# Perturbative origin of azimuthal anisotropy in nuclear collisions

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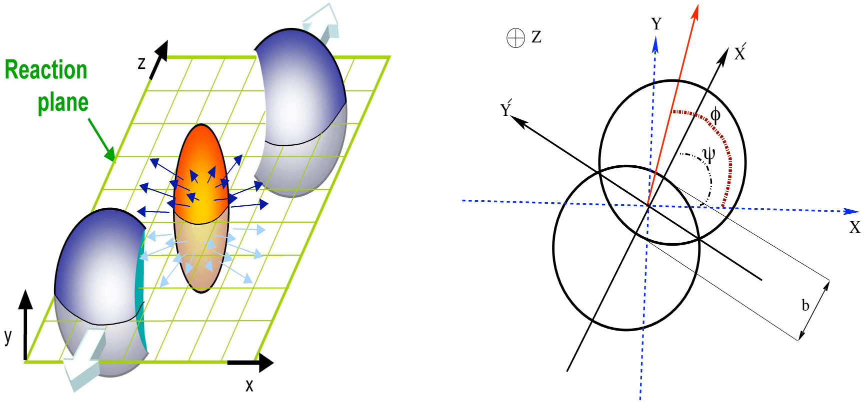
# Non-centeral heavy-ion collisions and elliptic flow

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



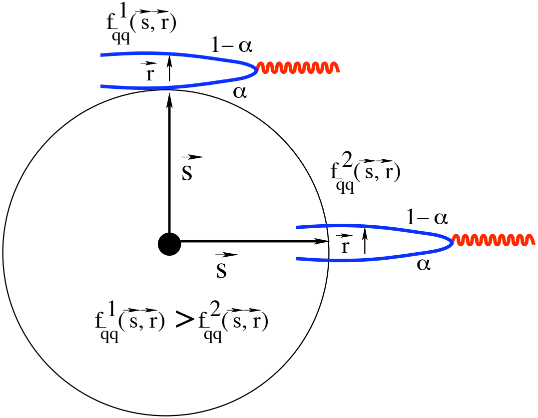

- $E\frac{d^3N^i}{d^3p_T} = \frac{1}{2\pi}\frac{d^2N^i}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n^i cos(n(\phi-\psi))\right)$
- $v_2 = \langle cos(2(\phi-\psi))\rangle$ $\qquad \phi = tan^{-1}p_y/p_x$

# 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 prepherial need to be described.
  - Hydrodynamics breakdown for more prepherial 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 properites of azimuthal anisotropy: mass ordering, eccentricity scaling, valence quark number scaling (where are gluons?)...
- 7: v2 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.

$$\mathrm{Im} f^{q}_{\bar{q}q}(\vec{s},\vec{r}) = \frac{2}{9\pi^2}\int \frac{d^2q\, d^2q'\, \alpha_s(q^2)\alpha_s(q'^2)}{(q^2+\mu^2)(q'^2+\mu^2)}$$

$$\times \quad \left[e^{i\vec{q}\cdot(\vec{s}+\vec{r}/2)} - e^{i\vec{q}\cdot(\vec{s}-\vec{r}/2)}\right]\left[e^{i\vec{q}\,'\cdot(\vec{s}+\vec{r}/2)} - e^{i\vec{q}\,'\cdot(\vec{s}-\vec{r}/2)}\right]$$

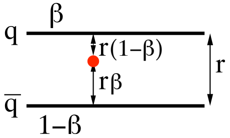
$$= \quad \frac{8\alpha_s^2}{9}\left[K_0\left(\mu\left|\vec{s}+\frac{\vec{r}}{2}\right|\right) - K_0\left(\mu\left|\vec{s}-\frac{\vec{r}}{2}\right|\right)\right]^2$$

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)

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

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




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

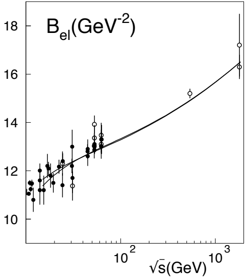
$$\sigma^N_{q\bar{q}}(r) = 2\int d^2\vec{s}\ \mathrm{Im} f^N_{q\bar{q}}(\vec{s},\vec{r})$$
$$= \frac{4\pi}{3}\int \frac{d^2q}{q^4}(1-e^{-i\vec{q}.\vec{r}})\alpha_s(q^2)\mathcal{F}(x,q). \qquad (1)$$

# Color dipole orientation

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

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

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, $B_{el}^{(\bar{q}q)N}(r) \approx 5\,\mathrm{GeV}^{-2}$, agrees with the expected value $B_{el}^{(\bar{q}q)N}(r) \approx B_{el}^{pp}/2$.



# Color dipole orientation

Generalized unintegrated gluon density:

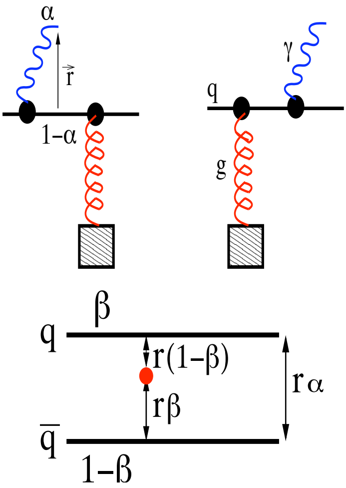
$$\alpha_s \mathcal{F}(x, \vec{q}, \vec{q}\,') = \frac{3\sigma_0}{16\pi^2} q^2 q'^2 R_0^2(x) e^{-\frac{1}{8}R_0^2(x)\left(q^2+q'^2\right)} e^{-\frac{1}{2}R_N^2\left(\vec{q}-\vec{q}\,'\right)^2},$$

$\sigma_0 = 23.03$ 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 $B_{el}^{pp} = 2R_N^2 + 2\alpha'_{\mathbf{P}} \ln(s/s_0)$.

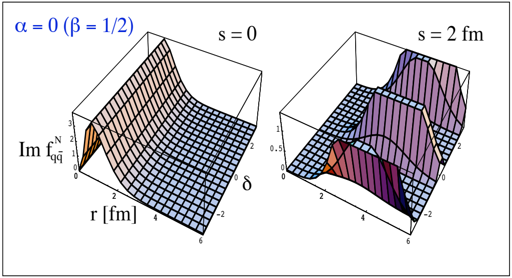
$$\mathrm{Im} f_{\bar{q}q}^N(\vec{s}, \vec{r}, x, \beta) = \frac{\sigma_0}{8\pi B_{el}} \left\{ \exp\left[-\frac{[\vec{s}+\vec{r}(1-\beta)]^2}{2B_{el}}\right] + \exp\left[-\frac{(\vec{s}-\vec{r}\beta)^2}{2B_{el}}\right] - 2\exp\left[-\frac{r^2}{R_0^2} - \frac{[\vec{s}+(1/2-\beta)\vec{r}]^2}{2B_{el}}\right] \right\},$$

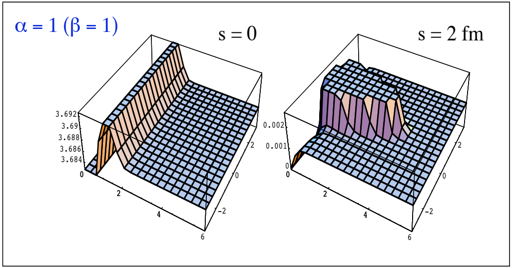
where we defined $B_{el} = R_N^2 + R_0^2(x)/8$.

# Color dipole orientation




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



- 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

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

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 $\vec{b}$,

$$F_t(\vec{b},\alpha\vec{r}_1,\alpha\vec{r}_2,x) = \mathrm{Im}f^t_{q\bar{q}}(\vec{b},\alpha\vec{r}_1,x) + \mathrm{Im}f^t_{q\bar{q}}(\vec{b},\alpha\vec{r}_2,x) - \mathrm{Im}f^t_{q\bar{q}}(\vec{b},\alpha(\vec{r}_1-\vec{r}_2),x),$$

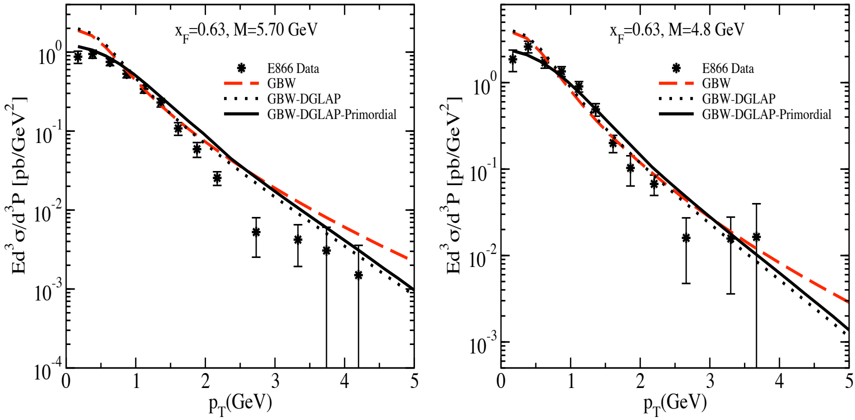
with

$$\mathrm{Im}f^A_{q\bar{q}}(b,\vec{r}) = 1-\exp[\int d^2\vec{s}\ \mathrm{Im}f^N_{q\bar{q}}(\vec{s},\vec{r})T_A(\vec{b}+\vec{s})]$$

$$\sigma^N_{q\bar{q}}(r) = 2\int d^2\vec{b}\ \mathrm{Im}f^N_{q\bar{q}}(\vec{b},\vec{r})$$

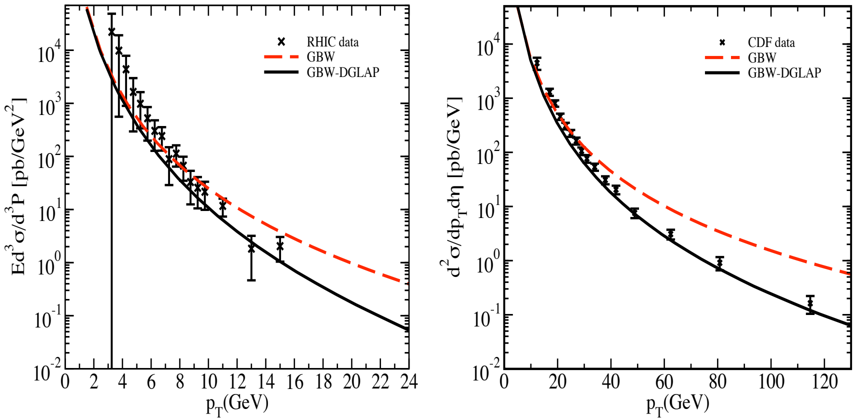
# Dilepton spectrum in 800− GeV *pp*

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



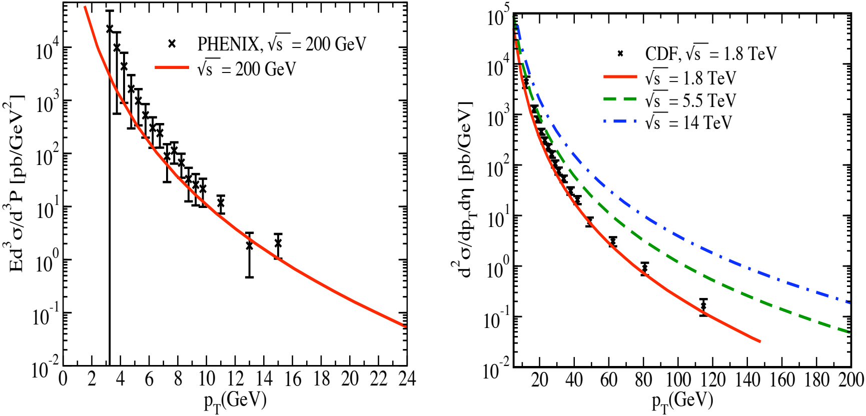

- constant primordial momentum $\langle k_0^2 \rangle = 0.4\mathrm{GeV}^2$ is incorporated within the GBW-DGLAP dipole model (solid line)

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



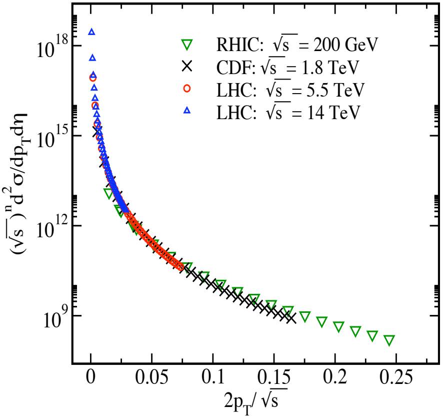
# Direct photon productions at RHIC and LHC

AHR *et al.* arXiv: 0707.2040



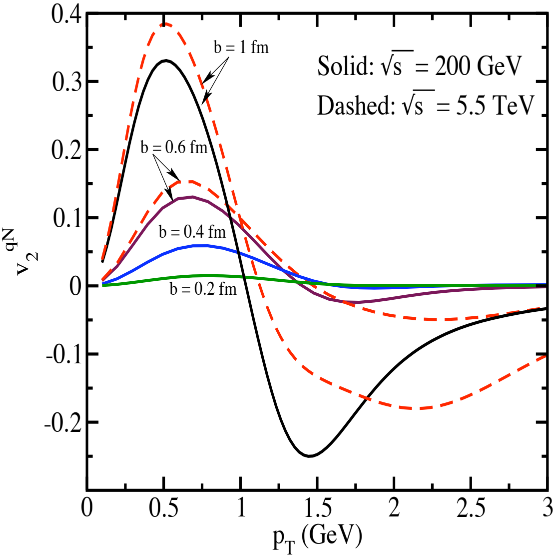

- Neither *K*-factor, nor higher twist corrections, no quark-to-photon fragmentation function are to be added.

# 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

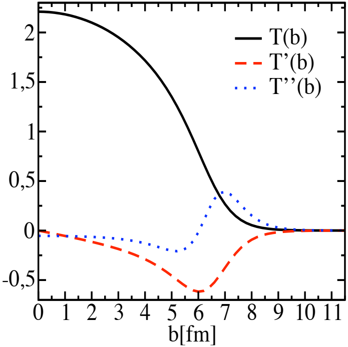
# Direct photon v2 for qN collisions



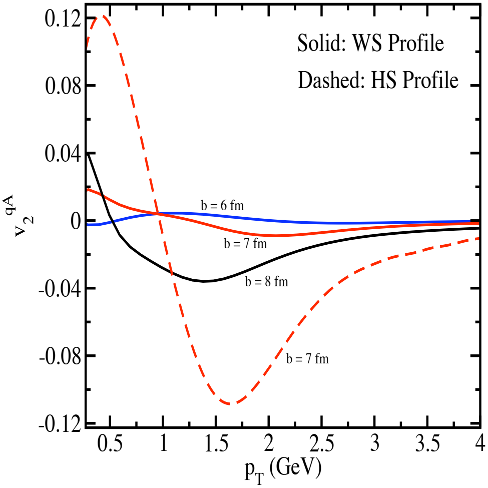
# Direct photon v2 for qA collisions

$$\mathrm{Im} f^{A}_{q\bar{q}}(b,\vec{r}) \;=\; 1-\exp[\int d^2\vec{s}\;\mathrm{Im} f^{N}_{q\bar{q}}(\vec{s},\vec{r})\,T_A(\vec{b}+\vec{s})].$$

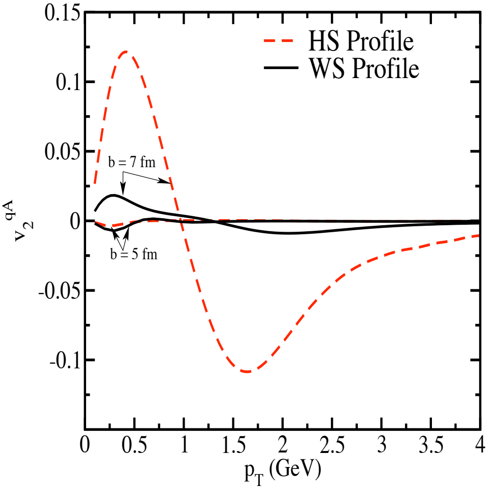
Sources of azimuthal anisotropy: rescatterings and shape of the system



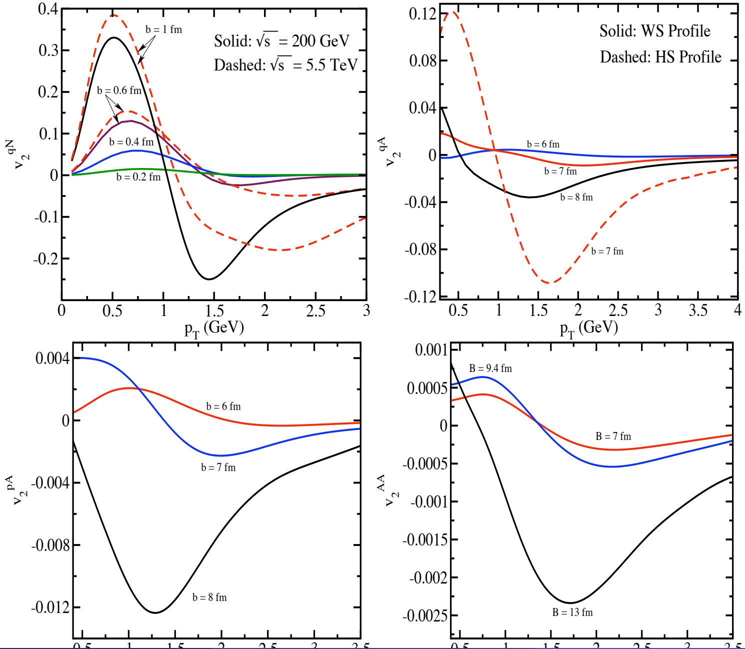
# Prompt photon v2 for qA collisions at RHIC



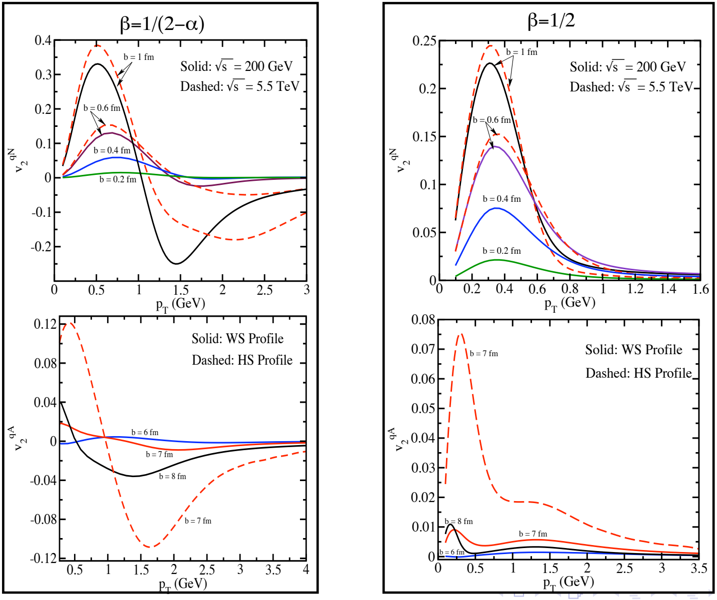
# Prompt photon v2 for qA collisions at RHIC: the uncertainty of nuclear profile



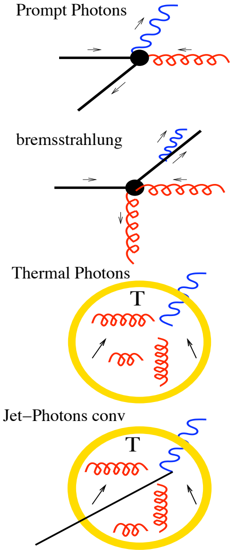
# Kopeliovich, A.H.R., Schmidt, arXiv:0712.2829, to appear in NPA



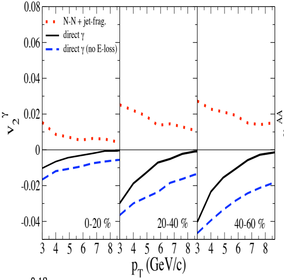
# On the sign of v2



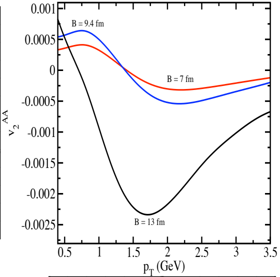
# Direct photon v2 at RHIC

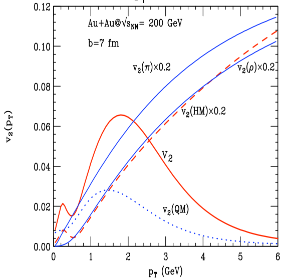



Turbide et al, PRL 96, 032303 (2006)

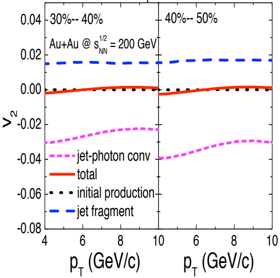



Kopeliovich, AHR, Schmidt, arXiv:0712.2829



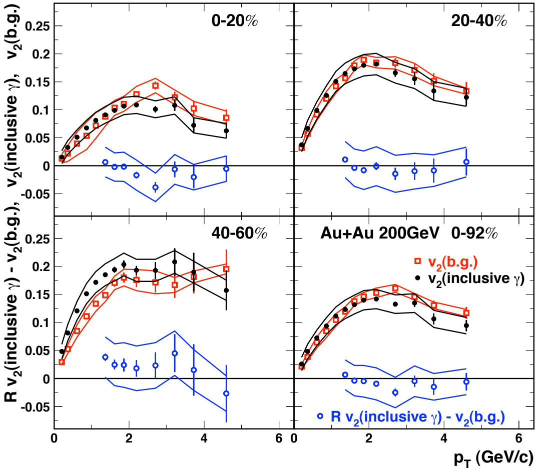




Chatterjee et al, PRL 96, 202302 (2006)



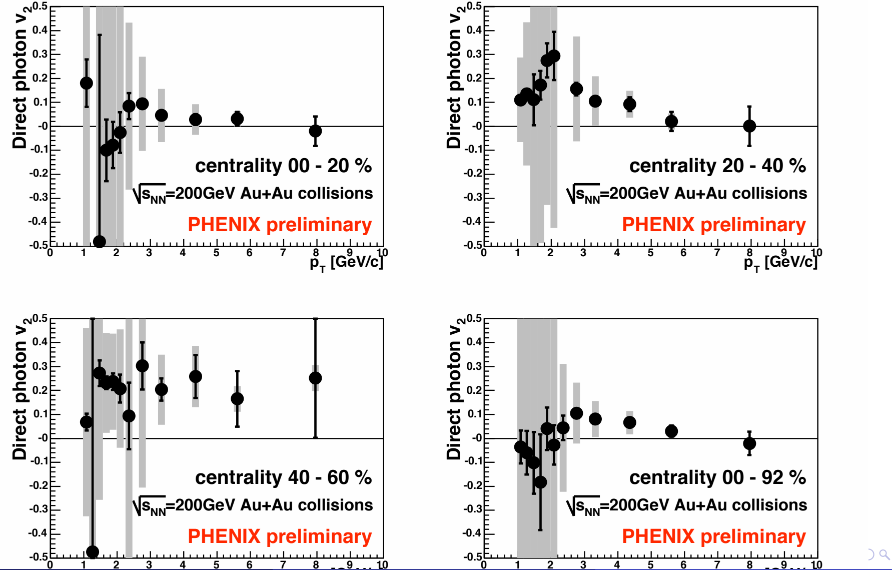

Liu and Fries, arXiv:0801.0453

# Direct photon Elliptic flow at RHIC: published data

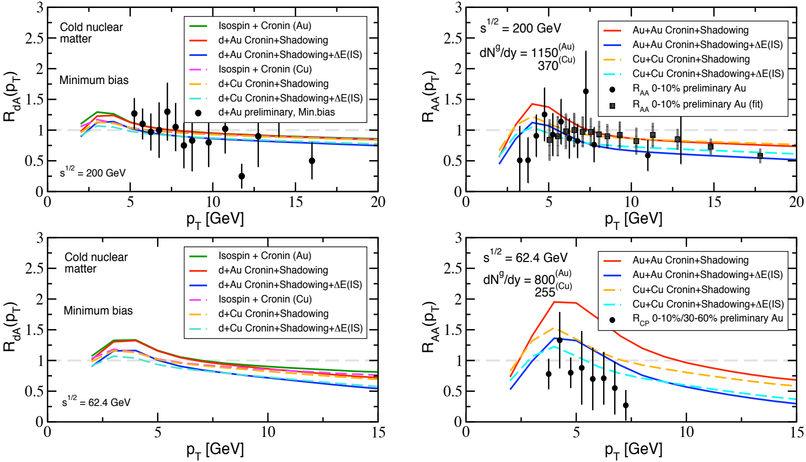



PHENIX collaboration, PRL. 96 (2006) 032302

# Direct photon Elliptic flow at RHIC: preliminary data



# Direct photon at RHIC: Cronin effect and suppression



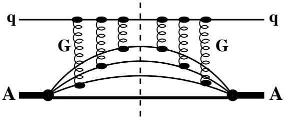

The contribution of the final-state photon production at $p_T < 5$ GeV is limited to 35%, and at high transverse momenta, the modification of the direct photon cross section is dominated by initial-state cold nuclear matter effects.

Vitev, *et al.*, arXiv:0804.3805

# Pion v2 at RHIC in d+Au collision

$$\frac{d\sigma^h_{pA}}{d^2p_T} = K \sum_{i,j,k,l} F_{i/p} \otimes F_{j/A} \otimes \frac{d\hat{\sigma}}{d\hat{t}}(ij \to kl) \otimes D^h_k$$

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

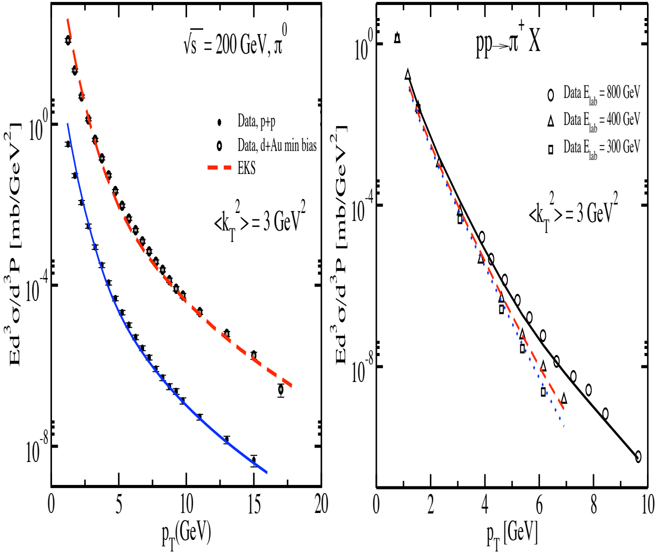



Johnson, Kopeliovich and Tarasov, PRC 63 (2001) 035203

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

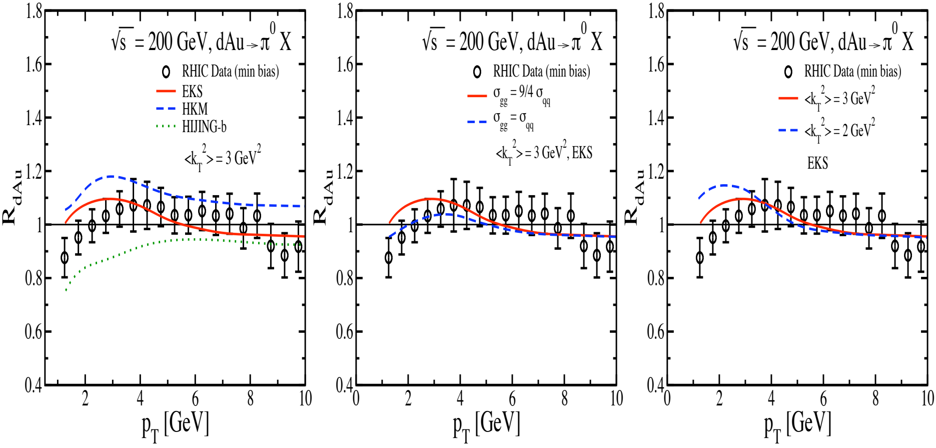
$$\sigma^N_{\bar{q}q}(\vec{r}_1 - \vec{r}_2, x)\, T_A(b) \to \int d^2\vec{s}\ \mathrm{Im} f^N_{q\bar{q}}(\vec{s}, \vec{r}_1 - \vec{r}_2, x) T_A(\vec{b} + \vec{s})$$

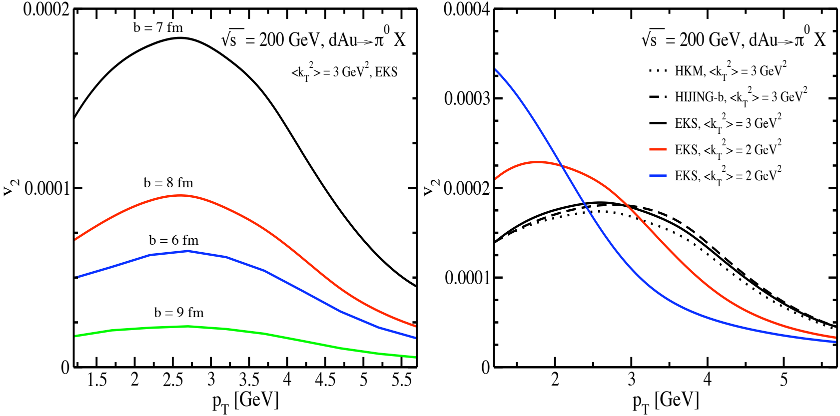
# Hadron production from SPS to RHIC energies



# Cronin effect at RHIC

AHR, *et al.*(Preliminary results)






The bigger the cronin effect, the bigger $v2$ for dAu collisions

# Summary and outlook

- We introduced dipole orientation which satisfies all the imposed boundary consitions.
  - 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 v2 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 $\sigma_{tot}^{\gamma^\star p}$ for $Q^2 > 20$ GeV$^2$, where the the model predictions are below the data.

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

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

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

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

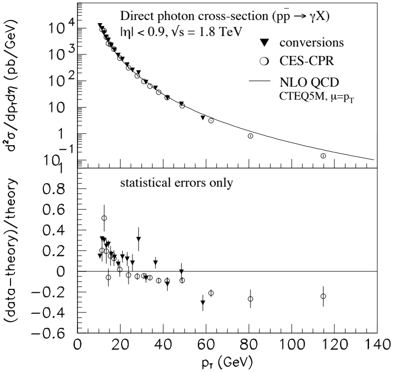
$$\frac{\partial xg(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi^2} \int_x^1 dz P_{gg}(z) \frac{x}{z} g(\frac{x}{z}, \mu^2).$$

# Direct photon v2 for AA collisions

$$v_2^{A_1 A_2}(B, p_T) =$$

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

# puzzel #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