Quarkonium-flow measurements from AA to *pp* collisions

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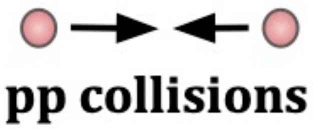
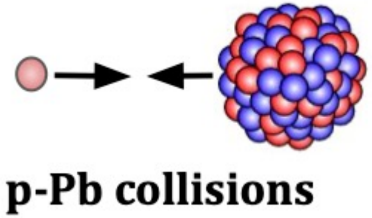
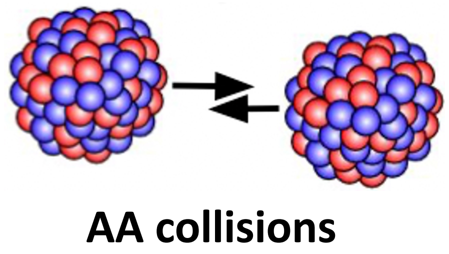
Quarkonia as Tools, Aussois

Quarkonium production in different collisions

- The heavy quark production cross section can be well calculated by pQCD.
- The hadronisation of quarkonium is still theoretically not well understood.
  - ➢ Color-evaporation model (Improved)
  - ➢ Color-singlet model
  - ➢ NRQCD factorisation







- Multiple partons interactions

- Cold nuclear matter effects : nPDF, CGC, coherent energy loss, nuclear absorption, comovers…

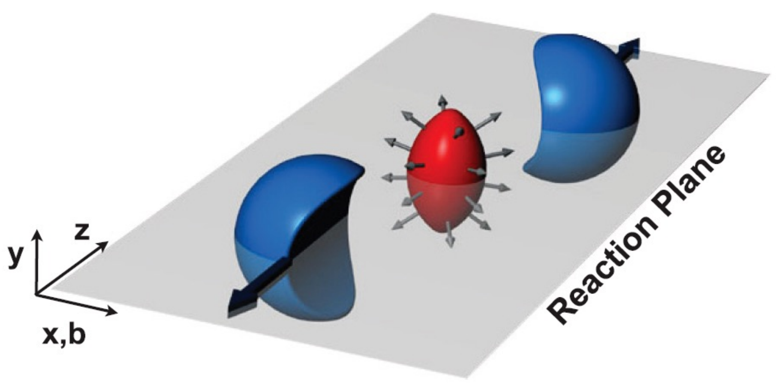
- Medium properties : melting, recombination, parton energy loss, collectivity…

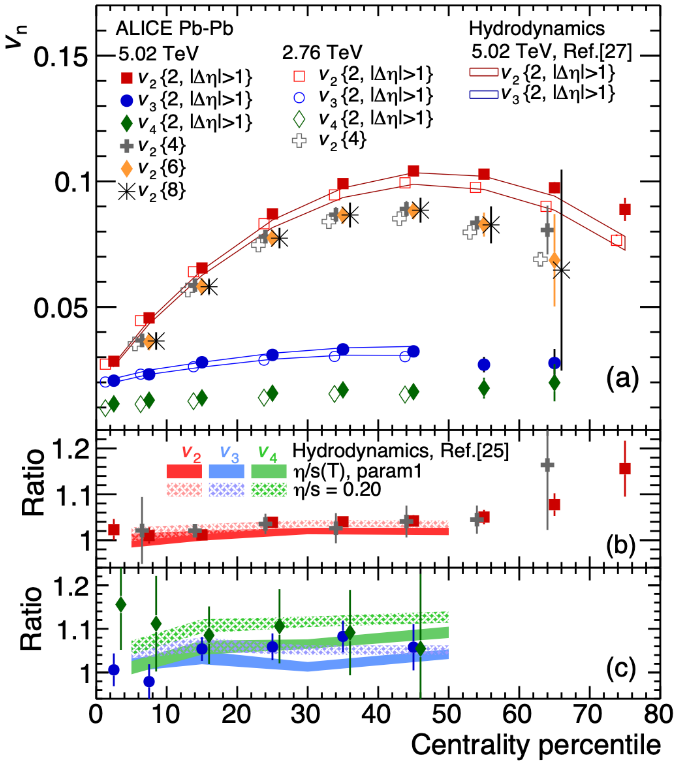
Phys. Lett. B 372, 127
Phys. Lett. B 102, 364 (1981)
Phys. Rev. D 46, R3703

Flow in large collision systems

- For non-central AA collisions, due to the difference in pressure gradient, the charge particles produced in the collision exhibit anisotropic flow .
- The azimuthal anisotropic flow is defined as the Fourier expansion coefficients on the final particle azimuthal probability distribution.

$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left(1 + \sum_n 2v_n \cos(n(\phi - \Psi_n)) \right)$$





- In AA collisions, there is sufficient particle multiplicity to reconstruct the reaction plane.
- v_1: Direct Flow, v_2: Elliptic Flow, v_3: Triangular Flow.
- Non-zero flow coefficients could be caused by the anisotropic expansion of the strongly coupled QGP.

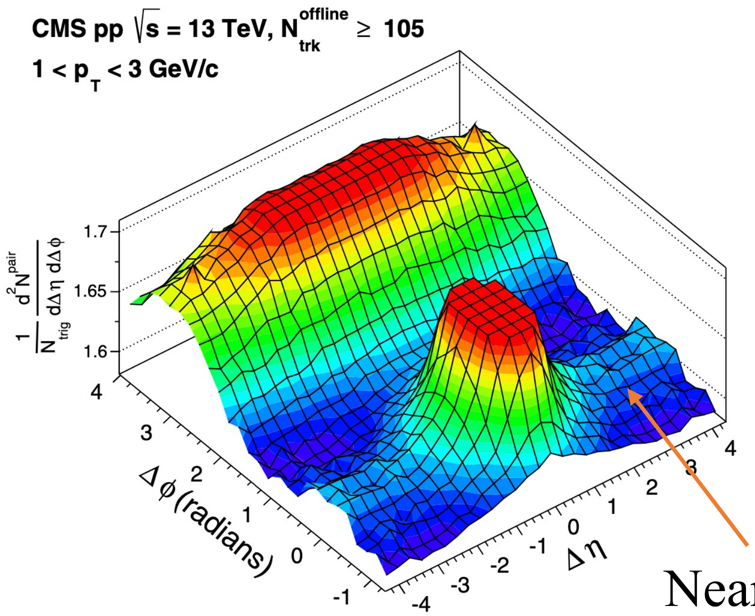
Phys.Rev.Lett. 116 (2016) 13, 132302

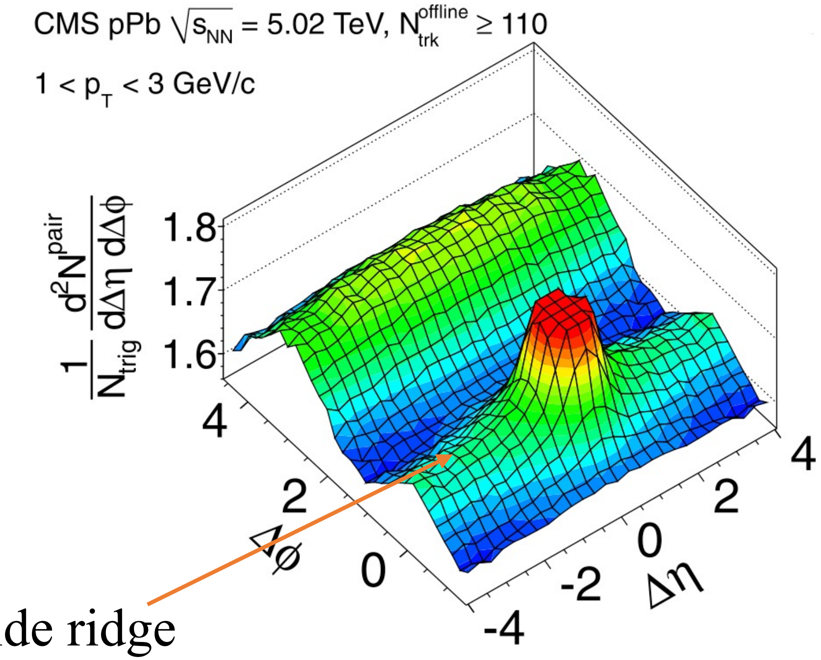
Flow in small collision systems

- In *pp* and *p*Pb collisions, the particle multiplicity is not enough to define the reaction plane. The anisotropy can be measured by two-particle correlation technique.

$$\frac{dN_{\text{pairs}}}{d\Delta\phi} = \left\langle \frac{dN_{\text{pairs}}}{d\Delta\phi} \right\rangle \left(1 + \sum_n 2v_n^2 \cos(n\Delta\phi) \right)$$

- The long-range correlations are observed in high particle multiplicity *pp* and *p*Pb collisions, only different magnitude





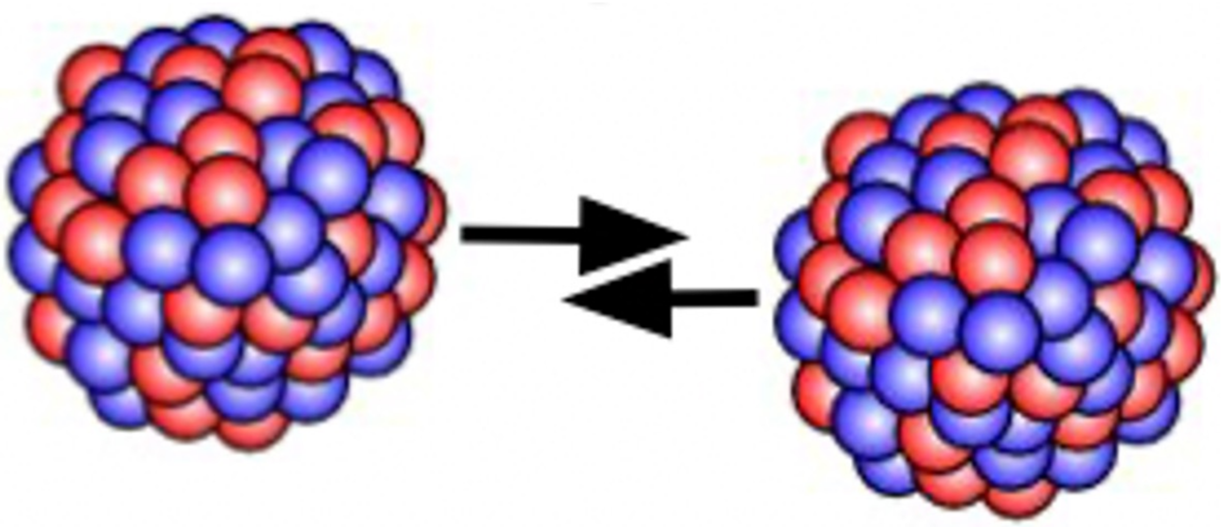
Near-side ridge

- No QGP, why collectivity?
  - ➢ Color Glass Condensate ?
  - ➢ Hydrodynamics ?
  - ➢ Parton-parton scattering ?

Phys. Rev. Lett. 116, 172302
Phys.Lett.B 718 (2013) 795-814
Phys.Rev.D 87 (2013) 9, 094034
Phys.Rev.C 85 (2012) 014911
Phys.Rev.Lett. 113 (2014) 25, 252301

Quarkonium-flow

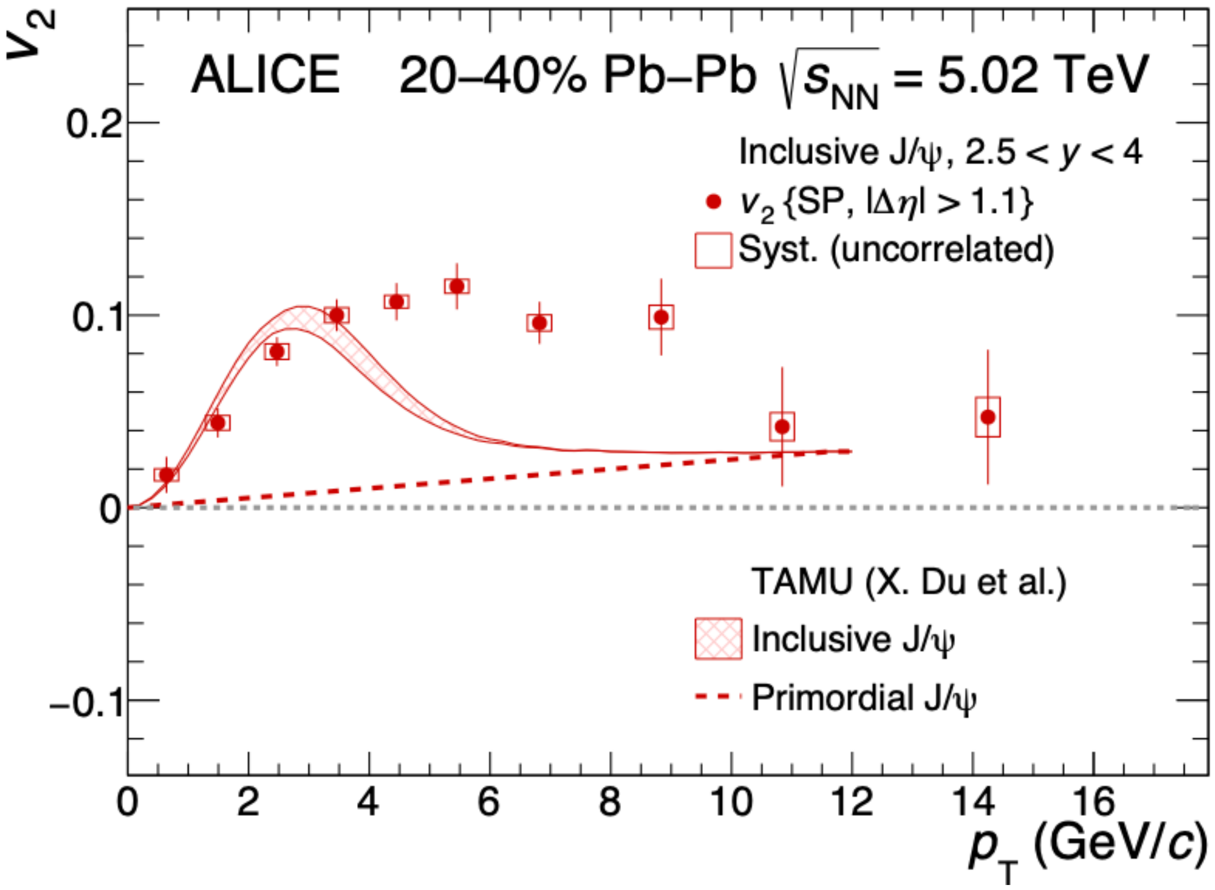
- Light-flavor particles flow. Does the quarkonium “flow” in different collision system?
  - Recombination of partially thermalized heavy quarks.
  - Path-length angular dependent suppression.
  - Initial strong magnetic field.
- Potential influencing factors
  - Beam type
  - Collision energy
  - Quark mass of Quarkonium



AA collisions

Inclusive J/ψ flow in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (ALICE)

- The all PbPb data sample collected during Run2 is used.
- At forward (midrapidity) rapidity, J/ψ are reconstructed in the $\mu^+\mu^-$ (e^+e^-) decay channel.



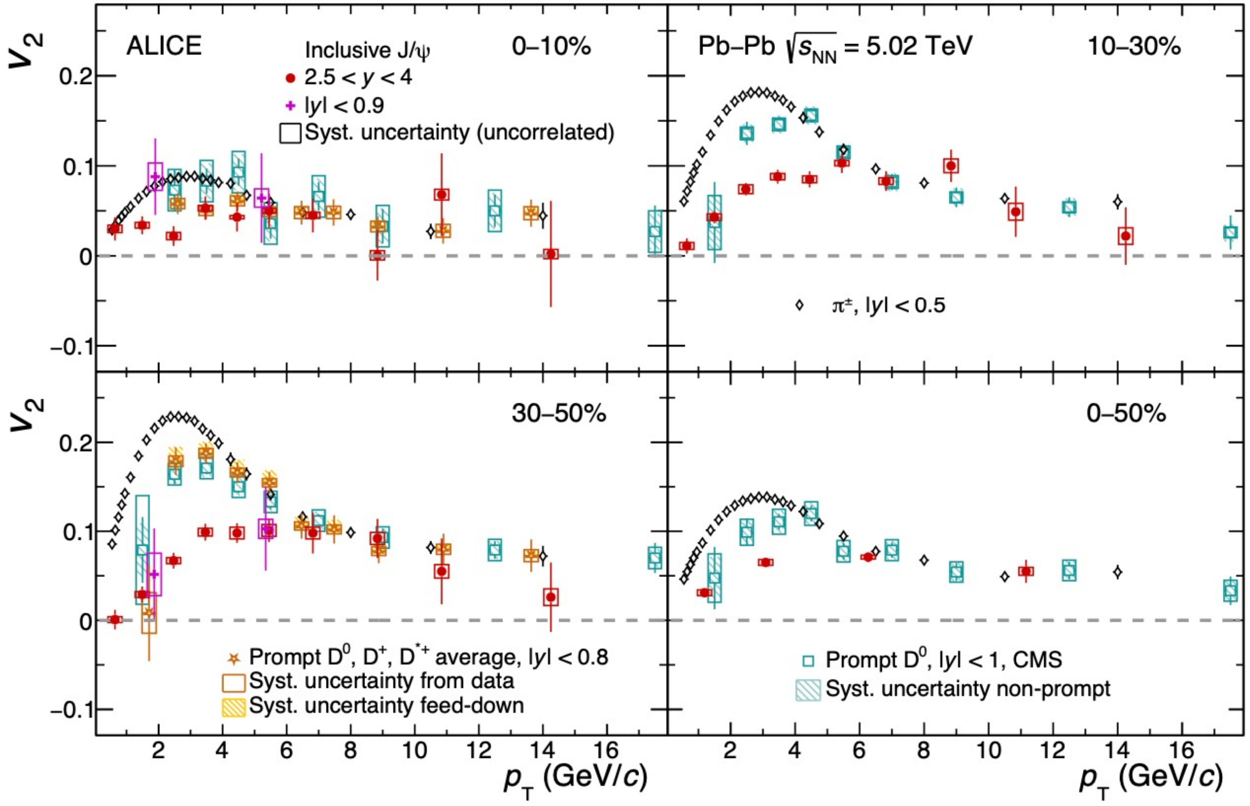
- Positive J/ψ v_2 is clearly observed
- Consistent with transport model up to 4 GeV/c
  - ➢ Charm quark thermalization and flow
- Exceeds model predictions above 4 GeV/c
  - ➢ Jet contribution

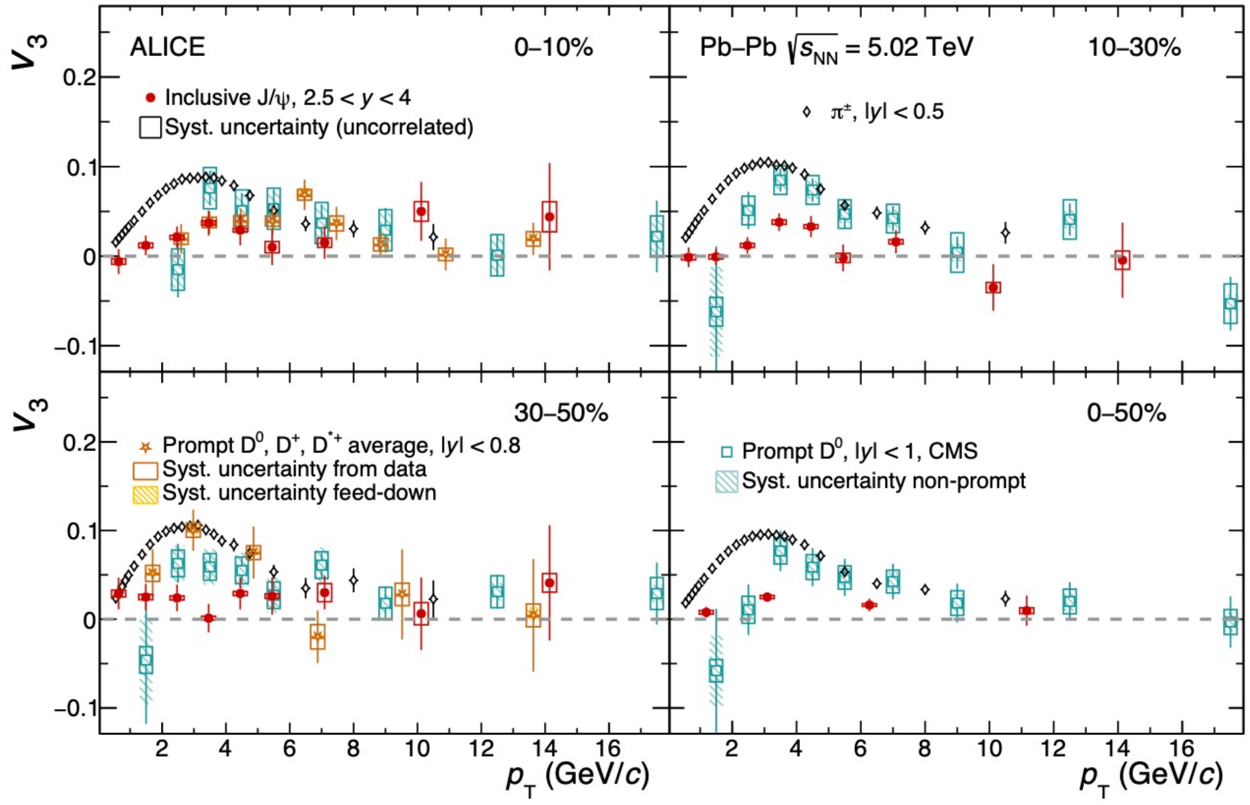
JHEP 10 (2020) 141
Landolt-Bornstein 23 (2010) 293-333

Compare with light flavor and open heavy flavor flow

- $v_2(\pi) > v_2(\mathrm{D}) > v_2(J/\psi)$ and $v_3(\pi) > v_3(\mathrm{D}) > v_3(J/\psi)$ at $p_\mathrm{T} < 6$ GeV/c
  - ➢ Charm quarks may be partially thermalized
- Elliptic flow values converge to same values at high p_T
  - ➢ Suggests origin from from path-length dependent energy-loss effects

JHEP 10 (2020) 141
JHEP 09 (2018) 006
Phys. Rev. Lett. 120, 202301
Phys.Lett.B 813 (2021) 136054

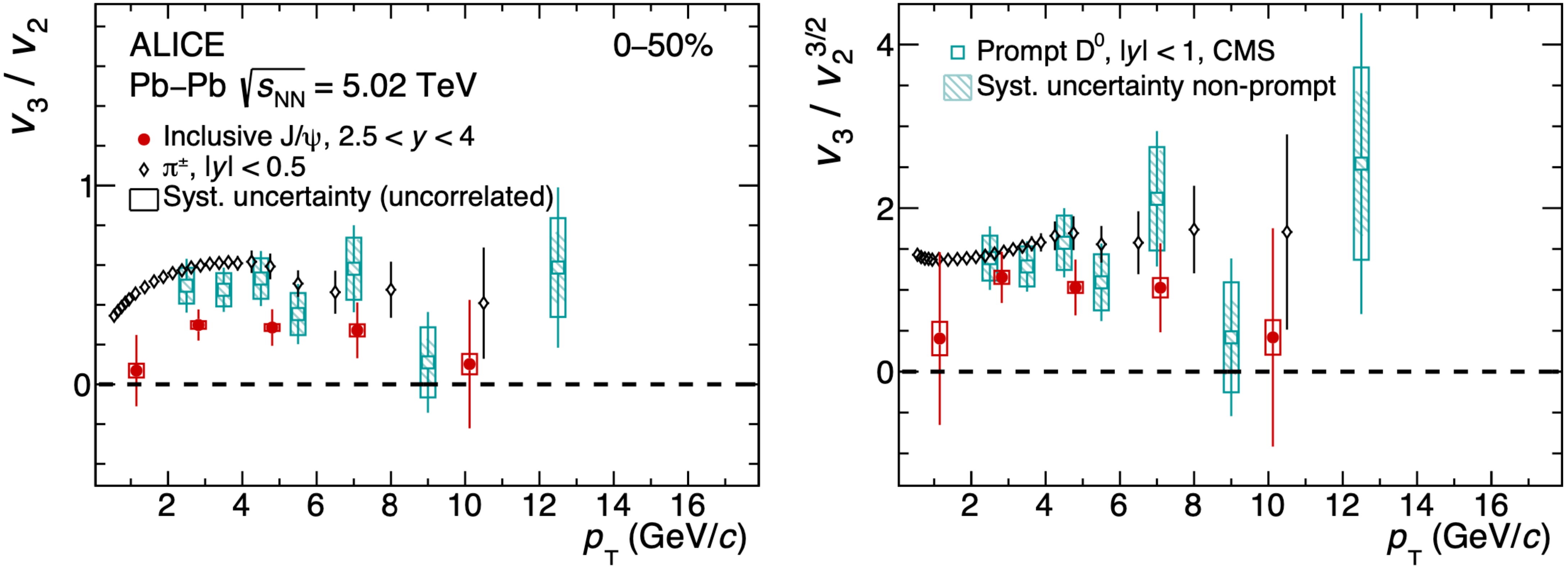




JHEP 10 (2020) 141
JHEP 09 (2018) 006
Phys. Rev. Lett. 120, 202301
Phys.Lett.B 813 (2021) 136054

v_3/v_2 ratio

- Similar mass hierarchy for v_3/v_2 suggests that higher harmonics are damped faster for heavy quarks than for the light ones.
- The flow coefficients for light flavor follow a power-law scaling: $v_n^{1/n} \propto v_m^{1/m}$

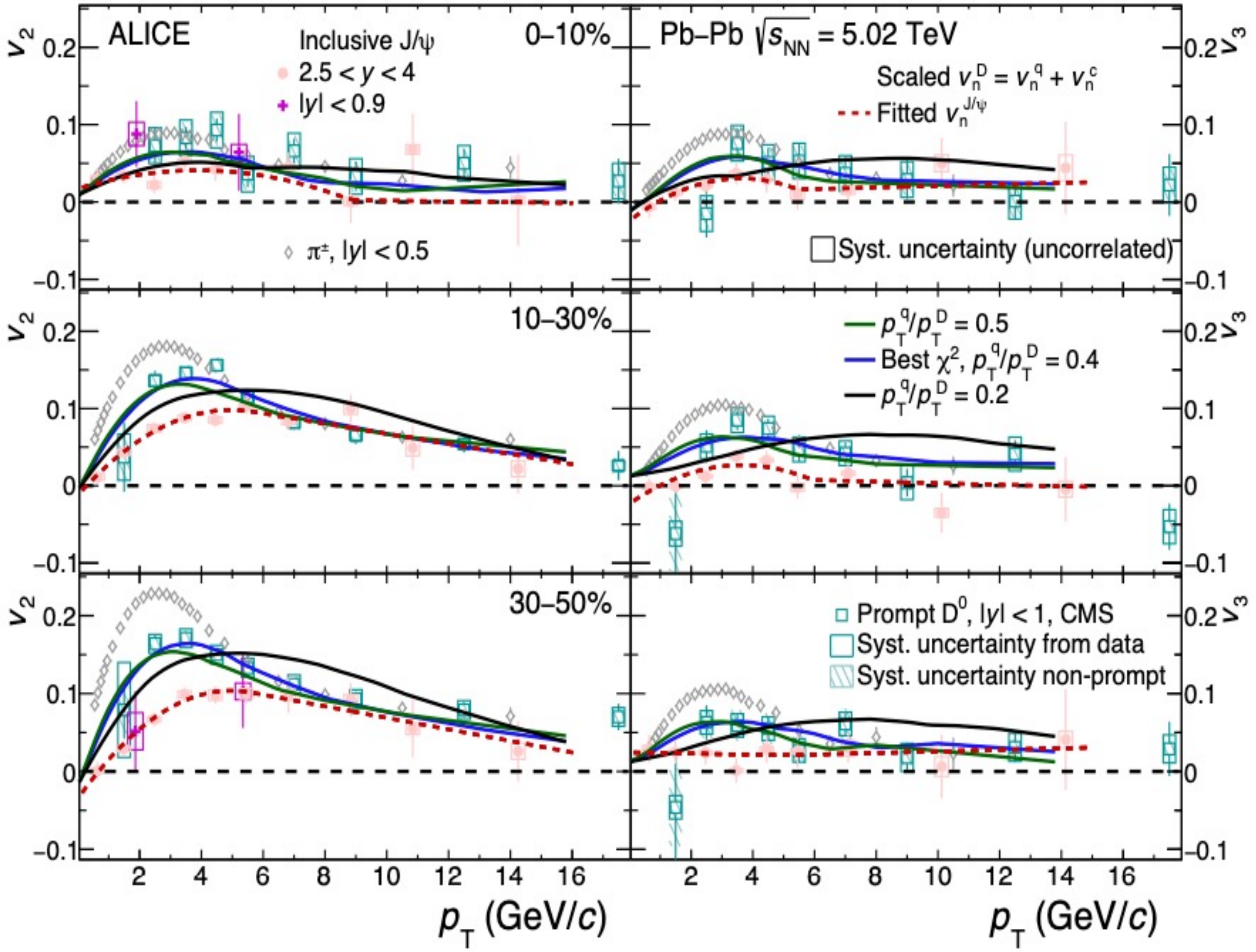


Flow to quark coalescence

- If the coalescence mechanism dominates the hadronization of heavy-flavor hadrons, *D* mesons flow can be constructed as the sum of light and charm quarks flow.

$$v_n^D(p_T^D) = v_n^q(p_T^q) + v_n^c(p_T^c)$$

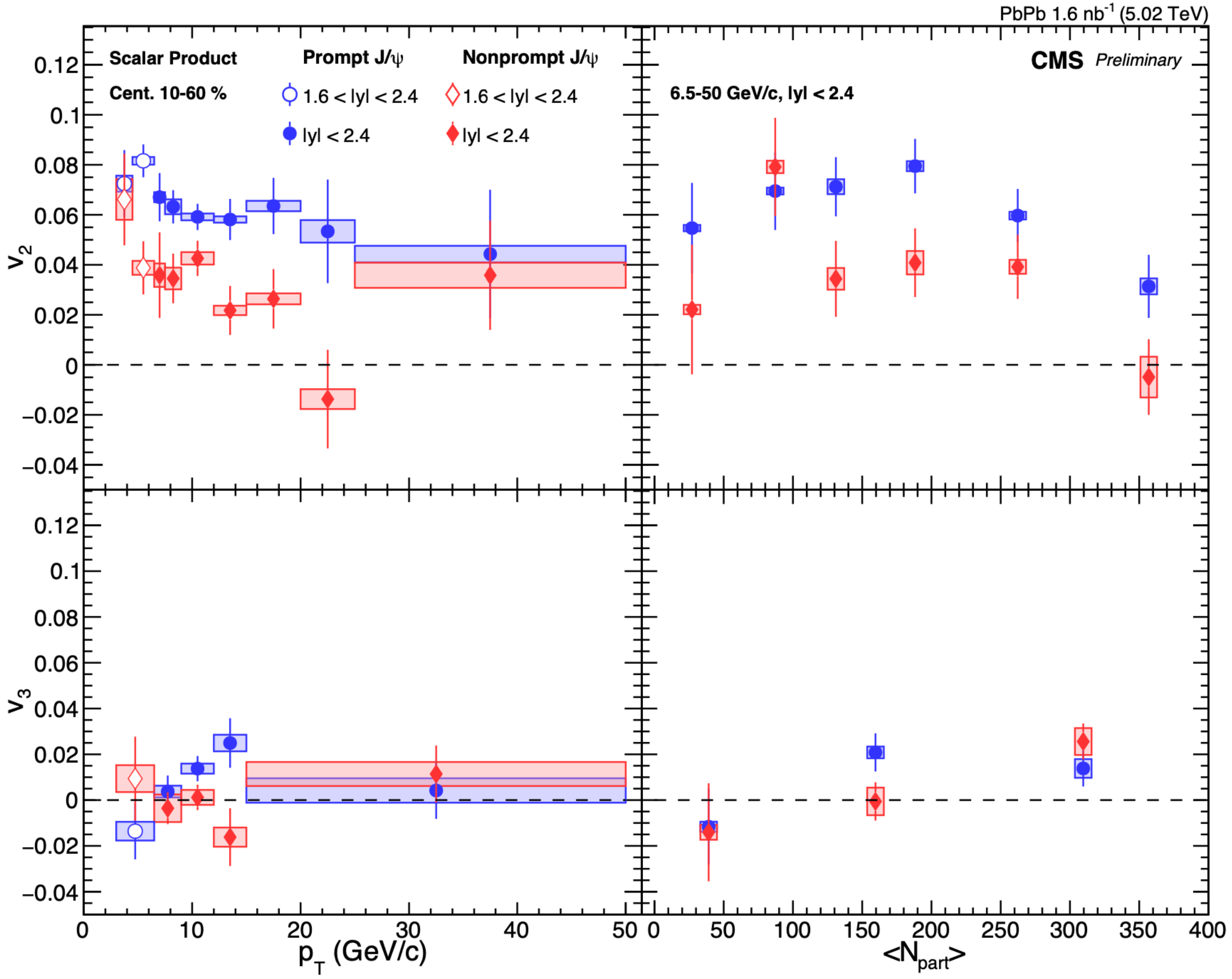
- Supports that charm quarks and light quarks share equally *D* mesons p_T.



JHEP 10 (2020) 141

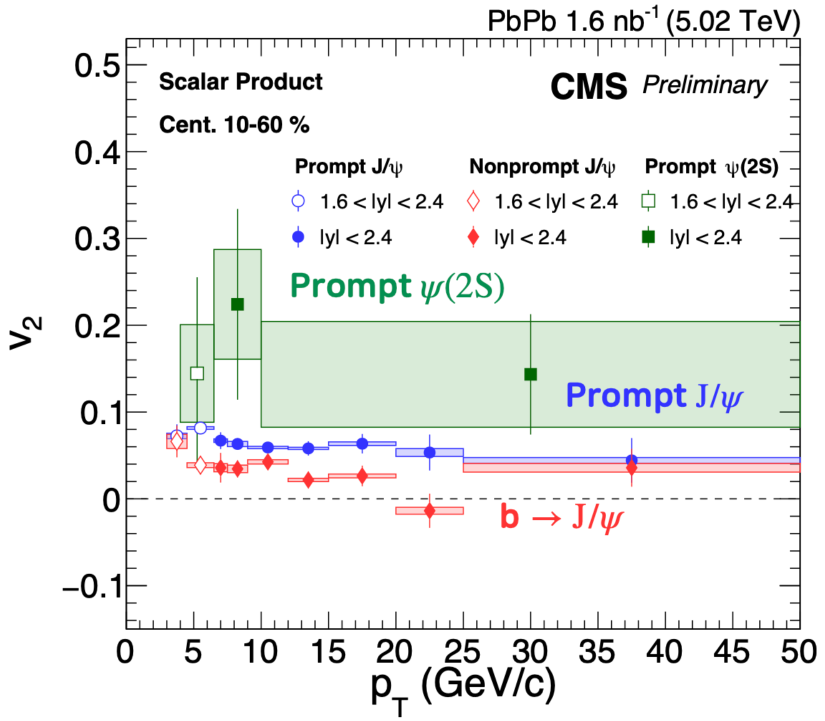
J/ψ flow in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (CMS)

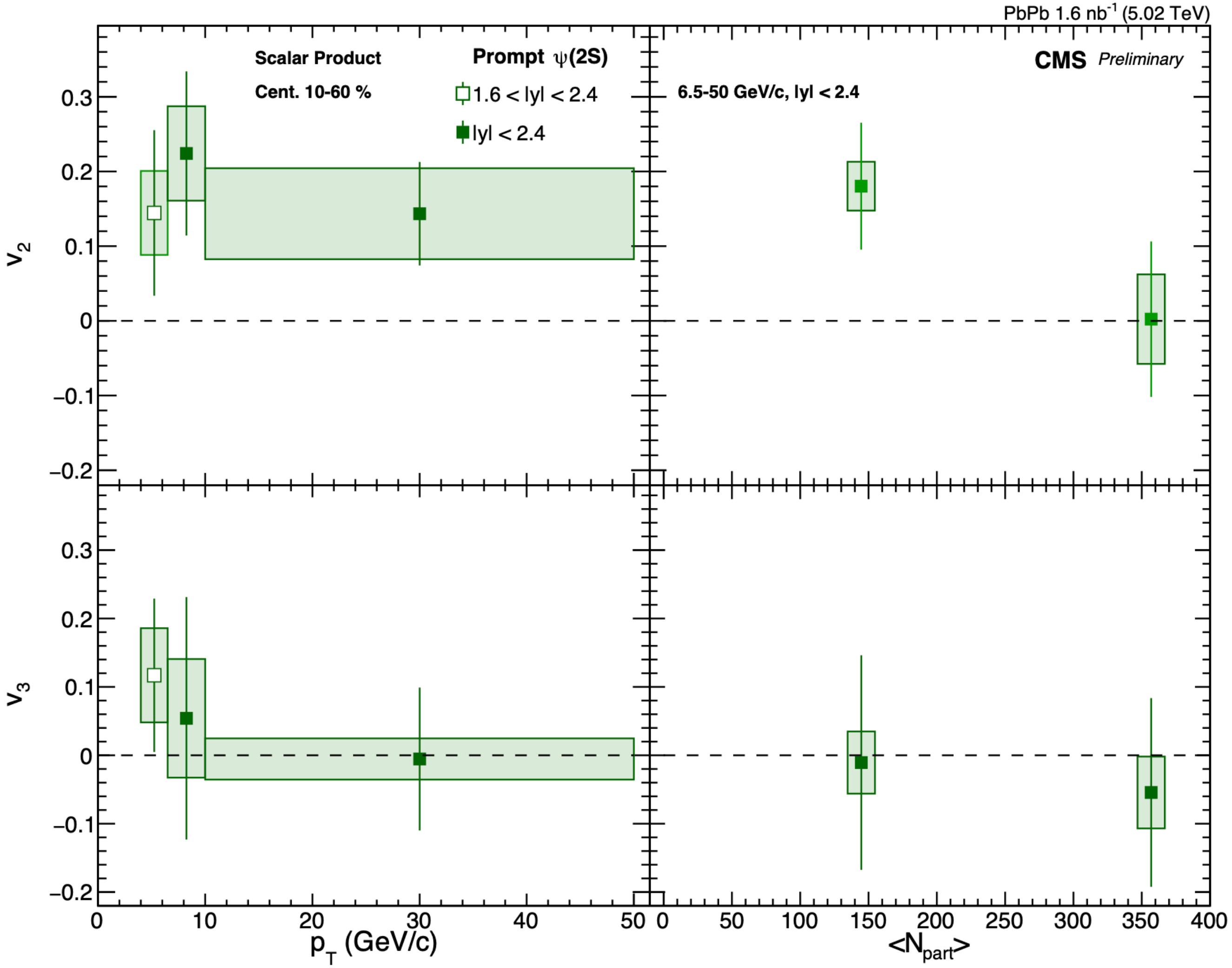
- Obvious non-zero v_2 up to 50 GeV/c
- Prompt J/ψ v_2 larger than Non-prompt J/ψ v_2 suggest different dynamics for b and c quark
- No significant nonzero v_3 values are found in the studied kinematic intervals



CMS PAS HIN-21-008

$\psi(2S)$ flow in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (CMS)





- Obvious non-zero v_2 up to 50 GeV/c
- No significant nonzero v_3 values are found in the studied kinematic intervals
- Prompt $\psi(2S)$ v_2 larger than prompt J/ψ v_2 indicating different degrees of recombination contribution for J/ψ and $\psi(2S)$ mesons

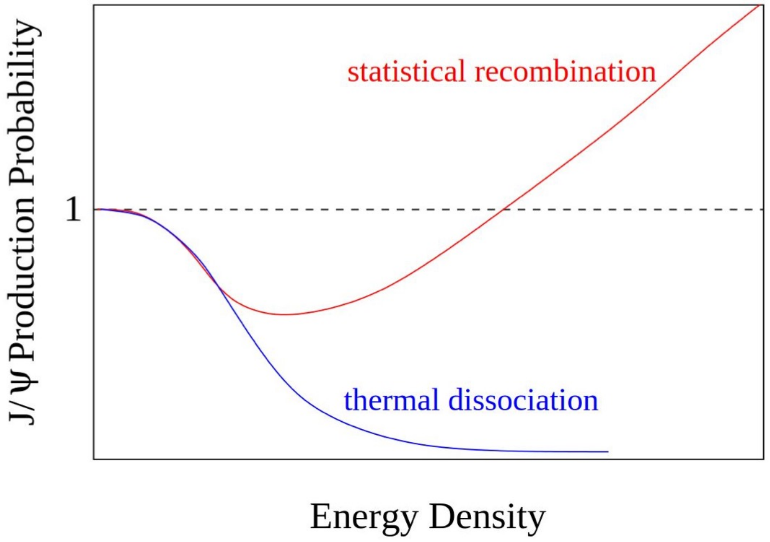
CMS PAS HIN-21-008

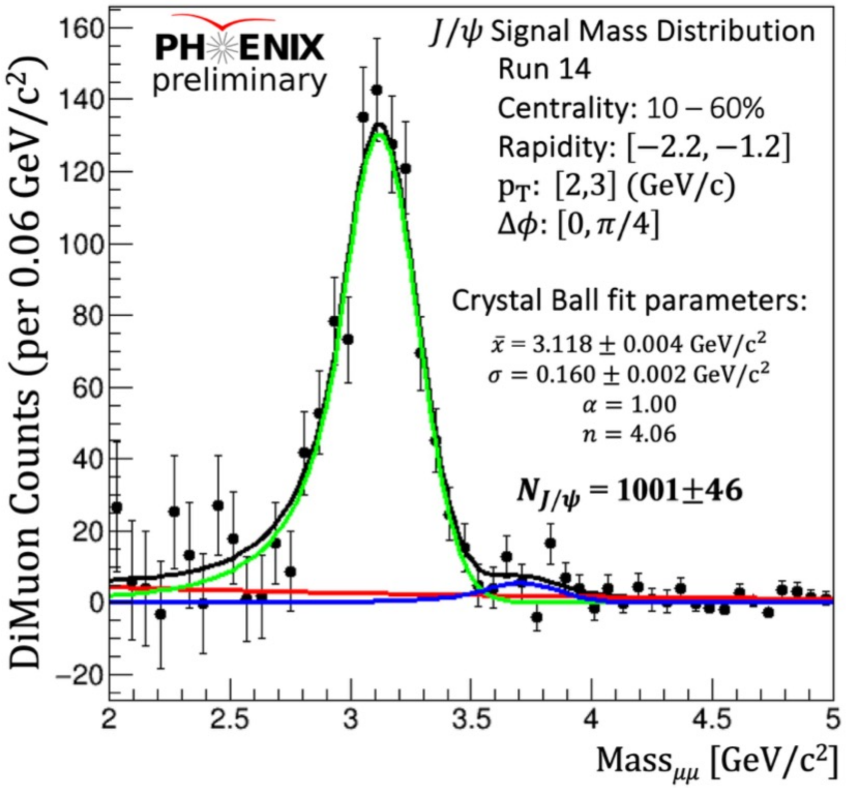
J/ψ elliptic flow in AuAu collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV (PHENIX)

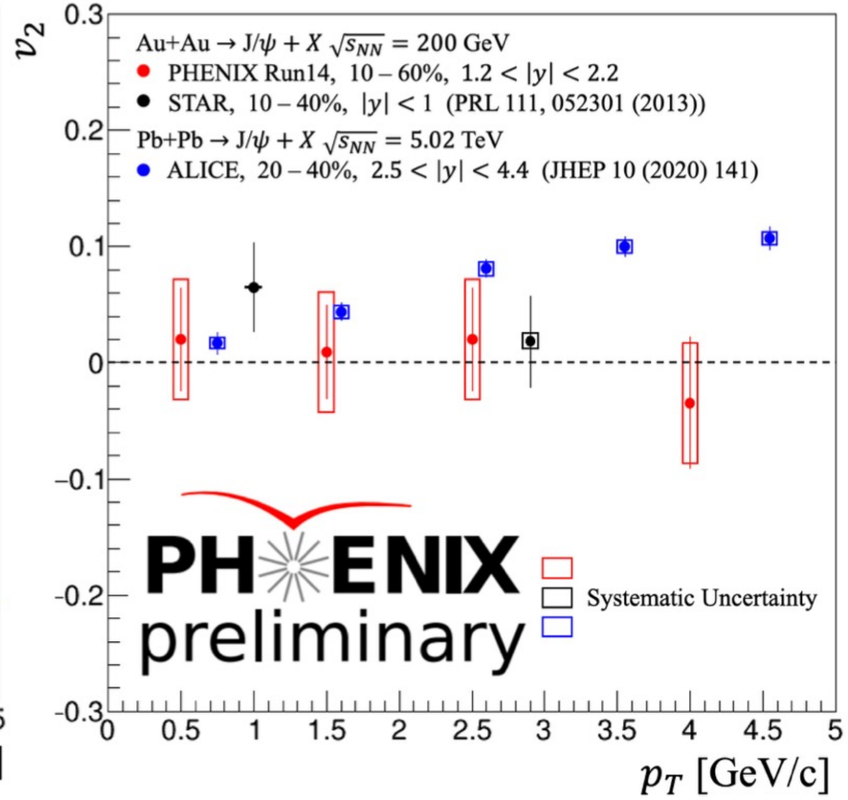
- The reconstructed J/ψ are divided into 2 bins: in-event-plane ($0 < \Delta\phi < \pi/4$) and out-of-event-plane ($\pi/4 < \Delta\phi < \pi/2$)

$$v_2^{\mathrm{obs}} = \frac{\pi}{4}\frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$

- Correcting with the event plane resolution: $v_2 = \frac{v_2^{\mathrm{obs}}}{\sigma_{EPR}}$
- J/ψ elliptic flow at forward rapidity consistent with zero.

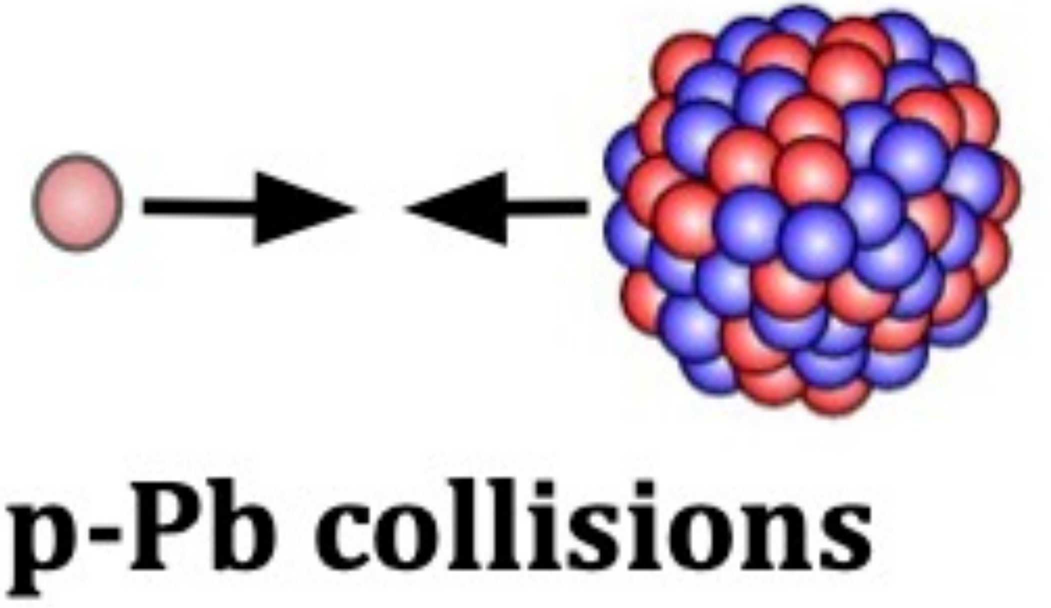






lower collision energy ⟶ fewer $c\bar{c}$ pairs ⟶ smaller azimuthal anisotropy

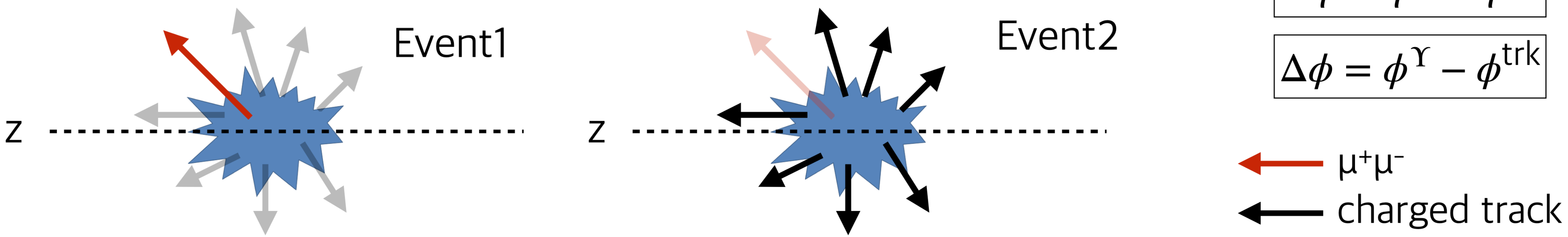
Preliminary
Phys.Rev.Lett. 111 (2013) 5, 052301
JHEP 10 (2020) 141


p-Pb collisions

$\Upsilon(1S)$ flow in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV (CMS)

- The $\Upsilon(1S)$ signals are reconstructed by dimuon decay channel
- The azimuthal anisotropy results are reported for high-multiplicity events ($70 < N_{track}^{offline} < 300$)
- Same event correlation: $S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{same}}{d\Delta\eta\ d\Delta\phi}$
  - The dimuon as trigger particle correlated with the charged track associators from the same event
- Mixed event correlation: $B(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{mix}}{d\Delta\eta\ d\Delta\phi}$
  - The dimuon as trigger particle correlated with the charged track associators from the different event
  - These mixed events are randomly selected from the same $N_{track}^{offline}$ and p_T range and fall within $|Z_{vertex}^1 - Z_{vertex}^2| < 2cm$

$N_{track}^{offline}$ is the number of reconstructed primary charged particle tracks



$$\Delta\eta = \eta^{\Upsilon} - \eta^{trk}$$

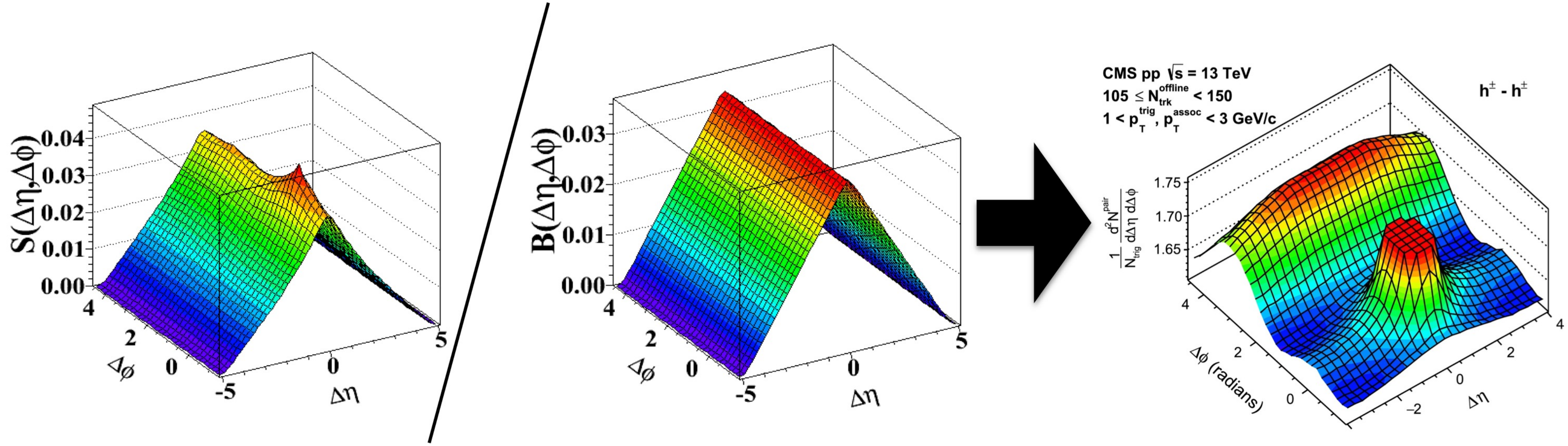
$$\Delta\phi = \phi^{\Upsilon} - \phi^{trk}$$

arXiv:2310.03233

Two-particle correlation method

- The ratio of same event correlation and mixed event correlation cancel out the random combinatorial background and acceptance effects, obtaining the correlation function.

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\ \mathrm{d}\Delta\phi} = \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)} \times B(0,0)$$

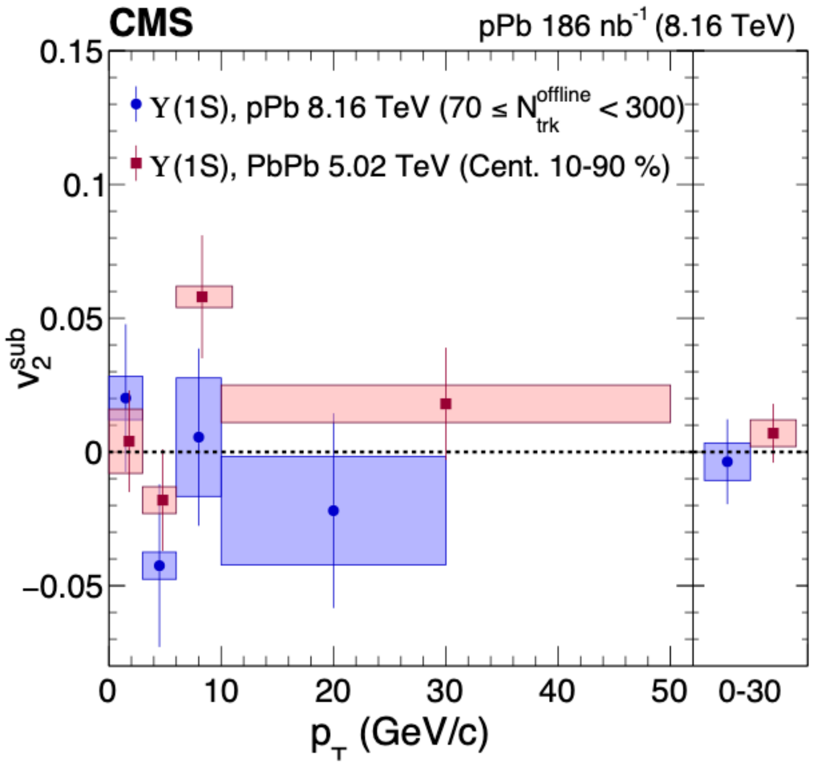


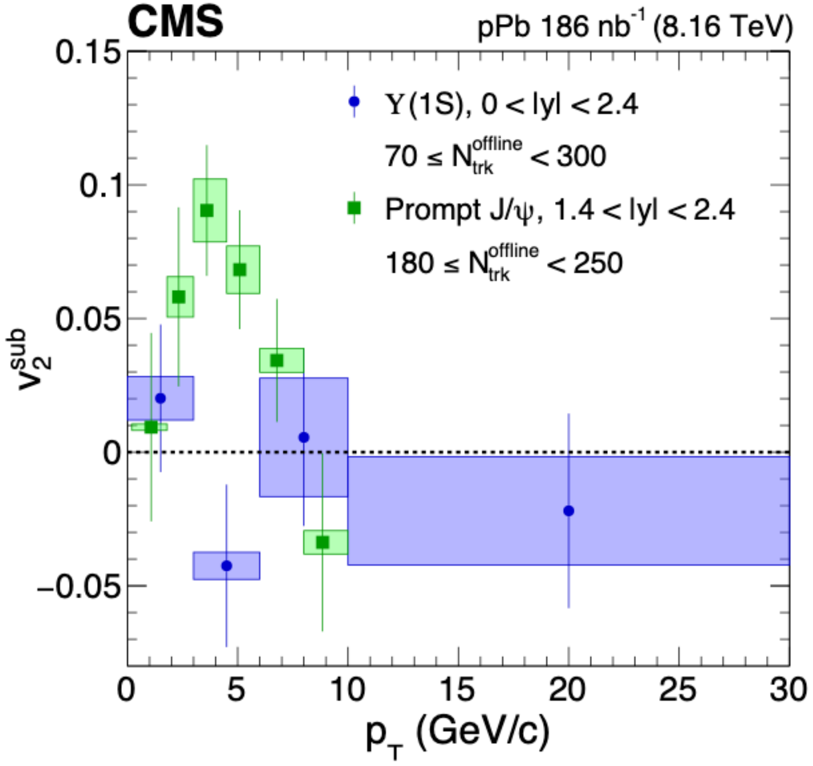
- The most obvious jet peak and a little near-side ridge can be observed.

arXiv:2310.03233
Phys.Lett.B 765 (2017) 193-220

$\Upsilon(1S)$ v_2^{sub} results

- $\Upsilon(1S)$ v_2^{sub} is consistent with zero over the measured p_T range in pPb collisions, as also found for centrality-integrated PbPb collisions.
- Comparing the non-zero v_2^{sub} for J/ψ shows that bottom quarks experience less collective motion than charm quarks in pPb collisions.

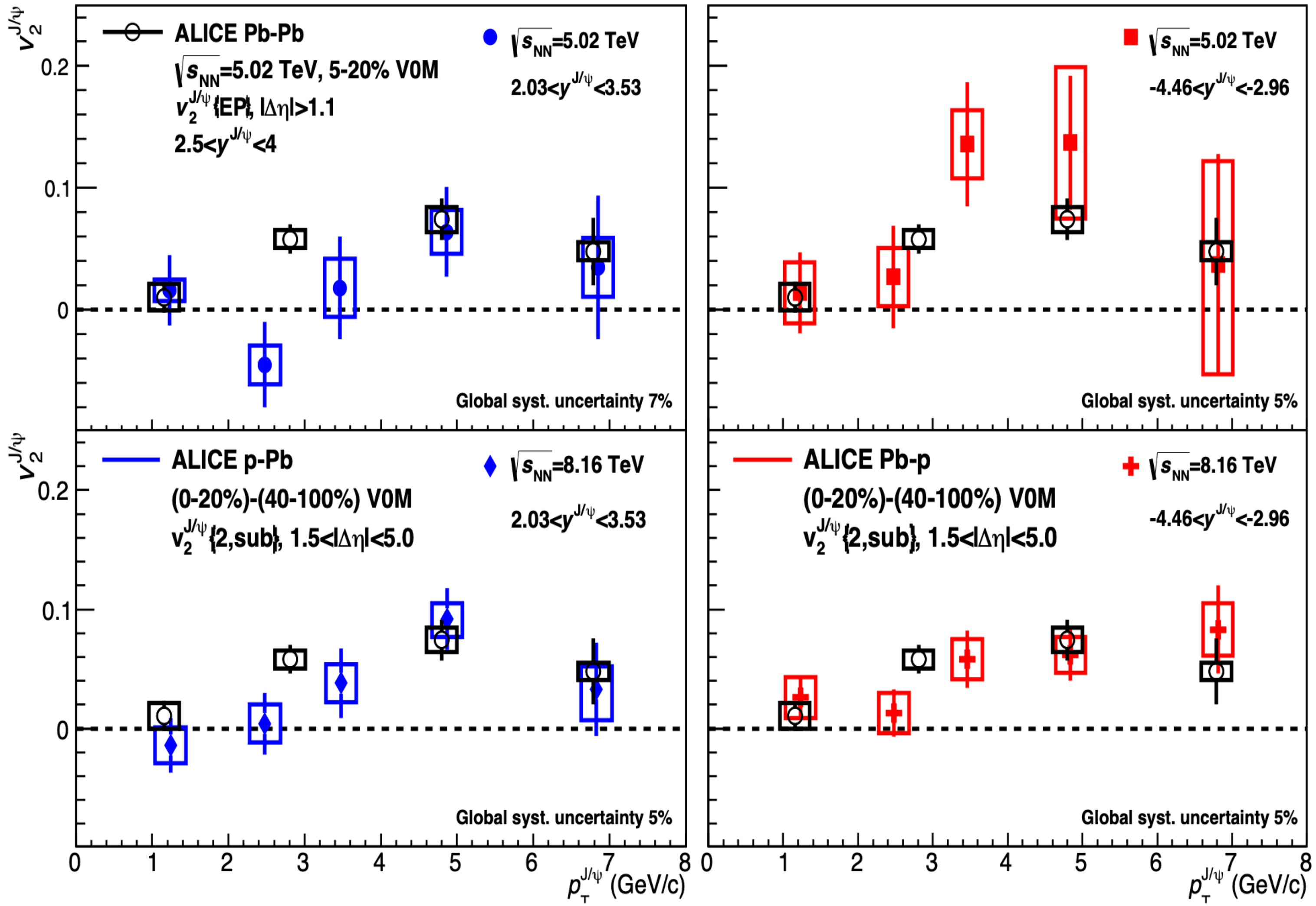




arXiv:2310.03233
Phys.Lett.B 819 (2021) 136385
Phys.Lett.B 791 (2019) 172-194

J/ψ elliptic flow in pPb collisions (ALICE)

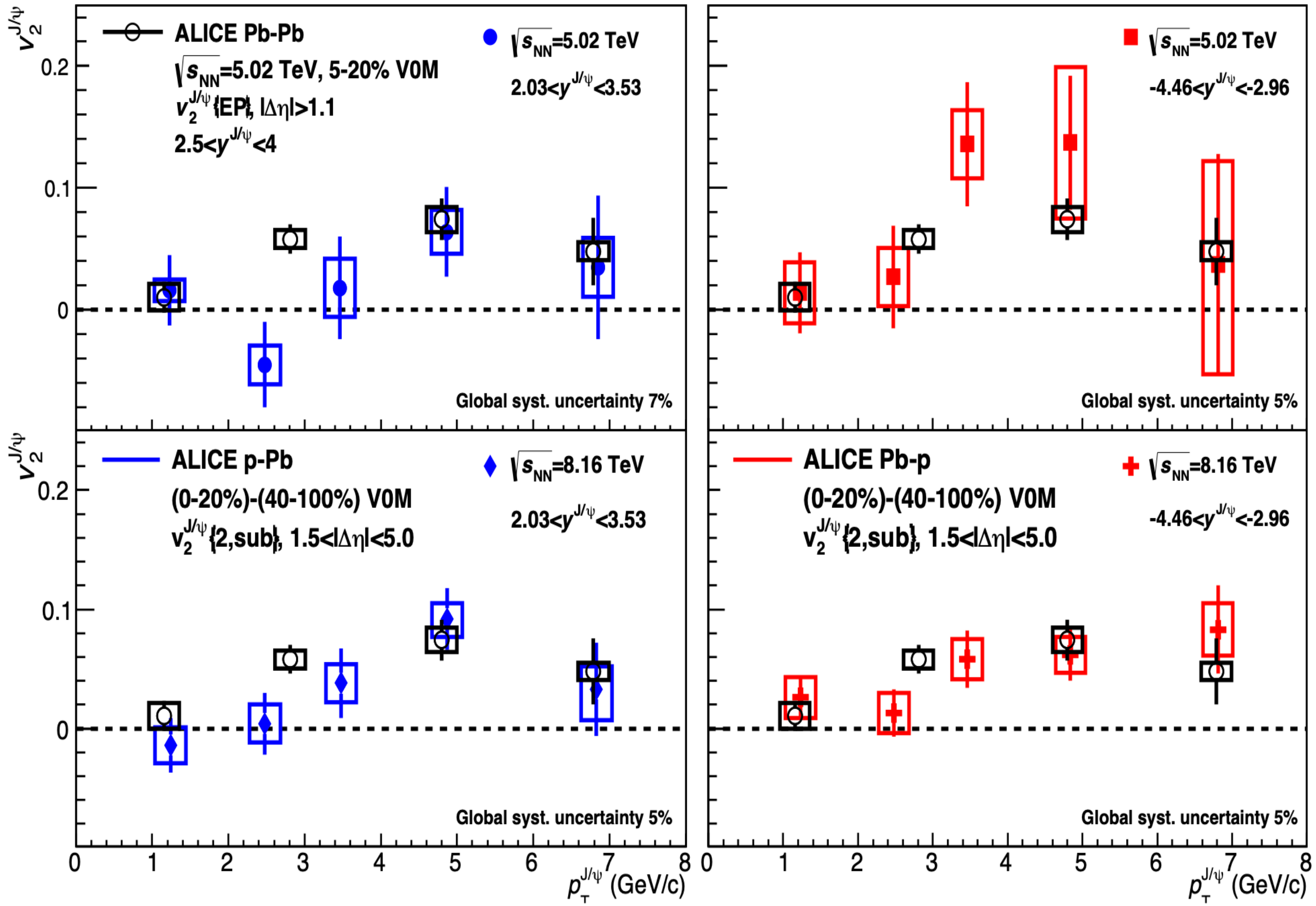
- The pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.02 TeV are collected during 2013 and 2016.
- J/ψ are reconstructed by the $\mu^+\mu^-$ decay channel at forward (p-going, $2.03 < y < 3.53$) and backward (Pb-going, $-4.46 < y < -2.96$) rapidity, the charge hadrons are reconstructed at mid-rapidity ($|\eta| < 1.8$).
- The v_n coefficients are obtained using two-particle correlation method.



Phys.Lett.B 780 (2018) 7-20

J/ψ elliptic flow in pPb collisions (ALICE)

- In pPb collisions, J/ψ v_2 is compatible with zero at $p_{\mathrm{T}} < 3$ GeV/c, which is different from PbPb collision. This may come from the negligible recombination effect.
- Positive J/ψ v_2 is clearly observed in 3< $p_{\mathrm{T}} < 6$ GeV/c



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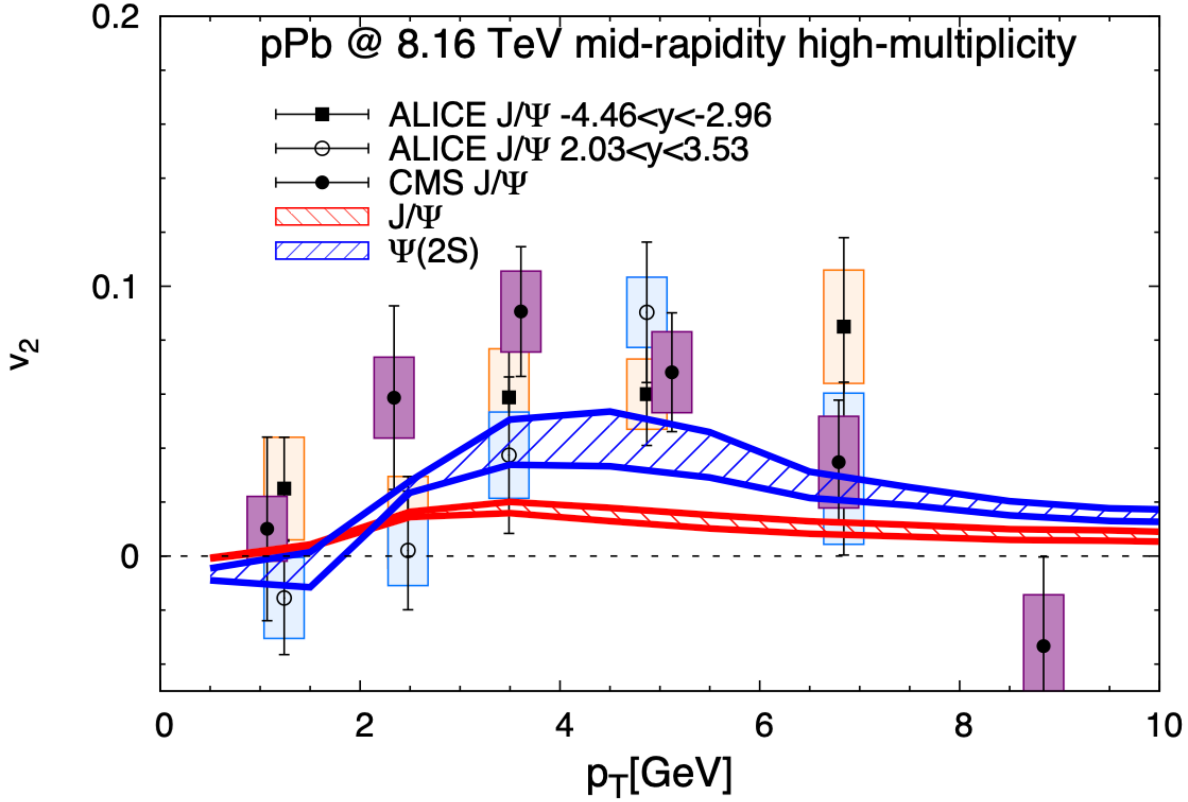
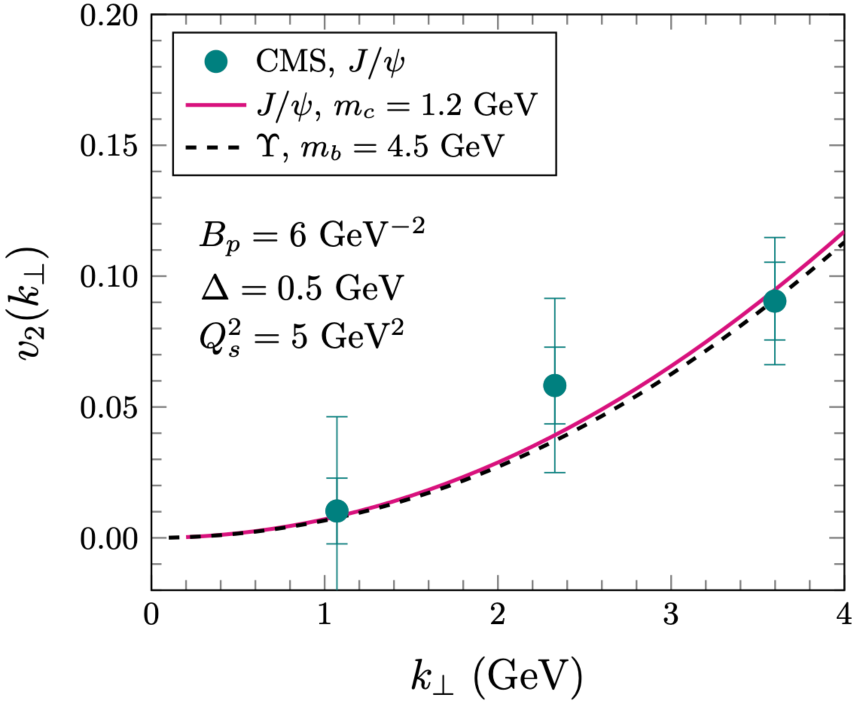
Compare with CMS and transport model



- Positive J/ψ v_2 is clearly observed in CMS
- Transport models underestimate the v_2
  - Negligible path-length dependent effects & regeneration in pPb collisions.
  - The similar v_2 at backward and forward rapidities indicate the non-zero v_2 may not originate from final-state interactions alone. Initial state effect ?



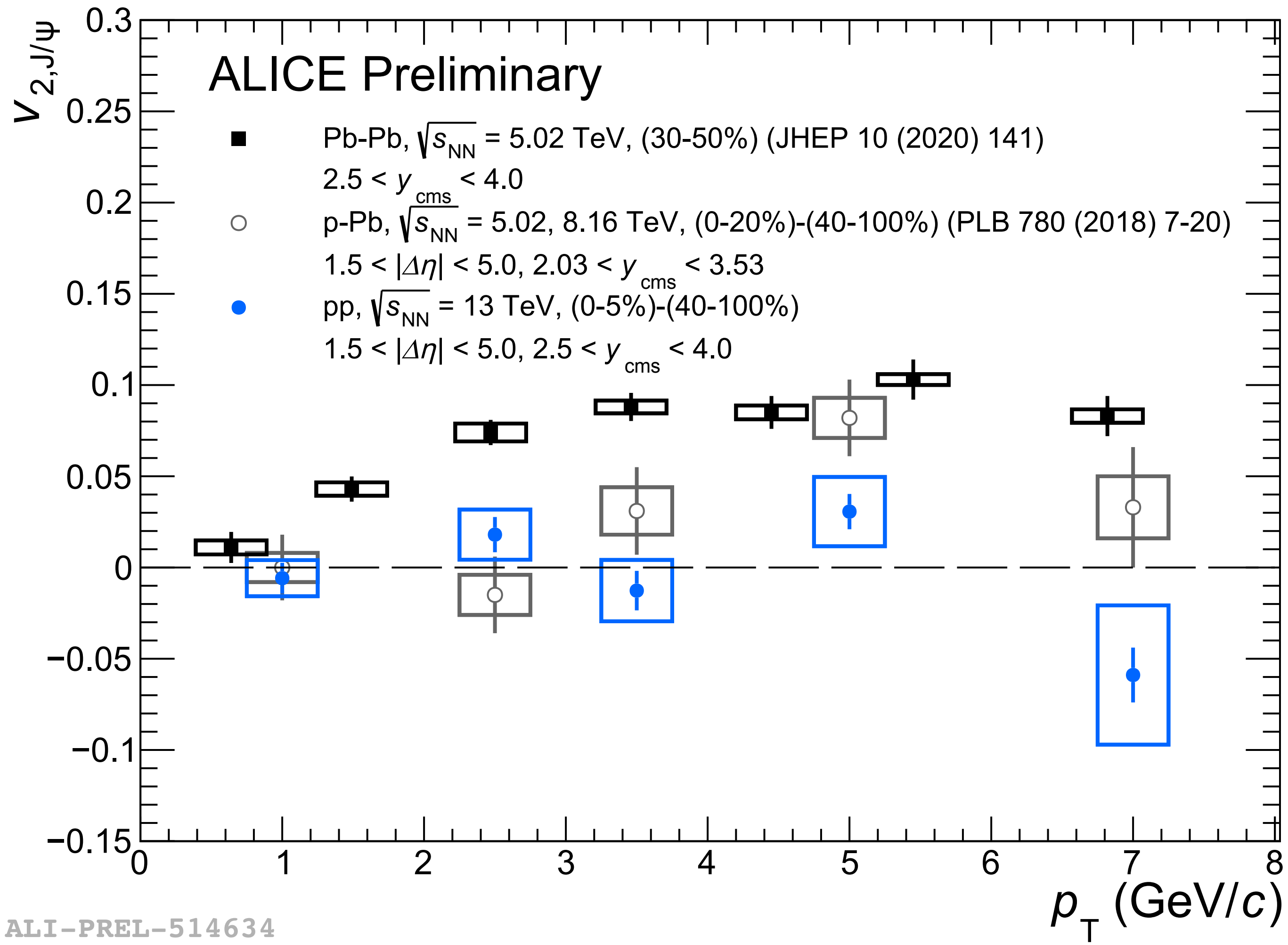
Both J/ψ and Υ flow in pPb collisions?

Phys.Lett.B 780 (2018) 7-20
JHEP 03 (2019) 015
Phys.Rev.Lett. 122 (2019) 17, 172302

pp collisions

Inclusive J/ψ flow in pp collisions at $\sqrt{s} = 13$ TeV (ALICE)

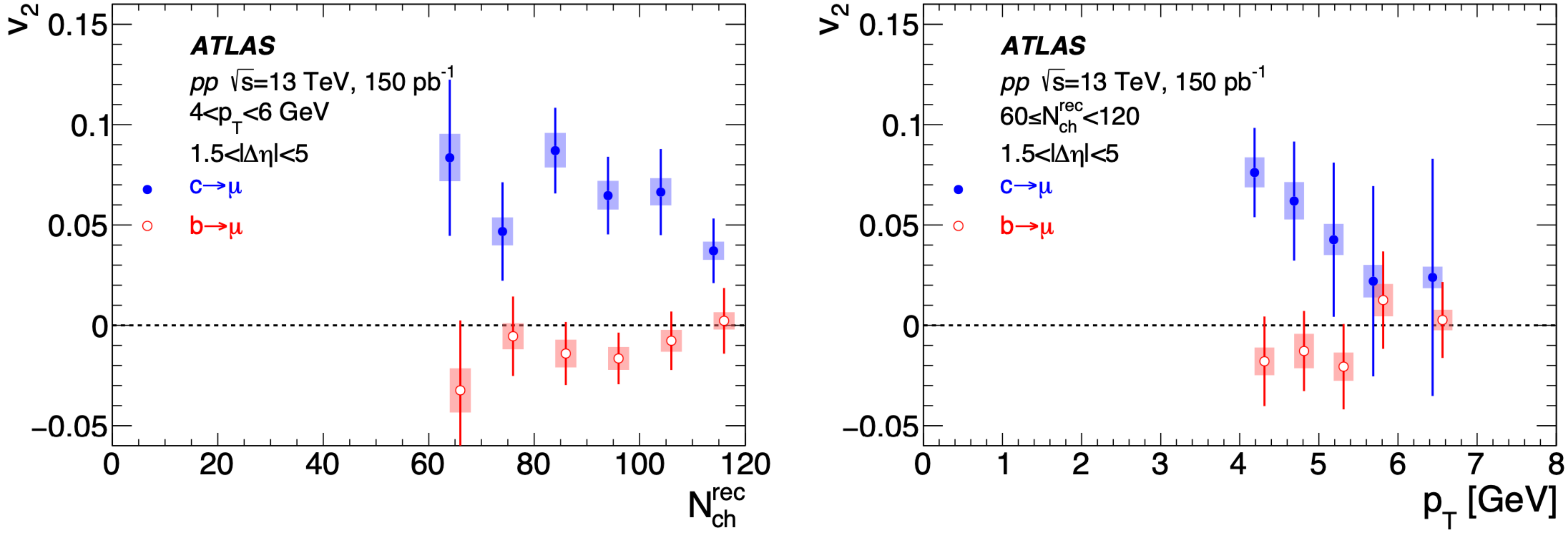
- The First measurement of J/ψ elliptic flow in pp collisions.
- No significant J/ψ elliptic flow observed in pp collisions.
- J/ψ elliptic flow shows collisions system size dependency ($v_{2,J/\psi}^{pp} < v_{2,J/\psi}^{p\mathrm{Pb}} < v_{2,J/\psi}^{\mathrm{PbPb}}$)



preliminary

Anisotropy flow of muons from charm and bottom hadrons in *pp* collisions at $\sqrt{s} = 13$ TeV (ATLAS)

- The inclusive heavy-flavor muon v_2 are not dependent on N_{ch}^{rec} in the range 60–120.
- The bottom-decay muons have v_2 values consistent with zero, while the charm-decay muons have significant non-zero v_2 values.
- These results indicate that bottom quarks, unlike light and charm quarks, do not participate in the collective behavior in high-multiplicity *pp* collisions



Phys.Rev.Lett. 124 (2020) 8, 082301

Summary

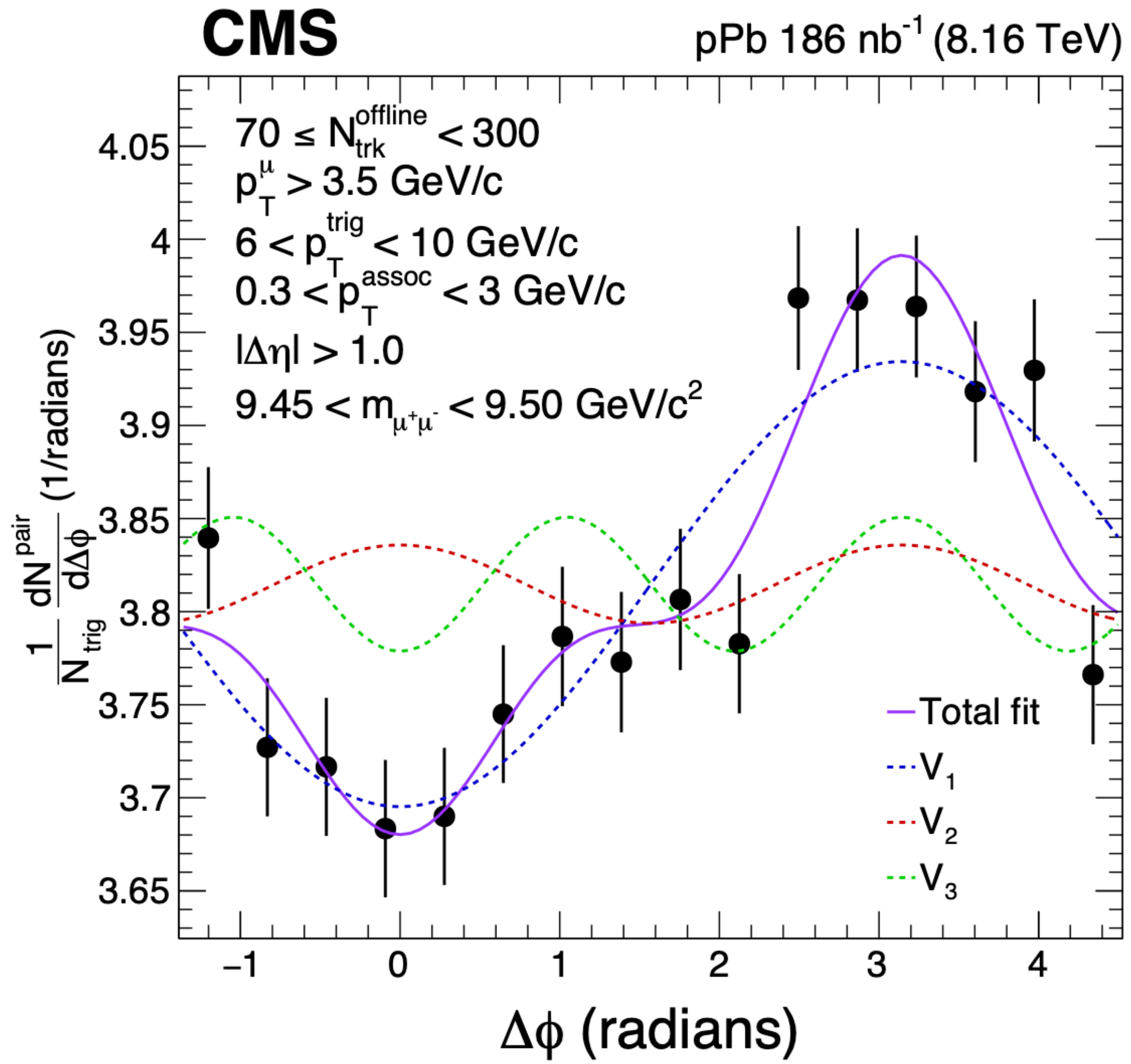
- In AA collisions, the J/ψ and $\psi(2S)$ flow are clearly observed at LHC energies but not at RHIC energies. This may be related to the fact that fewer $c\bar{c}$ pairs are produced at low collision energies. In addition, no obvious $\Upsilon(1S)$ elliptic flow is observed in PbPb collisions. This implies different collective flow behavior for *b* and *c* quarks
- In *p*Pb collisions, J/ψ shows a elliptic flow at $3 < p_{\mathrm{T}} < 6$ GeV/*c*, consistent with zero at high p_{T}, which is different with PbPb collisions. The underlying mechanism needs further study. $\Upsilon(1S)$ elliptic flow has not been observed in *p*Pb collisions.
- In *pp* collisions, no significant J/ψ elliptic flow is observed.

Back up

Azimuthal anisotropy extraction

- Long-range ($|\Delta\eta| > 1$) events projected to $\Delta\phi$ axis in order to reject jet contribution
- $V_{n\Delta}$ is determined from a Fourier decomposition.

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left\{1 + \sum_{n} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$



arXiv:2310.03233

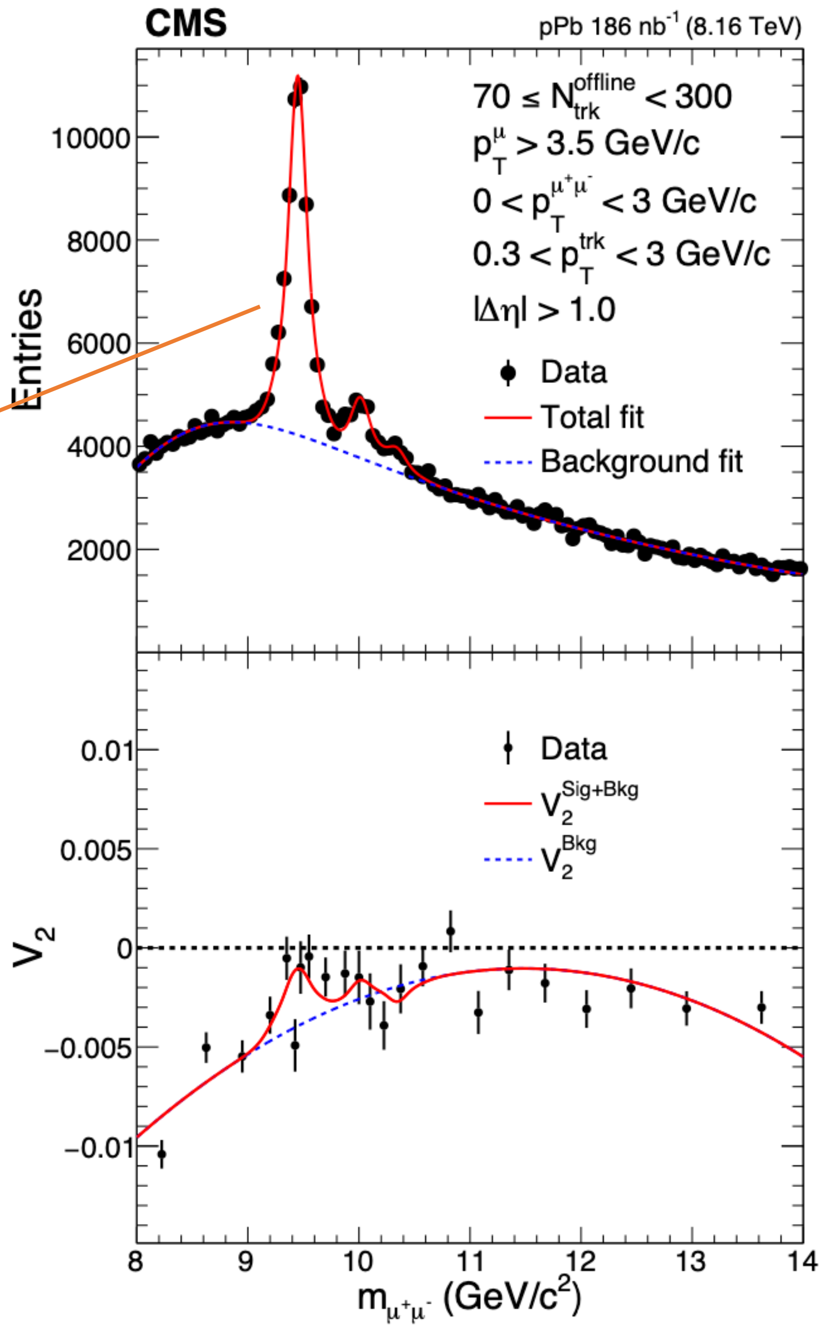
Elliptic flow extraction

- $V_{n\Delta}$ contains four components: $V_n^{\Upsilon(1S)}$, $V_n^{\Upsilon(2S)}$, $V_n^{\Upsilon(3S)}$, V_n^{Bkg}
- The $\alpha_i(m_{\mu^+\mu^-})$ factors are the signal fraction for $\Upsilon(\text{iS})$ as a function of $m_{\mu^+\mu^-}$. The values are get from $m_{\mu^+\mu^-}$ fit.

$$\alpha_i(m_{\mu^+\mu^-}) = \text{Sig}_{\Upsilon(iS)}(m_{\mu^+\mu^-})/[\text{Sig}_{\Upsilon(1S)}(m_{\mu^+\mu^-}) + \text{Sig}_{\Upsilon(2S)}(m_{\mu^+\mu^-}) + \text{Sig}_{\Upsilon(3S)}(m_{\mu^+\mu^-}) + \text{Bkg}(m_{\mu^+\mu^-})].$$

$$V_2^{\text{Sig+Bkg}}(m_{\mu^+\mu^-}) = \alpha_1(m_{\mu^+\mu^-})V_2^{\Upsilon(1S)} + \alpha_2(m_{\mu^+\mu^-})V_2^{\Upsilon(2S)} + \alpha_3(m_{\mu^+\mu^-})V_2^{\Upsilon(3S)} + [1 - \alpha_1(m_{\mu^+\mu^-}) - \alpha_2(m_{\mu^+\mu^-}) - \alpha_3(m_{\mu^+\mu^-})]V_2^{\text{Bkg}}(m_{\mu^+\mu^-}),$$

- $V_2^{\Upsilon(\text{iS})}$ is assumed to be independent of $m_{\mu^+\mu^-}$, V_2^{Bkg} is described by a second order polynomial function.



arXiv:2310.03233

Dijet subtraction

- Low-multiplicity subtraction is used to remove back-to-back jet correlation.

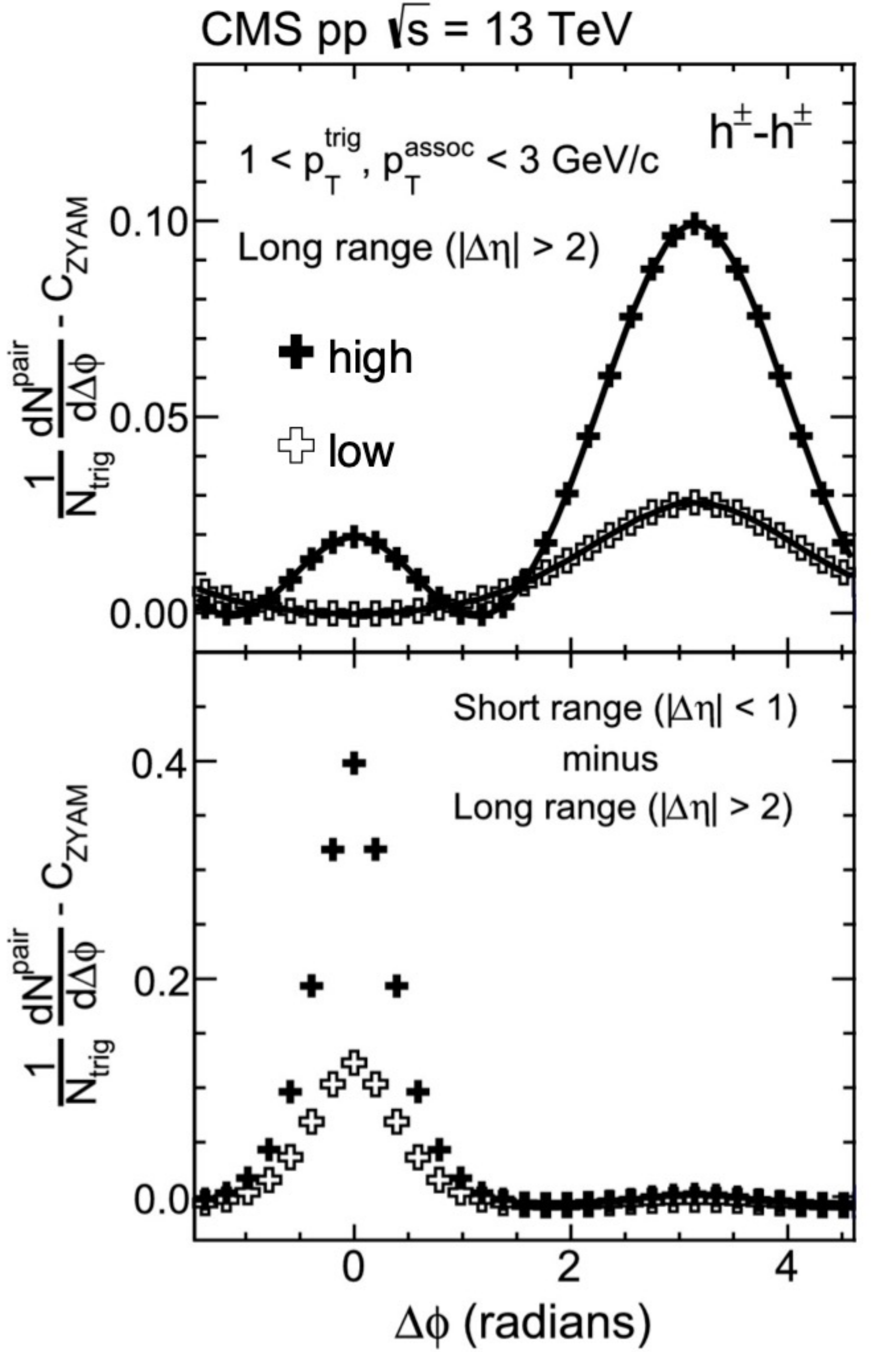
$$V_2^{\text{sub}} = V_2^{\text{Sig}}(70 \le N_{\text{trk}}^{\text{offline}} < 300) - V_2^{\text{Sig}}(N_{\text{trk}}^{\text{offline}} < 50) \times \frac{N_{\text{assoc}}(N_{\text{trk}}^{\text{offline}} < 50)}{N_{\text{assoc}}(70 \le N_{\text{trk}}^{\text{offline}} < 300)} \frac{J_{\text{jet}}(70 \le N_{\text{trk}}^{\text{offline}} < 300)}{J_{\text{jet}}(N_{\text{trk}}^{\text{offline}} < 50)}$$

Account for the enhanced jet yield

Account for the enhanced jet correlations

- $\Upsilon(1S)$-track V_2 is taken as the product of single particle v_2 for $\Upsilon(1S)$ and associated charged hadrons

$$v_2^{\text{sub}}(p_T^{\text{trig}}) = \frac{V_2^{\text{sub}}(p_T^{\text{trig}}, p_T^{\text{assoc}})}{\sqrt{V_2^{\text{sub}}(p_T^{\text{assoc}}, p_T^{\text{assoc}})}}$$



arXiv:2310.03233
arXiv:1902.11290
Phys.Lett.B 765 (2017) 193-220