



**ALICE**

# **Panoramica sui risultati recenti di ALICE**

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(i risultati non ancora pubblici mostrati alla riunione sono stati eliminati)



Riunione ALICE - Referee

Roma, 20 luglio 2023

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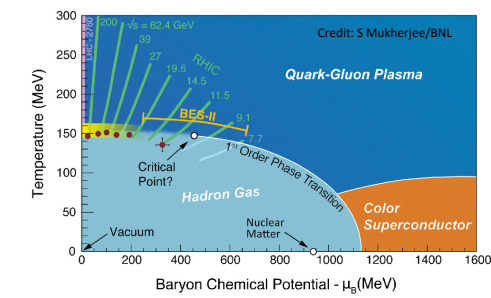
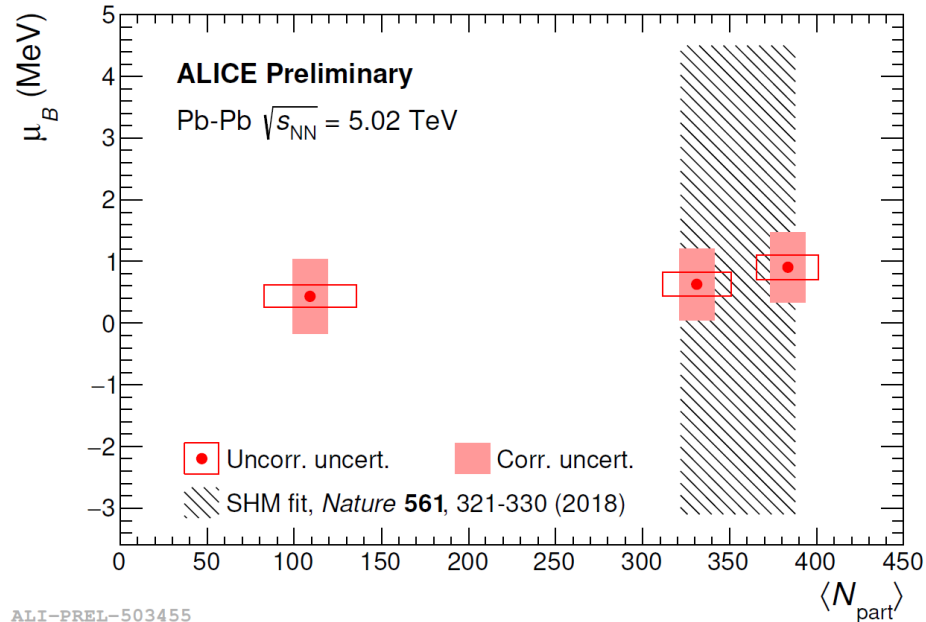
- properties of hot QCD matter
- collectivity in small systems
- hadronisation
- QCD and hadronic physics



# Properties of hot QCD matter

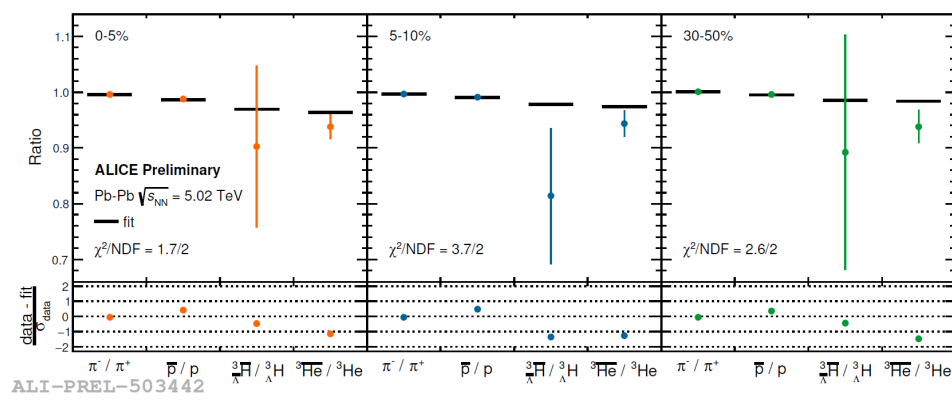
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# Antimatter – matter imbalance at the LHC



$$\bar{h}/h \propto \exp \left[ -2 \left( B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2I_3 \frac{\mu_{I_3}}{T} \right]$$

with  $T = 156.2 \pm 2$  MeV



✓ determination of  $\mu_B$  within Statistical Hadronisation Model

✓ reduced uncertainties w.r.t. global SHM fits thanks to the cancellation of correlated uncertainties

# Azimuthal asymmetry

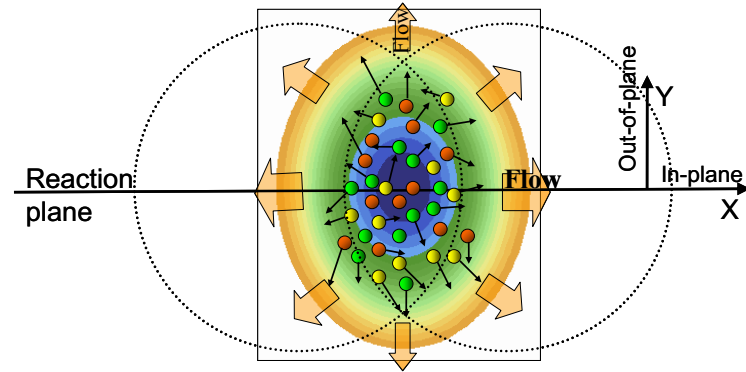
... in the transverse momentum distribution of produced particles

- why is it important?
- non-central collisions are asymmetric in azimuth

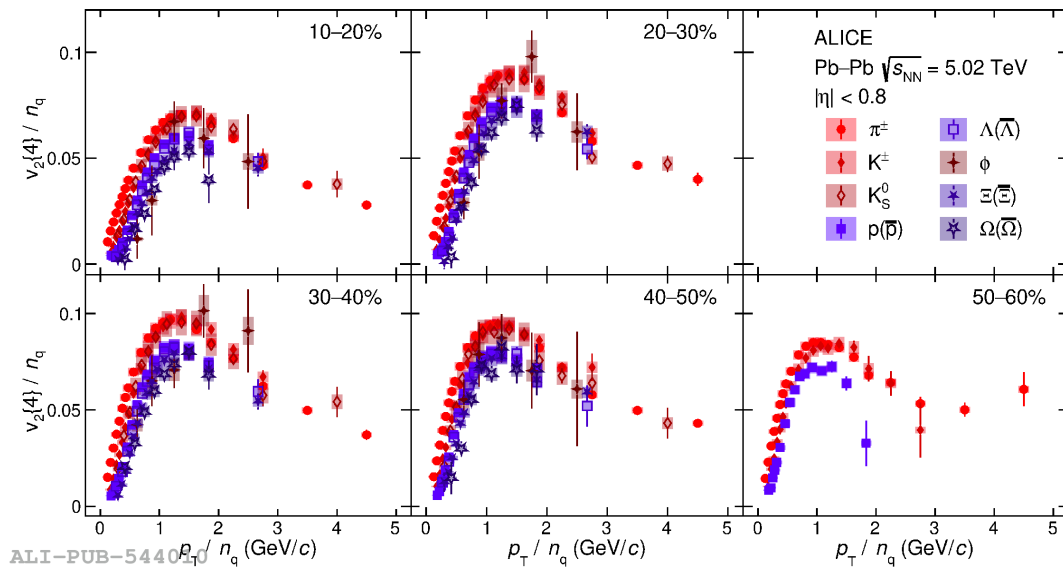
azimuth = angle in the plane of the screen

→ transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

- large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- small mean free path
  - larger density gradient  $\rightarrow$  larger pressure gradient  $\rightarrow$  larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)



# Anisotropic flow of identified hadrons



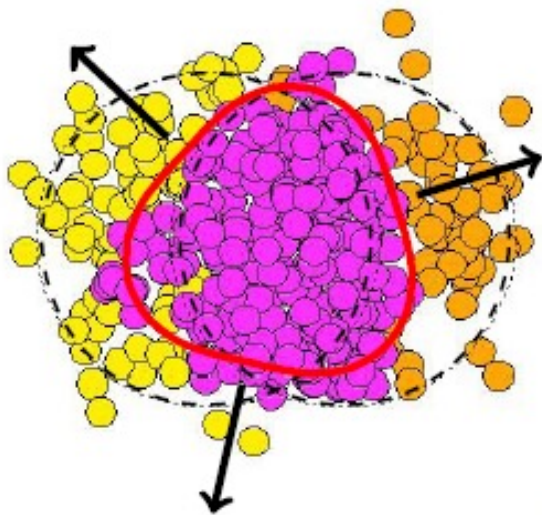
- ✓ mass ordering at low  $p_T$   
→ common expansion velocity field
- ✓ meson-baryon splitting at intermediate  $p_T$
- ✓ approximate scaling with  $n_q$   
✓ (number of constituent quarks)  
→ coalescence contribution

JHEP 05 (2023) 243

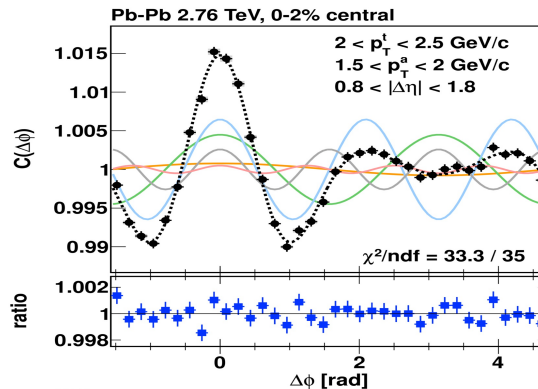
# Higher harmonics: a beautiful phenomenon...

initial-state geometrical asymmetries  $\longrightarrow$  final state momentum asymmetries

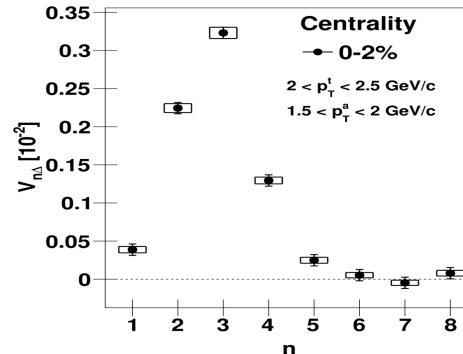
- dynamic response of QCD medium
- interaction of hard probes with QCD medium



- $\rightarrow$  Fourier decomposition of azimuthal distribution
- “flow harmonics”
  - sensitive to transport parameters of medium



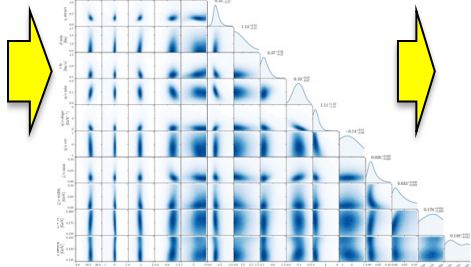
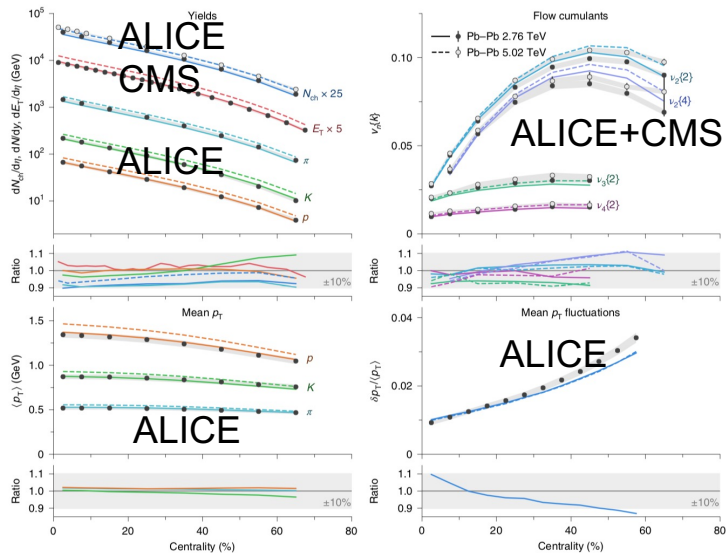
ALI-PUB-14115



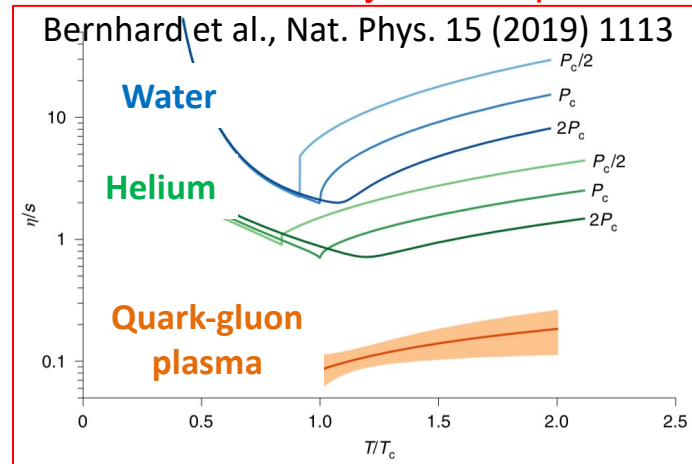
ALI-PUB-14119

# Entering precision era

- High data quality enables quantitative extraction of medium parameters
  - e.g.: Bayesian parameter estimation from ALICE (mainly) data (Duke group)
  - extraction of temperature dependence of medium bulk and shear viscosity



## QGP shear viscosity vs. temperature

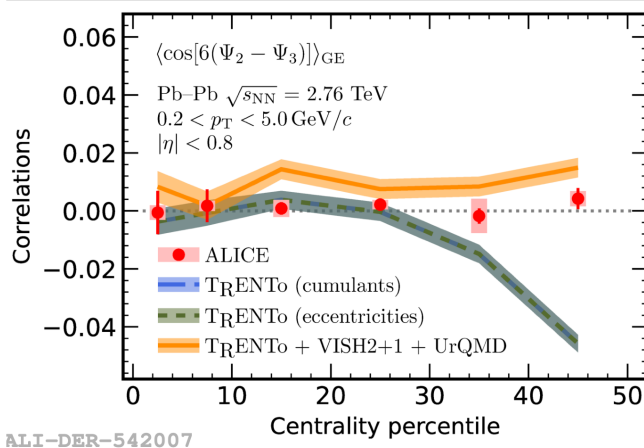
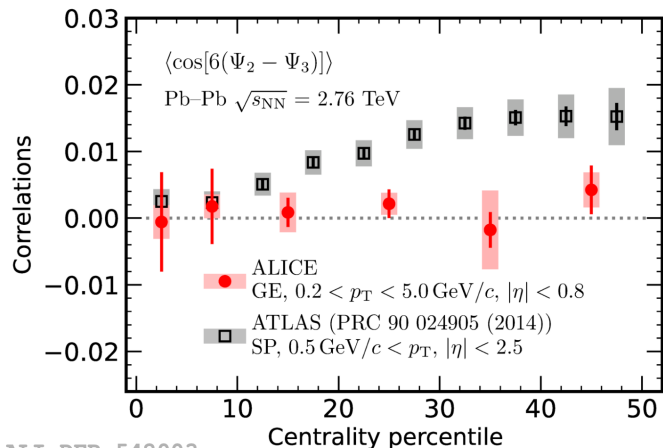


- QGP viscosity with  $\sim 20\%$  precision
- QGP  $\sim 10$  times less viscous than any other form of matter



# Event-plane correlations

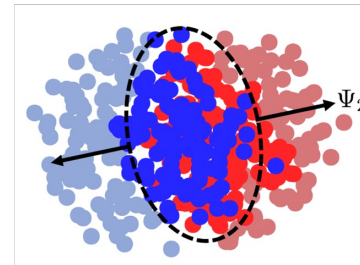
- correlations between event-plane orientations



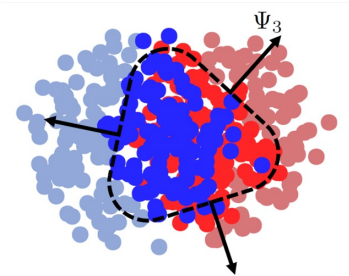
ALI-DER-542003

ALI-DER-542007

Elliptic deformation

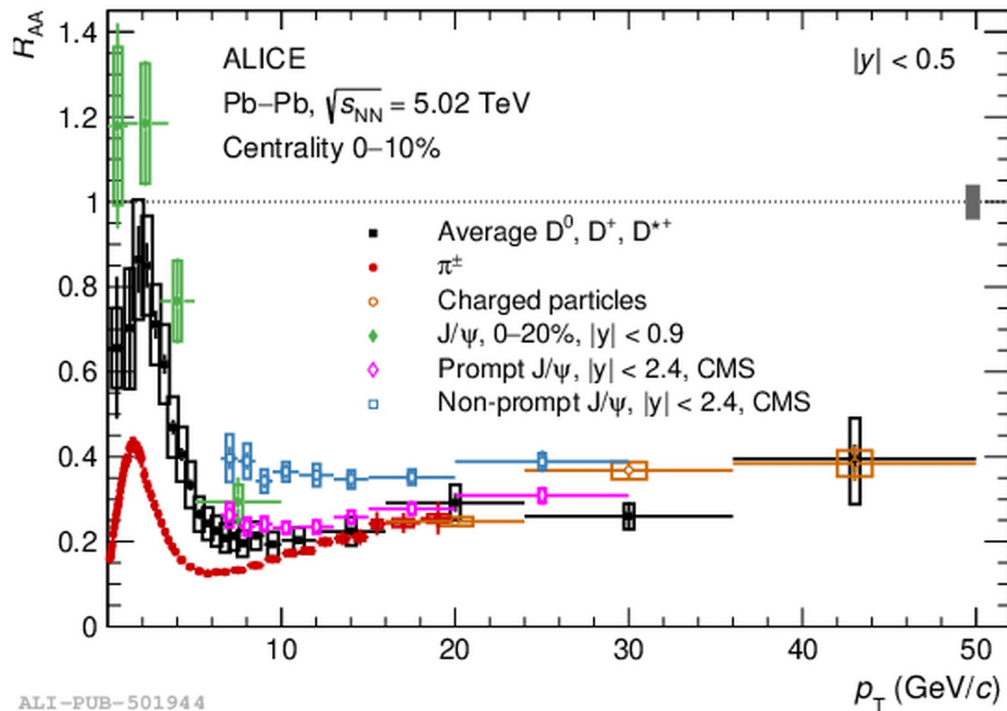


Triangular deformation



- improved method: reduced sensitivity to numerical fluctuations
  - no significant correlation between  $\psi_2$  and  $\psi_3$
  - triangular deformation dominated by geometrical fluctuations

# Heavy flavour: a gold mine



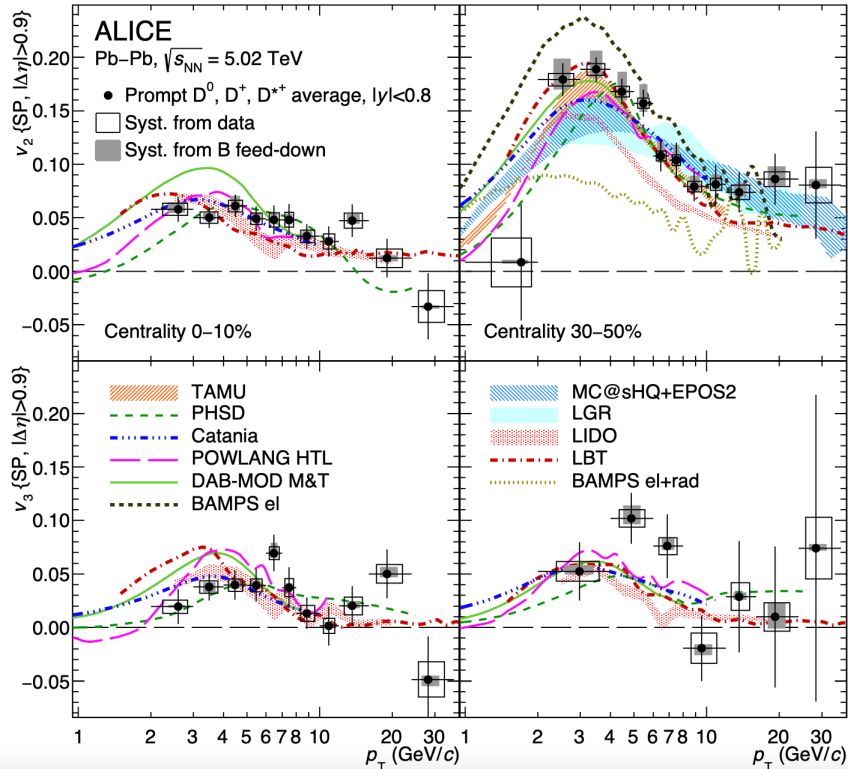
ALICE: JHEP01 (2022) 174

- controlled probe
  - mass
  - colour charge
  - pQCD
- generated in initial parton scattering
- conserved throughout evolution
- large mass  $\rightarrow$  “Brownian” probe
- powerful probe of hadronisation

experimentally:

- strongly coupled to medium
- clear hierarchy at low  $p_T$

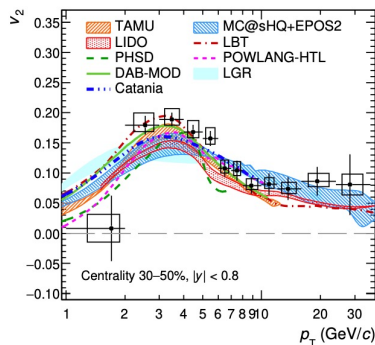
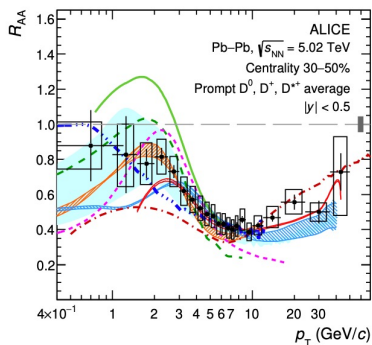
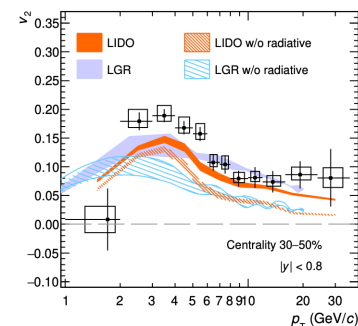
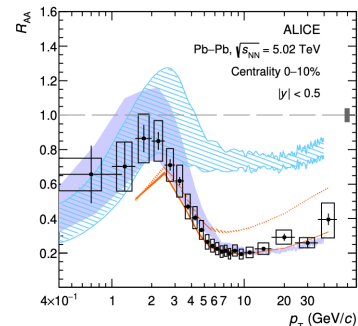
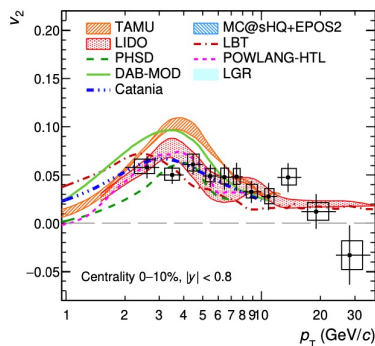
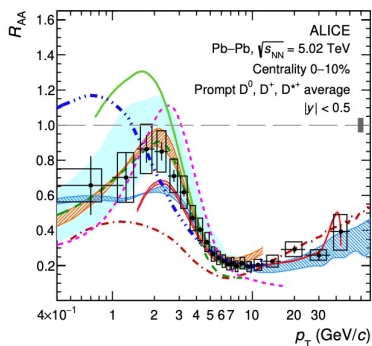
# Strong involvement in the flow



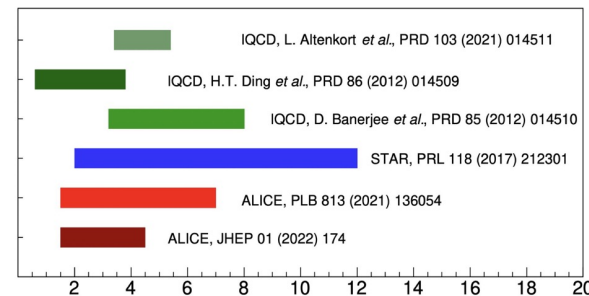
- initial production isotropic!
- sensitive to coupling to medium

ALICE: Phys. Lett. B 813 (2021) 136054

# Strong model constraints

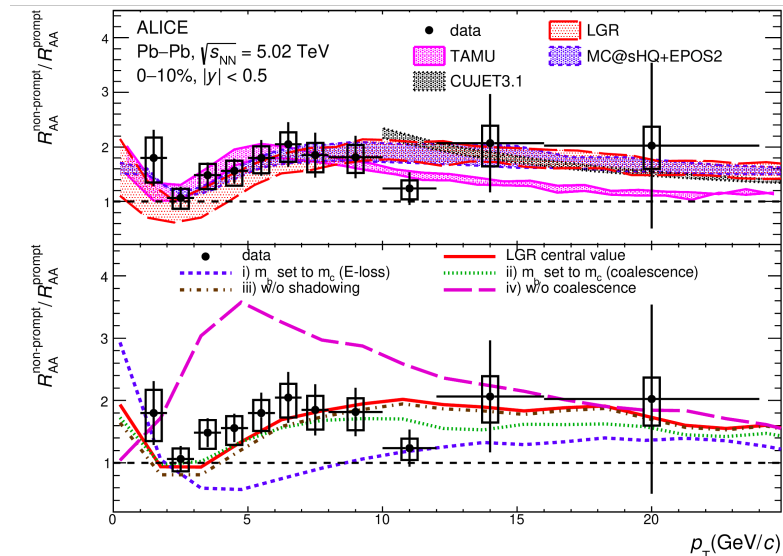
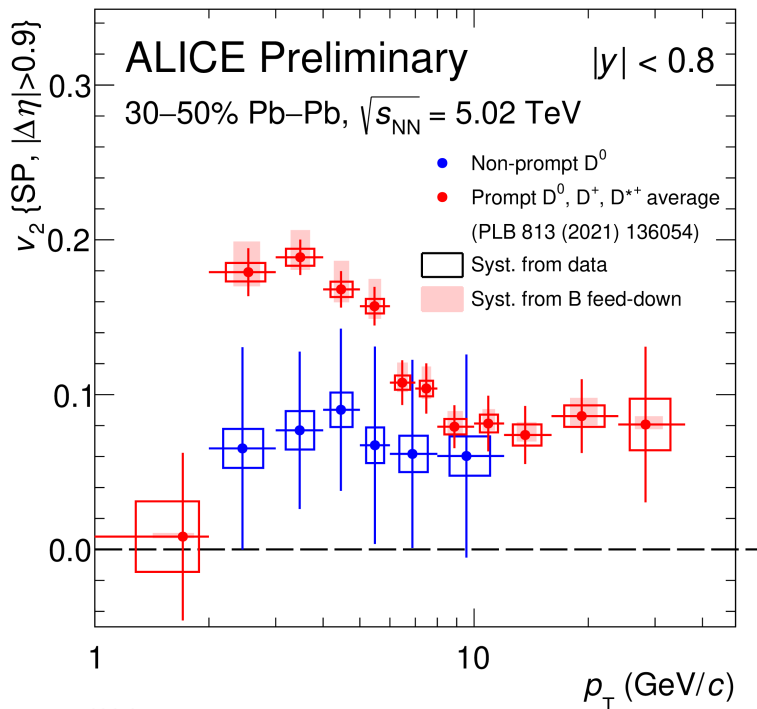


- 50% uncertainty on  $D_s$ 
  - it starts to be a measurement!



# beauty vs charm

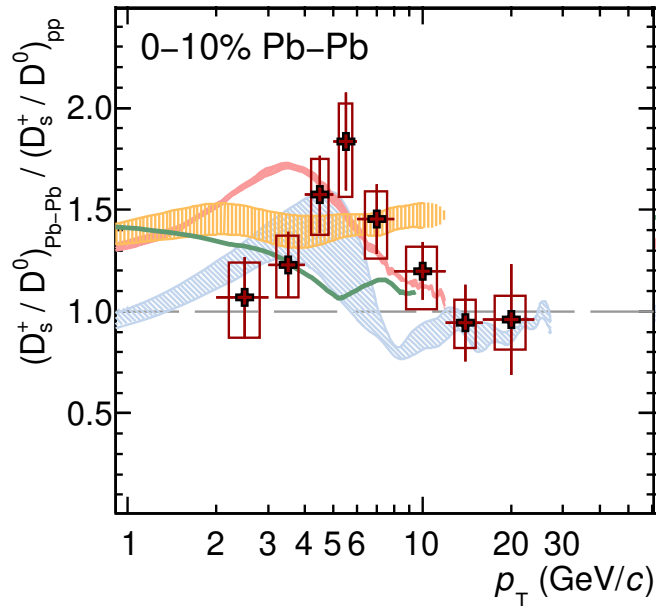
- non-prompt vs prompt D



ALI-PUB-534213

- b less suppressed than c
- b less involved in collective flow than c

# Strangeness enhancement in HF sector

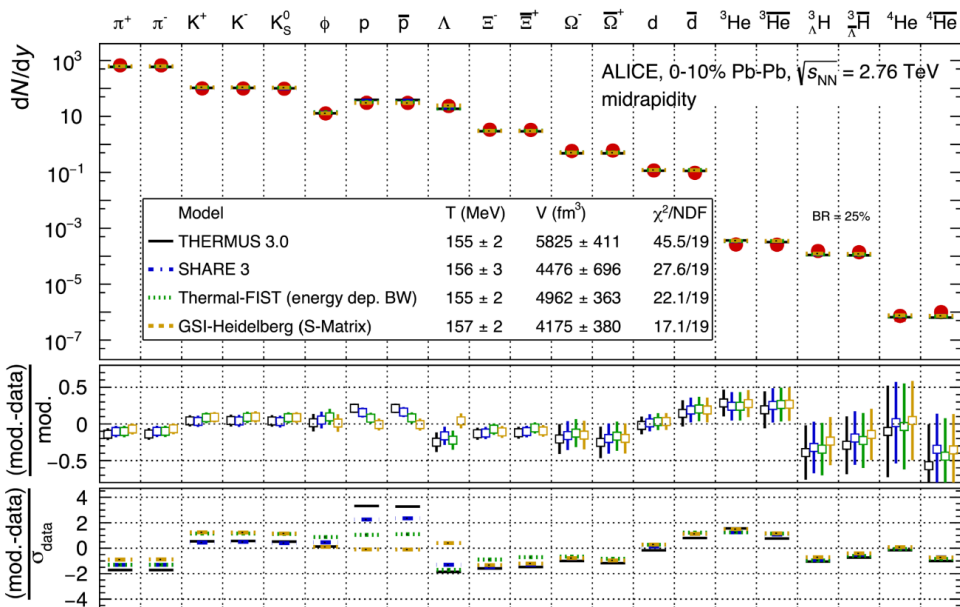


ALI-PUB-522154

ALICE: PLB 827 (2022) 136986

- $D_s/D^0$  enhanced in Pb-Pb wrt pp
- strangeness chemistry also affects HF!
- chemical equilibration?

# Chemical equilibrium in light-flavour sector

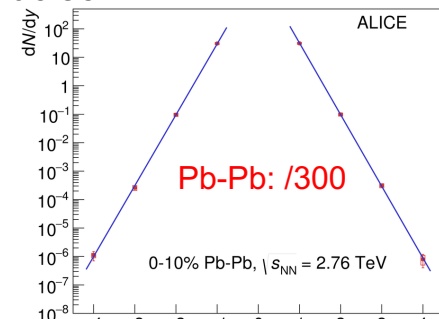
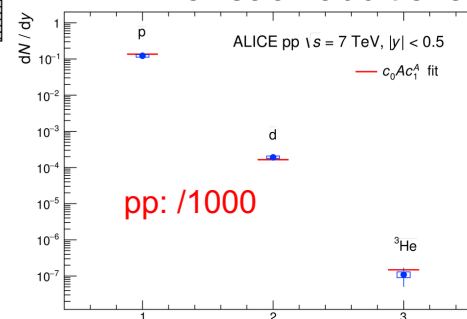


- AA light hadron yields ~ at chem. equilibrium
  - very different from pp!
  - strangeness enhancement!
  - looking at the fine print: some deviations
    - a few  $\sigma$ :  $K^*$ ,  $p/\Lambda/\Xi$
    - key window on interactions in hadronic final state
- ... even for nuclei, hypernuclei
  - in spite of very low binding energy!
  - substantial enhancement wrt pp
  - AA is a (hyper-)nuclei factory
  - for each additional nucleon:

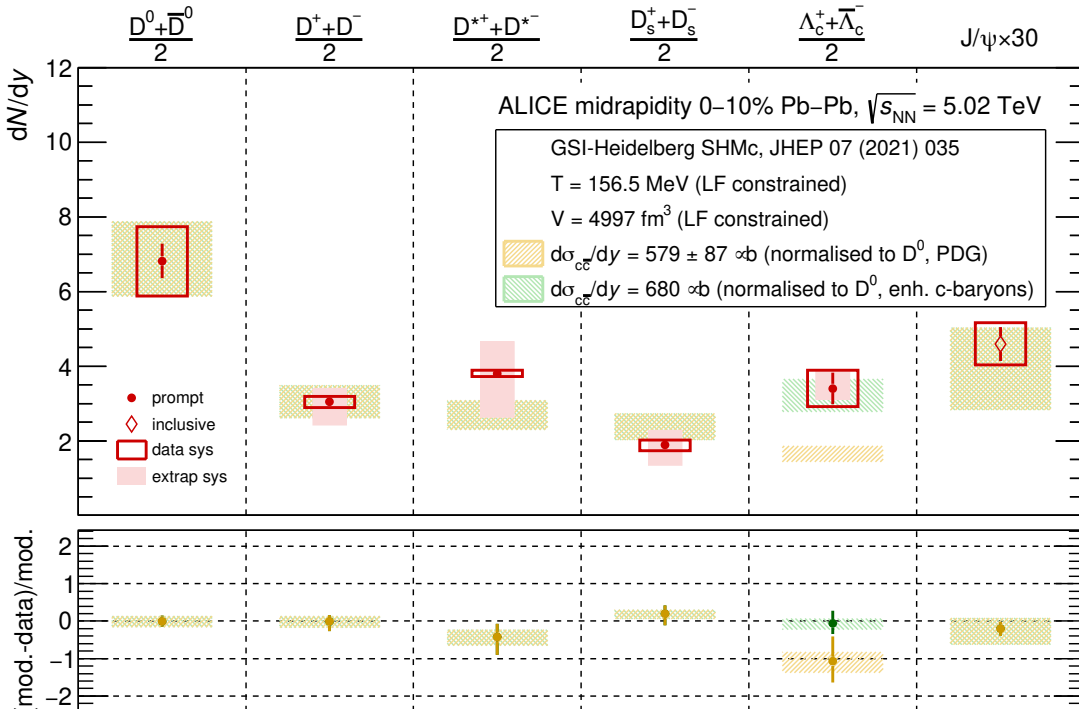
$T_{\text{chem}} \approx T_C \approx 156 \text{ MeV}$

arXiv:2211.04384

→ hadronisation very close to the phase transition

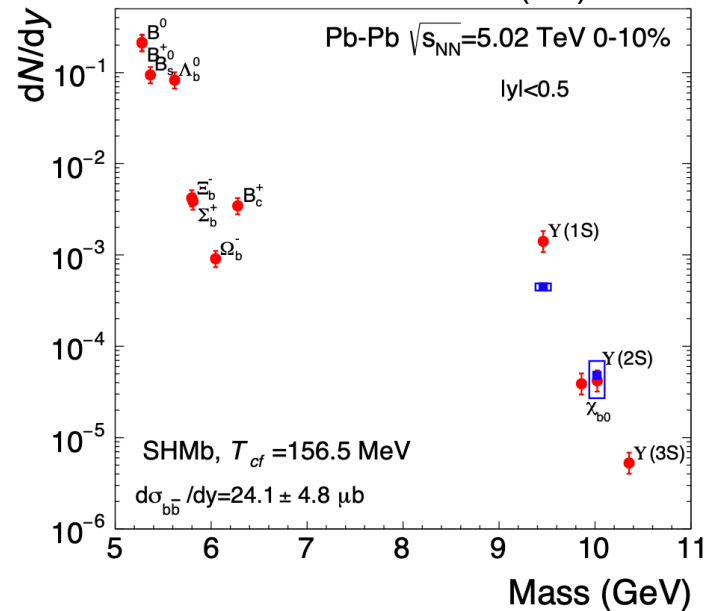


# Chemical equilibrium in HF sector?



ALI-DER-500416

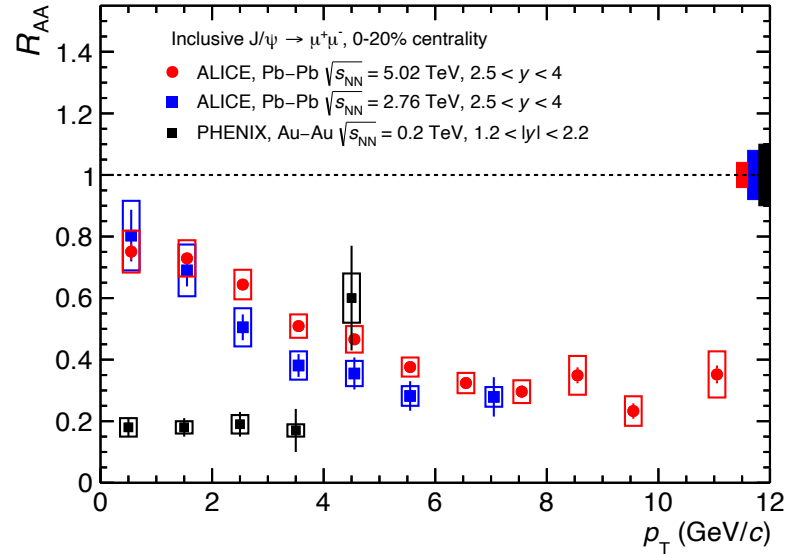
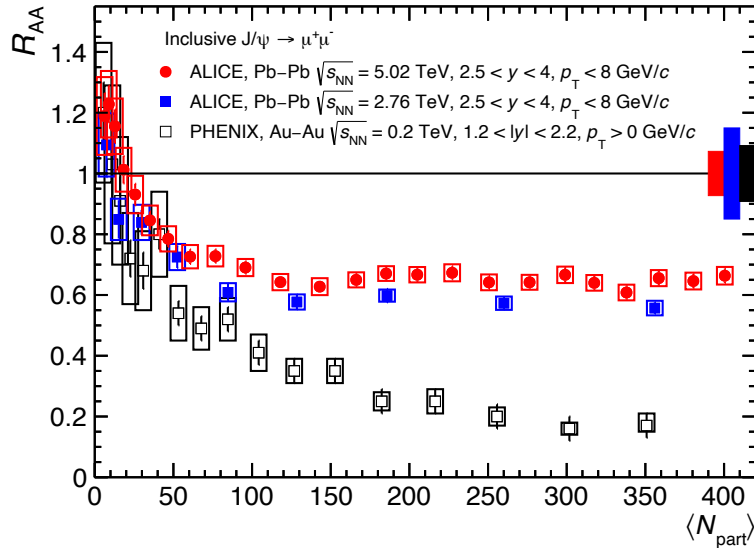
- for charm, looks like...
  - not for absolute  $\sigma$ , of course...
  - $\gamma_c \sim 30$  for 0-10%
- and, once again, b is different...
  - SHMb  $\sim 3 \times$  data for  $\Upsilon(1S)$





# New regime for $J/\psi$ production at the LHC

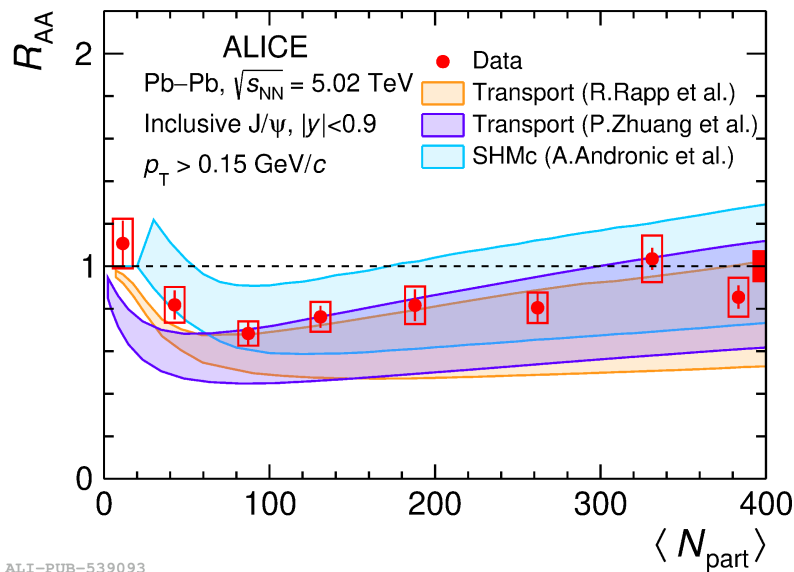
- complete change of behaviour from SPS/RHIC



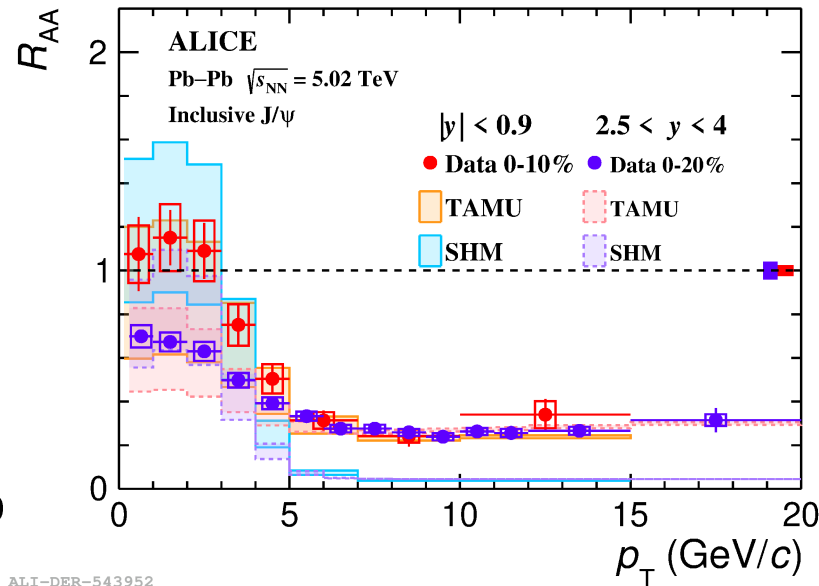
- in both the centrality and the  $p_T$  dependence
- evidence for production by recombination of exogamous  $c\bar{c}$  pairs!

# $J/\psi$ : central vs forward rapidity

arXiv:2303.13361



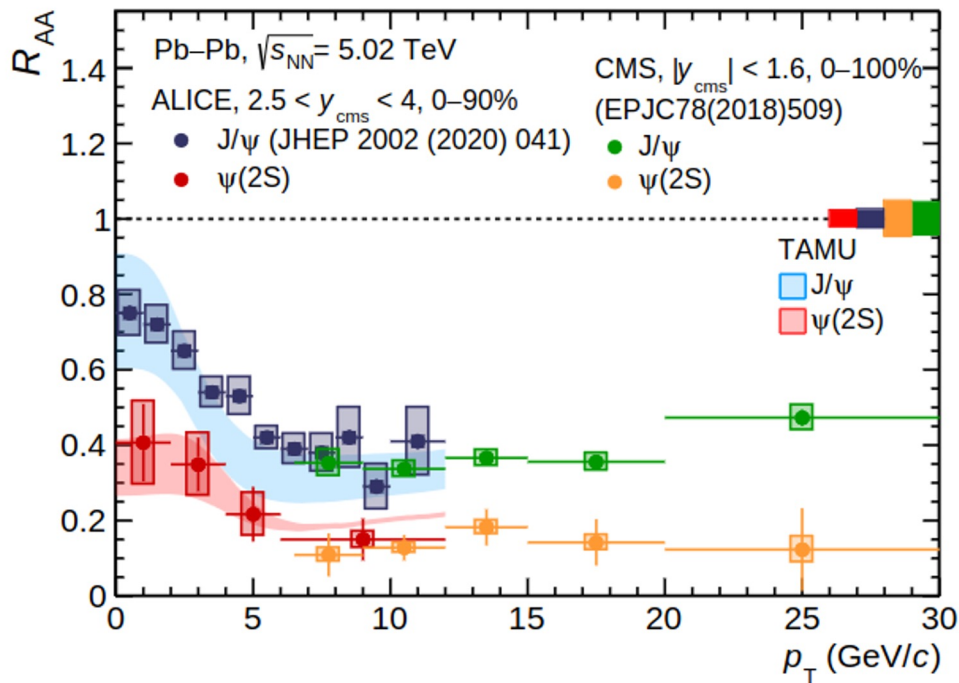
ALI-PUB-539093



ALI-DER-543952

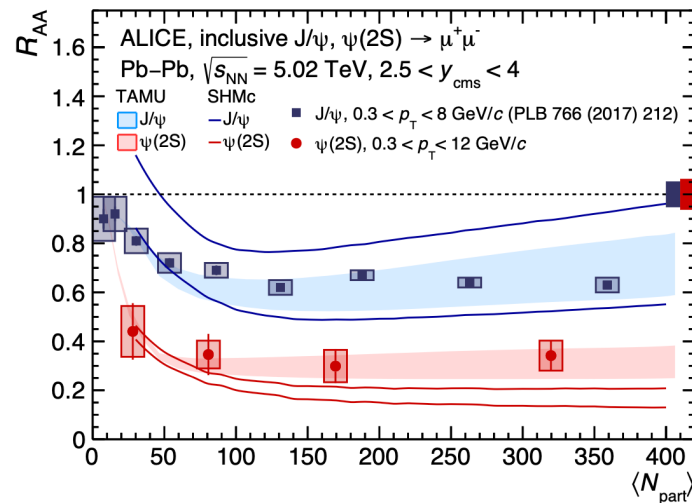
- more recombination expected at central than at forward rapidity
  - at low  $p_T$ !

# $\psi(2S)$ vs $J/\psi$

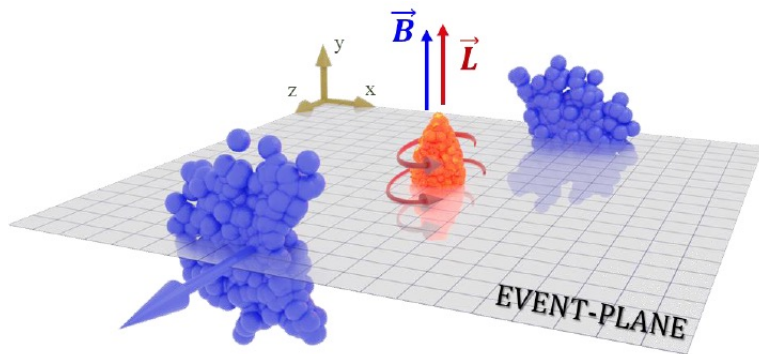


arXiv:2210.08893

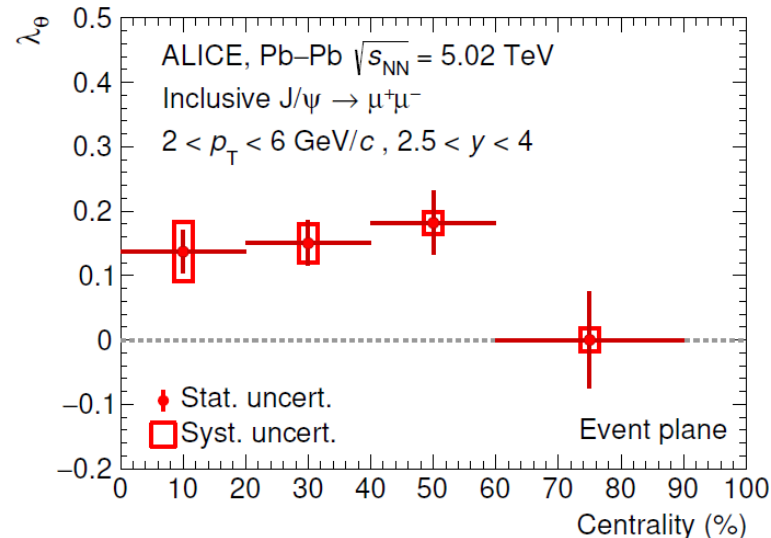
- more suppressed than  $J/\psi$ 
  - looser binding
- evidence for recombination at low  $p_T$
- statistical hadronisation undershoots?
  - for central collisions



# $J/\psi$ polarisation wrt event plane



- significant B and L in early collision stages
- polarisation in event plane (EP) frame
- amount sensitive to medium properties
- theoretical modelling still in early stages...

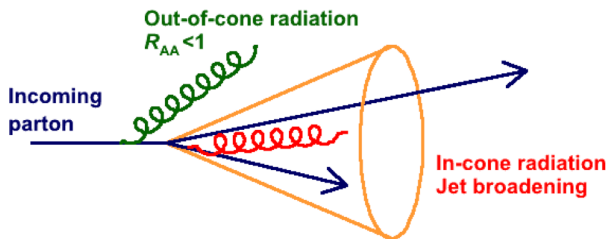


ALI-PUB-521052

- significant polarisation observed ( $3.5 \sigma$ )

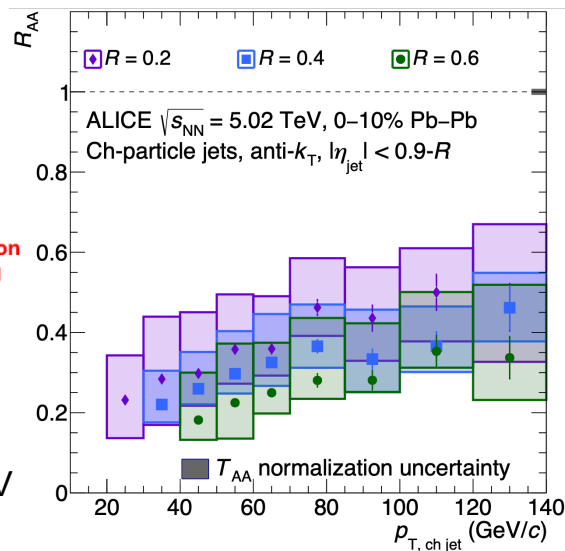
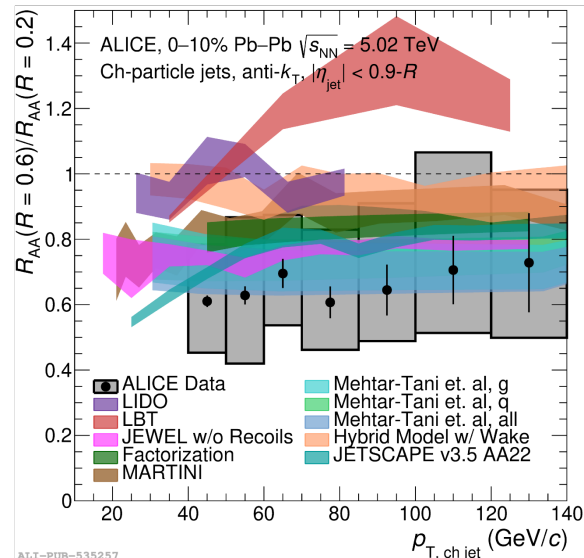
# Jet radius dependence of energy loss

- in- vs out-of-cone



- machine-learning approach
  - background subtraction!
  - R up to 0.6 @  $p_T = 50$  GeV

Nuclear modification factor

 $R$ -dependence: ratio  $R=0.6/R=0.2$ 

- wider  $\rightarrow$  more suppressed (easier to quench softer components?)

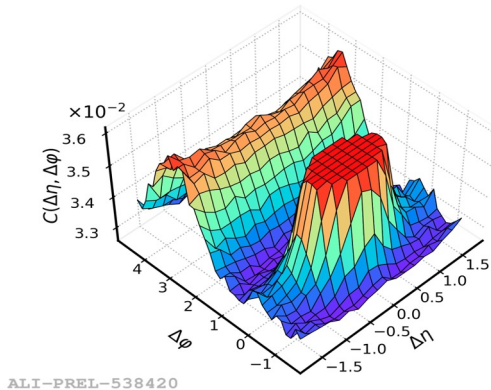
arXiv:2303.00592



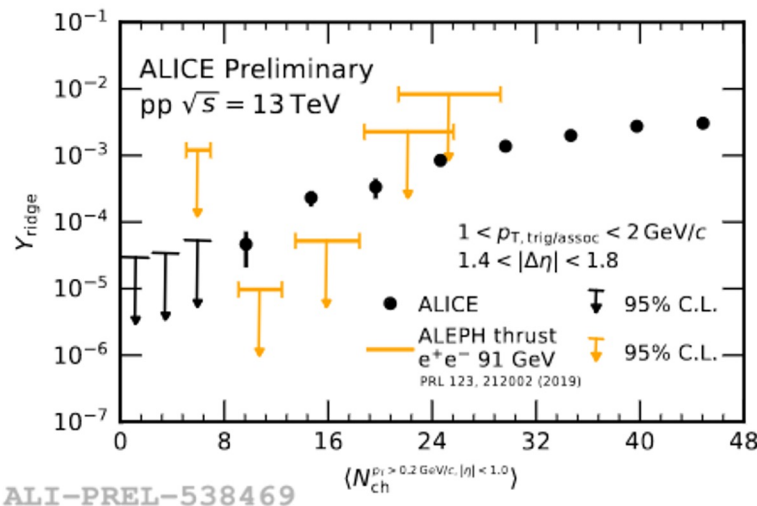
# Collectivity in small systems

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# pp “ridge” correlations extending to low multiplicities



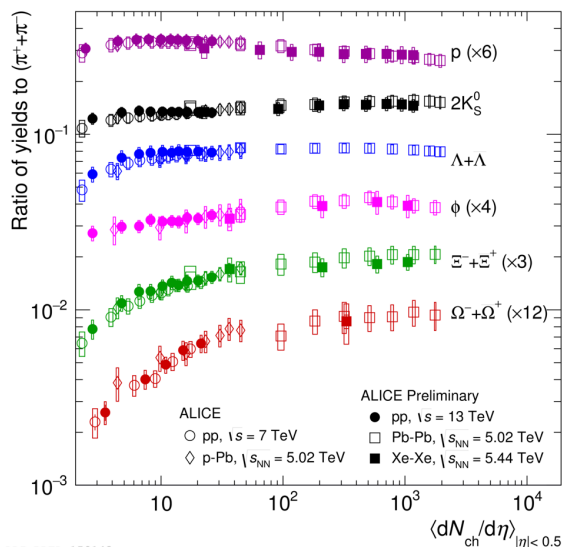
- origin yet unknown
- low-mult “non-flow” component?
  - significant biases
  - notoriously hard to control...



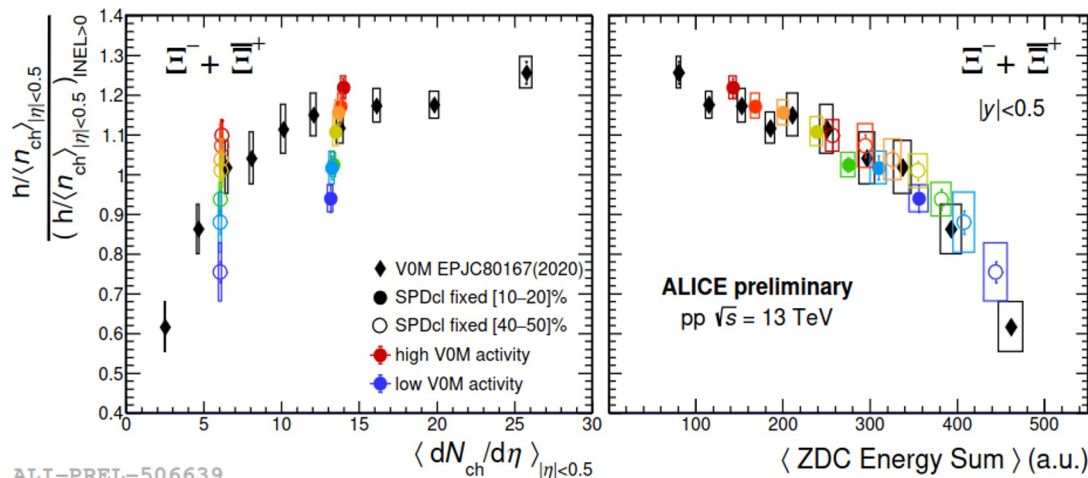
- interesting to compare to e+e-
- correlations wrt thrust axis (ALEPH)
  - similar multiplicities
  - no evidence for ridge

# Strangeness production vs effective energy

- s enhancement vs system size
  - controlled by event multiplicity?



- study behaviour with “effective energy”
  - $E_{\text{eff}} = \sqrt{s} - E_{\text{leading}}$
  - $E_{\text{leading}}$  estimated from Zero Degree Calorimeters
- no significant  $E_{\text{eff}}$  dependence
- supports “final state” interpretation



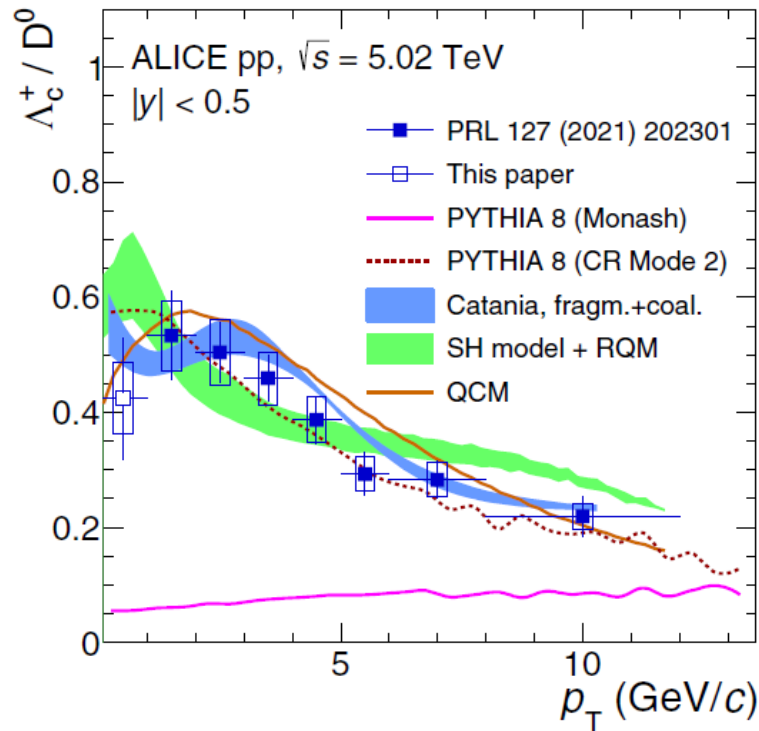




# Hadronisation

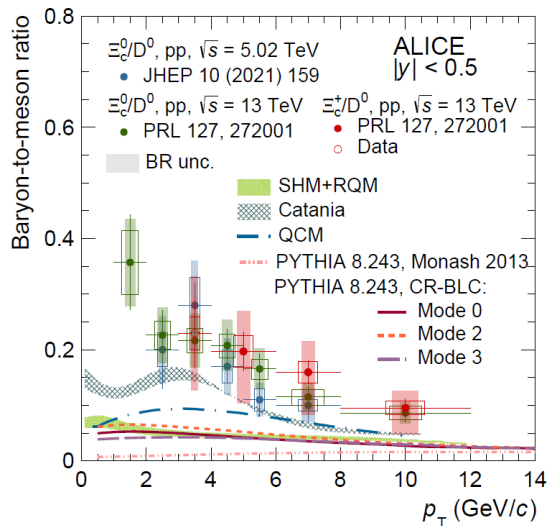
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# Baryon anomalies in the charm sector

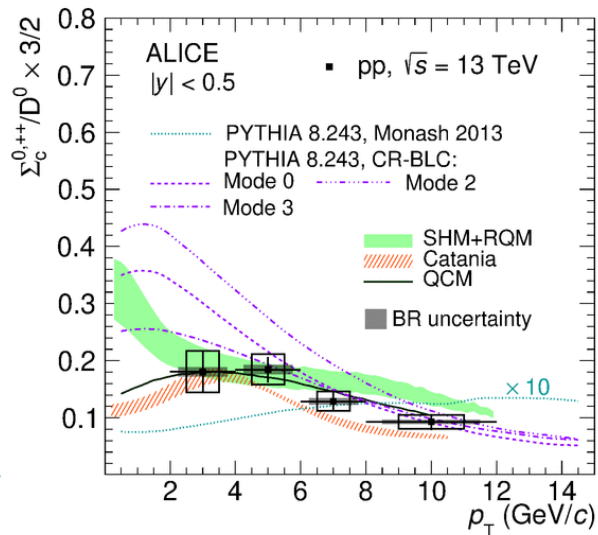


- $\Lambda_c$  down to  $p_T = 0$  in pp (first at LHC)
- $\Lambda_c/D_0$  significantly enhanced wrt  $e^+e^-$
- new mechanisms at play in pp
  - colour reconnection?
  - coalescence?
  - feed-down from higher mass states?

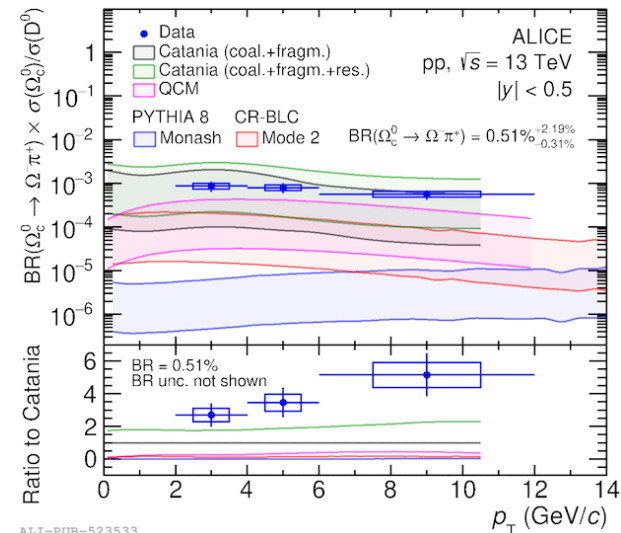
# Baryon anomalies in the charm sector



PRL 127 (2021) 272001



PRL 128 (2022) 012001

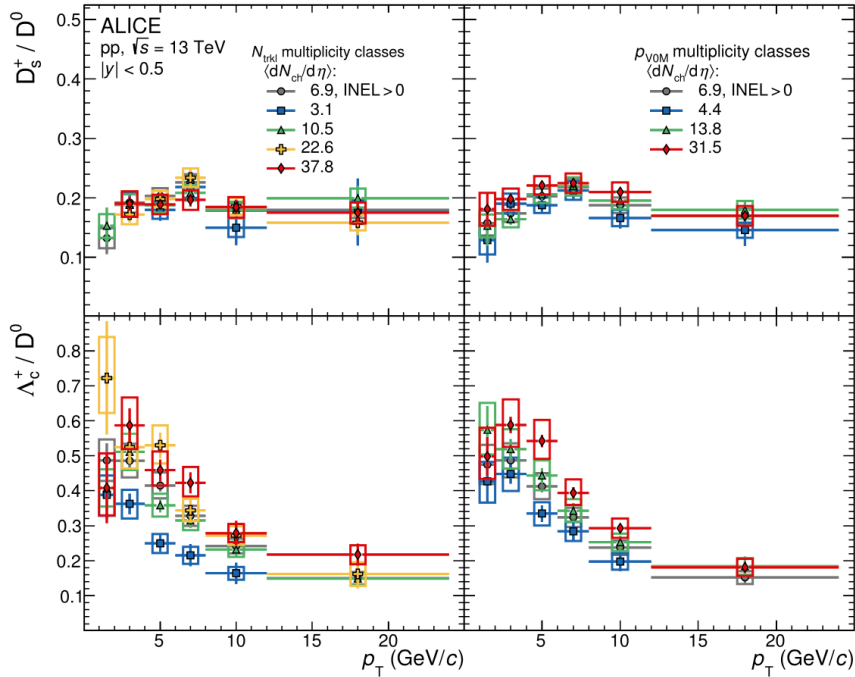


ALI-PUB-523533

arXiv:2205.13993

- currently up to  $\Omega_c$  (enhanced by orders of magnitude!)

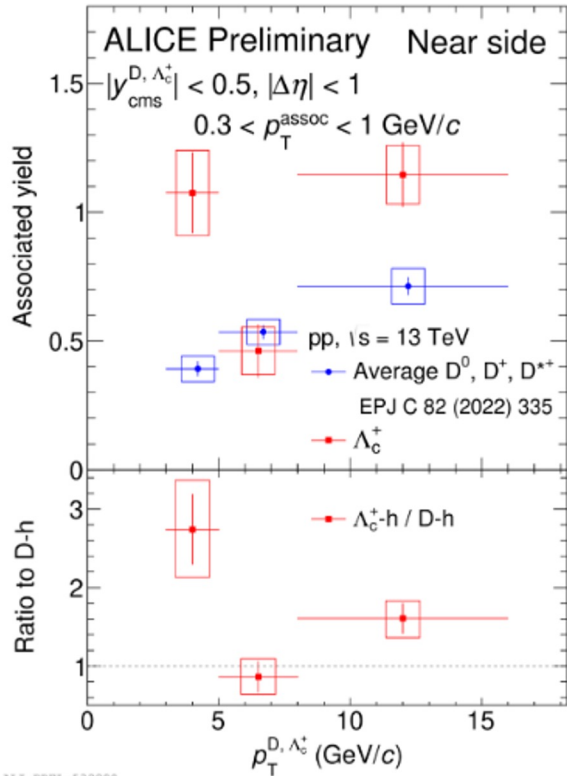
# ... but multiplicity dependence in $p_T$ spectra



- evolution with multiplicity for  $\Lambda_c/D$ 
  - (not so much for  $D_s/D$ ...)
  - (wrt neither to cent nor to fwd mult'y)

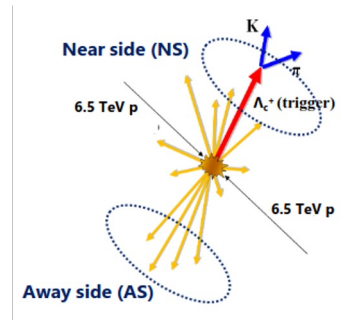
ALICE: PLB 829 (2022) 137065

# $\Lambda_c$ - hadron correlations



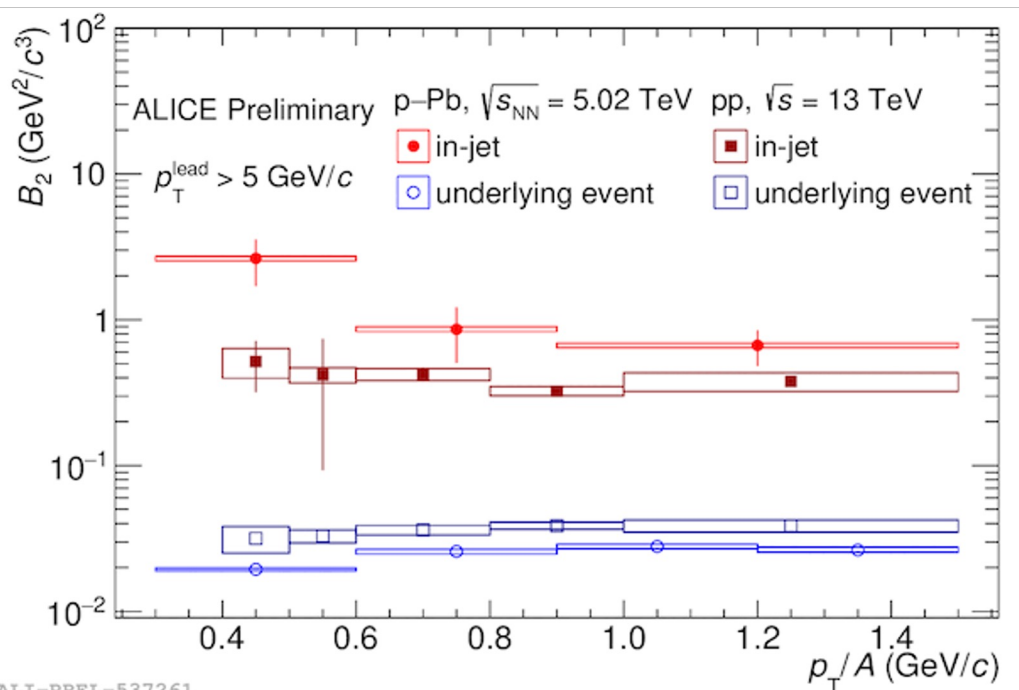
ALI-PREL-539990

- new preliminary study
- associated yield correlated with  $\Lambda_c$  and D
- larger near-side yield for  $\Lambda_c$  ?
- connected to softer fragmentation for c baryons?



# Deuteron production in and out of jets

- coalescence probability is significantly enhanced inside jets!



arXiv:2211.15204

ALI-PREL-537261

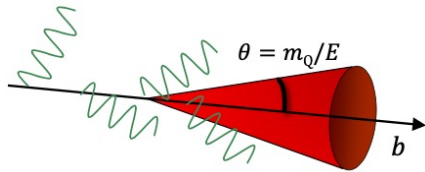


# QCD and hadronic physics

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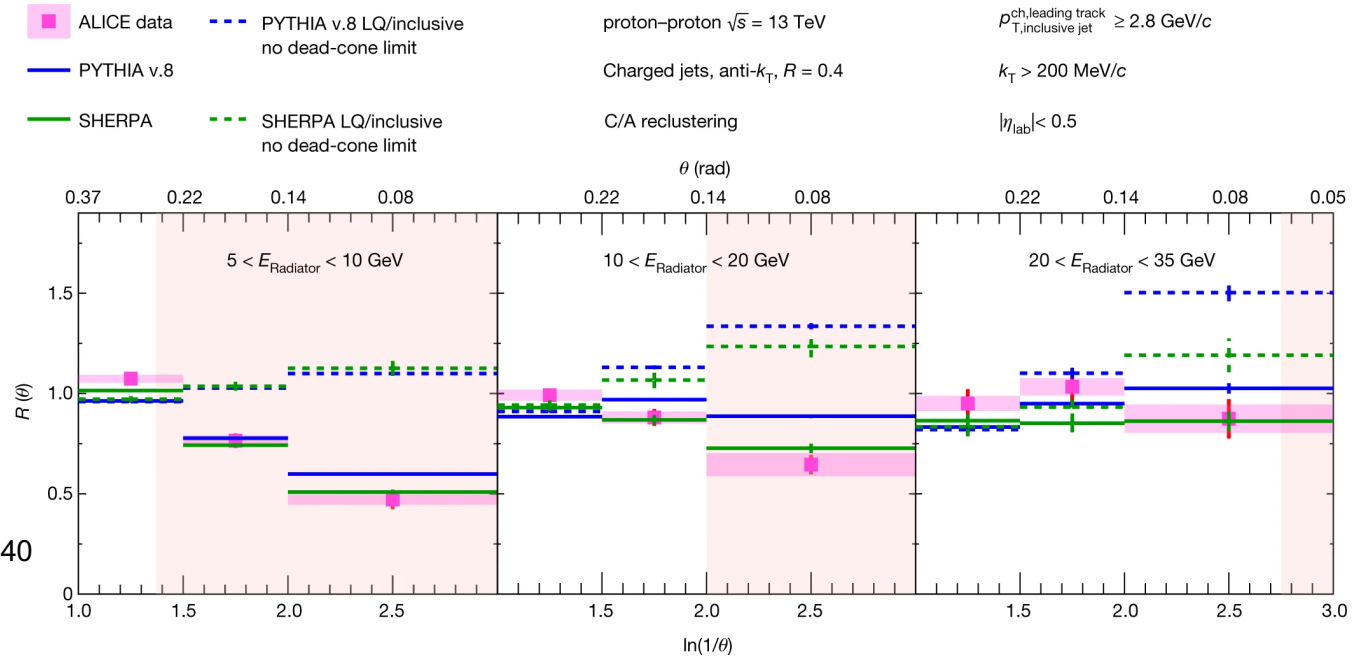
# Direct observation of the dead-cone effect

- suppression of gluon radiation at small angles ( $\theta < m_Q/E$ ) for massive quarks



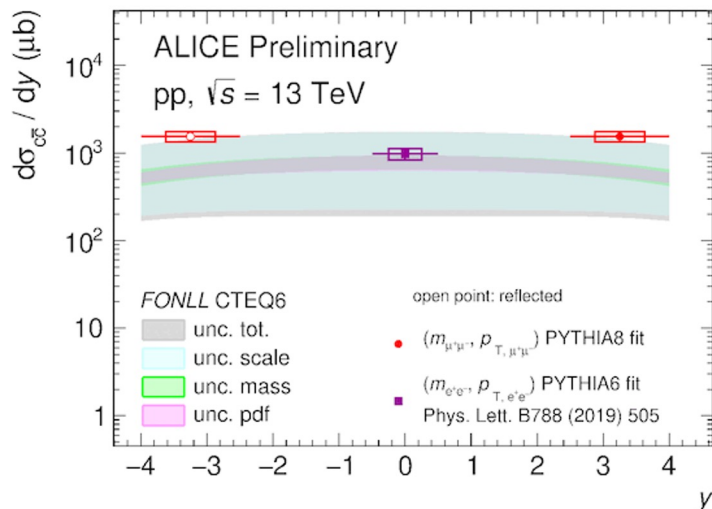
pink: dead-cone  
for  $m_c = 1.275 \text{ GeV}/c^2$

ALICE, Nature 605 (2022) 7910, 440

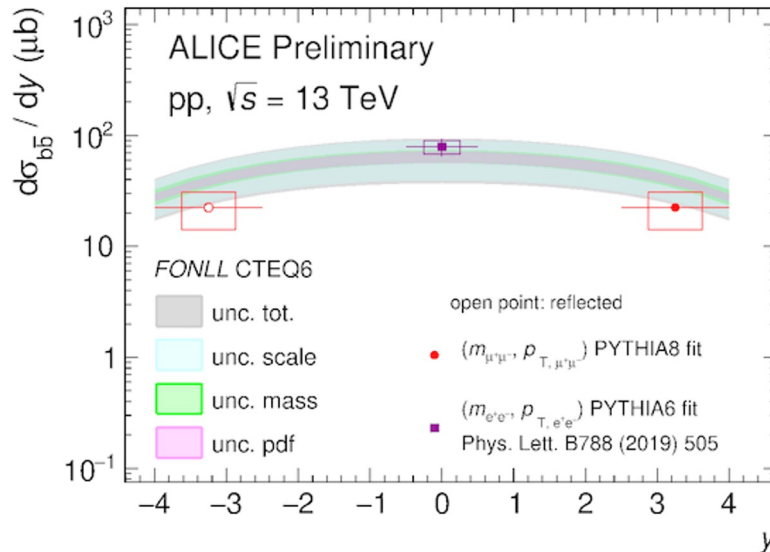




# Separating charm and beauty at forward $y$



ALI-PREL-538716

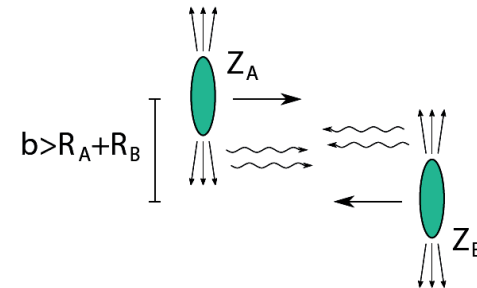
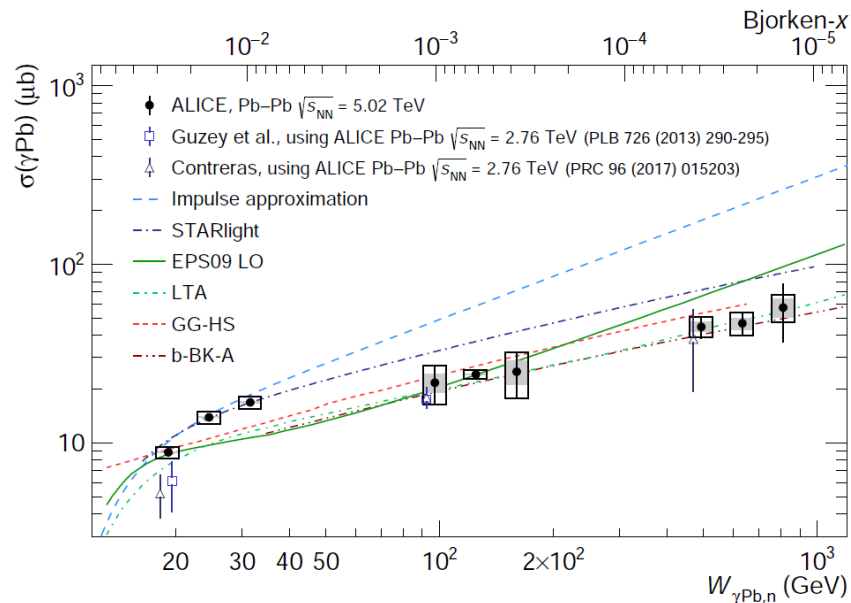


ALI-PREL-538708

- combined fit of c + b components in high-mass dimuon distributions
  - using PYTHIA 8 for now, POWHEG (+ DY) ongoing

# Probing gluon PDFs in nuclei

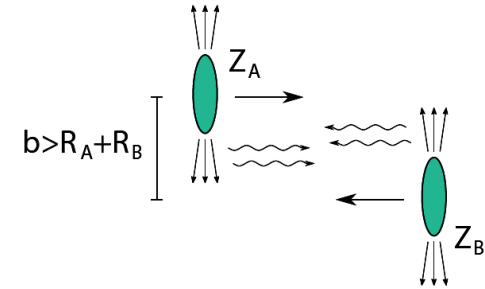
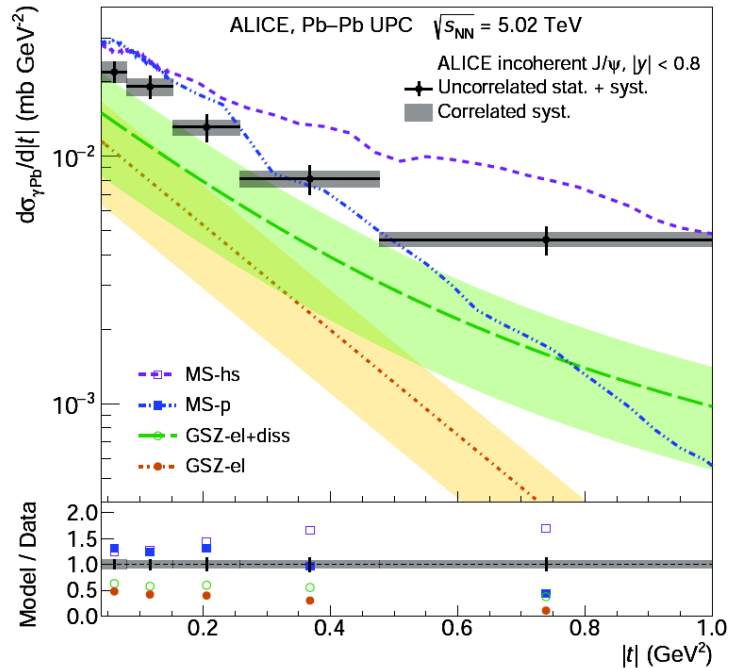
- ultraperipheral collisions: use nucleus as photon beam
- coherent  $J/\psi$  production (vs  $\gamma$ -Pb energy)



- constrain nuclear PDF down to  $x \sim 10^{-5}$
- sensitive to shadowing, saturation
- behaviour at 25-30 GeV?

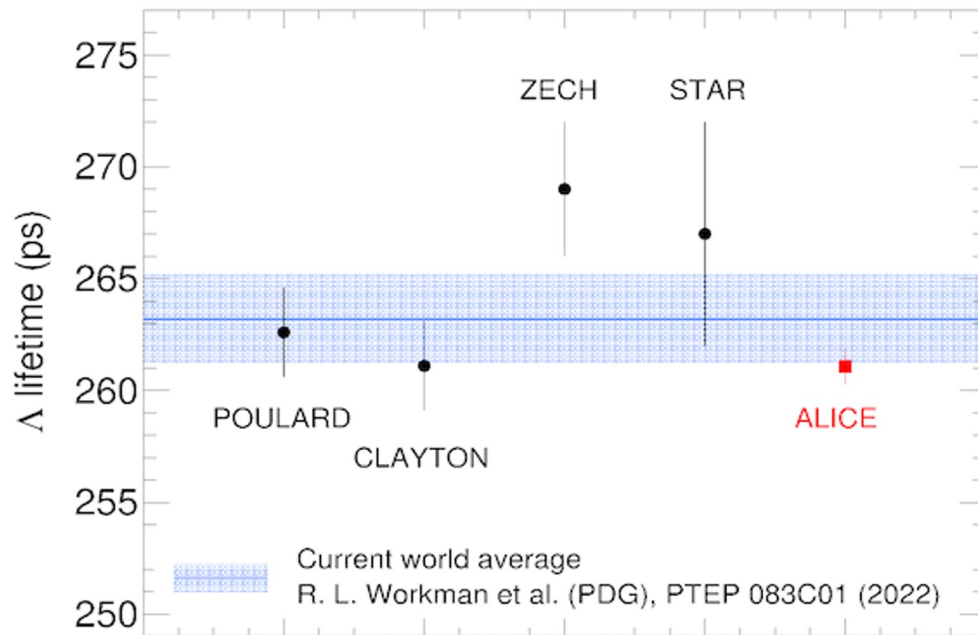
# Probing gluon PDFs in nuclei

- first measurement of incoherent  $J/\psi$  production

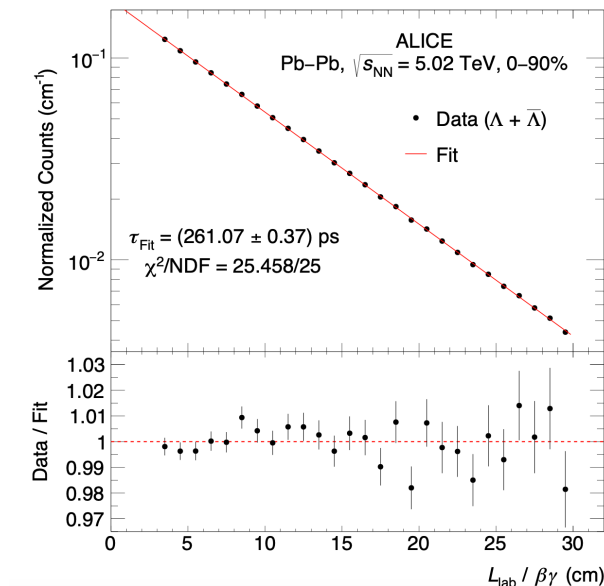


- sensitive to structures at subnuclear scale
- hard for models to catch both  $\sigma$  and  $|t|$  dep

# New measurement of $\Lambda$ lifetime



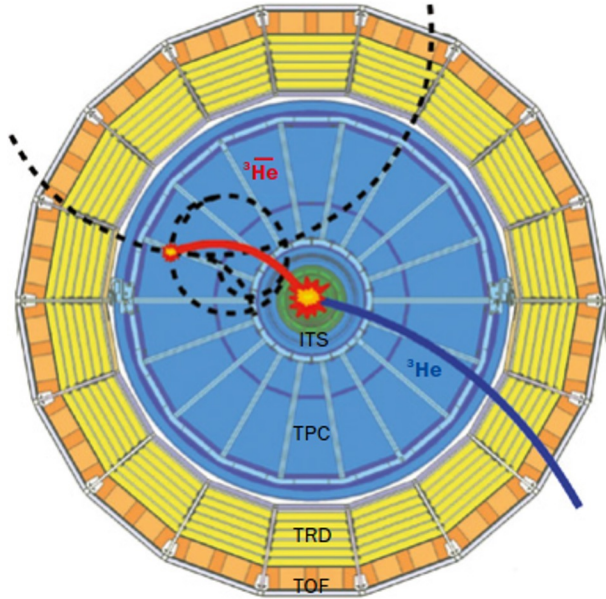
- most precise measurement so far



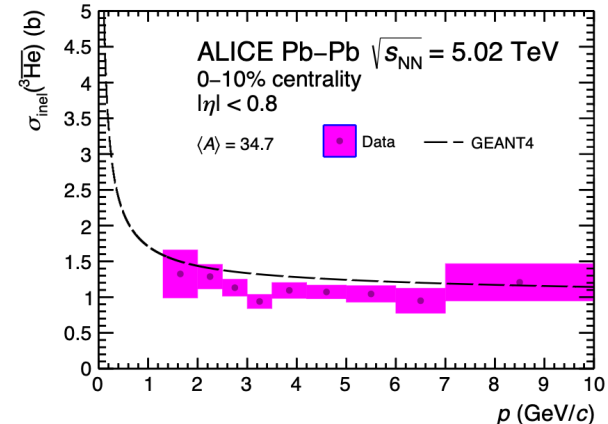
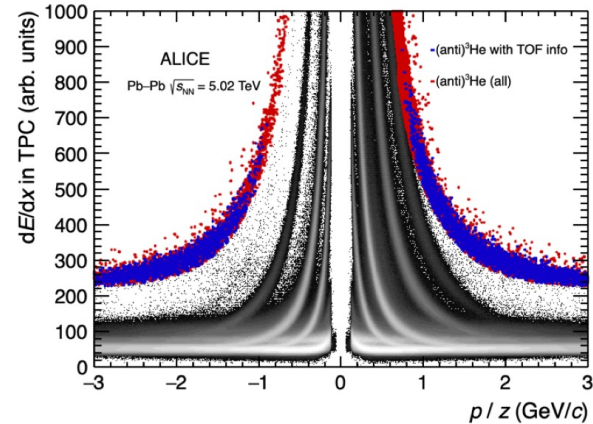
arXiv:2303.00606

# Measurement of absorption of ${}^3\overline{\text{He}}$ in matter

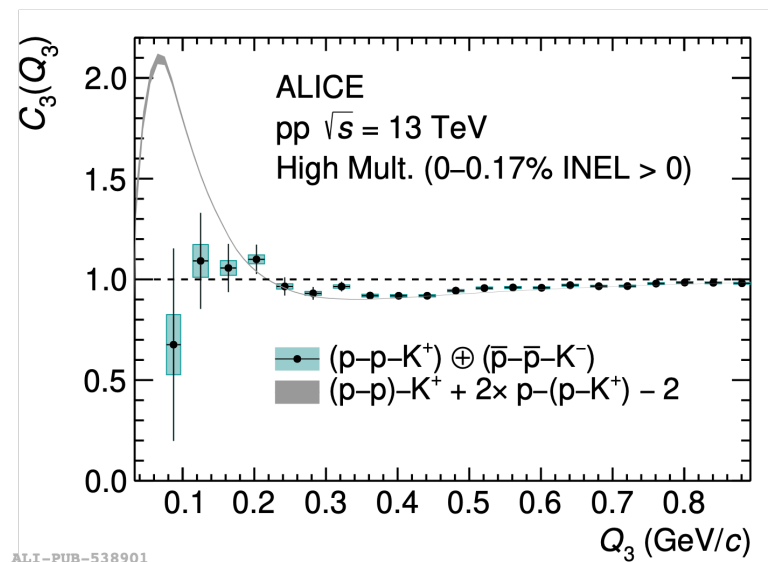
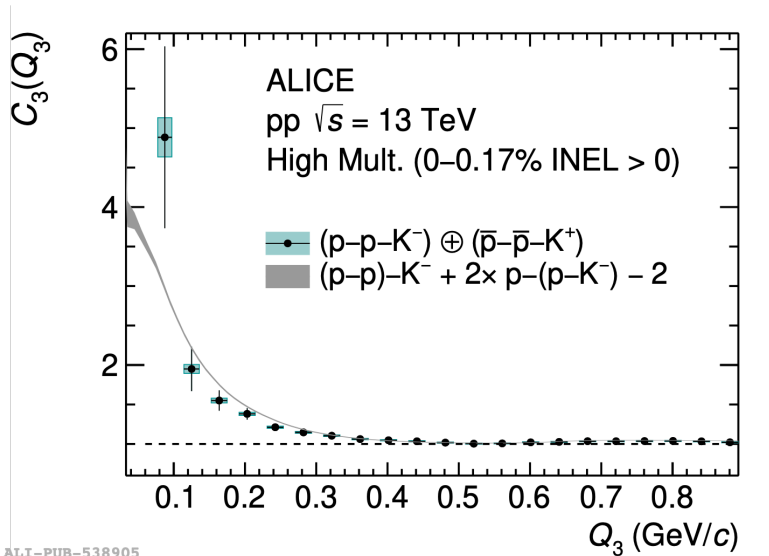
- using ALICE apparatus as target



→ input for modelling of propagation in galaxy

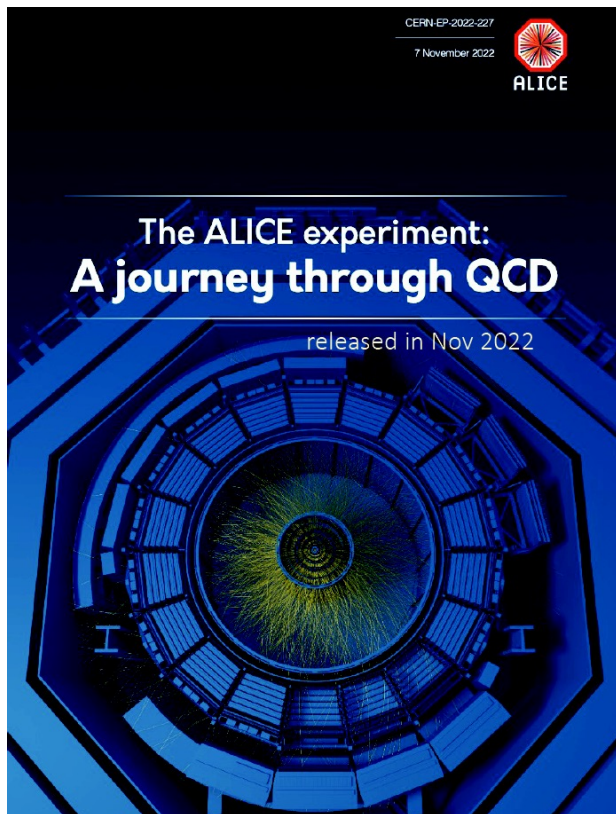


# Femtosceny: 3-body potential (ppK)



- first direct study of ppK potential
- no evidence of true 3-body force (correlation fully explained by 2-body forces)

# A journey through QCD



- 326-page assessment of ALICE results so far
  - bulk properties and thermodynamics of the QGP
  - QGP dynamics and evolution
  - interactions of partons with the QGP medium
  - hadronization mechanisms in the QGP medium
  - electromagnetic properties and phenomena
  - initial state
  - QGP-like effects in small systems
  - and many more...

arXiv:2211.04384



# ... il viaggio continua...

