Measuring gluon shadowing with prompt photons at RHIC and LHC

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Quark Matter 2008

February 2008 – Jaipur, India

Outline

- Motivations
  - why probing small-x gluons
  - why using prompt photons
- Extracting gluon distributions
  - pQCD prompt photon production in p A collisions
  - limitations
- Phenomenology
  - predictions in p A collisions at RHIC and LHC
  - measuring shadowing without pp data

[FA, T. Gousset, Phys. Lett. B 660 (2008) 181, arXiv: 0707.2944]

Gluon distributions at small x

The accurate knowledge of gluon density in a proton or in a nucleus is essential for two reasons

- Fundamental pQCD ingredient
  - tool for reliable predictions of hard processes at LHC
- Probe of non-linear QCD evolution
  - looking for saturation at small x

In a proton

Strong activity over the last decade to probe proton densities

- Impressive results from HERA [H1, ZEUS]
- Important theoretical developments in global fit analyses

[CTEQ, GRV, MRST]

In a proton

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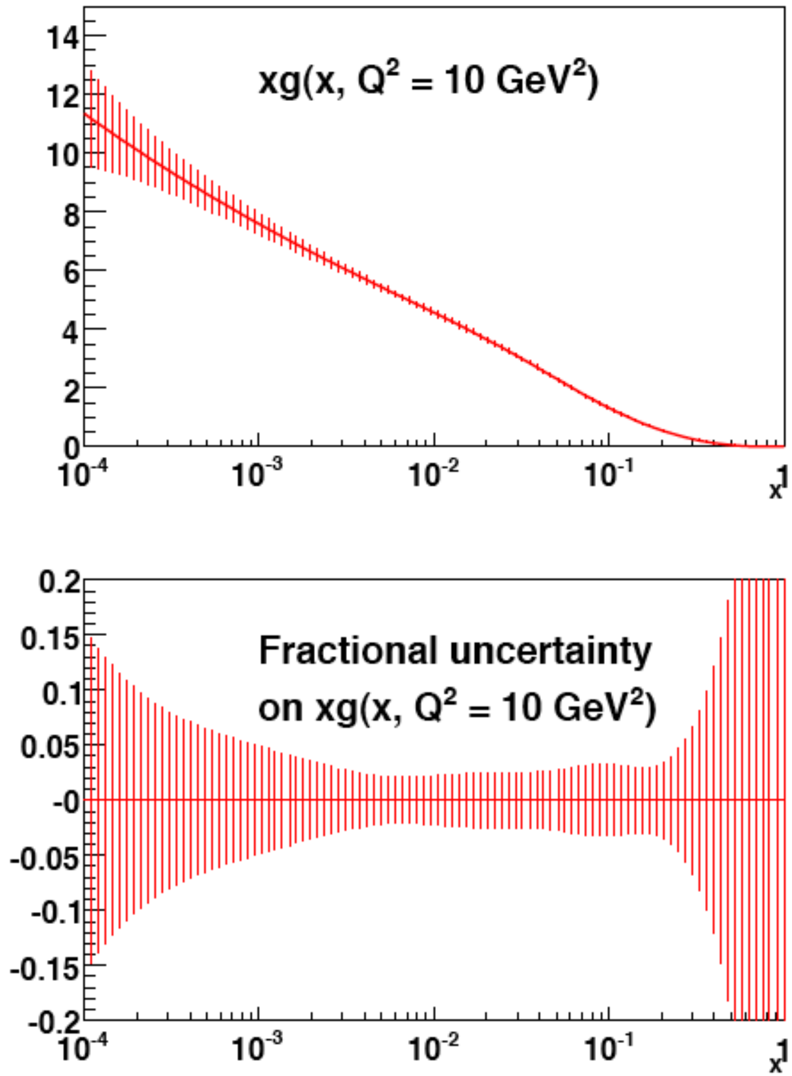
$G^p(x, Q^2)$ fairly well known over a large kinematical range

$x \sim 10^{-4}$–10^{-1} and $Q^2 \sim 10$–10^5 GeV^2

In a proton



[From R. Thorne DIS 2007]

In a nucleus

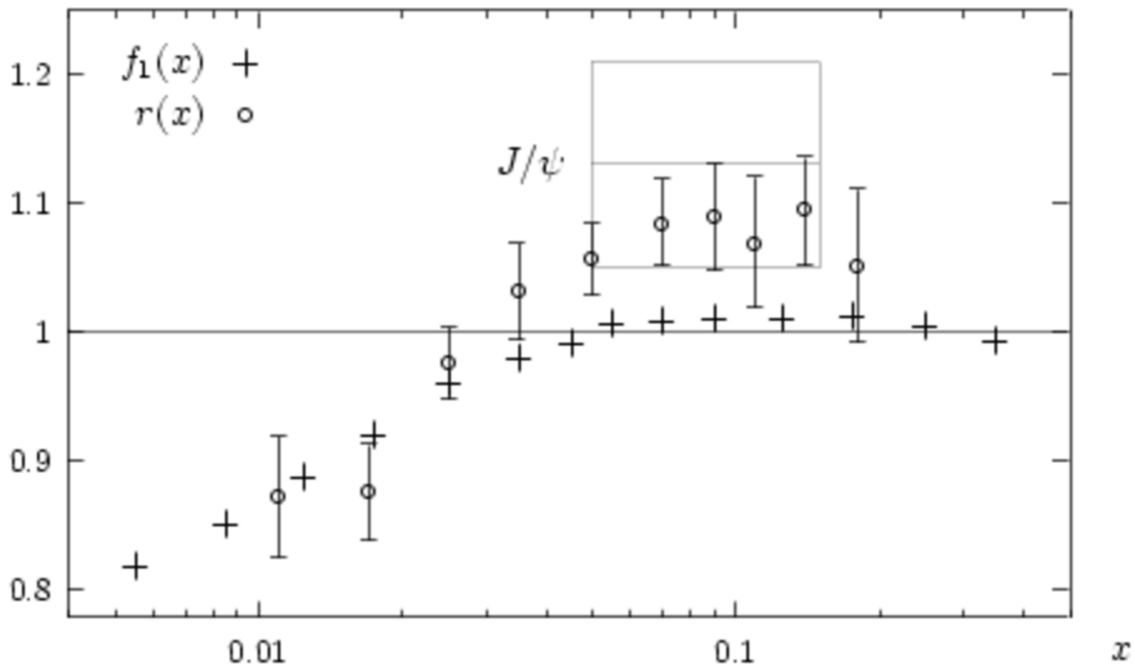
Gluon distributions in nuclei over that in a proton

$$R_G(x, Q^2) = G_{\mathrm{A}}(x, Q^2)/G_p(x, Q^2)$$

poorly constrained experimentally!

In a nucleus

From NMC data



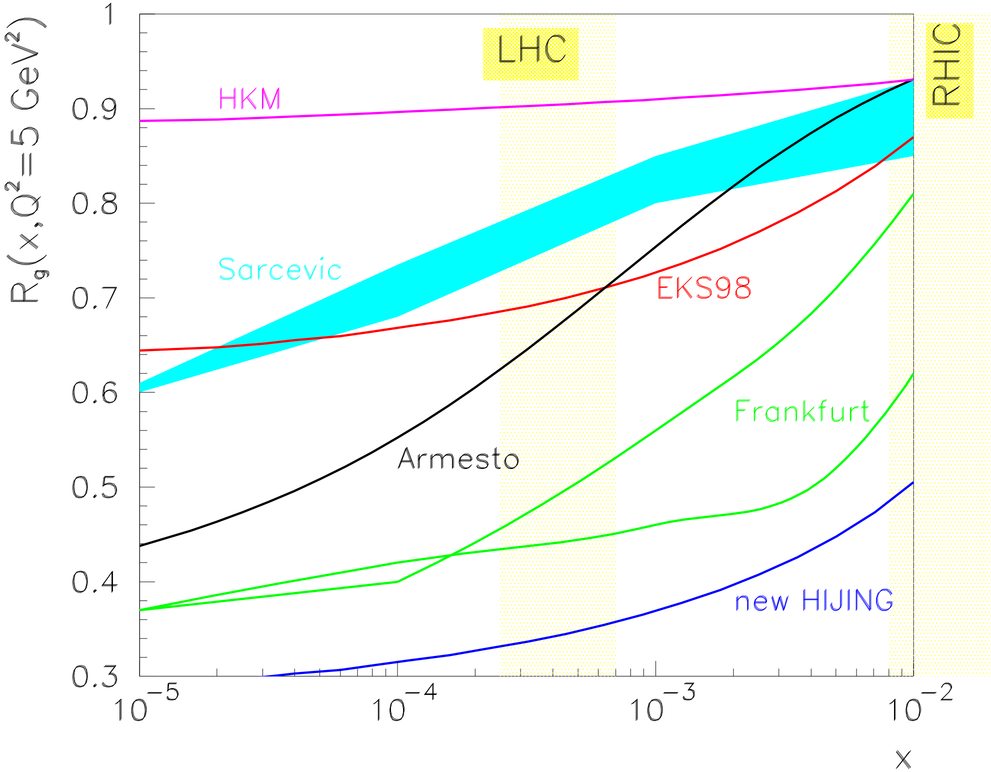
[Gousset, Pirner 1996]

- Tiny constraints from the scaling violation of $F_2^A(x, Q^2)$
- Fairly large $x \sim 10^{-2}$–10^{-1}

In a nucleus

From global analyses of DIS and Drell-Yan data

[EKS/EPS, HKM, nDS]



[Armesto, Salgado 2003]

- Huge uncertainties at small $x \ll 1$

In a nucleus

Gluon distributions in nuclei over that in a proton

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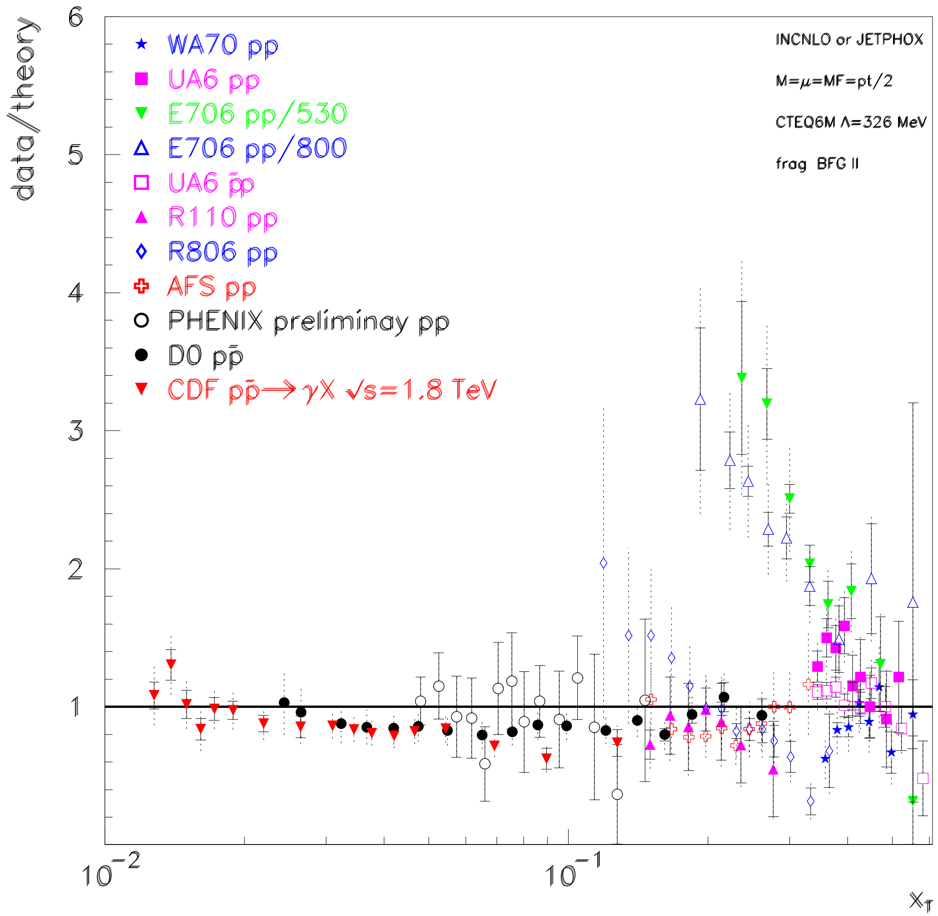
How to probe small-x gluon shadowing at LHC ?

- which observables
- why prompt photons

Observables

- Jets
  - :-) high rates, rich phenomenology, forward rapidities
  - :-(large scales $Q^2 \gtrsim 10^3$ GeV^2
- Large $p_\perp$ dileptons
  - :-) no strong background
  - :-(very low rates
- Heavy-bosons
  - :-) constraints on sea-quark shadowing
  - :-(large scales $Q^2 \gtrsim 10^4$ GeV^2
- Prompt photons
  - :-) low $Q^2 \gtrsim 10$–10^3 GeV^2, rich phenomenology
  - :-(parton-to-photon fragmentation process

Observables



[Aurenche et al. 2006]

- Good description of isolated/inclusive photon world-data

Observables

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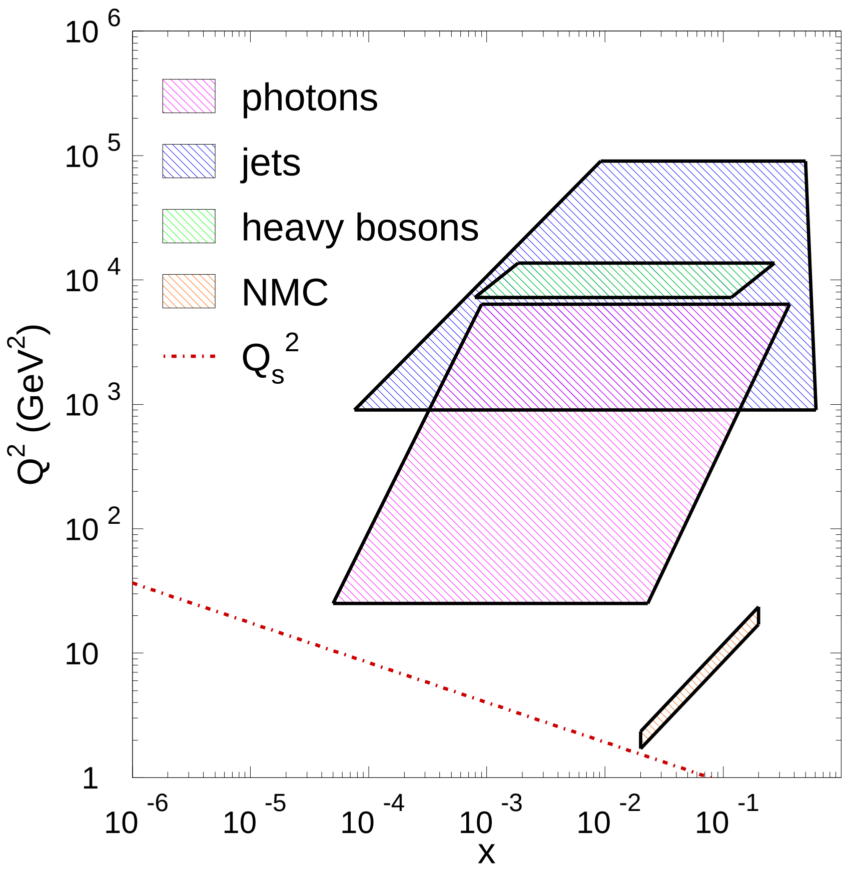
Kinematics

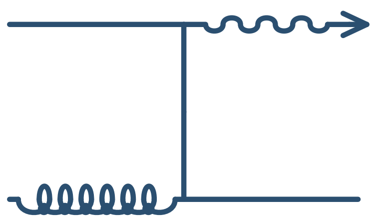


- Photons and jets are clearly complementary
- Photons cover small Q^2 where shadowing should be large

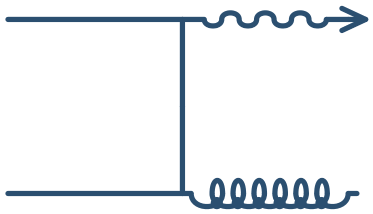
Perturbative production

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

- Compton scattering $q(\bar{q})\ g \rightarrow q(\bar{q})\ \gamma$



- Annihilation process $q\ \bar{q} \rightarrow g\ \gamma$



At high energy, only the Compton scattering process is relevant

Perturbative production

Production cross section at LO $(x_\perp \equiv 2p_\perp/\sqrt{s},\ F(x) \equiv F_2(x)/x)$

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}y\ \mathrm{d}^2p_\perp} = \int_{x_\perp e^y/2}^{1-x_\perp e^{-y}/2} \mathrm{d}v \quad \left[F^{\mathrm{P}}\left(\frac{x_\perp e^y}{2v}\right) G^{\mathrm{T}}\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(v) + G^{\mathrm{P}}\left(\frac{x_\perp e^y}{2v}\right) F^{\mathrm{T}}\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(1-v) \right]$$

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Due to the fast variation of $F(x)$ and $G(x)$, the integrand is strongly peaked at $v \simeq 1/2$

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}y\ \mathrm{d}^2p_\perp} \simeq \hat{\sigma}(1/2)\left[F^{\mathrm{P}}(x_\perp e^y)\, G^{\mathrm{T}}(x_\perp e^{-y}) + G^{\mathrm{P}}(x_\perp e^y)\, F^{\mathrm{T}}(x_\perp e^{-y})\right]$$

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Simple relationship between prompt photon production

and parton densities!

Nuclear production ratio

Define the production ratio in p A collisions

$$R_{p\mathrm{A}}(x_\perp) = \frac{1}{A} \frac{\mathrm{d}^3\sigma}{\mathrm{d}y\, \mathrm{d}^2p_\perp}(p+\mathrm{A} \to \gamma+\mathrm{X}) \Big/ \frac{\mathrm{d}^3\sigma}{\mathrm{d}y\, \mathrm{d}^2p_\perp}(p+p \to \gamma+\mathrm{X})$$

Most naive estimates

- Around mid-rapidity

$$R_{p\mathrm{A}}(p_\perp, y) \simeq \frac{1}{2} \left[R_{F_2}(x_\perp e^{-y}) + R_G(x_\perp e^{-y})\right]$$

- At (very) forward rapidity

$$R_{p\mathrm{A}}(p_\perp, y) \simeq R_G(x_\perp e^{-y})$$

- At (very) backward rapidity

$$R_{p\mathrm{A}}(p_\perp, y) \simeq R_{F_2}(x_\perp e^{-y})$$

Limitations: fragmentation photons

Photons can also be produced by fragmentation

$$\frac{d^3\sigma^{\rm frag}(p\,A \to \gamma\,X\,)}{dy\;d^2p_\perp} \propto \int_0^1 dz \int_0^1 dv\;\ldots(x_\perp/z, Q^2)\;\; D_{\gamma/k}(z, Q^2)$$

The extra integration spoils the relationship $R_{pA} \Leftrightarrow R_{F_2}$ and R_G

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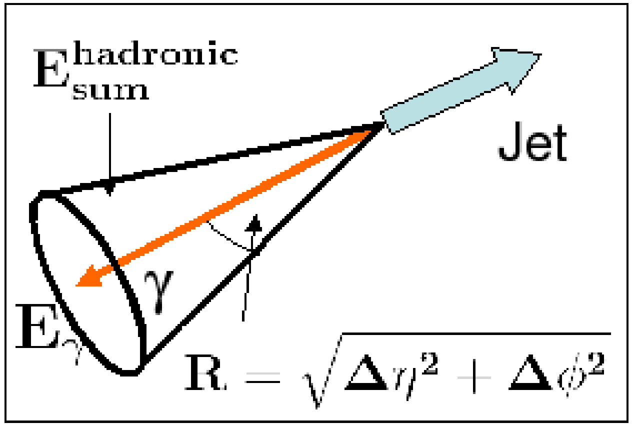
We get rid of (most of) them by means of isolation criteria

$$E_\perp^{\rm had} \leq E_\perp^{\rm max}$$

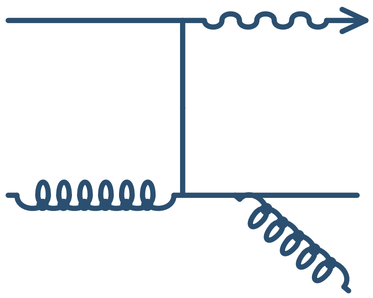
for particles in a cone

$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



Limitations: NLO corrections

Next-to-leading order (NLO) corrections



3-body kinematics in the final state $\Rightarrow$ needs to integrate over the momentum of the extra-particle radiated

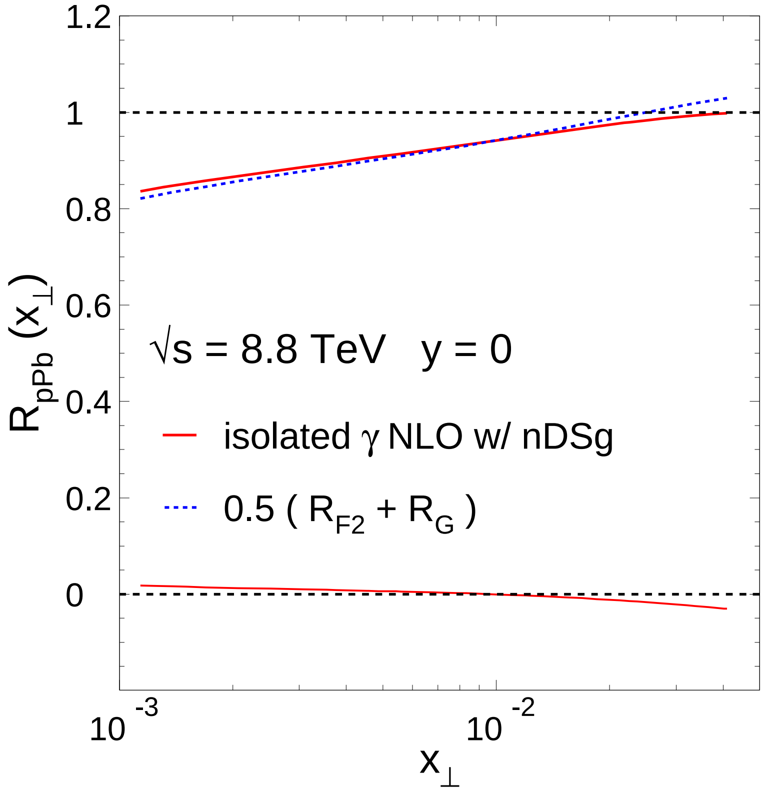
Strategy

To illustrate / check these estimates, let's compute $R_{pA}(x_\perp, y)$ at NLO using nDSg nuclear PDF in p A collisions

- At LHC
  - $\sqrt{s_{\rm NN}} = 8.8$ TeV at $y = 0, 2.5, -2.5$
- At RHIC
  - $\sqrt{s_{\rm NN}} = 200$ GeV at $y = 3$

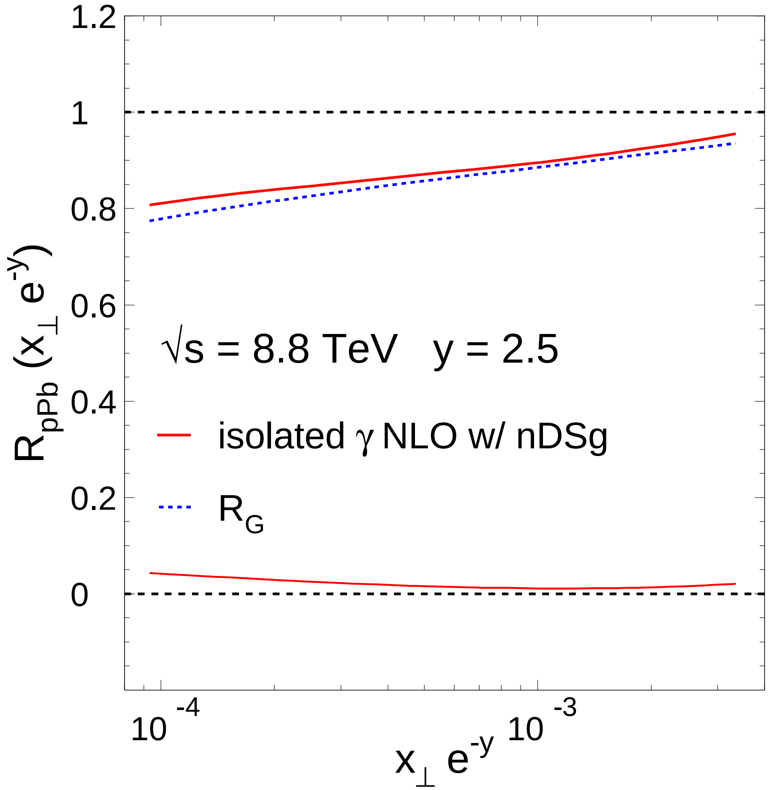
LHC

Mid-rapidity



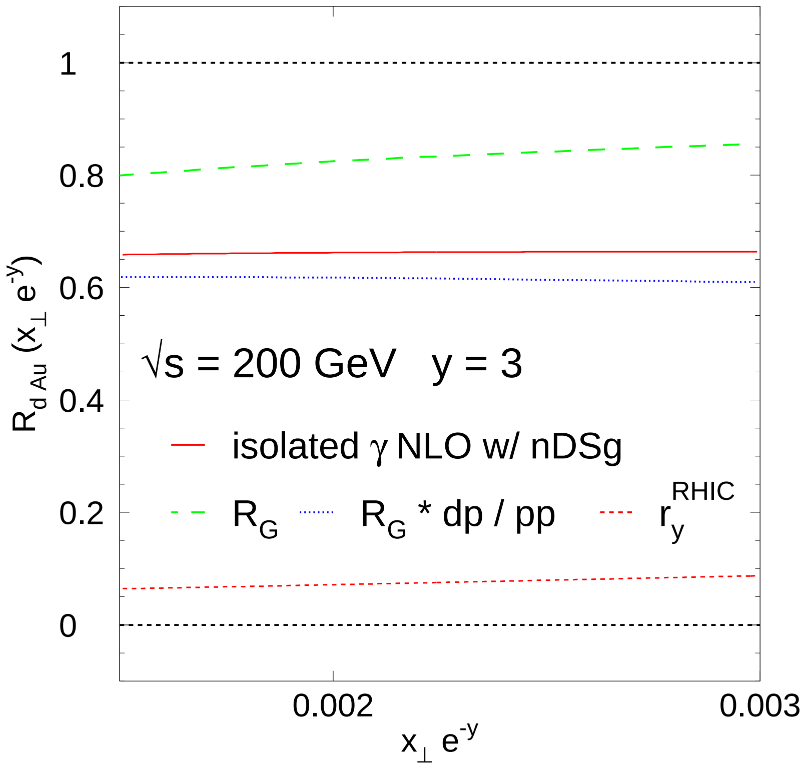
- 20% attenuation at $x_\perp \sim 10^{-3}$ measurable (statistically)
- perfect (< 2–3%) matching between R_{pA} and nuclear density ratios

Forward rapidity $y = 2.5$



- Gives "direct" access to R_G (within 5%) at $x = 10^{-4}$–10^{-3} !

Forward rapidity



- Fair matching ($\lesssim 10\%$) between R_{pA} and R_G
- Needs to be corrected for (trivial) isospin effects though

Shadowing without p p data

Problem: no p p collision at $\sqrt{s} = 8.8$ TeV

How to measure $R_G(x)$ without any p p reference data ?

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Compare forward w/ backward production in p A collisions

$$\frac{\mathrm{d}\sigma(p\ \mathrm{A} \to \ \gamma(+y)\ \mathrm{X}\ )}{\mathrm{d}\sigma(p\ \mathrm{A} \to \ \gamma(-y)\ \mathrm{X}\ )} = R_{p\mathrm{A}}(x_\perp, +y)/R_{p\mathrm{A}}(x_\perp, -y)$$

$$\simeq R_G(x_\perp e^{-y})/R_{F_2}(x_\perp e^{y})$$

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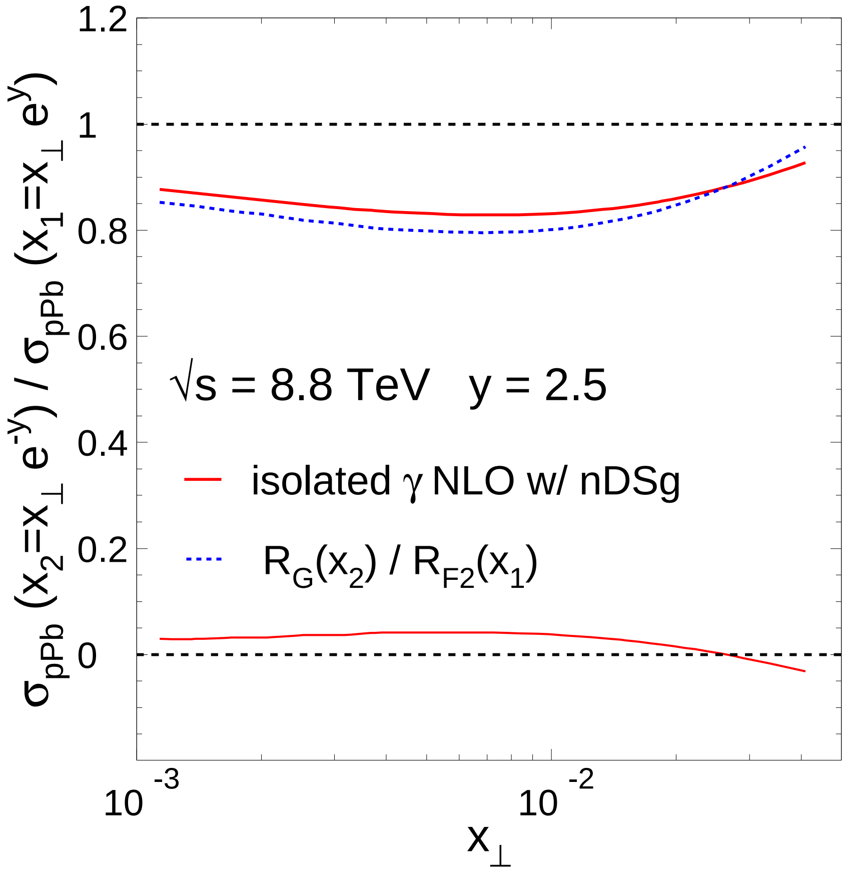
$$\simeq R_G(x_\perp e^{-y})/R_{F_2}(x_\perp e^{y})$$

R_{F_2} at large x gives access to R_G at small x !

Shadowing without p p data



- Encouraging yet a larger y would be better
- Need to correct for isospin effects

Counting rates

- LHC $\left(\mathcal{L} = 1.4\ 10^{30}\ \text{cm}^{-2} s^{-1},\ \Delta t = 10^6 s\right)$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}y\ \mathrm{d}p_\perp}\right|_{p_\perp = 100\ \text{GeV}} \simeq\ 8\ 10^2\ \text{pb/GeV}\ \Rightarrow\ \mathcal{N} \sim 10^3/\text{GeV}$$

- RHIC $\left(\mathcal{L}_{\text{int}} = 0.45\ \text{pb}^{-1}\right)$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}y\ \mathrm{d}p_\perp}\right|_{p_\perp = 7\ \text{GeV}} \simeq\ 8\ 10^3\ \text{pb/GeV}\ \Rightarrow\ \mathcal{N} \sim 4\ 10^3/\text{GeV}$$

[At RHIC-I, $\mathcal{L}_{\text{int}} = 0.02\ \text{pb}^{-1} \Rightarrow p_\perp \lesssim 5$ GeV]

Statistical accuracy in a year much better than the present spread of theoretical predictions for R_G at small x

Summary

- Essential to further constrain $G(x)$ at small x
  - needed for pQCD predictions at LHC
  - looking for saturation
- Prompt photon production in p A collisions
  - an ideal observable to probe parton densities
- Phenomenology at RHIC and LHC
  - reliable estimate of R_G from $R_{p\mathrm{A}}$ at forward rapidity
  - extracting R_G witout pp data at the same energy