Direct Photon Production In Association With A Heavy Quark - from the Tevatron to the LHC

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Direct Photons and Heavy Quarks

What are Direct Photons and Why are they important?

- Any photon that is produced during the hard scattering process or via fragmentation
- Not to be confused with γ coming from the decay of hadrons, such as $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$
- Carriers of electromagnetic force
- Escape confinement
- Photon acts as a probe of the hard scattering
- Charge coupling allows for a distinction between charm and bottom

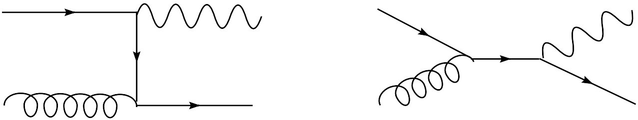
$\gamma + Q$ production

- Direct photons are produced in association with many different particles
- Look at one part of the cross section → piece with heavy quarks
- Better understand the role of heavy quarks in high p_T collisions
- Possibility to better constrain Parton Distribution Functions of heavy quarks

Hardscattering Production

- Leading Order - $\mathcal{O}(\alpha\alpha_s)$ - Only one hard-scattering subprocess

Compton Subprocess $g + Q \rightarrow Q + \gamma$



- Next-to-Leading Order - $\mathcal{O}(\alpha\alpha_s^2)$

$2 \rightarrow 3$ hard-scattering subprocesses

$$\begin{aligned} &g + g \rightarrow Q + \bar{Q} + \gamma \\ &g + Q \rightarrow g + Q + \gamma \\ &Q + q \rightarrow q + Q + \gamma \\ &Q + \bar{q} \rightarrow Q + \bar{q} + \gamma \end{aligned}$$

$$\begin{aligned} &Q + Q \rightarrow Q + Q + \gamma \\ &Q + \bar{Q} \rightarrow Q + \bar{Q} + \gamma \\ &q + \bar{q} \rightarrow Q + \bar{Q} + \gamma \end{aligned}$$

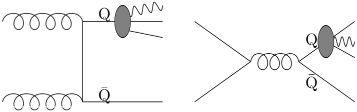
- Also need to include Direct Photons which are produced via fragmentation

Photon Fragmentation

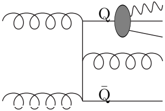
- If photon is emitted collinearly to a quark → singularity
- Absorb singularity in $D_{\gamma/q,g}(z,\mu_F)$; resume large logs in $D_{\gamma/q,g}(z,\mu_F)$ FF via DGLAP
- Photon couples to quark, responsible for behavior of $D_{\gamma/q,g}(z,\mu_F) \sim \mathcal{O}(\alpha/\alpha_s)$

Fragmentation Effects

- LO: include all 2 → 2 subprocesses $\sim \mathcal{O}(\alpha_s^2)$, $\mathcal{O}(\alpha_s^2) \otimes D_{\gamma/q,g} \sim \alpha_s^2\alpha/\alpha_s = \alpha\alpha_s$

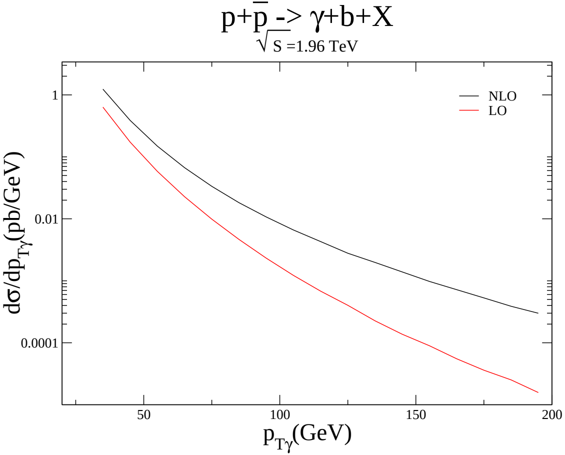


- NLO: same idea as in LO case, convolute all 2 → 3 $\sim \mathcal{O}(\alpha_s^3)$ with γ FF



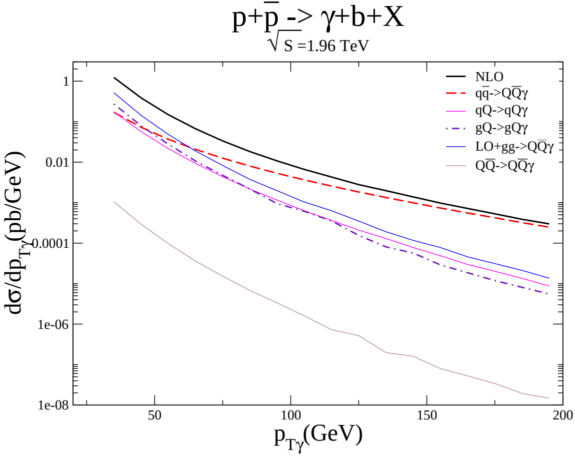
Tevatron Predictions

- **DØ** cuts: $p_{T\gamma} > 30\ \mathrm{GeV}, p_{Tb} > 15 GeV, |y_\gamma| < 1, |y_Q| < 0.8$



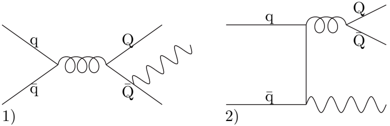
- As $p_{T\gamma}$ increases the difference between LO and NLO grows
- What drives this difference?

Subprocess Contributions

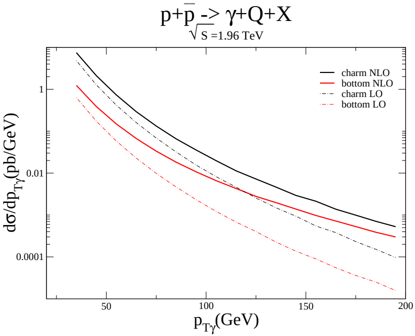


- At $p_{T\gamma} \sim 70\ \mathrm{GeV}$ $q\bar{q} \to Q\bar{Q}\gamma$ starts to dominate
- PDFs of light valance quarks are prevalent
- Take a closer look at the annihilation subprocess

Annihilation Subprocess

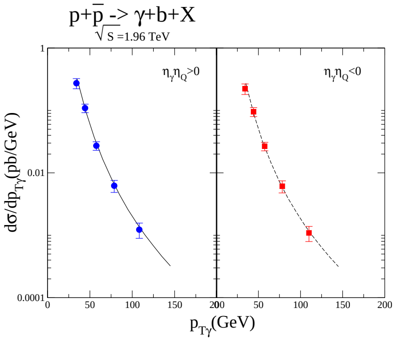


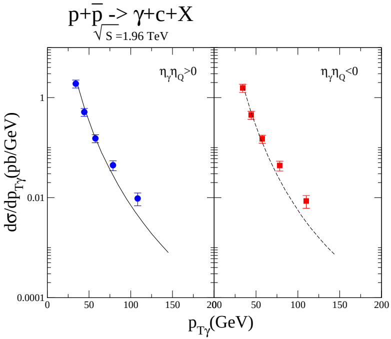
- Diagram 1)$\sim e_Q^2$ - photon couples to heavy quark, Diagram 2)$\sim e_q^2$ - photon couples to initial quarks
- Diagram 2) - dominant → difference between c and b decreases with p_T



Comparison between theory and data

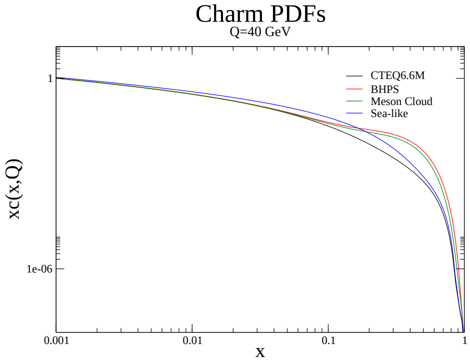
Measurements by DØ Collaboration





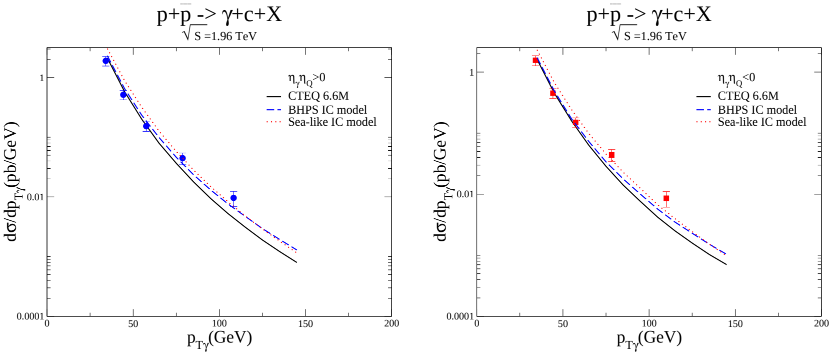
- There is really good agreement between data and theory for the bottom cross section
- For charm the data points at large $p_{T\gamma}$ lie above the theory curve → possible explanation - existence of intrinsic charm

Intrinsic Charm



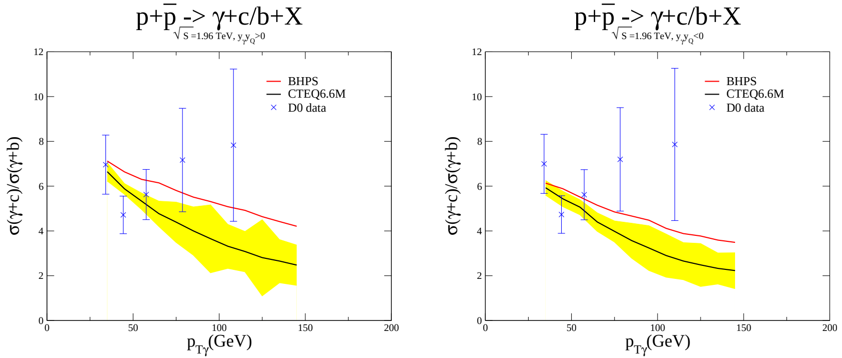
- CTEQ6.6M - radiatively generated charm - $c(x, \mu = m_c) = 0$
- Three intrinsic charm models - Non-perturbative charm component of the nucleon
  - Sea-like model - $c(x) \sim \bar{u}(x) + \bar{d}(x)$
  - BHPS - IC appears mainly at large x
  - Meson Cloud model - IC appears mainly at large x

Comparison between theory and data - IC $c + \gamma$



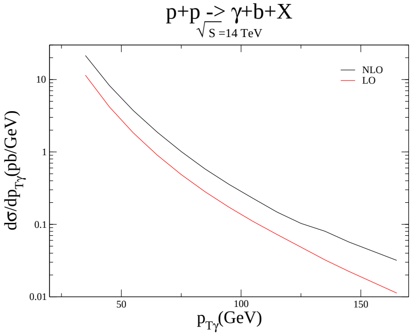
- With the use of the BHPS PDFs the cross section grows at large $p_{T\gamma}$, but is still below the data
- However if we are to look at the ratio of the c to b cross section ...

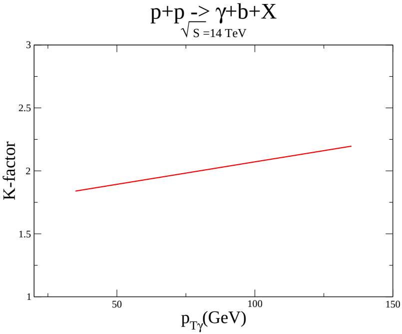
Ratio of c and b



Things look better

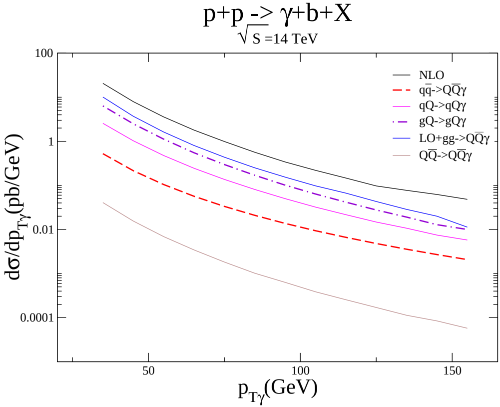
LHC Predictions





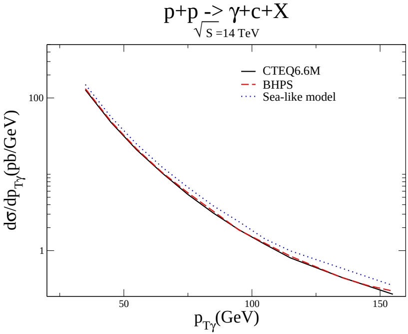
The difference between NLO and LO no longer grows at large $p_{T\gamma}$

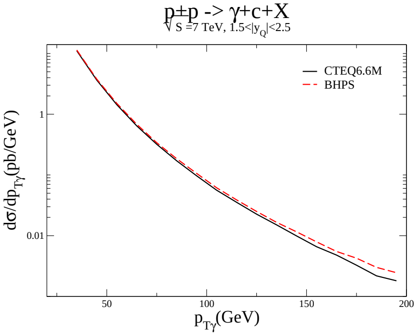
Subprocess Contributions



- $q\bar{q}$ no longer dominates
    - No valence $\bar{q}$
- LO and subprocesses with initial g dominate →
    - Larger center of mass energy probes lower values of x ($\sim \frac{p_T}{\sqrt{S}}$), region where gluon PDF dominates

Intrinsic Charm at the LHC





- Due to smaller x probed at the LHC can still test IC, but mainly the Sea-like model
- At 7 TeV and forward rapidity can slightly differentiate between BHPS and radiatively generated charm

Conclusions

Tevatron

- At Tevatron energies $q\bar{q}$ dominates the cross section at large $p_{T\gamma}$
- Good distinction between different IC models, can test for BHPS, Sea-like
- Good comparison between data and experiment for $\gamma + b$, for $\gamma + c$ some discrepancy at high p_T

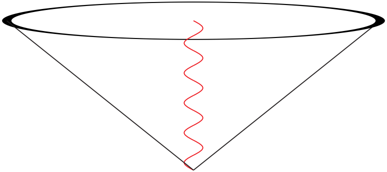
LHC

- At the LHC (pp 14 TeV) subprocesses with initial gluons and heavy quarks dominate
- Sensitivity to initial state heavy quarks
- Can test the low x behavior of heavy quark PDFs once LHC data is available

Isolation

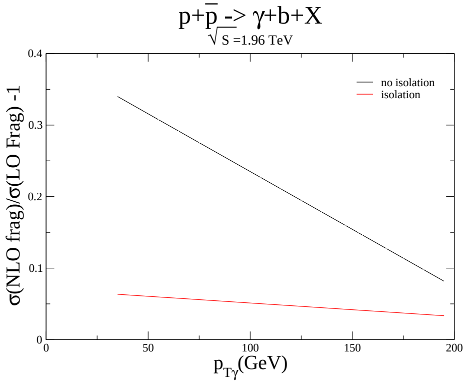
To be detected a direct photon needs to be isolated

- Helps acquire a reliable measurement of the photon's energy
- Helps reduce background from photons coming from the decay of hadrons



- Hadronic energy less than $E_h = \epsilon * E_\gamma$ in $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- Isolation requirements modeling the DØ requirements: $R_1 < 0.2$, $\epsilon_1 < 0.04$ and $R_2 < 0.4$, $\epsilon_2 < 0.07$

NLO Fragmentation



- No isolation - NLO fragmentation increases the cross section up to $\sim 30\%$
- Isolation requirement decreases the NLO fragmentation contribution to a few %

Photon Fragmentation Function

$$\frac{dD_{\gamma/Q}(z)}{dt} = \frac{\alpha}{2\pi} P_{\gamma\leftarrow Q}(z) + \frac{\alpha_s}{2\pi} \int \frac{dy}{y} [D_{\gamma/Q}(z/y) P_{Q\leftarrow Q}(y) + D_{\gamma/g}(z/y) P_{g\leftarrow Q}(y)$$

$$\frac{dD_{\gamma/g}(z)}{dt} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} [D_{\gamma/Q}(z/y) P_{Q\leftarrow g}(y) + D_{\gamma/g}(z/y) P_{g\leftarrow g}(y)]$$