# Associated production of a photon and a heavy quark in heavy ion collisions

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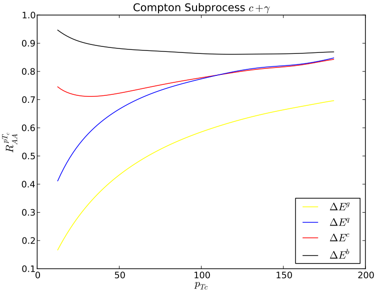
# $\gamma + Q$ in $A - A$ Collisions

- Hard Probes - excellent tools for testing properties of QGP
- Compare to $p - p$ observables to estimate parton energy loss
- Can have
  - Medium sensitive processes - Jets, hadrons, ...
  - Medium insensitive processes - photons, Z bosons, ...
- Combine both types of observables in one process
- $\gamma$ - medium insensitive $\rightarrow E^{\gamma}$ not modified - a gauge for initial energy of jet
- (heavy) jet probes (massive) parton energy loss
- Concentrate on heavy quarks $Q$ (charm/bottom)
- Help clarify energy loss in the heavy quark sector and the expected hierarchy $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ [Dokshitzer Kharzeev 2001]

# $\gamma + Q$ Energy Loss Implementation

- Modify $E_Q^{vac}$ so that $E_Q^{med} = E_Q^{vac} - \epsilon_Q$
- $\epsilon_Q$ computed on an event by event basis, with quenching weight obtained perturbatively [Armesto Dainese Salgado Wiedemann 2005]
  - $P(\epsilon) = p_0\delta(\epsilon) + p(\epsilon)$
  - through multiple soft scattering - BDMPS-Z
  - Mass dependence enters as - $m_Q/E_Q$
- Parton keeps its direction:
  $p^{vac} = p_T(\cosh y, \vec{e}_T, \sinh y) \rightarrow p^{med} = [p_T - \epsilon](\cosh y, \vec{e}_T, \sinh y)$

# Comparing energy loss




$$R_{AA}^{p_{TQ}} = \frac{\frac{d\sigma(AA\rightarrow\gamma \;\; Q \;\; \mathrm{X})}{dp_{TQ}}}{\frac{d\sigma(pp\rightarrow\gamma \;\; Q \;\; \mathrm{X})}{dp_{TQ}}}$$

- Expected hierarchy observed
- $R_{AA}^g < R_{AA}^q < R_{AA}^c < R_{AA}^b$
- Differences for quarks disappear at large $p_T$

# 2 particle final state observables

- The two-particle final state further offers a range of observables
- Photon-jet energy asymmetry:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \pi/2$$

- Momentum imbalance:

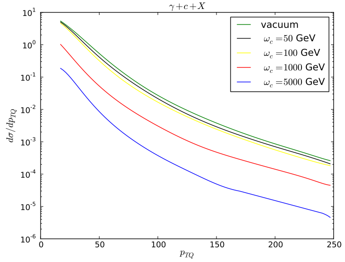
$$z_{34} = -\frac{\vec{p}_{T\gamma} . \vec{p}_{TQ}}{p^2_{T\gamma}}$$

- Photon-jet pair momentum:

$$q_\perp = |\vec{p}_{T\gamma} + \vec{p}_{TQ}|$$

- Need to move to NLO to utilize them

# NLO Energy Loss

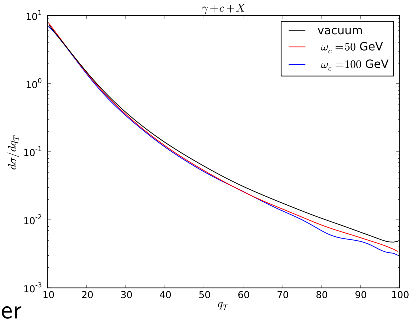



- $p_{TQ}$ spectra suppressed (naturally suppression increases with larger $\omega_c$)
- $p_{T\gamma}$ spectrum almost unchanged at small $\omega_c$

# Photon-jet pair momentum

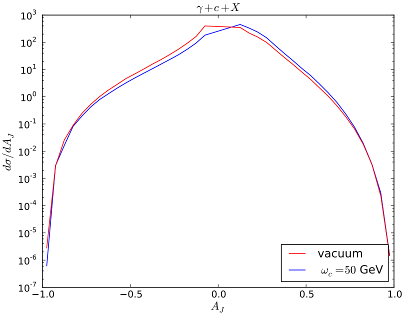
- LO direct production:

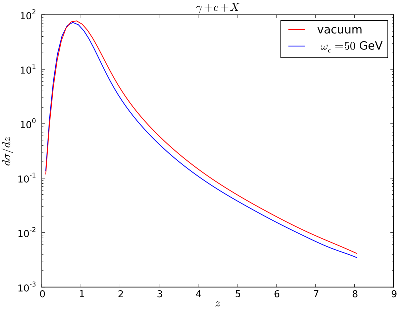
$$\begin{aligned} q_{\perp}^{M} &= p_{T\gamma}^{M} - p_{TQ}^{M} \\ &= p_{TQ}^{V} - (p_{TQ}^{V} - \epsilon) \\ &= \epsilon \end{aligned}$$




- At NLO however
  - if $p_{T\gamma} > p_{TQ}$ , $q_T^M \sim q_T^V + \epsilon$
  - if $p_{TQ} > p_{T\gamma}$ , $q_T^M \sim q_T^V - \epsilon$
- Effect largely cancels out

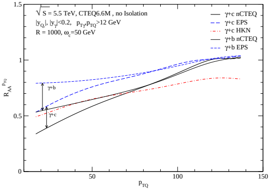
# $A_J$ & $z$

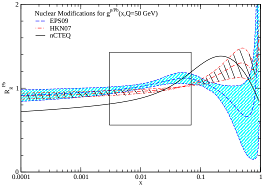



- $z_{LO}^{M} = 1 - \frac{\epsilon}{p_{T\gamma}}$
- $A_J^{M,LO} = \frac{\epsilon}{2p_{T\gamma} - \epsilon}$

# nPDF effects



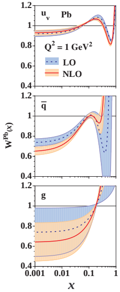



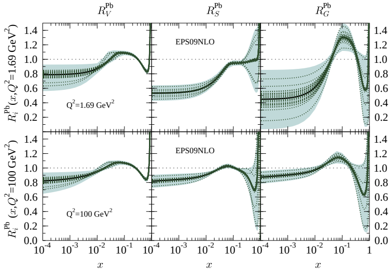

- Overlap of $\gamma + b$ & $\gamma + c$ within different nPDFs
- Need better constrained gluon nPDF!

# nPDFs

- Difference between $p - p$ & $A - A$ observables also due to nPDF effects
- Desentangle parton energy loss from initial state nPDF effects $\rightarrow$ need well constrained nPDFs

# Nuclear Gluon Distribution




- The nuclear gluon distribution only weakly constrained by data $(F_2^{Sn}(x, Q^2)/F_2^C(x, Q^2)$, NMC collaboration)
- Represented in large error bands (EPS09,HKN07)!
- Poorly constrained in $x < 0.02$ and $x > 0.1$
- Currently no error bands for nCTEQ - perform a series of global fits to assess it

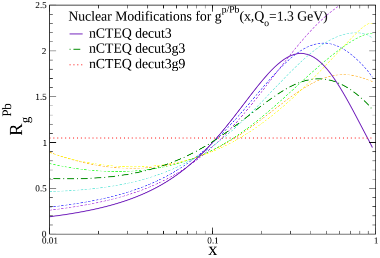
# gluon nCTEQ decut3gx fits

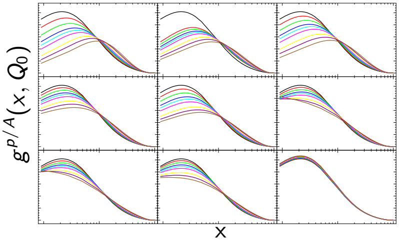
- Vary $c_1 = c_{1,0} + c_{1,1}(1 - A^{-c_{1,2}})$ influencing small $x$ behavior of gluon nPDF

| Name | (initial) fit parameter | $c_{1,1}$ | $c_{1,2}$ |
|---|---|---|---|
| decut3 | free | -0.29 | -0.09 |
| decut3g1 | fixed | 0.2 | 50.0 |
| decut3g2 | fixed | -0.1 | -0.15 |
| decut3g3 | fixed | 0.2 | -0.15 |
| decut3g4 | free | 0.2 | -0.15 |
| decut3g5 | fixed | 0.2 | -0.25 |
| decut3g7 | fixed | 0.2 | -0.23 |
| decut3g8 | fixed | 0.35 | -0.15 |
| decut3g9 | fixed – free proton | 0.0 | — |

- Each fit equally acceptable with an excellent $\chi^2$/dof= 0.88–0.9.

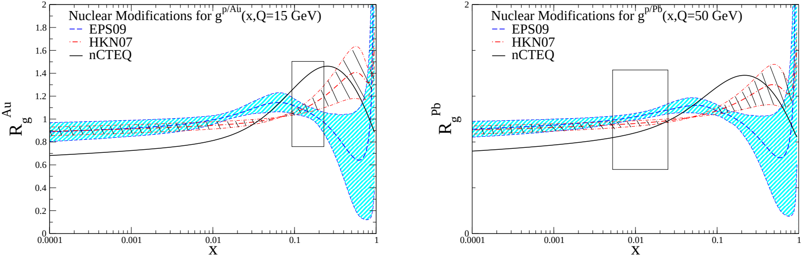
# gluon nCTEQ decut3gx fits



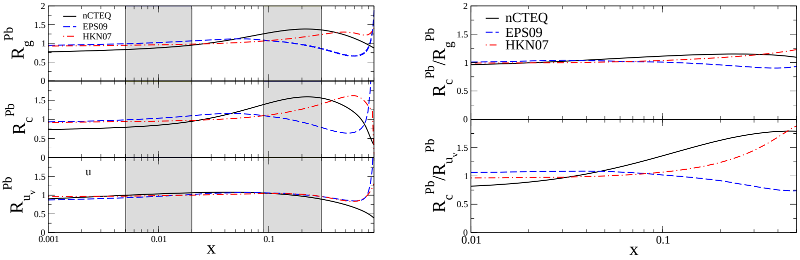

- The different fits cover quite a range of nuclear corrections
- Each fit will come with own error band → individual fits underestimate true uncertainty

# gluon Nuclear Corrections




- At larger $Q$ error still large
- Different nPDF sets, quite different
- Need to distinguish between them

# charm nPDF



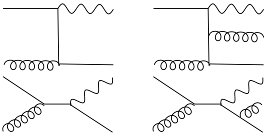

- Standard approach: HQ PDFs are generated radiatively $\rightarrow$ $R_g^{Pb} \simeq R_c^{Pb}$
- For $u_v$, $R_{u_v}^{EPS} \simeq R_{u_v}^{HKN} \simeq R_{u_v}^{nCTEQ}$

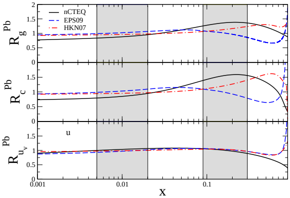
# Hard Processes constraining $g^{p/A}(x, Q)$

- Inclusive jet data (like Tevatron for free gluon)
- Inclusive hadron production
- Heavy quark ; Quarkonium production
- Isolated direct photons
- Direct Photons + jet
- **Direct Photon + Heavy Quark Jet**

# How can $\gamma + Q$ help ?

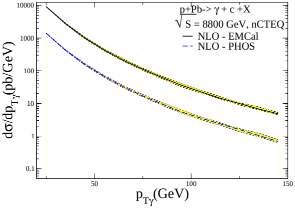
- At LO - only one hard scattering subprocess Compton subprocess - $g - Q$ initiated + fragmentation contributions
- Standard approach: HQ PDFs are generated radiatively ⇒ $R_g^{Pb} \simeq R_c^{Pb}$

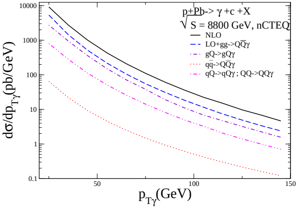





- Direct access to gluon nPDF

# $\gamma + Q$ production in $p - Pb$ collisions @ the LHC

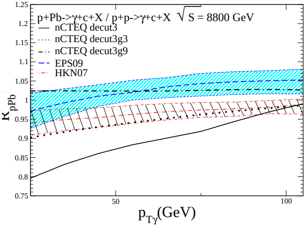


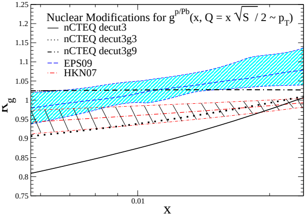




- $g$ & $Q$ initiated subprocesses dominate ( $> 80\%$ ) $\Rightarrow$ sensitivity to gluon and HQ PDFs.
- Using an integrated yearly luminosity of $\mathcal{L} = 10^{-1} pb^{-1}$ a precursory number of events per year at EMCal for $\gamma + c$ is $\mathcal{N}^{pPb}_{\gamma+c} = 11900$ ($\sigma^{pPb}_{\gamma+c} = 119 nb$) and for $\gamma + b$ is $\mathcal{N}^{pPb}_{\gamma+b} = 2270$ ($\sigma^{pPb}_{\gamma+b} = 22.7 nb$ )

# Constraining the gluon nPDF

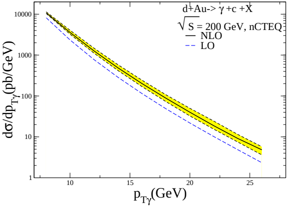
$$R_{pA}^{\gamma Q} = \frac{\sigma(pA \to \gamma\ Q\ \mathrm{X})}{A\ \sigma(pp \to \gamma\ Q\ \mathrm{X})}$$

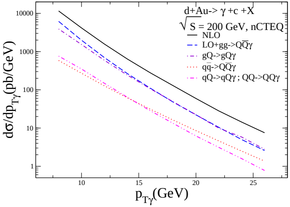



- $R_{pA}^{\gamma Q} \simeq R_g^{Pb}$ - in the $x$ region probed at ALICE
- Measurements of $\gamma + Q$ with appropriate error bars will allow to distinguish between the different nPDF sets and place useful constraints on the gluon nPDF (arXiv:1012.1178)

# $\gamma + Q$ production in $p - Pb$ collisions @ RHIC

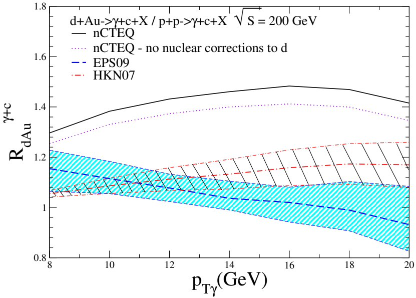


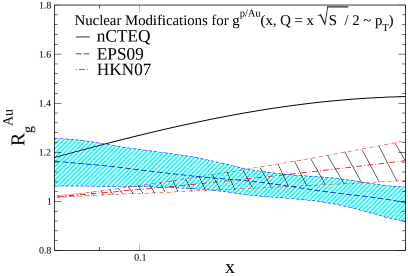




- $g$ & $Q$ initiated subprocesses dominate again $\Rightarrow$ sensitivity to gluon and HQ PDFs.
- A precursory number of events per year for $\gamma + c$ - $\mathcal{N}^{dAu}_{\gamma+c} = 28000$ and for $\gamma + b$ - $\mathcal{N}^{dAu}_{\gamma+b} = 24$

# Constraining the gluon nPDF

$$R_{pA}^{\gamma Q} = \frac{\sigma(pA \to \gamma \ Q \ X)}{A \ \sigma(pp \to \gamma \ Q \ X)}$$




- At RHIC higher x region is probed
- $R_{dAu}^{\gamma Q} \simeq R_g^{Au}$ - in the $x$ region probed at RHIC
- Complimentary information to ALICE
- Measurements of $\gamma + Q$ with appropriate error bars will allow to distinguish between the different nPDF sets and place useful constraints on the gluon nPDF (arXiv:1012.1178)

# Summary

- In AA collisions $\gamma + Q$ can be used to probe HQ energy loss
- Access the mass hierarchy of parton energy loss
- In pA collisions photon + HQ production can be used to constrain nuclear gluon PDF
- (In pp collisions can be used to constrain HQ PDF )