Overview of soft physics results from ALICE

Victor Riabov for the ALICE Collaboration

Outline

❖ ALICE studies the properties of strongly interacting matter at extreme temperatures and energy densities, Quark-Gluon Plasma

❖ Excellent capabilities for reconstruction and identification of π, K, ρ, K^*, p, ϕ, Λ, Σ, Ξ, Σ^*, Λ^*, Ξ^*, Ω, … in a wide transverse momentum range (p_T) → test the phase transition, hadrochemistry and reaction dynamics

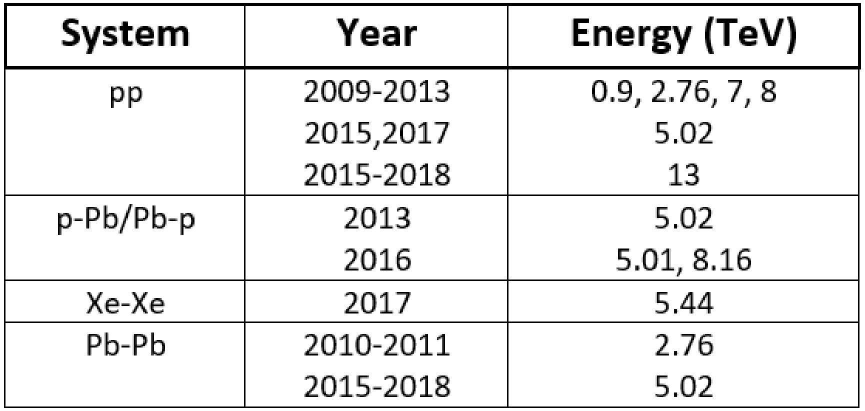
❖ Report recent results for low-to-intermediate p_T (soft probes) light-flavor hadrons in different collision systems:

✓ integrated yields and ratios:
  - chemical freeze-out conditions
  - strangeness enhancement

✓ p_T spectra and ratios:
  - kinetic freeze-out temperature and expansion velocity
  - baryon-to-meson ratios

✓ short-lived resonances:
  - properties of the hadronic phase

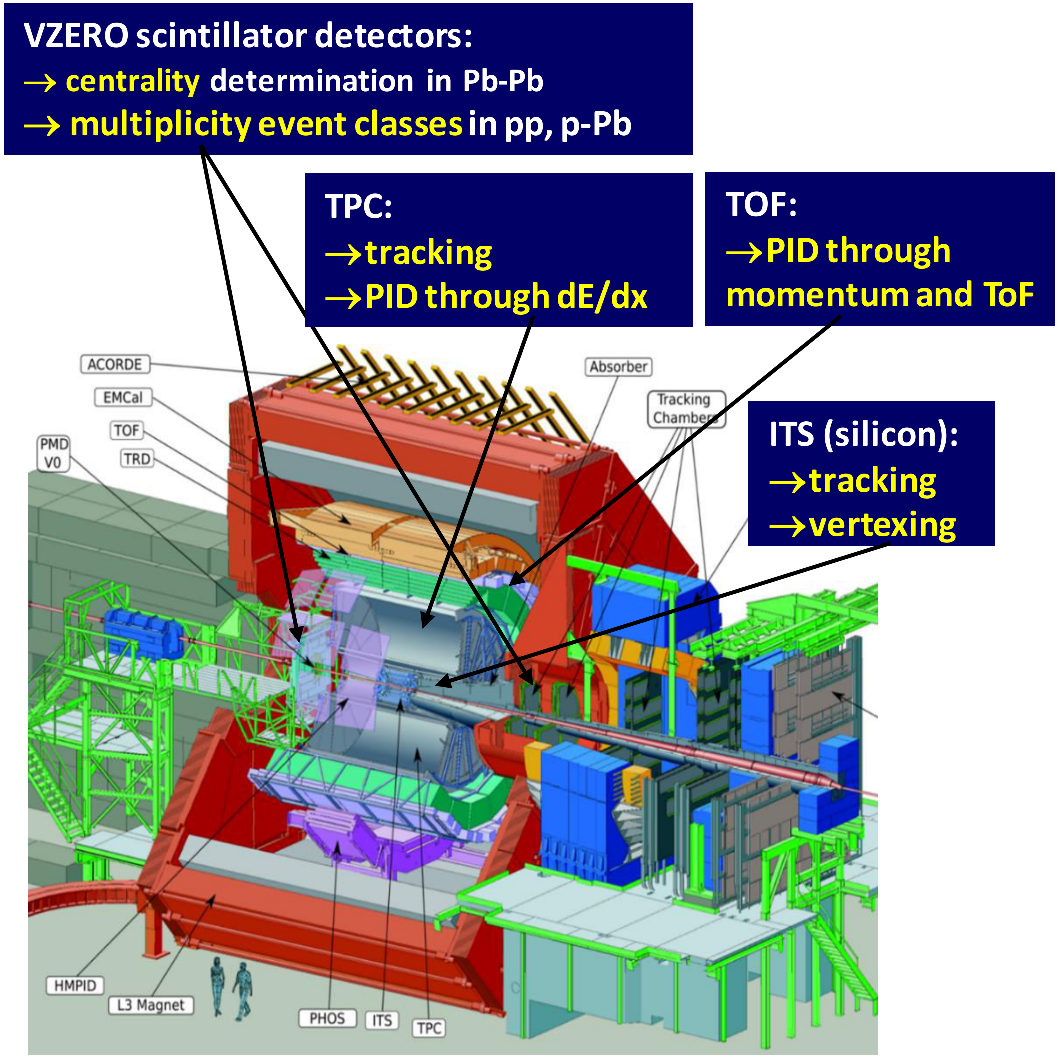
✓ light (anti)nuclei production



System	Year	Energy (TeV)
pp	2009-2013 2015,2017 2015-2018	0.9, 2.76, 7, 8 5.02 13
p-Pb/Pb-p	2013 2016	5.02 5.01, 8.16
Xe-Xe	2017	5.44
Pb-Pb	2010-2011 2015-2018	2.76 5.02

ALICE experiment

Int. J. Mod. Phys. A 29 1430044 (2014)



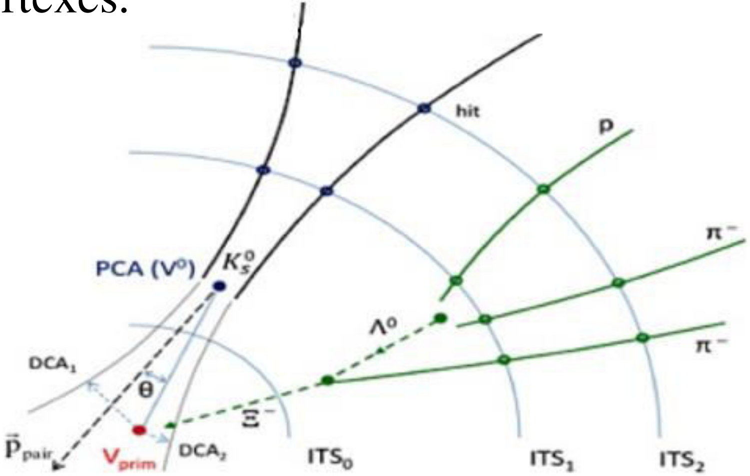
VZERO scintillator detectors:
→ centrality determination in Pb-Pb
→ multiplicity event classes in pp, p-Pb

TPC:
→tracking
→PID through dE/dx

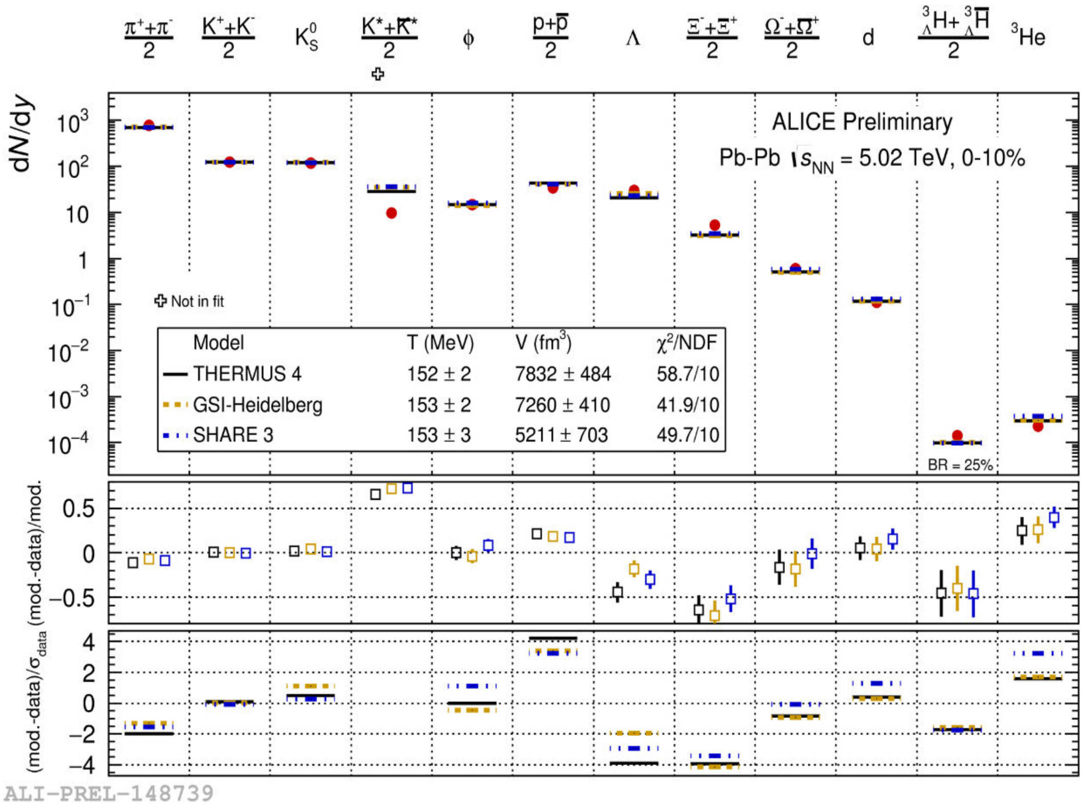
TOF:
→PID through momentum and ToF

ITS (silicon):
→tracking
→vertexing

- ❖ Moderate magnetic field (B = 0.5 T) at mid-rapidity, $|\eta| < 0.9$
- ❖ Tracking down to p_T ~ 100 MeV/c
- ❖ High granularity to deal with high occupancy in heavy-ion collisions
- ❖ Particle identification in a wide p_T range by combining various detectors and techniques (ITS, TPC, TOF, TRD, HMPID, calorimetry)
- ❖ Decay topology cuts, secondary vertexes:



Hadron yields, thermal model fits: Pb-Pb@5.02, 0-10%



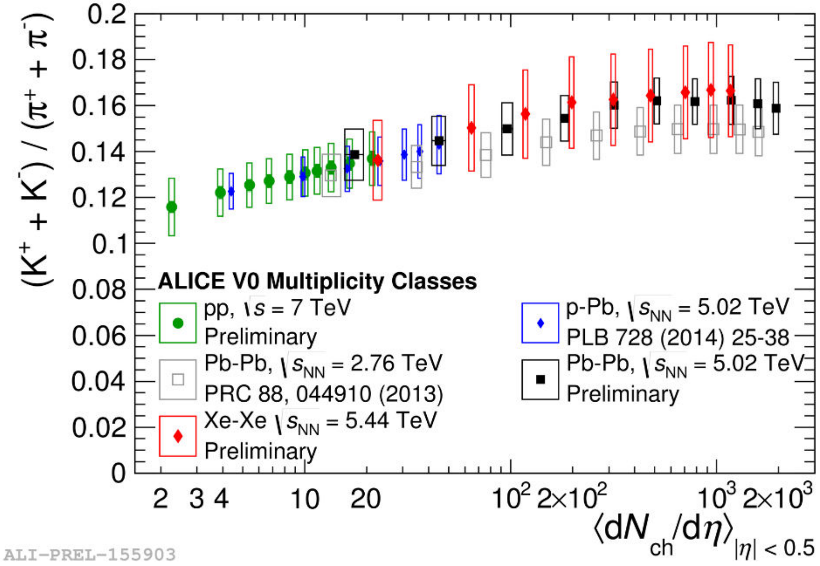
Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

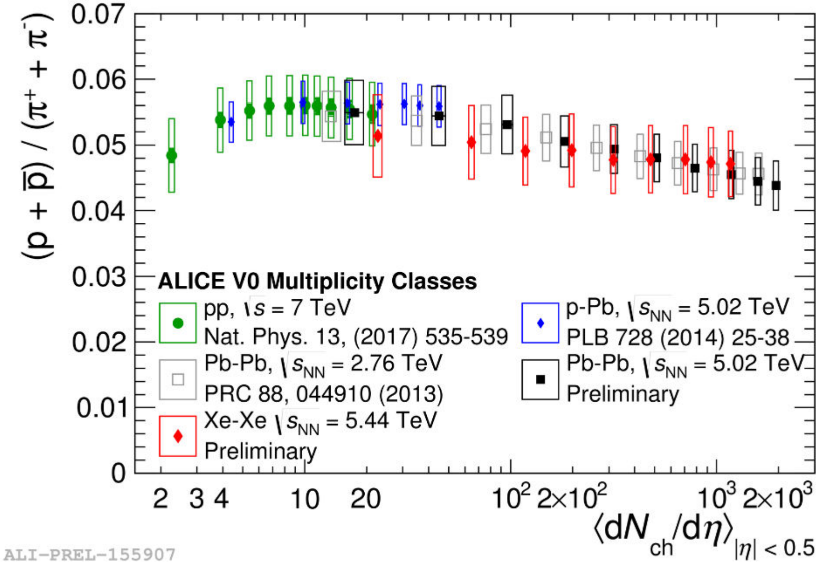
ALI-PREL-148739

- ❖ Model assumptions:
  - ✓ hadrons are emitted from statistically equilibrated system, chemical equilibrium
  - ✓ key parameter is a chemical freeze-out temperature, T_{ch}
- ❖ Yields of light-flavor hadrons and light (hyper)nuclei are described over seven orders of magnitude with a common chemical freeze-out temperature of T_{ch} = 153 ± 3 MeV
- ❖ Similar observations in Pb-Pb@2.76, slightly higher T_{ch} = 156 ± 3 MeV
- ❖ Short-lived resonances, ρ(770), $K^*(892)^0$, Λ(1520) etc., are overestimated due to rescattering in the late hadronic phase → excluded from the fit
- ❖ Tensions for protons and multi-strange baryons → incomplete hadron spectrum, baryon annihilation in hadronic phase, interacting hadron gas, ... ???

THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84 (2009)
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142 (2009)
SHARE: Petran et al, Comp. Phys. Commun. 195 (2014) 2056

Particle ratios: pp, p-Pb, Xe-Xe and Pb-Pb



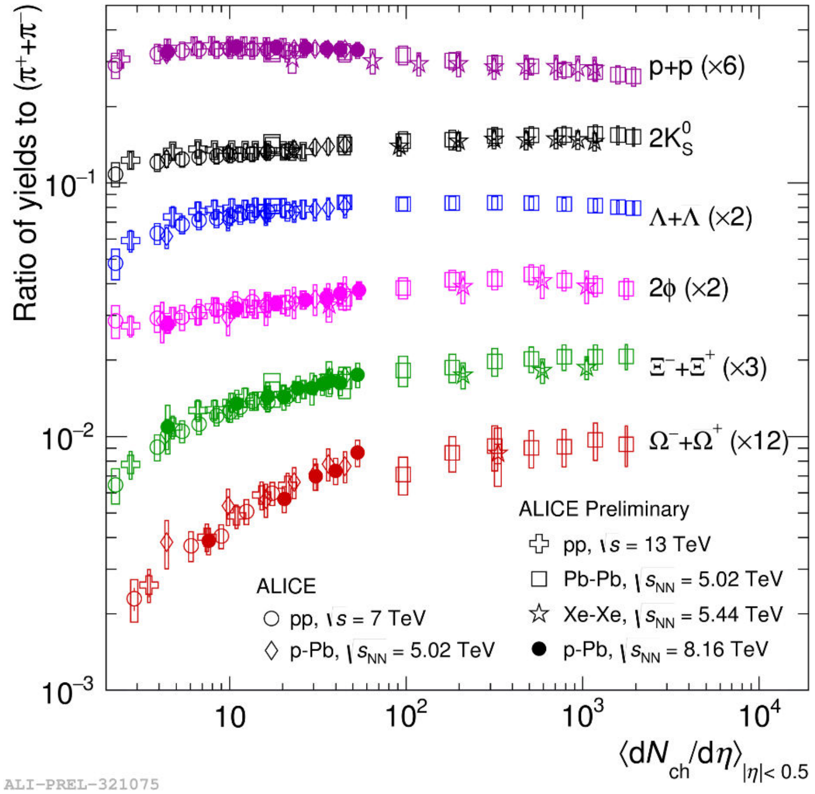


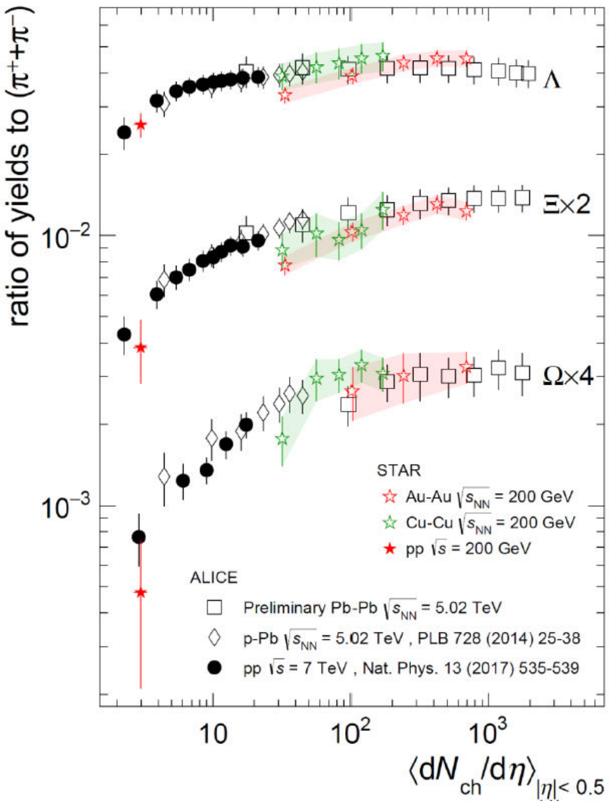
- At similar multiplicities, particle ratios (K/π, p/π etc.) are consistent for different collision systems (pp, p-Pb, Xe-Xe, Pb-Pb) at different energies, $\sqrt{s_{NN}} = 2.76\text{-}13$ TeV
- Hadrochemistry is dominantly driven by event activity rather than by type of colliding nuclei and/or collision energy
- p/π shows a small decrease with centrality consistent with antibaryon-baryon annihilation in the hadronic phase, which is more important in dense systems*
- Increasing K/π ratio is consistent with strangeness enhancement (next slide)

* Phys. Rev. Lett. 110, 042501

Strangeness production: pp, p-Pb, Xe-Xe and Pb-Pb

Nature Phys. 13 (2017) 535

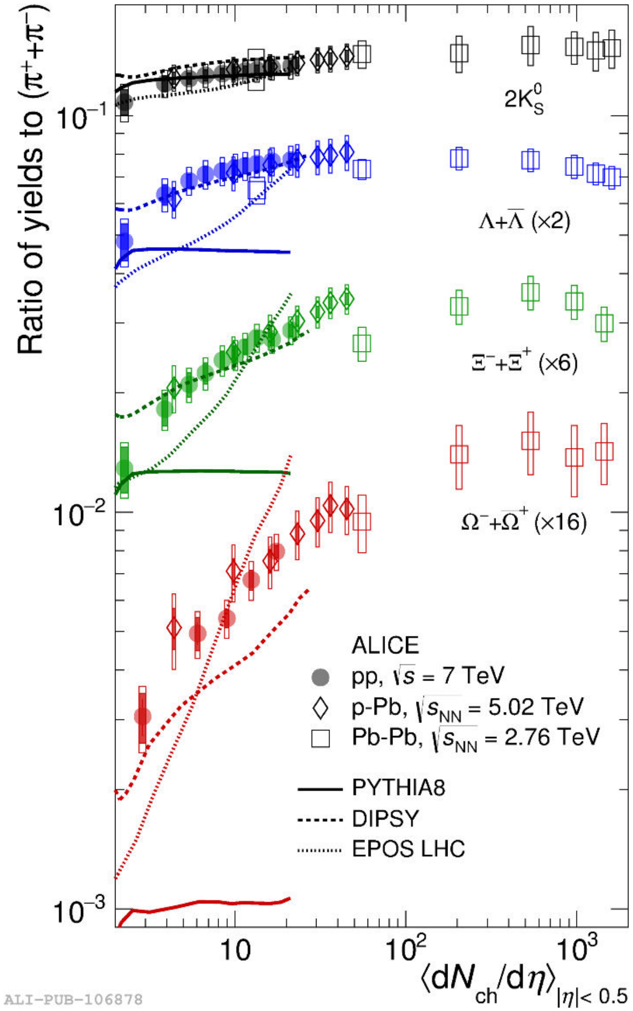


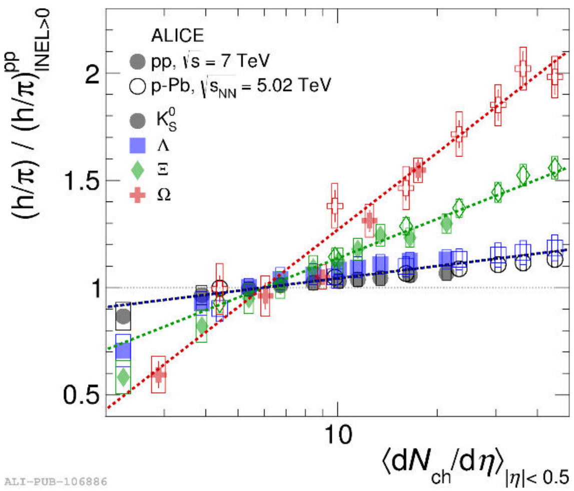


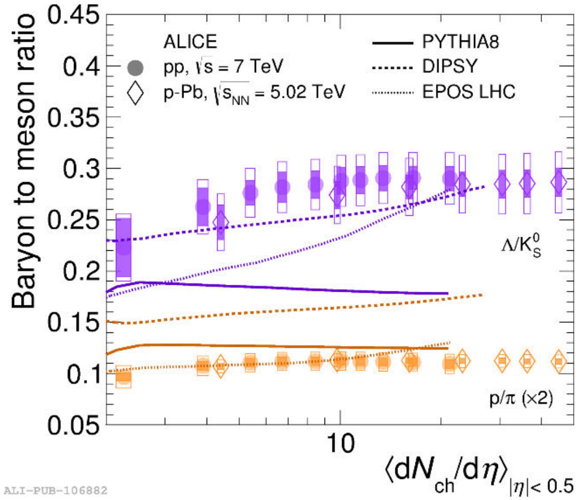
- Strangeness enhancement increases with strangeness content and charged particle multiplicity
- Ratios saturate in peripheral A-A at values predicted by statistical hadronization models
- Smooth evolution vs. multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$-13 TeV
  → hadrochemistry is driven by the multiplicity
- STAR measurements at $\sqrt{s_{NN}} = 200$ GeV are in agreement at high multiplicities (Cu-Cu, Au-Au), also consistent at low multiplicity (pp) within larger uncertainties
- Origin of the strangeness enhancement in small/large systems is still debated

Strangeness enhancement vs. microscopic models

Nature Phys. 13 (2017) 535





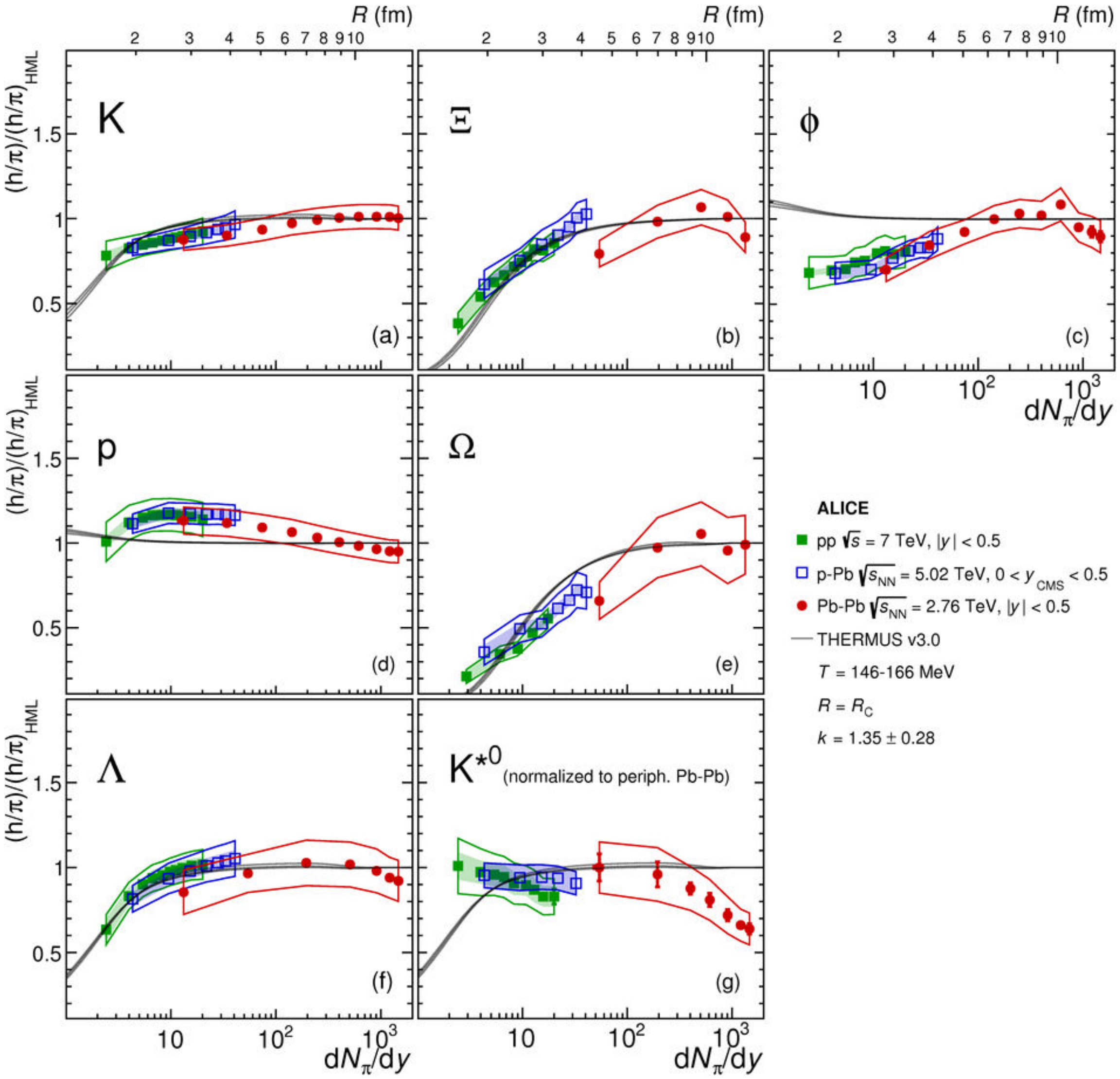


- ❖ For non-strange particles like protons enhancement is not observed
- ❖ Strength of enhancement is determined by the hadron strangeness content
- ❖ Baryon-to-meson ratios do not depend on multiplicity within uncertainties → enhancement is driven by particle strangeness content, not by mass

- ❖ “Microscopic” models do not reproduce results in small systems:
  - ✓ DIPSY and EPOS-LHC qualitatively describe the increased strangeness production but fail to reproduce constant baryon-to-meson ratios
  - ✓ Pythia8 with color reconnection fails to reproduce enhancement

Strangeness enhancement vs. thermal models

arXiv:1610.0300



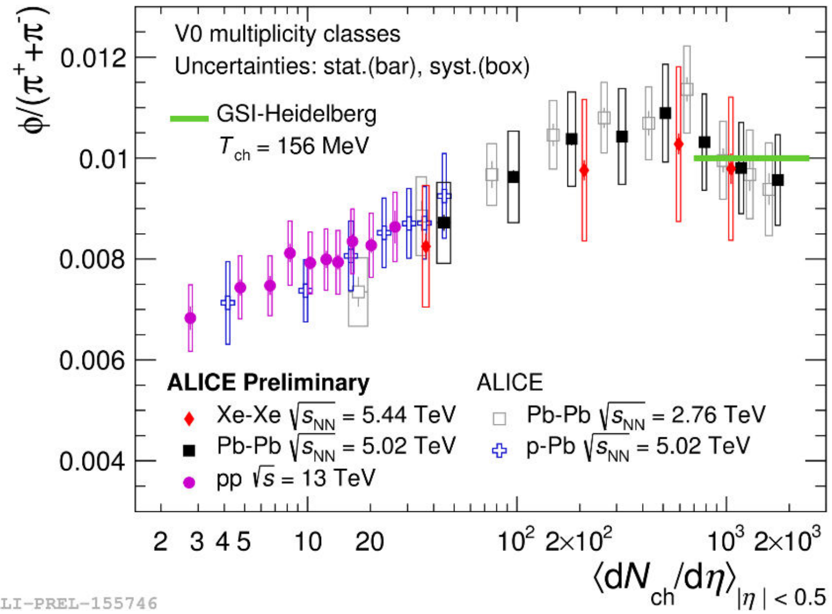
❖ Particle ratios are normalized to the high-multiplicity limit (except for K^{*0})

❖ Ratios are compared to the THERMUS strangeness canonical suppression model → strangeness production is suppressed in small systems due to canonical suppression (local conservation of strangeness)

❖ Model provides good description of most of the ratios except for ϕ and K*

Strangeness enhancement: ϕ

- ϕ with hidden strangeness is a key probe to study strangeness enhancement
  - ✓ ϕ/π increases with multiplicity in pp/ p-Pb → not expected for canonical suppression
  - ✓ ϕ/π saturates in Pb-Pb and is consistent with thermal model predictions
- Non-equilibrium production (γ_s) ???
- Ratios ϕ/K and Ξ/ϕ show weak dependence on multiplicity
  → ϕ has an effective strangeness of 1-2



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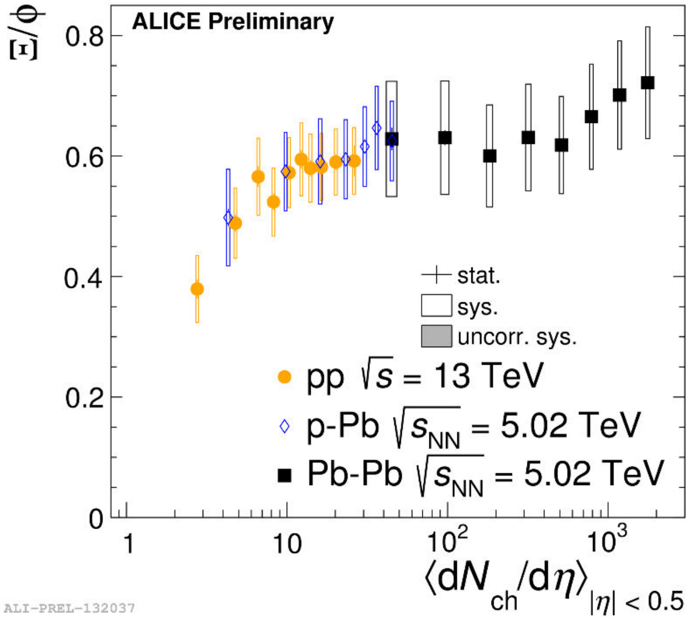

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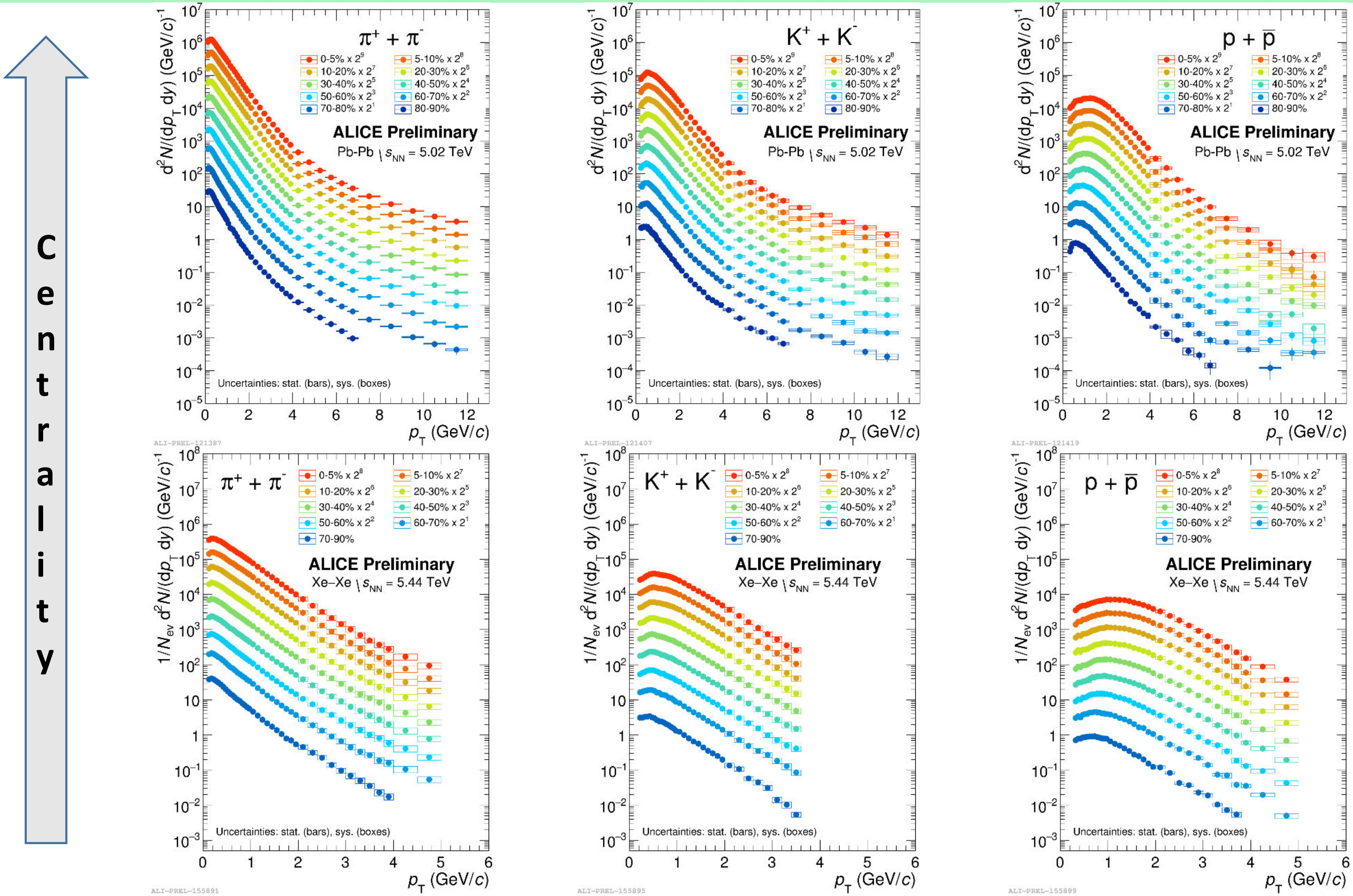
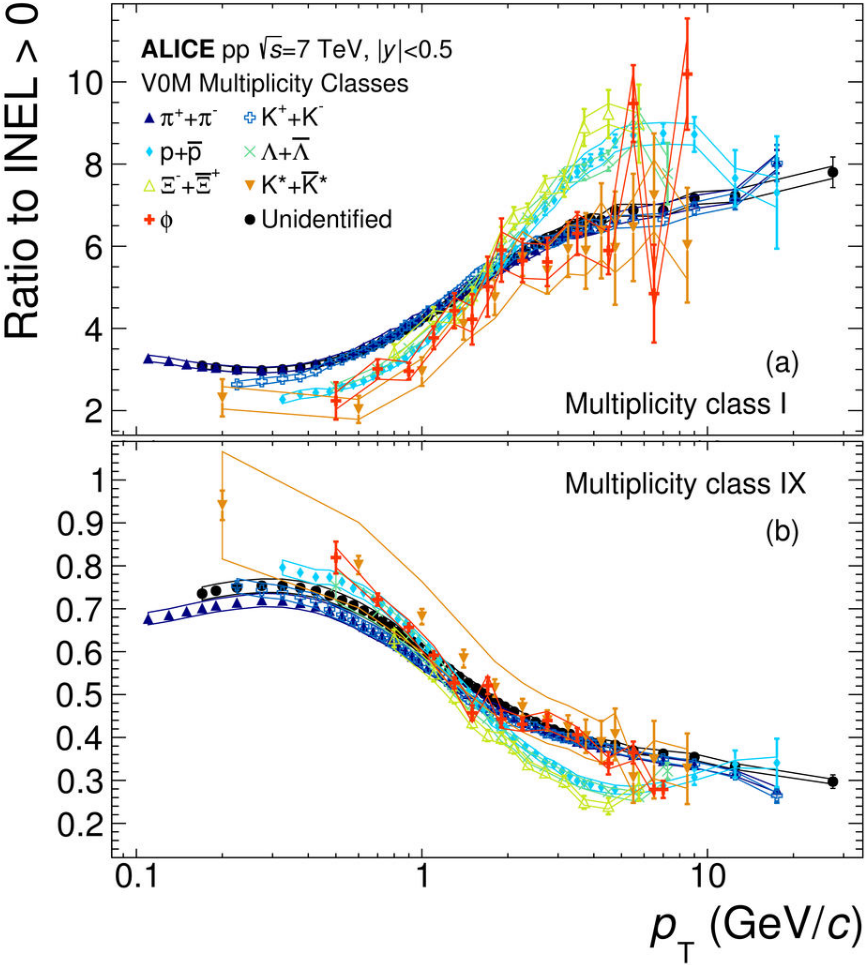
p_T - spectra for π/K/p : Pb-Pb@5.02, XeXe@5.44



❖ Observe mass-dependent hardening of particle spectra for $p_T < 3$ GeV/c going from peripheral to central collisions → collective radial flow ($m_T \rightarrow m_T + m_0\gamma\beta_T$)

Hadronic spectra in pp vs. multiplicity



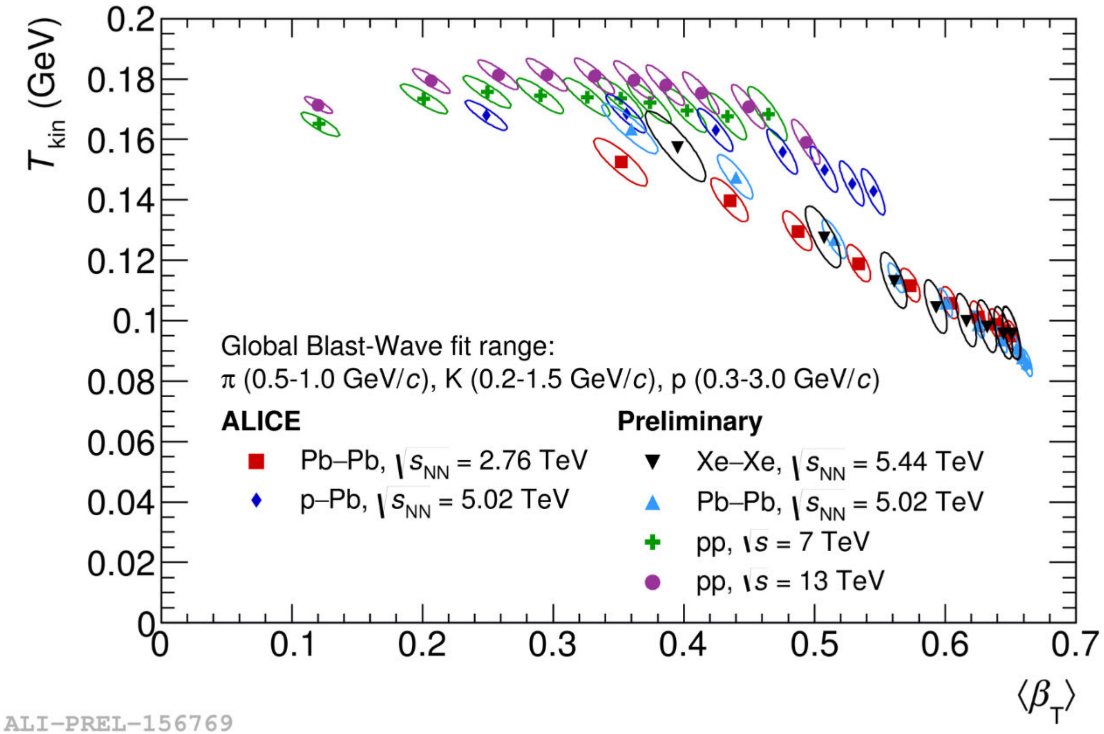
V0M Multiplicity Classes:

$[\langle dN_{ch}/d\eta\rangle^{INEL} \approx 6.0]$

$$\begin{cases} \text{I} \rightarrow \langle dN_{ch}/d\eta\rangle^{INEL} \approx 3.5 \times \langle dN_{ch}/d\eta\rangle^{INEL} \\ \text{IX} \rightarrow \langle dN_{ch}/d\eta\rangle^{INEL} \approx 0.65 \times \langle dN_{ch}/d\eta\rangle^{INEL} \end{cases}$$

- ❖ In pp collisions spectra get harder with increasing multiplicity
- ❖ Effect is mass-dependent, it is more pronounced for p, Λ and Ξ than for π, K, K^*
  → baryon/meson effect???
- ❖ Similar observations in pp and p-Pb collisions at different energies
  → radial flow ???

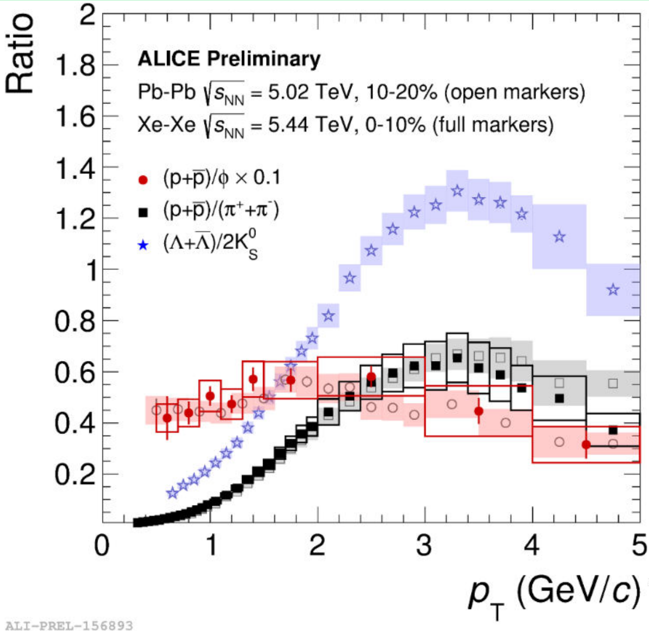
Blast-Wave model fits to ALICE data

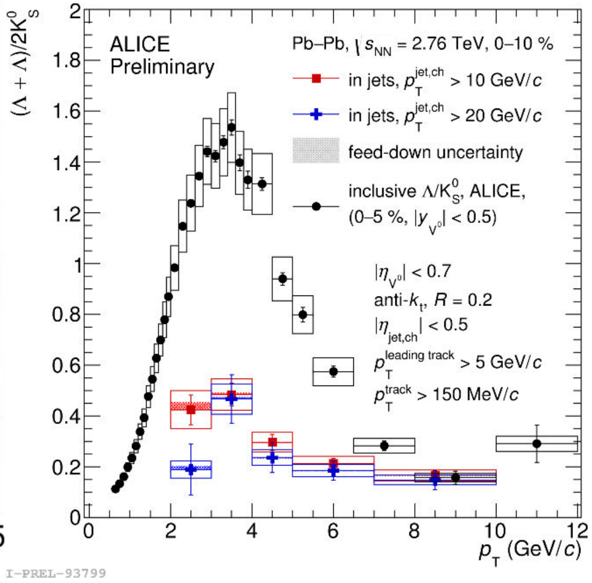


- Boltzmann-Gibbs Blast-Wave fits are used to determine parameters of the radial flow:
  - ✓ $T_{\rm kin}$ – kinetic freeze-out temperature
  - ✓ $<\beta_T>$ - transverse velocity
  - ✓ n – velocity profile
- Fit parameters are obtained from a simultaneous fit to π, K, p production spectra in a limited p_T range, results are sensitive to the fitting range

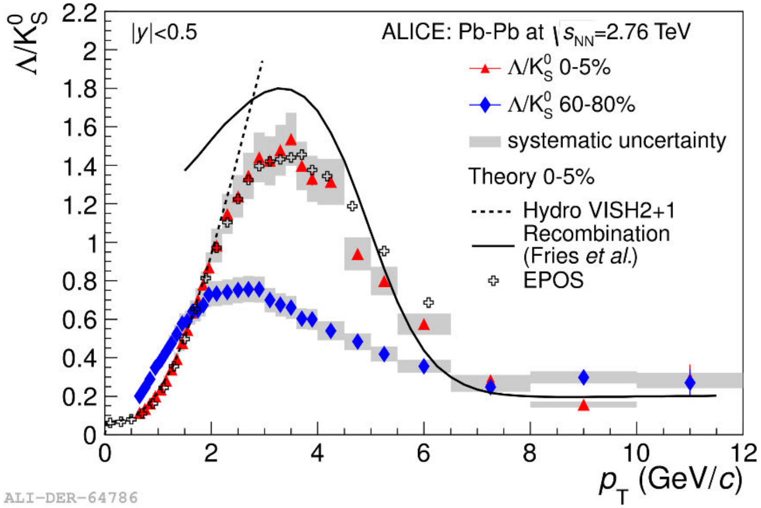
- Kinetic freeze-out temperature decreases, transverse flow velocity increases with multiplicity
- Consistent results for Pb-Pb and Xe-Xe at similar multiplicities, $T_{\rm kin}$ ~ 100 MeV < $T_{\rm ch}$
- pp and p-Pb are also consistent but with larger values of $<\beta_T>$ at similar multiplicities
- $T_{\rm kin}$ stays constant in pp and slightly decreases in p-Pb, $T_{\rm kin}$ ~ 160 MeV ~ $T_{\rm ch}$ → earlier decoupling compared to heavy-ion collisions
- Color reconnection (Pythia8) mimics radial flow-like effects in pp collisions

Baryon-to-meson ratios: Pb-Pb & Xe-Xe





- Enhanced baryon-to-meson ratios (p/π, Λ/K) in central heavy-ion collisions at intermediate p_{T}
- Enhancement is consistent between Pb-Pb and Xe-Xe at similar multiplicities
- Bulk effect, not present in jets



- Model comparison:
  - ✓ hydrodynamics reproduces the rise at p_{T} < 2 GeV/c
  - ✓ recombination reproduces ratios at intermediate p_{T}
  - ✓ EPOS provides good description by radial flow

- p/ϕ ratio is flat vs. p_{T} at intermediate momenta in Pb-Pb and Xe-Xe collisions → spectral shapes are driven by particle masses:
  - ✓ consistent with hydrodynamics
  - ✓ recombination models are not ruled-out [1]

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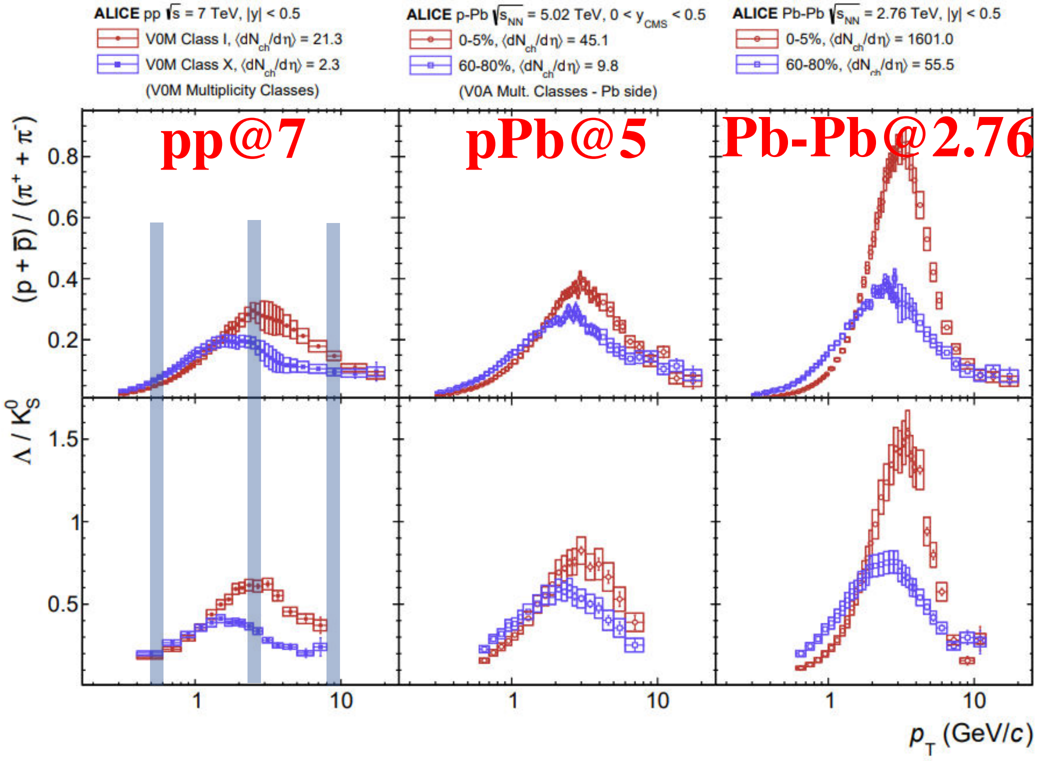
[1] V. Greco et al, PRC 92 054904 (2015)

Baryon-to-meson ratios: pp, p-Pb and Pb-Pb

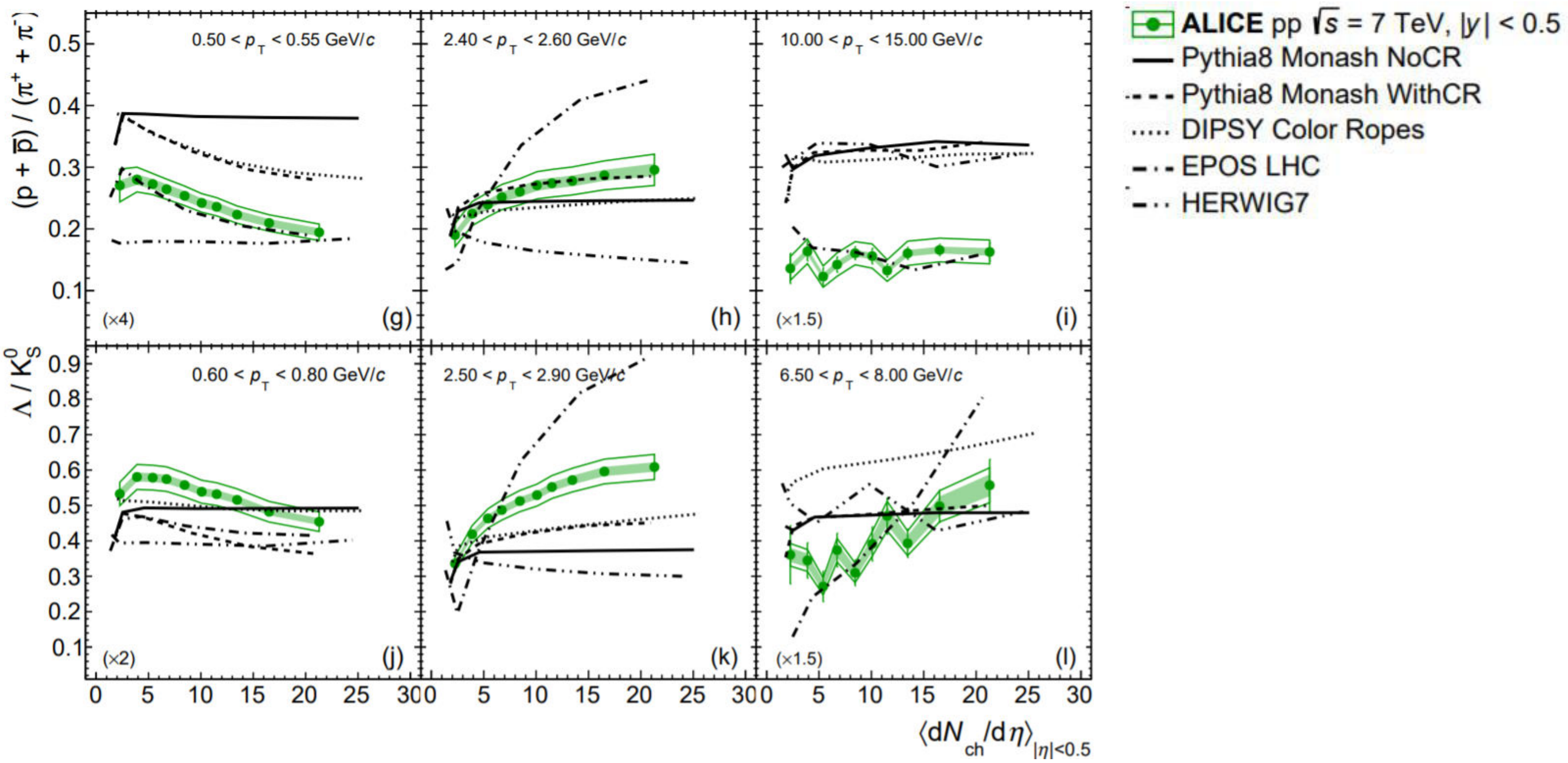
Phys. Rev. C99 (2019) no.2, 024906



- ❖ Similar behavior for three systems, from peripheral to central collisions:
  - ✓ depletion at low p_T
  - ✓ enhancement at intermediate p_T
  - ✓ consistent at high p_T

Baryon-to-meson ratios: pp

Phys. Rev. C99 (2019) no.2, 024906

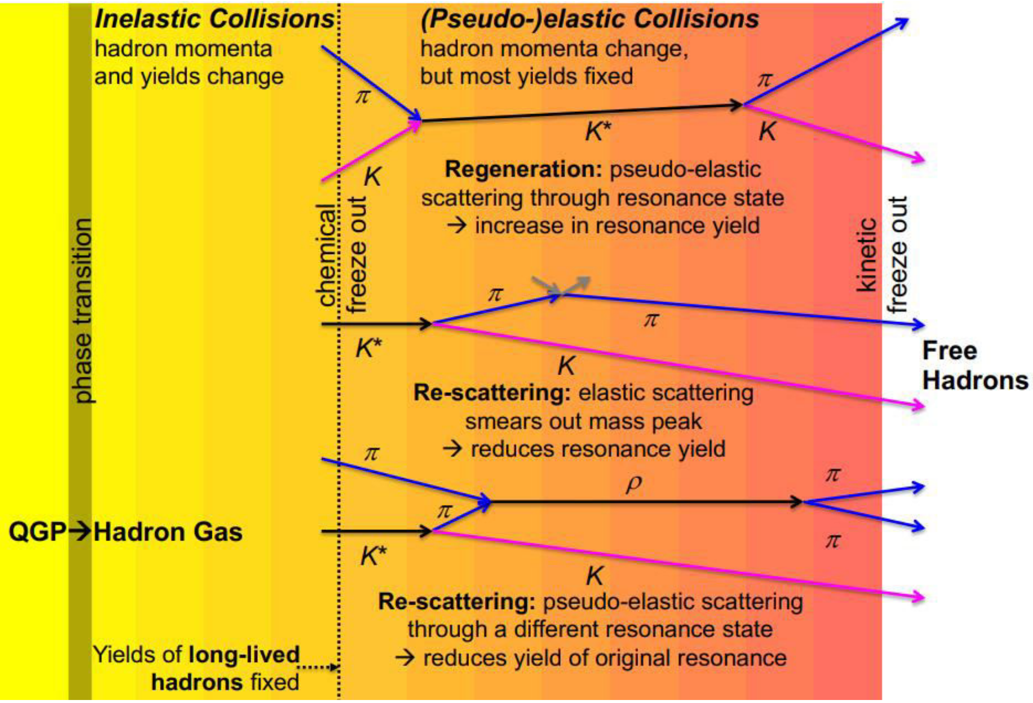


- No unique explanation for baryon-to-meson ratios in small systems
- Pythia8 with color reconnection and DIPSY with color ropes qualitatively describe pp data
- EPOS-LHC over-predicts effect by collective radial expansion

Short-lived resonances

increasing lifetime →

	$\rho(770)$	$K^*(892)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$



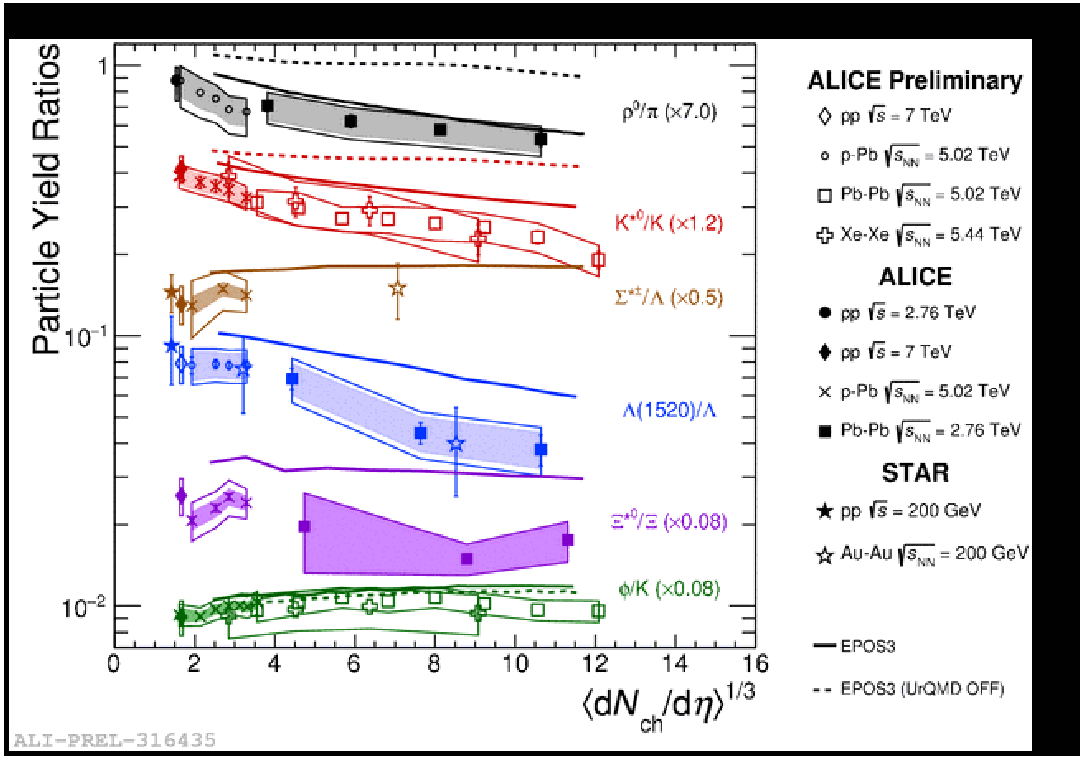
❖ Final state yields of resonances depend on:

- ✓ resonance yields at chemical freeze-out
- ✓ lifetime of the resonance and the hadronic phase
- ✓ type and scattering cross sections of daughter particles

Short-lived resonances

increasing lifetime →

	ρ(770)	K*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	ϕ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi \sigma_\pi$	$\sigma_\pi \sigma_K$	$\sigma_\pi \sigma_\Lambda$	$\sigma_K \sigma_p$	$\sigma_\pi \sigma_\Xi$	$\sigma_K \sigma_K$



- Reproduced by EPOS3 with a hadronic phase simulated by UrQMD
- Results support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields of short lived resonances
- Lower limit for the lifetime of the hadronic phase, τ > 2 fm/c*

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* G. Torrieri and J. Rafelski, J. Phys. G 28, 1911 (2002); C. Markert et al., arXiv:hep-ph/0206260v2 (2002)

Light (anti)nuclei production

- ❖ Light (anti)nuclei are measurable in pp, p-Pb and Pb-Pb collisions at LHC energies
- ❖ The production mechanisms are not well understood
- ❖ Two classes of models are available

Thermodynamic models

- ✓ particle abundancies are fixed at chemical freeze-out, T_{ch}
- ✓ because of large masses nuclei are very sensitive to T_{ch}, ${}^{dN}/_{dy} \sim exp\left({}^{m}/_{T_{ch}}\right)$
- ✓ exponential dependence of the yields on particle masses

Coalescence models

- ✓ baryons which are close enough in the phase-space after kinetic freeze-out can form a nucleus
- ✓ probability to form a nucleus with mass number A is defined by B_A, where:

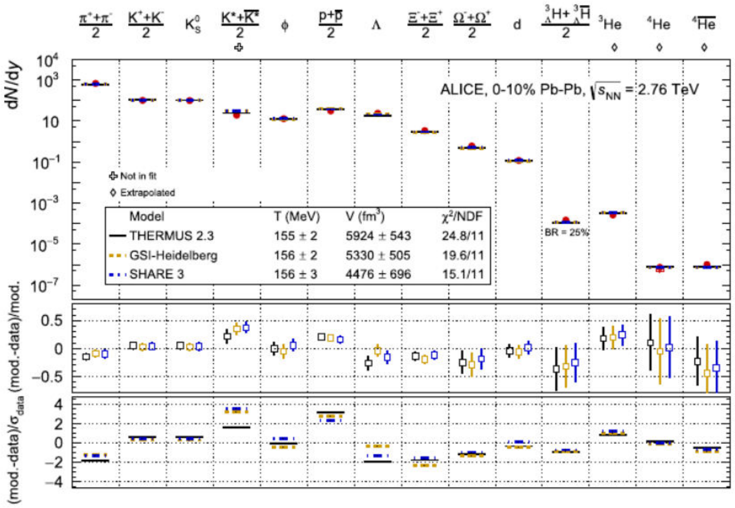
$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^A$$

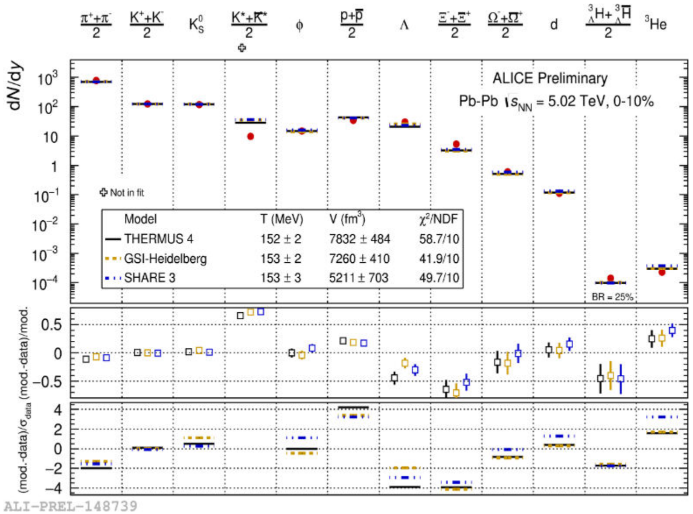
- ✓ nuclei produced at chemical freeze-out can break up and re-form before kinetic freeze-out

- ❖ Light (anti)nuclei probe the thermal equilibrium and collectivity in pp, p-Pb and Pb-Pb

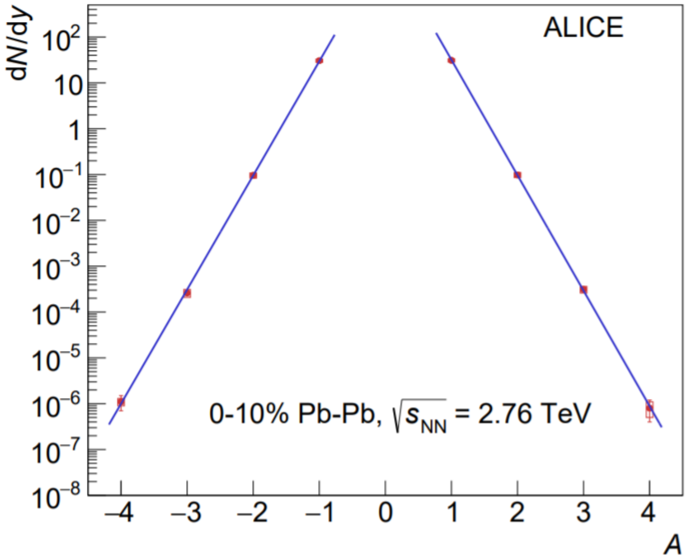
Thermal model fits: Pb-Pb

- ❖ Thermal model fits describe particle yields, including light (hyper)nuclei with T_{ch} ~ 155 MeV



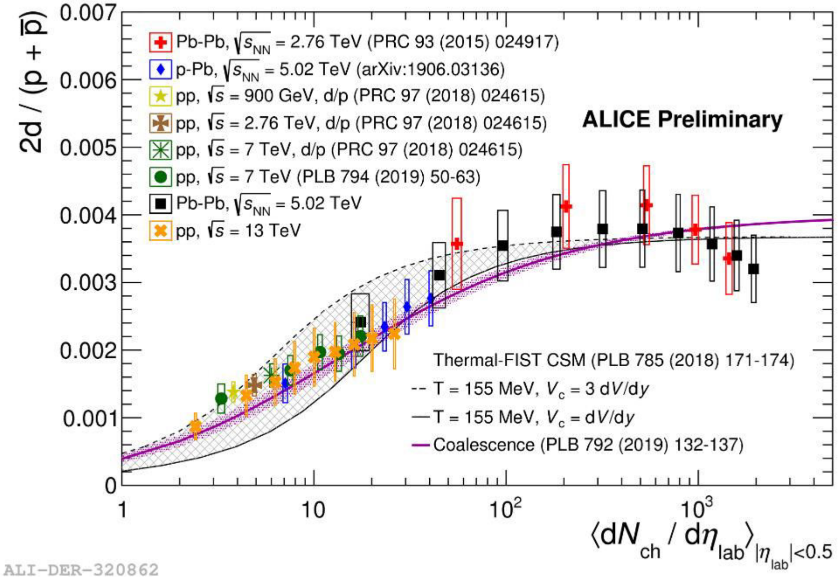


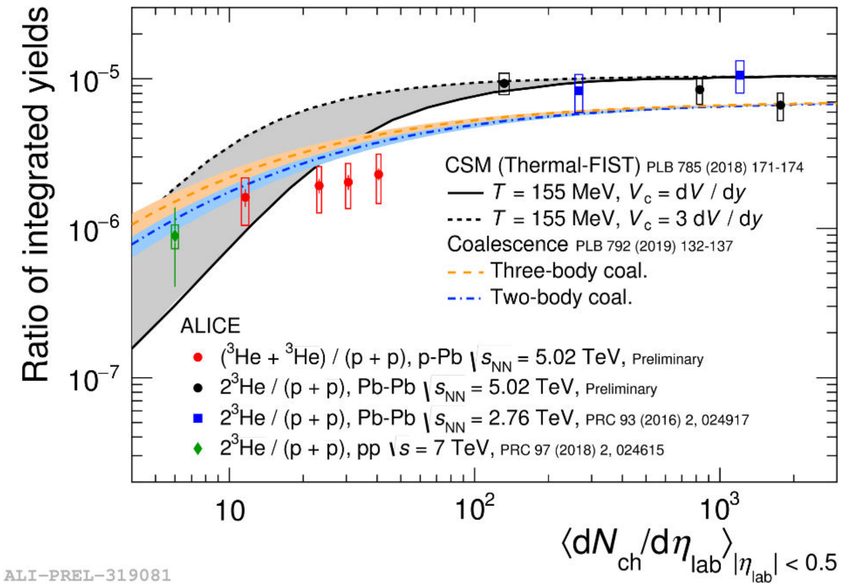
Nucl.Phys. A971 (2018) 1-20



- ❖ Thermal model prediction of exponential decrease of the yield with mass, $^{dN}/_{dy} \sim exp\left(^{m}/_{T_{ch}}\right)$, is confirmed up to A=4
- ❖ In Pb-Pb, the penalty factor for adding a nucleon is ~ 300 for particles and antiparticles

Deuteron and ^{3}He production, ratios





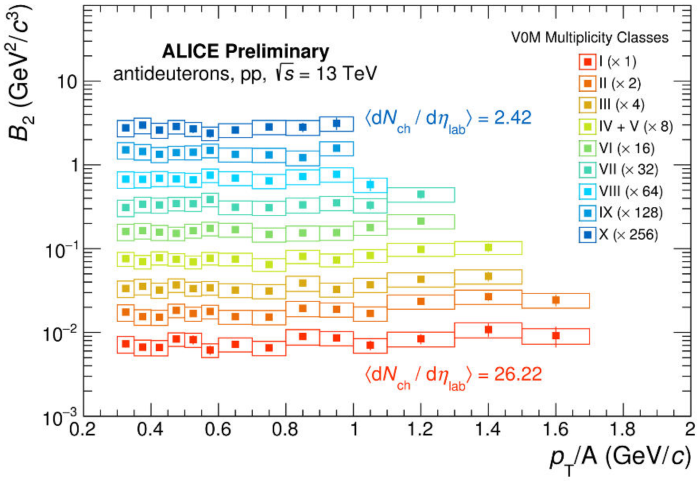
- d/p and ^{3}He/p ratios do not show discontinuity vs. multiplicity going from pp to central Pb-Pb collisions at different energies → hint of a common production mechanisms controlled by the system size

- Ratios are increasing in small systems described by:
  - ✓ canonical suppression in thermal models
  - ✓ small phase space in coalescence models

- Ratios saturate in heavy-ion collisions:
  - ✓ described by thermal and coalescence models

- More data is needed to cover a multiplicity gap for ^{3}He/p ratio

Deuteron production



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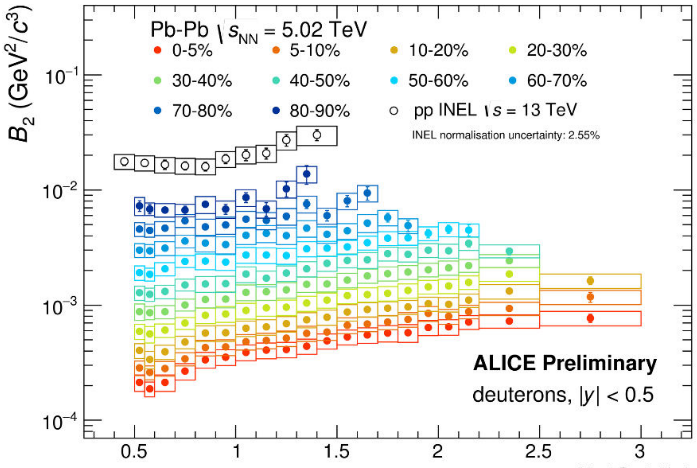
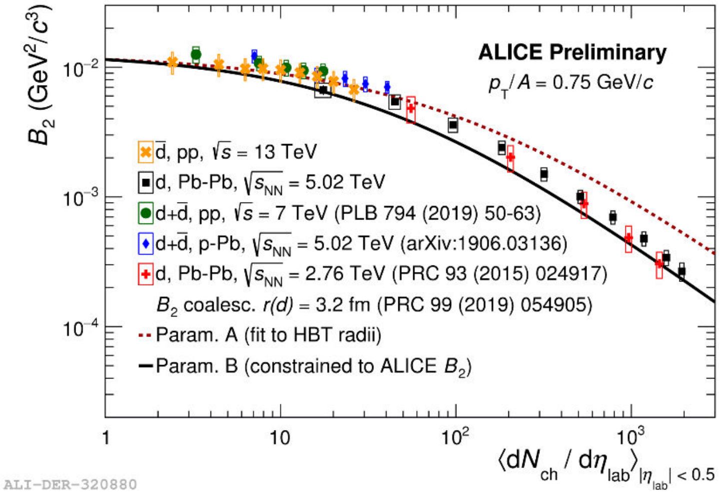


ALI-PREL-130476

- ❖ $$B_2 = \frac{E_d \frac{d^3N_d}{dp_p^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^2}$$ vs. p_T/A in different multiplicity/centrality pp/Pb-Pb collisions

- ❖ B_2 is predicted to be flat vs. p_T by simple coalescence
  - ✓ consistent with measurements in pp
  - ✓ the higher the centrality the stronger the rise of B_2 with p_T in Pb-Pb → not consistent

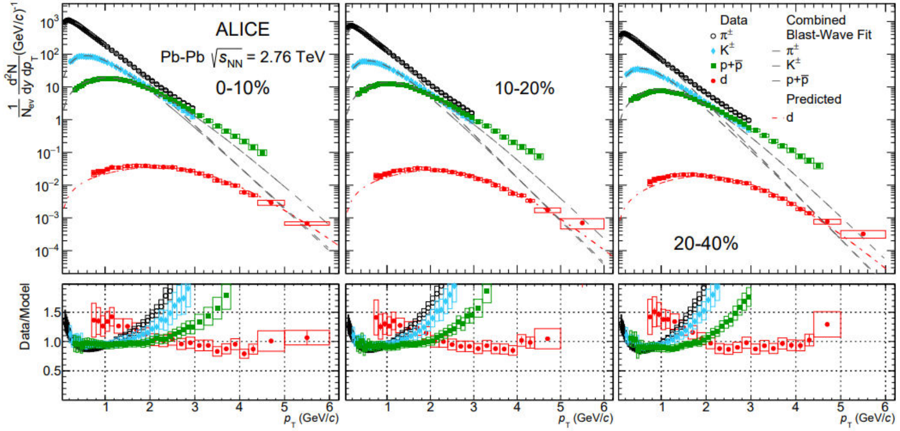
- ❖ B_2 does not show discontinuity vs. multiplicity going from pp to central Pb-Pb collisions at different energies → hint of a common production mechanisms controlled by the system size

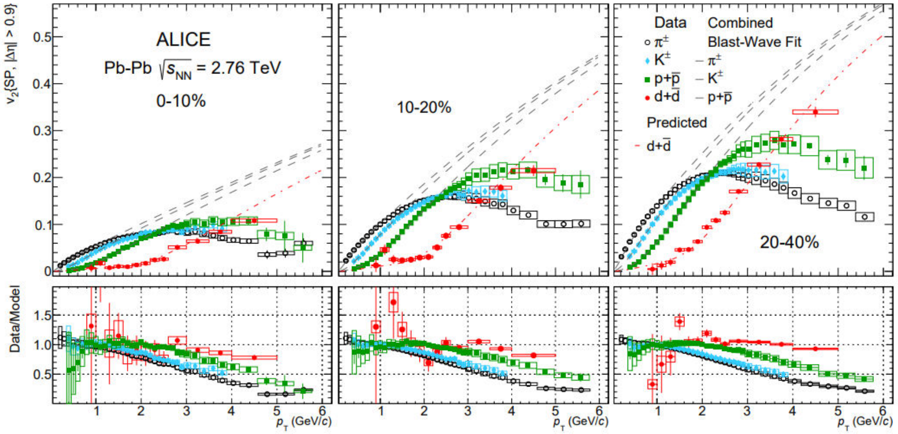


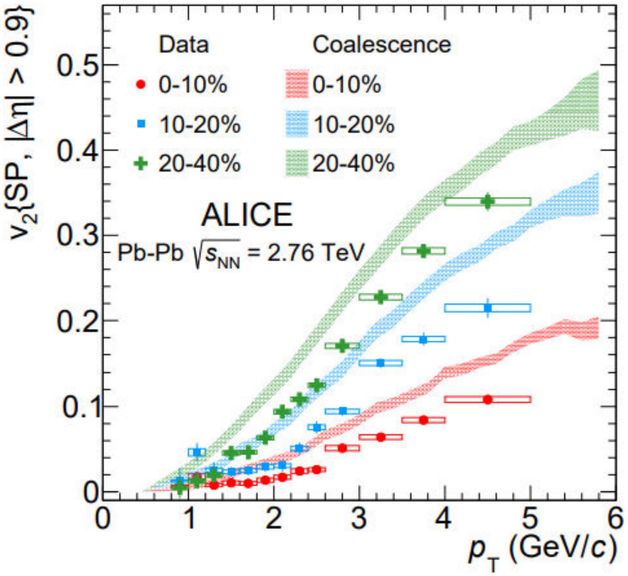
ALI-DER-320880

Deuteron production

Eur.Phys.J. C77 (2017) no.10, 658







- Blast-Wave model fits to charged π/K/p are used to predict p_T spectra and v_2 of deuterons

  → results are consistent with common freeze-out for light hadrons and deuterons

- Coalescence model relates flow of deuteron ($v_{2,\mathrm{d}}$) to flow of proton ($v_{2,\mathrm{p}}$) :

$$v_{2,\mathrm{d}}(p_\mathrm{T}) = \frac{2v_{2,\mathrm{p}}(p_\mathrm{T}/2)}{1+2v_{2,\mathrm{p}}^2(p_\mathrm{T}/2)}.$$

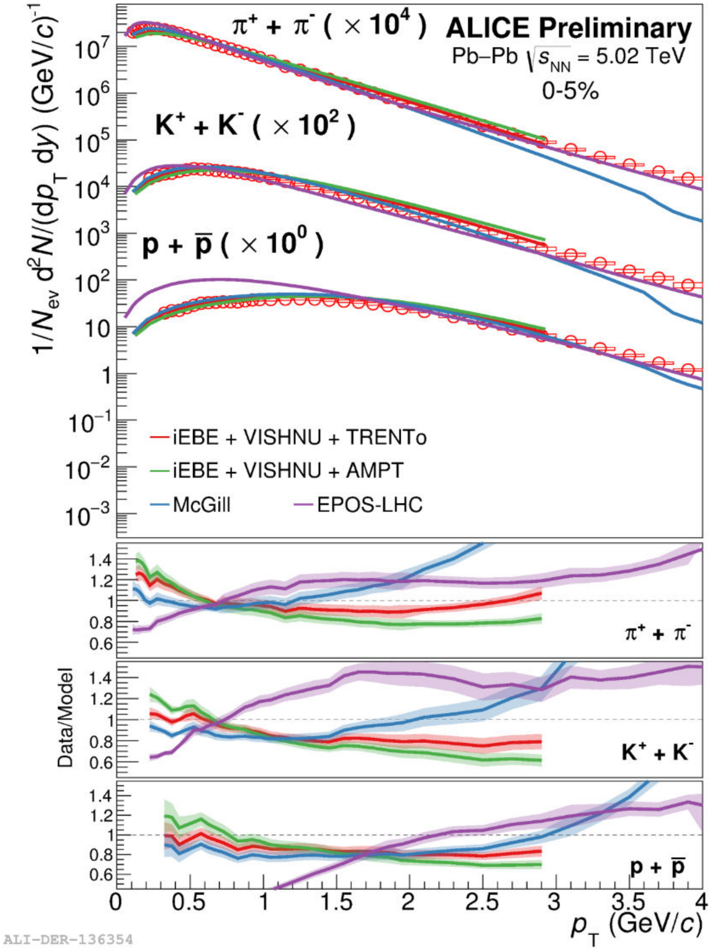
→ coalescence does not describe $v_{2,\mathrm{d}}$

Conclusions

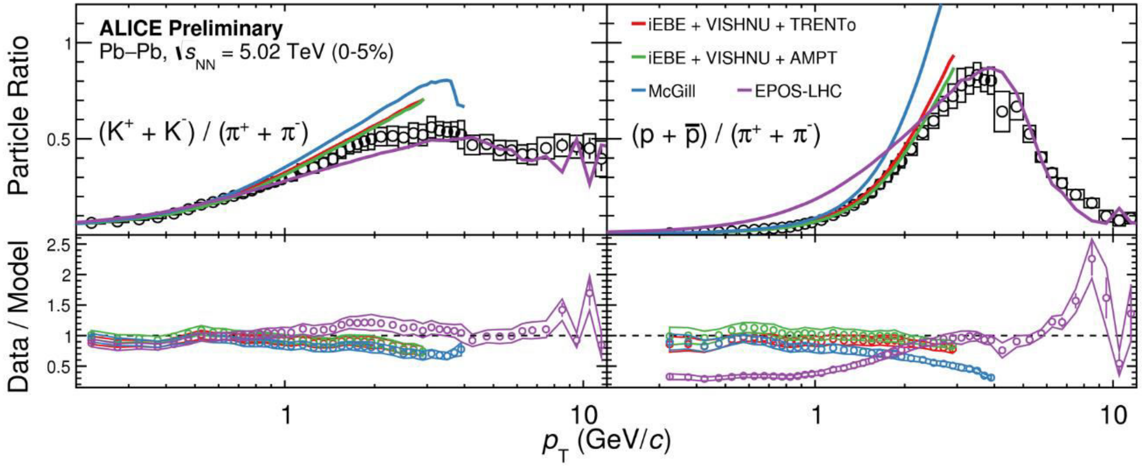
- Hadrochemistry is driven by final state particle multiplicity, not by type of colliding nuclei or collision energy
- Thermal models describe most particle yields with a common value of the chemical freeze-out temperature, T_{ch} ~ 155 MeV
- Strangeness enhancement is observed in small and large collision systems. Canonical suppression is able to reproduce results except for ϕ, which has hidden strangeness
- Radial flow hardens particle p_{T} spectra in A-A. Hint of radial flow is also observed in small systems although interpretation is not unique.
- Baryon-to-meson ratios show similar trends in small and large collision systems
- Results for short-lived resonances support the existence of a hadronic phase that lives long enough to cause a significant reduction of the measured yields
- Production of light (anti)nuclei is consistent with thermal production and hydrodynamic flow in heavy-ion collisions and coalescence in pp

BACKUP

p_T spectra in 0-5% Pb-Pb@5 vs. models



ALI-DER-136354



ALI-DER-139092

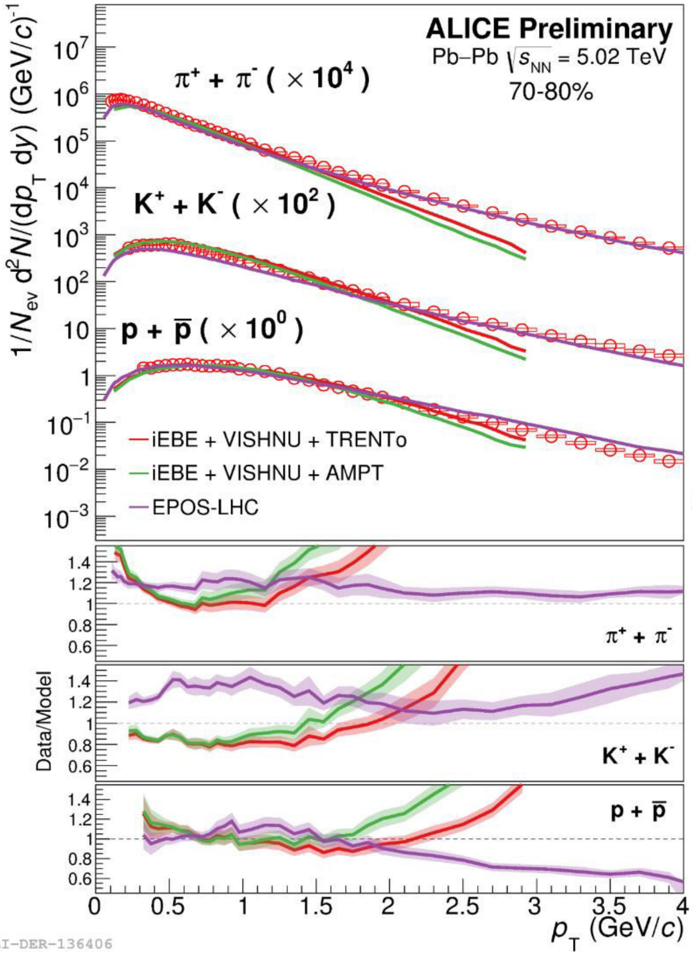
- Spectra for π/K/p are compared to:
  - ✓ EbyE + VISHNU + Trento/AMPT: viscous hydrodynamics (QGP) + hadron cascades (hadronic phase) by UrQMD with different initial conditions [1]
  - ✓ McGill: MUSIC viscous hydrodynamics with IP-Glasma initial conditions [2]
  - ✓ EPOS-LHC: fireball divided in core (QGP) and corona [3]

[1] arXiv:1703.10792v1; Phys.Rev. C92, 014903; (2015) &011901(R) (2015)

[2] Phys. Rev. C 95, 064913 (2017); [3] Phys.Rev. C 92, 034906 (2015)

- Hydrodynamic models reproduce basic features of spectra and ratios at p_T below ~ 2 GeV/c
- EPOS-LHC reproduces ratios up to higher momenta but not the spectra

p_T spectra in 70-80% Pb-Pb@5 vs. models



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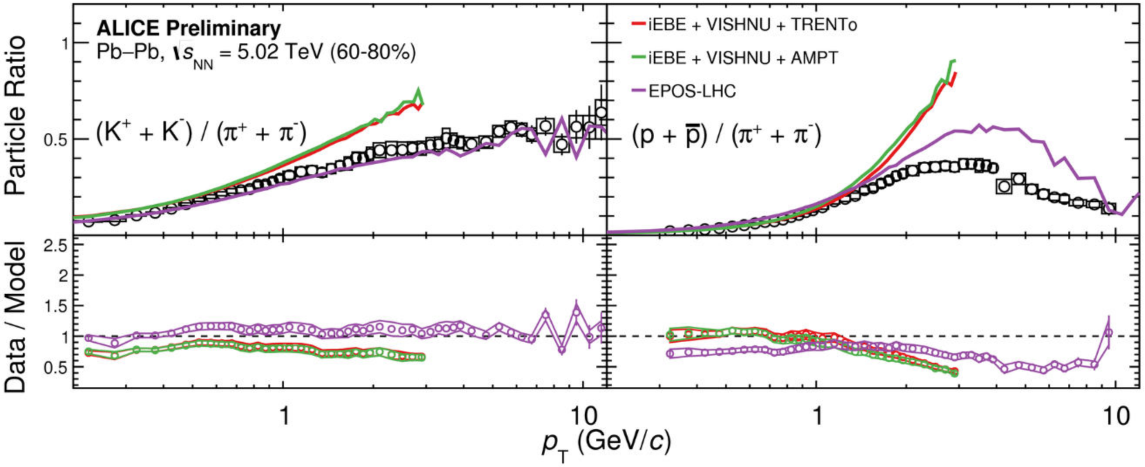
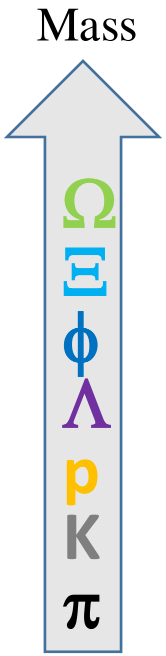
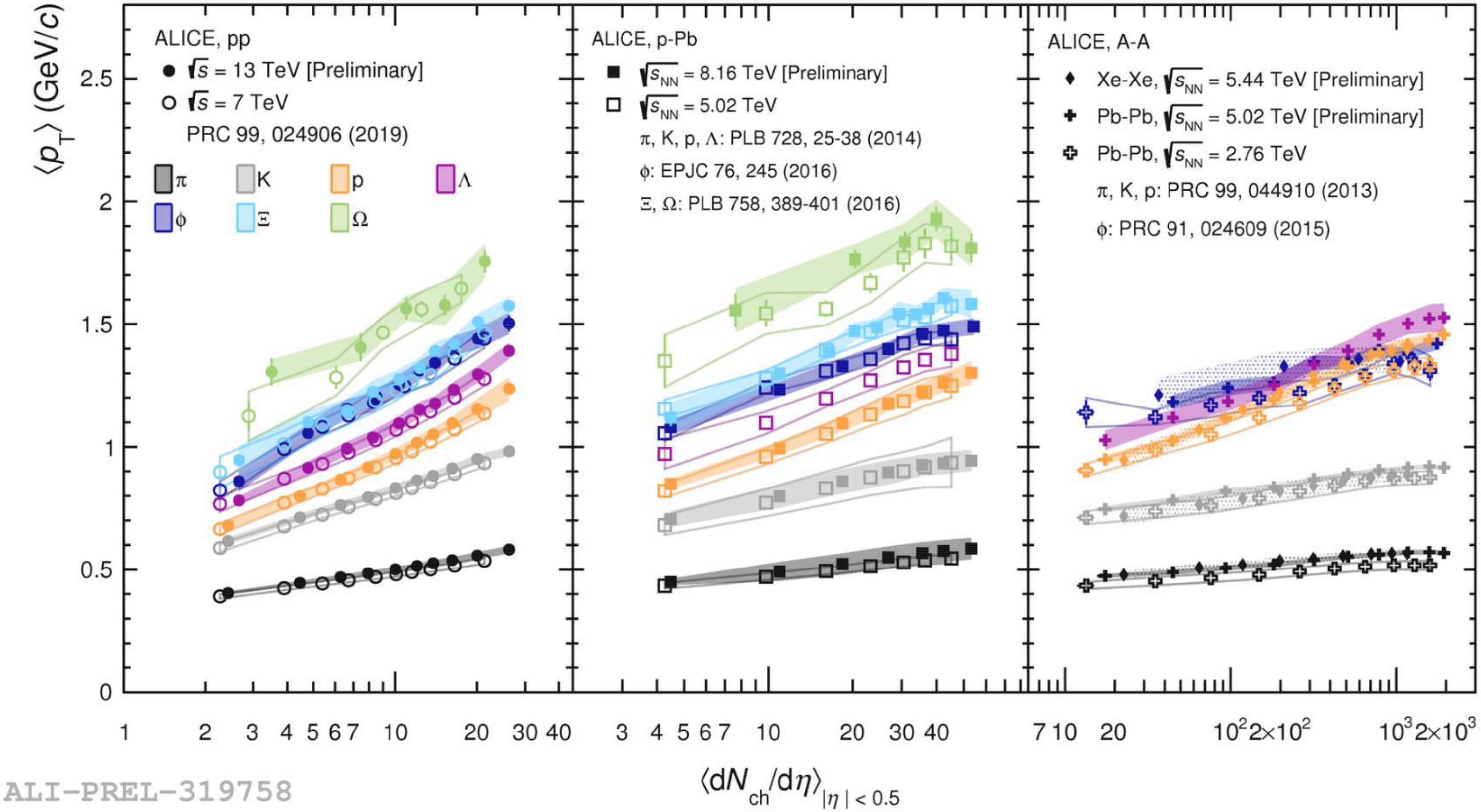


ALI-DER-139104

- ❖ Agreement worsens towards more peripheral collisions

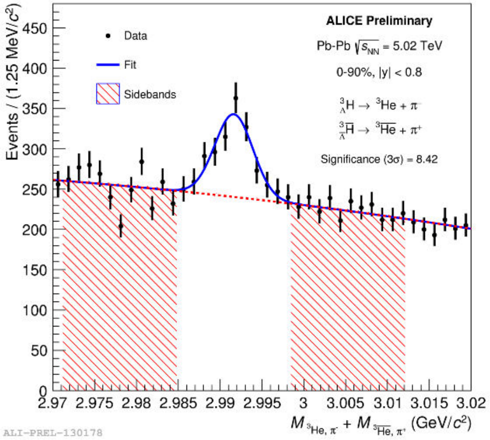
Mean p_T: pp → p-Pb → Pb-Pb

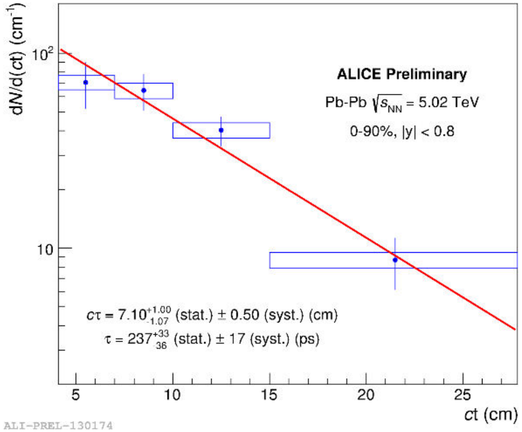


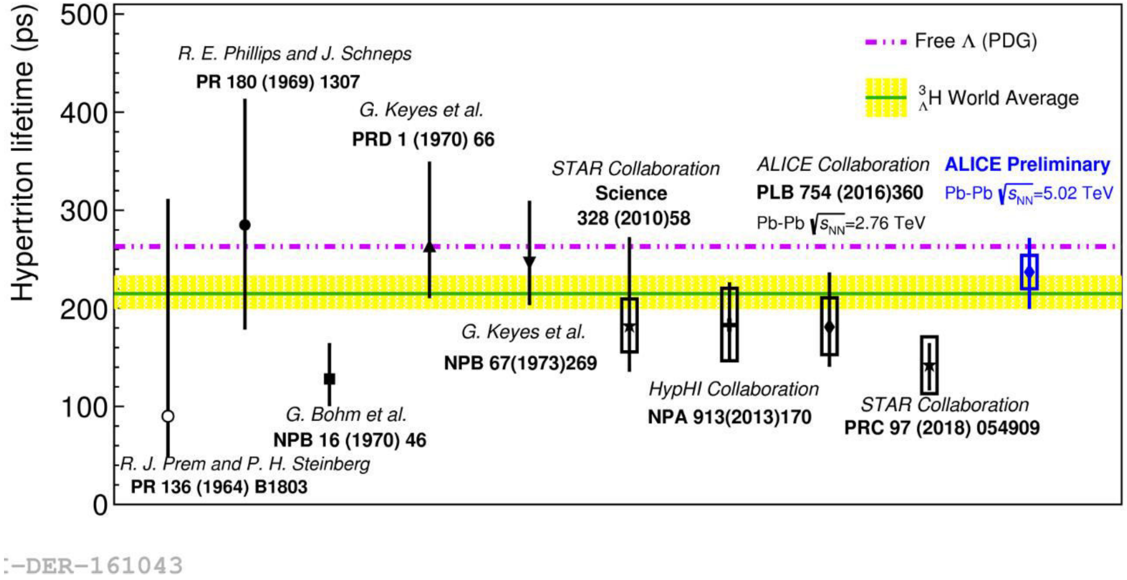


- ❖ Growth of <p_T> with multiplicity is generally attributed to radial flow, especially in Pb-Pb
- ❖ pp, p-Pb and peripheral Pb-Pb:
  - ✓ similar dependence of <p_T> on particle mass
  - ✓ ϕ and K^* meson have larger <p_T> than p and Λ → mass ordering is violated, baryon/meson effect ???
- ❖ central Pb-Pb:
  - ✓ particles with similar masses have the same <p_T> → expected from hydrodynamics

Hypertriton lifetime, Pb-Pb@5







❖ Due to small binding energy, hypertriton lifetime is expected to be close to the free Λ lifetime

❖ Previous heavy-ion results at RHIC and the LHC reported lifetimes below the free Λ lifetime

❖ New results from Pb-Pb@5 with improved precision are compatible with world average and free Λ lifetime