Low Mass Lepton Pair Production at Large Transverse Momentum

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- ✓ Why low mass Drell-Yan
- ✓ QCD factorization for low mass Drell-Yan
- ✓ Sensitivity of low mass Drell-Yan on gluon distribution
- ✓ Summary

CTEQ 2008 Meeting
Argonne, IL, Dec 05-07, 2008

based on work with J. -W. Qiu, and W. Vogelsang

arXiv:0811.3662

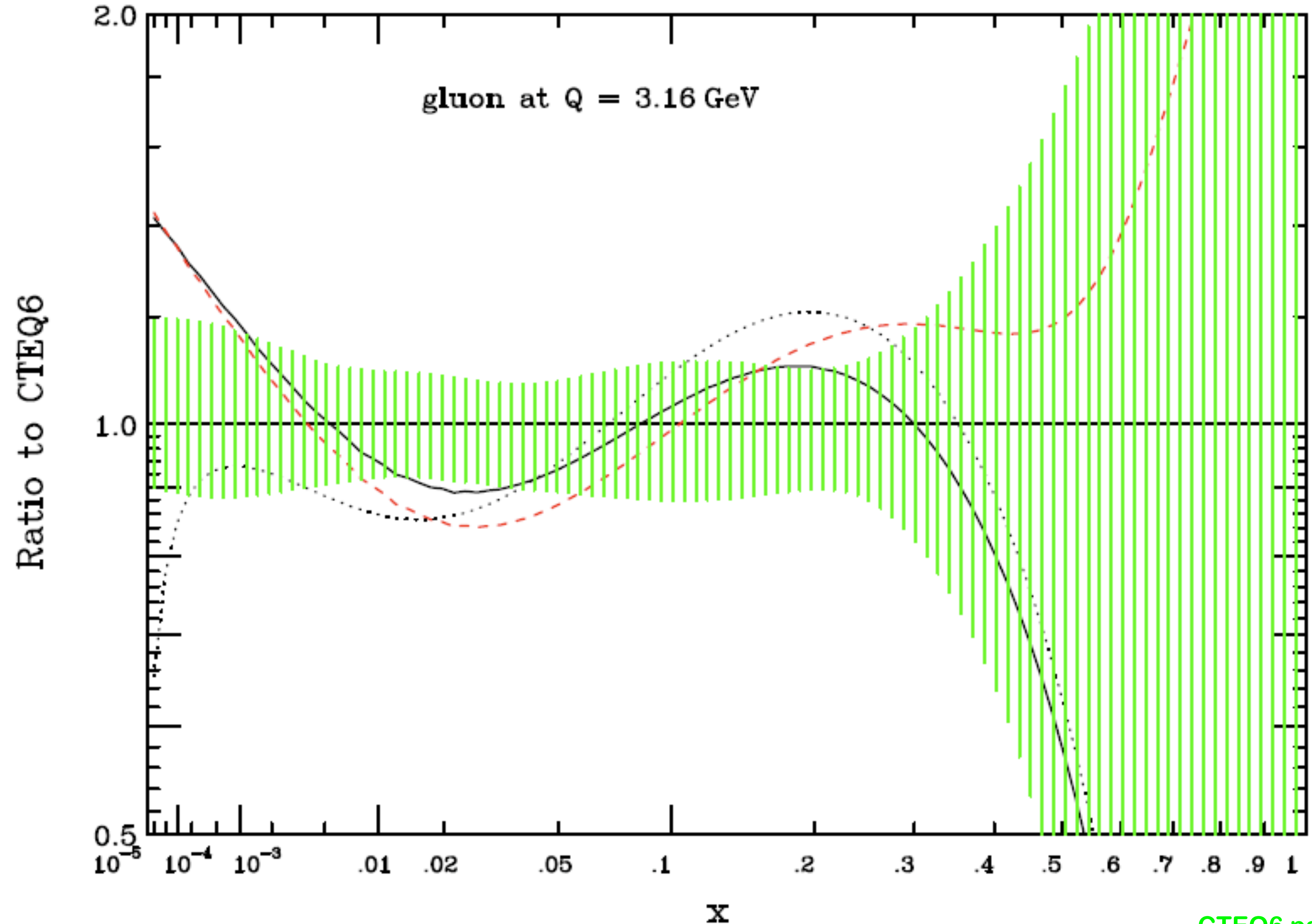
Why low mass Drell-Yan

- **Gluon distribution of a proton or an nucleus**
  is essential for discovering new physics at any hadron and heavy ion colliders, as well as EIC

- **Low mass Drell-Yan at high transverse momentum**
  is a good probe of gluon distribution, and is complementary to prompt photon production due to the cleaner lepton signal, but, relatively lower rate

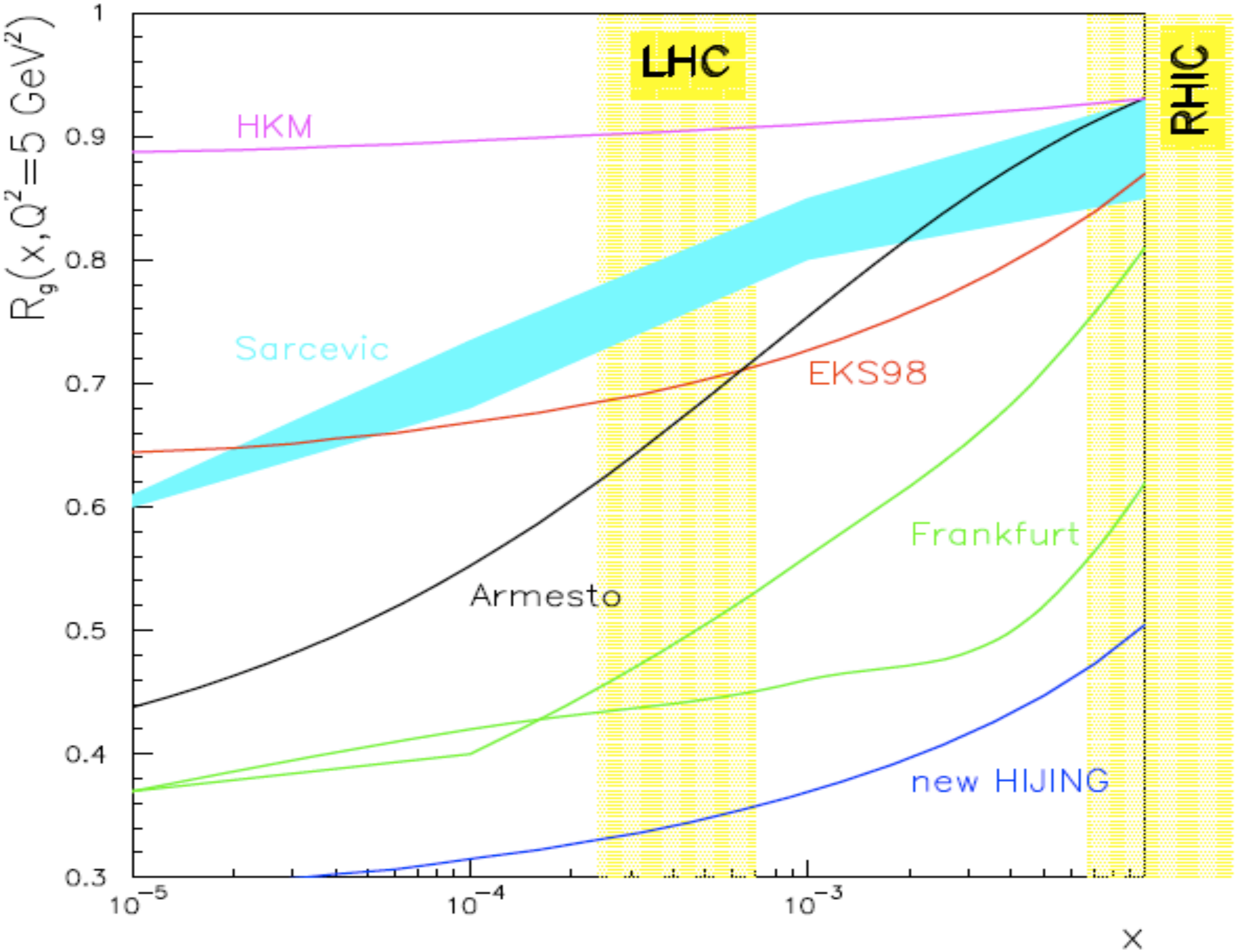
$$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy} = \left(\frac{\alpha_{\rm em}}{3\pi Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

Gluon distribution of a proton



CTEQ6 paper

Gluon distribution of a nucleus

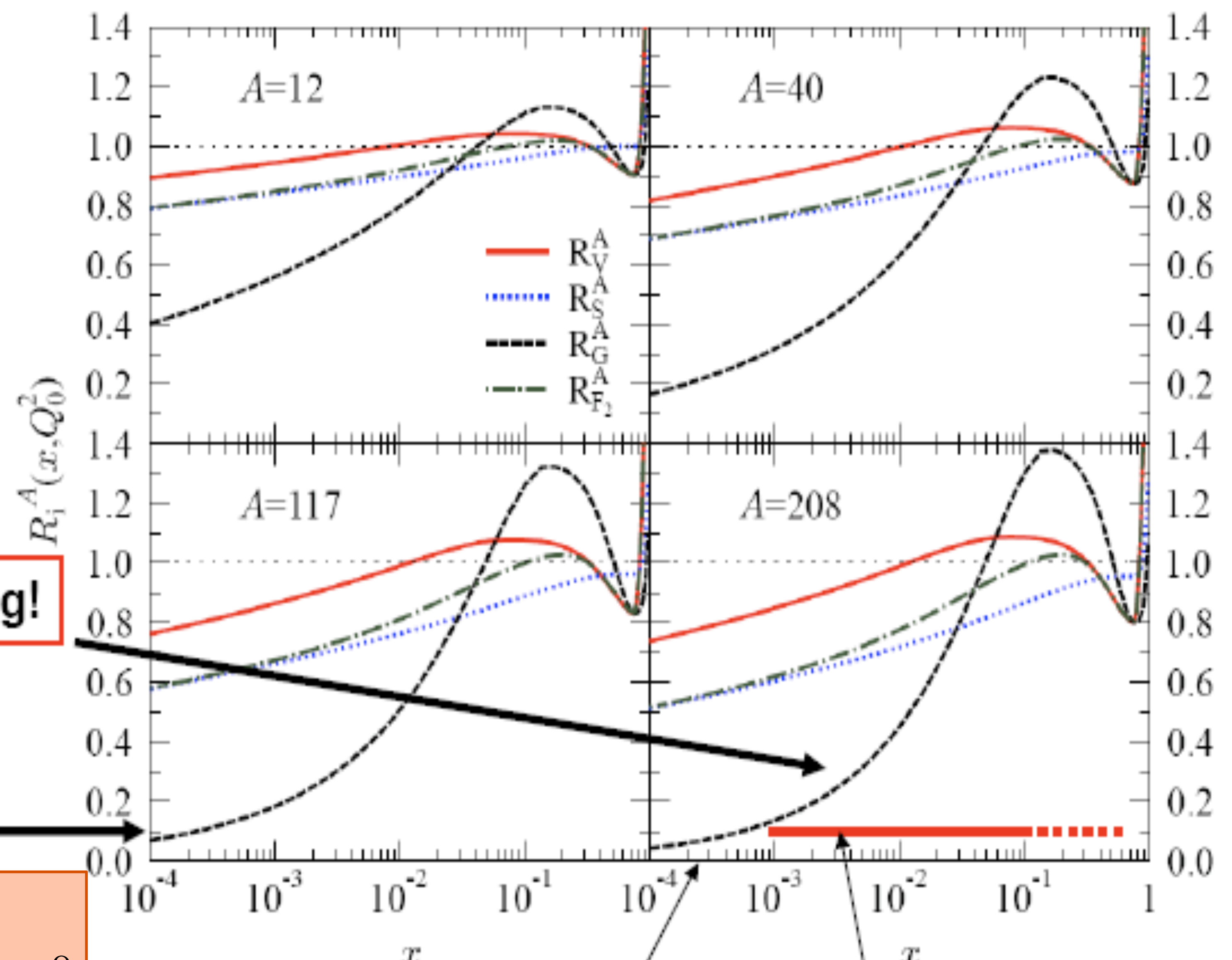


CERN Yellow Book – hep-ph/0308248

Latest gluon distribution of a large nucleus

- **EPS08** *(fit DIS-DY-RHIC data)*

Eskola, et al. 0802.0139 (hep-ph), JHEP 2008



Strong gluon shadowing!

assume no saturation of shadowing

$g(x,Q_0) \sim x^{-d}$

$R_G(x \to 0) \sim x^{-d_A}/x^{-d_p} \to 0$

$0 < d_A < d_p$

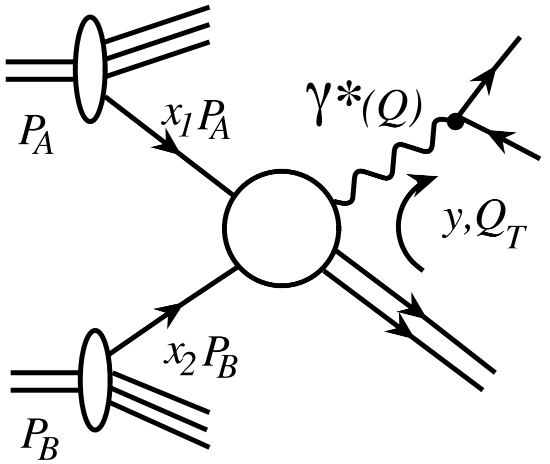
Unconstrained region

Constrained region

Low mass lepton pair production

Process:

$$Q_T \sim Q$$



QCD Factorization:

$$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy} = \left(\frac{\alpha_{\rm em}}{3\pi Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

$$\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy} = \sum_{a,b}\int dx_1 f_a^A(x_1,\mu)\int dx_2 f_b^B(x_2,\mu)\,\frac{d\hat{\sigma}^{\rm Pert}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}(x_1,x_2,Q,Q_T,y;\mu)$$

Dominated by Compton subprocess

Power series of α_s

Low mass lepton pair at high Q_T

- If $Q_T \gg Q \gg \Lambda_{QCD}$:

Berger, Qiu, Zhang, PRD64, 2001

Perturbative hard part has large logarithm: $\ln\left(Q^2/Q_T^2\right)$

Resummation of the large logarithms
= re-organization of the perturbative hard part:

All logarithms

$$\frac{d\hat{\sigma}^{\rm Pert}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy} = \frac{d\hat{\sigma}^{\rm Dir}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy} + \frac{d\hat{\sigma}^{\rm Asym}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

Short-distance + power

$$\frac{d\hat{\sigma}_{ab\to cX}}{dp_{c_T}^2\,dy} \otimes D_{c\to\gamma^* X}$$

Perturbative

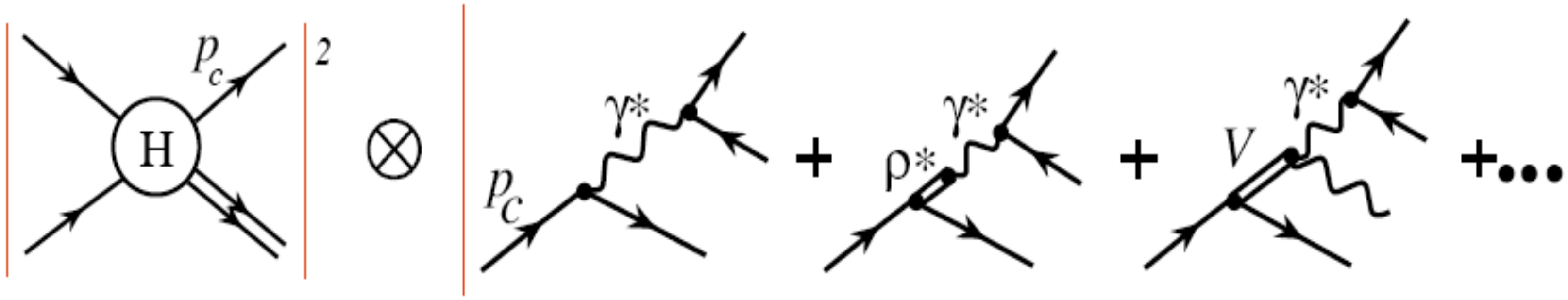
- If $Q_T \gg Q \gtrsim \Lambda_{QCD}$:

Q_T is the perturbative scale, but, Q is not!

QCD factorization is still valid, except the fragmentation function now involves non-perturbative physics

Non-perturbative fragmentation function

- **Factorization:**



- **Fragmentation function:**

$$D_{f\to\ell^+\ell^-(Q)}(z,\mu_0^2;Q^2) = \left(\frac{\alpha_{\rm em}}{3\pi Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)D_{f\to\gamma^*}(z,\mu_0^2;Q^2)$$

- **Same evolution - perturbative kernel:**

$$\begin{aligned}\mu_F^2\frac{d}{d\mu_F^2}D_{c\to\gamma^*}(z,\mu_F^2;Q^2) &= \left(\frac{\alpha_{\rm em}}{2\pi}\right)\gamma_{c\to\gamma^*}(z,\mu_F^2,\alpha_s;Q^2)\\ &+ \left(\frac{\alpha_s}{2\pi}\right)\sum_d\int_z^1\frac{dz'}{z'}P_{c\to d}(\frac{z}{z'},\alpha_s)\,D_{d\to\gamma^*}(z',\mu_F^2;Q^2)\end{aligned}$$

- **Input fragmentation function:**

$$D_{f\to\gamma^*}(z,\mu_0^2;Q^2)\equiv D_{f\to\gamma^*}^{\rm QED}(z,\mu_0^2;Q^2)+D_{f\to\gamma^*}^{\rm NonPert}(z,\mu_0^2;Q^2)$$

Model the input fragmentation function

QED part:

$$D^{\mathrm{QED}(0)}_{q\to\gamma^*}(z,\mu_0^2;Q^2) = e_q^2\left(\frac{\alpha_{\mathrm{em}}}{2\pi}\right)\left[\left(\frac{1+(1-z)^2}{z}\right)\ln\left(\frac{z\mu_0^2}{Q^2}\right) - z\left(1-\frac{Q^2}{z\mu_0^2}\right)\right],$$

$$D^{\mathrm{QED}(0)}_{\bar{q}\to\gamma^*}(z,\mu_0^2;Q^2) = D^{\mathrm{QED}(0)}_{q\to\gamma^*}(z,\mu_0^2;Q^2),$$

$$D^{\mathrm{QED}(0)}_{g\to\gamma^*}(z,\mu_0^2;Q^2) = 0$$

Non-perturbative part (need to be fixed by the data)

Assumption: $$\frac{D^{\mathrm{NonPert}}_{f\to\gamma}(z,\mu_0^2;Q^2)}{D_{f\to V}(z,\mu_0^2)} \propto \frac{e^2}{f_V^2} = \frac{4\pi\alpha_{\mathrm{em}}}{f_V^2}$$

$$\longrightarrow \quad D^{\mathrm{NonPert}}_{q\to\gamma^*}(z,\mu_0^2;Q^2) \propto D_{q\to V}(z,\mu_0^2)\,\frac{4\pi\alpha_{\mathrm{em}}}{f_V^2}\,|F(Q^2)|^2\left(1-\frac{Q^2}{m_V^2}\right)^3$$

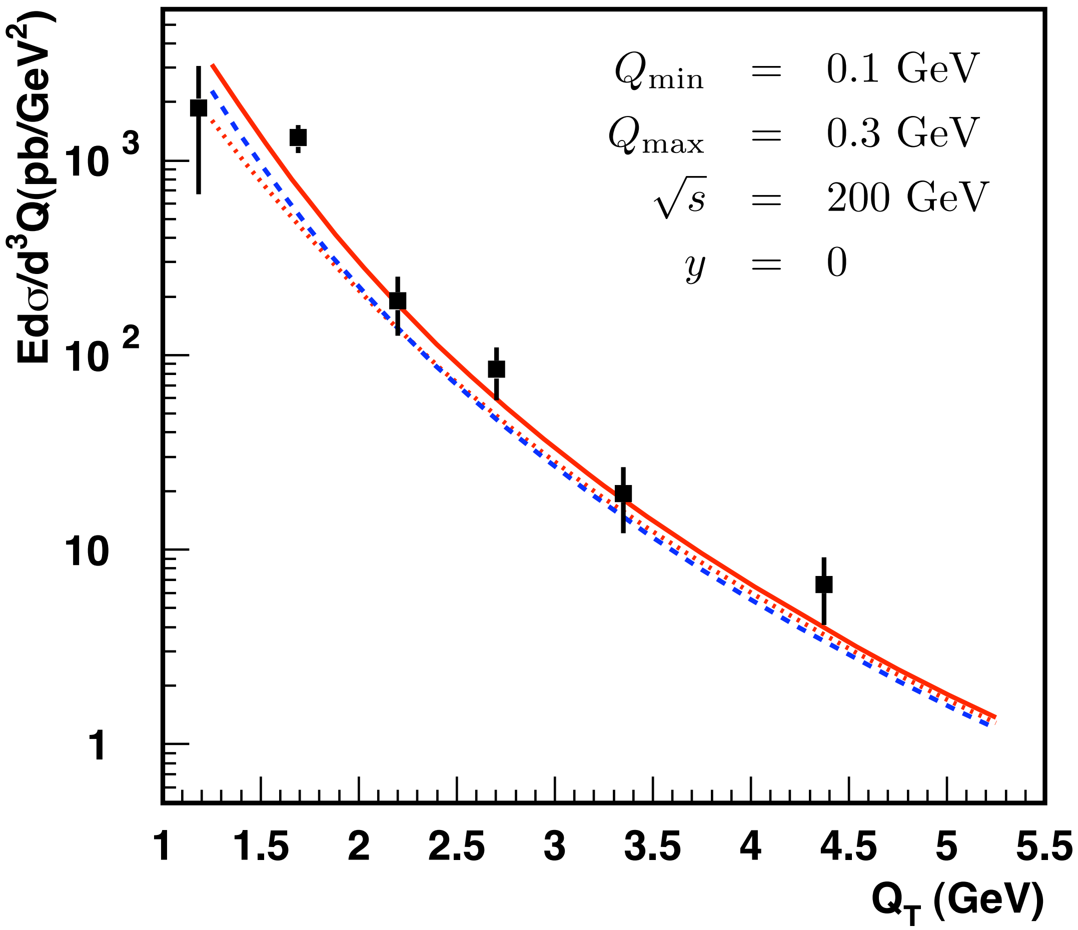
Model: $$D^{\mathrm{NonPert}}_{q\to\gamma^*}(z,\mu_0^2;Q^2) \equiv \kappa\, D_{q\to V}(z,\mu_0^2)\,\frac{4\pi\alpha_{\mathrm{em}}}{f_V^2}\left(1-\frac{Q^2}{m_V^2}\right)^3$$

$$D_{f\to V}\approx D_{f\to\pi} \qquad f_\rho^2/4\pi = 2.2 \qquad m_V = m_\rho$$

One fitting constant: κ

Invariant cross section

- **Defintion:** $$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \equiv \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2\,\frac{1}{\pi}\,\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy}$$
- **Role of non-perturbative fragmentation function:**



Data from PHENIX: arXiv:0804.4168

❖ **QED Input FF:**

$\kappa = 0$ **at** $\mu_0 = 1$ GeV

❖ **QED + NonPert Input:**

$\kappa = 1$ **at** $\mu_0 = 1$ GeV

Hadronic component of fragmentation is very important at low Q_T

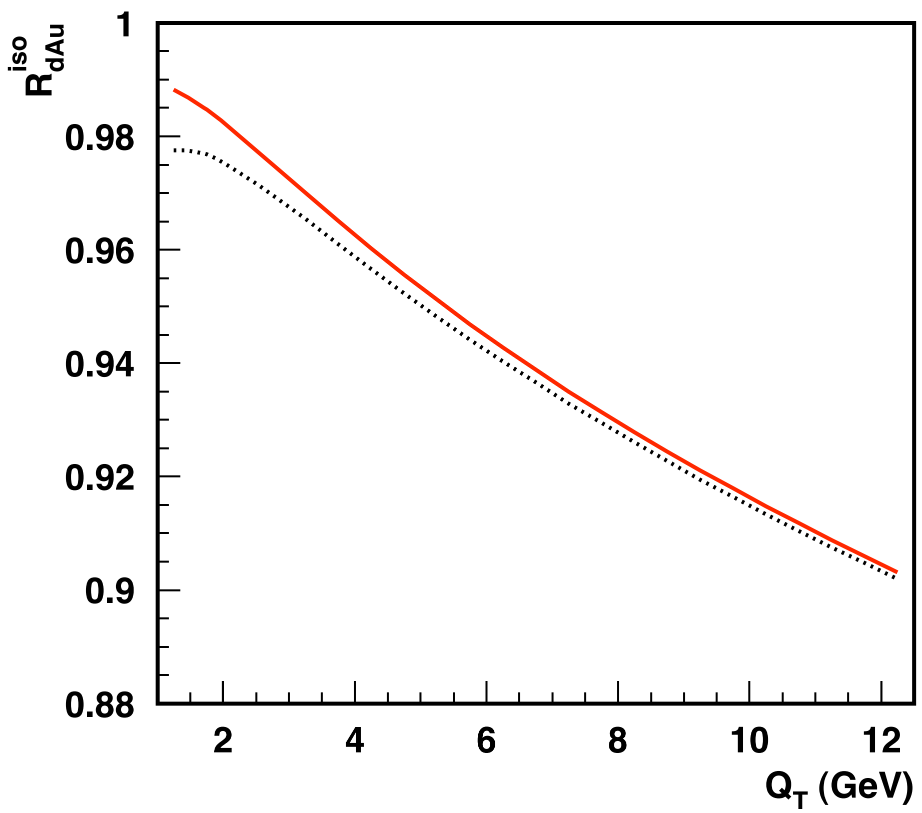
Isospin effect in nuclear collisions

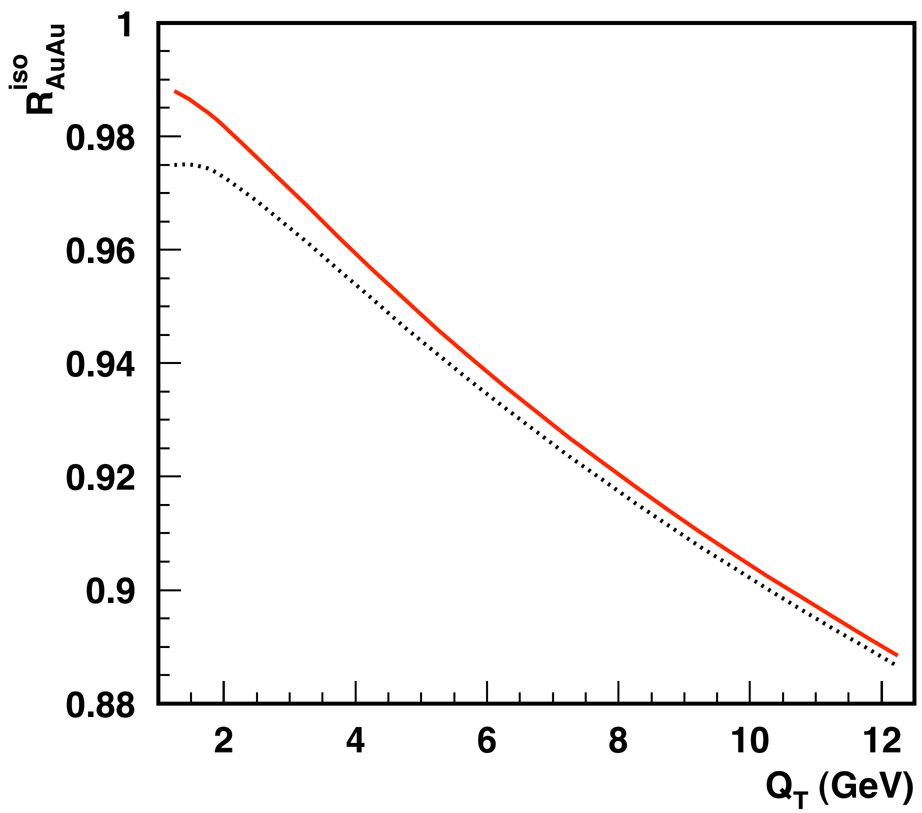
□ Defintion:

$$R^{iso}_{dAu} \equiv \frac{\frac{1}{2A} d^2\sigma^{dAu}/dQ_T dy}{d^2\sigma^{pp}/dQ_T dy}$$

$$f_i^p(x,Q^2) \to F_i(x,Q^2) = \left[Z \cdot f_i^p + (A-Z)\cdot f_i^n\right]/A \qquad i = q, \bar{q}, g$$

□ Strong isospin effect:





$$\sigma_{qg} \propto \frac{4}{9} f_u^n + \frac{1}{9} f_d^n = \frac{4}{9} f_d^p + \frac{1}{9} f_u^p \qquad f_u^p > f_d^p$$

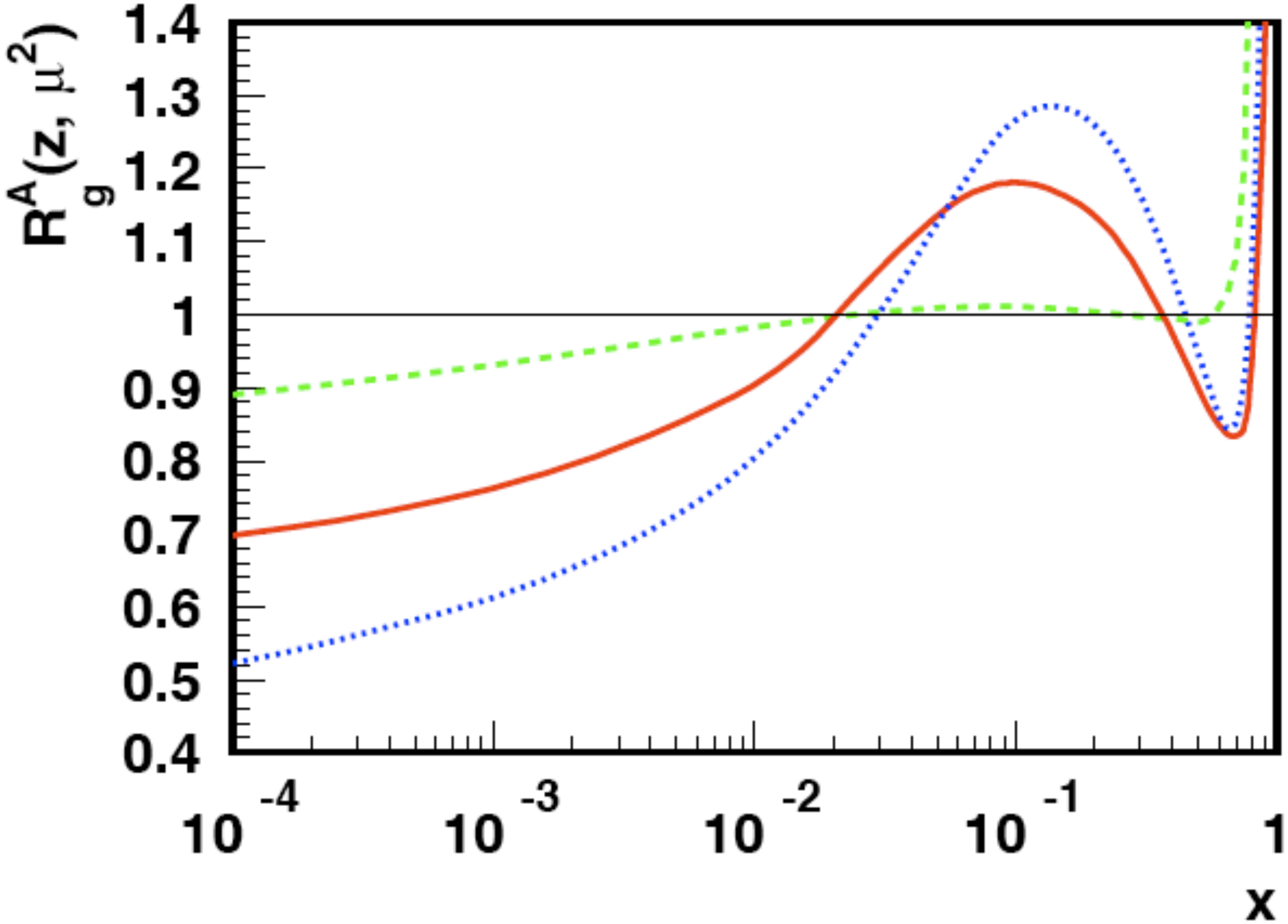
$$\Rightarrow \quad \sigma^{nn} < \sigma^{np} = \sigma^{pn} < \sigma^{pp} \quad \Rightarrow \quad R^{iso}_{AB} < 1$$

Nuclear parton distributions

- **Nuclear PDFs:**

$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2) f_i^p(x,Q^2)$$

- **Sample nuclear gluon distribution:**



Solid: EKS98

Dotted: EPS08

Dashed: FS2003

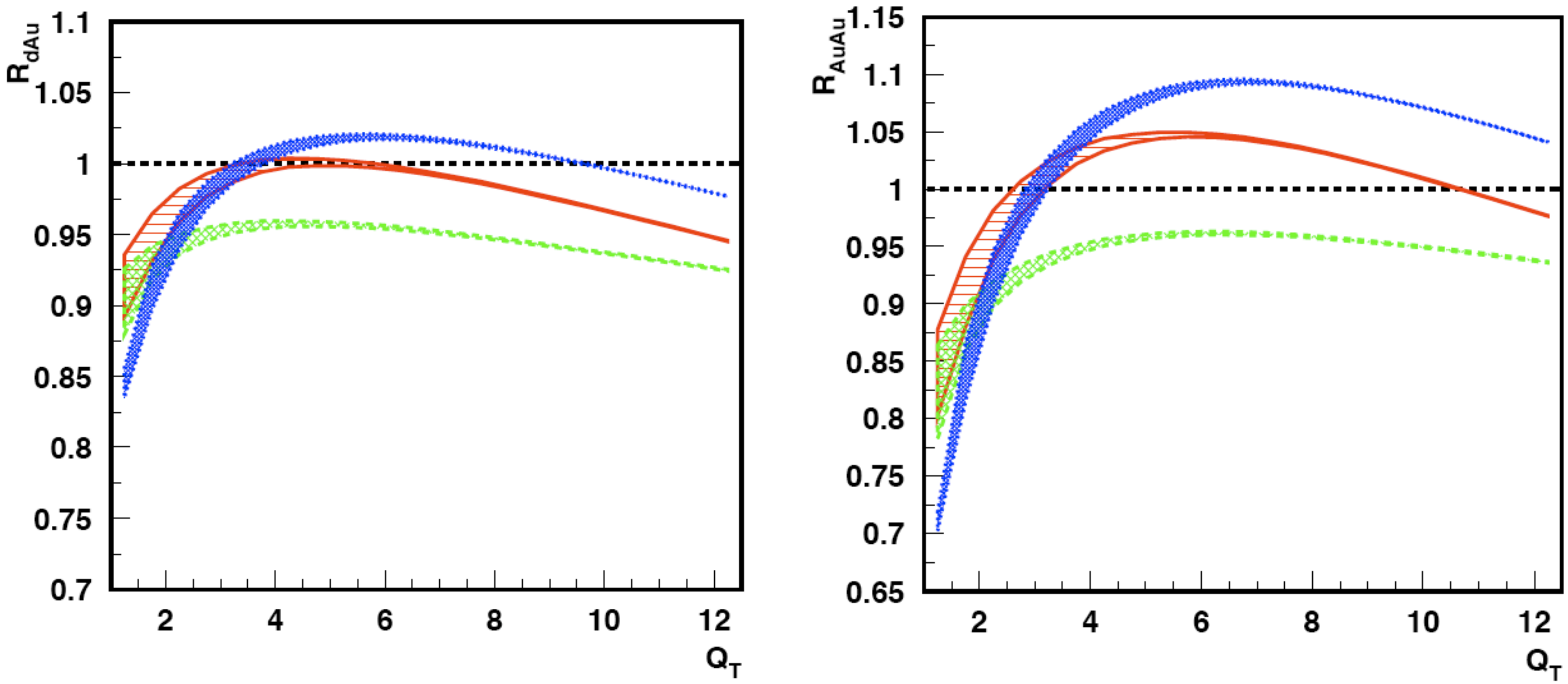
All nPDFs fit existing data!

Sensitivity on gluon distribution

- **Nuclear modification factor:**

$$R_{dAu} \equiv \frac{1}{\langle N_{coll}\rangle}\frac{d^2N^{dAu}/dQ_T dy}{d^2N^{pp}/dQ_T dy} \overset{\text{min.bias}}{=} \frac{\frac{1}{2A}d^2\sigma^{dAu}/dQ_T dy}{d^2\sigma^{pp}/dQ_T dy}$$

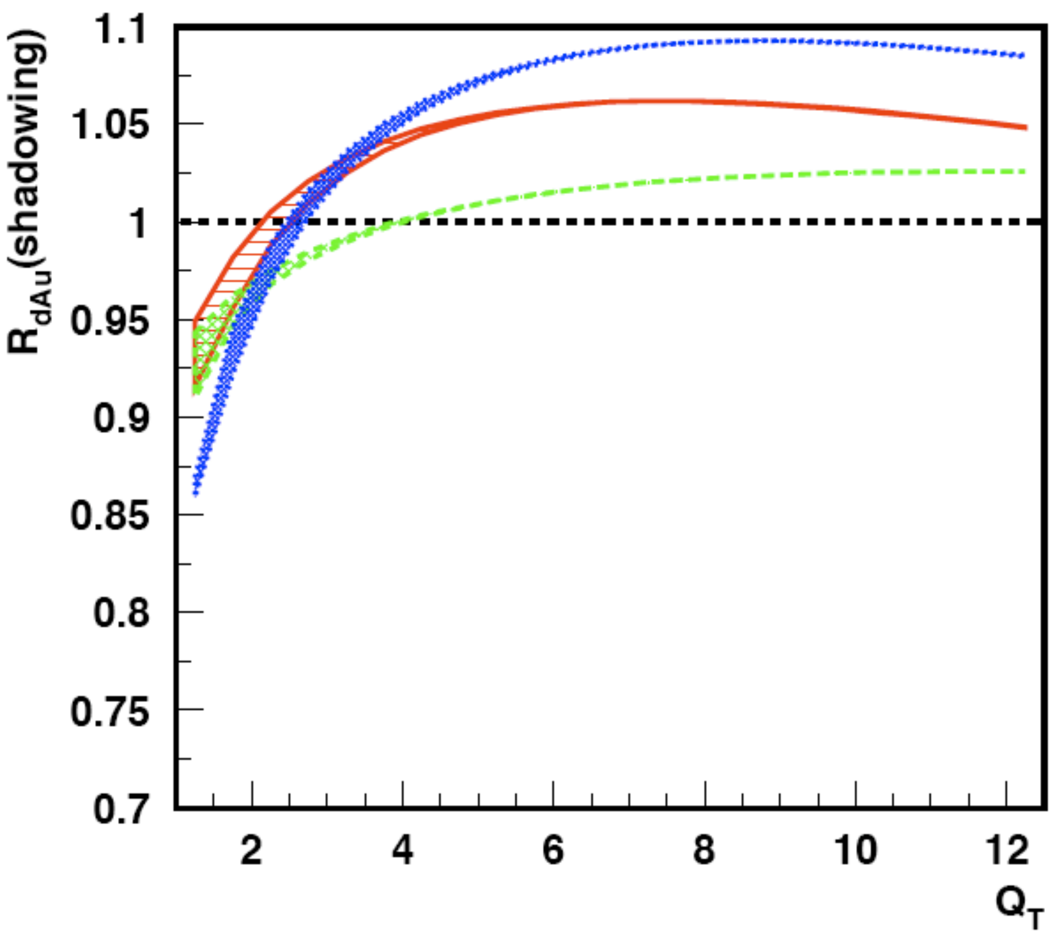
- **Prediction for RHIC kinematics:**

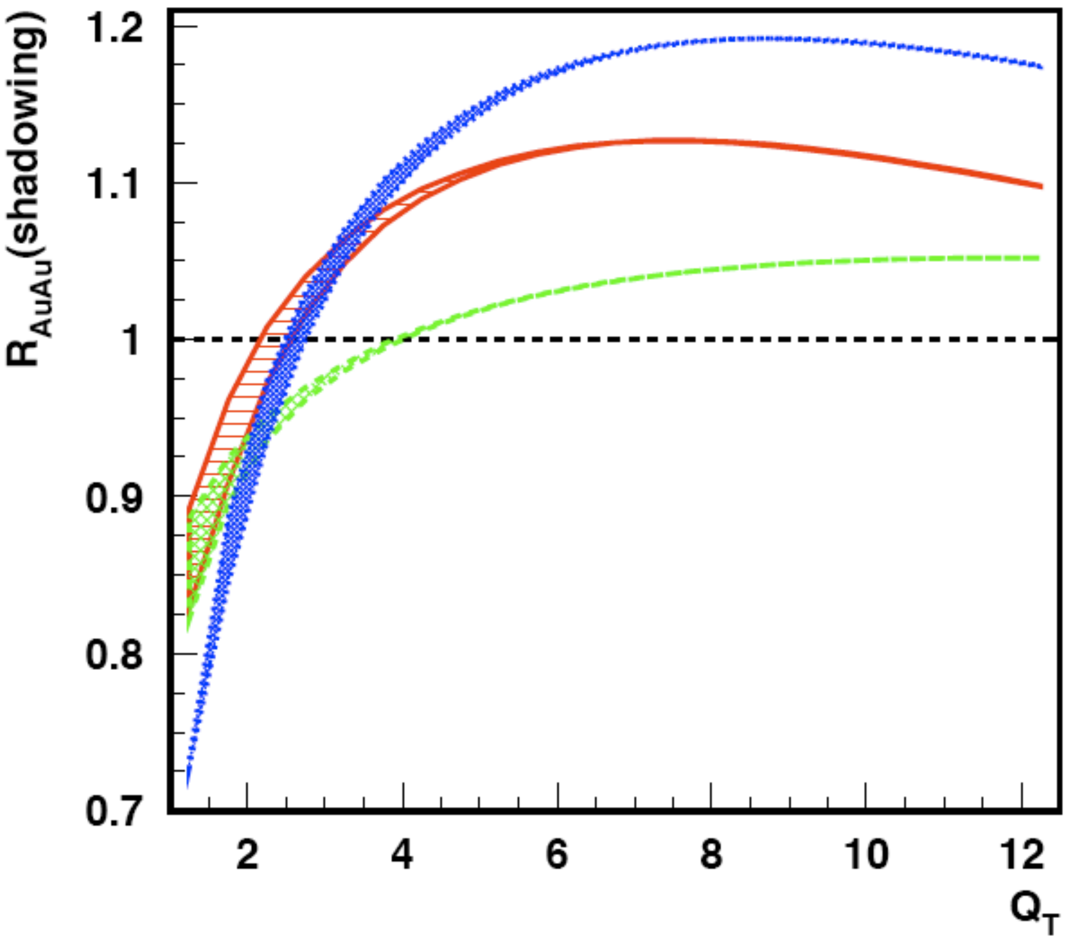


The band is given by κ=1 (top lines) and κ=0 (bottom lines)

Pure shadowing effect

☐ **Remove isospin effect - "pure" shadowing effect:**

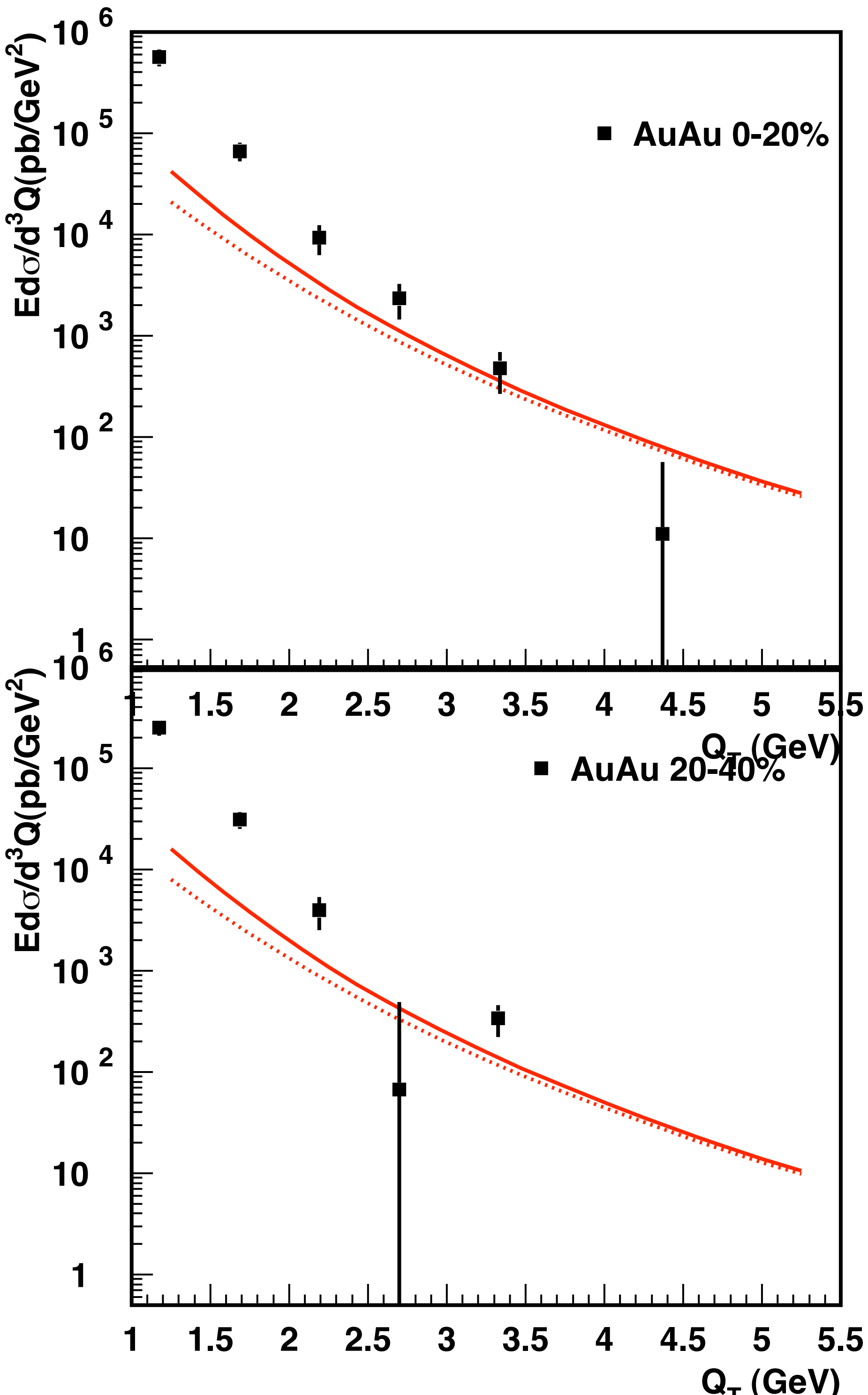


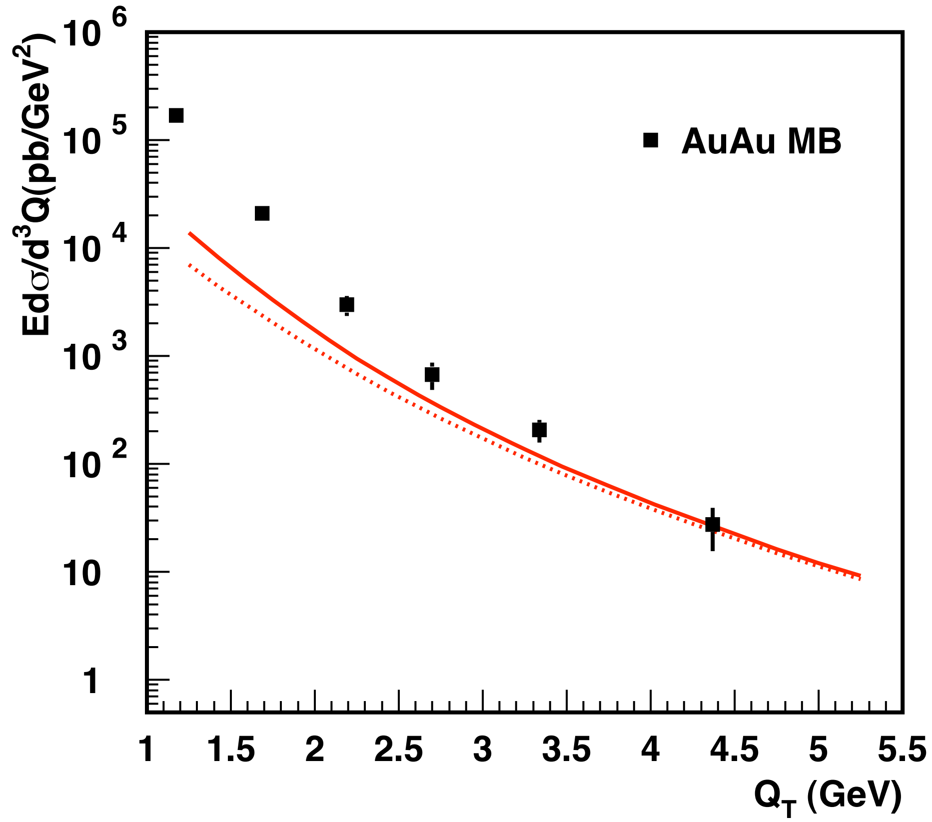


- ✧ **Isospin effect for nuclear modification factor R is very important**
- ✧ **Q_T dependence is very sensitive to the shape of gluon distribution**

Comparison to AuAu data

☐ Enhancement at low Q_T:





❖ **Effects other than shadowing:**
parton multiple scattering
thermal radiation

Summary

- Low mass lepton pair production at large transverse momentum is perturbatively calculable

  Its factorization is equally good as that for prompt photon production

- Low mass lepton pair production is complementary to prompt photon production in getting information on gluon distribution

  cleaner lepton signals, no complication on isolation cut

  but, relatively lower rate