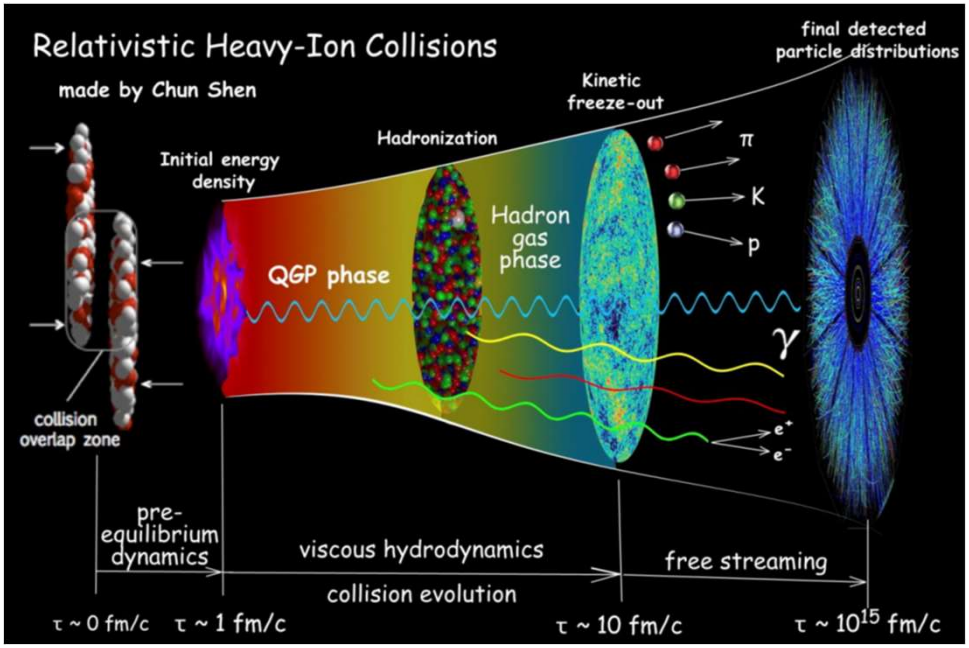
Recent results on light flavor hadron production in the ALICE experiment at the LHC

Victor Riabov for the ALICE Collaboration

Introduction

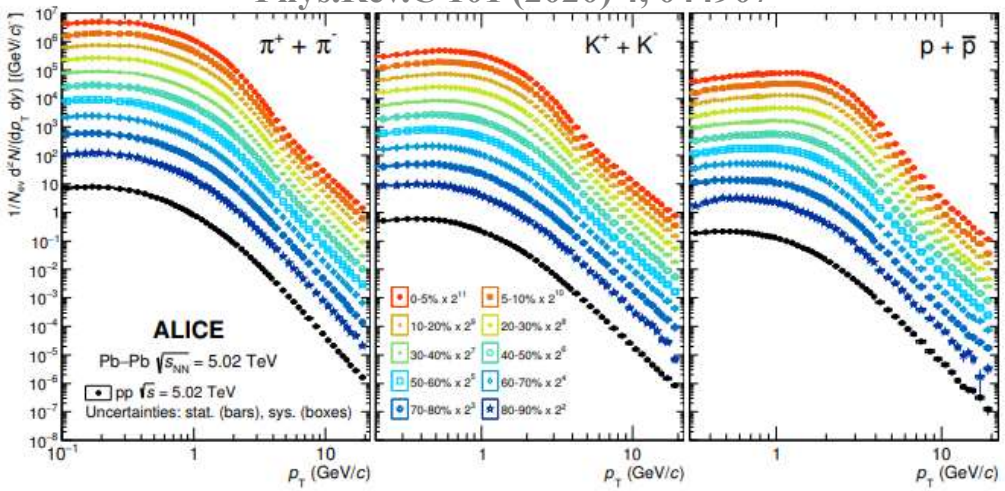


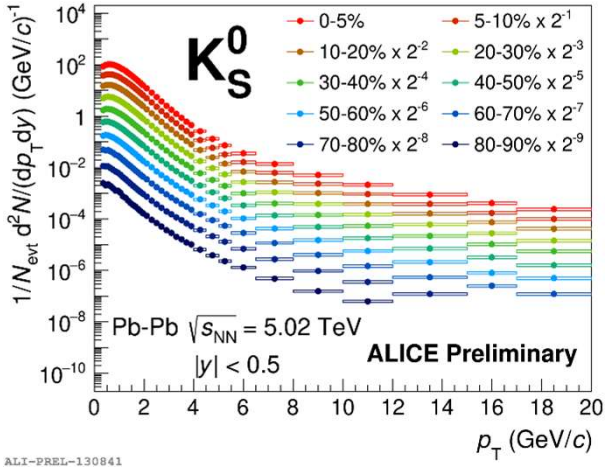
System	Year	Energy (TeV)
pp	2009-2013 2015,2017 2015-2018	0.9, 2.76, 7, 8 5.02 13
p-Pb/Pb-p	2013 2016	5.02 5.01, 8.16
Xe-Xe	2017	5.44
Pb-Pb	2010-2011 2015-2018	2.76 5.02

- In heavy-ion collisions, the interacting system evolves through different stages and then cools down. Light flavor hadrons are the most copiously produced particles in the final state
- Measurements of light flavor hadrons are used to probe the collective evolution of the system, test the phase transition, properties of the system at chemical and kinetic freeze-out, the particle production mechanisms and reaction dynamics.
- ALICE studies the system size and collision energy dependence of particle production with the same apparatus using different data samples accumulated in Run-1 and Run-2

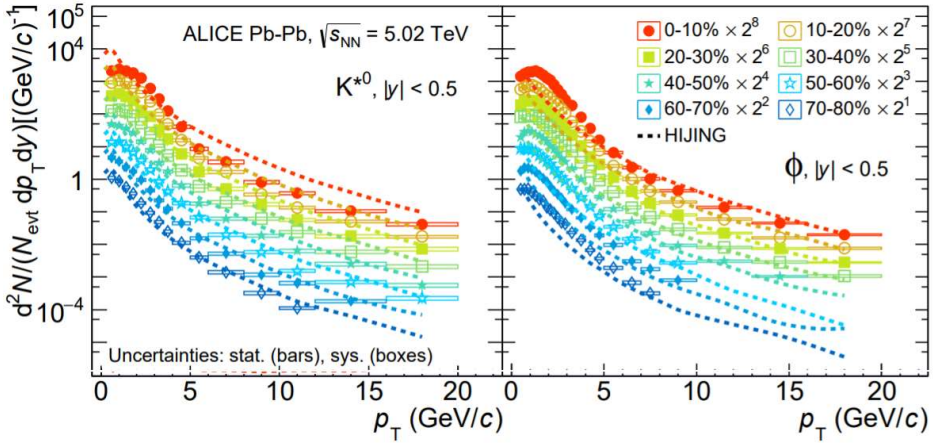
Particle spectra in heavy-ion collisions

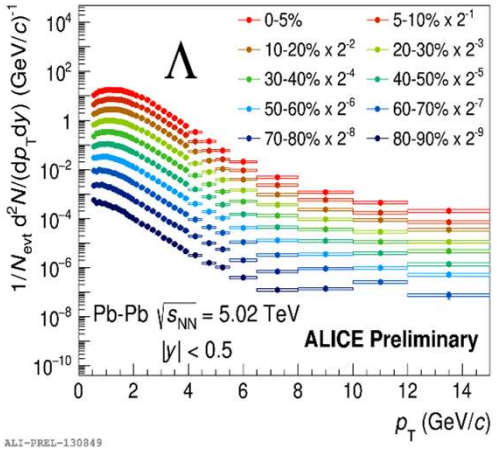
Phys.Rev.C 101 (2020) 4, 044907





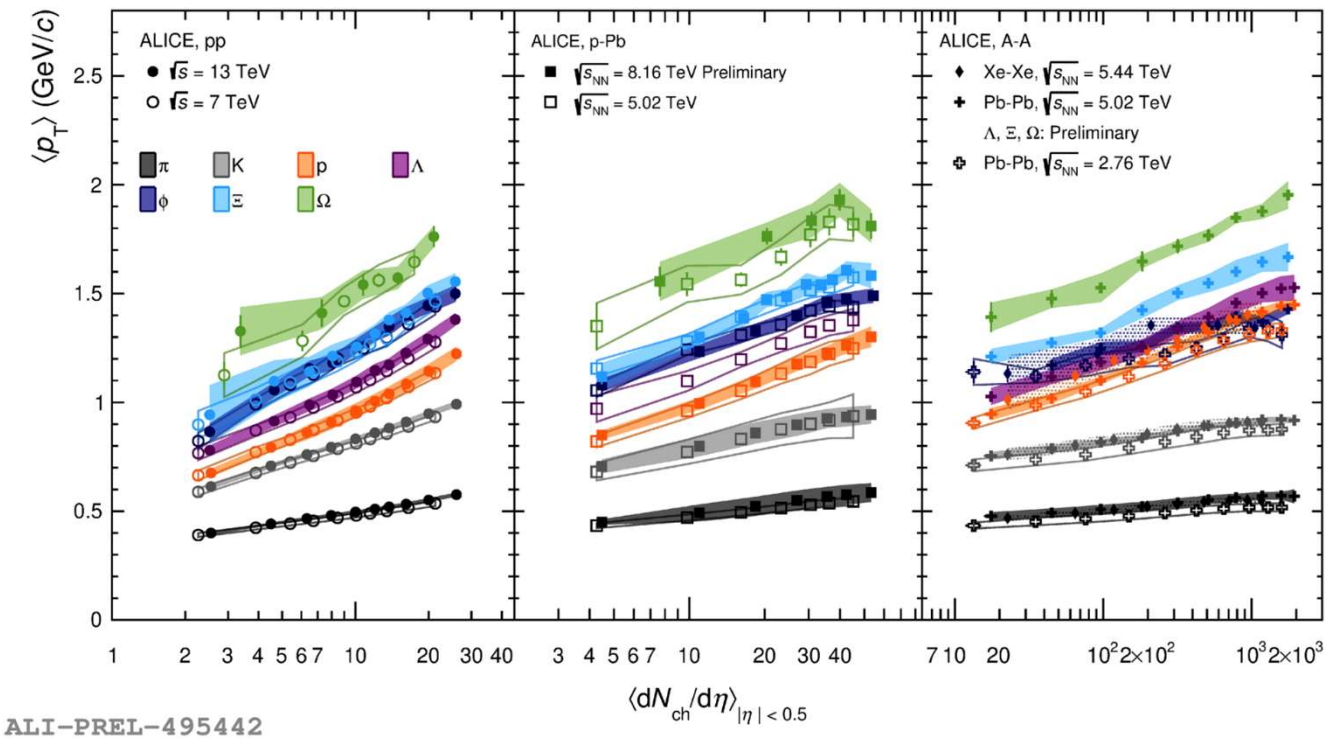
arXiv:2106.13113





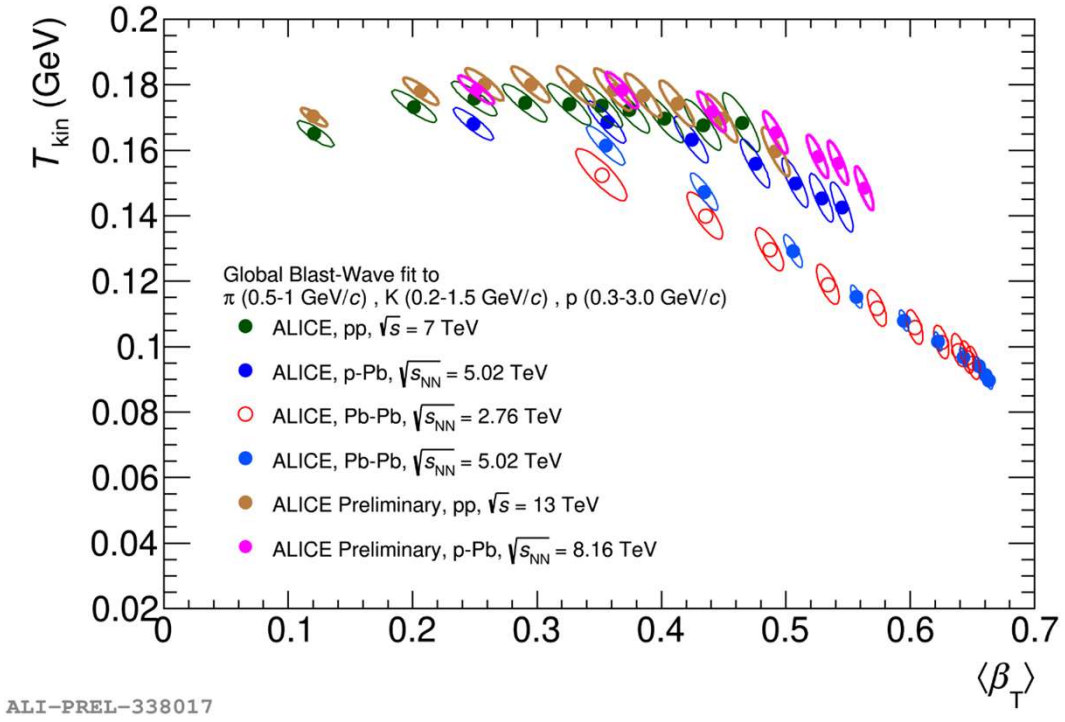
- A variety of hadrons measured in wide p_T ranges at different centralities
- Spectra become harder with increasing multiplicity (flatten at low p_T), most pronounced for heavier particles → expected from collective hydrodynamic expansion (radial flow)
- Similar hardening of spectra has been also observed in high-multiplicity pp and p-Pb collisions

Mean transverse momenta



- Mass-dependent hardening of spectra manifests itself in $\langle p_T \rangle$ increasing with multiplicity
- Steeper increase of $\langle p_T \rangle$ in smaller collision systems
- Modest increase of $\langle p_T \rangle$ with collision energy
- In heavy-ion collisions $\langle p_T \rangle$ is independent of the size of colliding nuclei (Xe-Xe vs. Pb-Pb)
- In central heavy-ion collisions particles with similar masses have similar values of $\langle p_T \rangle$ as expected from hydrodynamic flow
- The mass ordering of $\langle p_T \rangle$ is violated in peripheral heavy-ion collisions as well as in pp and p-Pb

Blast-Wave model fits to π/K/p spectra

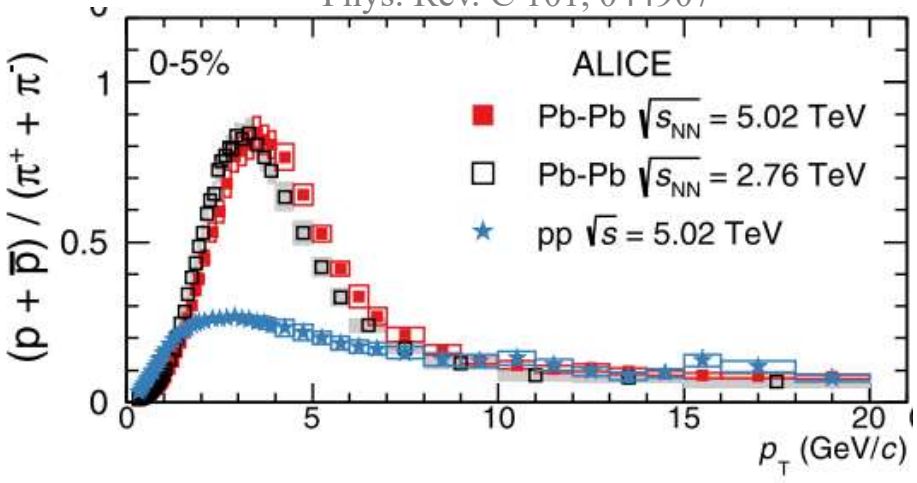


- Boltzmann-Gibbs Blast-Wave fits are used to determine parameters of the radial flow:
  - ✓ T_{kin} – kinetic freeze-out temperature
  - ✓ $\langle\beta_T\rangle$ - transverse velocity
  - ✓ n – velocity profile
- Fit parameters are extracted from a simultaneous fits to π, K, p spectra, results are 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, $T_{kin} \sim 100$ MeV $< T_{ch}$
- pp and p-Pb are also consistent but with larger values of $\langle\beta_T\rangle$ at similar multiplicities
- T_{kin} stays constant in pp and slightly decreases in p-Pb, $T_{kin} \sim 160$ MeV $\sim T_{ch}$ → earlier decoupling compared to heavy-ion collisions

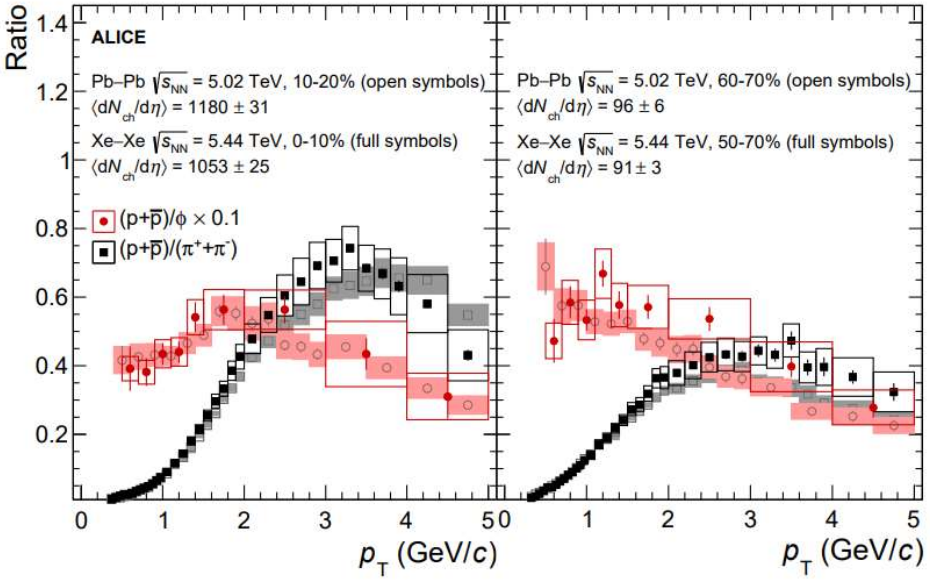
Baryon-to-meson ratios in heavy-ion collisions

Phys. Rev. C 101, 044907



- Enhanced baryon-to-meson ratios (p/π, Λ/K) in central heavy-ion collisions at intermediate p_T → quark coalescence + flowing medium
- Enhancement is similar at different energies, peak is shifted to the right at higher energy

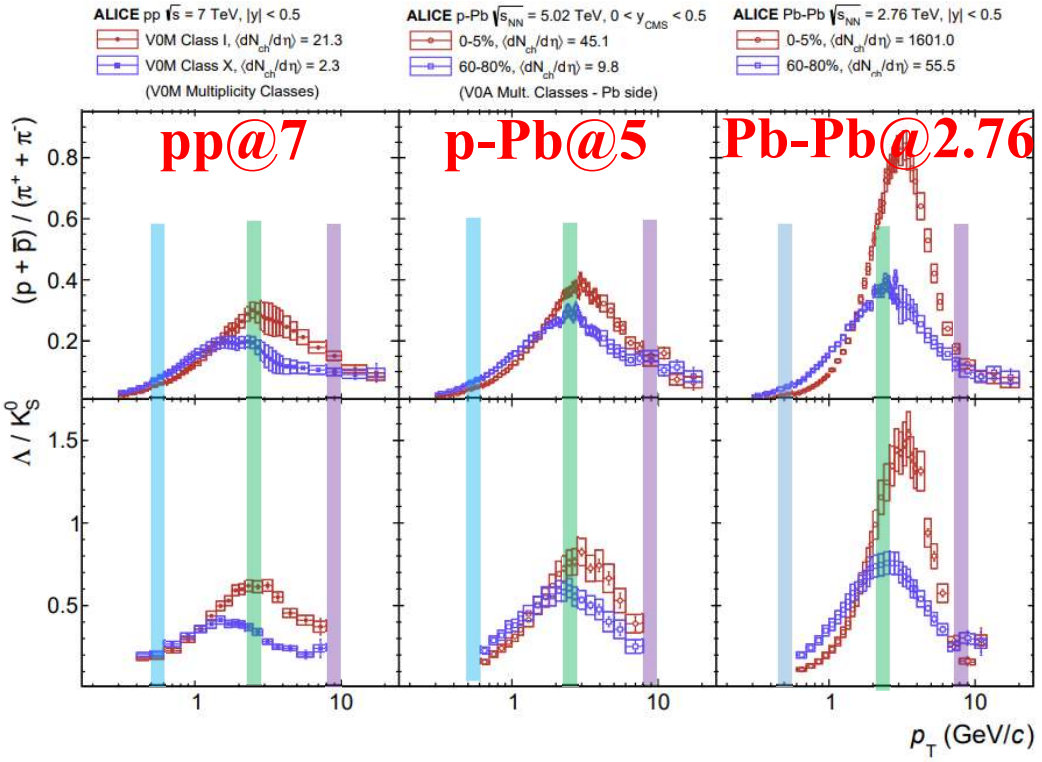
Eur.Phys.J.C 81 (2021) 7, 584



- p/ϕ ratio is almost constant 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 (V. Greco et al, PRC 92 054904 (2015))

Baryon-to-meson ratios in small systems

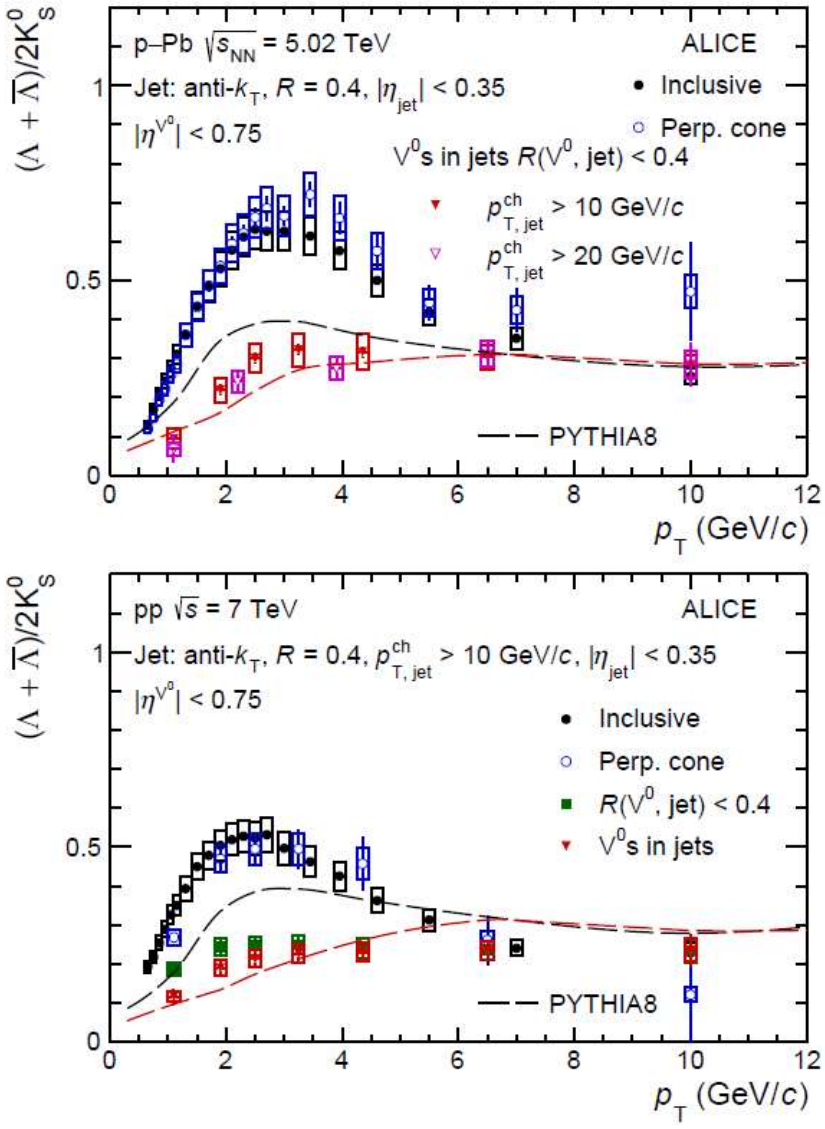
Phys. Rev. C99 (2019) no.2, 024906

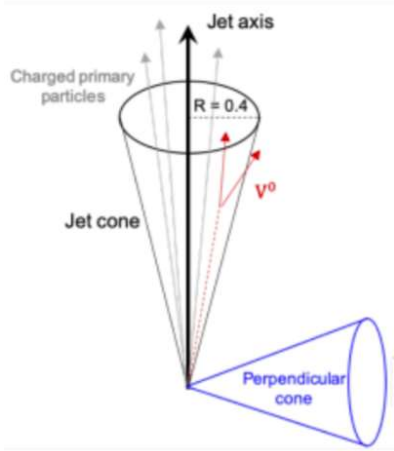


- Qualitatively similar behavior for three systems, from peripheral to central collisions:
  - ✓ depletion at **low p_T**
  - ✓ enhancement at **intermediate p_T**
  - ✓ consistent at **high p_T**
- Smooth evolution with multiplicity between the collision systems at given p_T

Baryon-to-meson ratios in jets

arXiv:2105.04890

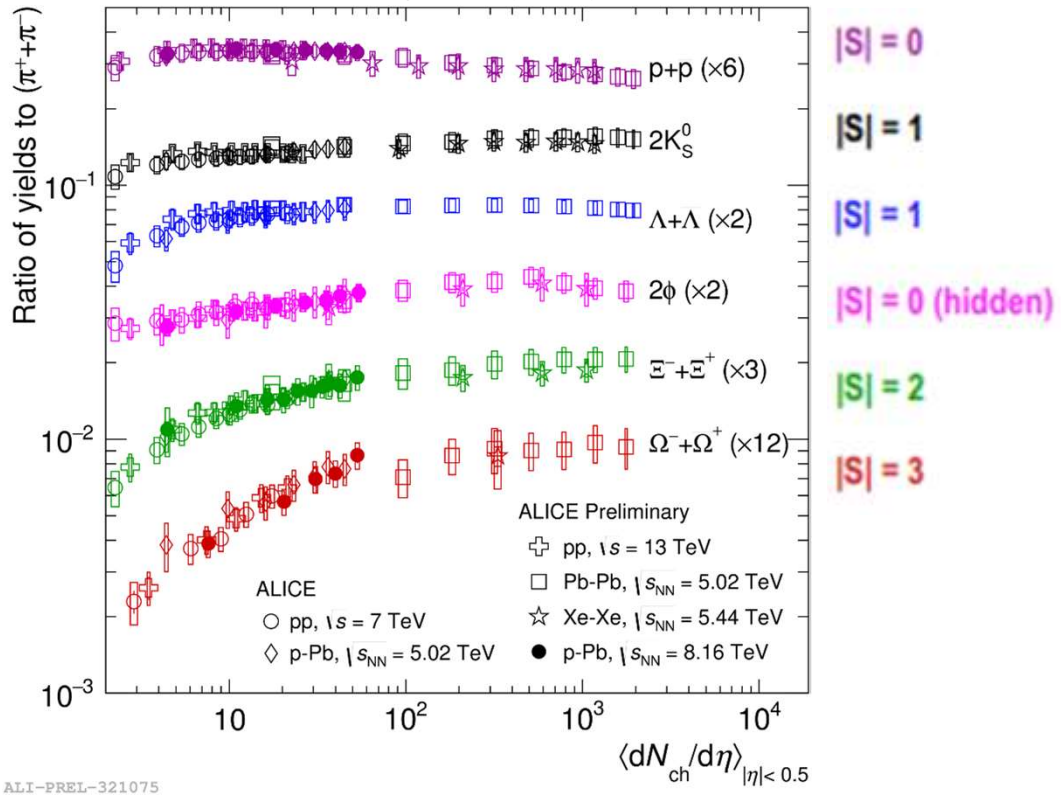


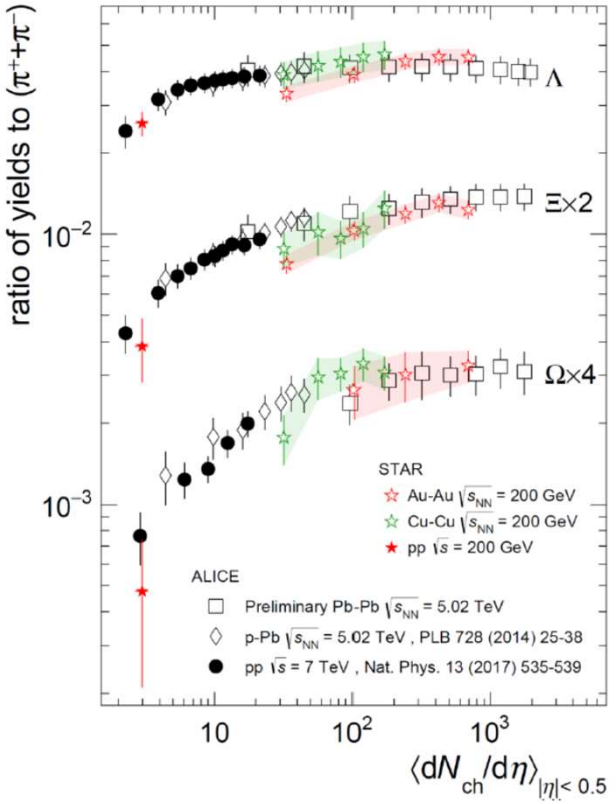


- Baryon-to-meson enhancement in p-Pb and pp collisions:
  - ✓ not seen in jets
  - ✓ driven by soft processes (bulk effect)
- PYTHIA 8 is consistent with ratios in jets but does not reproduce the inclusive ratios at intermediate p_T
- Input for model tuning → contributions of the fragmentation, coalescence and flow

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

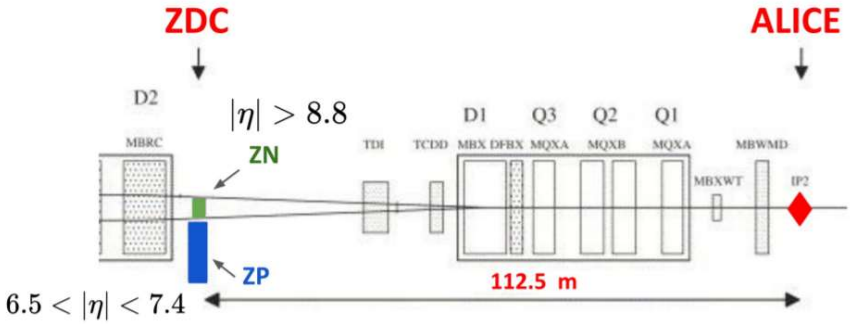
Nature Phys. 13 (2017) 535



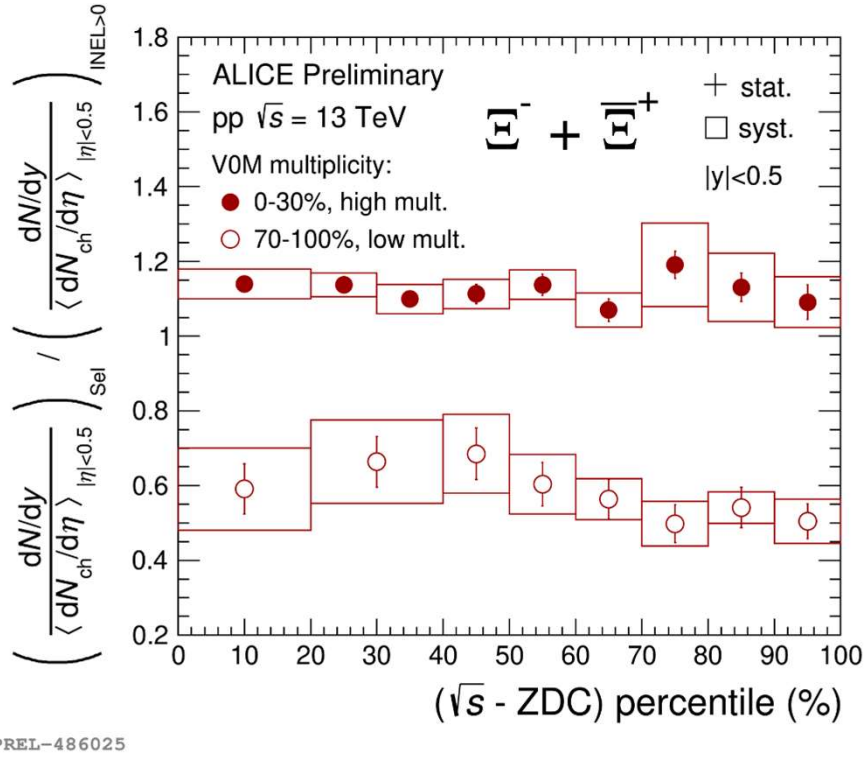


- Strangeness enhancement increases with strangeness content and particle multiplicity
- Ratios saturate in central A-A at values predicted by statistical hadronization models
- Smooth evolution vs. multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb collisions at various $\sqrt{s_{NN}}$
- STAR measurements in Cu-Cu, Au-Au at $\sqrt{s_{NN}} = 200$ GeV are in agreement with ALICE p-Pb results at similar $\langle dN_{ch}/d\eta \rangle$. Results from pp collision at $\sqrt{s} = 200$ GeV are consistent within the large uncertainties with ALICE results
- Origin of the strangeness enhancement in small/large systems is still under debate

Effective energy analysis in pp



- Energy available for particle production in the initial state $E_{eff} = \sqrt{s} - E_{ZDC}$ is measured with ZDC at |η| > 8.8

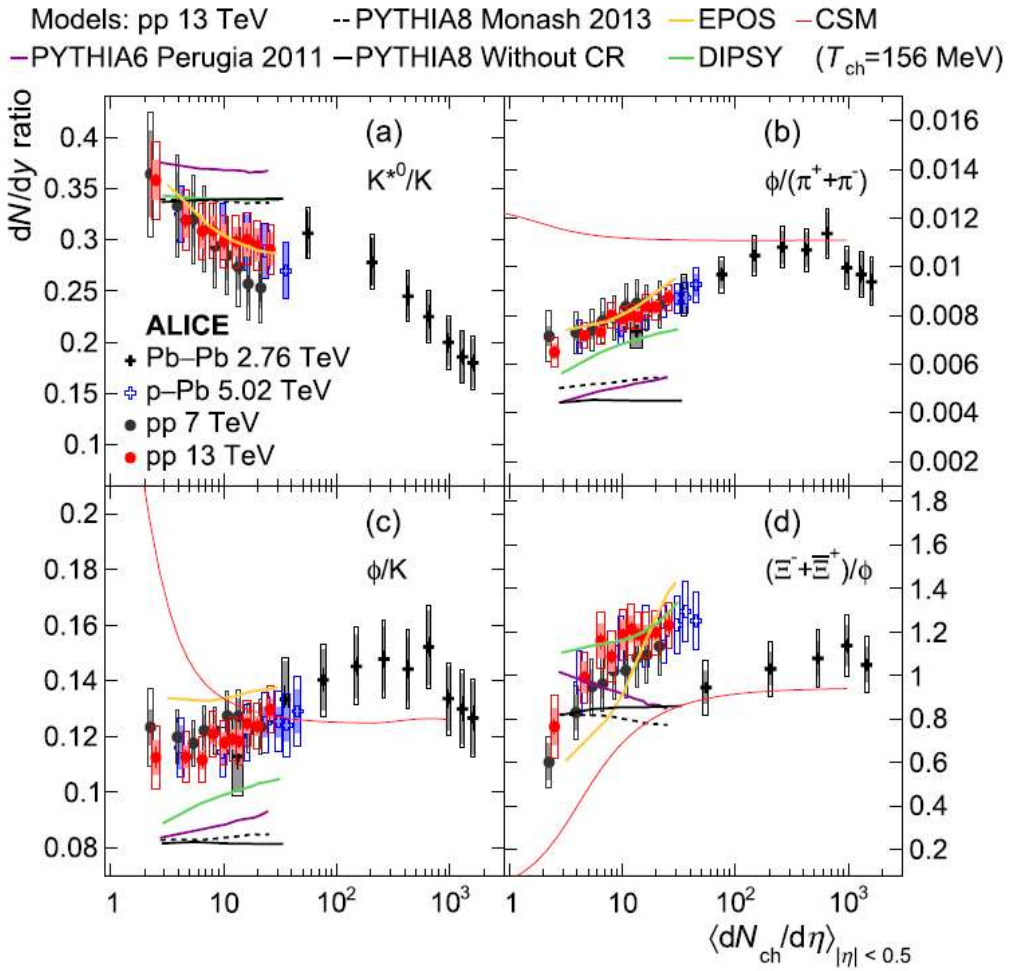


ALI-PREL-486025

- Relative Ξ production has been shown to depend on the final state multiplicity in the previous slide
- Relative Ξ production does not show dependence on E_{eff} (initial state)

Strangeness enhancement for ϕ(1020)

Phys. Lett. B807 135501(2020)



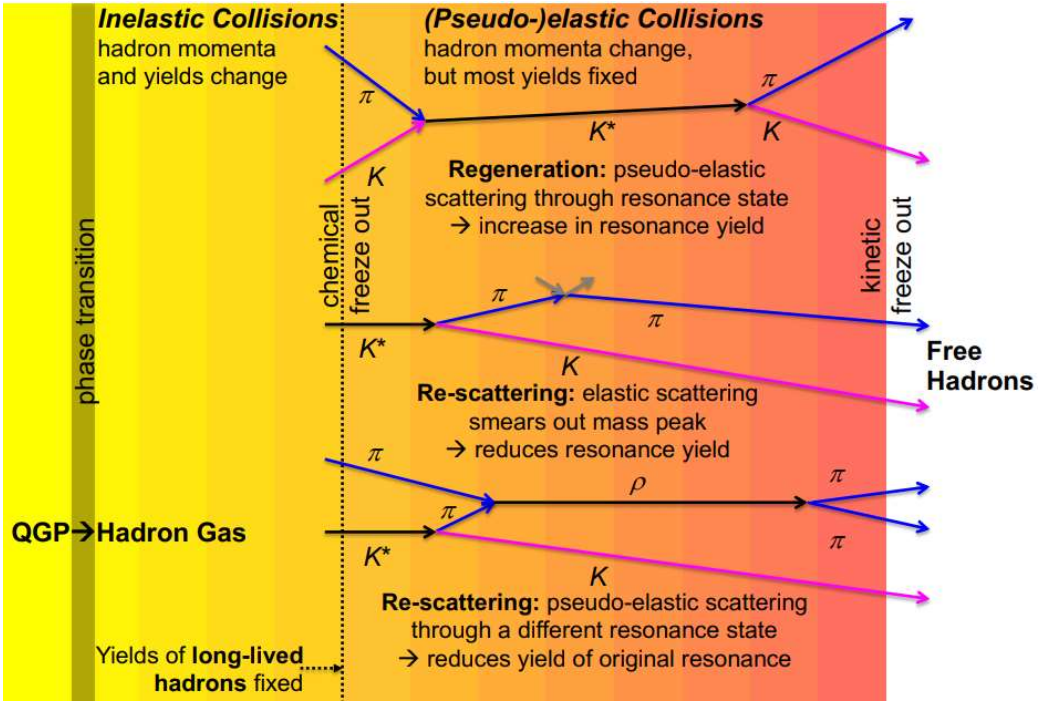
- ϕ with hidden strangeness is a key probe to study strangeness enhancement
  - ✓ ϕ/π increases with multiplicity in pp/p-Pb → not expected for canonical suppression
  - ✓ ϕ/π saturates in Pb-Pb and is consistent with thermal model predictions

- Ratios ϕ/K and Ξ/ϕ show weak dependence on multiplicity
  → ϕ has an effective strangeness of 1 or 2

Short-lived resonances

increasing lifetime ⟶

	ρ(770)	K*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	ϕ(1020)
cτ (fm/c)	1.3	4.2	5-5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

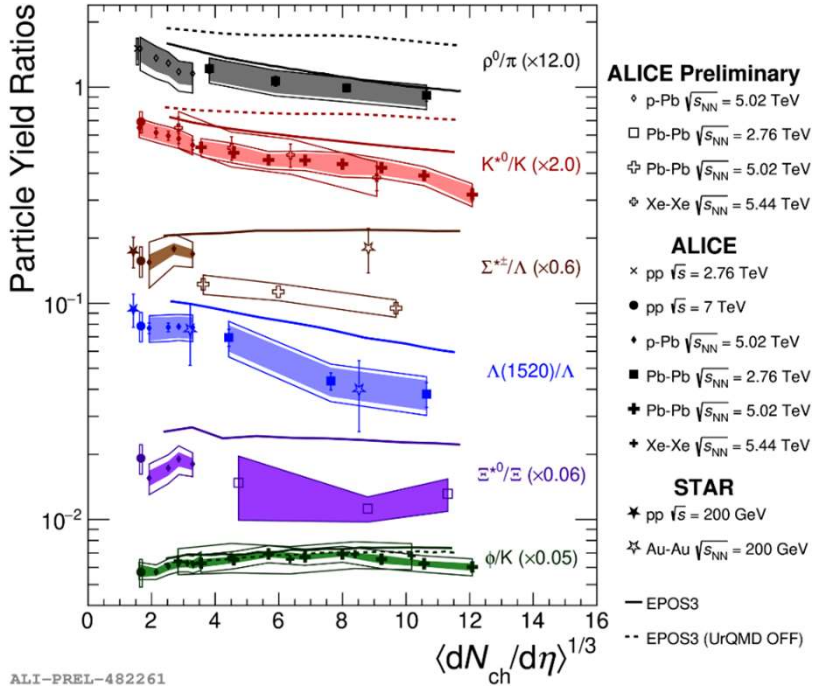


- Final state yields of resonances depend on:
  - ✓ resonance yields at chemical freeze-out
  - ✓ lifetime of the resonance and the hadronic phase
  - ✓ type and scattering cross sections of daughter particles

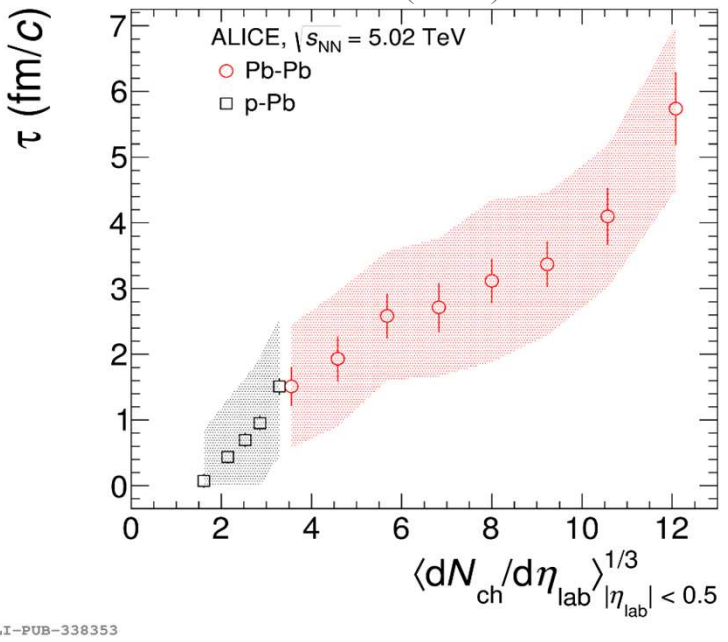
ρ/π, K^{*0}/K, $\Sigma^{*\pm}/\Lambda$, Λ^*/Λ, Ξ^{*0}/Ξ and ϕ/K ratios

increasing lifetime →

	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$



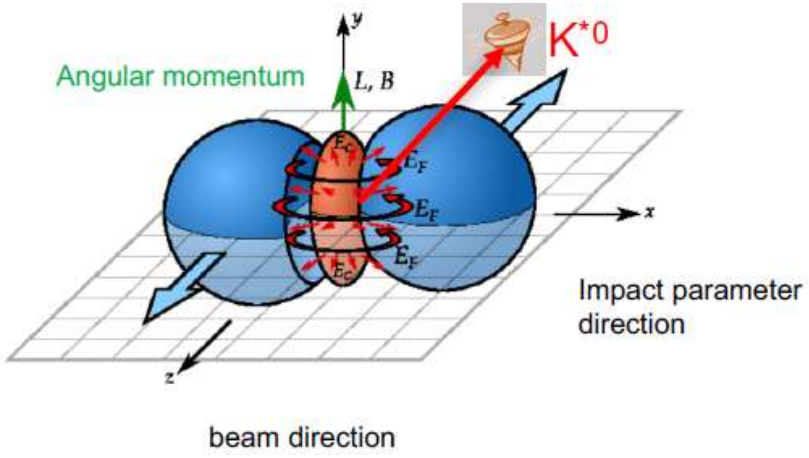
PLB 802 (2020) 135225



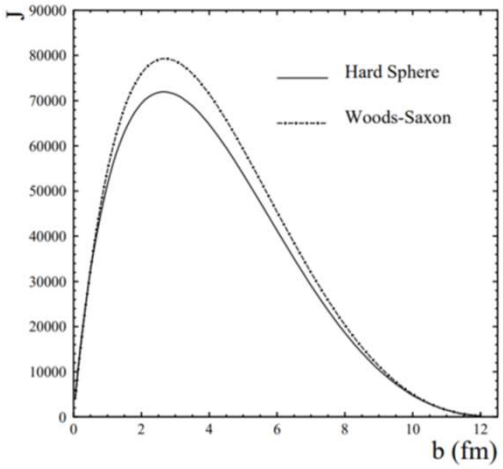
- Smooth evolution of the ratios with multiplicity from pp to Pb-Pb; suppression for short-lived ρ^0, $K^*(892)^0$, $\Sigma(1385)^\pm$ and $\Lambda(1520)$ → dominance of rescattering over regeneration; no significant effects for longer lived $\Xi(1530)^0$ and $\phi(1020)$
- EPOS + UrQMD qualitatively describe the trends; consistency between RHIC and the LHC
- Lower limit on the hadronic phase lifetime, $\tau_{had.phase}$ ~ 5-7 fm/c in central Pb-Pb
- Hint of the finite lifetime of hadronic phase in high multiplicity pp/p-Pb

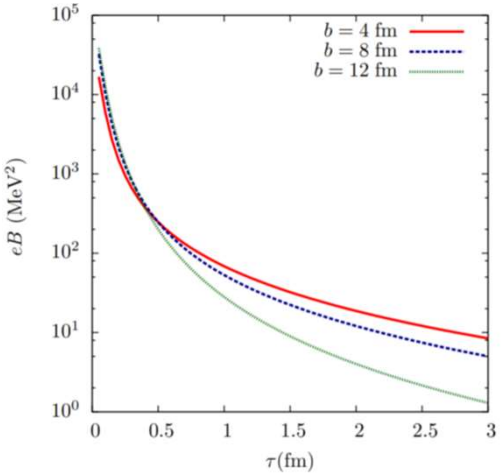
Polarization of vector mesons

Non-central heavy-ion collisions:



- ✓ large angular momentum due to medium rotations (PRC 77 (2008) 024906, Beccattini et al.)
- ✓ very high magnetic field (~ 10^{14} T) formed for a short period of time (NPA 803 (2008), Kharzeev et al.)





- Light quarks can be polarized by $|\bar{J}|$and $|\bar{B}|$
- If vector mesons are produced via recombination their spin may align
- Quantization axis:
  - ✓ normal to the production plane (momentum of the vector meson and the beam axis)
  - ✓ normal to the event plane (impact parameter and beam axis)
- Measure as anisotropies in angular distributions:

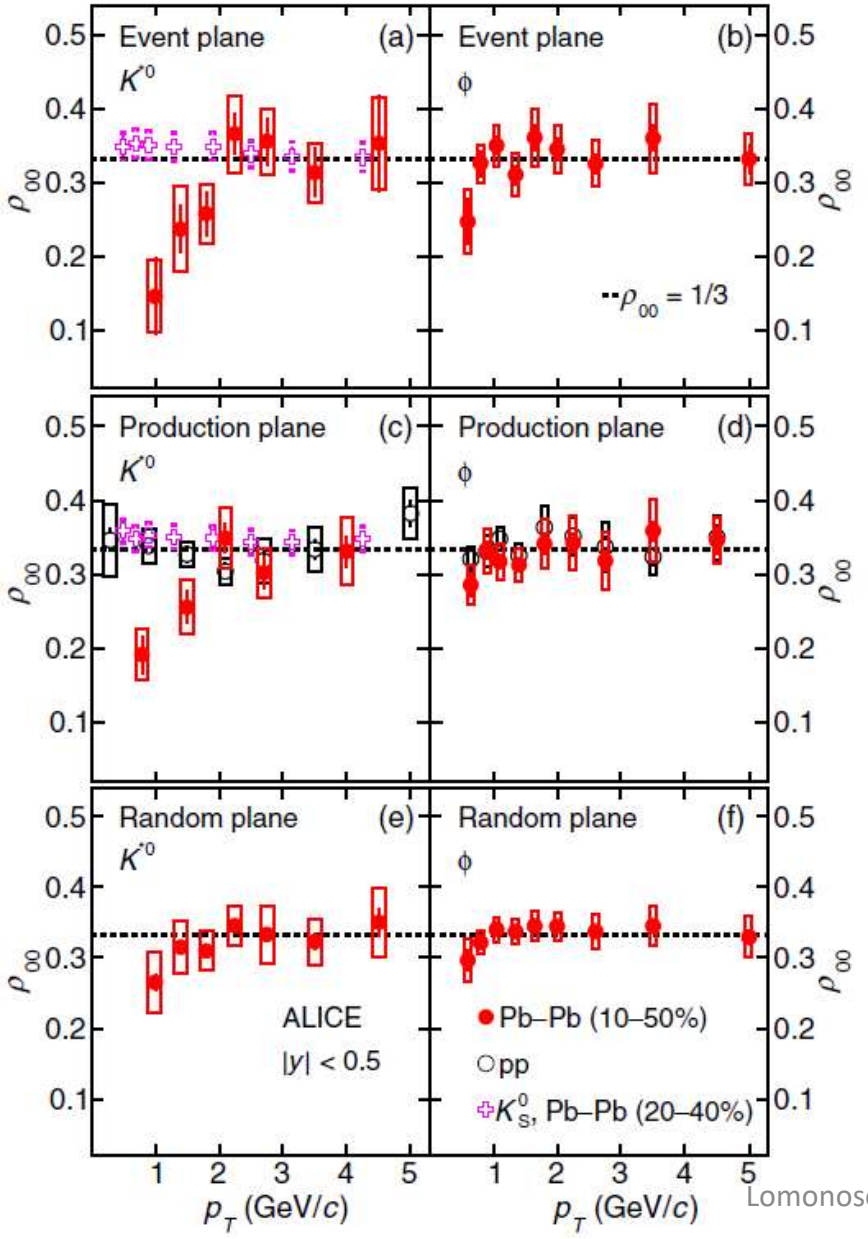
$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\left(3\rho_{0,0} - 1\right)\right]$$

$\rho_{0,0}$ is a probability for vector meson to be in spin state = 0 → $\rho_{0,0}$ = 1/3 corresponds to no spin alignment

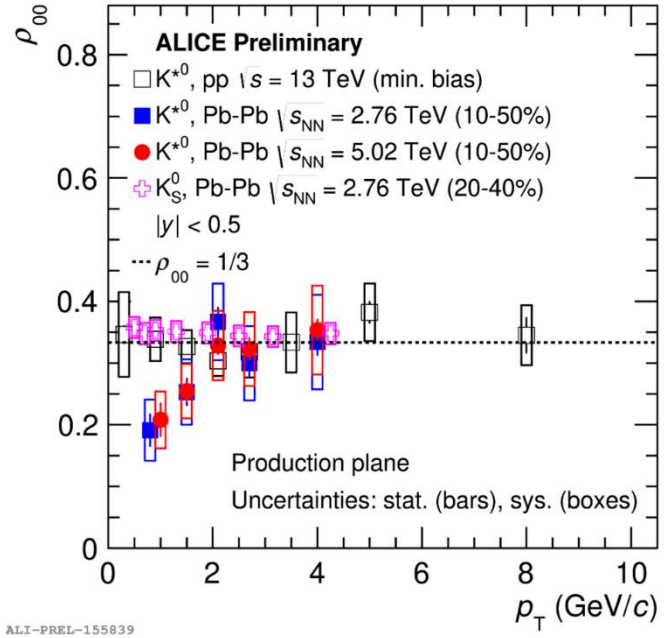
- Measure using $K^*(892)^0$ and $\phi(1020)$

Results for K^{*0} and ϕ vs. p_T

PRL 125, 012301 (2020)



- $\rho_{00} \sim 1/3$ for:
  - ✓ $p_T(K^{*0}) > 2$ GeV/c and $p_T(\phi) > 0.8$ GeV/c
  - ✓ K^0_s with zero spin
  - ✓ K^{*0} and ϕ in pp collisions
  - ✓ K^{*0} and ϕ with random plane in Pb-Pb@2.76
- $\rho_{00} < 1/3$ for K^{*0} and ϕ at low p_T in semi-central Pb-Pb@2.76 collisions
- Confirmed with new measurements in Pb-Pb@5.02



- Results for p_T and centrality dependence of ρ_{00} are qualitatively consistent with quark recombination in a polarized medium

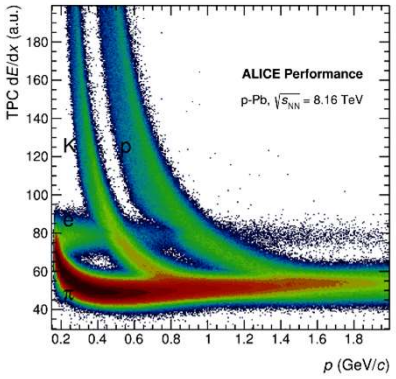
Summary

- Light-flavor hadron spectra become harder with increasing multiplicity, mean transverse momenta show mass ordering in central A-A collisions, the ordering is broken in peripheral collisions as well as in p-Pb and pp
- Blast-Wave fits allow to extract common expansion velocity and kinetic freeze-out temperature
- Enhancement of baryon to meson ratios at intermediate p_T is a bulk effect driven by flow and quark coalescence
- Relative particle abundances are driven by the final state multiplicities rather than by collision system size or energy
- Strangeness enhancement smoothly evolves with final state multiplicity, increasing ϕ/π ratio does not support the canonical suppression scenario
- Short-lived resonance yields are suppressed, the hadronic phase lifetime > 5-7 fm/c, a hint of finite hadronic phase lifetime is observed in small systems
- Spin alignment for vector mesons is qualitatively consistent with quark recombination in a polarized medium, more theoretical efforts are required for understanding of the data

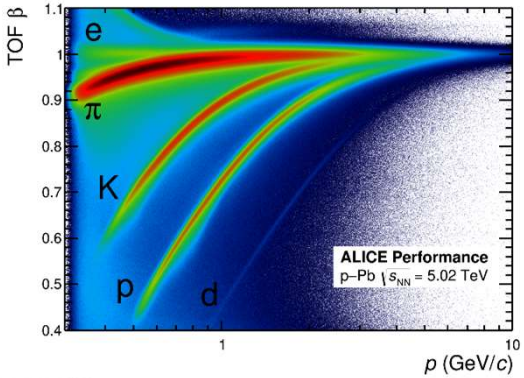
BACKUP

Particle identification, ALICE

TPC



TOF



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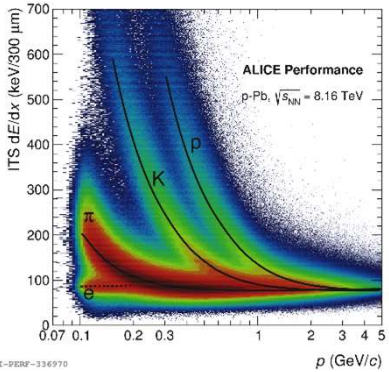
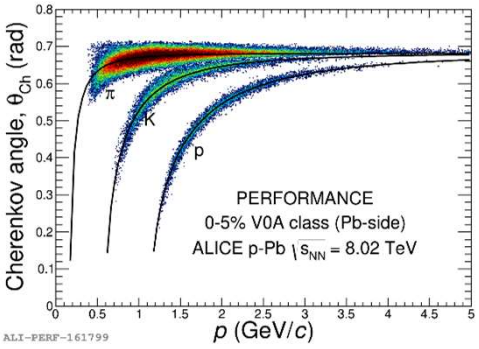
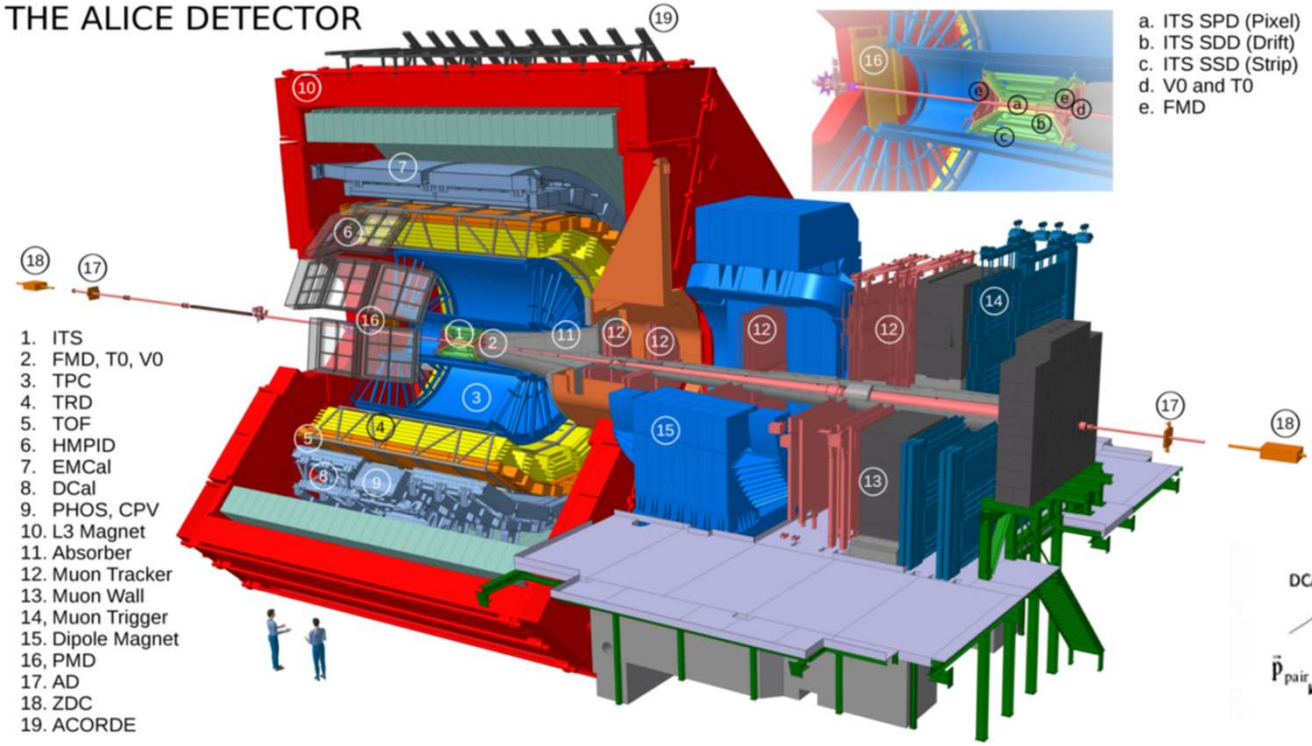


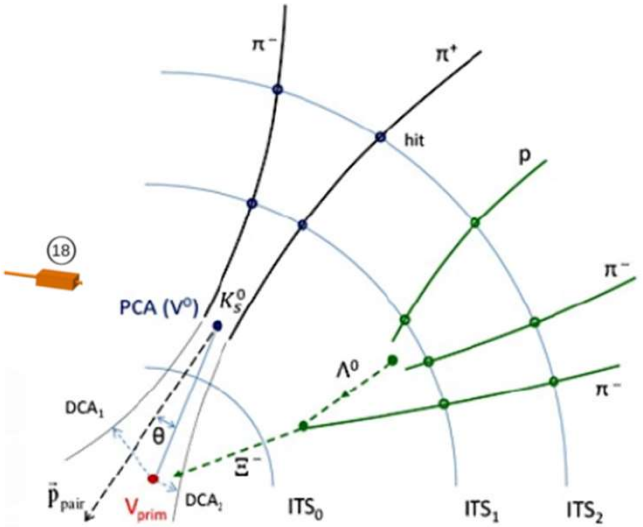
HMPID



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

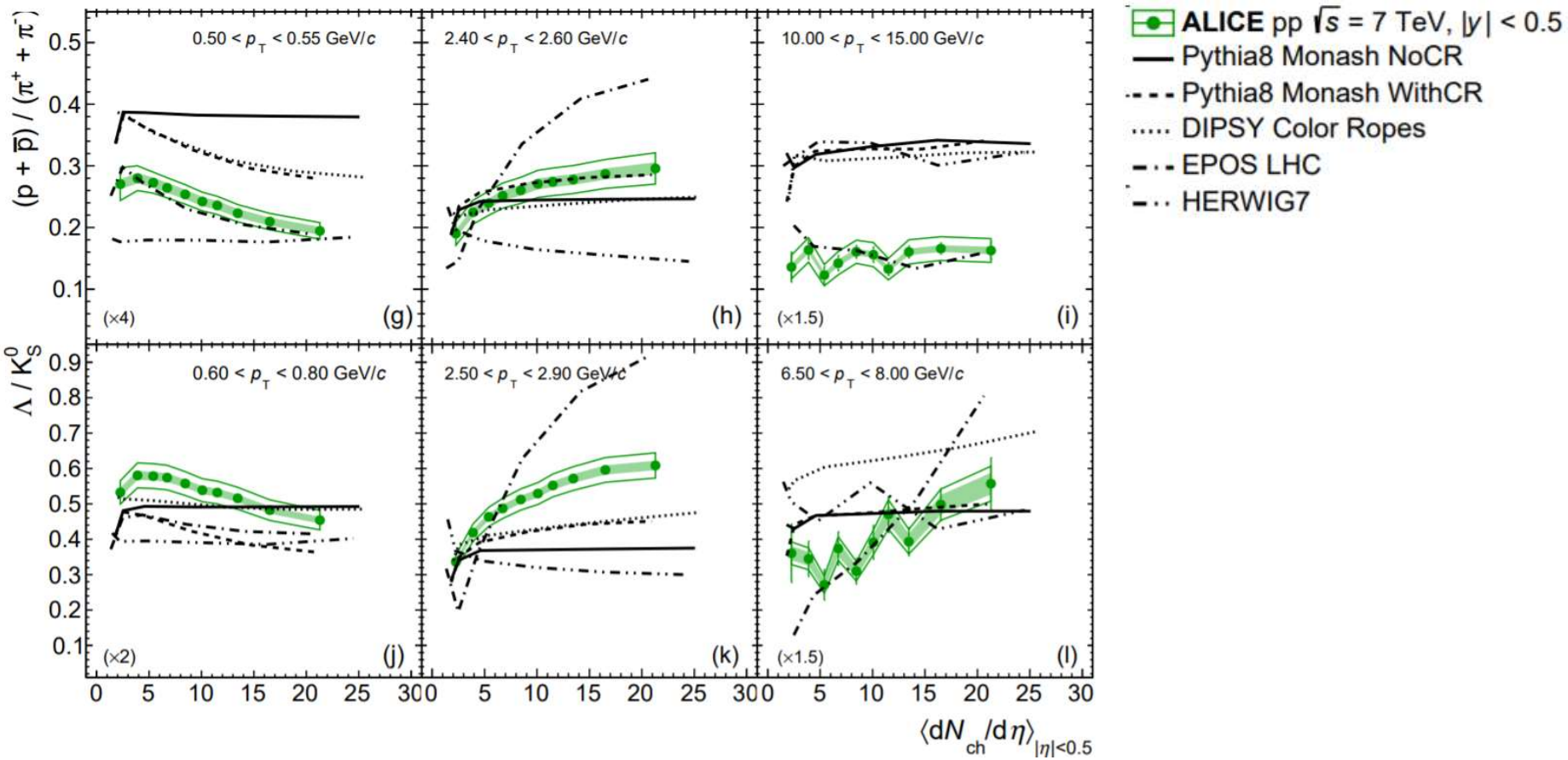


Secondary vertex reconstruction and topology selections



Baryon-to-meson ratios: pp

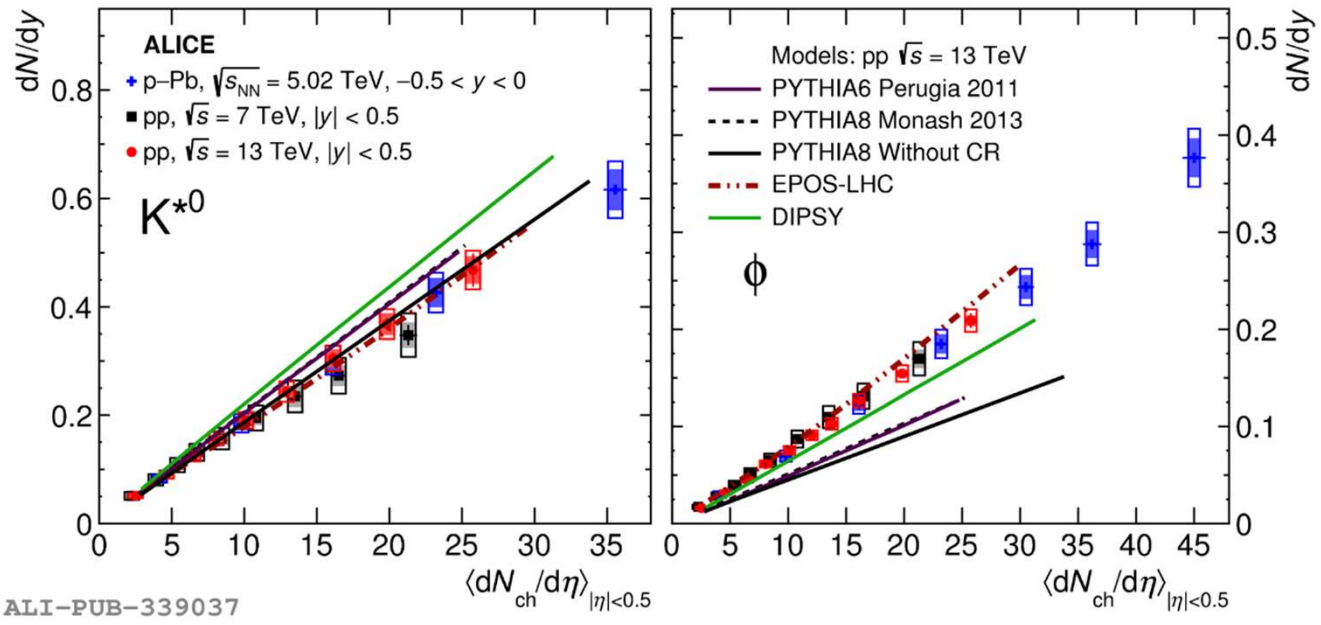
Phys. Rev. C99 (2019) no.2, 024906



- 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

Particle yields in pp and p-Pb vs. $dN_{ch}/d\eta$

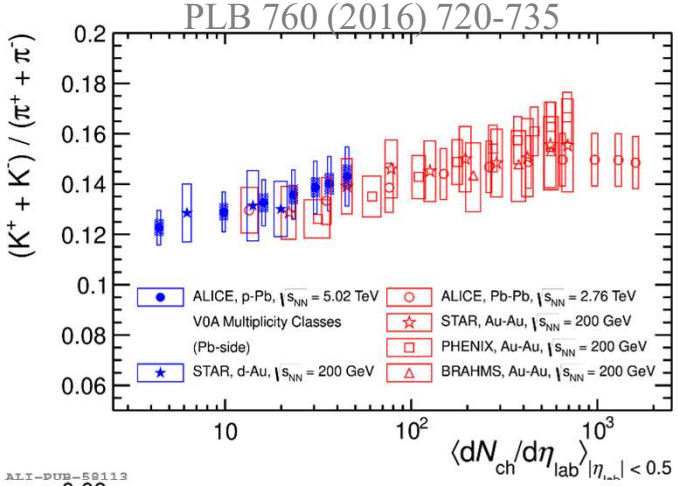
PLB 807 (2020) 135501

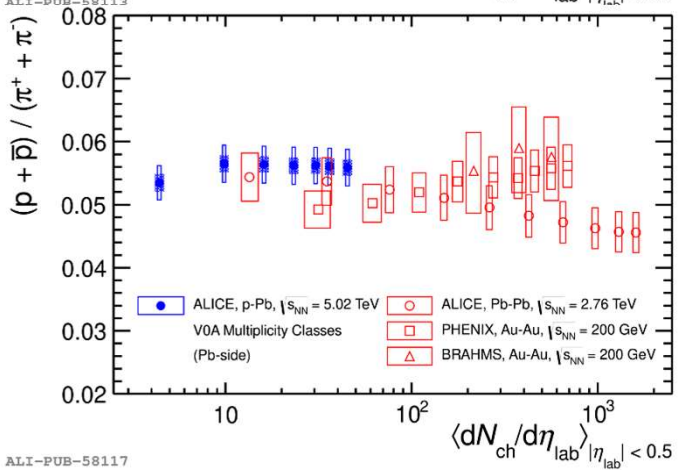


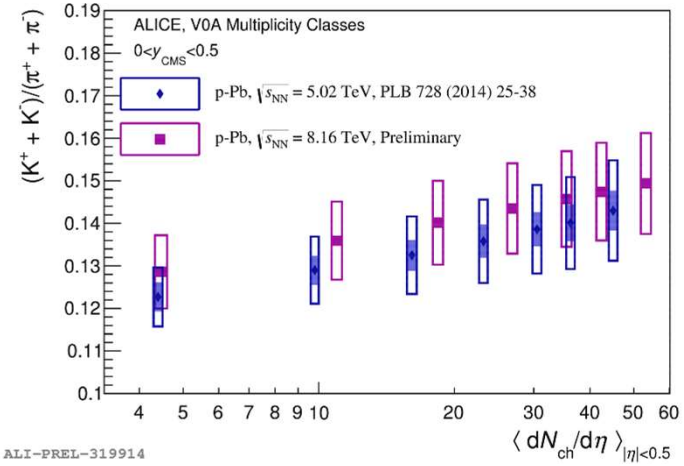
- Hadron yields increase ~ linearly with multiplicity, consistently for pp and p-Pb collisions at different energies
- Hadrochemistry is driven by event activity rather than by collision energy or size of the collision system
- Qualitative description by models

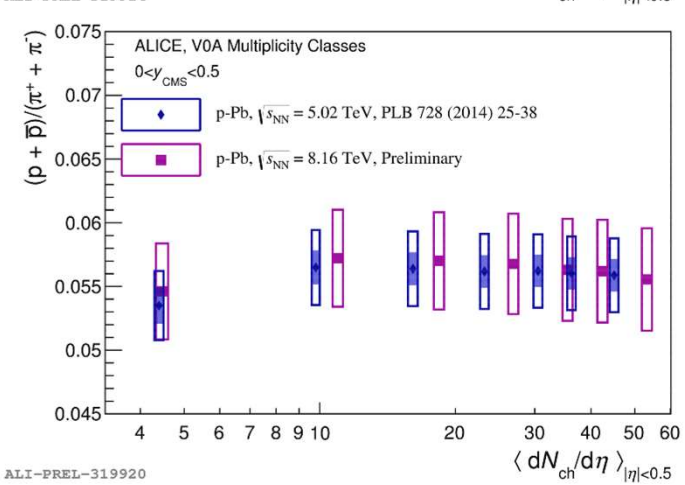
p/π and K/π ratios

PLB 760 (2016) 720-735









- At similar multiplicities, particle ratios are consistent for different collision systems at different $\sqrt{s_{NN}}$ → driven by event activity rather than by type of colliding nuclei and/or collision energy
- p/π shows a modest decrease with centrality at the LHC, consistent with antibaryon-baryon annihilation in the hadronic phase, which is more important in dense systems (Phys. Rev. Lett. 110, 042501)
- Increasing K/π ratio is consistent with strangeness enhancement