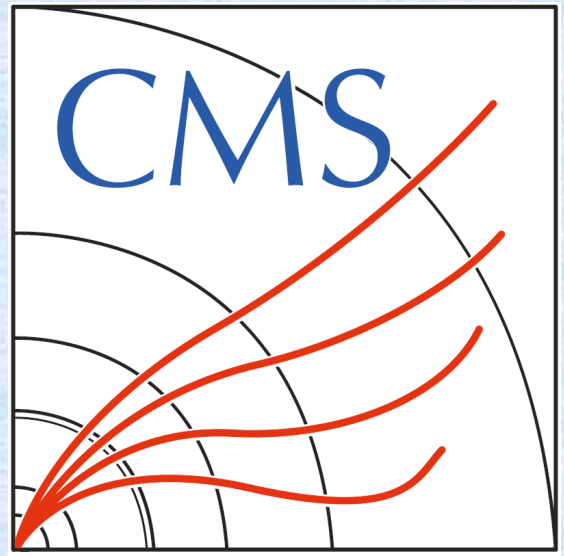
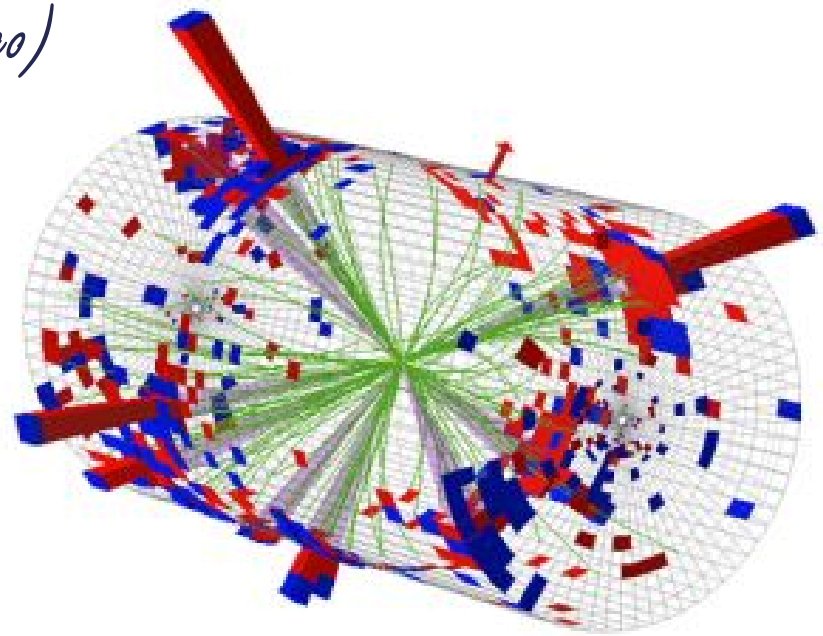


Recent Heavy-Ion Physics Results

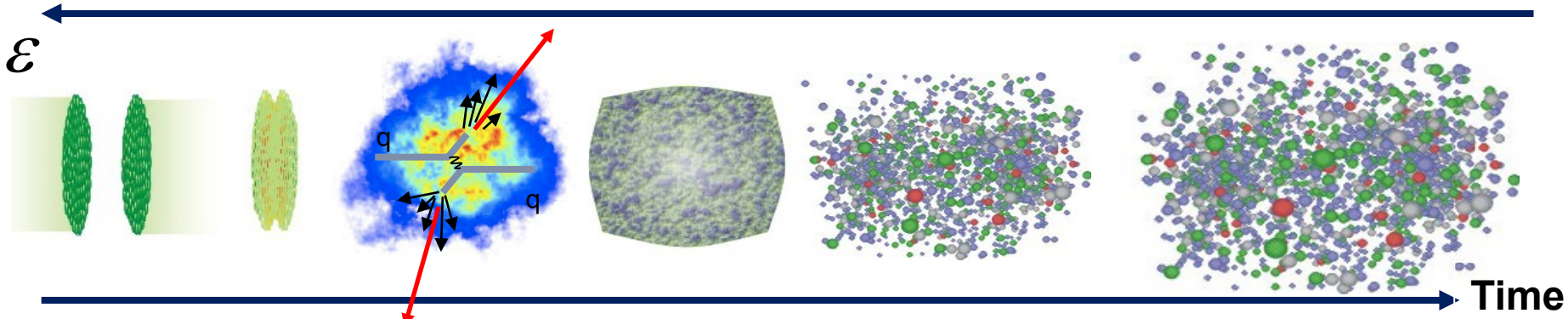
Olga Evdokimov (University of Illinois at Chicago)

For the CMS Collaboration



Introduction:

20+ years of QGP exploration on a quest to understand the strong force and confinement by creating a system of deconfined colored quarks and gluons

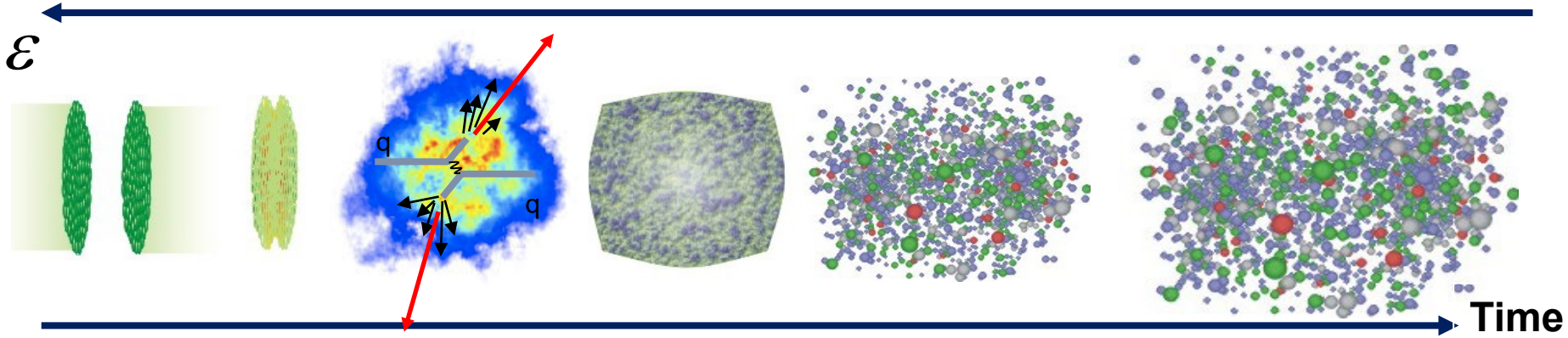


Experimental evidence of QGP formation in light hadron data:

- Initial medium temperature is well above predicted T_c
- The final system appears to be in thermal equilibrium, and is very explosive
- Medium evolution is well-described by near-ideal hydrodynamics
- Constituent quark degrees of freedom are important at hadronization

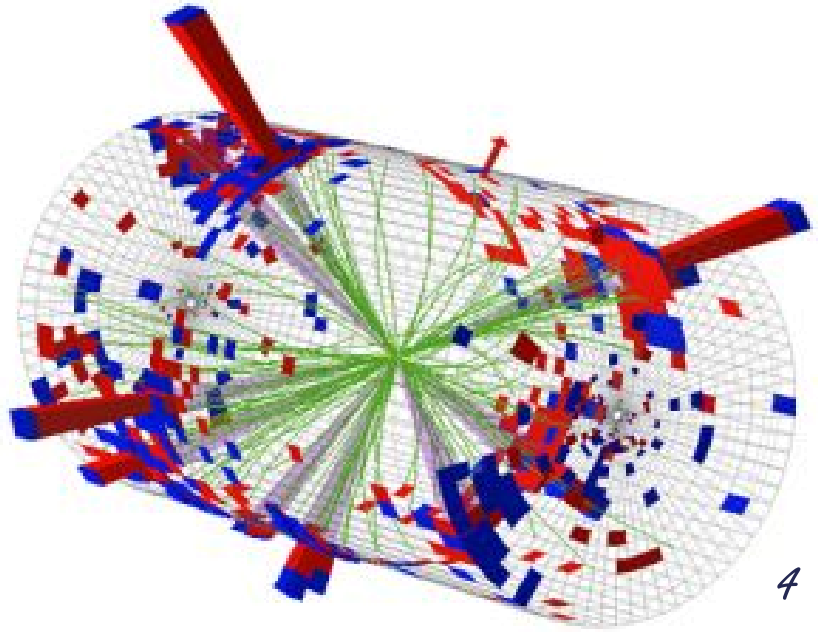
- Wealth of new experimental results hones the detailed understanding of medium properties and collision dynamics

Outline:

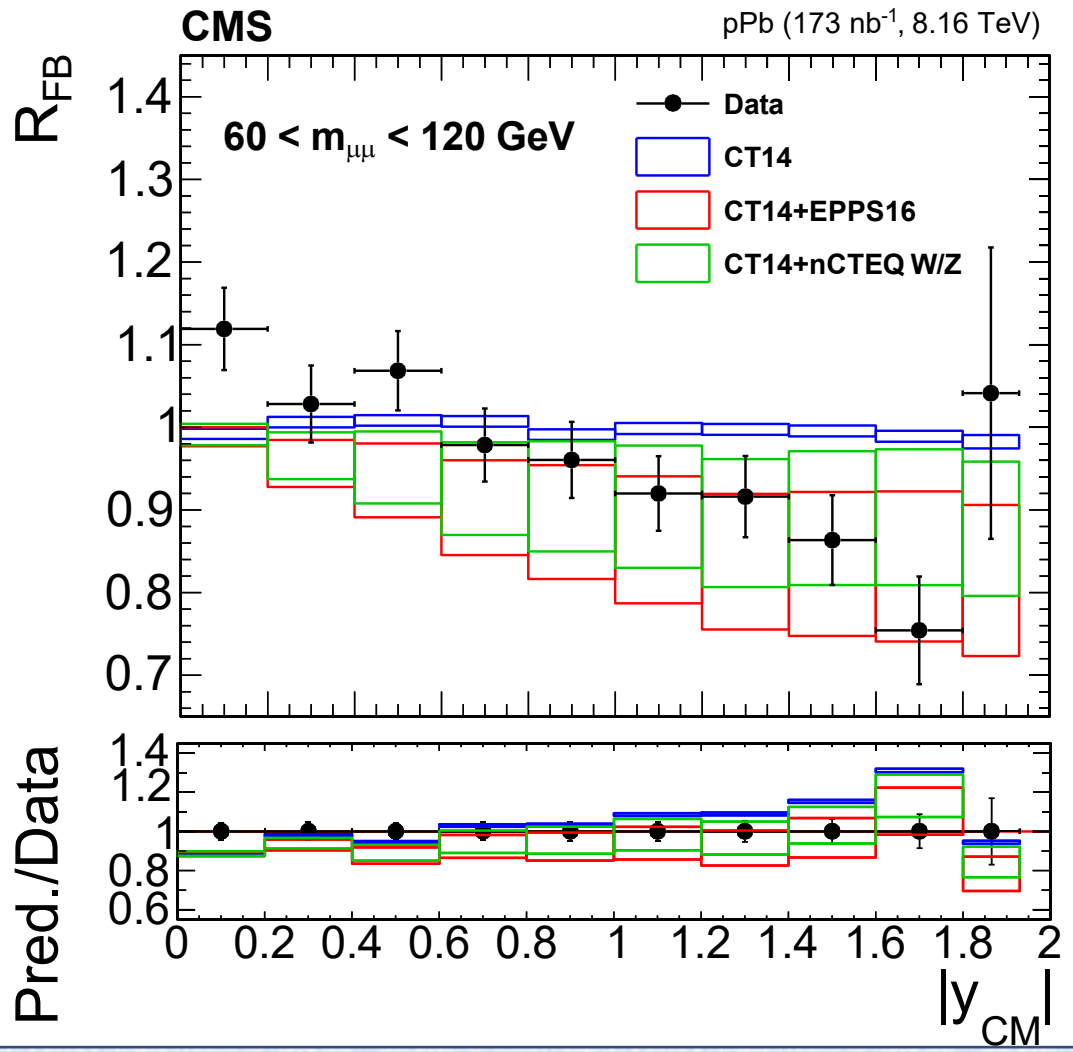


- A (biased) selection of recent experimental results from CMS on:
  - Initial state properties
  - Medium effects on hard probes: heavy flavors and jets
  - New insights on hadronization
  - Ultra-peripheral collisions: QED meets QCD

Initial State and Flow Fluctuations



Nuclear PDFs with Drell-Yan



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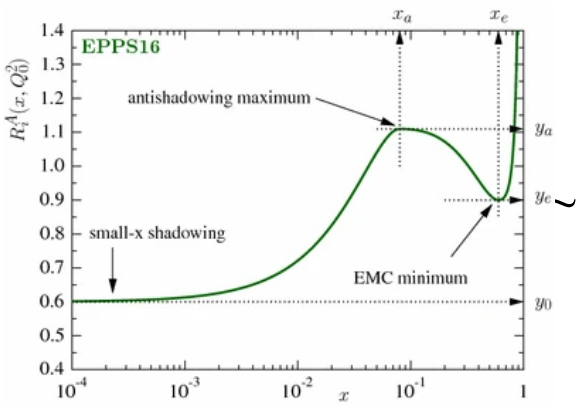
- Forward/Backward ratio for 8TeV pPb

$Z/\gamma^* \rightarrow \mu\mu$

Access small x domain with $m_{\mu\mu}$ down to 15 GeV



$x \sim m_{\mu\mu}\ e^{-y_{CM}}$

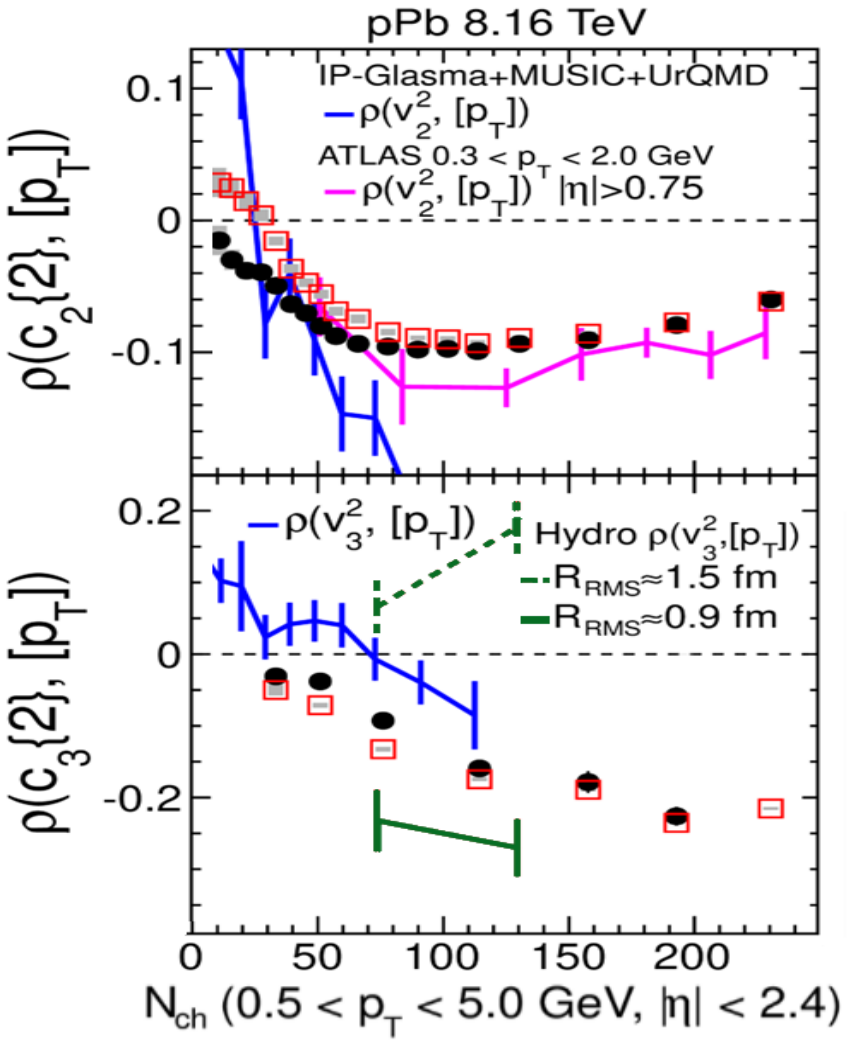
~ shadowing/anti-shadowing

Data favor nPDF (EPPS16, nCTEQ) over proton PDF

Uncertainties:

Experimental < Theoretical

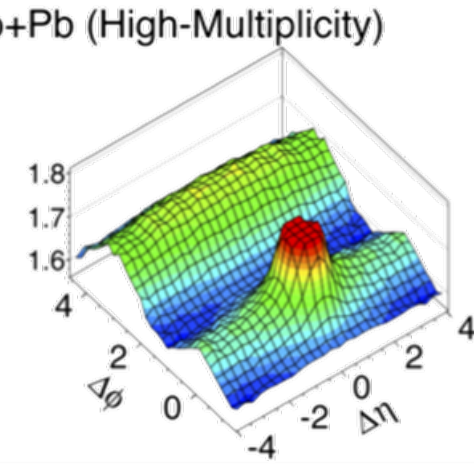
Initial state through correlations



CMS-PAS-HIN-21-012

Origins of collectivity in small systems can be explored through correlations between average p_T and multiparticle cumulants:

- v_2-p_T: sign change with N_{ch} (due to initial momentum anisotropy predicted by CGC):
  - Could be seen in the data but disappear with large pseudorapidity gap
  - Measurements are sensitive to nonflow effects
- v_3-p_T: no sign change
- Model comparisons:
  - IP-Glasma+MUSIC+UrQMD
  - Hydro



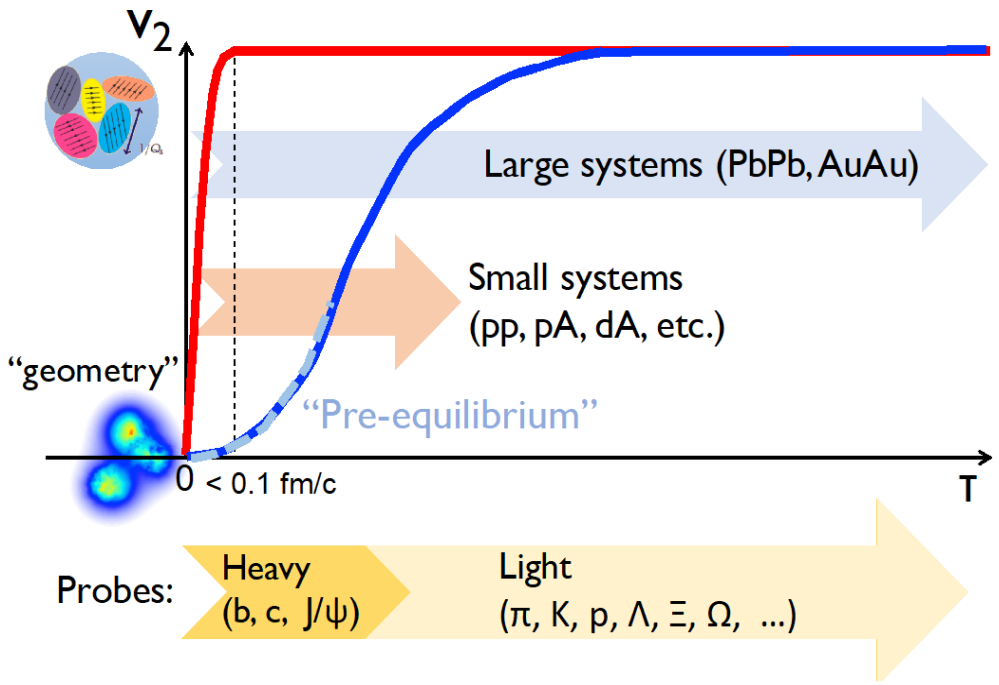
Collectivity in small systems

PLB 813 (2021) 136036

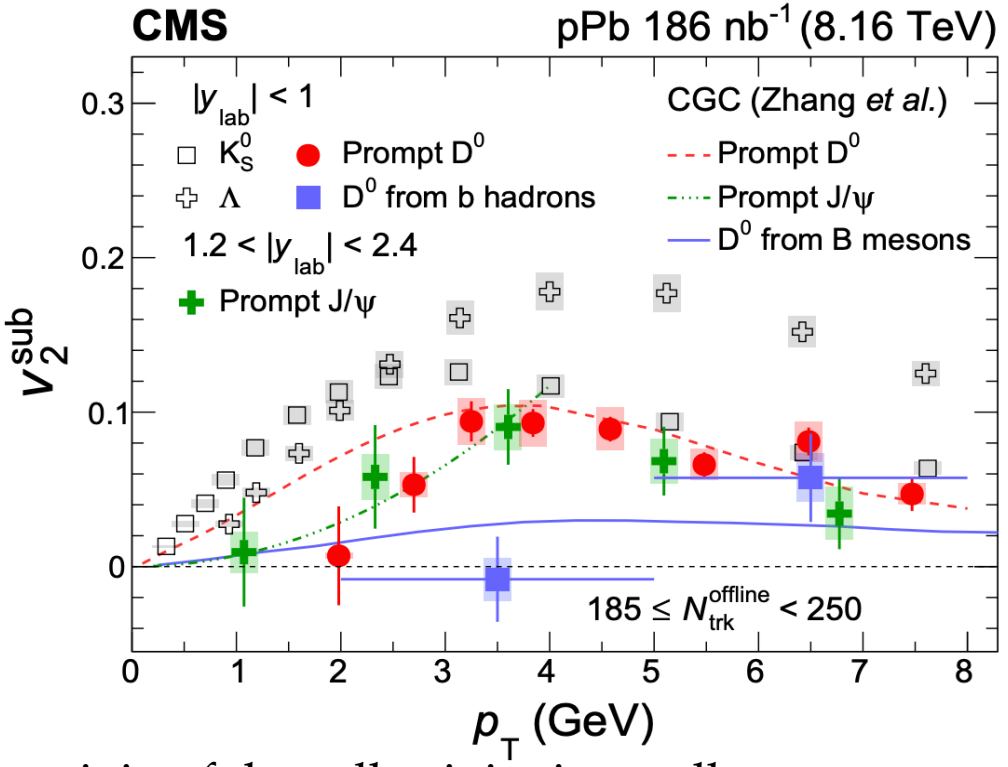
Initial-state collectivity
(initial color fields)

OR

Final-state collectivity:
("geometry" + rescatterings)

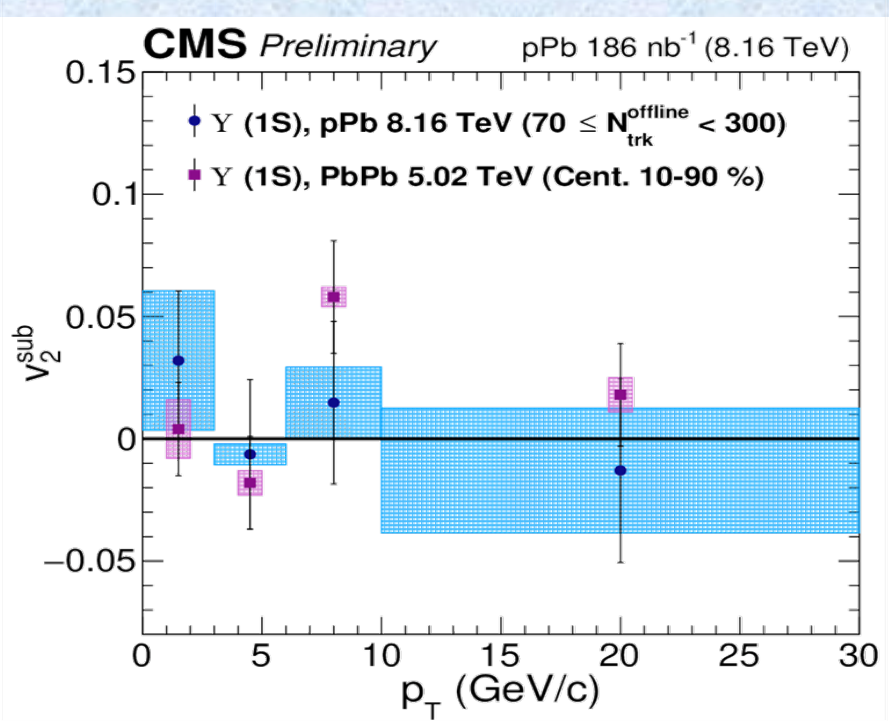


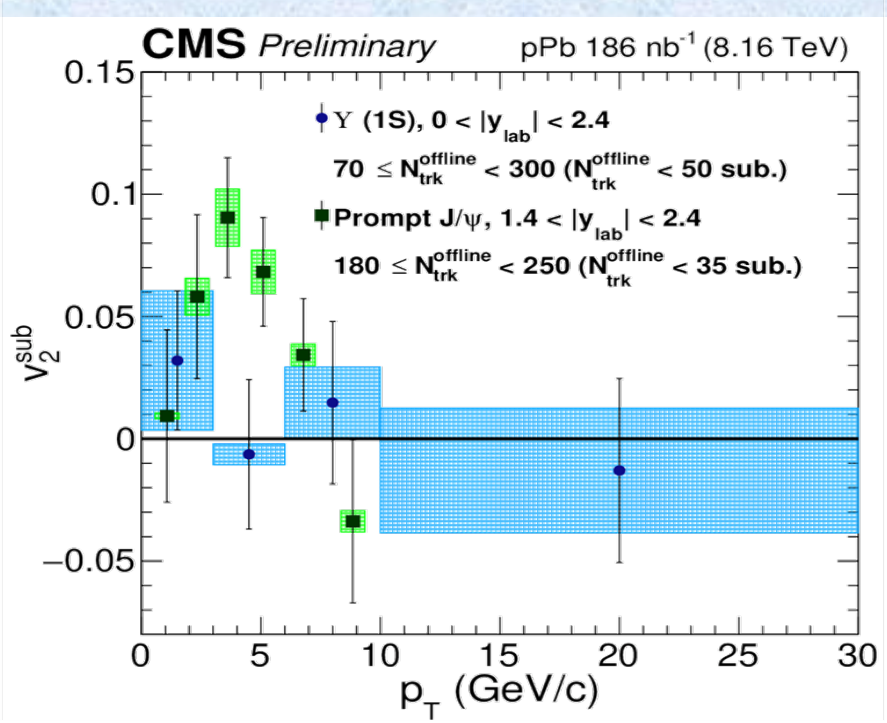
Collectivity of light and heavy flavor hadrons in pPb



- Heavy flavor collective dynamics can shed light of the origin of the collectivity in small systems
- Future high precision measurements will provide definitive input on the origins of collectivity

Collectivity in small systems



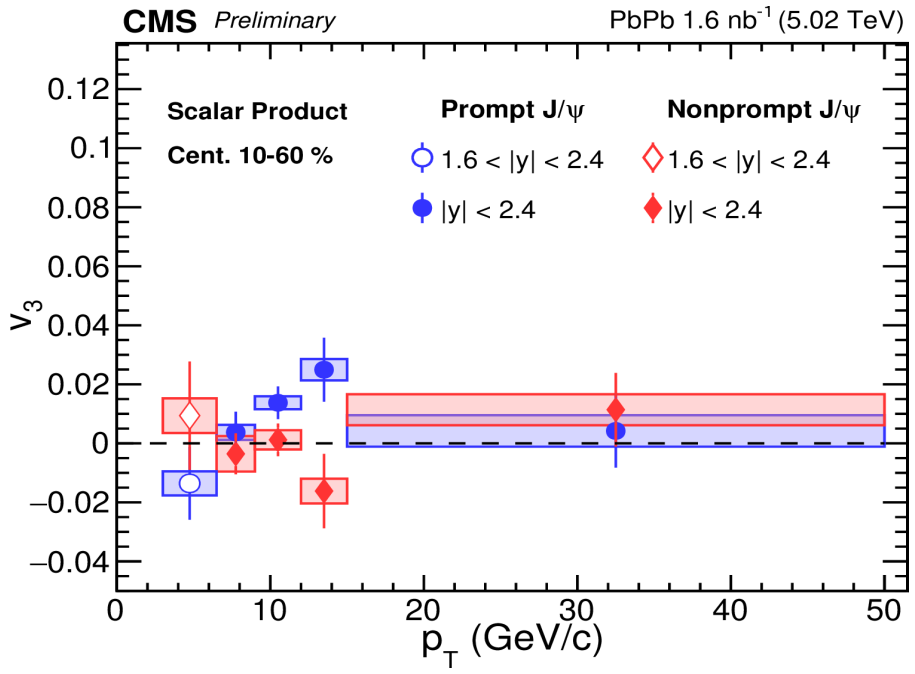


CMS-PAS-HIN-21-001

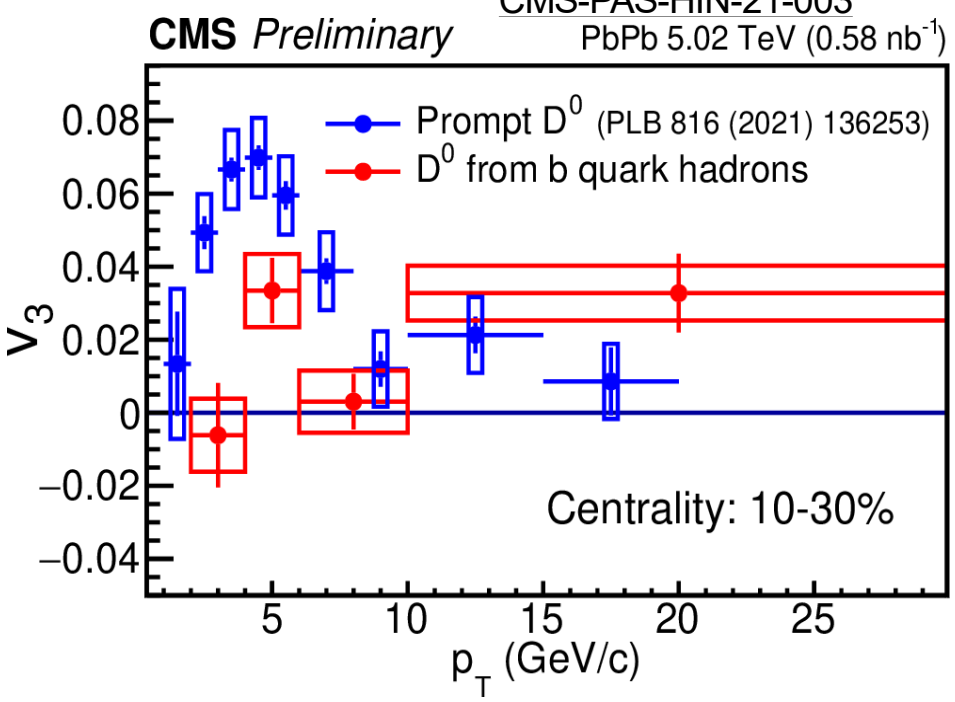
- New results on Y(1S) flow in 8 TeV pPb: no significant v_2 even in high multiplicity events. Similarly, no significant v_2 was seen in PbPb
- The expectation of similar v_2 for Υ and J/ψ (CGC) seem not to be favored by the data
- No sensitivity to initial geometry for Υ measurements with current precision

Initial state HF probes for PbPb

CMS-PAS-HIN-21-008

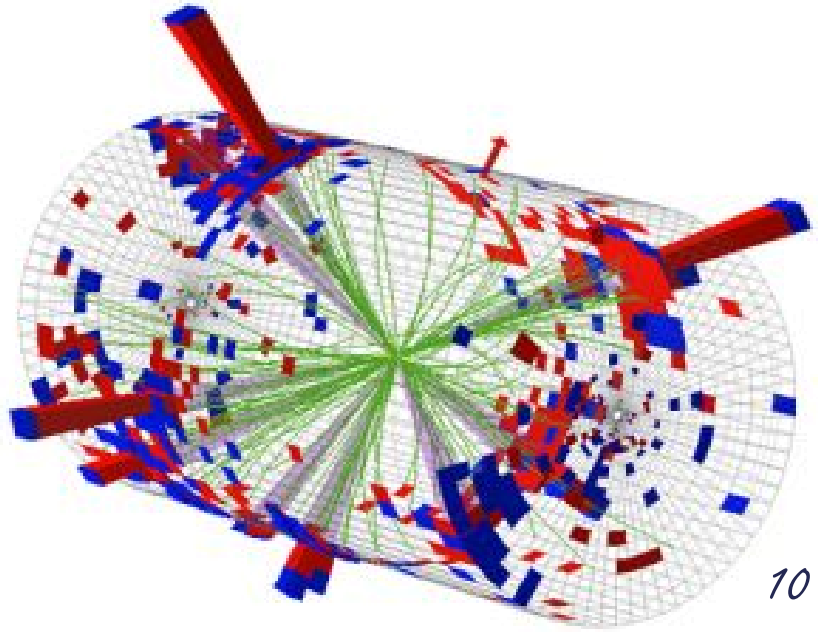


CMS-PAS-HIN-21-003



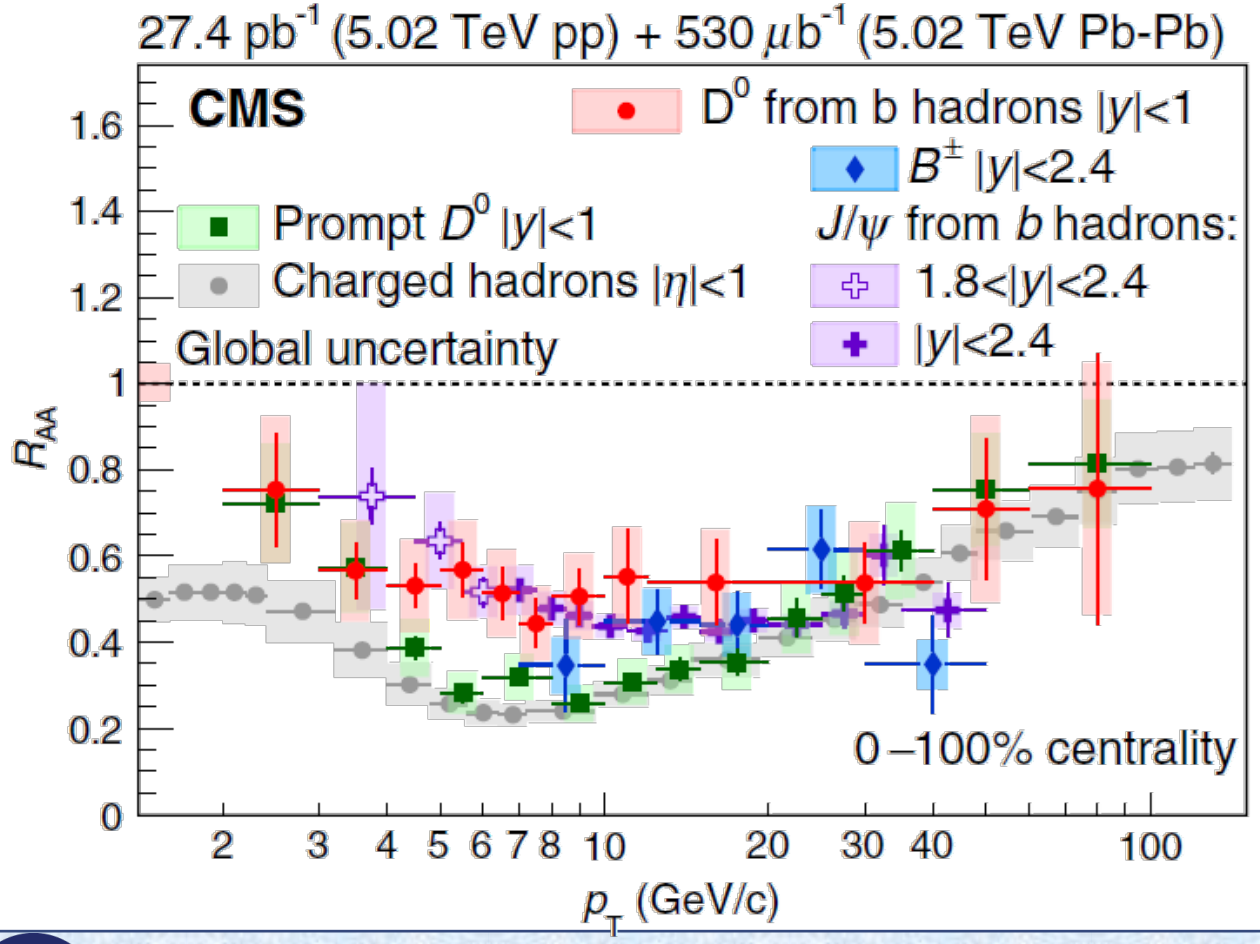
- Prompt components: $v_3(D^0) > v_3(J/\psi)$ – expected hierarchy if light quarks are more sensitive to initial state fluctuations than charm
- Non-prompt components: similar v_3 for $b \rightarrow D^0$ and $b \rightarrow J/\psi$?
- Smaller v_3 for non-prompt components – less sensitivity to fluctuations for bottom than charm?

QGP effects on heavy quarks



Heavy Flavor R_{AA} at LHC

PRL 123(2019)022001

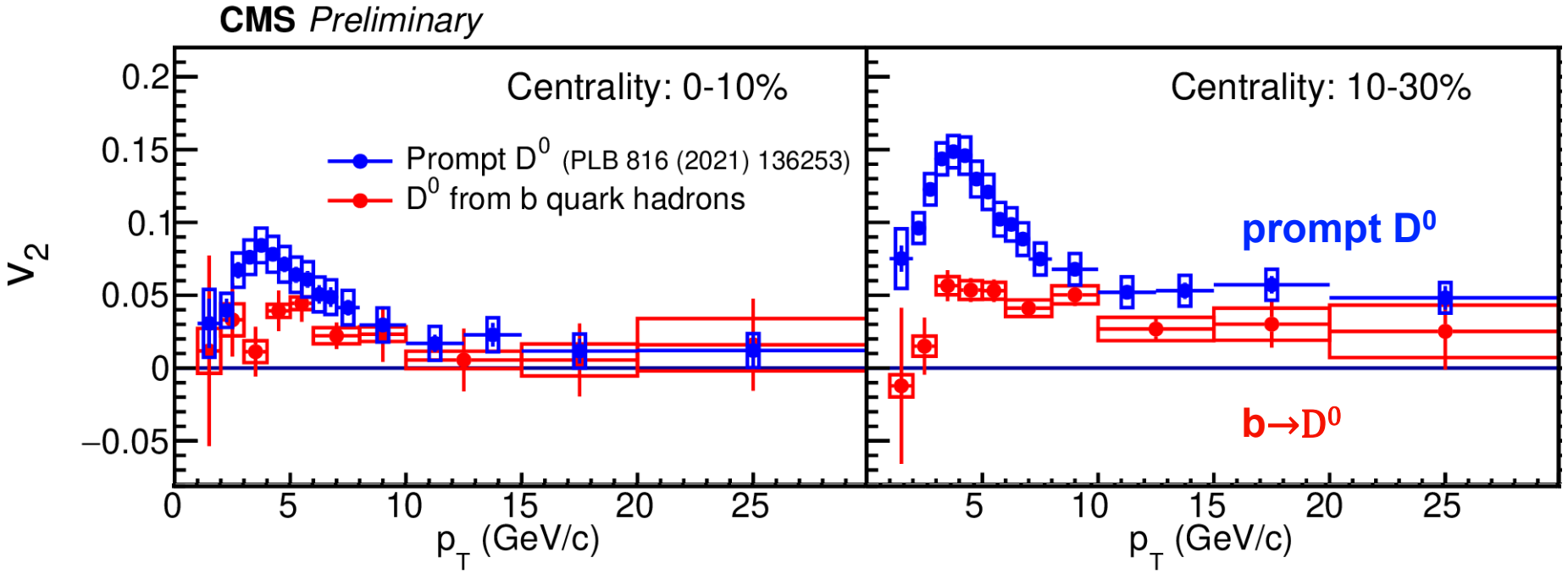


- Nuclear modification for prompt- and non-prompt D^0 , non-prompt J/ψ, $B^{\pm}$
- Mid-p_T : flavor dependence of energy loss
  - $R_{AA}(b) > R_{AA}(c) \sim R_{AA}$(light flavors)
- High p_T : radiative energy loss dominates
  - $R_{AA}(b) \sim R_{AA}(c) \sim R_{AA}$(light flavors)
- What about v_2 ?

Heavy flavor anisotropies

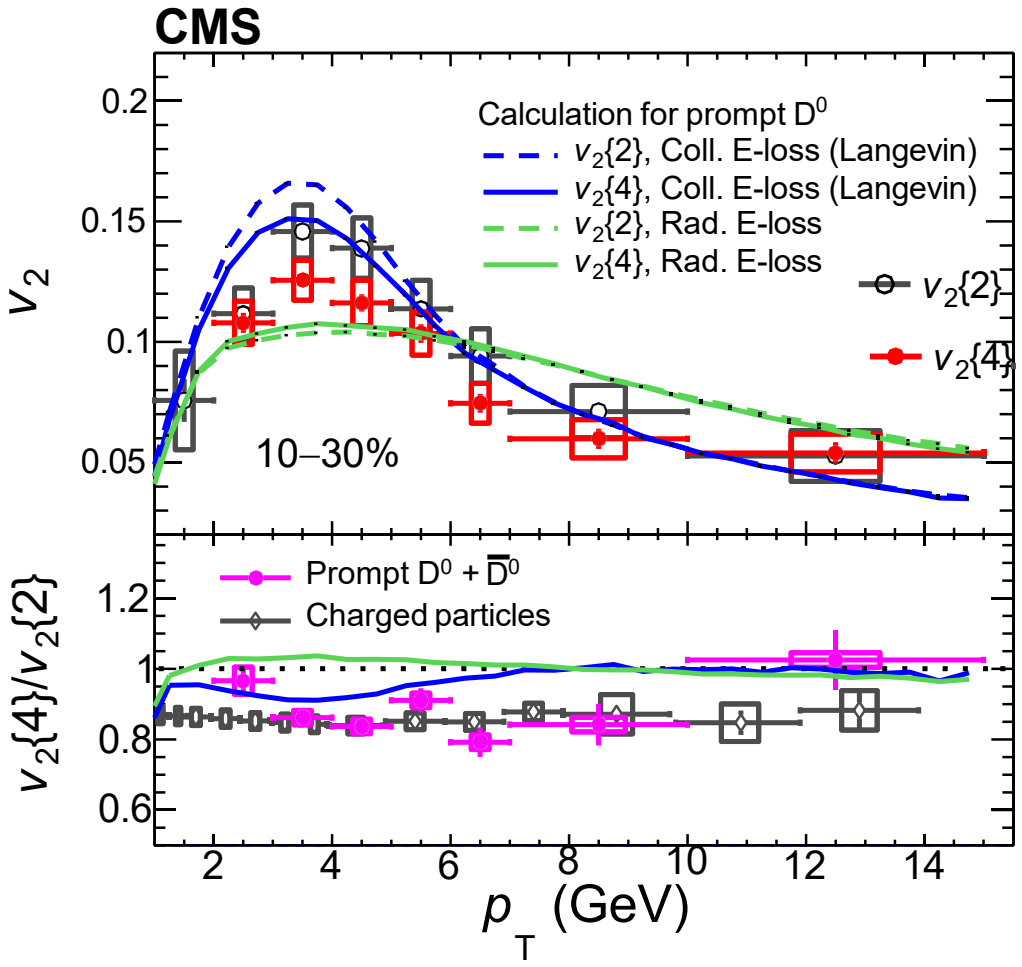
- D-meson flow measurements

CMS-PAS-HIN-21-003



- Significant v_2 for prompt and non-prompt D^0
- Initial raise consistent with hydro expansion; high p_T – path-length dependence of energy loss
- Higher degree of parton-medium coupling for charm than bottom

A different look at fluctuations



PRL 129 (2022), 022001

- Charm flow with (prompt) D^0
  - Prompt D^0 flow patterns are similar patterns to charged hadrons (but different magnitude) – PLB 816 (2021) 136253
- What about event-by-event fluctuations?

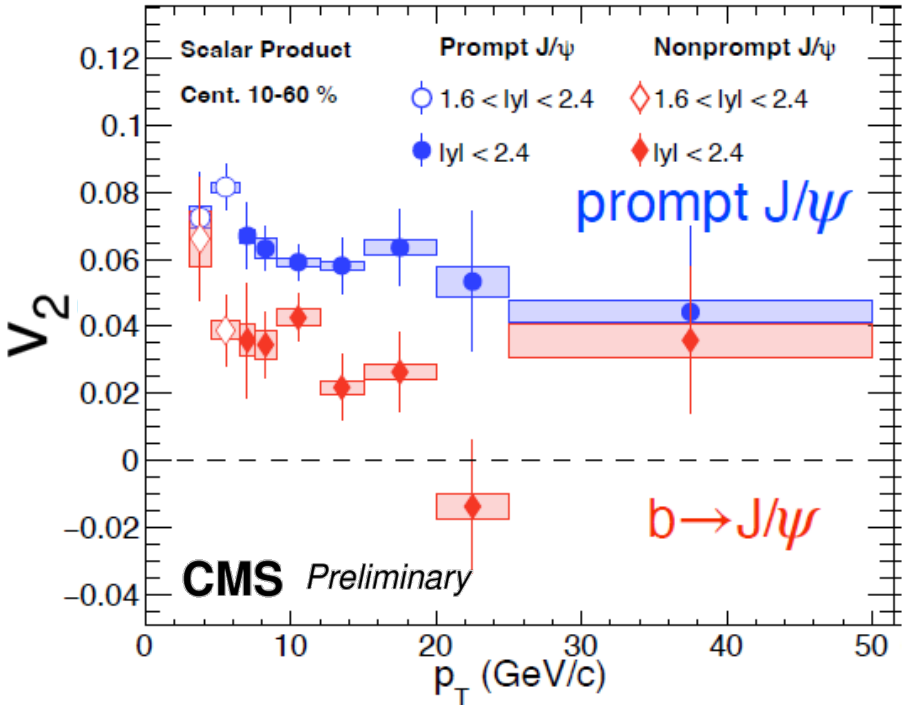
$$v_2\{4\} \;/\; v_2\{2\}$$

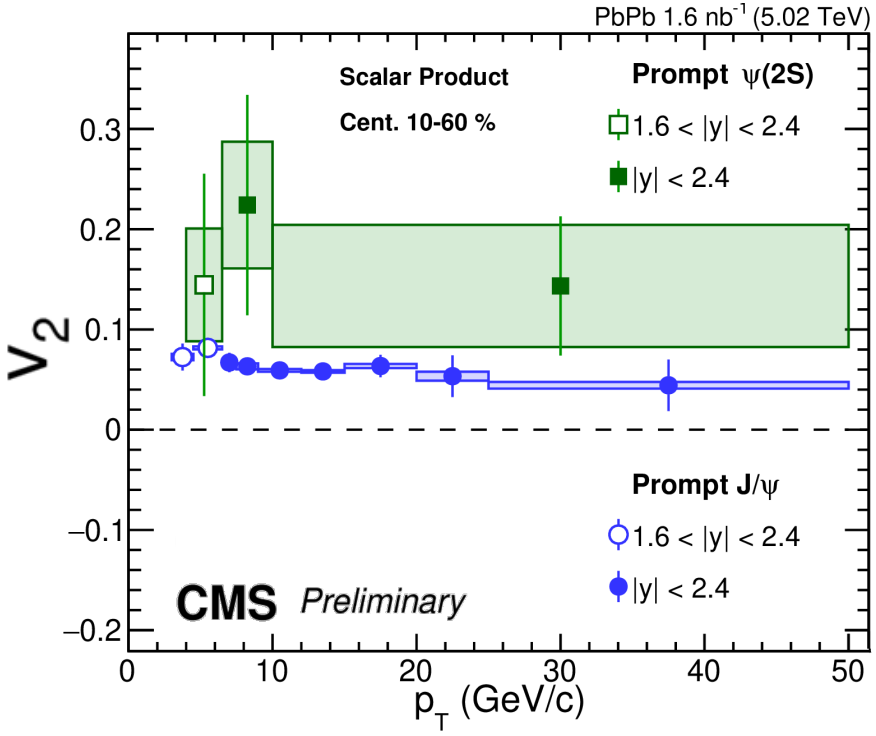
- Similar fluctuations for D^0 and charged hadrons?
- Inclusion of collisional energy loss allows to reproduce data trends better

Heavy flavor anisotropies

- What about quarkonia? Everything "flows"!

CMS_PAS-HIN-21-008



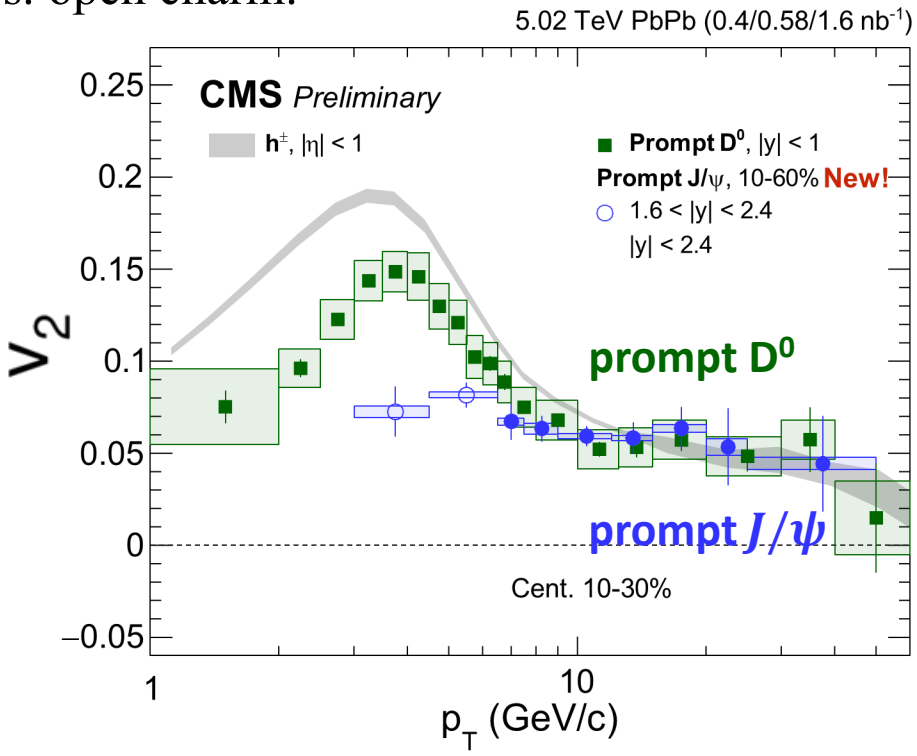


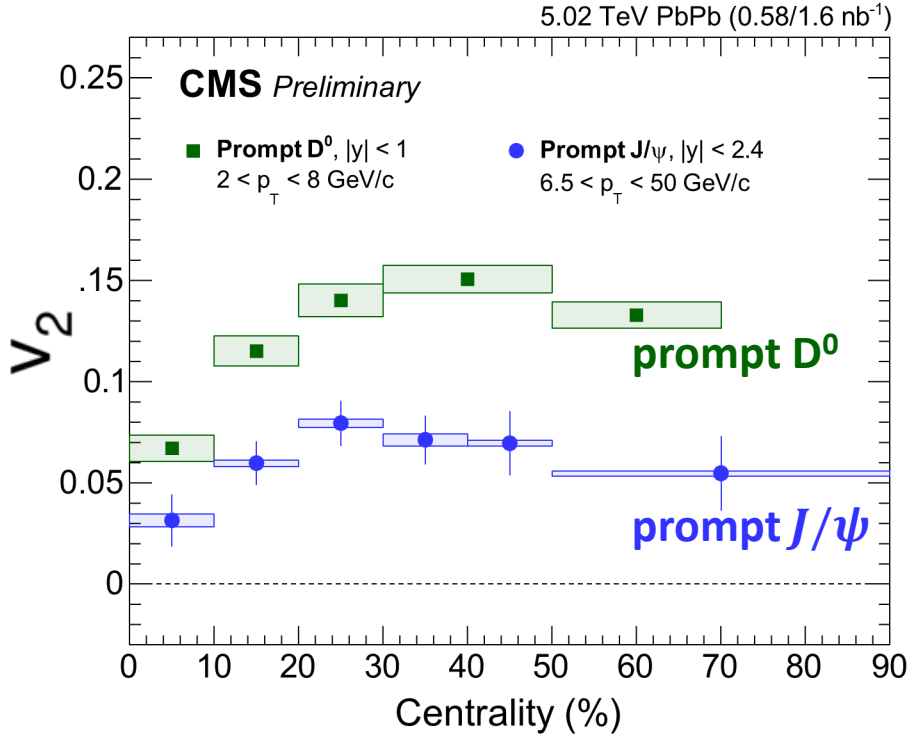
- Prompt J/ψ: significant v_2 up to high p_T; b → J/ψ: smaller v_2, high p_T behavior?
- Stronger (?) v_2 for prompt $\psi(2S)$ – difference in regeneration contributions?

Heavy flavor anisotropies

CMS-PAS-HIN-21-008
PLB 816 (2021) 136253

- Hidden vs. open charm:

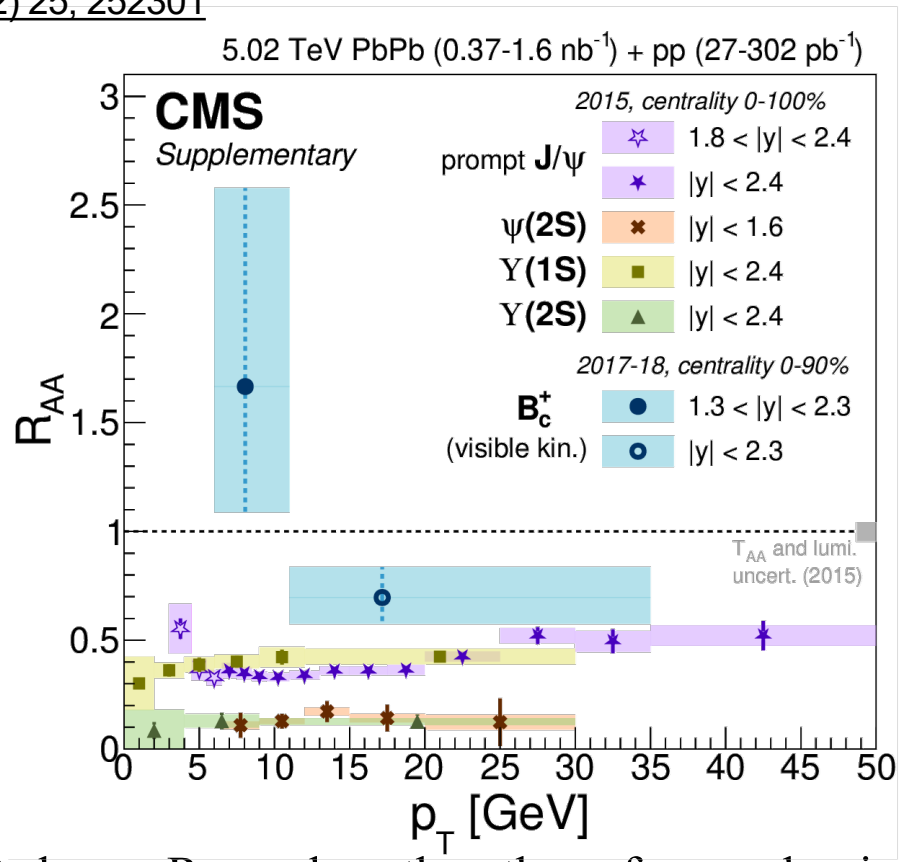




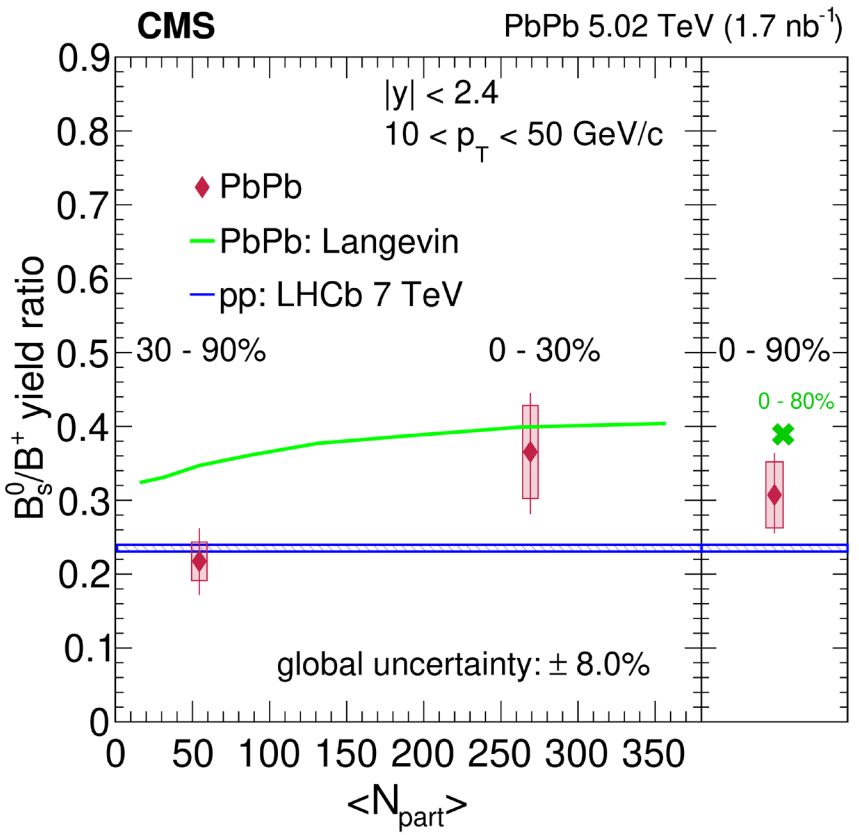
- High p_T – no mass dependence; path-length dependent energy loss
- Low p_T: $v_2(h^{\pm}) > v_2(\text{prompt } D^0) > v_2(\text{prompt } J/\psi)$ – constituent quark differences? Recombination!

Evidence for recombination in HF yields

PRL 128 (2022) 25, 252301



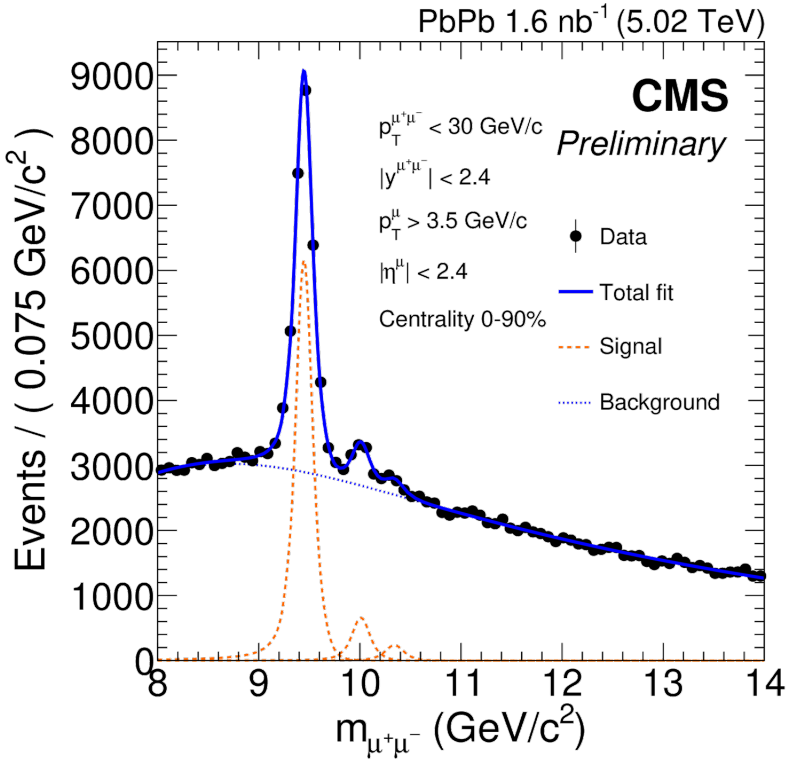
PLB 829 (2022) 137062

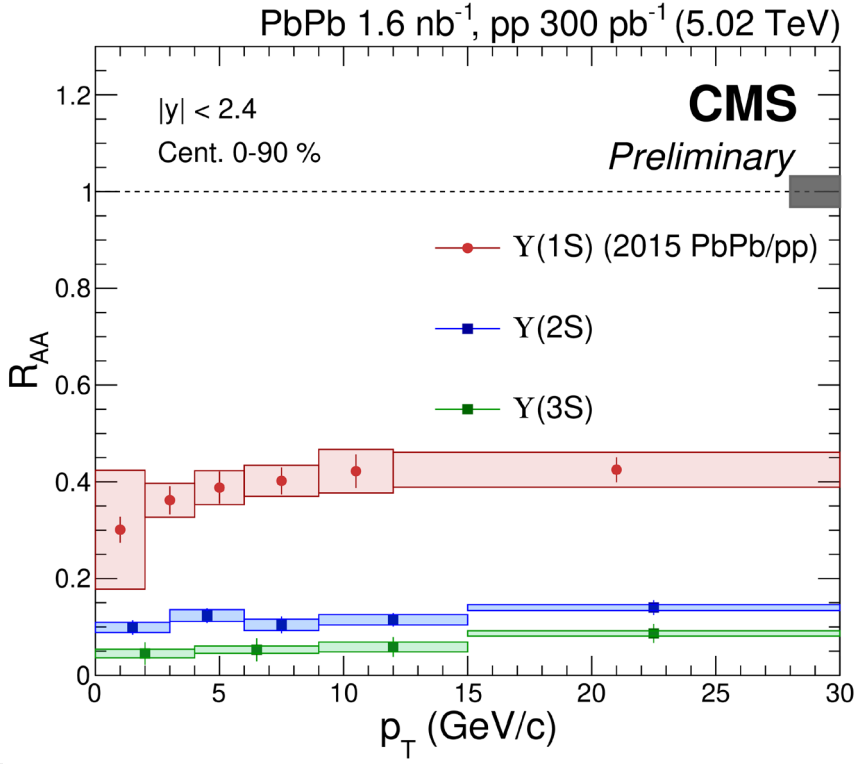


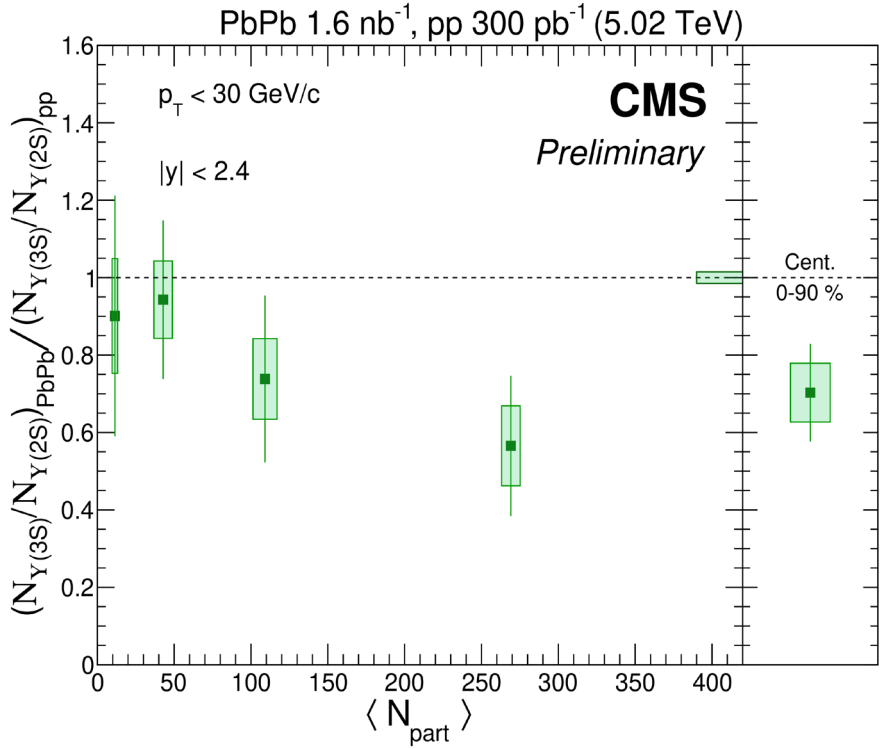
- B_c ($\bar{b}c$): larger R_{AA} values than those for quarkonia (particularly at most relevant for coalescence lower p_T)
- B_s($\bar{b}s$) vs. B+ production: enhancement in more central collision (where strangeness production is most enhanced)

Quarkonia Melting

CMS-PAS-HIN-21-007

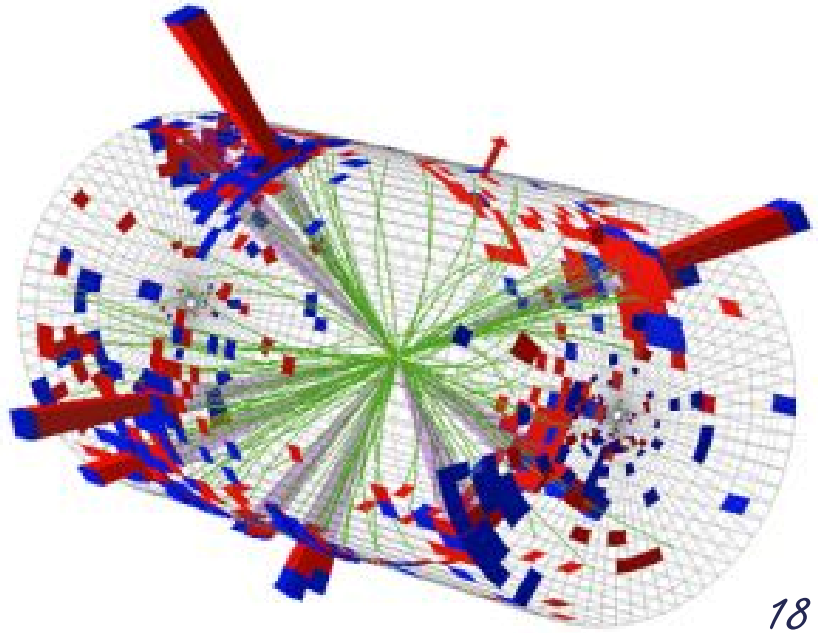




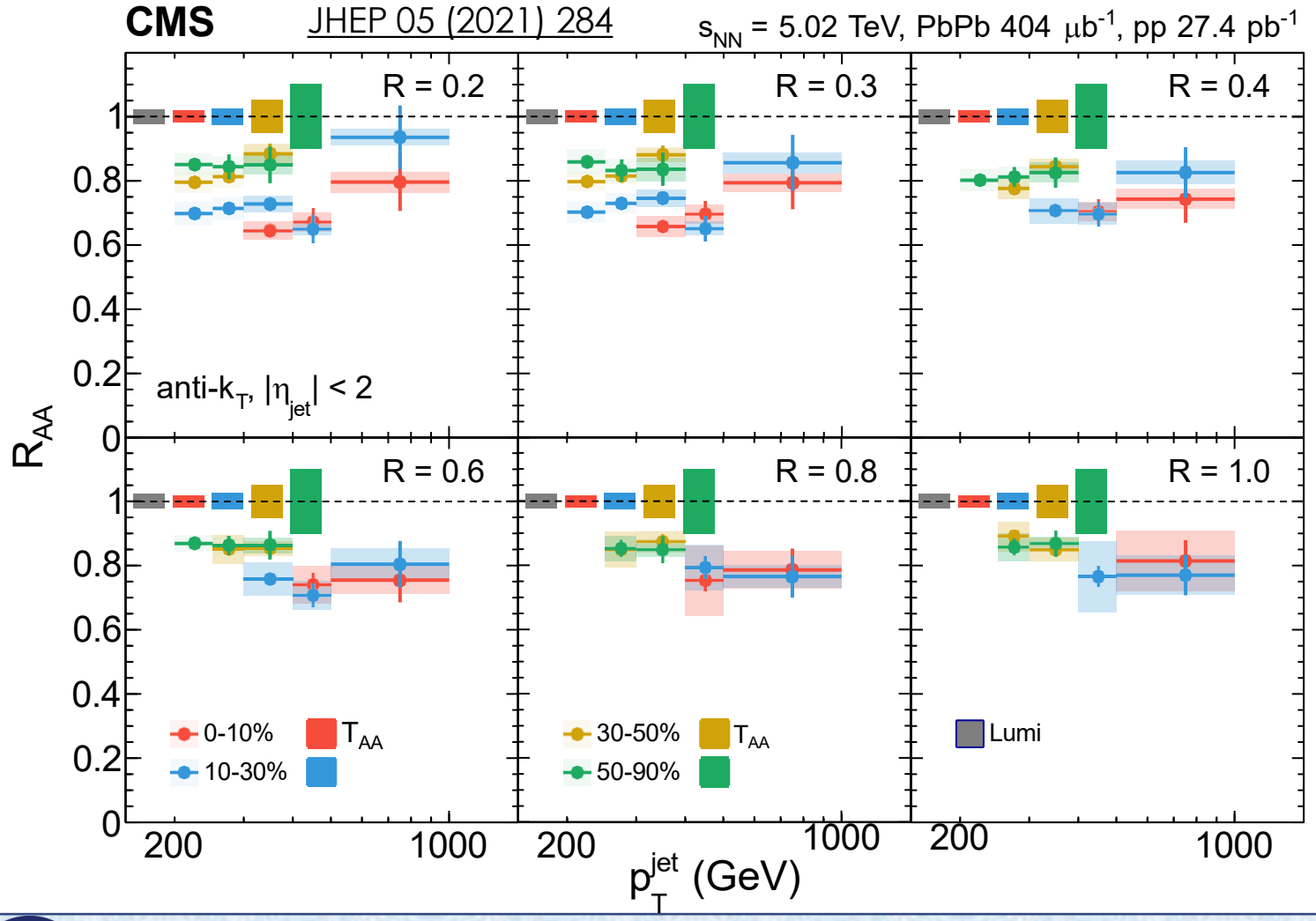


- First observation of Υ(3S) in heavy ion collisions: 2018 data, 4 times more data, now with BDT selections
- Nuclear modification factors: Υ(3S)<Υ(2S)<Υ(1S)

Probing the medium with Jets



Jet quenching for different jet sizes



- Nuclear modifications for jets of different sizes
- Systematic studies of R, centrality and jet p_T dependence
- Challenging constraints for theoretical models

Jet quenching for different jet sizes

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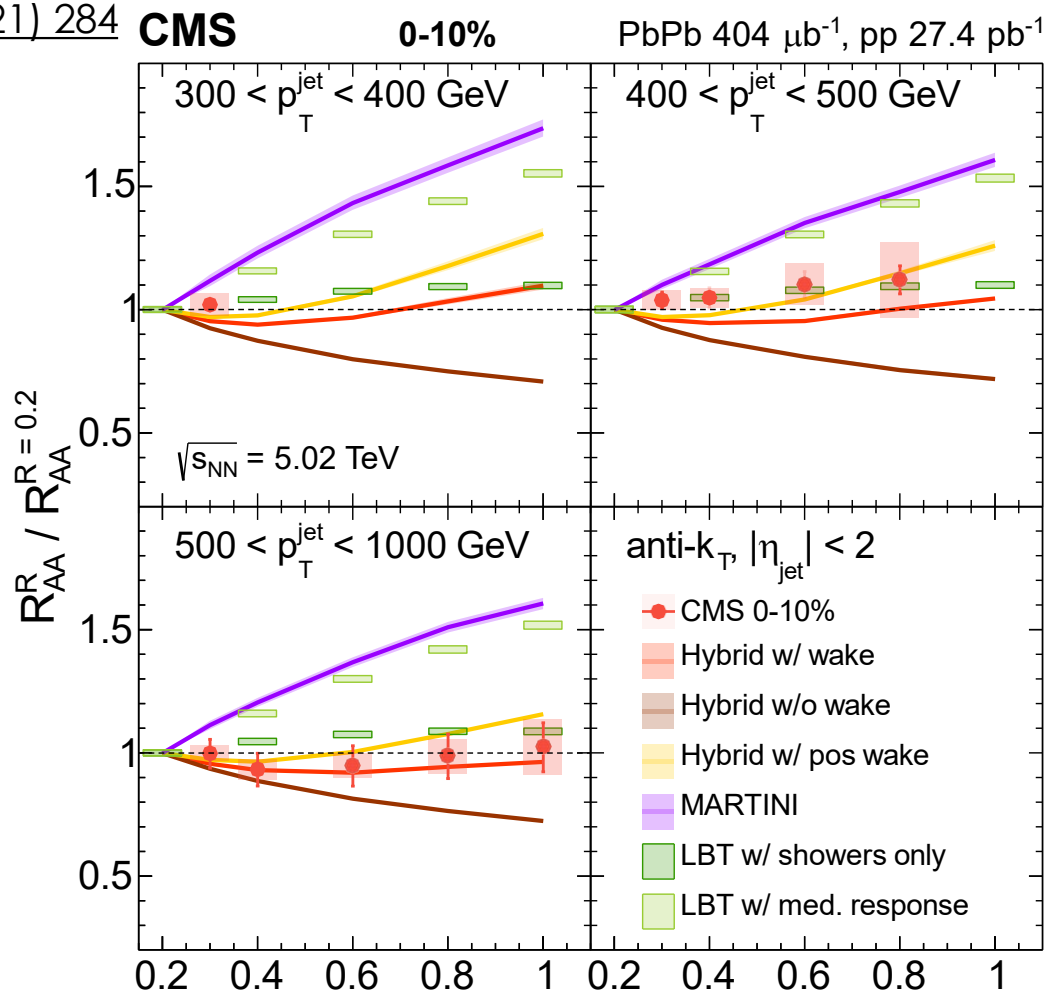
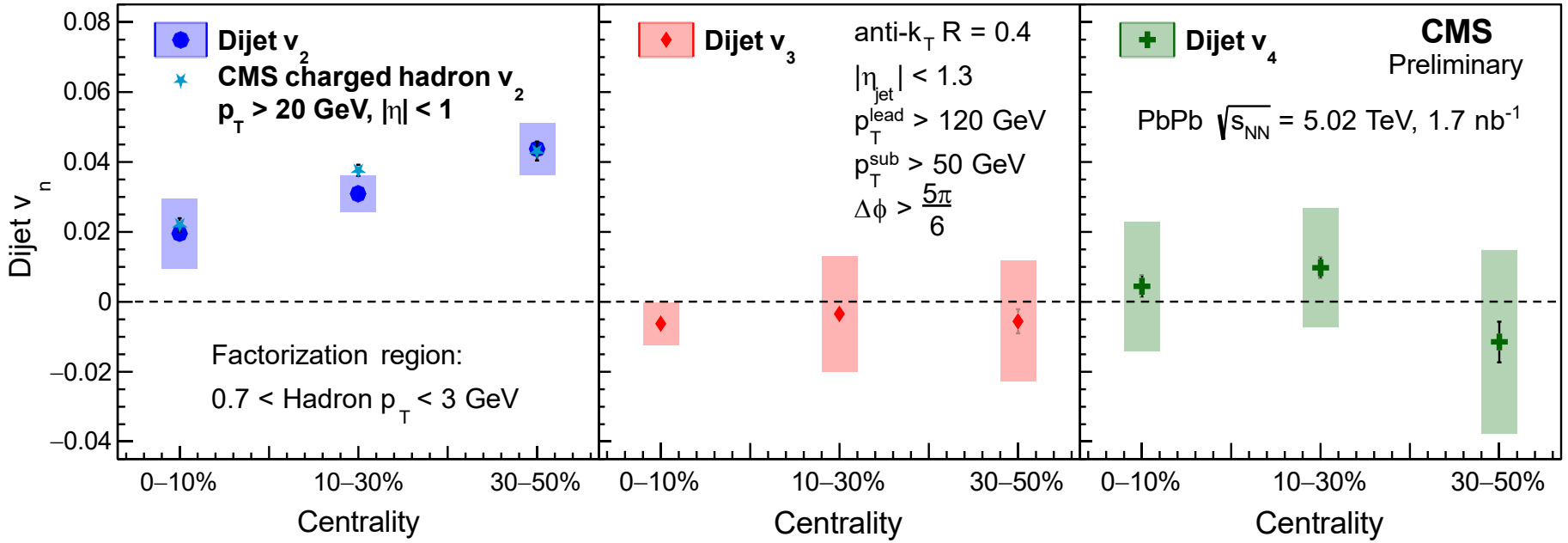


- Radius dependence via double R_{AA} ratios:
- Surprisingly consistent with unity for all R and p_T selections studies
- Medium response is important to capture the data trend

Di-jet anisotropies

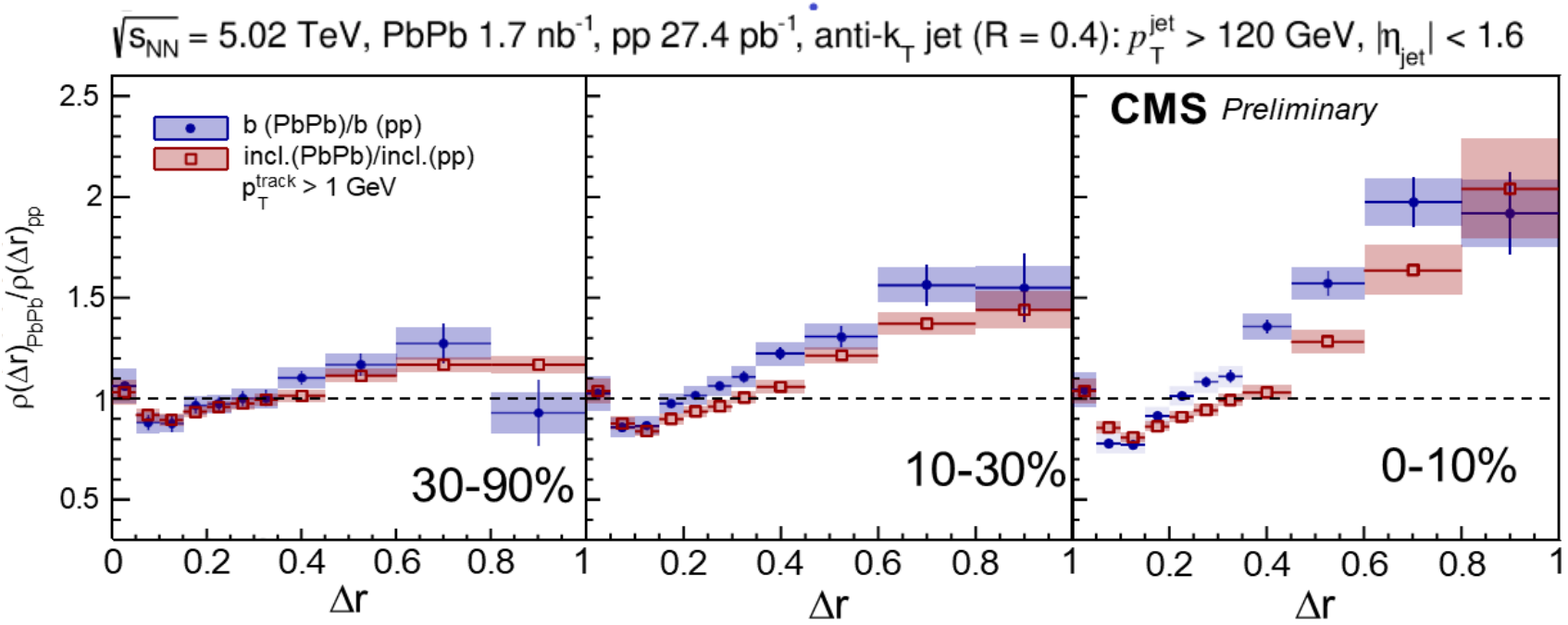
CMS-PAS-HIN-21-002

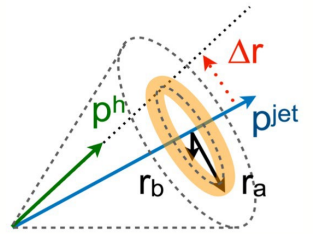


- First v_2, v_3, and v_4 measurements for dijets: p_{T1}>120 GeV, p_{T2}>50 GeV, $\Delta\phi > 5/6$
- Exclusive di-jet selection removes non-flow contribution from Fourier analysis
- Significant v_2 for all centralities ~ high p_T charged hadron v_2 : constrains path-length dependence of quenching
- v_3 and v_4 ~ zero: sensitivity to density/geometry fluctuations remains uncertainty-limited

Medium effects on jet shapes

CMS-PAS-HIN-20-003



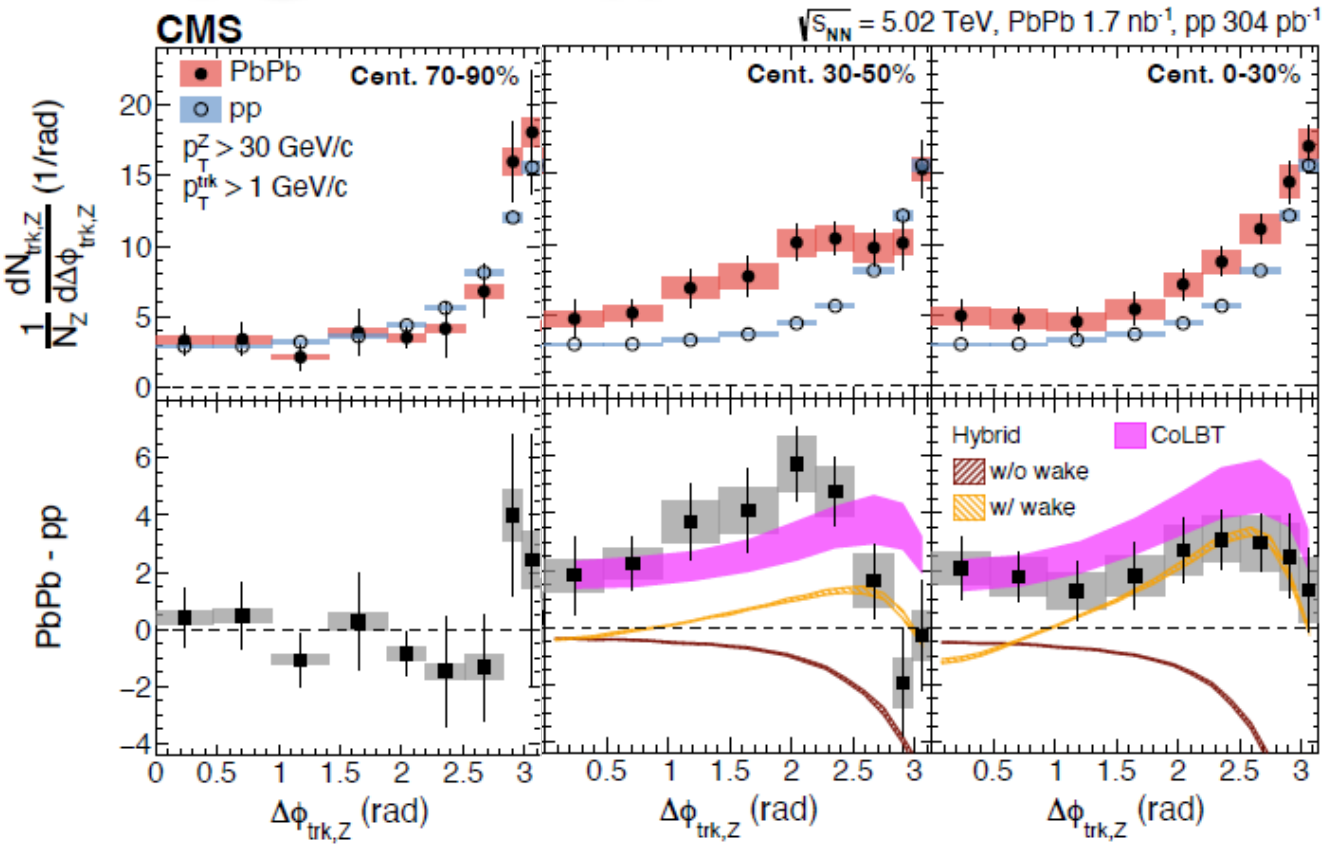


$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{particle}\in(\Delta r_a, \Delta r_b)} p_T^{\text{trk}}}{\sum_{\text{jets}} \sum_{\text{trk}} p_T^{\text{trk}}}$$

- Energy redistribution in jet constituents: PbPb/pp jet shape ratios for inclusive and heavy flavor jets
- Jet momentum is shifted from small to large angles; carried by softer constituents than in pp
- The large-R momentum excess in PbPb vs pp measurement is larger for b jets than for inclusive jets – larger "wake" caused by heavy quarks?

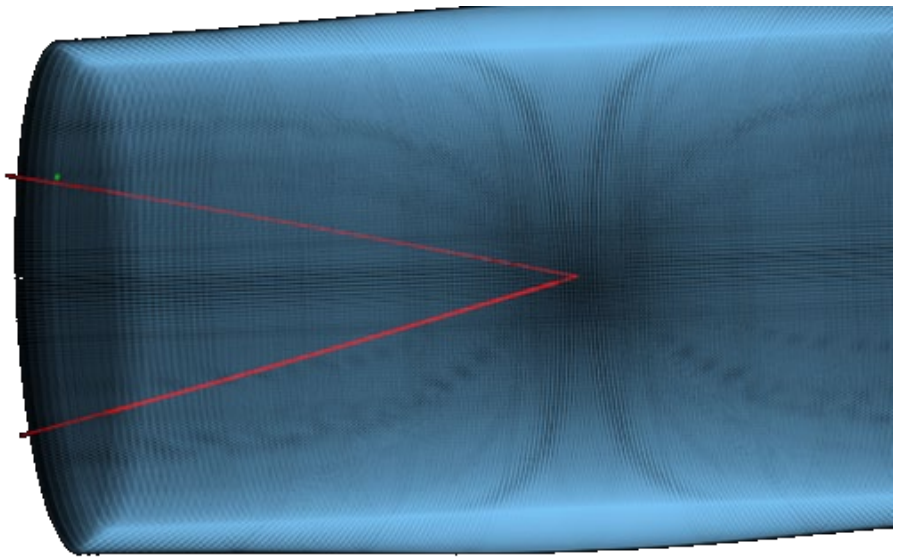
Shockwave medium response to jets

PRL 128 (2022) 122301



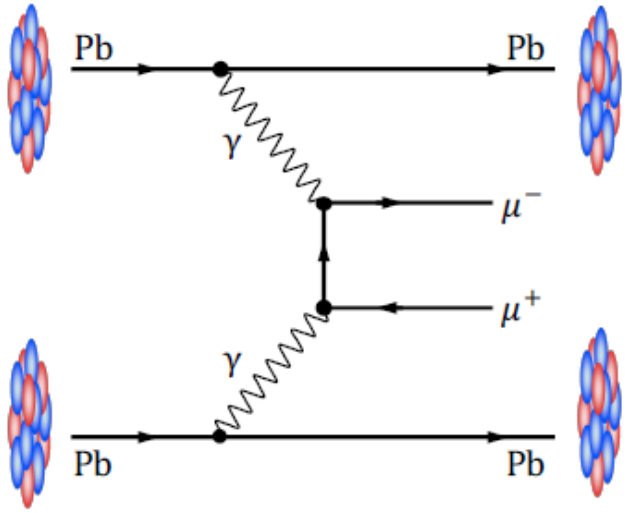
- Z-jet angular correlations:
  - Z-boson constrains initial parton kinematics
  - PbPb to pp differences in correlated yields show excess of particles
  - Magnitude and details of the φ-dependence of excess yield provide new constraints for theoretical modeling

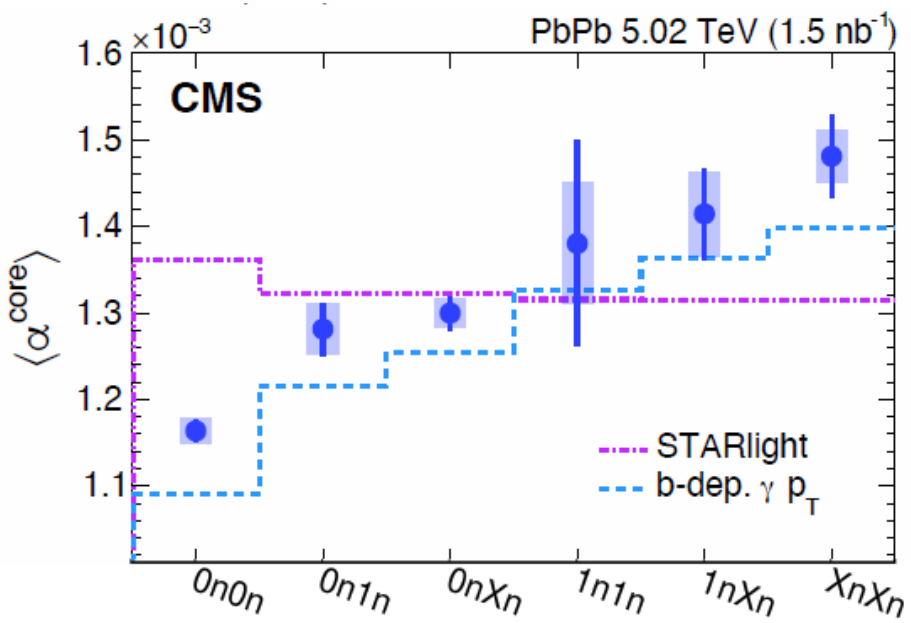
Ultra-peripheral collisions



Dimuon photoproduction $\gamma\gamma \rightarrow \mu\mu$

PRL 127 (2021) 122001





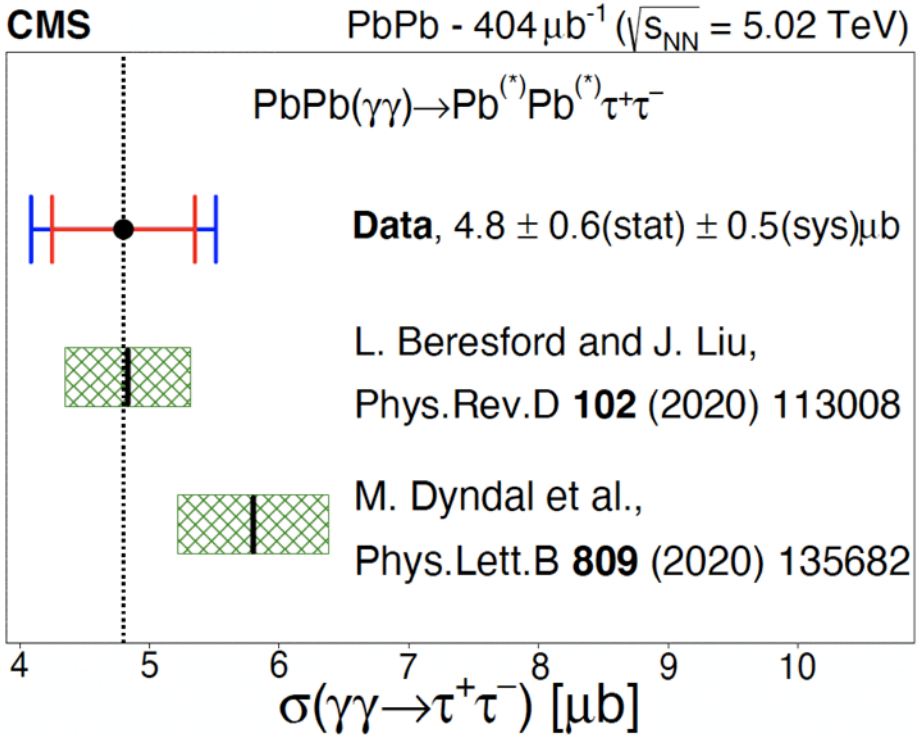
$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

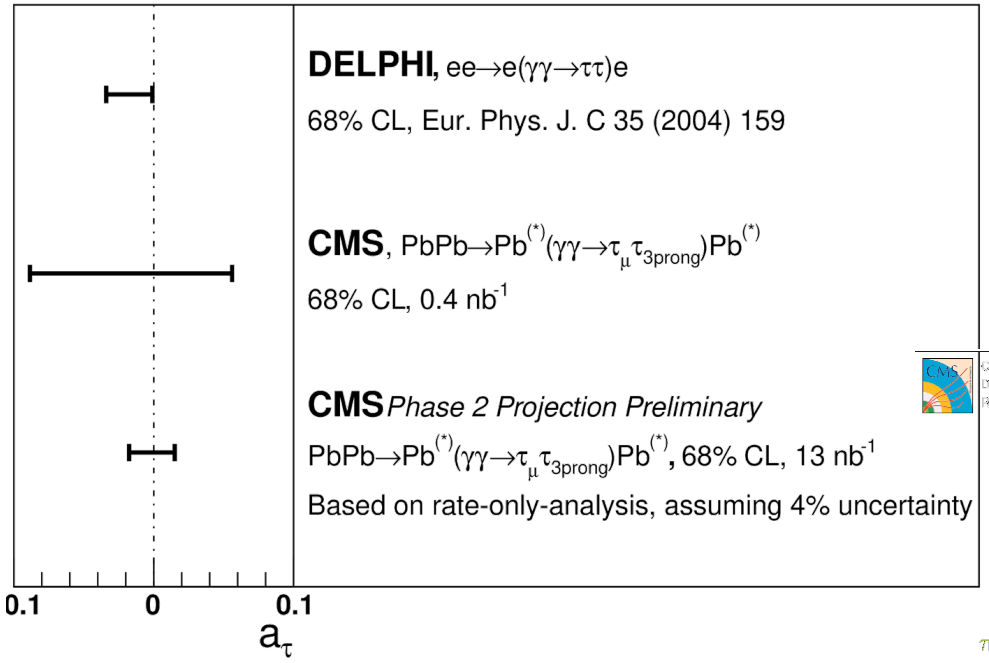
Forward neutron multiplicity dependence of dimuon acoplanarity in ultra-peripheral PbPb:

- Impact parameter dependence is observed
- QED calculations incorporating the b-dependence of initial photon p_T reproduce the data

First observation of $\gamma\gamma \rightarrow \tau\tau$

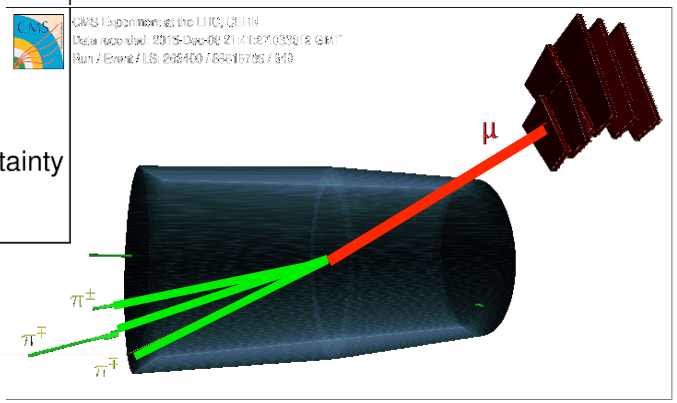
arXiv:2206.05192





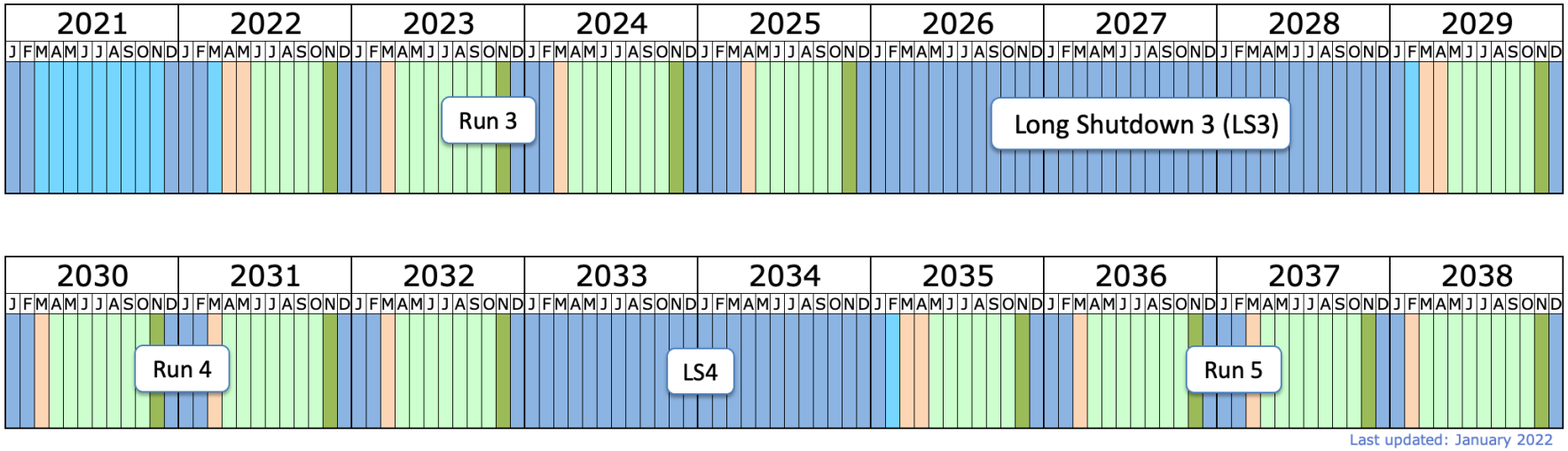
- 77 event counts

$$Pb+Pb \rightarrow Pb+Pb+\tau+\tau$$



- Constrains the anomalous magnetic moment $a_\tau = \frac{(g-2)_\tau}{2}$ for the first time at the LHC

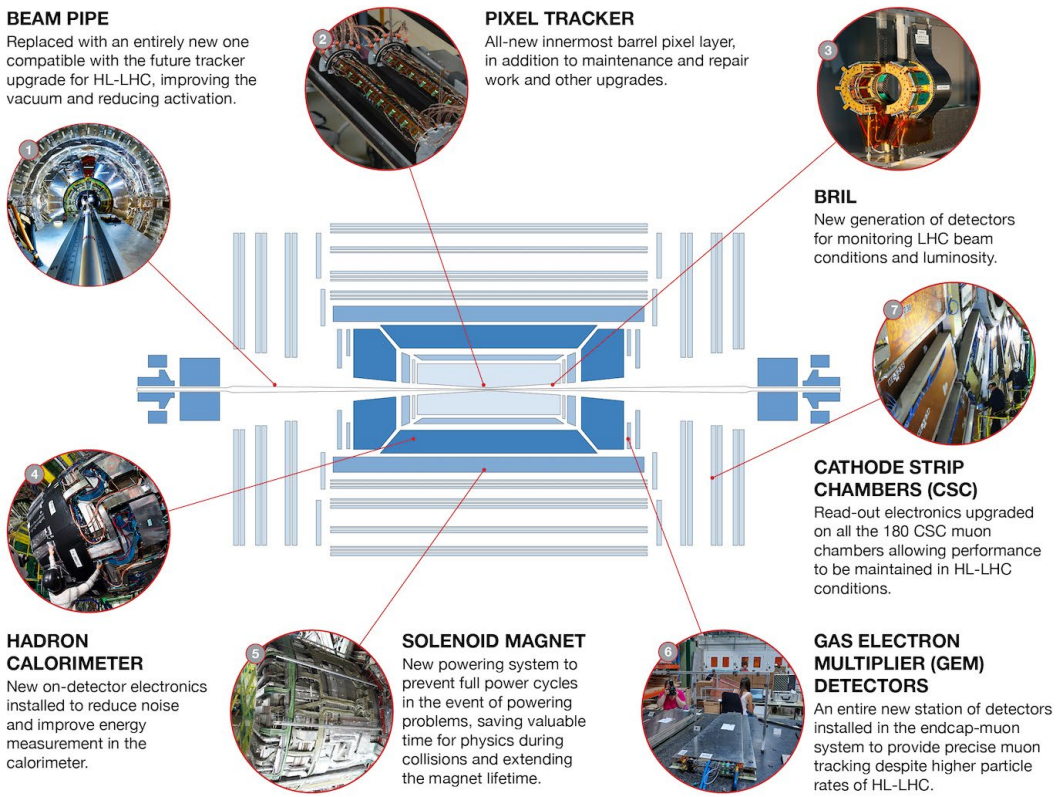
Looking forward:



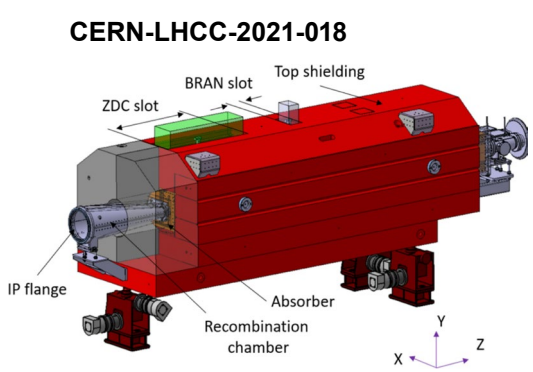
CMS upgrades

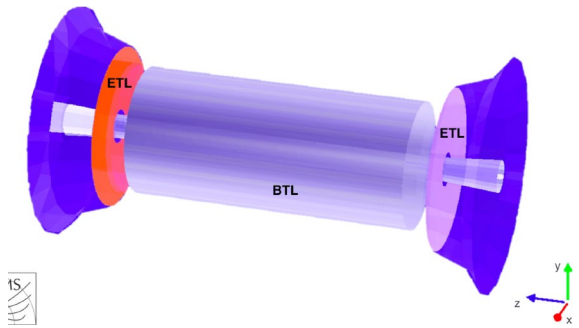
- Exciting opportunities around the corner:

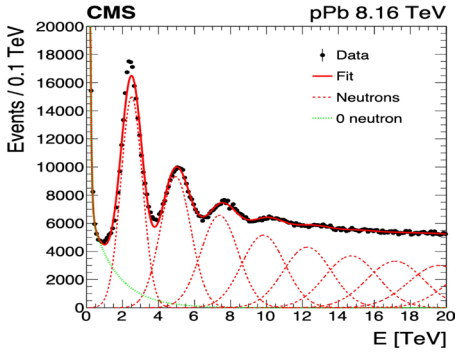
CMS @ LS2

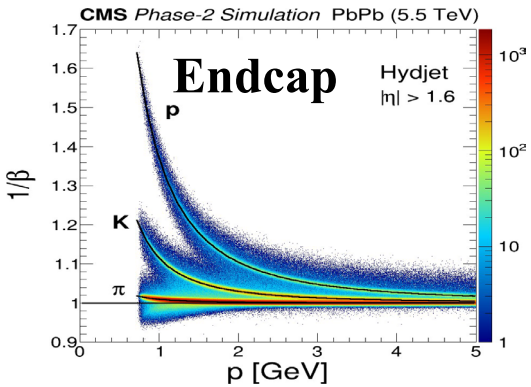


CMS @ LS3









- New ZDC – improved resolution for neutrons
- MTD – particle identification in $|\eta| < 3$

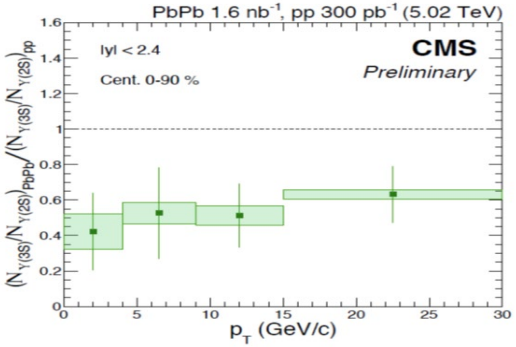
Summary and Outlook

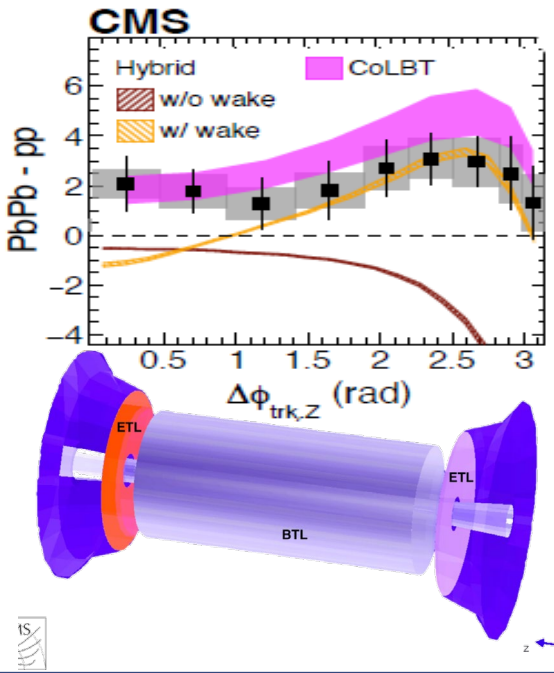
- Wealth of experimental data on initial state, collision dynamics, and medium properties at LHC energies

- Flavor dependence on parton-medium coupling:
  - $v_2(s, \text{light}) \gtrsim v_2(c) > v_2(b)$; $R_{AA}(b) > R_{AA}(c) \approx R_{AA}(s, \text{light})$
  - New insights on quarkonia melting
- Jet probes highlight the importance of medium response
- Unique UPC program provides new constraints for the theory

- Completed and upcoming upgrades will enhance the quality of the data and open new avenues for physics studies

More work to be done!





Thank you!

The UIC Group's work is supported by DOE-NP