Exploring the hadron gas phase of relativistic heavy-ion collisions with ALICE

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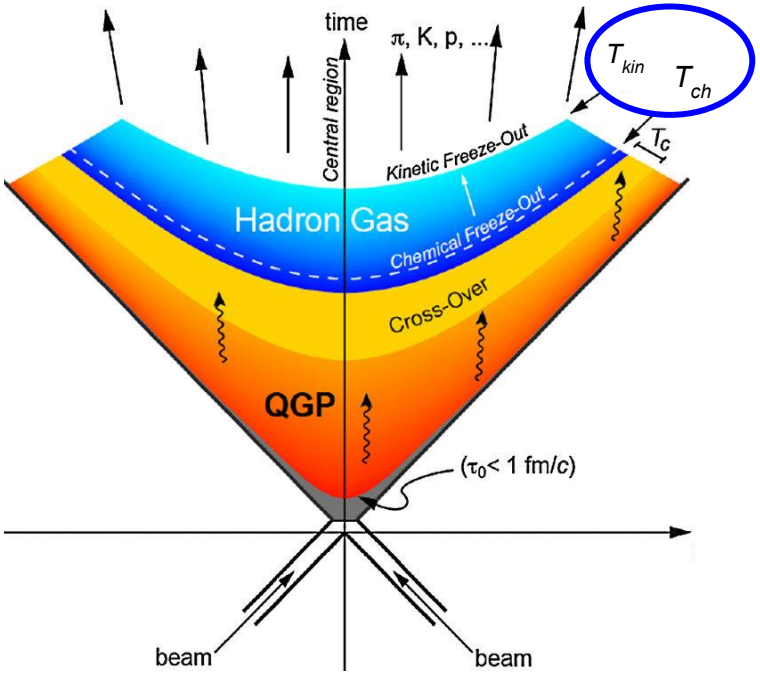
QM 2023, September 3-9, 2023, Houston Texas

High energy collision and Evolution



- At the LHC, **quark–gluon plasma** (QGP) state is created in high energy heavy-ion collisions.
- **After hadronization, all inelastic collisions stops, fixed chemical composition** of the system (chemical freeze-out; **T_{ch}≈ 150 - 160 MeV**).
- The hadron gas **continues to expand** until **all interactions cease** (kinetic freeze-out; at **T_{kin} ≈ 100 - 120 MeV**), fixed momentum distributions of particles.
- **The duration of the hadron-gas phase** between chemical freeze-out and kinetic freeze-out is of the same order of magnitude as of the resonance lifetimes (τ ~ few fm/c).
- Afterwards, **particles fly towards detectors as free hadrons** and can be measured.

Light-Flavour Hadronic Resonances in ALICE

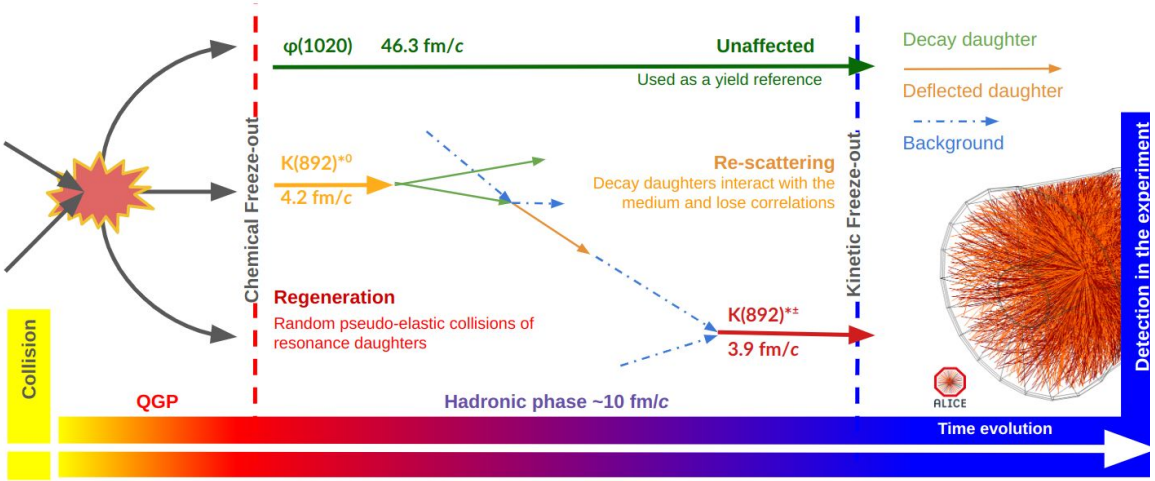
Resonance	$\rho(770)$	$K(892)^{\pm}$	$K(892)^{0}$	$f_0(980)^{0}$	$\Sigma(1385)^{\pm}$	$\Xi(1820)^{\pm}$	$\Lambda(1520)$	$\Xi(1530)^{0}$	$f_1(1285)$	$\Phi(1020)^{0}$
Decay	$\pi\pi$	$K_s^0\,\pi$	$K\pi$	$\pi\pi$	$\Lambda\pi$	ΛK	pK	$\Xi\pi$	$K_s^0\,K\pi$	KK
B. R. (%)	100	33.3	66.6	46	87	*unknown*	22.5	66.7	2.25	48.9
Quark constituents	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$u\bar{s},\ \bar{u}s$	$d\bar{s},\ \bar{d}s$	*unknown*	$uus,\ dds$	uss	uds	uss	*unknown*	$s\bar{s}$
$\tau(fm/c)$	1.3	3.6	4.2	*large unc.*	$5-5.5$	8.1	12.6	21.7	22.7	46.4

More by S. Padhan on 5th Sept, 11:40

- **Short lifetimes,** comparable to the one of the **hadronic gas phase** (τ ~ few fm/c)
  → suitable probe to study the properties of the hadronic phase in heavy-ion collisions.

- **ALICE** is the perfect detector to study these resonances
  → A rich set of data collected in pp, p-Pb, Xe-Xe and Pb-Pb collisions at high energy ($\sqrt{s_{NN}}$~ TeV) over the years.
  → Extensive PID capabilities from low momentum region (~ 150 MeV) to high momentum region.

Resonance as probe of the hadronic phase



Hadronic phase (~10 fm/*c*) can be **probed with hadronic resonances** (τ ~ few fm/*c*).

Reconstructible yield affected by

→**Regeneration:** Pseudo-elastic scattering of decay daughters, gain resonance (e.g. Kp → Λ(1520) – Kp)

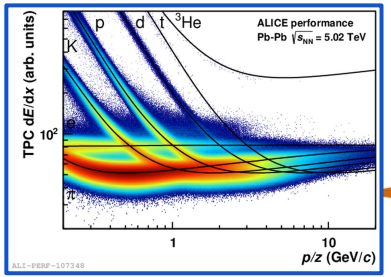
→**Rescattering:** elastic or pseudo-elastic scattering smears out mass peak, looses resonance

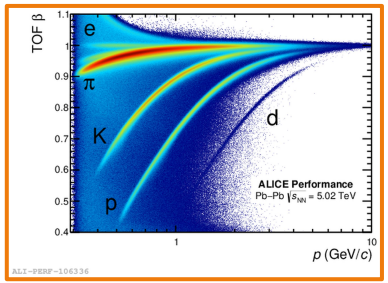
- **Final yield** at kinetic freeze-out **depends on**
  → **chemical freeze-out temperature** (T_{ch}),
  → **duration of hadronic phase,**
  → **lifetime of resonance**
  → **scattering cross section** of decay products

- **Resonance yield to stable particle with similar quark content** encodes the effects of such interactions

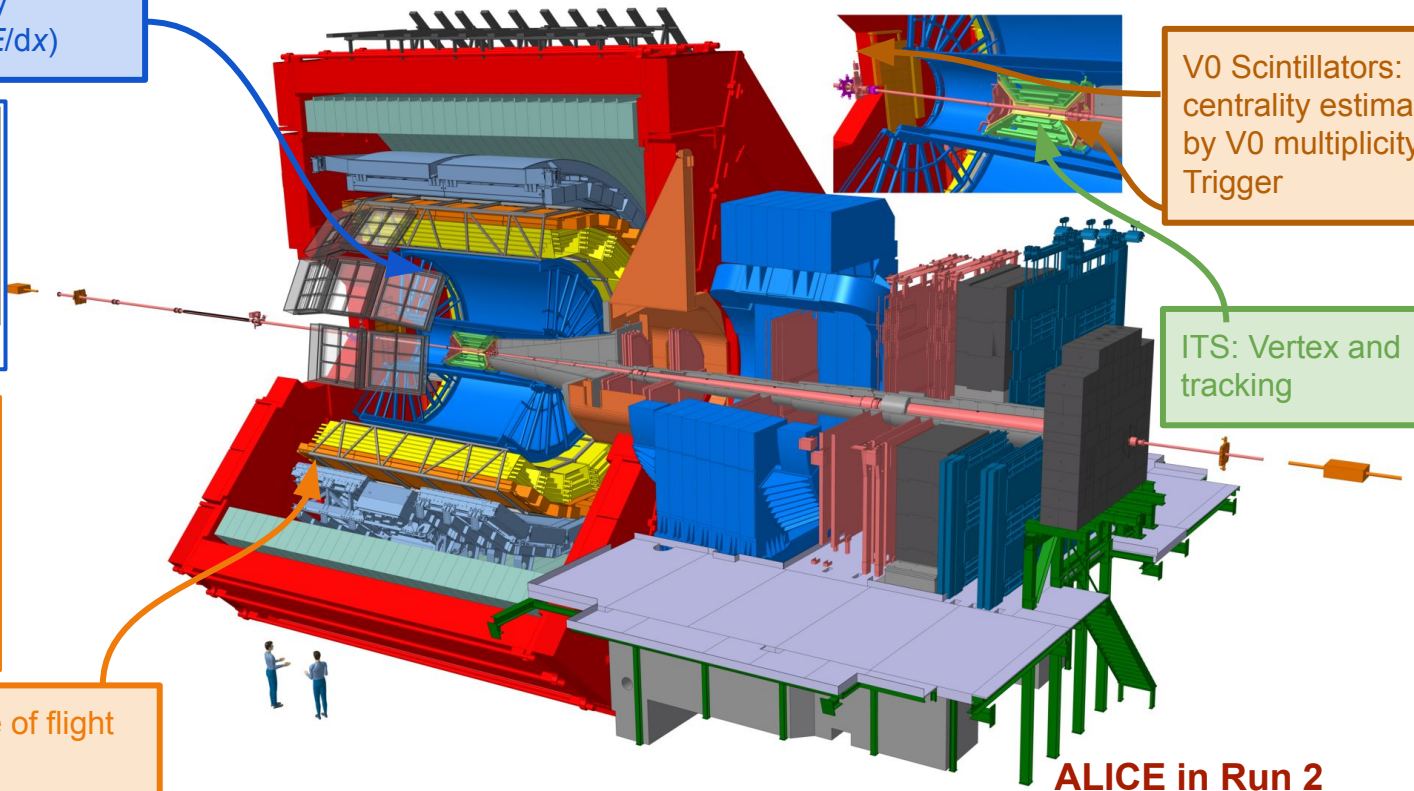
The ALICE detector: excellent PID at low-p_T

TPC: Tracking and PID by ionisation energy loss (d*E*/d*x*)





TOF: PID by particle time of flight (β) and event timing

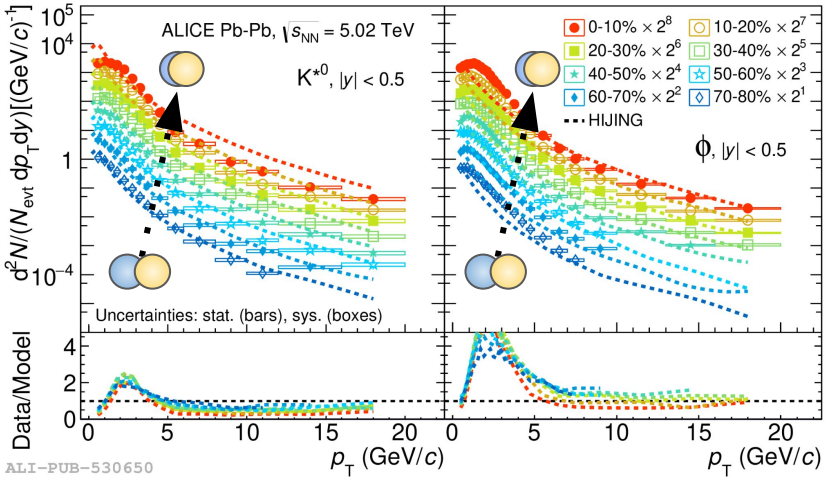


V0 Scintillators: centrality estimation by V0 multiplicity and Trigger

ITS: Vertex and tracking

ALICE in Run 2

K*(892) and ϕ(1020), p_T-spectra in heavy-ion collisions



- The p_T-spectra of K*(892) and ϕ(1020) measured in **Pb–Pb collisions** at $\sqrt{s_{NN}}$ = **5.02 TeV**
  → fine centrality intervals, from 0-10% to 70-80%.
  → **hardening of the p_T-spectrum** from peripheral to central collisions for both particles.

ALICE, Phys. Rev. C 106 (2022) 034907

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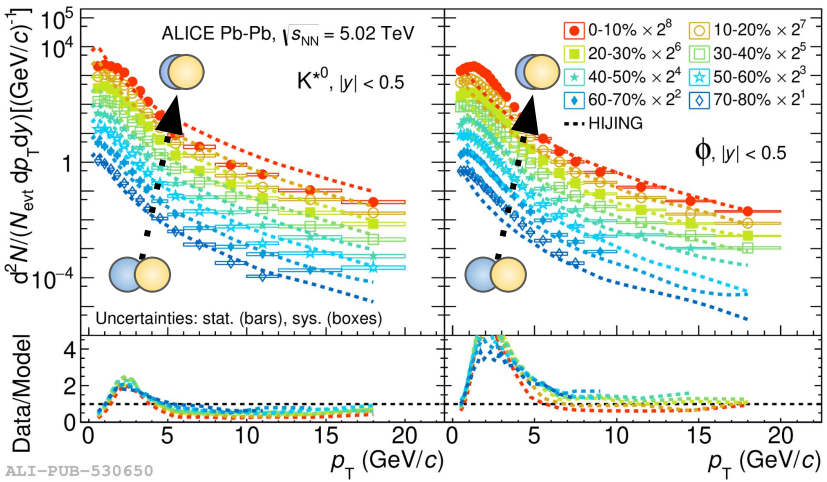

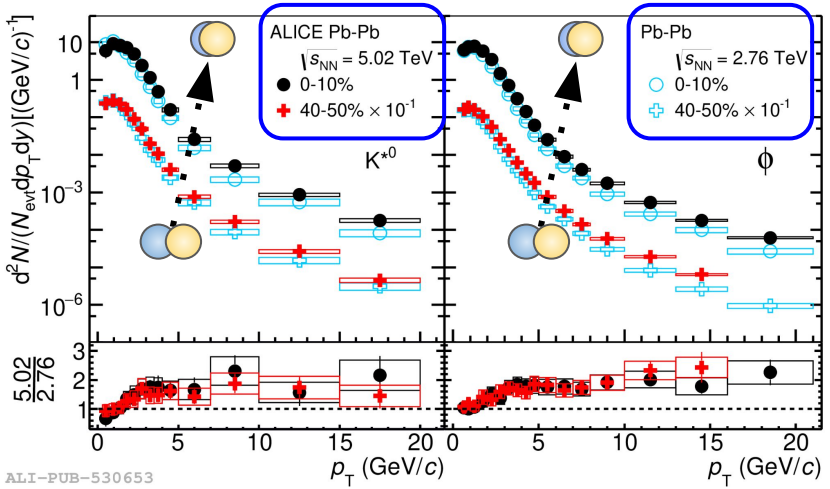

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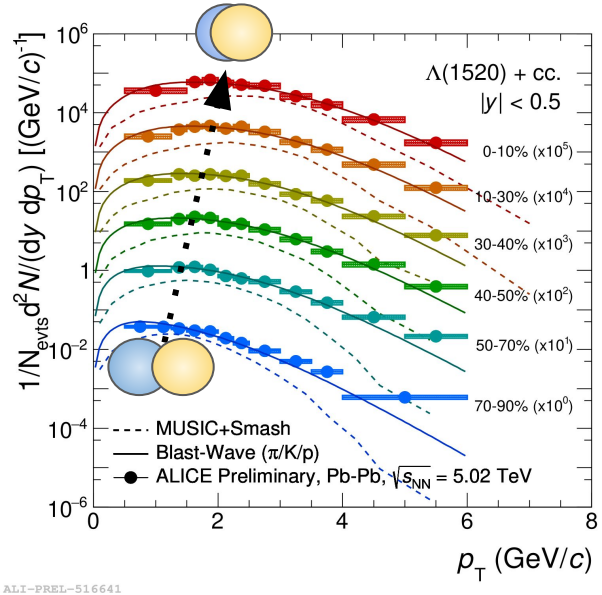
  → fine centrality intervals, from 0-10% to 70-80%.
  → **hardening of the p_T-spectrum** from peripheral to central collisions for both particles.

- The p_T-spectra ratio of 5.02 TeV to 2.76 TeV
  → yield increase of both K*(892) and ϕ(1020) in **Pb–Pb collisions** from $\sqrt{s_{NN}}$ = **2.76 TeV to 5.02 TeV.**
  → ratio of p_T-spectra from two energies increases with p_T and tend to saturate at high p_T for both mesons.

ALICE, Phys. Rev. C 106 (2022) 034907

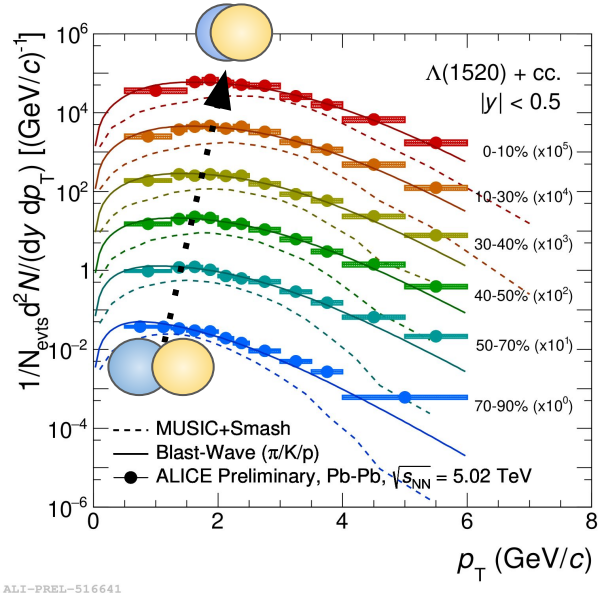
Λ(1520), p_T-spectra and <p_T> in heavy-ion collisions

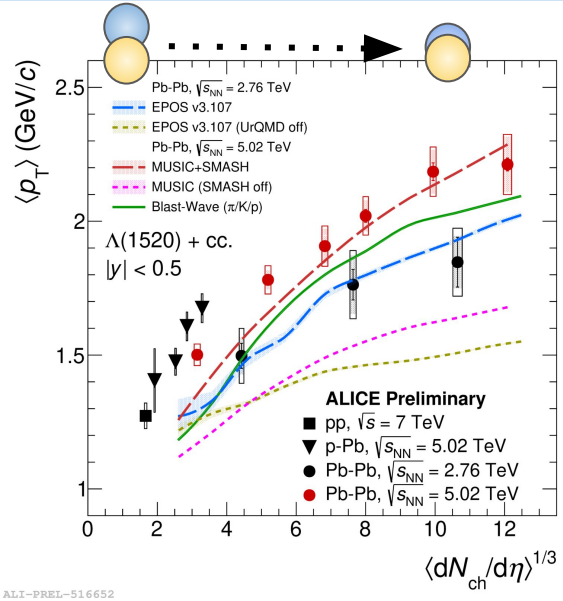


[1] ALICE, Phys. Rev. C 99, 024905 (2019)
[2] ALICE: Phys. Rev. C 101, 044907 (2020)
[3] EPOS3:10.1103/PhysRevC.93.014911
[4] MUSIC:arXiv:2105.07539

- **The spectral shapes show**
  → good agreement with **Blast-Wave** (π/K/p fits).
  → close to **MUSIC hydrodynamic models** [3] with **SMASH afterburner** predictions at low p_T, diverge at high p_T.
  → **MUSIC slightly underestimates the data** as model underestimates overall strangeness production at midrapidity.

Λ(1520), p_T-spectra and $\langle p_T \rangle$ in heavy-ion collisions





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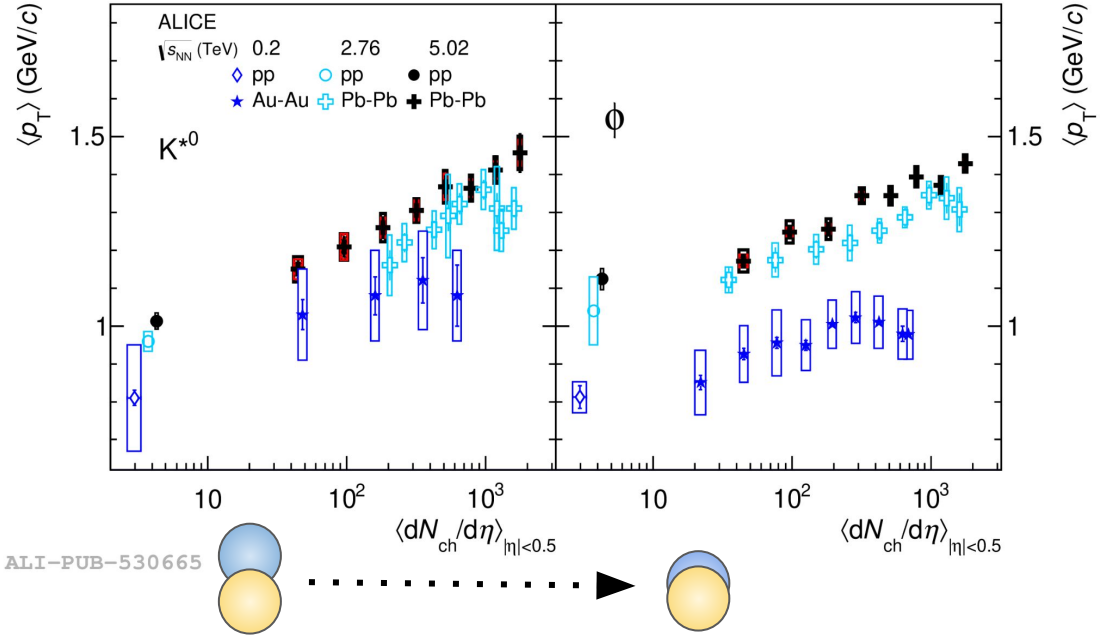
  → **MUSIC slightly underestimates the data** as model underestimates overall strangeness production at midrapidity.

- **The $\langle p_T \rangle$ values increase from peripheral to central collisions** (~47% higher)
  → **higher than Pb-Pb 2.76 TeV** values and Blast-wave model predictions (π/K/p) [2].
  → MUSIC[4] and EPOS3 [3] models give better predictions with hadronic phase modelling (SMASH [4] and UrQMD).
  → When **SMASH** is turned **off**, the **$\langle p_T \rangle$ is underestimated.**

K* and ϕ, mean transverse momentum, $\langle p_T \rangle$



- **The $\langle p_T \rangle$ values**
  → **increase towards higher centrality/multiplicity**
  → **5.02 TeV values are higher than 2.76 TeV** results
  → energy dependence between RHIC and LHC energies

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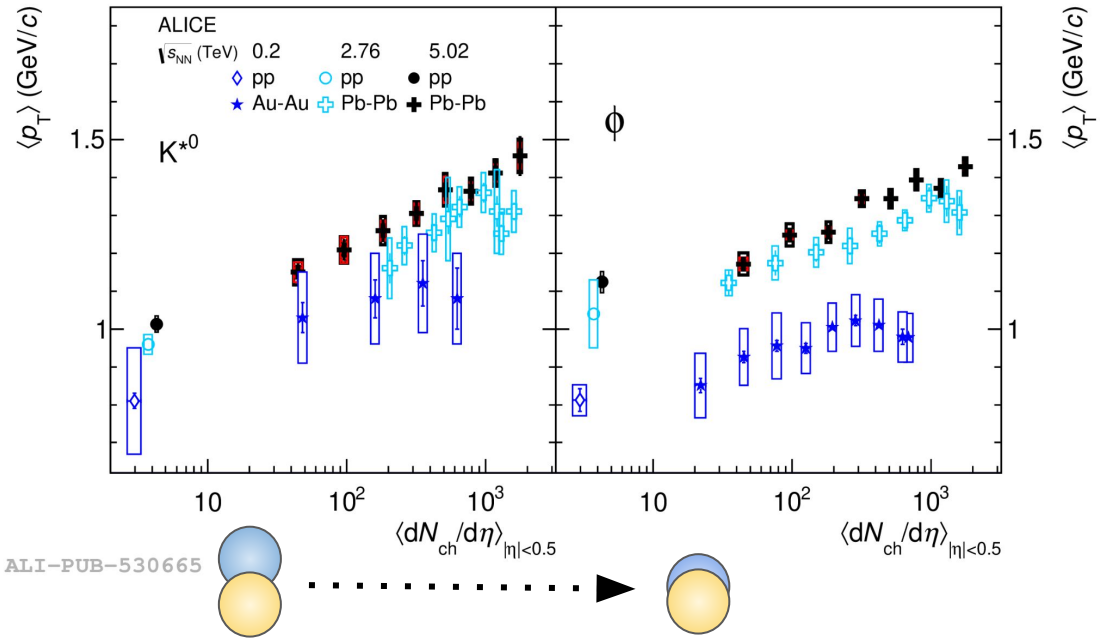

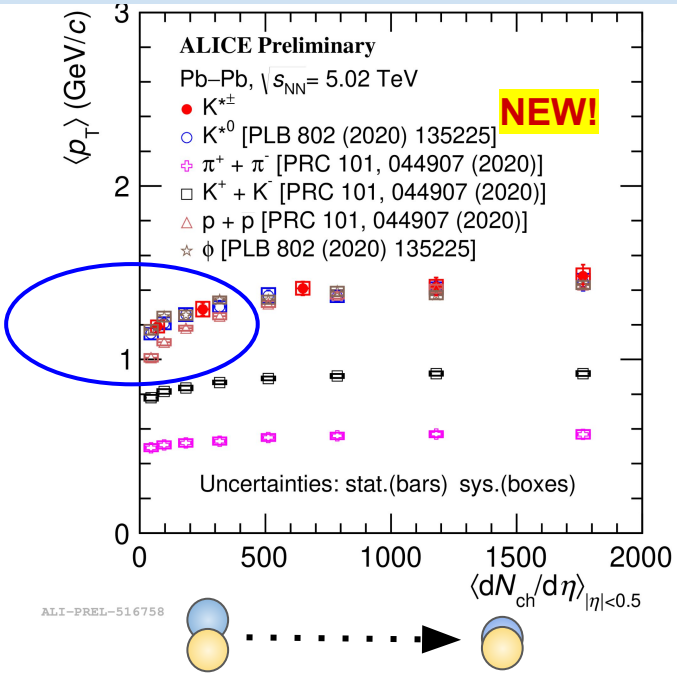

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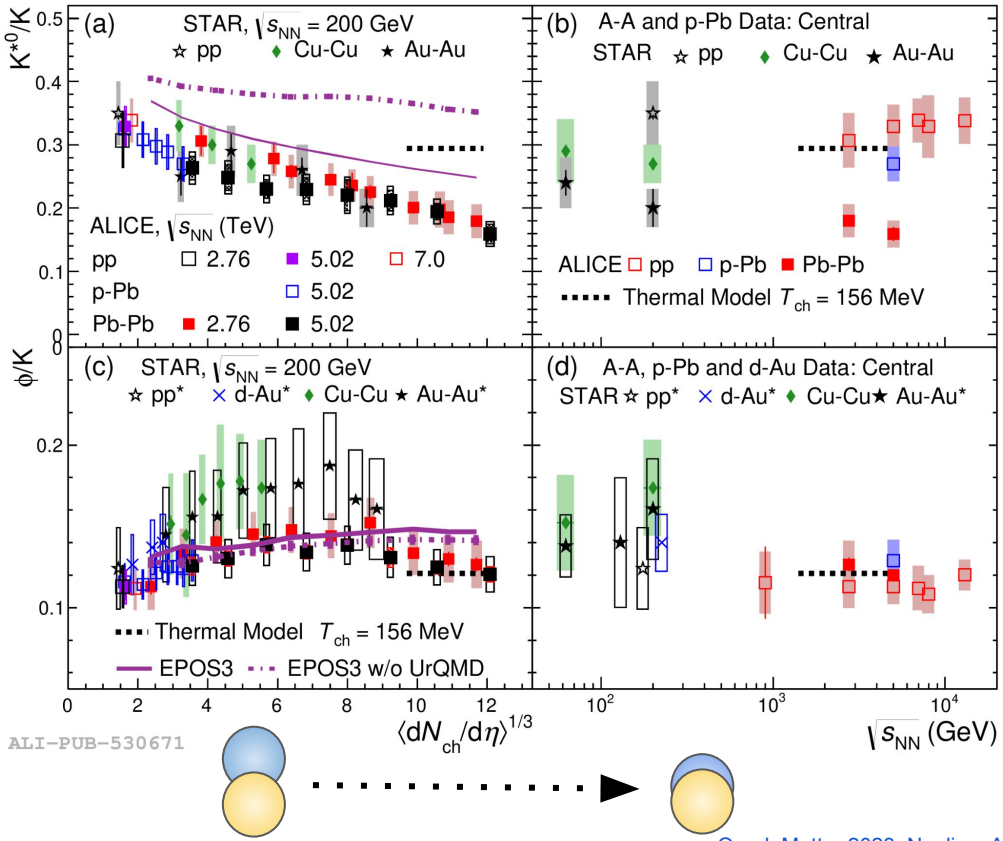
- **The $\langle p_T \rangle$ values of particles follow mass ordering**
  → Indicative of radial flow in central collisions
  → **Violated in peripheral collisions, $\langle p_T \rangle$ (ϕ > p)**

ALICE, Phys. Rev. C 106 (2022) 034907

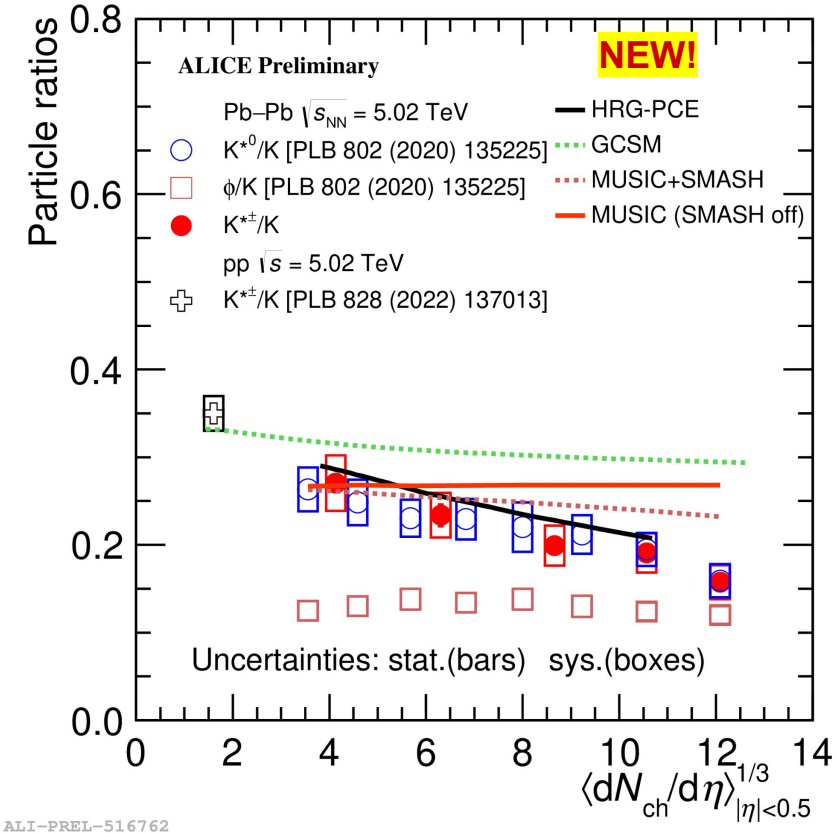
K*/K and ϕ/K ratio; multiple collision systems & energies



- **K*/K shows clear suppression**
  →going from pp, p-Pb and peripheral Pb-Pb collisions to central Pb-Pb
  → EPOS3 with UrQMD overestimates the data but reproduces the suppression trend
- **ϕ/K shows no suppression**
  →almost constant behaviour
  → EPOS3 reproduces the data
- **K* suppression by dominance of rescattering over regeneration**
- **rescattering not significant for ϕ**
  → $\tau(\phi) >> \tau(K^*)$

ALICE, Phys. Rev. C 106 (2022) 034907
***EPOS3:** 10.1103/PhysRevC.93.014911*
***Thermal Model:** J. Phys.: Conf. Ser. 509, 012019 (2014).*

K*±/K measurements in heavy-ion collision



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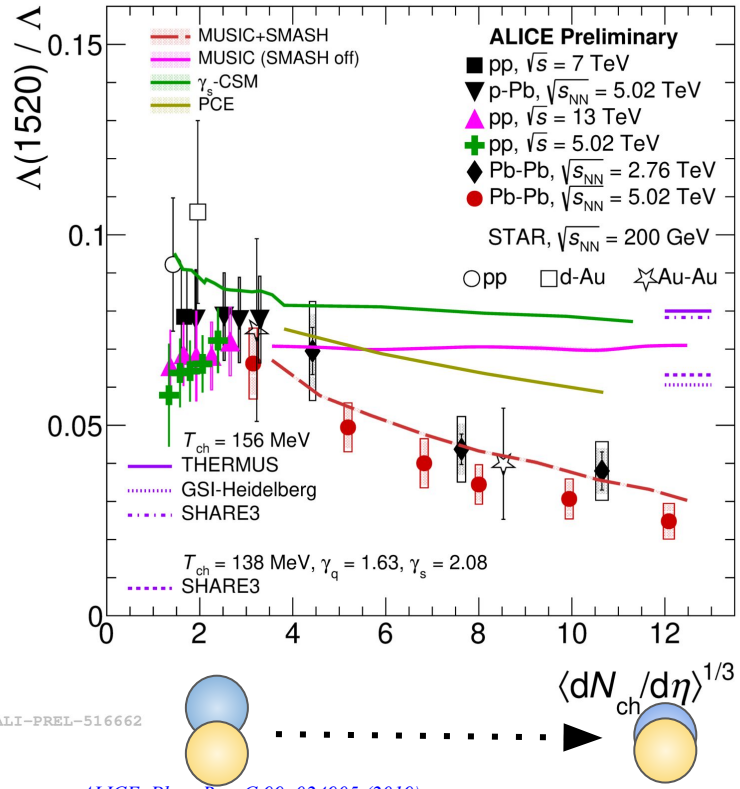
- **ϕ/K shows no suppression**
  →almost constant behaviour
  → EPOS3 reproduces the data
- most favoured explanation of **K* suppression is dominance of rescattering over regeneration**
- **re-scattering is not significant for ϕ**
  → $\tau(\phi) >> \tau(K^*)$
- **K*±/K shows similar suppression trend** and agrees with K*/K values

ALICE: arXiv:2308.16119

ALI-PREL-516762

Λ(1520)/Λ ratio; multiple collision systems & energies

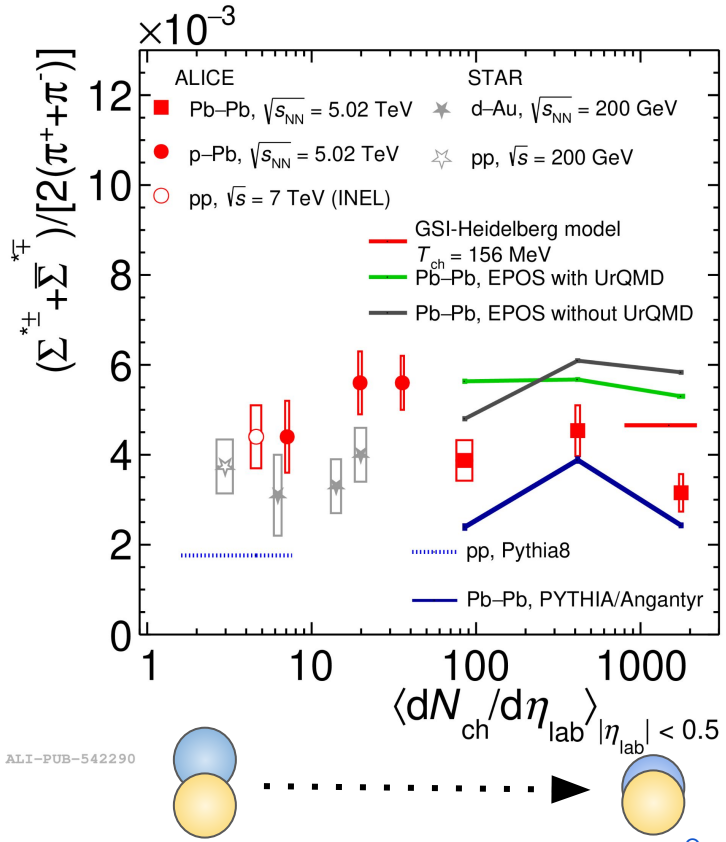


ALICE, Phys. Rev. C 99, 024905 (2019)
ALICE, Phys. Rev. C 101, 044907 (2020)

- The **Λ(1520)/Λ yield ratio is suppressed in central collisions (0-10%)**
  →compared to the peripheral Pb-Pb, p–Pb, pp collisions and statistical hadronization models predictions
  →**lower than 70-90% peripheral Pb–Pb at 7.1σ level**.
- **MUSIC with SMASH afterburner**
  →**reproduces the multiplicity suppression trend,** better agreement.
- **MUSIC without SMASH** afterburner
  → first ever prediction without an afterburner, gives a flat curve.
  → matching to peripheral 70-90% Pb-Pb collisions & near to pp values.
- **Thermal models do not reproduce the suppression trend.**

PCE: *Phys.Rev.C 102 (2020) 2, 024909*
CSM: *Phys.Rev.C 100 (2019) 5, 054906*
EPOS3: *10.1103/PhysRevC.93.014911*
MUSIC: *arXiv:2105.07539*

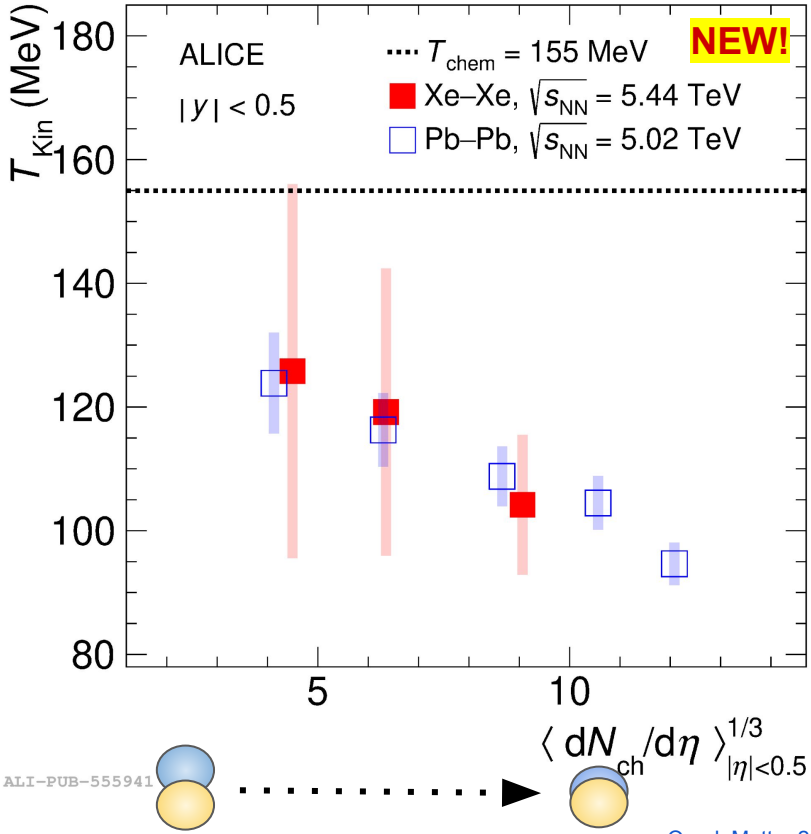
$\Sigma^{*\pm}/\pi^{\pm}$ ratio; multiple collision systems & energies



- Yield **Σ(1385)$^{\pm}$** is measured in three centrality classes (0-10%, 30-50%, 50-80%) in Pb-Pb collisions at 5.02 TeV.
- The **p_T-integrated $\Sigma^{*\pm}/\pi^{\pm}$ yield ratio** is shown → the ratio is **suppressed in central collisions (0-10%)** if compared to the values observed in peripheral collisions, p-Pb, pp collisions and predictions from statistical hadronisation models.
- **EPOS3 with UrQMD afterburner** overestimates the data.
- **Suppression at a level of 3.6σ in central Pb-Pb collisions (0-10%) with respect to thermal model calculation.**

ALICE, Eur. Phys. J. C 83 (2023) 351
ALICE, arXiv:2308.16116

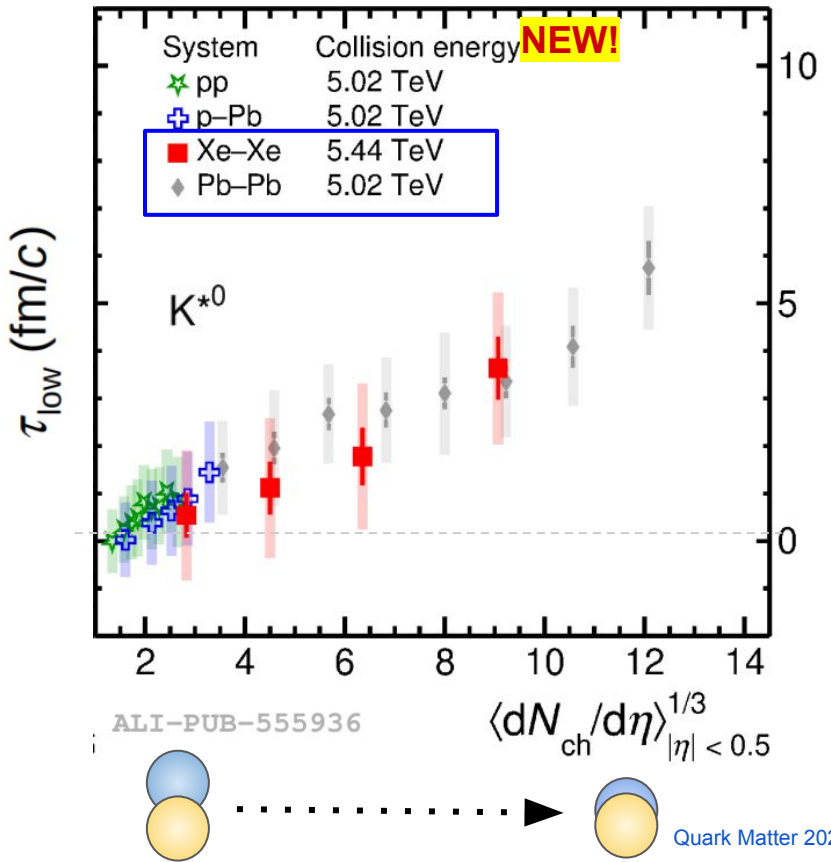
Findings on T_{kin}, Xe-Xe collisions



- Kinetic freeze-out temperature is measured in Xe-Xe (new) and Pb-Pb collisions
  →Estimated **T_{kin} value ≈ 100 - 120 MeV**
  →used hadron resonance gas in partial chemical equilibrium, **HRG-PCE**
  → by model fit to the measured yield of π, K, p, ϕ, K* and their anti-particles for different centrality classes

ALICE: arXiv:2308.16115
HRG-PCE: *Phys. Rev. C 102 no. 2, (2020) 024909*

Findings on hadronic phase lifetime, Xe-Xe collisions



Lower limit of the timespan between chemical and kinetic freeze-out is estimated by the exponential law:

$r_{kin} = r_{chem} \times \exp(-(\tau_{kin} - \tau_{chem})/\tau_{res})$

→ r_{kin} = measured yield ratios in heavy-ion (Pb-Pb) collisions

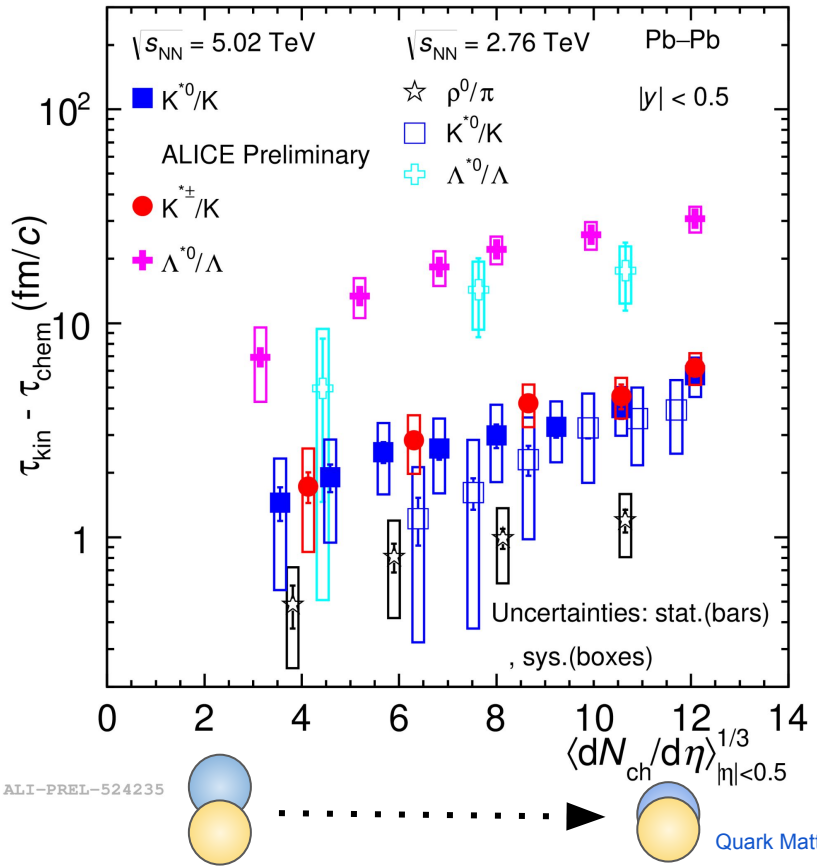
→ r_{chem} = measured yield ratios in pp collisions

→ τ_{res} = lifetime of the resonance particle

- Assumptions
  →**simultaneous freeze-out of all the particles.**
  →**Negligible regeneration of resonances.**
- Xe-Xe values in agreement with Pb-Pb collisions values.
- smoothly **increases with centrality/multiplicity.**

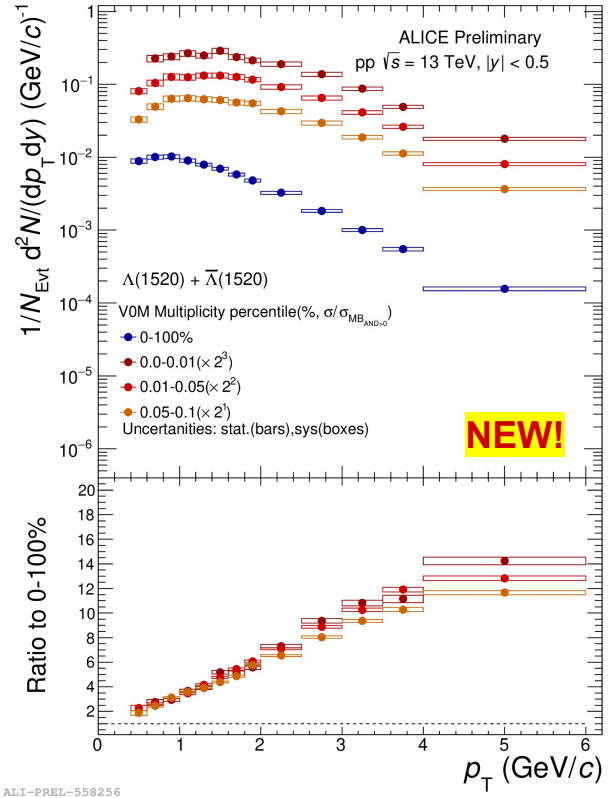
ALICE: arXiv:2308.16115

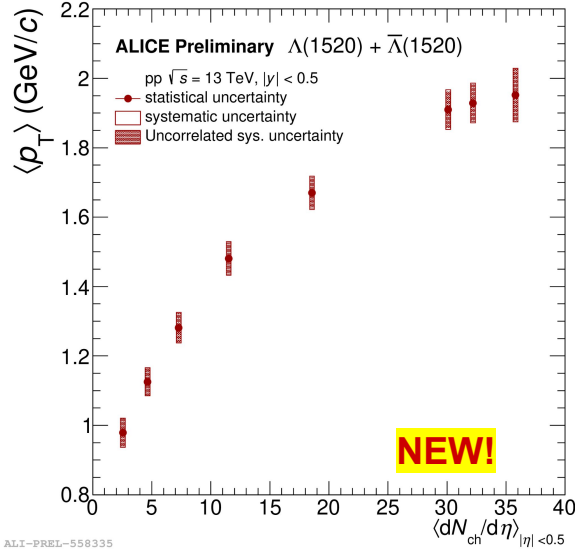
Findings on hadronic phase lifetime

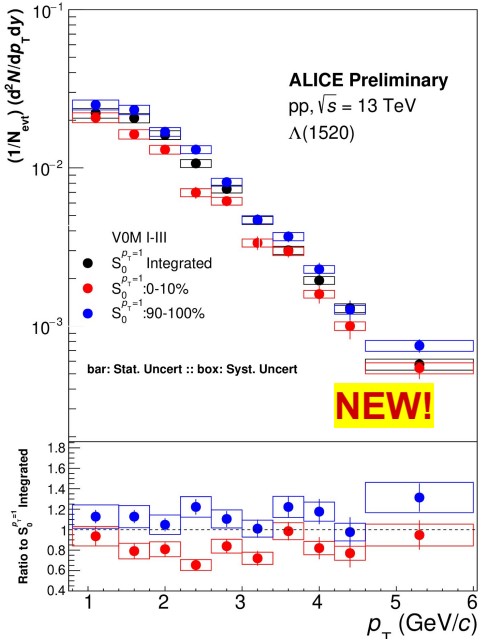


- **Estimated hadronic phase life-time** in Pb-Pb collisions at 5.02 and 2.76 TeV
- **Measurement uses K*, Λ* and ρ^0 results**
- **Lifetime** of the hadronic phase smoothly **increases with centrality/multiplicity.**
- **Confirmed signature of presence of hadronic medium lasting long enough to reduce the reconstructable yield of short-lived resonances**

New results in pp collisions in run 2 data

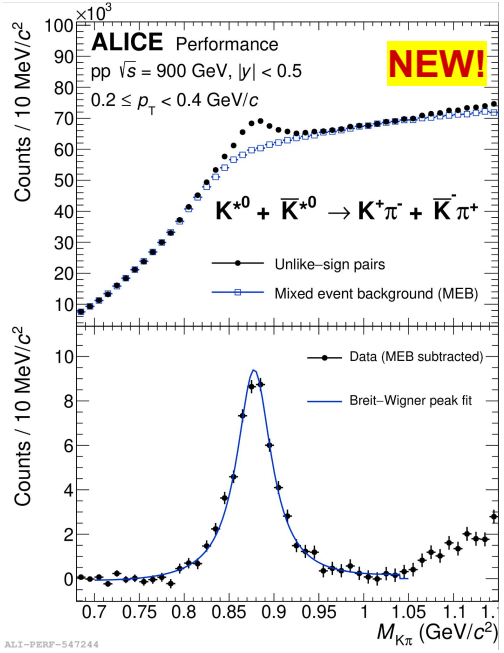


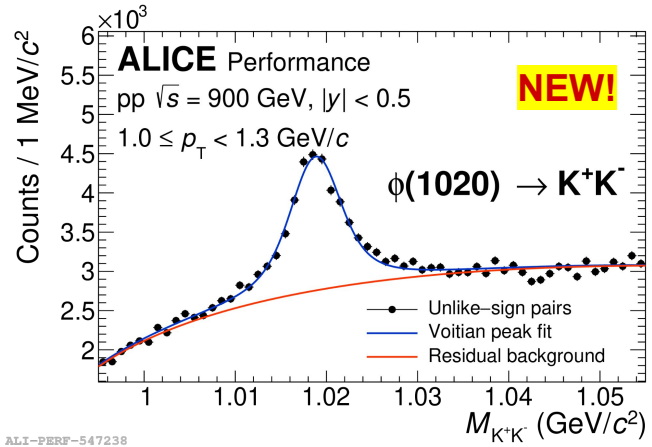


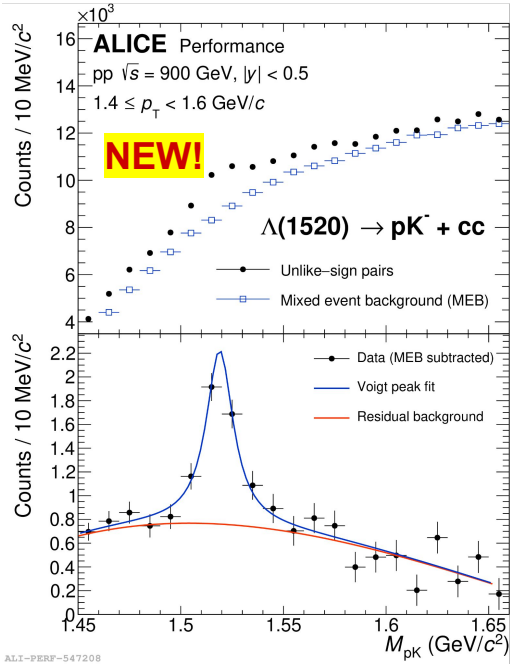


- High multiplicity, pp@ 13 TeV
  → The spectral shapes get **harder from low to high multiplicity class.**
  → **Mean p_T increases** and saturates for high multiplicity classes.
  → Spherocity analysis, using large data sample to perform differential analysis.

ALICE measures resonances in Run 3







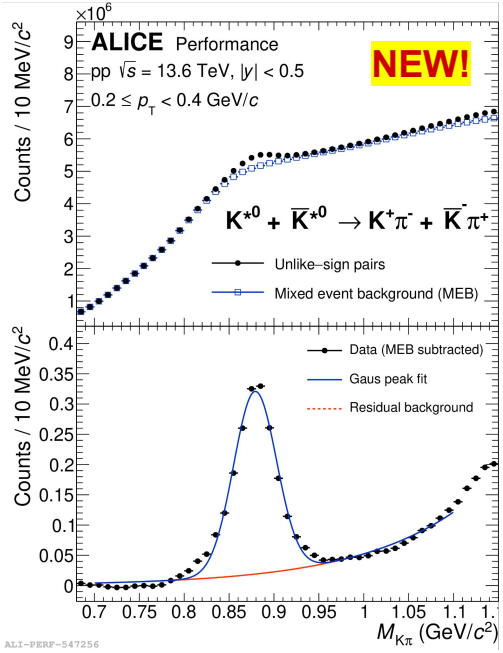
Run 3 resonance measurements are ongoing in full swing

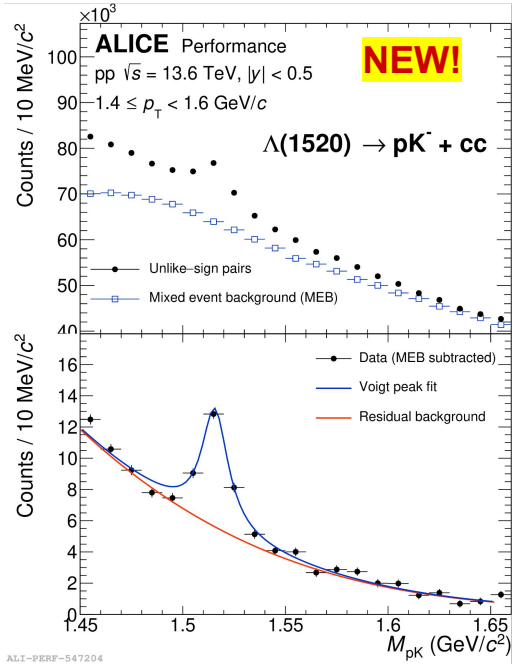
→ Extracted signals for **K*(890), ϕ(1020) and Λ(1520).**

→ ALICE performance is good in Run 3

→ full analysis for each particle is under progress

ALICE measures resonances in Run 3





Stay tuned for more results...

Summary

- **A complete set of resonances is measured in ALICE**
  → exploited full Run 2 statistics by using pp, p-Pb, Xe-Xe and Pb-Pb collision data at various centre-of-mass energies

- **Highlights the suppression of short-lived resonances**
  → no suppression of longer lifetime resonance

- **Estimated Kinetic freeze-out temperature** in heavy ion collisions in Xe-Xe at 5.44 TeV and Pb-Pb at 5.02 TeV (100 - 120 MeV)

- **Measured lifetime of the hadronic phase by the yields of various short-lived resonances**
  → Increases with centrality/multiplicity
  → **Confirmed signature of presence of hadronic medium lasting long enough to reduce the reconstructable yield of short-lived resonances in heavy-ion collisions**

- **ALICE shines in Run 3 with its good performance**
  → already exhausting Run 3 data for measurements on resonances

Thank you very much for your attention…

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