HADRON2023

Light flavour resonance production with the ALICE at the LHC

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Light-Flavour Hadronic Resonances in ALICE

Resonance	$\rho(770)$	$K(892)^{\pm}$	$K(892)^{0}$	$f_0(980)^{0}$	$\Sigma(1385)^{\pm}$	$\Xi(1820)^{\pm}$	$\Lambda(1520)$	$\Xi(1530)^{0}$	$\Phi(1020)^{0}$
Decay	$\pi\pi$	$K_s^0\pi$	$K\pi$	$\pi\pi$	$\Lambda\pi$	ΛK	pK	$\Xi\pi$	KK
$B.R.$ (%)	100	33.3	66.6	46	87	*unknown*	22.5	66.7	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	$s\bar{s}$
$\tau(fm/c)$	1.3	3.6	4.2	*large unc.*	$5-5.5$	8.1	12.6	21.7	46.4

Table: Resonances studied in ALICE in Run1 and Run2

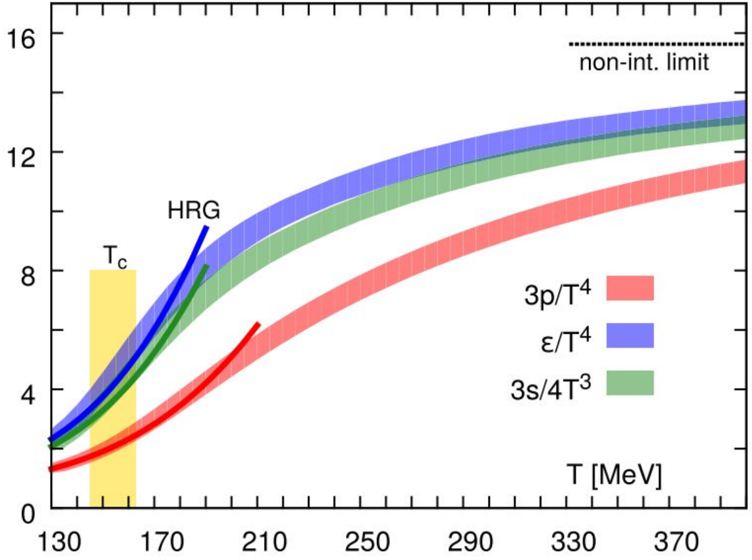
- **Short lifetimes,** comparable to the one of the **hadronic gas phase** (τ ~ few fm/c)
  → suitable probe to study the properties of the hadronic phase in heavy-ion collisions.

- **ALICE** is the perfect detector to study these resonance
  → 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

Heavy-ion Physics

Study QCD matter under extreme conditions
→ high temperature and energy density

PHYSICAL REVIEW D **90**, 094503 (2014)



Prediction of phase transition from **Lattice QCD**

Calculations of ε/T^4 vs temperature
→ ε/T^4 ~ #degrees of freedom

For T~ 150 MeV, sharp increase in ε/T^4 (degrees of freedom)
hadrons → quarks and gluons

Lattice QCD indicate **phase transition of ordinary nuclear matter to QGP** at a critical temperature (T_c) of
→ **T_c = 155 - 158 MeV**

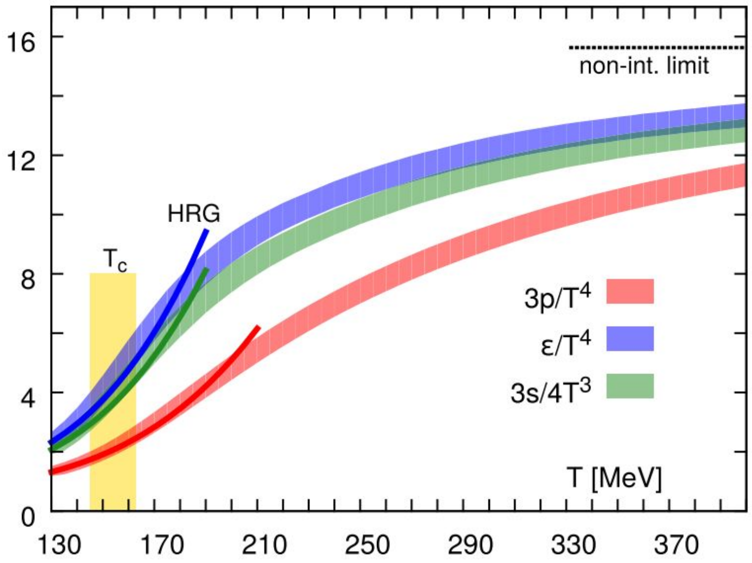
HotQCD Coll. Phys.Lett.B 795 (2019) 15,

Borsaniy et al. PRL 125 (2020) 5, 052001

Heavy-ion Physics

Study QCD matter under extreme conditions
→ high temperature and energy density

PHYSICAL REVIEW D **90,** 094503 (2014)



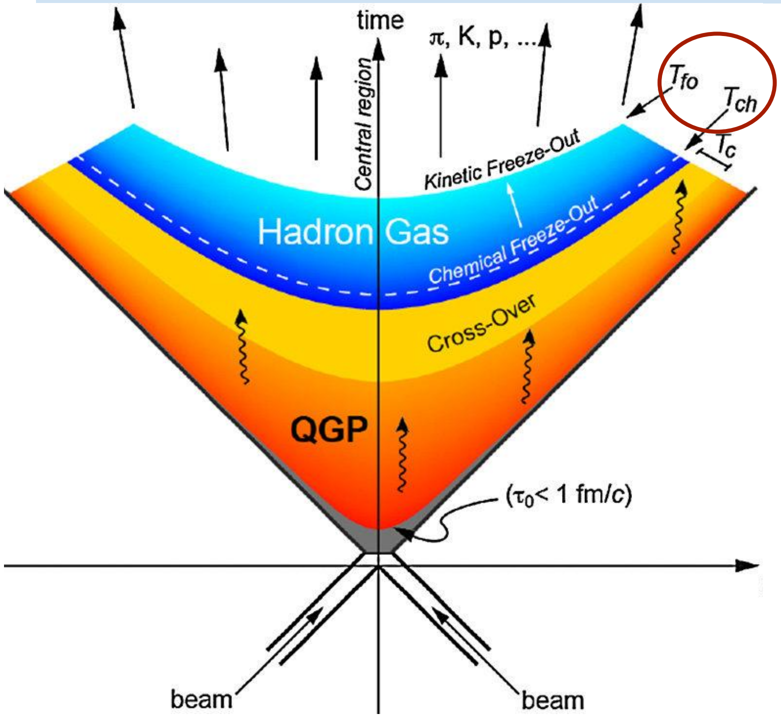
These conditions can be achieved by **colliding heavy ions at high energy** (at LHC, Pb-Pb at 2.76 and 5.02 TeV)

At very **high energy density** (> 1 GeV/fm^3)

Nuclear matter expected to undergo a **phase-transition** from hadronic matter to deconfined state of quarks and gluons, known as **quark-gluon plasma (QGP)**

Physical Review D 90, 094503 (2014)

High energy collision and Evolution

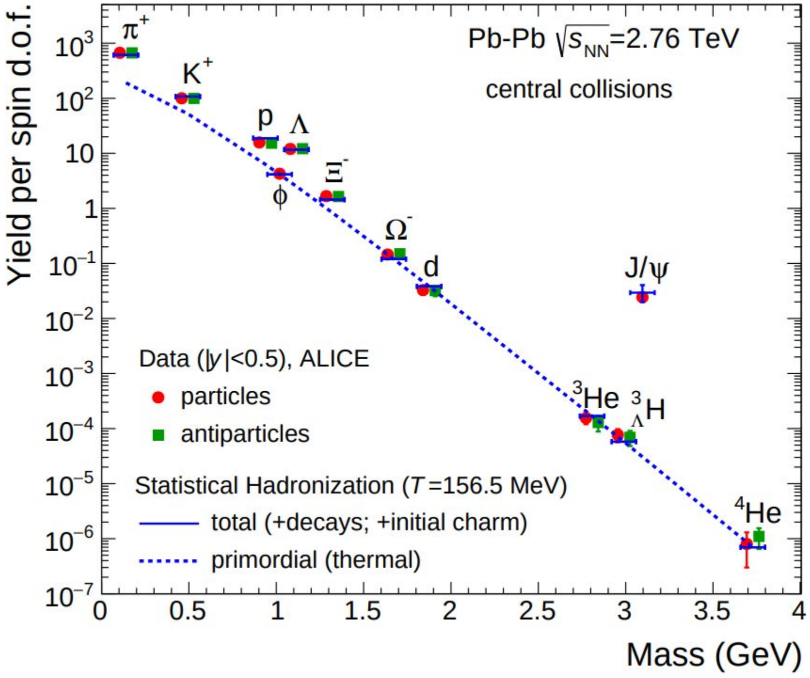


Schematic diagram of the space time evolution of a heavy-ion collision in case of with QGP

- At the LHC, **quark–gluon plasma** (QGP) state is created in high energy heavy-ion collisions. As the system expands, it cools down and transitions back to hadronic matter.
- **After hadronization,** the system reaches a stage at which **all inelastic collisions stops** and **chemical composition** of the system is **fixed** (chemical freeze-out; at T_{ch}).
- The hadron gas **continues to expand** until **all interactions cease** (kinetic freeze-out; at T_{fo}) and particle momentum distributions get fixed
- **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.

Temperature at chemical freeze-out

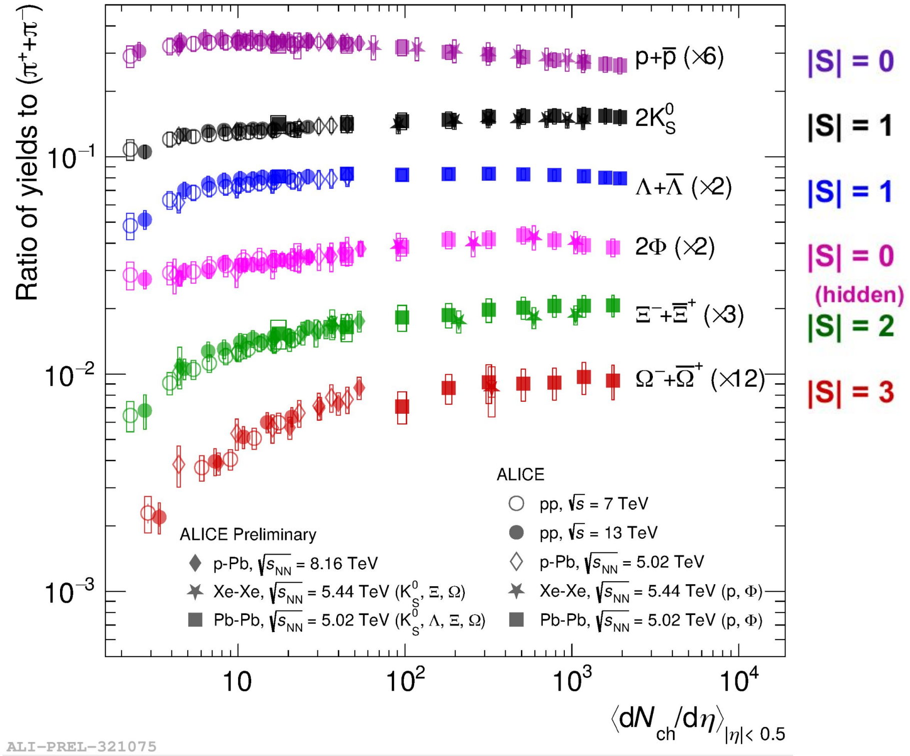
Statistical Hadronization Model (SHM)



A. Andronic et al., Phys.Lett.B 797 (2019) 134836

- At the hadronization stage, the system is close to thermal equilibrium
- A rapid hadrochemical freeze-out takes place at the phase boundary (at ***T_{ch}***)
- The **relative abundances** of stable particles are successfully **described by statistical hadronisation models (SHMs) over 9 orders of magnitude!**
- Resonances are expected to be produced with abundances consistent with the chemical equilibrium parameters (T_{ch}, μ_B).
- Note that also loosely bound objects (light nuclei and hyper nuclei) and heavy-flavour hadron (J/ψ) are described by the SHMs
- **Total yield include contributions from resonance decays**

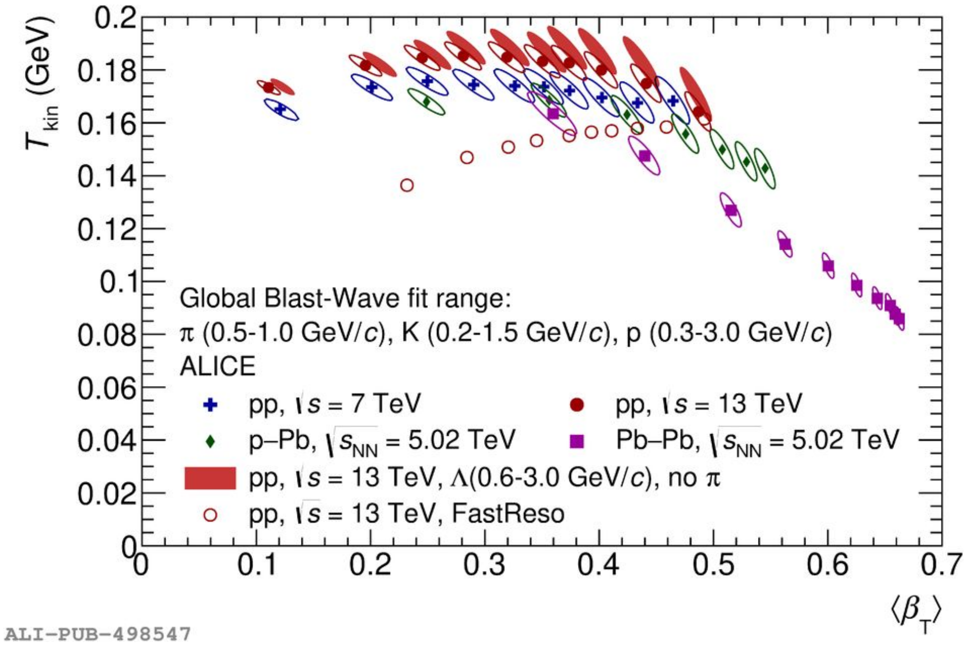
Hadrochemistry



ALICE, Nature Physics 13, 535-539 (2017)

- **Smooth evolution of particle production from small to large systems** vs charged-particle multiplicity
- Strangeness production increases with multiplicity until saturation (grand-canonical plateau) is reached
- **Steeper increase for particle with more strangeness content**
- High-multiplicity pp shows same hadrochemistry as p-Pb and peripheral Pb-Pb system at similar multiplicity
- Common particle production mechanism for all systems?

Temperature at kinetic freeze-out

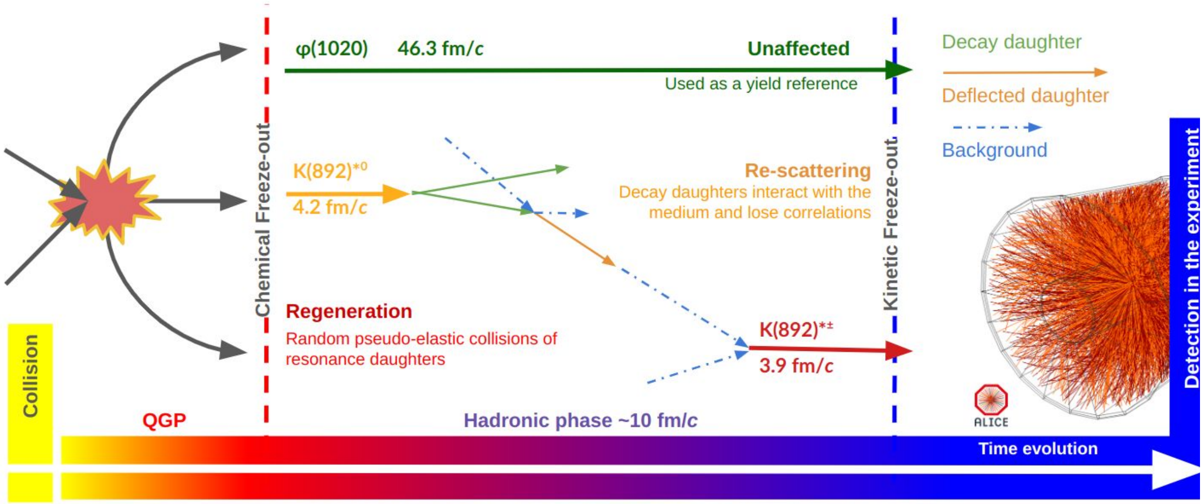


ALICE, Eur. Phys. J. C 80 (2020) 693
ALICE: Phys. Rev. C 101, 044907 (2020)

- **Boltzmann-Gibbs Blast-Wave fits** are used to **characterise the kinetic freeze-out stage** by
- **T_{kin} - kinetic freeze-out temperature** →decreases with increasing collision centrality/multiplicity
- **<β_T> - transverse flow velocity** → increases with increasing collision centrality /multiplicity
- Fit parameters are extracted from **simultaneous fits to π, K, p spectra**

Resonance as probe of the hadronic phase

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

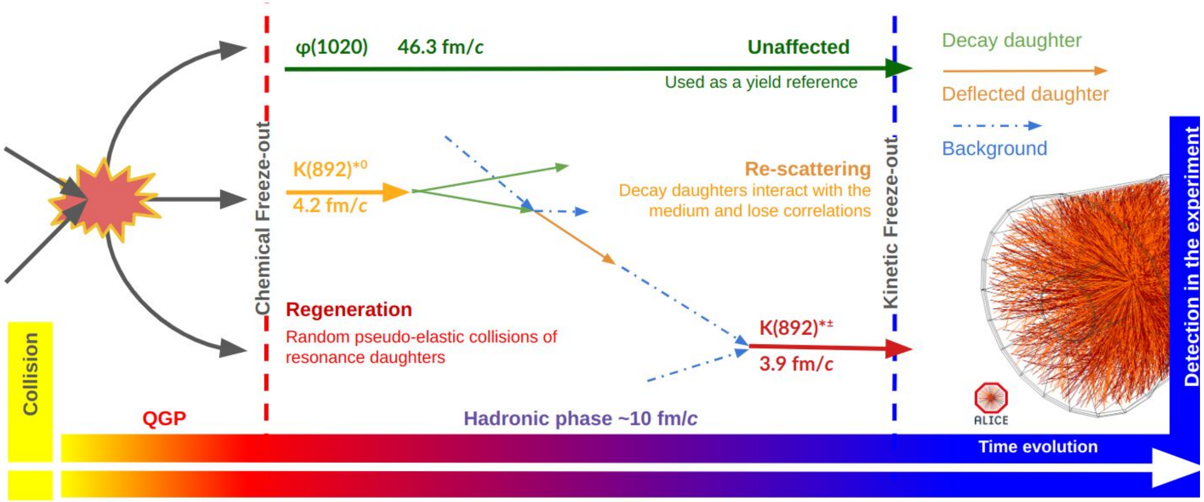


- **Due to their short lifetimes** (τ ~ few fm/c), resonances **can decay within the hadronic medium.** In turn, this can alter their final measured yields.

- **Reconstructible yield affected by following two hadronic processes**
  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

Resonance as probe of the hadronic phase

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

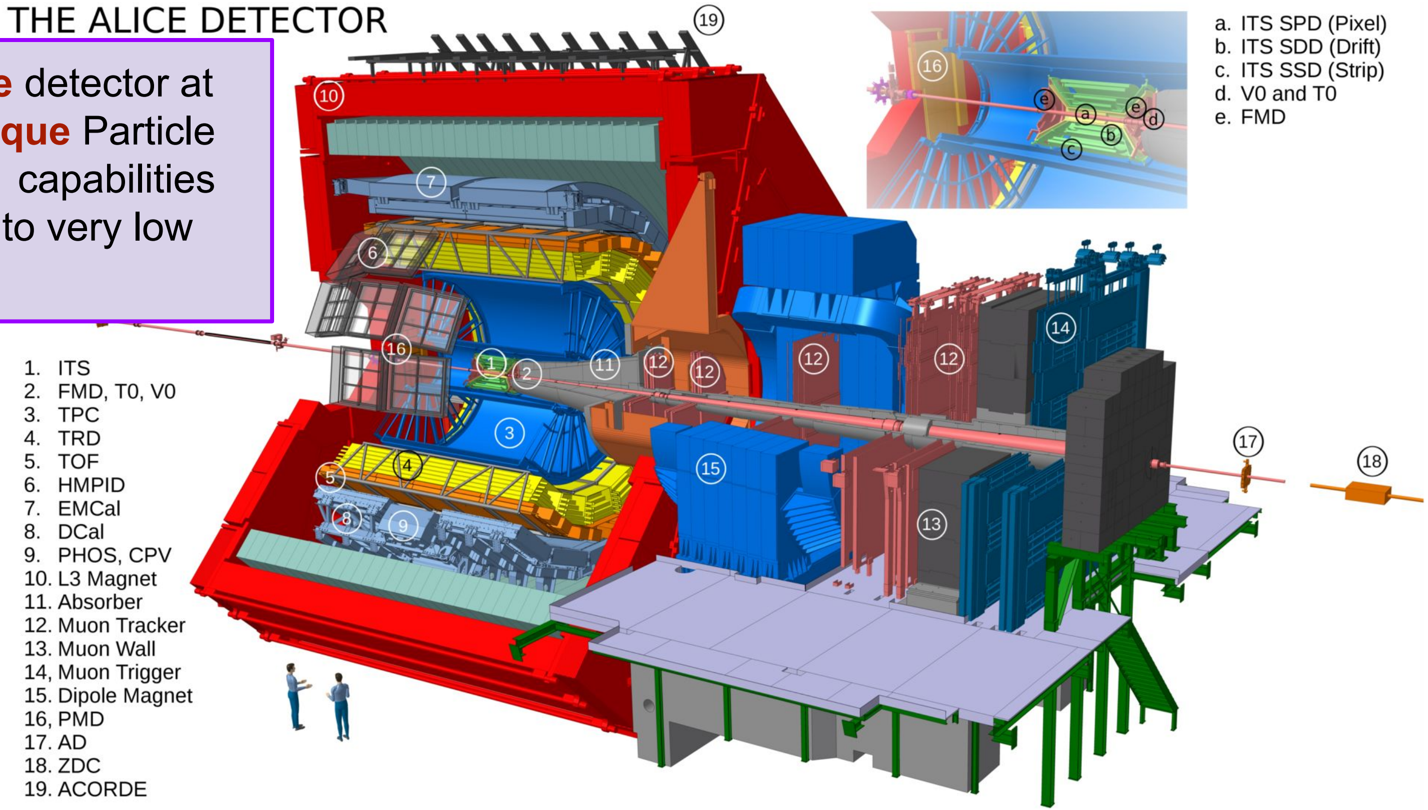


- **Final yield** at kinetic freeze-out **depends on the chemical freeze-out temperature** (T_{ch}), **duration of hadronic phase, lifetime of resonance** and **scattering cross section** of decay products

- **Resonance yield to stable particle with similar quark content** encodes the effects of such interaction in the extended hadronic phase created in heavy-ion collisions

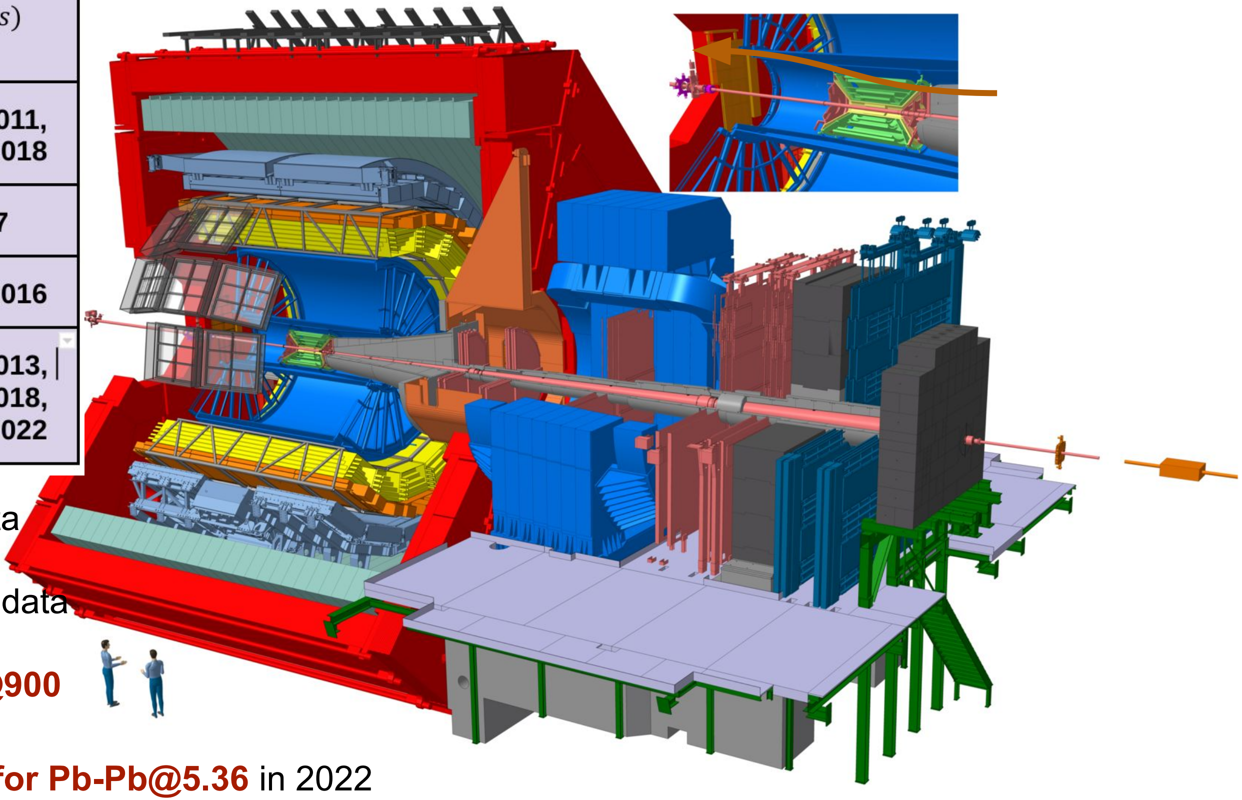
A Large Ion Collider Experiment: schematic overview

A **general purpose** detector at the LHC with a **unique** Particle Identification **(PID)** capabilities and tracking down to very low momentum



ALICE detector: collection of rich datasets

Collision system	$\sqrt{s_{NN}}(TeV)$	$Year(s)$
Pb-Pb	2.76, 5.02	2010-2011, 2015, 2018
Xe-Xe	5.44	2017
p-Pb	5.02, 8.16	2013, 2016
pp	0.9, 2.76, 8,8, 5.02, 13, 13.6	2009-2013, 2015-2018, 2021, 2022



Upgraded detectors to collect Data from Run3

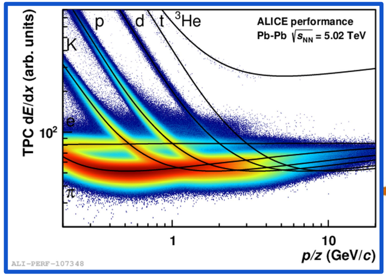
→ already collected **pp@13.6 TeV** data in 2022

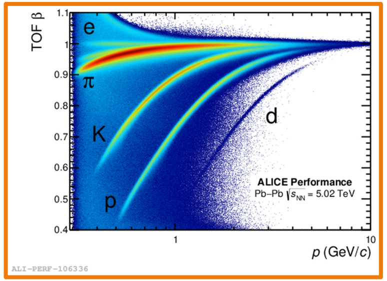
→ collected **pilot beam data, pp@900** GeV in 2021 and 2022

→ also collected **pilot beam data for Pb-Pb@5.36** in 2022

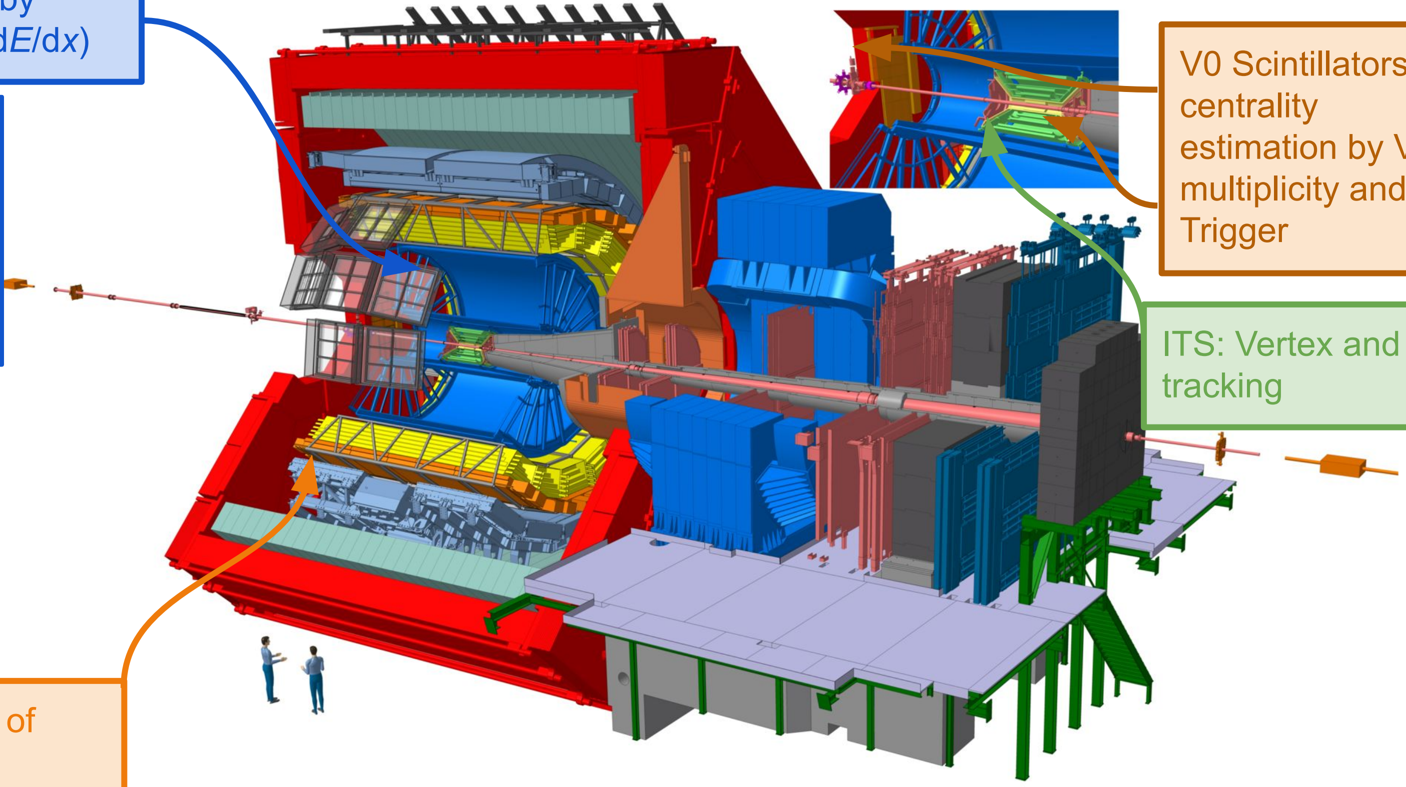
ALICE detector: excellent PID at low-p_T

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





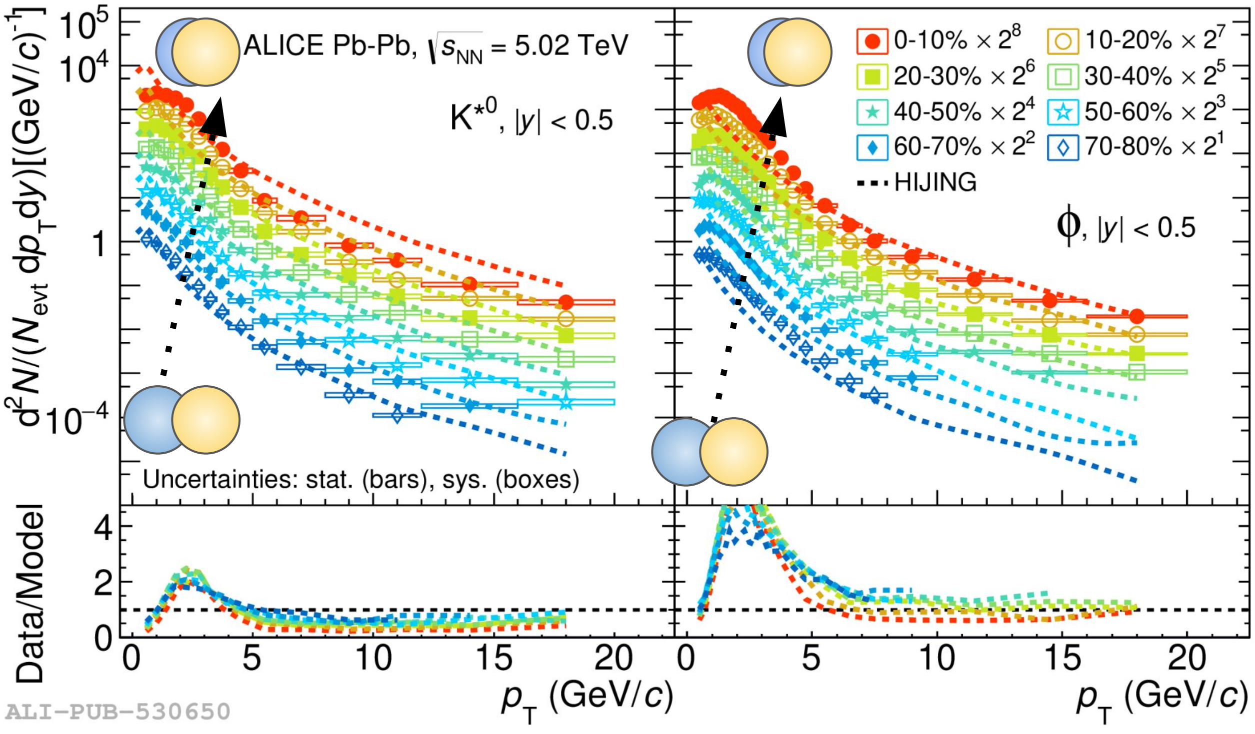
TOF: PID by particle time of flight (β) and Event timing



V0 Scintillators: centrality estimation by V0 multiplicity and Trigger

ITS: Vertex and tracking

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



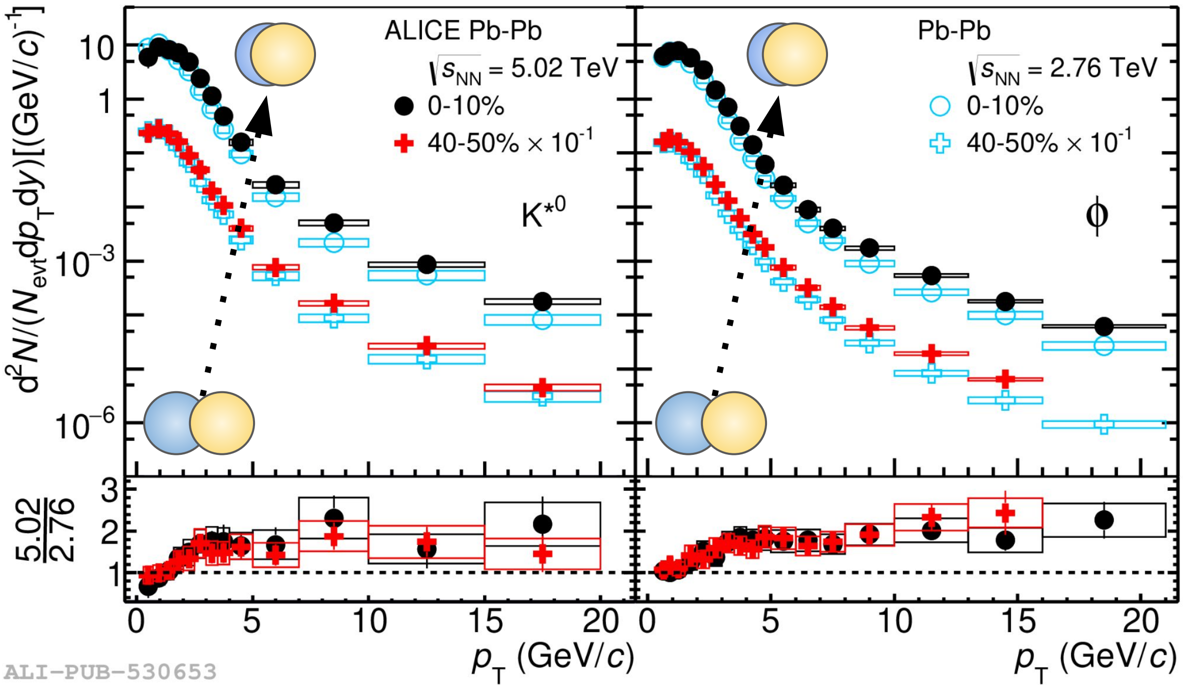
ALICE, Phys. Rev. C 106 (2022) 034907

→ The p_T-spectra of K*(892) and ϕ (1020) measured in **Pb–Pb collisions** at $\sqrt{s_{NN}}$ = **5.02 TeV**

→ measurements in fine centrality intervals, ranging from 0-10% to 70-80%

→ **observed hardening of the p_T-spectrum** going from peripheral to central collisions for both particles

K* and ϕ, energy dependence in heavy-ion collisions

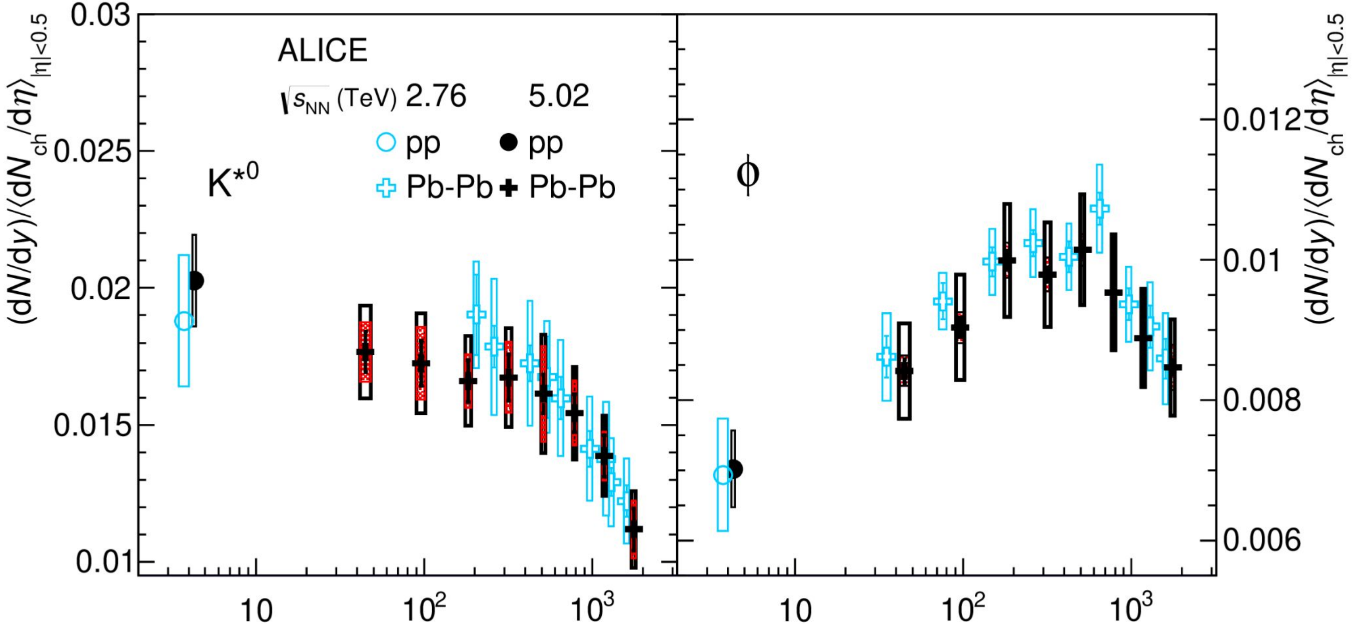


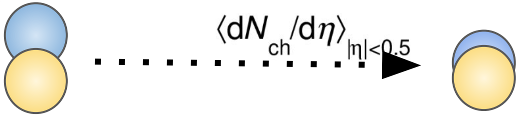
→ comparison of the p_T-spectra of K*(892) and ϕ(1020) in **Pb–Pb collisions** at $\sqrt{s_{NN}}$ = **5.02 TeV to 2.76 TeV**

→ ratio of p_T-spectra from two energy increases with p_T and tend to saturate at high p_T for both mesons

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

K* and ϕ, p_T-integrated yields (d*N*/d*y*)



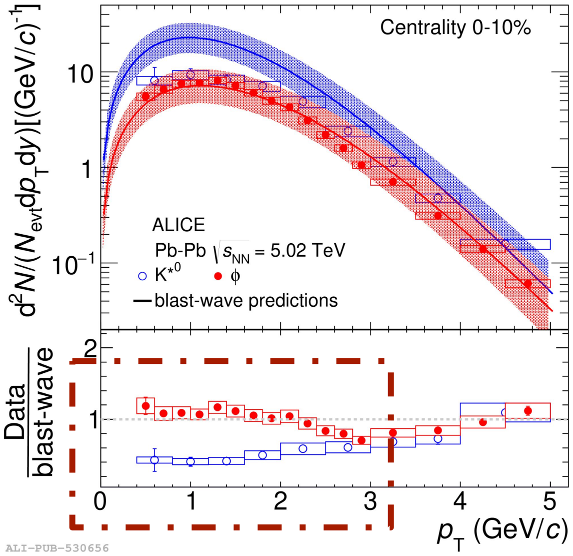


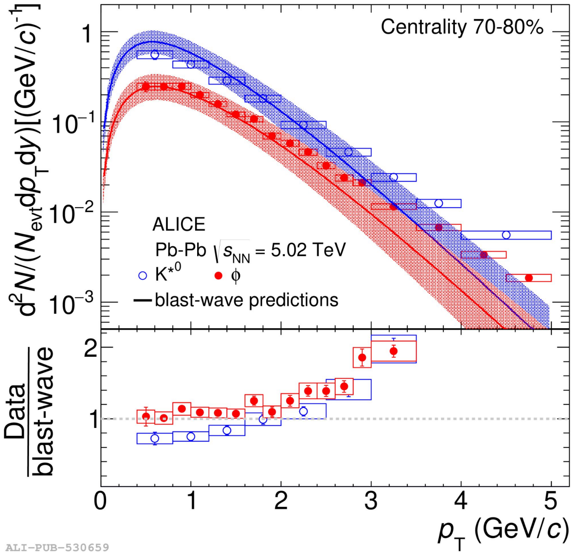
→ The ***p*$_T$ integrated yields** of K*(892) and ϕ(1020) are **scaled by the charged particle multiplicity** measured at midrapidity as a function of multiplicity for pp and Pb-Pb collisions

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

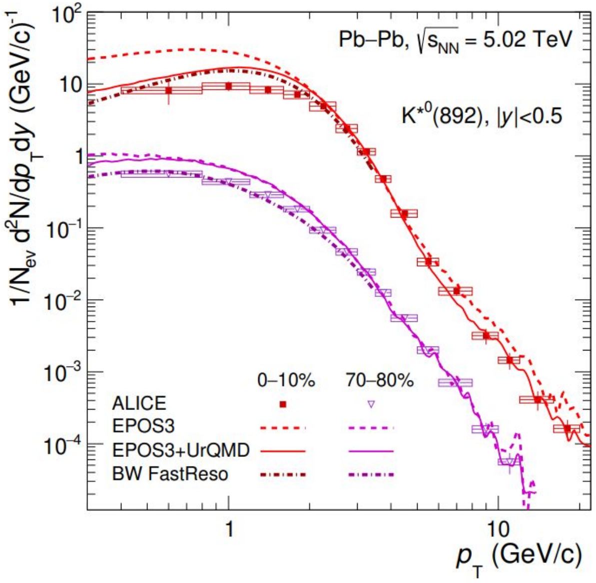
→ **Normalised yield (d*N*/dy) shows similar trend for 5.02 TeV and 2.76 TeV**, regardless of different collison beam energy

K* and ϕ, data to model comparison





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



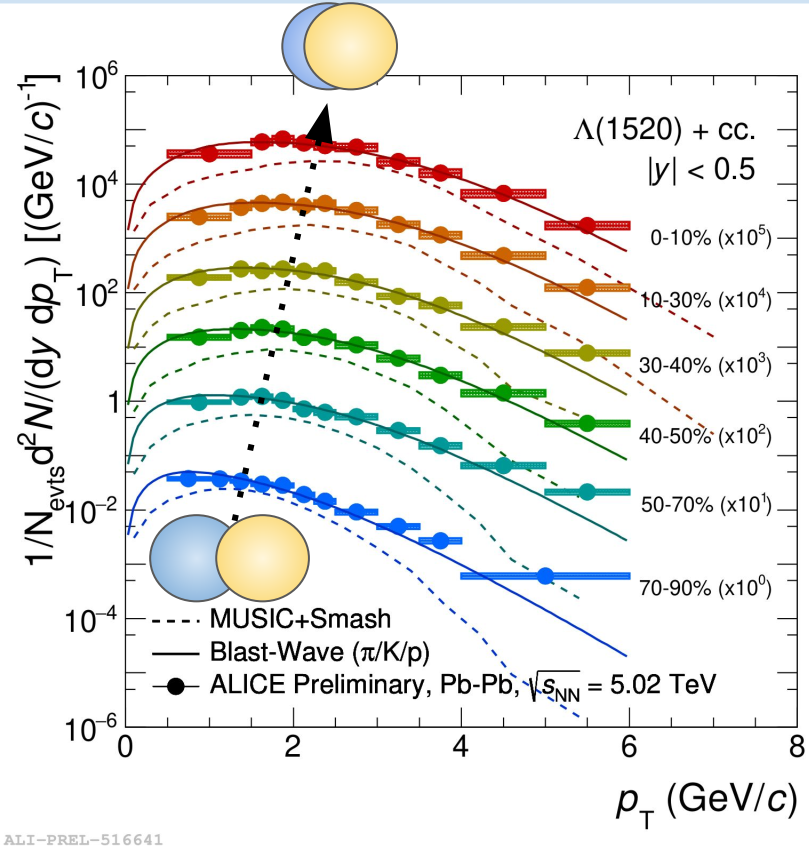
ALICE, arXiv:2211.04384

→ The **low-p_T spectrum part of K*(892) is observed to be lower than** Blast-Wave model prediction as compared to high-p_T in central collisions (0-10%), suppressed as expected from the rescattering

→ better matching in the peripheral collisions

→ ϕ meason is consistent in both the central and and peripheral collisions, as expected no scattering

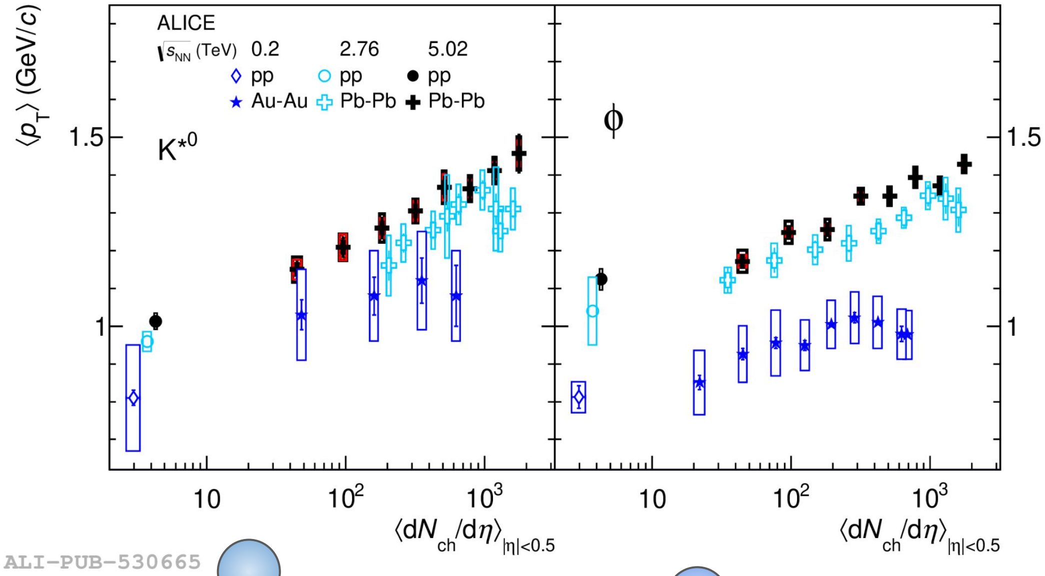
Λ(1520), p_T-spectra in heavy-ion collisions

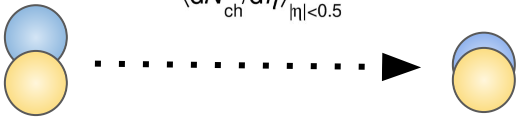


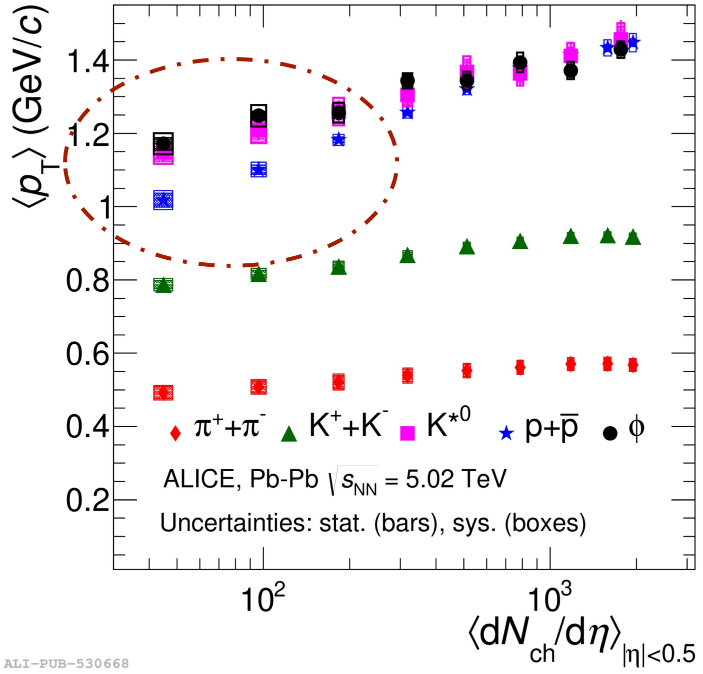
- The spectral shapes shows good agreement with **Blast-Wave** (parameters obtained from π/K/p fits)
- The **spectral shapes** are close to **MUSIC hydrodynamic models** [2] with **SMASH afterburner** (used for model hadronic rescattering in the hadronic phase) from Pb-Pb@5.02 TeV predictions at low p_T while diverge at high p_T.
- **MUSIC slightly underestimates the data** with possible explanation that this model underestimates overall strangeness production at midrapidity.

[1]ALICE: Phys. Rev. C 101, 044907 (2020)
[2]MUSIC:arXiv:2105.07539

K* and ϕ, mean transverse momentum, <p_T>





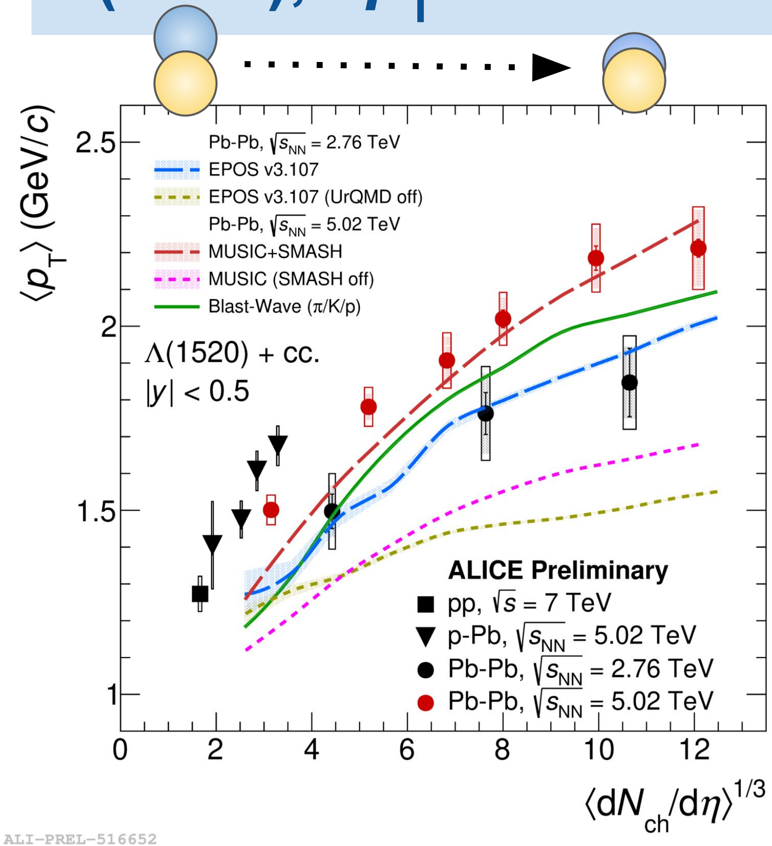


- increases towards higher centrality/multiplicity
- energy dependence between RHIC and LHC energies

- **follows mass ordering**
  - Indicative of radial flow in central collisions
  - **Violated in peripheral collisions (ϕ > p)**

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

Λ(1520), <p_T> and comparison to the models

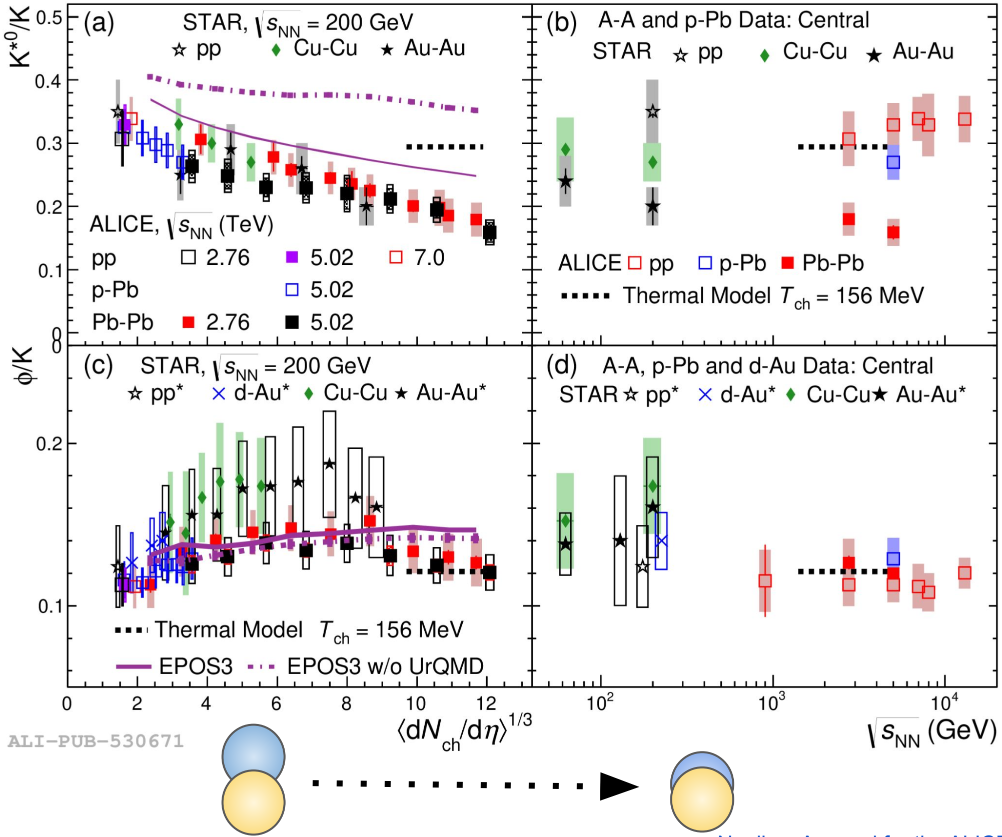


ALI-PREL-516652

- **increases from peripheral to central collisions** (~47% higher in 0-10% than 70-90% class)
- The <p_T> values are **higher than Pb-Pb 2.76 TeV values and Blast-wave model** (π/K/p) [2]
- MUSIC and EPOS3 [3] models gives **better predictions with hadronic phase modelling (SMASH [4] and UrQMD)** in general to reproduce the <p_T> values
- When **SMASH** is turned **off**, the **<p_T> is underestimated**.

[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

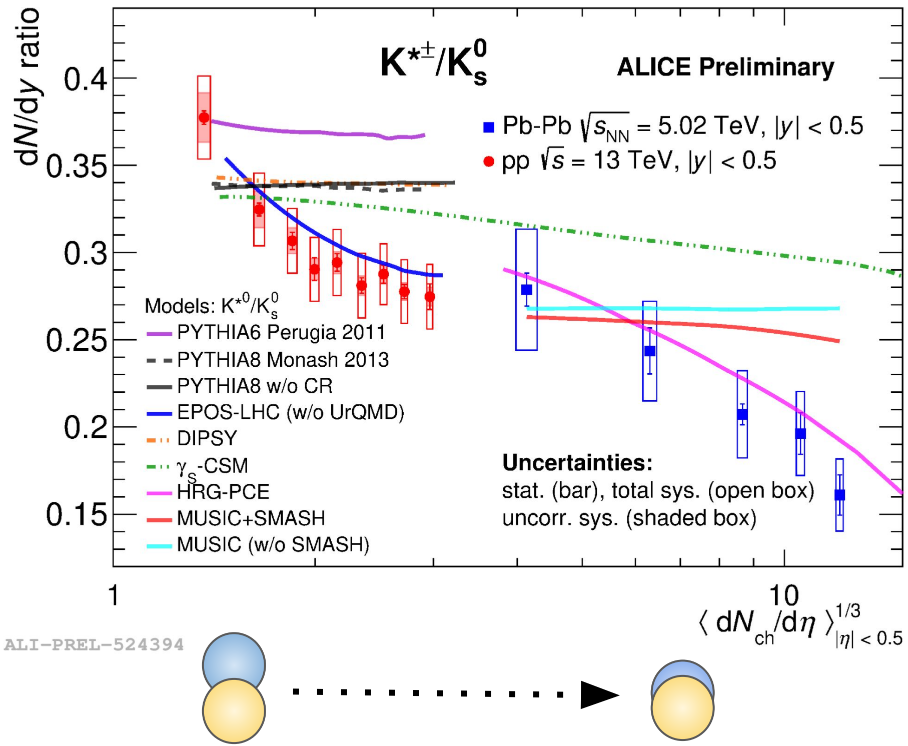
K*/K and ϕ/K ratio; multiple collision systems & energies



- **Ratio of p_T integrated yield**
- **K*/K shows clear suppression**
  →going from pp, p-Pb and peripheral Pb-Pb collisions to central Pb-Pb
  → Pb-Pb at 5 TeV results confirmed the trend observed in Pb-Pb at 2.76 TeV
  → EPOS3 with UrQMD overestimated the data but reproduces the suppression trend
- **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
  → τ(ϕ) >> τ(K*)

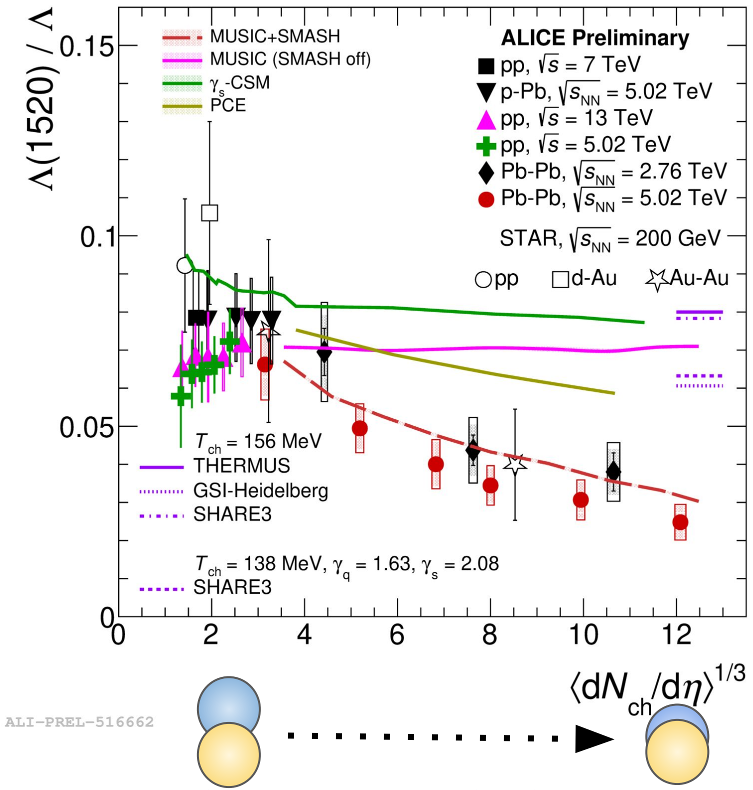
ALICE, Phys. Rev. C 106 (2022) 034907

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



- **Consistent with previous K* results**
- **$K^{*\pm}/K$ shows clear suppression**
  →going from pp, p-Pb and peripheral Pb-Pb collisions to central Pb-Pb
  → EPOS-LHC without UrQMD reproduces qualitatively the data for pp collisions
  → HRG-PCE reproduces the suppression trend for heavy-ion data
- most favoured explanation of $K^{*\pm}$ suppression is also **dominance of rescattering** over regeneration
- $K^{*\pm}/K$ also shows **suppression trend in high multiplicity pp collisions**

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



- The **p_T-integrated Λ(1520)/Λ yield ratio** is shown
  → the ratio is **suppressed in central collisions (0-10%)** compared to the peripheral collisions, p–Pb, pp collisions and predictions from statistical hadronization models
  →**62.55% lower than 70-90% peripheral Pb–Pb at 7.1σ level**.
  → 60% lower than thermal model predictions .
  → **follows published Pb–Pb@2.76 TeV suppression trend**.
  →Higher precision and wider multiplicity coverage.

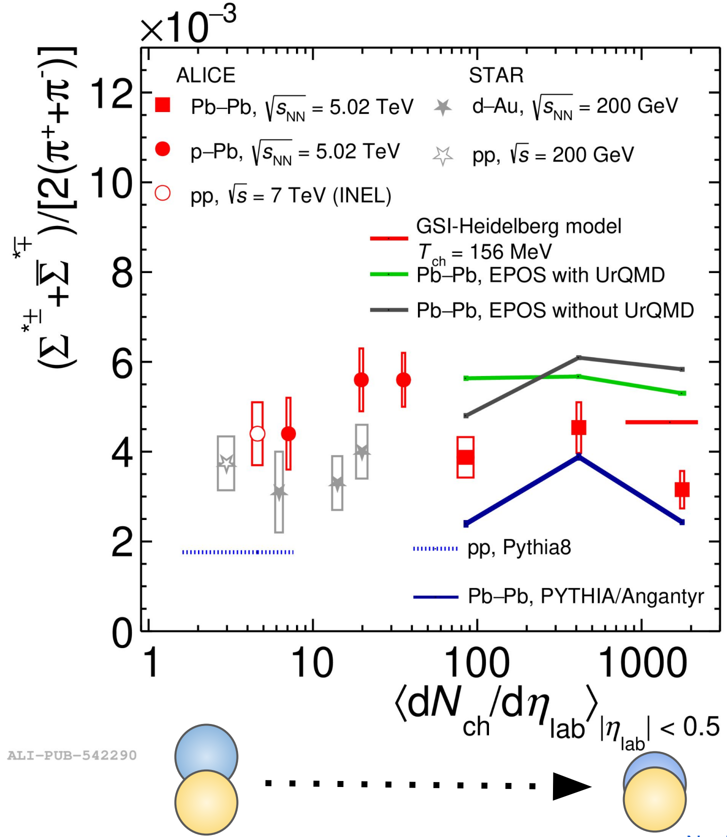
- **MUSIC with SMASH afterburner**
  →**reproduce the multiplicity suppression trend**, better agreement.

- **MUSIC without SMASH**
  → first ever prediction without an afterburner, gives a flat curve
  → matching to peripheral 70-90% Pb-Pb collisions & near to pp values.

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

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*

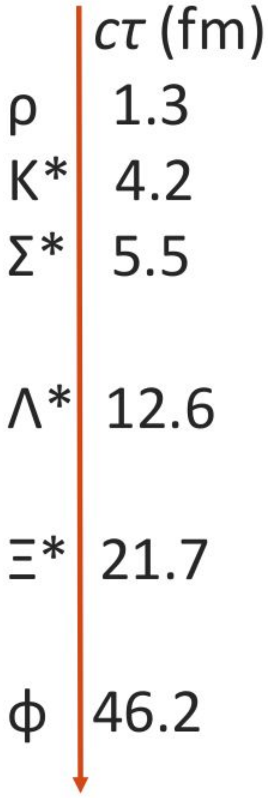
$\Sigma^{*\pm}/\pi^{\pm}$ ratio; multiple collision systems & energies

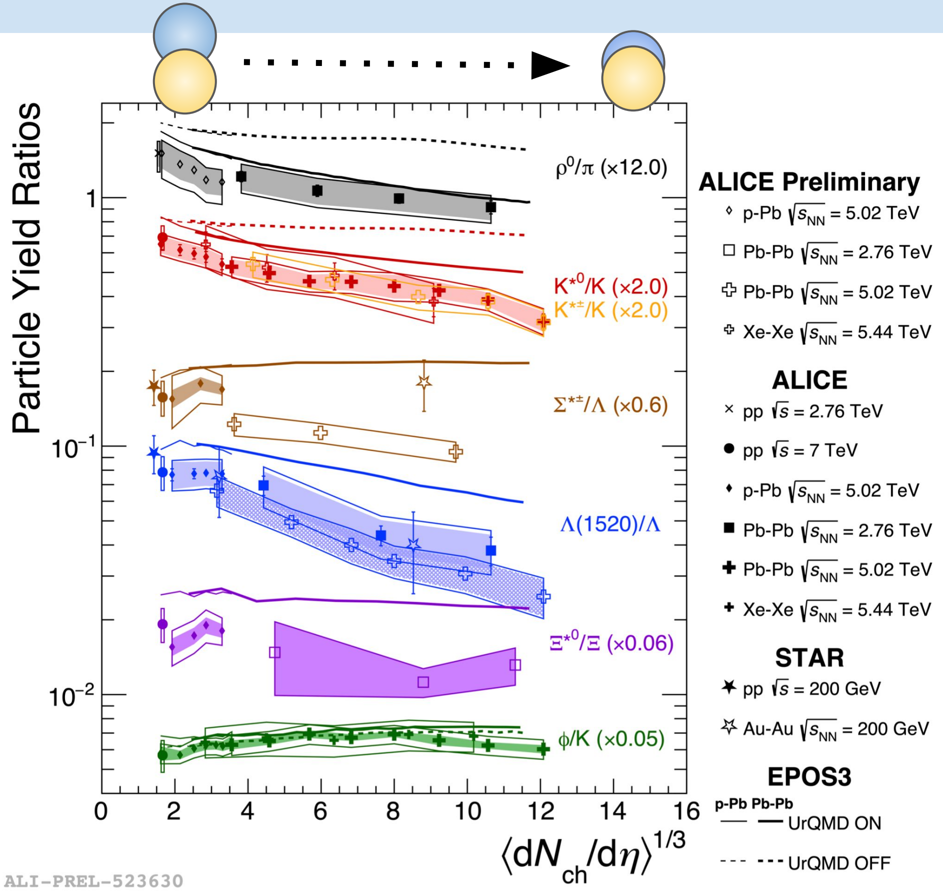


- Yield **Σ(1385)$^{\pm}$** is measured in three centrality (0-10%, 30-50%, 50-80%) in Pb-Pb collisions at 5.02 TeV
- The ***p_T*-integrated $\Sigma^{*\pm}/\pi^{\pm}$ yield ratio** is shown
  → the ratio is **suppressed in central collisions (0-10%)** if compared to the values observed in peripheral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

Particle ratios in a nutshell measured by ALICE

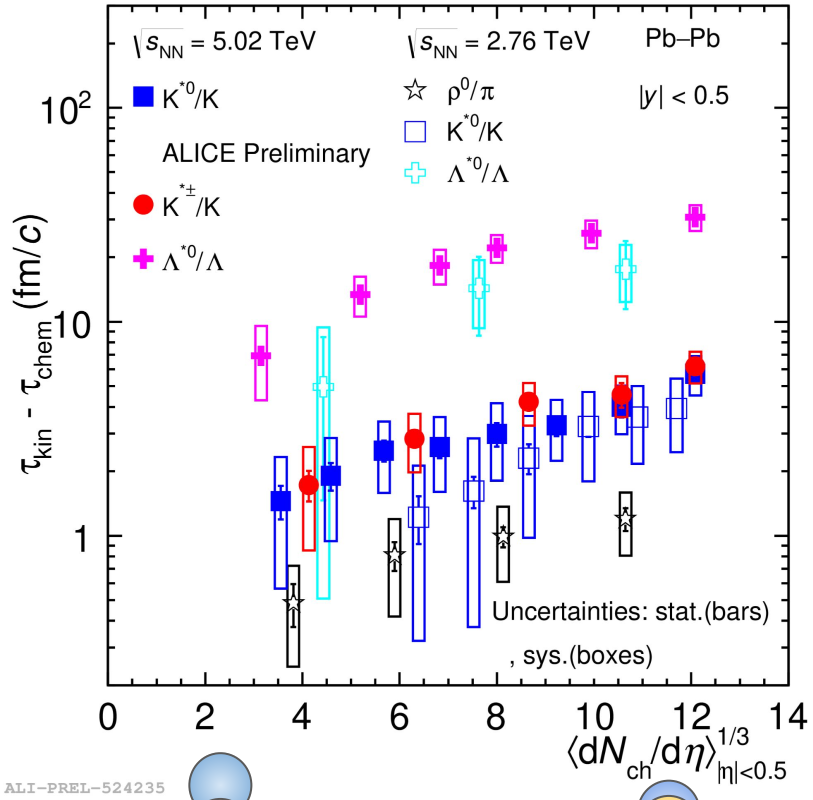


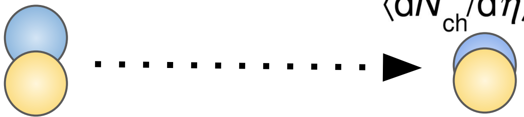


Neelima Agrawal for the ALICE collaboration

These measurements with **highest multiplicity and improved accuracy** further confirm the existence of a **hadronic phase lasting enough** to cause a significant reduction of the reconstructible yield of short-lived resonances

Findings on hadronic phase lifetime





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

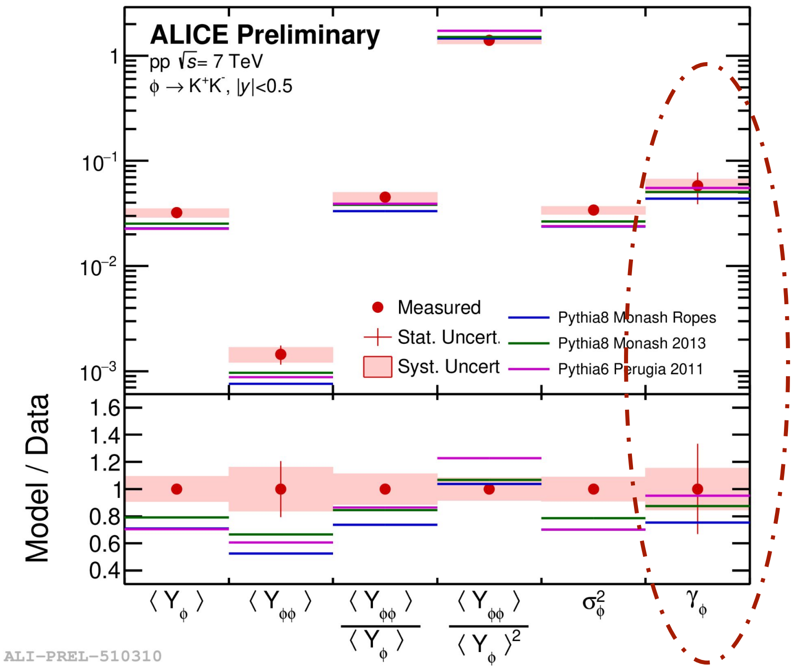
→ r_{chem} = measured yield ratios in pp collisions

→ τ_{res} = lifetime of the resonance particle

- Assumptions
  →simultaneous freeze-ot of all the particles
  →Negligible regeneration of resonances
- **Lifetime** of the hadronic phase smoothly **increases with the centrality/multiplicity**

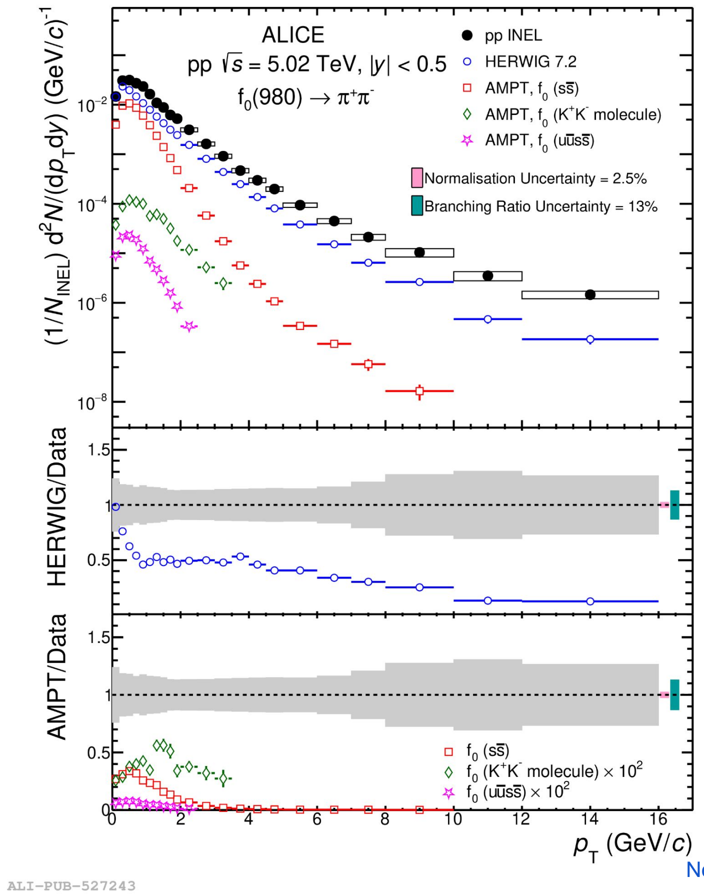
Selected new pp results

Measurement of ϕ meson pair



- Study of **double-ϕ production** in pp collisions at √s = 7 TeV → strangeness enhancement in small system
- Φ meson pair production, $\langle Y_{\phi\phi} \rangle$
  - $\sigma_\phi^2 = 2\langle Y_{\phi\phi} \rangle + \langle Y_\phi \rangle - \langle Y_\phi \rangle^2$
  - $\boldsymbol{\gamma_\phi = \sigma_\phi^2 / \langle Y_\phi \rangle - 1 = \langle Y_{\phi\phi} \rangle / \langle Y_\phi \rangle - \langle Y_\phi \rangle}$
    - **for γ_ϕ = 0**, the double-ϕ production is purely statistical following a poissonian distribution
    - **For $\gamma_\phi \neq 0$,** the double-Φ production the production either **enhanced or suppressed**
- **Analysis result:**
  - **γ_ϕ > 0 → not purely statistical but enhanced**
- **None of the Pythia models can describe the measurement** for $\langle Y_{\phi\phi} \rangle$, $\langle Y_\phi \rangle$ and γ_ϕ at once

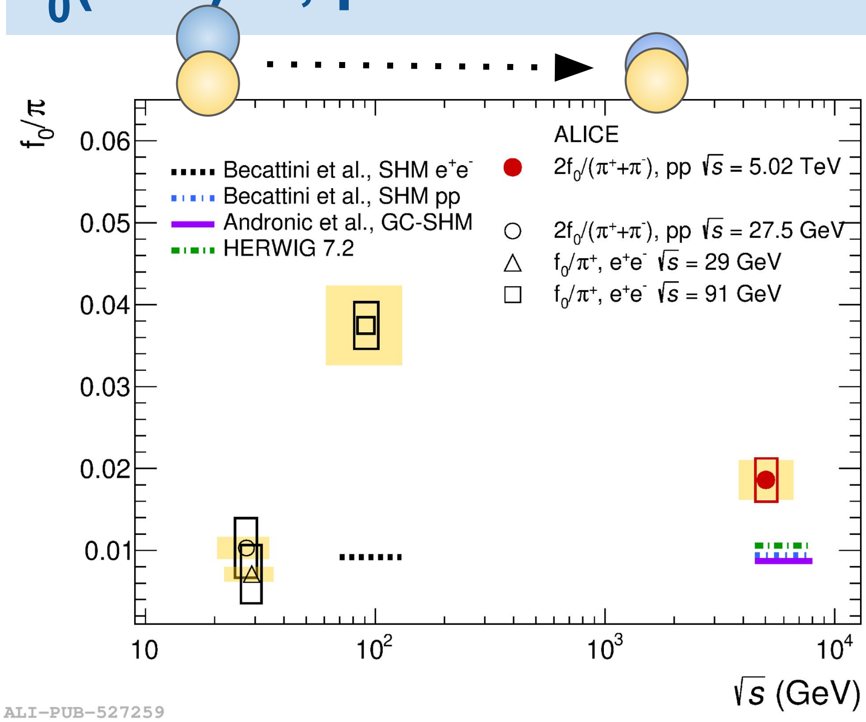
f_0(980) resonance measurement in pp collisions



- **The p_T-spectra of f_0(980) is measured in wide momentum range upto 16 GeV/*c***
- **Comparison with a coalescence calculation** that uses the **AMPT model coupled with a coalescence afterburner** with Gaussian wigner function in three configurations
  1) as a $s\bar{s}$ meson (differ by a factor of 3)
  2) as a $u\bar{u}s\bar{s}$ meson (differ by a factor of ~ 10^3)
  3) as a K^+K^- molecule (differ by a factor of ~ 10^2)
- The shape of p_T-spectra from case 1) to 2) configuration is significantly steeper than the data
- Ratio of K^+K^- molecule configuration to data show a milder p_T dependence
- **Herwig underpredicts the data by a factor of 2 but reproduces the spectral shape in the 1 < p_T < 5 GeV/c**

ALICE, ArXiv:2206.06216 [nucl-ex], accepted by PLB

f_0(980)/π, particle ratios



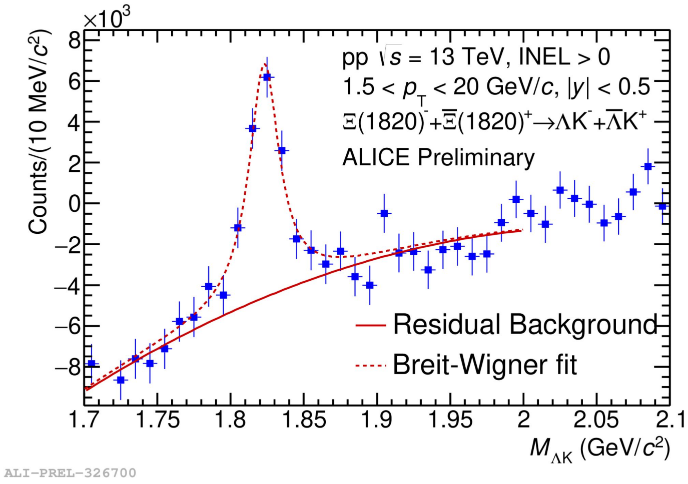
ALICE, ArXiv:2206.06216 [nucl-ex], accepted by PLB

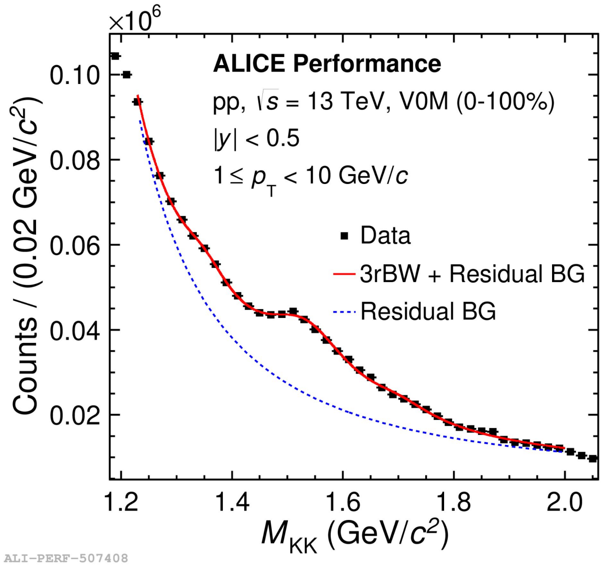
- Particle ratio value from the fixed-target **NA27** experiment at the CERN SPS*, measured in pp collisions at **27.5 GeV[1] is lower by 44.5%**
- Particle ratios from **e^+ e^- collisions* at 29[2]** and **91[3] GeV** are lower by **61% and higher by a factor of two, respectively**
- The **statistical hadronization models [4-6]** and **HERWIG predictions underestimate** the measurement in pp collisions by about a factor two

*In order to compare the new measurement of the p_T-integrated f_0(980) to pion ratio with low energy data, the low energy points were updated with the latest branching ratio

1. *M. Aguilar-Benitez et. al., Z. Phys. C50 (1991) 405.*
2. *W. Hofmann, Ann. Rev. Nucl. Part. Sci. 38 (1988) 279.*
3. *P. V. Chliapnikov, Phys. Lett. B462 (1999) 341.*
4. *F. Becattini et. al., Eur. Phys. J. C 56 (2008) 493.*
5. *F. Becattini et. al., Z. Phys. C 76 (1997) 269.*
6. *A. Andronic et. al., Nature 561 no. 7723, (2018) 321.*

Search for higher mass resonance in ALICE





- First attempt for the signal extraction of higher mass resonance such as **Ξ(1820) in its ΛK decay daughter channel**
- The **invariant mass distribution of KK pair** shows the prominent signal peak for **f_2(1525)**

Thank you for your time :-)