Searching for the elusive graviton with solitary photons

2008-11-11

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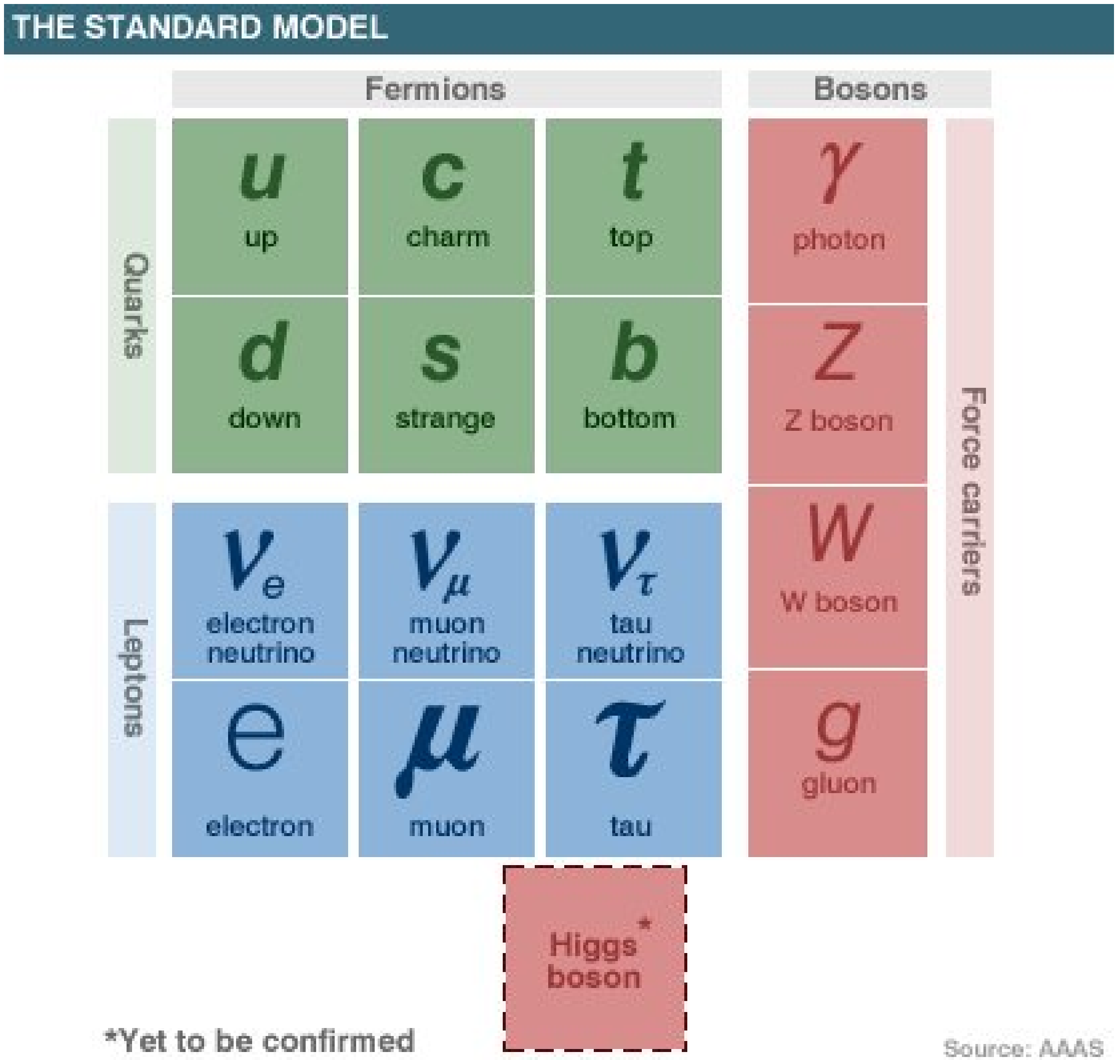
Outline

- Introduction
- Photon identification
- EM pointing algorithm
- Single photon selection and background estimation
- Results and Summary

Where is Gravity?

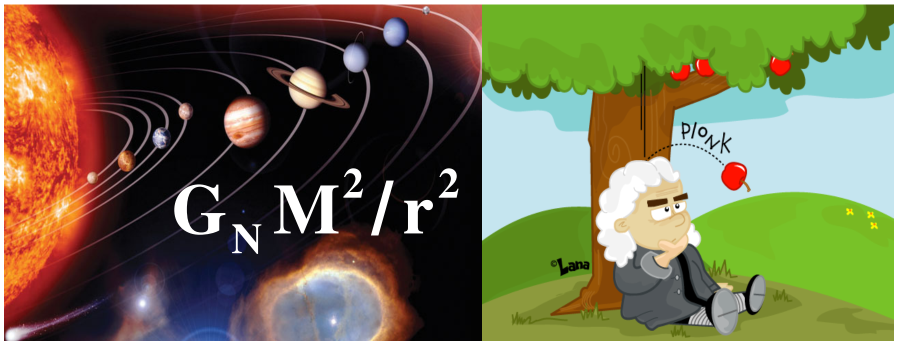


We are way too familiar with the effects of gravity...

...but we don't yet understand it completely.

Gravity and the Standard Model

- Einstein's General Relativity good up to solar system scale.



- At larger scales the situation is not as clear.
  - Modified dynamics?
  - Dark Matter?

- Great efforts have been made to try to come up with a quantum description of gravity.
- Gravity is very weak, negligible in SM

$$\frac{G_F}{G_N} \sim 10^{33}$$

G_F : Fermi const.

G_N : Newton const.

- Extrapolation defines the **Planck energy** scale:

$$M_{Pl} \sim G_N^{-1/2} \sim 10^{19}\,\text{GeV}$$

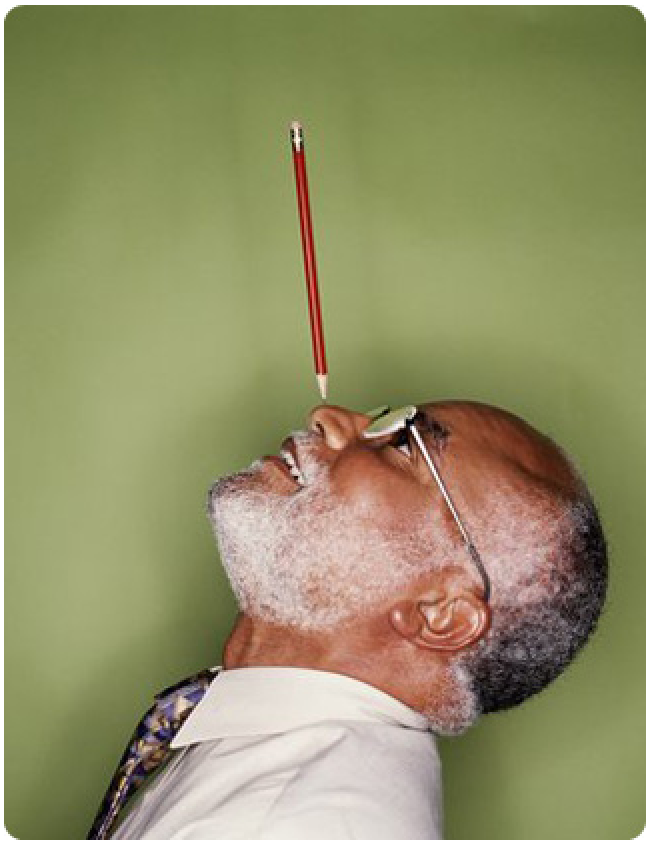
Great jump in energy

$$m_{EW} \sim 10^3\,\text{GeV}$$

Electroweak scale

Hierarchy Problem, Naturalness, and Fine Tuning

- Naturalness: belief that a small parameter in Nature can not be an accident. It must be associated with a symmetry.



- Additional contribution to the squared Higgs-boson mass:

$$\delta m_H^2 = \kappa \Lambda^2 \qquad (m_H \sim G_F^{-1/2})$$

κ : constant parameter

Λ : energy size of the quantum fluctuations

- Amount of fine tuning required for the SM to work at the Planck scale:

$$(m_{EW}/M_{Pl})^2 \sim 10^{-32}$$

- Analogy: balancing a pencil (***R*** long), on its tip of length ***r***, where:

R ~ size of the solar system **r** ~ 1 mm

- Supersymmetry and technicolor solve the problem.

ADD (Arkani-Hamded, Dimopoulos, Dvali) Large Extra Dimensions

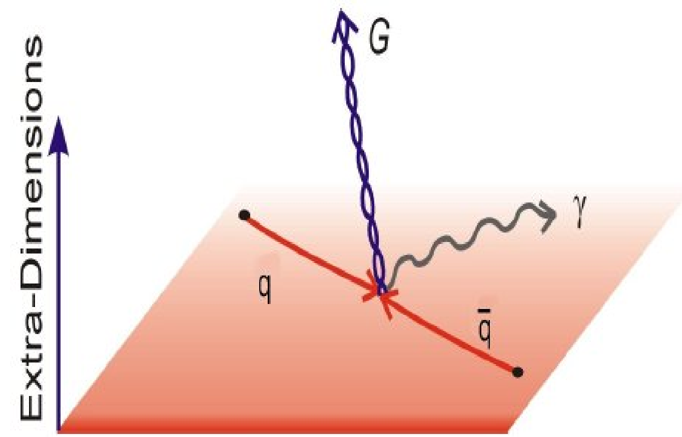
- **m_{EW}** the only fundamental scale in nature.
  - experimentally tested as opposed to **M_{Pl}**

- n large extra spatial dimensions (LED).
  - **large compared to the electroweak scale**
  - gravity is diluted in large compactified volume.
  - SM particles bound to the 3D brane
    - localization is non trivial
    - compactification in a torus

- The greatness of the size of the extra volume **R** conceals the smallness of the fundamental Planck scale **M_D** (4+n D), the result: the effective Planck scale **M_{Pl}** (4 D).

- **Hierarchy (fine tuning) problem is solved**,

- Constraints from astrophysics, cosmology, and table-top experiments (dark energy length scale!!) rule out n = 2.



EW distance scale:

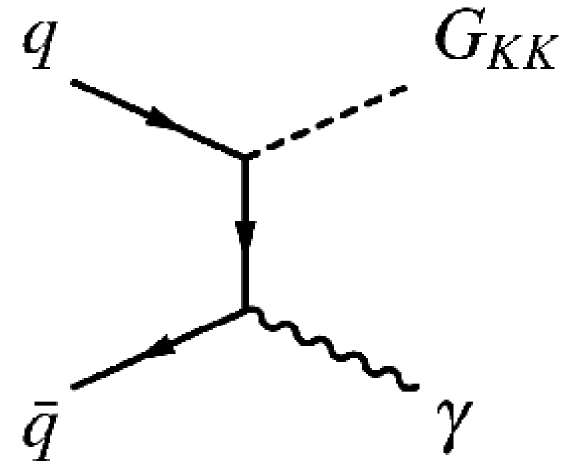
$$1 \ \ \mathrm{TeV}^{-1} \approx 10^{-19} \ \ \mathrm{m}$$

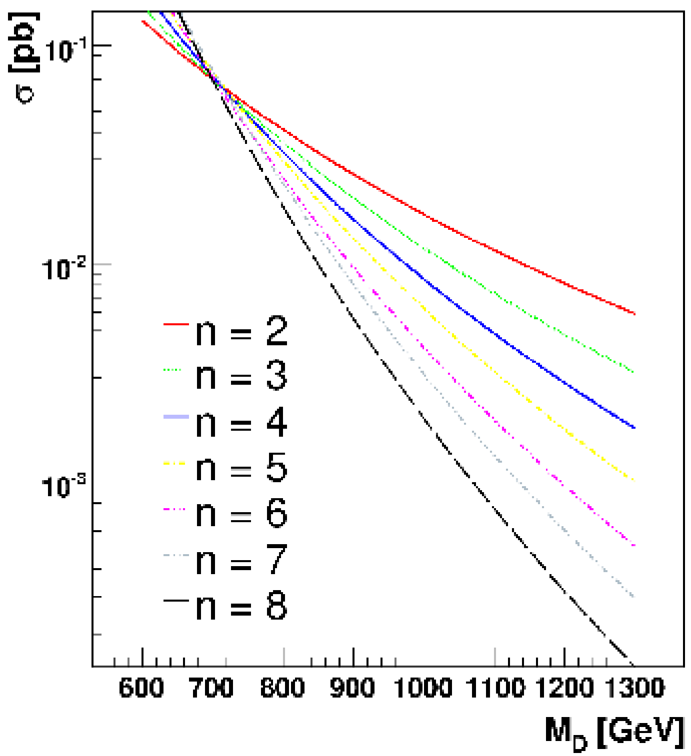
$$M_{Pl}^2 = 8\pi \, M_D^{n+2} R^n$$

At M_D = 1 TeV:
n = 1 » R ~ 10^{13} cm (solar system)
n = 2 » R ~ 1 mm
n = 3 » R ~ 1 nm
n = 7 » R ~ 1 fm (proton)

Direct Graviton Production

- Kaluza Klein (KK) gravitons: towers of KK modes.
- Single graviton production suppressed by $1/M^2_{Pl}$. Large phase space compensates this suppression.
- We search for LED studying the **exclusive photon (γ) + missing transverse energy (MET) channel**.
- We generate the signal using PYTHIA, for n = 2 to n = 8, at M_D= 1.5 TeV.





Same Signature Backgrounds

- Electroweak boson production:

$$Z+\gamma \rightarrow \nu\,\bar{\nu}+\gamma$$

Irreducible physics background; an excess in events could also indicate the presence of anomalous ZZγ or Zγγ couplings.

$$W \rightarrow e\,\nu$$

The electron is misidentified as a photon due to tracking inefficiency or hard bremsstrahlung.

$$W+\gamma \rightarrow l\,\nu+\gamma$$

The charged lepton from a leptonic W boson decay is not detected.

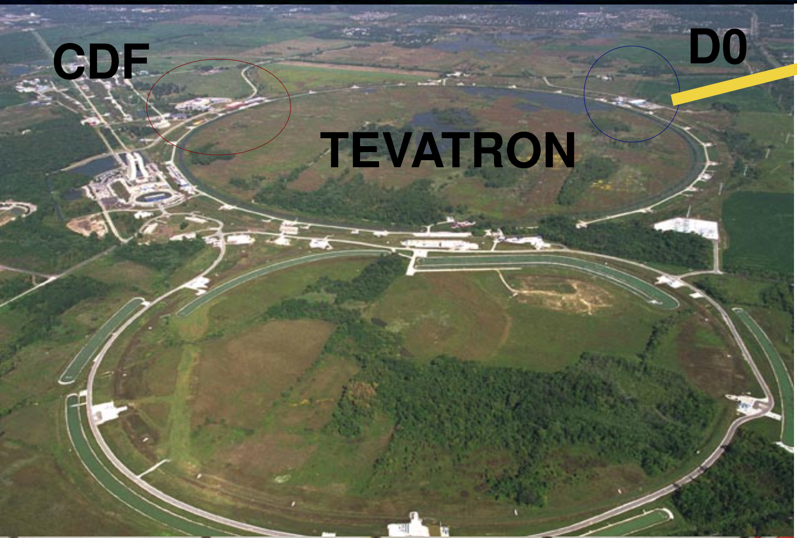
$$W/Z+\text{jet}$$

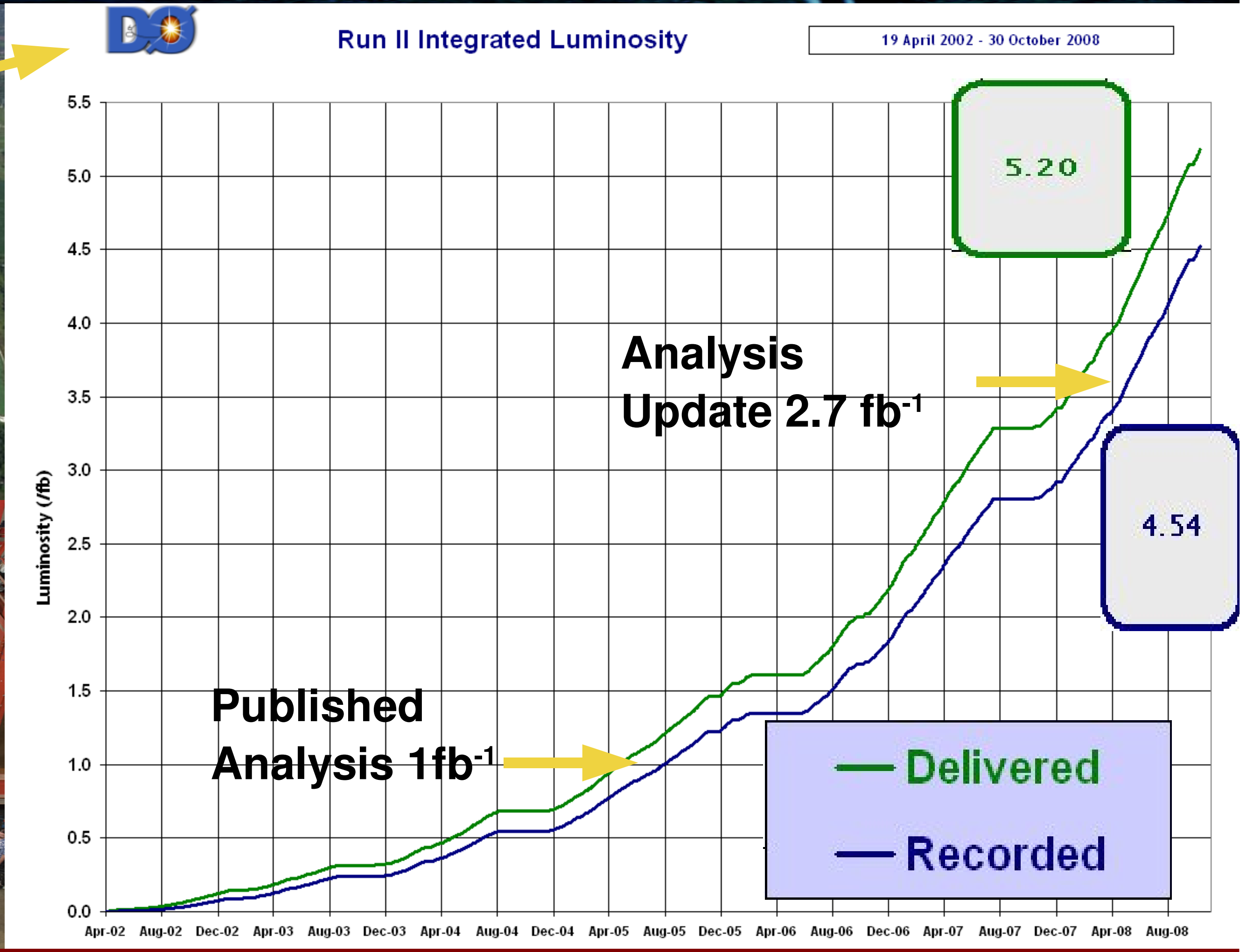
The jet is misidentified as a photon.

- Non-collision background:

Muons from the beam halo or cosmic rays undergo bremsstrahlung, producing an energetic photon.

The Apparatus: D0 Detector at the Tevatron

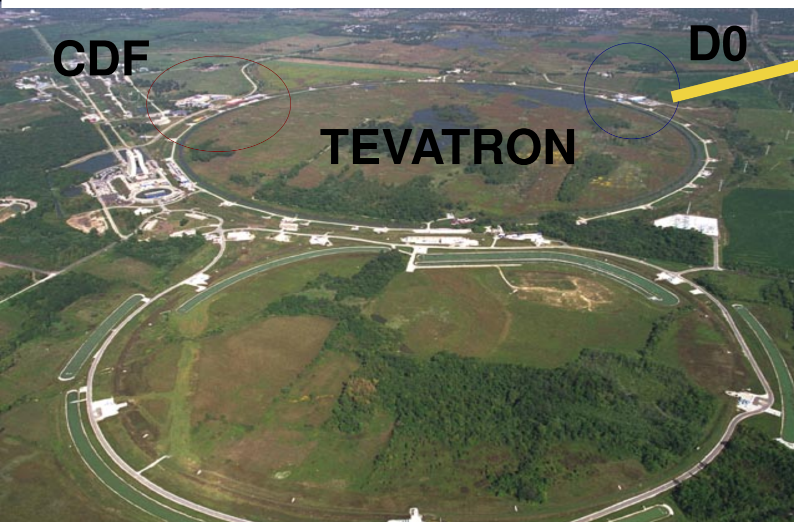


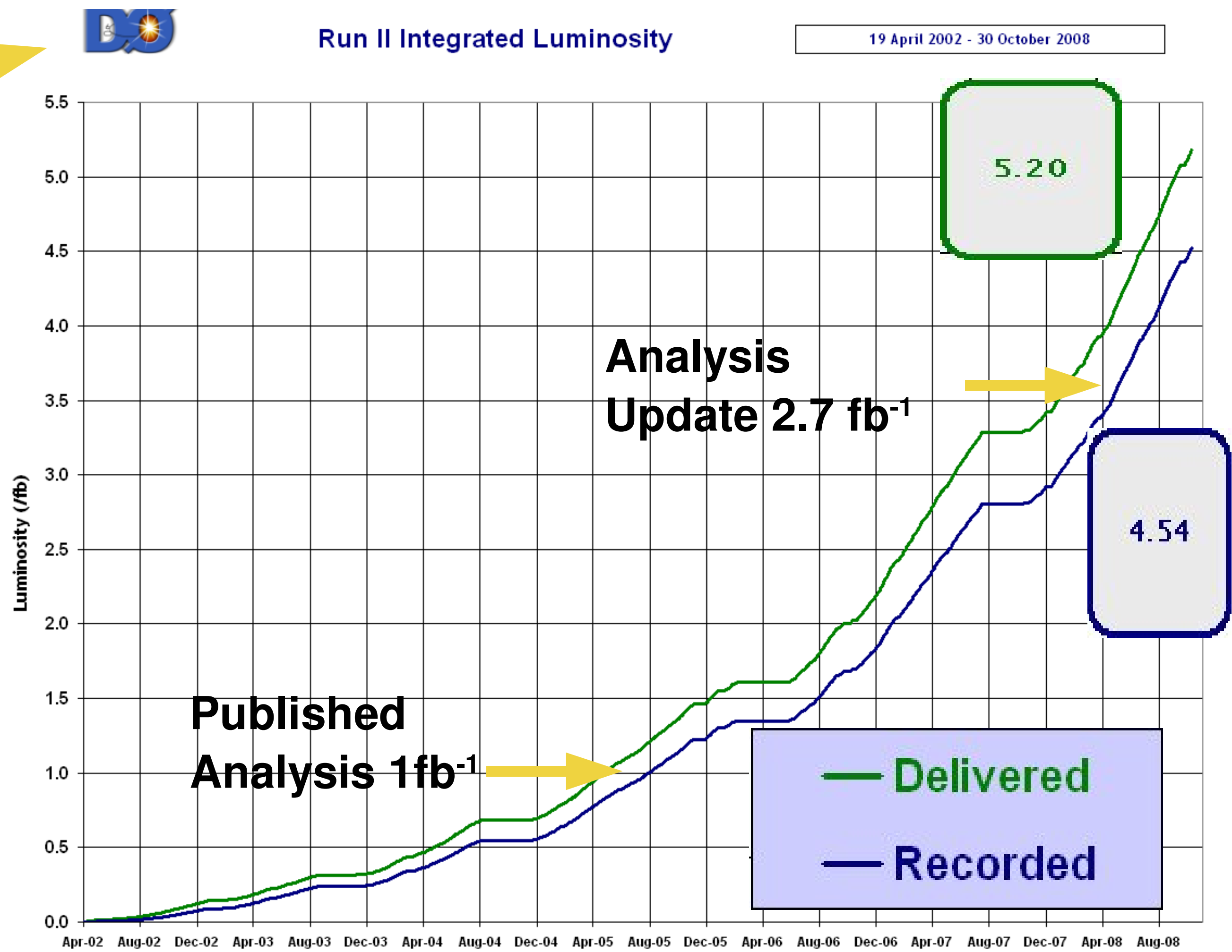


The Apparatus: D0 Detector at the Tevatron

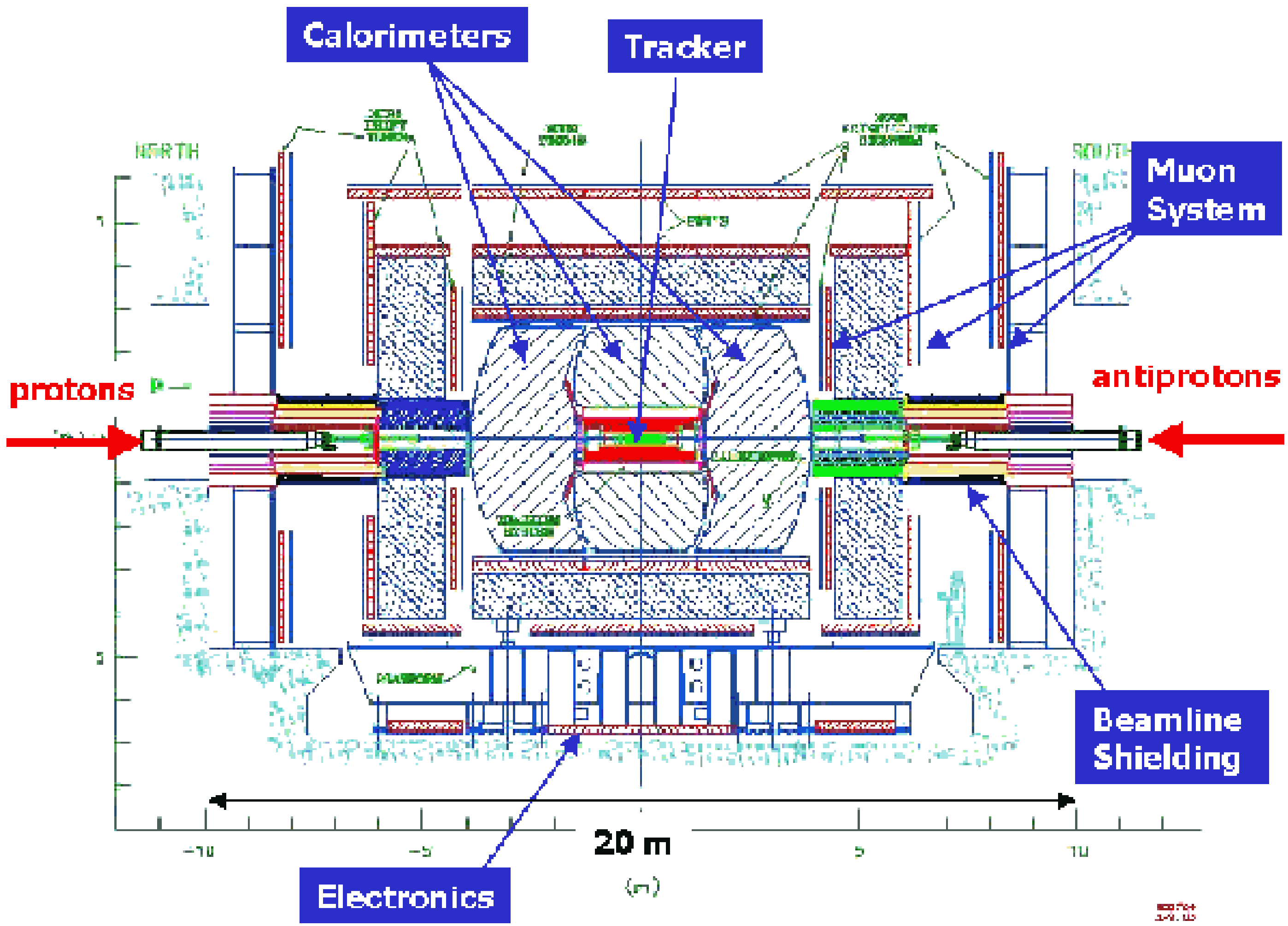
PRL 101, 011601 (2008) PHYSICAL REVIEW LETTERS week ending 4 JULY 2008

Search for Large Extra Dimensions via Single Photon plus Missing Energy Final States at $\sqrt{s} = 1.96$ TeV



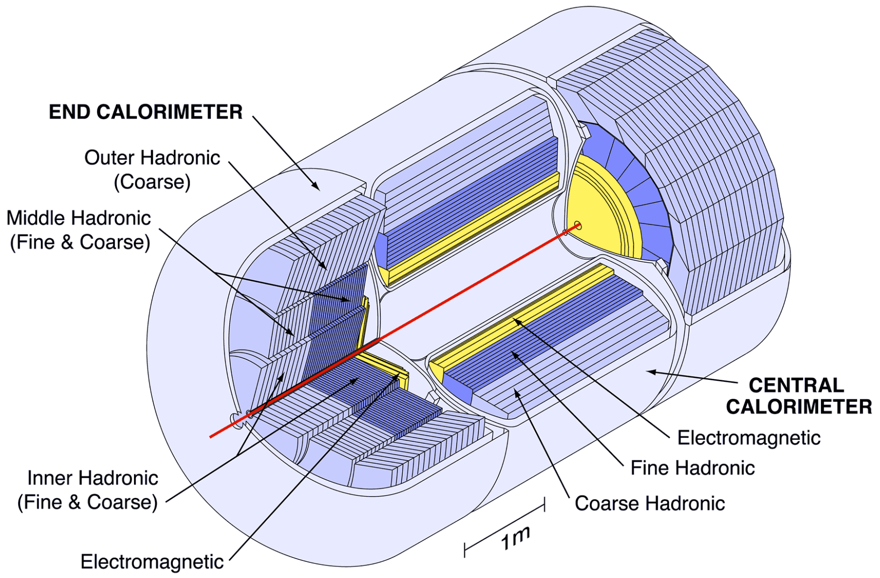


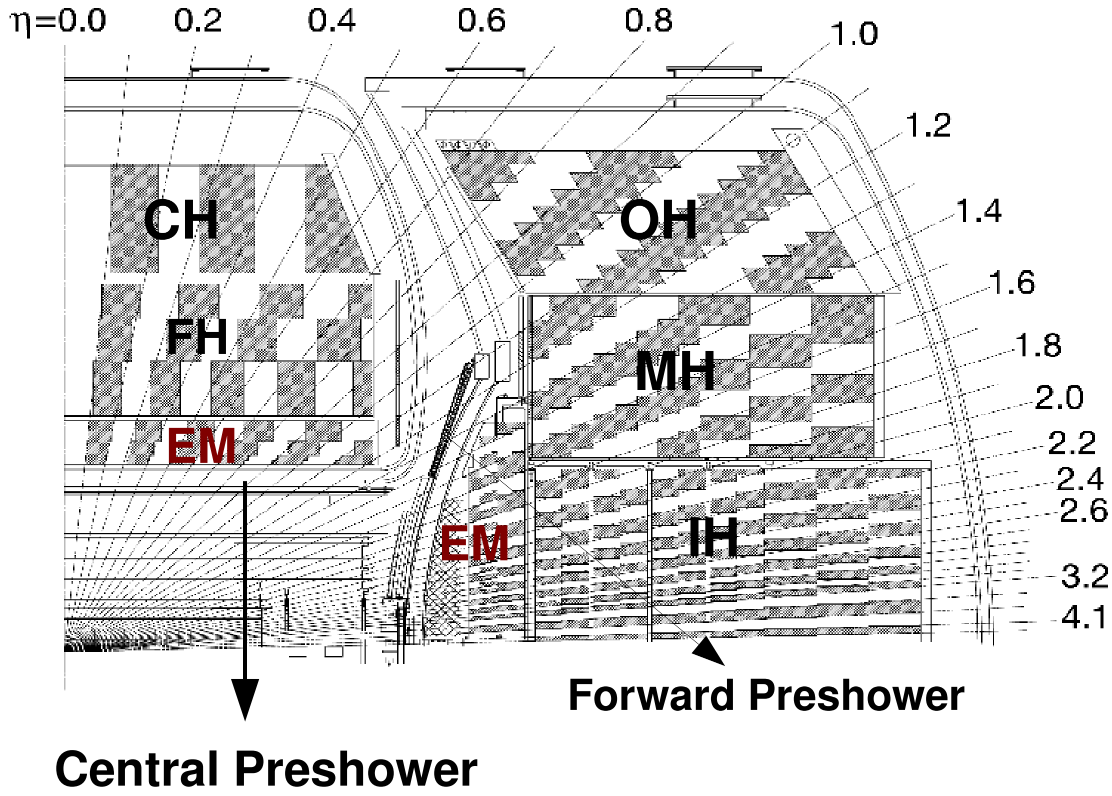
The D0 Detector



Photon Identification

CALORIMETER



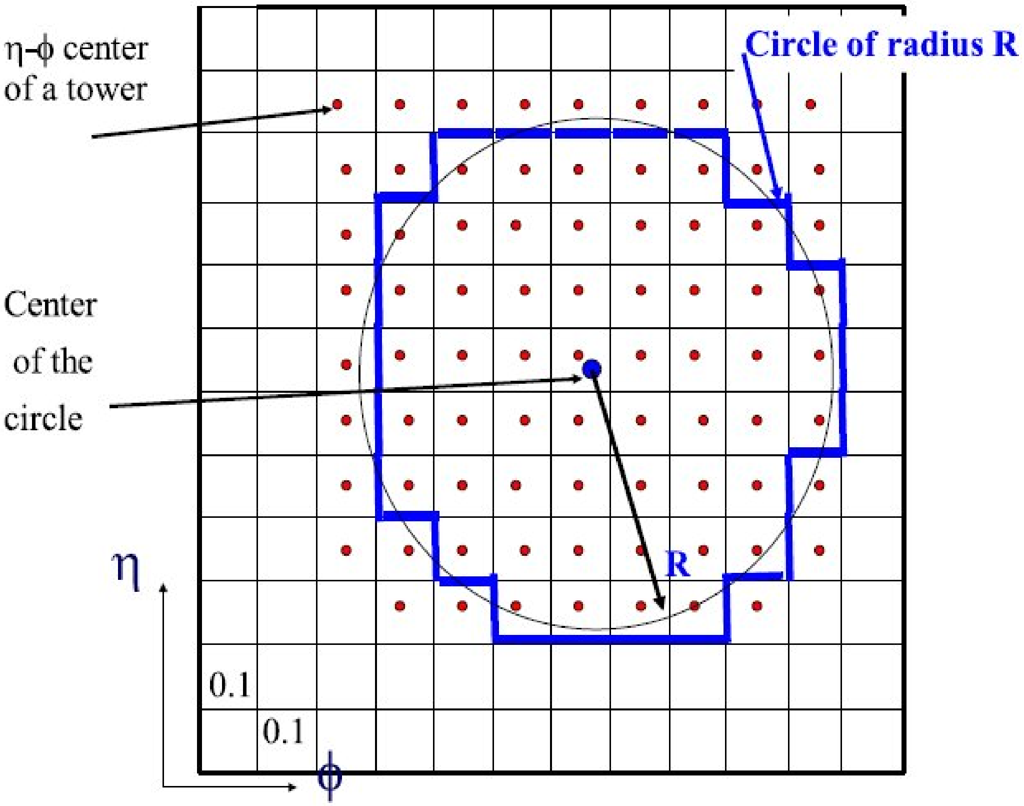


- Cells with **liquid Ar** as active medium. Uranium (EM+fine HD) and Cu/Steel (CC/EC coarse HD) as absorber.
- Central Calorimeter (CC) $|\eta| < 1.1$.
- Endcap Calorimeters (EC) $1.3 < |\eta| < 4$

Module Type	EM	Fine Had.	Coarse Had.
Central			
$\eta_{detector}$	±1.1	±1.0	±0.7
Absorber Material	Uranium	Uranium (1.7% Nb)	Copper
Readout Layers	4	3	1
Segmentation ($\Delta\eta \times \Delta\phi$)	0.1×0.1 (Layer 1, 2, 4) 0.05×0.05 (Layer 3)	0.1×0.1	0.1×0.1
Radiation Lengths	2, 2, 7, 10 X_0 (0.76 λ_a)	1.3, 1.0, 0.9 λ_a	3.2 λ_a
Total X_0	21	96	33
Total λ_a	0.76	3.2	3.2

Photon Identification

CALORIMETER EM CLUSTERS



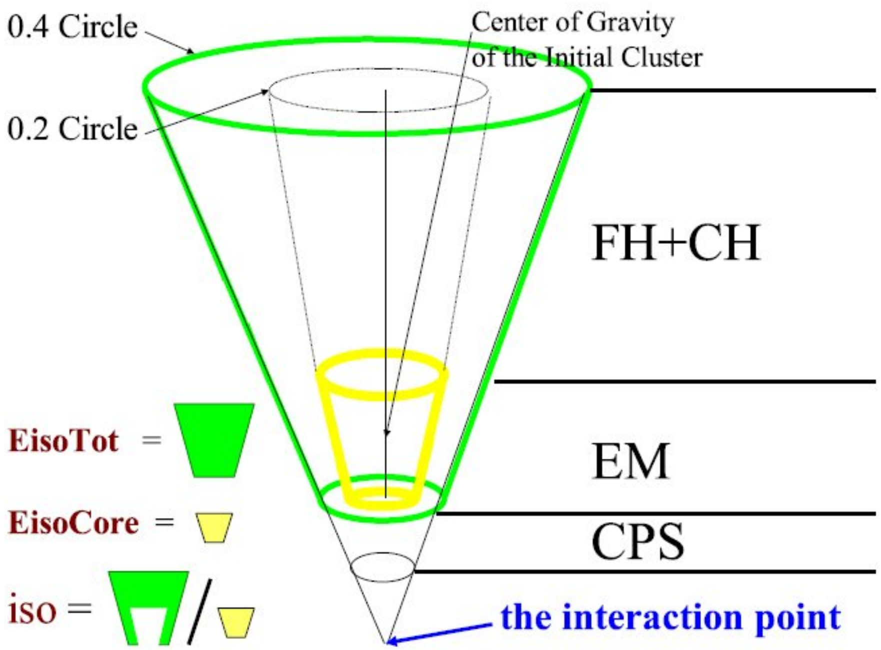
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Towers: cells close in (η,ϕ) space, that pass quality filters.
- Problematic cells are removed (hardware failures, electronic or uranium noise, liquid Ar contamination, non-collision events).
- Simple Cone Algorithm forms clusters with towers around seed towers (500 MeV) within $\Delta R < 0.4$
- Only clusters with EM/(EM+HD) > 0.9 and pT > 1.5 GeV accepted.

Photon Identification

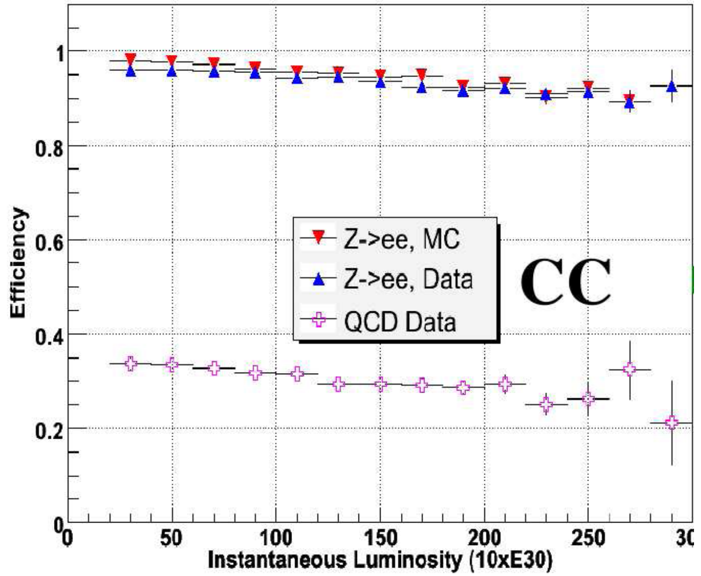
CLUSTER ISOLATION

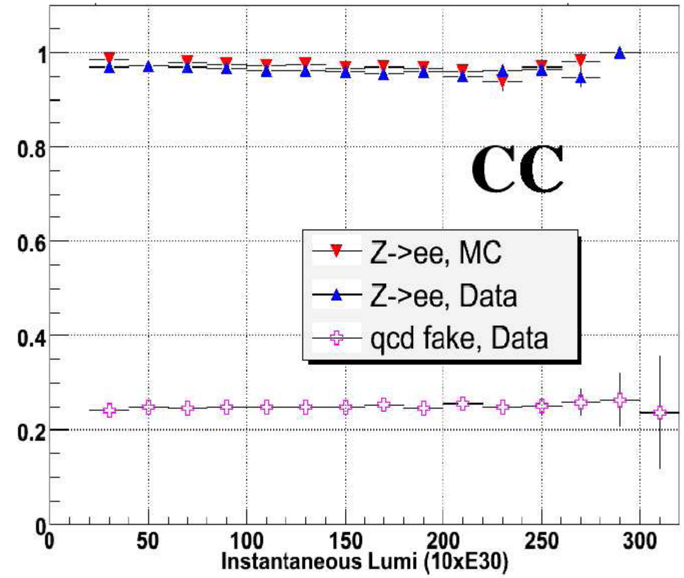
➲ Photon showers are narrow compared to hadronic ones.



$$\text{iso} = \frac{\left(E_{0.4}^{tot} - E_{0.2}^{core}\right) - \alpha_{lumi}}{E_{0.2}^{core}}$$

$\text{iso} < 0.07$



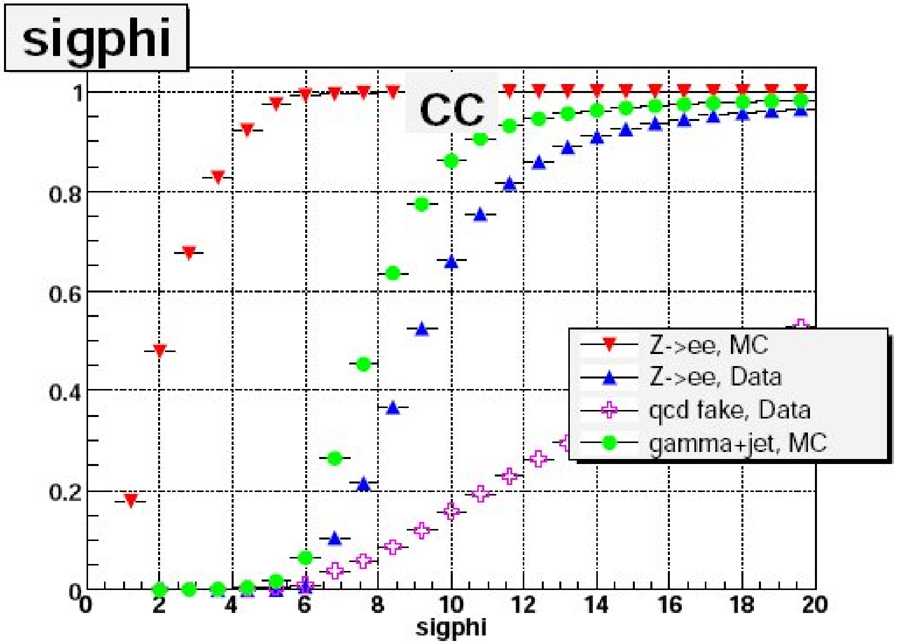


Photon Identification

CLUSTER WIDTH

➲ **SHOWER WIDTH**:

- EM showers narrower than jets.
- Calculate shower width In the azimuthal direction(transverse development).
- We use the shower width calculated at the 3rd EM layer.
- Individual cell energy and azimuthal angle position are used together with the total cluster energy and the energy-weighted azimuthal position of the cluster.



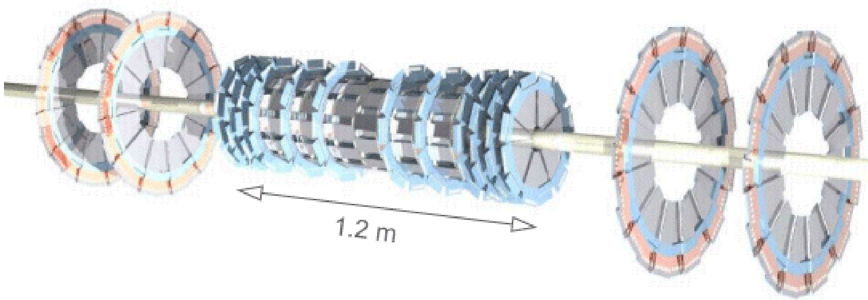
➲ Fine segmentation of the calorimeter provides additional information that can be used to discriminate backgrounds:

- Energy fractions at each layer
- Cluster widths in the longitudinal direction.

Photon Identification

ANTI-USING THE TRACKER

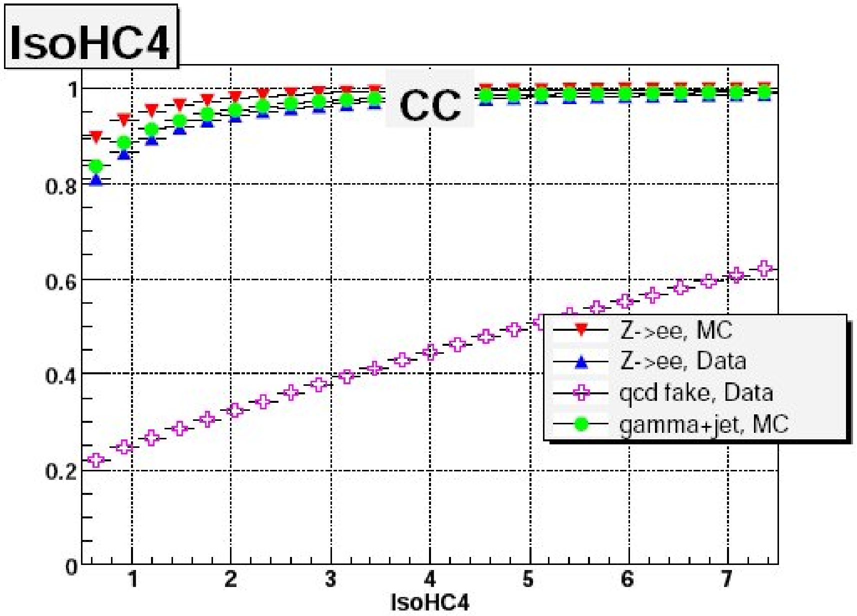
➲ SMT: doped silicon detectors, with barrel and disk configuration

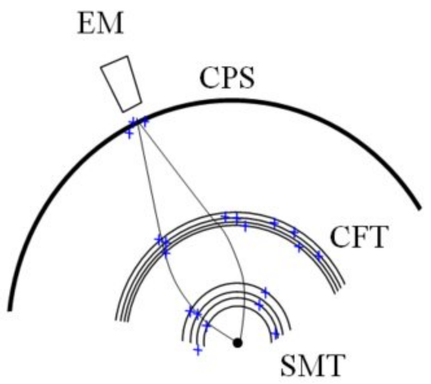


➲ CFT: scintillating fibers arranged in 32 concentric layers with axial and stereo angles.

➲ **TRACK ISOLATION**:

- Fake photon removal.
- Scalar sum of the transverse momenta of all tracks in an annulus of $0.05 < \Delta R < 0.4$ around the cluster less than 2 GeV.





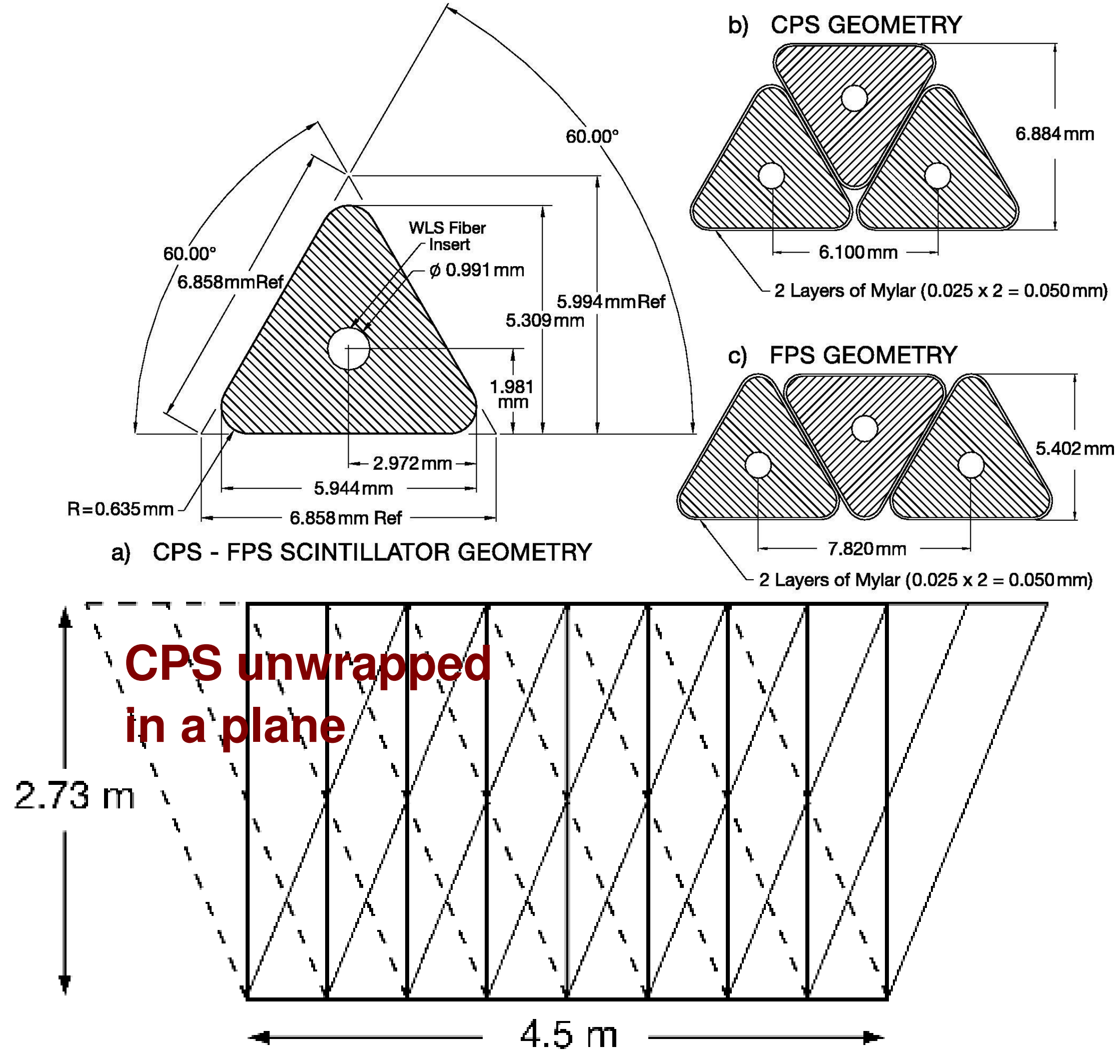
➲ **ANTI-TRACK MATCH**

- non-converted photons do not have charged tracks.
- no significant density of “hits on the road” in the SMT or CFT systems consistent with a track.

Photon Identification

CENTRAL PRESHOWER

- Located between solenoid magnet and the calorimeter, $|\eta| < 1.31$
- There is a lead radiator between the CPS and the solenoid (0.9 Xo) of approximately 1 Xo.
- Fast measurement of position and energy.
- Three cylindrical layers of triangular extruded **strips of scintillating plastic** (WLS fibers embedded collect ionization energy in form of light)
- WLS fiber split at z = 0

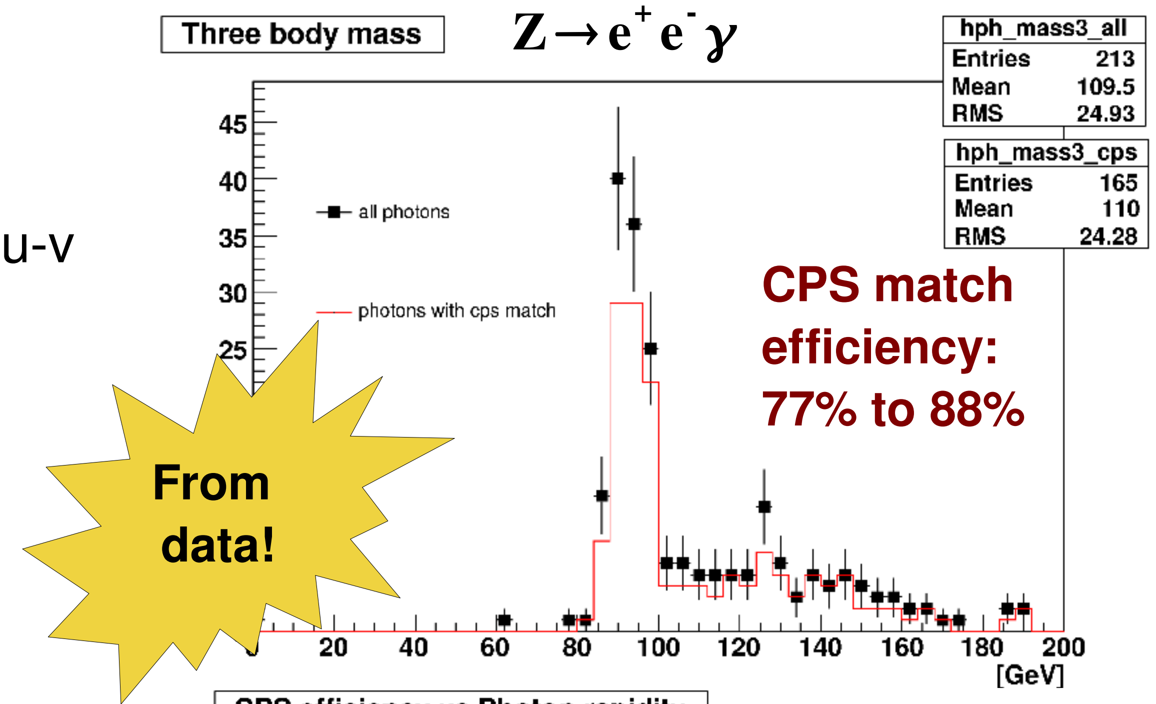


- Each layer has 1280 strips
- Axial layer: strips parallel to beam pipe
- Stereo layers: u and v stereo angles of 23.774° and 24.016° with respect to x layer

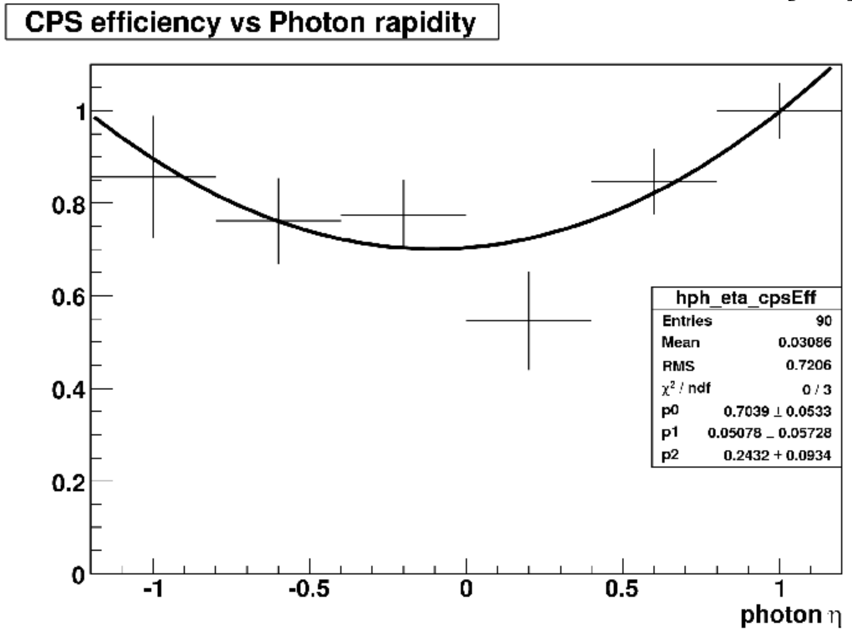
Photon Identification

CPS CLUSTER MATCH

- Single layer clusters (SLC's) formed from contiguous strips.
- Axial layer SLC's matched to u-v layer combinations to form 3D clusters
- Energy and position of 3D clusters determined.
- Important combinatorial background (ghosts) taken care of by deghosting algorithm.
- Merging of clusters at z = 0 is done if necessary.
- **Final EM clusters matched to CPS cluster** in window of 0.1 x 0.1 in (η,ϕ) space.

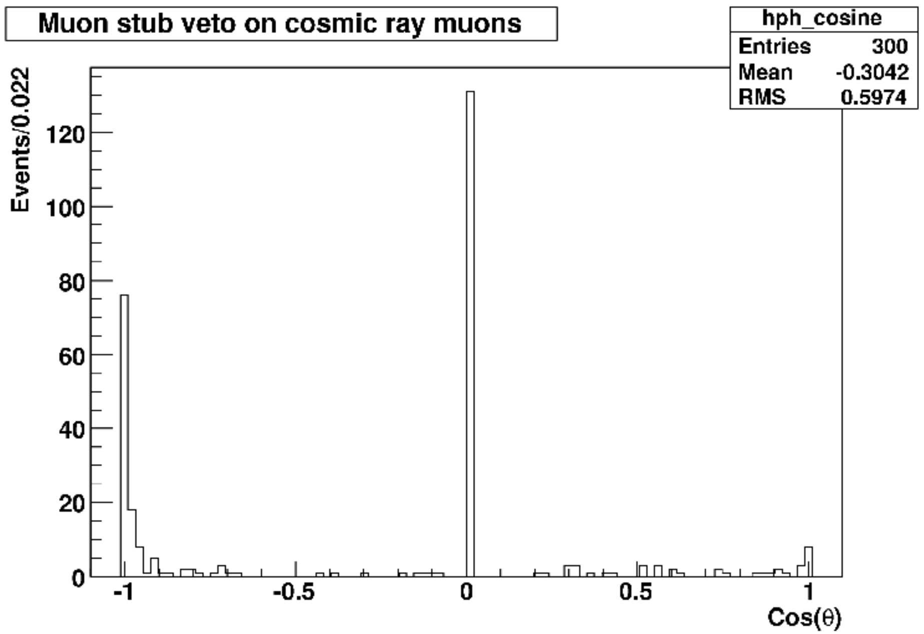


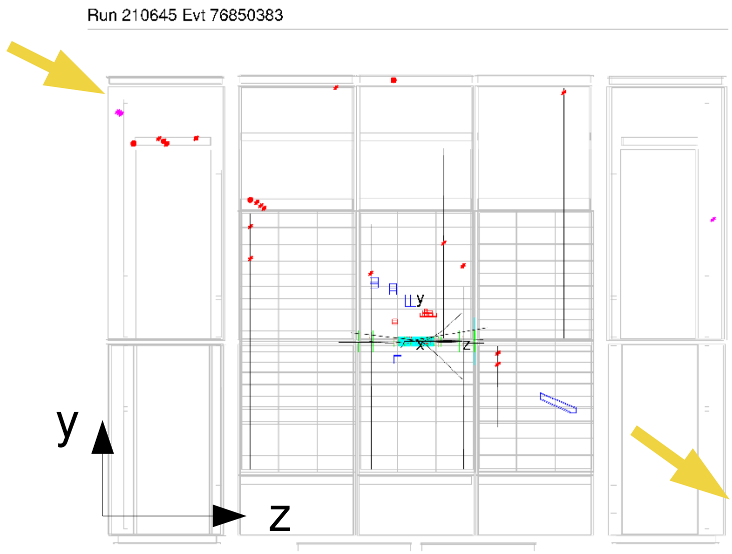
CPS match efficiency: 77% to 88%

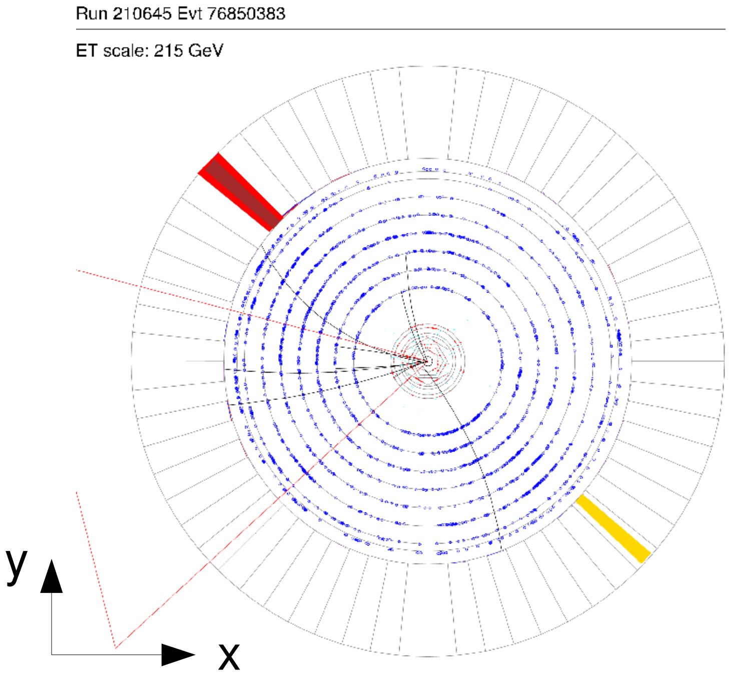


Non-collision background: event display of a cosmic ray event

- Cosmic rays or halo particles can deposit energy in the calorimeter.
- This signature makes a perfect fake LED signal.
- Not too many handles to reject these events, just the photon as an actual physical object.
- Rejection of cosmic muons by timing signal in the muon scintillators and/or presence of characteristic pattern consistent with a cosmic muon.







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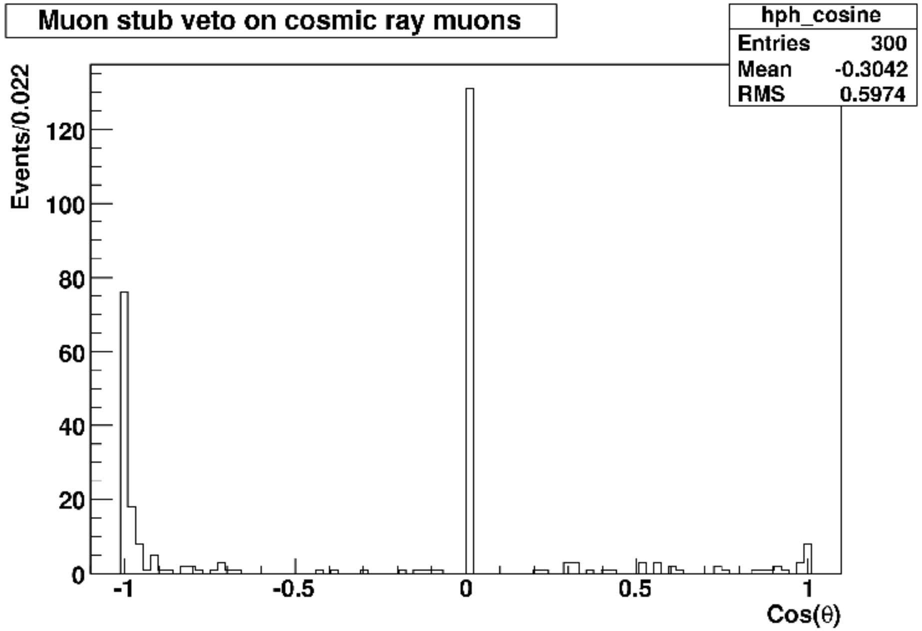
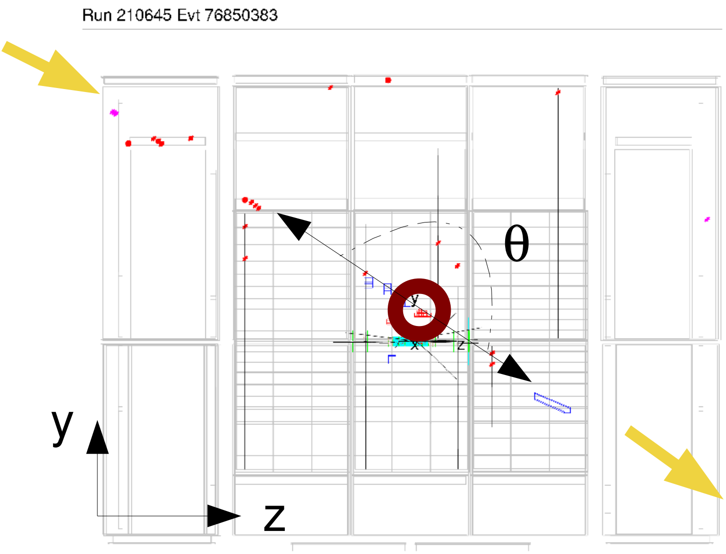
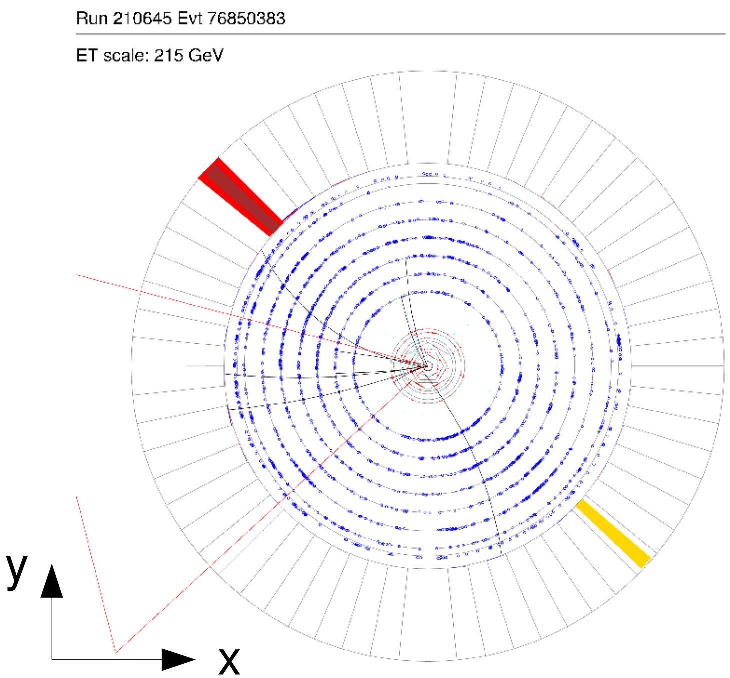
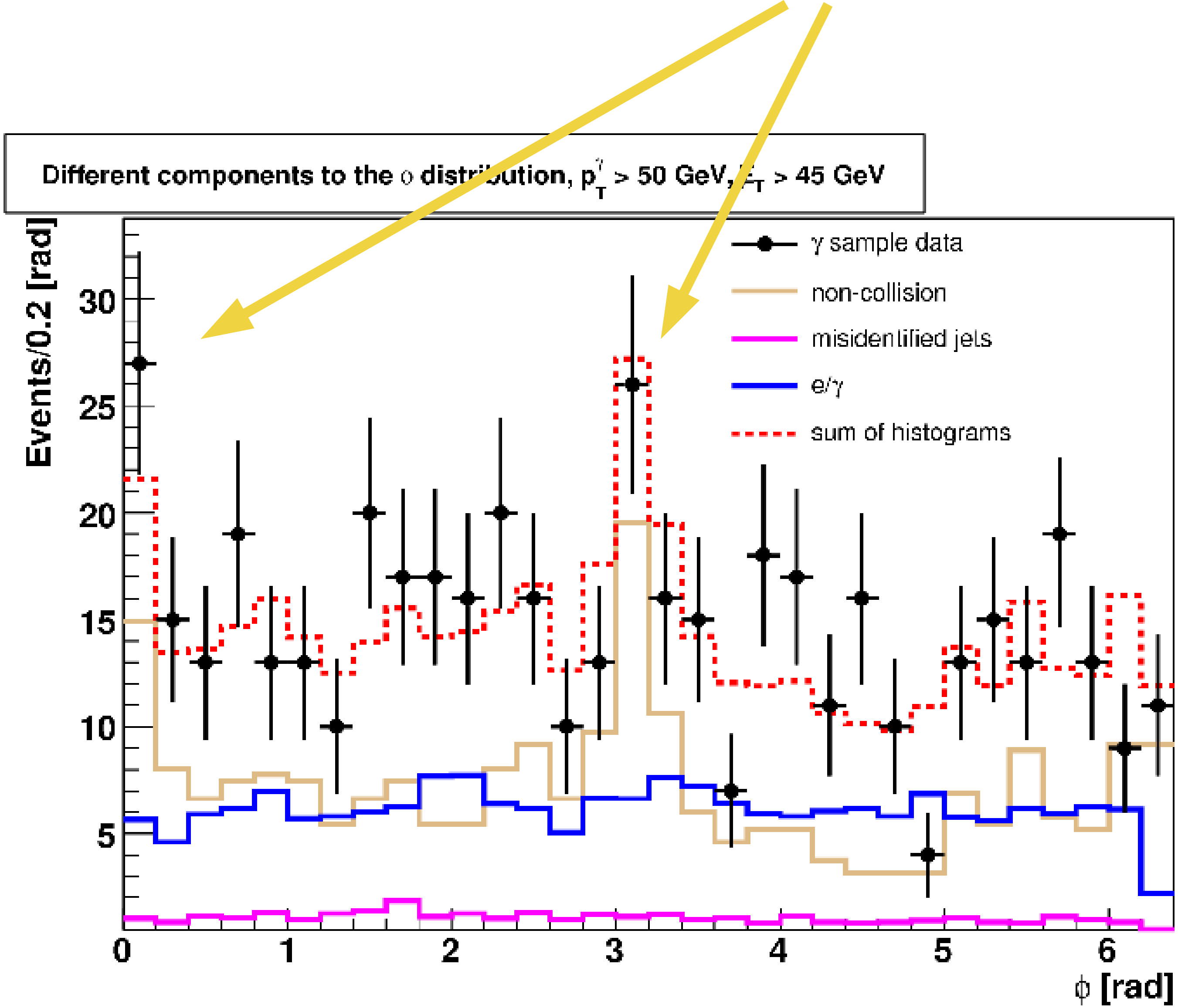






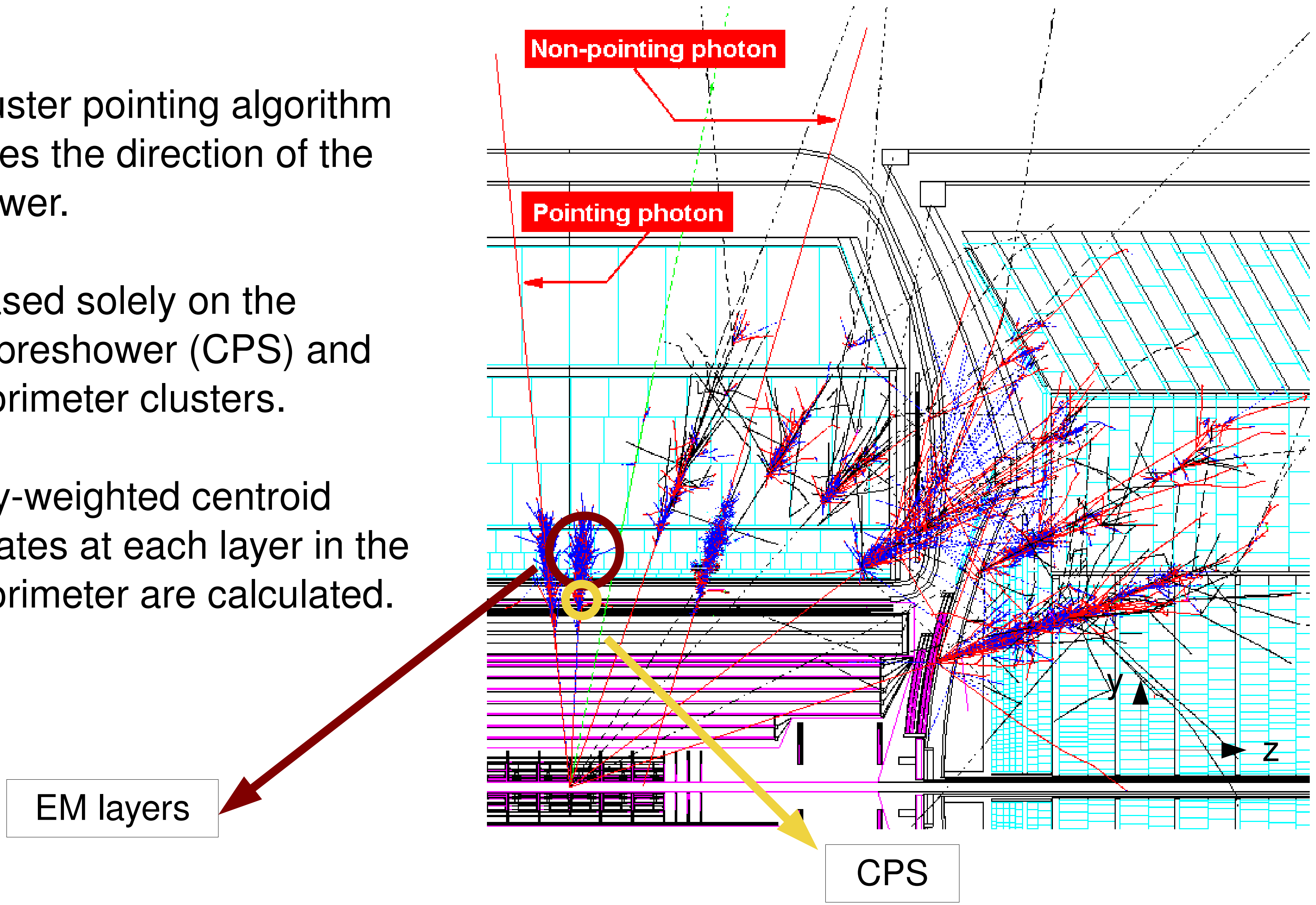
Non-collision background

Non-collision events



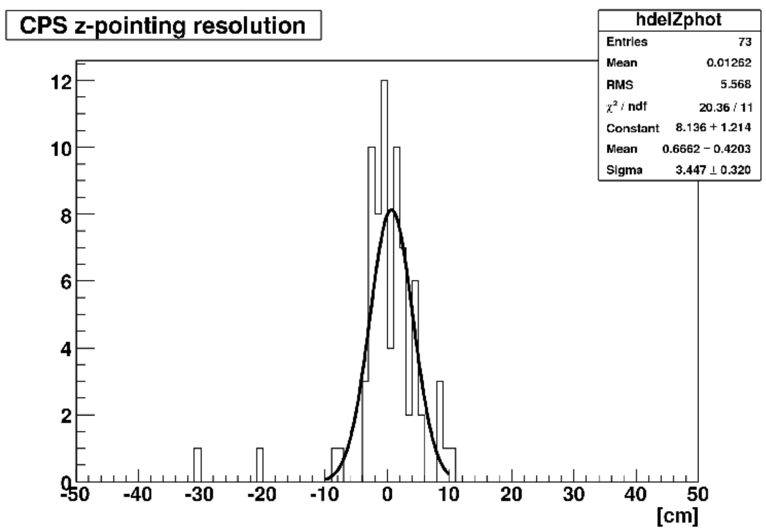
EM Cluster Pointing Algorithm

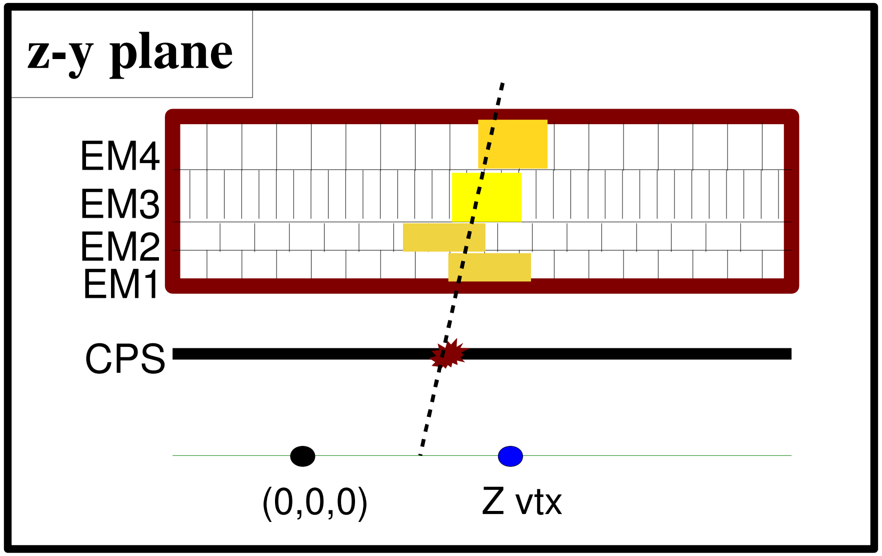
- EM cluster pointing algorithm calculates the direction of the EM shower.
- It is based solely on the central preshower (CPS) and EM calorimeter clusters.
- Energy-weighted centroid coordinates at each layer in the EM calorimeter are calculated.

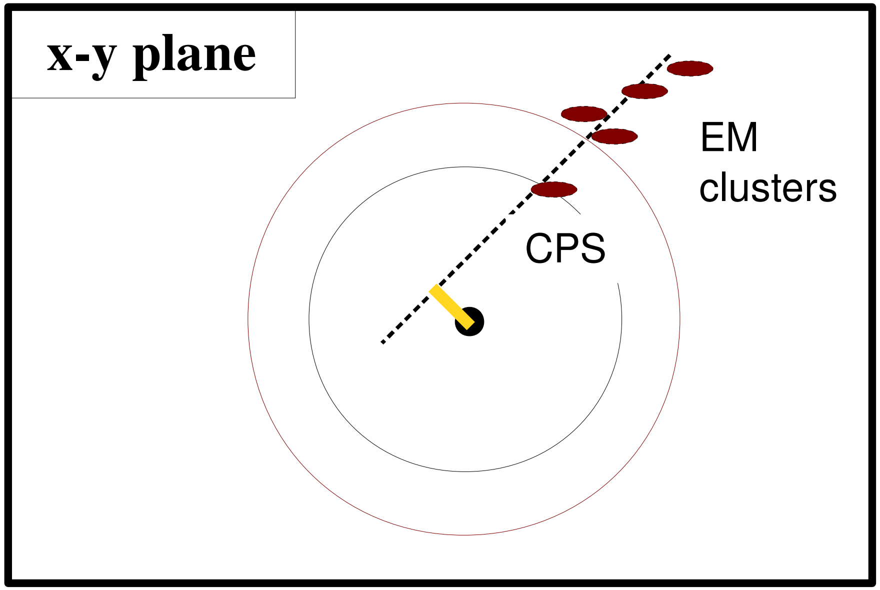


EM Cluster Pointing Algorithm

- Fit of all five floor coordinates of the EM object and the CPS cluster to a straight line.
- Polar plane: **z position of vertex**.
- Azimuthal plane: distance of closest approach to the beam line (**DCA**).
Resolution is about 2-3 cm.





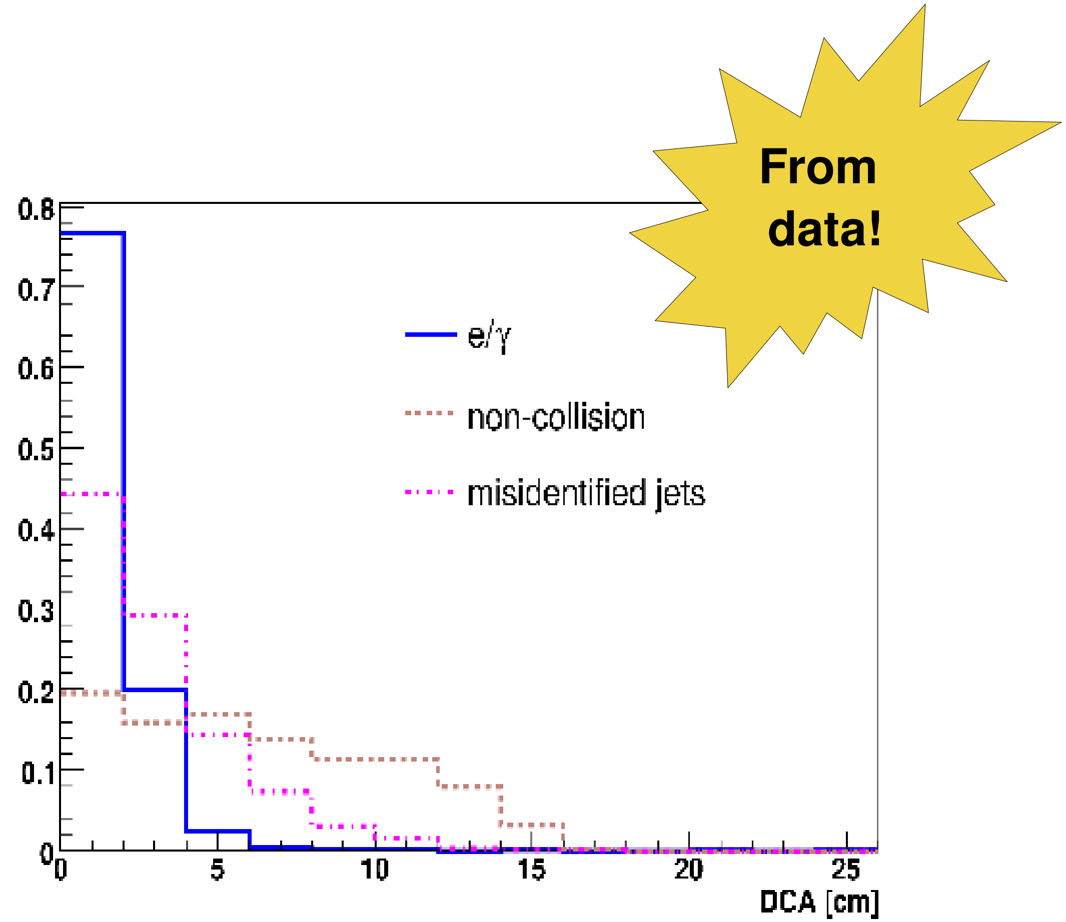


DCA Templates Construction

- **non-collision template** (widest DCA distribution): events with no hard scatter (no reconstructed primary vertex or reconstructed tracks fewer than three), or from cosmic ray events.

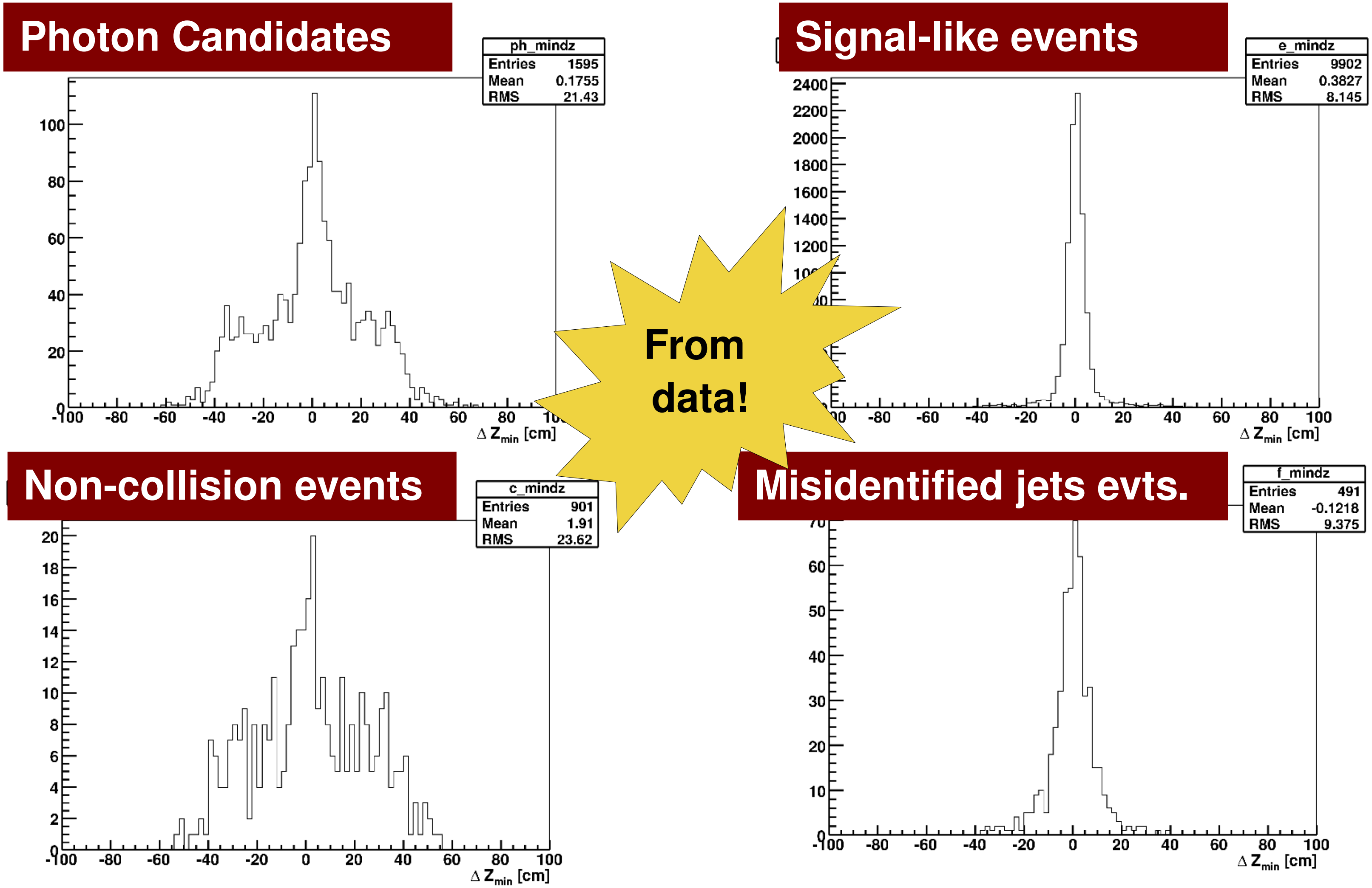
- **misidentified jets template** (wider DCA distribution): EM objects with reversed track isolation.

- **e/γ template** (narrow DCA distribution): Obtained from sample of isolated electrons.



Pointed Vertex

- Require at least one reconstructed interaction vertex consistent with the measured direction of the photon.
- Difference in the z-coordinate position less than 10 cm.
- Re-vertexing at high luminosities.



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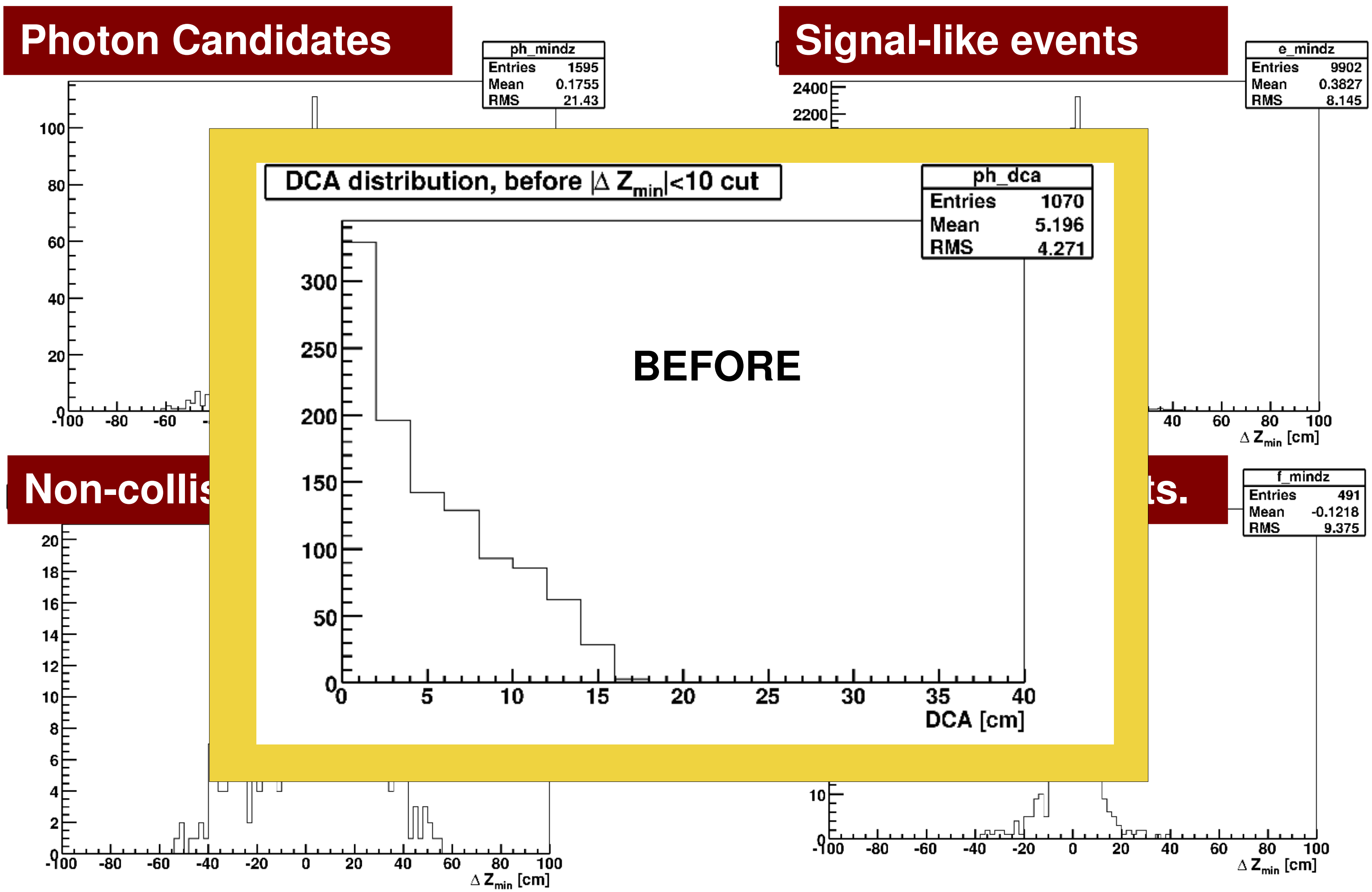

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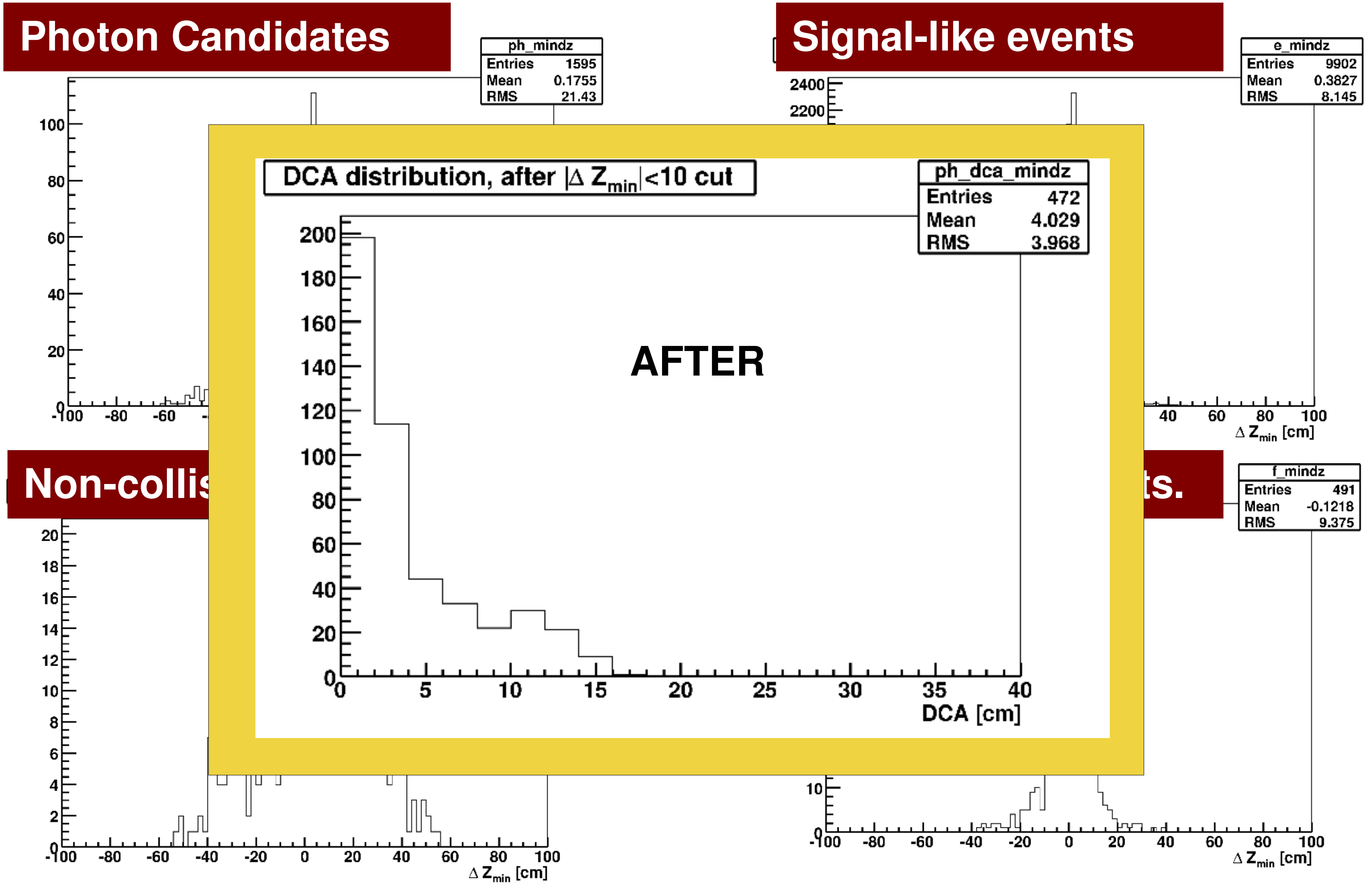
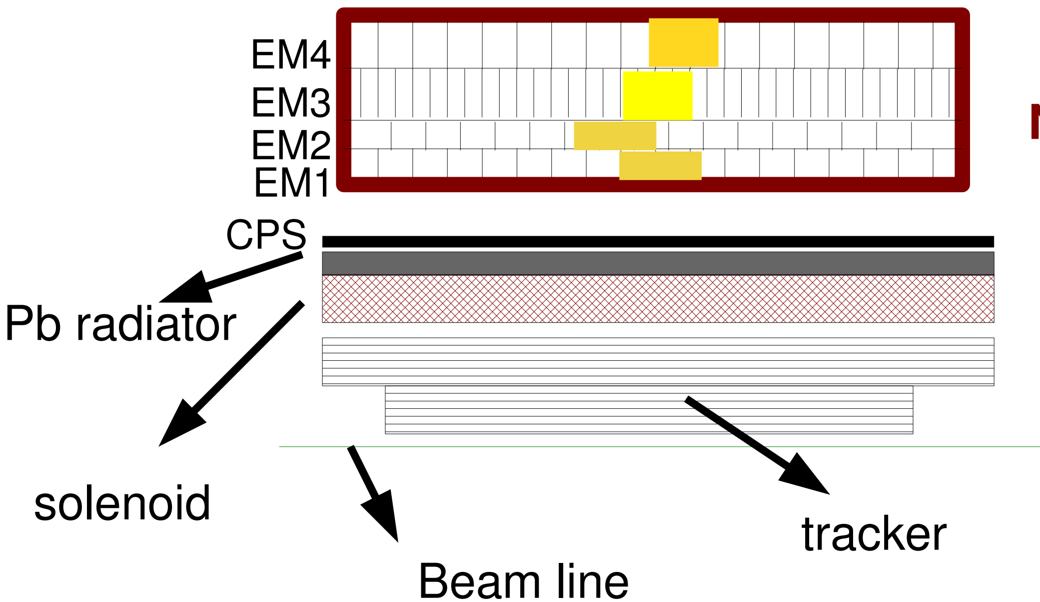
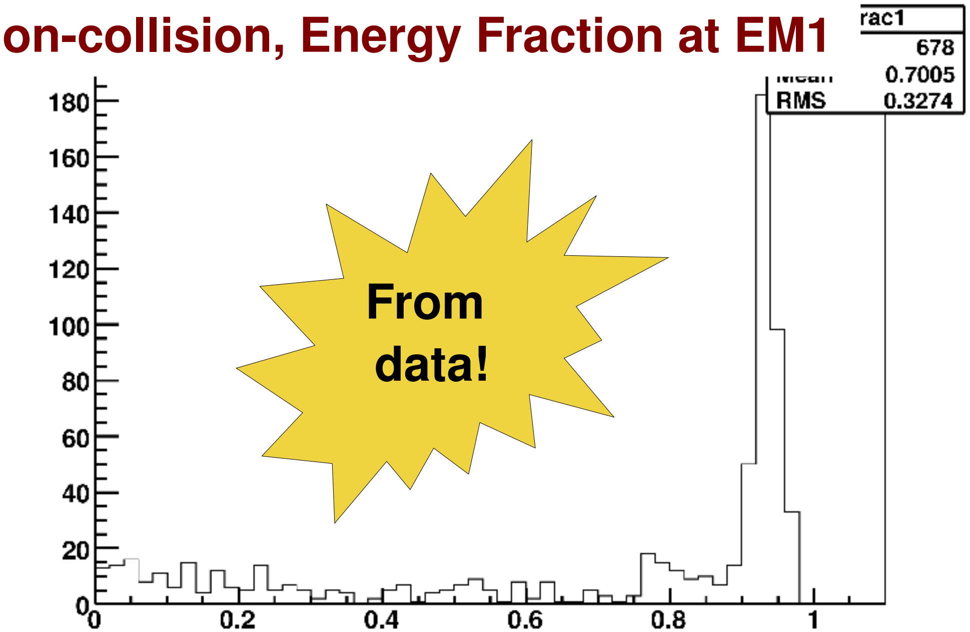


Shower Shape

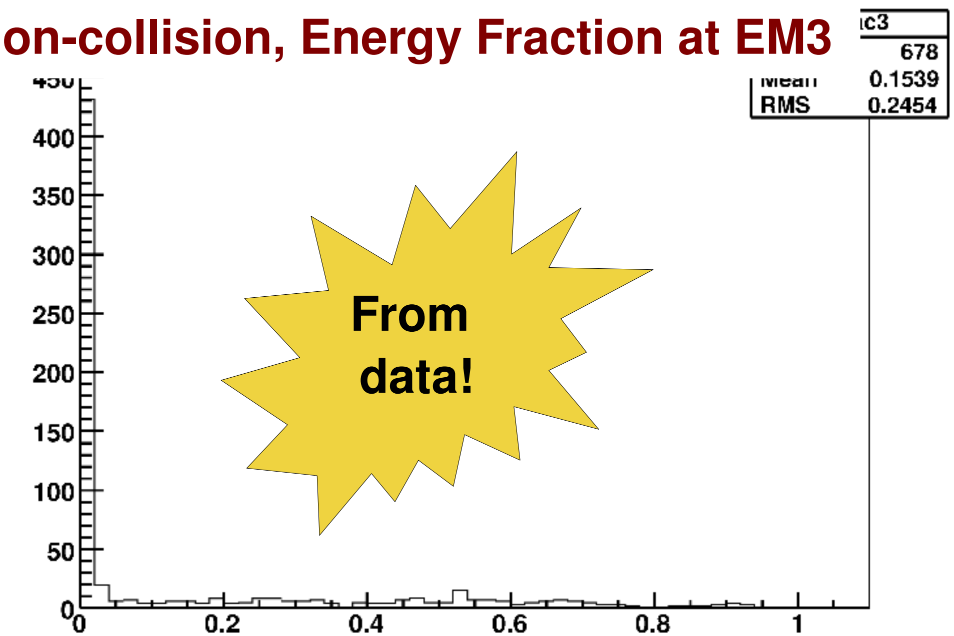
- EM objects from interaction region expected to deposit most of their energy in the 3rd layer of the EM calorimeter.
- Particles not from the interaction region deposit all their energy in the first EM layer.



Non-collision, Energy Fraction at EM1

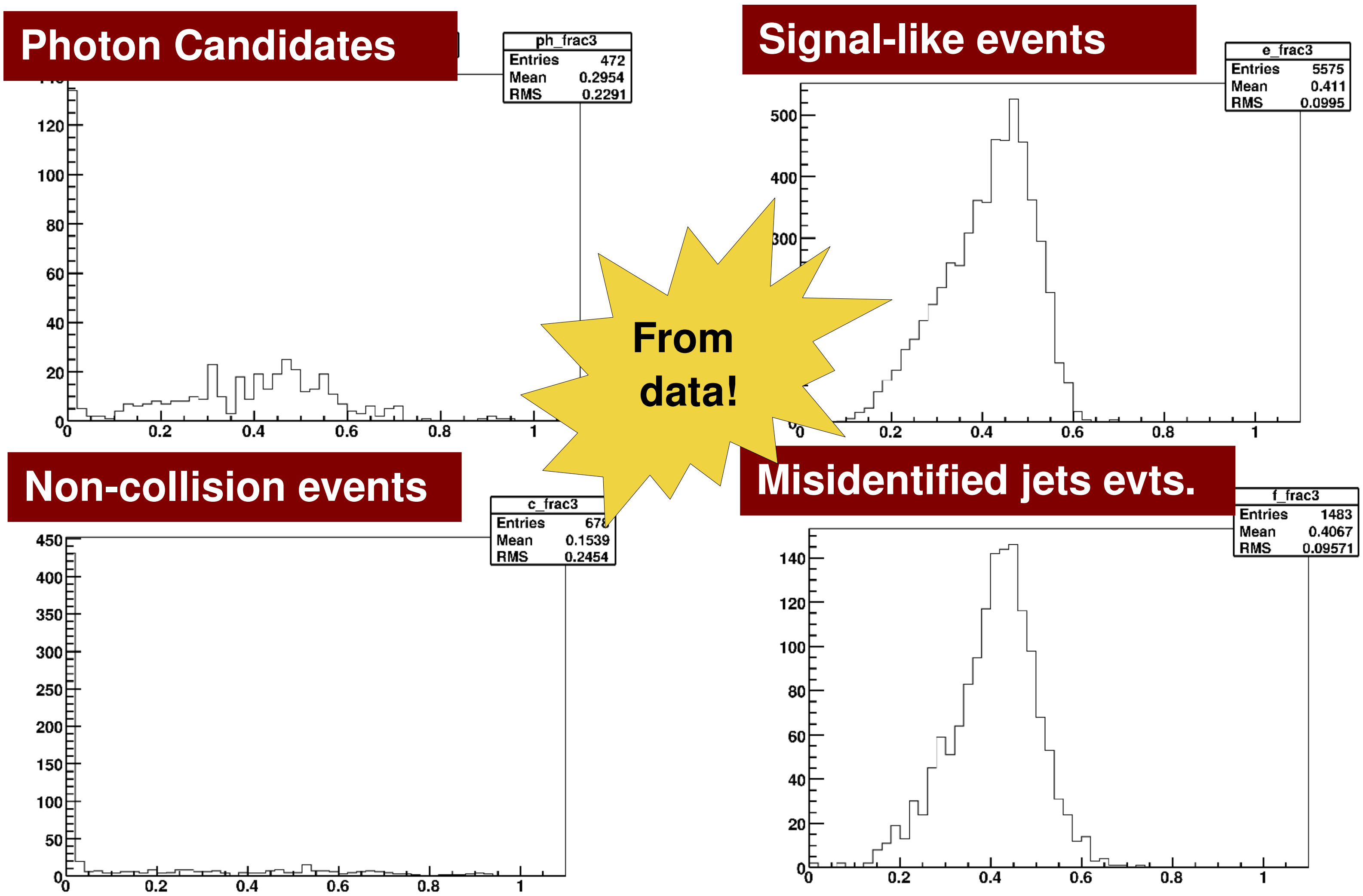


Non-collision, Energy Fraction at EM3



Shower Shape (EM3 fraction)

➲ Require photon showers to deposit at least 10% of their total energy in the third layer of the EM calorimeter.



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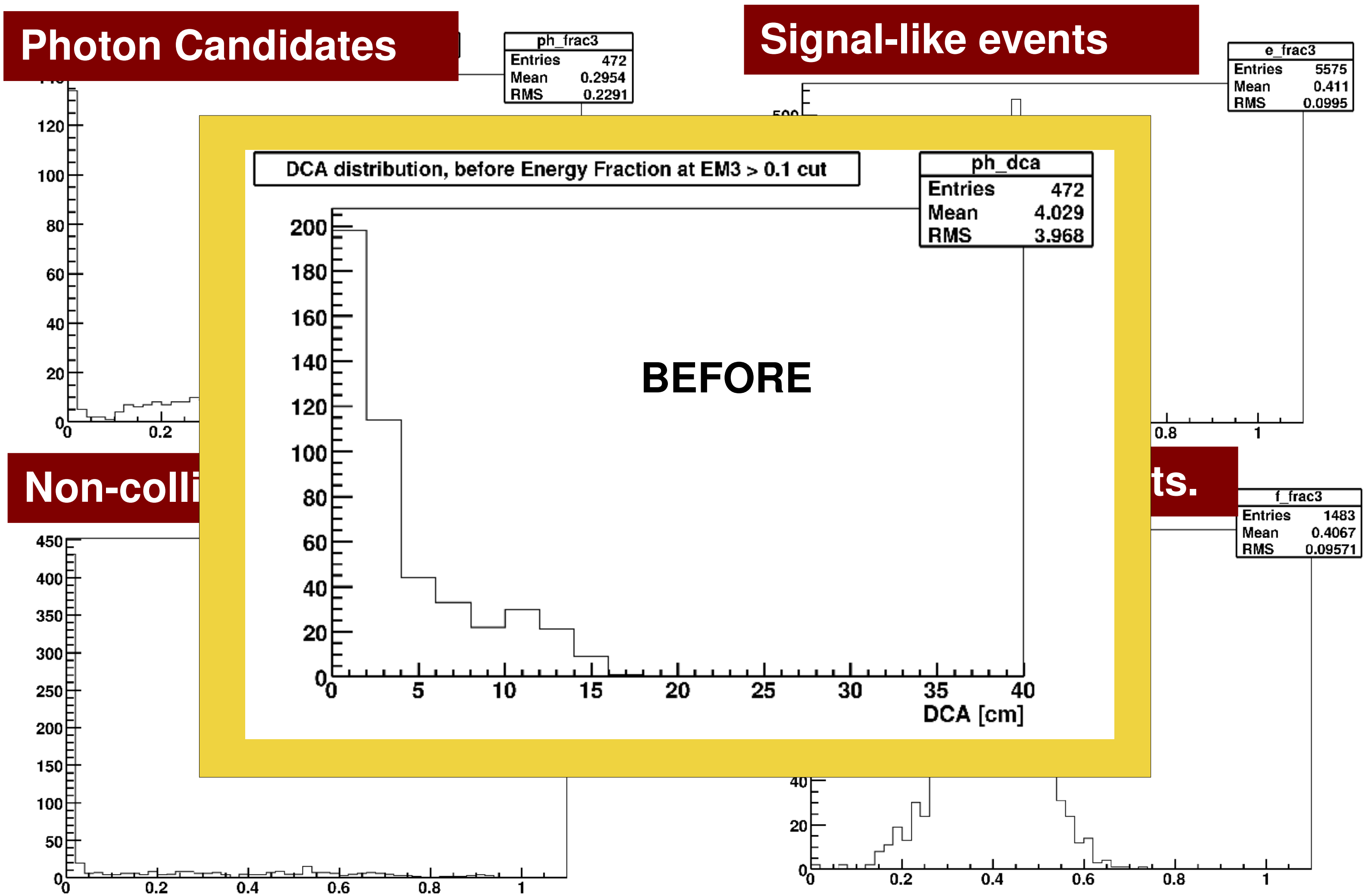

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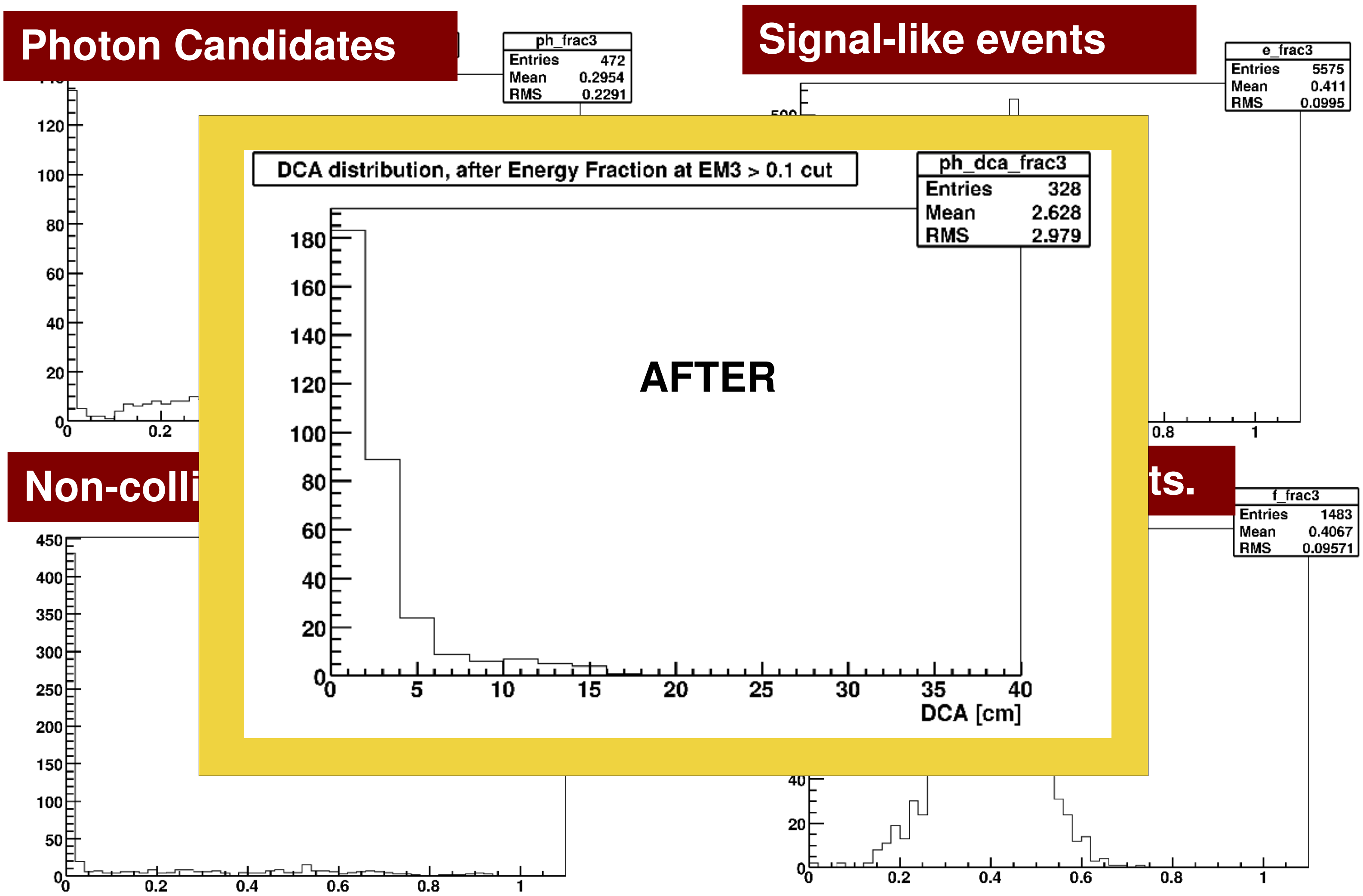
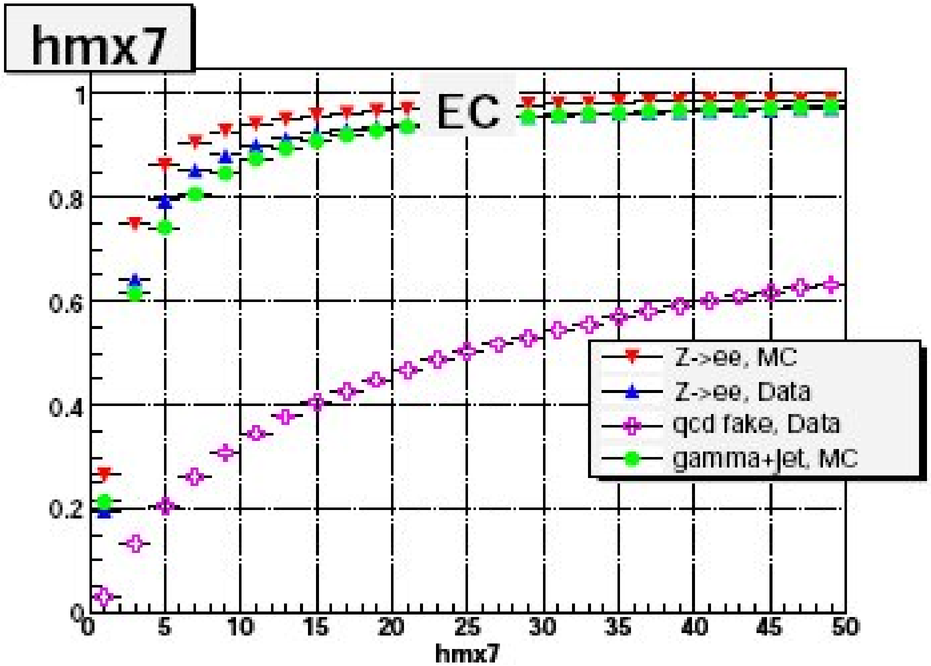


Shower Shape (H-Matrix)

- Additional quantity, in principle designed for electrons.
- Can be used loosely for photon identification to achieve some additional background rejection.
- Eight or seven variables can be used to construct a covariance matrix.
- The H-Matrix χ^2 is calculated using the inverted covariance matrix, data, and the mean values from MC electron profile.
- A shower matching the MC profile will have low χ^2.



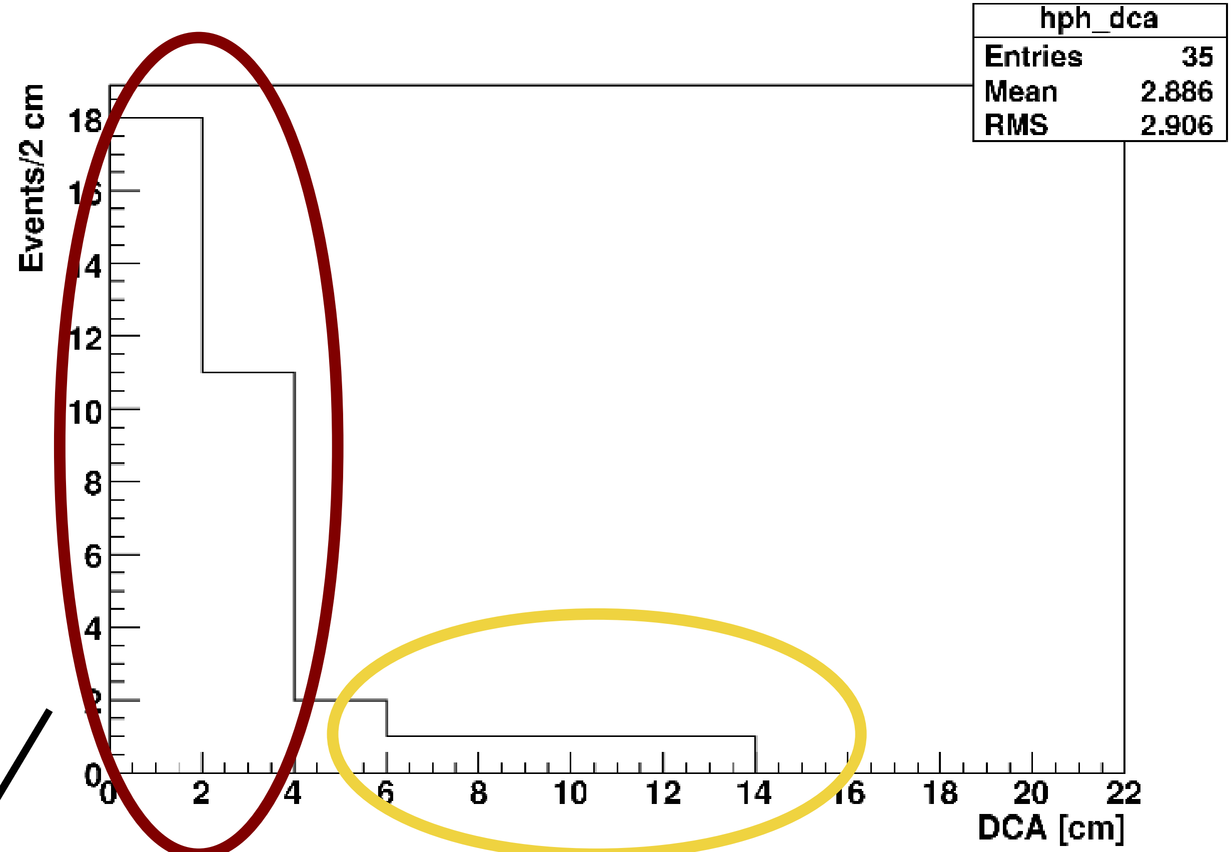
- Variables x used:
  - Fractional energy in each of the EM layers.
  - The total electromagnetic energy.
  - The energy weighted shower width in z and azimuthal directions
  - The z vertex distribution.

The *Photon* sample

ADDITIONAL REQUIREMENTS

Photon selection:

- pT > 90 GeV
- MET > 70 GeV, to guarantee no multijet background.
- No jets with pT > 15 GeV to avoid large MET due to mismeasurement of jet energy.
- No muons and no energetic tracks in the event.



Most of signal-like events concentrated in this region (e/gamma) events + EM jets.

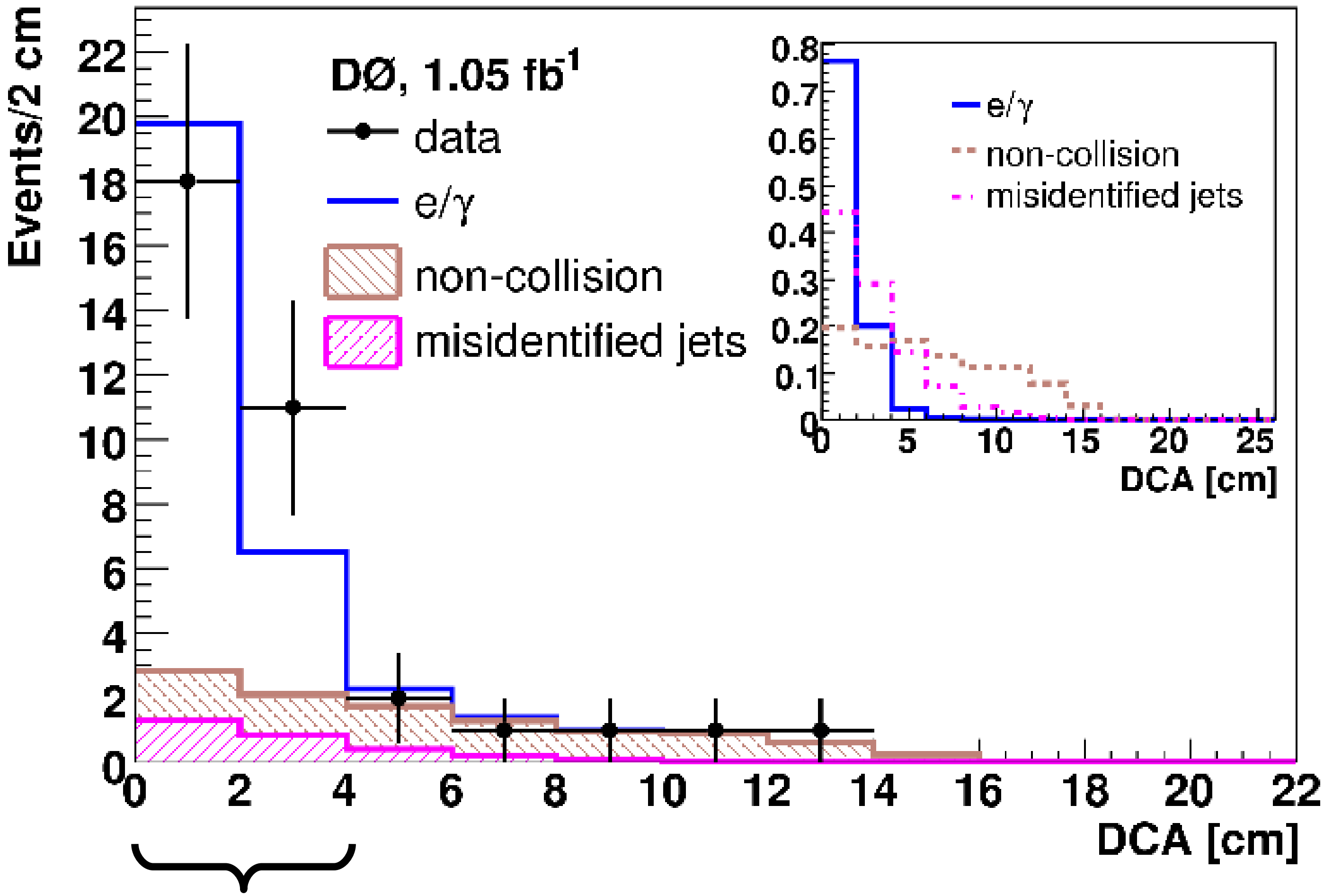
We use DCA templates to estimate these contributions.

Non-collision events + some misidentified jets

e/γ and non-collision background determination

DCA TEMPLATE FIT

- We fit the DCA distribution in the photon sample to a linear sum of the three templates, fixing the contribution of the misidentified jets.



Most of the signal is concentrated in this region.

Prediction of *misidentified jets* background

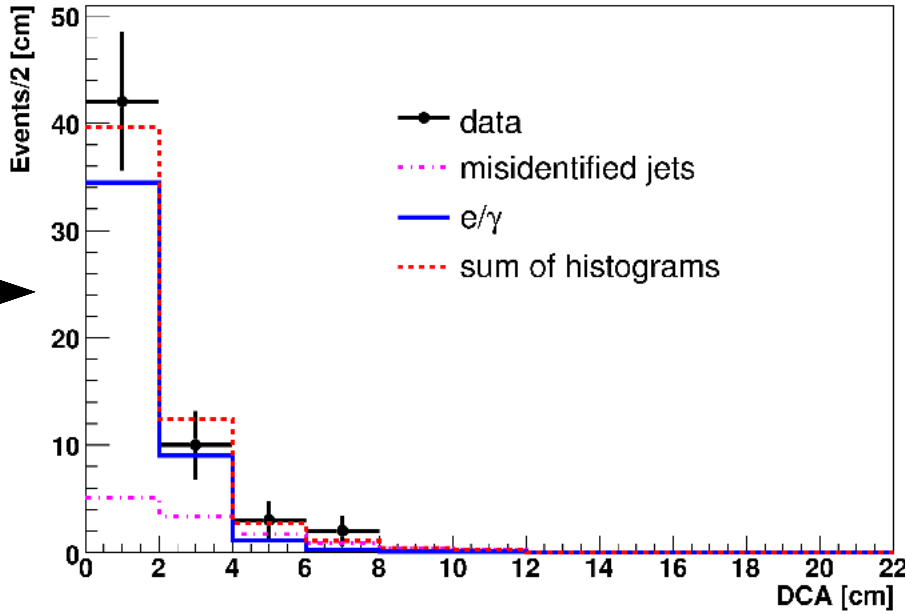
photon sample: number of events from misidentified jets N_{misid} -> **unkown**.
fake photon sample (inverted track isolation): number of events N_{fake}-> **known**.

N_{misid} can be predicted from the fake photon sample based on the rates at which jets, passing all other photon ID criteria, fail or pass the track isolation.

EM + jet sample

fake (inverted track isolation) + jet: N_1

photon (track isolation) + jet: has N_2 **(from the fit)** events from misid jets



$$N_{misid} = N_{fake} \times (N_2/N_1)$$

Remaining Backgrounds Estimation

$$Z + \gamma \rightarrow \nu \bar{\nu} + \gamma$$

$$W + \gamma \rightarrow l \nu + \gamma$$

- Estimated from a sample of Monte Carlo (MC) events generated with PYTHIA.
- Same selection requirements as for data plus correction factors to account for differences in simulation.

$$W \rightarrow e \nu$$

- Estimated from data using a sample of isolated electrons. Same requirements as for the photon sample. The remaining number of events is scaled by:

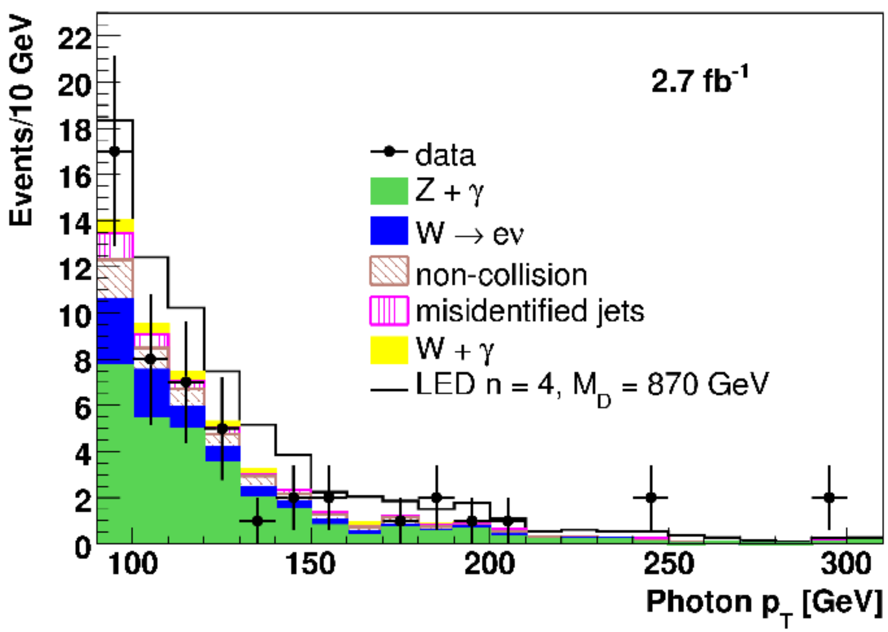
$$\frac{(1 - \epsilon_{trk})}{\epsilon_{trk}}$$

ϵ_{trk}: track reconstruction efficiency

Results

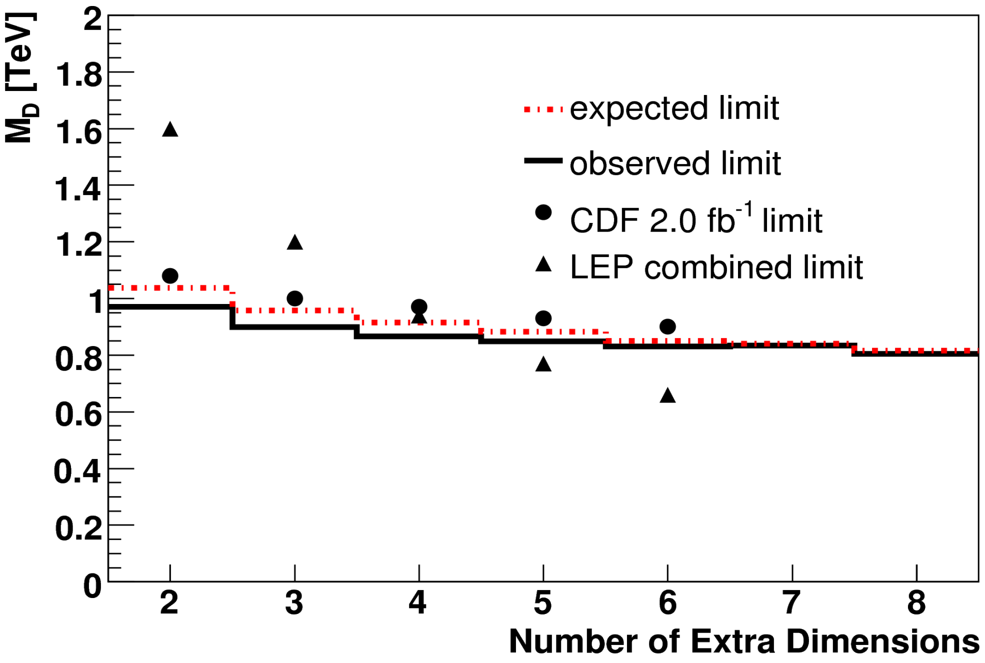
FINAL COUNTS

Background	Number of expected events, combination (2.7 fb^{-1})
$Z + \gamma \to \nu\bar{\nu} + \gamma$	29.5 ± 2.5
$W \to e\nu$	8.5 ± 1.7
Non-collision	6.6 ± 2.3
Misidentified jets	3.1 ± 1.5
$W + \gamma$	2.22 ± 0.3
Total Background	49.9 ± 4.1
Data	51



LIMITS

n	Combination 2.7 fb^{-1} observed (expected) cross section limit (fb)	Combination 2.7 fb^{-1} observed (expected) M_D lower limit (GeV)
2	19.0 (14.6)	970 (1037)
3	20.1 (14.7)	899 (957)
4	20.1 (14.9)	867 (916)
5	19.9 (15.0)	848 (883)
6	18.2 (15.2)	831 (850)
7	15.9 (14.9)	834 (841)
8	17.3 (15.0)	804 (816)



Summary

➲ A search for the direct production of gravitons in association with single photons has been presented.

➲ Standard D0 photon identification is not enough to reject non-collision backgrounds for final states with just one single photon.

➲ The EM pointing algorithm has been proved to be an important tool to discriminate against these unwanted events.

➲ No evidence for the presence of LED has been found.

➲ Some of the ideas presented in this talk might be used in new hadron collider experiments (ATLAS in particular due to the fine segmentation of its calorimeter).

Backup Slides

Backup slides

Shower Width Formulas

$$\sigma_{r\phi} = \frac{\sum_{i}^{cells} E_i \times R^2 \times \sin^2(\phi_C - \phi_i)}{E_C} < 16\,\mathrm{cm}^2$$

$$\phi_C = \frac{\sum_{i}^{cells} E_i \phi_i}{\sum_{i}^{cells} E_i}$$

E_C : energy of the cluster

EM Pointing Centroid Postion Calculation

- Centroid position calculation (f can be x, y, or z coordinates):

$$f^{layerN} = \frac{\sum_{cells}^{layerN} w_{cell}^{layerN} f_{cell}}{\sum_{layerN}^{cells} w_{cell}^{layerN}}$$

$$w_{cell}^{layerN} = \max\left\{0, \left[w_0 + \ln\left(\frac{E_{cell}^{layerN}}{E_{total}^{layerN}}\right)\right]\right\}$$

H-Matrix

- Covariance Matrix:

$$M_{ij} = \frac{1}{N} \sum_{n=1}^{N} (x_i^n - \bar{x}_i)(x_j^n - \bar{x}_j)$$

MC simulation

- H-Matrix χ^2 :

$$X_{HM}^2 = \sum_{i,j=1}^{8} (x_i' - \bar{x}_i) H_{ij} (x_j' - \bar{x}_j)$$

Data