The elliptic flow of heavy quarkonia in pA collisions from the initial state

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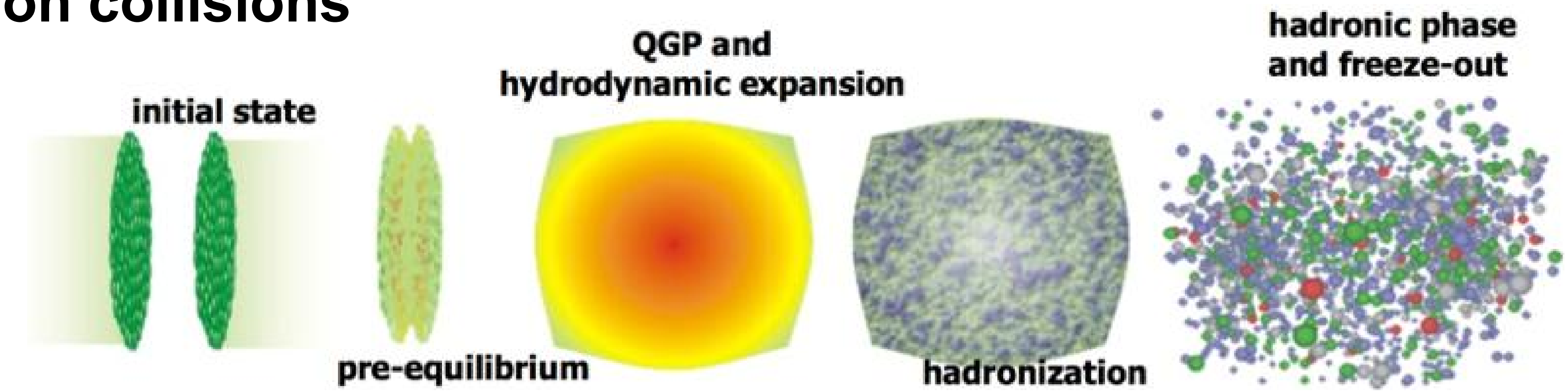
1. C. Zhang, C. Marquet, G. Y. Qin, S. Y. Wei and B. W. Xiao, Phys. Rev. Lett. 122, no. 17, 172302 (2019).
2. C. Zhang, C. Marquet, G. Y. Qin, Y. Shi, L. Wang, S. Y. Wei and B. W. Xia, in preparation.

QM 2019

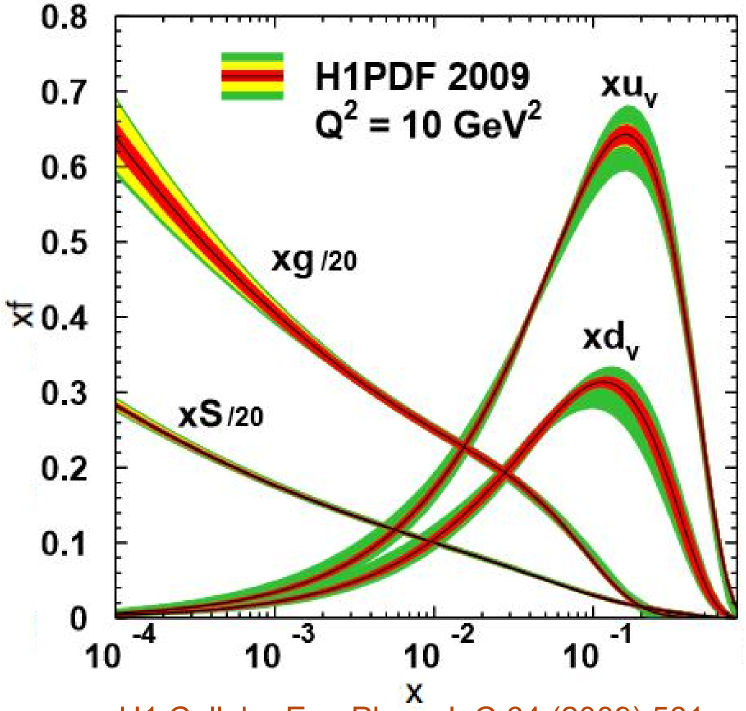
Outline

- Introduction to Color Glass Condensate and Mclerran-Venugopalan model
- J/ψ v2 in pA collisoins
- Summary and outlook

Heavy-ion collisions



Color Glass Condensate Hydrodynamics



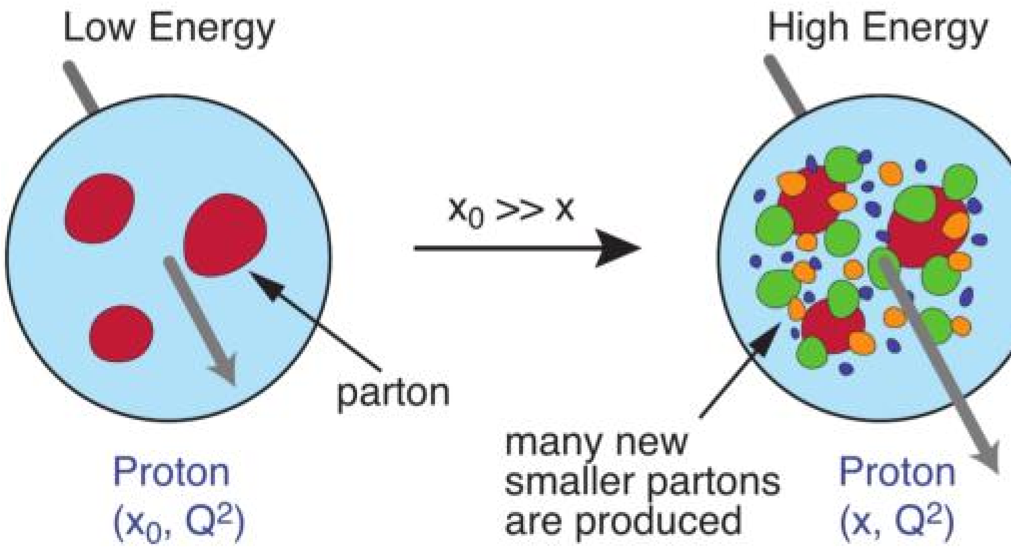
H1 Collab., Eur. Phys. J. C 64 (2009) 561

Parton distrbutions as functions of momemtum fraction x inside the proton.

Gluons rapidly increase as x decreases.

Small x region, gluons dominate.

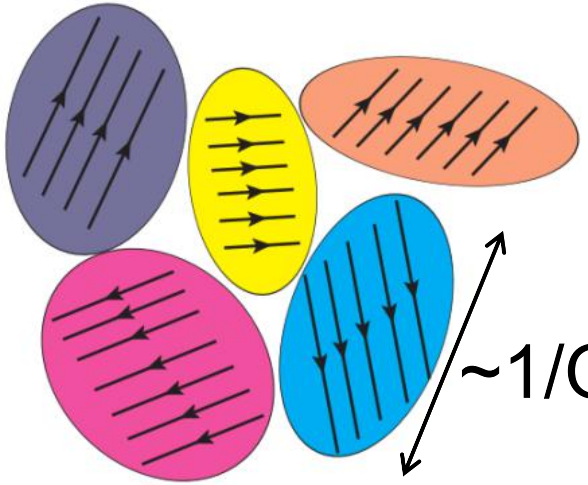
Color Glass Condensate: gluon saturation



EIC White Paper

Small x partons (mostly gluons) density increases with energy, and finally tends to saturate.

Dense small x gluon field —— Color Glass Condensate.



Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061

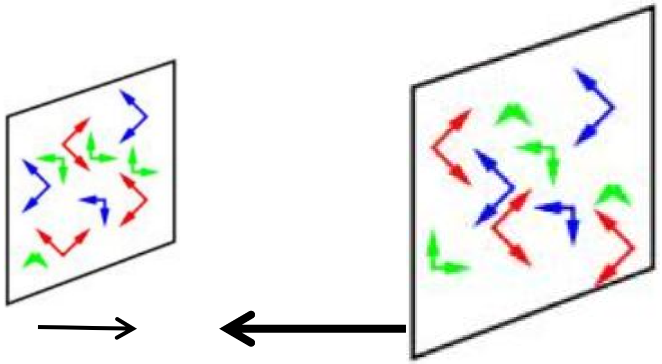
Qs :saturation scale/momentum,
characteristic transverse momentum of the small x gluons.

~1/Qs: size of color domain.

$$Q_s^2 \sim \alpha_s(Q_s^2) \frac{xg(x, Q_s^2)}{\pi R^2}$$

Small x region, gluons dominate.

Color Glass Condensate: Mclerran-Venugopalan model



MV model:
Dense gluon field——
a classical Yang-Mills field.

1. Solve the classical Yang-Mills equation

$$-\nabla_\perp^2 A_a^\mu(x) = g\delta^{\mu-}\delta(x^+)\rho_{A,a}(x_\perp)$$

$$\Rightarrow A_a^\mu(x) = -g\delta^{\mu-}\delta(x^+)\frac{1}{\nabla_\perp^2}\rho_{A,a}(x_\perp)$$

$\rho_{A,a}$: color density in the nucleus

2. Write the physical observable in terms of gluon field A^μ as $f[A]$

3. Calculate the expectatation value in the target background gluon field

McLerran, Venugopalan, 1994; Iancu, Leonidov, McLerran, 2000.

In Mclerran - Venugopalan (MV) model :

$$\langle f(A)\rangle = \int D\rho_a \exp\left\{-\int dx^+ d^2x_\perp \frac{(\rho_a)^2}{2\mu^2(x^+)}\right\} f(A)$$

$\Rightarrow$ An essential correlator :

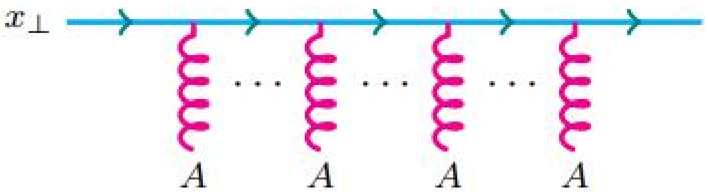
$$g^2\left\langle A_a^-(x_1^+, x_{1\perp}) A_b^-(x_2^+, x_{2\perp})\right\rangle = \delta_{ab}\delta(x_1^+ - x_2^+)\mu^2(x_1^+) L_{12}$$

L_{12}: a massless propogator

Color Glass Condensate: scattering amplitude in pA collisions, Wilson line

Fast moving partons in the proton multi-scatter with target background gluon field

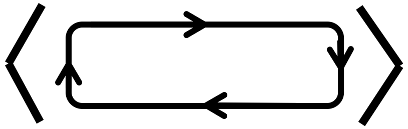
Dumitru, Jalilian-Marian, PRL 89 (2002)



One-quark scattering operator——
A Wilson line：

$$U(\boldsymbol{x}_\perp) = \mathcal{P} \exp\left[-ig \int_{-\infty}^{+\infty} \mathrm{d}x^+ A_a^-(x^+, \boldsymbol{x}_\perp) t^a\right]$$

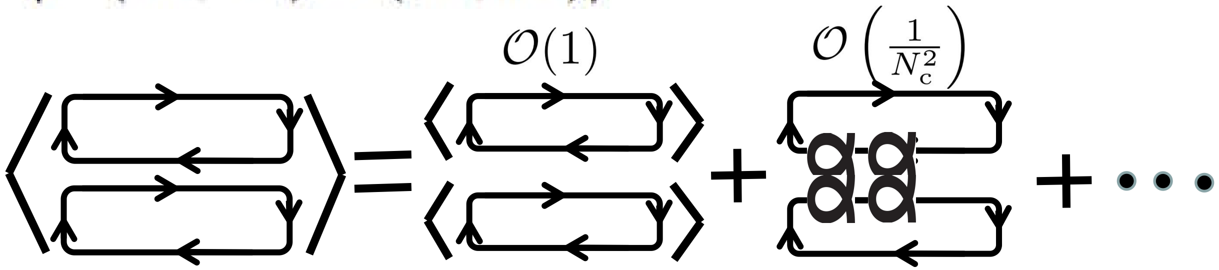
One-quark scattering amplitude square
——A Wilson loop (dipole):



$$\langle D(\boldsymbol{x}_{1\perp}, \boldsymbol{x}_{2\perp})\rangle \equiv \frac{1}{N_c} \langle \mathrm{Tr}\left[U(\boldsymbol{x}_{1\perp}) U(\boldsymbol{x}_{2\perp})^\dagger\right]\rangle$$

Two-quark scattering amplitude square
——2-dipole:

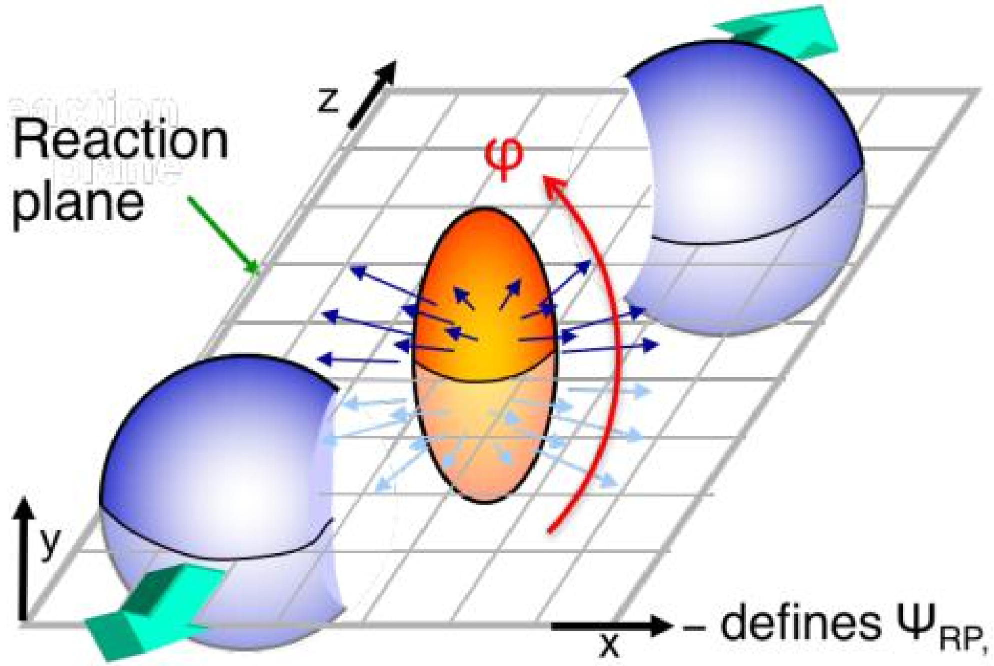
$$\langle D\left(\boldsymbol{x}_1, \boldsymbol{x}_2\right) D\left(\boldsymbol{x}_3, \boldsymbol{x}_4\right)\rangle$$



no correlations

correlations

Anisotropic flow (vn) in heavy-ion collisions



non-central AA collisons

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}(a_n \cos n\phi + b_n \sin n\phi)\right]$$
$$= \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n\,(\phi - \Psi_{RP,n})\right]$$

$$a_n = \{\cos n\phi\} \equiv \frac{\int \mathrm{d}\phi \cos n\phi \frac{\mathrm{d}N}{\mathrm{d}\phi}}{\int \mathrm{d}\phi \frac{\mathrm{d}N}{\mathrm{d}\phi}}$$

$$b_n = \{\sin n\phi\} = \frac{\int \mathrm{d}\phi \sin n\phi \frac{\mathrm{d}N}{\mathrm{d}\phi}}{\int \mathrm{d}\phi \frac{\mathrm{d}N}{\mathrm{d}\phi}}$$

$$v_n^2 = a_n^2 + b_n^2$$

Two-particle correlation method

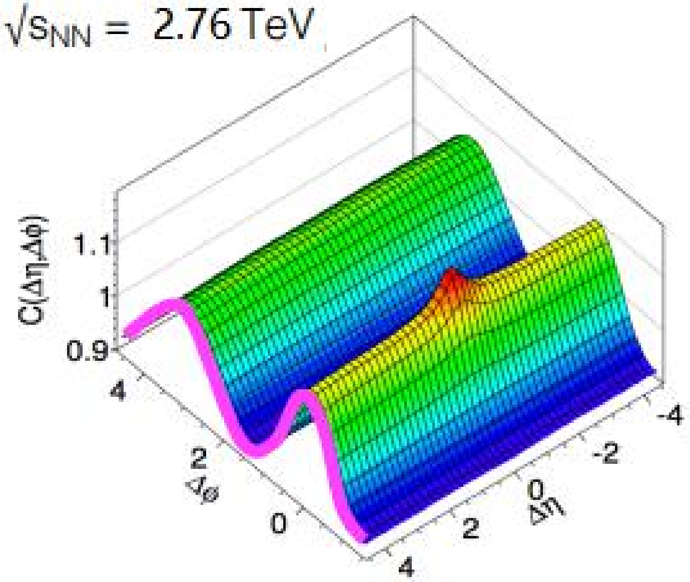
Two-particle azimuthal correlated Fourier harmonic:

$$
\begin{aligned}
c_n\{2\} \quad &\equiv \quad \{e^{in(\phi_1-\phi_2)}\} = \frac{\int \mathrm{d}\phi_1 \mathrm{d}\phi_2 e^{in(\phi_1-\phi_2)} \frac{\mathrm{d}N}{\mathrm{d}\phi_1 \mathrm{d}\phi_2}}{\int \mathrm{d}\phi_1 \mathrm{d}\phi_2 \frac{\mathrm{d}N}{\mathrm{d}\phi_1 \mathrm{d}\phi_2}} = \frac{\int \mathrm{d}\phi_1 \mathrm{d}\phi_2 e^{in(\phi_1-\phi_2)} \frac{\mathrm{d}N}{\mathrm{d}\phi_1} \frac{\mathrm{d}N}{\mathrm{d}\phi_2}}{\int \mathrm{d}\phi_1 \mathrm{d}\phi_2 \frac{\mathrm{d}N}{\mathrm{d}\phi_1} \frac{\mathrm{d}N}{\mathrm{d}\phi_2}} \\
&= \quad \{e^{in\phi_1}\}\{e^{-in\phi_2}\} = (a_n + ib_n)(a_n - ib_n) = v_n^2
\end{aligned}
$$

$$
\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi} \propto 1 + 2c_1\{2\}\cos\Delta\phi + 2c_2\{2\}\cos 2\Delta\phi + \cdots
$$

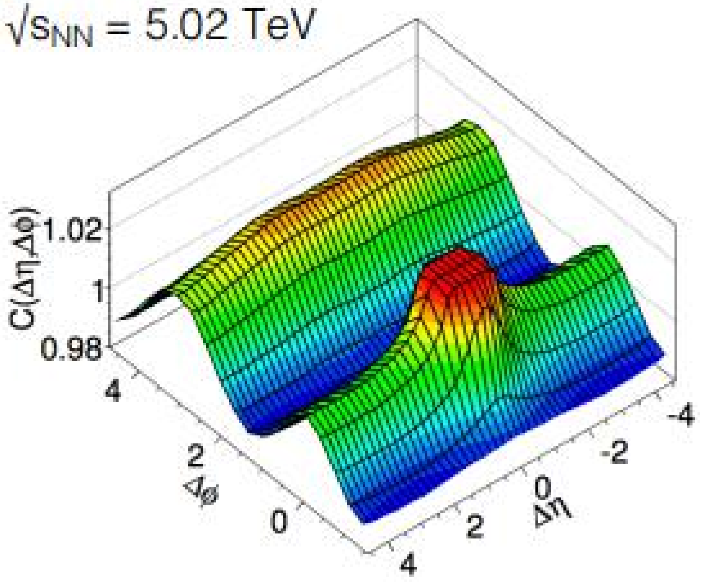
Pb+Pb

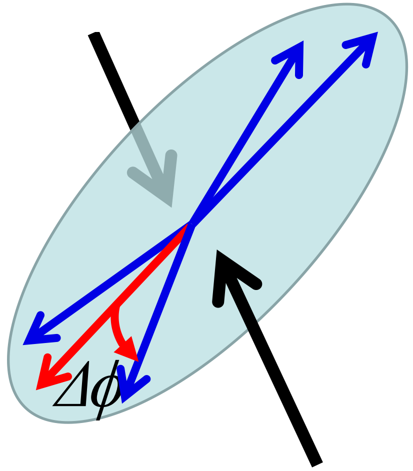
$\sqrt{s_{NN}}$ = 2.76 TeV



p+Pb

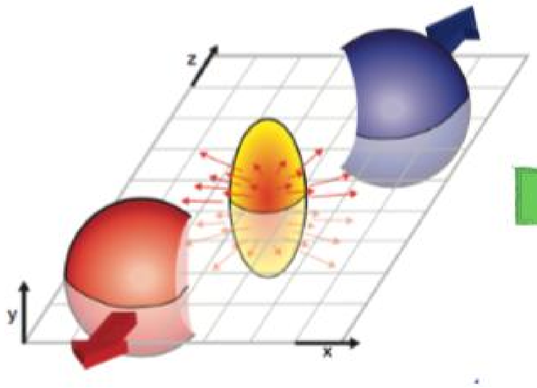
$\sqrt{s_{NN}}$ = 5.02 TeV



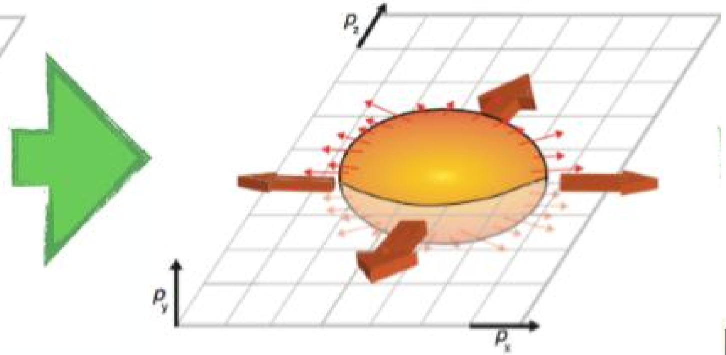


$$
v_2 = \sqrt{\{e^{i2\Delta\phi}\}}
$$

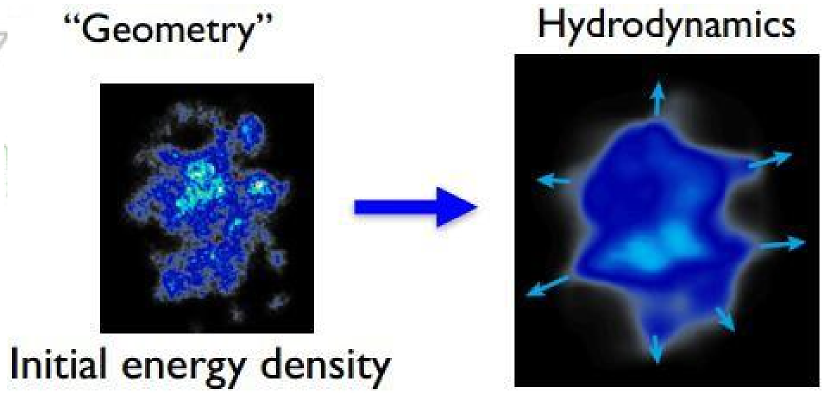
Anisotropic flow (vn) in small collisions: hydrodynamics

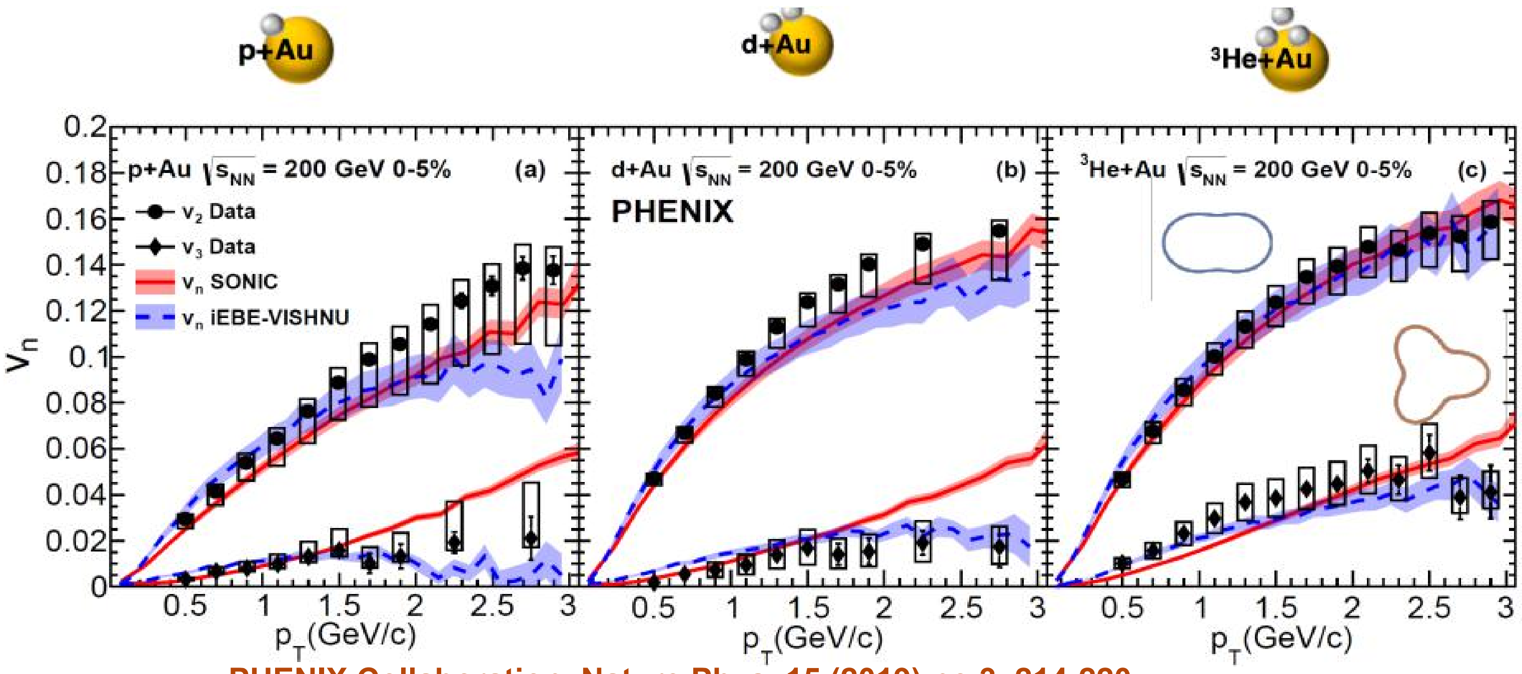


Initial geometric anisotropy (eccentricity)



Final state anisotropy (collectivity flow) — vn



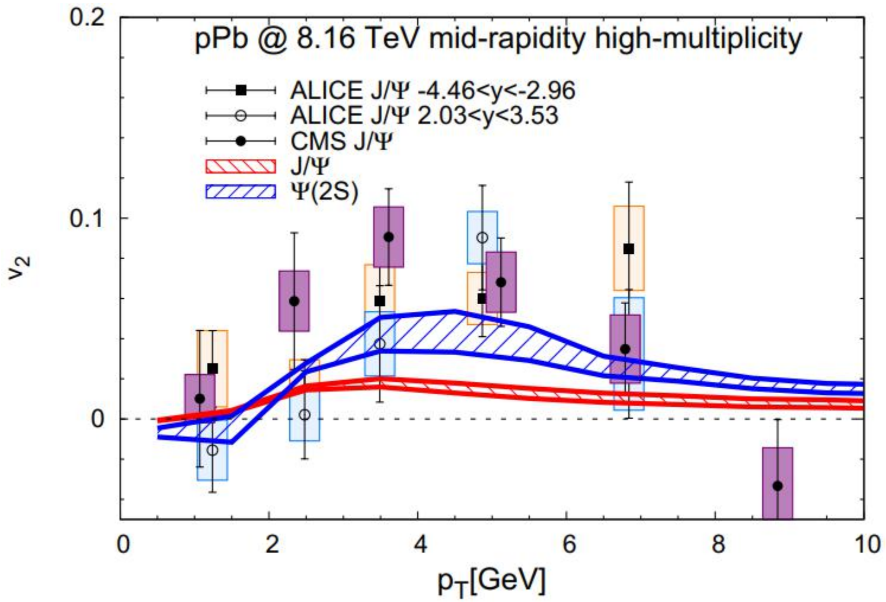


PHENIX Collaboration. Nature Phys. 15 (2019) no.3, 214-220.

has been well described by hydrodynamics.

J/ψ v_2 in pA collisions

Xiaojian Du, Ralf Rapp, JHEP 1903 (2019) 015.

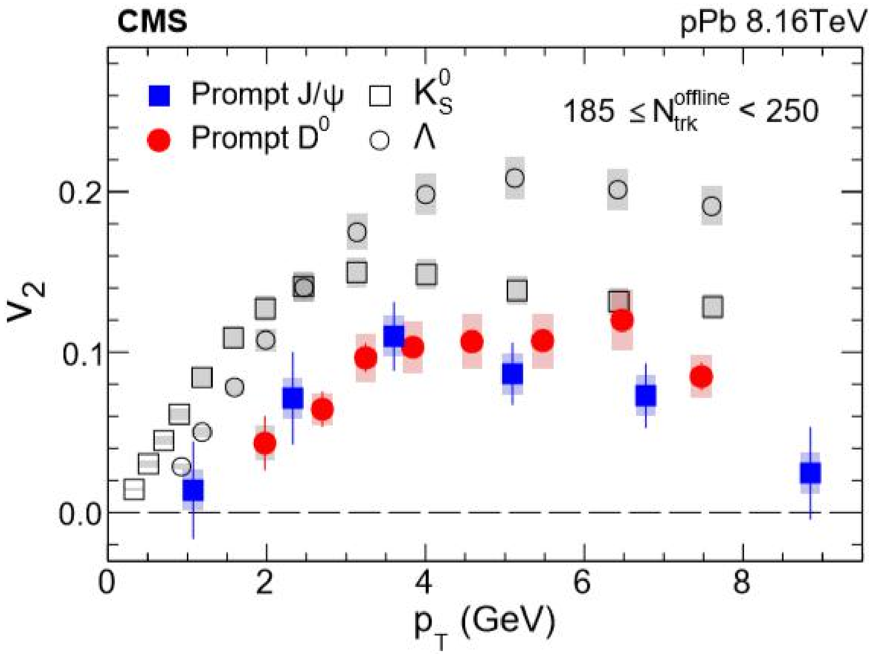


Pt dependent v2 for J/ψ within the elliptic fireball model (from final-state interactions).

Rarely flow due to its large mass.

not more than 2%

A. M. Sirunyan et al. [CMS Collaboration],Phys.Lett. B791 (2019) 172-194.

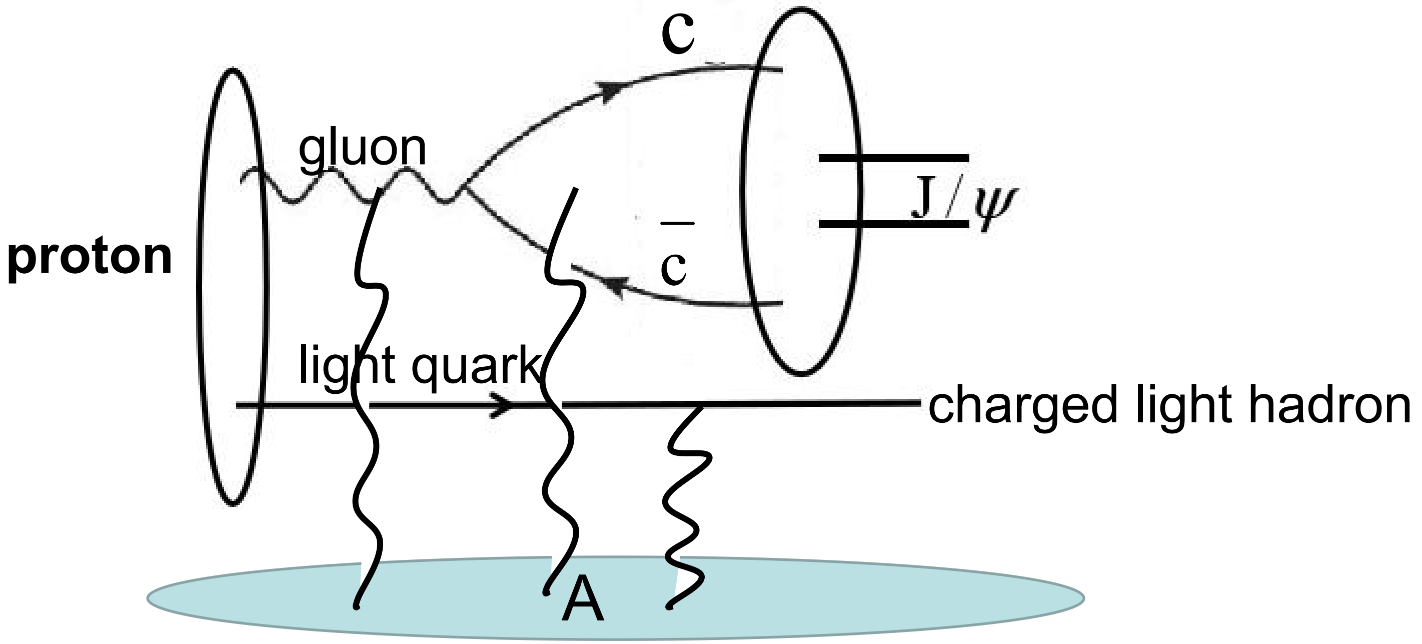


Pt dependent v2 for J/ψ at forward rapidities (−2.86 < ycm < −1.86 or 0.94 < ycm < 1.94).

up to 12%

The observed v2 cannot originate from final-state interactions alone.

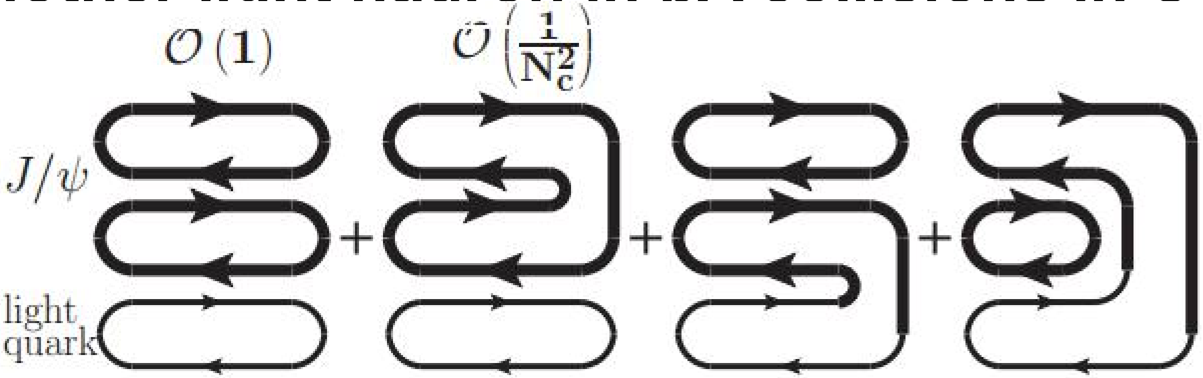
CGC model calculation: J/ψ production with another light hadron in pA collisions



$$\frac{\mathrm{d}N^{\mathrm{pA}\to \mathrm{J}/\psi \mathrm{qX}}}{\mathrm{d}^2\boldsymbol{k}\mathrm{d}^2\boldsymbol{k}_\mathrm{q}} = \mathcal{N}\int \mathrm{d}^2\boldsymbol{r}\prod_{i=1}^{2}\int \frac{\mathrm{d}^2\boldsymbol{b}_i\mathrm{d}^2\boldsymbol{r}_i\mathrm{d}^2\boldsymbol{p}_i}{(2\pi)^2 B_\mathrm{p}\Delta^2} W(\boldsymbol{b}_i,\boldsymbol{p}_i)e^{-\mathrm{i}(\boldsymbol{k}-\boldsymbol{p}_1)\cdot\boldsymbol{r}_1-\mathrm{i}(\boldsymbol{k}_\mathrm{q}-\boldsymbol{p}_2)\cdot\boldsymbol{r}_2}\left\langle DDD\right\rangle |\psi(\boldsymbol{r})|^2 F_{Q\bar{Q}\to \mathrm{J}/\psi}$$

$$\frac{\mathrm{d}N^{\mathrm{J}/\psi\mathrm{q}}}{\mathrm{d}\Delta\phi} = \kappa_0\left(1+2\sum_{n=1}^{\infty}\frac{\kappa_n}{\kappa_0}\cos n\Delta\phi\right) \quad v_2 \equiv \frac{\kappa_2}{\kappa_0}\Big/\sqrt{\frac{\kappa_2^\mathrm{q}}{\kappa_0^\mathrm{q}}}$$

J/ψ production with another light hadron in pA collisions in CGC



Correlations of J/ψ with the light hadron by scattering with gluon fields.

1. Wigner function

$$W(\boldsymbol{b},\boldsymbol{p}) = \frac{1}{\pi^2} e^{-\frac{\boldsymbol{b}^2}{B_p} - \frac{\boldsymbol{p}^2}{\Delta^2}}$$

2. Spliting function

$$\psi(\boldsymbol{r})\psi^*(\boldsymbol{r}') \equiv \sum_{\lambda\alpha\beta} \psi^{T\lambda}_{\alpha\beta}(\boldsymbol{r})\psi^{T\lambda *}_{\alpha\beta}(\boldsymbol{r}') = \frac{8\pi^2 m_Q^2}{k_g^+}\left[\frac{1}{2}K_1(m_Q r)K_1(m_Q r')\frac{\boldsymbol{r}\cdot\boldsymbol{r}'}{rr'} + K_0(m_Q r)K_0(m_Q r')\right]$$

propogator~$1/M_Q$

3. Gluon and quark scattering operator

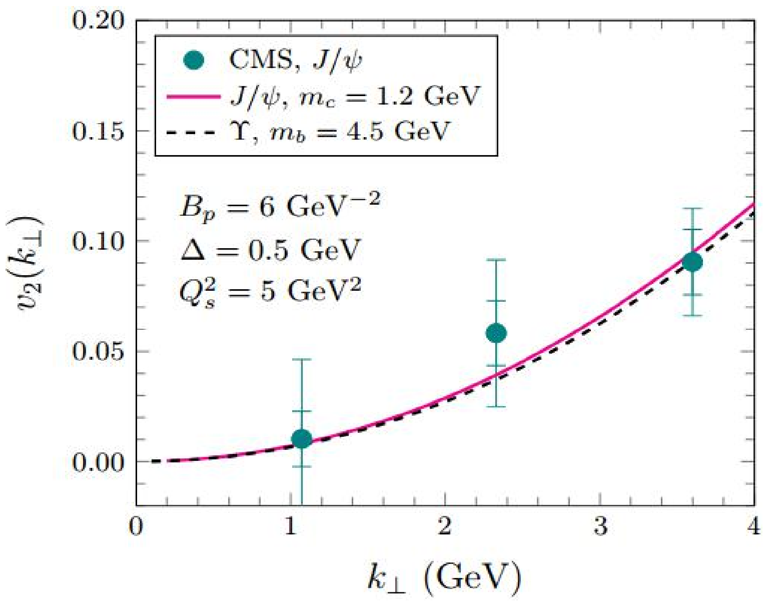
$$\begin{aligned} DDD \equiv\ & [D(\boldsymbol{x}_Q,\boldsymbol{x}'_Q)D(\boldsymbol{x}'_{\bar{Q}},\boldsymbol{x}_{\bar{Q}}) + D(\boldsymbol{x}_g,\boldsymbol{x}'_g)D(\boldsymbol{x}'_g,\boldsymbol{x}_g) - D(\boldsymbol{x}_Q,\boldsymbol{x}'_g)D(\boldsymbol{x}'_g,\boldsymbol{x}_{\bar{Q}}) \\ & -D(\boldsymbol{x}'_{\bar{Q}},\boldsymbol{x}_g)D(\boldsymbol{x}_g,\boldsymbol{x}'_Q)]D(\boldsymbol{x}_q,\boldsymbol{x}'_q) \end{aligned}$$

In MV model:

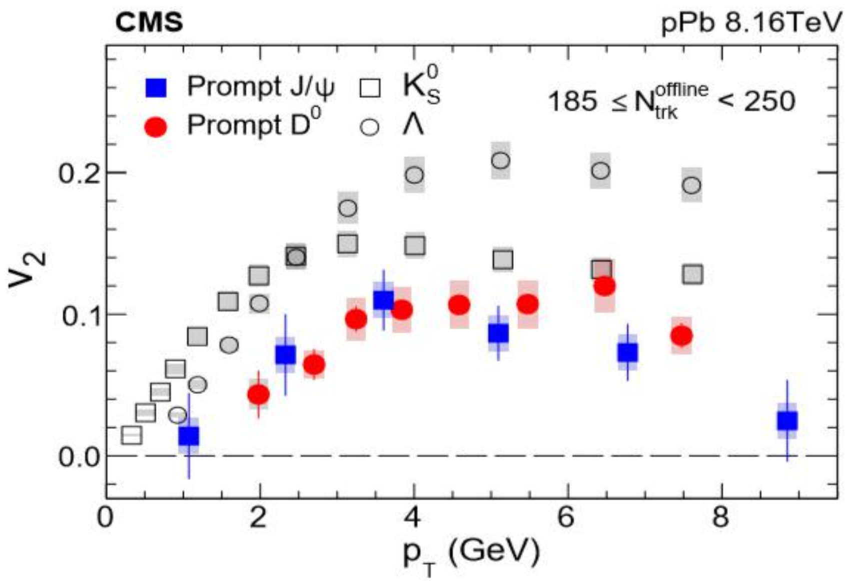
$$\begin{aligned} \langle D(\boldsymbol{x}_1,\boldsymbol{x}'_1)D(\boldsymbol{x}_2,\boldsymbol{x}'_2)D(\boldsymbol{x}_3,\boldsymbol{x}'_3)\rangle =\ & e^{-\frac{Q_s^2}{4}\left[(\boldsymbol{x}_1-\boldsymbol{x}'_1)^2+(\boldsymbol{x}_2-\boldsymbol{x}'_2)^2+(\boldsymbol{x}_3-\boldsymbol{x}'_3)^2\right]}\left[1 + F(\boldsymbol{x}_1,\boldsymbol{x}'_1,\boldsymbol{x}_2,\boldsymbol{x}'_2)\right. \\ & \left.+F(\boldsymbol{x}_2,\boldsymbol{x}'_2,\boldsymbol{x}_3,\boldsymbol{x}'_3) + F(\boldsymbol{x}_1,\boldsymbol{x}'_1,\boldsymbol{x}_3,\boldsymbol{x}'_3)\right], \end{aligned}$$

$$F(\boldsymbol{x}_1,\boldsymbol{x}'_1,\boldsymbol{x}_2,\boldsymbol{x}'_2) \equiv \frac{\left[Q_s^2(\boldsymbol{x}_1-\boldsymbol{x}'_1)\cdot(\boldsymbol{x}_2-\boldsymbol{x}'_2)\right]^2}{4N_c^2}\int_0^1 d\xi \int_0^\xi d\eta\, e^{\frac{\eta Q_s^2}{2}(\boldsymbol{x}_1-\boldsymbol{x}_2)\cdot(\boldsymbol{x}'_2-\boldsymbol{x}'_1)}$$

Heavy quakonia (J/ψ, Y) v2 in pA collisions: numerical results



C. Zhang, C. Marquet, G. Y. Qin, S. Y. Wei and B. W. Xiao, Phys. Rev. Lett. 122, no. 17, 172302 (2019).



A. M. Sirunyan et al. [CMS Collaboration], Phys.Lett. B791 (2019) 172-194.

Y meson has a similar v2, which can be tested in future measurements.

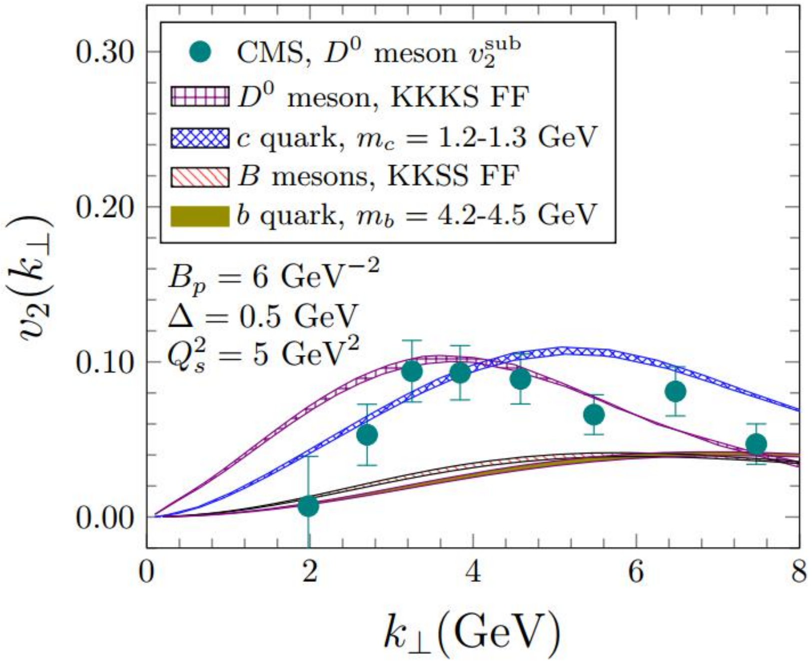
In high kt region:

1. Higher order large Nc corrections to be considered (Our calculation is only up to 1/Nc^2).
2. Higher order gluon radiations to be considered.
3. Our simple Gaussian parametrization of dipole amplitudes is not accurate.

Our simple model calcualtion should be improved.

Recent results: v2 of open heavy flavor D0, B mesons in pA collisions

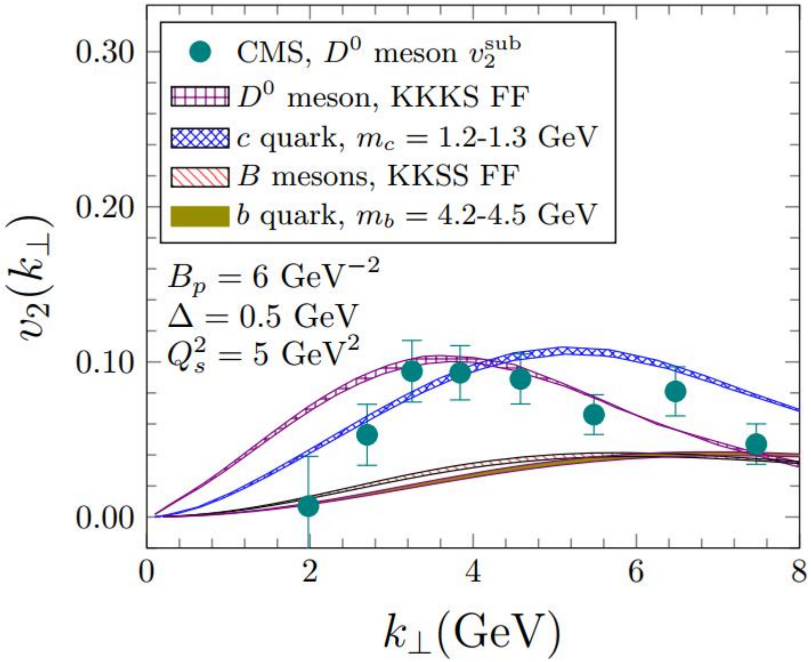
v2 subtracts (jet-like) correlations
from low multiplicity events

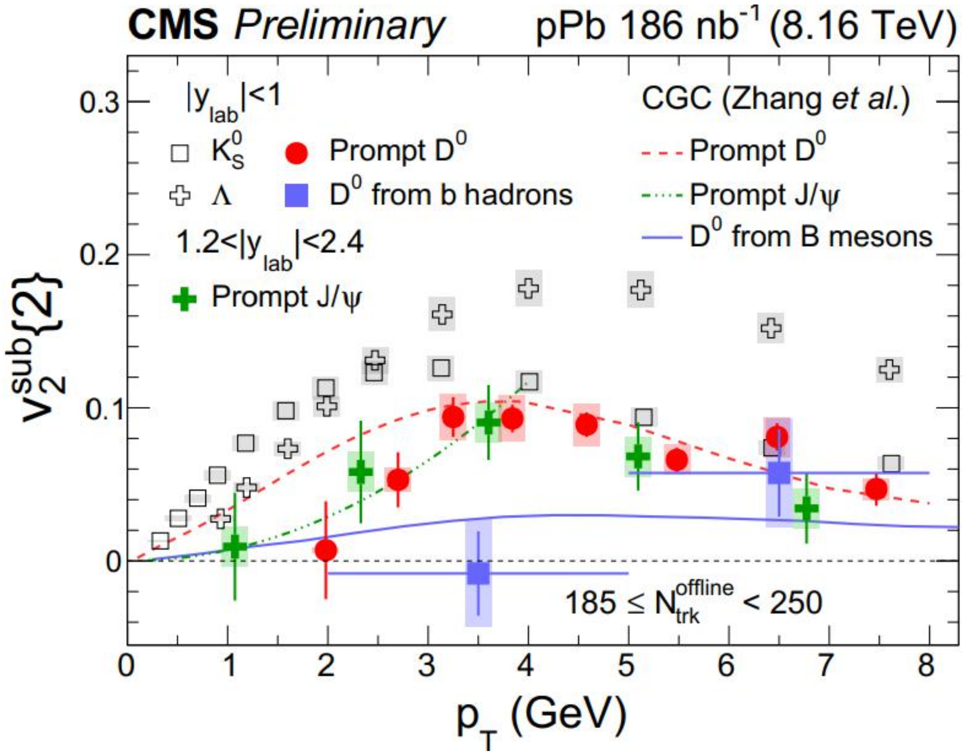


1. Using the same set of parameters and framework, our D meson v2 agrees with CMS data.
2. We predict that B meson v2 is much smaller than D meson v2 (strong mass dependence). Mc<Qs<Mb

Recent results: v2 of open heavy flavor D0, B mesons in pA collisions

v2 subtracts (jet-like) correlations from low multiplicity events





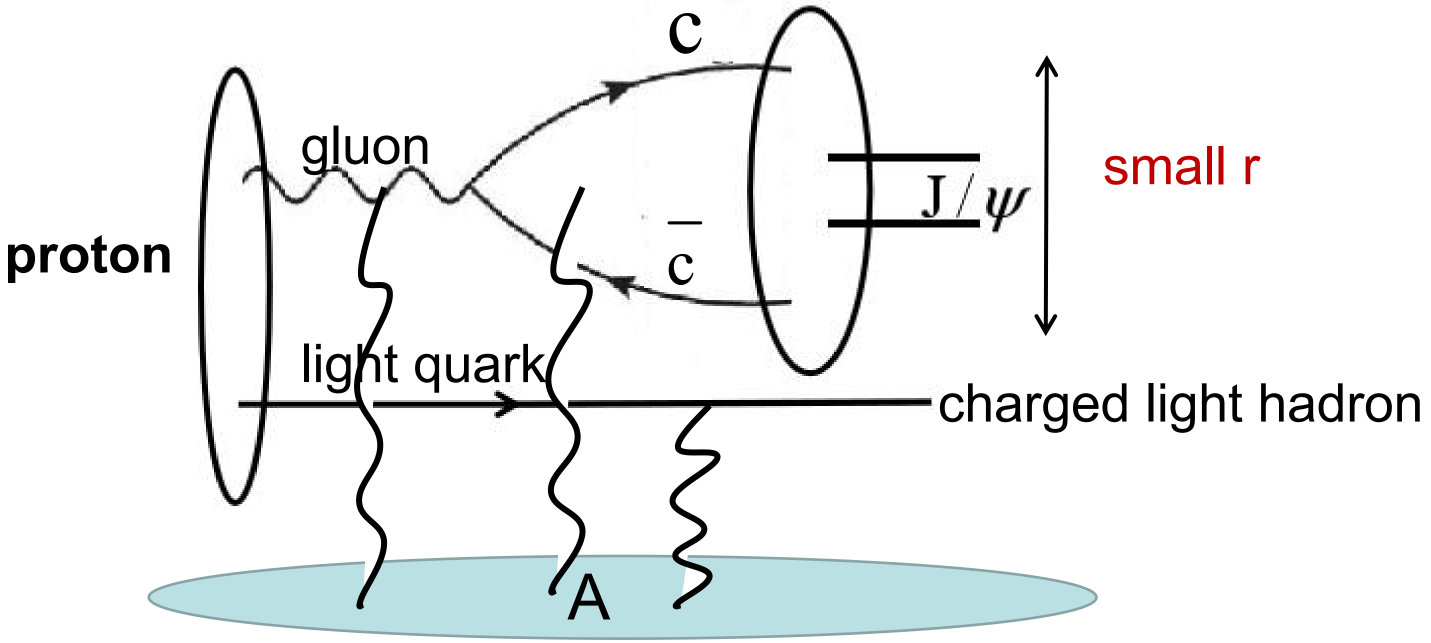
A prediction of B meson v2 (no-prompt D0 v2) precisely agrees with CMS data.

[500] A. Baty Tue 08:40
CMS-PAS-HIN-19-009

1. Using the same set of parameters and framework, our D meson v2 agrees with CMS data.
2. We predict that B meson v2 is much smaller than D meson v2 (strong mass dependence). Mc<Qs<Mb
3. Convolute B meson v2 with a decay kinematics to get a D meson v2, which precisely agrees with CMS data.
4. Although the total kt of heavy-quark pair should be small, both of them can have a large kt in opposite directions. (hard splitting)

(Poster by Yu Shi & Lei Wang, small system 34)

Mass dependence in v2: Heavy quakonia vs. open heavy flavor

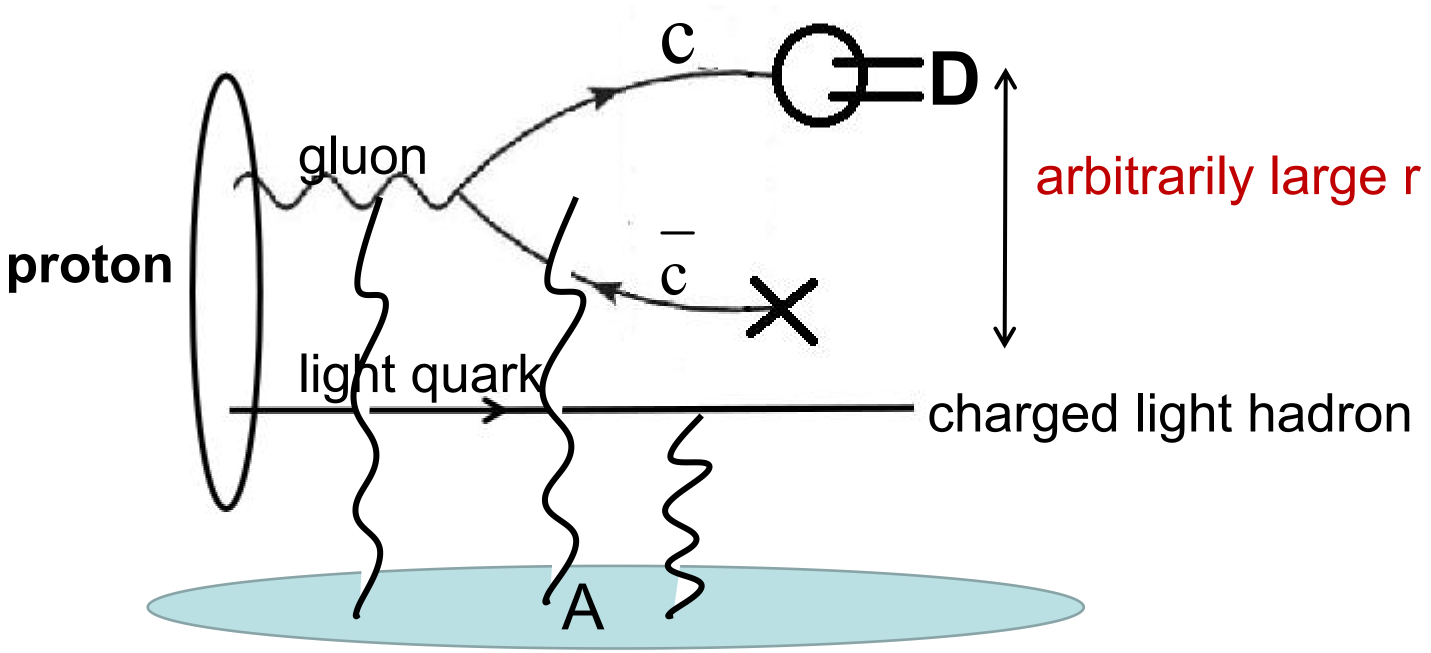


$$\frac{dN^{\mathrm{pA}\to \mathrm{J}/\psi \mathrm{qX}}}{d^2\boldsymbol{k}^{\mathrm{J}/\psi} d^2\boldsymbol{k}_{\mathrm{q}}} = \int d^2\Delta\boldsymbol{k}_{c\bar{c}} \int_{\boldsymbol{b},\boldsymbol{p},\boldsymbol{r}} W(\boldsymbol{b},\boldsymbol{p}) \langle DDD\rangle |\psi(\boldsymbol{r}, m_c)|^2 F_{Q\bar{Q}\to \mathrm{J}/\psi}$$

mass dependence

$$\frac{dN^{\mathrm{J}/\psi \mathrm{q}}}{d\Delta\phi} = \kappa_0 \left(1 + 2\sum_{n=1}^{\infty} \frac{\kappa_n}{\kappa_0} \cos n\Delta\phi\right) \quad v_2 \equiv \frac{\kappa_2}{\kappa_0} \Big/ \sqrt{\frac{\kappa_2^{\mathrm{q}}}{\kappa_0^{\mathrm{q}}}}$$

Mass dependence in v2: Heavy quakonia v.s. open heavy flavor



$$\frac{dN^{pA\to D^0 qX}}{d^2\boldsymbol{k}^{D^0} d^2\boldsymbol{k}_q} = \int d^2\boldsymbol{k}_{\bar{c}} \int_{\boldsymbol{b},\boldsymbol{p},\boldsymbol{r}} W(\boldsymbol{b},\boldsymbol{p}) \langle DDD \rangle |\psi(\boldsymbol{r}, m_c)|^2 D_{c\to D^0}(z)$$

mass dependence

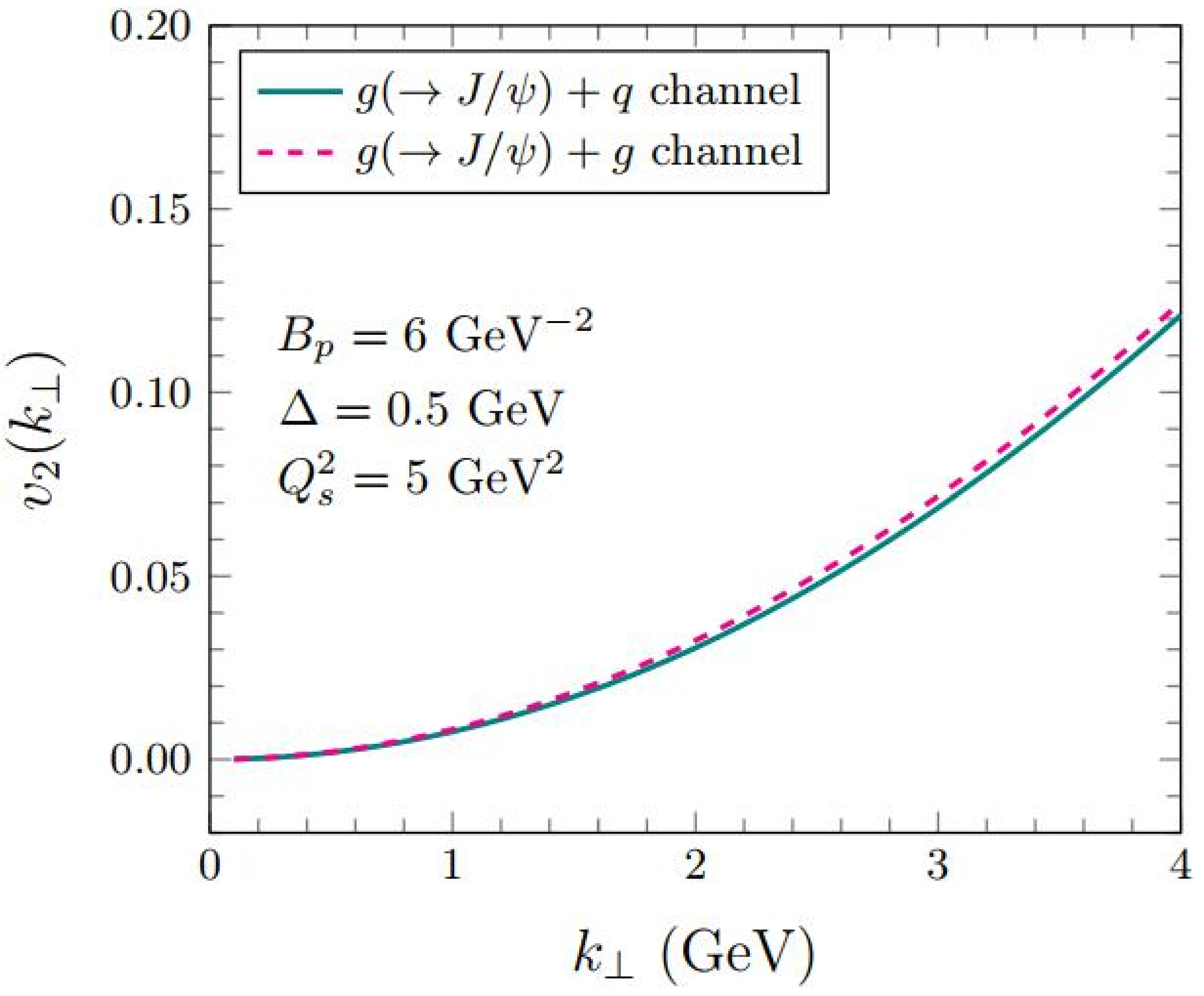
$$\frac{dN^{D^0 q}}{d\Delta\phi} = \kappa_0 \left(1 + 2\sum_{n=1}^{\infty} \frac{\kappa_n}{\kappa_0} \cos n\Delta\phi\right) \quad v_2 \equiv \frac{\kappa_2}{\kappa_0} \Big/ \sqrt{\frac{\kappa_2^q}{\kappa_0^q}}$$

Summery and outlook:

- Heavy quarkonia & open heavy flavor can have a significant v2 in small system due to azimuthal angular correlations from the initial state.
- A weak mass dependence among heavy quarkonia v2 & A strong mass dependence among open heavy flavor.
- Integrating over one heavy quark's momentum and measure the other heavy quark, one can compute v2 for open heavy flavor, namely, D0, B mesons.

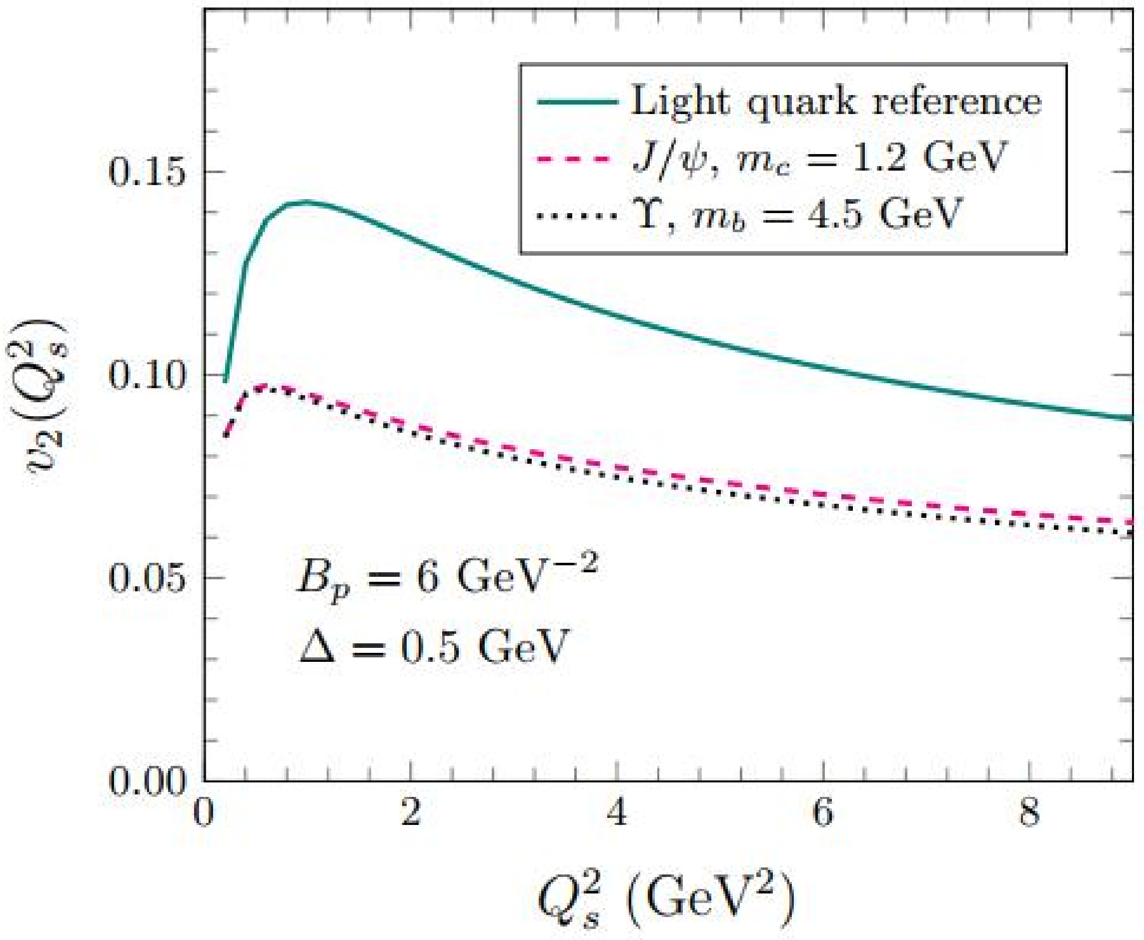
(Poster by Yu Shi & Lei Wang, small system 34)

Back up



The comparison between the elliptic flow from the quark channel and the gluon channel, which shows these two channels have similar magnitudes in v2.

Back up



The integrated v2 of J/ψ and Y compared with the v2 of the reference light quark as functions of the saturation momentum Qs^2.