WG3 – High multiplicities and small systems

Experimental review

Christian Bierlich, Fabio Colamaria

14° edition of MPI@LHC, 24/11/2023

THE PARADIGM OF SMALL SYSTEMS

- Old paradigm: reference systems for larger systems for isolating QGP effects in Pb-Pb

pp collisions

In-vacuum QCD

→

p-Pb collisions

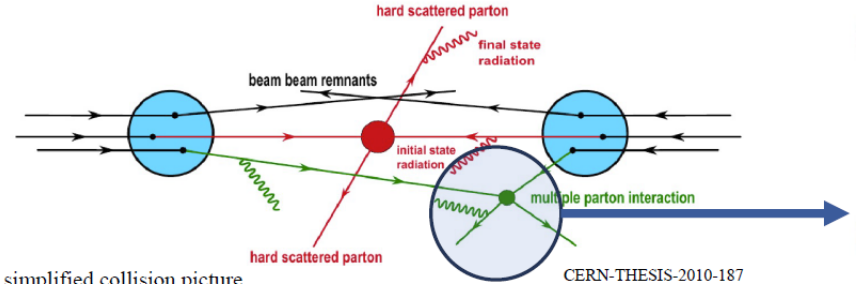
In-vacuum QCD + initial-state effects

→

Pb-Pb collisions

In-vacuum QCD + initial-state effects + QGP effects

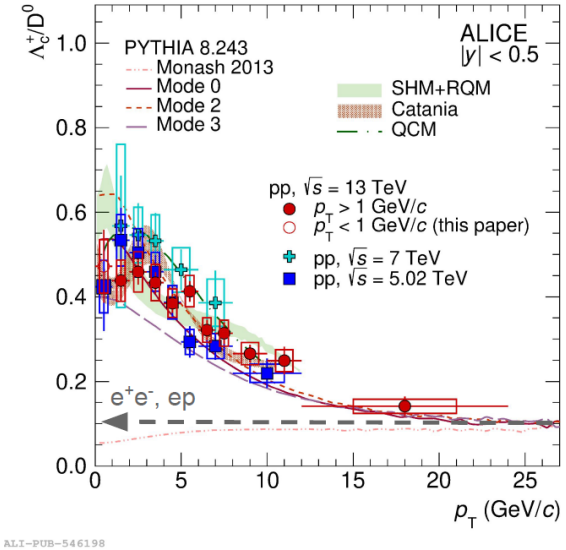
- Very different reality: pp already a very complex system
  - Multi-parton interactions, collective-like effects, strangeness enhancement… but no significant jet quenching!
  - Substantially different from e^+e^- collisions (not just "many independent scatterings")

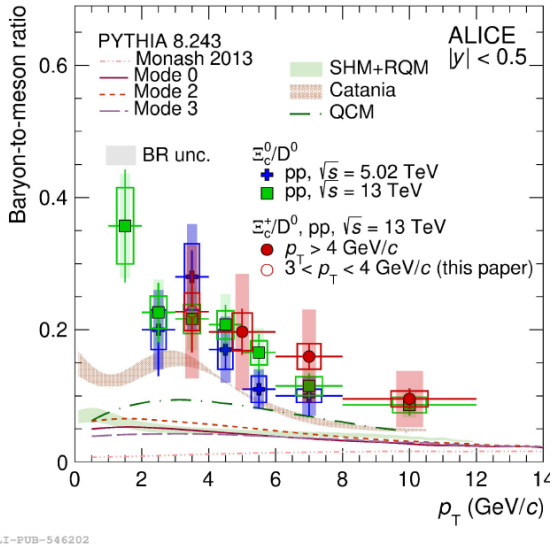


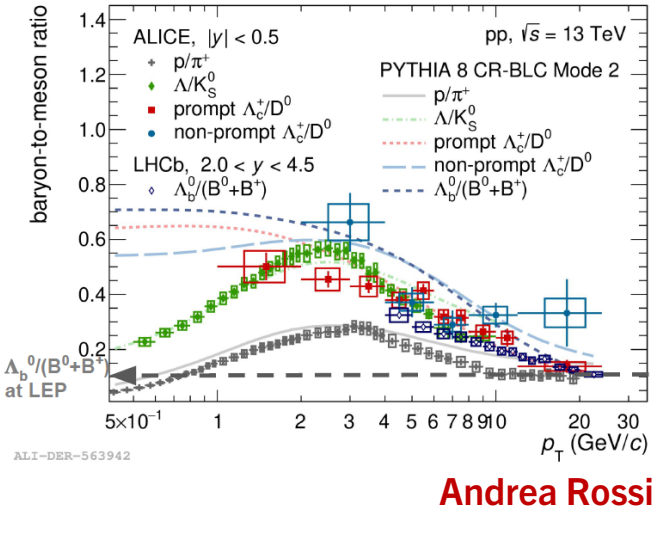
- Let's go through a few (selected) topics discussed at the workshop that confirm this idea

Hadronisation in the (heavy) baryon sector

c AND b BARYON HADRONISATION IN pp



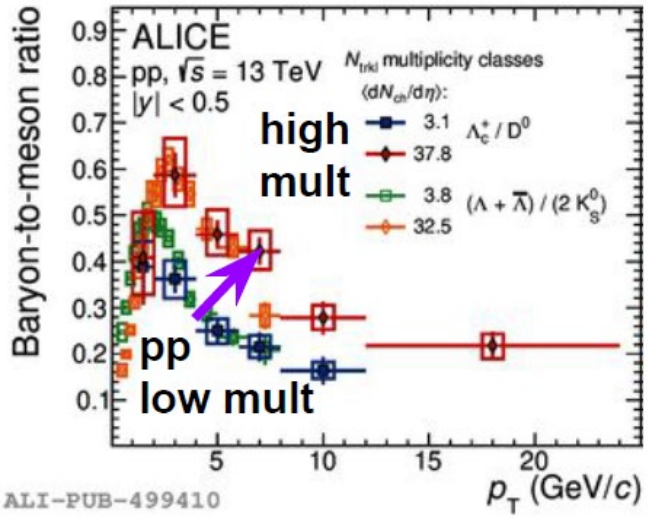


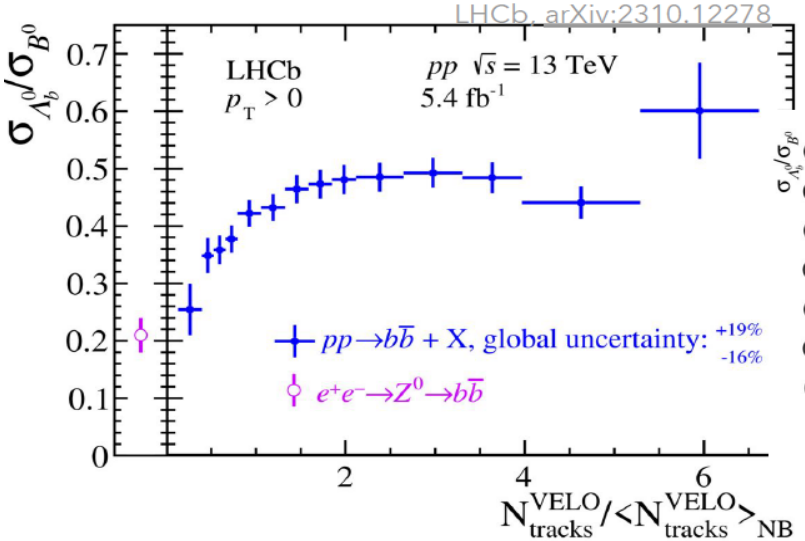


Andrea Rossi

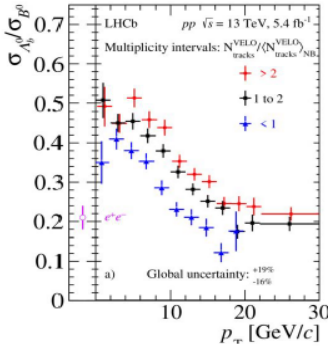
- Significant enhancement of charm baryon-to-meson ratios at low/intermediate pT w.r.t. e+e- collisions
  - Needs modified hadronisation (CR BLC, coalescence), or augmented feed-down from higher charm baryon resonances
  - Even larger enhancement measured for charm-strange baryons (more difficult to be caught by models)
  - Similar behaviour observed in beauty sector

c AND b BARYON HADRONISATION IN pp VS MULTIPLICITY



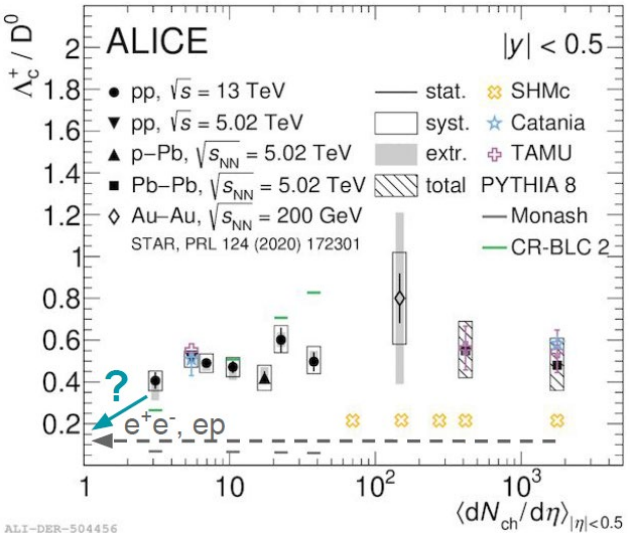


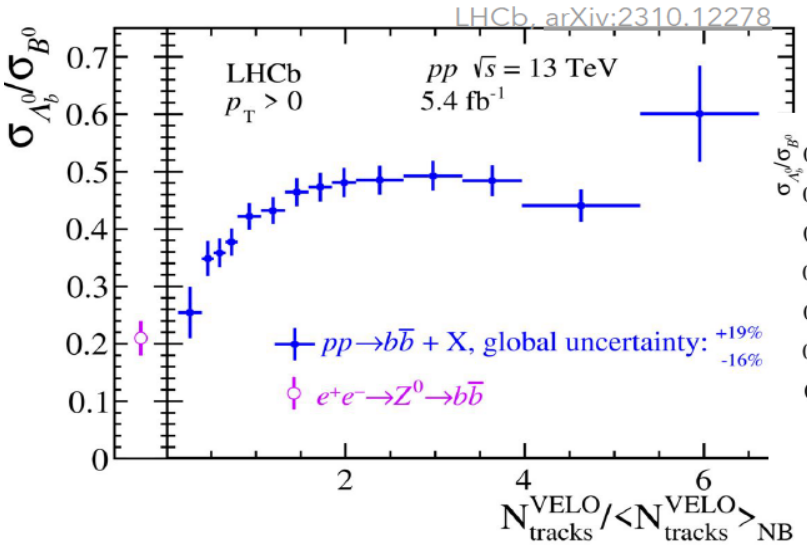
Andrea Rossi



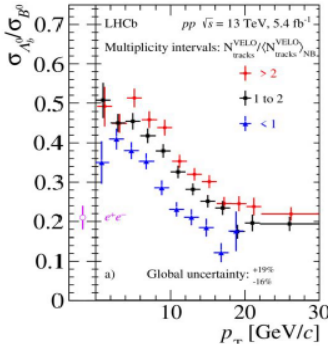
- Hierarchy from low to high multiplicity for Λ_c^+/D^0 ratios in $1 < p_T < 12$ GeV/c by ALICE
  - Follows what observed in LF sector
- Similar hierarchy observed also for Λ_c^+/D^0 at forward rapidity by LHCb
  - Common mechanism at play for c and b?

c AND b BARYON HADRONISATION IN pp VS MULTIPLICITY



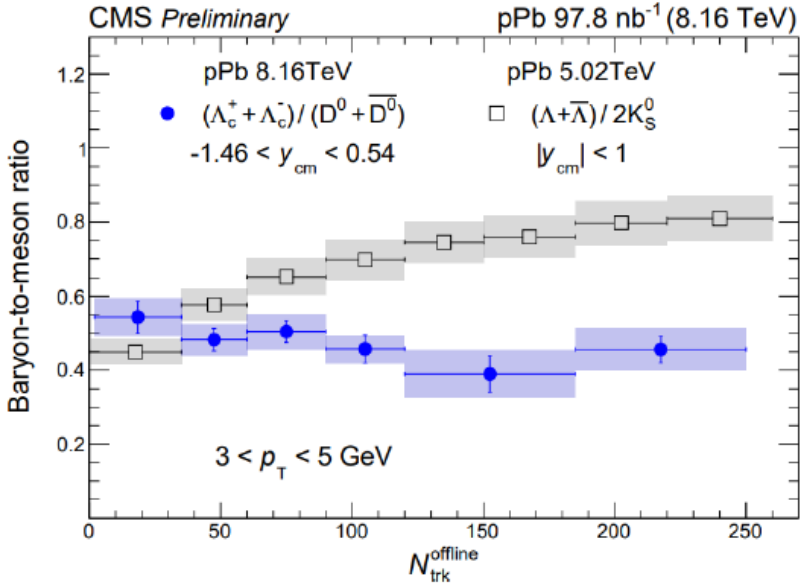


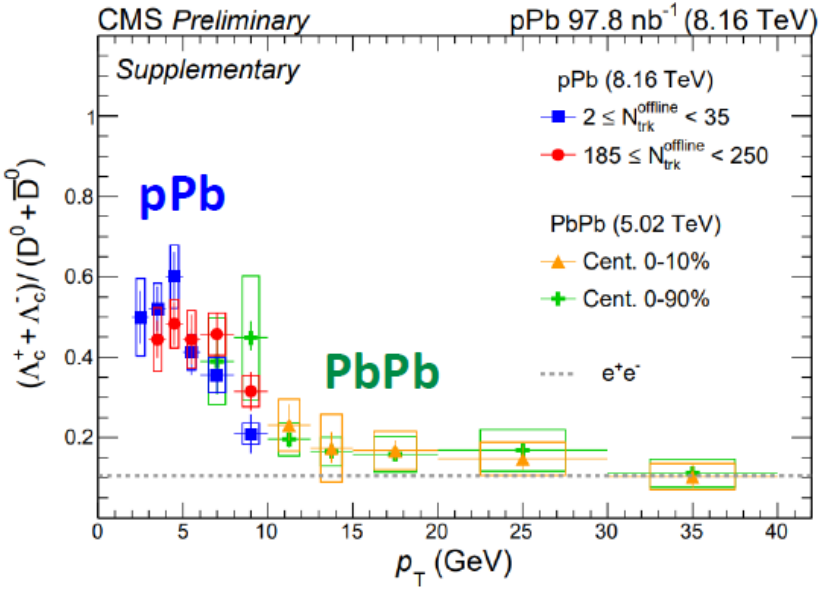
Andrea Rossi



- Hierarchy from low to high multiplicity for Λ_c^+/D^0 ratios in $1 < p_T < 12$ GeV/c
  - Follows what observed in LF sector
- Similar hierarchy observed also for Λ_c^+/D^0 at forward rapidity
  - Common mechanism at play for c and b?
  - Though p_T-integrated trends across multiplicities seem to differ… (but different rapidity, different x scale)

c AND b BARYON HADRONISATION IN p-Pb VS MULTIPLICITY





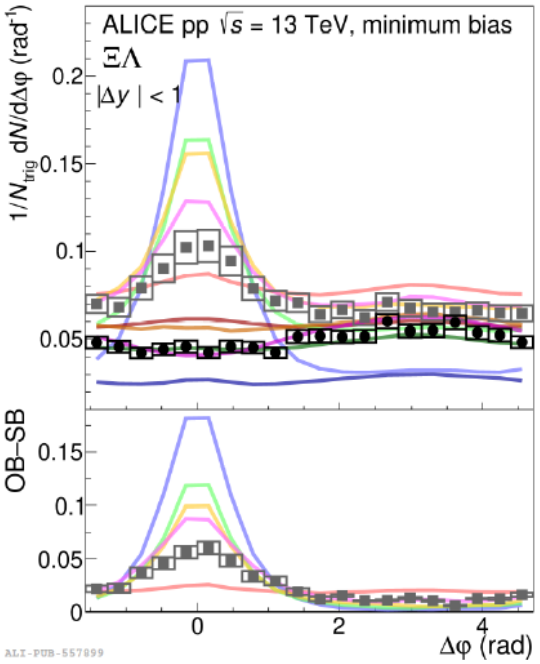
- In p-Pb collision, scarce multiplicity dependence on Λ_c^+/D^0 ratio observed by CMS
  - Similarity to LF is broken
  - Saturation effect for charm baryon production at large multiplicities?
  - Is there a common mechanism at play for all hadronic collision systems?

Georgios Krintiras

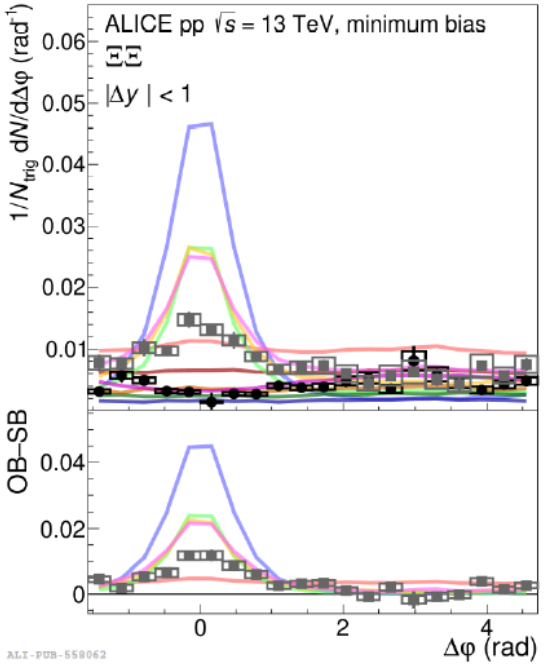
WHAT ABOUT STRANGE-BARYON PRODUCTION?

- Strange-charged particle and strange-strange correlation studies
  - Increase the sensitivity to different mechanisms modelling strangeness production in small systems
  - Strings, junctions/ropes, cluster hadronization, core/corona, …
- No model currently catching data
  - It is only a matter of tuning, or novel s-production scenarios should be considered?
- Good perspectives for addressing Ω (sss) correlations with Run3 data in ALICE

$\Delta\varphi$ projection



$\Delta\varphi$ projection



OS correlations

SS correlations

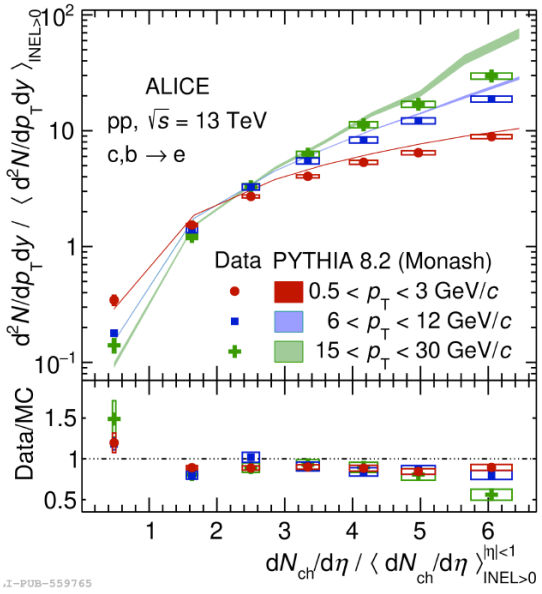
Roman Nepeivoda

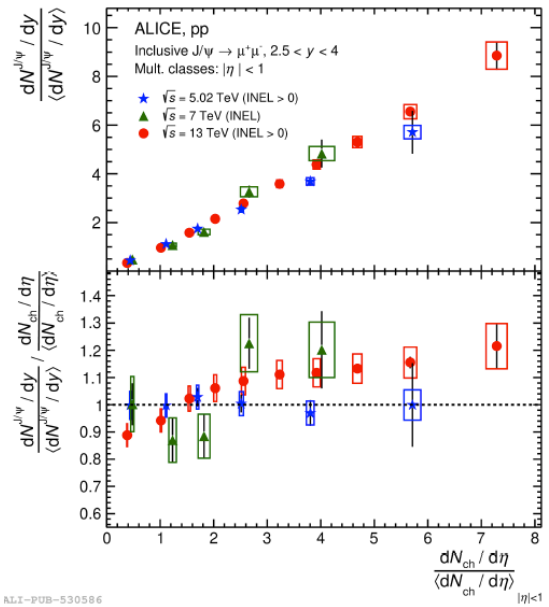
Particle production and multiplicity dependence

HF PRODUCTION VS CHARGED-PARTICLE MULTIPLICITY

- Several studies of HF production as a function of charged-particle multiplicity at the LHC
  - Assess the role of MPI for hard parton production
  - Study the interplay between soft and hard processes

Yoshini Bailung
Chi Zhang





- Stronger-than-linear increase observed for D-meson, HF-decay electrons, HF-decay muons, J/Ψ at midrapidity
- Well reproduced by PYTHIA8 or EPOS model with hydro contribution switched on
- Only linear increase for J/Ψ at forward rapidity

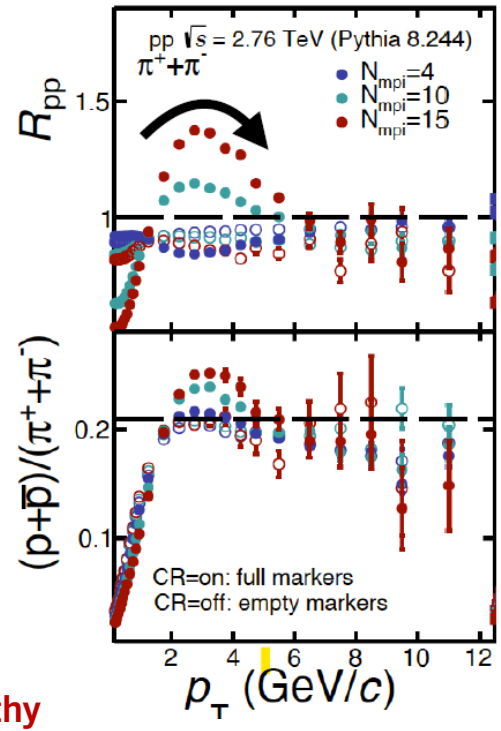
REMOVING EVENT SELECTION BIASES

- Multiplicity-based measurement anyway subject to biases
  - Selecting high-multiplicity events skewes the sample toward hard processes
  - Presence of auto-correlation

- Several observables proposed to better classify the events, in terms of their:
  - Topology, i.e. jetty vs isotropic (transverse spherocity)
  - Charged-particle uniformity (flattenicity)
  - Effective UE activity (R_T)

- Better suited to study the impact of MPI

PYTHIA 8



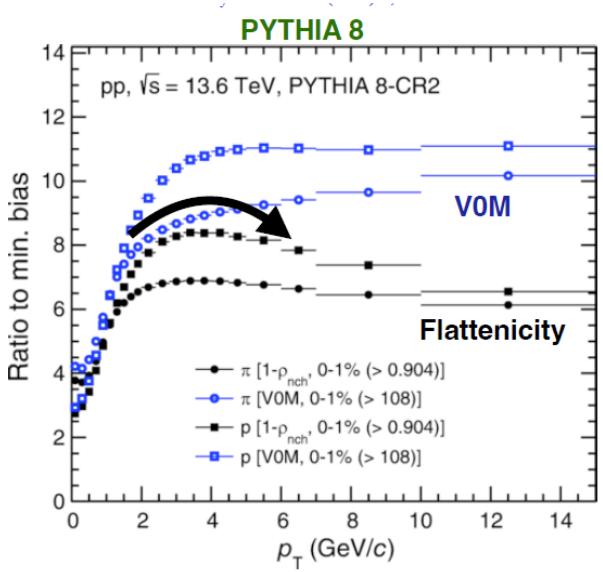
Sushanta Tripathy

FLATTENICITY CLASSIFIER

- Selection based on flattenicity rather than just on event multiplicity recovers, for isotropic events, the mid-p_T «bump» observed in PYTHIA for large-MPI events
  - More sensitive to soft particle production and less subject to a jet bias

$$Q_{pp} = \frac{d^2N^{1-\rho\ \mathrm{class}}/(\langle dN_{ch}/d\eta\rangle dy dp_T)}{d^2N^{MB}/(\langle dN_{ch}/d\eta\rangle dy dp_T)}$$

Sushanta Tripathy

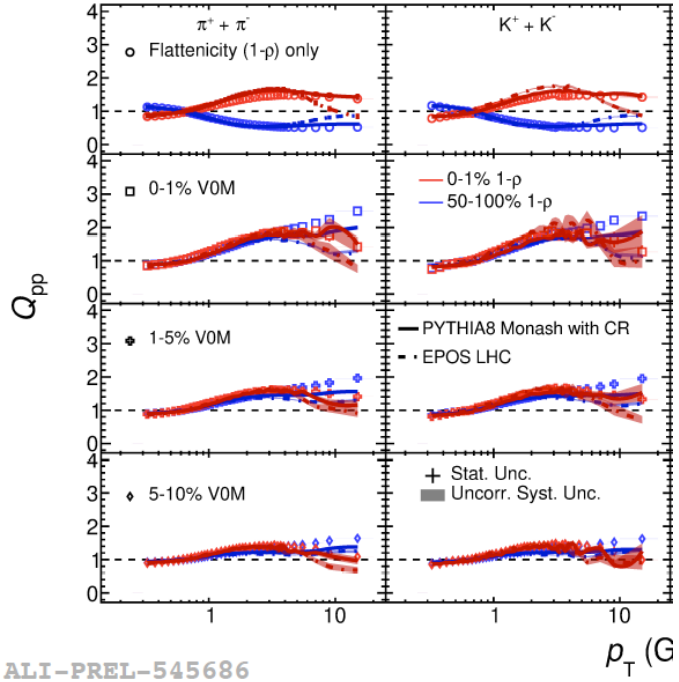


Flattenicity class only

Flattenicity + 0-1% V0M

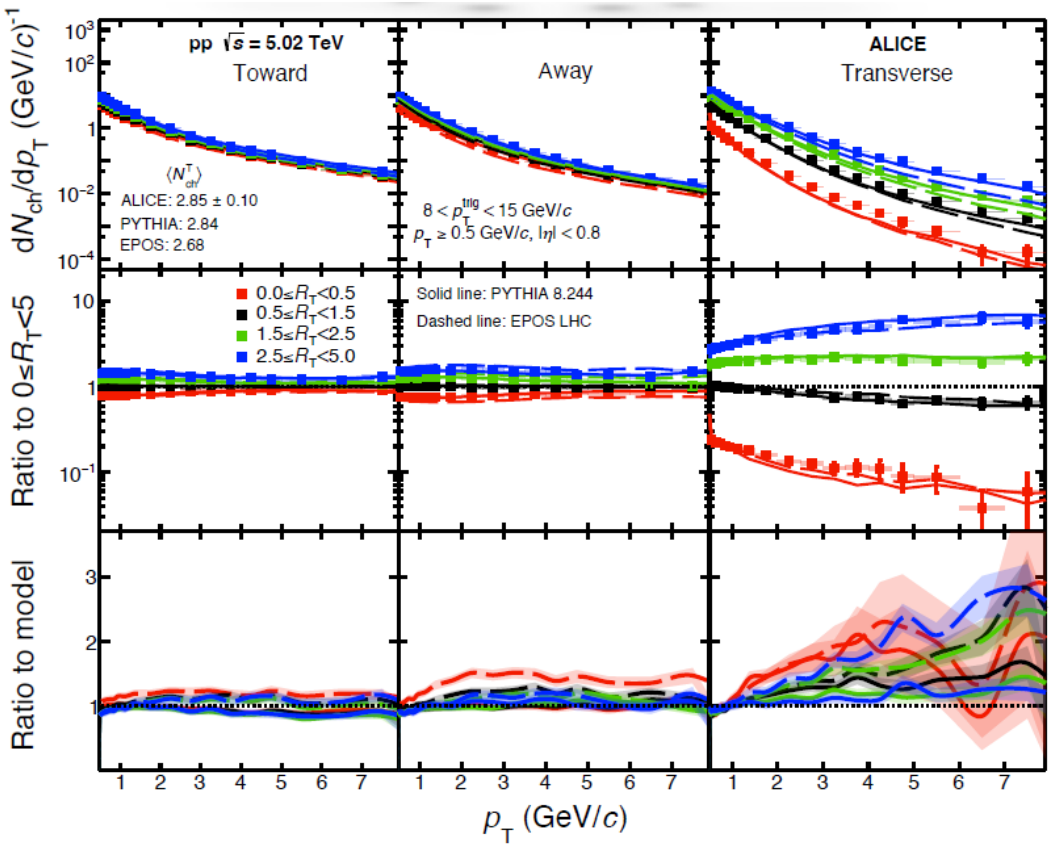
Flattenicity + 1-5% V0M

Flattenicity + 5-10% V0M



ALI-PREL-545686

RELATIVE TRANSVERSE ACTIVITY (R_T) CLASSIFIER



$$R_T = \frac{N_{ch}^{TS}}{\langle N_{ch}^{TS} \rangle}$$

Paola Vargas

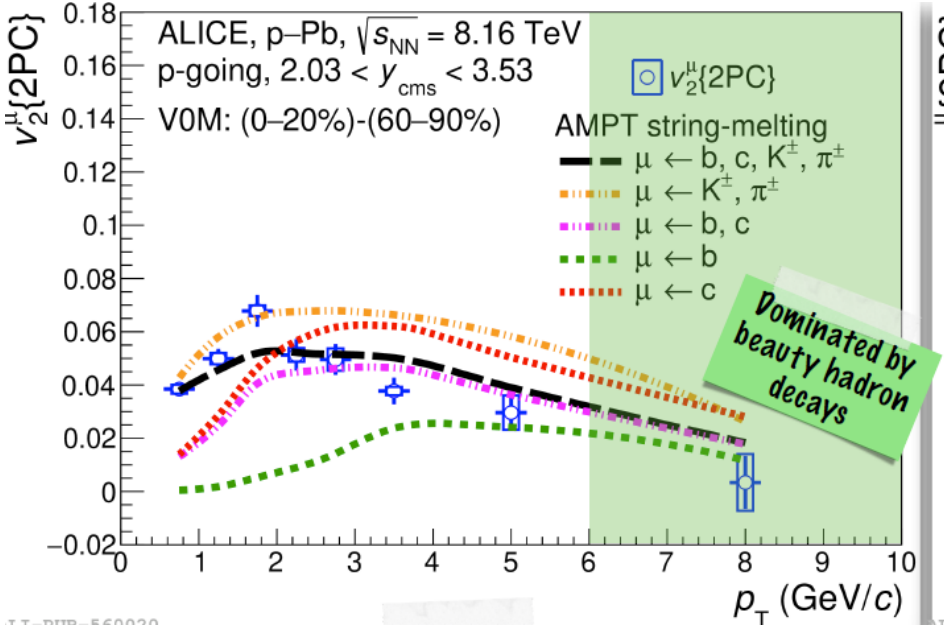
- Particle spectra for different R_T values
- Transverse region: strong dependence with R_T (autocorrelation effects)
- Towards and away side:
  - p_T < 4 GeV/c: some dependence of p_T spectra on R_T, possibly due to radial flow
  - Above 4 GeV/c, spectra are almost independent of R_T
- Very similar findings for p-Pb collisions

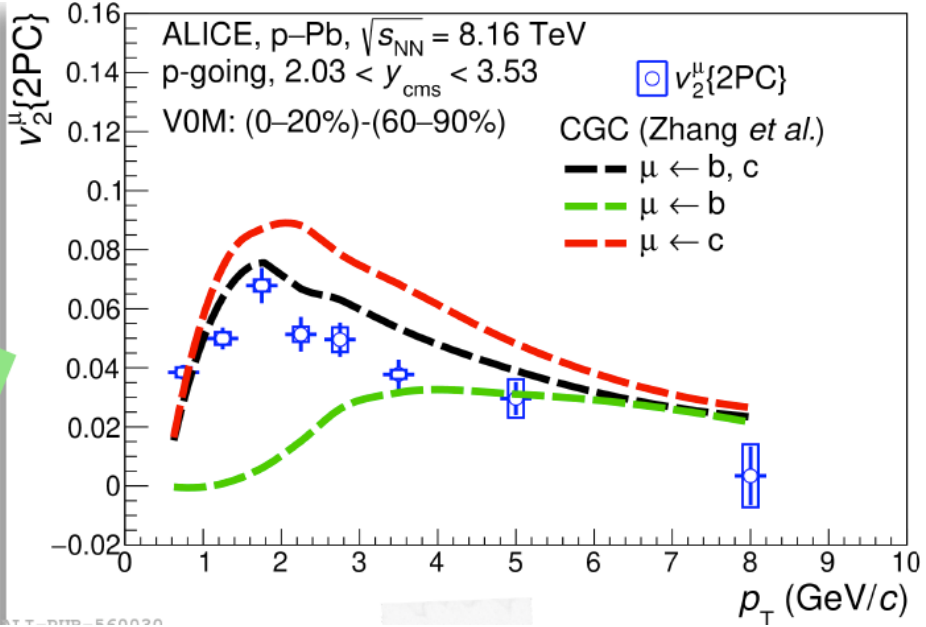
Collectivity in small systems

OPEN HF FLOW IN SMALL SYSTEMS - LHC

- Established observation of non-zero flow of light- and heavy-flavour particles in small systems
  - For multiple particles, measurements by different collaborations
  - **Origin still debated!** MPIs with CR? Glasma diagrams within CGC? QGP droplets?

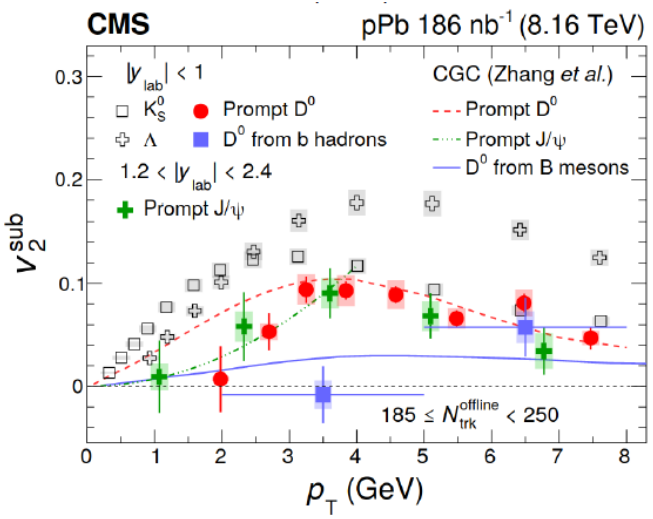
Yoshini Bailung

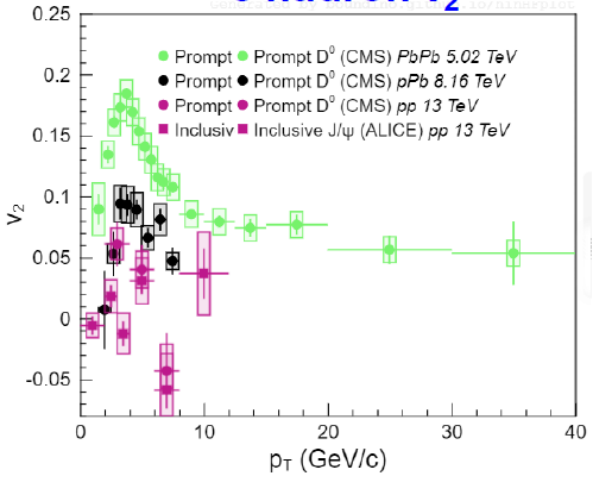




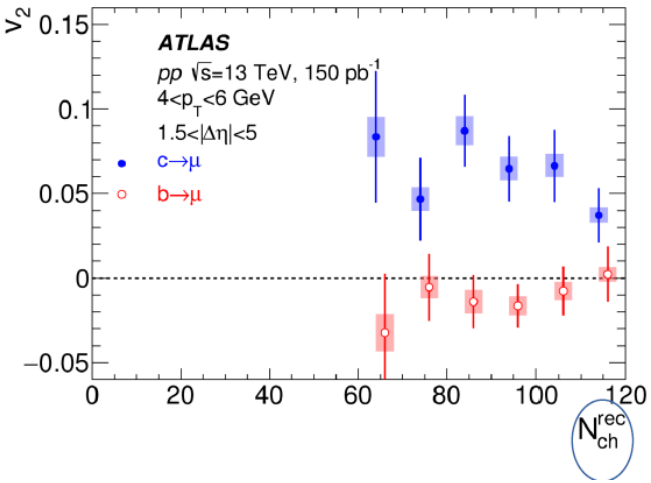
OPEN HF FLOW IN SMALL SYSTEMS - LHC

- Established observation of non-zero flow of light- and heavy-flavour particles in small systems
  - Apparent ordering for charm: v_2(PbPb) > v_2(pPb) > v_2(pp)
  - Different behaviour for beauty (not flowing at all in pPb and pp)
  - What's the lowest multiplicity limit for the onset of collectivity?
  - Can small-ion collisions (e.g. O-O) help in understanding the underlying phenomena?



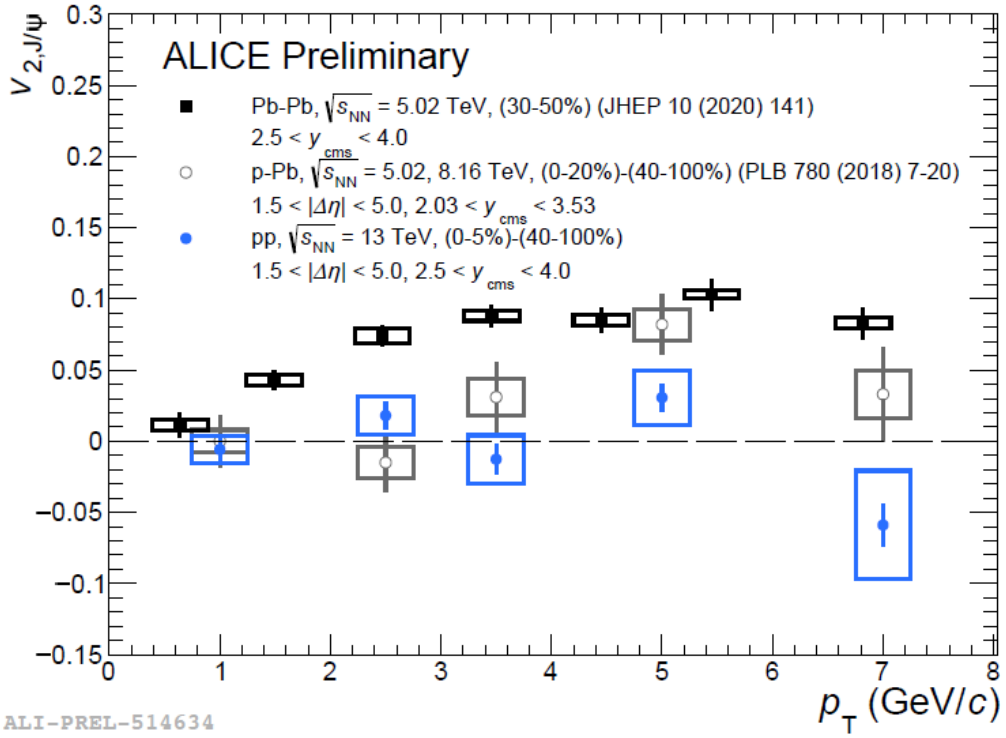


Georgios Krintiras



QUARKONIUM FLOW IN SMALL SYSTEMS - LHC

- Established observation of non-zero flow of light- and heavy-flavour particles in small systems
  - Hidden charm: hierarchy across collision systems is confirmed…
  - …but no signal of flow in proton-proton collisions
- Different behaviour w.r.t. open charm!
  - Pick-up of flow from light quarks for D mesons?

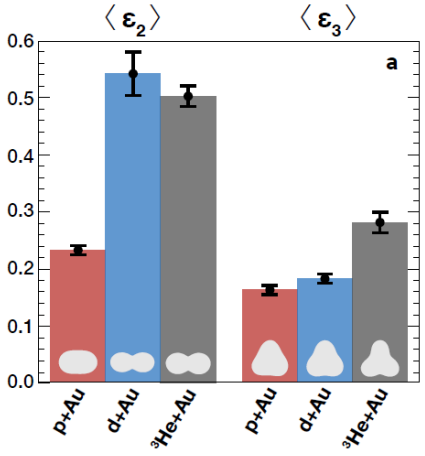


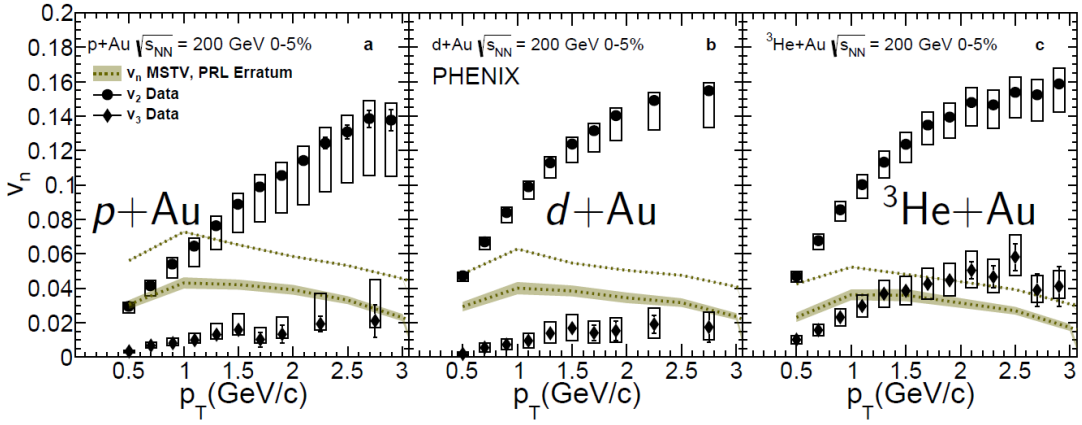
Ida Storehaug

CHARGED PARTICLE FLOW IN SMALL SYSTEMS - RHIC

- Established observation of non-zero flow of light- and heavy-flavour particles in small systems
  - Also at lower energies (STAR and PHENIX), close connection of v_2 and v_3 to system eccentricity and triangularity
  - PHENIX vs STAR discrepancy, under investigation: rapidity dependence seems to play a relevant role
  - Initial state effects not enough to reproduce the measurements
    - Differently from LHC findings!

Ron Belmont





FULL LIST OF CONTRIBUTIONS

Thanks to all the speakers for their intriguing presentation and for the exciting material shown!

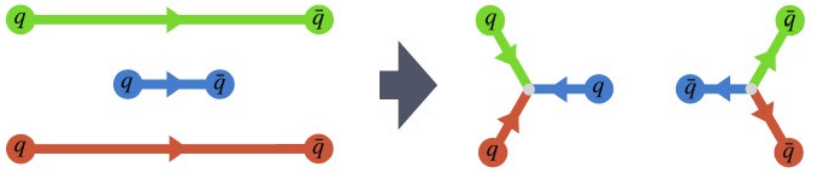
• Heavy-quark production and hadronisation as a function of event multiplicity with ALICE	**Andrea Rossi**
• Updates on junction formation and charm production in PYTHIA	**Javira Altmann**
• ALICE measurements of particle production as a function of event topology in small systems	**Sushanta Tripathy**
• Probing the Mechanisms of Strangeness Enhancement in Small Systems with ALICE	**Roman Nepeivoda**
• Quarkonium production as a function of charged-particle multiplicity with ALICE: a probe for MPI in pp and p-Pb	**Chi Zhang**
• Recent heavy-flavour results in small systems with ATLAS and CMS	**Georgios Krintiras**
• Collectivity in Small Systems at RHIC	**Ron Belmont**
• Quark spin in string hadronization	**Albi Kerbizi**
• Searching collective-like effects for heavy-flavour in small systems with ALICE	**Yoshini Bailung**
• Investigating collective effects in small collision systems using PYTHIA8 and EPOS4 simulations	**Alexandru Manea**
• Charged-particle production as a function of the relative transverse activity classifier in pp, pPb and PbPb	**Paola V. Torres**
• Fitting a deep generative hadronization model	**Andrzej K. Siodmok**
• Quarkonium as a probe of multiple parton interaction and collectivity in pp collisions with ALICE	**Ida Storehaug**

Backup slides

MODELING BARYON-TO-MESON RATIOS

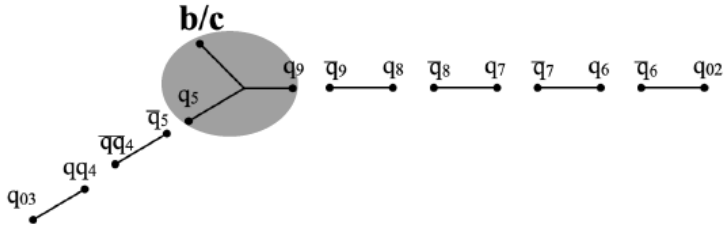
- PYTHIA8 description of baryon-to-meson ratios: need junctions to enhance heavy baryon production
  - 70% of heavy baryons produced by junctions
  - Continuous improvements on the junction modeling

Javira Altmann



New treatment:

- Considers pull on junction over time and average over junction motion
- Includes pearl-on-a-string
- Allow endpoint oscillations
- No reliance on convergence



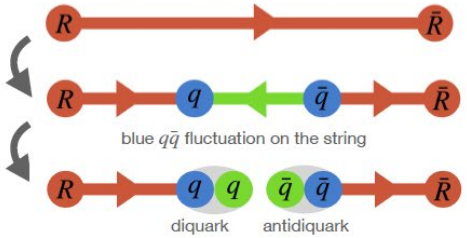
MODELING BARYON-TO-MESON RATIOS

- Work ongoing also for the strangeness description
  - Popcorn mechanism recovering p/π ratios via diquark suppression

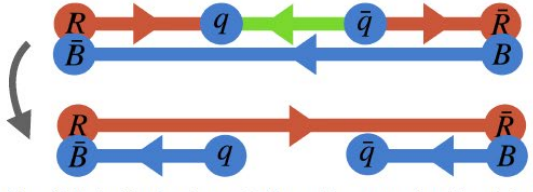
Javira Altmann

Popcorn Mechanism

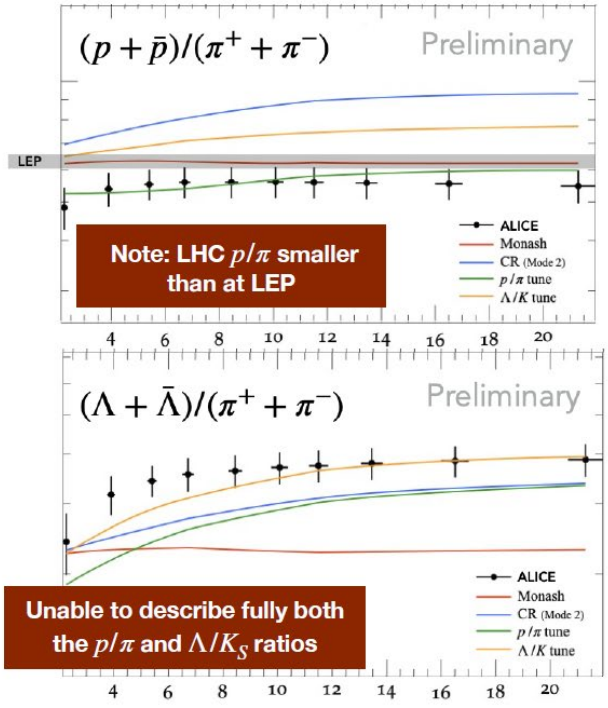
Diquark formation via **successive colour fluctuations**



What if there's a blue string nearby?

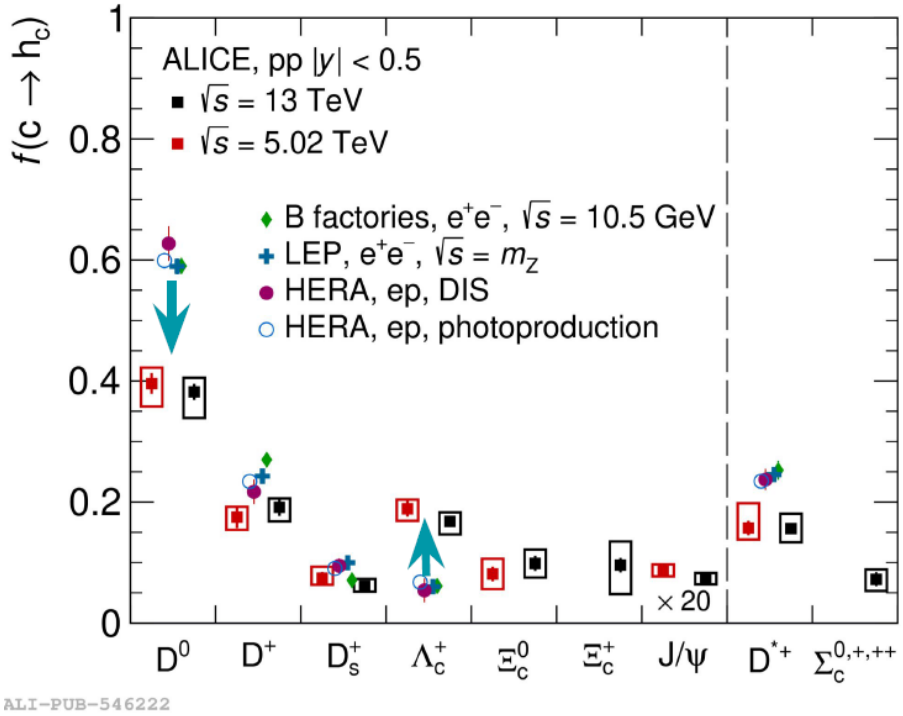


blue $q\bar{q}$ fluctuation breaks nearby blue string, preventing diquark formation



Fragmentation fractions: pp vs. e^+e^- collisions

ALICE, arxiv 2308.04877



Calculated from sum of cross sections of weakly decaying hadrons

Values for mesons significantly lower than in e^+e^-

About 30-40% of charm quarks hadronise to baryons

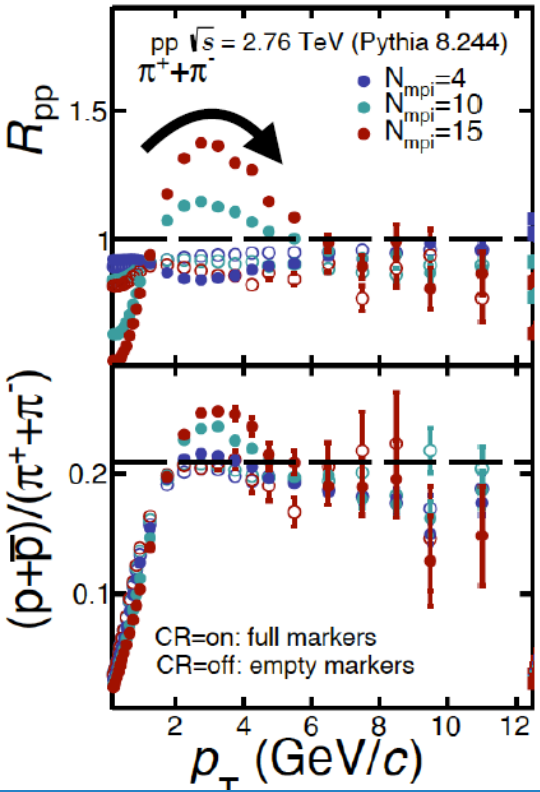
No evidence of energy dependence

Lower p_T reach expected with Run 3 data will allow to further reduce extrapolation uncertainties

Andrea Rossi

MPI AND COLOR RECONNECTION

PYTHIA 8



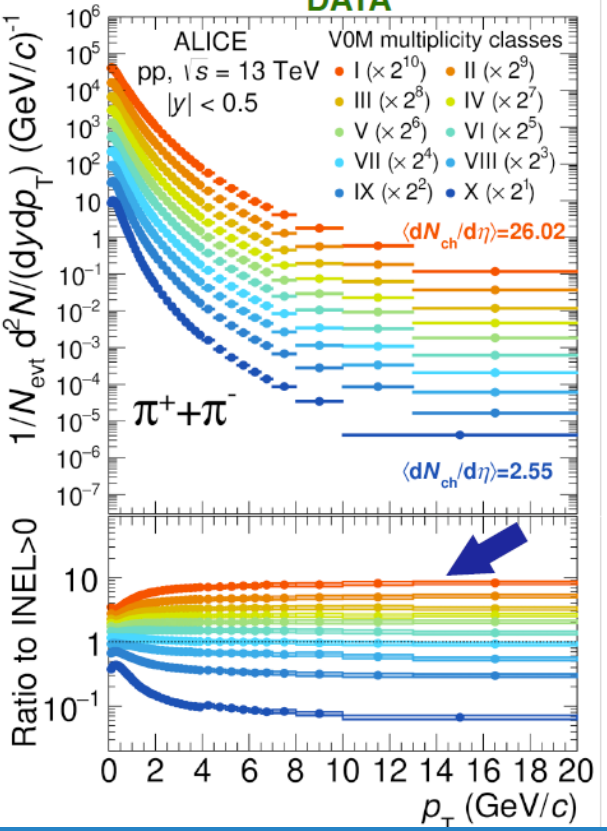
Ratio of yield in MPI-enhanced pp collisions to yield for minimum bias (MB) pp collisions:

$$R_{pp} = \frac{d^2N_\pi^{mpi}/(\langle N_{mpi}\rangle dy dp_T)}{d^2N_\pi^{MB}/(\langle N_{mpi,\,MB}\rangle dy dp_T)}$$

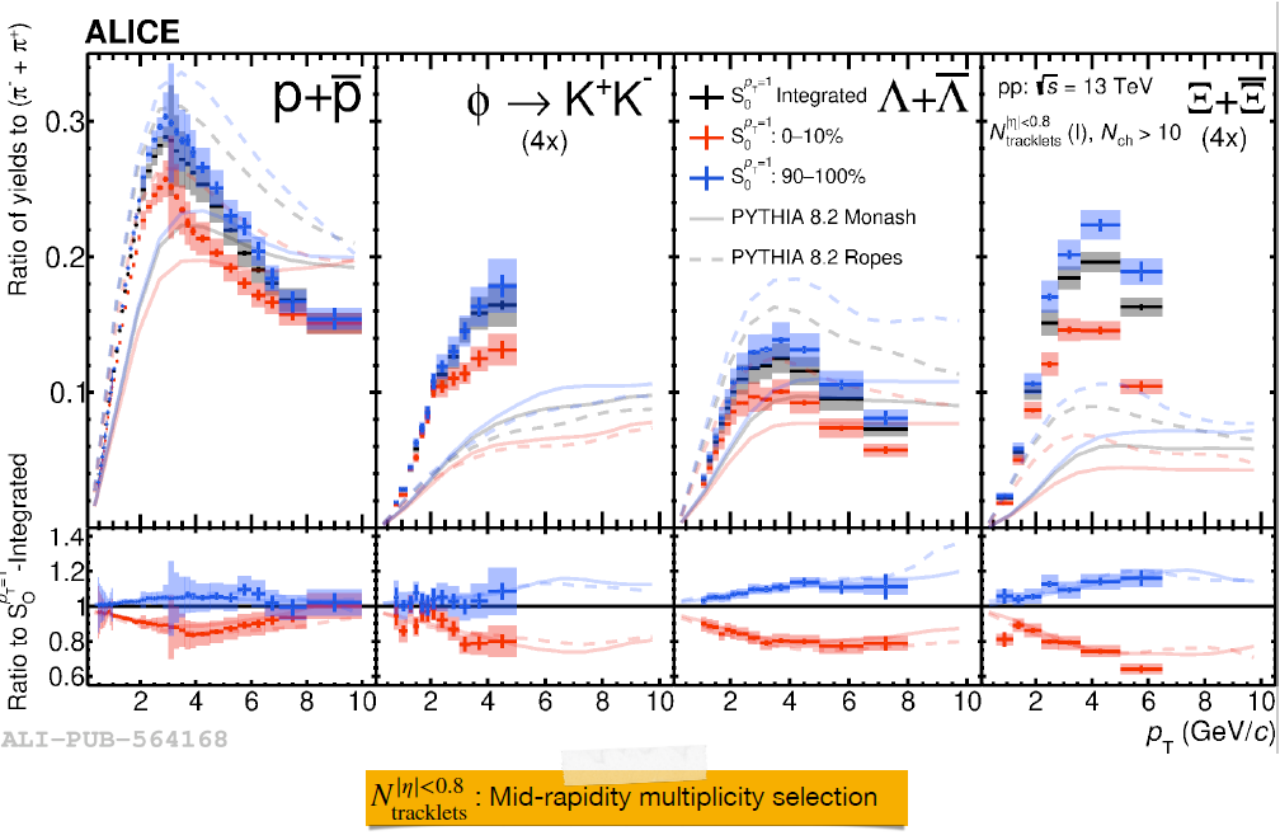
- Up to 40% increase w.r.t. the binary parton-parton scaling: "bump" structure in p_T = 1-6 GeV/c: The effect is driven by CR
- MPI selection does not bias the high-p_T yield
- The "bump" structure is not seen in measurements as a function of multiplicity and a selection bias is seen in high-p_T yield
- Explore event classifier: sensitivity to MPI with reduced selection bias

Sushanta Tripathy

DATA



STRANGENESS VS SPHEROCITY



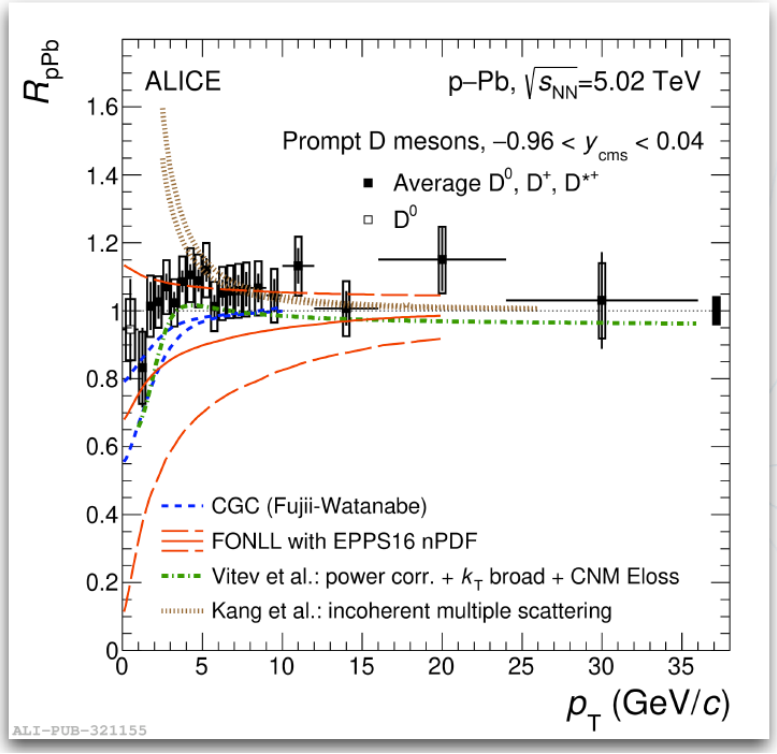
$N^{|\eta|<0.8}_{\text{tracklets}}$: Mid-rapidity multiplicity selection

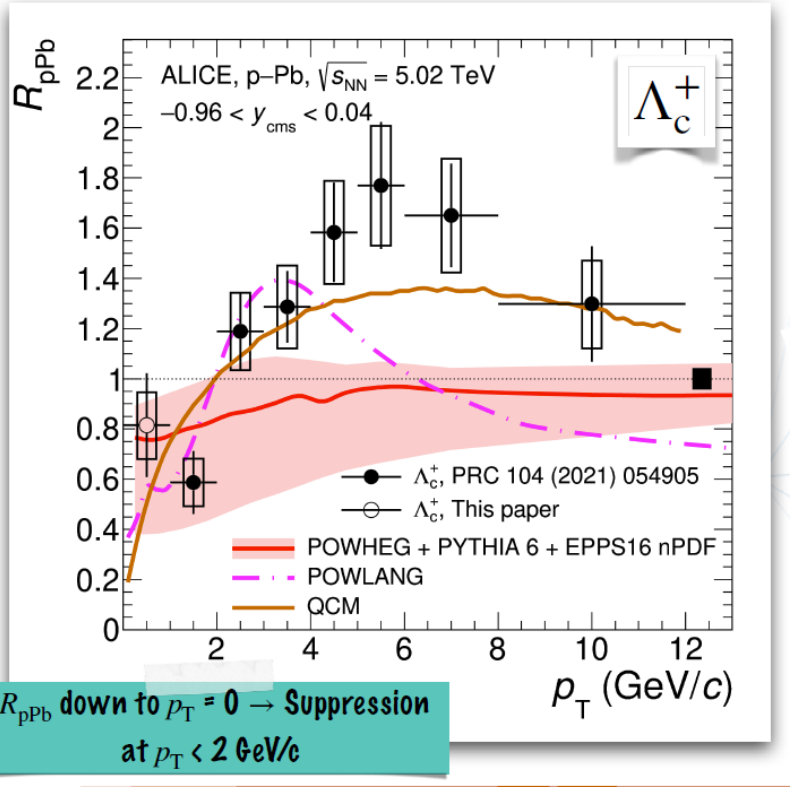
- Reduction of ratios relative to pion yields in jet-like events for all particle species -> significant strangeness suppression
- Both PYTHIA Monash and Ropes fail to capture the absolute trends but the ratios to $S_0^{p_T=1}$-integrated events are well explained by the models

Sushanta Tripathy

ALICE, arXiv:2310.10236

RpPb OF CHARM MESONS VS CHARM BARYONS

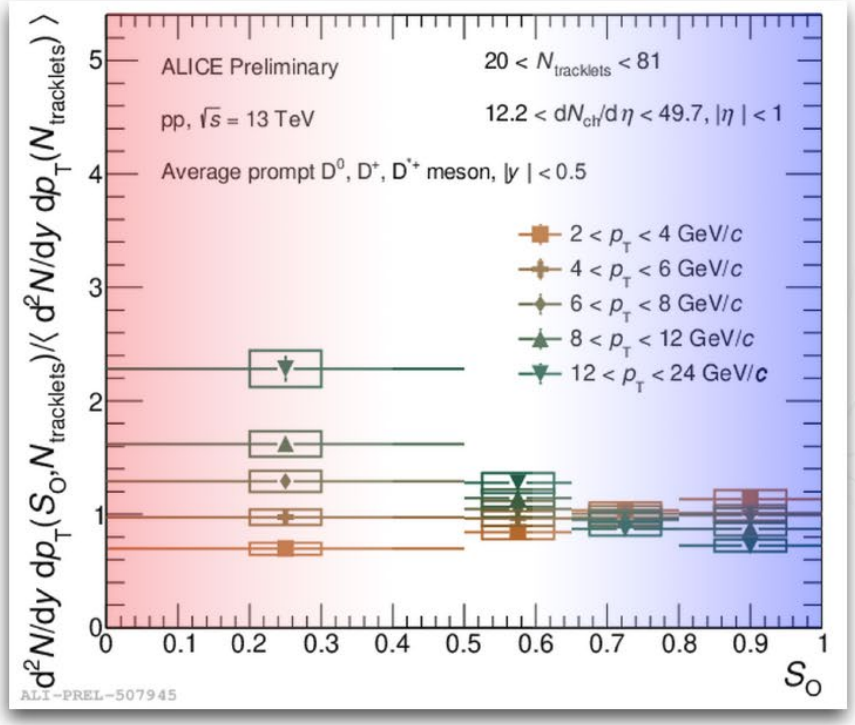




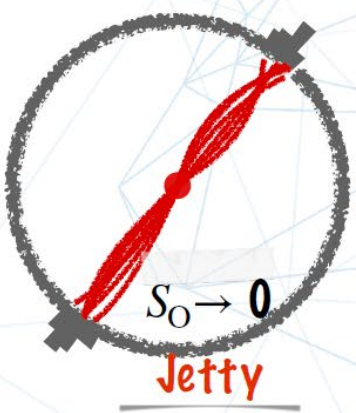
R_{pPb} down to p_T = 0 → Suppression at p_T < 2 GeV/c

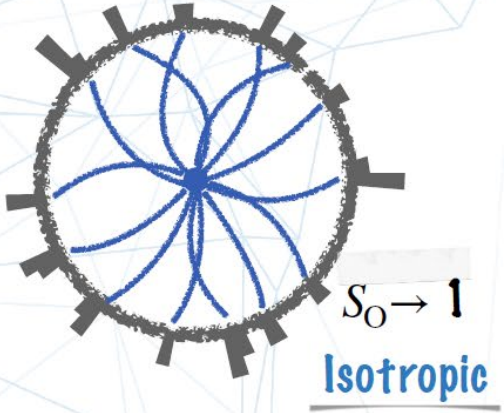
Yoshini Bailung

Heavy-Flavour and Transverse Spherocity



$$S_O^{(p_T=1.0)} = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\Sigma_i |\hat{p}_{T_i}^{(p_T=1.0)} \times \hat{n}|}{N_{tracks}} \right)^2$$

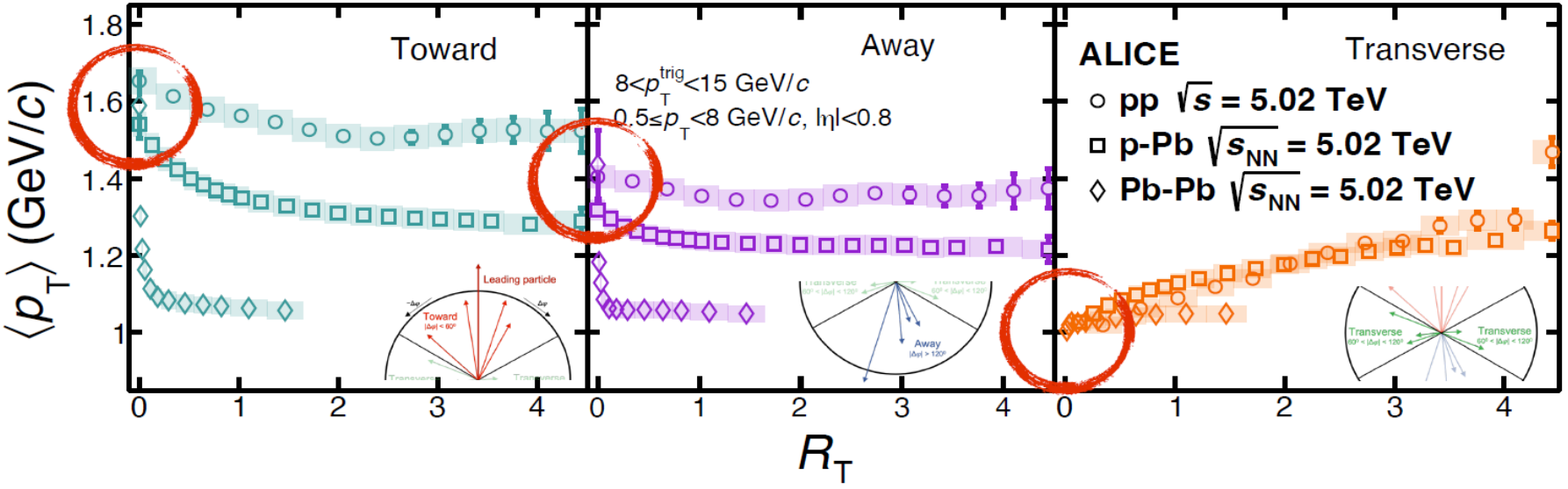




Sensitive to initial hard scatterings and the "underlying event"

Yoshini Bailung

$\langle p_T \rangle$ as a function of R_T



The jet contribution dominates at low R_T, as expected for $R_T \to 0$

For large R_T, the $\langle p_T \rangle$ is dominated by bulk contribution and exhibits an ordering that depends on the system size

Explanation for the strangeness enhancement

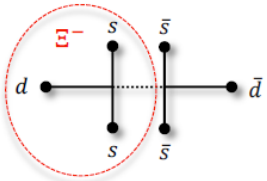
Roman Nepeivoda

PYTHIA 8

Monash

Includes color reconnection mechanism

Individual MPI systems may be color-connected

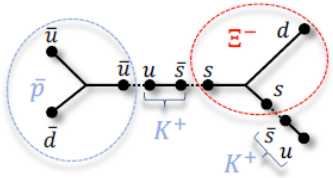


Phys. Rev. Lett. 111(4), 042001

Junctions

Allows more possibilities for balancing the strange number

$\Xi^-(\bar{\Xi}^+)$ could be balanced by the $\bar{p}(p)$ and $2K^+(2K^-)$

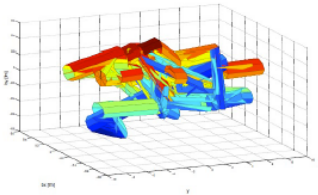


Phys. Rev. D, 92(9), 094010

Ropes

Allows strings to fuse together in high-density regions

Increased string tension leads to the enhanced production of strange quarks



Journal of High Energy Phys., 2015(3), 1-49

HERWIG

Parton showers are generated via string breaking

Cluster hadronization mechanism is introduced

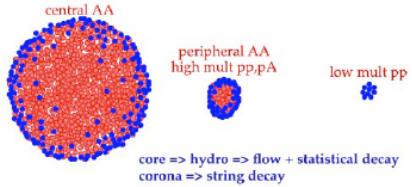
Own colour reconnection model where 3 mesons can recombine to a baryon and an anti-baryon

Eur. Phys. J., C 76 (2016), 196

EPOS-LHC

Core-corona model where strangeness is dominantly produced in the core, which is assumed to be thermal (grand canonical)

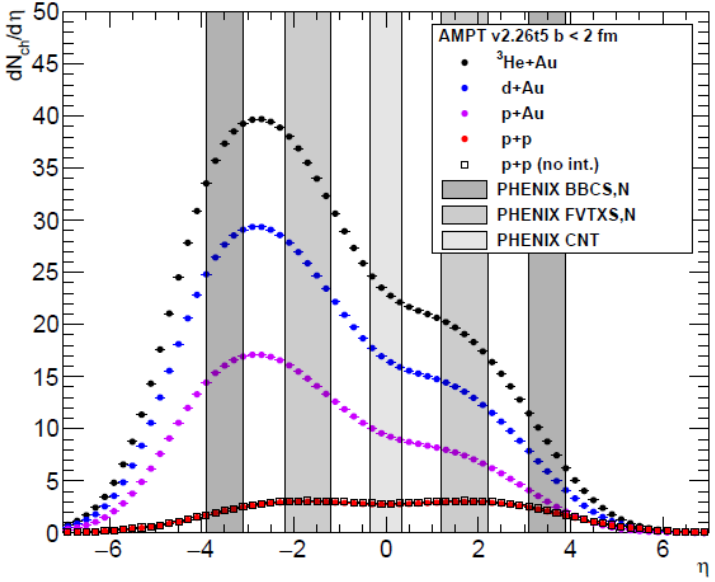
More long-ranged correlations

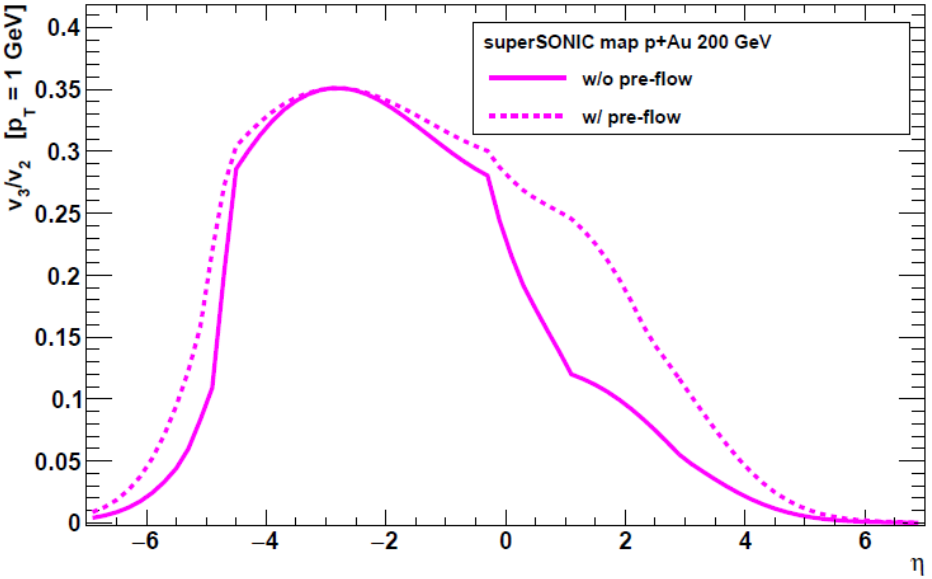


Phys. Rev. C 92, (2015), 034906

Pseudorapidity dependence in small systems

J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)





Ron Belmont

- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger pseudorapidity dependence of v_3 compared to v_2 is an essential ingredient in understanding different measurements

HF PRODUCTION VS CHARGED-PARTICLE MULTIPLICITY

- Similar behavour also for J/Ψ at midrapidity
- When probing larger rapidities, charmonium and bottomonium recover a linear trend with charged particle multiplicity
  - Models explain this via a relative reduction of charged particle multiplicity, due to several physics mechanisms

Chi Zhang