Dark matter, extra dimensions, and Z decays at CMS

Tia Miceli

Indiana University Seminar
26 October 2012

Outline

- Physics models studied
  - Standard model
  - Dark matter
  - Extra dimensions
- Overview of CMS
  - Photons
  - Missing transverse energy
- Monophoton analysis
- Measurement of the Z→νν cross section
- ADD large extra dimensions search
- Dark matter search

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Standard Model

UP QUARK
A teeny little point inside the proton and neutron, it is friends forever with the down quark.

CHARM QUARK
A second generation quark, it is charmed, indeed.

TOP QUARK
This heavyweight champion doesn't live long enough to make friends with anyone.

DOWN QUARK
A tiny little point inside the proton and neutron, it is friends forever with the up quark.

STRANGE QUARK
Why is this second generation quark so strange?

BOTTOM QUARK
This third generation quark is puttin' on the pounds.

ELECTRON-NEUTRINO
These miniscule bandits like to steal away energy and escape detection.

MUON-NEUTRINO
A slightly heavier bandit than its sibling to the left.

TAU-NEUTRINO
Wily and sneaky, this bandit is the newest particle to arrive at the Zoo.

ELECTRON
A familiar friend, this negatively charged, busy l'il guy likes to bond.

MUON
A "heavy electron" who lives fast and dies young.

TAU
A "heavy muon" who could stand to lose a little weight.

PHOTON
The massless wavicle we know and love.

GLUON
The "glue" of the strong nuclear force.

W BOSON
Z BOSON
As the carrier particles of the weak nuclear force, they're downright obese.

HIGGS BOSON
It's the one everyone wants to meet, but for now it's playing hard to get. You'd be smiling too if everyone was looking to interview you.

Standard Model

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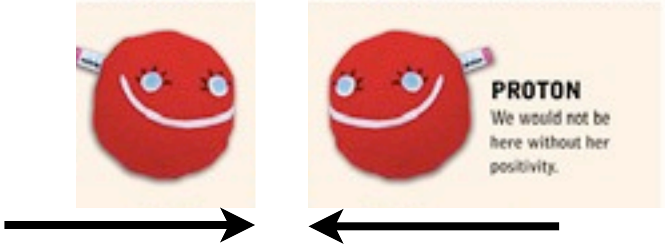
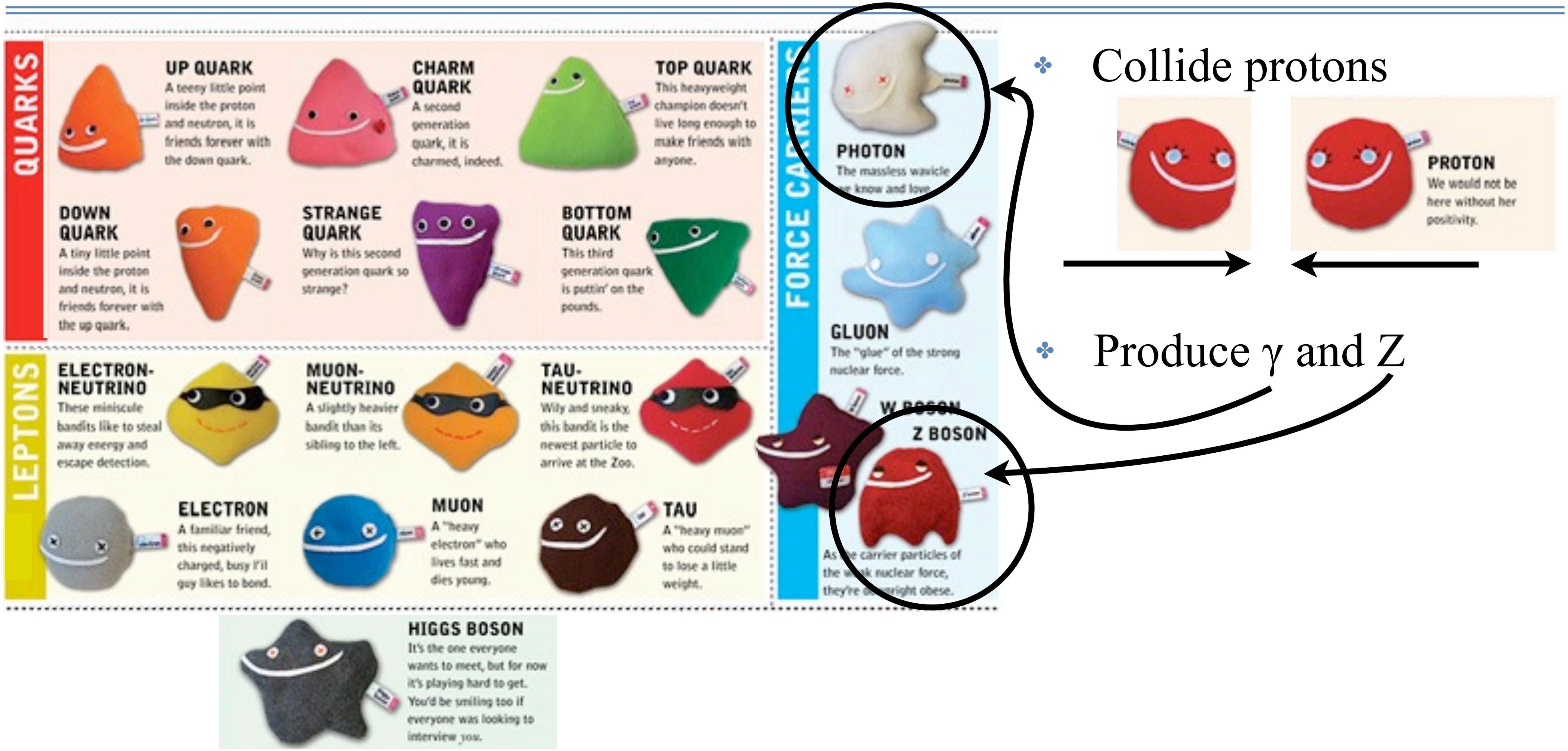
- Collide protons



PROTON We would not be here without her positivity.

Standard Model



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- Collide protons

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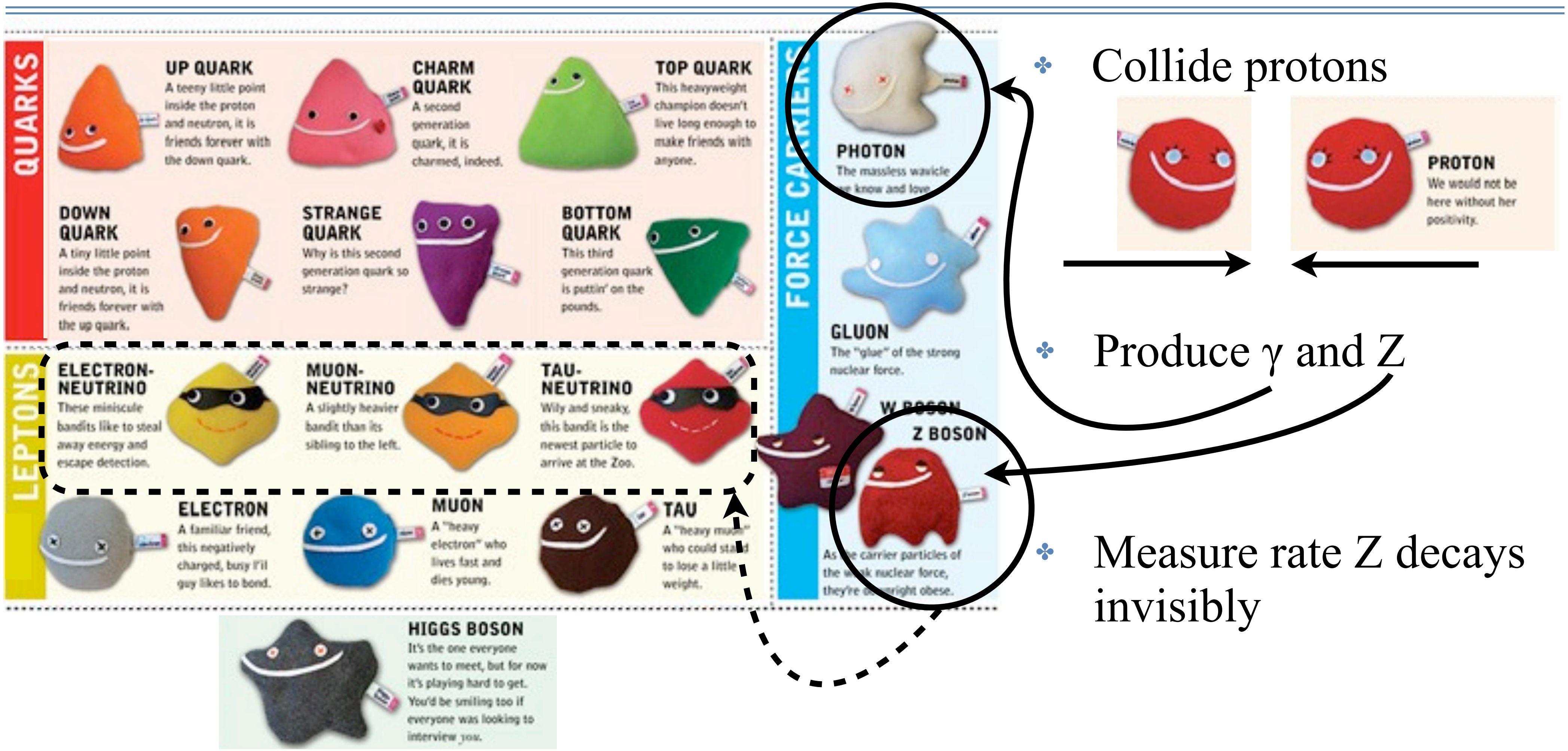
- Produce γ and Z

Standard Model



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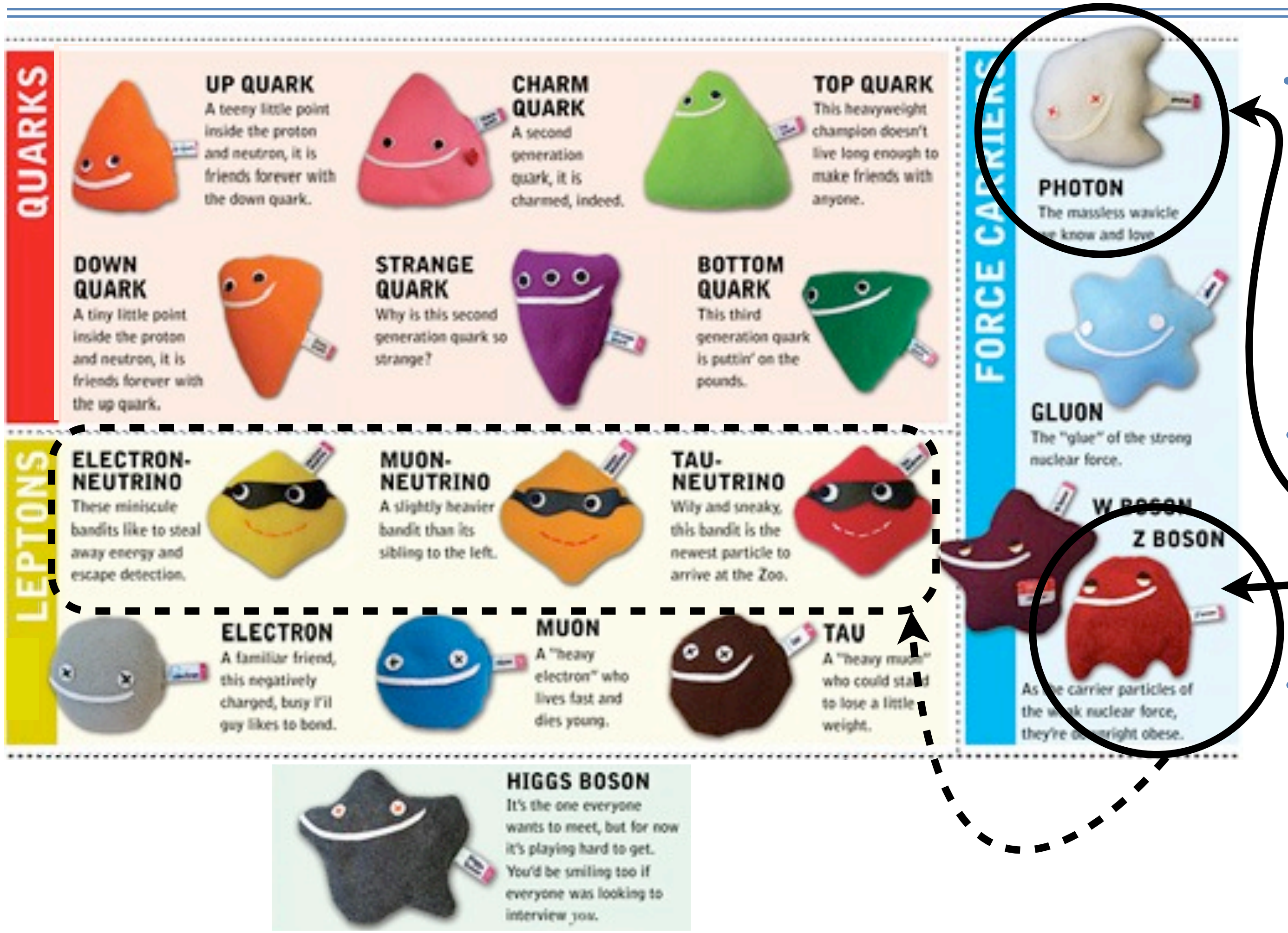
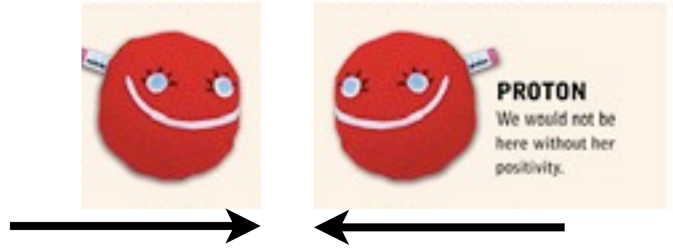
- Collide protons
- Produce γ and Z
- Measure rate Z decays invisibly

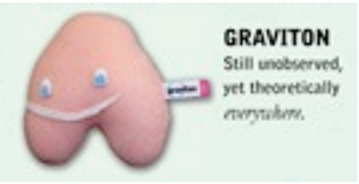
Standard Model



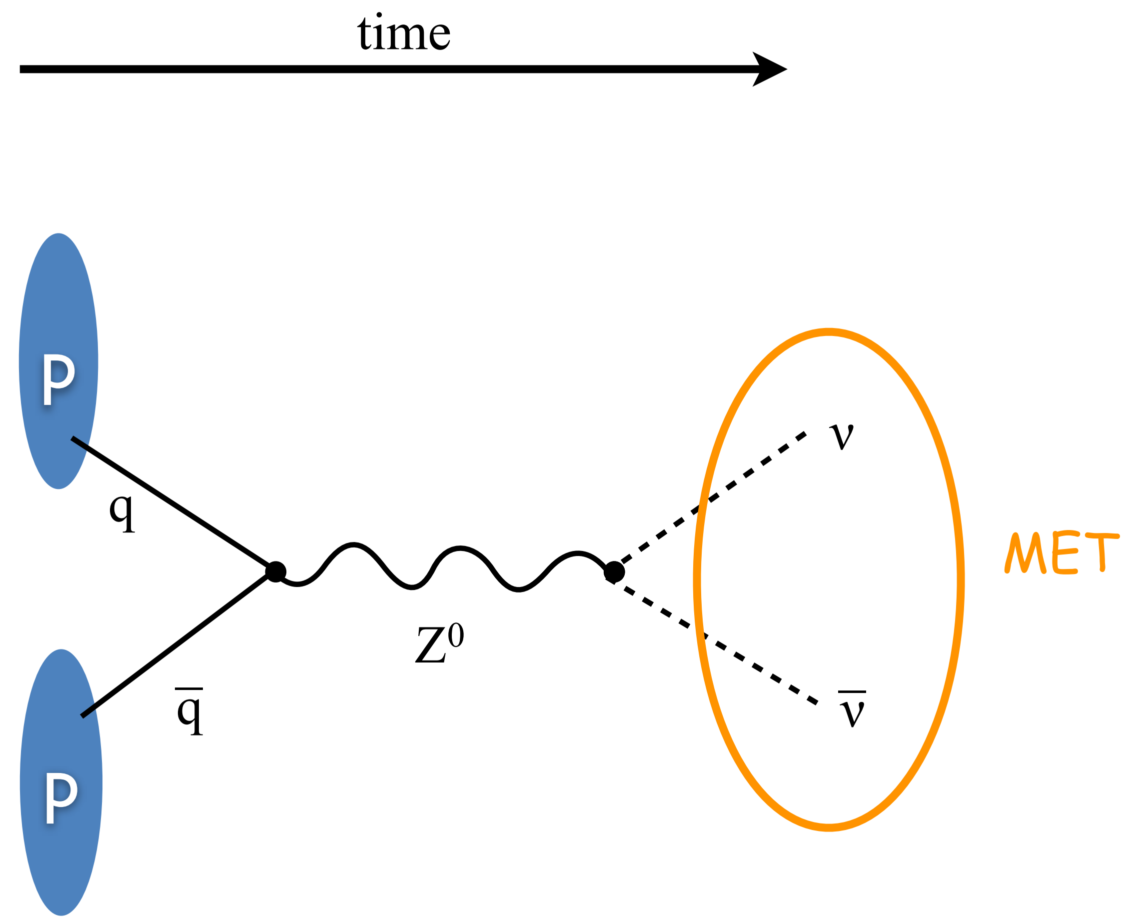
- Collide protons



- Produce γ and Z
- Measure rate Z decays invisibly
- Z decay is invisible… perhaps it's actually something beyond the SM?

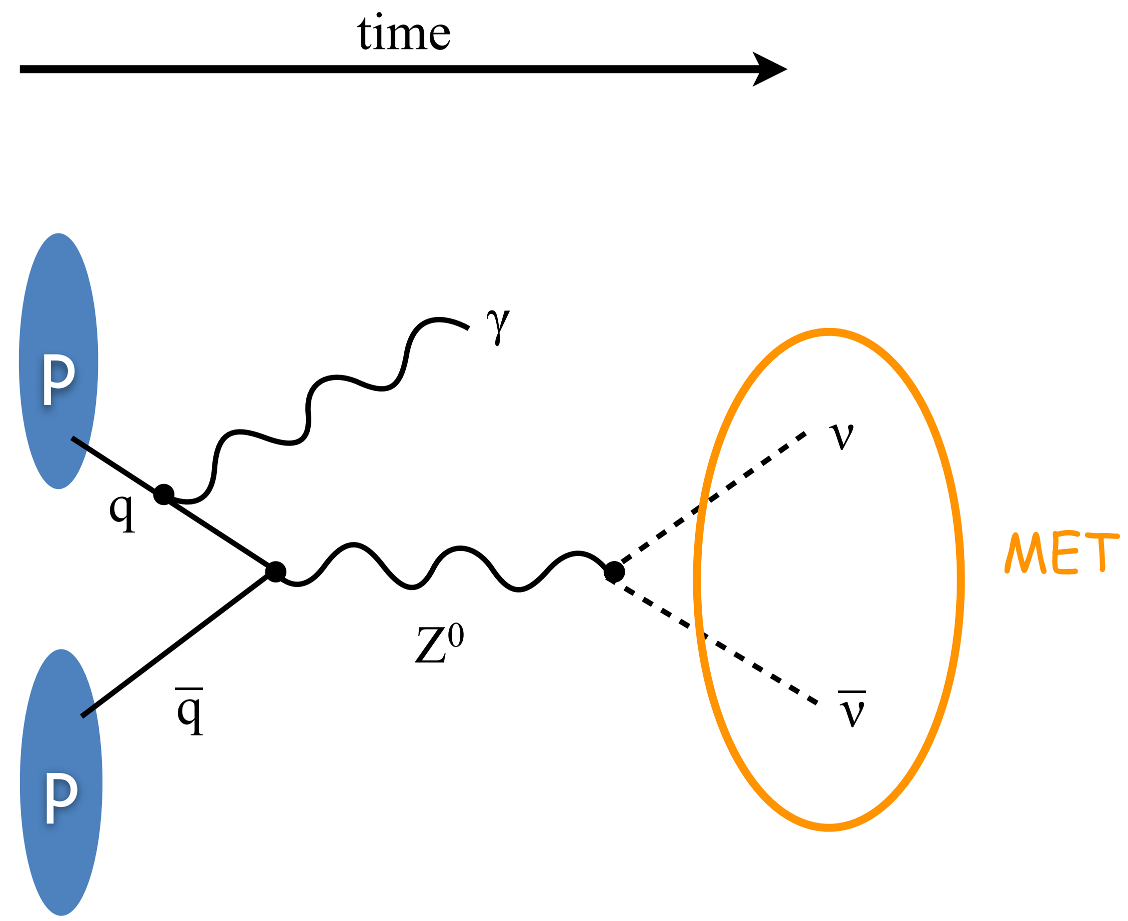


Zγ→νν̄γ cross section



+ forward and/or soft
initial state jets

Zγ→ννγ cross section



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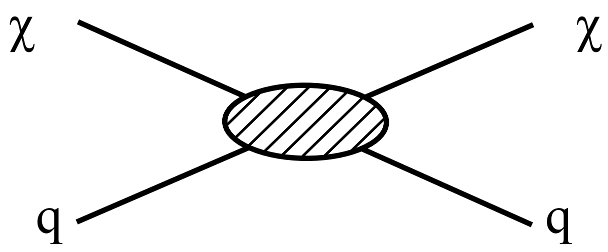
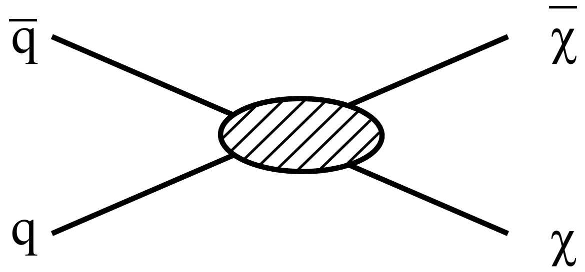
Dark matter (χ) production

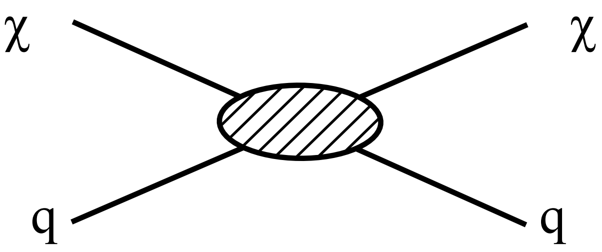


Direct Searches
Nuclear Recoil
(t-channel)



Collider Searches
Pair Production
(s-channel)

Dark matter (χ) production



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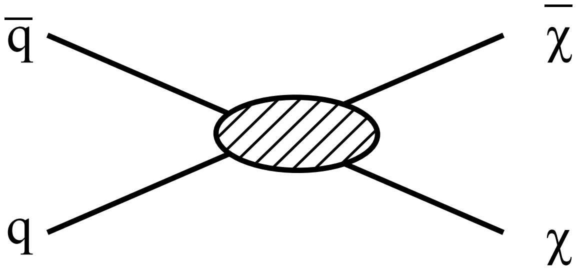
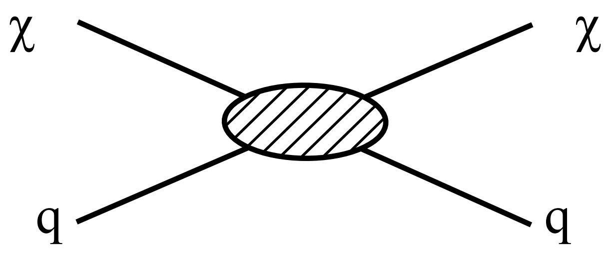


Collider Searches
Pair Production
(s-channel)

- Dark matter passes through CMS undetected, giving rise to "missing transverse energy", E_T^{miss}.

Dark matter (χ) production



Direct Searches
Nuclear Recoil
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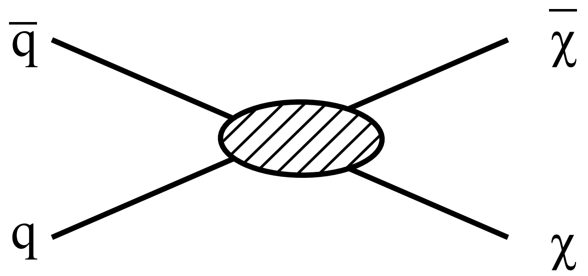
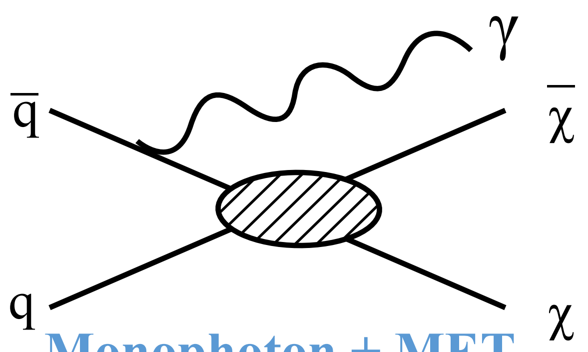


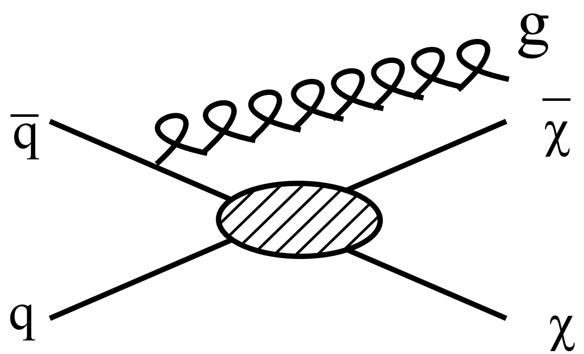
Collider Searches
Pair Production
(s-channel)

- Dark matter passes through CMS undetected, giving rise to "missing transverse energy", E_T^{miss}.

- To make this process visible, radiation of a photon or gluon is required.



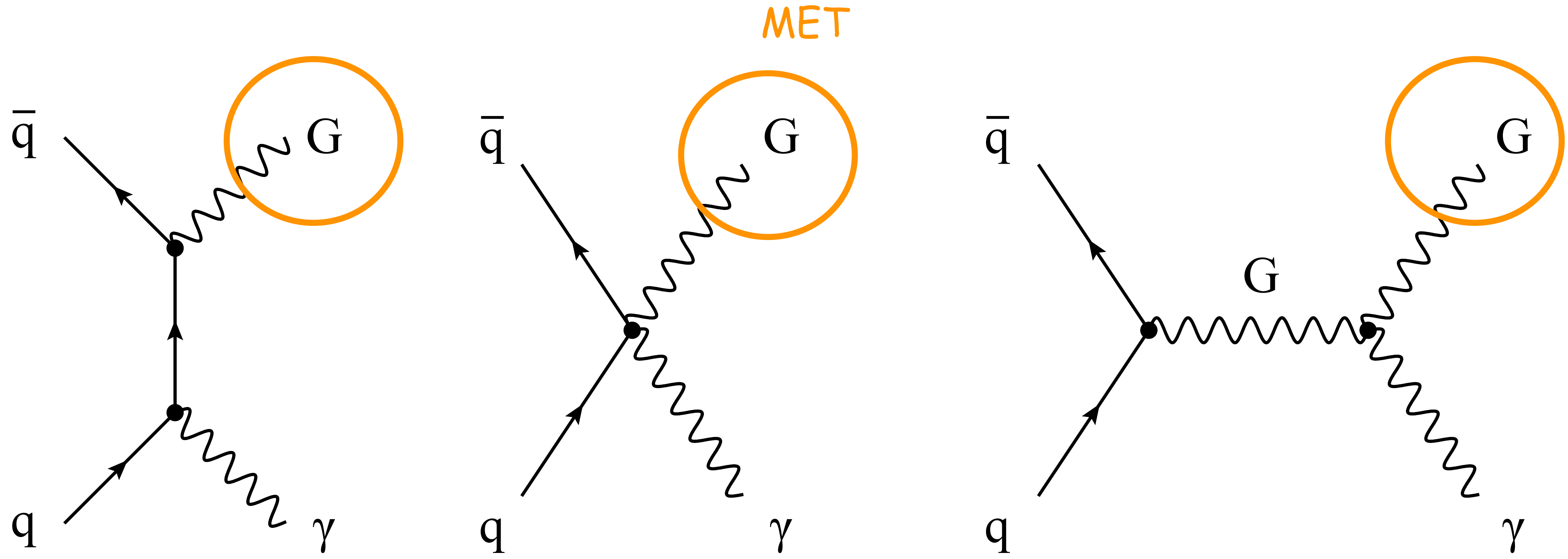
Monophoton + MET



Monojet + MET

ADD extra dimensions

- A proposed solution to the hierarchy problem predicts a type of graviton, G.
- G weakly interacts with SM particles, so it would not interact with CMS, leading to missing transverse energy.



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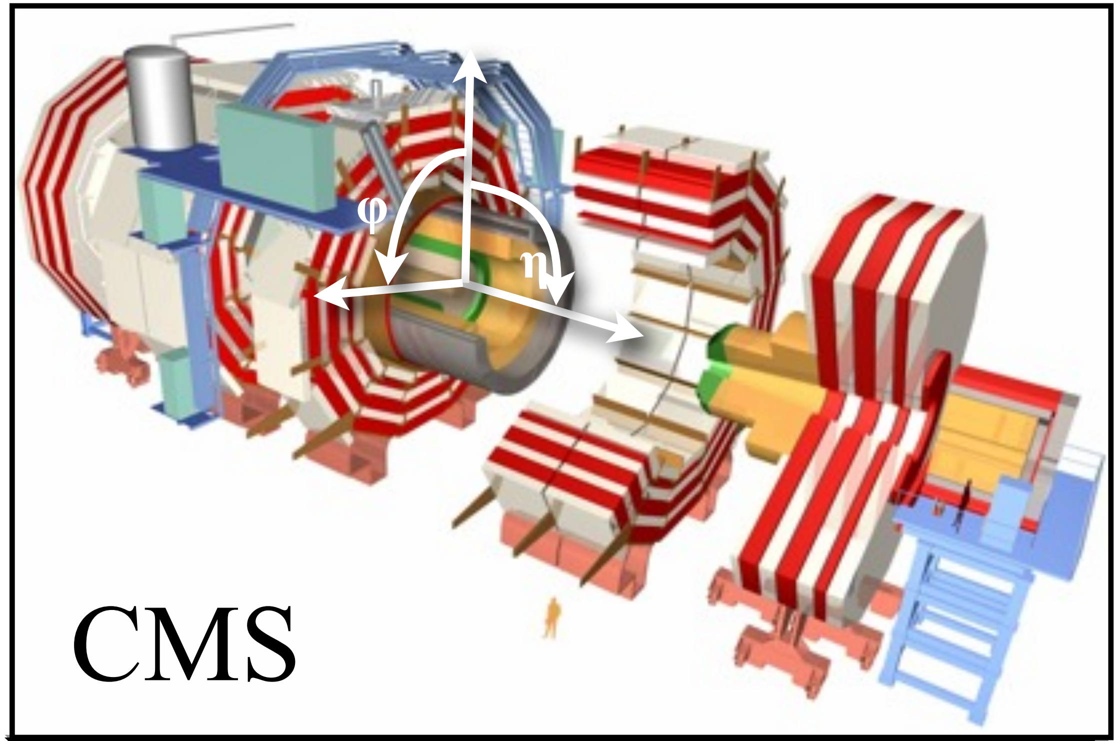
The Large Hadron Collider and the Compact Muon Solenoid

- p-p collisions at the LHC running @ 7 TeV (2011)

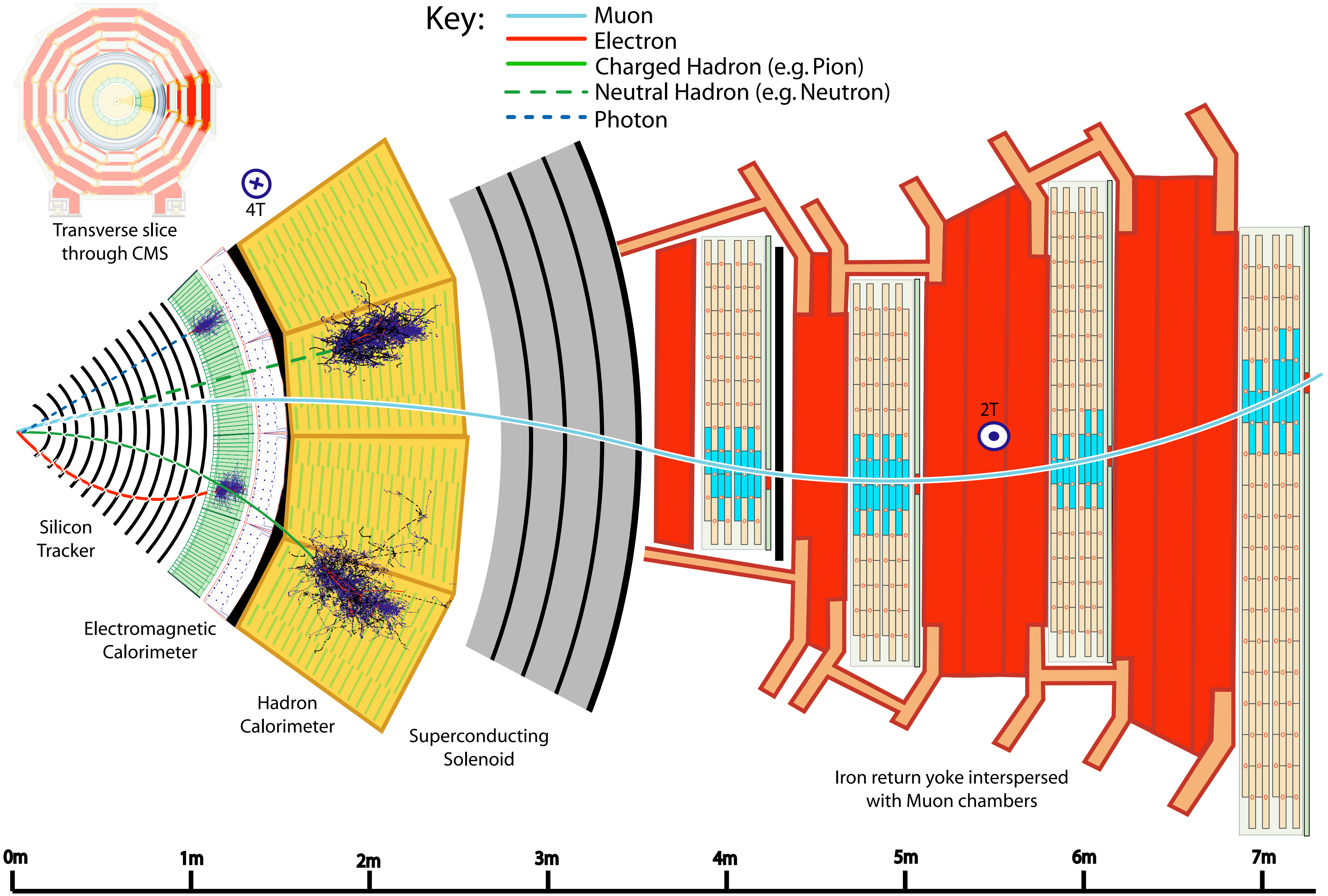
The Large Hadron Collider and the Compact Muon Solenoid

- p-p collisions at the LHC running @ 7 TeV (2011)
- CMS: Compact Muon Solenoid
- 5.0 fb^{-1} of integrated luminosity

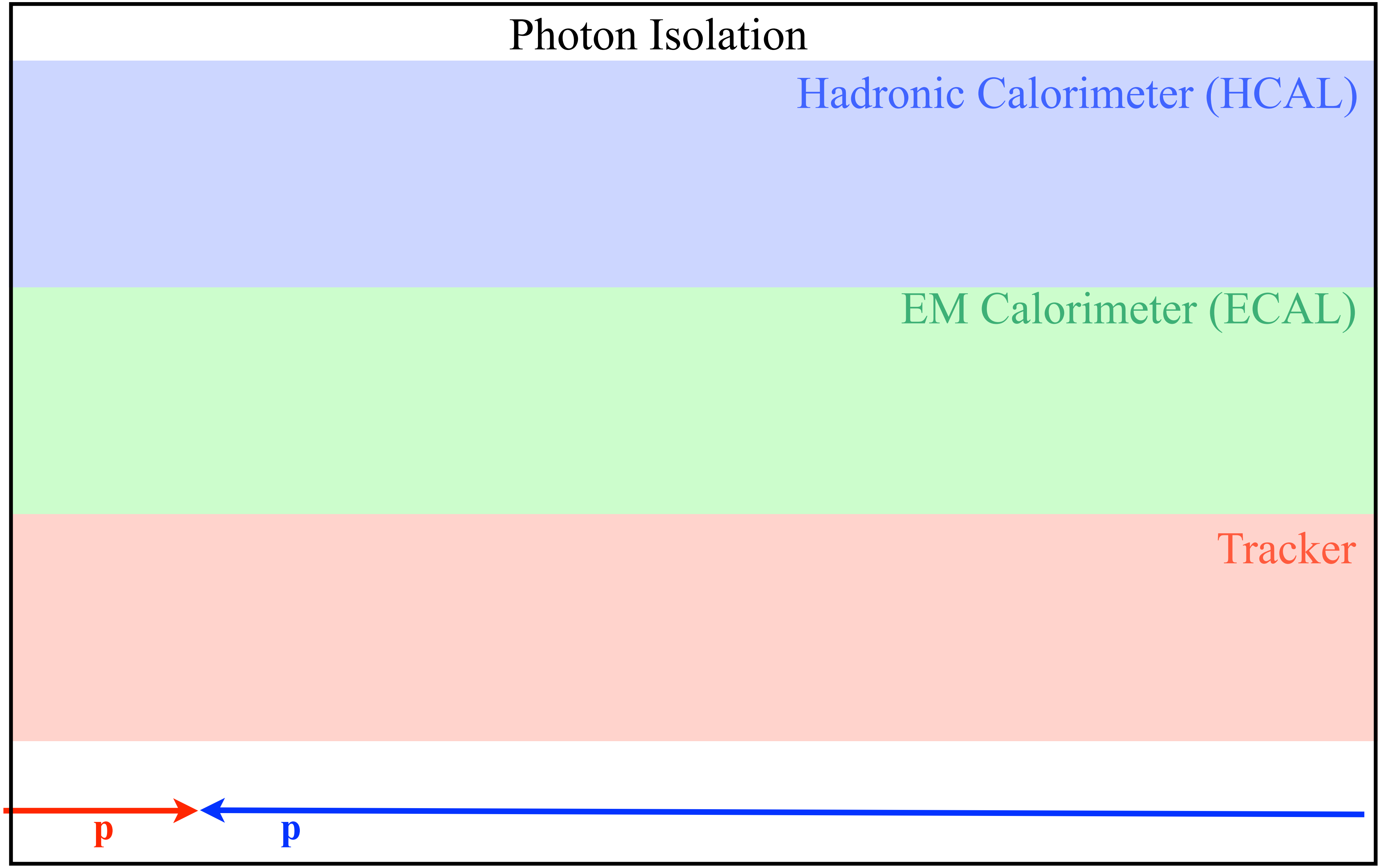
$$\begin{aligned} N_{\text{collisions}} &= L_{\text{int}} \times \sigma(pp@7\text{TeV}) \\ &= 5\ \text{fb}^{-1} \times 110\ \text{mb} \\ &= \sim 550 \times 10^{12}\ \text{collisions!} \end{aligned}$$



CMS Particle ID Overview



Photon Identification



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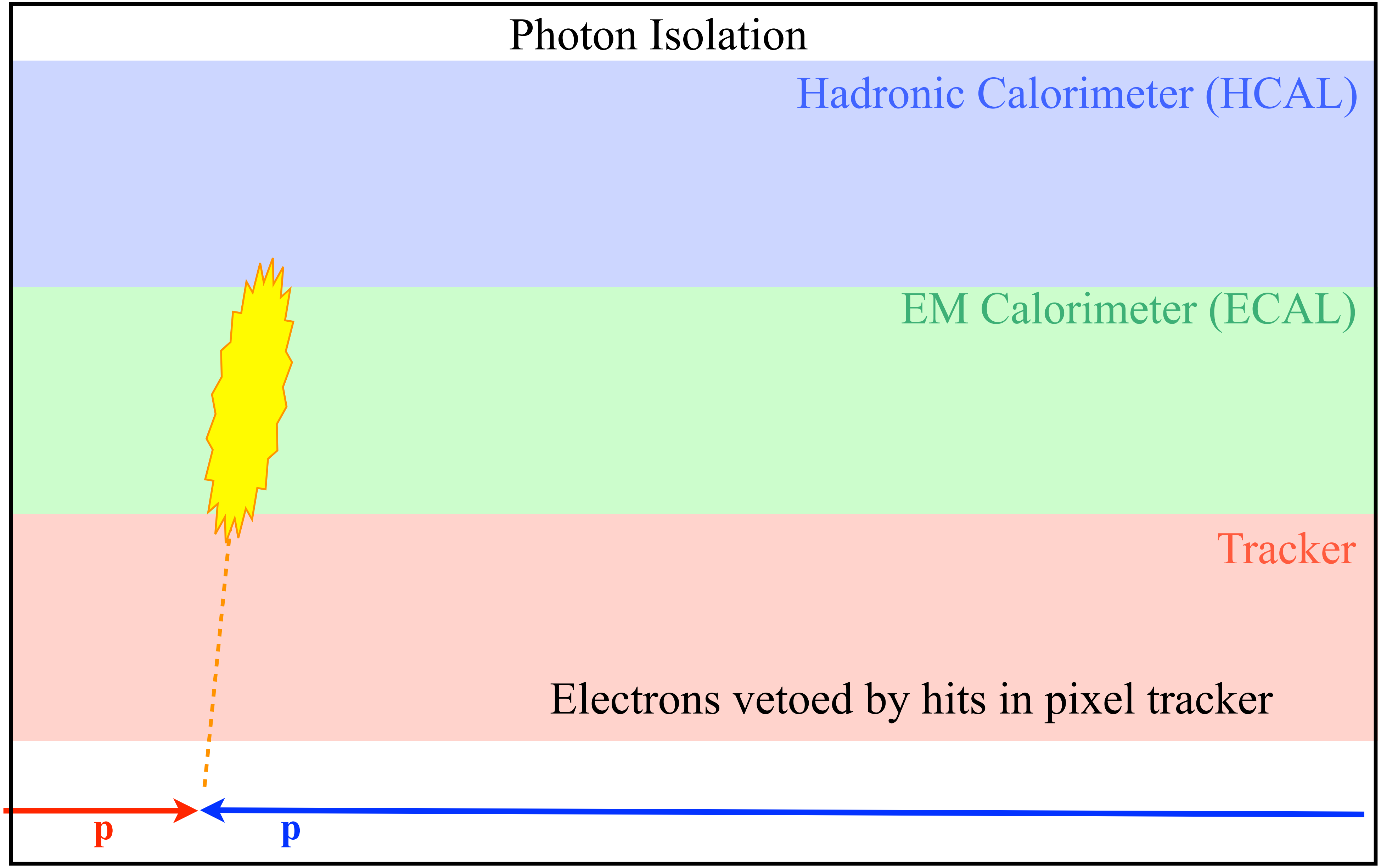
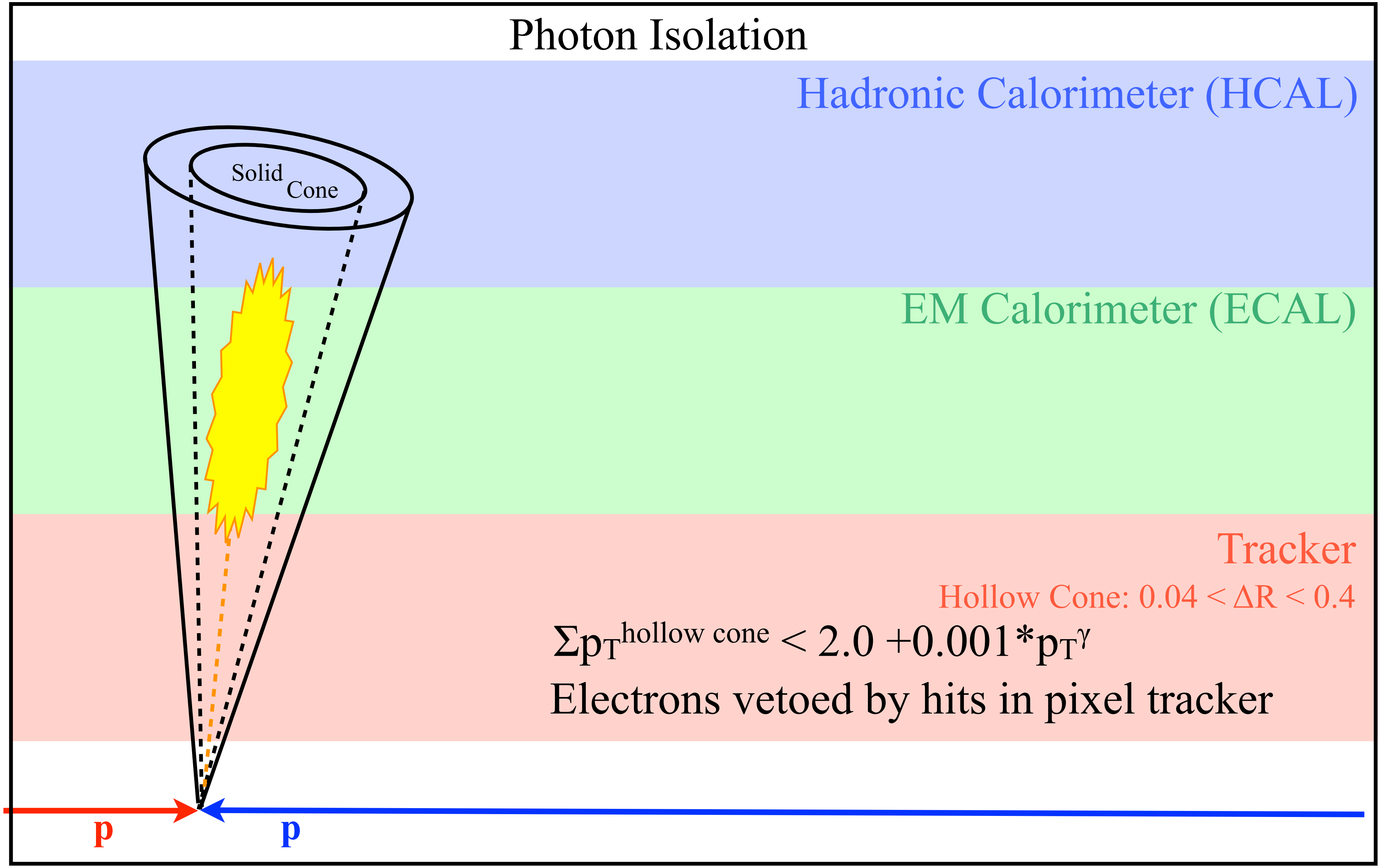


Photon Isolation

Electrons vetoed by hits in pixel tracker

Photon Identification



Photon Isolation

Hadronic Calorimeter (HCAL)

EM Calorimeter (ECAL)

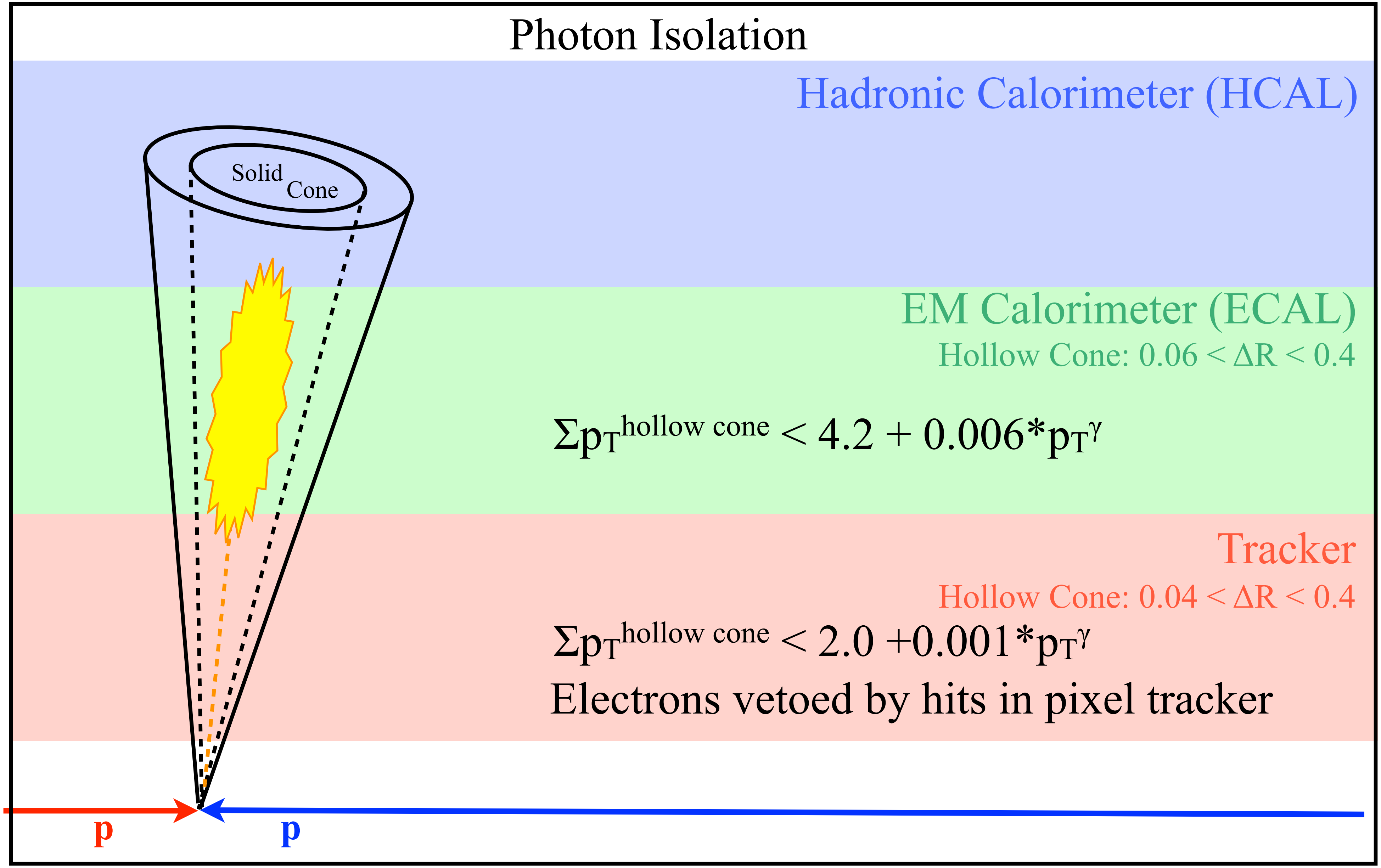
Tracker

Hollow Cone: $0.04 < \Delta R < 0.4$

$\Sigma p_T^{\text{hollow cone}} < 2.0 +0.001 * p_T^{\gamma}$

Electrons vetoed by hits in pixel tracker

Photon Identification



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Hollow Cone: $0.06 < \Delta R < 0.4$

$\Sigma p_T^{\text{hollow cone}} < 4.2 + 0.006 * p_T^{\gamma}$

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Electrons vetoed by hits in pixel tracker

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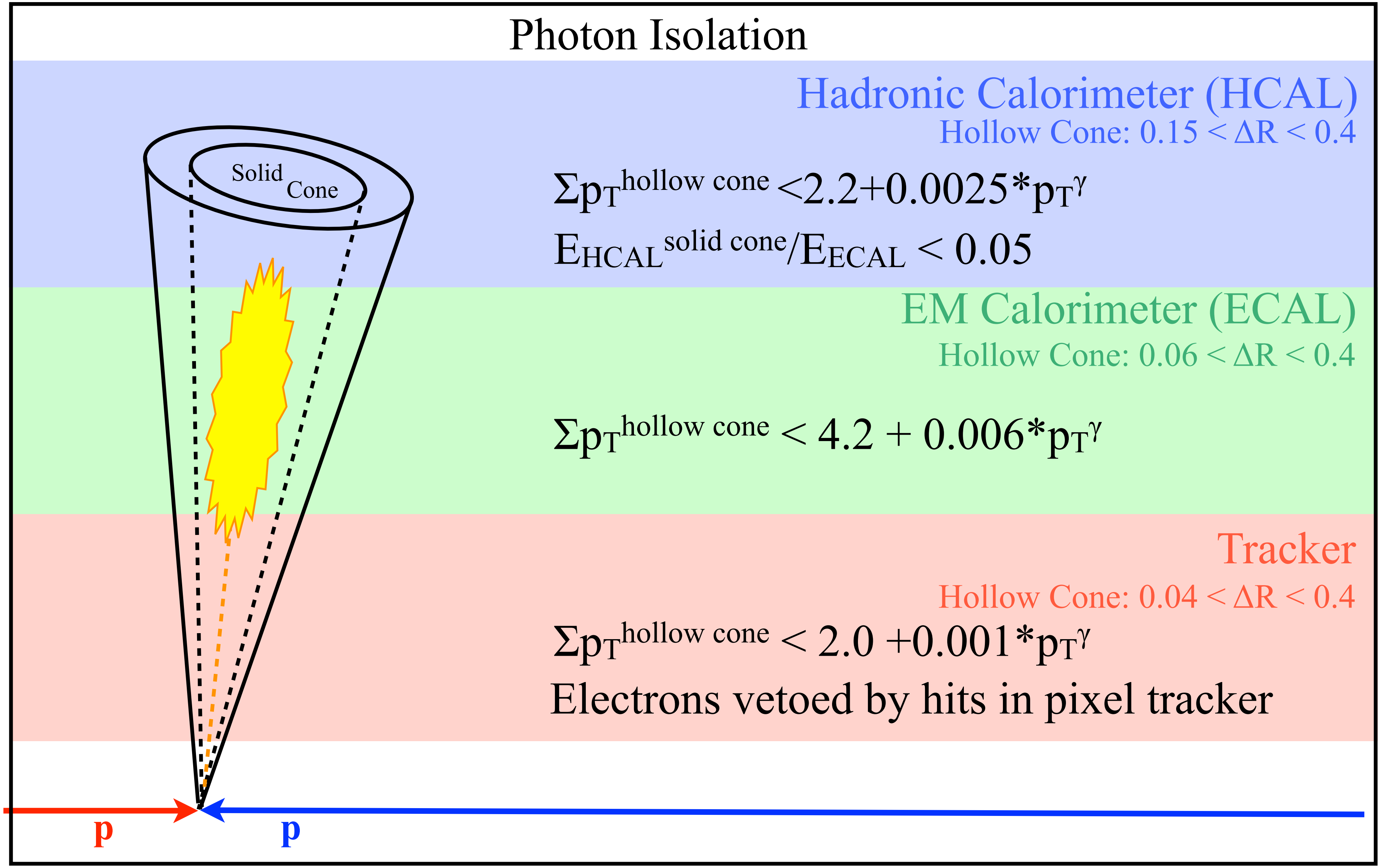

Photon Isolation

Hadronic Calorimeter (HCAL)

Hollow Cone: $0.15 < \Delta R < 0.4$

$\Sigma p_T^{\text{hollow cone}} <2.2+0.0025*p_T^{\gamma}$

$E_{HCAL}^{\text{solid cone}}/E_{ECAL} < 0.05$

EM Calorimeter (ECAL)

Hollow Cone: $0.06 < \Delta R < 0.4$

$\Sigma p_T^{\text{hollow cone}} < 4.2 + 0.006*p_T^{\gamma}$

Tracker

Hollow Cone: $0.04 < \Delta R < 0.4$

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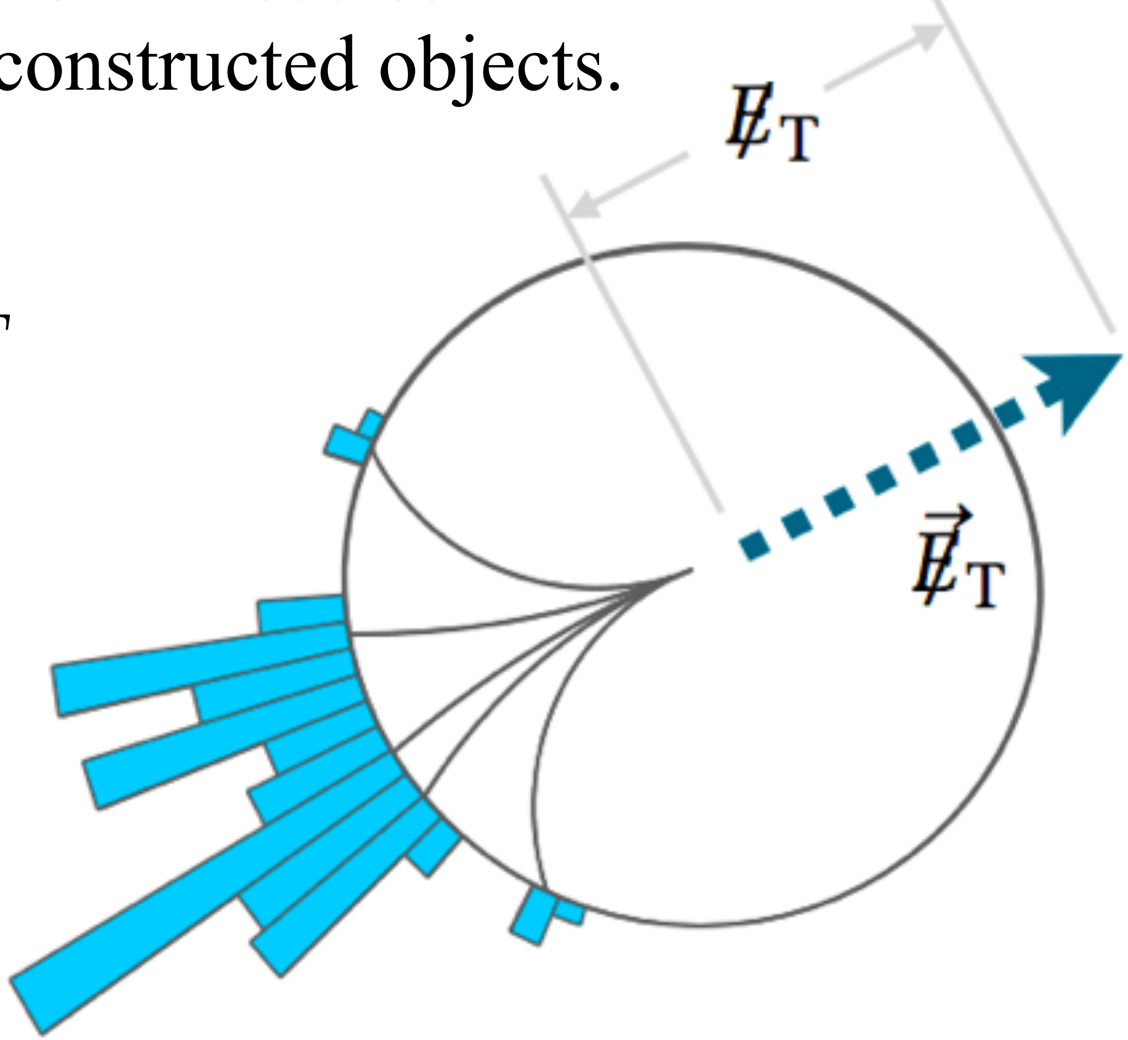
Electrons vetoed by hits in pixel tracker

Missing transverse energy (MET)

- Negative vector sum of transverse momentum of all reconstructed objects.

$$\not{E}_T = -\sum_{\substack{\text{all}\\\text{particles}}} p_T$$



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Monophoton Analysis Outline

- Identify cuts to reduce backgrounds
- Measure residual backgrounds
- Estimate acceptance and efficiency
  - Focus on data/MC scale factor: ρ

$$A \times \epsilon = \underbrace{A \times \epsilon_{MC}}_{\text{MC only}} \times \underbrace{\rho}_{\text{data vs. MC}}$$

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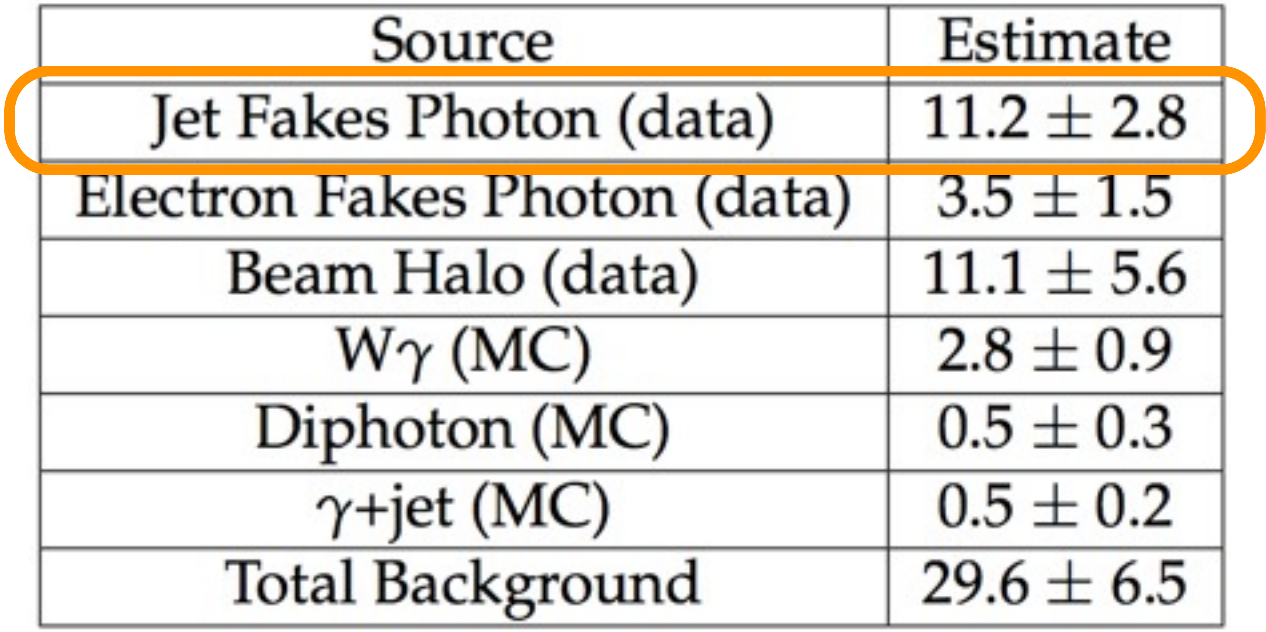
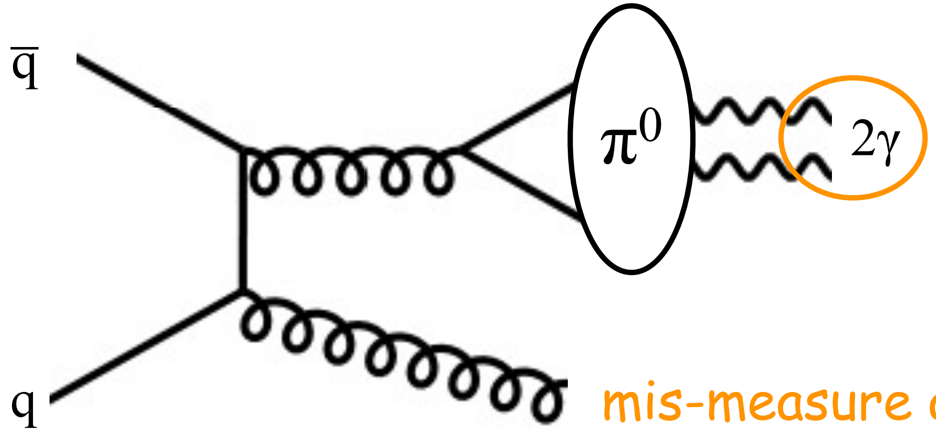


Source	Estimate
Jet Fakes Photon (data)	11.2 ± 2.8
Electron Fakes Photon (data)	3.5 ± 1.5
Beam Halo (data)	11.1 ± 5.6
$W\gamma$ (MC)	2.8 ± 0.9
Diphoton (MC)	0.5 ± 0.3
γ+jet (MC)	0.5 ± 0.2
Total Background	29.6 ± 6.5

Candidate Criteria

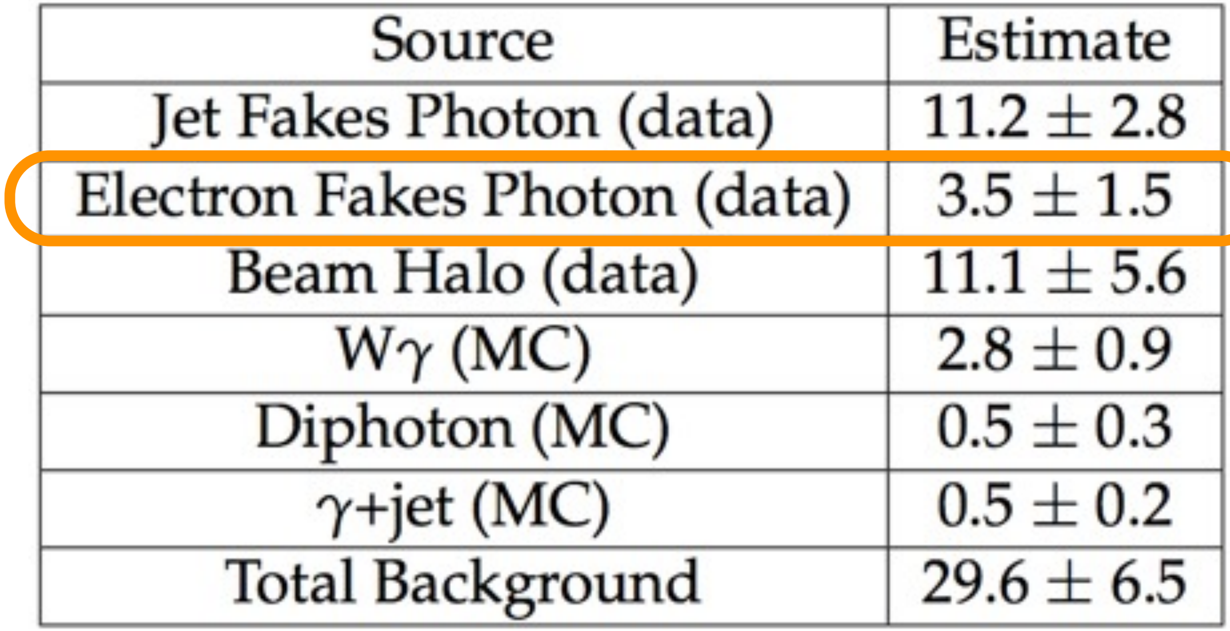
- Tight Photon ID
  - $E_{HCAL}/E_{ECAL} < 0.05$
  - Isolated in ECAL, HCAL, Tracker
  - $\sigma_{i\eta i\eta} < 0.013$



mis-ID as 1 γ

mis-measure as MET

Monophoton Backgrounds



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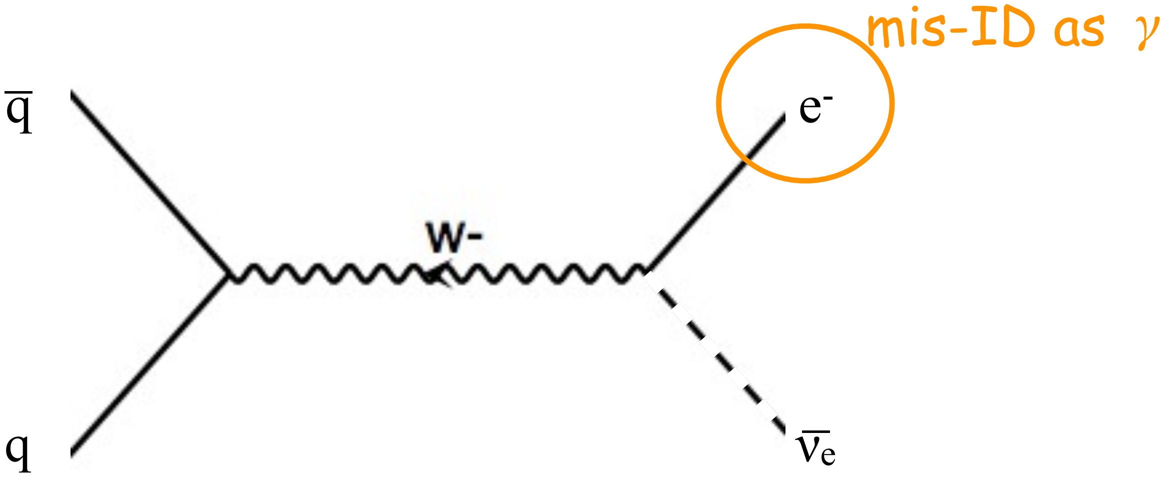

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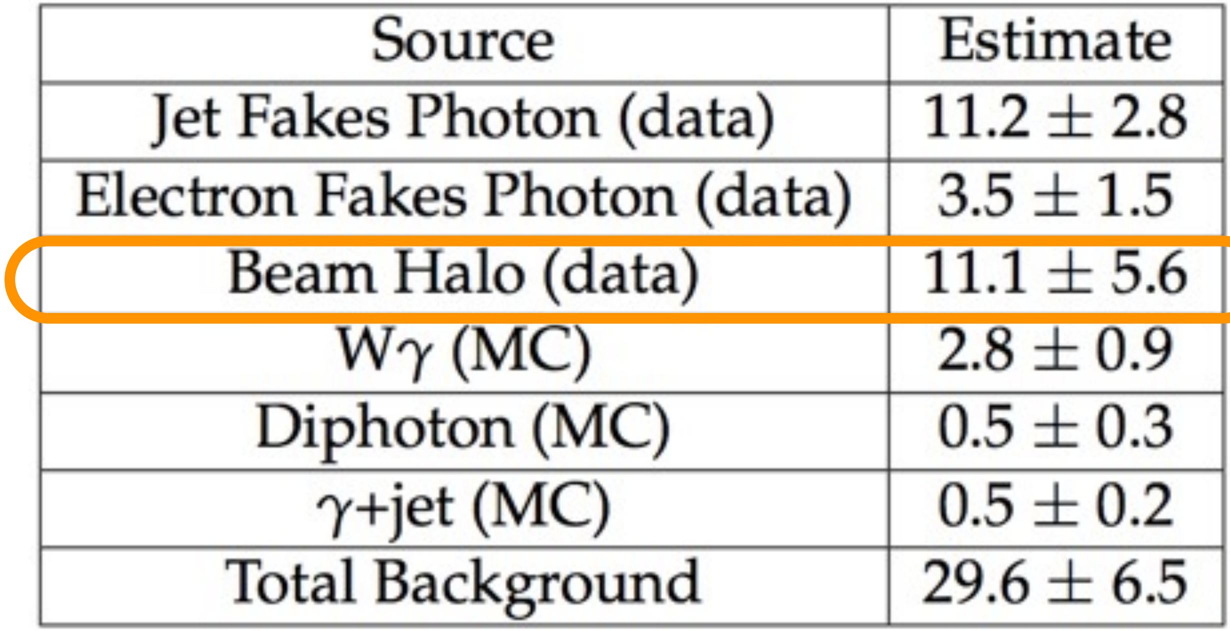

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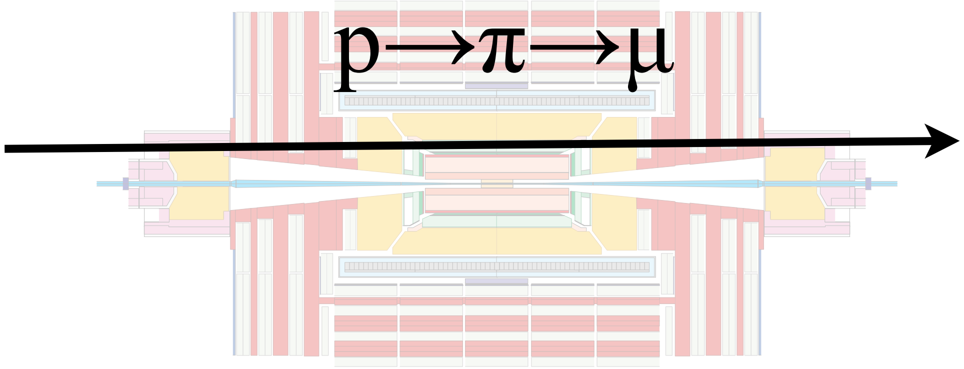
- clean beam (no “scraping”)
- veto events with muons
- $|t_\gamma| < 3$ ns

defocused proton remnants



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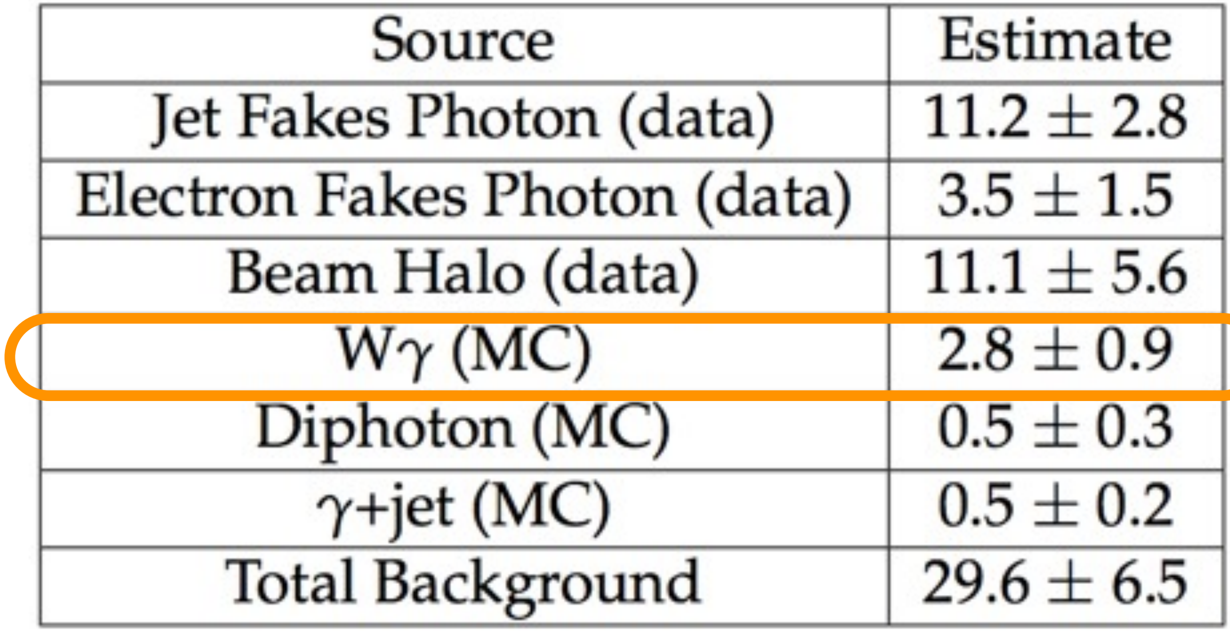

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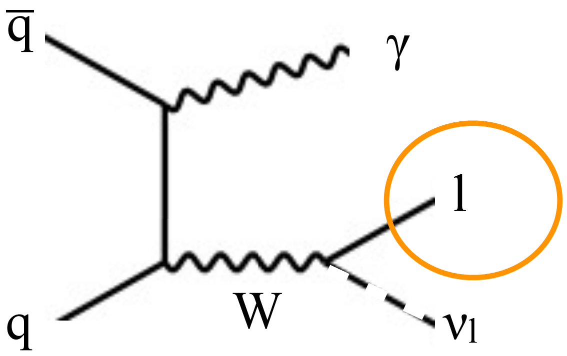
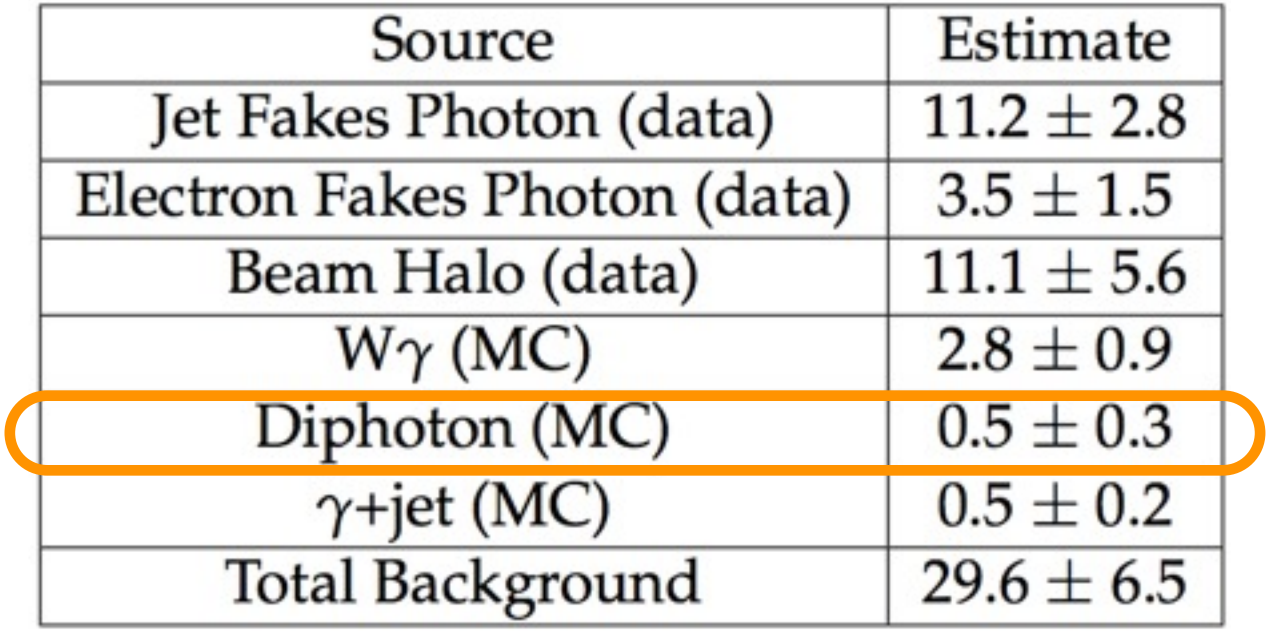
- No tracks with $p_T > 20$ GeV within $\Delta R(\text{track},\gamma) > 0.04$



escapes detection

Monophoton Backgrounds



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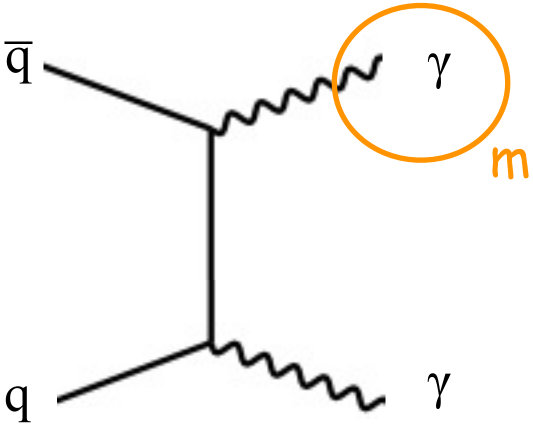
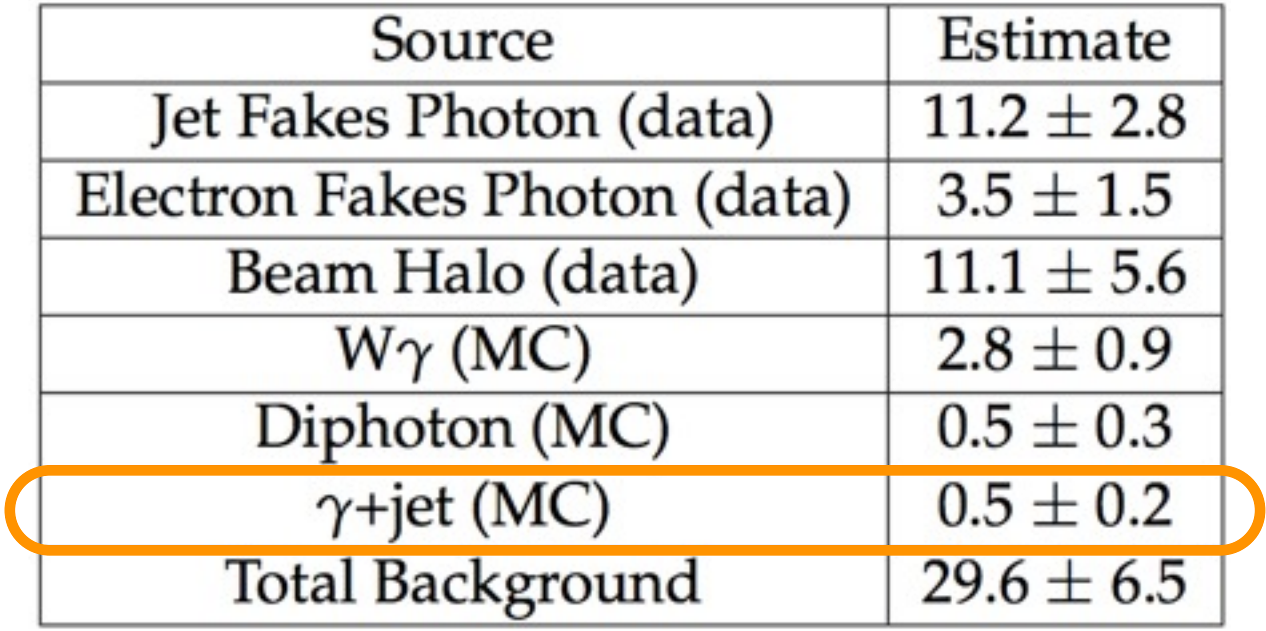
- MET > 130 GeV



mis-measured as MET

Monophoton Backgrounds



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Total Background	29.6 ± 6.5

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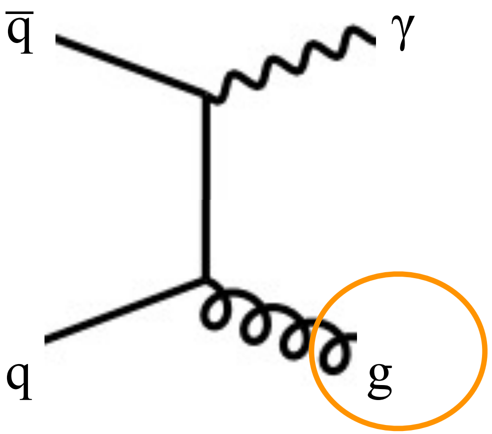
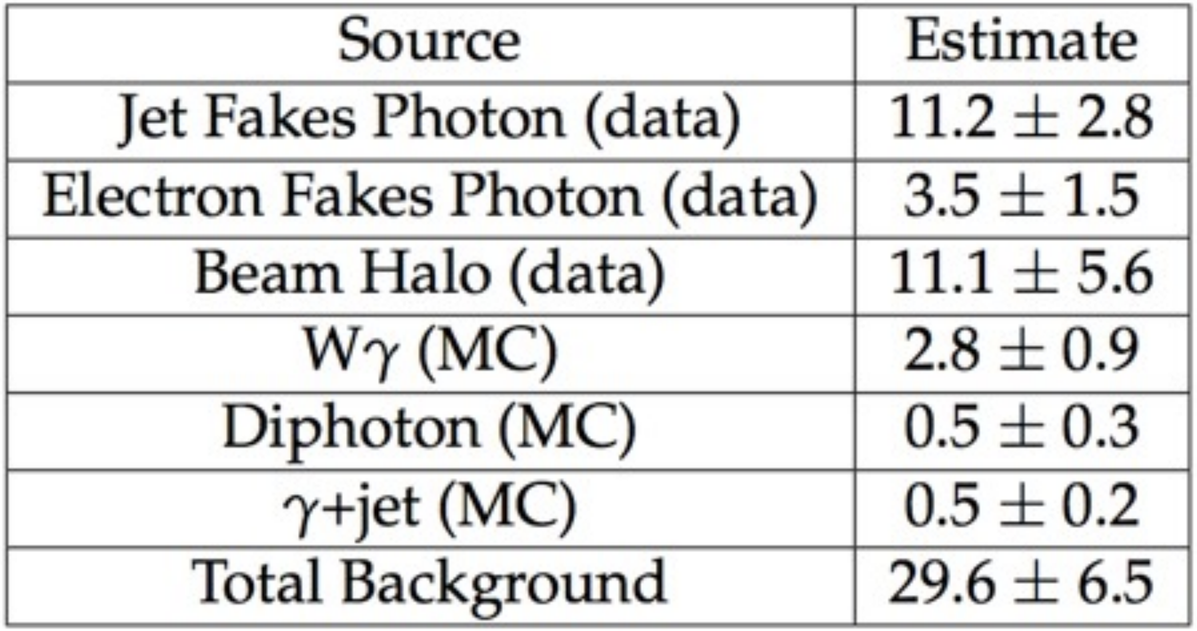


mis-measured as MET

Monophoton Backgrounds



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Anomalous ECAL deposits

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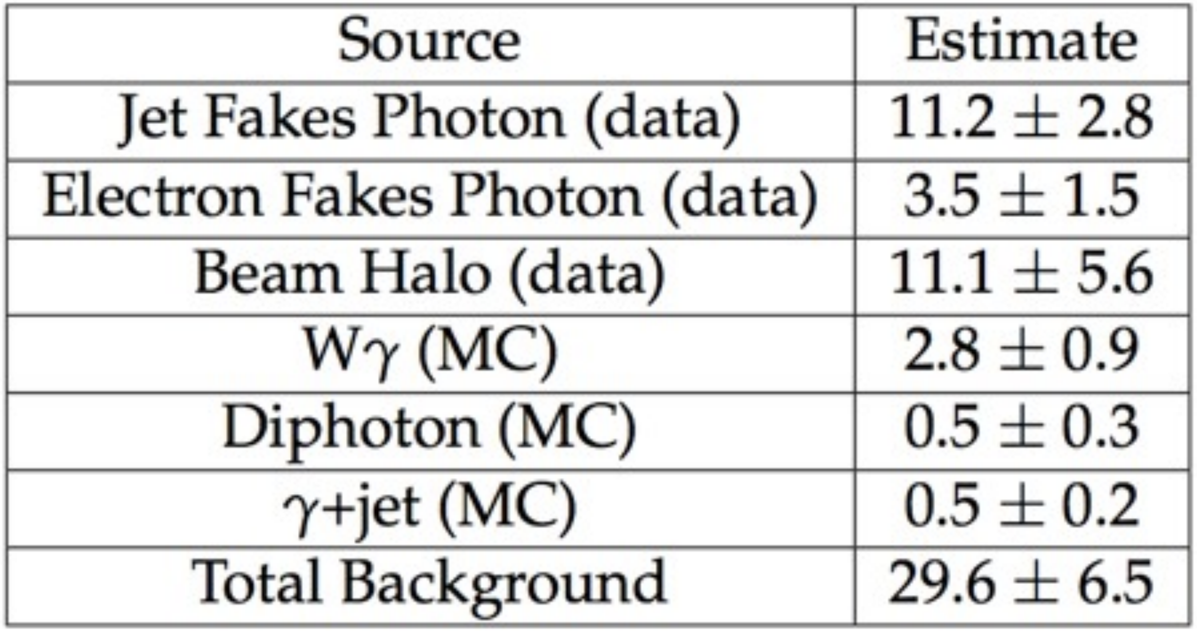
Monophoton Backgrounds



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- time spread within shower < 5ns
- $E_T^\gamma > 145$ GeV
- photon in central barrel

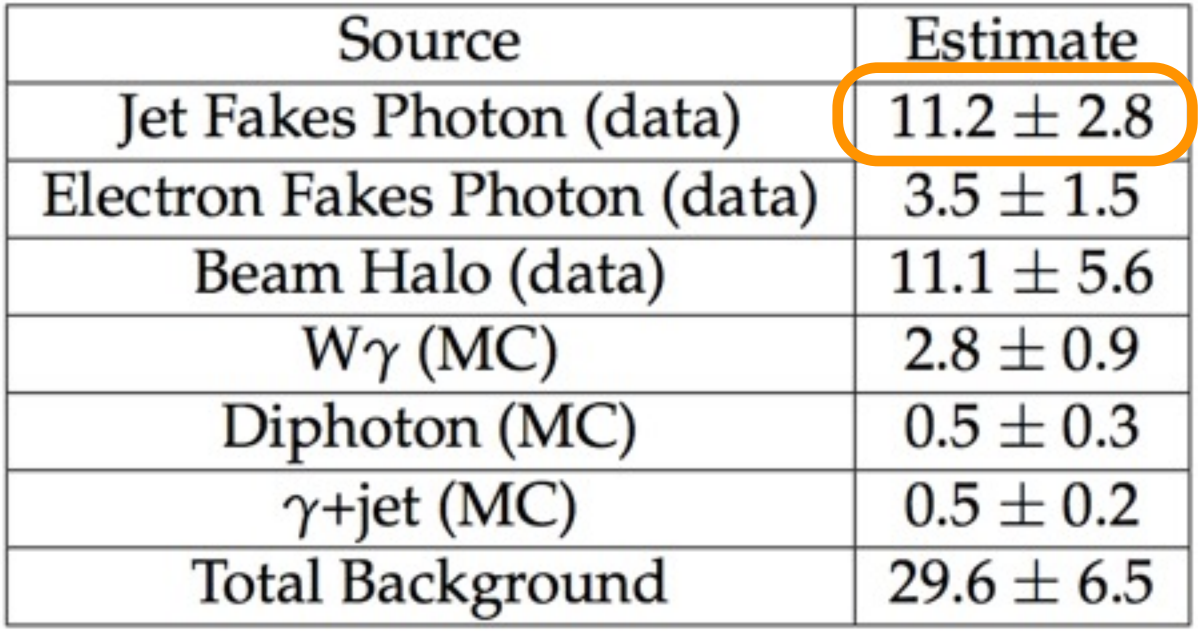
photon trigger

Monophoton Analysis Outline

- Identify cuts to reduce backgrounds
- Measure residual backgrounds
- Estimate acceptance and efficiency
  - Focus on data/MC scale factor: ρ

$$A \times \epsilon = \underbrace{A \times \epsilon_{MC}}_{\text{MC only}} \times \underbrace{\rho}_{\text{data vs. MC}}$$

Monophoton Backgrounds



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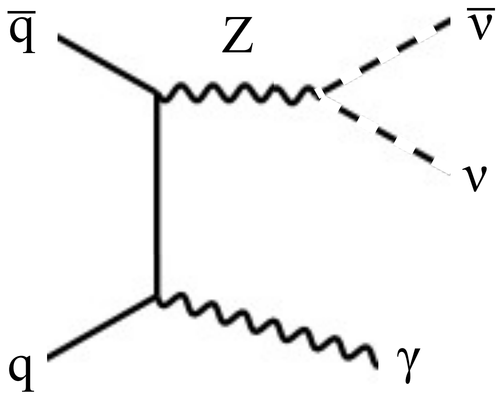
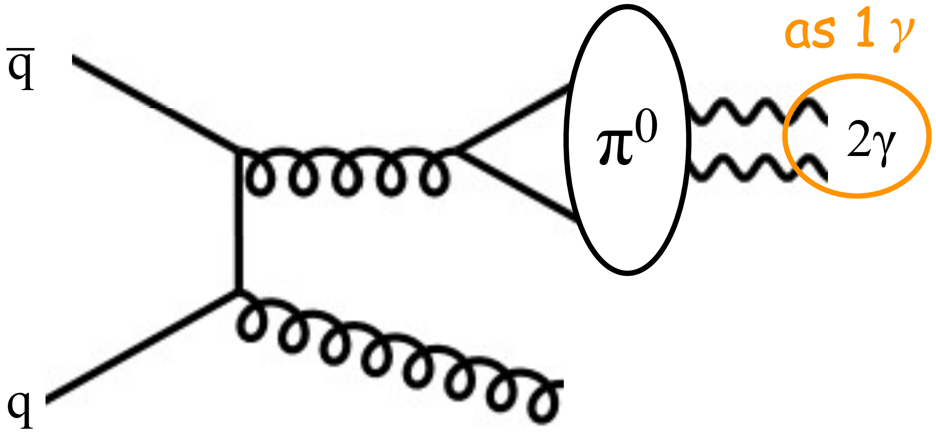
Estimating Backgrounds: EM-like jets



signal:
prompt photon



mis-ID
as 1 γ

background:
jet faking a photon

Estimating Backgrounds: EM-like jets

Jet Sample

- require jet trigger
- MET < 20 GeV
- allow tracks and jets

Photon Sample

- require γ trigger
- MET > 130 GeV
- veto tracks and jets

Estimating Backgrounds: EM-like jets

Jet Sample

- require jet trigger
- MET < 20 GeV
- allow tracks and jets

Require loose γ ID

Photon Sample

- require γ trigger
- MET > 130 GeV
- veto tracks and jets

Require loose γ ID

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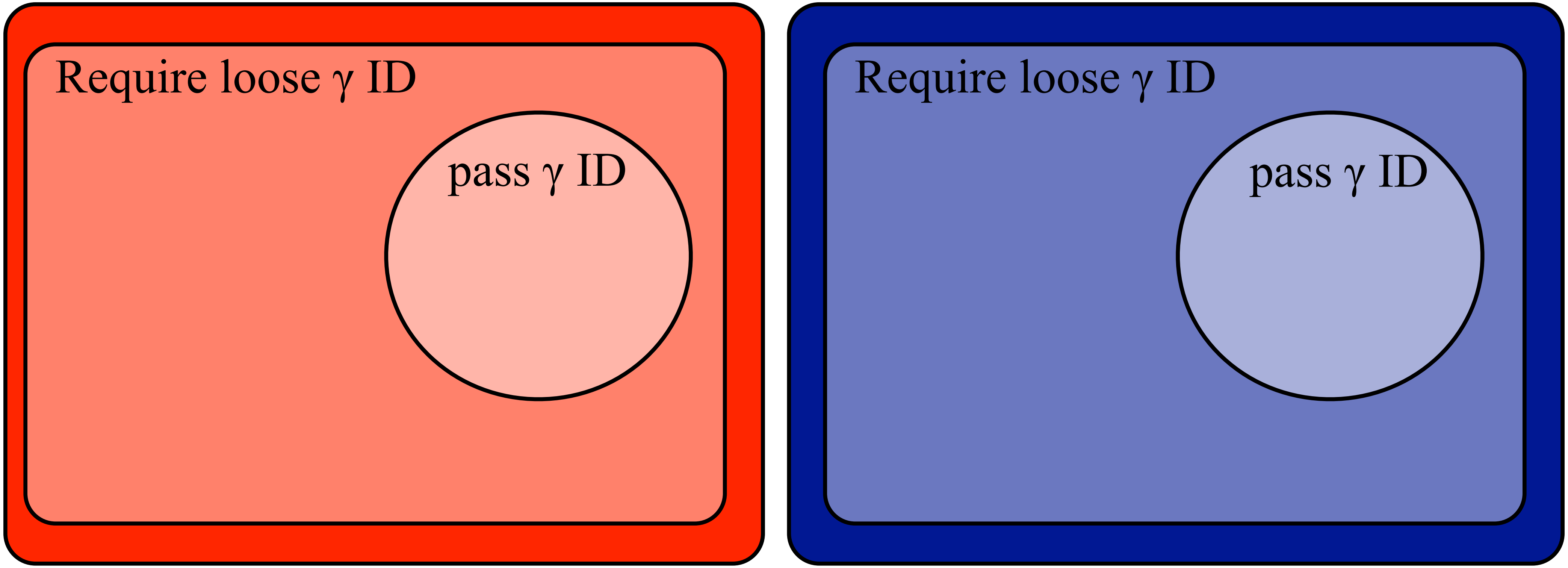

Require loose γ ID

pass γ ID

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pass γ ID

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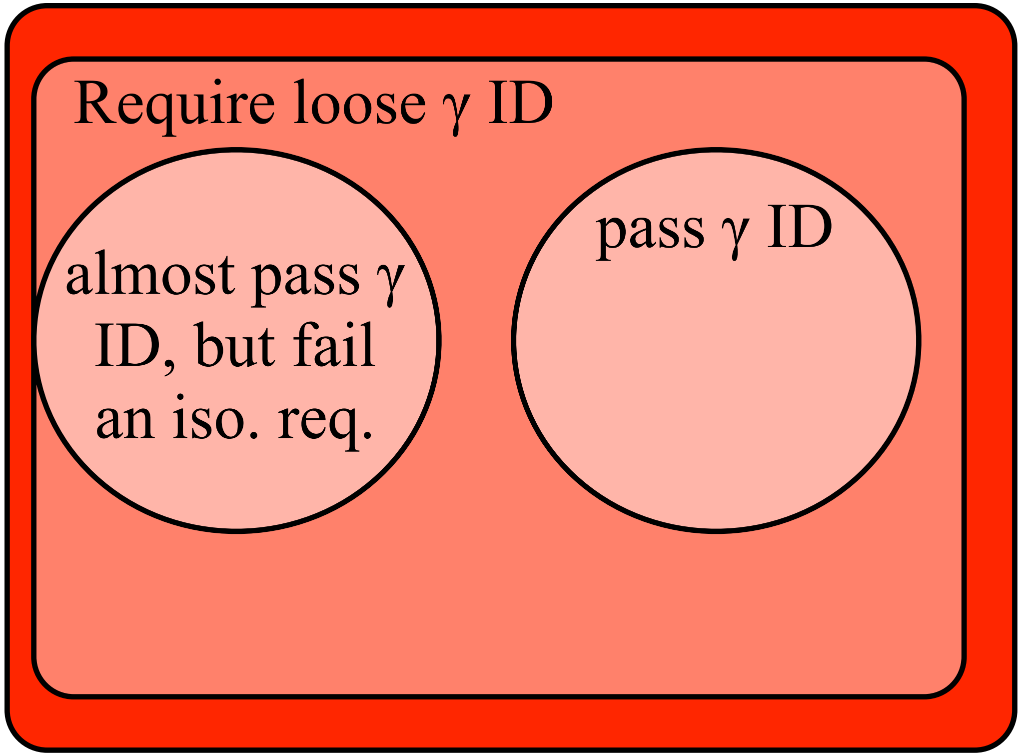
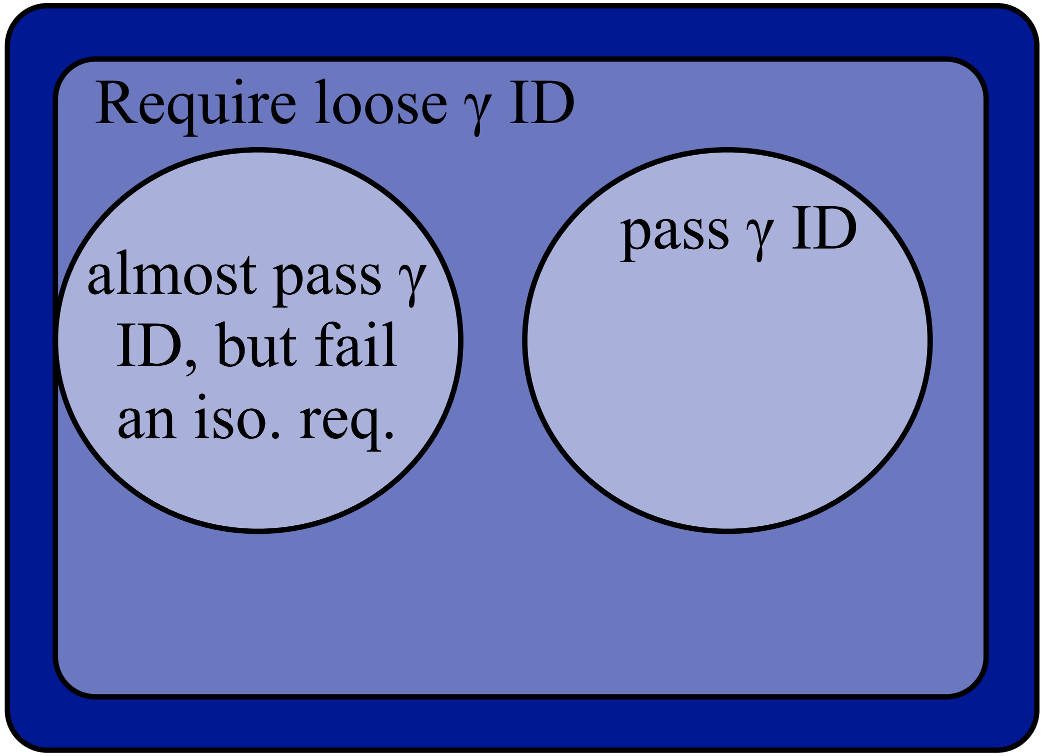


Require loose γ ID

almost pass γ ID, but fail an iso. req.

pass γ ID



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Estimating Backgrounds: EM-like jets

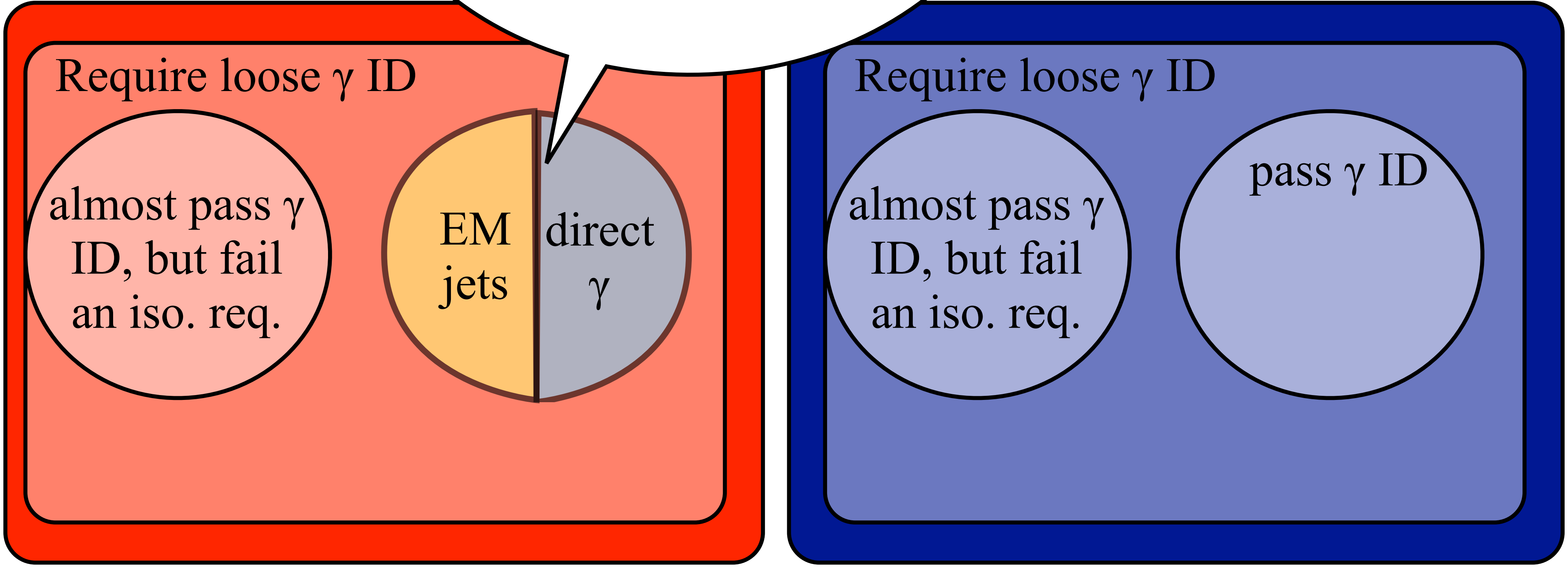
Jet Sample

- require je
- MET < 2(
- allow track

on Sample

- ire γ trigger
- T > 130 GeV
- o tracks and jets

fraction determined by fitting the shower shape with jet and γ templates



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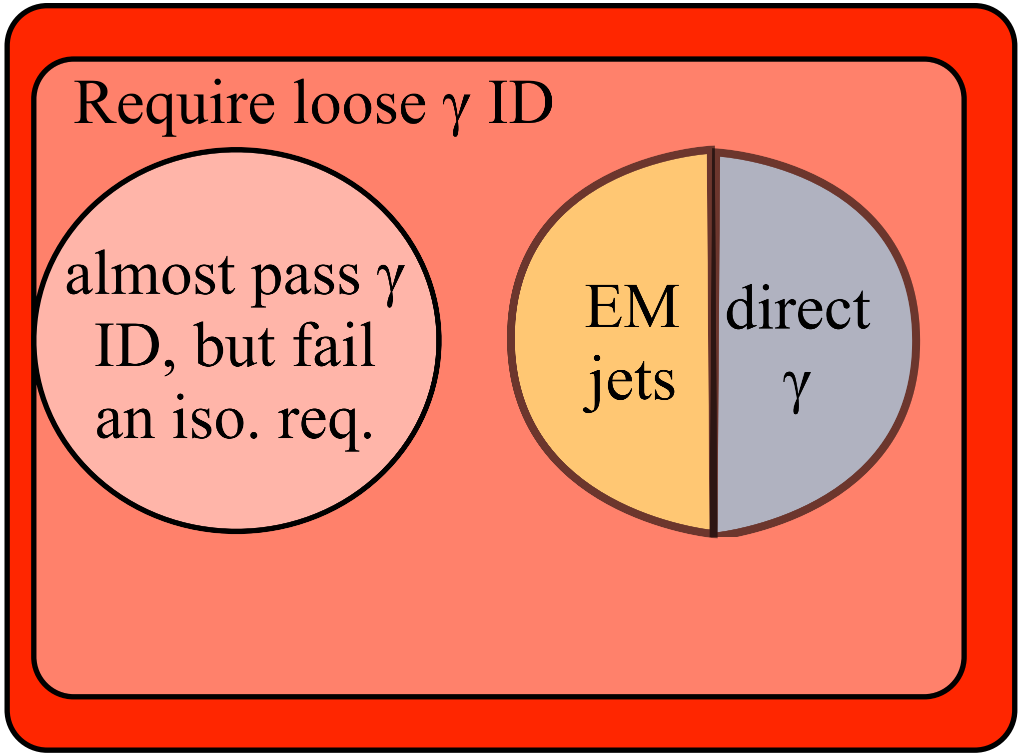
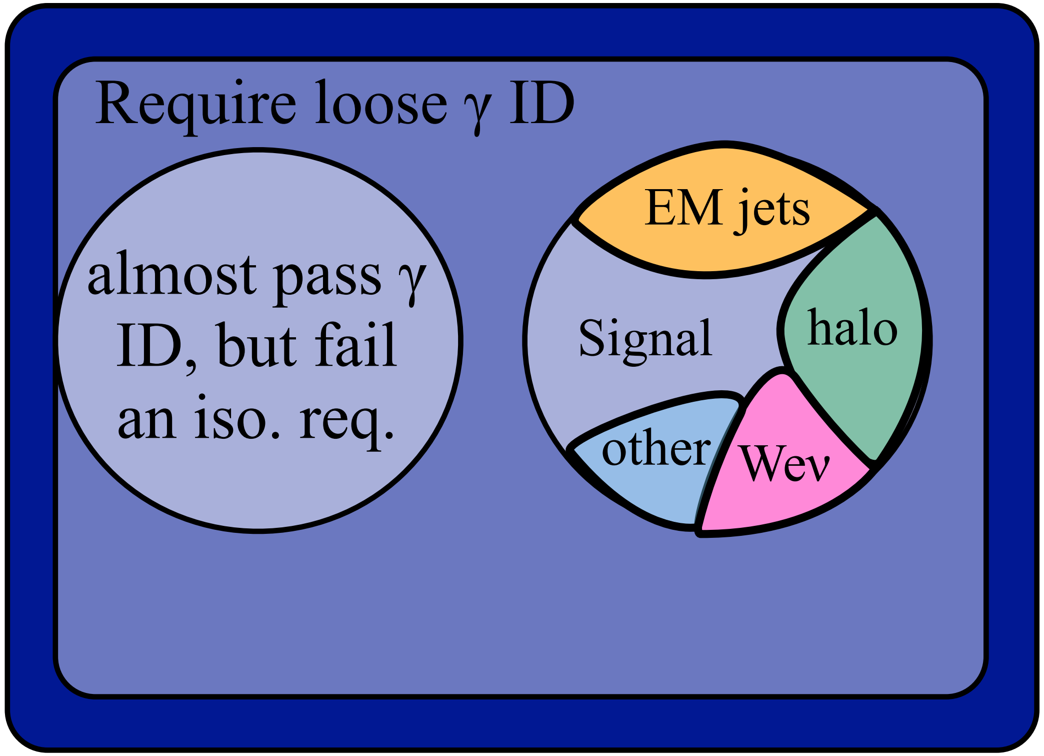
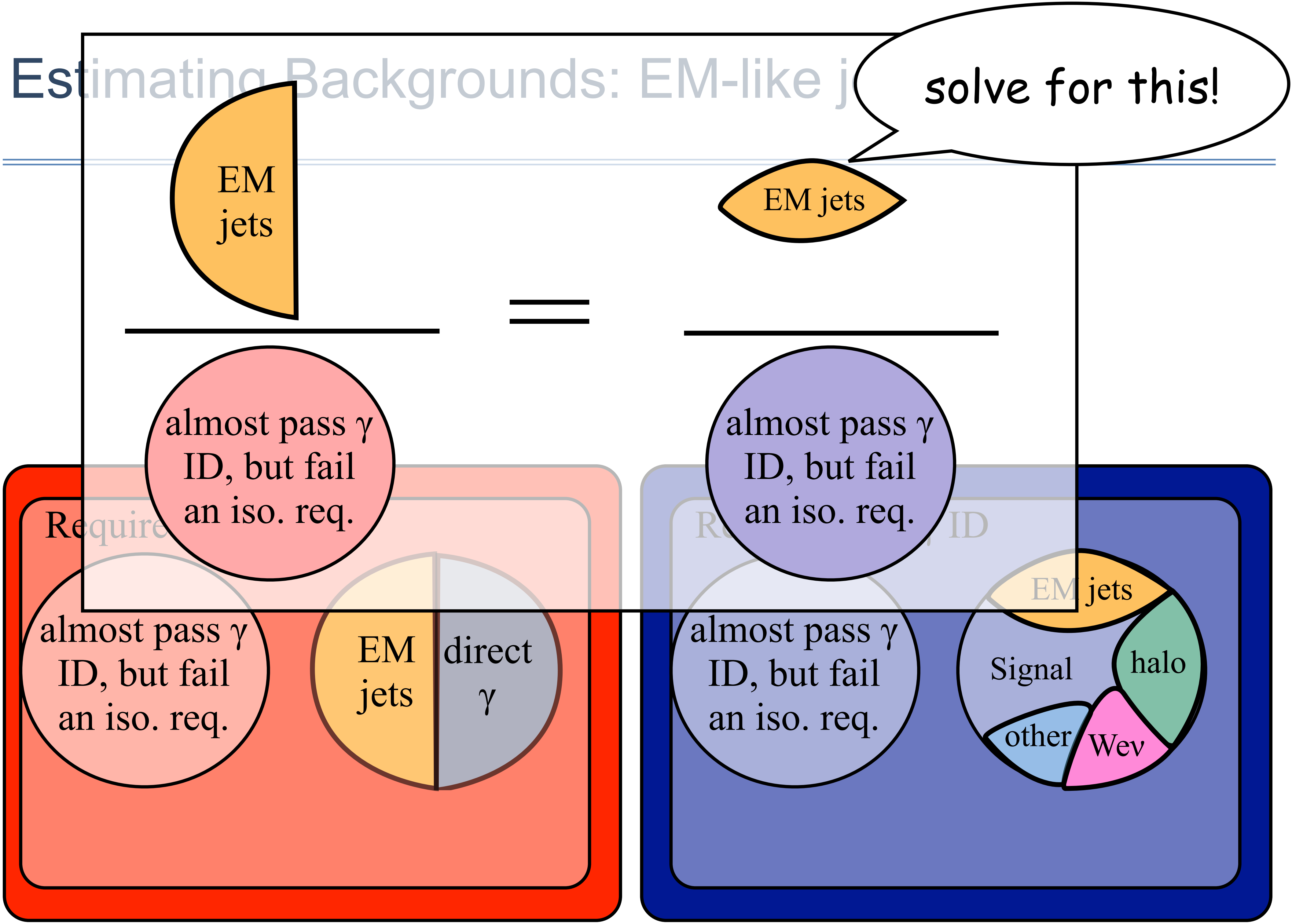




Estimating Backgrounds: EM-like j



solve for this!

EM jets

EM jets

=

almost pass γ ID, but fail an iso. req.

almost pass γ ID, but fail an iso. req.

Require

R

ID

almost pass γ ID, but fail an iso. req.

EM jets

direct γ

almost pass γ ID, but fail an iso. req.

EM jets

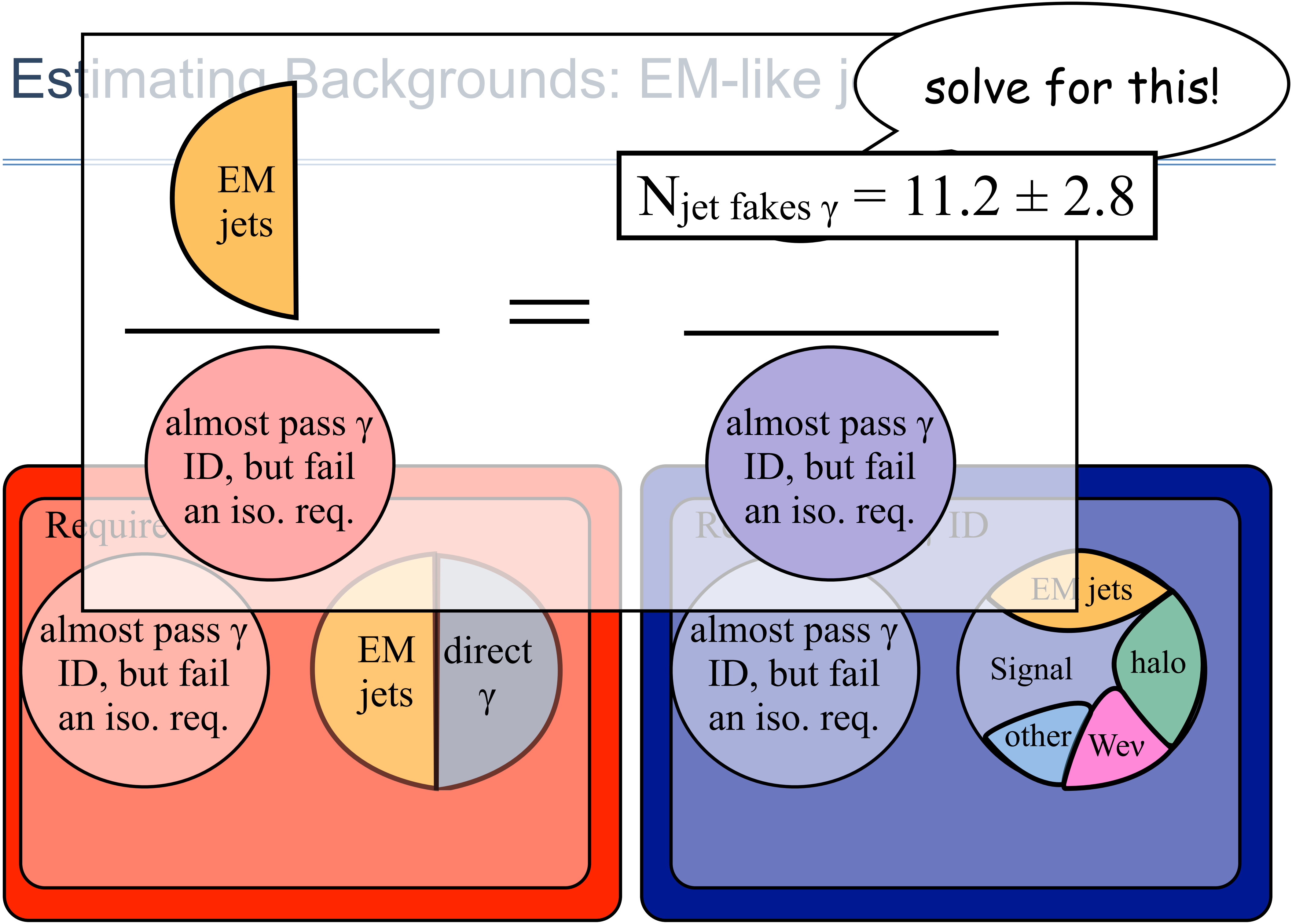
Signal

halo

other

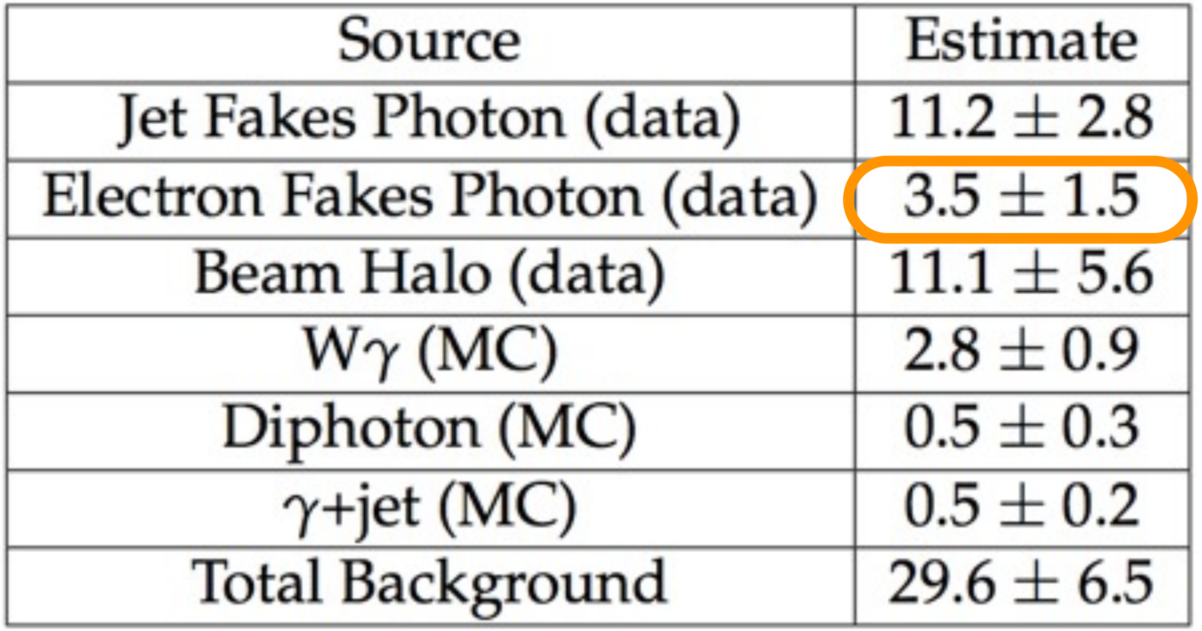
Weν

Estimating Backgrounds: EM-like j



$$N_{\text{jet fakes } \gamma} = 11.2 \pm 2.8$$

Monophoton Backgrounds



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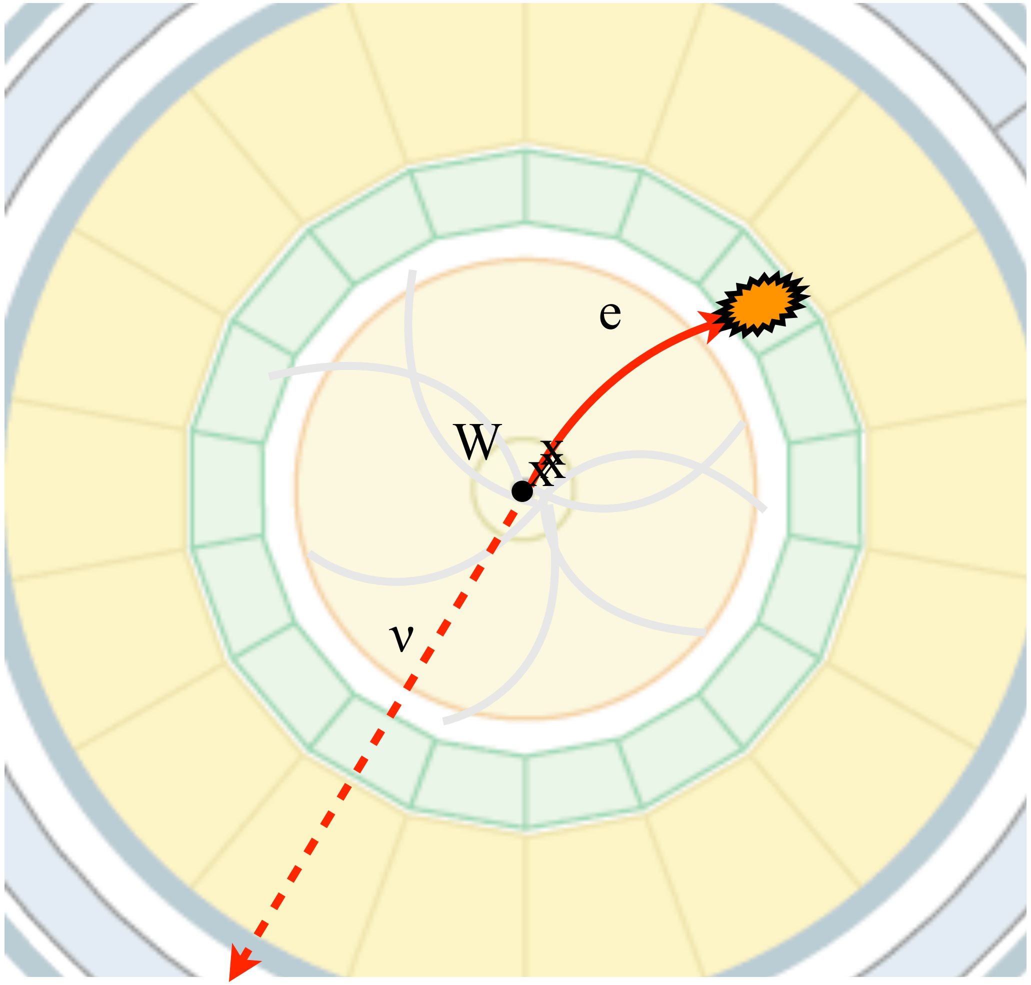
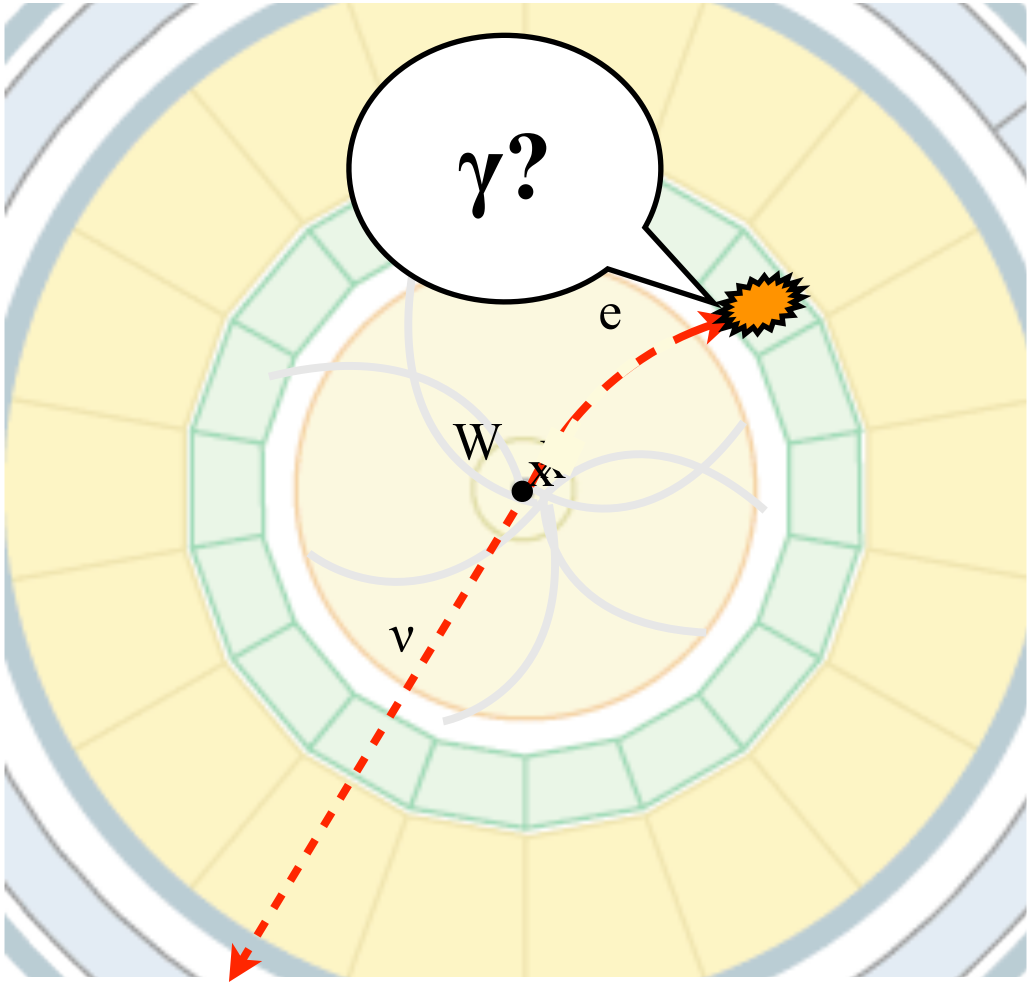
Estimating Backgrounds: electrons

- W→eν could mimic a monophoton event



Estimating Backgrounds: electrons

- W→eν could mimic a monophoton event
- small inefficiency in the pixel detector may cause track to not be reconstructed



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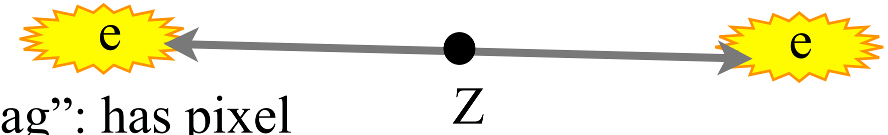
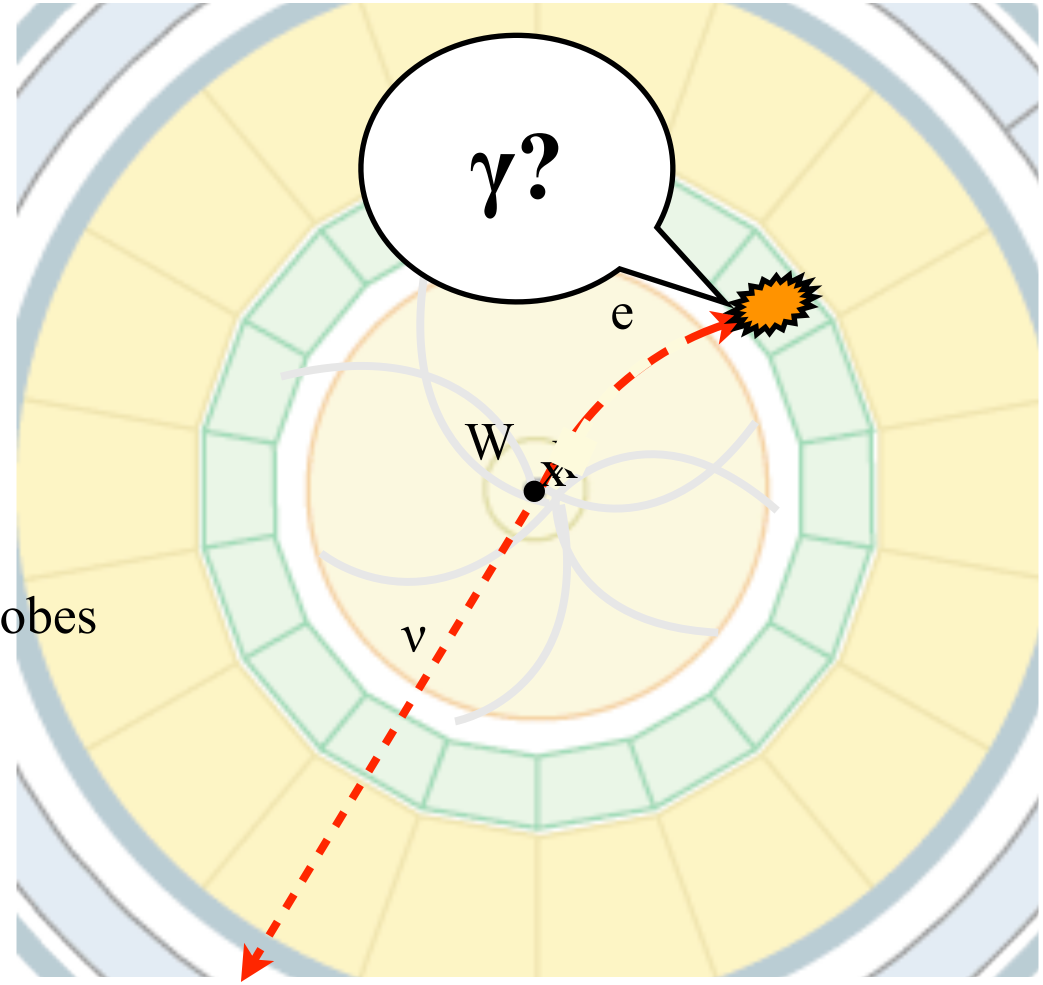
1. Use events where 2 EM showers reconstruct to the Z



"tag": has pixel seed

"probe": does this have pixel seed?

- $\varepsilon_{\text{pixel seed}} = N^{\text{e probes}}_{\text{pixel seed}} / N^{\text{e probes}}$



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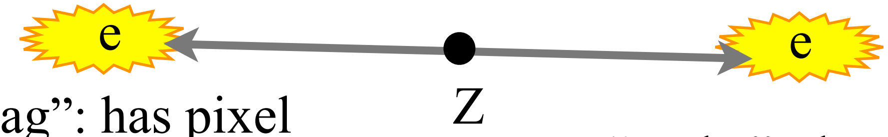

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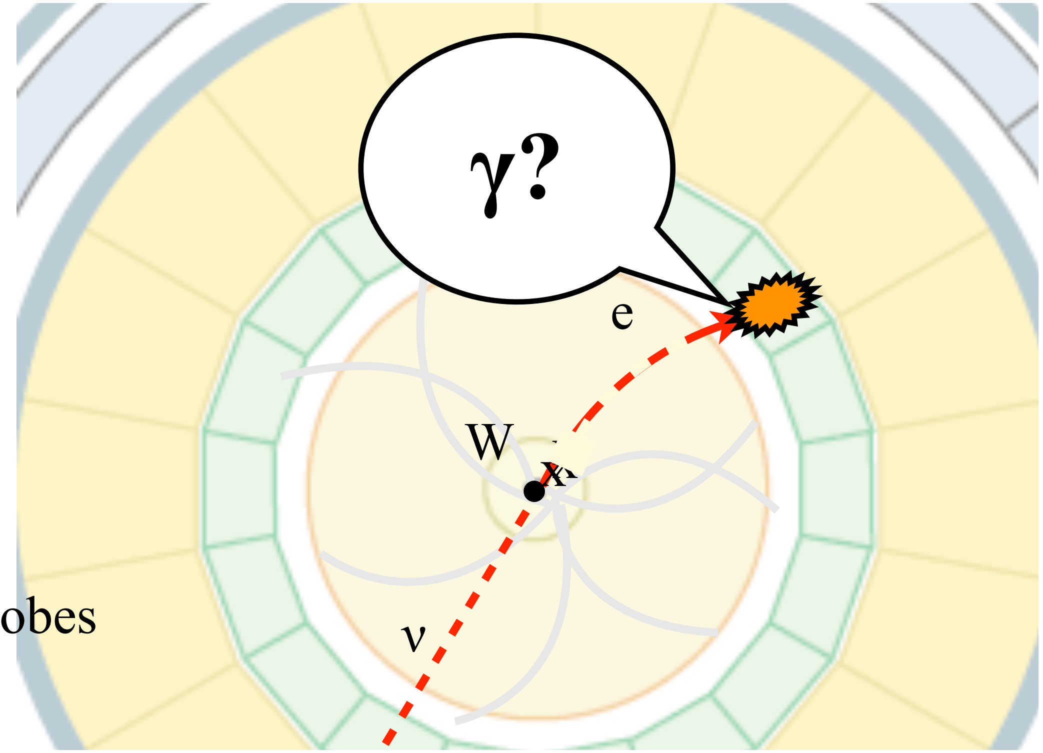
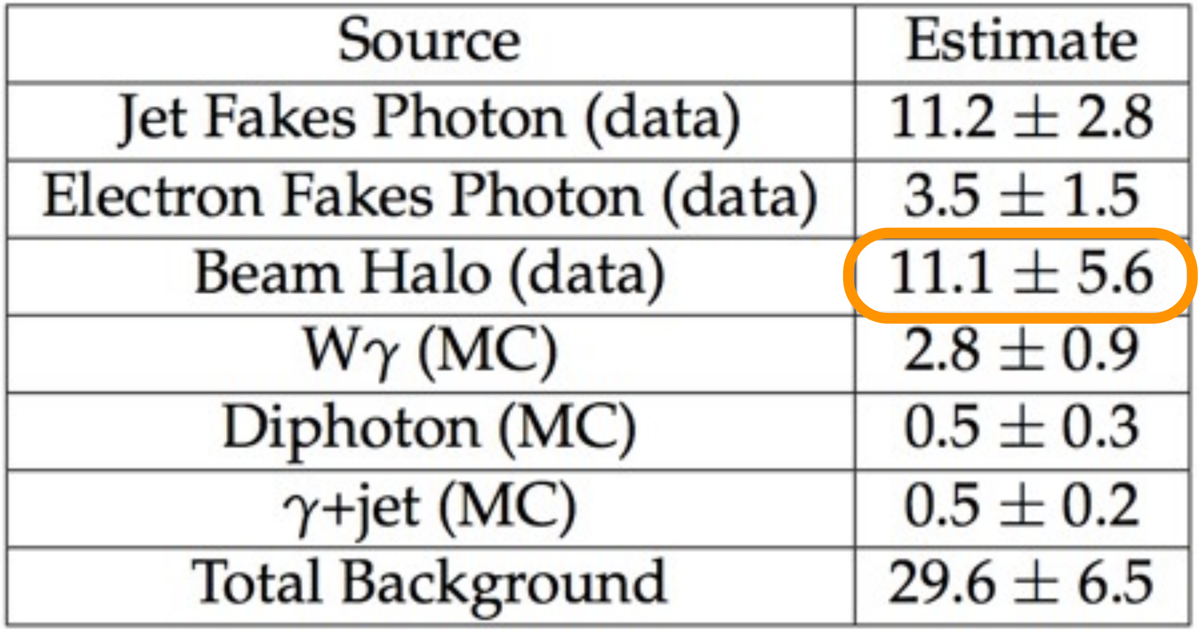


2. Use good W→eν events to estimate contamination to monophotons.

- $N_{W\rightarrow e\nu} = 583$
- $N_{\text{e fakes } \gamma} = N_{W\rightarrow e\nu} \times (1-\varepsilon)/\varepsilon$

  $= 3.52 \pm 1.48$

Monophoton Backgrounds



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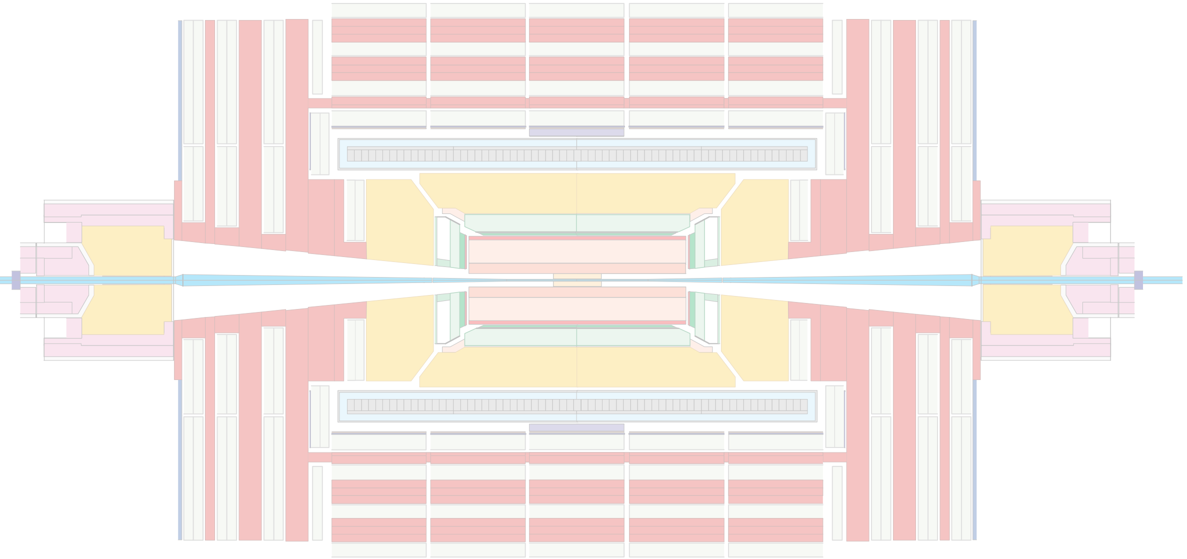
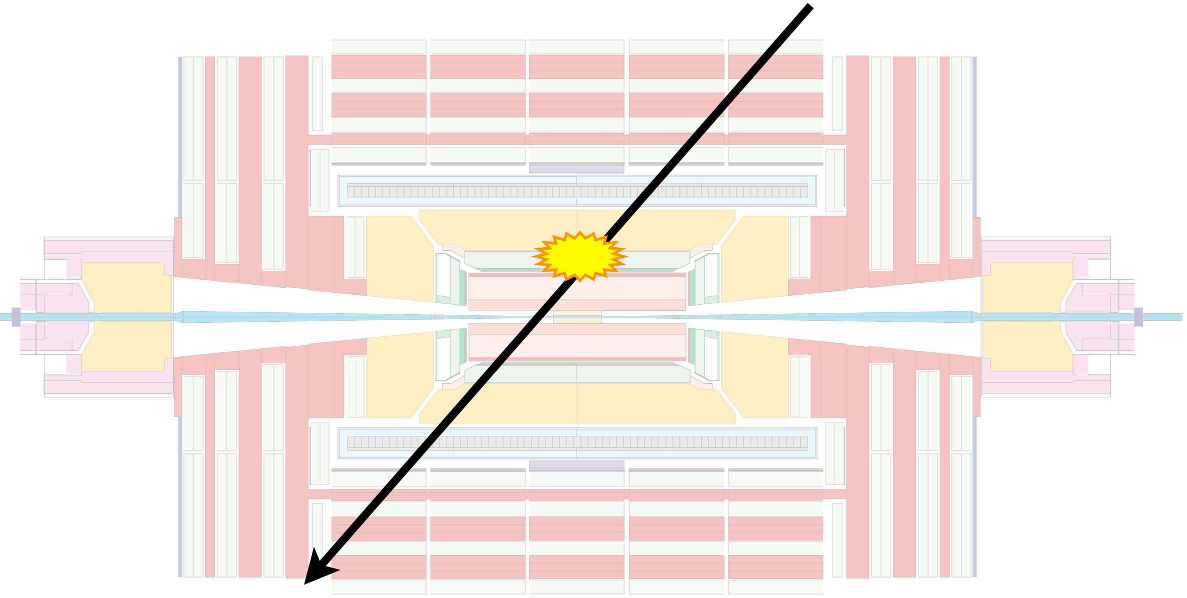
Estimating Backgrounds: non-collision

- Some unusual backgrounds



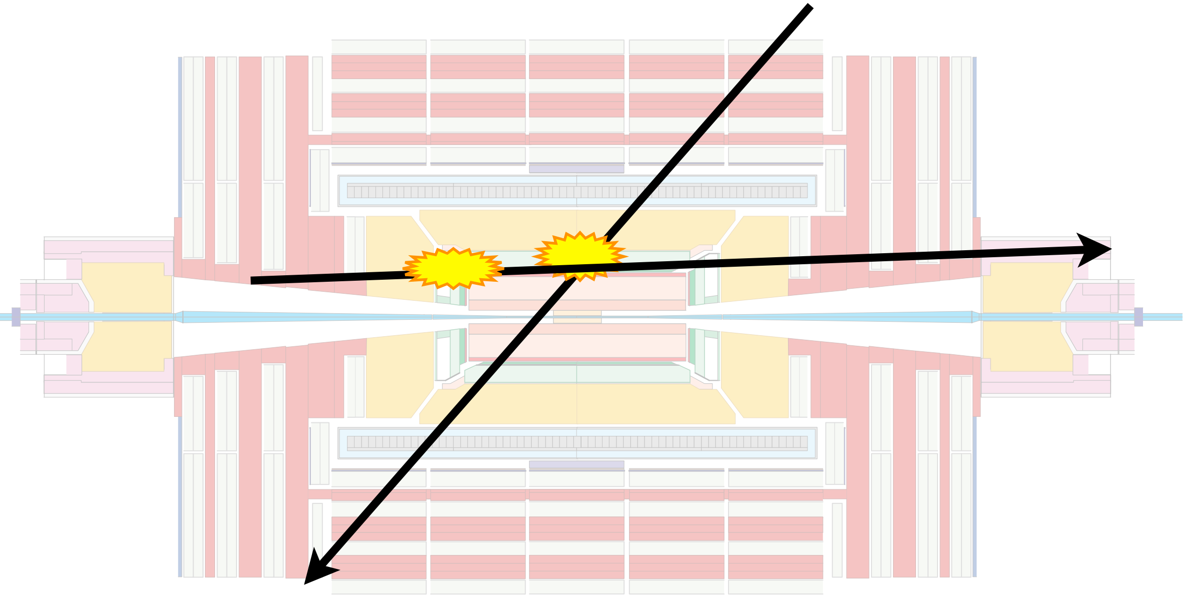
Estimating Backgrounds: non-collision

- Some unusual backgrounds
  - cosmic rays



Estimating Backgrounds: non-collision

- Some unusual backgrounds
  - cosmic rays
  - beam halo



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- Some unusual backgrounds
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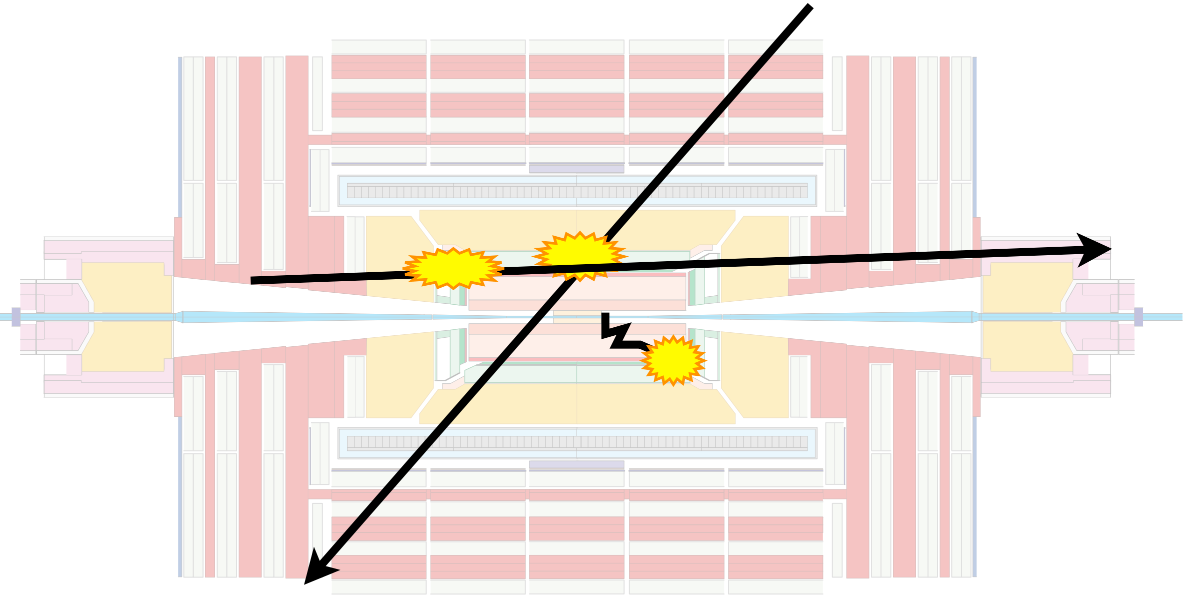
  - beam halo
  - anomalous ECAL deposits



Estimating Backgrounds: non-collision

- Some unusual backgrounds
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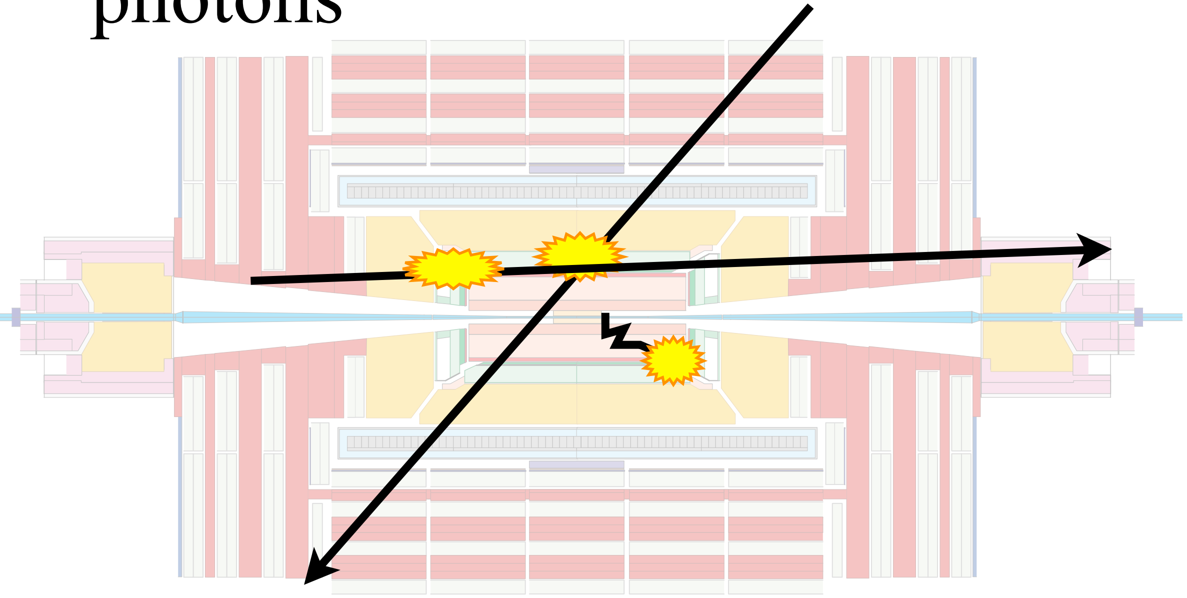
  - anomalous ECAL deposits
- Estimate each contribution by comparing the time distribution to prompt photons



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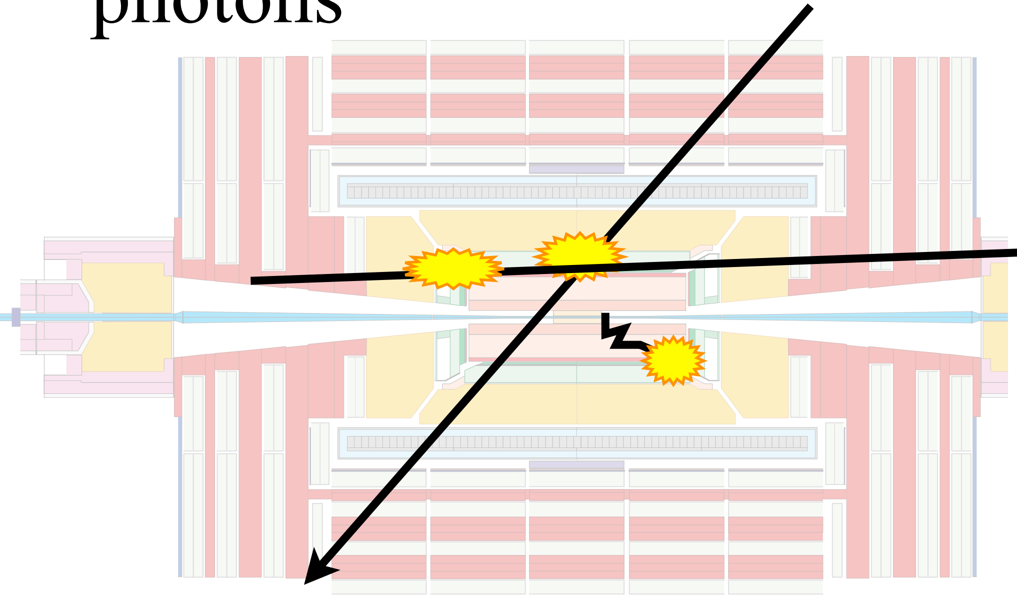
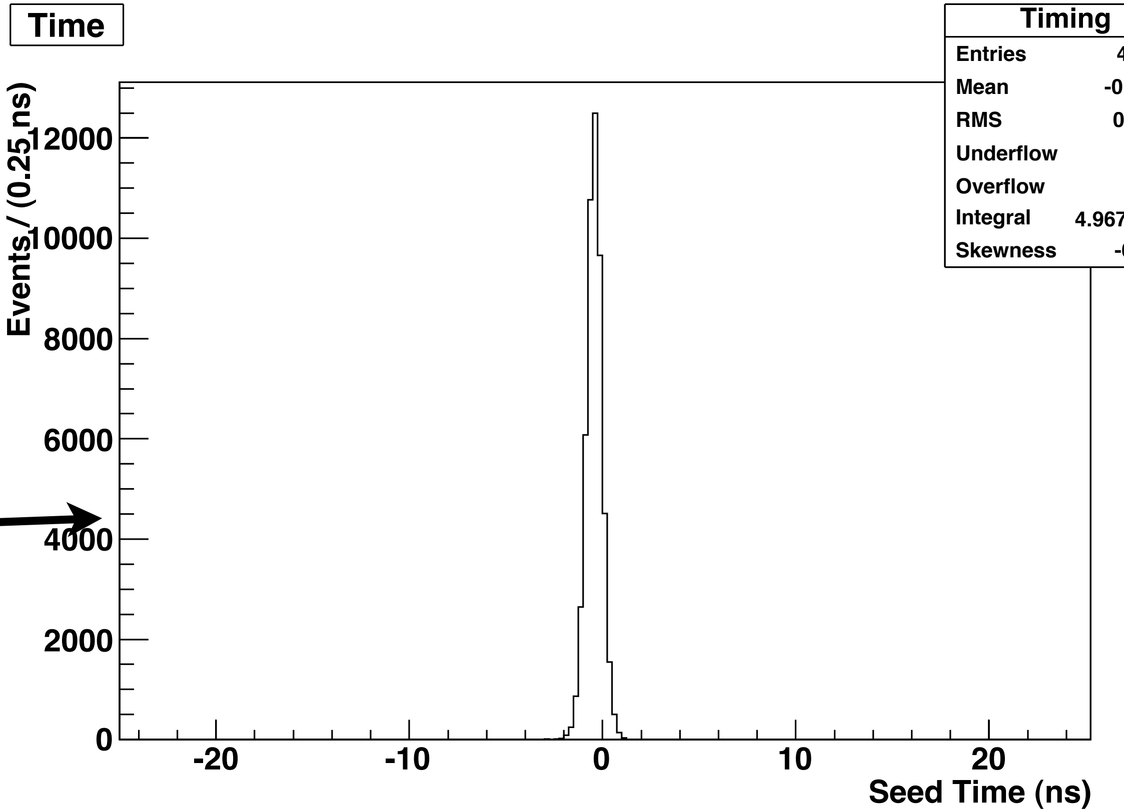


prompt photons



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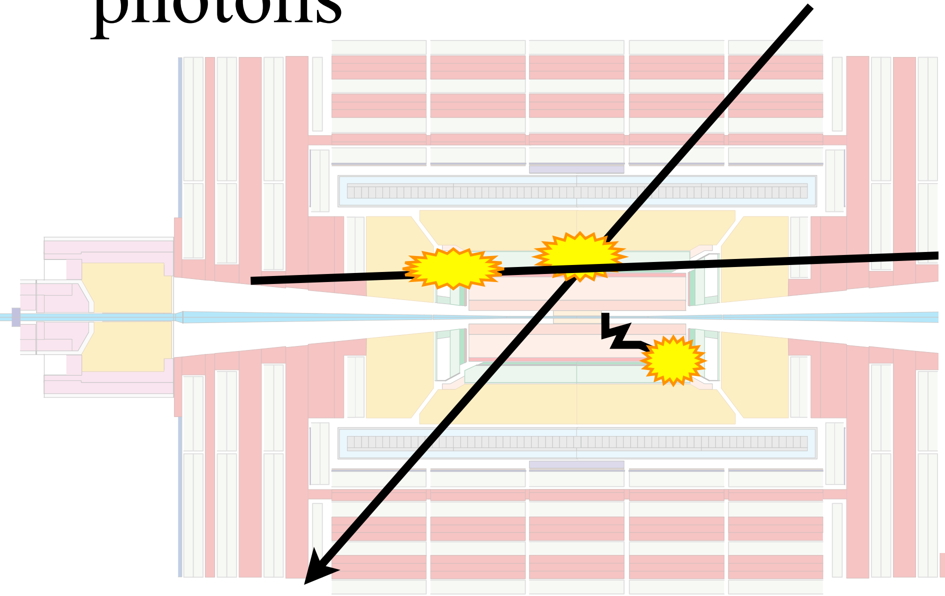
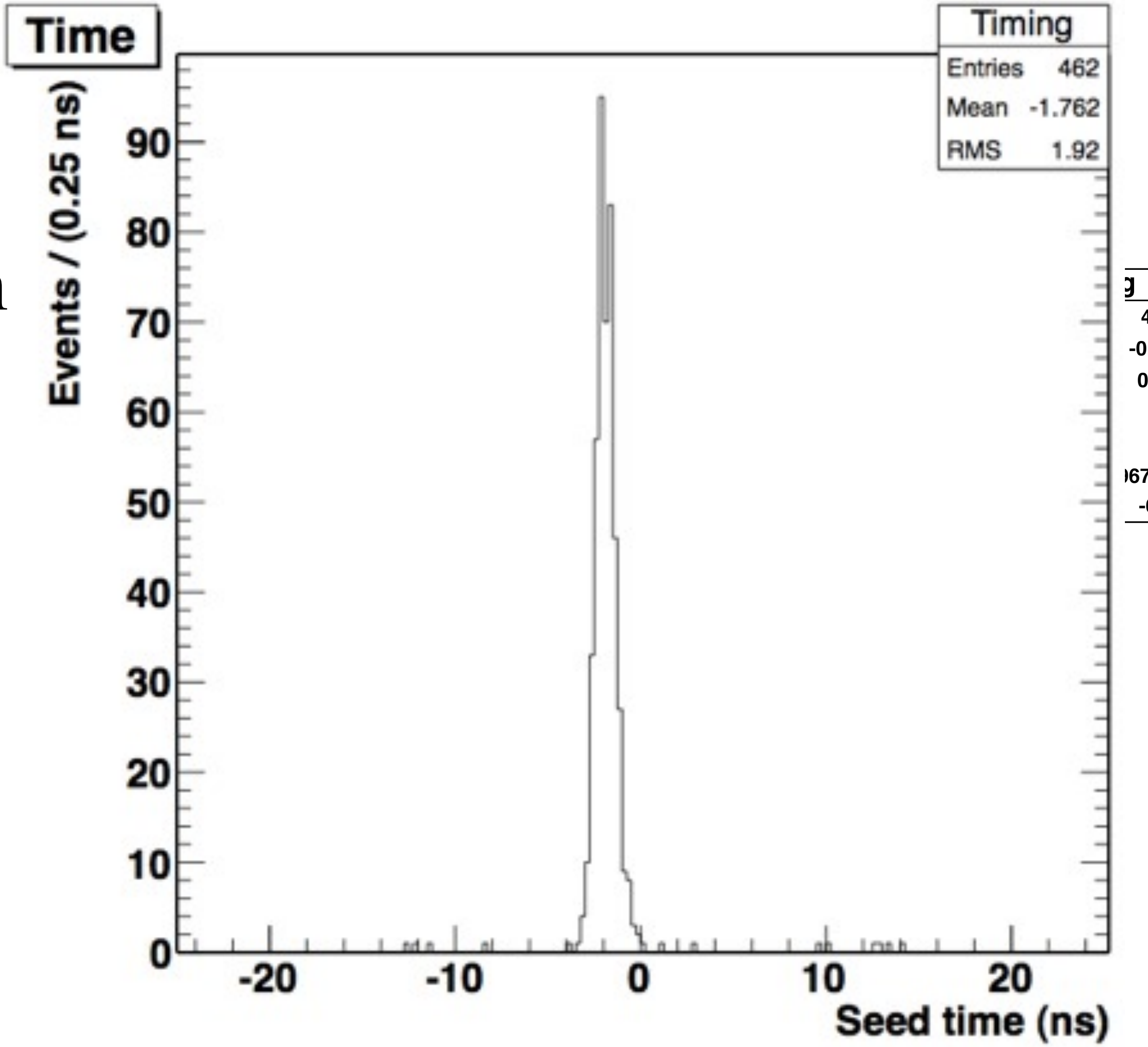


beam halo



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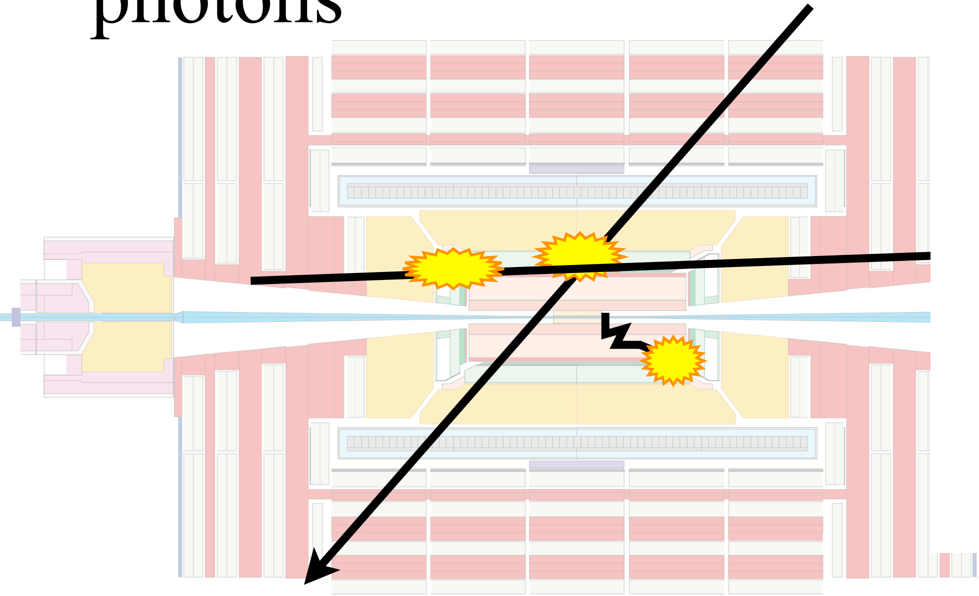
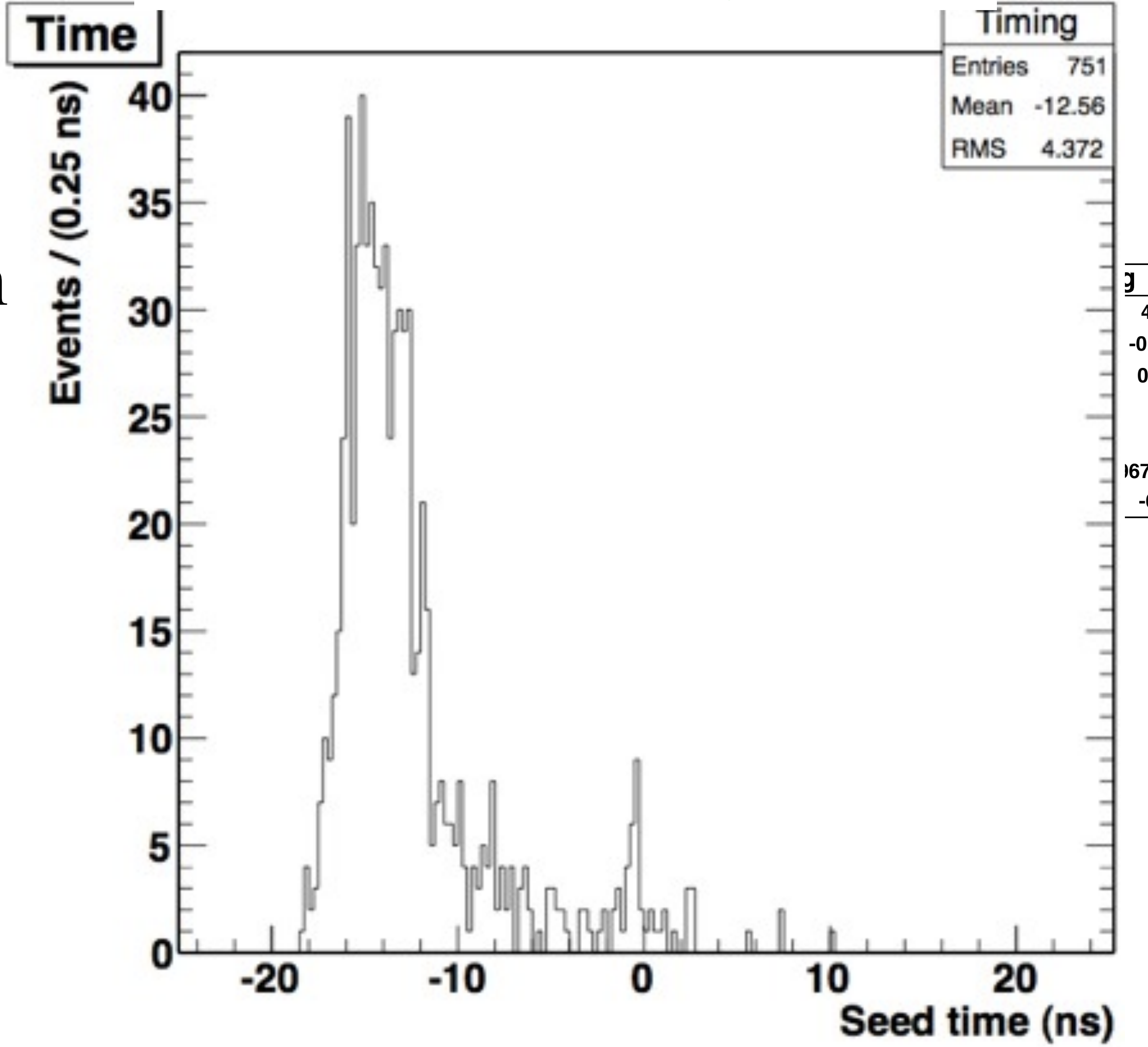


anomalous deposits



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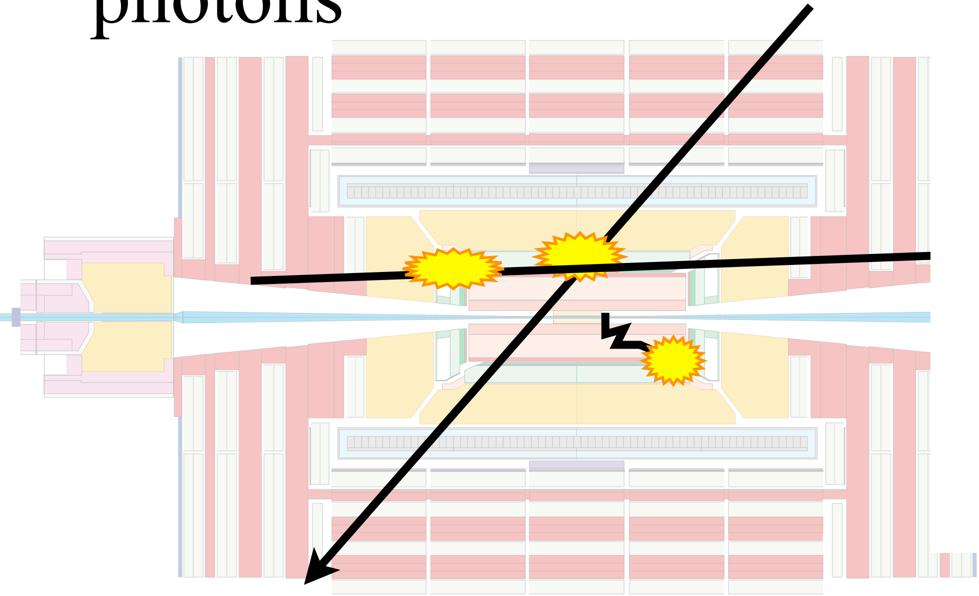
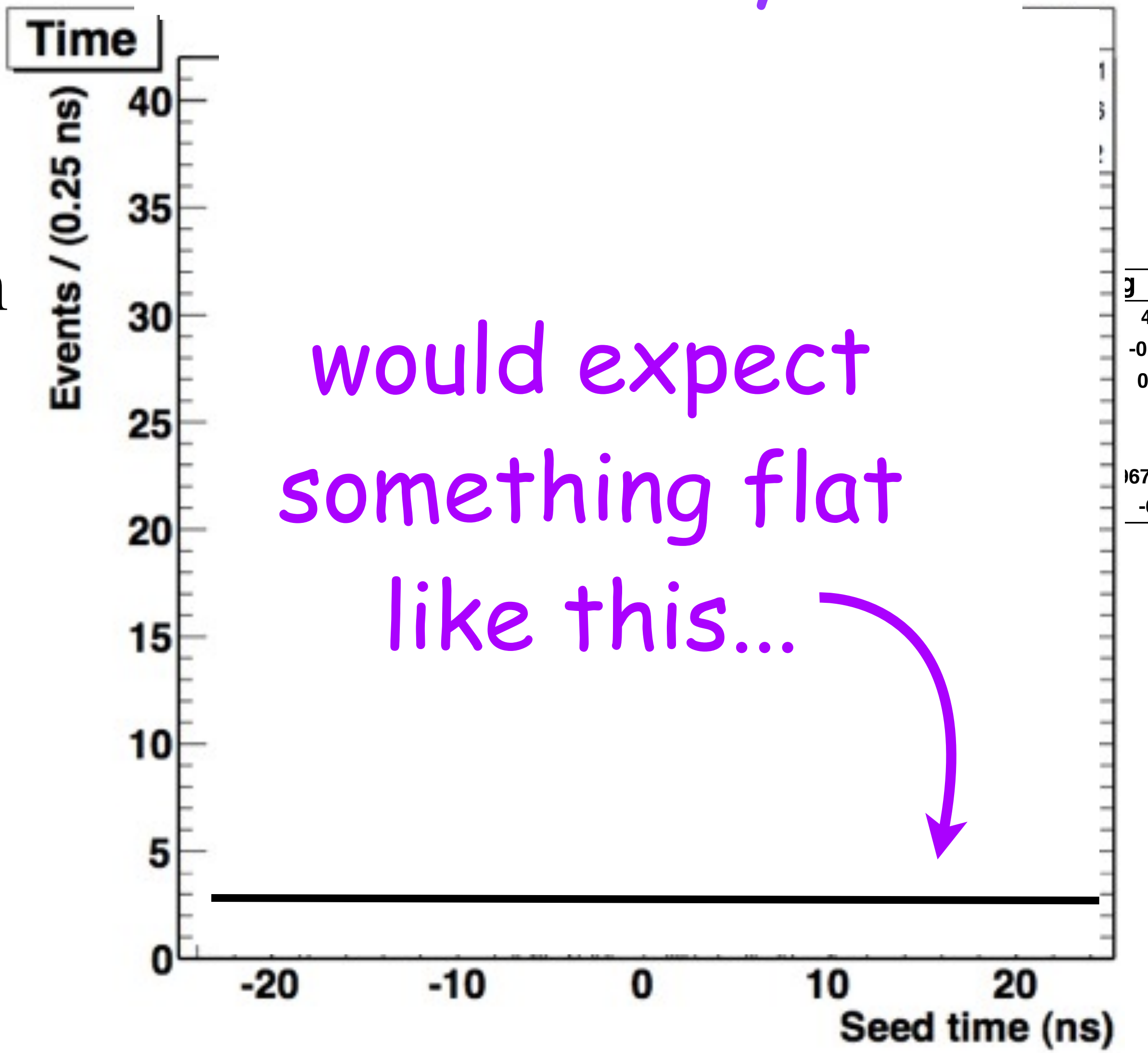


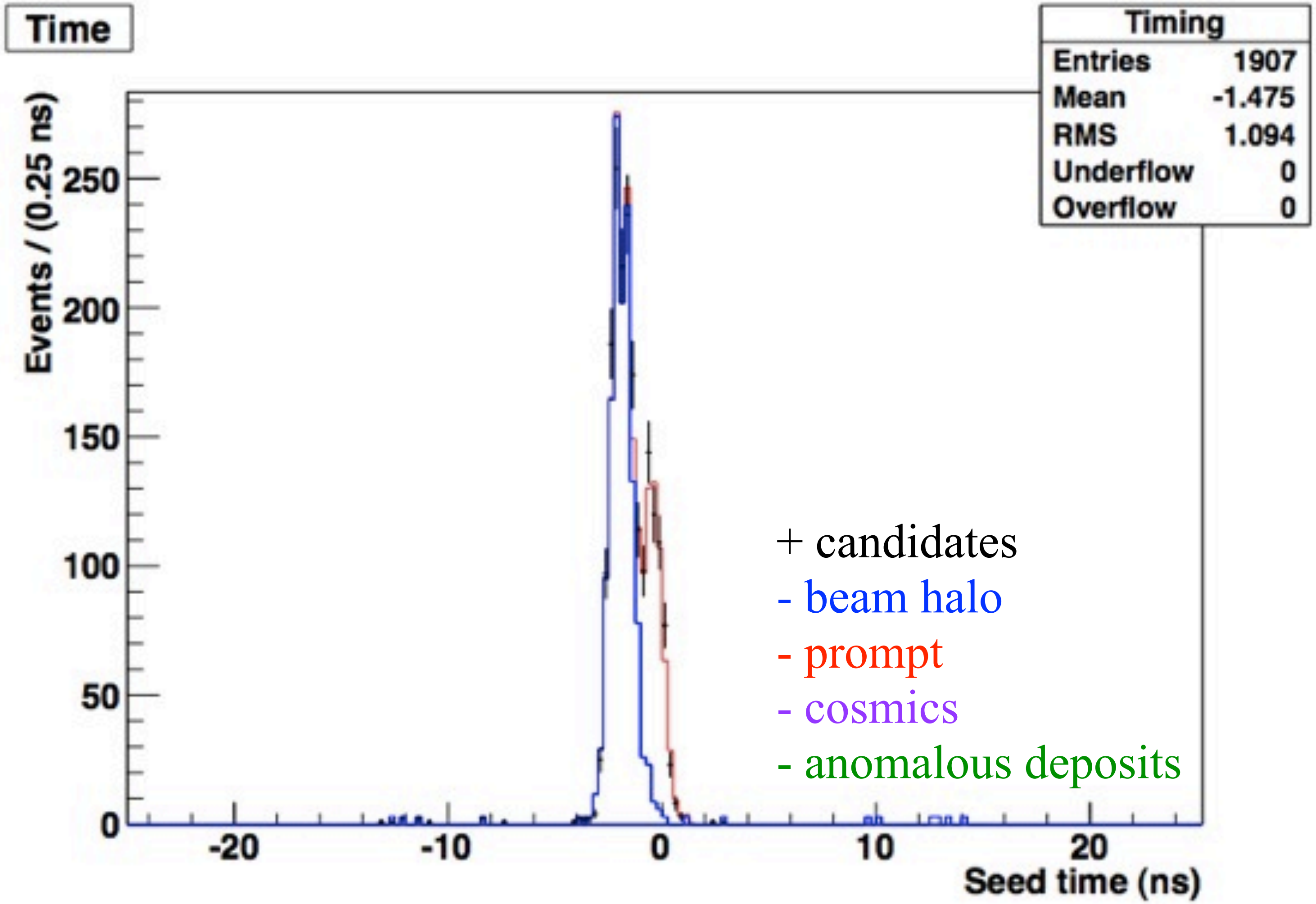
cosmic rays



would expect something flat like this...

Estimating Backgrounds: non-collision

- Best fit shows candidates are composed of:
  - prompt photon
  - beam halo



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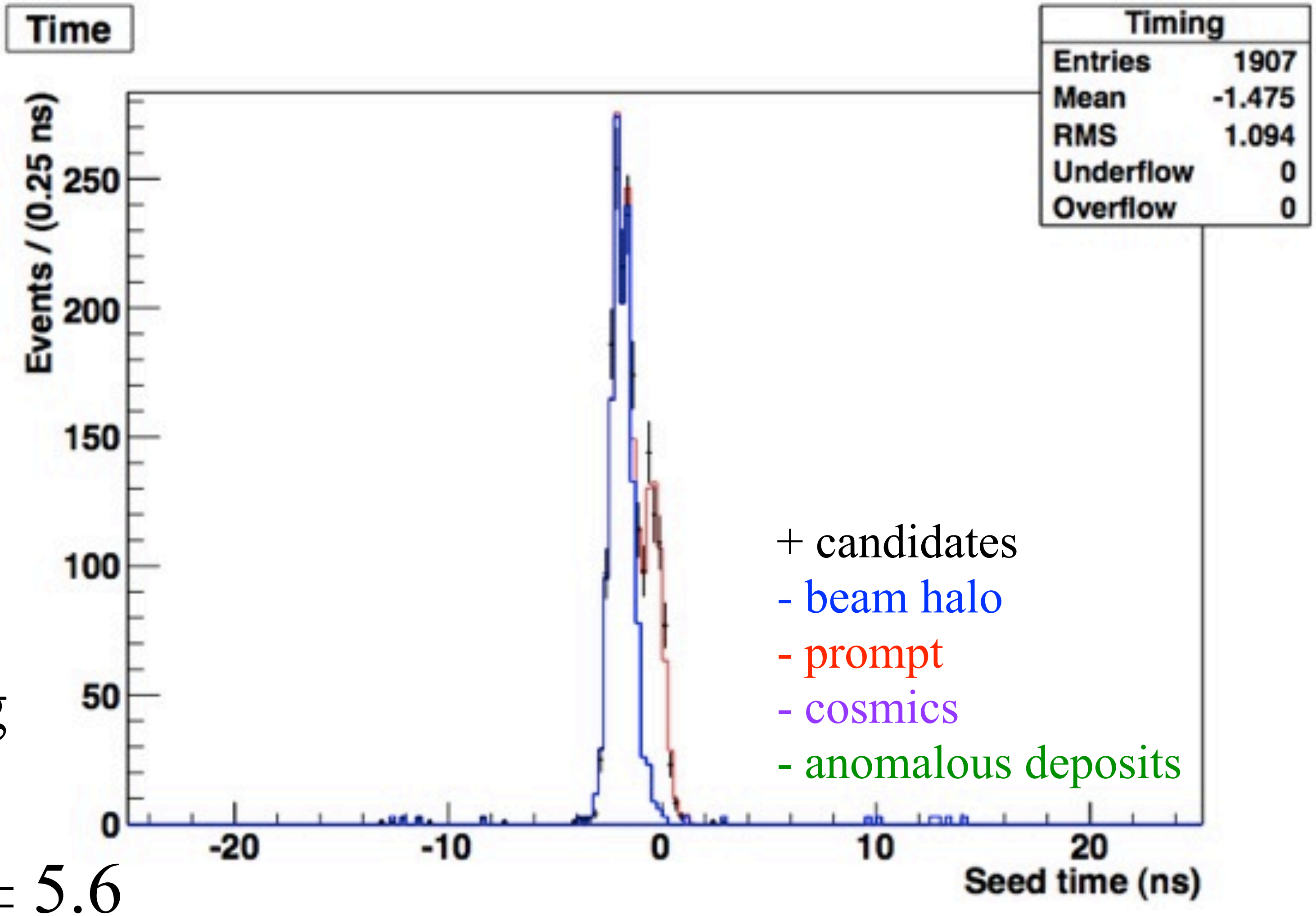
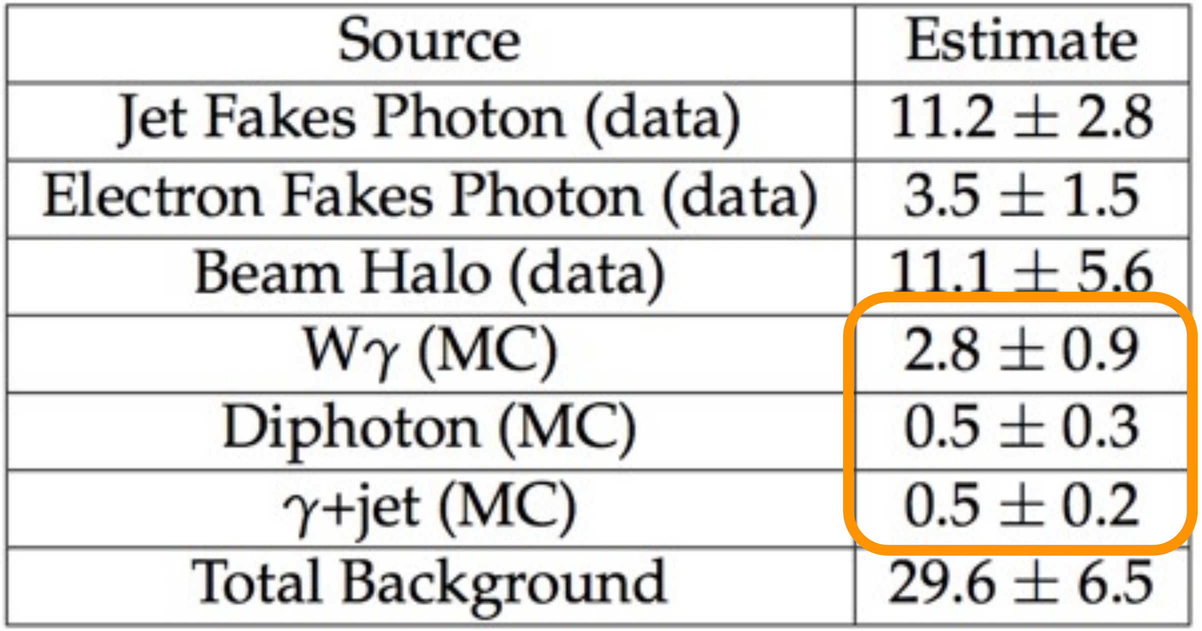


- After reapplying shape and timing cuts:

$N_{\text{halo fakes } \gamma} = 11.1 \pm 5.6$

Monophoton Backgrounds



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Total Background	29.6 ± 6.5

These smaller backgrounds from MC.

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- E_T^γ >145 GeV
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For BSM searches: $Z(\nu\bar{\nu})\gamma\ (\text{MC}) = 75.1 \pm 9.5$

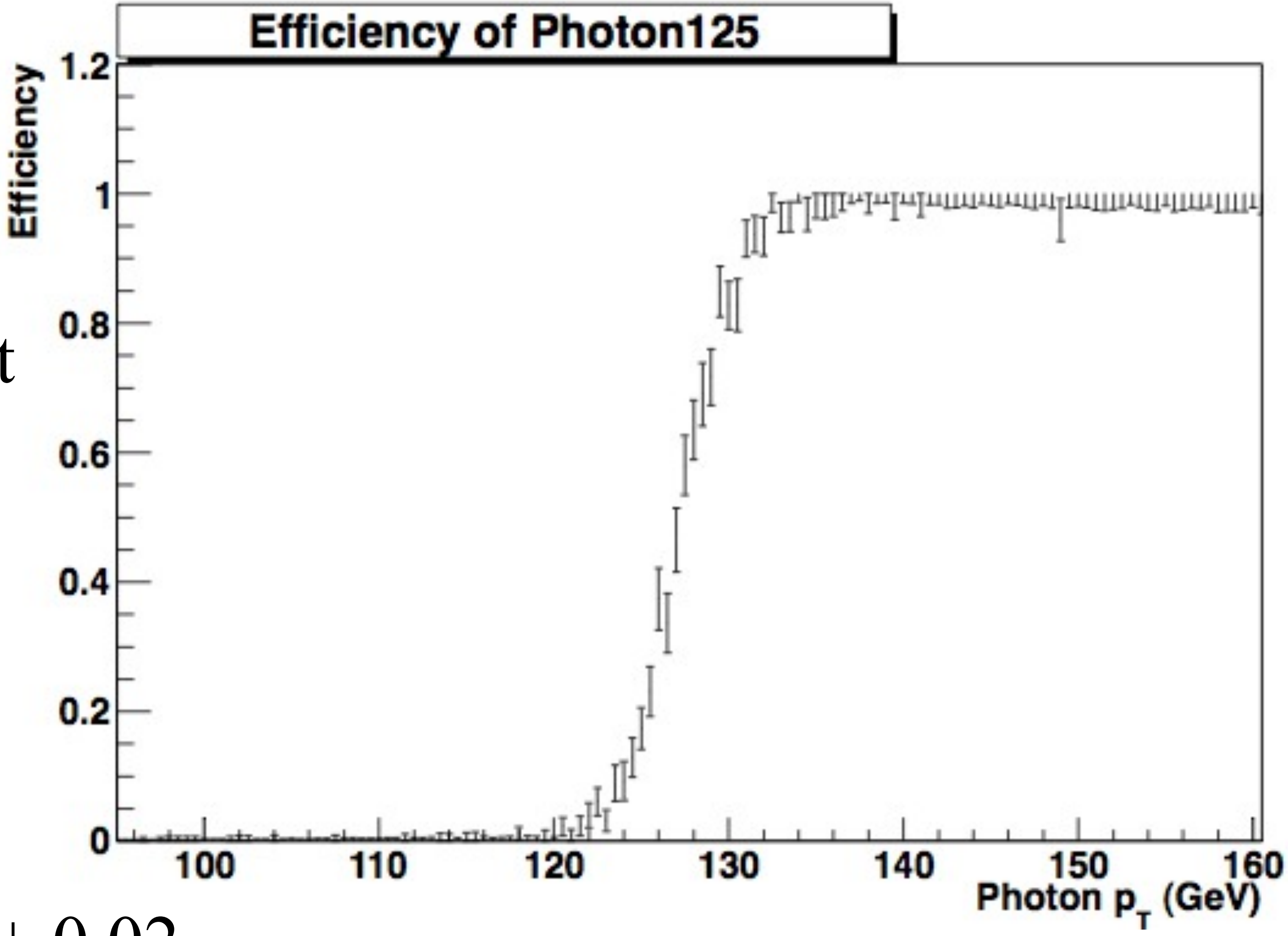
Monophoton Analysis Outline

- Identify cuts to reduce backgrounds
- Measure residual backgrounds
- Estimate acceptance and efficiency
  - Focus on data/MC scale factor: ρ

$$A \times \epsilon = \underbrace{A \times \epsilon_{MC}}_{\text{MC only}} \times \boxed{\underbrace{\rho}_{\text{data vs. MC}}}$$

Scale Factor: Trigger Cut Efficiency

- Relative efficiency of our offline selection to prescaled triggers.



- The MC and data both 100% efficient by 145 GeV in the barrel region of the ECAL, informing our kinematical cuts.

- scale factor = 1.00 ± 0.02.

Scale Factor: Photon ID Efficiency

- Photon ID reduces jet backgrounds, etc. but on rare occasion loses the photon
- photon showers ≈ electron showers (except for the track)

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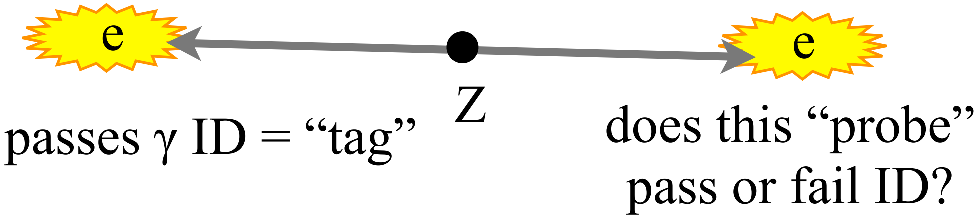
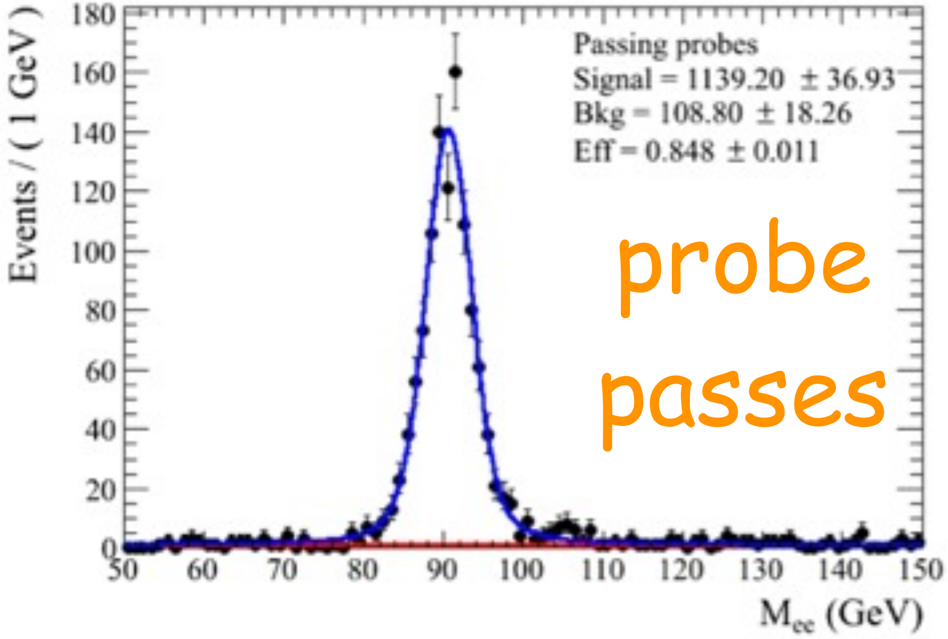
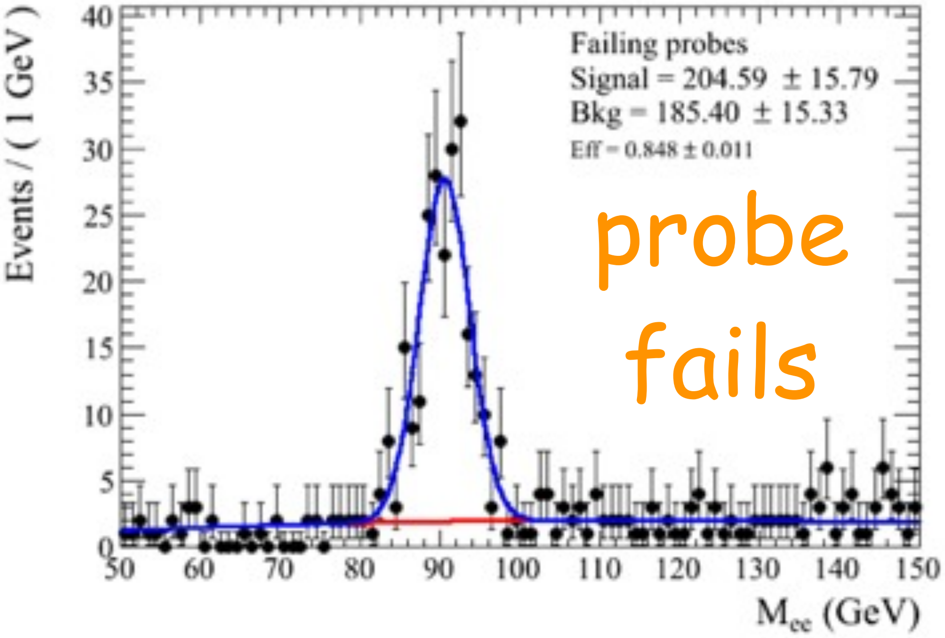


e passes γ ID = “tag”

does this “probe” pass or fail ID?



probe passes



probe fails

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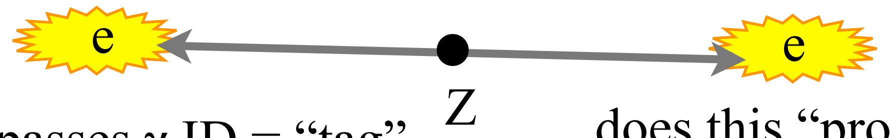
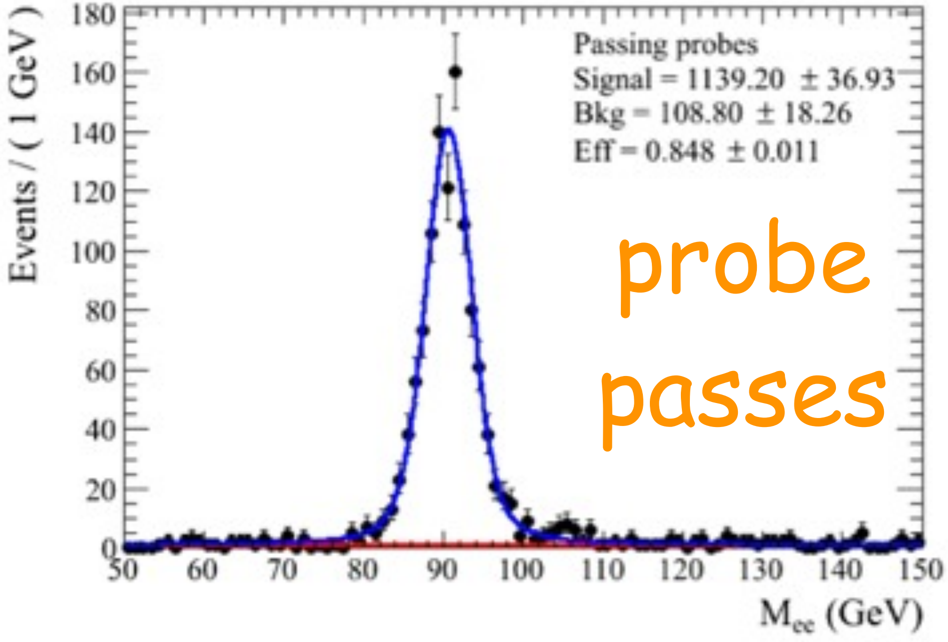


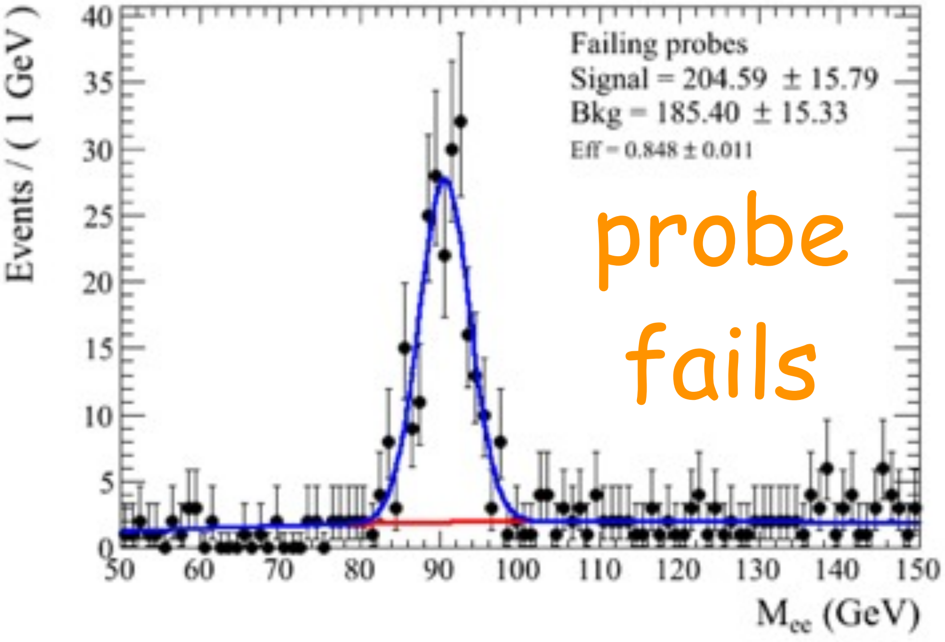
e passes γ ID = “tag”

does this “probe” pass or fail ID?

- $\varepsilon = N^{probes}_{pass}/(N^{probes}_{pass} + N^{probes}_{fail})$
- $\varepsilon_{data} = 0.848 \pm 0.011$
- $\varepsilon_{MC} = 0.883 \pm 0.022$
- scale factor $=\varepsilon_{data}/\varepsilon_{MC}= 0.96 \pm 0.02$



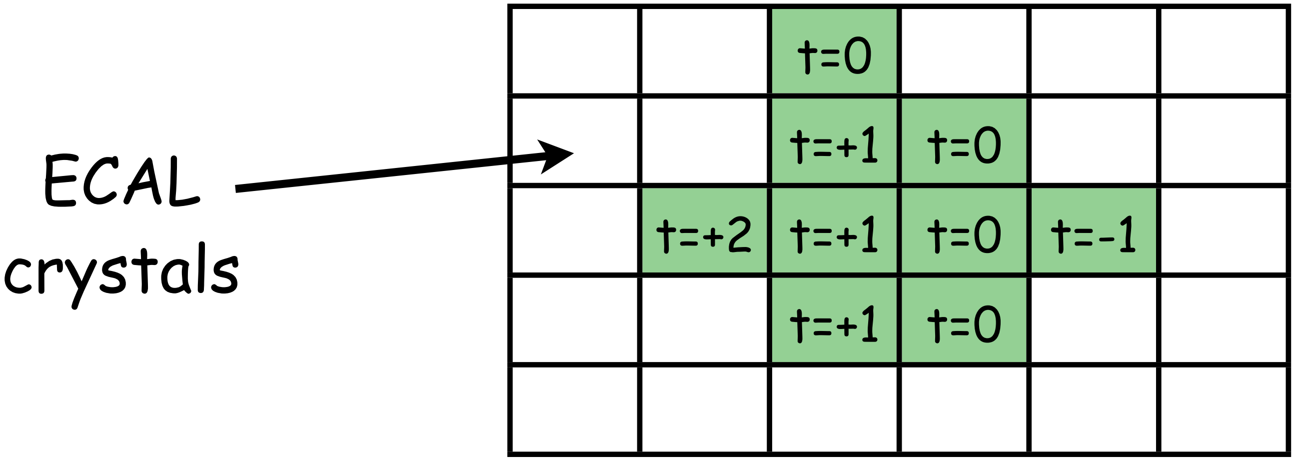
probe passes



probe fails

Scale Factor: Shower Timing Window Efficiency

- Reduce anomalous ECAL deposits overlapping with real EM showers
- Timing of detector hits of the EM shower should fit inside a window of 5 ns



		t=0			
		t=+1	t=0		
	t=+2	t=+1	t=0	t=-1	
		t=+1	t=0		

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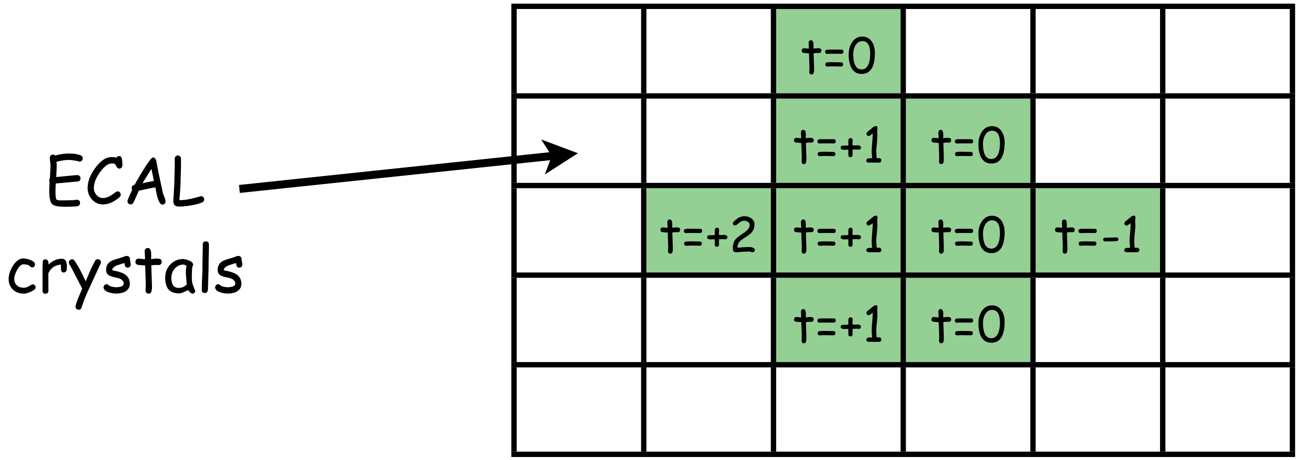
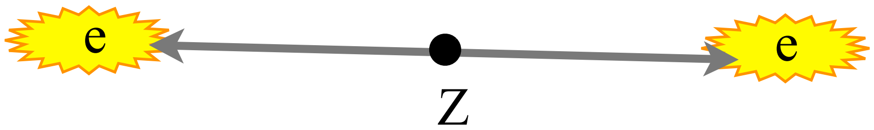


- Use Z→ee sample, since we know the showers are prompt



does this shower satisfy t_{window}?

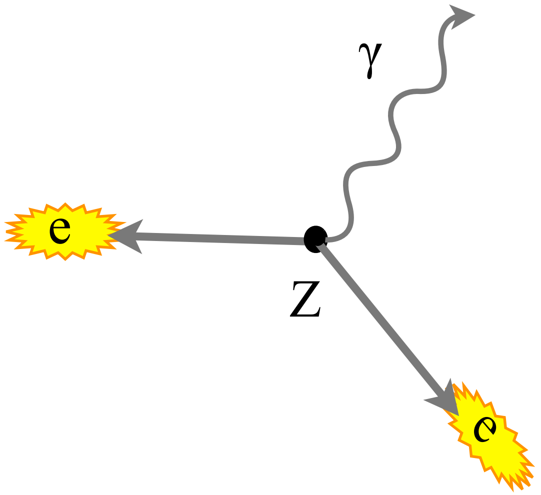
does this shower satisfy t_{window}?

- scale factor = $\varepsilon_{data}/\varepsilon_{MC} = \varepsilon_{data}/1 = N^{e}_{satisfy\ twindow}/N^{e} = 0.983 \pm 0.009$

Scale Factor: Jet and Track Veto Efficiency

- Monophoton events should not have lots of energy in jets (sprays of hadrons) or tracks, so we veto such events.

- Use Z→eeγ (kinematics similar to our signal (also confirmed with W→eν))



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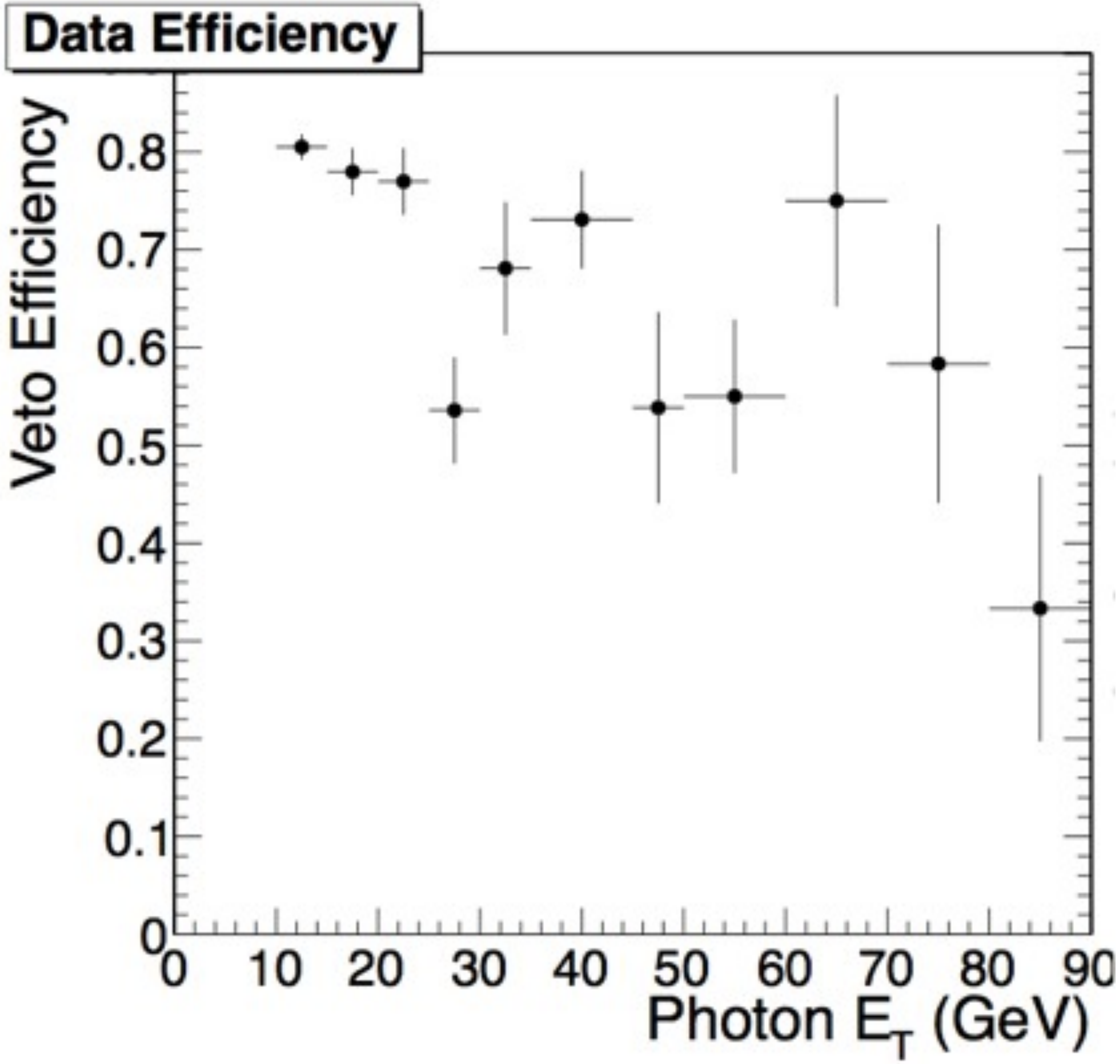

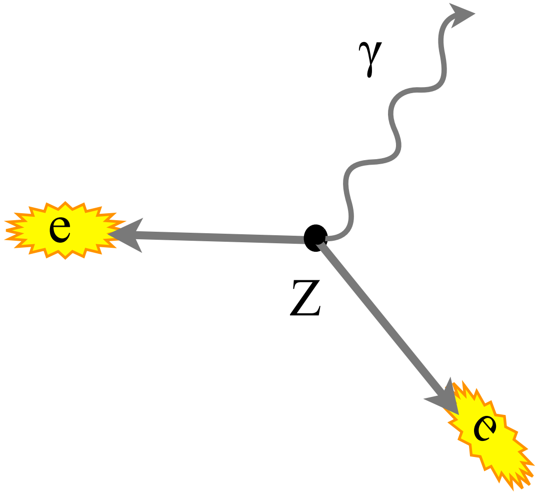

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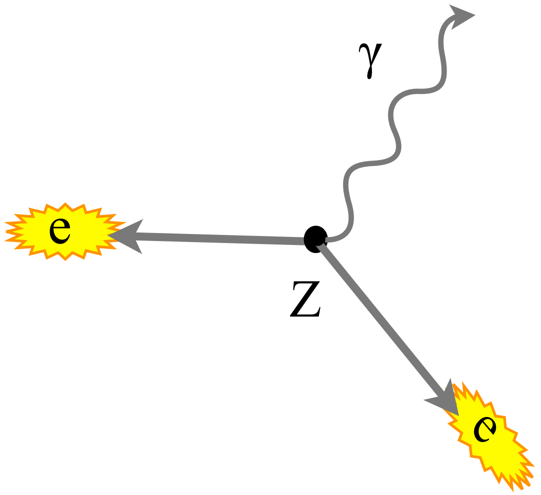

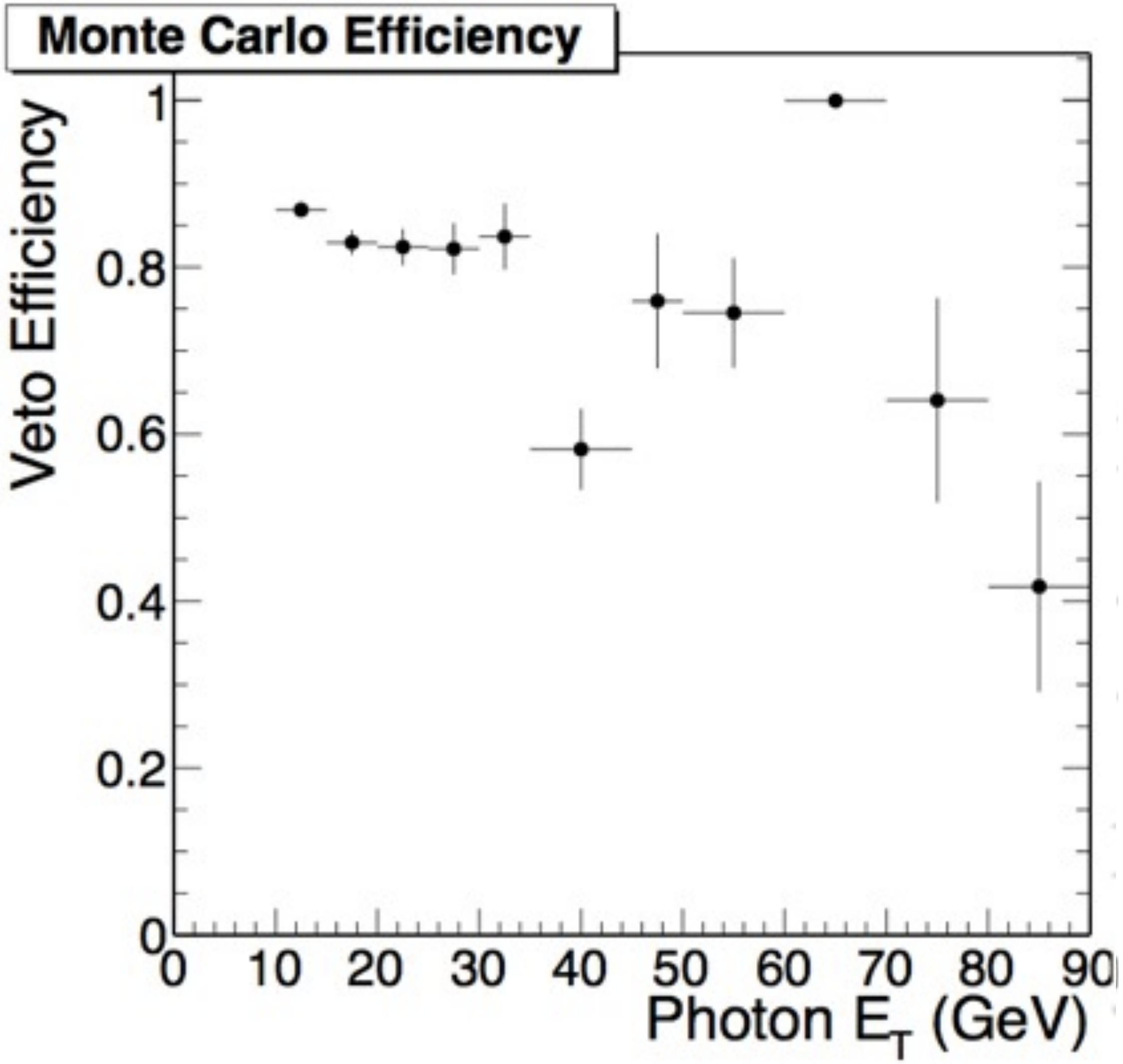

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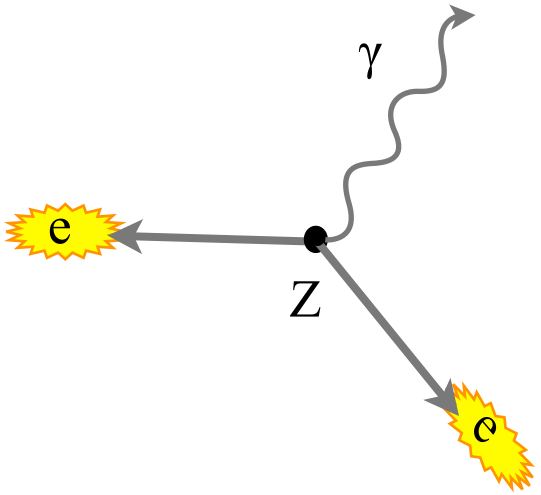
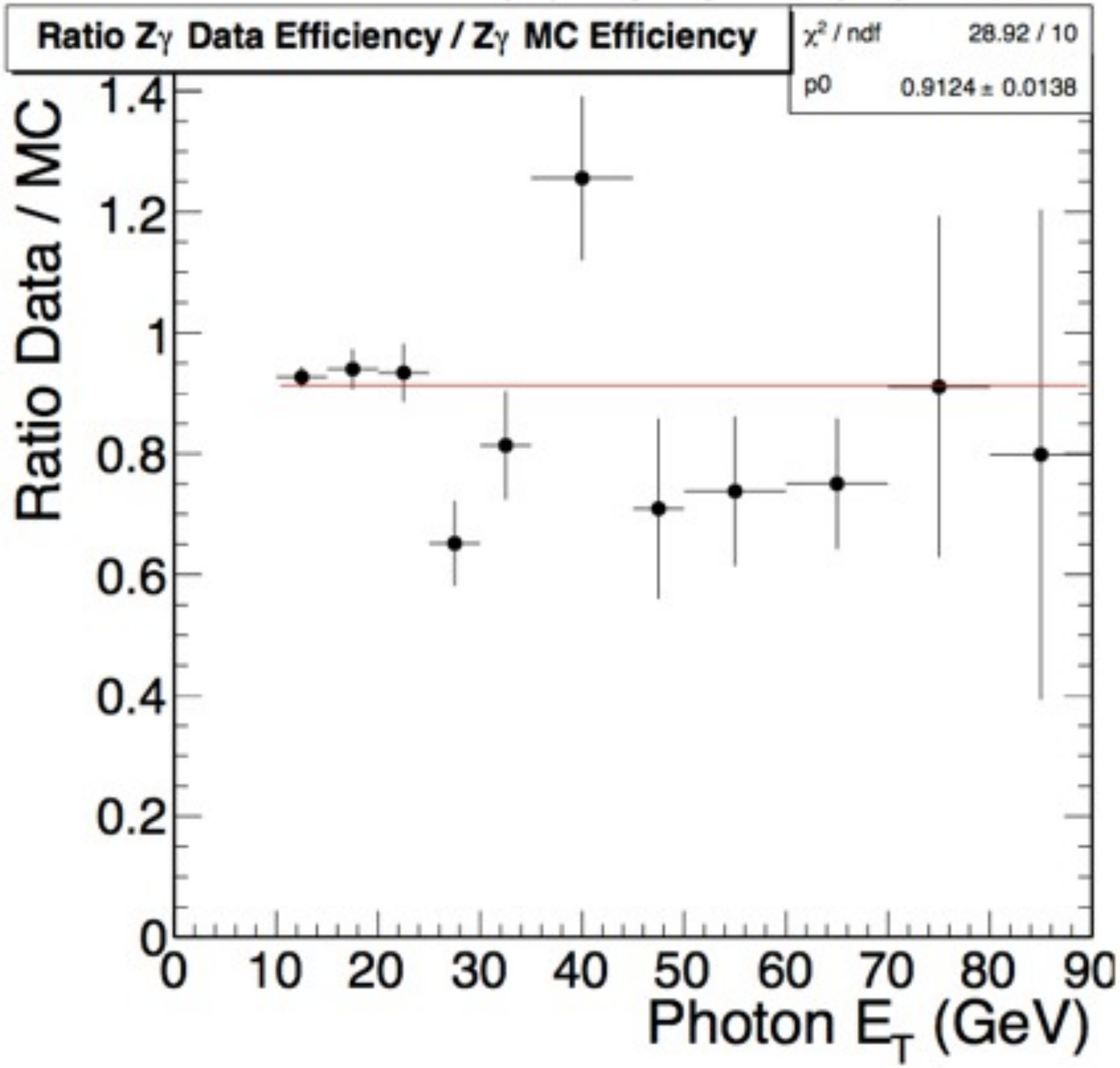
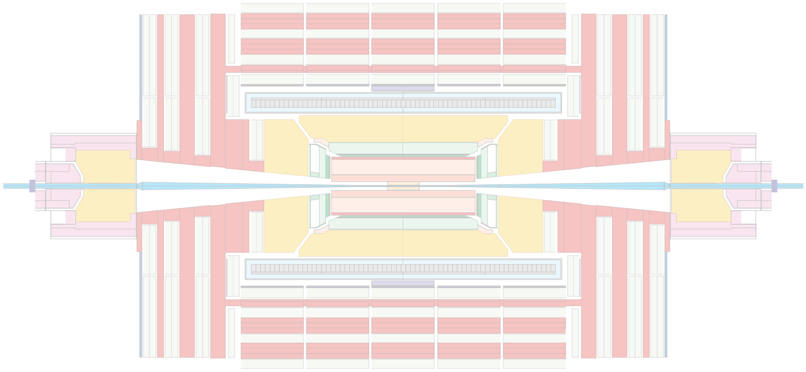




scale factor = $\varepsilon_{data} / \varepsilon_{MC}$ = 1.00 ± 0.10
(includes generous unc. due to W→e ν)

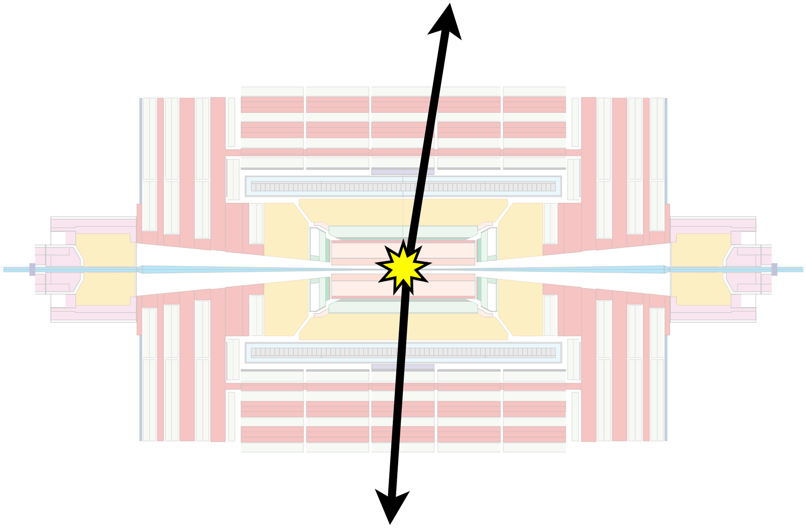
Scale Factor: Muon Veto Efficiency

- Muons may arise from many sources



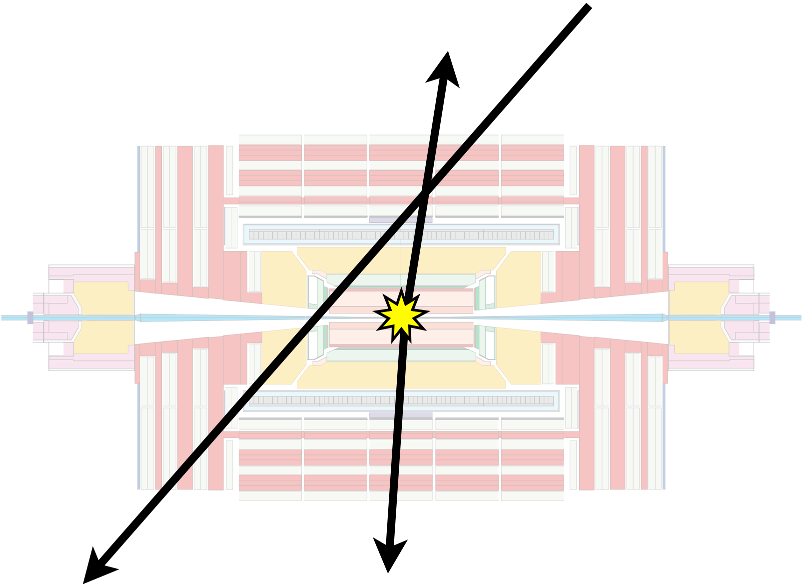
Scale Factor: Muon Veto Efficiency

- Muons may arise from many sources
  - pp collision



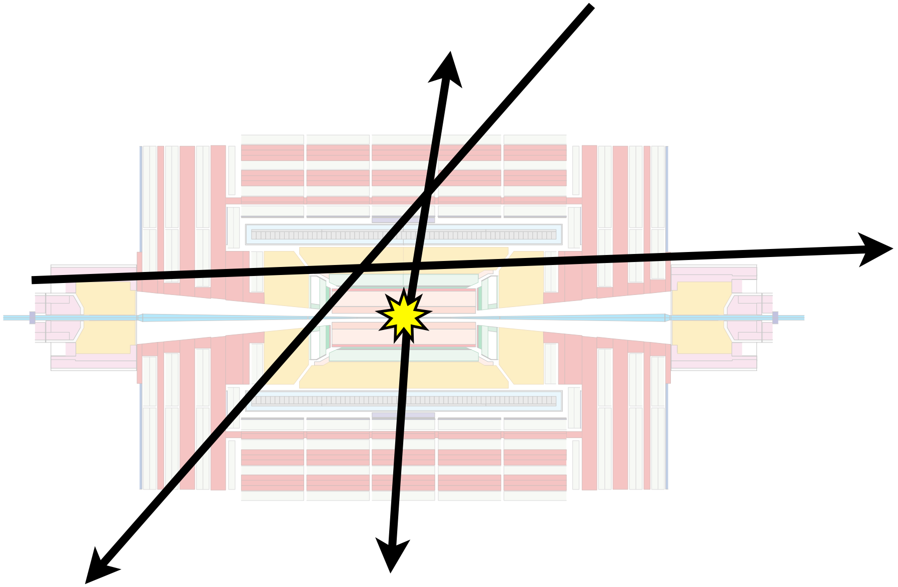
Scale Factor: Muon Veto Efficiency

- Muons may arise from many sources
  - pp collision
  - cosmic rays



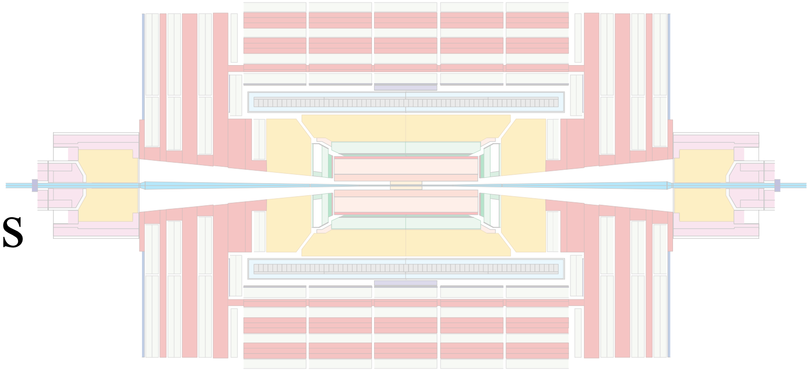
Scale Factor: Muon Veto Efficiency

- Muons may arise from many sources
  - pp collision
  - cosmic rays
  - beam halo



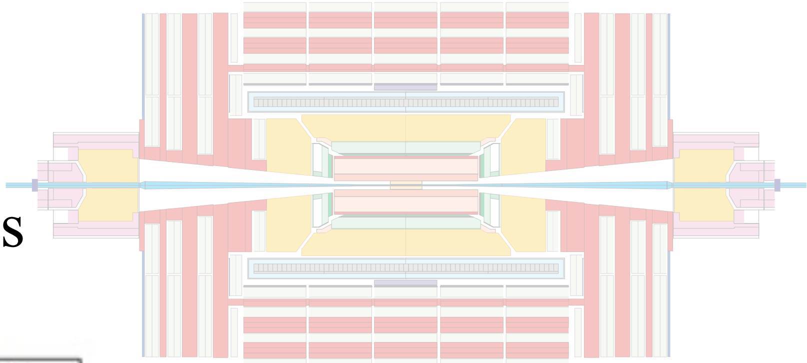
Scale Factor: Muon Veto Efficiency

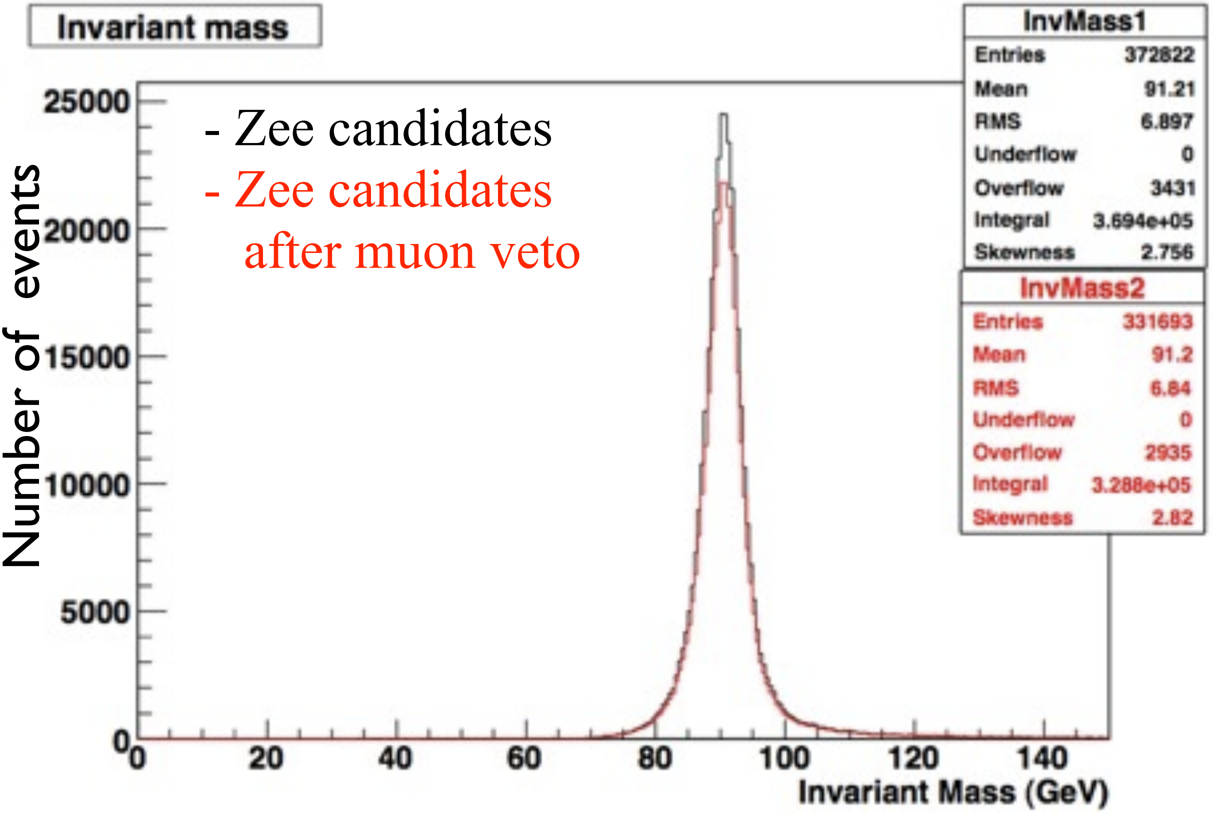
- Muons may arise from many sources
  - pp collision
  - cosmic rays
  - beam halo
- Require signal events to have no muons



Scale Factor: Muon Veto Efficiency

- Muons may arise from many sources
    - pp collision
    - cosmic rays
    - beam halo
- Require signal events to have no muons
- Again, test veto in Z→ee





InvMass1	
Entries	372822
Mean	91.21
RMS	6.897
Underflow	0
Overflow	3431
Integral	3.694e+05
Skewness	2.756

InvMass2	
Entries	331693
Mean	91.2
RMS	6.84
Underflow	0
Overflow	2935
Integral	3.288e+05
Skewness	2.82

- scale factor $= \varepsilon_{data}/\varepsilon_{MC}$
  $= \varepsilon_{data}/1$
  $= N^{Zee}_{remaining}/N^{Zee}$
  $= 0.95 \pm 0.01$

Outline

- Physics models studied
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Z(νν)γ cross section

$$\sigma \times Br = \frac{N_{data} - N_{BG}}{A \times \epsilon_{MC} \times \rho \times L}$$

Z(vv)γ cross section

$$\sigma \times Br = \frac{N_{data} - N_{BG}}{A \times \epsilon_{MC} \times \rho \times L}$$

$$\begin{aligned} N_{data} &= 73 \\ N_{BG} &= 29.6 \pm 6.5 \\ A \times \epsilon_{MC} &= 0.153 \pm 0.020 \\ \rho &= 0.90 \pm 0.11 \\ L &= 4.7 \text{ fb}^{-1} \pm 4.5\% \end{aligned}$$

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$$\sigma(Z(\nu\bar{\nu}) + \gamma) = 60 \pm 12(\text{stat.}) \pm 13(\text{syst.}) \pm 3.0(\text{lumi.})\ \text{fb}$$

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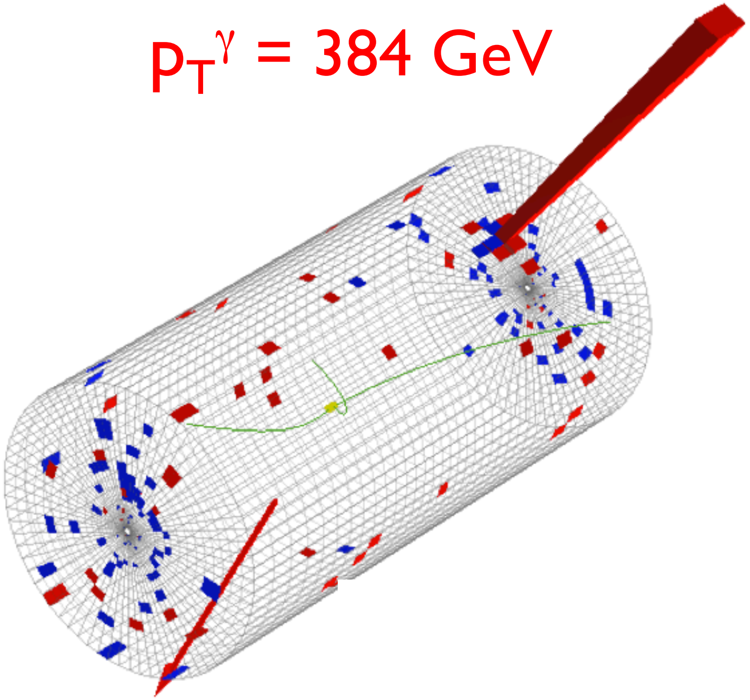
NLO prediction: 59 ± 3.0 fb

measurement agrees with SM!

Highest p_T^γ Event



p_T^γ = 384 GeV

E_t^{miss} = 407 GeV

Highest p_T^γ Event

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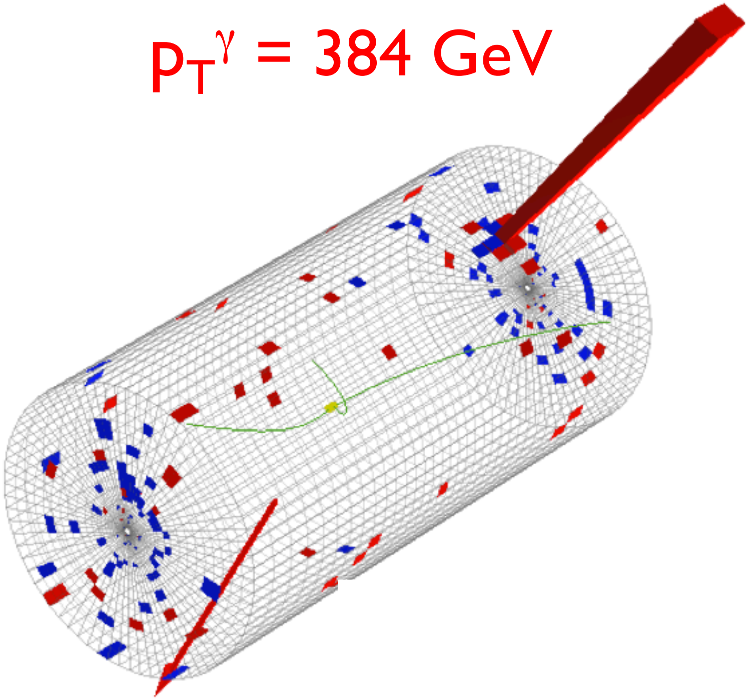

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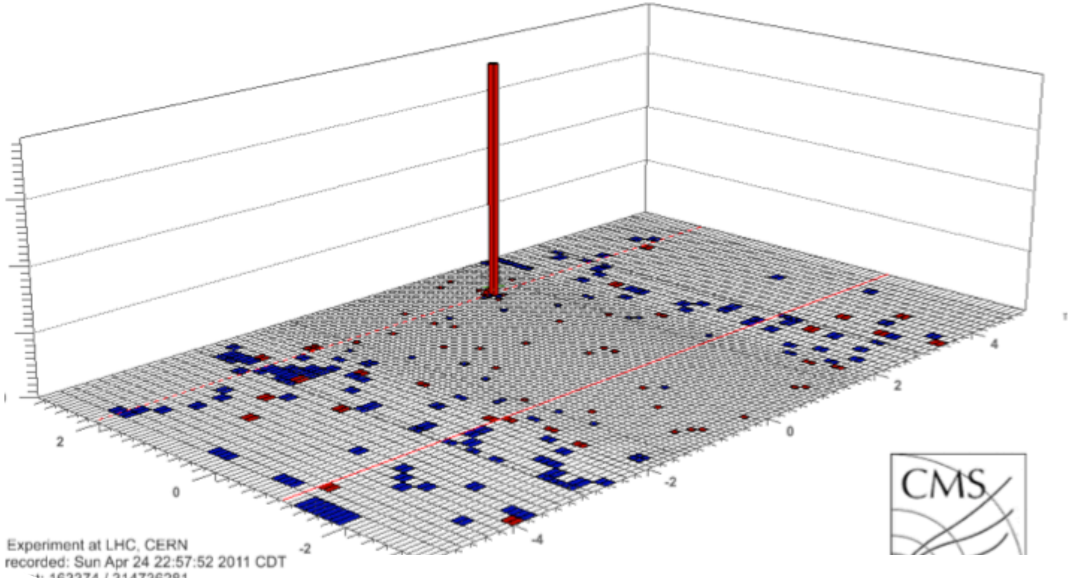
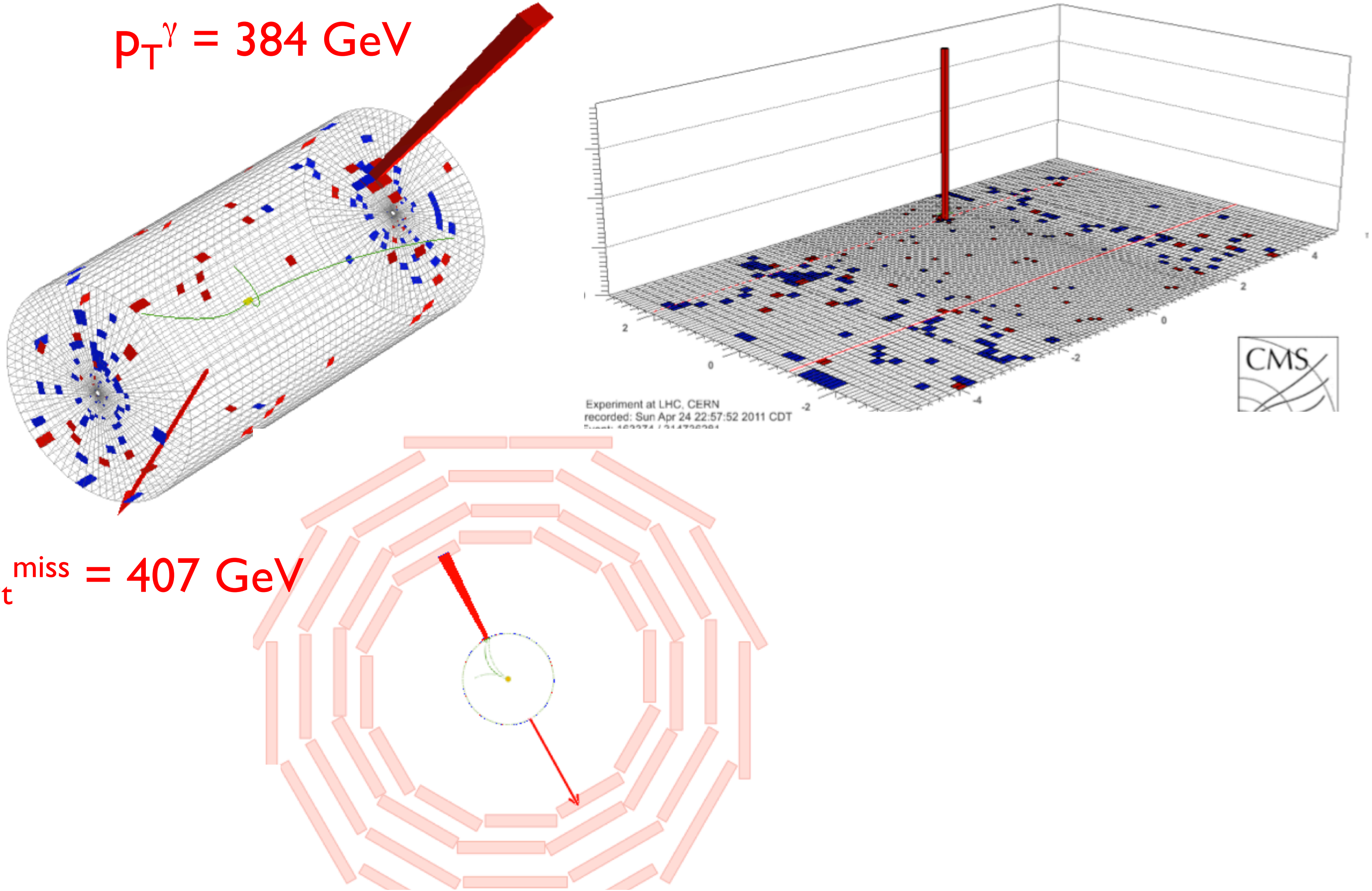


Experiment at LHC, CERN
recorded: Sun Apr 24 22:57:52 2011 CDT

Highest p_T^γ Event



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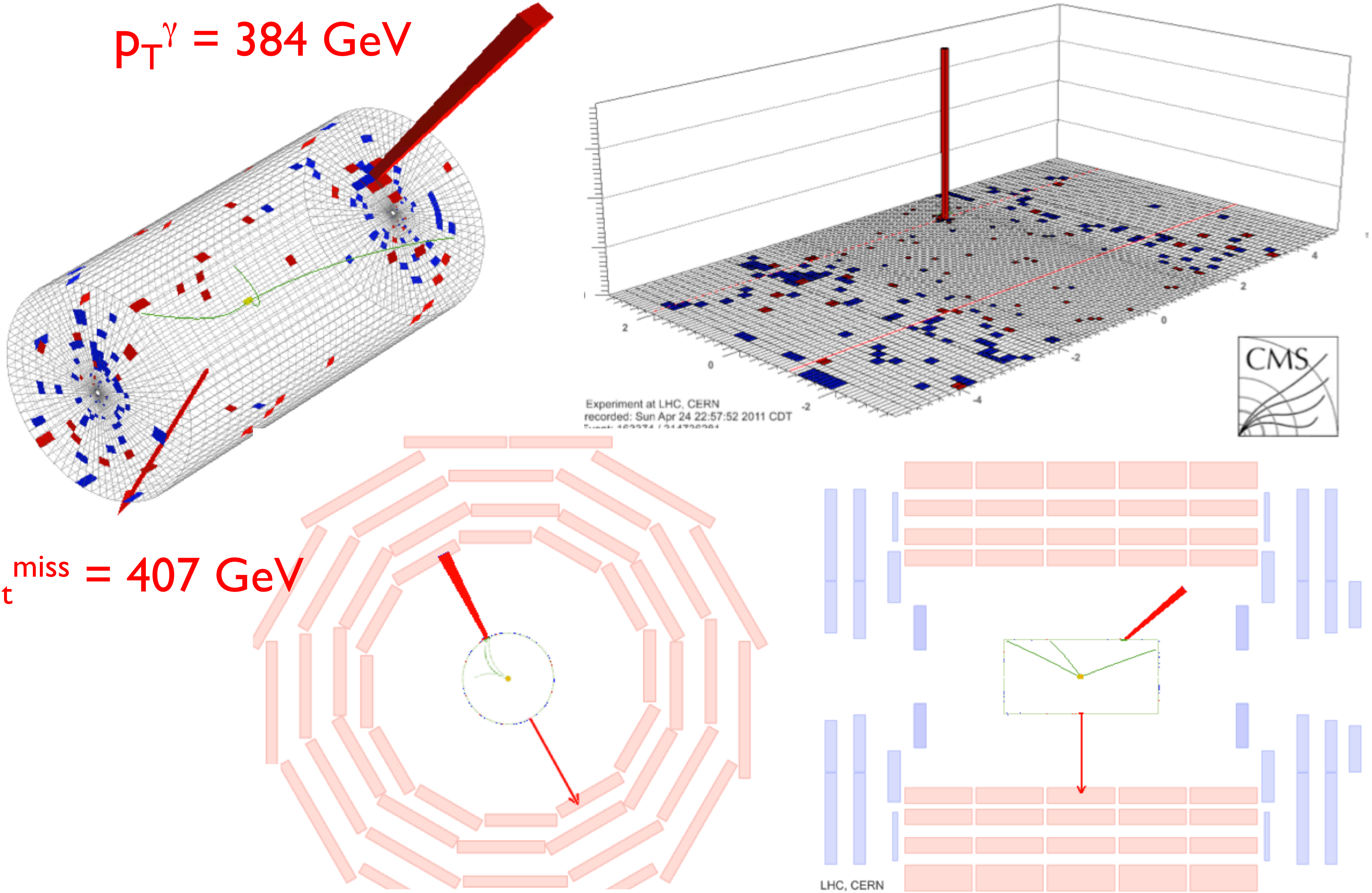

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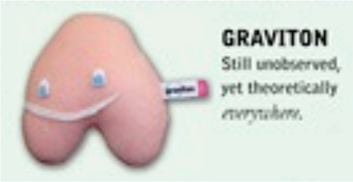
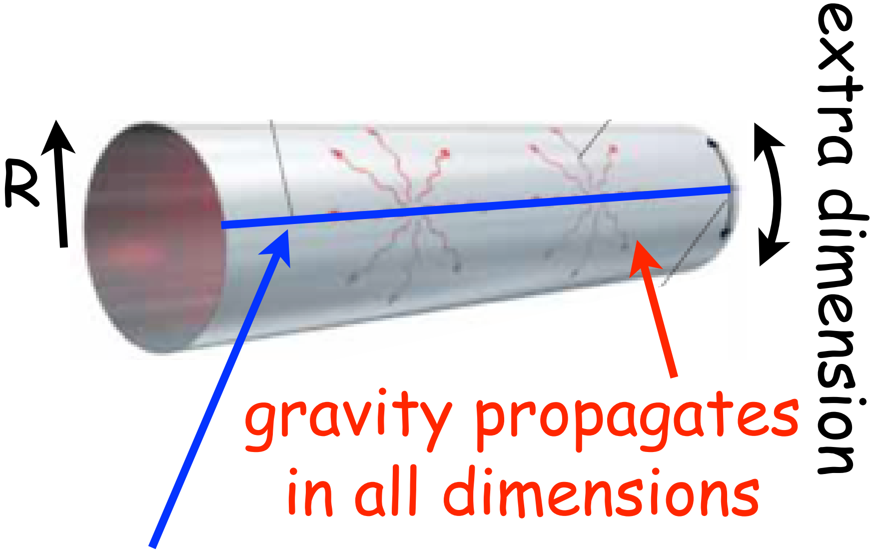
ADD Extra Dimensions

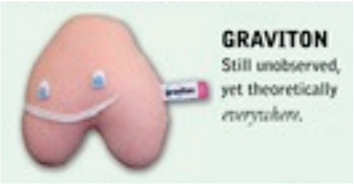


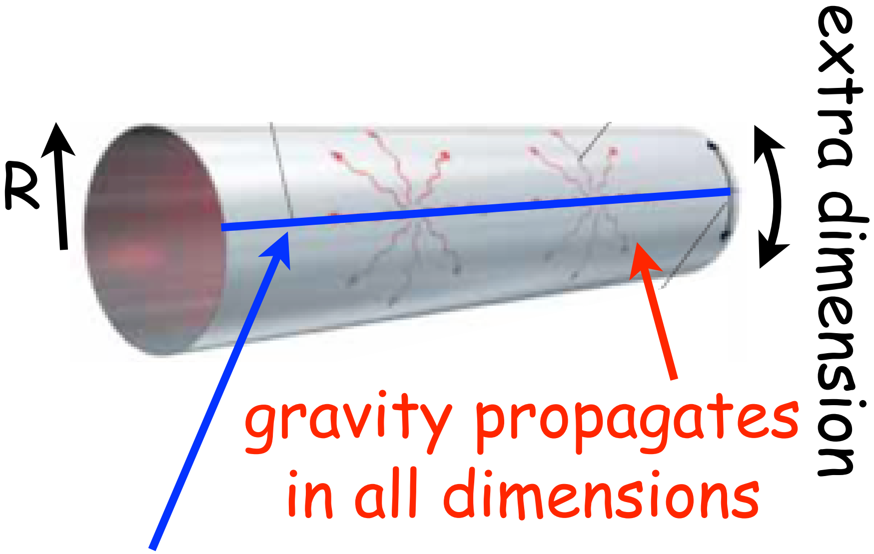


gravity propagates in all dimensions

EM, strong, weak live on brane

ADD Extra Dimensions





gravity propagates in all dimensions

EM, strong, weak live on brane

- Start with Newton's law of gravity

$$V(r) = G_N \frac{m_1 m_2}{r}$$

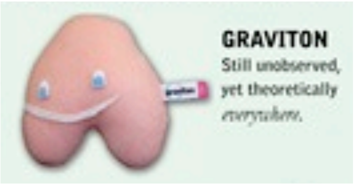
- Allow dilution into extra dimensions, for small distances

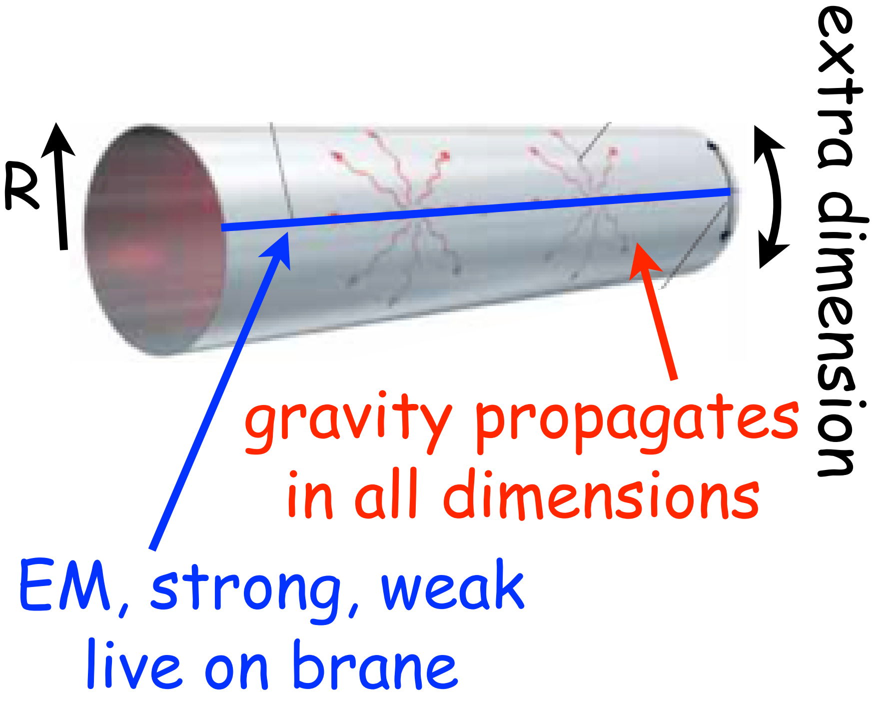
$$V(r < R) = \frac{1}{M_D^{n+2} r^n} \frac{m_1 m_2}{r}$$

$$V(r > R) = \frac{1}{M_D^{n+2} R^n} \frac{m_1 m_2}{r}$$

- M_D is modified planck mass
- n is # extra dimensions
- R is radius of compactified extra dim.

ADD Extra Dimensions





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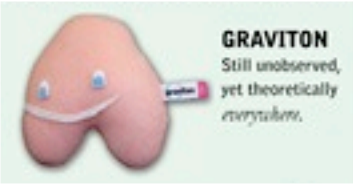
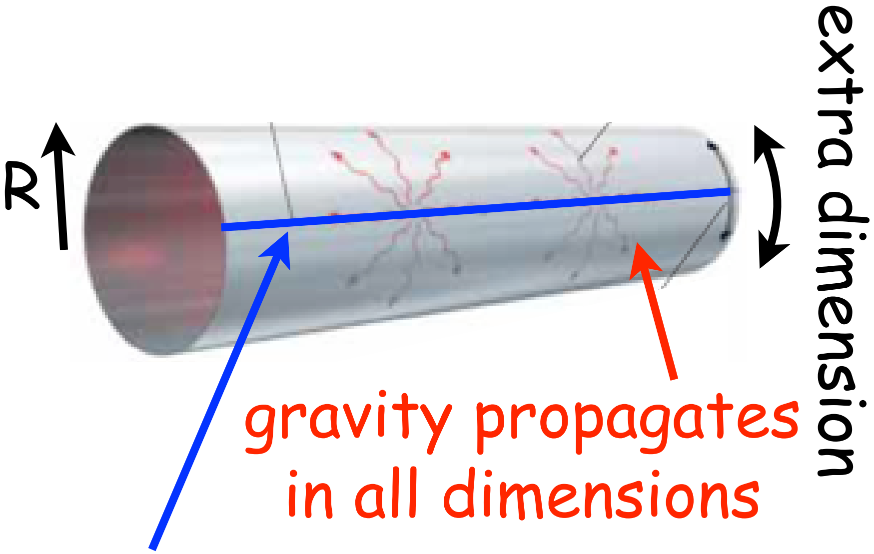




gravity propagates in all dimensions

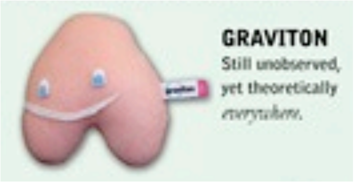
EM, strong, weak live on brane

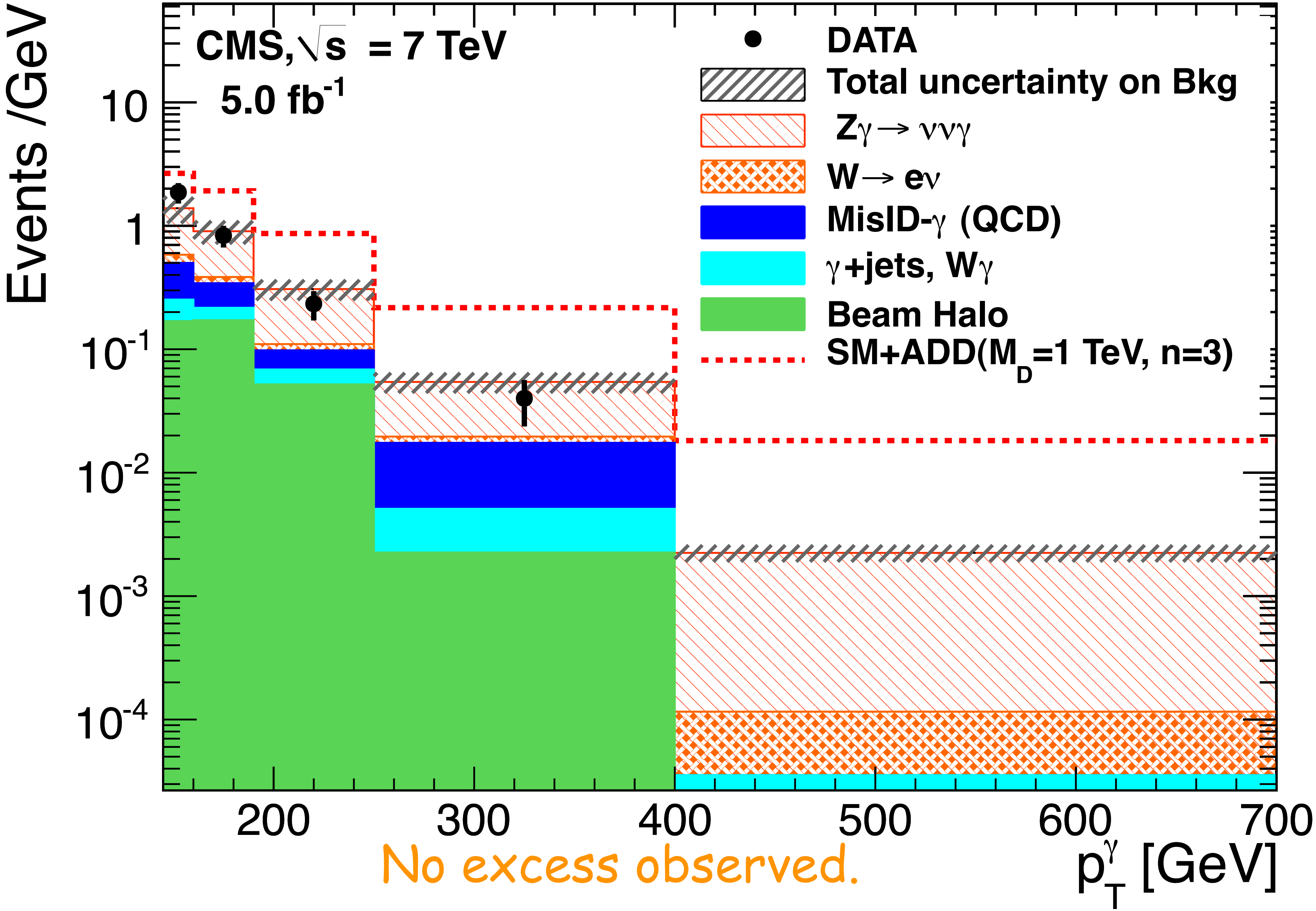
$$G_N = \frac{1}{M_D^{n+2} R^n}$$

$$\frac{1}{M_{Pl}^2} = \frac{1}{M_D^{n+2} R^n}$$

- Request $M_D \approx M_{EW}$, take M_D and n as parameters

ADD Extra Dimensions

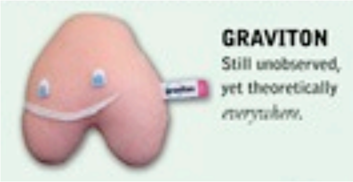


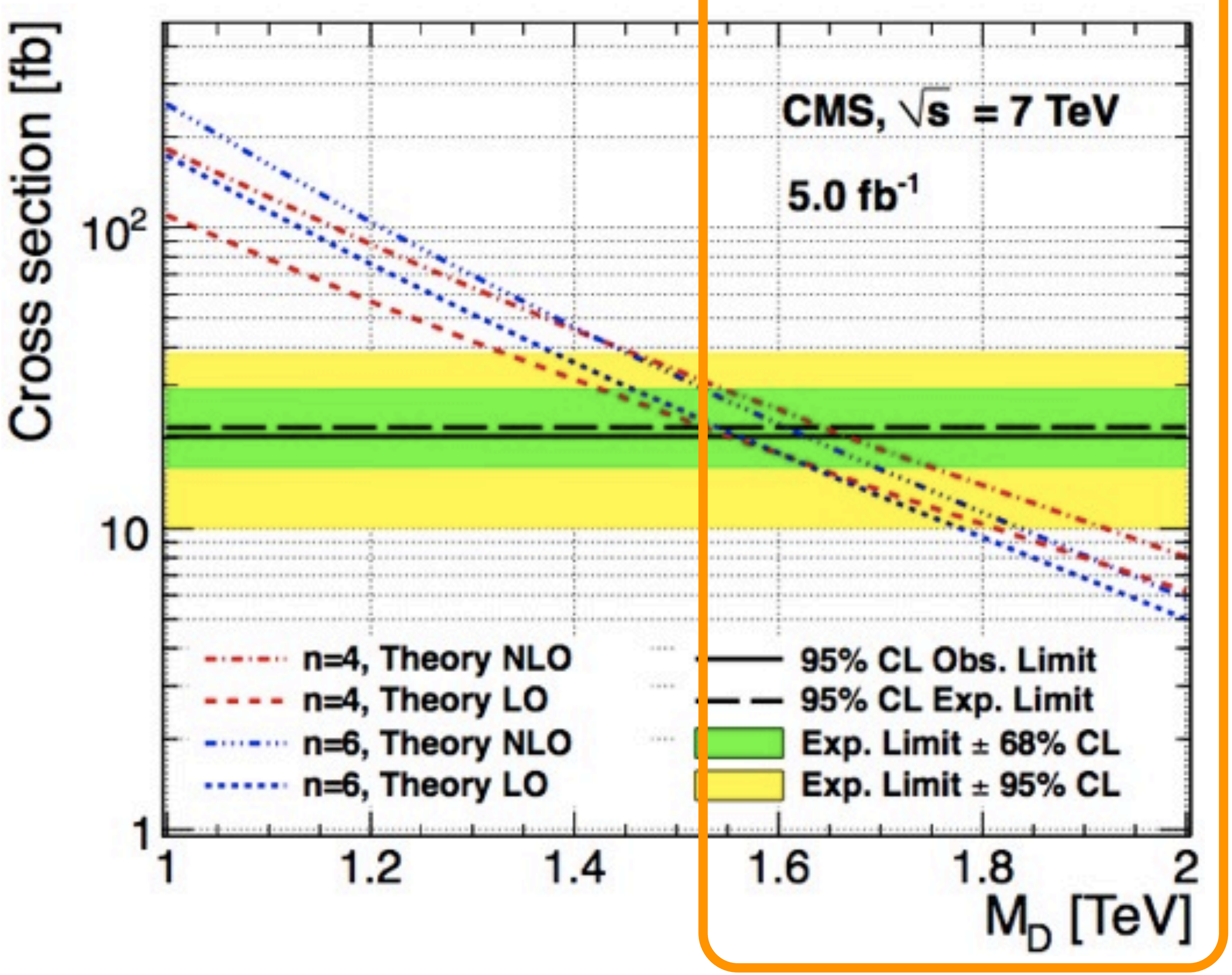


No excess observed.

Background describes data well.

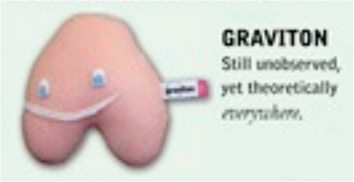
ADD Extra Dimensions



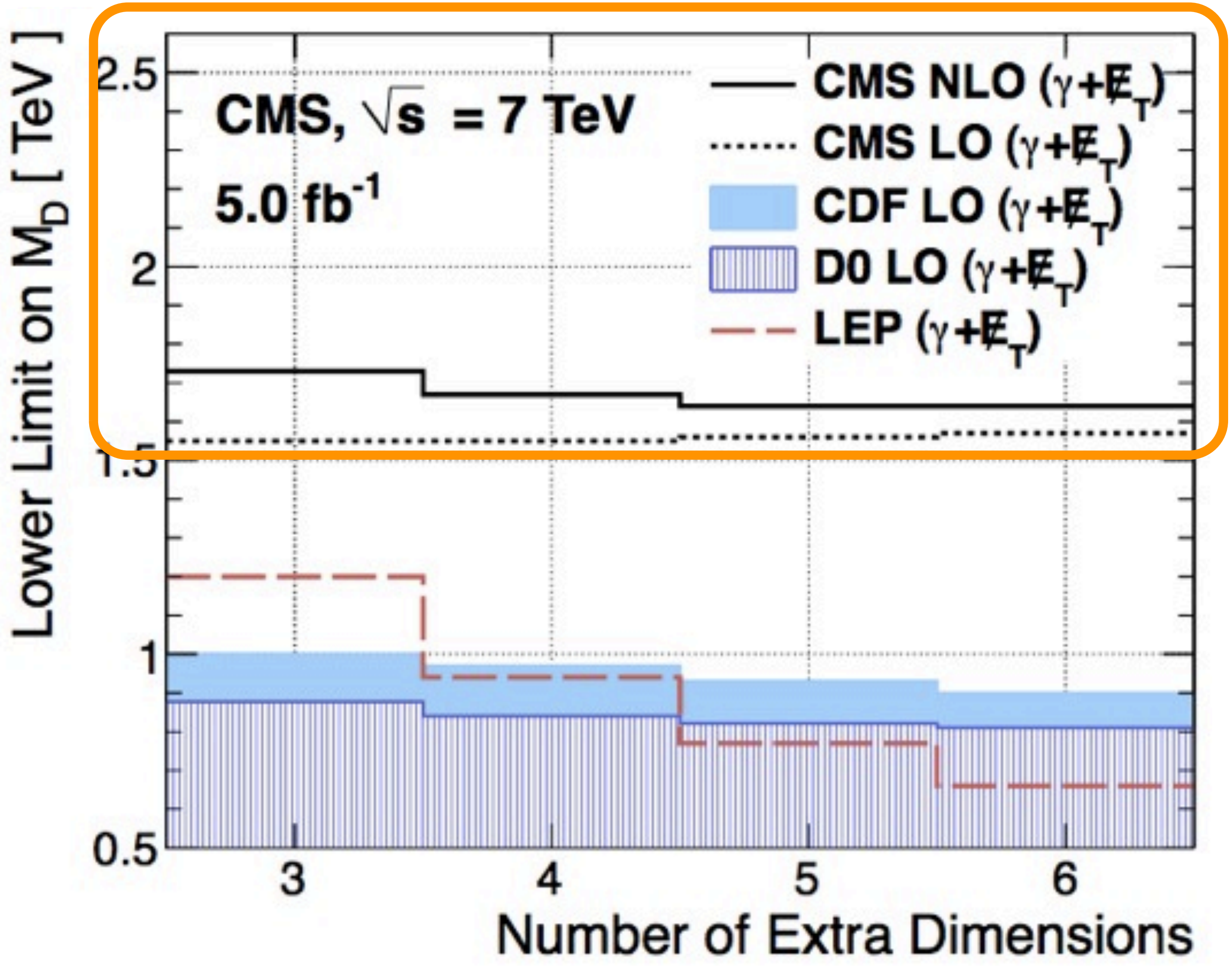


- If theory is true, M_D >~1.6 TeV

ADD Extra Dimensions



- CMS pushed up the lower limits on the M_D
- If theory is true, $M_D > \sim 1.6$ TeV



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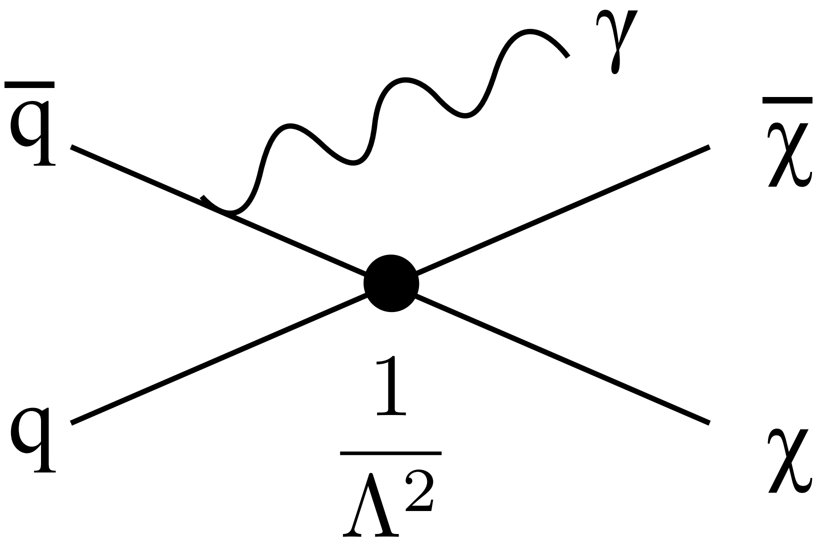
Dark Matter Limit Setting

$$O_V = \frac{(\bar{\chi}\gamma_\mu \chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Vector Operator ⇒ Spin Independent

$$O_A = \frac{(\bar{\chi}\gamma_\mu \gamma^5 \chi)(\bar{q}\gamma^\mu \gamma_5 q)}{\Lambda^2}$$

Axial-Vector Operator ⇒ Spin Dependent



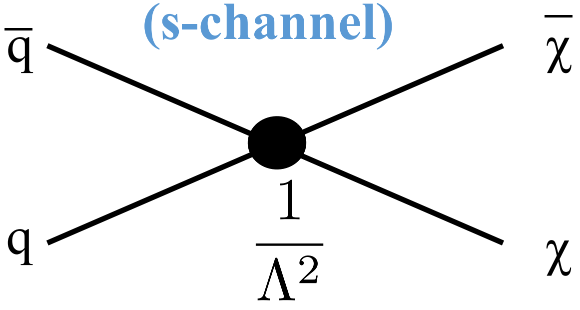
$$\sigma_{\chi\bar{\chi}} \propto \Lambda^{-4}$$

Dark Matter Limit Setting

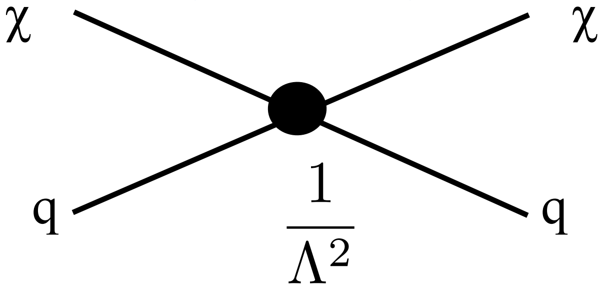
- CMS measures $\sigma_{\chi\bar{\chi}}$, but to compare with direct detection experiments, transform this into $\sigma_{\chi-N}$

$$\frac{\sigma_{\text{meas.}}}{\sigma_{10\text{TeV}}} = \frac{\Lambda_{\text{meas.}}^{-4}}{(10\ \text{TeV})^{-4}}$$

Pair Production (s-channel)



Nuclear Recoil (t-channel)



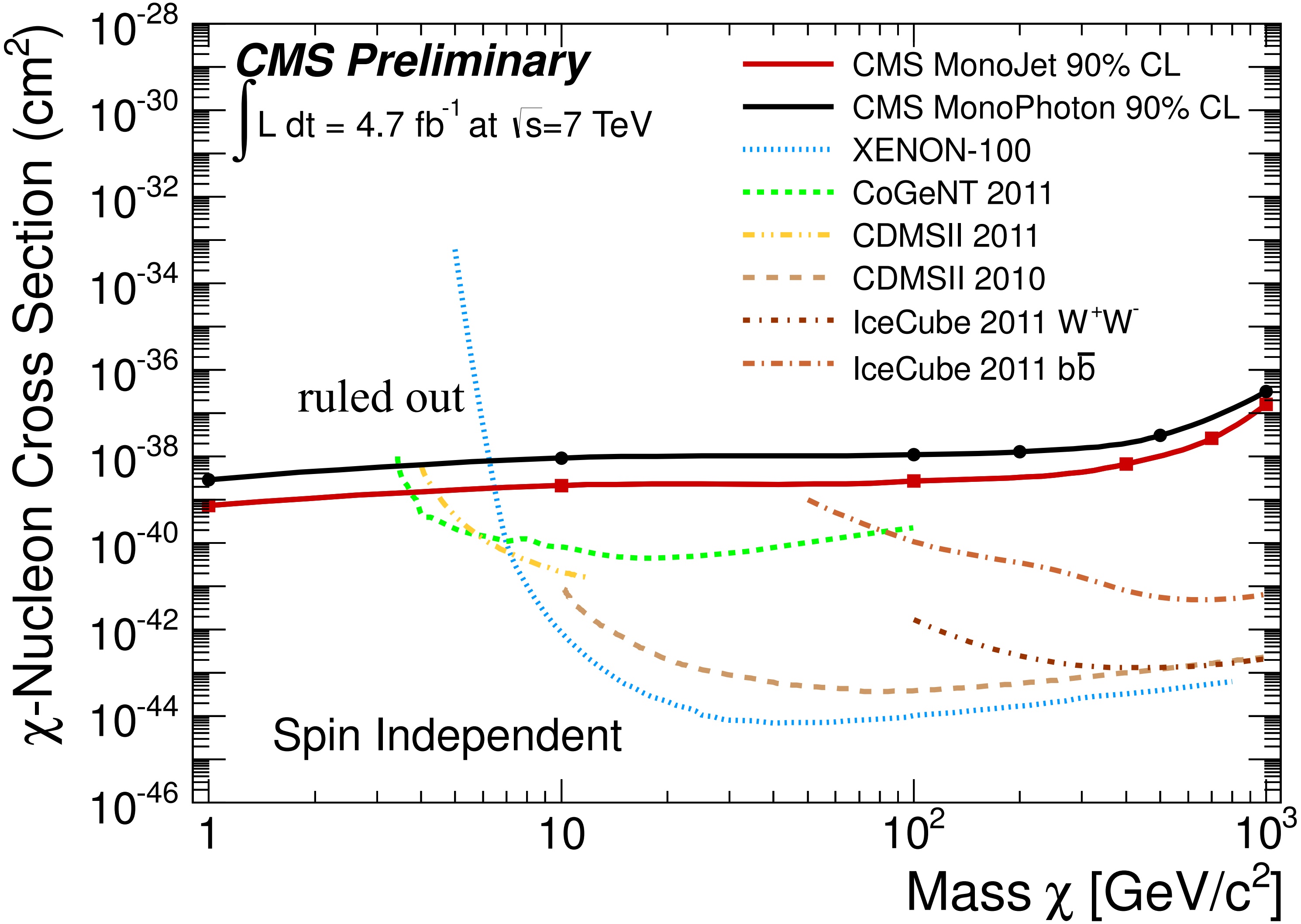
$$\sigma_{SI}^{\chi\text{-N}} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

$$\sigma_{SD}^{\chi\text{-N}} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

$$\mu = \left(\frac{m_{DM}\ m_p}{m_{DM} + m_p}\right)$$

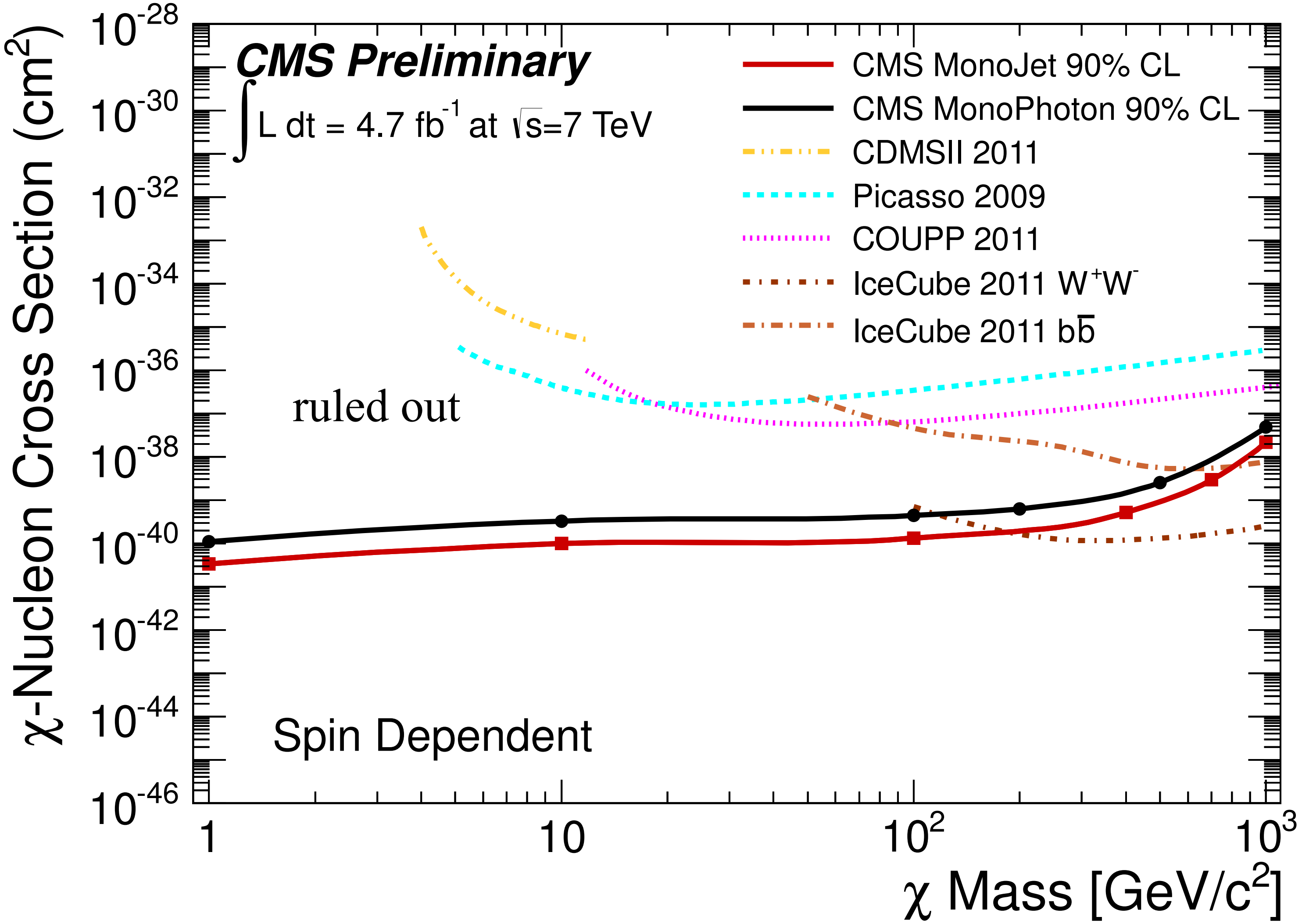
DM - Spin Independent Limits

- Extends the cross-section lower limits for $M_\chi < 3.5$ GeV.



DM - Spin Dependent Limits

- Extends the cross-section lower limits for $M_\chi < 100$ GeV.



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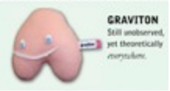

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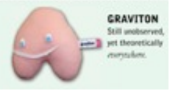

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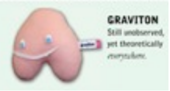

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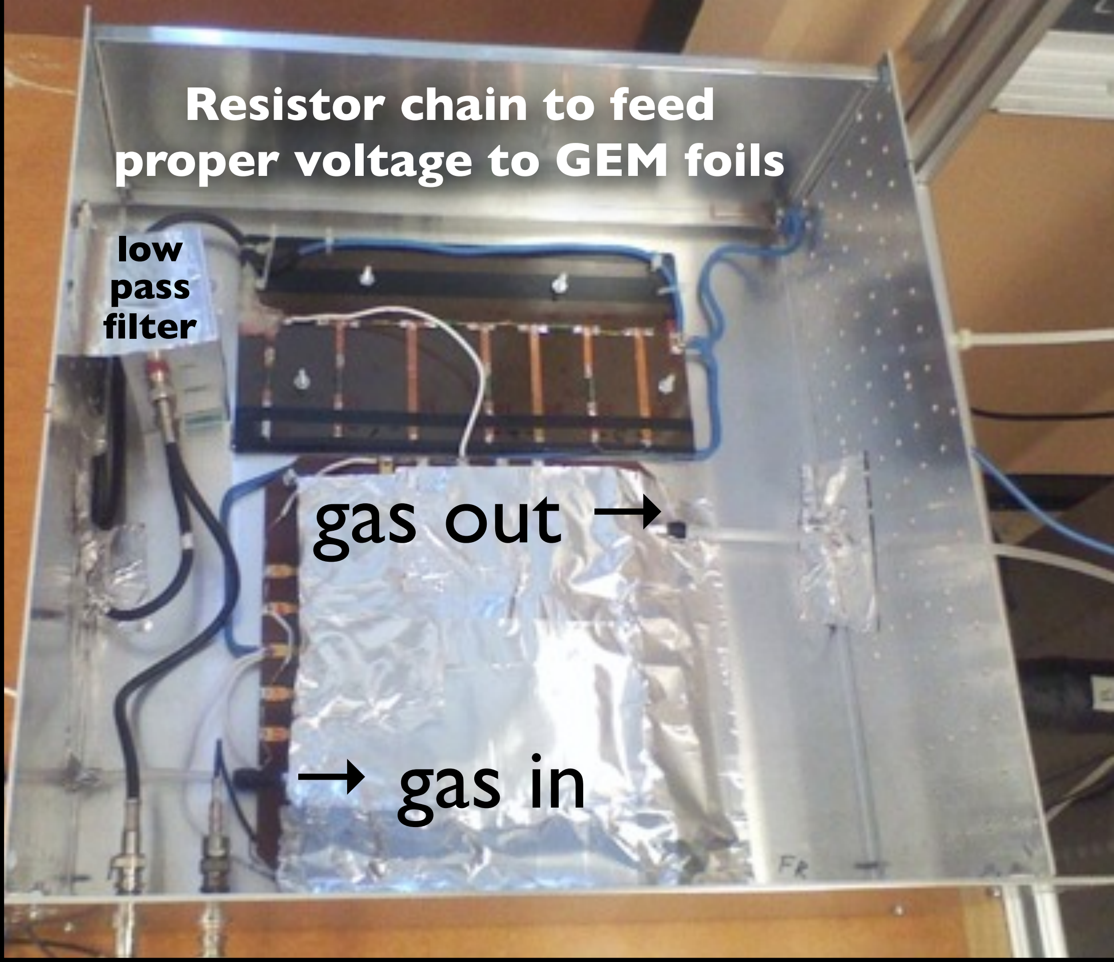
Thank You!

Extra Slides

- MET
- Jet fakes photon details
- Monojet
- ADD Monophoton phenomenology
- acceptance and efficiency
- Jet contamination estimation details

2 Scintillators and PMTs set in coincidence to identify a cosmic μ test particle for GEM

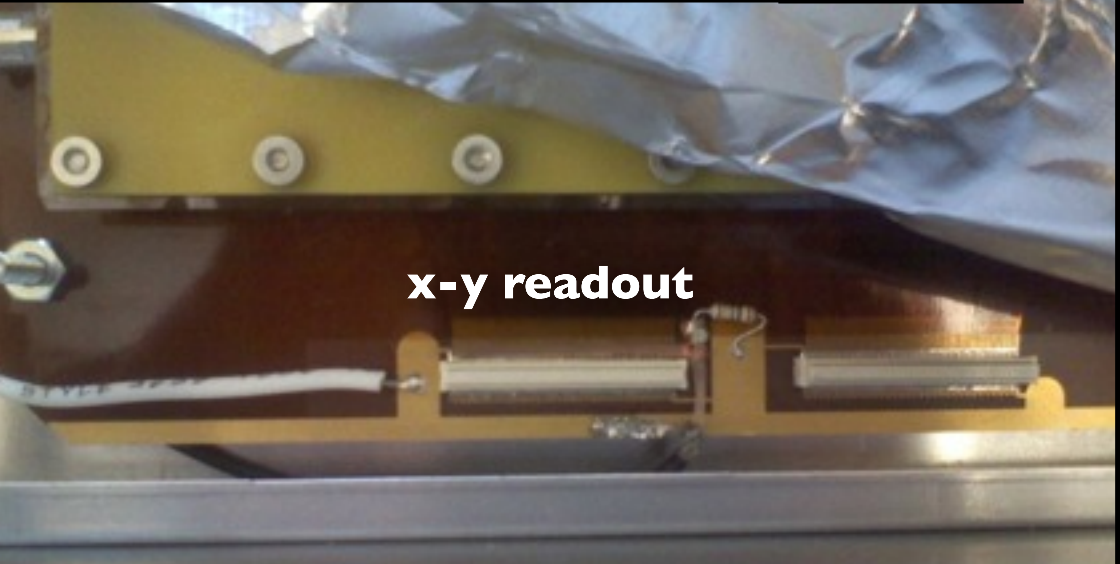


Resistor chain to feed proper voltage to GEM foils

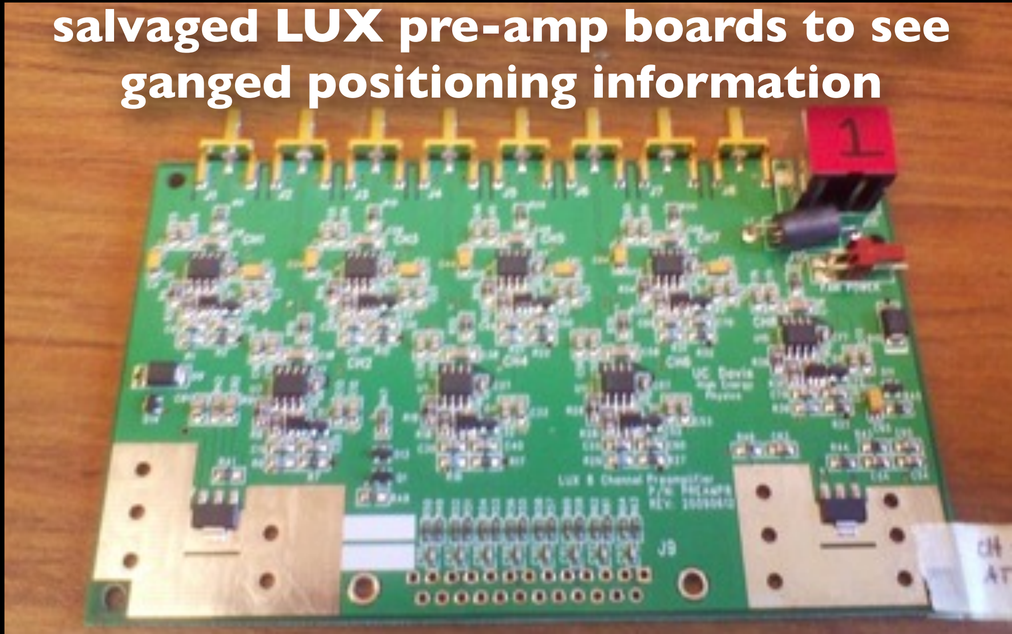
low pass filter

gas out →

→ gas in



x-y readout

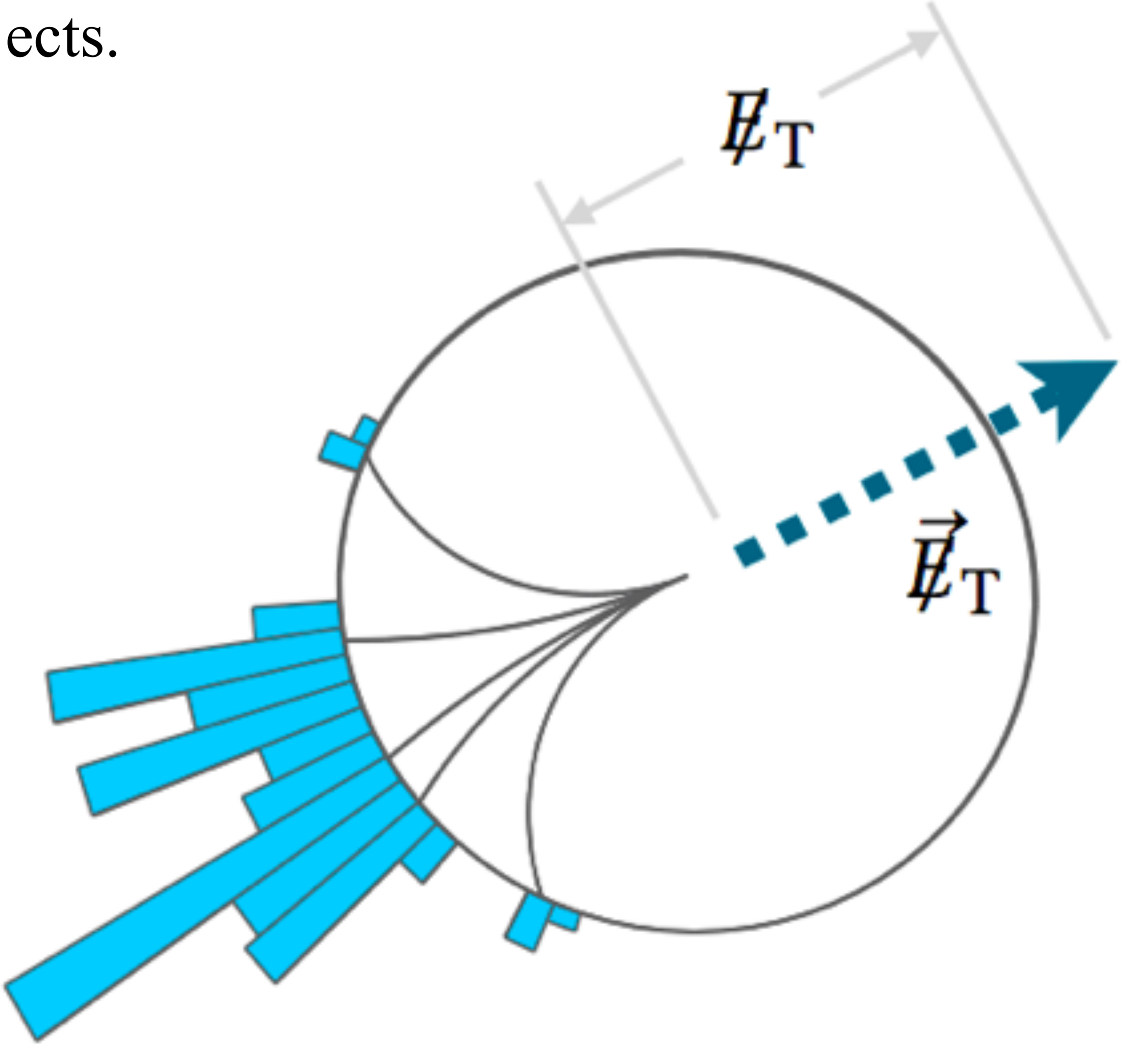


salvaged LUX pre-amp boards to see ganged positioning information

Missing transverse energy (MET)

- Negative vector sum of transverse momentum of all reconstructed objects.

$$\not{E}_T = -\sum_{\substack{\text{all}\\\text{particles}}} p_T$$



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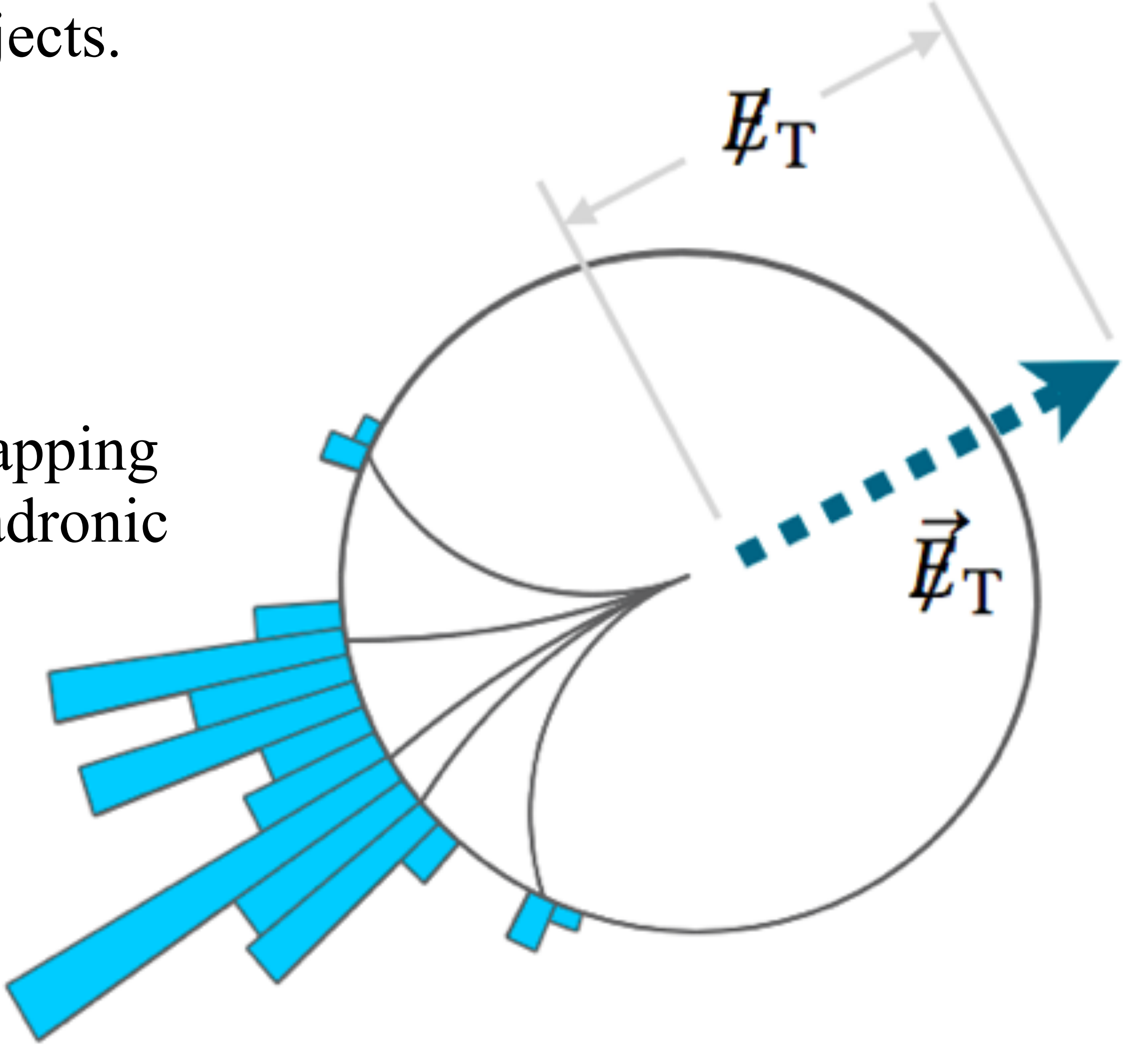

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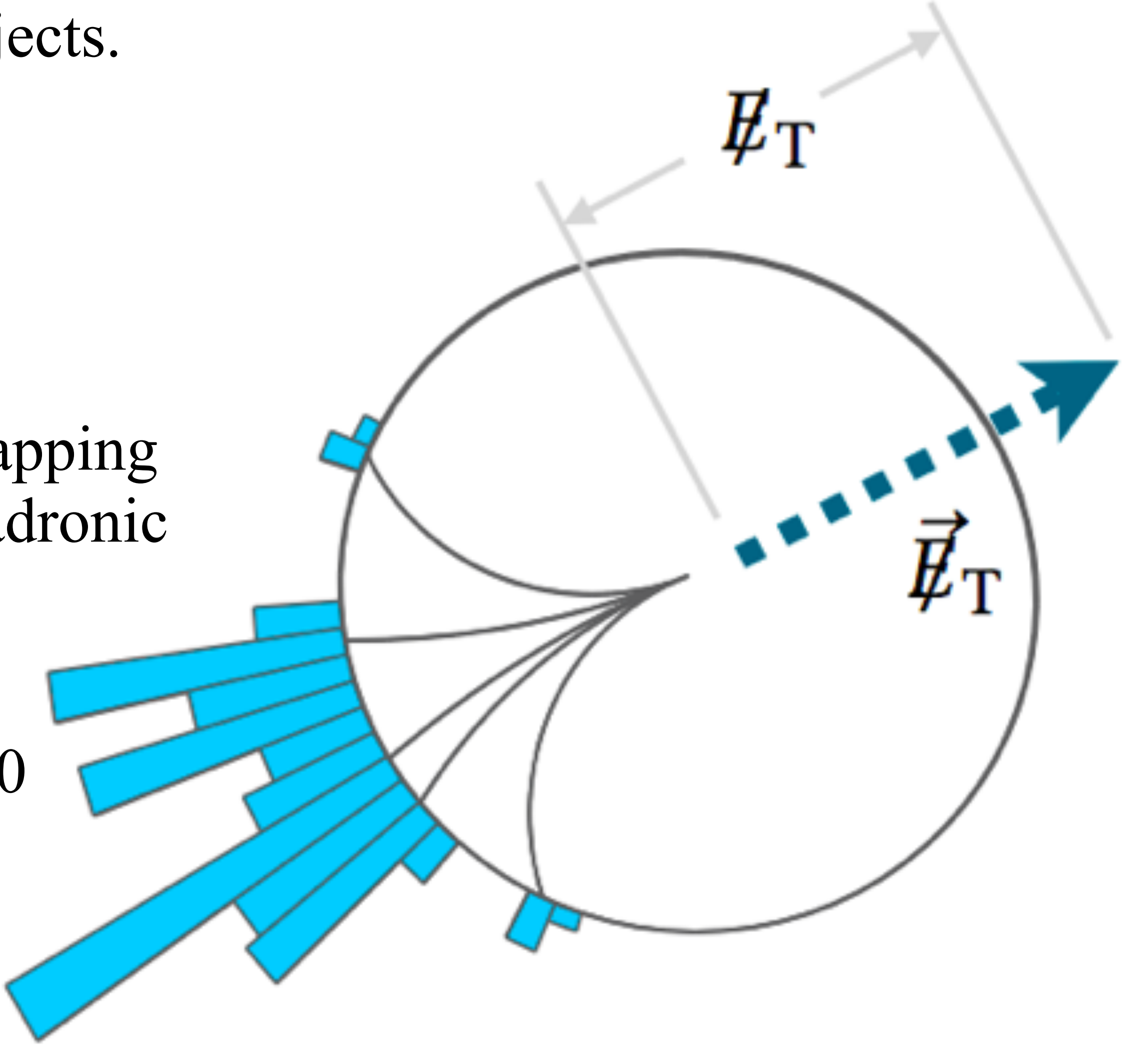

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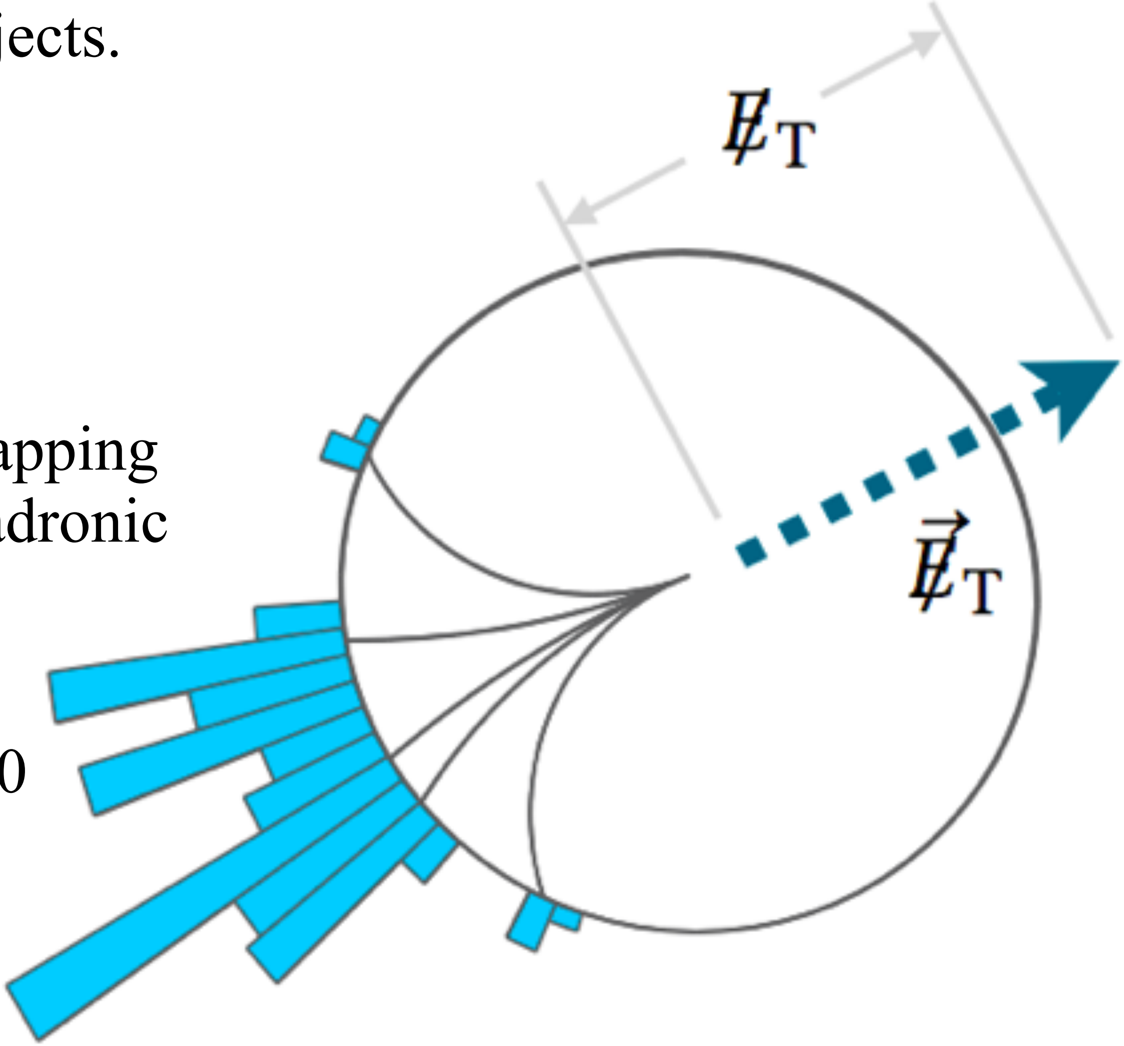


- “Type 0” correction: assume overlapping events have MET=0 and neutral hadronic energy is underestimated.
- “Type I” correction: propagate jet energy scale correction for jets > 10 GeV.
- “Type II” correction: account for unclustered jets (p_T < 10 GeV)

Jets background (1/4)

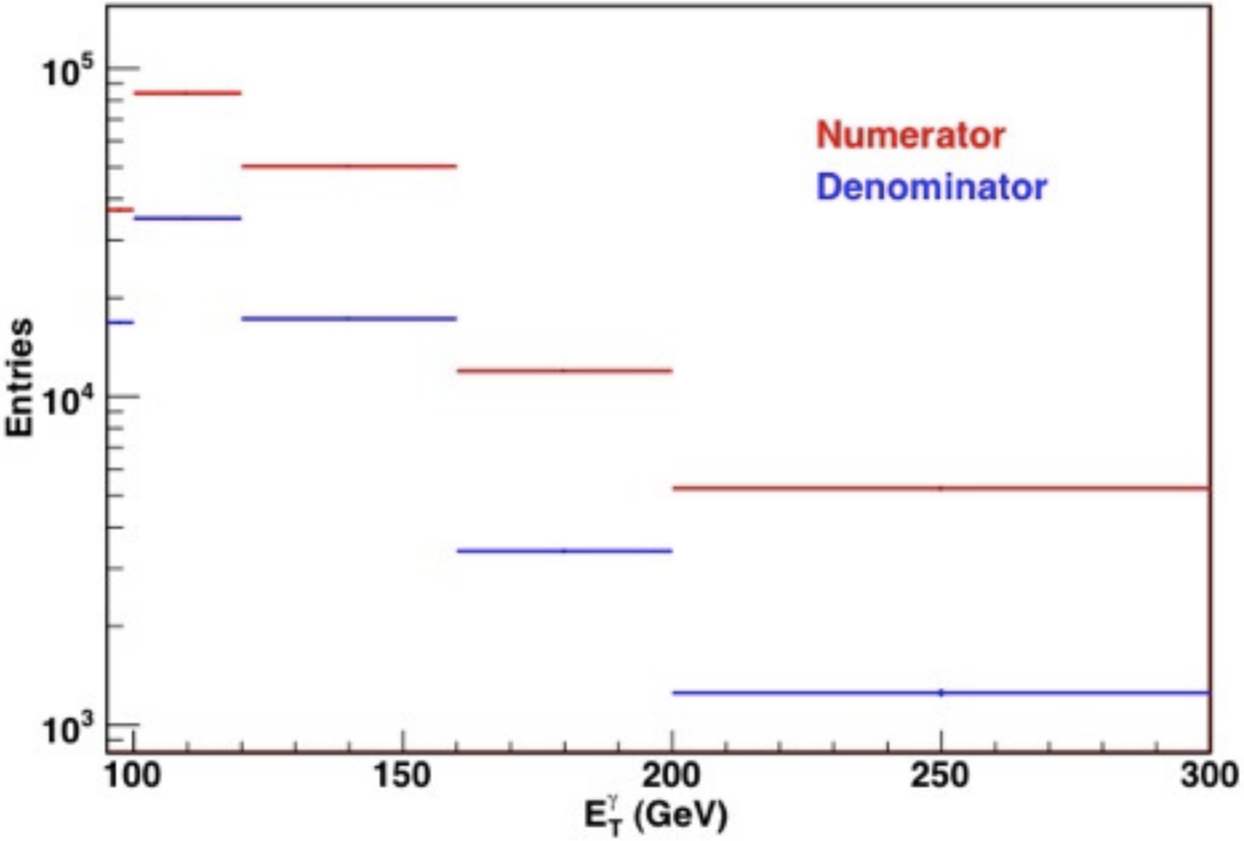
- Goal: We measure our own photon/jet "fake ratio" in data, for our particular E_T range, and for our particular triggers.

- First, make a jet data sample:
  - require low MET (<20 GeV)
  - no vetoes on tracks or jets
  - the jet fires and is matched with one of our HLT triggers

Jets background (2/4): constructing the fake ratio

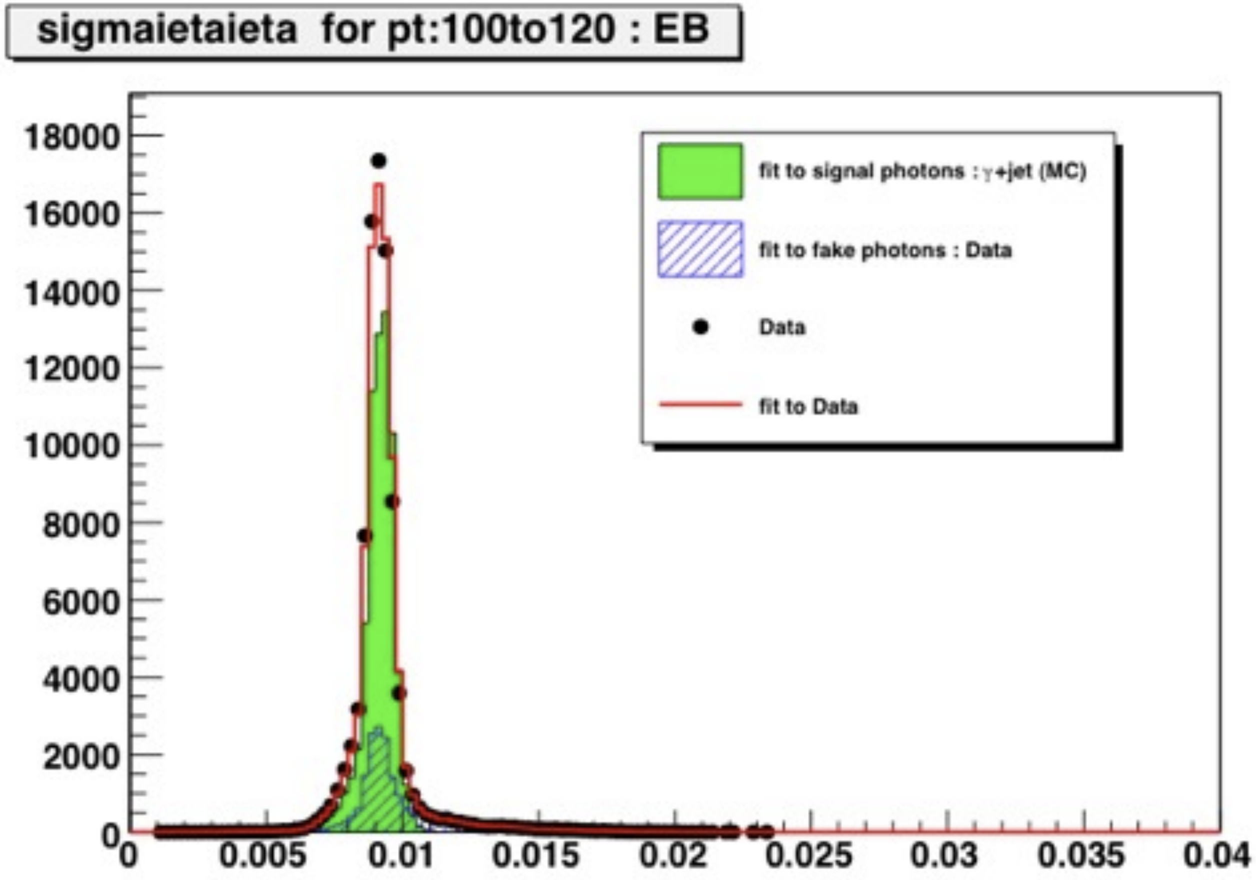
- Numerator: Same tight photon ID as our candidates. Large contamination from true photons! (must correct!)

- Denominator: Pass all of the very loose photon ID criteria (in back up) and most of the tight photon ID criteria except that it must fail at least one of EcalIso, HcalIso, or TrackIso requirements.



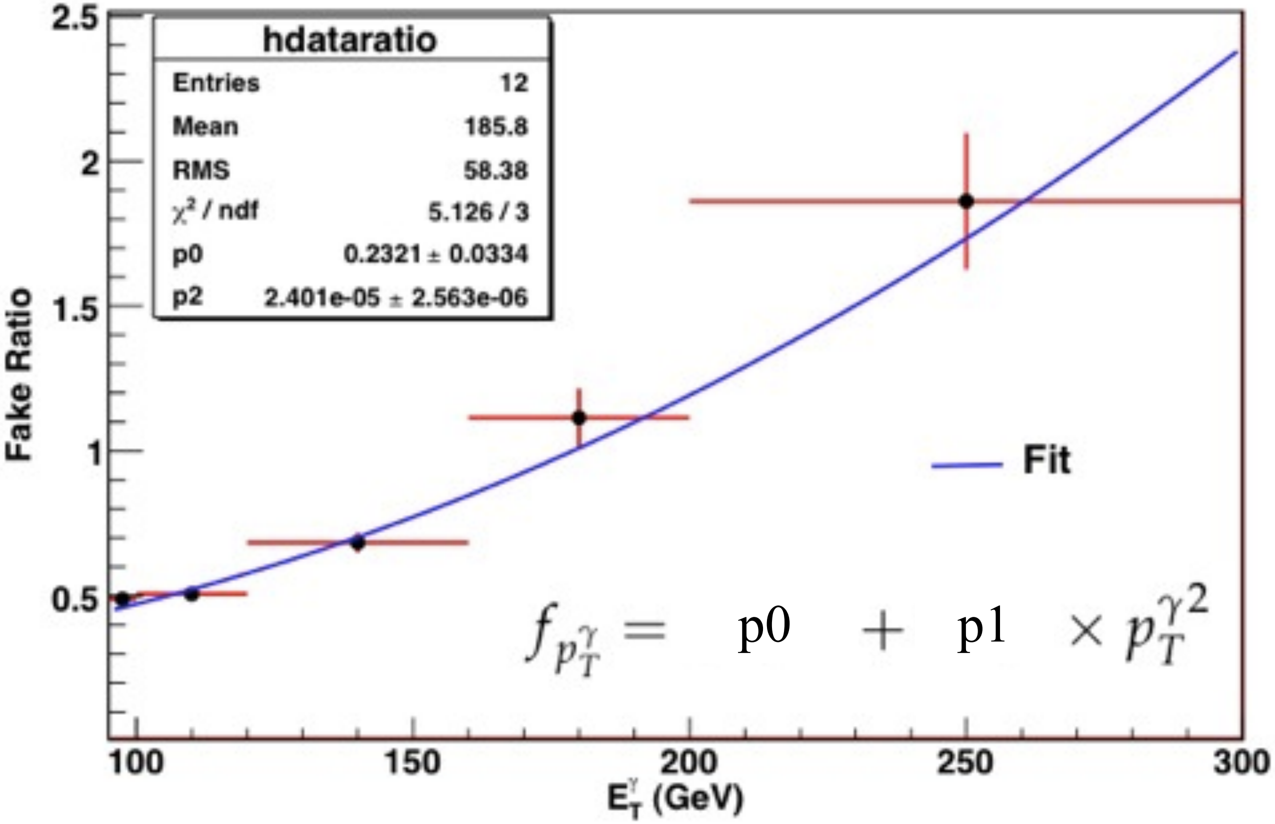
Jets background (3/4): correcting the numerator

- Example of correcting P_T bin 100-120 GeV.
- Black data points show the numerator events.
- Fraction fit so we can subtract the true photons (the green) from the numerator.
- The blue are taken from events that pass the denominator, but are within a track isolation band.
- We will only use the number reported within our cuts $0.001<\sigma_{i\eta i\eta}<0.013$.



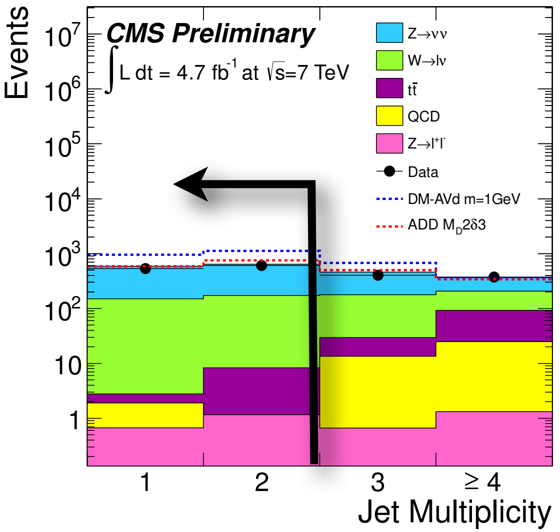
Jets background (4/4): the actual fake ratio

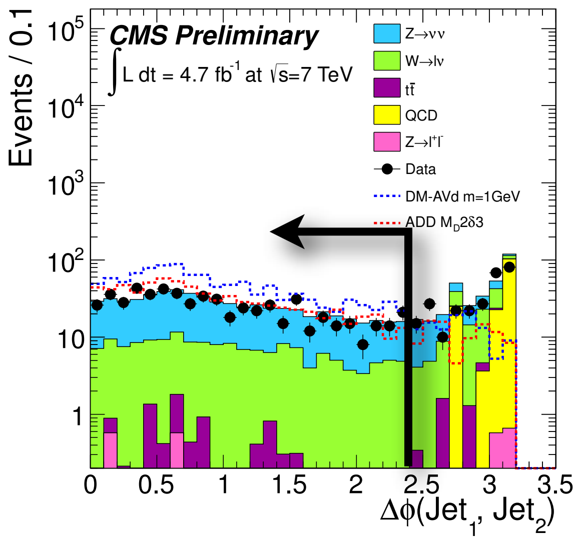
- After removing the true photons from the numerator we get this photon/jet "fake ratio".
- Now we make a normalization subset by applying the full candidate selection but replacing the tight photon ID by the denominator sample.
- Multiply the number in the normalization subset by the "fake ratio" to get the number of jet background.
- 14.1 ± 3.3 events from jets.

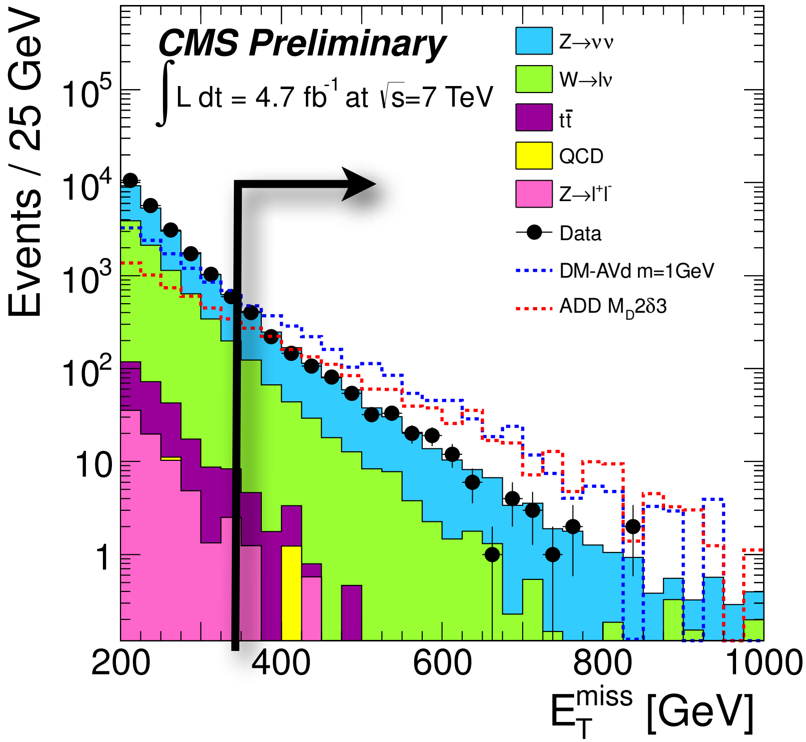


Monojet - Candidate Selection

- Basic Topological Selection → reject prolific multijet events
  - $n_{jets} = 1$ or 2, $E_T^{miss} > 200$ GeV later tightened to 350 GeV
  - particle flow jets clustered using anti-k_T with $R = 0.5$
  - $p_T^{lead\ jet} > 110$ GeV, $|\eta|<2.4$
  - $p_T^{second\ jet} > 30$ GeV
  - $\Delta\varphi(jet1, jet2) < 2.5$
- Lepton removal
  - Reject events with isolated e or μ ($\Delta R_{isolation}$=0.3).
  - Reject events with isolated tracks ($\Delta R_{isolation}$=0.3).
- Optimize E_T^{miss} cut for DM search: $E_T^{miss} > 350$ GeV.

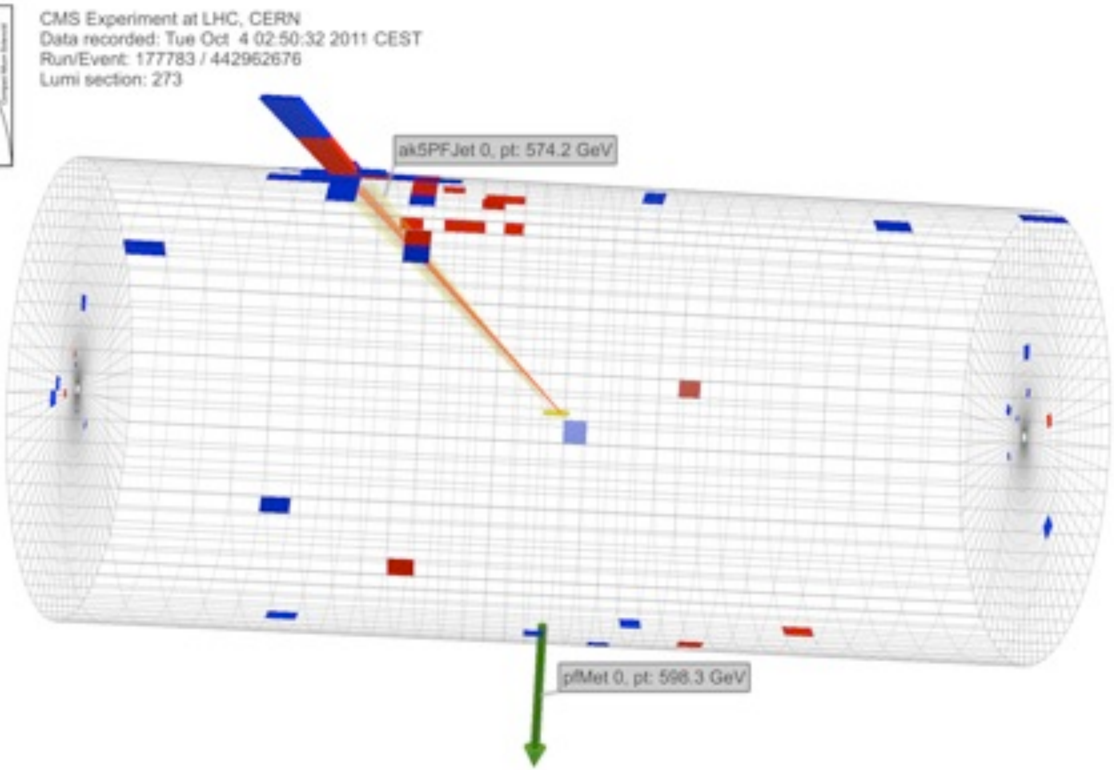


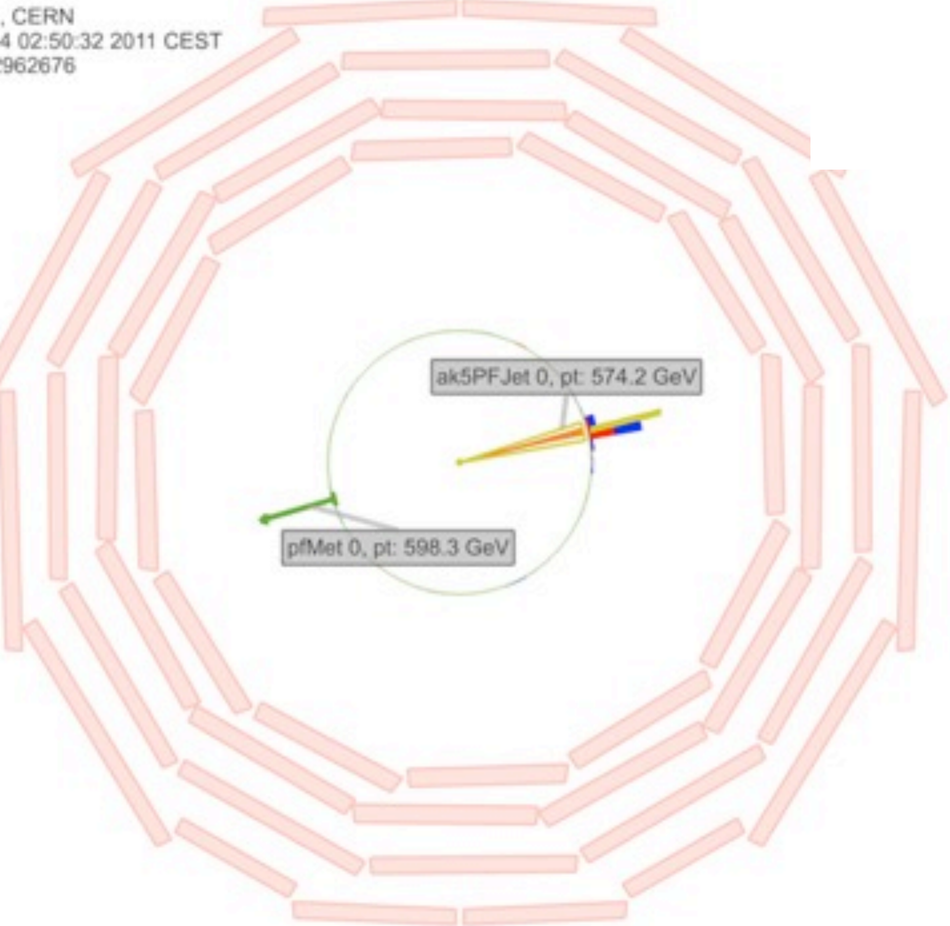


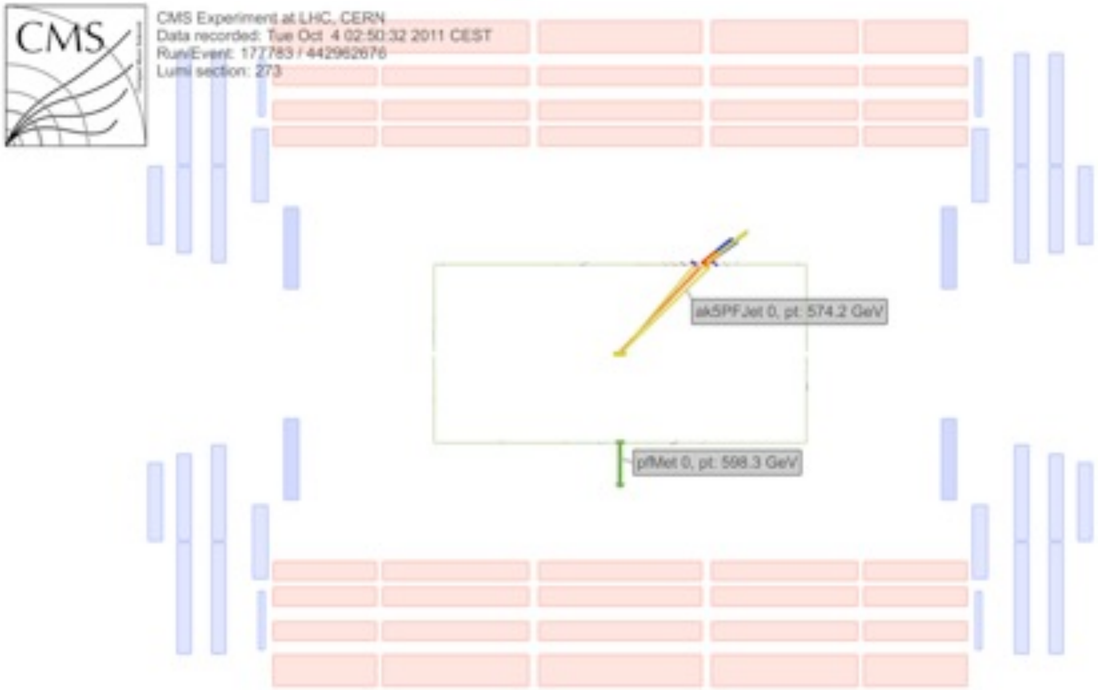


Monojet Event

p_T^{jet} = 574.2 GeV
E_T^{miss} = 598.3 GeV

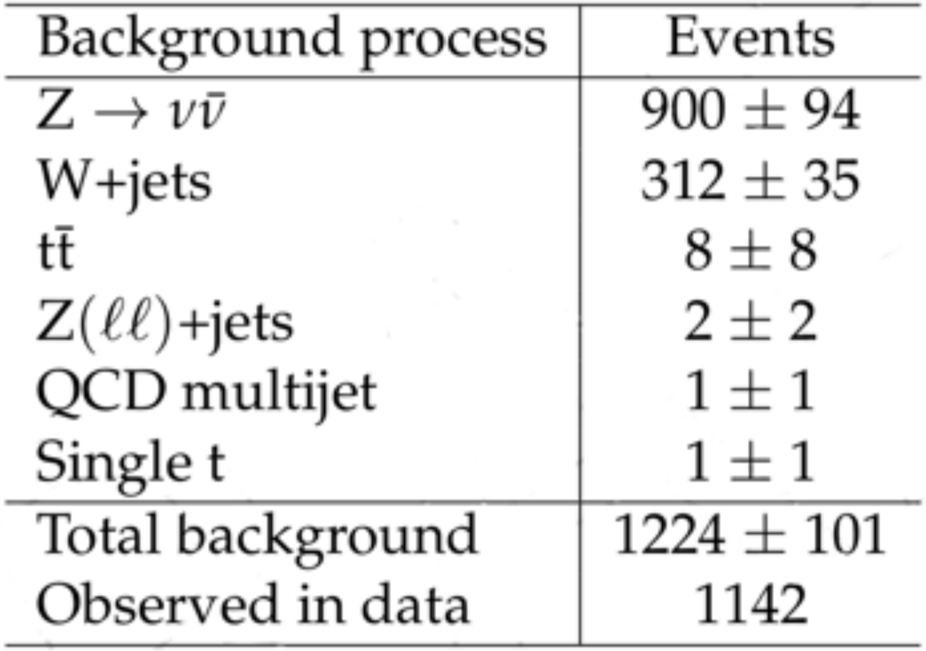






Monojet - Backgrounds & Search Results

- Some backgrounds estimated with data-driven techniques, while others use Monte Carlo simulations



Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

- Estimated Zνν from a Z(→μμ)+jet control sample
- Estimated W(→lν)+jet using Wμν control sample and detector acceptance and reconstruction efficiencies
- Remainder are from simulation

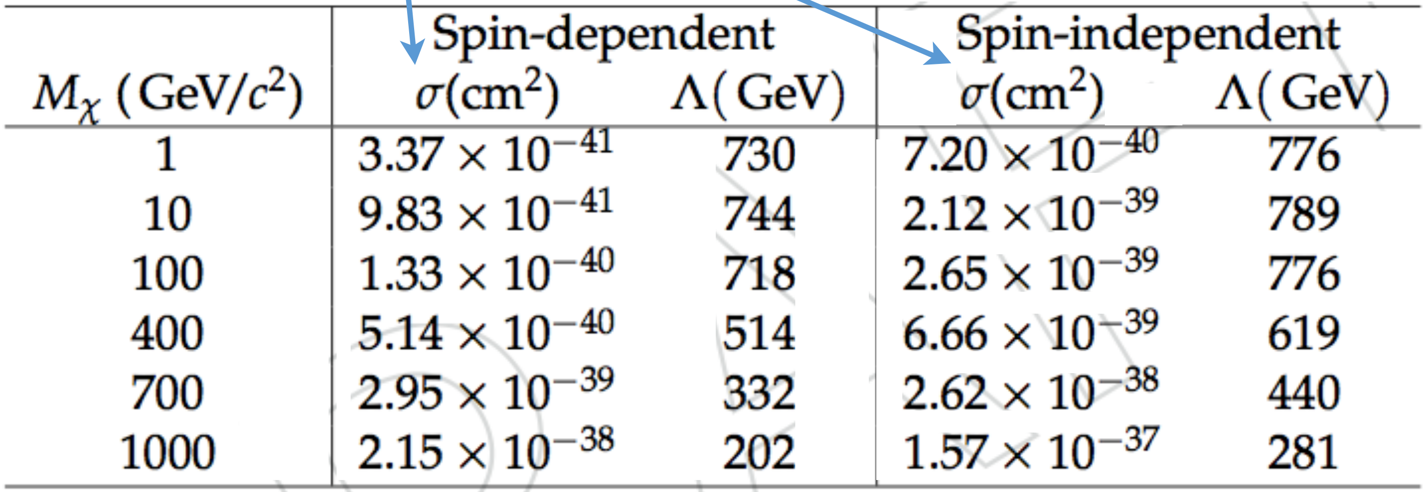
No excess observed.
Background describes data well.

Monojet - Uncertainties and Limit Setting

- Limit setting as before, but with a $\Lambda_{th.}$ set to 40 GeV instead.

$$\Lambda = \Lambda_{th.} \left(\frac{\sigma_{th.}^{\chi\bar{\chi}}}{\sigma_{meas.}^{\chi\bar{\chi}}} \right)^{1/4}$$

$$\boxed{\begin{array}{c} \Lambda_{th.} \equiv 40 \text{ TeV} \\ \sigma_{th.}^{\chi\bar{\chi}} \text{ from MC} \end{array}}$$



M_χ (GeV/c^2)	Spin-dependent σ(cm^2)	Λ(GeV)	Spin-independent σ(cm^2)	Λ(GeV)
1	3.37×10^{-41}	730	7.20×10^{-40}	776
10	9.83×10^{-41}	744	2.12×10^{-39}	789
100	1.33×10^{-40}	718	2.65×10^{-39}	776
400	5.14×10^{-40}	514	6.66×10^{-39}	619
700	2.95×10^{-39}	332	2.62×10^{-38}	440
1000	2.15×10^{-38}	202	1.57×10^{-37}	281

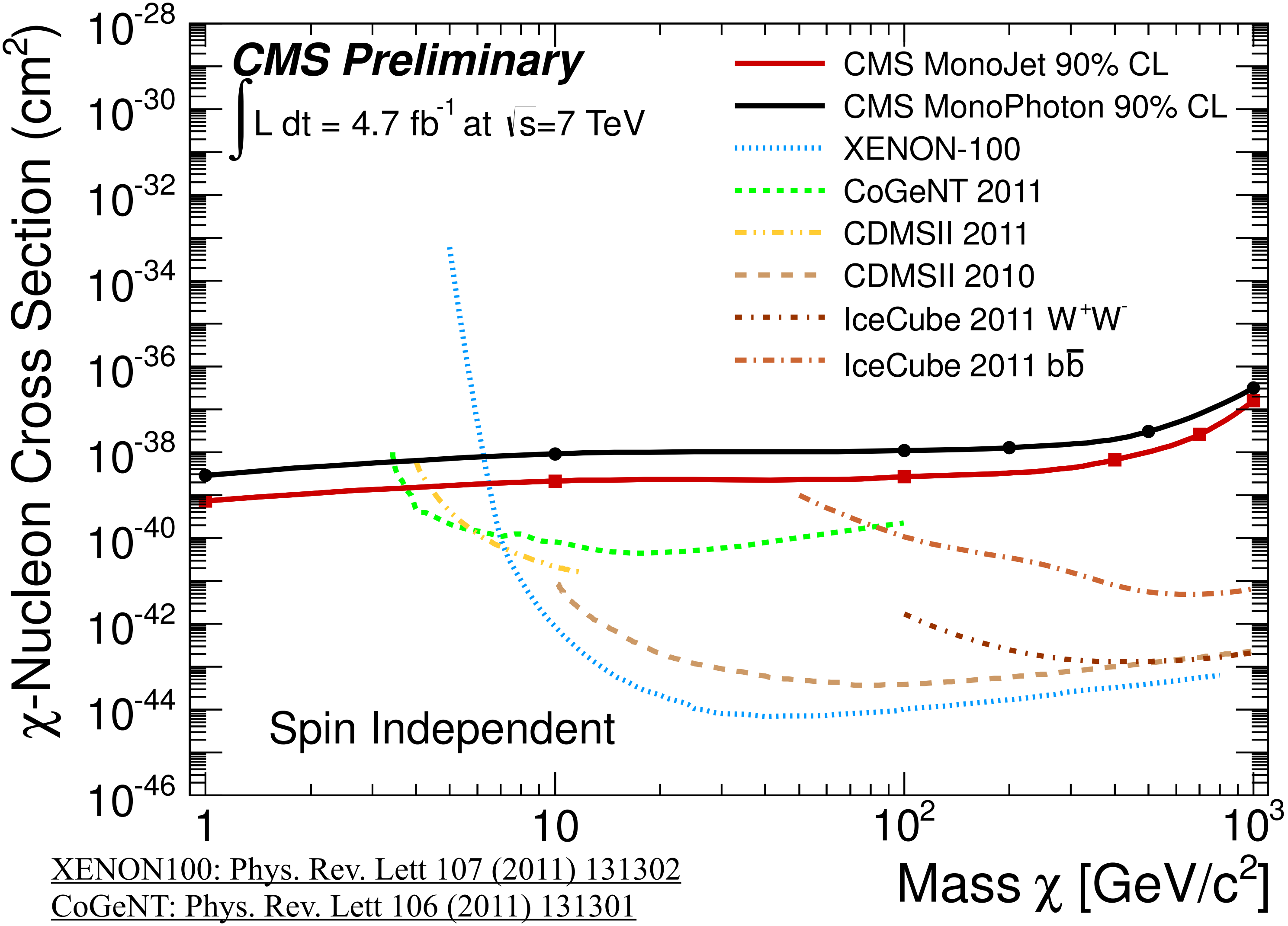
Borrowed from S. Worm
Moriond 2012

Monojet - Spin Independent Limits

- Lower limit on Λ used to compute χ-N cross-section.

$$\sigma_{SI}^{\chi\text{-N}} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

- Extends the cross-section lower limits for $M_\chi < 3.5$ GeV.



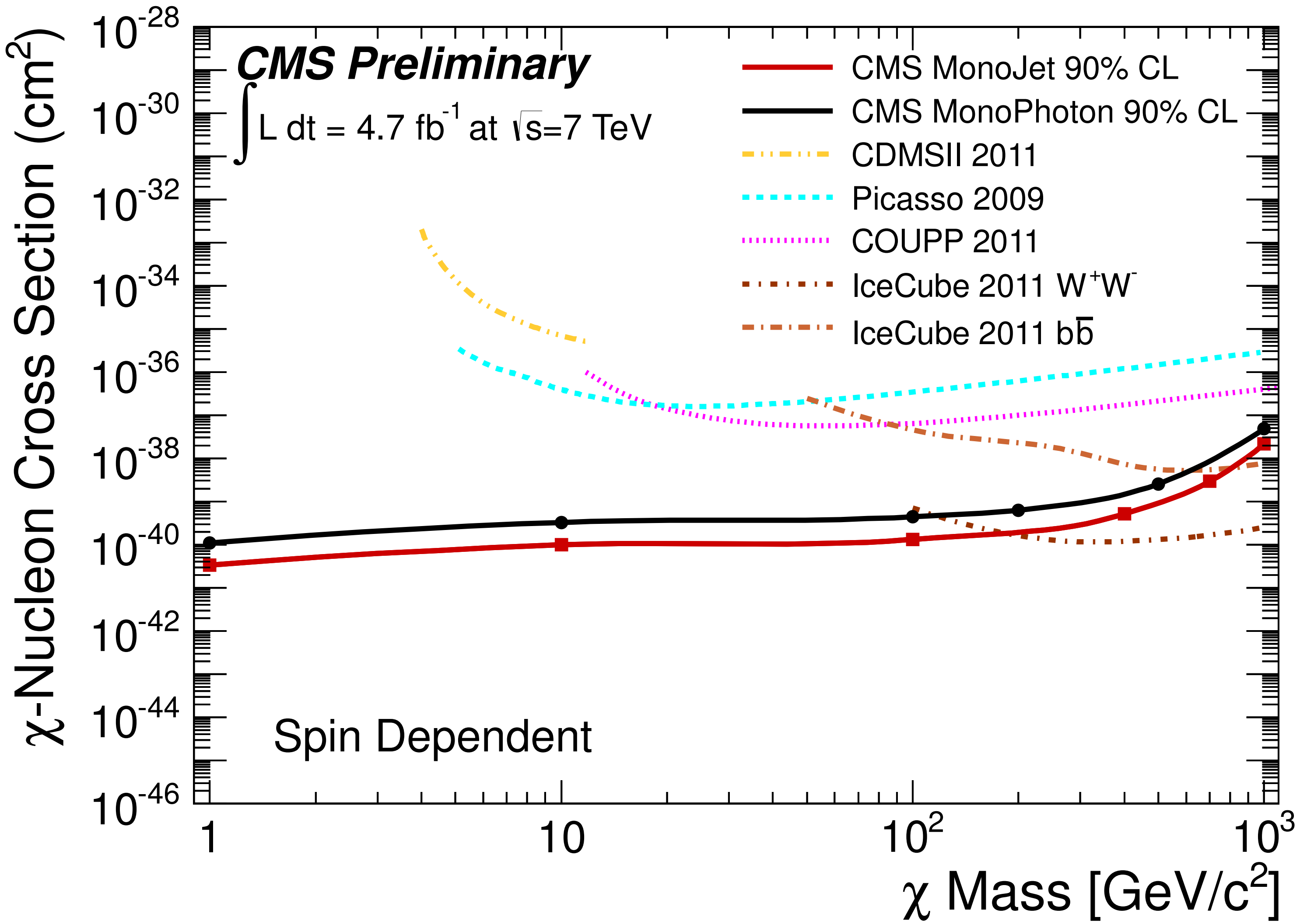
XENON100: Phys. Rev. Lett 107 (2011) 131302
CoGeNT: Phys. Rev. Lett 106 (2011) 131301
CDMS II: Science 327 (2010) 1619. Phys. Rev. Lett. 106 (2011) 131302.
IceCube:

Monojet - Spin Dependent Limits

- Lower limit on Λ used to compute χ-N cross-section.

$$\sigma_{SD}^{\chi\text{-N}} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

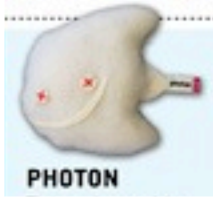
- Extends the cross-section lower limits for $M_\chi < 100$ GeV.



CDMSII: Phys. Rev. Lett. 106 (2011) 131302.
Picasso: Phys. Lett. B 682 (2009) 185.
COUPP: Phys. Rev. Lett. 106 (2011) 021303.
IceCube: Phys. Rev. D 85 (2012) 042002.

Signal MC


Z BOSON

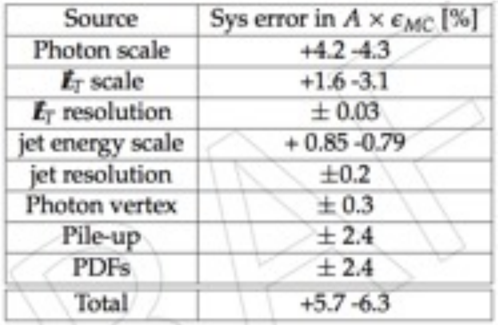

PHOTON


DARK
MATTER
The mysterious
missing mass.
Difficult to see
ecause it's so *dark*.

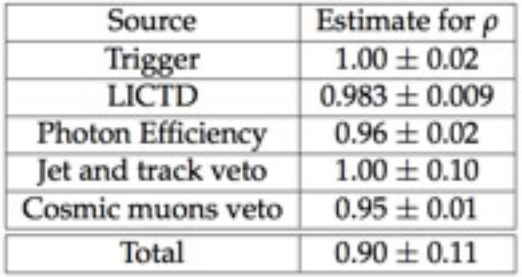

GRAVITON
Still unobserved,
yet theoretically
everywhere.

5 fb-1 analyses 2011

- Z (AN2011_108_v20)
  - The product of A × εMC in the cross section calculation is determined from the Monte Carlo simulation, based on a Pythia LO sample a with pT cutoff at 130 GeV/c. Events are re-weighted to match the pileup profile predicted for data using the procedure described in Sec. 4.4. The obtained value for A × εMC is 0.223 ± 0.001, where the error indicates the statistical uncertainty on the estimation due to the size of the MC sample

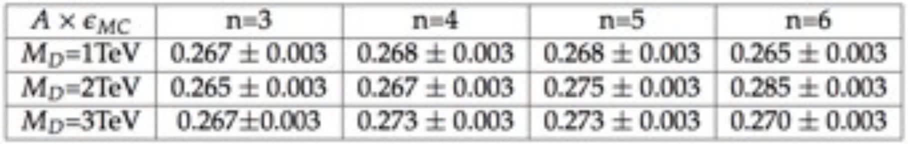


Source	Sys error in $A \times \epsilon_{MC}$ [%]
Photon scale	+4.2 -4.3
$\not{E}_T$ scale	+1.6 -3.1
$\not{E}_T$ resolution	± 0.03
jet energy scale	+ 0.85 -0.79
jet resolution	±0.2
Photon vertex	± 0.3
Pile-up	± 2.4
PDFs	± 2.4
Total	+5.7 -6.3

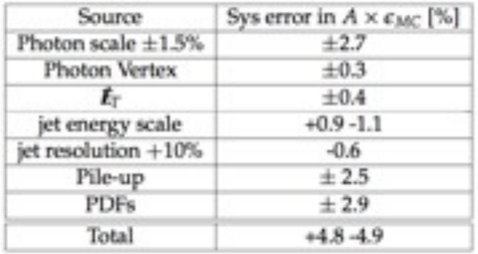


Source	Estimate for ρ
Trigger	1.00 ± 0.02
LICTD	0.983 ± 0.009
Photon Efficiency	0.96 ± 0.02
Jet and track veto	1.00 ± 0.10
Cosmic muons veto	0.95 ± 0.01
Total	0.90 ± 0.11

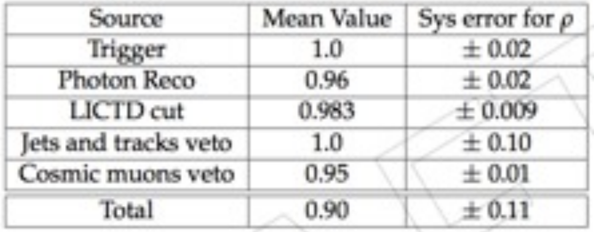
- ADD graviton (AN2011_319_v15)



$A \times \epsilon_{MC}$	n=3	n=4	n=5	n=6
M_D=1TeV	0.267 ± 0.003	0.268 ± 0.003	0.268 ± 0.003	0.265 ± 0.003
M_D=2TeV	0.265 ± 0.003	0.267 ± 0.003	0.275 ± 0.003	0.285 ± 0.003
M_D=3TeV	0.267±0.003	0.273 ± 0.003	0.273 ± 0.003	0.270 ± 0.003

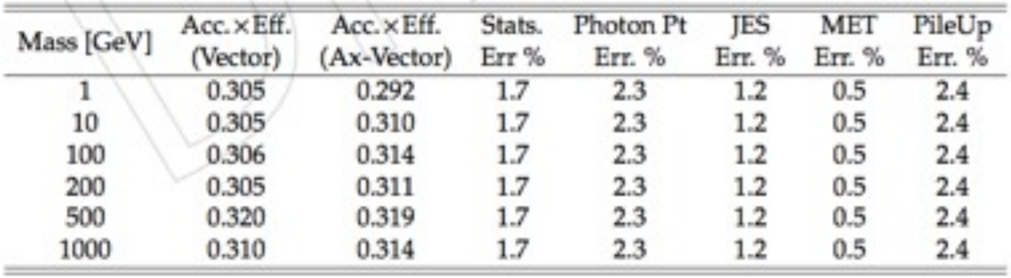


Source	Sys error in $A \times \epsilon_{MC}$ [%]
Photon scale ±1.5%	±2.7
Photon Vertex	±0.3
$\not{E}_T$	±0.4
jet energy scale	+0.9 -1.1
jet resolution +10%	-0.6
Pile-up	± 2.5
PDFs	± 2.9
Total	+4.8 -4.9



Source	Mean Value	Sys error for ρ
Trigger	1.0	± 0.02
Photon Reco	0.96	± 0.02
LICTD cut	0.983	± 0.009
Jets and tracks veto	1.0	± 0.10
Cosmic muons veto	0.95	± 0.01
Total	0.90	± 0.11

- Dark Matter (AN2012 053 v4)



Mass [GeV]	Acc.×Eff. (Vector)	Acc.×Eff. (Ax-Vector)	Stats. Err %	Photon Pt Err. %	JES Err. %	MET Err. %	PileUp Err. %
1	0.305	0.292	1.7	2.3	1.2	0.5	2.4
10	0.305	0.310	1.7	2.3	1.2	0.5	2.4
100	0.306	0.314	1.7	2.3	1.2	0.5	2.4
200	0.305	0.311	1.7	2.3	1.2	0.5	2.4
500	0.320	0.319	1.7	2.3	1.2	0.5	2.4
1000	0.310	0.314	1.7	2.3	1.2	0.5	2.4

- ρ is same as 108

- ADD & Dark Matter from EXO-11-096-v16
- Axe uncertainty: PDF, photon vertex, PU, energy calib.&res.: pho, jet, met: +4.8% -4.9%
- ρ is same as 108

DM Phenomenology 1

- Bai, Fox, and Harnik [JHEP 1012:048(2010)] have cast this process as a contact interaction with the effective operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Vector Operator ⇒ Spin Independent

$$O_A = \frac{(\bar{\chi}\gamma_\mu\gamma^5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Axial-Vector Operator ⇒ Spin Dependent

- The observed upper limit on the $\chi\bar{\chi}$ production cross section, $\sigma^{\chi\bar{\chi}}_{meas.}$, is transformed into a lower limit on the cut-off scale Λ (=$M_{moderator}/\sqrt{g_\chi g_q}$) taking advantage of the fact that $\sigma \propto \Lambda^{-4}$.
  - $\Lambda_{th.} \equiv 10$ TeV
  - $\sigma^{\chi\bar{\chi}}_{th.}$ is computed using Madgraph-4 and Pythia-6, for a given phase space

$$\Lambda = \Lambda_{th.} \left(\frac{\sigma^{\chi\bar{\chi}}_{th.}}{\sigma^{\chi\bar{\chi}}_{meas.}} \right)^{1/4}$$

DM Phenomenology 2

- With this lower limit on Λ, the upper limits on χ-N cross-sections for the spin-independent and spin-dependent interactions can be computed for various dark matter masses, m_{DM}.

$$\sigma_{SI}^{\chi\text{-N}} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

Spin-Independent

$$\sigma_{SD}^{\chi\text{-N}} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

Spin-Dependent

$$\mu = \left(\frac{m_{DM}\; m_p}{m_{DM} + m_p}\right)$$

Monophoton - Acceptance, Efficiency, and Uncertainties

- A x ε_{MC} is stable over the range m_{χ}=1-1000 GeV because the signal is an ISR γ
  - Vector χ (spin independent): 30.5%-31.0%
  - Axial-Vector χ (spin dependent): 29.2%-31.4%
- Uncertainties in A x ε_{MC} total to +4.8% -4.9% from:
  - photon energy scale
  - missing transverse energy scale and resolution
  - jet energy scale and resolution
  - photon vertex assignment
  - overlapping events (pile up)
  - parton distribution function
- The scale factor between this MC A x ε and data is estimated

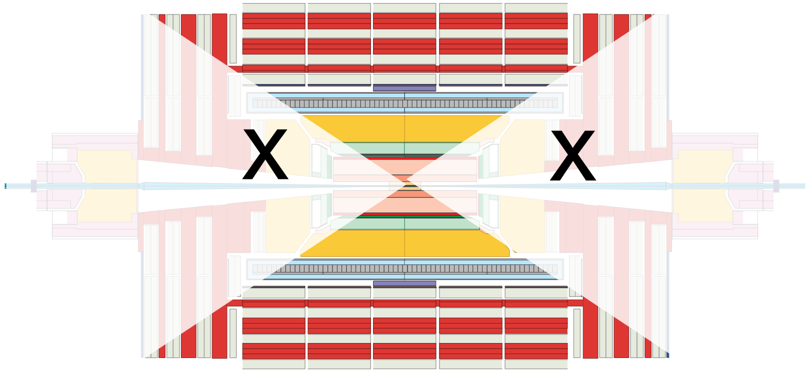
Source	**Estimate for SF**
Trigger	1.00 ± 0.02
Consistent Cluster Timing	0.98 ± 0.01
Photon ID Efficiency	0.96 ± 0.02
Jet and Track Veto	1.00 ± 0.10
Cosmic Muon Veto	0.95 ± 0.01
Total	**0.90 ± 0.11**

$A \times \varepsilon_{MC}$

- A is for acceptance. How many MC signal events fall within the detector for given kinematic cuts.

A×ε_{MC}

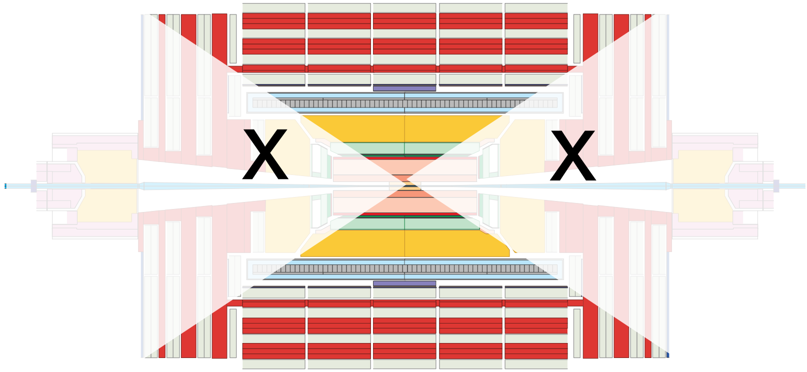
- A is for acceptance. How many MC signal events fall within the detector for given kinematic cuts.



p_T^{γ} >145 GeV
MET>130 GeV

A×ε_{MC}

- A is for acceptance. How many MC signal events fall within the detector for given kinematic cuts.



p_T^γ >145 GeV
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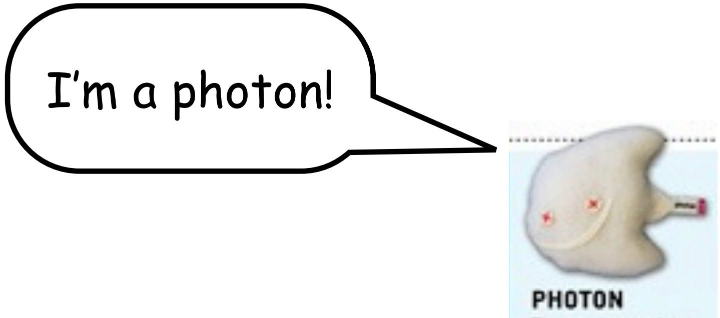

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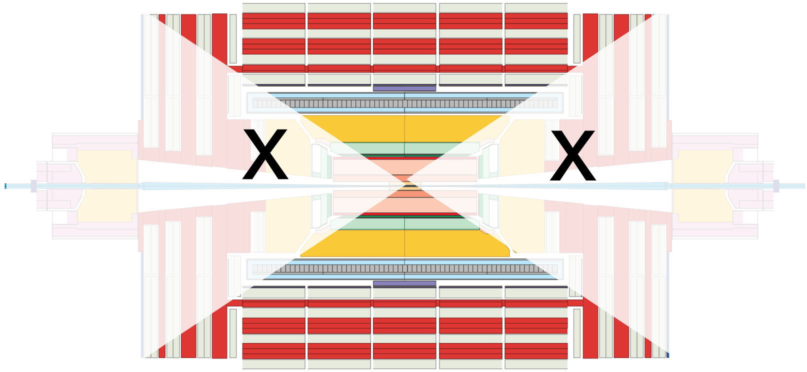

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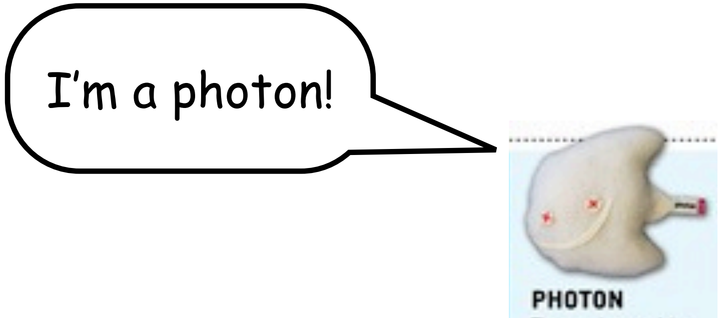
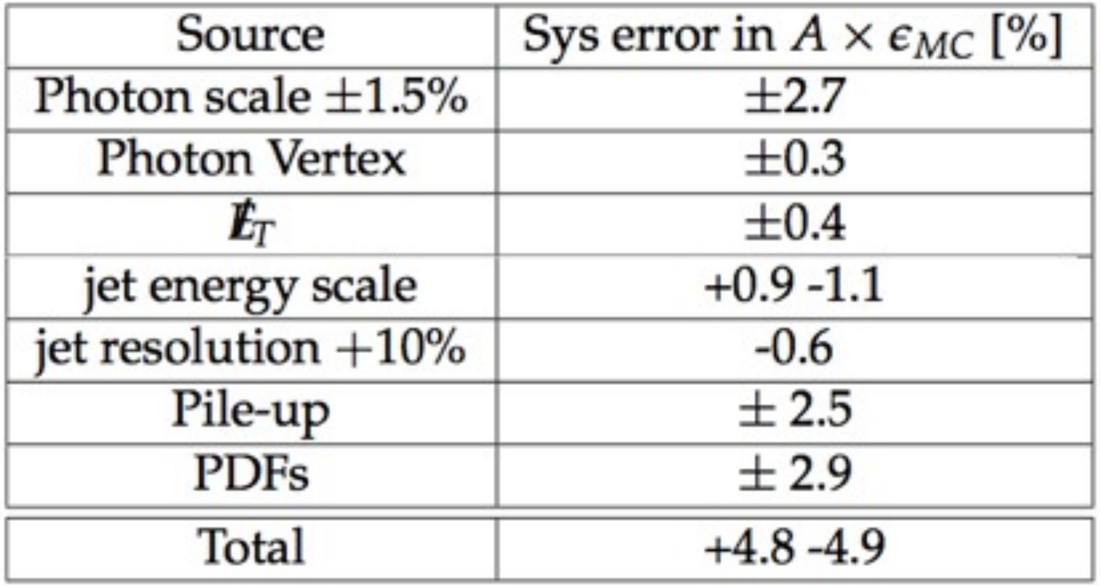


- By knowing how many MC events we miss detecting, we can correct our theoretical cross section to compare to measurement.

Systematic Uncertainties for A×ε_{MC}

- There are large working groups within the collaboration to determine these numbers.

ADD Extra Dimensions



Source	Sys error in $A \times \epsilon_{MC}$ [%]
Photon scale ±1.5%	±2.7
Photon Vertex	±0.3
$\not\!\!E_T$	±0.4
jet energy scale	+0.9 -1.1
jet resolution +10%	-0.6
Pile-up	± 2.5
PDFs	± 2.9
Total	+4.8 -4.9

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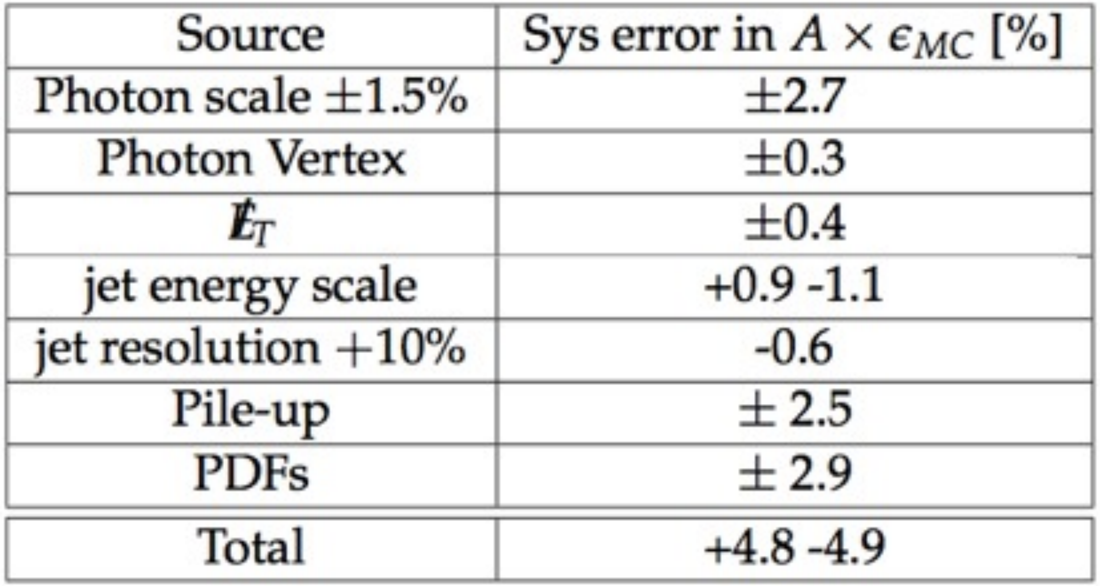

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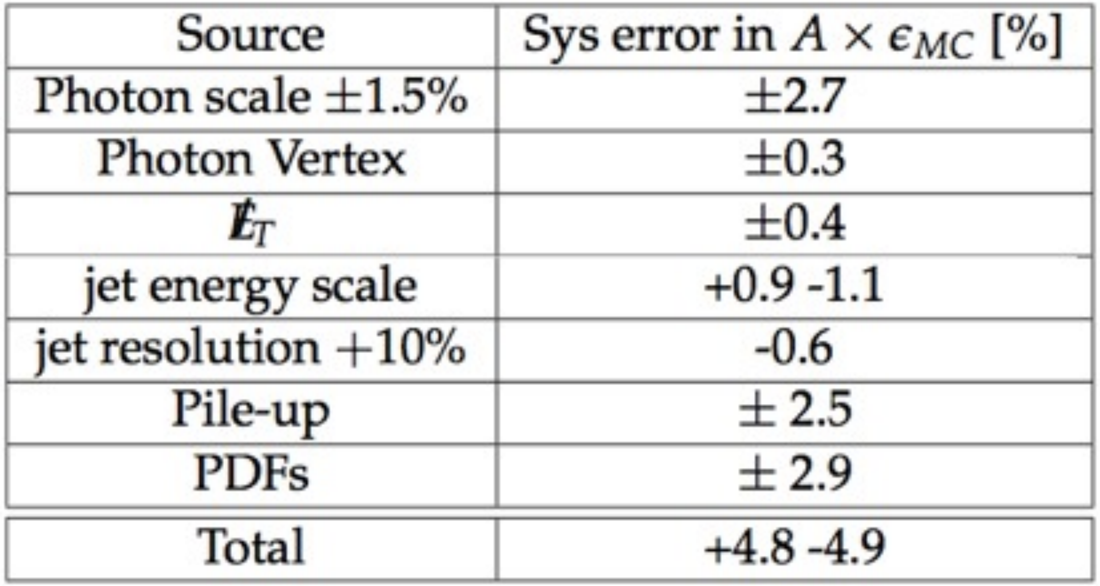

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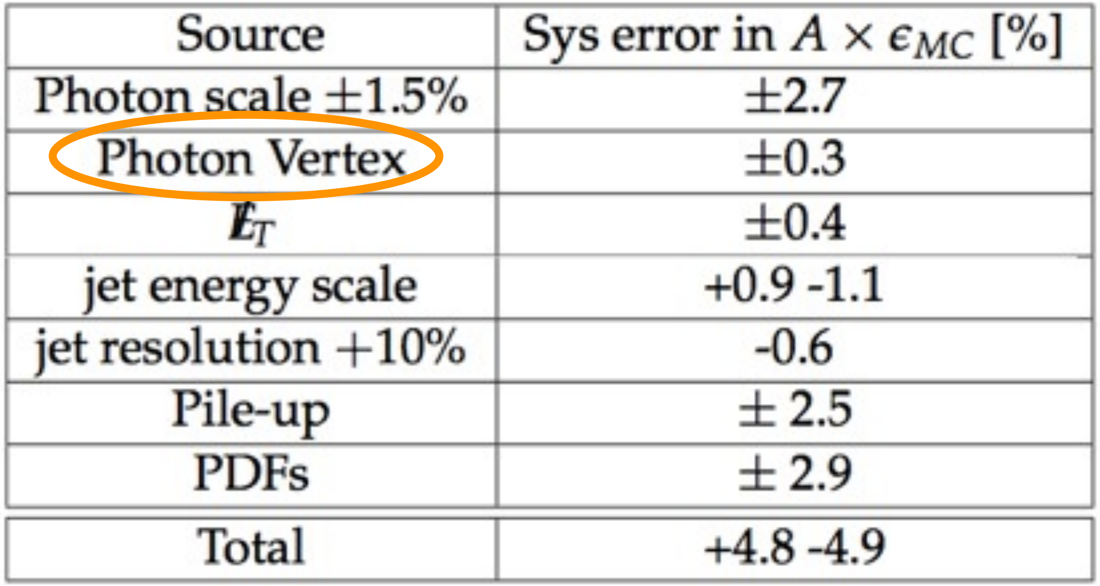

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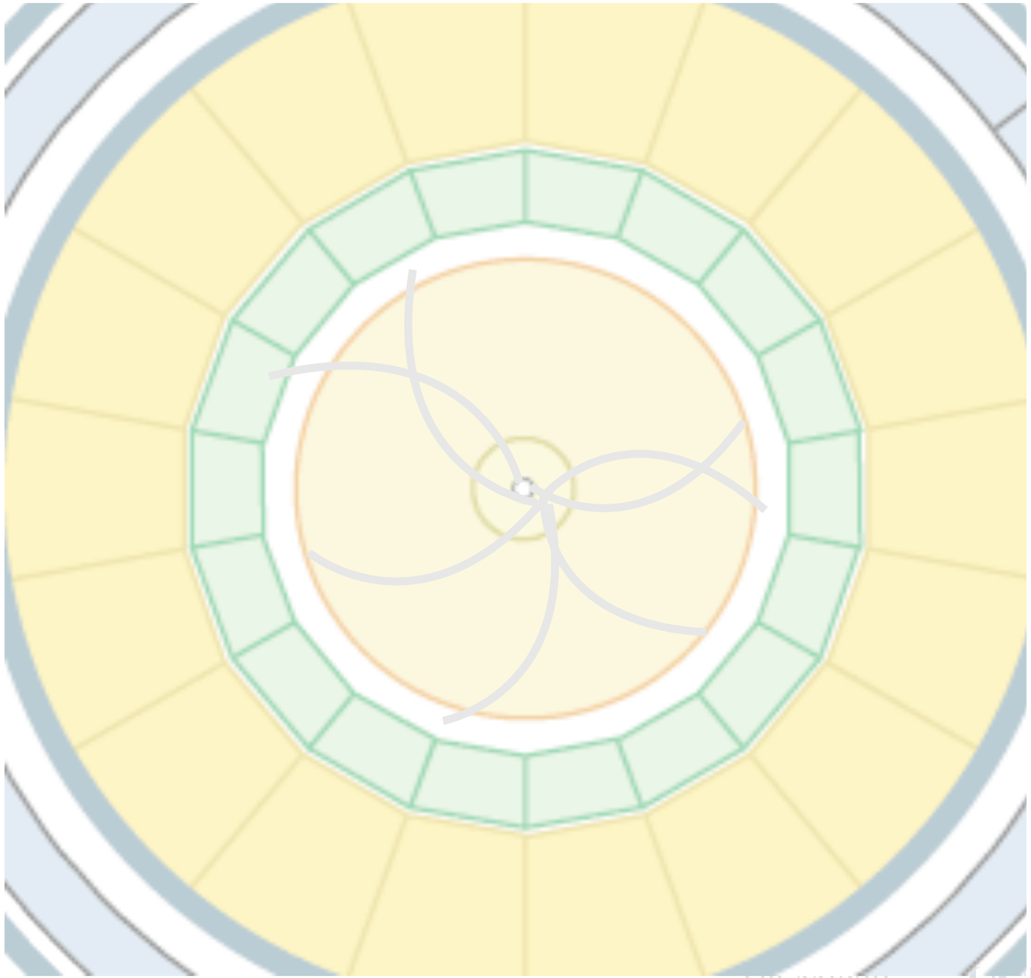
- We especially had to consider uncertainty in photon vertex assignment because there is an ambiguity in deciding the vertex from which the photon originated, since the photon is neutral and doesn't leave tracking information.

Systematic Uncertainty for A×ε_{MC}: Vertex Assignment

Systematic Uncertainty for $A\times\varepsilon_{MC}$: Vertex Assignment



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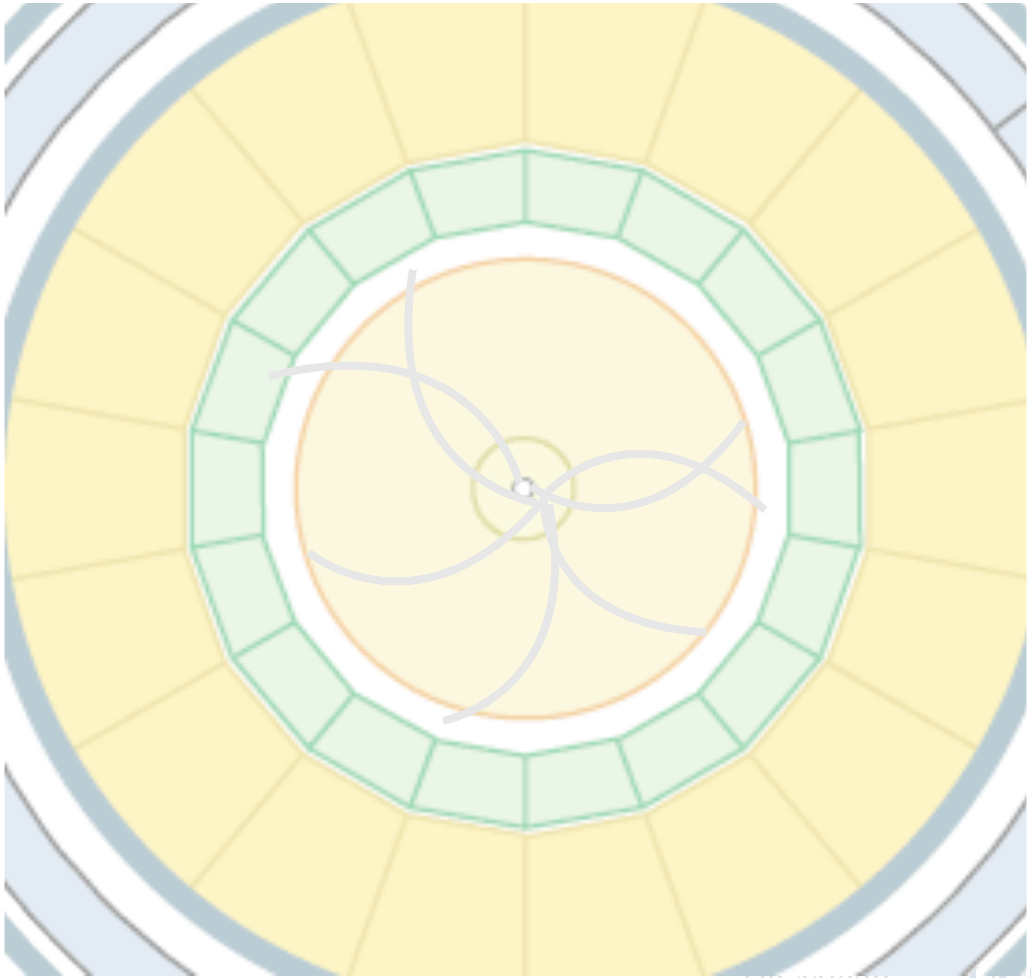

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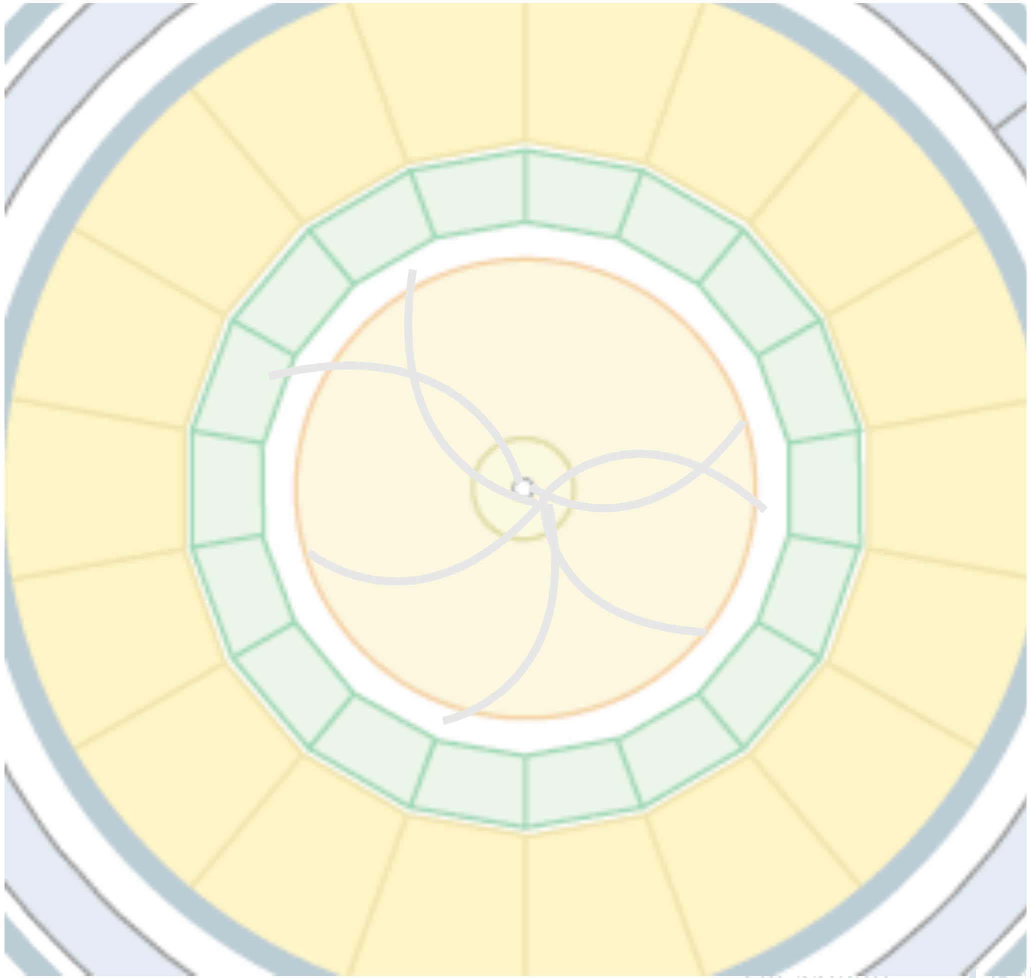

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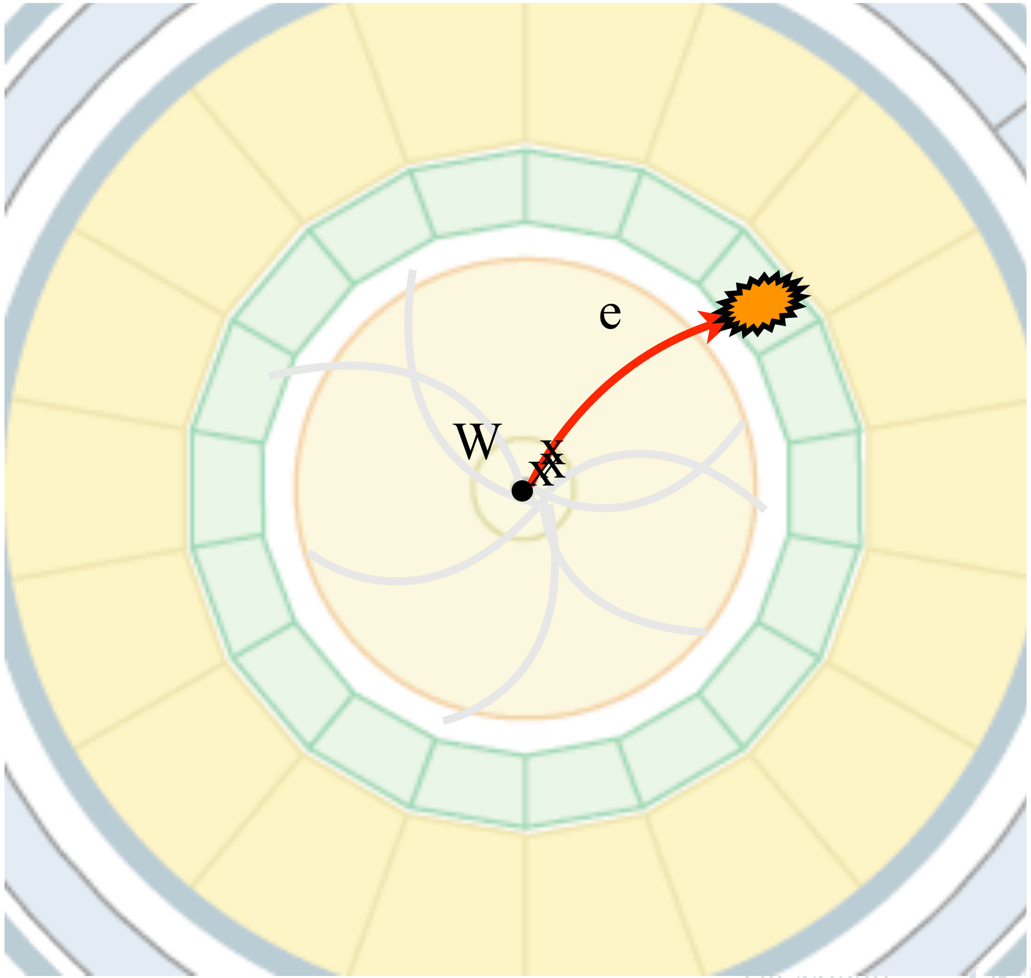

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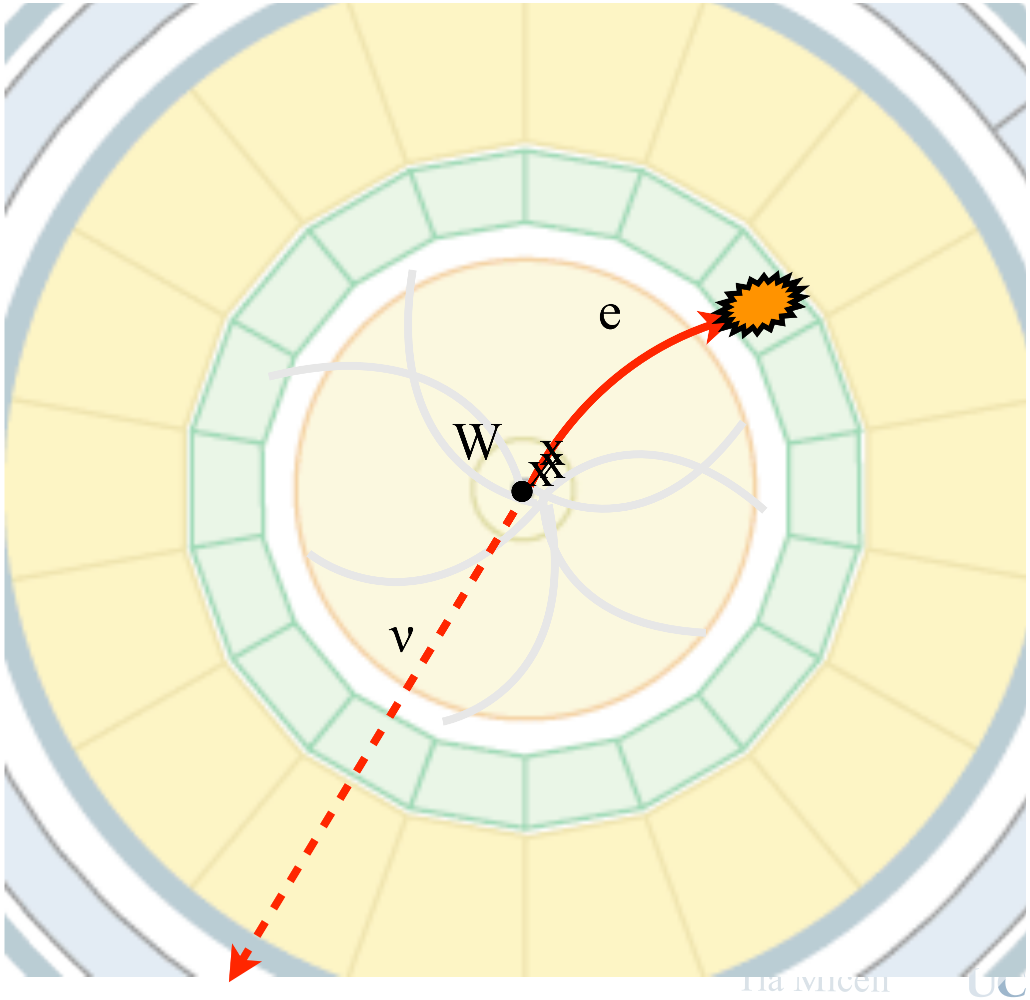

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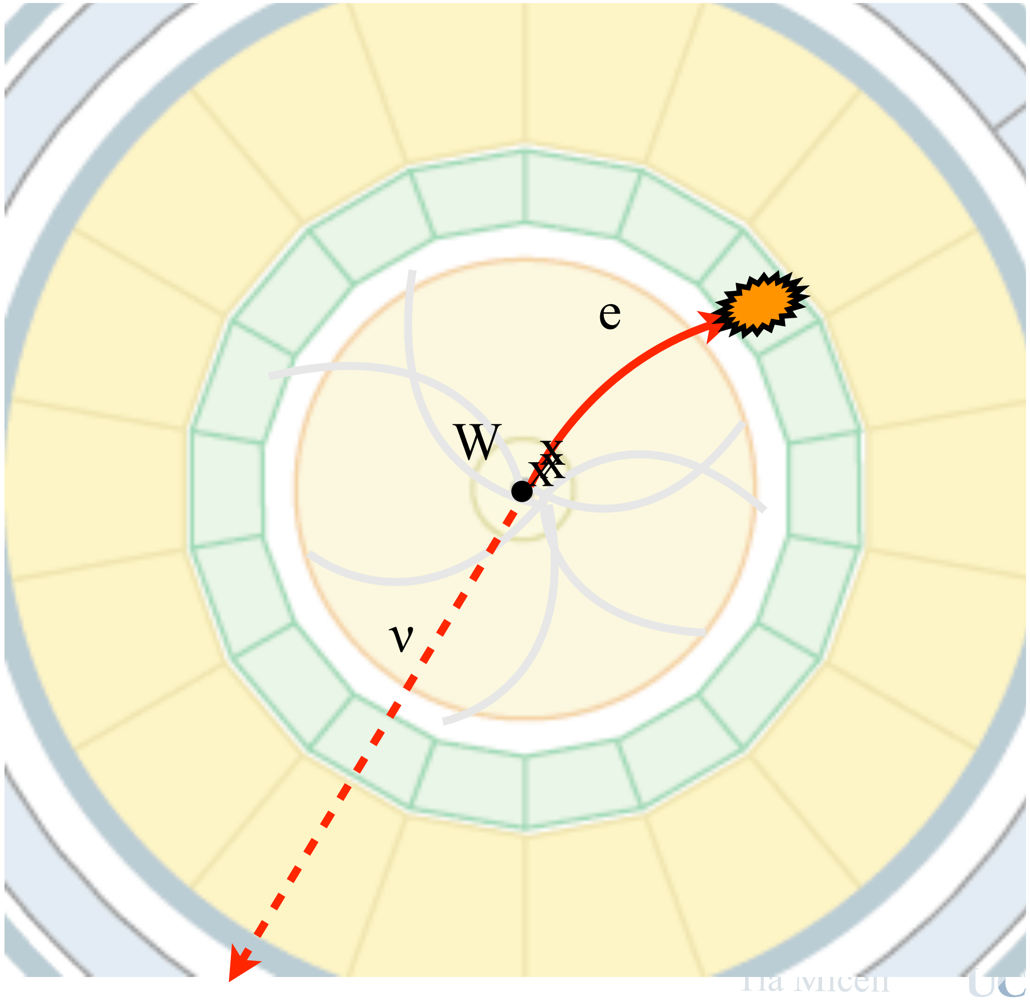

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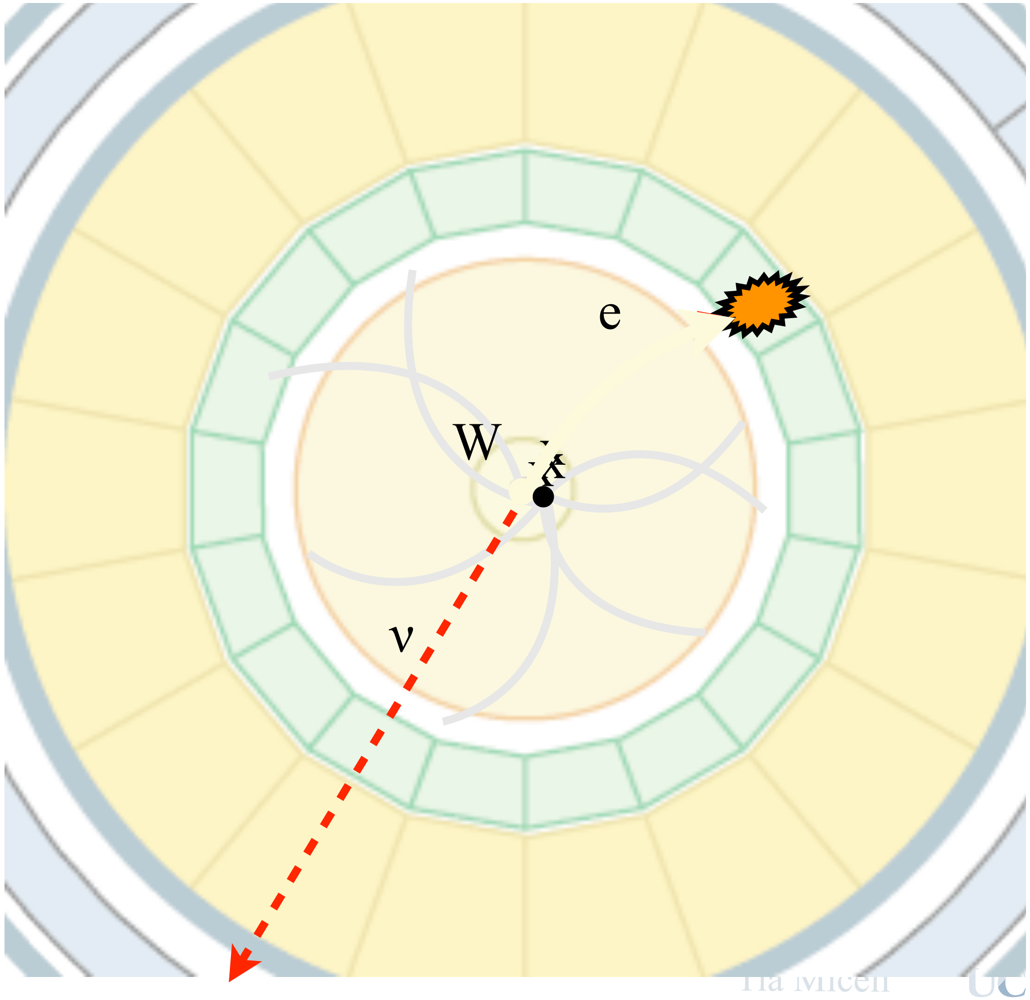

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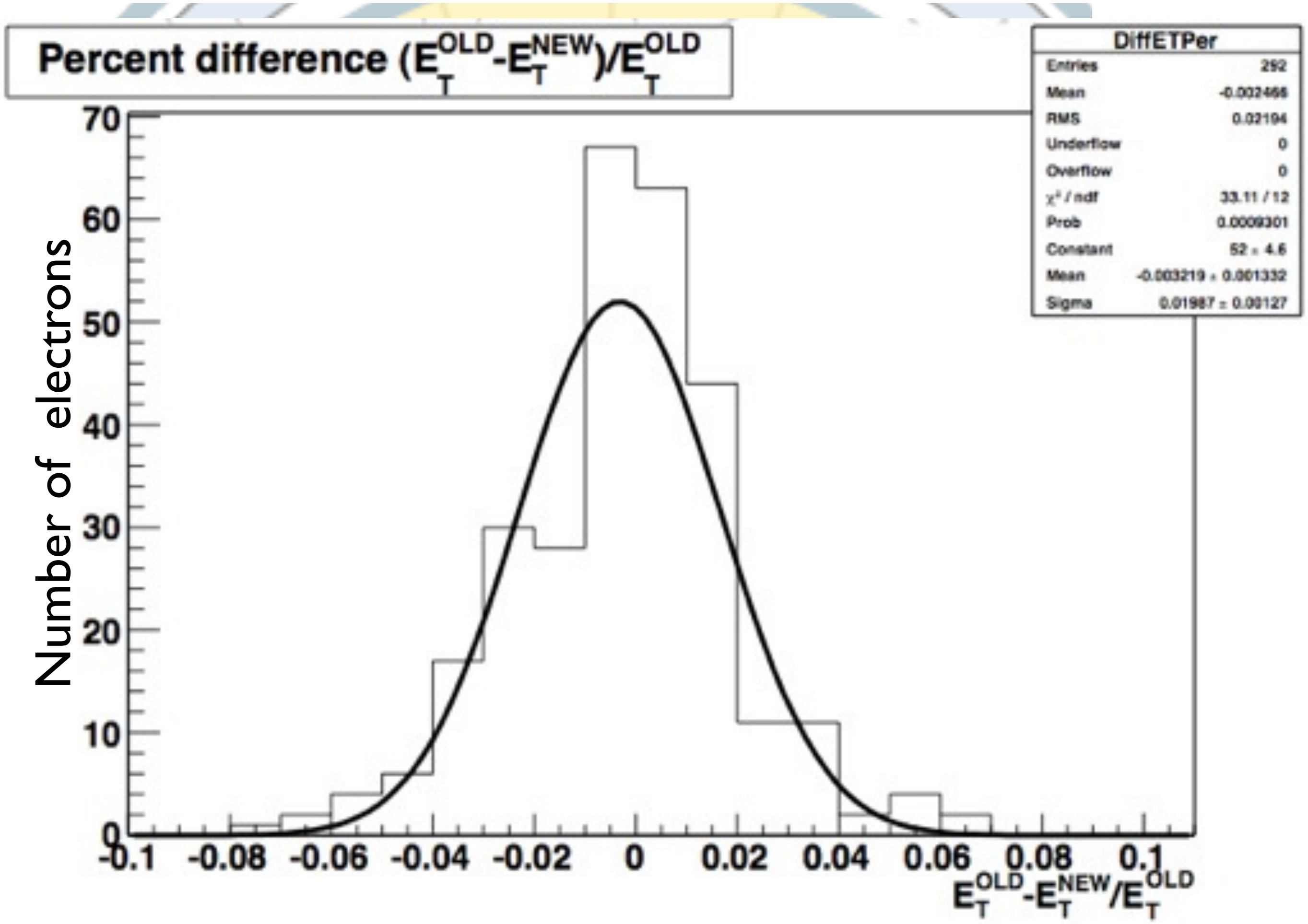
- Recompute E_T^γ for this new vertex and compare with the original E_T^γ. Assign an uncertainty of 2%.



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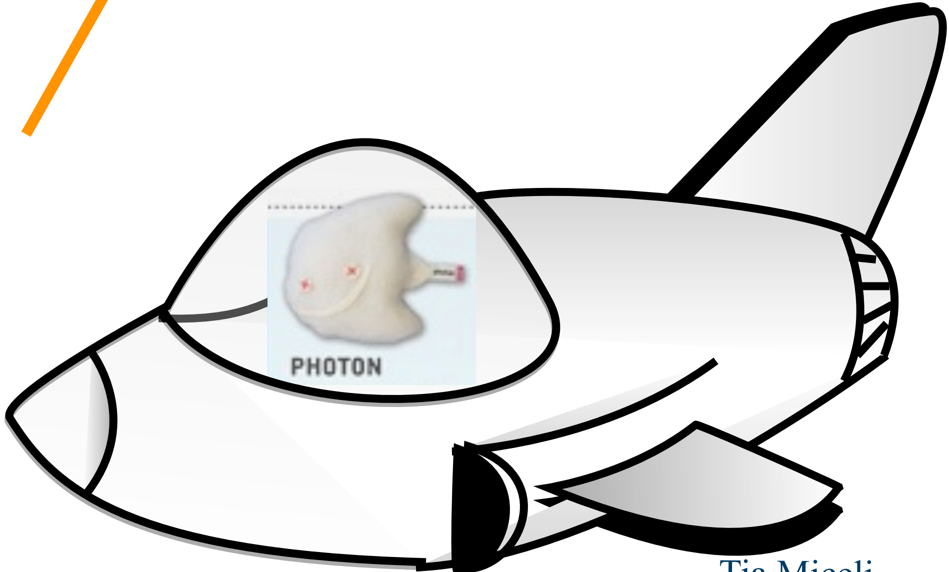
But there are real photons in these jets!



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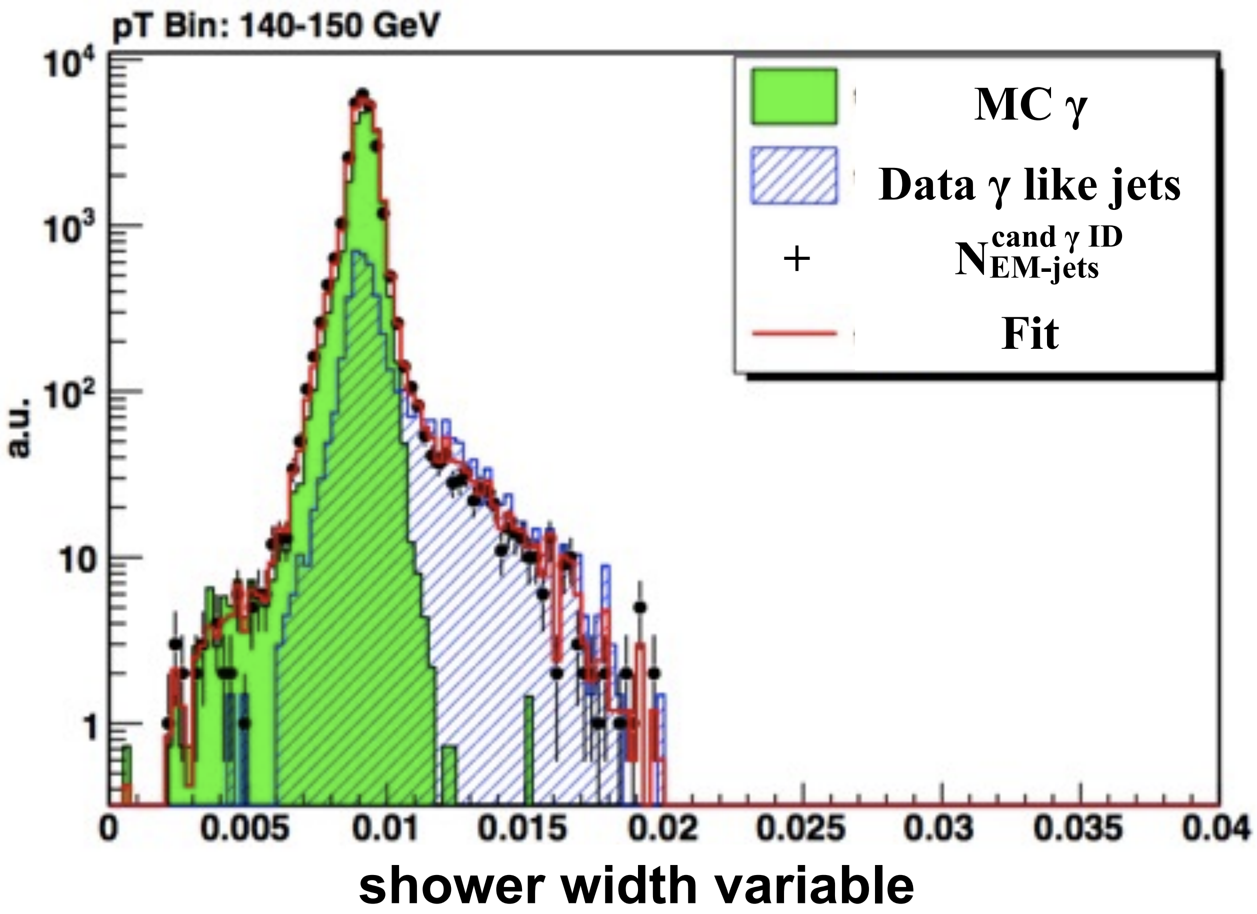

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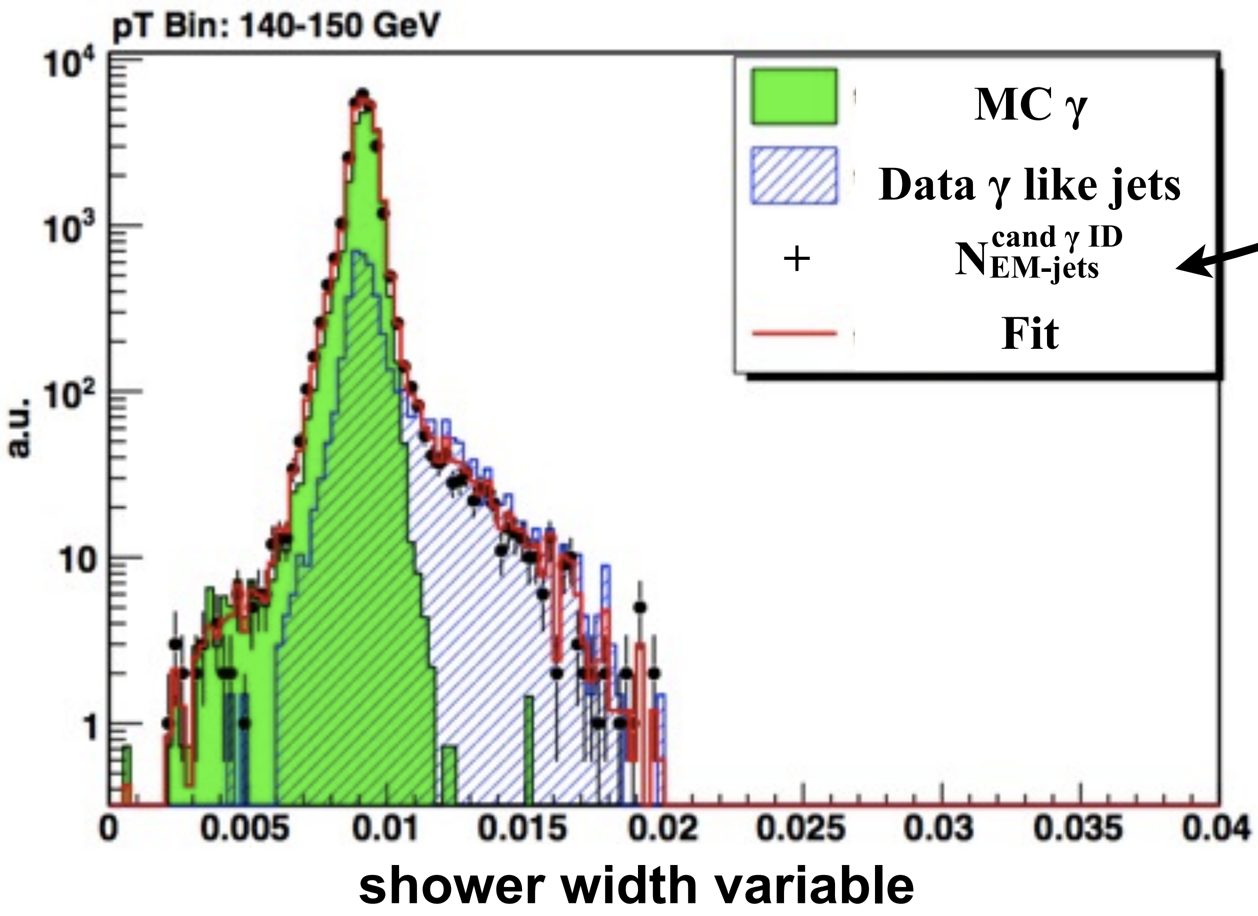

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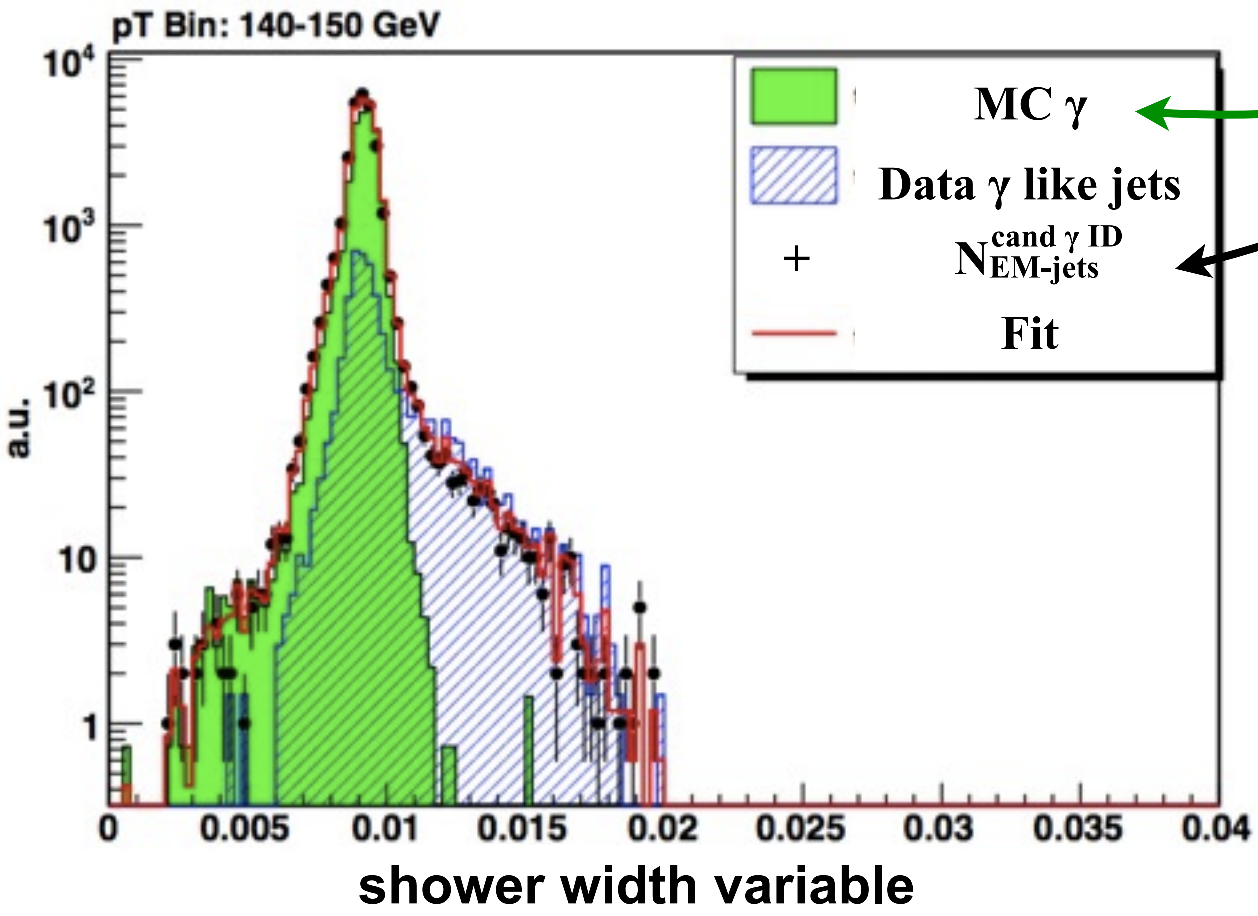

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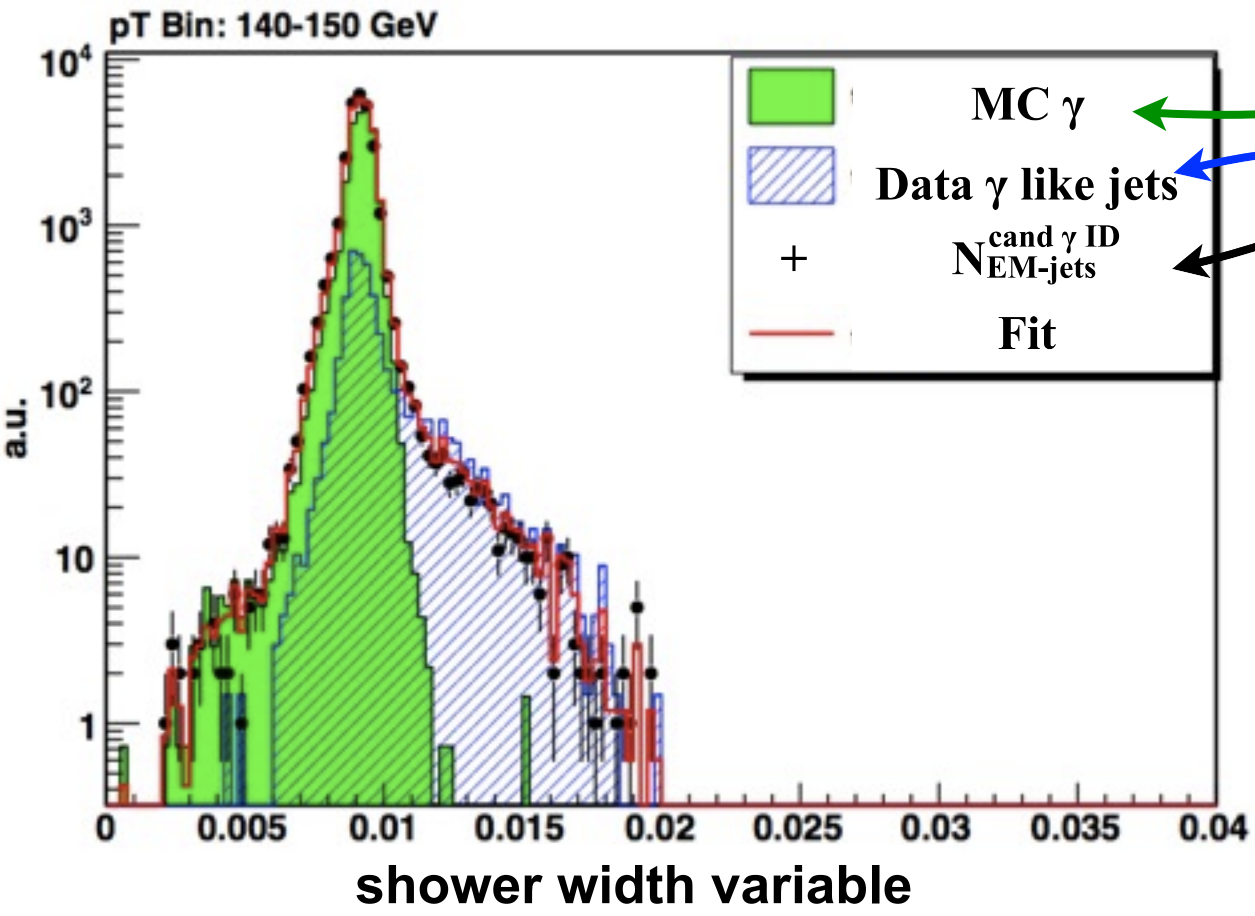

Similar to denominator, but from an orthogonal sample created by requiring some tracks in the isolation annulus

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$$N_{\text{jet fakes } \gamma} = 11.2 \pm 2.8$$