Direct Photon Production In Association With A Heavy Quark Jet at Hadron and Ion Colliders

Workshop on nuclear Parton Distribution Functions

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Direct Photons and Heavy Quarks

Direct Photons

- Any photon that is produced during the hard scattering process or via fragmentation
- Escape confinement
- Photon acts as a probe of the hard scattering
- Useful for acquiring information on (n)PDFs (gluon)

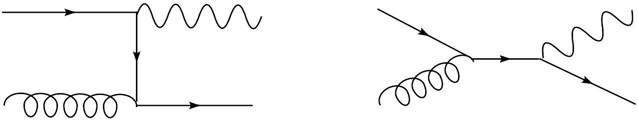
$\gamma + Q$ production

- Direct photons are produced in association with many different particles
- Look at one part of the cross section $\rightarrow$ piece with heavy quarks
- Better understand the role of heavy quarks in high p_T collisions
- Possibility to constrain (n)PDFs 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

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

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

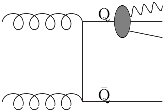
- Also need to include Direct Photons which are produced via fragmentation

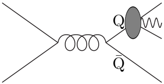
Photon Fragmentation

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

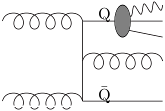
Fragmentation Effects

- LO: include all $2 \longrightarrow 2$ 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 $2 \longrightarrow 3 \sim \mathcal{O}(\alpha_s^3)$ with γ FF



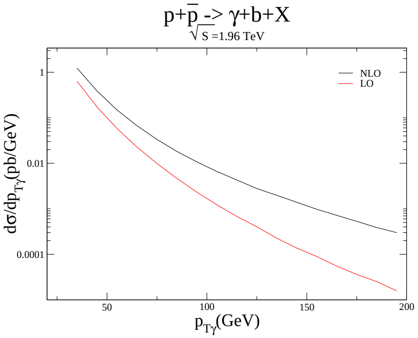
Photon Isolation

- Fragmentation contributions are greatly reduced due to isolation requirements
- Helps minimize background from photons coming from the decay of hadrons, e.g. $\pi^0 \rightarrow \gamma\gamma$
- Hadronic energy less than $E_h = \epsilon * E_\gamma$ in $R = \sqrt{(\eta_\gamma - \eta_h)^2 + (\phi_\gamma - \phi_h)^2}$
- Restrictions on z in theoretical calculation: $z > \frac{1}{1+\epsilon}$

Subprocesses and PDFs

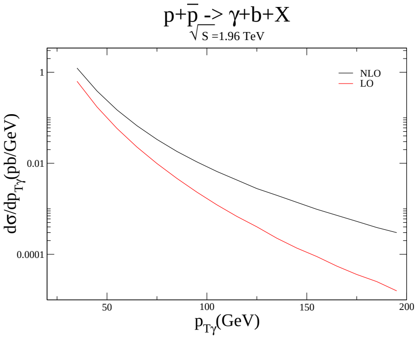
- Which subprocess dominates is highly dependent on collider type (pp, $p\bar{p}$) and center of mass energy
- Dependent on this is what (n)PDF and what x range can be probed

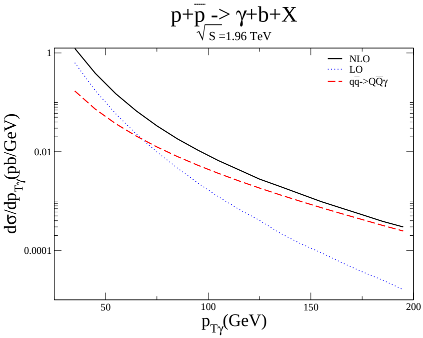
Tevatron Predictions



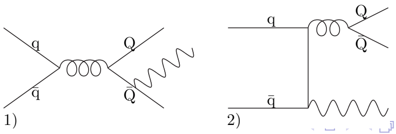
- As $p_{T\gamma}$ increases the difference between LO and NLO grows
- What drives this difference?

Tevatron Predictions

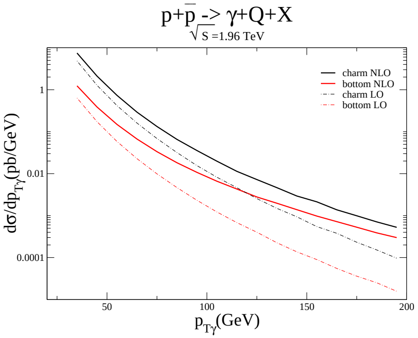


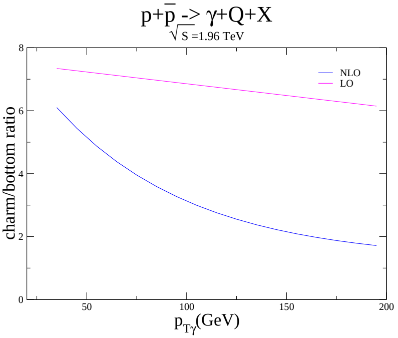


- As $p_{T\gamma}$ increases the difference between LO and NLO grows
- What drives this difference?
- Abundance of q and $\bar{q}$ $\rightarrow$ annihilation subprocess dominates $q\bar{q} \rightarrow \gamma Q\bar{Q}$



Comparison between charm and bottom

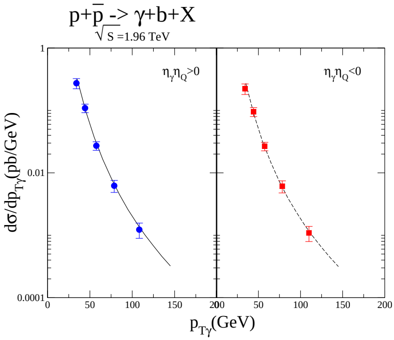


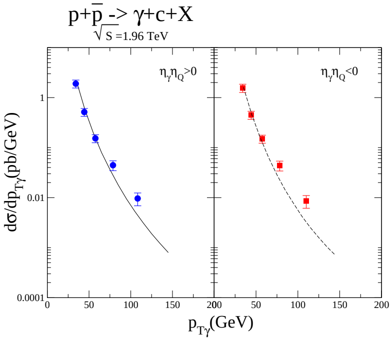


- Difference between b and c: quark charge $e_c^2 = 4/9, e_b^2 = 1/9$ and c PDF larger than b PDF - LO
- At higher $p_{T\gamma}$, $q\bar{q}$ dominates and difference is reduced - NLO

Comparison between theory and data

Measurements by DØ Collaboration

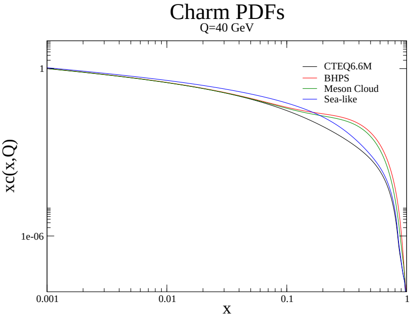




- There is really good agreement between data and theory for the bottom cross section
- For charm the data points at large $p_{T\gamma}$ lie above the theory curve $\longrightarrow$ possible explanation - existence of intrinsic charm

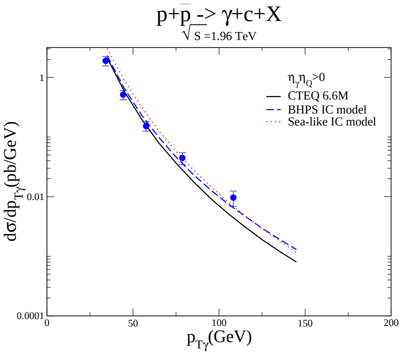
Intrinsic Charm

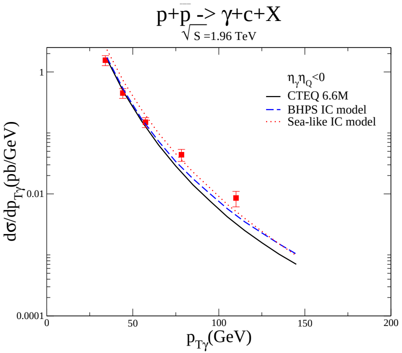
- Even if annihilation process dominates due to the center of mass energies can probe for IC at Tevatron
- Presently assumed that $c(x, \mu = m_c) = 0$, $i.e.$ need only knowledge of gluon PDF, $c(x, Q) \sim g(x, Q)$
- Three intrinsic charm models - Non-perturbative charm component of the nucleon



- For central rapidity $x \sim \frac{2p_T}{\sqrt{S}} \rightarrow$ at higher p_T can test for BHPS model

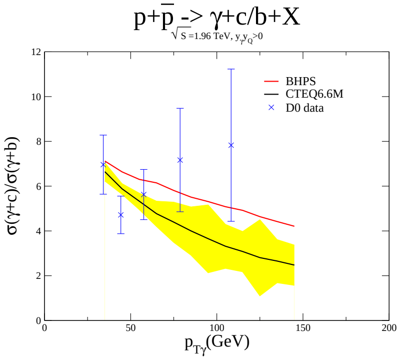
Comparison between theory and data - IC $c + \gamma$

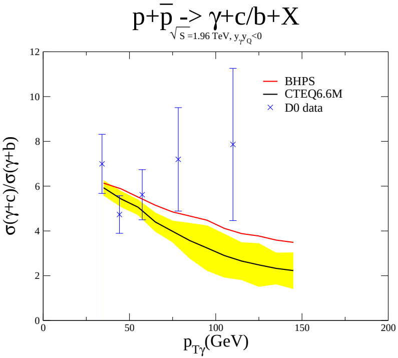




- With the use of the BHPS PDFs the cross section grows at large $p_{T\gamma}$, but is still below the data
- However if we are to look at the ratio of the c to b cross section ...

Ratio of c and b

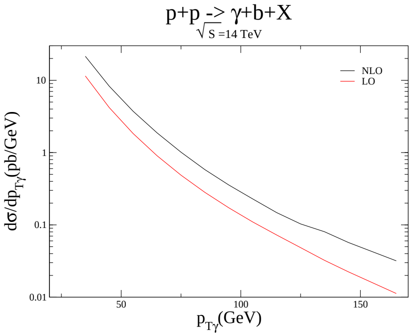


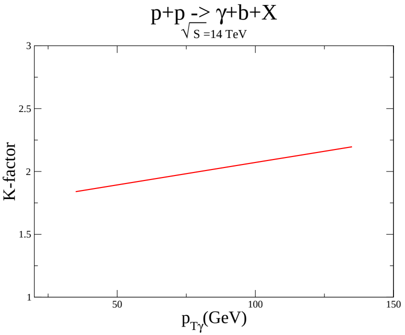


Things look better

LHC at 14 TeV

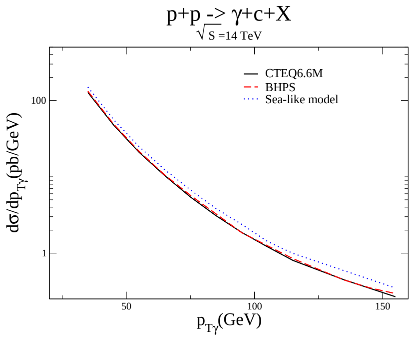
- At LHC *p* beams and higher center of mass
- No longer such a difference between LO and NLO

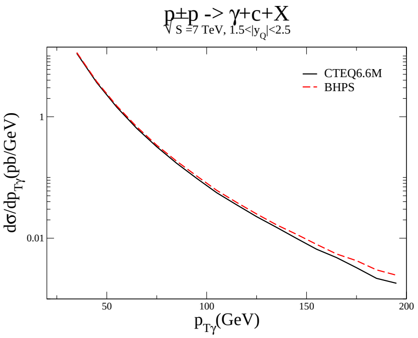




- Due to this there is great sensitivity to gluon and Q PDFs

Intrinsic Charm at the LHC

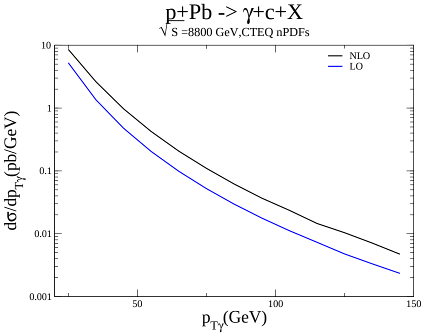


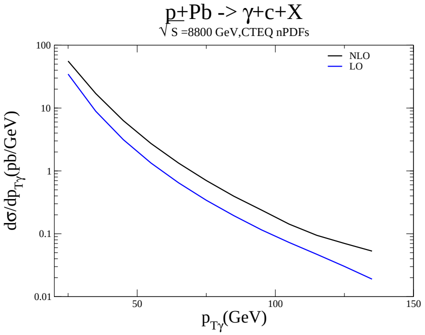


- Due to smaller x probed at the LHC can still test IC, but mainly the Sea-like model
- At 7 TeV and forward rapidity can slightly differentiate between BHPS and radiatively generated charm

pPb collisions at the LHC

- $p_{T\gamma min} > 20\ \mathrm{GeV}, p_{TQmin} > 15 GeV, |y_Q| < 0.7$



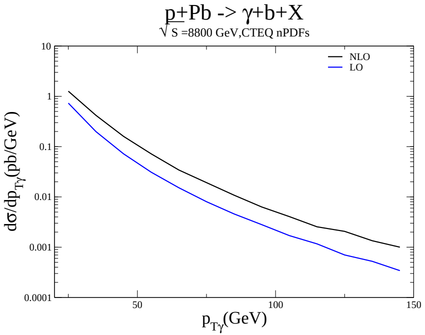


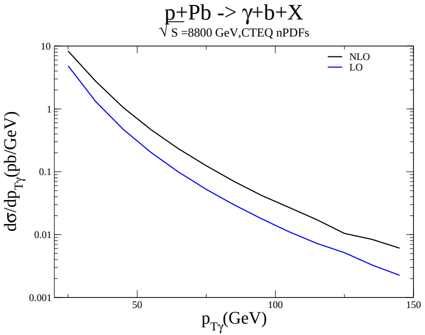
PHOS : $|y_\gamma| < 0.12, 220^\circ < \phi_\gamma < 320^\circ$ EMCAL : $|y_\gamma| < 0.7, 60^\circ < \phi_\gamma < 180^\circ$

- $\mathcal{L}_{pPb} = 10^{29} cm^{-2} s^{-1}$ (ALICE:Phys.Perf.Rep.Vol.II); $\mathcal{L}_{pPb}^{integ} = 53.9 pb^{-1}$
- PHOS: $\sigma_{\gamma+c}^{tot} = 130.5 pb$ naive estimate $\mathcal{N}_{events} = \sigma_{\gamma+c}^{tot} \mathcal{L}_{pPb}^{integ} \sim 7000$
- EMCAL: $\sigma_{\gamma+c}^{tot} = 850 pb$ naive estimate $\mathcal{N}_{events} = \sigma_{\gamma+c}^{tot} \mathcal{L}_{pPb} \sim 45000$

pPb collisions at the LHC

- $p_{T\gamma} > 20\ \mathrm{GeV}, p_{TQ} > 15 GeV, |y_Q| < 0.7$



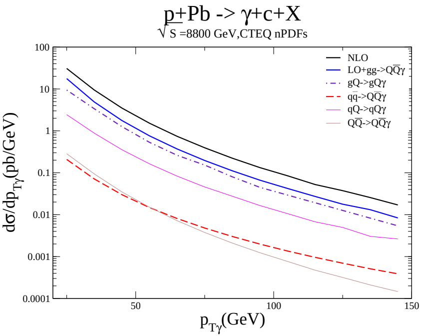


PHOS : $|y_\gamma| < 0.12, 220^\circ < \phi_\gamma < 320^\circ$ EMCAL : $|y_\gamma| < 0.7, 60^\circ < \phi_\gamma < 180^\circ$

- PHOS: $\sigma^{tot}_{\gamma+b} = 20pb$ naive estimate $\mathcal{N}_{events} = \sigma^{tot}_{\gamma+b}\mathcal{L}^{integ}_{pPb} \sim 1000$
- EMCAL: $\sigma^{tot}_{\gamma+b} = 131pb$ naive estimate $\mathcal{N}_{events} = \sigma^{tot}_{\gamma+b}\mathcal{L}^{integ}_{pPb} \sim 7100$
- Not a big difference between NLO and LO $\rightarrow$ check other contributing subprocesses

pPb collisions - subprocess contributions

- $p_{T\gamma} > 20\ \mathrm{GeV}, p_{TQ} > 15 GeV, |y_\gamma| < 0.12, |y_Q| < 0.7$



- The Compton subprocess dominates
- $\gamma + Q$ great probe of gluon + HQ nuclear PDFs

$\gamma + Q$ and nuclear PDFs

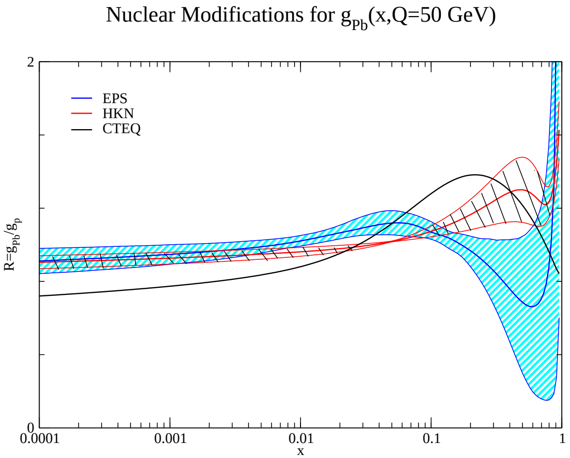
nuclear PDFs

- Give probability of finding a parton with a momentum fraction x in a nucleus
- Needed for heavy ion collisions, at ALICE , RHIC
- Gluon nPDF largely unconstrained

$\gamma + Q$

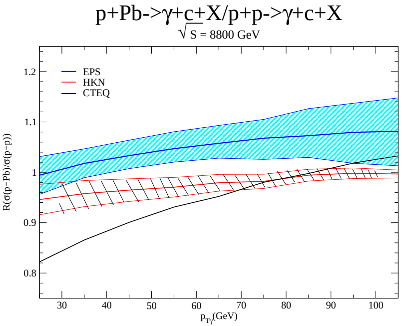
- Over 80% of the cross section is from $g + Q$ initiated subprocesses
- Can test both g & c PDF in $\gamma + c$ studies
- If no IC charm all this sensitivity is due to the gluon PDF
- Same in $\gamma + b \rightarrow$ test g PDF

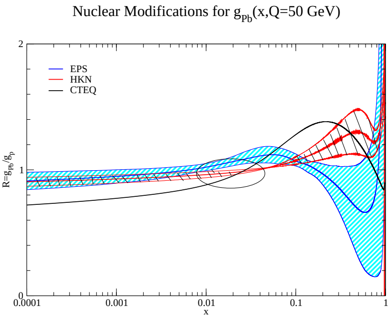
Nuclear Modifications



- Comparison between different nPDF sets for the gluon nuclear modifications $R_g^{Pb} = \frac{g_{Pb}(x,Q)}{g_p(x,Q)}$

Nuclear Modifications to $\gamma + c$

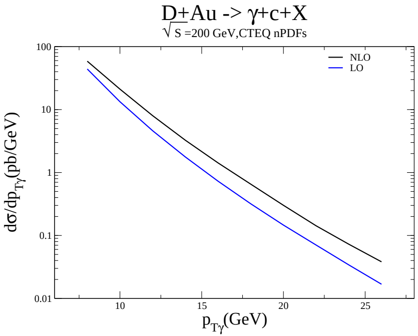


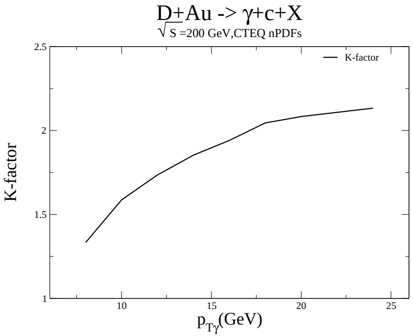


- Probes relatively small x
- Measurements with appropriate error bars can distinguish between the different nPDFs

gamma+Q at RHIC

- $p_{T\gamma} > 7 \text{ GeV}, p_{TQ} > 5GeV, |y_\gamma| < 0.35, |y_Q| < 0.8$

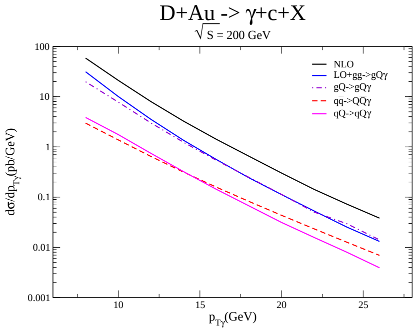




- $\mathcal{L}_{DAu} = 62nb^{-1}$ per week (H.F.Work.Group.Report) $\rightarrow \mathcal{L}^{integ} = 290pb^{-1}$
- $\sigma^{tot}_{\gamma+c} = 190pb$ naive estimate $\mathcal{N}_{events} = \sigma^{tot}_{\gamma+c}\mathcal{L}^{integ} \sim 55000$

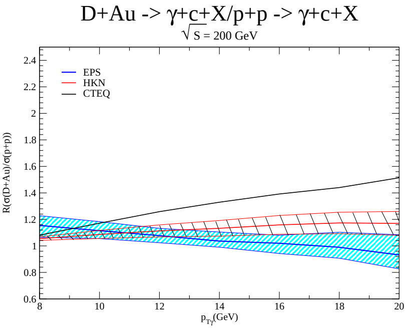
gamma+Q at RHIC - subprocess contributions

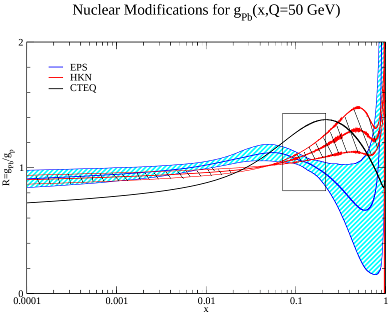
- $p_{T\gamma} > 7\ \mathrm{GeV}, p_{TQ} > 5 GeV, |y_\gamma| < 0.35, |y_Q| < 0.8$



- The Compton subprocesses dominate
- The annihilation subprocess picks up slightly at higher $p_T \to q$ PDF grows at large x

gamma+Q at RHIC





- At RHIC higher x region is probed
- Complimentary information to ALICE

Conclusions

- 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
- At the LHC (pp 14 TeV or pPb) subprocesses with initial gluons and heavy quarks dominate
- Great process for constraining g and Q (n)PDFs
- Can distinguish between different nPDF sets, CTEQ, HKN, EPS
- ALICE and RHIC probe different x regions $\rightarrow$ supplemental information
- Future work - Energy Loss $\rightarrow$ predictions for **AA collisions**