Experimental state-of-the art

Maximiliano Puccio (CERN)

SCM Strasbourg 2024

3rd June 2024

The 21st International Conference on Strangeness in Quark Matter

This conference will focus on new experimental and theoretical developments on the role of strange and heavy-flavour quarks in high energy heavy-ion collisions and in astrophysical phenomena.

SQM 2024 will be the 21st edition of the conference series and, for the first time, takes place in France. It follows the recent events in Busan (2022), New York (2021), Bari (2019) and Utrecht (2017). The full history of the SQM conferences is listed here.

Scientific topics

Strangeness and heavy quark production in nuclear collisions and hadronic interactions
Hadron resonances in the sQGP (strongly-interacting Quark-Gluon Plasma)
Bulk matter phenomena associated with strange and other heavy quarks
Chirality, vorticity and spin polarisation phenomena
Strangeness in astrophysics
QCD phase structure
Collectivity in small systems
Open questions and new developments

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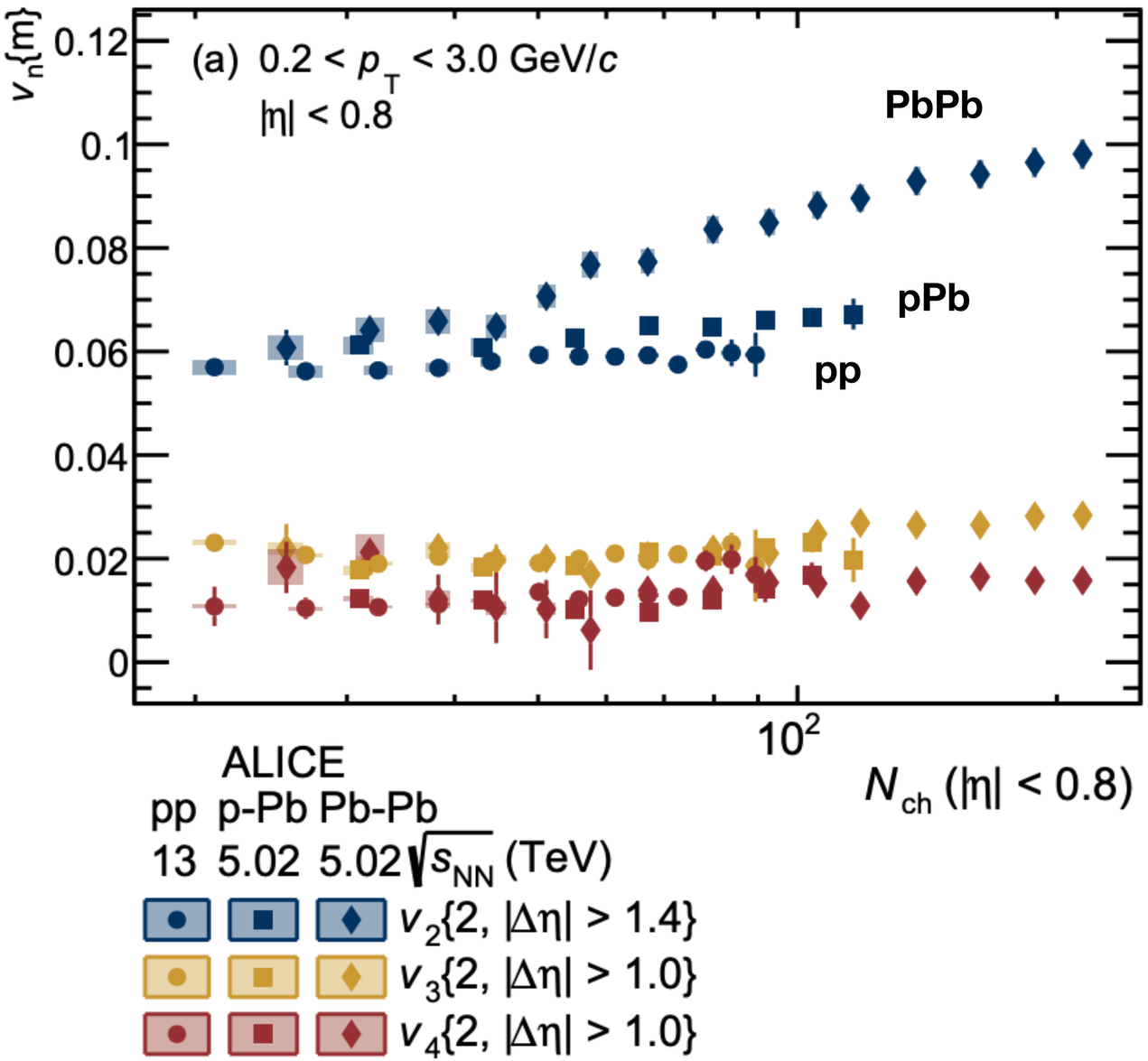
Focus on the issues I would like
to discuss this week

Chasing the onset of collective effects

ALICE, arXiv:2211.04384



What we observe:

- Ordering of the v_2 with system size
- v_3 and v_4 show no evolution with multiplicity nor system size

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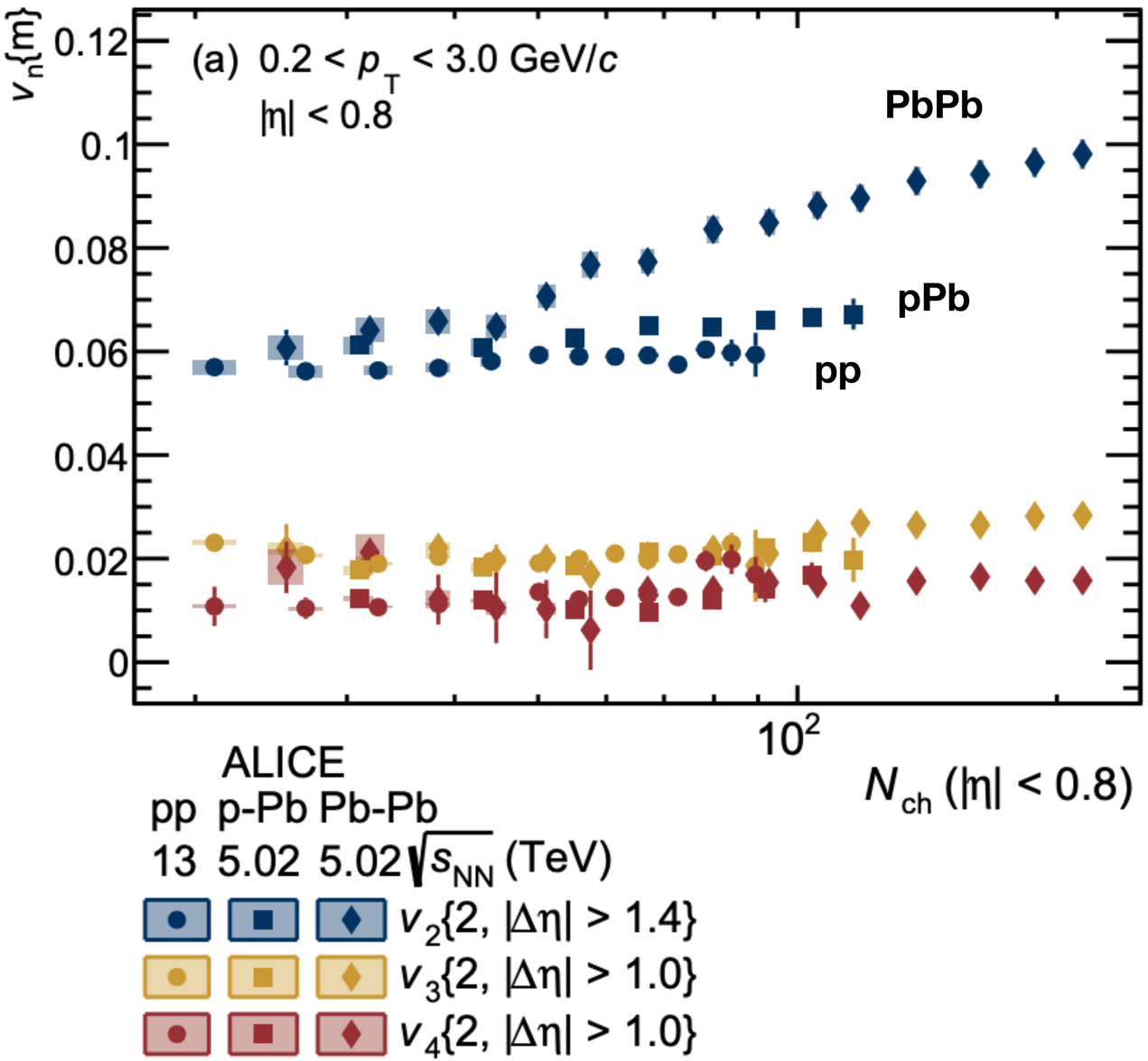

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How can we interpret it:

- v_3 and v_4 are sensitive to fluctuations of the initial geometry
- v_2 is the response of the system to the initial geometry of the collision
  - In pp and p-Pb geometry fluctuation only
  - In peripheral Pb-Pb initial anisotropy create the v_2

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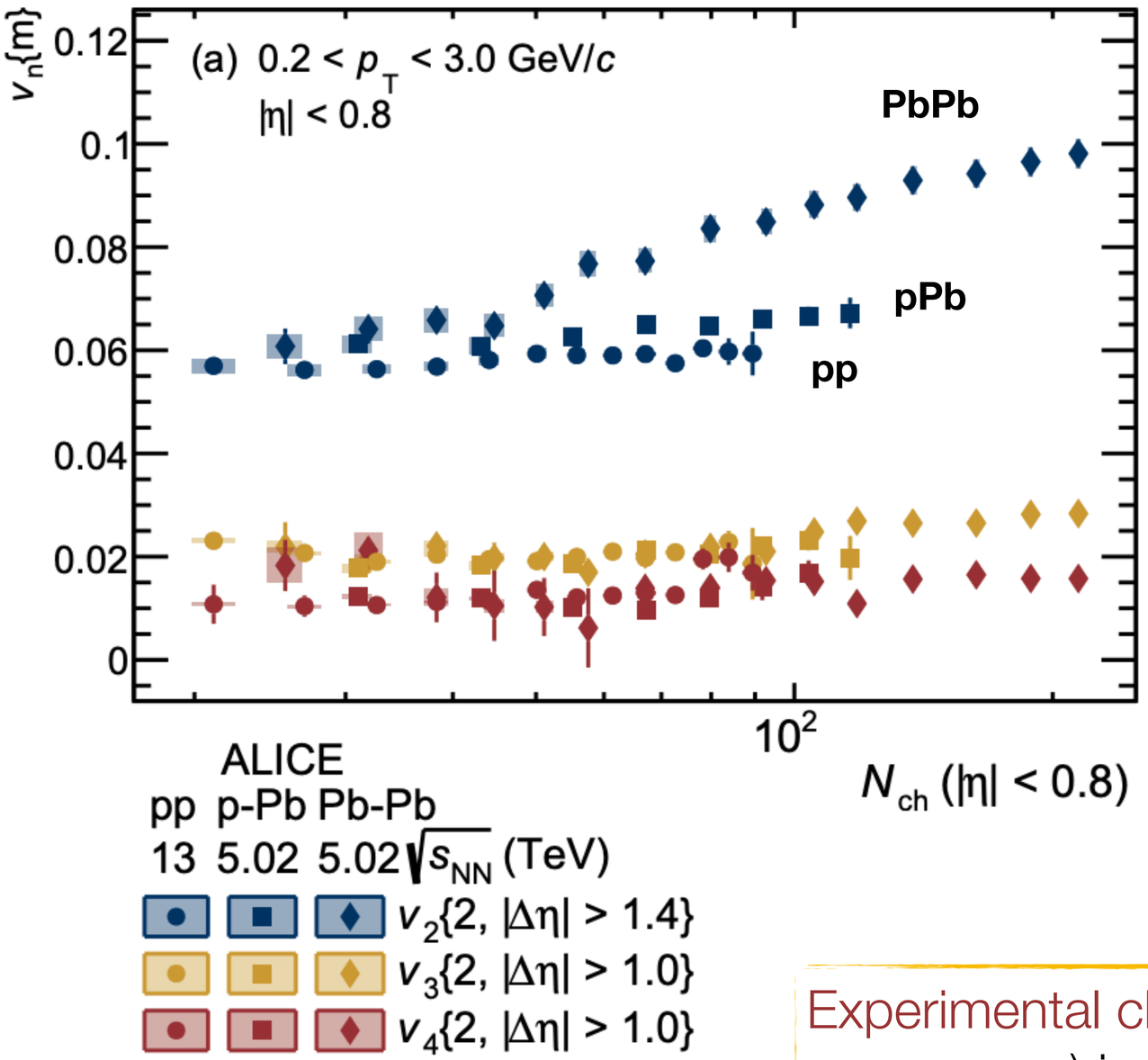

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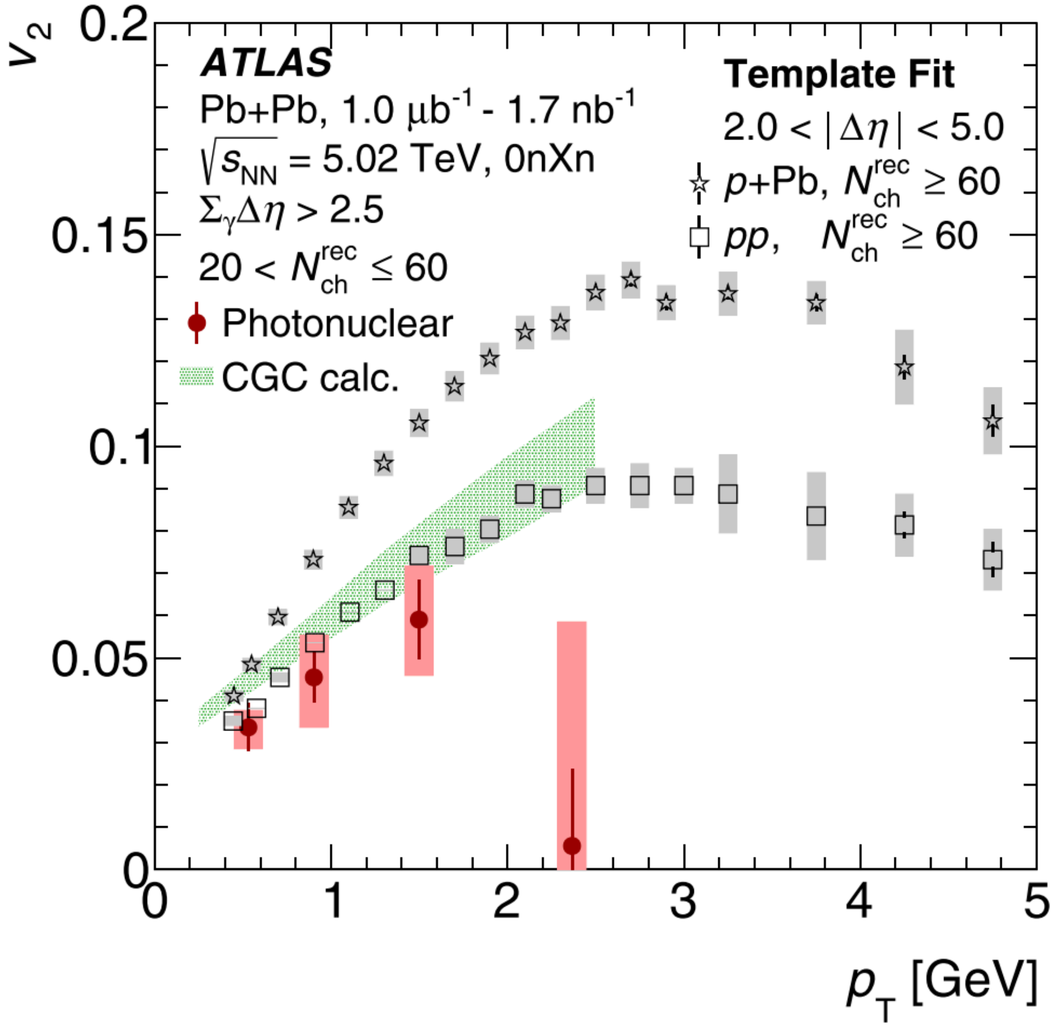
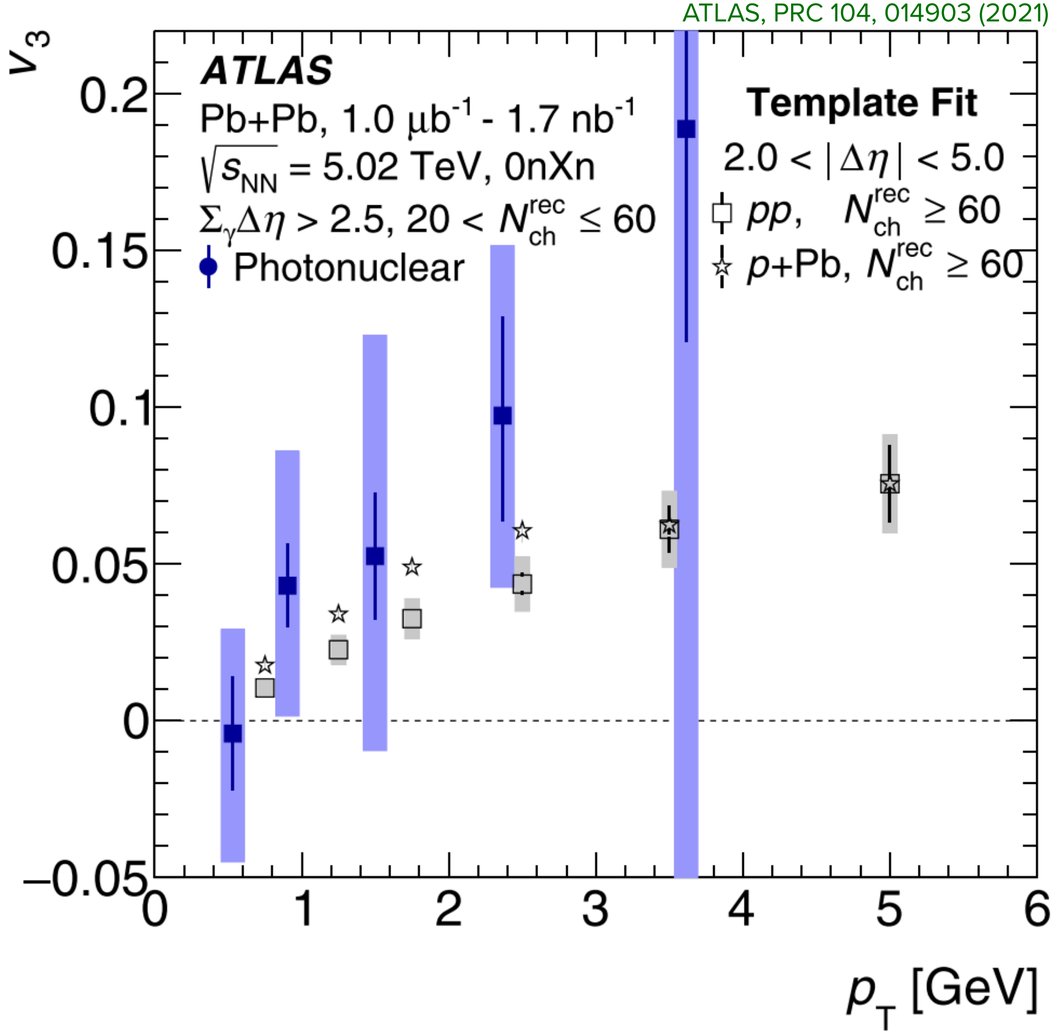
  - In peripheral Pb-Pb initial anisotropy create the v_2
- Can we turn them off?

Experimental challenge: removing non-flow effect (e.g. jets, resonances) in small systems

Chasing the onset of collective effects: γPb collisions

ATLAS, PRC 104, 014903 (2021)

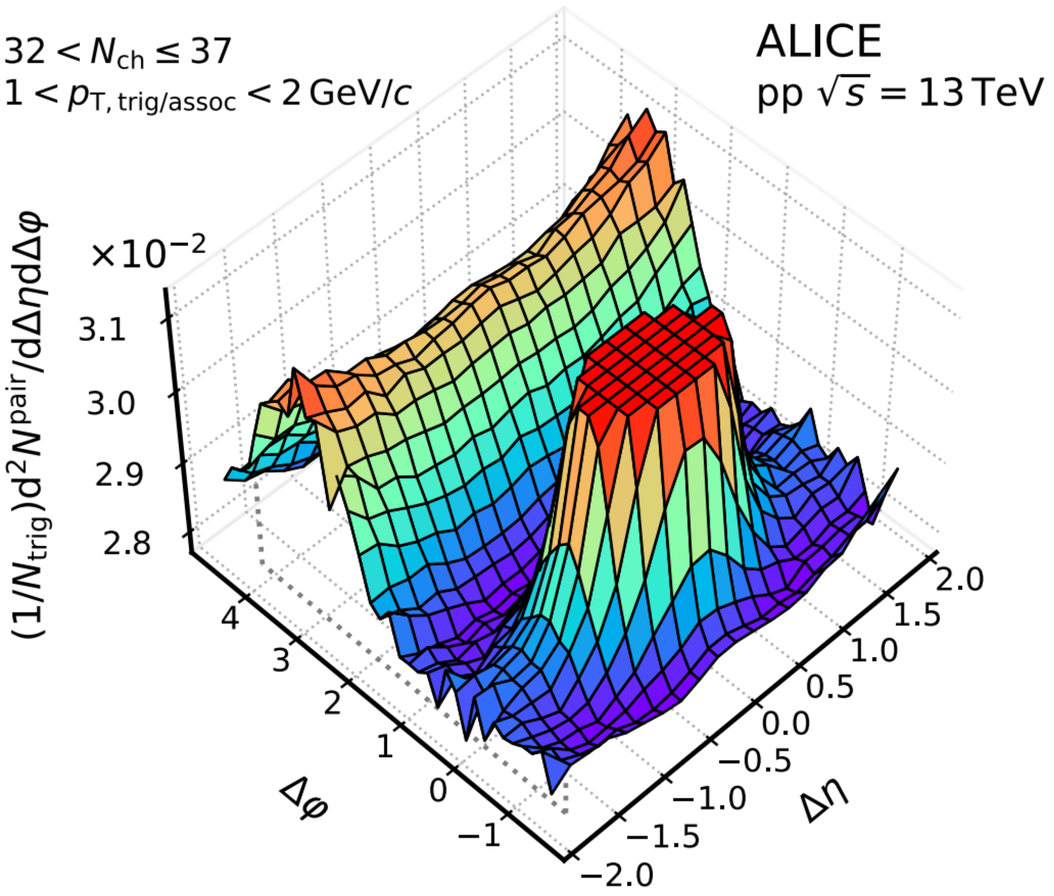




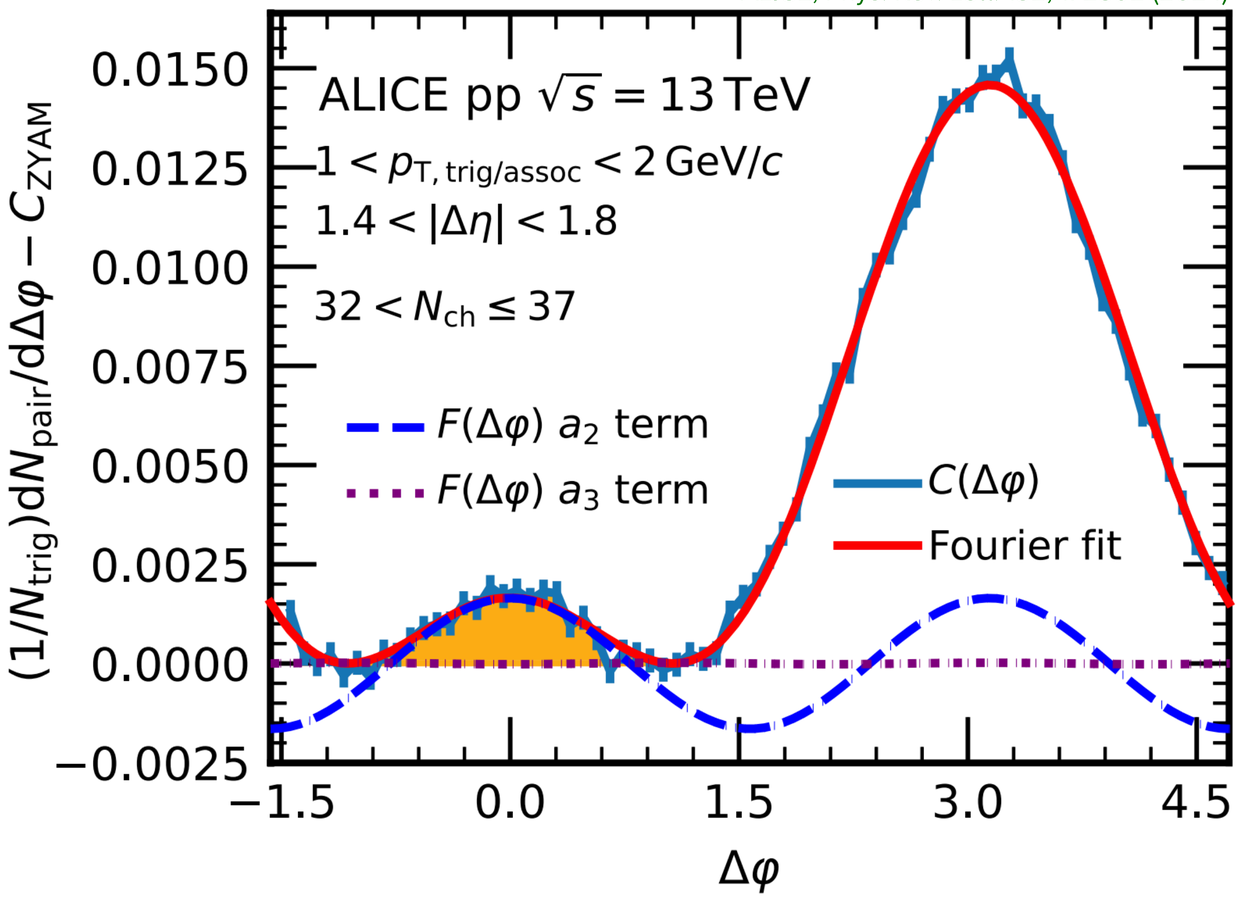
Measurement of v_2 and v_3 in photonuclear reactions (γPb) at the LHC

- Hint of v_2 smaller than in pp, v_3 compatible with other systems

Chasing the onset of collective effects: pp and e^+e^-

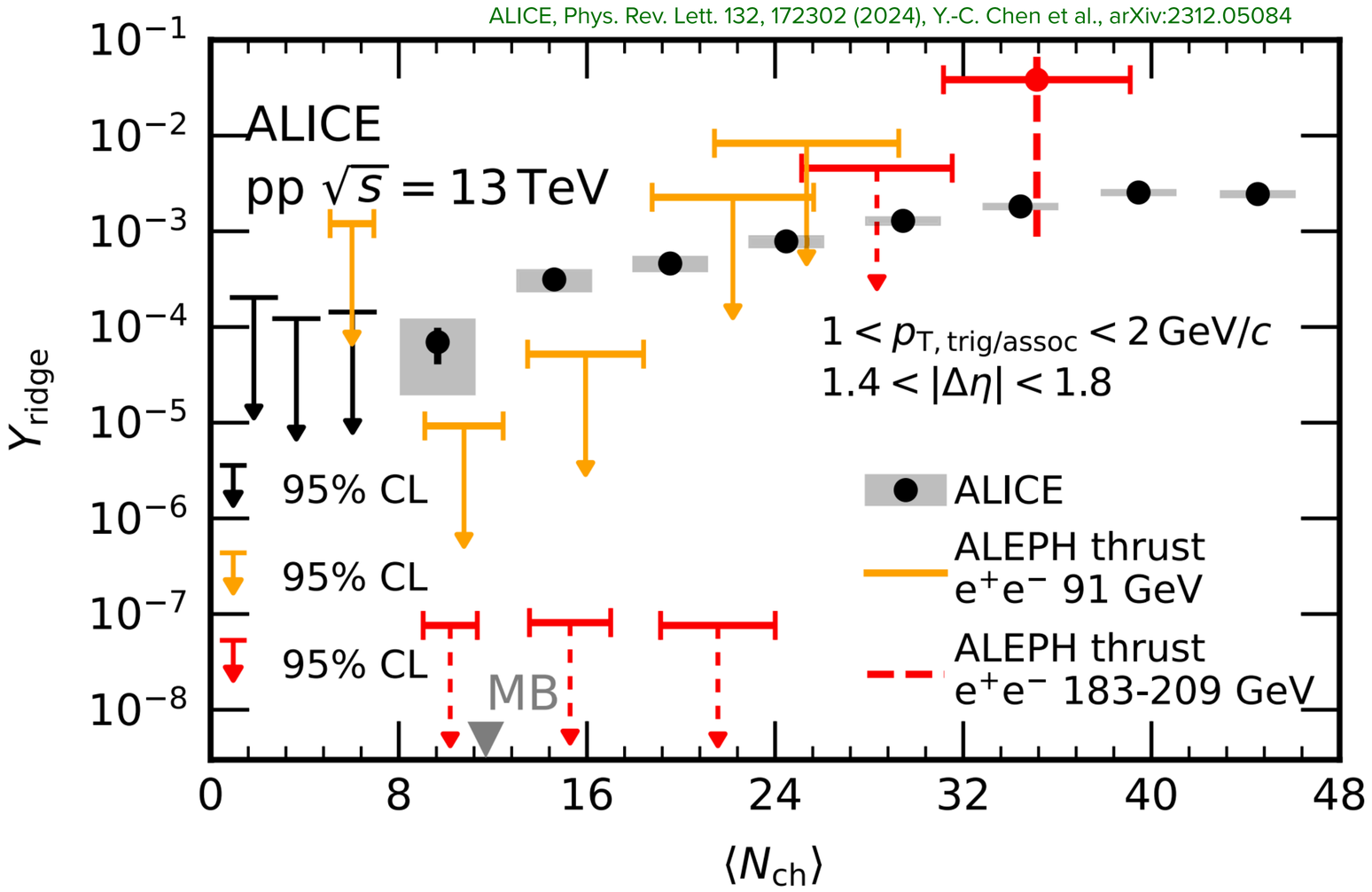


ALICE, Phys. Rev. Lett. 132, 172302 (2024)



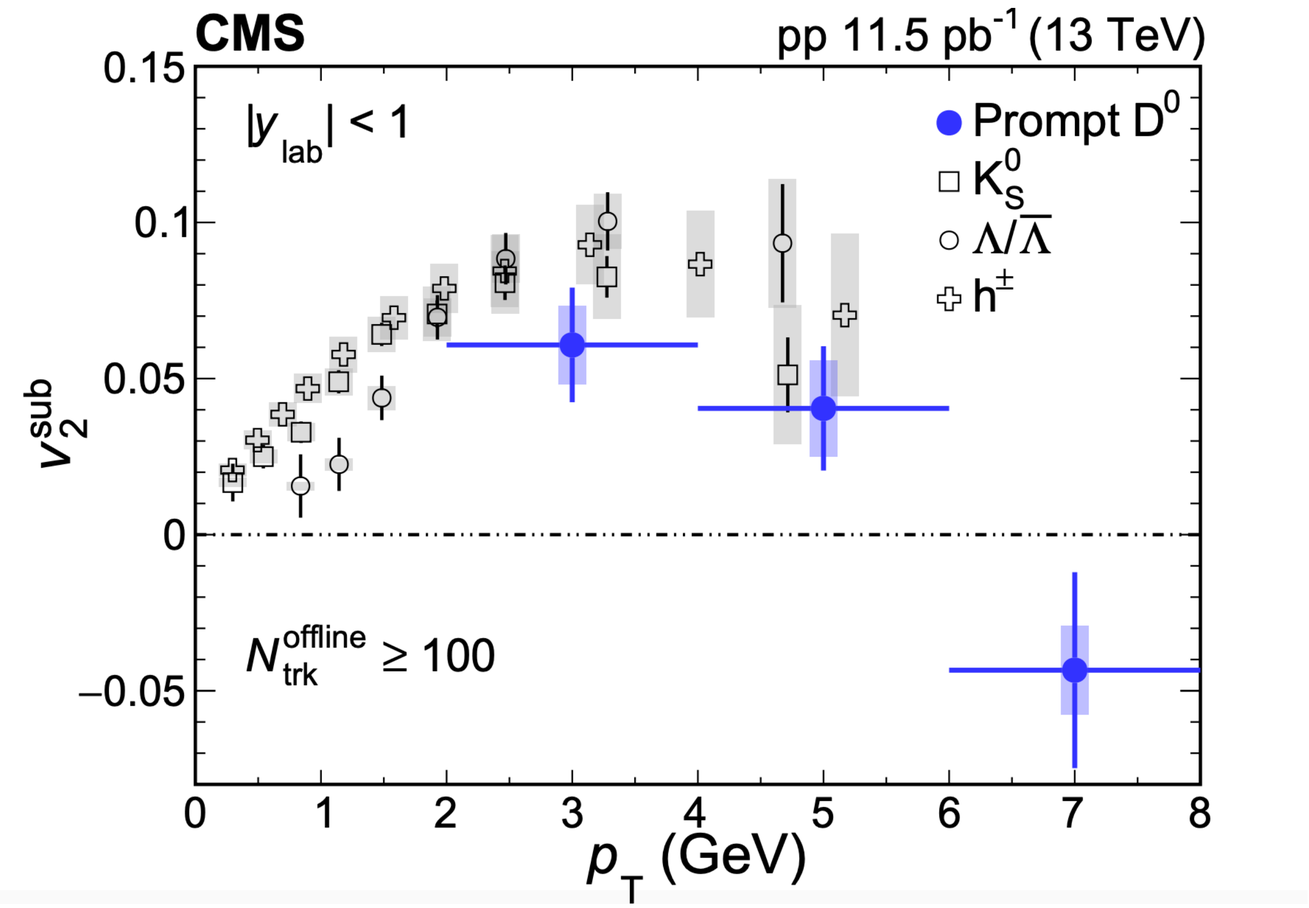
- Significant near-side ridge yield observed in pp collisions down to very low multiplicity

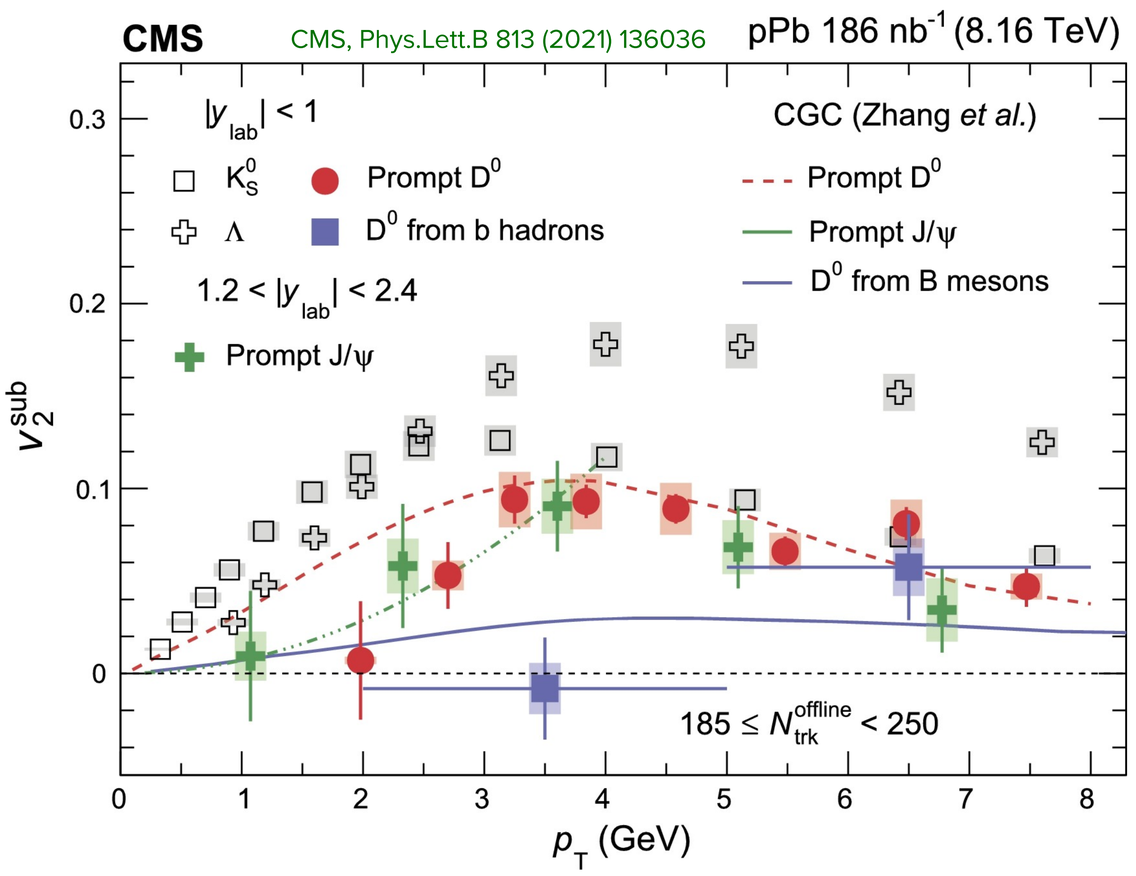
Chasing the onset of collective effects: pp and e^+e^-



- Significant near-side ridge yield observed in pp collisions down to very low multiplicity
- Below 30 charged particles, no significant signal in e^+e^-, > 3σ away from pp
  - ➡ At higher multiplicity hint of a signal… significance not at the level to firmly conclude

Even charm flows in small systems, but beauty doesn't





Charm hadrons have non-zero v2 in pp and p-Pb collisions too!!

- Not (only?) due to coalescence with lighter quarks as J/Ψ v_2 != 0
- Meson grouping visible
- Beauty v_2 still consistent with 0

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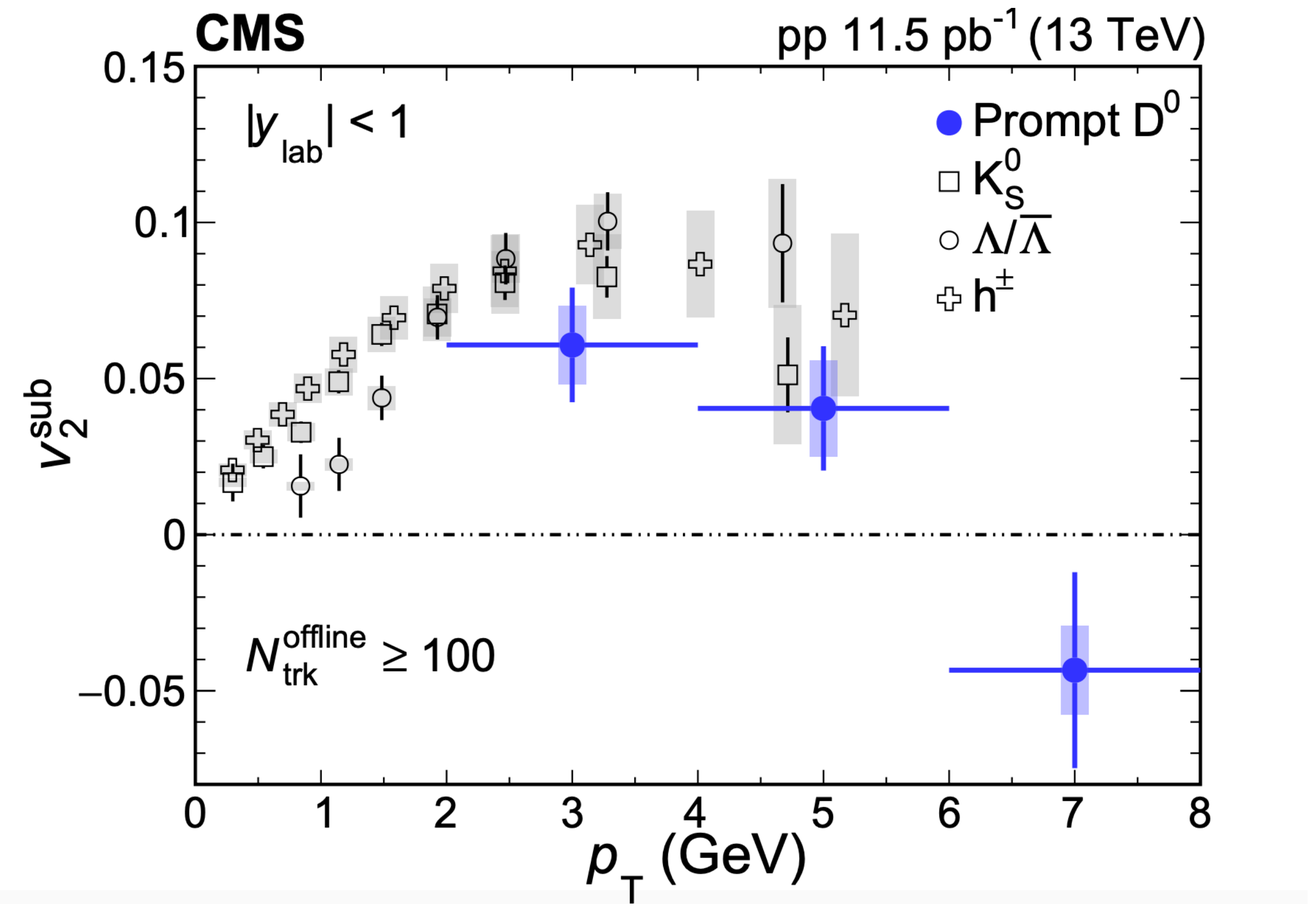

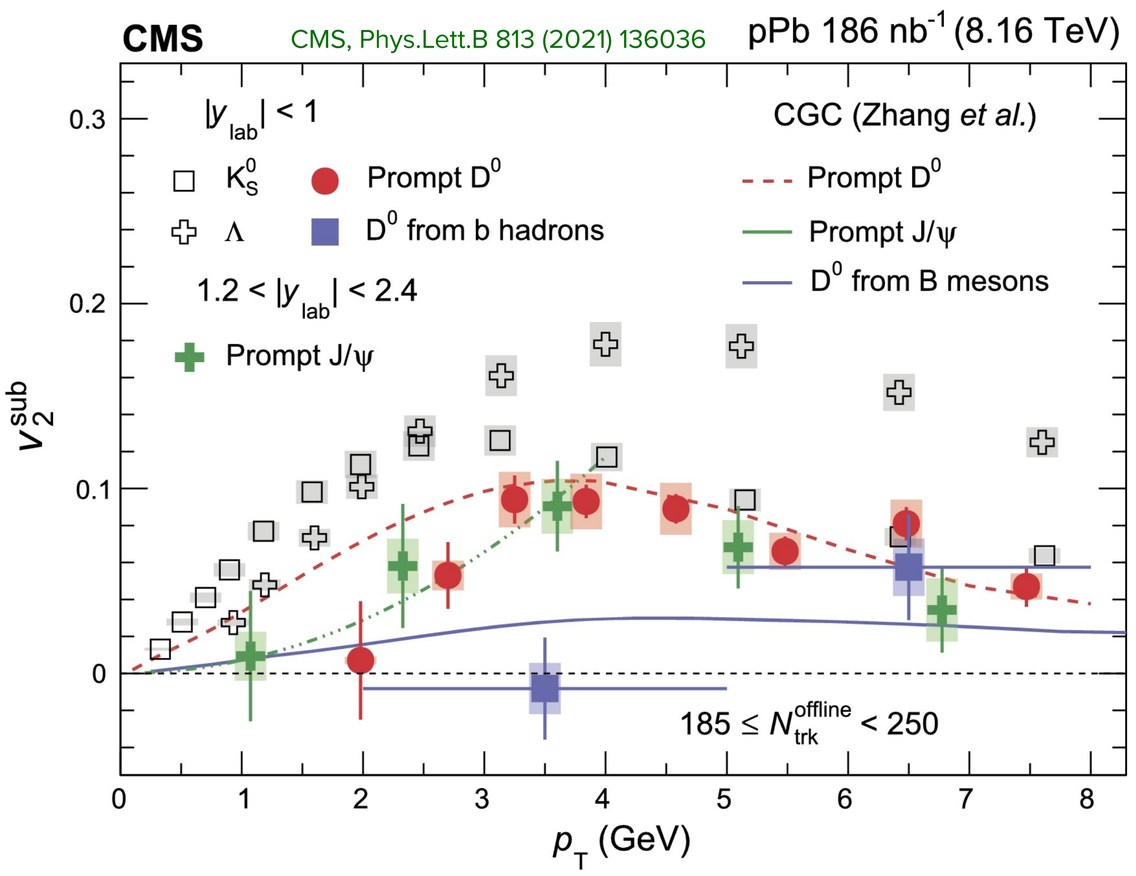

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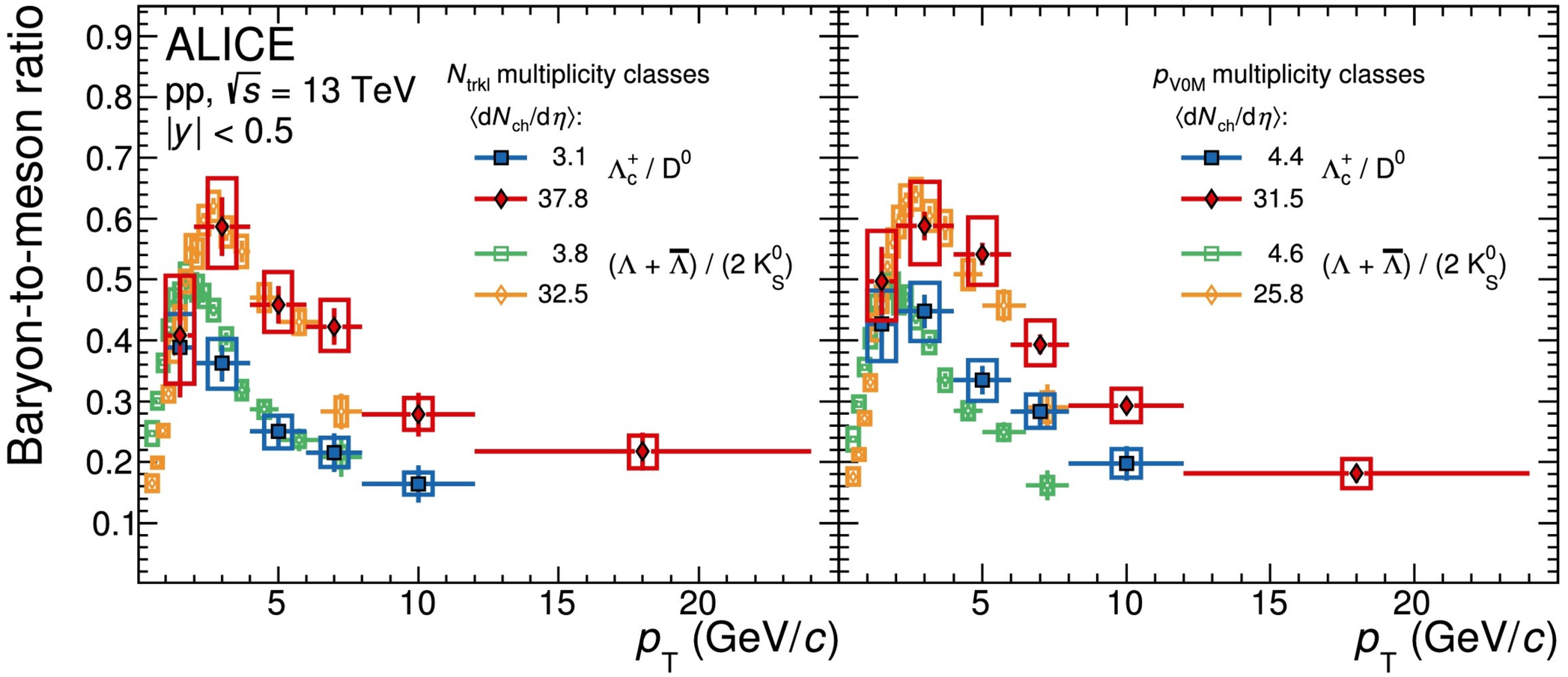
} Also CGC explains this behaviour

More precision and species needed

Baryon-to-meson ratio: radial flow?

ALICE, Phys. Lett. B 829 (2022) 137065



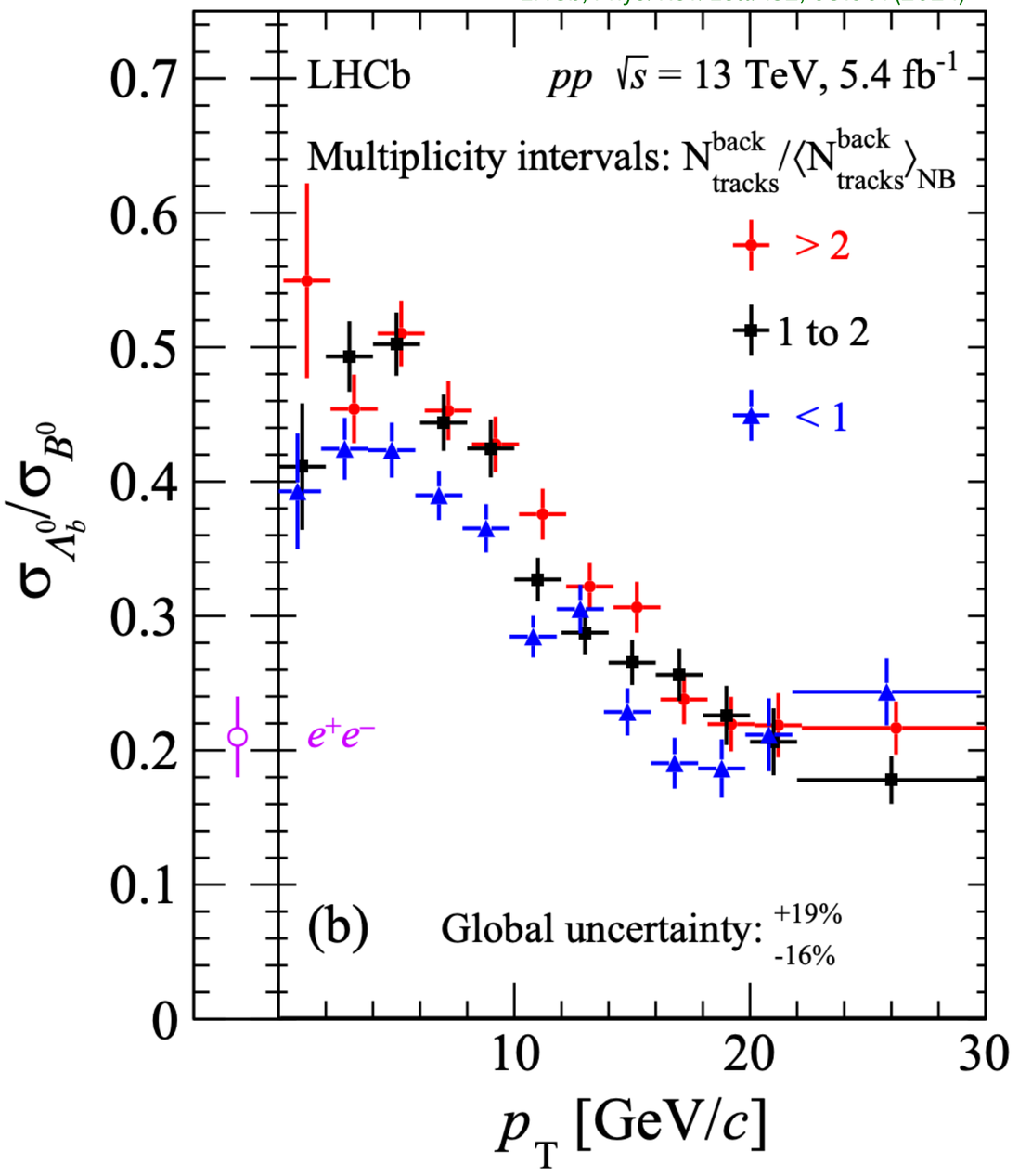
- Charm baryons/meson like for strangeness
- in ee these ratios are flat in p_T, in pp at low p_T peak of the ratio —> quark coalescence
- peak pushed to higher momenta at high mult.
- Experimentally important to check the effect of different multiplicity estimators

Baryon-to-meson ratio: beauty edition

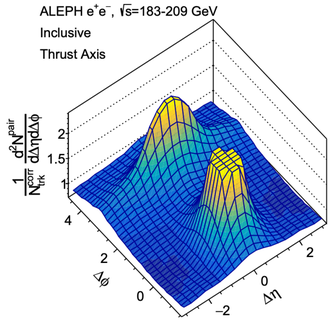
Similar pattern for beauty hadrons at forward rapidity

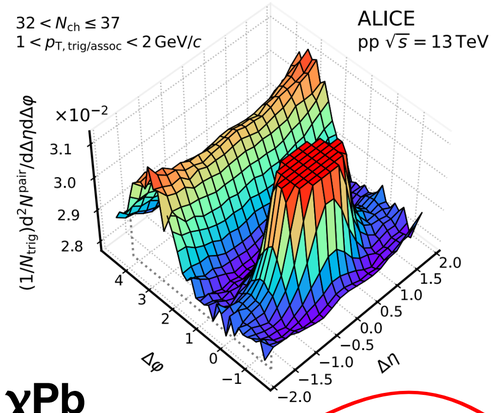
- In this case different multiplicity estimators give a slightly different picture
  - With rapidity gap between the multiplicity estimator and the measurement milder multiplicity dependence

LHCb, Phys. Rev. Lett. 132, 081901 (2024)

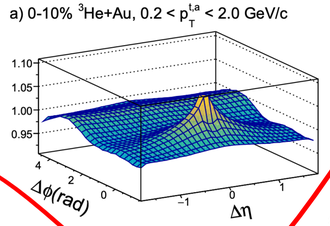


Collectivity in small system summary



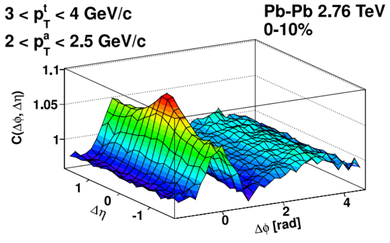


γPb

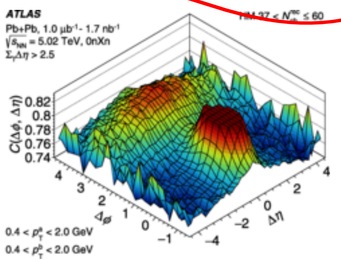


p-Pb

A-A

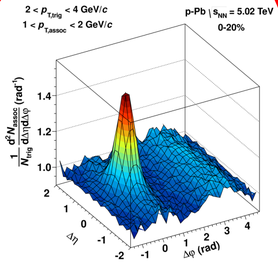


e-e+



pp

³He-Au



Wherever there is a hadron involved in the collisions we see non-zero v_n

- Meson/baryon grouping observed even in small systems
  - Charm behaves like strangeness

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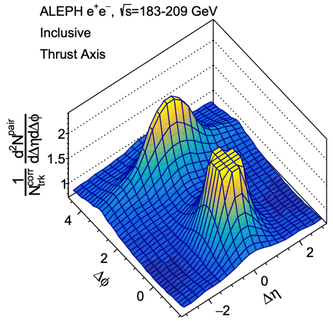

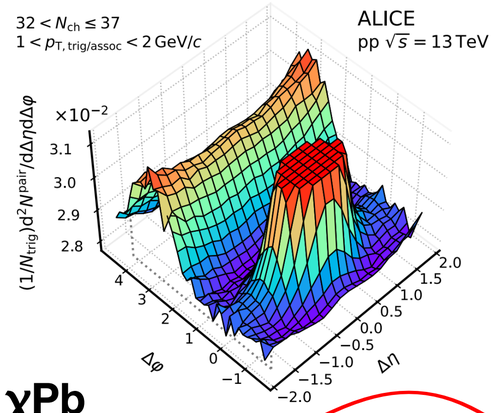

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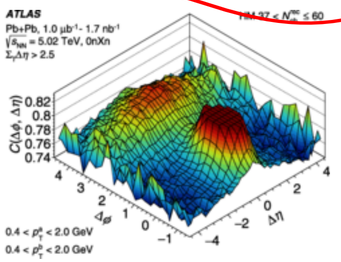

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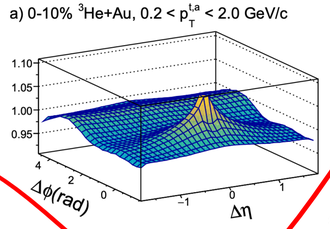

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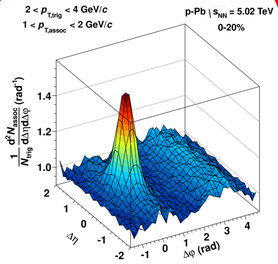

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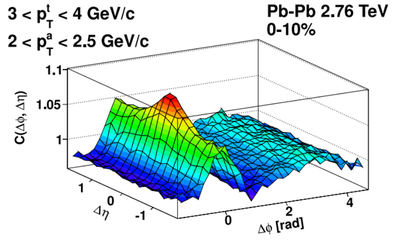

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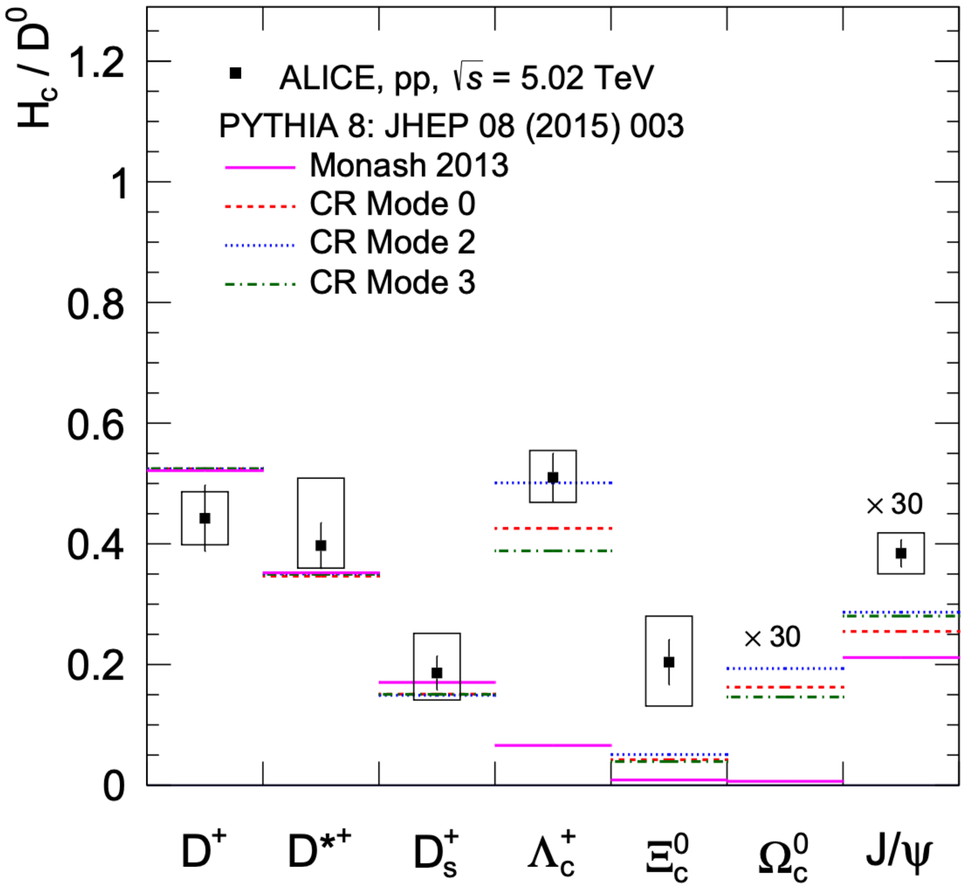
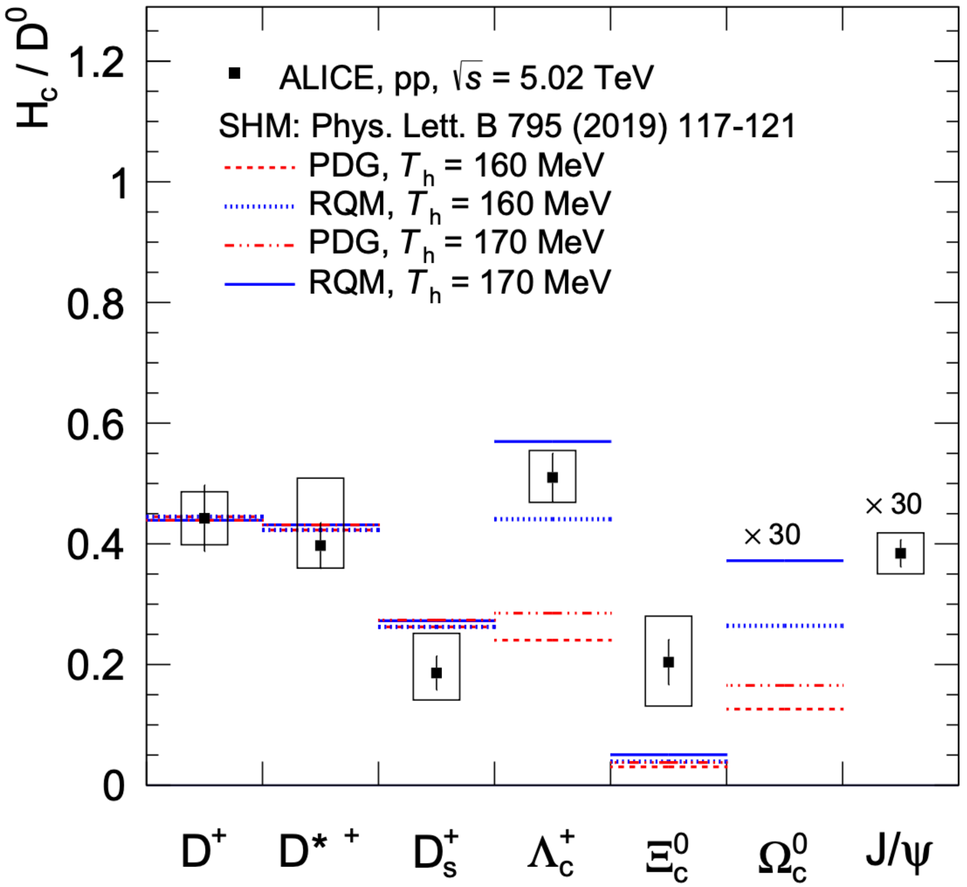
Are we seeing a thermalised expanding medium in small systems?

- Non-thermal models actively evolving and able to explain some of the observations
- Collectivity is only one piece of the puzzle

Charm chemistry in details

ALICE, Phys. Rev. D 105, L011103 (2022)





Charm hadron production, like light quark hadrons, is surprisingly close to the thermal model expectation, and it is not far from PYTHIA8 advanced color reconnections mode as well

- Resonances play a major role: we need precise measurements of yields (and to discover them all)

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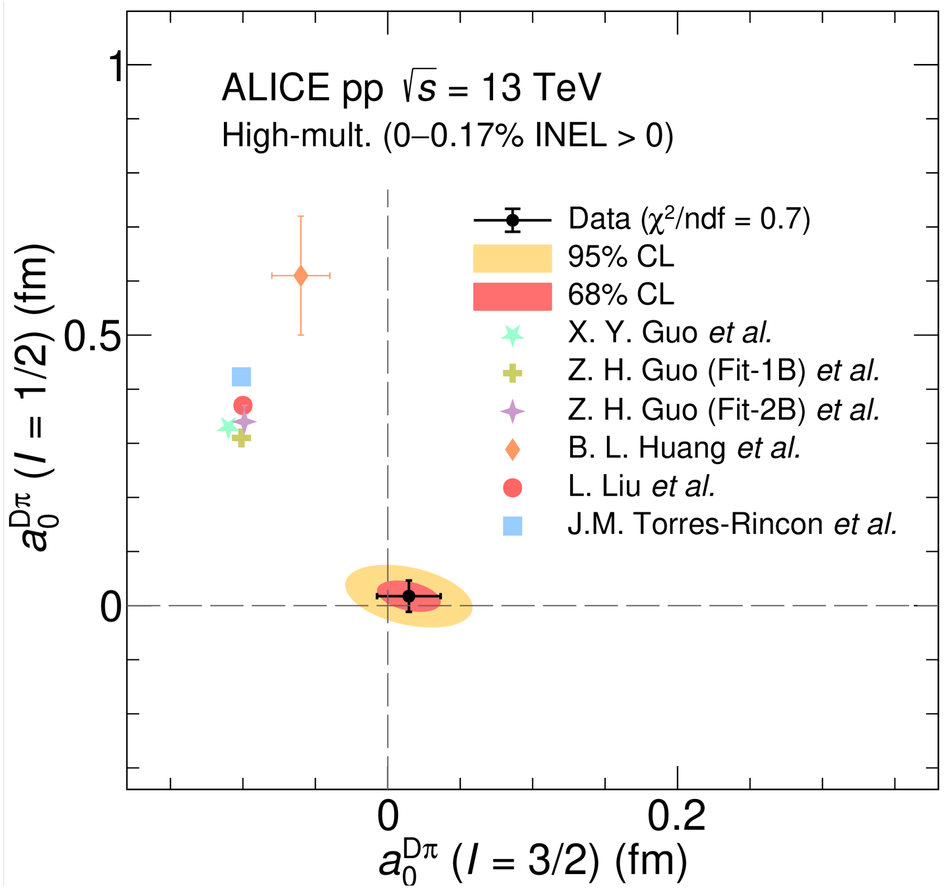
ALICE, arxiv2401.13541



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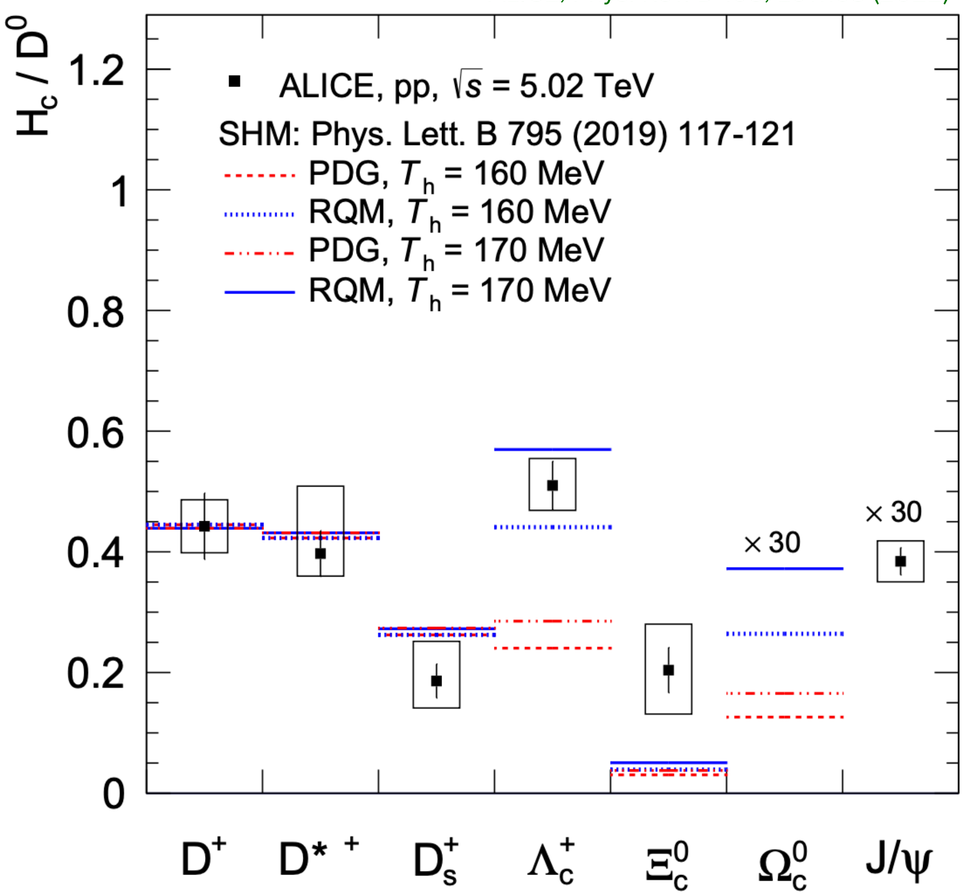

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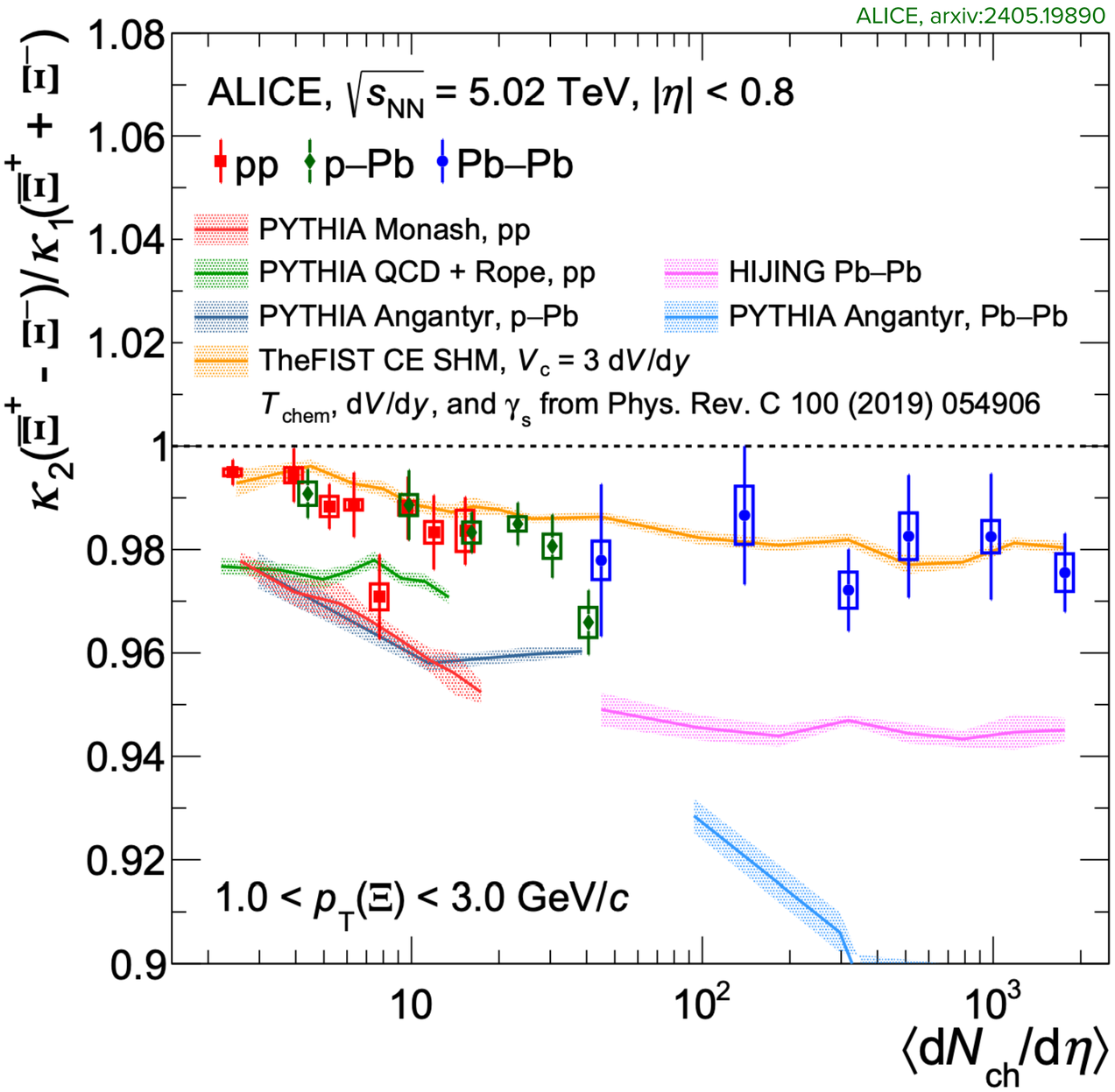
- How can charm hadrons reach equilibrium in a Hadron resonance gas, given their small interaction with other particles?

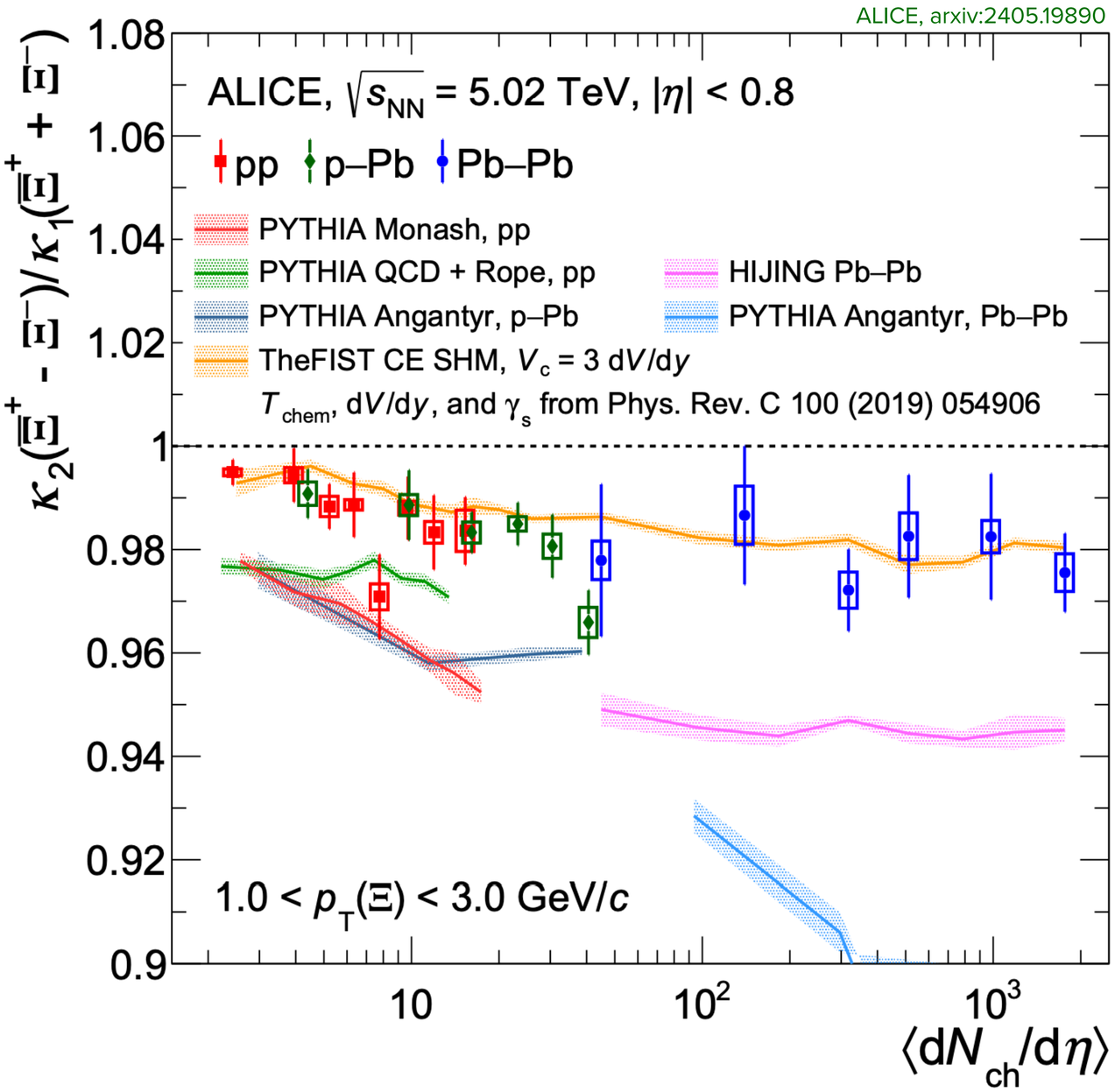
Fluctuation measurements across systems



Yields of strange particles are reproduced

- In pp within 20% by both SHM and PYTHIA
- In p-Pb, Pb-Pb good agreement with SHM

Fluctuation measurements across systems



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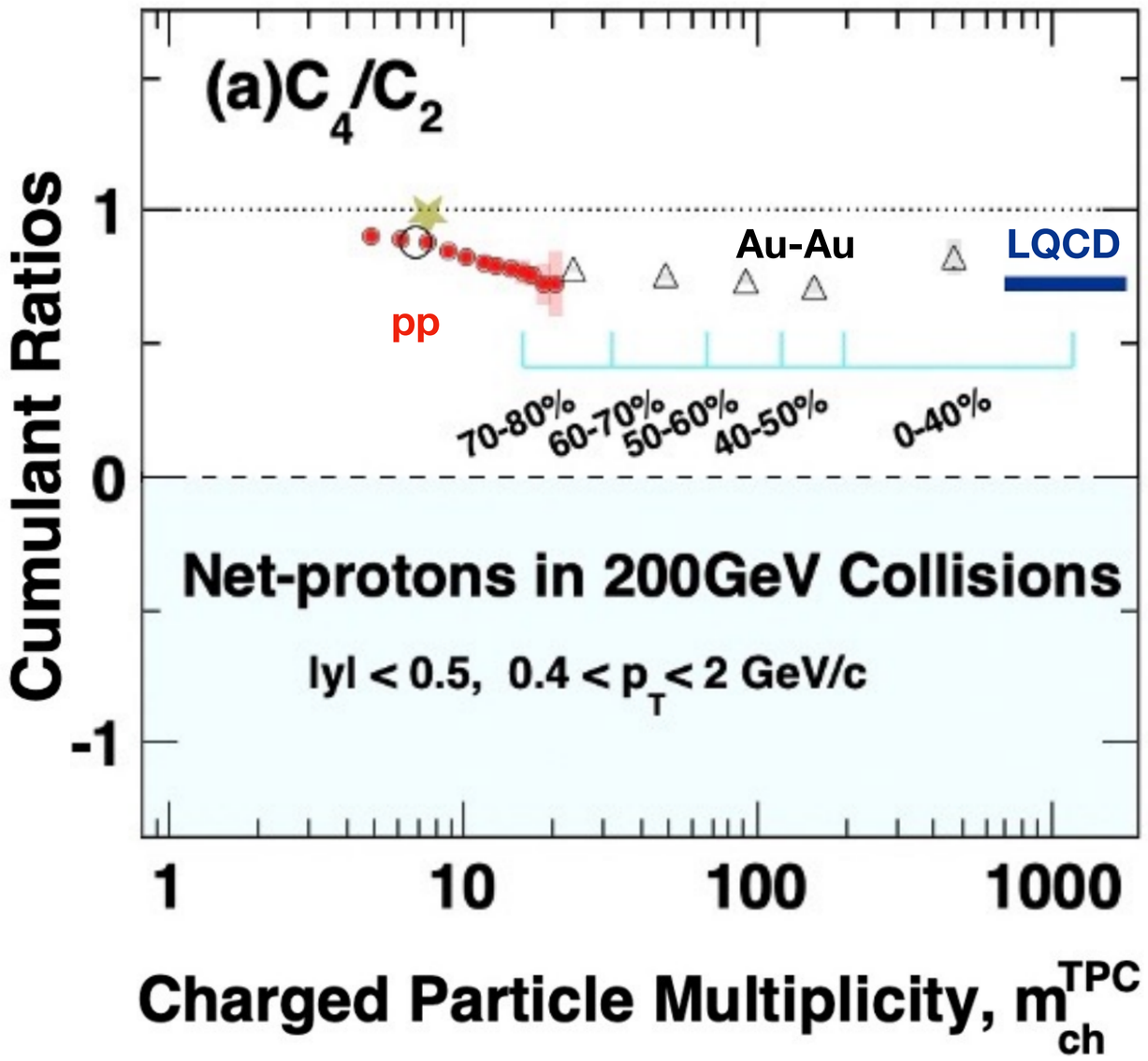
We test models looking at higher moments:

- Smooth evolution across systems
- Net-Ξ agrees with the SHM and more than 5σ away from PYTHIA in pp collisions

Fluctuation measurements across systems

STAR, arxiv:2311.00934



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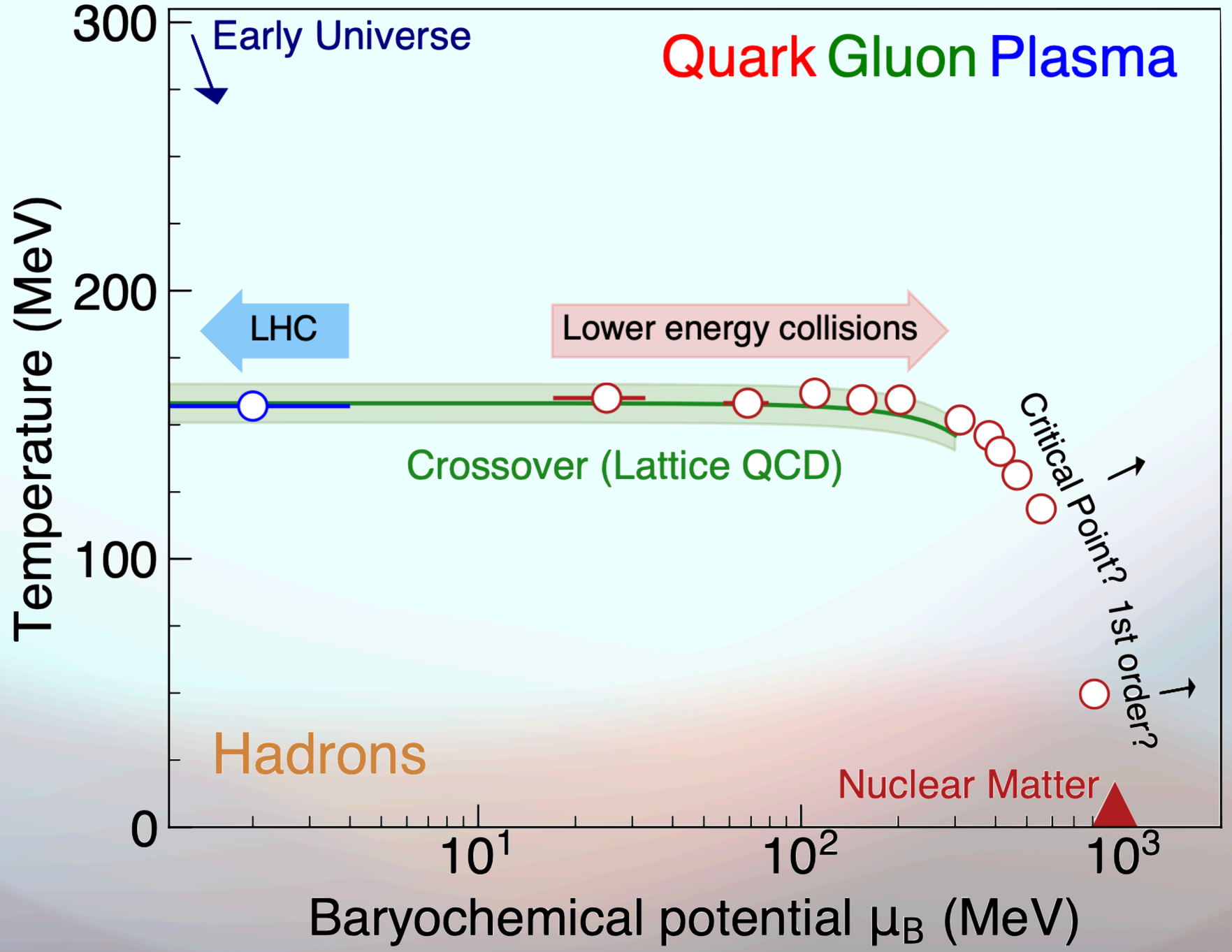
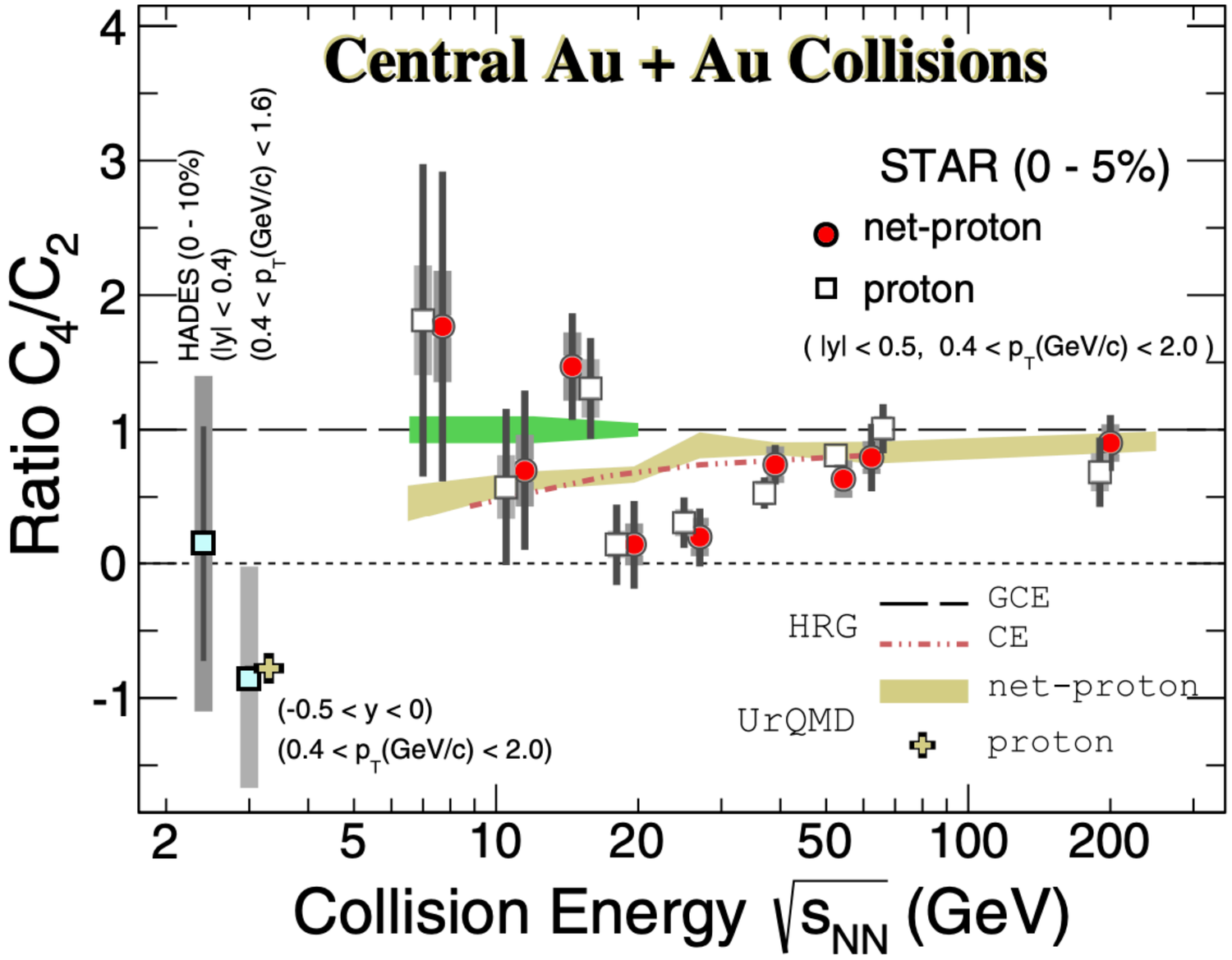
At RHIC, net-proton higher order cumulants show a smooth evolution as well

- HM pp collisions reach the Au-Au measurement that is in line with the LQCD net-baryon expectation


Early Universe
Quark Gluon Plasma
LHC
Lower energy collisions
Crossover (Lattice QCD)
Critical Point? 1st order?
Hadrons
Nuclear Matter
Temperature (MeV)
300
200
100
0
10^1
10^2
10^3
Baryochemical potential μ_B (MeV)

Search for the critical point

STAR, Phys. Rev. Lett. 128, 202303 (2022)

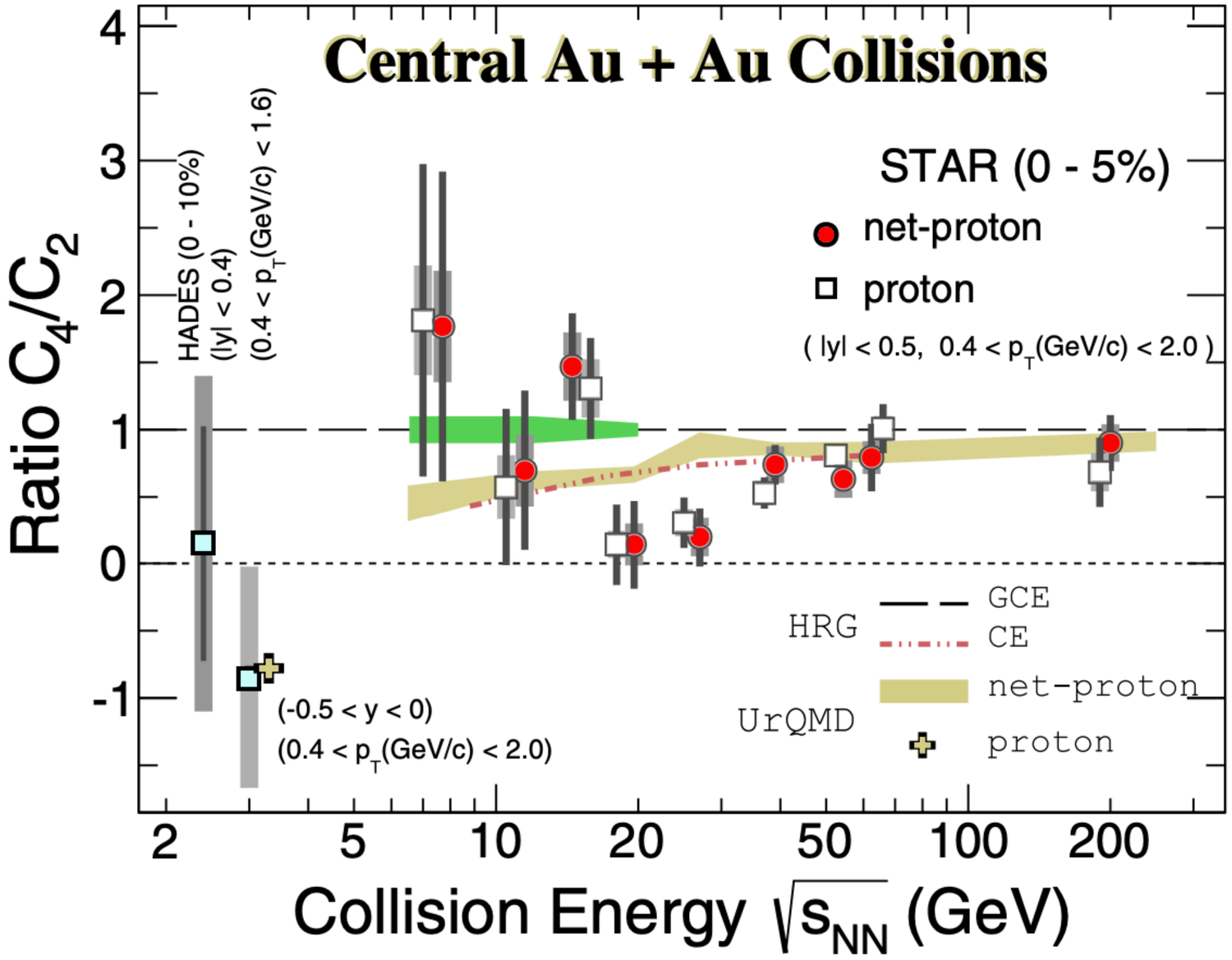


Hint of non-monotonic behaviour around 20 GeV

- New measurement out last week…

Search for the critical point

STAR, Phys. Rev. Lett. 128, 202303 (2022)



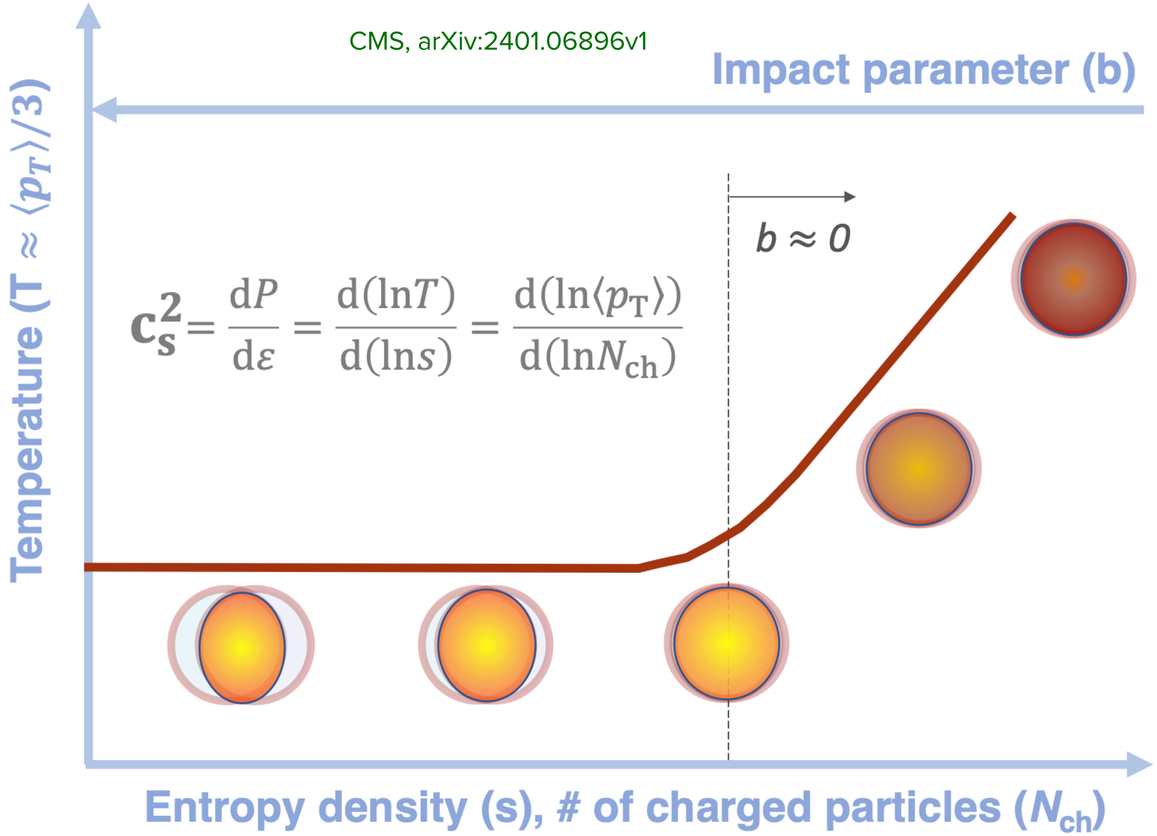
Hint of non-monotonic behaviour around 20 GeV

- New measurement out last week…

No spoilers here, but I guess we will have a lot of discussion on:

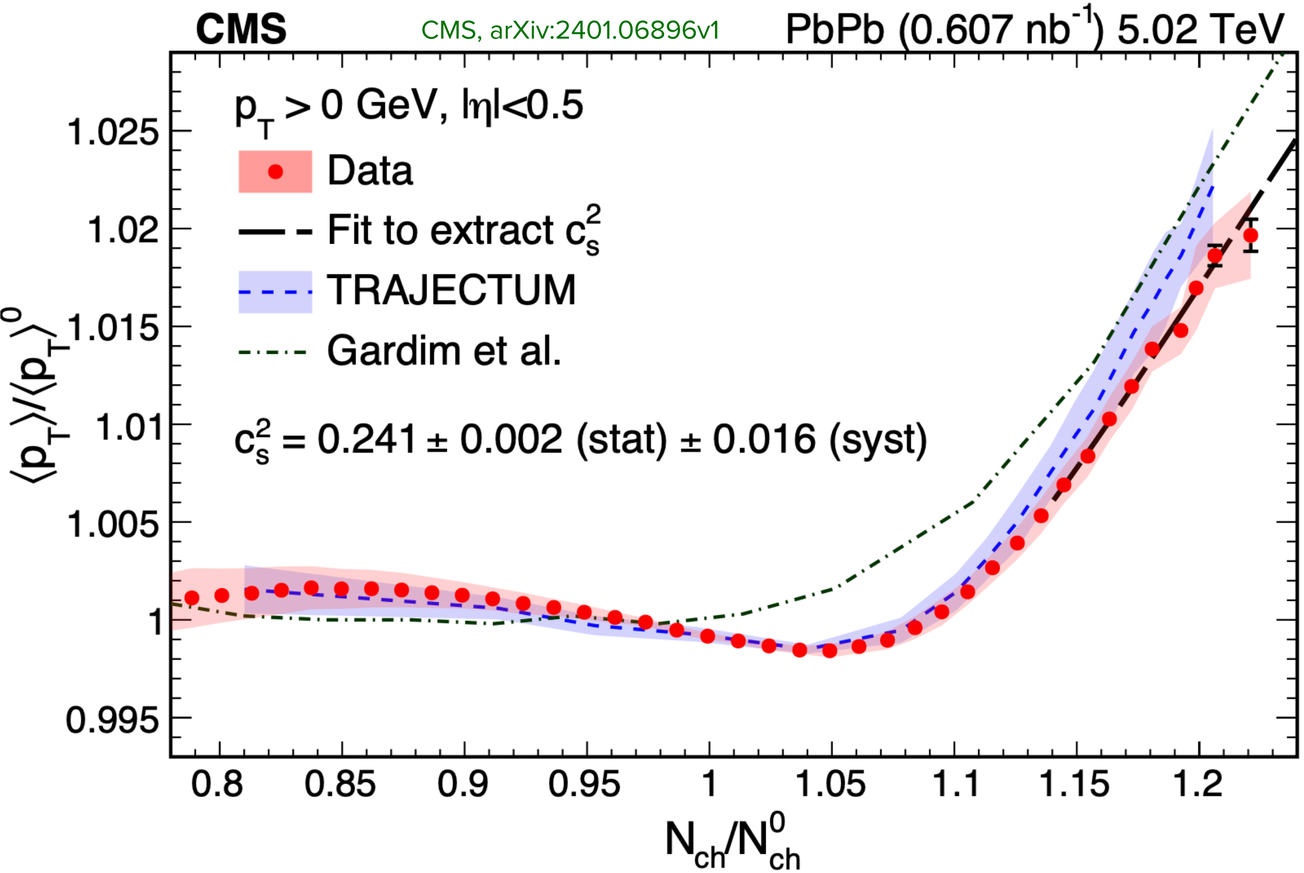
- The effect of multiplicity fluctuations on these observables
- Establishing a solid non-critical baseline

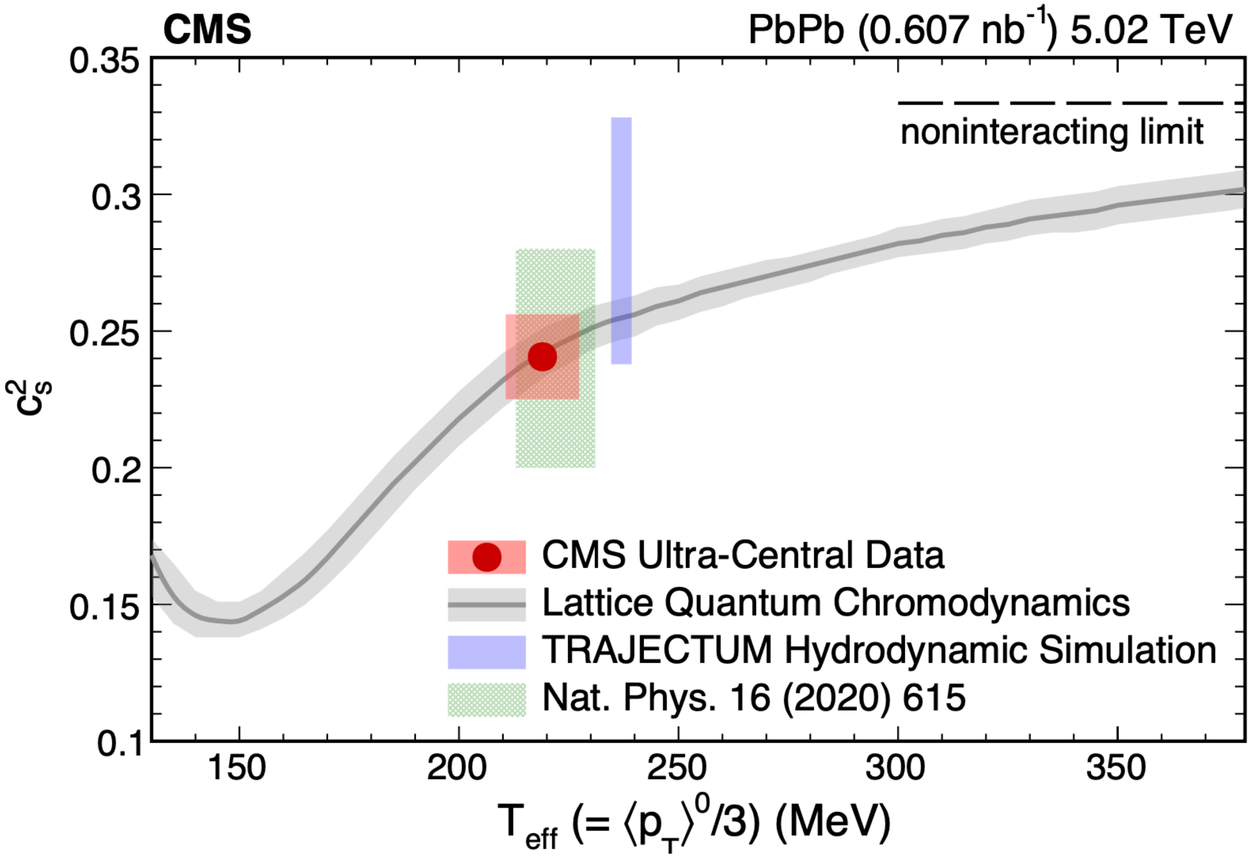
Speed of sound



- Amount of energy deposited in the collision depends on the overlap among the nuclei
- With complete overlap, fluctuations in the number of partonic interactions can still change the amount of energy in the system
  - At b ~ 0, $\langle p_T \rangle$ and N_{ch} are proxies for temperature and entropy density

Speed of sound





Impressive precision in determining the speed of sound with a single measurement

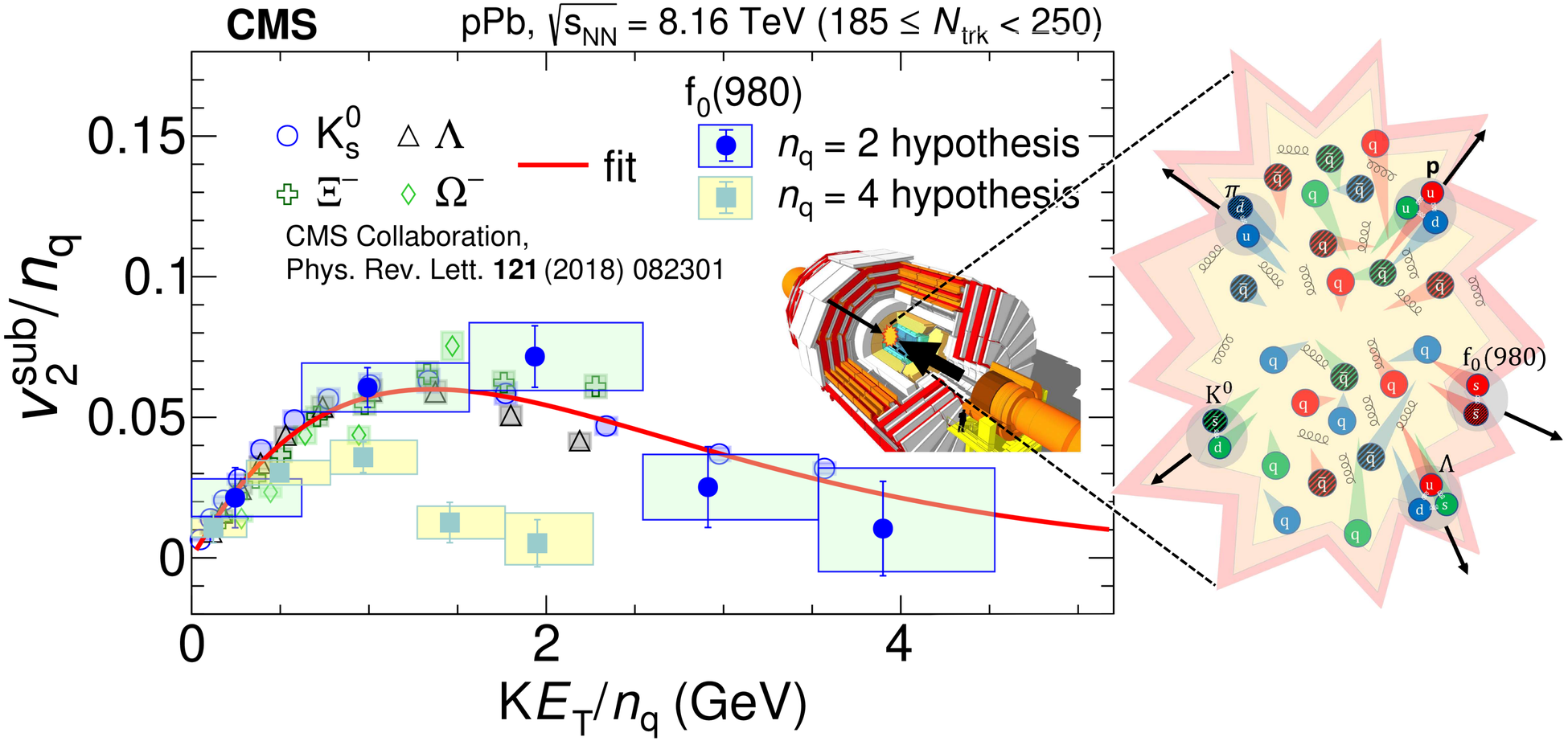
- Compatible with LQCD and state-of-the-art hydro simulations
- … but going ultracentral might come with selection biases!

➡ Discussion this week will unpack many of this issues and maybe some new observables for c_s

Hadronic structure and interactions

Not only QGP properties: understanding hadrons composition

CMS, arXiv:2312.17092



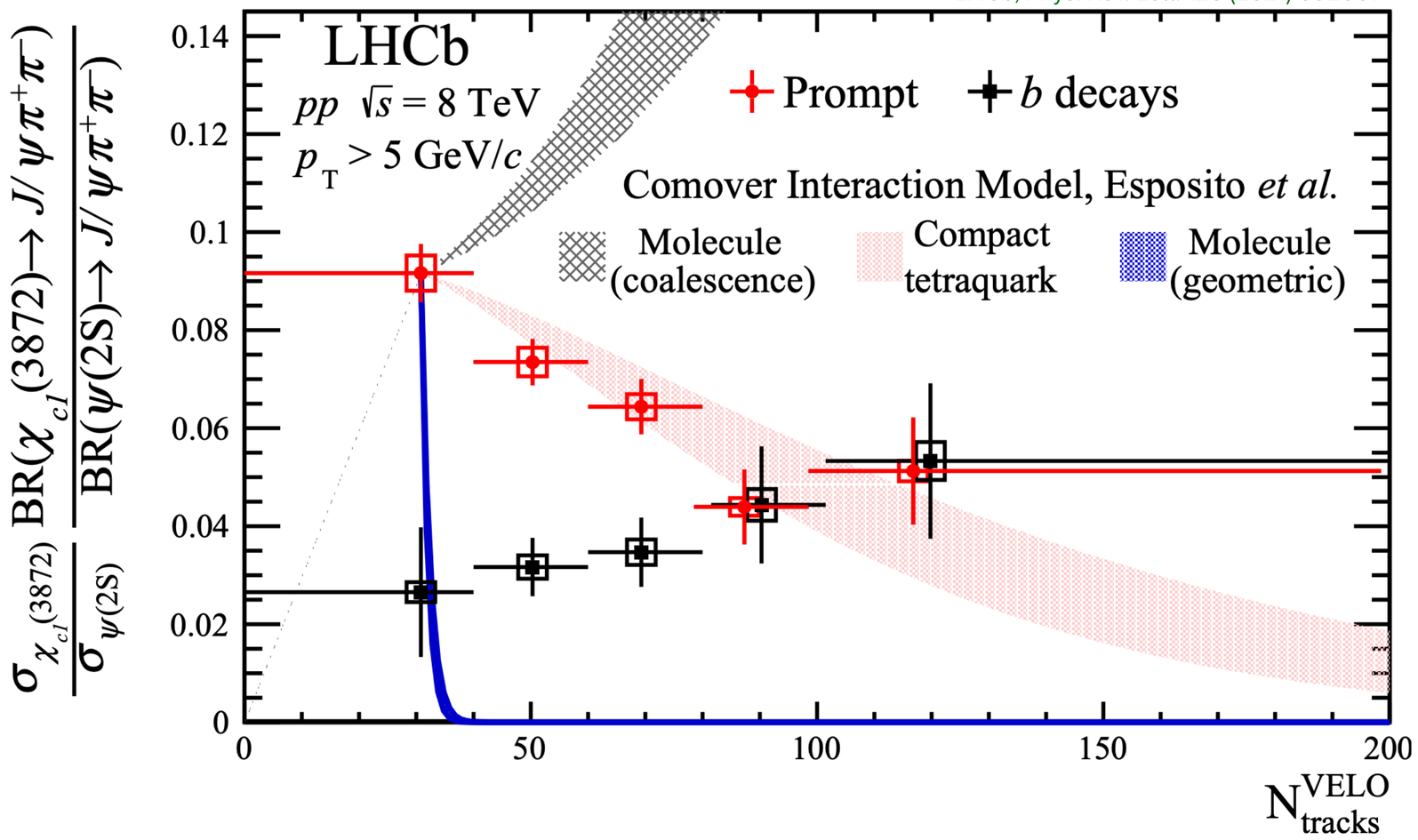
Coalescence works for explaining flow of light flavour particles in p-Pb

- Under this hypothesis, f_0 flows like a meson
- Is the production cross section agreeing with this hypothesis?

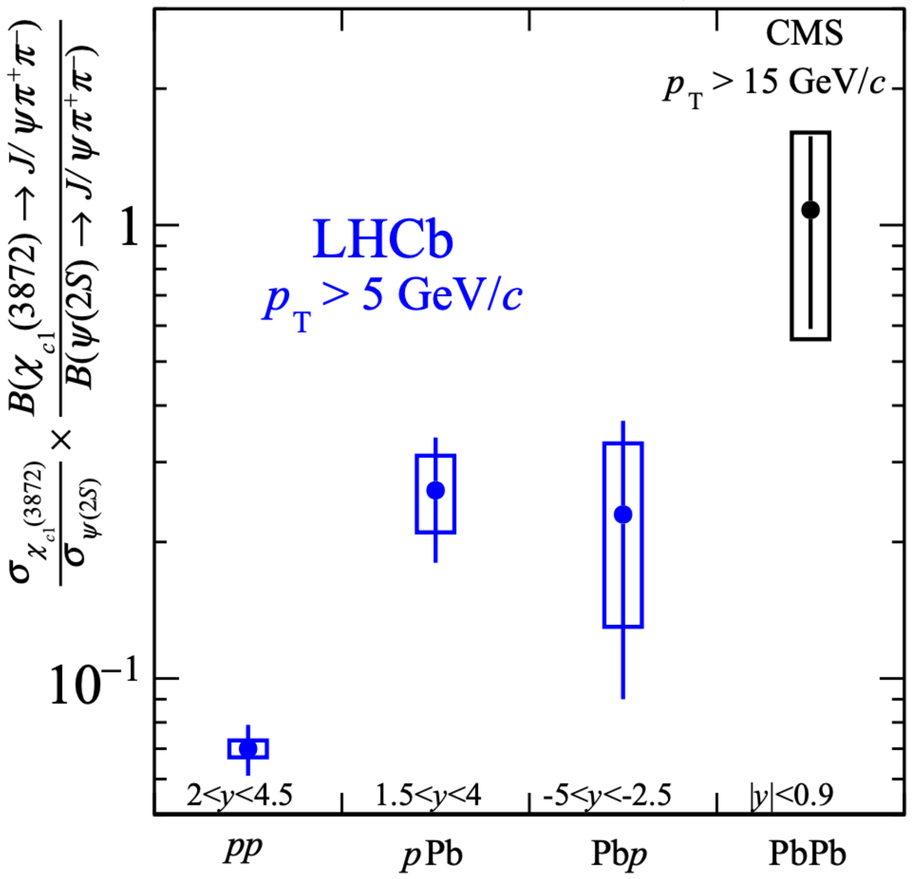
} We should use the same method for other particles!

The case of $\chi_{c1}(3872)$

LHCb, Phys. Rev. Lett. 126 (2021) 092001



LHCb, arxiv:2402.14975



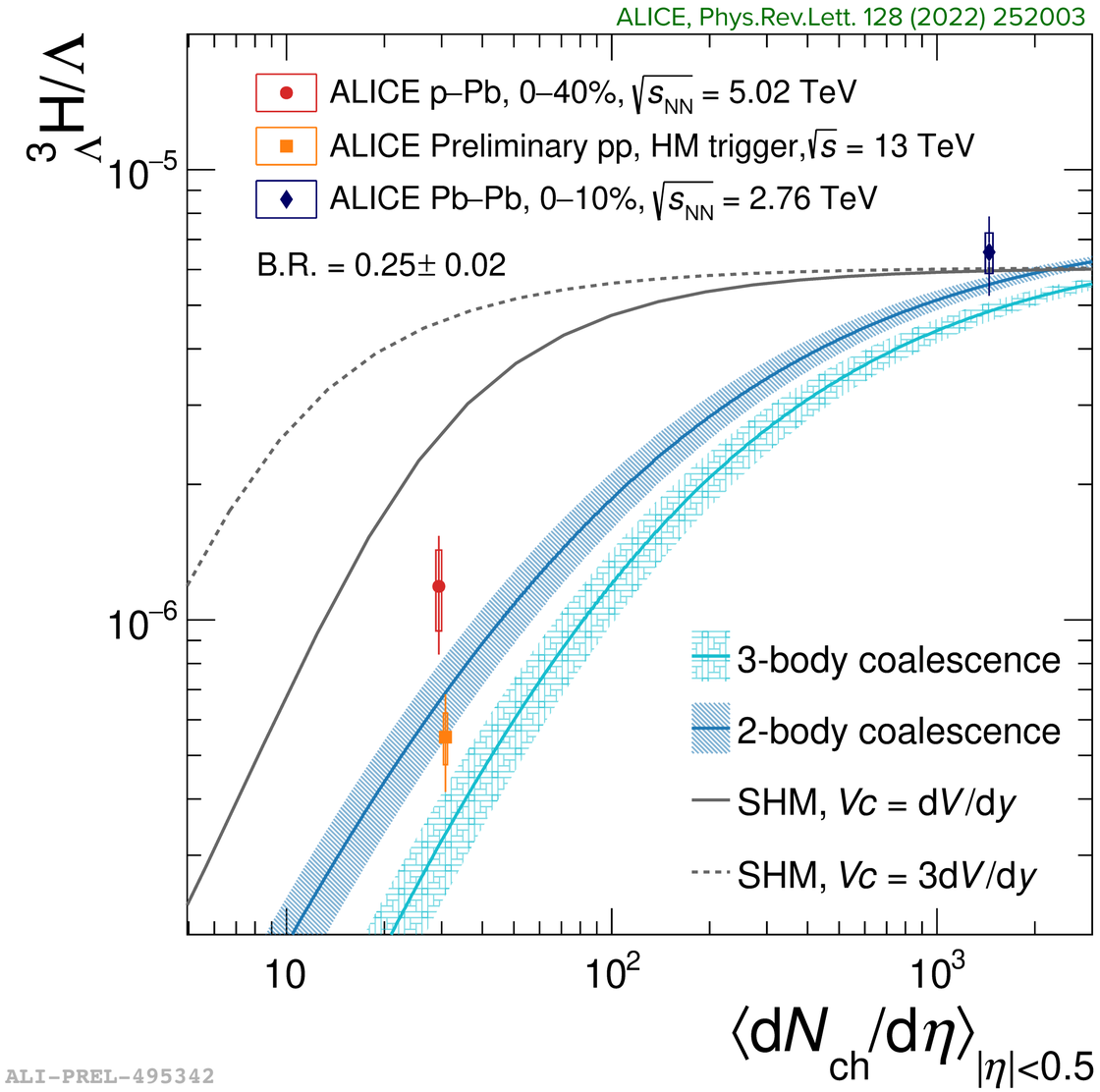
If $\chi_{c1}(3872)$ is a molecule, it is 5-10 fm wide: the production rate should reflect this

- Models predicts rising trend with multiplicity for the molecule, not seen in data
- Case closed?

A real 10 fm wide bound state: the hypertriton

Vovchenko, et al., Phys. Lett., B785, 171-174, (2018)
Sun. et al., Phys. Lett. B, 792, 132–137, (2019)

ALICE, Phys.Rev.Lett. 128 (2022) 252003



ALI-PREL-495342

$^3_\Lambda$H / Λ in small systems: large separation between production models

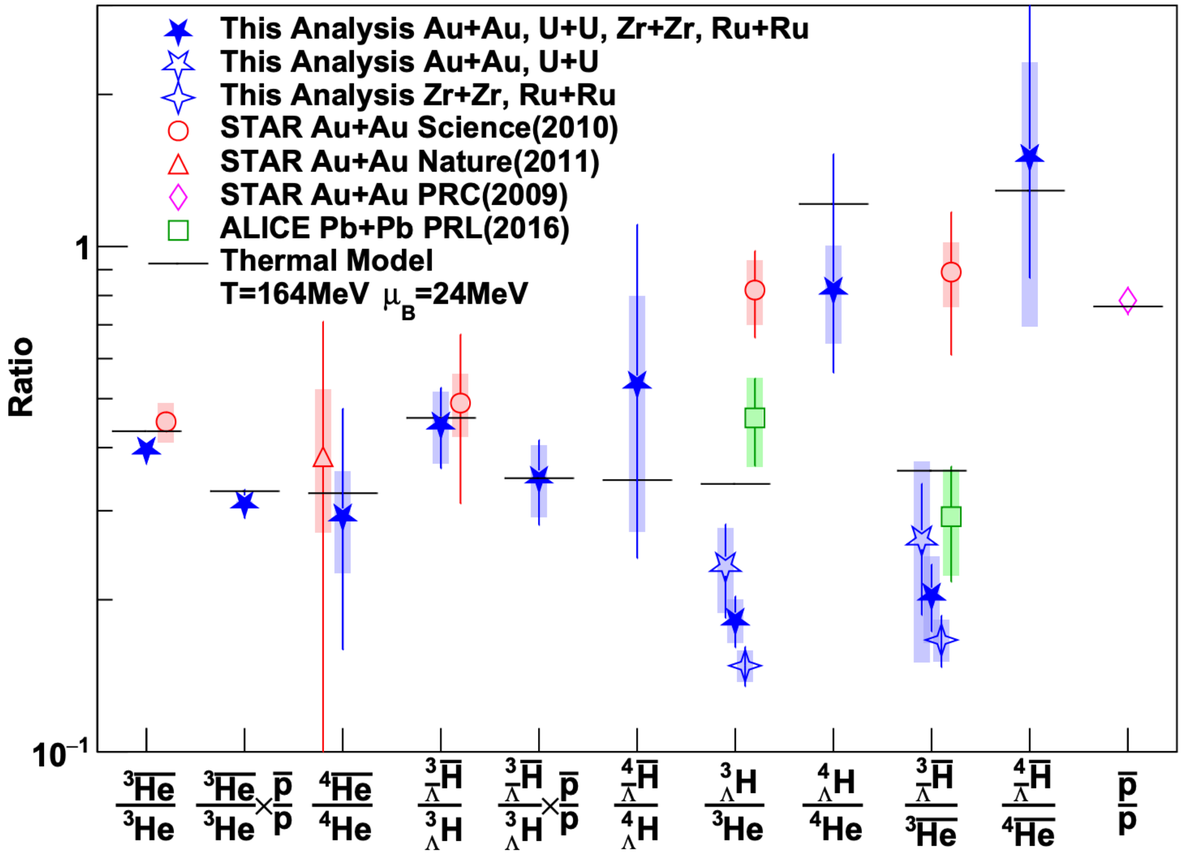
- SHM: insensitive to size of the hypertriton
- Coalescence: yield suppressed with assumed hypertriton radius ~10 fm

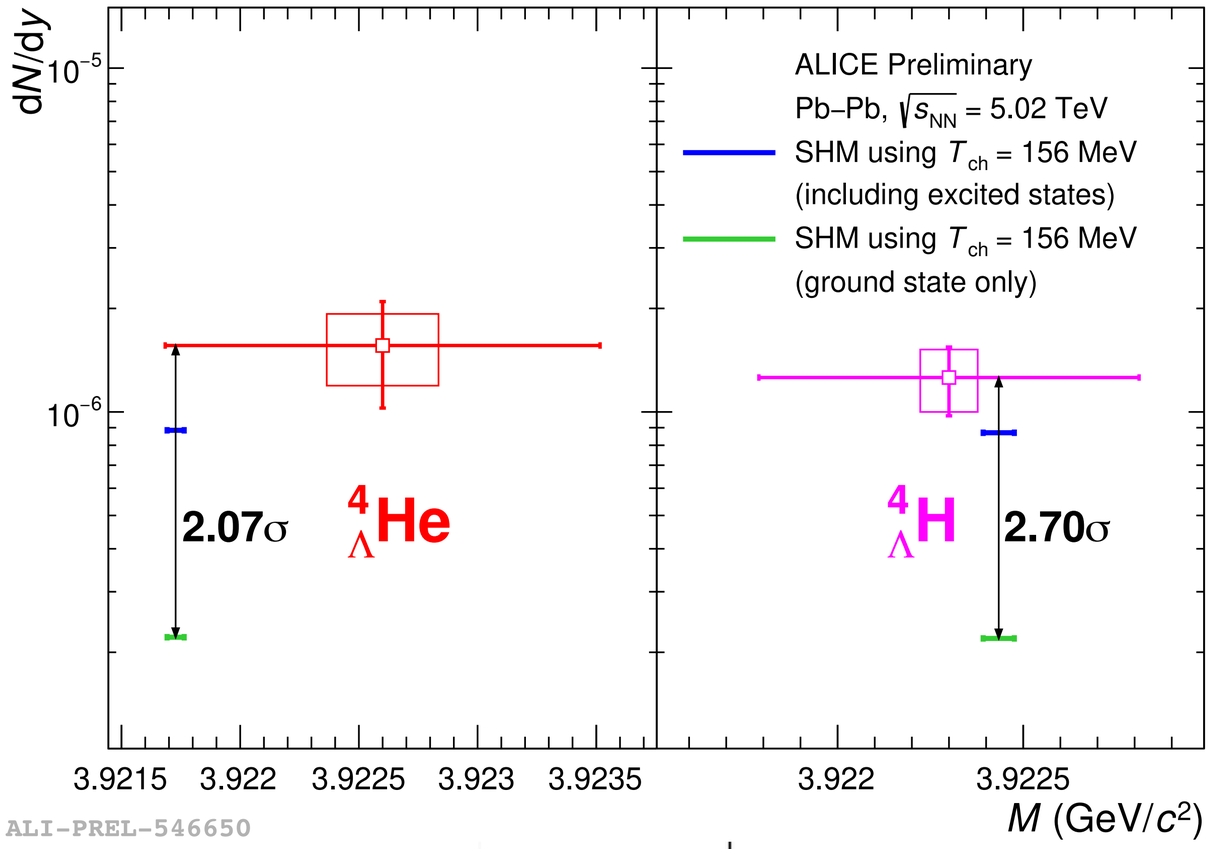
- Measurements favour coalescence
  - Sensitivity to the wave function shape: 2-body coalescence favoured

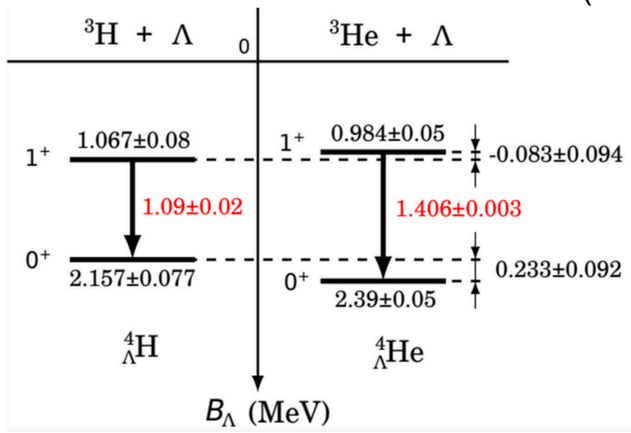
Production of hypertriton in pp and p-Pb collisions as a doorway to the study of its structure: coalemetry

Heavier antihypernuclei

STAR, https://arxiv.org/abs/2310.12674



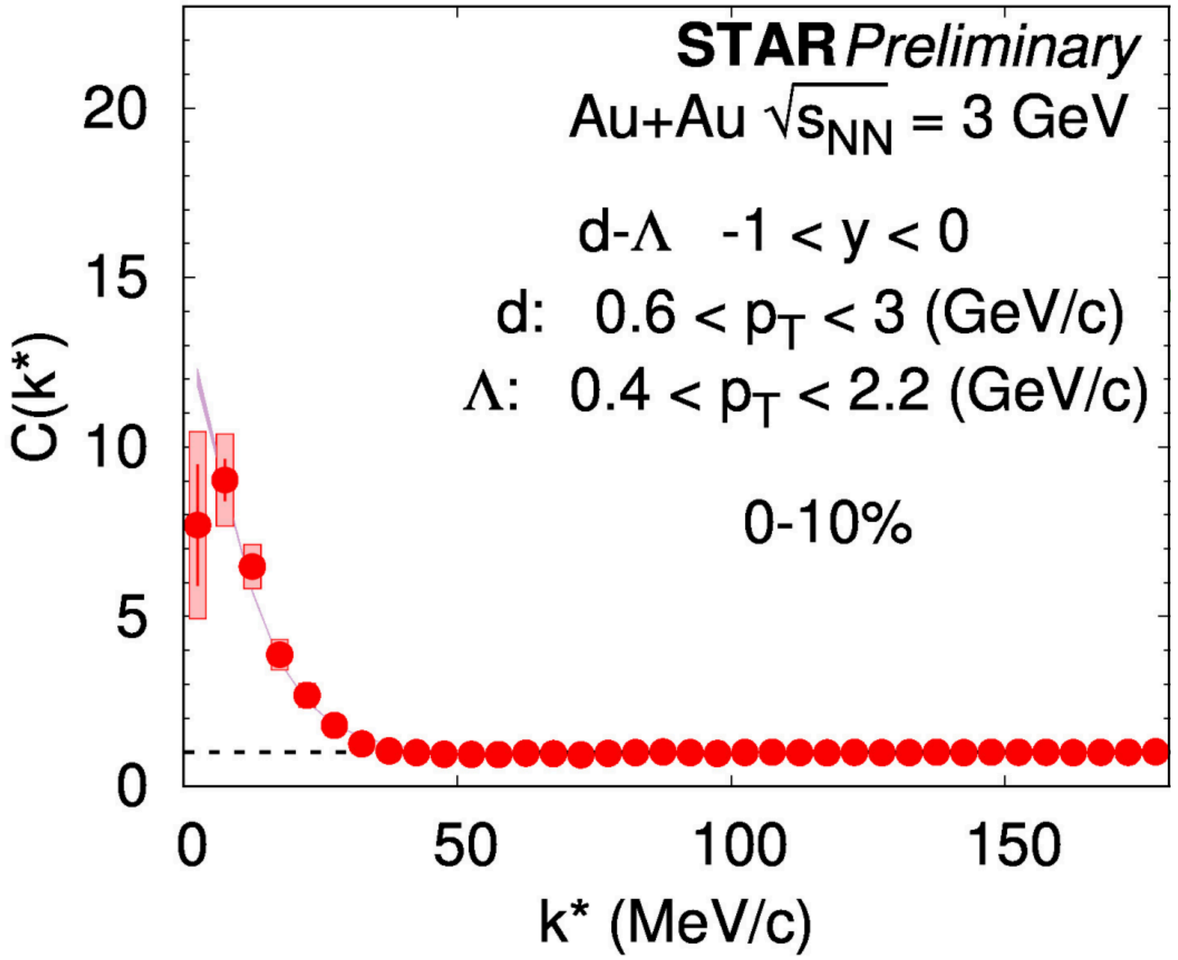




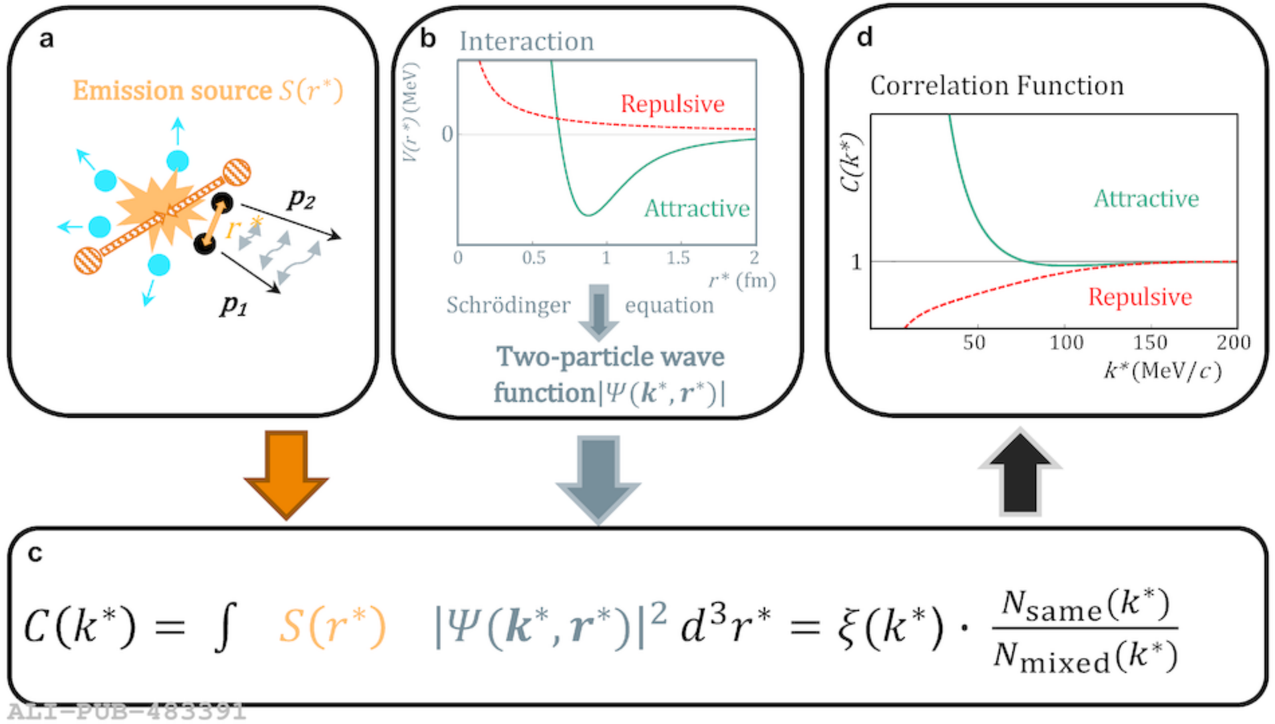
First observations of antihypernuclei with A=4 at RHIC and LHC!

- More compact than $^{3}_{\Lambda}$H: in Pb-Pb they agree with the SHM
- Sensitivity to the presence of excited states

Another way to investigate hyperon-nucleon interactions

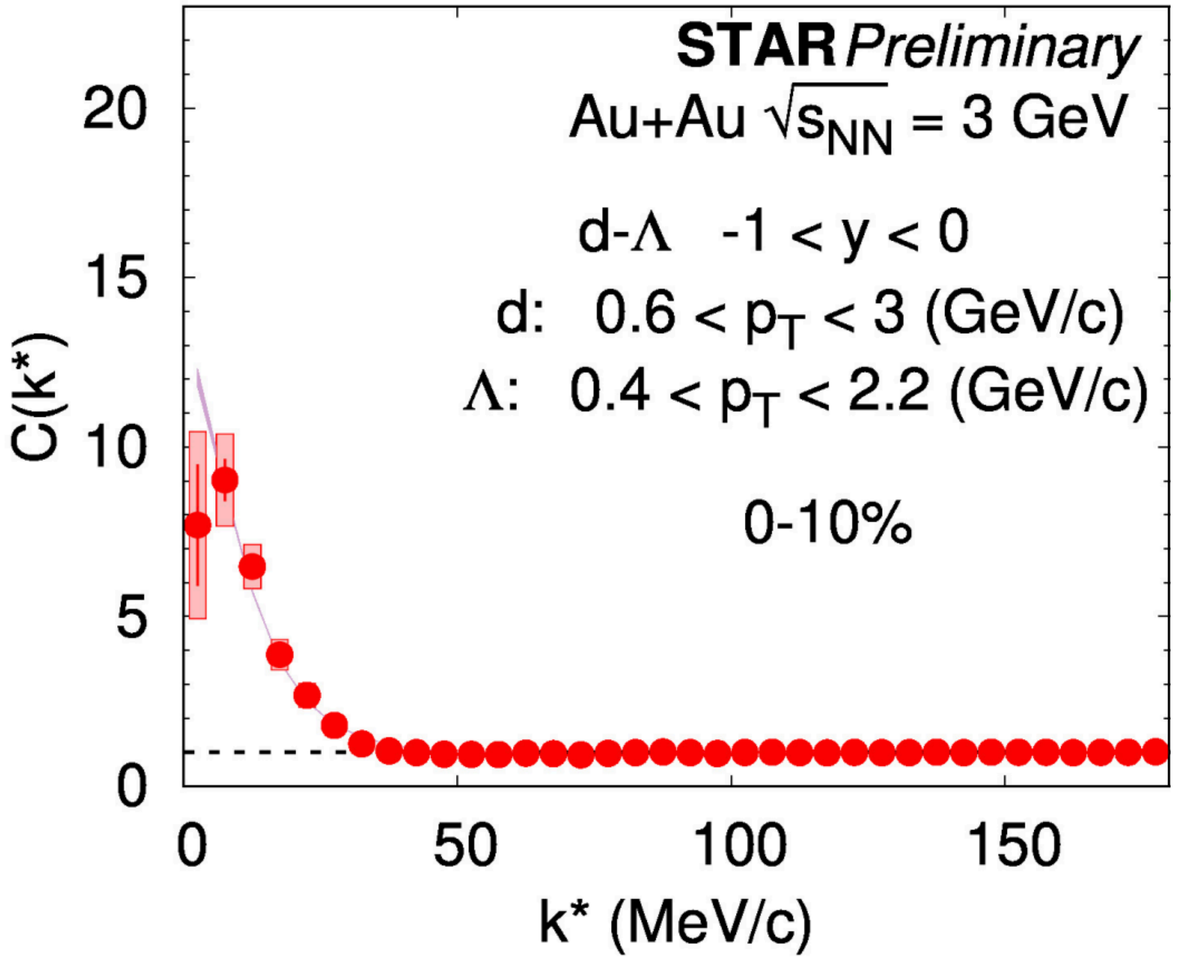


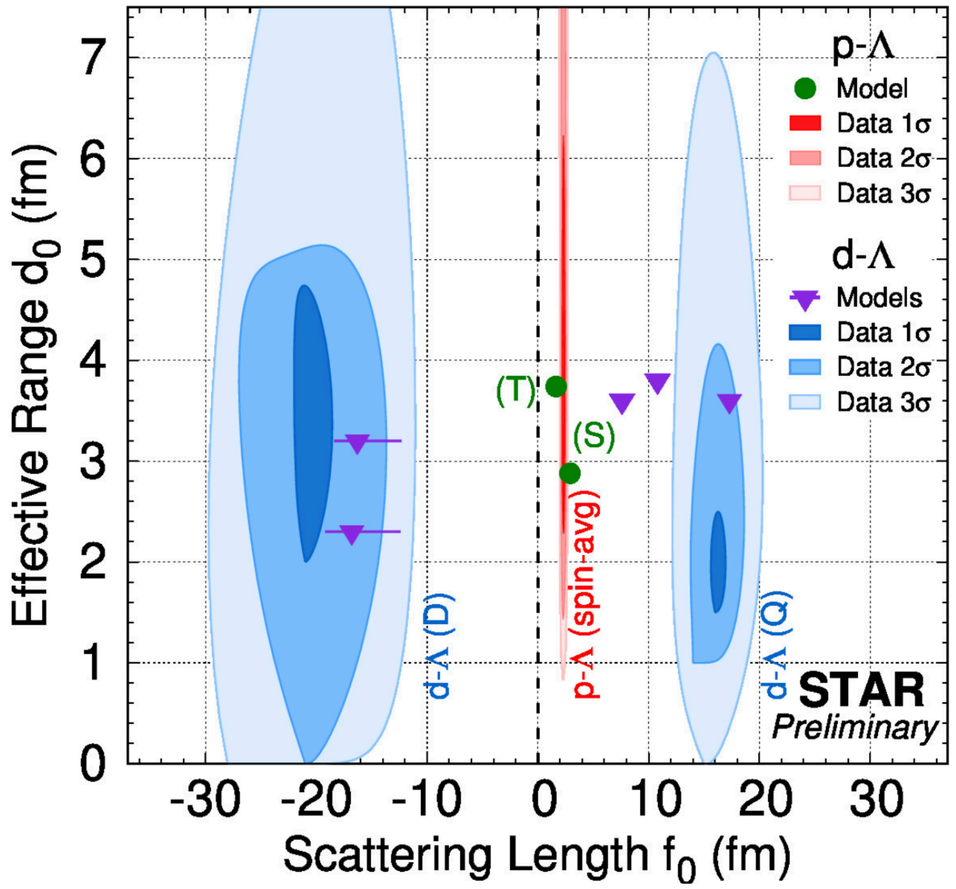
Sketch from ALICE, Nature 588 (2020) 232–238



- 2-particles correlation function: a proven method to access hadron interaction that would be otherwise impossible to measure with scattering experiments

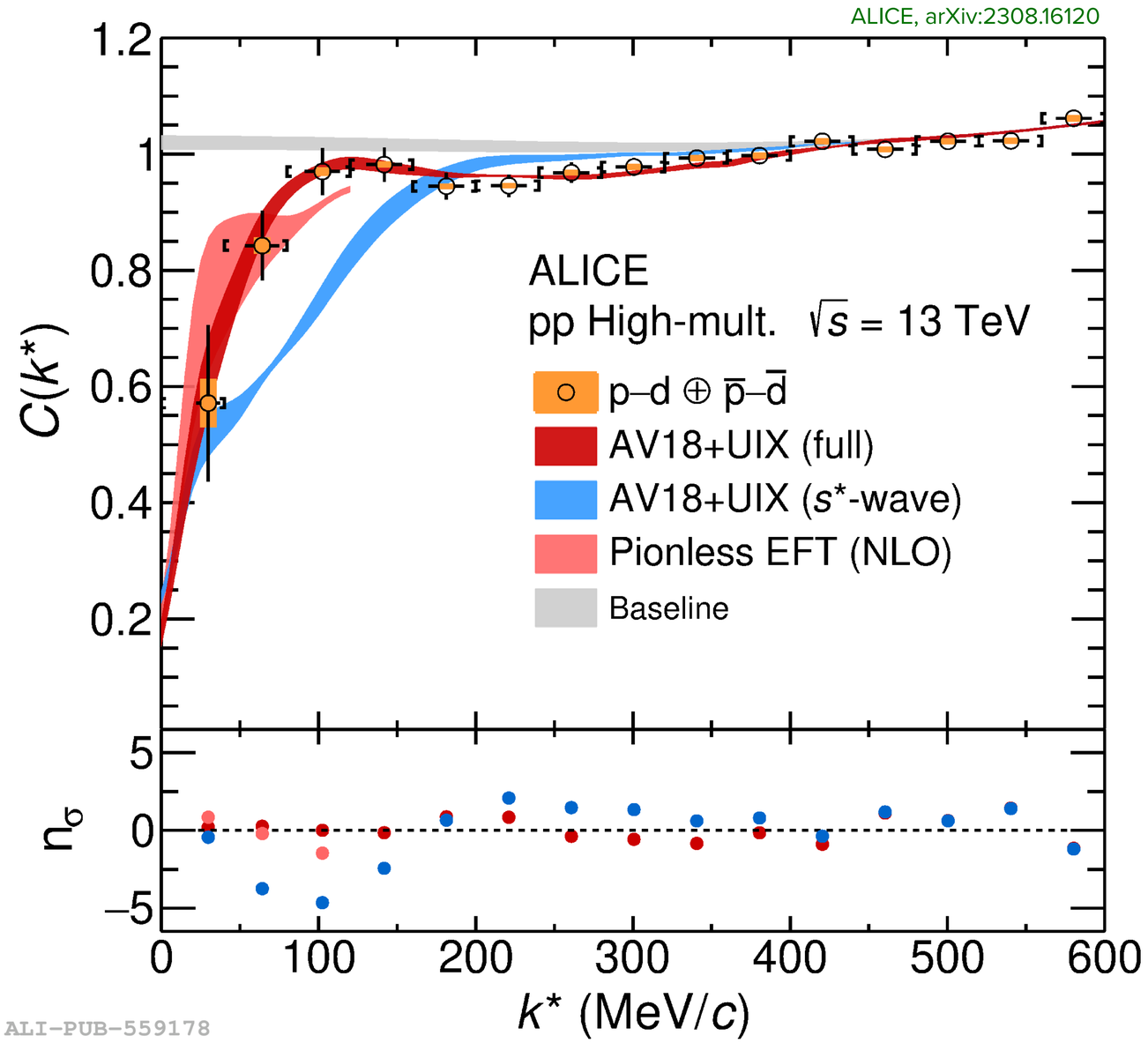
Another way to investigate hyperon-nucleon interactions





- 2-particles correlation function: a proven method to access hadron interaction that would be otherwise impossible to measure with scattering experiments
- Fit to d-Λ correlations can give us the isospin-1 component of the Λ-N interaction

The three-body problem in nuclear physics

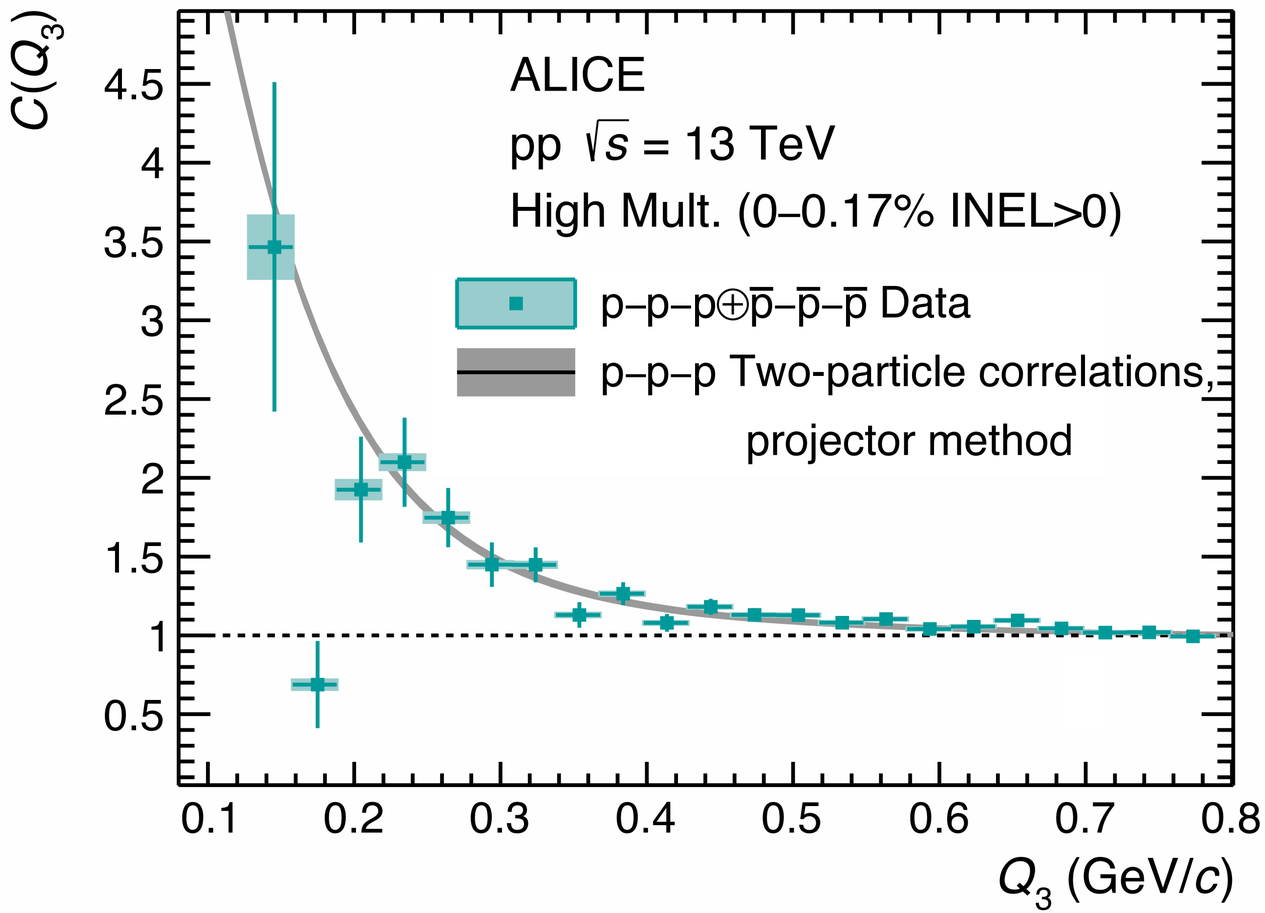


In pp collisions particles are emitted closer to each other

- In the d-p femtoscopy the proton resolves the deuteron structure
- Correlation function cannot be fitted with point-like particle assumption (Lednisky formalism)
  - Full 3-body calculation using 2-body forces only describes the data

The three-body problem in nuclear physics

ALICE, Eur. Phys. J. A 59 (2023) 145



ALI-PUB-564560

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  - Full 3-body calculation using 2-body forces only describes the data

New technique: direct access to 3-body system dynamics with 3 body femtoscopy

- Statistical precision limited
  - … but LHC Run 3 data is becoming available

Conclusions

Any collision system involving hadrons at high multiplicity show circumstantial evidence for collectivity and thermalisation

- Non-zero v_n, yields and fluctuations close to SHM and heavy-ion measurements
- Charm in Quark Matter suspiciously similar to Strangeness in Quark Matter at the LHC…
  - Non-flow, improvements in “non-heavy-ion“ models… jury is still out

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We are specialising in the physics of the extremes

- Ultra central, ultra peripheral, ultra high mult pp, ultra low mult pp…
- Experimental biases will give us a lot of fun discussions this week

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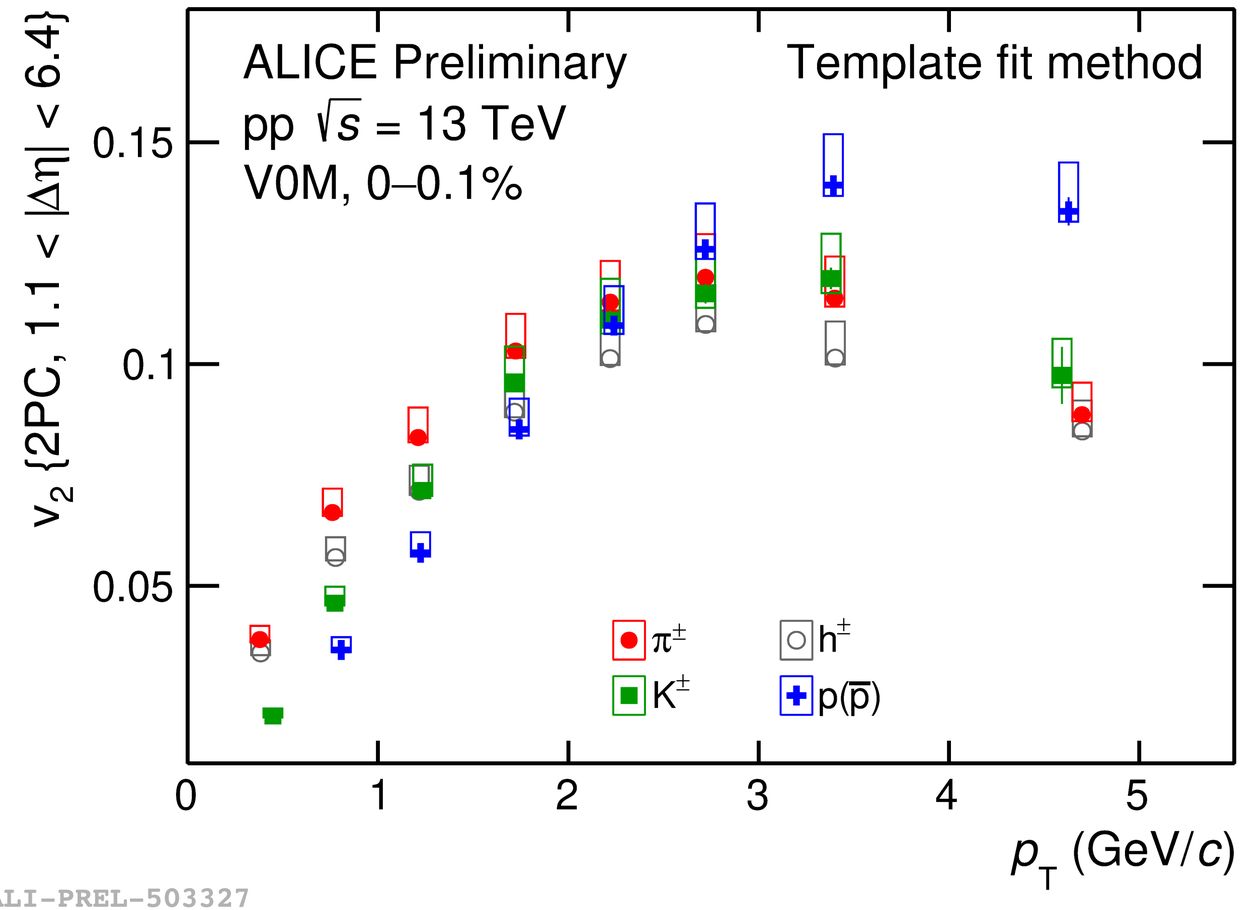
Thank you!!

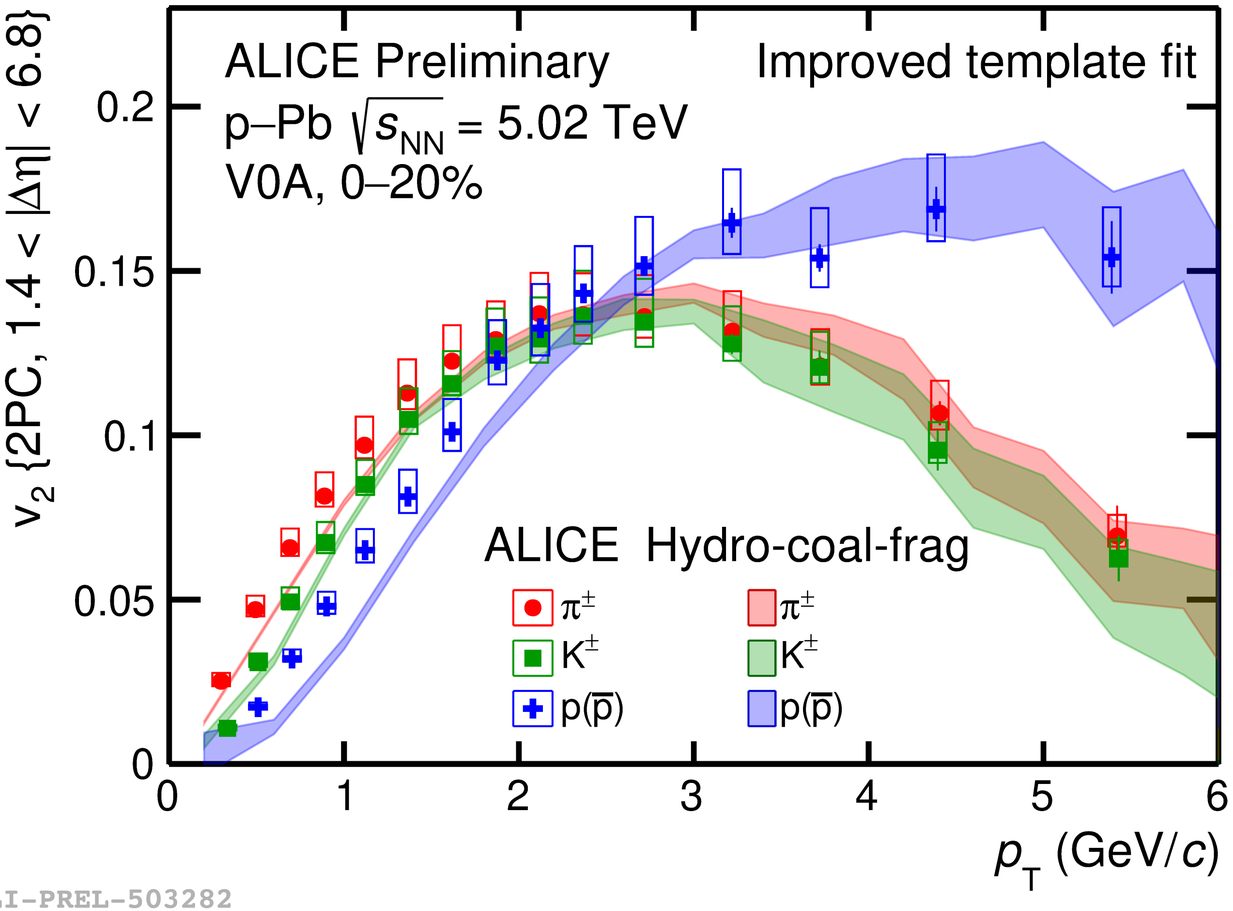
And special thanks to: Laura Fabbietti, Sourav Kundu, Andrea Dainese, Fabrizio Grosa, Alexander Kalweit, Federico Antinori, Jan Fiete Grosse-Oetringhaus

Backup

The identified particle case



ALI-PREL-503327



ALI-PREL-503282

- Mass ordering at low transverse momentum
- Baryon - meson splitting in both pp and p-Pb
- p-Pb model comparison indicates partonic flow + coalescence

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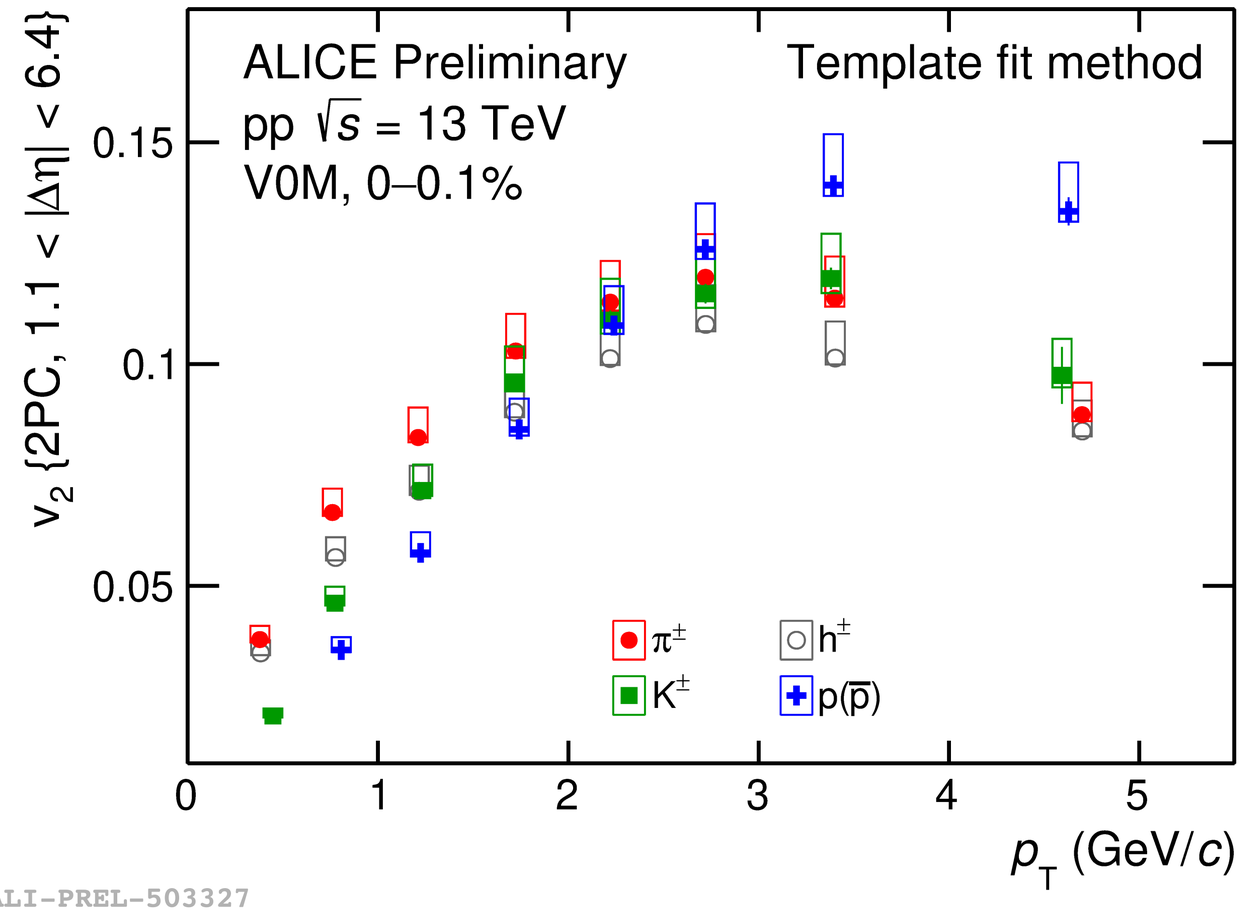

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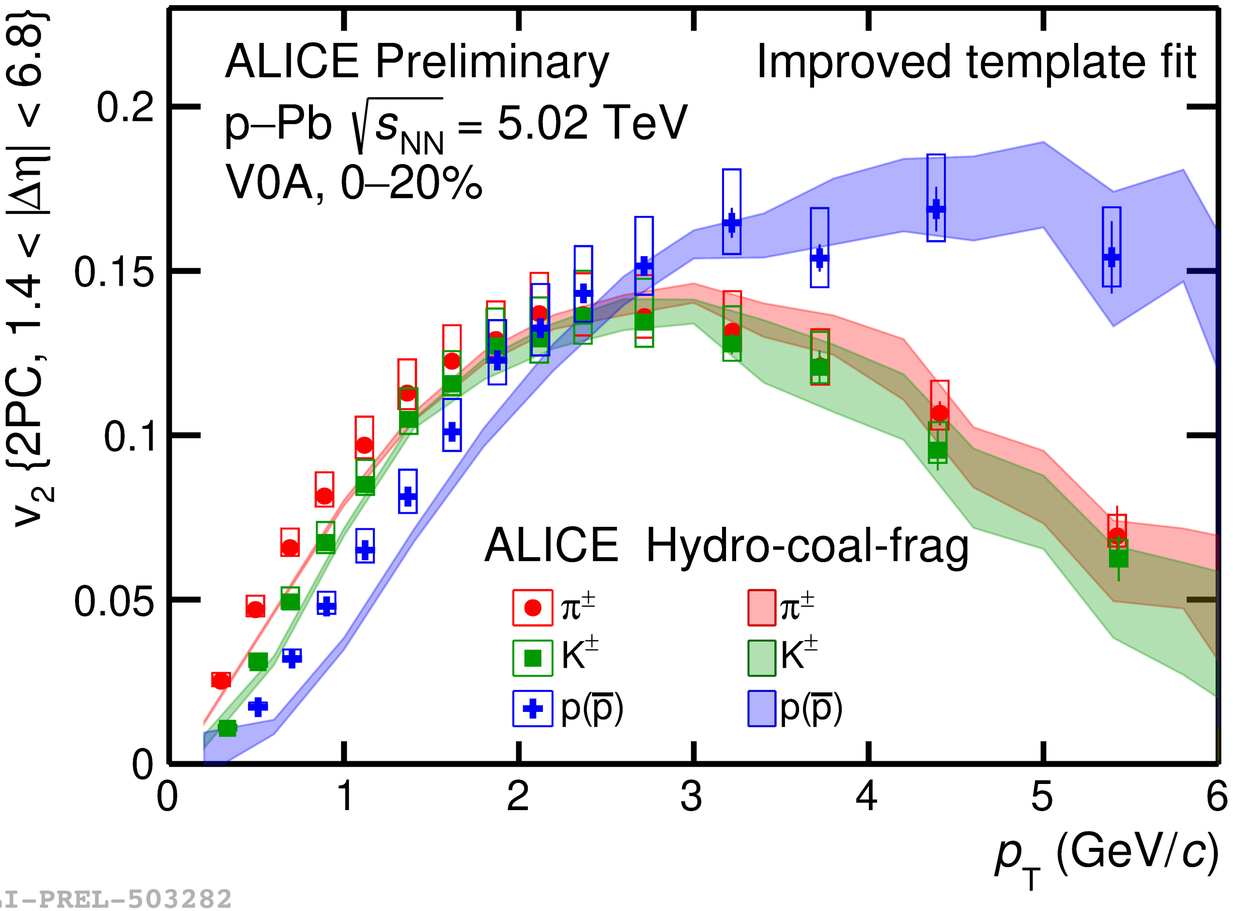


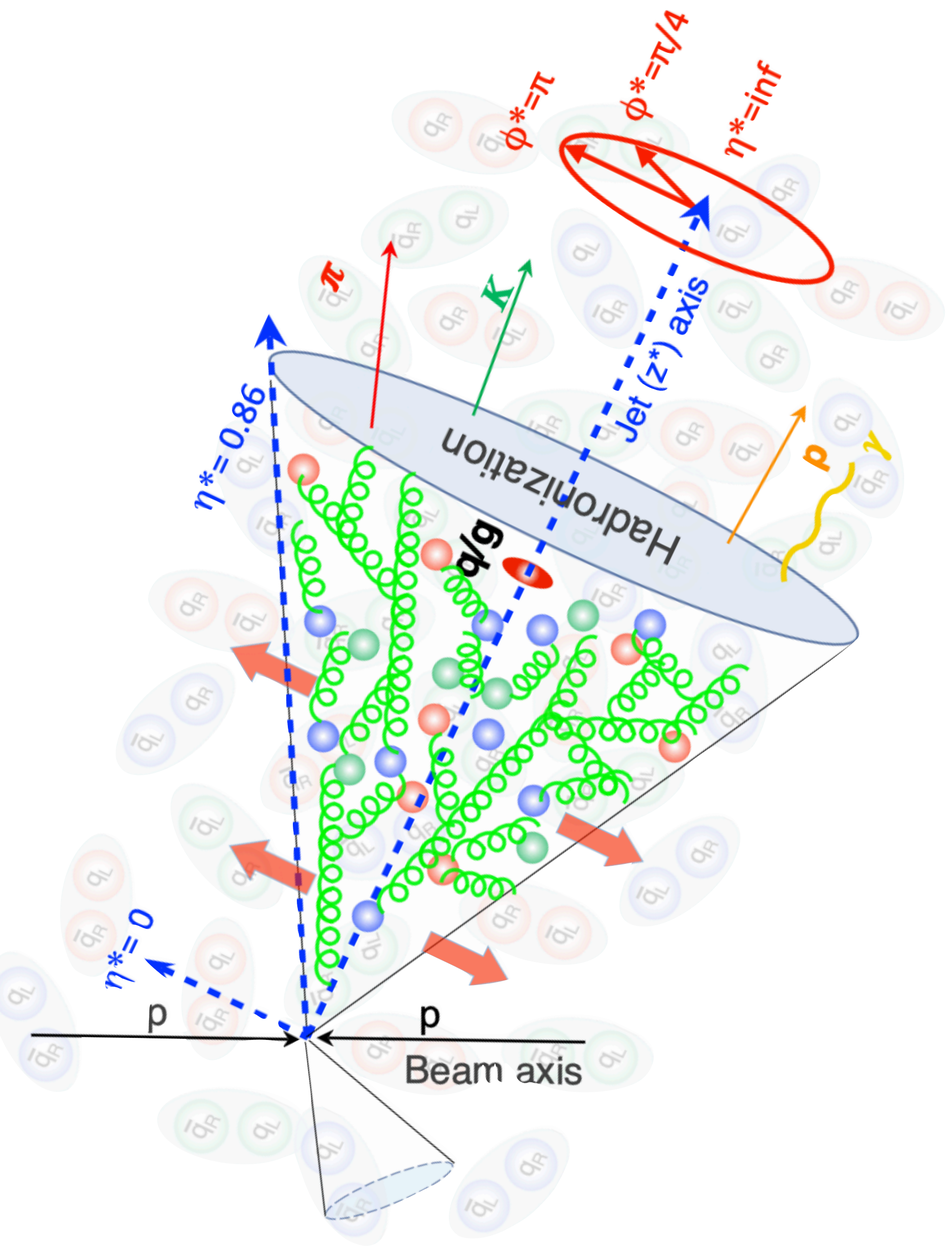
ALI-PREL-503282

- Mass ordering at low transverse momentum
- Baryon - meson splitting in both pp and p-Pb

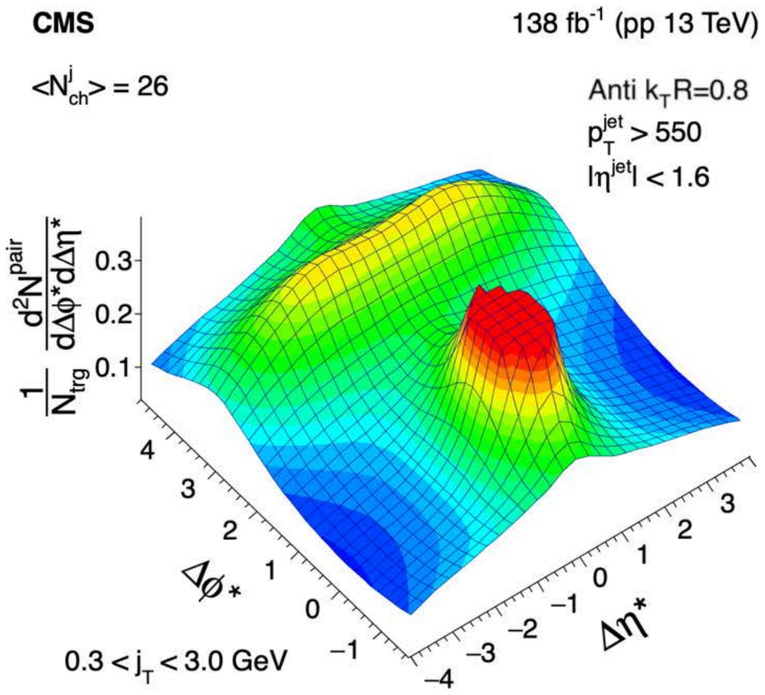
} Typical features we observe in AA collisions

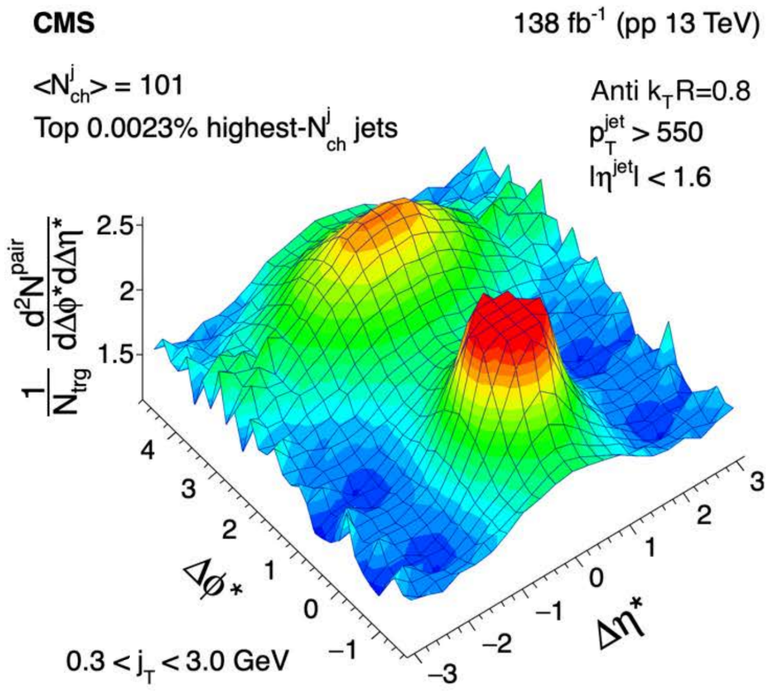
- p-Pb model comparison indicates partonic flow + coalescence

Bonus track: 2 particle correlations in jet



CMS, arxiv:2312.17103

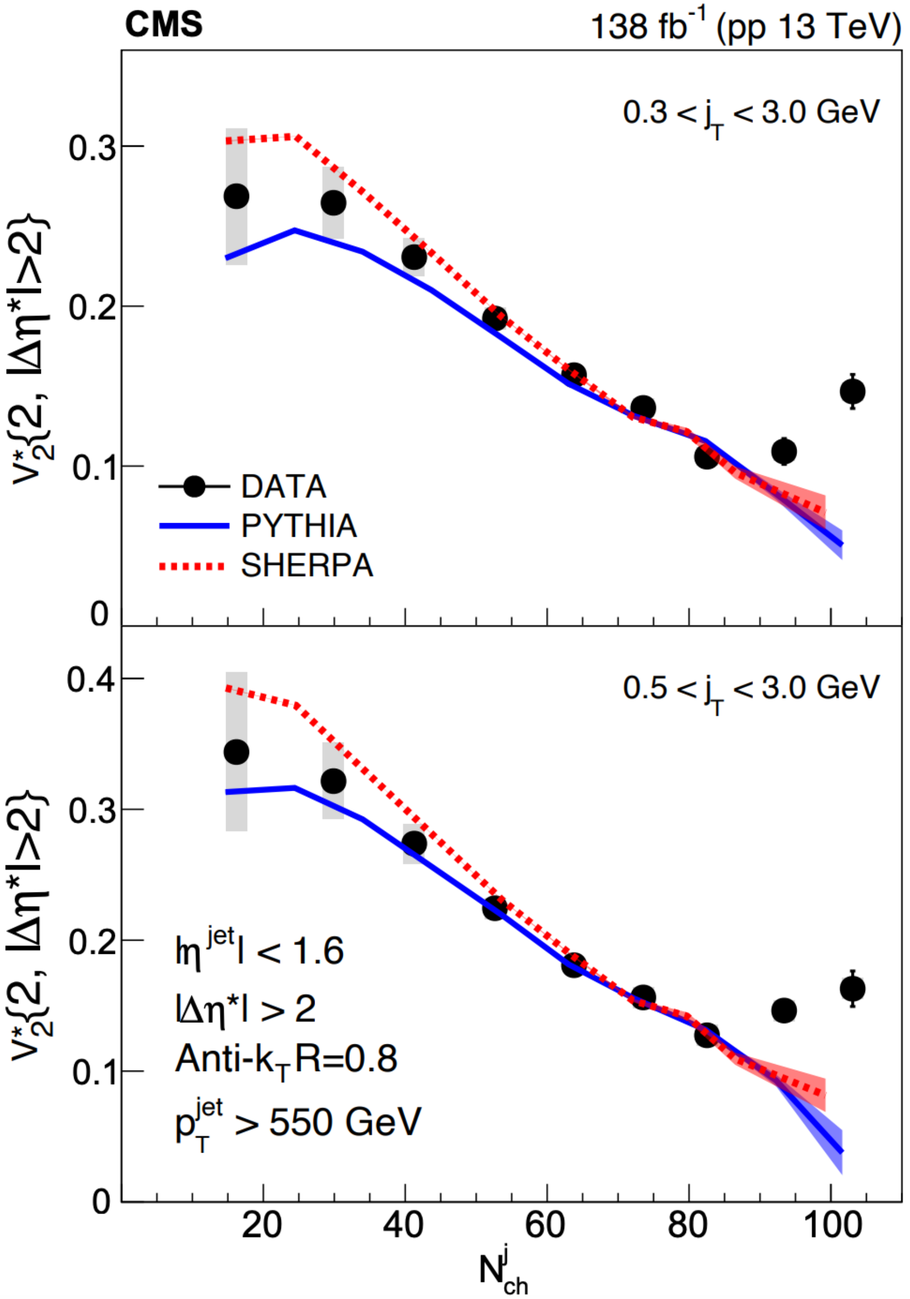




Angular correlation among particles inside a jet after an appropriate change of coordinates

- Double ridge structure in high multiplicity jets

Bonus track: 2 particle correlations in jet



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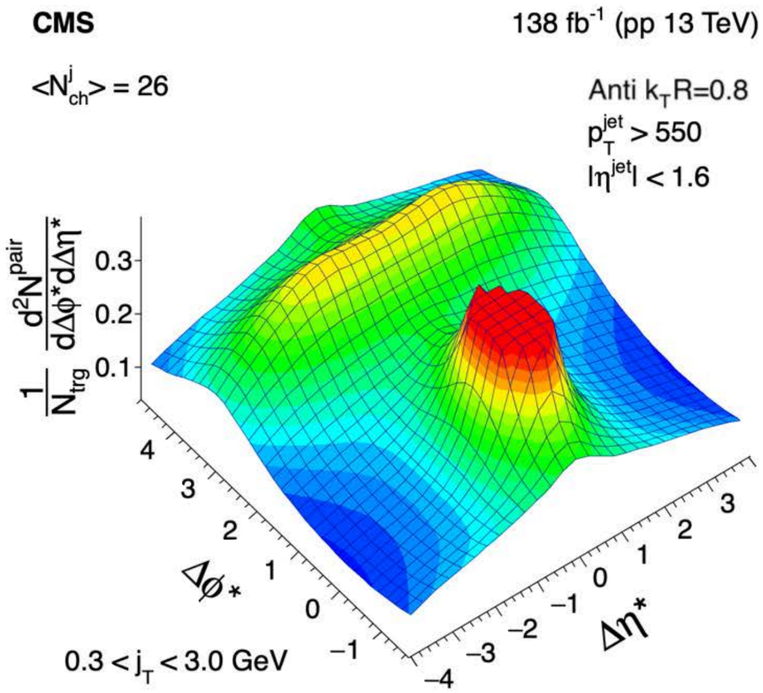
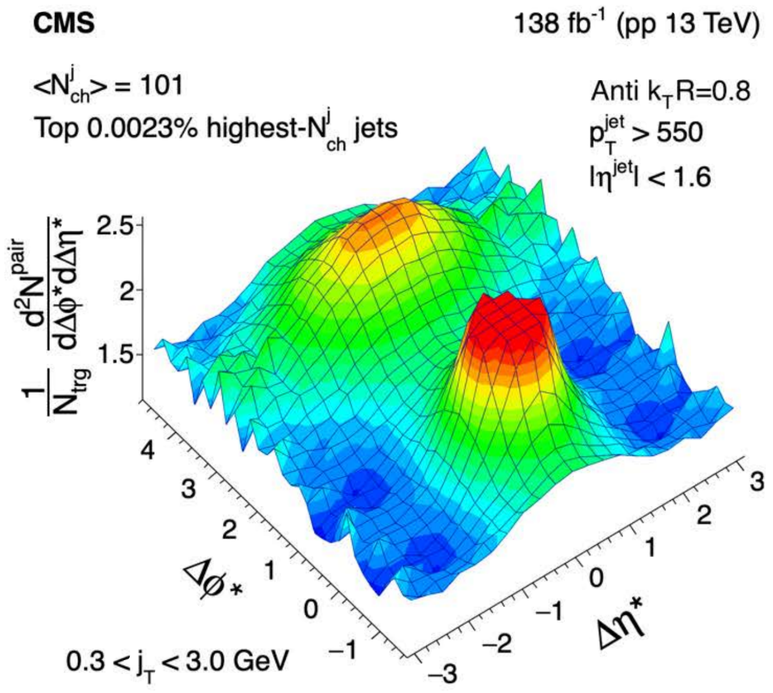




Angular correlation among particles inside a jet after an appropriate change of coordinates

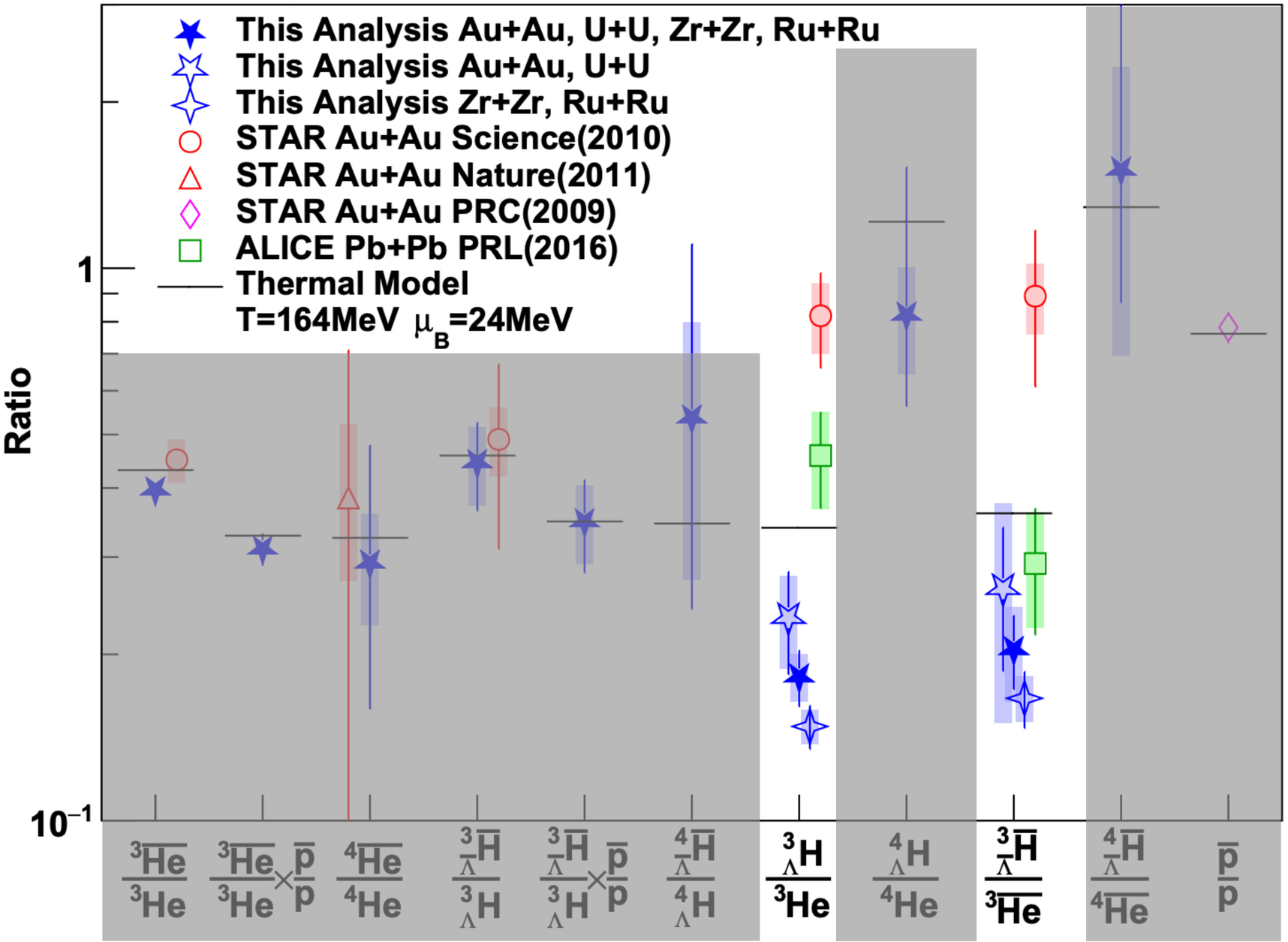
- Double ridge structure in high multiplicity jets

Extracted v2 deviates from MC generators at high mult.

- Collectivity or missing correlation among sub-jets?

Same phenomenology at RHIC?

STAR, https://arxiv.org/abs/2310.12674



Indication of larger deviation from the SHM prediction in the collision among “small” ions (careful with the log scale…)

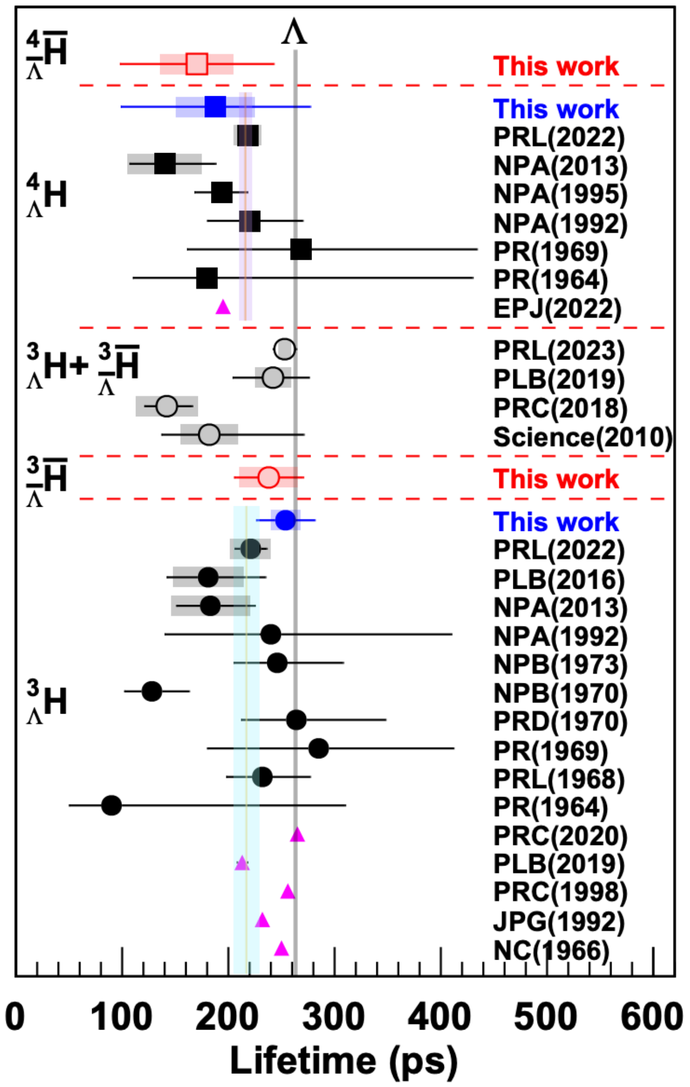
- Same effect as going to p-Pb or pp collisions at the LHC!

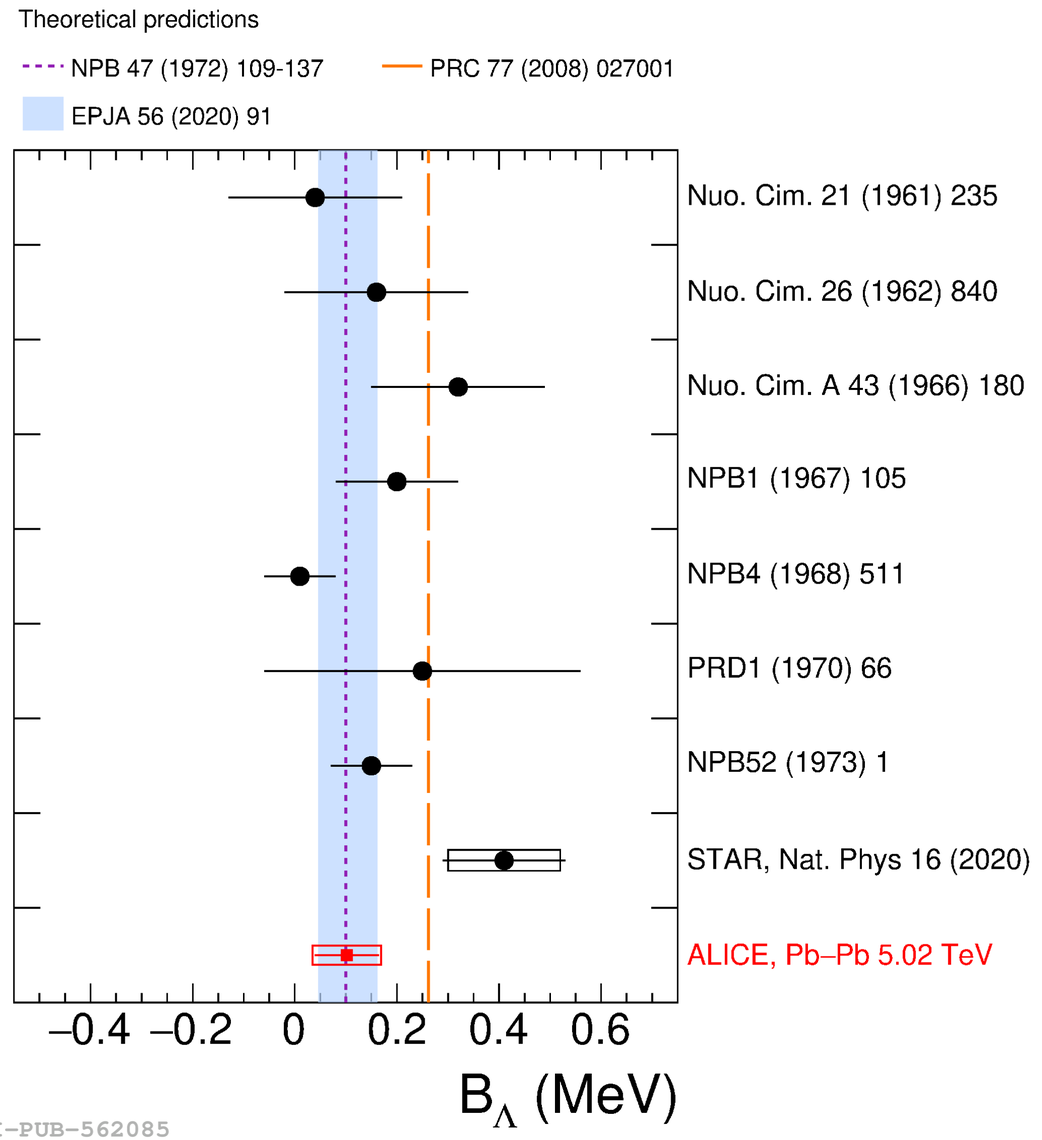
Precision hyper nuclear physics

Heavy-ion experiments deliver the best or close to the best performance in determining the properties of light hypernuclei

- Input to Λ-N and Λ-N-N interaction models

STAR, https://arxiv.org/abs/2310.12674





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