Measurement of the Inclusive Isolated Prompt Photon Cross Section at CDF

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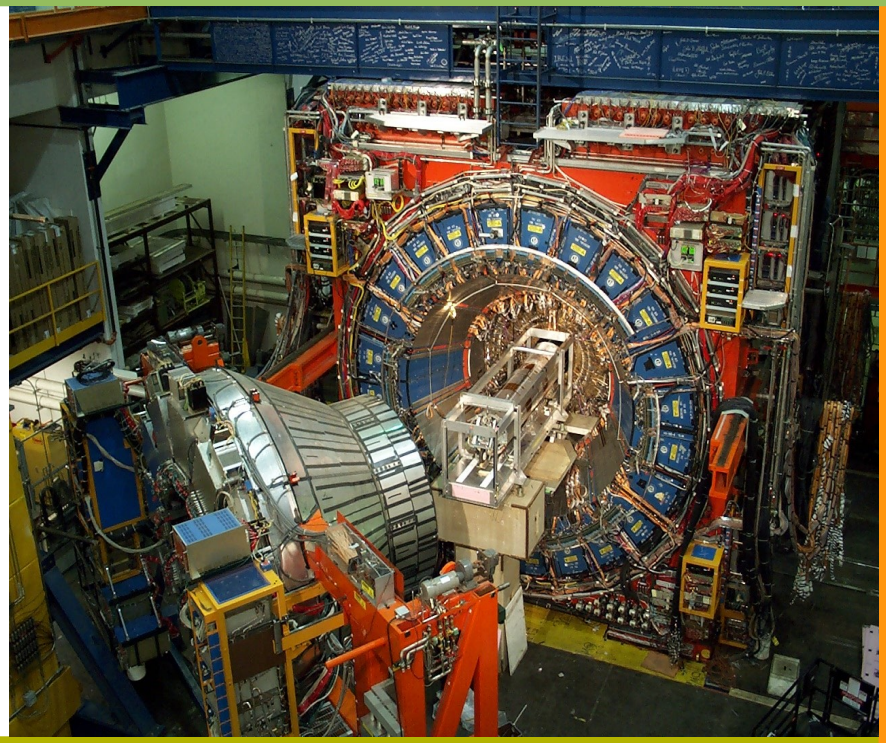
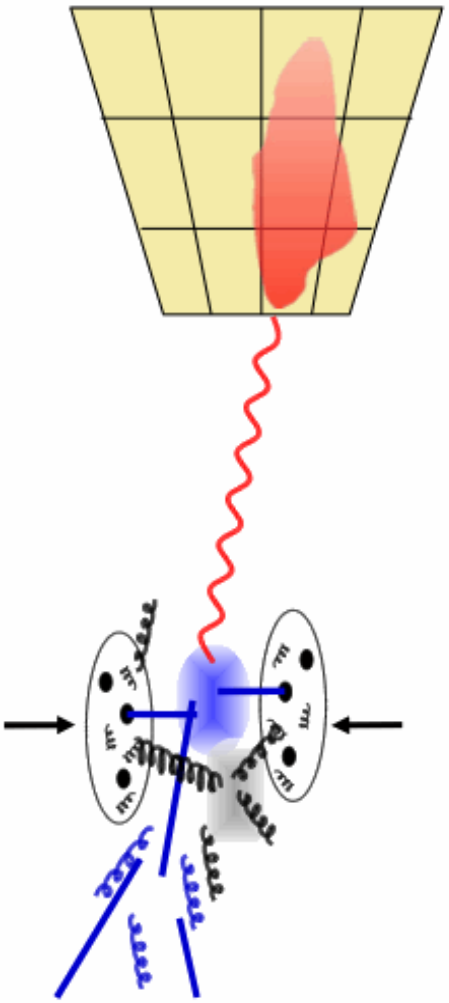


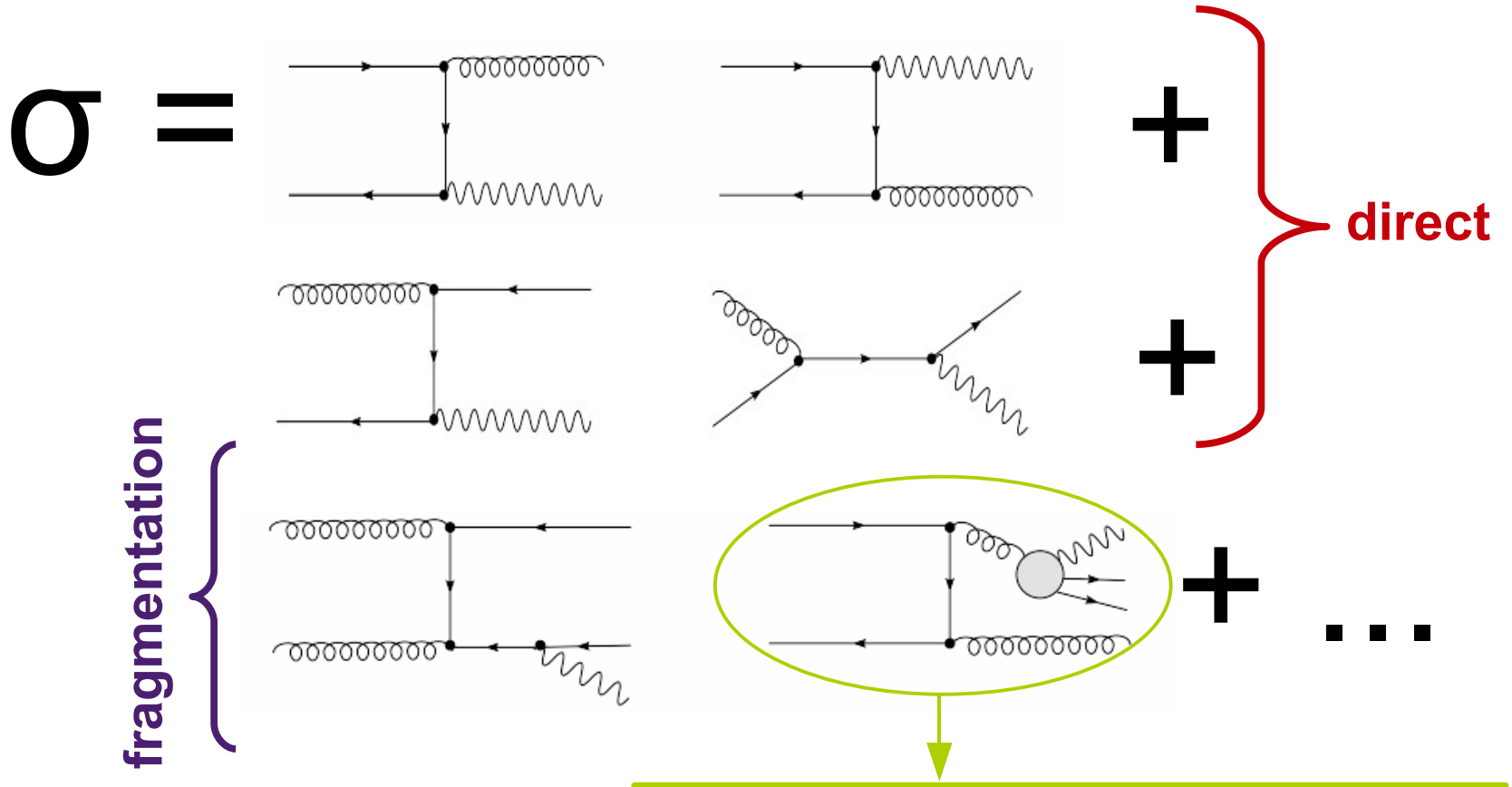
Outline



- **Theoretical introduction**
  - Prompt photon production
  - Motivation
- **The Experiment**
  - The Tevatron
  - CDF
- **The Measurement**
  - Photon detection
  - Photon purity
  - Unfolding factors
  - Systematic uncertainties
- **Theory prediction**
  - The pQCD NLO prediction
  - Non-perturbative effects
- **Results**
  - The cross section result
  - Comparison to theory
- **Summary**

Prompt Photon Production

Prompt photons are produced directly in the hard scattering or from the fragmentation of a parton into a photon



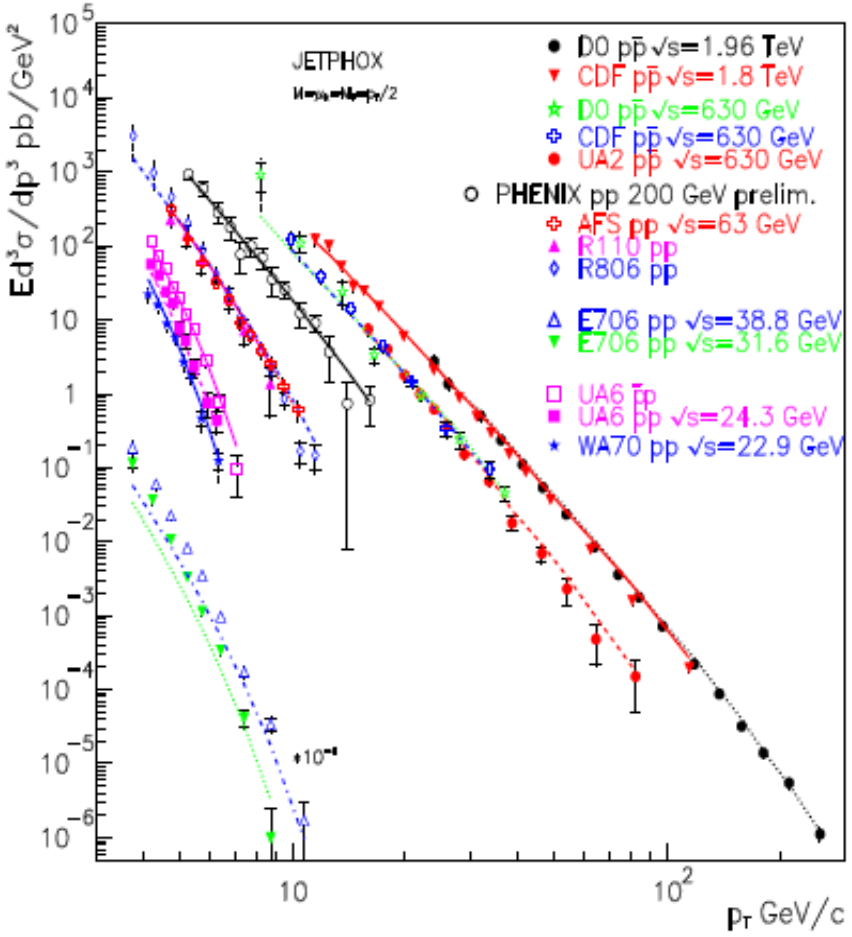
When the fragmentation process is soft, this component is given by the pure QCD cross section convoluted with a fragmentation function → **new scale in the calculations**

Motivation

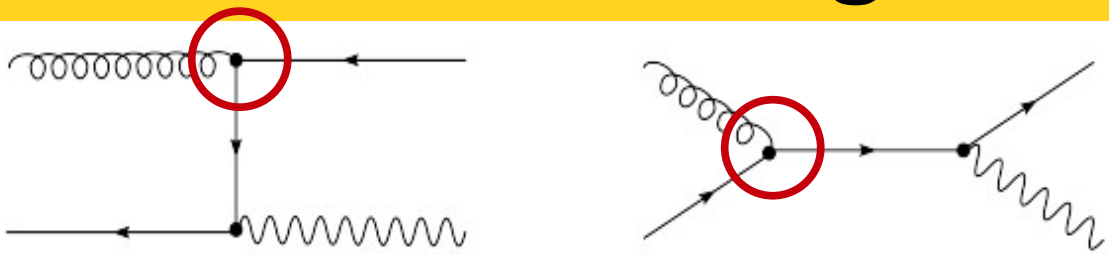
- **Test pQCD predictions over several orders of magnitude**
- Constrain the **gluon PDF**

- **Advantages over pure QCD**
  - ★ **Point-like coupling** of quarks and photons
  - ★ **No need of algorithms** to define photons
  - ★ **Better energy resolution** (EM calorimeters)

- **Irreducible background** for SM and BSM searches
  - H →γγ, graviton
- **Probe photon tools** over a wide energy range

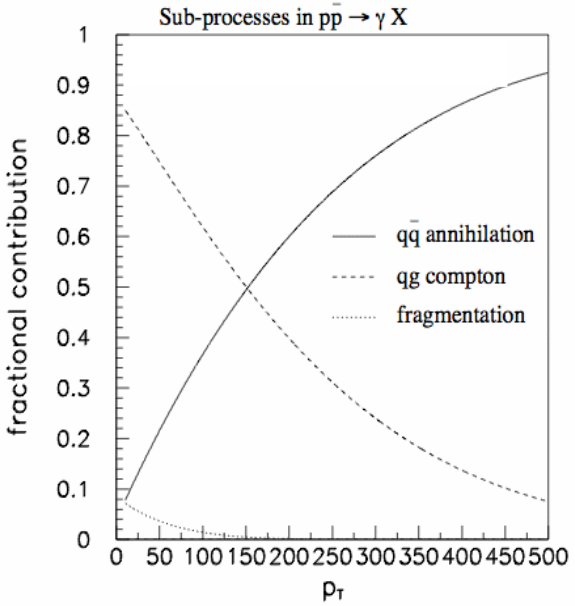


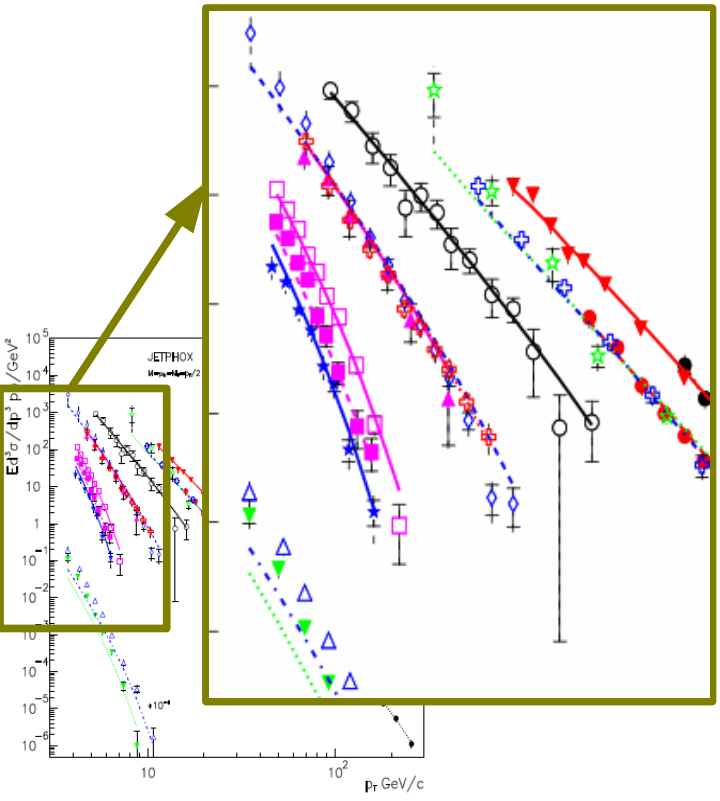
Motivation: the gluon PDF



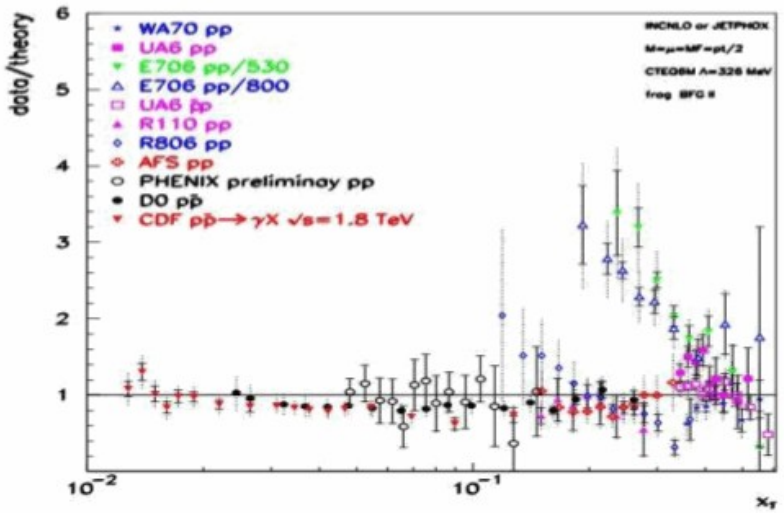
- **Since 1998 no photon data is included in the PDF fits**
  - Different shapes at low p_T and x_T~0.1-0.3
- Introduction of **k_T enhancement** to account for **soft gluon emission** effects

Dominate the cross section up to ~150 GeV/c
→ Constrain gluon PDF





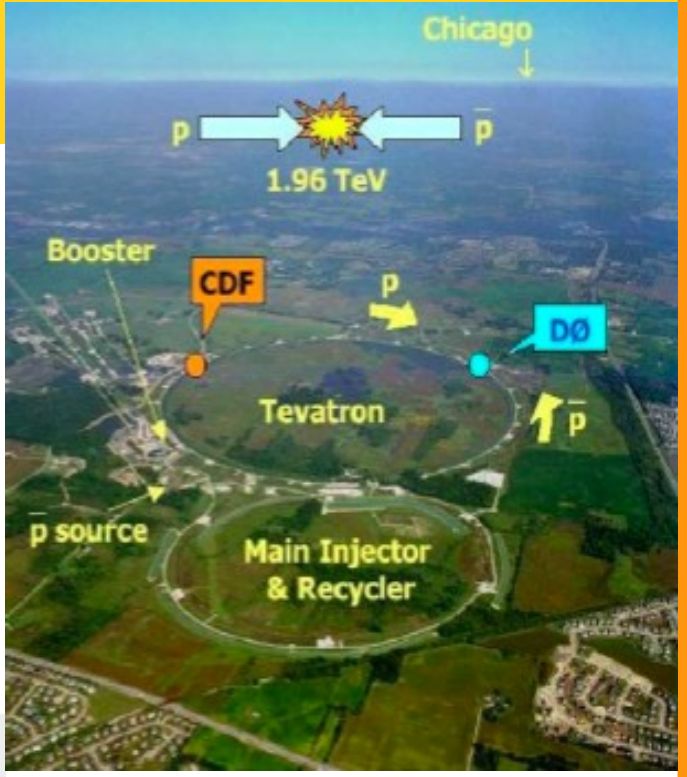
Need more confirmation from data and additional understanding

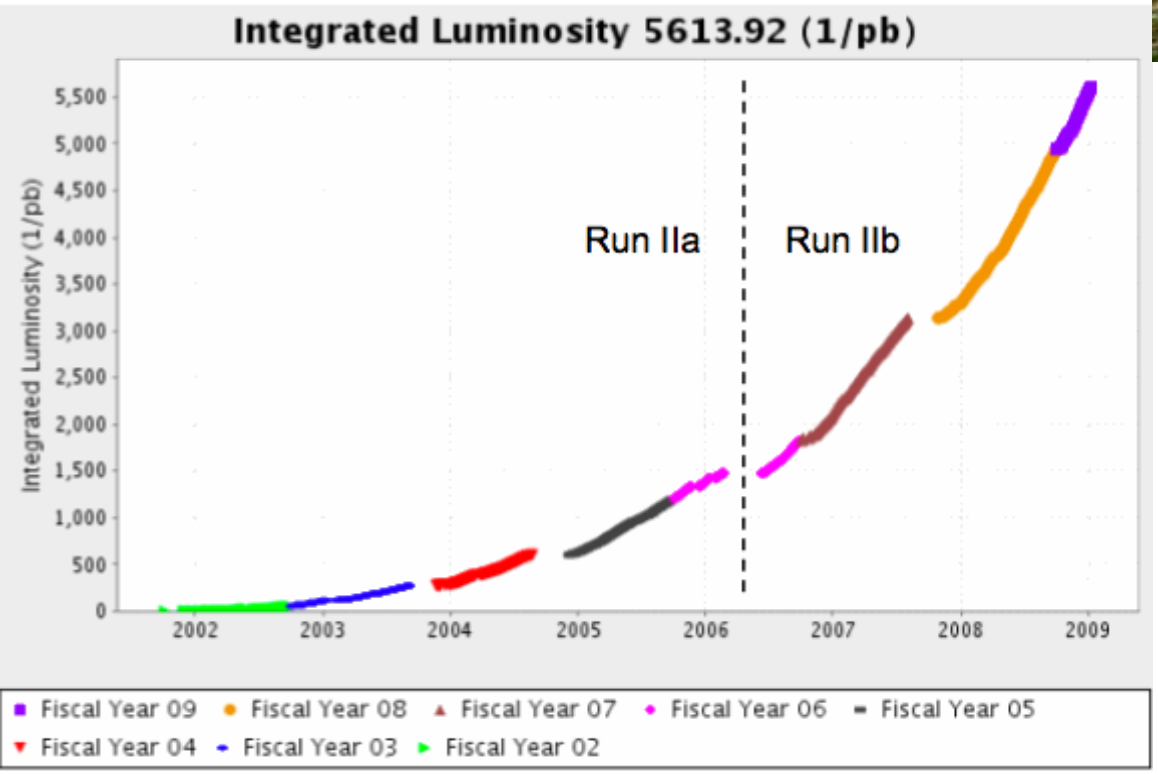


Tevatron Accelerator

- Superconducting **proton-antiproton collider at $\sqrt{s}$ = 1.96 TeV** located at Fermilab (Illinois, USA)

- Beams collide in 36x36 bunches every 396ns

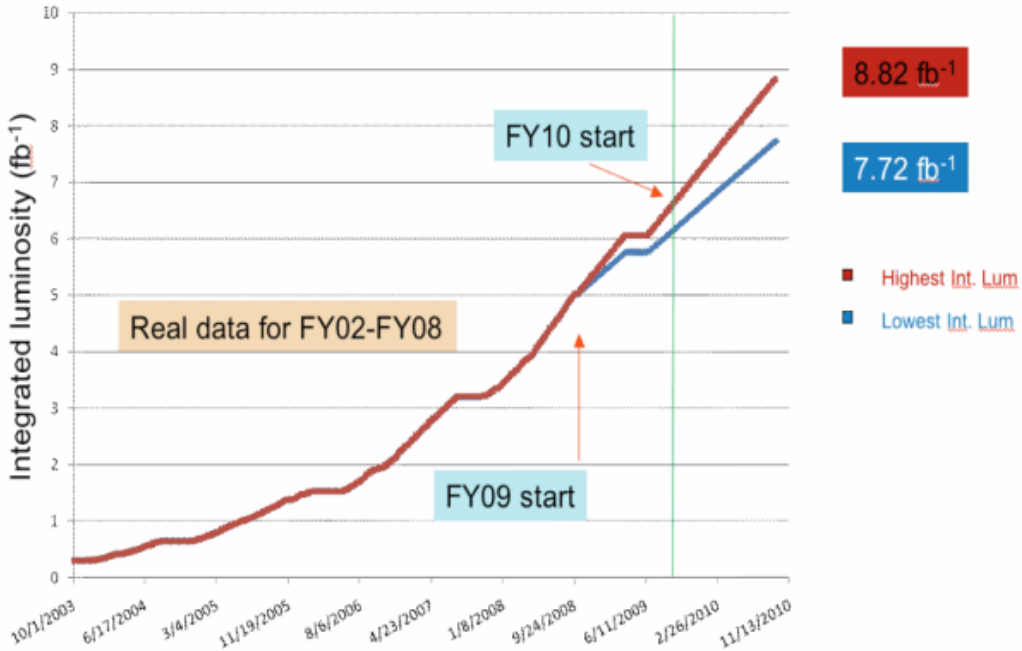


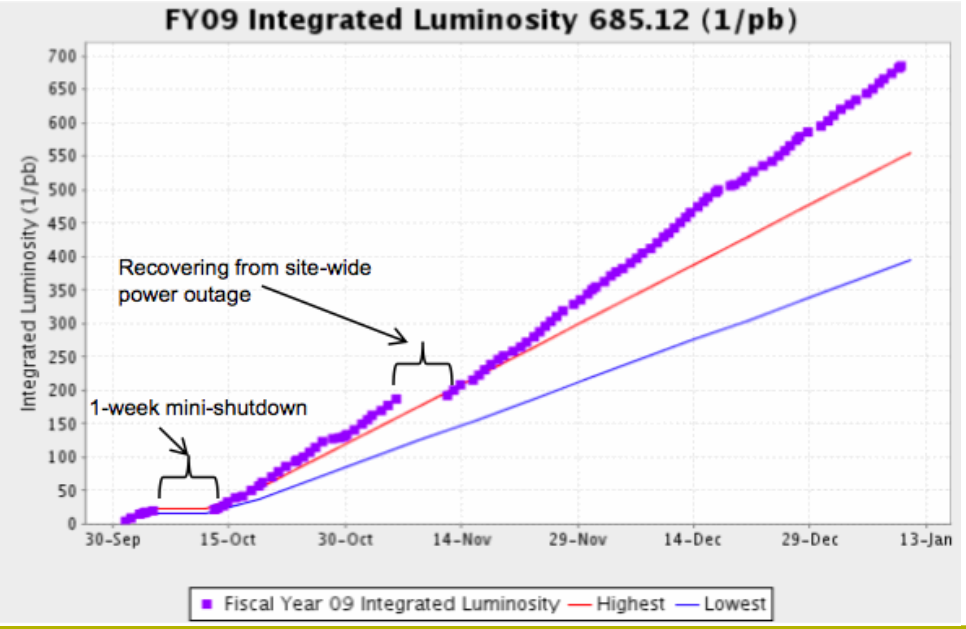


In the Run II the Tevatron has delivered more than 5.5 fb^{-1} of data

Tevatron Accelerator

- **Excellent performance:**
  - Typical instantaneous luminosity > $3.0 \times 10^{32} cm^{2} s^{-1}$
  - Record inst. lum. $3.6 \times 10^{32} cm^{2} s^{-1}$
  - Delivered ~ 5.6 fb^{-1}

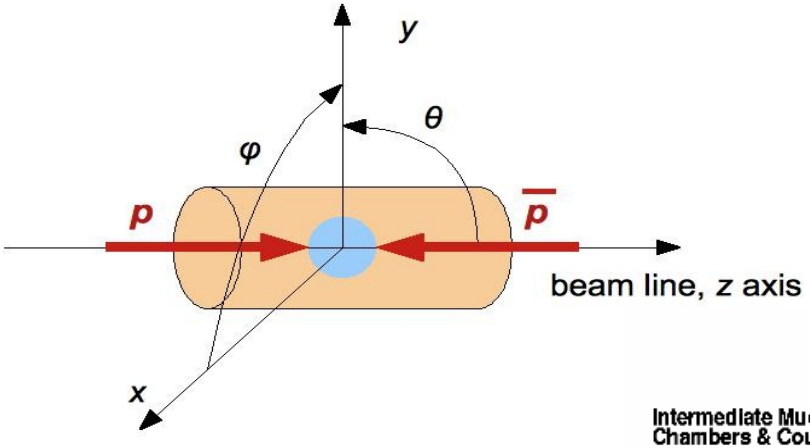




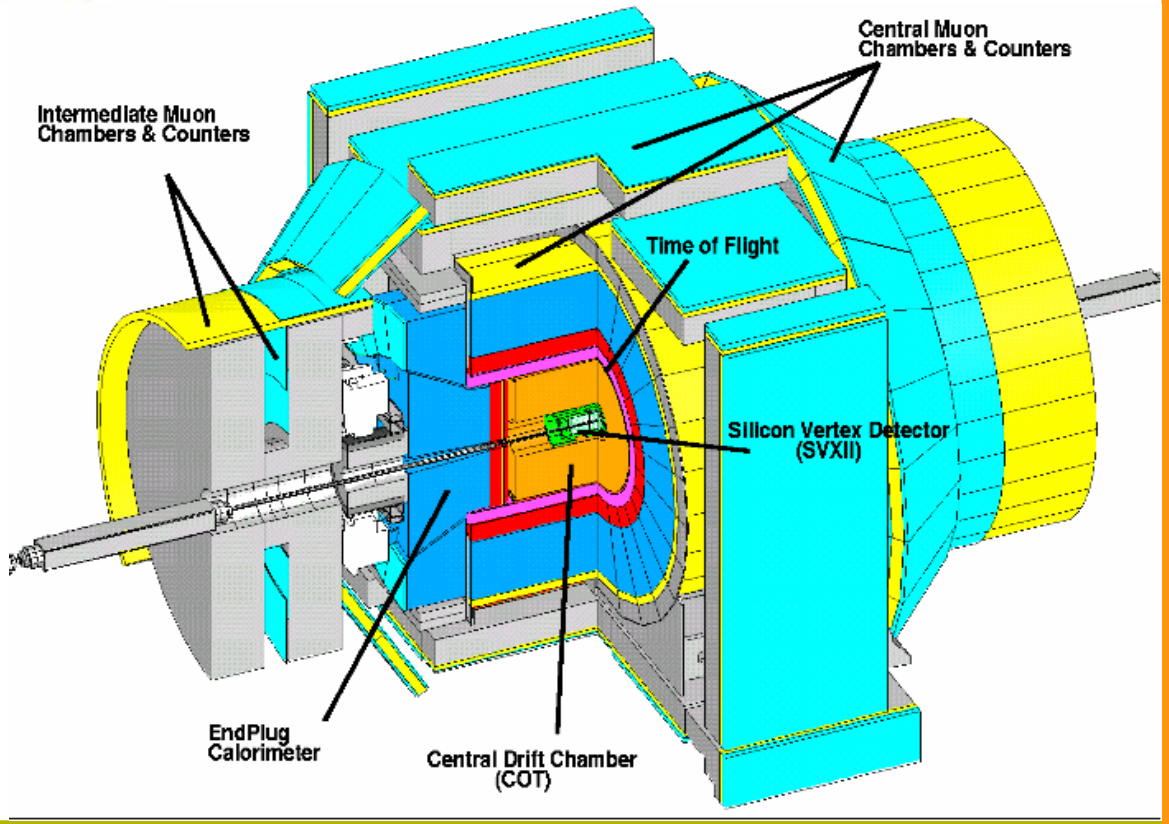
Project ~ 7.7 – 8.8 fb^{-1} by the end of FY10...
.... but
in the end of FY08 and the beginning of FY09 better slope than the "Highest Lum" projection!

The CDF detector

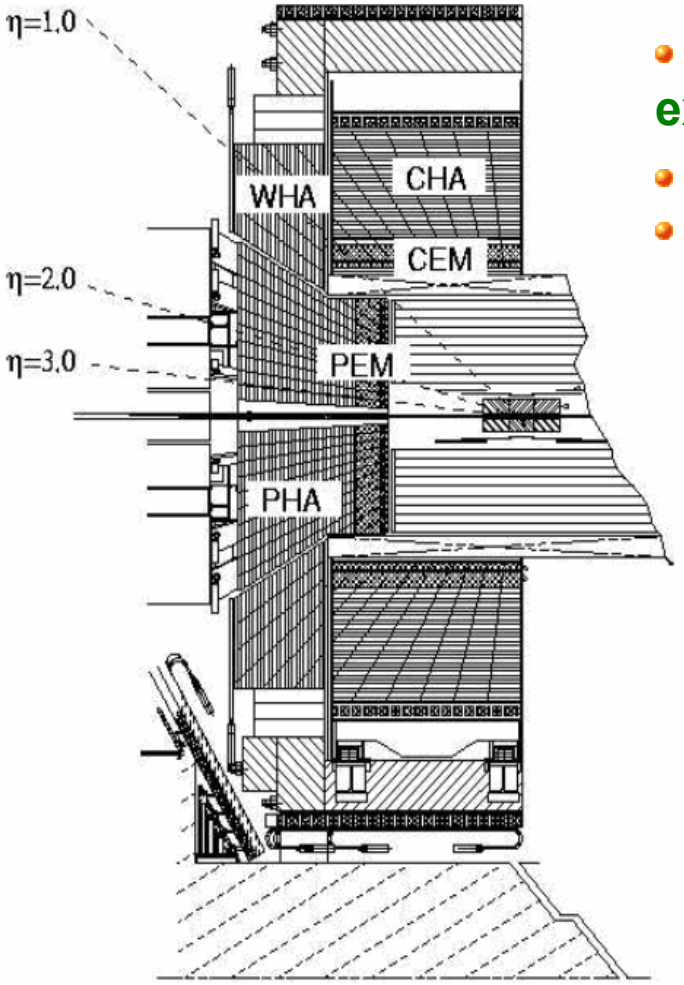
- CDF is a multipurpose particle detector
- Cylindrical, constructed as an onion around the nominal interaction point



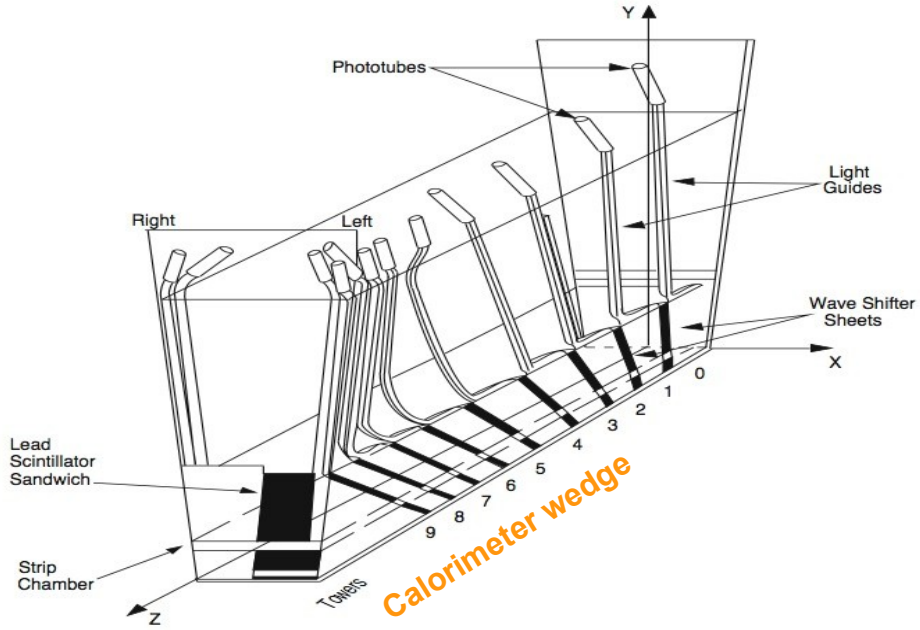
Silicon Vertex detector (L00, SVXII, ISL)
Central Drift Chamber (COT)
SC solenoid (B=14T)
Calorimeters
(central: CEM, CHA, WHA)
(forward: PEM, PHA)
Muon chambers



The Central EM Calorimeter



- The CEM calorimeter covers |η|<1.1 and extends up to 18X_0
- Projective tower geometry
- Scintillator tiles with lead as sampling material



- Strip-wire chamber (CES) at the shower max position provides precise shower shape and position measurements
- The CES is used for photon ID and selection
- Resolution for 50 GeV electron ~2 mm

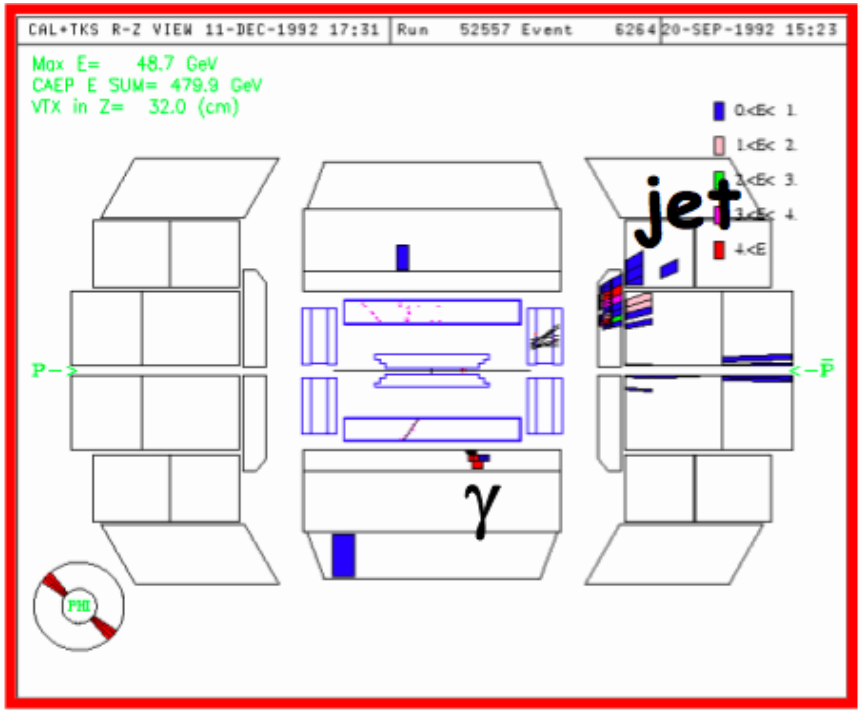
Samples

- **INCLUSIVE PHOTON DATA**
  - **Triggers get the interesting events from the large number of p-pbar collisions**
  - **Photon trigger requirements:**
    - Central EM cluster with $p_T^{\gamma} > p_T^{THRES}$ and small HAD depositions
    - Only low p_T:

      Isolation < $0.10 p_T$, CES χ^2<20
  - **TRIGGERS:**

    $30 < p_T < 90$ GeV/c: ISOLATED,

    $p_T > 90$ GeV/c: NON ISOLATED



OTHER DATA SAMPLES

Electron data: photon energy scale, trigger efficiencies, systematics

Jet data: trigger efficiencies

MONTE CARLO SAMPLES

Inclusive photon: photon purity, ID efficiencies, unfolding factors

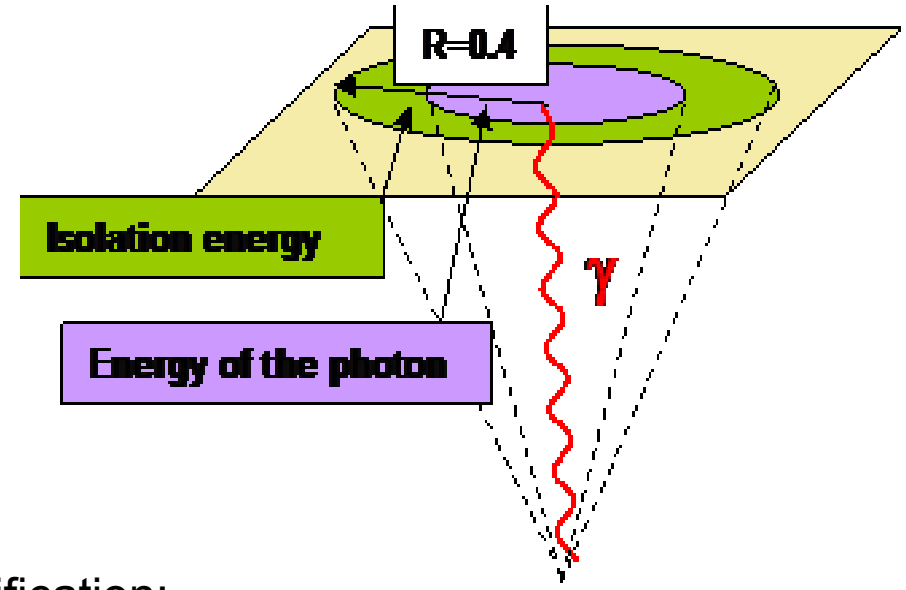
Dijet: photon purity

Electron: photon energy scale, systematics

Event Selection

- Only fully operational calorimeter and tracker runs
- **Trigger required for all candidates (trigger simulation for MC)**
- **Photons must be central ($|\eta|<1.0$), with $p_T>30$ GeV/c and calorimeter isolation < 2 GeV**

$$\text{Isolation } E_T = E_T^{(R=0.4)} - E_T^{\gamma}$$



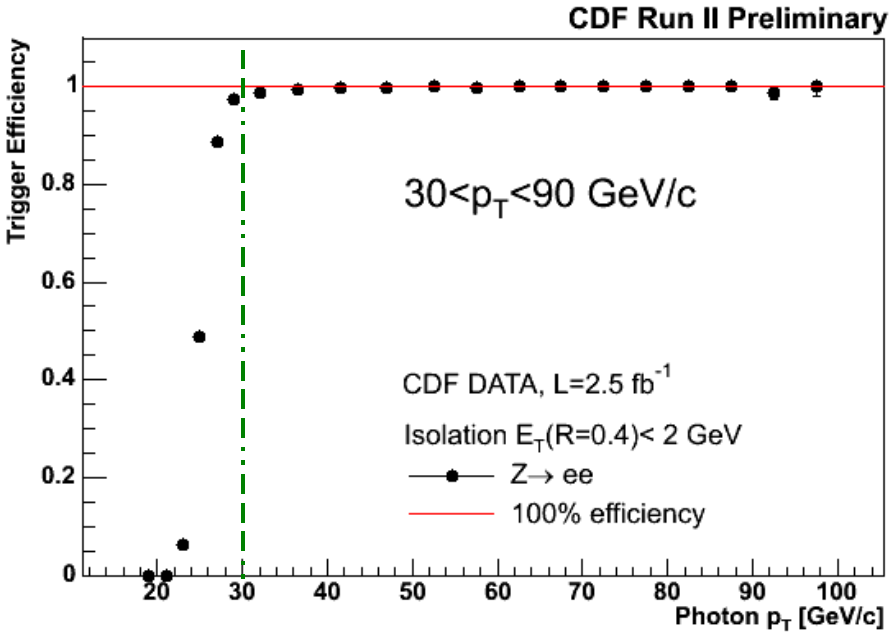
- **Other cuts** for standard photon identification:
  - Fiducial cuts, good EM shower, small HAD/EM, no high p_T tracks associated
  - **ONLY for low p_T:** Shower shape compatible with that expected for a single particle shower (extracted from electrons in a test beam): agreement quantified with a χ^2 (CES χ^2)

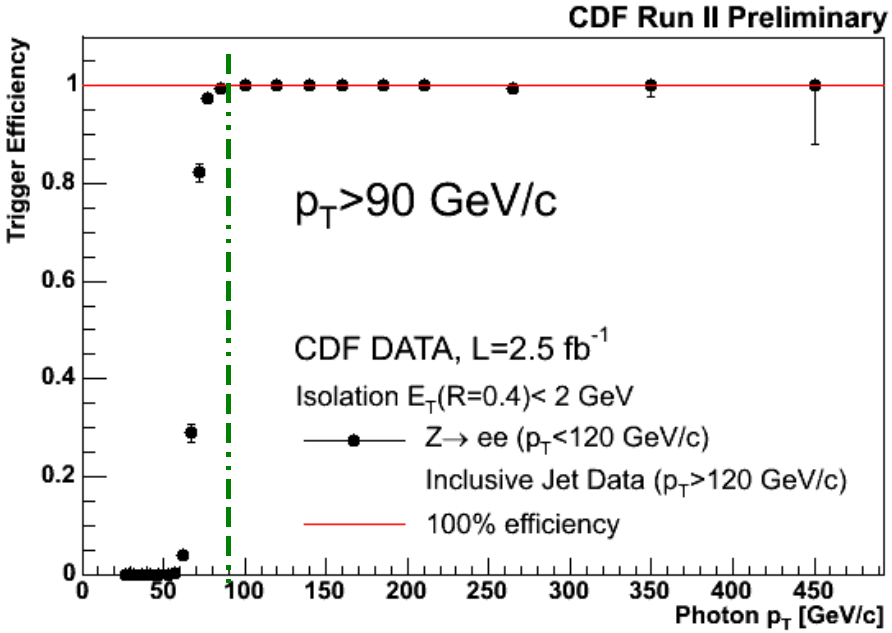
Trigger efficiency

- Measured w.r.t. the offline cuts using data samples:
  - Electrons from $Z \rightarrow ee$ decays for $p_T < 120$ GeV/c
  - Inc. jet for $p_T > 120$ GeV/c

$$\varepsilon_{trig} = \frac{N_{photons+trig}}{N_{photons}}$$

The trigger is > 99% efficient in the whole measured range



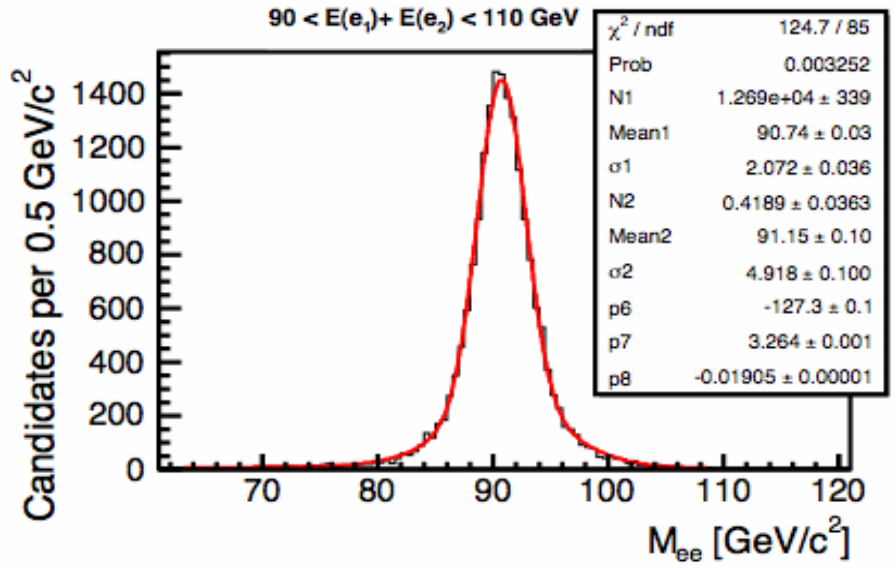


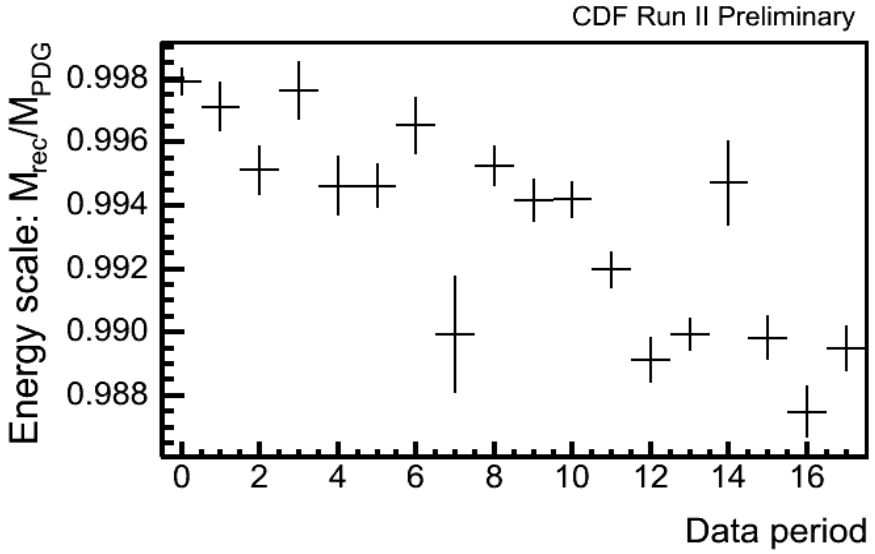
Photon energy scale

- Photon energy scale corrected back to generator level with the **Z mass scale in both data and MC**
- Z mass from electrons in $Z \rightarrow ee$ decays in data and run-dependent MC

$$E^{scale} = M_z^{rec} / M_Z^{PDG}$$

- **Correction in the data is run-dependent and increases with luminosity (mean ~ 0.994)**
- **In MC, constant at ~ 1.0035**



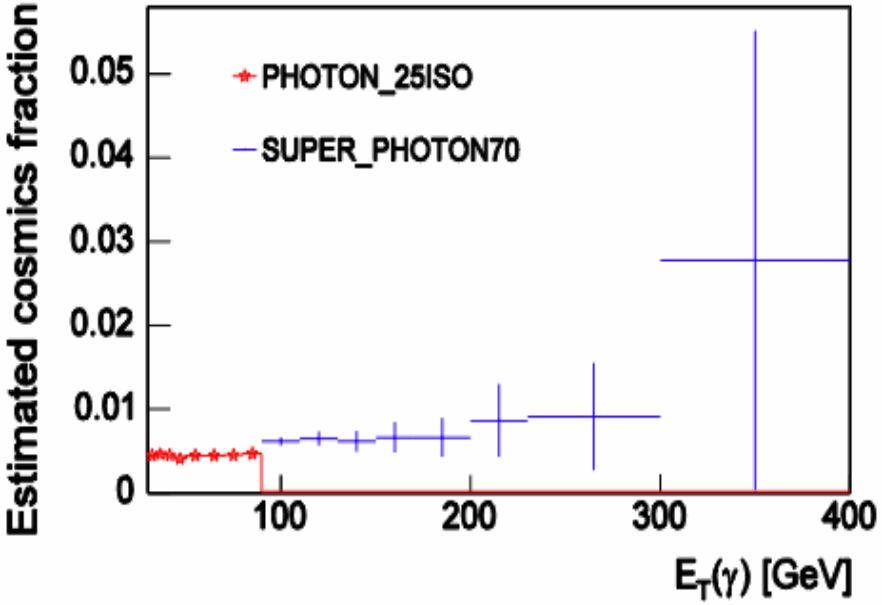


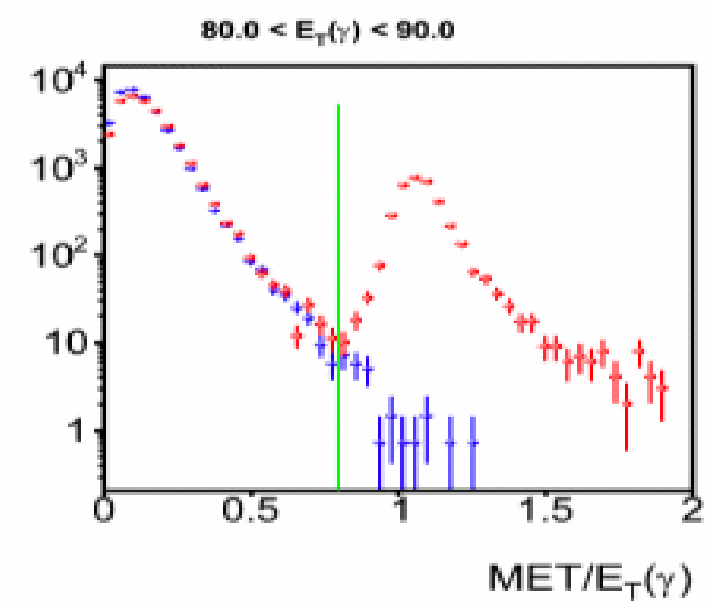
Cosmics background

- Cosmic rays may interact with the detector material and produce **bremsstrahlung photons**

- These photons are in most cases isolated, but their energy is not compensated by the rest of the event, producing **large missing transverse energy *(MET)***

Cosmic background is rejected with $MET/E_T^{\gamma}<0.8$

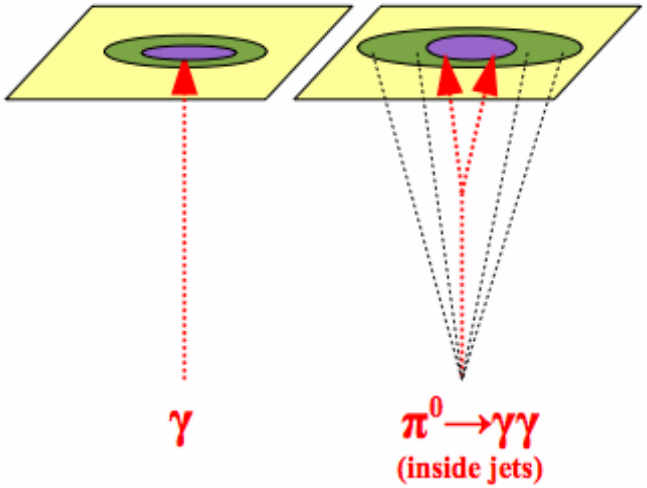


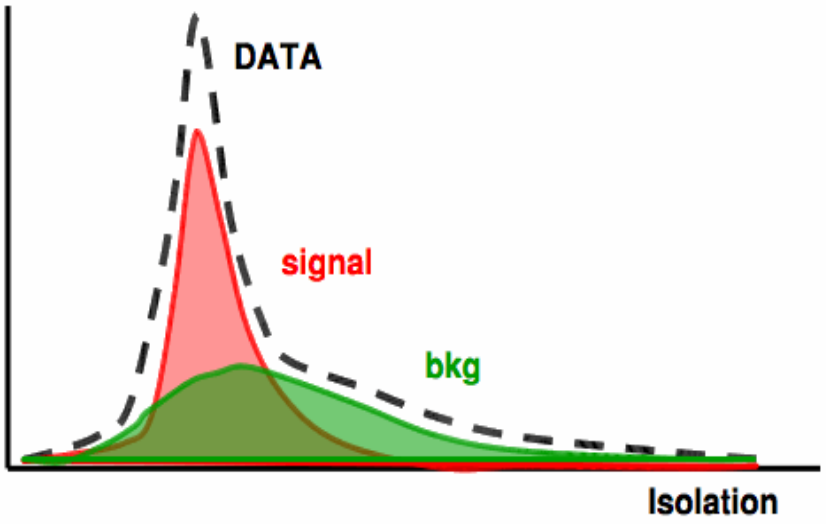


After this cut, remaining cosmic fraction is < 1%

Meson background

- **Main source of background are photons from light meson decays (mainly π^0's)**
- Large energy depositions around → rejected with the isolation cut
- **Remaining isolated component is removed with statistical techniques**



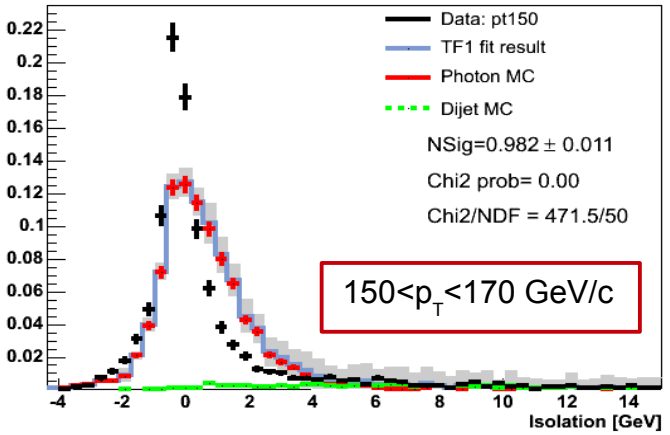


- **Signal fraction extraction:**
  Fit the calorimeter isolation in the data to signal and background templates

  Signal: Inclusive photon MC
  Bkg: photons from meson decays in dijet MC

Isolation in data and MC

- Signal MC template does not reproduce the peak in data at high p_T
- This discrepancy has been investigated
- **In the signal, most of the isolation energy comes from the underlying event and from the photon shower itself**



REGION 1 n=1 Small |x| **UE**	**REGION 2** n>1 Small |x| **PILE-UP**
	REGION 3 n=1 Large |x| **LEAKAGE**

- **Corrections to the measured isolation:**
  - Pile-up (n vertex dependent)
  - Shower leakage (energy and shower |x|-position dependent)

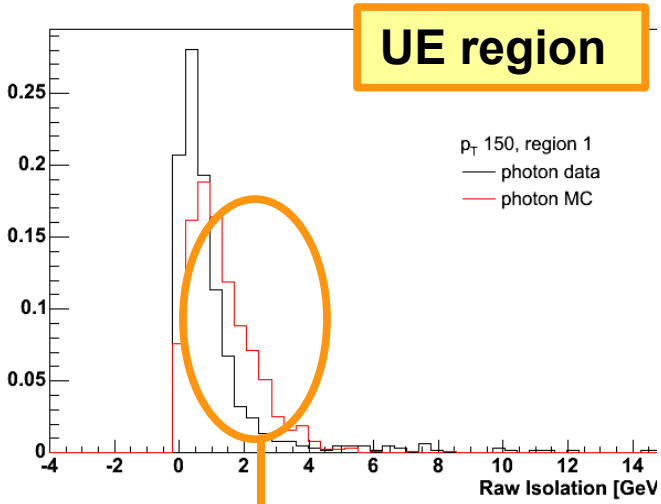
Study of Raw, Leakage and fully corrected isolation distributions

Different regions of the (n,|x|) space have different sensitivity to each contribution

Isolation in data and MC

Different isolation levels in the various (n,|x|) regions for 150<p_T<170 GeV/c

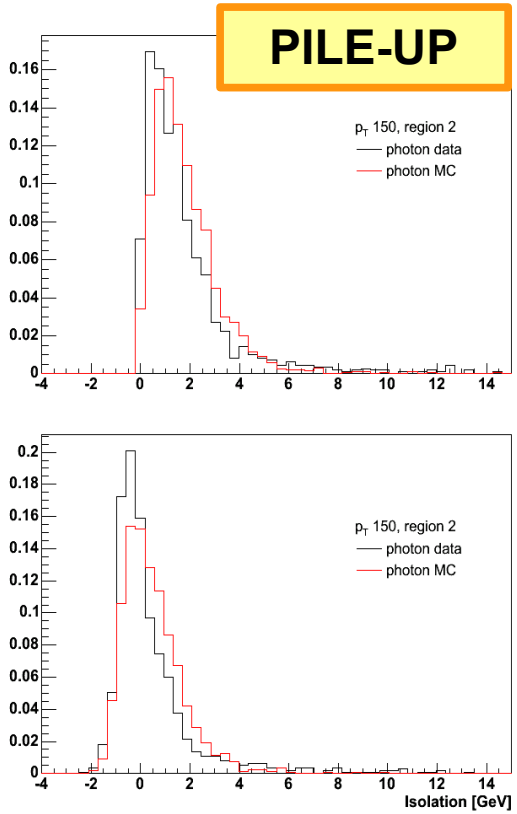
UE region



Already at RAW level the MC isolation is wider and shifted

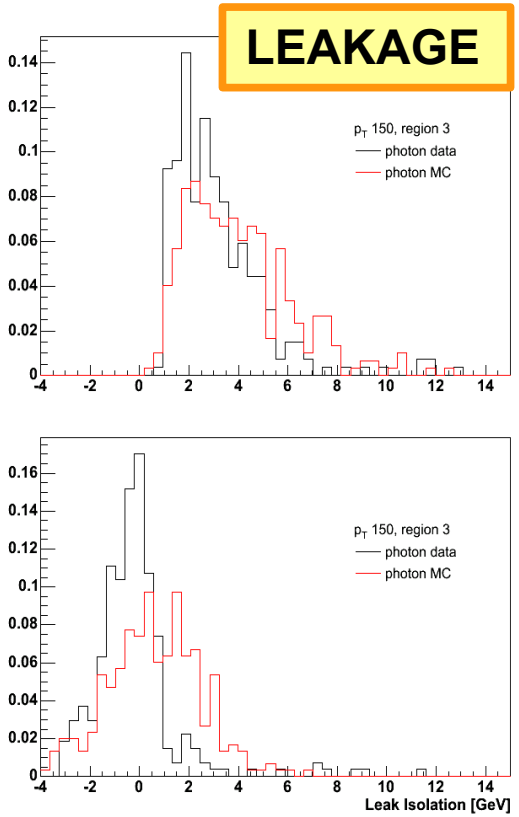
Problem with the Underlying Event?

PILE-UP



Pile-up is not an important contribution

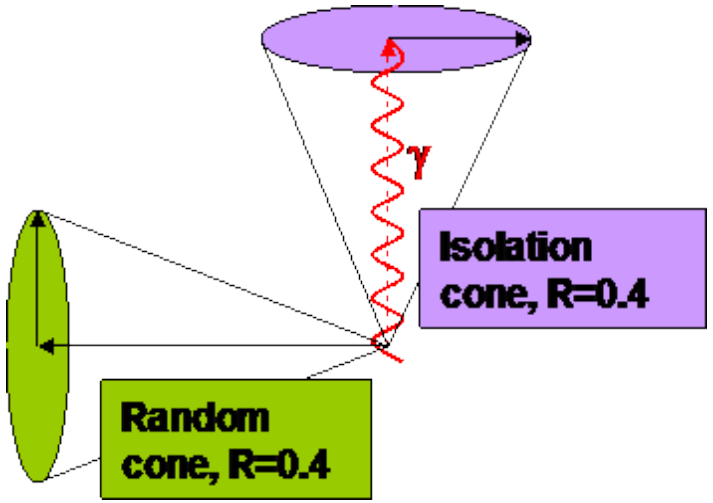
LEAKAGE

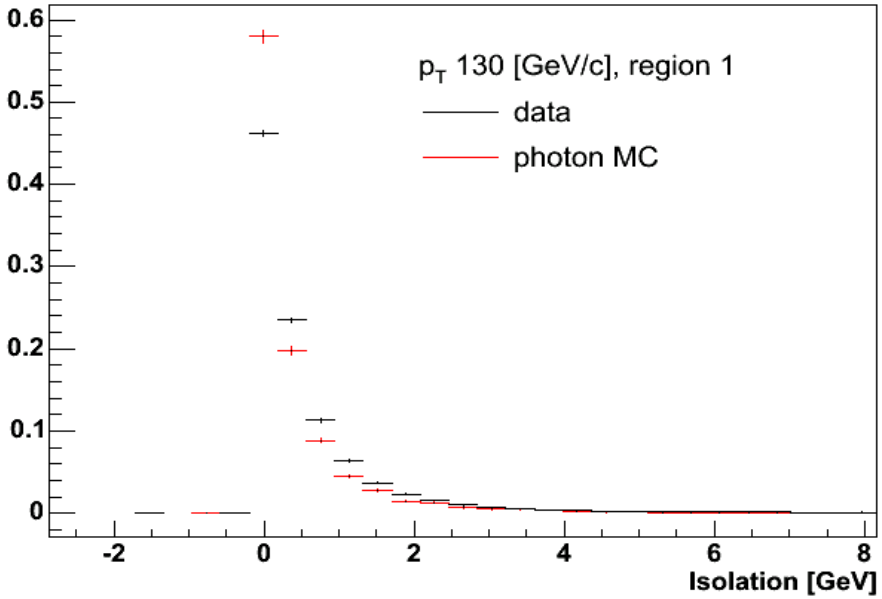


Leakage contributes at large |x| but is not the primary cause

Isolation in Random Cones

- **Dig further in the underlying event with RANDOM CONES**
- Measure energy of a R=0.4 cone within 35º-145º from the photon axis in data and MC
- Only REGION 1 to remove other effects





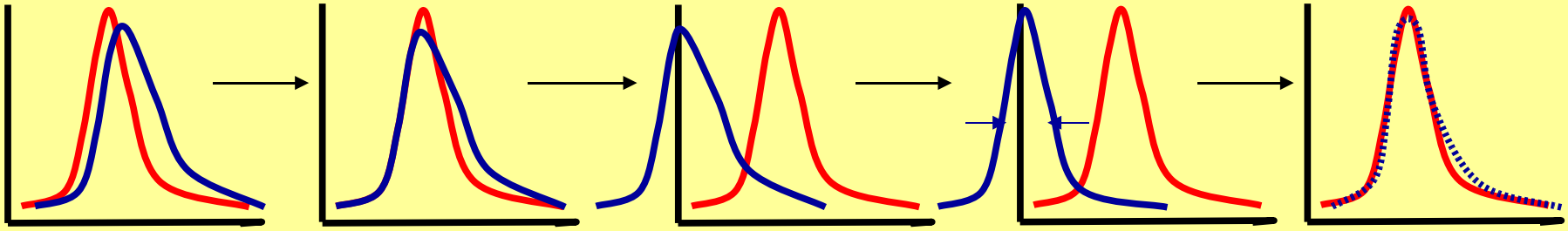
- Energy in the random cone is always higher for data, contrary to the trend seen in the isolation cone

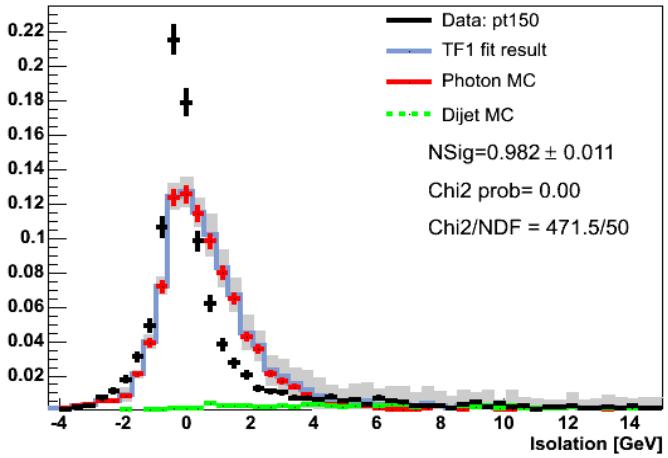
The underlying event by itself does not explain the differences

Isolation templates

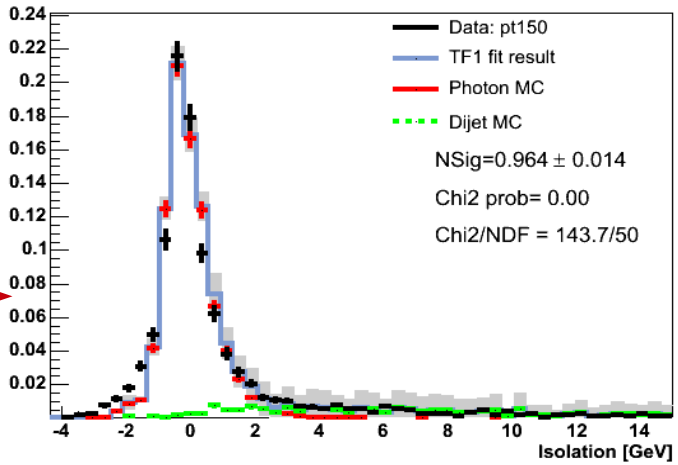
- Discrepancies not due to the underlying event, the leakage or the pile-up

- The MC peak position and shape is corrected using the peak in the data



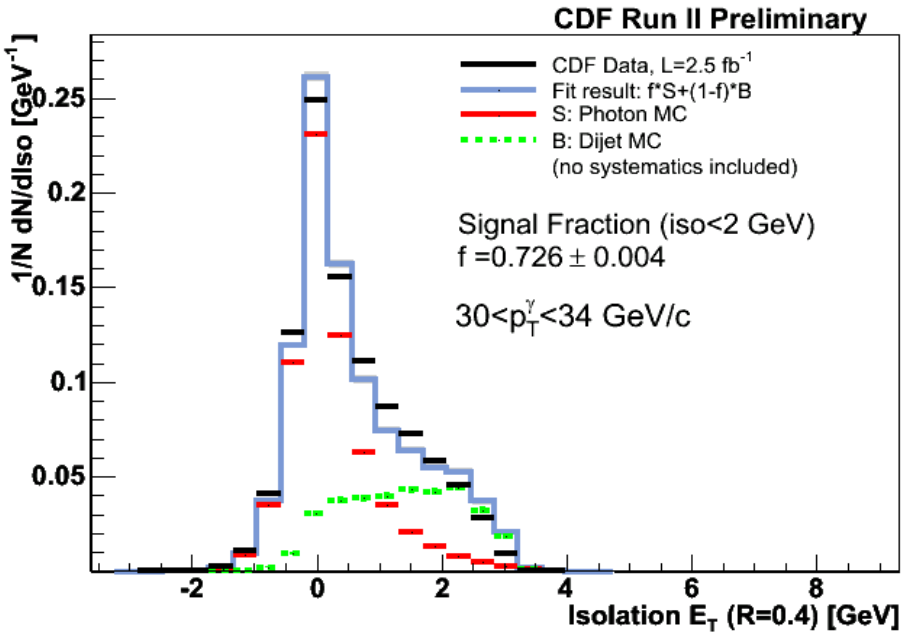


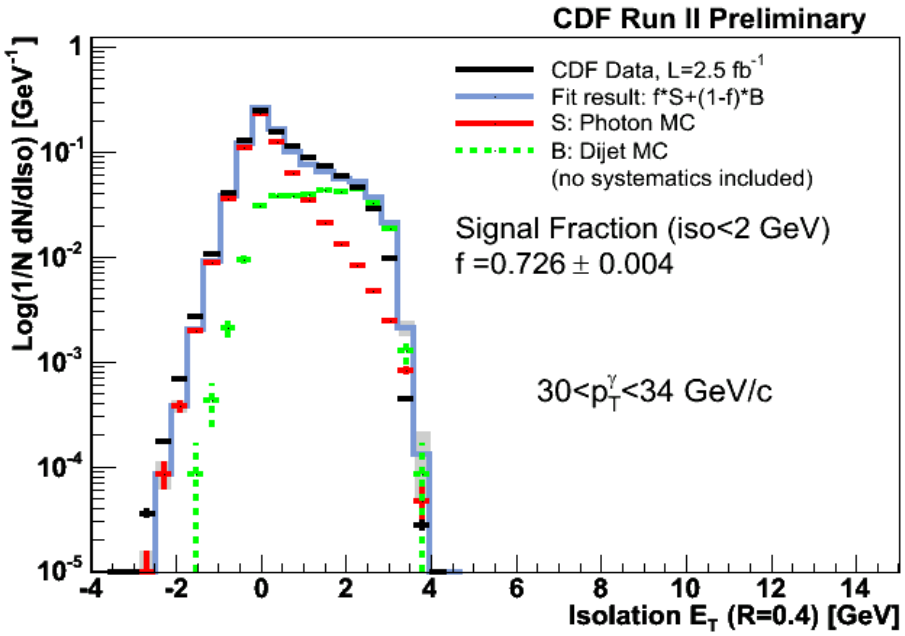
Signal fraction changes only by 2%



Fit results

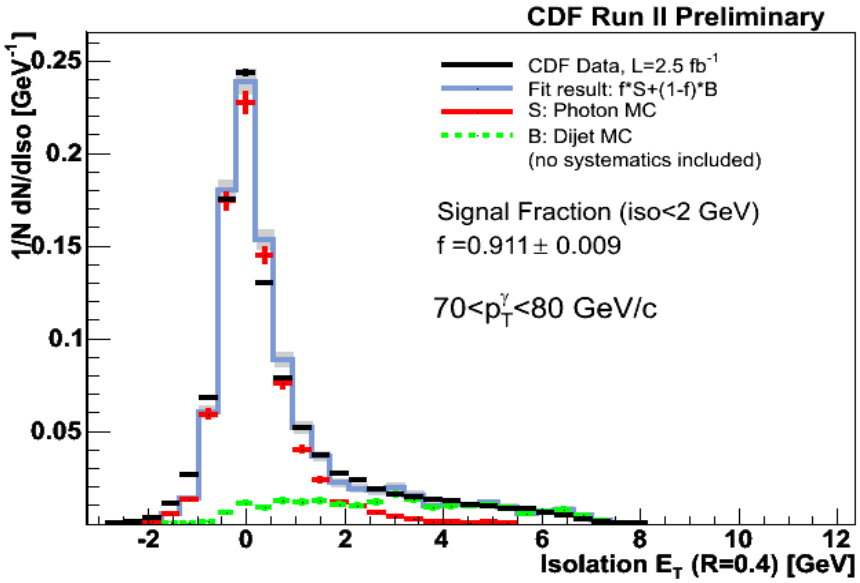
Data
Fit result
Signal template
Background template

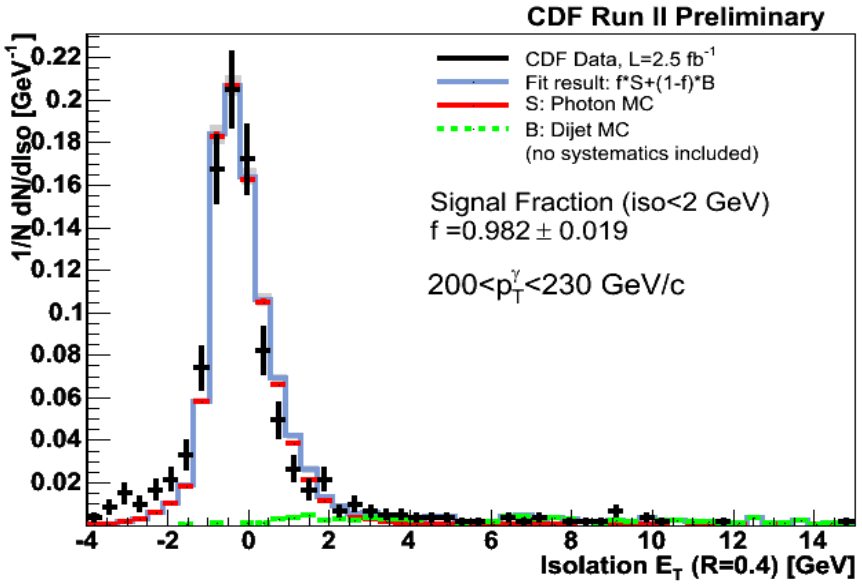


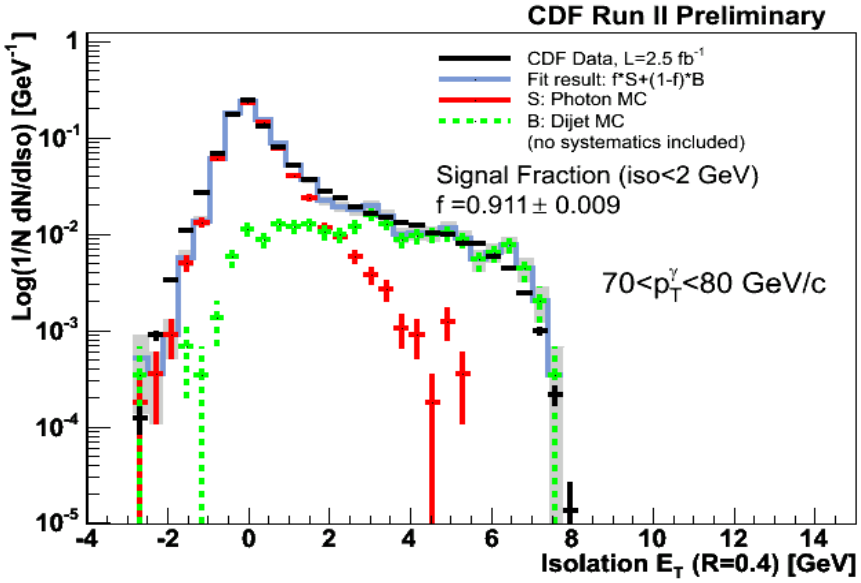


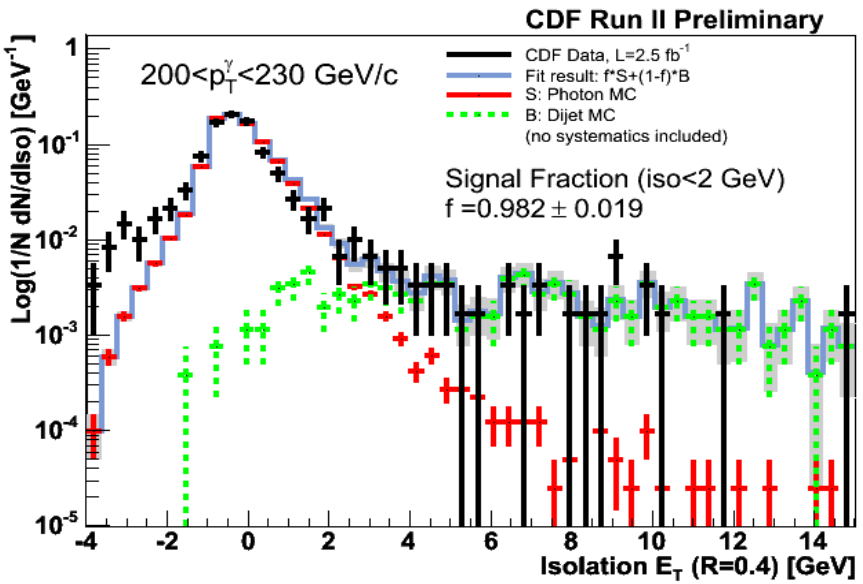
χ^2 fit: takes into account the statistical uncertainties in the templates and in the data

Fit results

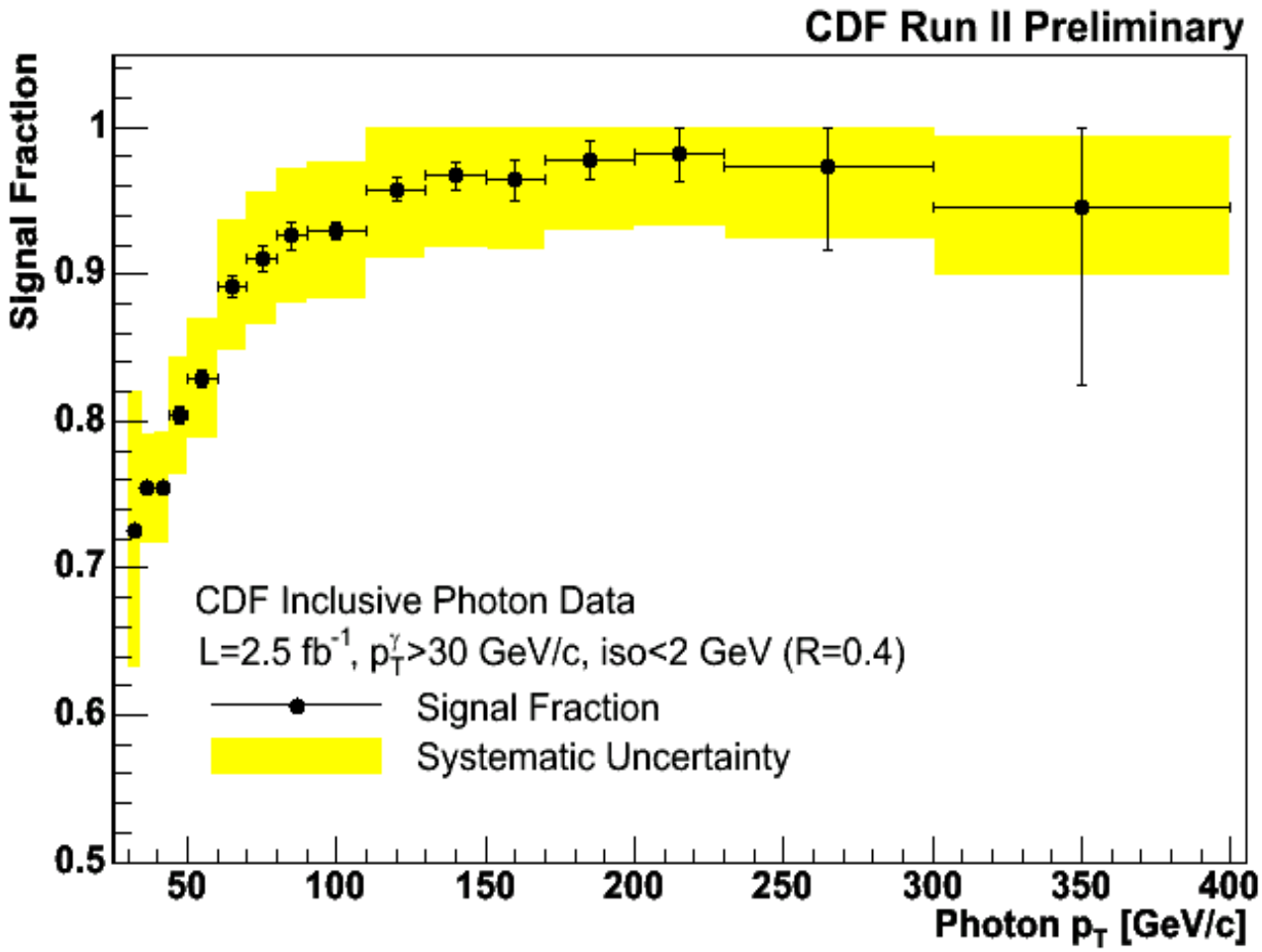






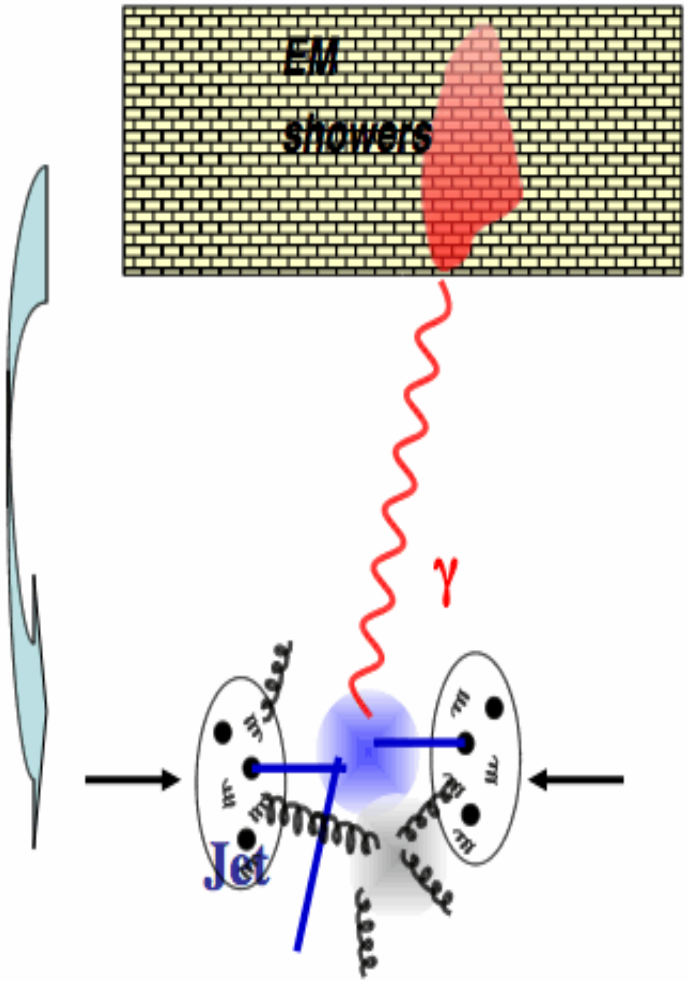


Photon Purity



The signal fraction goes from ~70% to >98% as the photon p_T increases

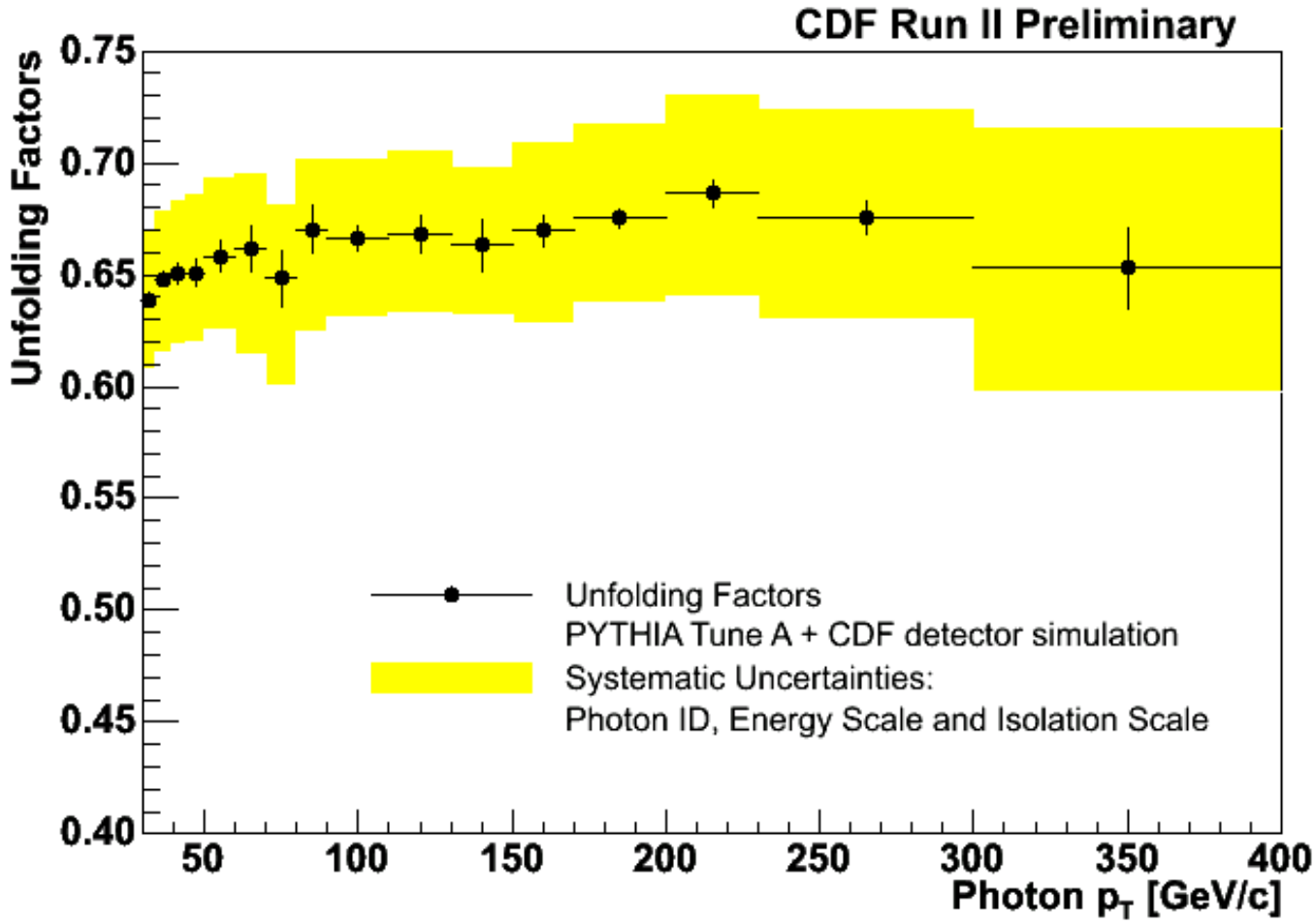
Unfolding factors



- **Correct the cross section for acceptance, efficiency and resolution effects back to hadron level**
- Calculated with photon MC
- Shape of the p_T in the MC reweighted to reproduce the shape of signal photons in data

$$U = \frac{\text{Reconstructed photons passing offline cuts}}{\text{Generated photons with } p_T > 30 \text{ GeV/c}, |\eta| < 1.0 \text{ and iso} < 2 \text{ GeV}}$$

Unfolding factors



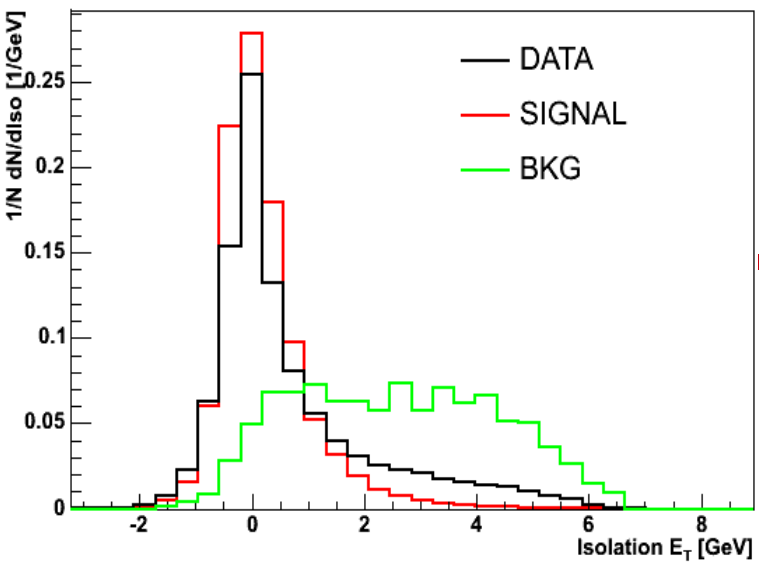
The unfolding factors vary between 64% and 69% as the photon p_T increases and do not have strong p_T dependence

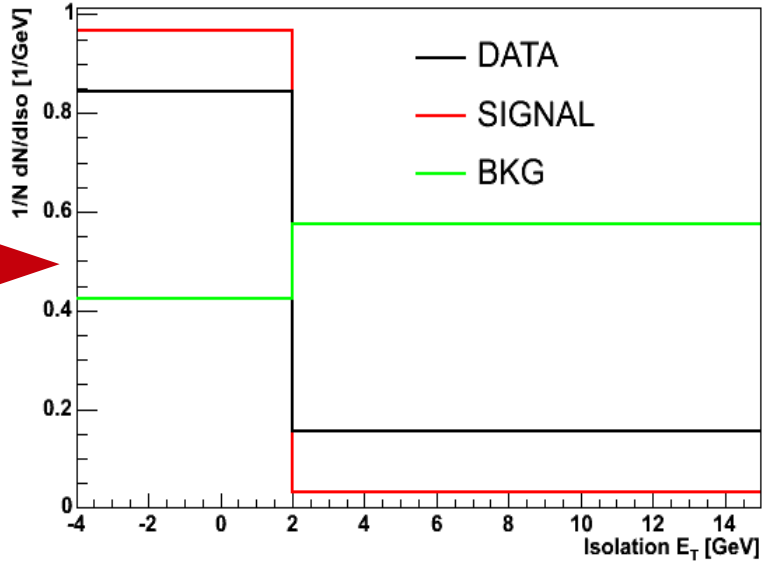
Systematic Uncertainties

- **Sources of systematics**
  - **Two major sources**
    - **Photon purity**
    - **Photon energy scale**
  - **Others**
    - ± 1% due to the **photon isolation scale**
    - **Photon ID and acceptance**
      - Acceptance: ± 3% (studied in previous photon analyses with PYTHIA samples with different PDF)
      - CES χ^2 efficiency: + 5% at low p_T where the cut is applied (removed above 90 GeV due to the high uncertainty in its efficiency)
  - **Negligible**
    - Trigger efficiency
    - Cosmics background
    - Detector material
    - Reweighting of the MC

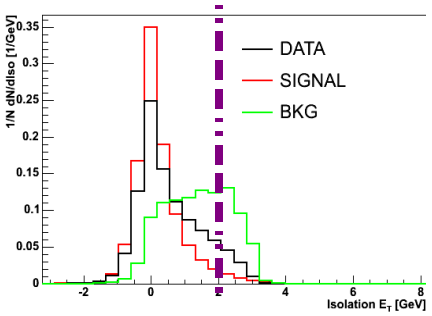
Systematics: photon purity

- **Different methods to cross-check the photon purity**
  - **Shower-shape and conversion probability for p_T < 70 GeV/c**
  - **Templates from electrons in $Z \rightarrow ee$ decays for p_T < 70 GeV/c**
  - **Corrected dijet templates**
  - **2-bin templates**



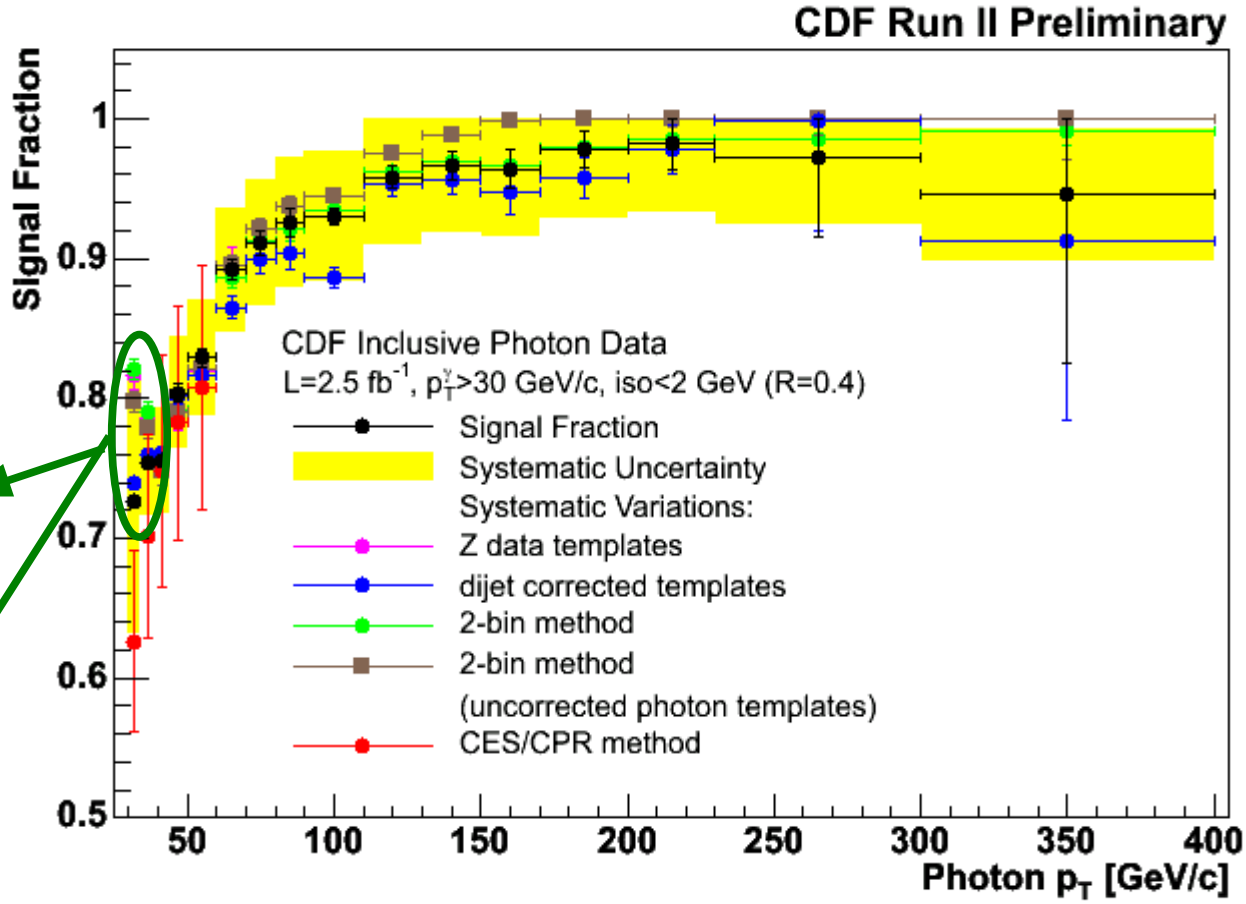


Systematics: photon purity



2-bin separation at 2 GeV does not have enough resolution for the two first bins

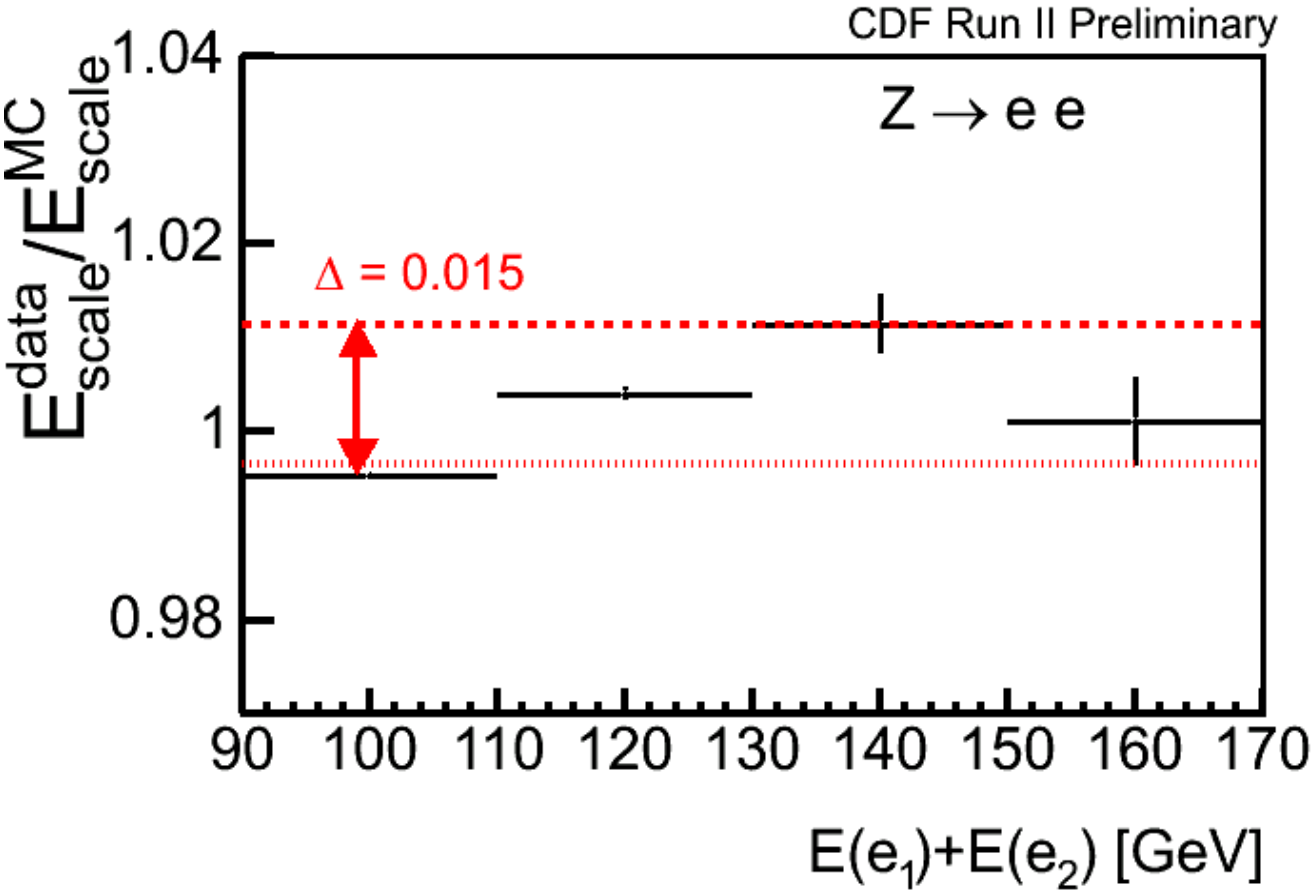
Residual bkg in the Z templates



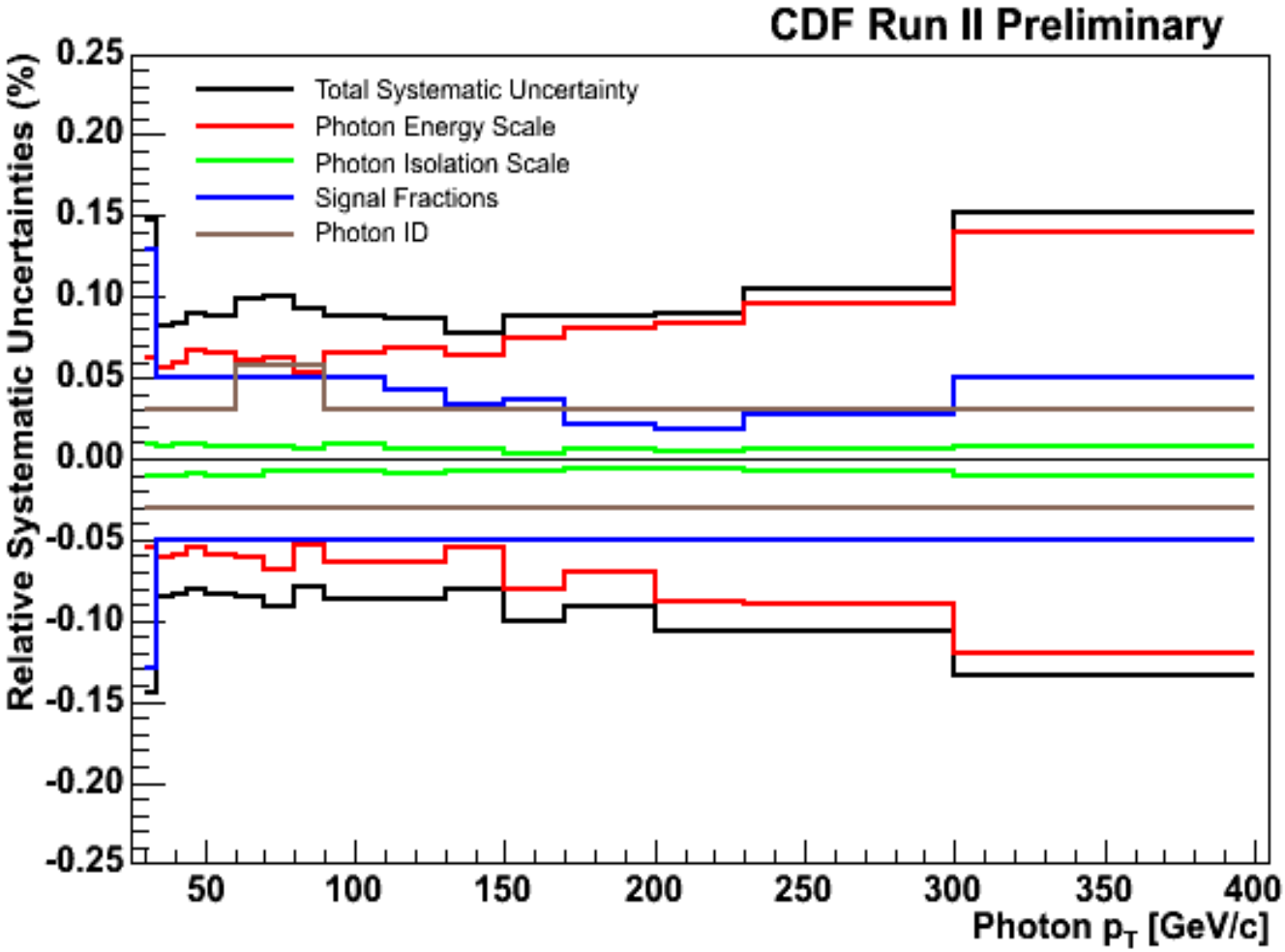
The systematic uncertainty due to the signal fraction is ± 13% for the first bin and ± 5% for the rest

Systematics: energy scale

- Estimated using **electrons from *Z*→*ee* decays** in data and MC samples
- **± 1.5% uncertainty** covers energy and geometrical dependences



Total systematic uncertainty



Signal fraction dominates for the 1st bin and the energy scale at high p_T

Total systematic uncertainty is around ± 10-15%

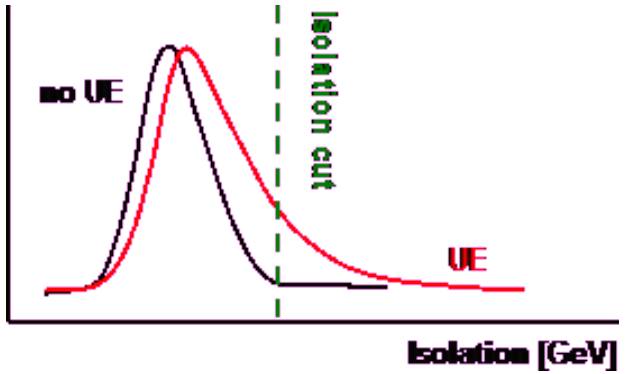
Theory prediction

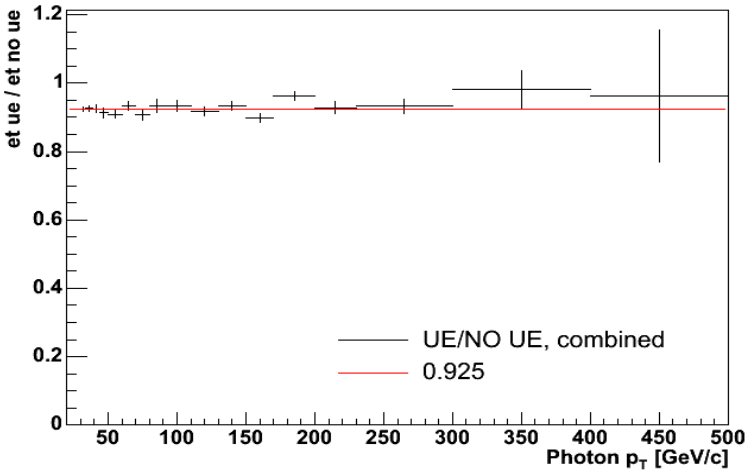
- **Next-to-Leading Order (NLO) perturbative QCD (pQCD) JETPHOX predictions, with CTEQ6.1M PDFs, BFGII fragmentation functions and at scale $\mu=\mu_F=\mu_f=\mu_R=p_T$**

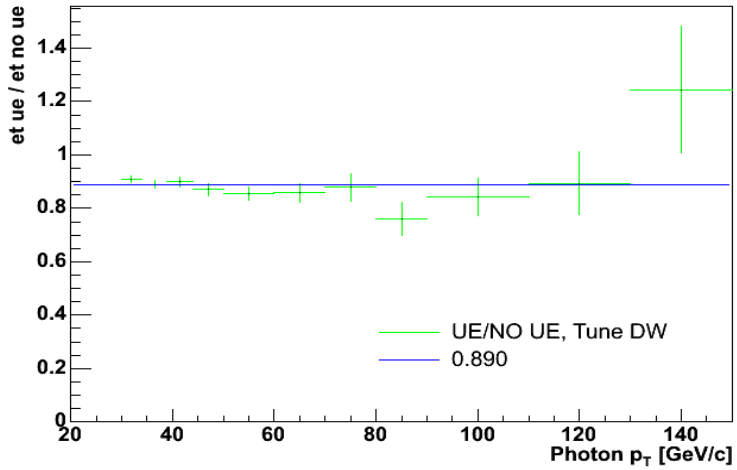
- **Corrected for non-perturbative**

QCD effects: UNDERLYING EVENT

- UE reduces the efficiency of the isolation cut
- Estimated using two different UE tunes in PYTHIA samples
- Correction factor: mean of the two

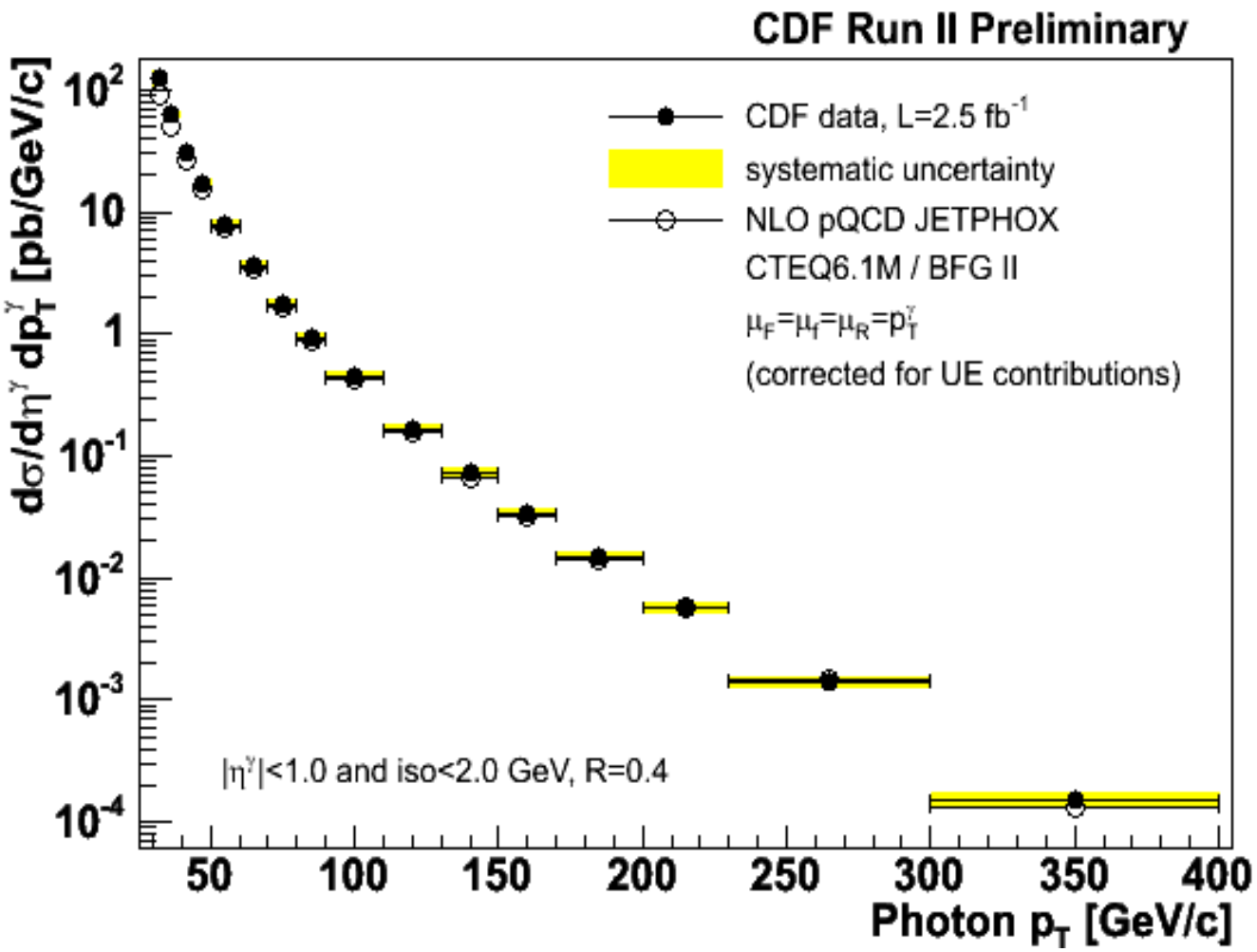






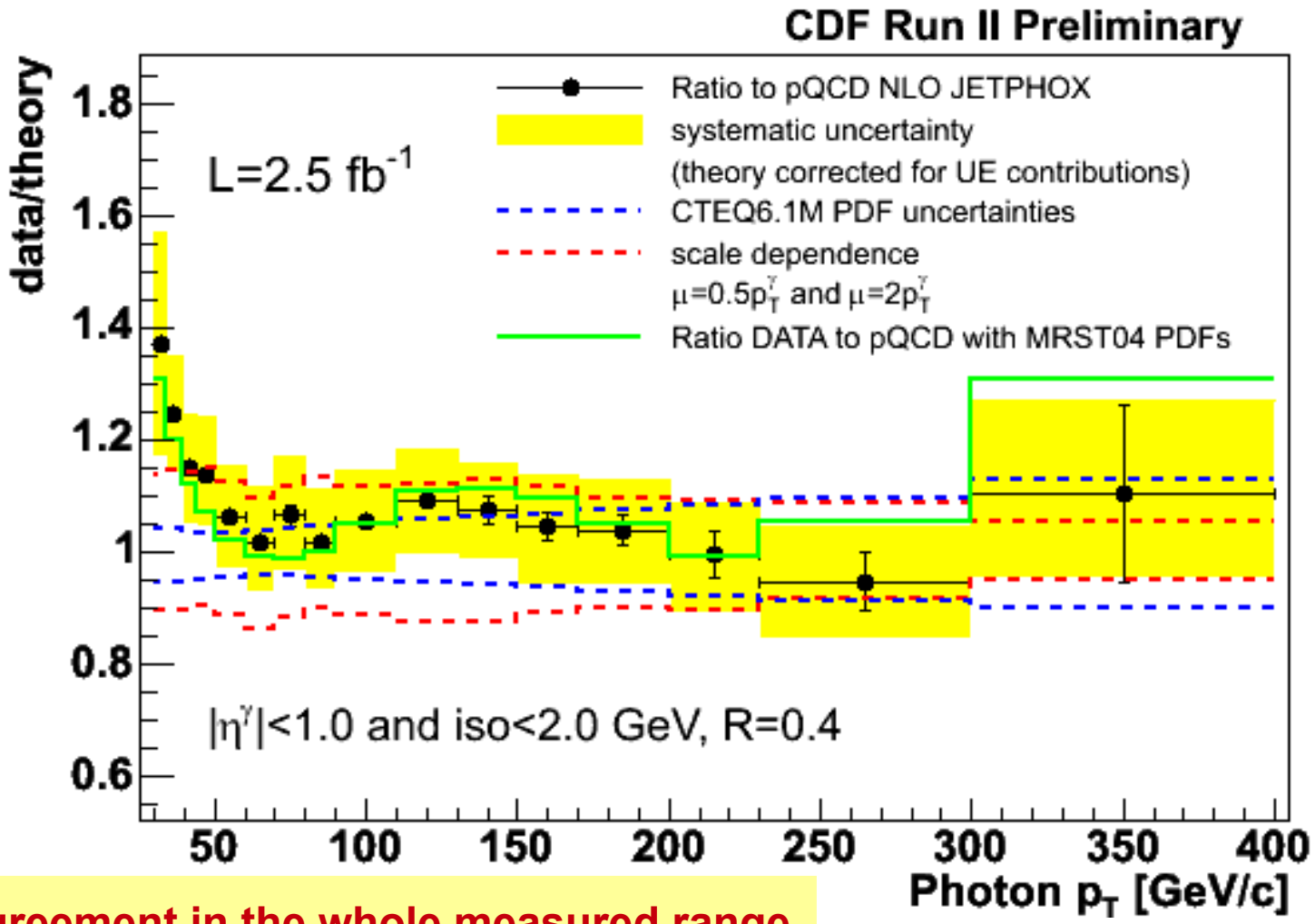
$C_{UE} = 0.913 \pm 0.004\ (stat) \pm 0.03\ (sys)$

The Cross Section



Measured up to 400 GeV/c and covering 6 orders of magnitude

Data and Theory comparison



Good agreement in the whole measured range

Differences in the shape at low p_T already seen in previous measurements

Comparison to both CTEQ6.1M and MRST04: *differences are not explained only by the PDF*

Summary

- **Cross section with 2.5 fb^{-1} of data and up to 400 GeV/c → test pQCD over 6 orders of magnitude**
- Uncertainties data ~ uncertainties theory

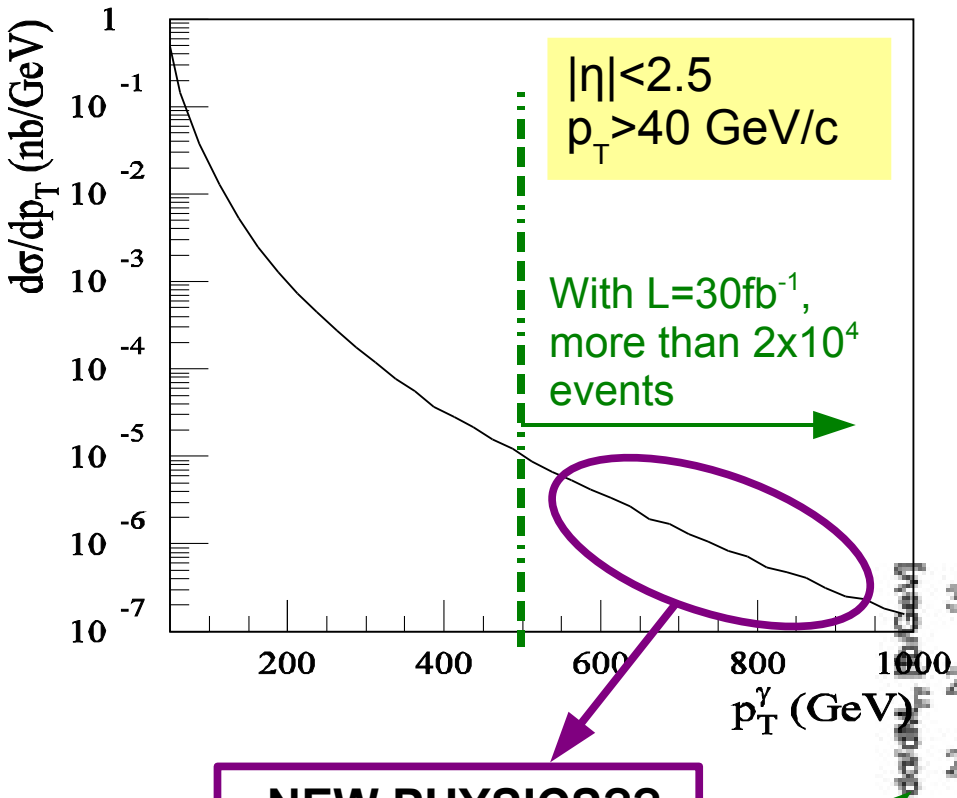
- **Good agreement**
- Differences at low p_T seen in prev. meas.
- Gluon PDF for $40<p_T<150$ GeV/c?

- **New method to estimate the photon purity using the isolation energy**
- Systematic uncertainty reduced from ~30% in prev. CDF measurements to 5%
- Powerful tool for future analyses at the LHC

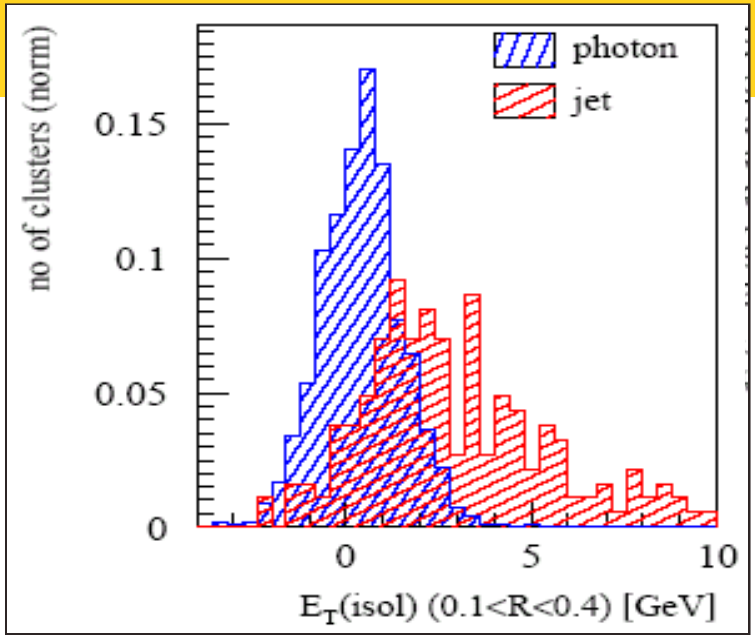
Already reviewed by the Collaboration
PRL in progress
Thesis defense expected by May 2009

For the future...

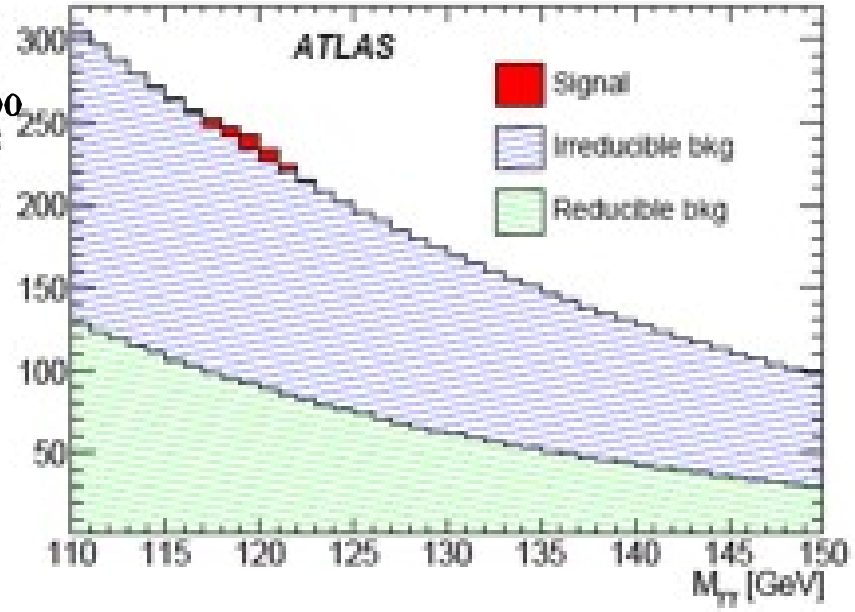
Expected inclusive photon cross section at the LHC Luminosities



NEW PHYSICS??



Isolation studies at the LHC!



One step further:
Diphoton → Light Higgs

Back up slides

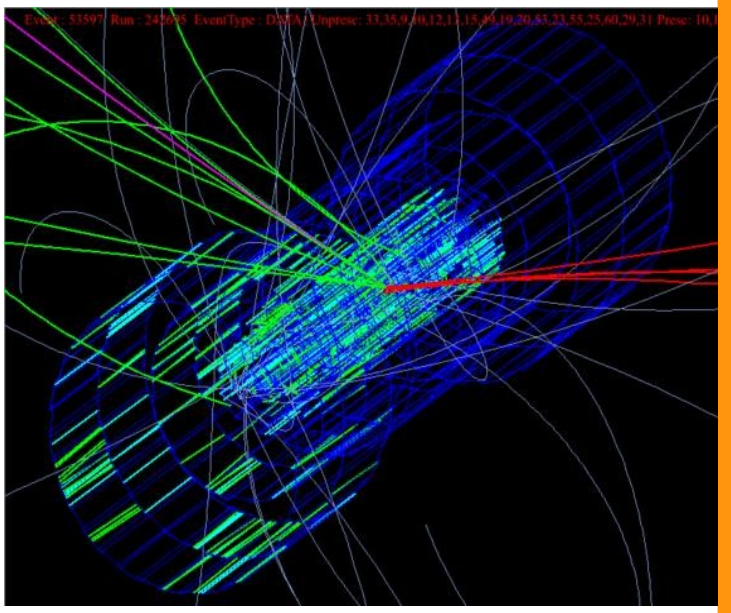
Event reconstruction

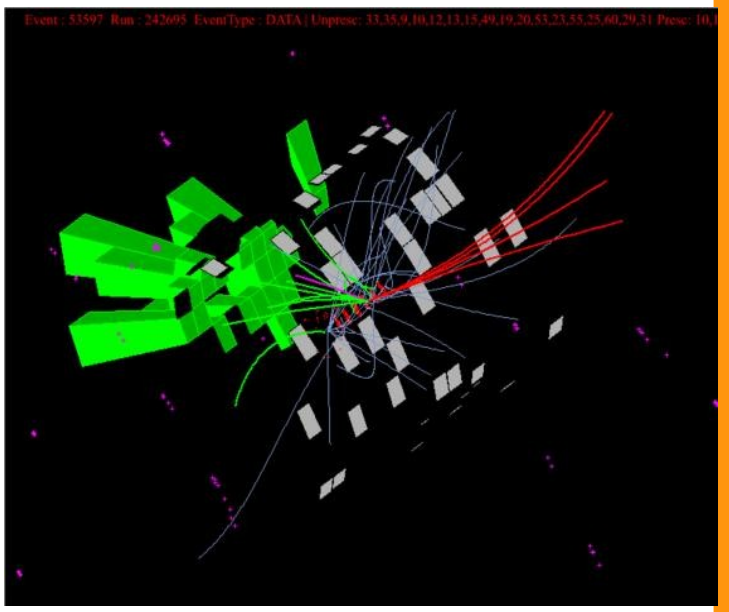
- **Vertex and track measurement**
  - Silicon detectors provide high resolution track and vertex measurements
    - Impact parameter for HF jet tagging
  - Immersed in a magnetic field

- **Energy measurement**
  - EM calorimeters to measure EM particles (photons and electrons)
    - Distinguished using the tracker
  - Hadrons (jets) measured (mostly) in the HAD calorimeters

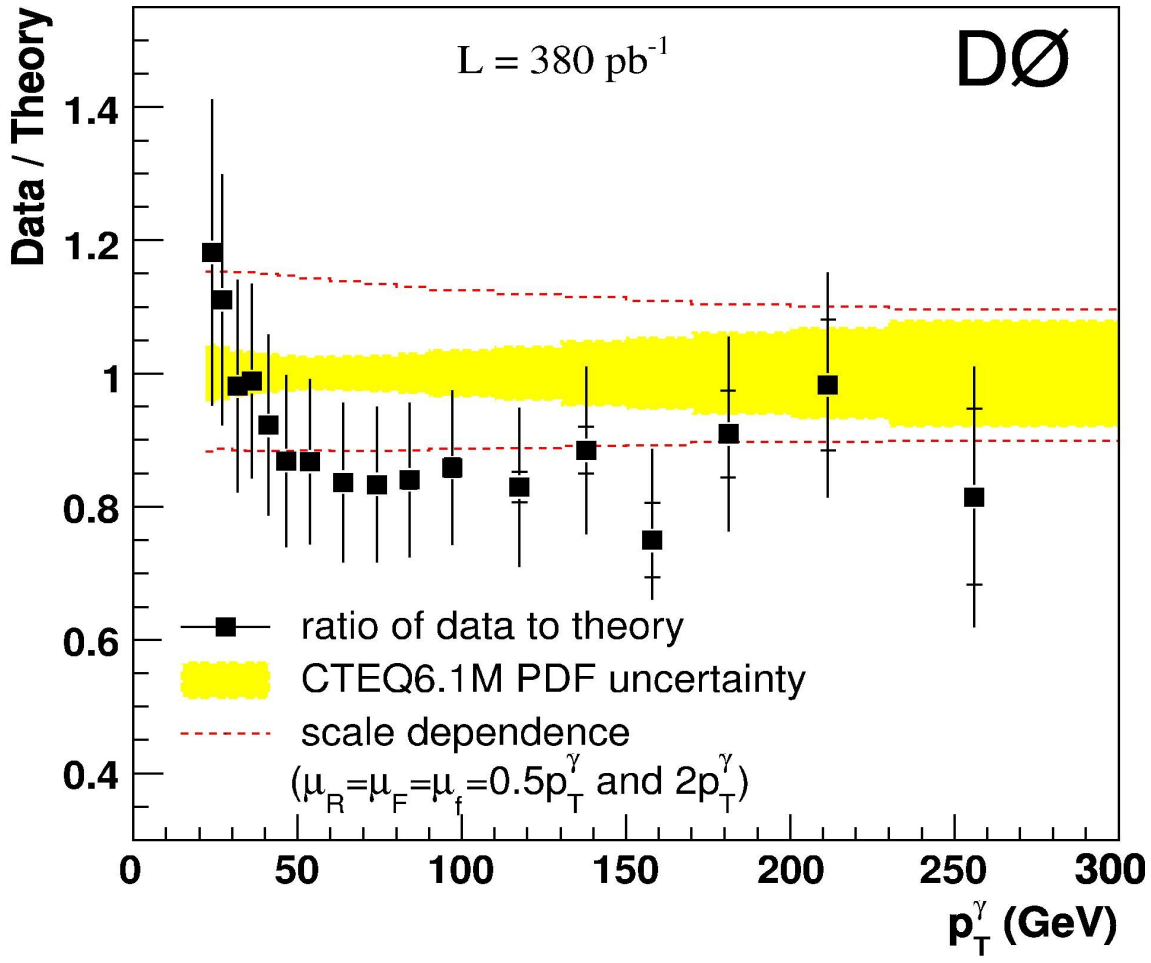
- **Missing Energy**
  - Imbalance of the total transverse energy of the event
  - Measured using all the different subdetectors

- **Events are selected with a 3-level trigger system**
  - L1 (hardware) nodes can work in parallel and store up to 14 bunch crossings. Reduce the event latency from 1.7MHz to ~50 kHz
  - L2 (hardware+software) reduces the event rate to ~300 Hz
  - L3 (software) and similar to the offline reconstruction, final latency is of ~75 Hz



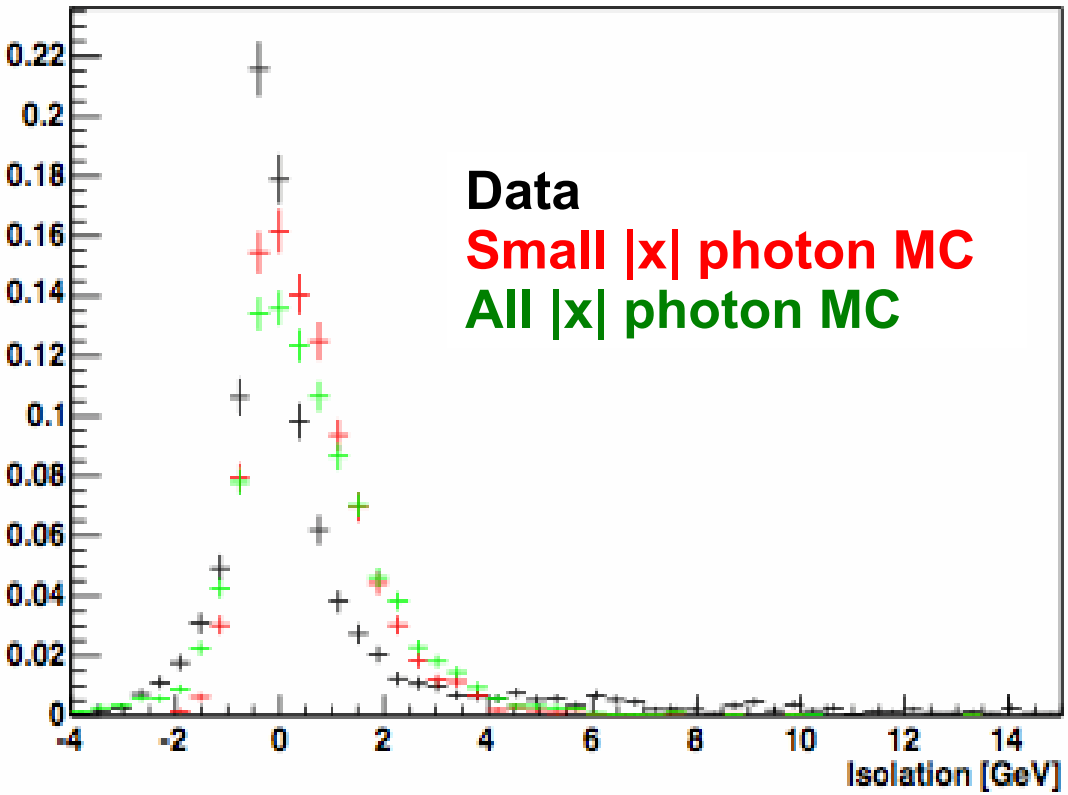


Previous Tevatron results (by DØ)



- **Same shape at low p_T**
- Theory NOT corrected for UE contributions
- Agreement within uncertainties

Isolation – Shower Leakage



Effect of restricting the shower |x| position in the templates

The shower leakage does not explain the discrepancy

Cosmics fraction – EM Timing

Remaining cosmics fraction after the MET/ET cut estimated using the EM Timing system of the EM calorimeter