50TH INTERNATIONAL SYMPOSIUM ON MULTIPARTICLE DYNAMICS
(ISMD2021), 12-16 JULY 2021, ONLINE CONFERENCE

ISMD2021

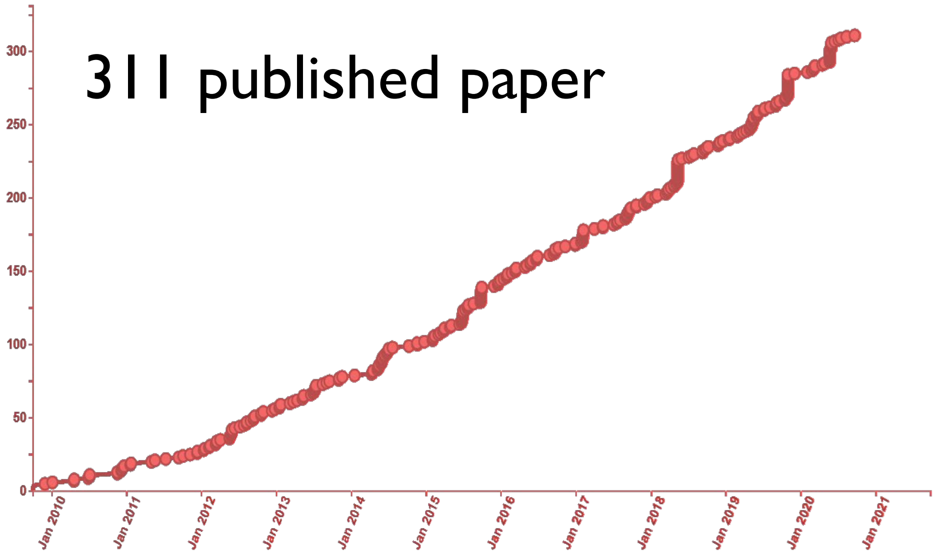
LIGHT-FLAVOUR PRODUCTION ACROSS DIFFERENT COLLISION SYSTEMS

ENRICO FRAGIACOMO
INFN – TRIESTE
ON BEHALF OF THE ALICE COLLABORATION

THE ALICE COLLABORATION @ LHC

39 countries, 175 institutes, 1025 authors

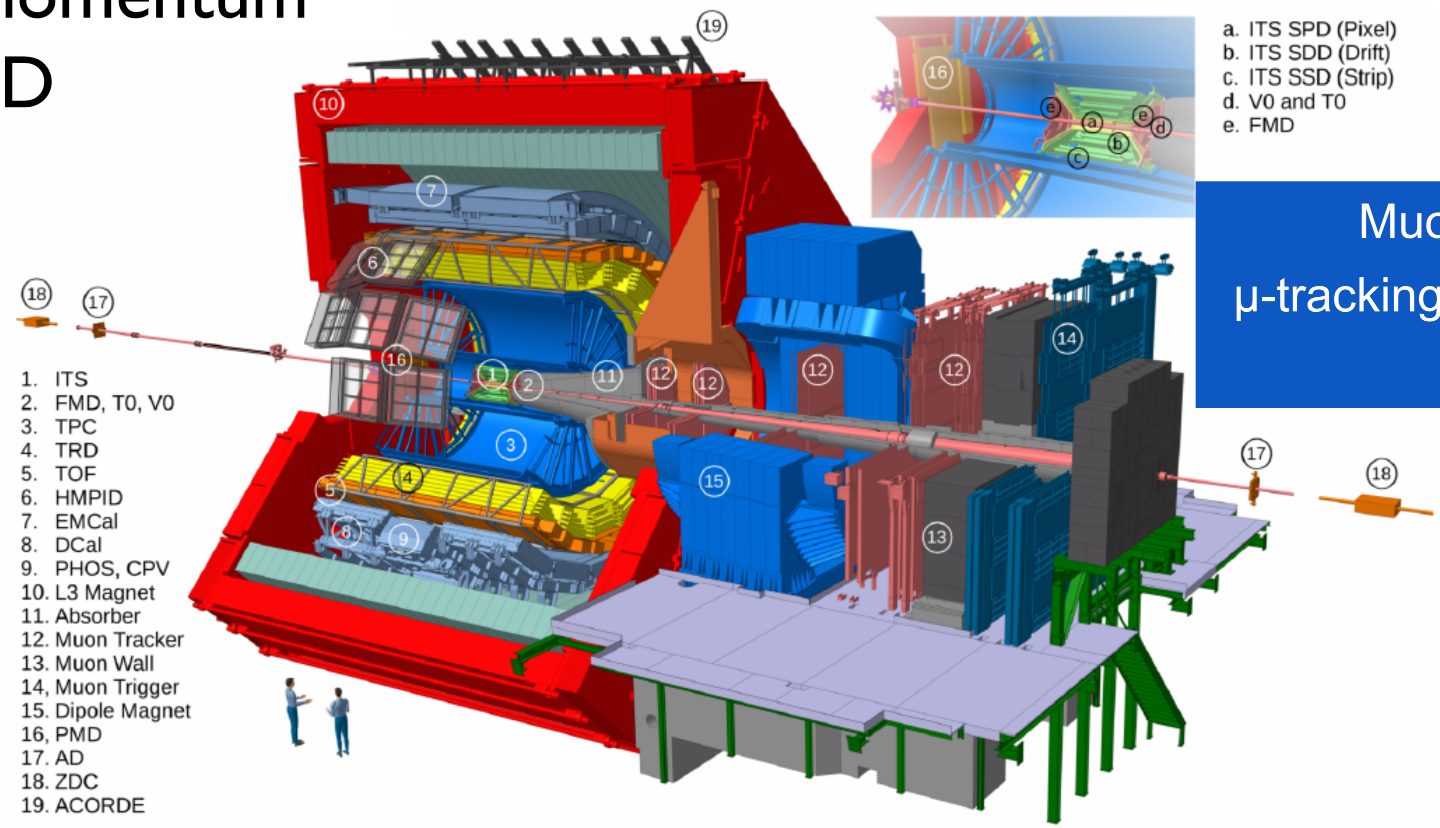
311 published paper



System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 μb^{-1} 800 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1}, 25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	200 μb^{-1}, 100 nb^{-1} 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 36 pb^{-1}

- Harvest of the past 10 years operation
- Large integrated luminosity in Run 2 allows precise measurements, new observables

Excellent track-momentum resolution and PID

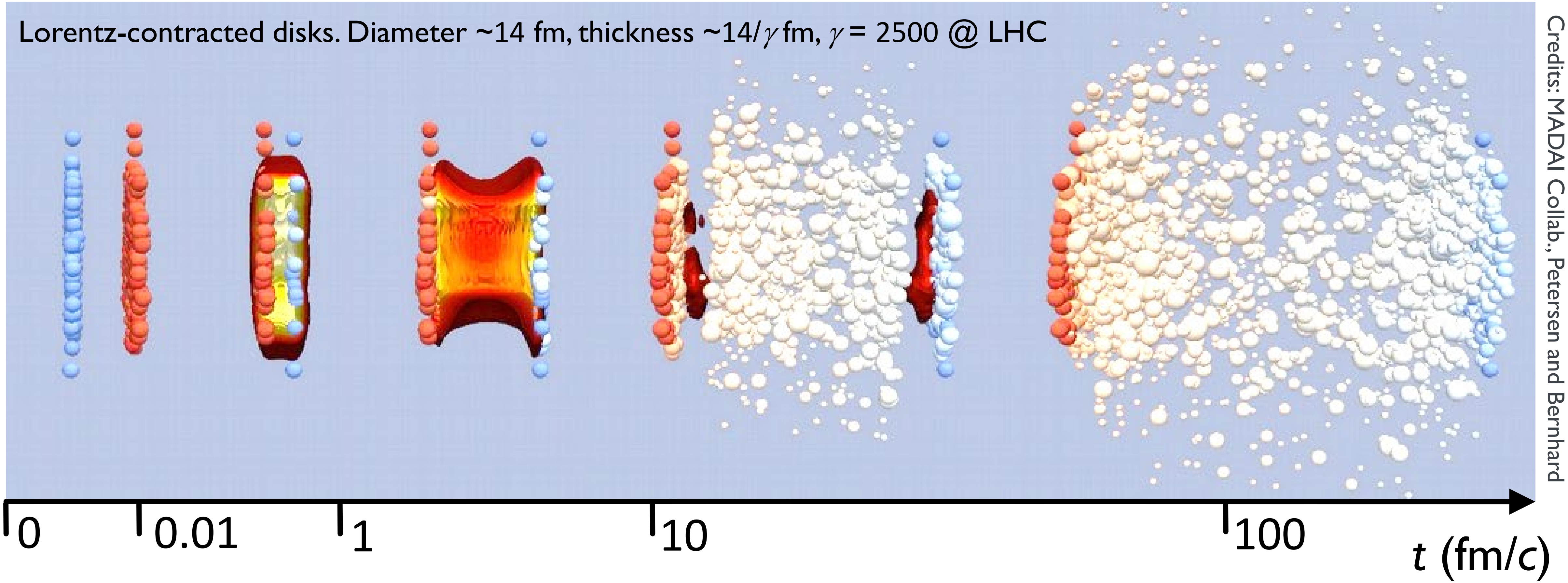


Muon spectrometer:
μ-tracking and trigger chambers
$-4 < \eta < -2.5$

Central barrel:
vertexing, tracking, PID, EM calos
$|\eta| < 0.9$

Forward detectors:
multiplicity, trigger, centrality, time zero

COLLISION EVOLUTION



Credits: MADAI Collab., Petersen and Bernhard

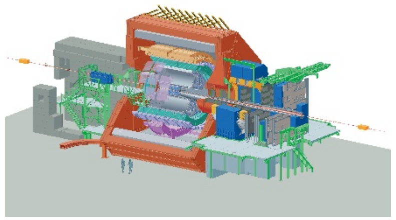
Initial stage
nPDF,
saturation,
shadowing

Gluon and
quark-pair creation
All heavy quarks
created at this stage

QGP: deconfined
nuclear matter
expanding
hydrodynamically

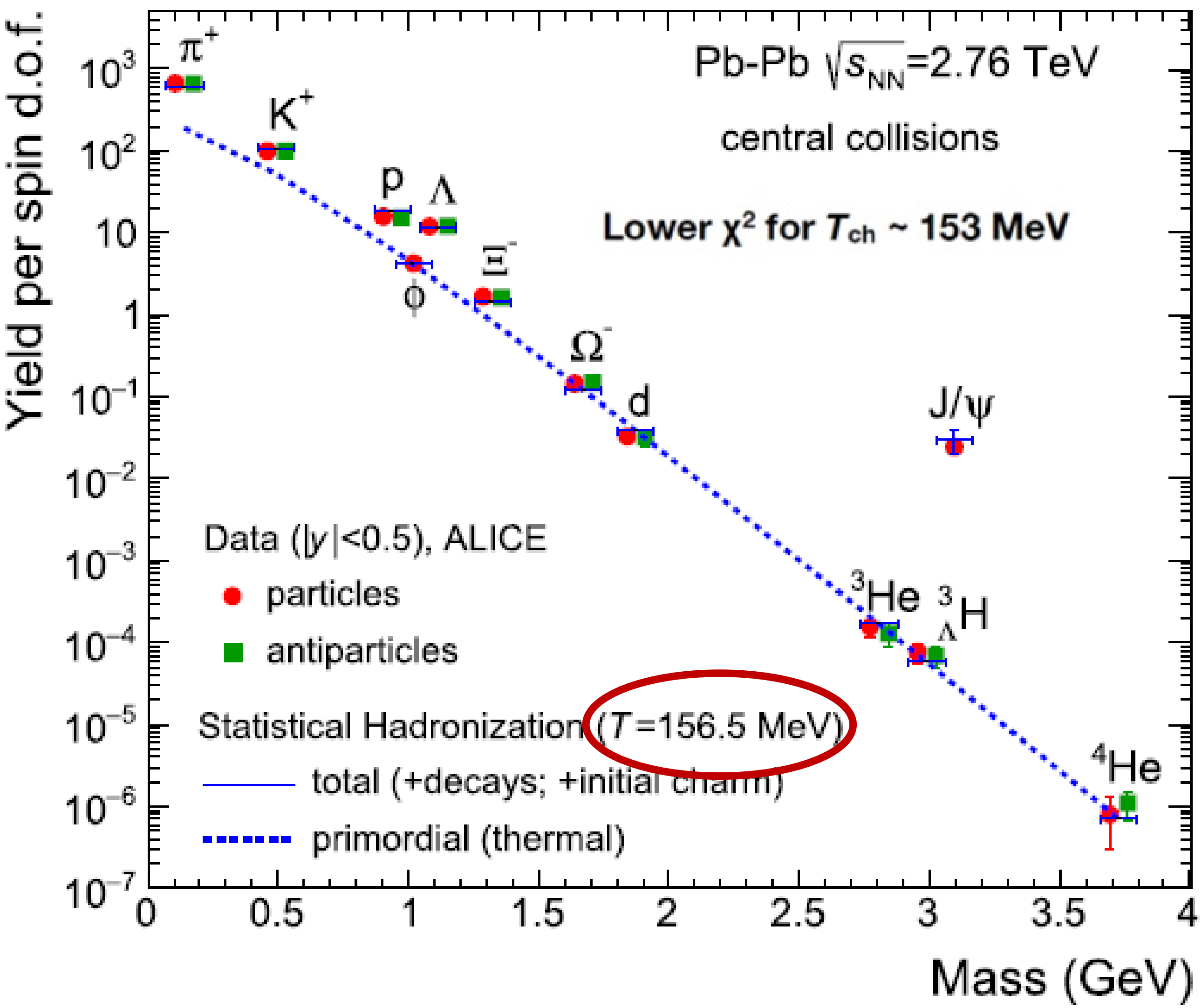
Hadronization and
chemical freeze-out
Inelastic collisions
cease

Kinetic freeze-out
Elastic collisions cease
Free streaming particles
to the detectors



TEMPERATURE AT HADRONIZATION FROM PARTICLE ABUNDANCES

Statistical Hadronization Model (SHM)

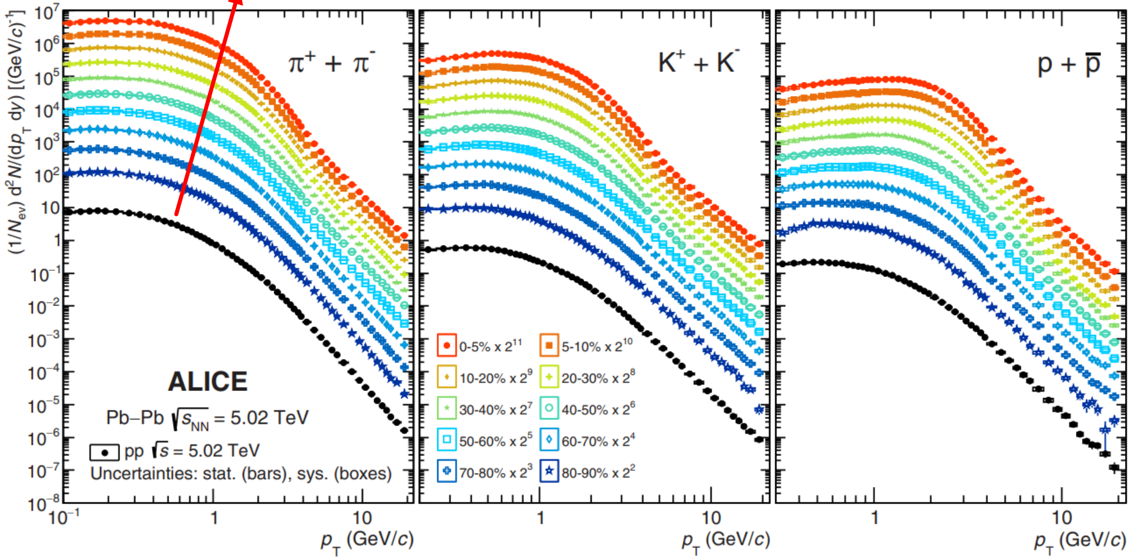


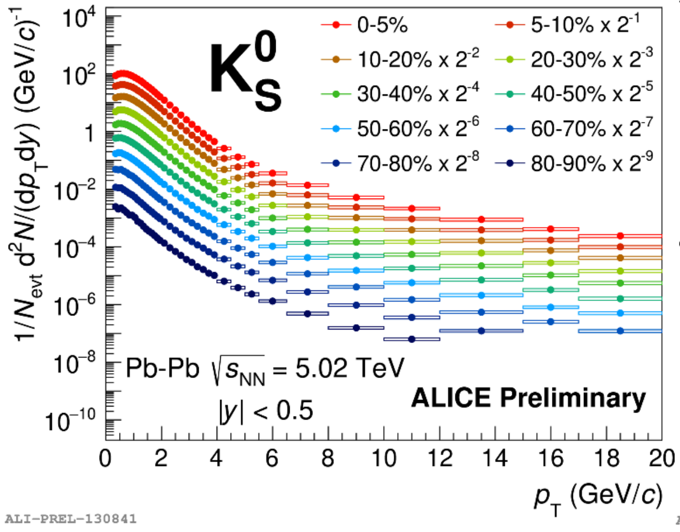
A.Andronic et al., Physics Letters B 797 (2019) 134836

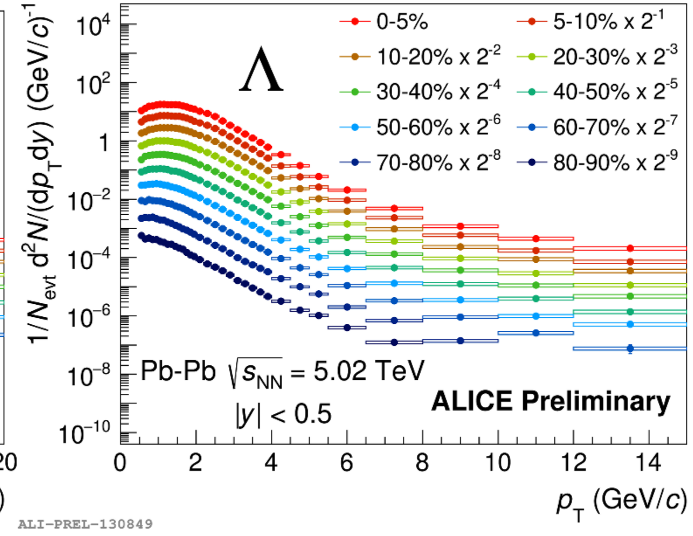
- At hadronization the system is close to thermal equilibrium
- A rapid hadrochemical freeze-out takes place at the phase boundary
- Hadron abundances described by SHM over 9 orders of magnitude!
- Note that also loosely bound objects (light nuclei and hyper-nuclei) and heavy-flavour hadrons (J/ψ) are described by SHM

DIFFERENTIAL TRANSVERSE MOMENTUM SPECTRA

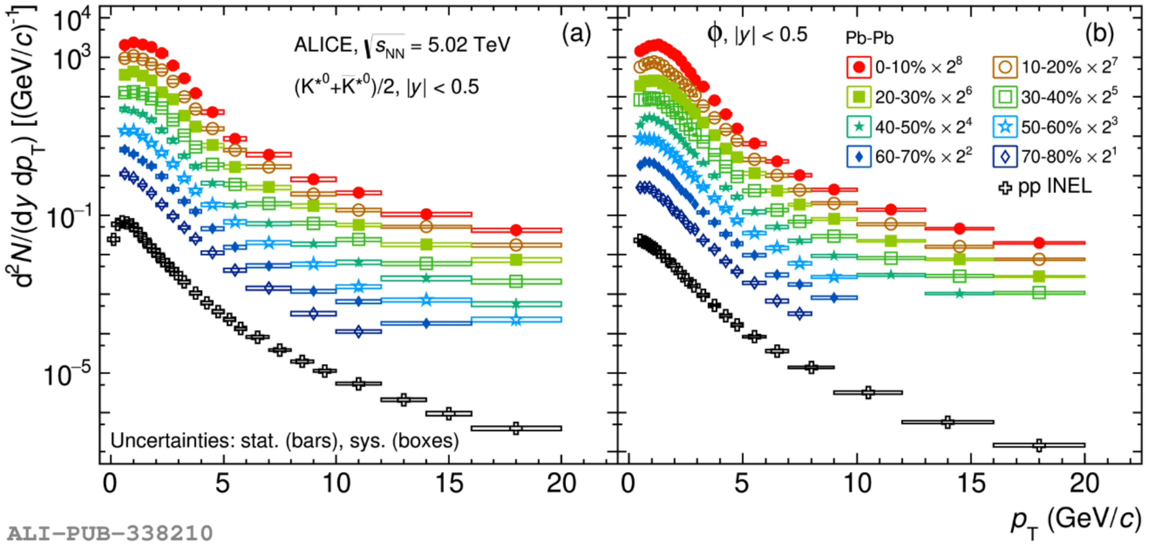
Phys. Rev. C 101 (2020) 4, 044907







Phys. Lett. B 802 (2020) 135225

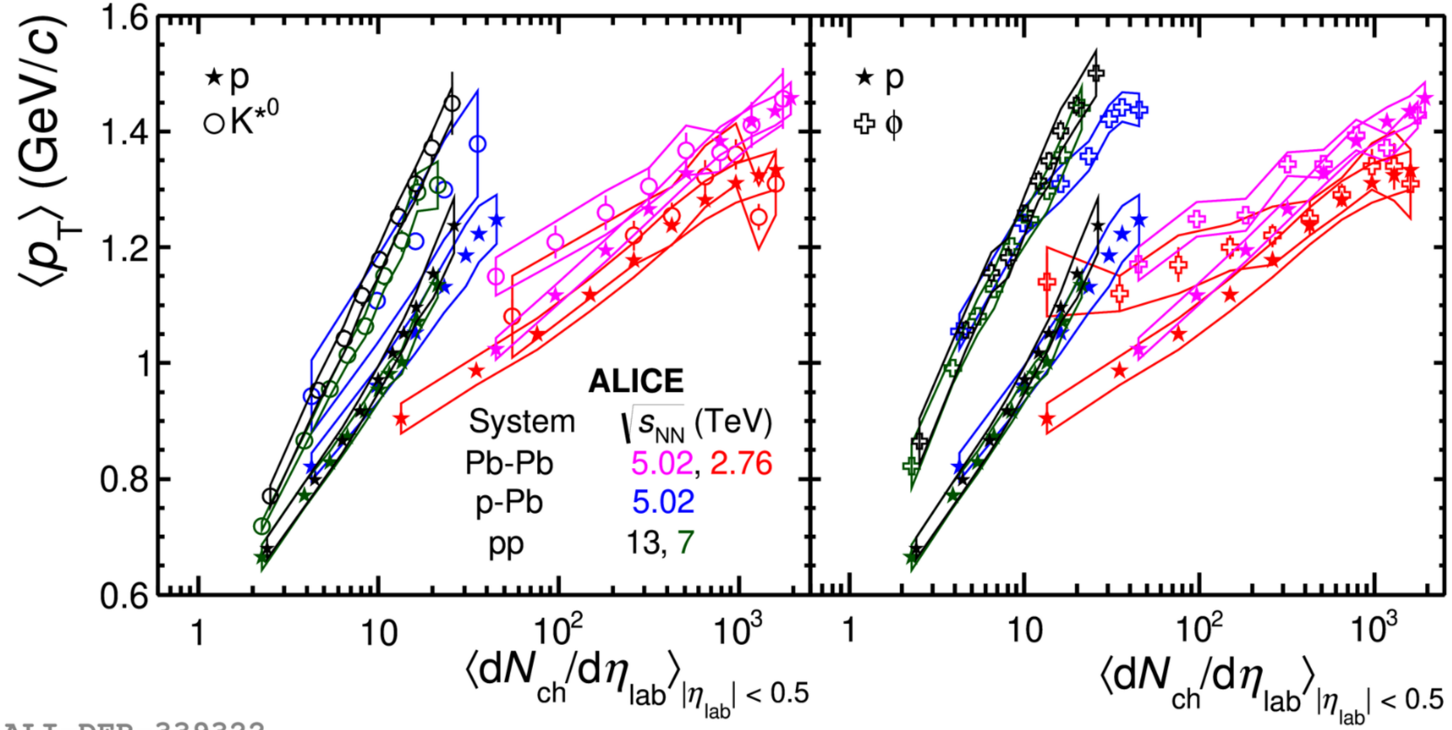


A variety of hadrons has been measured in wide p_T ranges at different multiplicities

- ❑ 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 MOMENTUM

Mass-dependent hardening manifests itself in <p_T> increasing with multiplicity

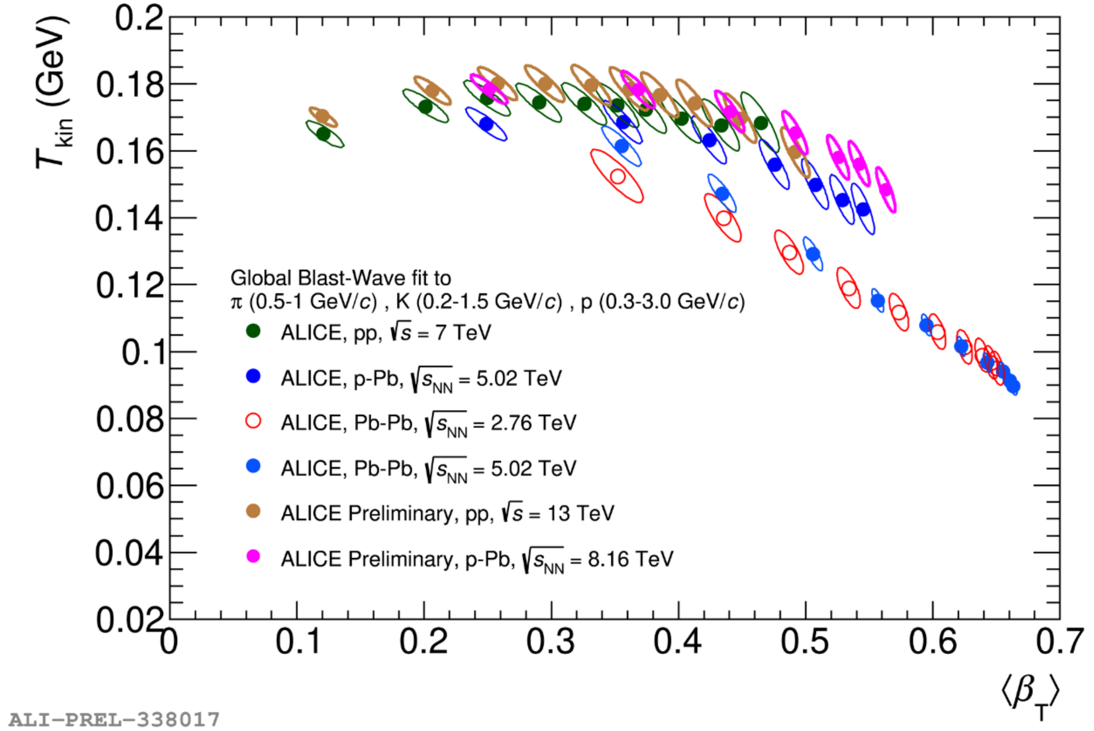


ALI-DER-339322

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 evolution
- The mass ordering of <p_T> 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
- $<\beta_T>$ - transverse flow velocity

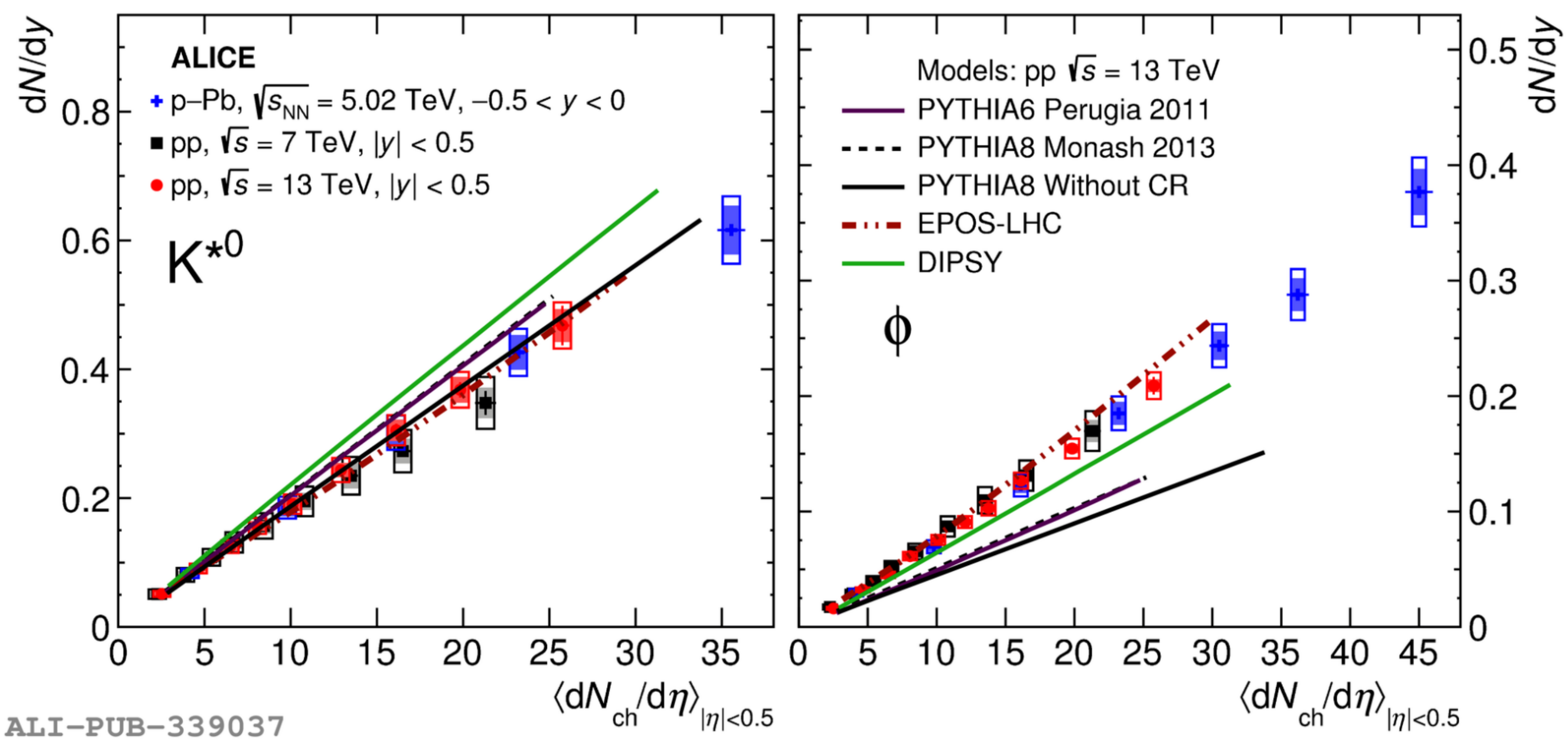
Fit parameters are extracted from simultaneous fits to π, K, p spectra

Results are sensitive to fitting range

- T_{kin} decreases, $<\beta_T>$ increases with multiplicity
- Consistent results for Pb-Pb and Xe-Xe at similar multiplicities (T_{kin} ~ 100 MeV)
- $<\beta_T>$ from pp and p-Pb are consistent with each other, but with larger values wrt. heavy ions at similar multiplicities
- T_{kin} stays constant (~ 160 MeV) in pp and slightly decreases in p-Pb

PARTICLE YIELDS IN pp AND p-Pb VS. dN_{ch}/dη

Phys. Lett. B 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 system size
- Qualitative description by models

NUCLEAR MODIFICATION FACTOR, R_{AA}

$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \times \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$

N_{coll}: Total number of nucleon pairs that collide, assuming transparency of the collision

At high p_T > 8 GeV/*c*, production of light hadrons is similarly suppressed

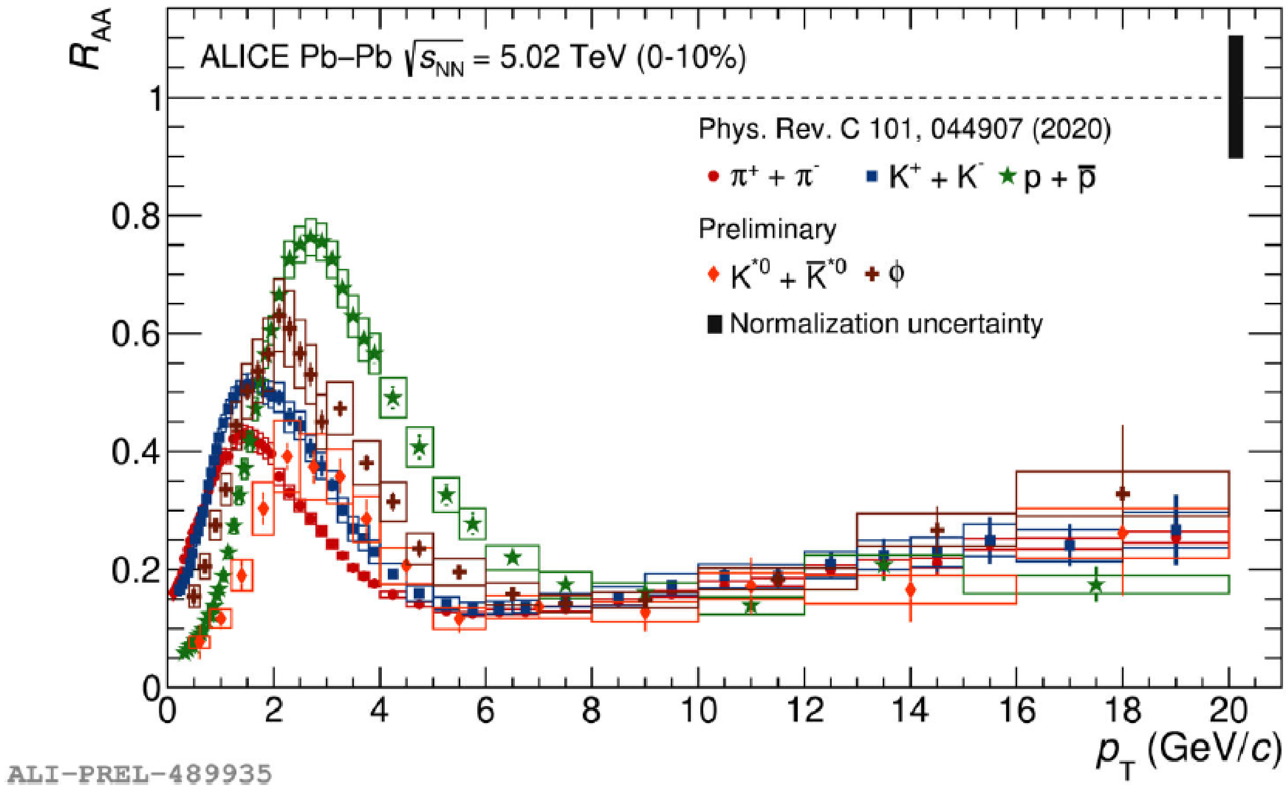
→ No dependence on hadron properties (mass, baryon number, quark content)

At intermediate 2 < p_T < 8 GeV/*c*:

- mass ordering of R_{AA} for mesons

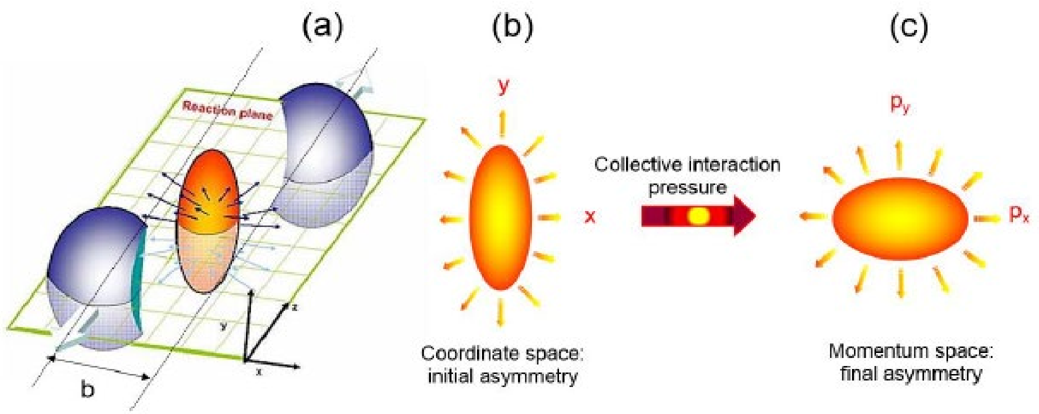
  → indication of the radial flow
- baryon-to-meson splitting (proton vs. Φ)

  → difference in shapes of pp references



HYDRODYNAMICS OF THE MEDIUM: ANISOTROPIC FLOW

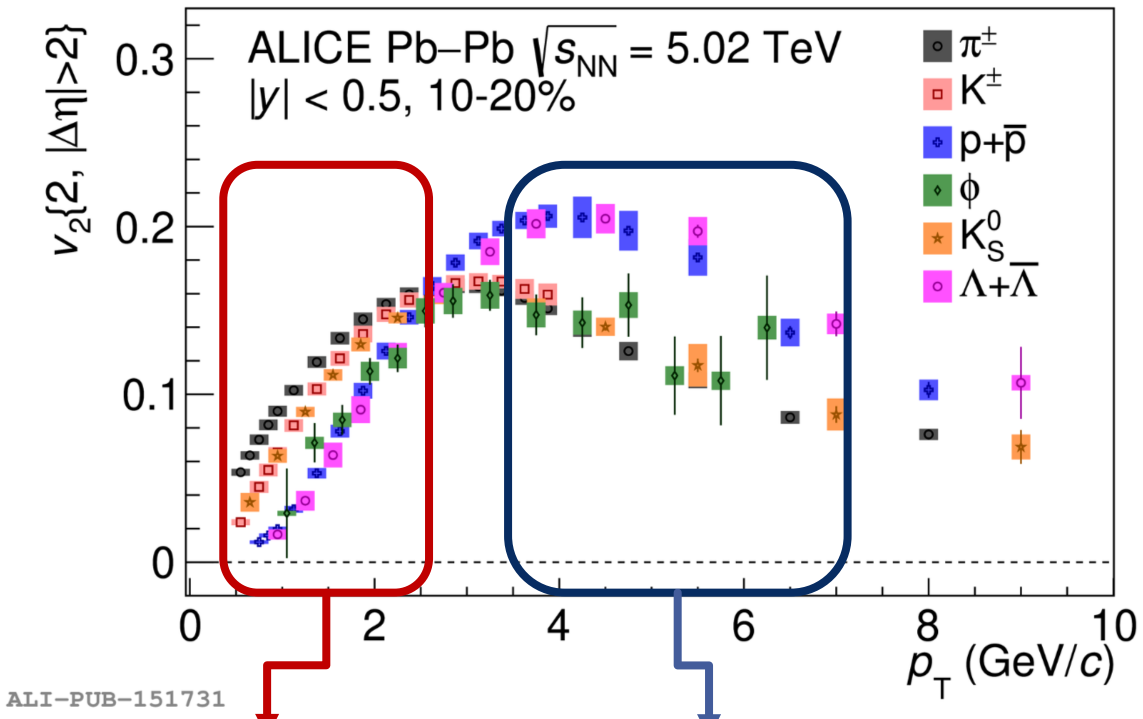
Anisotropies in the initial energy density distribution lead to azimuthal anisotropies in particle production



- Depends on EOS and fluid viscosities
- Measured via Fourier expansion

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]$$

ALICE, JHEP 09 (2018) 006

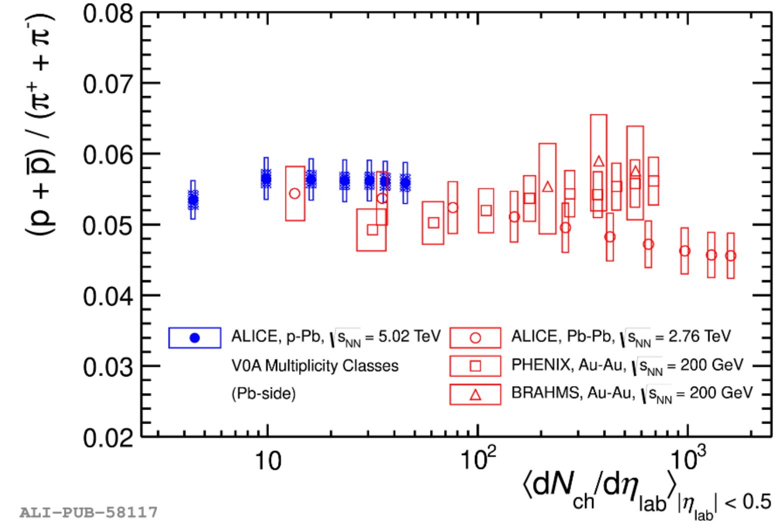


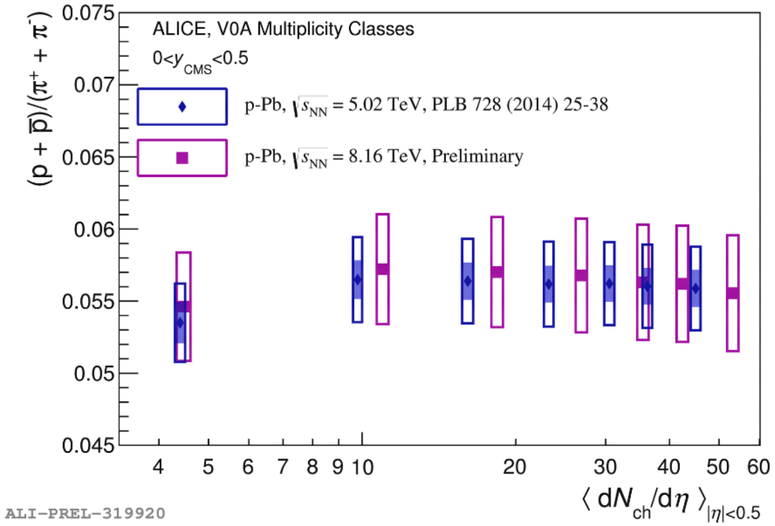
Mass ordering (higher mass → lower v_2): interplay between radial and elliptic flow

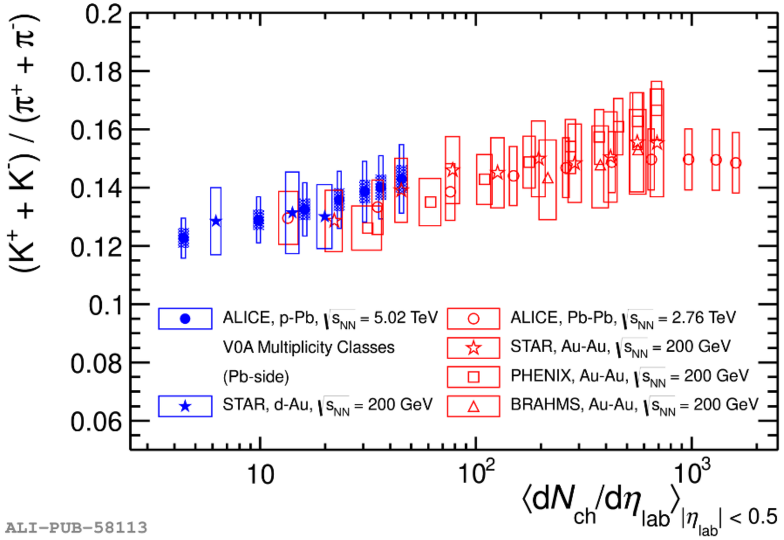
Higher n_q higher v_2 → quark coalescence as dominant particle production mechanism

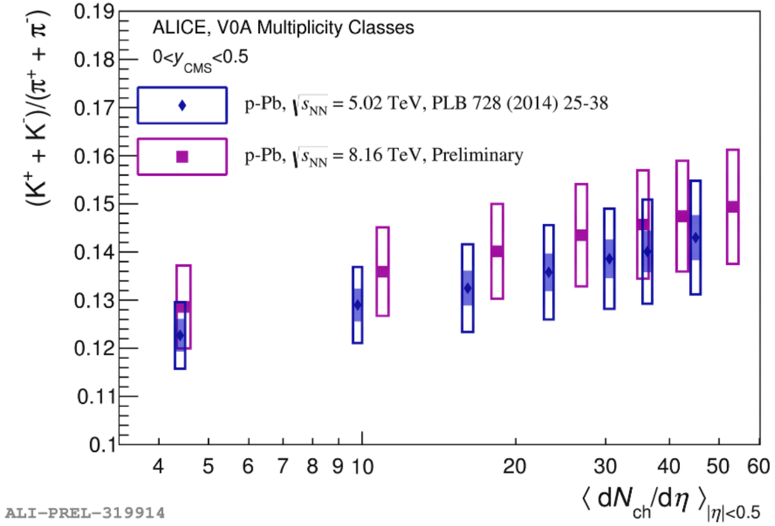
p/π AND K/π RATIOS

- At similar multiplicities, particle ratios are consistent for different collision systems at different $\sqrt{s_{NN}}$
- p/π shows a modest decrease with centrality at the LHC wrt to RHIC, consistent with smaller antibaryon-baryon asymmetry at the LHC
- Increasing K/π ratio is consistent with strangeness enhancement



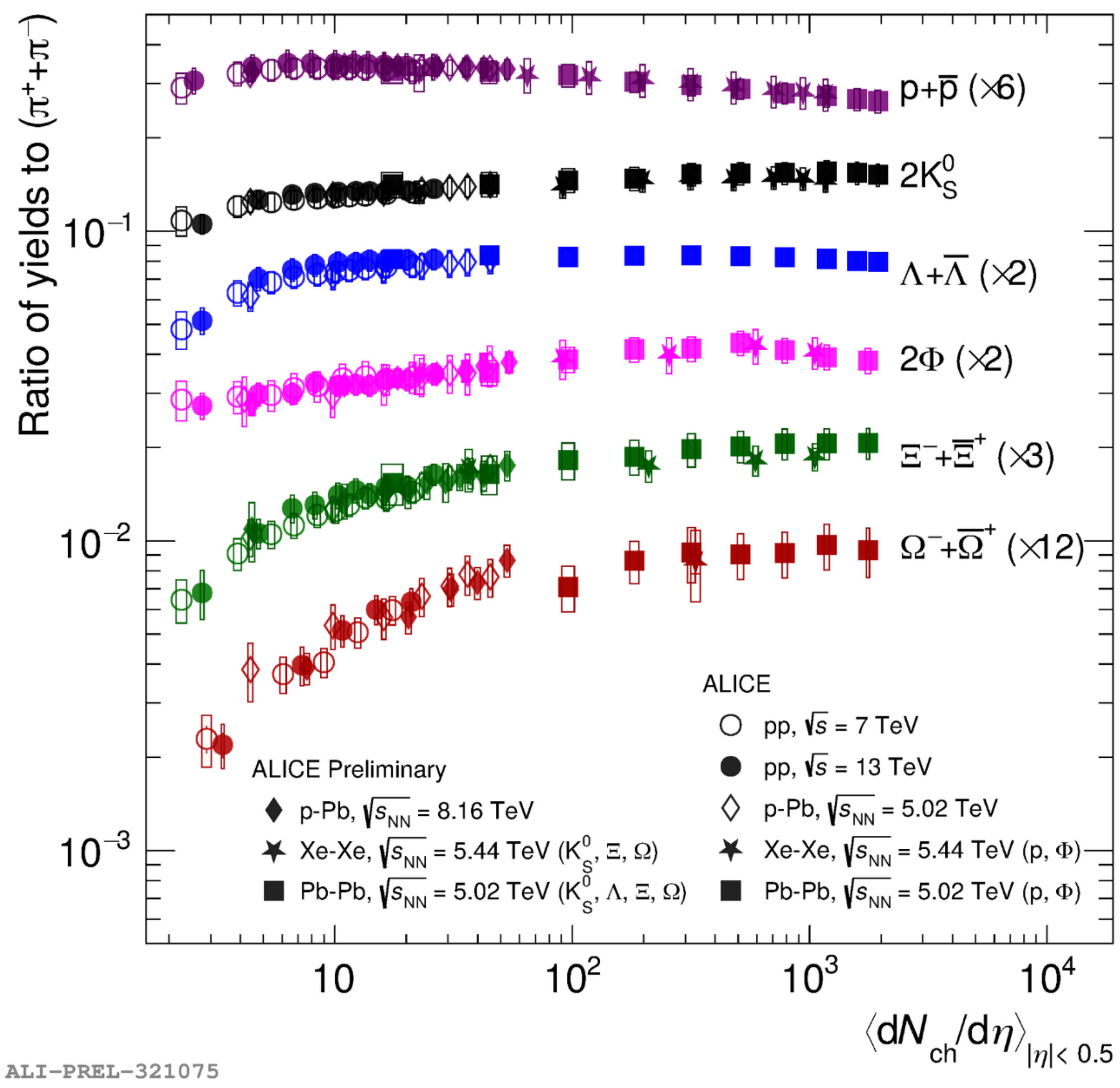






HADROCHEMISTRY: RELATIVE ABUNDANCES OF HADRONS

Nat. Phys **13,** 535–539 (2017)



|S| = 0

|S| = 1

|S| = 1

|S| = 0 (hidden)

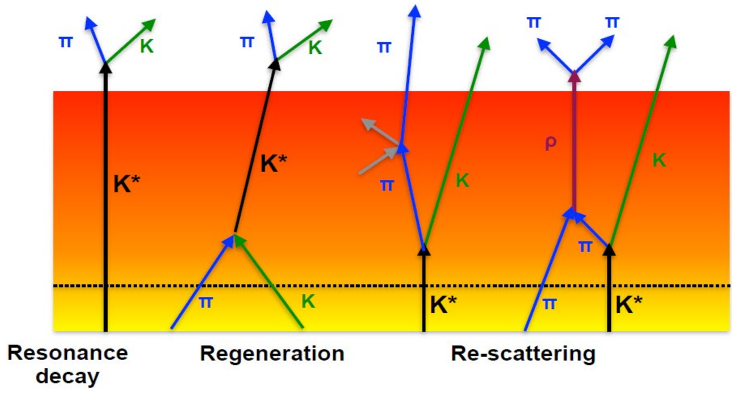
|S| = 2

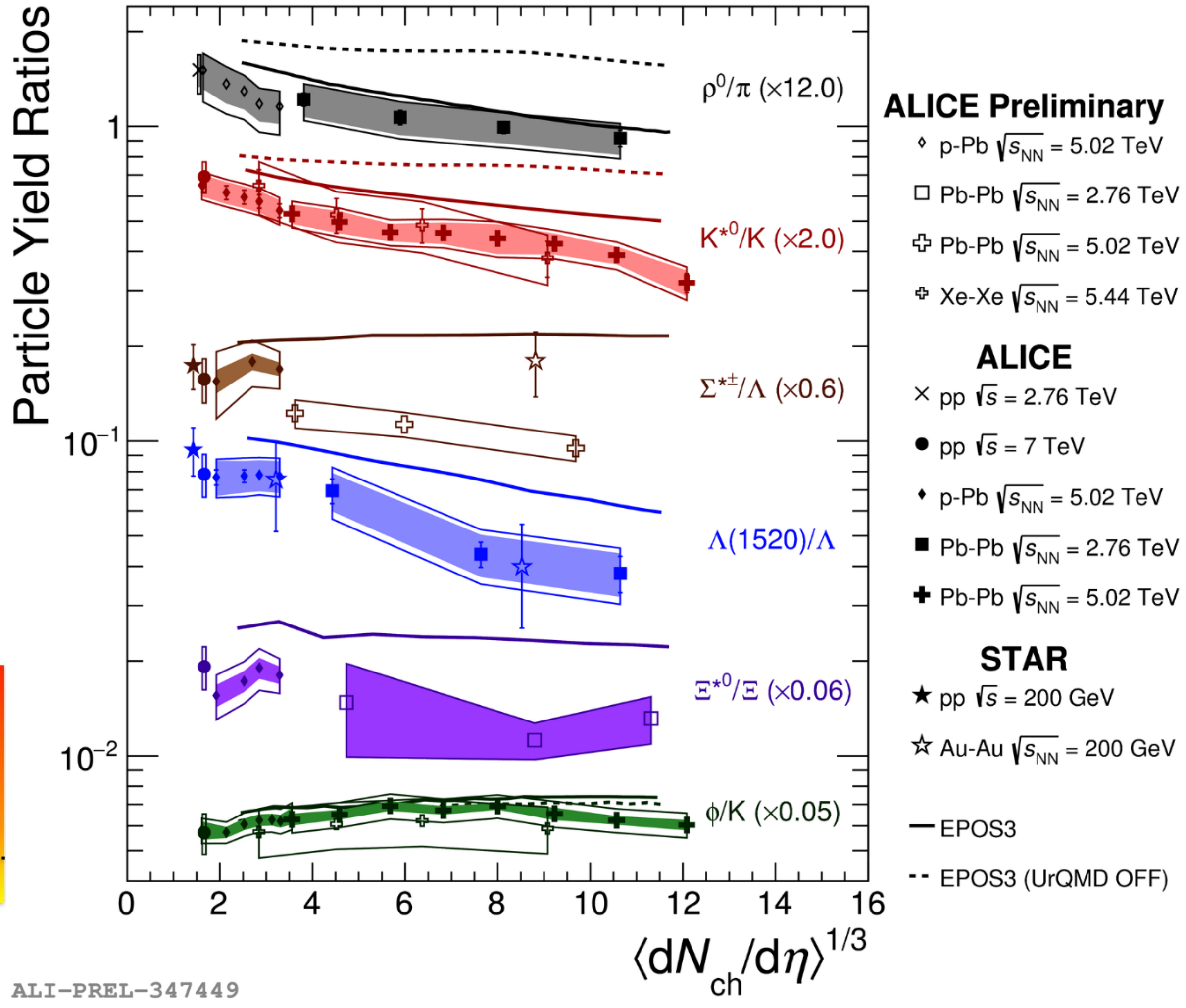
|S| = 3

- **Smooth evolution of particle production from small to large systems** vs. charged-particle multiplicity
- Strangeness production increasing with multiplicity until saturation (grand-canonical plateau) is reached
- Steeper increase for particles with more strangeness content
- High-multiplicity pp: same hadrochemistry as larger (p-Pb, peripheral Pb-Pb) systems
- **Common particle production mechanism for all systems?**

LIGHT-FLAVOUR RESONANCES PROVES THE LATE HADRON PHASE

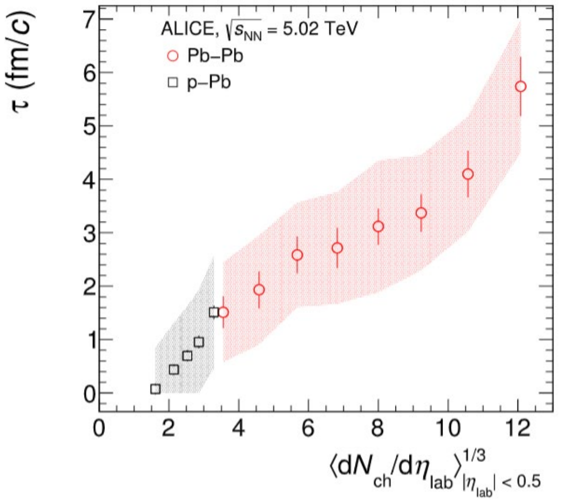
Resonances have **lifetimes similar to the lifetime of the hadron phase** → they are subject to regeneration and re-scattering effects





Estimate the duration between chemical and kinetic freeze-out

Phys. Lett. B 802 (2020) 135225



Resonance lifetime(fm/*c*): ρ(1.3) < K*(4.2) < Σ*(5.5) < Λ*(12.6) < Ξ*(21.7) < ϕ(46.4)

CONCLUSIONS AND OUTLOOK

Harvest from Run 1 + 2 offers:

- Detailed insights into QGP characteristics
- Fundamental advances in QCD at high density

Run 2 + 3 and beyond:

- Major LS2 upgrade on track for pp in 2022
- In preparation: ITS3, FoCal in LS3
- Ambitious plans for Run 5+: the next generation