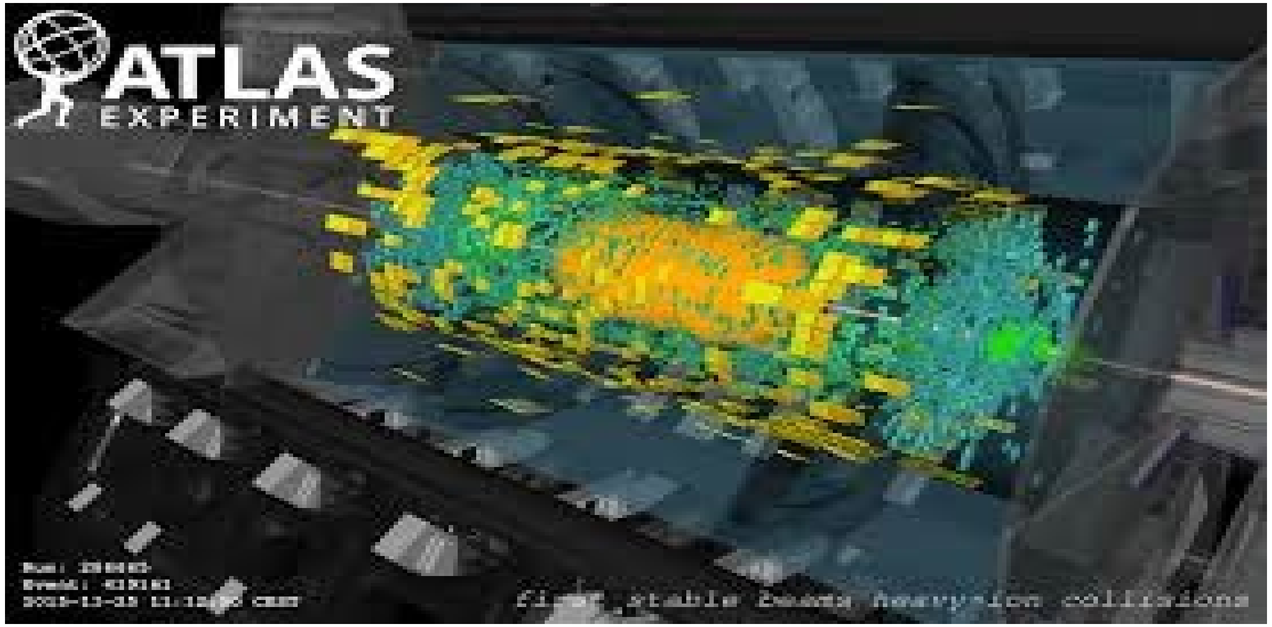
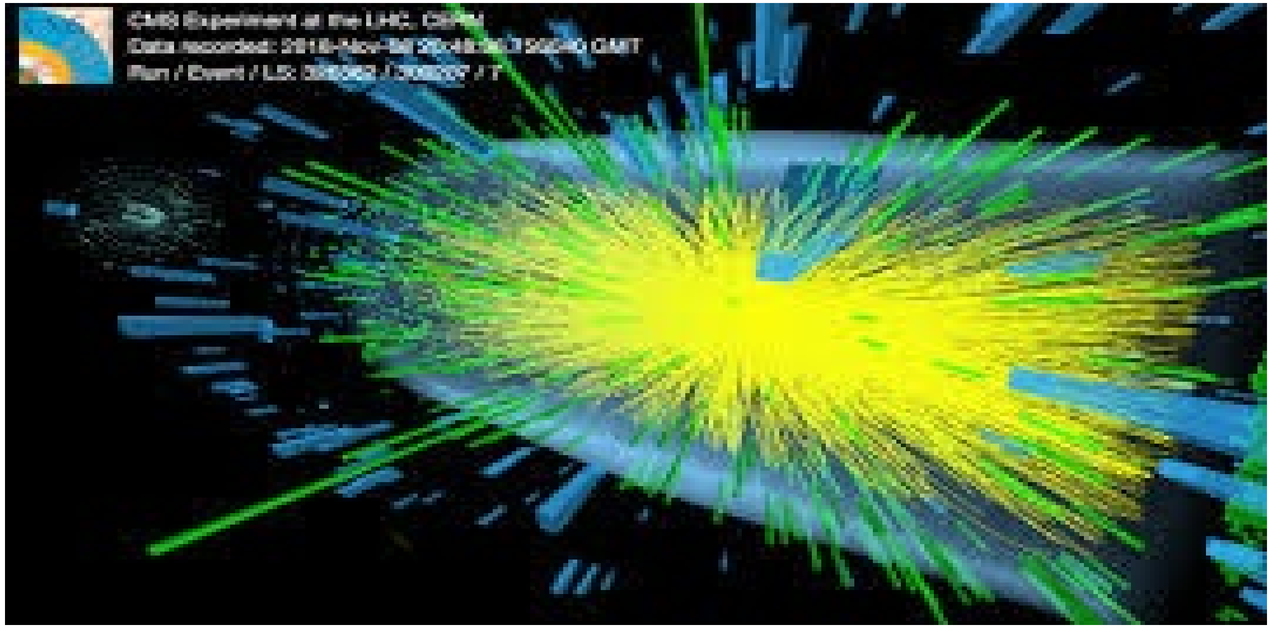
Recent Heavy-Ion Physics Results from ATLAS and CMS

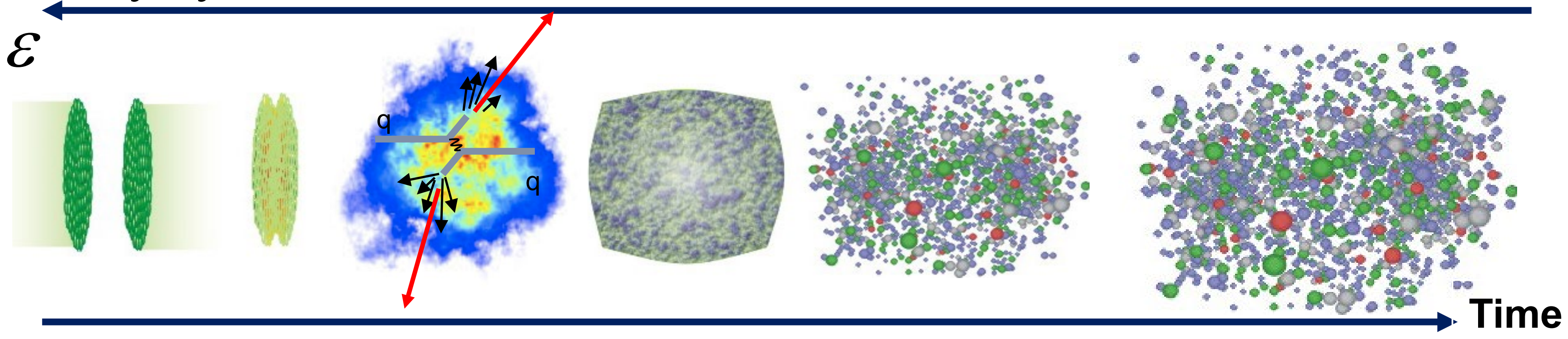
Olga Evdokimov (University of Illinois at Chicago) for the ATLAS and CMS Collaborations





Outline:

- "Standard Model" of heavy ion collisions: a complex dynamics of intrinsically many-body system



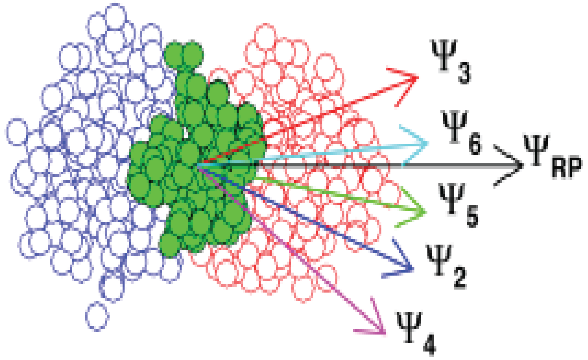
- A (biased) selection of recent experimental results from ATLAS and CMS on:
  - Initial state properties
  - QGP properties through heavy flavor and quarkonia
  - Progress in jet quenching studies
  - Ultra-peripheral collisions: QED meets QCD

Introduction: "tools of the trade"

- **Azimuthal anisotropies** ("flows"): Fourier coefficients v_1, v_2, v_3, v_4, v_5

$$\frac{d^3N}{p_T dp_T d\eta d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T d\eta}\left(1 + \sum_{k=1}^{\infty} 2 v_{n=km}(p_T,\eta)\cos\left[n\left(\phi - \Psi_m\right)\right]\right)$$

Glauber-based picture:



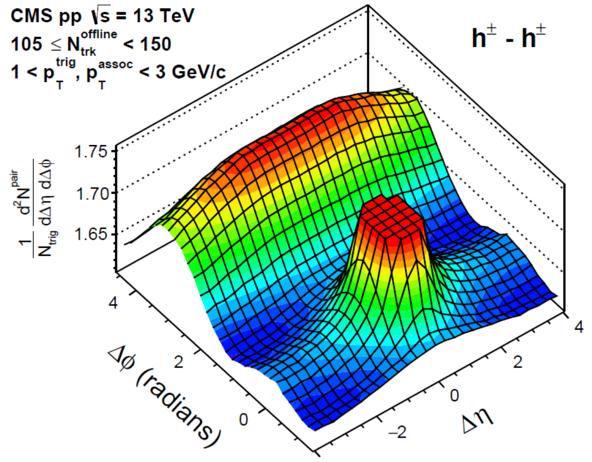
$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}} r_i^m \sin(m\phi_i)}{\sum_{i=1}^{N_{part}} r_i^m \cos(m\phi_i)}\right\} - \frac{\pi}{m}$$

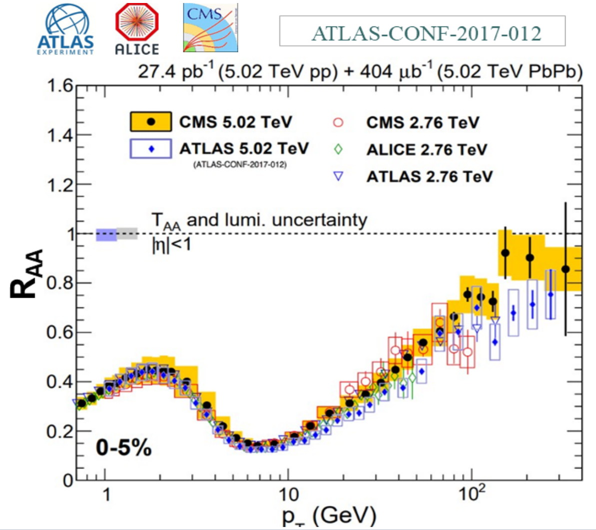
- **Nuclear modification factors R_{AA}**

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{< N_{bin} > d^2N^{pp}/dp_T d\eta}$$

*Number of binary collisions N_{bin} is extracted from Glauber calculations

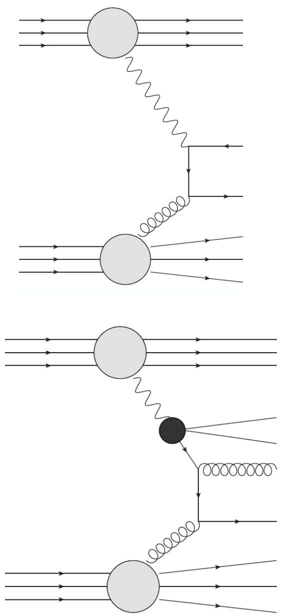
CMS PLB 765 (2017) 193



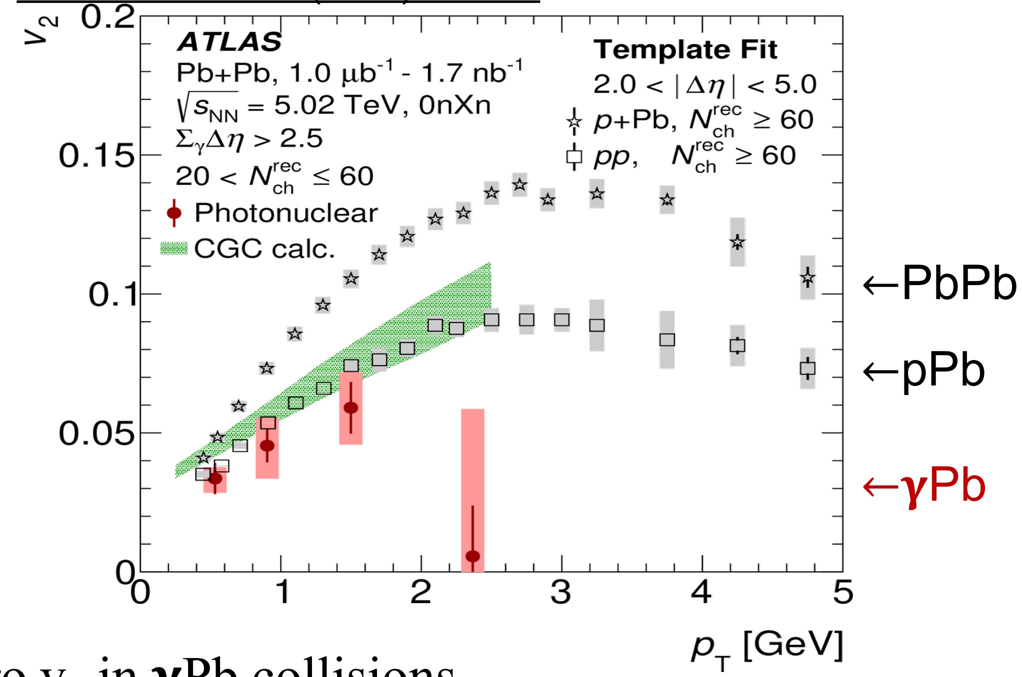


Anisotropies in small systems

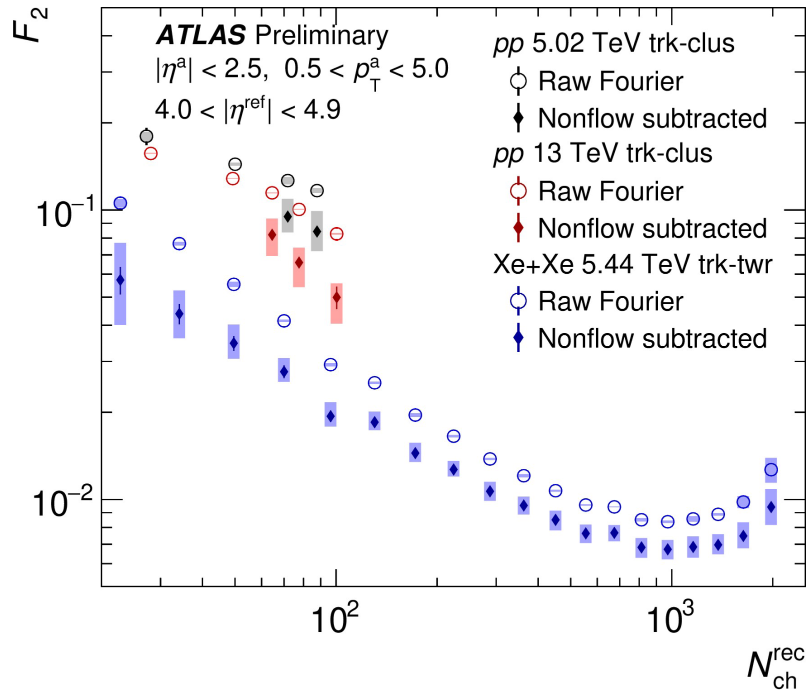
- **Understanding the initial state:**



ATLAS: PRC. 104 (2021) 014903



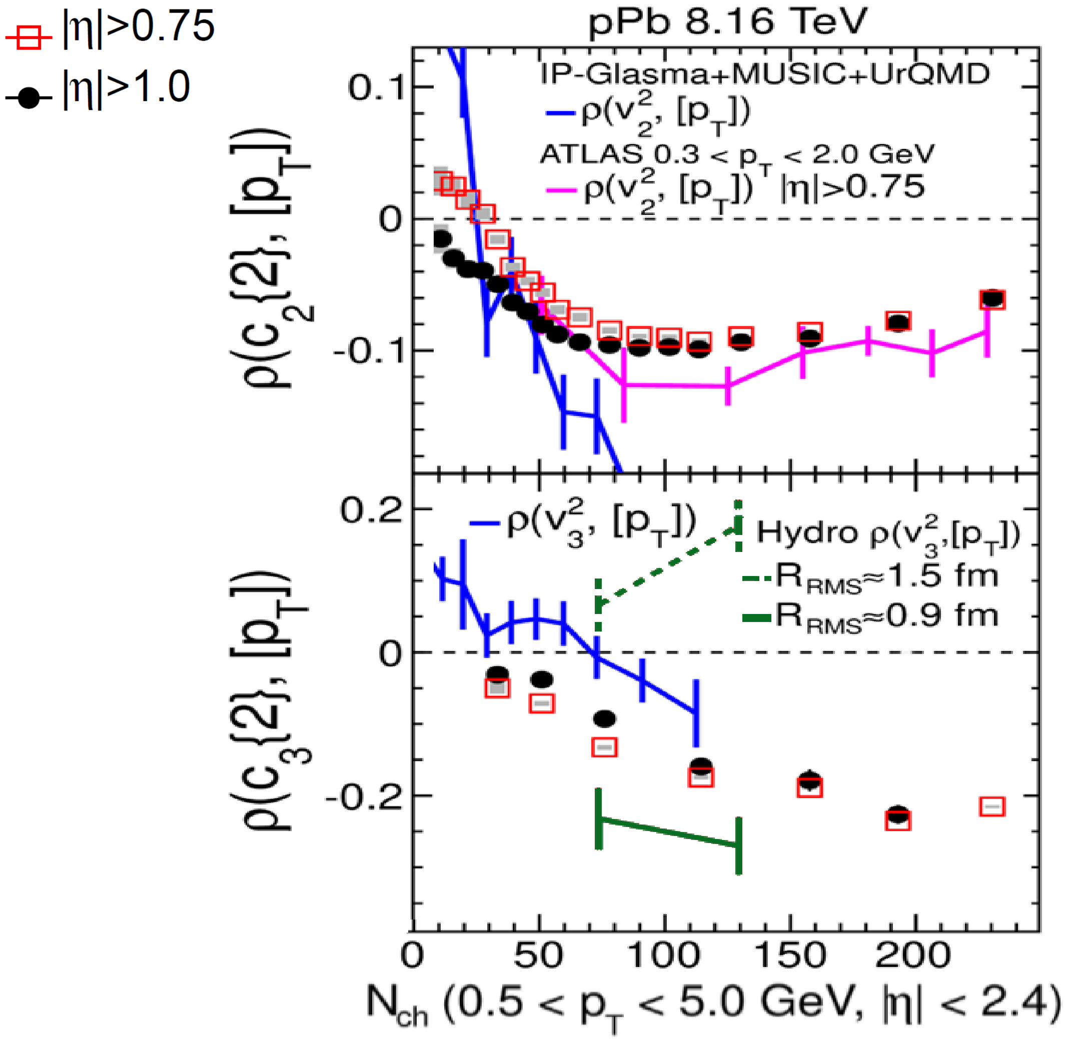
ATLAS-CONF-2022-020



- Non-zero v_2 in **γ**Pb collisions
- Consequence of **ρ**Pb interactions? Gluon fields interactions of Color Glass Condensate framework?

- Understanding of non-flow effects is critical
- Longitudinal structure of initial state: decorrelation signals in pp, XeXe

Anisotropies in small systems



CMS-PAS-HIN-21-012

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

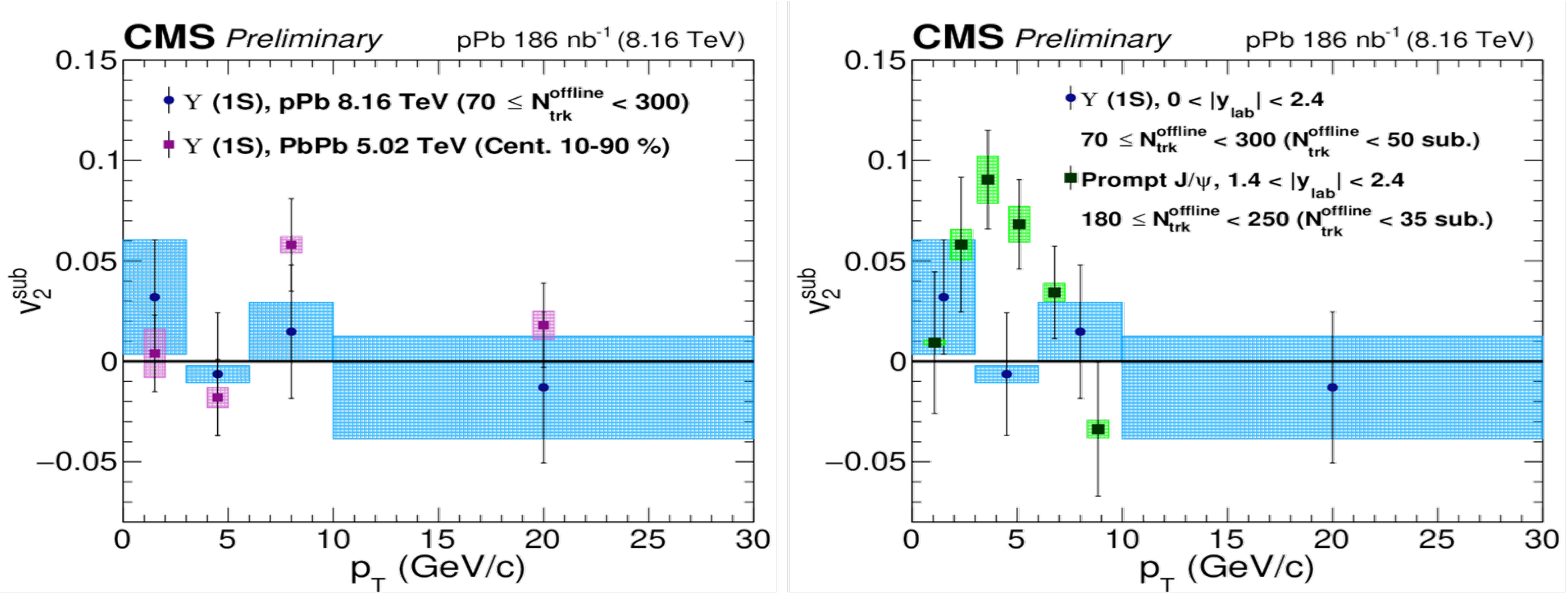
- v_2-p_T: sign change with N_{ch} (due to initial momentum anisotropy predicted by Color Glass Condensate framework):
  - Could be seen in the data but disappear with large pseudorapidity gap
  - Measurements are sensitive to nonflow effects (jet/minijet correlations, resonance decays,…)
- v_3-p_T: no sign change
- Model comparisons:

IP-Glasma+MUSIC+UrQMD

Hydro

Anisotropies in small systems

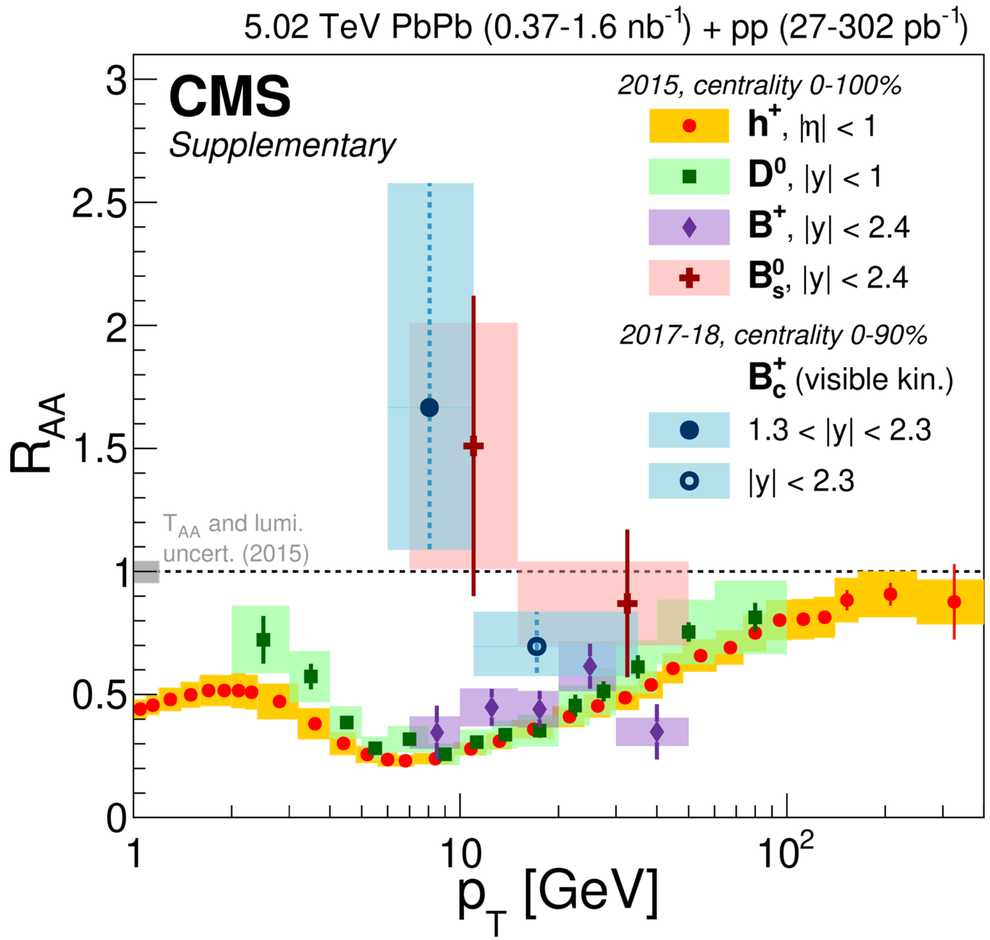
- **Understanding the initial state & search for final state effects:** CMS-PAS-HIN-21-001



- New results on Υ(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

Heavy flavor: nuclear modification

CMS PRL. 128 (2022) 252301

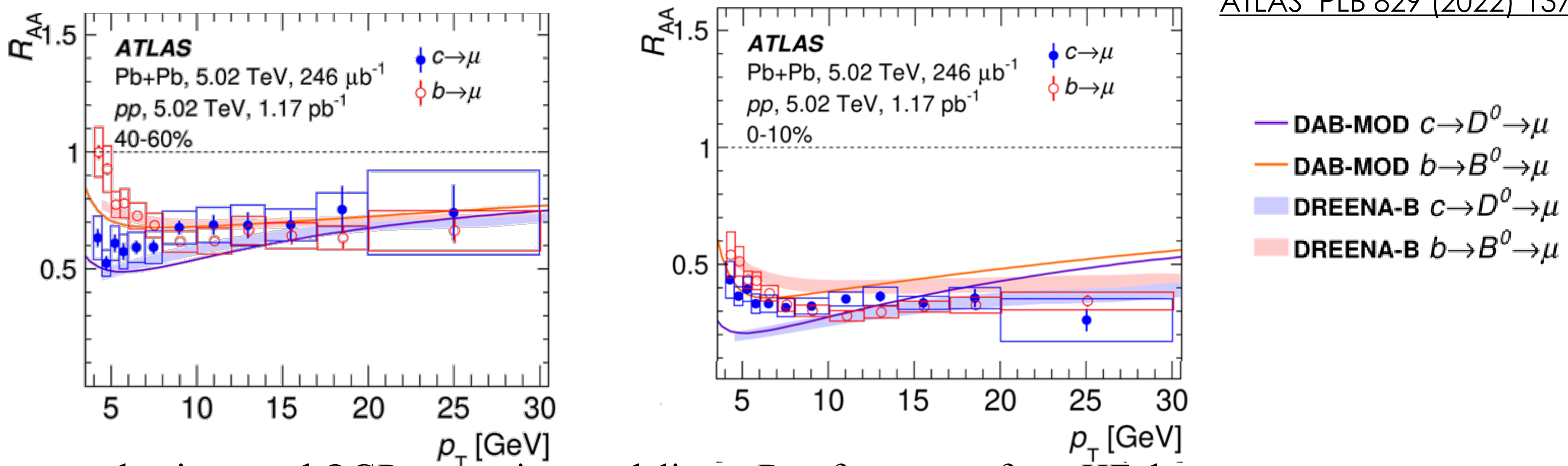


- Nuclear modification for prompt- and non-prompt D^0 , non-prompt J/ψ, $B^{\pm}$
- Mid-p_T : flavor dependence of energy loss
  - $R_{AA}(b) > R_{AA}(c) \sim R_{AA}(\text{light flavors})$
- High p_T : radiative energy loss dominates
  - $R_{AA}(b) \sim R_{AA}(c) \sim R_{AA}(\text{light flavors})$
-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

Heavy flavor: nuclear modification

- New high precision measurements of heavy flavor nuclear modification factors from ATLAS

ATLAS PLB 829 (2022) 137077

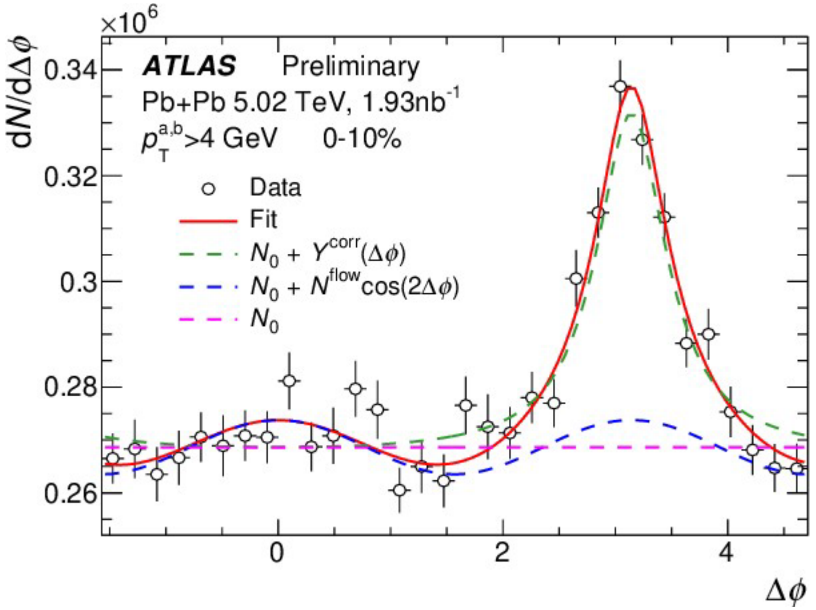


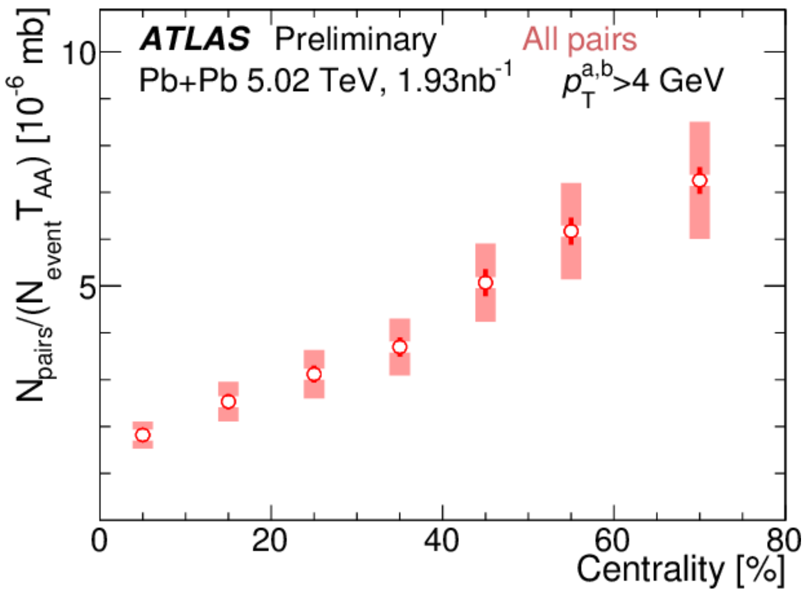
- Energy loss mechanisms and QGP expansion modeling – R_{AA} for muons from HF decays
- Mass splitting at low p_T , similar behavior at high p_T
- Need measurements of both R_{AA} and v_2 for separated charm and bottom for rigorous constraints on models

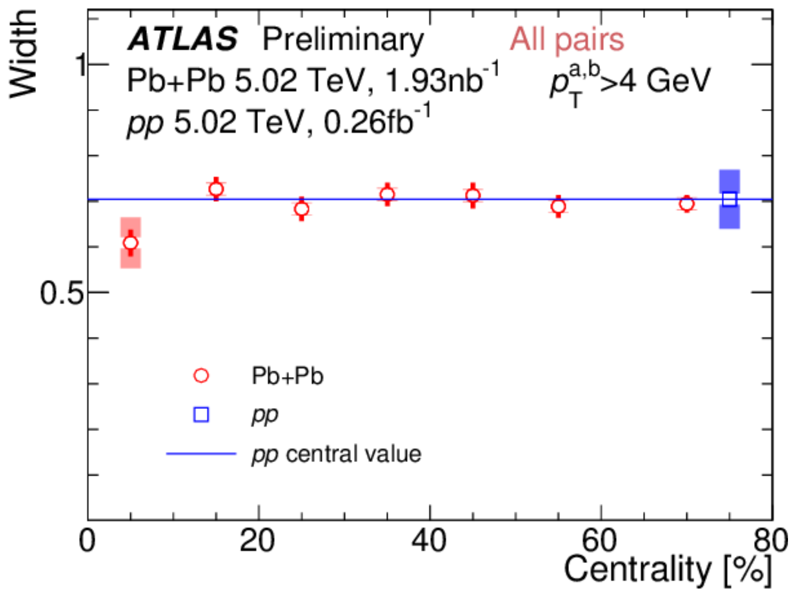
Heavy flavor: nuclear modification

- Back-to-back muon pairs - dominated by HF decays (both opposite and same sign pairs are signal)

ATLAS-CONF-2022-022

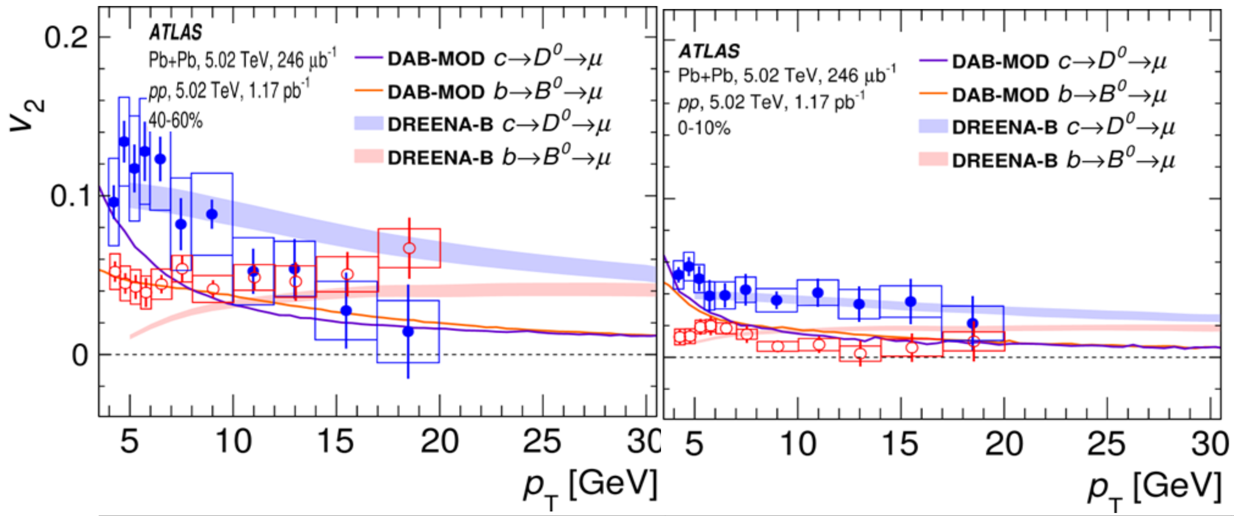


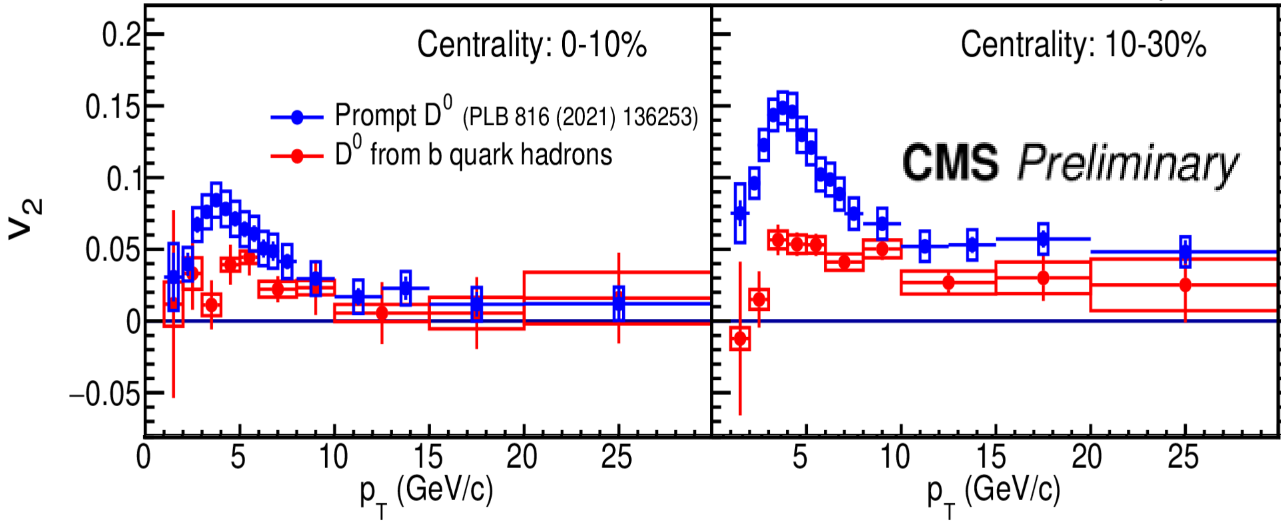




- Collisional vs. radiative energy loss: possible differences in the angular correlations
- Expected centrality trend in binary-scaled yields
- No significant changes in the widths of correlated signal

Heavy flavor: anisotropies





- ATLAS: muons from HF decays

  ATLAS PLB 829 (2022) 137077

- CMS: prompt and non-prompt D^0

  CMS-PAS-HIN-21-003

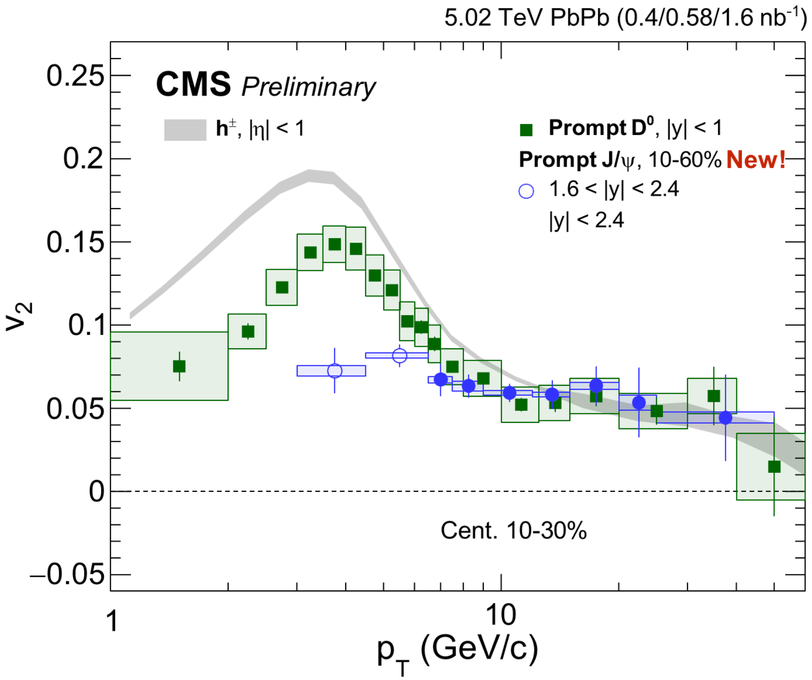
Consistent picture:

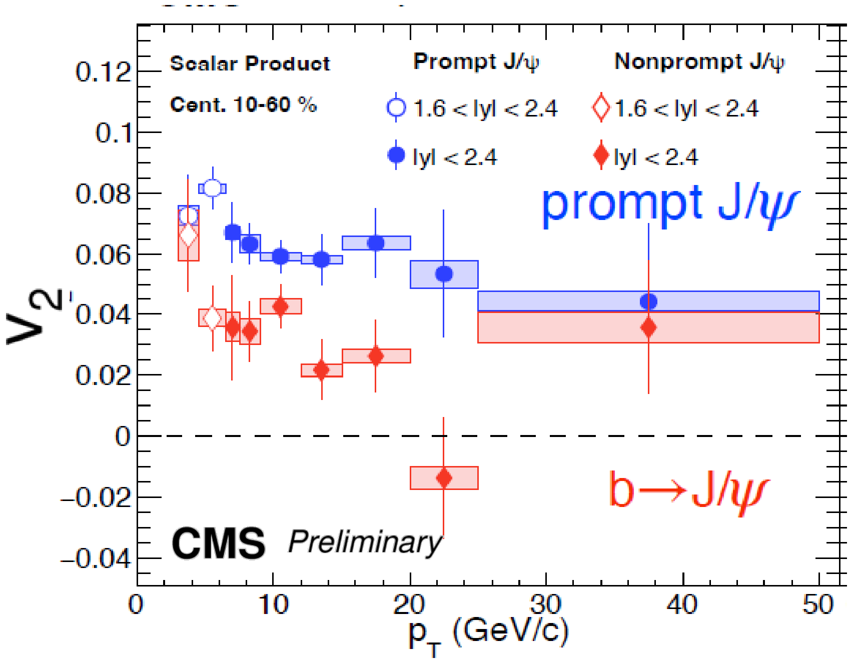
- Significant v_2 for charm and bottom
- Initial raise consistent with hydro expansion; high p_T – path-length dependence of energy loss
- Higher degree of parton-medium coupling for charm than bottom

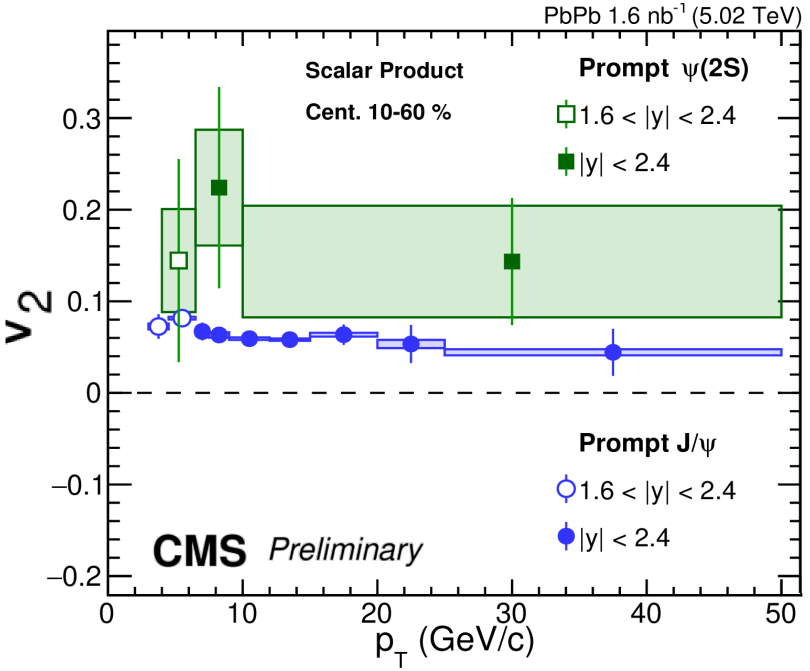
Quarkonia: anisotropies

- What about quarkonia? Everything "flows"!

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





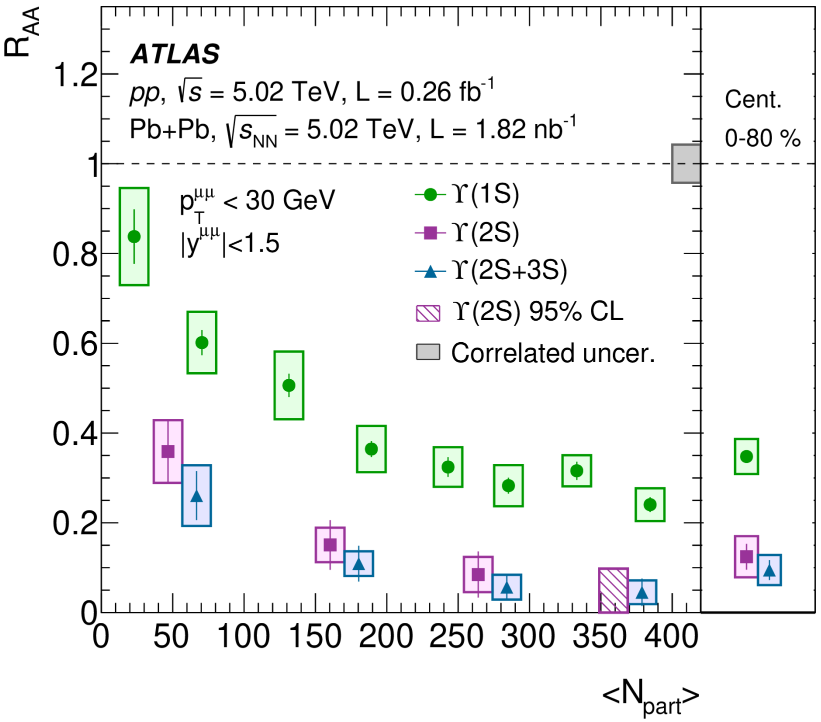


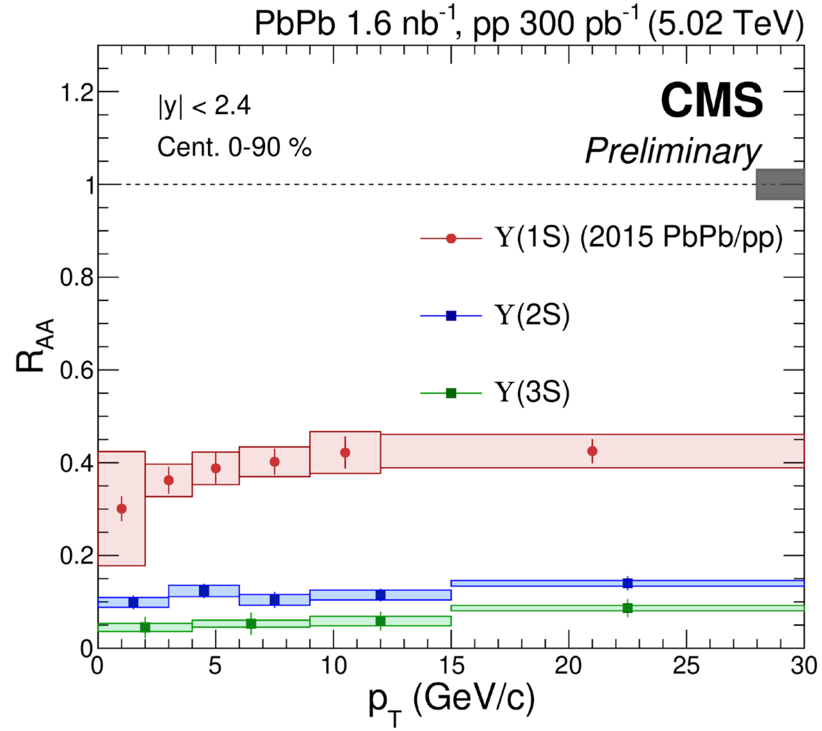
- Hidden vs. open charm:
  - high p_T – no mass dependence; path-length dependent E-loss
  - Low p_T: $v_2(h^{\pm}) > v_2(\text{prompt } D^0) > v_2(\text{prompt } J/\psi)$ – constituent quark differences? Recombination!
- Charm vs. bottom:
  - Prompt J/ψ: significant v_2 up to high p_T; $b \rightarrow J/\psi$: smaller v_2, high p_T behavior?
  - Stronger (?) v_2 for prompt $\psi(2S)$ – difference in regeneration contributions?

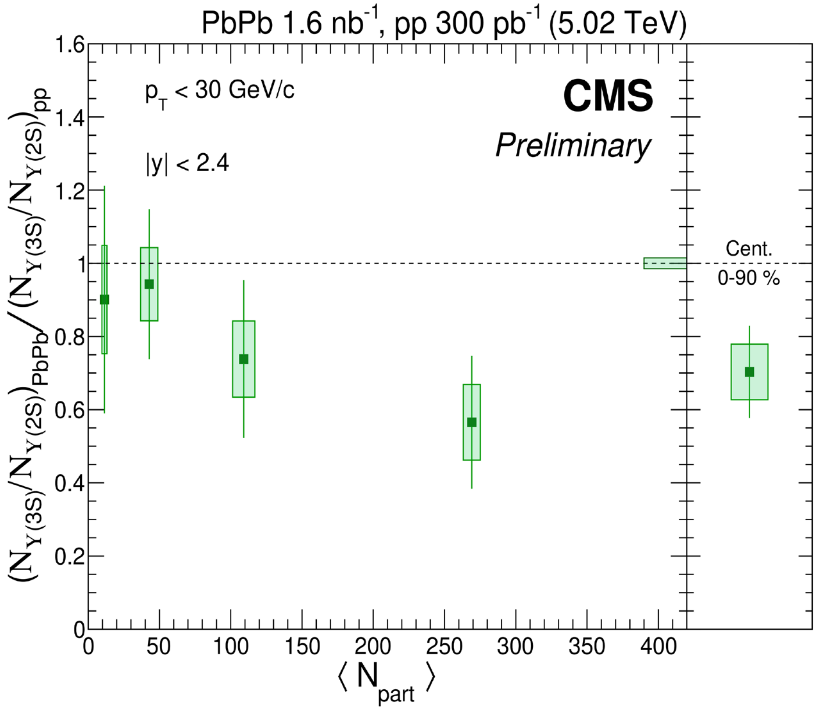
Quarkonia: melting

ATLAS arXiv:2205.03042

CMS-PAS-HIN-21-007



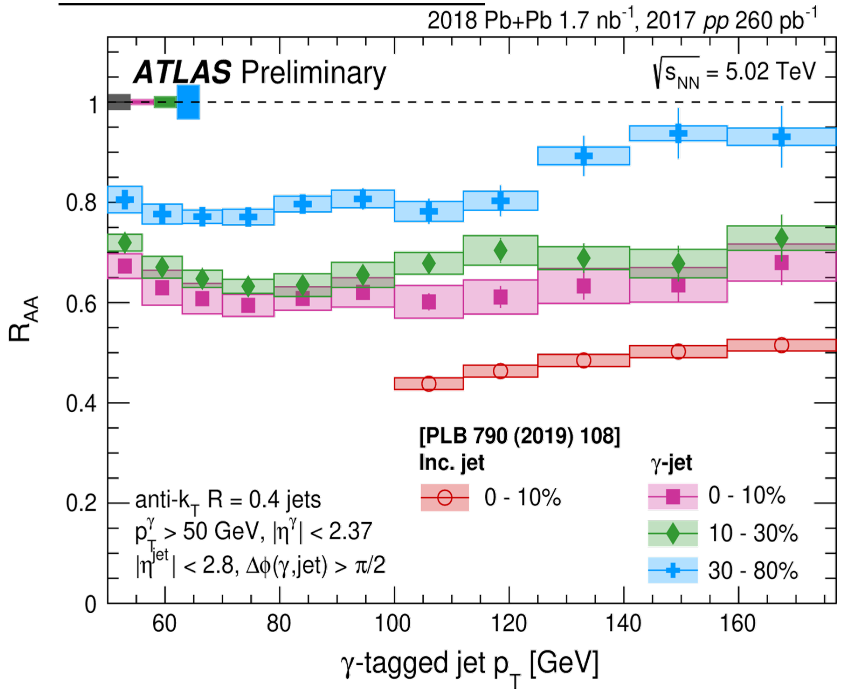




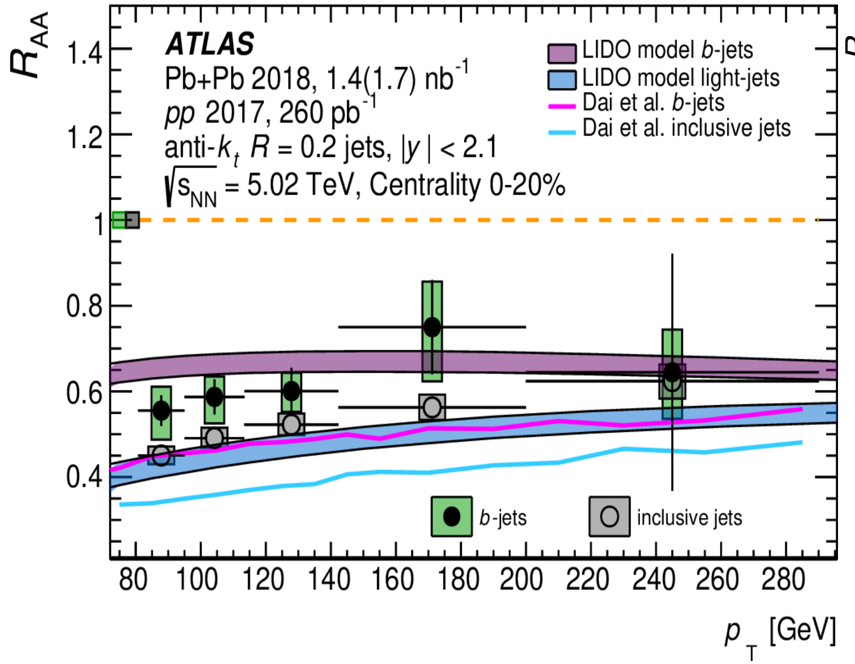
- Clear signature of sequential melting of ϒ(ns) states: nuclear modification factors: ϒ(3S)< ϒ(2S)< ϒ(1S)
- First direct observation of ϒ(3S) in heavy ion collisions

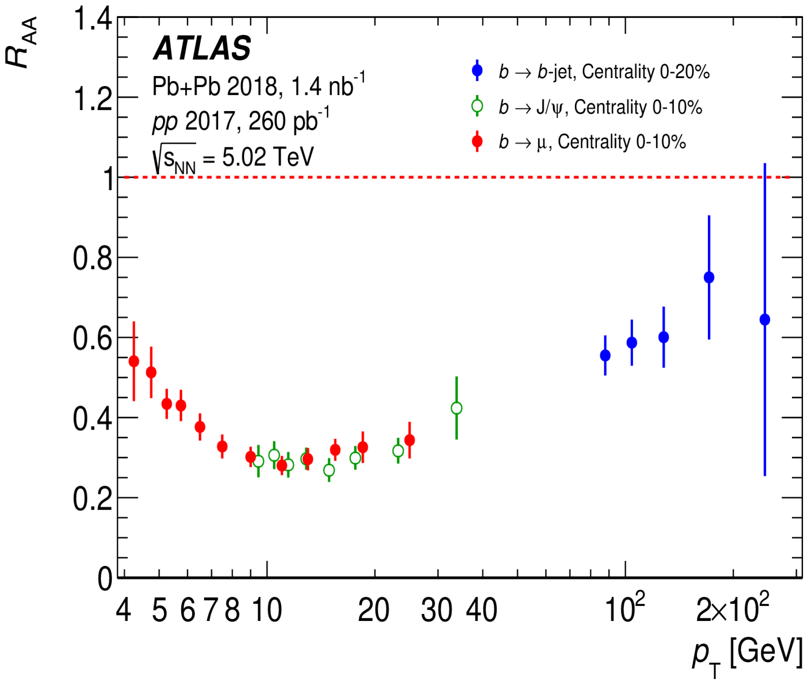
Jet quenching: nuclear modifications

ATLAS-CONF-2022-019



ATLAS arXiv:2204.13530

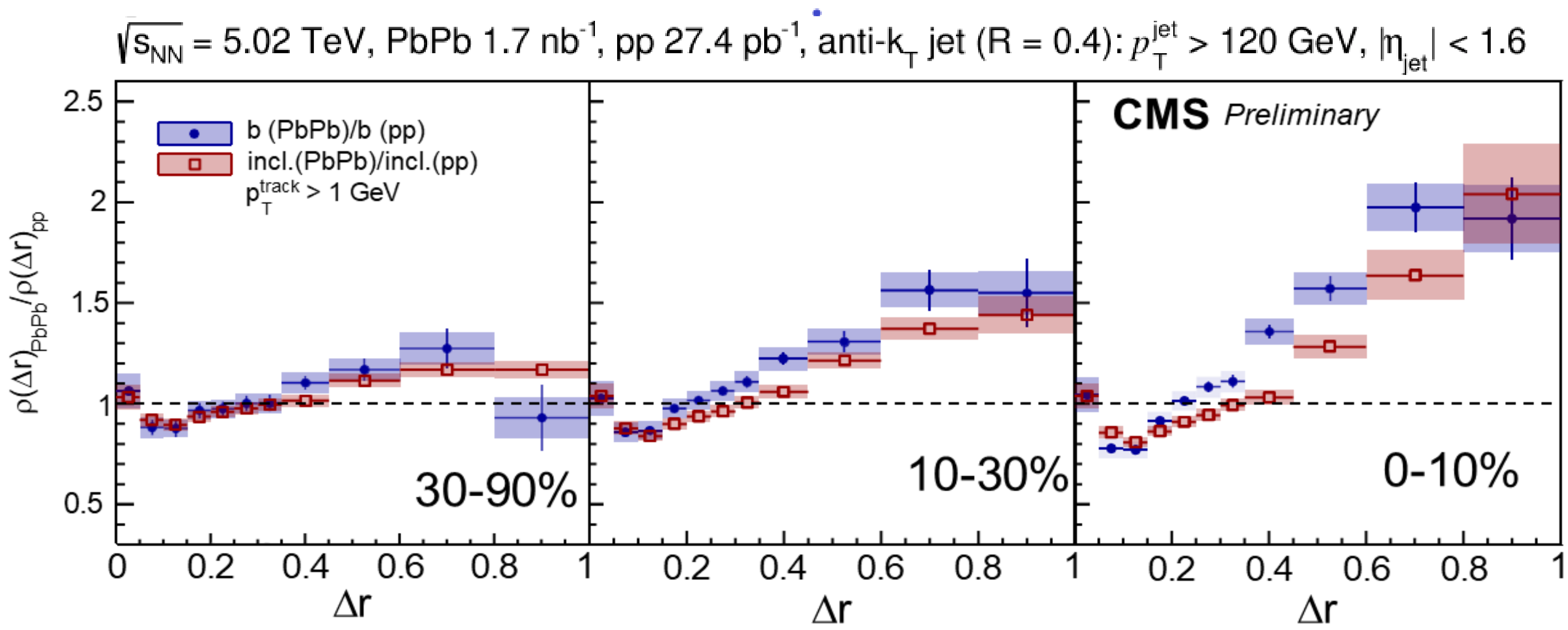


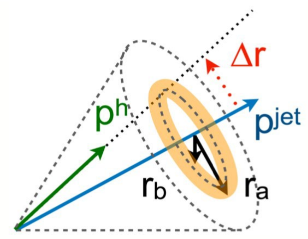


- Search for color-charge, mass, and/or flavor effects in energy loss:
  - Photon-tagged jets (higher fraction of quark-initiated jets): less suppressed compared to inclusive jets
  - b-jets (muon tagger): less suppressed compared to inclusive jets

Jet quenching: energy flow changes

CMS arXiv:2210.08547



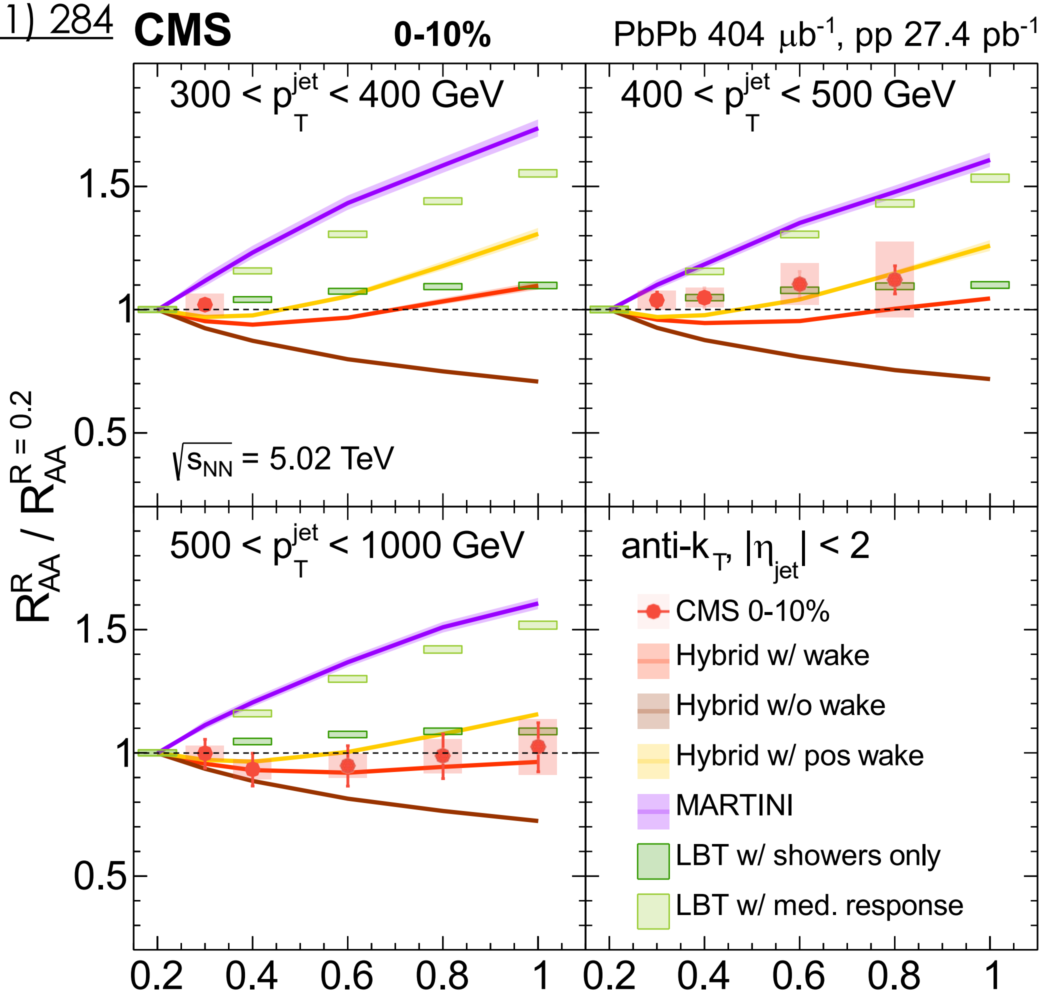


$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{particle} \in (\Delta r_a, \Delta r_b)} p_T^{\text{trk}}}{\sum_{\text{jets}} \sum_{\text{trk}} p_T^{\text{trk}}}$$

- 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?

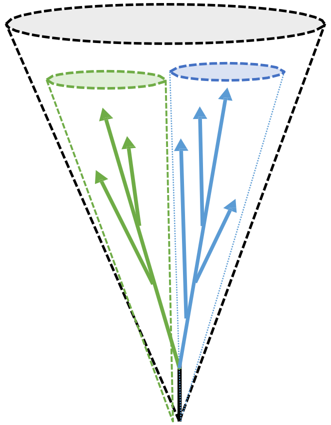
Jet quenching: jet size dependence

JHEP 05 (2021) 284



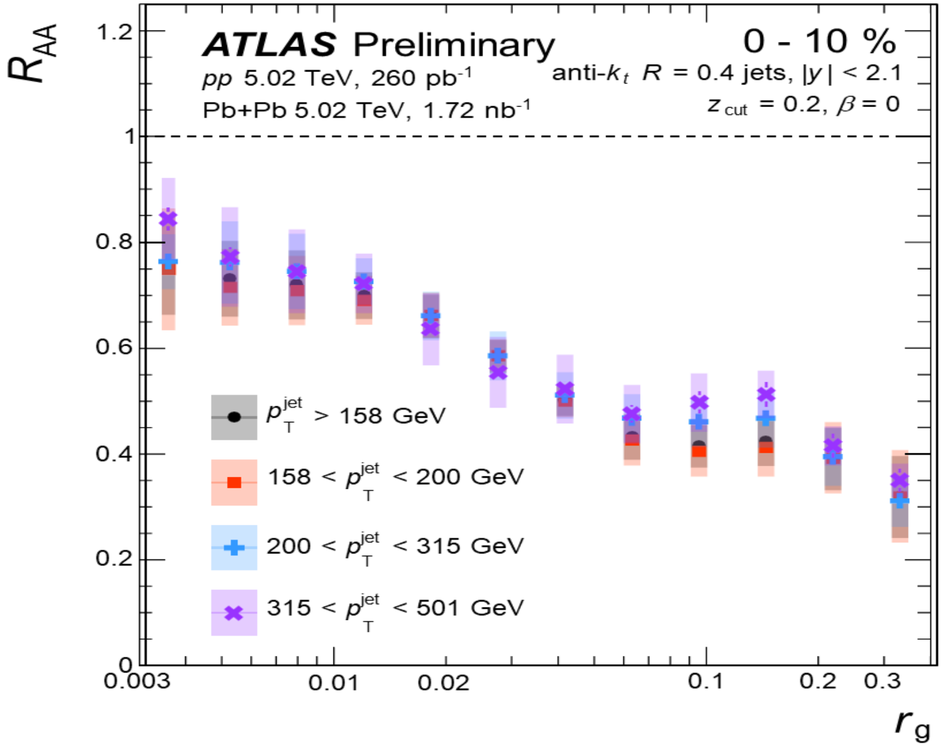
- Nuclear modifications for jets of different sizes: systematic studies of R, centrality and jet p_T dependence
- Radius dependence via double R_{AA} ratios:
  - Surprisingly consistent with unity for all R and p_T selections studies
  - Medium response is important to capture the data trend

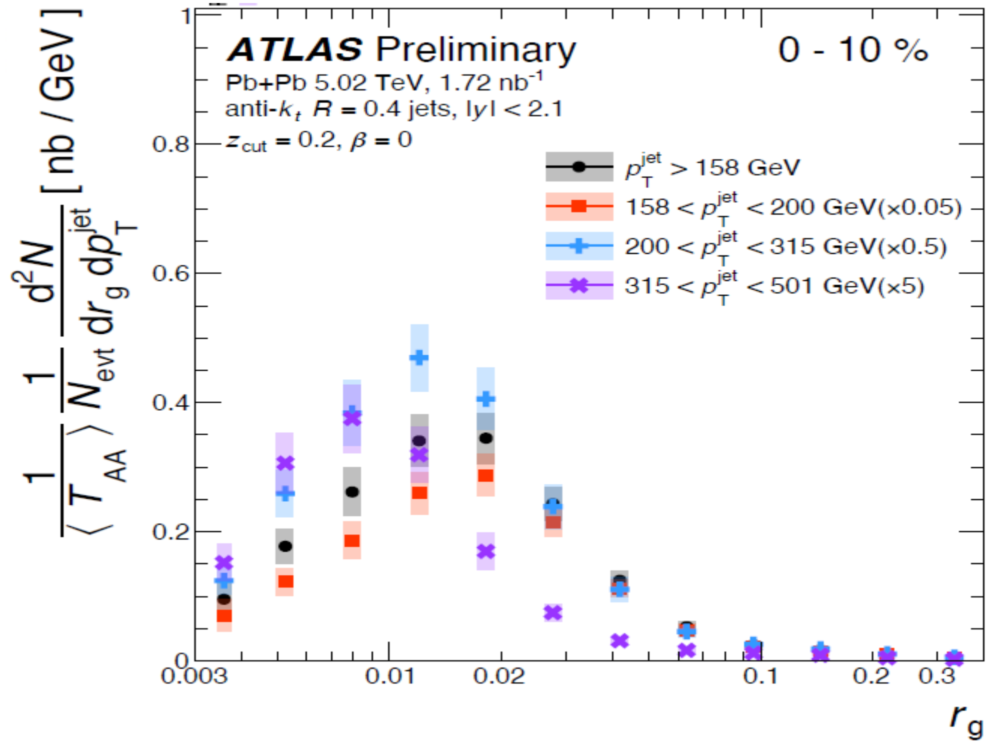
Jet quenching: opening angle dependence



Soft drop grooming
($\boldsymbol{\beta} = 0$ and $z_{cut} = 0.2$)
→
r_g – opening angle of the hardest splitting

ATLAS-CONF-2022-026



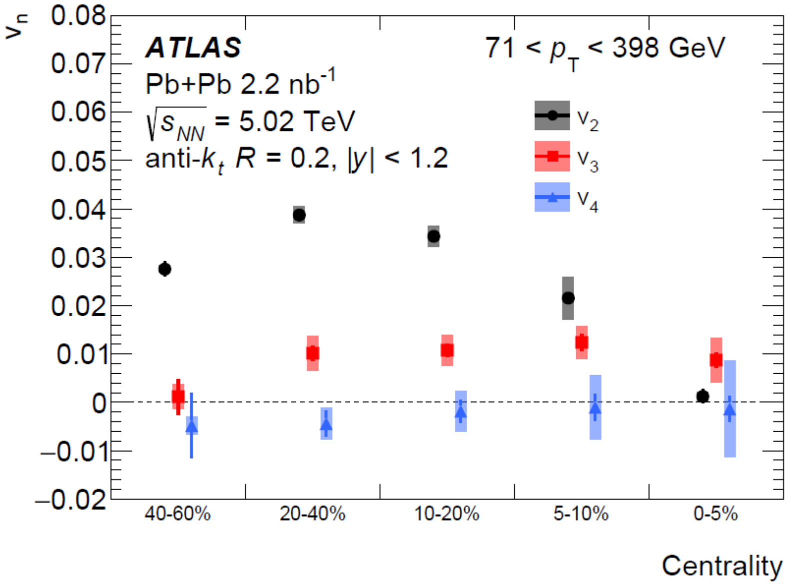


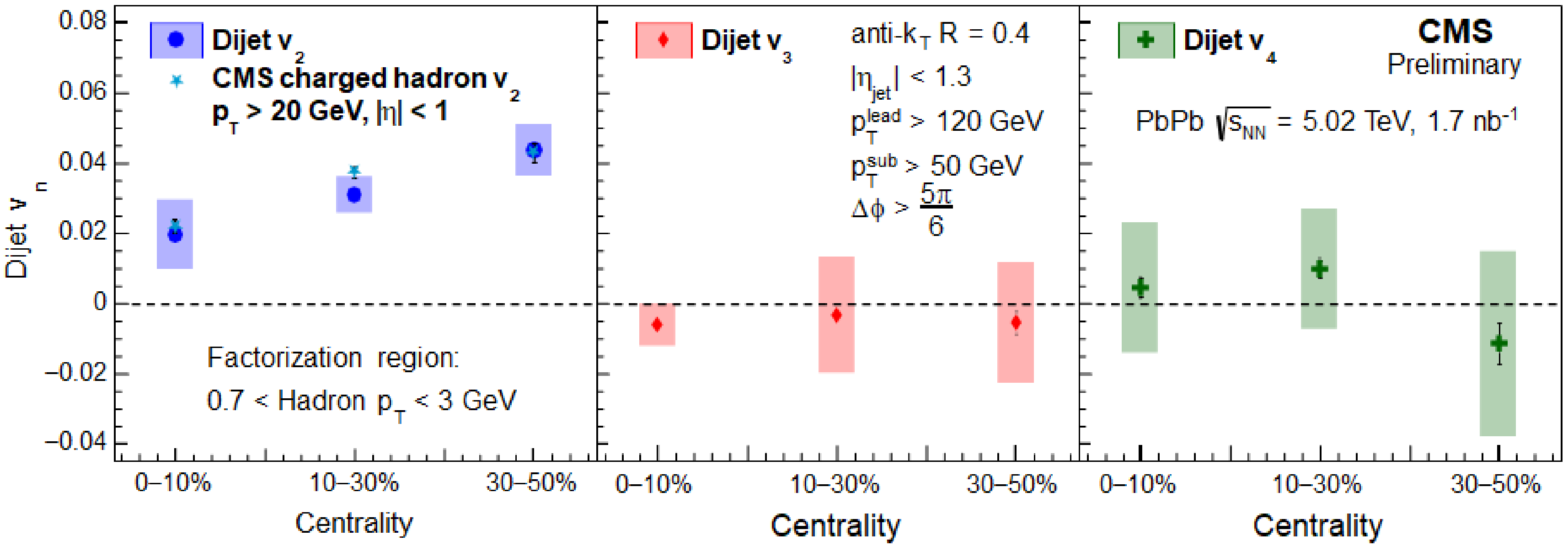
- Detailed measurement of jet energy loss dependence on opening angles:
  - R_{AA} depends significantly on opening angle of hardest splitting
  - Jet p_T dependence in r_g but not R_{AA} distributions

Jet and dijet anisotropies

ATLAS PRC 105 (2022) 064903

CMS arXiv:2210.08325

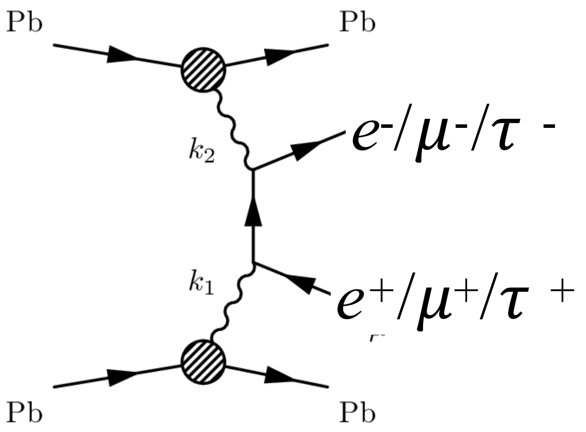


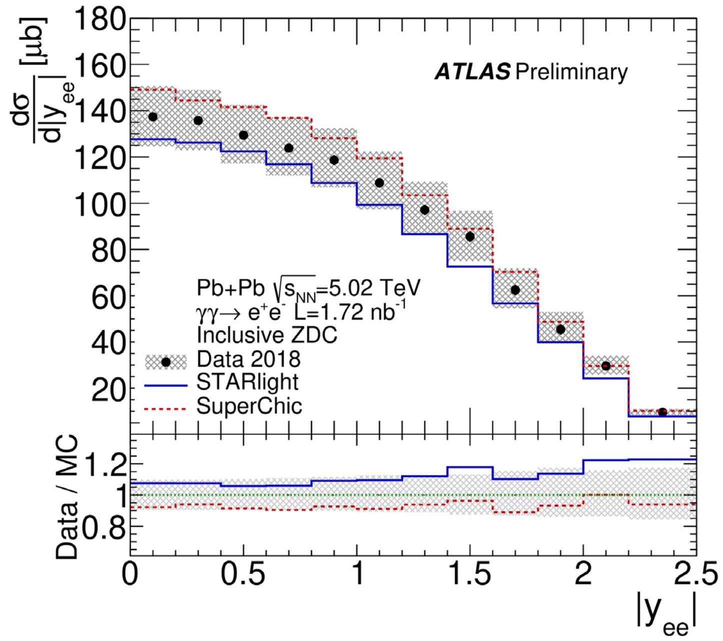


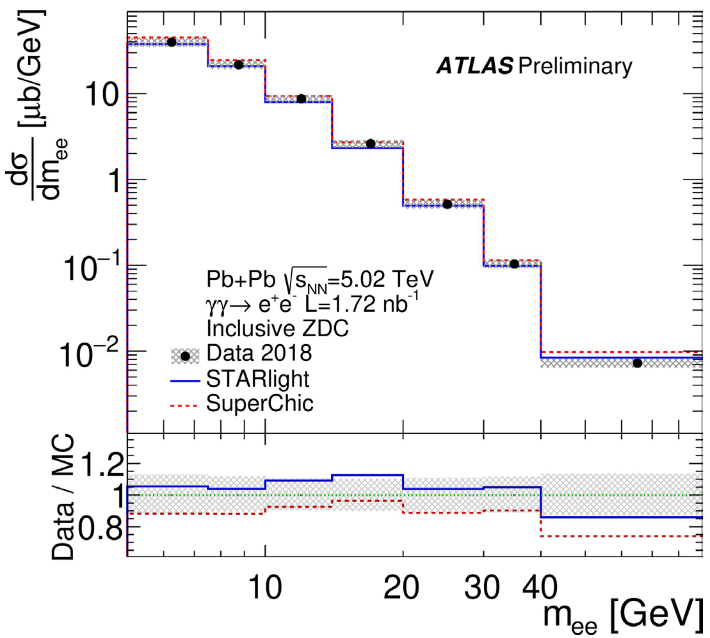
- Measurements of v_2, v_3, and v_4: ATLAS jets 71<p_T<398GeV, CMS dijet : p_{T1}>120 GeV, p_{T2}>50 GeV, $\Delta\phi > 5/6$
- Significant v_2 for all centralities (most central ATLAS?) – constrains path-length dependence of quenching
- v_3, v_4 –sensitivity to density/geometry fluctuations. Differences in selections/non-flow? Uncertainty-limited

UPC dilepton production: $\gamma\gamma \rightarrow ee$

ATLAS-CONF-2022-025





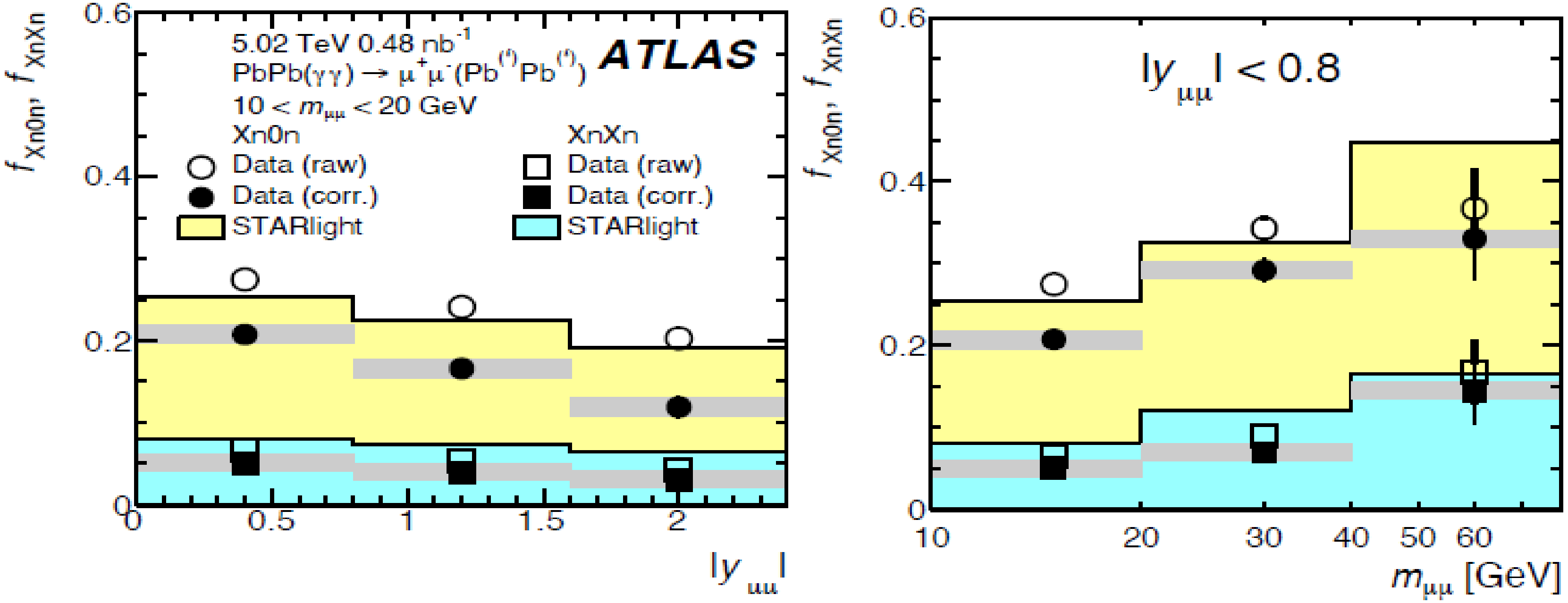


cross sections in inclusive and 0n0n ZDC events

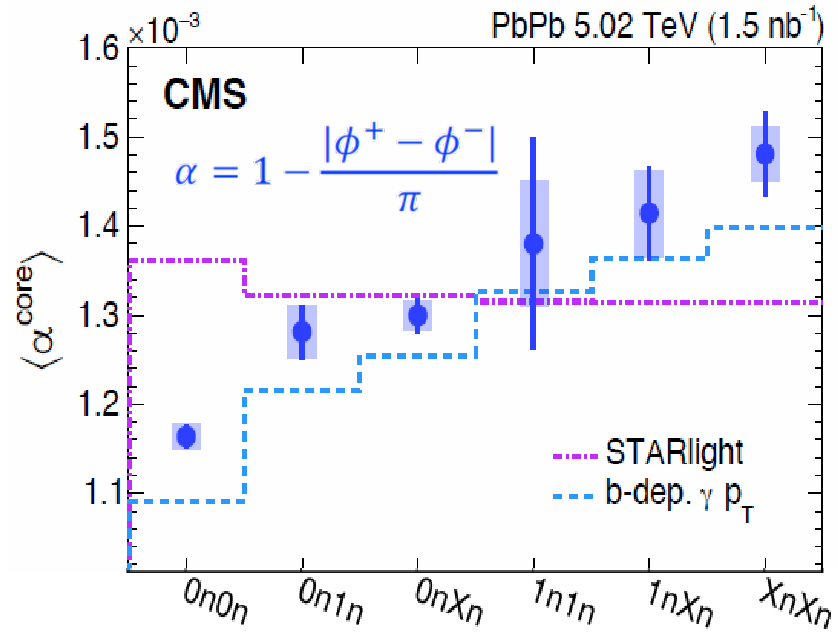
- UPC dilepton production is one of the fundamental processes in $\gamma\gamma$ interaction
- Exclusive $\gamma\gamma \rightarrow ee$ benchmark process for other γ induced processes
- Provides new constraints on photon fluxes from nuclei

UPC dilepton production: $\gamma\gamma \to \mu\mu$

ATLAS PRC 104 (2021) 024906



CMS PRL 127 (2021) 122001

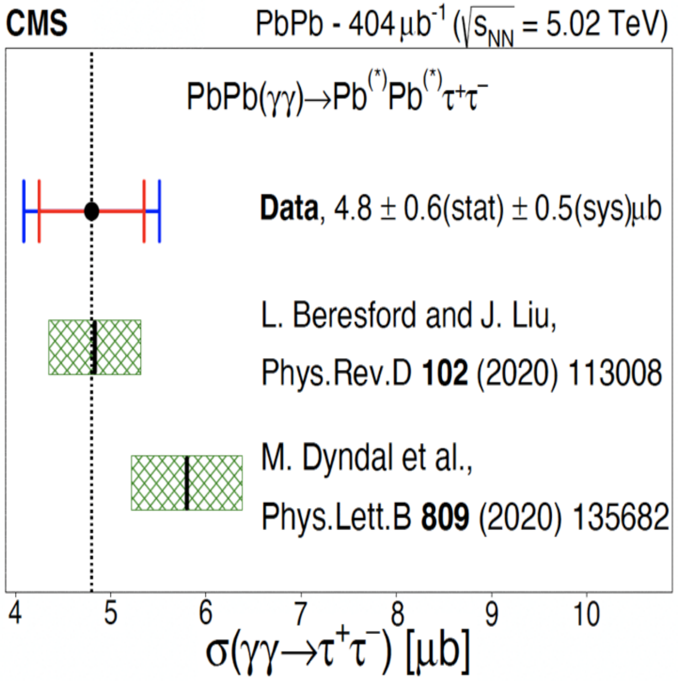


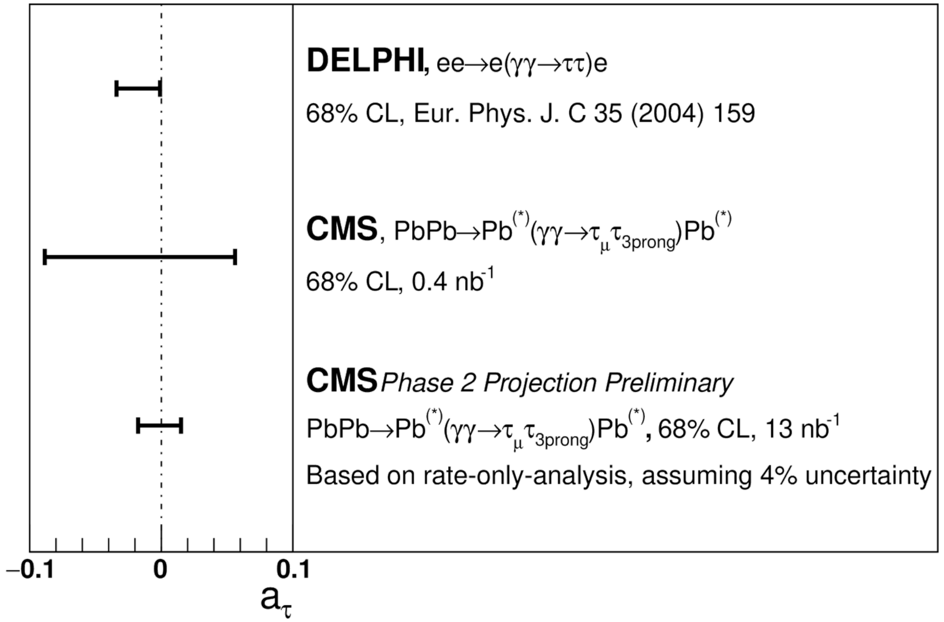
- Forward neutron multiplicity dependence of dimuon distributions:
  - Events with neutrons have a harder $m_{\mu\mu}$ spectrum and narrower $y_{\mu\mu}$
- Dimuon acoplanarity:
  - Clear impact parameter dependence
  - QED calculations need b-dependence of initial photon p_T

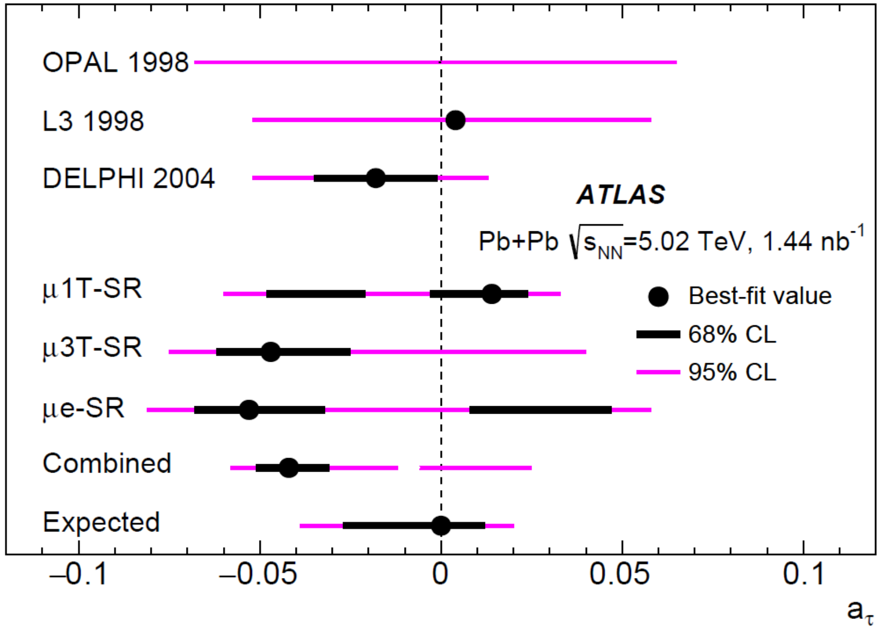
UPC dilepton production: $\gamma\gamma \to \tau\tau$

CMS arXiv:2206.05192

ATLAS arXiv:2204.13478







- Observation of $\gamma\gamma \to \tau\tau$ by both CMS and ATLAS in UPC heavy ion collisions
- Constrains the anomalous magnetic moment $a_\tau = \frac{(g-2)_\tau}{2}$ for the first time at the LHC

Summary and Outlook

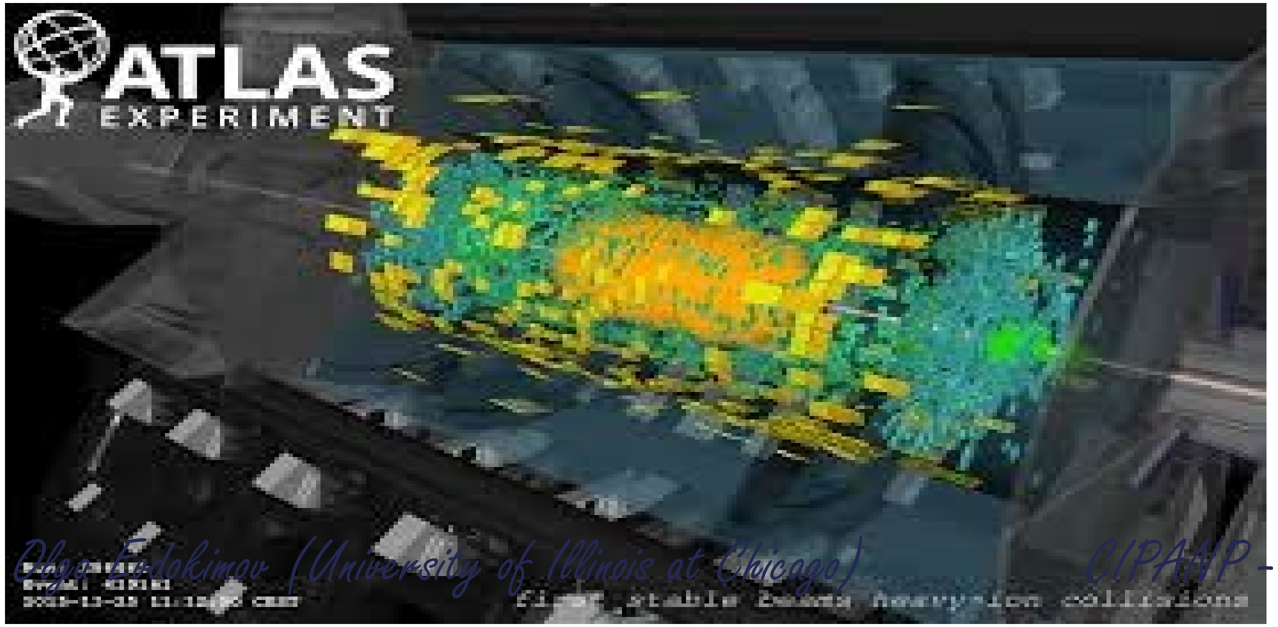
- Wealth of experimental data on initial state, collision dynamics, and medium properties at LHC energies

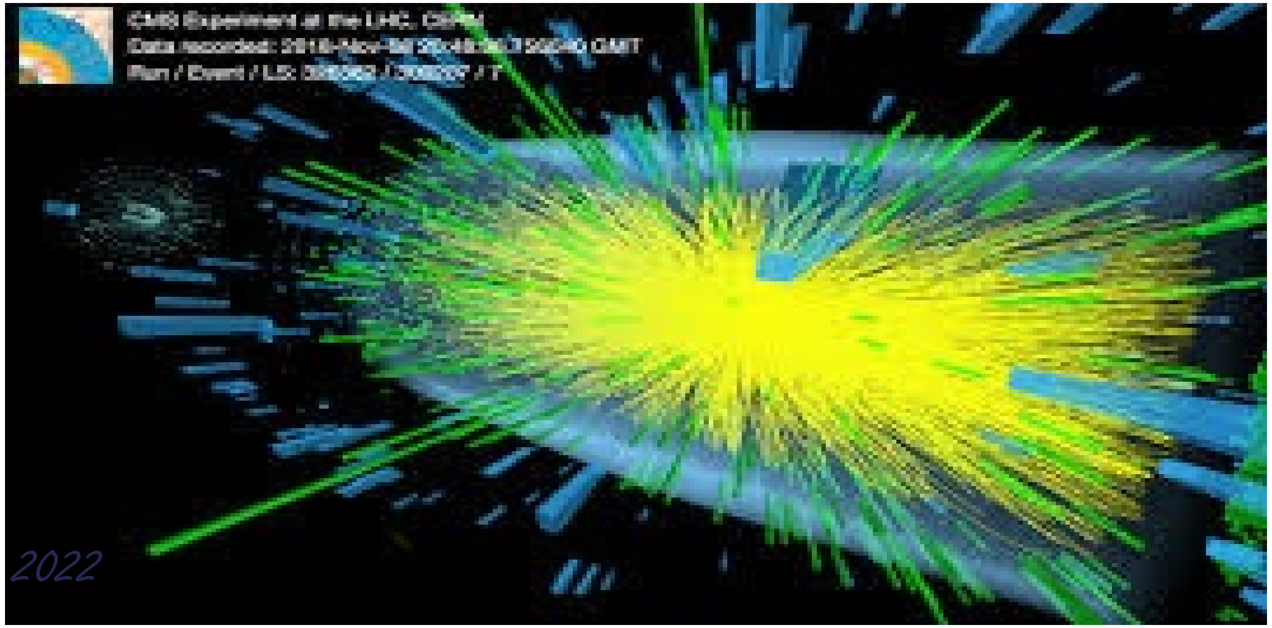
- Flavor dependence on parton-medium coupling:
  - $v_2(s, \text{light}) \gtrsim v_2(c) > v_2\,(b)$; $R_{AA}(b) > R_{AA}(c) \approx R_{AA}(s, \text{light})$
  - New insights on quarkonia melting
- Jet probes explore color-charge and parton flavor dependance of quenching and highlight the importance of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

More work to be done!

Thank you!

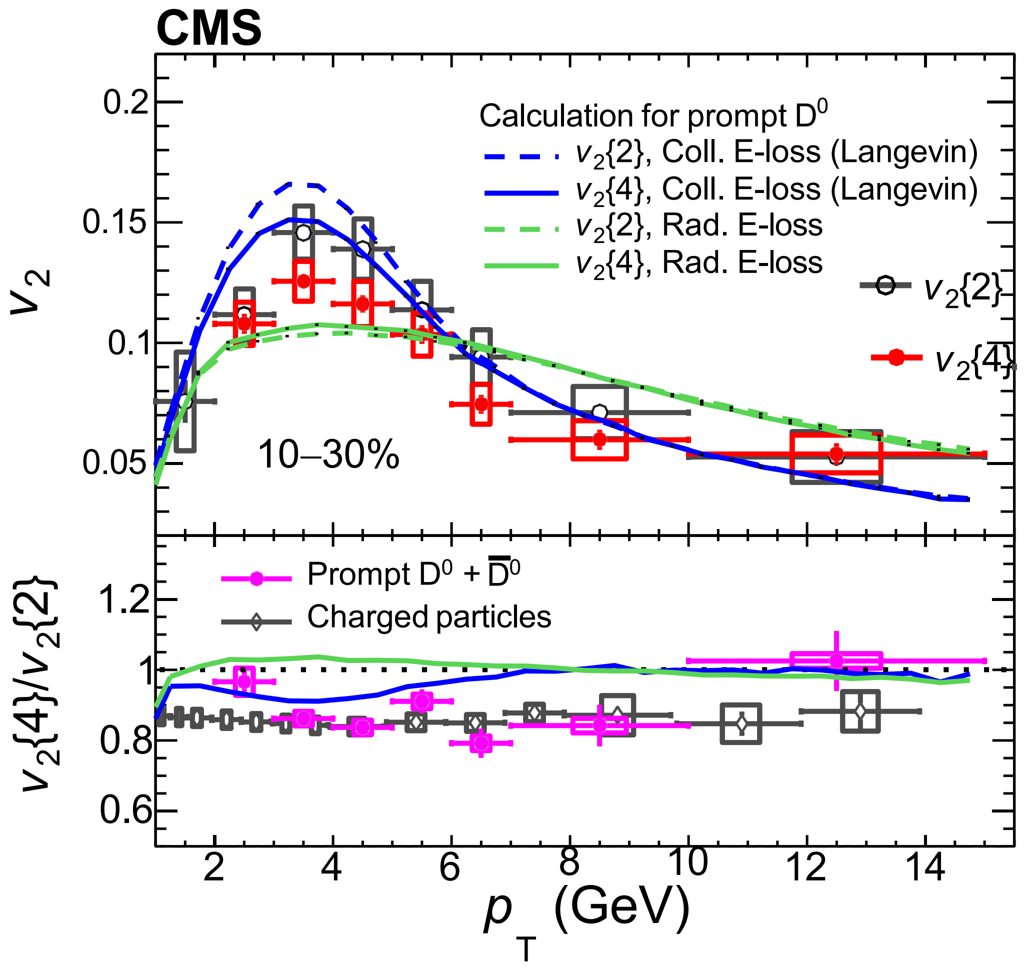
The UIC Group's work is supported by US DOE-NP





Heavy flavor: anisotropies

PRL 129 (2022), 022001



- 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