Photon Measurements in the CMS Experiment at the LHC

Kadir Ocalan
Physics Dept., METU
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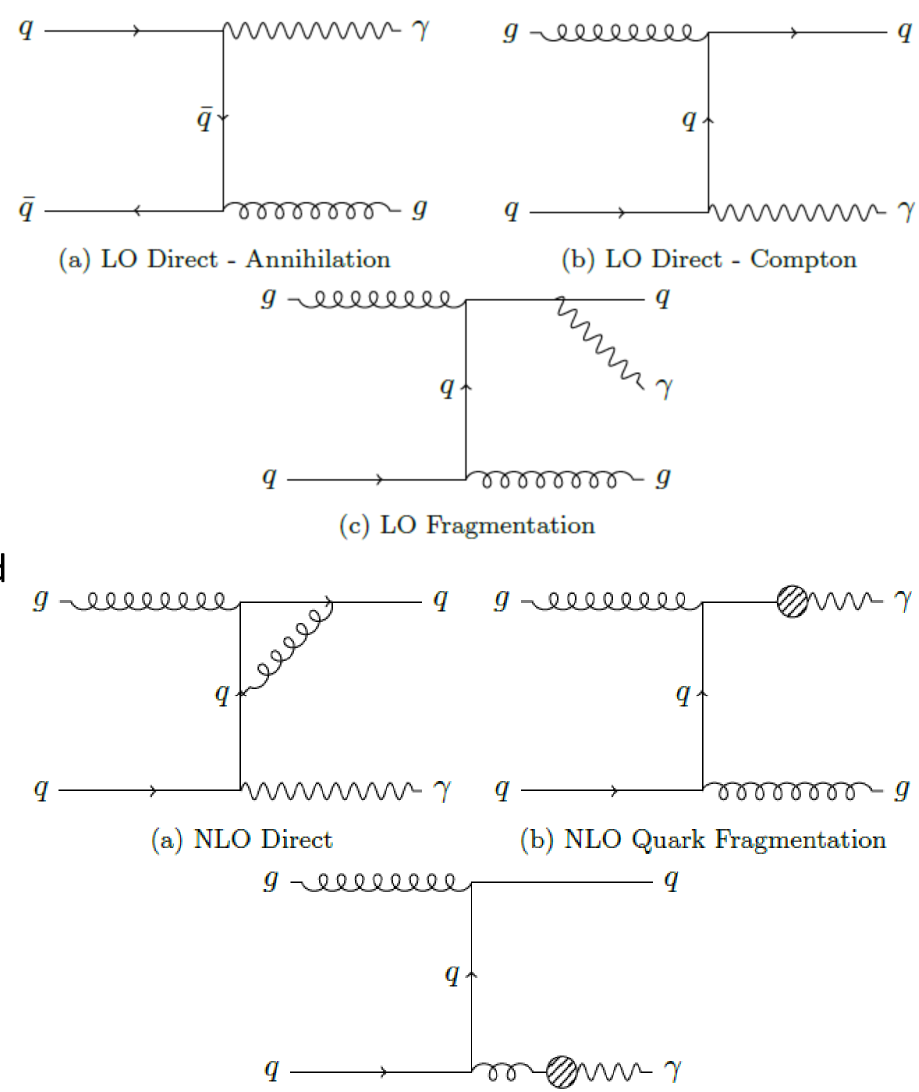


(a) LO Direct - Annihilation (b) LO Direct - Compton

(c) LO Fragmentation

(a) NLO Direct (b) NLO Quark Fragmentation

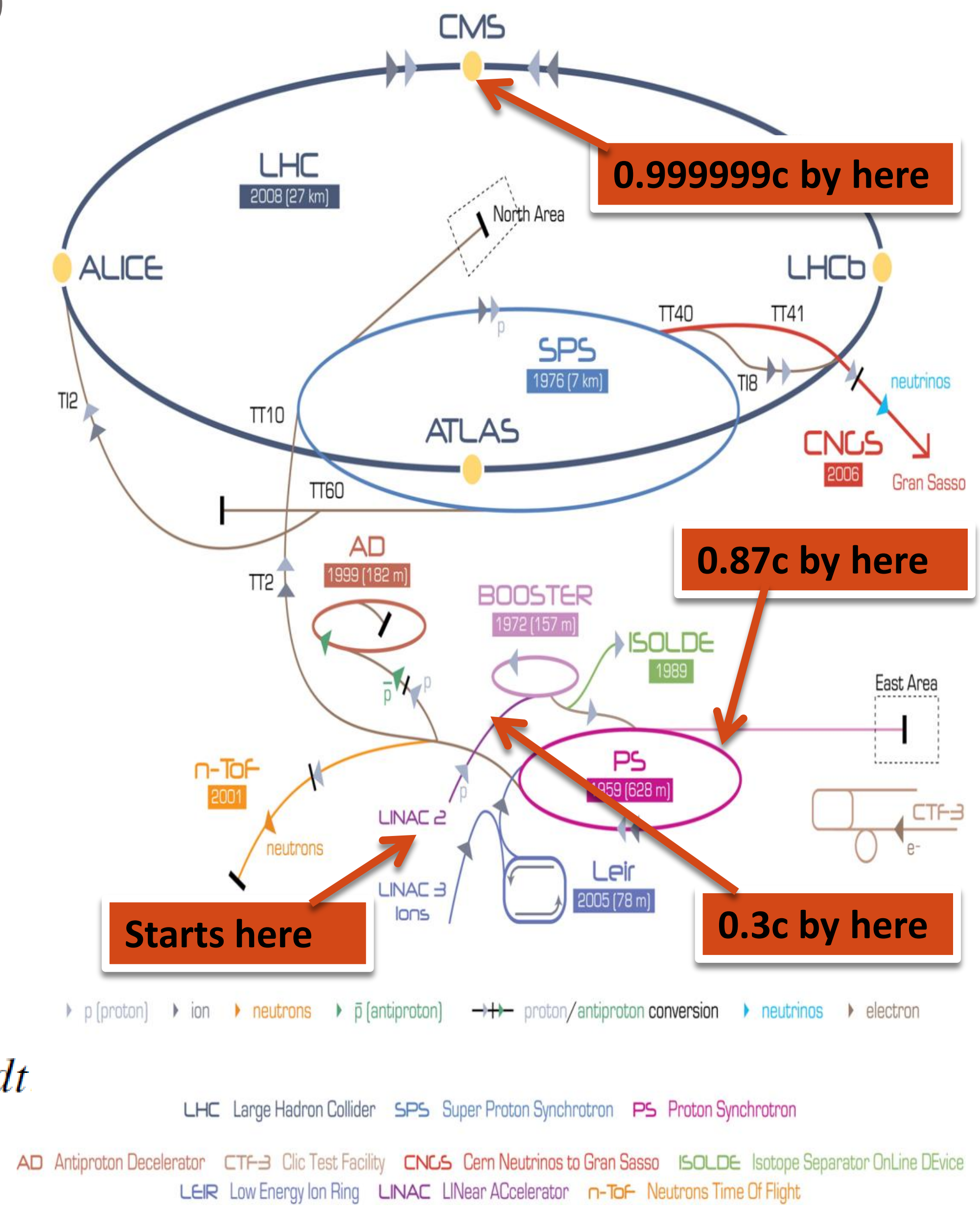
(c) NLO Gluon Fragmentation

2. Experimental Setup

- Large Hadron Collider (LHC)
  - 7 TeV p-p collider (14 TeV design)
    - 4T magnet (8T design)
    - Circumference of 27 km
    - 1232 dipoles (NbTi) for steering
    - 392 quadrupoles for focusing
  - Luminosity of **3.5×10^{33} cm^{-2}s^{-1} (2011)**
    - Design: 10^{34} cm^{-2}s^{-1}
  - Acceleration process
    - Linac2, produces 50 MeV protons
    - PSB increases energy to 1.4 GeV
    - PS increases energy to 24 GeV
    - SPS increases energy up to 450 GeV
  - Luminosity calculation

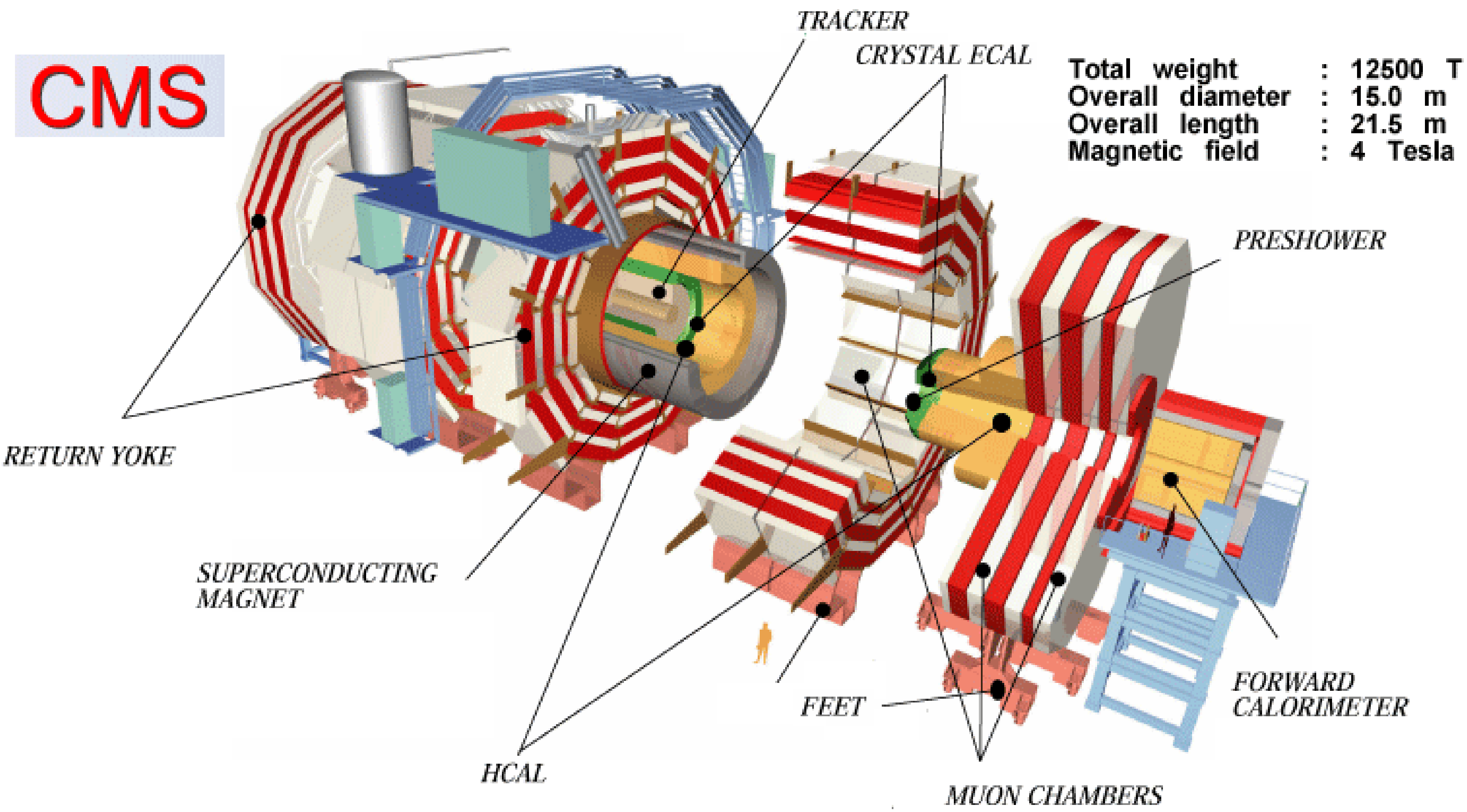
$$\mathcal{L} = \frac{N_b^2 \cdot n_b \cdot f}{A_{eff}} \quad A_{eff} = \frac{4\pi \cdot \epsilon_n \cdot \beta^\star}{\gamma_r \cdot F}$$

    - Integrated Luminosity (L) $L = \int \mathcal{L}dt$



2. Experimental Setup

- Compact Muon Solenoid (CMS)

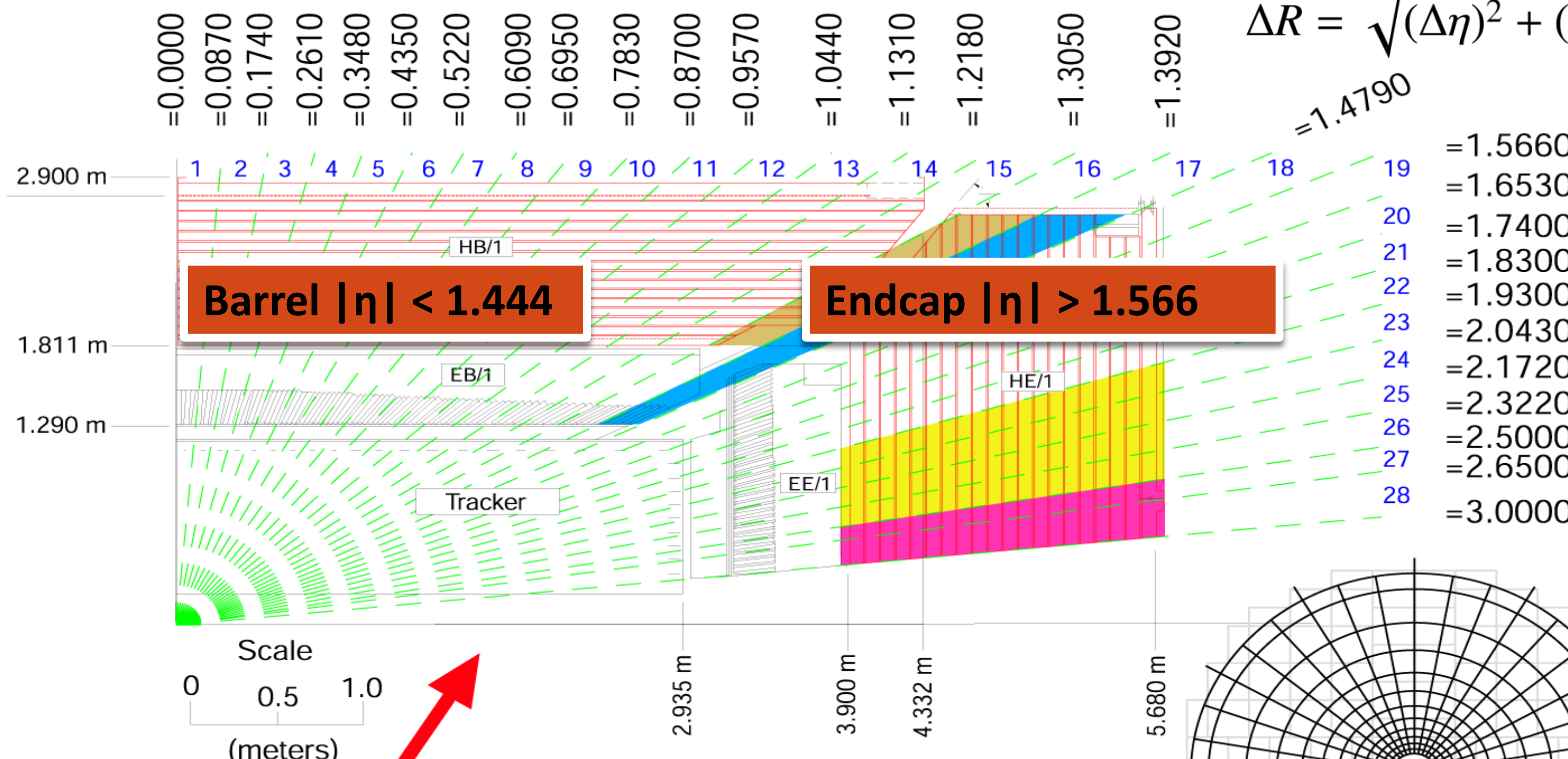


2. Experimental Setup

- CMS Geometry (η-ϕ space)

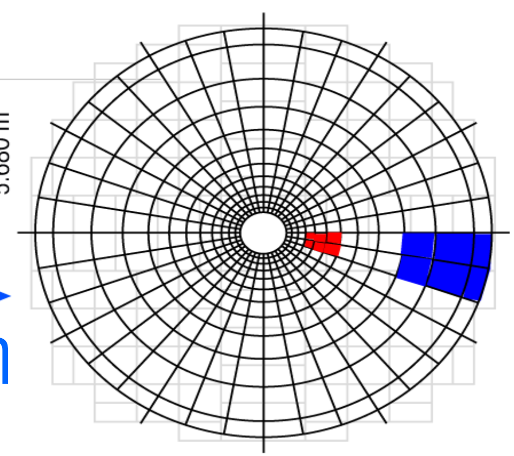
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

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



Barrel & Endcap:
E & H: 72 φ x 56 η
(|η| < 3.0)

Forward:
H only: 18 φ x 4 η
(3.0 < |η| < 5.0)

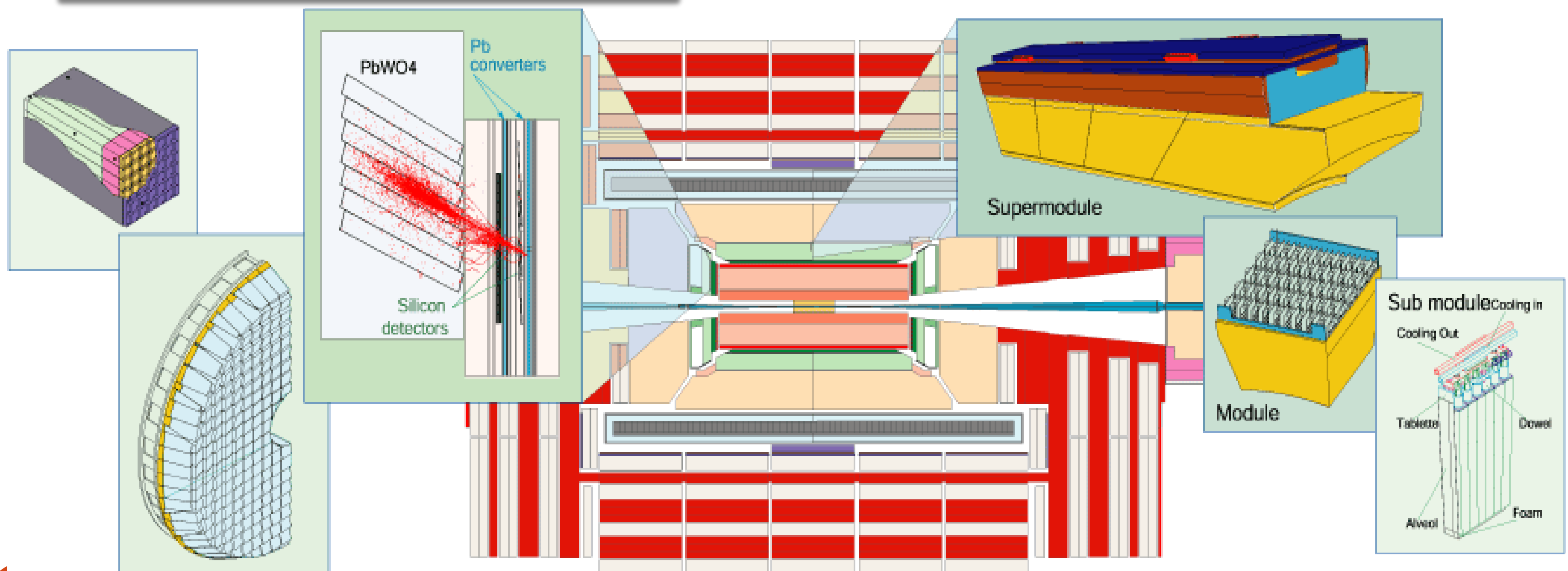


2. Experimental Setup

- CMS Electromagnetic Calorimeter (ECAL)
  - Measures e/γ energy using 76,832 lead tungstate ($PbWO_4$) crystals
  - Energy of photons from the energy deposit of groups of crystals (superclusters)

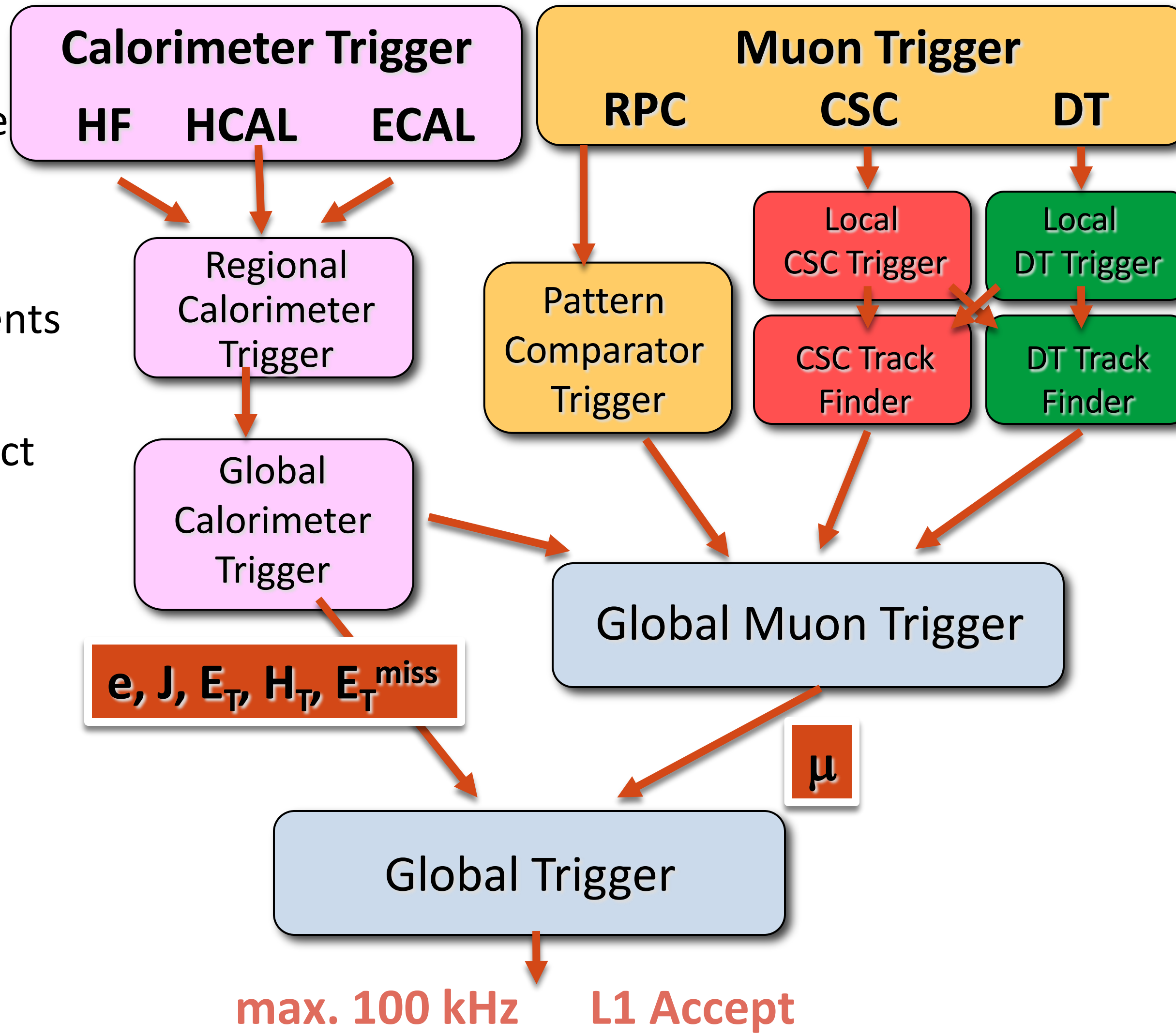
Lead tungstate crystals:
Density 8.3 g/cm3
Molière radius 2.2 cm
Radiation length 0.89 cm
Crystal size: 2.2x2.2 cm x 25.8 X_0

ECAL coverage extends to |η|<2.5



2. Experimental Setup

- Level-1 Trigger (L1)
  - 40 MHz frequency collision rate needs to be reduced (~25 ns bunch crossings), not all of the 0.25 MB events can be stored
  - L1 trigger electronics select **50-100 kHz** of interesting events
  - Triggers
    - Electron/photon
      - 12 or 15 GeV
      - ~100% efficient
    - Jets
    - Missing E_T
    - Muon



2. Experimental Setup

- High Level Trigger (HLT)
  - Software trigger
    - Multi-processor farm
    - Reduces Level-1 rate from 100kHz to 300 Hz
    - Processes events every 40 ms (compared to L1 in 3.2 μs)
  - Photon HLT
    - Start from L1 electron/photon seed (E_T = 12 or 15 GeV)
    - Energy deposits (superclusters) in the ECAL
      - H/E < 0.05
    - Track reconstruction
    - Match ECAL and track information
    - Required 20, 30, 50, 75, 90, 125, 135 or 400 GeV photon (2011)
      - Additional selection applied as the luminosity increased
      - 2011 HLT photon paths are highly prescaled
      - Photon isolation cuts applied at the HLT level (more on this later)

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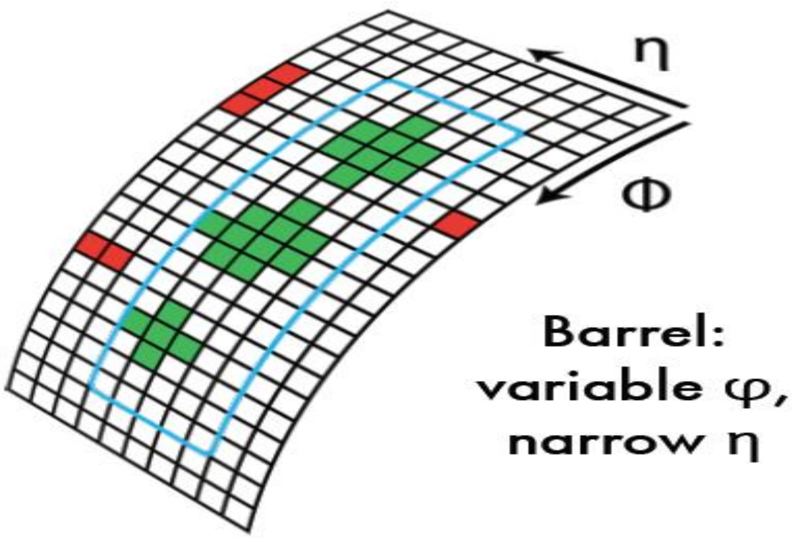
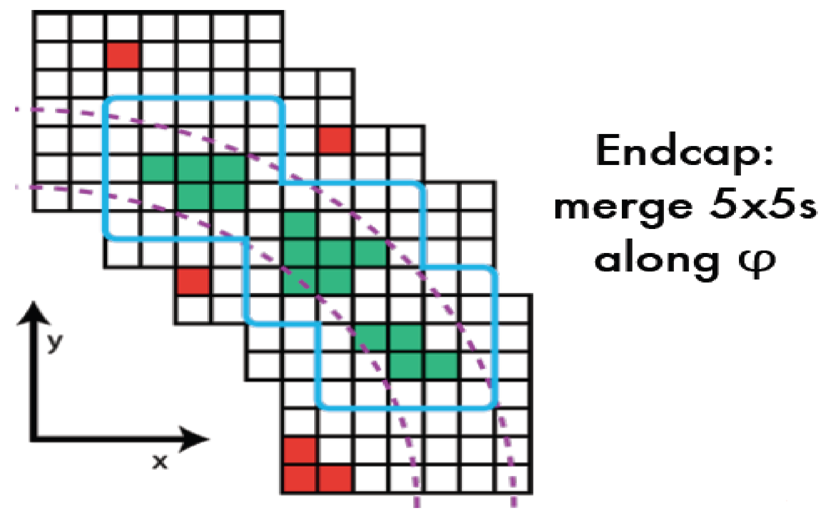
3. Photon Measurements in the CMS

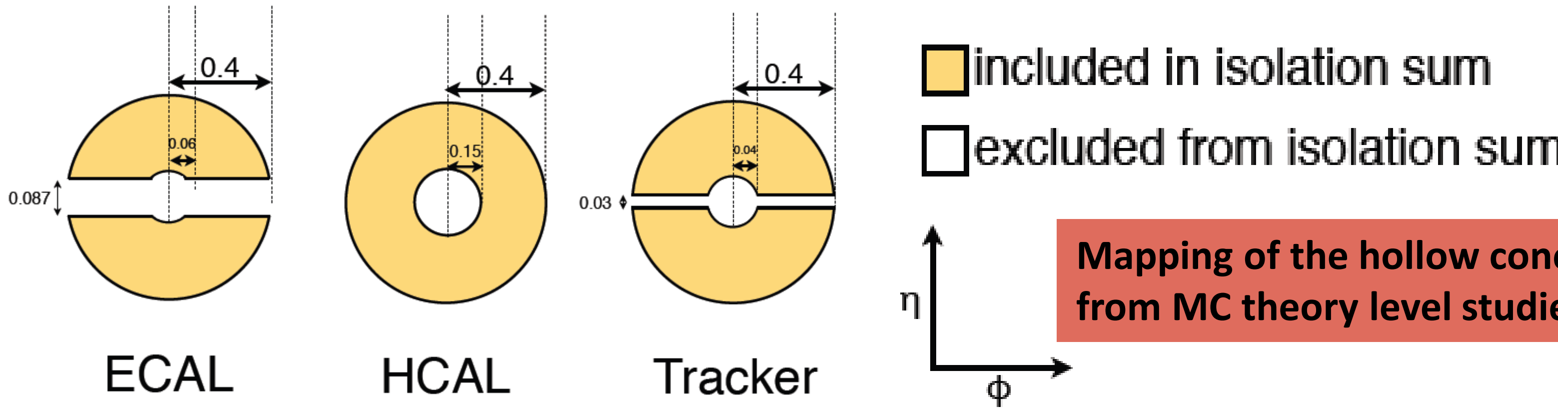
- Photon Reconstruction
  - Reconstructed from superclusters of the ECAL
    - In the ECAL barrel region (|η| < 1.4442), 35 crystals wide in ϕ and 5 crystals in η
    - In the ECAL endcap region (1.566 < |η| < 2.5), arrays of 5x5 crystals
    - Similar with electron reconstruction
    - Hybrid (in Barrel) and Multi5x5 (in Endcap) clustering algorithms are used
    - Energy is corrected for better resolution (the material losses in front of the tracker)





3. Photon Measurements in the CMS

- Photon Identification
  - Jet background ($\pi^0, \eta \rightarrow \gamma\gamma$) needs to be suppressed by limiting the energy of other particles surrounding photon in different sub-systems.
  - Different isolation variables are used, **H/E, ECAL Iso, HCAL Iso, TRACK Iso**



Mapping of the hollow cones comes from MC theory level studies

  - Shower shape varible:

$$\sigma^2_{i\eta i\eta} = \frac{\sum_i^{5\times5} w_i(\eta_i - \overline{\eta}_{i5\times5})^2}{\sum_i^{5\times5} w_i}, w_i = max(0, 4.7 + ln\frac{E_i}{E_{5\times5}})$$

Transver se shape of the supercluster in η direction

  - Pixel seed match veto: ensures that background from electrons no longer contaminate signal photon spectra

3. Photon Measurements in the CMS

- Signal Extraction Templates
  - Photon ID selection might not make sure fully that neutral hadrons do not fake prompt photon signal, so templates are developed.
  - Two complementary templates are used
  - Shower Shape template
    - Use $\sigma_{i\eta i\eta}$ and apply calorimetric isolation to fit by the extended maximum likelihood method to extract photon signal
  - Isolation template
    - Use **Sum Iso** and apply shower shape varibale cut to fit by the ARGUS function and Lifetime function with Gaussian distribution to have signal photon yield

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

Minimization of maximum likelihood function

$$S(x) = \frac{1}{p_0} \times e^{(p_2^2/2p_0^2)-((x-p_1)/p_0)} \times [1 - Freq(p_2/p_0 - (x-p_1)/p_2)]$$

$$B(x) = \left[1 - e^{p_3(x-p_4)}\right] \times [1 - p_5(x-p_4)]^{p_6}$$

Lifetime fnc. for signal and ARGUS fnc. for background

3. Photon Measurements in the CMS

- Signal Extraction Templates
  - Shower Shape template selections

Variable	Selection
pixel seed	require none
Tracker Isolation	$< 2.0 + 0.002 \cdot E_T^\gamma$ GeV
ECAL Isolation	$< 4.2 + 0.012 \cdot E_T^\gamma$ GeV
HCAL Isolation	$< 2.2 + 0.005 \cdot E_T^\gamma$ GeV
H/E	< 0.05

Photon ID signal selection for SS

Variable	Selection
pixel seed	require none
Tracker Isolation	$> 2.0 + 0.002 \cdot E_T^\gamma$ GeV
Tracker Isolation	$< 5.0 + 0.002 \cdot E_T^\gamma$ GeV
ECAL Isolation	$< 4.2 + 0.012 \cdot E_T^\gamma$ GeV
HCAL Isolation	$< 2.2 + 0.005 \cdot E_T^\gamma$ GeV
H/E	< 0.05

Photon ID side-band selection for SS

  - Isolation template selections

Variable	Selection
pixel seed	require none
$\sigma_{i\eta i\eta}$ (Barrel)	< 0.01
$\sigma_{i\eta i\eta}$ (Endcap)	< 0.028
H/E	< 0.05

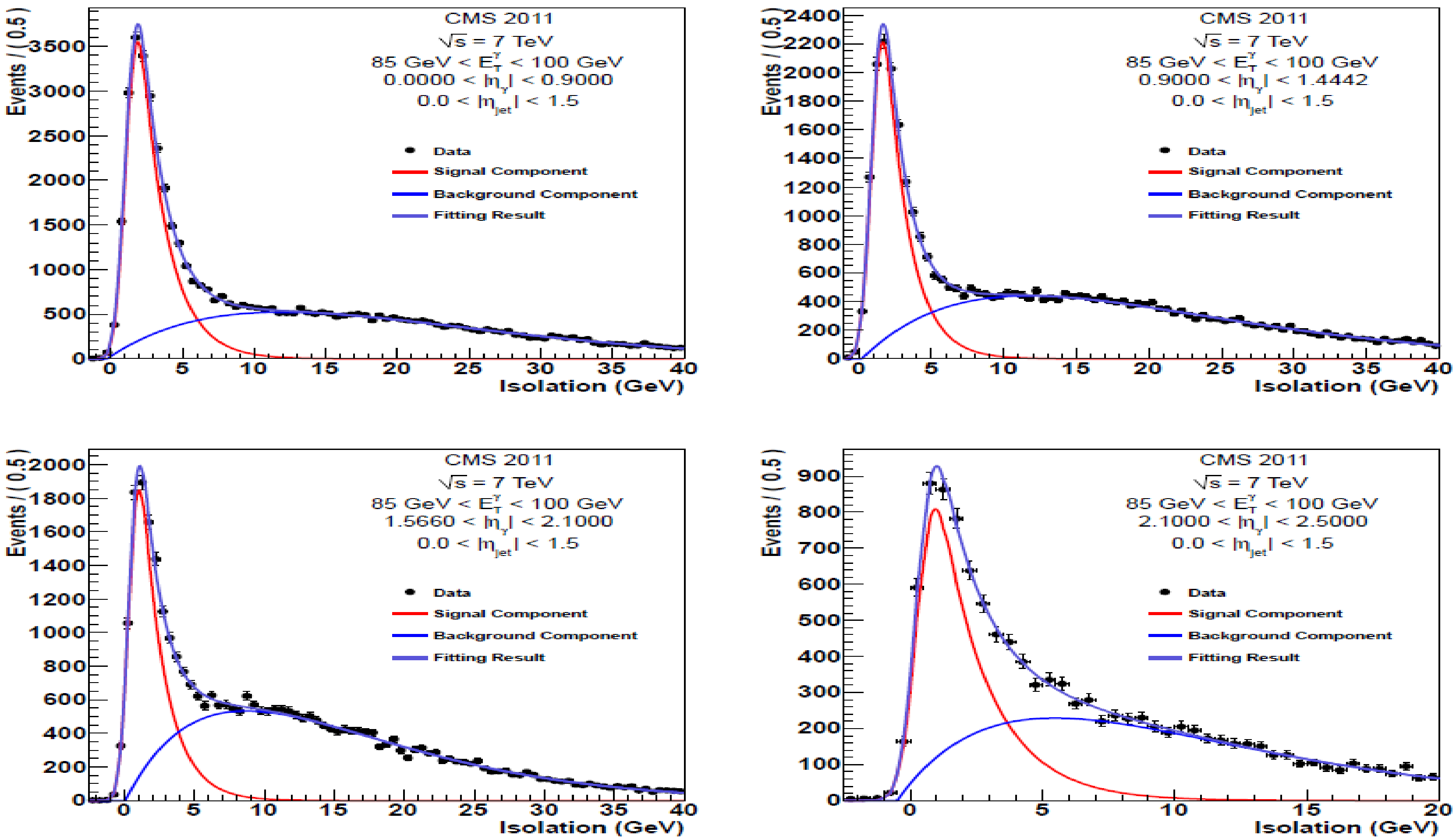
Photon ID signal selection for Iso

Variable	Selection
$\sigma_{i\eta i\eta}$ (Barrel)	> 0.011
$\sigma_{i\eta i\eta}$ (Endcap)	> 0.035
H/E	< 0.05

Photon ID side-band selection for Iso

3. Photon Measurements in the CMS

- Signal Extraction Templates
  - Examples to the isolation templates



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3. Photon Measurements in the CMS

- Previous Cross Section Measurements
  - Elements of isolated single photon cross section measurements in the CMS.

$$\frac{d^2\sigma^{\gamma}_{isolated}}{dE^{\gamma}_T d\eta^{\gamma}} = \frac{1}{\Delta E^{\gamma}_T \cdot \Delta\eta^{\gamma}} \frac{N^{\gamma}_{signal} \cdot U}{L \cdot \epsilon}$$

ΔE^{γ}_T → Photon ET size

$\Delta\eta^{\gamma}$ → Photon ET size

U → Unfolding

L → Int. luminosity

N^{γ}_{signal} → Photon yields

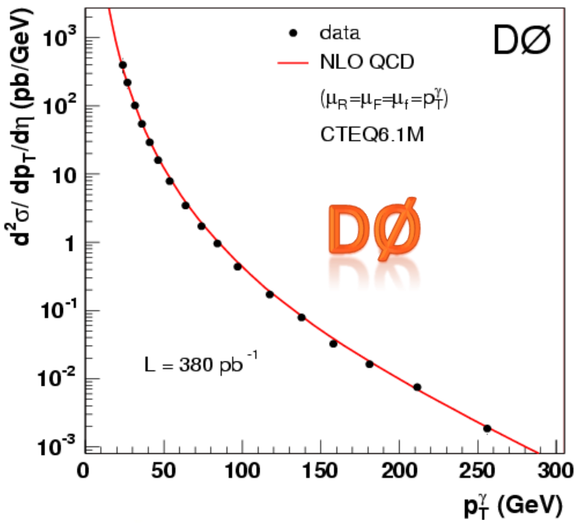
$$\epsilon = \epsilon_{trigger} \times \epsilon_{RECO} \times \epsilon_{ID}$$ → Efficiency

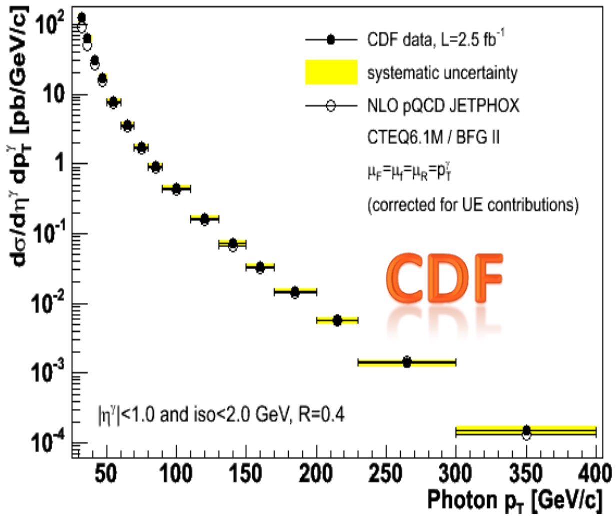
  - The earliest measurements of prompt photon production were carried out at the ISR (Intersecting Storage Rings) hadron collider at CERN
  - Later studies (ZEUS HERA, PHENIX RHIC, TEVATRON FERMILAB, LHC results) established prompt photons as a useful probe of hadron interactions

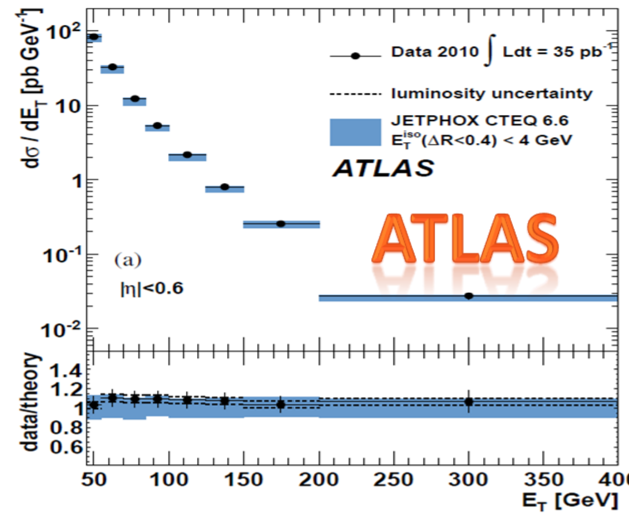
E. Anassontzis et al., High p(t) Direct Photon Production in pp Collisions, Z. Phys. C 13, 277-289 (1982).
CMOR Collaboration, A. L. S. Angelis et al., Direct Photon Production at the CERN ISR, Nucl. Phys. B327, 541 (1989).
UA2 Collaboration, J. A. Appel et al., Direct Photon Production at the CERN anti-pp Collider, Phys. Lett. B176, 239 (1986).
UA1 Collaboration, C. Albajar et al., Direct Photon Production at the CERN protonantiproton Collider, Phys. Lett. B209, 385 (1988).
UA6 Collaboration, M. Werlen et al., A New determination of s using direct photon production cross-sections in pp and anti-pp collisions at S(1/2) = 24.3 GeV, Phys. Lett.B452, 201-206 (1999).

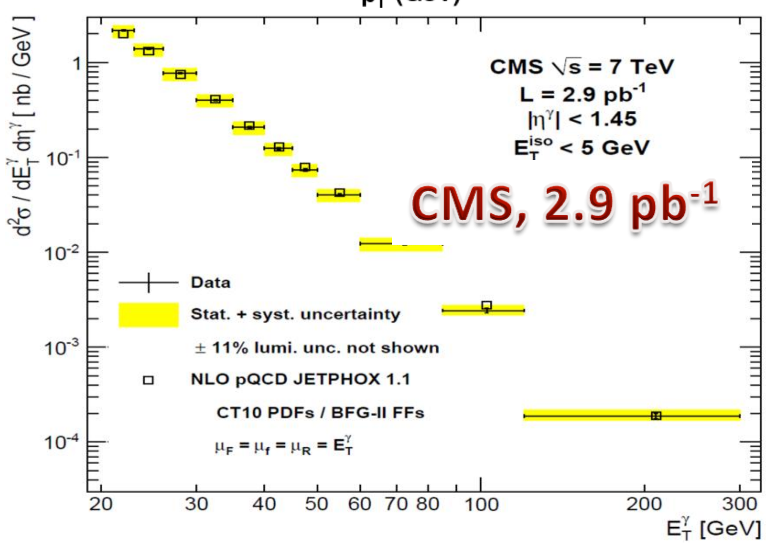
3. Photon Measurements in the CMS

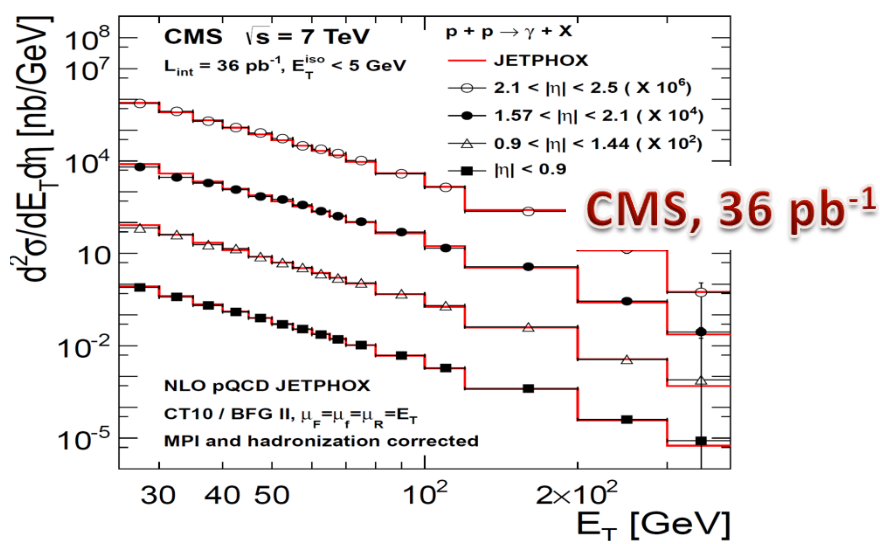
- Previous Cross Section Measurements (the most recent studies)











4. Photon Efficiency Measurements

- Introduction
  - Goal is to measure photon trigger, reconstruction, and identification efficiencies from collision data and Monte Carlo simulation samples for the inclusive photon and photon+jet cross section measurements

$$\epsilon = \epsilon_{trigger} \times \epsilon_{RECO} \times \epsilon_{ID}$$

  - $\epsilon_{trigger}$ is the probability for a reconstructed signal photon to be selected by the trigger system
  - ϵ_{RECO} represents the probability for a signal photon produced inside the detector geometrical acceptance to be reconstructed by the clustering algorithms
  - ϵ_{ID} is the probability for a reconstructed signal photon to pass the photon identification criteria
  - We used 2011 data (**2.2 fb^{-1}** integrated luminosity) recorded by the CMS dedector at a center-of-mass energy of 7 TeV to measure efficiencies.

4. Photon Efficiency Measurements

- Trigger Efficiency
  - Measure single photon HLT efficiencies from 2011 collision data

HLT_PhotonE_T_WPs_version → Structure of single photon HLT paths

HLT trigger path	Run range	Eff. (pb^{-1})
HLT_Photon50_CaloIdVL_IsoL	161217-163261	40.95
HLT_Photon75_CaloIdVL	160431-163869	216.06
HLT_Photon75_CaloIdVL_IsoL	160431-165633	355.5
HLT_Photon90_CaloIdVL_IsoL	165088-167913	934.0
HLT_Photon125	165088-166967	665.70
HLT_Photon135	167039-173198	1053.98

WPs	Iso	CaloId Barrel	CaloId Endcap
VeryLoose 'VL'	Iso_{ECAL} <6.0+0.012×E_T Iso_{ECAL} <4.0+0.005×E_T Iso_{TRACK} <4.0+0.002×E_T	H/E<0.15 $\sigma_{i\eta i\eta}$ <0.024	H/E<0.10 $\sigma_{i\eta i\eta}$ <0.040
Loose 'L'	Iso_{ECAL} <5.5+0.012×E_T Iso_{ECAL} <3.5+0.005×E_T Iso_{TRACK} <3.5+0.002×E_T	H/E<0.15 $\sigma_{i\eta i\eta}$ <0.014	H/E<0.10 $\sigma_{i\eta i\eta}$ <0.035
Tight 'T'	Iso_{ECAL} <5.0+0.012×E_T Iso_{ECAL} <3.0+0.005×E_T Iso_{TRACK} <3.0+0.002×E_T	H/E<0.10 $\sigma_{i\eta i\eta}$ <0.011	H/E<0.075 $\sigma_{i\eta i\eta}$ <0.031
VeryTight 'VT'	NA	H/E<0.05 $\sigma_{i\eta i\eta}$ <0.011	H/E<0.05 $\sigma_{i\eta i\eta}$ <0.031

- H/E < 0.05
- Tracker Isolation < 2.0 + 0.002 ×p_T GeV
- ECAL Isolation < 4.2 + 0.012×p_T GeV
- HCAL Isolation < 2.2 + 0.005×p_T GeV
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.020 for ECAL Barrel ($|\eta|$ < 1.4442)
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.039 for ECAL Endcap (1.566 < $|\eta|$ < 2.5)

- H/E < 0.05
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.010 for ECAL Barrel ($|\eta|$ < 1.4442)
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.028 for ECAL Endcap (1.566 < $|\eta|$ < 2.5).

Photon ID seelction for CaloIdVL_IsoL

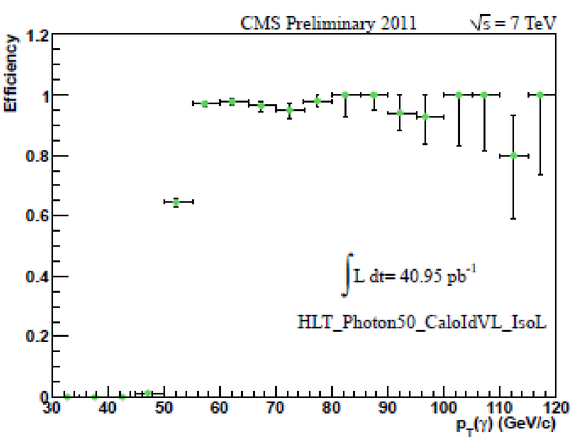
Photon ID selection for CaloIDVL

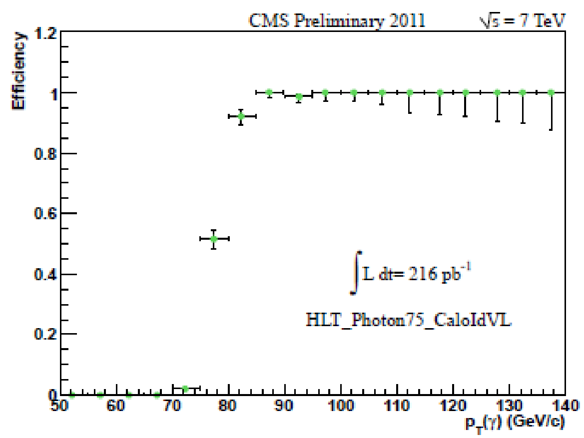
4. Photon Efficiency Measurements

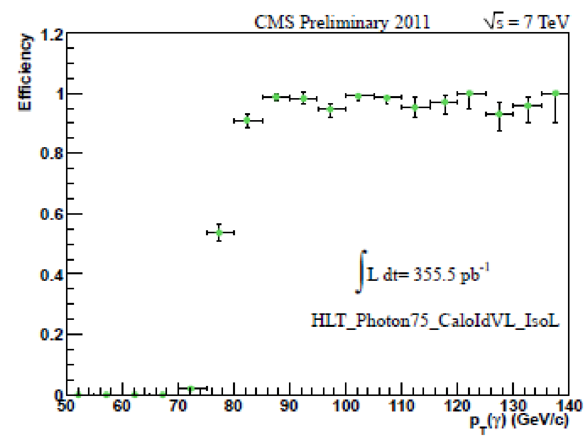
- Trigger Efficiency
  - Number of passing and failing probe photons after HLTs

HLT path	E_T (GeV)	Passing	Failing	Total
HLT_Photon50_CaloIdVL_IsoL	> 50	1686	417	2103
HLT_Photon75_CaloIdVL	> 75	889	154	1043
HLT_Photon75_CaloIdVL_IsoL	> 75	1209	218	1427
HLT_Photon90_CaloIdVL_IsoL	> 90	1728	237	1965
HLT_Photon125	> 125	351	36	387
HLT_Photon135	> 135	624	80	704

  - Trigger turn-on curves to exploit maximally efficient region on photon p_T







4. Photon Efficiency Measurements

- Trigger Efficiency (results)
  - Counting method

HLT path	Probe E_T (GeV)	$-\eta$ Endcap	Barrel	$+\eta$ Endcap
HLT_Photon50_CaloIdVL_IsoL	60 - Inf.	93.5 ± 3.5	97.8 ± 0.8	96.4 ± 3.4
HLT_Photon75_CaloIdVL	85 - Inf.	100 ± 1.4	99.8 ± 0.3	100 ± 1.6
HLT_Photon75_CaloIdVL_IsoL	85 - Inf.	97.7 ± 2.2	97.3 ± 0.7	95.6 ± 2.7
HLT_Photon90_CaloIdVL_IsoL	100 - Inf.	95.6 ± 2.1	97.3 ± 0.5	95.1 ± 2.6
HLT_Photon125	135 - Inf.	100 ± 3.7	100 ± 0.4	100 ± 4.4
HLT_Photon135	145 - Inf.	92.6 ± 5.4	99.8 ± 0.3	94.8 ± 4.1

  - Fitting method (fitted to electron-photon inv. mass using the convolution of a Bereit Wigner and a Crystal-Ball function,

HLT path	Probe E_T (GeV)	$-\eta$ Endcap	Barrel	$+\eta$ Endcap
HLT_Photon50_CaloIdVL_IsoL	60 - Inf.	93.5 ± 2.8	97.8 ± 1.4	96.4 ± 2.5
HLT_Photon75_CaloIdVL	85 - Inf.	100 ± 1.4	99.8 ± 0.2	100 ± 1.6
HLT_Photon75_CaloIdVL_IsoL	85 - Inf.	97.7 ± 1.6	97.5 ± 0.6	98.3 ± 1.8
HLT_Photon90_CaloIdVL_IsoL	100 - Inf.	95.6 ± 1.8	97.3 ± 0.5	100 ± 0.8
HLT_Photon125	135 - Inf.	100 ± 3.7	100 ± 0.4	100 ± 4.5
HLT_Photon135	145 - Inf.	92.5 ± 4.2	100 ± 0.6	95.0 ± 5.3

4. Photon Efficiency Measurements

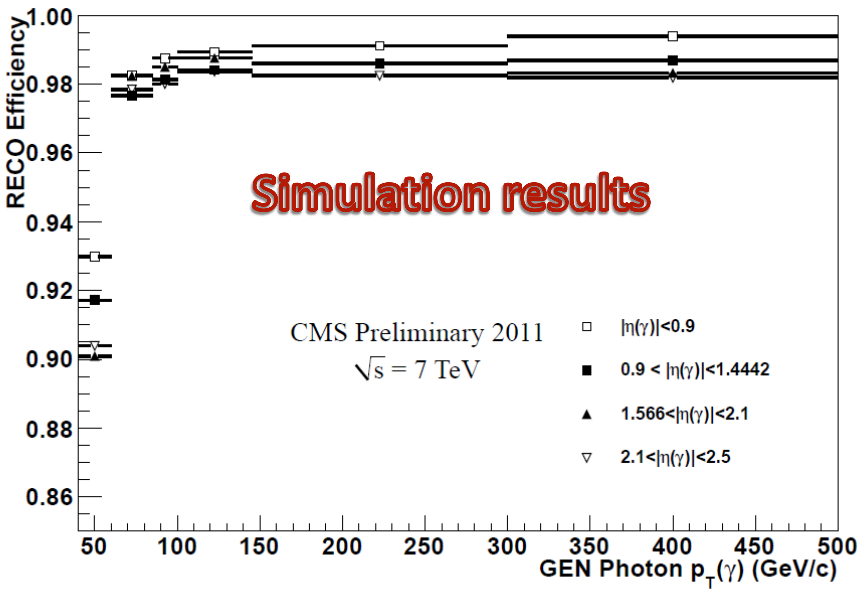
- Photon Reconstruction Efficiency (geometrical acceptance eff.)
  - Measure it from photon+jets MC samples

$$\epsilon_{RECO} = \frac{G_R(p_T,\eta)}{G(p_T,\eta)}$$

$G(p_T,\eta)$ → Generated photon spectrum

$G_R(p_T,\eta)$ → Generated photon spectrum with a reco match

PYTHIA6 RECO EFFICIENCY



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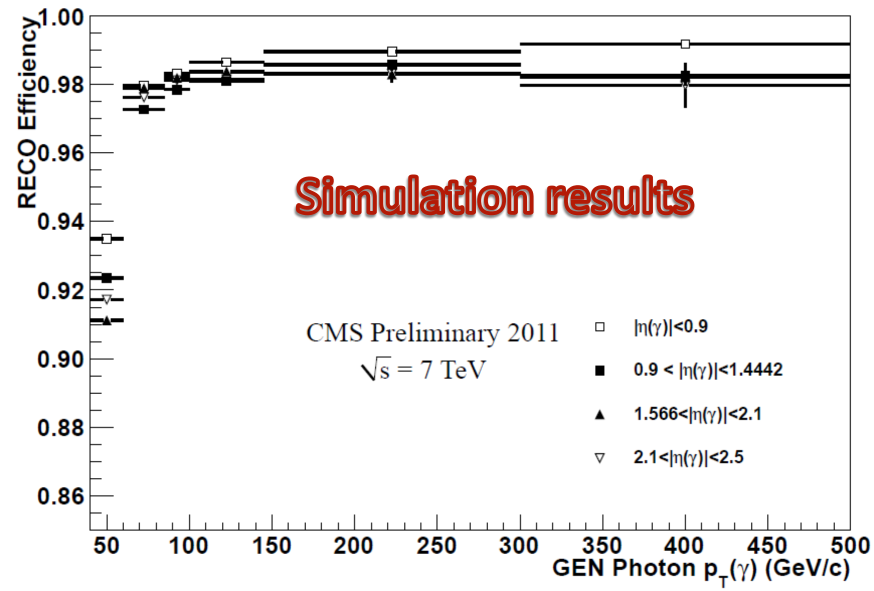


4. Photon Efficiency Measurements

- Photon Reconstruction Efficiency (geometrical acceptance eff.)

Photon p_T	$\lvert\eta\rvert < 0.9$	$0.9 < \lvert\eta\rvert < 1.4442$	$1.566 < \lvert\eta\rvert < 2.1$	$2.1 < \lvert\eta\rvert < 2.5$
40-60	93.00 ± 0.06	91.72 ± 0.08	90.10 ± 0.09	90.40 ± 0.10
60-85	98.26 ± 0.03	97.67 ± 0.04	98.24 ± 0.03	97.84 ± 0.06
85-100	98.76 ± 0.02	98.13 ± 0.04	98.50 ± 0.03	98.00 ± 0.05
100-145	98.94 ± 0.02	98.41 ± 0.03	98.76 ± 0.03	98.37 ± 0.04
145-300	99.12 ± 0.01	98.61 ± 0.02	98.60 ± 0.02	98.24 ± 0.03
300-500	99.40 ± 0.01	98.67 ± 0.01	98.32 ± 0.02	98.20 ± 0.07

- Photon Identification Efficiency

$$\epsilon_{ID} = \frac{R_{ID}(p_T, \eta)}{R(p_T, \eta)}$$

$R(p_T, \eta)$ → **Reconstructed photon spectrum**

$R_{ID}(p_T, \eta)$ → **Reconstructed photon spectrum passing photon ID cuts**

- H/E < 0.05
- Tracker Isolation < 2.0 + 0.002 $\times p_T$ GeV
- ECAL Isolation < 4.2 + 0.012$\times p_T$ GeV
- HCAL Isolation < 2.2 + 0.005$\times p_T$ GeV
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.020 for ECAL Barrel ($\lvert\eta\rvert < 1.4442$)
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.039 for ECAL Endcap ($1.566 < \lvert\eta\rvert < 2.5$)

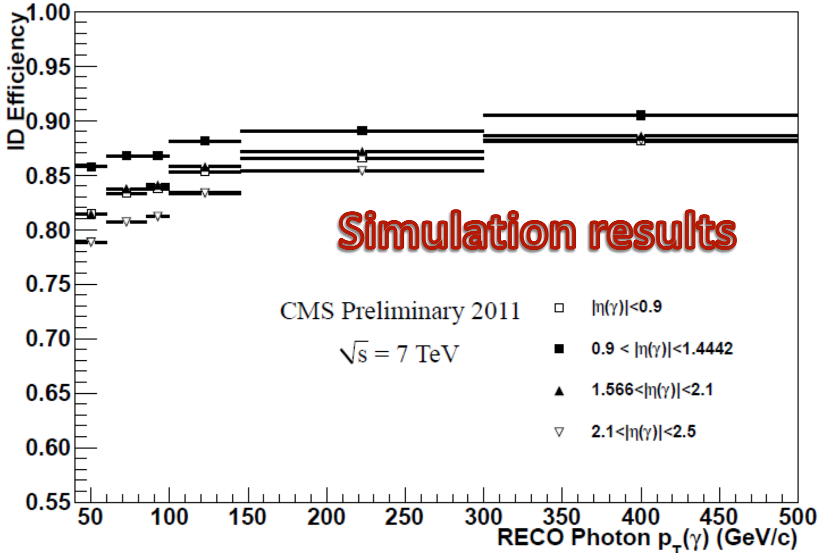
- H/E < 0.05
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.010 for ECAL Barrel ($\lvert\eta\rvert < 1.4442$)
- Shower shape ($\sigma_{i\eta i\eta}$) < 0.028 for ECAL Endcap ($1.566 < \lvert\eta\rvert < 2.5$)

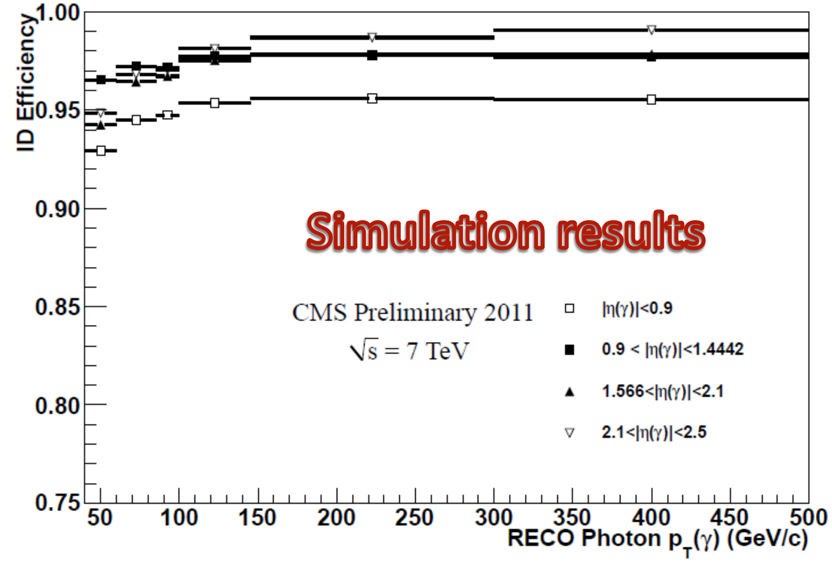
Photon ID seelction for SS template

Photon ID selection for Iso template

4. Photon Efficiency Measurements

- Photon Identification (ID) Efficiency





SHOWER SHAPE TEMPLATE

ISOLATION TEMPLATE

Photon p_T	$\|\eta\| < 0.9$	$0.9 < \|\eta\| < 1.4442$	$1.566 < \|\eta\| < 2.1$	$2.1 < \|\eta\| < 2.5$
40-60	81.44 ± 0.08	85.77 ± 0.09	81.40 ± 0.10	78.84 ± 0.13
60-85	83.32 ± 0.07	86.75 ± 0.08	83.75 ± 0.09	80.70 ± 0.12
85-100	83.74 ± 0.07	86.77 ± 0.08	84.08 ± 0.09	81.20 ± 0.12
100-145	85.32 ± 0.06	88.11 ± 0.07	85.75 ± 0.08	83.35 ± 0.11
145-300	86.55 ± 0.04	89.06 ± 0.05	87.15 ± 0.06	85.38 ± 0.10
300-500	88.12 ± 0.03	90.47 ± 0.04	88.57 ± 0.07	88.18 ± 0.18

Shower shape template ID efficiencies

5. Outlook

- Prompt photon cross section measurement s at hadron colliders are driven by several motivations.
- Photon efficiencies (in parallel to other ingredients) must be measured from data and simulation samples to correct final cross section spectra.

- We measure differential gamma+jet cross section with 2011 collision data that will be published in *JHEP* for the CMS collaboration:

(CMS Internal) K. Ocalan et al., Measurement of the triple differential γ+jet cross section using 2011 data, CMS Analysis Note CMS-AN-11-31, (2011).

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