Study of Wγ Events at the CMS with 7 TeV LHC data

Devdatta Majumder

Tata Institute of Fundamental Research, Mumbai

for the CMS Collaboration

Outline

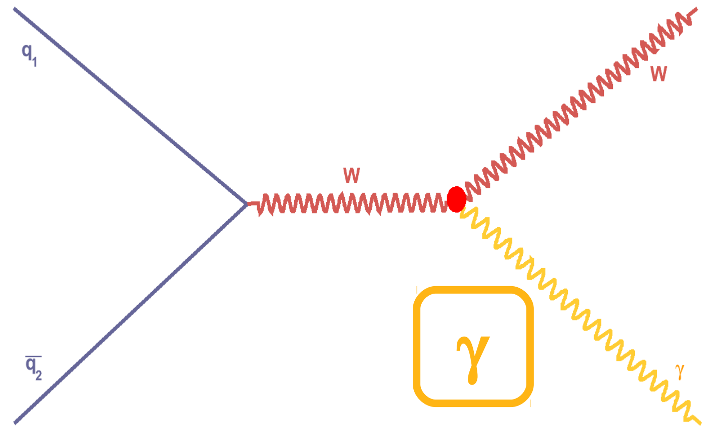
- Selecting Wγ events
- Estimating the cross section of Wγ process
- Observing the *radiation amplitude zero*

Young Scientist Forum

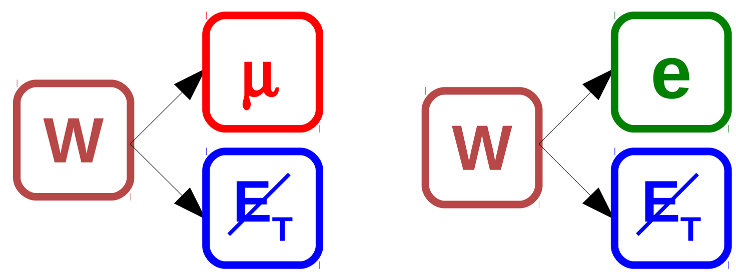
Rencontres de Moriond, EWK, 2011

Motivation

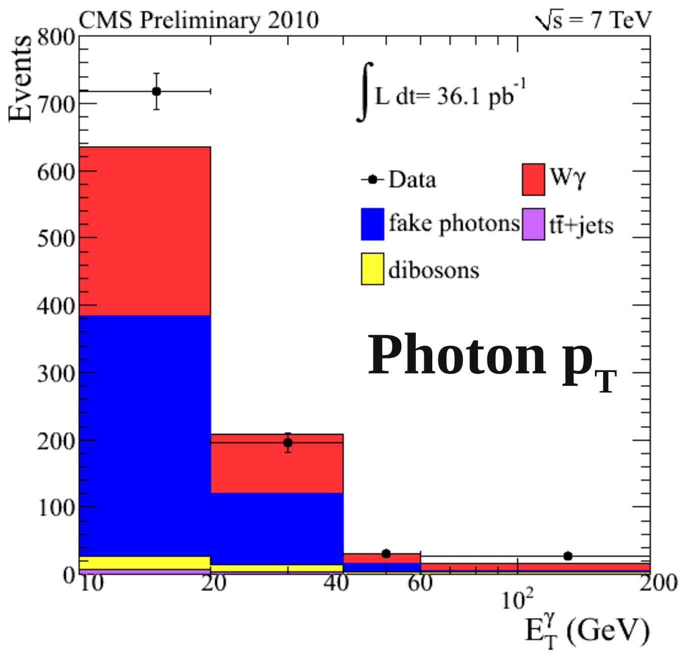
- Diboson physics - one of the last frontiers of the Standard Model before discovery searches.
- Wγ production – one of the highest cross sections of all dibosons. Study with early data feasible.
- New physics leads to modified WWγ coupling –
  - reflected in distribution of photon p_T
- Measure the cross section of Wγ production and compare with Standard Model value:
  - $$\sigma \times BR\,(\mathbf{W} \to l\nu) = \frac{\mathbf{N_{events} - N_{bkg}}}{A.\in.L}$$



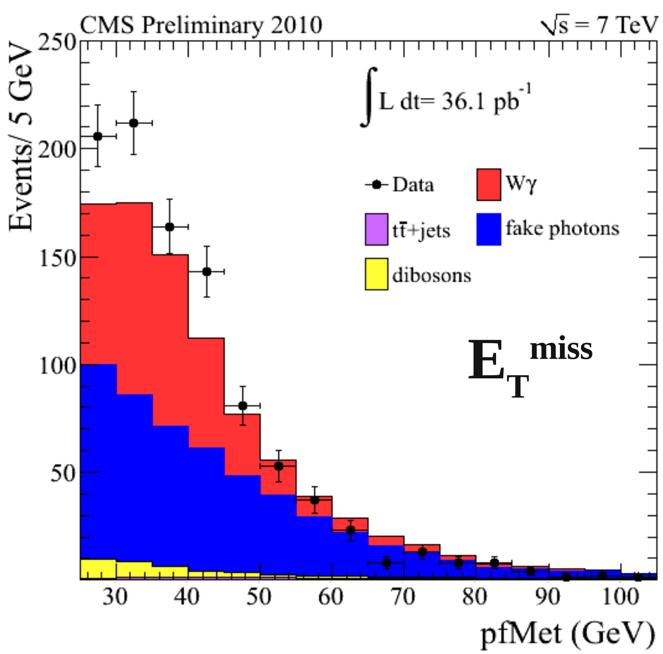
- Uses 36 pb^{-1} data
- Both electron and muon decay modes of W-boson:

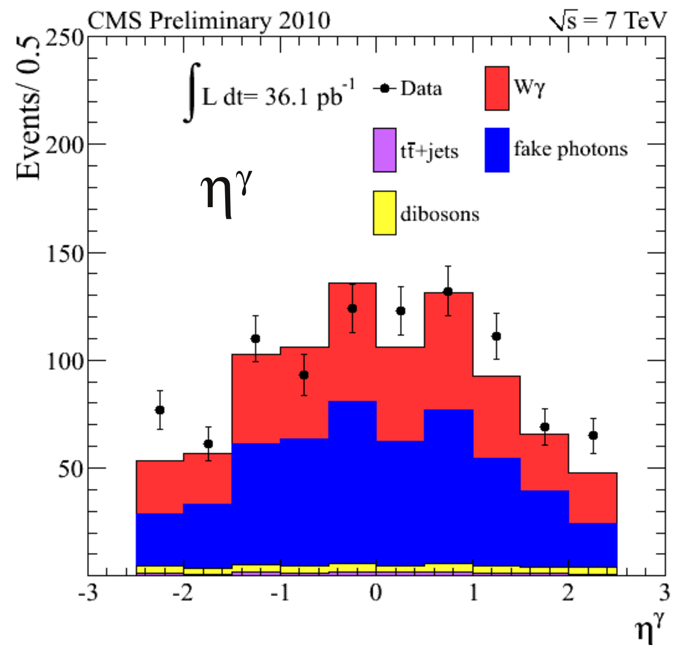


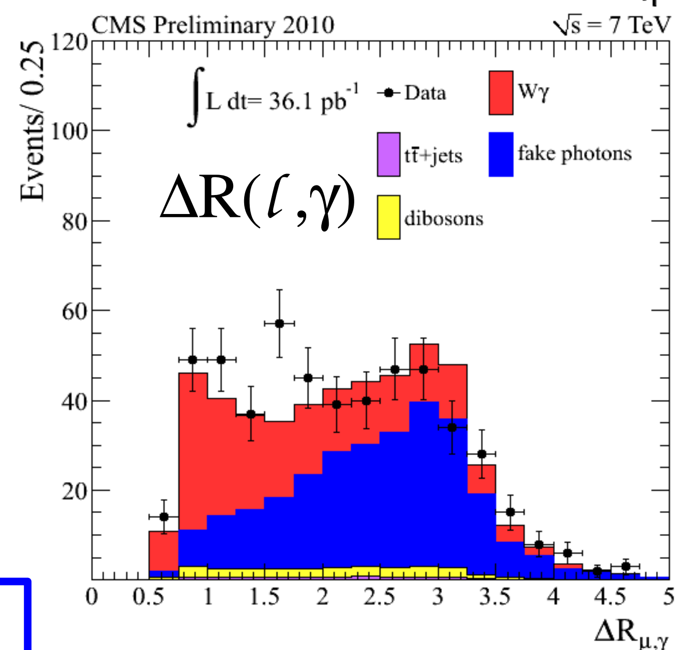
Event selection



1. Trigger: select events based on single electron or muon trigger.
2. Reconstruct W-boson
   - Reconstruct lepton
   - E_T^{miss} > 25 GeV applied.
3. Reconstruct photon
   - Good quality photon
   - Photon separated from lepton: $\Delta R(\ell,\gamma) > 0.7$
   - $p_T^{\gamma} > 10$ GeV/c.
   - Choose leading p_T photon.







Large background from jets faking as photons

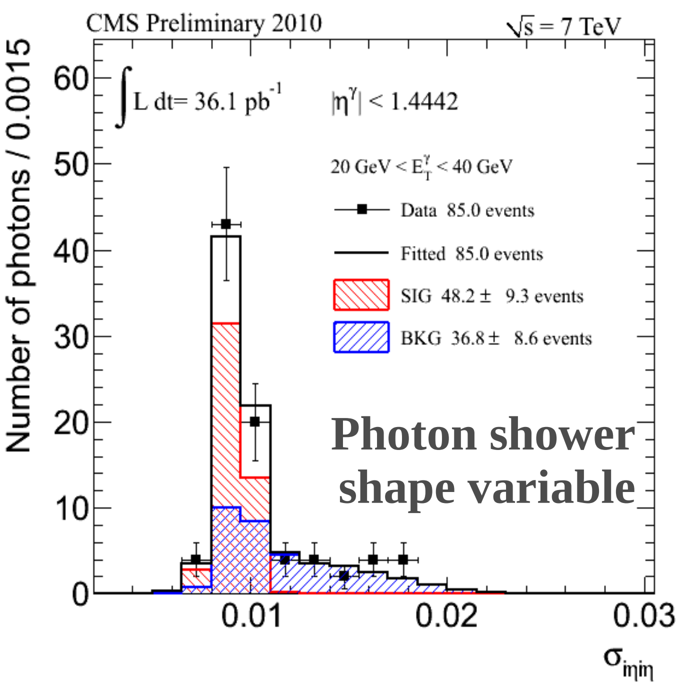
Backgrounds

- Jets from W+jets: jets fragmeting to π_0/η_0 with $\pi_0/\eta_0 \rightarrow \gamma\gamma$

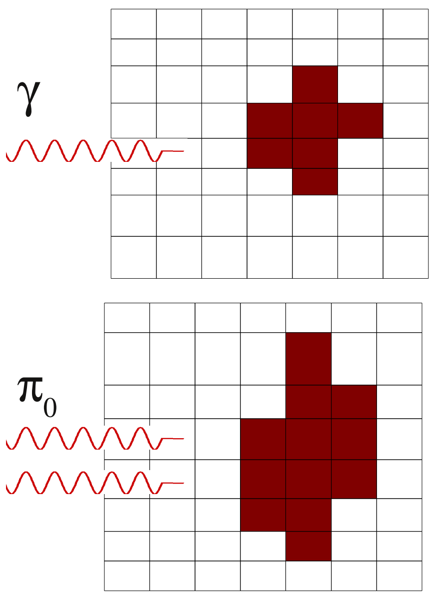
Use data-driven methods

A Template method

Shape of photon shower different from jet (fake photon) shower in calorimeter.



Real photons vs fake photons

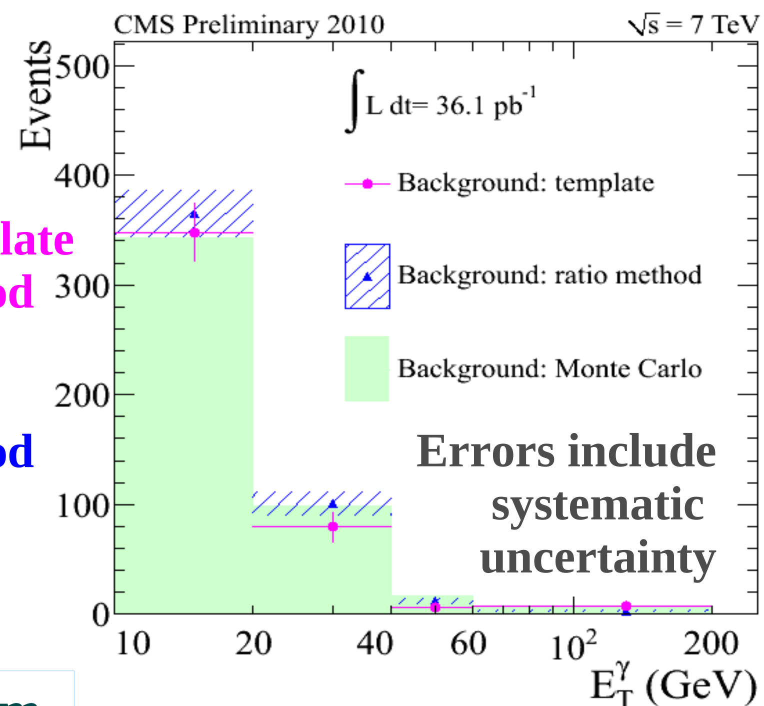


B Ratio method

Ratio of isolated fake photons to non-isolated fake photons equal in W+jets and jet-triggered events.

$$N_{W+jets} = \left(\frac{N_{isolated\,\gamma}}{N_{non\text{-}isolated\,\gamma}}\right)_{QCD} N_{W+non\text{-}isolated\,\gamma}$$

Template method and Ratio method *agree*



Ratio method systematics smaller

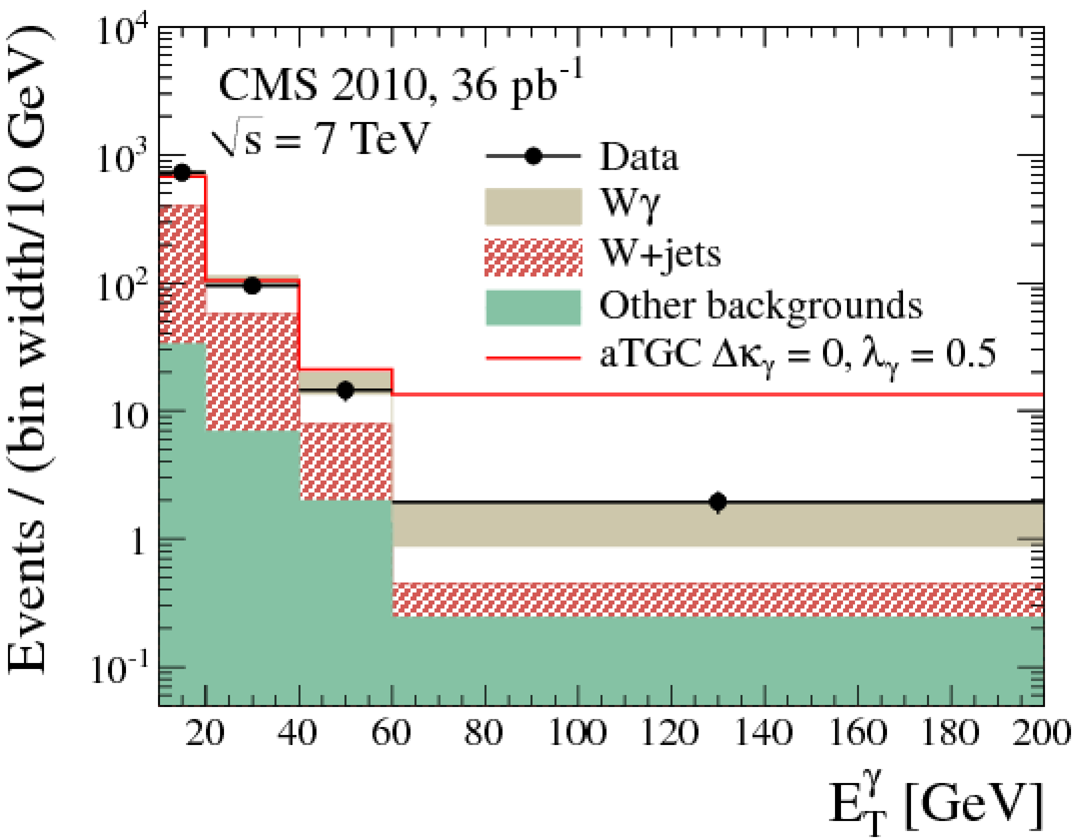
Smaller backgrounds

- $Z\gamma \rightarrow \gamma\ell\ell$ or $W\gamma \rightarrow \tau\,(\rightarrow \ell\nu_\ell\nu_\tau)\,\nu_\tau\gamma$
- Dibosons (WW, WZ, ZZ), $t\bar{t}$

Obtain from Monte Carlo

Wγ cross section

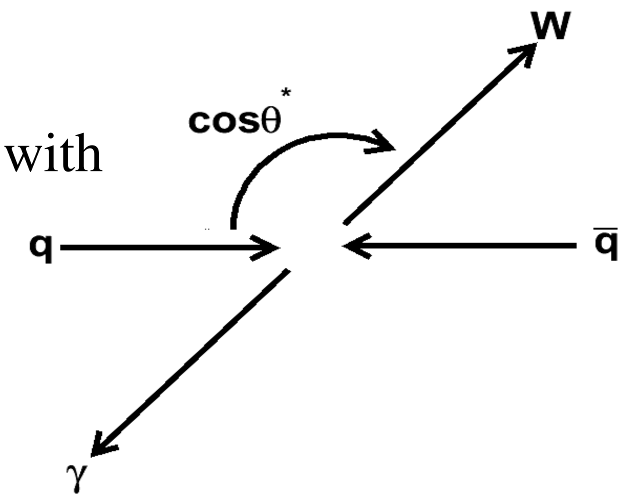
- Estimated cross section with $p_T^{\gamma} > 10$ GeV/c and $\Delta R(\ell,\gamma) > 0.7$
  $\sigma(pp \to W\gamma X) \times BR(W \to \ell\nu) = 55.4 \pm 7.2$ (stat.) ± 5.0 (syst.) ± 2.2 (lumi.) pb
- Standard Model prediction: 49.44 ± 3.8 pb.
- Standard Model prediction in good agreement with measured cross section.

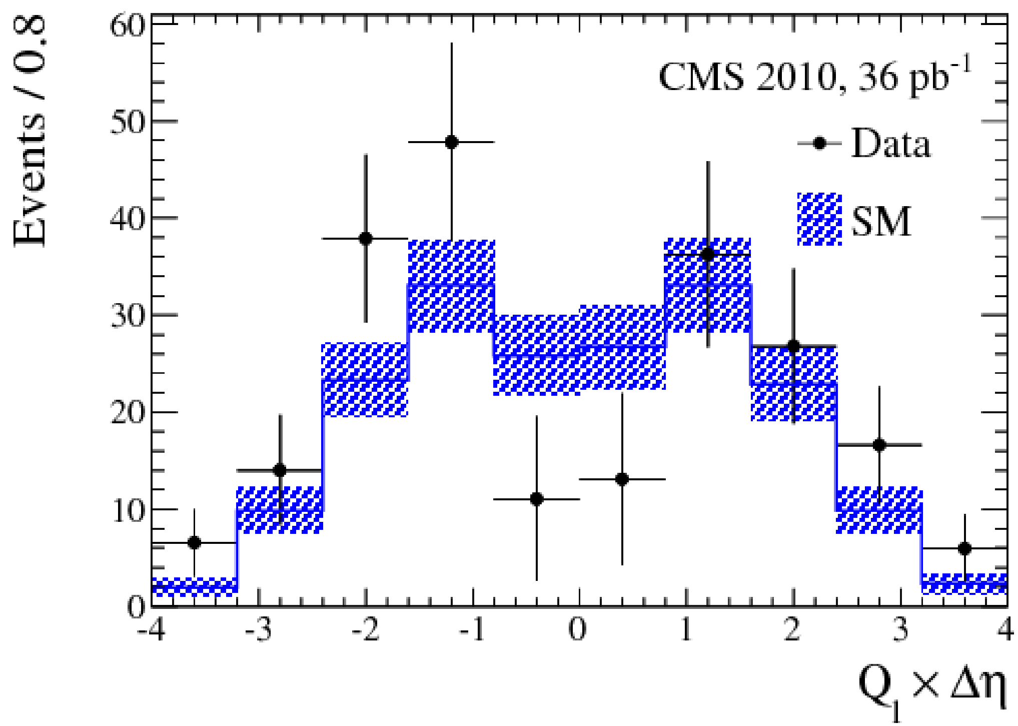


- **Systematic uncertainties:**
  - Background estimation:
    use ratio method
    - 6.3% (electron)
    - 6.4% (muon)
  - Photon energy scale:
    - 4.2% (electron)
    - 4.5% (muon)
  - Luminosity: 4%

The Radiation amplitude zero (*RAZ*)

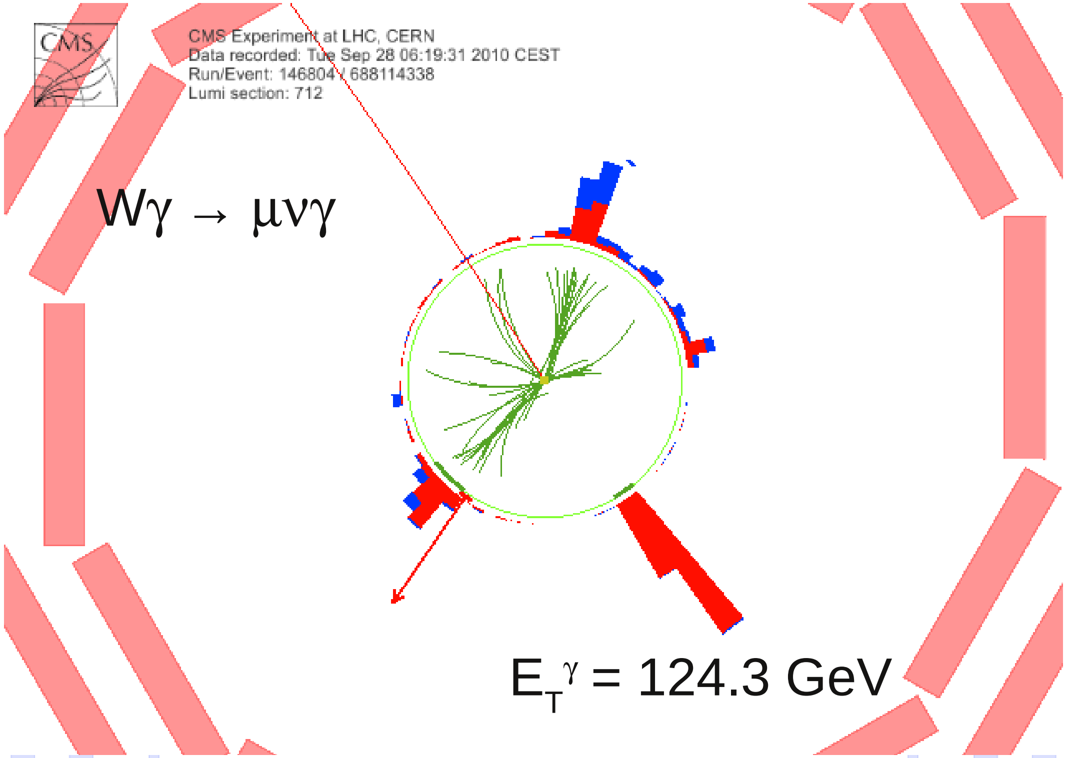
- Unique feature of W-boson coupling to massless photon.
- $\sigma(q_1 q'_2 \rightarrow W\gamma)$ vanishes at certain angles of W-boson with the quark. ($\cos\theta^* = \pm 1/3$).
- May vanish for non-Standard WWγ couplings.
- First study at LHC energy.
- Data consistent with SM *RAZ* within errors.

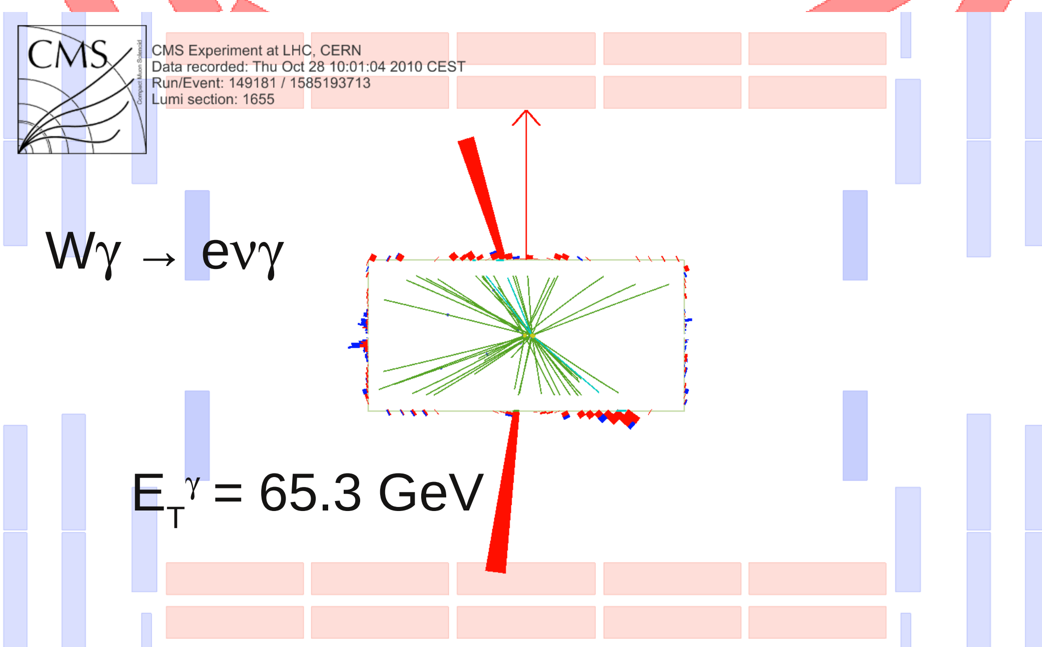




- Lab frame variable:
  - $Q_\ell \times (\eta_\gamma - \eta_\mu)$
- Data-Monte Carlo compatibility:
  - Kolmogorov-Smirnov test outcome is 57%

Conclusion

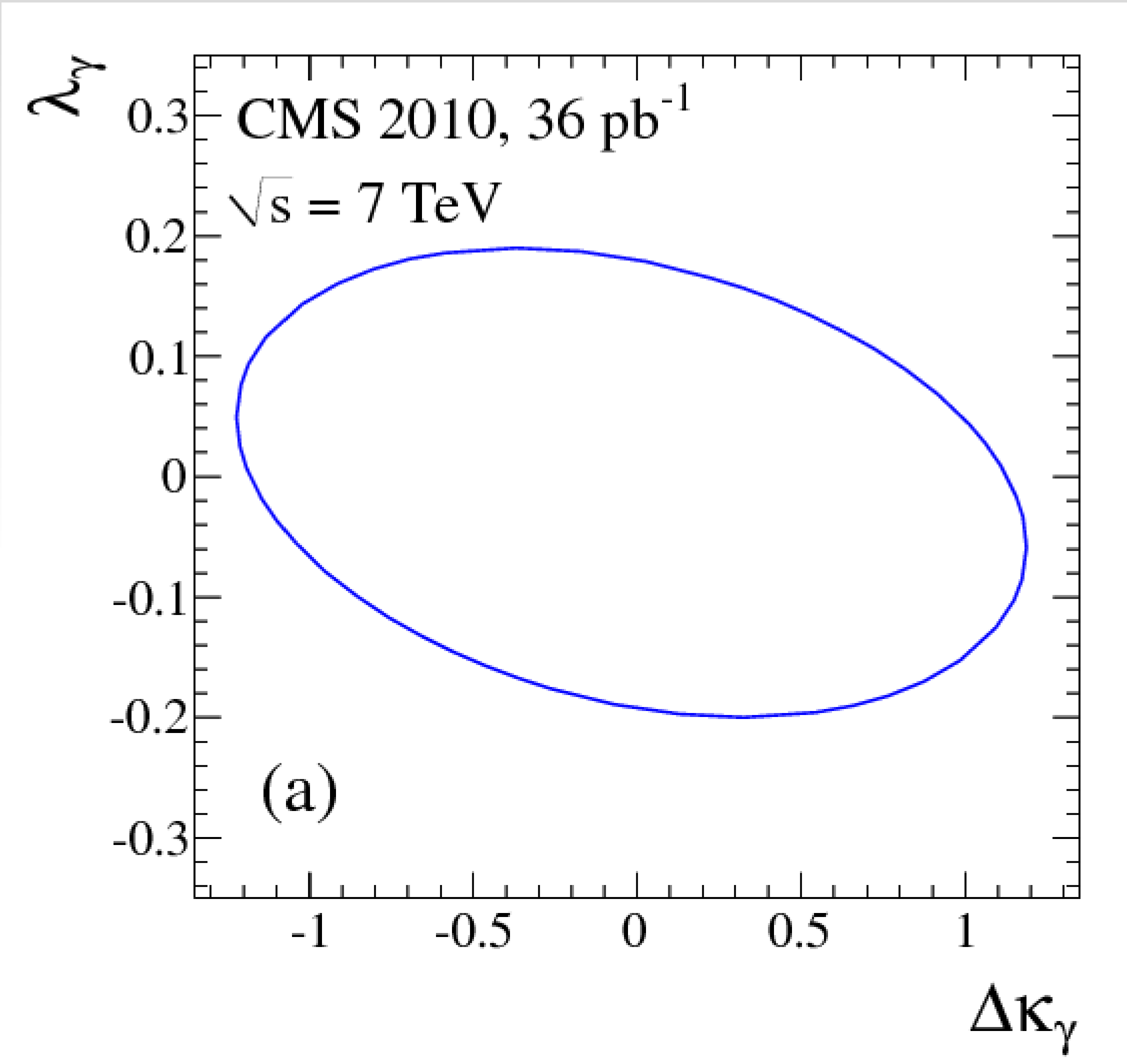




1. First observation of Wγ events at the LHC with W-boson decaying into electrons and muons.
2. Wγ cross section measured is in agreement with Standard Model predictions within measurement uncertainties.
3. First attempt at observing the Radiation amplititude zero feature of Wγ process.

Backup

Anomalous WWγ couplings



D0 limits (0.7 / fb)

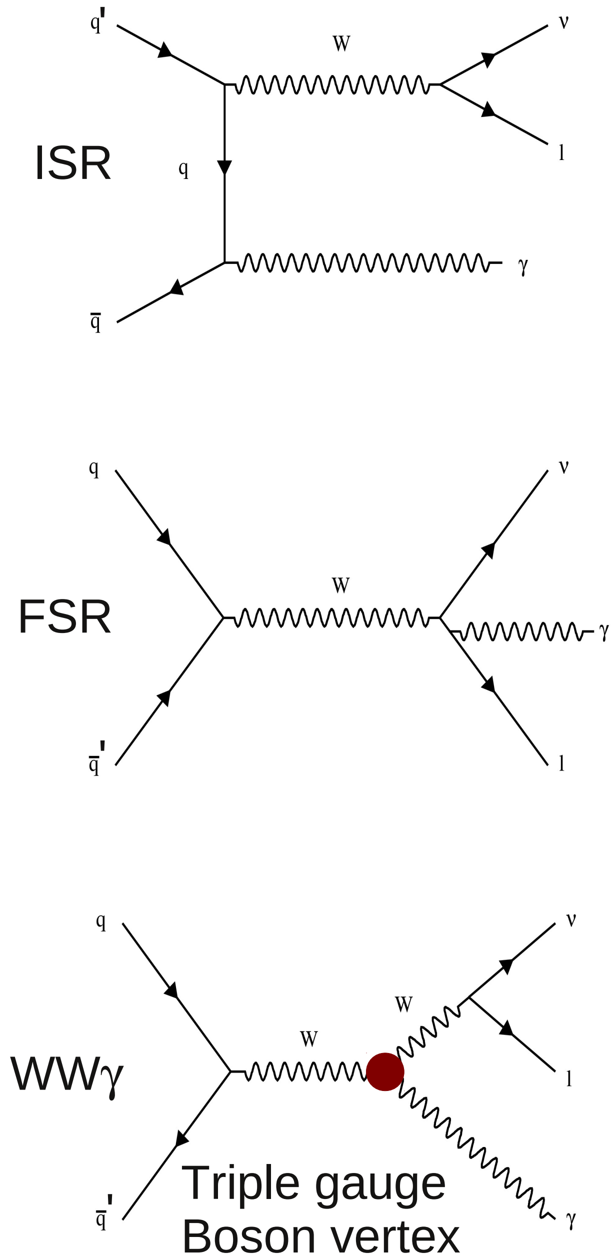
- $0.49 < \kappa < 1.51$
- $-0.12 < \lambda < 0.13$
- With form factor $\Lambda =$ 2 TeV

CMS limits (36 / pb)

- $-1.09 < \kappa < 1.03$
- $-0.18 < \lambda < 0.17$
- No form factor

Signal ($W\gamma \rightarrow \ell\nu\gamma X$) process

Born level diagrams

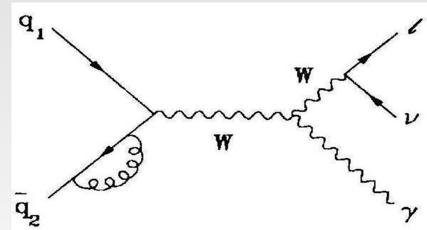


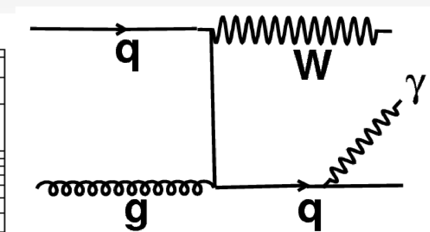
- Measure inclusive Wγ cross section with $W\rightarrow\ell\nu$:
  $pp\rightarrow W\gamma \rightarrow \ell\nu\gamma X$
  - X = mostly hadrons from underlying events and sometimes hard jets.
- LO cross section using PYTHIA = 23.2 pb
  with $p_T^\gamma > 10$ GeV/c
- PYTHIA does not have the FSR diagram.
- NLO cross-section = 49.44 ± 3.8 pb
  with $p_T^\gamma > 10$ GeV/c and $\Delta R(\mu,\gamma) > 0.7$
  - $\mathbf{\Delta R}_{\mu\gamma} = \sqrt{(\eta_\gamma - \eta_\mu)^{\mathbf{2}} + (\phi_\gamma - \phi_\mu)^{\mathbf{2}}}$
- NLO cross section calculated using Madgraph LO cross section scaled by mean k-factor of 1.29.
  - FSR photons k-factor from MCFM
  - WWγ and ISR k-factor (p_T^γ-dependent) from Baur.
  - Cross section error from k-factor (7%) and PDFs (2%)CTEQ61 PDF set used.

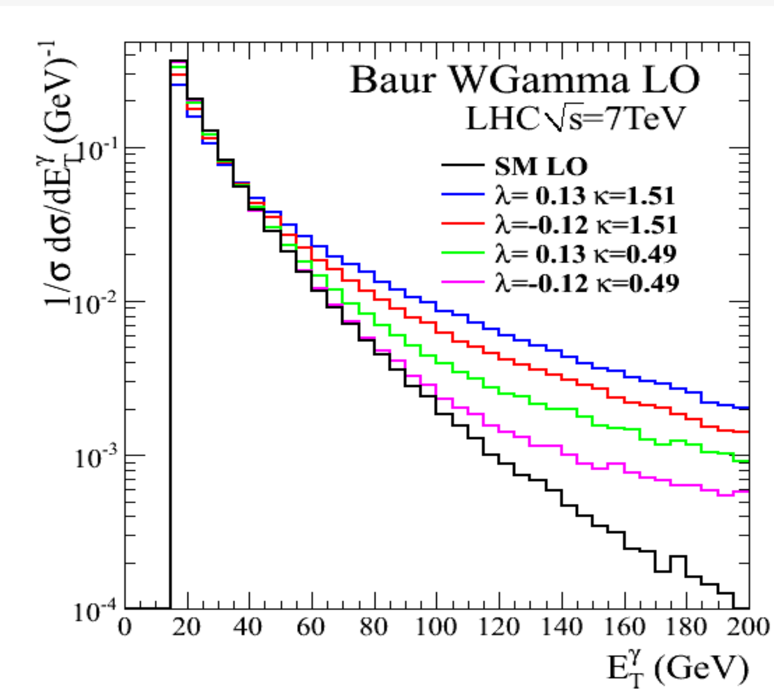
Measurement of Wγ cross-section

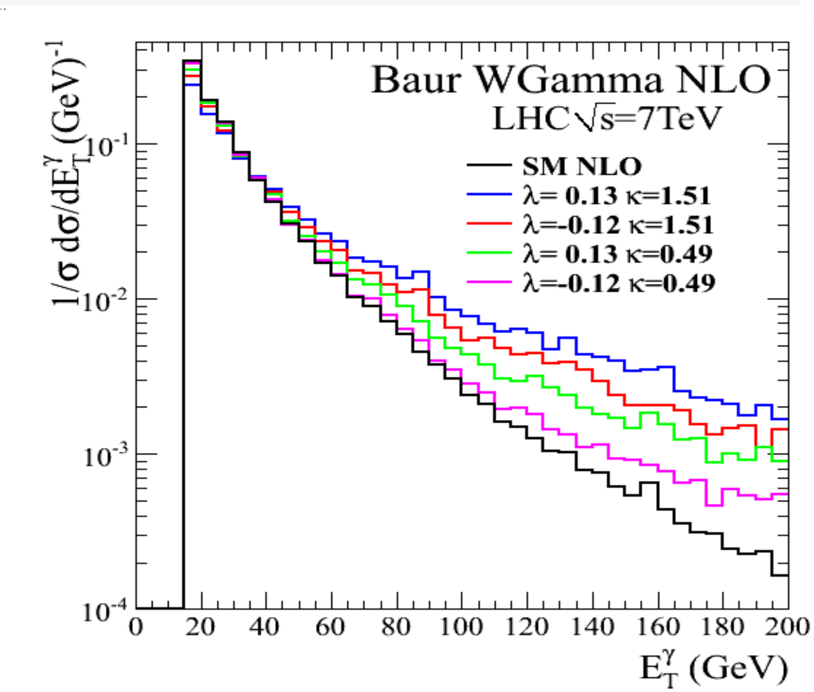
- Anomalous WWγ couplings increases the tail of p_T^γ spectrum
- QCD corrections (NLO effects) also enhances the p_T^γ s

Two competing effects:
Cross-section measurement 1st step towards aTGC measurement







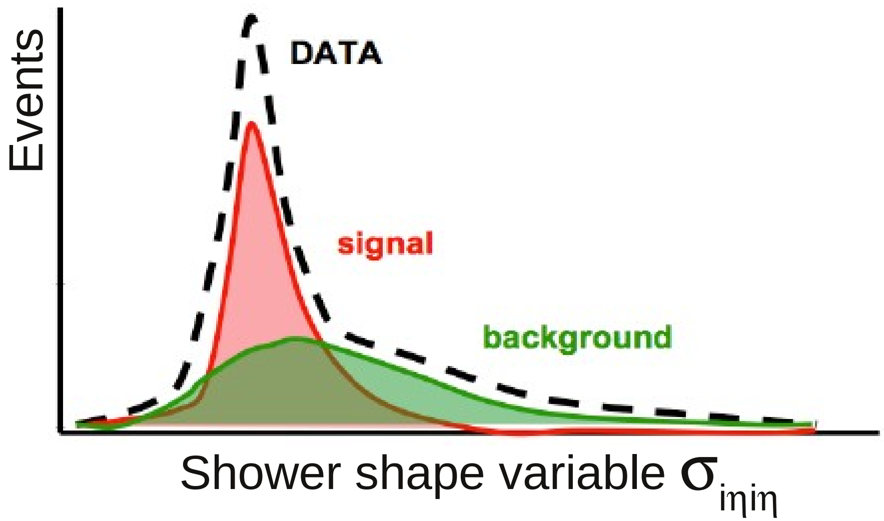


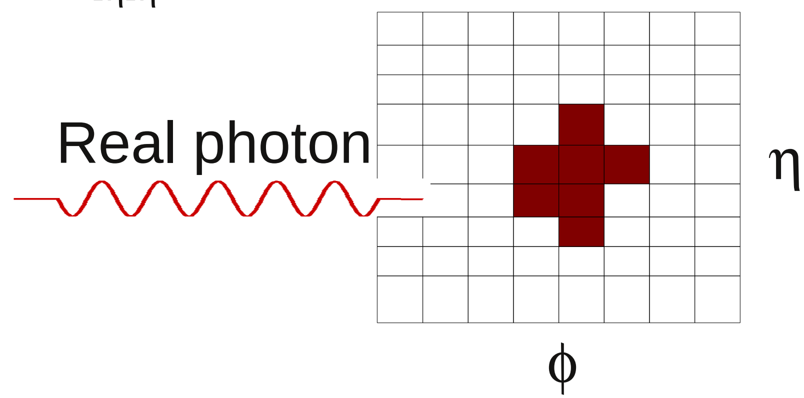
- **U. Baur, T.Han, J. Ohnemus, Phys. Rev. D, Vol. 48,11 (1993): QCD Corrections to hadronic Wγ production with nonstandard WWγ couplings.**

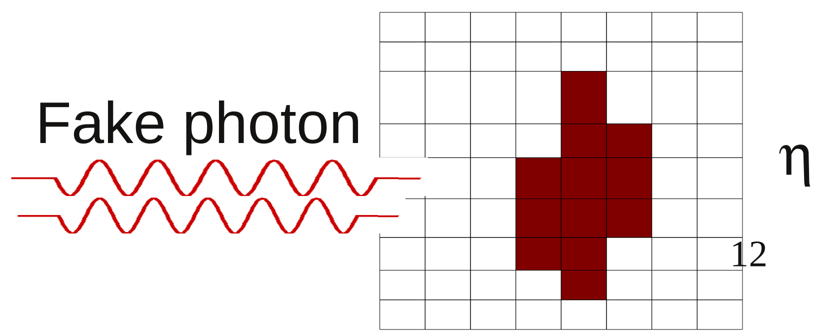
Estimating backgrounds from fake photons

- Template method:
  1. Choose variable with distinct shape for signal and background.
  2. Make templates for signal (real prompt photons)
  3. Make templates for fakes (from independent data sample)
  4. Fit simultaneously candidate events
- We make templates using a variable called $\sigma_{i\eta i\eta}$ (sigma i-eta i-eta)

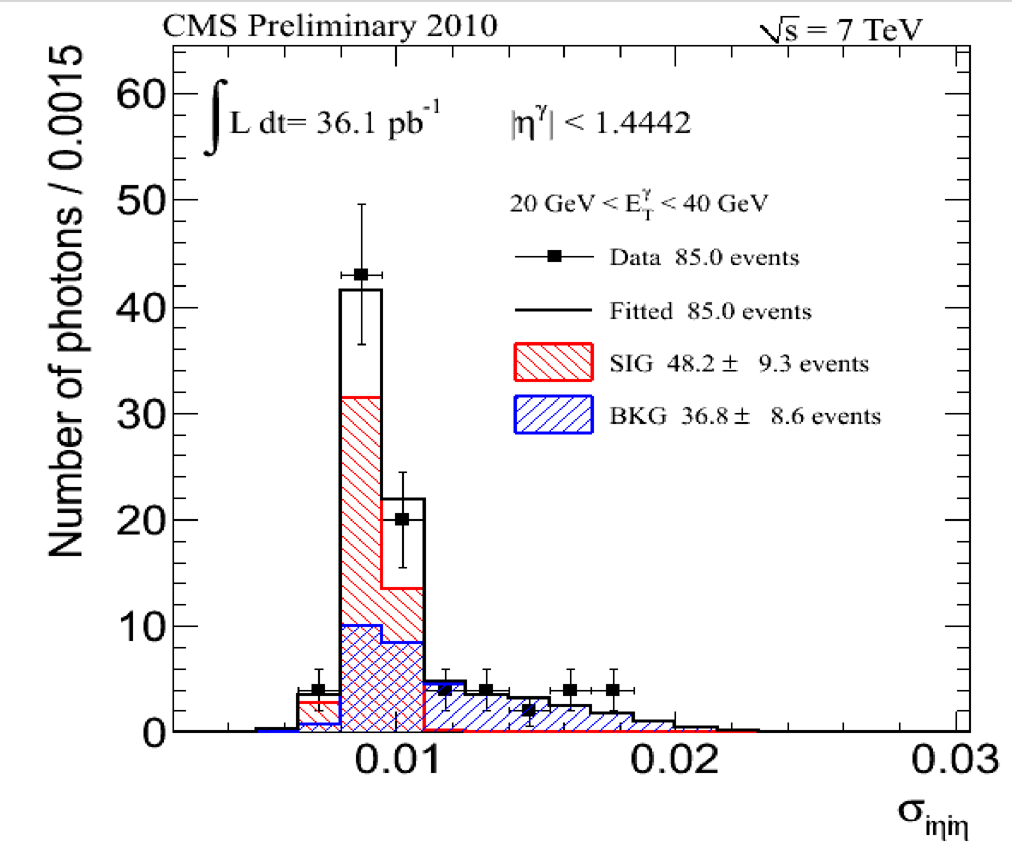
$$\sigma^{2}_{i\eta i\eta} = \frac{\sum_{\mathbf{i}}^{\mathbf{5\times5}} \mathbf{w_i}(i\eta_{\mathbf{i}} - i\eta_{\mathbf{seed}})^{\mathbf{2}}}{\sum_{\mathbf{i}}^{\mathbf{5\times5}} \mathbf{w_i}}$$







Fitting templates to data



- Make distribution of $\sigma_{i\eta i\eta}$ for signal and background in different E_T^{γ} ranges : 10-20 GeV, 20-40 GeV, 40-60 GeV, 60-200 GeV.
- Signal shapes are generated using Wγ Madgraph Monte Carlo.
- Background shapes are from data:
- Use jet-triggerred events:
  - Apply track isolation criteria:
    - 2 GeV < (Track Iso – 0.001 E_T^{γ}) < 5 GeV (barrel photons)
    - 2 GeV < (Track Iso – 0.001 E_T^{γ}) < 3 GeV (endcap photons)

- Fit the $\sigma_{i\eta i\eta}$ distribution from data with the signal and background templates using a binned extended maximum likelihood fit.
  - This gives the number of signals (N_S) and background (N_B) in data.

$$\mathcal{L} = -\mathbf{lnL} = (\mathbf{N_S} + \mathbf{N_B}) - \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{N_i ln}(\mathbf{N_S S_i} + \mathbf{N_B B_i})$$

Estimating backgrounds from fake photons using *Ratio Method*

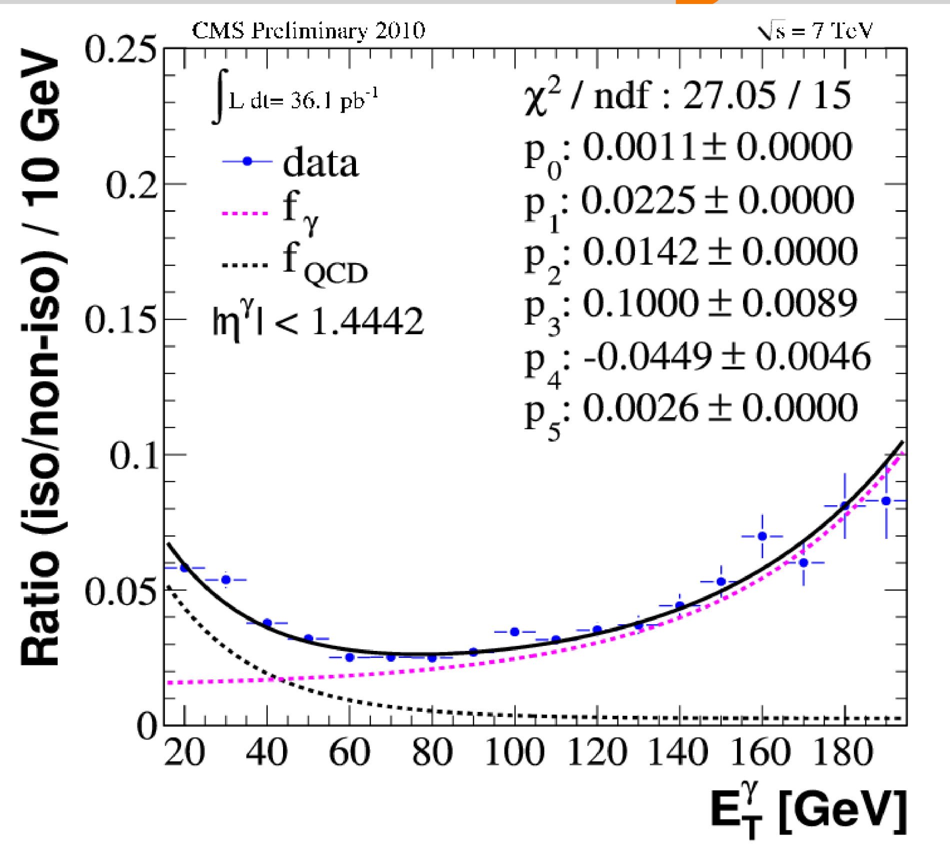
- Exploit the fact that the ratio of fake to real photons are same in W+jets and QCD multijet processes
- Define two selection for photon objects

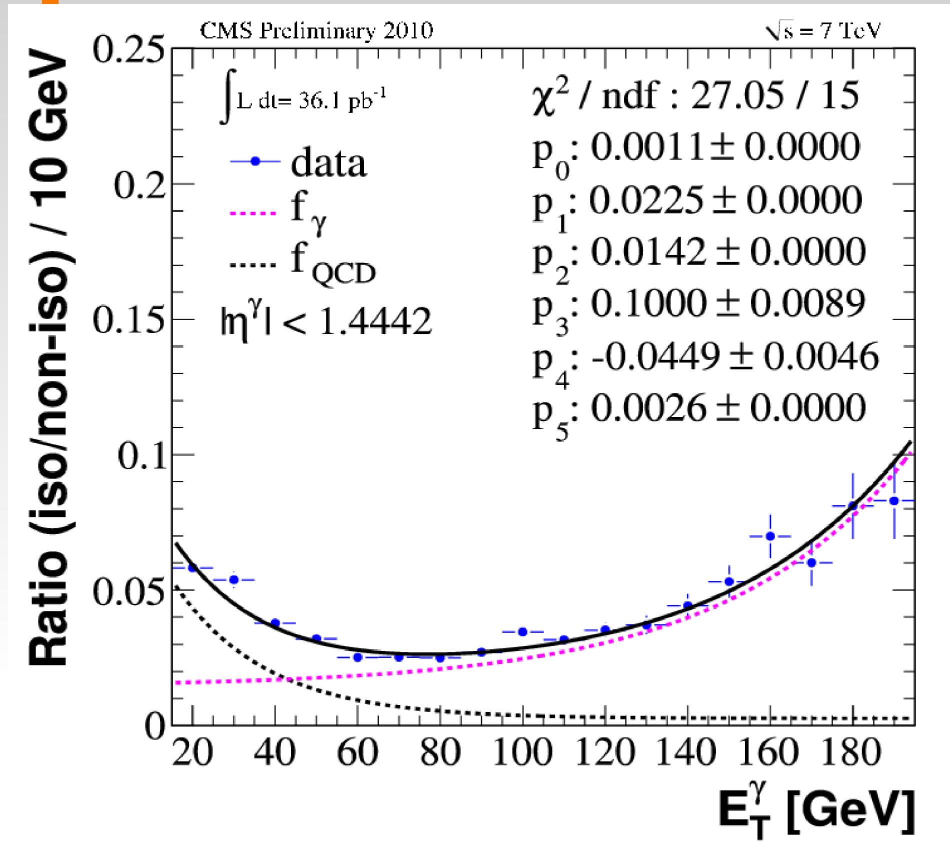
  Selection 1. Tight selection (photon selection for Wγ events)

  Selection 2. *Flipped isolation:* (Track Iso – 0.001 E_T^{γ}) > 3 GeV

- Ratio $r = \dfrac{\text{No. of events passing Selection 1}}{\text{No. of events passing Selection 2}}$
- Measure ratio *r* in jet-triggered QCD multijet sample in data.
- $N_{\text{fake}\ \gamma} = r.N^{\text{W+jets}}_{\text{Flipped isolation}}$
- The ratio *r* is determined by fitting a function:
  - $r = p_0 + p_1 exp(p_2 E'),\ E' = E_T^{\text{fake}\ \gamma}$

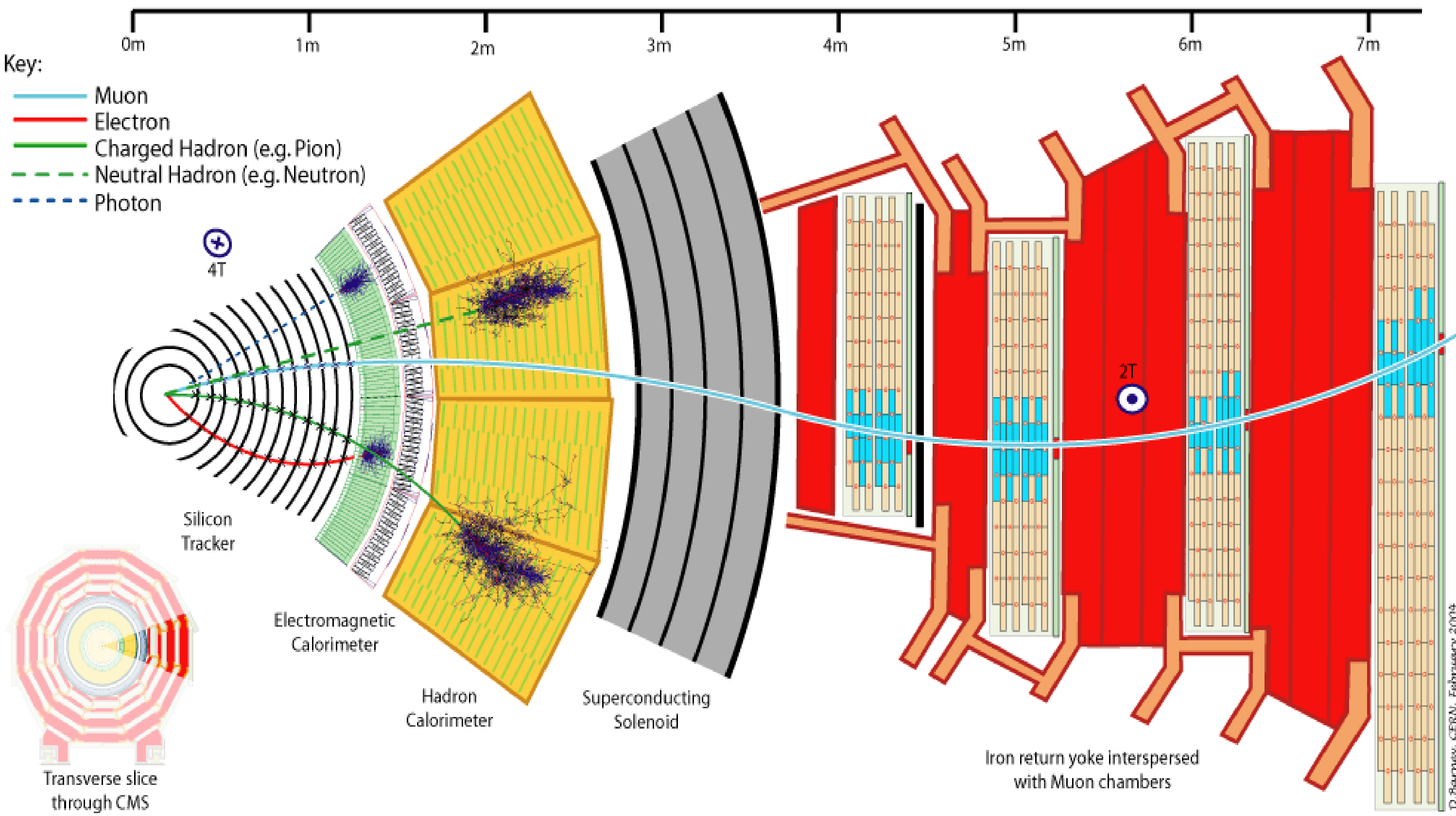
Getting ratio parameters

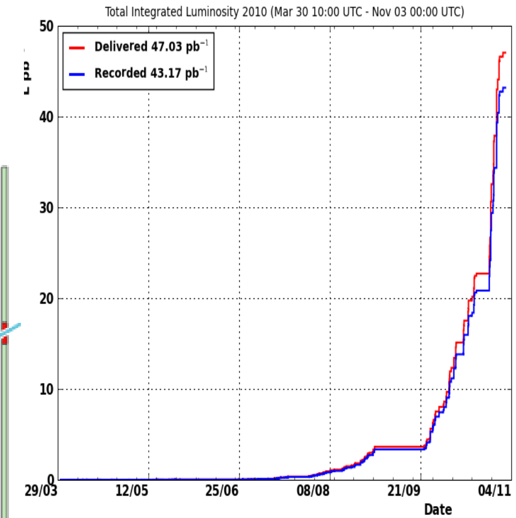




- Ratio r modelled as $f = r_{QCD} + r_{photon}$ since in data the QCD samples also contain real prompt photon.
- Iterative fit of ratio distribution in data with function f to obtain ratio parameters corresponding to r_{QCD}
- Use r_{QCD} and $N^{W+jets}_{flipped\ isolation}$ to estimate number of fake photons in selected Wγ candidate events.

The CMS detector





This analysis: uses 36.1pb^{-1} Integrated luminosity

CMS: general purpose detector

Approximate scale:

66M pixel channels, 10M tracker channels,
76k ECAL crystals, 150k silicon preshower channels,
15k HCAL channels,
250 DT chambers (170k wires), 470 CSC chambers (200k wires), 900 RPCs

Good muon selection

1. Highest p_T muon in event should be matched to HLT muon
2. |d0(PV)| < 2 mm
3. Muon should be reconstructed both in the tracker and muon chamber.
4. Global track χ^2/ndf > 10
5. Muon kinematics: $p_T^\mu > 20$ GeV/c and $|\eta^\mu| < 2.1$
6. Muon ID:
   - Pixel hits > 0 and Tracker hits > 10
   - Muon chamber hits > 0 and Matched muon segments > 1
7. Muon Isolation: (energy deposit in tracker+ ECAL+ HCAL in a cone of $\Delta R < 0.3$ around the muon's direction) less than 15% of p_T^μ

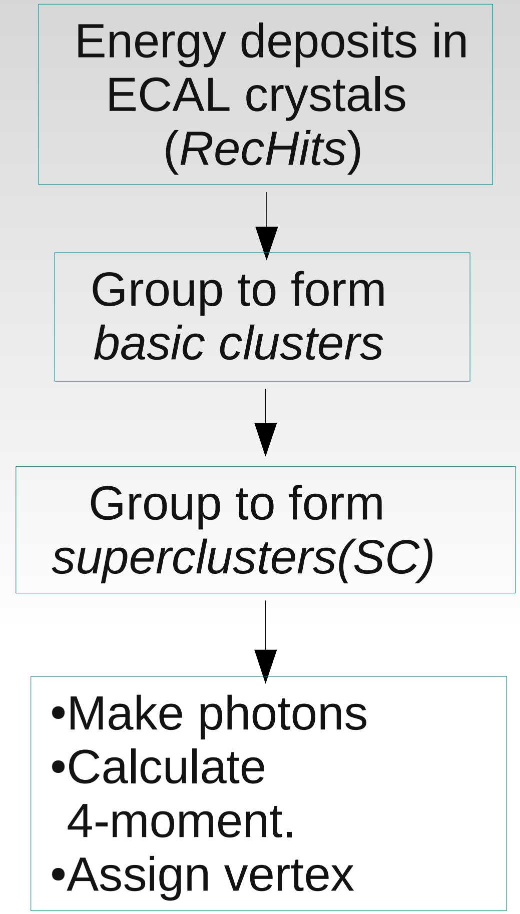
Good electron selection

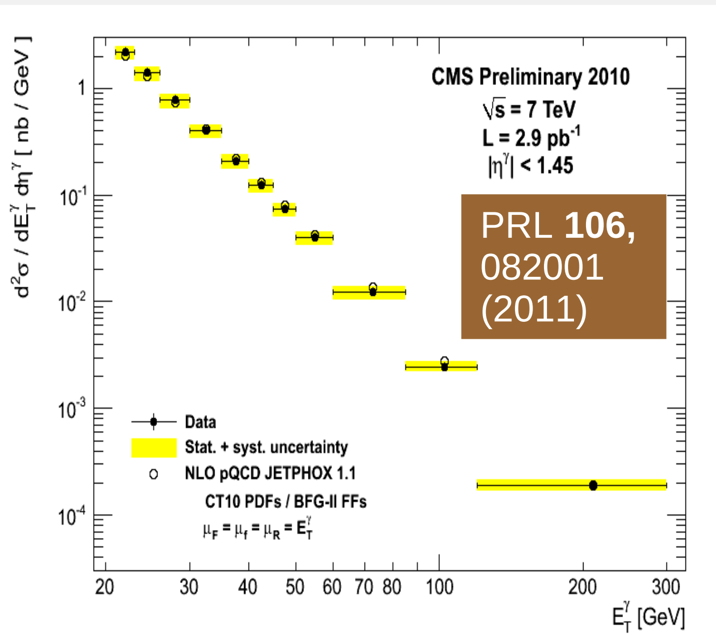
- $p_T^e > 20$ GeV in ECAL fiducial volume
- Relative isolation
- Conversion suppression
- Track-ECAL cupercluster matching
- Separate electron ID for barrel and endcap

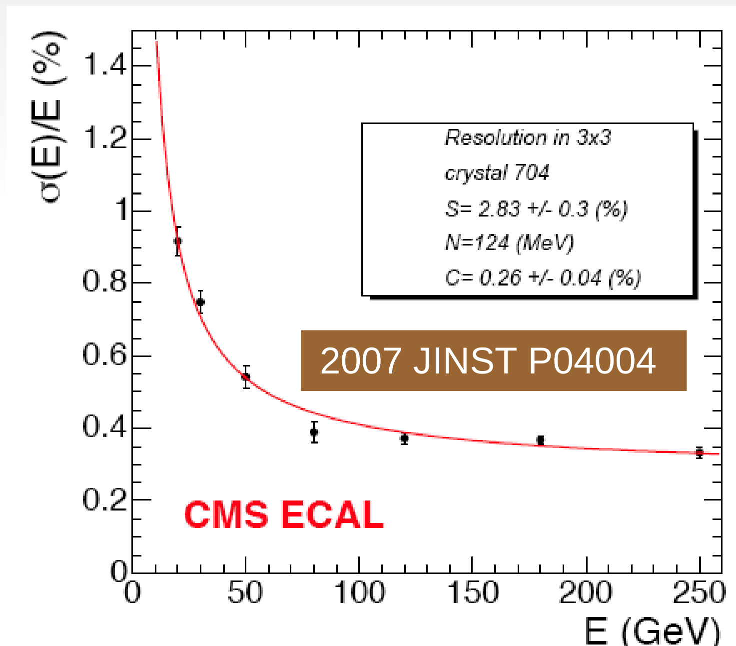
	WP95		WP80	
	Barrel	Endcap	Barrel	Endcap
I_{trk}/E_T	0.15	0.08	0.09	0.04
I_{ECAL}/E_T	2.0	0.06	0.07	0.05
I_{HCAL}/E_T	0.12	0.05	0.10	0.025
Missing hits $\leq$	1	1	0	0
Dcot	–	–	0.02	0.02
Dist	–	–	0.02	0.02
$\sigma_{i\eta i\eta}$	0.01	0.03	0.01	0.03
$\Delta\phi_{in}$	0.8	0.7	0.06	0.03
$\Delta\eta_{in}$	0.007	0.01	0.004	0.007
H/E	0.15	0.07	0.04	0.025

Photon reconstruction

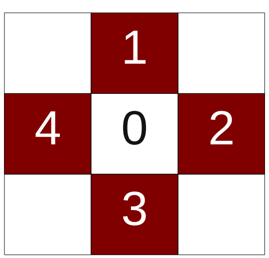
- CMS ECAL coverage: $|\eta| < 3$
- For measurement:
  - Barrel (EB): $|\eta| < 1.4442$ Encap(EE): $1.566 < |\eta| < 2.5$
- 76K $PBWO_4$ crystals, $26X_0$ long
- Preshower detector in front of endcap , made of Pb absorbers and Si strip detectors for better γ-π separation







$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.83\%}{\sqrt{E}}\right)^2 + \left(\frac{124\text{MeV}}{E}\right)^2 + (0.26\%)^2$$



Spike cleaning:

•Remove ”spikes”: energy deposited by heavily ionizing particles in the avalanche photodiode.

- Energy in 0 < 95% of energies in (1+2+3+4)

Good Photon selection

1. Photon ID: H/E < 0.05 for the photon supercluster.
2. No hits in the pixel detector: removes electron background.
3. Photon Isolation:
   - (Track Iso - 2.2) < 0.001*E_T^γ
     - Annulus 0.04 < ΔR < 0.4 excluding $\Delta\eta\times\Delta\phi$ = 0.015×0.4
   - (ECAL Iso - 4.2) < 0.006*E_T^γ
     - Annulus 0.06 < ΔR < 0.4 excluding $\Delta\eta\times\Delta\phi$ = 0.04×0.4
   - (HCAL Iso - 2.2) < 0.0025* E_T^γ
     - Annulus 0.15 < ΔR < 0.4
4. $\sigma_{i\eta i\eta}$ < 0.013 for barrel and $\sigma_{i\eta i\eta}$ < 0.03 for endcap photons where

$$\sigma^2_{i\eta i\eta} = \frac{\sum w_i(\eta_i - \bar{\eta})^2}{\sum w_i}, \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i} \quad w_i = \max(0, 4.7 + \log(E_i/E))$$

sum over 5x5 crystal array

5. Photon kinematics: E_T^γ > 10 GeV and $|\eta^\gamma|$ < 2.5
   - Photons in barrel-endcap gap (1.4442 < $|\eta^\gamma|$ < 1.566) are removed