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**Perturbative origin of azimuthal anisotropy in nuclear collisions.**

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# Perturbative origin of azimuthal anisotropy in nuclear collisions

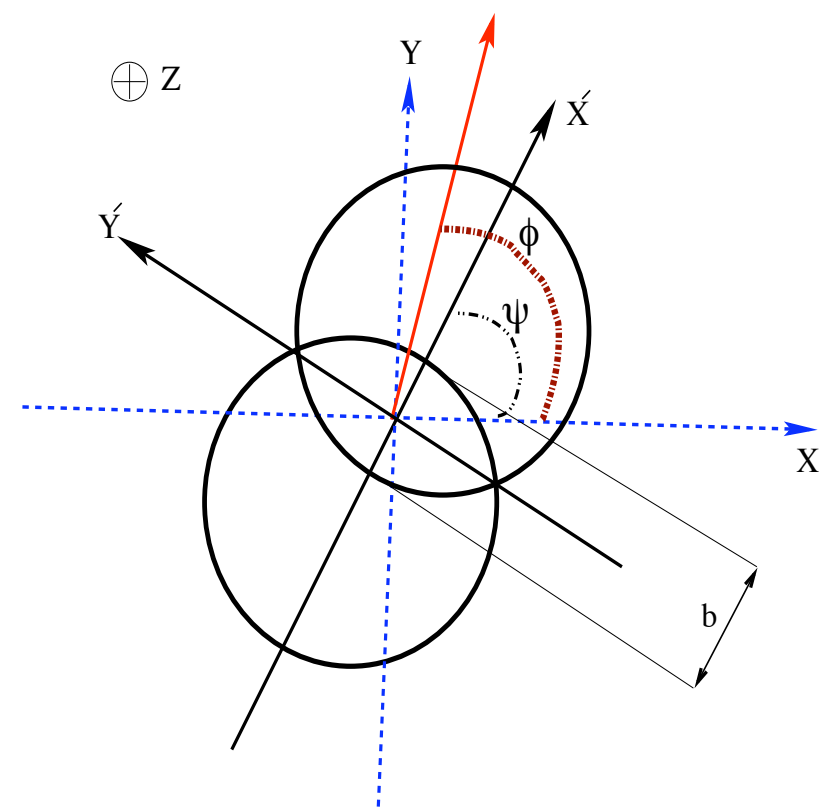
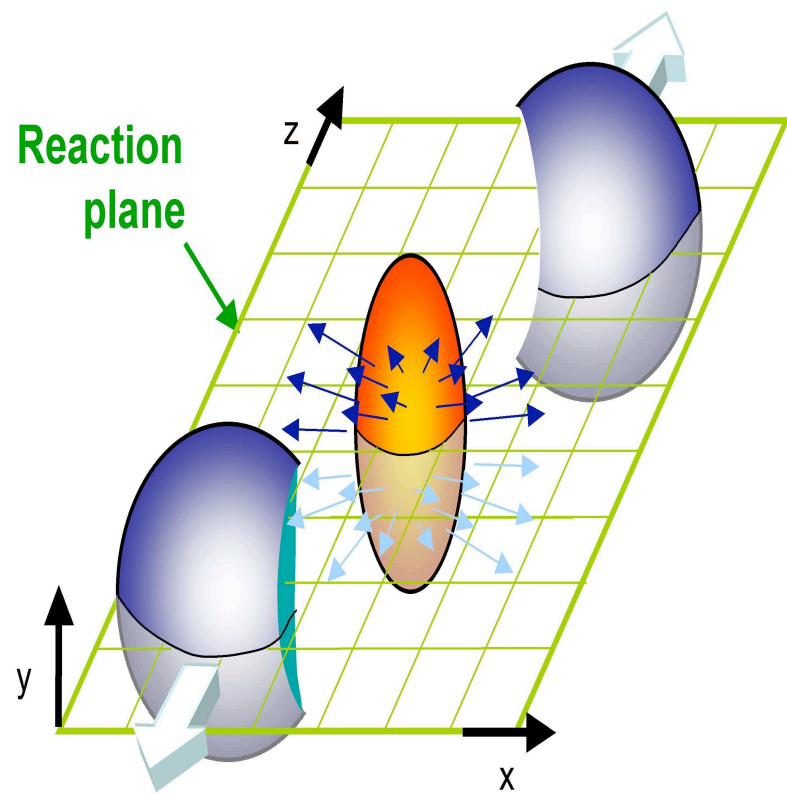
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ICTP 2008

# Non-central heavy-ion collisions and elliptic flow

Observables will become azimuthally dependent if they are sensitive to the density and size of system → A good test of many features of QGP



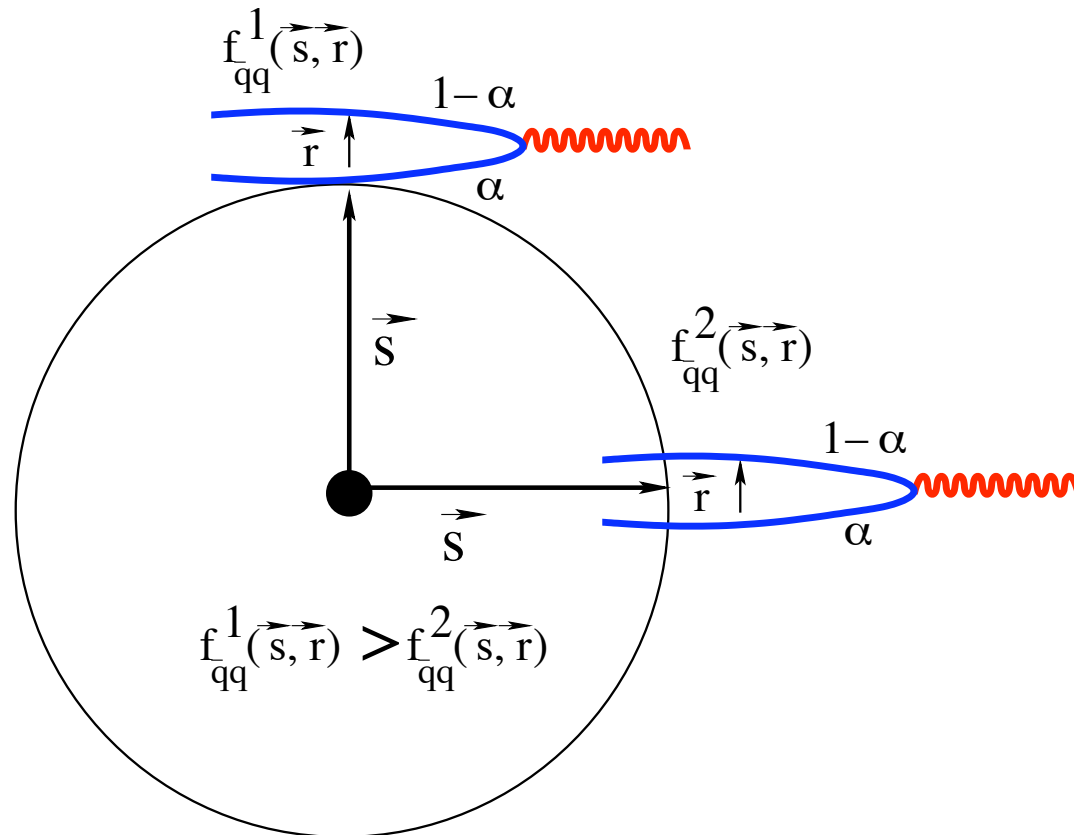
- $E \frac{d^3 N^i}{d^3 p_T} = \frac{1}{2\pi} \frac{d^2 N^i}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n^i \cos(n(\phi - \psi)) \right)$
- $v_2 = \langle \cos(2(\phi - \psi)) \rangle$        $\phi = \tan^{-1} p_y / p_x$

# Outstanding questions yet at RHIC:

Which microscopic interaction mechanism is responsible for the large observed elliptic flow?

- 1: What is the origin of Fast thermalization.
- 2: Why Hydrodynamics with  $\eta = 0$ .
- 3: Initial conditions for Hydro ( $\tau, T, s$ ) are yet to be understood.
- 4: Elliptic flow at non-zero rapidity and for more peripheral need to be described.
  - Hydrodynamics breakdown for more peripheral collisions.
  - Do longitudinal boost invariance and local thermal equilibrium breakdown away from **midrapidity**?
- 5: What is the fate of elliptic flow at high  $p_T$ .
- 6: Need to understand scaling properties of azimuthal anisotropy: mass ordering, eccentricity scaling, valence quark number scaling (**where are gluons?**)...
- 7:  $v_2$  for direct photon.

# Azimuthal asymmetry and color dipole orientation



- **The main idea:** An azimuthal asymmetry appears due to dependence of the interaction of a dipole on its orientation.

# Azimuthal asymmetry and dipole orientation

## A toy model: two-gluon exchange

An azimuthal asymmetry appears due to dependence of the interaction of a dipole on its orientation.

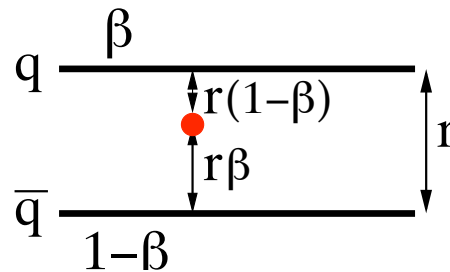
$$\begin{aligned}\text{Im}f_{\bar{q}q}^q(\vec{s}, \vec{r}) &= \frac{2}{9\pi^2} \int \frac{d^2q d^2q' \alpha_s(q^2)\alpha_s(q'^2)}{(q^2 + \mu^2)(q'^2 + \mu^2)} \\ &\times \left[ e^{i\vec{q}\cdot(\vec{s}+\vec{r}/2)} - e^{i\vec{q}\cdot(\vec{s}-\vec{r}/2)} \right] \left[ e^{i\vec{q}'\cdot(\vec{s}+\vec{r}/2)} - e^{i\vec{q}'\cdot(\vec{s}-\vec{r}/2)} \right] \\ &= \frac{8\alpha_s^2}{9} \left[ K_0 \left( \mu \left| \vec{s} + \frac{\vec{r}}{2} \right| \right) - K_0 \left( \mu \left| \vec{s} - \frac{\vec{r}}{2} \right| \right) \right]^2\end{aligned}$$

This expression explicitly exposes a correlation between  $\vec{r}$  and  $\vec{s}$ : **the amplitude vanishes when  $\vec{s} \cdot \vec{r} = 0$ .**

Kopeliovich, Pirner, A.H.R., Schmidt, PRD **77**, 034011 (2008)

$$\text{Im}f_{\bar{q}q}^N(\vec{s}, \vec{r}, \beta) = \frac{1}{12\pi} \int \frac{d^2q d^2q'}{q^2 q'^2} \alpha_s \mathcal{F}(x, \vec{q}, \vec{q}') e^{i\vec{s} \cdot (\vec{q} - \vec{q}')} \\ \times \left( e^{-i\vec{q} \cdot \vec{r}\beta} - e^{i\vec{q} \cdot \vec{r}(1-\beta)} \right) \left( e^{i\vec{q}' \cdot \vec{r}\beta} - e^{-i\vec{q}' \cdot \vec{r}(1-\beta)} \right)$$

where  $\alpha_s = \sqrt{\alpha_s(q^2)\alpha_s(q'^2)}$



$$\mathcal{F}(x, q) = \mathcal{F}(x, \vec{q}, \vec{q} = \vec{q}').$$

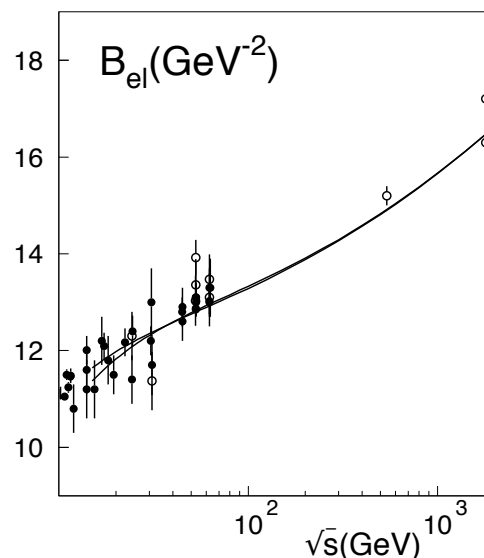
$$\sigma_{q\bar{q}}^N(r) = 2 \int d^2\vec{s} \text{Im}f_{q\bar{q}}^N(\vec{s}, \vec{r}) \\ = \frac{4\pi}{3} \int \frac{d^2q}{q^4} (1 - e^{-i\vec{q} \cdot \vec{r}}) \alpha_s(q^2) \mathcal{F}(x, q). \quad (1)$$

# Color dipole orientation

The forward slope of the differential cross section of dipole-nucleon scattering,

$$B_{el}^{(\bar{q}q)N}(r) = \frac{1}{\sigma_{\bar{q}q}^N(r)} \int d^2s s^2 \text{Im} f_{\bar{q}q}^N(\vec{s}, \vec{r}). \quad (2)$$

The slope for small-dipole-proton elastic scattering was measured in diffractive electroproduction of  $\rho$ -mesons at high  $Q^2$  at HERA. The measured slope,  $B_{el}^{(\bar{q}q)N}(r) \approx 5 \text{ GeV}^{-2}$ , agrees with the expected value  $B_{el}^{(\bar{q}q)N}(r) \approx B_{el}^{pp}/2$ .





# Color dipole orientation

Generalized unintegrated gluon density:

$$\alpha_s \mathcal{F}(x, \vec{q}, \vec{q}') = \frac{3\sigma_0}{16\pi^2} q^2 q'^2 R_0^2(x) e^{-\frac{1}{8} R_0^2(x)(q^2+q'^2)} e^{-\frac{1}{2} R_N^2(\vec{q}-\vec{q}')^2},$$

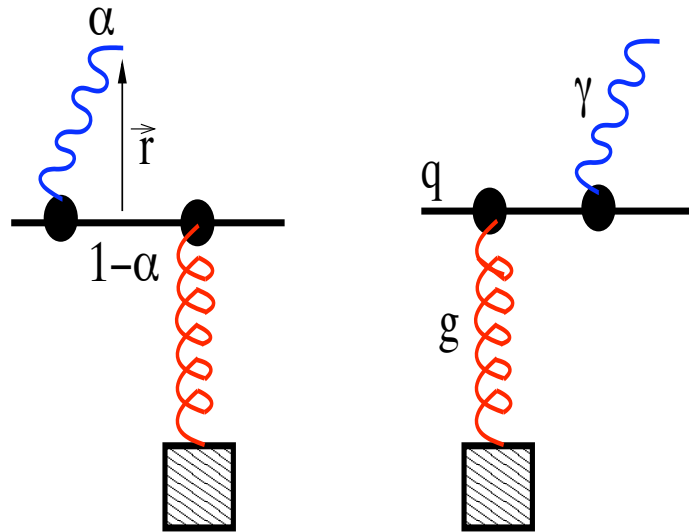
$\sigma_0 = 23.03$  mb,  $R_0(x) = 0.4 \text{ fm} \times (x/x_0)^{0.144}$  with  $x_0 = 3.04 \times 10^{-4}$

**Assumption:** The Pomeron-proton form factor  $F_{\mathbf{P}}^p(k_T^2) = \exp(-k_T^2 R_N^2/2)$ , so the slope of the  $pp$  elastic differential cross section is  $B_{el}^{pp} = 2R_N^2 + 2\alpha'_{\mathbf{P}} \ln(s/s_0)$ .

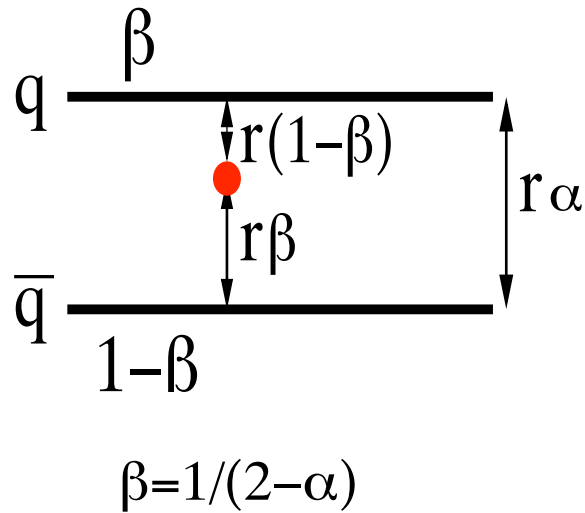
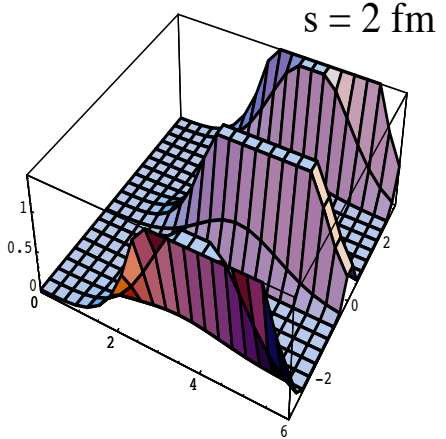
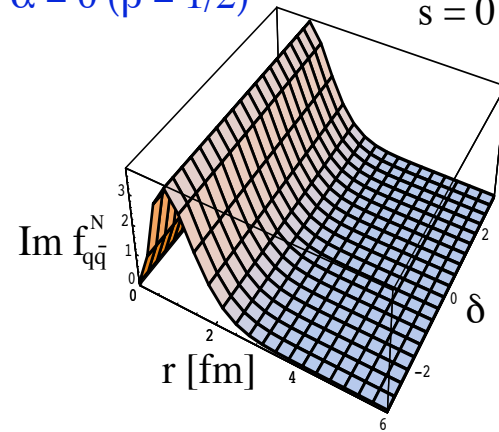
$$\begin{aligned} \text{Im} f_{\vec{q}q}^N(\vec{s}, \vec{r}, x, \beta) &= \frac{\sigma_0}{8\pi B_{el}} \left\{ \exp\left[-\frac{[\vec{s} + \vec{r}(1-\beta)]^2}{2B_{el}}\right] + \exp\left[-\frac{(\vec{s} - \vec{r}\beta)^2}{2B_{el}}\right] \right. \\ &\quad \left. - 2 \exp\left[-\frac{r^2}{R_0^2} - \frac{[\vec{s} + (1/2 - \beta)\vec{r}]^2}{2B_{el}}\right] \right\}, \end{aligned}$$

where we defined  $B_{el} = R_N^2 + R_0^2(x)/8$ .

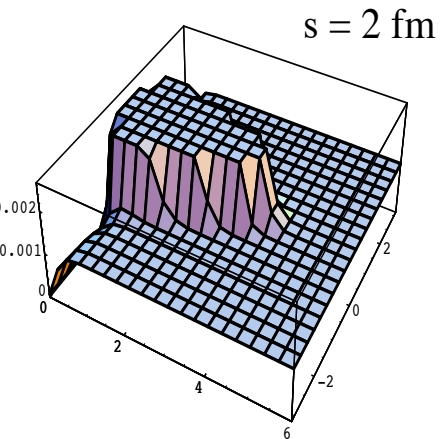
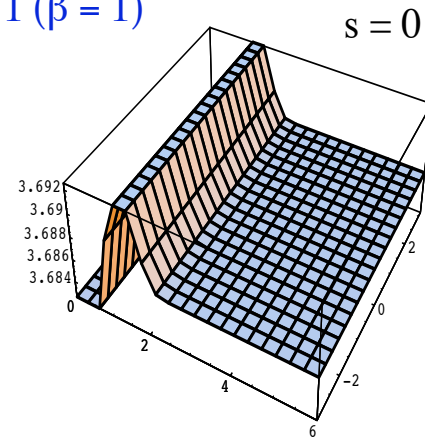
# Color dipole orientation



$\alpha = 0 (\beta = 1/2)$



$\alpha = 1 (\beta = 1)$



- The transverse momentum  $p_T$  distribution of photon bremsstrahlung from interaction of quark with a target  $t$  ( nucleon:  $t=N$ , nucleus  $t=A$ )  
Kopeliovich, A.H.R., Schmidt, arXiv:0712.2829, to appear in NPA

$$\frac{d\sigma^{qt \rightarrow \gamma X}(b, p, \alpha)}{d(\ln\alpha) d^2\vec{p}_T d^2\vec{b}} = \frac{1}{(2\pi)^2} \sum_{in,f} \int d^2\vec{r}_1 d^2\vec{r}_2 e^{i\vec{p}_T \cdot (\vec{r}_1 - \vec{r}_2)} \times \phi_{\gamma q}^*(\alpha, \vec{r}_1) \phi_{\gamma q}(\alpha, \vec{r}_2) F_t(\vec{b}, \alpha\vec{r}_1, \alpha\vec{r}_2, x),$$

where  $\alpha = p_\gamma^+ / p_q^+$  and  $F_t(\vec{b}, \alpha\vec{r}_1, \alpha\vec{r}_2, x)$  which is a linear combination of  $\bar{q}q$  dipole partial amplitudes on a target  $t$  at impact parameter  $\vec{b}$ ,

$$F_t(\vec{b}, \alpha\vec{r}_1, \alpha\vec{r}_2, x) = \text{Im}f_{q\bar{q}}^t(\vec{b}, \alpha\vec{r}_1, x) + \text{Im}f_{q\bar{q}}^t(\vec{b}, \alpha\vec{r}_2, x) - \text{Im}f_{q\bar{q}}^t(\vec{b}, \alpha(\vec{r}_1 - \vec{r}_2), x),$$

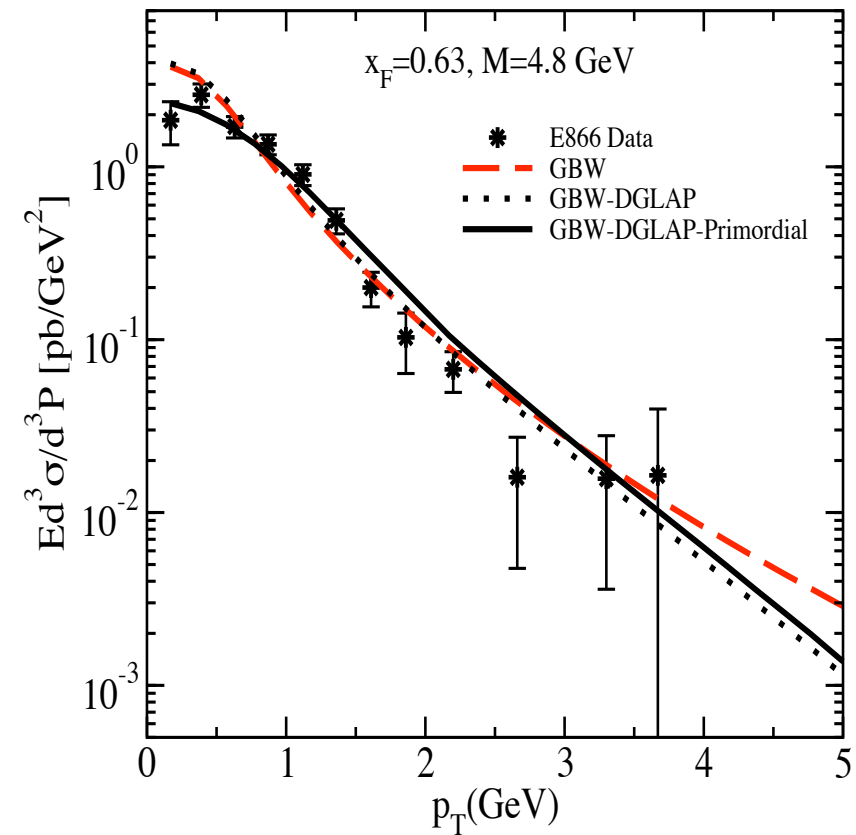
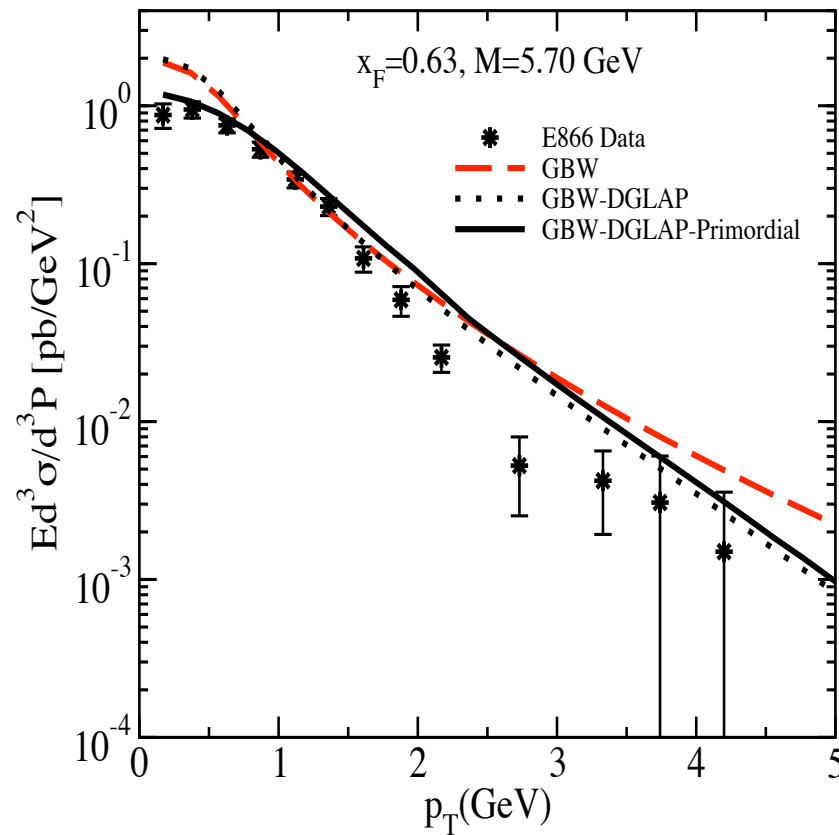
with

$$\text{Im}f_{q\bar{q}}^A(b, \vec{r}) = 1 - \exp\left[\int d^2\vec{s} \text{Im}f_{q\bar{q}}^N(\vec{s}, \vec{r}) T_A(\vec{b} + \vec{s})\right]$$

$$\sigma_{q\bar{q}}^N(r) = 2 \int d^2\vec{b} \text{Im}f_{q\bar{q}}^N(\vec{b}, \vec{r})$$

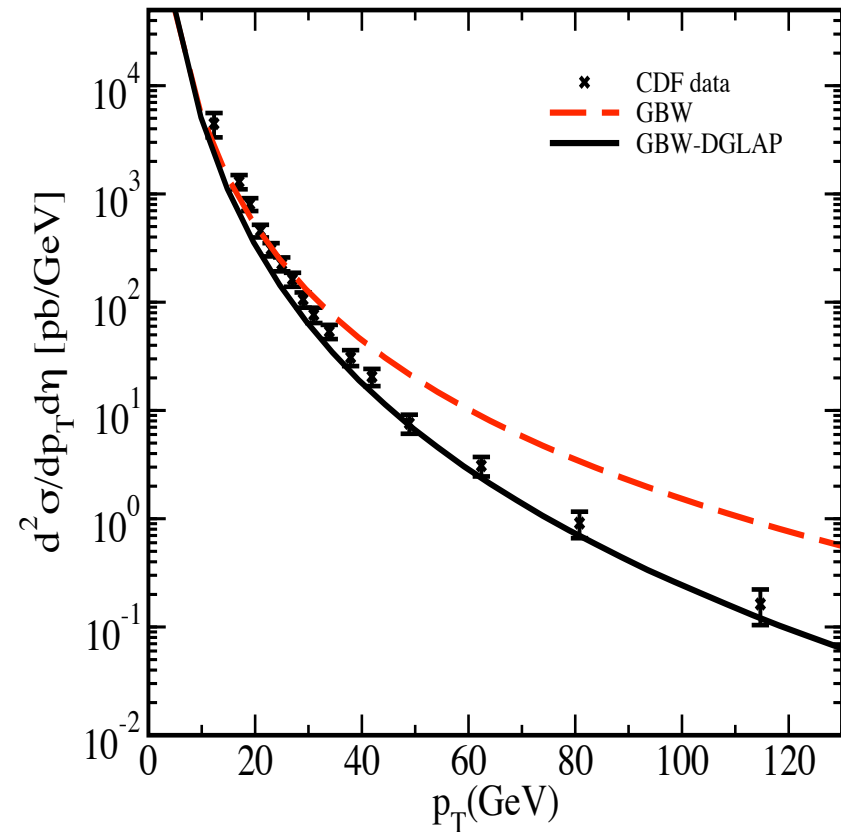
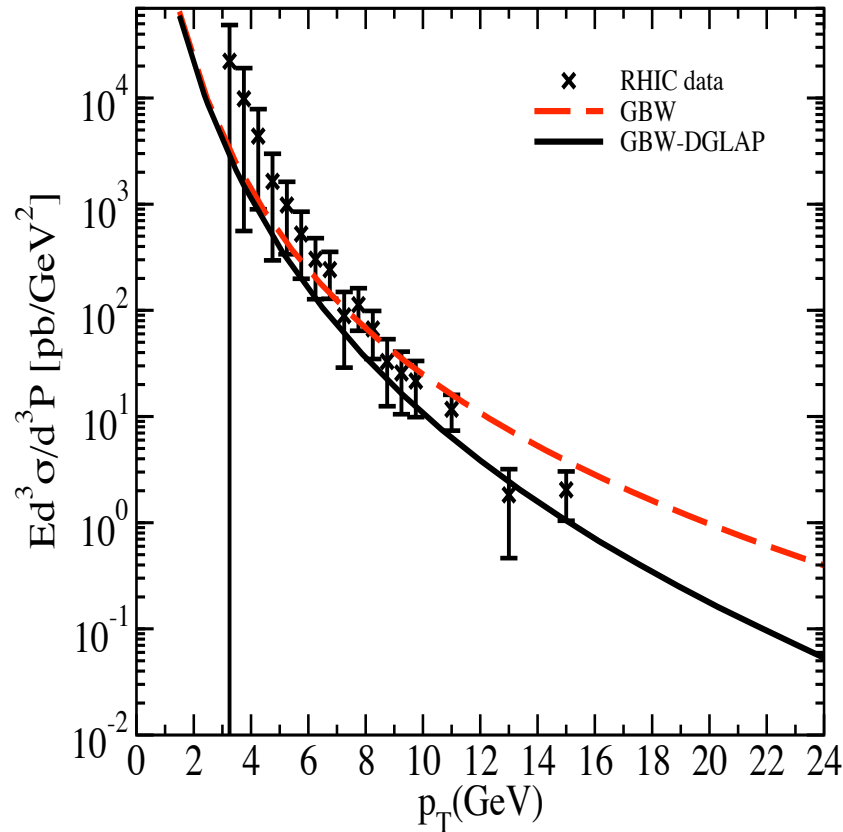
# Dilepton spectrum in 800– GeV $pp$

Kopeliovich, A.H.R, Pirner, Schmidt, PLB 653, 210 (2007)



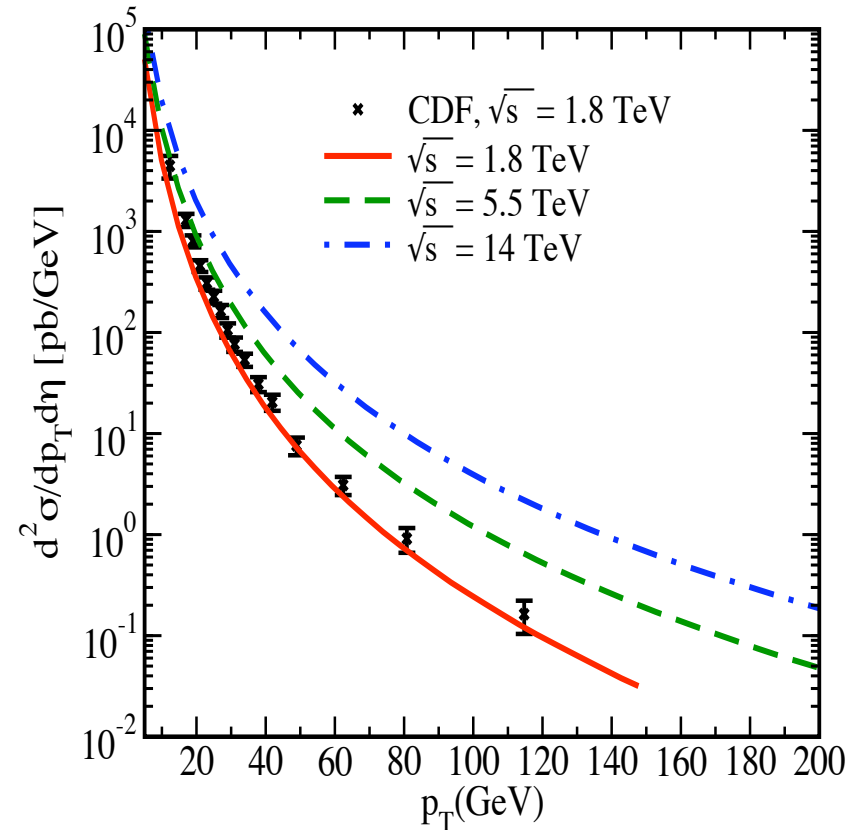
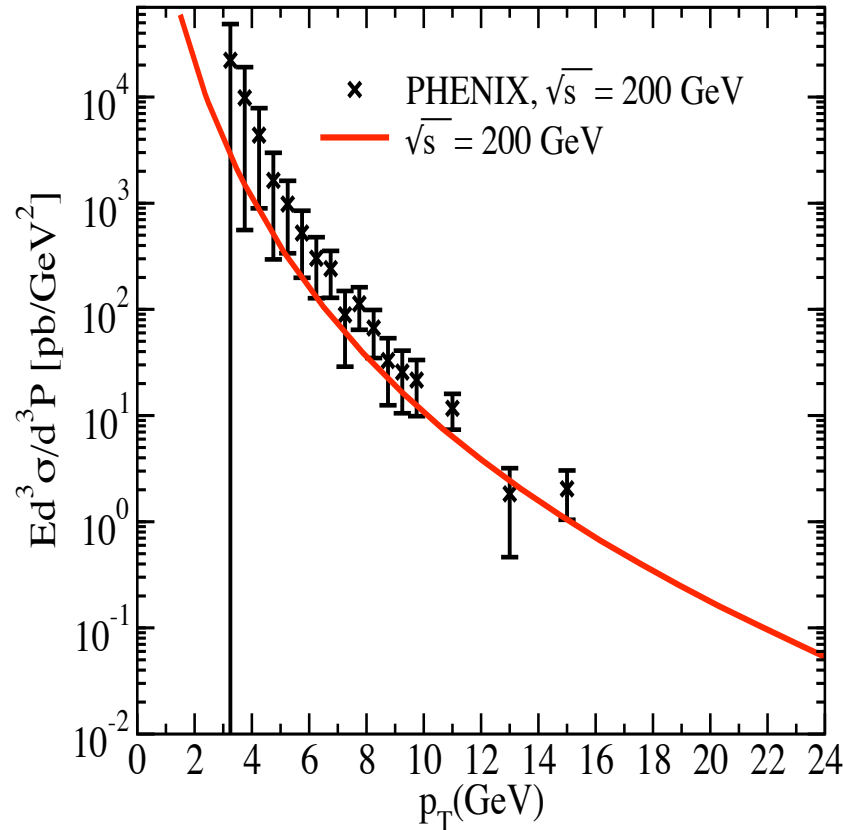
- constant primordial momentum  $\langle k_0^2 \rangle = 0.4 \text{ GeV}^2$  is incorporated within the GBW-DGLAP dipole model (solid line)

# Direct photon productions at RHIC and Tevatron for $pp$



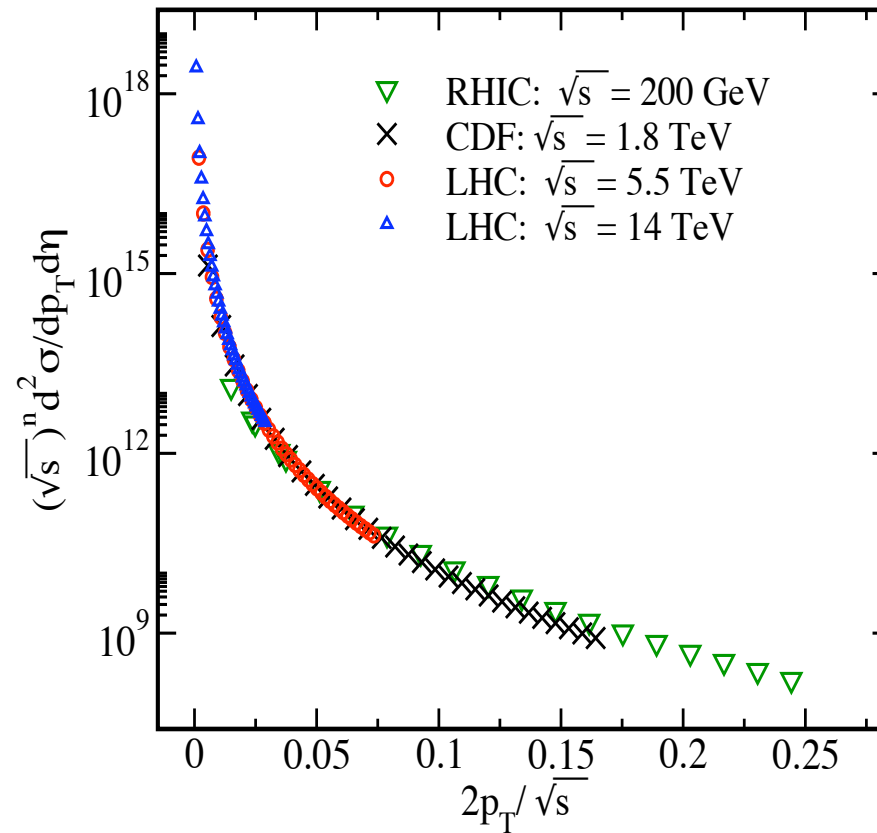
# Direct photon productions at RHIC and LHC

AHR *et al.* arXiv: 0707.2040



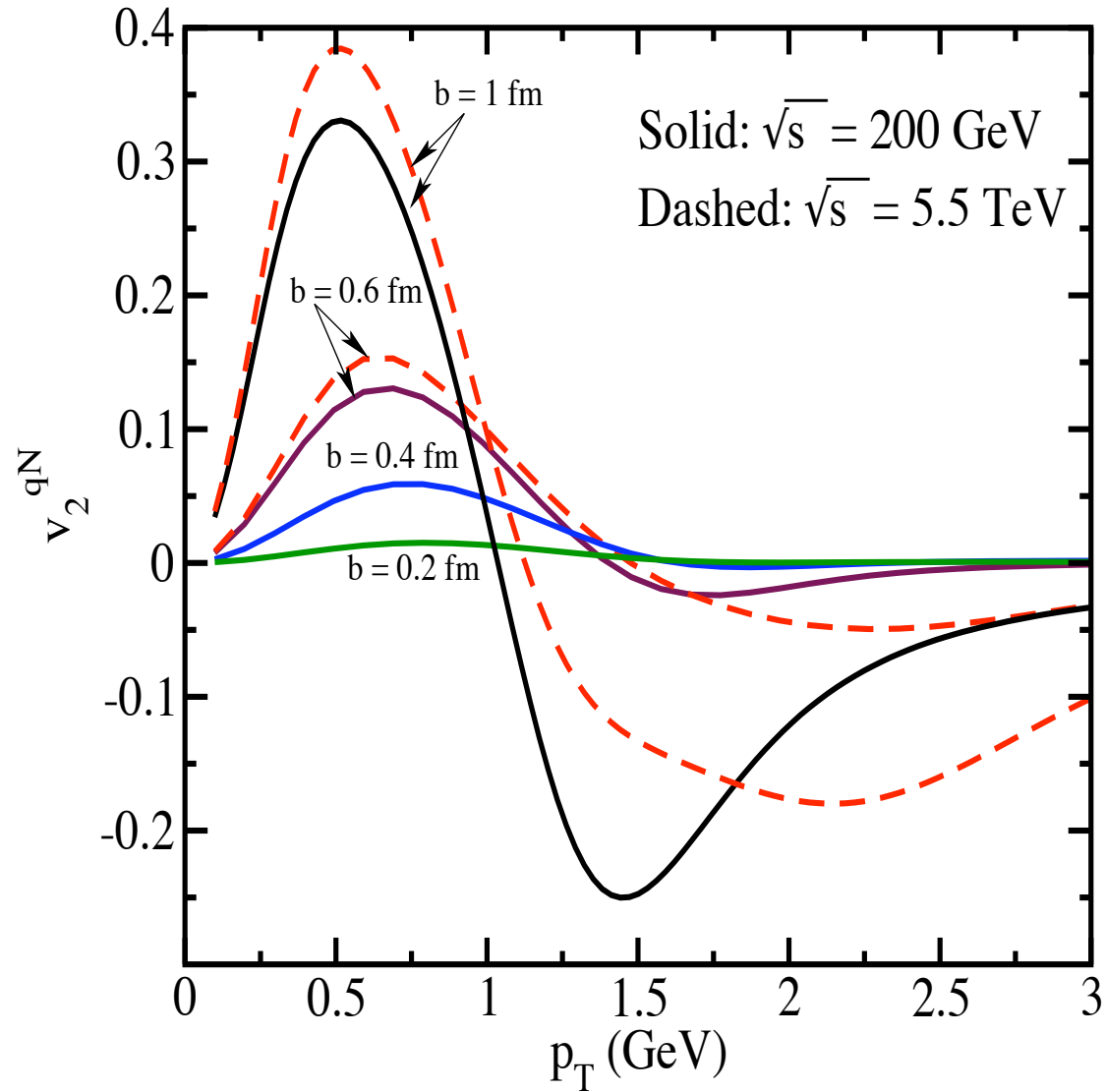
- Neither *K-factor*, nor *higher twist corrections*, no quark-to-photon fragmentation function are to be added.

# Direct photon productions and scaling



- $d^2\sigma/dp_T d\eta \approx (s/s_0)^{-n/2} F(x_T)$ , prediction:  $n=3.2$

# Direct photon $v_2$ for qN collisions

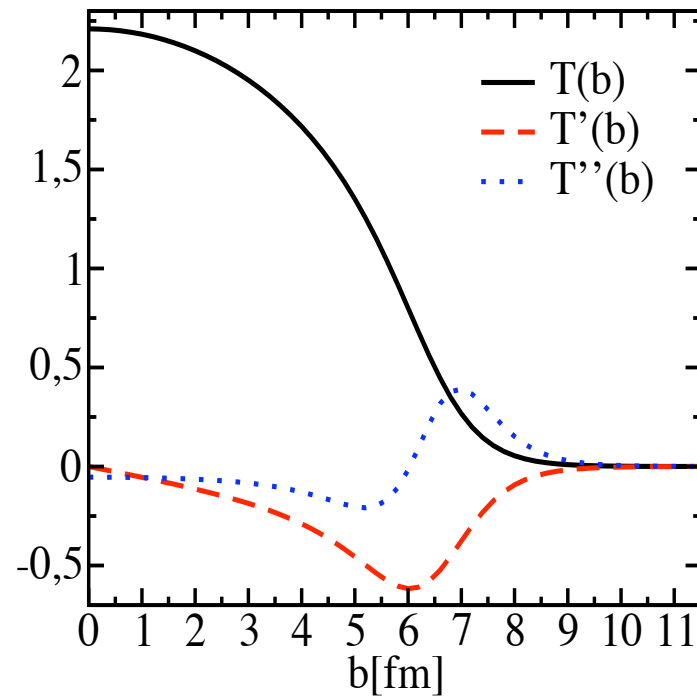




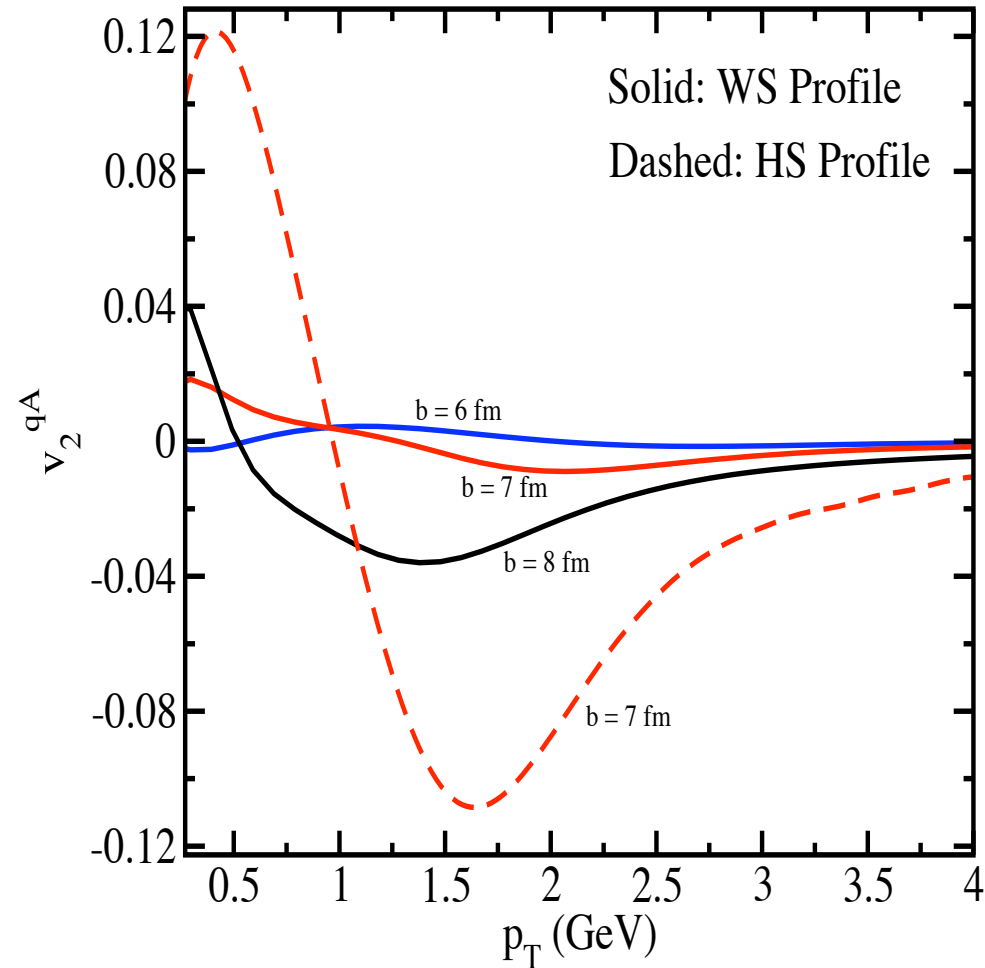
# Direct photon v2 for qA collisions

$$\text{Im}f_{q\bar{q}}^A(b, \vec{r}) = 1 - \exp\left[\int d^2\vec{s} \text{Im}f_{q\bar{q}}^N(\vec{s}, \vec{r}) T_A(\vec{b} + \vec{s})\right].$$

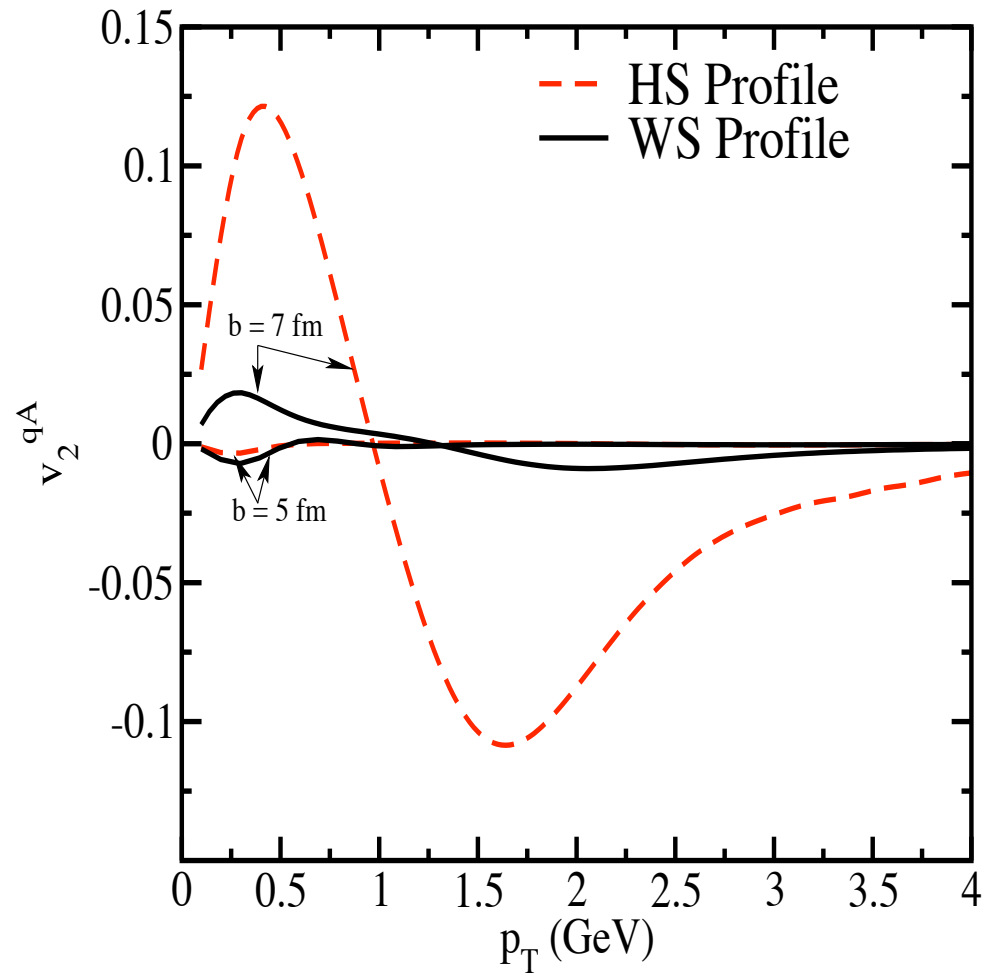
Sources of azimuthal anisotropy: rescatterings and shape of the system

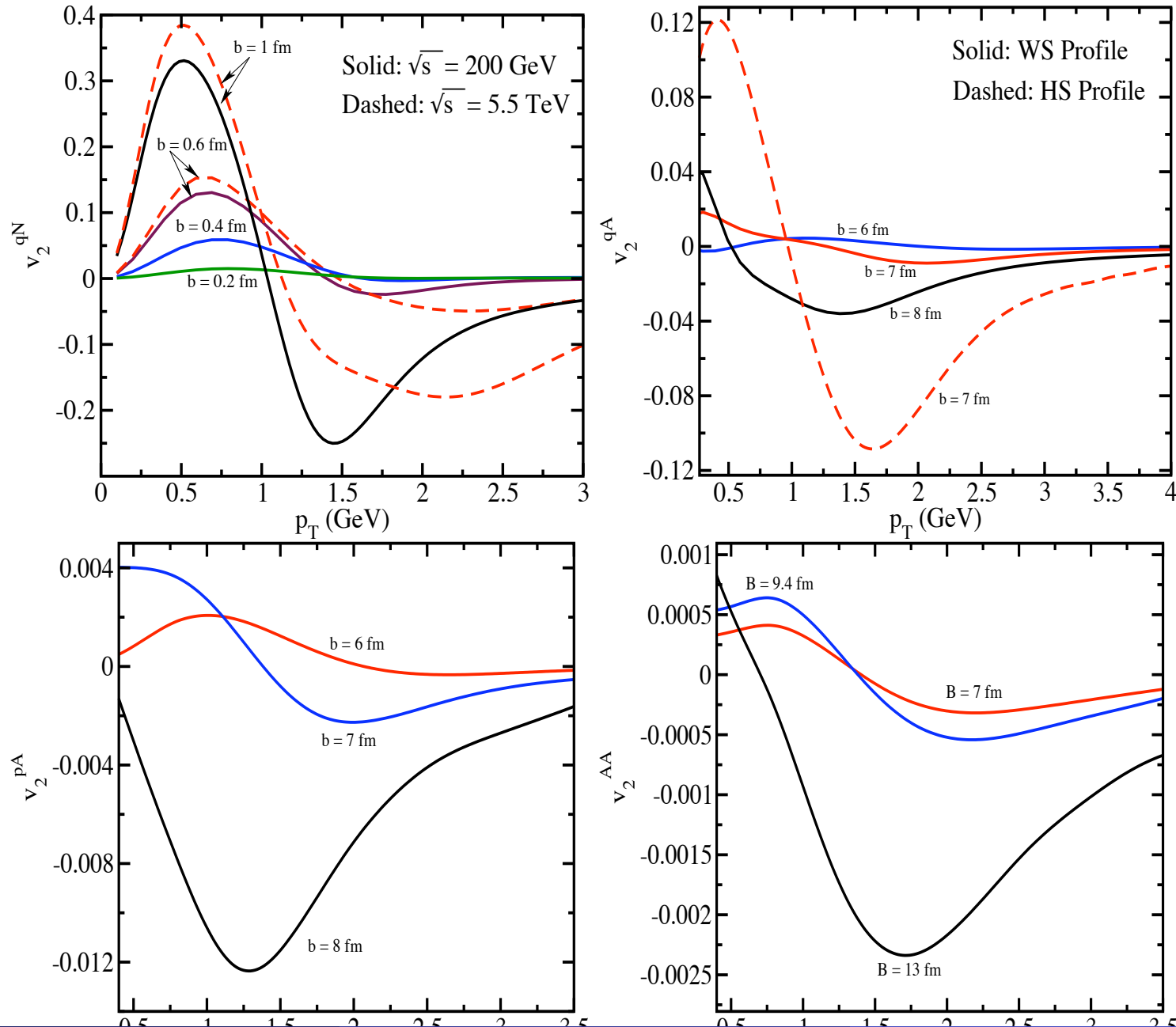


# Prompt photon $v_2$ for qA collisions at RHIC

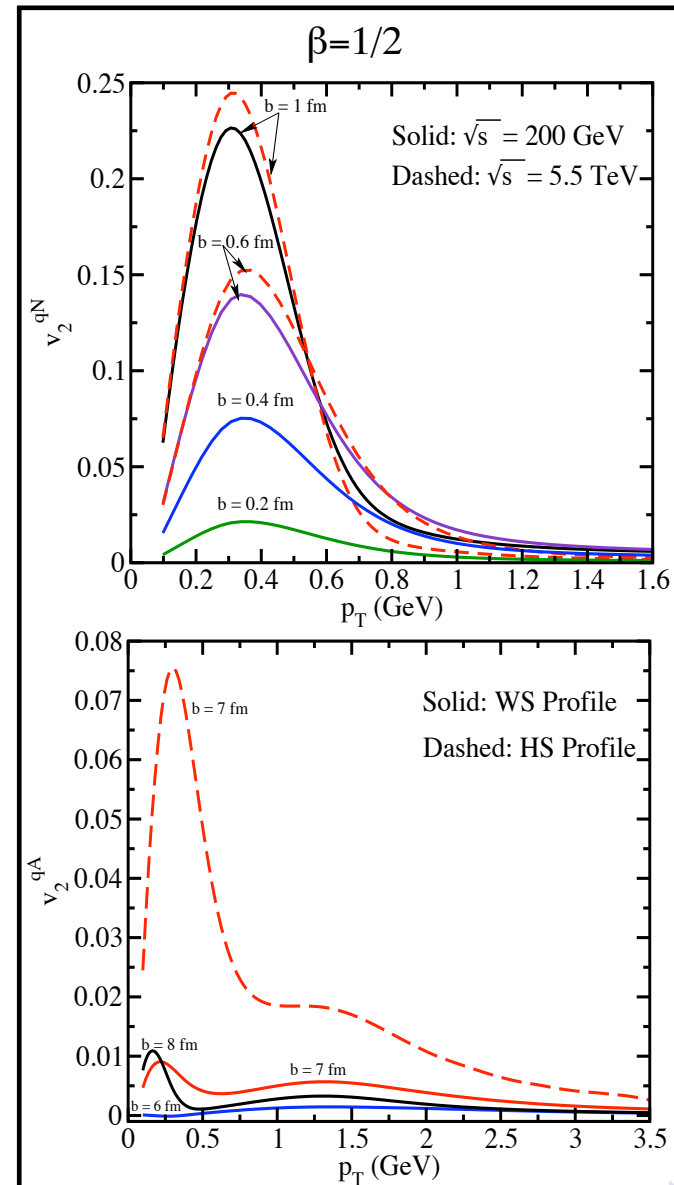
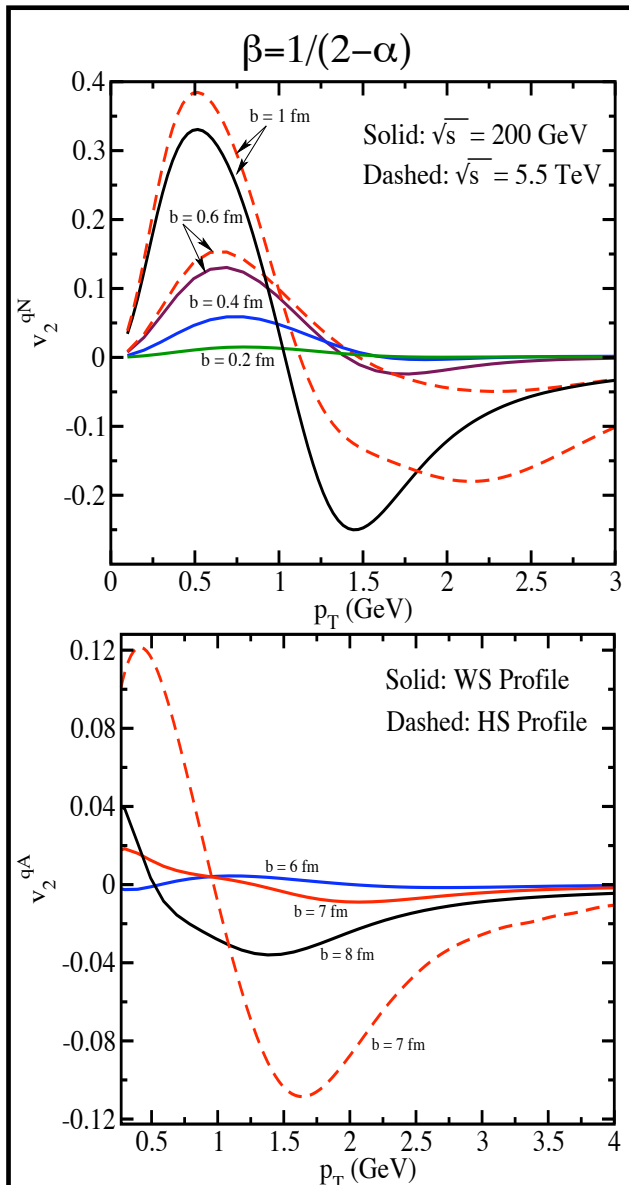


# Prompt photon $v_2$ for qA collisions at RHIC: the uncertainty of nuclear profile

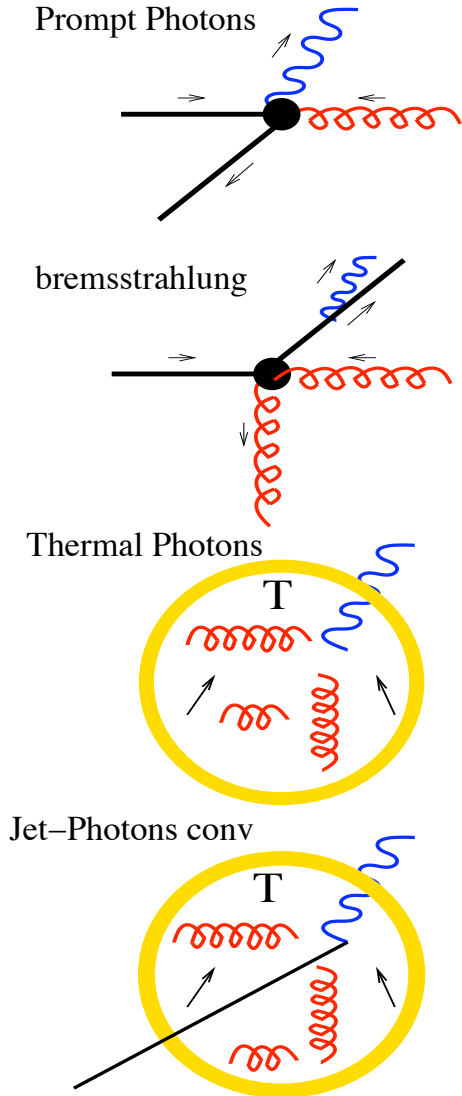




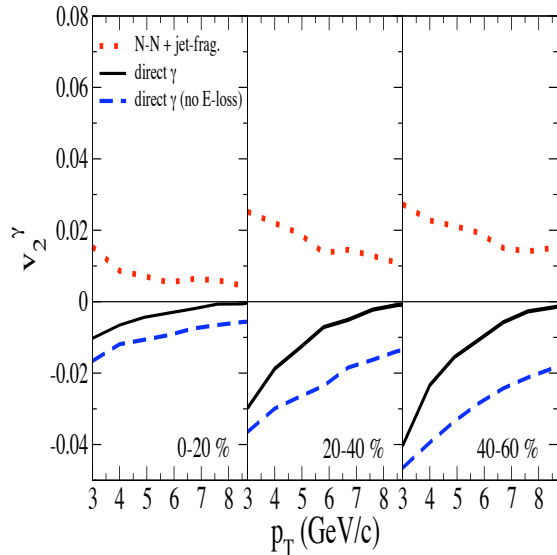
# On the sign of $v_2$



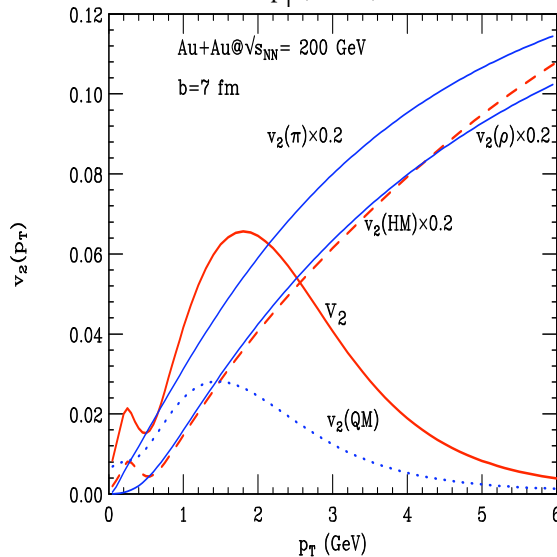
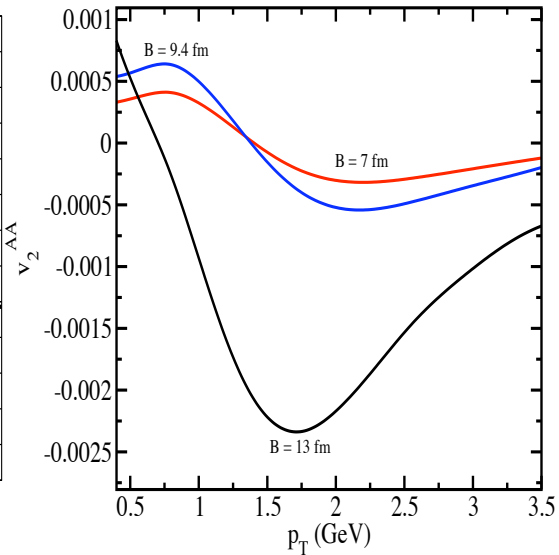
# Direct photon $v_2$ at RHIC



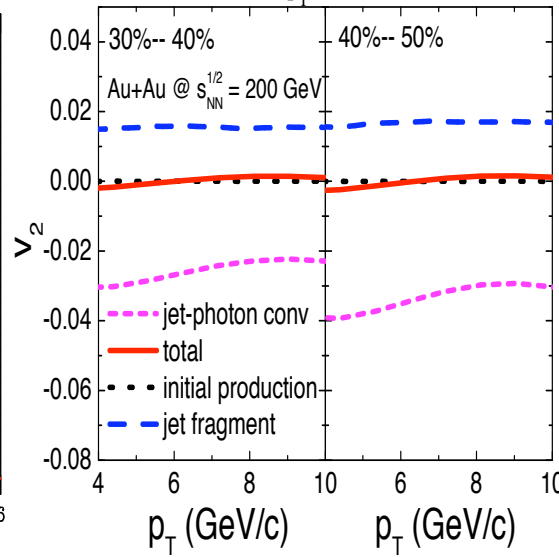
Turbide et al, PRL 96, 032303 (2006)



Kopeliovich, AHR, Schmidt, arXiv:0712.2829

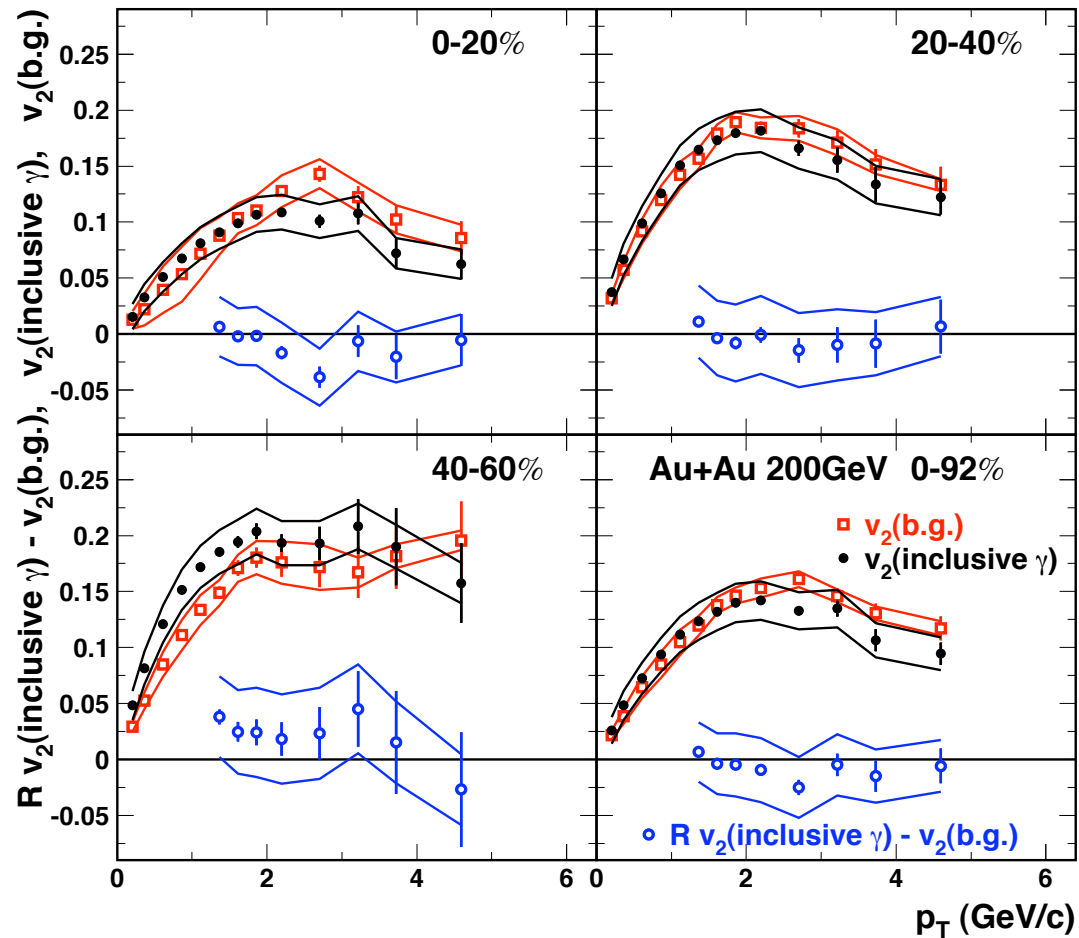


Chatterjee et al, PRL 96, 202302 (2006)



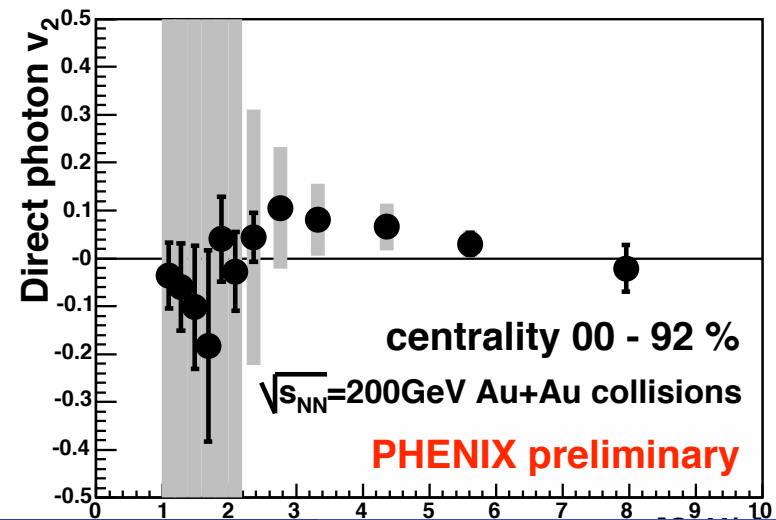
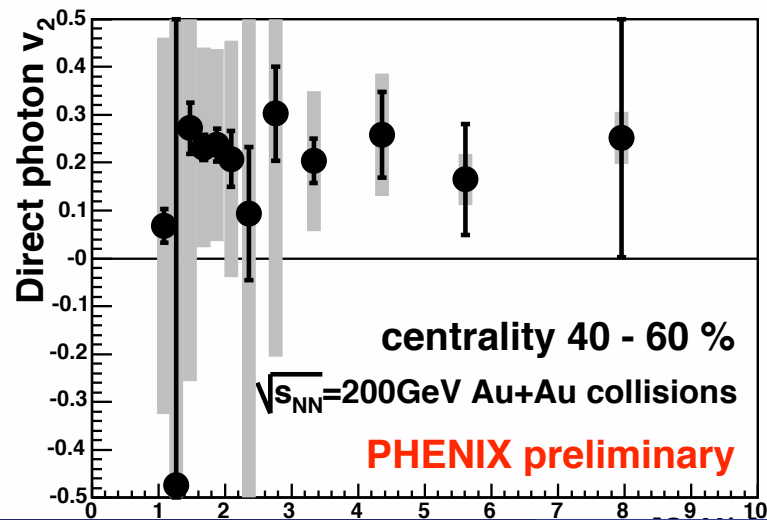
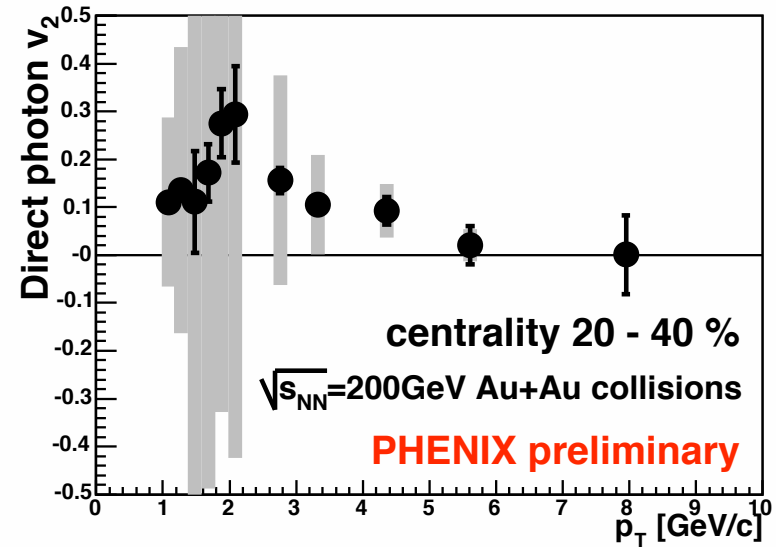
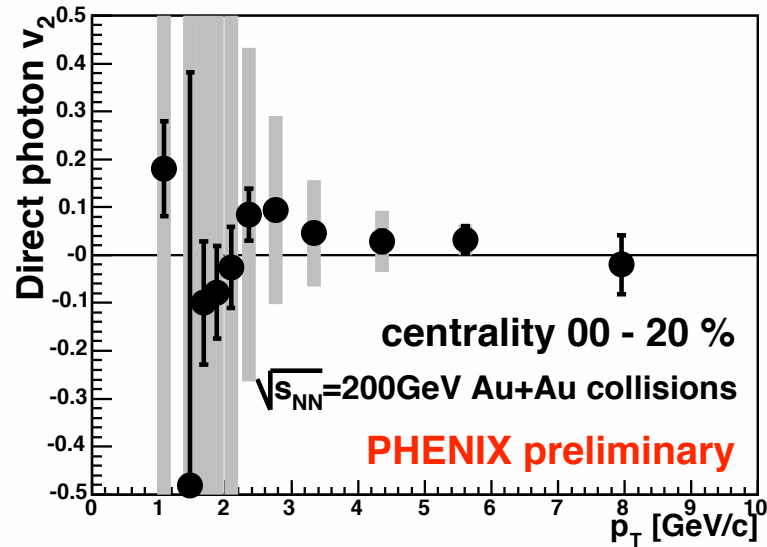
Liu and Fries, arXiv:0801.0453

# Direct photon Elliptic flow at RHIC: published data



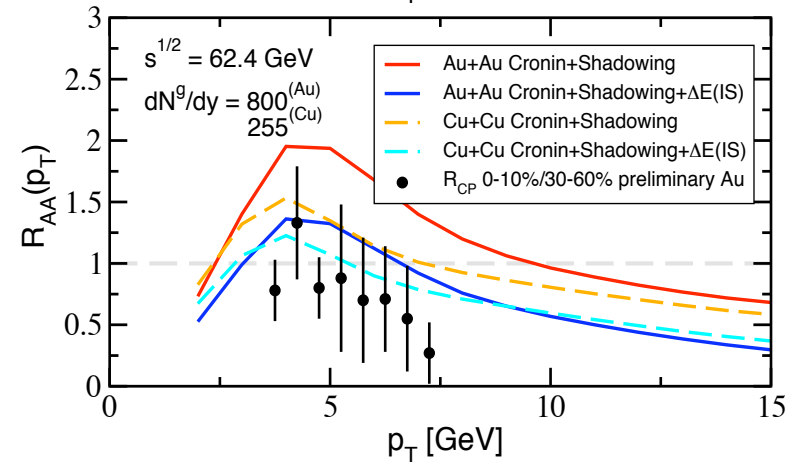
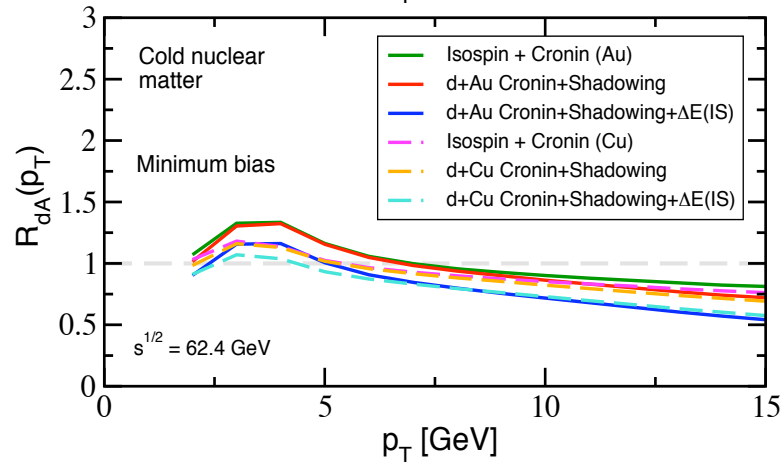
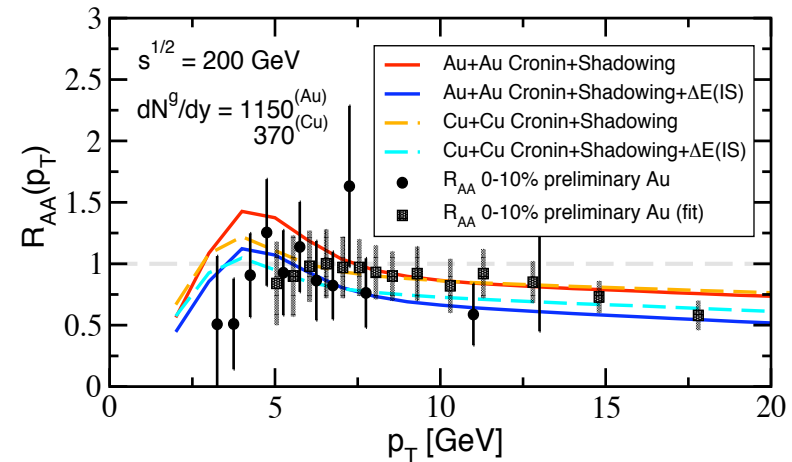
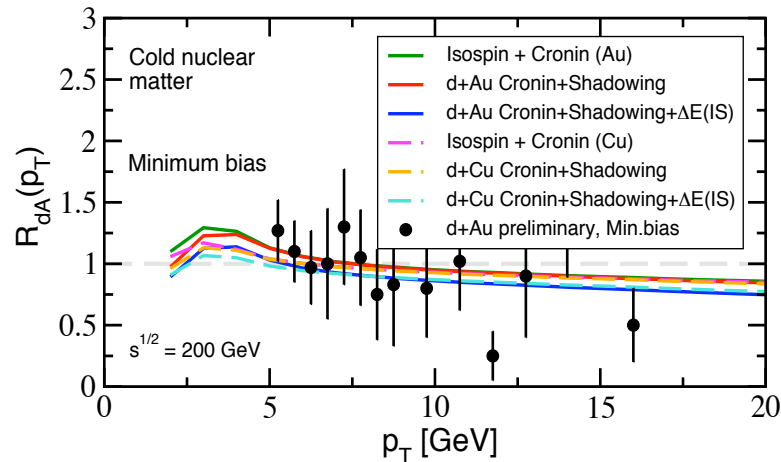
PHENIX collaboration, PRL. 96 (2006) 032302

# Direct photon Elliptic flow at RHIC: preliminary data





# Direct photon at RHIC: Cronin effect and suppression



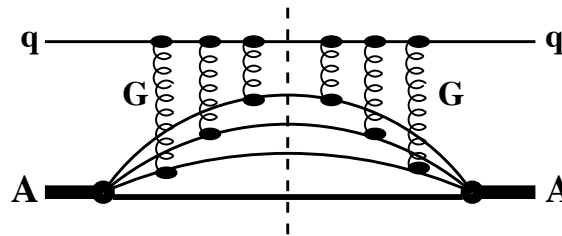
The contribution of the final-state photon production at  $p_T < 5$  GeV is limited to 35%, and at high transverse momenta, the modification of the direct photon cross section is dominated by initial-state cold nuclear matter effects.

Vitev, *et al.*, arXiv:0804.3805

# Pion v2 at RHIC in d+Au collision

$$\frac{d\sigma_{pA}^h}{d^2p_T} = K \sum_{i,j,k,l} F_{i/p} \otimes F_{j/A} \otimes \frac{d\hat{\sigma}}{d\hat{t}}(ij \rightarrow kl) \otimes D_k^h$$

$$F_{i/p} = f_{i/p}(x_i, Q^2) \frac{dN_i}{d^2k_{iT}}(x_i, b) \quad \text{and} \quad F_{j/A} = T_A(b) f_{j/p}(x_j, Q^2) \frac{dN_j^{(0)}}{d^2k_{jT}}(x_j, b) .$$

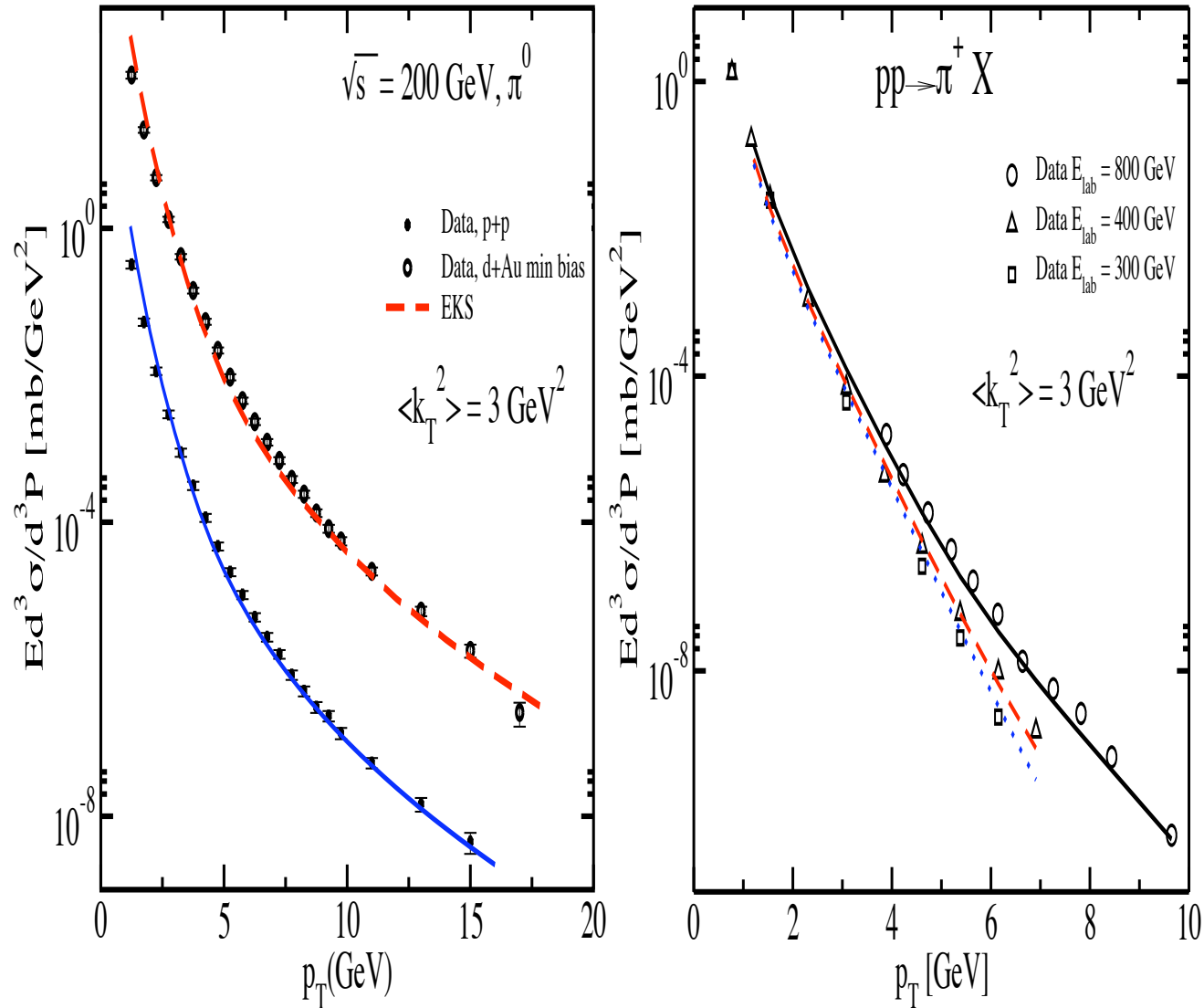


Johnson, Kopeliovich and Tarasov, PRC 63 (2001) 035203

$$\frac{dN_i}{d^2k_{iT}} = \frac{1}{(2\pi)^2} \int d^2r_1 d^2r_2 e^{i\vec{k}_T \cdot (\vec{r}_1 - \vec{r}_2)} \left[ \frac{\langle k_T^2 \rangle}{\pi} e^{-\frac{1}{2}(r_1^2 + r_2^2)\langle k_T^2 \rangle} \right] \left[ e^{-\frac{1}{2} \sigma_{q\bar{q}}^N(\vec{r}_1 - \vec{r}_2, x)} T_A(b) \right]$$

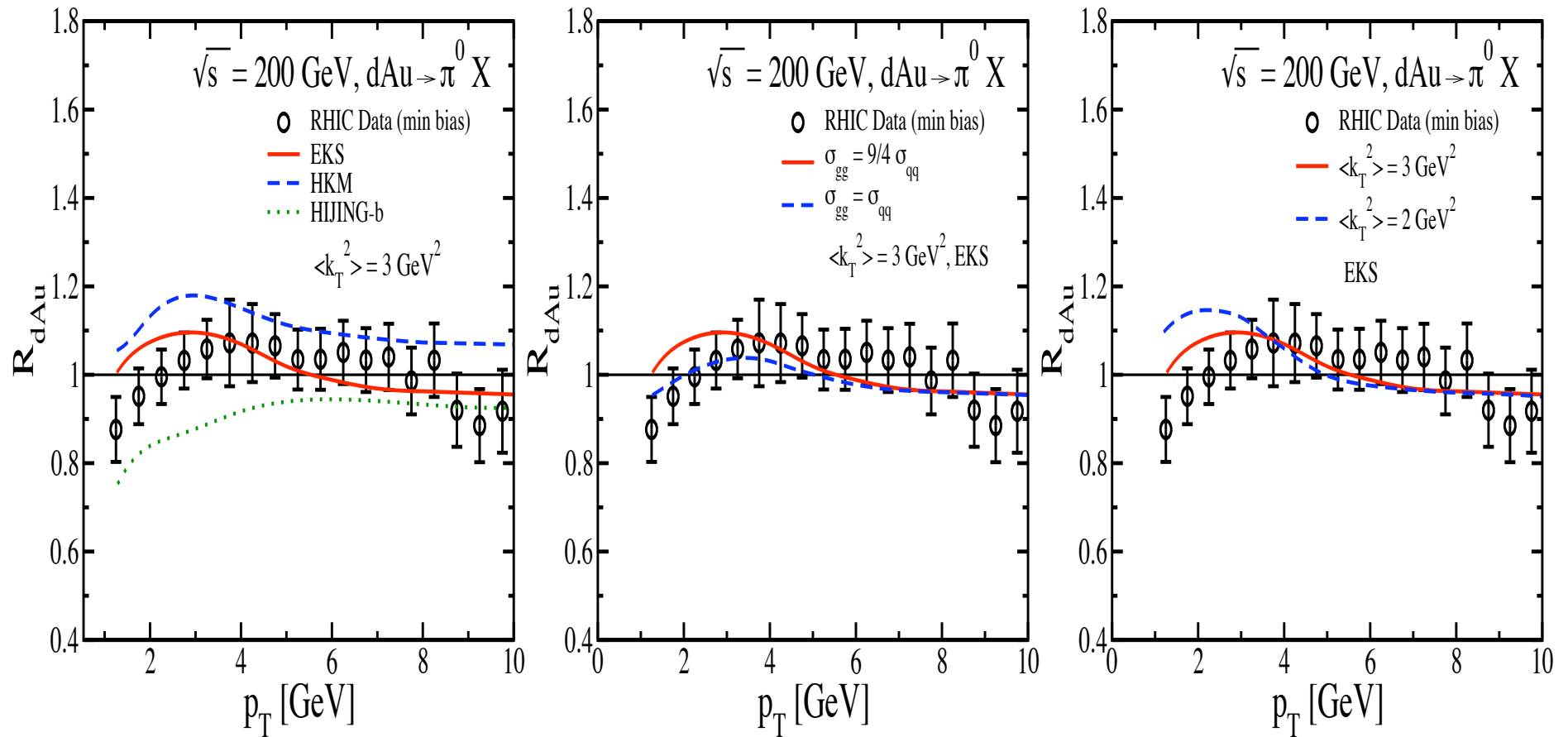
$$\sigma_{q\bar{q}}^N(\vec{r}_1 - \vec{r}_2, x) T_A(b) \rightarrow \int d^2\vec{s} \text{Im} f_{q\bar{q}}^N(\vec{s}, \vec{r}_1 - \vec{r}_2, x) T_A(\vec{b} + \vec{s})$$

# Hadron production from SPS to RHIC energies

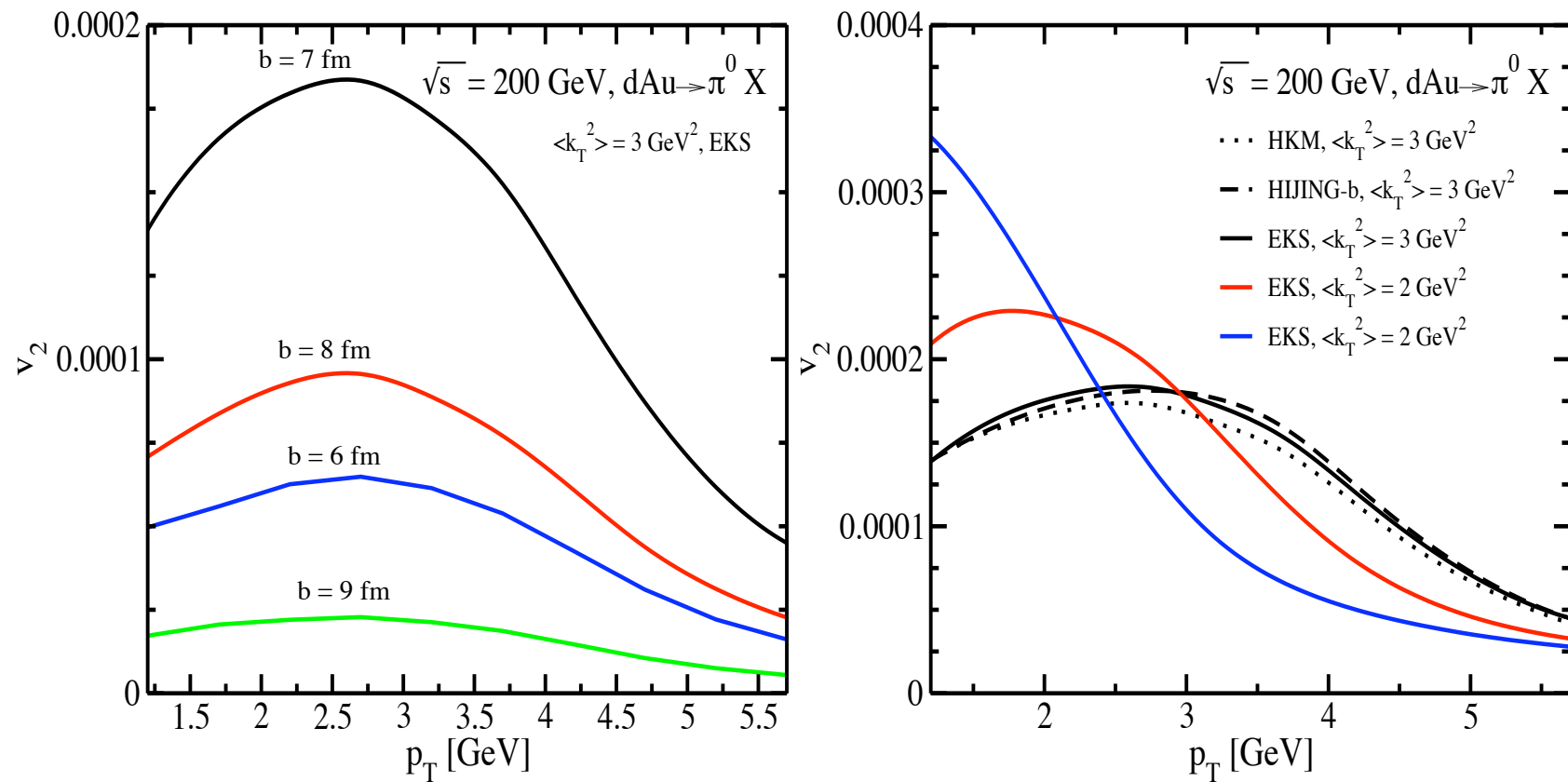


# Cronin effect at RHIC

AHR, *et al.* (Preliminary results)



# pion $v_2$ for $d + Au$ collision



The bigger the Cronin effect, the bigger  $v_2$  for dAu collisions

# Summary and outlook

- We introduced dipole orientation which satisfies all the imposed boundary conditions.
  - The developed theoretical tools can be applied to the calculation of the azimuthal asymmetry in DIS and in Drell-Yan reactions on a proton, as well as to the production of direct photons and Drell-Yan pairs in proton-nucleus and heavy ion collisions.
- We have computed the azimuthal asymmetry of direct photon originates from primary hard scatterings between partons. **This can be accounted for by the color dipole orientation which is sensitive to the rapid change of the nuclear profile.** We show that the direct photon elliptic anisotropy  $v_2$  coming from this mechanism changes sign and becomes negative for peripheral collisions, albeit it is quite small for nuclear collisions at the RHIC energy.

# Dipole parametrizations

- Golec-Biernat, Wusthoft (GBW) 1999:

$$\sigma_{q\bar{q}}(x, \vec{r}) = \sigma_0 \left( 1 - e^{-r^2/R_0^2} \right),$$

it does not match with QCD evolution DGLAP at large value of  $Q^2$ . This failure can be clearly seen in the energy dependence of  $\sigma_{tot}^{\gamma^*P}$  for  $Q^2 > 20 \text{ GeV}^2$ , where the the model predictions are below the data.

- GBW couple to DGLAP, Bartels *et al* 2002:

$$\sigma_{q\bar{q}}(x, \vec{r}) = \sigma_0 \left( 1 - \exp \left( -\frac{\pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2)}{3\sigma_0} \right) \right),$$

where the scale  $\mu^2$  is related to the dipole size by

$$\mu^2 = \frac{C}{r^2} + \mu_0^2.$$

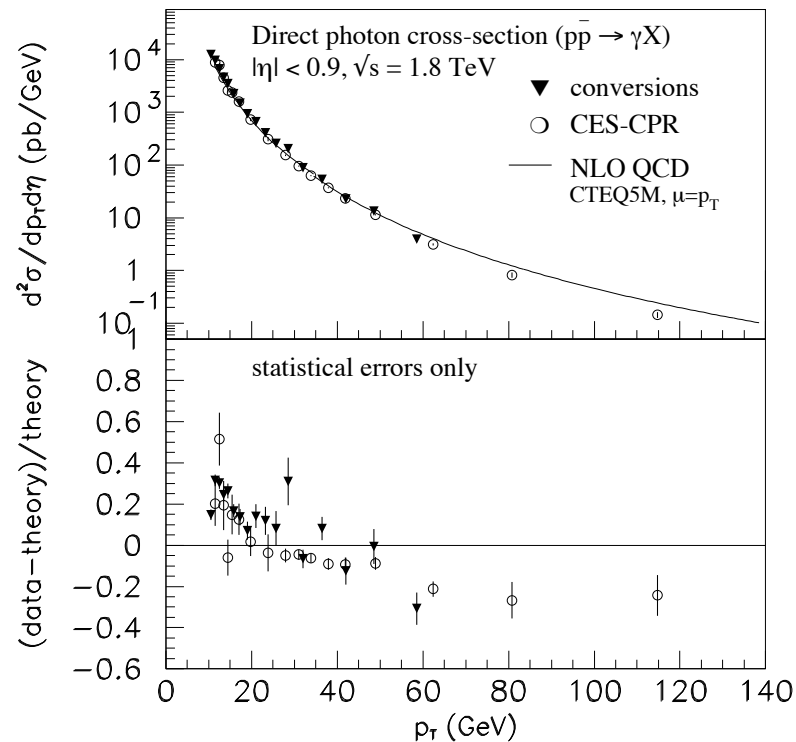
$$\frac{\partial x g(x, \mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi^2} \int_x^1 dz P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}, \mu^2\right).$$

# Direct photon $v_2$ for AA collisions

$$v_2^{A_1 A_2}(B, p_T) = \frac{\int d\phi \int d^2\vec{b} \cos(2\phi) \left( \cos(2\Theta_1) \frac{d\sigma^\gamma(pA_1 \rightarrow \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_1} T_{A_2}(\vec{b}_2) + \cos(2\Theta_2) \frac{d\sigma^\gamma(pA_2 \rightarrow \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_2} T_{A_1}(\vec{b}_1) \right)}{\int d\phi \int d^2\vec{b} \left( \frac{d\sigma^\gamma(pA_1 \rightarrow \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_1} T_{A_2}(\vec{b}_2) + \frac{d\sigma^\gamma(pA_2 \rightarrow \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_2} T_{A_1}(\vec{b}_1) \right)},$$



# puzzle #2, high $p_T$ problem



- “We find that the shape of the cross section as a function of  $p_T$  is poorly described by next-to-leading-order QCD predictions, but agrees with previous CDF measurements” .... [CDF collaboration, PRD 70 \(2004\) 074008](#)