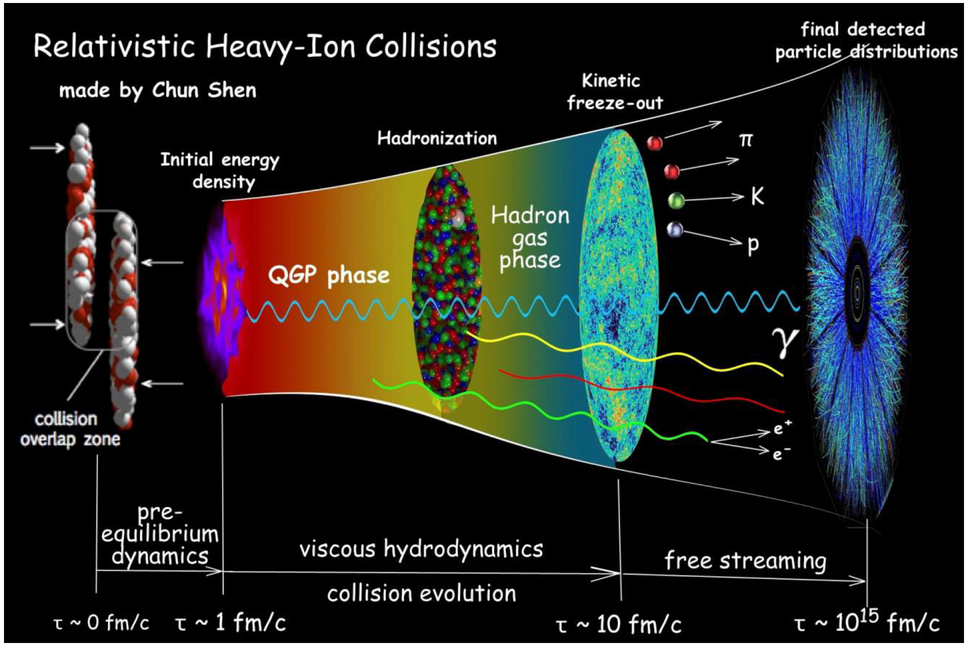
Meson as messengers for hot and dense QCD matter

Victor Riabov for the ALICE Collaboration

MESON 2021

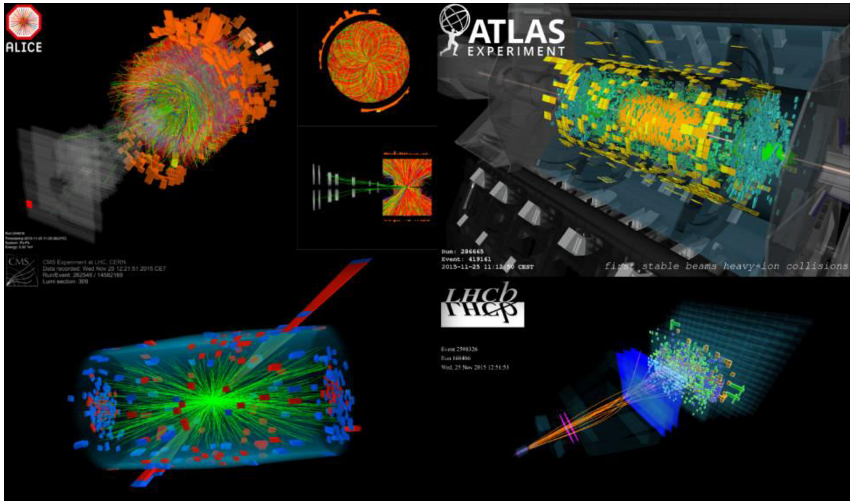
Introduction



- In heavy-ion collisions, the interacting system evolves through different stages and then cools down: hot and dense partonic matter → phase transition → chemical and kinetic freeze-out
- Light flavor mesons 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.

Beams at the LHC

- Experiments at the LHC study the properties of strongly interacting matter at extreme temperatures and energy densities

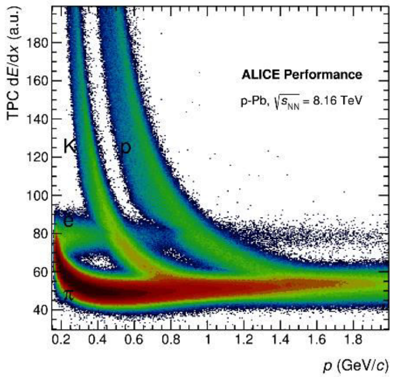


- Study of system size and collision energy dependence of particle production with the same apparatus using different data samples

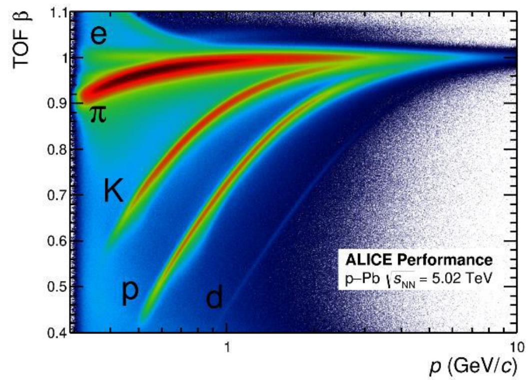
System	Year	Energy (TeV)
pp	2009-2013 2015,2017 2015-2018	0.9, 2.76, 7, 8 5.02 13
p-Pb/Pb-p	2013 2016	5.02 5.01, 8.16
Xe-Xe	2017	5.44
Pb-Pb	2010-2011 2015-2018	2.76 5.02

Particle identification, ALICE

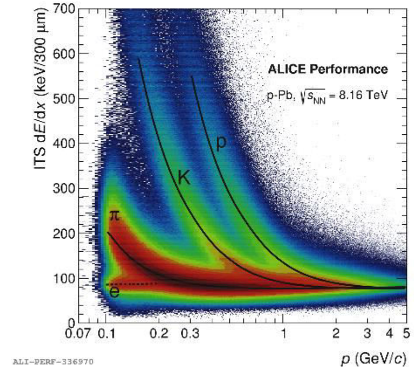
TPC



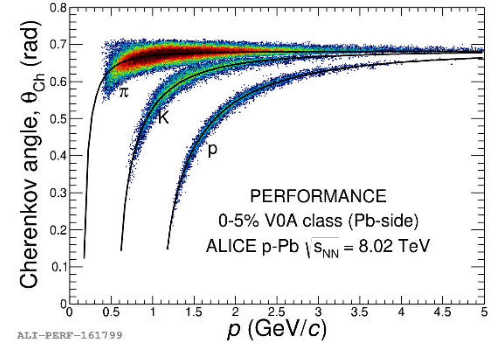
TOF



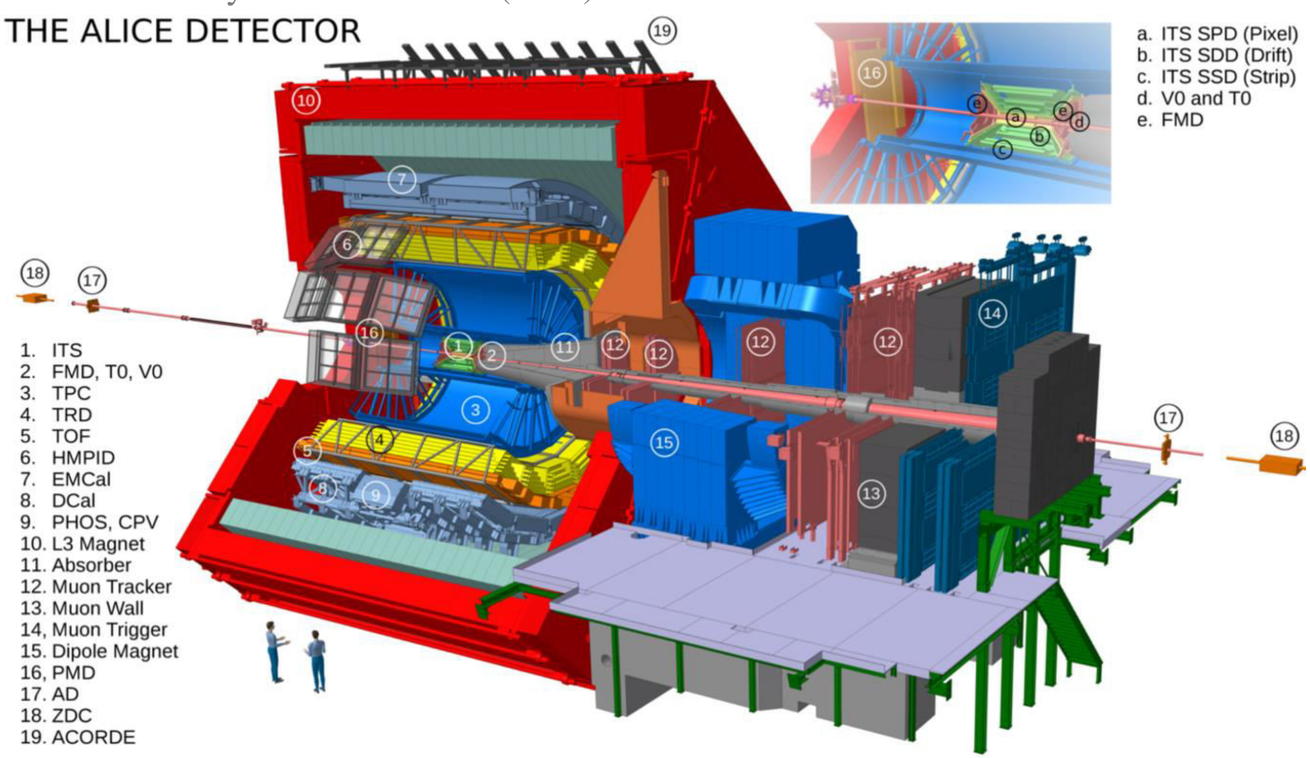
ITS



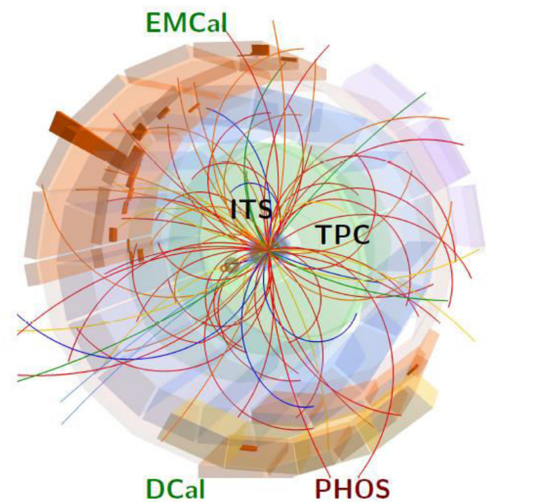
HMPID



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



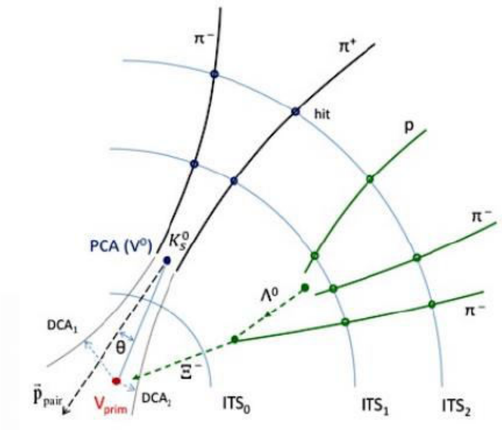
Reconstruction of photons (photonic decays)

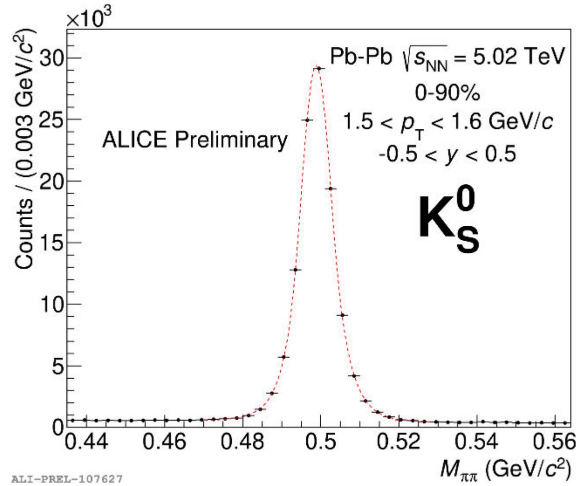


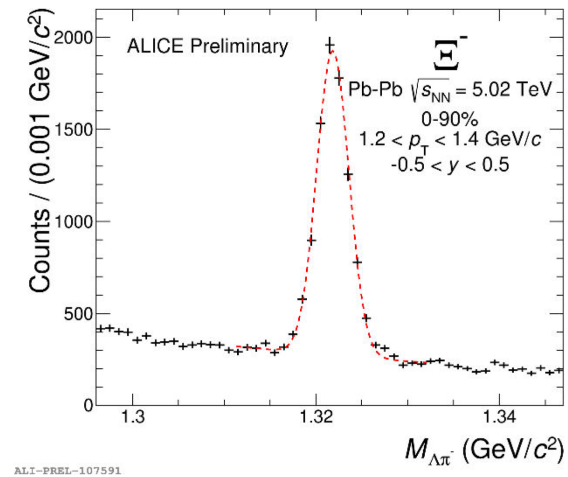
PHOS, EMC, Photon Conversion Method (PCM), hybrid PCM-EMC etc.

Particle reconstruction, ALICE

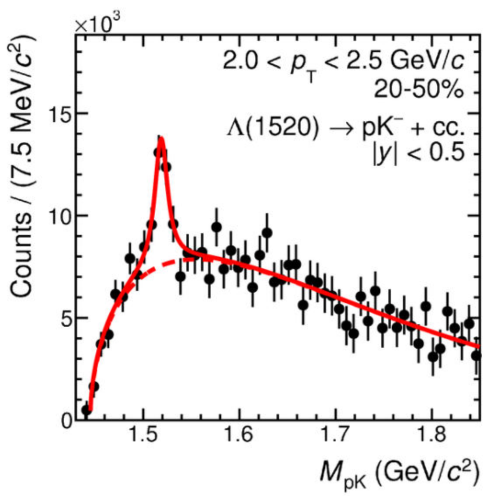
- Secondary vertex reconstruction and topology cuts

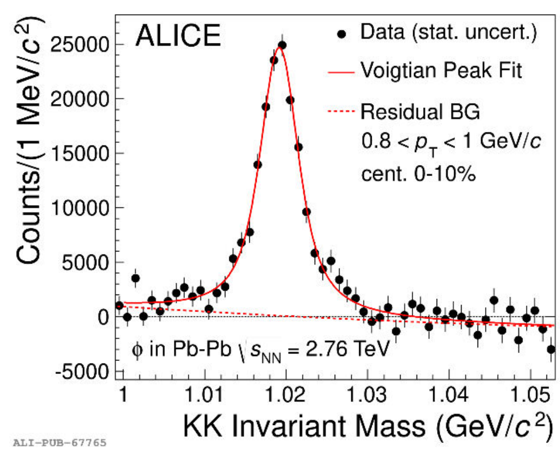






- Invariant mass method:

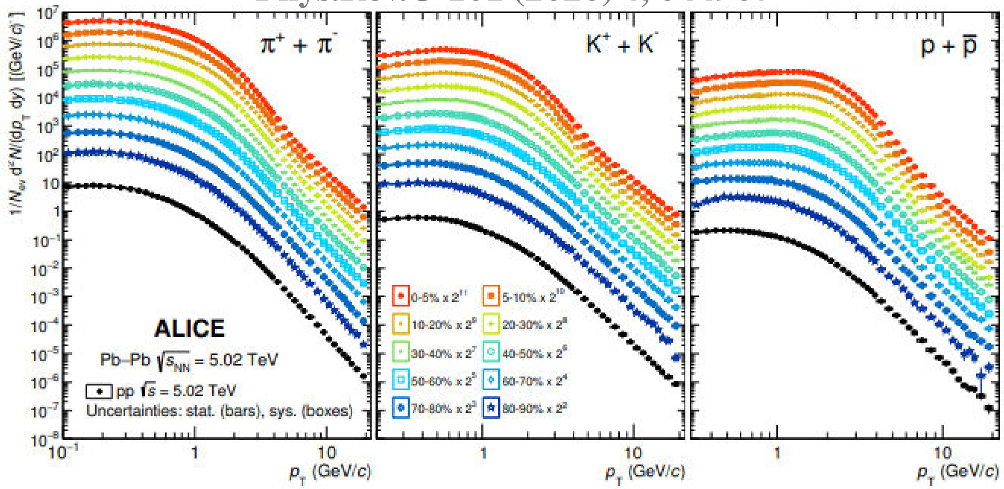


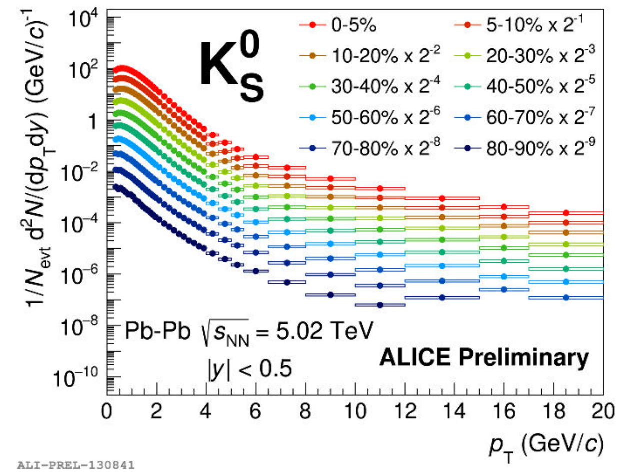


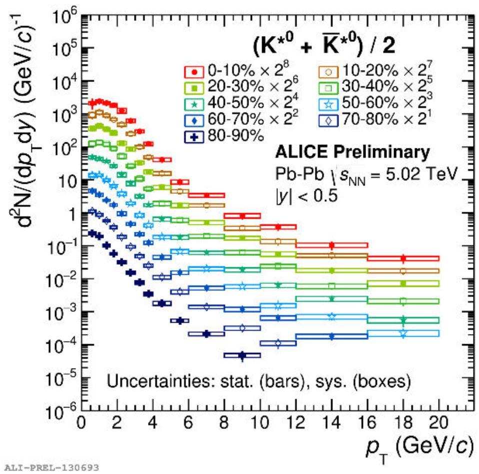
- ✓ combinatorial background is estimated with mixed-event or like-sign pairs
- ✓ remaining background is described with a polynomial
- ✓ signal is described with a predefined peak model (Breit-Wigner or Voigtian function), estimated by bin counting etc.

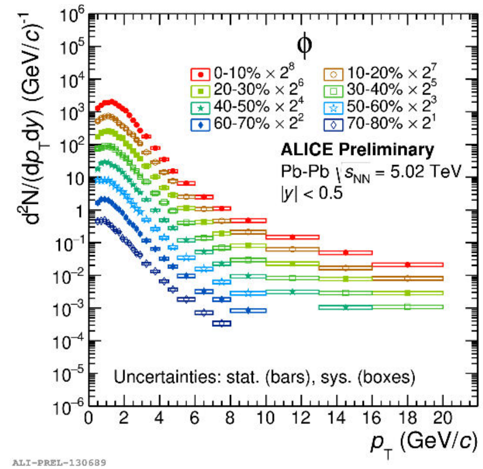
Particle spectra in heavy-ion collisions

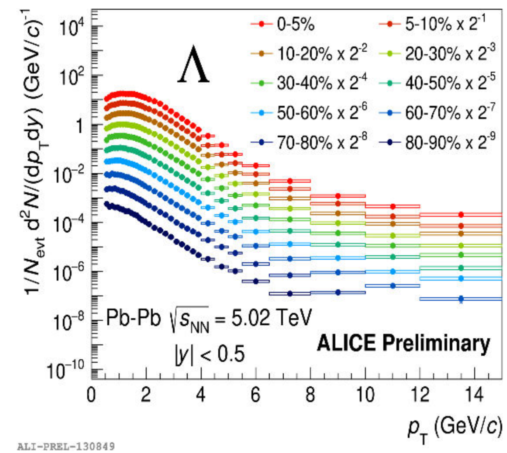
Phys.Rev.C 101 (2020) 4, 044907





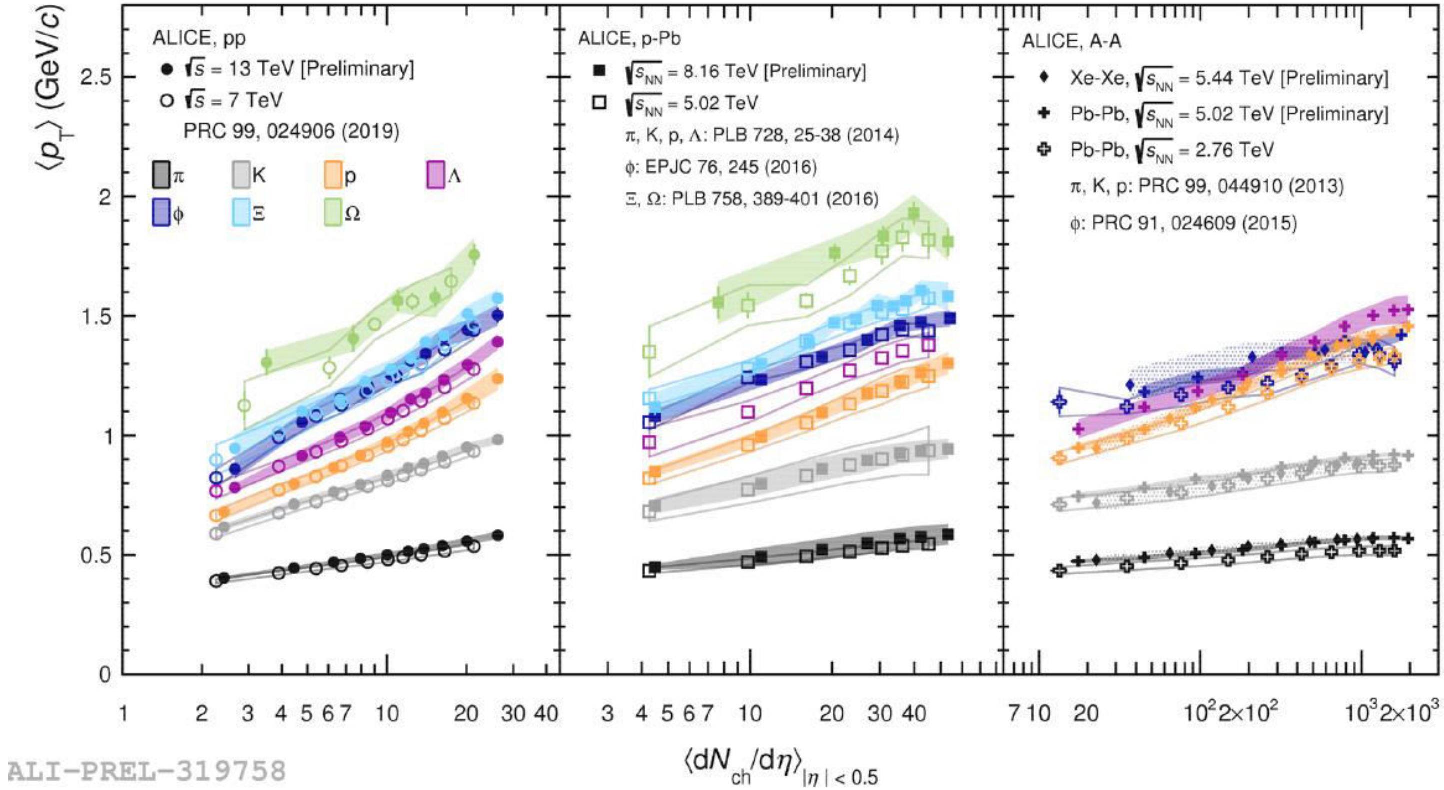






- A variety of hadrons measured in wide p_T ranges at different centralities
- Spectra become harder with increasing multiplicity (flatten at low p_T), most pronounced for heavier particles $\rightarrow$ expected from collective hydrodynamic expansion (radial flow)
- Similar hardening of spectra has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

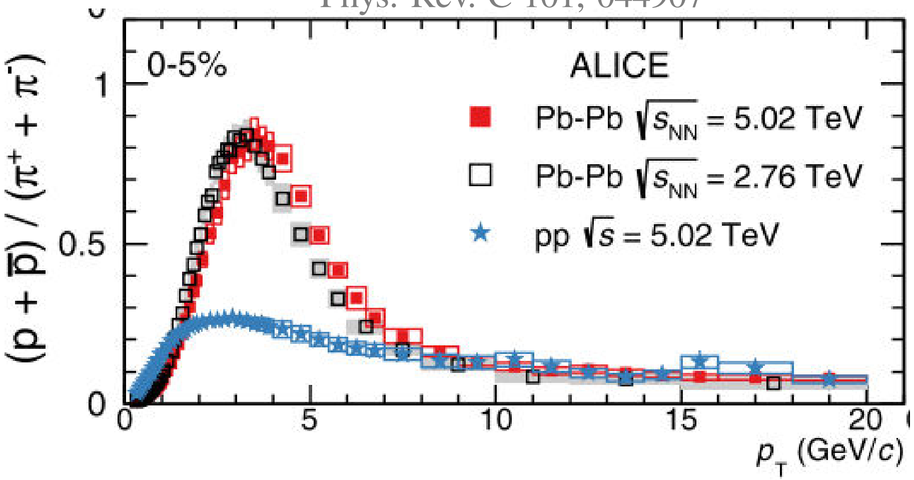
Mean transverse momenta

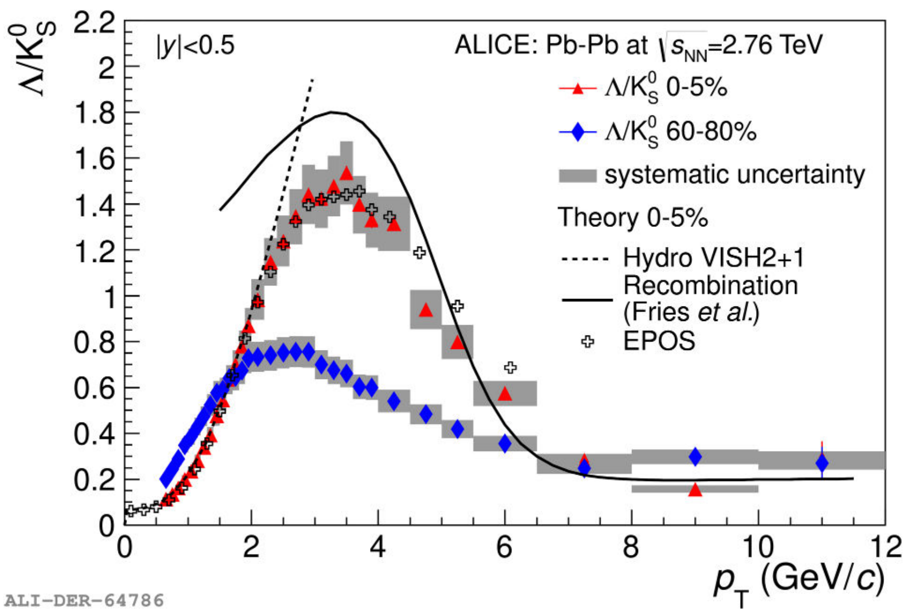


- Mass-dependent hardening manifests itself in $<p_T>$ increasing with multiplicity
- Steeper increase of $<p_T>$ in smaller collision systems
- Modest hardening of particle spectra with increasing collision energy
- In heavy-ion collisions $<p_T>$ is independent of the size of colliding nuclei (Xe-Xe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

Baryon-to-meson ratios in heavy-ion collisions

Phys. Rev. C 101, 044907

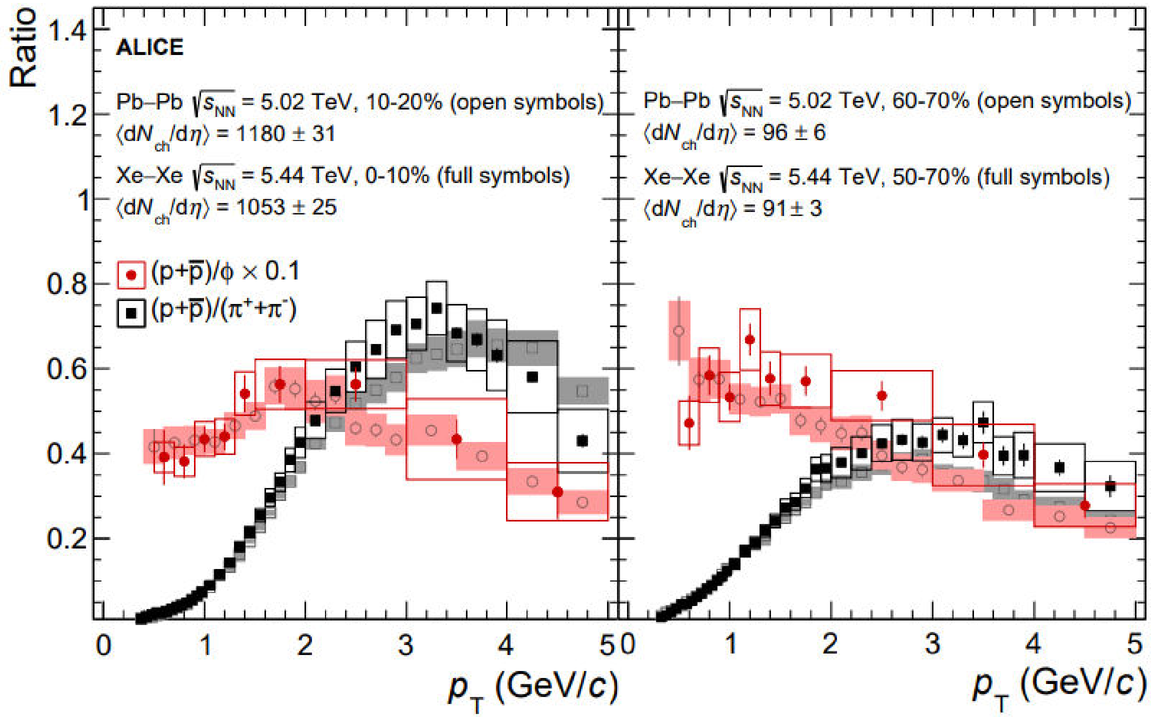




- Enhanced baryon-to-meson ratios (p/π, Λ/K) in central heavy-ion collisions at intermediate p_T
- Enhancement is similar at different energies, peak is shifted to the right at higher energy
- Bulk effect, not present for ratios within the jet cone
- Hydro reproduces the rise for p_T < 2 GeV/c
- EPOS provides good description by including radial flow

Baryon-to-meson ratios in heavy-ion collisions

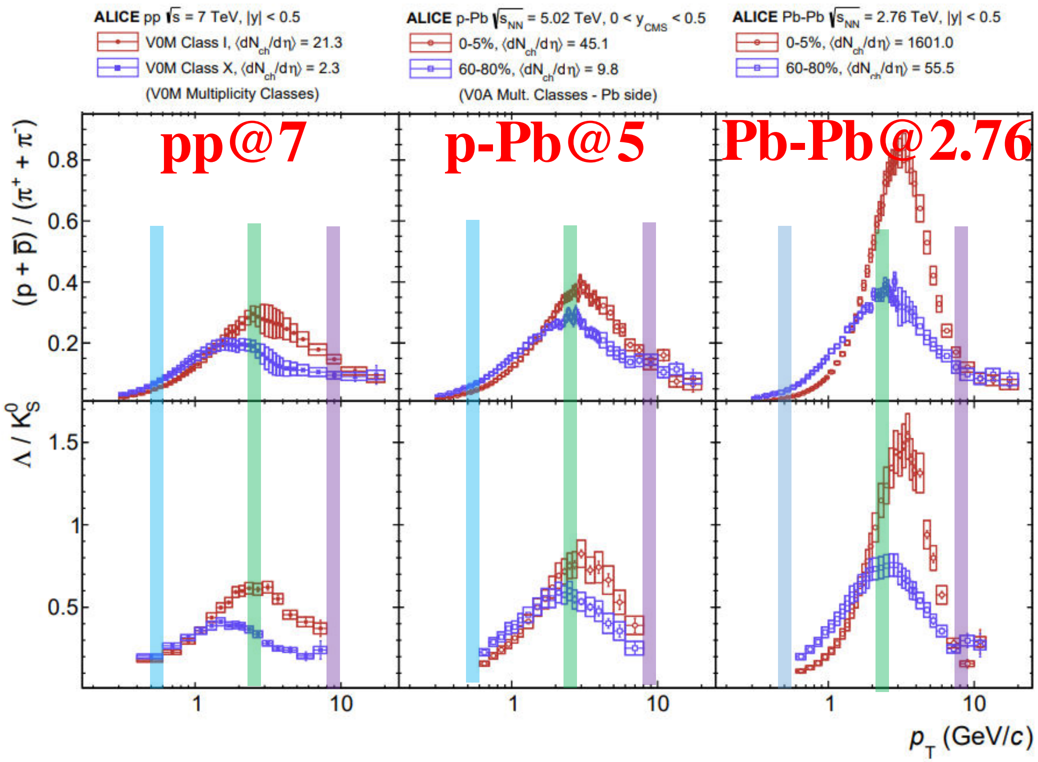
arXiv:2101.03100



- 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))

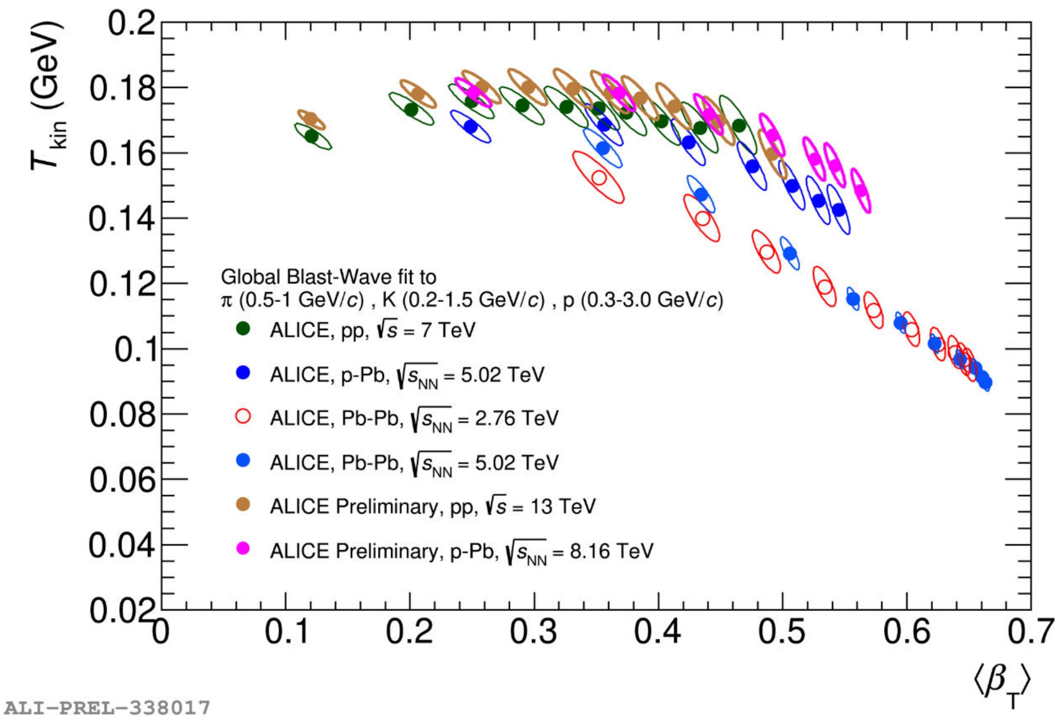
Baryon-to-meson ratios in small systems

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

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

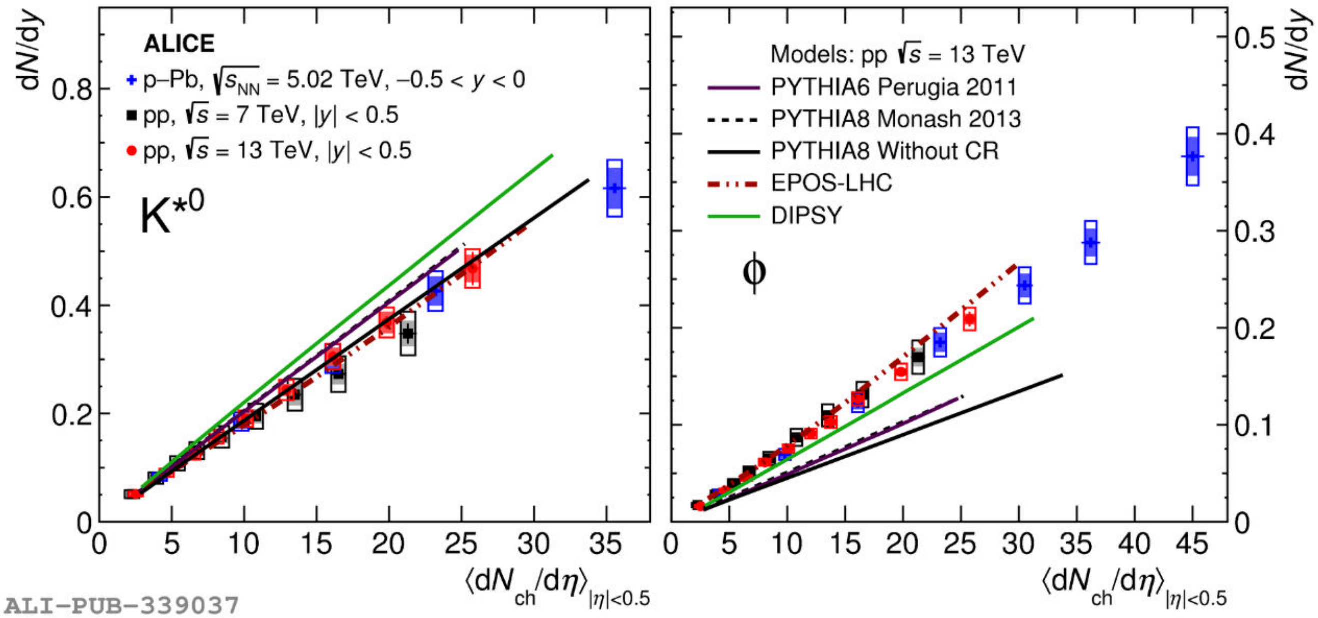


- Boltzmann-Gibbs Blast-Wave fits are used to determine parameters of the radial flow:
  - ✓ T_{kin} – kinetic freeze-out temperature
  - ✓ $<\beta_T>$ - transverse velocity
  - ✓ n – velocity profile
- Fit parameters are extracted from a simultaneous fits to π, K, p spectra, results are sensitive to the exact 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} ~ 100 MeV < T_{ch}
- pp and p-Pb are also consistent but with larger values of $<\beta_T>$ at similar multiplicities
- T_{kin} stays constant in pp and slightly decreases in p-Pb, T_{kin} ~ 160 MeV ~ T_{ch} → earlier decoupling compared to heavy-ion collisions
- Color reconnection (Pythia8) mimics radial flow-like effects in pp collisions

Particle yields in pp and p-Pb vs. dN_{ch}/dη

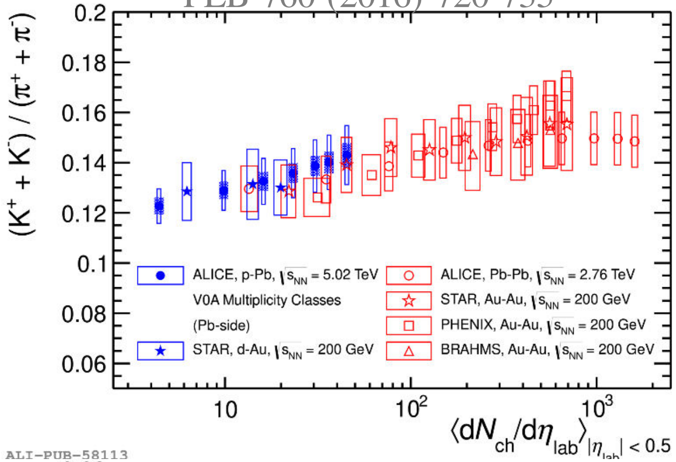
PLB 807 (2020) 135501

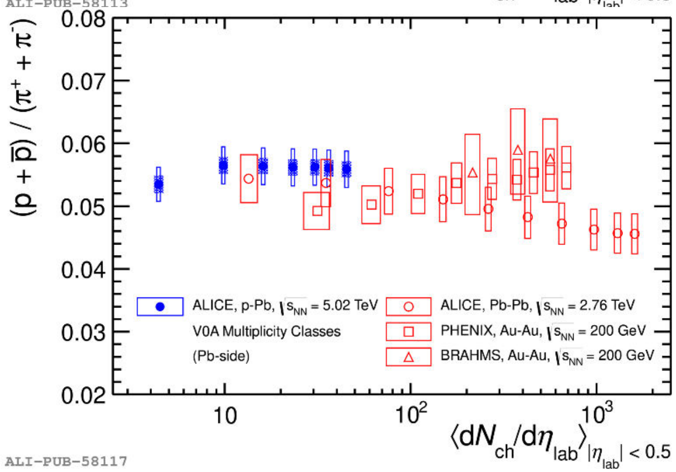


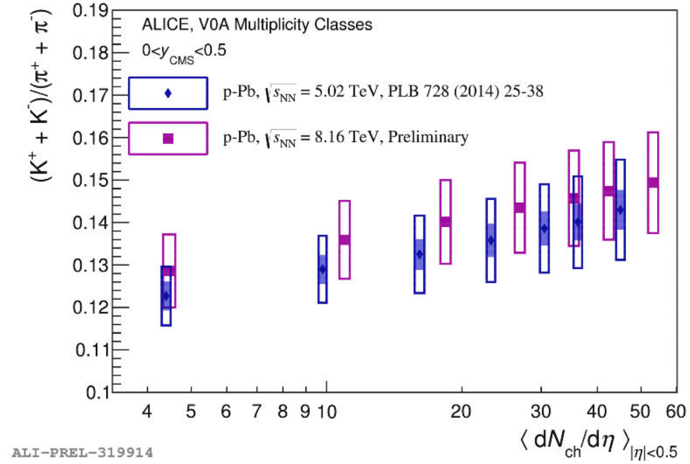
- Hadron yields increase ~ linearly with multiplicity, consistently for pp and p-Pb collisions at different energies
- Hadrochemistry is driven by event activity rather than by collision energy or size of the collision system
- Qualitative description by models

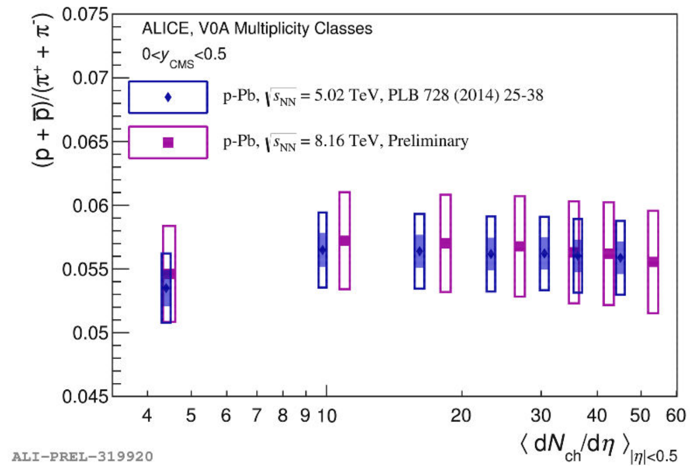
p/π and K/π ratios

PLB 760 (2016) 720-735





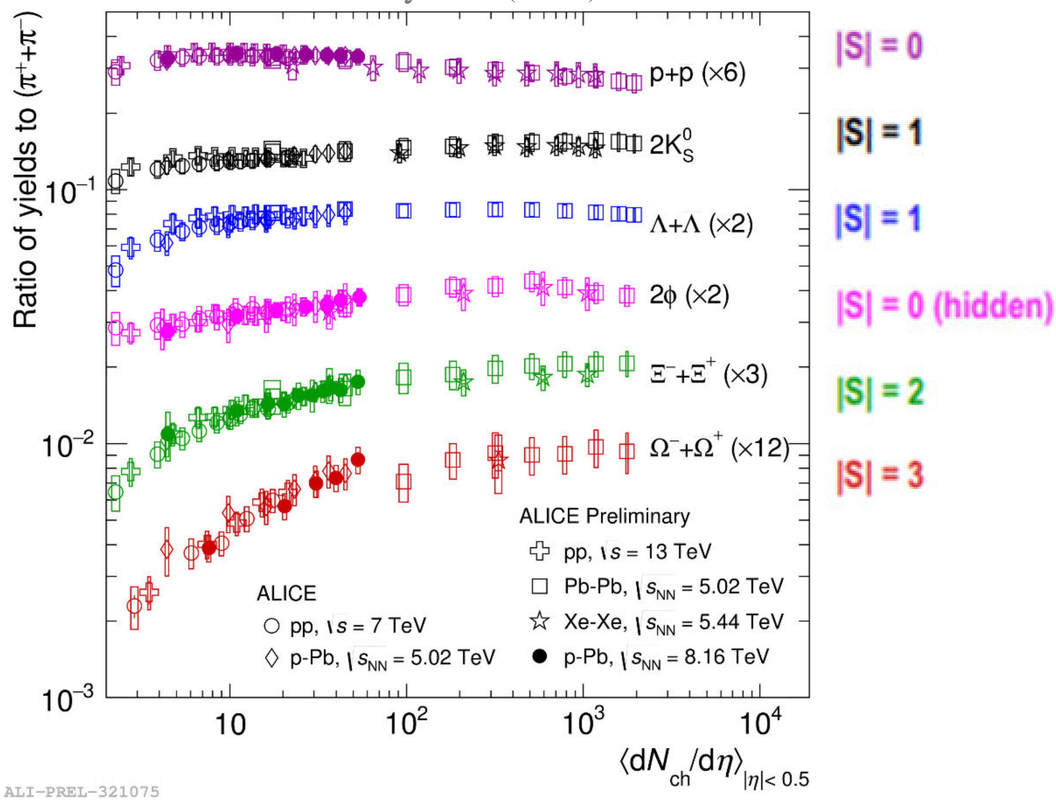


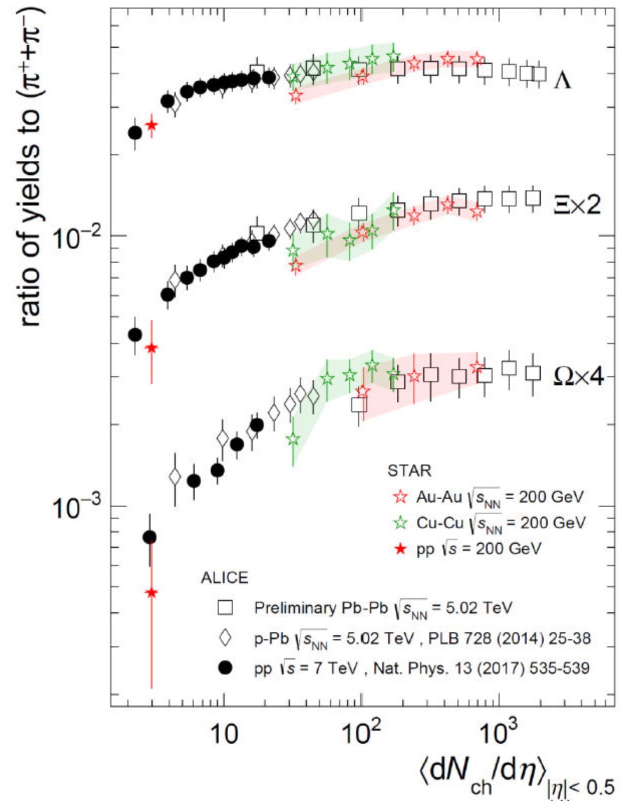


- At similar multiplicities, particle ratios are consistent for different collision systems at different $\sqrt{s_{NN}}$ → driven by event activity rather than by type of colliding nuclei and/or collision energy
- p/π shows a modest decrease with centrality at the LHC, consistent with antibaryon-baryon 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

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

Nature Phys. 13 (2017) 535

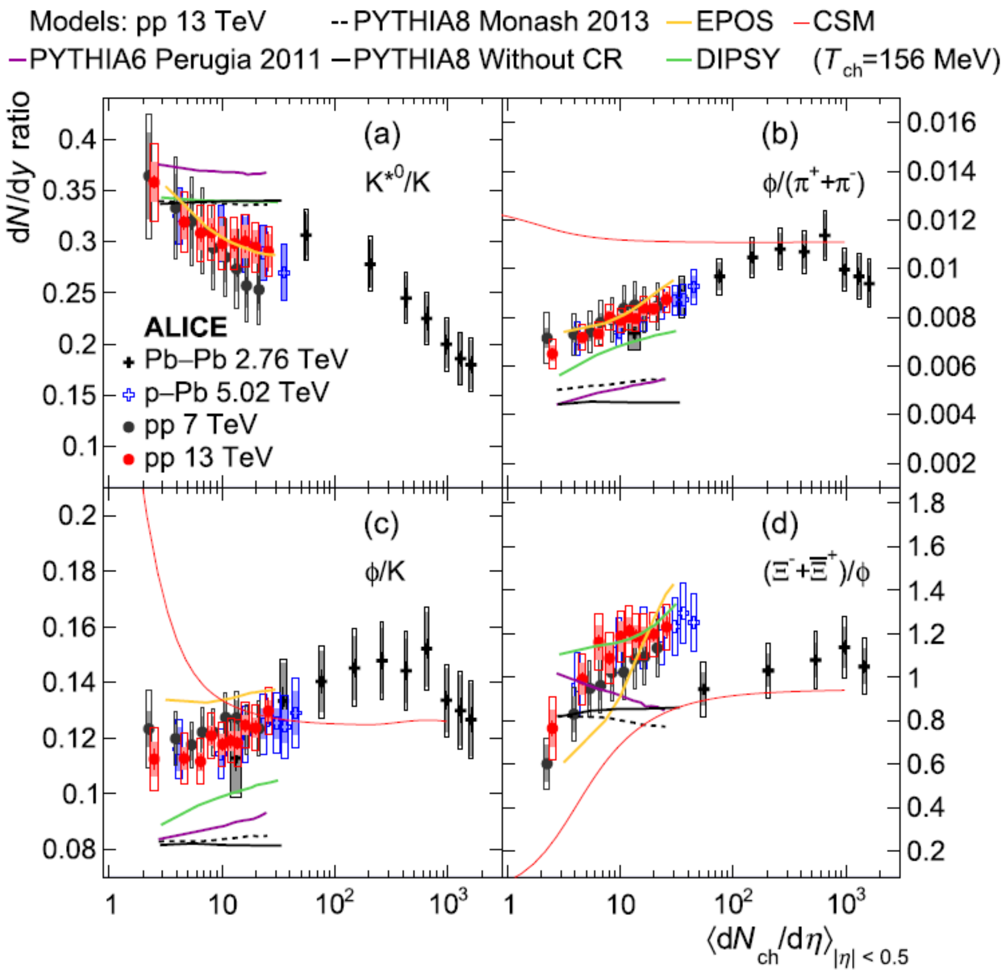




- Strangeness enhancement increases with strangeness content and particle multiplicity
- Ratios saturate in peripheral A-A at values predicted by statistical hadronization models
- Smooth evolution vs. multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76-13 TeV
- STAR measurements 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

Strangeness enhancement for $\phi(1020)$

Phys. Lett. B807 135501(2020)



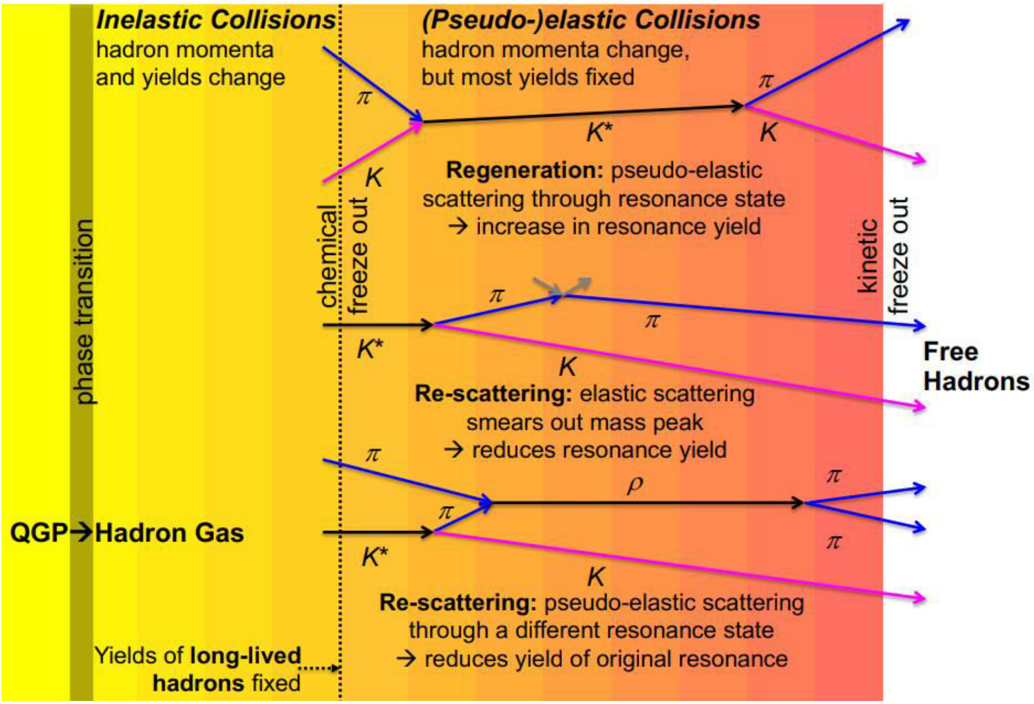
- ϕ with hidden strangeness is a key probe to study strangeness enhancement
  - ✓ ϕ/π increases with multiplicity in pp/p-Pb → not expected for canonical suppression
  - ✓ ϕ/π saturates in Pb-Pb and is consistent with thermal model predictions

- 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 →

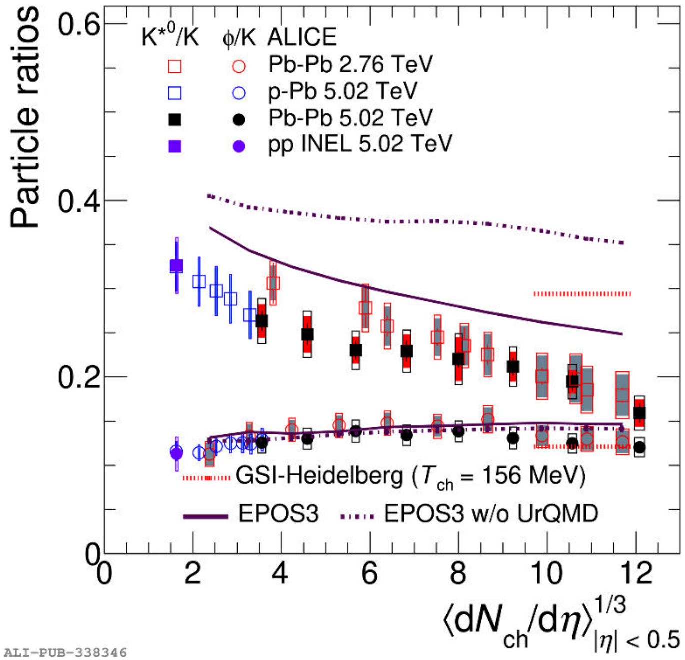
	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5-5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

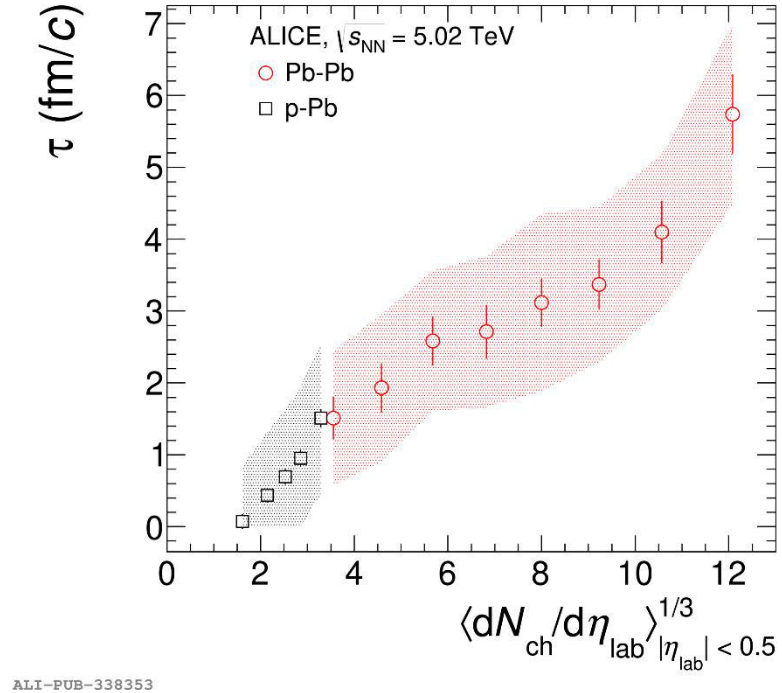


- Final state yields of resonances depend on:
  - ✓ resonance yields at chemical freeze-out
  - ✓ lifetime of the resonance and the hadronic phase
  - ✓ type and scattering cross sections of daughter particles

$K^*(892)^0$/K and $\phi(1020)$/K ratios

PLB 802 (2020) 135225; PRC 93 no. 1, (2016) 014911





- ✓ smooth evolution of K^{*0}/K and ϕ/K ratios with multiplicity from pp to Pb-Pb
- ✓ ϕ/K ~ constant → decay outside of the fireball
- ✓ $K^*(892)^0$/K is suppressed going from pp to central Pb-Pb collisions → rescattering becomes dominant over regeneration
- ✓ EPOS3 with UrQMD afterburner reproduces the trends

Assumptions: K^{*0} decaying before kinetic freeze-out are lost due to rescattering, regeneration is neglected

$$(K^*(892)^0/K)_{kinetic} = (K^*(892)^0/K)_{chemical} \times e^{-\tau_{had.phase}/\tau_{K^*}}$$

$$(K^*(892)^0/K)_{chemical} \approx (K^*(892)^0/K)_{pp}$$

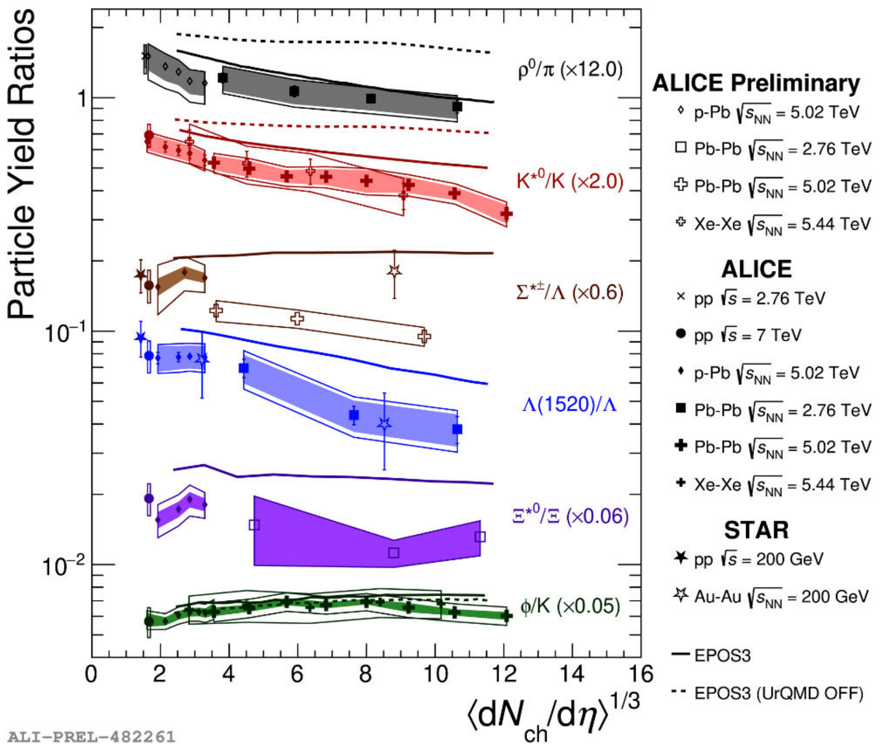
$$(K^*(892)^0/K)_{kinetic} \approx (K^*(892)^0/K)_{PbPb}$$

- ✓ lower limit on the hadronic phase lifetime , $\tau_{had.phase}$ ~ 5-7 fm/c in central Pb-Pb
- ✓ smooth increase of the lifetime with system size

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

increasing lifetime →

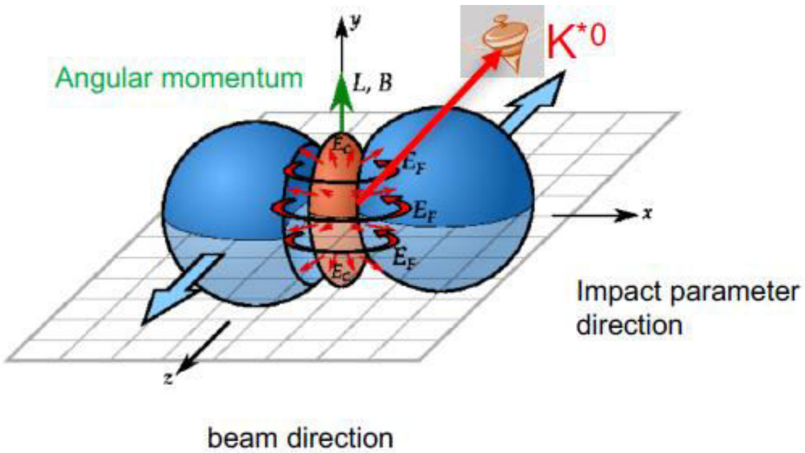
	ρ(770)	K*(892)	Σ(1385)	Λ(1520)	Ξ(1530)	φ(1020)
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$



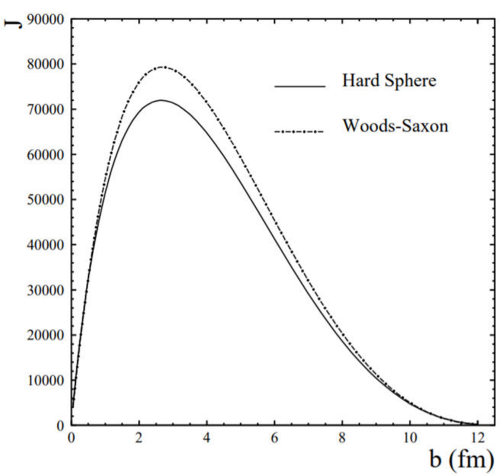
- Suppression is for short-lived ρ^0, $K^*(892)^0$, $\Sigma(1385)^\pm$ and $\Lambda(1520)$ → dominance of rescattering over regeneration; no significant effects for longer lived $\Xi(1530)^0$ and $\phi(1020)$
- EPOS + UrQMD qualitatively describe the trends; consistency between RHIC and the LHC
- Hint of the finite lifetime of hadronic phase in high multiplicity pp/p-Pb

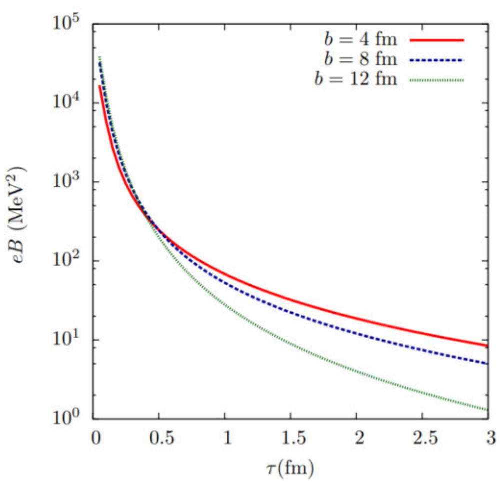
Polarization of vector mesons

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:

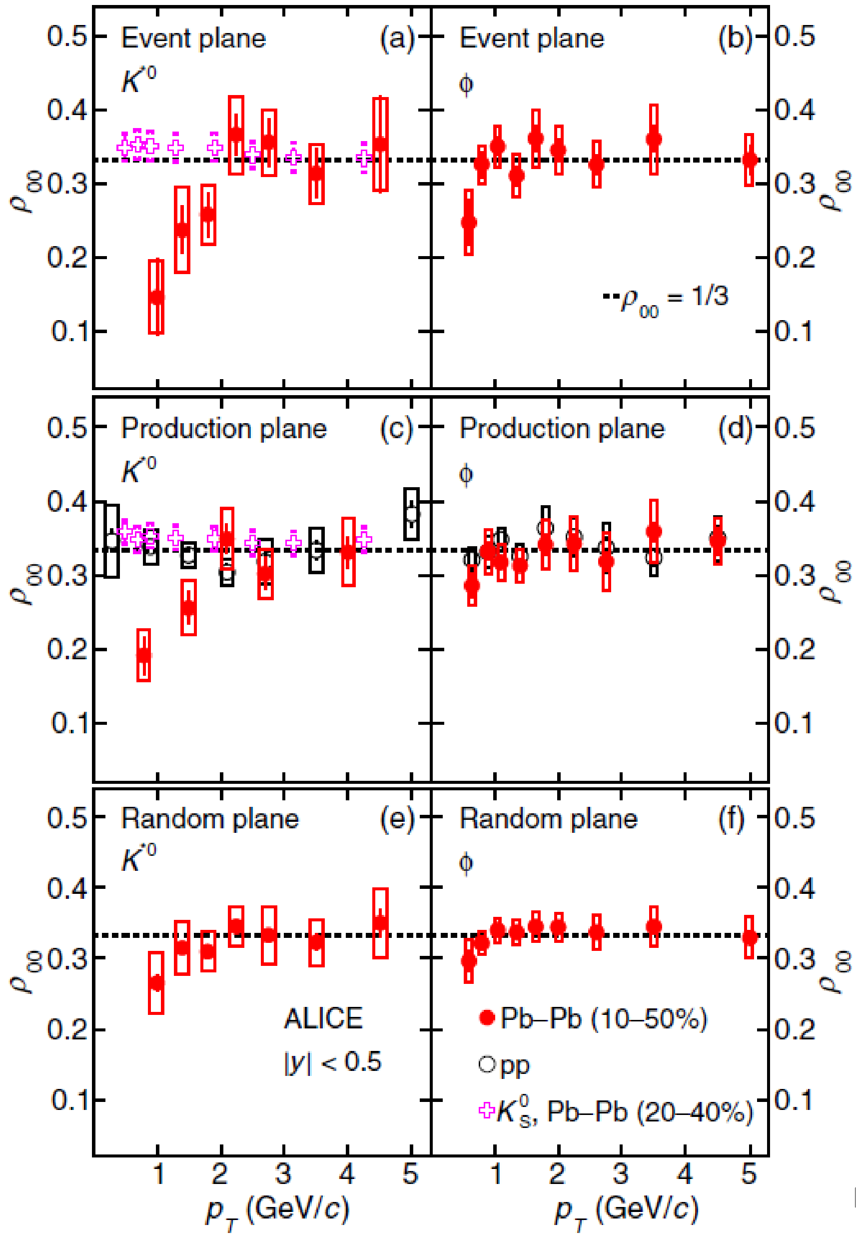
$$\frac{dN}{dcos\theta} = N_0[1 - \rho_{0,0} + cos^2\theta(3\rho_{0,0} - 1)]$$

$\rho_{0,0}$ 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 φ(1020)

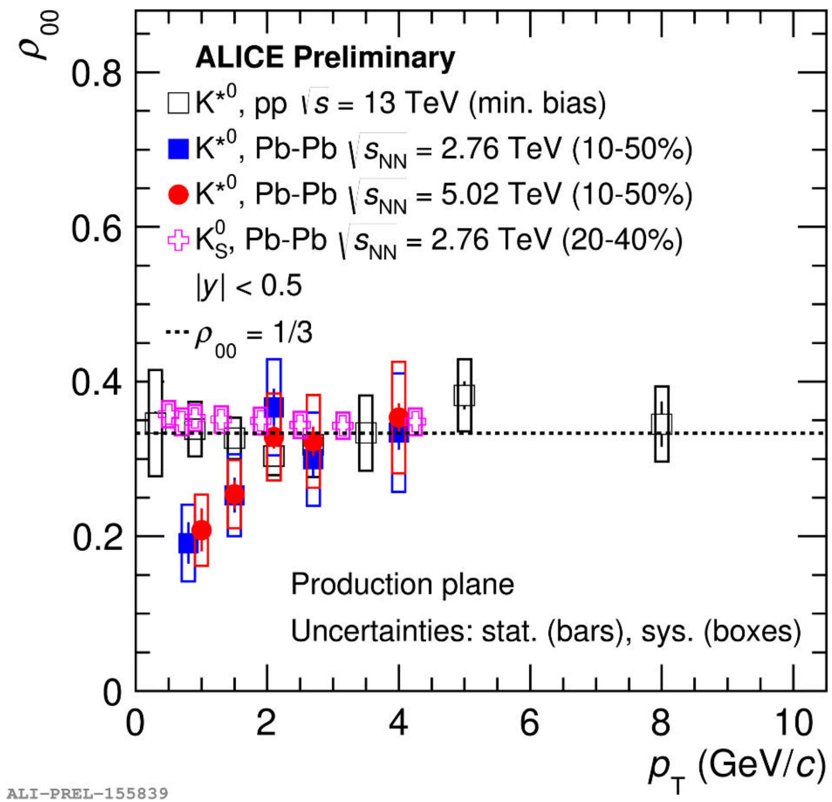
Results for K^{*0} and ϕ vs. p_T

PRL 125, 012301 (2020)



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

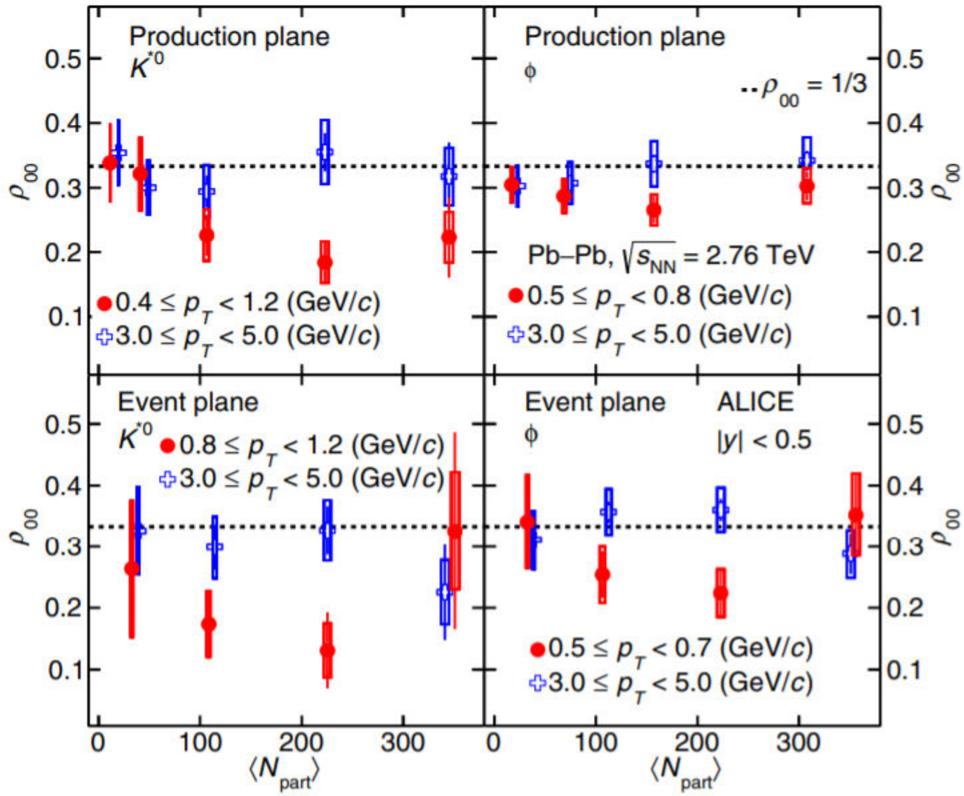
Results for K^{*0} and ϕ vs. p_T



- Results are now confirmed with new preliminary measurements for K^{*0} in Pb-Pb@5.02 TeV

Results for K^{*0} and ϕ vs. centrality

PRL 125, 012301 (2020)

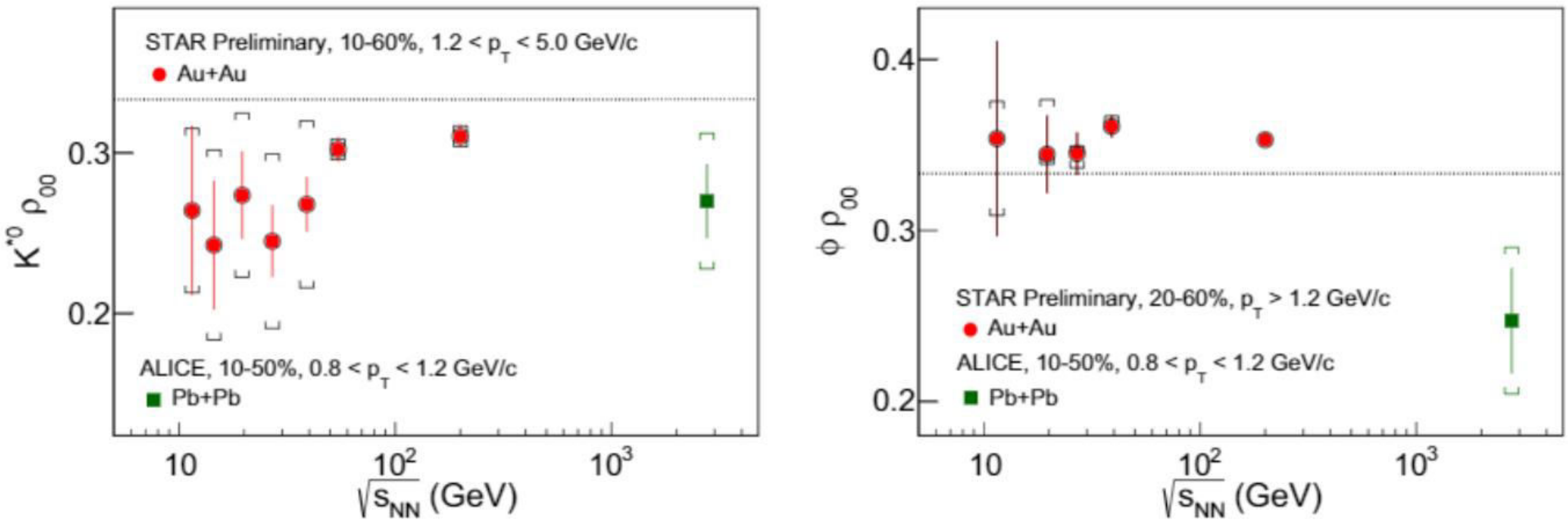


- Low p_T (0.8-1.2 GeV/c for K^{*0} and 0.5-0.7 GeV/c for ϕ):
  - ✓ ρ_{00} < 1/3 in semi-central PbPb@2.76 by 2-3 σ
- High p_T (3-5 GeV/c):
  - ✓ ρ_{00} ~ 1/3

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

Energy dependence

NPA 1005 (2021) 121733, Singha et al.

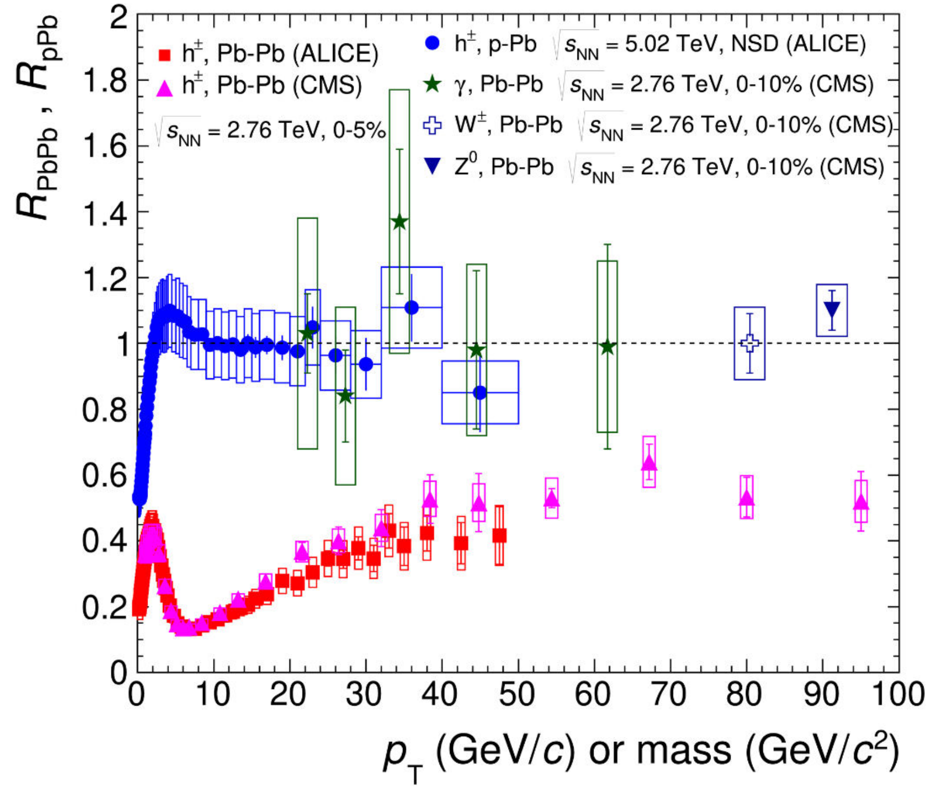


- ρ_{00} for K^{*0} is smaller than 1/3 at low p_T in semi-central heavy-ion collisions; no significant collision energy dependence within uncertainties
- ρ_{00} for ϕ is > 1/3 at RHIC and is < 1/3 at the LHC
- Observed large deviation of ρ_{00} from 1/3 challenges theoretical understanding → ρ_{00} can depend on multiple physics mechanisms (vorticity, magnetic field, hadronization scenarios, lifetimes and masses of the particles etc.) → more theoretical efforts are required for understanding of the data

High-p_T hadron production, R_{AA}

$$R_{AA} = \frac{1}{<N_{coll}>} \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

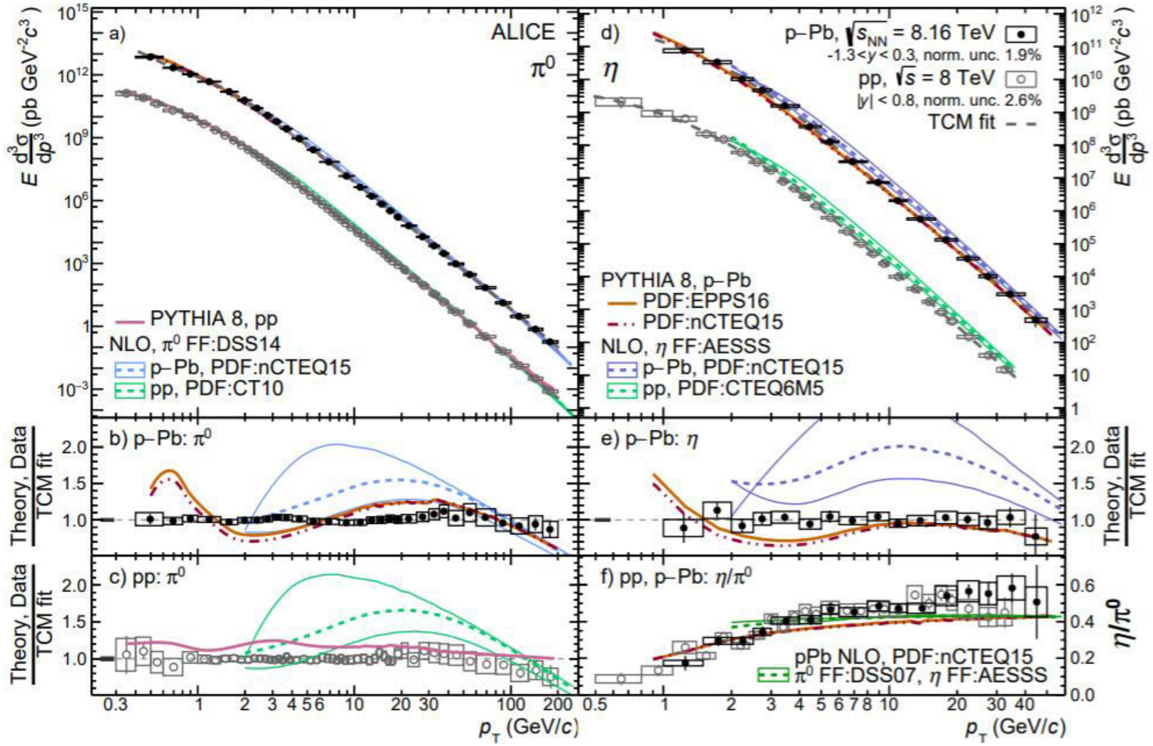
- Measurements in pp → baseline for comparison, tests and tunes of pQCD calculations
- If nucleus-nucleus collisions is a superposition of NN collisions → R_{AA} ~ 1
- $R_{AA} \neq 1$ points to collective effects



- In central relativistic heavy-ion collisions a dense and hot partonic medium (QGP) is formed → partons traversing the medium loose part of their energy → R_{AA} < 1
- The QGP is transparent for weakly interacting particles ($W^{\pm}$, Z^0) and photons, R_{AA} ~ 1 → test of N_{coll} scaling
- Measurements in p-Pb → probes of initial and final state effects (gluon saturation, p_T broadening, energy loss) and nuclear PDFs

High-p_T hadron production: pp and p-Pb

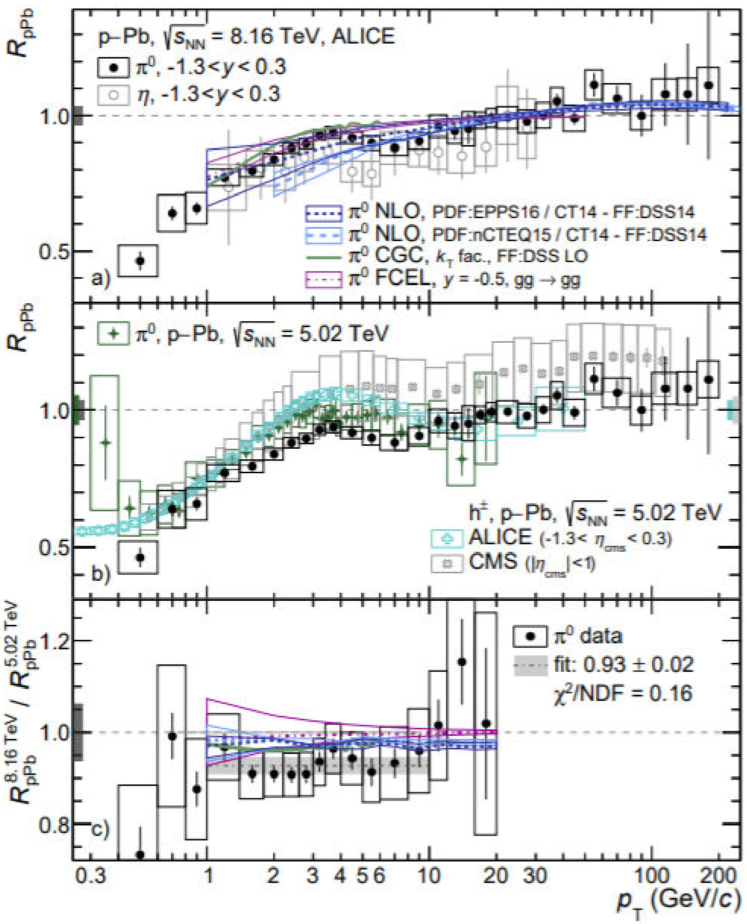
arXiv:2104.03116



- New measurements for π^0 and η in pp/p-Pb collisions over an unprecedented kinematic range (up to 200 GeV/*c* and 50 GeV/*c*, respectively) → constraints for nPDF and FF functions over a wide range:
  - ✓ NLO calculations generally overestimate π^0 and η spectra; steeper falling spectrum at high p_T
  - ✓ PYTHIA 8 describes the data but without fully capturing the spectral shapes
  - ✓ η/π^0 ratio is fairly well reproduced: at p_T > 4 GeV/c it is 0.479 ± 0.009(stat) ± 0.010(syst) in p-Pb and 0.473 ± 0.006(stat) ± 0.011(syst) in pp

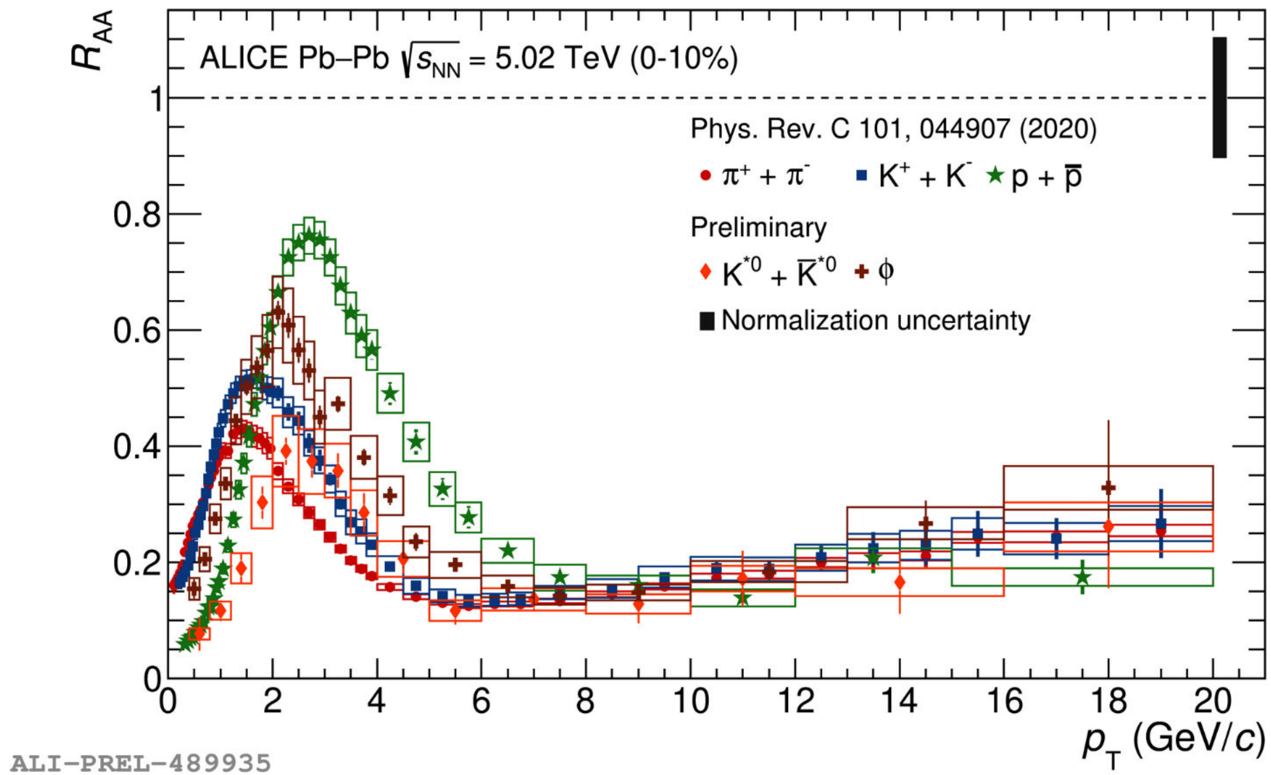
R_{pPb}

arXiv:2104.03116



- Measurements up to 200 GeV/c probe larger Q^2
- R_{pPb} is consistent between π^0 and η
- Significant suppression of R_{pPb} at low p_T:
  - ✓ reproduced by NLO, ECEL (energy loss) and CGC (gluon recombination)
- $R_{\mathrm{pPb}} \sim 1$ at $p_T > 10$ GeV/c, slightly lower compared with CMS measurements for charged hadrons → negligible final state effects
- R_{pPb} for charged hadrons exhibits an enhancement compared to π^0, → stronger Cronin effect for baryons
- Hint of stronger suppression at higher energy:
  - ✓ consistent with larger shadowing in nPDFs due to the smaller x probed at higher energy
  - ✓ consistent with the increasing relevance of gluon saturation by the CGC calculations

R_{AA}



- At high $p_T > 8$ GeV/c, production of light hadrons is similarly suppressed → no dependence on hadron properties (mass, baryon number, quark content)
- At intermediate $2 < p_T < 8$ GeV/c:
  - ✓ mass ordering of R_{AA} for mesons → indication of the radial flow
  - ✓ baryon-to-meson splitting (proton vs. ϕ) → difference in shapes of pp references

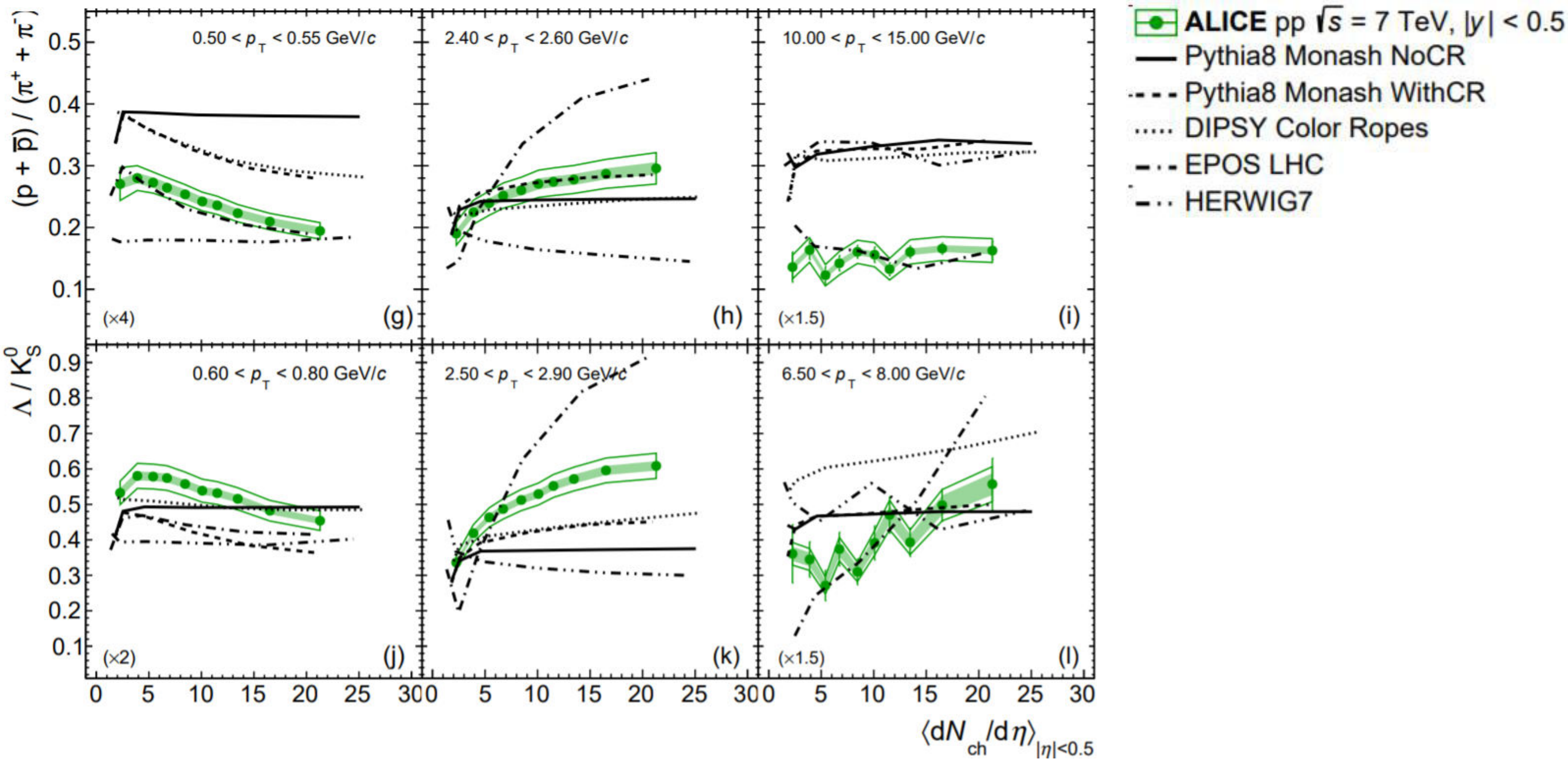
Summary

- 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
- Enhancement of baryon to meson ratios at intermediate p_T hints at collective motion of the system
- Blast-Wave fits allow to extract common expansion velocity and kinetic freeze-out temperature
- Relative particle abundances are driven by the final state multiplicities rather than by collision system size or energy
- Strangeness enhancement smoothly evolves with 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
- R_{AA} factors for light neutral mesons are consistent at high p_T, measurements in small systems are used to tune and test pQCD calculations
- Spin alignment for K^{*0} and ϕ vector mesons is qualitatively consistent with quark recombination in a polarized medium, more theoretical efforts are required for understanding of the data

BACKUP

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