Physics with Single Photon plus Missing Energy Final States at DØ

Fermilab Research Associate Interview

2009-03-10

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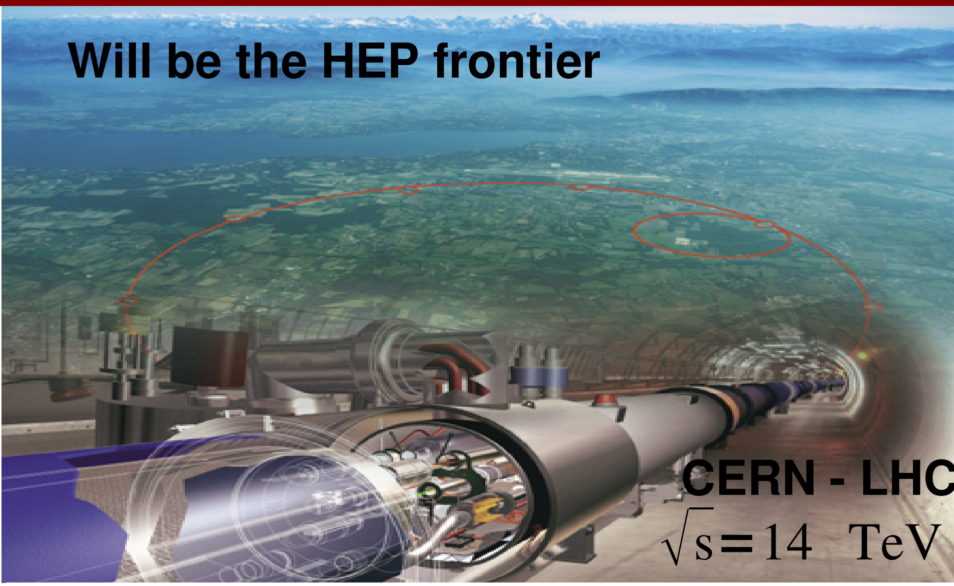
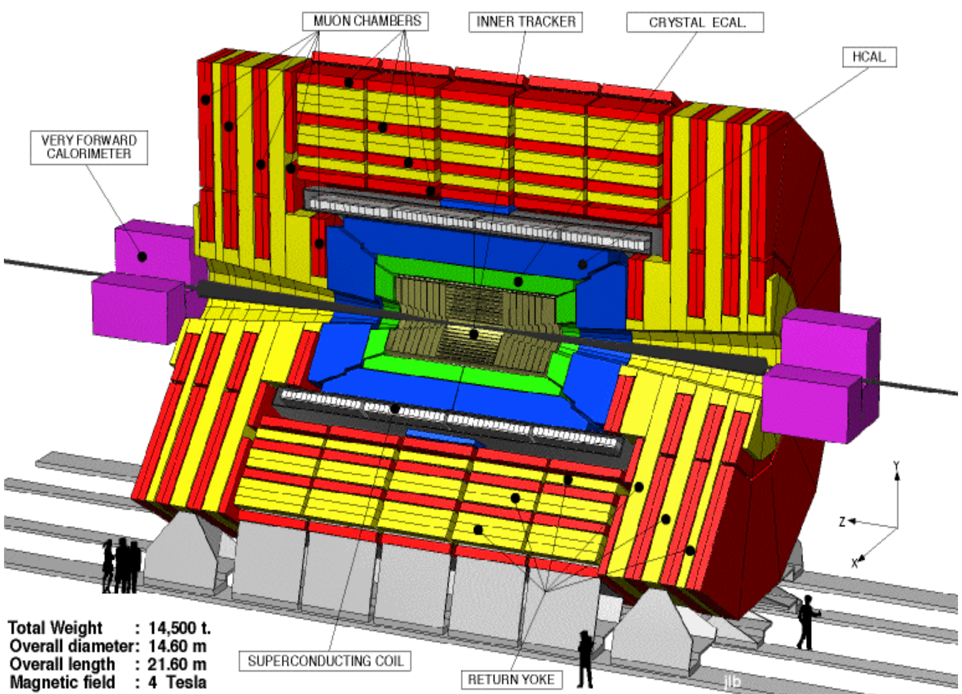
Outline

- Back from the future: from the CMS experiment at the LHC to the DØ experiment at the Tevatron
- $Z\gamma$ production and Large Extra Dimensions (LED)
- Photon identification
- Non-collision background and the EM pointing algorithm
- Single photon events selection and background estimation
- Results/Summary

From the CMS Experiment at the LHC...





Compact Muon Solenoid (CMS) detector

Early years as a graduate student

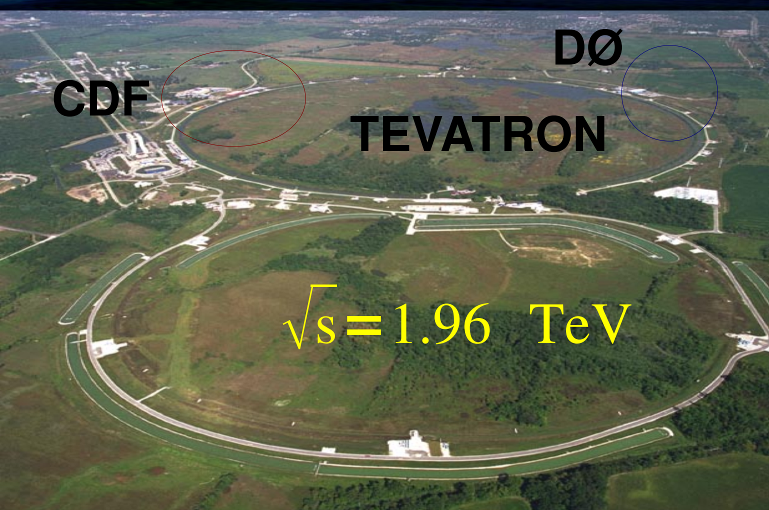
As part of the ECAL group:
Test Beam 2006, combined HCAL + ECAL at the H2 facility at CERN:
- Intercalibration of one ECAL supermodule.
- Data quality for all intercalibration efforts.

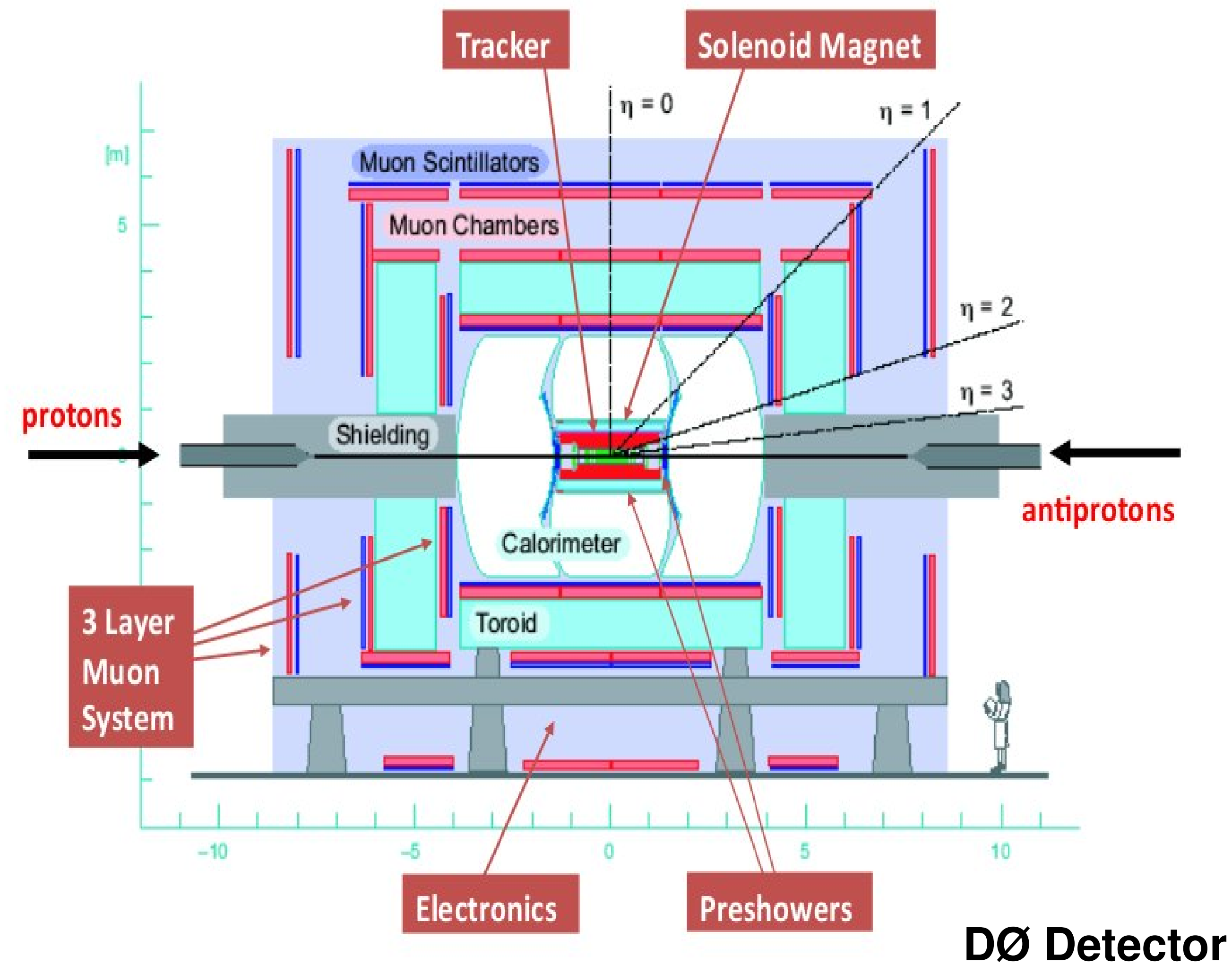
As part of the HEEP group:
Developed and implemented high energy electron calibration technique.

+ MC production for physics analyses at the LPC.

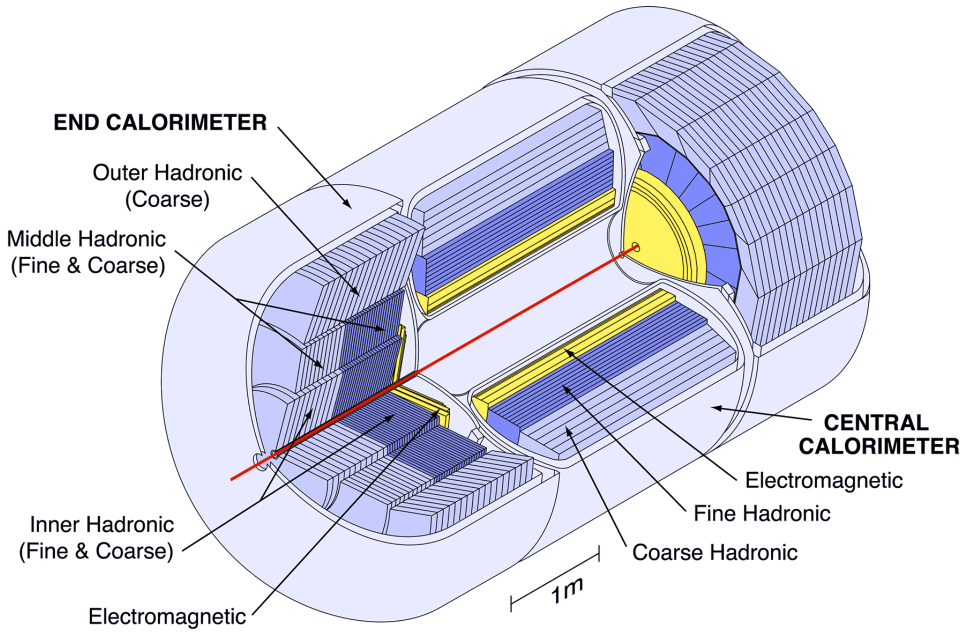
Everything towards the discovery of new physics

…to the DØ Experiment at the Tevatron





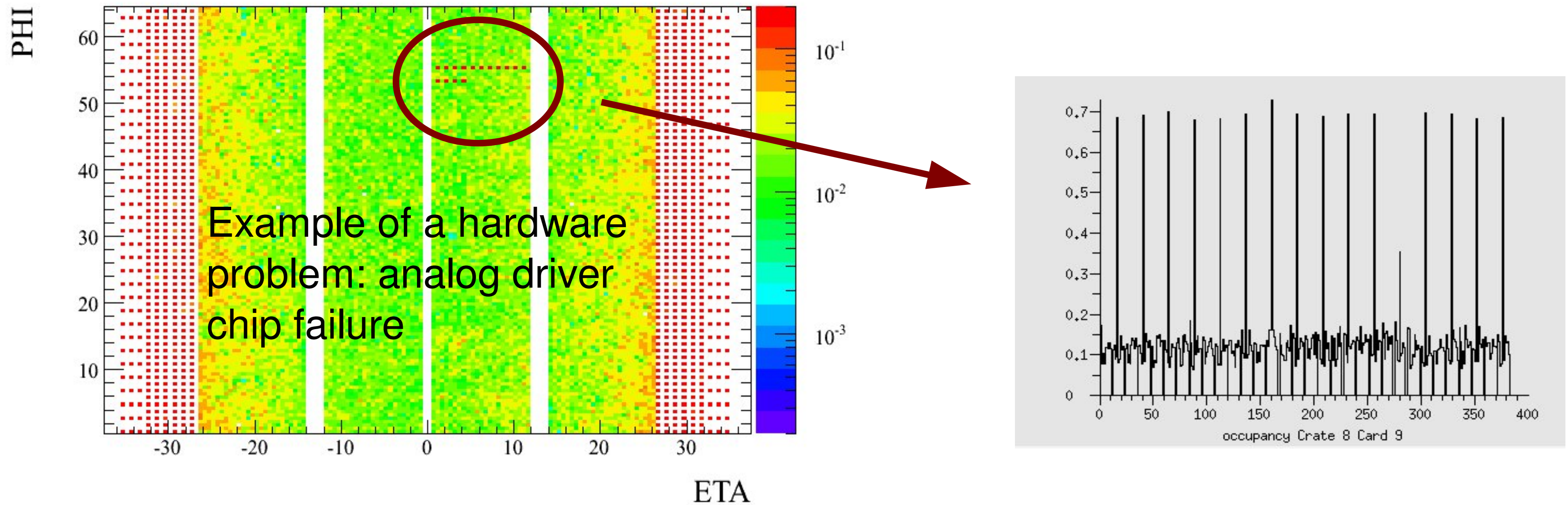
DØ Calorimeter and Operations



The DØ calorimeter operations and on-call expert work:

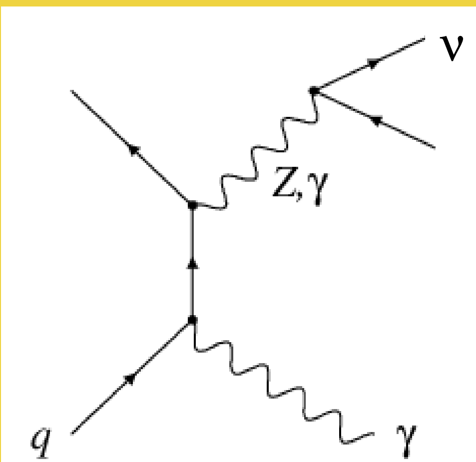
- Detect/prevent hardware problems.
- Assist, train other experts and shifters.
- Create and maintain on-line instructions for efficient data taking (91% during 2008!!).

Cell occupancy 2D. EM3 (ZERO BIAS)

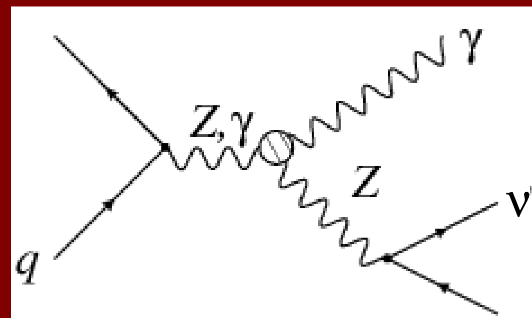


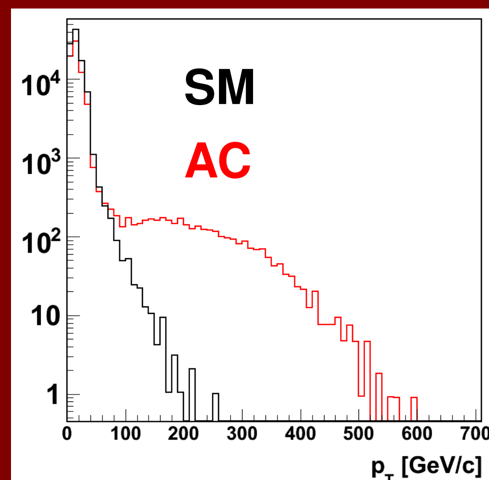
$Z\gamma \rightarrow \nu\bar{\nu}\gamma$ Production and Trilinear Anomalous Couplings (AC)

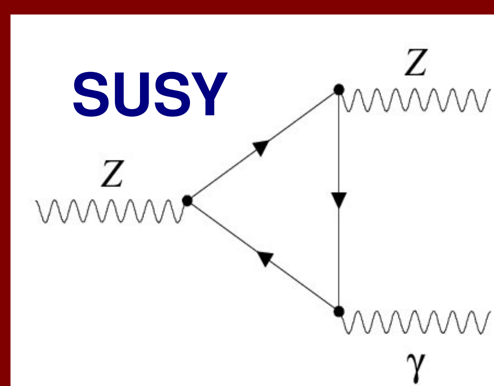
Standard Model



- Only contribution at tree level
- QED corrections at the 10^{-4} level







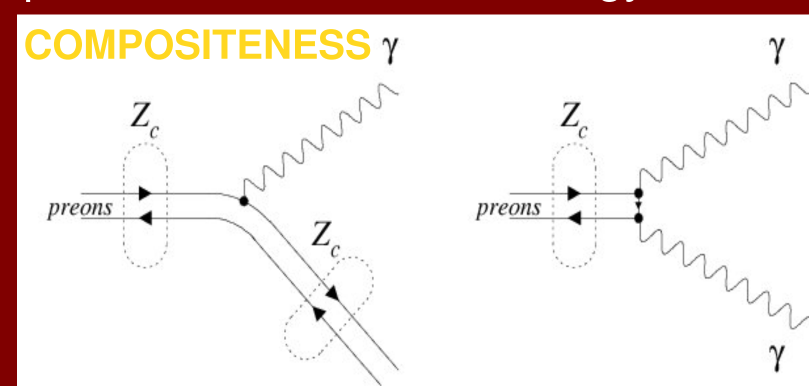
Beyond the Standard Model

ZZγ and **Zγγ** couplings can be parameterized by 8 form factors:

$$h_i^{Z,\gamma} = \frac{h_{i0}^{Z,\gamma}}{(1+\hat{s}/\Lambda^2)^n}$$

$h_{i0}^{Z,\gamma}$ → Low energy approx.

Λ is the energy scale for new physics, we choose $\boldsymbol{n = 3}$ for $h_{1,3}^{Z,\gamma}$ and $\boldsymbol{n = 4}$ for $h_{2,4}^{Z,\gamma}$, which satisfy unitarity conditions. $\hat{s}$ is the square of the parton center of mass energy.



Large Extra Dimensions

- m_{EW} the only fundamental scale in nature.
- n large extra spatial dimensions (LED).
  - **large compared to the electroweak scale**
    - gravity is diluted in extra volume
    - SM particles bound to the 3D brane
- Large size of the extra volume R^n conceals the true (rather small) size of the fundamental Planck scale M_D (4+n D), the result: a large 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.

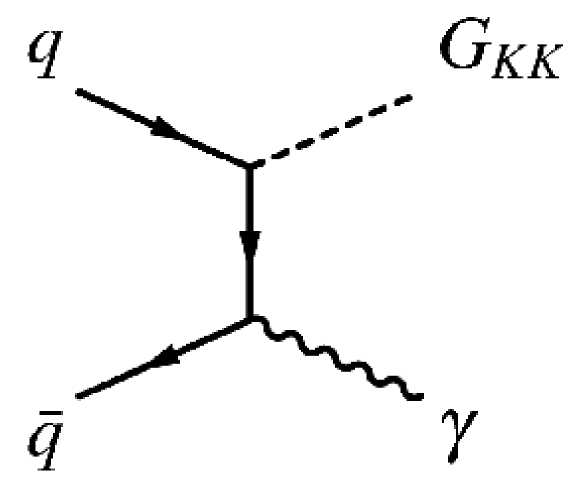
$$M_{Pl} \sim G_N^{-1/2} \sim 10^{19}\ \mathrm{GeV}$$

Planck scale

Great jump in energy
HIERARCHY PROBLEM

$$m_{EW} \sim 10^{3}\ \mathrm{GeV}$$

Electroweak scale



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

EW distance scale:

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

Summary of Selection Requirements

➲ **Select event with single EM triggers**: at least one energy cluster in the EM section of the calorimeter. Fully efficient at 40-50 GeV.

➲ **Photon candidate has pT > 90 GeV** with a shower profile consistent with that of a photon.

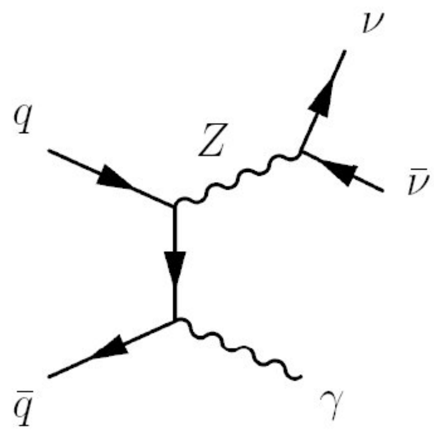
➲ **Photon candidate must be central** (|n| < 1.1)

➲ **Require event to have missing transverse energy (MET) > 70 GeV**

➲ **Require a clean event**:
- no jets with pT > 15 GeV, isolated tracks, cosmic rays, muons, or additional energetic EM objects.

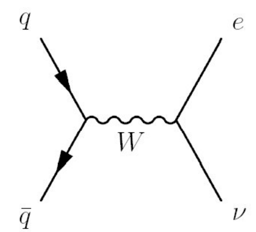
Backgrounds:Electroweak Boson Production

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



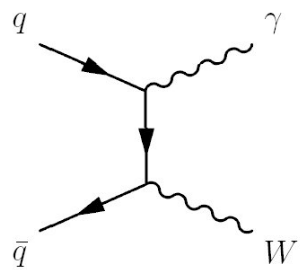
Signal for the Zγ and AC analysis. Irreducible physics **background for the LED analysis.**

$W \to e\nu$



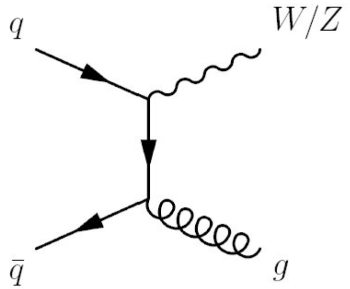
The electron is misidentified as a photon due to tracking inefficiency or hard bremsstrahlung.

$W+\gamma \to l\nu+\gamma$



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

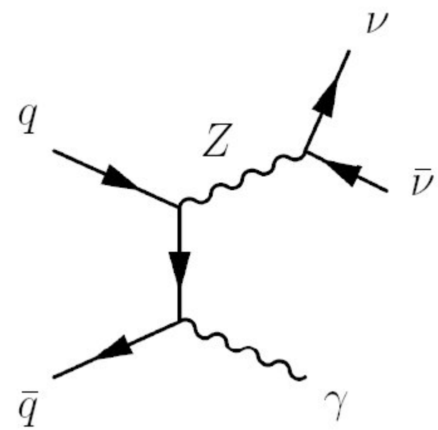
W/Z+ jet



The jet is misidentified as a photon.

Backgrounds:Electroweak Boson Production

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



Signal for the Zγ and AC analysis. Irreducible physics **background for the LED analysis.**

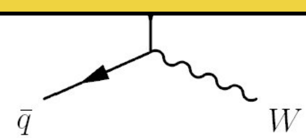
$W \rightarrow e$ ...

...tified as a ... inefficiency ... .

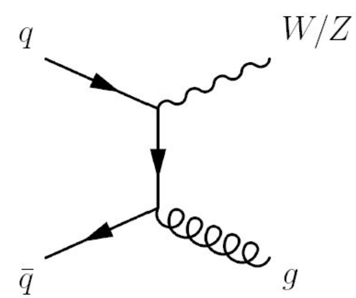
Plus large background from **cosmic ray muons** and **particles from beam halo** depositing energy in the calorimeter.

$W+\gamma \rightarrow l$ ...

...n a leptonic W boson decay is not detected.

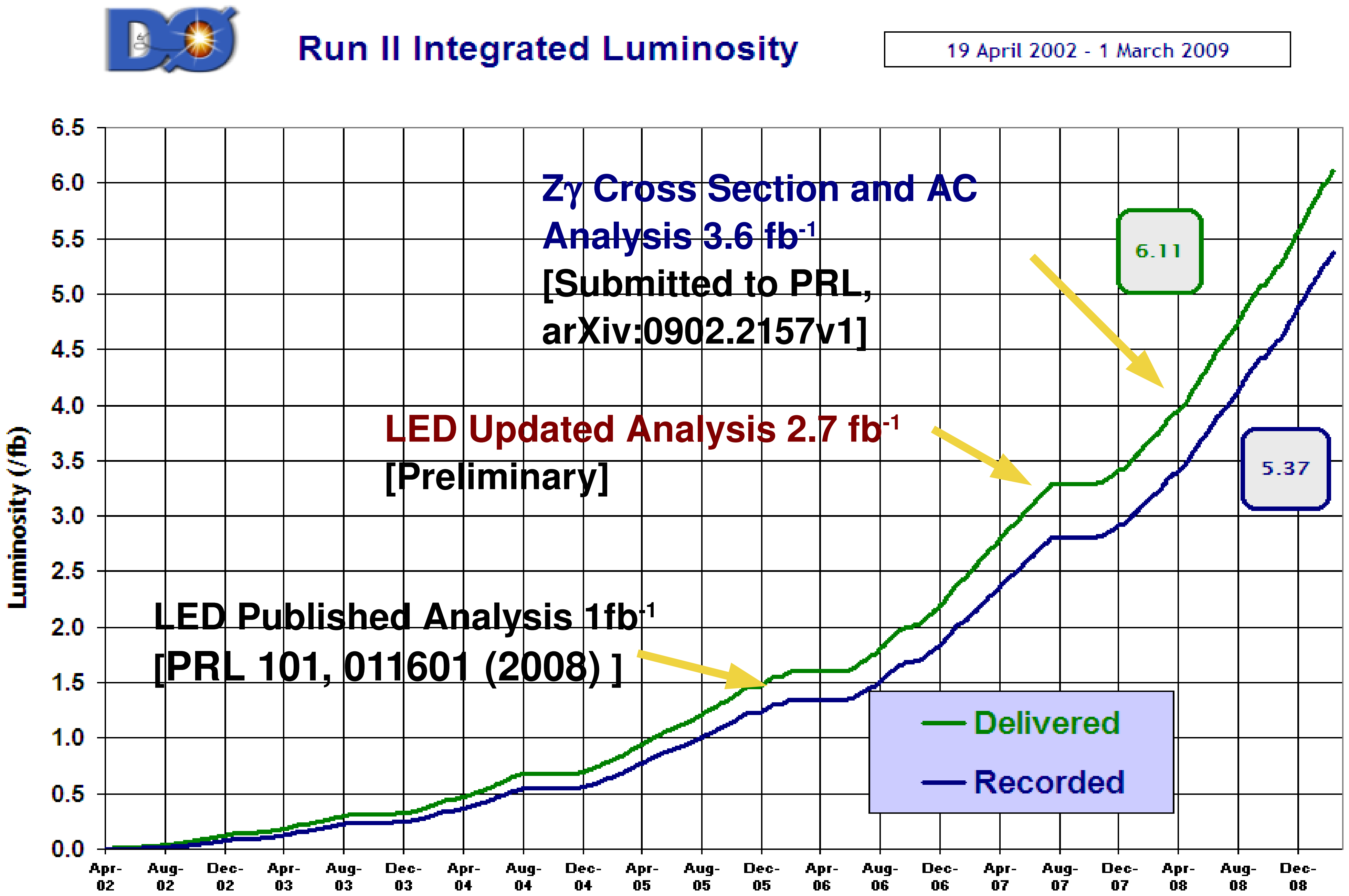


W/Z+jet



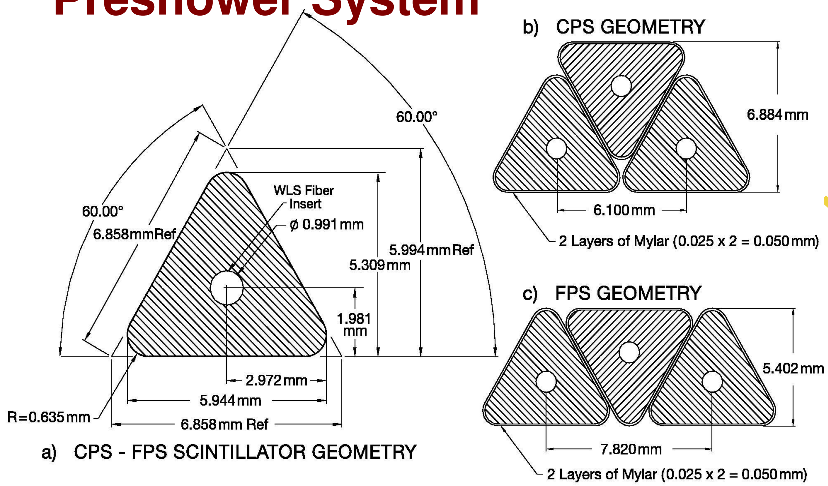
The jet is misidentified as a photon.

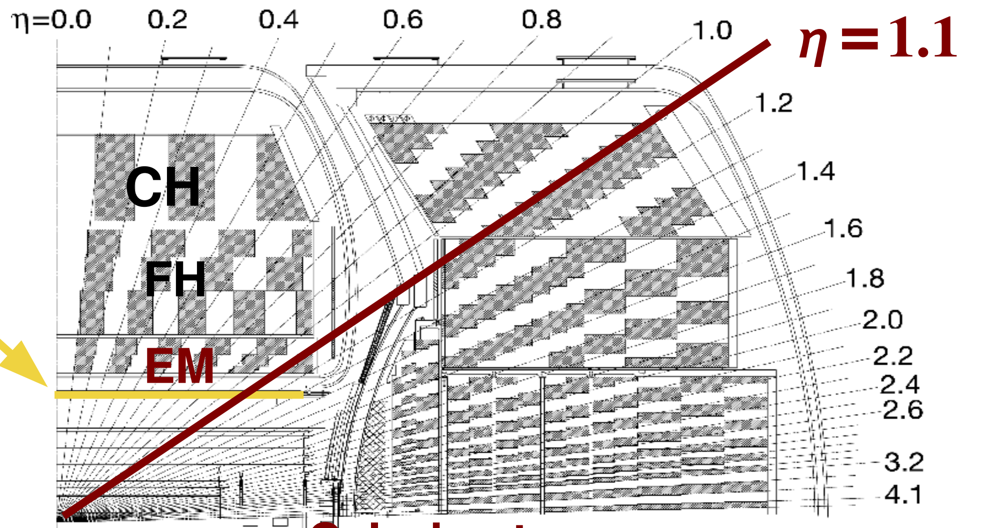
Data Taken at DØ



Photon Identification

Preshower System



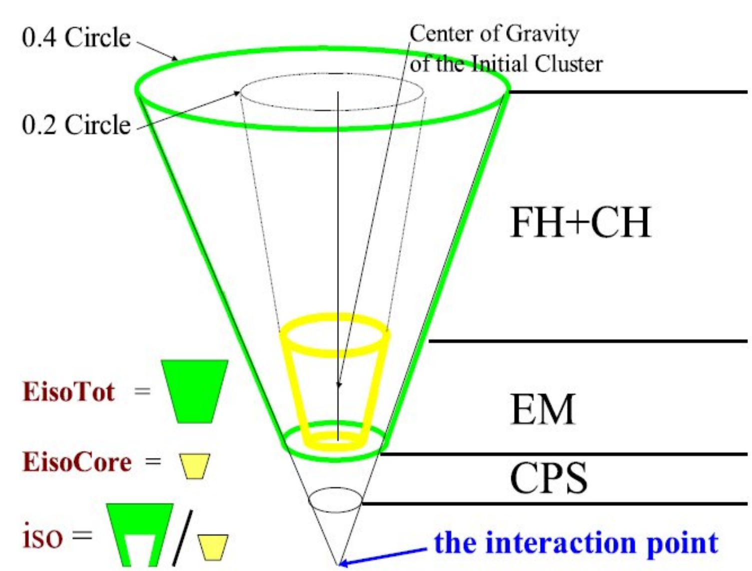


Calorimeter

- ➲ Photons are identified as narrow deposits of energy, mainly in the electromagnetic part of calorimeter.
- ➲ Are **isolated in the calorimeter**

$$iso = (E_{0.4}^{tot} - E_{0.2}^{core}) / E_{0.2}^{core} < 0.07$$

- ➲ Are **isolated in the tracker**: sum of track p_Ts in (0.05 < R < 0.4) around the cluster < 2 GeV
- ➲ Photons do not leave tracks. We make sure there are no tracks associated with them.
- ➲ Matched to a central preshower (CPS) cluster, which improves position and energy determination.

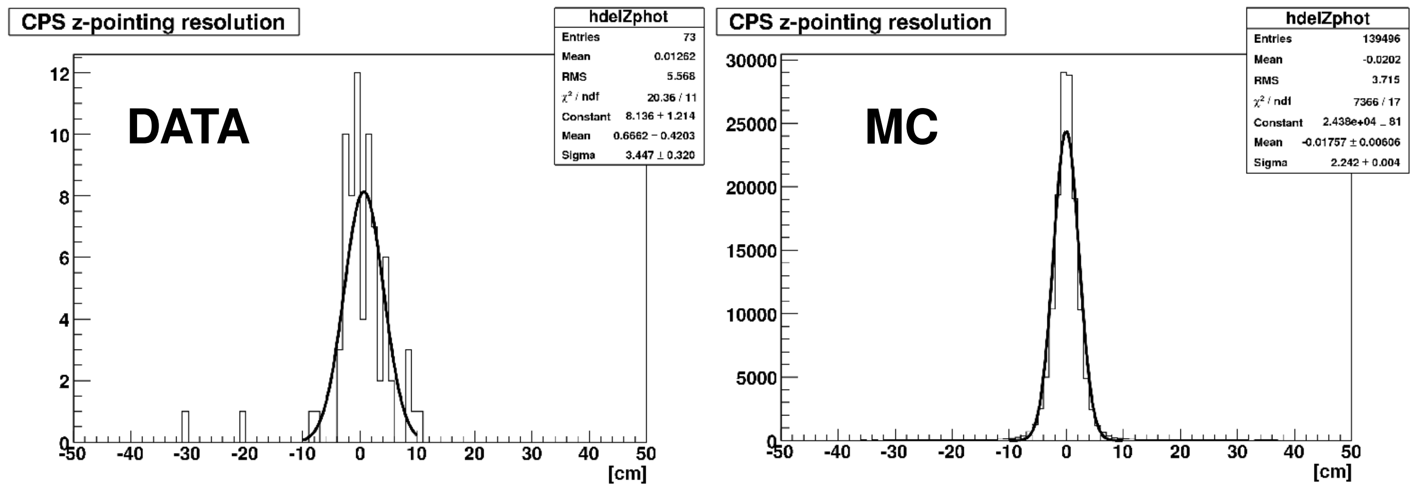


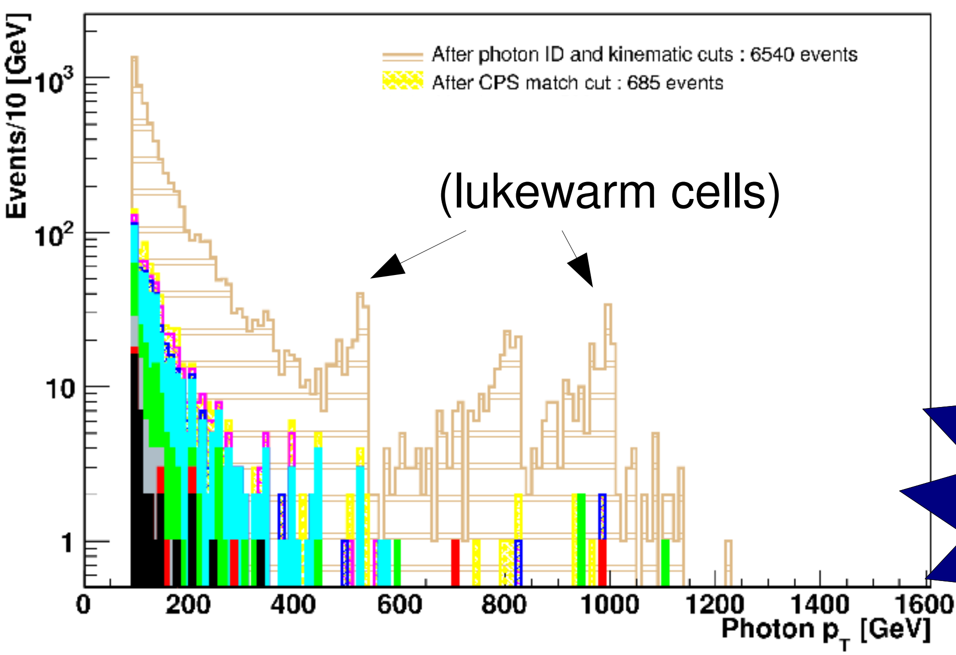
Calorimeter Cluster Isolation

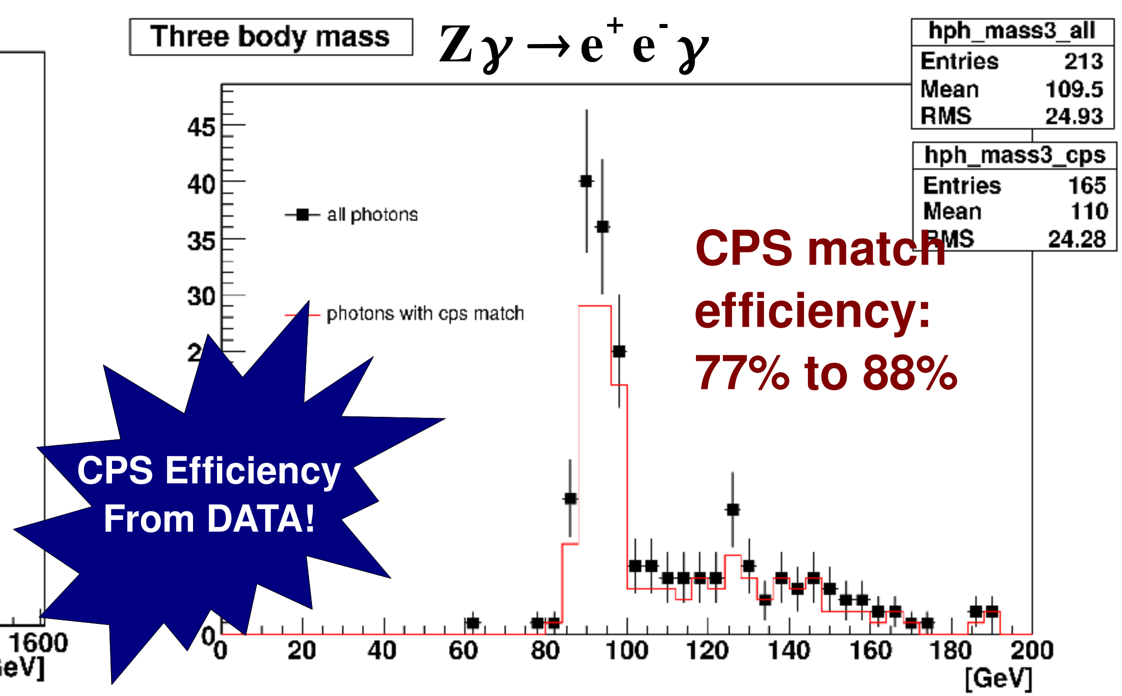
The Importance of the Preshower

- Preshower is very important for these analyses.
- CPS provides redundancy and pointing.
- Removes events with hardware problems.
- Reduces non-collision background.

Pointing resolution:

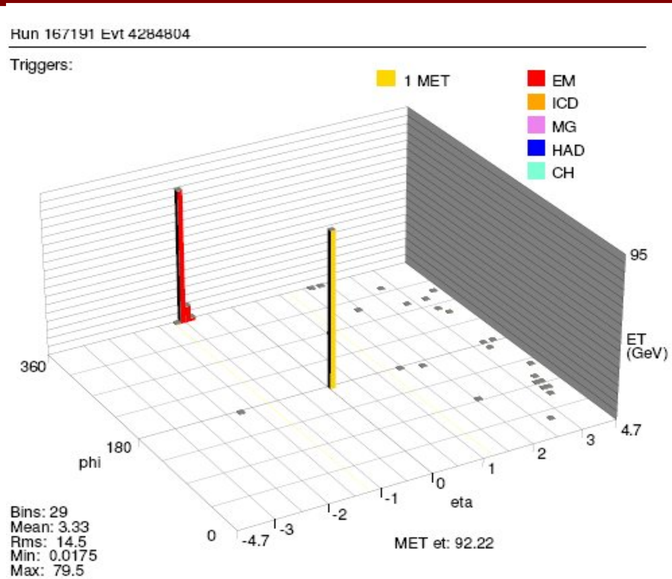




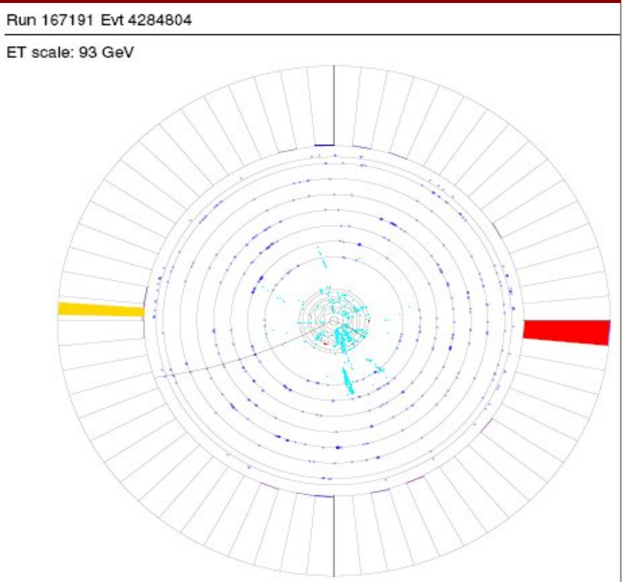


Non-collision: Beam Halo Event Display

- Very low track multiplicity; empty events
- Deposit energy in the calorimeter
- Mostly in the plane of the beam line
- Same signature as our final state signal
- Difficult to deal with
- Number of these events are greatly reduced by simply requiring a reconstructed vertex

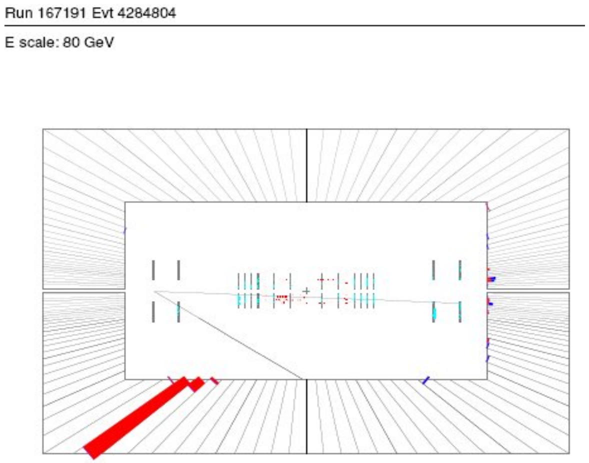


(a) $\eta - \phi$ lego plot



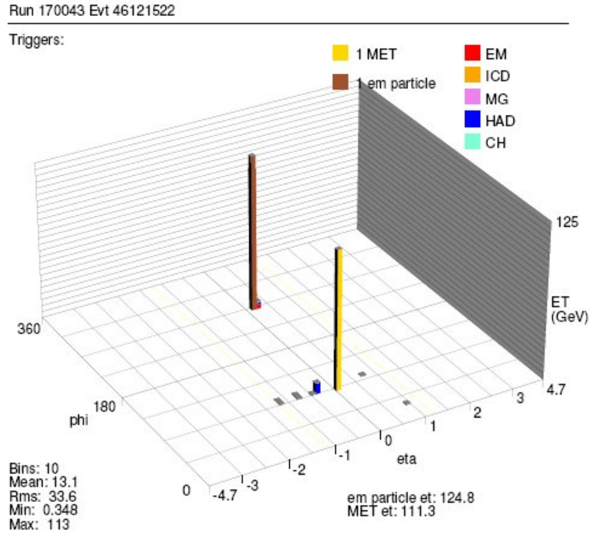
(b) $x - y$ view

(c) $z - y$ view

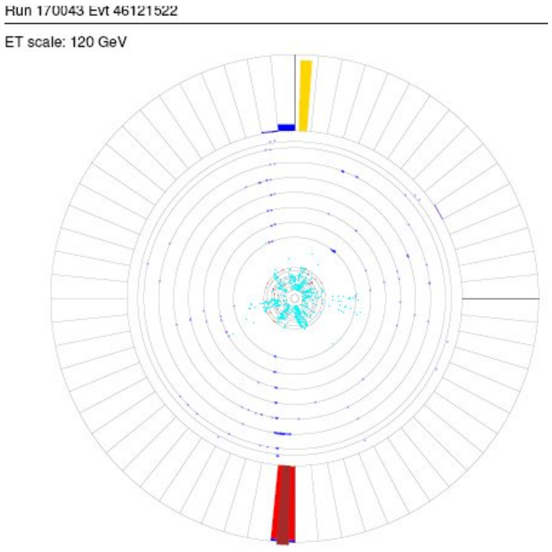


(d) $r - z$ view tracker and calorimeter

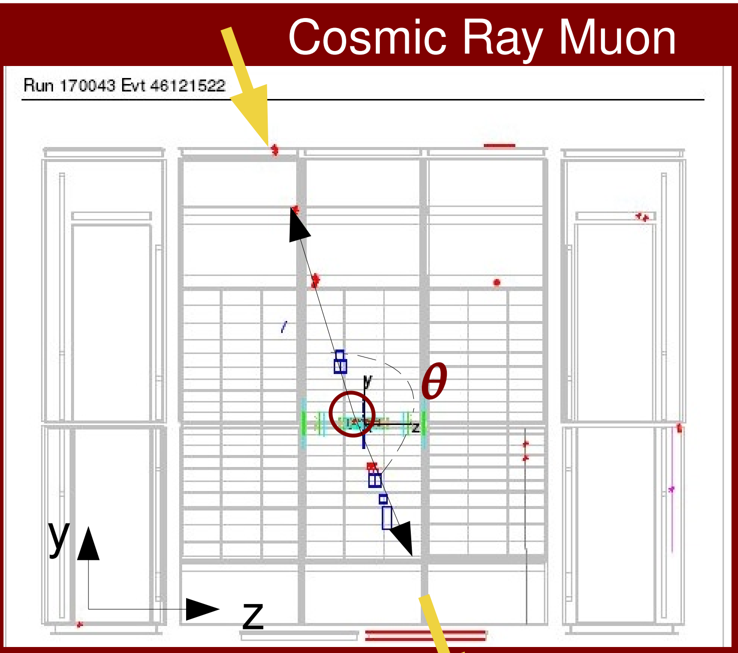
Non-collision Background: Cosmic Ray Muon Event Display

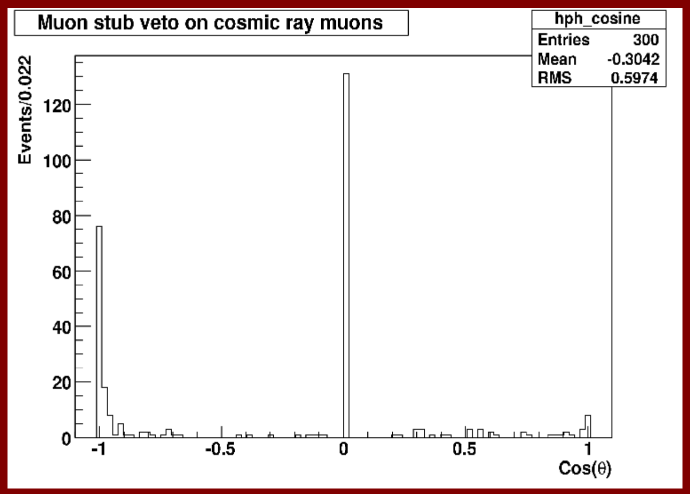


(a) $\eta - \phi$ lego plot



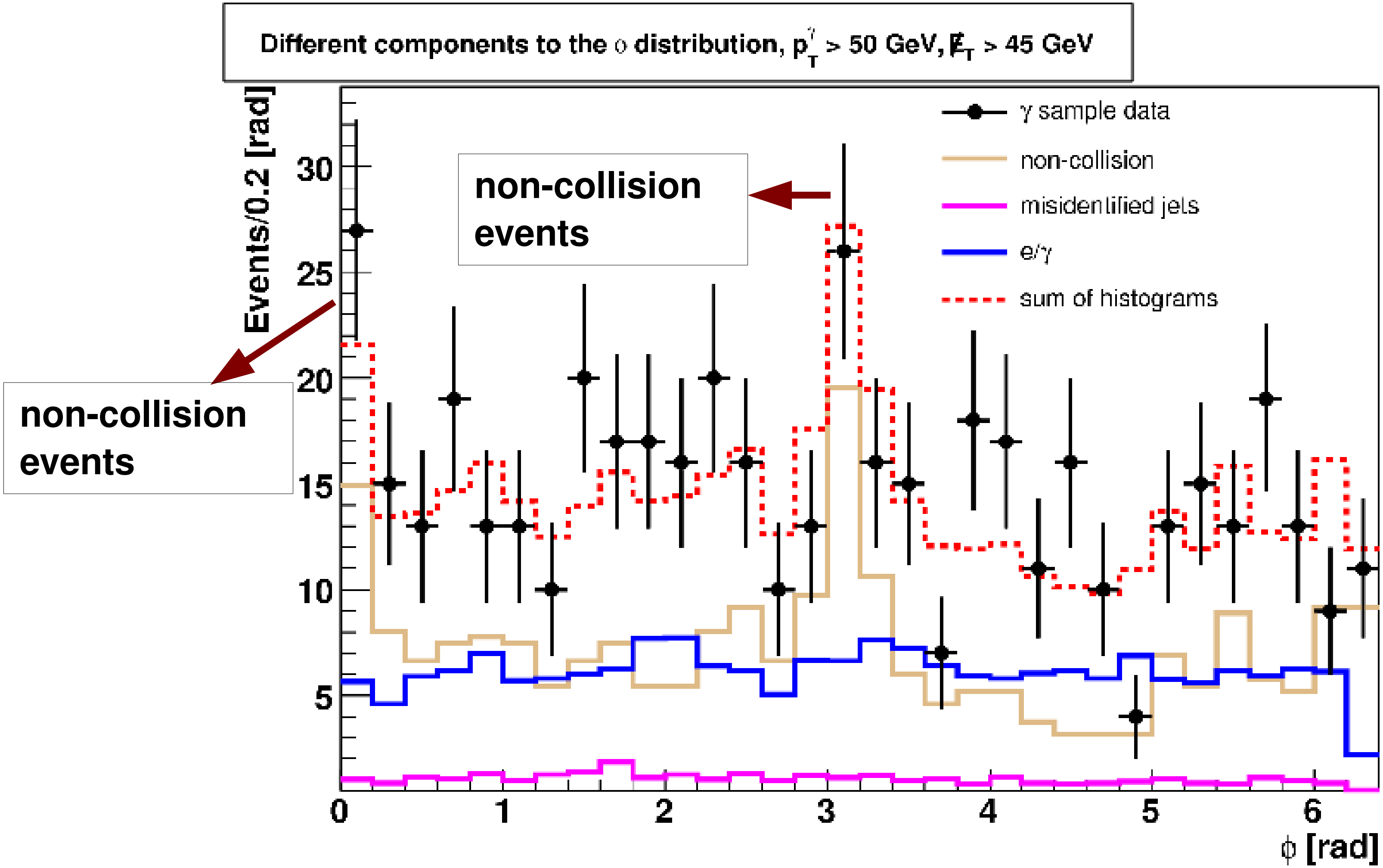
(b) $x - y$ view





- Not too many handles to reject these events, just the photon as an actual physical object.
- Rejection of cosmic ray muons by timing signal in the muon scintillators and/or presence of characteristic pattern consistent with a cosmic muon.

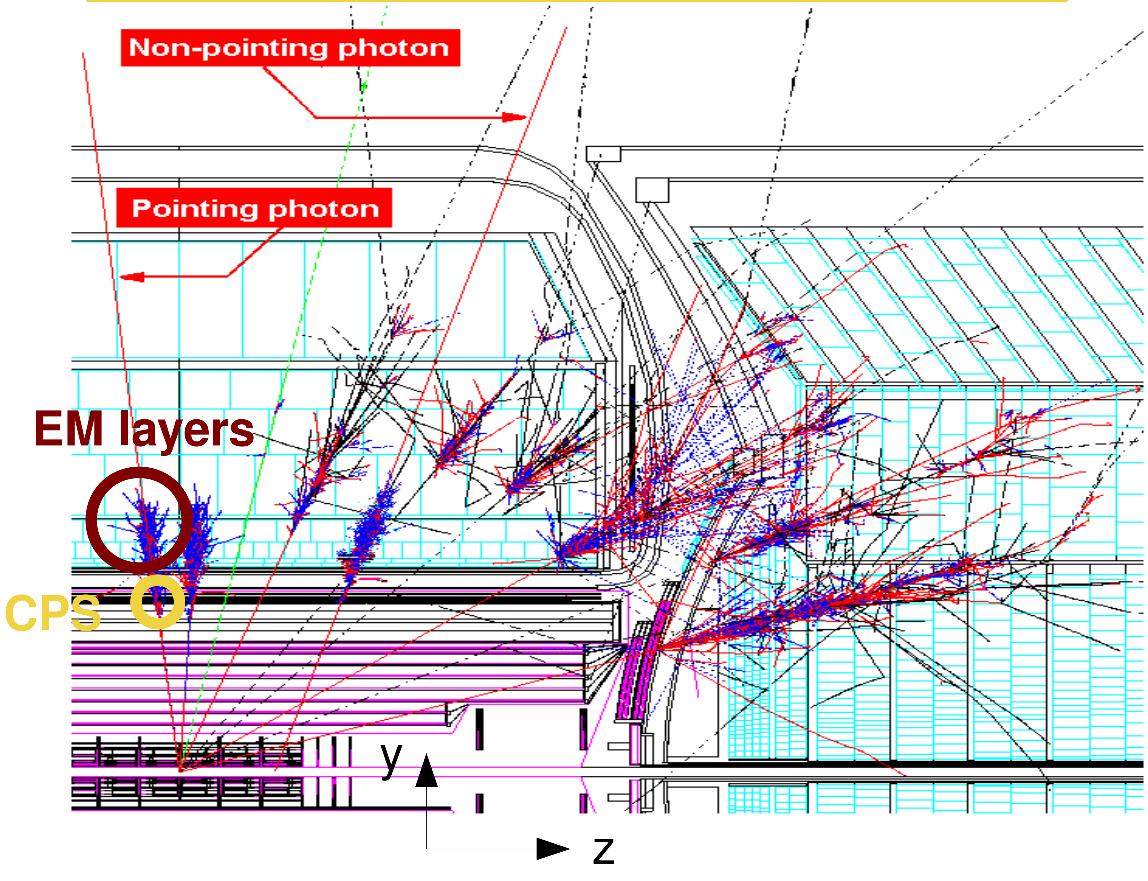
Non-collision Background Still Dominates



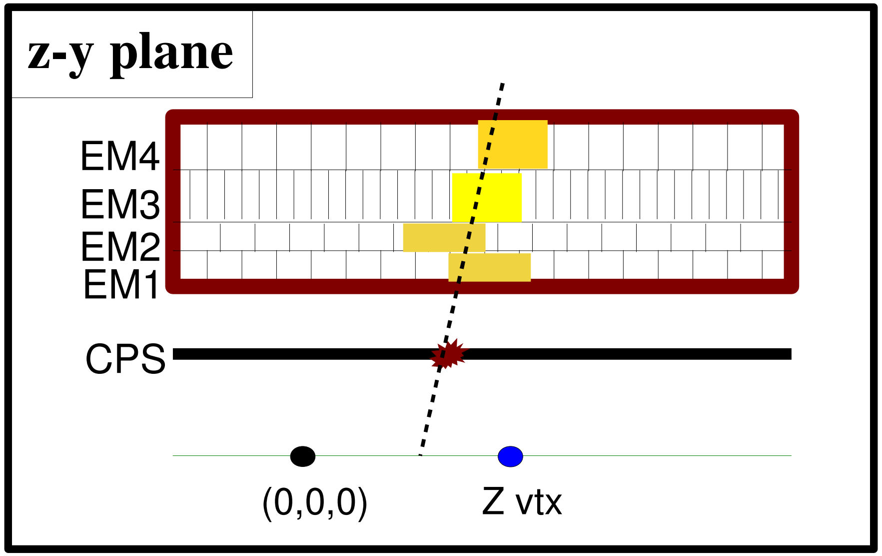
After applying standard photon identification, non-collision background (particularly from beam halo) remains important.

Electromagnetic (EM) Cluster Pointing Algorithm

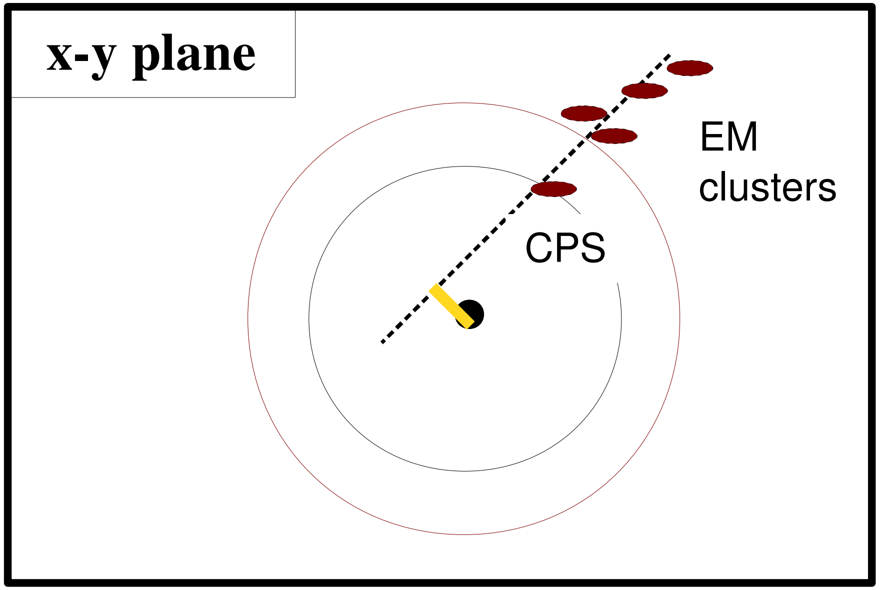
- EM cluster pointing algorithm calculates the direction of the EM shower.
- It is based solely on the central preshower (CPS) and EM calorimeter clusters.
- Energy-weighted centroid coordinates at each layer in the EM calorimeter are calculated.



Prediction of interaction vertex z-position

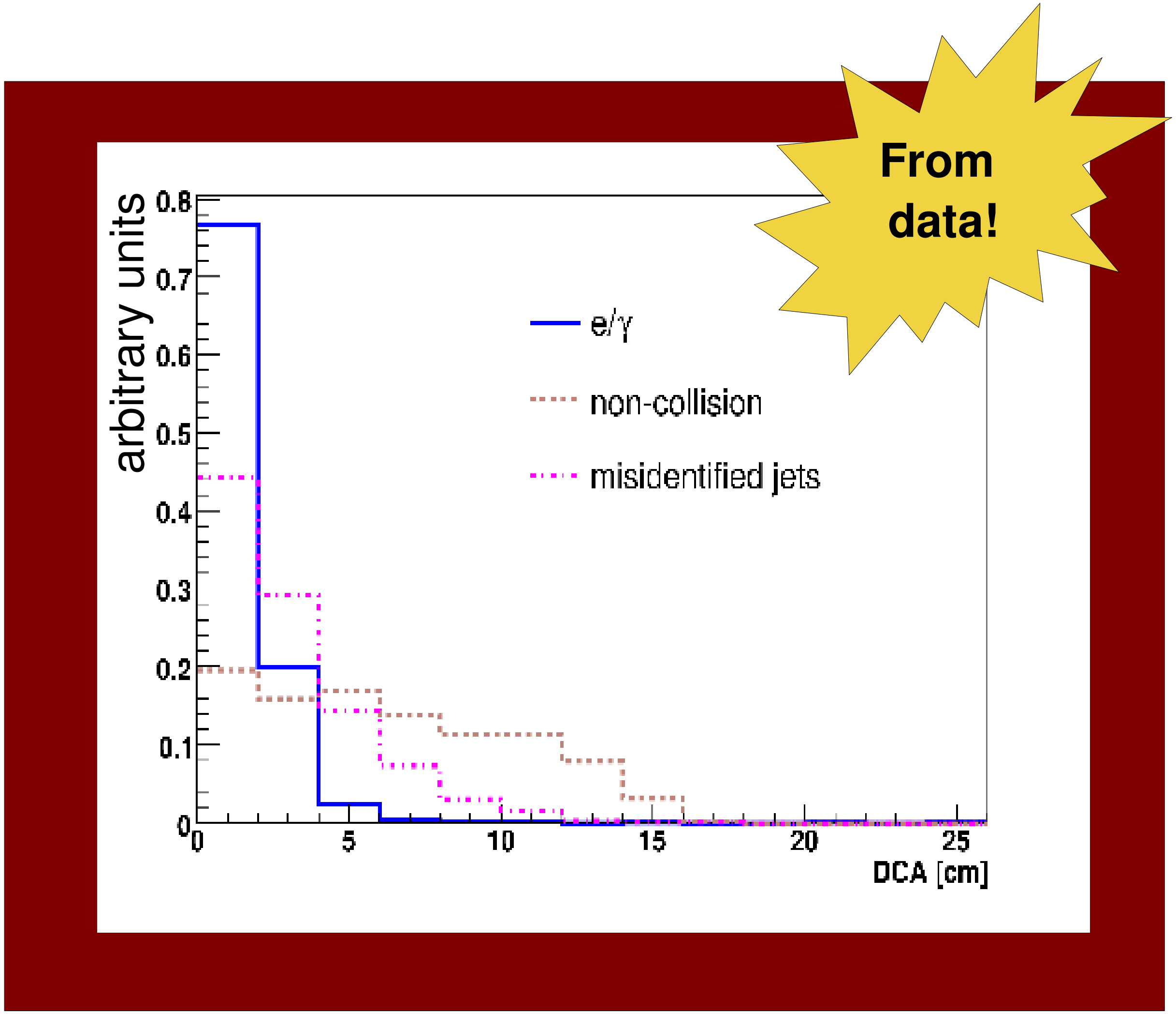


Distance of closest approach (DCA)



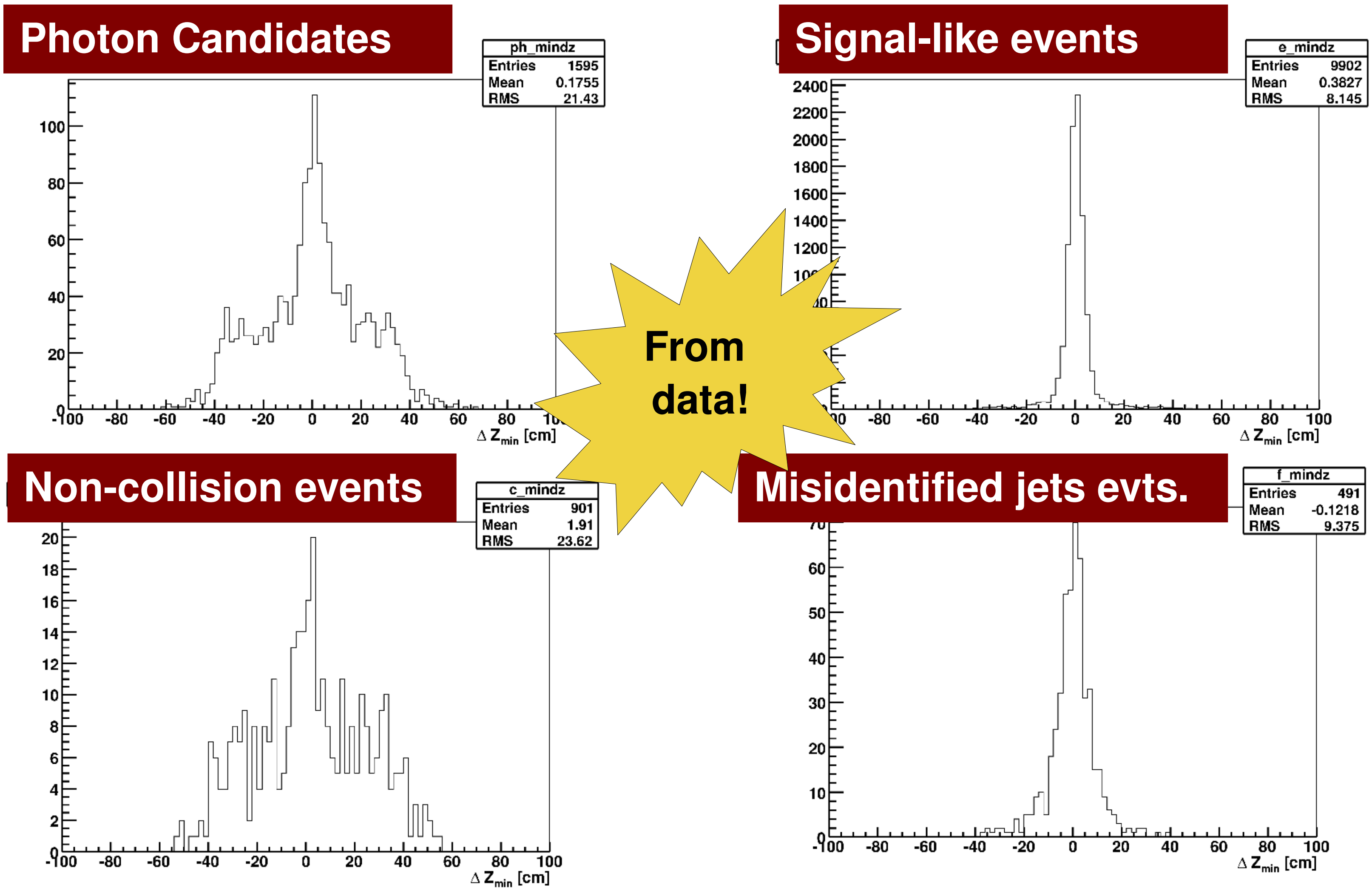
DCA Templates Construction

- **e/γ template** (narrow DCA distribution): Obtained from sample of isolated electrons.
- **misidentified jets template** (wider DCA distribution): EM objects with reversed track isolation.
- **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.



Pointed Vertex Requirement

- ➲ **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 (recalculate kinematics) at high luminosities.**



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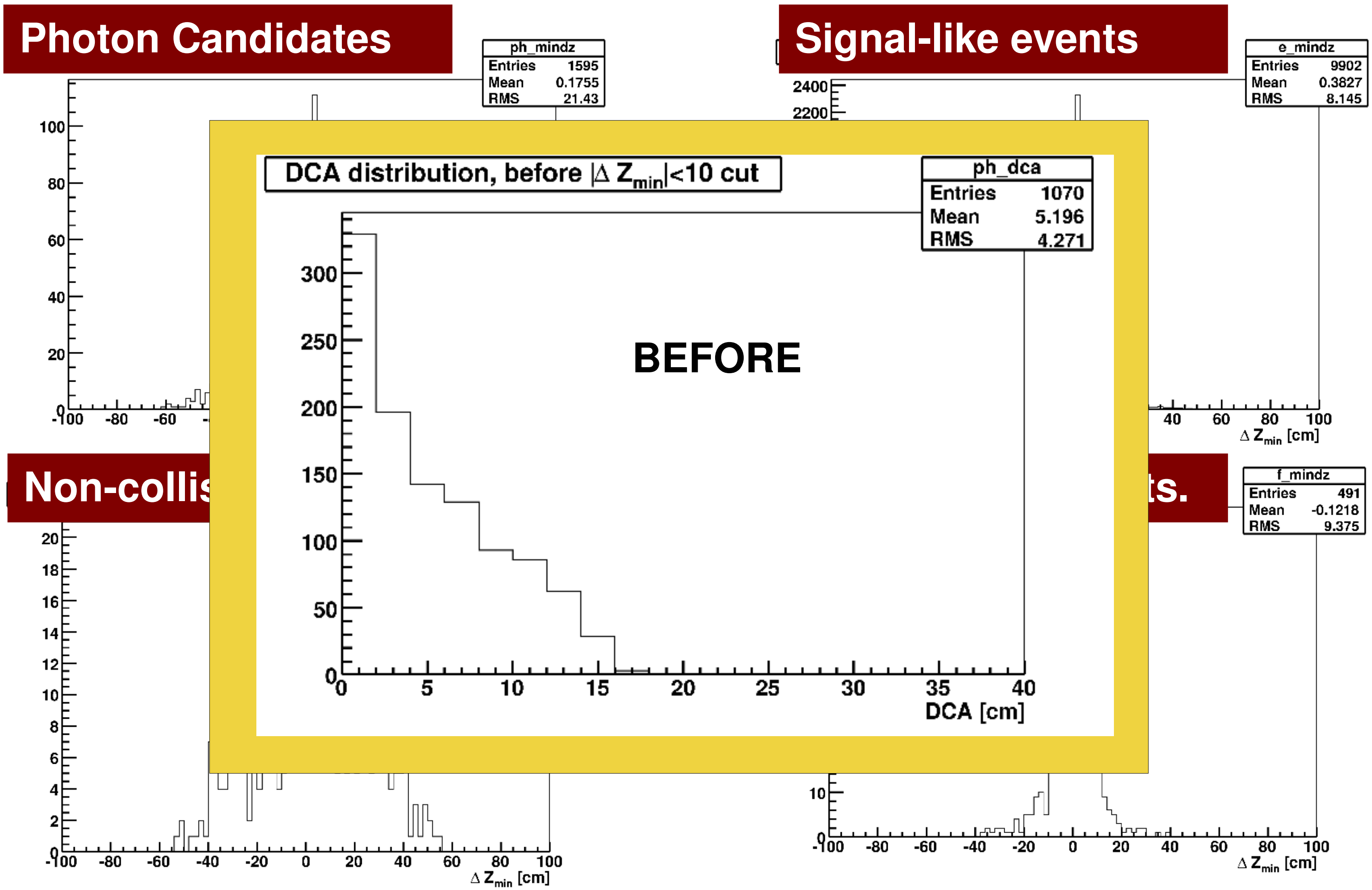

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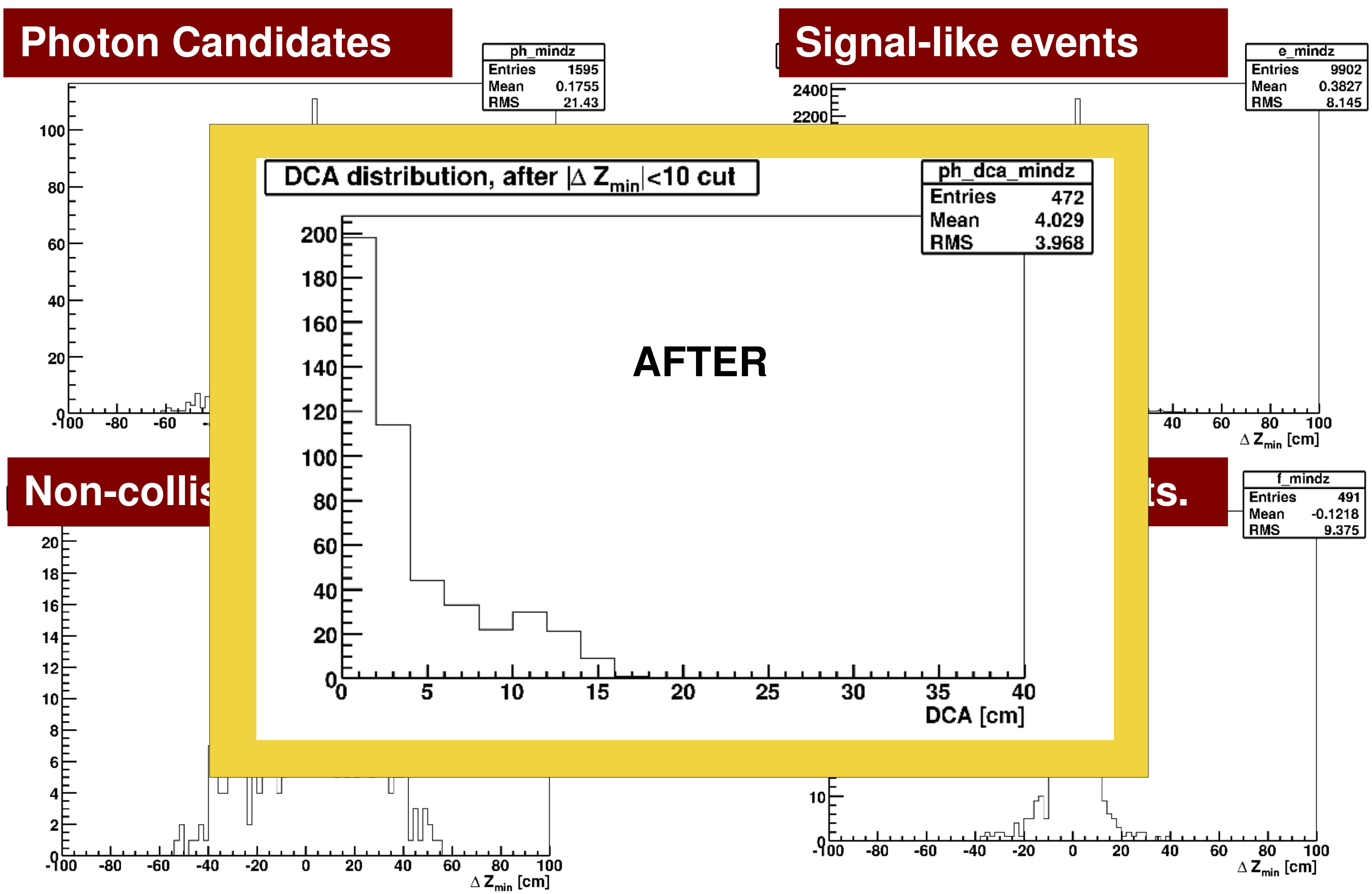
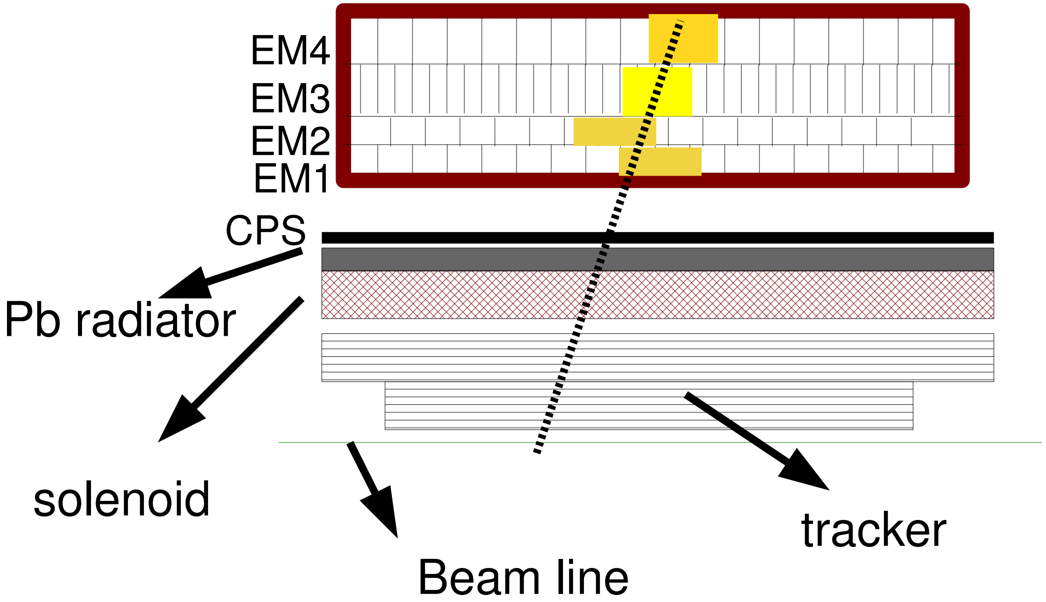
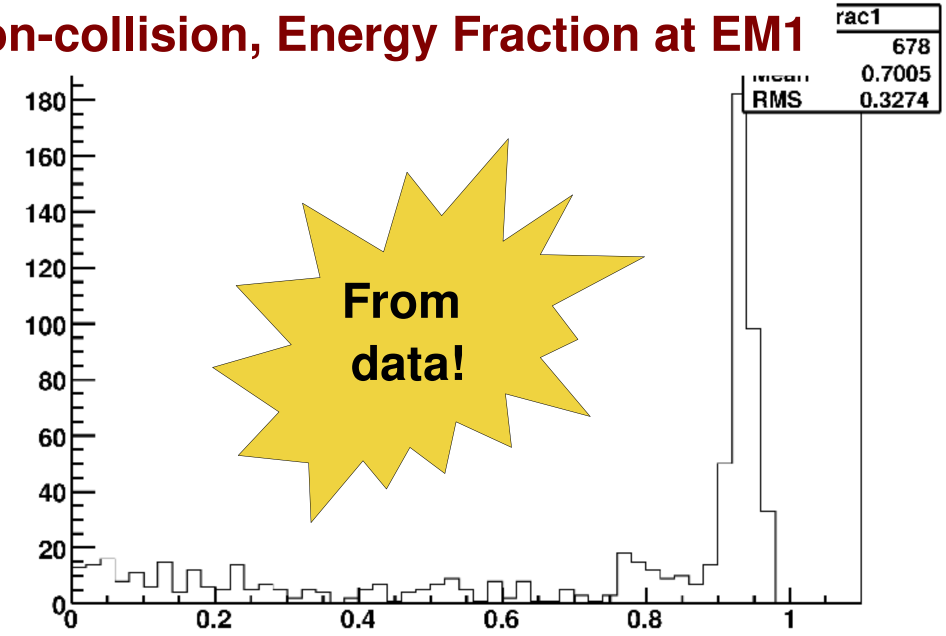


Understanding Non-collision EM Showers

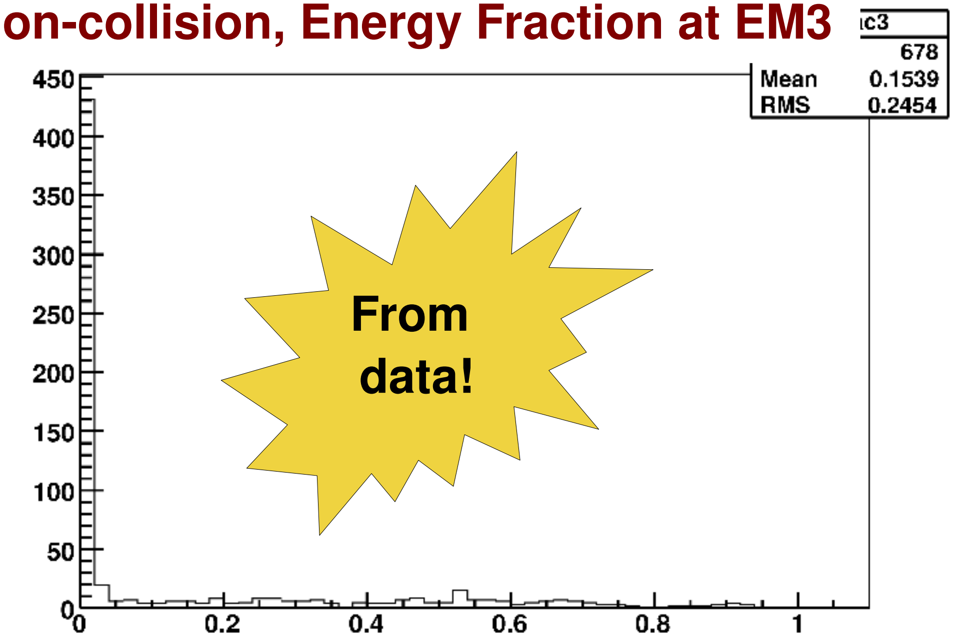
- EM objects from interaction region expected to deposit most of their energy in the 3rd layer of the EM calorimeter.
- Particles not from the interaction region appear to deposit all their energy in the first EM layer.



Non-collision, Energy Fraction at EM1

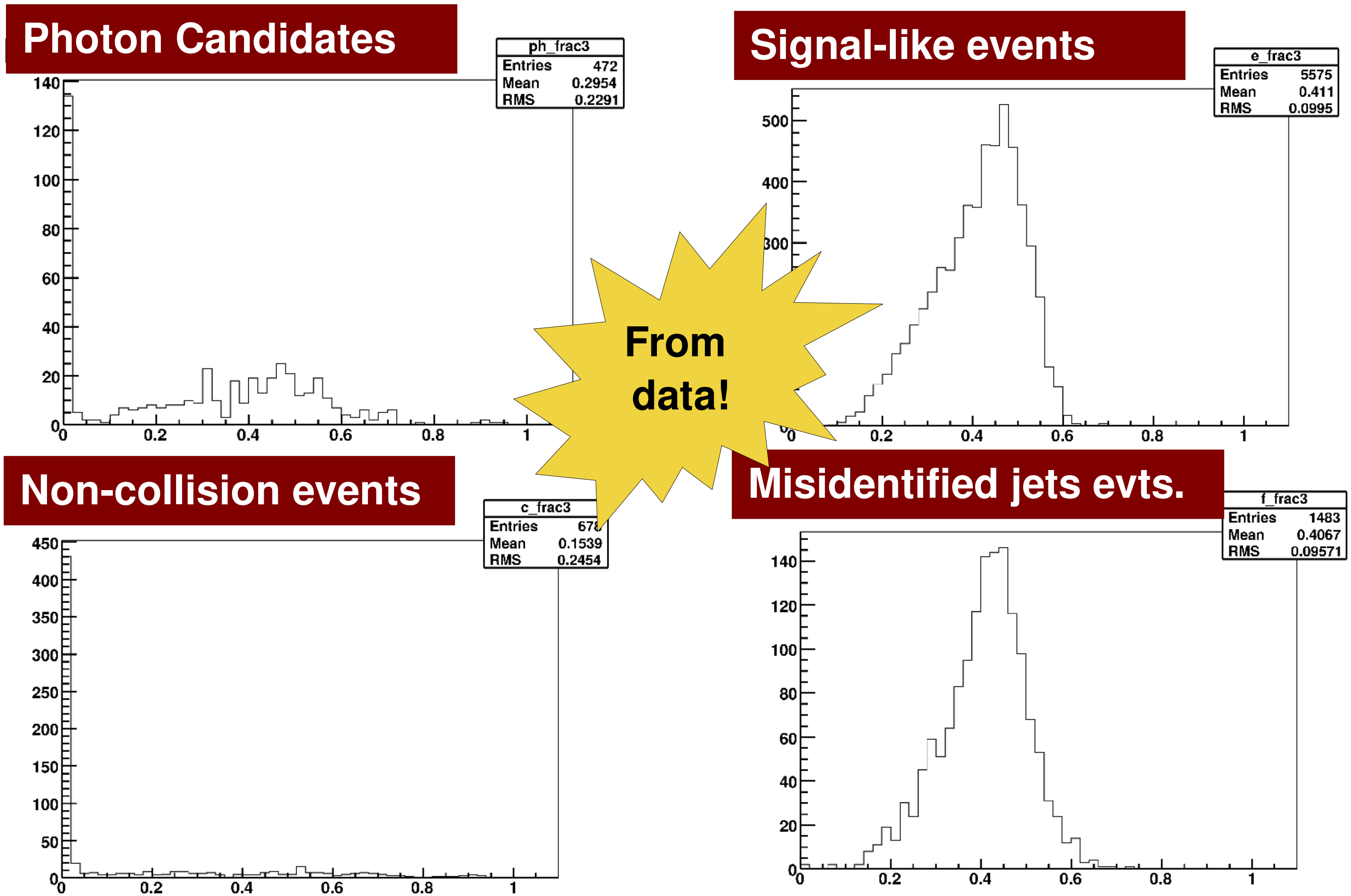


Non-collision, Energy Fraction at EM3



Energy Fraction Requirement at EM Layer 3

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



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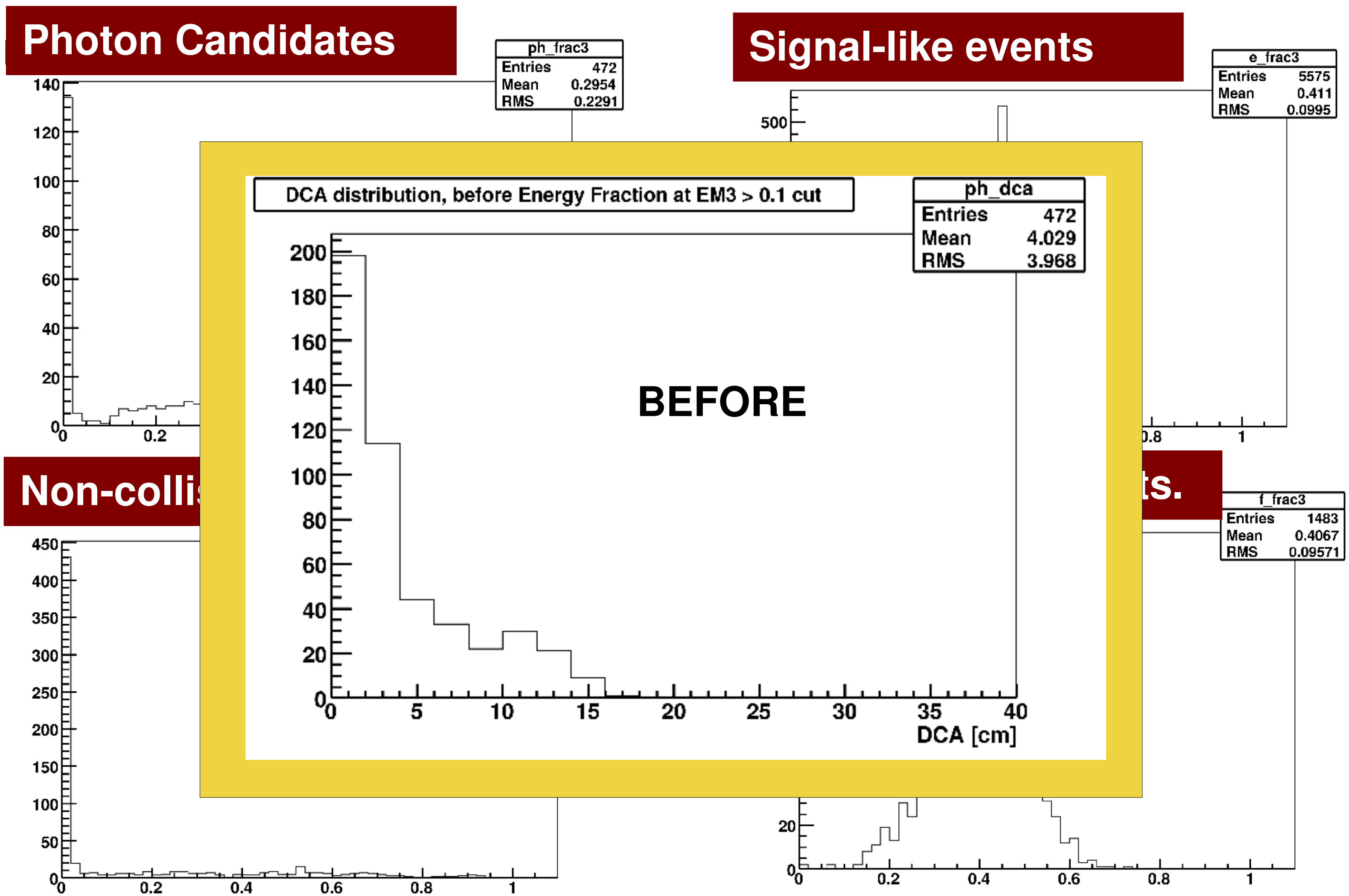

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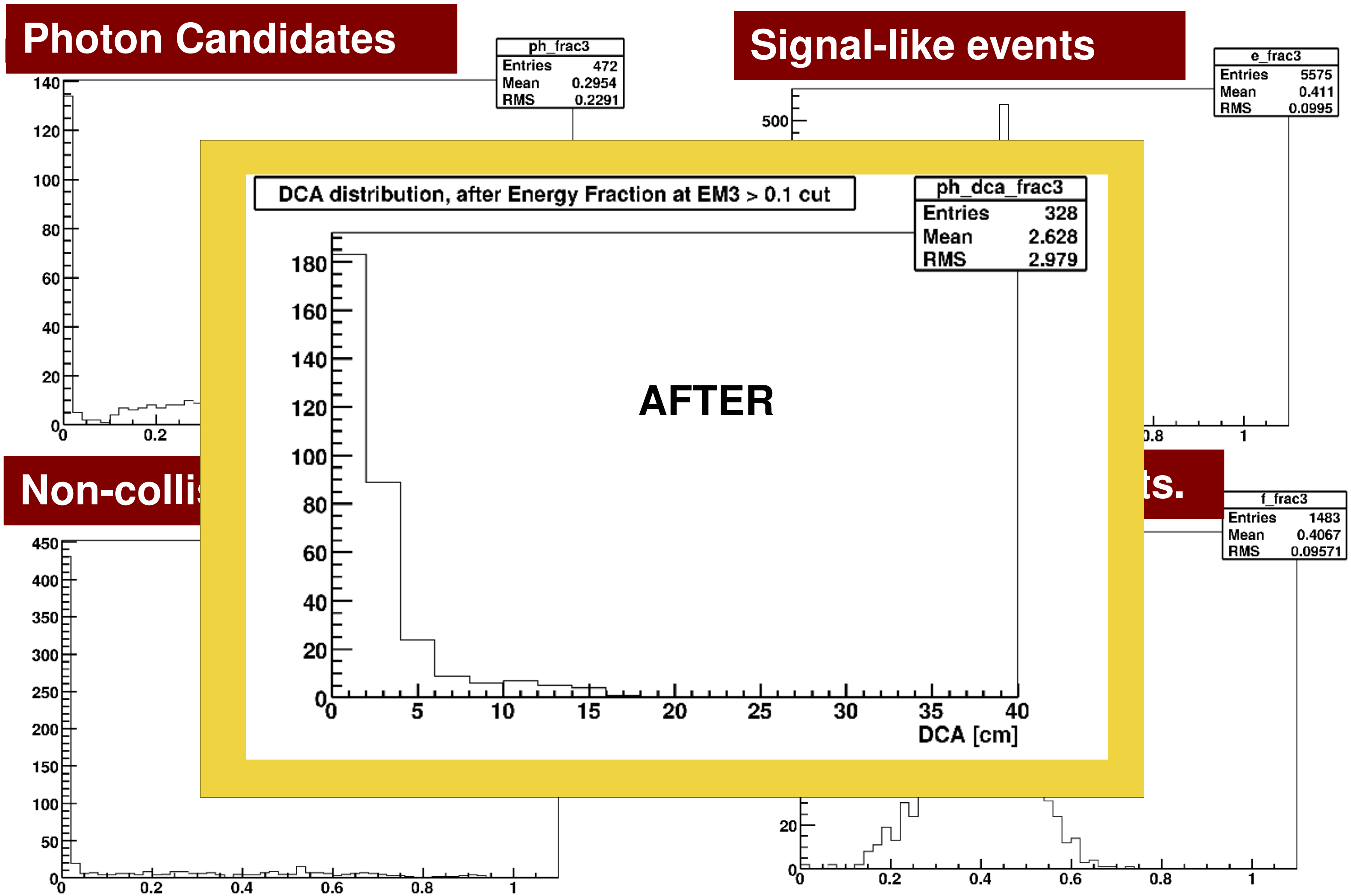


The Photon Sample Selection

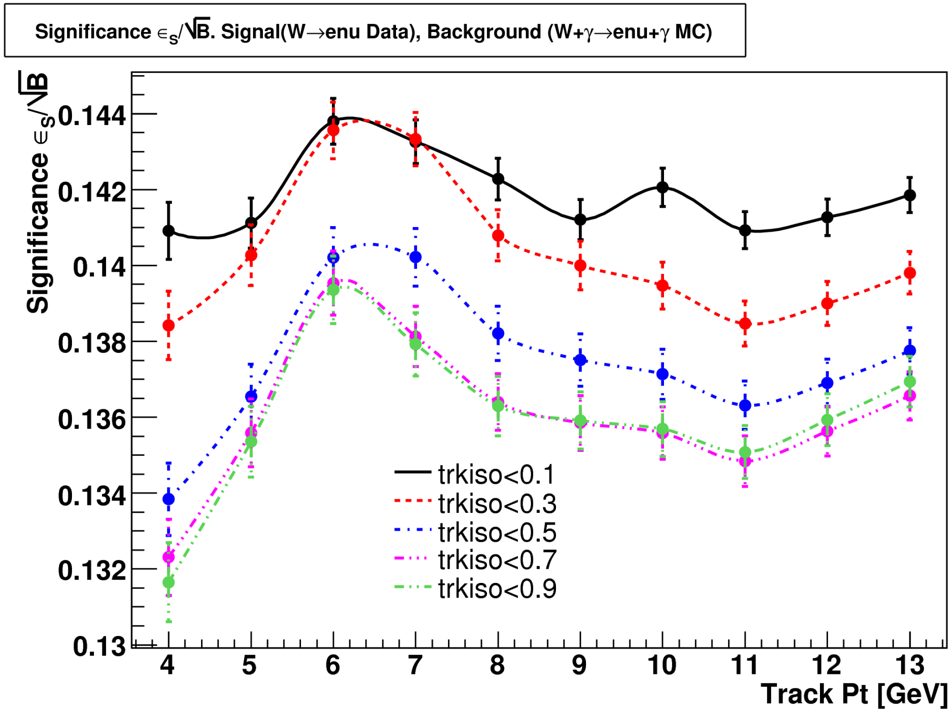
Photon selection:

- pT > 90 GeV
- MET > 70 GeV, to guarantee no multijet background.
- Fiducial |η| < 1.1
- No jets with pT > 15 GeV to avoid large MET due to mismeasurement of jet energy.
- No muons, and no energetic tracks or additional EM objects in the event.
- Some differences in the efficiency of selection requirements between analyses.

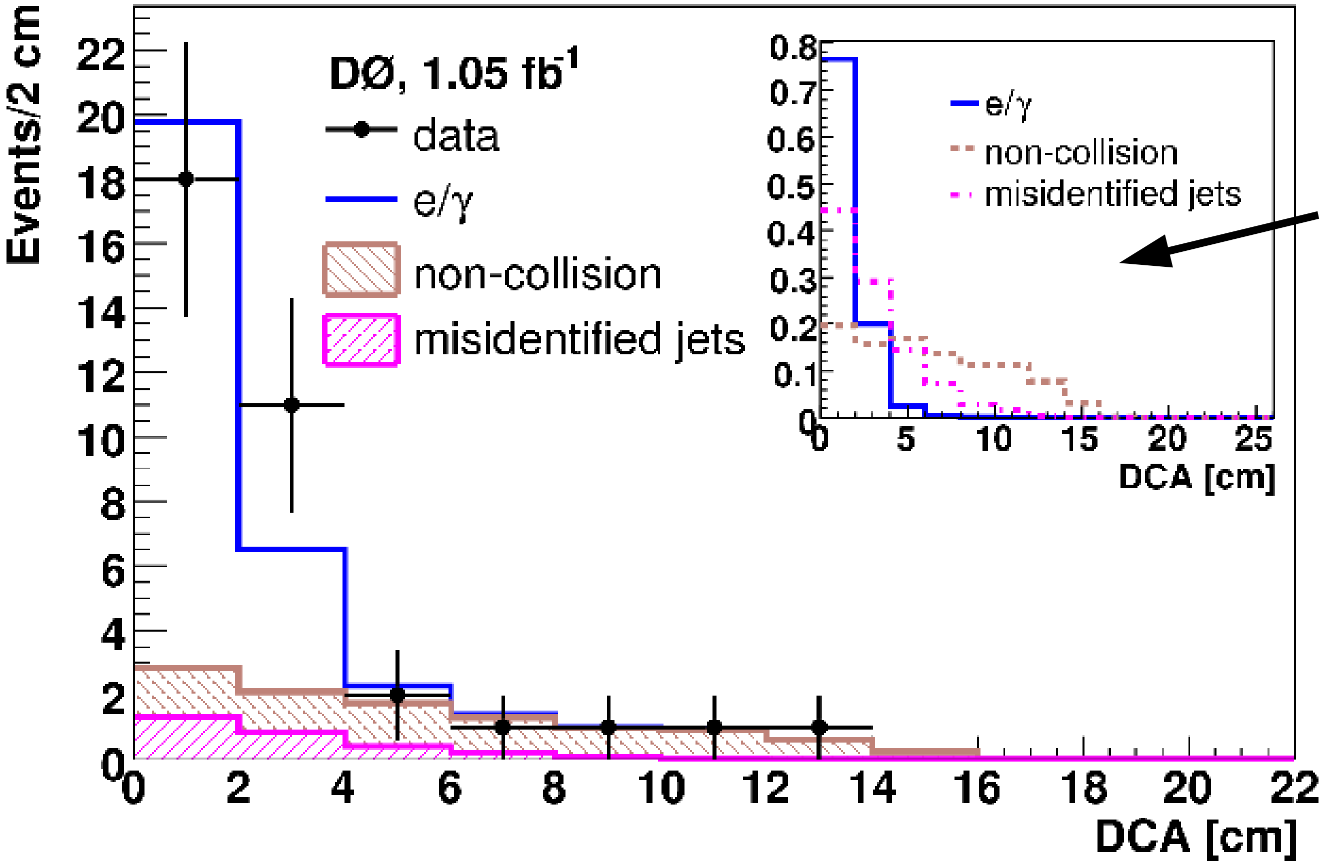
Veto on energetic tracks:

- aim at isolating leptonic tracks
- track required to be within 2 cm (in z-coordinate) from interaction vertex.
- do not veto any track within ΔR < 0.3 around the photon EM cluster.

$$\mathrm{trkiso} = \frac{\sum_{i \neq j} p_T^i}{p_T^j} \quad (0.1 < \Delta R < 0.4)$$



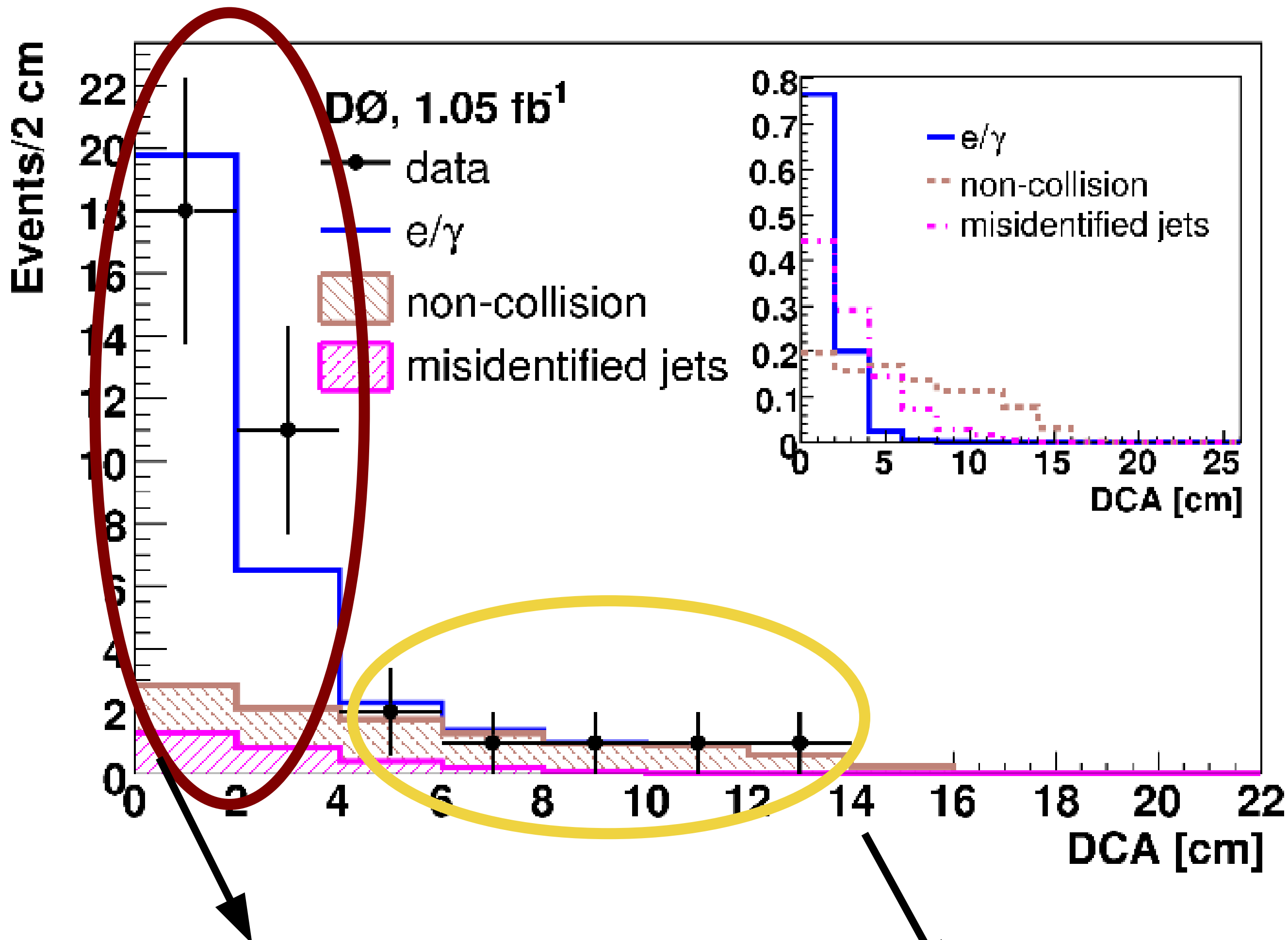
DCA Template Fit



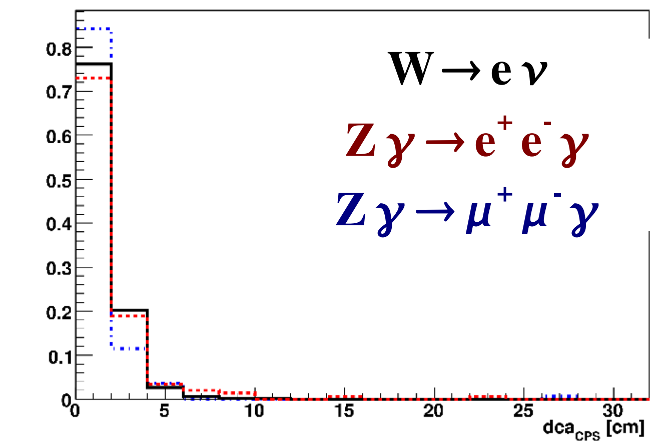
Different shapes in DCA

Fit the DCA distribution in the photon sample to a linear sum of the three templates fixing the normalization for misid jets

DCA Template Fit



DCA signal-like shapes from different samples.



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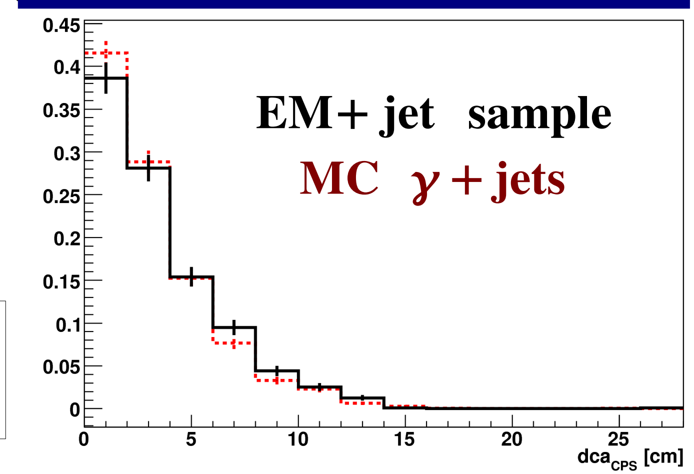


Most of signal-like events concentrated in this region (e/gamma) events + EM jets.

Non-collision events + some misidentified jets

Prediction of misidentified jet background

photon sample: need to know th enumber of misidentified jets N_{misid} → **unkown**

we can use:

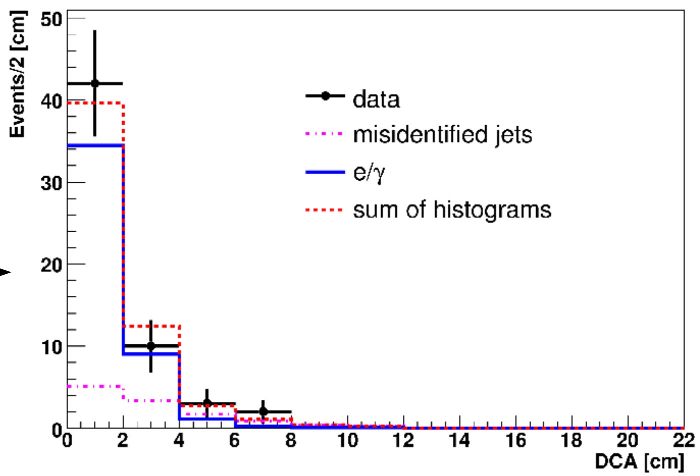
fake photon sample (inverted track isolation): number of events N_{fake-} → **known**.

To estimate N_{misid} we assume that the rate at which events "leak out" from fake sample (N_{misid}/N_{fake}) is the same as the analogously defined quantity in a fake sample extracted from an EM + jet data sample.

EM + jet sample

fake (inverted track isolation) + jet: N_1

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



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

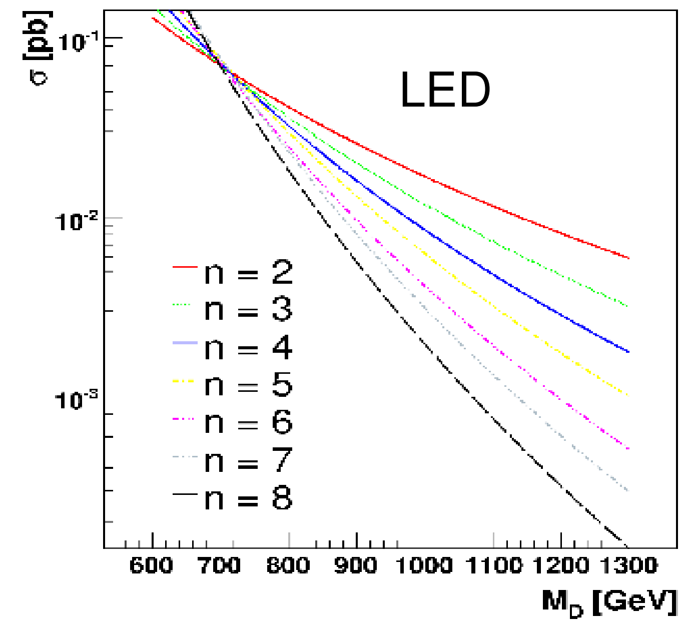
Estimation of Remaining Backgrounds

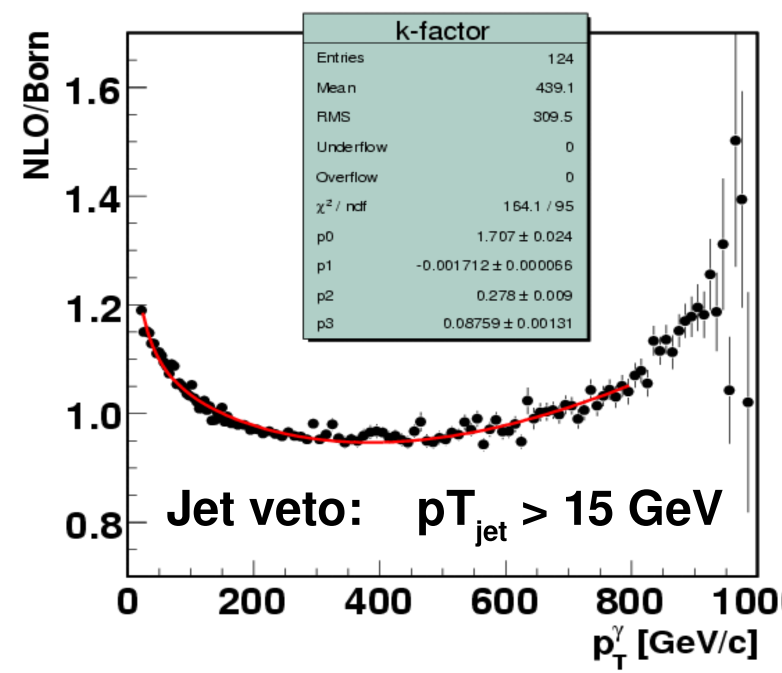
$W \rightarrow e\nu$	- Estimated using sample of isolated electrons. - Apply same kinematic requirements as in the photon sample, then scale the final number of events by the measured rate of electron-photon misidentification: $\frac{1-\epsilon_{trk}}{\epsilon_{trk}}$ Where ϵ_{trk} (~98.6%)is the tracking efficiency.
$Z+\gamma \rightarrow \nu\bar{\nu}+\gamma$ * $W+\gamma \rightarrow l\nu+\gamma$ * For the LED analysis only.	- Estimated using samples of Monte Carlo events generated with PYTHIA program. - Passed trough full detector simulation chain. - Use same reconstruction software as for data. - Scale factors are applied to correct for differences between simulation and data.

Signal and Systematics

SIGNAL	
LED	Generated using PYTHIA (thanks to Stephen Mrenna for his help) for n = 2 to n = 8 at M_D = 1.5 GeV. Easily scalable for other M_D points.
- Zγ production **- Anomalous Couplings**	- Generated using LO Baur Monte Carlo Zγ generator. - We correct for NLO QCD corrections (effect < 2%, with our jet veto)

Main sources of systematic uncertainty	
Photon Identification	5%
Kinematic requirements	6%
NLO K-factor (fit, jet energy and resolution)	5.5%
Choice of PDF	7%
Integrated Luminosity	6.1%





$Z\gamma \rightarrow \nu\bar{\nu}\gamma$ Production Cross Section

3.6 fb^{-1} of data, $\epsilon_{\nu\bar{\nu}\gamma} \sim 25\%$	
Background	**Number of events**
W → eν	9.67 ± 0.30 (stat) ± 0.30 (syst)
non-collision	5.33 ± 0.39 (stat) ± 1.91 (syst)
mis-id jets	1.37 ± 0.26 (stat) ± 0.91 (syst)
W + γ	0.90 ± 0.07 (stat) ± 0.12 (syst)
Total Background	**17.3 ± 0.6 (stat) ± 2.3(syst)**
Data Candidates	**51**
SM Predicted	**33.7 ± 3.4**

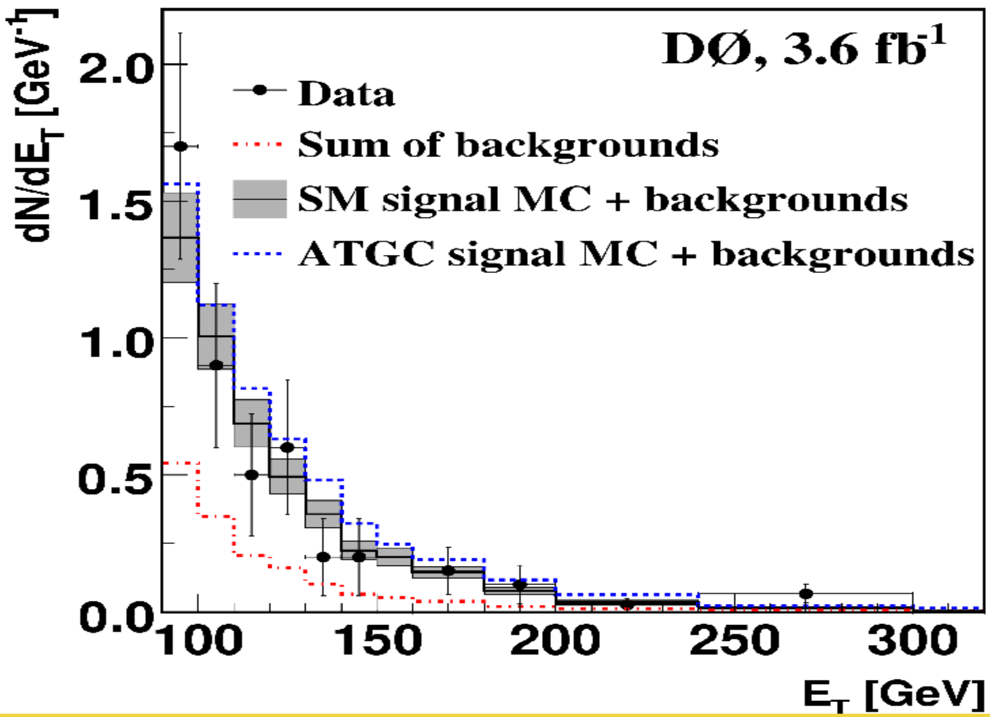
$$\sigma \cdot Br = \frac{N_{cand} - N_{bkg}}{\epsilon_{\nu\bar{\nu}\gamma} \cdot \int Ldt}$$

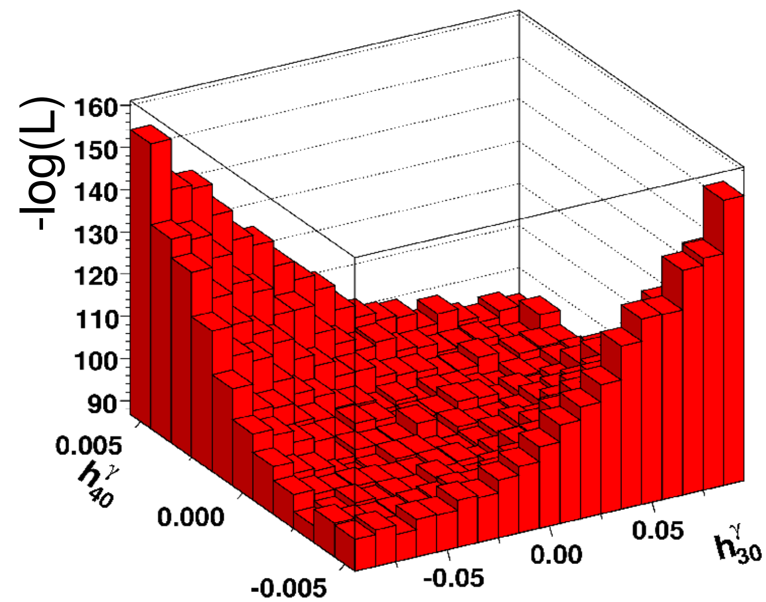
- Perform 10^8 pseudo-experiments to test the background only hypothesis.
- Calculate the probability of estimated background fluctuating to the number of observed events

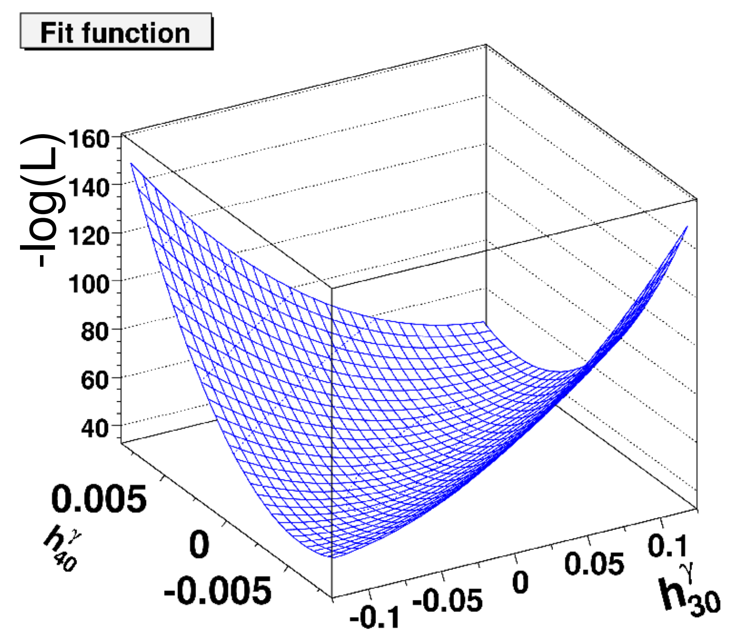
Measured cross section x Br:
32 ± 9 (stat/sys) ± 2 (lum) fb
SM NLO cross section x Br:
39 ± 4 fb

Probability = 3.1 x 10^{-7} or
5.1σ
First observation of
$Z\gamma \rightarrow \nu\bar{\nu}\gamma$
production at the Tevatron!!!!

Limits on Anomalous Couplings







- Generate **2D grid** of Zγ events with non zero values of $h_{30}^{Z,\gamma}$ and $h_{40}^{Z,\gamma}$.
- For each pair of $h_{30,40}^{Z,\gamma}$ **calculate the likelihood** at each point between data E_T spectrum and simulation + background to estimate result of the fit.
- Measure 95% C.L. limits, one and two-dimensional.

Limits on Anomalous Couplings

In a previous DØ publication [**PLB 653 (2007)**] :

electron + muon channel, Λ = 1.2 TeV, 1 fb^{-1}	
$Z\gamma\gamma$	$\lvert h_{30}\rvert < 0.085$, $\lvert h_{40}\rvert < 0.0054$
$ZZ\gamma$	$\lvert h_{30}\rvert < 0.083$, $\lvert h_{40}\rvert < 0.0054$

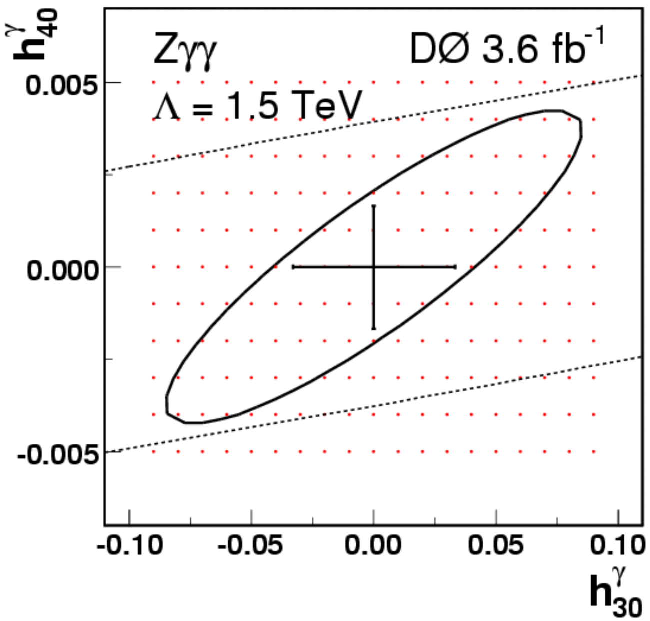
This analysis, neutrino channel only:

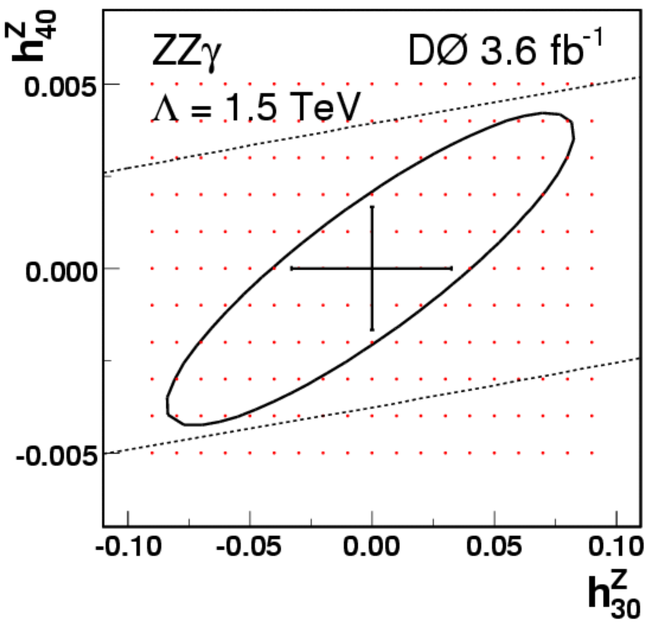
neutrino channel, Λ = 1.5 TeV, 3.6 fb^{-1}	
$Z\gamma\gamma$	$\lvert h_{30}\rvert < 0.037$, $\lvert h_{40}\rvert < 0.0020$
$ZZ\gamma$	$\lvert h_{30}\rvert < 0.036$, $\lvert h_{40}\rvert < 0.0020$

Combination:

neutrino + elect. + muon, Λ = 1.5 TeV	
$Z\gamma\gamma$	**$\lvert h_{30}\rvert < 0.033$, $\lvert h_{40}\rvert < 0.0017$**
$ZZ\gamma$	**$\lvert h_{30}\rvert < 0.033$, $\lvert h_{40}\rvert < 0.0017$**

h_{30}^{Z}, h_{40}^{Z}, and h_{40}^{γ} improve on the LEP2 constraints. They are the most restrictive to date!!!

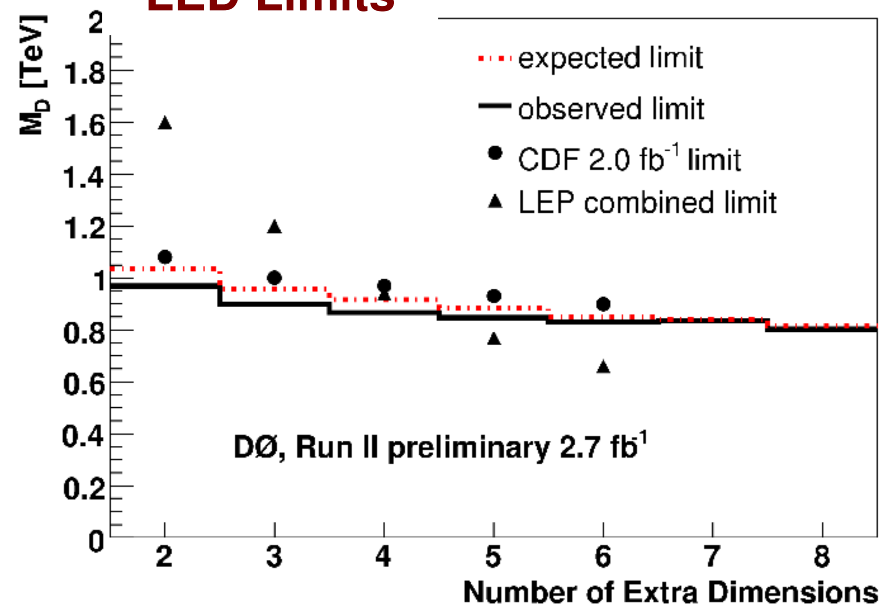


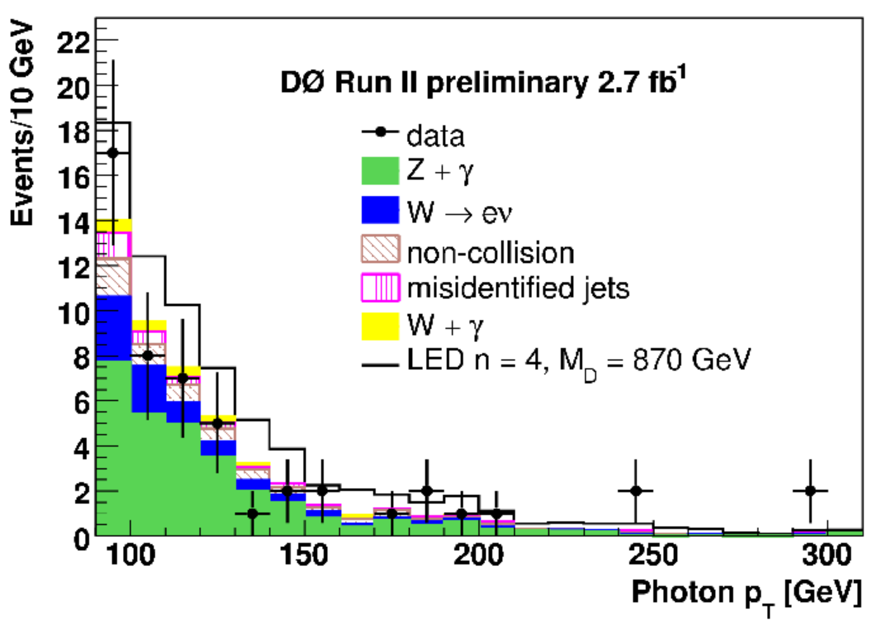


COMBINED

LED Results and Limits on M_D

2.7 fb^{-1} of data	
Background	**Number of events**
$Z + \gamma$	29.5 ± 2.5
$W \to e\nu$	8.5 ± 1.7
non-collision	6.6 ± 2.3
mis-id jets	3.1 ± 1.5
$W + \gamma$	2.22 ± 0.3
Total Background	**49.9 ± 4.1**
Data Candidates	**51**





n	Observed (expected) cross section limit (fb)	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 and Conclusions

- We tested the strength of the electroweak force and searched for KK gravitons leaking to large extra dimensions in the hope to find hints of new physics.

- **We observed the production of $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ process for the first time at the Tevatron**.

- No physics beyond the Standard Model from studying $Z\gamma$ production. We set limits on the form factors for the trilinear anomalous couplings $ZZ\gamma$ and $Z\gamma\gamma$, which are the best at hadron colliders. Three out of four improve on constraints set by LEP2.

- No evidence for the presence of LED has been found up to ~ 1 TeV. We set limits on the fundamental Planck scale.

- The techniques presented can be of great importance for future analyses with photons at D0.