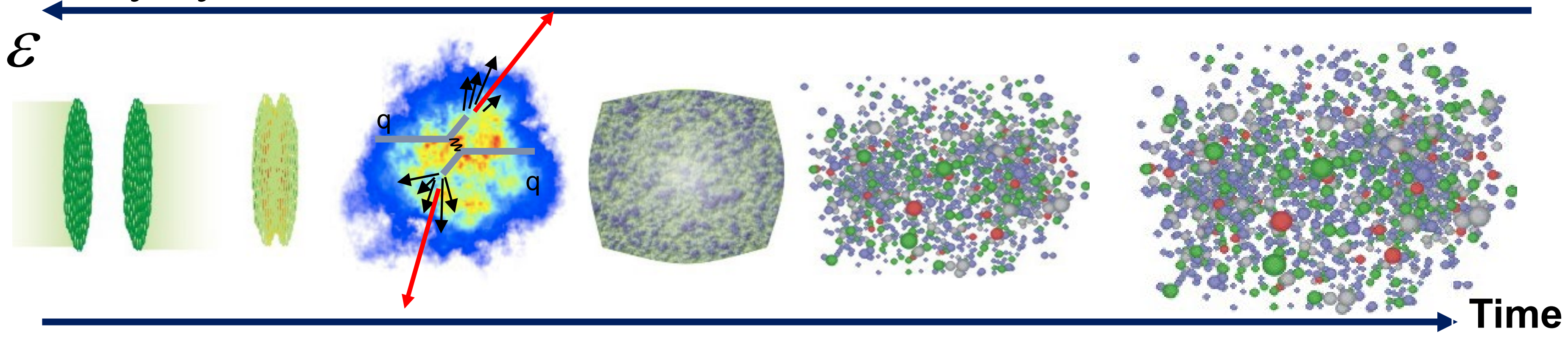
Recent highlights on QCD and QED studies with heavy ion collisions

Outline:

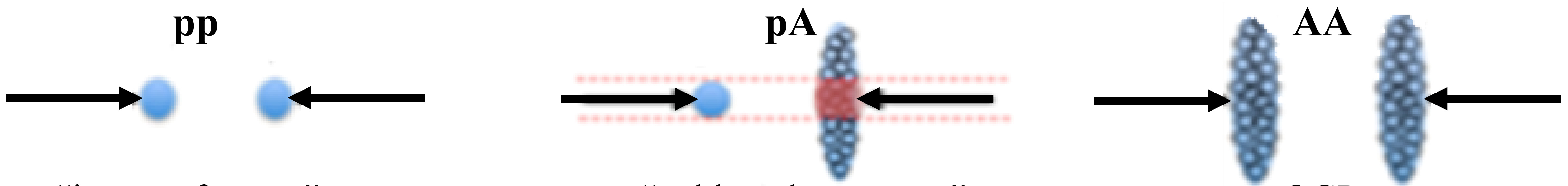
- "Standard Model" of heavy ion collisions: a complex dynamics of intrinsically many-body system



- A (biased) selection of recent experimental results:
  - 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"

- **System size for control over initial and final state effects**



"just a reference"	"cold nuclear matter"	QGP
for hard processes/ vacuum fragmentation	initial state effects (e.g., shadowing, anti-shadowing,)	with centrality "dial" final state effects

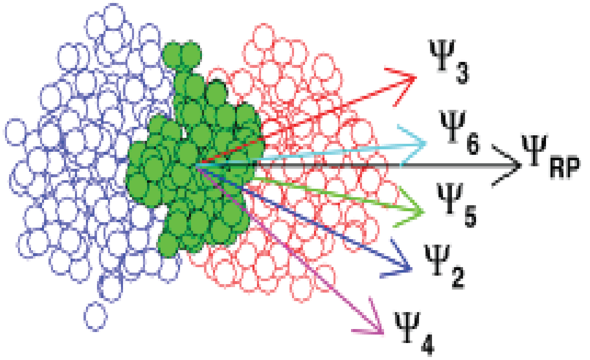
Now: changing paradigm of the old division, blurring the edges of applicability of initial/final state language; interesting new phenomena across the board.

Introduction: "tools of the trade"

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

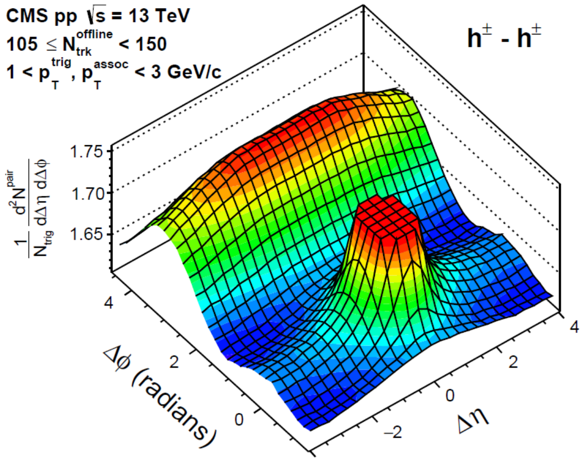
$$\frac{d^3N}{p_T dp_T d\eta d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T d\eta}\left(1+\sum_{k=1}^{\infty} 2v_{n=km}(p_T,\eta)\cos\left[n(\phi-\Psi_m)\right]\right)$$

Glauber-based picture:



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

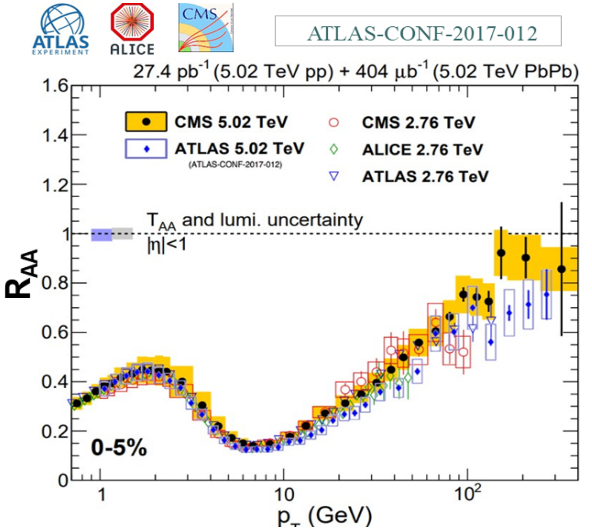
CMS PLB 765 (2017) 193



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

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

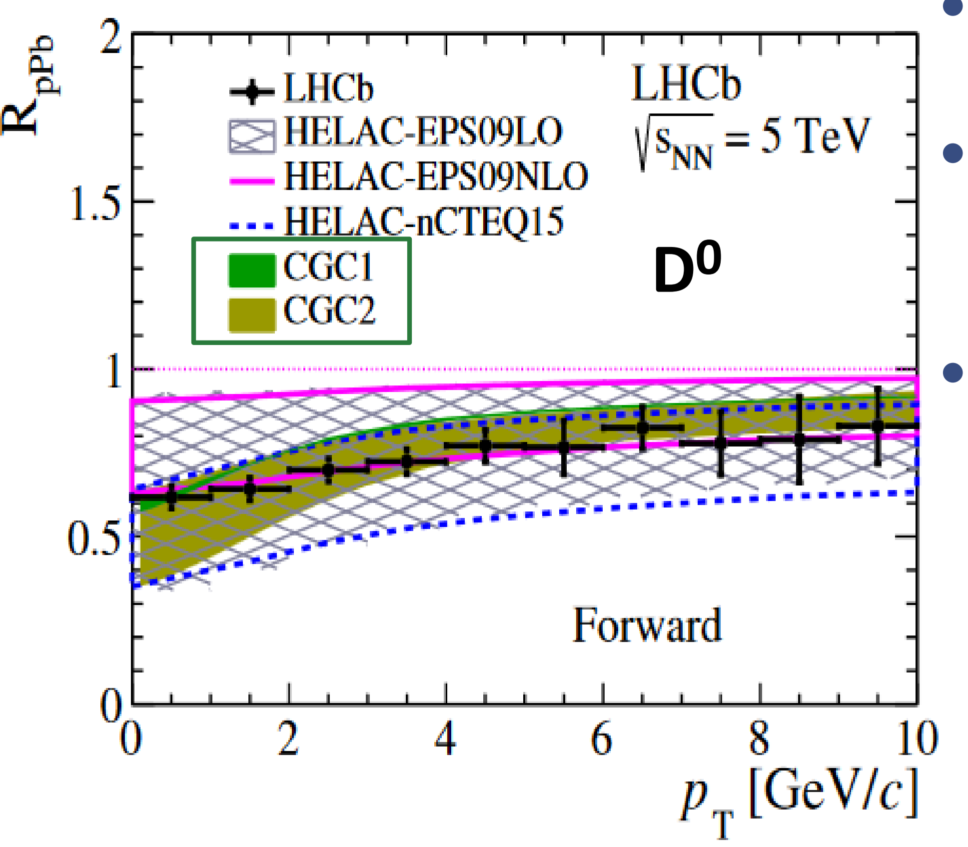
ATLAS-CONF-2017-012

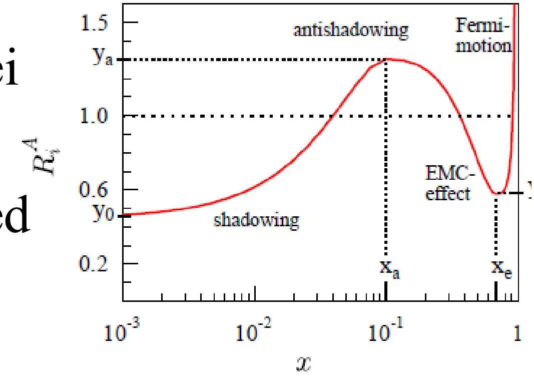


*Number of binary collisions N_{bin} is extracted from Glauber calculations

Understanding initial state

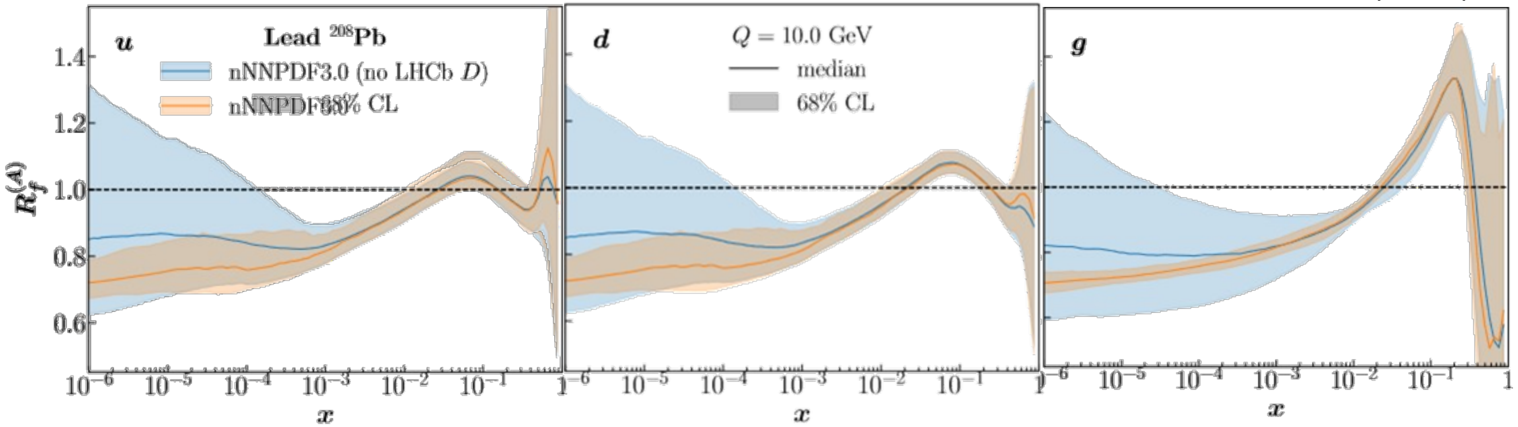
LHCb, JHEP 10 (2017) 090





- Nuclear PDFs: parton densities modified in nuclei with respect to free nucleon PDF
- Low-x ("shadowing") region is poorly constrained by previous data
- LHCb forward prompt D^0 R_{pA} – major reduction of nPDF uncertainties down to $x{\sim}10^{-6}$

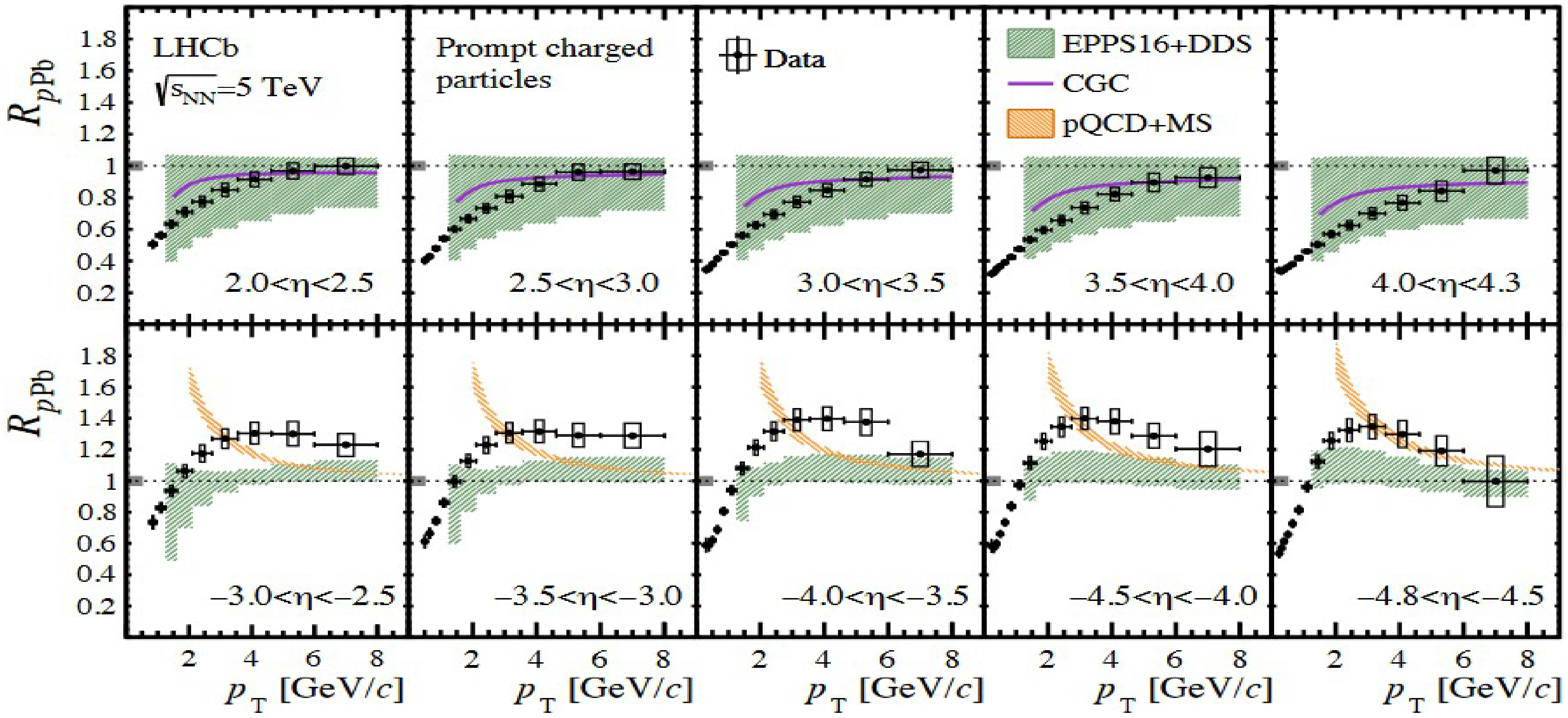
Khalek et al. EPJ C 82 (2022) 6



Understanding initial state

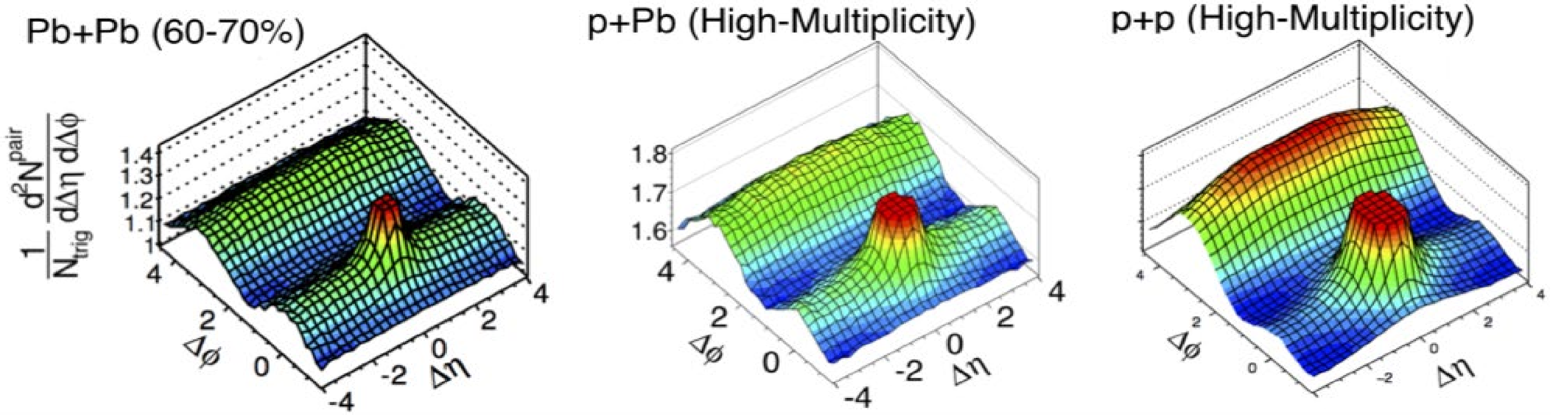
More nuclear modification factor measurements from pPb data

LHCb PRL 128 (2022)142004

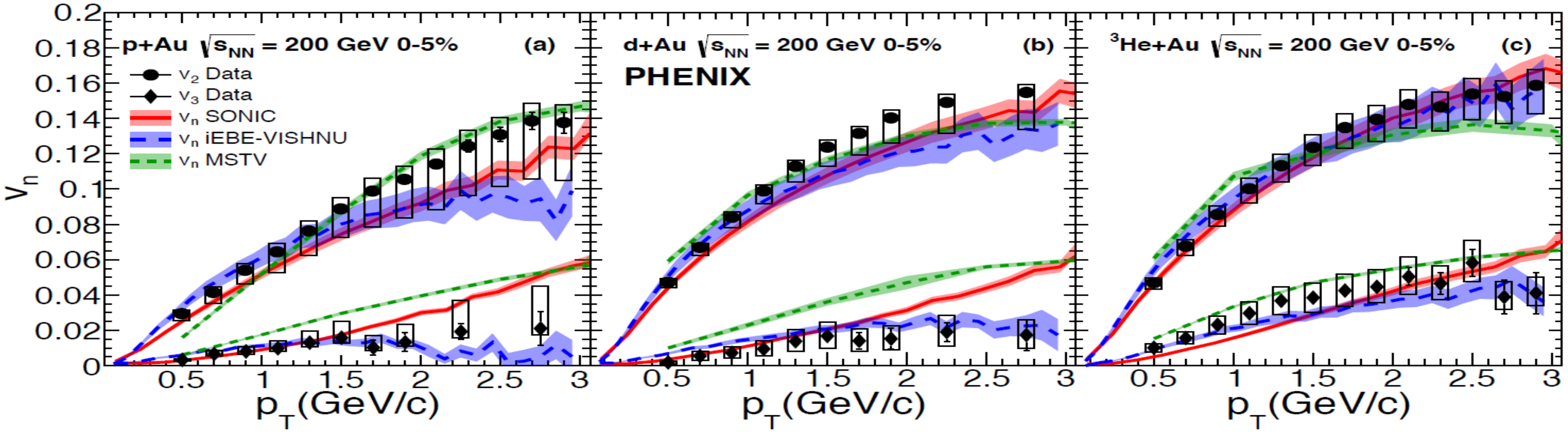


- New measurements for nuclear modification with charged hadrons
- Suppression at forward rapidities
  - Captured by several models
- Enhancement at backward rapidities
  - Presents difficulty for the models
  - No simultaneous description of RHIC and LHC

Collectivity in small systems



PHENIX NP15 (2019) 214; PRC105(2022) 024901



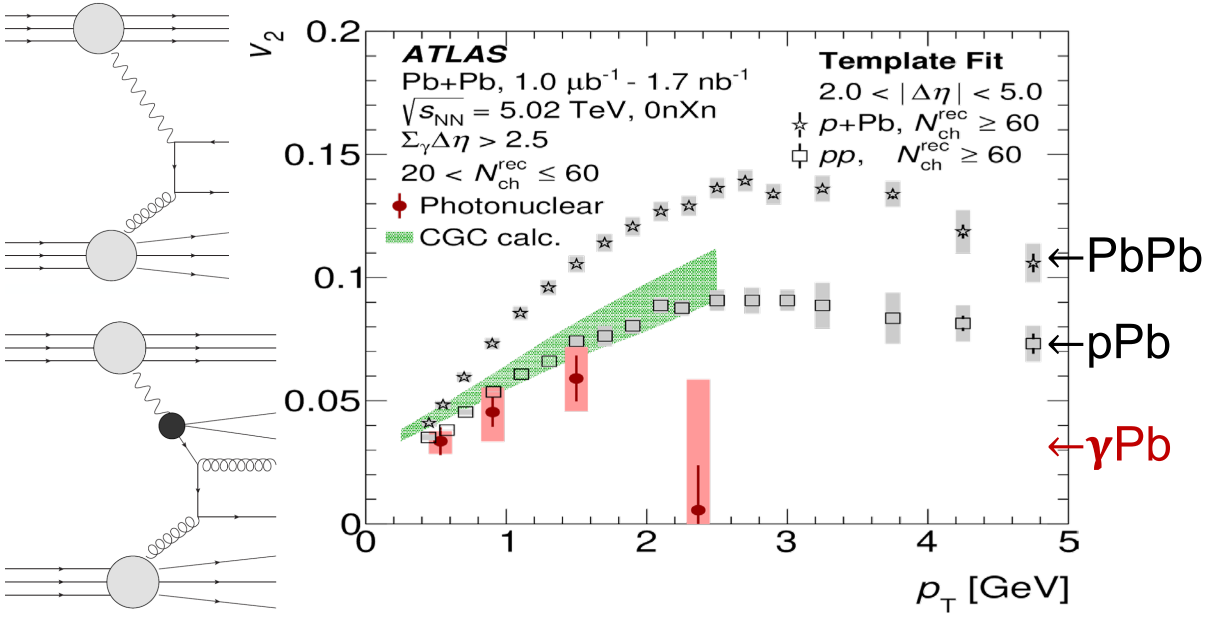
- Discovery of collective effects in small systems:
  - CMS: high multiplicity pp @ 7 TeV and pPb @ 5 TeV
  - PHENIX: pAu, dAu, ^{3}HeAu @ 200GeV

- Long range correlations: everywhere!
  - Can the system that small reach an equilibrium?
  - Could this be an initial state phenomena? CGC?
  - NOT reproduced for pp in any established MC generators
  - Details of nucleon structure is critical for understanding these phenomena

Collectivity in small systems

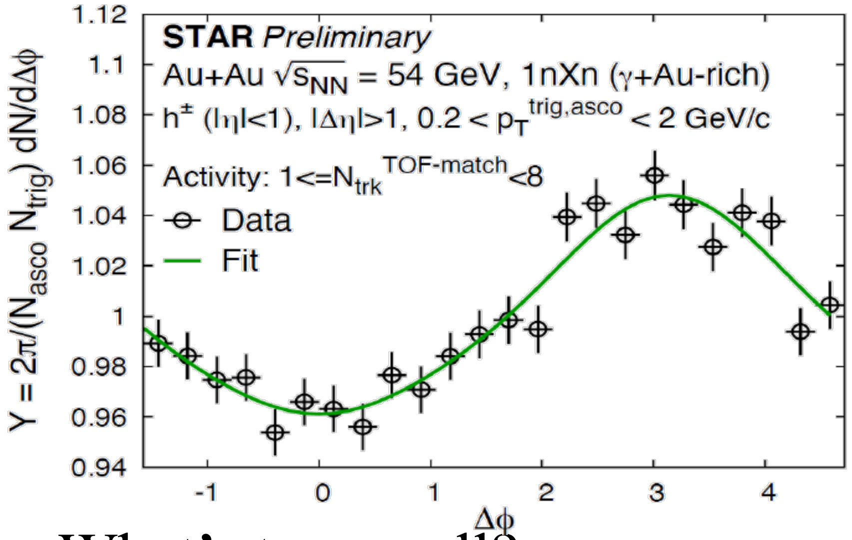
- Anisotropies in ever-smaller systems

  ATLAS: PRC. 104 (2021) 014903

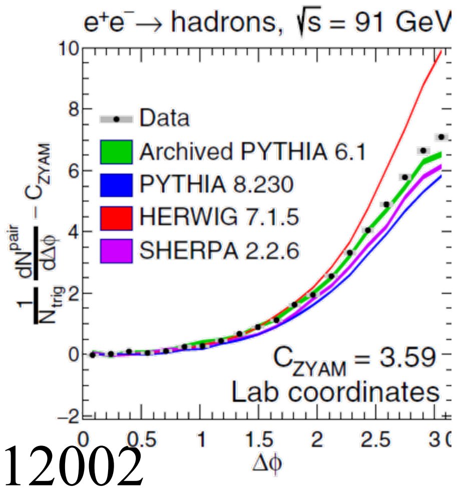


- Non-zero v_2 in γPb collisions
- Consequence of **ρ**Pb interactions? CGC?

- STAR: correlations from γAu collisions
  - No non-flow subtraction yet – a critical step!



What's too small?

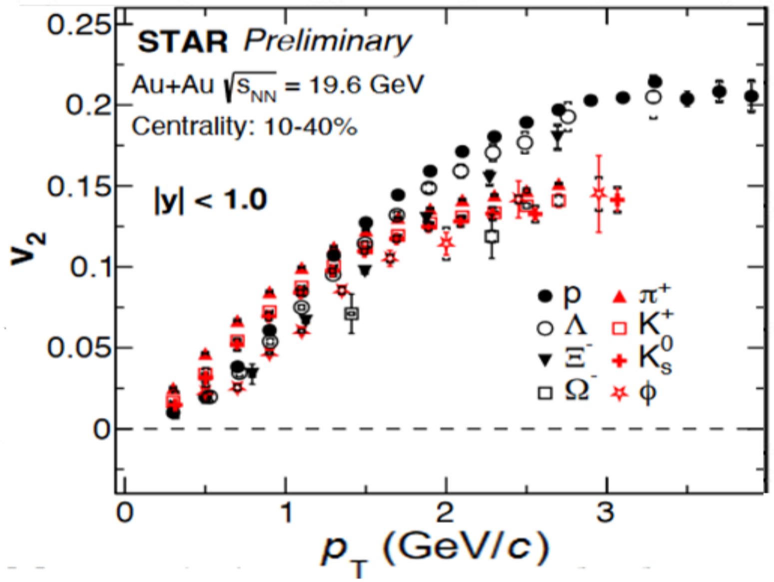


- ALEPH: e^+e^- PRL123(2020)212002
- ZEUS *ep* JHEP04(2020)070
  - No ridges at high multiplicity, described by MC

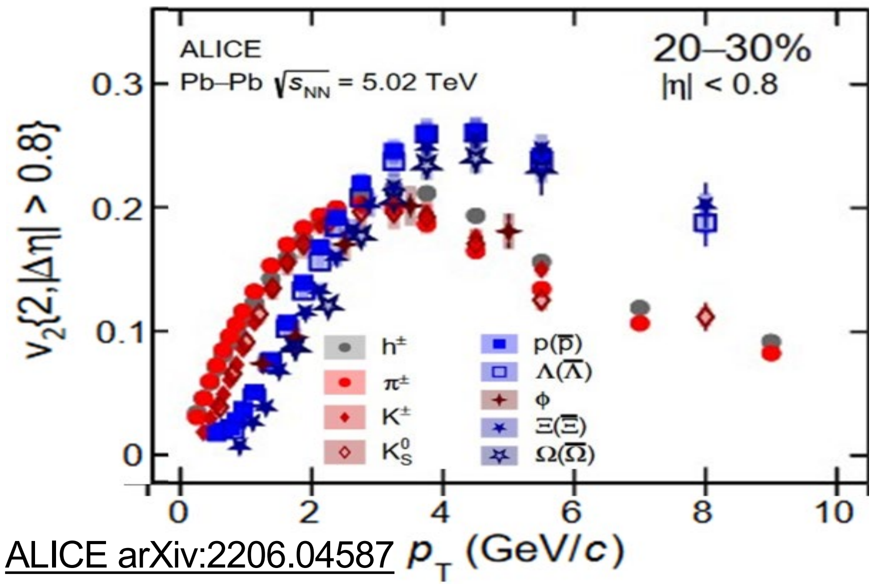
More on collectivity

- Anisotropic elliptic flow for identified particle species:

AuAu 19.6 GeV

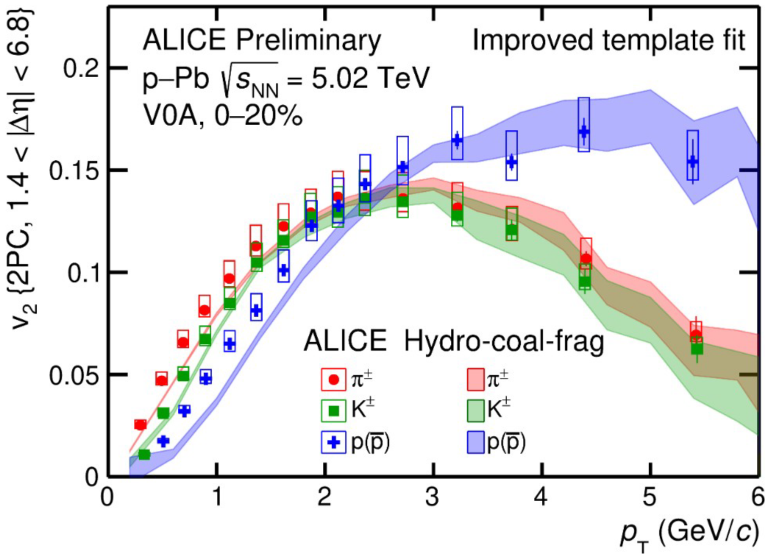


PbPb 5.02 TeV



ALICE arXiv:2206.04587

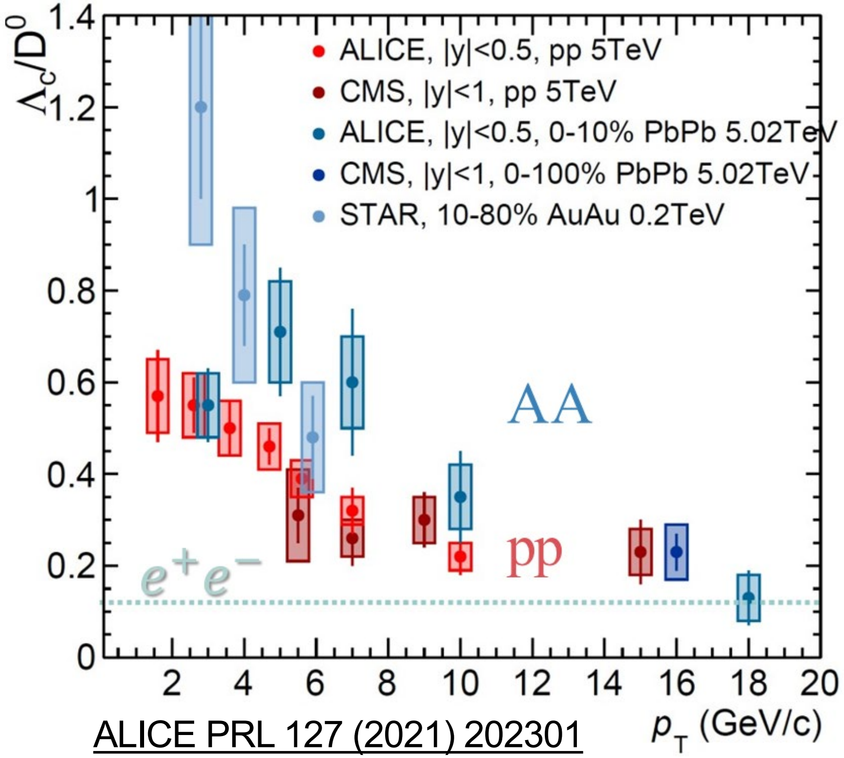
pPb 5.02 TeV



- Common for all energies and systems: mass ordering at low p_T, baryon/meson grouping at intermediate p_T
- Hadronization through recombination/coalescence ↔ partonic origin of the flow

Understanding hadronization

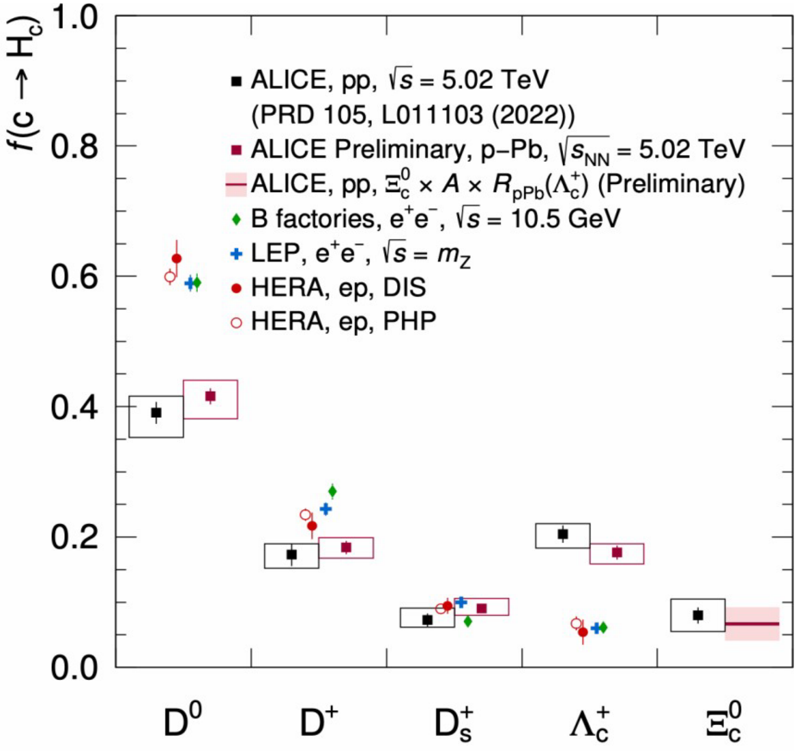
- Charm hadronization



ALICE PRL 127 (2021) 202301

CMS PLB 803 (2020) 135328

STAR PRL 124 (2020) 172301



- Baryon-to-meson ratios are sensitive to hadronization
- Enhancements are seen in light and strange sectors at RHIC and LHC

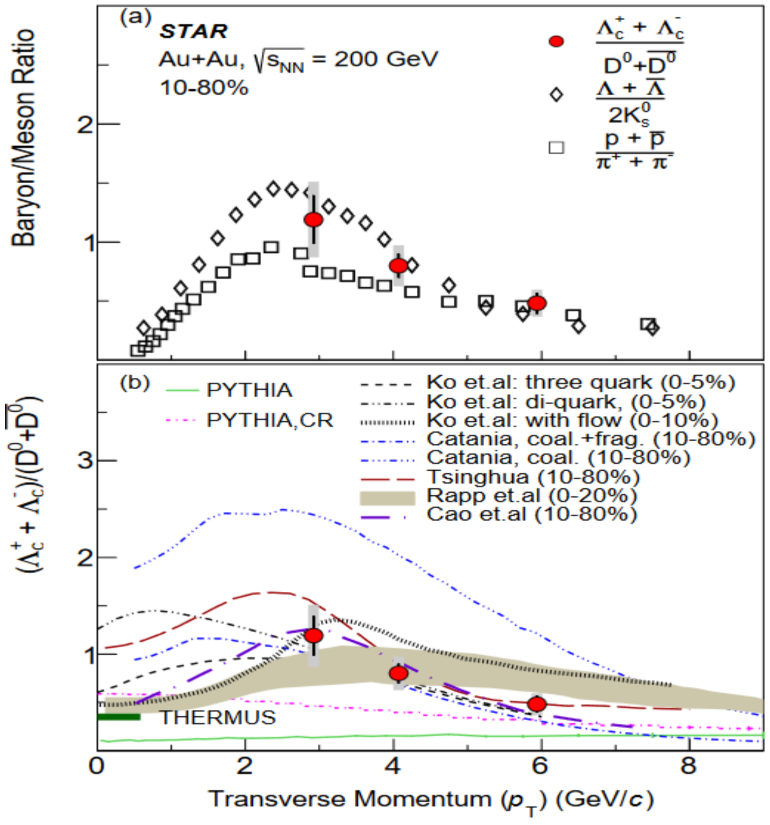
Charm sector: Λ_c/D^0

- High p_T: similar AA to pp ratios, enhancement at mid-p_T

- Most striking feature: enhancement over e^+e^-
- Charm-fragmentation fractions appear non universal

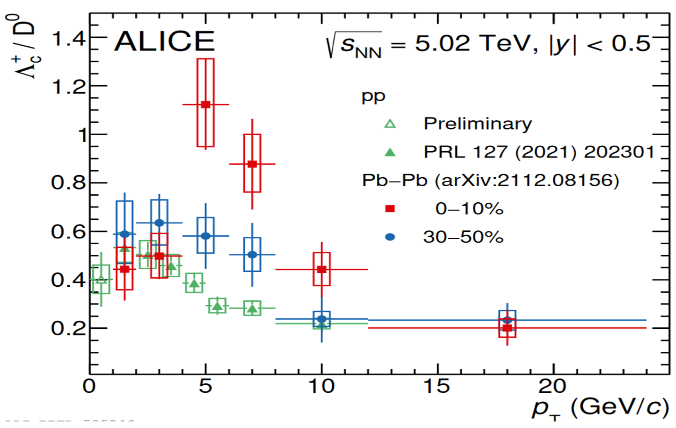
Understanding hadronization

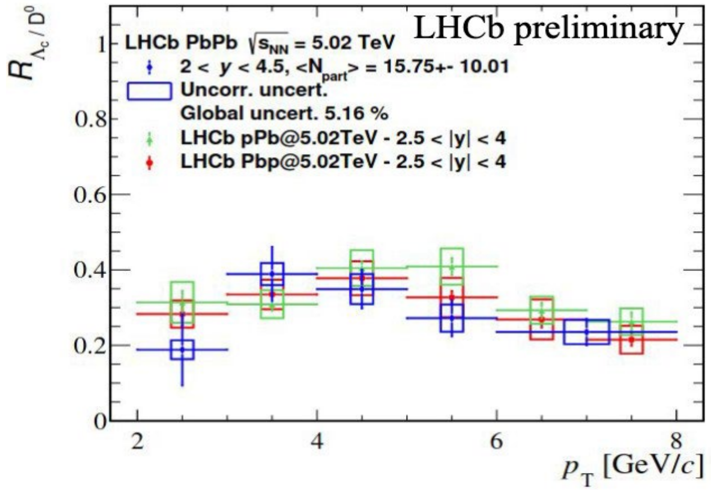
- A closer look at QGP effects



STAR PRL 124 (2020) 172301

ALICE PLB839 (2023) 137796





- Baryon-to-meson ratios are sensitive to hadronization
- Enhancements are seen in light and strange sectors at RHIC and LHC

Charm sector: Λ_c/D^0

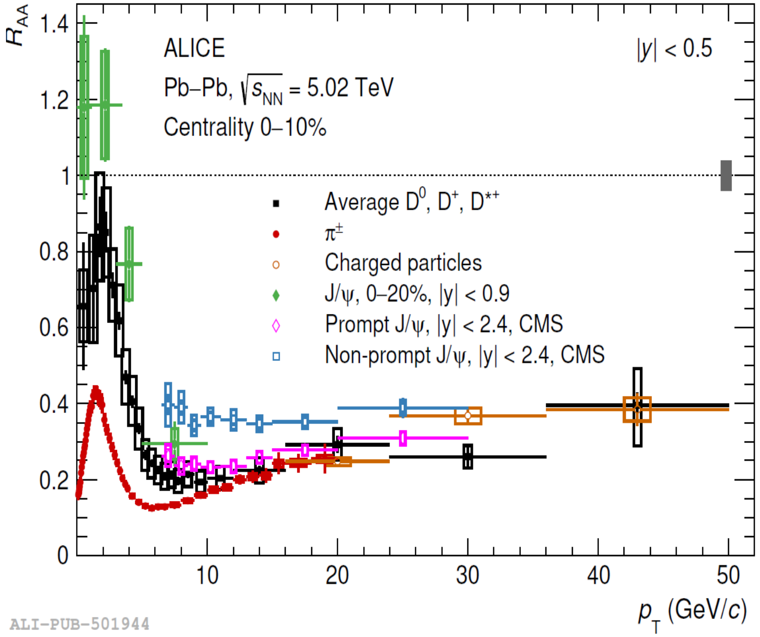
- Intermediate p_T: centrality dependent enhancement in AA over pp; peripheral ~ pp
- Enhancement levels are similar to that of light hadrons

- Parton recombination is likely contributing to charm hadronizations

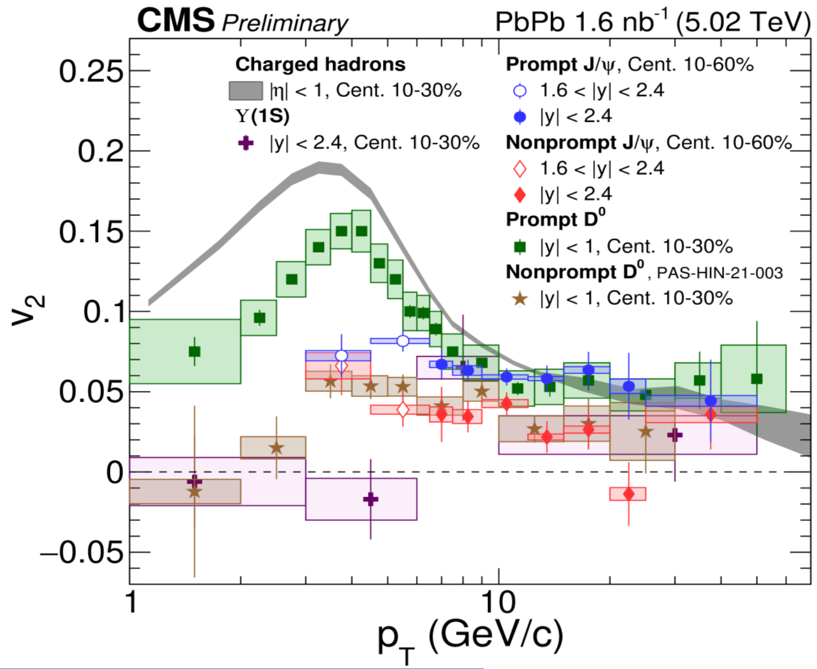
Medium effects on heavy flavor

- Nuclear modifications and anisotropies for heavy flavor hadrons:
  prompt- and non-prompt D^0 , prompt and non-prompt J/ψ, Υ

ALI-PUB-501944



CMS-PAS-HIN-21-001 CMS-PAS-HIN-21-008



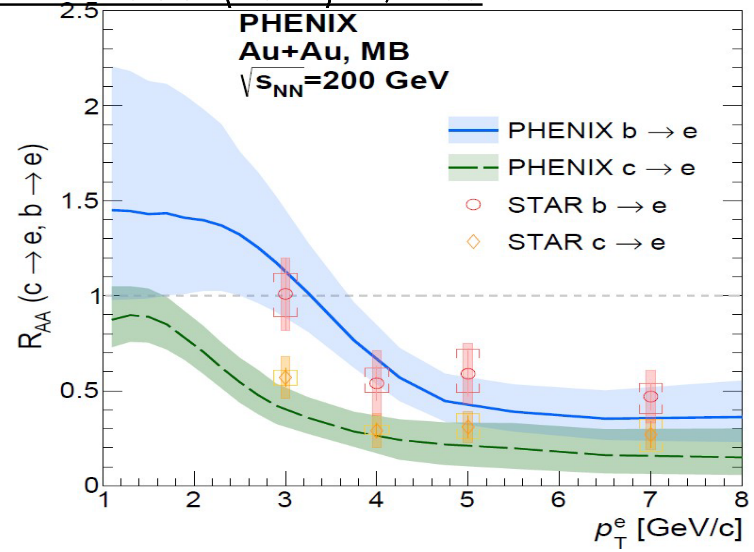
ALICE: $h^\pm$, D^0 , D^+, D^-, J/ψ
CMS: $h^\pm$, prompt & non-prompt J/ψ, prompt & non-prompt D^0, $\Upsilon(1S)$

- Mid-p_T : flavor dependence of energy loss
  - $R_{AA}(b) > R_{AA}(c) \sim R_{AA}$(light flavors)
  - $v_2(b) < v_2(c) \sim v_2$(light flavors)
- High p_T : radiative energy loss dominates
  - $R_{AA}(b) \sim R_{AA}(c) \sim R_{AA}$(light flavors)
  - $v_2(b) \sim v_2(c) \sim v_2$(light flavors)
- Need high precision simultaneous measurements of R_{AA} and v_2

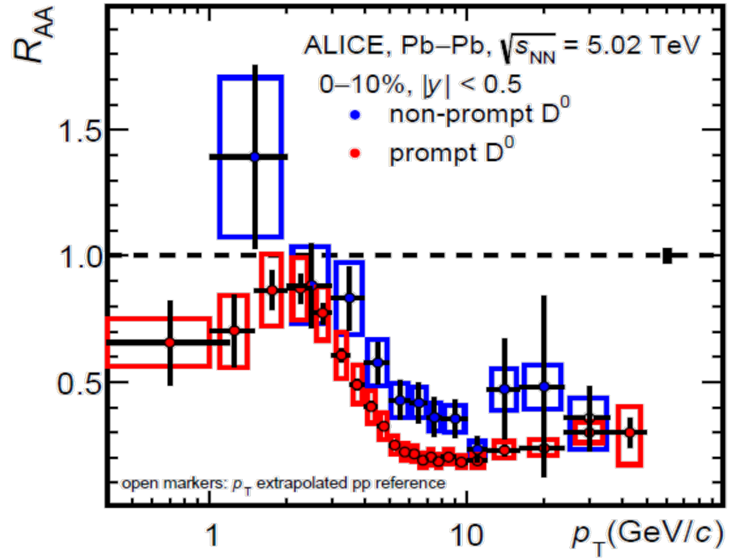
Heavy flavor: nuclear modification

- Measurements of heavy flavor nuclear modification factors from RHIC and LHC:

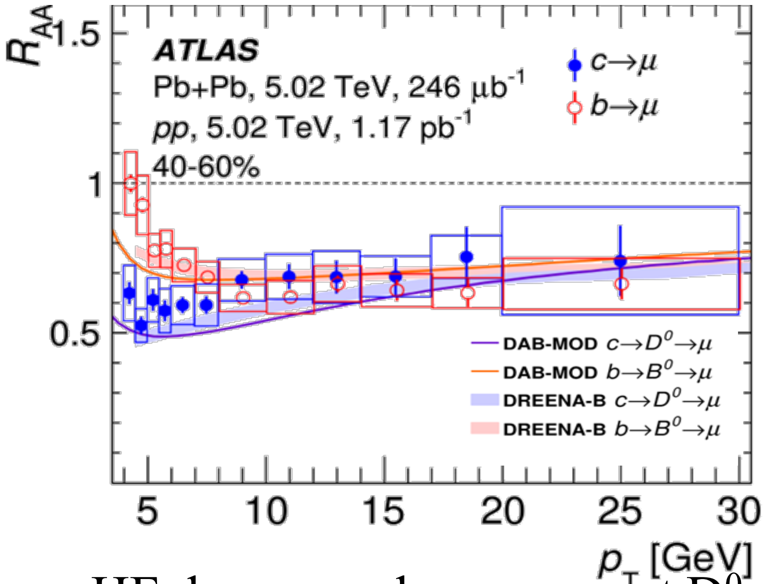
PHENIX arXiv:2203.17058
STAR EPJC82(2022)12,1150



ALICE JHEP 12 (2022) 126



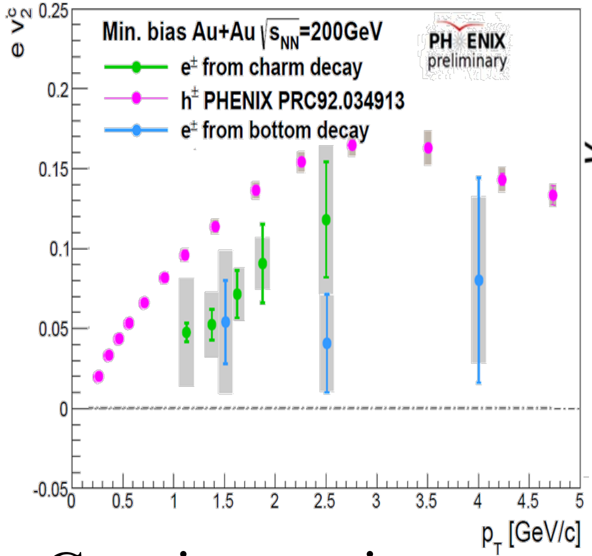
ATLAS PLB 829 (2022) 137077



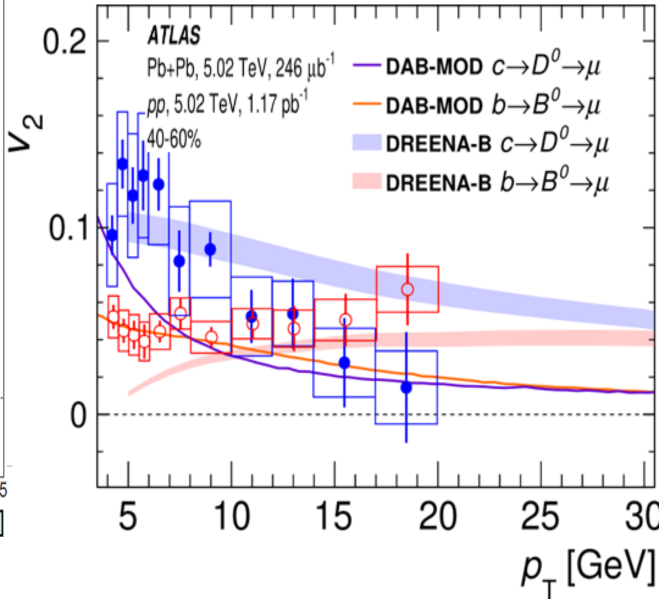
- Energy loss mechanisms and QGP expansion modeling – R_{AA} for leptons from HF decays and non-prompt D^0
- Mass splitting at low p_T , similar behavior at high p_T
- Less suppression for beauty, at least in the intermediate p_T regime

PHENIX, STAR: *e* from HF decays
ATLAS: μ from HF decays
ALICE: prompt and non-prompt D^0

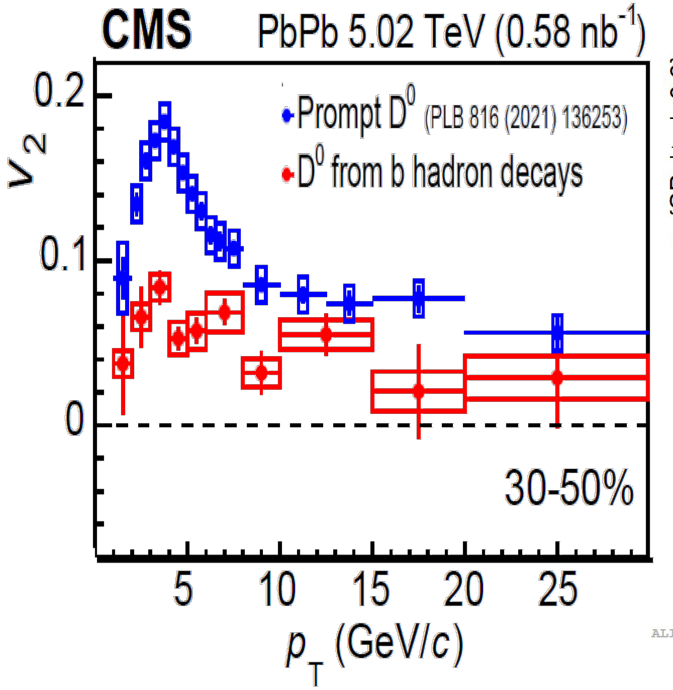
Heavy flavor: anisotropies



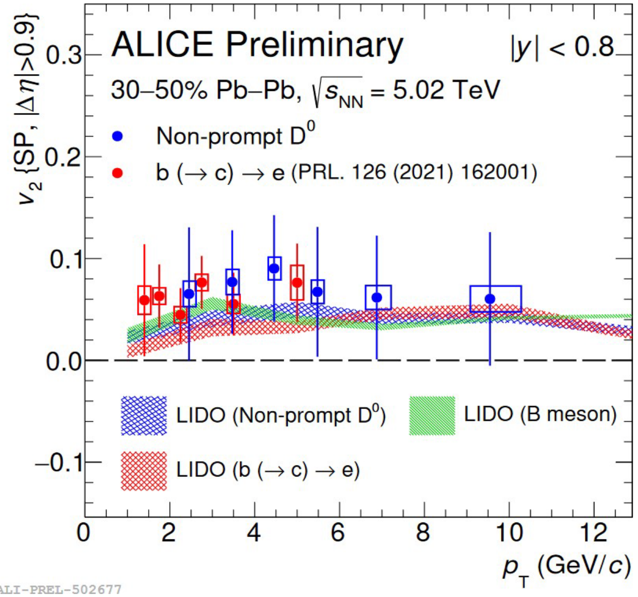
ATLAS PLB 829 (2022)137077



CMS arXiv:2212.01636



ALI-PREL-502677



Consistent picture:

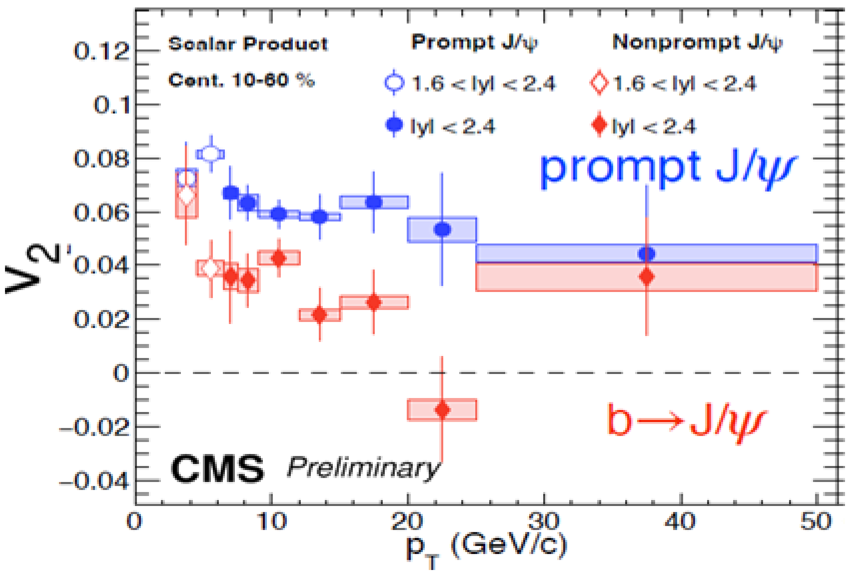
- Significant v_2 for charm and bottom
- Initial raise consistent with hydro expansion; high p_T – path-length dependence of energy loss
- Higher degree of parton-medium coupling for charm than bottom

PHENIX: *e* from HF decays
ATLAS: *μ* from HF decays
CMS: prompt and non-prompt D^0
ALICE: non-prompt D^0 and e from HF decays

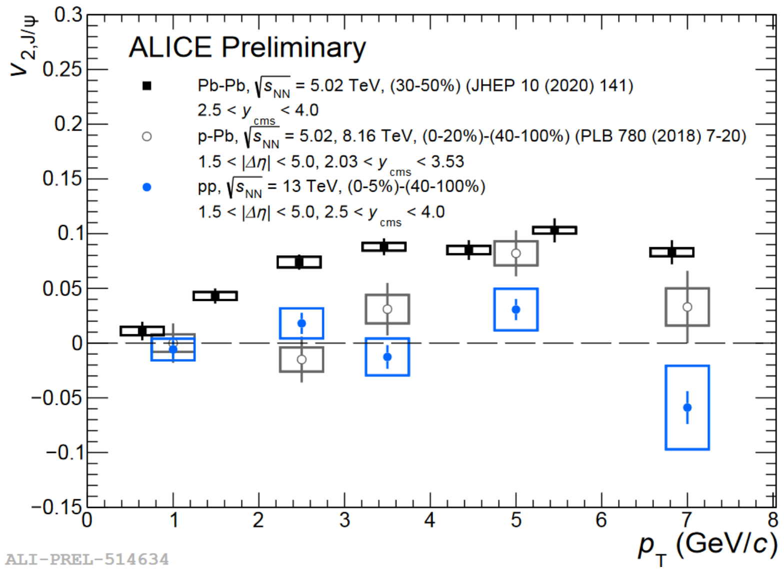
Quarkonia: anisotropies

- What about quarkonia? Everything "flows"!

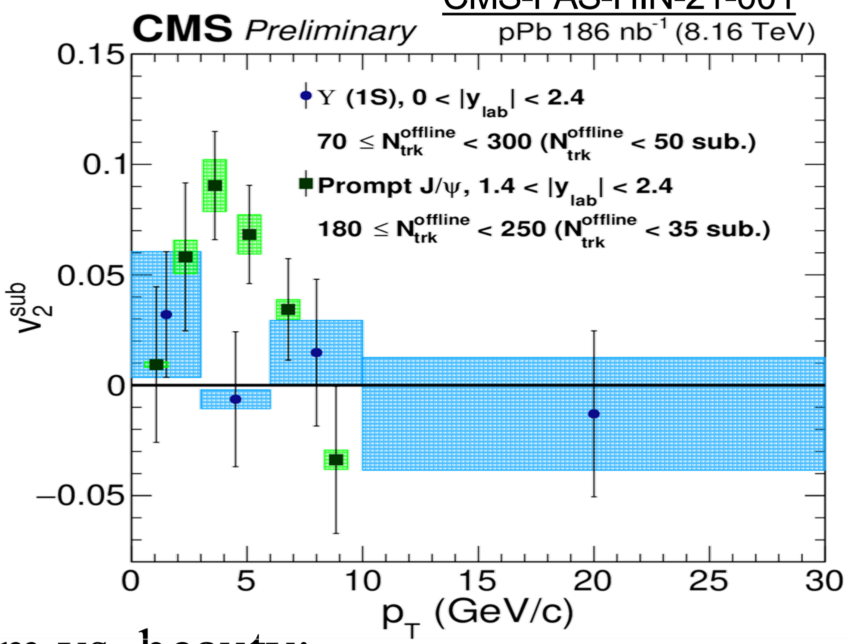
PLB 816 (2021) 136253



ALICE-PREL-514634



CMS-PAS-HIN-21-001

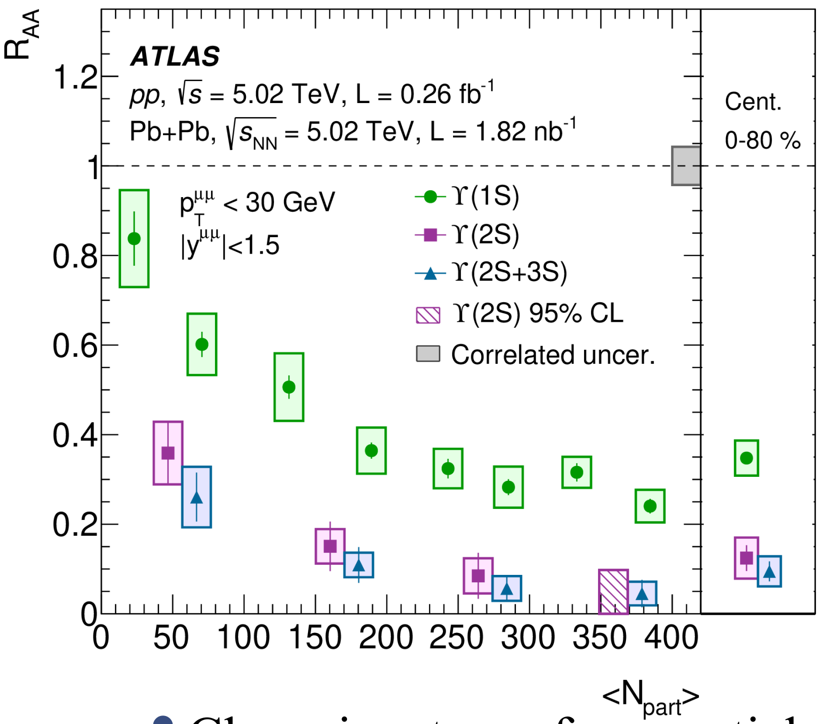


- **Large systems** – charm vs. beauty:
  - Larger v_2 for prompt J/ψ than b → J/ψ: smaller v_2, high p_T behavior?

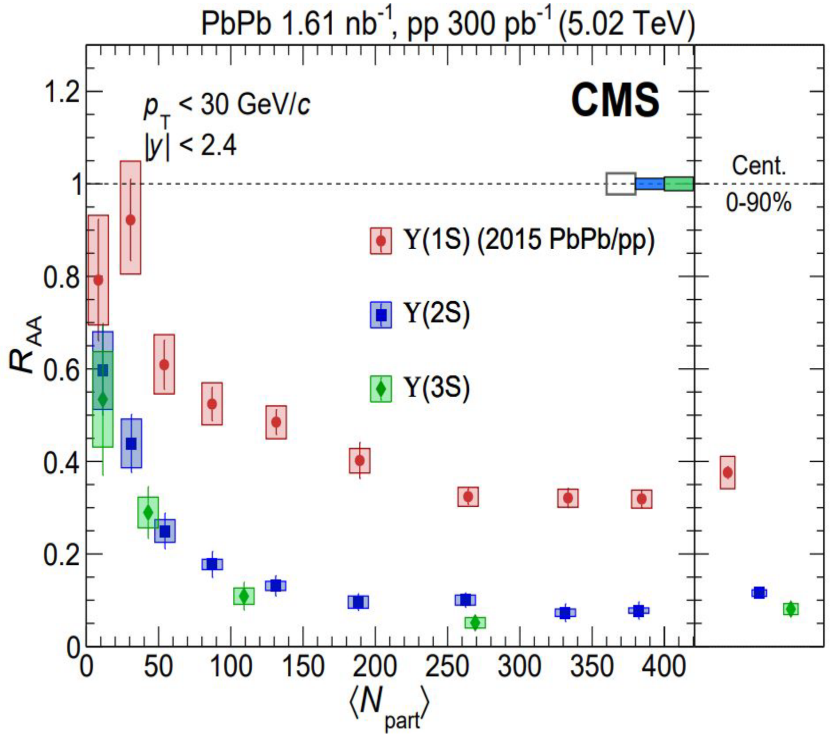
- **Small systems** – charm vs. beauty:
  - Prompt J/ψ: still flows!;
  - Υ(1S) – no significant v_2 even in high multiplicity events (but none was seen even in PbPb).

Quarkonia: melting

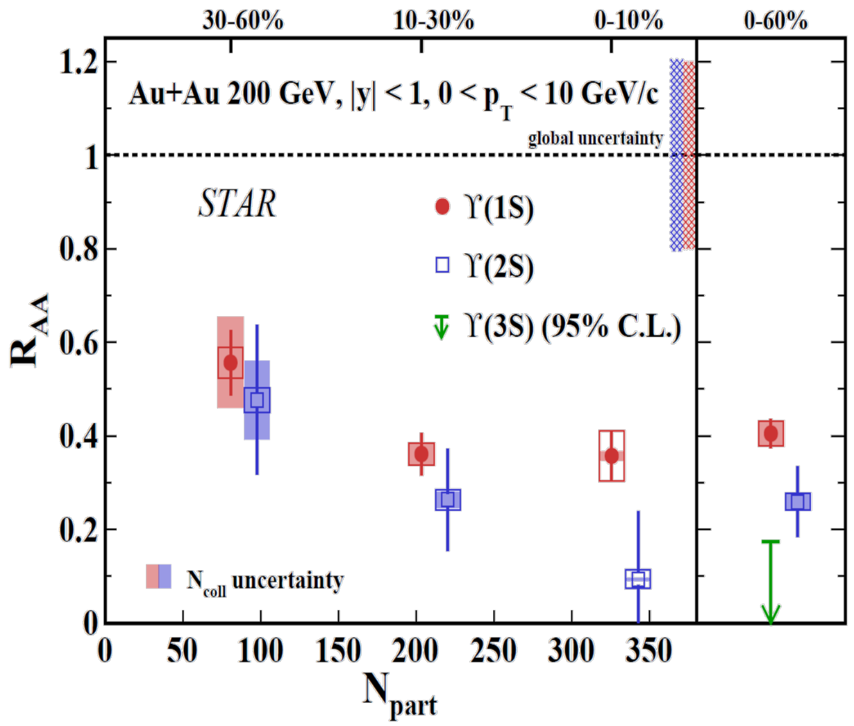
ATLAS arXiv:2205.03042



CMS-PAS-HIN-21-007, to appear



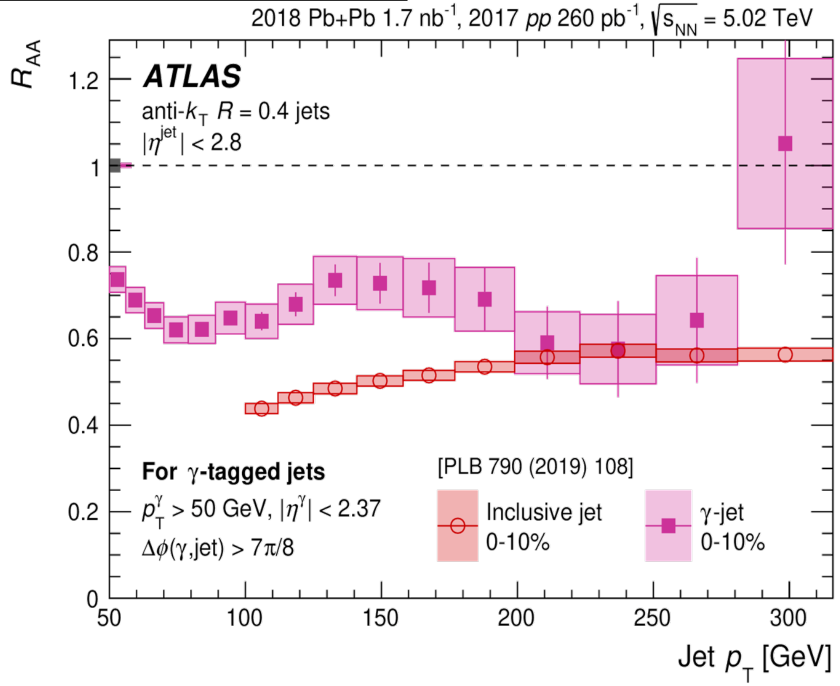
STAR PRL 130 (2023) 112301



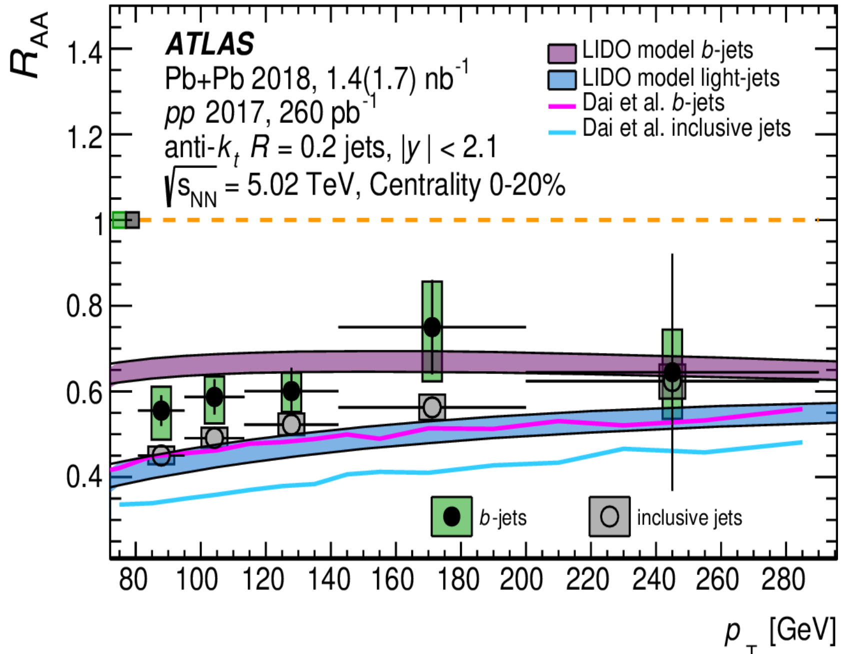
- Clear signature of sequential melting of ϒ(ns) states at RHIC and LHC
  - Ordering of nuclear modification factors: ϒ(3S)< ϒ(2S)< ϒ(1S)
- First direct observation of ϒ(3S) in heavy ion collisions

Jet quenching: parton dependence

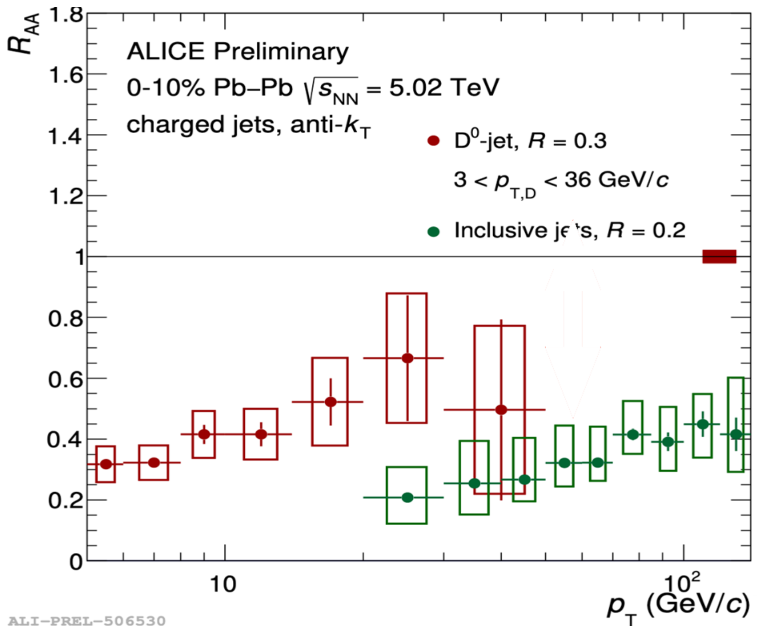
ATLAS arXiv:2303.10090



ATLAS arXiv:2204.13530



ALICE-PREL-506530

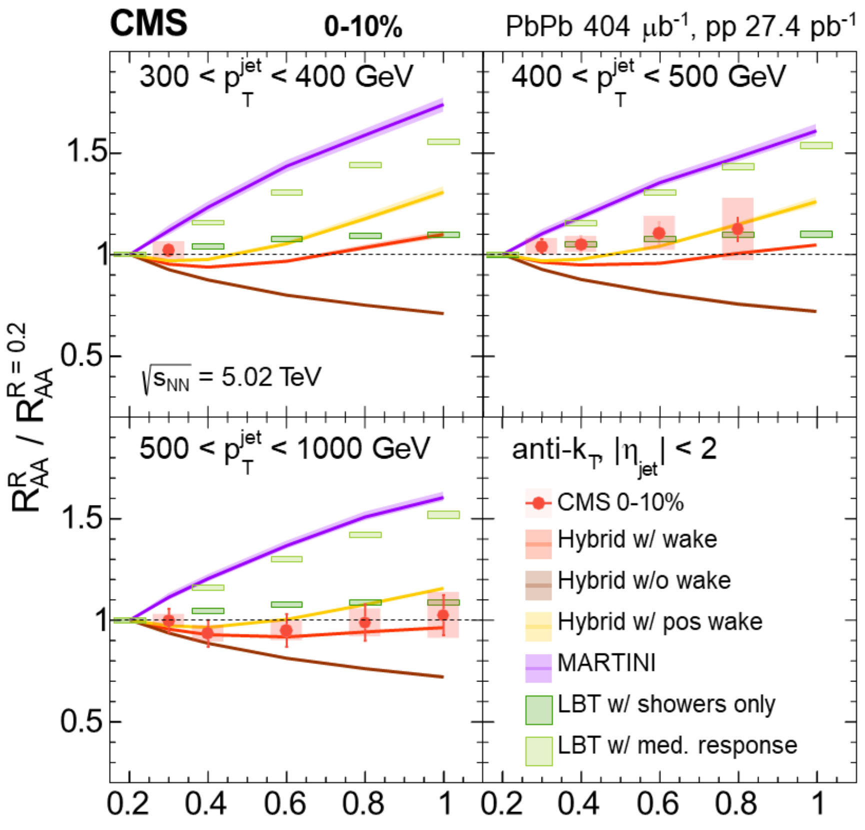


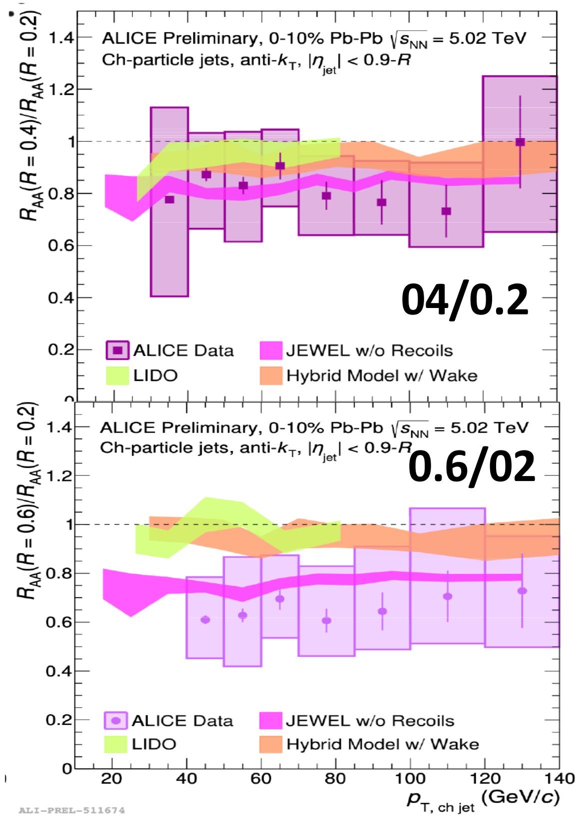
- Search for color-charge, mass, and/or flavor effects in energy loss:
  - Photon-tagged jets (higher fraction of quark-initiated jets): less suppressed compared to inclusive jets
  - b-jets (muon tagger): less suppressed compared to inclusive jets
  - D^0-tagged jets – indications of smaller suppression compared to inclusive jets

Jet quenching: jet size dependence

- Nuclear modifications for jets of different sizes: systematic studies of R, centrality and jet p_T

JHEP 05 (2021) 284

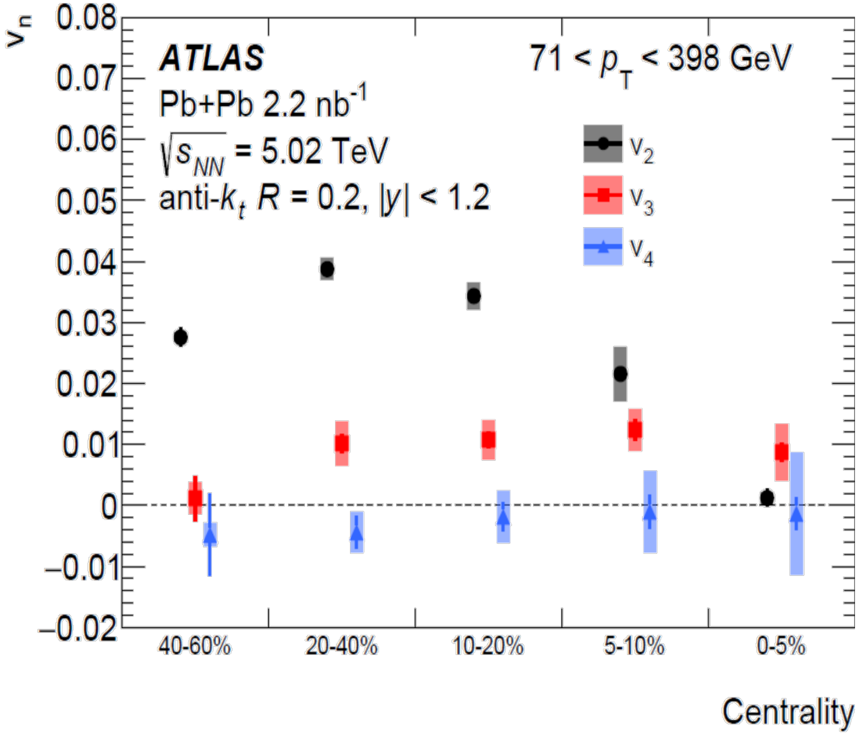




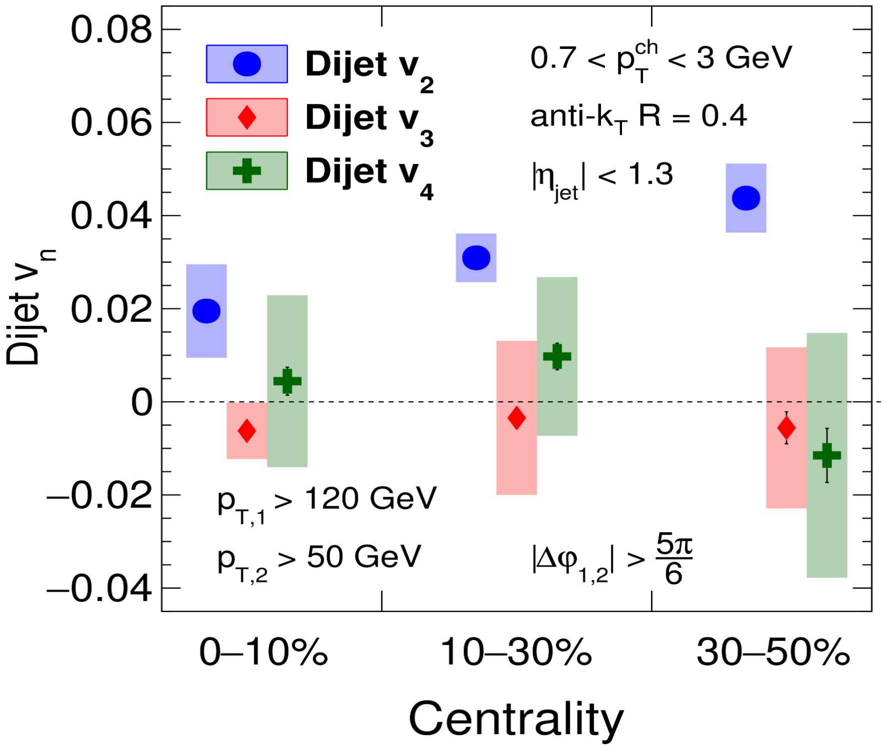
- CMS: Radius dependence via double R_{AA} ratios:
  - Surprisingly consistent with unity for all R and p_T selections studies
  - Medium response is important to capture the data trend
- ALICE: Radius dependence at low p_T:
  - Indicate differences in energy redistribution/recovery wrt high p_T jets
  - Bridge to comparisons with RHIC

Jet and dijet anisotropies

ATLAS PRC 105 (2022) 064903



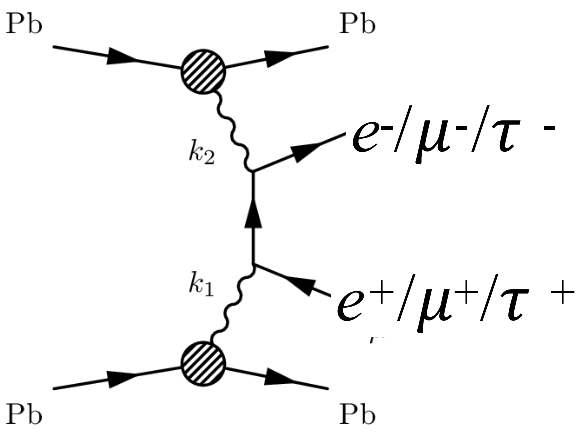
CMS arXiv:2210.08325

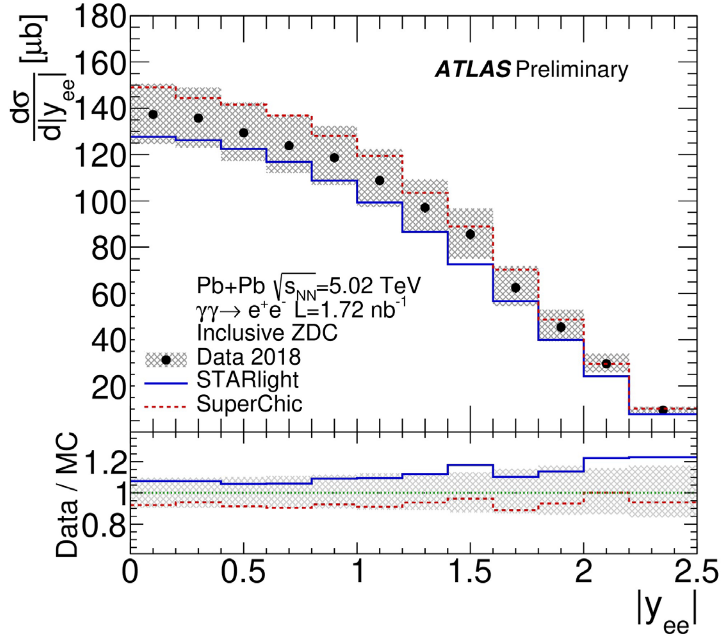


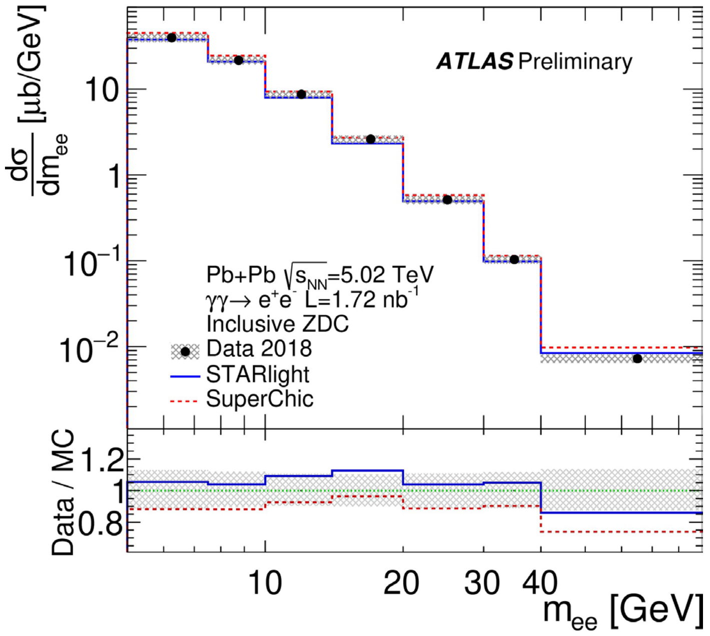
- Measurements of v_2, v_3, and v_4:
  - ATLAS jets 7p_T>71GeV
  - CMS dijet : p_{T1}>120 GeV, p_{T2}>50 GeV, $\Delta\phi >$ 5/6
- Significant v_2 for all centralities – constrains path-length dependence of quenching
- v_3, v_4 – sensitivity to density/geometry fluctuations. Differences in selections/non-flow?

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

ATLAS-CONF-2022-025







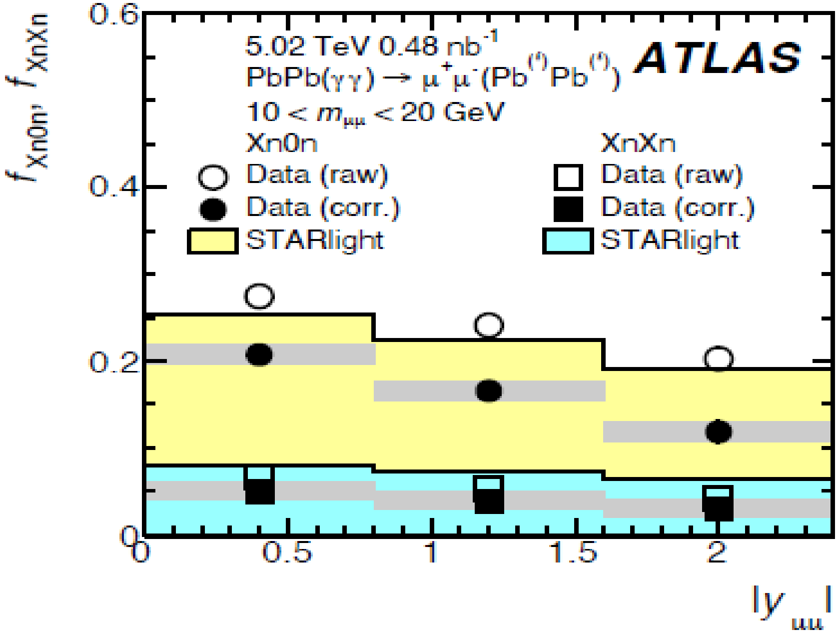
cross sections in inclusive and 0n0n ZDC events

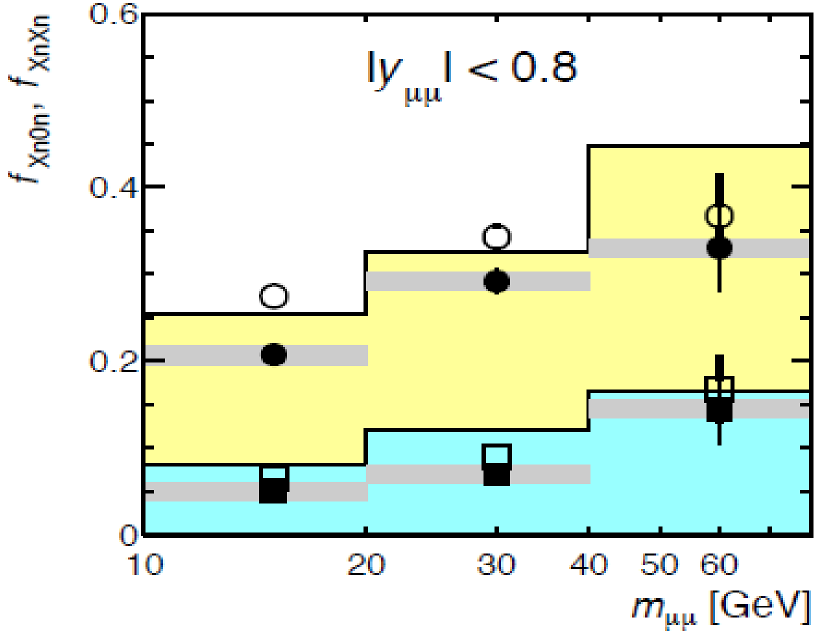
- UPC dilepton production is one of the fundamental processes in $\gamma\gamma$ interaction
- Exclusive $\gamma\gamma \rightarrow ee$ benchmark process for other γ induced processes
- Provides new constraints on photon fluxes from nuclei

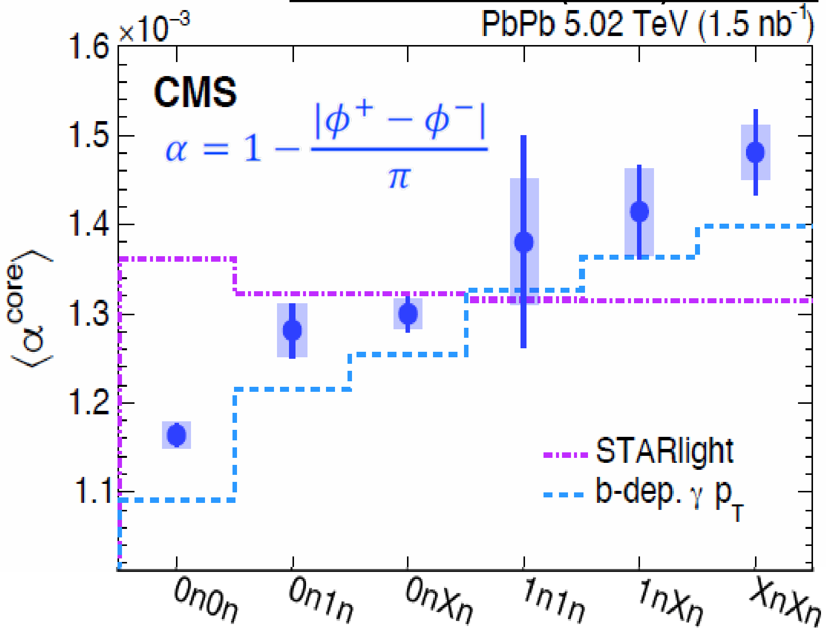
UPC dilepton production: $\gamma\gamma \rightarrow \mu\mu$

ATLAS PRC 104 (2021) 024906

CMS PRL 127 (2021) 122001





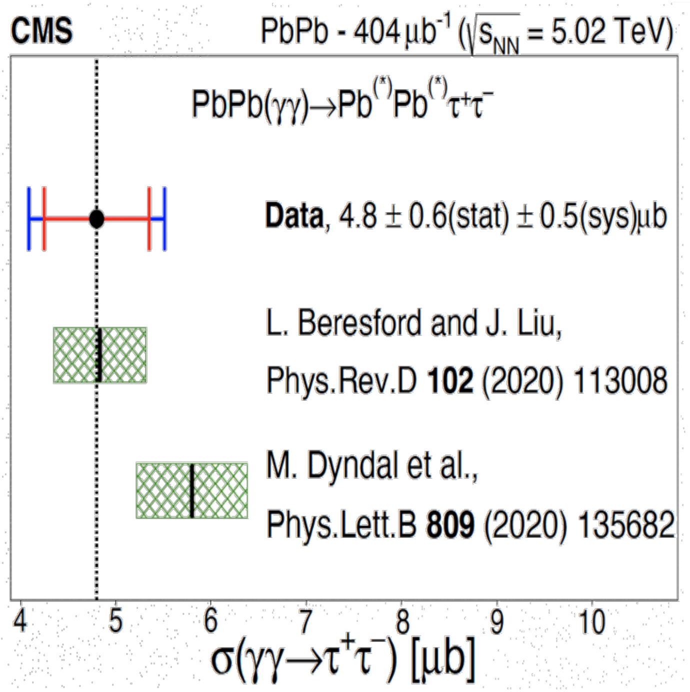


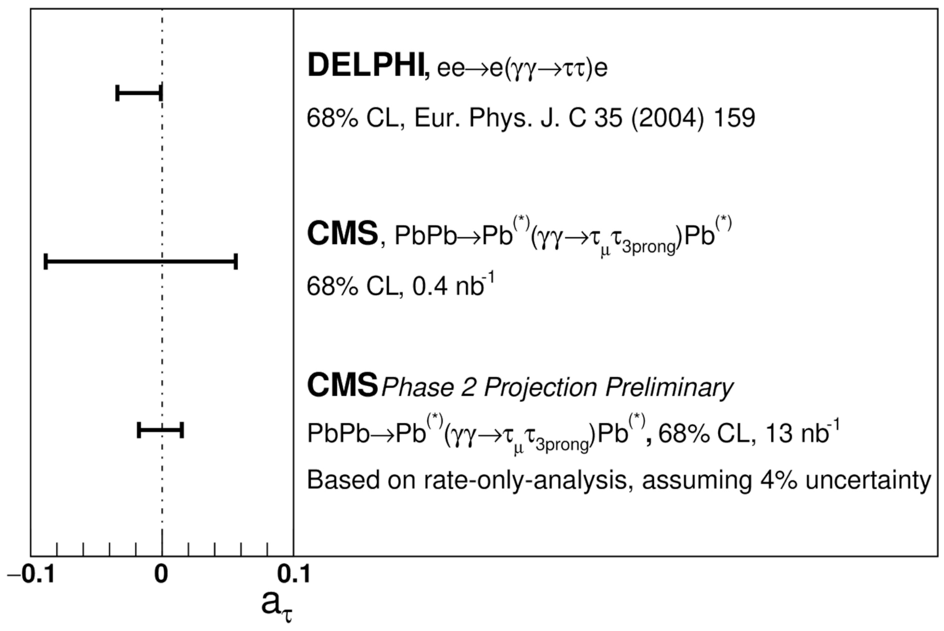
- Forward neutron multiplicity dependence of dimuon distributions:
  - Events with neutrons have a harder $m_{\mu\mu}$ spectrum and narrower $y_{\mu\mu}$
- Dimuon acoplanarity:
  - Clear impact parameter dependence
  - QED calculations need b-dependence of initial photon p_T

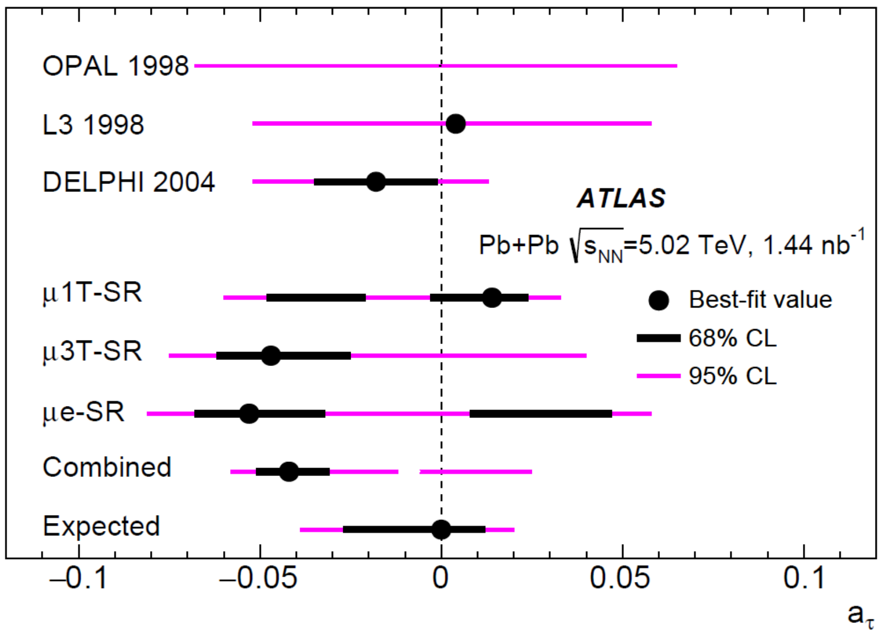
UPC dilepton production: $\gamma\gamma \to \tau\tau$

CMS arXiv:2206.05192

ATLAS arXiv:2204.13478



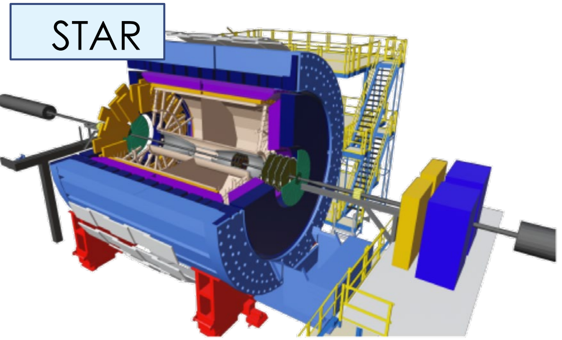




- Observation of $\gamma\gamma \to \tau\tau$ by both CMS and ATLAS in UPC heavy ion collisions
- Constrains the anomalous magnetic moment $a_\tau = \frac{(g-2)_\tau}{2}$ for the first time at the LHC

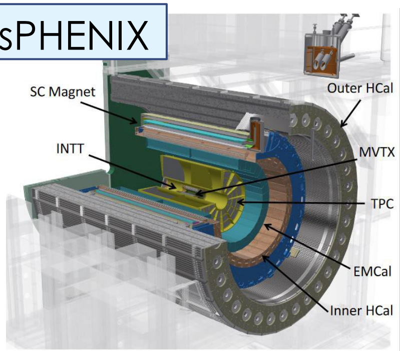
Looking into the Future

STAR



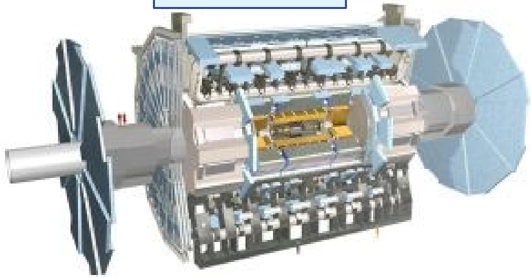
Forward upgrades

sPHENIX



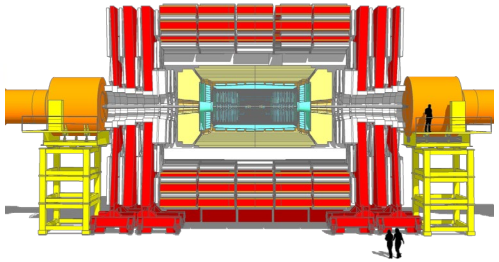
Brand new!
quarkonia, jets, b-tag

ATLAS



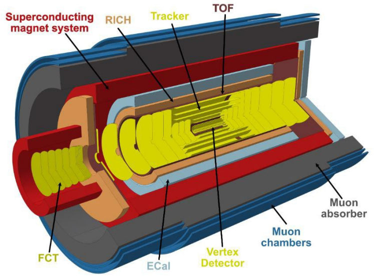
LS2 Upgrades
muon detectors, Lar, TDAQ,…

CMS



LS2 Upgrades
Pixel, Hcal, EMCal,…

ALICE (3)



LS2 Upgrades
TPC, Si tracker
ALICE3 proposal

RHIC

- Experimental operations in 2023-2025
- 200 GeV pp, pAu, AuAu collisions
- Data taking by upgraded STAR and sPHENIX
- Program completion in 2025

LHC

- Runs 3 & 4 with upgraded detectors
- High luminosity LHC era
- Precision QGP studies
- LHCb: SMOG upgrade for fixed-target mode

Thank you!

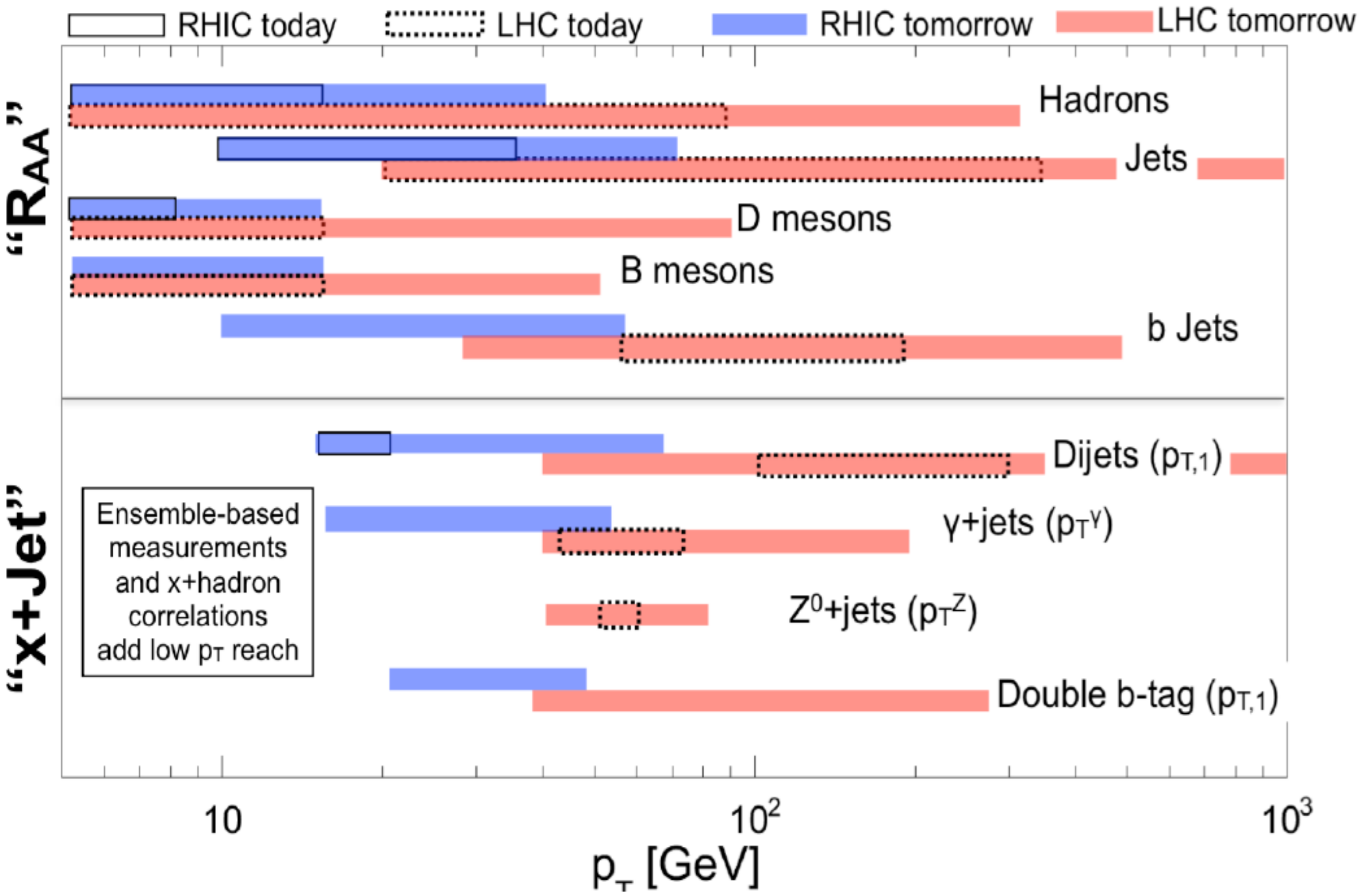
The UIC Group's work is supported by US DOE-NP

Looking into the Future

Looking forward to more/new physics results:

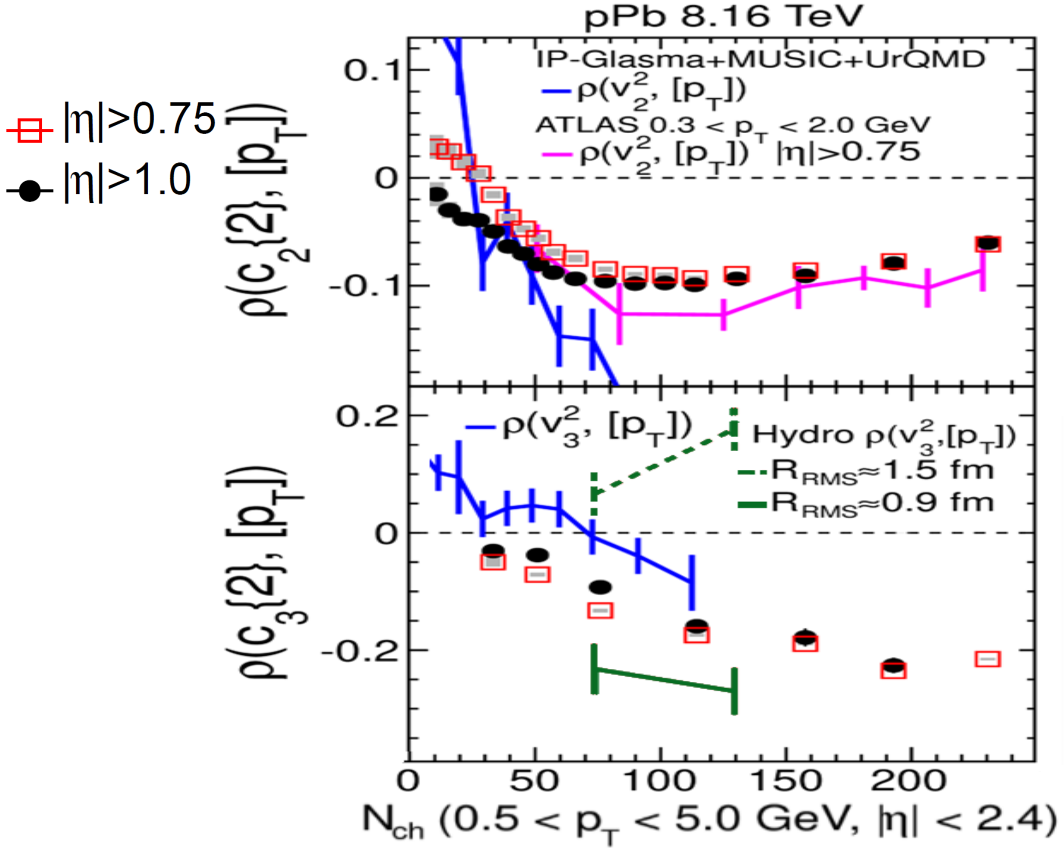
- Overlap of RHIC and LHC measurements
- Extended kinematic coverage
- Precision studies

- Completion of BES analyses



Collectivity in small systems

- Origins of collectivity?



CMS-PAS-HIN-21-012

- v_2-p_T:correlator proposed:

$$\rho(v_n^2,[p_T]) = \frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{var}(v_n^2)}\sqrt{\mathrm{var}([p_T])}}$$

- Predicted sensitivity to bulk-viscosity, EOS, initial geometry, and CGC effects (small systems)
- Search for sign change with N_{ch} (predicted by CGC)
  - Could be seen in the data but disappear with large pseudorapidity gap
  - Measurements are sensitive to nonflow effects (jet/minijet correlations, resonance decays,…)

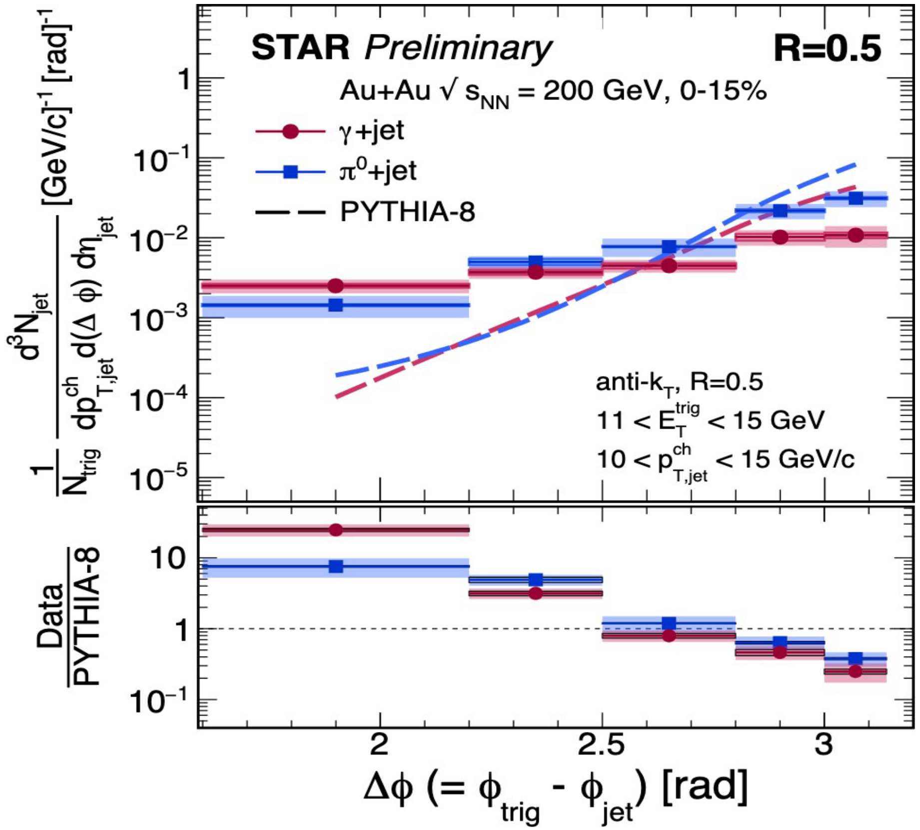
IP-Glasma+MUSIC+UrQMD

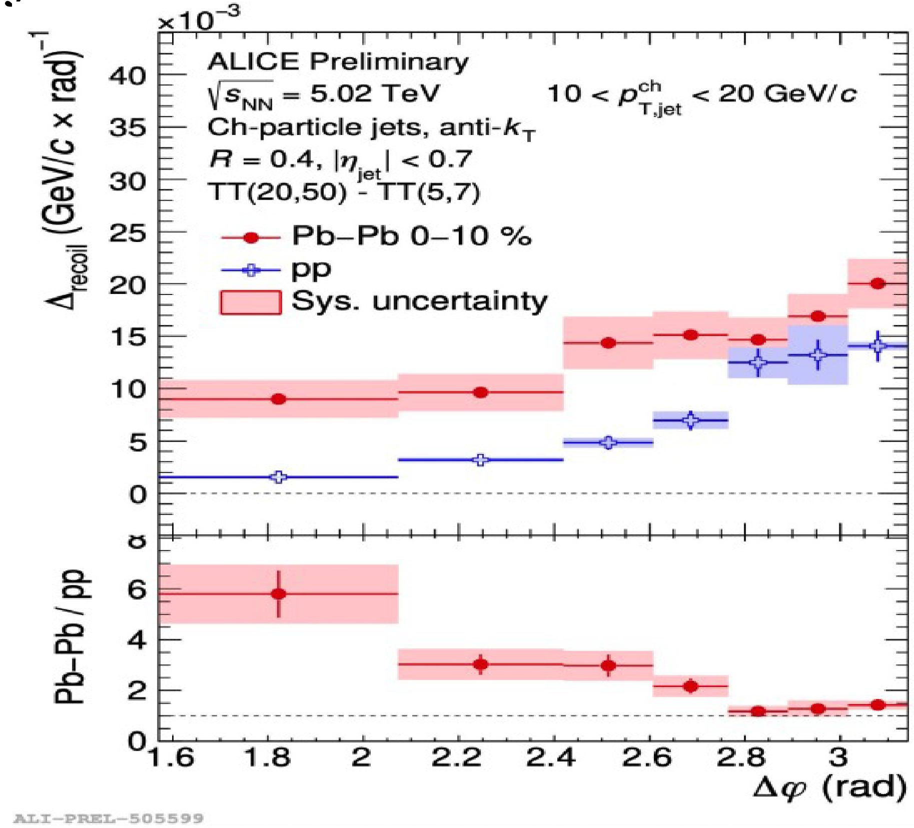
Hydro

(Many more studies in different AA systems at RHIC and LHC)

Jet quenching: (de)correlations

- Jet quenching studies via gamma-jet, hadron-jet coincidence measurements

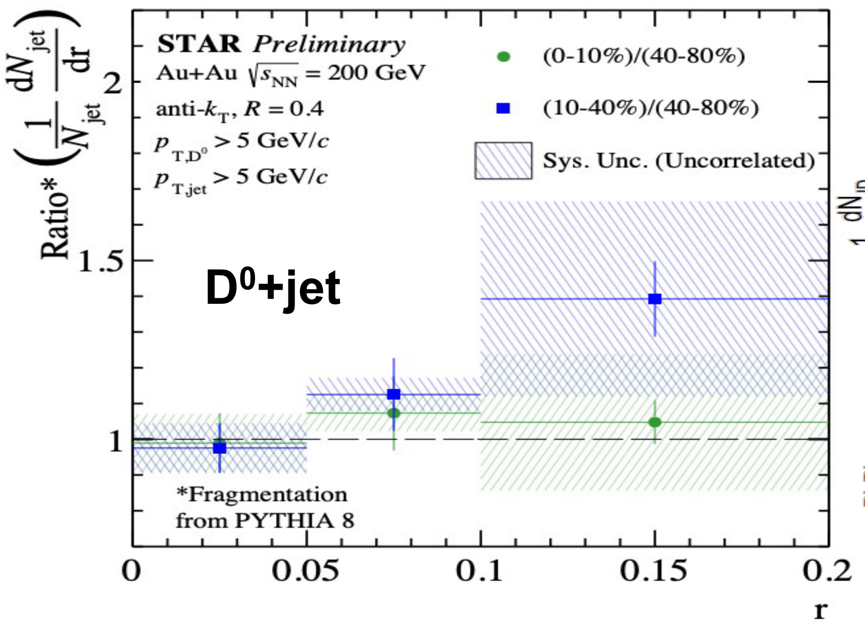




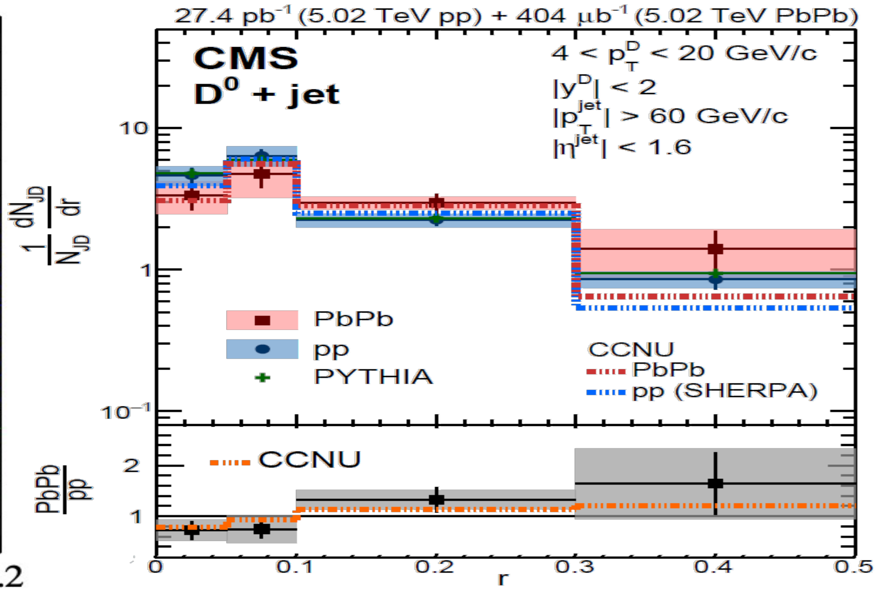
- First observation of decorrelation for soft(er) jets at RHIC and the LHC

Jet quenching: energy flow changes

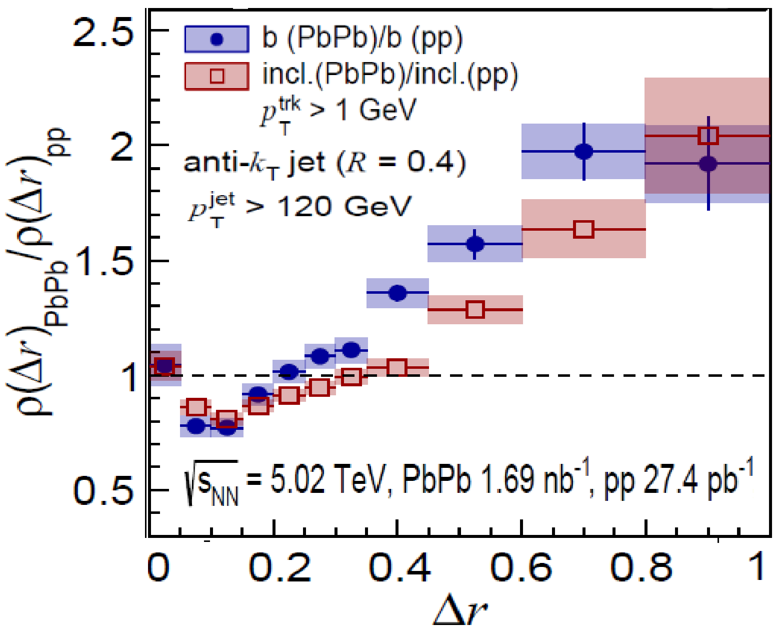
- Energy redistribution in jet constituents: medium/vacuum jet shape ratios for jets of different flavors:



CMS PRL 125 (2020) 102001



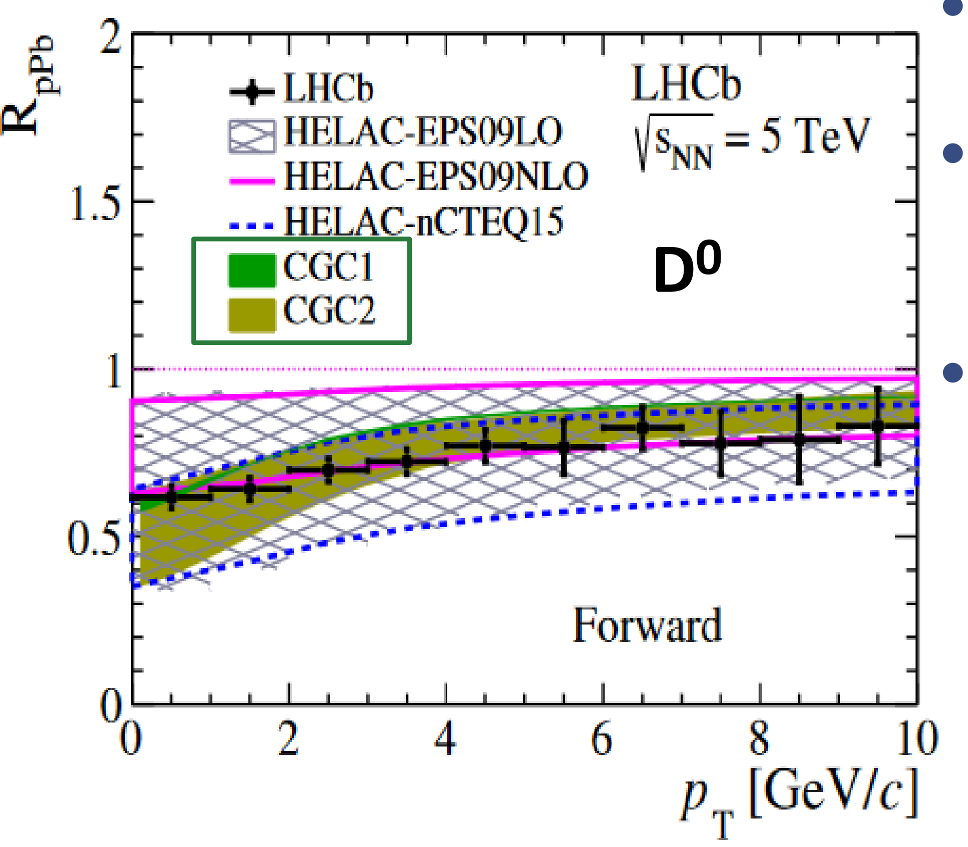
CMS arXiv:2210.08547



- Common trend: jet momentum is shifted from small to large angles; carried by softer constituents than in pp
- Radial profiles for heavy quarks in jets: indications of charm shift to larger R and smaller p_T → charm diffusion in AA?
- Larger off-axis momentum excess for b- than inclusive jets – larger "wake" caused by heavy quarks?

Understanding initial state

LHCb, JHEP 10 (2017) 090



- Nuclear PDFs: parton densities modified in nuclei with respect to free nucleon PDF
- Low-x ("shadowing") region is poorly constrained by previous data
- Smaller experimental than theoretical uncertainties