Measurement of isolated photons in PbPb collisions at $\sqrt{s} = 2.76\text{TeV}$ with CMS detector

Yongsun Kim for the CMS Collaboration
Motivation

$R_{AA}$

Ratio of PbPb spectrum to pp spectrum normalized by number of binary collisions $<N_{\text{coll}}>$

Charged particle $R_{AA} < 1$
Indirect evidence of jet quenching.

Andre Yoon (Thursday)
Yen-Jie Lee (Plenary)
Motivation

...and God said:

$$\mathcal{L}_{\text{QED}} = \bar{\psi} \gamma_0 (i \gamma^\mu D_\mu - m) \psi - \frac{1}{4} F_{\mu \nu} F^{\mu \nu}$$

where,

$$\{\gamma^\mu, \gamma^\nu\} = \gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^\mu\nu$$

$$D_\mu = \partial_\mu + ieA_\mu$$

$$F_{\mu \nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

... and there was light!
Motivation

...and God said:

\[ \mathcal{L}_{\text{qcd}} = \bar{\psi} \gamma_0 (i \gamma^\mu D_\mu - m) \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

where,

\[ \{\gamma^\mu, \gamma^\nu\} = \gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu} \]

\[ D_\mu = \partial_\mu + ieA_\mu \]

\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]

... and there was light!

which is colorless!!
**Motivation**

- Photon is not quenched in medium, therefore its $R_{AA}$ can be used to check the initial state of PbPb collision.
- First adaptation of pp photon identification methods to heavy ion experiment.

**$R_{AA}$**

Ratio of PbPb spectrum to pp spectrum normalized by number of binary collisions $<N_{coll}>$

- Photon measured 20 – 80 GeV

---

Yongsun Kim (MIT)  Quark Matter 2011
Why isolated photons?

**Leading order**
- Compton
- Annihilation

Ideally want to measure LO

**Higher orders**
- Bremsstrahlung
- Fragmentation

Isolated | Non-isolated
Why isolated photons?

**Leading order**
- Compton
- Annihilation

**Higher orders**
- Bremsstrahlung
- Fragmentation

Experimentally possible borderline = Isolation

Reasonable cut for theoretical calculation as well.
CMS is excellent for photon hunting

Ecal (PbWO$_4$)
- $|\eta| < 3$ with 75848 crystals
- $\Delta \eta \times \Delta \Phi = 0.017 \times 0.017$
- Transverse shower shape
- Superb energy resolution ($\sim 1\%$)

Si tracker
- Vertex determination
- Reject electron

Hcal for Isolation criteria.

2$\pi$ radians covered

Yongsun Kim (MIT)
- From PbPb Collision of
  \[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
  \[ \int L \, dt = 6.8 \, \mu \text{b}^{-1} \]
- Photons are measured
  - \(|\eta| < 1.44\)
  - \(E_T\) of 20 – 80 GeV (5 bins)
  - 3 centrality bins
    - 0 – 10%, 10 – 30%, 30 – 100% 
  - 6000 signals counted
    (before efficiency correction)
Photon reconstruction

- Photon is reconstructed in Ecal using **Island clustering algorithm**
  - Ref. (CERN-LHCC-2006-001)
- Main background is neutral mesons
  - $\pi^0$ and $\eta$ decaying into two photons
  - In high $E_T$, decayed photons are almost collinear, and make single cluster
- Background rejection strategies are described in following slides

Crystal size: 2.2 cm x 2.2 cm
94% of energy in 3x3 crystals
• \( \pi^0 \) and \( \eta \) are produced from jet fragmentation

• **Isolation cut** rejects such jets
  
  – \( \frac{E_{\text{Hcal}}}{E_{\text{Ecal}}} < 0.2 \)
  
  – \( \Sigma E_T \) of particles in cone around candidates measured \( \Sigma E_T < 5 \text{GeV} \)
Isolation criteria

• $\pi^0$ and $\eta$ are produced from jet fragmentation
• **Isolation cut** rejects such jets
  – $E_{\text{Hcal}}/E_{\text{Ecal}} < 0.2$
  – $\Sigma E_T$ of particles in cone around candidates measured $\Sigma E_T < 5\text{GeV}$
• Count out **background**
  – Energy in the cone is on top of Uncorrelated Background energy
  – Heavy ion background energy subtraction event-by event

Yongsun Kim (MIT)  Quark Matter 2011
Isolation criteria - example

Σ\(E_T < 5\text{GeV}\)

Σ\(E_T > 5\text{GeV}\)
Isolation criteria - example

\[ \Sigma E_T < 5 \text{GeV} \]

Background energy subtraction

\[ \Sigma E_T > 5 \text{GeV} \]

Non-isolated
Rejected

\[ \Sigma E_T > 5 \text{GeV} \]

in cone

Yongsun Kim (MIT)
Signal extraction

- Even after isolation cut, some $\pi^0$ and $\eta$ still remain
  - Fragmented from jets with high-$z$, becoming **Isolated** $\pi^0$ and $\eta$
- Impossible to reject event-by-event
Signal extraction

- Even after isolation cut, some $\pi^0$ and $\eta$ still remain
  - Fragmented from jets with high-$z$, becoming *isolated* $\pi^0$ and $\eta$
- Impossible to reject event-by-event $\Rightarrow$ statistical approach
- Use Ecal’s *fine* segmentation
  - $\Delta\eta \times \Delta\phi = 0.017 \times 0.017$
Signal extraction

- Quantify transverse shower shape on Ecal crystals

\[ \sigma_{i\eta\eta}^2 = \frac{\sum_{i=5}^{5\times5} w_i(\eta_i - \bar{\eta})^2_{5\times5}}{\sum_{i=5}^{5\times5} w_i} \]

, where \( w_i = \max(0, 4.7 + \ln(E_i/E)) \)

- Wider shape \( \rightarrow \) larger value

Transverse shower shape with fine crystals

Smaller width

Larger width
Signal extraction

- Quantify transverse shower shape on Ecal crystals

\[ \sigma_{\eta \eta}^2 = \frac{\sum_{i}^{5 \times 5} w_i (\eta_i - \bar{\eta})^2}{\sum_{i}^{5 \times 5} w_i} \]

, where \( w_i = \max(0, 4.7 + \ln(E_i/E)) \)

- Wider shape \( \Rightarrow \) larger value
- Probability distribution function of this value is called Template

**Probability distribution of width of transverse shower**

20-25GeV in 30-100% centrality

Photon (MC)

\( \pi^0 \) and \( \eta \)
(data driven)

Smaller width

Larger width

Yongsun Kim (MIT)  Quark Matter 2011
Data = Superposition of photon + background templates

Q : How many photons inside?
Data = Superposition of photon + background templates

Q : How many photons inside?
A : 802
• By the way, where did we get shower shapes of pure photon and pure $\pi^0/\eta$?
  
  – **Photon template** obtained from MC
  
  – **Background template** obtained from non-isolated $\pi^0$ and $\eta$ in jet

  • Data driven method

---

**Signal extraction**

![Graphs showing shower shapes and data analysis results](image-url)

- **2667 candidates in Data**
- Which passed isolation cut
- **Fit!**
- **802 photons extracted**
More examples

Central events
0 – 10%

Pb

Perepheral events
30 – 100%

Pb Pb

Yongsun Kim (MIT)
Quick review of analysis

- Photon reconstructed in Ecal
  \[ \text{Photon} : \pi^0 = 1 : O(100) \]
Quick review of analysis

- Photon reconstructed in Ecal
  \[ \text{Photon : } \pi^0 = 1 : O(100) \]

- Isolation cut using \( E_T \) in isolation cone
  \[ \text{Photon : } \pi^0 = 1 : O(1) \]
Quick review of analysis

• Photon reconstructed in Ecal
  ➔ Photon : $\pi^0 = 1 : O(100)$

• Isolation cut using $E_T$ in isolation cone
  ➔ Photon : $\pi^0 = 1 : O(1)$

• Count photons using template methods
Quick review of analysis

• Photon reconstructed in Ecal
  ➔ Photon : $\pi^0 = 1 : O(100)$

• Isolation cut using $E_T$ in isolation cone
  ➔ Photon : $\pi^0 = 1 : O(1)$

• Count photons using template methods

• Correction factors applied
  – Isolation efficiency : 70 – 90%
  – Acceptance : ~95%

• Now, PbPb photon spectra on next slide
Isolated photon spectrum

- $dN/dE_T$ is scaled by $T_{AA}$
  - $T_{AA}$: tickness factor, the cross-section of N-N inside PbPb collision
- Systematic uncertainty is 21 – 37%
- Compared to pp reference
Systematic uncertainty

• Shower shape of photon signal obtained from MC
  – Slightly different shower shapes of MC and data
  – Compared electrons from Z->ee events in MC VS data
  – 2 – 5% uncertainty propagates

• Shower shape of background from non-isolated probes in jets
  – Collinear particles around $\pi^0$ and $\eta$ may contaminate shower shape
  – MC study to check how much the results affected
  – 12 – 30% uncertainty

• Overall systematic uncertainty 21 – 37%
  – Including efficiency correction(5 – 9 %), energy resolution (10%), electron subtraction (4 – 8%), etc
• **Need pp spectrum at 2.76TeV as the denominator for $R_{AA}$**

• We have taken pp data from LHC, but not finished analysis.
pp reference from NLO calculation

- **JETPHOX [JHEP 05 (2002) 028]** NLO calculator
- CT10 PDFs and BFG-II fragmentation function
- Reasonable description of p+p(bar) at 7(1.96) TeV

![](image1.png)

- CMS 2010
  - $\sqrt{s} = 7$ TeV
  - $L = 2.9$ pb$^{-1}$
  - $|\eta| < 1.45$
  - $E_T^{\gamma} < 5$ GeV

- Data / JETPHOX 1.1
- CT10 PDFs / BFG-II FFs

- Plotted with
  - Stat. + syst. uncertainty ± 11% lumi. unc. not shown
  - Theory scale dependence $E_T/2 < E_T < 2 E_T$
  - PDFs uncertainty

- PRL 106,082001 (2011) $E_T^{\gamma} (\text{GeV})$

Yongsun Kim (MIT)  
Quark Matter 2011
$R_{AA}$ in the most central events

CMS Preliminary

$\sqrt{s_{NN}} = 2.76$ TeV  
$|\eta| < 1.44$, $\int L \, dt = 6.8 \, \mu b^{-1}$

Systematic uncertainty

PbPb(0-10%)/pp(CT10)

$T_{AA}$ scale uncertainty

NLO Scale uncertainty

CT10 PDF uncertainties

Expectation of $R_{AA}$ in theory

(nPDF / proton PDF)
$R_{AA}$ in the most central events

Message 1

$R_{AA}$ vs. $E_T$ is flat
$R_{AA}$ vs $N_{part}$

CMS Preliminary
PbPb $\sqrt{s_{NN}}=2.76$ TeV
$\int L dt = 6.8 \mu$b$^{-1}$

PbPb / pp (NLO)
- 0-10%
- 10-30%
- 30-100%
- Min Bias

Systematic uncertainties
NLO Scale uncertainties
CT10 PDF uncertainty

Yongsun Kim (MIT)  Quark Matter 2011
Message 2

No dependence of $R_{AA}$ on $N_{\text{part}}$
Conclusion

• **First ever measurement** of isolated photon spectra in heavy ion collision experiment

• **No evidence of modification in the initial state** of the particle production process in heavy ion collision
  
  – i.e. production of photon is same as in pp multiplied by the number of binary collisions

• Establishes the basis for the future researches which use photons as unmodified hard probes
Find Petit Prince(s)!

1500 Princes
3500 Elephants

$E_T : 20-25 \text{ GeV}$

Shower Shape ($\sigma_{\eta\eta}$)

Thanks for your attention
CMS $R_{AA}$

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $\int L \, dt = 7 \mu b^{-1}$

Gauge bosons
- $Z^0$
- Isolated photon $|y|<2.0$
- Charged particles $|\eta|<1.0$

$R_{AA}$

$m_T$ (GeV)

Non-prompt $J/\psi$

prompt $J/\psi$

0 – 20 %
Photon reconstruction

Yongsun Kim (MIT)
Isolated Photon $R_{AA}$ in PbPb at $\sqrt{s} = 2.76$ TeV
Quark Matter 2011
Signal extraction

- Yet, after isolation cut, there are pi0s and eta which are fragmented in Jet with high-z.
- We used statistical approach by quantifying the shower shape on EM calorimeter thanks to fine segments.

\[ \sigma_{\eta\eta}^2 = \sum_{i=1}^{25} w_i (\eta_i - \bar{\eta})^2 / \sum_{i=1}^{25} w_i, \]

\[ w_i = \max(0, 4.7 + \ln(E_i / E)) \]
Signal extraction

- Even after isolation cut, isolated $\pi^0$ and $\eta$ remained. (fragmented in jets with high-z)
- Statistical approach to separate photons from them, by quantifying shower shape on Ecal crystals.

$$\sigma_{\eta\eta}^2 = \sum_{i=1}^{25} w_i (\eta_i - \bar{\eta})^2 / \sum_{i=1}^{25} w_i,$$

$$w_i = \max(0, 4.7 + \ln(E_i/E))$$
- Probability distribution function of this value is called Template.
Signal extraction

- **Signal template**
- **Data-driven Background template** from non-isolated $\pi^0$ and $\eta$ in data.

How many are signals out of 2667 candidates? → Fit with signal and background templates → 802 are isolated photons

- 2667 candidates in Data
  Which passed isolation cut

- Probability distribution of $\sigma_{\text{inh}}$
  - Signal (Photon)
  - Background ($\pi^0$, $\eta$, etc)

- $E_T: 20-25$ GeV
  - 30 - 100%

- Shower Shape ($\sigma_{\text{inh}}$)

- Entries
  - 0 to 1000

- Normalized Entries
  - 0 to 0.8