Charm flow (v_2) measurements based on Quark Matter 2022

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Physics motivation

- ❑ Most HQ (charm) produced in primordial stage of collision(~ 0.1fm/c), due to large mass:

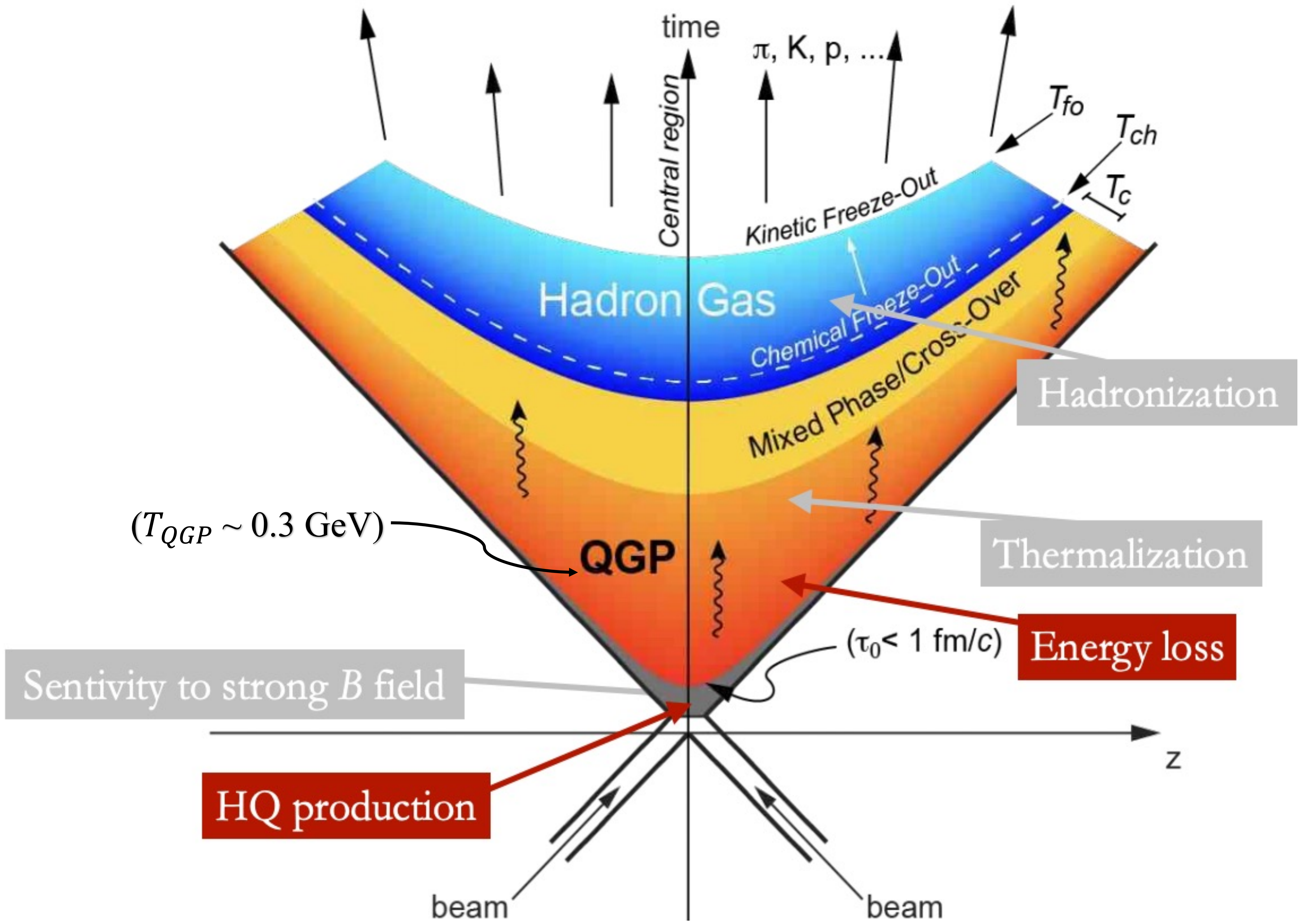
$$m_c \sim 1.3\ \mathrm{GeV}/c^2 \qquad\qquad m_Q \gg T_{QGP}$$

➔ Produced in the initial hard scatterings.

➔ Experience the full evolution of the system.

- ❑ Allow perturbative calculations[1].

$$m_Q \gg \Lambda_{QGP}. \quad (\Lambda_{QGP} \sim 0.226\ \mathrm{GeV})$$



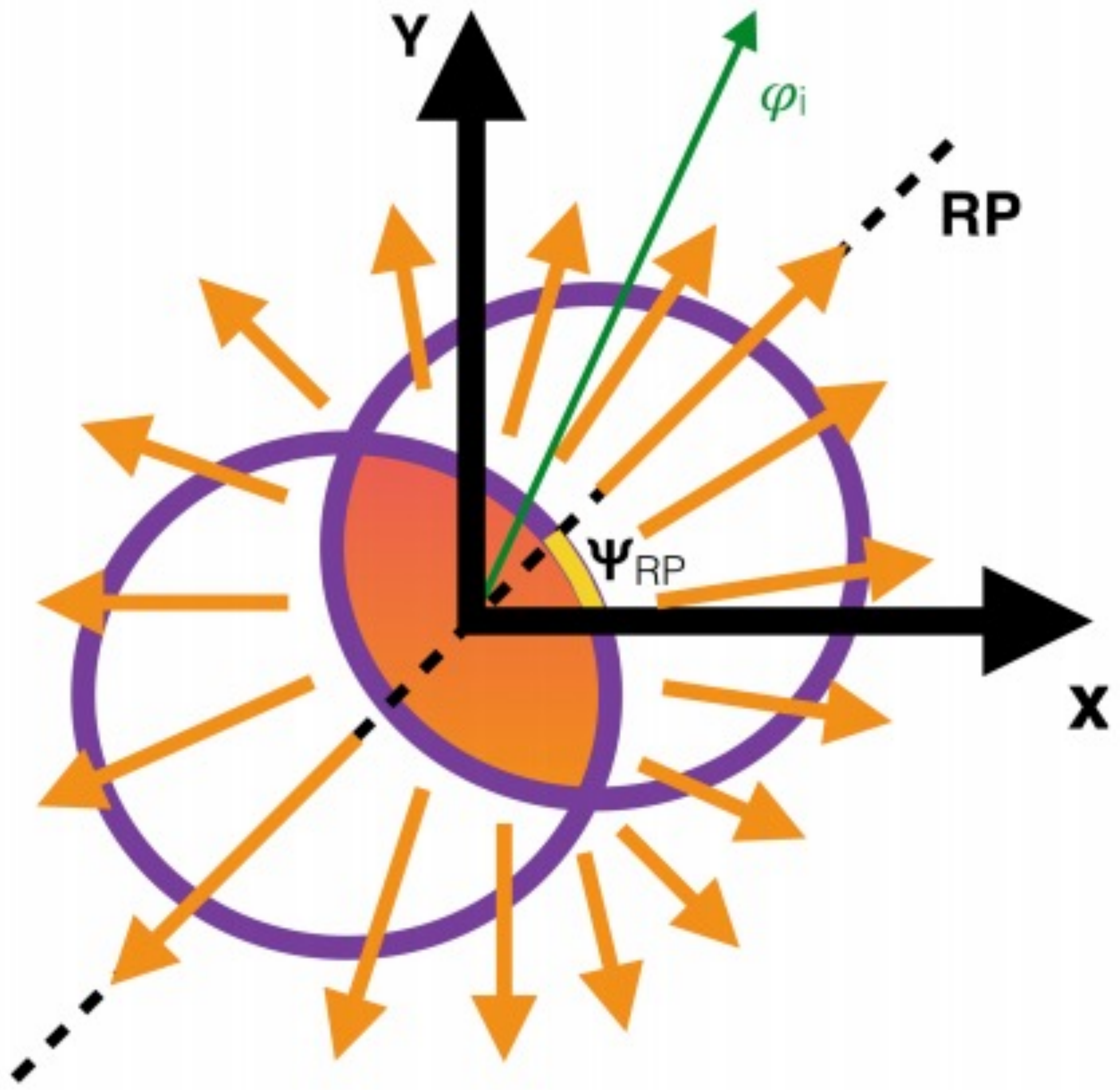
1. Cacciari M, Nason P, Vogt R. *Phys.Rev.Lett.*95:122001(2005)

Physics motivation (azimuthal anisotropies)

➢ The collectivity of participation in the fireball .

$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\{1 + \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_R)]\}$$

- Event plane [1]: $v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$. $(\Psi_{RP}$, Res.)
- 2-particle correlation [2]: $\frac{d^2N^{pair}}{d\Delta\eta\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$
- Scalar product [4] : $v_n\{SP\} \equiv \frac{\langle Q_n^{D^0} Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA}\ Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$
- Cumulants [3]: $v_n'\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}$ (for 4th-order)…
- Lee-Yang Zero [5]



[1]. Z. Phys. C 70, 665 (1996)

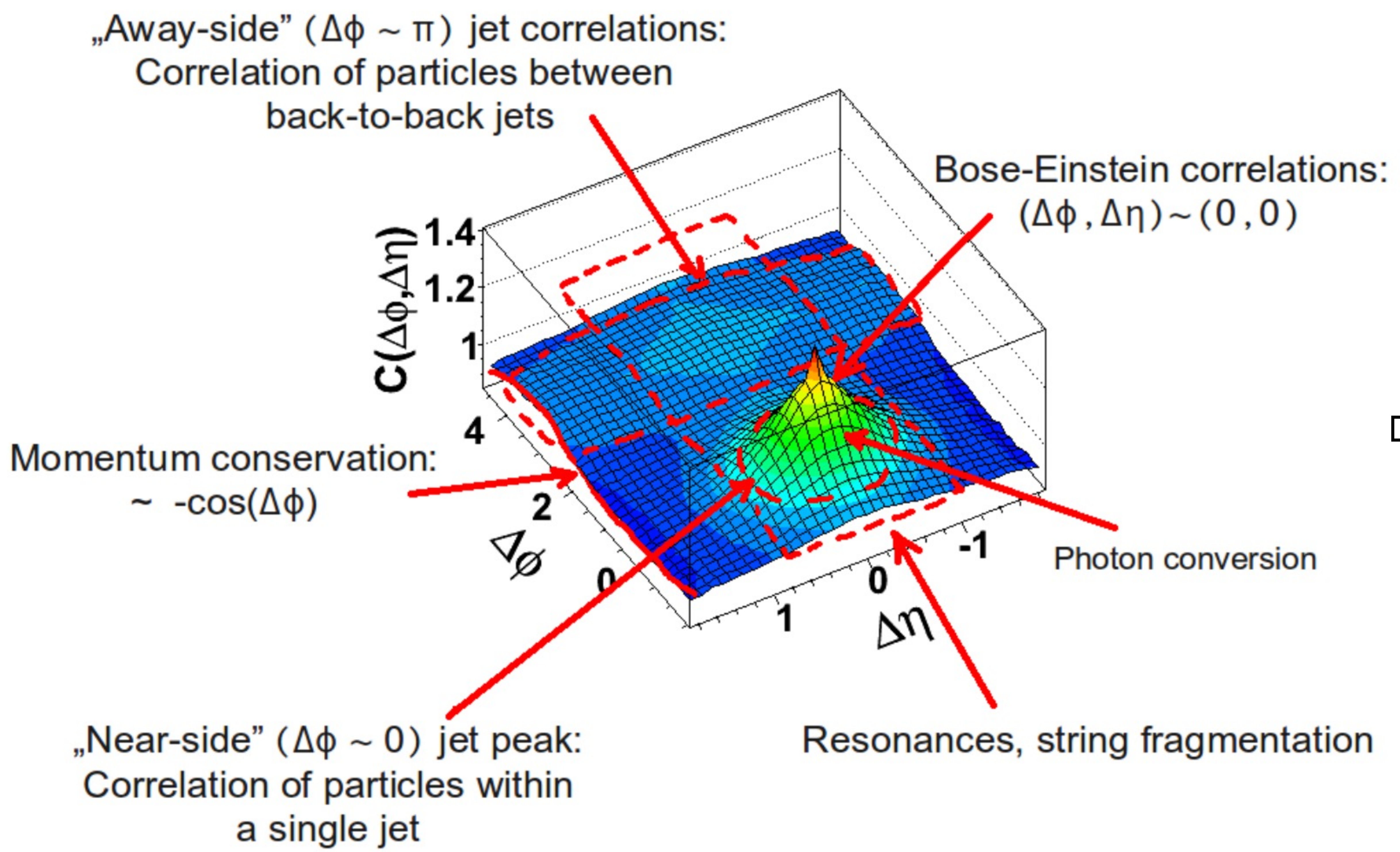
[2]. Phys. Rev. Lett. 121, 082301 (2018)

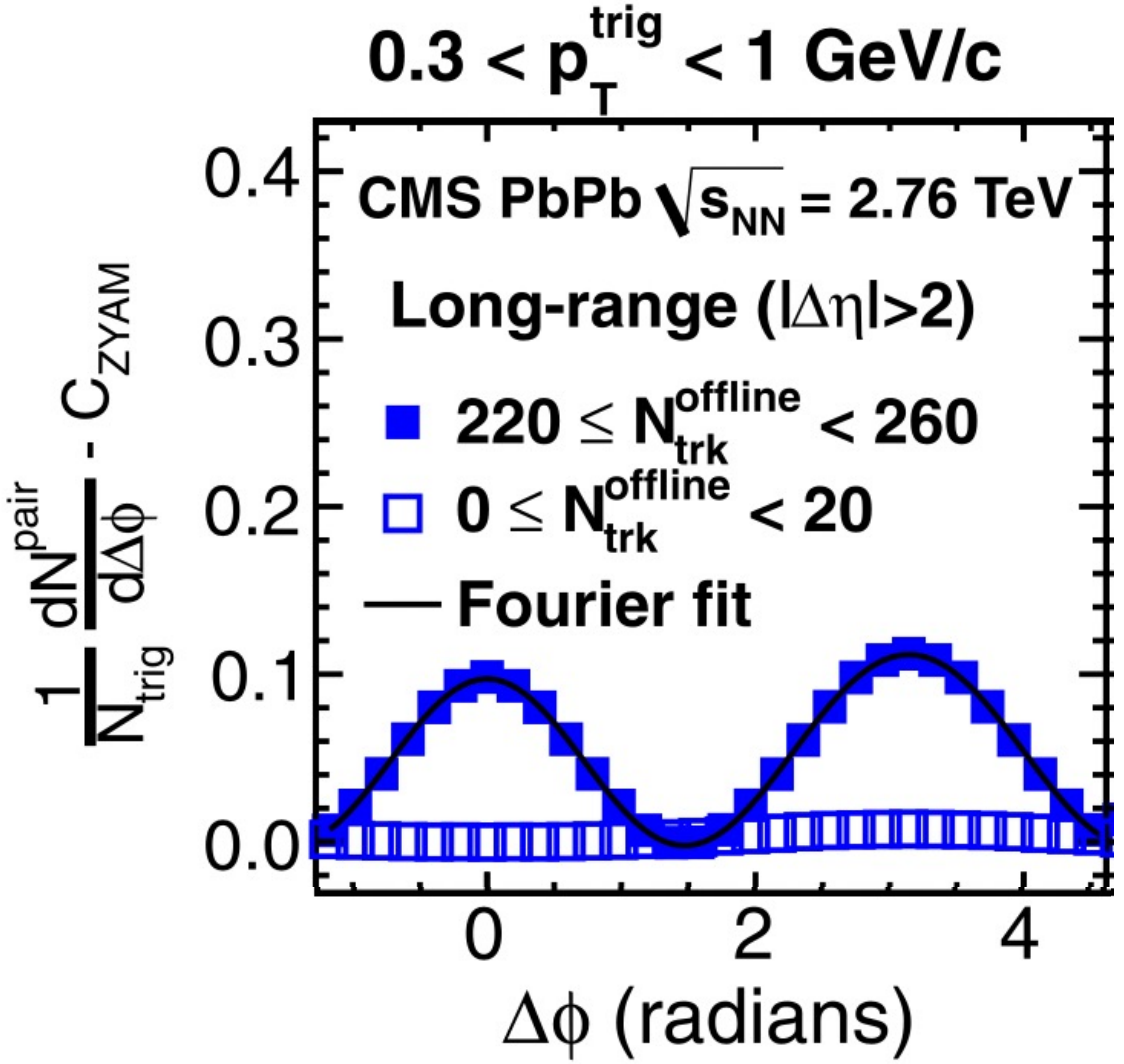
[3]. Phys. Rev. C 83, 044913 (2011)

[4]. Phys. Rev. Lett. 120, 202301 (2018)

[5]: Phys. Lett. B 580, 157(2004)

Two-particle correlation

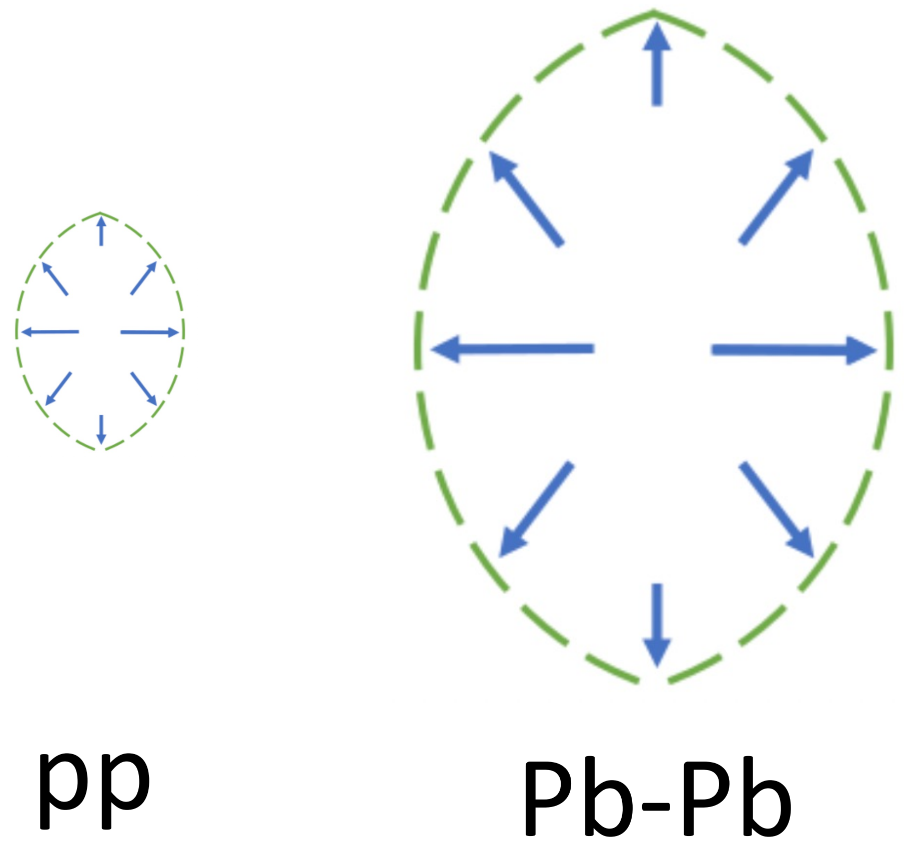


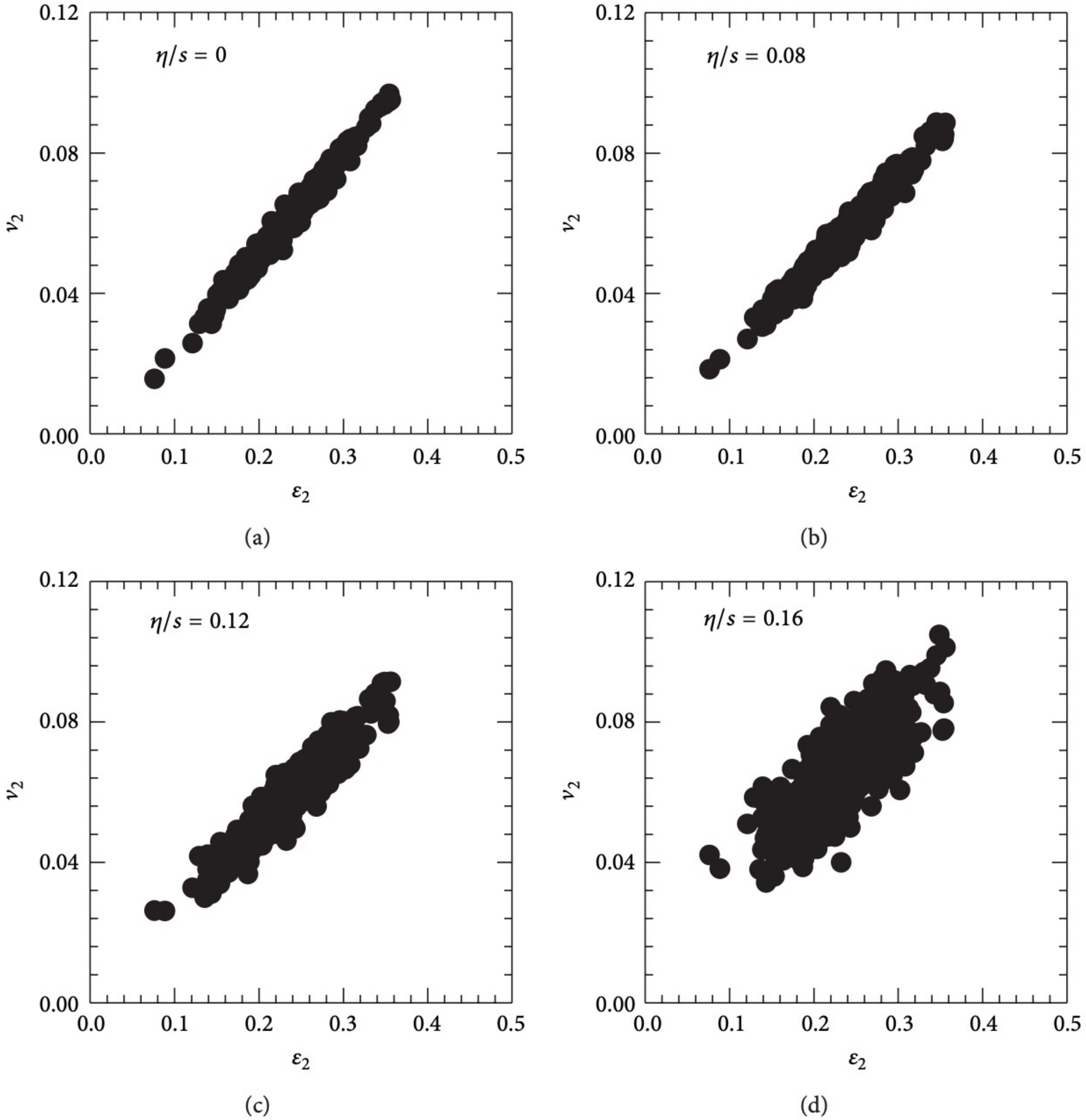


What sources influence the flow amplitude?

❑ Initial eccentricity

eccentricity (ϵ_2). Each panel contains 500 data points. In ideal fluid, v_2 and ϵ_2 are strongly correlated, $v_2 \propto \epsilon_2$. Evidently, the correlation is gradually weakened as the viscosity of the fluid is increased. The result is not unexpected. As argued earlier, in viscous fluid, correlation between elliptic flow and initial eccentricity is reduced due to introduction of the additional length scale. Cor-

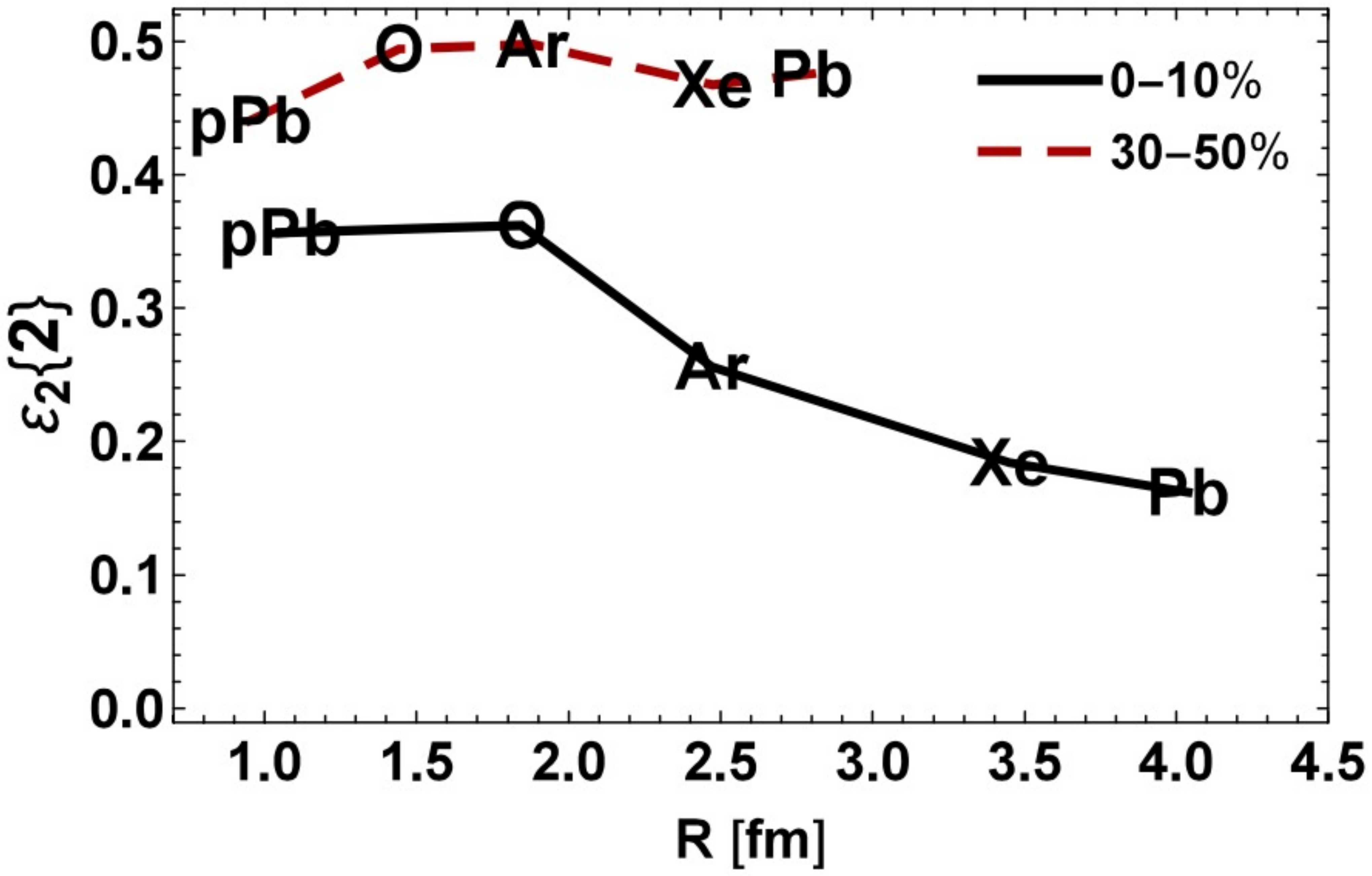


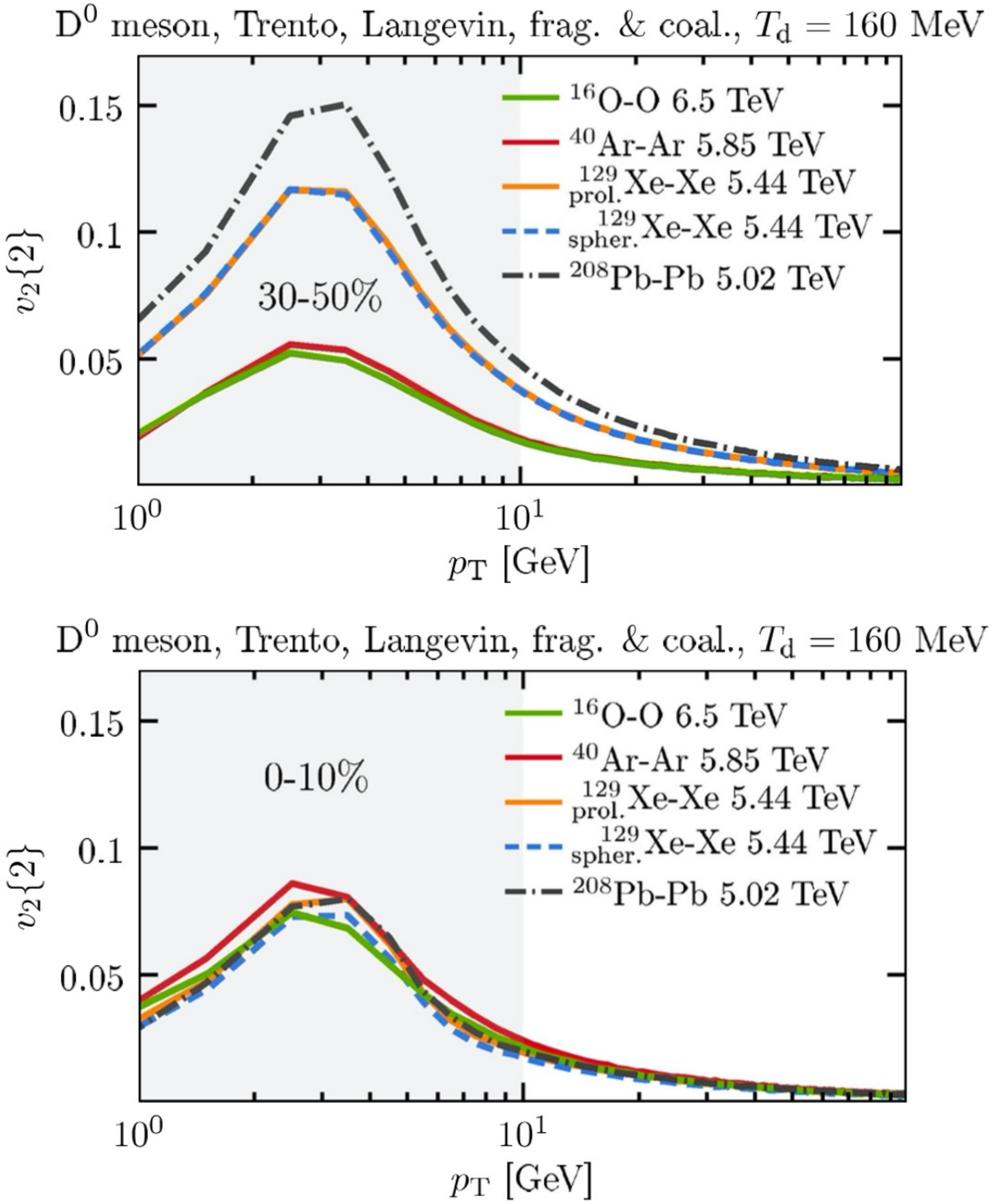


PLB 713 (2012) 91

What sources influence the flow amplitude?

❑ system length scale

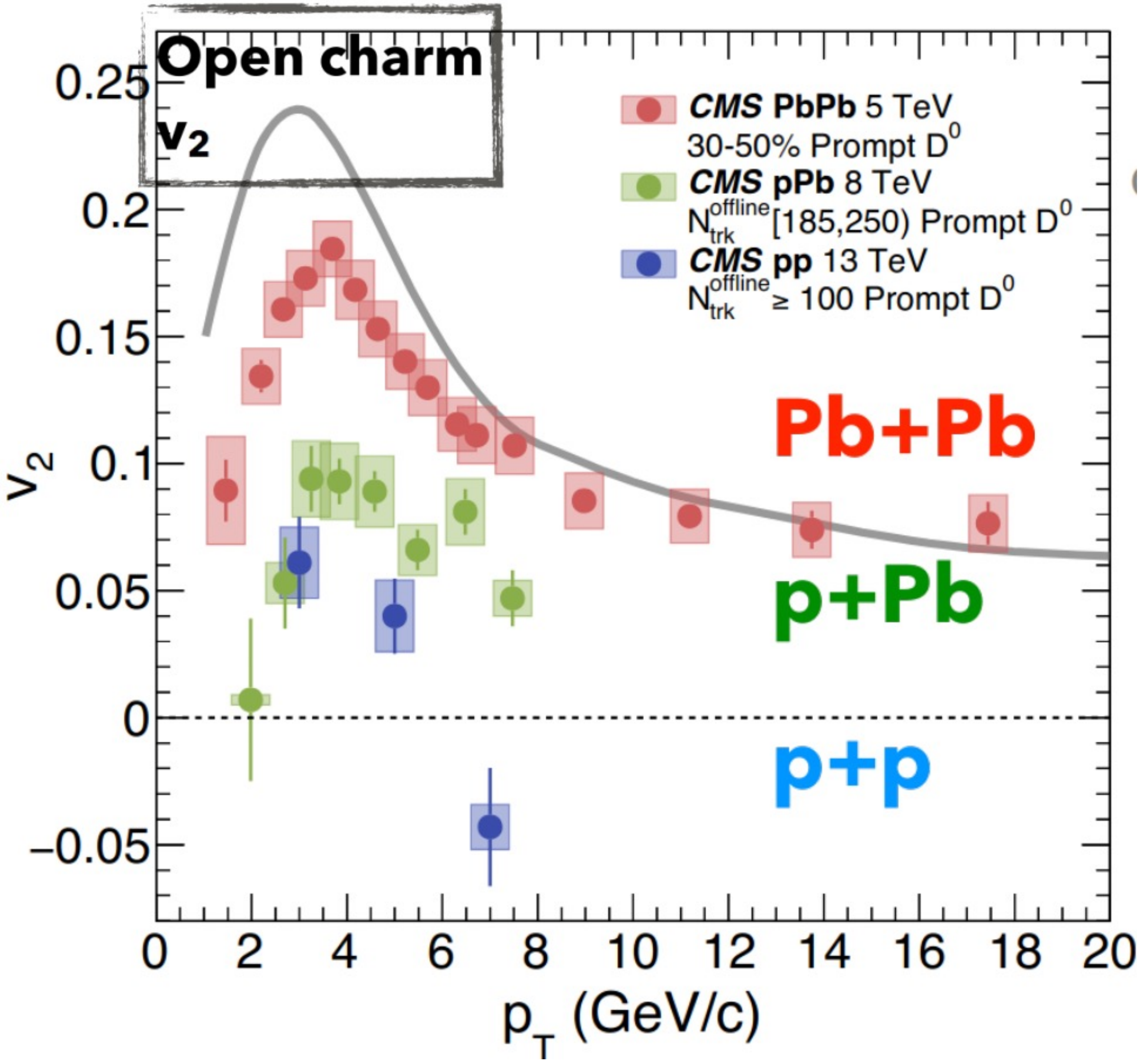




arXiv:1907.03308

$\varepsilon_2\uparrow\ v_2\uparrow$, $R\uparrow\ v_2\uparrow$

- Mid-central (30-50%): ε_2 const
- Most-central(0-10%): $\varepsilon_2\downarrow$



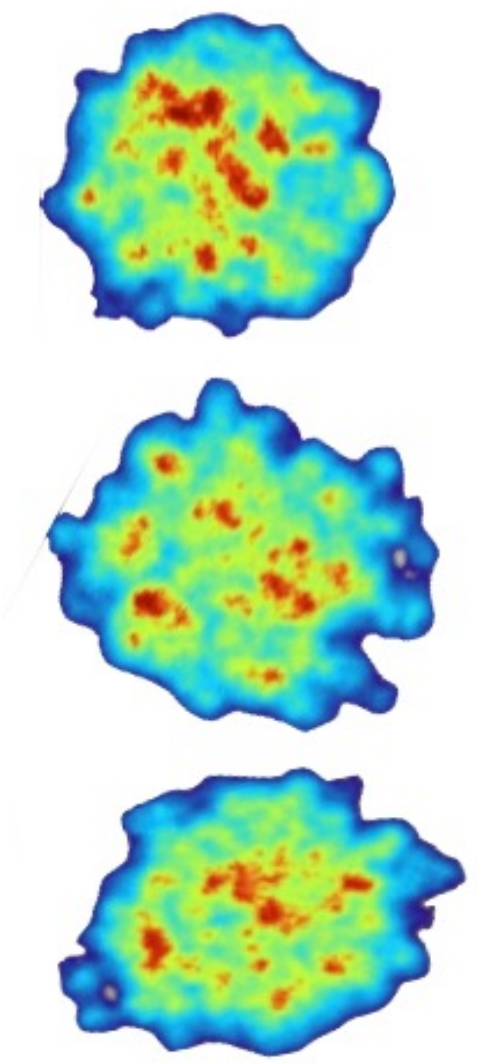
open charm v_2 ↑ with increasing system size

What sources influence the flow amplitude?

- flow fluctuation

What is flow fluctuation?

Many collisions



⋮

Each with own evolution

$$\frac{dN}{d\phi} = N_a\left[1+2\sum_n \mathrm{v}_{n,a}\cos n\left(\phi-\Phi_{n,a}\right)\right]$$

$$\frac{dN}{d\phi} = N_b\left[1+2\sum_n \mathrm{v}_{n,b}\cos n\left(\phi-\Phi_{n,b}\right)\right]$$

$$\frac{dN}{d\phi} = N_c\left[1+2\sum_n \mathrm{v}_{n,c}\cos n\left(\phi-\Phi_{n,c}\right)\right]$$

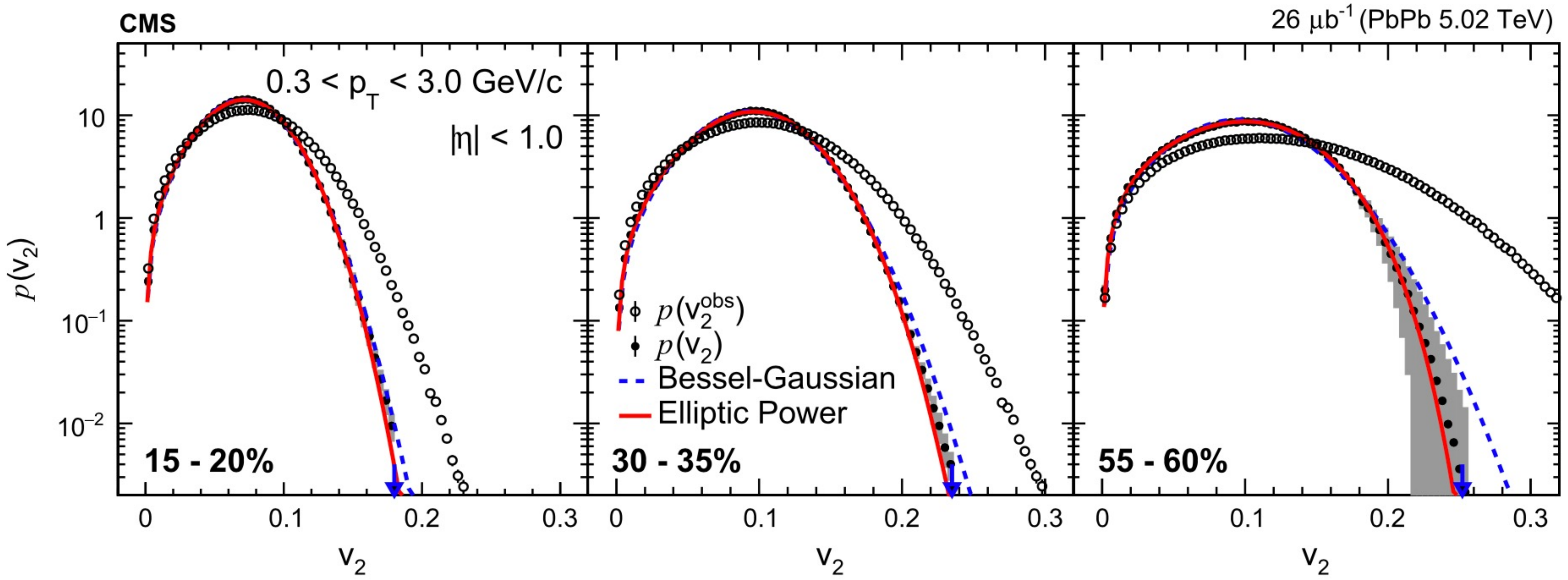
⋮

Event-by-event fluctuations

↓

$p(v_n)$

↓



PLB 789 (2019) 643–665

$$\boxed{\langle {v_n}^k \rangle \not\approx \langle v_n \rangle^k}$$

How to measure the flow fluctuation? $v_2\{4\}/v_2\{2\}$

$$v_2\{2\}^2 \sim \underbrace{\overset{\text{flow(EP)}}{\langle v\rangle^2} + \overset{\text{non-flow}}{\delta} + \overset{\text{flow fluctuation}}{\sigma_v^2}}$$

$$v_2\{4\}^2 \sim \underbrace{\overset{\text{flow(EP)}}{\langle v\rangle^2} - \overset{\text{flow fluctuation}}{\sigma_v^2}}$$

$\boxed{v_2\{4\}/v_2\{2\}}$: sensitive to flow fluctuations if non-flow is negligible.

Physics motivation: $v_2\{4\}/v_2\{2\}$ (fluctuation)

$$\frac{v_n\{4\}(p_\mathrm{T})}{v_n\{2\}(p_\mathrm{T})} = \frac{v_n\{4\}}{v_n\{2\}}\left[1 + \left(\frac{v_n\{2\}}{v_n\{4\}}\right)^4 \left(\underbrace{\frac{\langle v_n^4\rangle}{\langle v_n^2\rangle^2}}_{\text{soft fluctuations}} - \underbrace{\frac{\langle v_n^2 V_n V_n^*(p_\mathrm{T})\rangle}{\langle v_n^2\rangle\langle V_n V_n^*(p_\mathrm{T})\rangle}}_{\text{hard fluctuations}}\right)\right], \quad (1)$$

soft fluctuations ➡ initial condition fluctuation

hard fluctuations ➡ energy loss fluctuation

- only soft fluctuation:

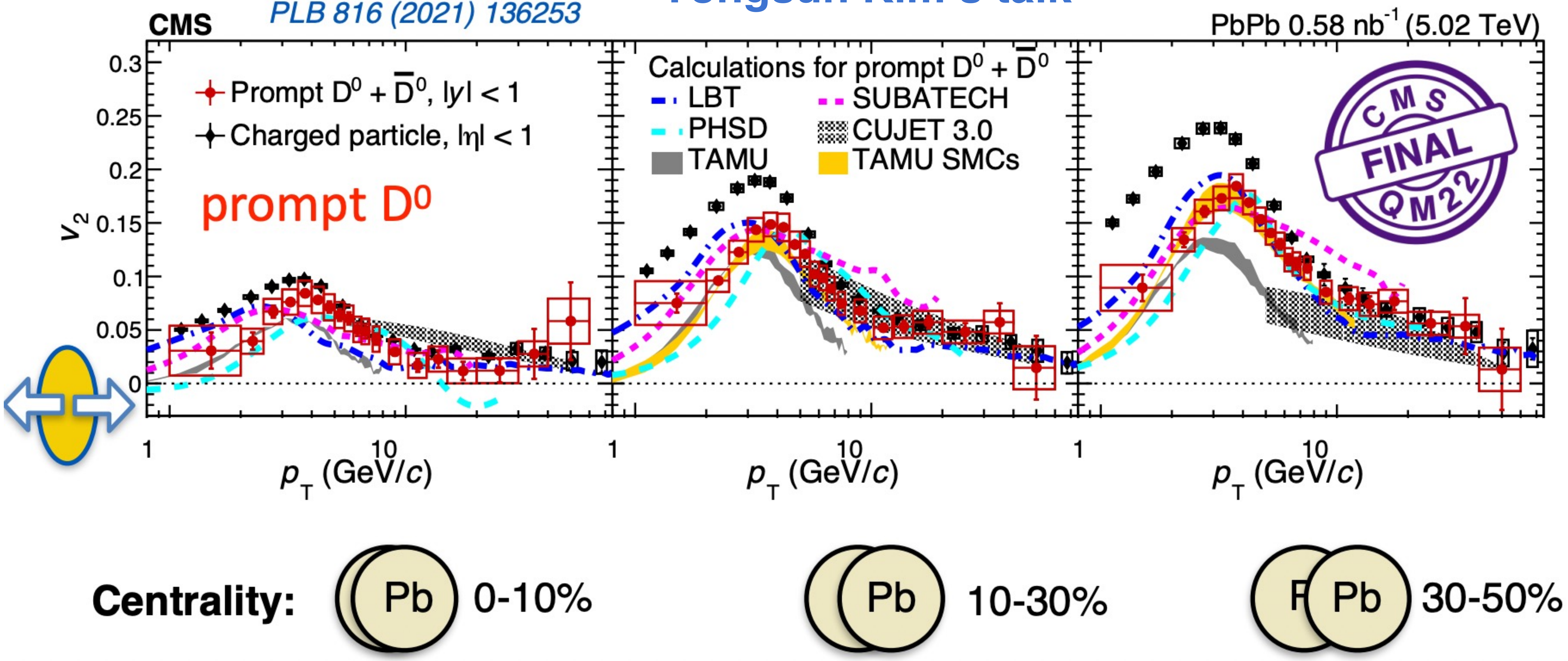
$$V_n(p_\mathrm{T}) = v_n(p_\mathrm{T})\,\mathrm{e}^{in\psi_n(p_\mathrm{T})} \; (2) \quad ➡ \quad V_n = v_n\,\mathrm{e}^{in\psi_n} \quad (3)$$

$$\frac{\langle v_n^2 V_n V_n^*(p_\mathrm{T})\rangle}{\langle v_n^2\rangle\langle V_n V_n^*(p_\mathrm{T})\rangle} \to \frac{\langle v_n^4\rangle}{\langle v_n^2\rangle^2}, \quad ➡ \quad \frac{v_n\{4\}(p_\mathrm{T})}{v_n\{2\}(p_\mathrm{T})} \to \frac{v_n\{4\}}{v_n\{2\}} \quad \text{(const.)}$$

In low p_T: $\frac{v_2\{4\}}{v_2\{2\}}$ judge the strength of the fluctuation.

QM2022 results: 2-particle correlation

Yongsun Kim's talk

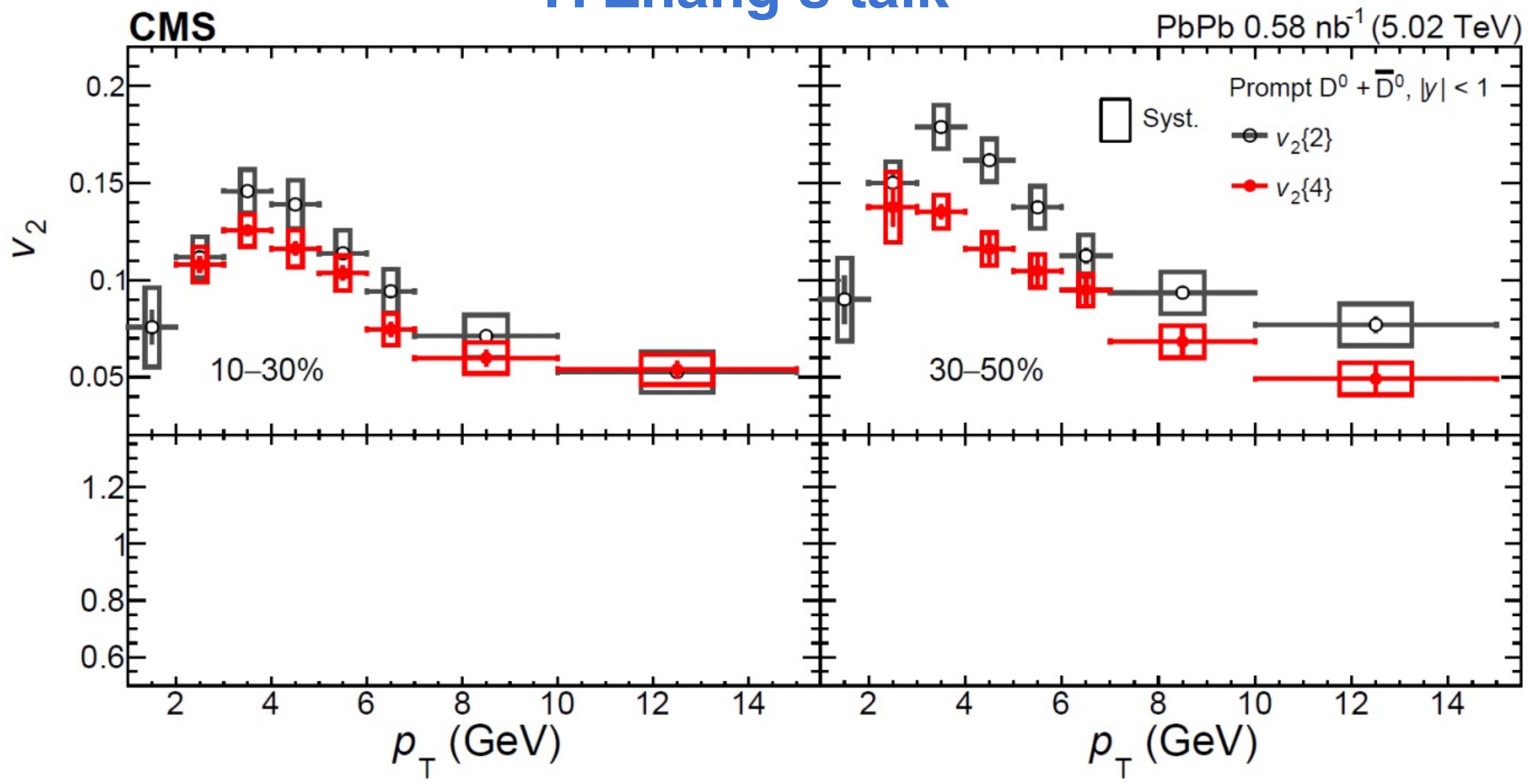


The elliptic flow of prompt D^0 has similar pattern to that of charged hadrons

QM2022 results: 4-particle correlation

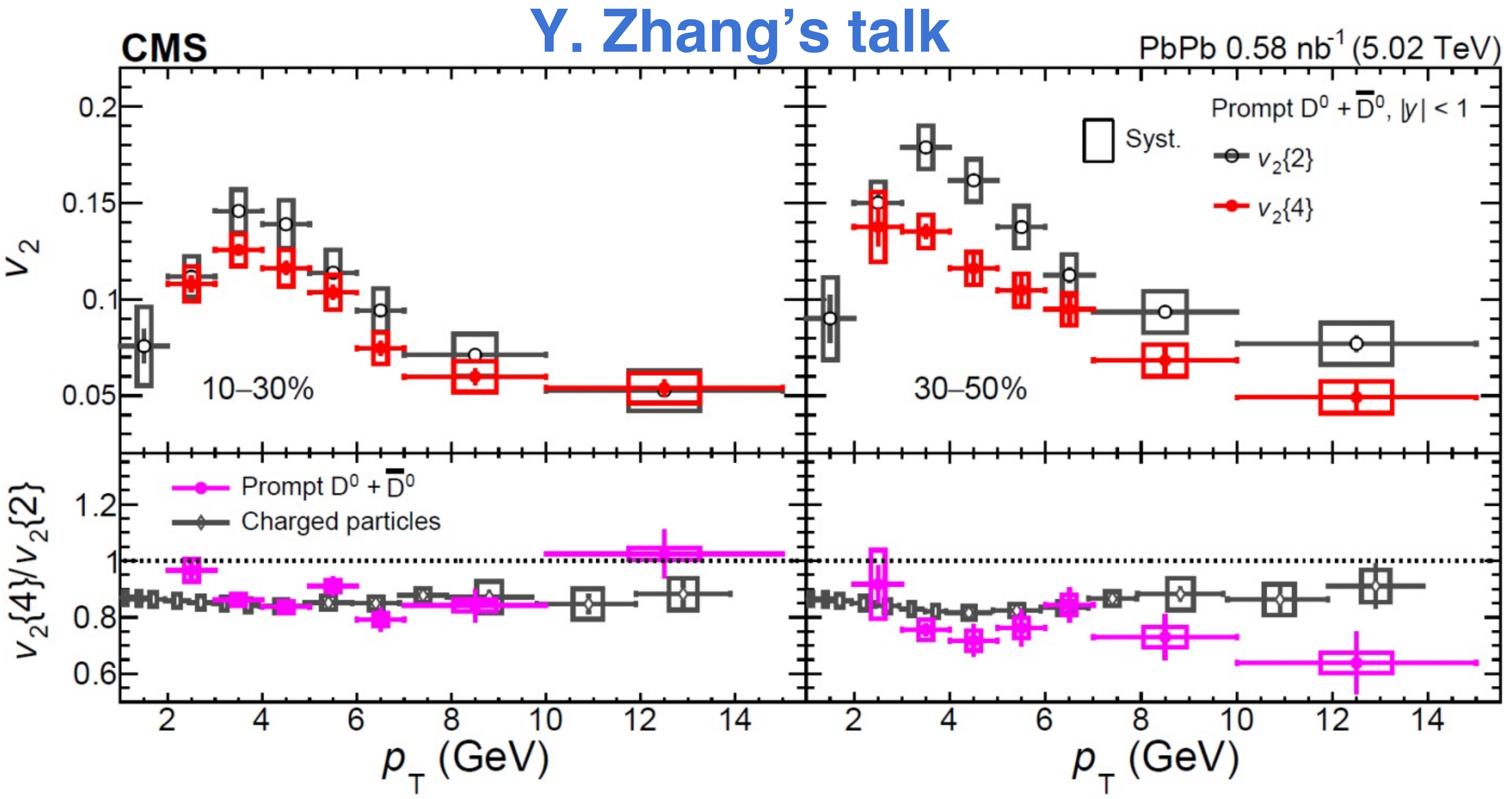
Y. Zhang's talk

arxiv:2112.12236



- $v_2\{2\} > v_2\{4\}$
- $v_2\{4\}$ has no obvious centrality dependence.

QM2022 results: 4-particle correlation

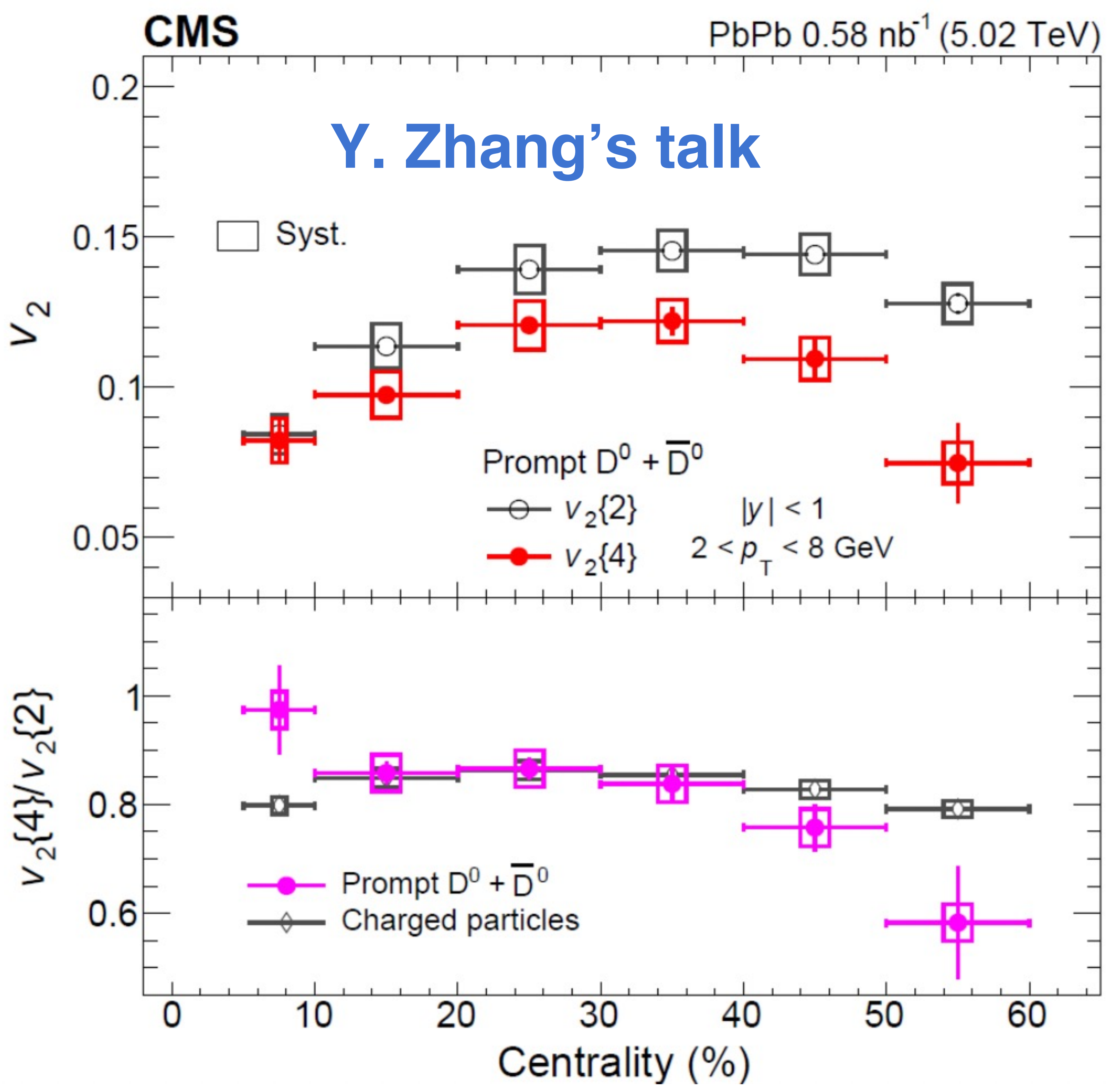


➢ $v_2\{4\}/v_2\{2\}\ (D^0) \sim v_2\{4\}/v_2\{2\}(\mathrm{Ch})$

$\Longrightarrow$ soft fluctuation is dominated.

QM2022 results: 4-particle correlation

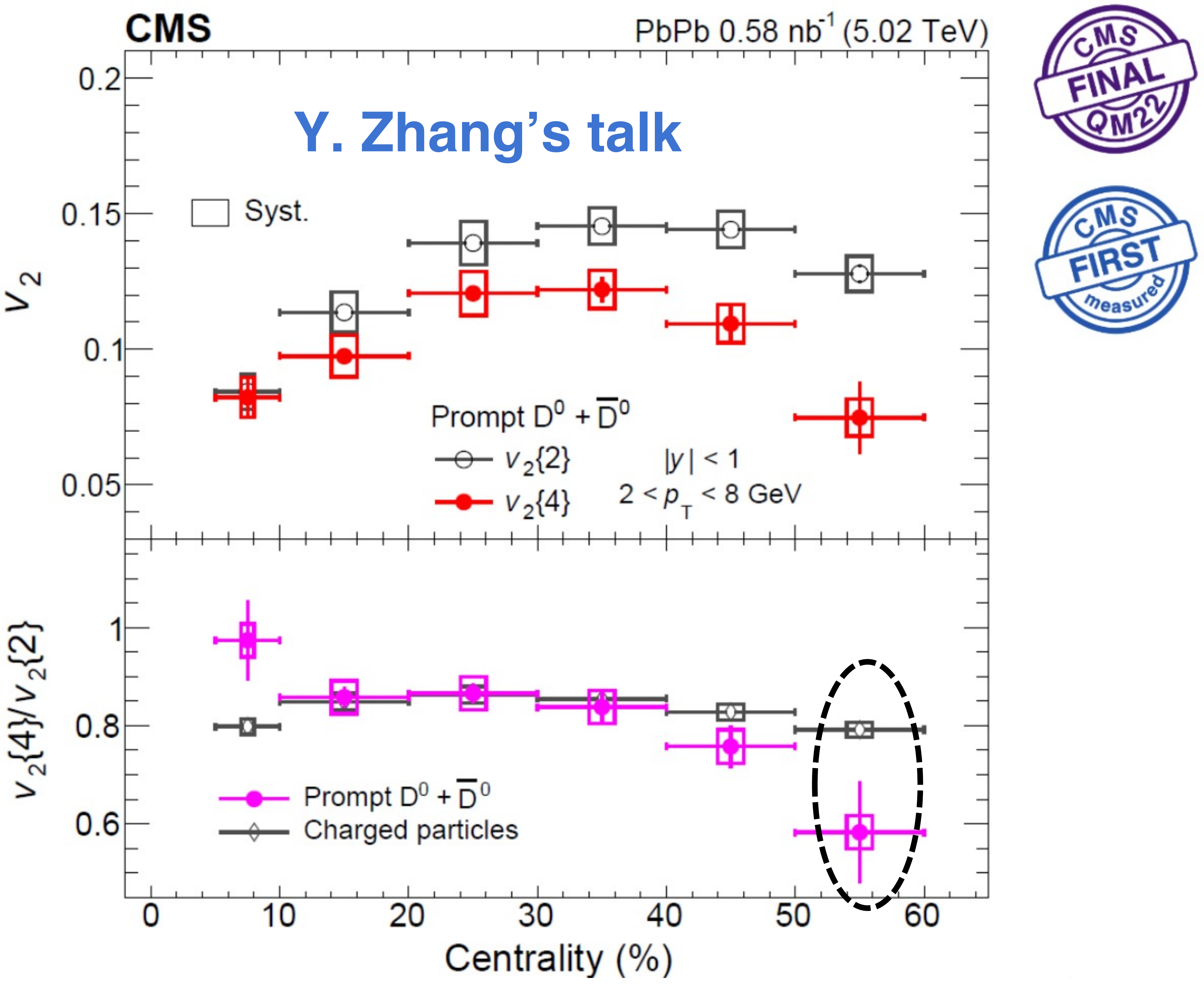
$v_2\{4\}$ / $v_2\{2\}$ for charm sectors are almost the same across different centrality classes – similar findings of charged particles – fluctuations almost from initial geometry



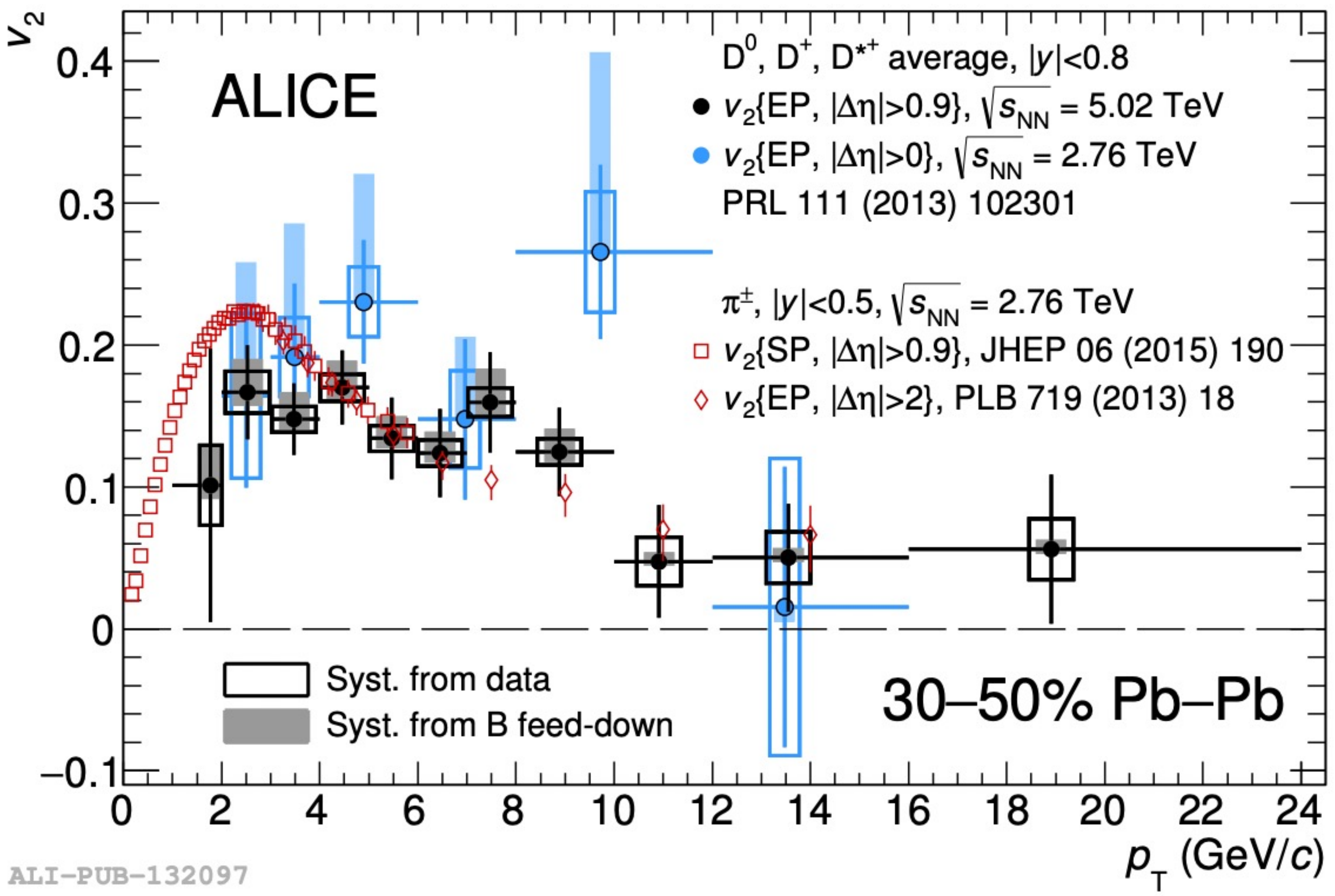
QM2022 results: 4-particle correlation

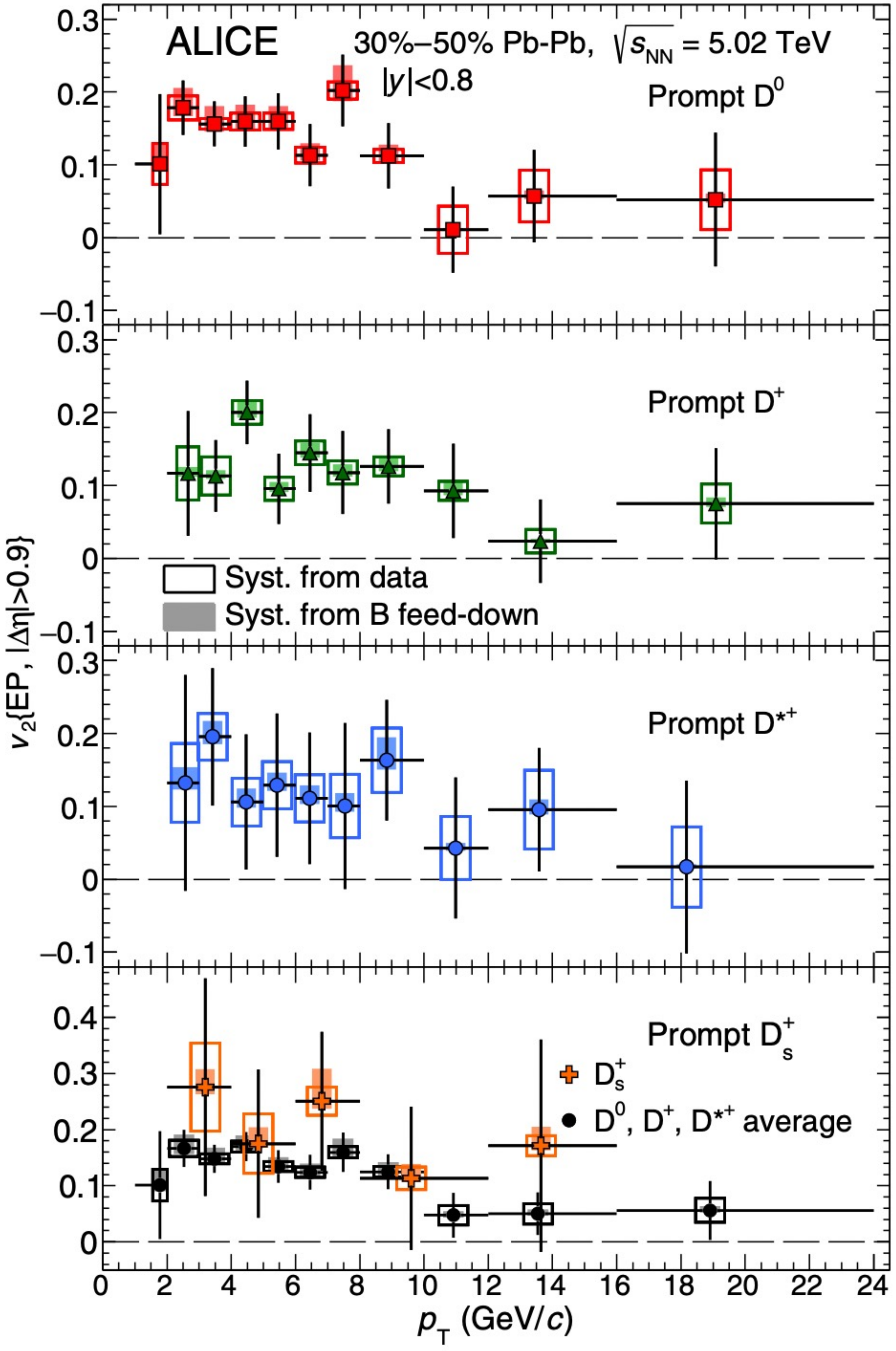
Indication of splitting between charged particles and charm sectors

– hint of fluctuations on energy loss towards smaller system



Event plane method in Alice

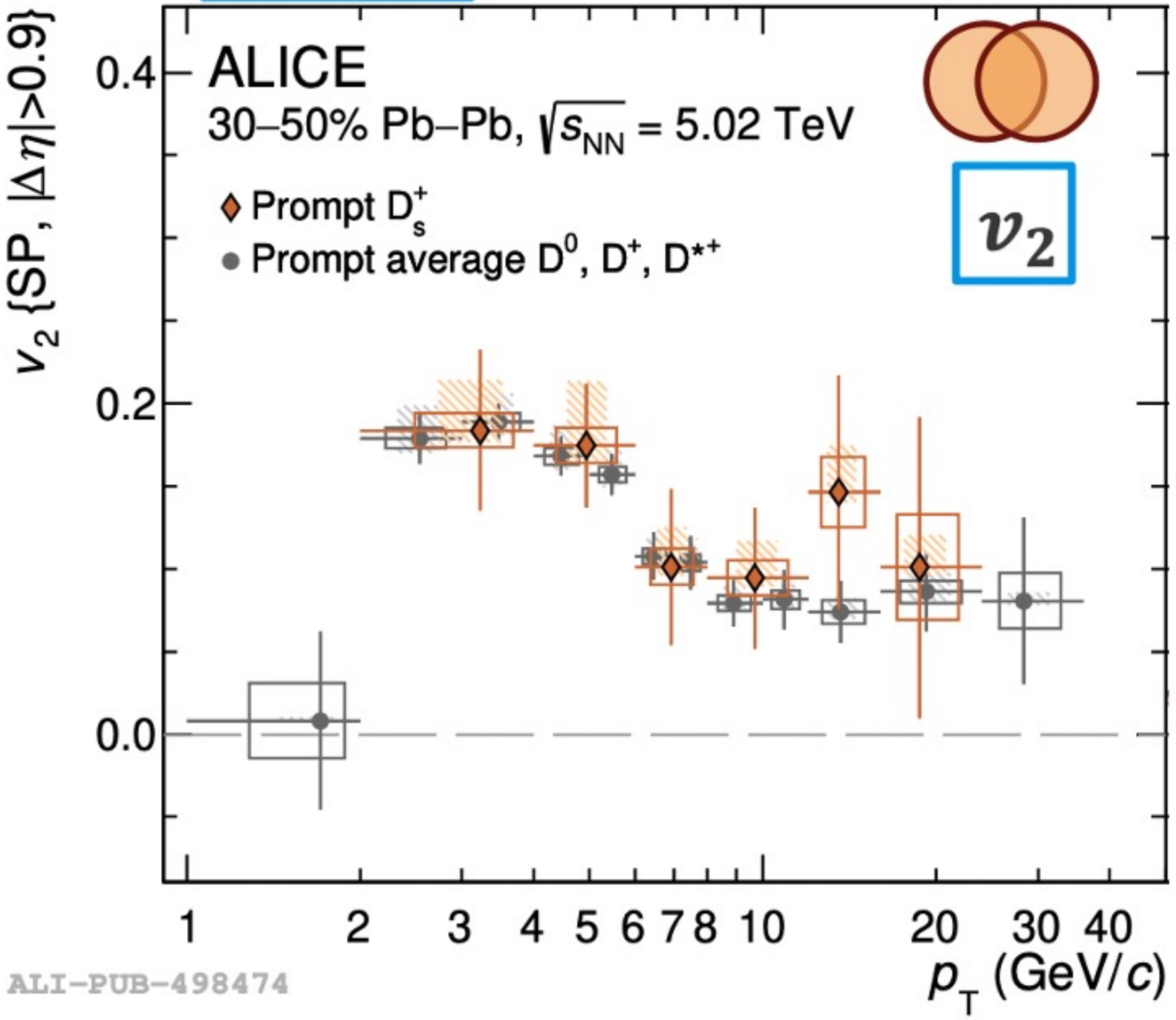


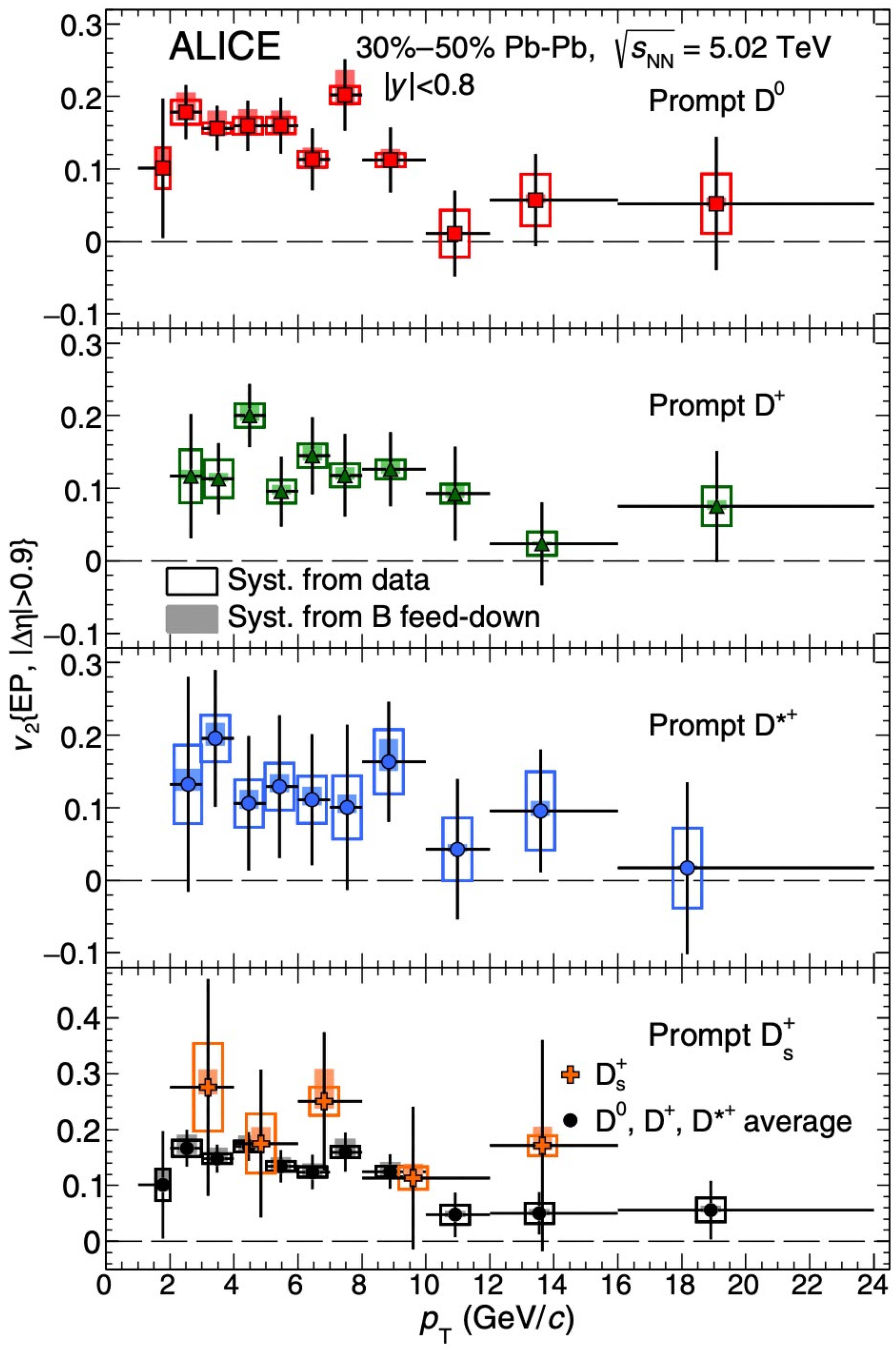


PRL 120, 102301 (2018)

➢ The v_2 of D mesons is comparable in magnitude to that of light-flavor hadrons.

New D_s^+: PLB 827 (2022) 136986





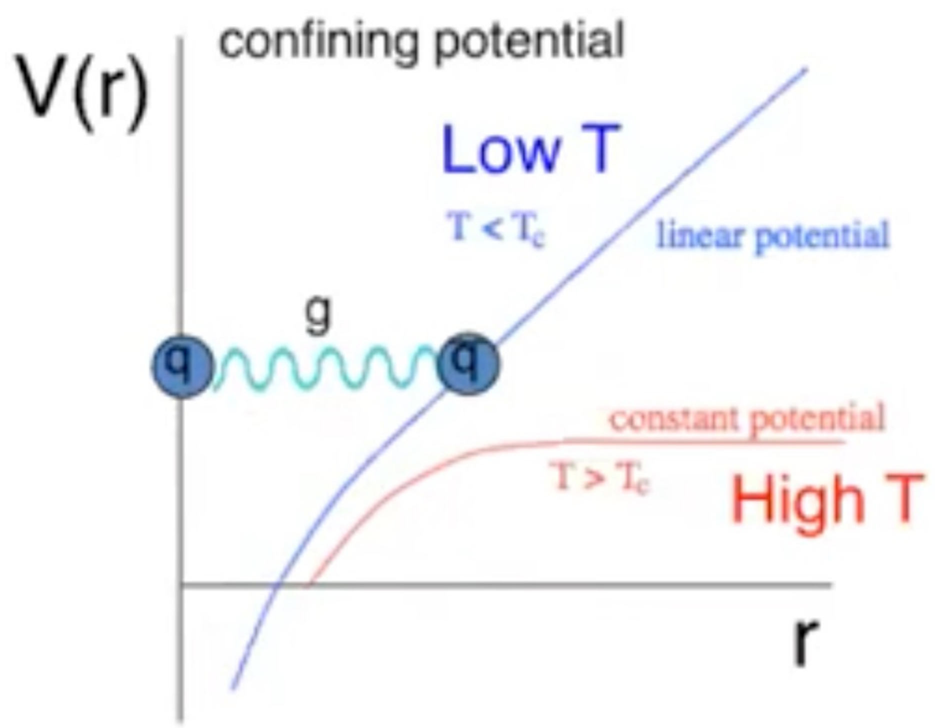
PRL 120, 102301 (2018)

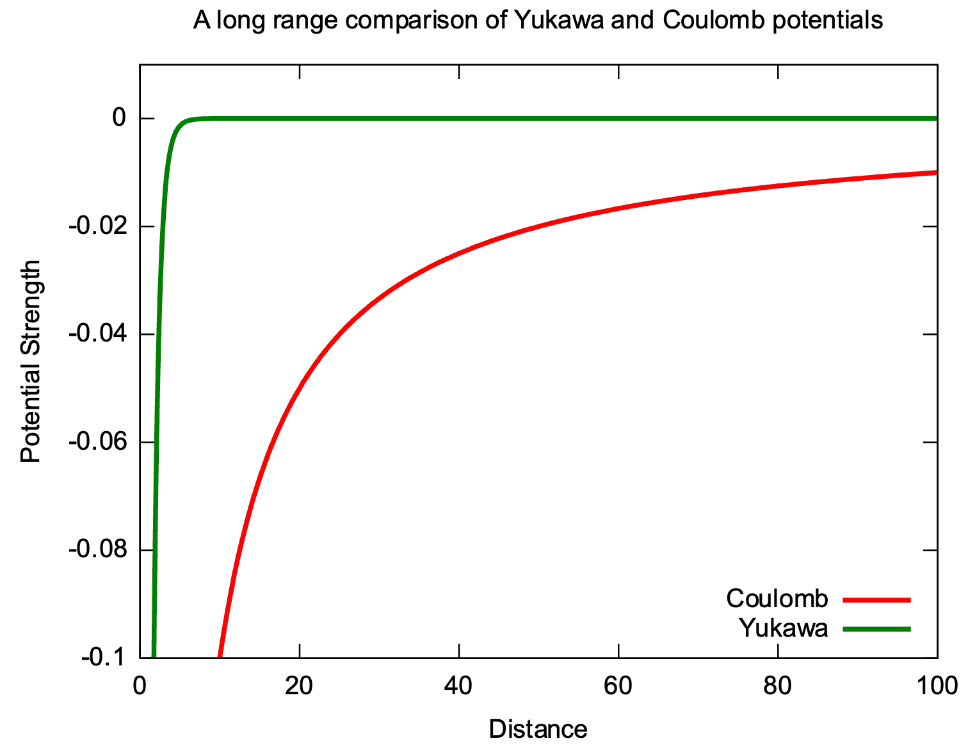
charmonium: J/ψ

the potential for $c\bar{c}$ system:

$$H_I = \boxed{(-q)^* \frac{q}{4\pi r}} + \boxed{\kappa r}$$

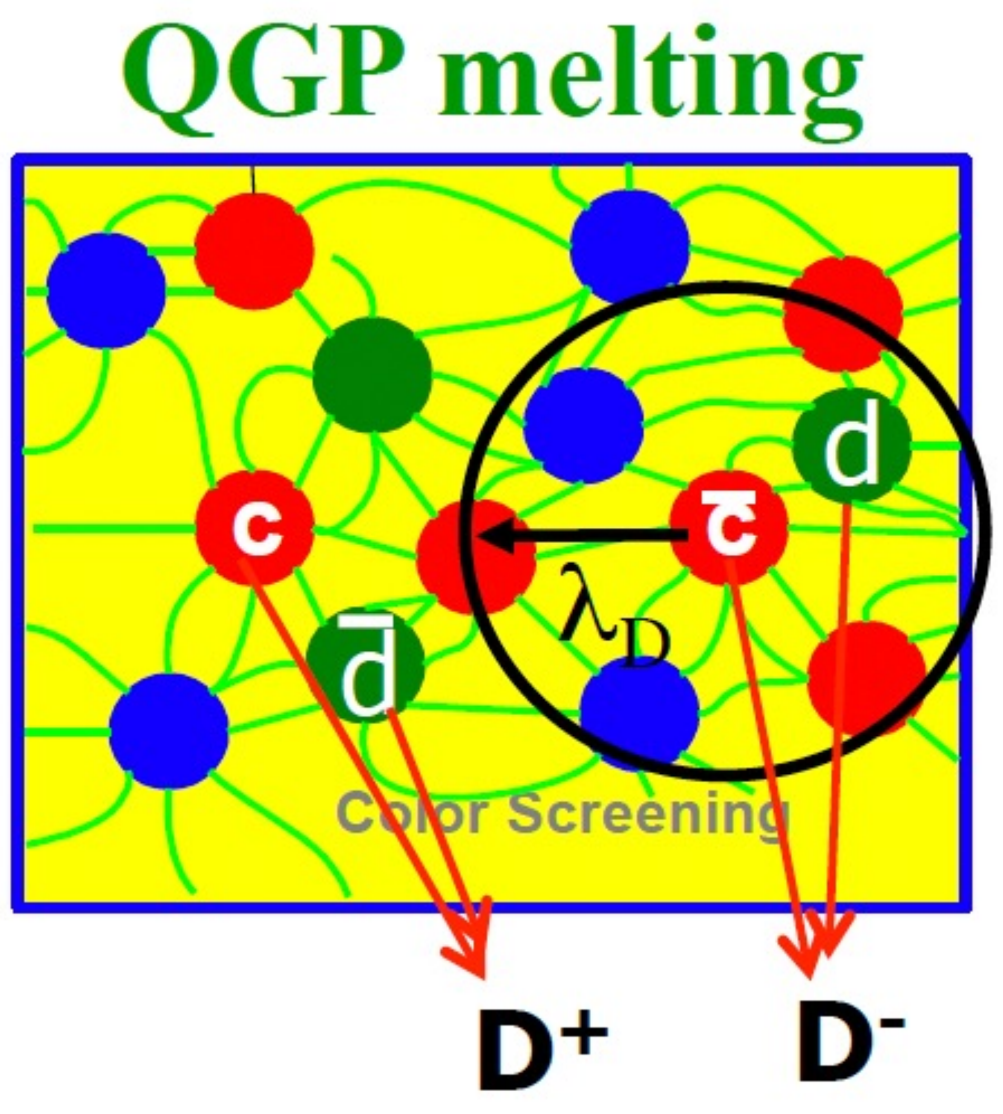
Coulomb potential   confining potential





QGP affect the $c\bar{c}$ system in three important ways:

1. the temperature T (string tension depends on T, T > T_c string tension disappear and Coulomb potential will transfer into Yukawa potential).
2. the presence of quark matter leads to the rearrangement of the densities of q, $\bar{q}$, and g around c and $\bar{c}$. The arrangement leads to the screening of the color charge of c and $\bar{c}$.



Debye screening radius:

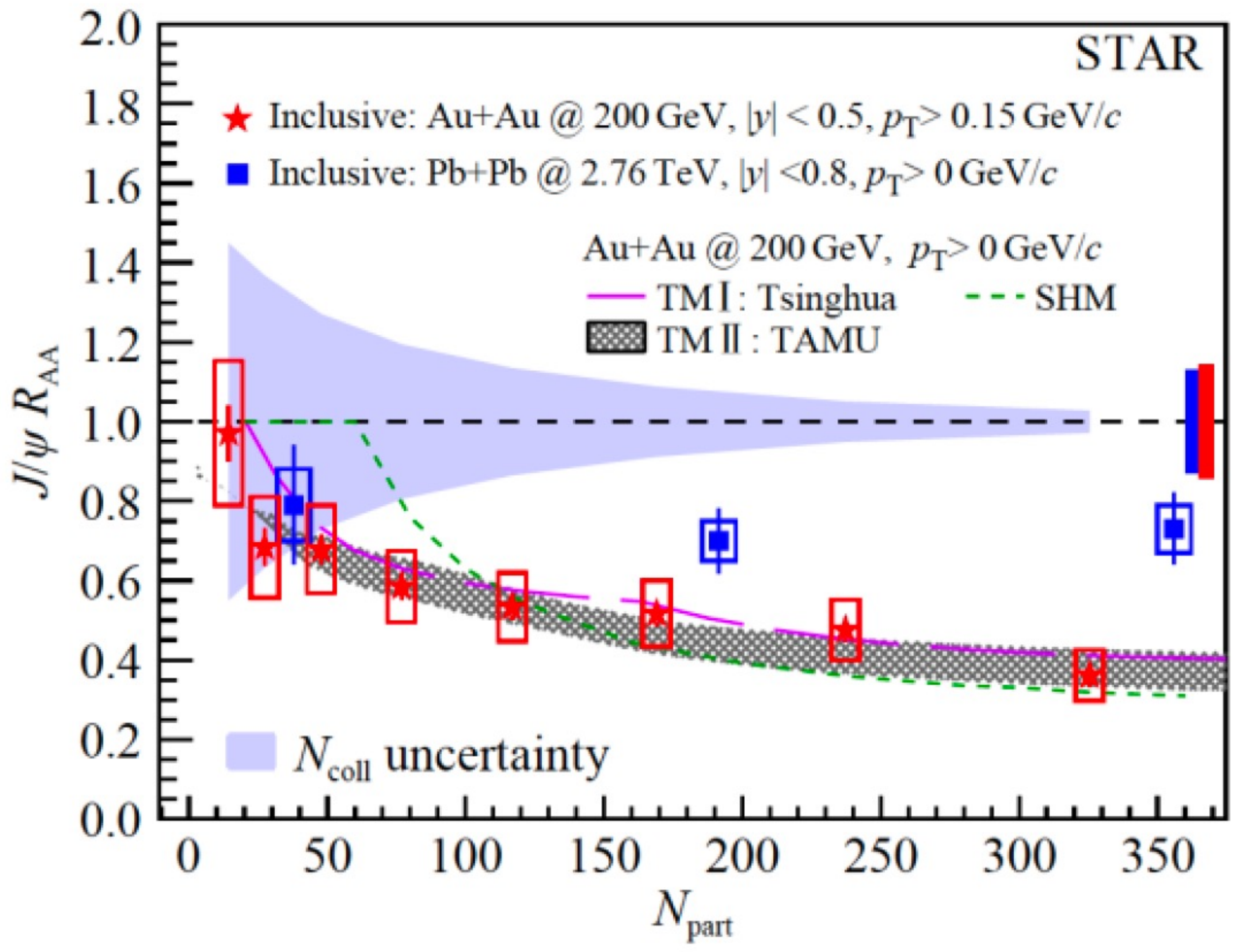
$$\lambda_D(\mathrm{PQCD}) = \sqrt{\frac{2}{3g^2}}\frac{1}{T}.$$

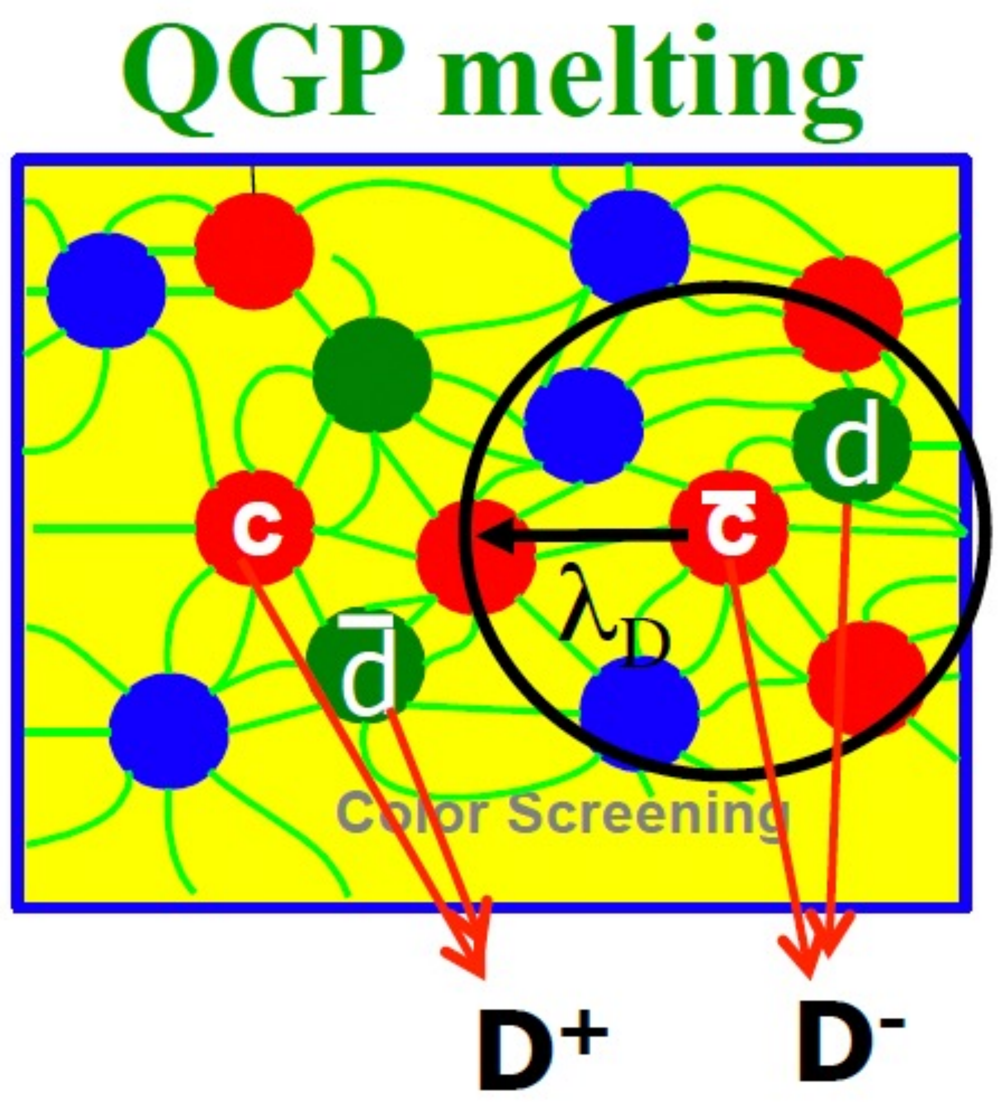
r < λ_D : $c\bar{c}$ attractive interaction is effective.

r > λ_D : $c\bar{c}$ attractive interaction in ineffective.
c will combine the u,d and form:

$$D^+ = c\bar{d},\ D^0 = c\bar{u},\ \overline{D}^0 = \bar{c}\,u,\ D^- = \bar{c}\,d,$$

3. recombination contribution:





Au-Au: R_{AA} ↓ with larger size system due to Debye screening.

Pb-Pb: Debye screening + recombination effect.

1986, T. Matsui, H. Satz

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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First J/ψ suppression observed at CERN-SPS

1987: O + U @ 200GeV

Conclusion: a considerable suppression of J/ψ production, increasing with the centrality of the collision.

PRODUCTION OF MUON PAIRS IN ^{16}O-URANIUM COLLISIONS AT 200 GEV/NUCLEON

NA38 COLLABORATION

M.C. Abreu[5], M. Alimi[6], Ch. Baglin[1], A. Baldit[3], G.P. Barreira[5], M. Bedjidian[6], P. Bordalo[5], S. Borenstein[4], J. Britz[8], A. Bussière[1], Ph. Busson[4], A. Casaca[5], R. Cases[9], J. Castor[3], C. Charlot[4], B. Chaurand[4], D. Contardo[6], E. Descroix[6], A. Devaux[3], J. Fargeix[3], X. Felgeyrolles[3], P. Force[3], J.M. Gago[5], C. Gerschel[7], P. Gomes[5], Ph. Gorodetzky[8], J.Y. Grossiord[6], A. Guichard[6], J.P. Guillaud[1], R. Haroutunian[6], L. Kluberg[4], L. Kraus[8], G. Landaud[3], I. Linck[8], A. Maio[5], L. Peralta[5], M. Pimenta[5], J.R. Pizzi[6], S. Ramos[5], A. Romana[4], R. Salmeron[4], A. Sinquin[7], P. Sonderegger[2], P. Vaz[5], J. Varela[5] and J. Velasco[9].

Annecy[1] - CERN[2] - Clermont-Ferrand[3] - Ecole Polytechnique[4] - Lisbon[5] - Lyon[6] - Orsay[7] - Strasbourg[8] - Valencia[9] -

Presented by C. Gerschel
IPN-Orsay

ABSTRACT: We present preliminary spectra of muon pairs obtained in O+U collisions at 200 GeV/nucleon in an attempt of detecting the formation of a quark-gluon plasma.

J/ψ reconstruction

$$\text{Signal}^{+-} = N^{+-} - 2\sqrt{N^{++}N^{--}} \;. \qquad (1)$$

Fit:

$$\begin{aligned} dN/dM &= N_0 \exp(-M/M_c)/M^3 \\ &+ N_1 \exp[-(M-M_\Psi)^2/2\sigma_\Psi^2] \\ &+ N_2 \exp[-(M-M_{\Psi'})^2/2\sigma_{\Psi'}^2] \;. \qquad (2) \end{aligned}$$

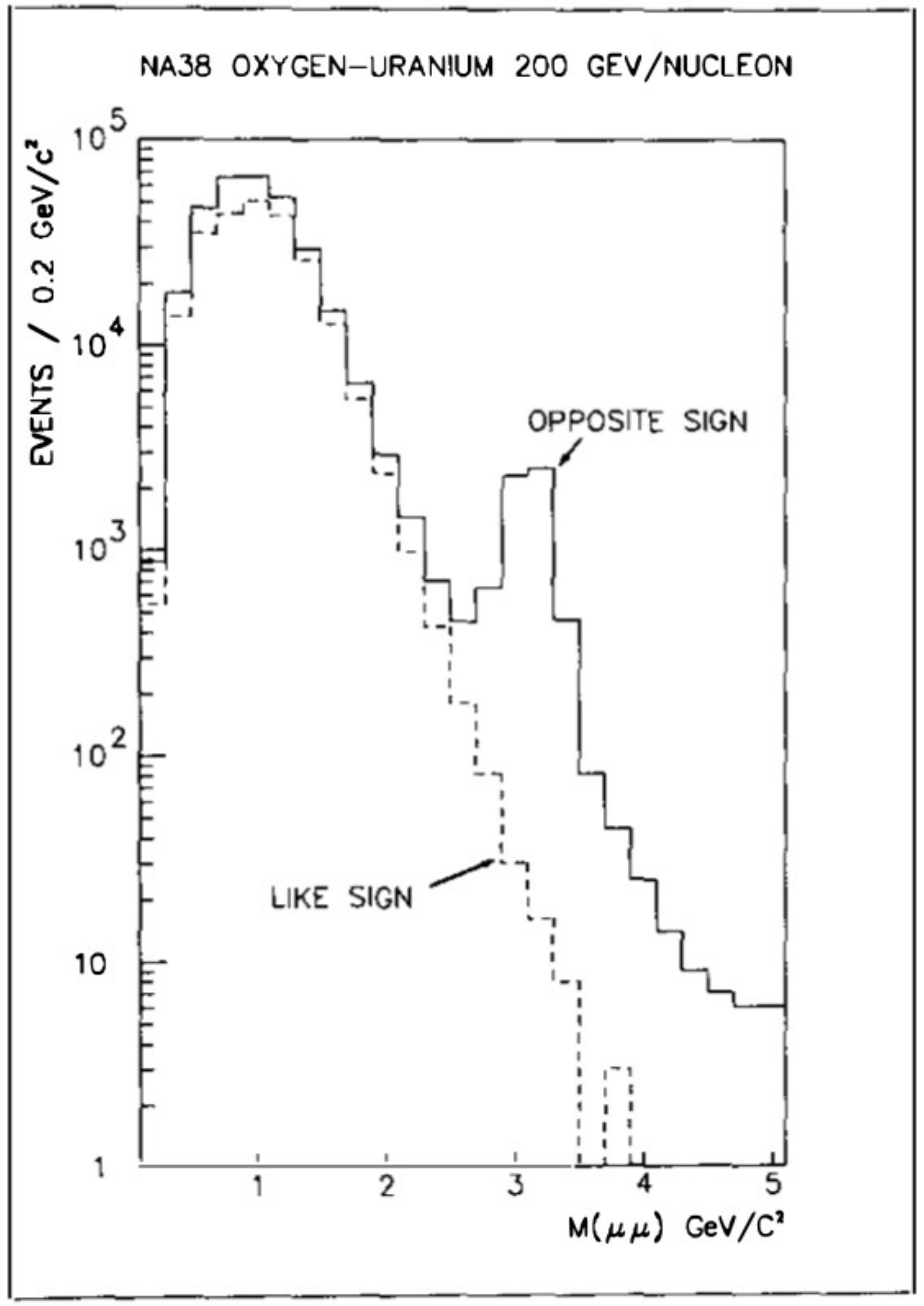


Fig.4:Mass spectra of opposite and like-sign muon pairs.

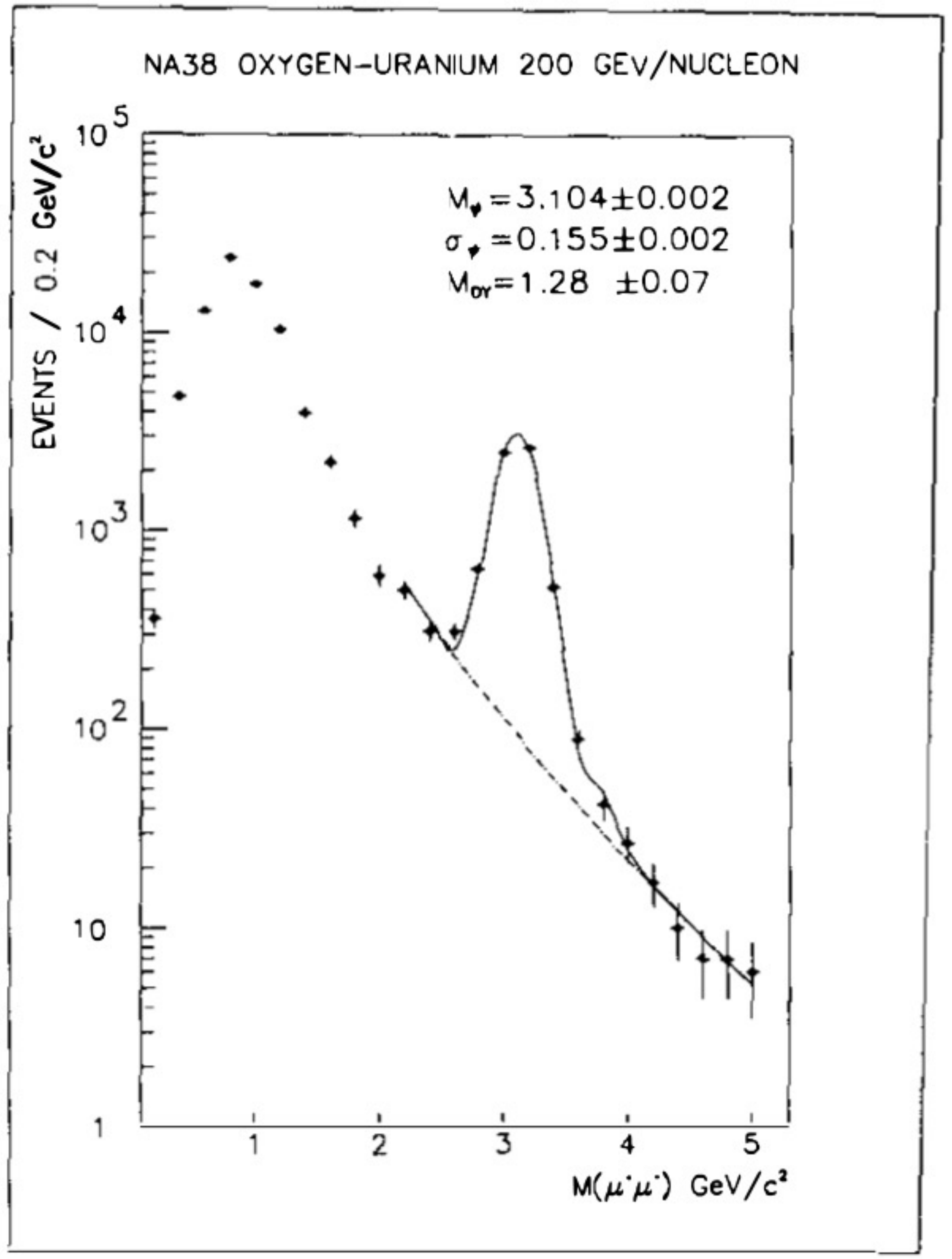


Fig.5 : Dimuons spectrum
The full line is a fit to the data assuming a superposition of Drell-Yan pairs and of J/Ψ and Ψ′ resonances.

Conclusion: a **considerable** suppression of J/ψ production, increasing with the centrality of the collision.

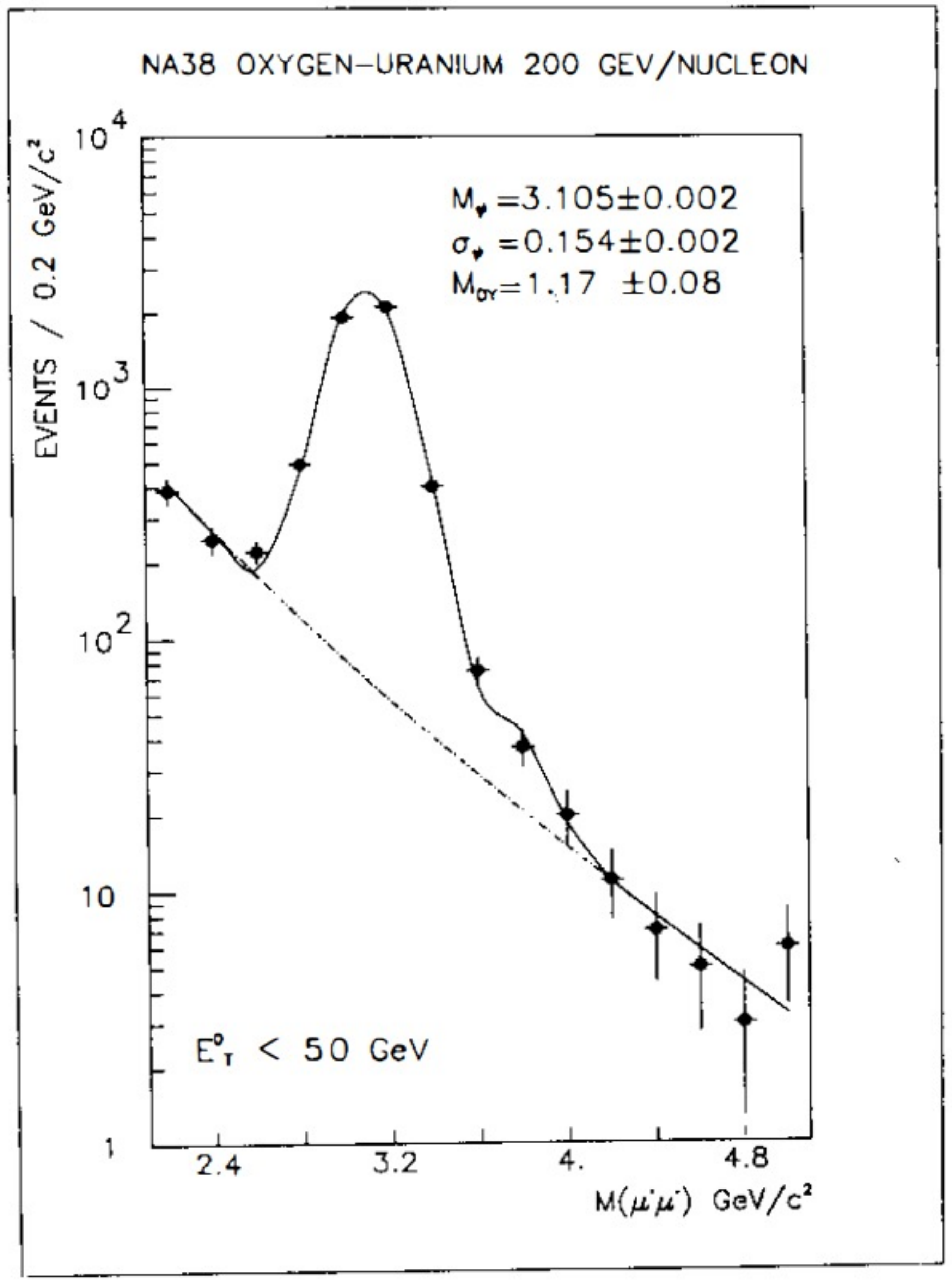


Fig. 8 : Dimuons spectrum for transverse energy E^o_T lower than 50 GeV. The fit is similar to that of Fig.3.

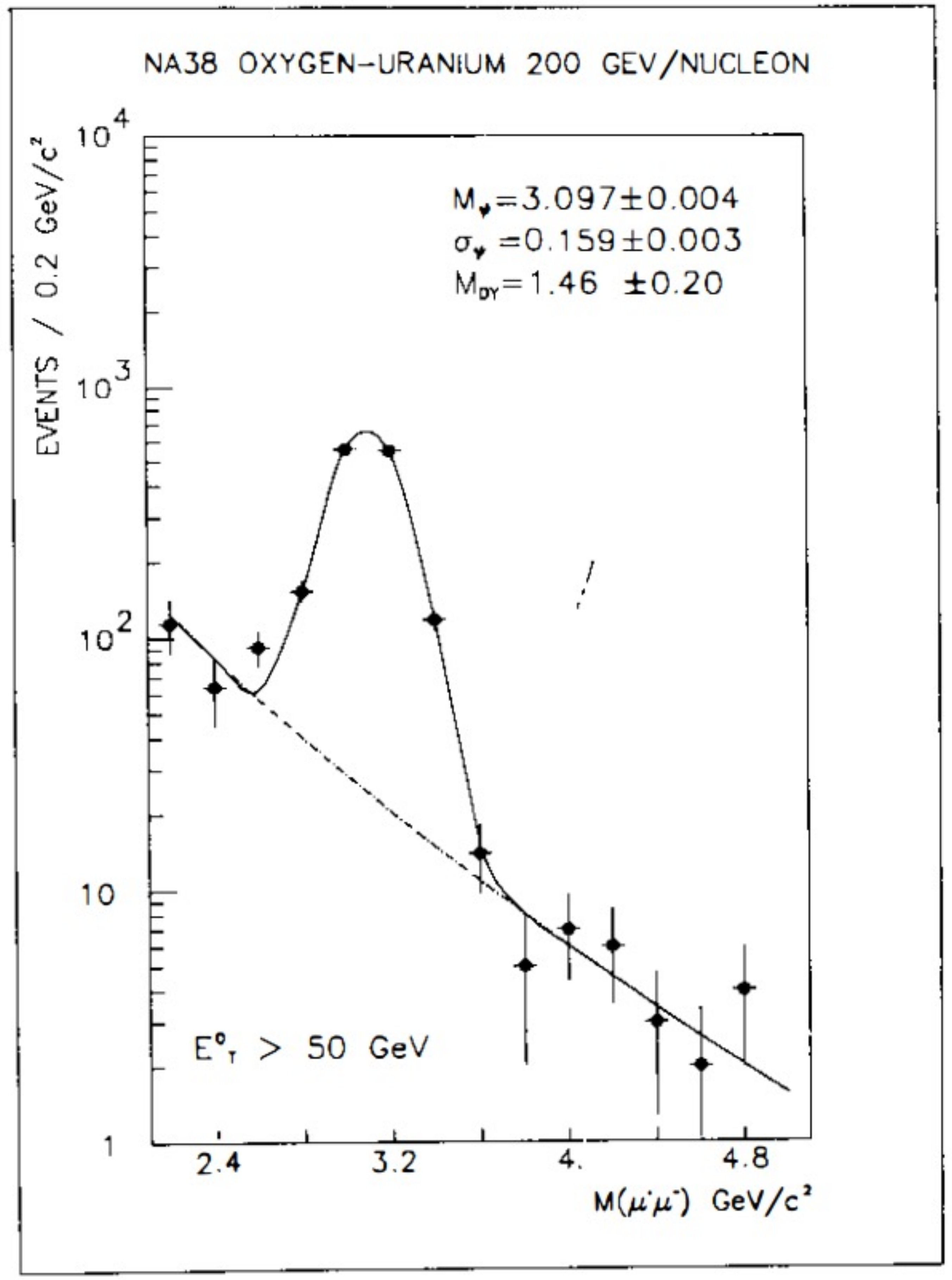
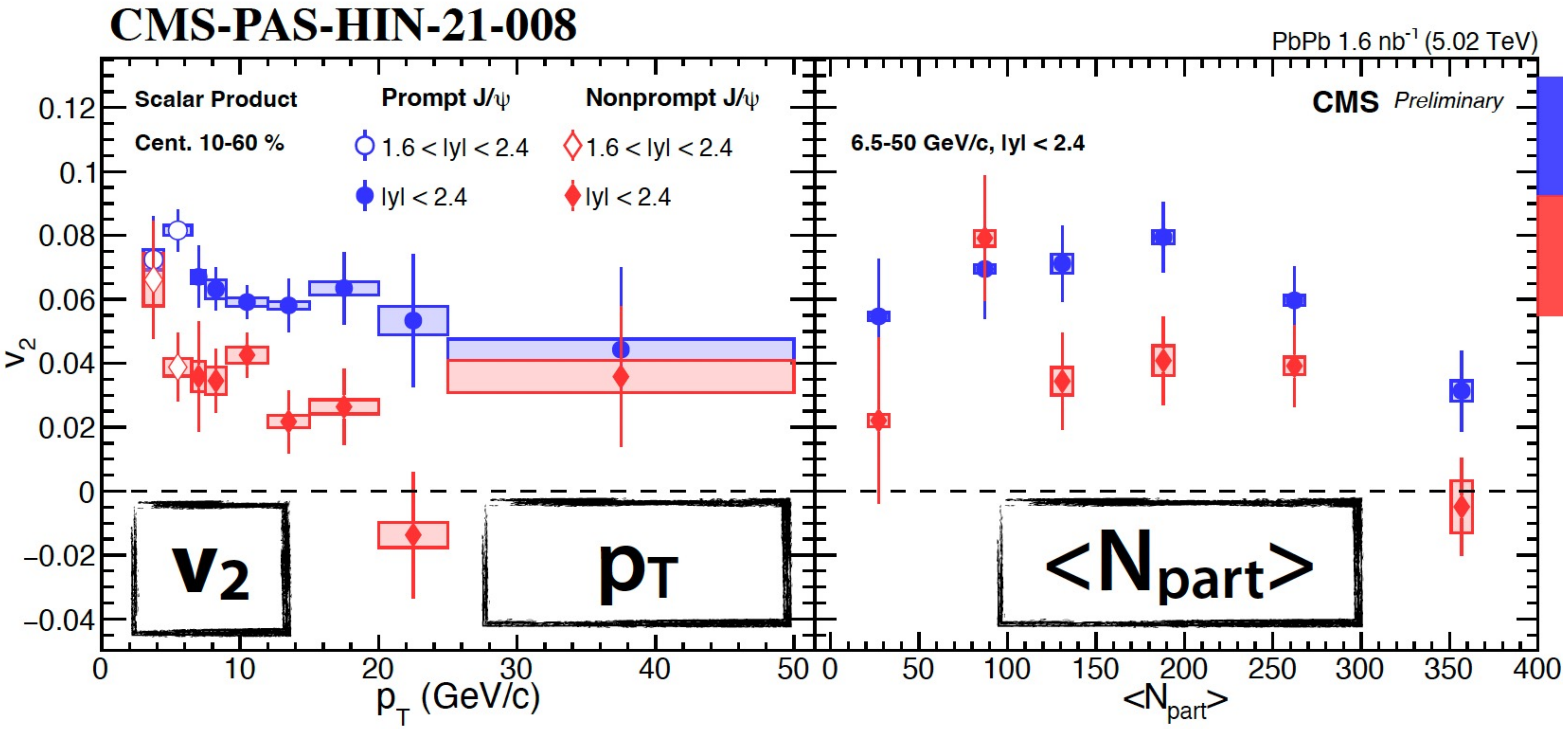
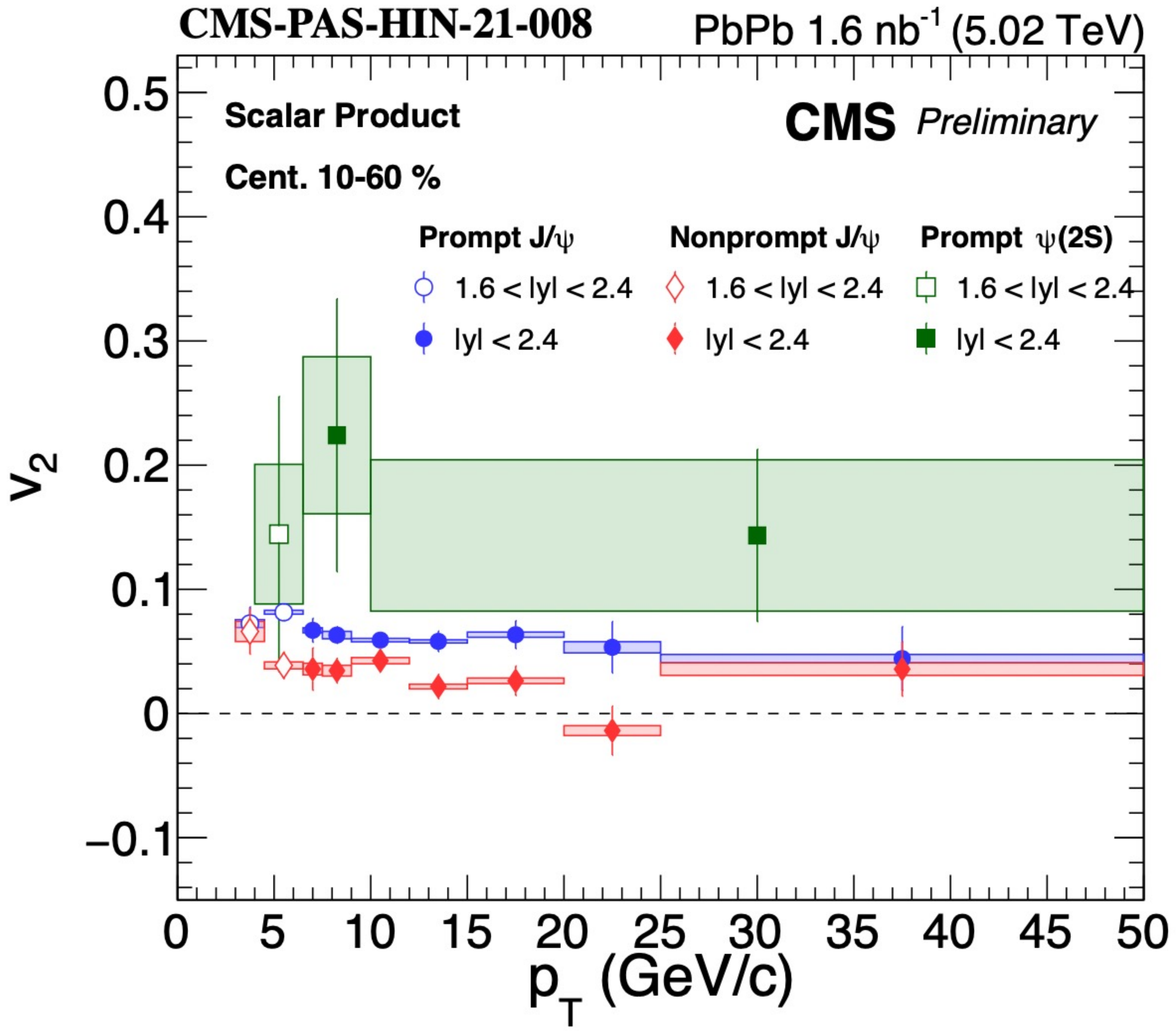


Fig. 9 : The same as Fig. 8 for E^o_T > 50 GeV.

QM2022 results: J/ψ v_2 from CMS



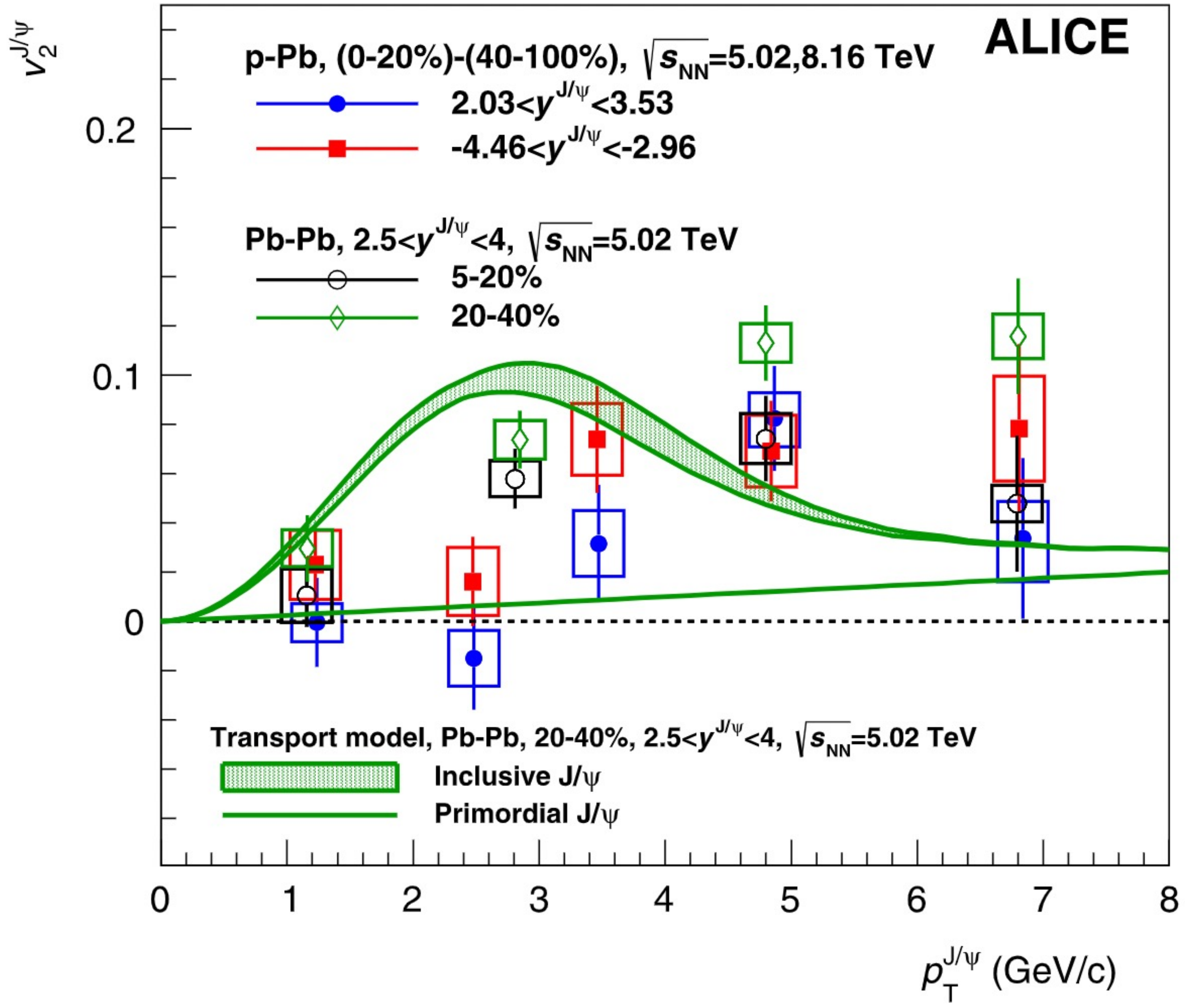


- Large v_2 up to 50 GeV/c.
- Smaller v_2 in most central collision event.

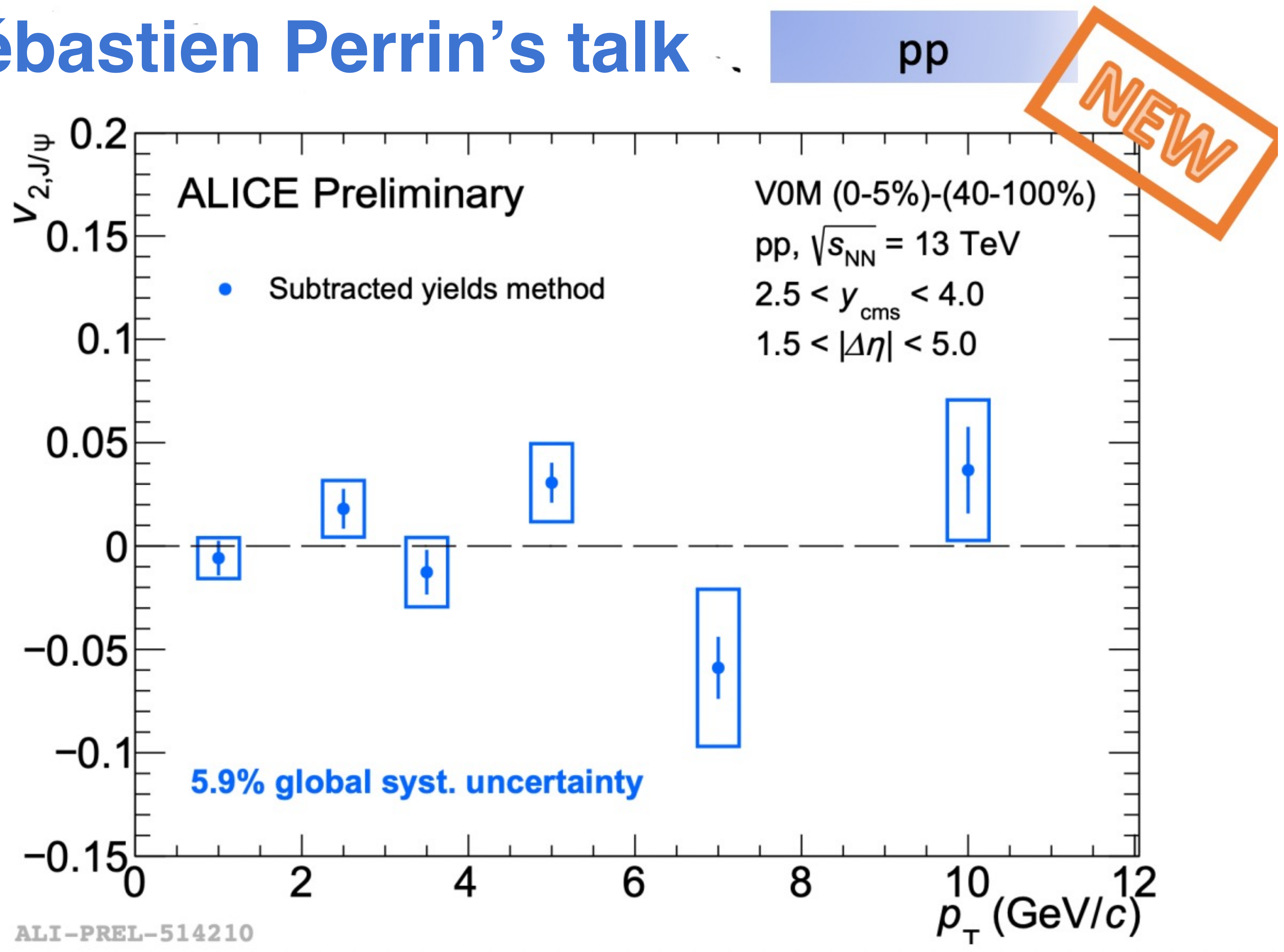
- ψ(2S) v_2 first measured!
- ψ(2S) v_2 >= J/ψ v_2

→ hint of different regeneration contribution for ground and excited states

QM2022 results: J/ψ v_2 from Alice



Sébastien Perrin's talk



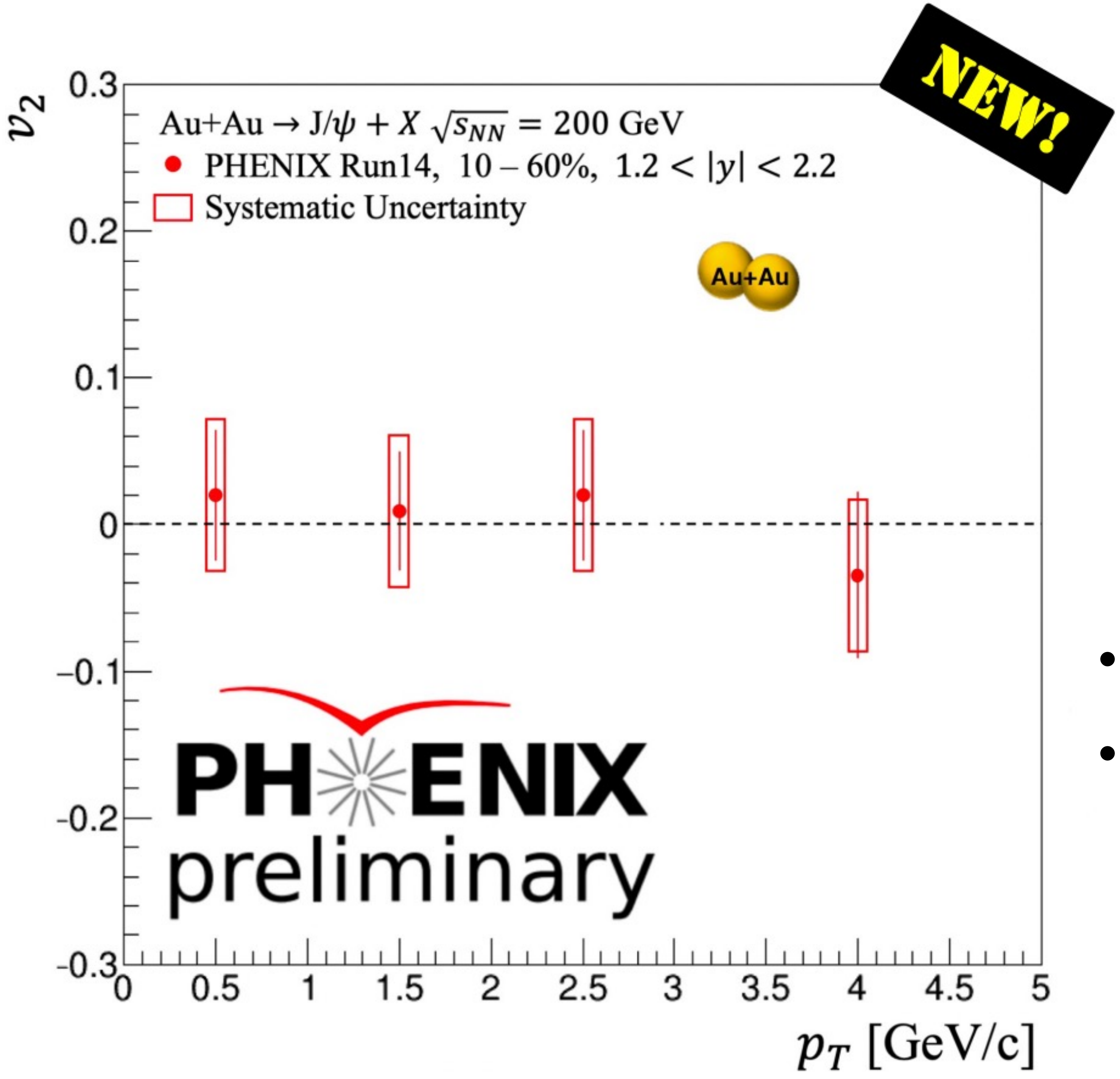
p-Pb: [PLB 780 (2018) 7-20]

- For p_T > 3 GeV/c, significant flow
- Results close to AA → hints at common flow mechanism regardless of system size

pp:

- No significant p_T dependence compatible with 0 (within 1 σ)

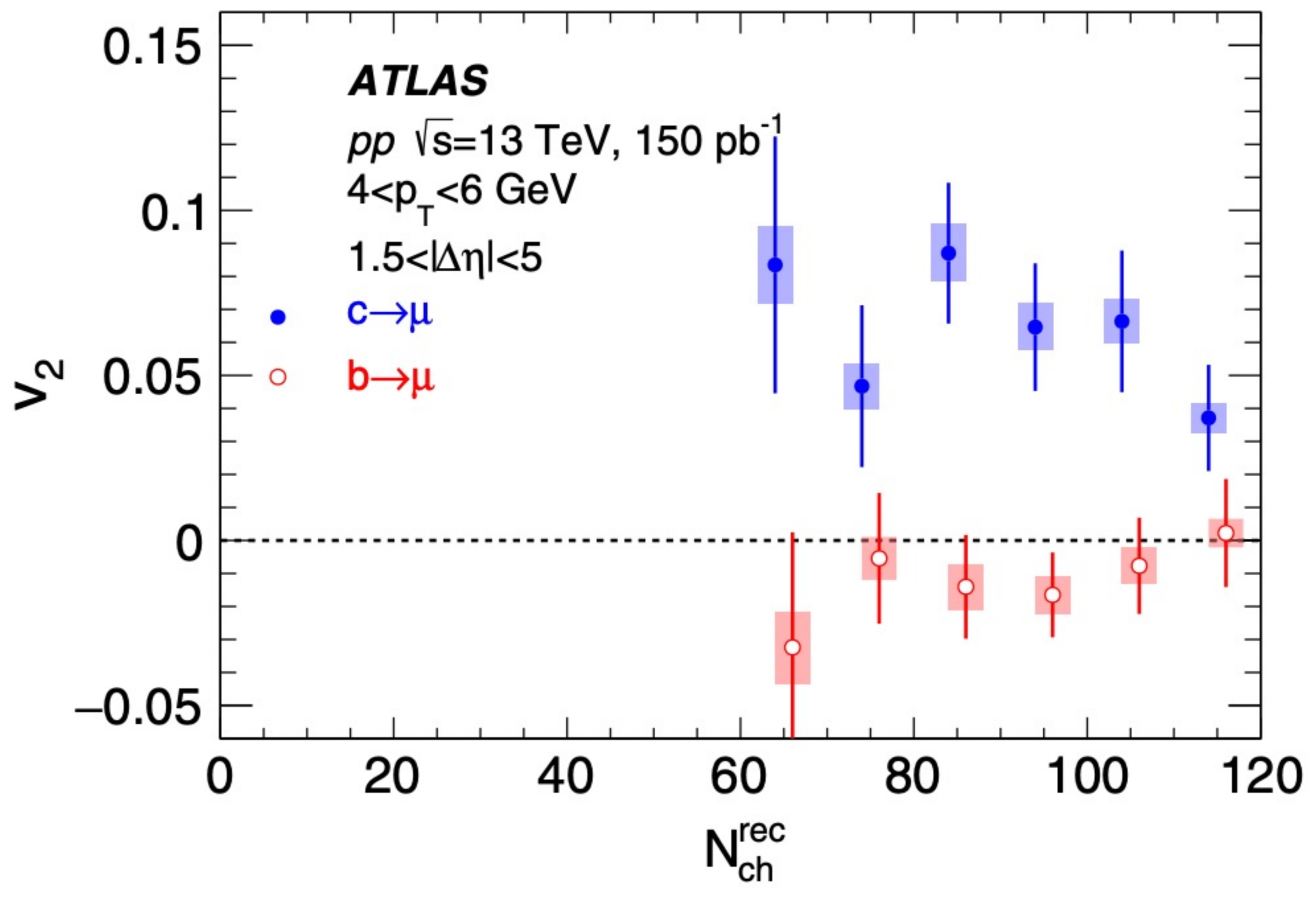
QM2022 results: J/ψ v_2 in Au-Au from phenix



- J/ψ v_2 at forward rapidity is consistent with zero.
- Different from the LHC results

QM2022 results: muon v_2 of charm h decays from Atlas

PRL 124, 082301 (2020)



Qipeng Hu's talk

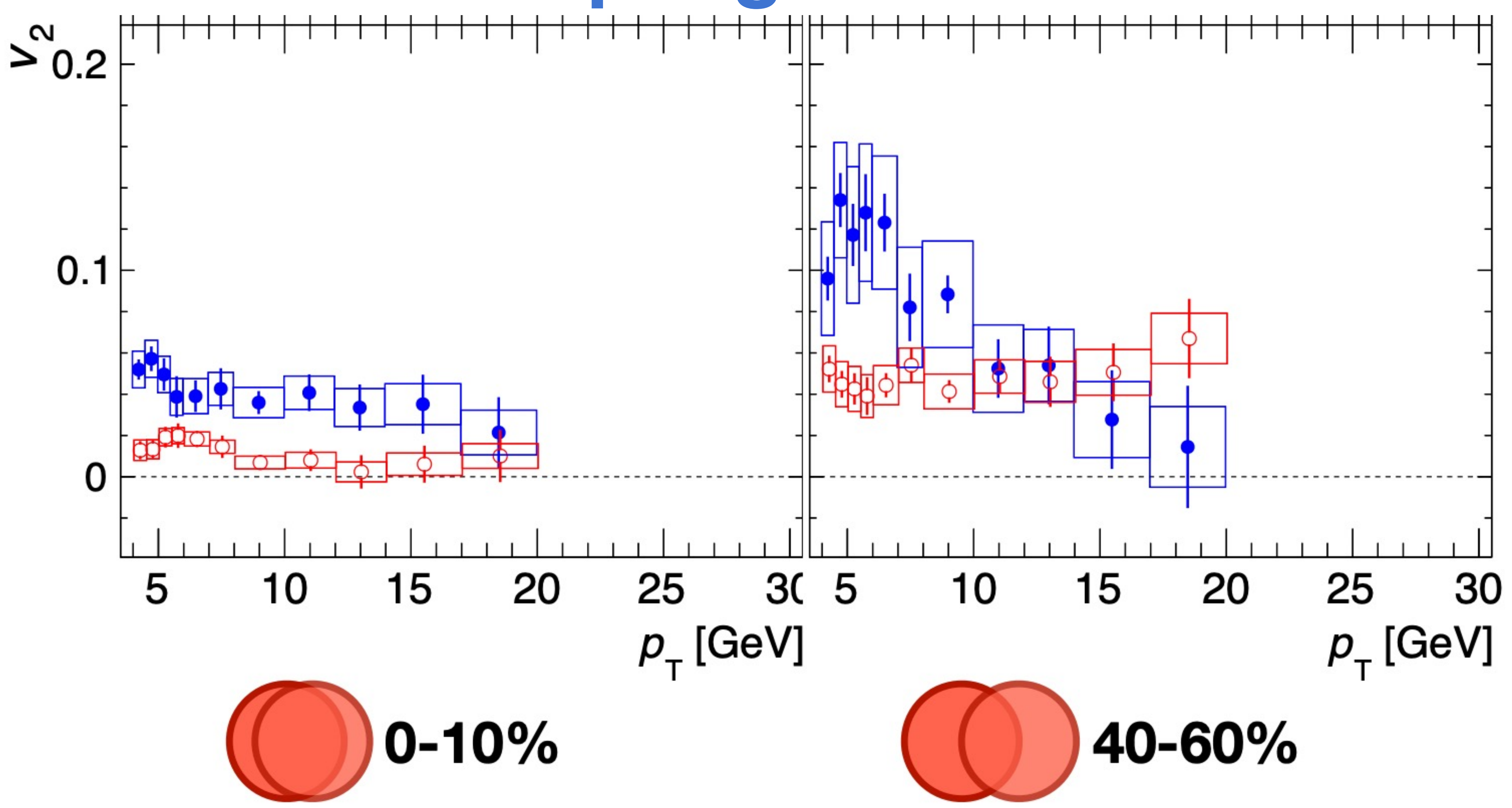


Figure 4 shows the v_2 values for muons from charm and bottom decays separately, as a function of N_{ch}^{rec} for $4 < p_T < 6$ GeV (left) and as a function of p_T for $60 \leq N_{ch}^{rec} < 120$ (right). The v_2 of muons from bottom decays is consistent with zero in the entire N_{ch}^{rec} range of the measurement and has no discernible p_T dependence. In contrast, the v_2 of muons from charm decays is nonzero at lower p_T but consistent with zero at higher p_T within the sizable uncertainties. It also shows no significant N_{ch}^{rec} dependence within the uncertainties.

- $v_2(c) > v_2(b)$
- Strong centrality dependence for R_{AA} and v_2

backup

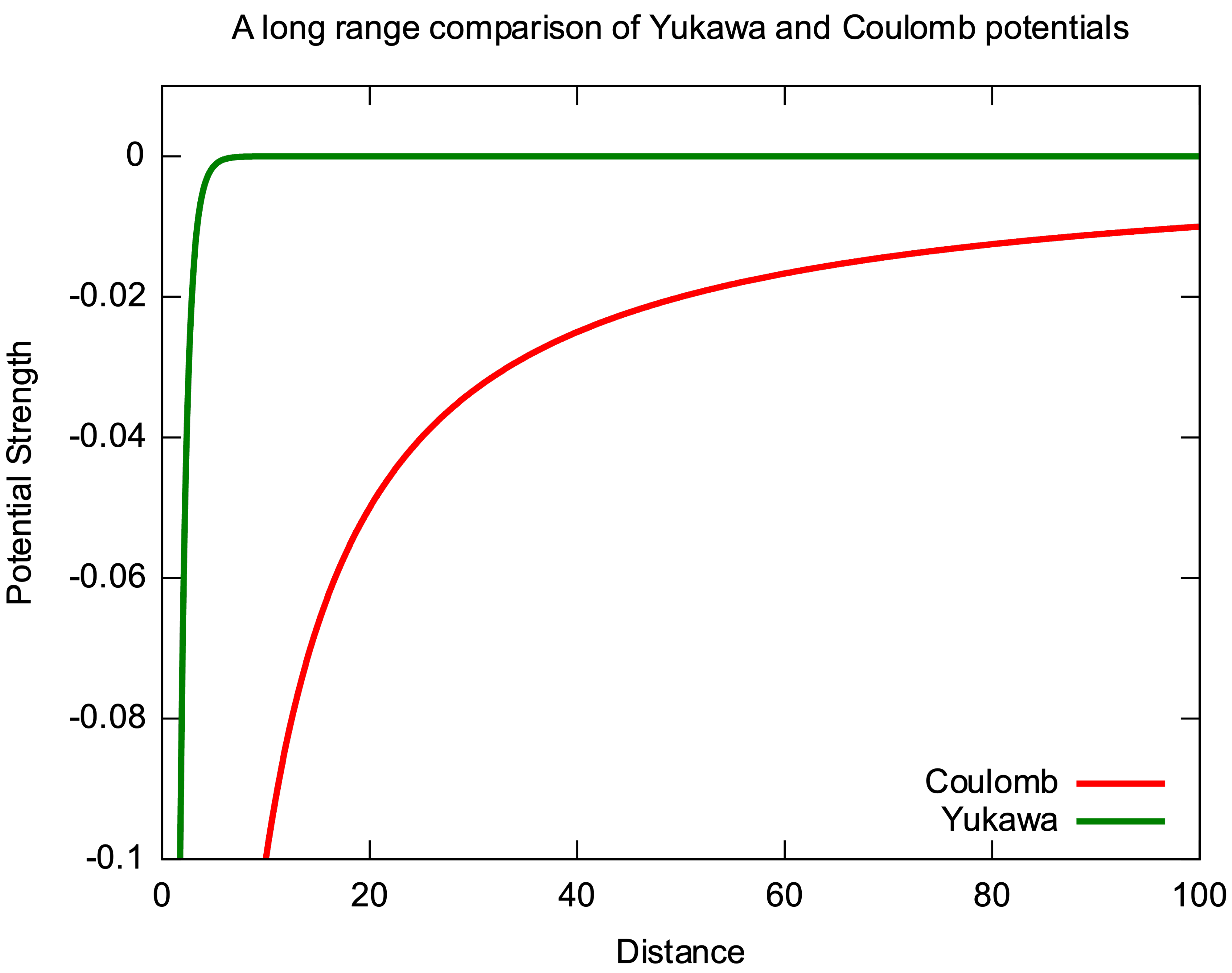
Debye screening: Coulomb → Yukawa

QGP exists: string tension disappear.

the potential for $c\bar{c}$ system:

$$\boxed{(-q)*\frac{q}{4\pi r}} \longrightarrow \boxed{\frac{q}{4\pi}\frac{e^{-r/\lambda_D}}{r}}$$

Coulomb potential Yukawa potential



prompt or non-prompt charm

- ✓ prompt charm (either directly or as decay products of excited charm resonances): D^0, D^+, D_s^+, and $D^*(2010)^+$ (denoted as D^{*+}) mesons.

- ✓ non-prompt charm (produced in beauty-hadron decays):