Search For Diphoton Resonances Using the CMS Detector

August 12, 2010

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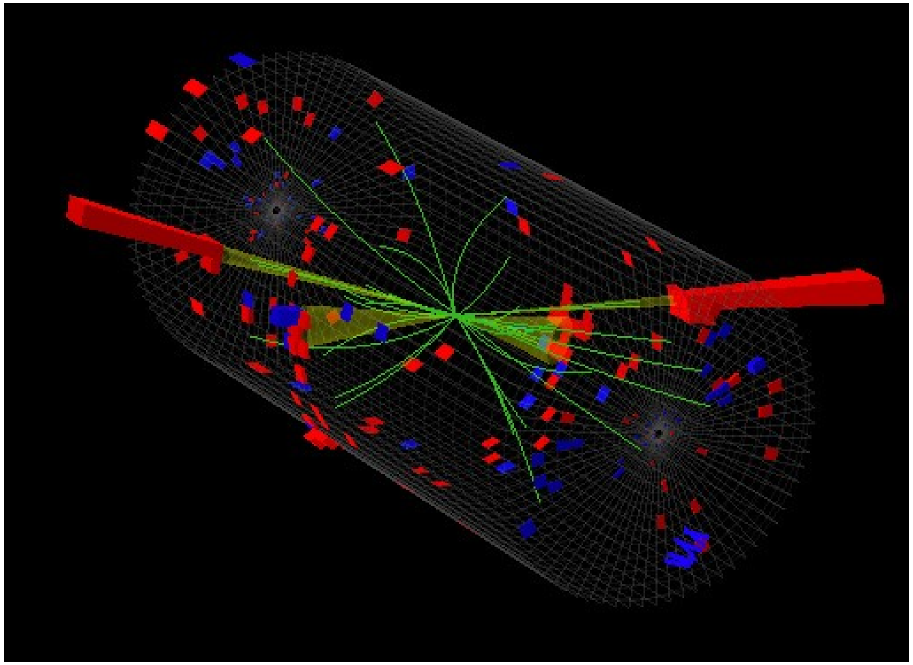
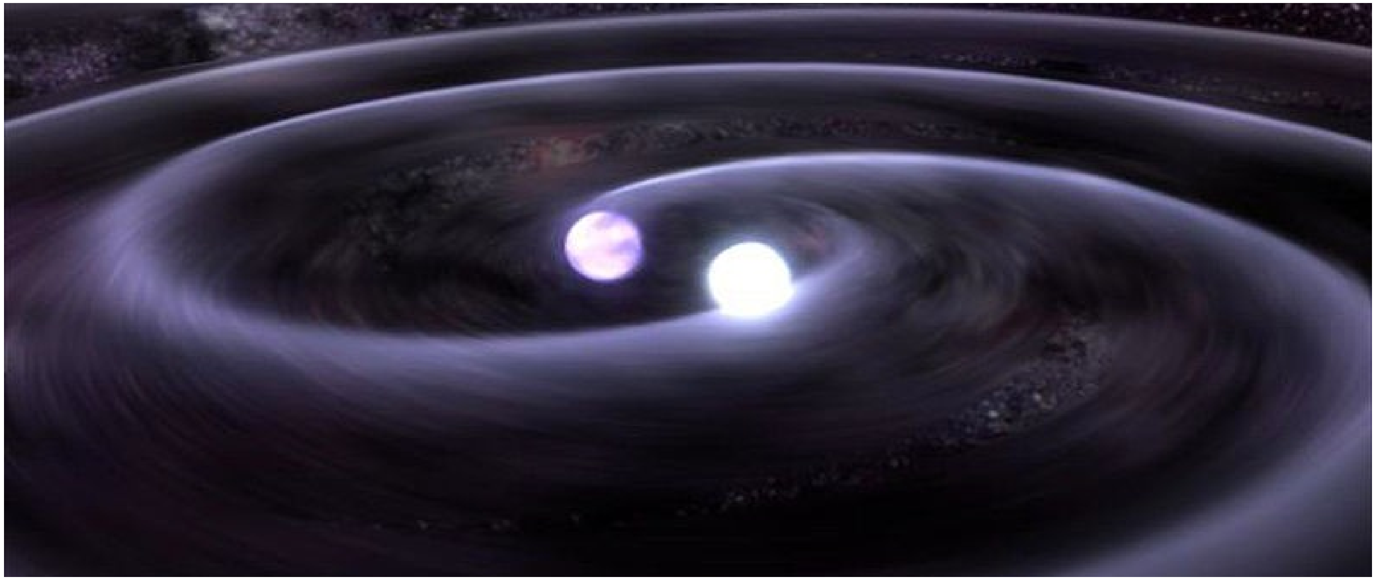
Introduction



- After protons collide at the LHC, their constituent quarks can interact and produce new particles
- These new particles are often unstable
  - They can decay and produce even more particles, like photons (the particles of light)

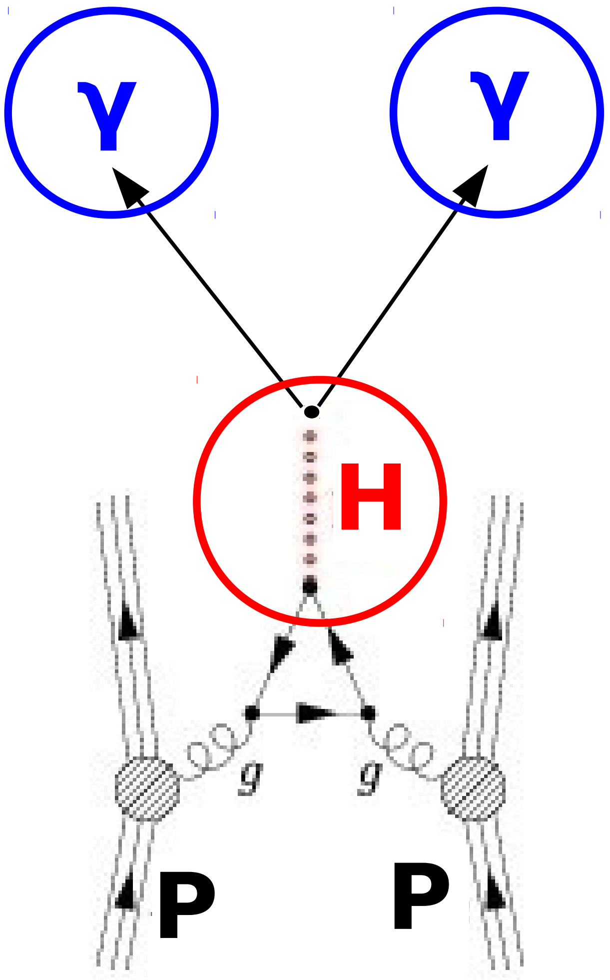
Diphotons



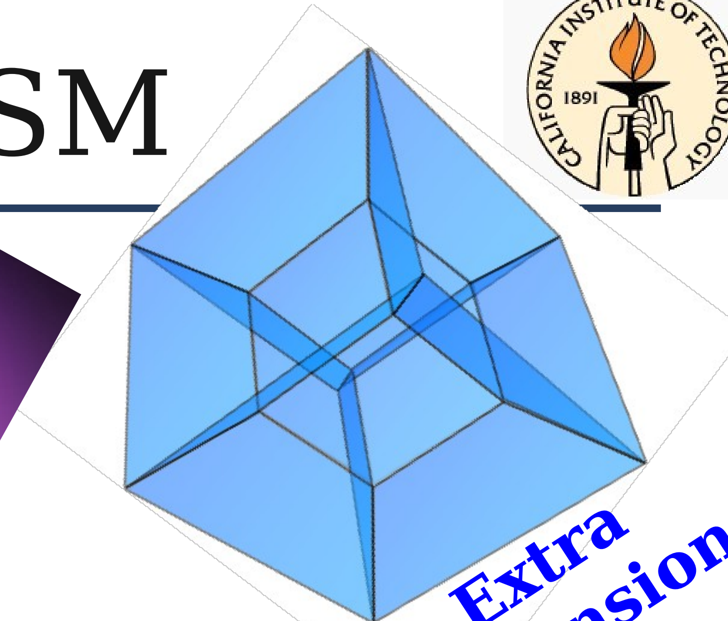
- We are searching for events where these interactions produce pairs of very energetic **photons**
- The **Standard Model** predicts many processes that can produce photon pairs
  - By 'rediscovering' these processes, we can confirm the physics we think we already understand

The Higgs

- The **Higgs boson** is the only particle predicted by the SM that has not been discovered yet
  - We believe it is responsible for giving mass to the other elementary particles
- And the Higgs should decay to two photons, $H \to \gamma\gamma$
  - So if we observe a **diphoton resonance** near the probable Higgs mass, it would give strong evidence for the Higgs!



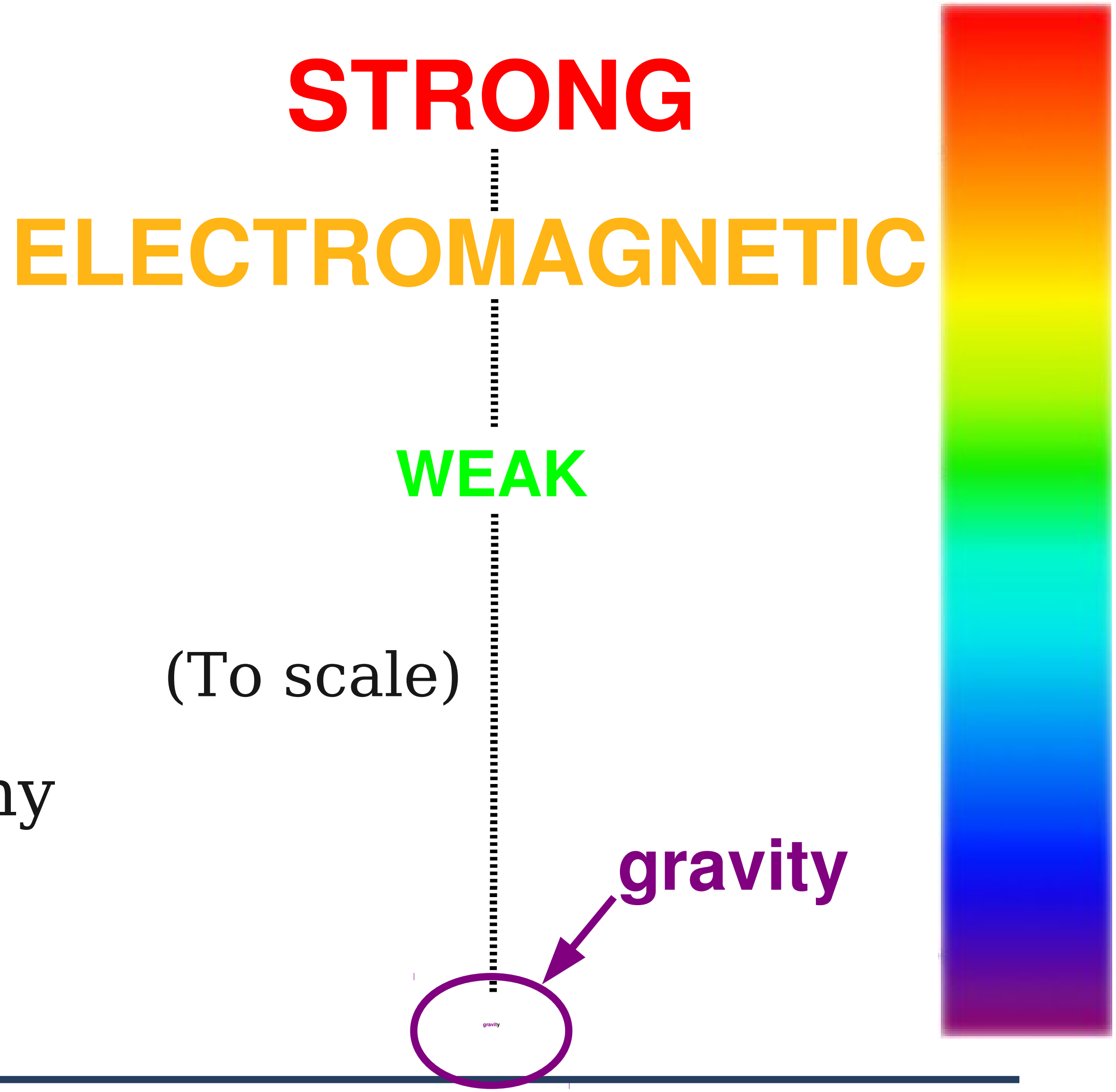
Beyond the SM



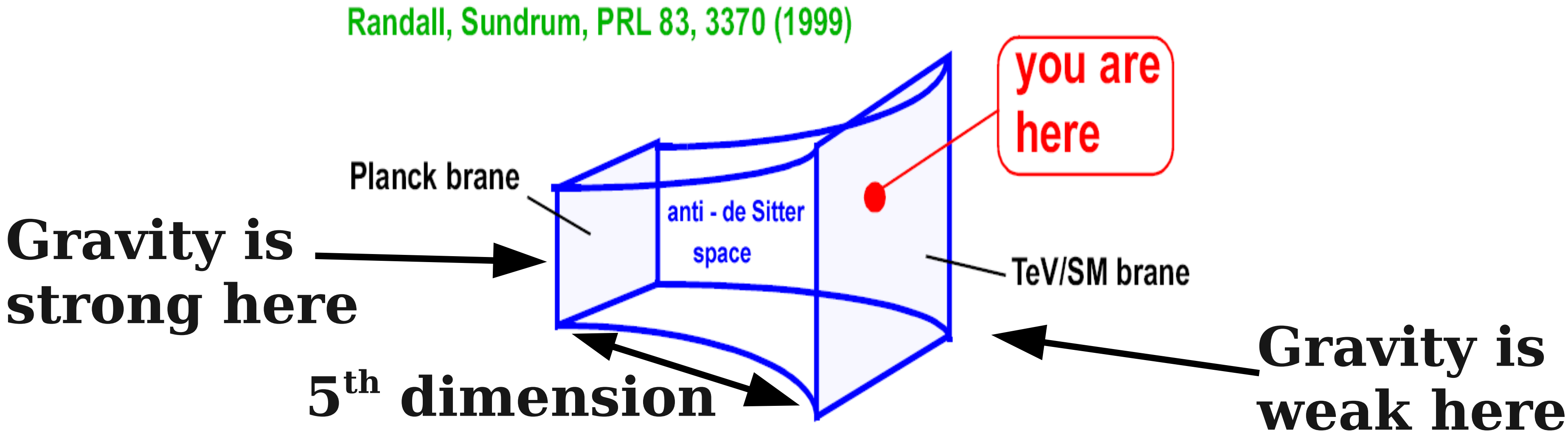
- Despite its great success, the Standard Model is an **incomplete** theory
  - It leaves many questions unanswered
- Theorists have suggested wild ideas to explain what the SM cannot
  - String theory, gravitons, extra dimensions, vanishing dimensions...

The Hierarchy Problem

- For example, the SM does not explain the **hierarchy problem**
- Of the four **fundamental forces**, gravity is weaker by over **25 orders** of magnitude
- And we do not know why



Randall-Sundrum Model

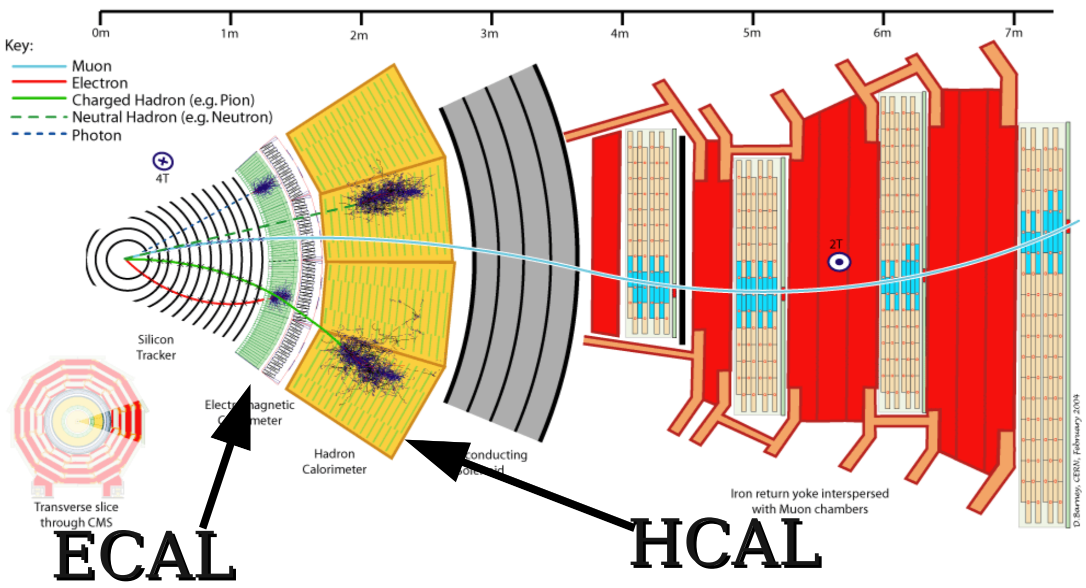


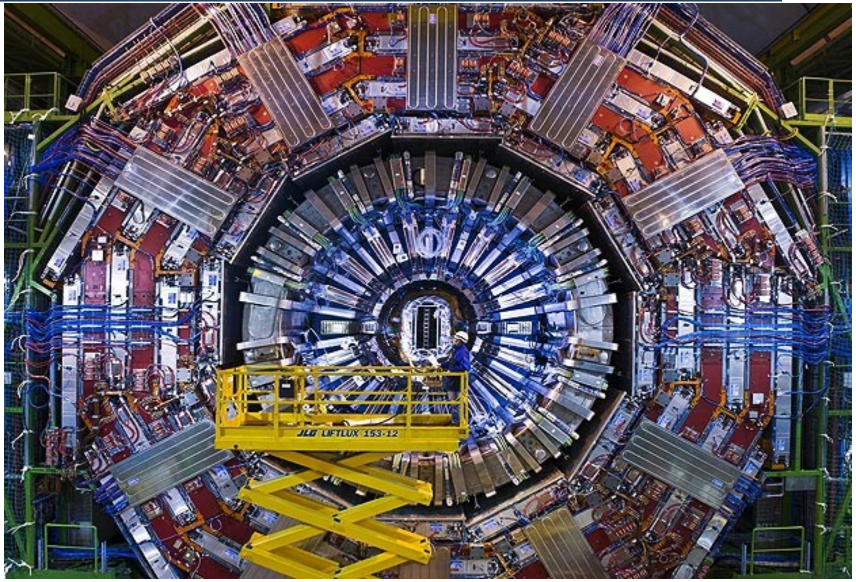
- L. Randall and R. Sundrum suggest a solution
- They imagine a **warped extra dimension** of space
  - Only **gravitons** can move in the new dimension
  - But it becomes exponentially harder for gravitons to propagate as they approach our **brane**
- Gravity is 'diluted' in the bulk and appears weaker

Gravitons

- The hypothesized **Randall-Sundrum graviton** would decay to two photons, $G \rightarrow \gamma\gamma$
- The graviton mass would be near 1 TeV
  - So if we observed a resonance in the diphoton **invariant mass** spectrum near 1 TeV, it would offer evidence for the graviton and an extra dimension!
- Aside from gravitons, we are looking for anything unexpected
- The SM does not predict a diphoton resonance above the Higgs mass
  - So if we observed a resonance above ~175 GeV, it would likley point to **new physics**

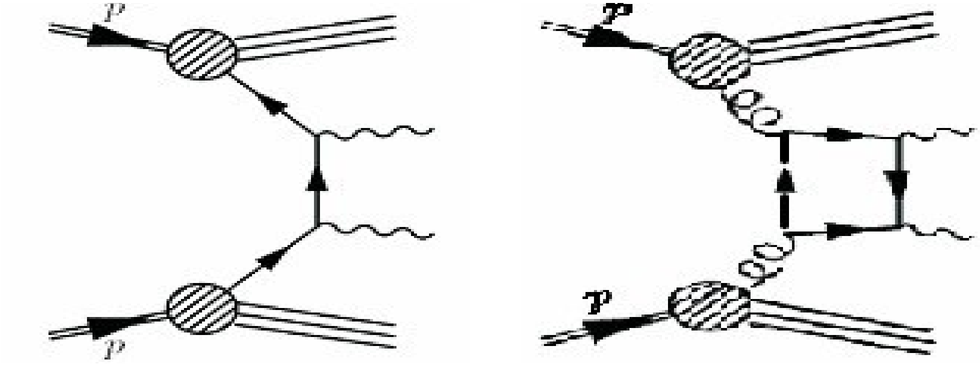
The Detector





- How do we actually detect these photons?
- Our detector is called the **Compact Muon Solenoid** (CMS)
- The Electromagnetic CALorimeter (ECAL) detects photons and electrons

Backgrounds

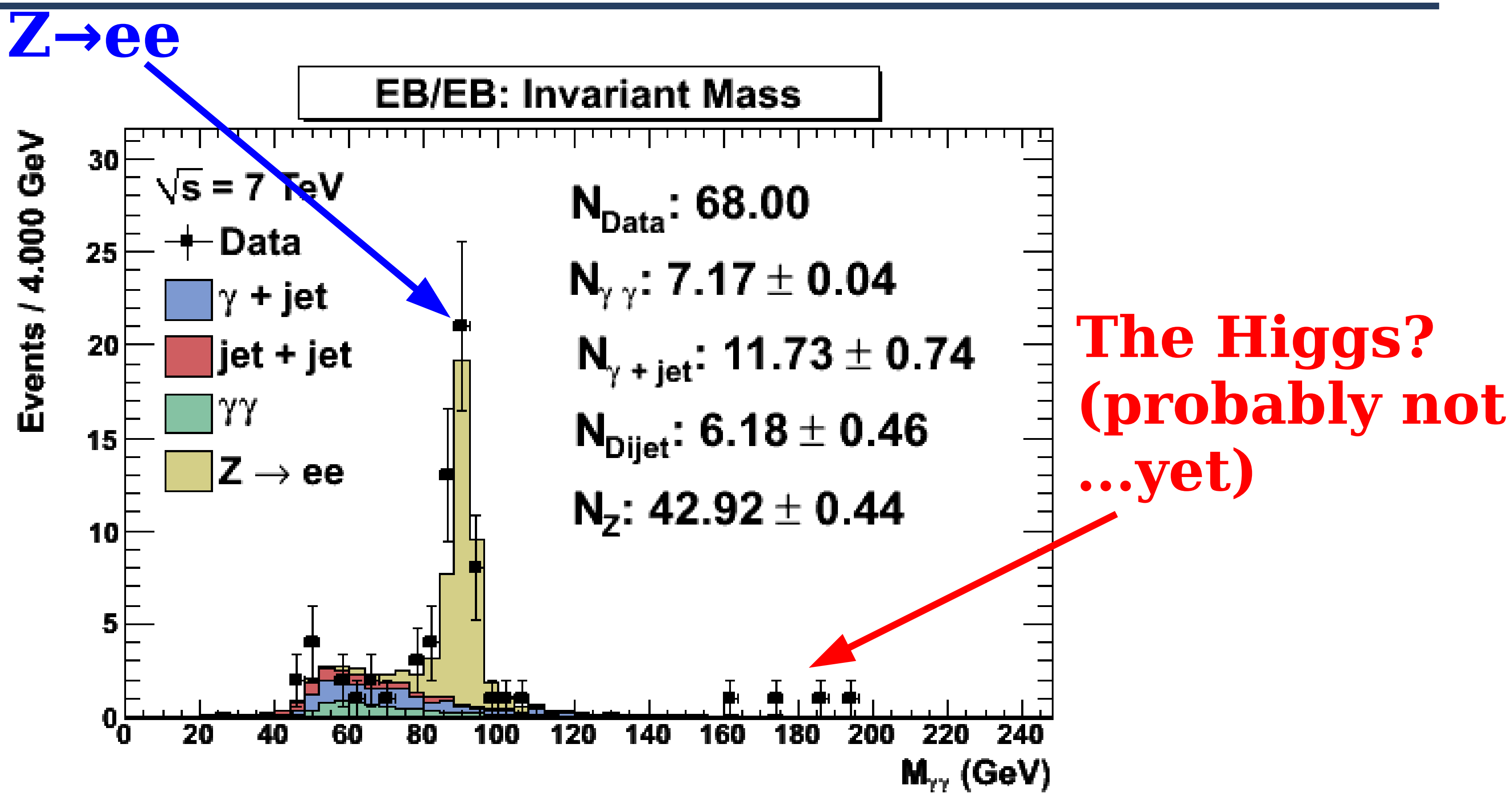


- Many other SM processes produce photons
- **Irreducible** backgrounds like $q\bar{q} \rightarrow \gamma\gamma$, $gg \rightarrow \gamma\gamma$ produce true photon pairs
- **Reducible** backgrounds produce **jets:** high energy hadrons that 'look like' photons in the ECAL
  - e.g. 'Brem' γ+jet events, QCD di-jet events
- We apply **isolations** to eliminate jet fakes and select real photons

Monte Carlo

- To estimate how effective our selection is at removing jets and preserving photons, we produce **simulated** data based on the SM
- By comparing the real data with the simulated data, we also verify our detector is working as expected
- And we can compare the diphoton continuum expected from the SM with the real data

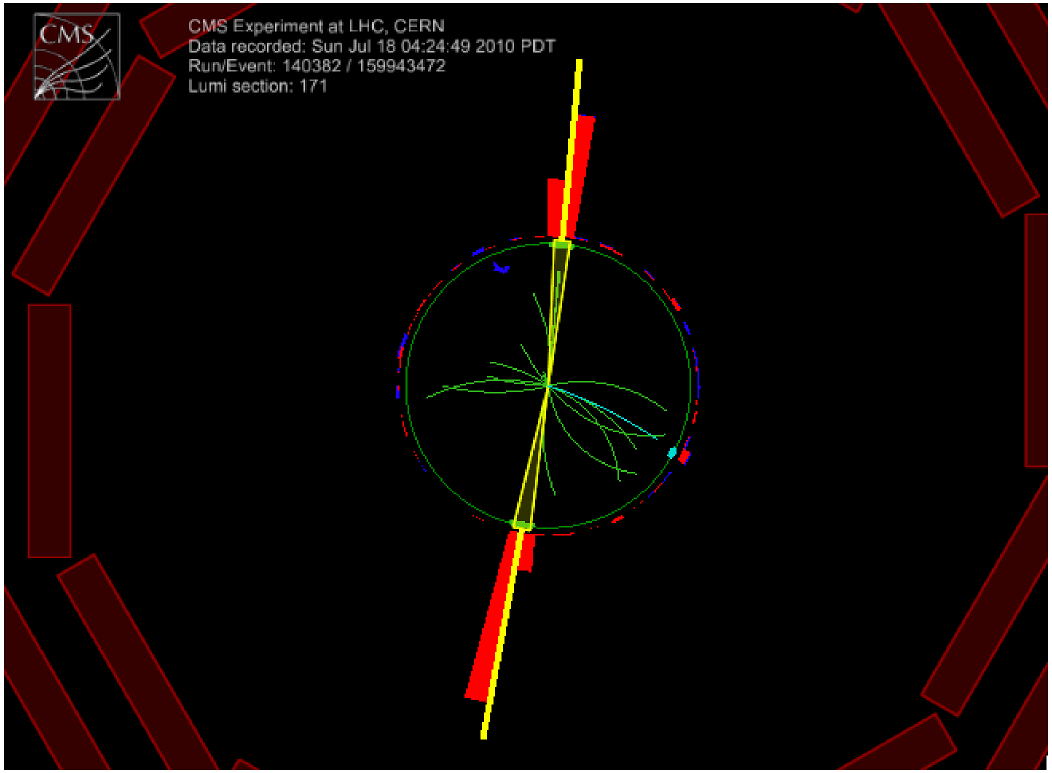
Invariant Mass

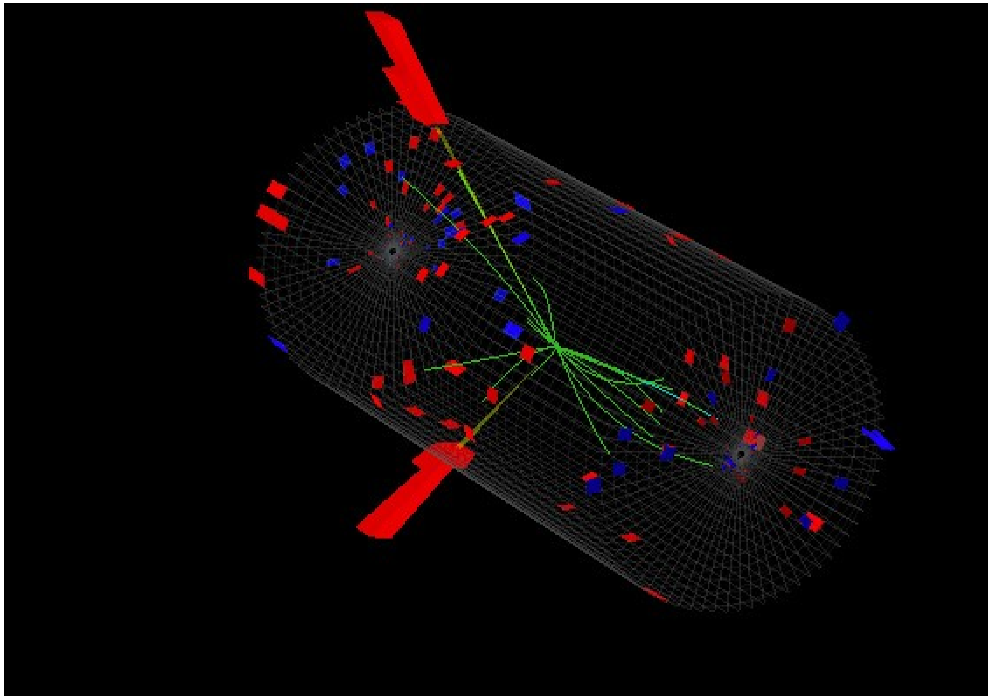


- After applying our selection, we get the **invariant mass distribution** for photon pairs
- Here, our isolation also selects electrons

$M_{\gamma\gamma} > 150$ GeV

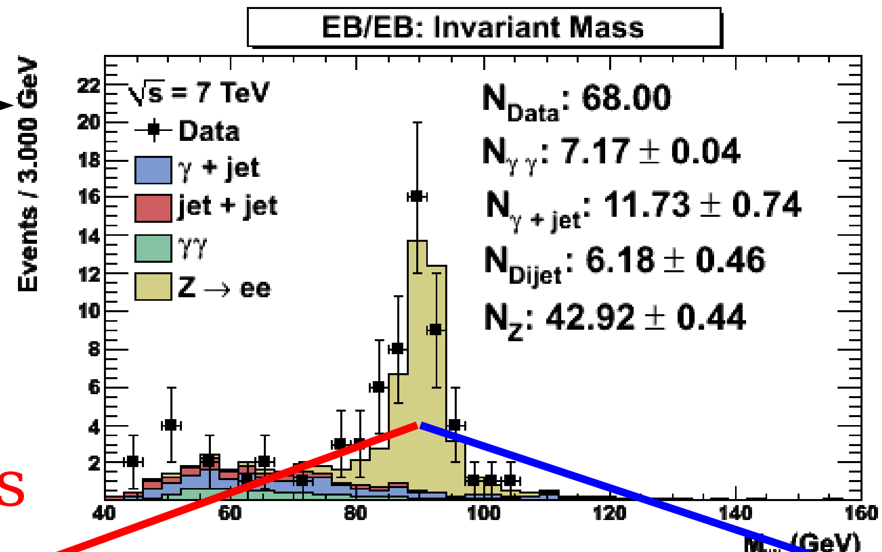
$M_{\gamma\gamma} = 194.7$ GeV
(Run: 140382, Event: 159943472)





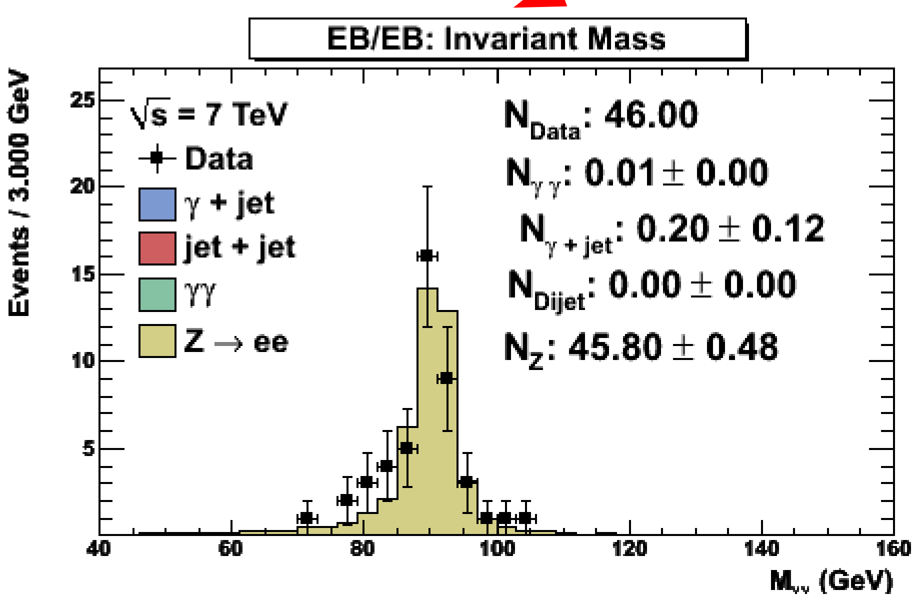
Pixel Seeds

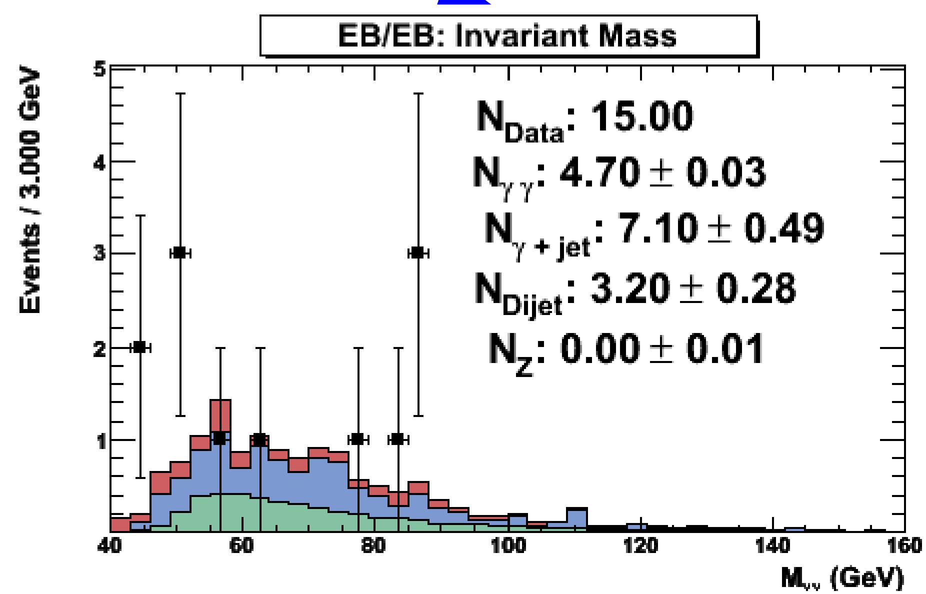
No pixel cut →



Require pixel seeds

Veto pixel seeds





Summary & Outlook

- We have developed and implemented isolations to select energetic photon pairs
- So far, not very much data is available
  - More coming fast!
- This is an ongoing project, and we will continue to update our results as more data becomes available
- As additional high-invariant-mass events appear, they must be investigated individually
- We may find the Higgs, the graviton, or some other particle no one has imagined yet!

Acknowledgements

- This work was done in partnership with Yousi Ma and in collaboration with Serguei Ganjour
  - Thank you!
- Thanks to Harvey Newman, Marat Gataullin, and the entire Caltech group
- Thanks to Homer, Jean, Jeremy, Steven, and the entire Michigan program

EXTRA

Data Sets

Data Set	$\int L$ (nb^{-1})
/MinimumBias/Commissioning10-SD_EG-Jun14thSkim_v1/RECO	7.99
/EG/Run2010A-Jun14thReReco_v1/RECO	4.92
/EG/Run2010A-PromptReco-v4/RECO	123.36
/EG/Run2010A-Jul16thReReco-v2/RECO	118.88
Total	255.15

Monte Carlo	σ (pb)	N Events
/PhotonJet_Pt15-30	192200	6.1×10^5
/PhotonJet_Pt30-80	20070	1.0×10^6
/PhotonJet_Pt80-170	556	1.3×10^6
/PhotonJet_Pt170-250	24	1.2×10^6
/Box_Pt10-25	358.2	550×10^3
/Box_Pt25-250	12.37	540×10^3
/Born_Pt10-25	236.4	536×10^3
/Born_Pt25-250	22.37	747×10^3
/Zee/Summer10-START36	970	1.0×10^5

Monte Carlo	σ (pb)	N Events	Filter Eff.
/QCD_EMEnriched_Pt20-30	235.5×10^6	30×10^6	0.0073
/QCD_EMEnriched_Pt30-80	59.3×10^6	40×10^6	0.059
/QCD_EMEnriched_Pt80-170	906000	5×10^6	0.148

Pre-Selection

- JSON good runs and LS certified
- HLT_Photon15_L1R || HLT_Photon15_Cleaned_L1R
- $P_T > 22$ GeV, $|\eta| < 2.5$ (excluding EB/EE gap)
- $H/E < 0.05$
- Spike rejection:
  - eMax / e3x3 < .95
  - seedRecoFlag = seedSeverity = 0
- Beam halo: reject TTBits 36, 37, 38, 39 (data only)
- nHfTowersP > 0, nHfTowersN > 0
- !vtxIsFake, vtxNTrkWeight05 > 3, |vtxZ| < 18 cm

Isolation

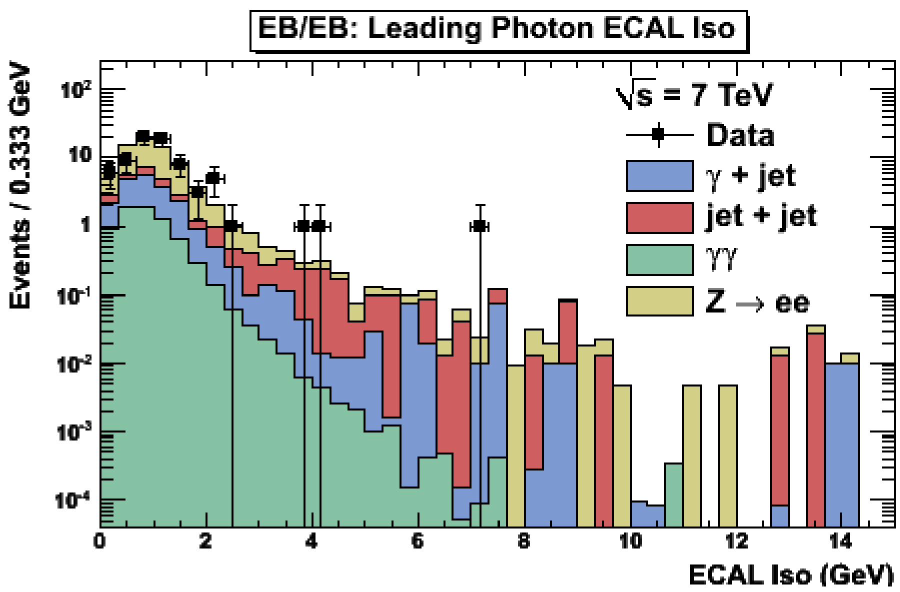
- ECAL Iso < 4.2 + 0.003 P_T
  - ECAL Iso = $\sum E_T$ of ECAL rechits in hollow cone of outer radius $\Delta R = 0.4$
- HCAL Iso < 2.2 + 0.001 P_T
  - HCAL Iso = $\sum E_T$ of HCAL towers in hollow cone of outer radius $\Delta R = 0.4$
- Tracker Iso < 2.0 + 0.001 P_T
  - Trk Iso = $\sum P_T$ of tracks in hollow cone of outer radius $\Delta R = 0.4$
- $\sigma_{i\eta i\eta} < 0.0105$ (EB), $\sigma_{i\eta i\eta} < 0.03$ (EE)

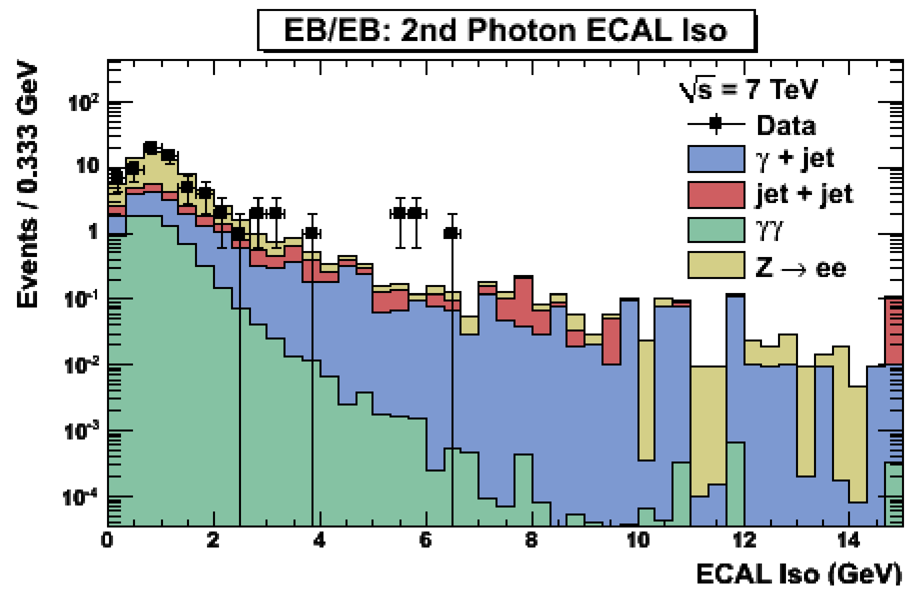
(QCD-10-019)

ECAL Isolation (N-1 Cuts)

- Cut on all quantities except ECAL isolation
- Normalized to N_{Data}

N_{Data}: 74.00
$N_{\gamma\gamma}$: 7.36 ± 0.04
$N_{\gamma + jet}$: 14.04 ± 0.81
N_{Dijet}: 7.75 ± 0.52
N_{Z}: 44.85 ± 0.46





Tracker Isolation (N-1 Cuts)

- Cut on all quantities except tracker isolation
- Normalized to N_{Data}

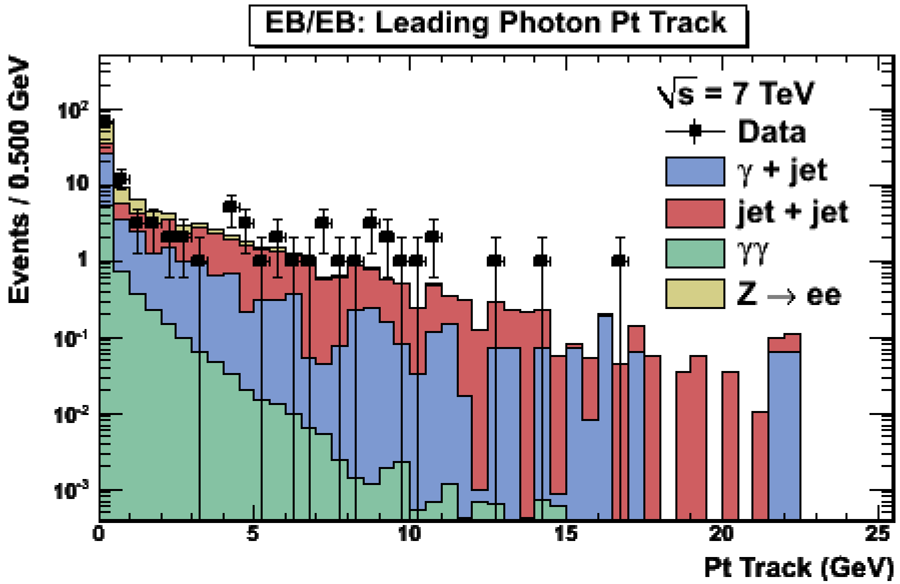
N_{Data}: 116.00

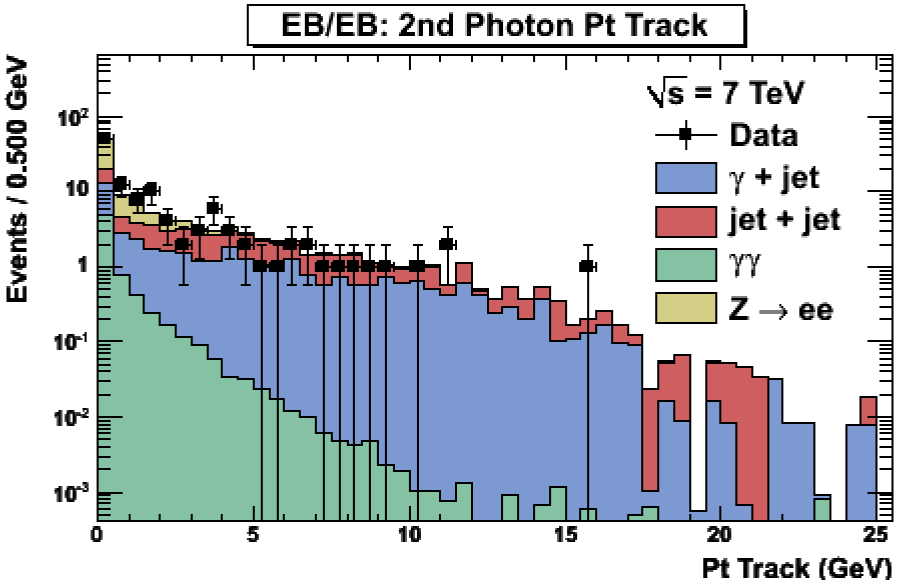
$N_{\gamma\gamma}$: 7.02 ± 0.04

$N_{\gamma + jet}$: 34.76 ± 1.22

N_{Dijet}: 31.91 ± 1.00

N_{Z}: 42.30 ± 0.40

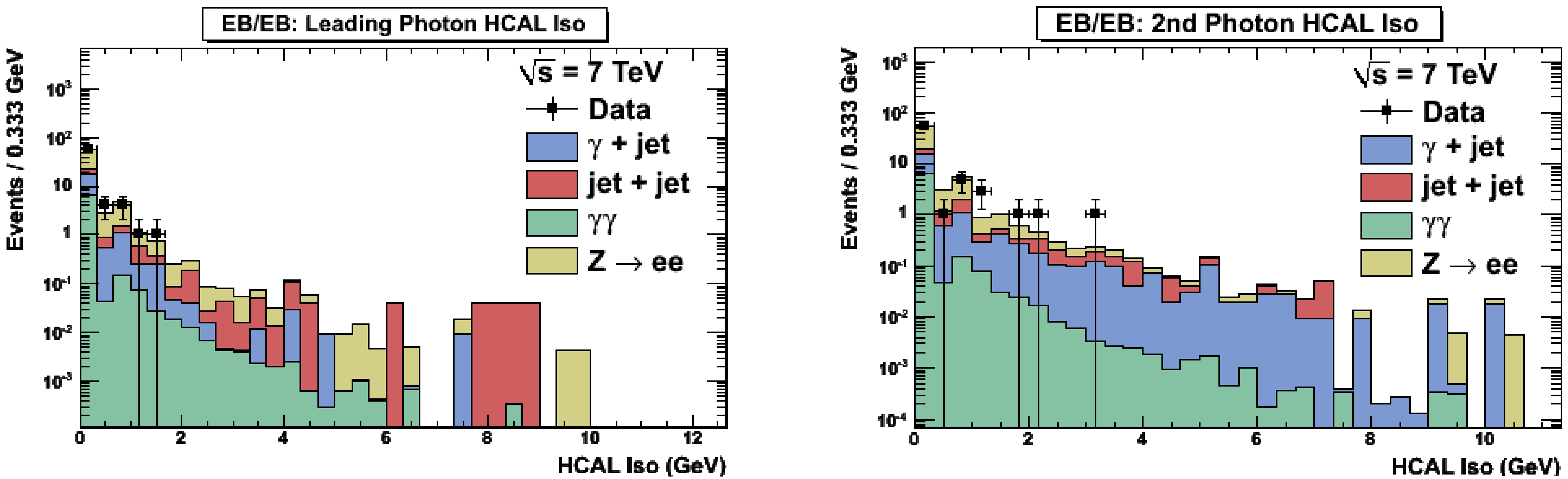




HCAL Isolation (N-1 Cuts)

- Cut on all quantities except HCAL isolation
- Normalized to N_{Data}

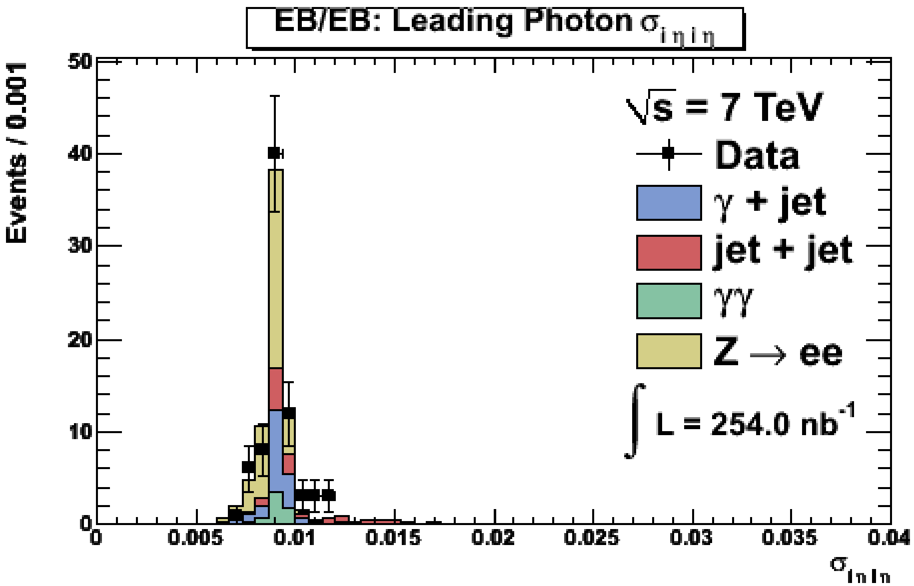
N_{Data}: 69.00
$N_{\gamma\gamma}$: 7.04 $\pm$ 0.04
$N_{\gamma + jet}$: 12.57 $\pm$ 0.76
N_{Dijet}: 6.97 $\pm$ 0.48
N_{Z}: 42.42 $\pm$ 0.43

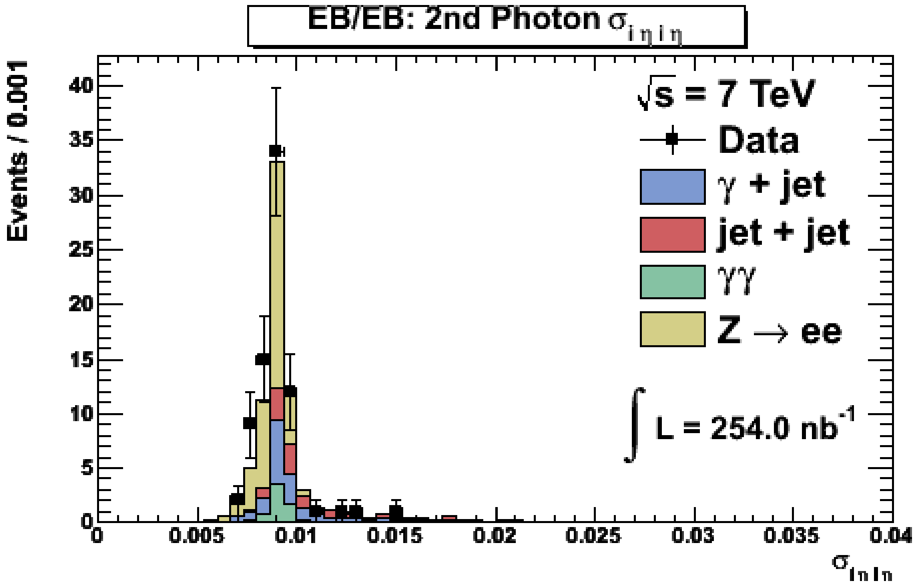


$\sigma_{i\eta i\eta}$ (N-1 Cuts)

- Cut on all quantities except $\sigma_{i\eta i\eta}$
- Normalized to N_{Data}

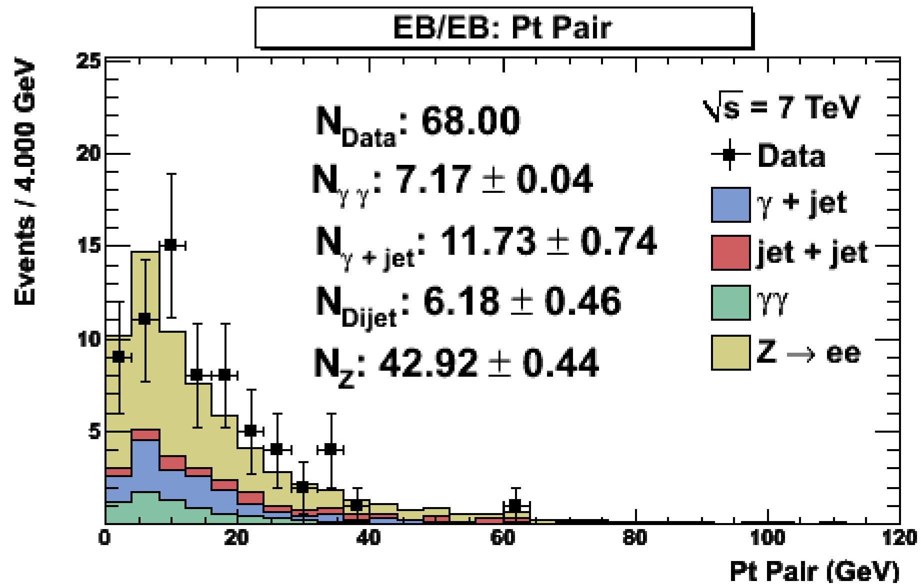
N_{Data}: 76.00
$N_{\gamma\gamma}$: 6.73 ± 0.04
$N_{\gamma + jet}$: 16.72 ± 0.86
N_{Dijet}: 11.87 ± 0.63
N_Z: 40.68 ± 0.41

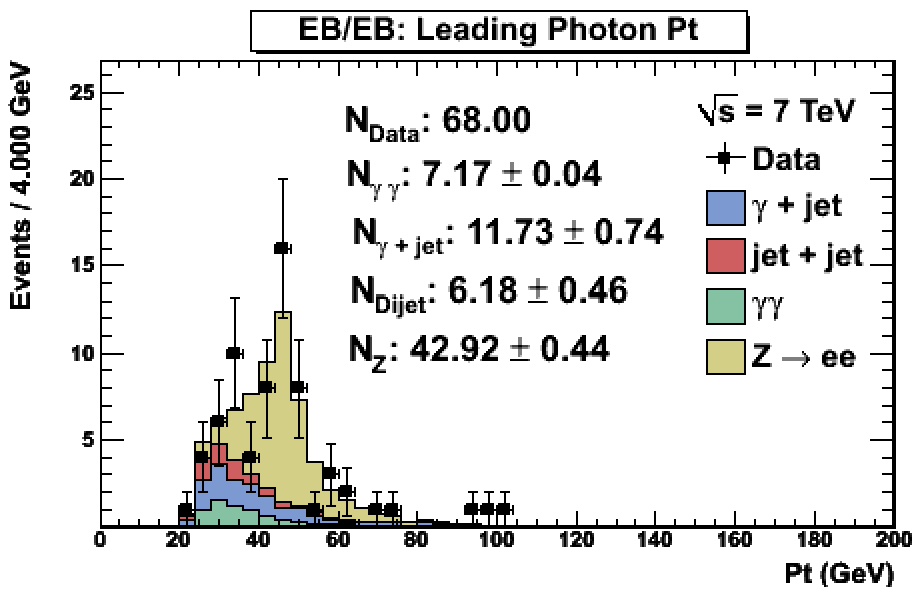


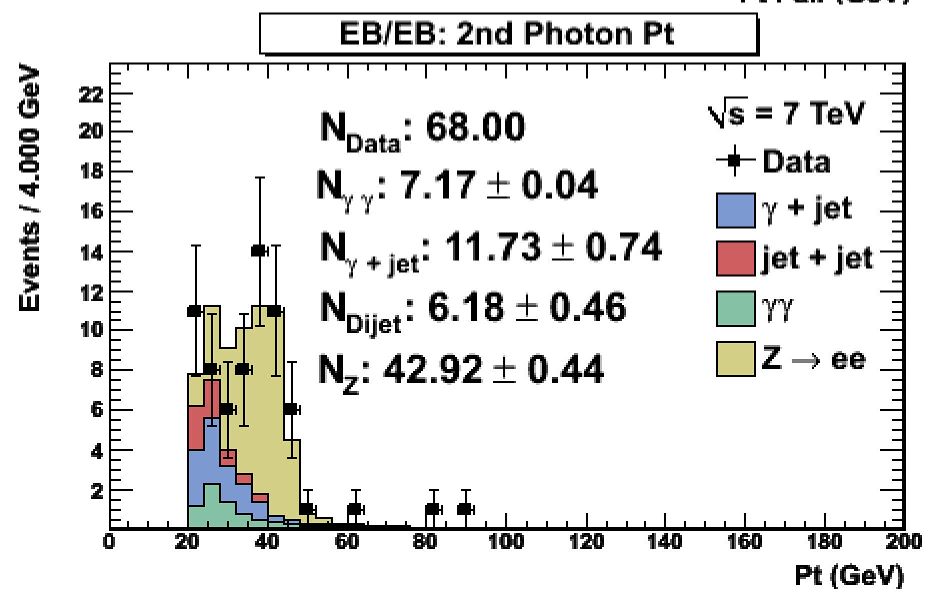


P_T

- Cut on all quantities except pixel seed
- Normalize to N_{Data}



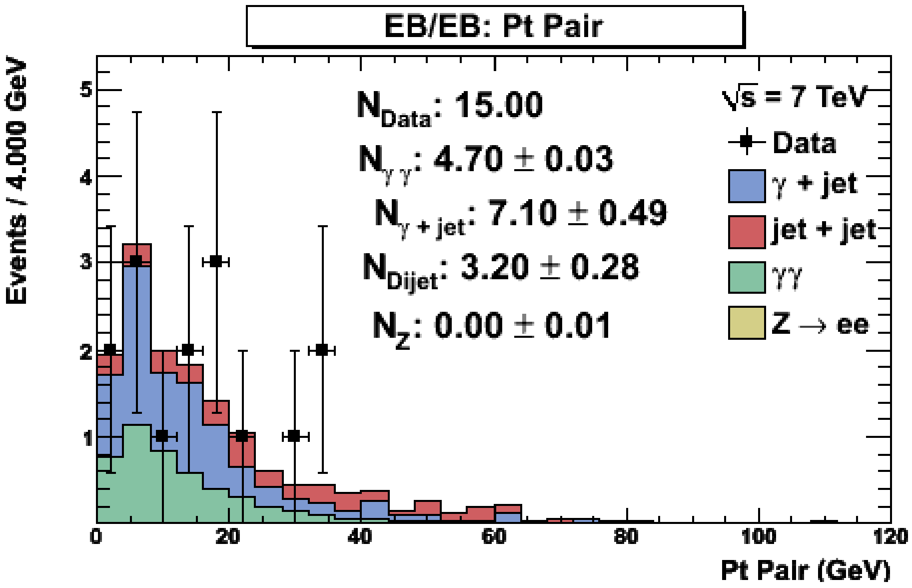




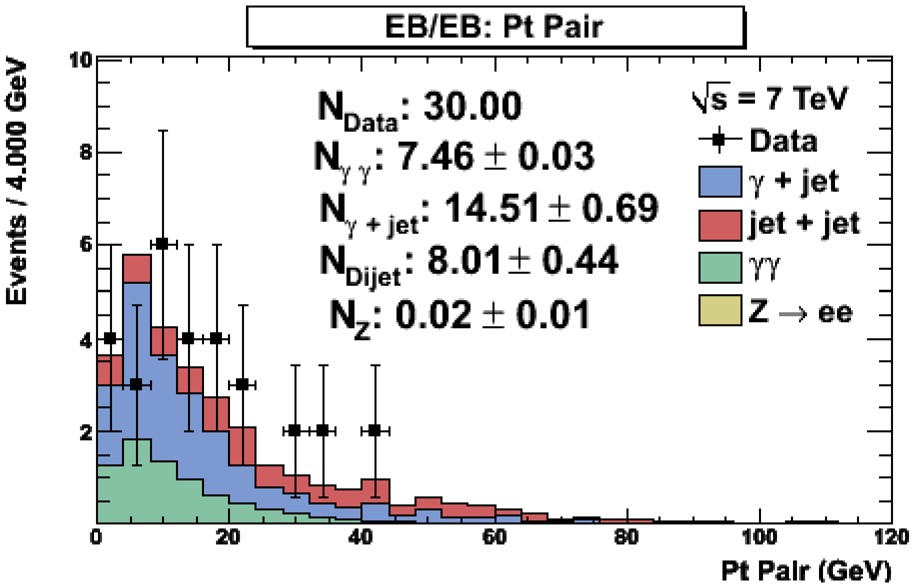
P_T Higgs

- Veto pixel seed match for each candidate
  - ⇒ eliminates electrons

Barrel Only

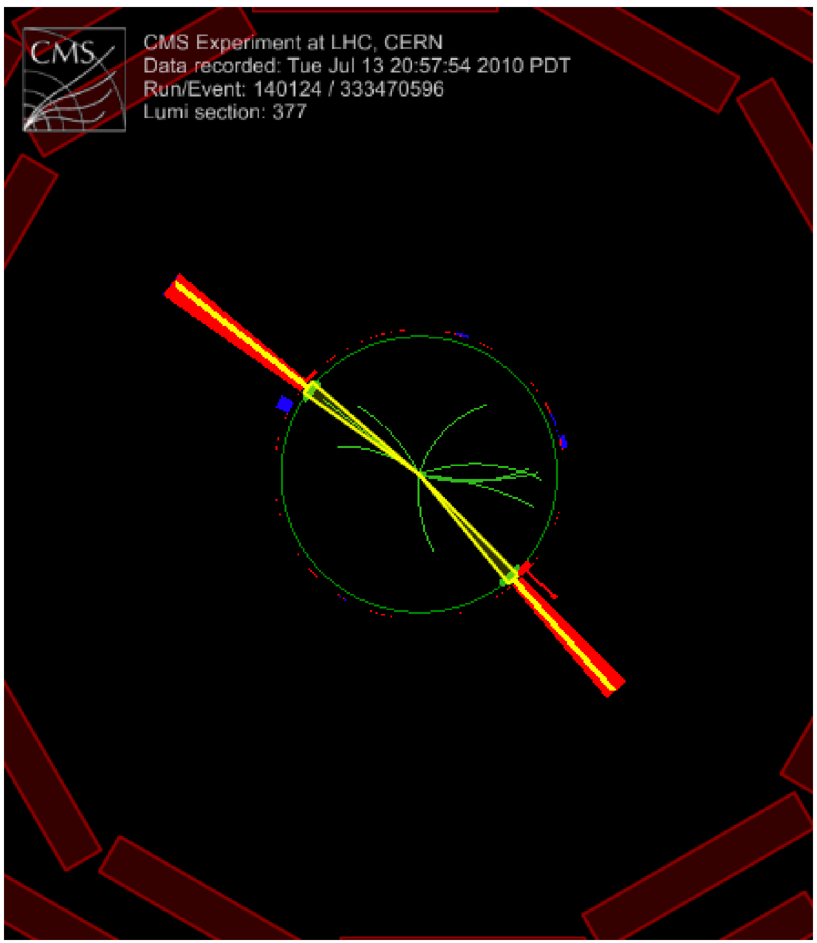


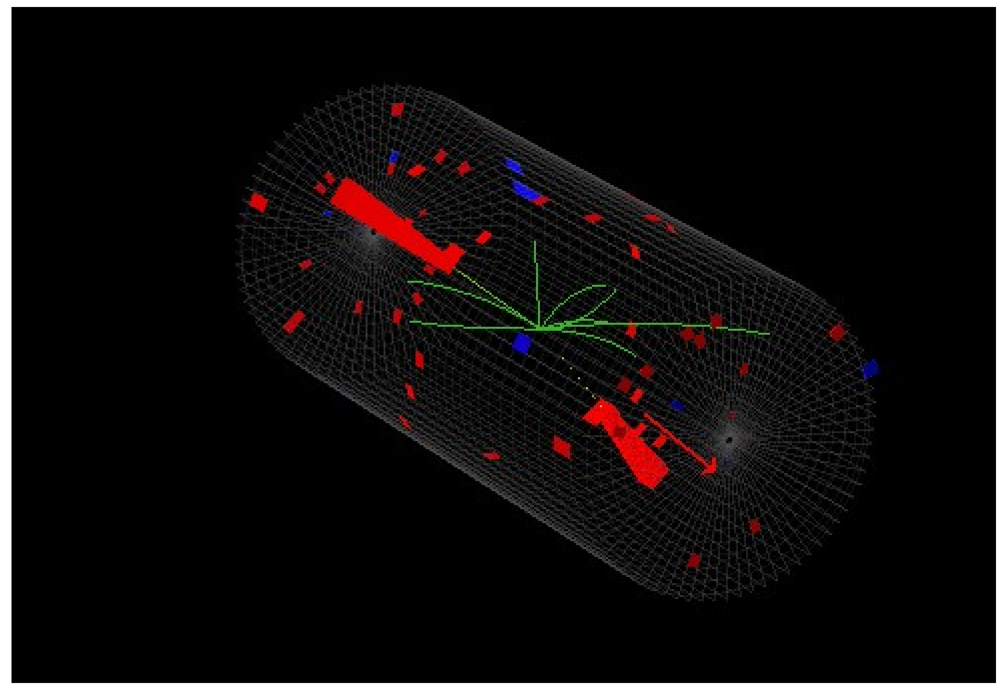
Barrel + Endcaps



$M_{\gamma\gamma} > 150$ GeV

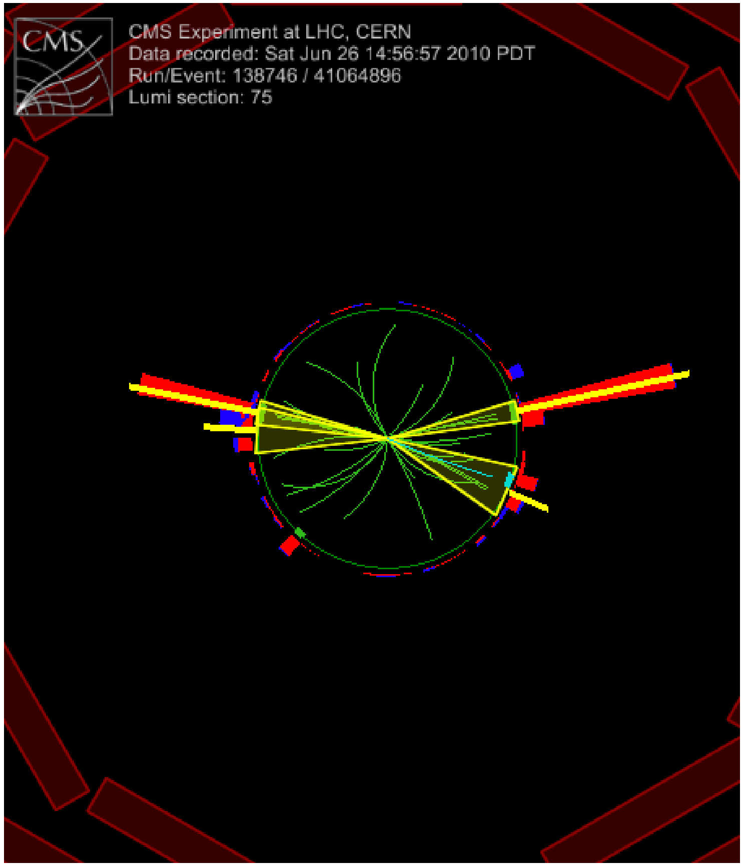
$M_{\gamma\gamma} = 186.0$ GeV
(Run: 140124, Event: 333470596)

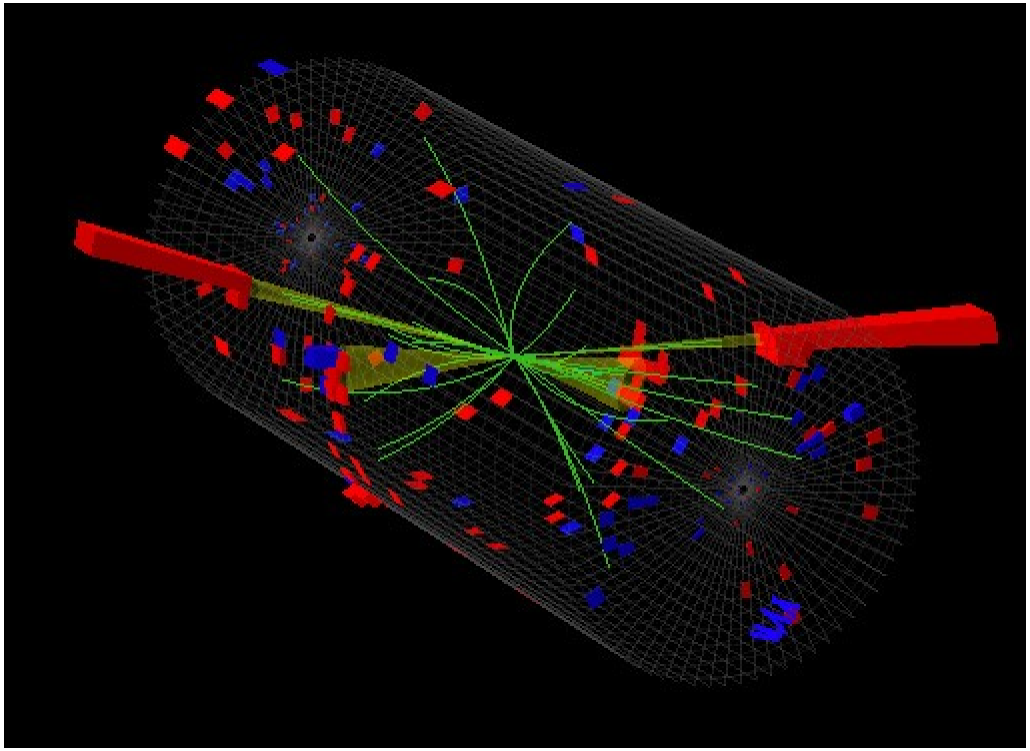




$M_{\gamma\gamma} > 150$ GeV

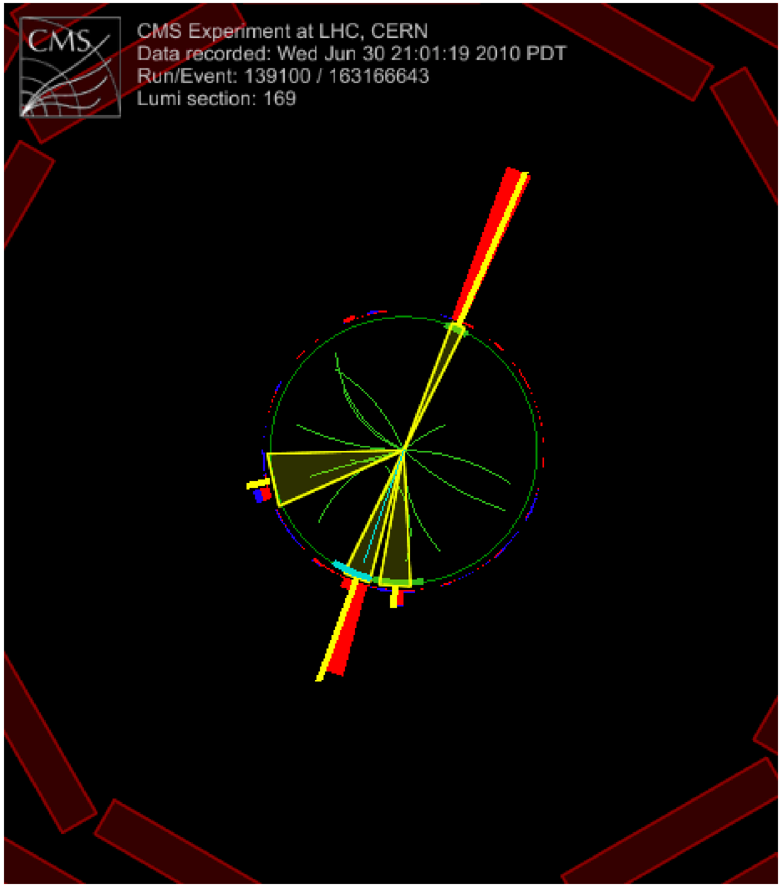
$M_{\gamma\gamma} = 172.0$ GeV
(Run: 138746, Event: 41064896)

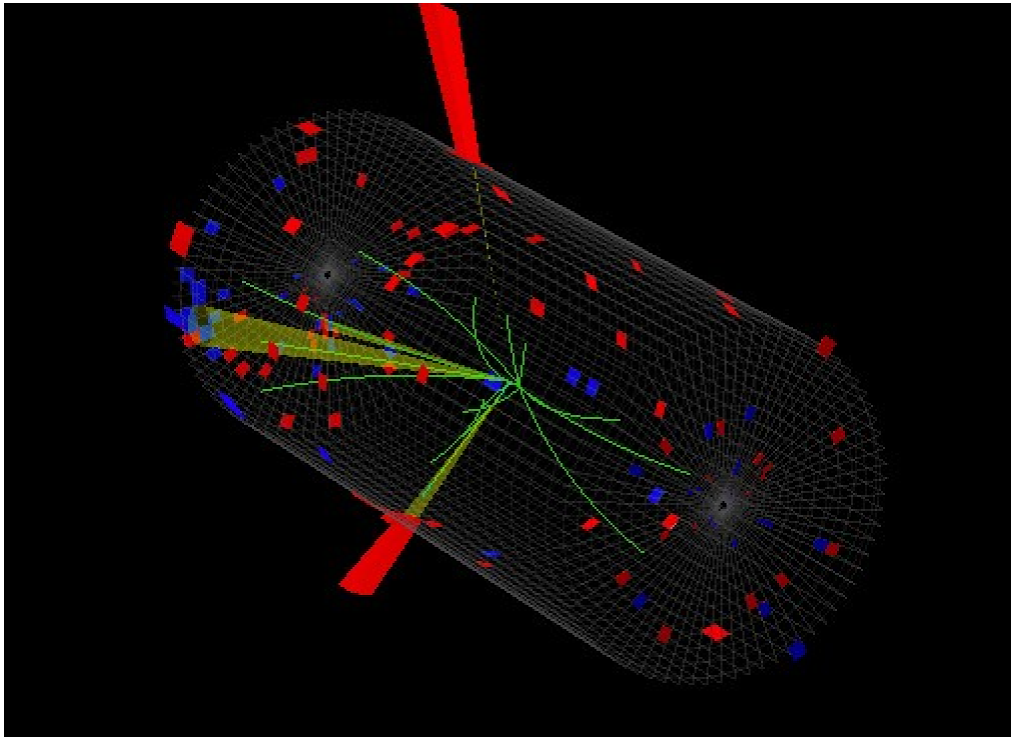




$M_{\gamma\gamma}$ > 150 GeV

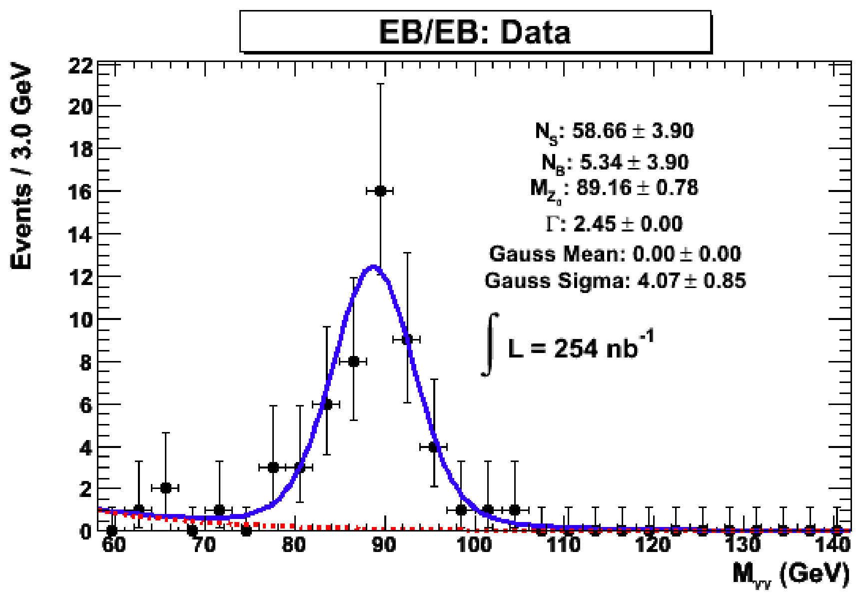
$M_{\gamma\gamma}$ =161.3 GeV
(Run: 139100, Event: 163166643)

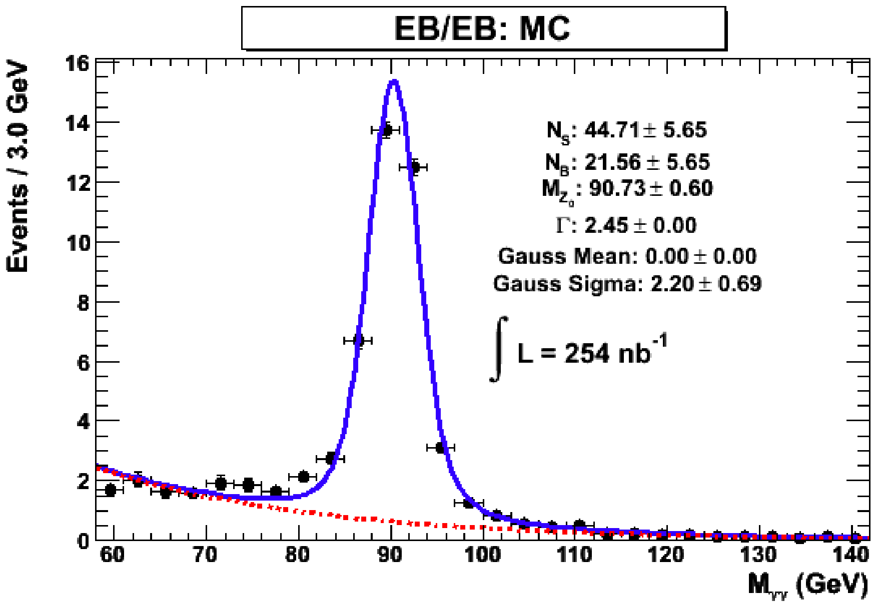




Z Peak

- Fit with Gaussian convolved with Breit-Wigner, plus exponential
  - Fix the BW width to the PDG value, 2.45 GeV
  - Free BW mean and Gaussian width

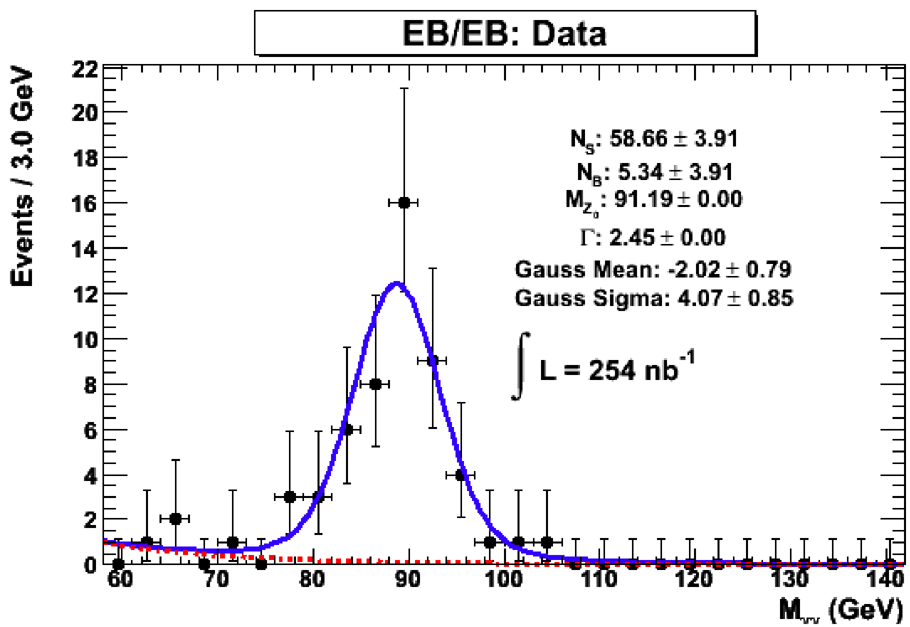


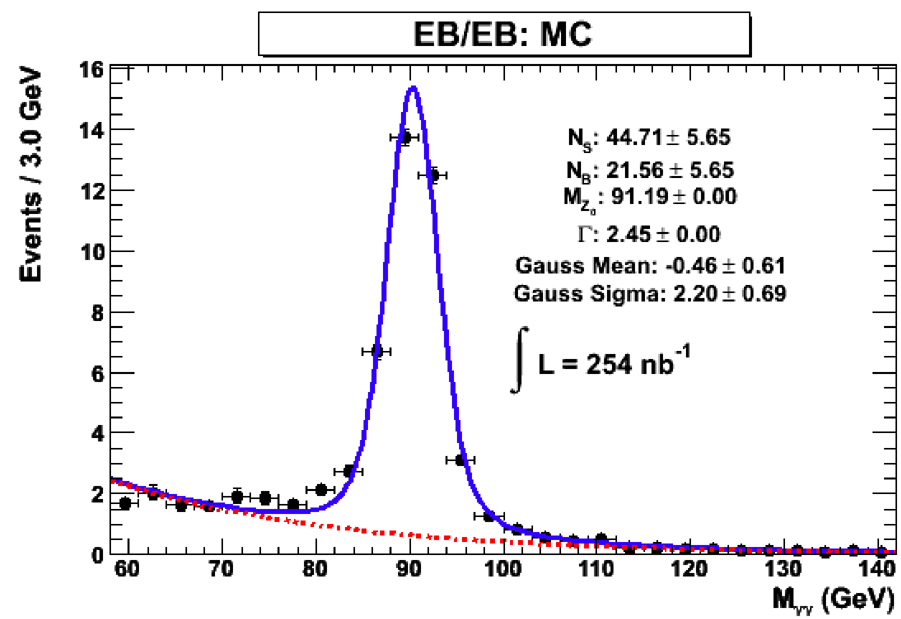


- The data peak is shifted below the MC
  - $\Delta m = -1.57 \pm 0.98$ GeV

Z Peak (2)

- Fix BW width AND BW mean to PDG values
  - Free Gaussian parameters

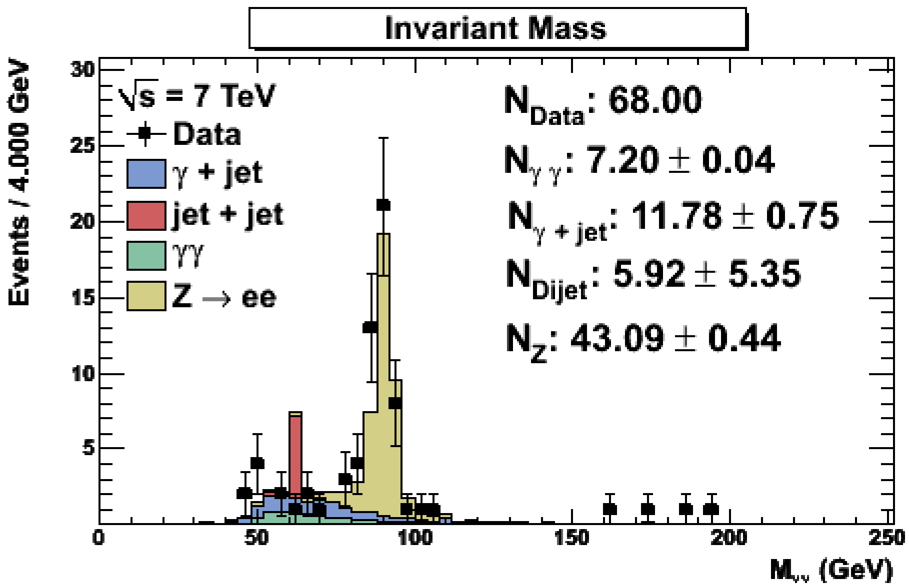




  - Δm = -1.56 ± 1.12 GeV (Gauss mean)

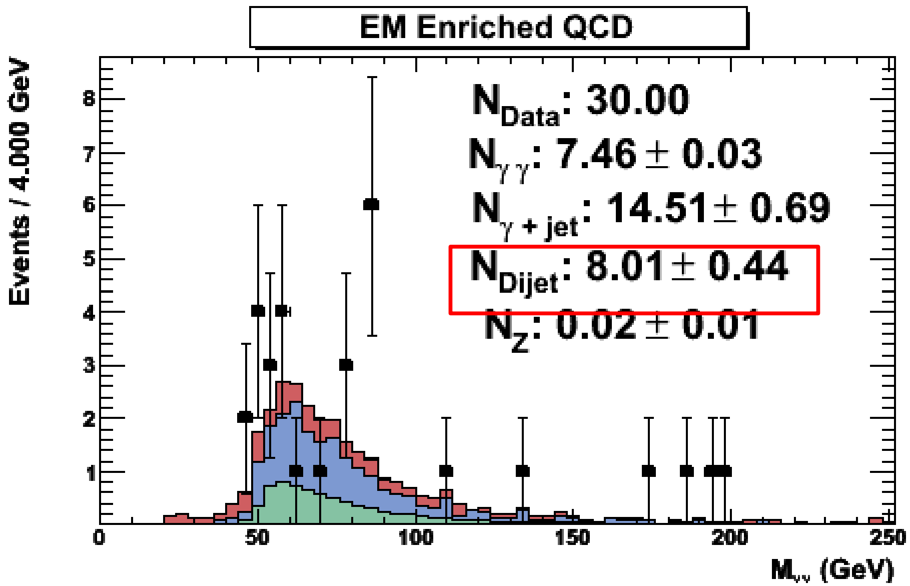
QCD Monte Carlo

- Previous slides show EM Enriched QCD MC
  - Generator Filter: $E_T > 20$ GeV, H/E < 0.5, Trk Iso < 5 GeV, Calo Iso < 10 GeV
  - Filter cuts need to be tuned
- Also considered unfiltered QCD
  - Poor statistics ⇒ scaling issues



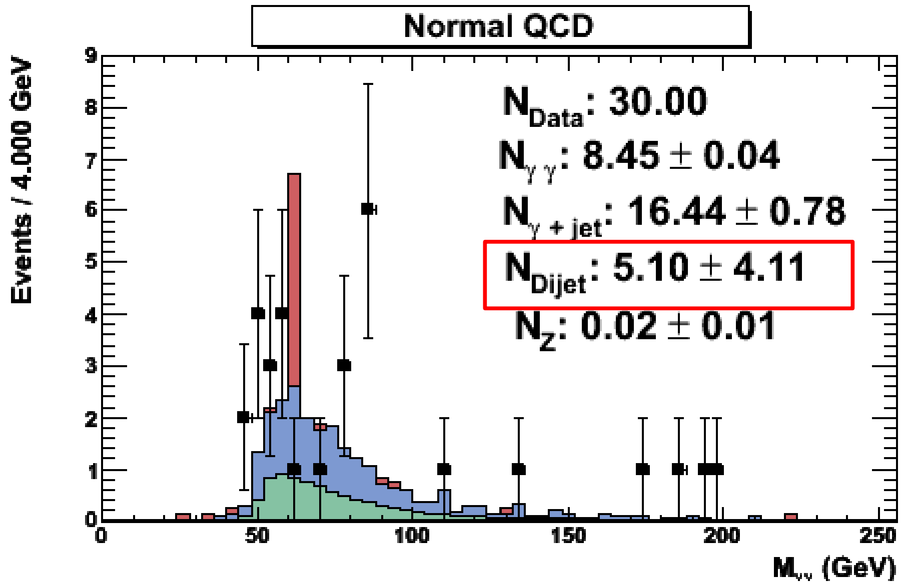
EM Enriched vs Normal QCD

- After pixel seed veto (barrel and endcaps):



Raw Counts

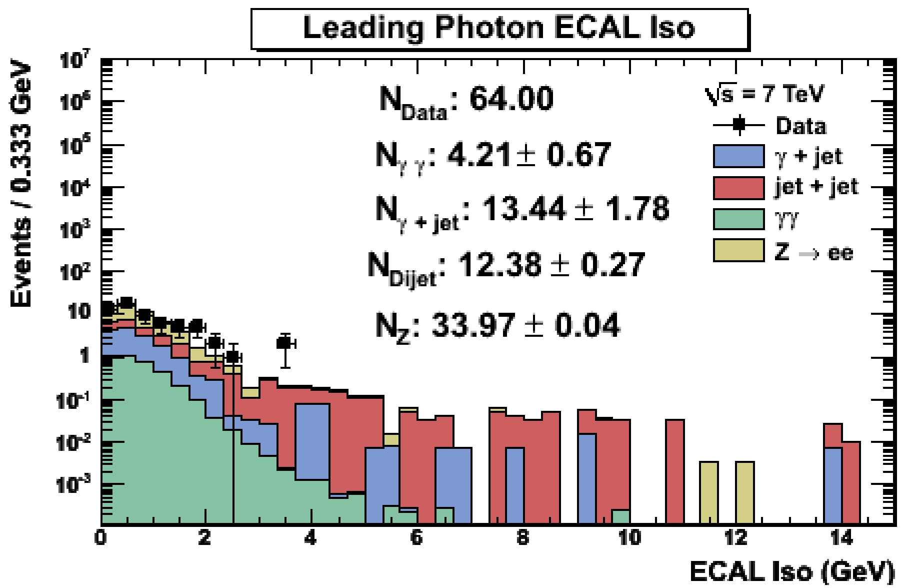
QCD 20-30: 91
QCD 30-80: 198
QCD 80-170: 95

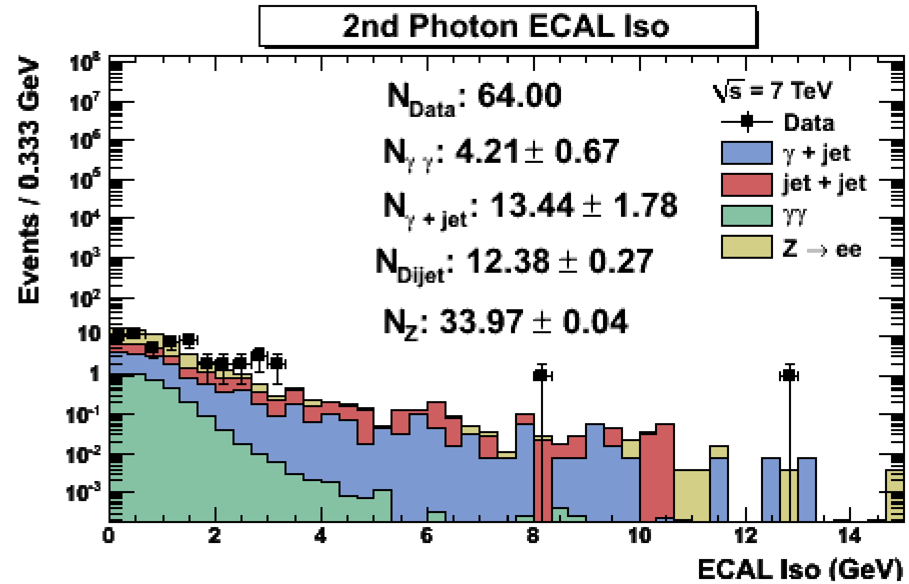


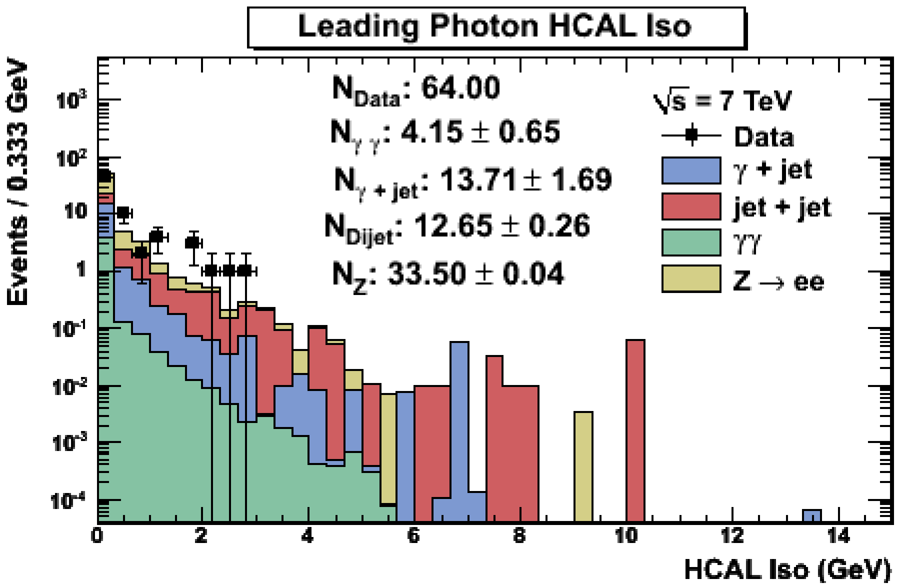
Raw Counts

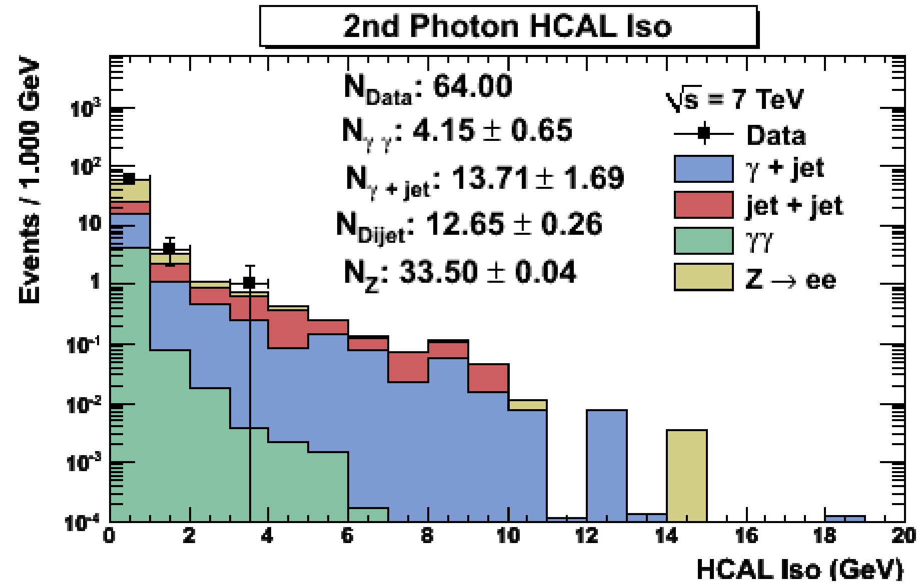
QCD 15-30: 0
QCD 30-80: 1
QCD 80-170: 9
QCD 170-250: 22

EB/EE || EE/EE

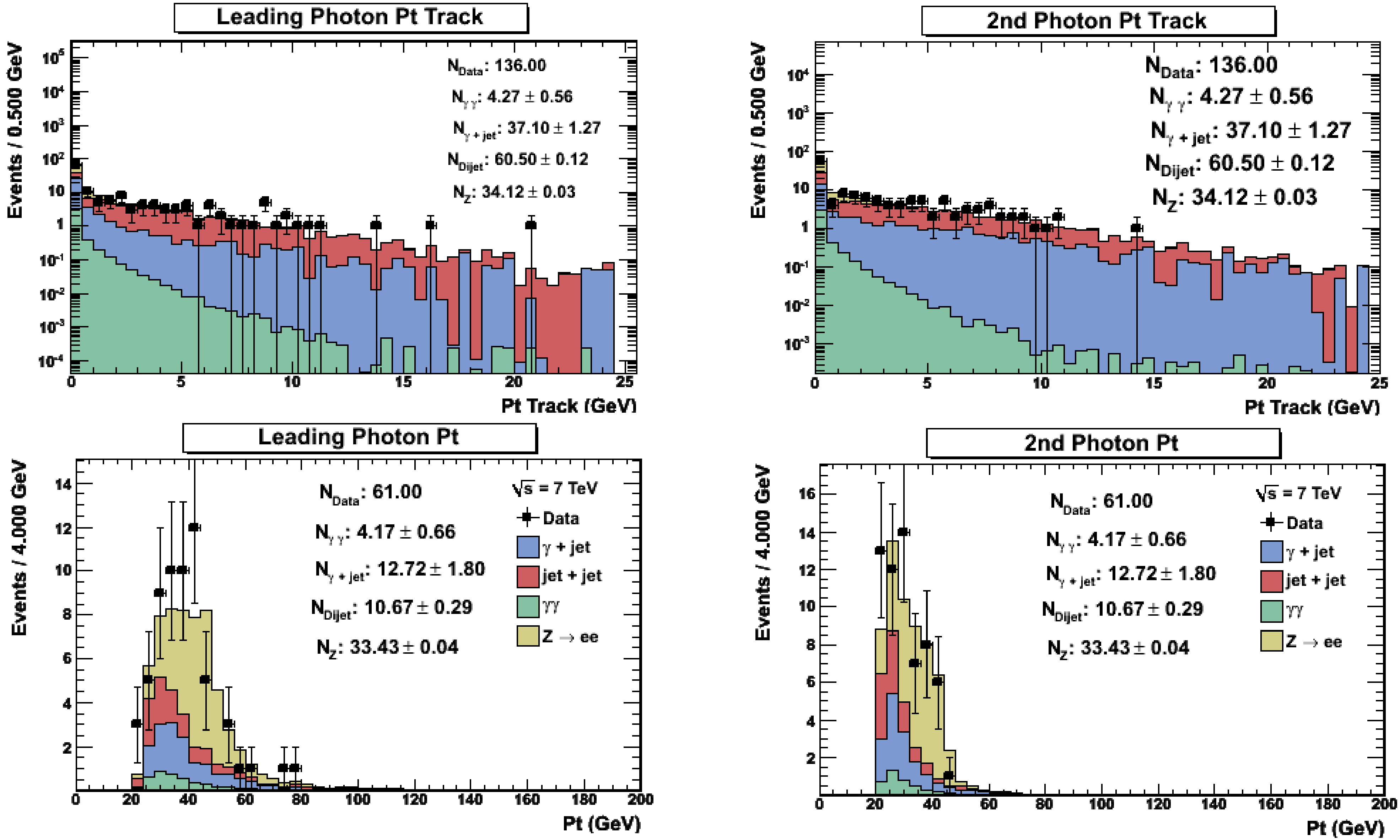

Leading Photon ECAL Iso
N_{Data}: 64.00
$N_{\gamma\gamma}$: 4.21 ± 0.67
$N_{\gamma+jet}$: 13.44 ± 1.78
N_{Dijet}: 12.38 ± 0.27
N_Z: 33.97 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Events / 0.333 GeV
ECAL Iso (GeV)


2nd Photon ECAL Iso
N_{Data}: 64.00
$N_{\gamma\gamma}$: 4.21 ± 0.67
$N_{\gamma+jet}$: 13.44 ± 1.78
N_{Dijet}: 12.38 ± 0.27
N_Z: 33.97 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Events / 0.333 GeV
ECAL Iso (GeV)


Leading Photon HCAL Iso
N_{Data}: 64.00
$N_{\gamma\gamma}$: 4.15 ± 0.65
$N_{\gamma+jet}$: 13.71 ± 1.69
N_{Dijet}: 12.65 ± 0.26
N_Z: 33.50 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Events / 0.333 GeV
HCAL Iso (GeV)

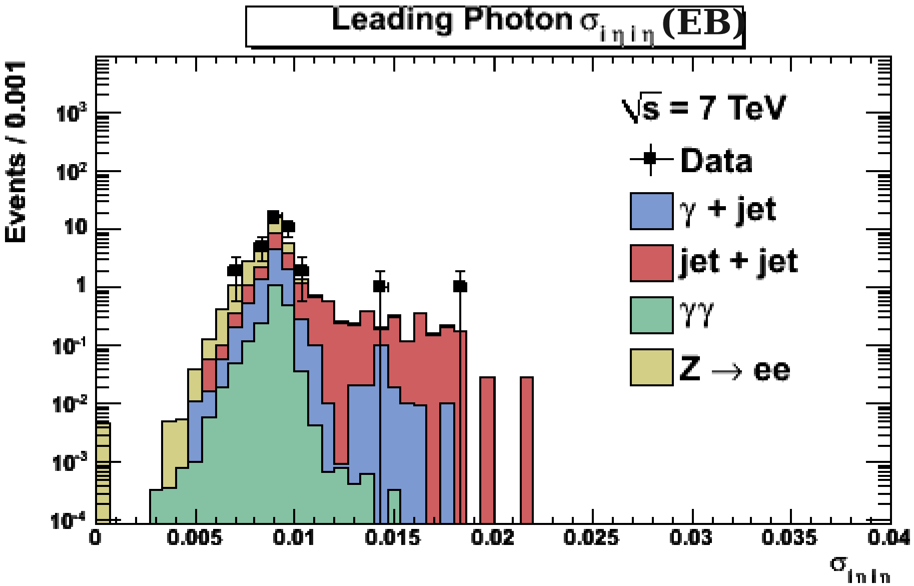

2nd Photon HCAL Iso
N_{Data}: 64.00
$N_{\gamma\gamma}$: 4.15 ± 0.65
$N_{\gamma+jet}$: 13.71 ± 1.69
N_{Dijet}: 12.65 ± 0.26
N_Z: 33.50 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Events / 1.000 GeV
HCAL Iso (GeV)

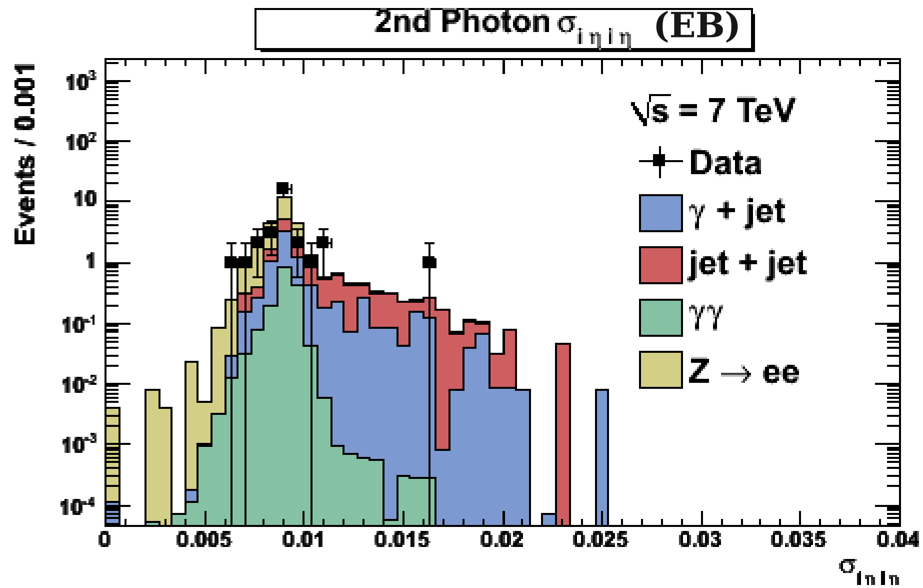
EB/EE || EE/EE

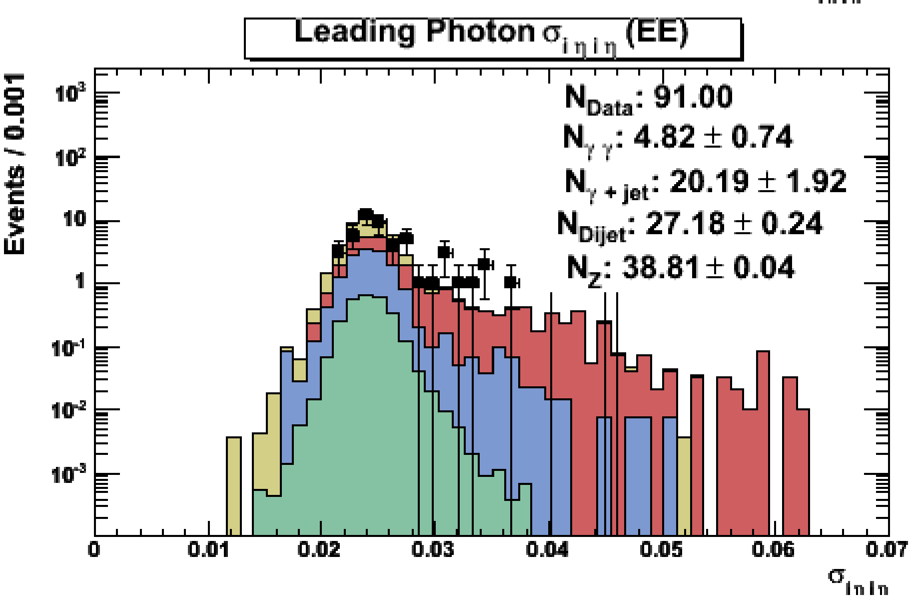


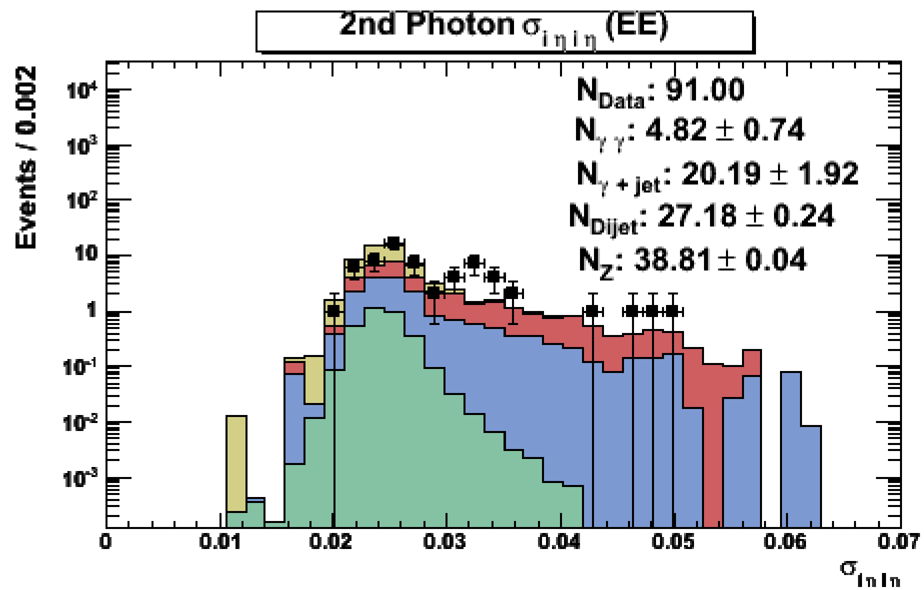
Leading Photon Pt Track
N_{Data}: 136.00
$N_{\gamma\gamma}$: 4.27 ± 0.56
$N_{\gamma+jet}$: 37.10 ± 1.27
N_{Dijet}: 60.50 ± 0.12
N_Z: 34.12 ± 0.03
Events / 0.500 GeV
Pt Track (GeV)
2nd Photon Pt Track
N_{Data}: 136.00
$N_{\gamma\gamma}$: 4.27 ± 0.56
$N_{\gamma+jet}$: 37.10 ± 1.27
N_{Dijet}: 60.50 ± 0.12
N_Z: 34.12 ± 0.03
Events / 0.500 GeV
Pt Track (GeV)
Leading Photon Pt
N_{Data}: 61.00
$N_{\gamma\gamma}$: 4.17 ± 0.66
$N_{\gamma+jet}$: 12.72 ± 1.80
N_{Dijet}: 10.67 ± 0.29
N_Z: 33.43 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Events / 4.000 GeV
Pt (GeV)
2nd Photon Pt
N_{Data}: 61.00
$N_{\gamma\gamma}$: 4.17 ± 0.66
$N_{\gamma+jet}$: 12.72 ± 1.80
N_{Dijet}: 10.67 ± 0.29
N_Z: 33.43 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Events / 4.000 GeV
Pt (GeV)

EB/EE || EE/EE

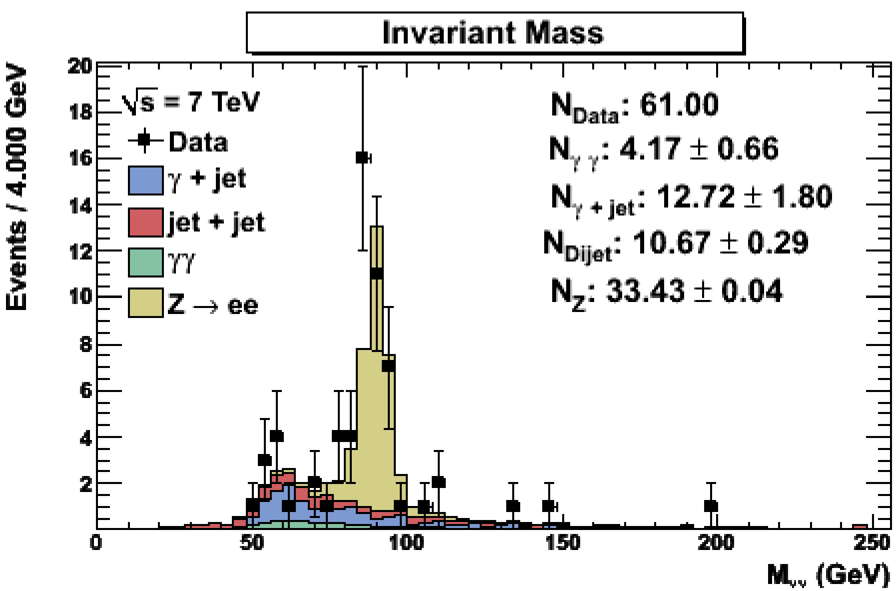

Leading Photon $\sigma_{i\eta i\eta}$ (EB)
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
$\gamma\gamma$
Z $\rightarrow$ ee
Events / 0.001
$\sigma_{i\eta i\eta}$

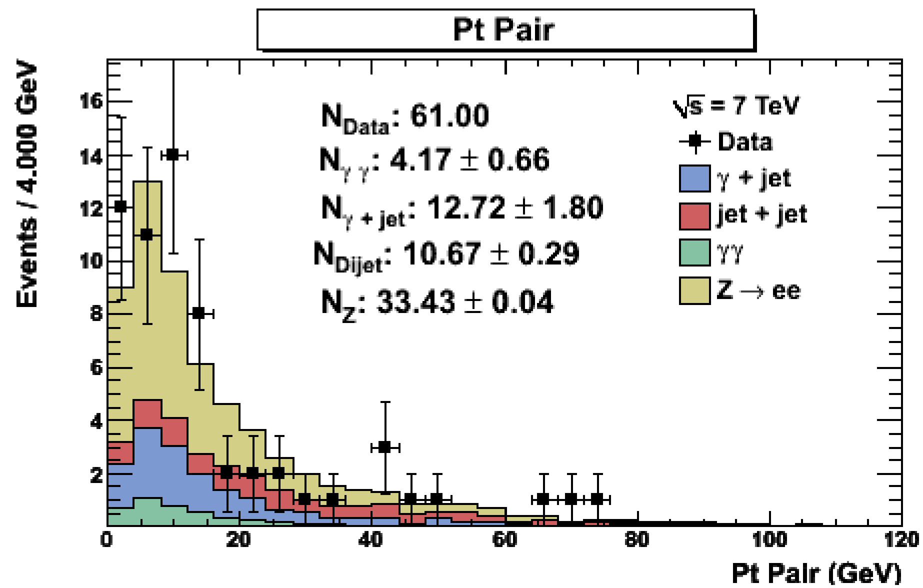

2nd Photon $\sigma_{i\eta i\eta}$ (EB)
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
$\gamma\gamma$
Z $\rightarrow$ ee
Events / 0.001
$\sigma_{i\eta i\eta}$


Leading Photon $\sigma_{i\eta i\eta}$ (EE)
N_{Data}: 91.00
$N_{\gamma\gamma}$: 4.82 $\pm$ 0.74
$N_{\gamma + jet}$: 20.19 $\pm$ 1.92
N_{Dijet}: 27.18 $\pm$ 0.24
N_Z: 38.81 $\pm$ 0.04
Events / 0.001
$\sigma_{i\eta i\eta}$


2nd Photon $\sigma_{i\eta i\eta}$ (EE)
N_{Data}: 91.00
$N_{\gamma\gamma}$: 4.82 $\pm$ 0.74
$N_{\gamma + jet}$: 20.19 $\pm$ 1.92
N_{Dijet}: 27.18 $\pm$ 0.24
N_Z: 38.81 $\pm$ 0.04
Events / 0.002
$\sigma_{i\eta i\eta}$

EB/EE || EE/EE


Invariant Mass
Events / 4.000 GeV
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
N_{Data}: 61.00
$N_{\gamma\gamma}$: 4.17 ± 0.66
$N_{\gamma + jet}$: 12.72 ± 1.80
N_{Dijet}: 10.67 ± 0.29
N_Z: 33.43 ± 0.04
$M_{\gamma\gamma}$ (GeV)


Pt Pair
Events / 4.000 GeV
N_{Data}: 61.00
$N_{\gamma\gamma}$: 4.17 ± 0.66
$N_{\gamma + jet}$: 12.72 ± 1.80
N_{Dijet}: 10.67 ± 0.29
N_Z: 33.43 ± 0.04
$\sqrt{s}$ = 7 TeV
Data
γ + jet
jet + jet
γγ
Z → ee
Pt Pair (GeV)