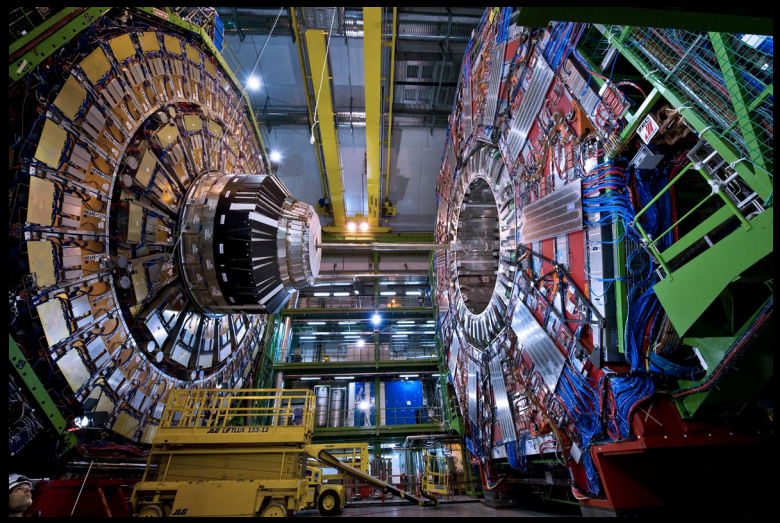
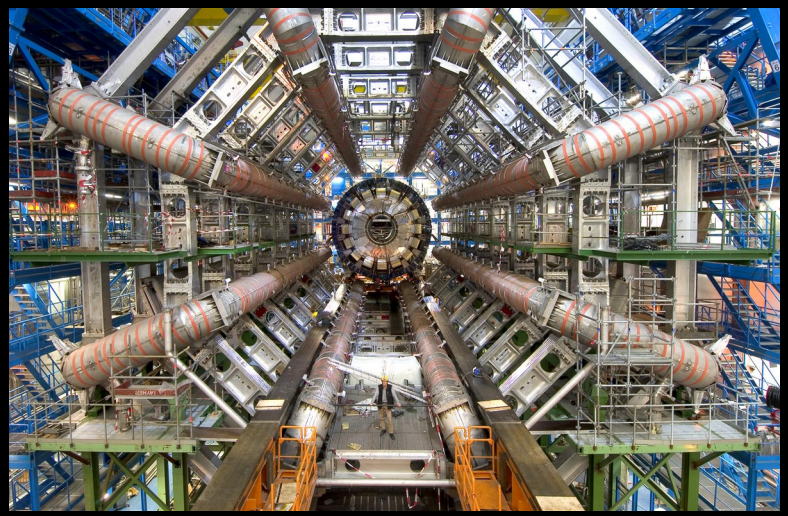
Heavy Ion Physics at ATLAS and CMS





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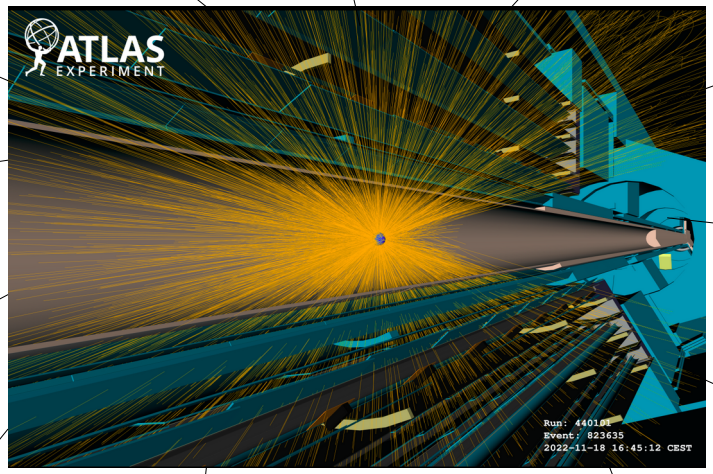
Rencontres de Physique
5th March, 2024

Questions in Heavy Ion Physics – for today



Hadronisation

Long range correlations

Phase transition

Fluctuations

Collectivity even in small systems

Coalescence

Quark content of hadrons

Sub-nucleon structure

Medium-parton interaction

Equation of State

Gluon saturation low-x

Heavy quark energy loss

Measurements addressing these questions

Bulk properties

- **dN/dη in Pb+Pb**
- **Net charge fluctuations**
- **Speed of sound**
- **Elliptic anisotropy of f_0 in p+Pb**
- **Flow decorrelations in p+p and Xe+Xe**

Jets

- **Dijet cross section, p+Pb**
- **Long-range anisotropies in high multiplicity jets, p+p**
- **Groomed jet radius and girth, p+p and Pb+Pb**
- **Photon-tagged jet R_{AA} in Pb+Pb**
- **Sensitivity of v_n to jets in p+p**

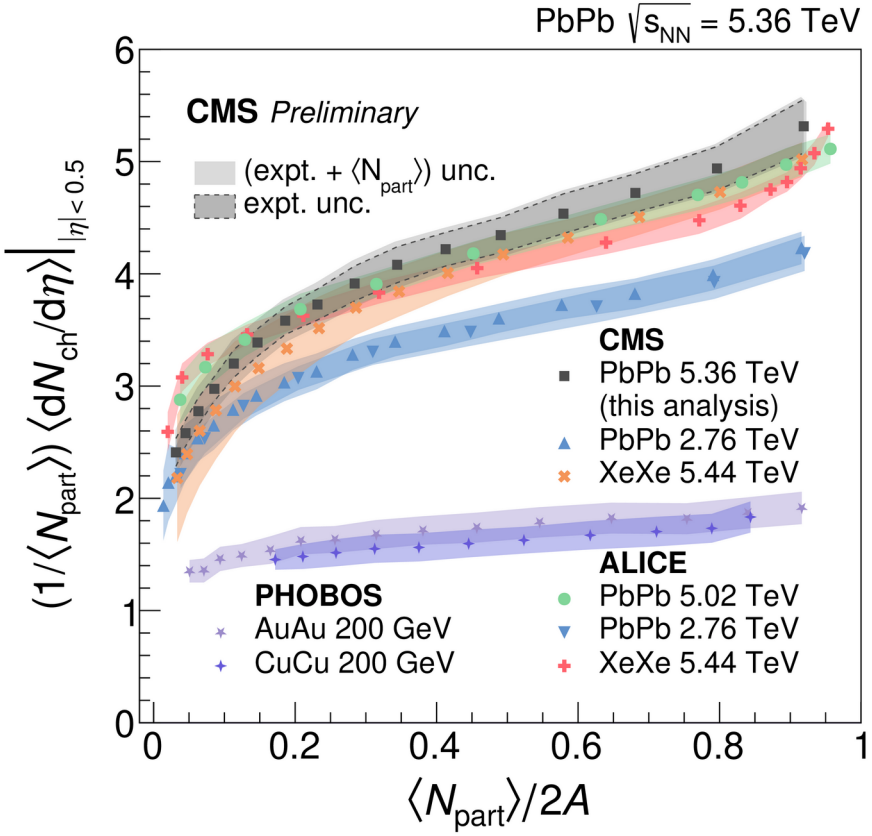
Heavy quarks

- **Di-muon correlations in p+p, Pb+Pb**
- **Charm hadronization, Λ_c^+, in p+p and Pb+Pb**
- **Charm baryon and meson production in p+Pb**
- **B^+ and B_s^0 nuclear modification factors, p+p and Pb+Pb**
- **B^+ production in p+Pb**

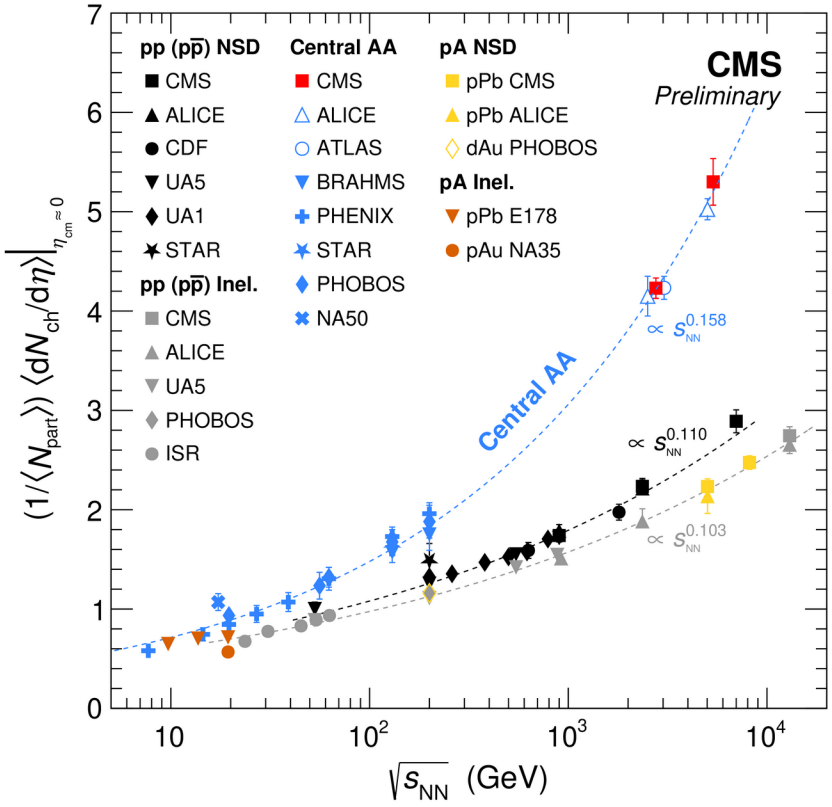
Various recent results related to the above topics from ATLAS and CMS will be discussed

Charged hadrons in Pb+Pb at 5.36 TeV

- **η distribution of charged hadrons**



First run-3 result



For 5% most central collisions, dN/dη = 2032 ± 91(syst)
Model comparisons: EPOS LHC, HYDJET, AMPT

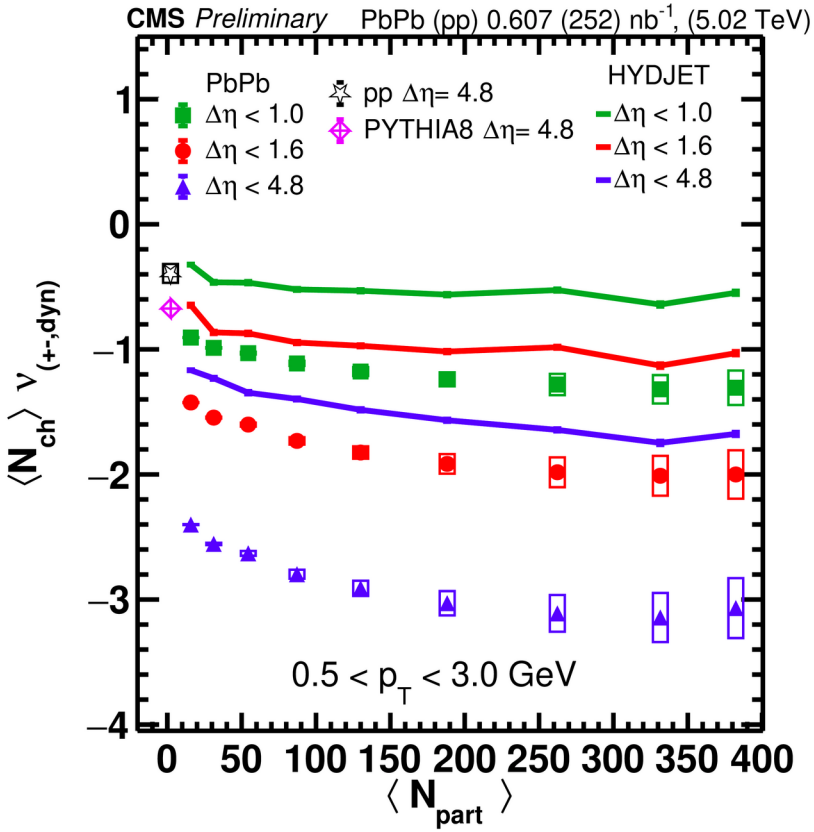
- **None of these fully describe the η and centrality dependence**

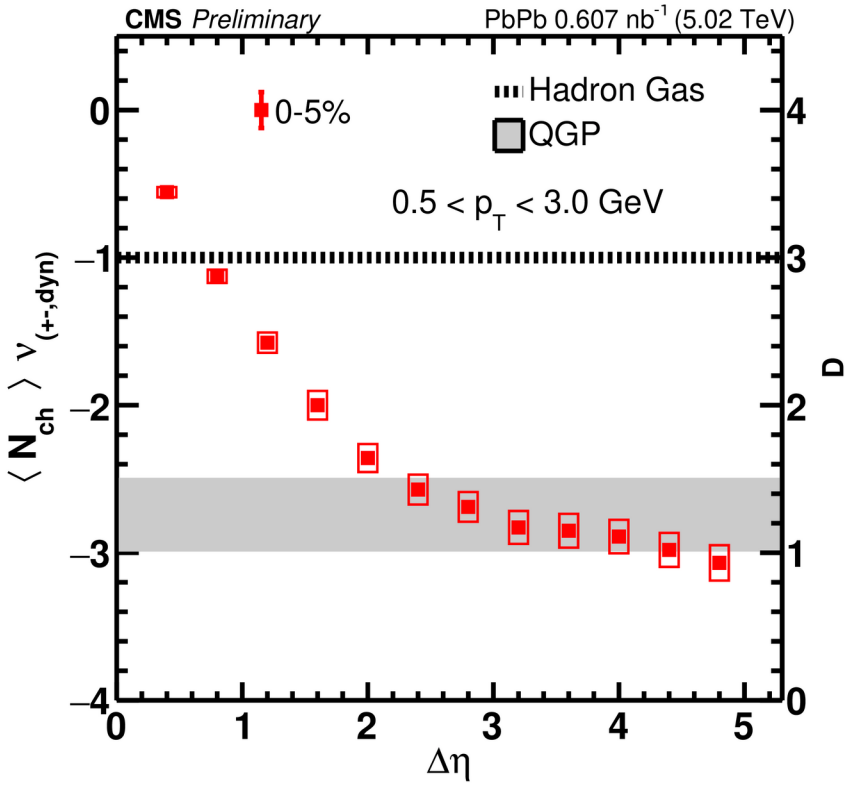
HIN-23-007

Net charge fluctuations in p+p and Pb+Pb collisions

- **Looking for dynamical fluctuations**

$$\nu_{(+-,\mathrm{dyn})} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_-\rangle\langle N_+\rangle}.$$



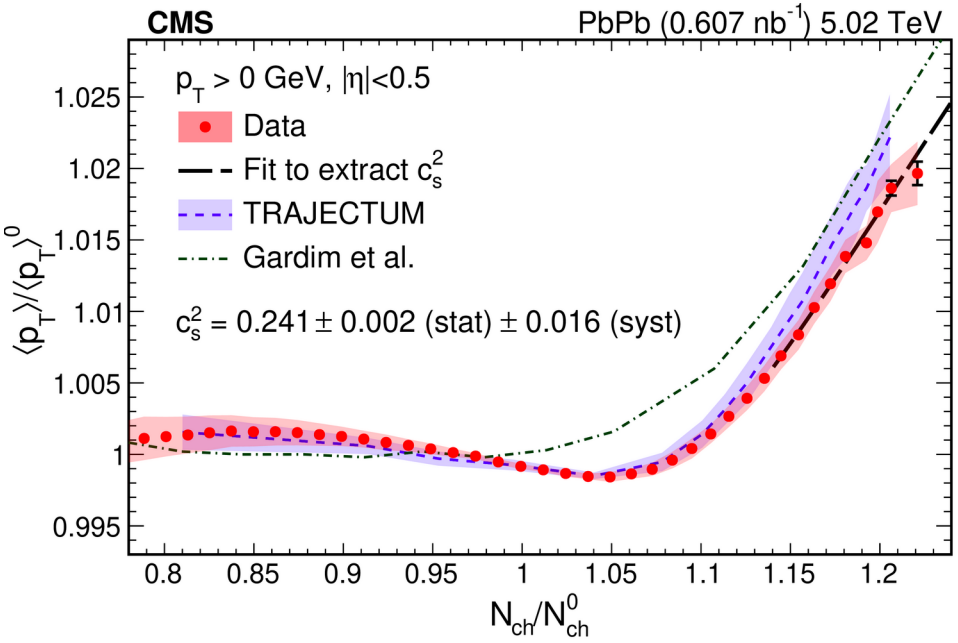


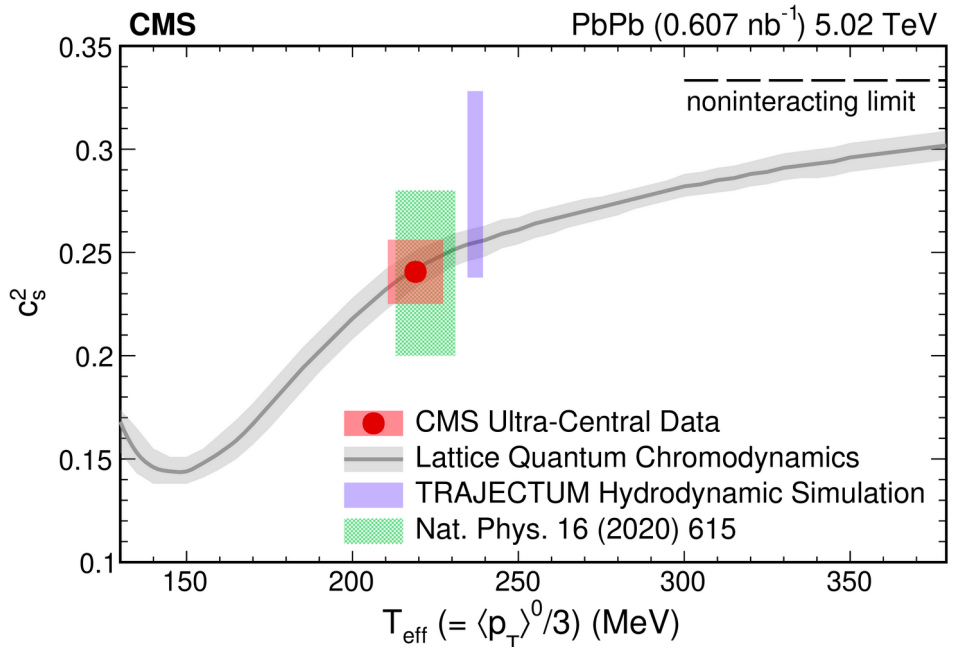
- **Negative sign: dominance of opposite sign correlations**
- **Disagreement with models in the magnitude**

HIN-22-005

Speed of sound measured in heavy ion collisions

- **Multiplicity dependence of average p_T in central collisions**





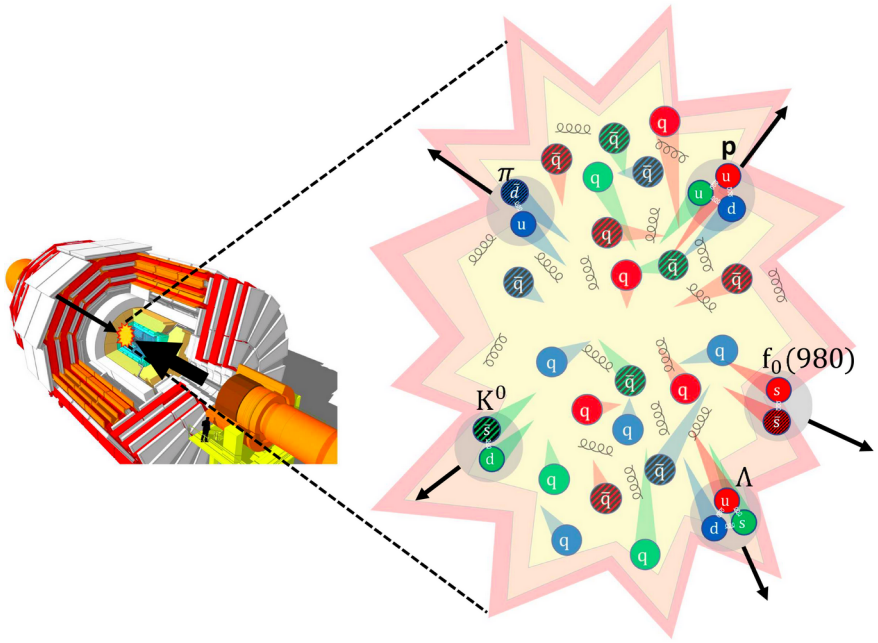
$(c_s/c)^2 = 0.241 \pm 0.002(\text{stat}) \pm 0.016(\text{syst})$, $T_{eff} = 219 \pm 8$ MeV

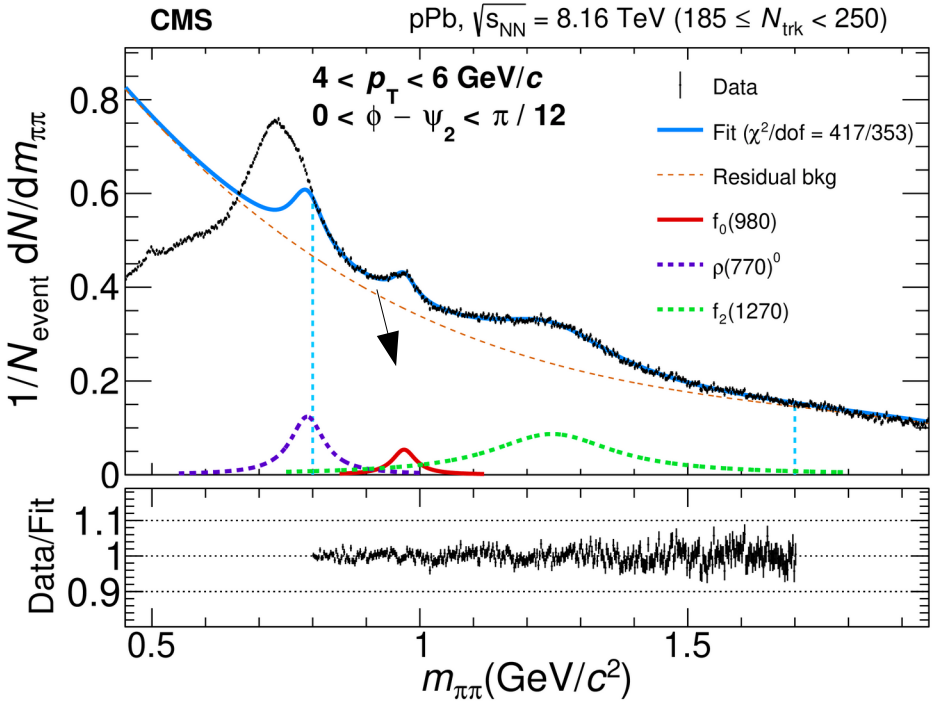
Agrees with lattice QCD, constraints EoS. Deconfined phase.

arXiv:2401.06896 submitted to Reports on Progress in Physics

Quark content of $f_0(980)$, measured in p+Pb collisions

- **So far undecided quark content: $q\bar{q}$, $q\bar{q}q\bar{q}$, $K\bar{K}$ or $q\bar{q}g$?**



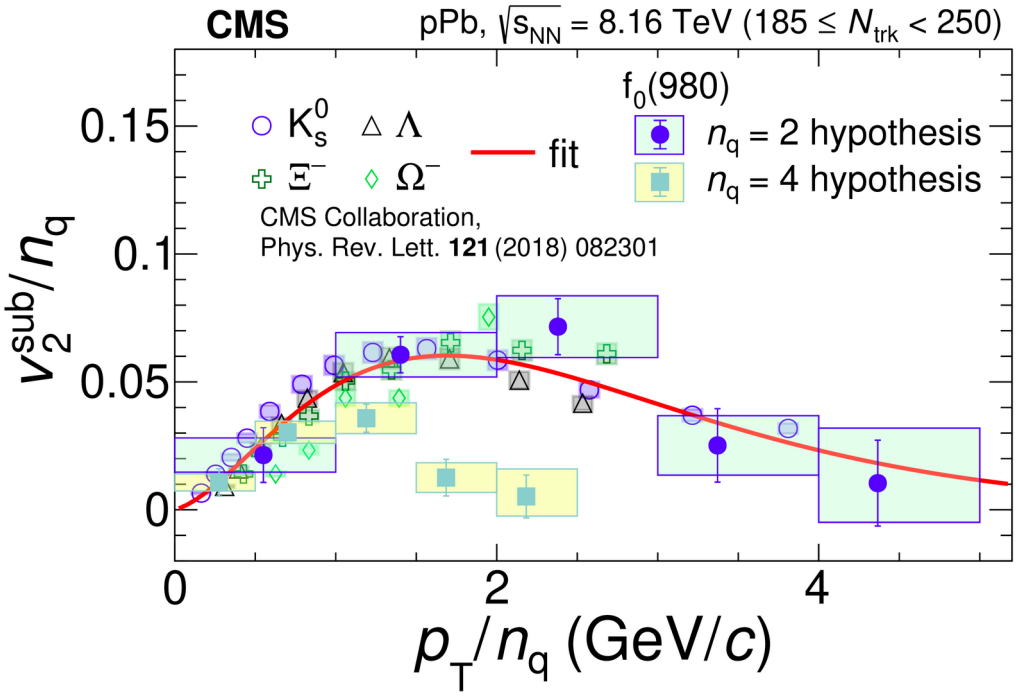


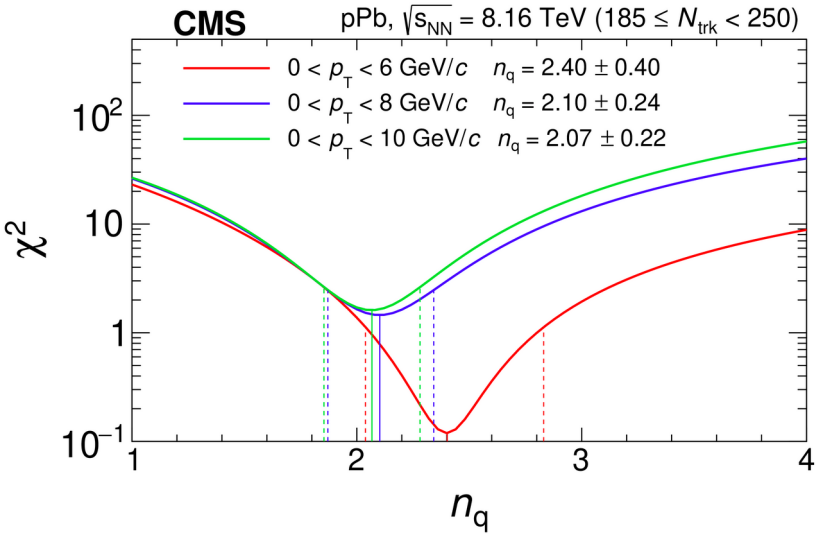
Coalescence hadronization in heavy ion collisions

Pion pair mass spectrum

arXiv:2312.17092 submitted to Nature Communications

Quark content of $f_0(980)$, measured in p+Pb collisions



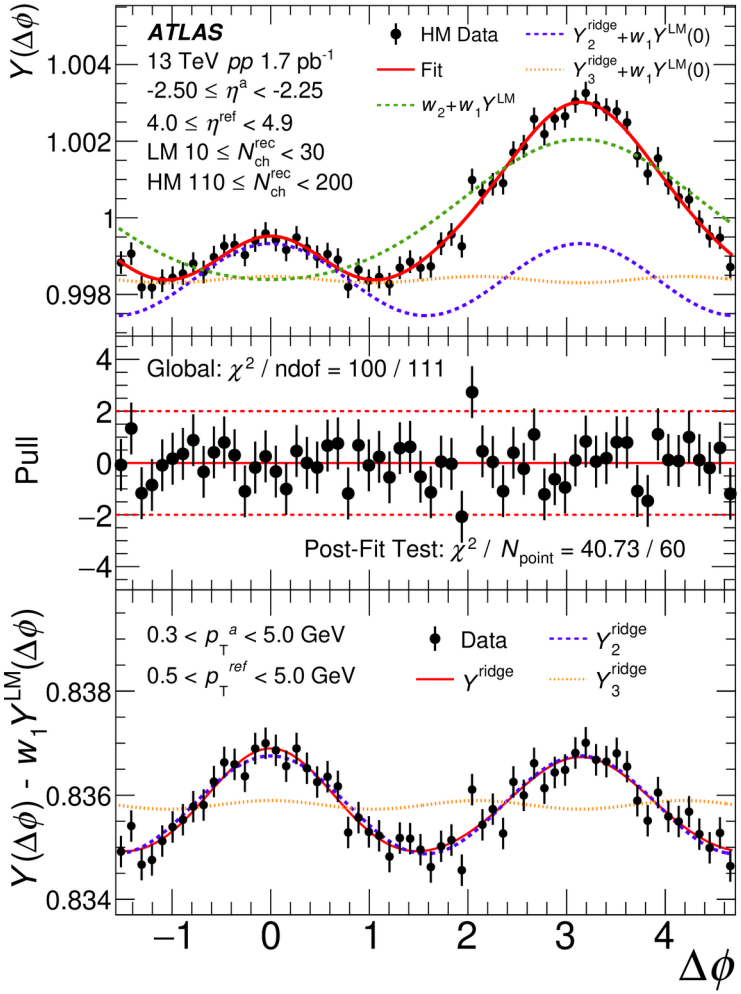


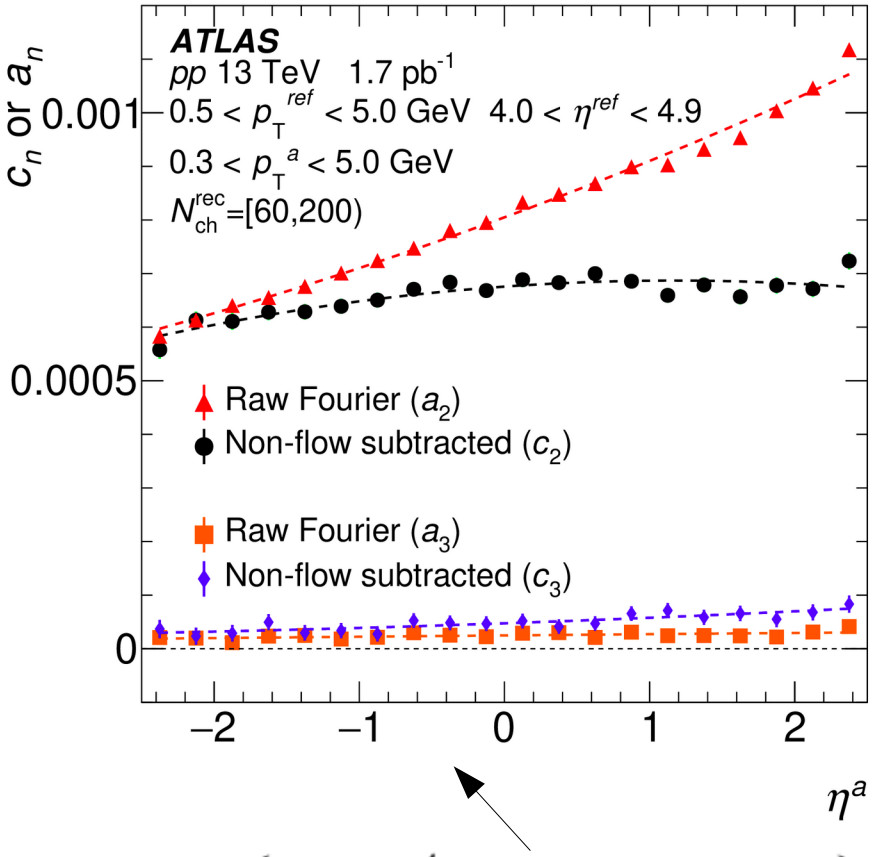
Elliptical anisotropy: scaling n_q: number of constituents

χ^2 scan: $f_0(980)$ is $q\bar{q}$ (more than 3σ significance)

arXiv:2312.17092 submitted to Nature Communications

Longitudinal flow decorrelations in p+p and Xe+Xe





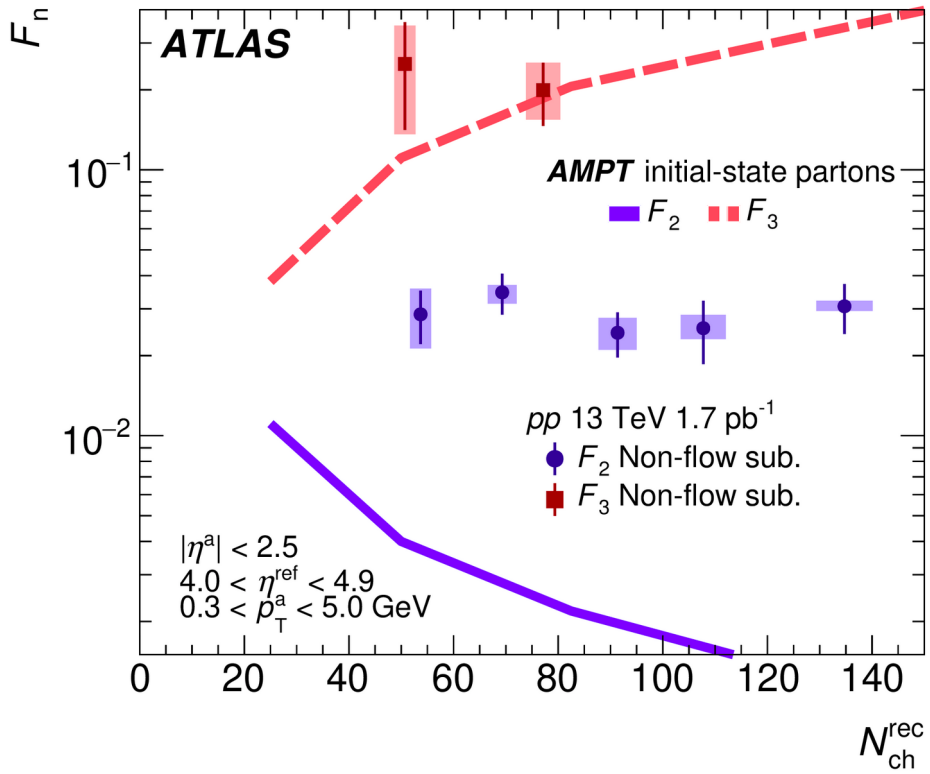
$$Y = G\left\{1 + 2\sum_{n=1}^{4} a_n(\eta^a)\cos(n\Delta\phi)\right\}$$

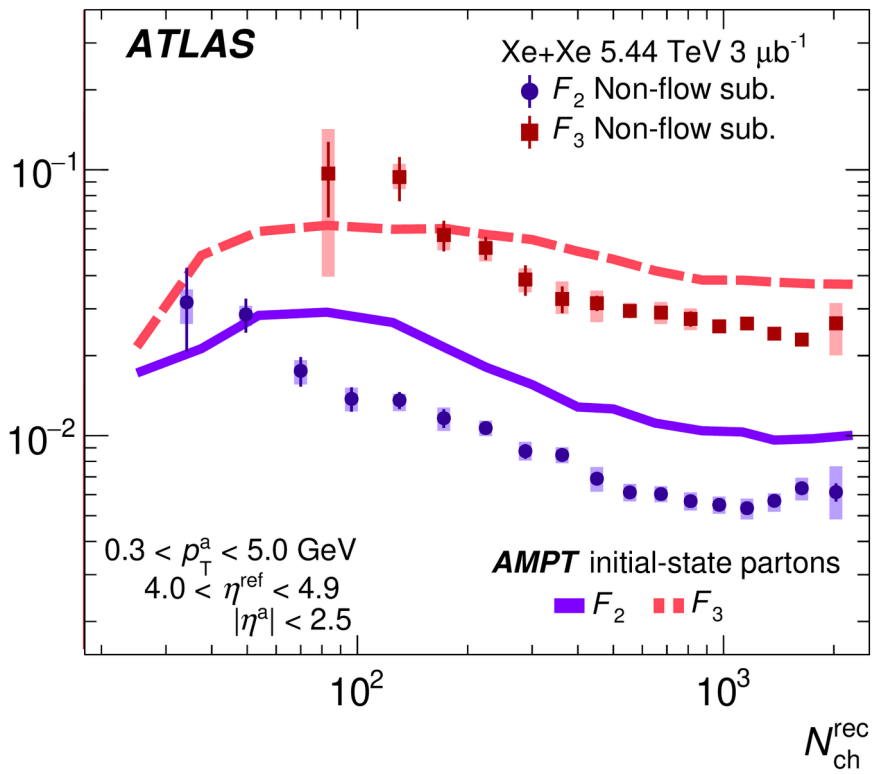
Particle - calo cluster correlations non-flow subtracted by templates

Slope is measured:

$$A_n\left(1 + F_n \cdot \eta^a + S_n \cdot (\eta^a)^2\right)$$

Longitudinal flow decorrelations in p+p and Xe+Xe





AMPT: color string geometry: underestimates data in p+p

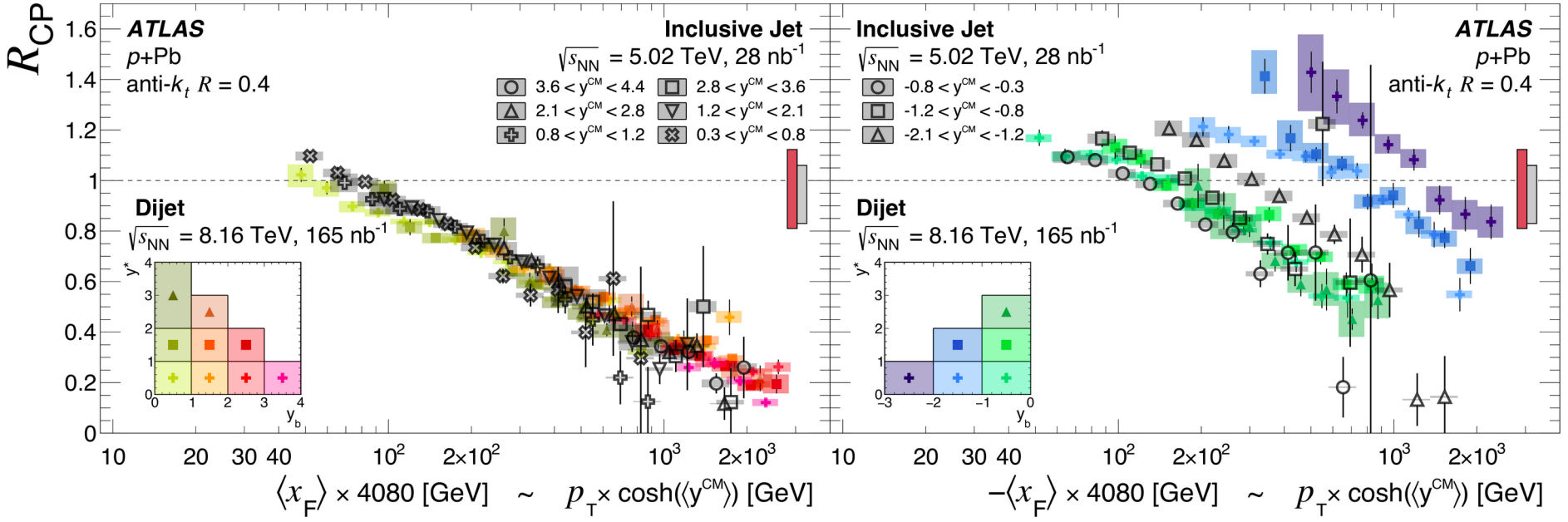
Hint for sub-nucleon structure and longitudinal energy deposition fluctuations

arXiv:2308.16745 submitted to PRL

Dijet yield in p+Pb collisions

$$y_b = \frac{y_1^{CM} + y_2^{CM}}{2} \qquad y^* = \frac{|y_1^{CM} - y_2^{CM}|}{2}$$

$$R_{CP}(p_{T,Avg}, y_b, y^*) = \frac{\frac{1}{\langle T_{AB}^{0-10\%} \rangle} \frac{1}{N_{evt}^{0-10\%}} \frac{d^3 N_{dijet}^{0-10\%}}{dp_{T,Avg} dy_b dy^*}}{\frac{1}{\langle T_{AB}^{60-90\%} \rangle} \frac{1}{N_{evt}^{60-90\%}} \frac{d^3 N_{dijet}^{60-90\%}}{dp_{T,Avg} dy_b dy^*}}$$



Central-to-peripheral ratio measured, R_{CP}

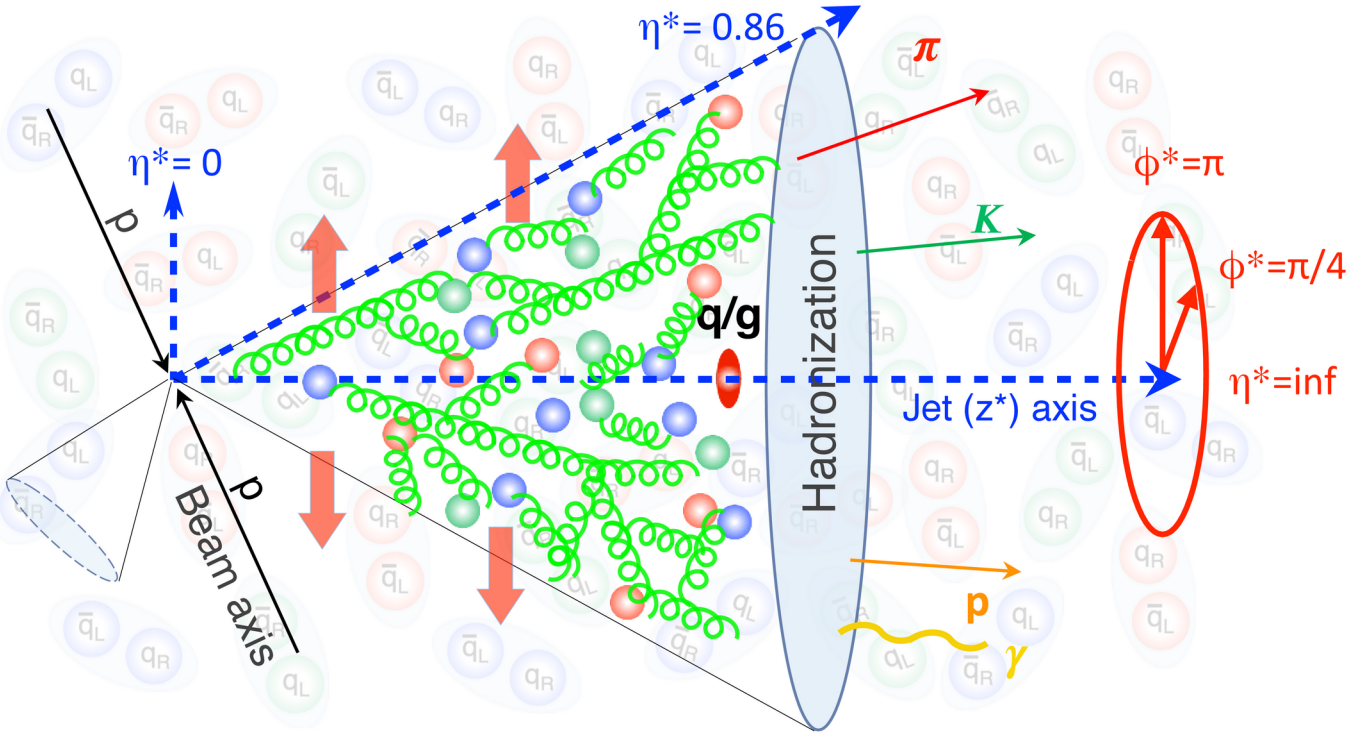
R_{CP} scales with Bjorken-x in the proton, x_p, not with x_{Pb}

x region covered: down to $x_p \sim 10^{-3}$ and $x_{Pb} \sim 4 \cdot 10^{-4}$

arXiv:2309.00033 accepted by PRL

Long range anisotropies in jets, in p+p collisions

- **Collectivity inside (high-multiplicity) jets?**

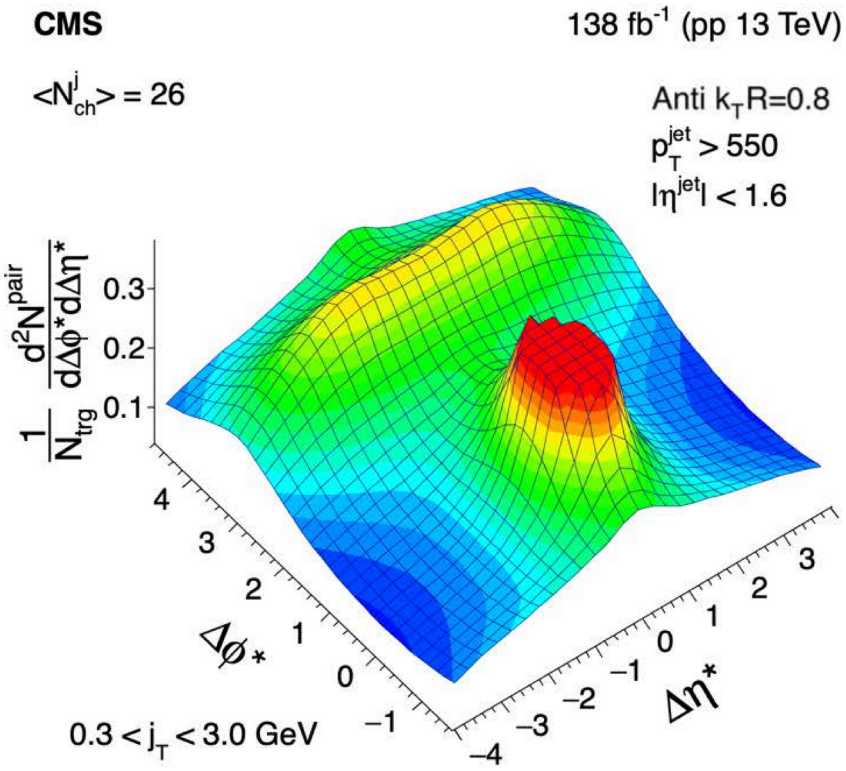


Kinematic variables defined in the basis of the jet itself

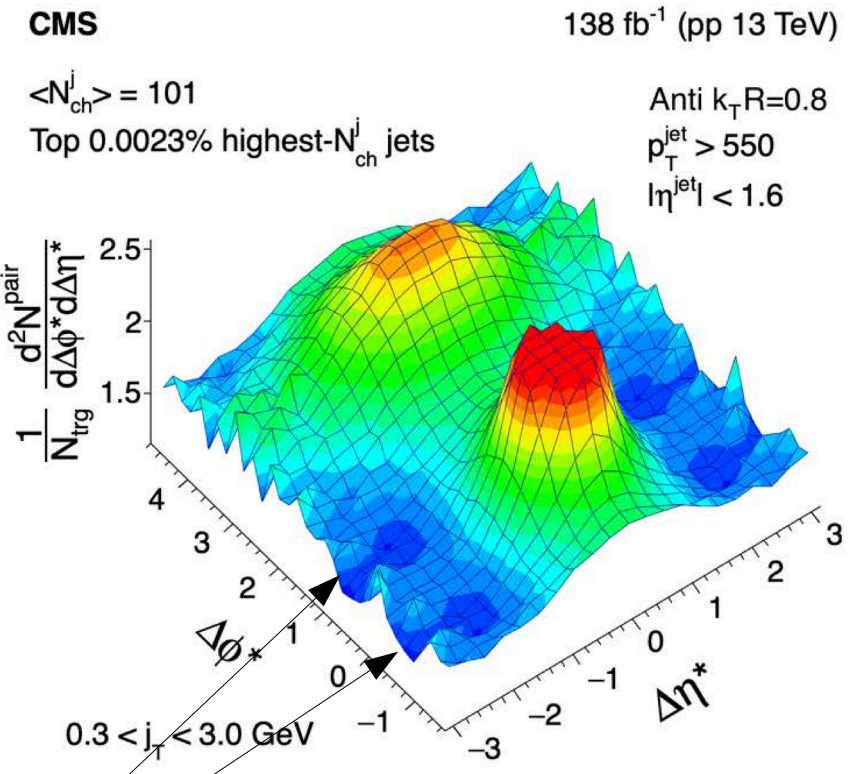
arXiv:2312.17103 submitted to PRL

Long range anisotropies in jets, in p+p collisions

low multplicity



high multiplicity

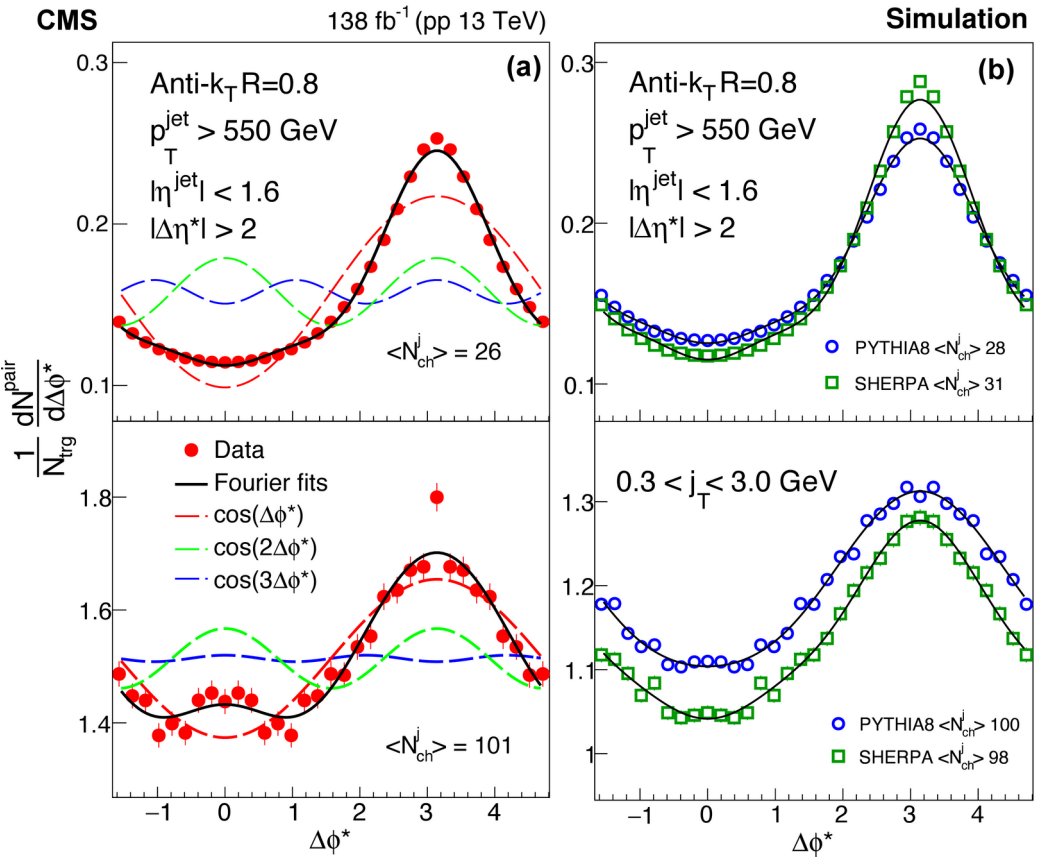


A double dip is already visible

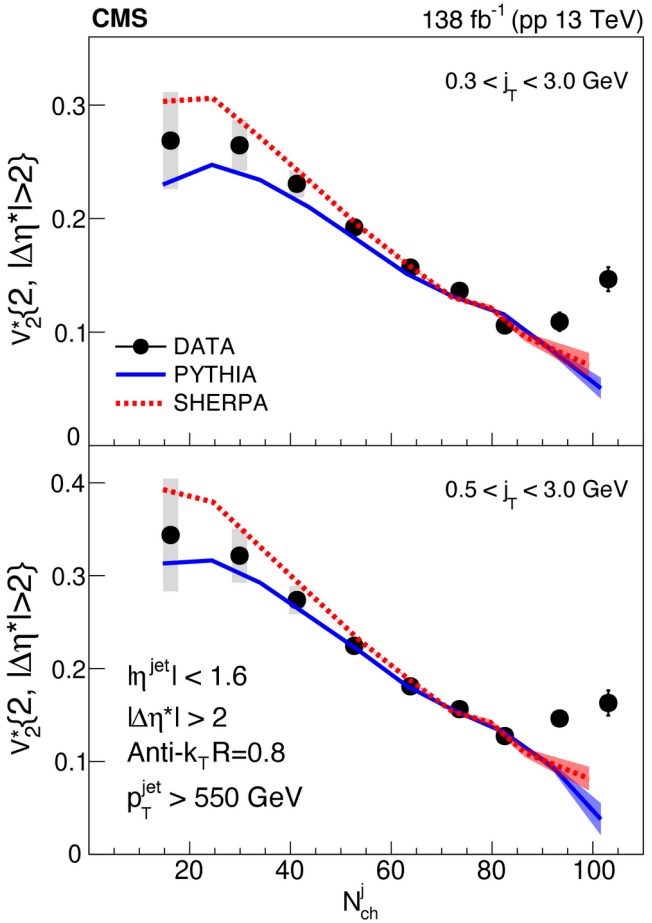
arXiv:2312.17103 submitted to PRL

Long range anisotropies in jets, in p+p collisions

projections onto Δϕ*



extracted v_2^*



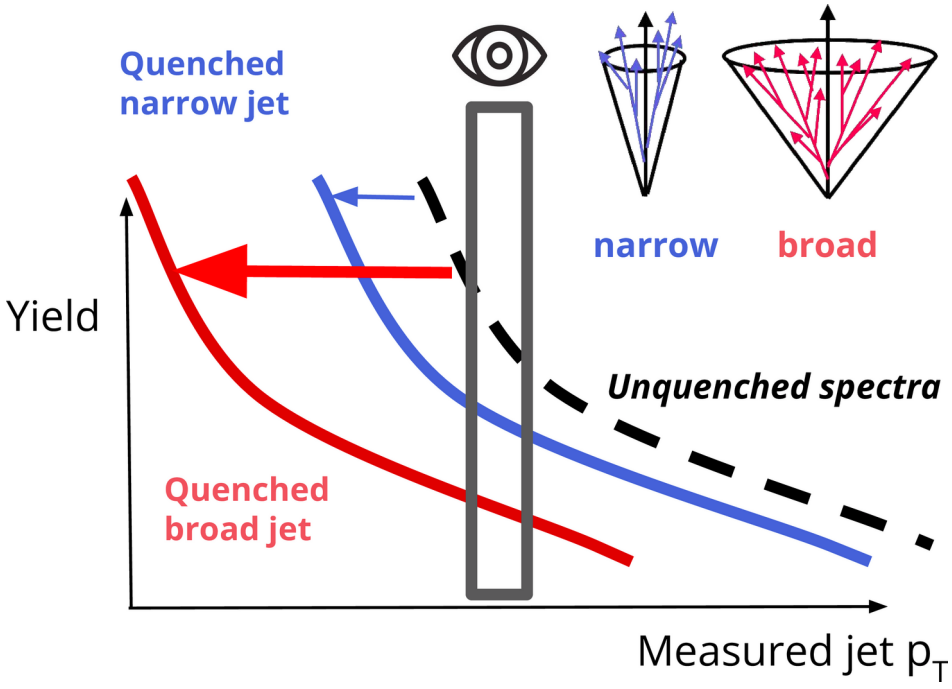
v_2^*: increase at high jet multiplicity

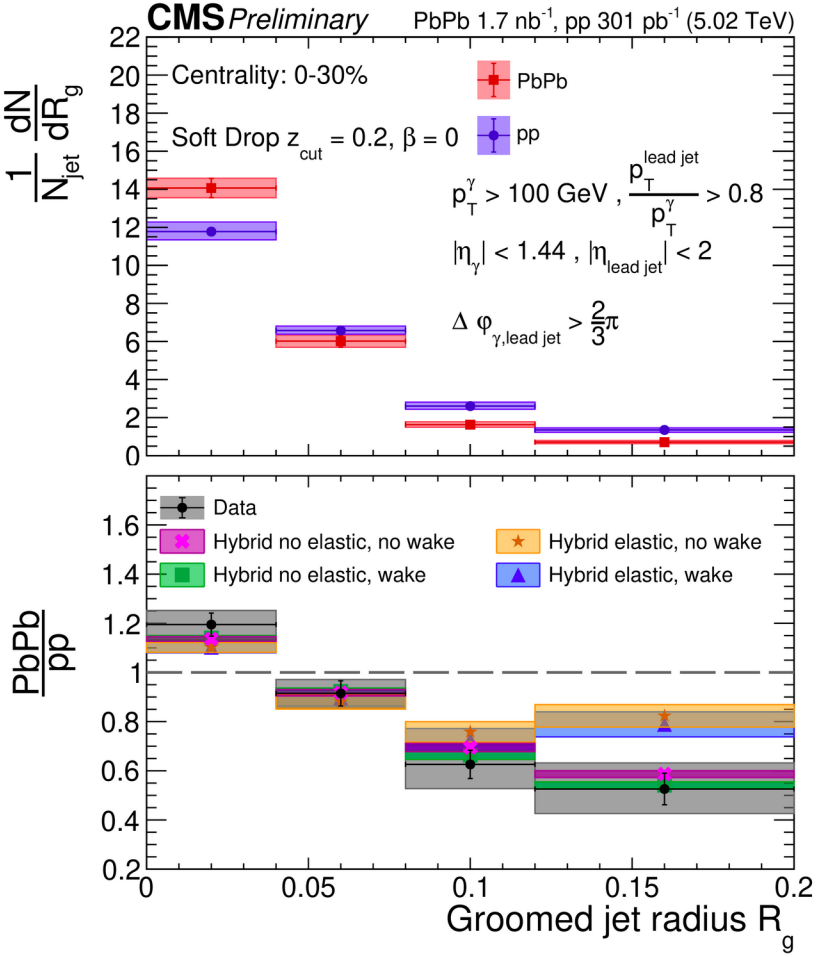
onset of collectivity in p+p jets?

arXiv:2312.17103
submitted to PRL

Groomed jet radius and girth in γ-jet events

- **Jet energy loss in heavy ion collisions leads to selection bias**
- **A calibrated jet energy is needed to compare jet modifications to pp collisions**





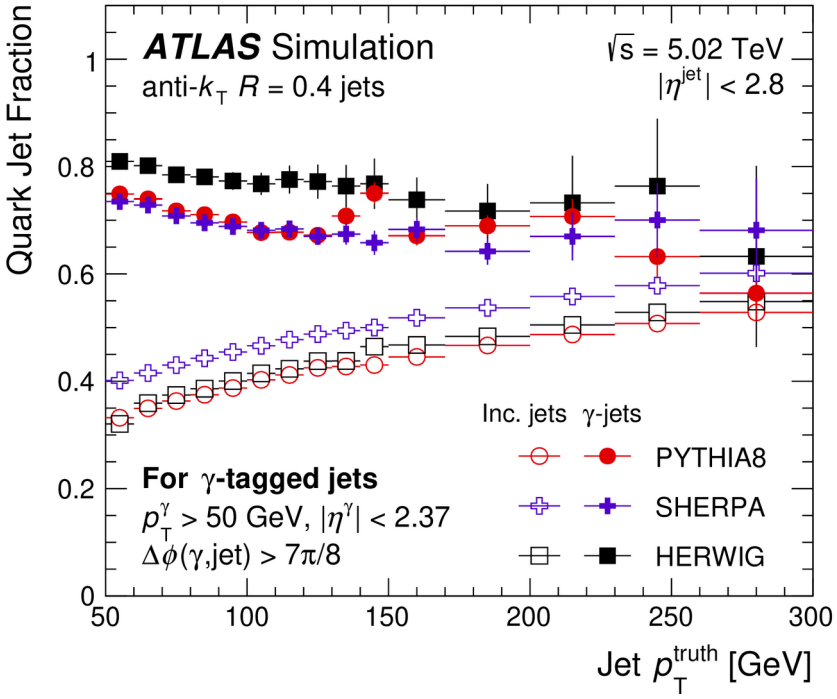
- **Pb+Pb: narrower jets than in p+p, but only for balanced γ-jet events**
- **Model comparisons, sensitivity at high R_g**

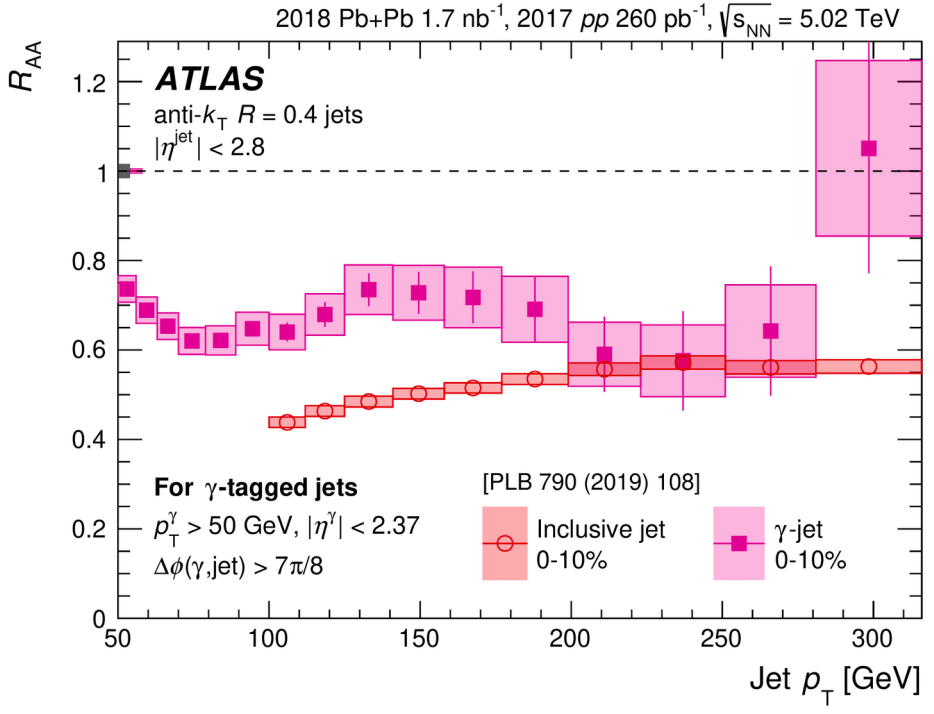
HIN-23-001

Photon tagged jet R_{AA} in Pb+Pb collisions

Nuclear modification factors
Mostly quark jets (photon tag)

$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N^{\mathrm{Pb+Pb}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \Big/ \langle T_{\mathrm{AA}} \rangle \frac{\mathrm{d}^2 \sigma^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta},$$





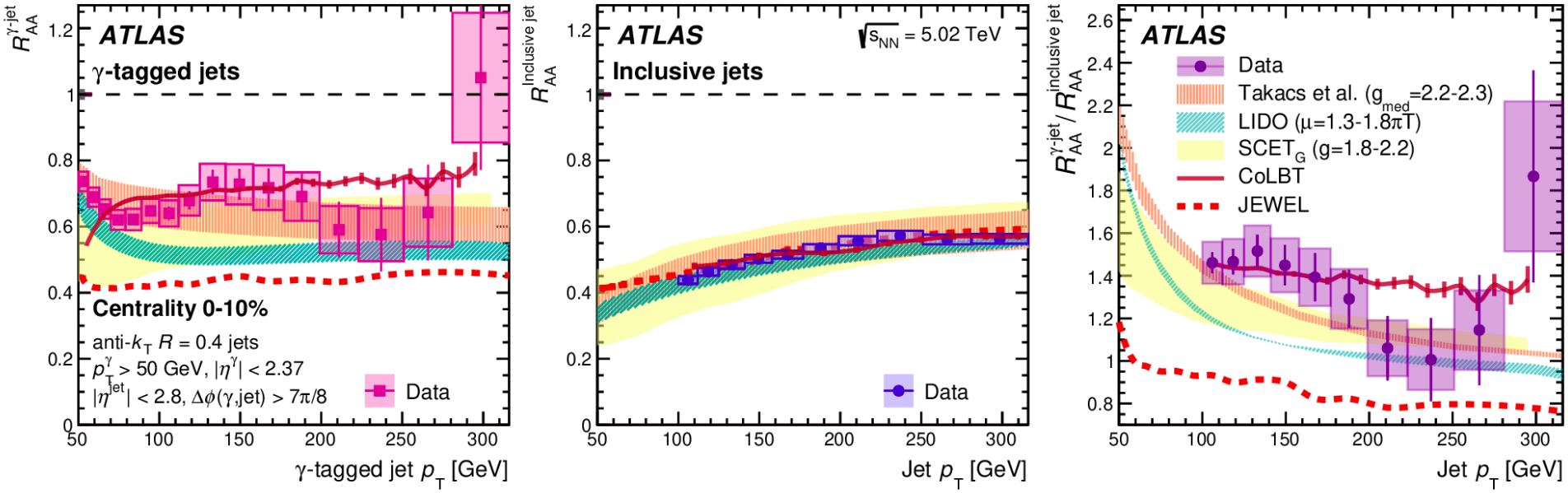
Difference between quark-jet and inclusive jets: energy loss is sensitive to color charge!

PLB 846 (2023) 138154

Photon tagged jet R_{AA} in Pb+Pb collisions

Nuclear modification factors
Mostly quark jets (photon tag)

$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N^{\mathrm{Pb+Pb}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \Big/ \langle T_{\mathrm{AA}} \rangle \frac{\mathrm{d}^2 \sigma^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta},$$

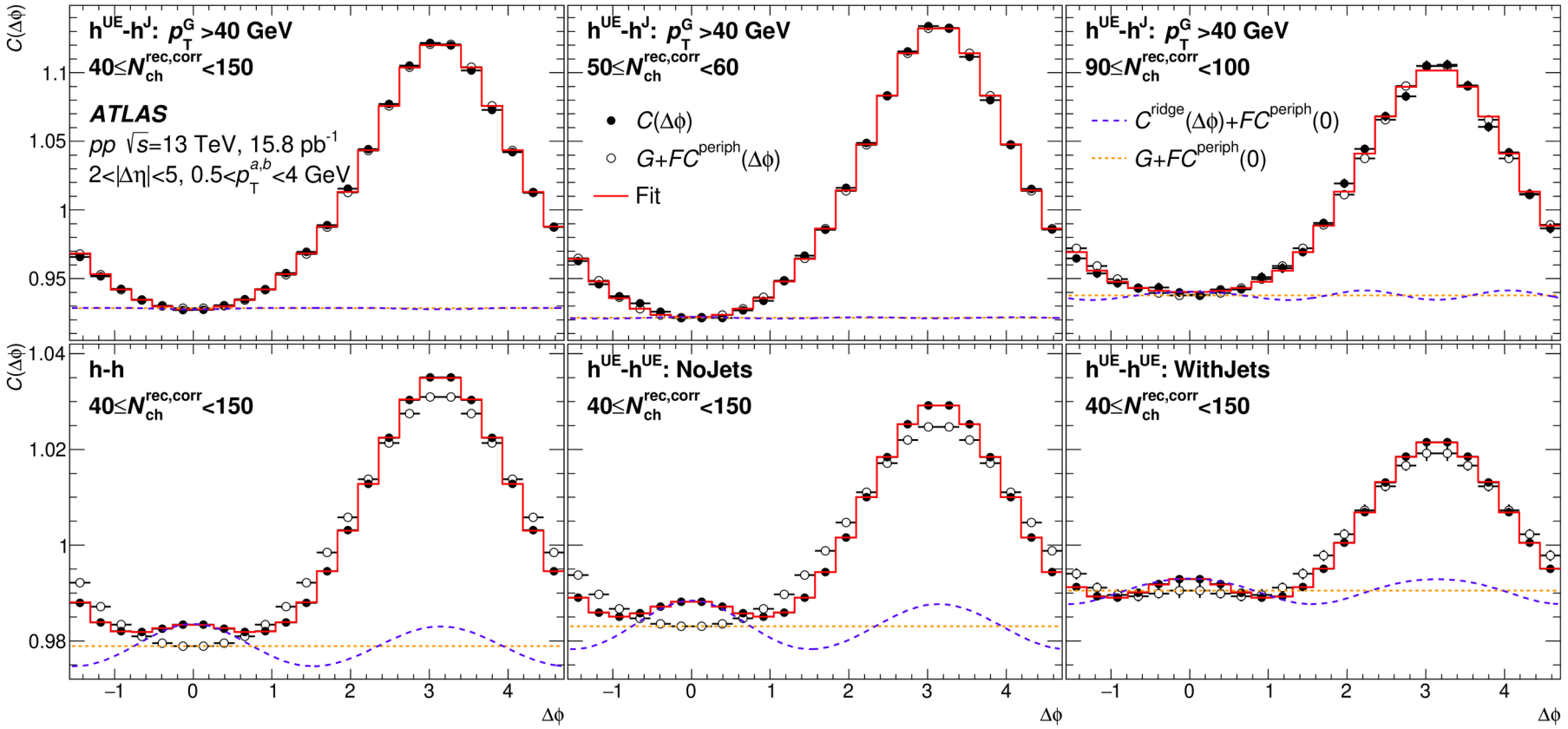


Models qualitatively describe the quark-jet suppression, but slightly overpredict the magnitude

PLB 846 (2023) 138154

Sensitivity of two-particle correlations to jets in p+p collisions

Soft jet fragments and underlying event: correlations?

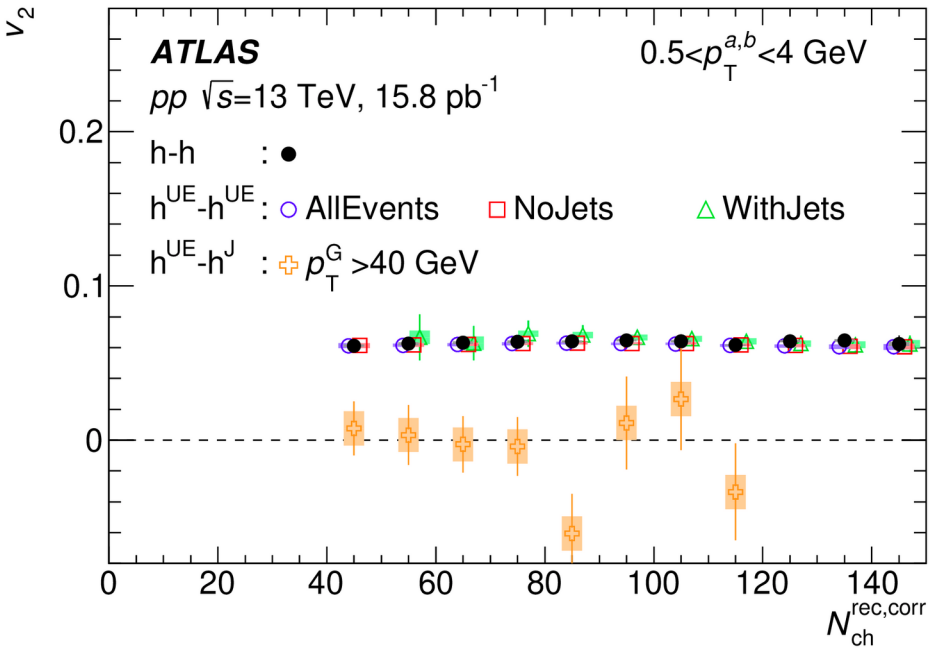


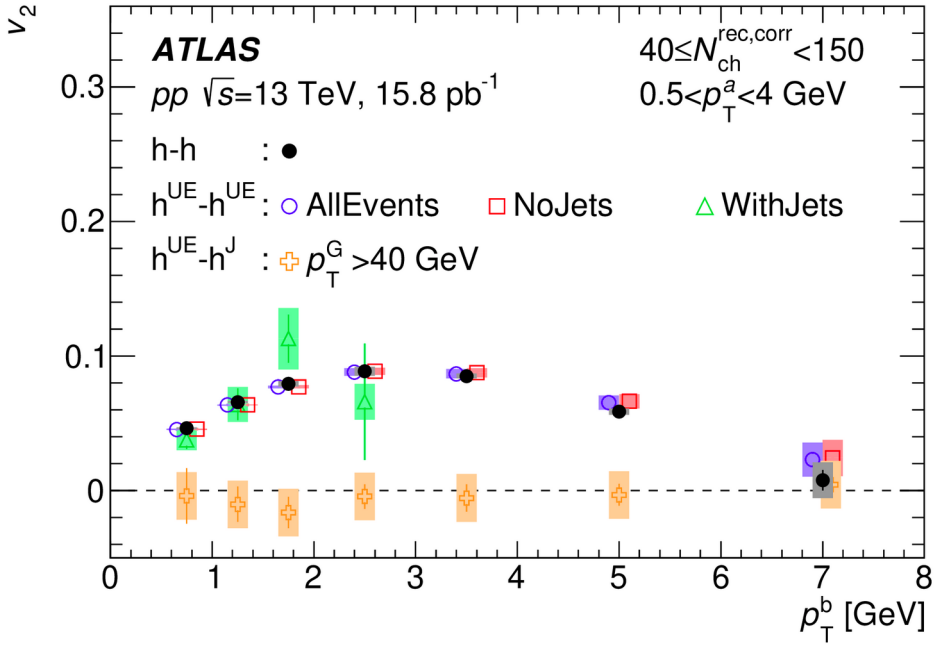
Template fit method used to extract the 2nd Fourier coefficient jet-UE correlations (top); event classes w/ and w/o jets (bottom)

PRL 131 (2023) 162301

Sensitivity of two-particle correlations to jets in p+p collisions

Soft jet fragments and underlying event: correlations?



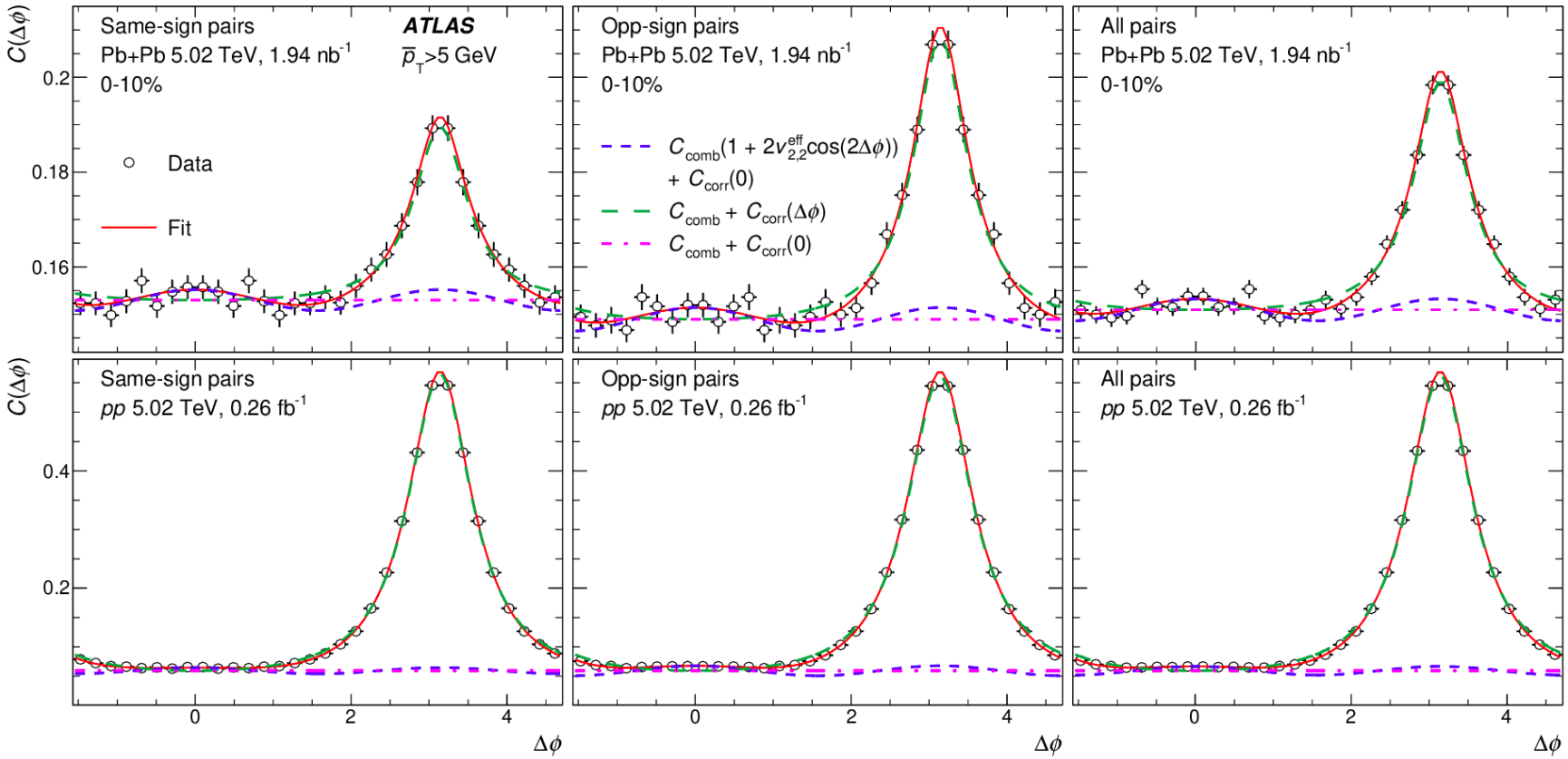


Excluding jet constituents does not affect the correlations
Jet constituents are not correlated with the underlying event

PRL 131 (2023) 162301

Dimuon correlations in p+p and Pb+Pb collisions

Muons from semileptonic decays of heavy quarks
Azimuthal angle separation (Δφ) of muons



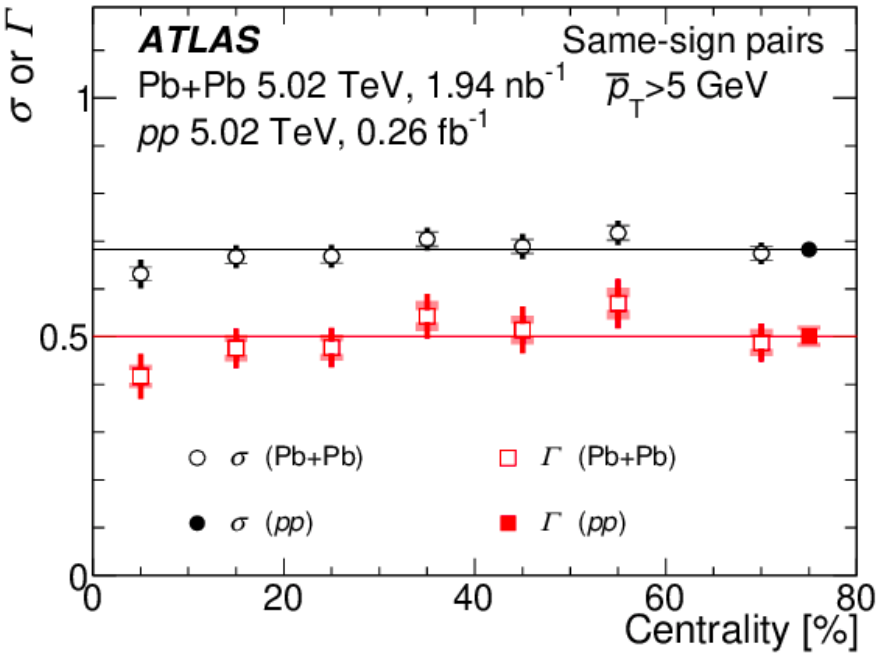
The width of the peak at Δφ~π is similar in p+p and Pb+Pb and not sensitive to the Pb+Pb centrality

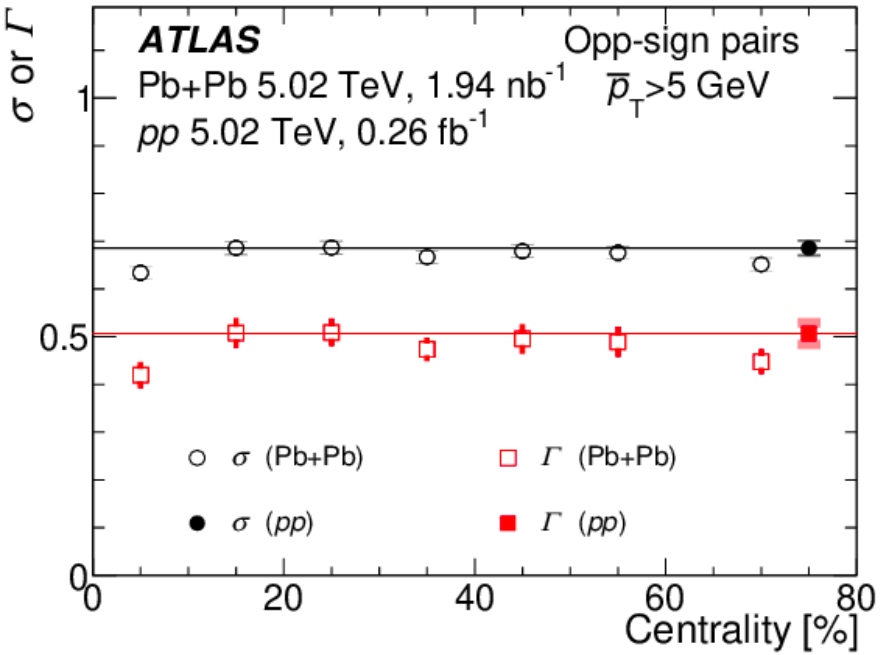
arXiv:2308.16652 submitted to PRL

Dimuon correlations in p+p and Pb+Pb collisions

Muons from semileptonic decays of heavy quarks
Azimuthal angle separation (Δφ) of muons

$$C_{\mathrm{corr}}(\Delta\phi) = \frac{C_{\mathrm{corr}}^{\mathrm{max}}\,\Gamma^2}{(\Delta\phi-\pi)^2+\Gamma^2}$$



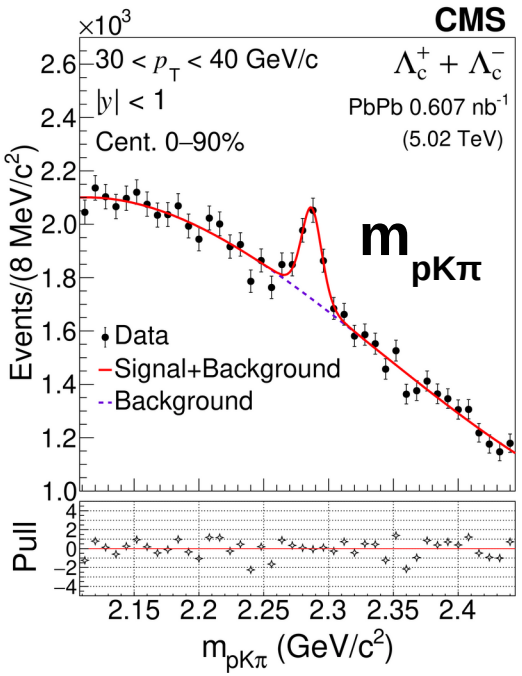


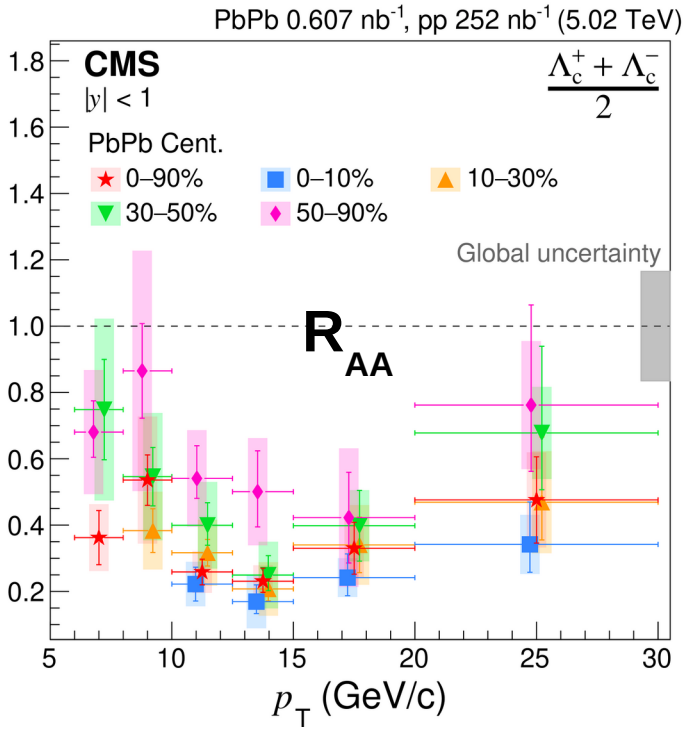
The width of the peak at Δφ~π is similar in p+p and Pb+Pb and not sensitive to the Pb+Pb centrality

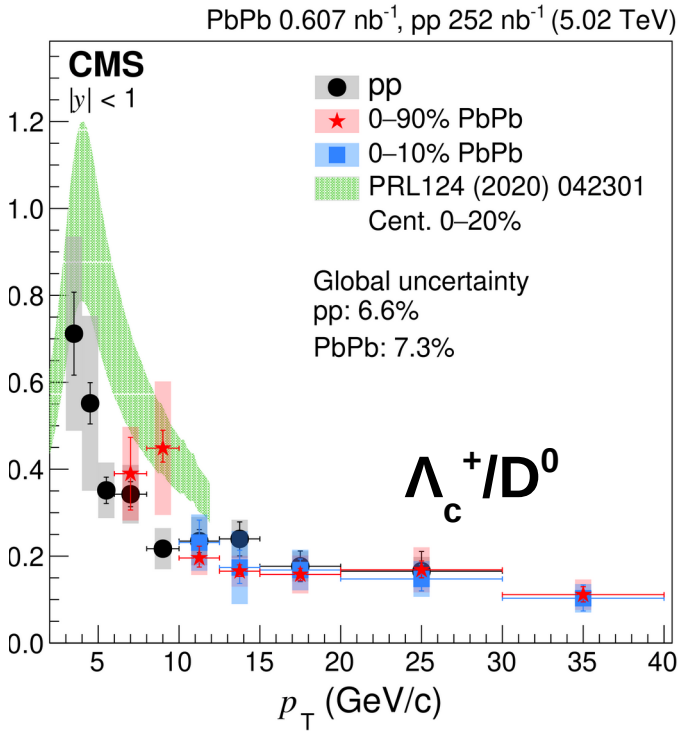
arXiv:2308.16652 submitted to PRL

Charm hadronisation with prompt Λ_c^+ baryons

- **$\Lambda_c^+ \rightarrow pK^-\pi^+$ decay**







- **Λ_c^+ yields stongly suppressed in Pb+Pb (compared to p+p)**
- **Λ_c^+/D^0 similar at high p_T: coalescence not dominant here**

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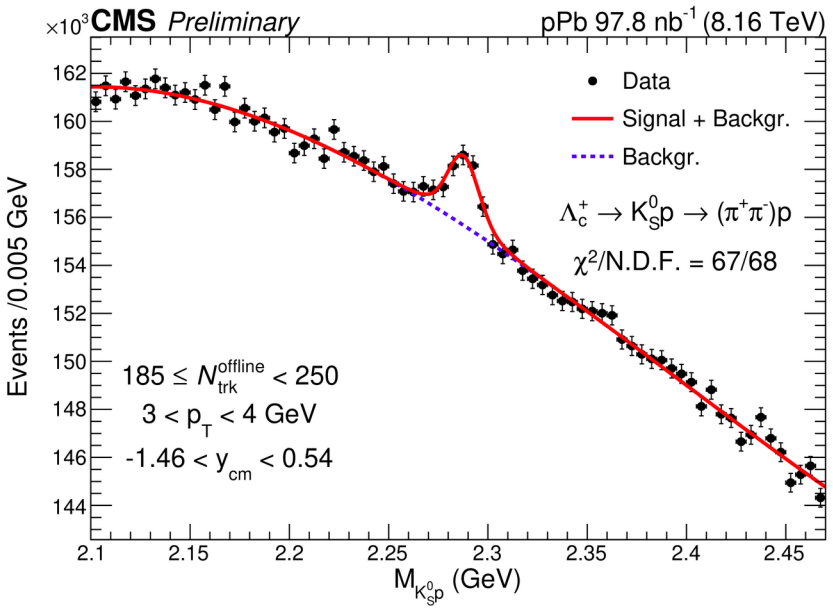
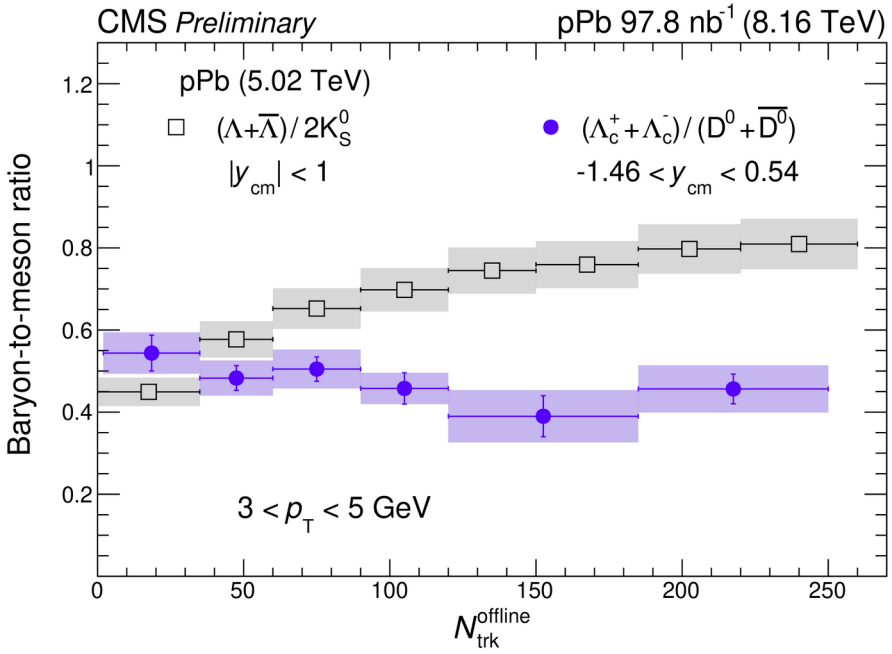
Charm baryon and meson production in p+Pb collisions

- **$\Lambda_c^+ \rightarrow K_S^0 p$ and $D^0 \rightarrow K^-\pi^+$ decays as a function of multiplicity**

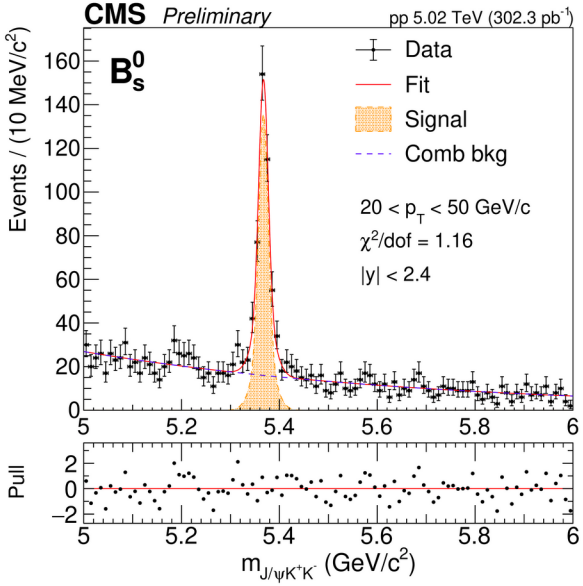


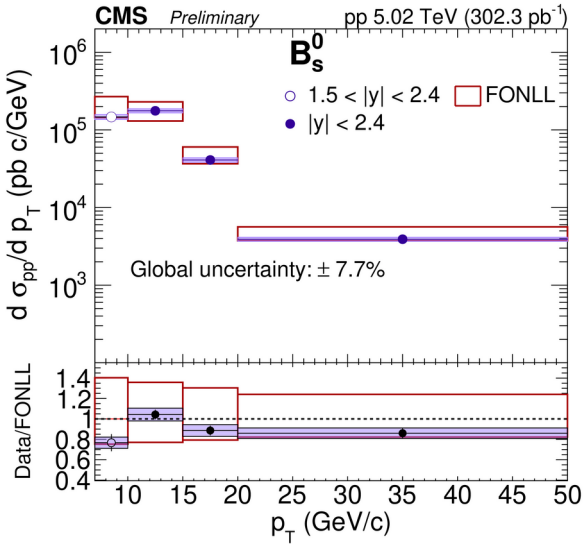


- **$\Lambda/\bar{\Lambda}$ to K_S^0 ratio: strong multiplicity dependence**
- **Λ_c^+/D^0 similar at high and low multiplicity**
- **Different hadronization of c and s?**
  (earlier saturation of coalescence for c)

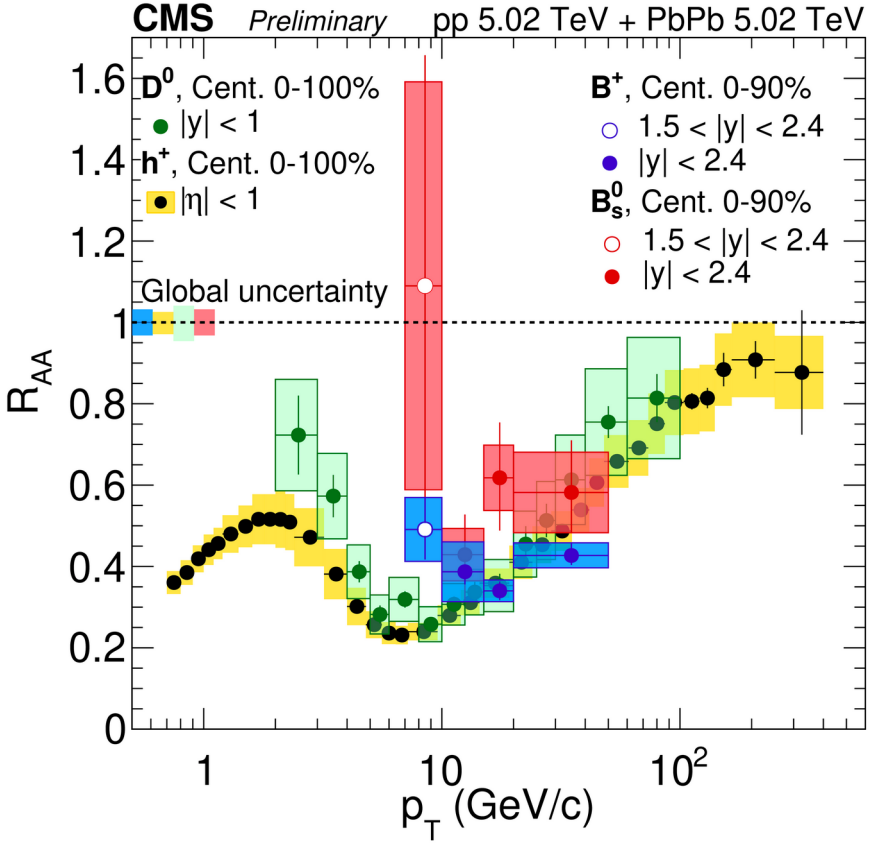
HIN-21-016

b quark energy loss with B^+ and B_s^0 in Pb+Pb and p+p





$B_s^0 \rightarrow J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$ and
$B^+ \rightarrow J/\Psi(\mu^+\mu^-)K^+$ decays

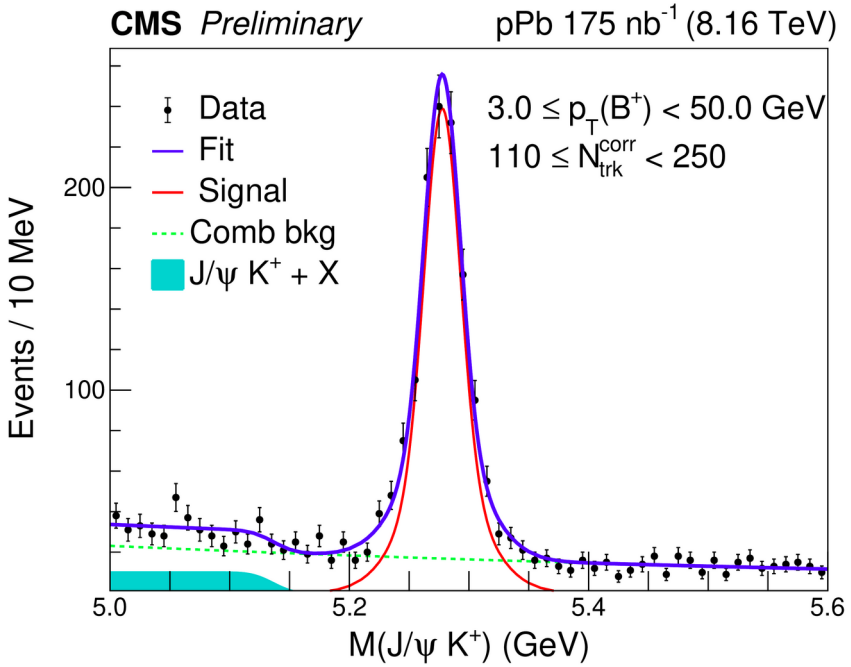


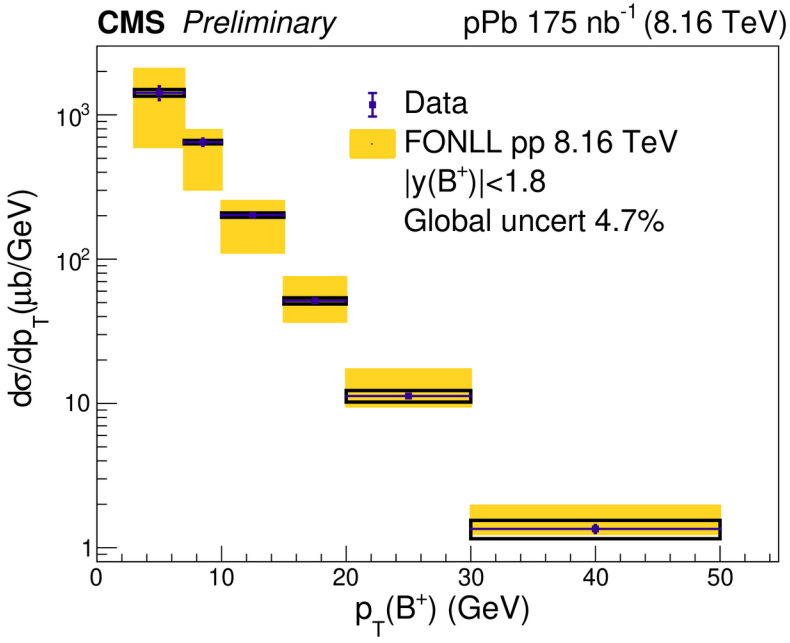
HIN-21-014

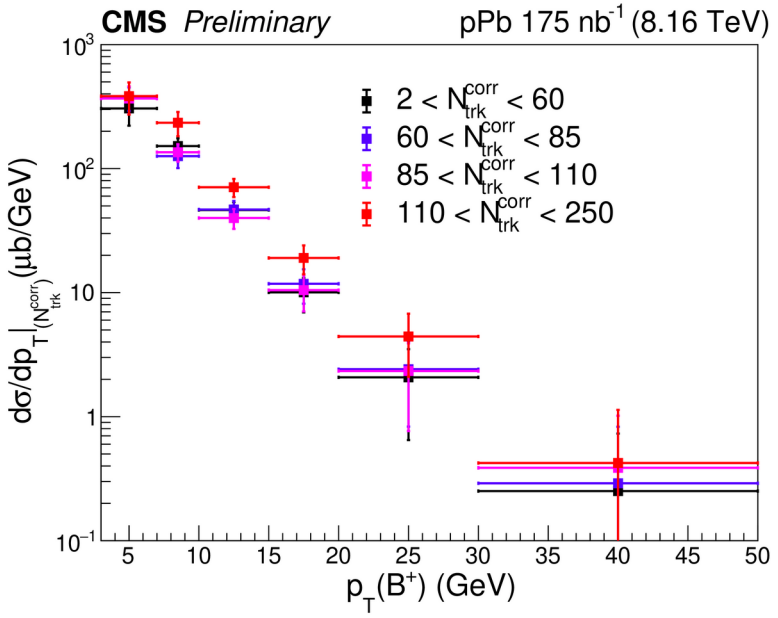
- **p+p data agrees with fixed-order+NLL**
- **B^+ R_{AA} similar to hadrons and D^0**

B^+ production in p+Pb collisions as a function of multiplicity

$B^+ \rightarrow J/\Psi(\mu^+\mu^-)K^+$ decays







- **p+Pb data agrees well with fixed-order+NLL**
- **First multiplicity dependent measurement**

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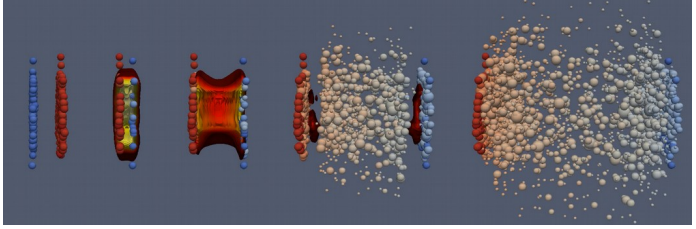
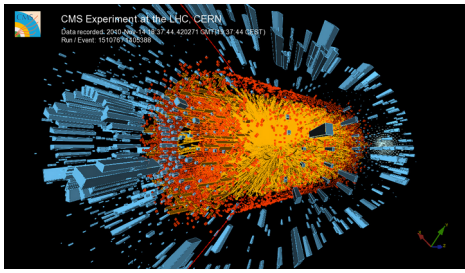


Summary



- Speed of sound agrees with Lattice, constrains EoS
- Collective motion reveals f_0 quark content
- Sub-nucleon structure and fluctuations affect collective flow
- Bjorken-scaling in p+Pb collisions
- Collectivity in very high multiplicity jets in p+p
- Precise jet radius can only be measured with γ tag
- Gluon jets lose more energy than quark jets
- Long-range correlations and jets factorize
- Heavy quarks show negligible angular broadening
- Coalescence does not play an important role at high momenta
- Different hadronization mechanism for s and c quarks
- Many challenges for model calculations

High precision and large data samples open(ed) the way to qualitatively new type of Heavy Ion measurements and improve understanding of the dynamics of the strong interaction!

Acknowledgements

CERN CMS and ATLAS experiments
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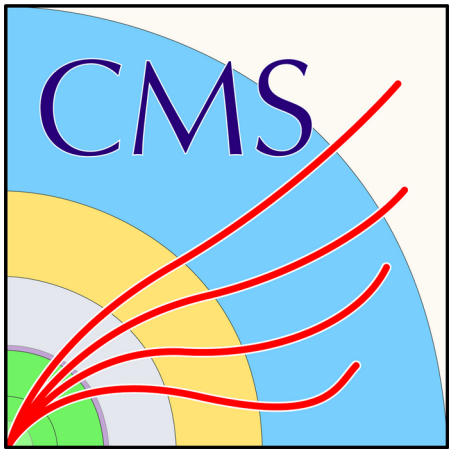

NEMZETI KUTATÁSI, FEJLESZTÉSI ÉS INNOVÁCIÓS HIVATAL