photon + heavy-quark production in pp collisions

AFTER@LHC ECT* Trento

Tzvetalina Stavreva

February 5, 2013

Prompt Photons

- What are they?
  - Any photon that is produced during the hard scattering process or via fragmentation
  - Not to be confused with γ's coming from the decay of hadrons, such as $\pi^0 \to \gamma\gamma$, etc.
- Why are they important?
  - 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

Prompt Photon and Heavy Quarks

- Prompt photons are produced in association with many different particles
- Look at one part of $\sigma \rightarrow$ piece with heavy quarks (charm or bottom)
- In p-p Collisions: Possibility to better constrain Parton Distribution Functions (PDFs) of heavy quarks
- In p-A Collisions: Can constrain nuclear PDFs (nPDFs), esp. the gluon nPDF
- In A-A Collisions: Can be used as a tool for investigating energy loss

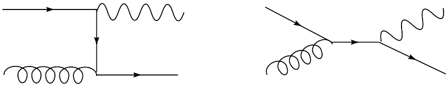
Theory Overview

Direct Photon and Heavy Quarks - hardscattering

how are they produced?

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

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



- Next-to-Leading Order - $\mathcal{O}(\alpha\alpha_s^2)$
  - Real Corrections - $2 \rightarrow 3$ body scattering subprocesses

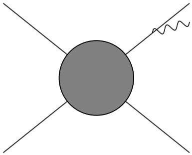
$$g + g \rightarrow Q + \bar{Q} + \gamma \qquad Q + Q \rightarrow Q + Q + \gamma$$
$$g + Q \rightarrow g + Q + \gamma \qquad Q + \bar{Q} \rightarrow Q + \bar{Q} + \gamma$$
$$Q + q \rightarrow q + Q + \gamma \qquad q + \bar{q} \rightarrow Q + \bar{Q} + \gamma$$
$$Q + \bar{q} \rightarrow Q + \bar{q} + \gamma$$

  - Virtual Corrections - interference between LO Born diagram and virtual diagrams

Final state collinear singularities

- Cancel when integrating over PS (KLN Theorem)
- Absorb in Fragmentation Functions (FF)

Photon Fragmentation

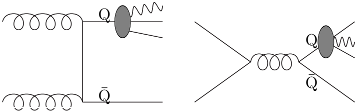


- When γ emitted collinearly to quark $\rightarrow$ absorb collinear singularity in Fragmentation Function into photons - $D_{\gamma/q,g}(z, \mu_F)$
- Large logs appear, while integrating over angle between photon and quark ; resum in γ FF via DGLAP
- Photon couples to quark, responsible for $\alpha \log(Q^2/\Lambda^2)$ behavior of γ FF; $\log(Q^2/\Lambda^2) \sim \frac{1}{\alpha_s}$
- $D_{\gamma/q,g}(z, \mu_F)$ is of order $\mathcal{O}(\alpha/\alpha_s)$

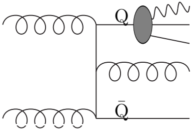
Direct Photon and Heavy Quarks - fragmentation

how are they produced?

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

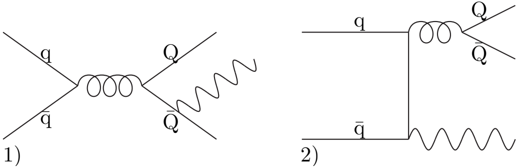


- Also need to include NLO fragmentation contributions - convolute all $2 \to 3 \sim \mathcal{O}(\alpha_s^3)$ with γ FF

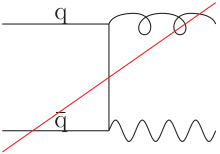


- Fragmentation contributions are greatly reduced due to isolation requirements
- Isolation useful for minimizing background from photons coming from the decay of hadrons, e.g. $\pi^0 \to \gamma\gamma$

Final State Collinear Singularity: $q\bar{q} \to Q\bar{Q}\gamma$



- Unlike for inclusive direct photon the annihilation subprocess does not appear at LO

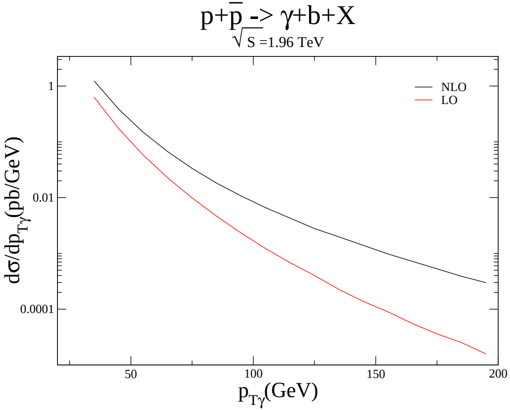


- Jet observed in final state (not meson → no HQ FF)
- Regulate singularity by retaining HQ mass: $(p_Q + p_{\bar{Q}})^2 > 4m_Q^2$

$p\bar{p}$ Collisions

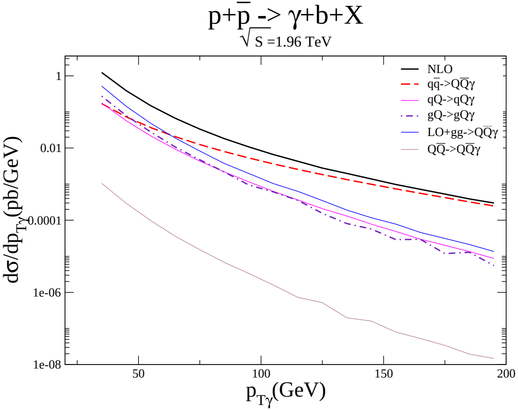
Tevatron Predictions

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



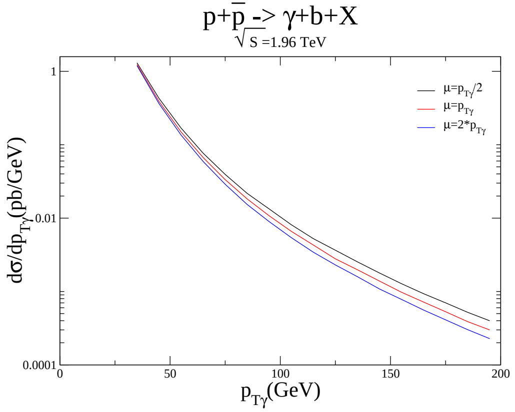
- As $p_{T\gamma}$ increases the difference between LO and NLO grows

Subprocess Contributions



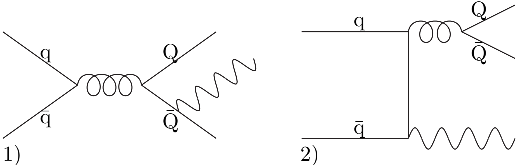
- At $p_{T\gamma} \sim 70\ \mathrm{GeV}$ $q\bar{q} \to Q\bar{Q}\gamma$ starts to dominate
- Abundance of q & $\bar{q}$ at $p\bar{p}$ colliders

Scale Dependence



- Scale dependence increases with $p_{T\gamma}$
- $q\bar{q} \rightarrow Q\bar{Q}\gamma$ dominates at large $p_{T\gamma}$, it should really be considered as a LO subprocess

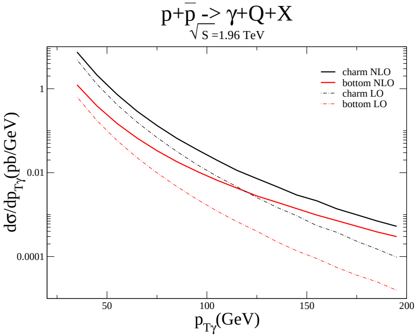
Comparison between charm and bottom

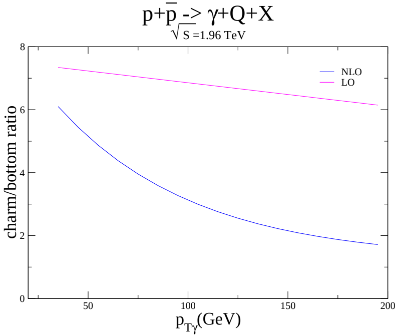


- Diagram 1)$\sim e_Q^2$ - photon couples to heavy quark
- Diagram 2)$\sim e_q^2$ - photon couples to initial quarks

Diagram 2) is the dominant one $\rightarrow$ the difference between the c and b distribution should decrease at large p_T

Comparison between charm and bottom



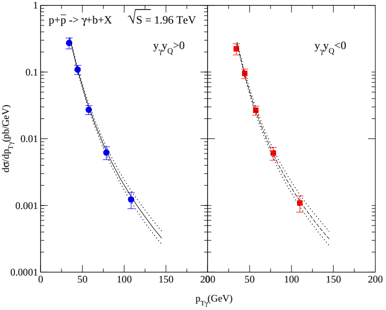


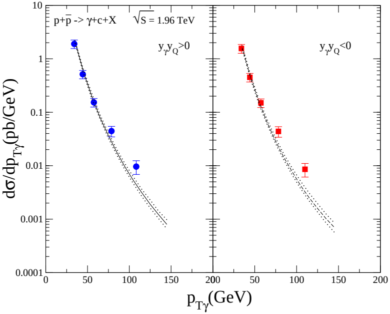
- Difference between b and c: quark charge $e_c^2 = 4/9, e_b^2 = 1/9$ and c PDF larger than b PDF - LO
- At higher $p_{T\gamma}$, $q\bar{q}$ dominates and difference is reduced - NLO

Data

Comparison between theory & data

Measurements by DØ Collaboration [arXiv:0901.0739]

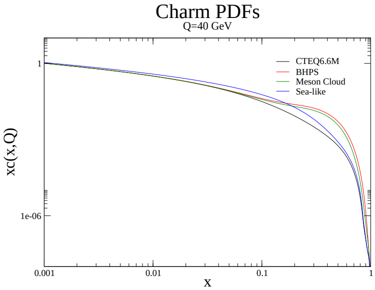




- Really good agreement for $\gamma + b$
- Not so for $\gamma + c$
- Given this: Possible explanation - existence of intrinsic charm rather than higher order corrections

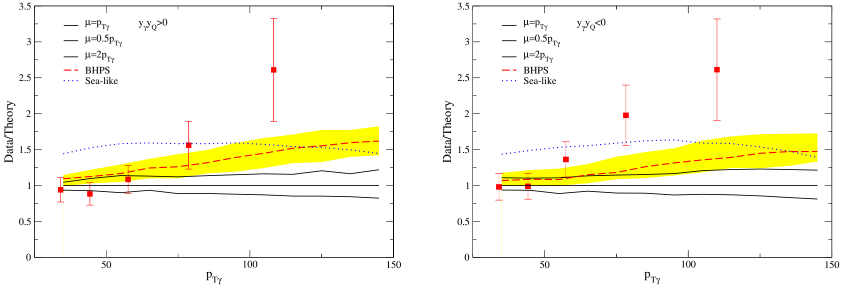
charm PDF

- Presently assumed charm PDF radiatively generated $c(x, \mu = m_c) = 0$, i.e. need only knowledge of gluon PDF $c(x, Q) \sim g(x, Q)$
- Some data (EMC charm structure function at large x suggest) IC component in nucleus - checked by global analysis by CTEQ6.5, CTEQ6.6
- Non perturbative models for IC component to nucleus:



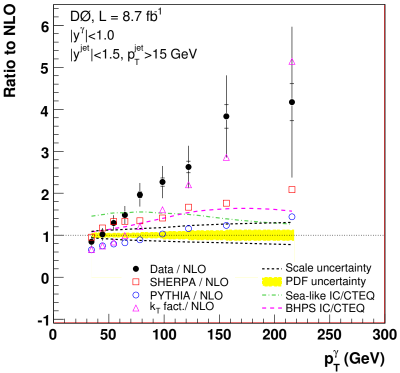
- BHPS (Brodsky et.al.) (CTEQ6.6C0, CTEQ6.6C1) & Meson Cloud (CTEQ6.5C2, CTEQ6.5C3) - light-cone models - IC at high x
- Sea-like model (CTEQ6.6C2, CTEQ6.6C3) - $c(x, Q) \sim \bar{u}(x, Q) + \bar{d}(x, Q)$

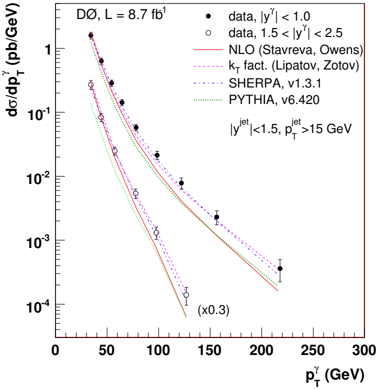
Intrinsic Charm effect on $\gamma + c$



- Sealike - overshoots data at low pT and undershoots at high pT
- BHPS - the cross section grows at large pT, but still below data
- Result inconclusive -
  - New Measurements - Tevatron - CDF & DØ
  - Test at pp Colliders - RHIC & LHC

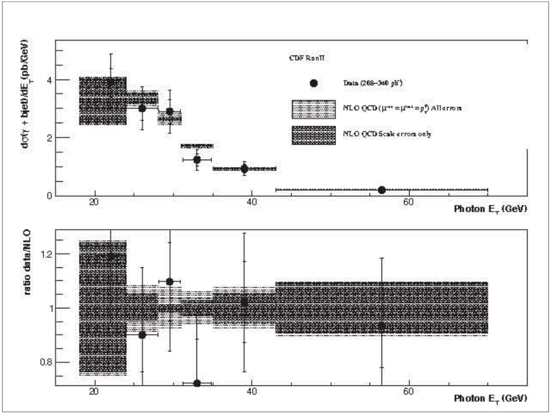
new results DØ





- $\gamma + c$ - left - arXiv:1210.5033
- $\gamma + b$ - right - arXiv:1203.5865
- Even higher discrepancy - now consider all leading jets

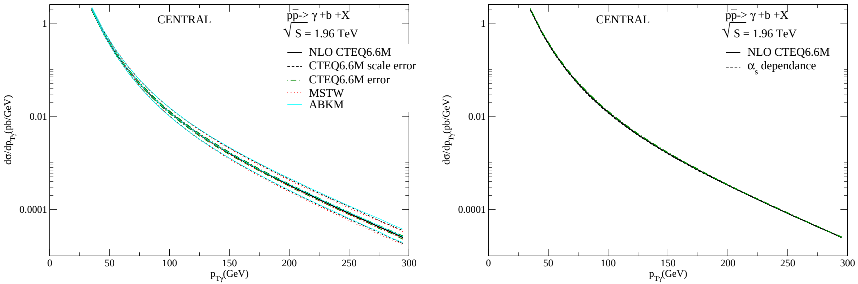
CDF



Tuesday, October 18, 2011

- arXiv:0912.3453
- Good agreement for $\gamma + b$
- New results indicate differently

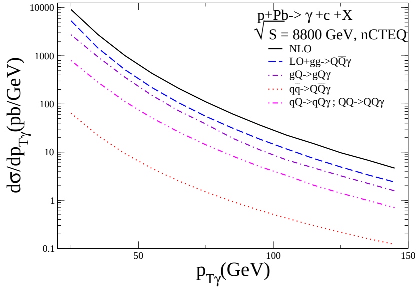
PDF Sets



- Different PDF sets: CTEQ6.6M,MSTW,ABKM - result unchanged
- $\alpha_s(M_Z) = 0.116, 0.117, 0.119, 0.120$ CTEQ6.6AS

pp Collisions

Subprocess Contributions

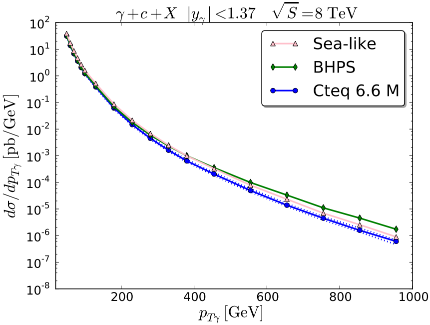


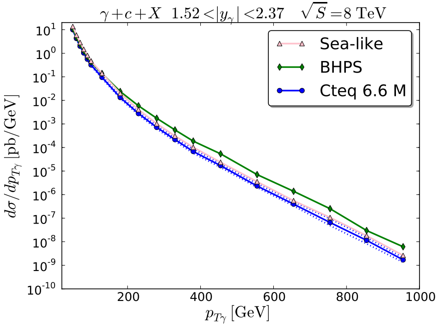
- *g & Q* initiated subprocesses dominate $(>80\%) \Rightarrow$ sensitivity to gluon and HQ PDFs.

LHC - ATLAS
Experimental Cuts

	p_T	Rapidity	Isolation Cuts
Photon	$p_{T,\gamma}^{min} = 45$ GeV	$\lvert y_\gamma \rvert < 1.37$	$R = 0.4,\ E_T = 7$ GeV
	$p_{T,\gamma}^{max} = 1000$ GeV	$1.52 < \lvert y_\gamma \rvert < 2.37$	
Heavy Jet	$p_{T,Q}^{min} = 20$ GeV	$\lvert y_Q \rvert < 2.4$	$R_{jet} > 0.4, R_{Q\gamma} > 1$

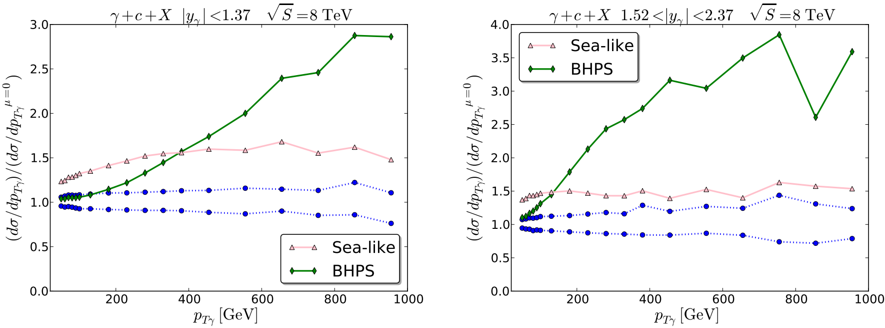
$\gamma + c$





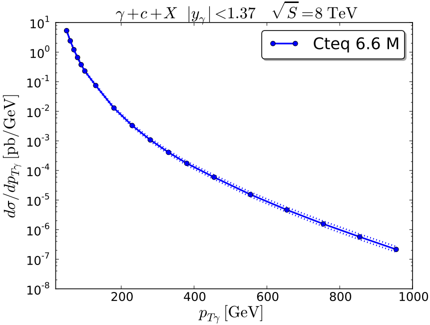
- IC shows up at much higher p_T
- dependence on rapidity

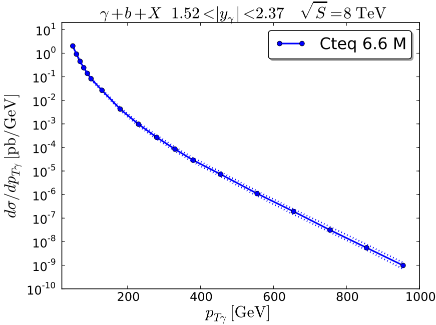
$\gamma + c$ ratio



- $x \sim \frac{p_T}{\sqrt{S}}(e^{y_1} + e^{y_2})$
- Need to consider forward rapidities - smaller x - to test for BHPS-IC at the LHC

$\gamma + c$



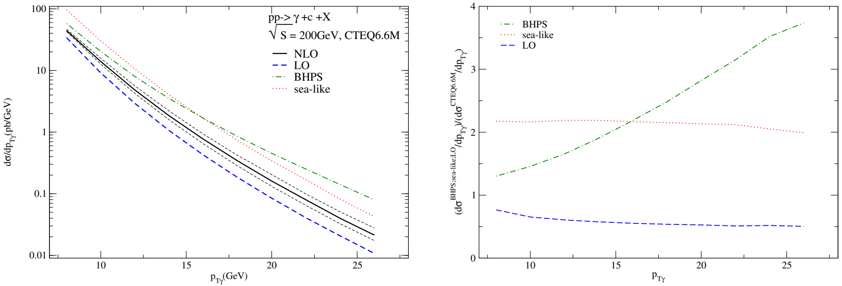


- IB PDFs necessary

Experimental Cuts

	p_T	Rapidity	Isolation Cuts
Photon*	$p_{T,\gamma}^{min} = 7$ GeV	$\lvert y_\gamma \rvert < 0.35$	$R = 0.5$, $\epsilon < 0.1 E_\gamma$
Heavy Jet	$p_{T,Q}^{min} = 5$ GeV	$\lvert y_Q \rvert < 0.8$	——

Intrinsic Charm at RHIC



- Small center of mass energy probes high $x \sim p_T/\sqrt{S}$
- Cross section is very sensitive to IC - especially BHPS

Summary

- $\gamma + Q$ production is a great probe of the heavy quark PDFs
- Discrepancy between pQCD predictions and data
- Need measurements probing high x - to resolve the case for IC & IB