DIRECT PHOTON AND HEAVY QUARK JET PRODUCTION AT THE LHC

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INTRODUCTION

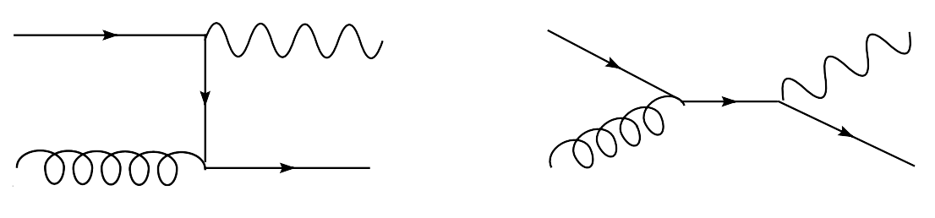
Direct photons can serve as an excellent probe of the structure of the proton due to their pointlike electromagnetic coupling to quarks and due to the fact that they escape confinement. However the information that can be obtained about the underlying subprocesses and separate parton PDFs by looking at direct photons alone can be somewhat limited. This can be rectified by investigating the associated production of direct photons with heavy quarks (charm or bottom), thereby, providing valuable information on the gluon and heavy quark PDFs. This study is also extended to high-energy nuclear collisions (p-A), where one can use direct photon plus heavy quark production to investigate the structure of the nucleus as well. These results represent a necessary baseline for future predictions for A-A collisions, as this process can be very useful for studying the effects of the hot nuclear medium, created in heavy ion collisions. On one hand there is the photon, which will traverse the medium unaffected, while on the other hand the heavy quark jet will interact with the medium. Thus the photon spectrum can act as a control on the validity of the measurements and calculation, as these would not require any medium modifications, and can be computed in the same way as for the p-p or p-A case. While the difference in the heavy quark spectrum will give an indication as to the type of interactions between it and the medium.

THEORY OVERVIEW - HOW ARE $\gamma + Q$ PRODUCED?

Leading Order - $\mathcal{O}(\alpha\alpha_s)$

- Hard Scattering

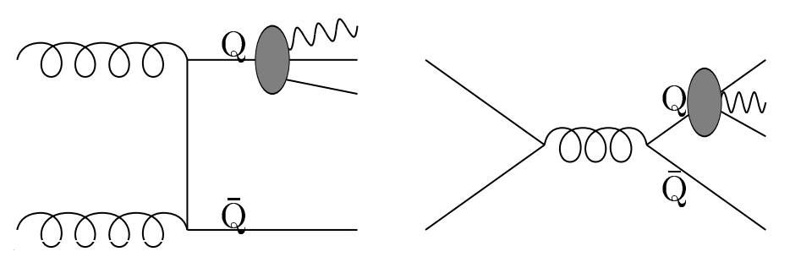
At LO there is only one hard scattering subprocess:



$gQ \rightarrow \gamma Q$ - Compton subprocess

- LO Fragmentation Effects

At each order there are also corresponding fragmentation effects (see details). The photon can be produced via quark or gluon fragmentation. All $2 \rightarrow 2$ subprocesses of $\sim \mathcal{O}(\alpha_s^2)$ containing at least one heavy quark convoluted with the corresponding photon fragmentation function need to be included. However isolation requirements (needed for a precise experimental measurement) greatly reduce the fragmentation effects. For e.g. $gg \rightarrow Q\bar{Q}$ succeeded by $Q \rightarrow \gamma + X$ or $q\bar{q} \rightarrow Q\bar{Q}$ succeeded by $Q \rightarrow \gamma + X$



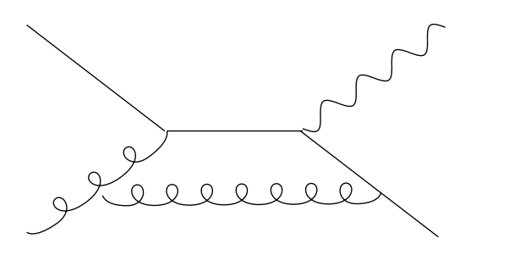
Next-to-Leading Order - $\mathcal{O}(\alpha\alpha_s^2)$

- Real Corrections

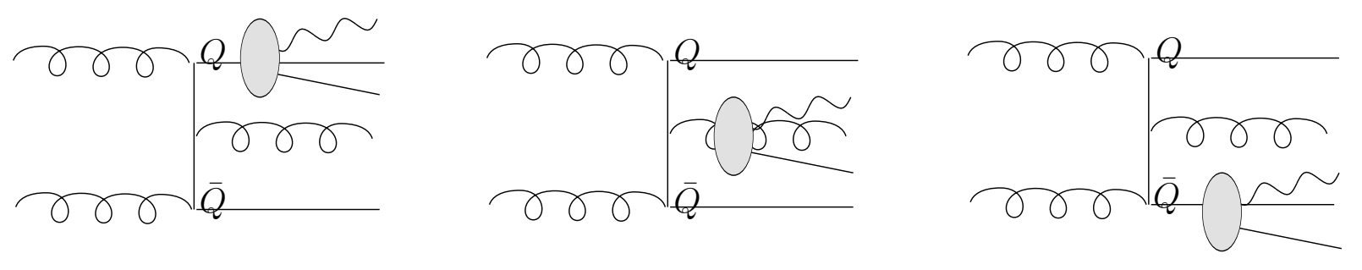
There are 7 hard scattering subprocesses at NLO

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

- Virtual Corrections - to the Born (Compton) subprocess, e.g.:

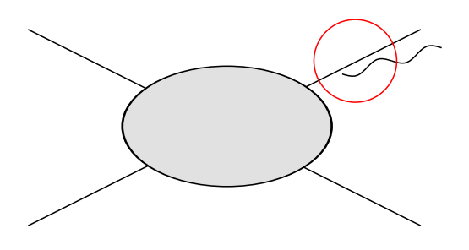


- NLO Fragmentation Effects - For e.g. $gg \rightarrow gQ\bar{Q}$ succeeded by $g \rightarrow \gamma + X$, or $Q \rightarrow \gamma + X$, or $\bar{Q} \rightarrow \gamma + X$



Photon Fragmentation - in more detail

- When a photon is emitted collinearly to a quark a collinear (or mass) singularity will occur

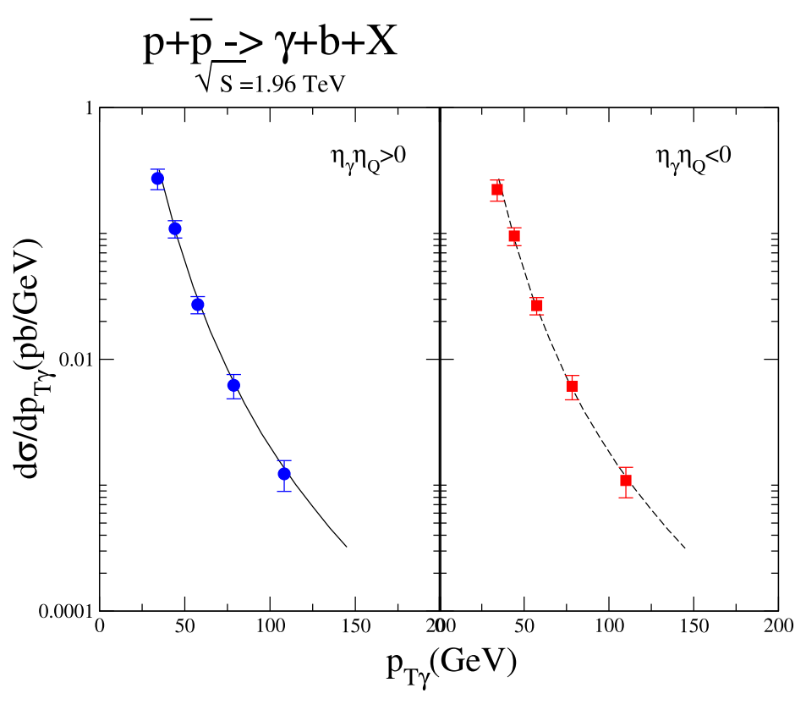


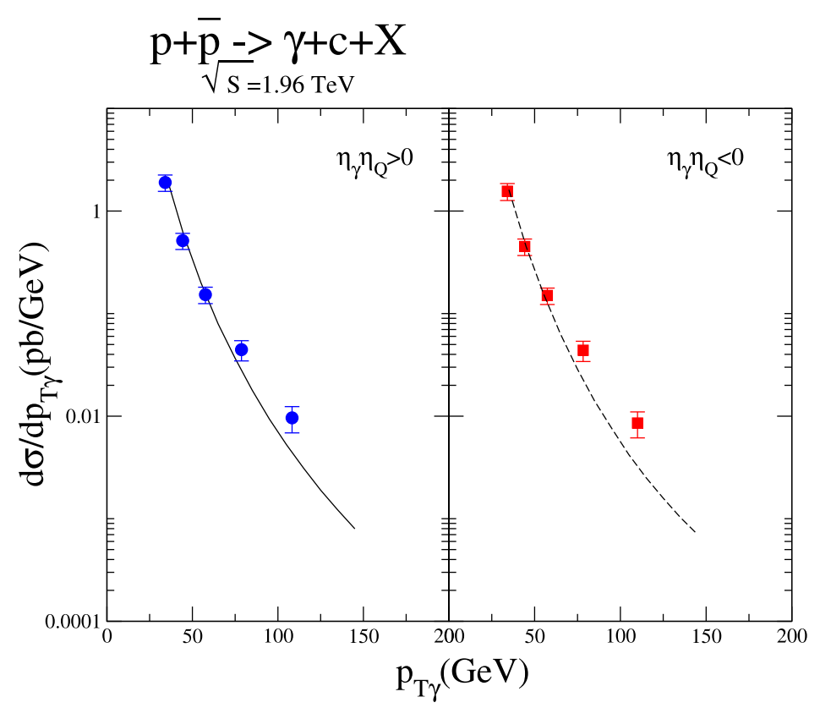
- In order to take care of the collinear singularity, it is absorbed in a Photon Fragmentation Function (γ FF) - $D_{\gamma/q,g}(z,\mu_F)$
- However large logs will still appear while integrating over the angle between the photon and the quark; These can be resummed in the γ FF via the DGLAP set of differential equations
- 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 $\mathcal{O}(\alpha/\alpha_s)$, therefore the convolution $\mathcal{O}(\alpha_s^2) \otimes D_{\gamma/q,g} \sim \alpha_s^2\alpha/\alpha_s = \alpha\alpha_s$ yields a process at LO

HADRONIC COLLISIONS

$p - \bar{p}$ Collisions

Recently measurements of this process have become available courtesy of the DØ Collaboration. Below we present the comparison between theory and data.

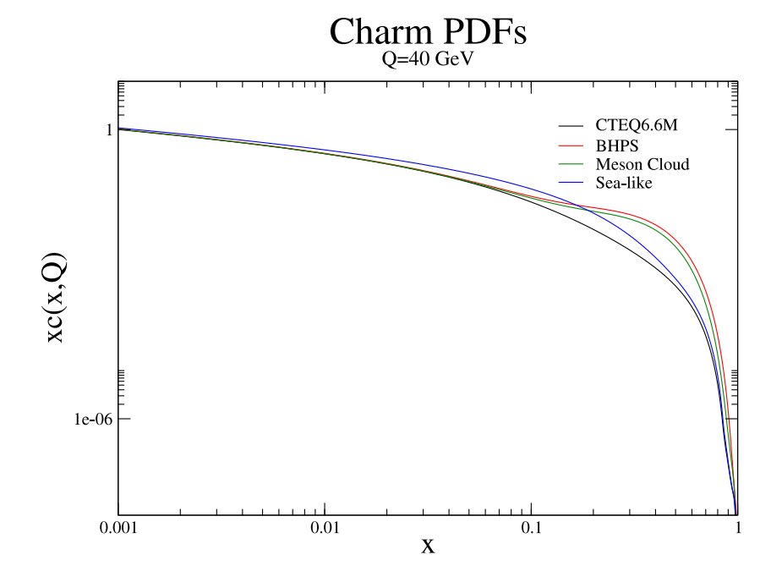


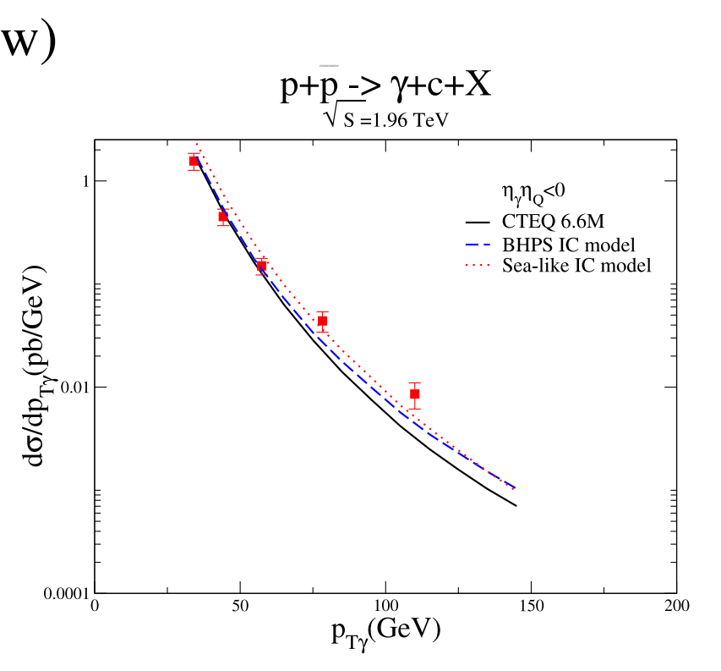


- There is really good agreement between data and theory for the bottom cross section
- For charm the data points at large $p_{T\gamma}$ lie above the theory curve → possible explanation - existence of intrinsic charm

Intrinsic Charm

- Presently it is assumed that there is no *intrinsic charm* in the hadron, $i.e.$ $c(x,\mu = m_c) = 0$, need only knowledge of gluon PDF, and via the DGLAP evolution equations the charm PDF can be obtained $c(x,Q) \sim g(x,Q)$
- There are however 3 intrinsic charm models describing the possibility of a non-perturbative charm component of the nucleon (These IC PDFs + 1 perturbative PDF are shown in the figure below)



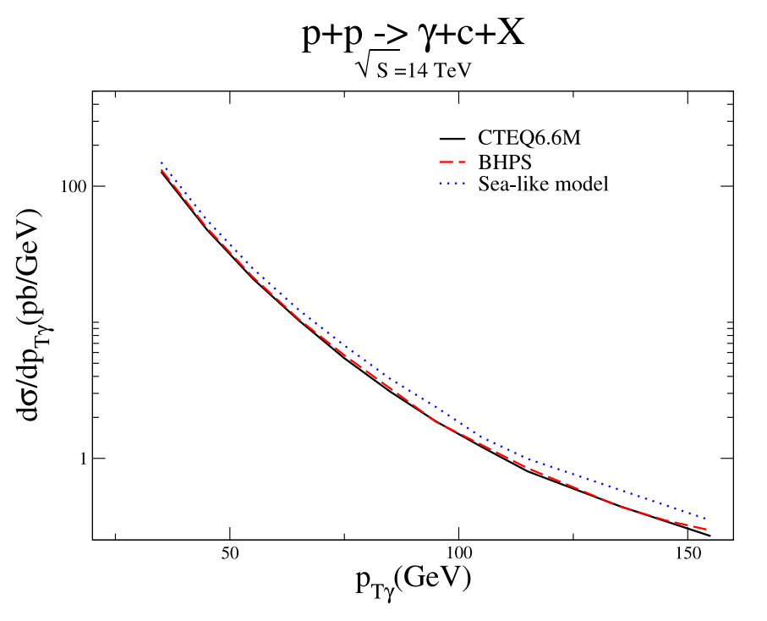


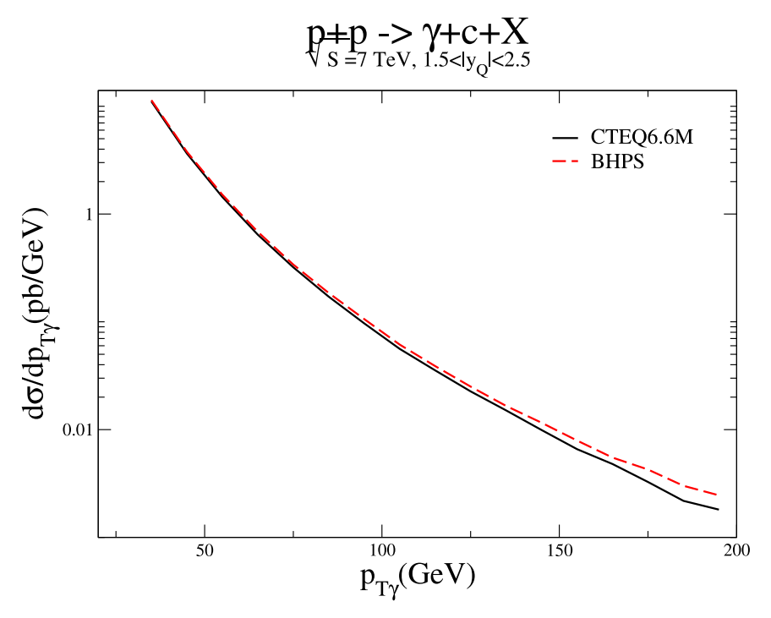
- The BHPS and the Meson Cloud models predict an IC that appears at large x, whereas in the sea-like model $c(x) \sim \bar{d}(x) + \bar{u}(x)$ making it larger than the perturbative charm PDF

- Comparing the theoretical predictions utilizing the IC PDFs shows that the sea-like IC increases the cross section at all p_T, while with the use of the BHPS PDFs the cross section grows at large $p_{T\gamma}$, thus following the trend of the experimental measurements but is still below the data

Can we test for intrinsic charm at the LHC?

- At the LHC - p beams and higher center of mass - due to this there is great sensitivity to gluon and Q PDFs





- Due to smaller x probed at the LHC, $x \sim \frac{2p_T}{\sqrt{S}}$, 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

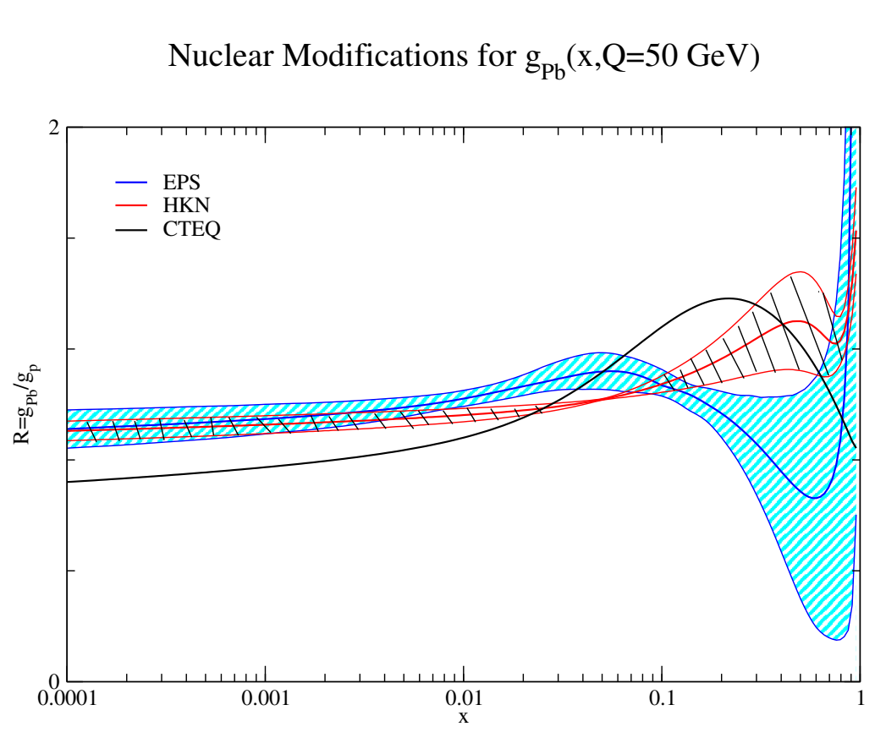
$p - A$ COLLISIONS

Nuclear PDFs

- nuclear PDFs give the probability of finding a parton with a momentum fraction x in a nucleus (while the free PDFs give this probability for a free hadron)
- They are needed for heavy ion collisions, such as the ones at ALICE, as they are an essential part of the cross section calculation
- They are also valuable in the determination of the free PDFs as some of the data needed for their constraint comes from nuclear targets
- Currently the gluon nuclear PDF is largely unconstrained. Of all the different sets of nuclear PDFs only one uses a small amount of data that directly constrains the gluon nPDF, while the rest of the constraints come from sum rules - which are not sufficient to have a well determined gluon. More data is needed!

Nuclear Gluon PDF

Below is shown how the gluon nuclear PDF is modified with respect to the free gluon PDF



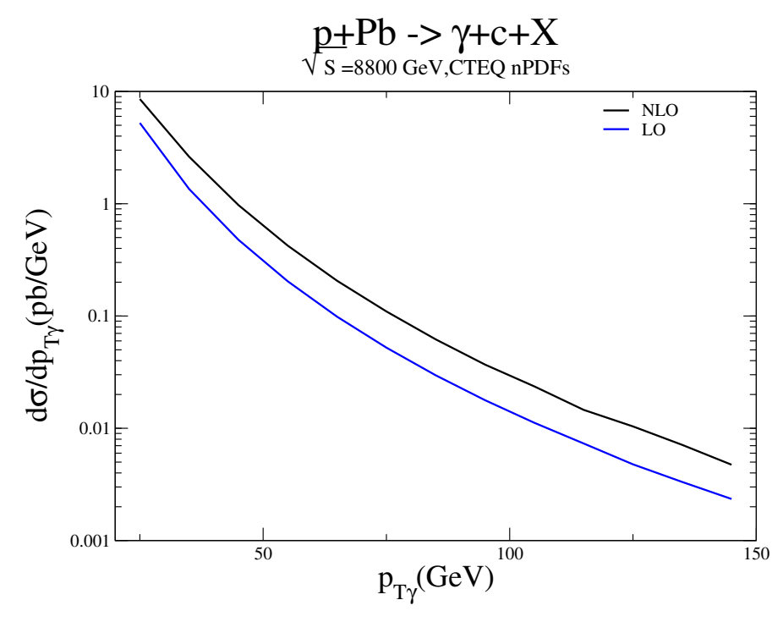
- The comparison between the different nPDF sets (nCTEQ, EPS and HKN) for the gluon nuclear modifications $R_g^{Pb} = \frac{g_{Pb}(x,Q)}{g_p(x,Q)}$ including the errors illustrates the need for a more precise determination of $g_{Pb}(x,Q)$

$p - Pb$ Collisions at the LHC

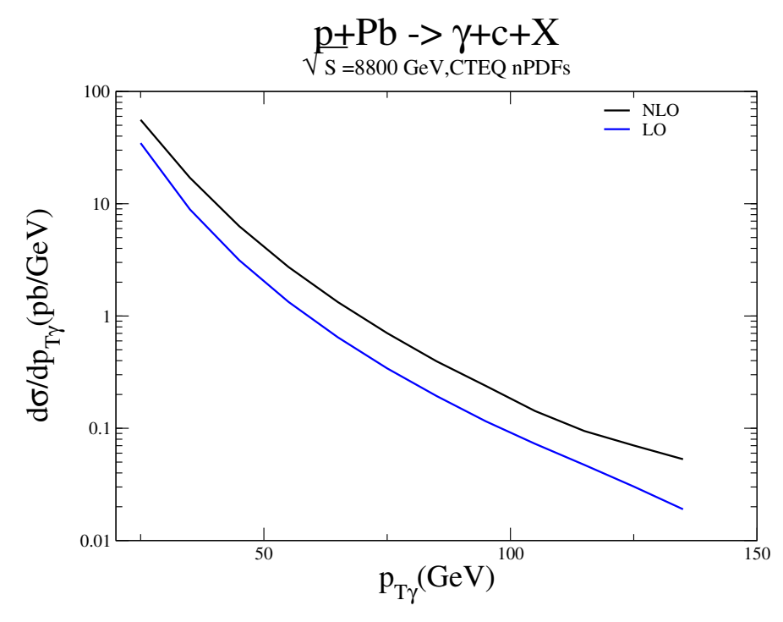
The experimental cuts appropriate for the ALICE detector are:

	p_T	Rapidity	ϕ	Isolation Cuts
Photon (PHOS)	$p_{T,\gamma}^{min} = 20$ GeV	$\lvert y_\gamma\rvert < 0.12$	$220° < \phi < 320°$	$R = 0.2$, $p_T^{\rm th} = 2$ GeV
Photon (EMCal)	$p_{T,\gamma}^{min} = 20$ GeV	$\lvert y_\gamma\rvert < 0.7$	$60° < \phi < 180°$	$R = 0.2$, $p_T^{\rm th} = 2$ GeV
Heavy Jet	$p_{T,Q}^{min} = 15$ GeV	$\lvert y_Q\rvert < 0.7$	——	——

- Utilizing them the following predictions are obtained



PHOS



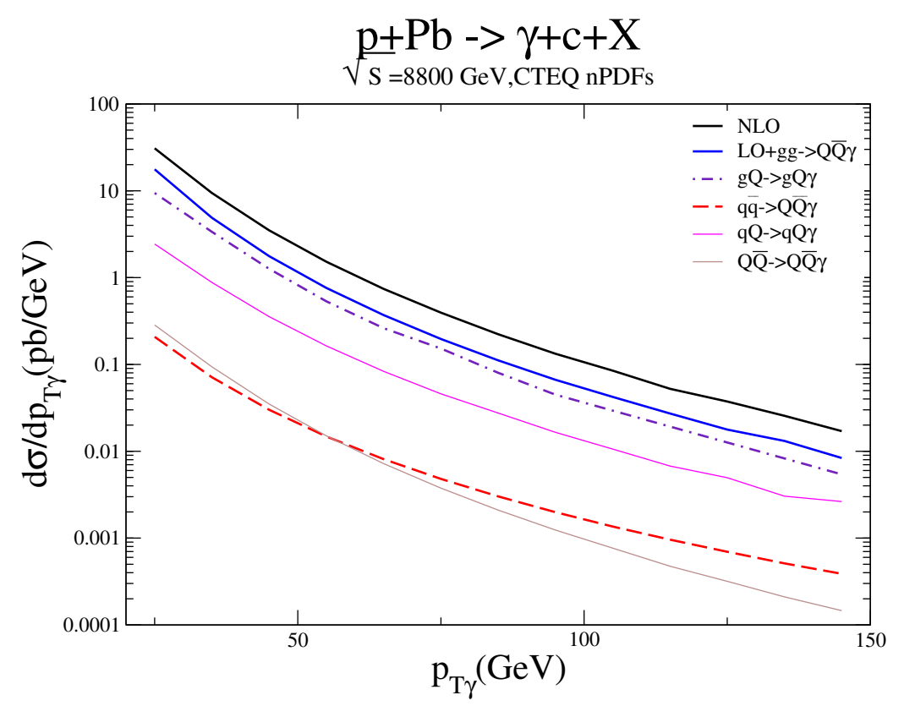
EMCal

- Using an instantaneous luminosity of $\mathcal{L}_{pPb} = 10^{29} cm^{-2}s^{-1}$ the following number of events per year and cross-sections are obtained

	σ^{tot}	N_{event}
$\gamma + c$ PHOS	131pb	2600
$\gamma + c$ EMCal	684pb	13700
$\gamma + b$ PHOS	20pb	400
$\gamma + b$ EMCal	131pb	2600

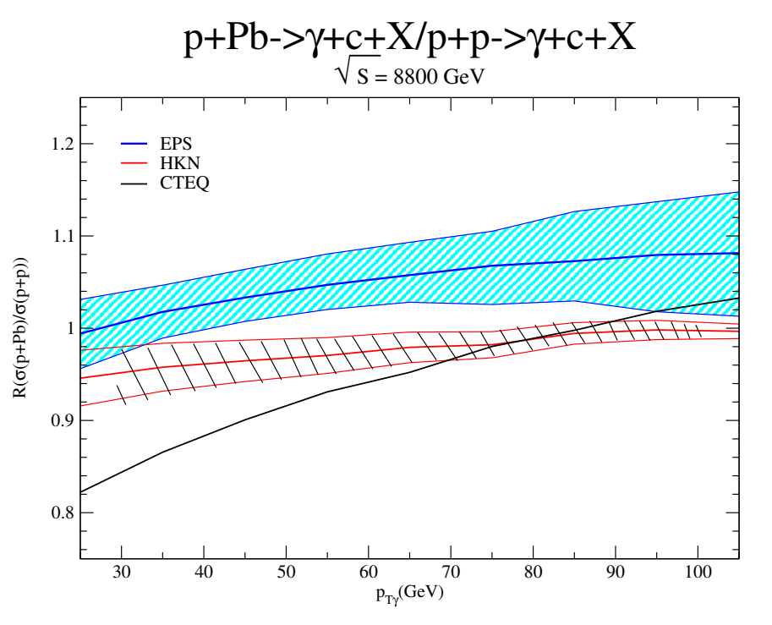
- To investigate the PDF dependence of the cross-section it is necessary to see how the different subprocesses contribute to it

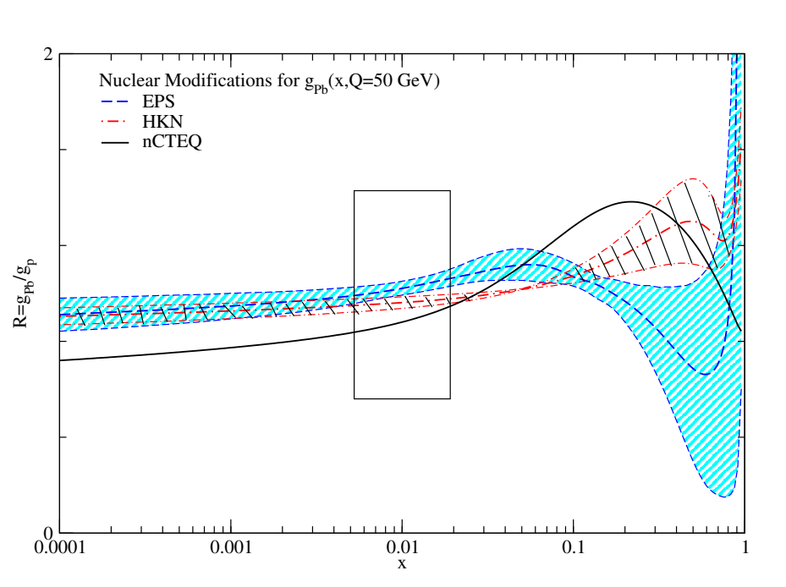
Subprocess Contributions



- The Compton subprocess dominates the cross-section, and over 80% of the cross-section comes from subprocesses containing initial gluons or heavy quarks. Therefore the $\gamma + Q$ process is a great probe of the gluon and the heavy quark nuclear PDFs
- If the $g + b$ cross-section is considered all the dependence of the bottom nPDF can be related to the gluon nPDF through the DGLAP equations, hence most of the nPDF dependence will come from the gluon nPDF. (The same will hold for the $g + c$ cross-section if there is no intrinsic charm.)

Nuclear Modifications - $\gamma + Q$ cross-section





- $R^{\sigma_{\gamma+c}} = \frac{1}{208}\frac{d\sigma/dp_{T\gamma}(d+Au\rightarrow\gamma+c+X)}{d\sigma/dp_{T\gamma}(p+p\rightarrow\gamma+c+X)}$
- The differences in the nuclear corrections to the cross section correspond strongly to the differences in the nuclear corrections to the gluon distribution - in the x region probed at ALICE
- Measurements with appropriate error bars can distinguish between the different nPDFs