From soft to hard observables: recent experimental results from ALICE

ALICE

Istituto Nazionale di Fisica Nucleare

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on behalf of the ALICE Collaboration
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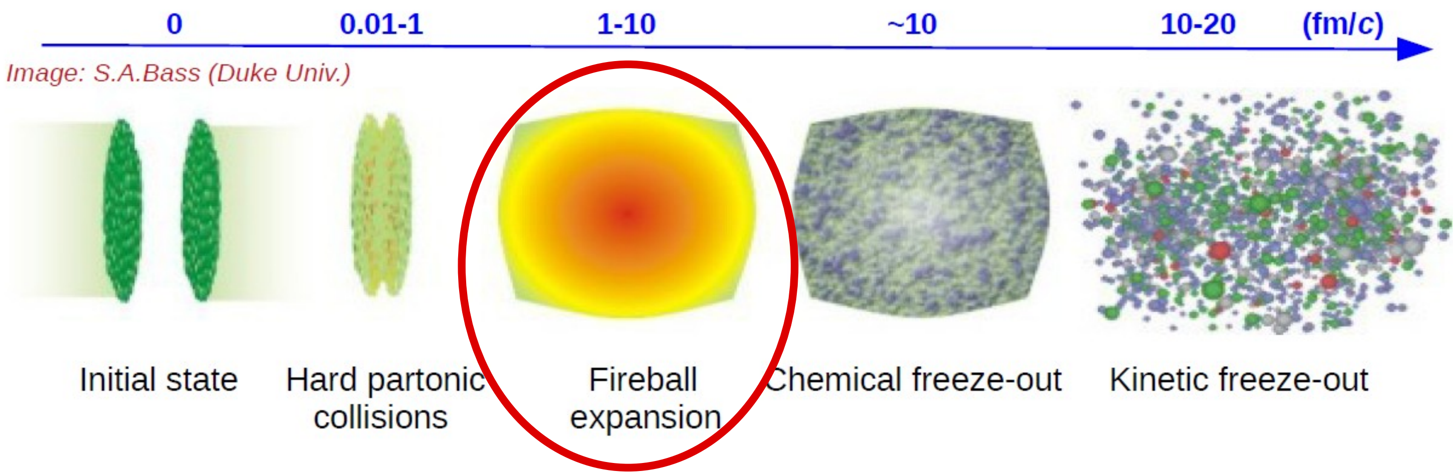
The physics of ALICE



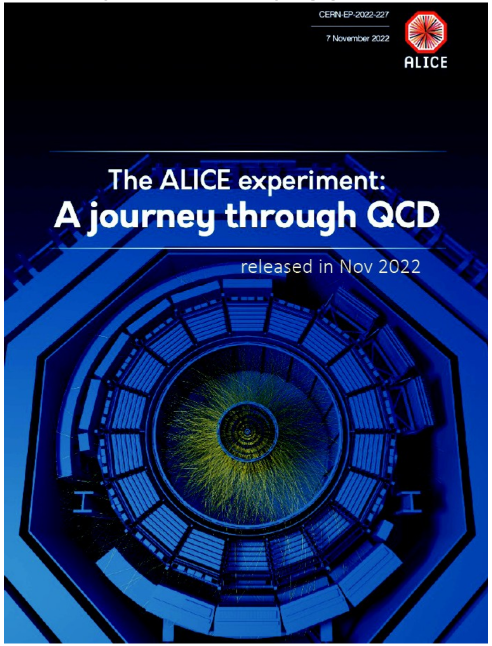
Quark-gluon plasma (QGP): deconfined state of strongly-interacting QCD matter

- ✔ Main goal of the ALICE Physics program: study the properties and the evolution of a heavy-ion collision, with a particular attention to the **QGP** state
- ✔ Rich program of measurements in **small systems**, namely **pp** and **p-Pb** collisions
  - **reference** measurements for interpreting heavy-ion results (e.g. vacuum production, Cold Nuclear Matter effects)
  - characterization of **high-multiplicity events** and search for **collectivity** in small systems

The physics of ALICE

- ✔ Very broad and multi-disciplinary physics program
- ✔ Only a selection of results shown in the following slides !
- ✔ A more comprehensive summary of ALICE highlights in Run 1 & 2 available in the ALICE review paper

arXiv:2211.04384



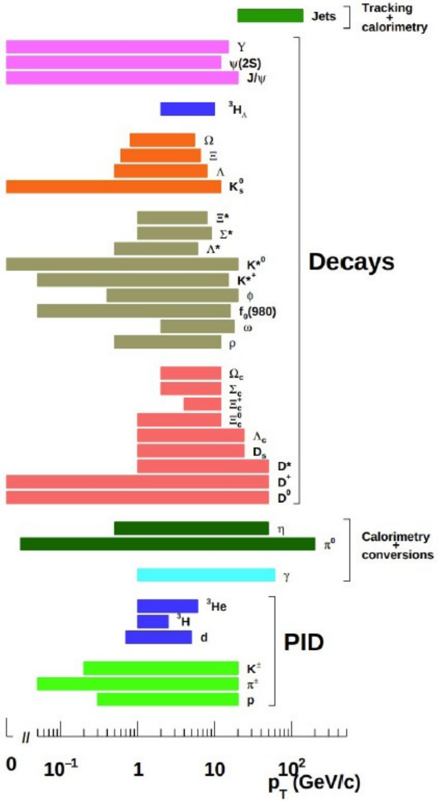


Image: S.
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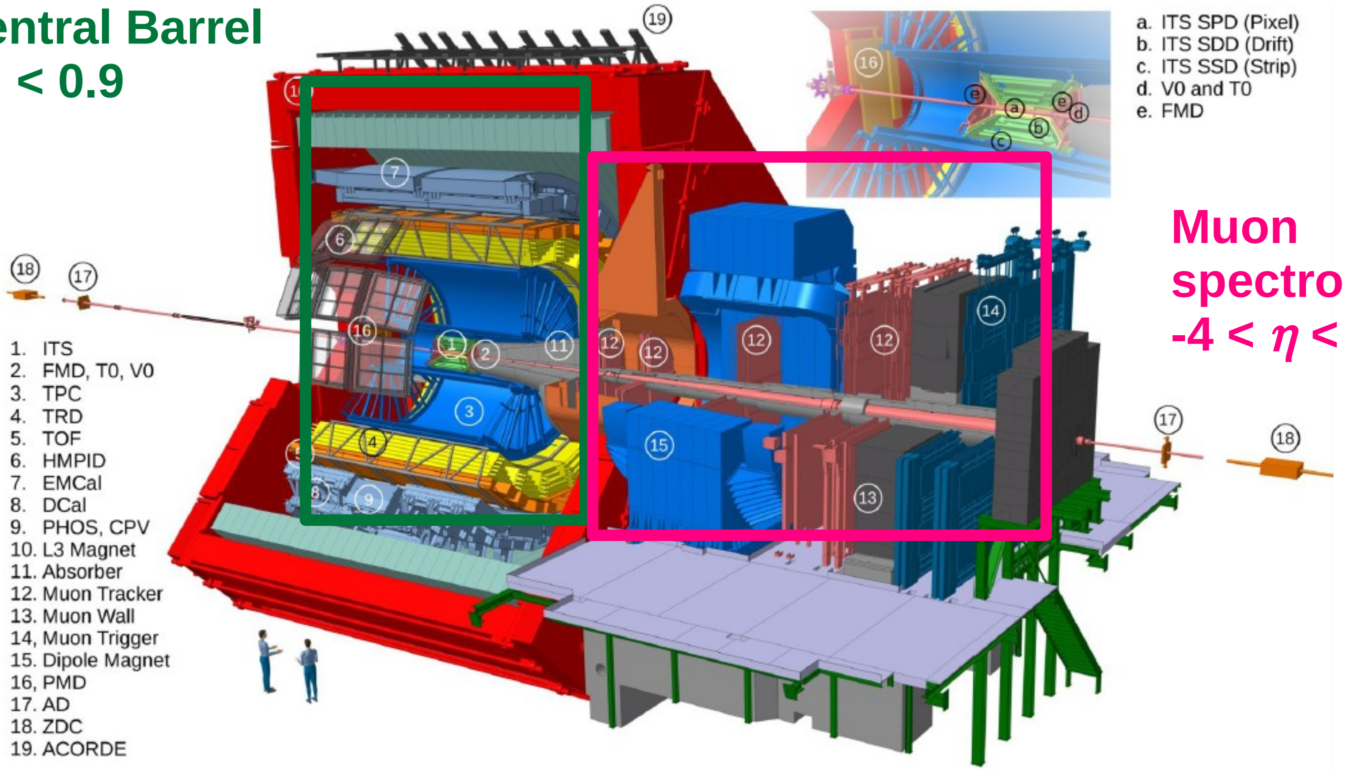
The ALICE detector in Run 1 & Run 2

Central Barrel
$|\eta| < 0.9$

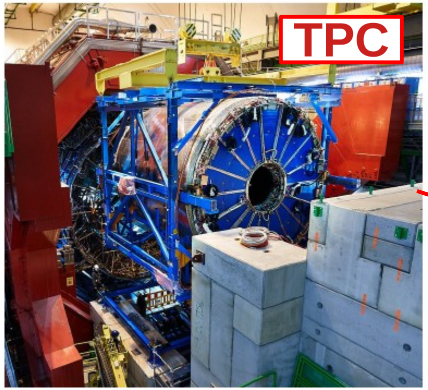


Muon spectrometer
$-4 < \eta < -2.5$

- ✔ Designed to study the QGP and heavy-ion collisions
- ✔ Excellent tracking, vertexing and PID up to very high multiplicities and low transverse momentum

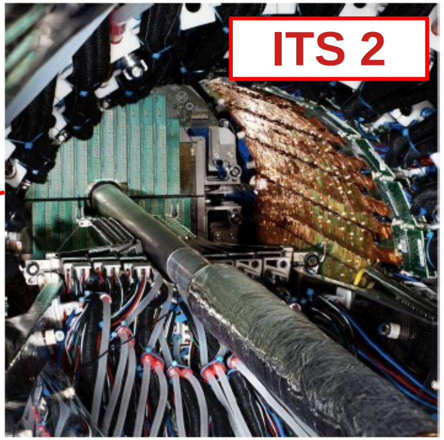
The ALICE detector in Run 3

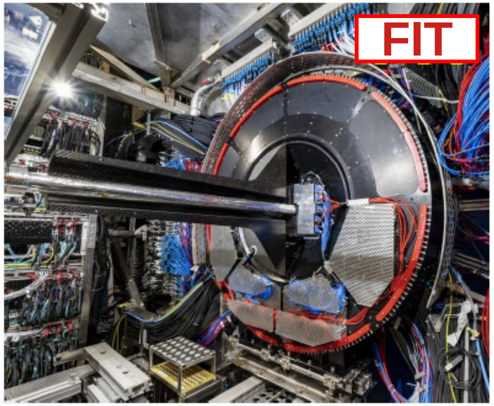
ALICE upgrades: arXiv:2302.01238
ITS: NIM 1032(2022)166632
TPC: JINST 16 P03022 (2021)
MFT: CDS link
FIT: NIM 1039 (2022) 167021

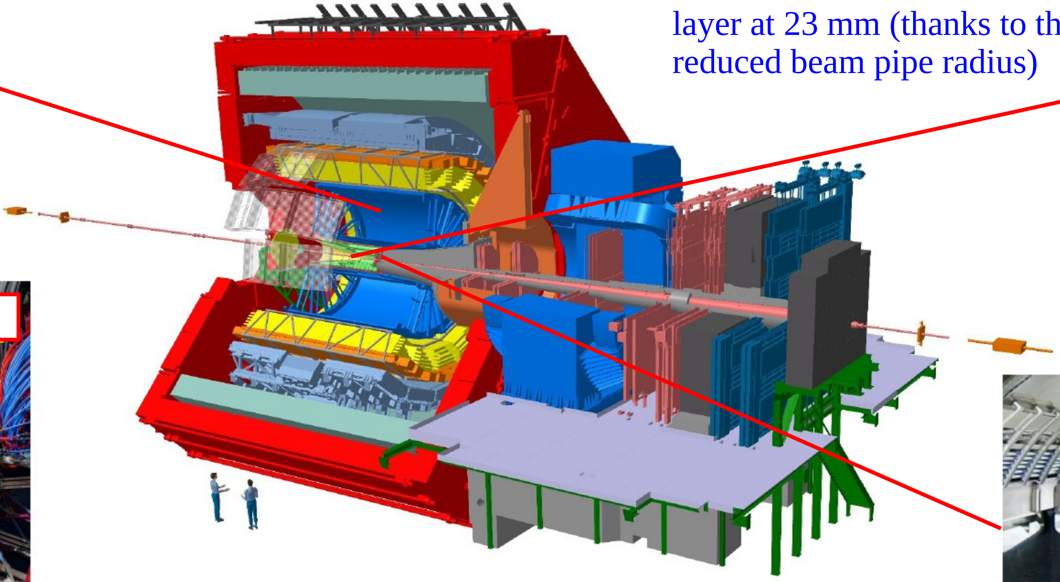


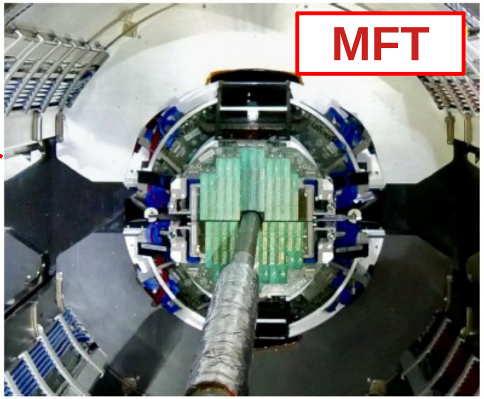
Upgraded Time Projection Chamber: new readout chambers with Gas Electron Multipliers (GEM)

Upgraded Inner tracking system: 7 layers (10 m^2 silicon tracker) based on MAPS. First detection layer at 23 mm (thanks to the reduced beam pipe radius)





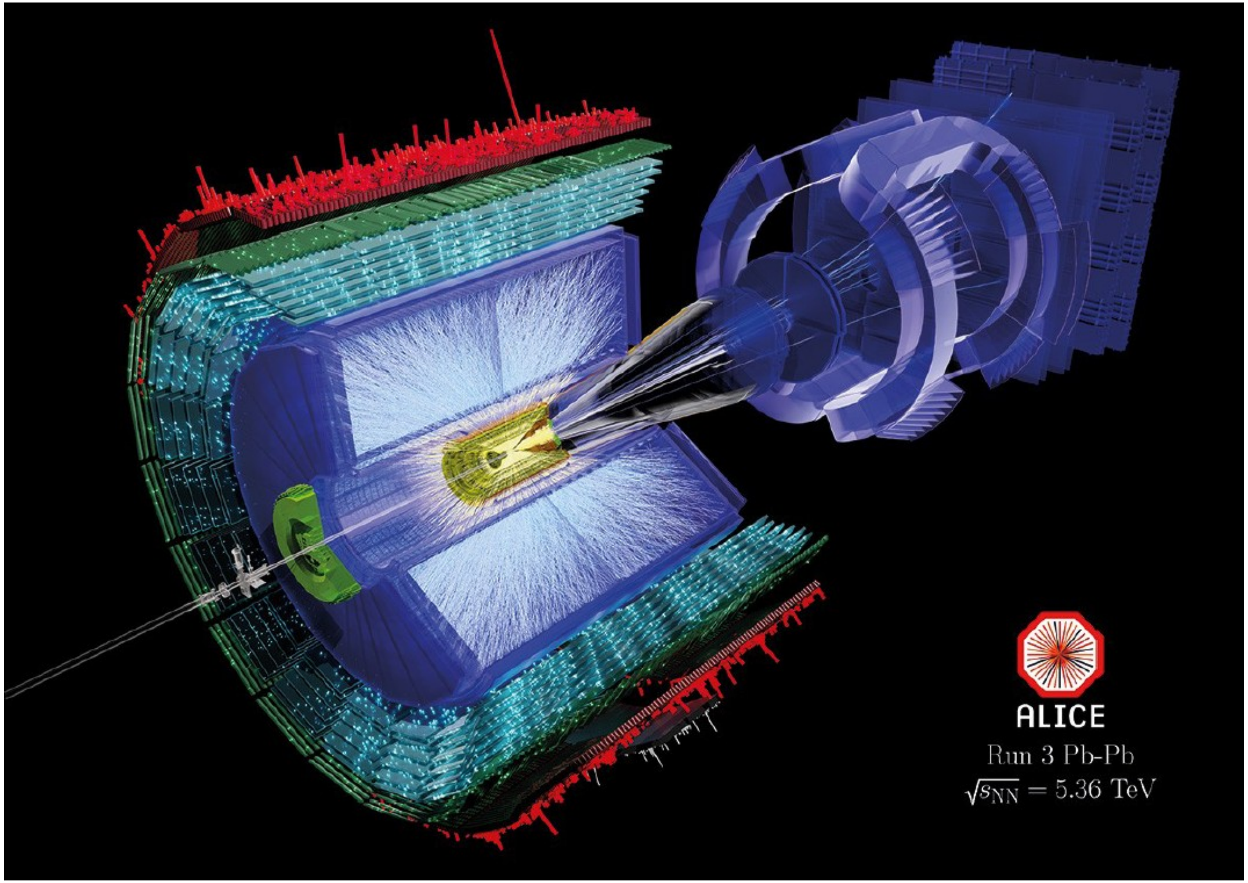




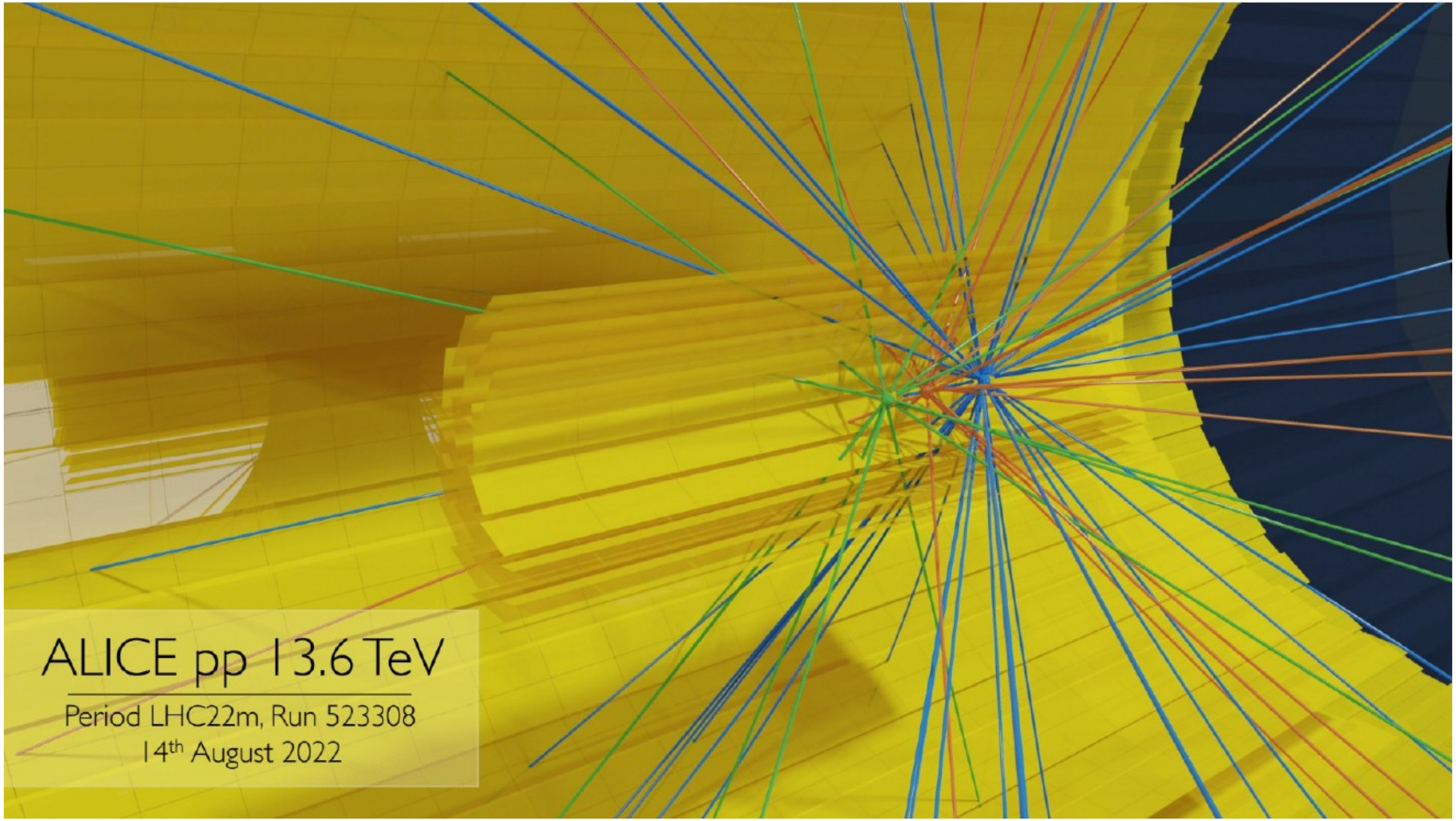
New Forward Muon Tracker: 5 planes of MAPS at forward rapidity, forward vertexing and tracking for muons

New Fast Interaction Trigger: interaction trigger, online luminometer, forward multiplicity

ALICE Run 3 data taking… a glimpse

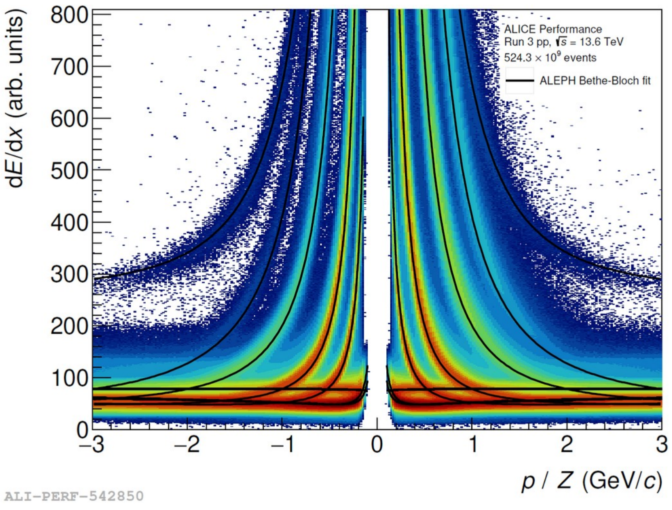


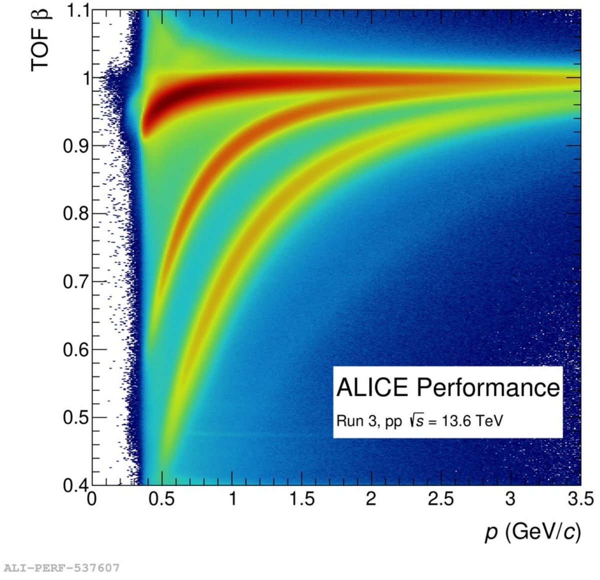
ALICE Run 3 data taking…
a glimpse

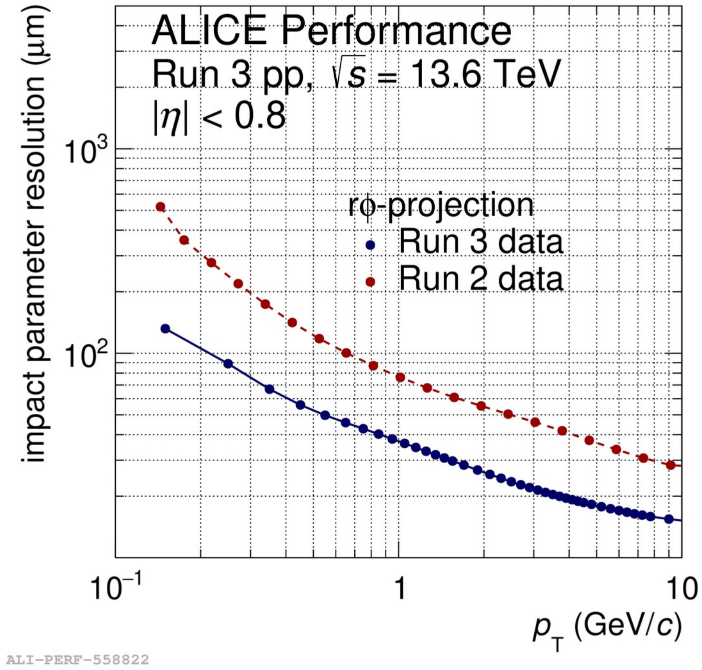


ALICE performance in Run 3

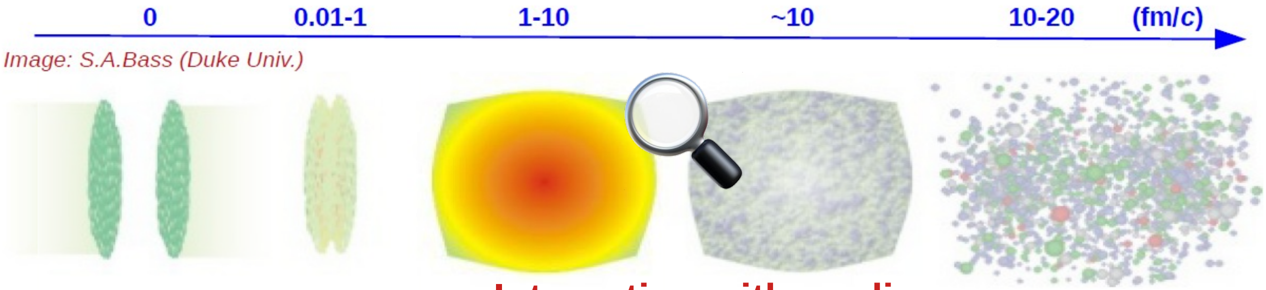
- ✔ Continuous readout
  - **500 kHz in pp** (software trigger for selecting rare events)
  - **goal: 50 kHz in Pb-Pb** (x 50 compared to Run 2)
  - between 500 and 1000 more events compared to Run 2!
- ✔ **Excellent performance of the detector in Run 3!**







The physics of ALICE



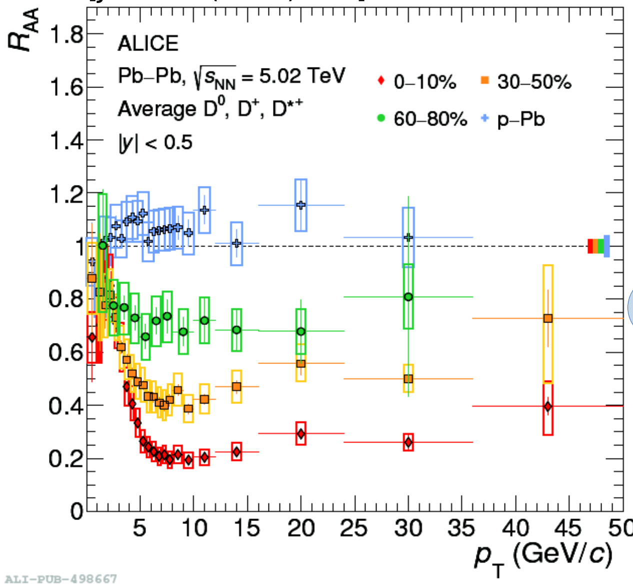
Interaction with medium and Hadronization

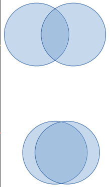
- ✔ For hard processes R_{AA} = 1 if no modifications induced by the nuclear medium
- ✔ Clear suppression for p_T > 3 GeV/c, beyond CNM effects (estimated via R_{pPb})
- ✔ Evolution with the centrality: increasing medium density, size and lifetime from peripheral to central collisions

Nuclear modification factor R_{AA}

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$

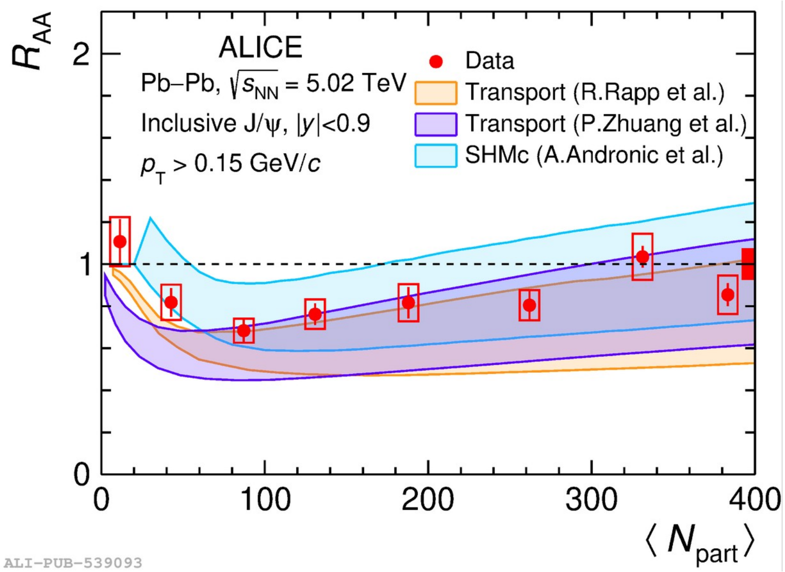
[JHEP 01 (2022) 174]



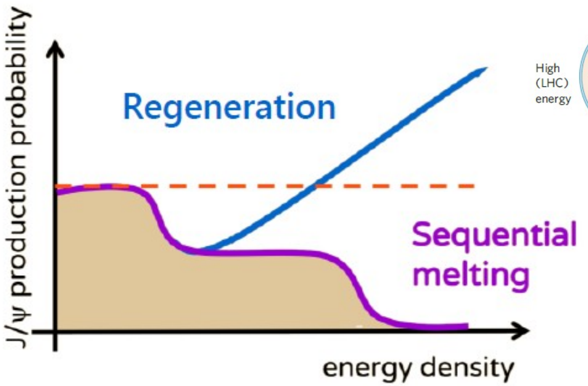


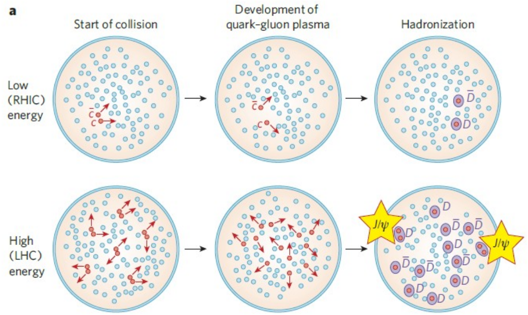
Quarkonia: dissociation vs regeneration

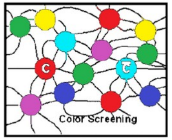
PLB 849 (2024) 138451



SHMC: Andronic A. et al., Phys. Lett. B797 (2019) 134836,
T1: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
T2: Zhou et al., Phys. Rev. C 89, 054911 (21 May 2014)







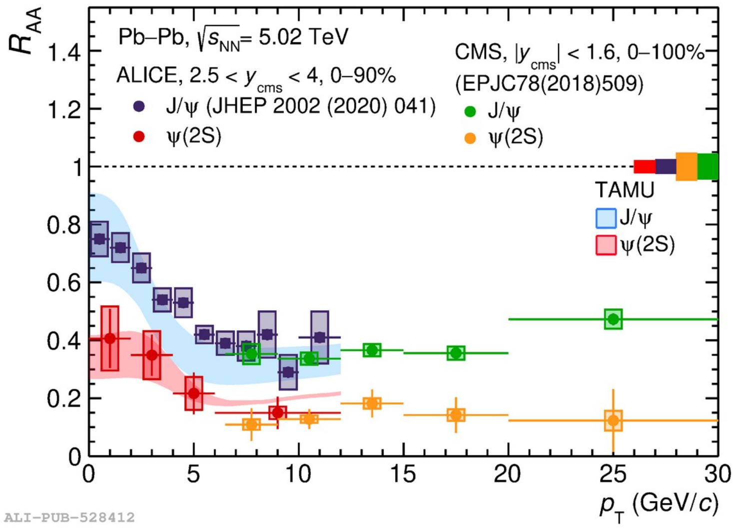
- **Models including regeneration mechanism in fair agreement with data**
  - Statistical Hadronization (SHMc):all charmonia produced at the QGP phase boundary with thermal weights
  - Transport model (TAMU): solve Boltzmann equation with gain (regeneration) and loss (melting) terms

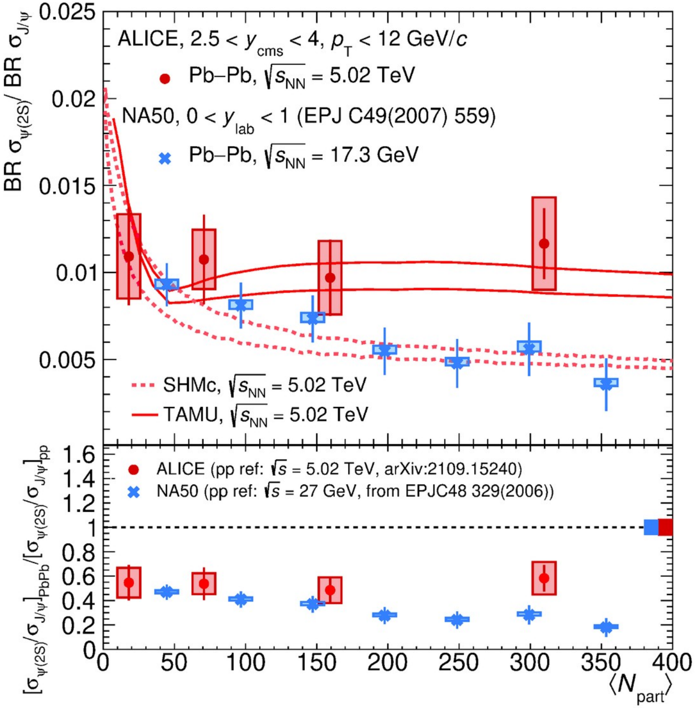
- **large uncertainties on the models arise from charm cross sections and poor constrained nuclear PDF**

Quarkonia: dissociation vs regeneration

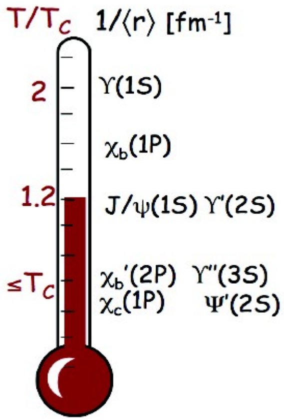
PRL 132 (2024) 042301

- ✔ ψ(2S) less bounded → relative contributions of suppression / regeneration expected to change





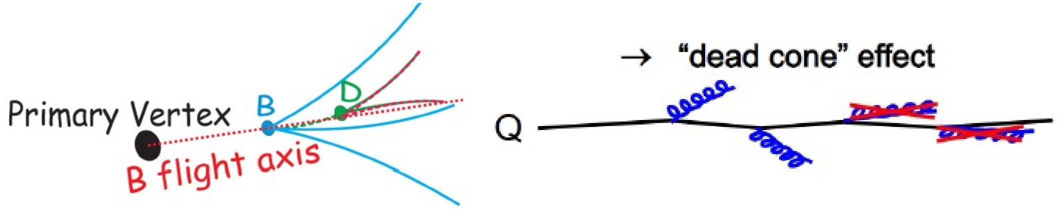
SHMc: Andronic A. et al., Phys. Lett. B797 (2019) 134836,
TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158



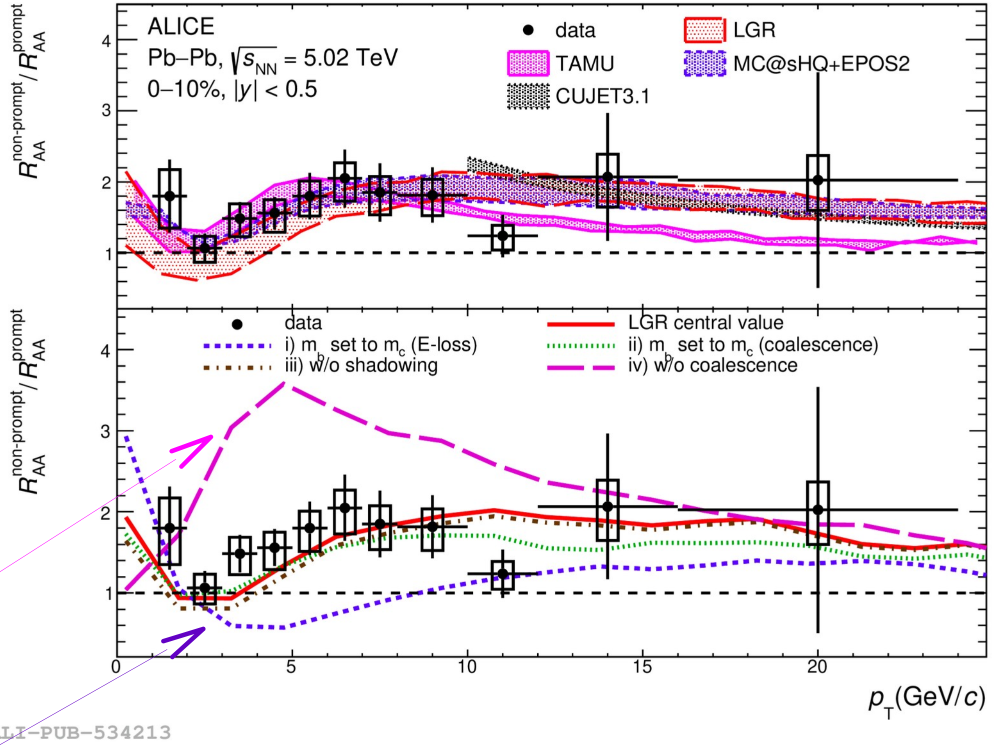
- ✔ ψ(2S) more suppressed compared to J/ψ
- ✔ ψ-to-J/ψ ratio: powerful tool for disentangle among different regeneration scenarios
  - good agreement with transport model; tensions visible with SHMc at higher centralities

Test energy loss mechanisms via prompt / non-prompt D mesons

JHEP 12 (2022) 126

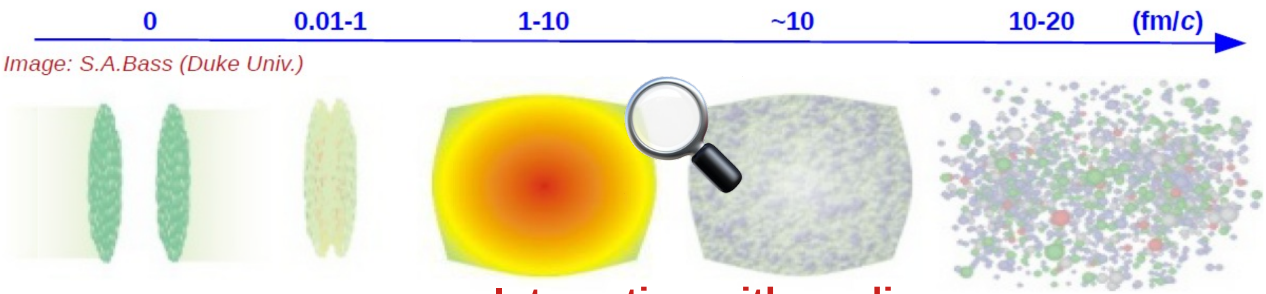


- ✔ Larger suppression observed for prompt compared to non-prompt D^0 (proxy of beauty hadrons) above 5 GeV/*c*
  - expected due to "dead-cone" effect (mass dependence of radiative energy loss)
- ✔ Well described within uncertainties by TAMU, CUJET3.1, LGR and MC@sHQ+EPOS2 → all, but TAMU, include both radiative and collisional energy loss mechanisms
- ✔ Coalescence can explain the minimum observed at low p_T in the non-prompt to prompt D^0 R_{AA} ratio
- ✔ Usage of charm (m_c) in place of beauty (m_b) quark mass significantly understimates the ratio at intermediate / high p_T → importance of radiative energy loss contribution !



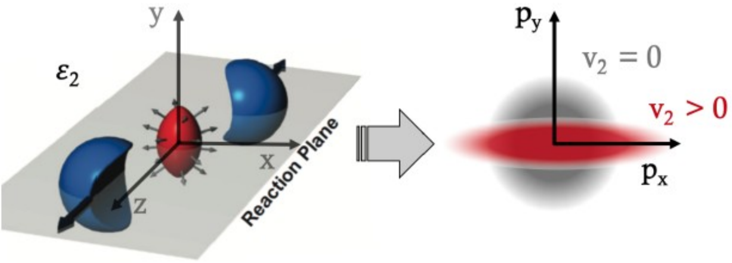
TAMU: PLB 735 (2014) 445–450
LGR: EPJC 80 (2020) 671, EPJC 80 (2020) 1113
MC@sHQ+EPOS2: PRC 89 (2014) 014905
CUJET3: Chin. Phys. C 43 (2019) 04410

The physics of ALICE



Interaction with medium and Hadronization

Anisotropic flow

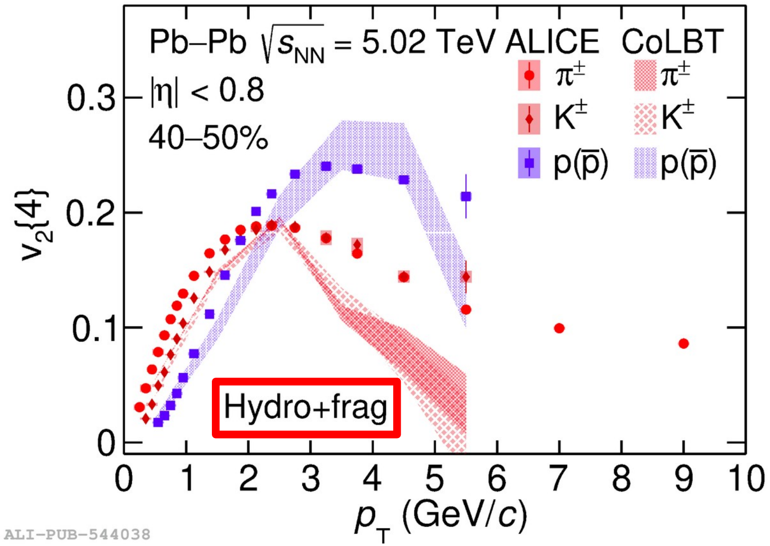


$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \quad v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

- ✔ pressure gradients convert any initial geometrical anisotropy into one in the momentum space
- ✔ anisotropy quantified by the 2nd order coefficient v_2 of the Fourier expansion

Anisotropic flow of identified hadrons

JHEP 05 (2023) 243

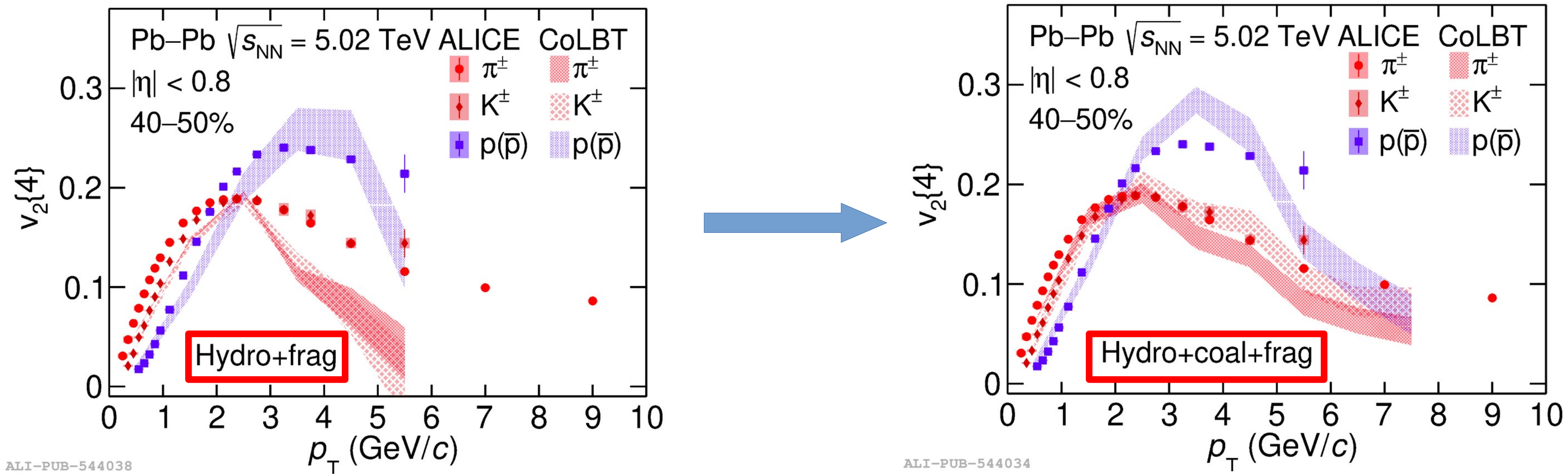


- ✔ Mass ordering at low p_T
- ✔ Meson-baryon splitting at intermediate p_T

CoLBT: W. Zhao et al., PRL 128 (2022) 022302

Anisotropic flow of identified hadrons

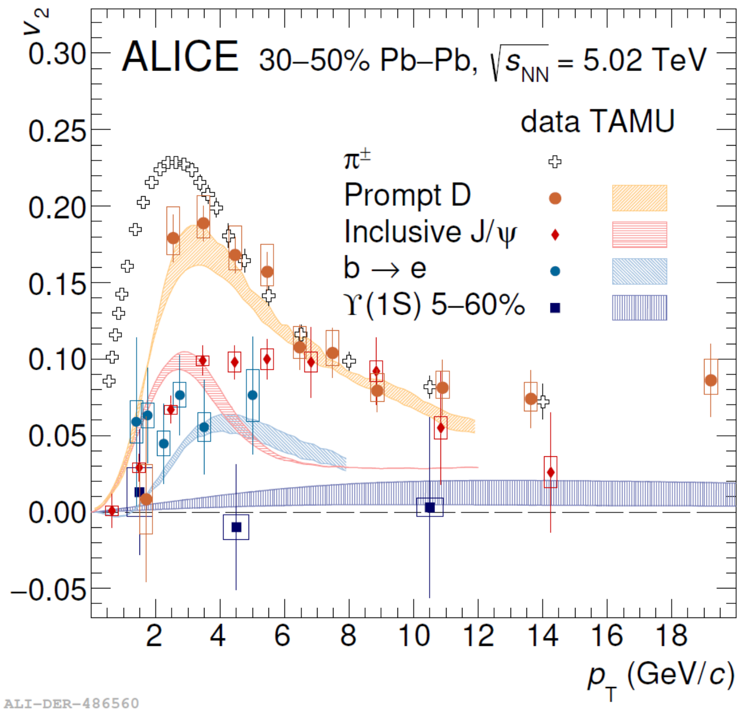
JHEP 05 (2023) 243



- ✔ Mass ordering at low p_T
- ✔ Meson-baryon splitting at intermediate p_T
- ✔ Overall good description provided by CoLBT model (including hydro+coalescence+fragmentation)

CoLBT: W. Zhao et al., PRL 128 (2022) 022302

Thermalisation of heavy-flavour hadrons in QGP



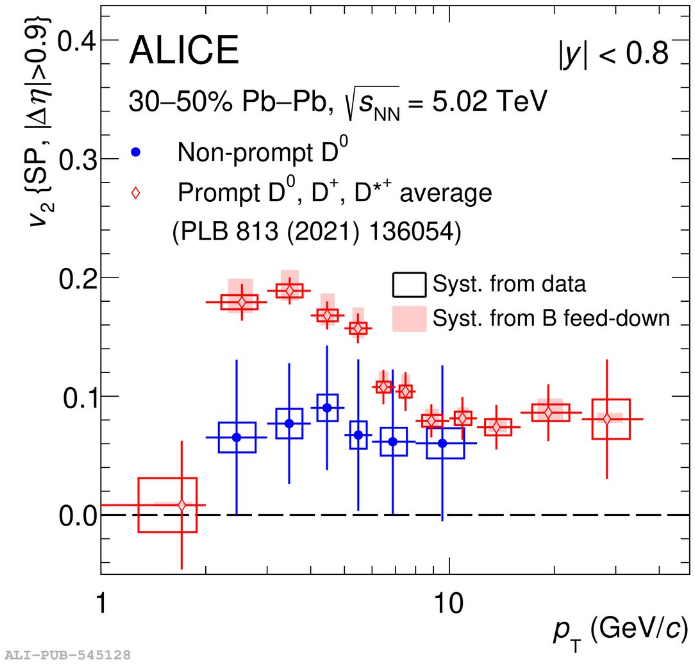
- ✔ Positive v_2 for heavy-flavour hadrons → consistent with the participation of charm / beauty quarks to collective motion in QGP medium
  - clear mass hierarchy at low-p_T: $v_2(\pi) > v_2(D) > v_2(J/\psi)$
  - specie independent v_2 at high-p_T
  - positive v_2 for beauty-hadron decay electrons
  - no significant flow for ϒ(1S) state
- ✔ Qualitatively well described by transport model including hadronization via coalescence / regeneration

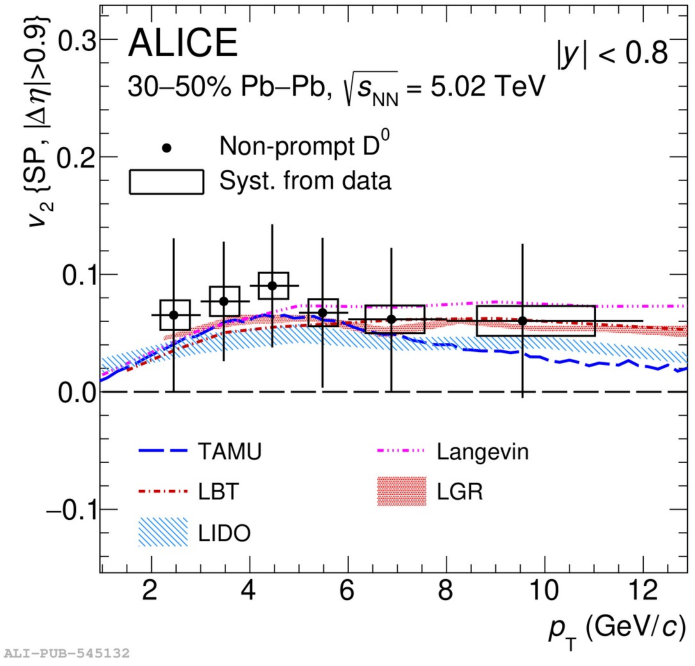
Phys. Lett. B 813 (2021) 136054
JHEP 09 (2018) 006
JHEP 10 (2020) 141
Phys. Rev. Lett. 126 (2021) 162001

TAMU: M. He et al. PLB 735 445-450 (2014)

Thermalisation of heavy-flavour hadrons in QGP

arXiv:2307.14084

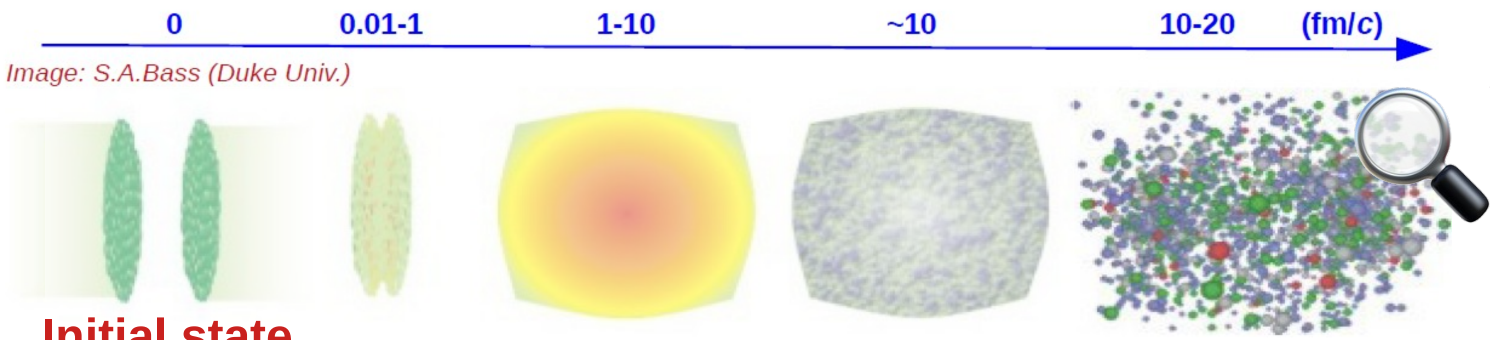




- ✔ Significant v_2 measured for non-prompt D mesons (significance: 2.7σ)
- ✔ v_2(prompt D) > v_2(non-prompt D) with a significance of 3.2σ in 2 < p_T < 8 GeV/c
- ✔ Described by models including hadronization via coalescence and fragmentation

TAMU: M. He et al. PLB 735 445-450 (2014)
LIDO: W. Ke et al. Phys. Rev. C 98, 064901 (2018)
LGR: S. Li et al. Eur. Phys. J. C (2020) 80
LBT: S. Cao et al. arXiv:1703.00822
Langevin: S.-Q. Li et al. Chin. Phys. C 44(2020)11, 114101

The physics of ALICE

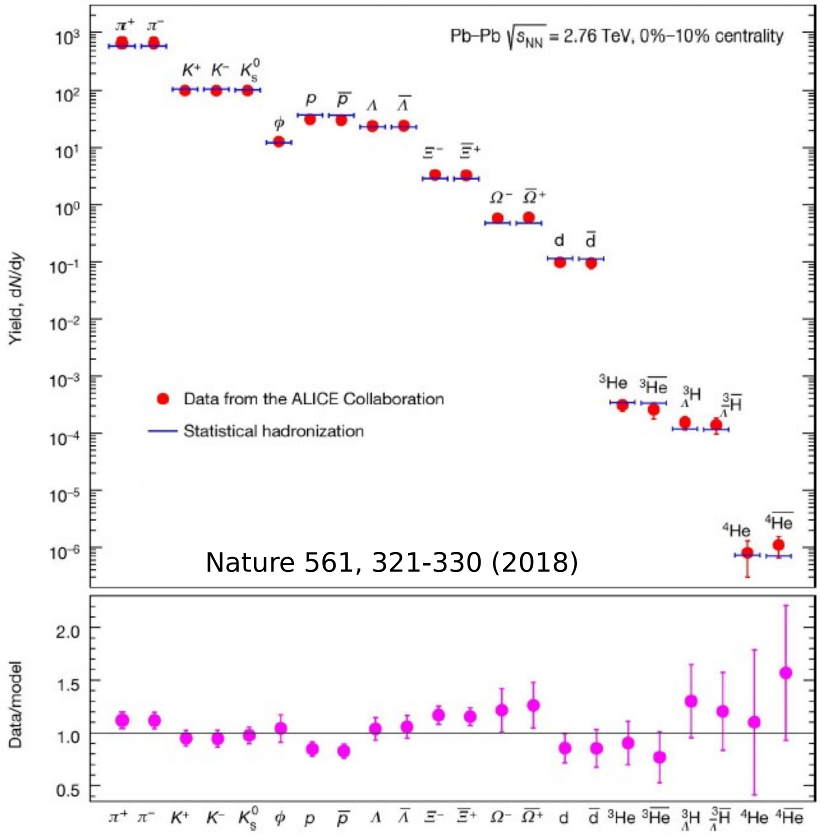


Initial state

See talk (+poster) by
Andrea Giovanni Riffero,
27th Feb., 10:05

Freeze-out

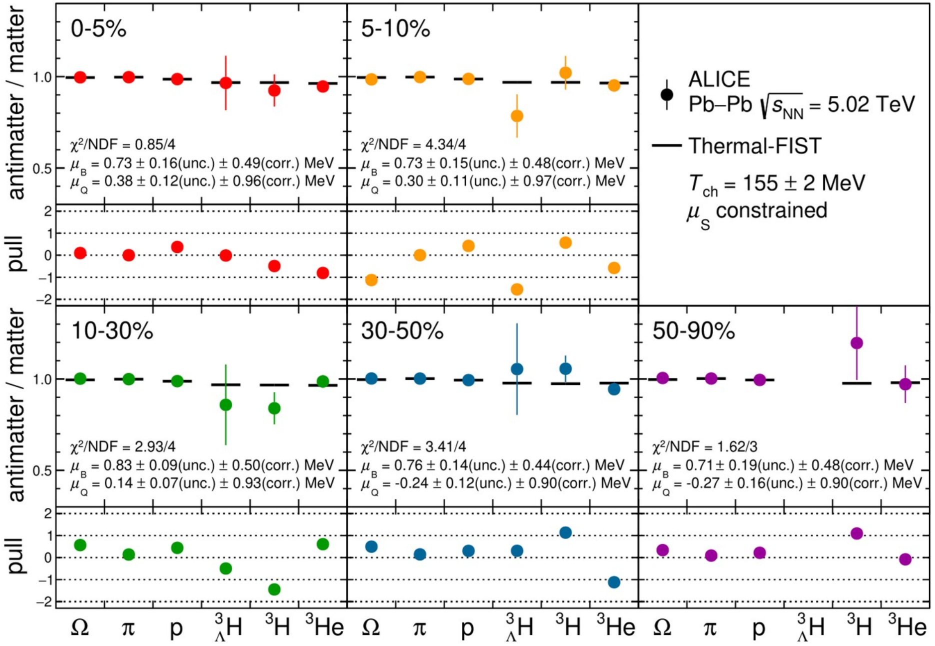
Light-flavour hadron abundances at the freeze-out



- Production of light-flavour hadrons well described by Statistical Hadronization Model (SHM) fit over 9 orders of magnitude (Grand Canonical ensemble forumulation)
- Hadron yields can be described as emerging from a hot Hadron-Resonance Gas in thermal equilibrium
  - **At LHC: $\mu_B \sim 0$, $T_{ch} \sim 156$ MeV**
- Precise determination of the parameters thanks to the wide variety of particle yields available with good experimental precision

Antimatter / matter imbalance at the LHC

arXiv:2311.13332

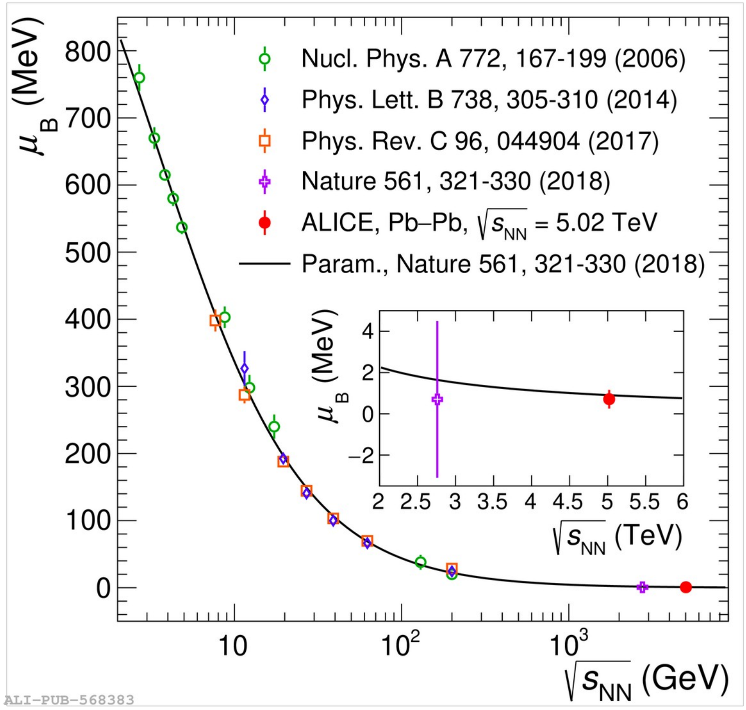


- Precise determination of μ_B from antimatter / matter imbalance within the SHM model by fitting:

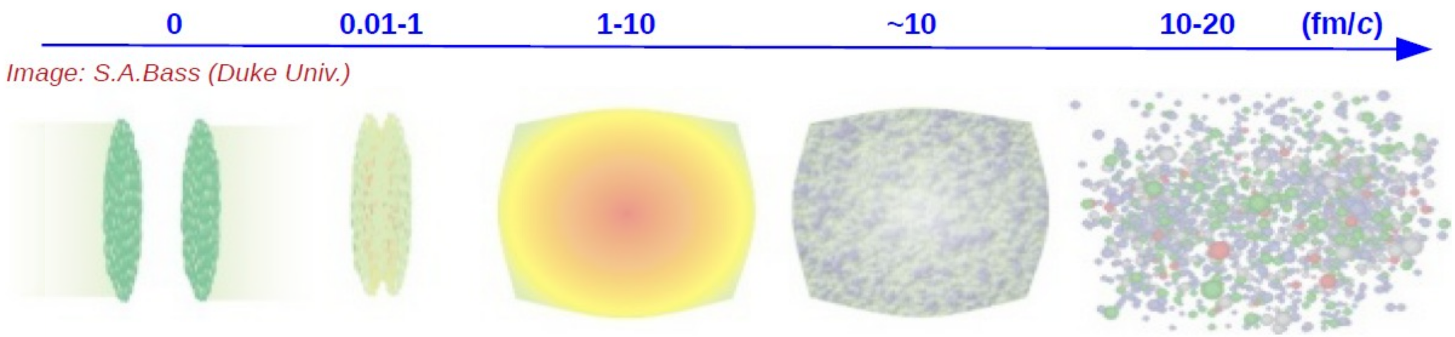
$$\overline{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

with $T = 156.2 \pm 2$ MeV

- Reduced uncertainties on μ_B w.r.t. global SHM fit thanks to the cancellation of correlated uncertainties in the ratio



The physics of ALICE

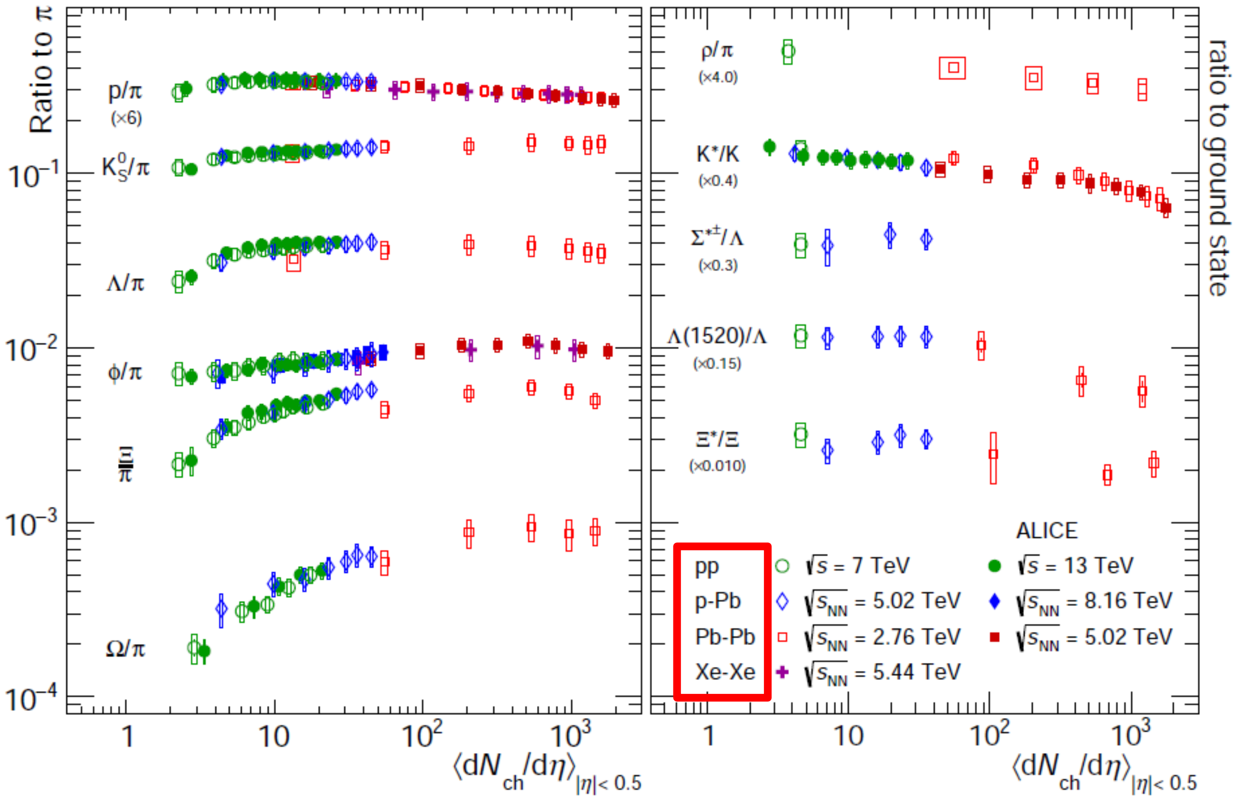


From large to small systems...

See also talks by:
Michele Pennisi, 26th Feb., 09:50
Sara Pucillo, 26th Feb., 15:10

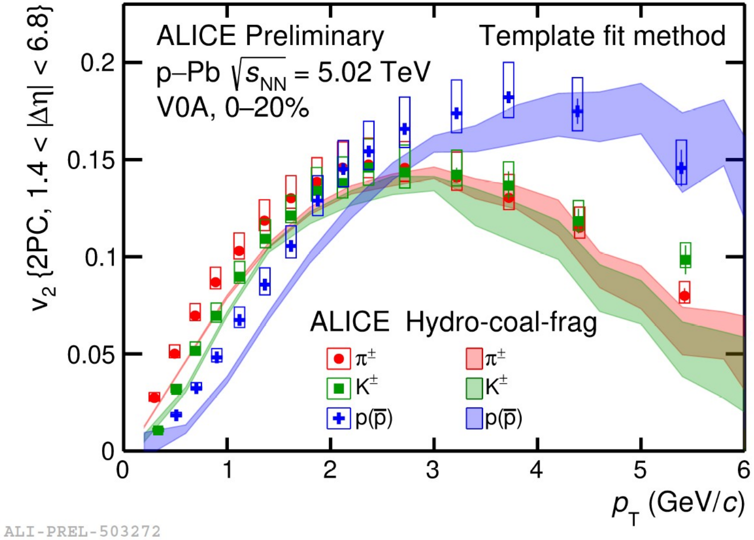
Particle production across systems

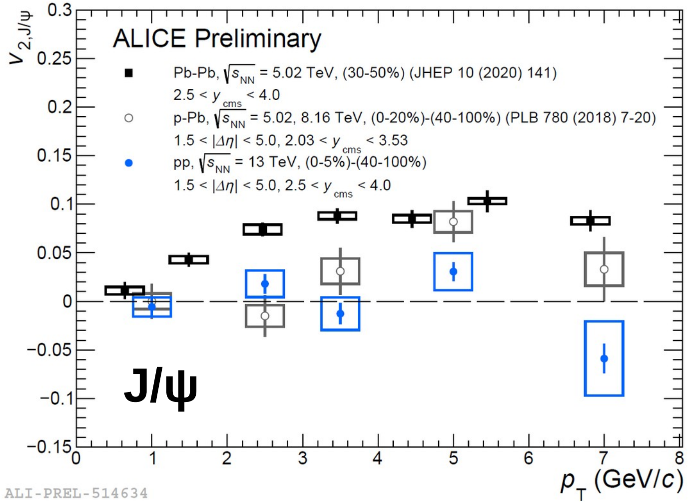
arXiv:2211.04384



- Smooth trend of multiplicity dependent particle production ratios from pp to Pb-Pb multiplicities
- Is charged particle multiplicity the relevant parameter to explain strangeness enhancement (or other “QGP-like” effects) in small systems ?

Collectivity in small systems ?





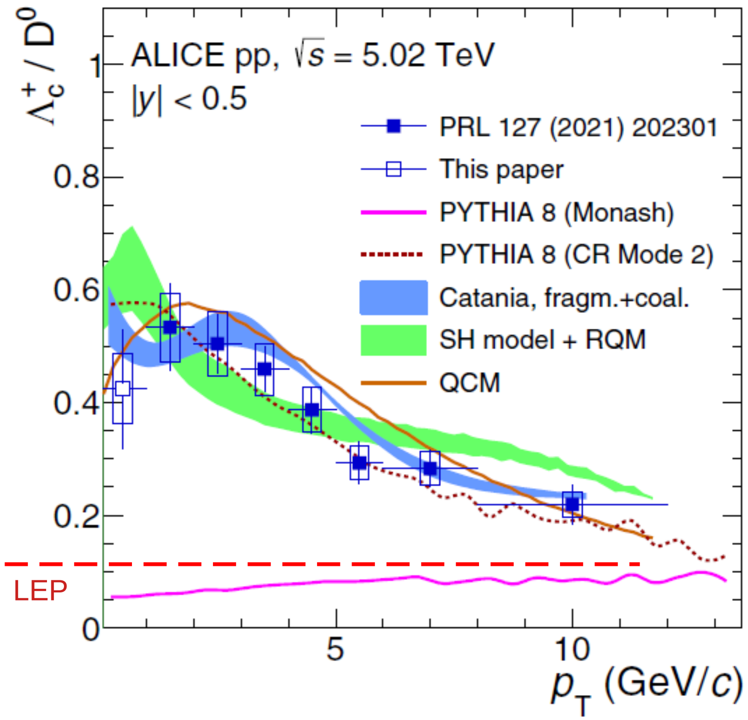
→ Common mechanism at the origin of the flow in large and small systems ?

- ✔ Similar mass ordering and meson-baryon splitting in p-Pb collisions as observed in Pb-Pb collisions
- ✔ Comparison with models indicate that coalescence is needed to describe the flow at intermediate p_T
- ✔ Collective behaviour observed in p-Pb collisions also for J/ψ, but only at high p_T

Hydro-coal-frag: Phys. Rev. Lett. 125, 072301 (2020)

The “baryon anomaly” in the HF sector

Phys. Rev. C 107 (2023) 064901



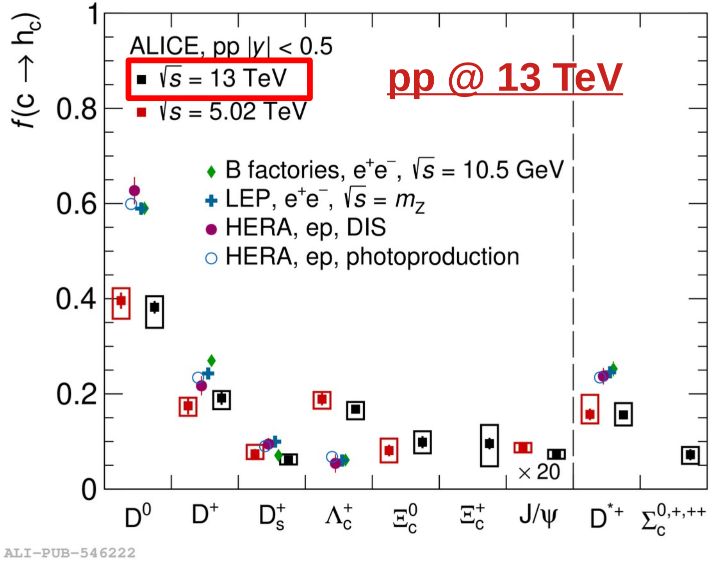
- First measurement of Λ_c production down to p_T = 0 in small systems !
- Enhancement of **Λ_c/D^0** ratio at low and intermediate momentum w.r.t. e^+e^- results (LEP average: 0.113 ± 0.013 ± 0.006 [EPJC 75 (2015) 19])
  - Significantly underestimated by PYTHIA8 Monash tune (which incorporates fragmentation parameters from e^+e^- data)
- Data qualitatively reproduced by models implementing baryon to meson ratio enhancement via various mechanisms (color reconnection, feed-down from unobserved resonant charm baryon states, quark coalescence)

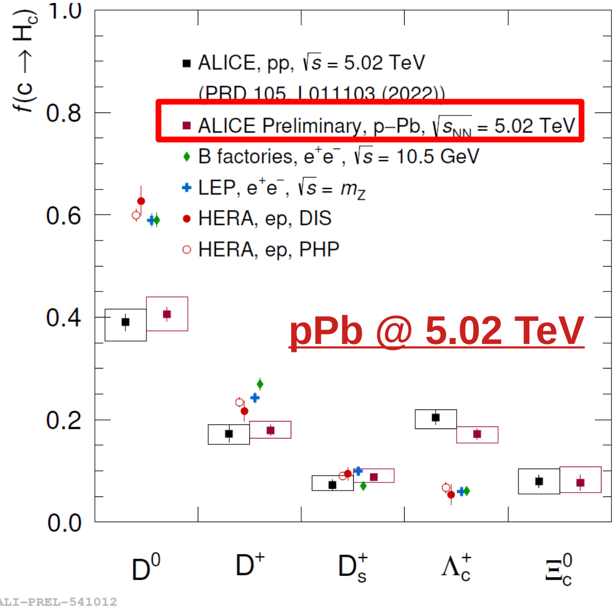
PYTHIA8: EPJC 74 (2014) 3024
PYTHIA 8 CR Mode: JHEP 08 (2015) 003
Catania: PLB 821 (2021) 136622

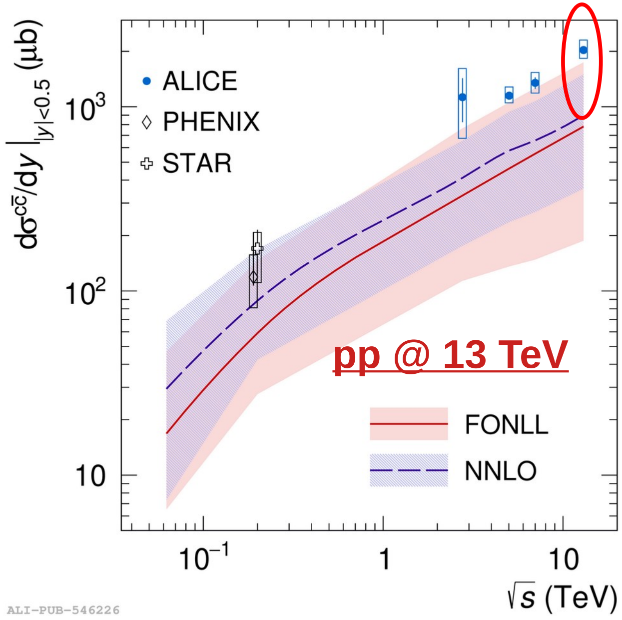
SHM + RQM: PLB 795 (2019) 117-121, PRD 84 (2011) 014025
QCM:EPJC 78 (2018) 344

Charm quark production and fragmentation in small systems

Phys. Rev. C 107 (2023) 064901







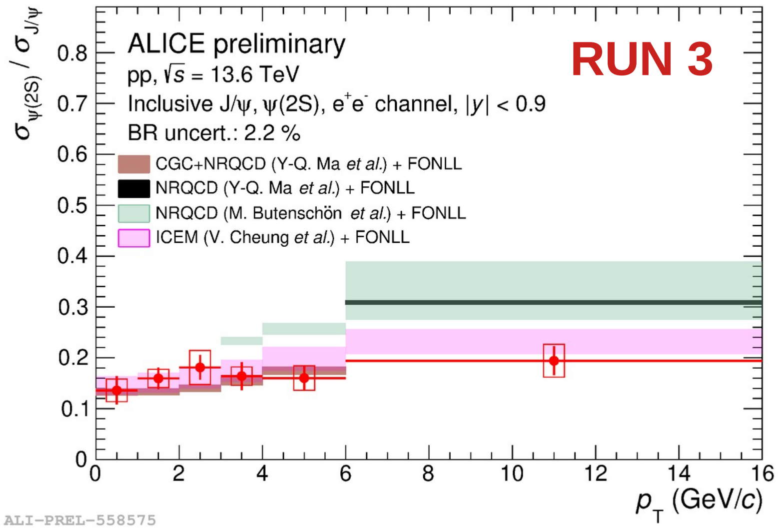
- ✔ Fragmentation fractions at LHC
  - independent of $\sqrt{s}$
  - consistent with system size
  - Significantly enhanced w.r.t. e$^+$e$^-$ and ep → **breaking of the universality of fragmentation functions**!

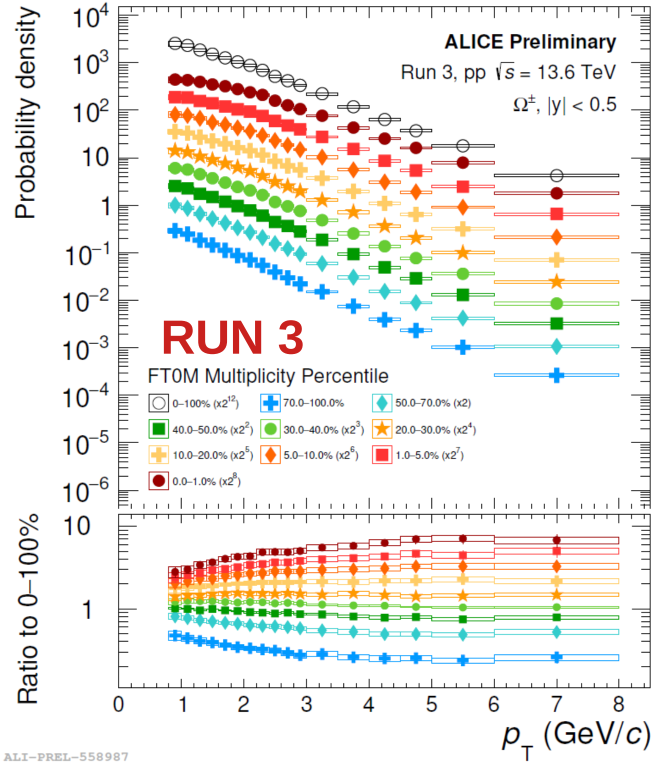
FONLL: JHEP 05 (1998) 007
NNLO: PRL 118 (2017) 122001

- ✔ Charm quark production cross section at midrapidity is at the **upper boundary** of state-of-art pQCD calculations

Summary

- Impressive collection of physics results from Run 1 & 2 !
- Detailed insight into initial and final stages of heavy-ion collisions at the LHC
- Intriguing results in small collisions systems
- Efficiently Run 3 data taking ongoing
  → preliminary measurements released for QM2023 !





See also talk by Giovanni Malfattore, 27th Feb., 9:00

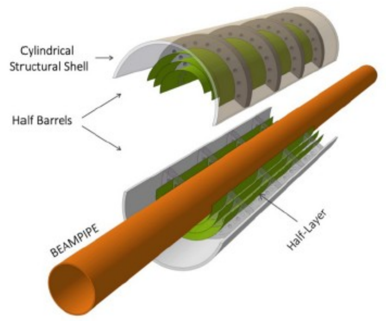
Outlook: Run4 and beyond

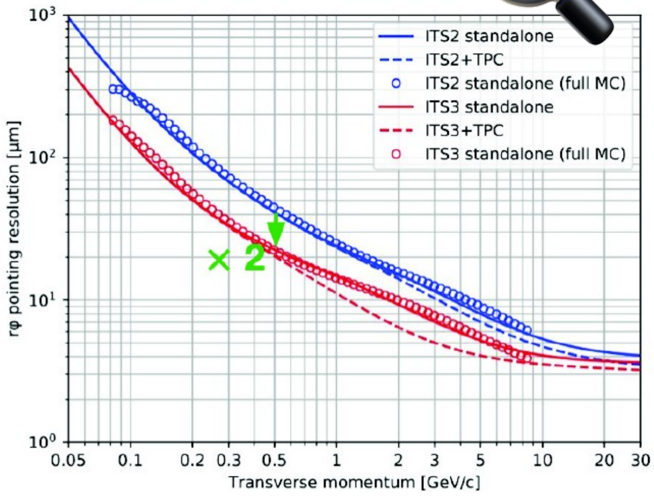
ITS3:
LoI: CERN-LHCC-2019-018
TDR: in preparation

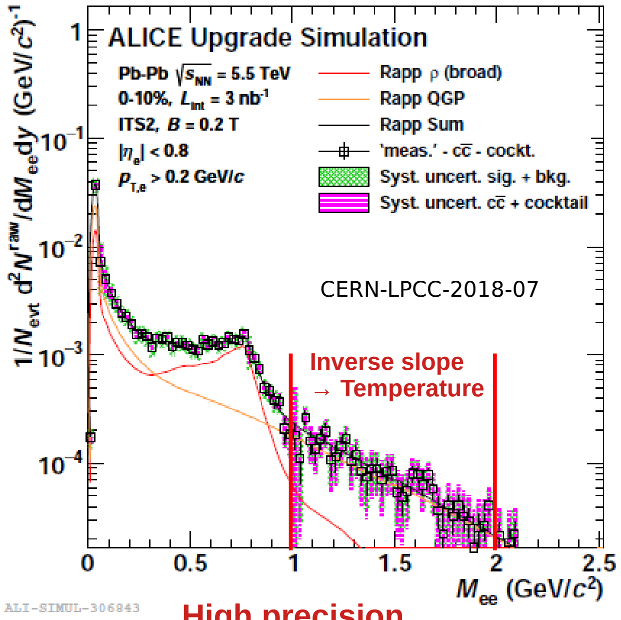
FOCAL:
LoI: ALICE, LHCC-I-036 (2020)

2010-2012		2015-2018		2022-2025		2029-2032		2035-2038		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

LS3: ITS3 (and FOCAL)







High precision measurement of medium temperature!

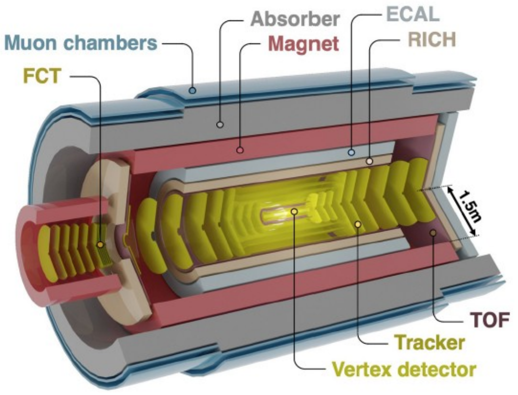
- ✔ Replacing the 3 innermost layers with new ultra-light, truly cylindrical layers
  - Reduced material budget (from 0.35% to 0.05% X_0)
  - Closer to the interaction point (from 23 to 18 mm)
- ✔ Main motivations:
  - Improve performance for **open heavy-flavour** and **dielectron** measurements

Outlook: Run4 and beyond

ALICE3:
LoI: CERN-LHCC-2022-009

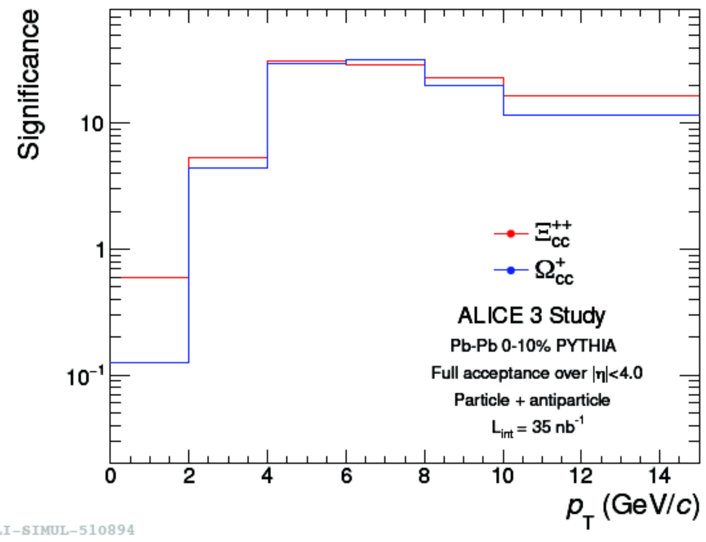
2010-2012		2015-2018		2022-2025		2029-2032		2035-2038		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

LS4: ALICE3



- ✔ Innovative detector concept focusing on silicon technology
  - Compact and lightweight all-silicon tracker
  - Large acceptance: $-4 < \eta < 4$, $p_T > 0.02$ GeV/c
  - Continuous readout

→ improved tracking and vertex performance at very low p_T
→ increased redout rate and η coverage
→ improved PID capabilities



- ✔ Physics goals: new observables for low-mass dileptons and heavy-flavour particles (and much more!)
  - direct tracking of Ξ / Ω baryons (strangeness tracking) → full reconstruction of multi-charm baryon decay vertices

Outlook: Run4 and beyond

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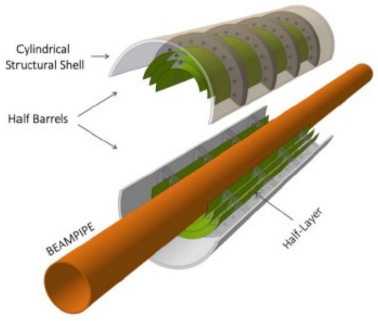
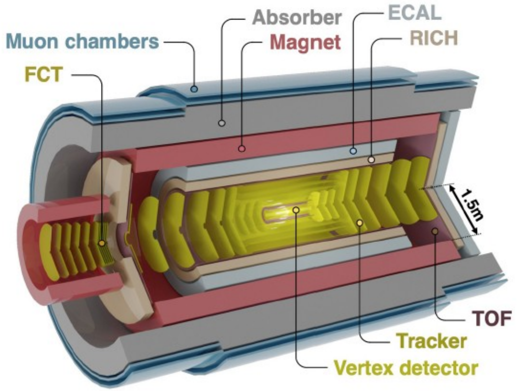


LS4: ALICE3



See also:

poster by Angelo Colelli
talk by Riccardo Ricci, 27th Feb., 9:20
poster by Alessandro Sturniolo

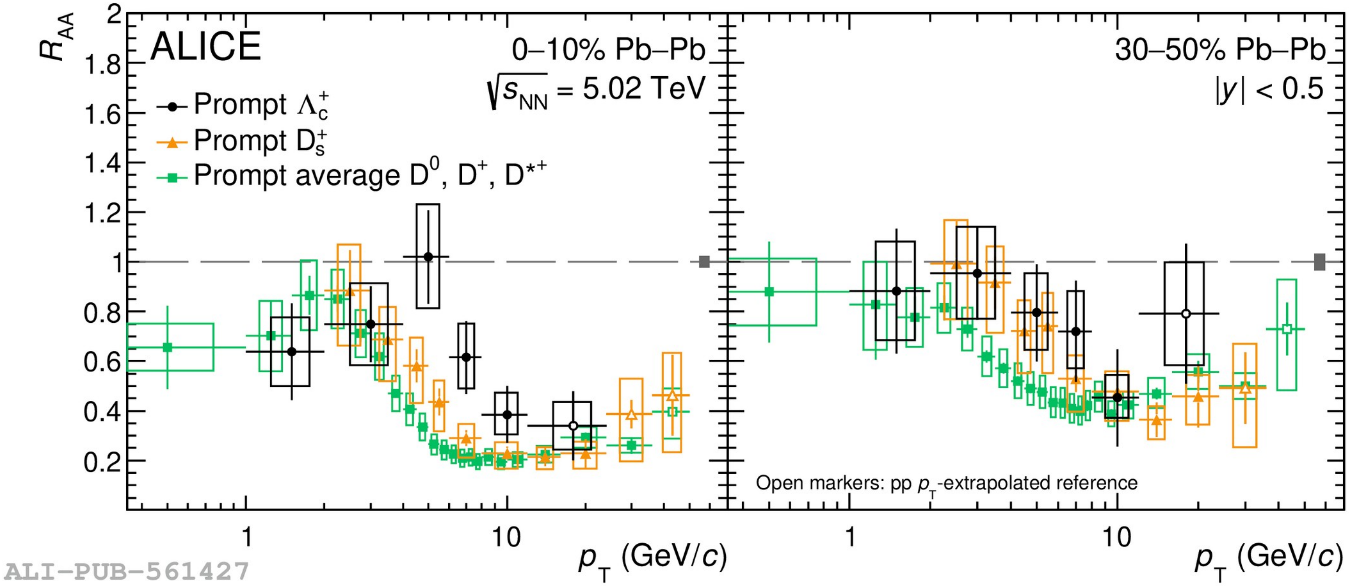
talk by Giulia Gioachin, 27th Feb., 10:10
talk by Nicola Nicassio, 27th Feb., 9:40
talk by Bianca Sabiu, 27th Feb., 10:00

Thank you for your attention!

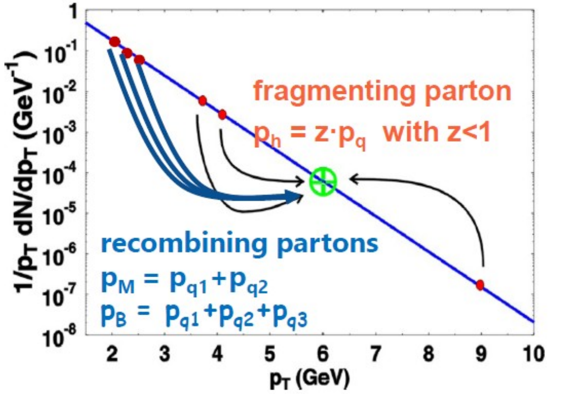
BACK-UP

Open-charm hadronization in medium

Phys. Lett. B 839 (2023) 137796



- Hadronization in presence of medium happens via **fragmentation** and **coalescence**



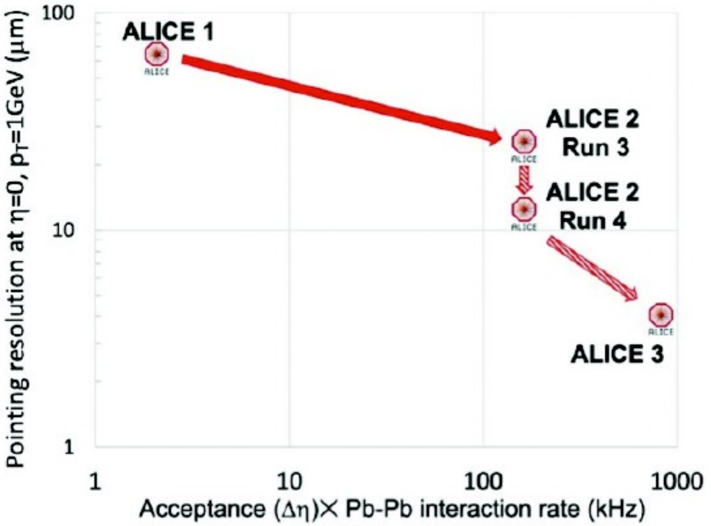
- Intermediate p_T: hint at hierarchy $R_{AA}(\Lambda_c) > R_{AA}(D_s) > R_{AA}(D)$ in centrality 0-10% (less pronounced in semicentral collisions) → indications that hadronisation occurs via coalescence
  - **$R_{AA}(D_s) > R_{AA}(D)$** → possible modifications of hadronisation in a **strangeness enriched** medium

- $R_{AA}(\Lambda_c) \approx R_{AA}(D_s) \approx R_{AA}(D)$ for $p_T > 10$ GeV/c → indication that fragmentation is the dominant mechanisms

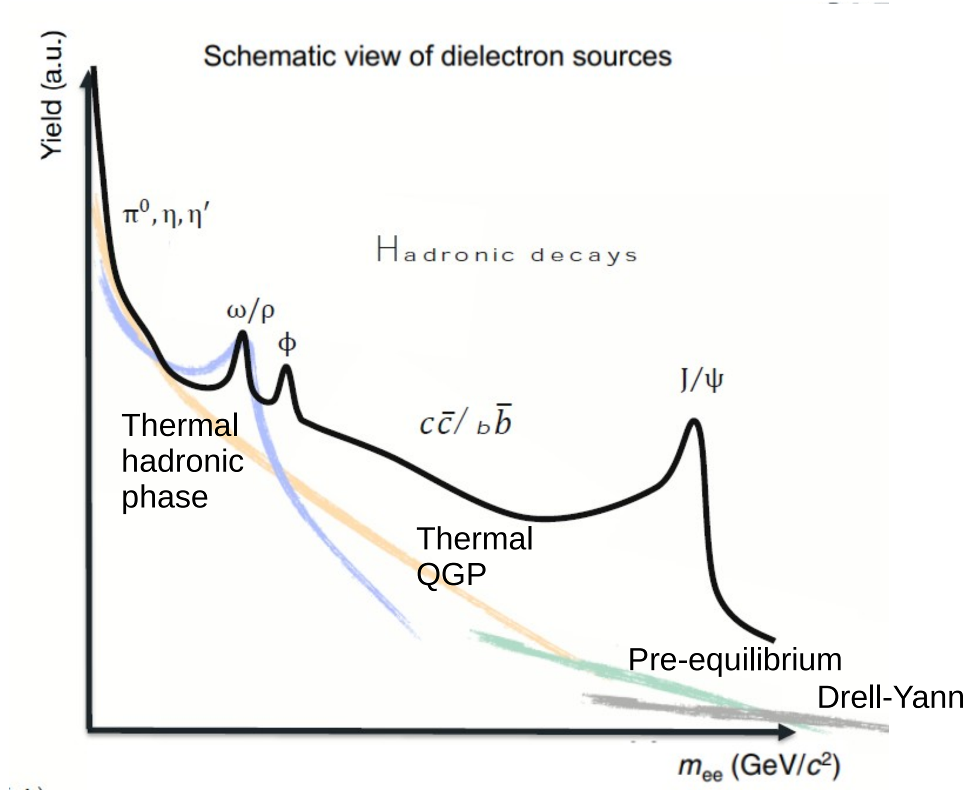
Upgrade physics goals and requirements

- **Heavy flavour hadrons** at low p_T (charm and beauty interaction and hadronisation in the QGP)
- **Quarkonia** down to $p_T = 0$ (melting and regeneration in the QGP)
- **Thermal dileptons, photons, vector mesons** (thermal radiation, chiral symmetry restoration)
- Precision measurements of **light (hyper)nuclei** and searches for **charmed hypernuclei**

→ Increased effective acceptance (acceptance x readout rate)
→ Improved tracking and vertexing performance at low pT for background suppression
→ PID capabilities: preserve in ALICE2 Run4 and enhance in ALICE3



Dilepton sources & background

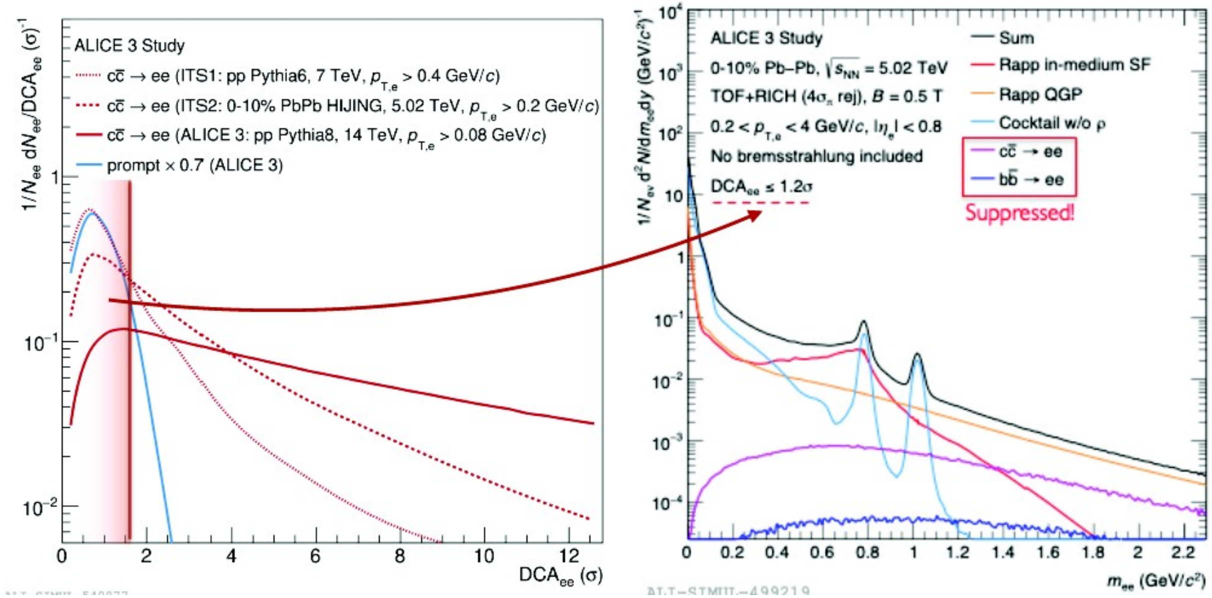


– Direct determination of the medium temperature from the exponential fit of (background subtracted) m_{ee} distribution in the intermediate mass region

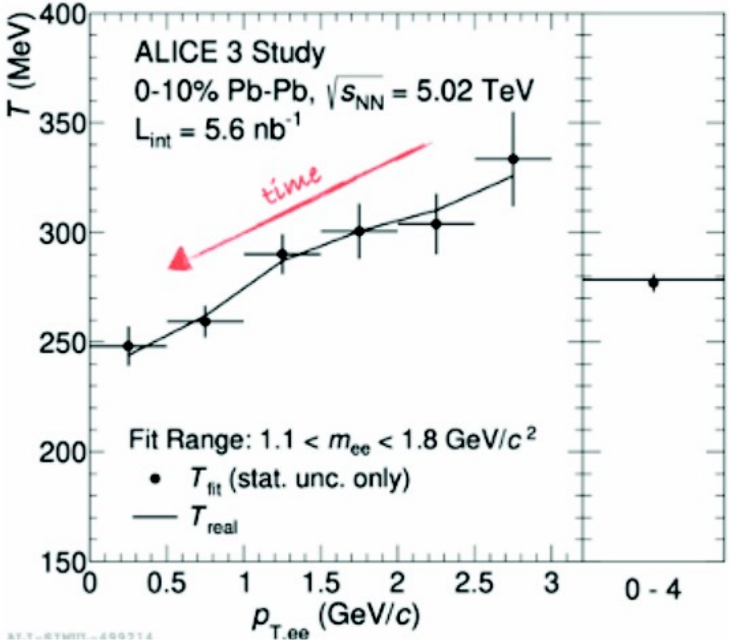
– Challenge:

- – large combinatorial background
- – physical background from pseudoscalar and vector mesons + dileptons from semileptonic HF decays (dominant)

ALICE3 – physics goals: dileptons

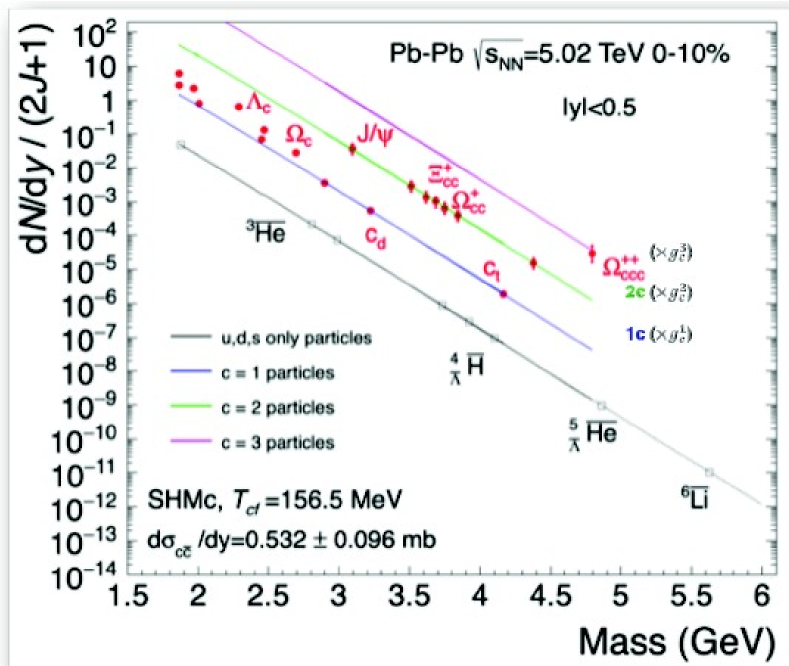


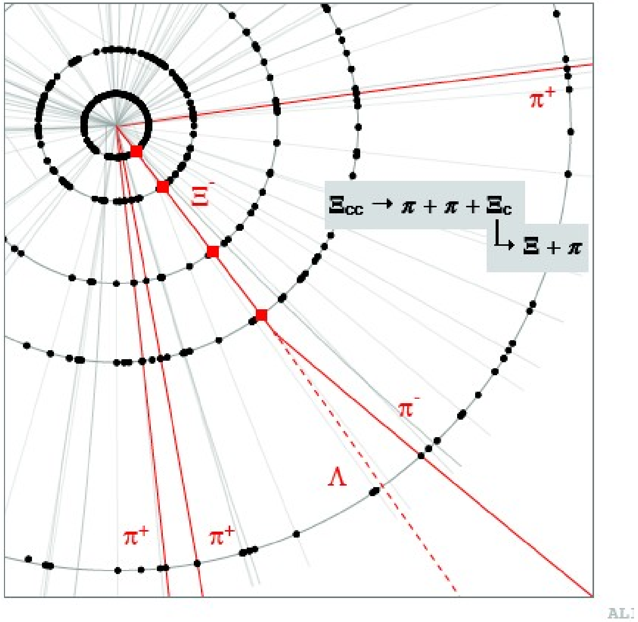
– extremely precise determination of medium temperature, for the first time differentially in pT_{ee}



– significantly suppressed background originated from HF semileptonic decays!

ALICE3 – physics goals: HF



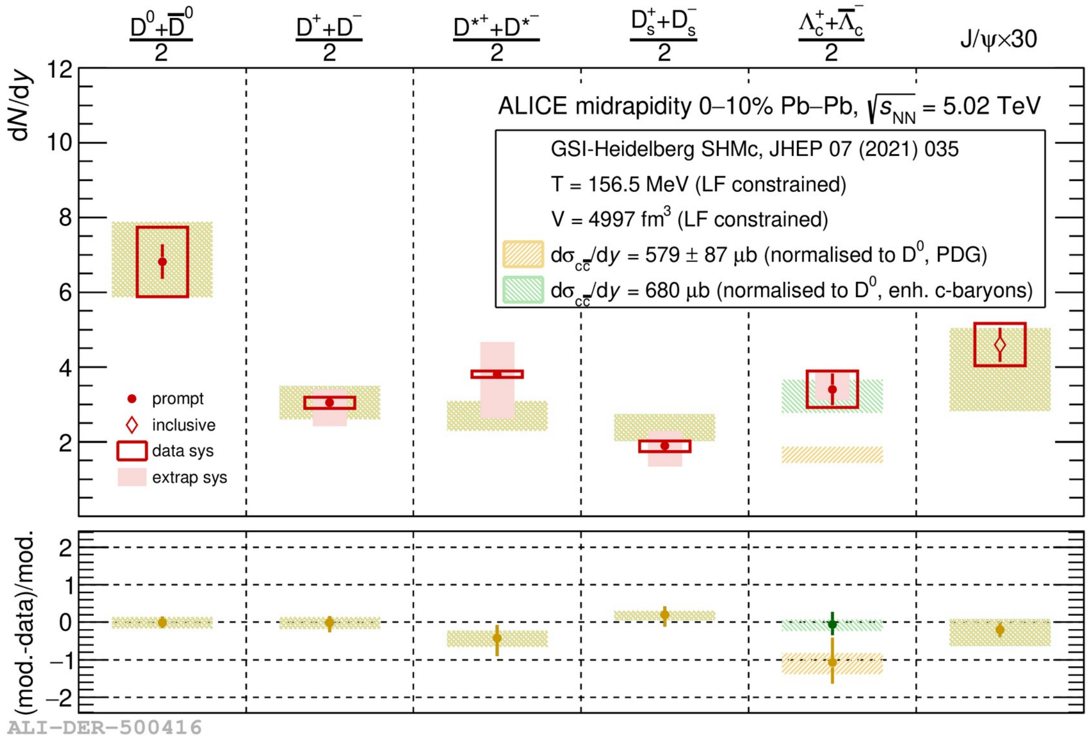


– determination of multi-charm hadron abundances → important input for testing SHM model (abundances dependent on fugacity g_c^n, with n = content of charm quarks)

– Silicon layers inside the beam pipe allow for direct tracking of **Ξ**/**Ω** baryons (strangeness tracking)
→ full reconstruction of multi-charm baryon decay vertices

Charm hadron abundances

arXiv:2211.04384

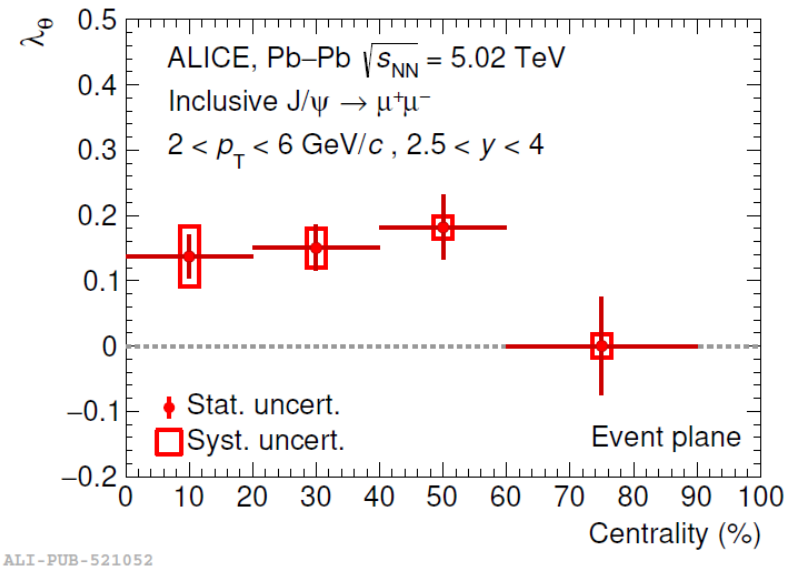


SHMc: JHEP 07 (2021) 035
[1] JHEP 01 (2022) 174

- ✔ Statistical hadronization model for charm hadrons
  - Thermal parameters (T and V) extracted from fitting LF hadron abundances
  - Charm quarks abundance determined in the initial hard scattering
    - total $c\bar{c}$ cross section extracted from prompt D^0 measurements in Pb-Pb [1]
  - Partially thermalized charmed quarks distributed into charmed hadrons at the phase boundary according to thermal weights, based on existing charmed meson and baryons in the PDG
    - Λ_c p_T-integrated yied underestimated
    - Agreement with Λ_c improves assuming an additional set of excited charmed baryons

J/ψ polarization w.r.t. event plane

PRL 131 (2023) 042303

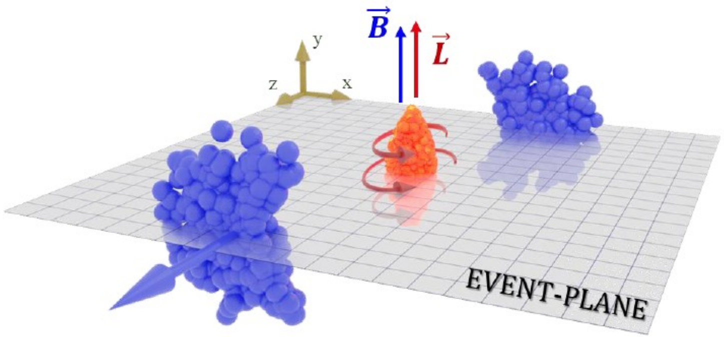


– **Polarization**: angular distributions of decay products w.r.t. a polarization axis

– **Event Plane based frame (EP)**: axis orthogonal to the event plane in the collision center of mass frame

- – Event Plane normal to ***B*** and ***L***

– **Heavy quarks produced early in the collisions can experience both *B* and *L* originated in the initial stage !**



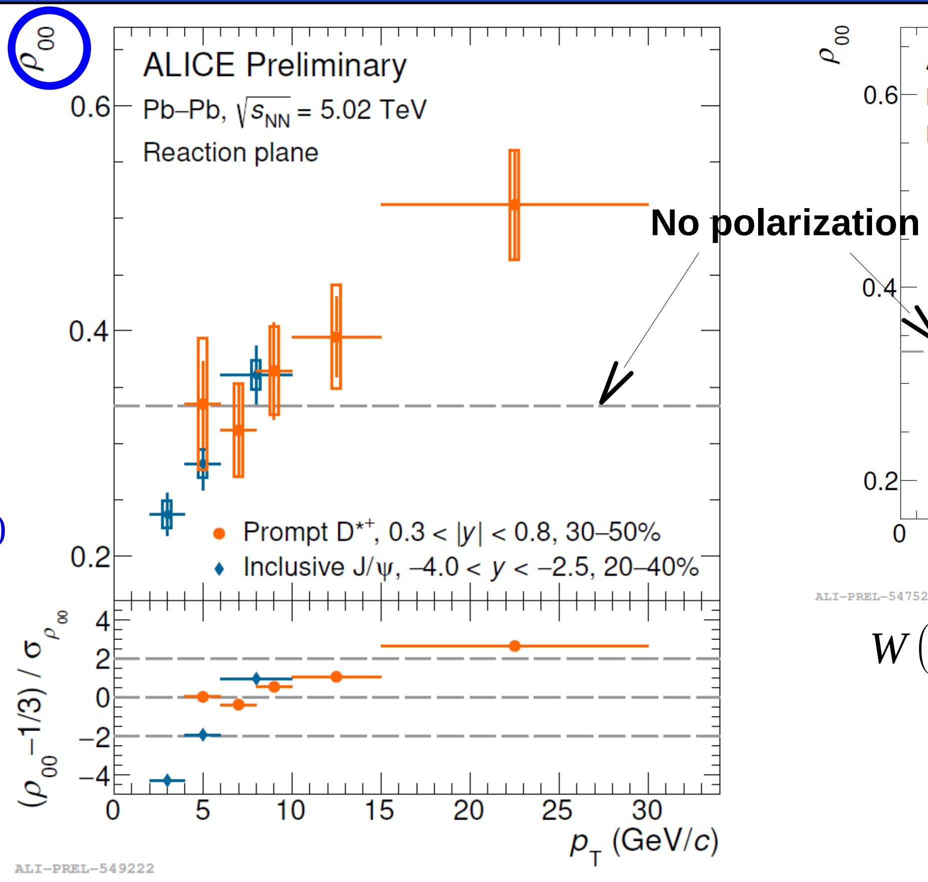
$$W(\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$$

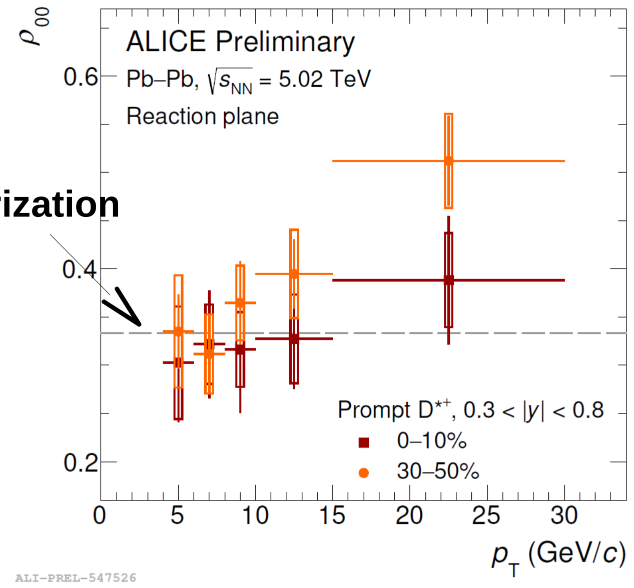
✓ Significant polarization (3.5σ) in 40-60% and 2 < p_T < 6 GeV/c

✓ Small centrality dependence

D^{*+} polarization w.r.t. the event plane

- 0-10% → compatible with no polarization
- 30-50% → ρ_{00}>1/3 at high-p_T, compatible with non-zero polarization
- Polarization sign opposite w.r.t. previous observations for low p_T J/ψ (and light vector mesons)
- **Theory guidance is needed**





$$W(\theta) \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta$$

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

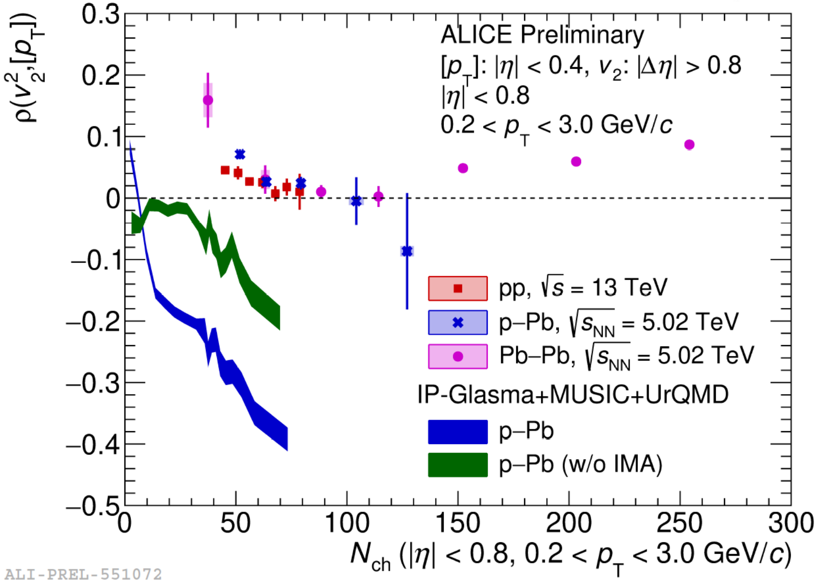
v_2^2 - $[p_T]$ correlations in small systems

- ✔ Correlations between average p_T and flow coefficients → in heavy-ion collisions sensitive to the overlap region shape and size in the initial state

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

– **Shape** of the fireball: ε_2 → observable: v_2

– **Size** of the fireball: R → observable: radial flow ∝ p_T



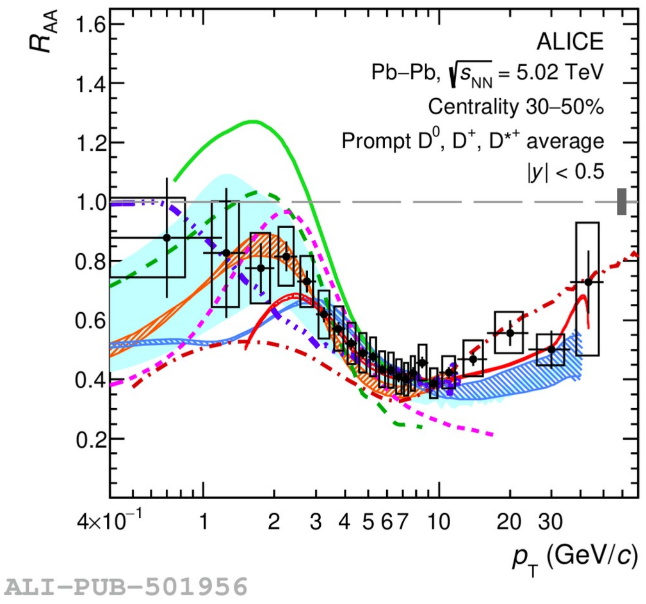
- ✔ Positive correlation measured between v_2 and p_T
- ✔ similar trend vs N_{ch} in all collision systems suggests common mechanisms at play
- ✔ IP-Glasma + MUSIC + UrQMD (with and w/o initial momentum anisotropy) fails to describe the data
  - Initial state effects likely not well modeled in state-of-art models

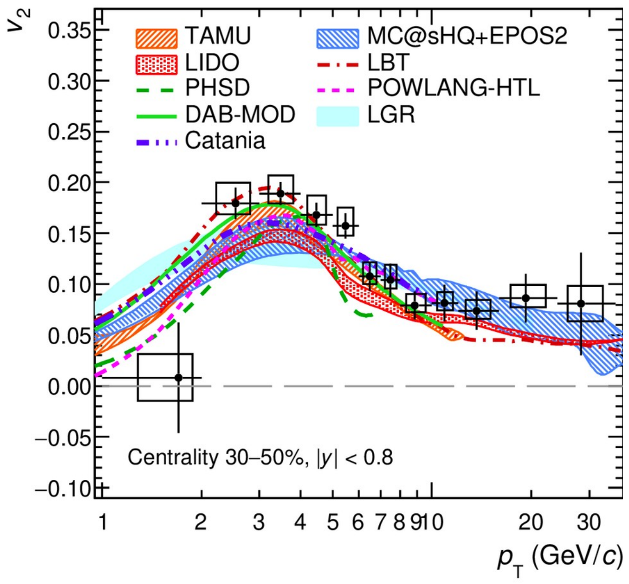
IP-Glasma+MUSIC+UrQM: Phys. Rev. C 95, 064913 (2017)

Extract medium parameters using R_{AA} & v_2 measurements

JHEP 01 (2022) 174

- First measurement of D^0 meson R_{AA} in Pb-Pb collisions down to $p_T = 0$
- The simultaneous description of R_{AA} and v_2 in central and semicentral collisions is a challenge for theoretical models





TAMU: PRL124 (2020) 042301
LIDO: PRC 100 n.6 (2019) 064911
PHSD: PRC 96 (2017) 014905
DAB-MOD: PRC 102 n.2 (2020) 024906

LBT: PRC 94 n.1 (2016) 014909
POWLANG+HLT: EPJC 75 n.3 (2015) 121
LGR: EPJC 80 (2020) 671, EPJC 80 (2020) 1113
MC@sHQ+EPOS2: PRC 89 (2014) 014905
Catania: PRC 96 (2017) 044905

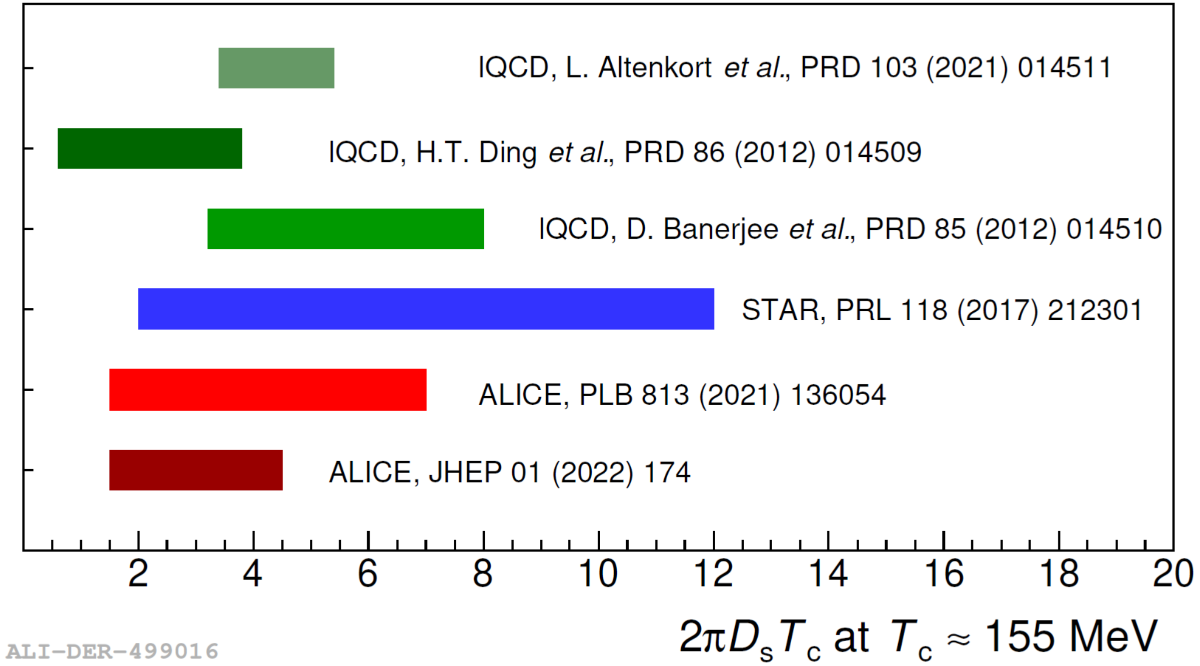
Extract medium parameters using R_{AA} & v_2 measurements

JHEP 01 (2022) 174

- First measurement of D^0 meson R_{AA} in Pb-Pb collisions down to $p_T = 0$
- The simultaneous description of R_{AA} and v_2 in central and semicentral collisions is a challenge for theoretical models
- Few models that are in fair agreement with both observables used to constrain the heavy-quark spatial diffusion coefficient:

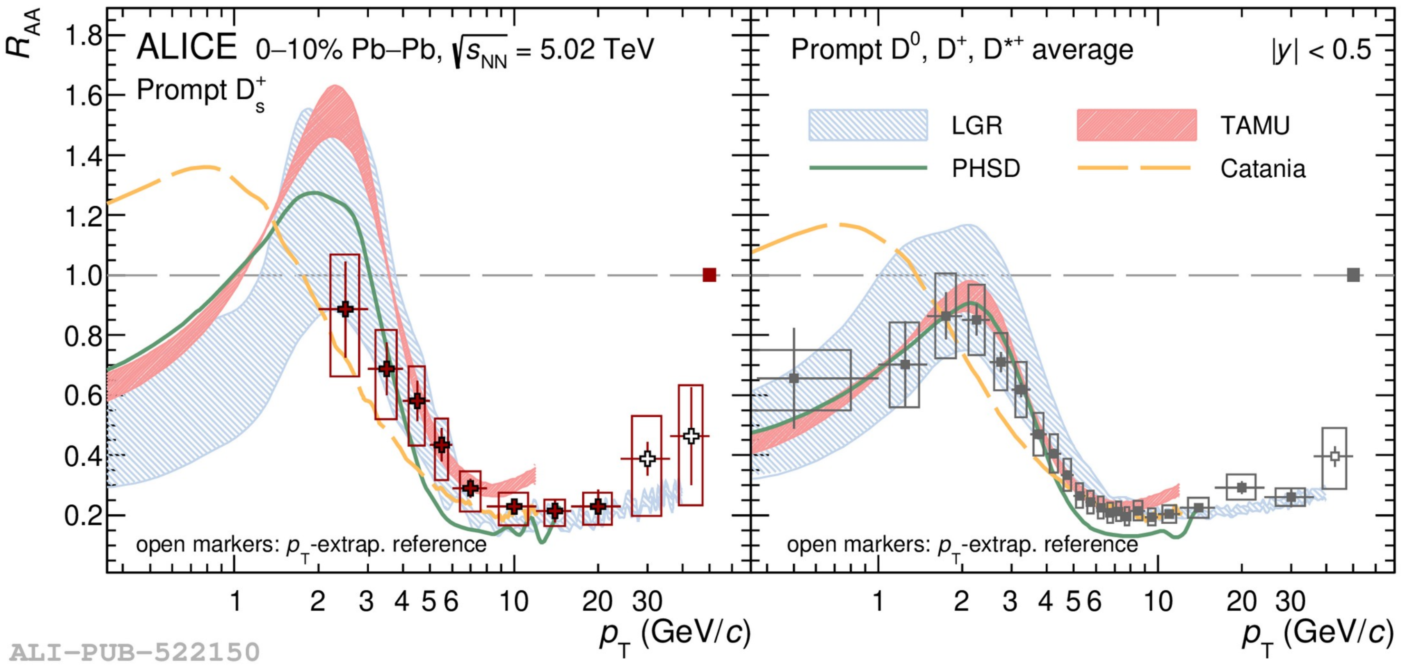
$$1.5 < 2\pi D_s T_c < 4.5$$

→ narrower interval w.r.t. previous estimations based on D-meson measurements at LHC energies



Open-charm hadronization in medium

Phys. Lett. B 827 (2022) 136986

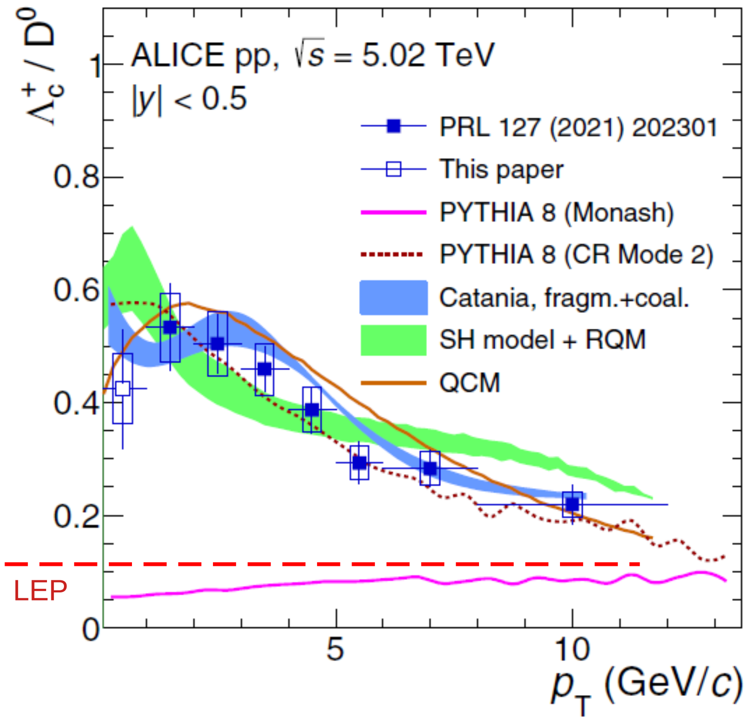


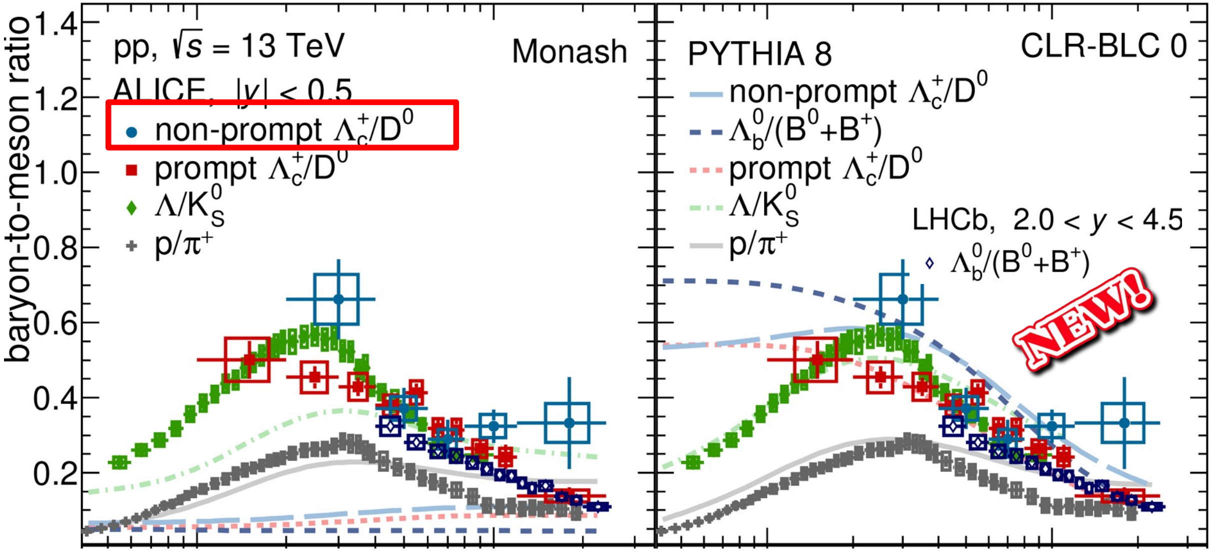
- ✔ Strange and non-strange D mesons R_{AA} well described by models including:
  - Strangeness enhancement and charm coalescence
  - Hadronization of charm via fragmentation or according to statisical weights
- ✔ Radiative processes needed to describe the data at high p_T

TAMU: PRL 124, 042301 (2020)
PHSD: PRC 93, 034906 (2016)
LGR: EPJC, 80 7 (2020) 671
CATANIA: PRC 96, 044905 (2017)

The “baryon anomaly” in the HF sector

Phys. Rev. C 107 (2023) 064901
Phys. Rev. D 108 (2023) 112003

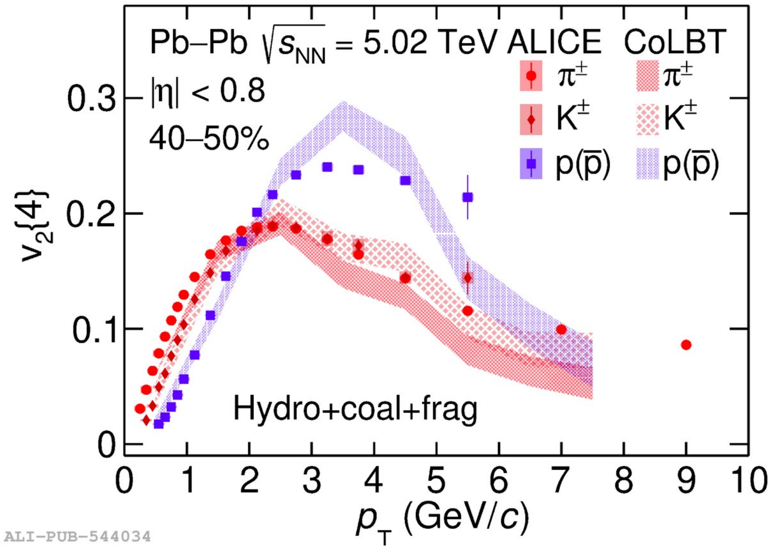




- ✔ First measurement of **non-prompt Λ_c/D^0** ratio in pp collisions
- ✔ All ratios, but p/π^+, are higher compared to corresponding values in e^+e^-
- ✔ PYTHIA8 including color reconnection meachanism beyond leading color (CLR-BLC) is able to predict the increasing trend at low transverse momentum
  - More precise data from Run 3 will help to constrain models

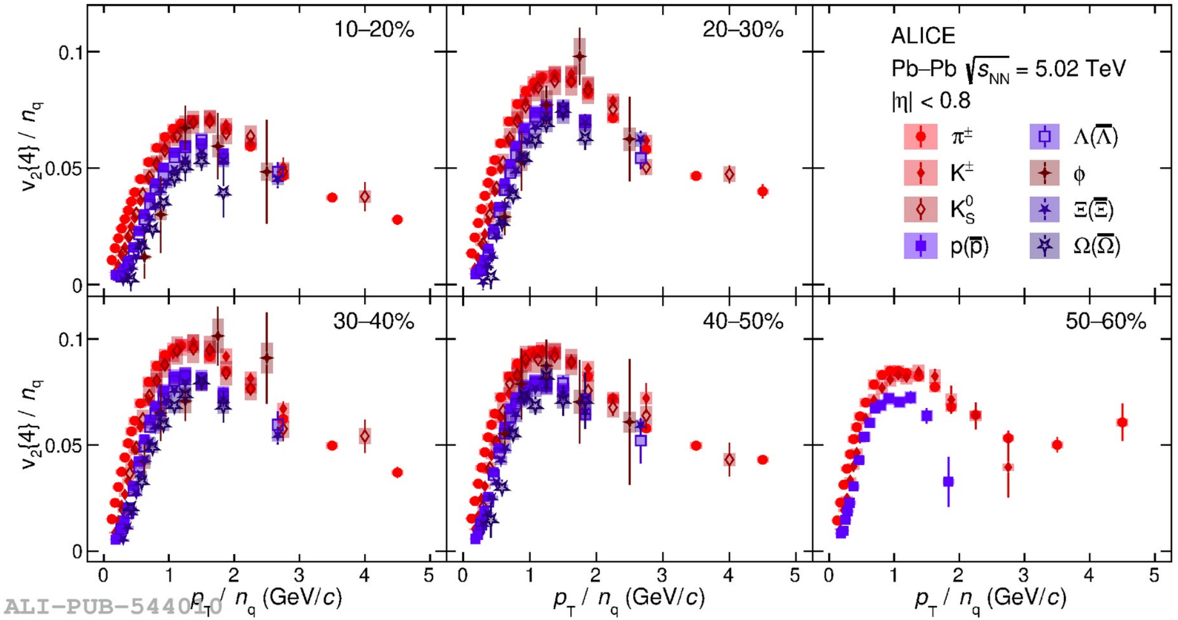
Anisotropic flow of identified hadrons

JHEP 05 (2023) 243



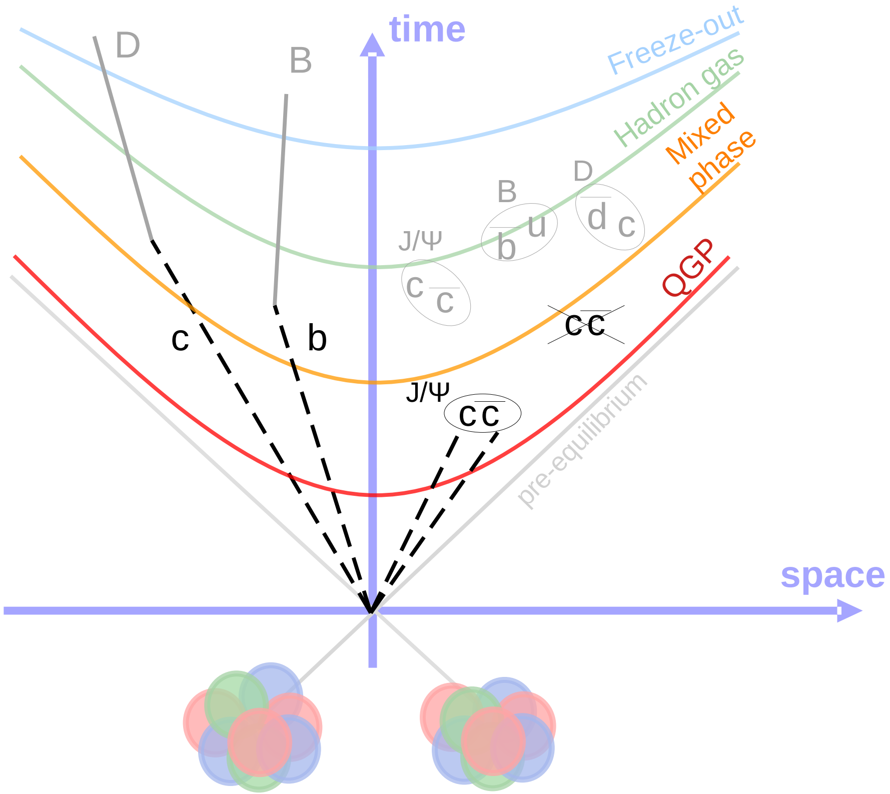
- ✔ Mass ordering at low p_T and meson-baryon splitting at intermediate p_T
- ✔ Overall good description provided by CoLBT model (including hydro+coalescence+fragmentation)

- ✔ Approximate scaling with number of constituent quarks observed (accuracy 20%)
  - Coalescence contribution needed for describing data at intermediate p_T (but not the only mechanism at play)

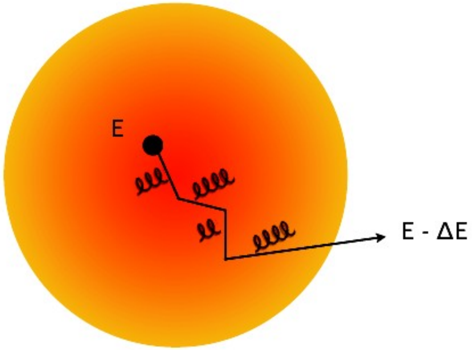


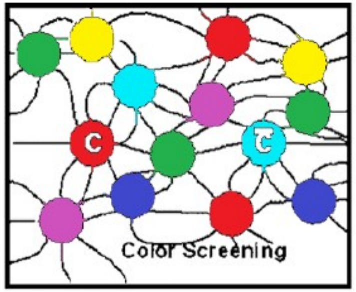
CoLBT: W. Zhao et al., PRL 128 (2022) 022302

Heavy flavour: testing in medium interaction

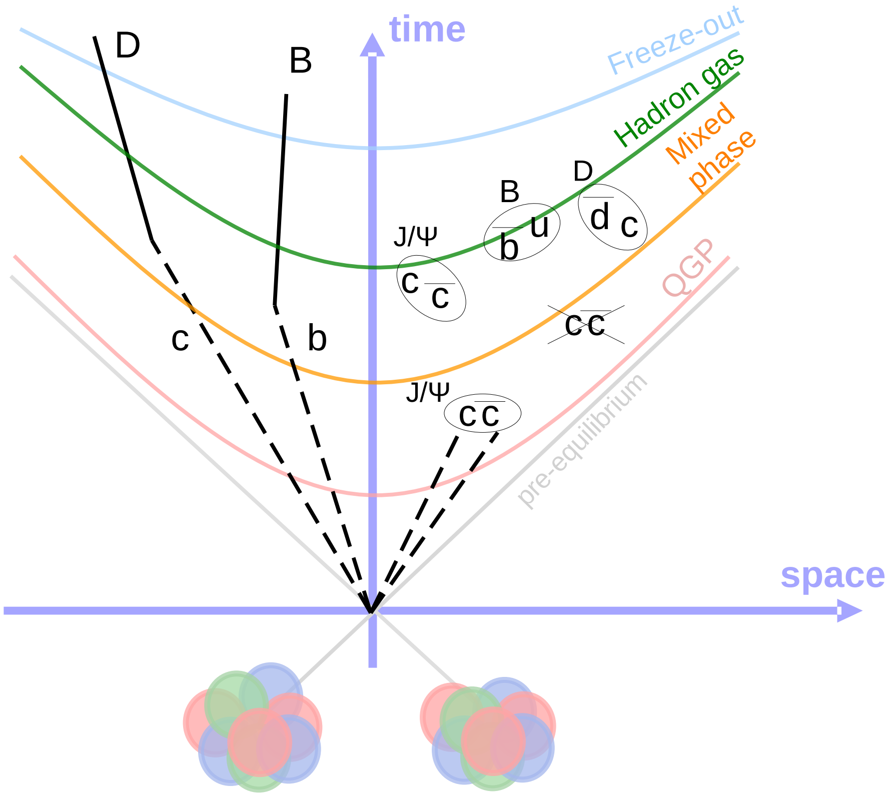


- Interaction with QGP medium constituents
  - energy loss of heavy quarks via elastic collisions and/or radiative processes
  - low-p_T heavy quarks: thermalisation in the medium?
  - dissociation of quarkonium states via color debye screening ($\tau_{QQ} \simeq$ 0.2-2 fm/c)





Heavy flavour: testing in medium interaction and hadronization



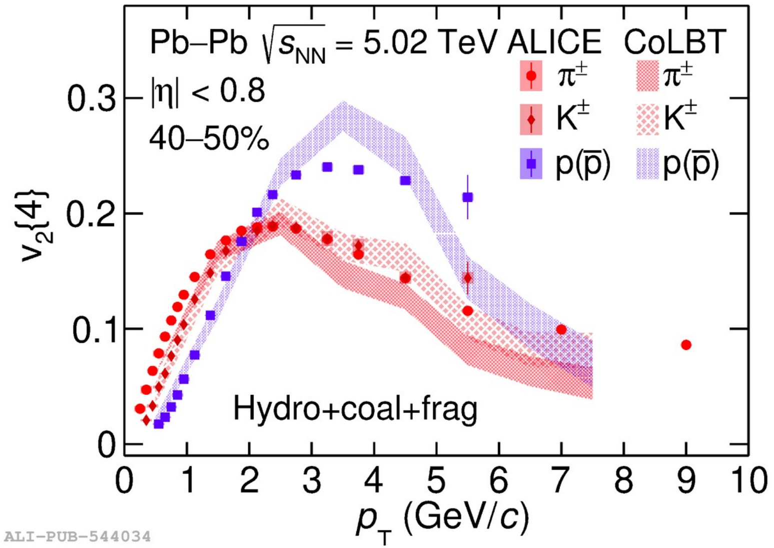
- Hadronization in presence of medium:
  - fragmentation → energy-loss of partons modifies the fraction of the parton momentum z_q taken by the hadron
  - Coalescence / regeneration
    - Through the QGP / mixed phases → partons close in space and with similar velocities can recombine into hadrons

      [V. Greco et al., PRL 90, 202302 (2003)]
    - At the chemical freeze-out → hadrons are formed according to thermal weights at the chemical freeze-out

      [A. Andronic et al., PLB 659 (2008) 149-155]

Anisotropic flow of identified hadrons

JHEP 05 (2023) 243



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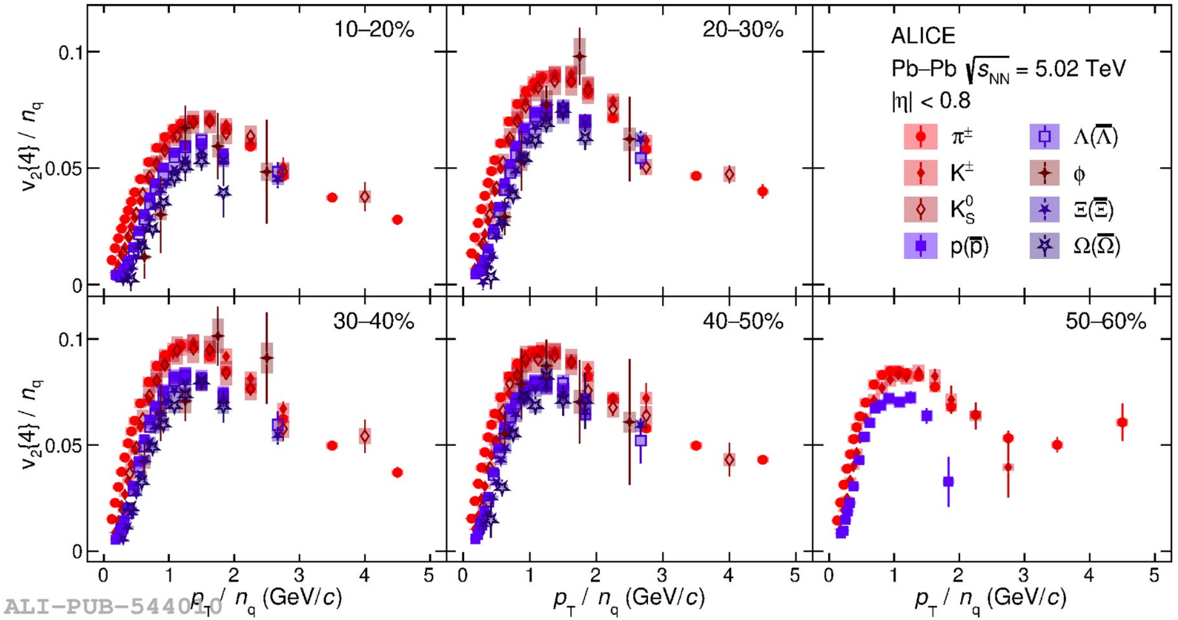

CoLBT: W. Zhao et al., PRL 128 (2022) 022302