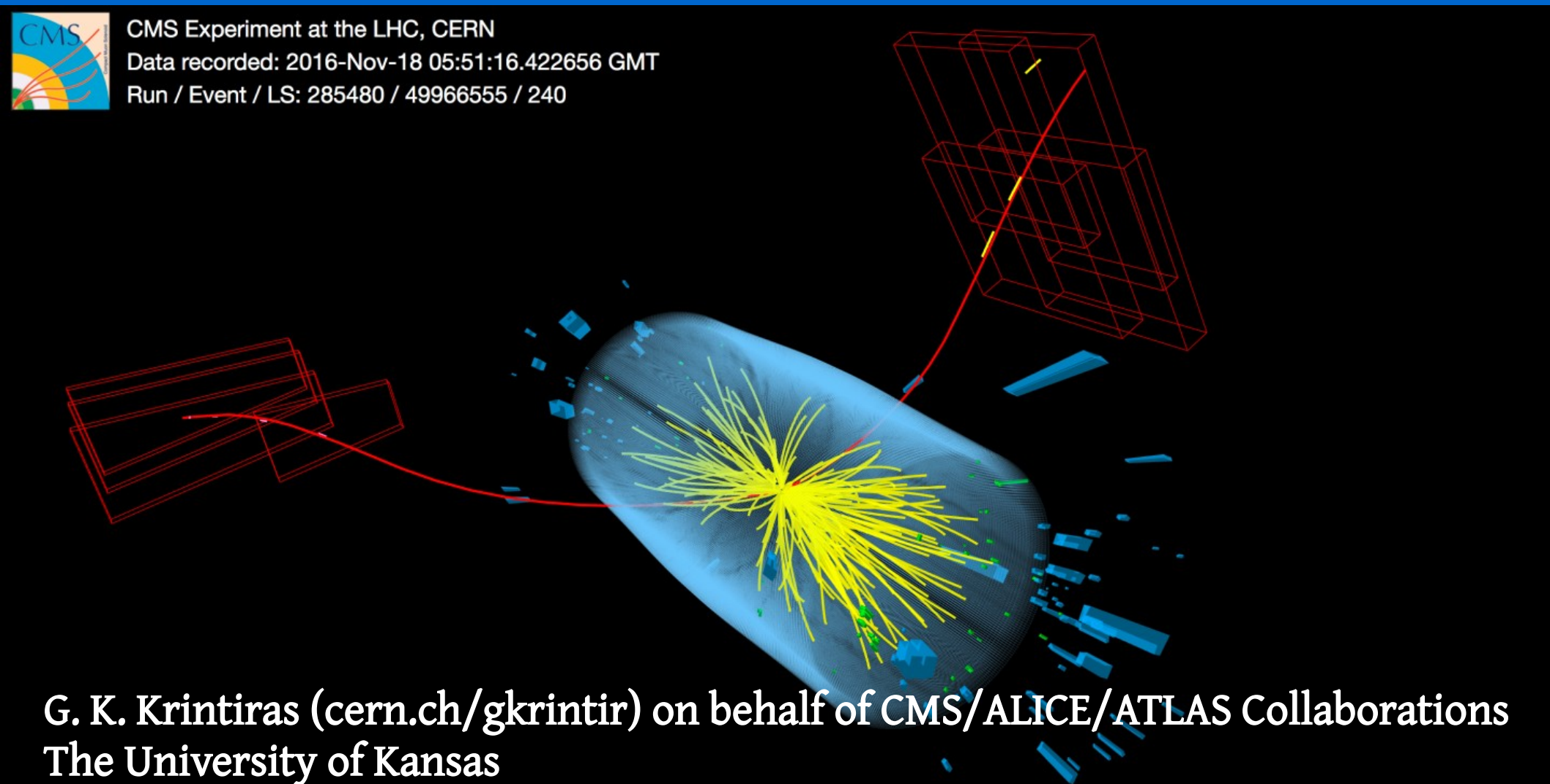
Heavy flavor collectivity in small systems

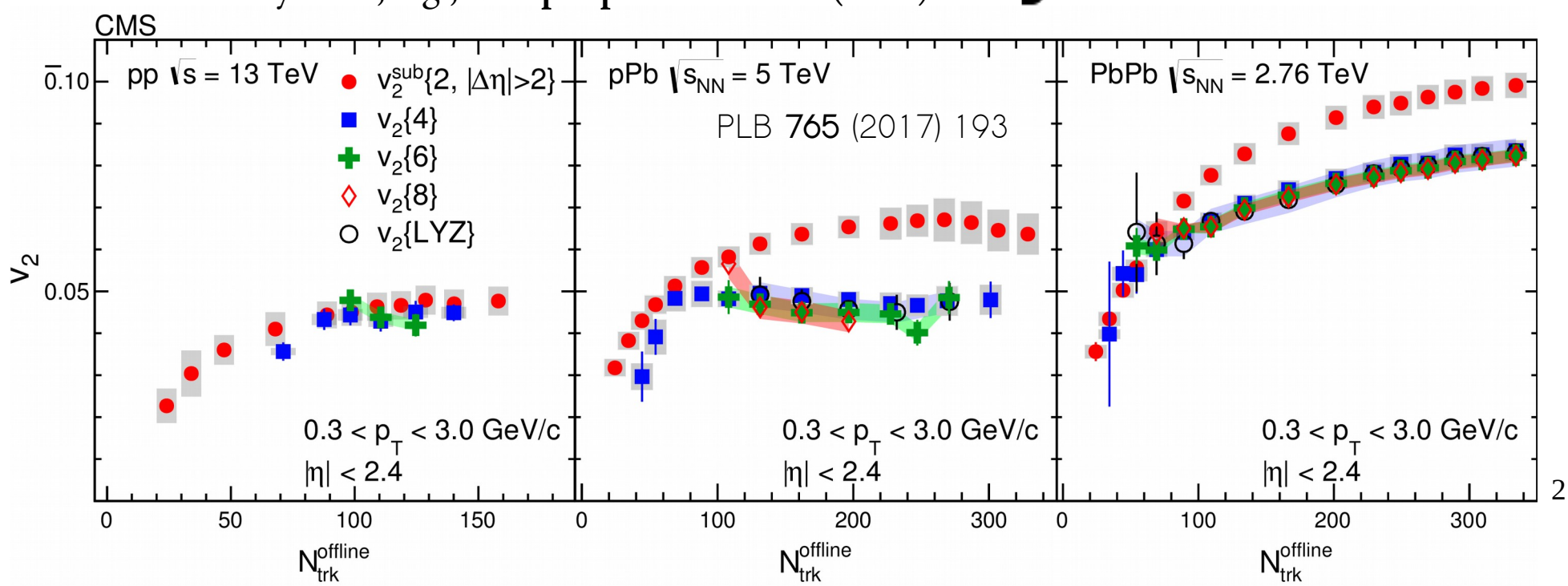


G. K. Krintiras (cern.ch/gkrintir) on behalf of CMS/ALICE/ATLAS Collaborations
The University of Kansas

Collectivity in small systems?

- Detailed flow measurements in **pp/pPb** indicate that
  - centrality/event activity and p_T dependence qualitatively **similar** to that in AA
  - identified particle and multiparticle correlation techniques support a **collective origin** of $\mathbf{v_n}$
    - encompassed by hydrodynamical models, but **not a unique** description
- We start answering whether a collective component in $\mathbf{v_n}$ exists by studying
  - the role of the **initial conditions**
  - the impact of **hard-scattering** processes and **energy loss**
  - alternative systems, e.g., **ultraperiphal collisions** (UPC)

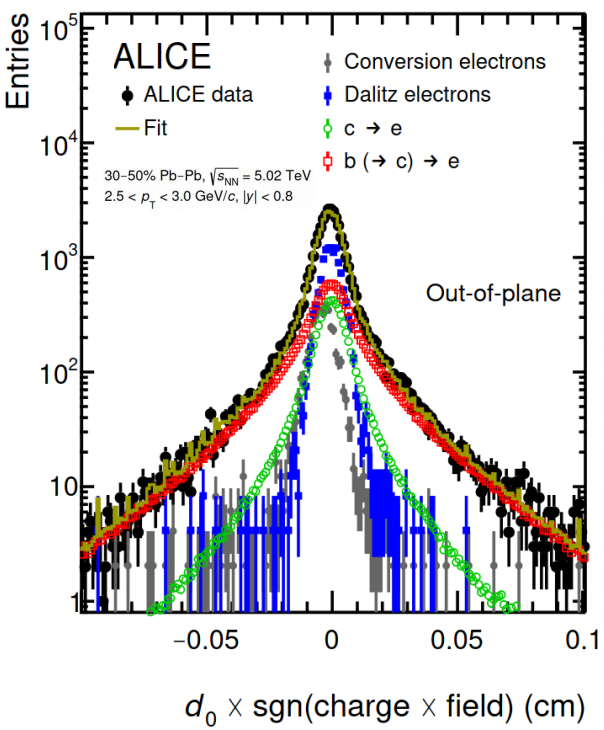
} Talks in this session



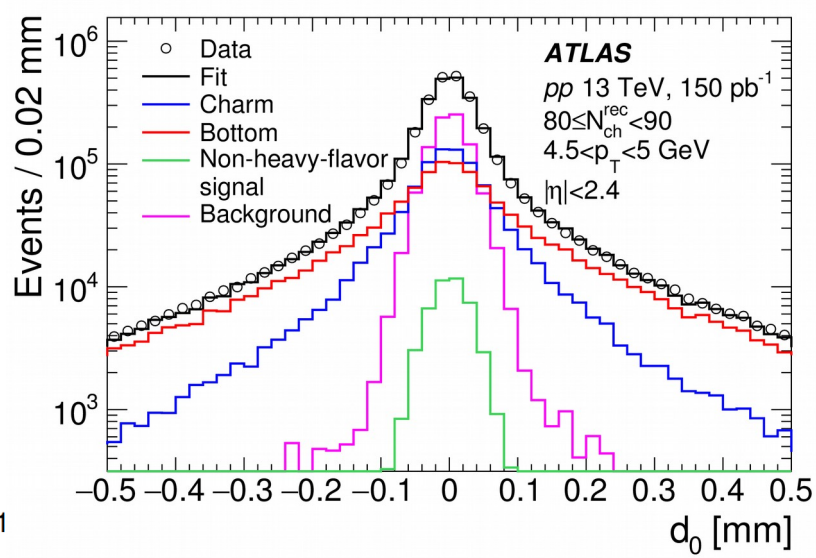
Key features of heavy flavor measurements

- Variety of meson/baryon states with different flavors in a broad kinematic range
  - techniques to **separate** heavy from light flavor decays
- We gain insight on
  - whether heavy quarks **flow** with the bulk
  - **parton interactions** in the QGP (thermalization, energy loss,...)
  - QGP **properties** (transport coeff)
  - pQCD predictions, parton shower modeling, hadronization mechanisms

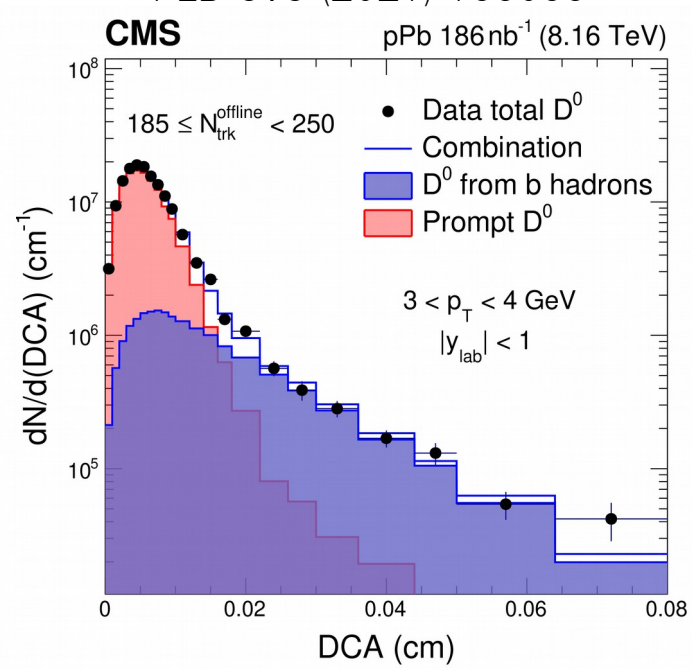
PRL **126** (2021) 162001



PRL **124** (2020) 082301



PLB **813** (2021) 136036



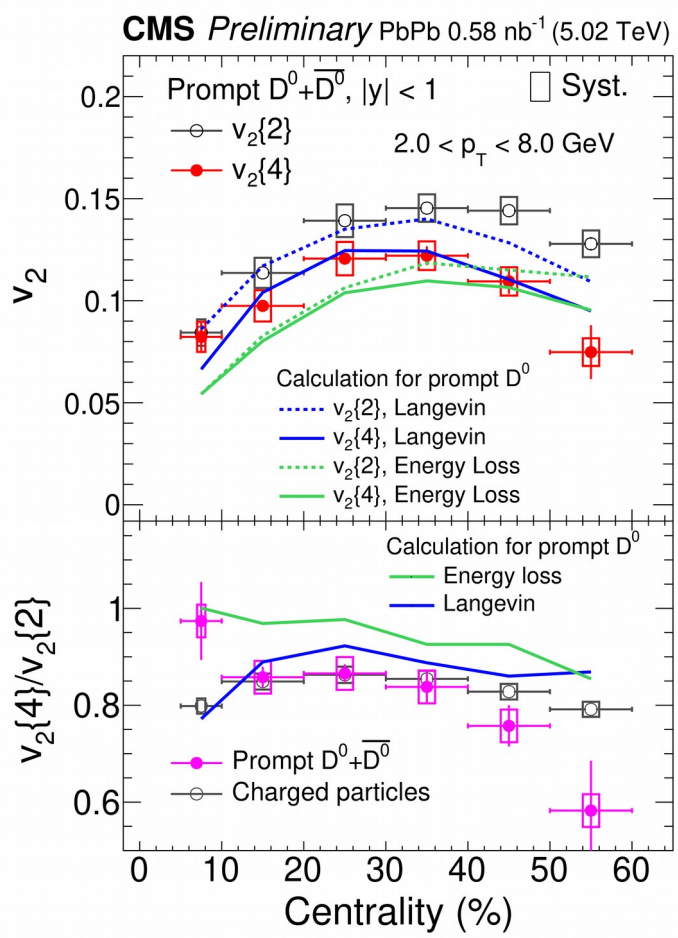
Measuring HF particle flow in PbPb

- Heavy-flavor hadrons and their decay products are effective probes of QGP

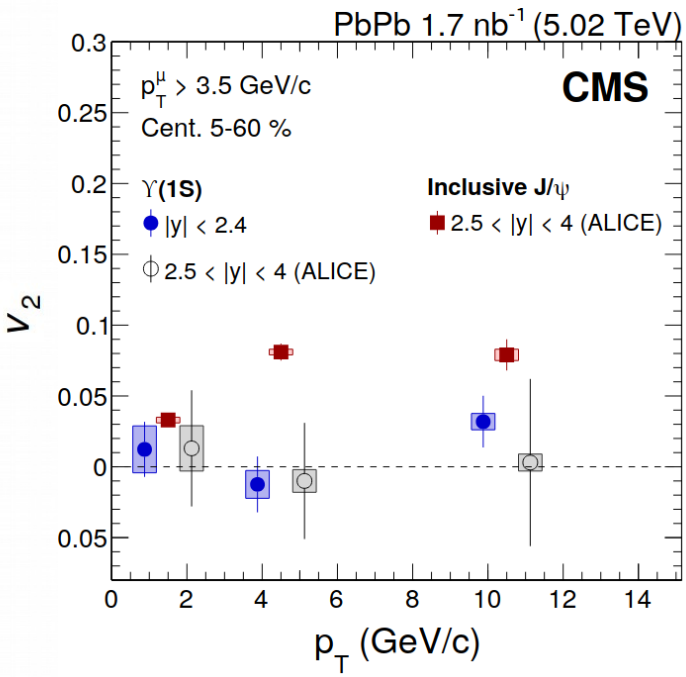
More on Fabrizio's talk

  - a series of measurements with, e.g., D^0, J/ψ, $\Upsilon(nS)$, and heavy-flavor decay leptons
    - extension to studies of **EM fields effects**, e.g., no rapidity dependence of Δv_2 (D^0–$\bar{D}^0$)
  - The harmonics for **c** mesons are **comparable to** the light-flavor hadrons
  - **Closer to zero** anisotropy observed for nonprompt D^0, $\Upsilon(nS)$ or beauty decay electrons/muons

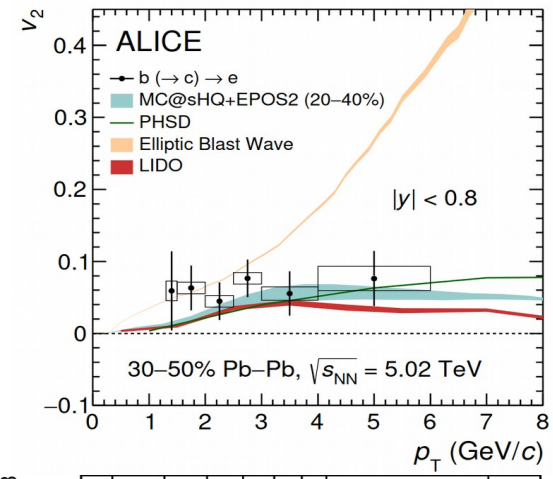
CMS-PAS-HIN-20-001



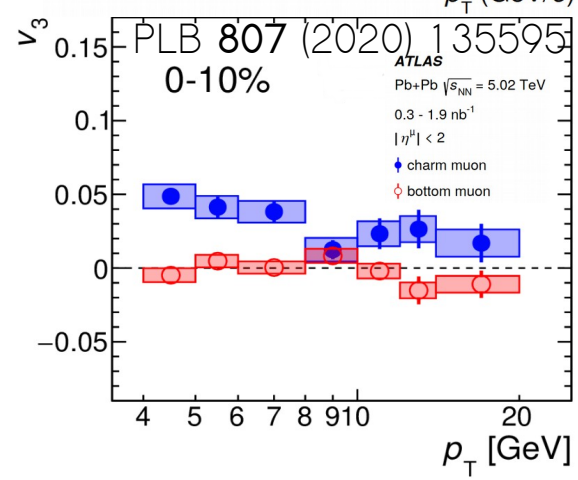
PLB 819 (2021) 136385



PRL 126 (2021) 162001



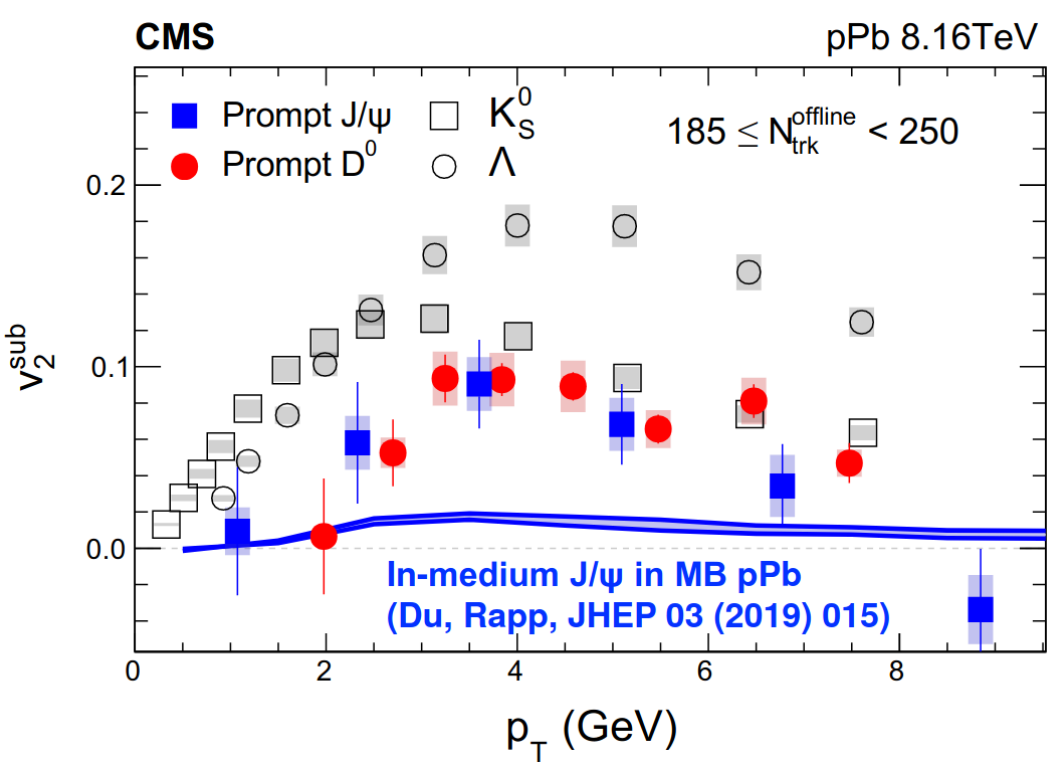
PLB 807 (2020) 135595



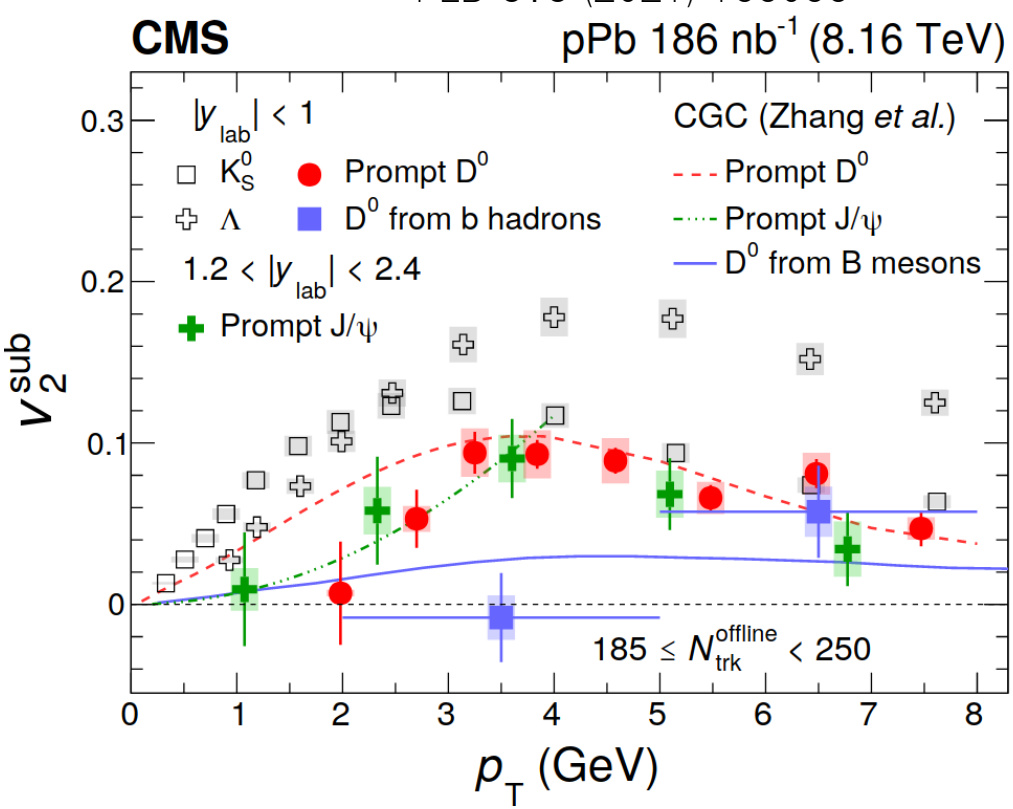
Measuring HF particle flow in pPb

- Observation of **c flow**
  - the number-of-constituent-quark (n_q) scaling holds for $KE_T/n_q < 1$ GeV
  - model with final-state interactions underestimates the v_2 signal
- First measurements of **b flow**
  - indication of flavor hierarchy between light, charm, and beauty at low p_T
  - qualitative agreement with CGC calculations and data → an important role for initial-state effects?

PLB **791** (2019) 172



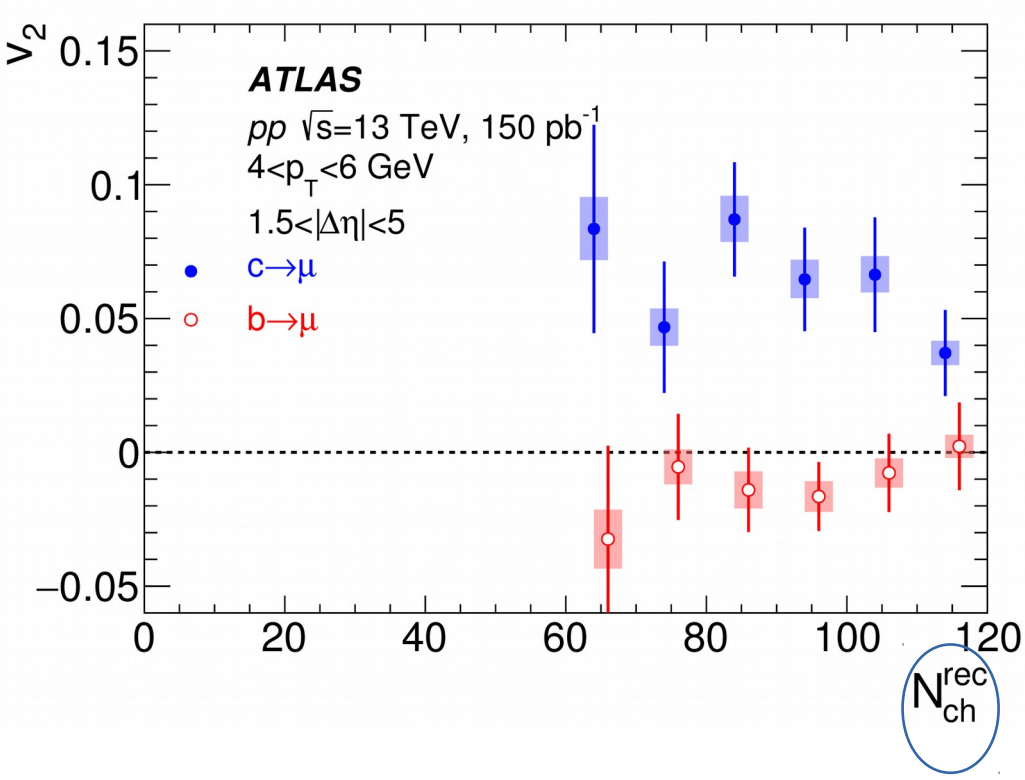
PLB **813** (2021) 136036

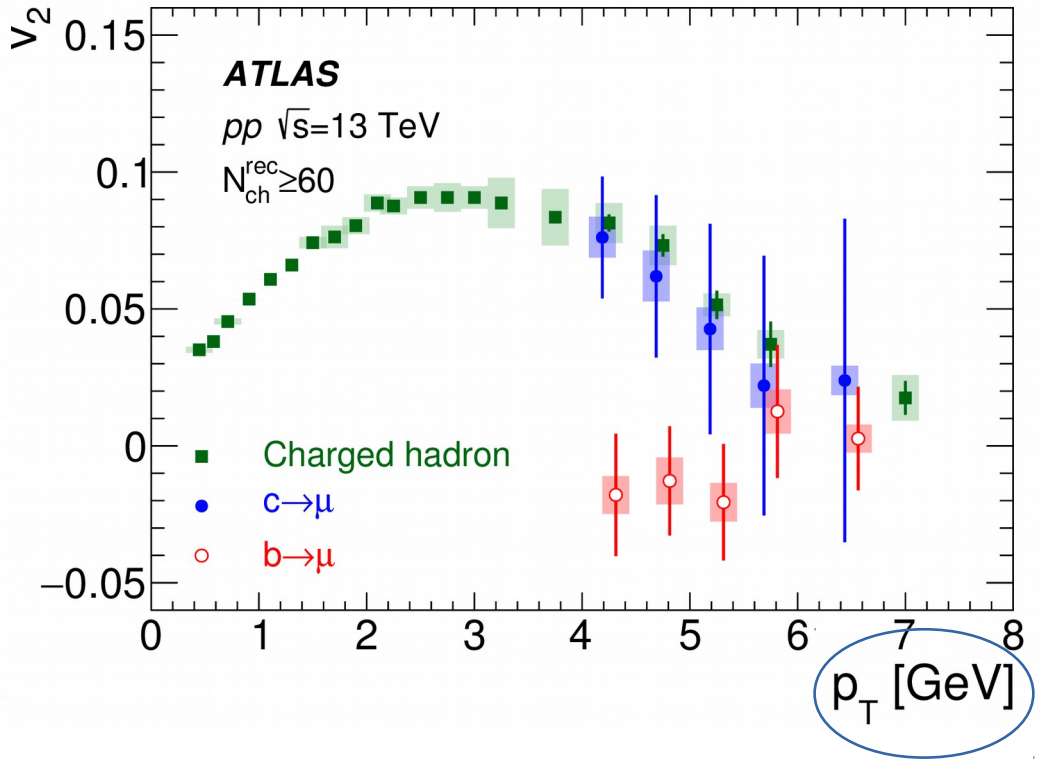


Measuring HF particle flow in pp

- First measurements of **c and b flow**
  - no dependency on track multiplicity
  - charm $v_2>0$ decreasing with p_T (similar to charged hadrons)
  - bottom v_2~0
- No calculation yet available in the smallest systems
  - in PbPb we can describe the larger v_2 for D than B mesons at $p_T<10$ GeV while being similar above

PRL **124** (2020) 082301

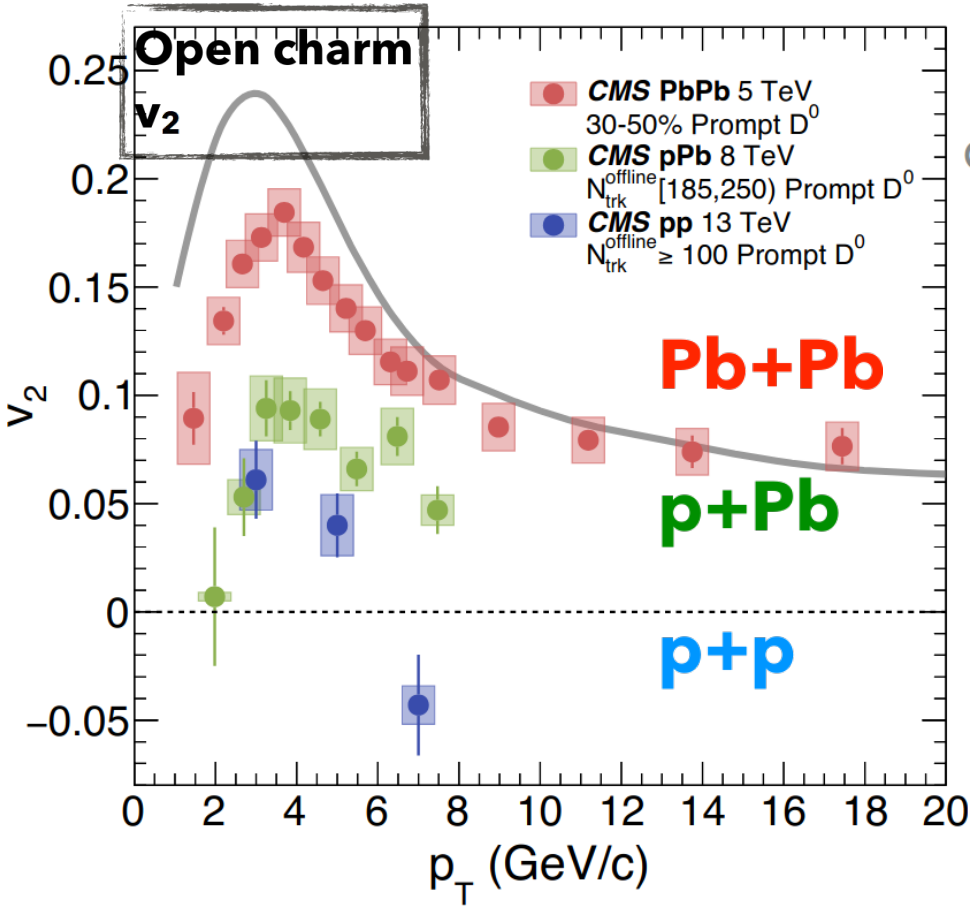


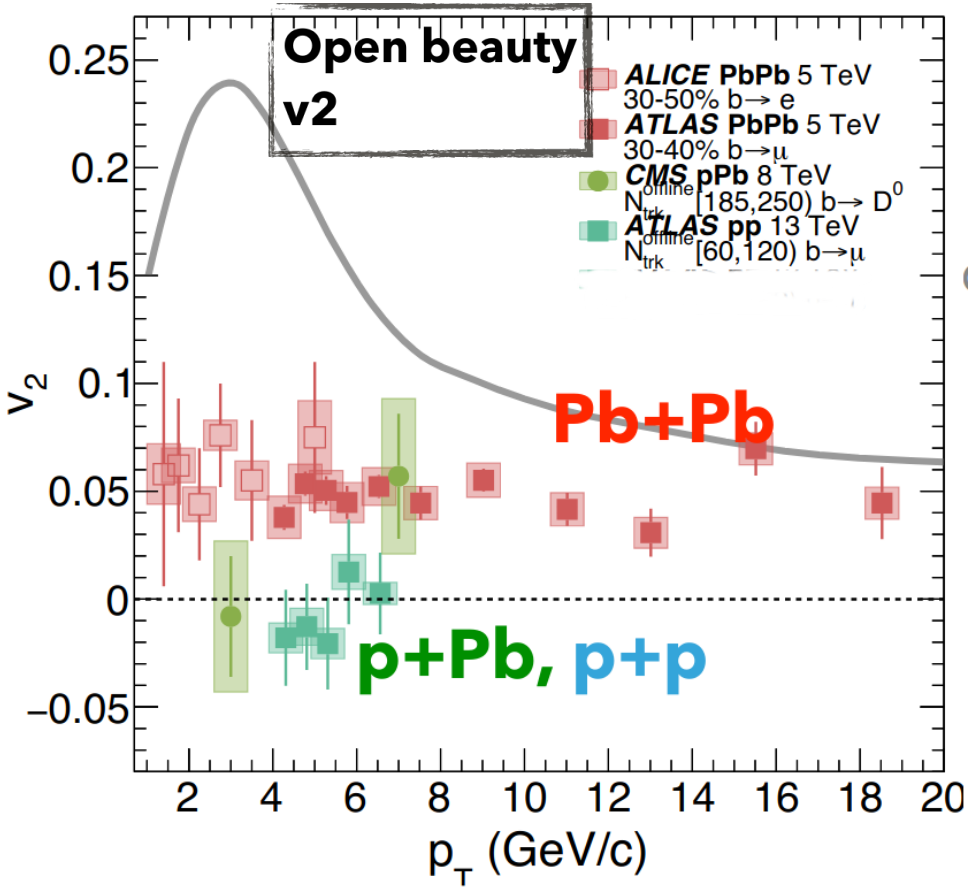


Comparing HF particle flow in all systems

- There is charm anisotropy… everywhere
  - apparent ordering: v_2 (PbPb) > v_2 (pPb) > v_2 (pp)
    - so **system size** should play a role?
- For open bottom hadrons: v_2 (PbPb) > 0 but v_2 (pPb) ~ v_2 (pp) ~ 0
  - do we hit some **threshold** between charm and beauty processes?
- **Novel input** to the description of heavy-quark transport and energy loss in small systems

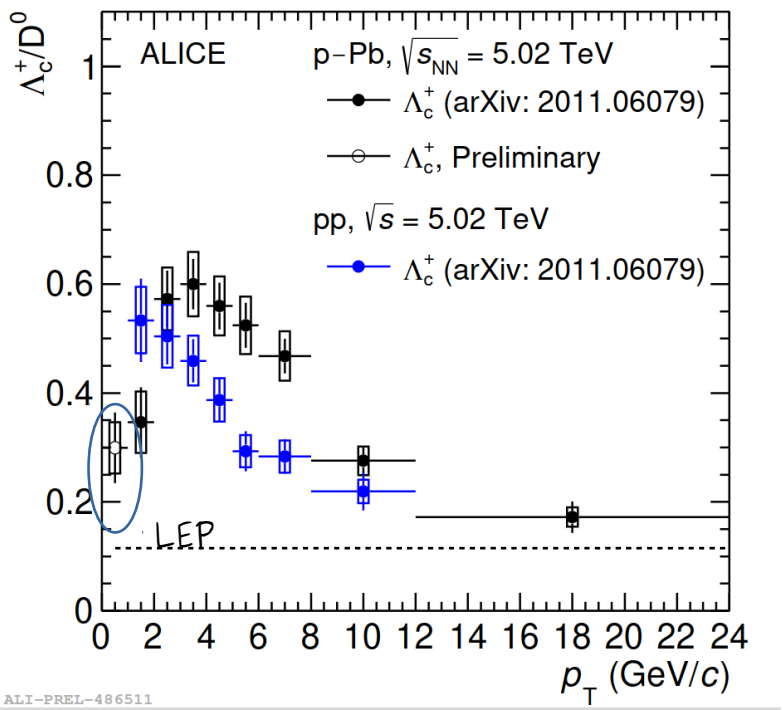
C. Mironov (HP2020)

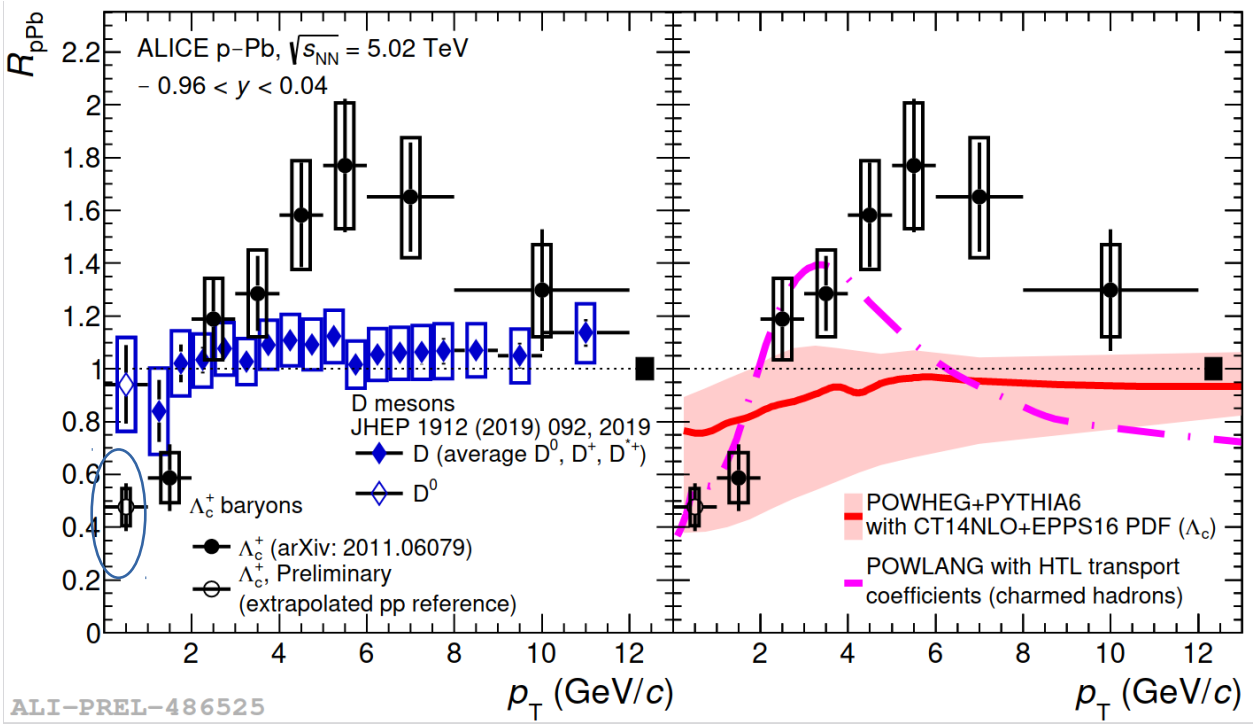




Precise charm cross section measurements in pPb

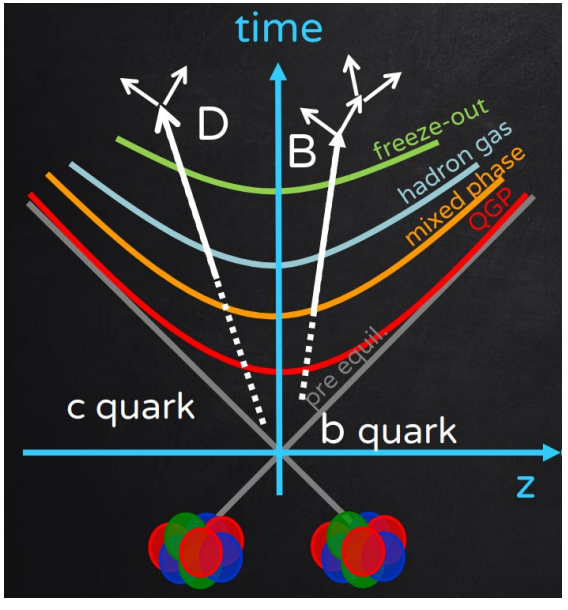
- New measurements of Λ_c^+ cross section **down to p_T= 0**
  - significant difference wrt to pp in Λ_c^+/D^0 → radial flow or multiplicity dependence of hadronization?
    - challenging further the universality of hadronization process
  - R_{pPb} >1 for 4 < p_T < 8 GeV → radial flow or hadronization?
    - similarities with the strange sector
  - significant suppression for p_T < 2 GeV/c
    - precision of Λ_c^+/D^0 and R_{pPb} measurements **improved** thanks to the pPb (2016) and pp ref samples





Summary

- **Long-range angular correlations** in heavy ion as well as high-multiplicity pPb&pp collisions
  - identified particle and multiparticle correlation techniques support a **collective origin** of v_n
- Comprehensive studies of heavy flavor collectivity in **all** systems
  - c quark flow is comparable to light quark whereas that of b quarks closer to 0 in PbPb
  - charm v_2 in pPb&pp is significant, but lower than in PbPb
  - b flows in PbPb, but seems not in pPb or pp
- Future data with improved precision will provide **crucial insights**
  - for example Λ_c^+/D^0 and Λ_c^+ R_{pPb} measurements **improved** thanks to the pPb (2016) and pp ref samples

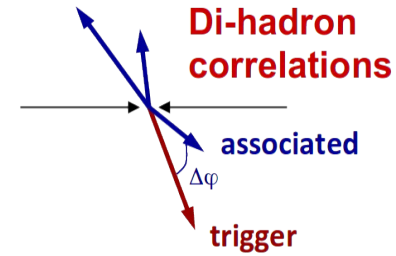


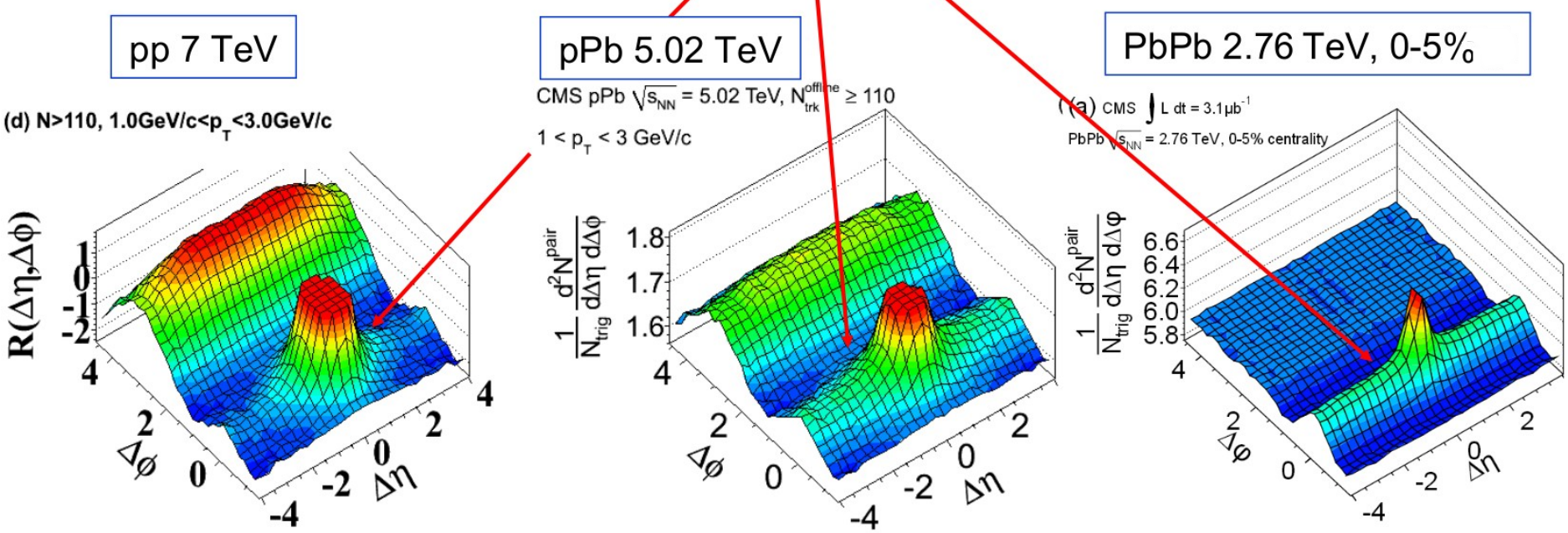
Plot here


S
BONUS
slides

"Everything…flows"(?)

- Long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\varphi \approx 0$) angular correlations are seen at LHC at various $\sqrt{s}$ in
  - heavy ion (XeXe and PbPb), **and**
  - "small systems", i.e., high-multiplicity pPb and pp collisions
- Signs reminiscent of **collective behavior** of a quark-gluon plasma (QGP)





JHEP **09** (2010) 091
(also in [1])

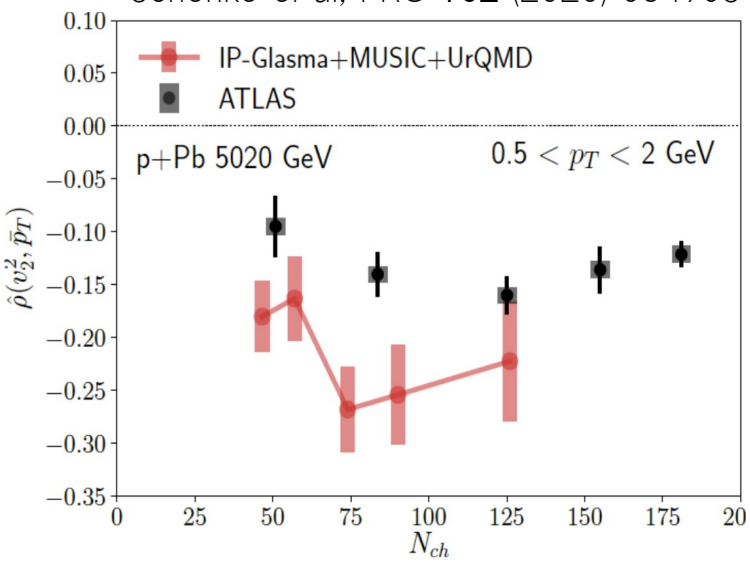
PLB **718** (2013) 795
(also in [2])

JHEP **07** (2011) 076
(also in [3])

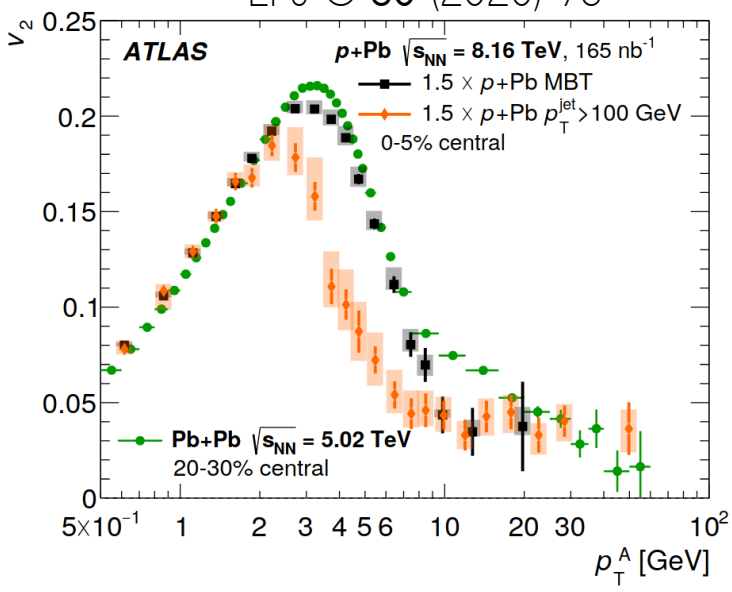
Understanding collectivity in small systems

- Correlation between $\mathbf{v_n}$ and the event mean p_T (radial flow) sensitive to initial conditions
  - $\mathbf{v_2}$–[p_T] in pPb favors **a more compact** initial state → stronger flow and prominent ridge
- **Process-dependent** $\mathbf{v_n}$ can distinguish complementary particle production mechanisms
  - $\mathbf{v_{2,3}}$ similarity (ordering) in MB vs jet-triggered pPb events indicative of flow (soft+hard admixture)
  - $\mathbf{v_{2\text{-}4}}$ largely independent of whether measured in jet enriched/depleted pp events [8]
- Photonuclear **collisions in UPC** offer an alternative dynamics of small systems
  - competing explanations can be tested in cases one of the "beams" has a **simpler** initial state
  - both ATLAS and CMS see **significant** $\mathbf{v_2}$ in UPC PbPb [9] and pPb collisions, respectively

Schenke *et al*, PRC **102** (2020) 034905



EPJ C **80** (2020) 73



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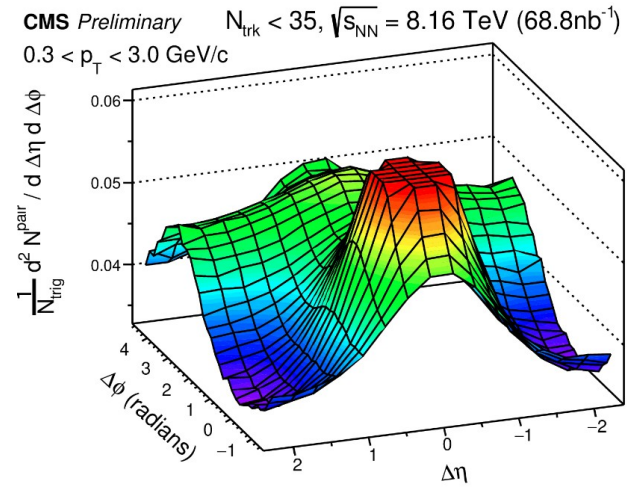
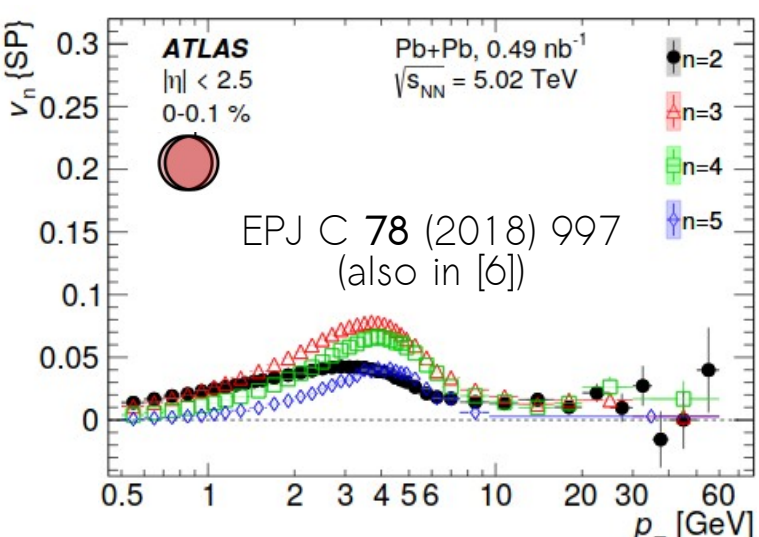
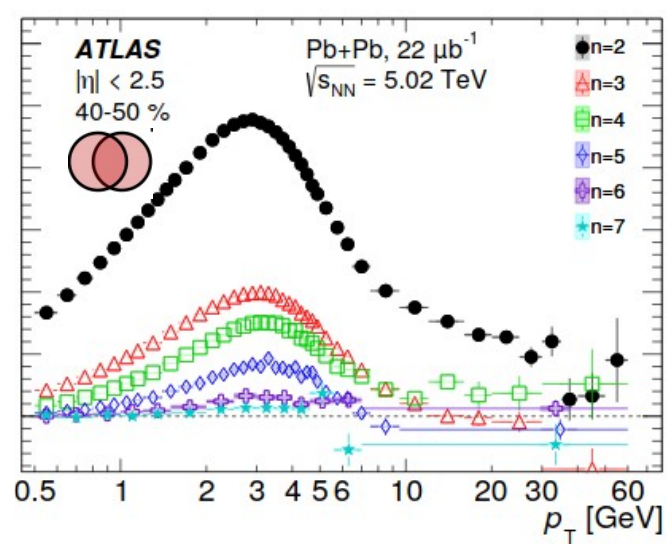


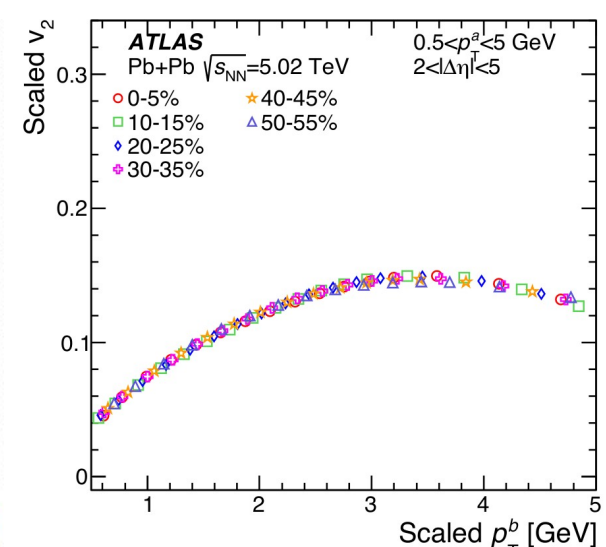
γp enhanced

Flow harmonics in heavy ion collisions

- Detailed measurements of up to $\mathbf{v_7}$ ($\mathbf{v_6}$) in PbPb (XeXe [4, 5]) collisions
  - found **positive** with their magnitude dependent on the **particle species** and **method of calculation**
    - heavier particles "flow more"; level of nonflow suppression and flow fluctuations impact v_n
  - centrality dependence – v_n are **the largest** in the 20-50% central events
    - $v_{n\geq3}$ show a weaker dependence
  - p_T dependence – an increase up to 3 GeV, depending on centrality, and then gradually decreasing
  - empirical **scaling behaviors** seen
    - for fixed *n* same scaled shape as a function of scaled p_T across centrality
    - the ratio $(\mathbf{v_n}/\mathbf{v_m})^{n/m}$ for two harmonics *m* and *n* is independent of p_T in a given centrality

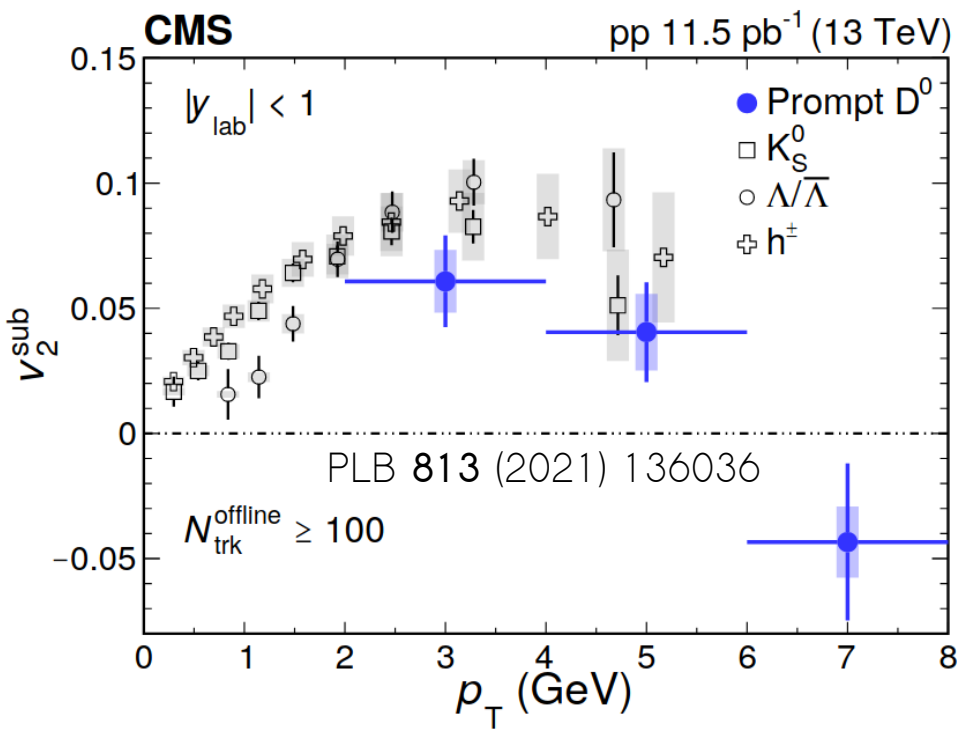


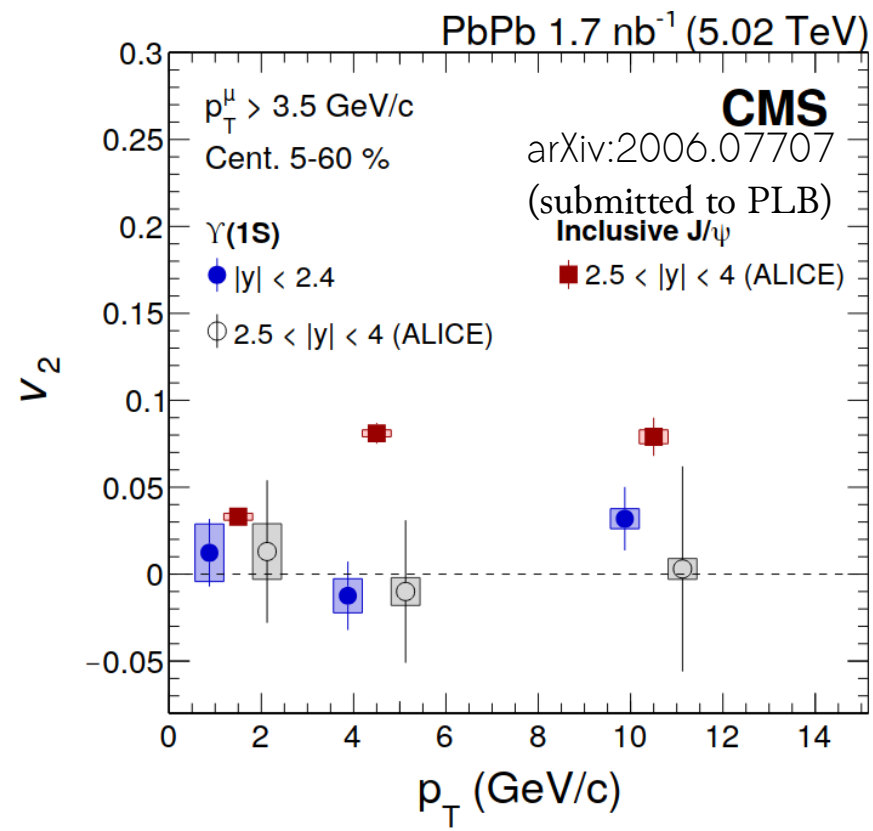




Prompt D^0 v_2 in pp and Υ(nS) v_2 in PbPb

- **First** measurement with high-multiplicity events in pp
  - $v_2 \neq 0$; close to the v_2 of light flavors
- Flow of bottomonia in PbPb
  - Precise Υ(1S) v_2 consistent with 0
  - **First** Υ(2S) v_2 measurement consistent with 0 too
    - in contrast to larger J/ψ v_2

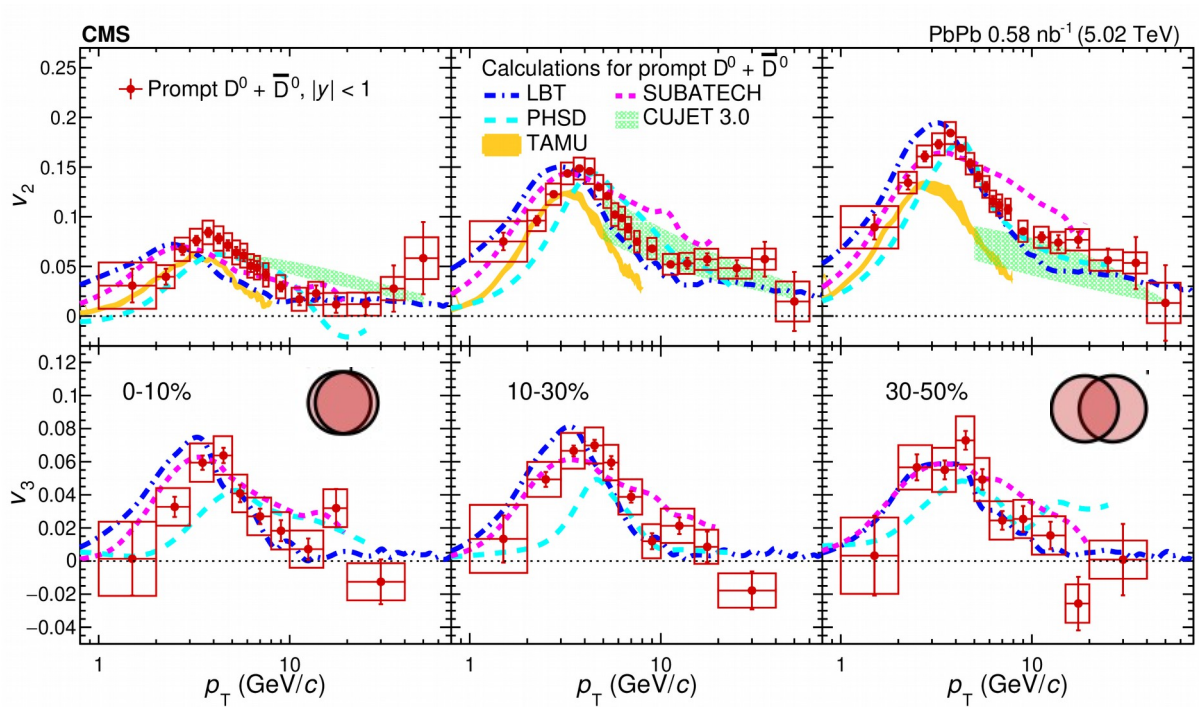


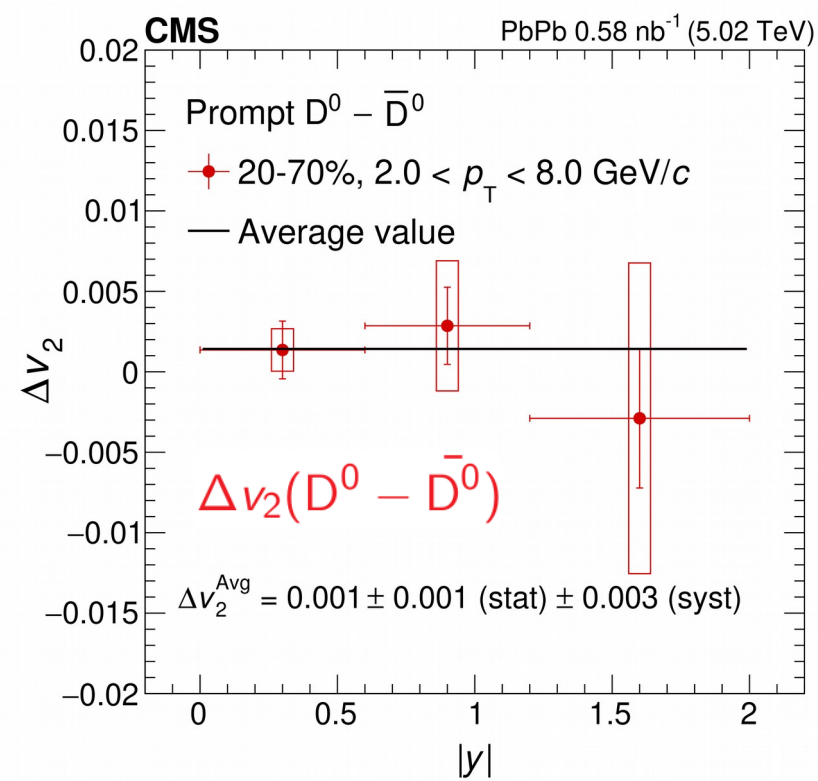


Prompt D^0 v_2 and v_3 in PbPb

- Multidifferential in p_T, $|y|$, and centrality
  - v_2, v_3 as expected from collision geometry
- Search for strong EM fields effects
  - **no** sign of rapidity dependence of Δv_2 (D^0–$\bar{D}^0$)

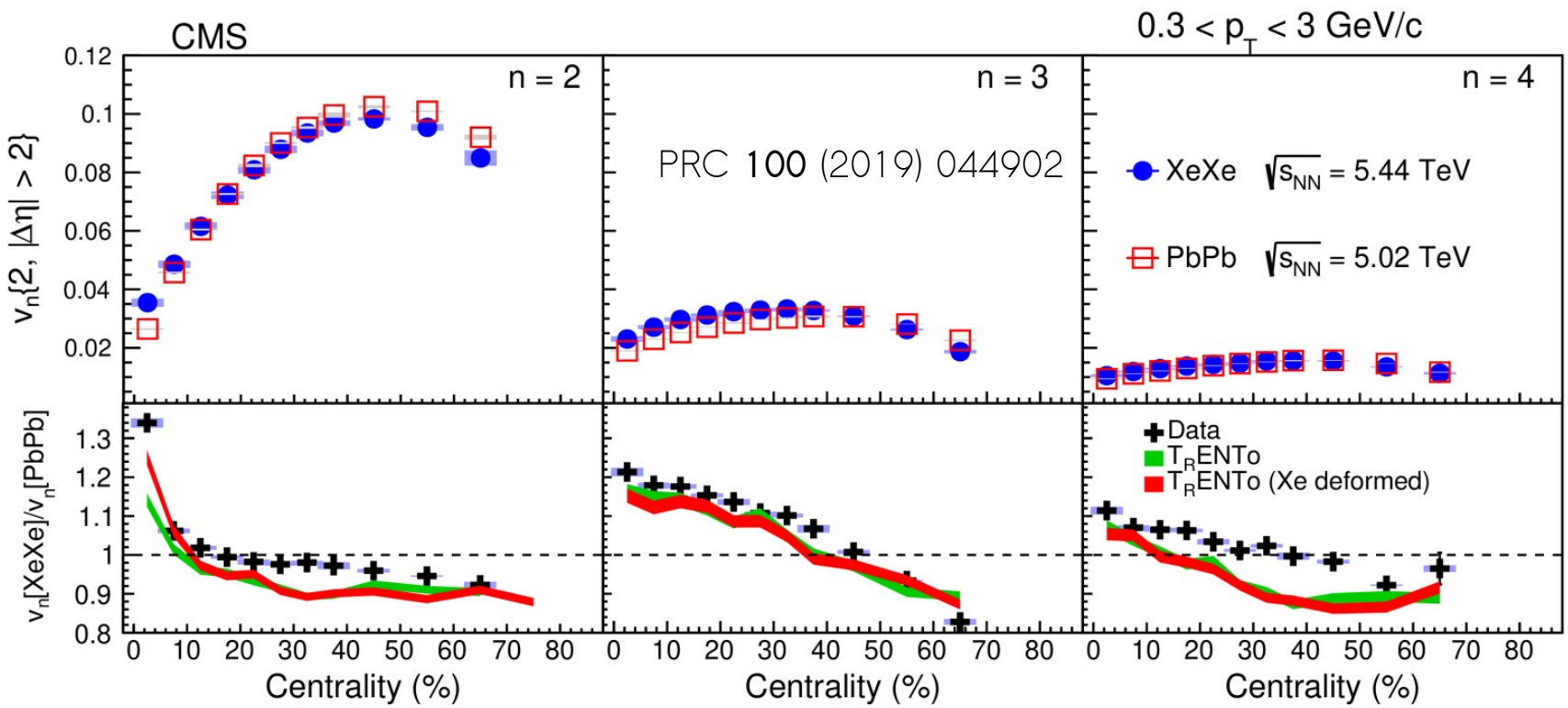
arXiv: 2009.12628
(accepted by PLB)





Flow harmonics in XeXe collisions

- Detailed measurements of v_2-v_6
  - p_T dependence **similar to** that in PbPb
  - centrality dependence – v_2 higher (lower) than PbPb in most central (peripheral) events
    - weaker dependence with higher n
    - qualitatively consistent with theoretical predictions
  - scaling behaviors from PbPb observed to **hold** in XeXe too
  - XeXe v_n and the cross-system comparisons an opportunity to **improve** the current modeling



Flow of heavy-flavor decay leptons

- Reconstruction of muons from c and b hadron decays separated from π/K bkg using
  - the momentum imbalance $\rho = (p^{ID} - p^{MS})/p^{ID}$
    - between the inner detector and muon spectrometer
    - real muons have a ρ distribution peaked around zero
    - π/K bkg a broader ρ shifted towards higher values
  - the transverse impact parameter d_0
    - different d_0 due to c and bo hadrons' decay lengths