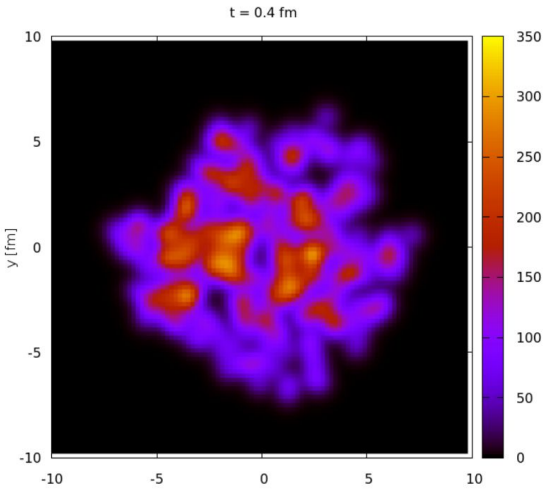
Measurements of open and hidden HF flow at LHC

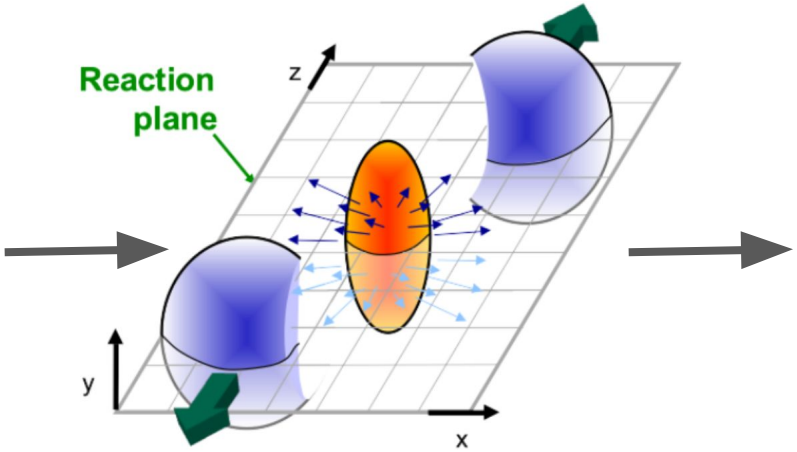
C.Cheshkov (IP2I Lyon)

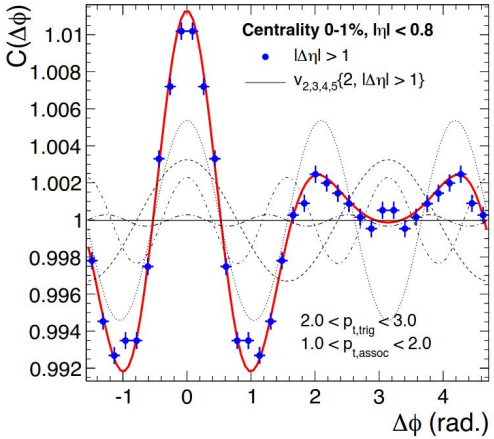
QGP flow

Flow in heavy-ion collisions



Phys.Rev.Lett.106:042301





ALICE PRL. 107, 032301

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)]$$

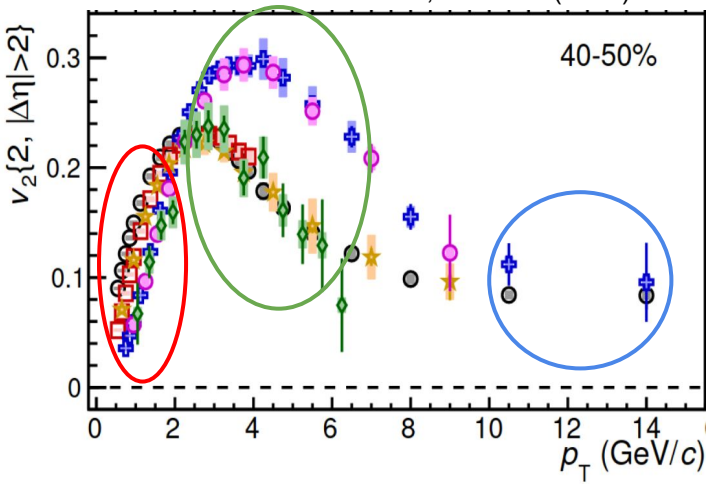
- Initial-state (IS) spatial anisotropies ε_n transferred by pressure gradients into final-state momentum anisotropies ⇨ anisotropic flow of QGP

- Elliptic v_2 ⇦ almond shape of overlap
  Triangular v_3 and higher ⇦ initial-state fluctuations
  $v_n \sim \varepsilon_n$ (n=2,3)

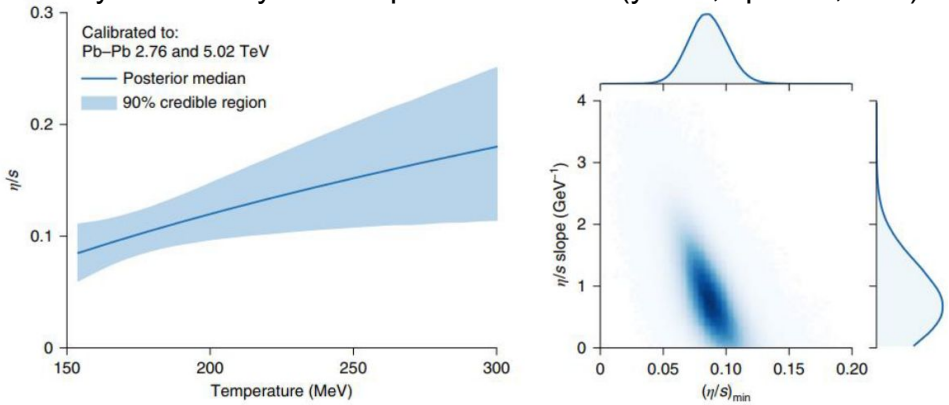
Flow in heavy-ion collisions

- Low pT: common velocity boost (radial flow) in hydrodynamically expanding QGP ⇨ mass ordering
- Intermediate pT: hadronization via coalescence
  ⇨ baryon/meson grouping, scaling with # of constituent quarks (NCQ)
- High pT: path-length dependence of parton energy loss in QGP
  ⇨ anisotropy, similar for all particle species

ALICE, JHEP 09 (2018) 006



Ratio of shear viscosity / entropy density as f(T) extracted via Bayesian analysis of experimental data (yields, spectra, flow)



Nature Phys. 15 (2019) 11, 1113-1117

- Anisotropic flow sensitive to QGP viscosity
  ⇨ flow measurements basic ingredient for extraction of η/s as f(T)
- η/s close to lower bound of 1/4π
  ⇨ QGP almost perfect liquid

HF flow in Pb-Pb

HQ transport in QGP

- HQ produced in initial hard scatterings (no thermal production)
- Interaction with QGP constituents ⇨ collective and energy-loss effects
- Due to large HQ mass ⇨ “Brownian motion” inside QGP
  - incomplete thermalization
  - encoded in a single parameter - diffusion coefficient $D_s = (T/m_Q)\tau_Q$
- Hadronization via coalescence at low and intermediate p_T

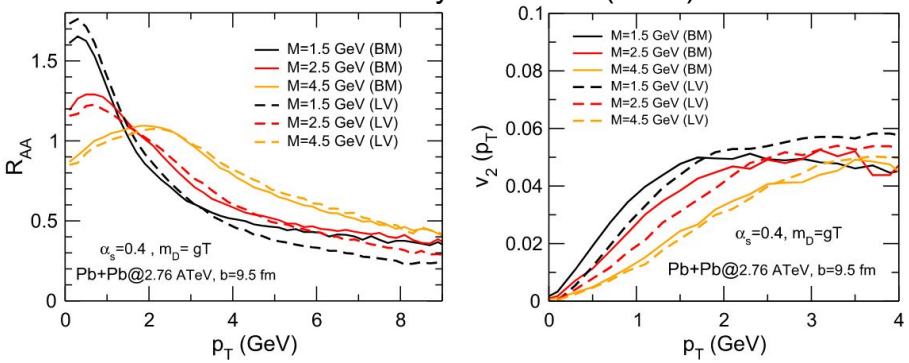
- Simultaneous measure of open-HF R_{AA} and $v_{2,3}$ ⇨ constrain D_s

- Bottom (vs charm)
  - Relaxation time > QGP lifetime
    ⇨ less thermalized
    ⇨ more sensitive probe of HQ transport

  - Better theory control in transport modelling

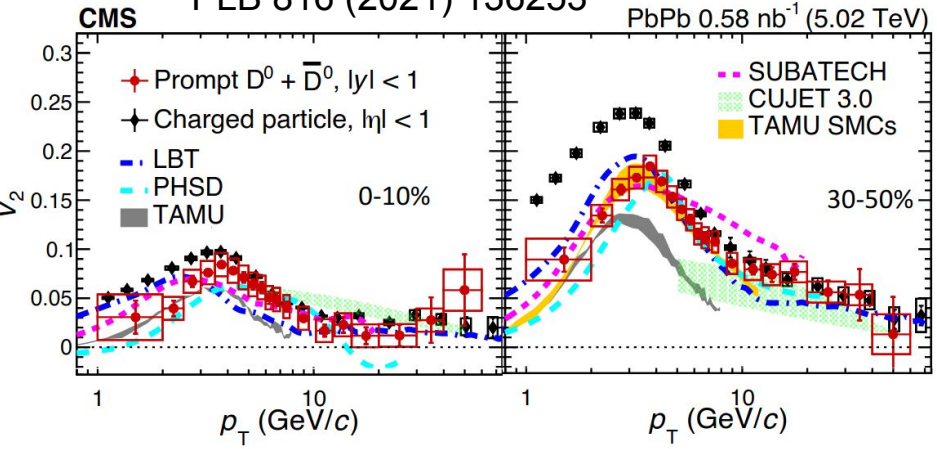
  - Disentangle collisional and radiative energy loss, because radiative one further suppressed due to dead-cone effect

Nuclear Physics A 979 (2018) 21

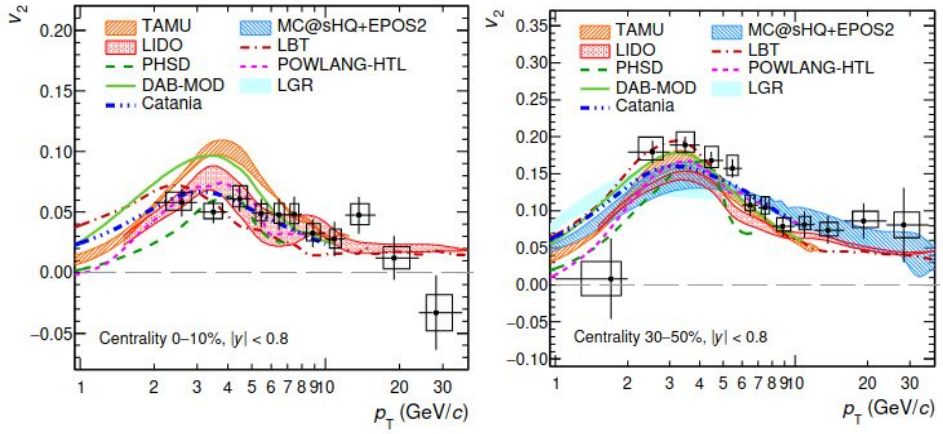


Charm quark v_2 in Pb-Pb

PLB 816 (2021) 136253



JHEP 01 (2022) 174

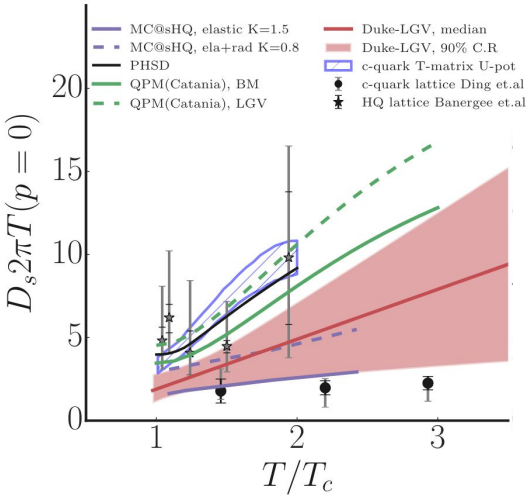


- **Low p_T: D v_2 < LF v_2**
  - Significant D-meson flow
    - ⇨ close to fully thermalized charm quark?
- **High pT: convergence, D v_2 ≈ LF v_2**
  - Common origin from parton energy loss

Constraining the charm diffusion coefficient

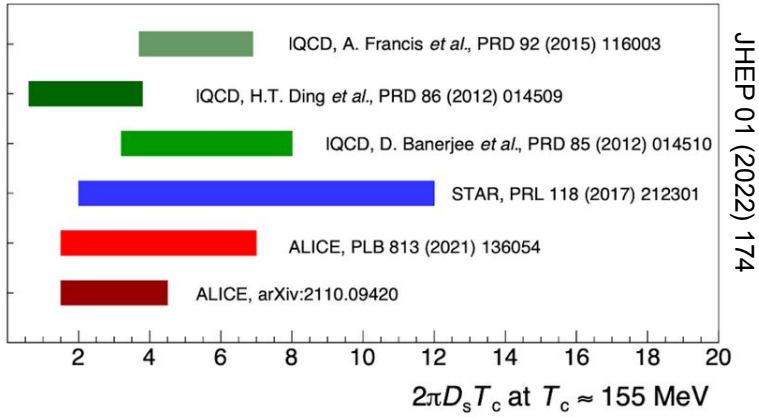
Open charm R_{AA} and $v_{2,3}$ data

Bayesian approach



Phys. Rev. C 97, 014907

Quantitative comparison between data and models



JHEP 01 (2022) 174

$1.5 < 2\pi T_c D_s < 4.5$

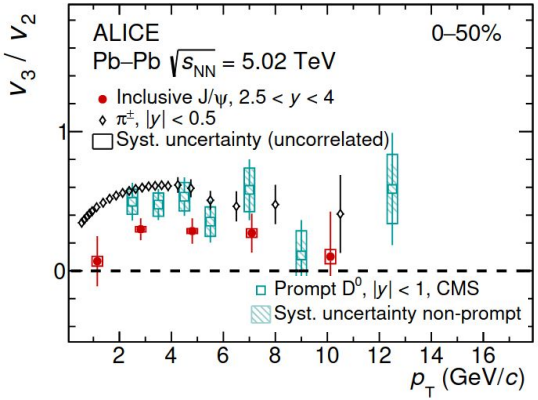
Charm themarization time: **3-9 fm/c**

⇨ close to full thermalization in Pb-Pb at LHC

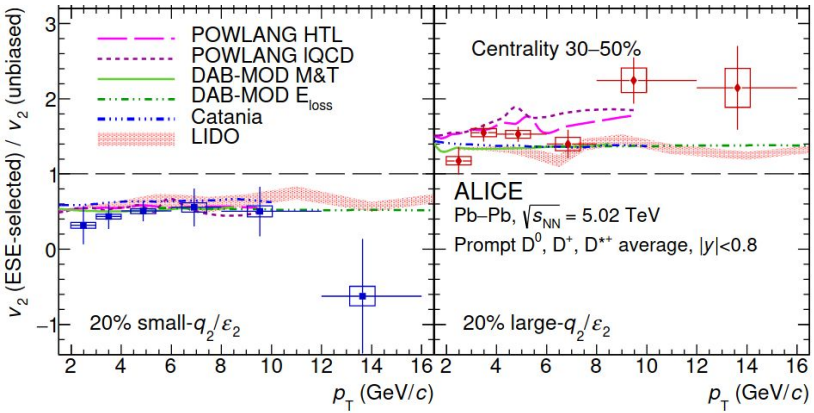
Charm flow: response to initial-state geometry (fluctuations)

- Beyond event-average measurements
- Ways to study response to IS (fluctuations) and compare to LF:
  - **v_3 vs v_2**
  - Flow fluctuations
    - High-order vs low-order correlations **$v_2\{4\}/v_2\{2\}$**
  - Event-shape engineering
    - Biasing initial-state by selecting more elliptic/isotropic collisions

- In general, charm flow shows similar response as LF, apart from possible:
  - a bit faster damping of v_3
  - bigger v_2 fluctuations in peripheral collisions



JHEP 10 (2020) 141



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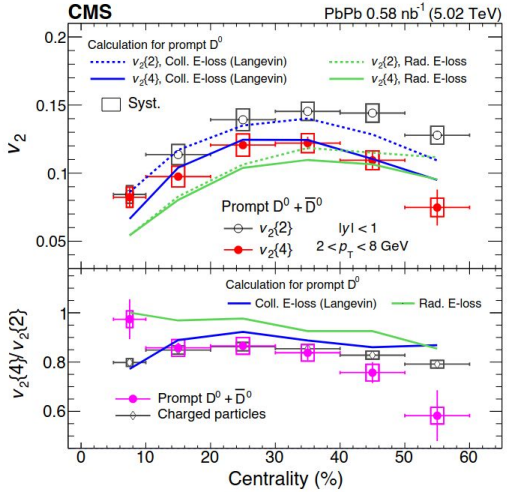
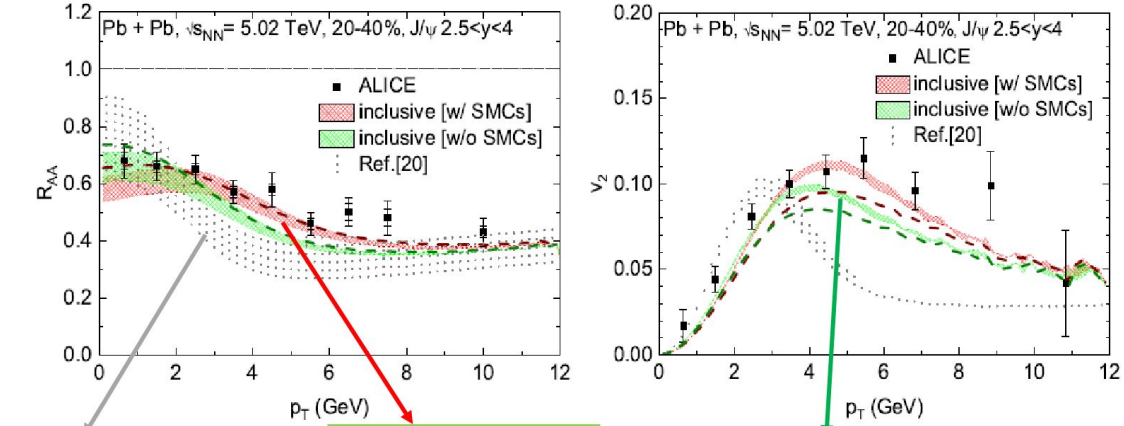


PRL 129 (2022) 022001

J/ψ flow in Pb-Pb

- Two competitive effects in J/ψ production at LHC:
  - **Dissociation** from colour screening in QGP ⇨ path-length dependence ⇨ anisotropy
  - **Regeneration** via recombination of thermalized charm quarks ⇨ J/ψ flow inherited from charm flow
- Puzzle: TAMU transport model underestimated v_2 (and less R_{AA}) for p_T > 3 GeV/c [20]
- Recently, the puzzle is largely solved:
  - Introduction of space-momentum correlations of diffusing charm quarks in QGP (calibrated on open charm data)
    ⇨ **regeneration component extends up to higher p_T**
  - Dissociation reworked using e-by-e hydro and taking into account density/temperature anisotropy
    ⇨ **significantly higher anisotropy at intermediate p_T**

Phys.Rev.Lett.128, 162301 (2022)

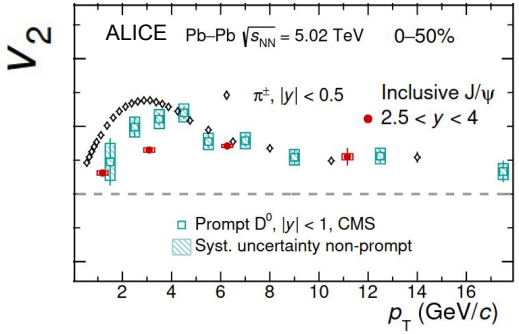


previous fireball blast wave, Du'15

w/ SMCs: red band= 5.2 fm/c, dashed =4.2 fm/c; Band: 15%-25% shadowing

w/o SMCs; green band= 5.2 fm/c, dashed =4.2 fm/c

But how to reconcile with J/ψ v_2 at p_T > 6 GeV/c converging to D and LF ?



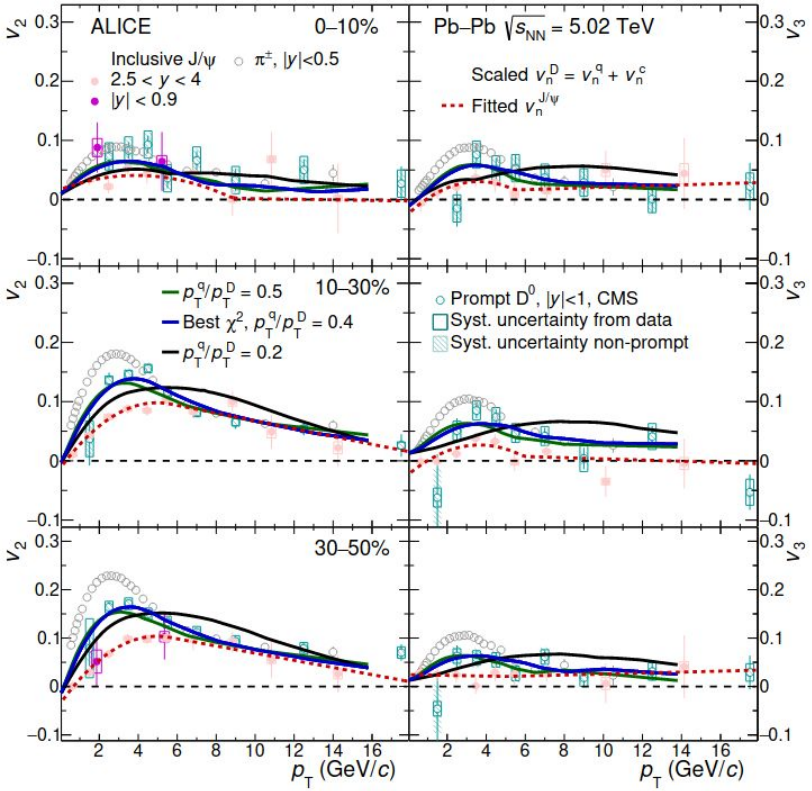
JHEP 10 (2020) 141

[20] Nucl. Phys. A 943, 147 (2015)

Alternative simplified coalescence picture of charm flow

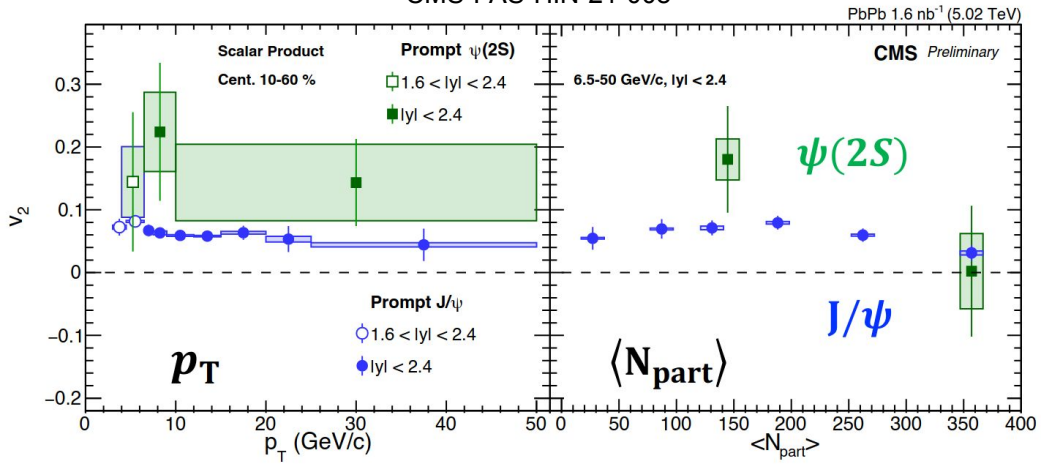
- NCQ model:
  - $v_n^{J/\psi}(p_T^{J/\psi}) = 2v_n^c(p_T^{J/\psi}/2)$
  - $v_n^{\pi}(p_T^{\pi}) = 2v_n^q(p_T^{\pi}/2)$
- Then D-meson v_n can be obtained as:
  $v_n^D(p_T^D) = v_n^q(p_T^q) + v_n^c(p_T^c)$
- In coalescence picture, q and c have similar velocities
  ⇨ $p_T^q/p_T^D \approx 0.2$
- Data disfavor this ratio, but **works remarkably well (v_2 and v_3 in all centrality bins) with $p_T^q/p_T^D = 0.4$**

JHEP 10 (2020) 141

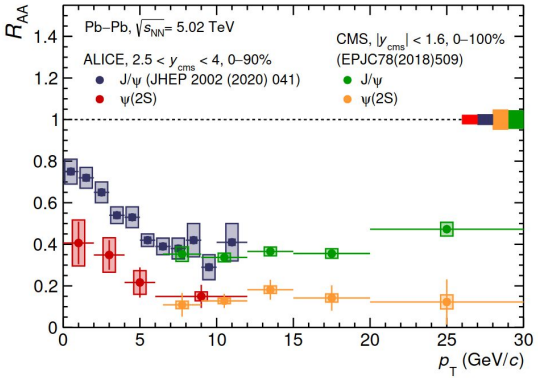


ψ(2S) flow in Pb-Pb

CMS-PAS-HIN-21-008



arXiv: 2210.08893



- Hint of **ψ(2S) v_2 > J/ψ v_2**

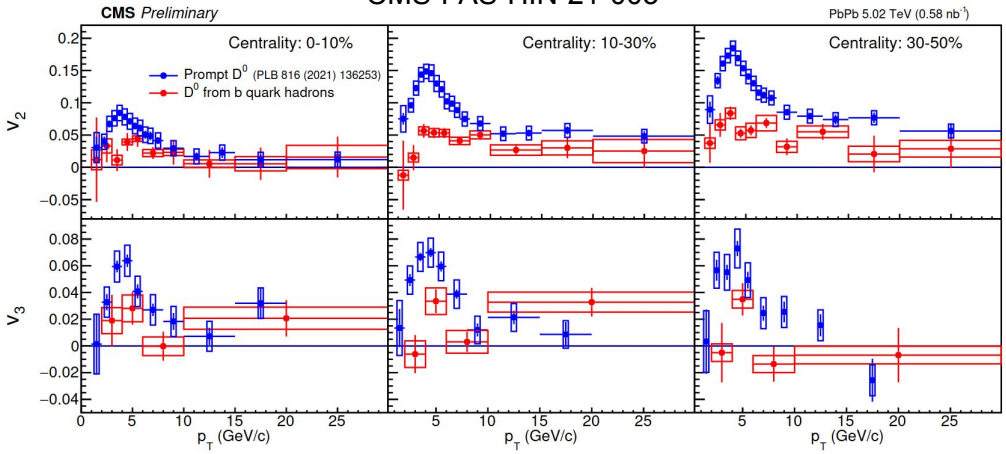
  Data covers mainly high pT where dissociation is dominant
  - Dissociation of ψ(2S) down to lower T ⇨ longer dissociation distances at the scale of system size ⇨ higher anisotropy ?

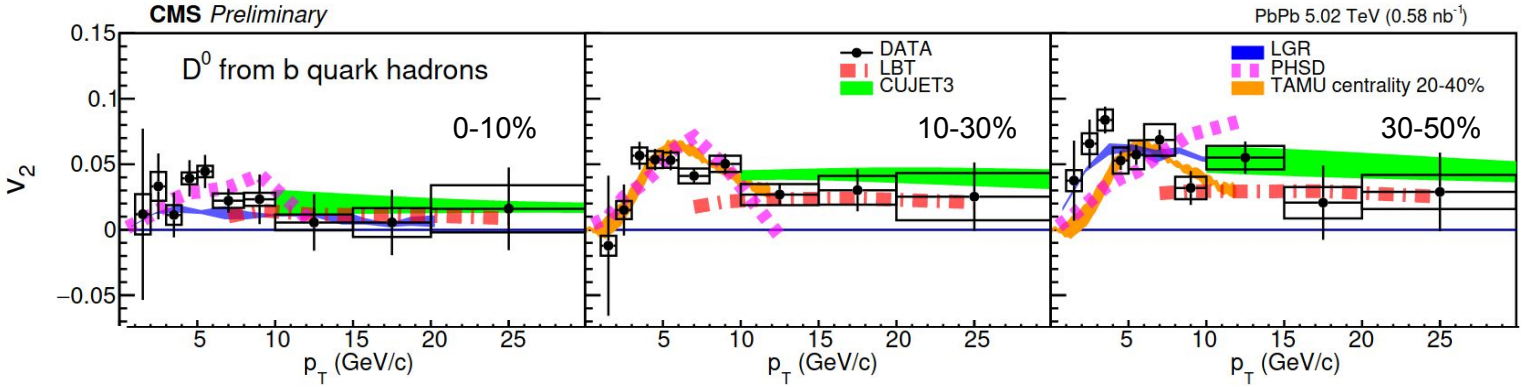
- Later ψ(2S) regeneration expected to yield higher flow due to more developed charm flow ? -> interesting future measurement at low p_T

Bottom quark flow in Pb-Pb (non-prompt D)

- **non-prompt D v_n < prompt D v_n**
  - At low p_T ⇨ **b significantly less thermalized**
  - At high p_T ⇨ **smaller parton energy loss (dead cone)**
- **non-prompt D v_3 - small, but > 0** at intermediate p_T
- Reasonable agreement with transport models

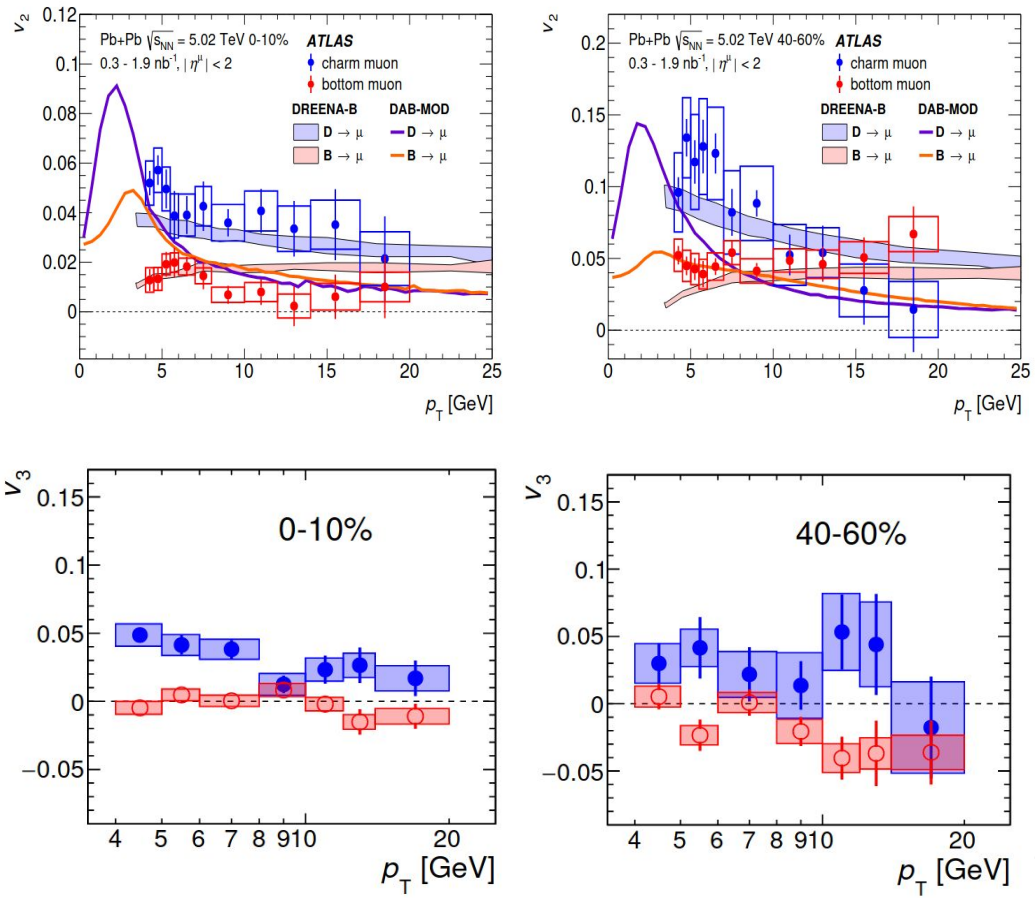
CMS-PAS-HIN-21-003





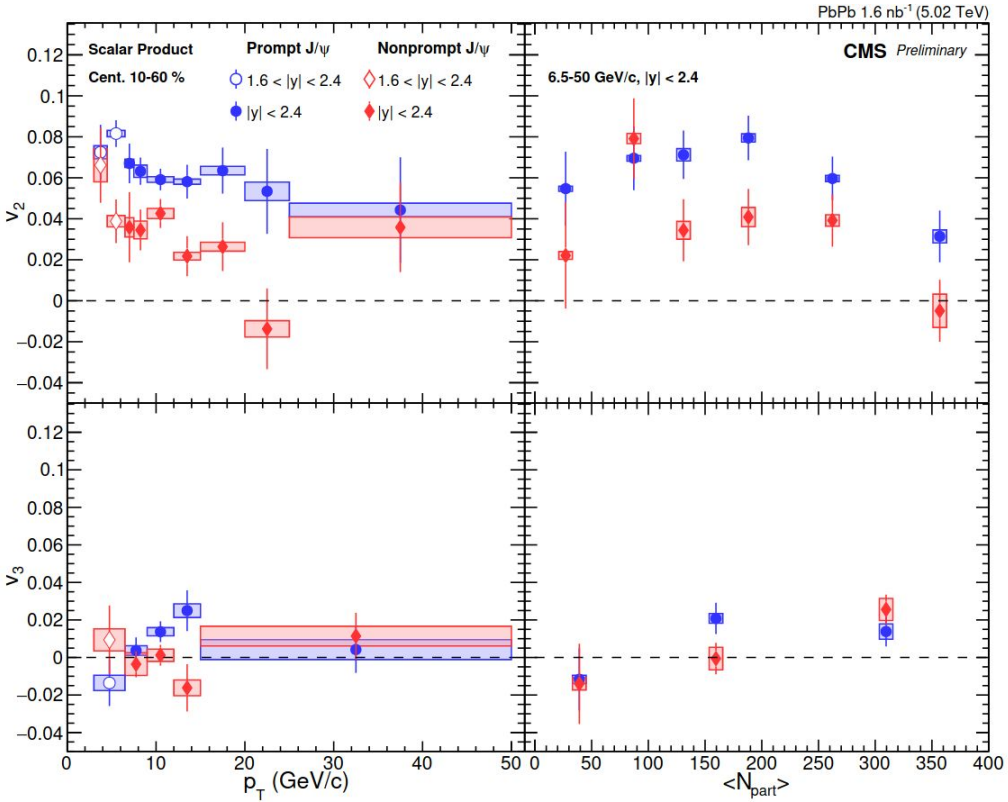
Bottom quark flow in Pb-Pb (b→μ)

- **b→μ v_2 < c→μ v_2**
- **b→μ v_3 compatible with 0**
- Satisfactory agreement of R_{AA}+ v_2 with model incorporating collisional + radiative energy losses



PLB 807 (2020) 135595

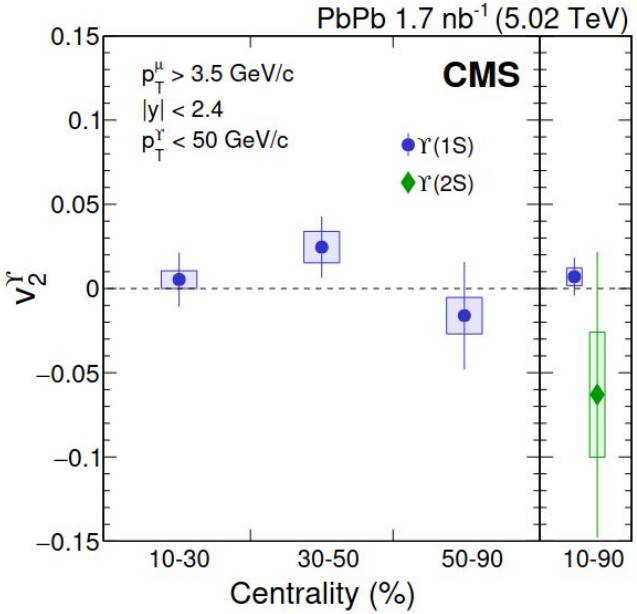
Bottom quark flow in Pb-Pb (non-prompt J/ψ)

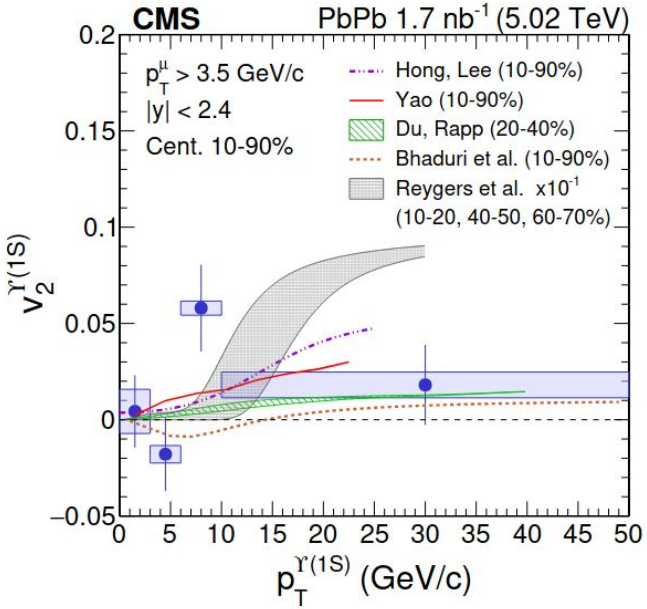


CMS-PAS-HIN-21-008

- **non-prompt J/ψ v_2 < prompt J/ψ v_2**
- **non-prompt J/ψ v_3 compatible with 0**

Y(1S) flow in Pb-Pb





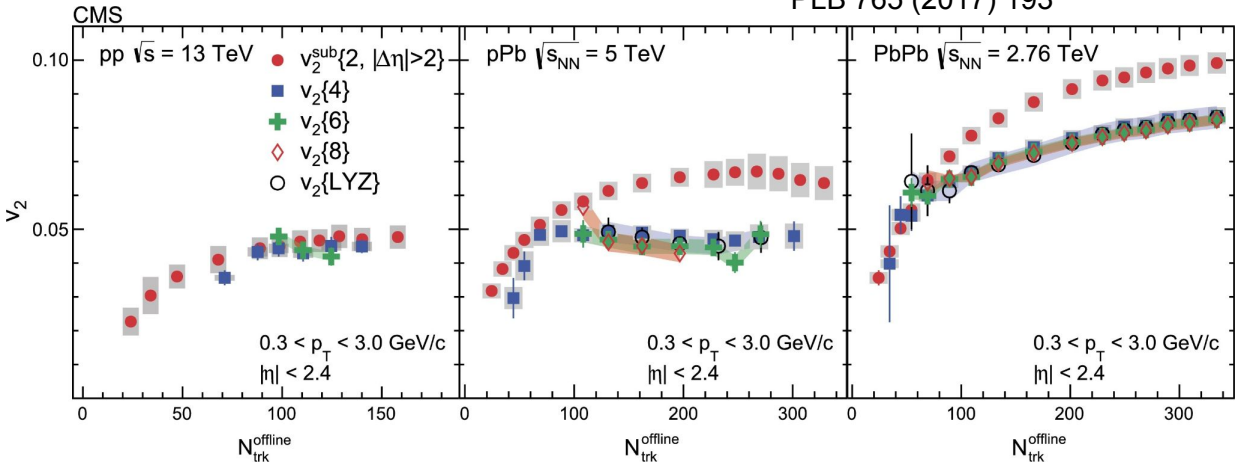
PLB 819 (2021) 136385

- Regeneration: negligible due to small # of bb-bar pairs
- Dissociation: only at high T at initial collision stages
  ⇨ dissociation distances << system size ⇨ small anisotropy
- As expected measured **Y(1S) $v_2 \approx 0$**
- Y(2S) expected to have higher v_2 ⇨ important future measurement

HF flow in small systems (pp, p-Pb)

Flow in small systems

PLB 765 (2017) 193

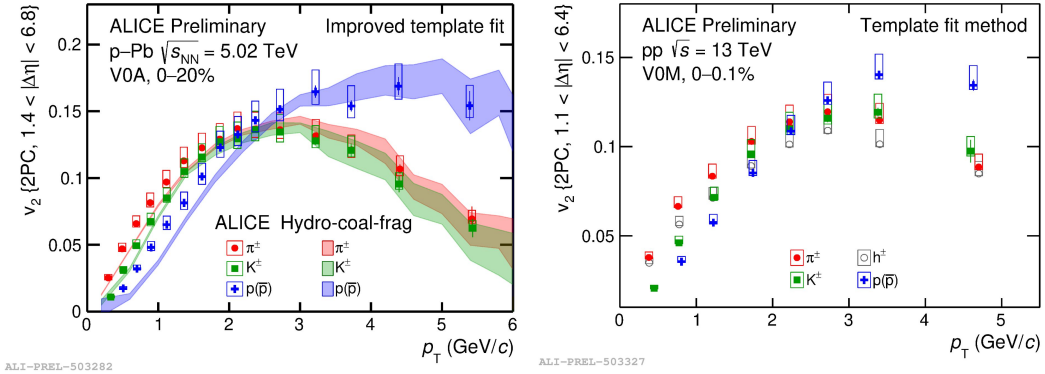


- Genuine collectivity: $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

- **Mass ordering at low p_T** and **baryon/meson grouping** at intermediate p_T

- Anisotropic flow in small systems **correlated to initial-state spatial anisotropies**, see for example: Nature Phys.15 (2019) 3, 214-220

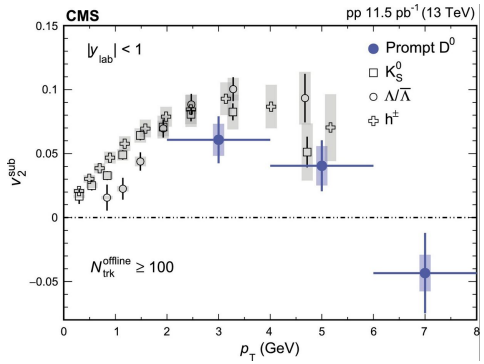
see link



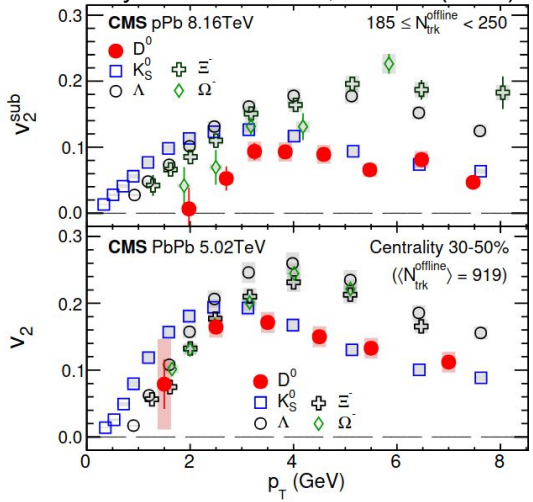
Charm flow in small systems

- Smaller and shorter-lived system ⇨ charm farther away from equilibrium
- Despite this:
  - **Significant open charm v_2 also in pp and p-Pb, similar to Pb-Pb ratio wrt LF particles**
  - **No significant modification of spectra** beyond possible mild shadowing effects at low p_T

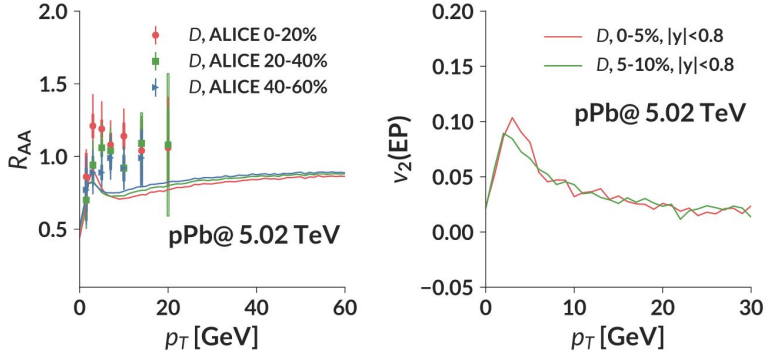
Phys. Lett. B 813 (2021) 136036



Phys. Rev. Lett. 121, 082301 (2018)



D-meson R_{AA} & v_2 in p+Pb: see talk



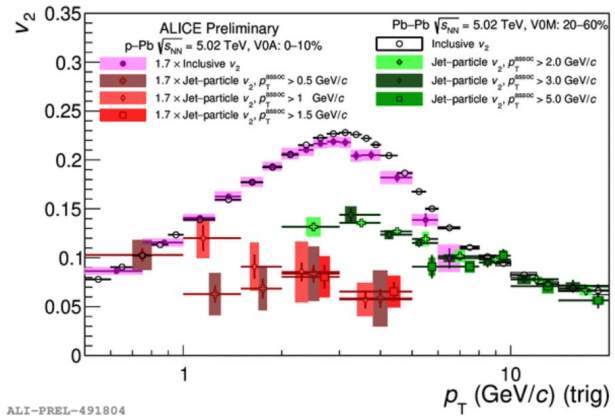
- **Transport model tuned on Pb-Pb: significant charm v_2 in p-Pb, but also sizeable modification of spectra**

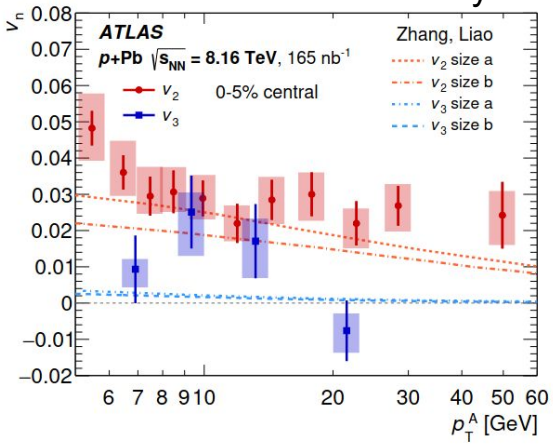
High-pT and (mini)jet v_2 and R_{pA} in p-Pb

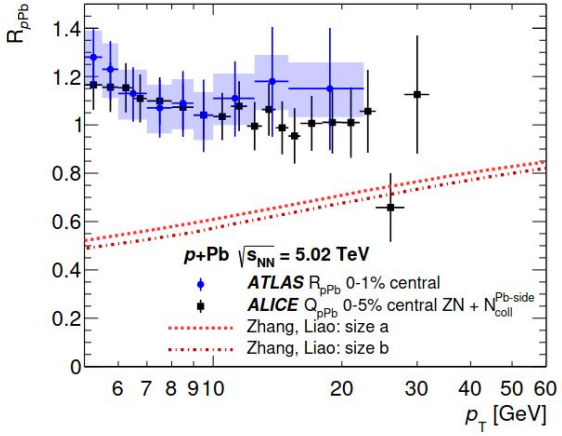
- **Sizeable positive v_2 of high-p_T hadrons and (mini)jets** observed, while **spectra shows no signs of medium-related modification**
- In jet quenching and parton energy-loss models:
  tight relation between **$R_{A(p)A}$** and **v_2/ε_2**, which is in general the case in AA data
- Indication that this relation is **'broken'** for hard probes in small systems
- **Observed anisotropy not driven by parton energy loss ?**

see link

Eur. Phys. J. C 80 (2020) 73

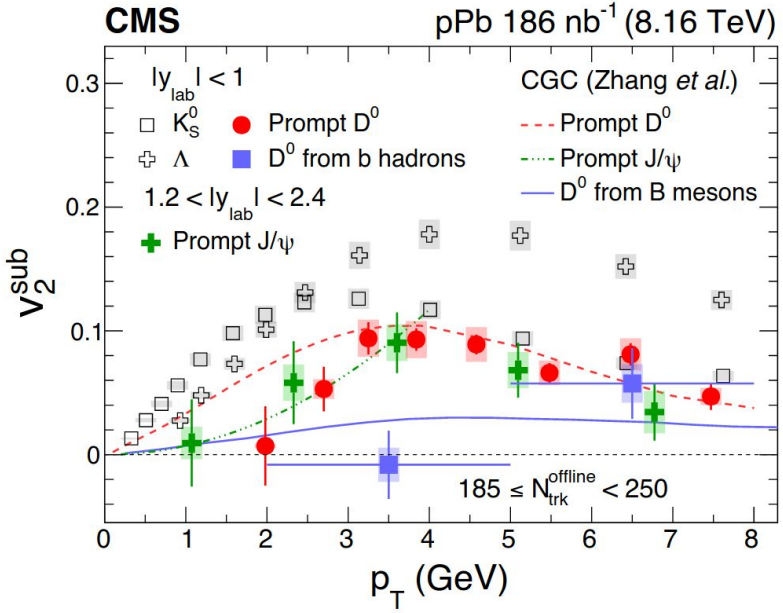




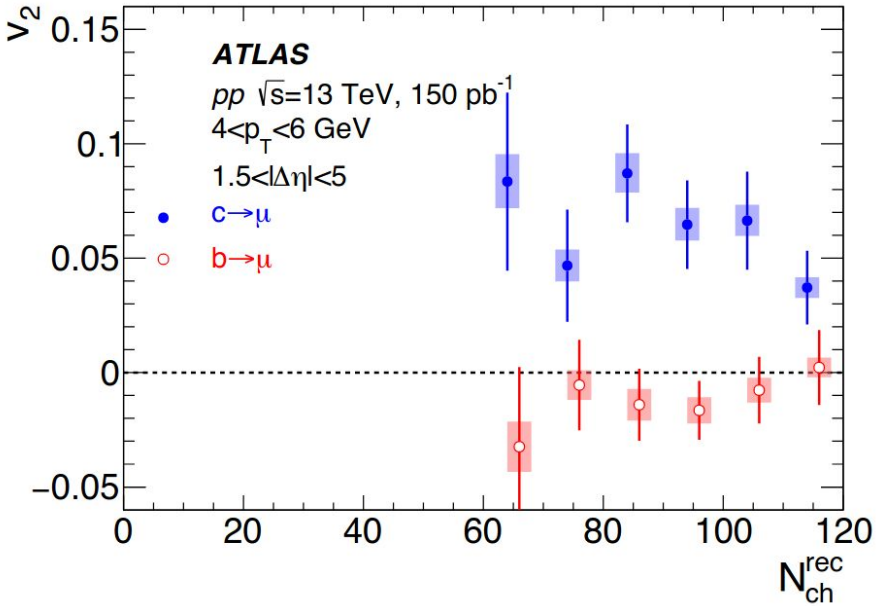


Bottom flow in small systems

PLB 813 (2021) 136036



PRL 124 (2020) 082301

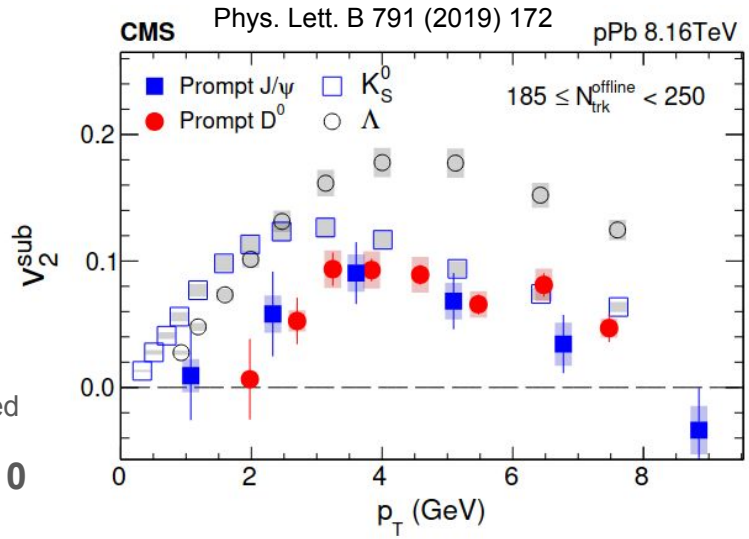


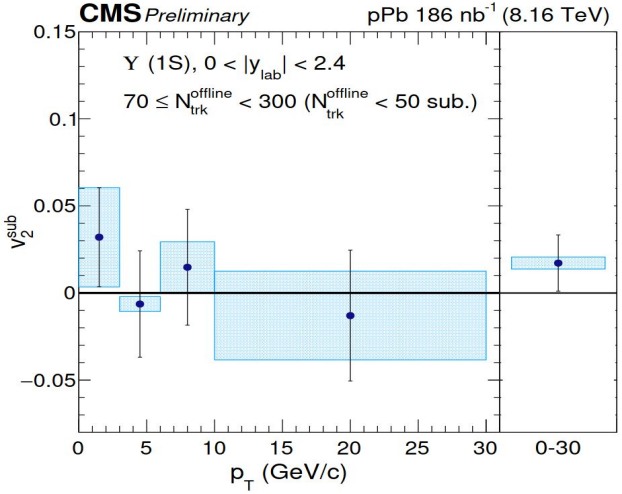
- **$b \rightarrow \mu$ $v_2 \approx 0$** in pp and p-Pb

Quarkonia flow in p-Pb

- Surprisingly, **significant J/ψ v_2 in p-Pb, close to D v_2**
- **No clear explanation**, expected negligible regeneration and dissociation in p-Pb

- CGC-based calcs agree with data, but:
  - In experiment, J/ψ v_2 measured via long-range correlations with bulk particles, which flow is driven by IS spatial anisotropies
    In model v_2 arises from IS momentum correlations, which are uncorrelated with IS spatial anisotropies
- CGC calcs: ≈ **same v_2 for Υ(1S)**, while **data hints v_2 close to 0**





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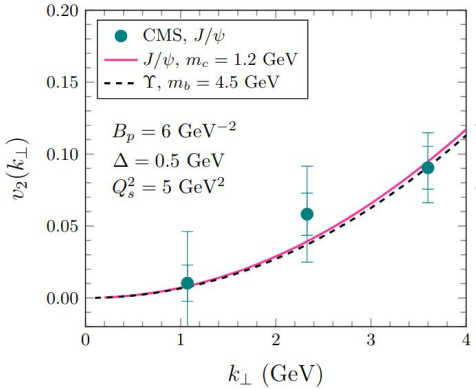
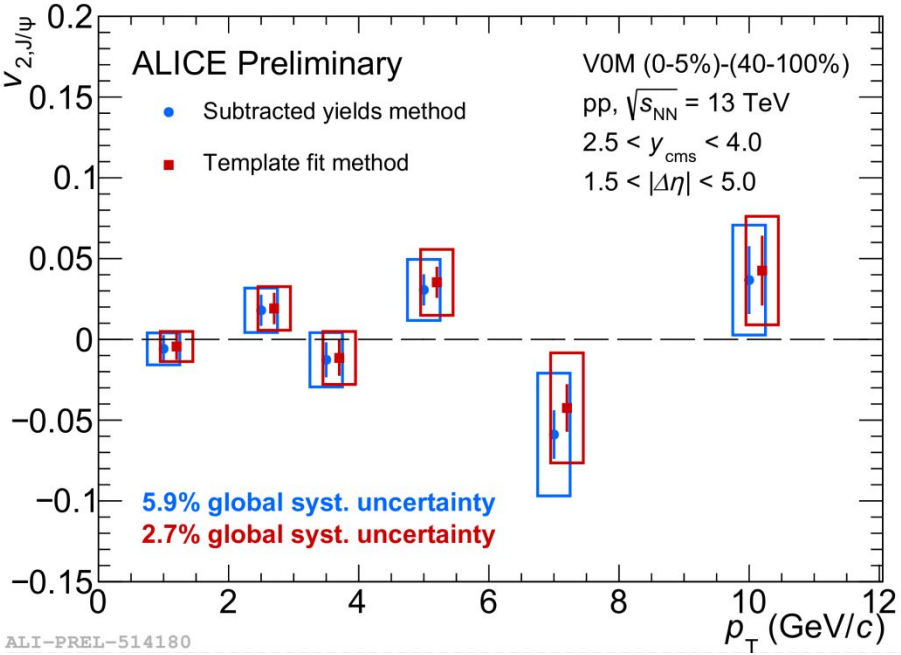
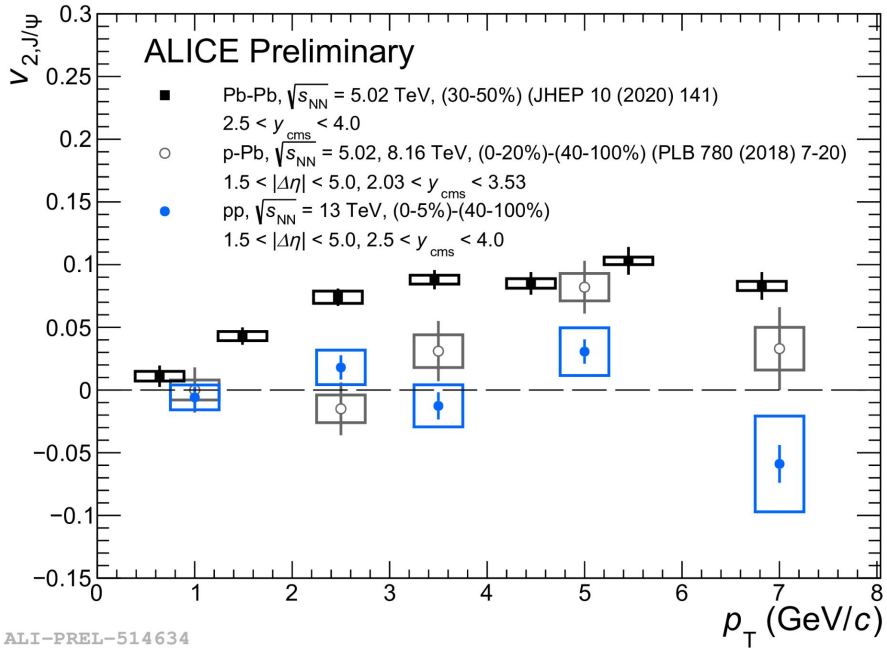


PRL 122 (2019) 17, 172302

J/ψ flow in pp

see link





- **J/ψ flow in pp consistent with 0** within uncertainties, significantly lower than in p-Pb and Pb-Pb

Conclusions

- **HF flow in Pb-Pb**
  - Precise measurements of **open charm flow** ⇨ Bayesian extraction of **charm diffusion coefficient**
  - Observed hierarchies at low p_T
    - **b v_n < c v_n < LF v_n**
      ⇨ partial thermalization of bottom, close to full thermalization of charm
    - **open HF v_n > hidden HF v_n > 0 for charmonia, ≈ 0 for bottomonia**
      ⇨ transport model now describes decently J/ψ flow data
  - **Convergence of v_n at higher p_T for charm** (open, hidden, LF), **lower anisotropy for bottom**
    ⇨ parton energy loss, smaller in case of bottom due to dead-cone effect
    ⇨ convergence of J/ψ flow to open charm and LF is still intriguing

- **HF flow in small systems**
  - **Open charm flow in p-Pb and pp similar to Pb-Pb**
    ⇨ difficult to explain together with absence of medium-related spectra modifications
  - **Hidden charm flow > 0 in p-Pb** and ≈ 0 in pp
    ⇨ so far no clear explanation of positive v_2 in p-Pb
  - **Bottom flow ≈ 0 both in p-Pb and pp**

Outlook

- **Hadronization - coalescence vs fragmentation**
  - Measurements of HF baryon/meson ratios and their flow
- **HQ transport in QGP - diffusion, energy loss**
  - More precise measurements of bottom production and flow, including B mesons
  - DD-bar, BB-bar correlations
- **Quarkonia production - deconfinement**
  - Measurements of ψ(2S), Υ(2S), … flow
- **Measurement of multi-charm baryons**
  - Ultimate experimentally-accessible manifestation of deconfinement

Thank you for your attention!

Backup

Phys. Rev. Lett. 125, 192301 (2020)

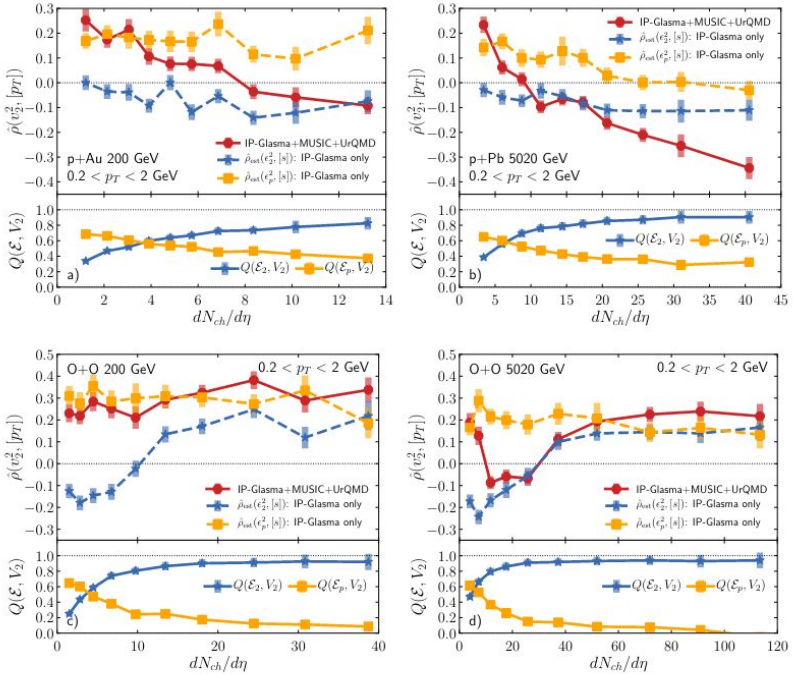
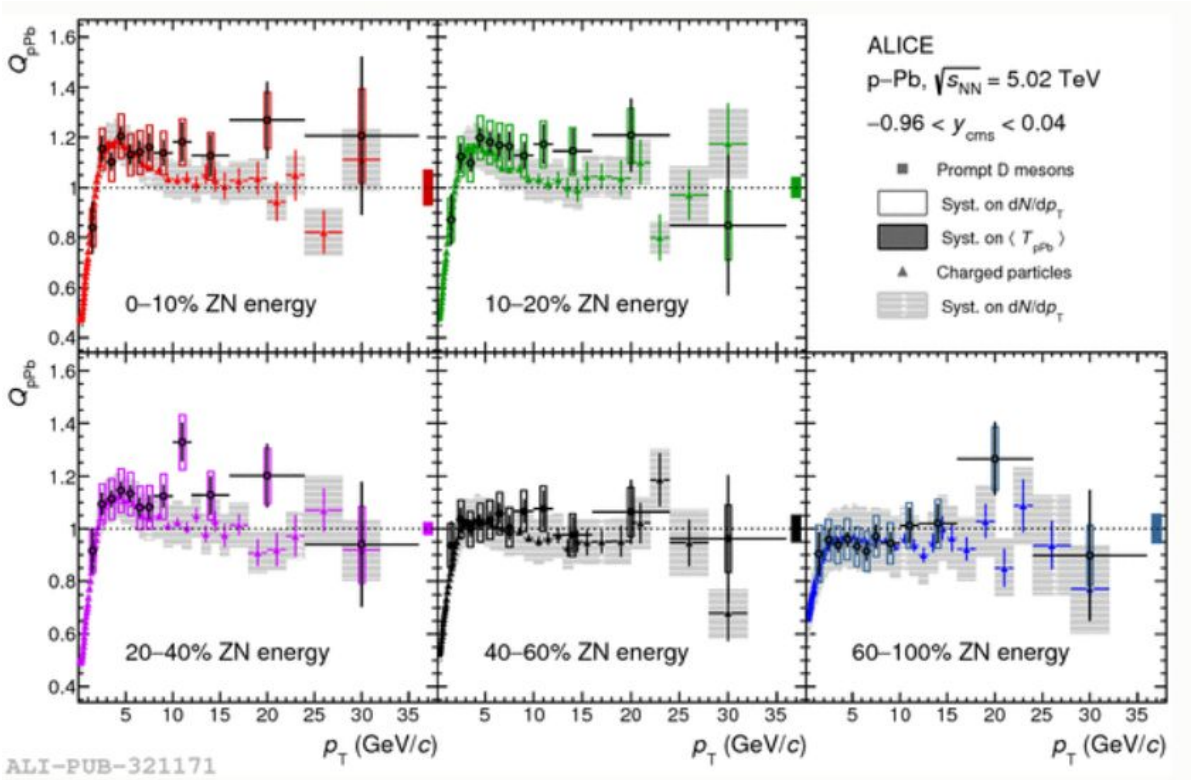


FIG. 2. The correlator $\hat{\rho}(v_2^2, [p_t])$ (circles) together with estimators based on the initial geometry ($\hat{\rho}_{\rm est}(\varepsilon_2^2, [s])$, stars) and the initial momentum anisotropy ($\hat{\rho}_{\rm est}(\varepsilon_{p'}^2, [s])$, squares) in a) $\sqrt{s} = 200\,$GeV p+Au, b) $\sqrt{s} = 5.02\,$TeV p+Pb, c) $\sqrt{s} = 200\,$GeV, and d) $\sqrt{s} = 5.02\,$TeV O+O collisions. Lower panels show the Pearson coefficients between v_2 and the initial ellipticity (stars) and the initial momentum anisotropy (squares), respectively.


ALICE
p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
$-0.96 < y_{cms} < 0.04$
Prompt D mesons
Syst. on dN/dp_T
Syst. on $\langle T_{pPb} \rangle$
Charged particles
Syst. on dN/dp_T
Q_{pPb}
0–10% ZN energy
10–20% ZN energy
20–40% ZN energy
40–60% ZN energy
60–100% ZN energy
p_T (GeV/c)
ALI-PUB-321171