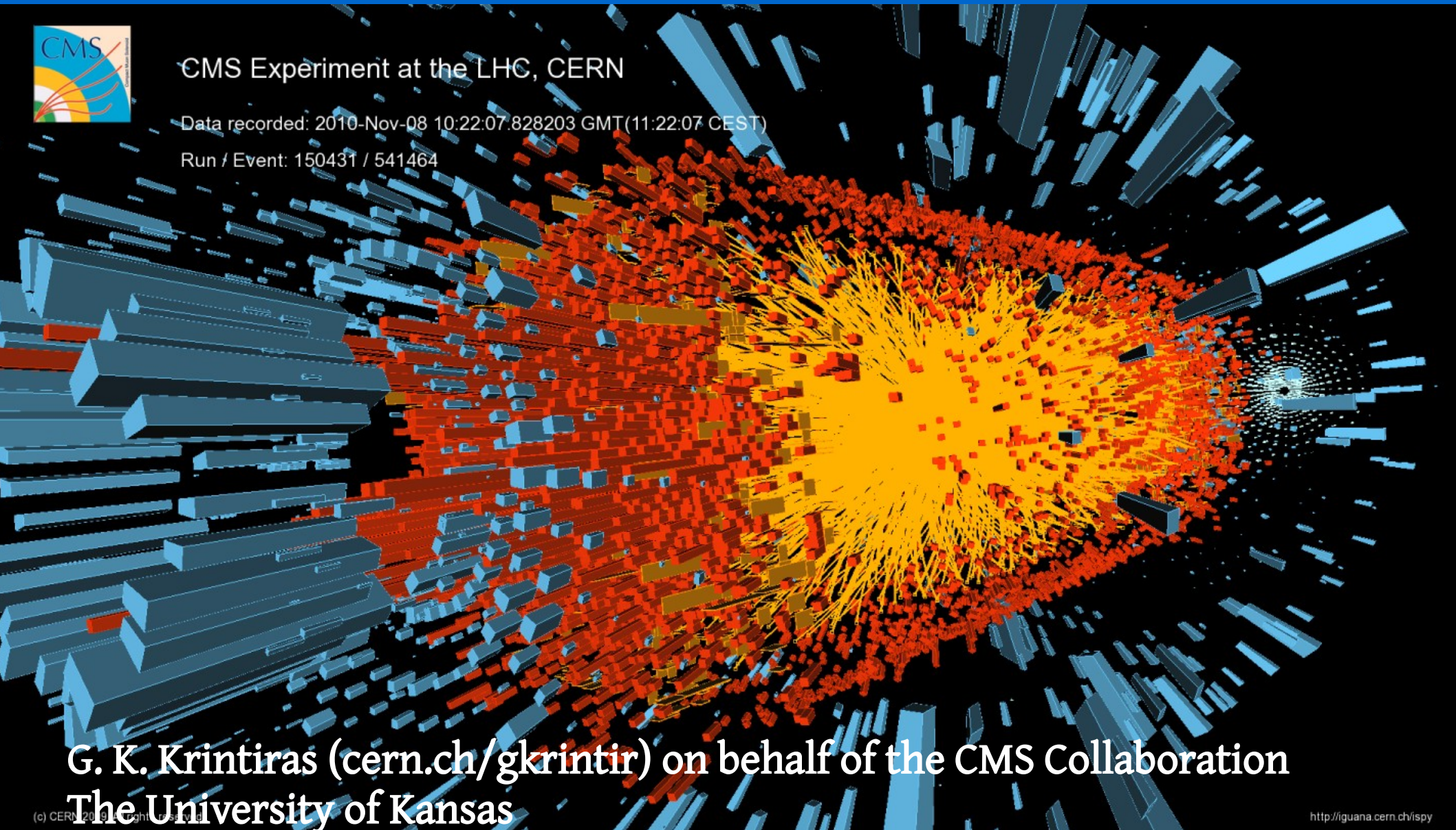
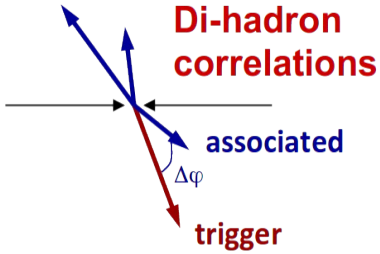
Collectivity in heavy ions at CMS



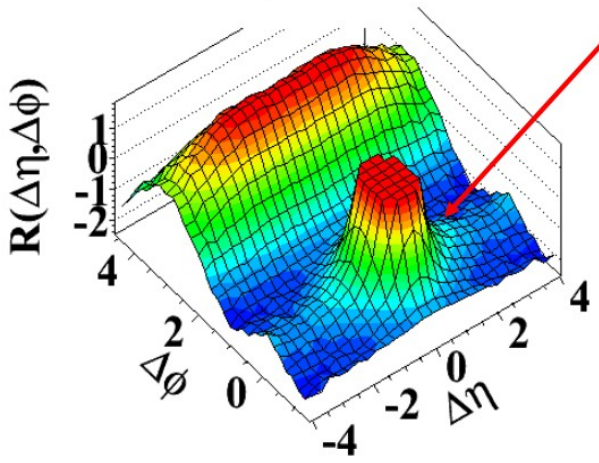
G. K. Krintiras (cern.ch/gkrintir) on behalf of the CMS Collaboration
The University of Kansas

"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 ions (XeXe and PbPb), **and**
  - "small systems", i.e., high-multiplicity (≳50–60) pPb and pp collisions
- Signs reminiscent of **collective behavior** of a quark-gluon plasma (QGP)

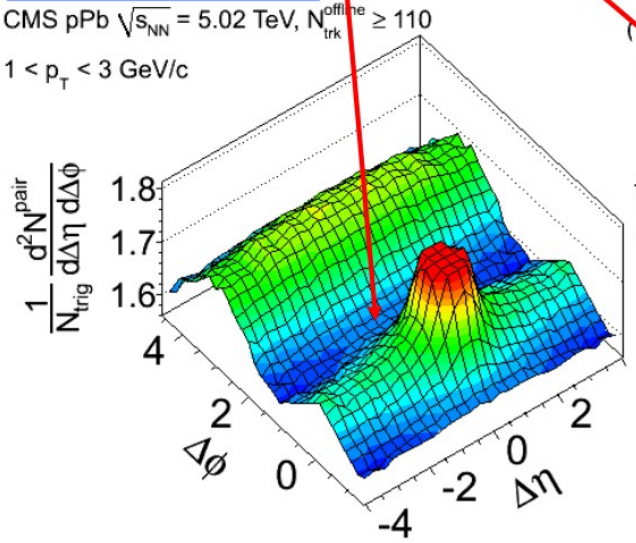


pp 7 TeV



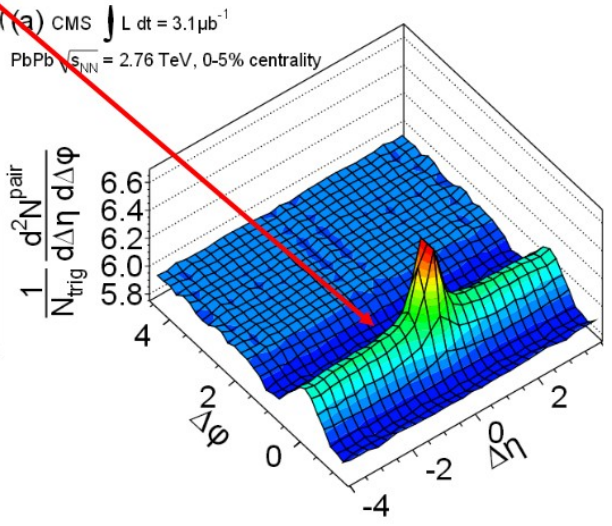
JHEP **09** (2010) 091

pPb 5.02 TeV



PLB **718** (2013) 795

PbPb 2.76 TeV, 0-5%



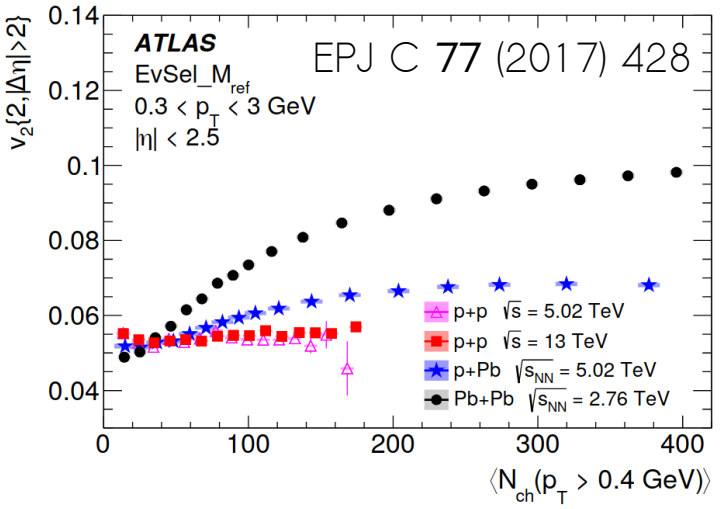
JHEP **07** (2011) 076

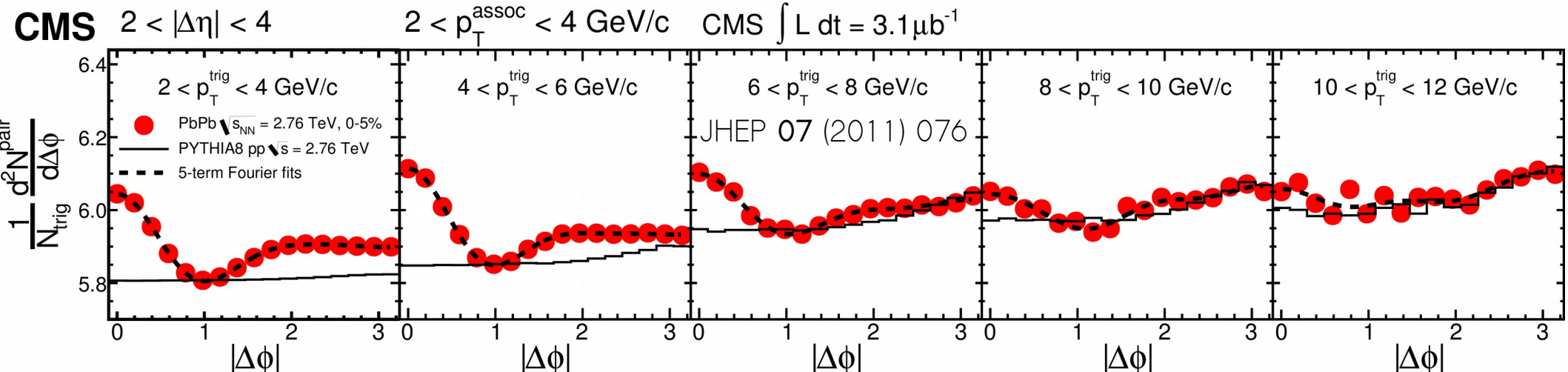
Fourier expansion of the projected Δφ

- Azimuthal correlations of particle pairs are decomposed via a **Fourier expansion**:

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

  - single-particle azimuthal anisotropy Fourier coefficients measured as $v_{n\geq 1}=\sqrt{v_{n\Delta}}$
    - as functions of kinematic and global-event variables





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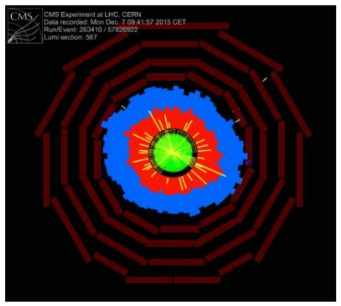
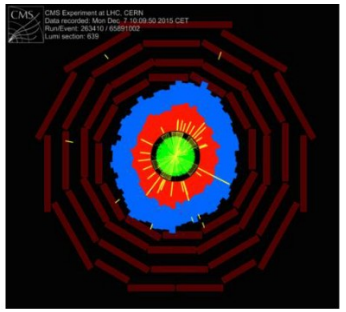
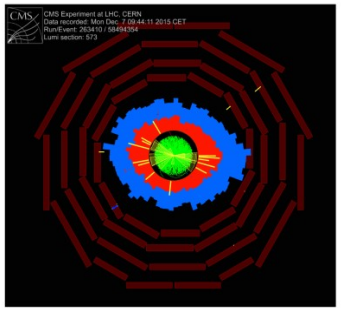
  - single-particle azimuthal anisotropy Fourier coefficients measured as $v_{n\geq 1}=\sqrt{v_{n\Delta}}$

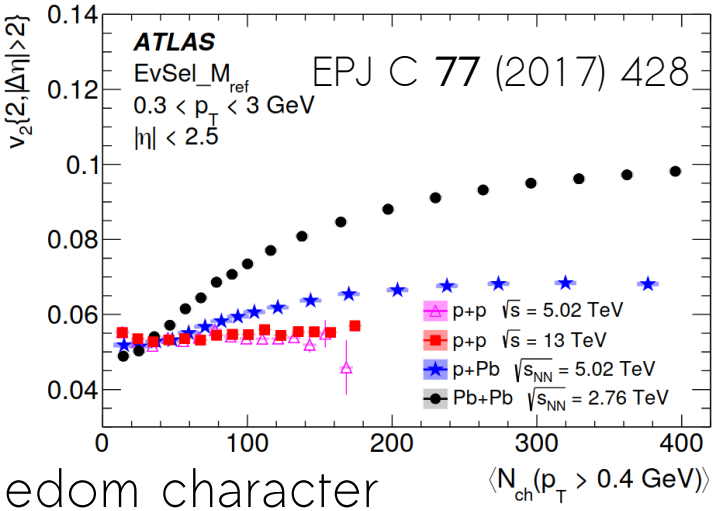
- Harmonics (e.g., v_2, v_3) can be interpreted as **flow** (e.g., elliptic, triangular) which are related to

  - **collision geometry,** its **fluctuations,** and **system's evolution**

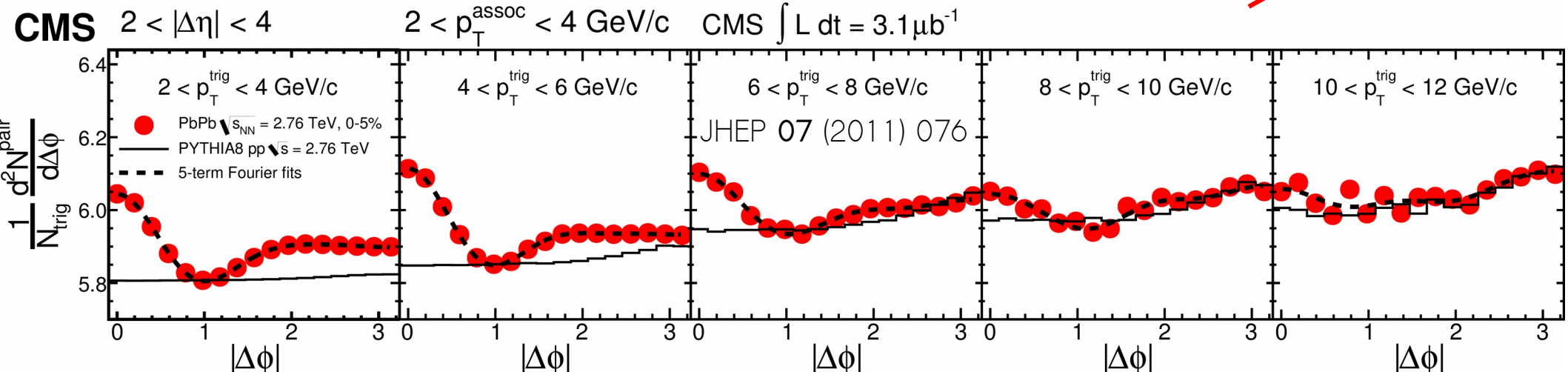






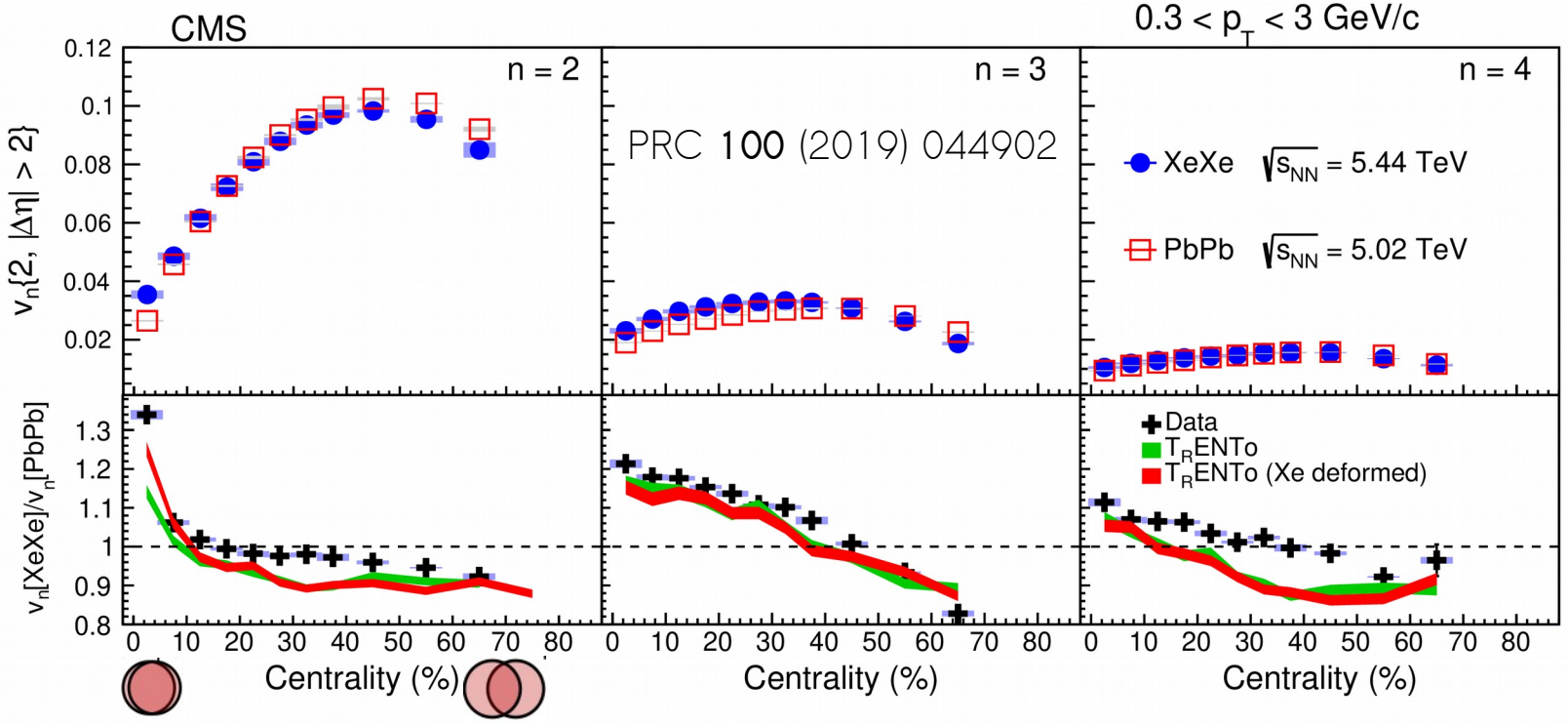


A fluid that retains its QCD asymptotic freedom character



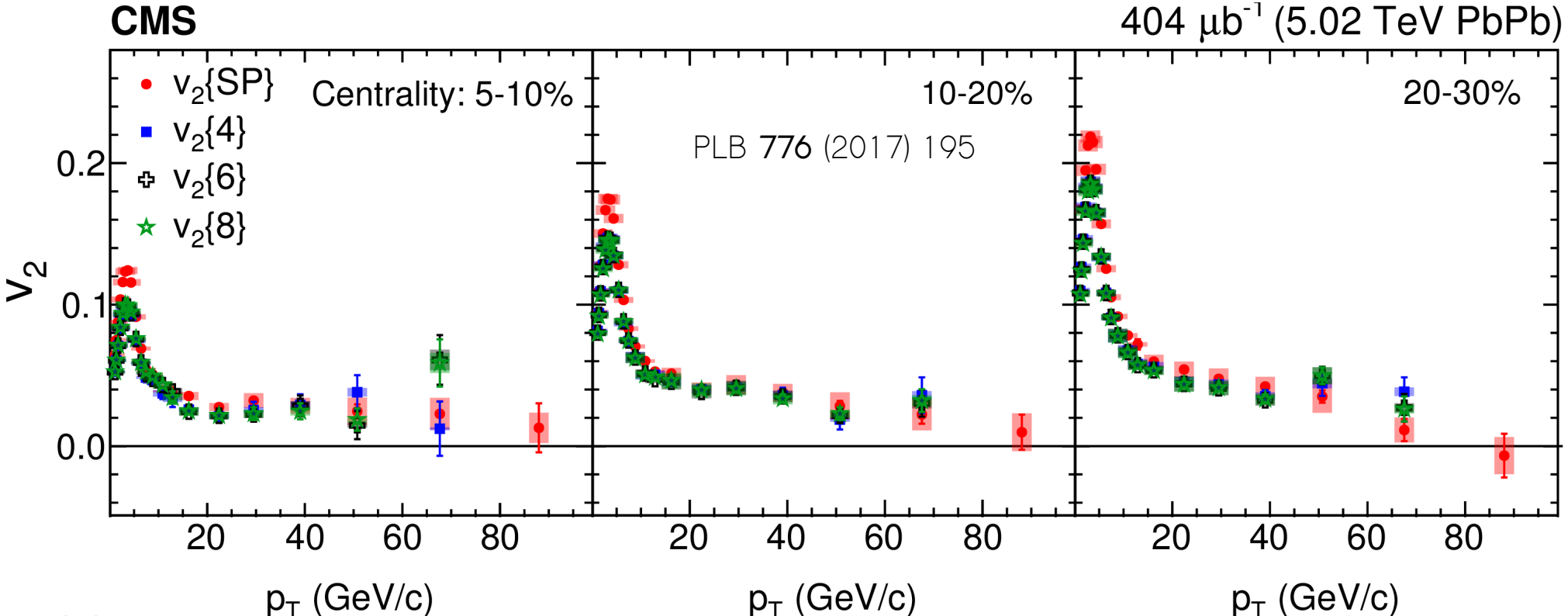
Flow harmonics in heavy ion collisions

- Detailed $\mathbf{v_n}$ measurements in XeXe and PbPb collisions
  - found **positive** with their magnitude dependent on the **particle species** and **method of calculation**
    - heavier particles "flow less"; level of nonflow suppression and flow fluctuations impact v_n
  - centrality dependence – v_n are **the largest** in the 20-50% central events
    - $v_{n\geq 3}$ show a weaker dependence
  - the cross-system v_n comparisons an opportunity to **improve** the current modeling



Flow harmonics in heavy ion collisions (high p_T)

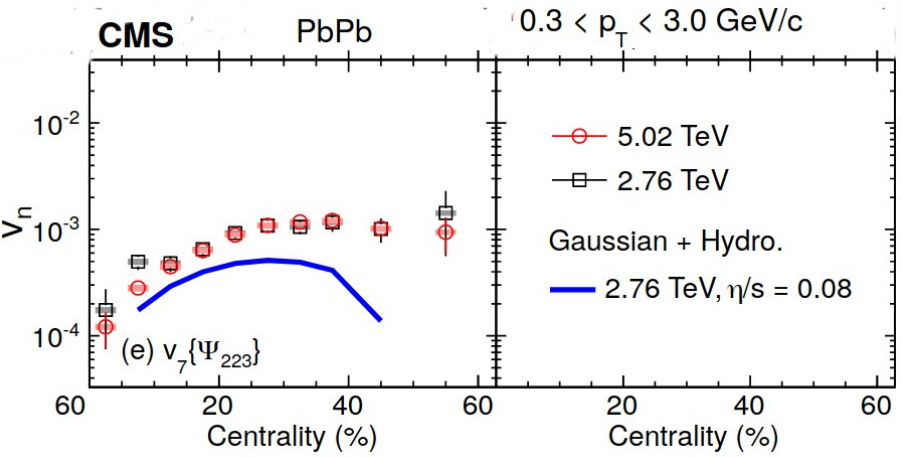
- Detailed v_n measurements in XeXe and PbPb collisions
  - found **positive** with their magnitude dependent on the **particle species** and **method of calculation**
    - heavier particles "flow more"; level of nonflow suppression and flow fluctuations impact v_n
  - centrality dependence – v_n are **the largest** in the 20-50% central events
    - $v_{n\geq 3}$ show a weaker dependence
  - **p_T dependence** – an increase up to 3 GeV, depending on centrality, and then gradually decreasing
    - similarity of v_n methods at high p_T suggests a **path-length dependent** origin of energy loss



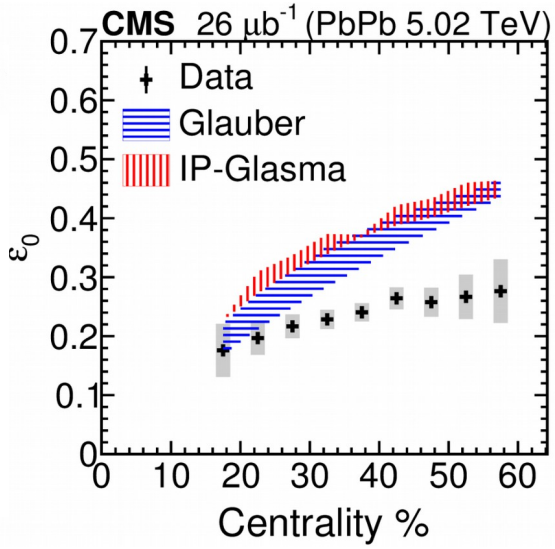
Flow cross talk, fluctuations, and decorrelation

- "mixed" harmonics $v_{n\geq 4} \propto v_n + \chi\,(v_{m\leq n})^p$ as a function centrality
  - models **cannot** describe well mixed v_n and the nonlinear coefficients χ
- fluctuations in the initial state (e.g., parameterized by mean eccentricity ε_0) lead to v_n fluctuations
  - significant difference in predictions from Glauber and IP-Glasma (gluon saturation effects)
  - might reflect a **nonlinear response** in the $v_n \propto \varepsilon_n$ correspondence
- Models tuned to describe the transverse dynamics may not necessarily grasp the initial state **longitudinally**
  - flow "decorrelations" (e.g., η-dependent factorization breakdown) provides insights into the v_n dynamics

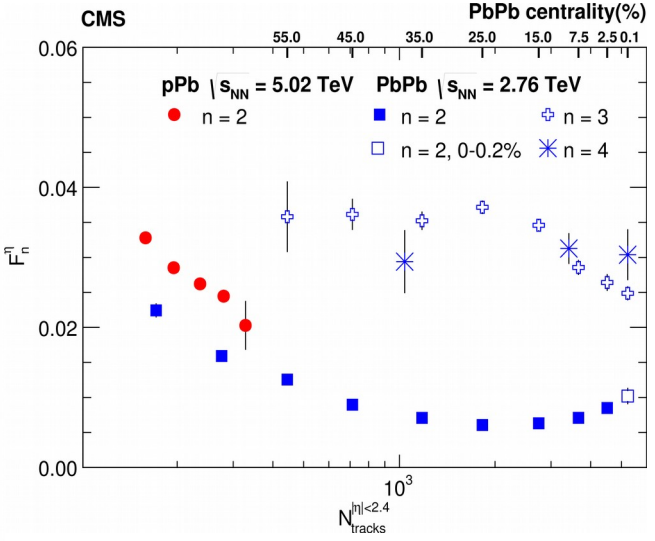
EPJ C **80** (2020) 534



PLB **789** (2019) 643



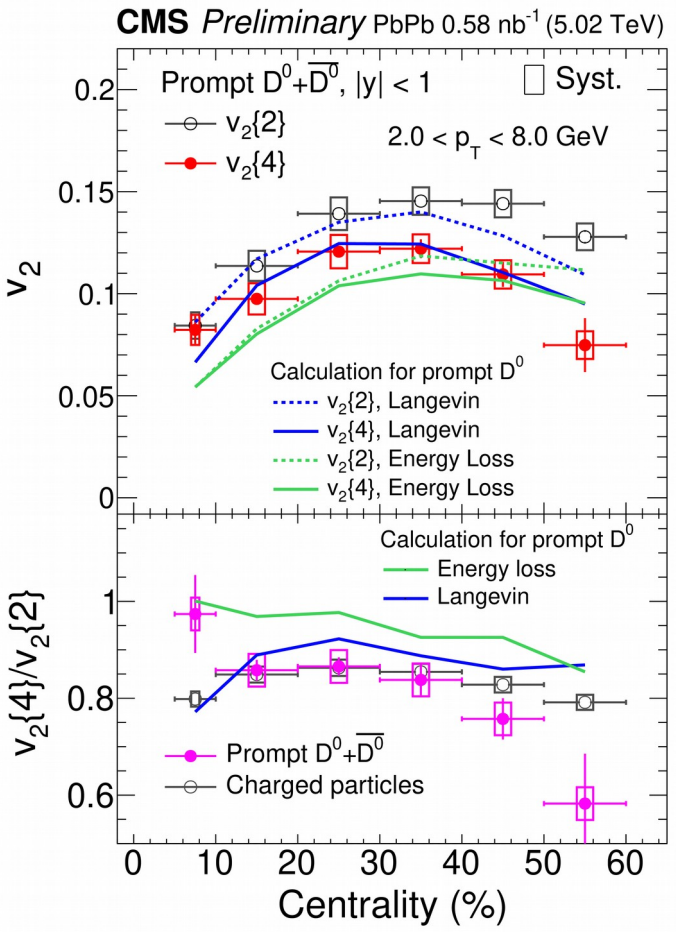
PRC **92** (2015) 034911



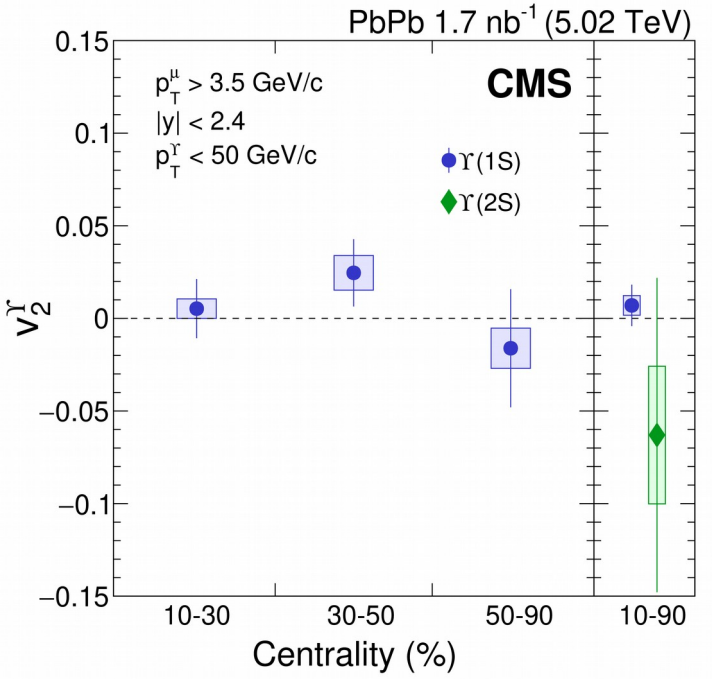
Measuring identified particle flow in PbPb

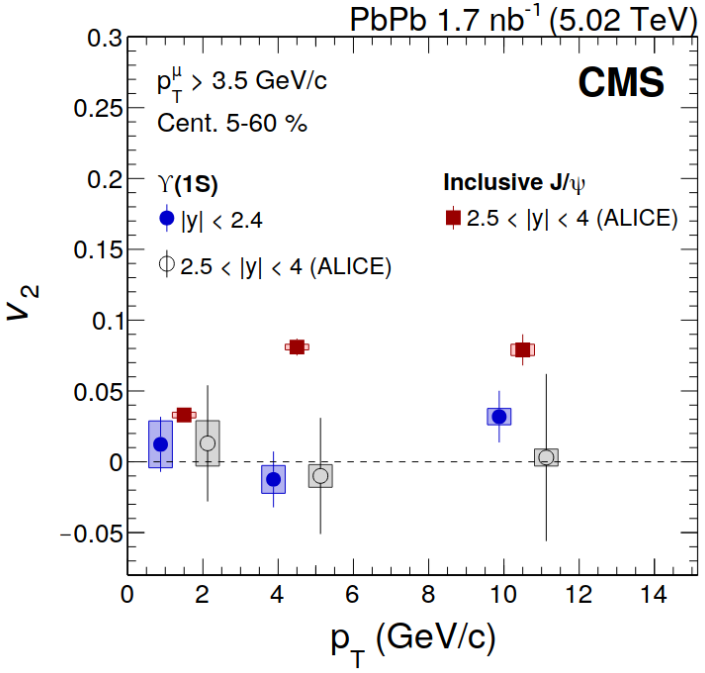
- Different interplay of energy loss processes for HF than light quarks is expected
  - a series of measurements with J/ψ, D^0, and ϒ(nS)
    - extension to studies of **EM fields effects**, e.g., no rapidity dependence of Δv_2 (D^0–$\bar{D}^0$) in PbPb
  - The harmonics for **c** mesons are **comparable to** the light-flavor hadrons
  - **Close to zero** anisotropy observed for ϒ(1S) and ϒ(2S)

CMS-PAS-HIN-20-001



PLB 819 (2021) 136385

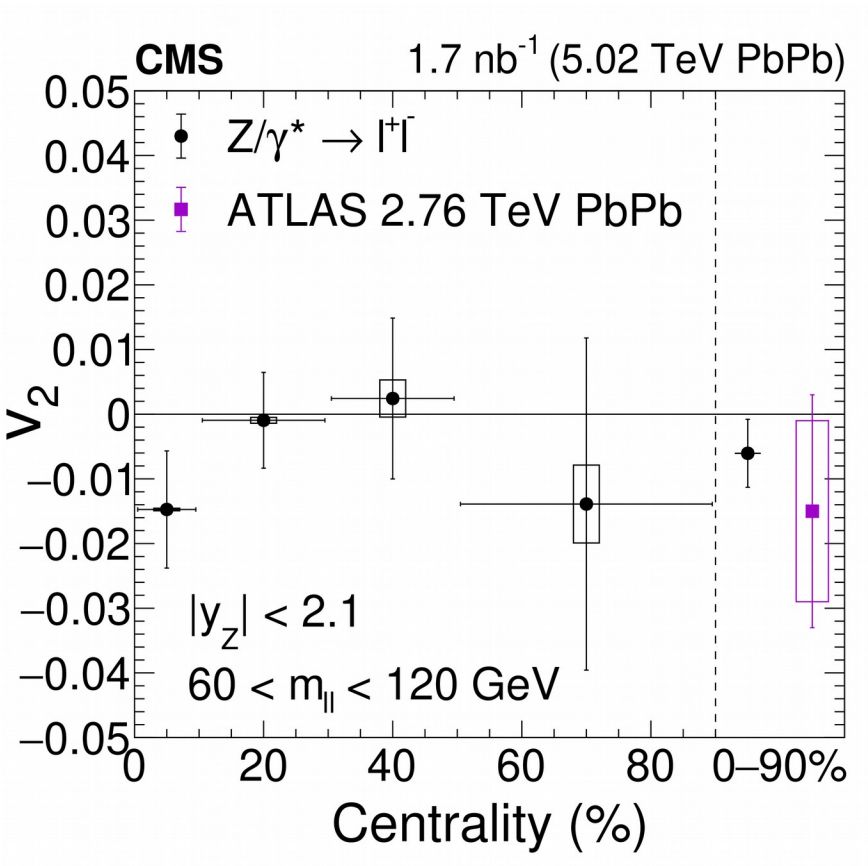


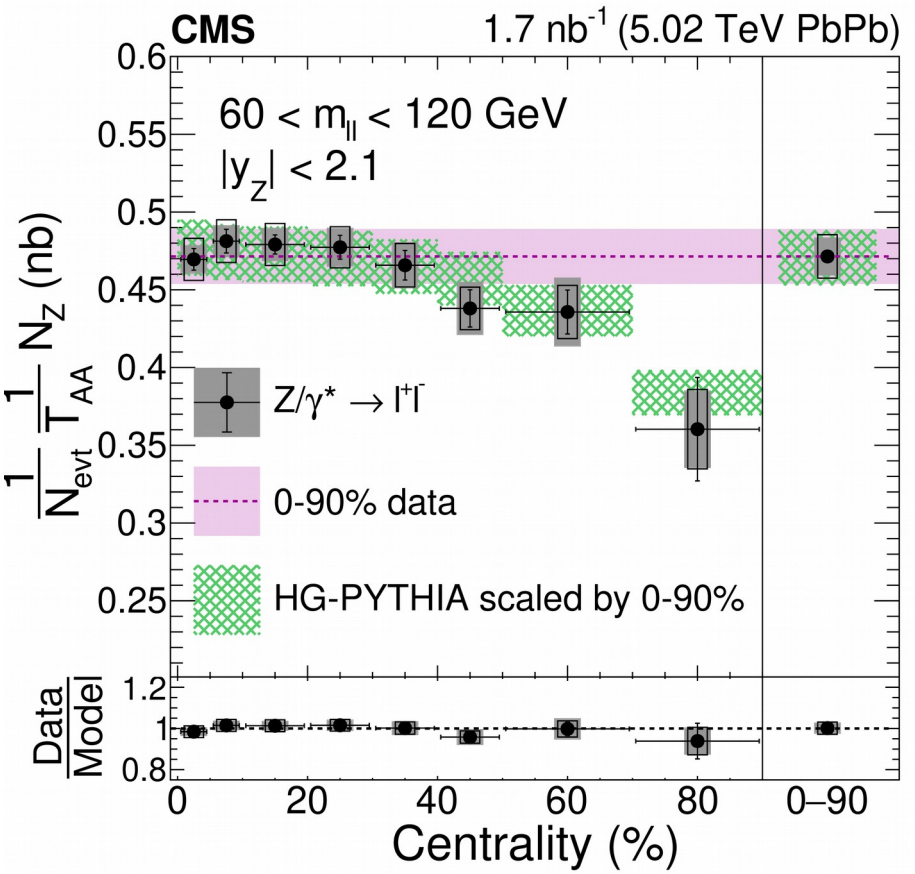


Measuring Z boson flow and production in PbPb

- Two decay channels combined into the final v_2 measurement
  - significant **improvement** relative to Run 1 result
- Consistent with Z bosons being created early and **not being modified** by the QGP
- Z boson yield in peripheral collisions consistent with HG-PYTHIA, i.e., incorporating selection bias
  - can be used for a data-based determination of **NN lumi vs centrality**

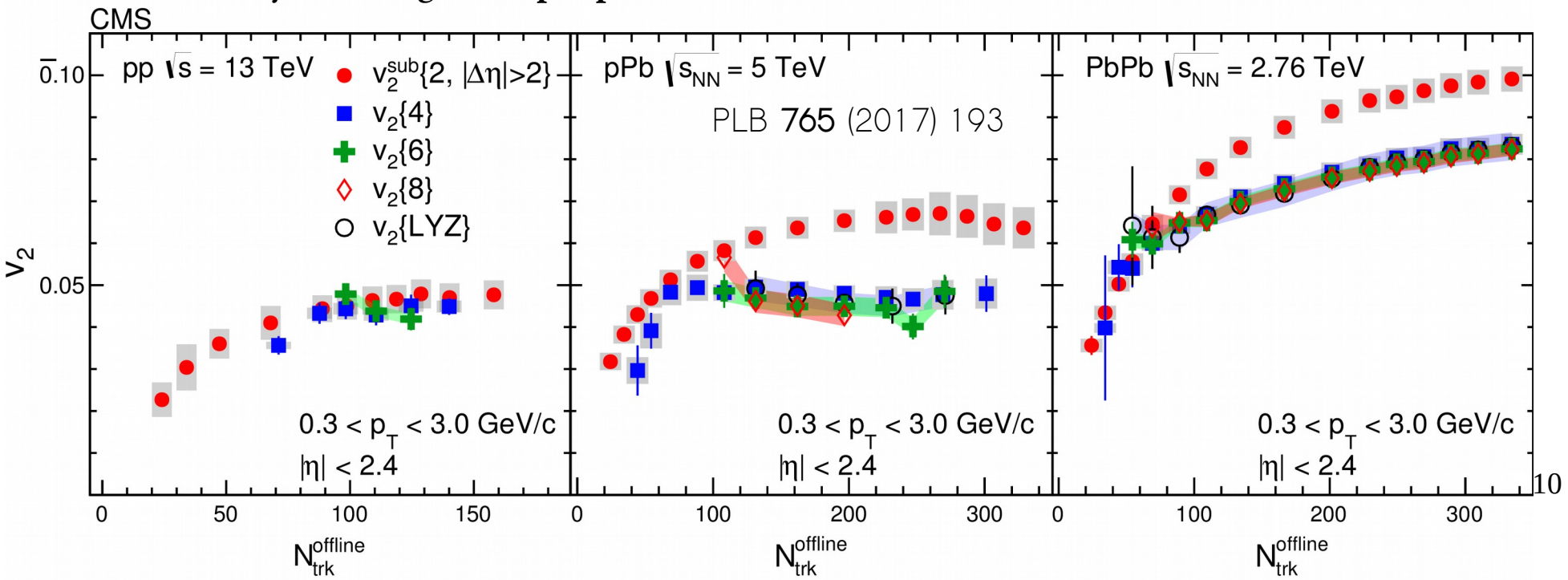
PRL **127** (2021) 102002





Measuring collectivity in small systems

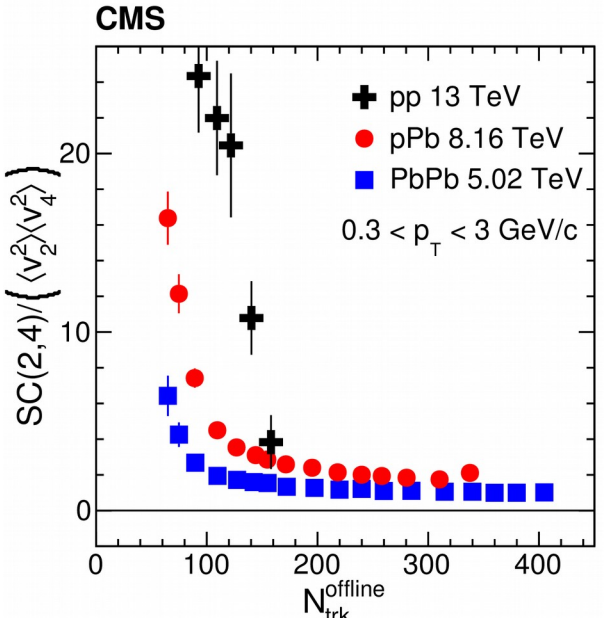
- Detailed measurements of v_2&v_3
  - centrality/event activity and p_T dependence qualitatively **similar** to that in heavy ions
  - identified particle and multiparticle correlation techniques support a **collective origin** of v_n
    - encompassed by hydrodynamical models, but **not a unique** description
- We start answering whether a collective component in 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)



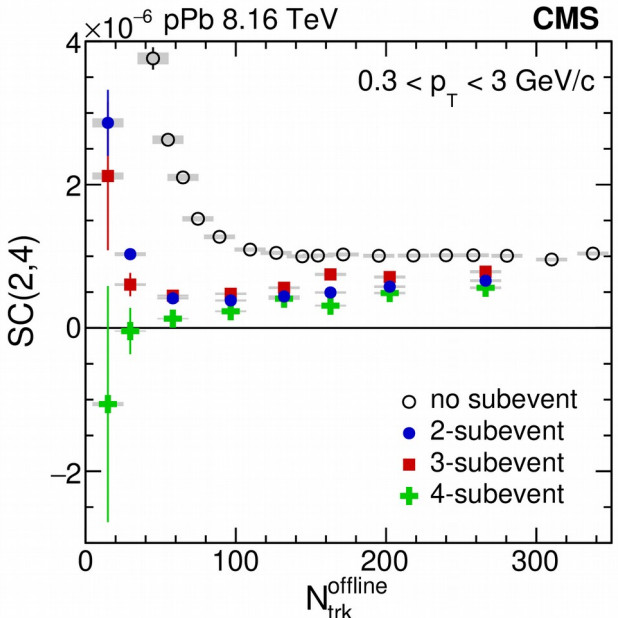
Understanding collectivity in small systems

- A negative (positive) correlation is observed between v_2 and v_3 (v_4) in pPb
  - **similar** to what is observed in PbPb → attributed to the hydrodynamic flow of QGP
- Consistent with "subevent" (i.e., two, three, or four distinct tracker η regions) cumulant technique **but**
  - at low-multiplicities the results from subevents diverge due to few-particle correlations
  - these findings significantly **lower** the multiplicity range for the onset of collective behavior
- 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
  - CMS sees **significant v_2** in UPC pPb collisions

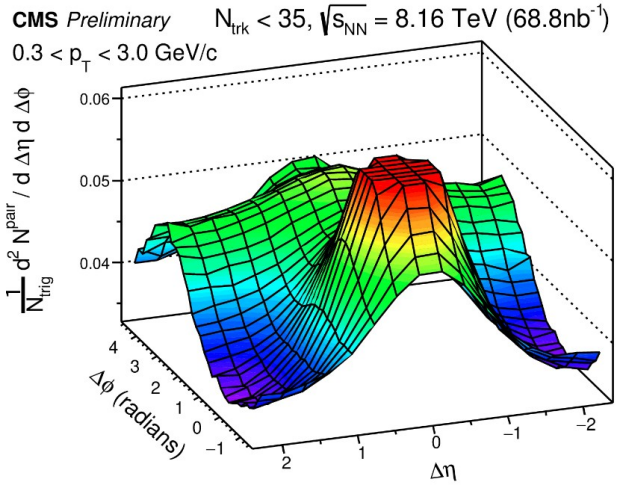
PRL 120 (2018) 092301



PRC 103 (2021) 014902



CMS-PAS-HIN-18-008

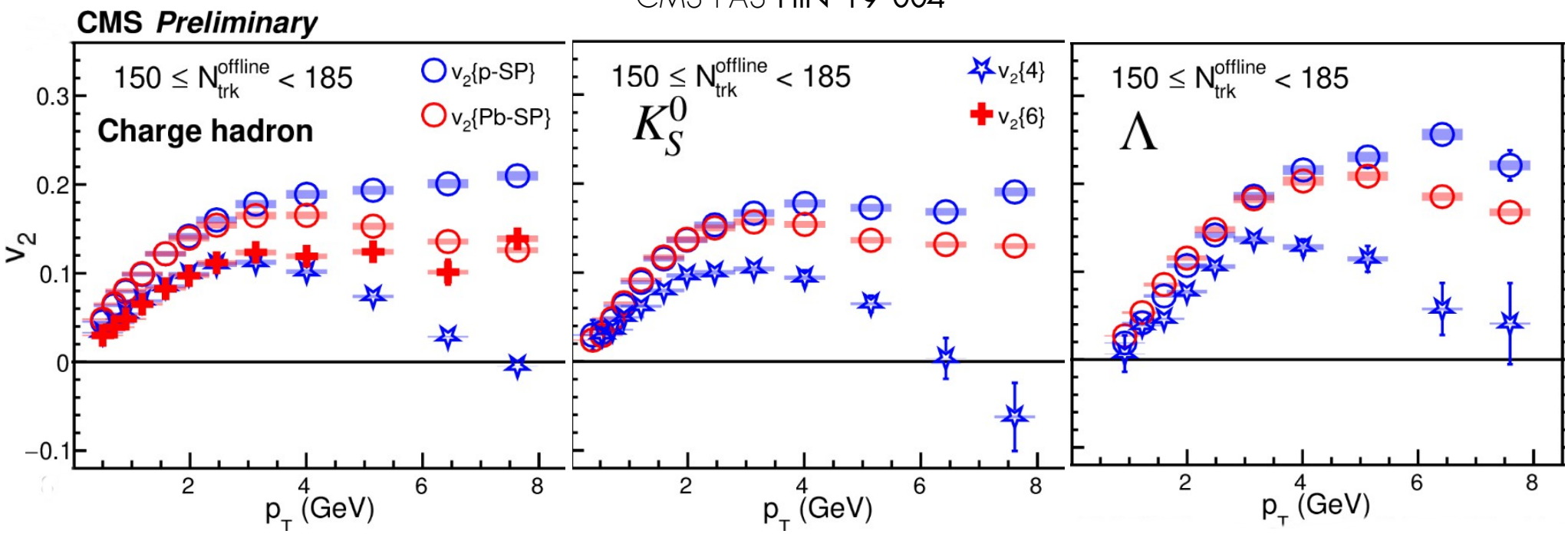


γp enhanced

Measuring identified particle flow in pPb

- First measurement of the collective **multiparticle** correlations for identified strange particles
  - Difference in 4- and 6-/8-particle correlation results can be explained by jet-related nonflow
    - **new approach**: suppressed nonflow by rejecting events with jet $p_T > 20$ GeV
  - two-particle correlation exhibits **dependency** with respect to the Pb-going or p-going side
  - Results **consistent** with event-by-event viscous hydrodynamic model calculations in PbPb
    - no calculation yet available in the smallest systems

CMS PAS HIN-19-004



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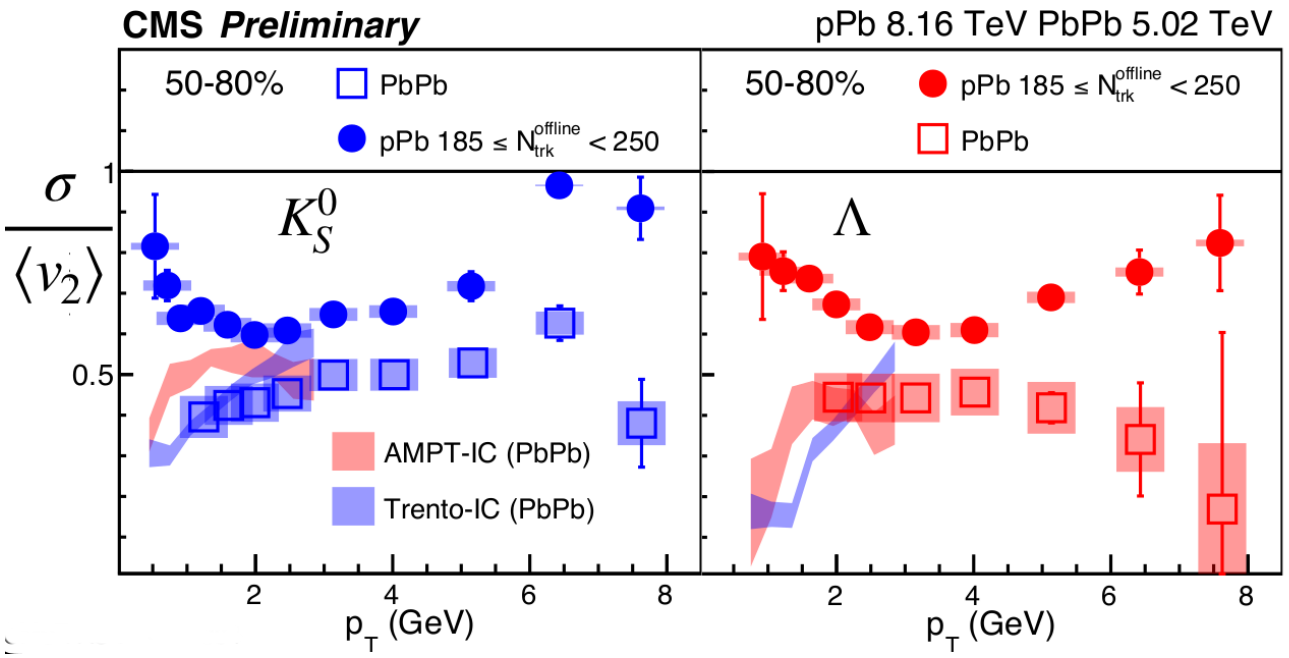
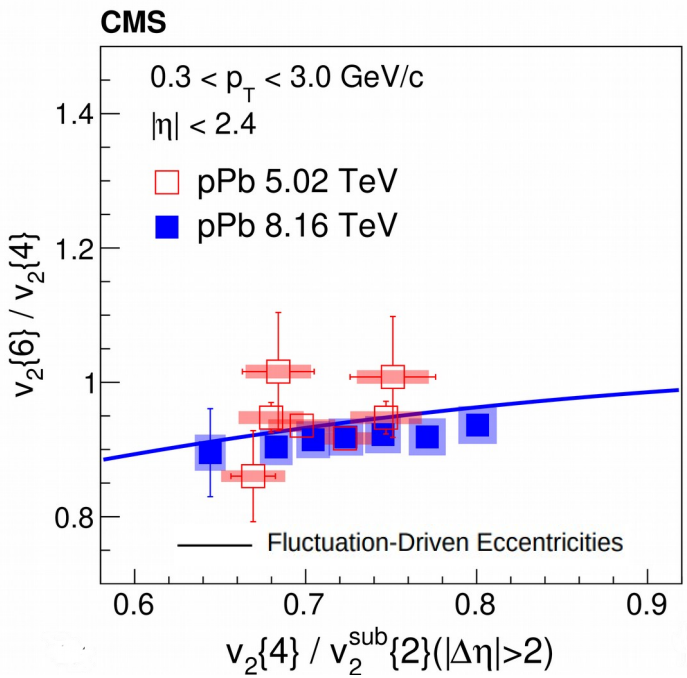
  - Difference in 4- and 6-/8-particle correlation results can be explained by jet-related nonflow
    - **new approach**: suppressed nonflow by rejecting events with jet $p_T > 20$ GeV
- Study the system-size dependence of flow **fluctuations**
  - **larger** in pPb with respect to PbPb with no obvious particle species dependence
    - fluctuations with respect to overall collision geometry **contribute** to multiparticle correlations
  - In PbPb, are relatively flat over the measured p_T range, replicated by model calculations

CMS PAS HIN-19-004



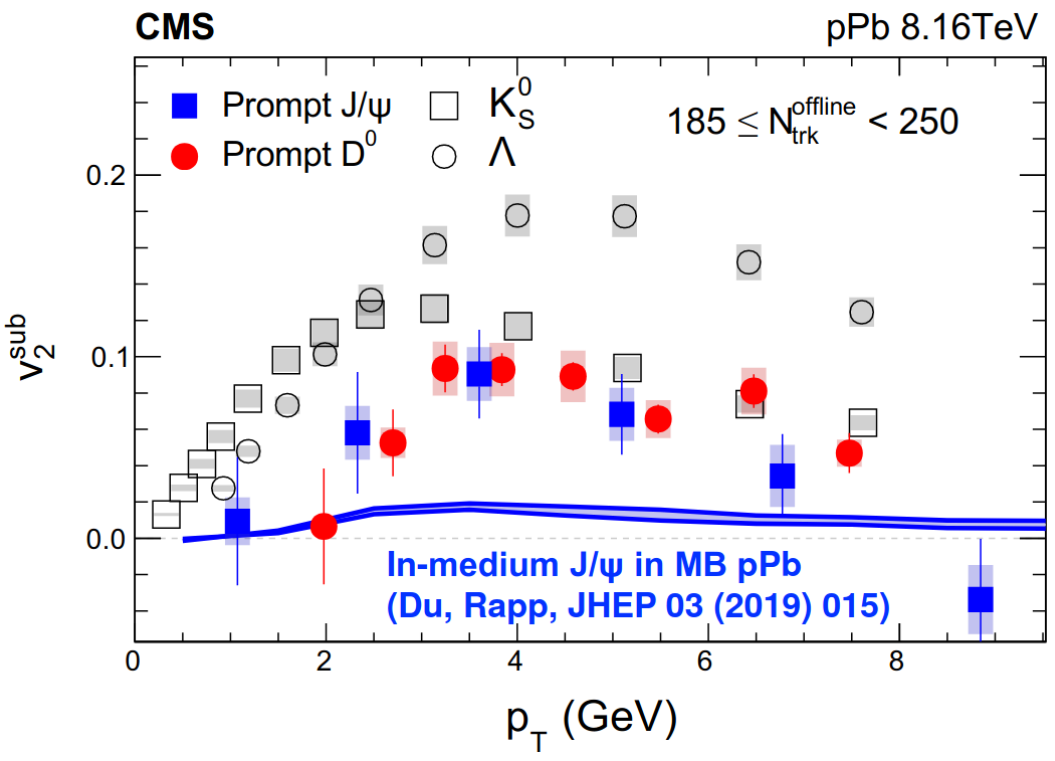
PRC 101 (2020) 014912



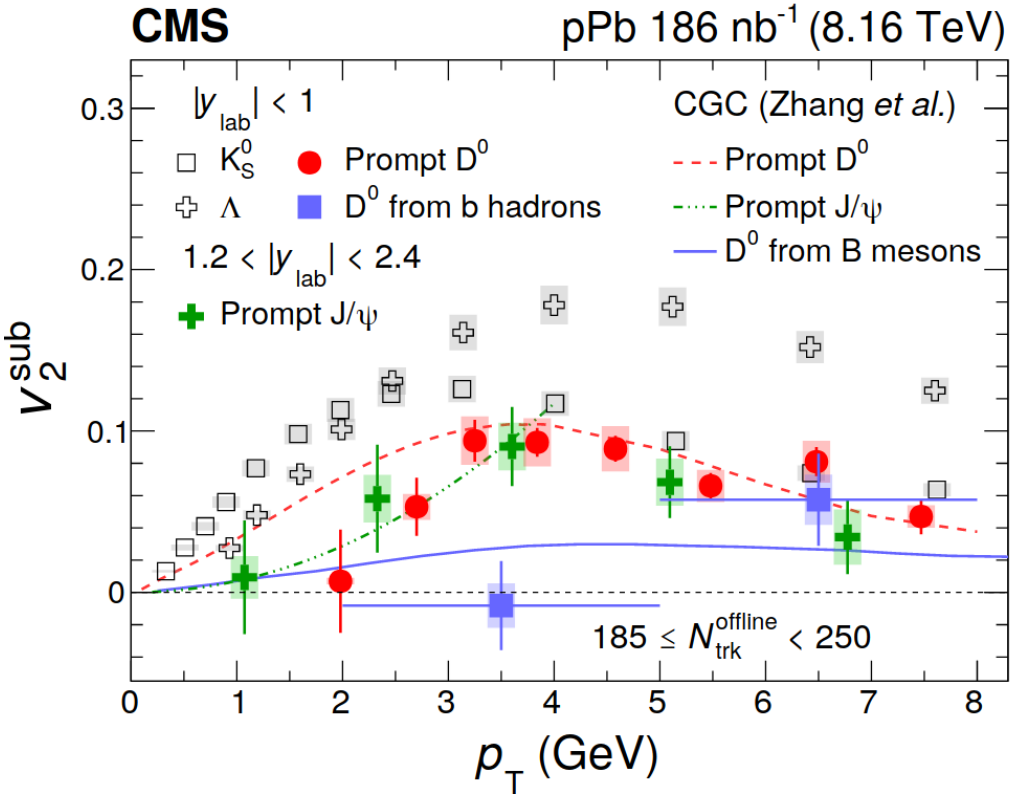
Comparison with HF particle flow in pPb

- Observation of **c flow**
  - model with final-state interactions underestimates the v_2 signal
  - the number-of-constituent-quark (n_q) scaling holds for $KE_T/n_q < 1$ GeV
- 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



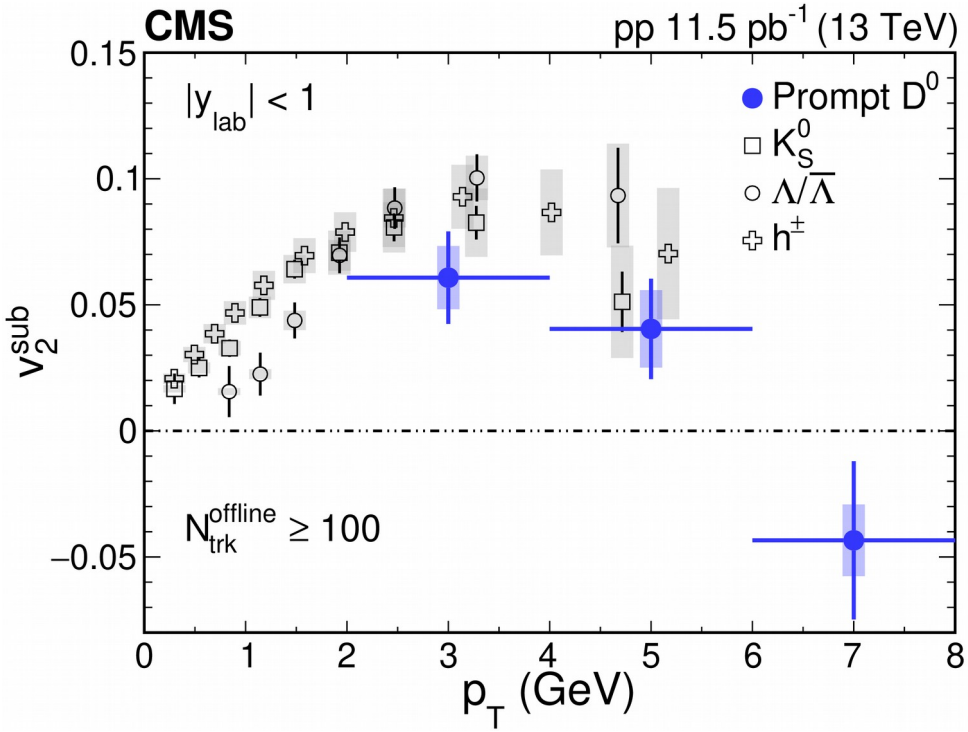
PLB **813** (2021) 136036

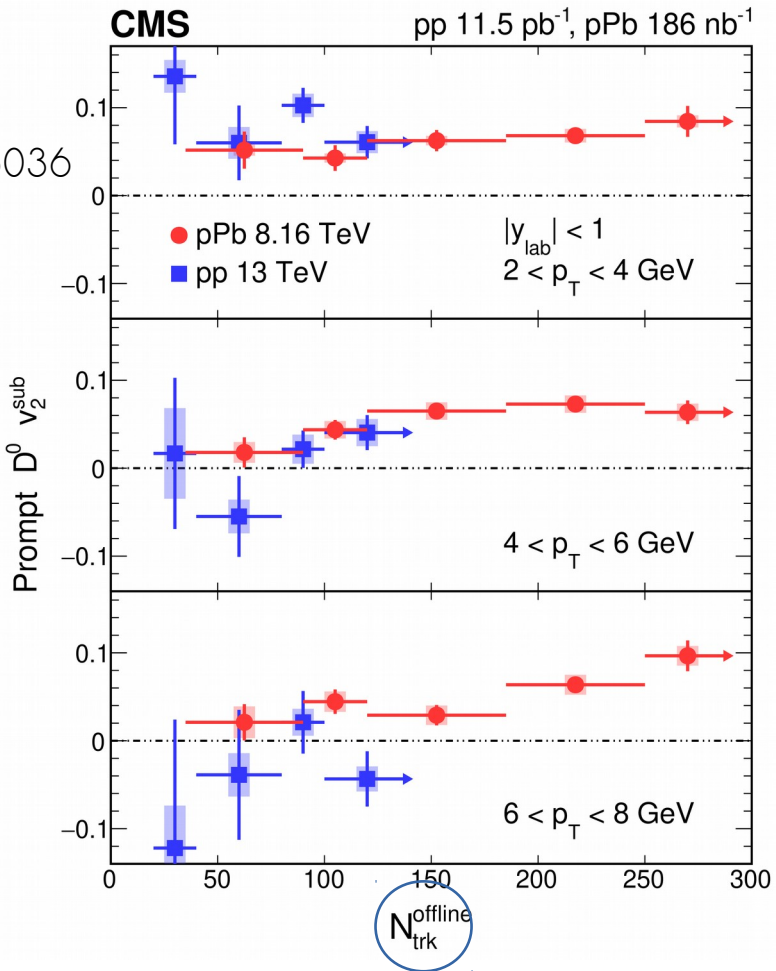


Measuring identified particle flow in pp

- **First** measurement of **c flow** with high-multiplicity events in pp
  - charm $v_2>0$ decreasing with p_T (similar to strange sector and charged hadrons)
  - no dependency on track multiplicity given the stat unc at low multiplicities
- No calculation yet available in the smallest systems

PLB **813** (2021) 136036

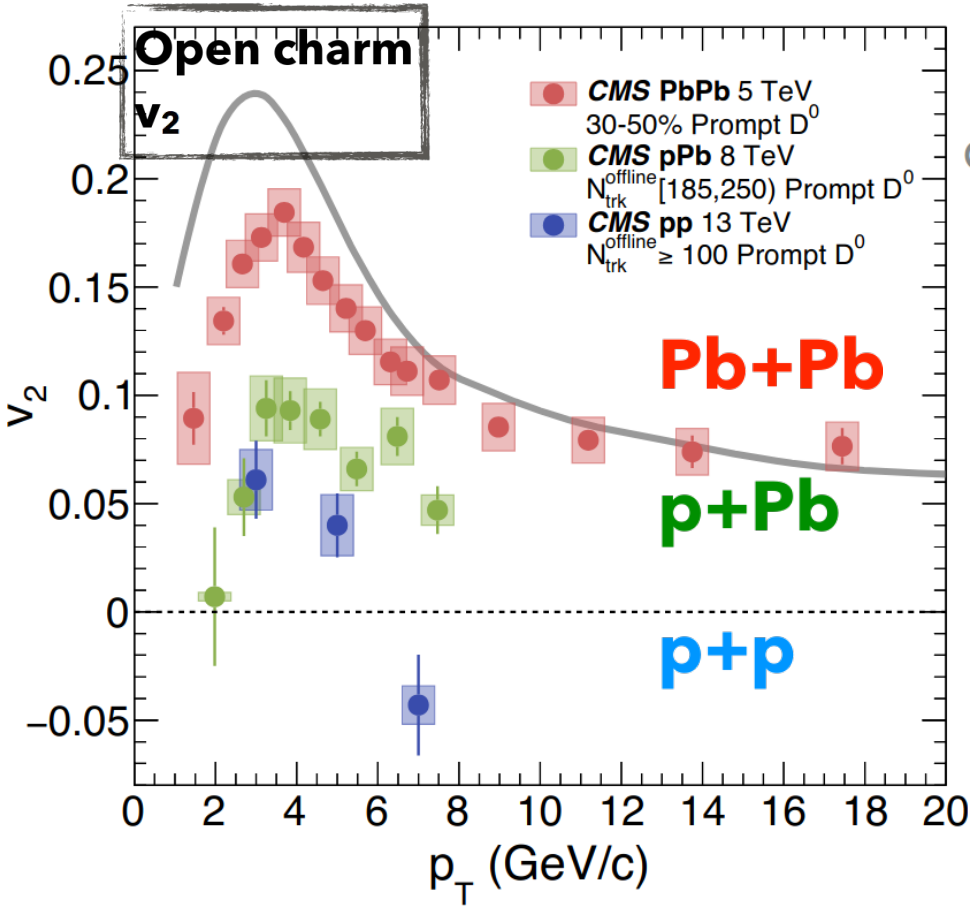


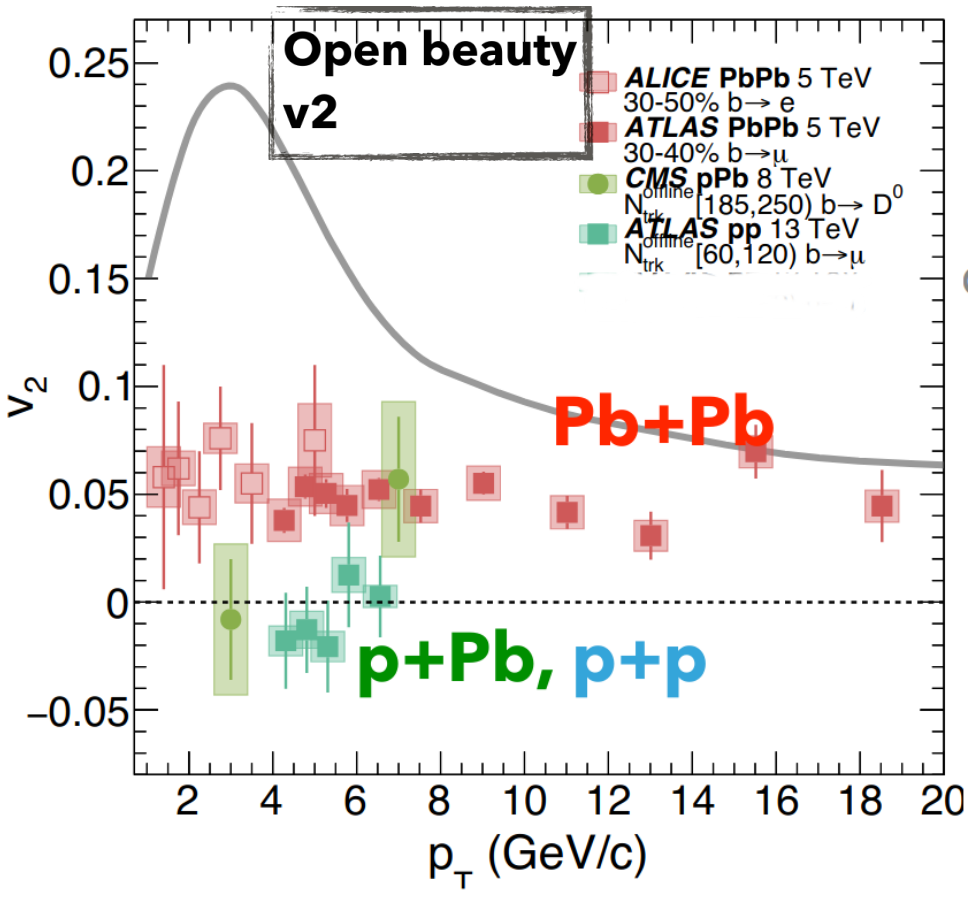


HF particle flow in all systems

- 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

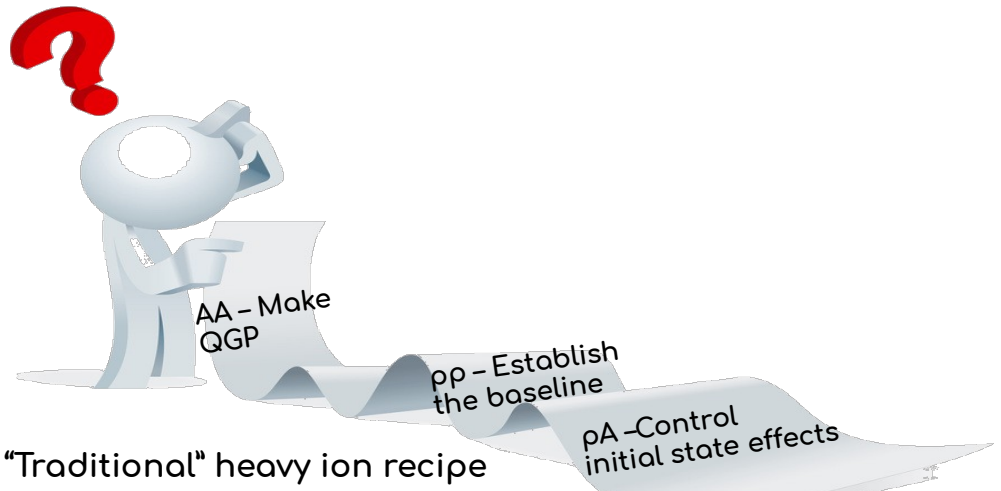
C. Mironov (HP2020)





Summary

- **Long-range angular correlations** in heavy ion (XeXe&PbPb) as well as high-multiplicity pPb&pp
  - are we missing a central component of particle production at LHC?
- Fourier harmonics v_n are extracted from two- and/or multiparticle correlations
- Detailed $\mathbf{v_n}$ measurements in XeXe & PbPb collisions
  - Flow cross-talk, fluctuations, and decorrelation **input to modeling** of initial conditions and QGP
- Identified particle and multiparticle correlation techniques support a **collective origin** of v_n
  - c quark flow is comparable to light quark whereas that of b quarks close to 0
- This isn't a **unique interpretation**, additional insight, e.g., from
  - flow correlations and process-dependent v_n

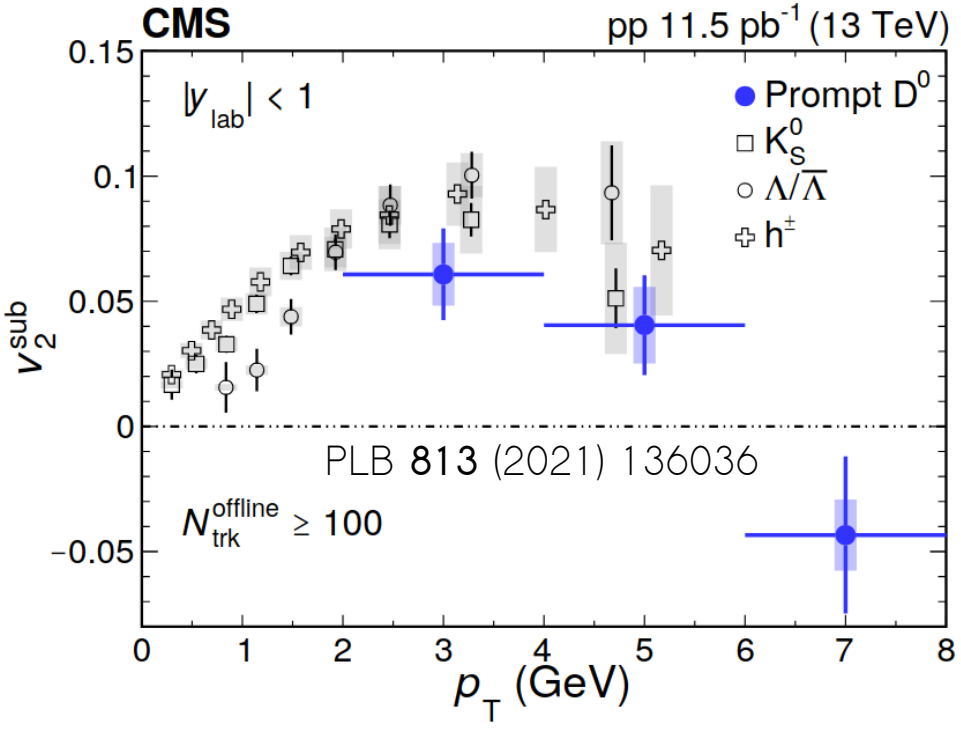


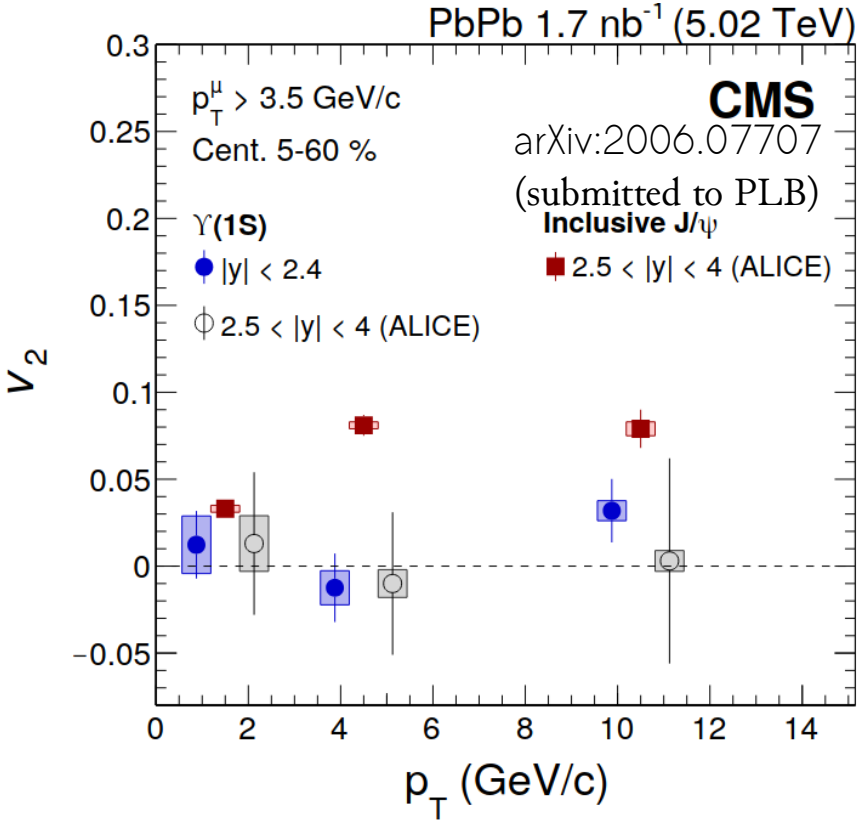
"Traditional" heavy ion recipe

slides

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

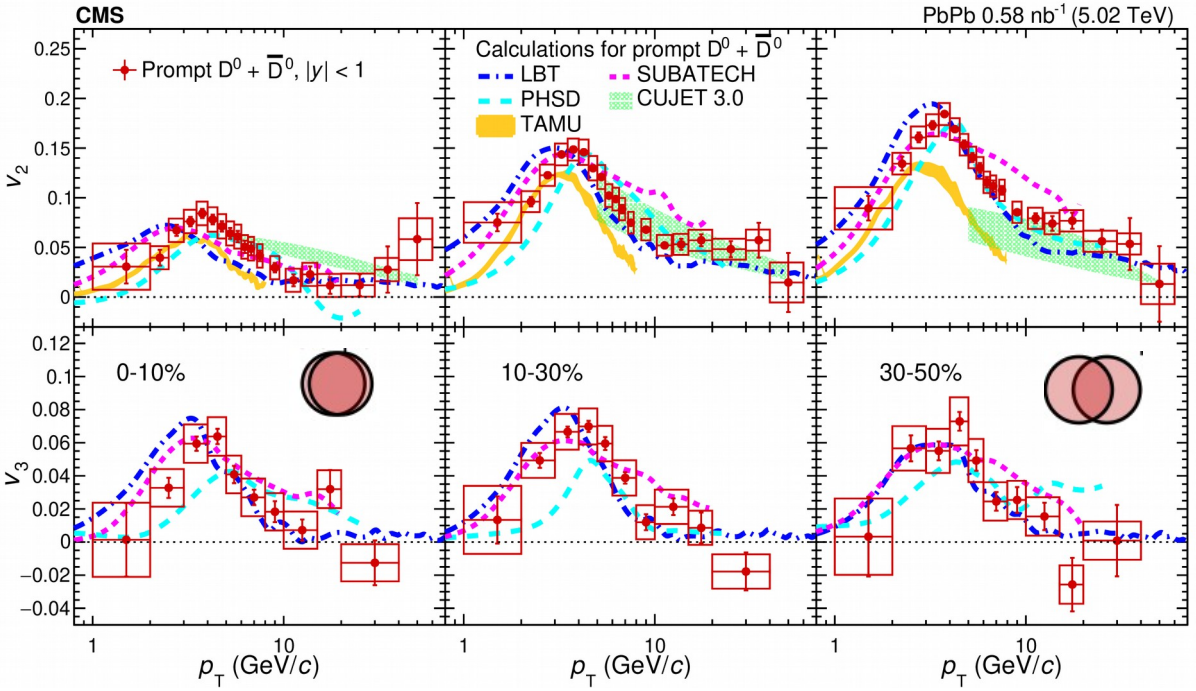


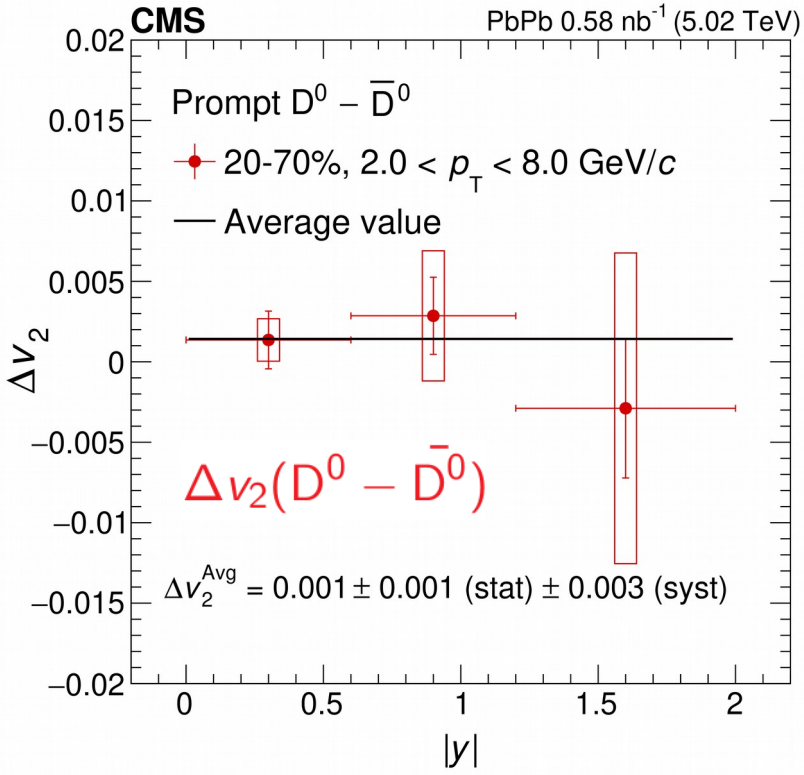


Prompt D^0 v_2 and v_3 in PbPb

- 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–$\bar{D}^0$)

PLB **816** (2021) 136253





Flow cross talk, fluctuations, and decorrelation

- "mixed" $v_{n\geq 4} \propto v_n + \chi (v_{m\leq n})^p$ and 2k-particle cumulants $c_n\{2k\}$ as a function centrality
  - models **cannot** describe well mixed v_n and the nonlinear coefficients χ
  - e.g., verification from $c_4\{4\}<0$ implying a **nonlinear** contribution to $v_4 \propto v_2^2$
- $c_n\{2k\}$ also provide information about the event-by-event v_n fluctuations
  - e.g., $c_n\{4\}$ change sign in **ultracentral** collisions → related to **centrality fluctuations**
- Models tuned to describe the transverse dynamics may not necessarily grasp the initial state **longitudinally**
  - XeXe vs PbPb dependence of flow "decorrelations" provides new insights into the dynamics of v_n

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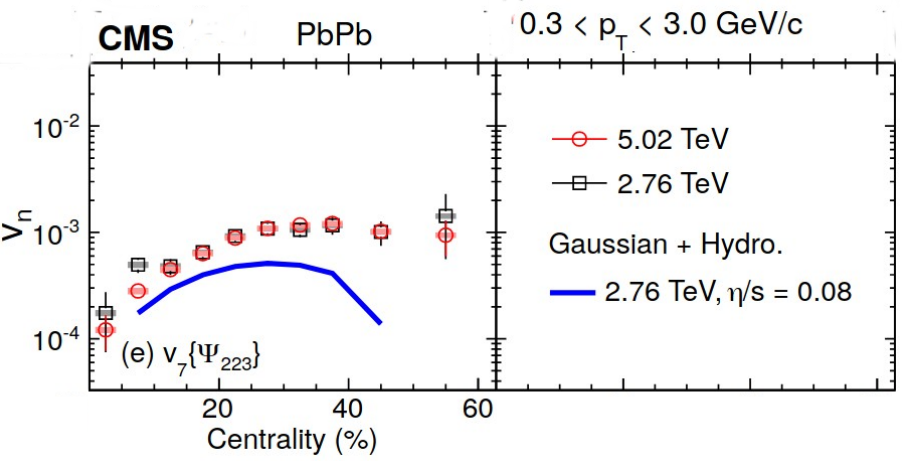
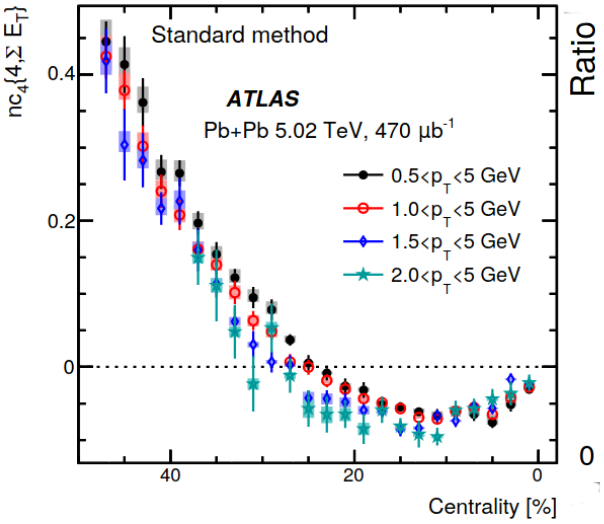
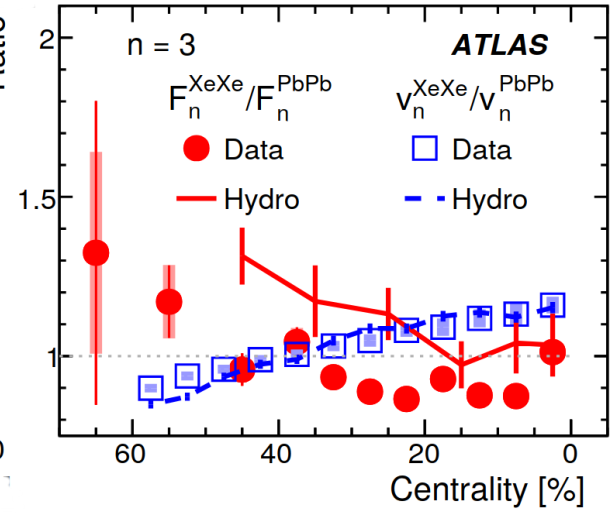


JHEP **01** (2020) 51

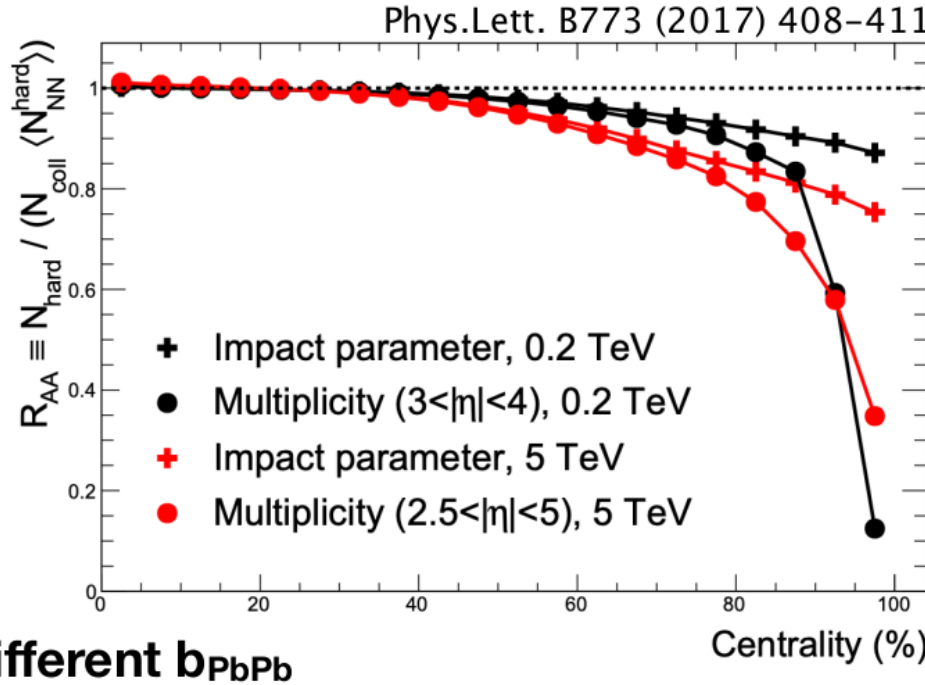


PRL **126** (2021) 122301



HG-PYTHIA

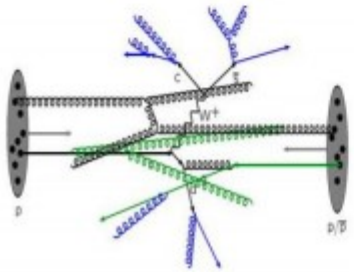
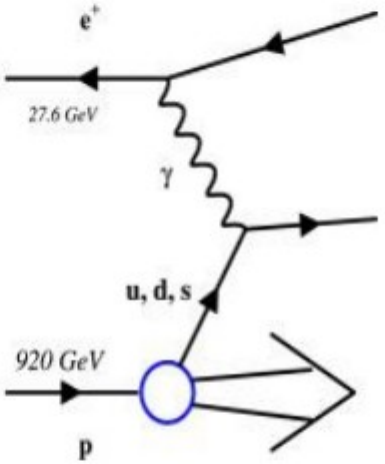
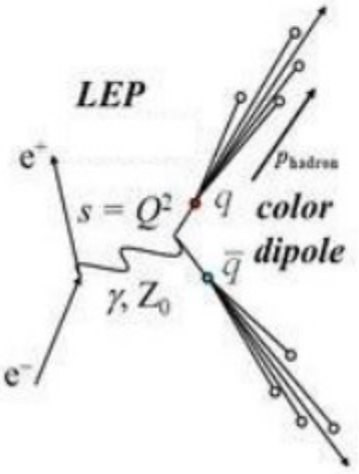
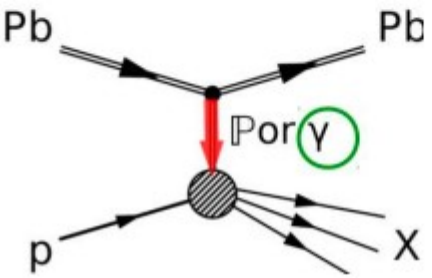
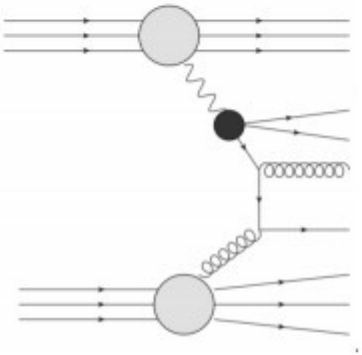
- Run HIJING to calculate N_{coll} and N_{MPI}
- Superimpose N_{coll} Pythia MB events that have the same number of MPIs
  - These events have no QGP physics
- Perform a centrality calibration
- Plot R_{AA} by comparing to cross section from pp collisions



- Geometry biases - $\langle b_{NN} \rangle$ can be biased for different b_{PbPb}
- Centrality selection bias - correlations in hard/soft production can cause migration of event with hard processes to higher centrality
  - Leads to depletion in peripheral events

Which small systems do we know flow?

B. Seidlitz

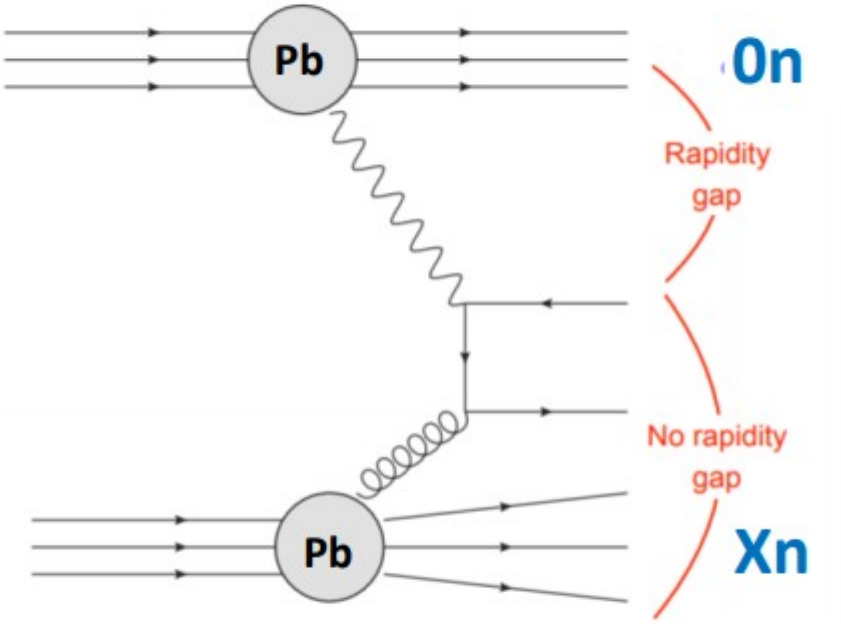
pp	e+*p*	$e^+ + e^-$	γ+*p*	γ+A
				
				
Near-side ridge	Cumulants say v_2< 5%	No near-side ridge		
	arXiv:1912.07431	arXiv:1906.00489		

Photonuclear interactions

B. Seidlitz

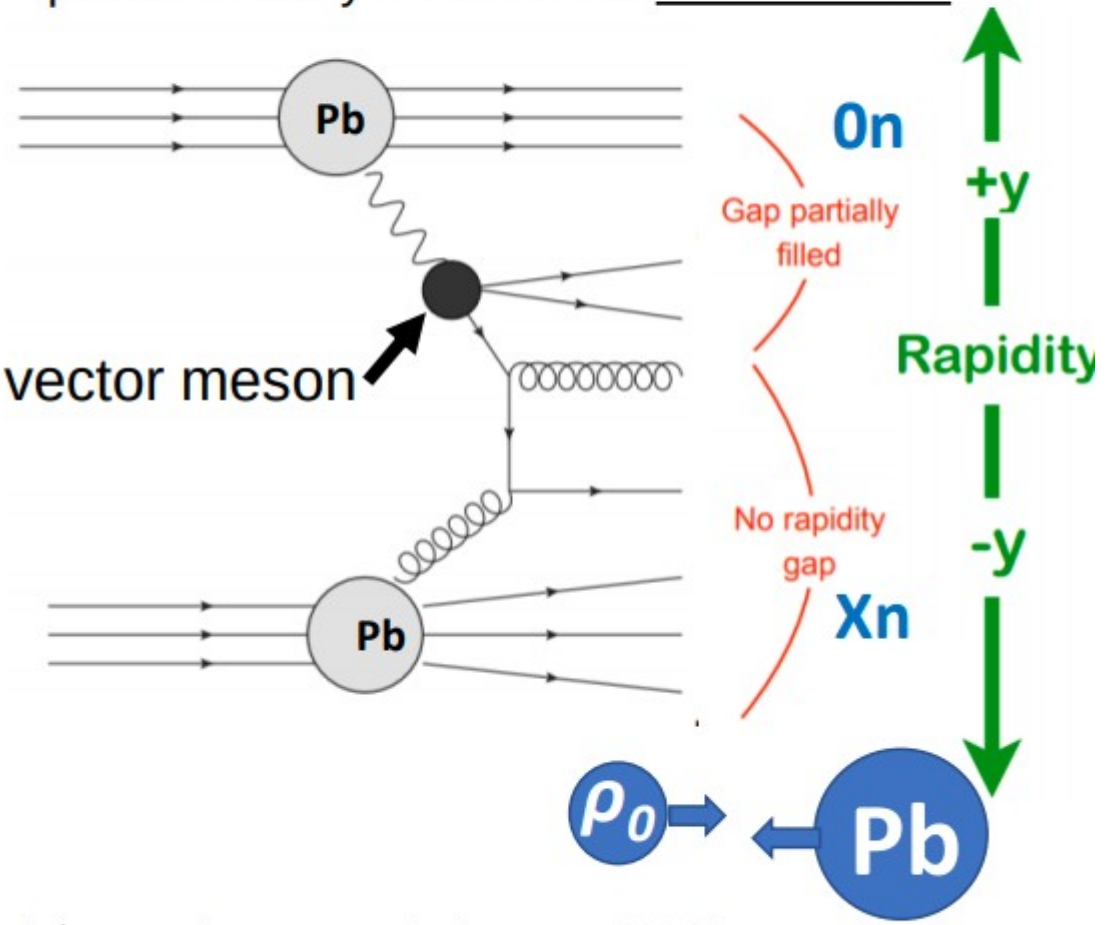
Direct γA collisions

Photon couples directly to nuclear parton



Resolved γA collisions

photon virtually resolved into hadronic state



Select events based on primarily

- Single-sided nuclear breakup "**0nXn**" (zero-degree calorimeter ZDC)
- Rapidity gaps

Minimum bias selection includes both but is dominated by resolved events.