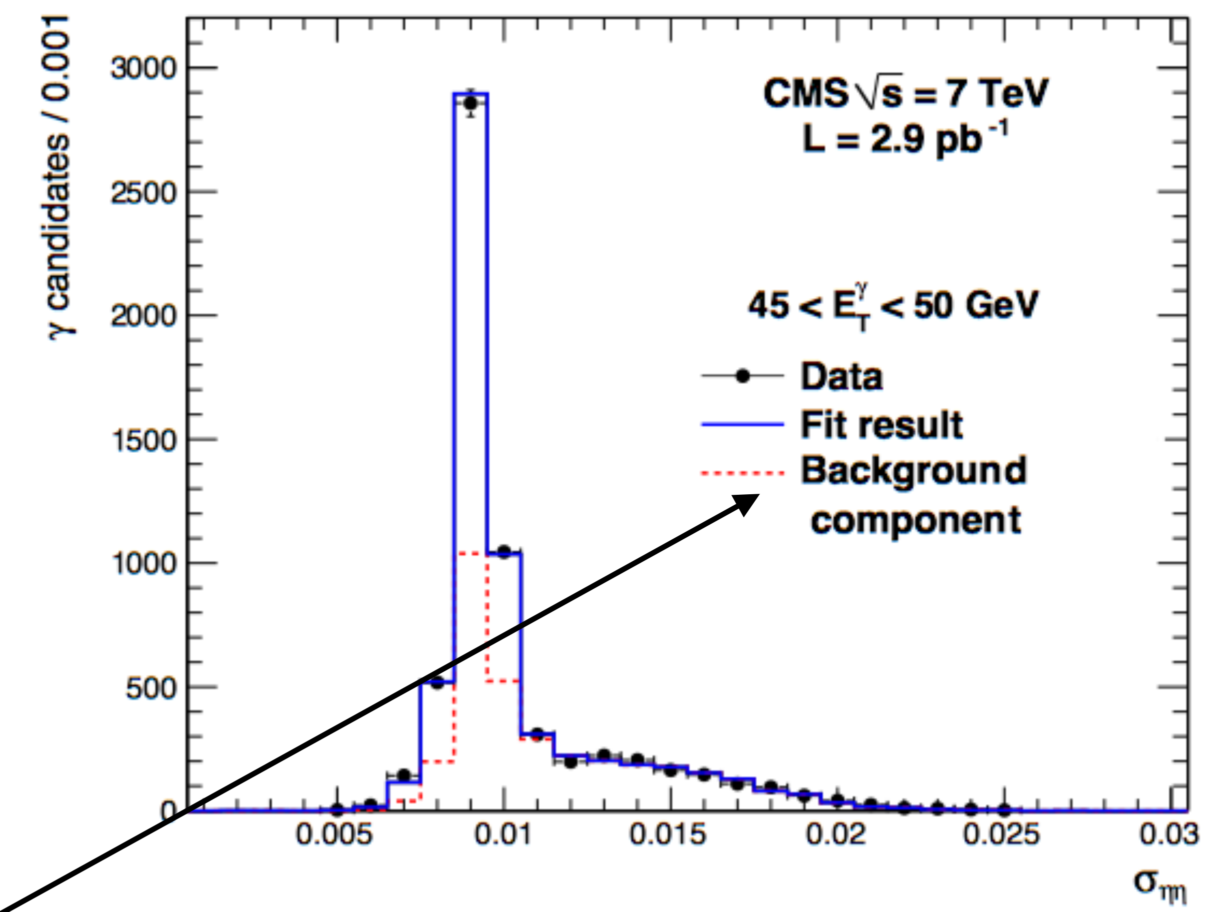
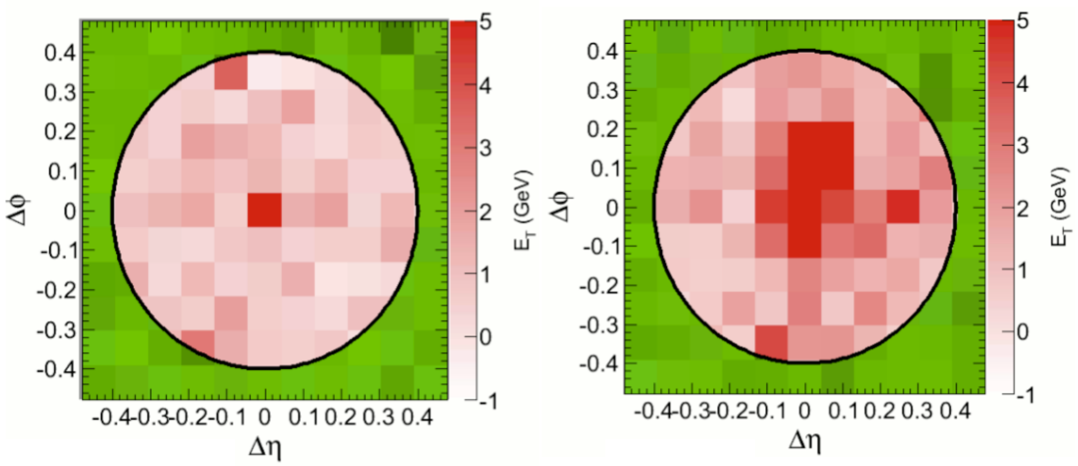


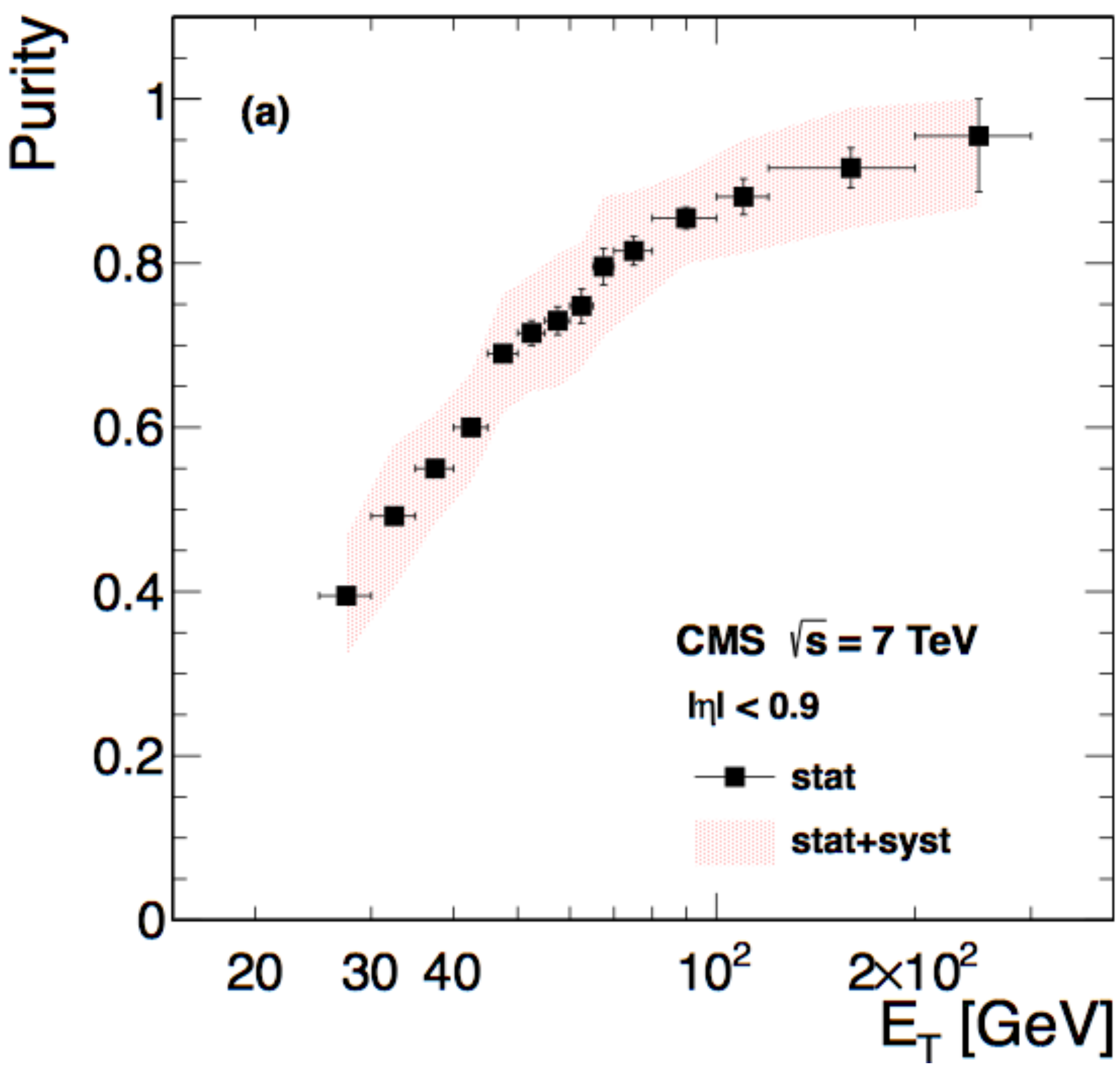


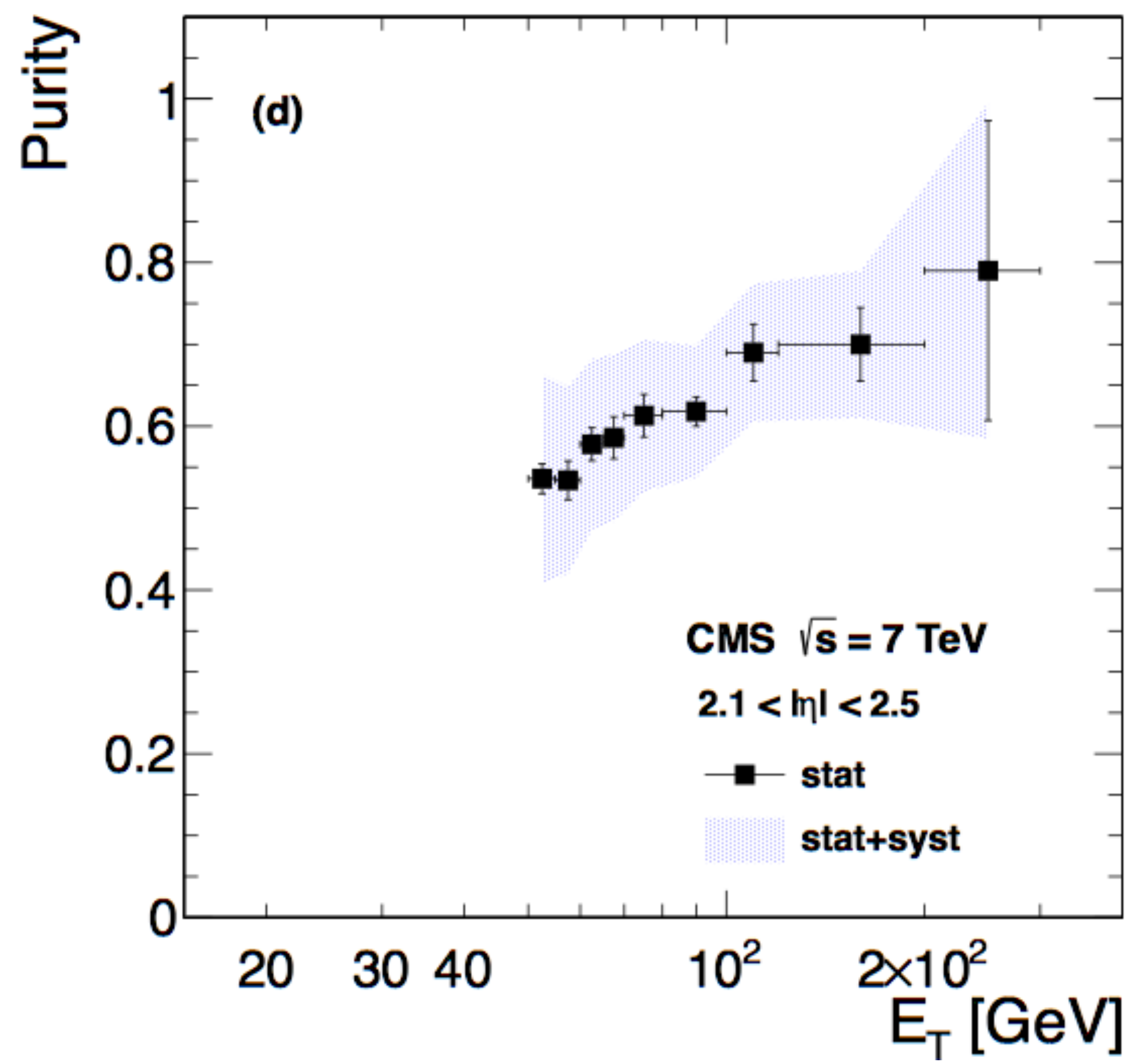
Signal Jet

Control sample from data with photon candidates failing track isolation requirements

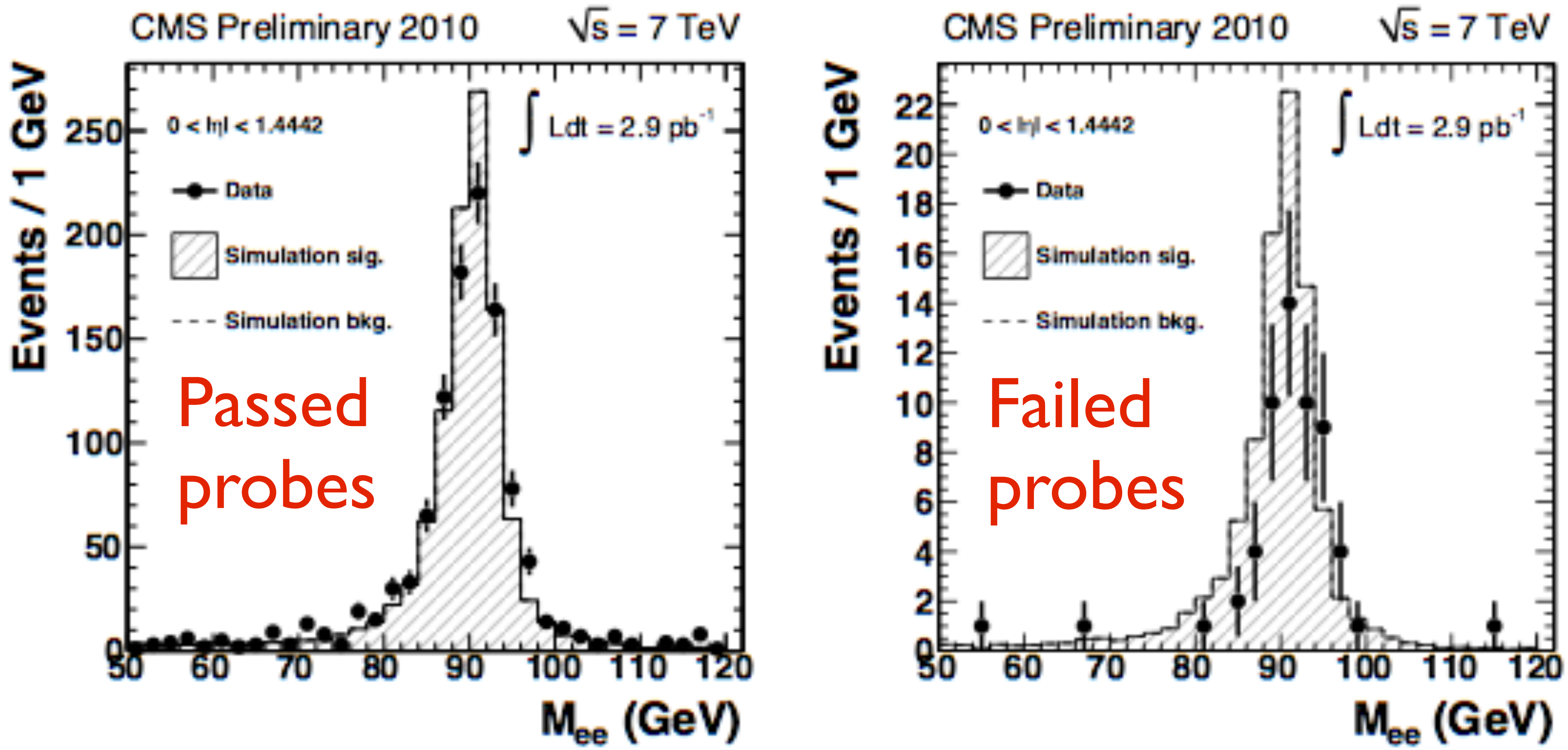
Signal fraction = 38% at 25GeV to 80% at 100GeV

Purity of Photon Candidates





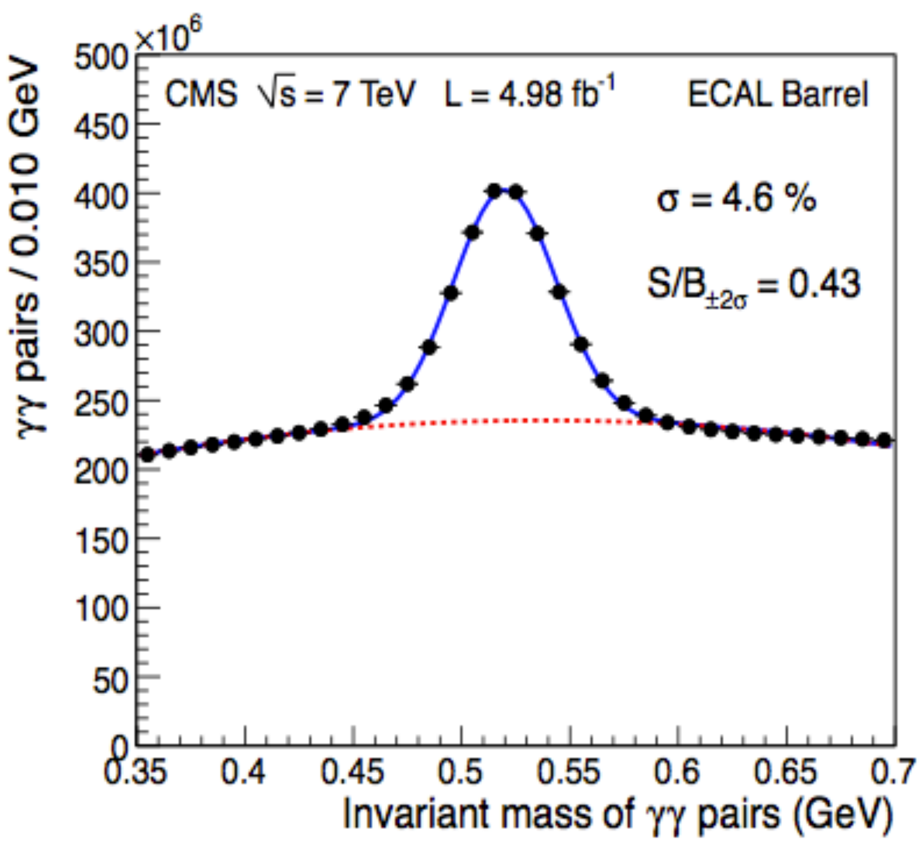
Identification Efficiency

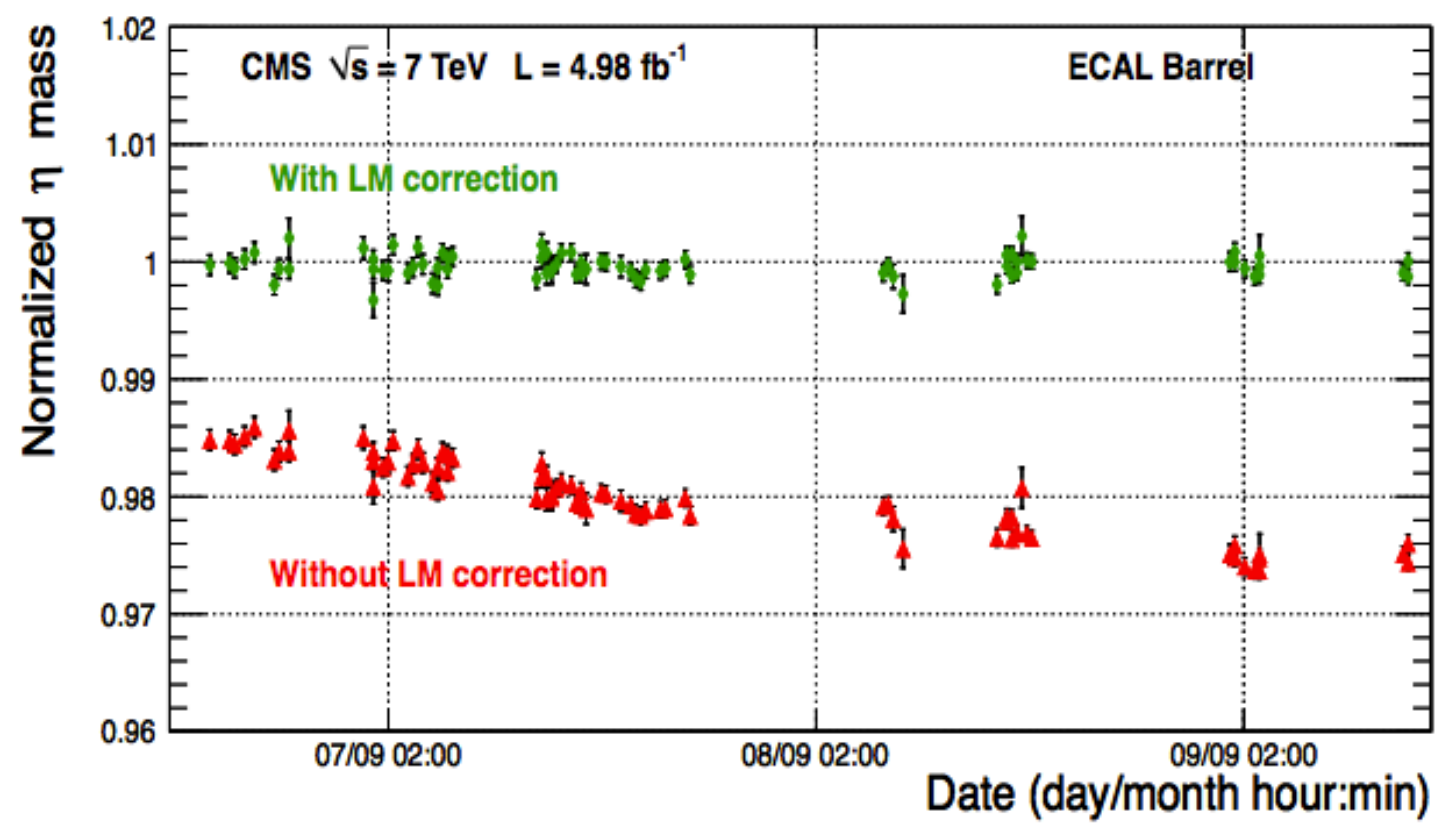


- Obtain data to MC scaling factors from W, Z electrons and photons from $Z \to \mu\mu\gamma$ (CMS no-pixel-seed requirement)
- Efficiency= 0.916 ± 0.034
- Systematic uncertainty from statistics of control samples and difference between electrons and photons

Photon Energy Resolution

- ECAL energy resolution calibrated with π^0, η^0, Z and cross-checked with $Z \to \mu\mu\gamma$
- For photon at p_T=60 GeV, resolution is 1.1-2.6% in barrel and 2.2-5.0% in endcaps





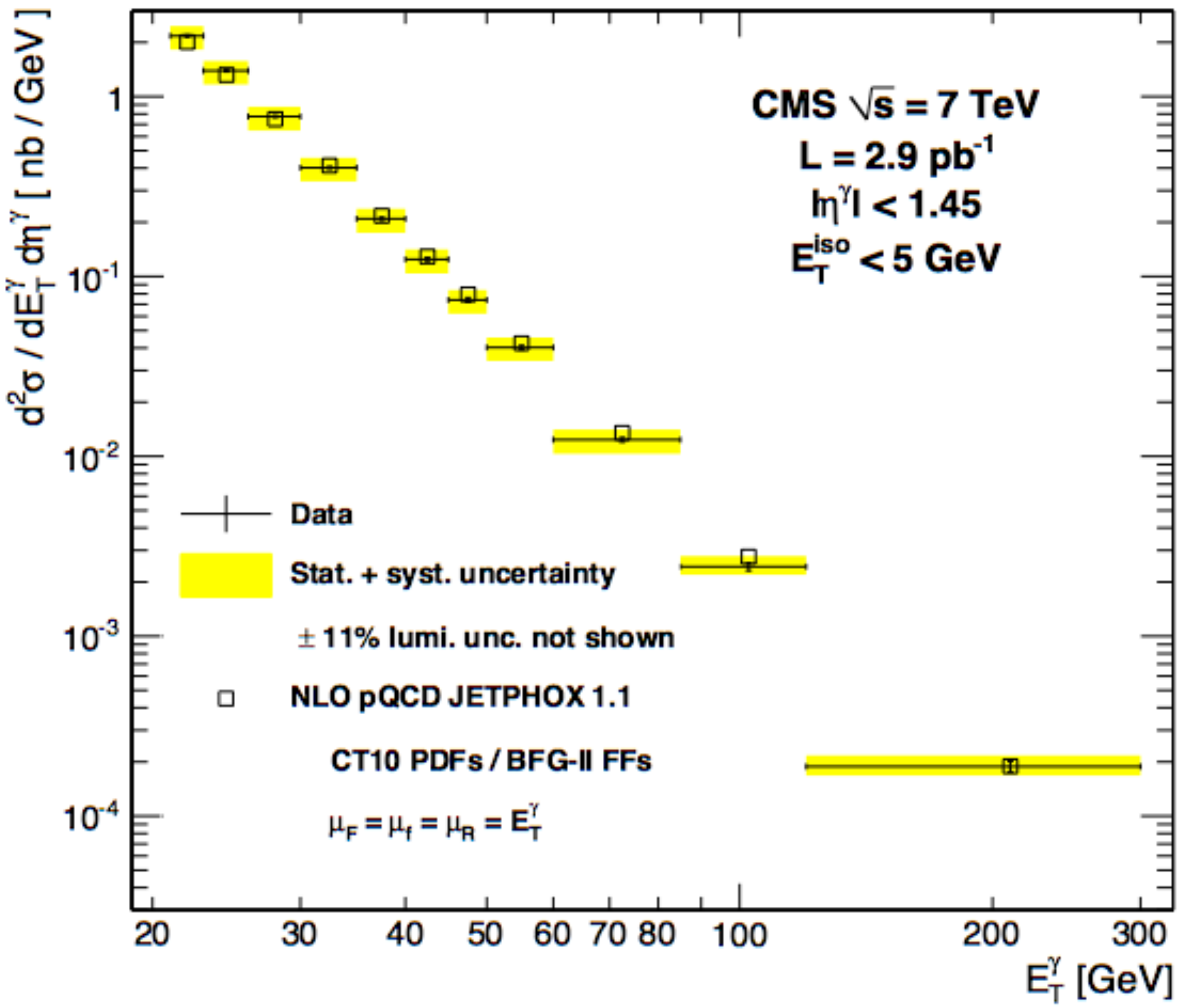
Comparison with Theory

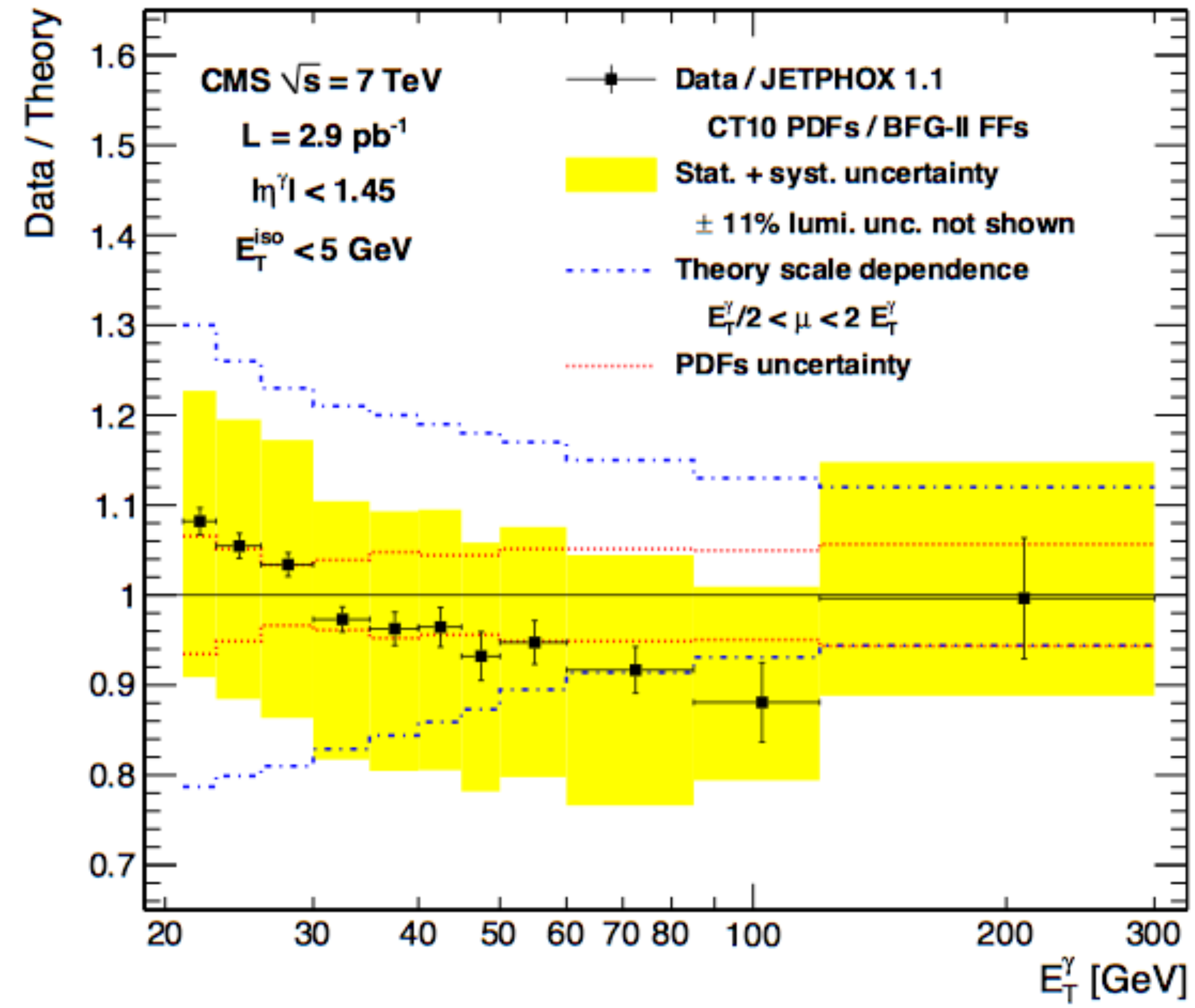
- NLO prediction with JETPHOX

  JHEP 0205:028(2002)

- $\mu_R = \mu_F = \mu_f = E_T(\gamma)$
- PDF: CT10
- Correction of UE and hadronization = 0.97±0.02

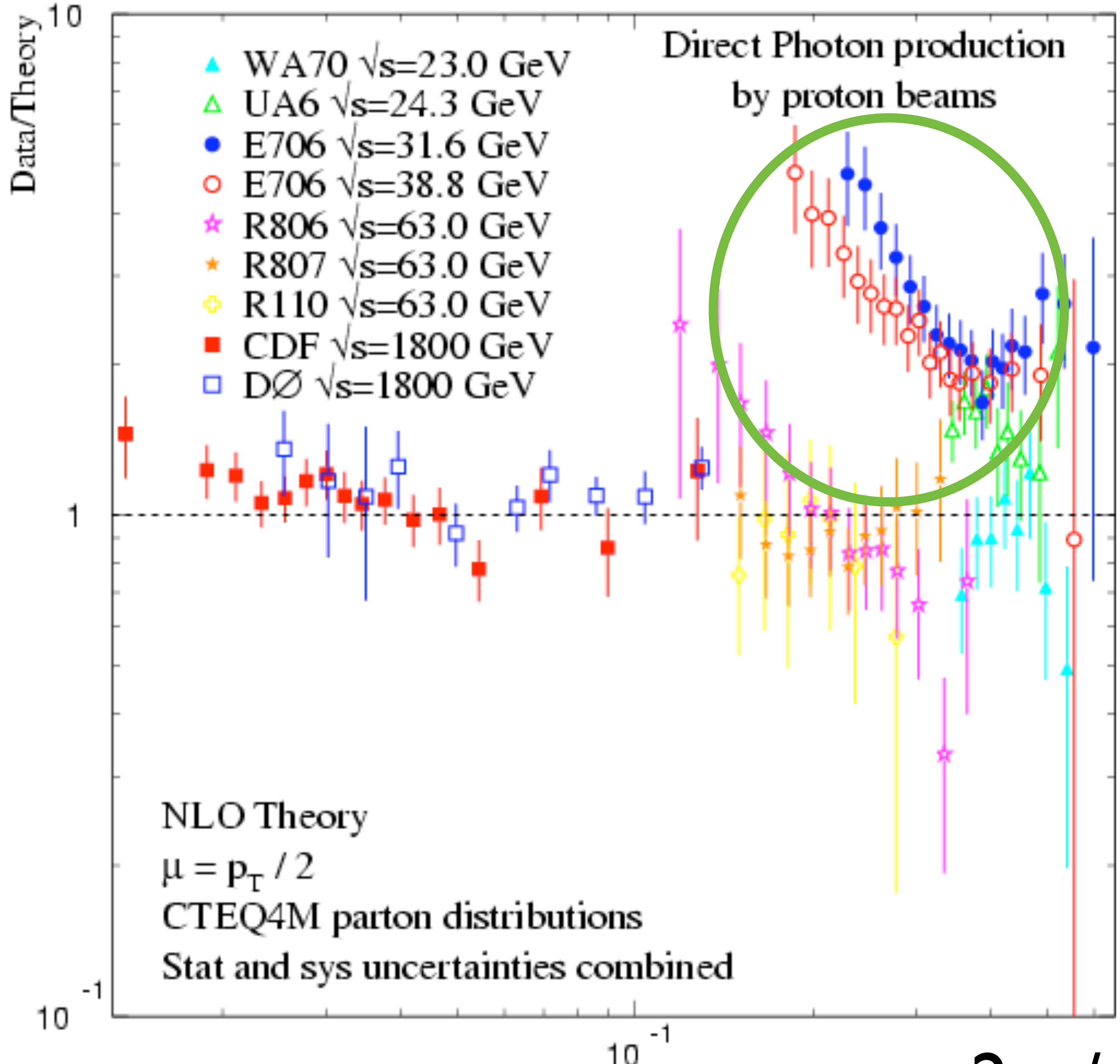
CMS Results





- Use only 10% of 2010 data
- Theory predictions agree with data from 21 to 300 GeV

Previous Photon Cross Sections



$x_T = 2p_T/\sqrt{s}$

People Involved

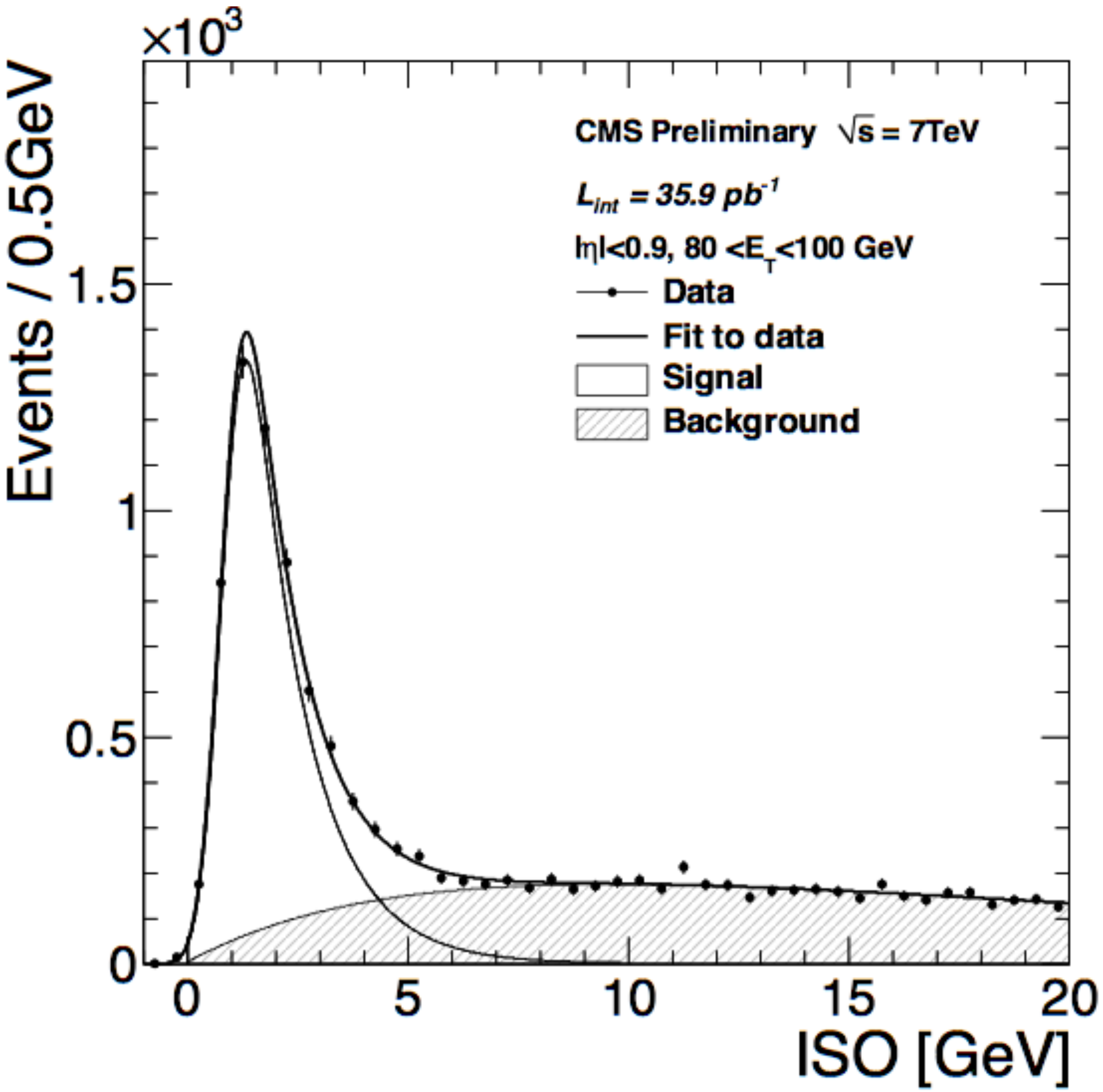
 

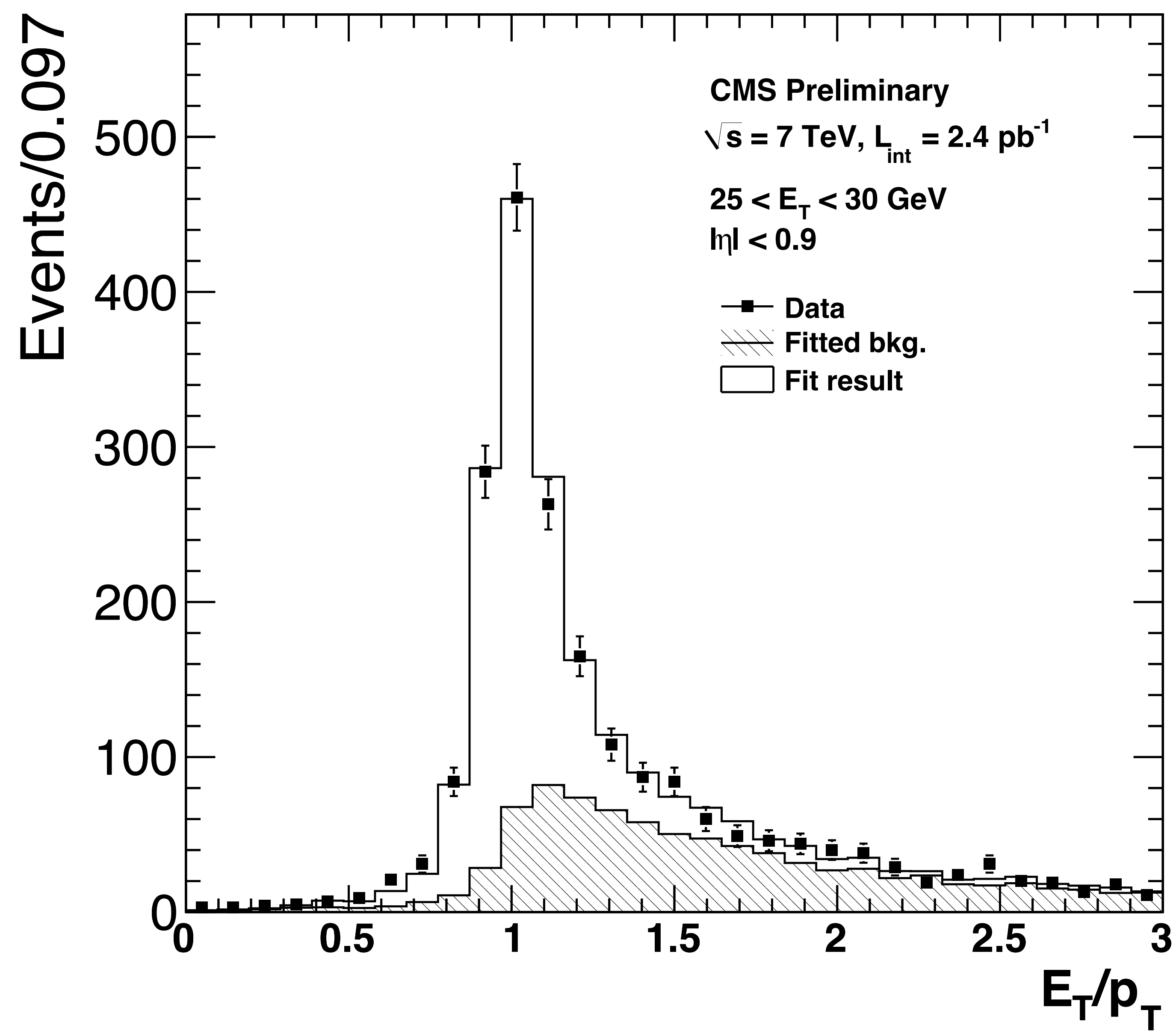
Analysis Contacts

2012 CMS Thesis Award

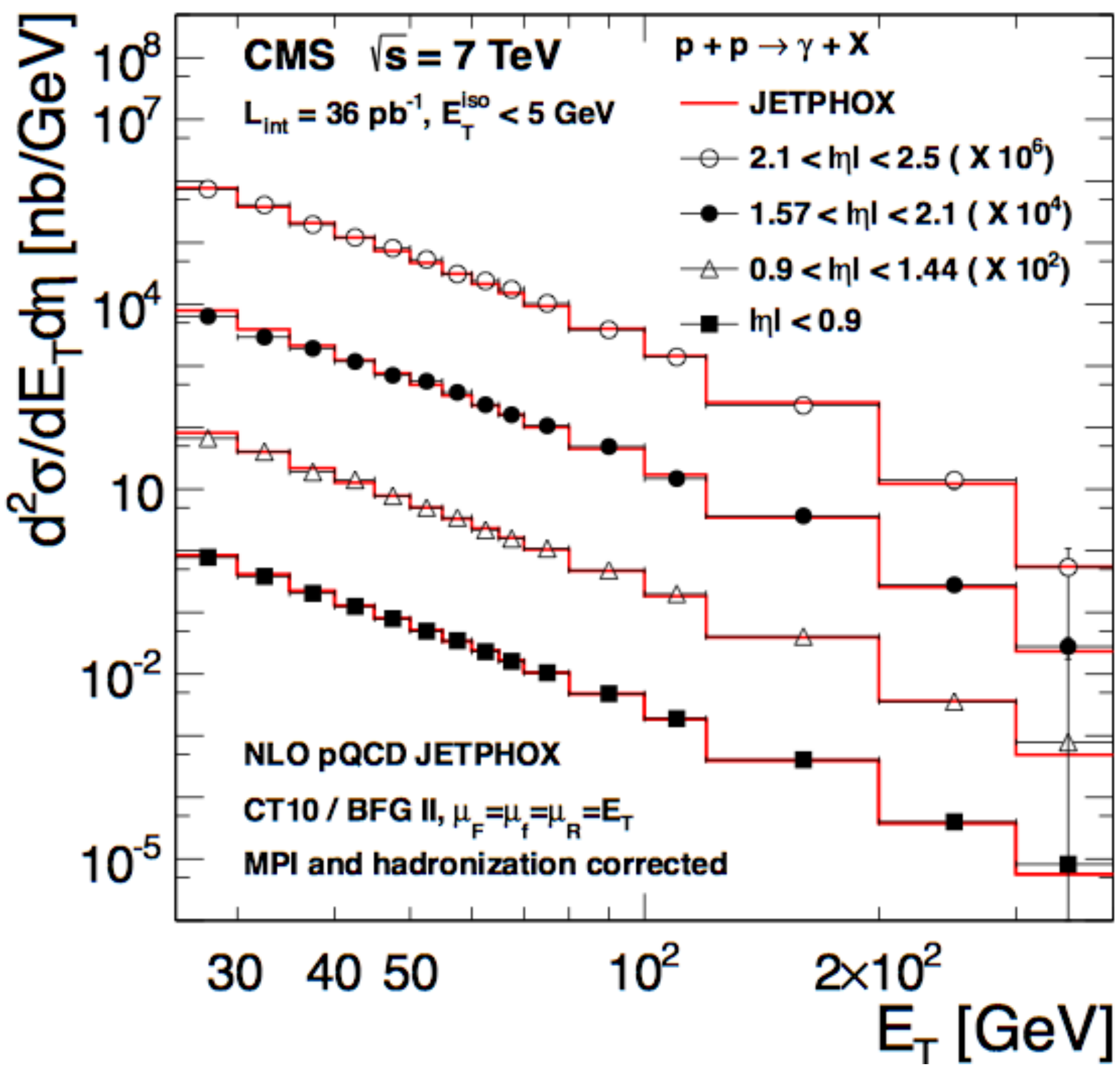
- Analysis contacts: Serguei Ganjour, Shin-Shan Yu
- ~30 active authors
- NCU and NTU group: Yun-Ju Lu, Darko Mekterovic, Rong-Shyang Lu, Chia-Ming Kuo, Syue-Wei Li, Zong-Kai Liu
- Institutions: NCU, NTU, Lisbon, CEA-Saclay, UCSD, MIT, Notre Dame, Wisconsin, Delhi, Fermilab, Virginia

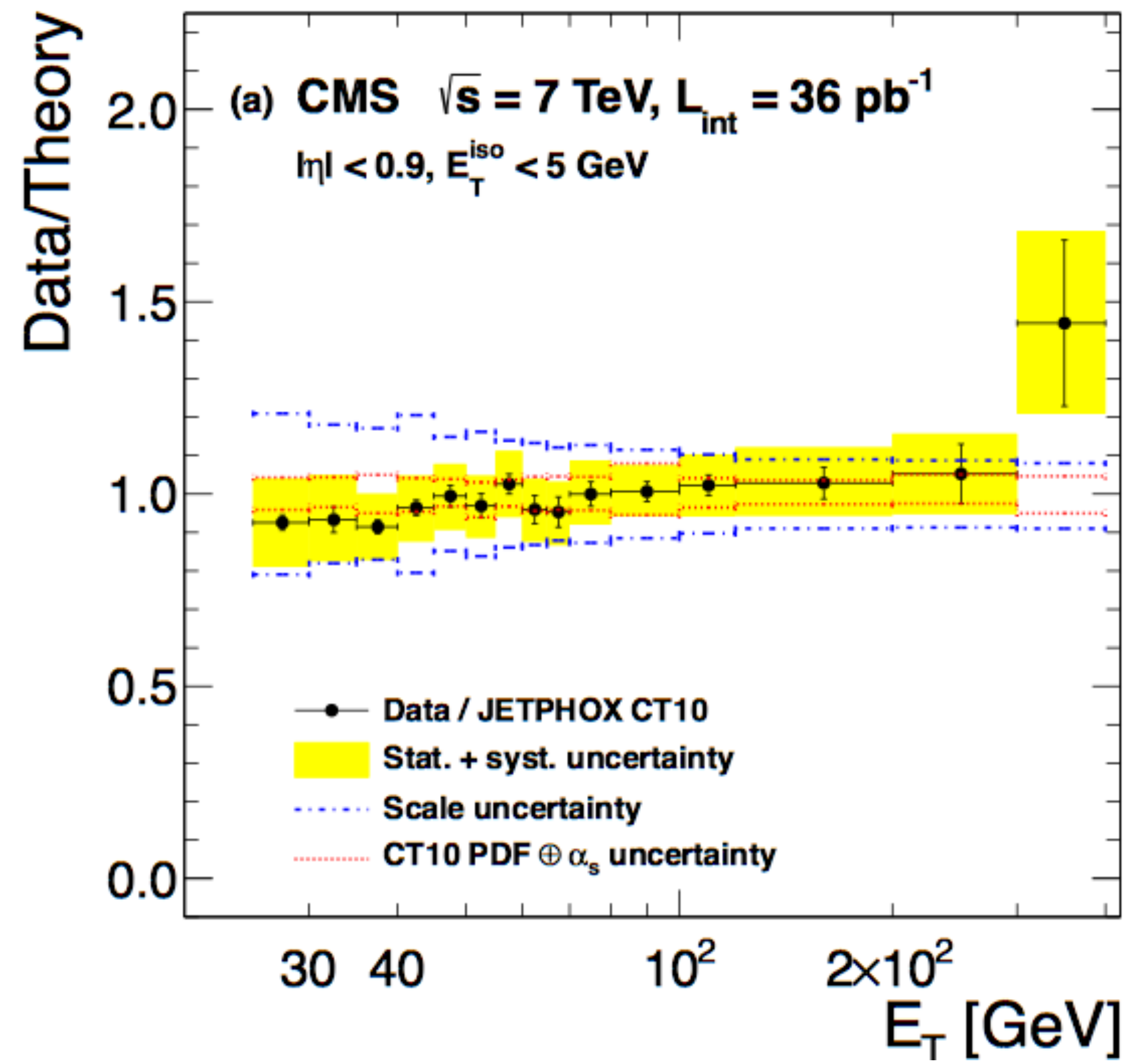
Isolation and Converted Photons





Results with Full 2010 Data





- Data are presented in four regions of η
- Predictions agree with data over 6 orders of magnitude