Direct Photon Production

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Outline of the lecture

- Why photons?
- Photon production at large transverse momentum
- Direct vs fragmentation contribution
- Isolation cut
- From fixed target to collider energies
- Summary
Why photons?

- Photon is a EM probe:
  - It can be produced at any stage of the collision
  - It does not interact strongly once produced

- Good probe of short-distance strong interaction:
  - Isolated or “direct” photon is produced at a distance $1/p_T \ll \text{fm}$
  - “snap shot” of what happened at the distance scale $1/p_T$
  - Key background of Higgs production if $M_H < 2 M_W$: $H^0 \rightarrow \gamma + \gamma$

- Photon can tell the full history of heavy ion collision
Theory behind the high $p_T$ photon

- **Production mechanism – leading power factorization:**

  \[
  \frac{d\sigma_{AB}}{dydp_T^2} = \int dx f_{a/A}(x, \mu) \int dx' f_{b/B}(x', \mu) \frac{d\hat{\sigma}_{ab}(\alpha_s(\mu))}{dydp_T^2} + \text{frag contribution} + \mathcal{O}\left(\frac{1}{p_T^n}\right)
  \]

  **Hard part:**

  \[
  \hat{\sigma}_{ab}(\alpha_s(\mu)) = \hat{\sigma}_{ab}^0 \alpha_s^m(\mu) + \hat{\sigma}_{ab}^1 (\log(\mu))\alpha_s^{m+1}(\mu) + \ldots
  \]

- **Predictive power:**
  - Short-distance part is Infrared-Safe, and calculable
  - Long-distance part can be defined to be Universal - PDFs

- **Factorization and renormalization scale dependence:**
  - **NLO is necessary**

- **Power correction could be important at low $p_T$**
Factorization is an approximation

- **Multiple scattering and power correction:**

  \[ \sigma(P_T) \sim \hat{\sigma}(P_T, x_1, x_2, \mu) \otimes \phi(x_1, \mu) \otimes \phi(x_2, \mu) + O\left(\frac{Q_s^2}{p_T^2}\right) \]

- **Fragmentation function and isolation cut:**

  \[ \sigma(P_T) \propto \hat{\sigma}(P_T, x_1, x_2, \mu) \otimes \phi(x_1, \mu) \otimes \phi(x_2, \mu) \otimes D(z) + O\left(\frac{Q_s^2}{p_T^2}\right) \]

  **Note:** \( \ln(R) \) Cone size cannot be too small

  \[ \ln\left(\frac{E_h}{E_\gamma}\right) \rightarrow \frac{E_h}{E_\gamma} \text{ Not too small} \]
Direct photon is sensitive to gluon

- Sensitive to gluon at the leading order – hadronic collision:
  - **Lowest order direct** $\mathcal{O}(\alpha_{em}\alpha_s)$:
    - Compton: $q(\bar{q}) + g \rightarrow \gamma + q(\bar{q})$
    - Annihilation: $q + \bar{q} \rightarrow \gamma + g$

- **Compton dominates in pp collision:**
  $$f_{g/p}(x, \mu^2) \gg f_{\bar{q}/p}(x, \mu^2) \quad \text{for all } x$$

Direct photon production could be a good probe of gluon distribution
Role of gluon in pp collision

- pp vs $\bar{p}\bar{p}$ – dominance of gluon in pp:
  - Isolation cut removes the most of fragmentation contribution!
  - More dominance in the forward region!

![Graphs showing subprocess fraction vs. $E_T^\gamma$ for $p\bar{p}$ and pp collisions]
Complication from high orders

- **Final-state collinear singularity:**

  \[
  \sum |M(qg \rightarrow \gamma qg)|^2 \approx \frac{\alpha_{em}}{2\pi} P_{q \rightarrow \gamma}^{(0)}(z) \frac{1}{s_{\gamma q}} \sum |M(qg \rightarrow qg)|^2
  \]

  \[P_{q \rightarrow \gamma}^{(0)}(z) = \frac{1 + (1 - z)^2}{z}\]

  \[s_{\gamma q} = (p_\gamma + p_5)^2 \rightarrow 0 \quad \text{when} \quad p_\gamma \parallel p_5\]

  An internal quark line goes on-shell signaling long-distance physics

- **Fragmentation contribution:**

  \[
  \frac{d\sigma_{AB \rightarrow \gamma}}{dy dp_T^2} = \sum_{abc} \int \frac{dz}{z^2} D_{c \rightarrow \gamma}(z, \mu) \int dx f_{a/A}(x, \mu) \int dx' f_{b/B}(x', \mu) \frac{d\sigma_{ab \rightarrow c}^{\text{Frag}}}{dy dp_T^2}
  \]

- **Photon fragmentation functions – inhomogeneous evolution:**

  \[
  \frac{\partial D_{c \rightarrow \gamma}(z, \mu)}{\partial \log(\mu)} = \frac{\alpha_{em}}{2\pi} P_{c \rightarrow \gamma}(z) + \sum_{a=q\bar{q}g} \frac{\alpha_s}{2\pi} P_{ac}(z) \otimes D_{a \rightarrow \gamma}(z, \mu)
  \]
Complication from the measurement

- Separation the signal photon from $\pi^0 \rightarrow \gamma\gamma$:

  - When $p_{\pi^0}$ increases, the opening angle between two photons decreases.
  - Two photons can be mis-identified as one photon at high $p_T$.

- Isolation cut – algorithms:
  - CDF cone algorithm - reduction of fragmentation contribution
    Require that there is less then 1 GeV hadronic transverse energy in a cone of radius: $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \sim 0.7$.
  - Modified cone algorithm – NO fragmentation contribution

Direct photon covers a wide range of $x$ and $Q^2$

- Photon energy vs gluon momentum fraction $x$:
Direct photon data

- **Fixed target energies**: $\sqrt{s} = 20 - 40$ GeV:
  - With $p_T = 3-10$ GeV, data have high $x_T = \frac{2p_T}{\sqrt{s}}$
  - Challenge for NLO theory to fit data – wrong shape!

- **Collider energies**:
  - pp at ISR with $\sqrt{s} = 44 - 62$ GeV
  - pp at CERN and Fermilab with $\sqrt{s} = 540 - 1960$ GeV
  - pp at RHIC with $\sqrt{s} = 200 - 500$ GeV, dA and AA as well
  - pp at LHC with $\sqrt{s} = 7 - 14$ TeV, and PbPb as well

- **Data sources**:
  - Online database at http://durpdg.dur.ac.uk/HEPDATA
Theory vs experimental data

- Tevatron data

- Agreement looks good when plotted on a logarithmic scale
- QCD description of direct photon production works
Compare with data from different expt’s

CTEQ global analysis:

- Neither PDFs nor photon FFs can significantly improve the shape
- Direct photon data were NOT in recent global fits

CTEQ Huston et al.
Experiments with both $pp$ and $p\bar{p}$

- **UA6:** both $pp$ and $p\bar{p}$ at $\sqrt{s} = 24.3$ GeV
  - $UA-6$ $p\bar{p} \rightarrow \gamma + X$ and $pp \rightarrow \gamma + X$
  - $-0.10 < y < 0.9$
  - $4.1 < p_T < 7.7$ GeV/c

- **Theory curves are below the data**
- **Rapidity curves are flatter**
Role of gluon distribution?

- **UA6**: $\bar{p}p - pp$  both $pp$ and $\bar{p}p$ at $\sqrt{s} = 24.3$ GeV

- **UA-6** $\bar{p}p \rightarrow \gamma + X$ and $pp \rightarrow \gamma + X$
  
  
  - $-1.0 < y < 0.9$
  
  
  - $4.1 < p_T < 7.7$ GeV/c

- **NO** gluon contribution to the difference!

- **Theory matches the data better – role of gluon?**
Theory works well at RHIC energy

PHENIX

STAR

E706 data
How about at the LHC?

- CMS:
  - Isolation cut: $E_T^{iso} < 5 \text{ GeV}$

- Shape in $x_T$ – within the PDF uncertainty?

Rapidity dependence at the LHC

- **ATLAS:**

  - Data is systematically lower than theory at central $\eta^\gamma$ and small $E_T^{\gamma}$
  - Small $E_T^{iso} < 3$ GeV, NOTE: CMS has $E_T^{iso} < 5$ GeV
Same excess seen in $\pi^0$ production
But, works at RHIC energy

\[ \pi^0 \]
Where do we stand?

- Agreement between theory and data improves with increasing energy and is excellent by $\sqrt{s} = 200$ GeV

- Situation with fixed target direct photon data is confusing:
  - Disagreement between experiments
    - See Apanasevich et al., hep-ph/0007191 for a discussion of the systematics of $\gamma/\pi^0$ ratios and consistency between experiments
  - A reassessment of systematic errors on the existing fixed target photon experiments might help resolve the discrepancies

- All experiments see an excess of data over theory at fixed target energies

- We need an improved method of calculating single particle inclusive cross sections in the fixed target energy
  - to improve agreement for both photon and $\pi^0$ production
Threshold resummation could help

- **Threshold resummation** – rate at fixed target energy:
  - Laenen, Sterman, Vogelsang, 2008

- **Intrinsic** $k_T - x_T$ dependence at fixed target energy:
  - Mimic the resummation of initial-state gluon shower
  - Large effect on a steep falling $P_T$ distribution

CTEQ Huston et al.
Resummation helps $\pi^0$ cross section too

de Florian and Vogelsang, hep-ph/0501258
What happens at RHIC energy?

Reduced enhancement at RHIC energies than fixed target energies
Photon can penetrate the medium

- Photon tells the history:

High $P_T$ photon penetrates the medium without suppression

$\sqrt{s_{NN}} = 200\text{GeV}, 0-10\%$

Isospin effect
“Photon” at low $p_T$ in Au-Au collisions

- Low mass $e^+e^-$ pairs $\rightarrow$ direct photon production:

$$\frac{d^3n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \frac{1}{m_{ee}} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) S d\alpha_{\gamma}$$

$S$ : process dependent factor

$\sqrt{s} = 200$ GeV

$m_{ee} < 0.3$ GeV/$c$

$1 < p_T < 5$ GeV/$c$

Difference pp vs AA
- thermal photon

Temperature

$$T = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}}$$ MeV
Invariant cross section in pp collision

Definition:

\[ E \frac{d\sigma_{AB \to \ell^+\ell^-}(Q)X}{d^3Q} \equiv \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ^2 \frac{1}{\pi} \frac{d\sigma_{AB \to \ell^+\ell^-}(Q)X}{dQ^2 dQ^2_T dy} \]

Role of non-perturbative fragmentation function:

- Input FF:
  \[ D(z, \mu_0) = D^{\text{QED}}(z) + \kappa D^{\text{NP}}(z) \]
- QED alone (dotted):
  \[ \kappa = 0 \text{ at } \mu_0 = 1 \text{ GeV} \]
- QED + hadronic input (solid):
  \[ \kappa = 1 \text{ at } \mu_0 = 1 \text{ GeV} \]

Hadronic component of fragmentation is very important at low \( Q_T \)

Data from PHENIX: arXiv:0804.4168
“Direct photon” approximation

Dilepton production vs direct photon production:

\[ E \frac{d\sigma_{AB\to \ell^+\ell^-}(Q)}{d^3Q} \approx \frac{d\sigma_{AB\to \gamma}(Q)}{dQ_T^2 dy} \int_{Q_{\text{min}}^2}^{Q_{\text{max}}^2} dQ^2 \left( \frac{\alpha_{\text{em}}}{3\pi^2Q^2} \right) \sqrt{1 - \frac{4m_{\ell}^2}{Q^2} \left( 1 + \frac{2m_{\ell}^2}{Q^2} \right)} \]

\approx \frac{\alpha_{\text{em}}}{3\pi} \ln \left( \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} \right) E_\gamma \frac{d\sigma_{AB\to \gamma}(Q)}{d^3Q}

Direct photon cross section

✧ Inclusive NLO direct photon (blue-dashed)

Gordon, Vogelsang, 1993

✧ Direct photon code has similar non-perturbative fragmentation functions

✧ Low mass dilepton ~ inclusive photon production

Data from PHENIX: arXiv:0804.4168

\( Q_{\text{min}} = 0.1 \text{ GeV} \)
\( Q_{\text{max}} = 0.3 \text{ GeV} \)
\( \sqrt{s} = 200 \text{ GeV} \)
\( y = 0 \)
Au-Au data: beyond shadowing + isospin

✧ EPS08 nPDFs
\[ \kappa = 1 \text{(solid), } \kappa = 0 \text{(dotted)} \]
✧ Clear enhancement at low $Q_T$

Hot medium effect?

\[ T = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}} \text{ MeV} \]

Data from PHENIX: arXiv:0804.4168

Kang, Qiu, Vogelsang, PRD 2009
- World data:

- Reasonably consistent picture covering 9 orders of magnitude

- Threshold resummation helps improve theory at fixed target energy
Thank you!
Backup slices
PDF uncertainties

- CMS and ATLAS use different PDFs: