Production of a photon in association with a heavy quark jet in pA and AA collisions

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Introduction

γ+Q production is a versatile process!

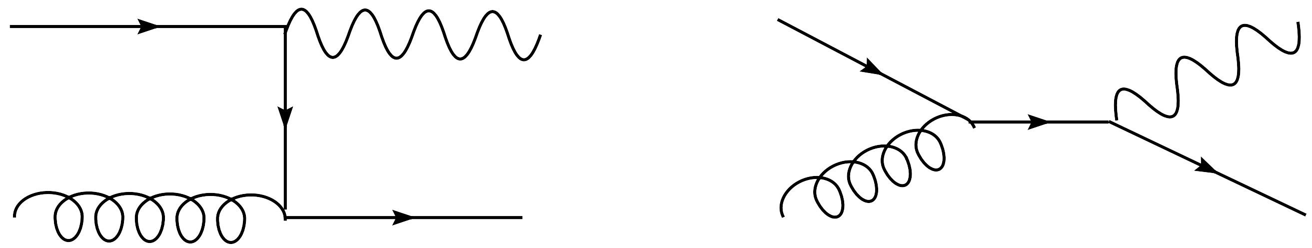
- **in pp collisions:**
  - probe of heavy quark PDFs
  - intrinsic charm (IC)/ intrinsic bottom (IB)
- **in pA collisions:**
  - probe of nuclear PDFs (gluon, heavy quarks)
- **in AA collisions:**
  - probe of heavy quark energy loss

γ+Q production at NLO

[T. Stavreva, J. Owens, PRD79(2009)054017]

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

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



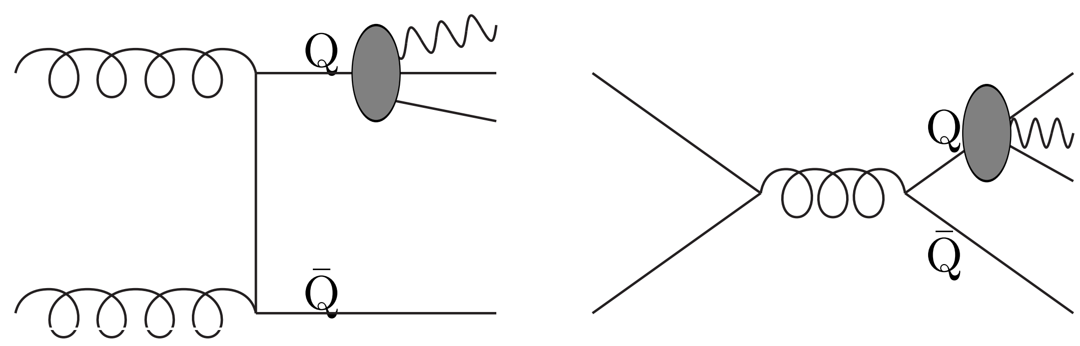
- Next-to-Leading Order - $\mathcal{O}(\alpha\alpha_s^2)$
  - Real Corrections - $2 \to 3$ body scattering subprocesses

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

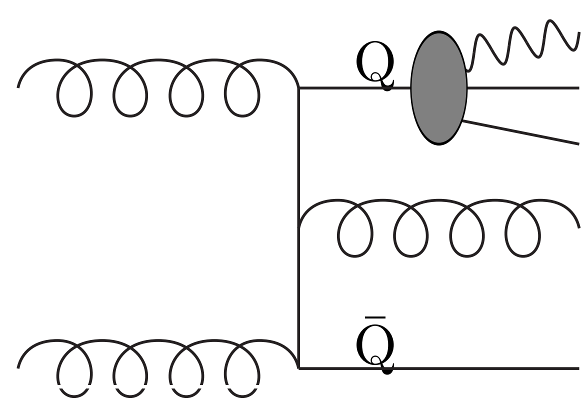
  - Virtual Corrections - interference between LO Born diagram and virtual diagrams

Fragmentation contribution

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

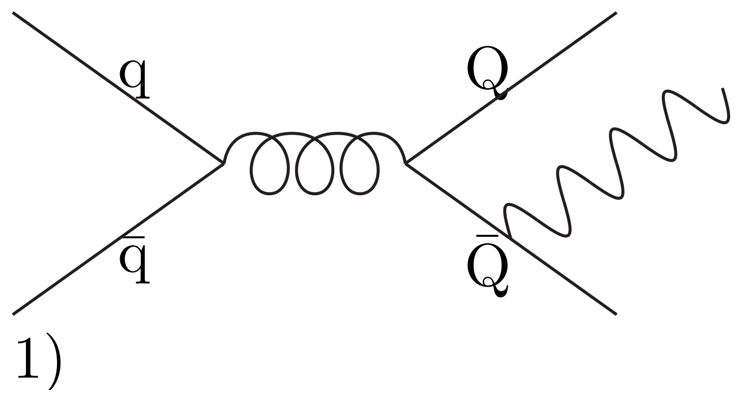


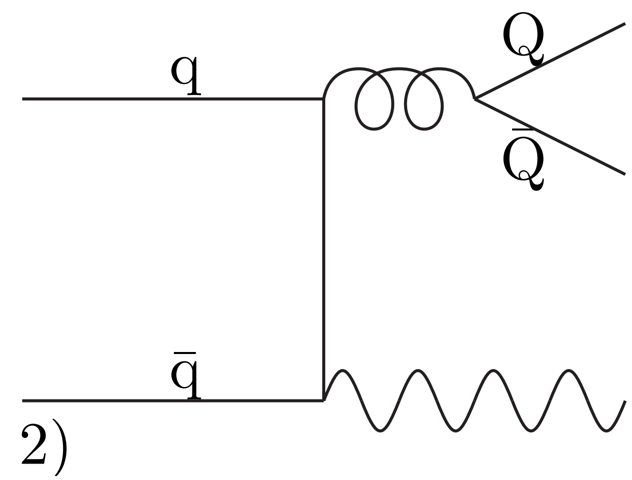
- Also need to include NLO fragmentation contributions - convolute all $2 \to 3 \sim \mathcal{O}(\alpha_s^3)$ with γ FF



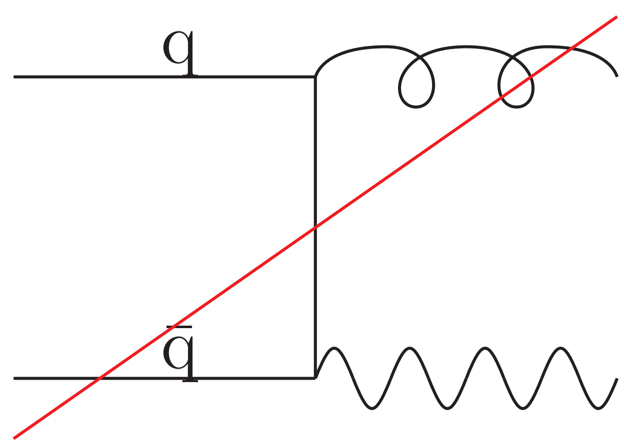
- Reduced due to isolation requirements
- minimizes background from photons : $\pi^0 \to \gamma\gamma$

Final state collinear singularity in $q\bar{q} \to Q\bar{Q} + \gamma$





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



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

γ+Q in pp collisions

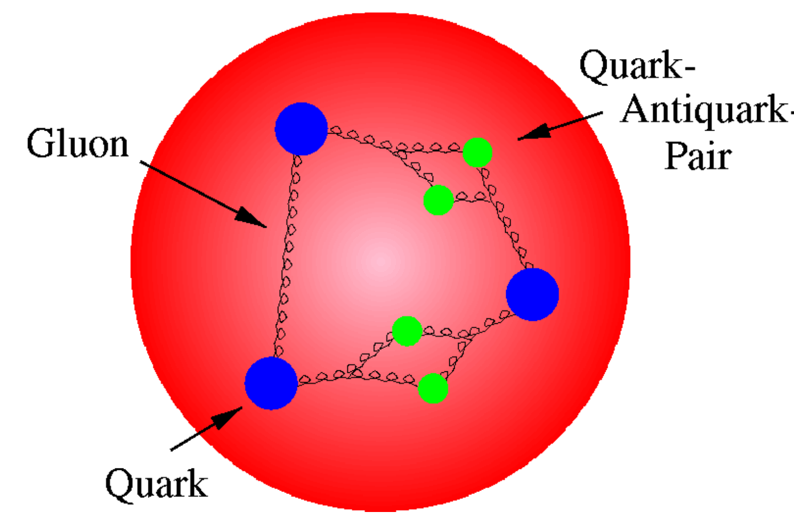
References:

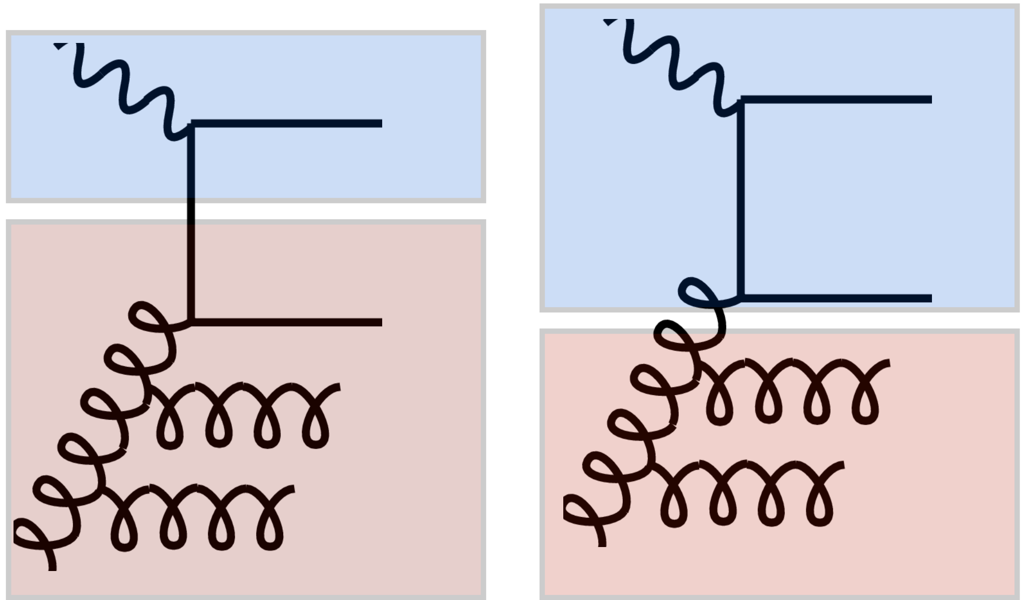
T. Stavreva, J. Owens, PRD79(2009)054017

Bednyakov, Demichev, Lykasov, Stavreva, Stockton,arXiv:1305.3548

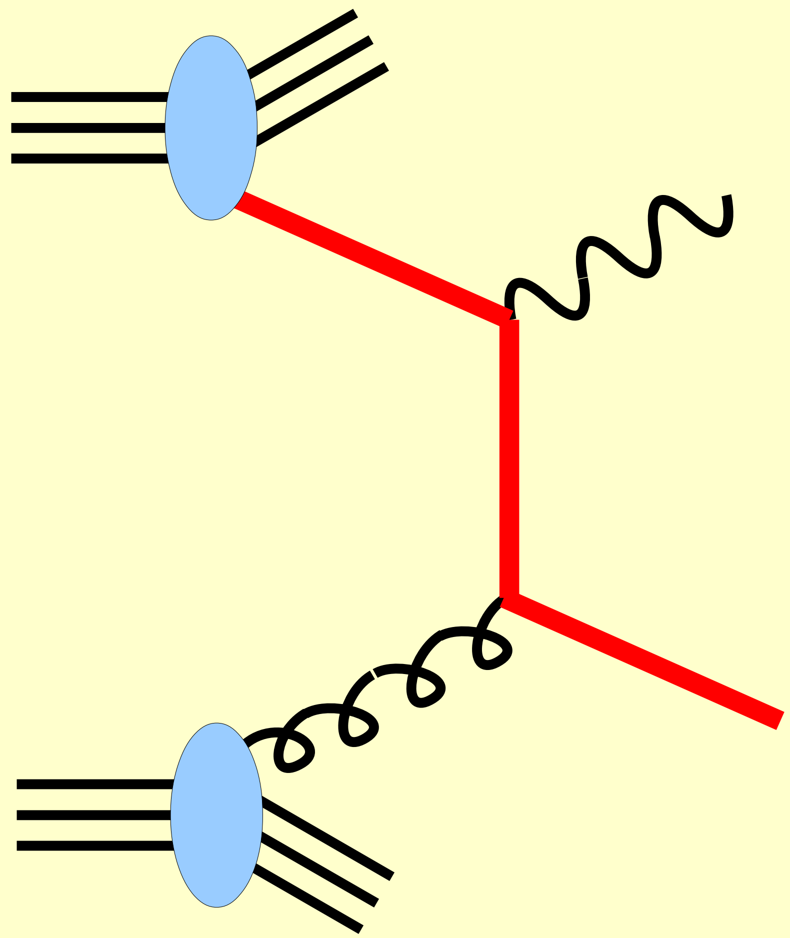
Is there charm in the nucleon?

- Standard approach: Charm entirely perturbative
- Heavy Flavour Schemes
  - FFNS: charm not in the proton
    keep logs(Q/m) in fixed order
  - VFNS: charm PDF in the proton
    resum logs(Q/m)
- Different Heavy Flavour Schemes = different ways to organize the perturbation series
- What is structure? What is interaction?
  Freedom to choose the factorization scale
- However, charm not so much heavier than Lambda_QCD
- There could be a non-perturbative **intrinsic charm** component
- Important to test the charm PDF experimentally





How to access the heavy quark PDFs directly?



$c\ g \to c\ \gamma$

$b\ g \to b\ \gamma$

$s\ g \to c\ W$

$c\ g \to b\ W$

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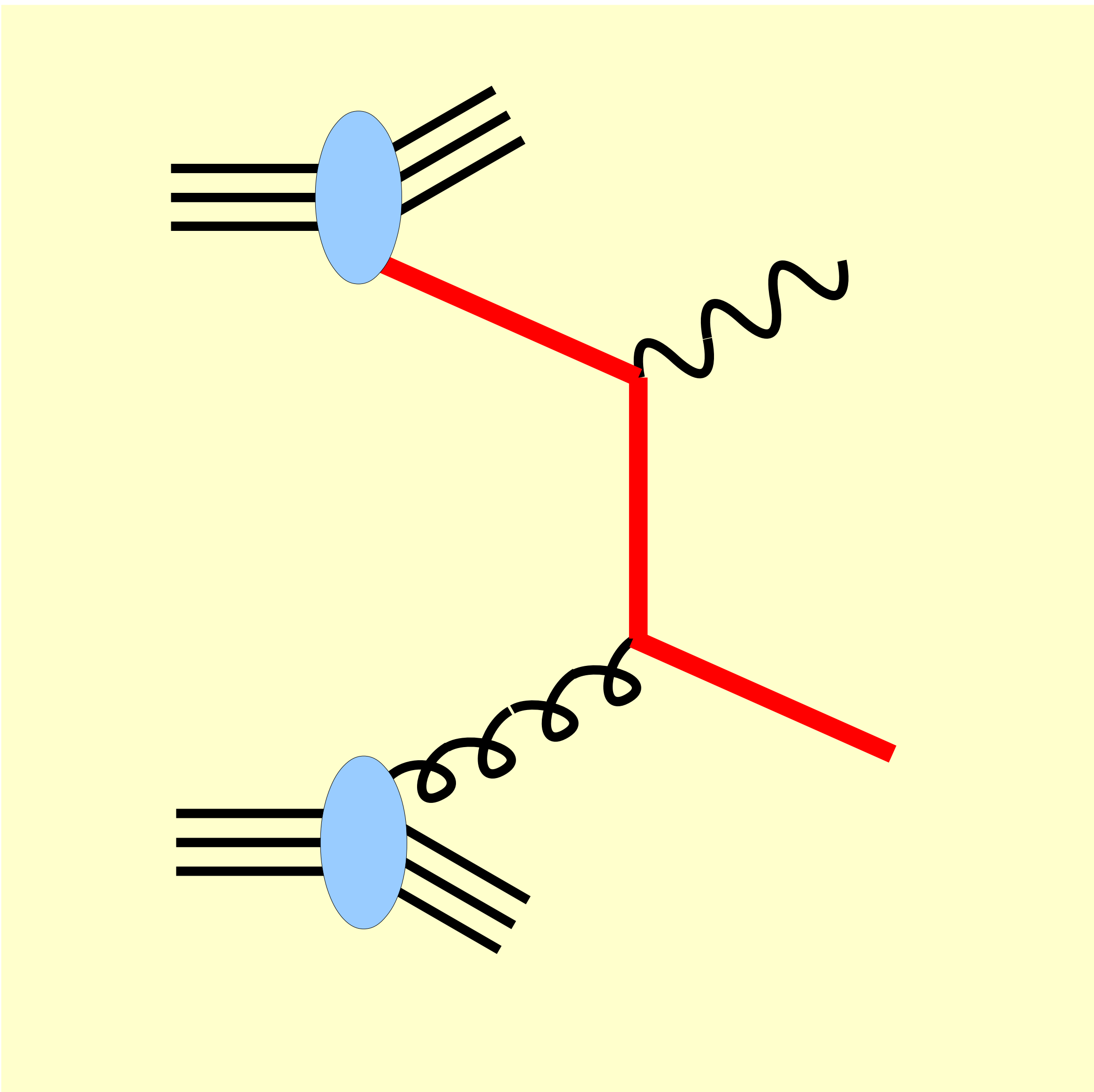
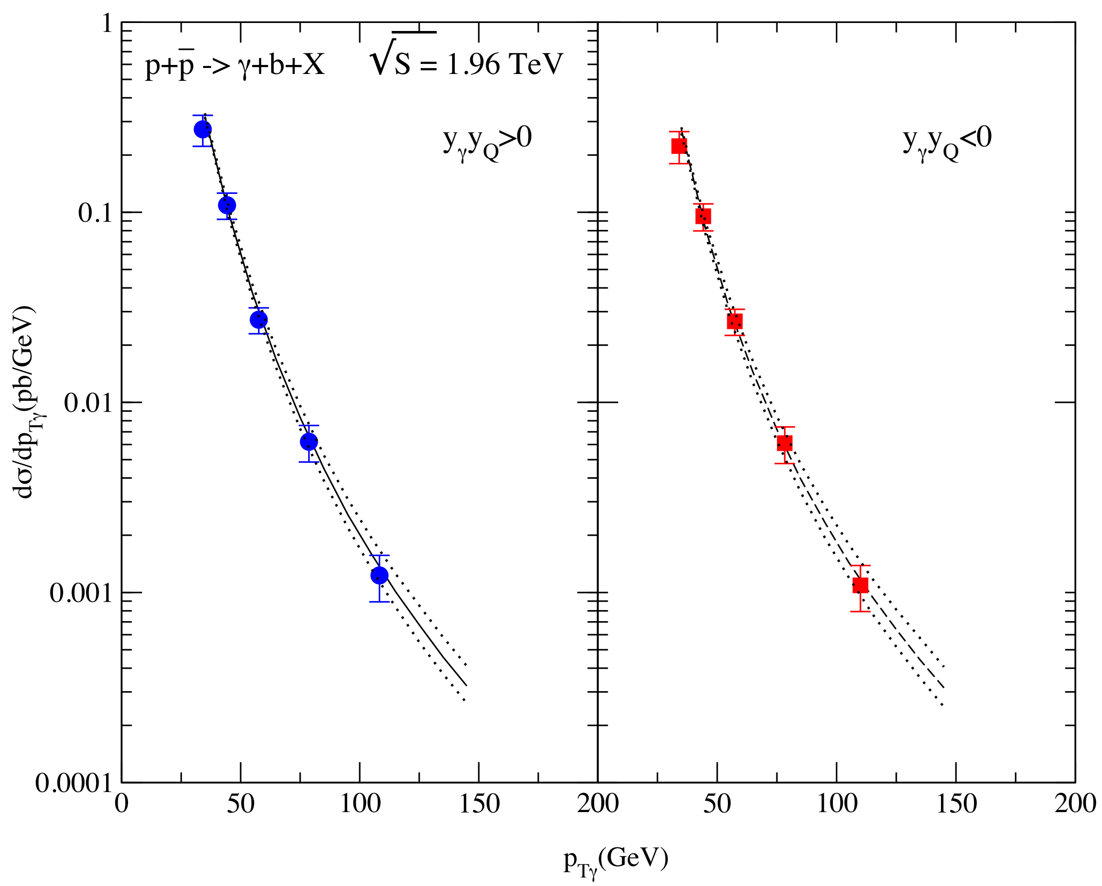


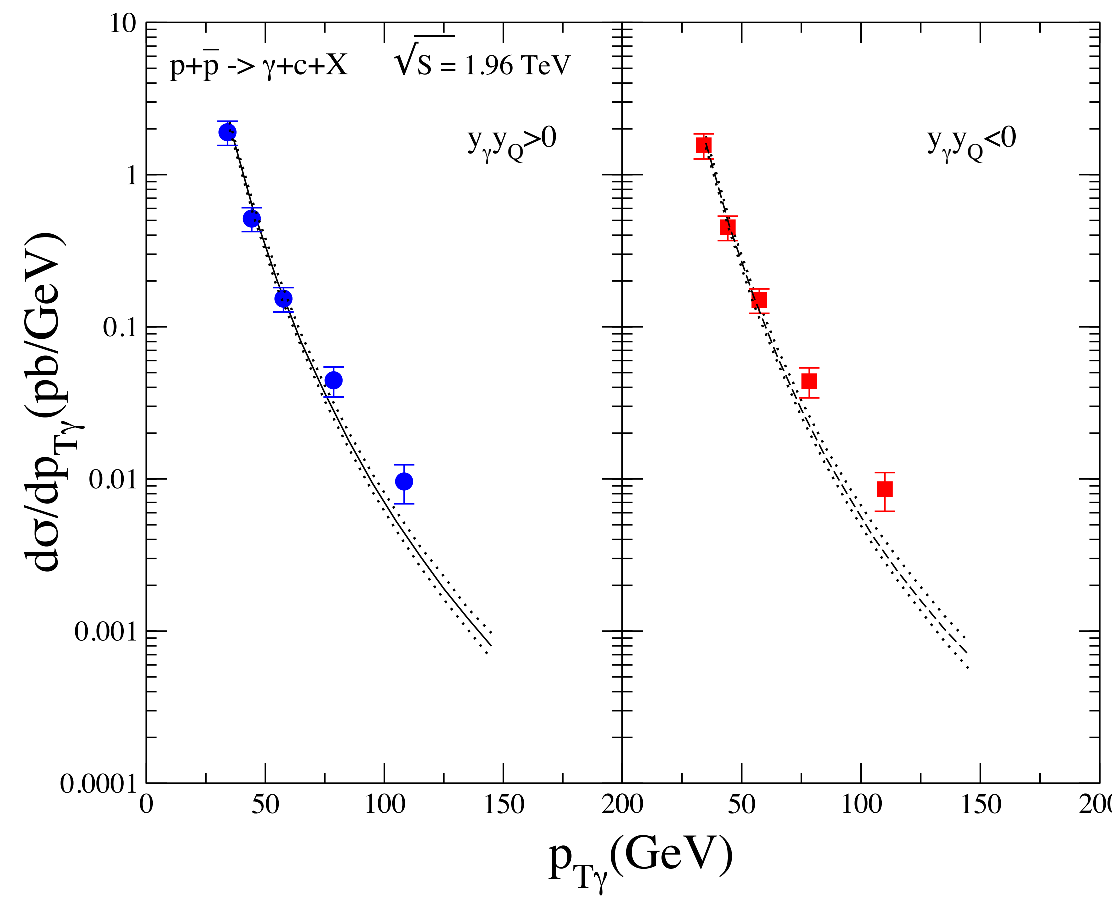
$$c\,g \rightarrow c\,\gamma$$
$$b\,g \rightarrow b\,\gamma$$

$$s\,g \rightarrow c\,W$$
$$c\,g \rightarrow b\,W$$

Results from Tevatron

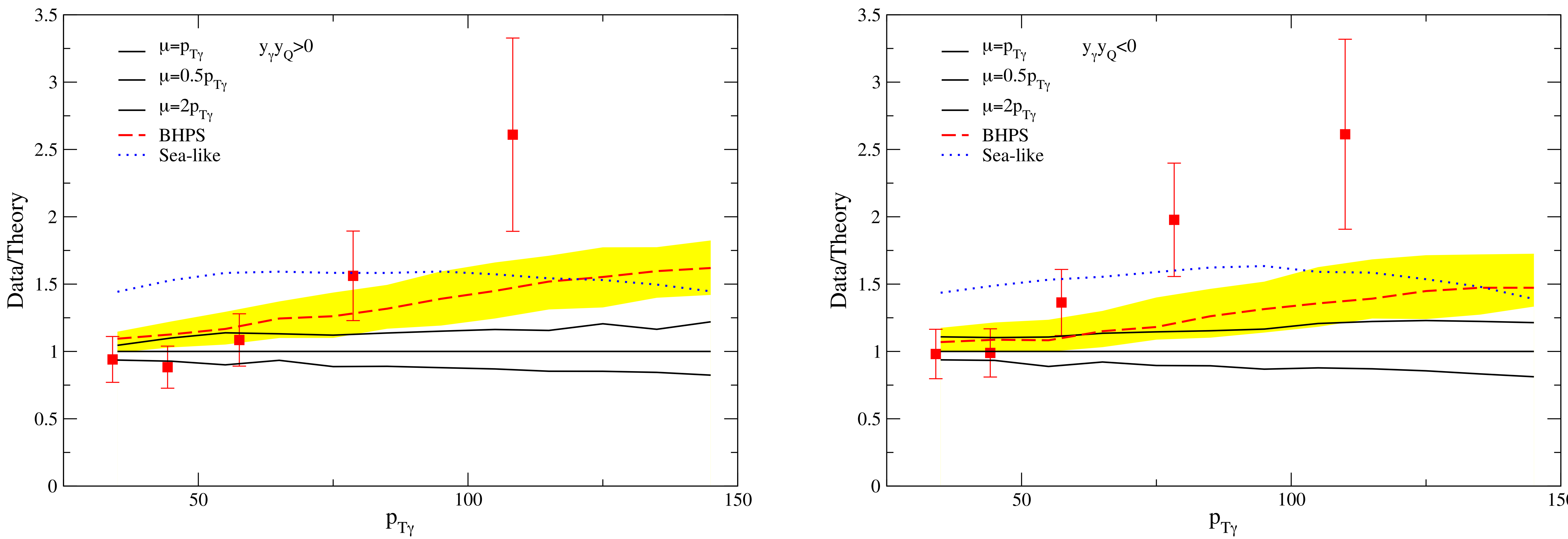
Measurements by DØ Collaboration [arXiv:0901.0739]





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

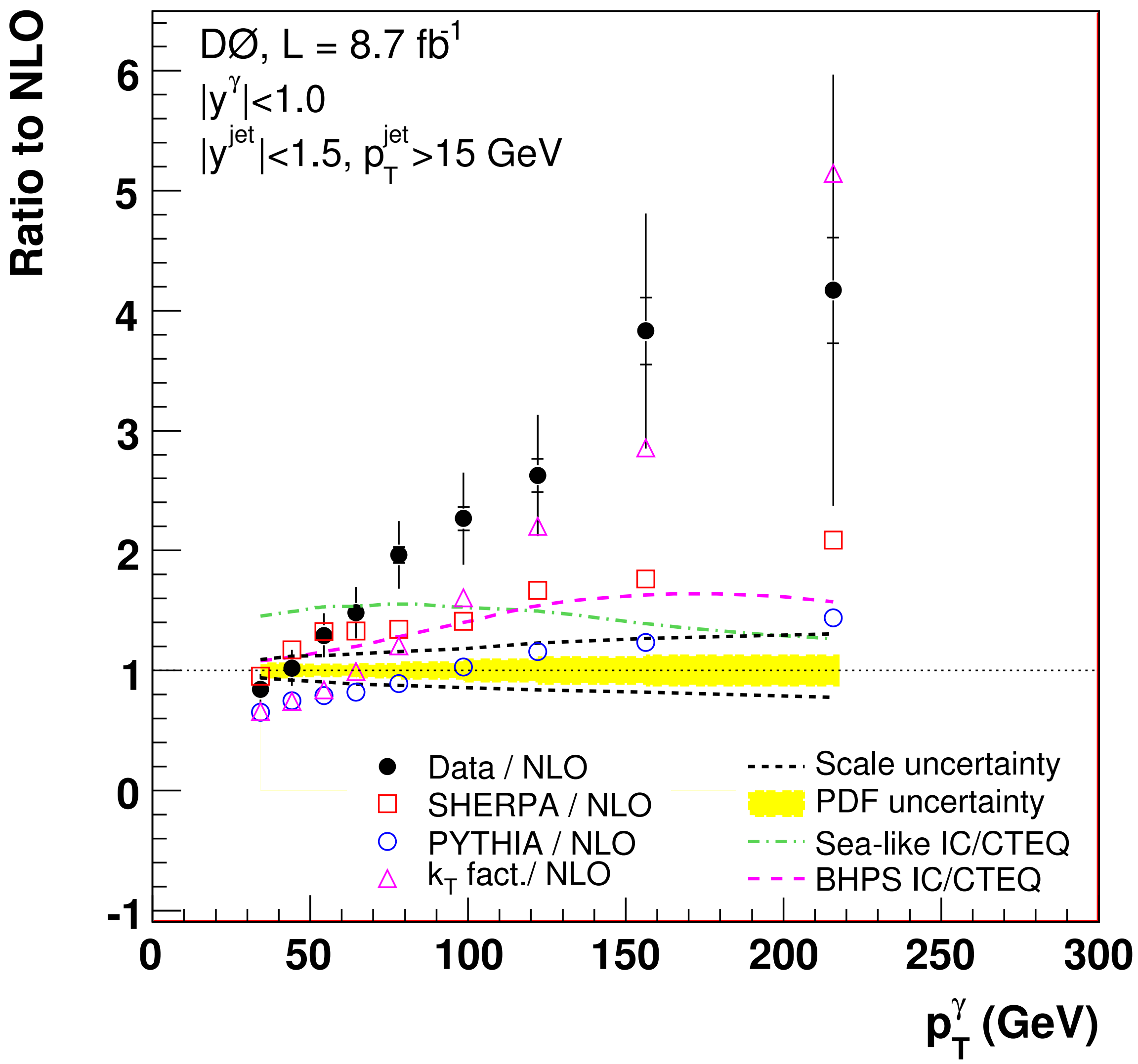
Intrinsic Charm effect on γ+c

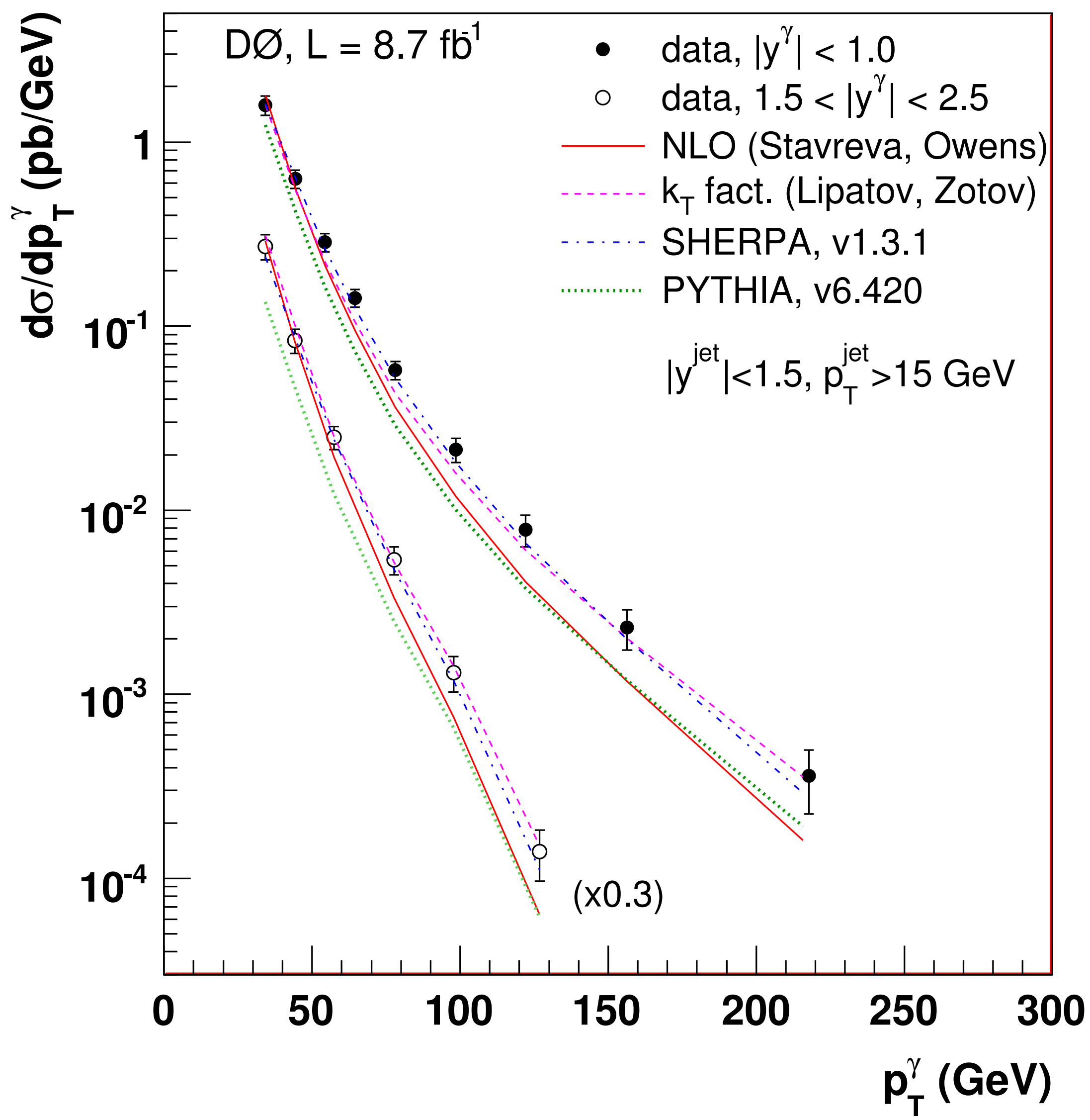


- BHPS IC: cross section grows at large pT but still below data

- Results inconclusive:
  - new measurements at Tevatron: CDF & D0
  - test at pp colliders: RHIC & LHC

New results from D0



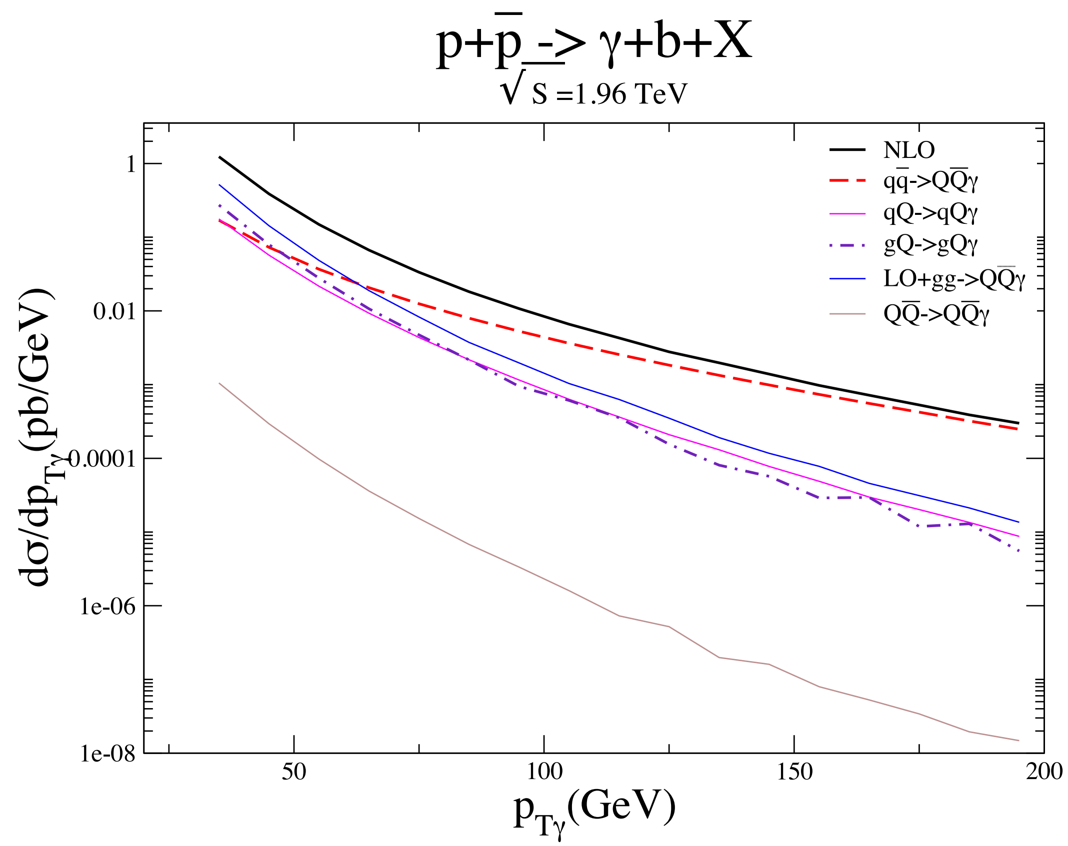


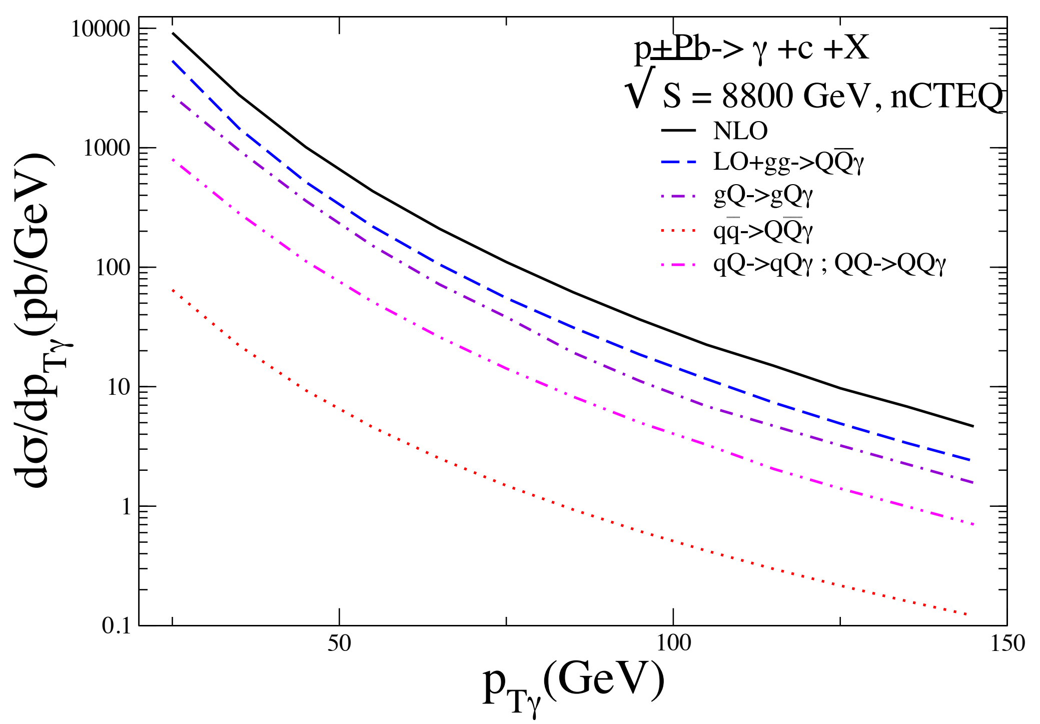
- $\gamma + c$ - left - arXiv:1210.5033
- $\gamma + b$ - right - arXiv:1203.5865

Even larger discrepancy now!

Discussion: Is there a QCD anomaly?

- **Tevatron:** q-qbar channel
  - effectively LO
  - dominant at pT > 70 GeV
  - large NNLO corrections!?
- **LHC:**
  - g & Q initiated subprocesses dominate (>80%)
  - expect no anomaly
  - important to measure, probe of IC
- For many more details (predictions for RHIC, LHC, used cuts, γ+b, etc.) see:
  - Talk T. Stavreva at DIS 2013
  - arXiv:1305.3548





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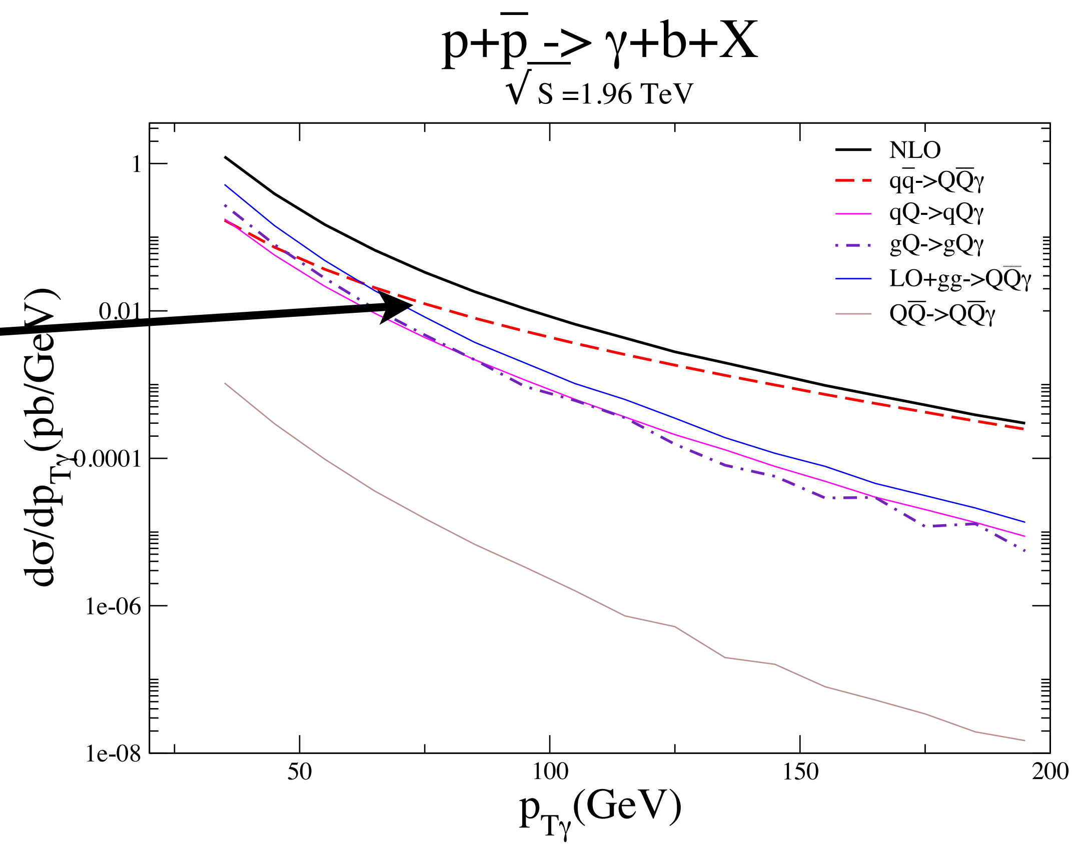

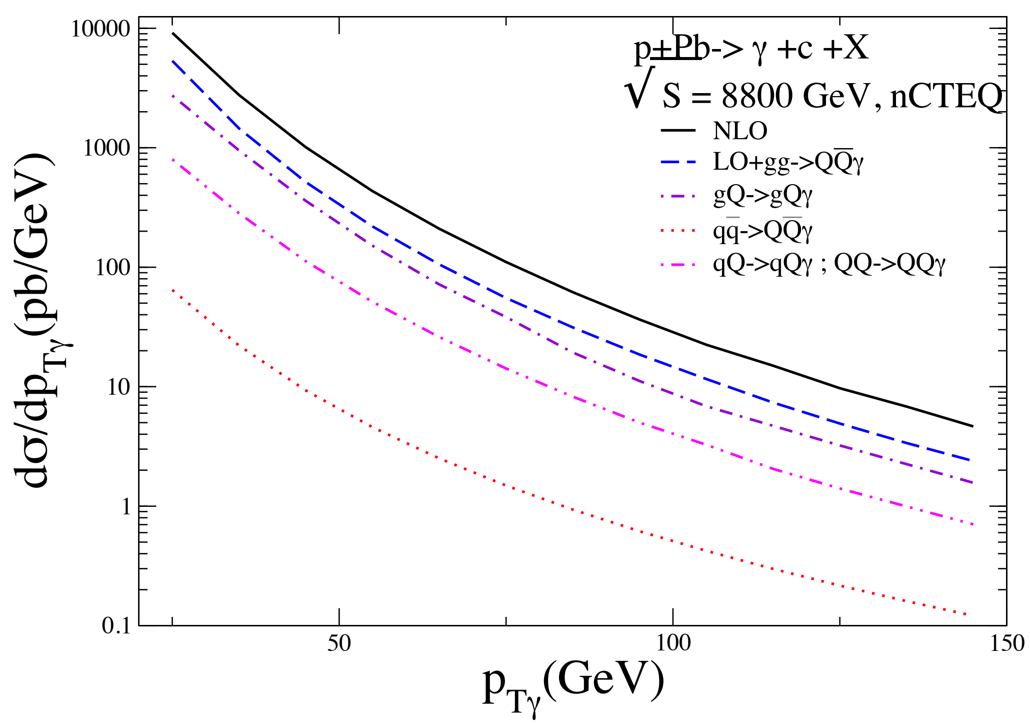

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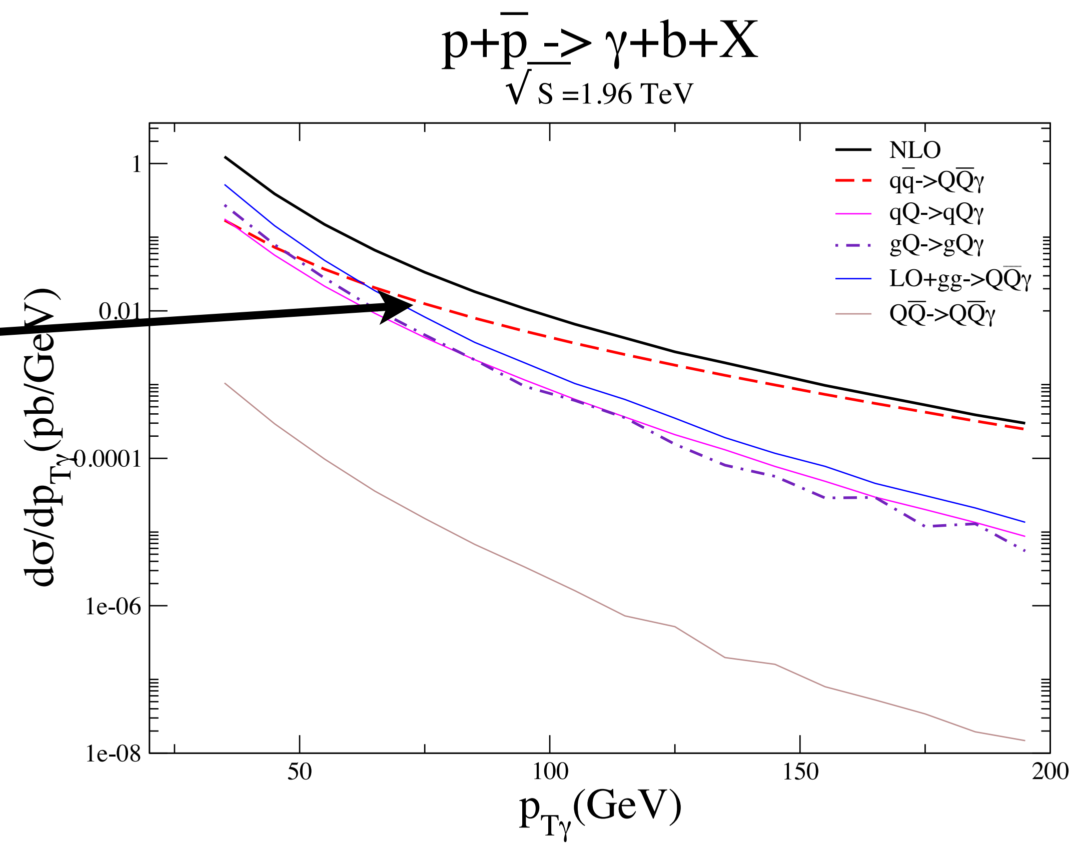
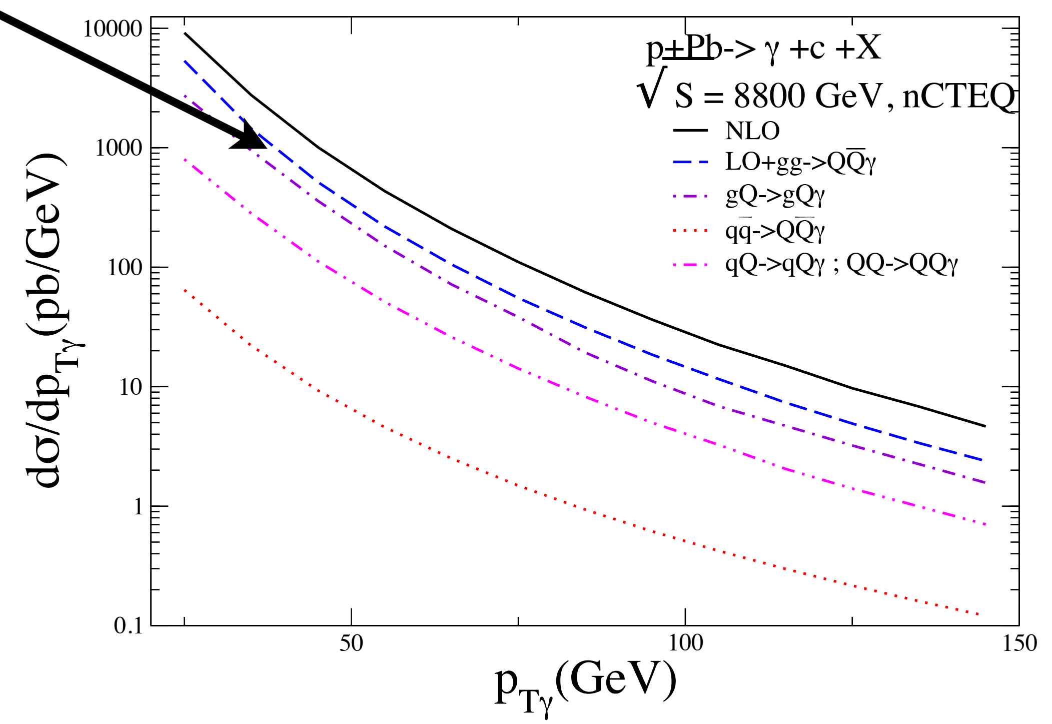




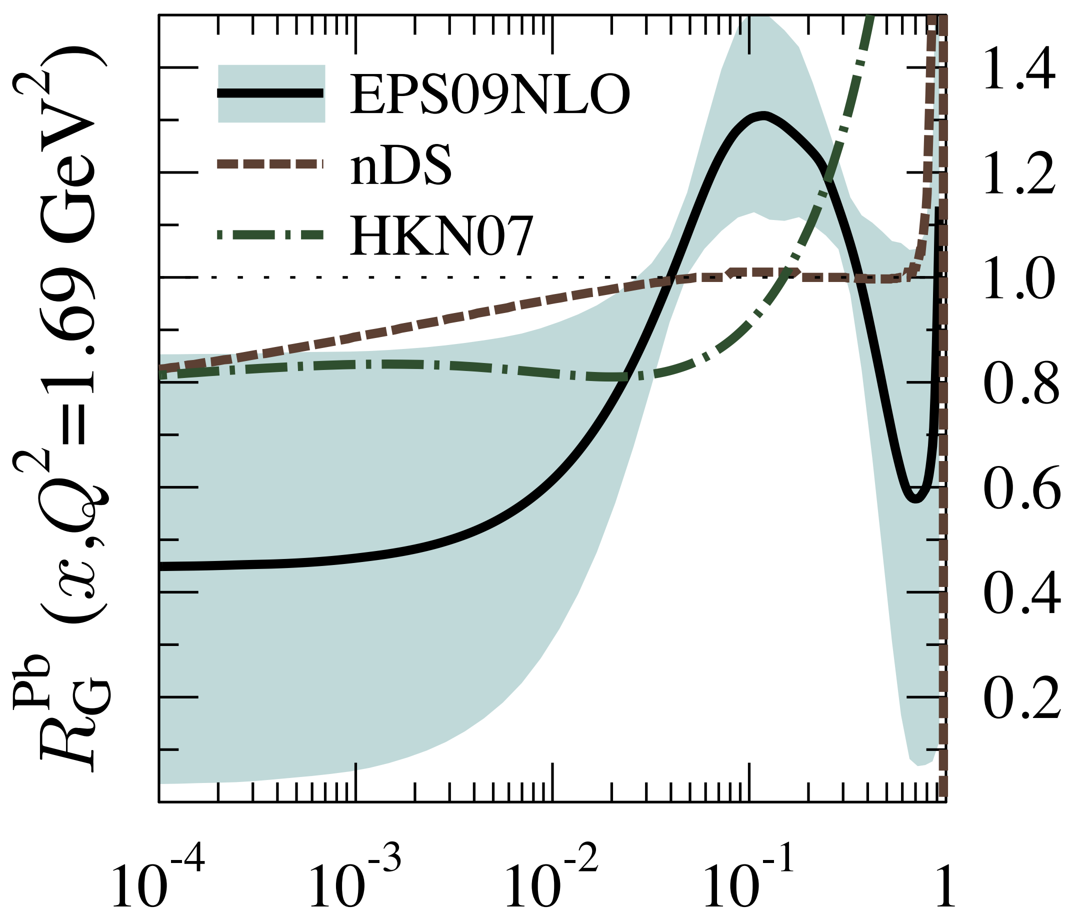
γ+Q in pA collisions

References:
T. Stavreva et al., JHEP1101(2011)152

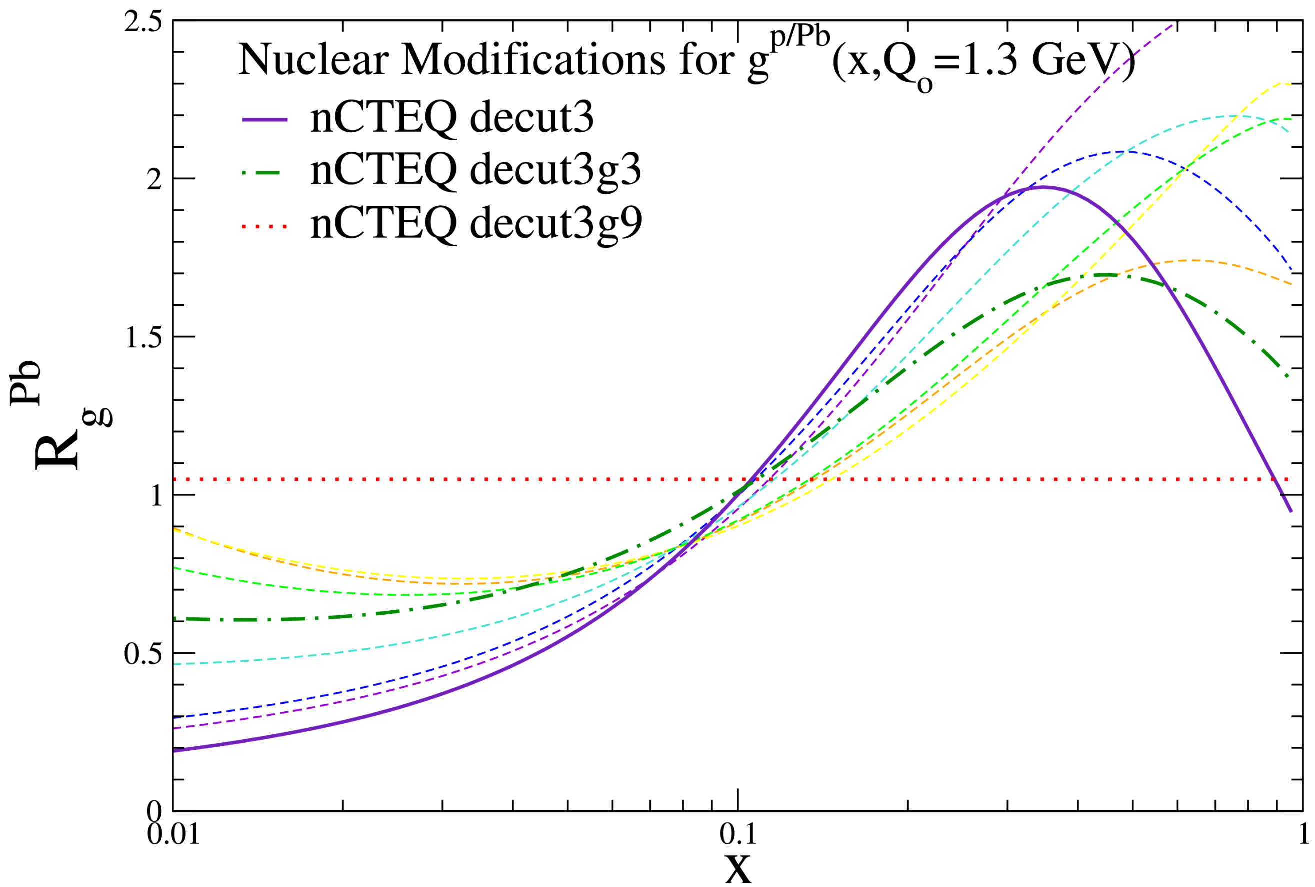
Nuclear PDFs: needed for pA collisions

Global fit analyses of nuclear parton densities

- DIS and Drell-Yan data [EKS98, HKM, nDS, nDSg, nCTEQ]
- ...and hadron production at RHIC [EPS09, DSSZ]



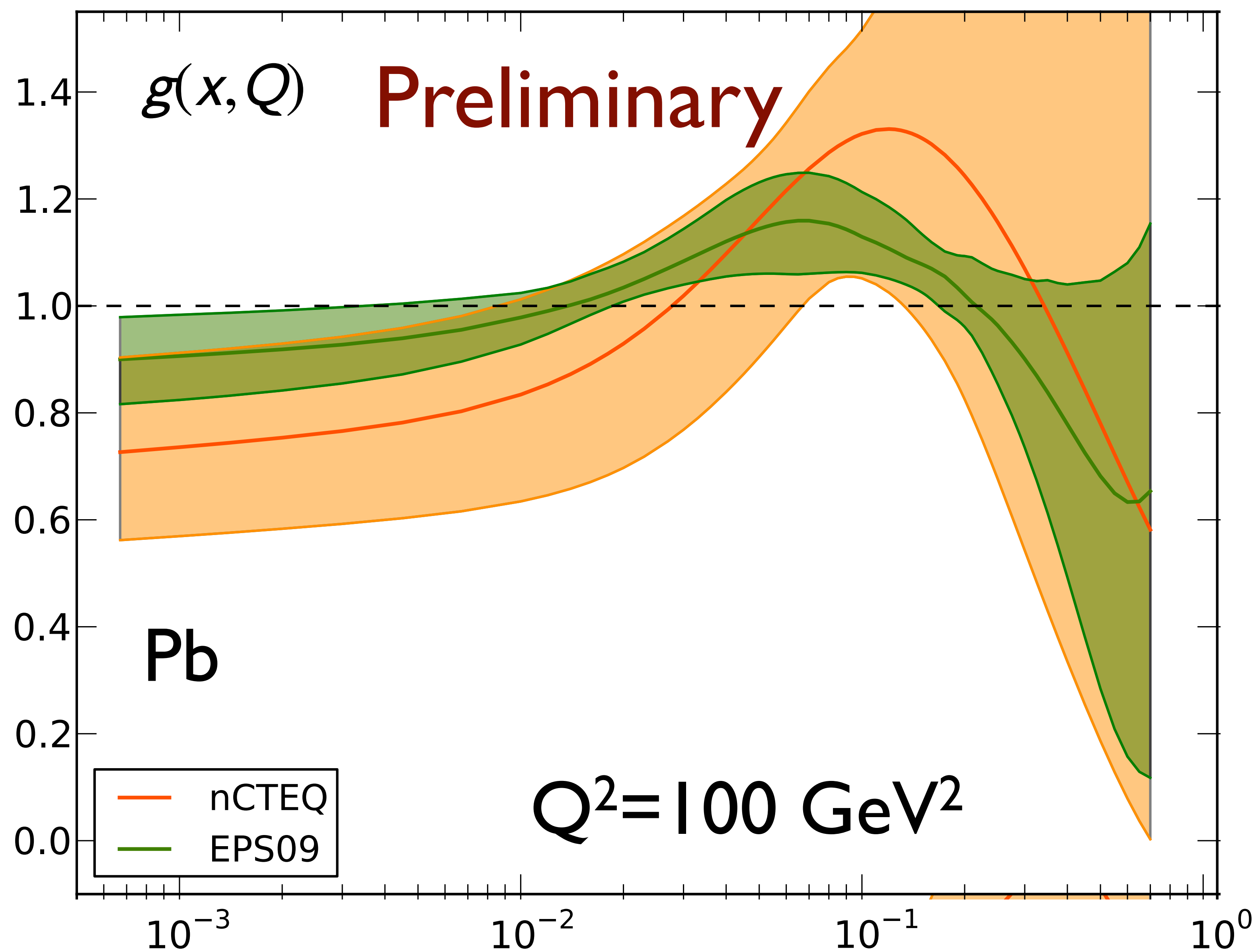
[EPS09, Eskola, Paukkunen, Salgado, 0902.4154]



[nCTEQ, 0907.2357 & 1012.1178]

nCTEQ PDFs with uncertainties

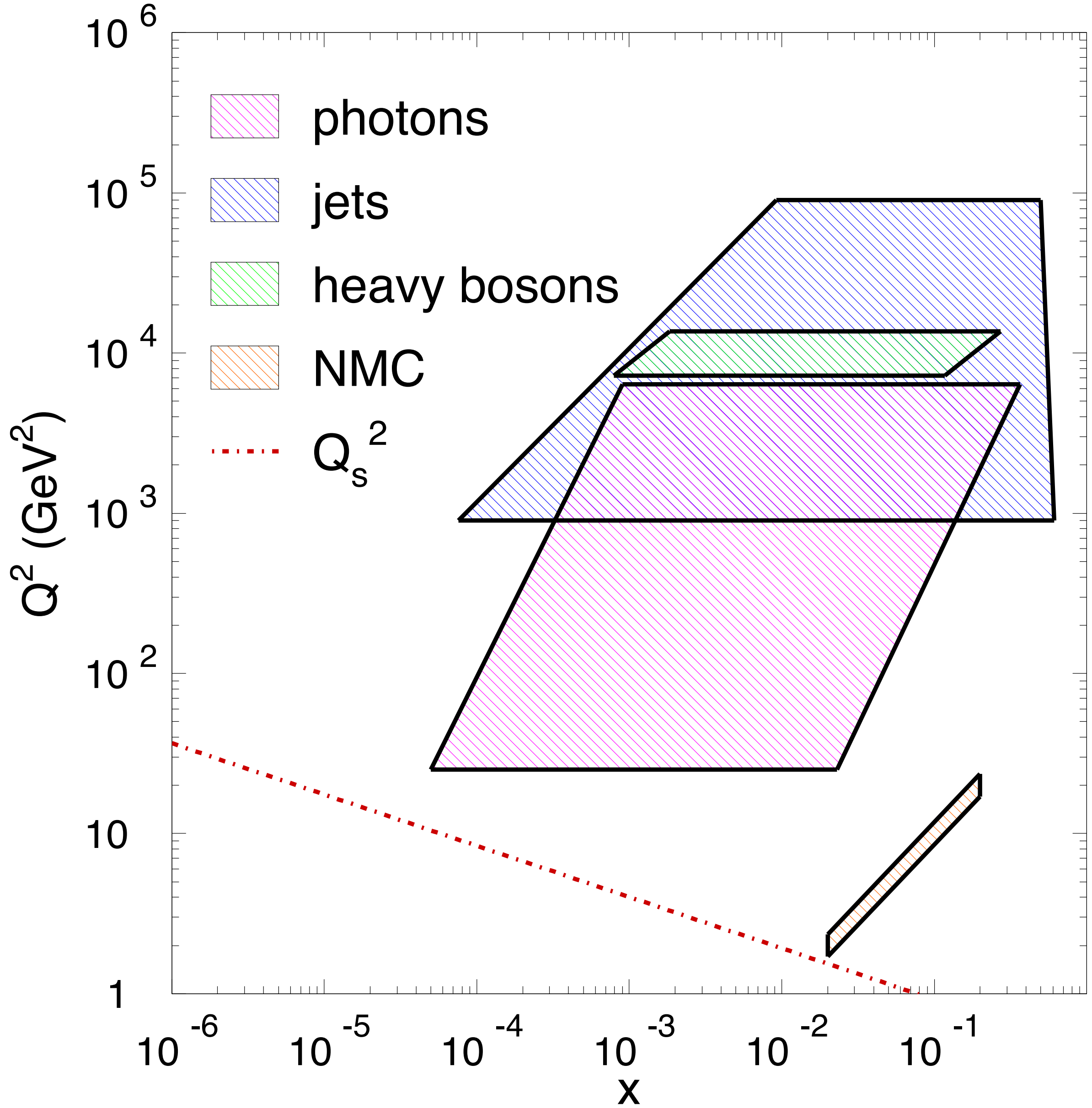
work in progress, see [K. Kovarik et al, 1307.3454]



How to probe the gluon distribution?

- Jets
  - Tevatron incl. jet data already used
- Prompt Photons
  - Arleo et al, JHEP1104(2011)055
  - d'Enterria, Rojo, NPB860(2012)311
- Virtual Photons
  - see talk by M. Klasen
- Photons + Heavy Quarks
  - T. Stavreva et al., JHEP1101(2011)152 (this talk)
- Open heavy quarks?
- Heavy Quarkonia?

LHC kinematics



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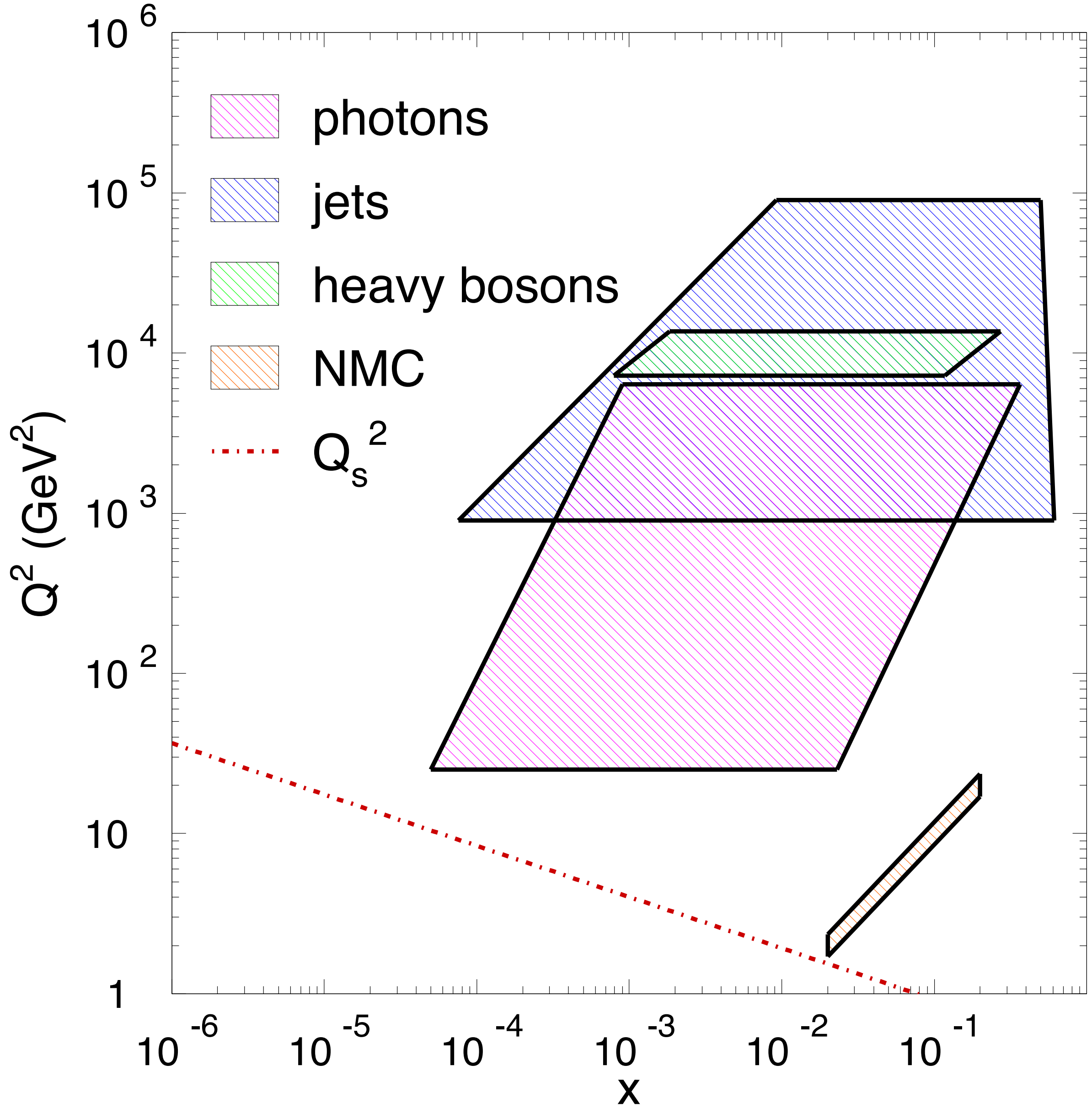


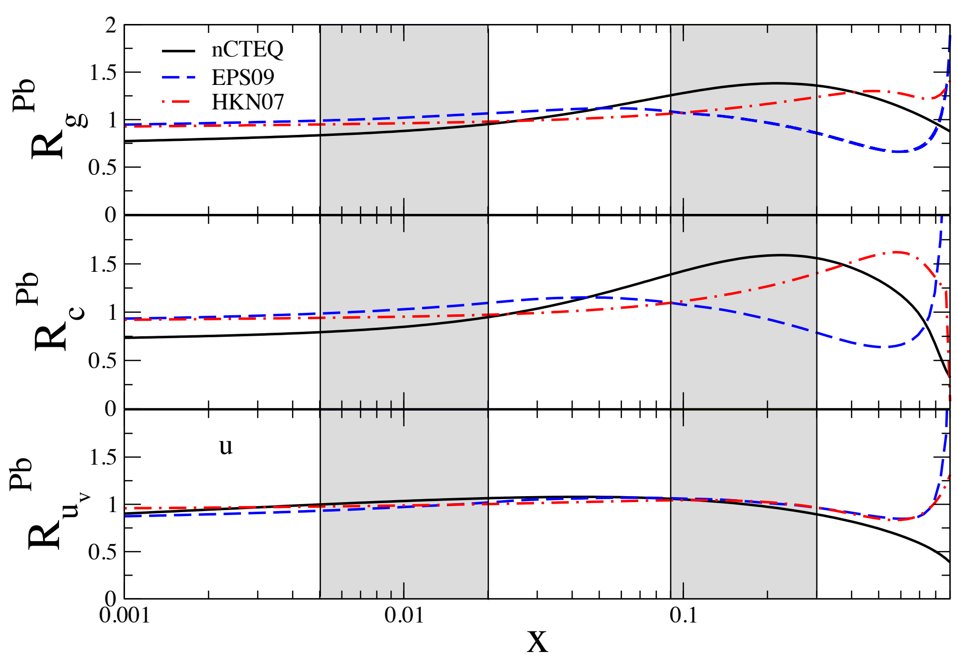
Predictions in pA

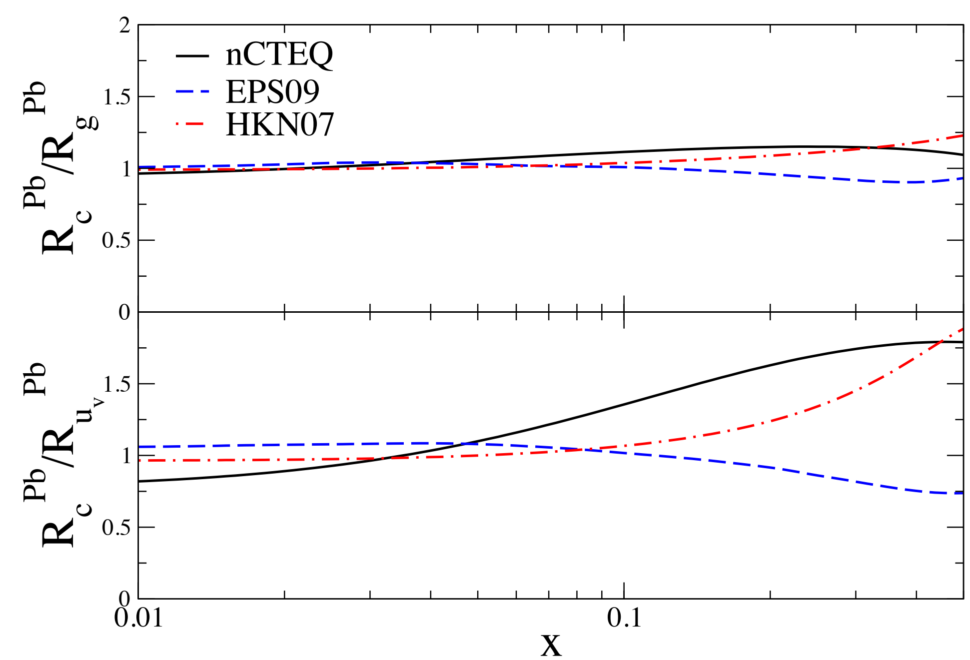
- NLO calculations assuming that charm PDF is radiatively generated ($c(x, \mu = m_c) = 0$)

$$\frac{dc(x,Q)}{dt} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} [c(x/y) P_{Q\leftarrow Q}(y) + g(x/y) P_{g\leftarrow Q}(y)]$$

in the variable flavour number scheme

Probing charm nPDF allows for constraining the gluon sector





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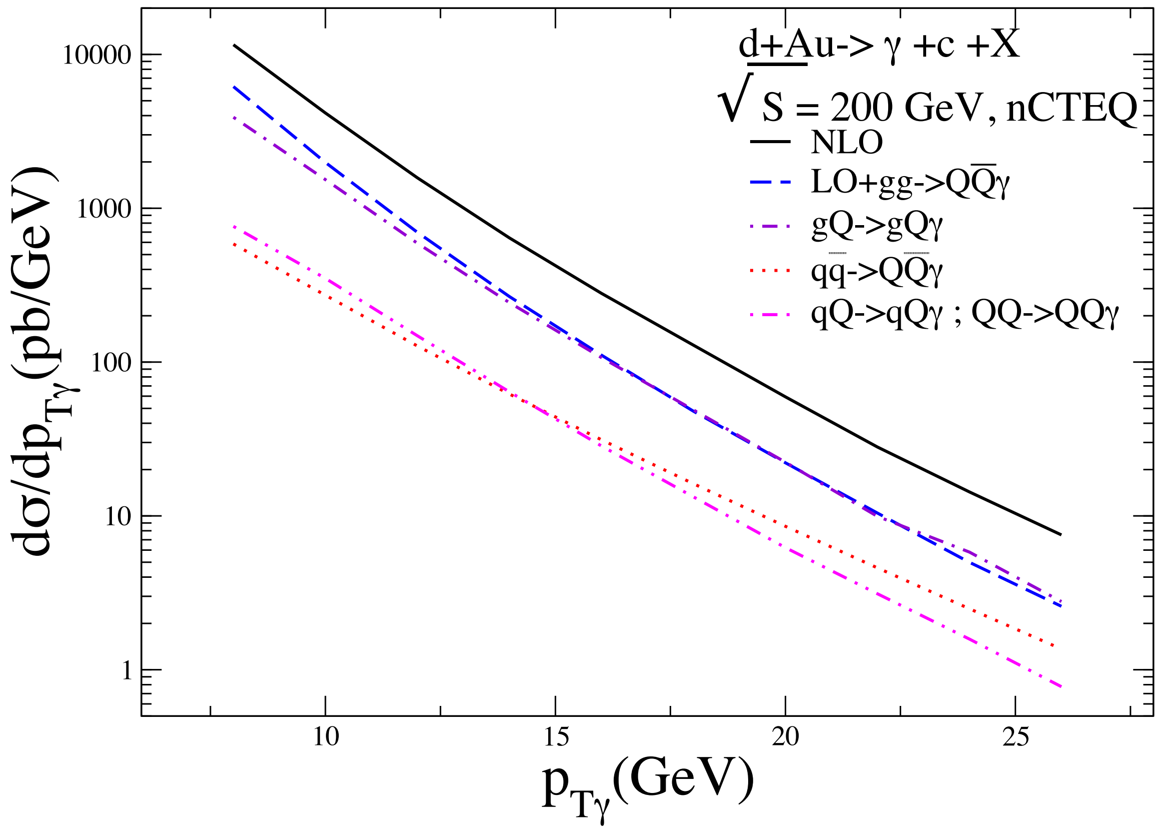
  in the variable flavour number scheme
- Predictions at RHIC and LHC
  - RHIC: d Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV
  - LHC: p Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV
- Calculation of quenching factors

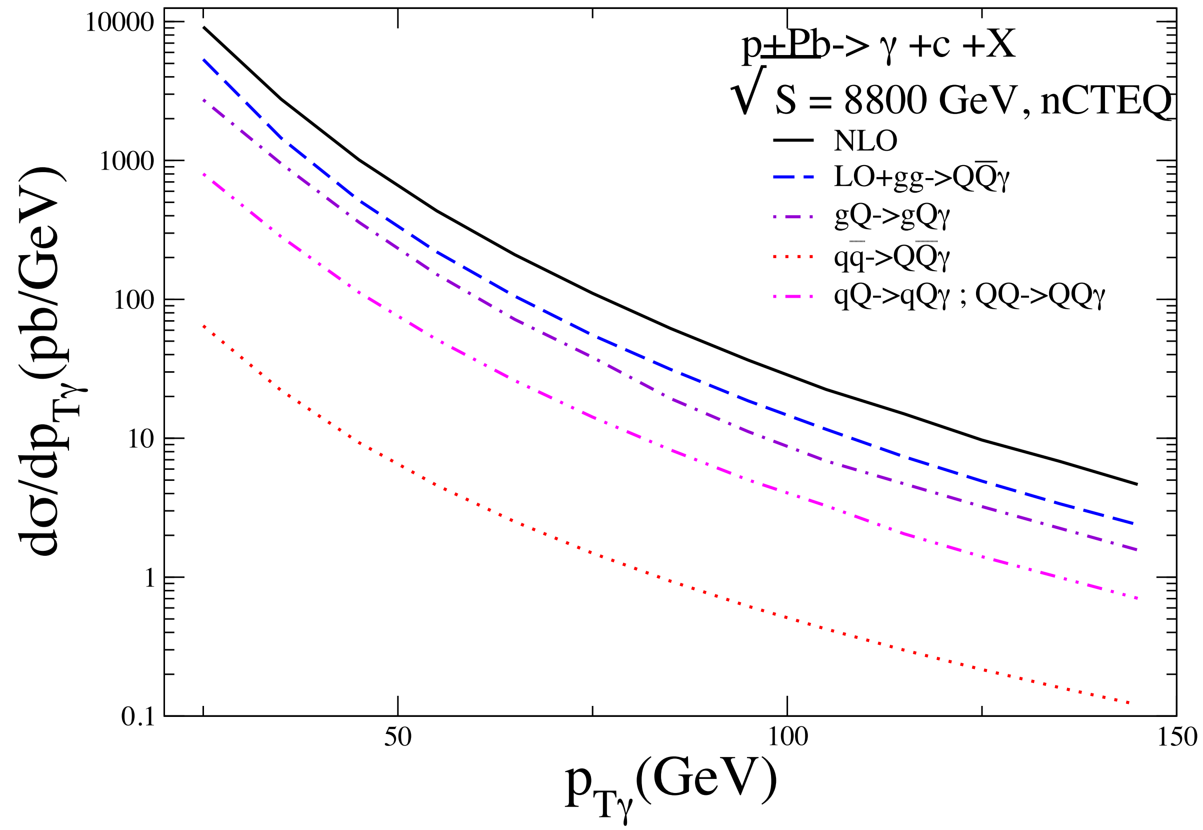
$$R_{pA}^{\gamma Q} = \frac{\sigma\,(pA \to \gamma\ Q\ \mathrm{X})}{A\ \sigma\,(pp \to \gamma\ Q\ \mathrm{X})}$$

  using different nPDF sets then available: nCTEQ, EPS09, HKN07

Spectra and rates

Absolute cross sections





- Cross section dominated by Compton scattering
- Important NLO corrections

Spectra and rates

Expected rates at RHIC (PHENIX kinematics)

Assuming $\mathcal{L}^{year} = 0.74\ \text{pb}^{-1}$

Photon + charm

- $\mathcal{N} \simeq 3 \times 10^4$ for $p_{T_\gamma} > 7$ GeV
- $\mathcal{N} \simeq 10^2$ for $p_{T_\gamma} > 20$ GeV

Photon + bottom

- < 100 events for $p_{T_\gamma} > 17$ GeV

Spectra and rates

Expected rates at LHC (ALICE kinematics)

Assuming $\mathcal{L}^{\mathrm{year}} = 0.1\ \mathrm{pb}^{-1}$

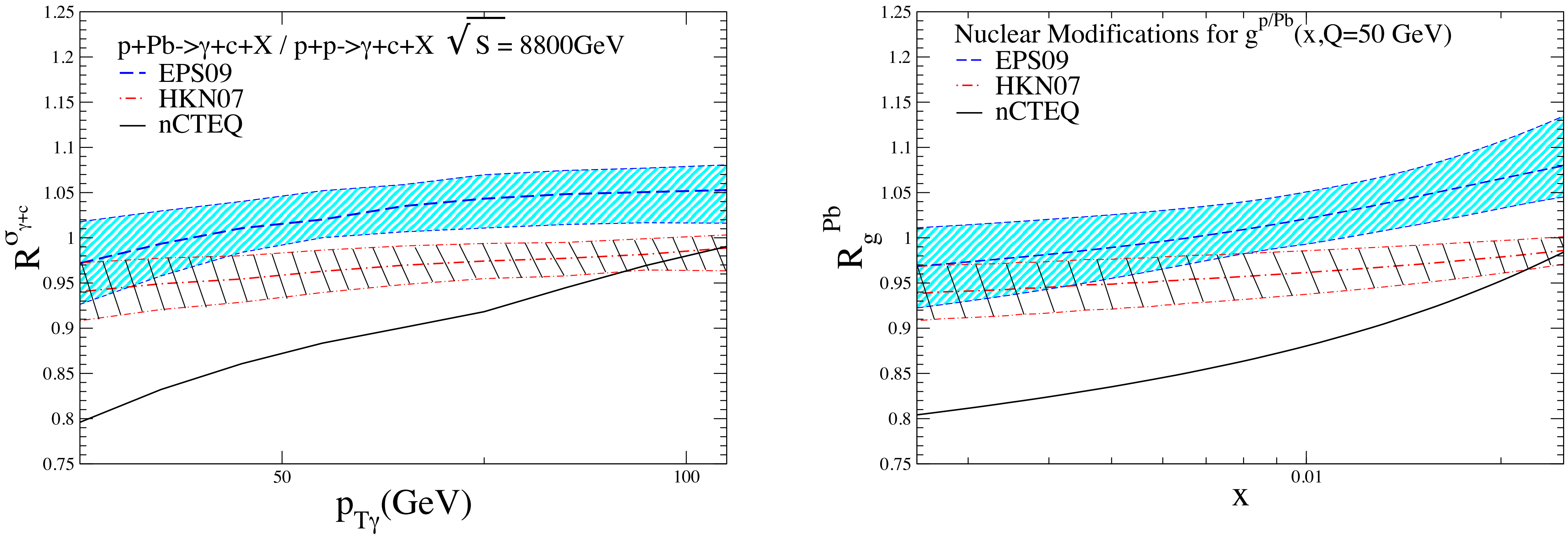
	$\sigma_{\gamma+Q}^{pPb}$	$N_{\gamma+Q}^{pPb}$
$\gamma + c$ PHOS	$22700\ \mathrm{pb}$	2270
$\gamma + b$ PHOS	$3300\ \mathrm{pb}$	330
$\gamma + c$ EMCal	$119000\ \mathrm{pb}$	11900
$\gamma + b$ EMCal	$22700\ \mathrm{pb}$	2270

- Large for $\gamma + c$ and $\gamma + b$ events at LHC

Constraining the gluon nPDF

LHC

Main result

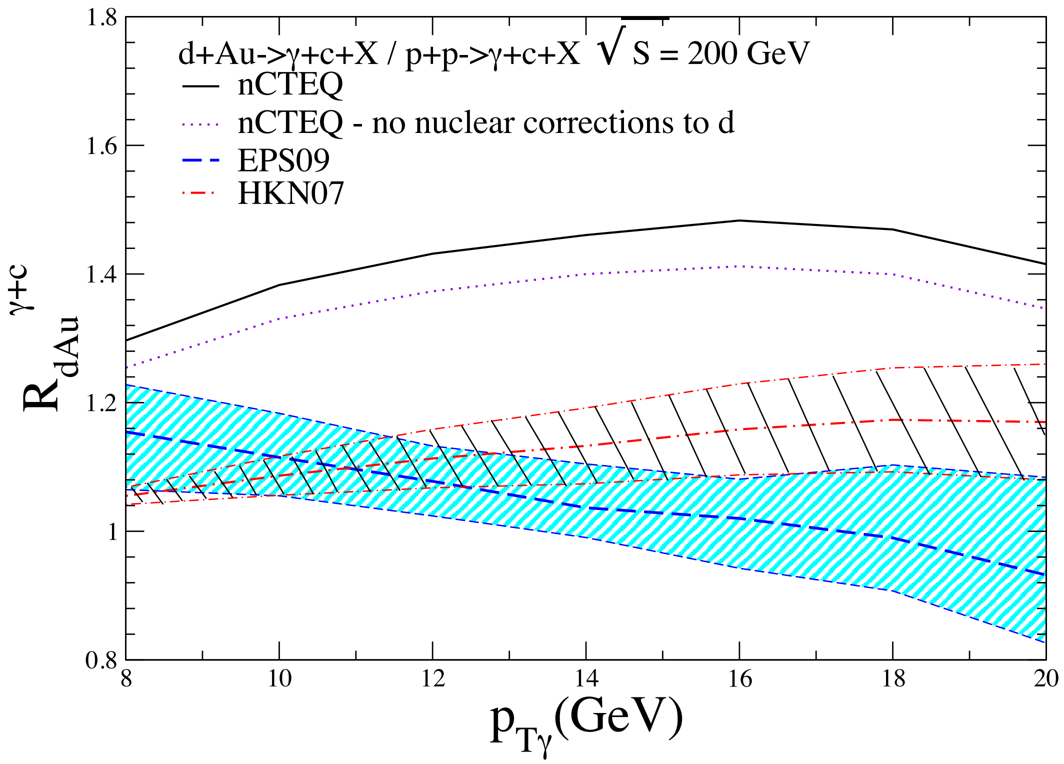


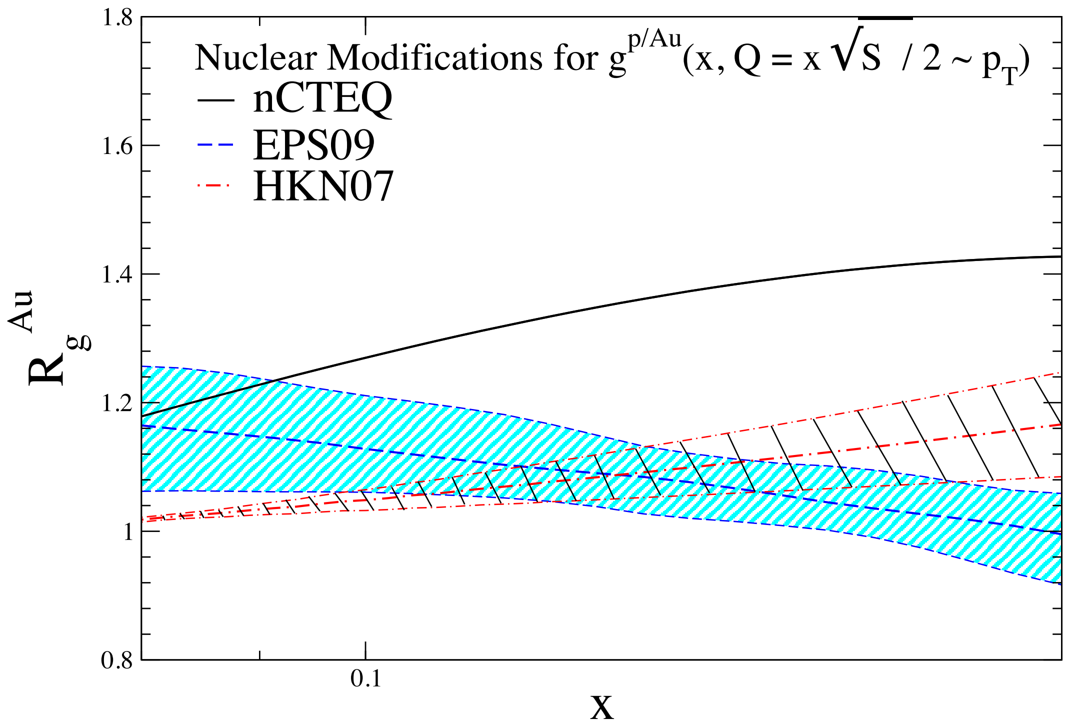
- $R_{pPb}^{\gamma+c}$ follows R_g^{Pb} very closely
- Almost no overlap between EPS09 and HKN07, and nCTEQ decut3
- Measurements with sufficiently small error bars should disentangle the various nPDF sets

Constraining the gluon nPDF

RHIC

Main result





- Same observation than at LHC : $R_{dAu}^{\gamma+c} \simeq R_g^{Au}$
- Kinematic region probed at RHIC ($x = 10^{-1}$–2×10^{-1}) complementary to that at LHC ($x = 5 \times 10^{-3}$–2×10^{-2})

Conclusions I

- g+Q initiated subprocesses dominate

- In standard approach:
  Heavy quark PDF dynamically generated;
  clean probe of gluon PDF

- No isospin effects!
  Quenching factor R=1 if no nuclear effects

- Cross sections large enough at RHIC and LHC

- $R_{pPb}^{\gamma+c}$ follows R_g^{Pb} very closely

- Baseline for photon+Q production in AA collisions

γ+Q in AA collisions

References:
T. Stavreva, F. Arleo, IS, JHEP1302(2013)072

Probing (massive) parton energy loss in QGP

Energy loss of massive partons

- Heavy quark mass acts as a collinear cutoff for medium-induced gluon radiation, just like in vacuum (dead cone) [Doskhitzer Kharzeev 2001]
- Clear hierarchy expected

$$\left(\Delta E\big|_g >\right) \Delta E\big|_q > \Delta E\big|_c > \Delta E\big|_b$$

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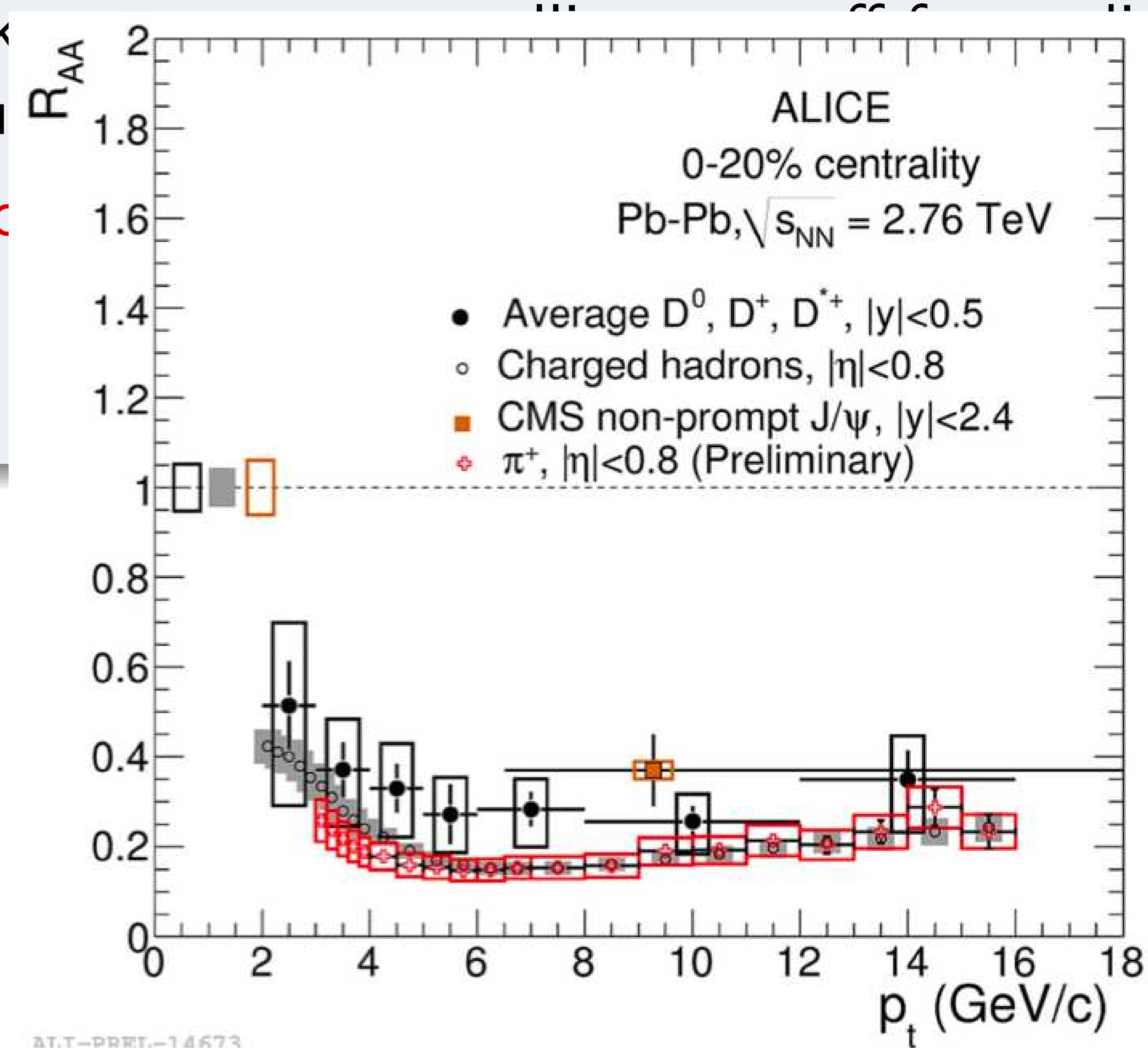

[ALICE]

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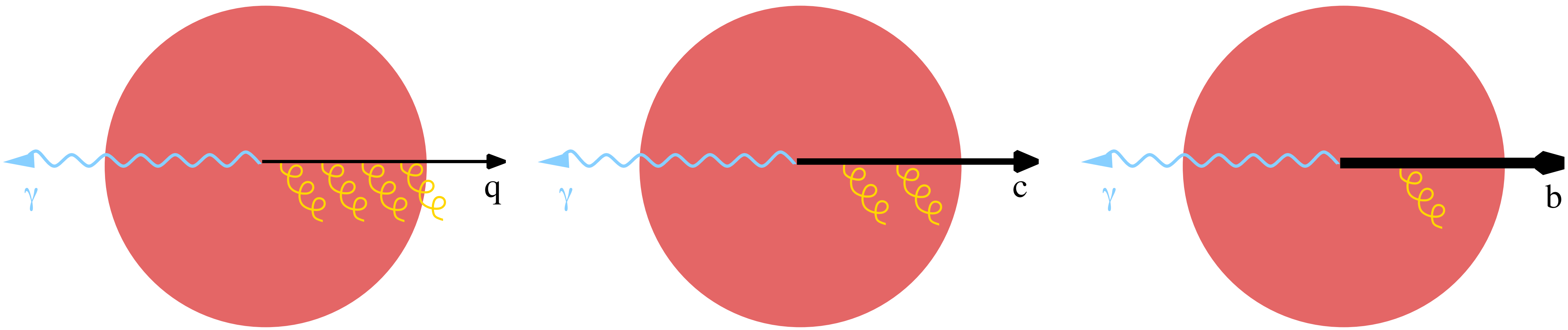
$\gamma + Q$ unique tool to probe Q energy loss in the plasma



Analysis in AA collisions

- Calculations performed at NLO accuracy at $\sqrt{s} = 5.5$ TeV
- Heavy quark energy loss ϵ_Q estimated on an event-by-event basis from the quenching weight (probability distribution) obtained perturbatively

[Armesto Dainese Salgado Wiedemann 2005]

- Various observables investigated
  - Photon–jet energy asymmetry A_J

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

  - Momentum imbalance $z_{\gamma Q}$

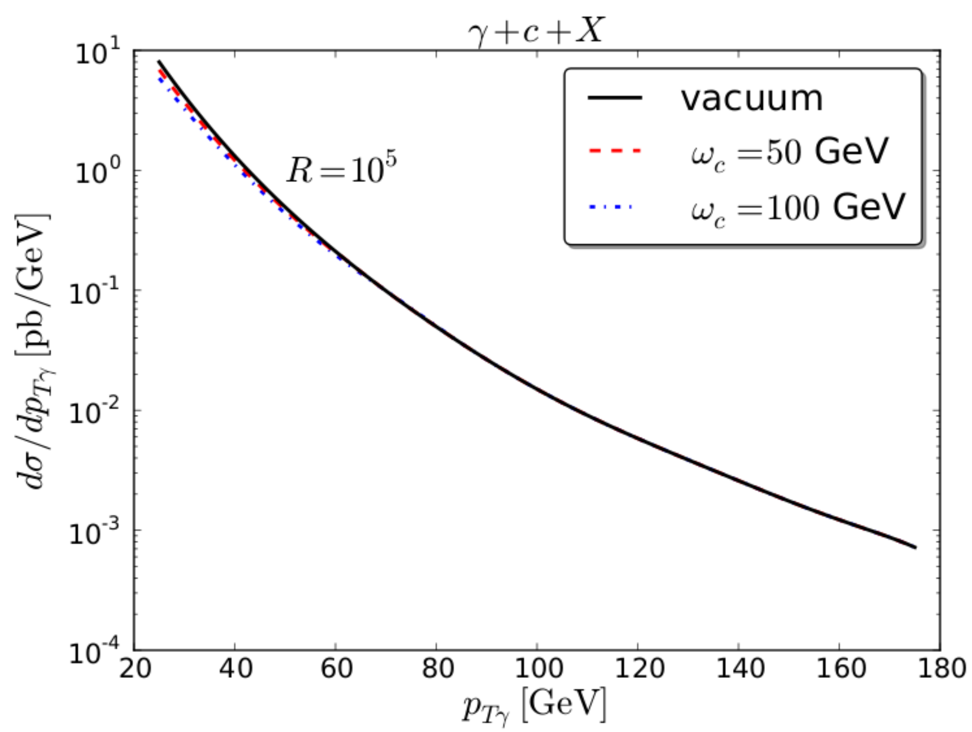
$$z_{\gamma Q} = -\frac{\vec{p}_{T\gamma}.\vec{p}_{TQ}}{p_{T\gamma}^2}$$

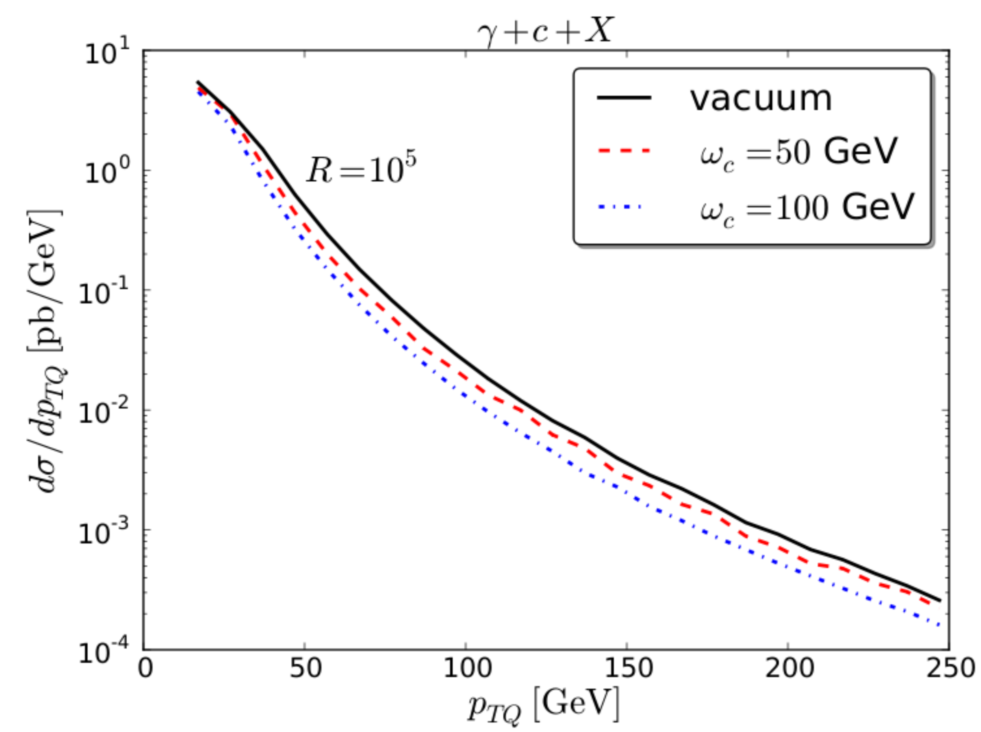
  - Photon–jet pair momentum $q_\perp$

$$q_\perp = |p_{T\gamma} + p_{TQ}|$$

Transverse momentum distributions

Comparing photon and jet $p_\perp$ spectra

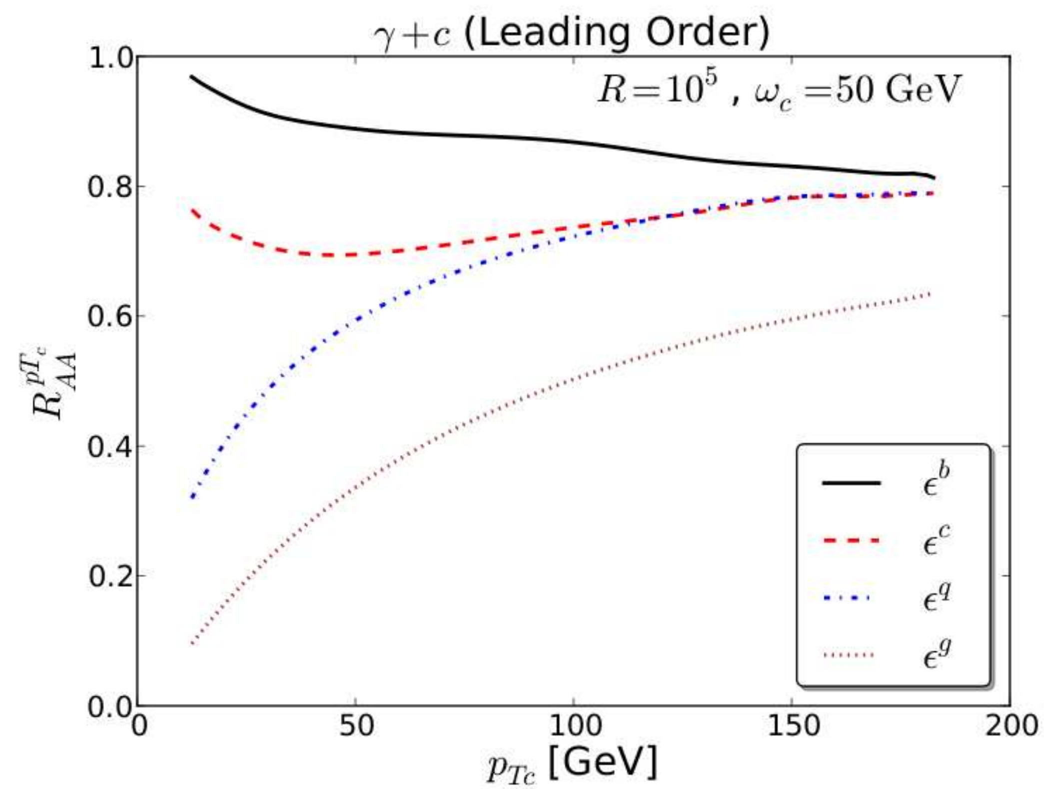




- No (or little) modifications of the photon $p_\perp$
- Stronger effects on the heavy quark jet spectrum

Transverse momentum distributions

Nuclear production ratios R_{AA}

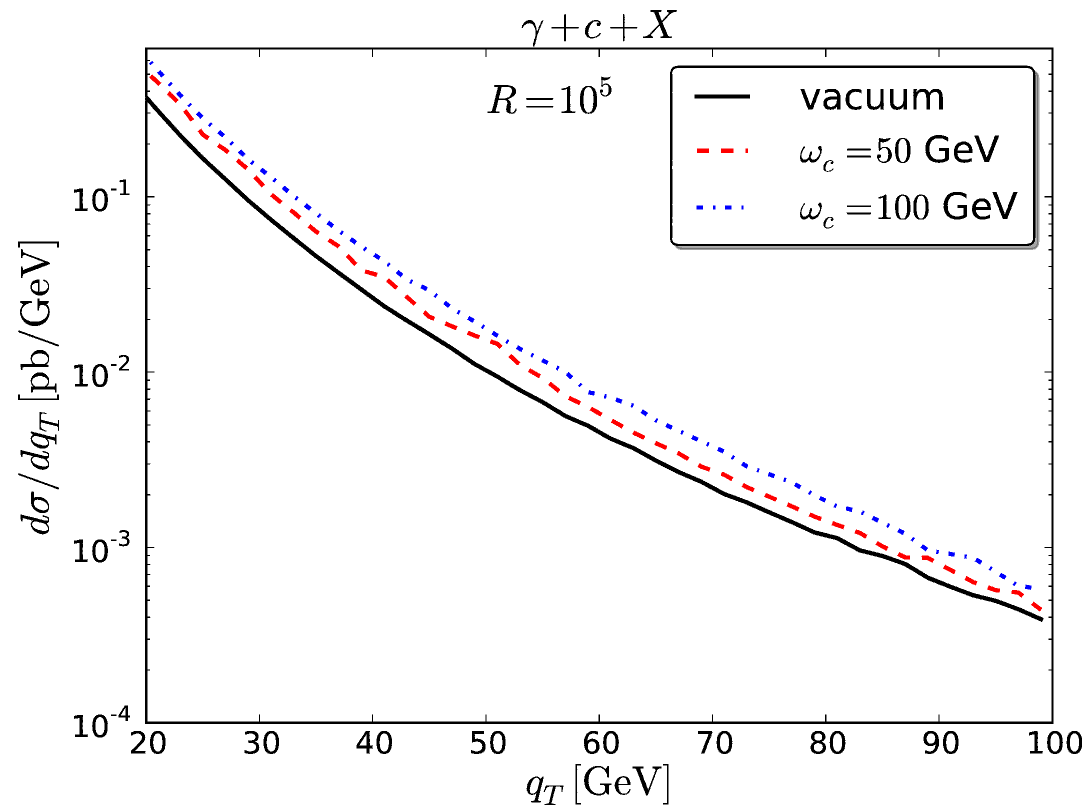


- Sensitive to the amount of energy loss assumed in the calculation
- Needs to be compared to $\gamma+$ inclusive jet production

Pair momentum distribution

Why $q_\perp$ distribution

$q_\perp \simeq \epsilon_Q$ at LO accuracy if the photon is produced directly



- The shift in the $q_\perp$ distributions should reflect the strength of heavy quark energy loss in the medium

Conclusions II

- $AA \to \gamma + Q$ very interesting process
  Allows to study heavy quark energy loss in the QGP calibrated against the photon
- Performed first exploratory study at NLO for the LHC

Merci!

Intrinsic Charm

A colleague: "If QCD is right, there has to be IC"
(which normalization?)

Intrinsic charm:
$c(x, \mu_0) \neq 0$ at initial scale $\mu_0 = m_c$

Models implemented in CTEQ 6.5C (PRD75, 2007)
global fit allows average momentum $\langle x \rangle_{c+\bar{c}}$ or order 1 %

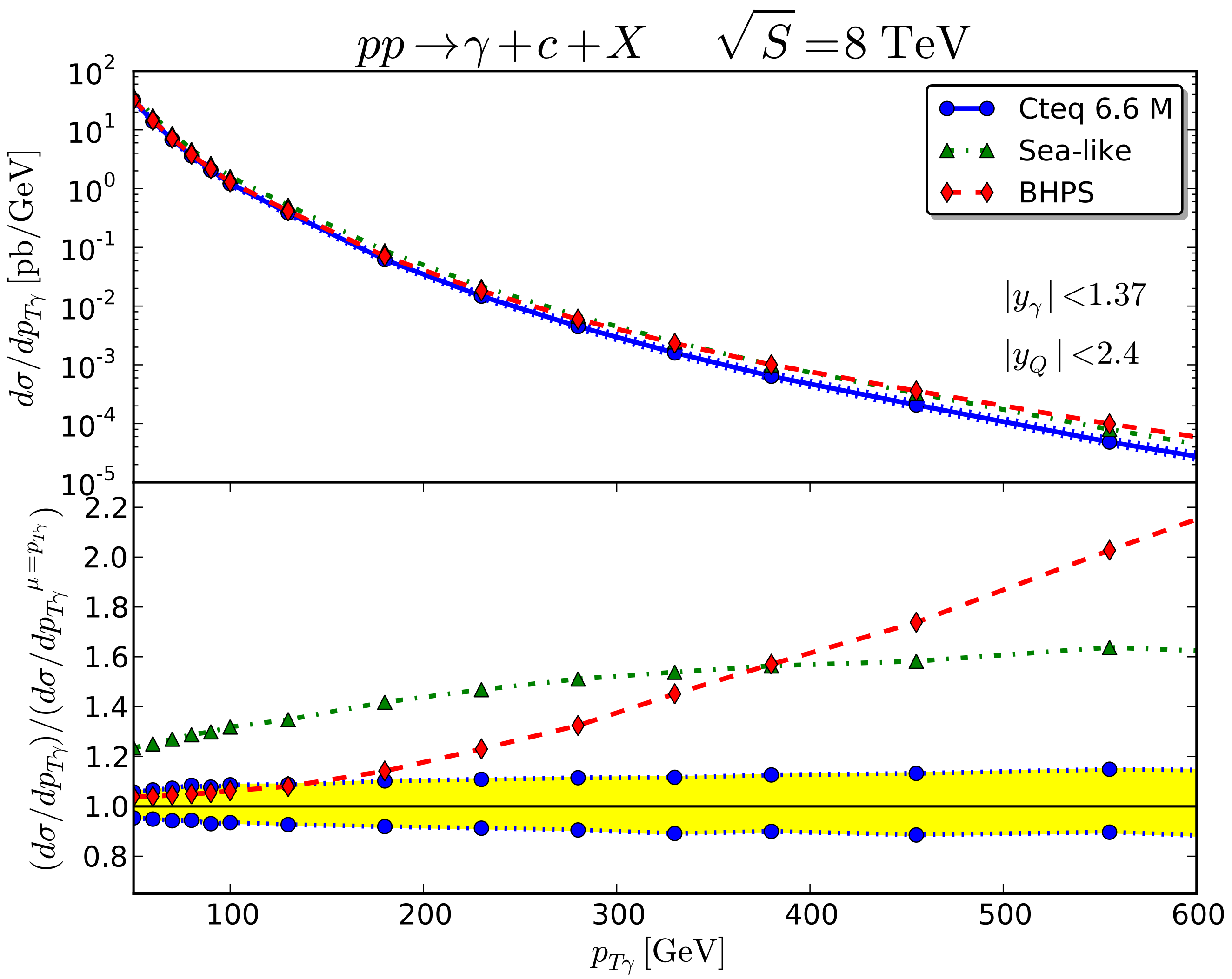
1. Light-cone Fock-space picture (Brodsky et al.), concentrated at large x
   $\langle x \rangle_{c+\bar{c}} = 0.57, 2.0\,\%$
2. Meson-cloud model (Navarra et al.)
   $\langle x \rangle_{c+\bar{c}} = 0.96, 1.8\,\%$
3. Phenomenological model: sea-like charm, broad in x
   $\langle x \rangle_{c+\bar{c}} = 1.1, 2.4\,\%$

Recent CTEQ-TEA analysis of IC: 1309.0025

Results for LHC - ATLAS

	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	$\lvert y_Q \rvert < 2.4$	$R_{jet} > 0.4, R_{Q\gamma} > 1$

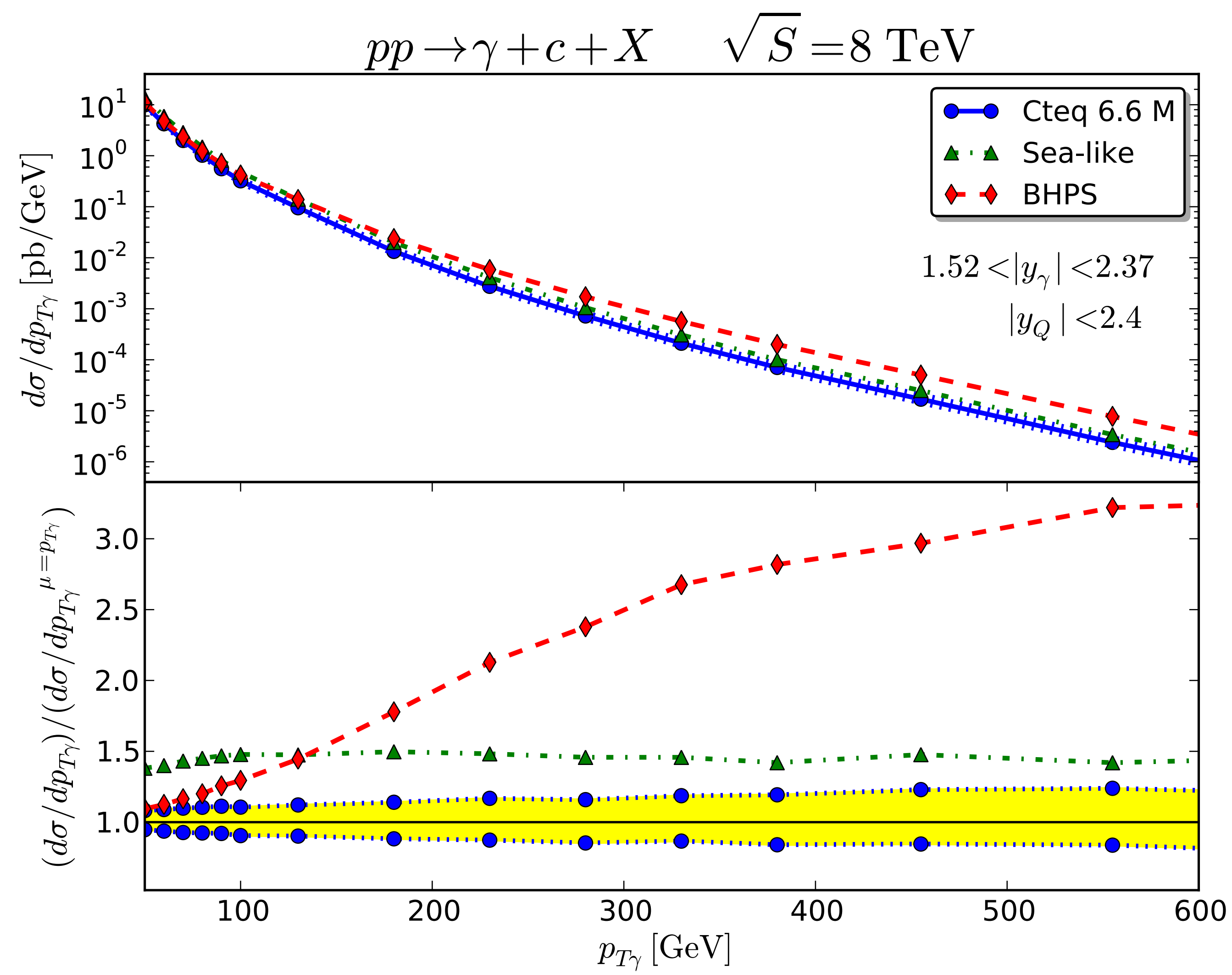
γ+c,
central rapidity



Results for LHC - ATLAS

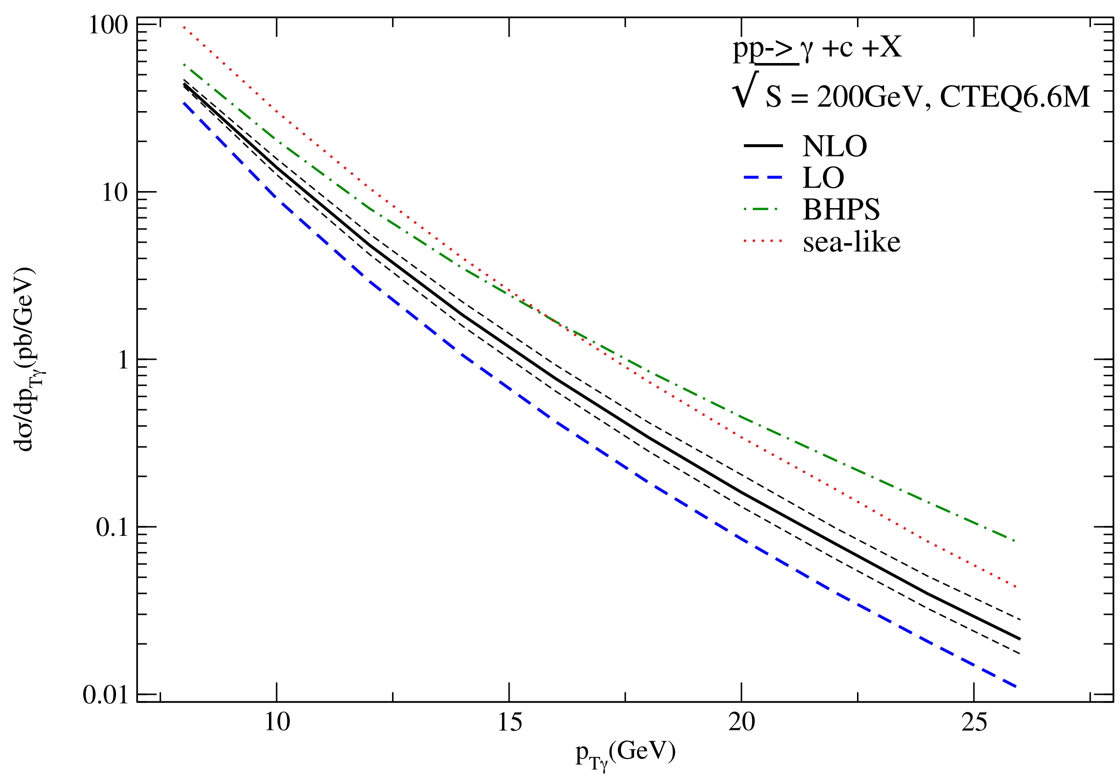
	p_T	Rapidity	Isolation Cuts
Photon	$p_{T,\gamma}^{min} = 45$ GeV	$\lvert y_\gamma \rvert < 1.37$	$R = 0.4,\ E_T = 7$ GeV
	$p_{T,\gamma}^{max} = 1000$ GeV	$1.52 < \lvert y_\gamma \rvert < 2.37$	
Heavy Jet	$p_{T,Q}^{min} = 20$ GeV	$\lvert y_Q \rvert < 2.4$	$R_{jet} > 0.4, R_{Q\gamma} > 1$

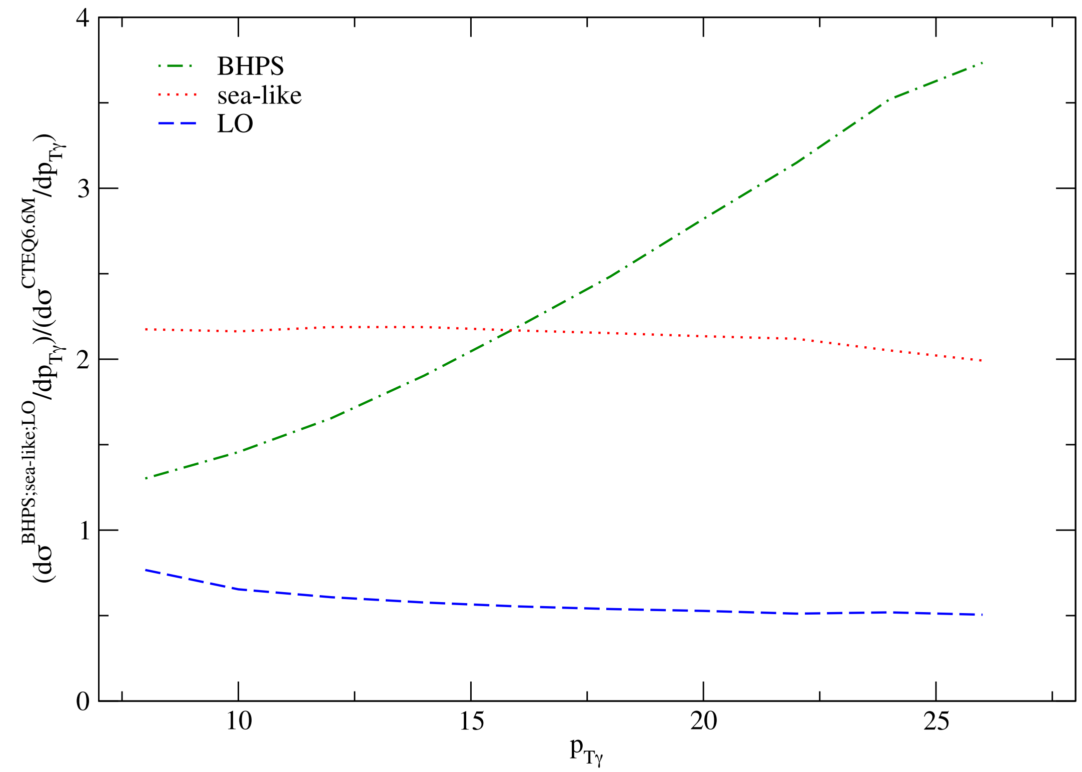
γ+c,
forward rapidity



Results for RHIC - PHENIX

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





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