HADRON

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ALICE

Light flavour baryon production from small to large collision systems at ALICE

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Istituto Nazionale di Fisica Nucleare, Sezione di Bari
on behalf of the ALICE Collaboration

Light flavour particle production in ALICE

ALICE is designed to study the physics of strongly interacting matter under extreme temperature and energy densities to investigate the properties of the **quark-gluon plasma**

LHC Run1 and Run2 data taking		
Colliding System	Year(s)	$\sqrt{s_{NN}}$ (TeV)
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13
p-Pb	2013 2016	5.02 5.02, 8.16
Xe-Xe	2017	5.44
Pb-Pb	2010-2011 2015-2018	2.76 5.02

Published and Preliminary results available for most light-flavour and strange hadron species in all the colliding systems provided by LHC: π, $K^{\pm}$, p, K^{*0}, ϕ, Ξ^{*0}, $\Sigma^{*\pm}$, K^0, Λ, Ξ, Ω, d, t, ^{3}He, $^3_\Lambda$H.

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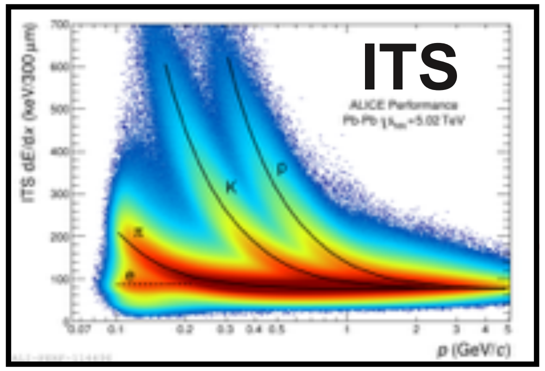
Highlight few interesting observations on the particle production mechanisms to be compared in small and large colliding systems

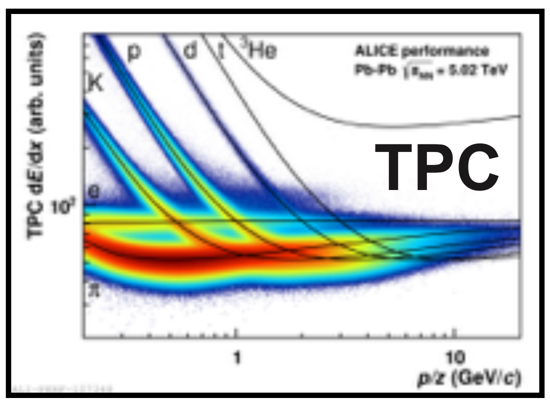
① Statistical hadronization models
② Strangeness enhancement and ϕ production
③ Resonances suppression
④ Baryon-To-Meson ratio
⑤ Light nuclei production

The ALICE detector in LHC Run 1 and Run 2

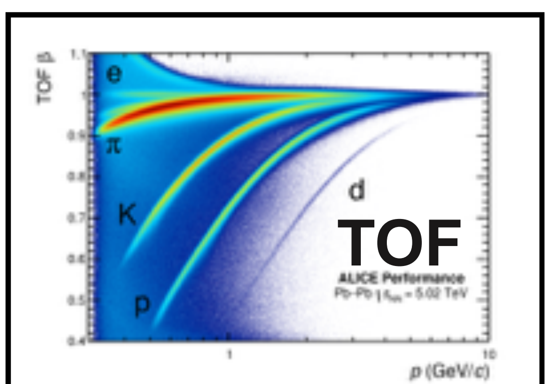
Multi-purpose detector at the LHC with unique particle identification capabilities and tracking down to very low momenta



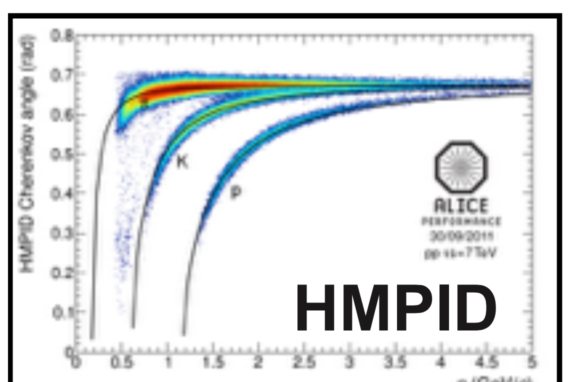
ITS $\sigma_{dE/dx}$ ~ 10-15%



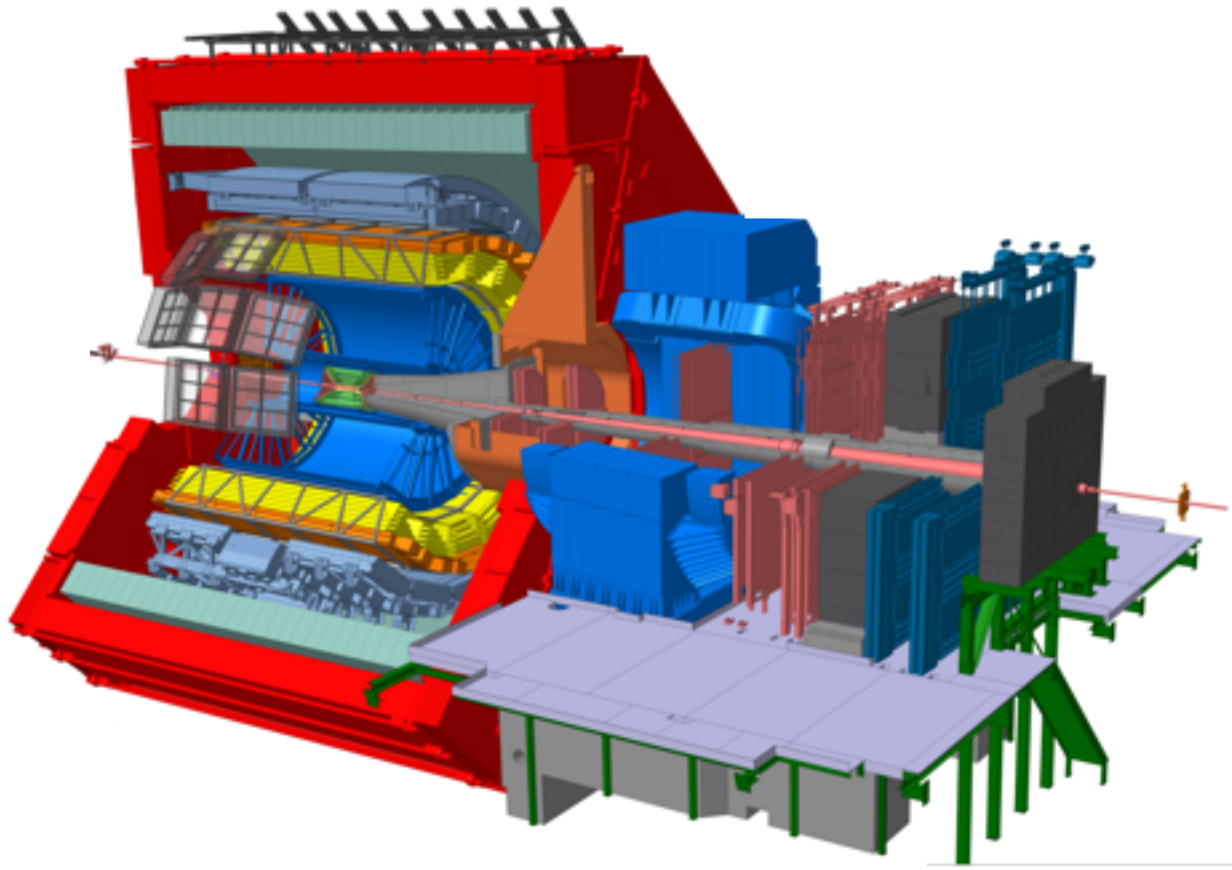
TPC $\sigma_{dE/dx}$ ~ 5%



TOF $\sigma_{Time\ Of\ Flight}$ ~ 56 ps



HMPID $\sigma_{Cherenkov\ Angle}$ ~ 3 mrad



<u>Central Barrel Detectors (|η| < 1)</u>

Inner Tracking System (**ITS**)

» Tracking, Vertexing, Triggering, Low momentum PID (dE/dx)

Time-Projection Chamber (**TPC**)

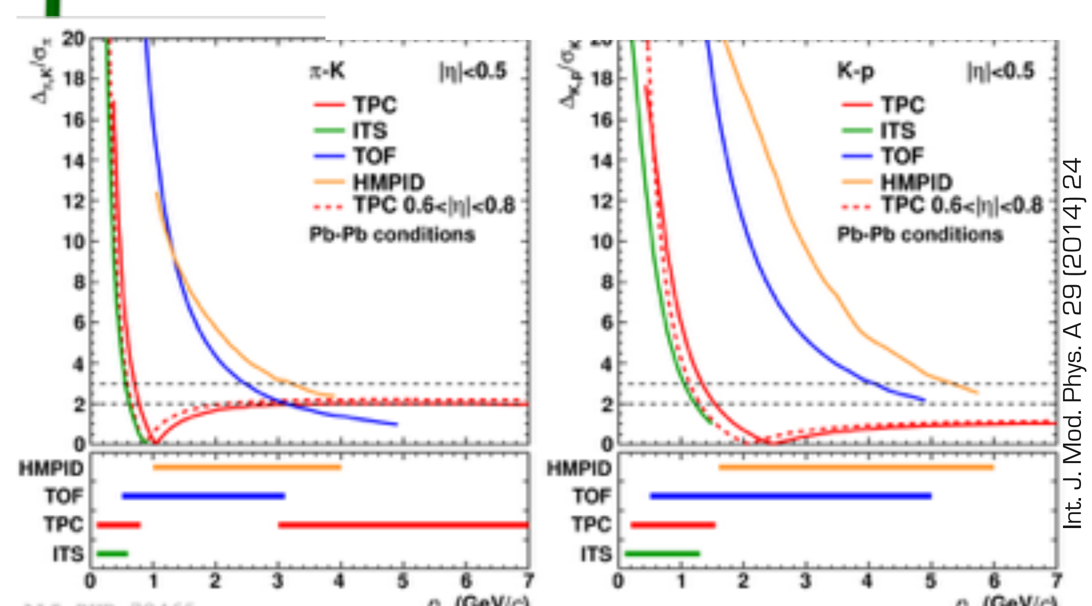
» Tracking, PID (dE/dx)

Time-of-flight detector (**TOF**)

» PID (time-of-flight)

High Momentum PID (**HMPID**)

» PID (Cherenkov)



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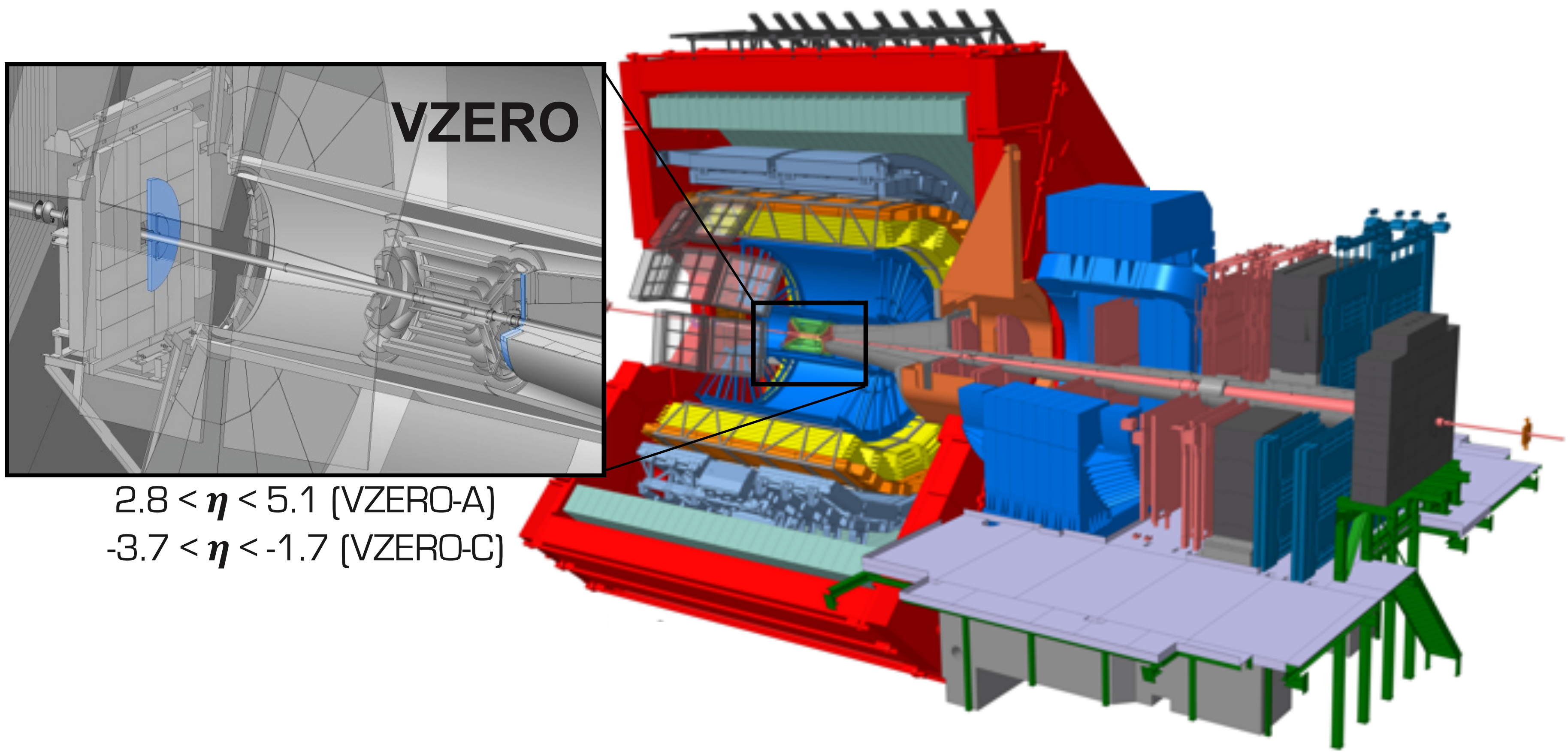

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VZERO

» Triggering, Event multiplicity determination

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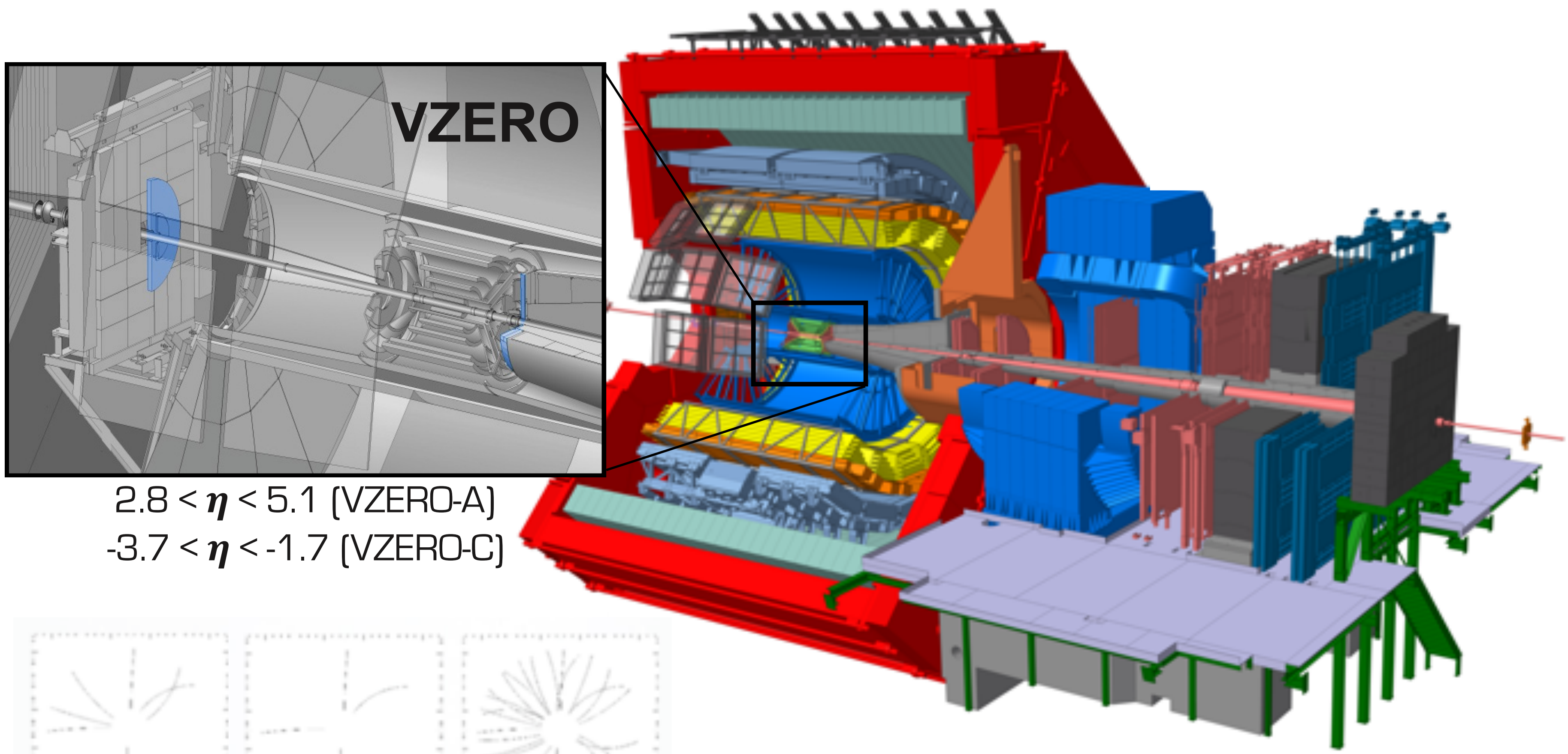

$2.8 < \eta < 5.1$ (VZERO-A)
$-3.7 < \eta < -1.7$ (VZERO-C)

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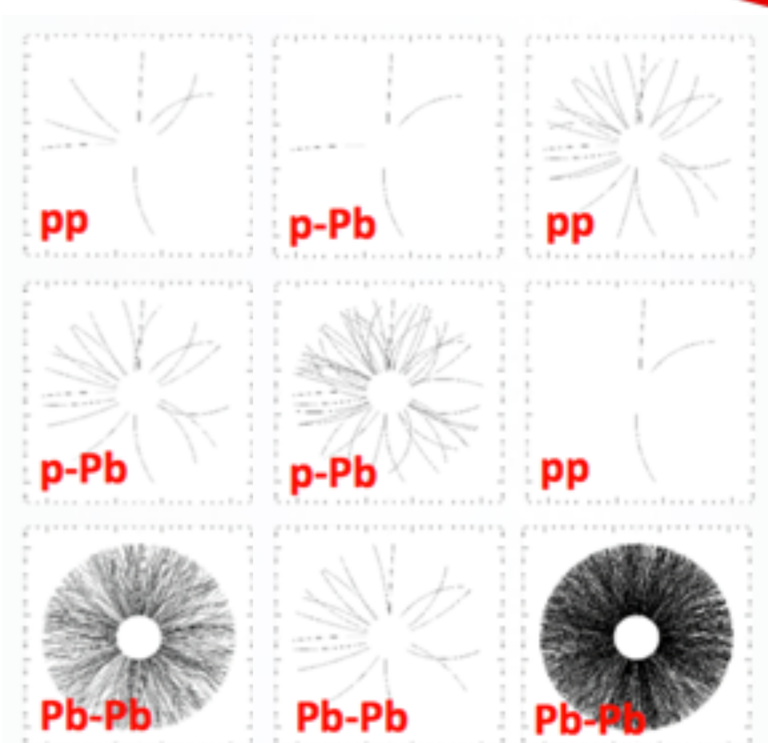
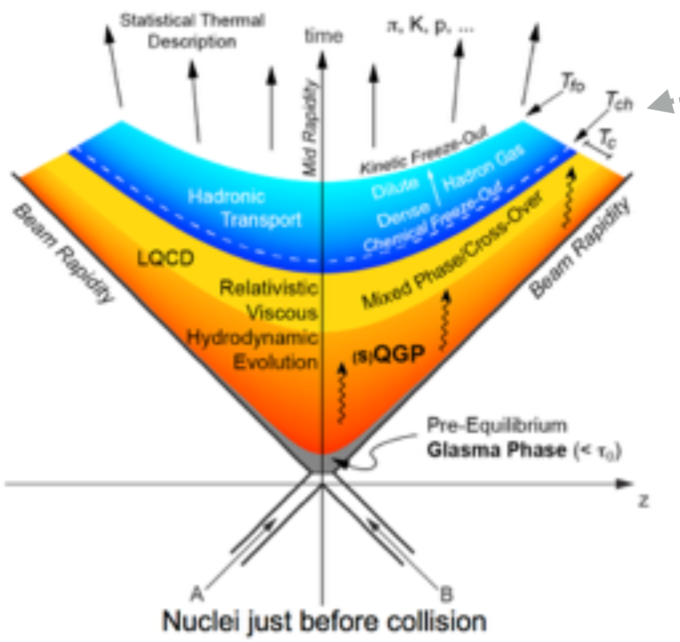


Small and large system definition

» Commonly referred to the colliding system size (ee < pp < p-A < A-A)
» In the following referred to the created medium size
  ✓ Defined in terms of charge particle multiplicity
  ✓ Correspondence to the previous true only on average
  ✓ Multiplicity estimator used to categorise event according to its multiplicity (best if unbiased from particle under study)

① Statistical Hadronization Models



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- Hadrons emitted from a source in statistical/thermal equilibrium
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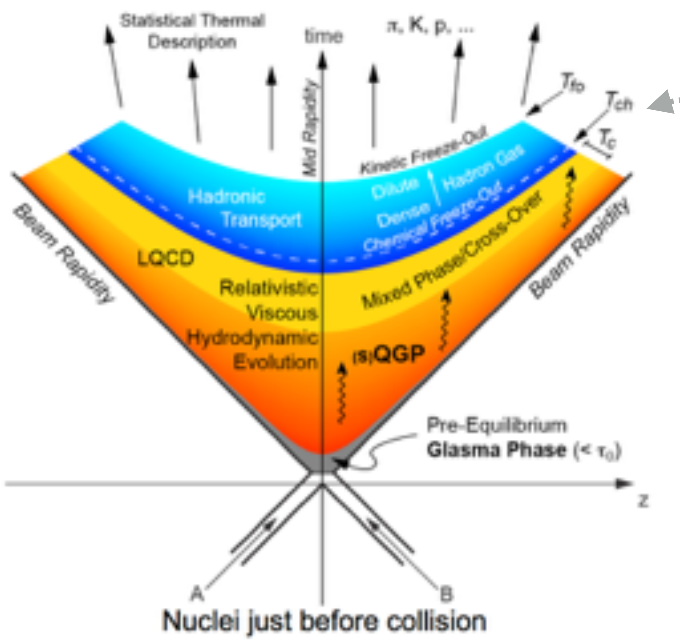

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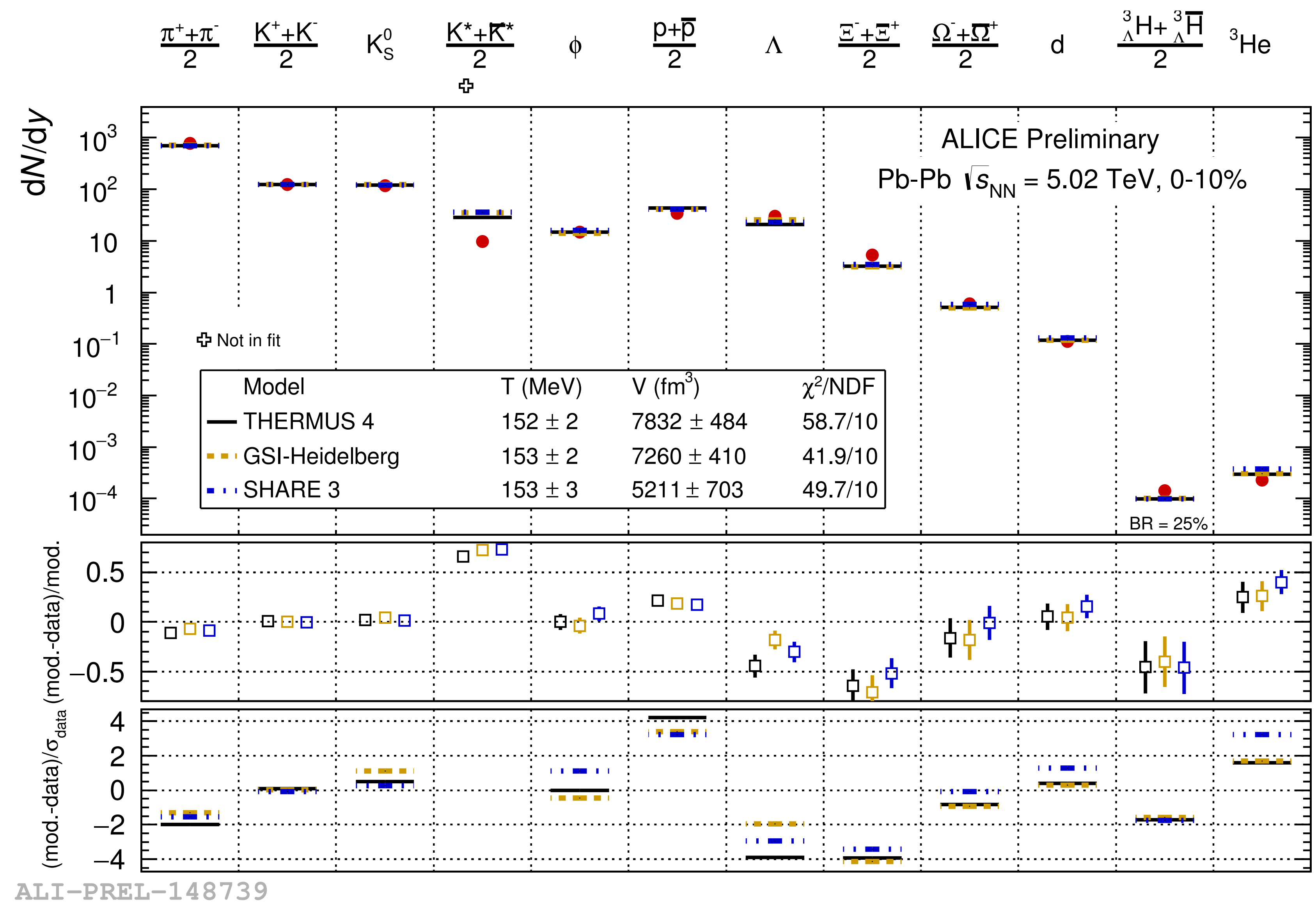

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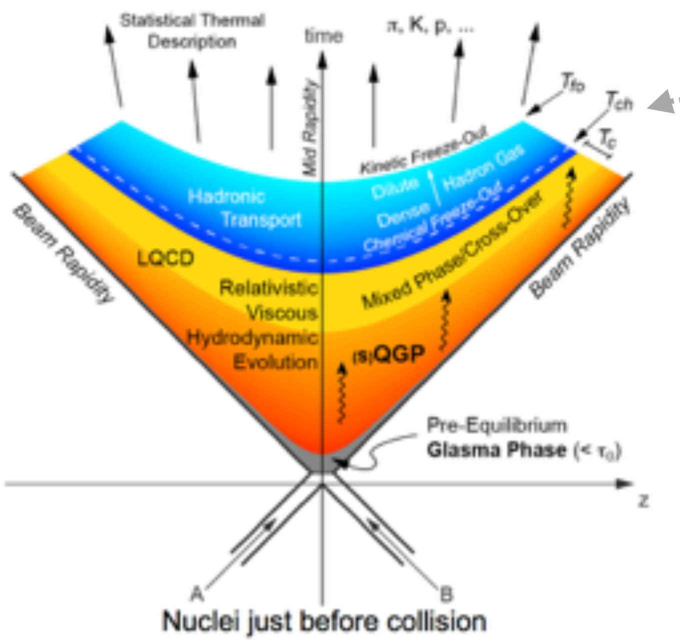

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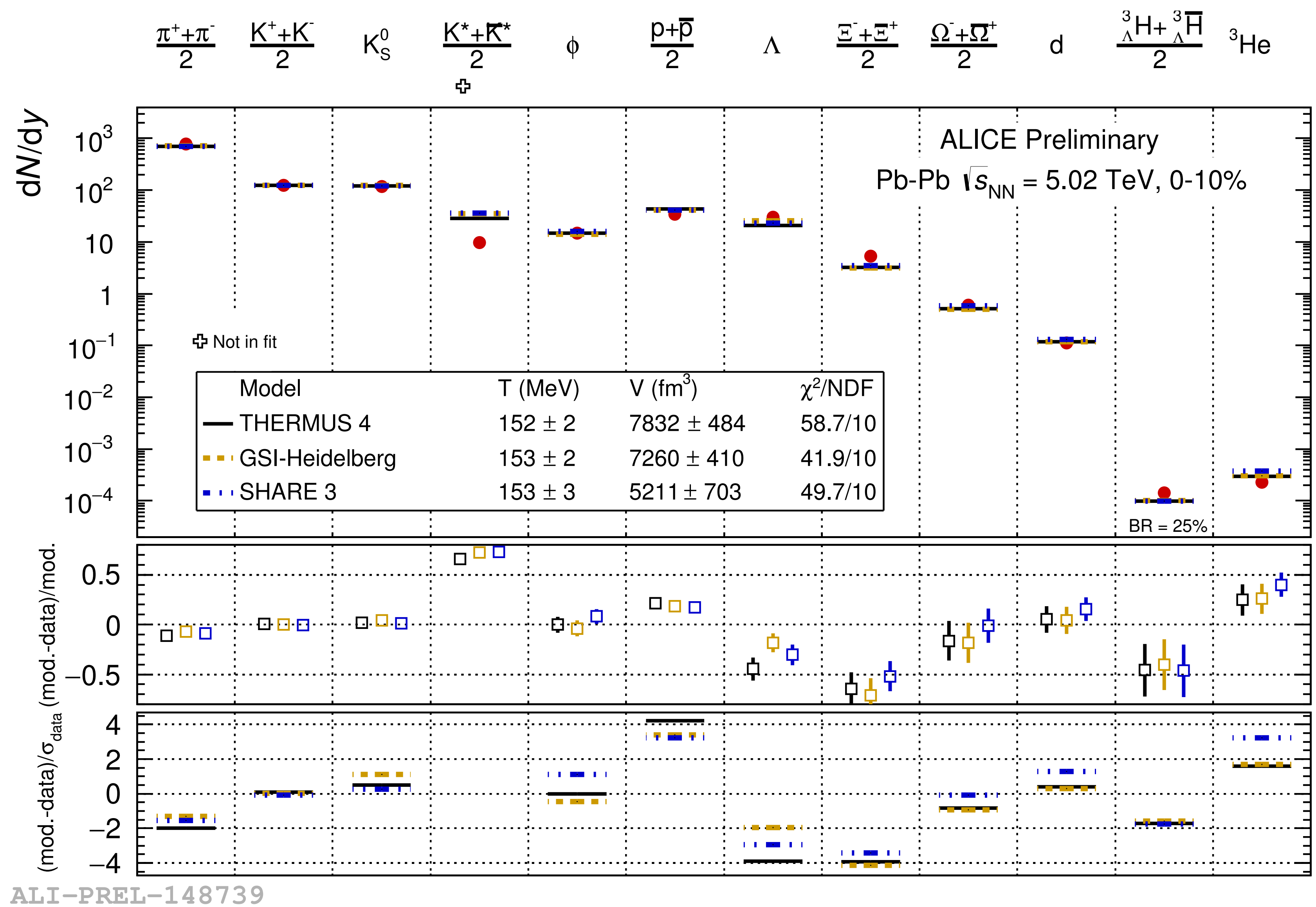

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» Similar behaviour in Pb-Pb@2.76TeV (T_{ch}=156±3) and Pb-Pb@5.02TeV (T_{ch}=153±3)

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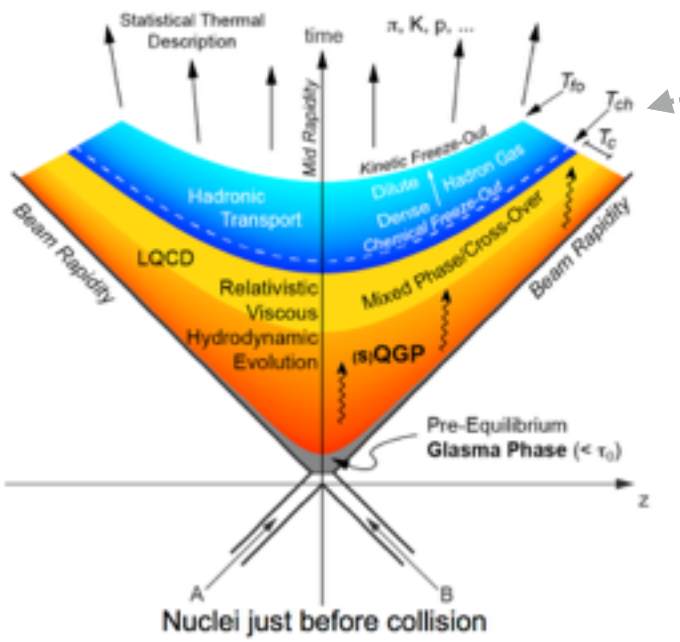

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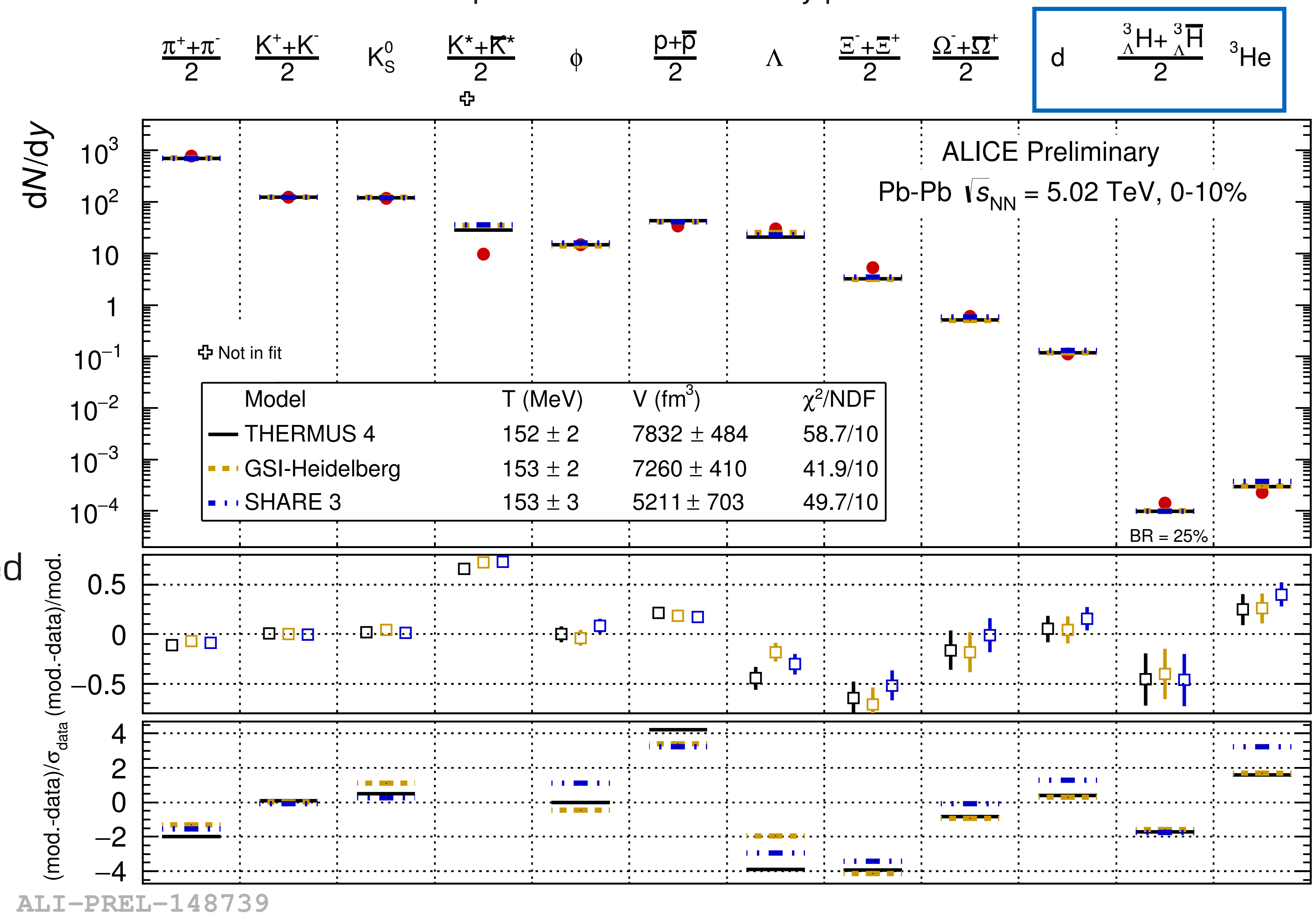

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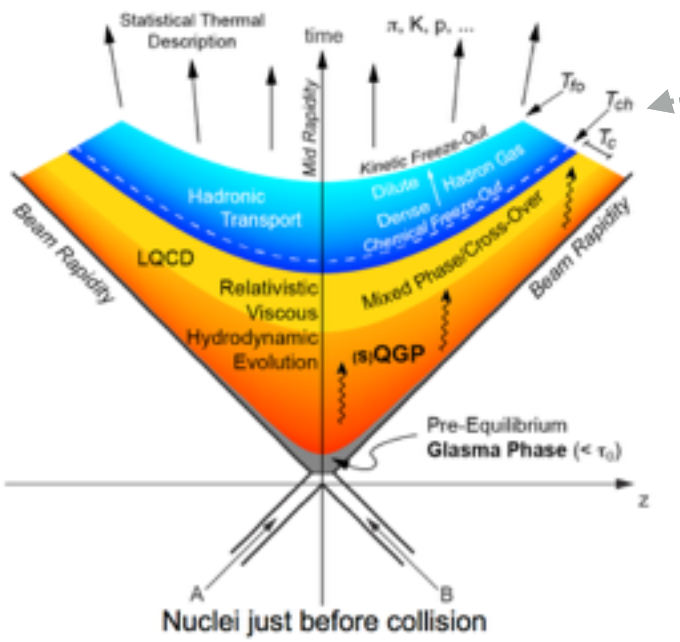

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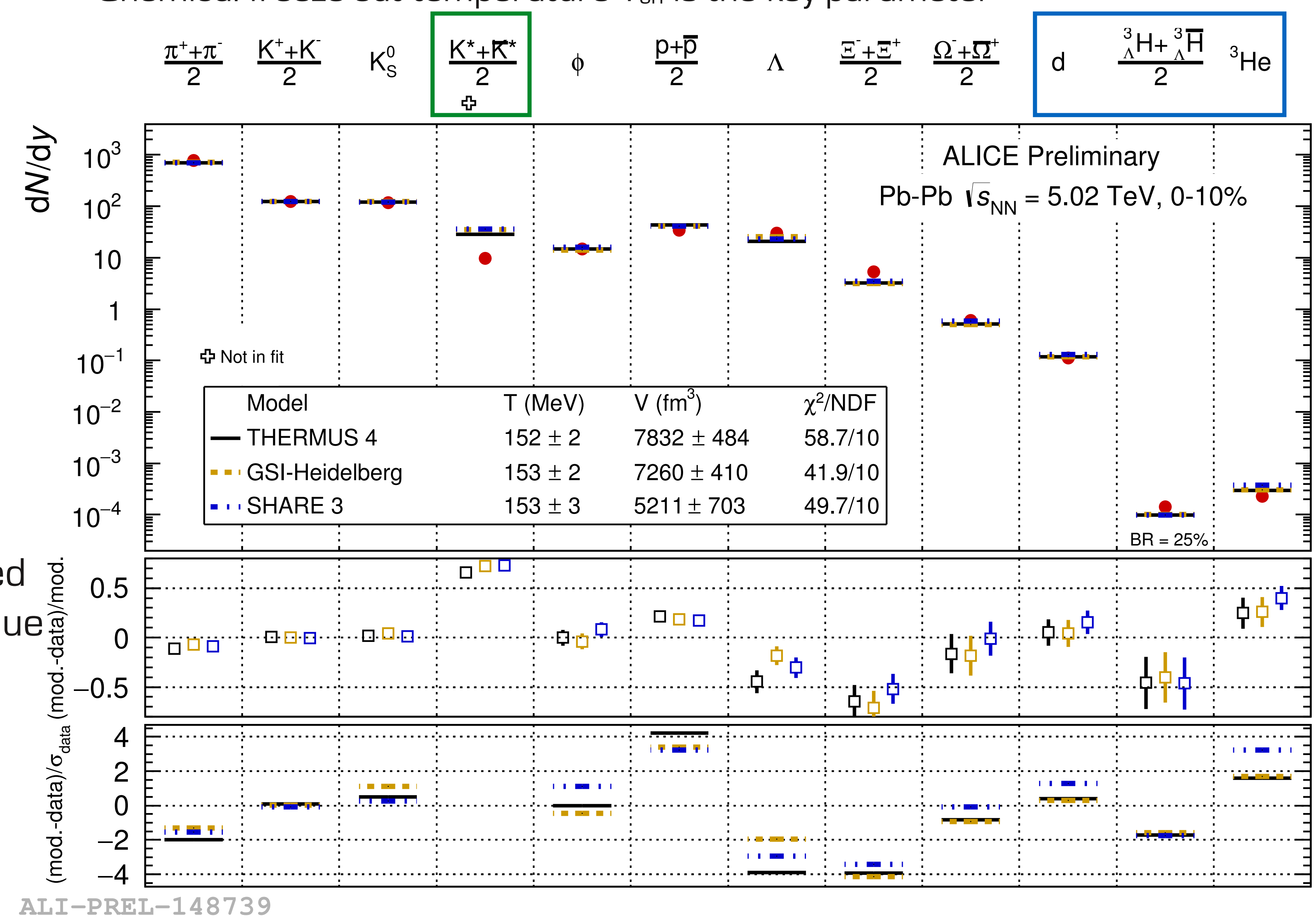

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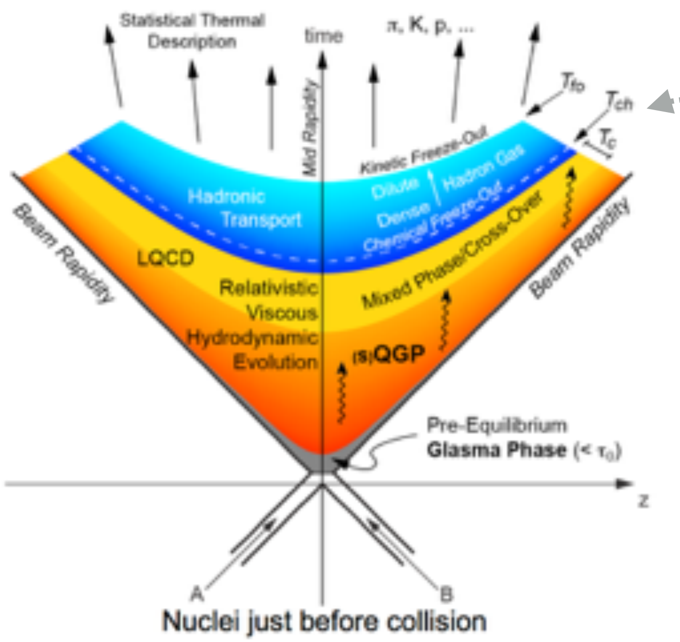

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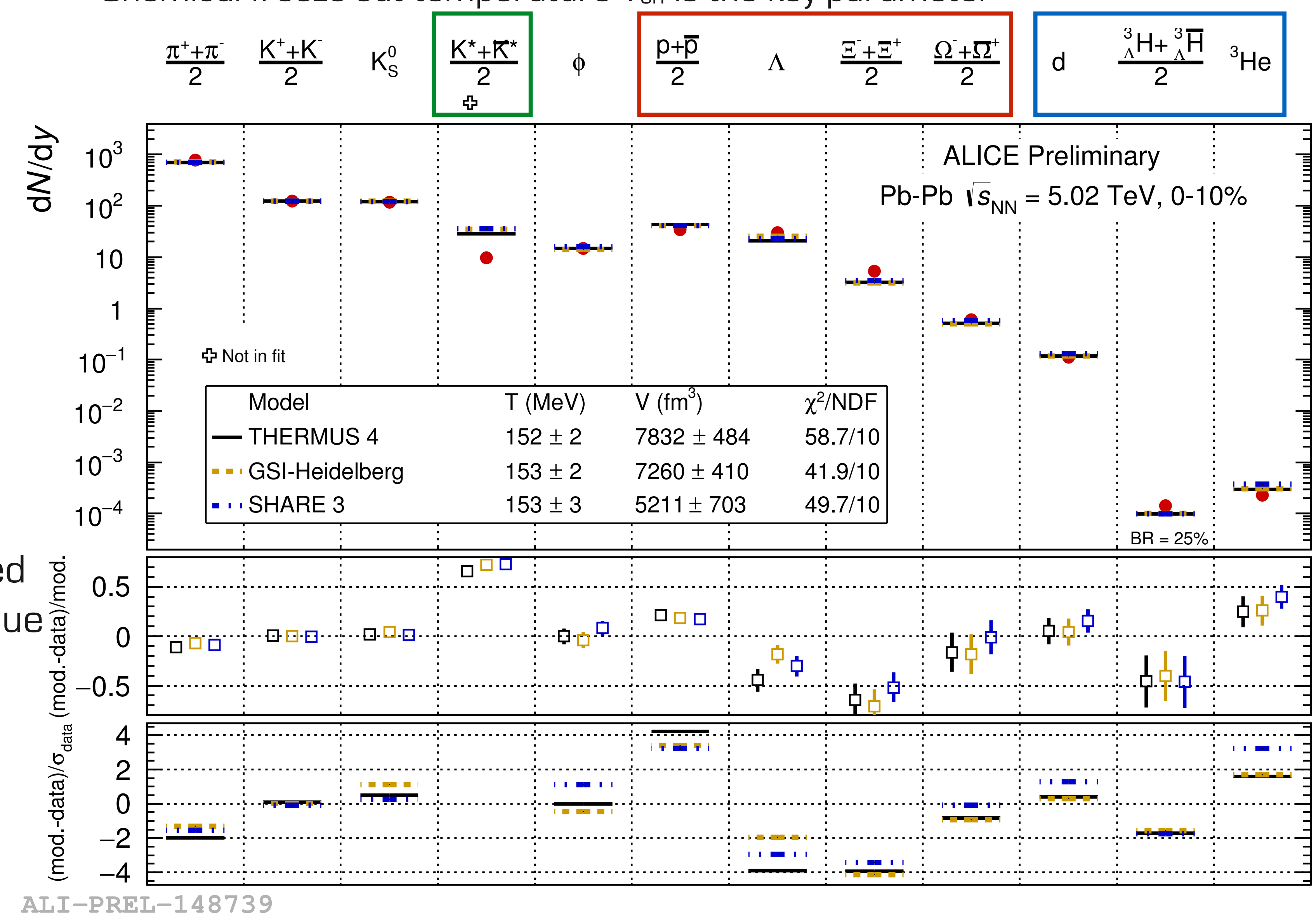

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» Tension for **protons** and **(multi)strange** baryons

- Additional effects needed?
  Baryon annihilation
  Interacting hadron gas
  Incomplete hadron spectrum

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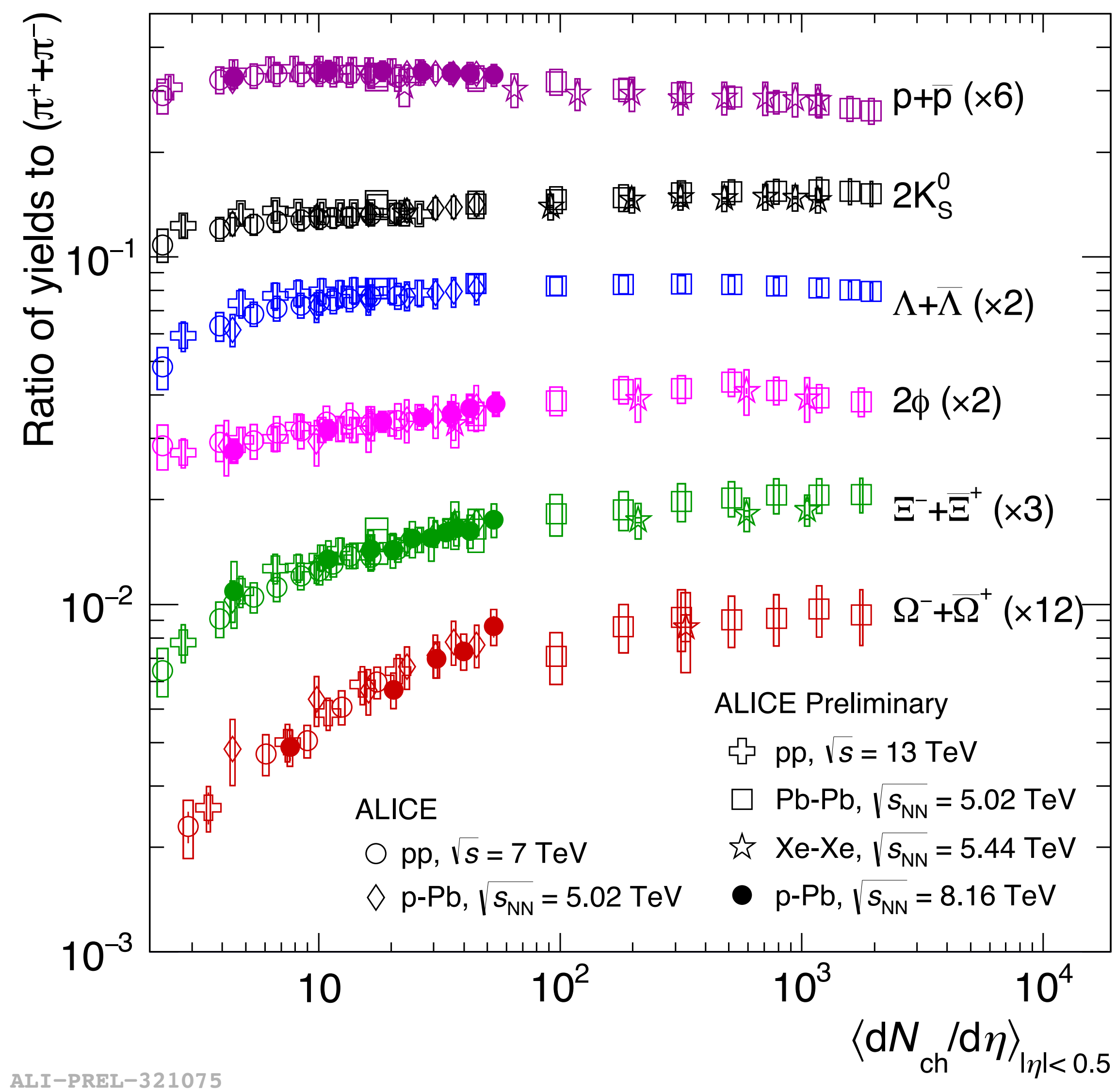
  - ✓ No energy dependence
  - ✓ Hadron chemistry is driven by the multiplicity



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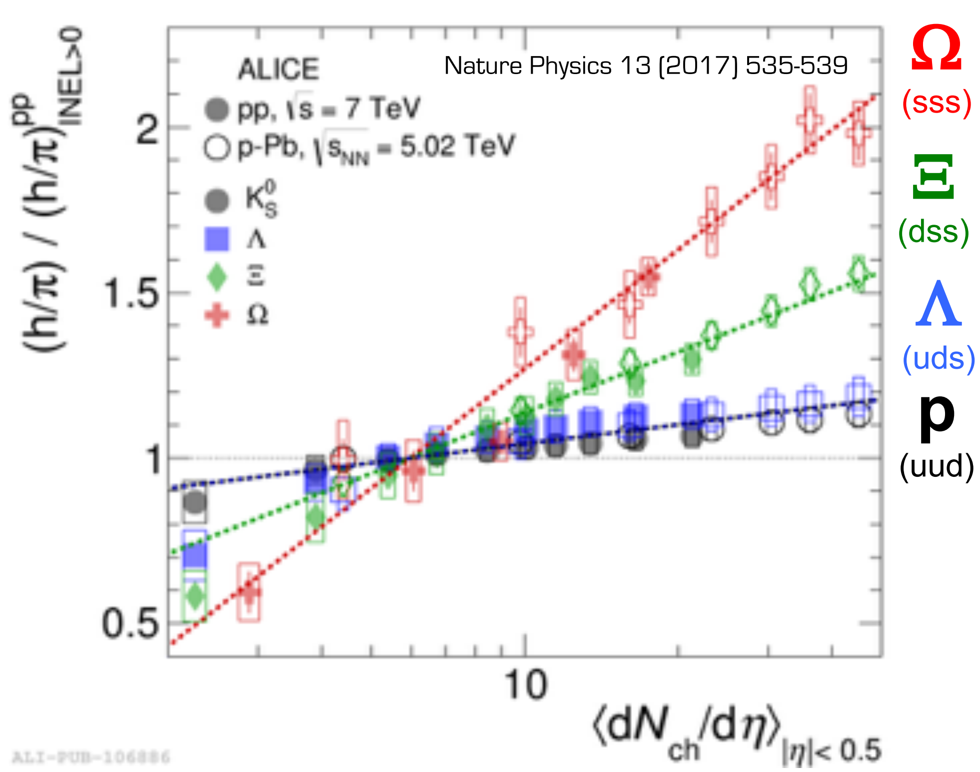
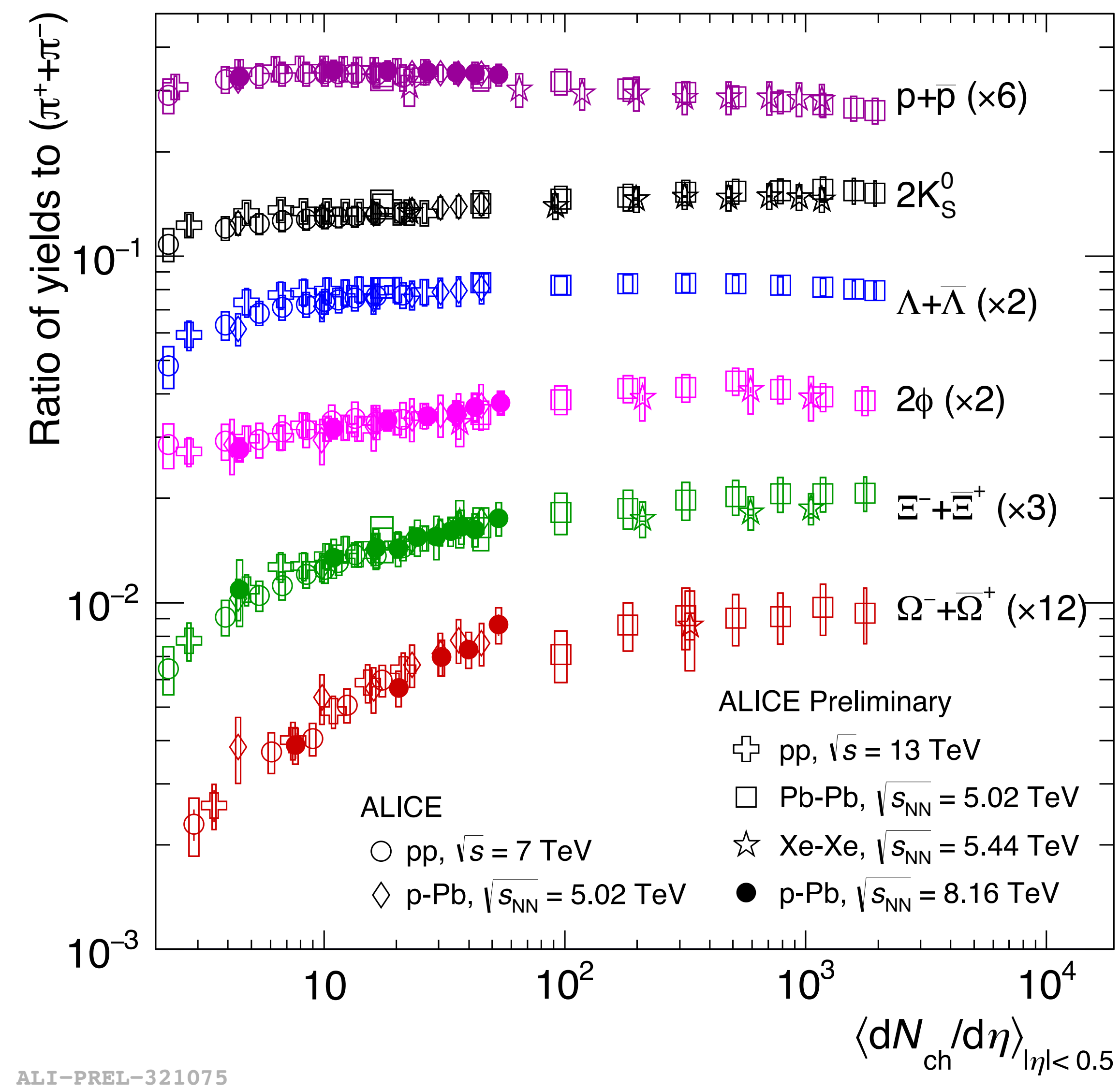
» Strangeness enhancement
- ✓ Increase of strange-particle production also present for small-systems
- ✓ Saturation around thermal-model values for large systems
- ✓ Magnitude of strangeness enhancement increases with strange-quark content





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② Strangeness enhancement and ϕ production

ALICE

» The ϕ meson ($s\bar{s}$) has hidden strangeness and is a key probe in studying strangeness production

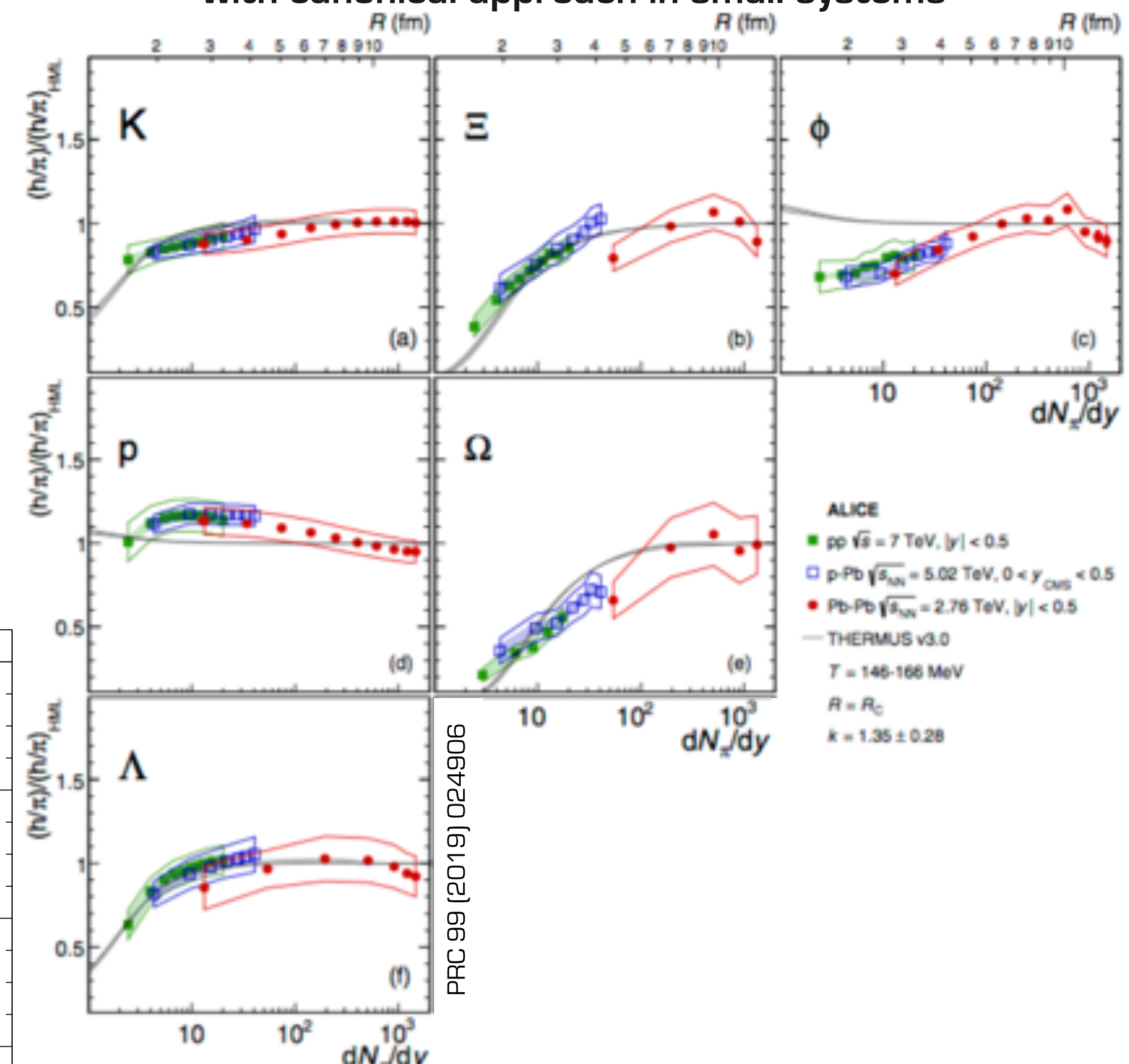
» In the SHM:

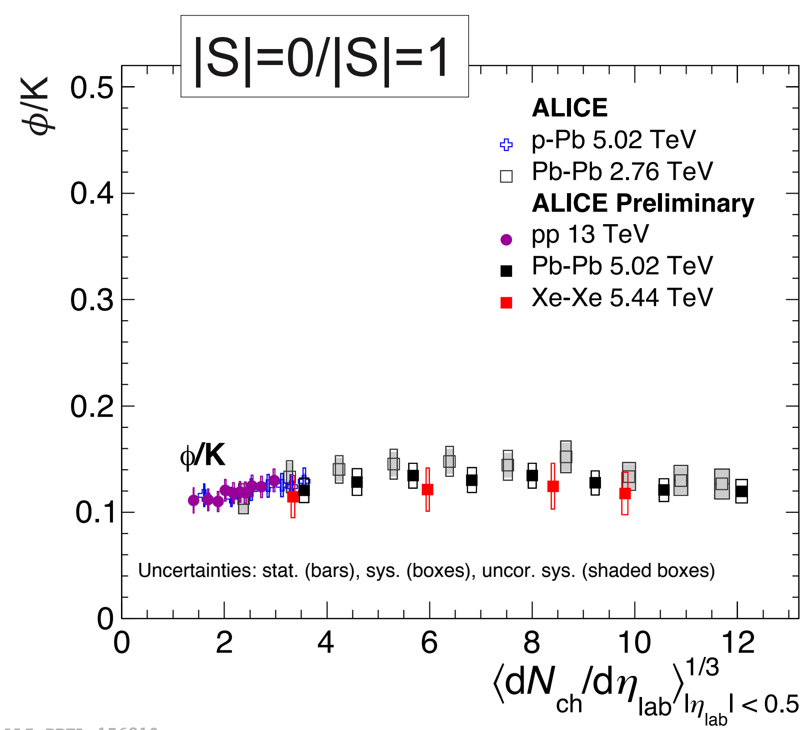
- ✓ Large systems: all particles well described
- ✓ Small systems: all particles but ϕ well fitted in a “canonical suppression” picture
  - Favours non-equilibrium production (γ_s) production of ϕ or all strange particles

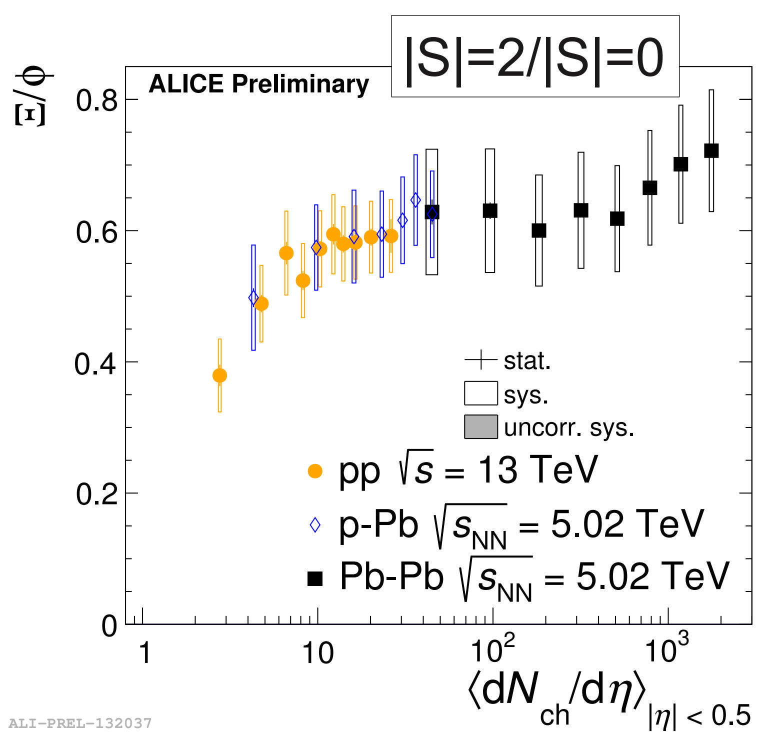
» Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range

- ✓ The ϕ has “effective strangeness” of 1−2 units

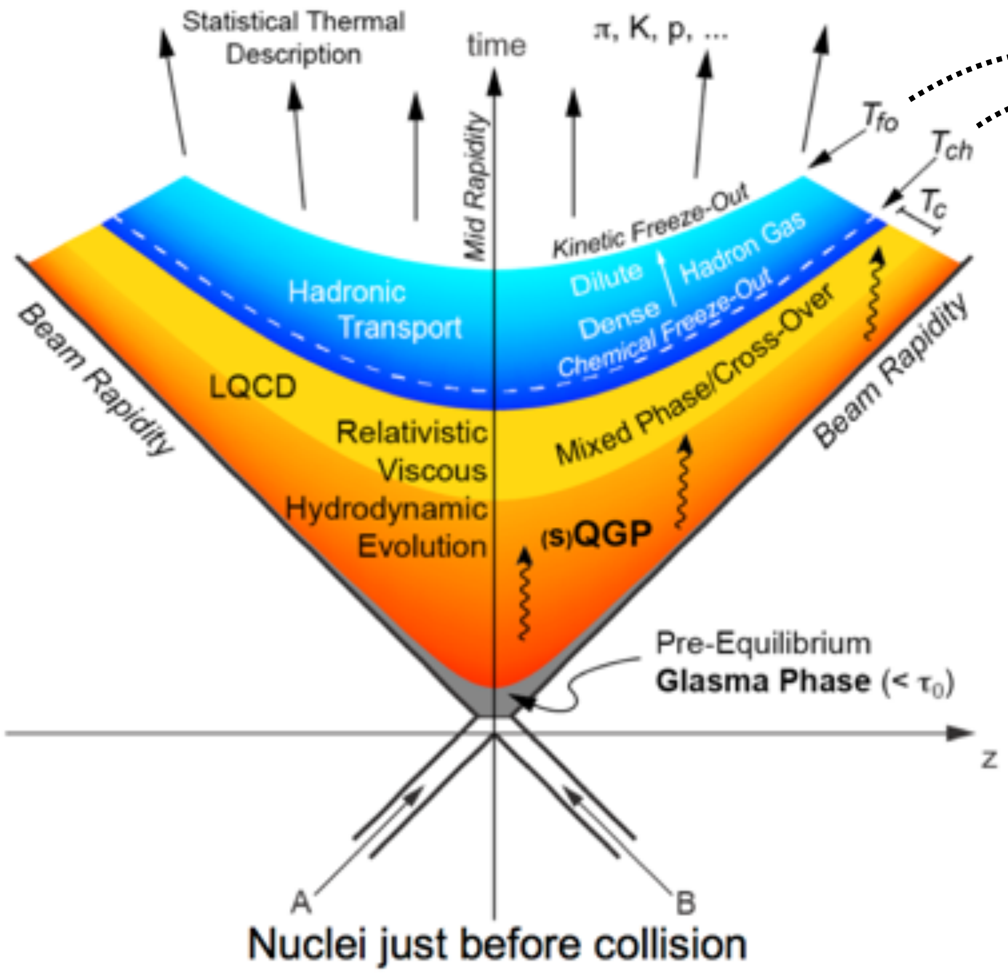
Statistical Hadronization Model with canonical approach in small systems

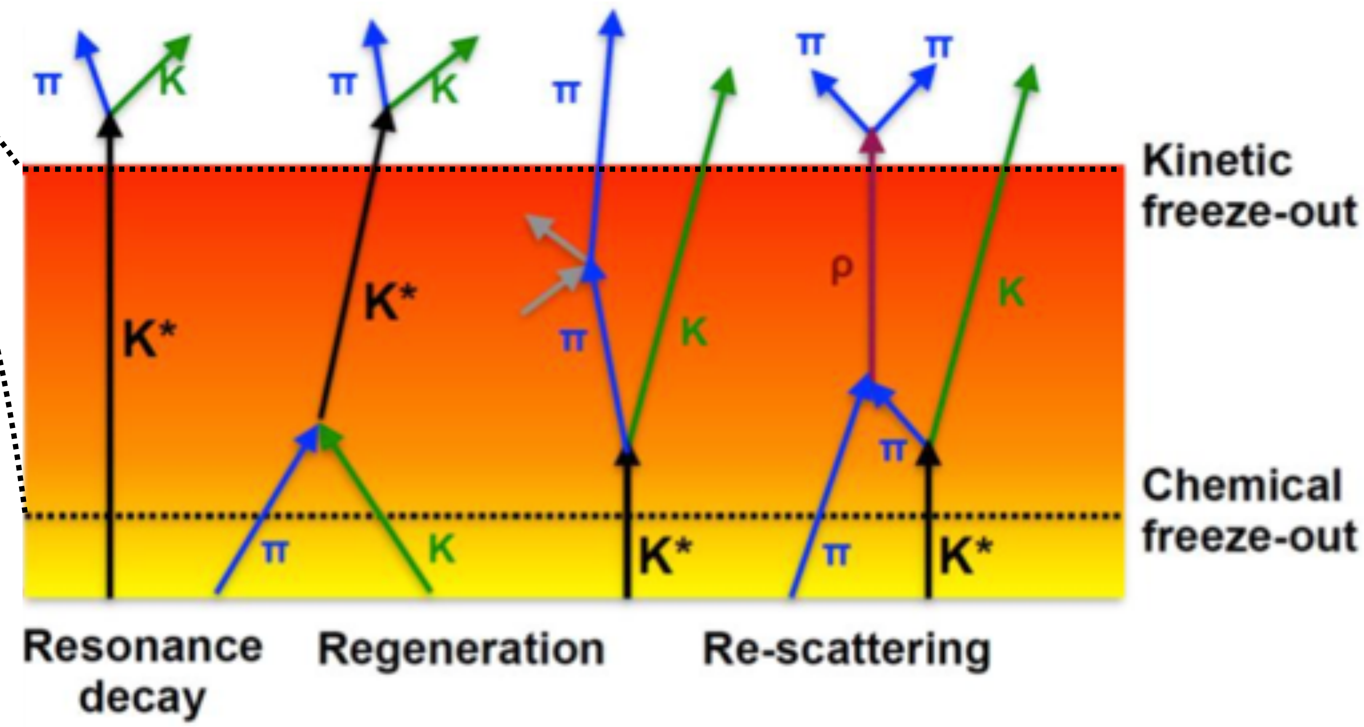






③ Resonances suppression





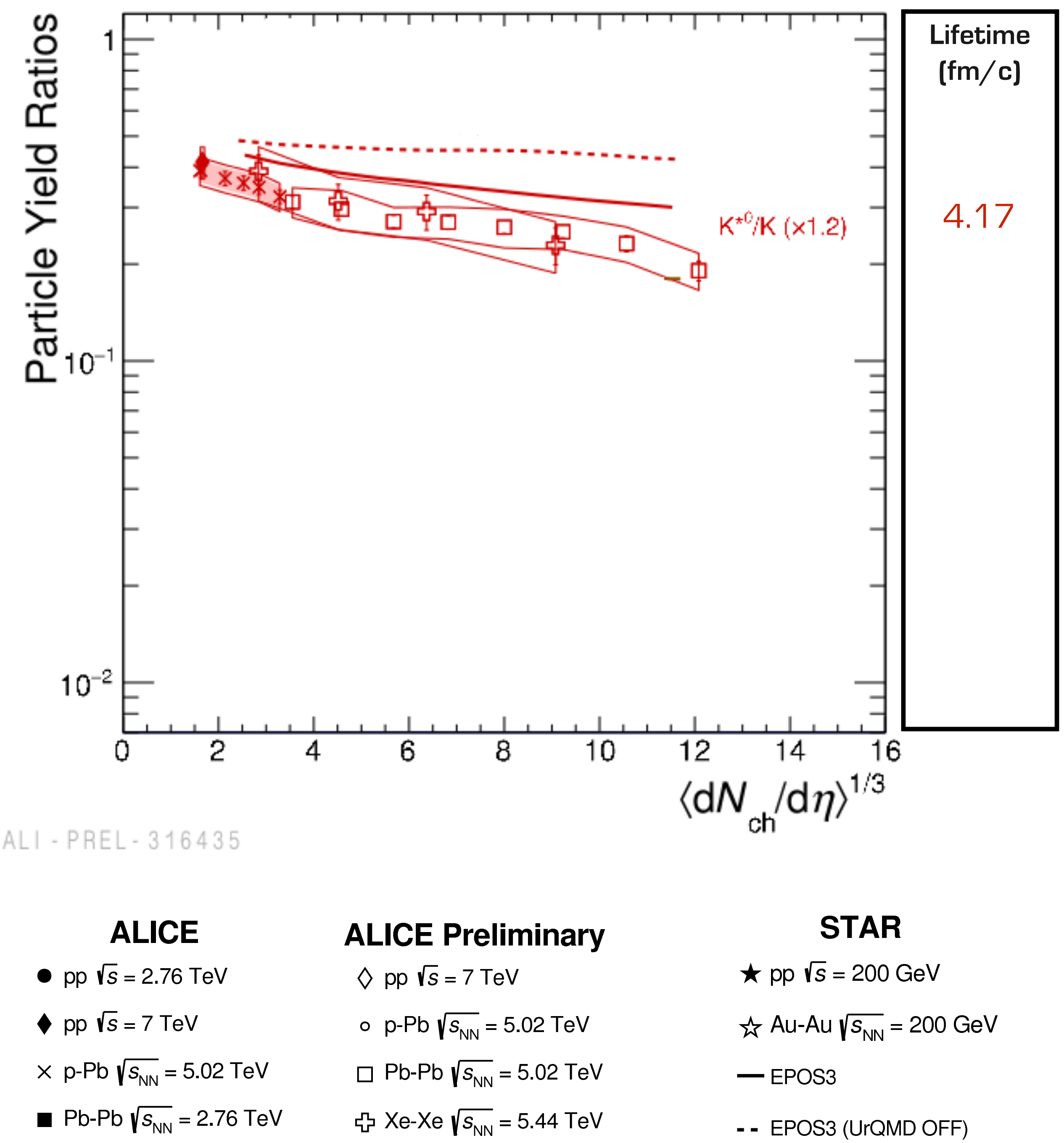
» Resonances are powerful tools to probe the hadronic phase after chemical freeze-out

» Final resonance yields depend on:

- ✓ Chemical freeze-out temperature
- ✓ Lifetime of hadronic phase
- ✓ Resonance lifetimes
- ✓ Scattering cross-section of decay products

③ Resonances suppression

» Suppression of K^{0*} in high multiplicity events
- ✓ K^{0*}/K reduction from low to high multiplicity
- ✓ Central Pb-Pb values below thermal model prediction
- ✓ Re-scattering of decay products in hadronic medium
- ✓ Hint of K^{0*} suppression in high-multiplicity pp and p-Pb



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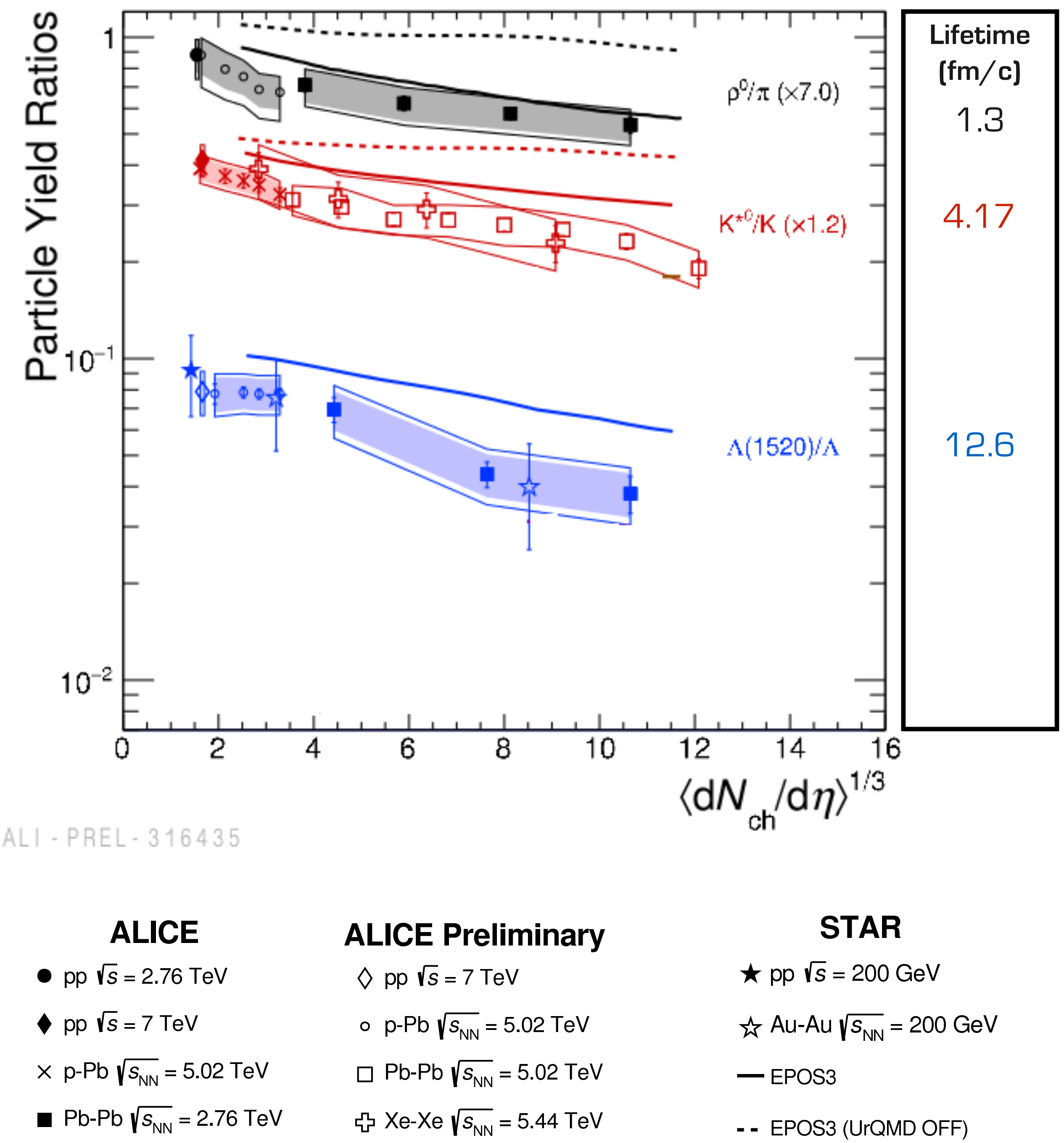
» Similar suppression of ρ^0 and $\Lambda(1520)$



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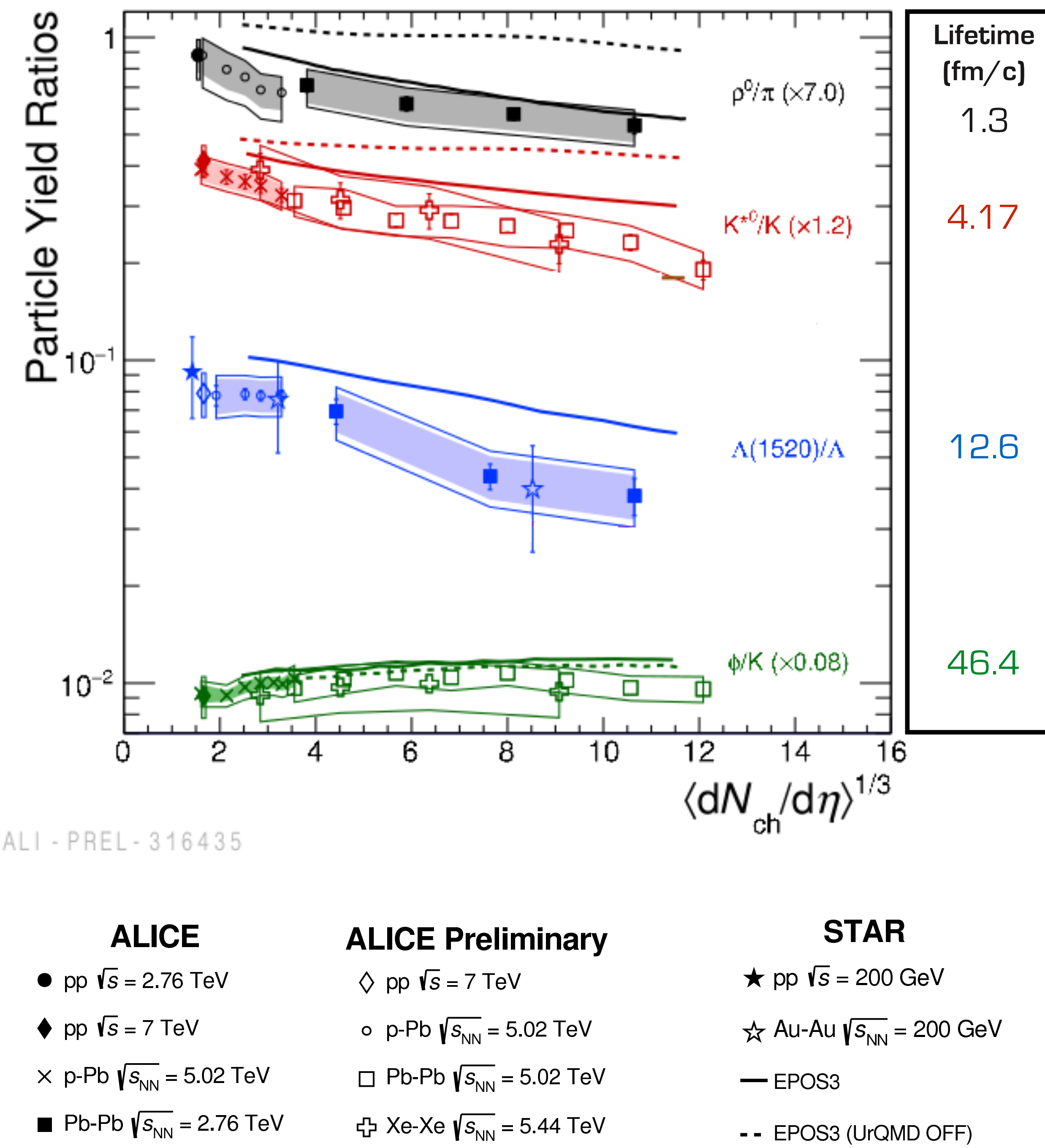

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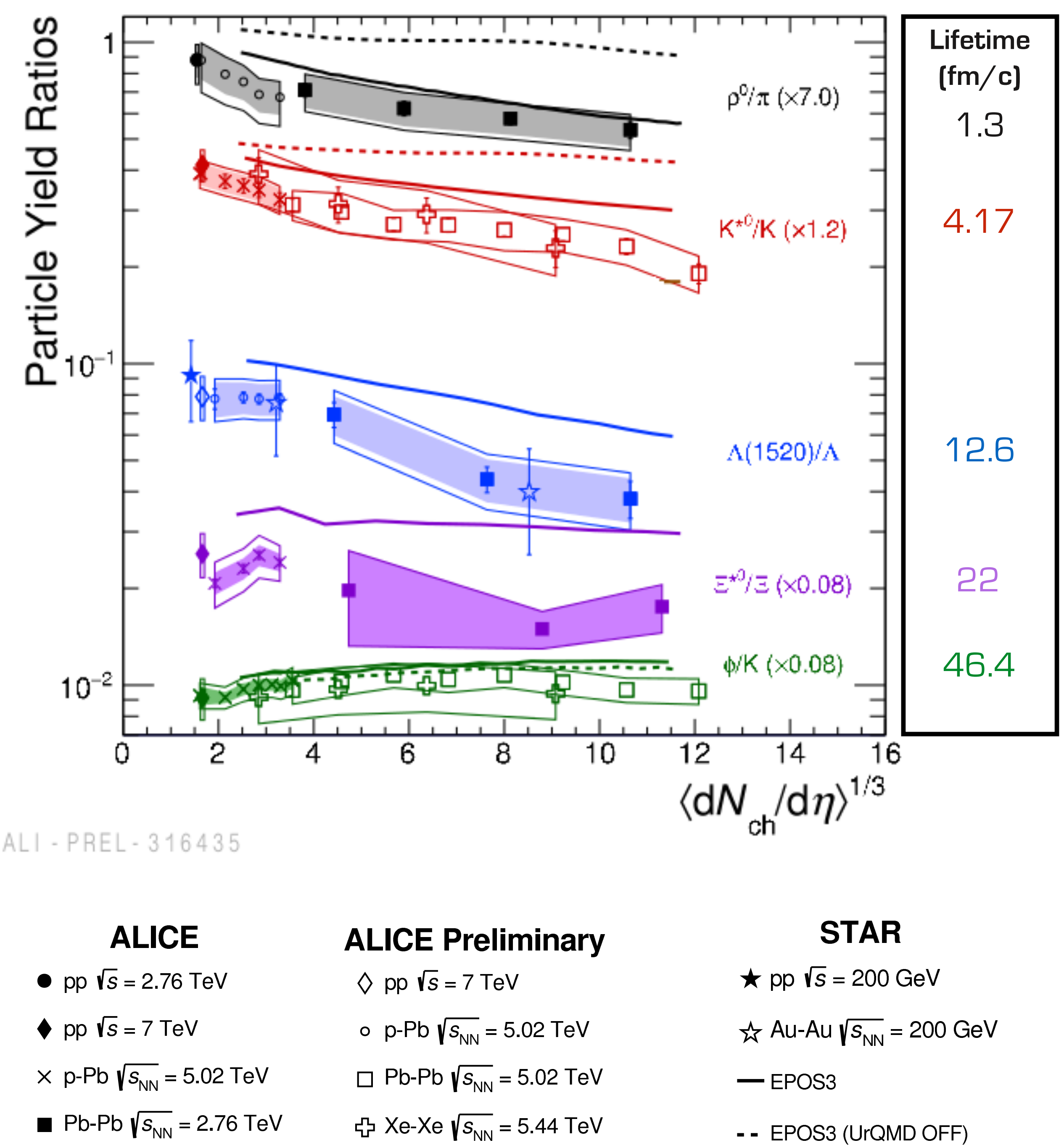

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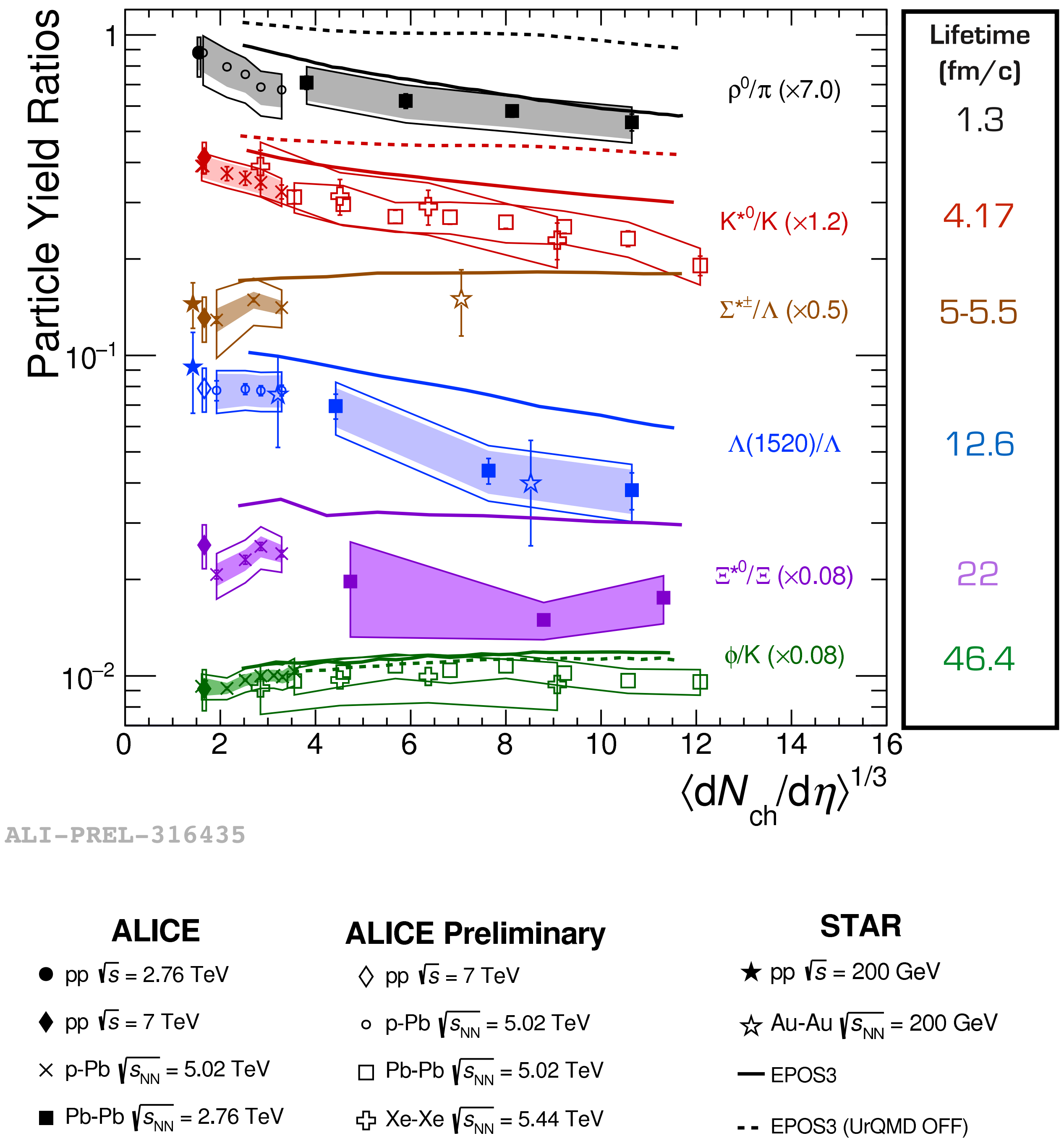

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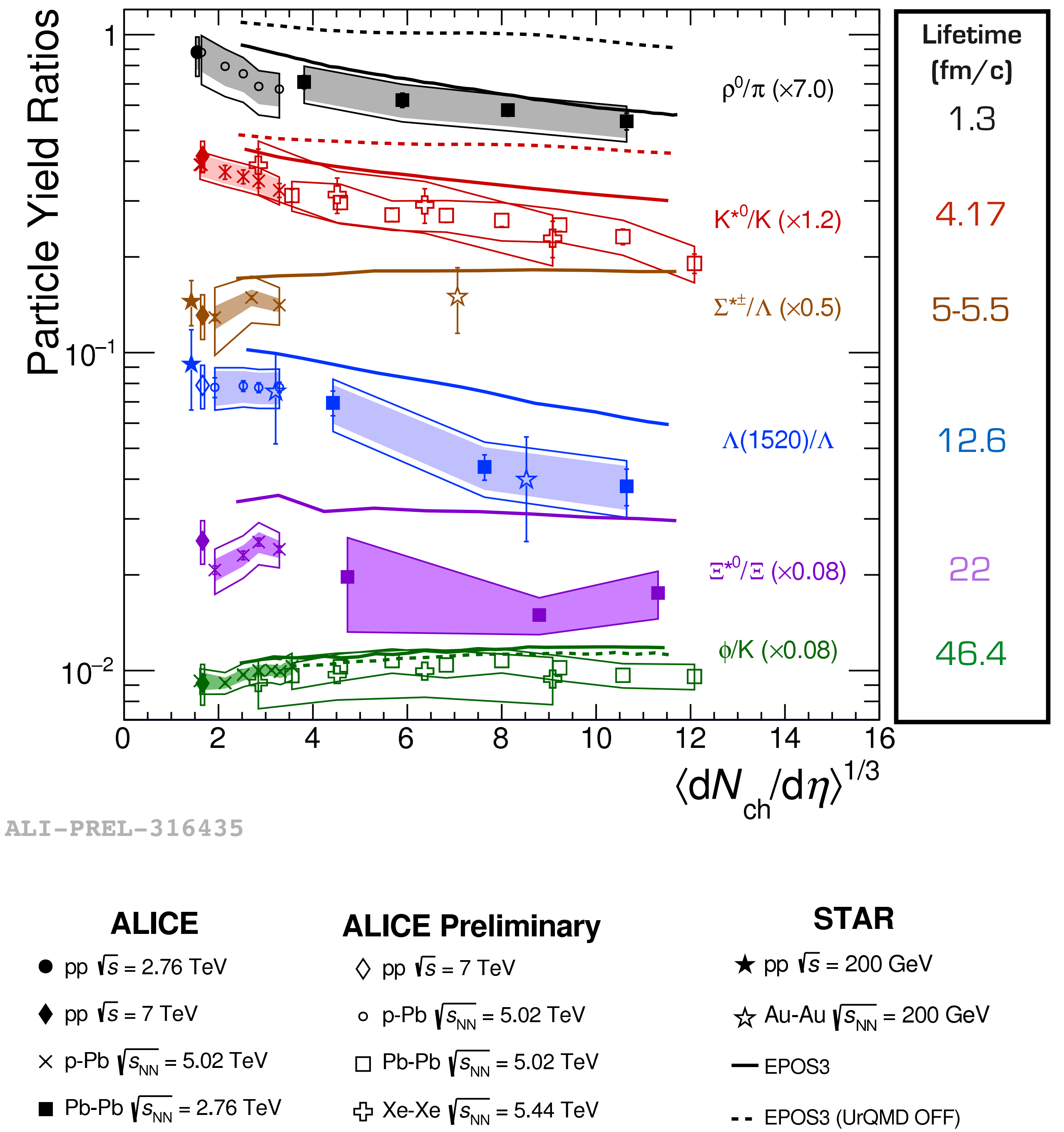
» Ratios do not depend on energy (RHIC → LHC) or collision system (same for p-Pb and Xe-Xe)



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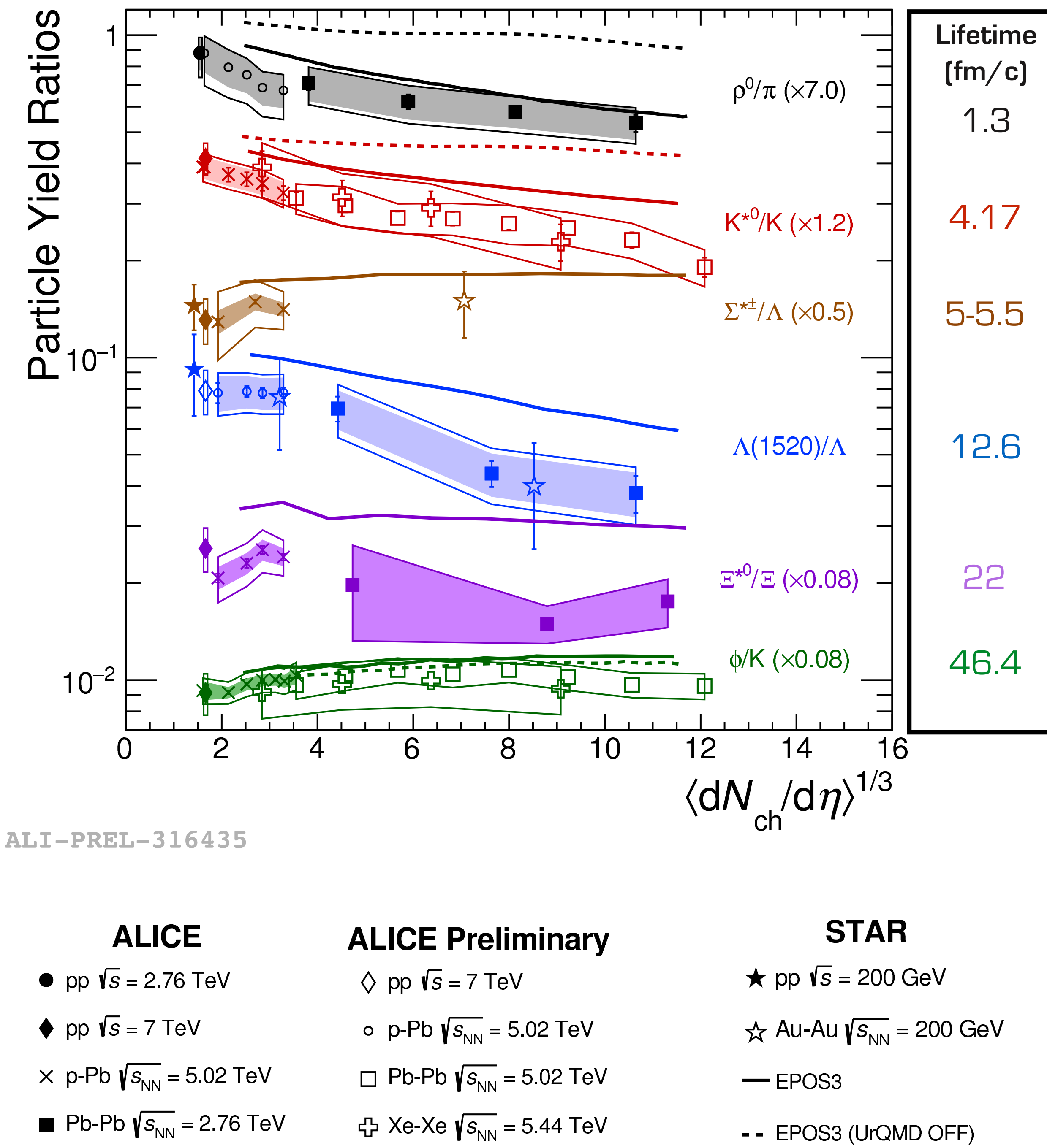
» Possible weak suppression of Ξ^{*0} w.r.t. pp collisions

» No measurement of $\Sigma^{*\pm}/\Lambda$ in Pb-Pb yet, but STAR point

» Ratios do not depend on energy (RHIC → LHC) or collision system (same for p-Pb and Xe-Xe)

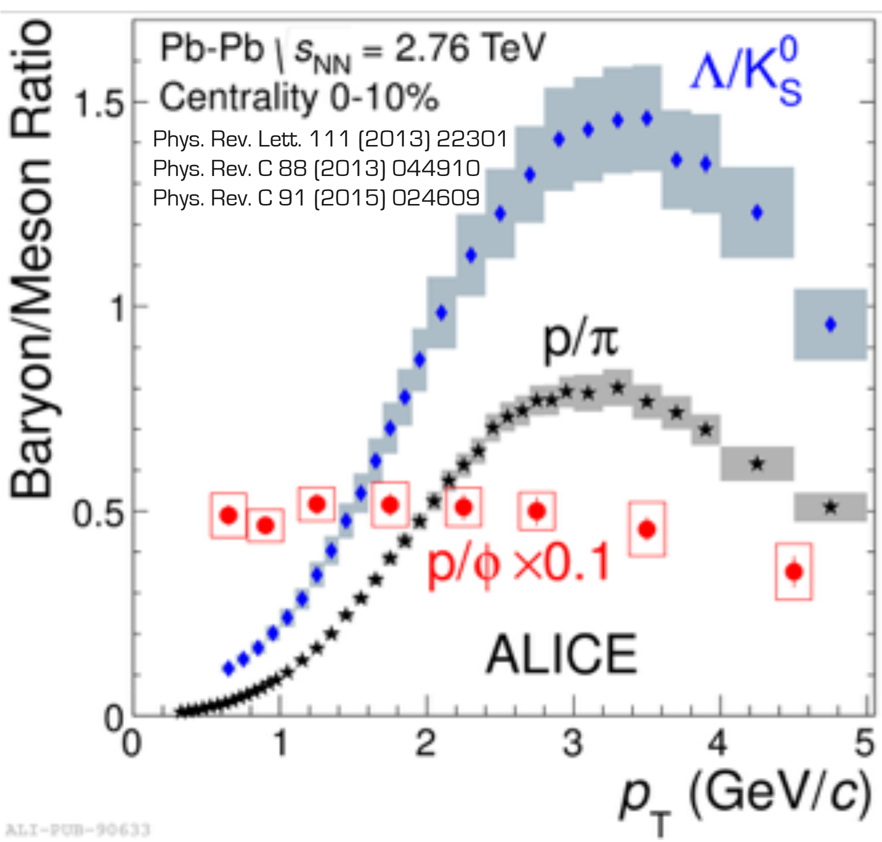
» Trends qualitatively described by EPOS
- ✓ Includes scattering effects modelled with UrQMD



Eur. Phys. J. C (2012) 72:2183
Eur. Phys. J. C (2015) 75:1
Eur. Phys. J. C (2016) 76:245
Eur. Phys. J. C (2017) 77:389
Physical Review C 91, 024609 (2015)
Physical Review C 95, 064606 (2017)
Physical Review C 99, 024905 (2019)
Physical Review C 93, 014911 (2016)

④ Baryon-To-Meson ratio

» Allow us to study the interplay of hydrodynamics and recombination
» In central Pb-Pb collisions
  ✓ p/π, Λ/K^0 enhancement at intermediate p_T



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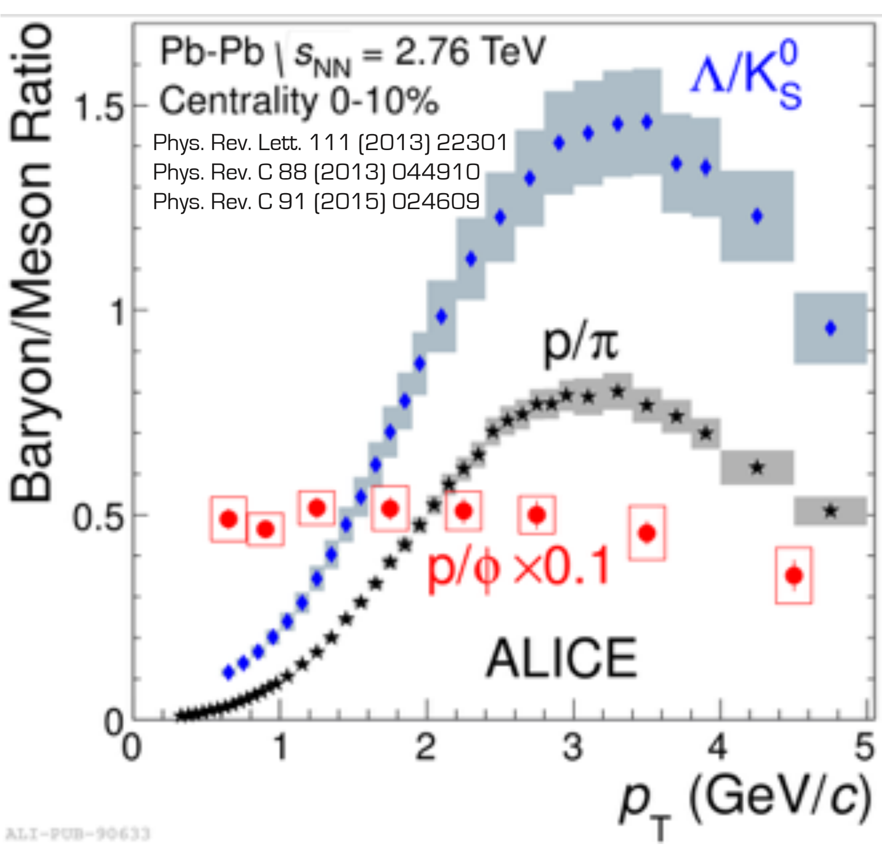

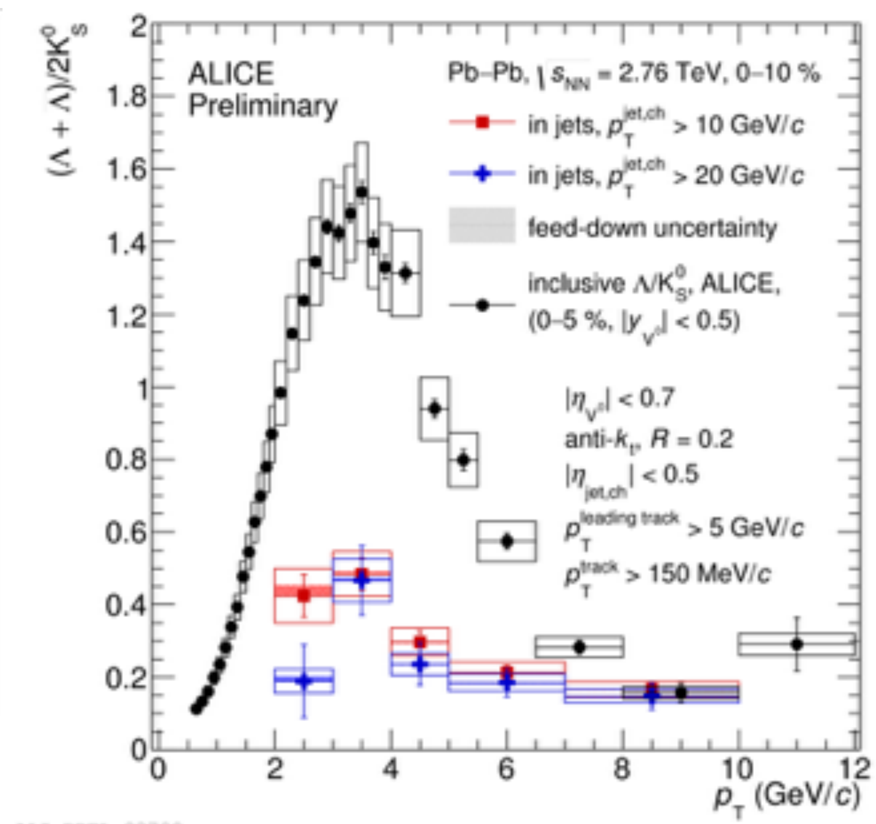

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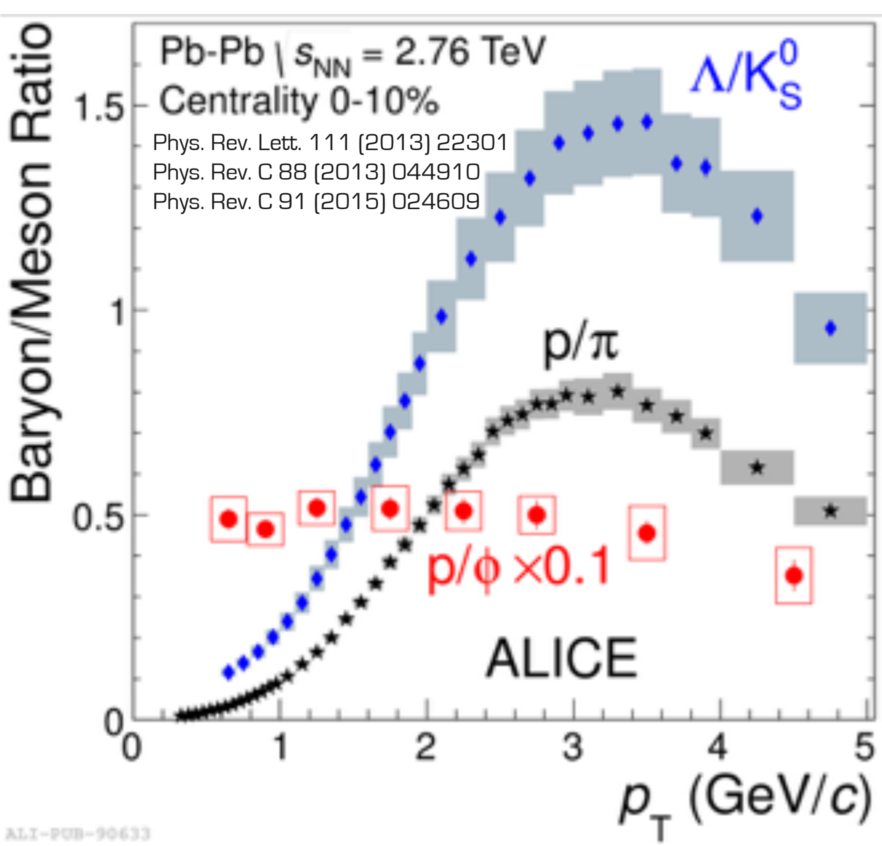
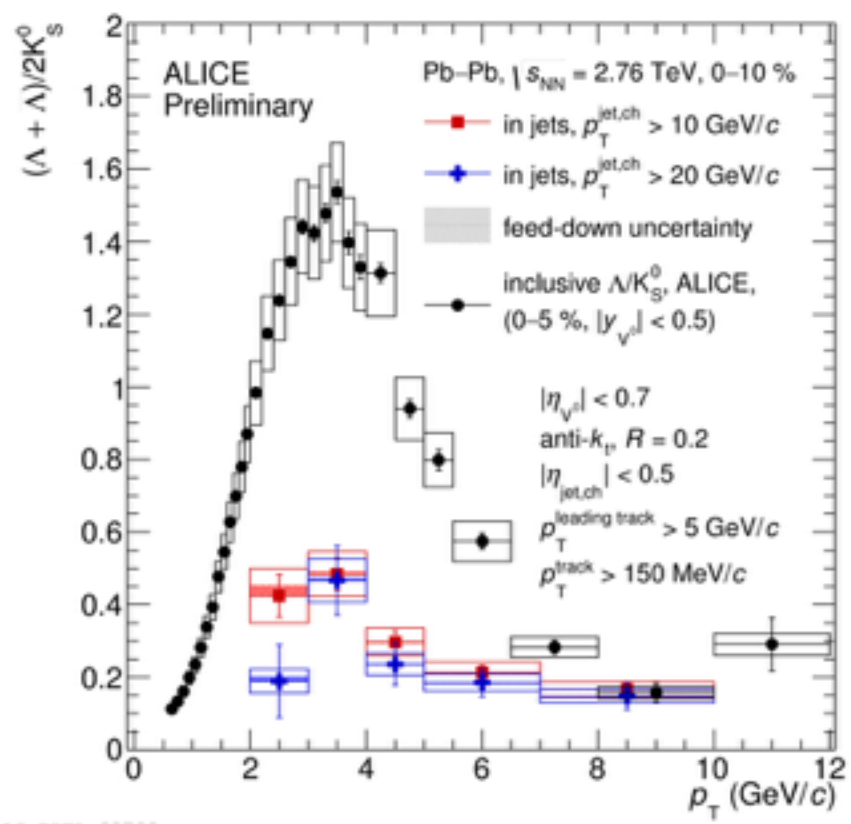
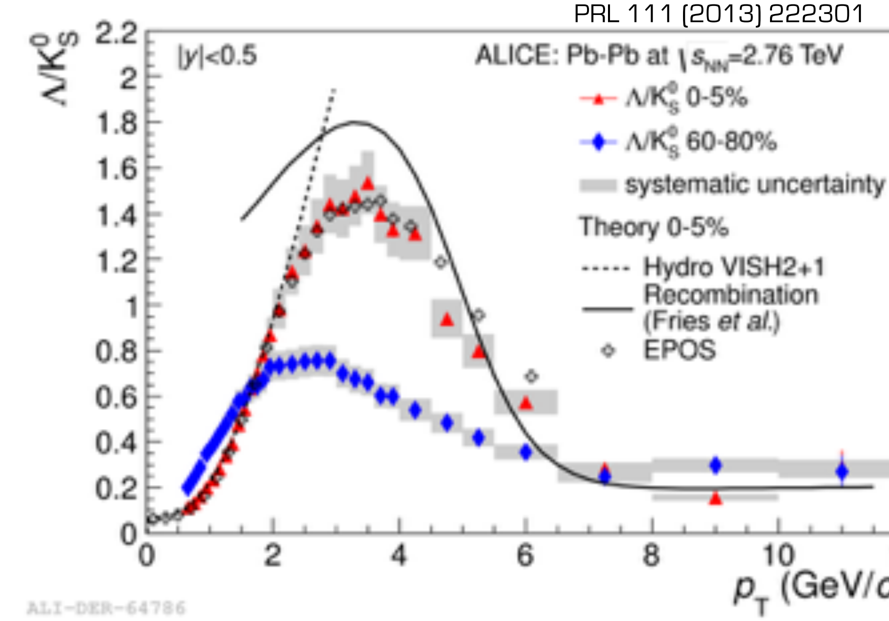
» In central Pb-Pb collisions
- ✓ p/π, Λ/K^0 enhancement at intermediate p_T
- ✓ Effect arising in the bulk and not from jets
- ✓ Models → Effect consistent with a flow boost pushing particles from low to high p_T
  - Hydro describes only the rise < 2 GeV/c
  - Recombination reproduces the effect at intermediate p_T but overestimates towards lower p_T
  - EPOS (with flow) gives good description





PRL 111 (2013) 222301



Song, Phys. Lett. B 658 (2008) 279
Fries et al., Ann. Rev. Nucl. Part. Sci. 58 (2008) 177
Werner, Phys. Rev. Lett. 109 (2012) 102301

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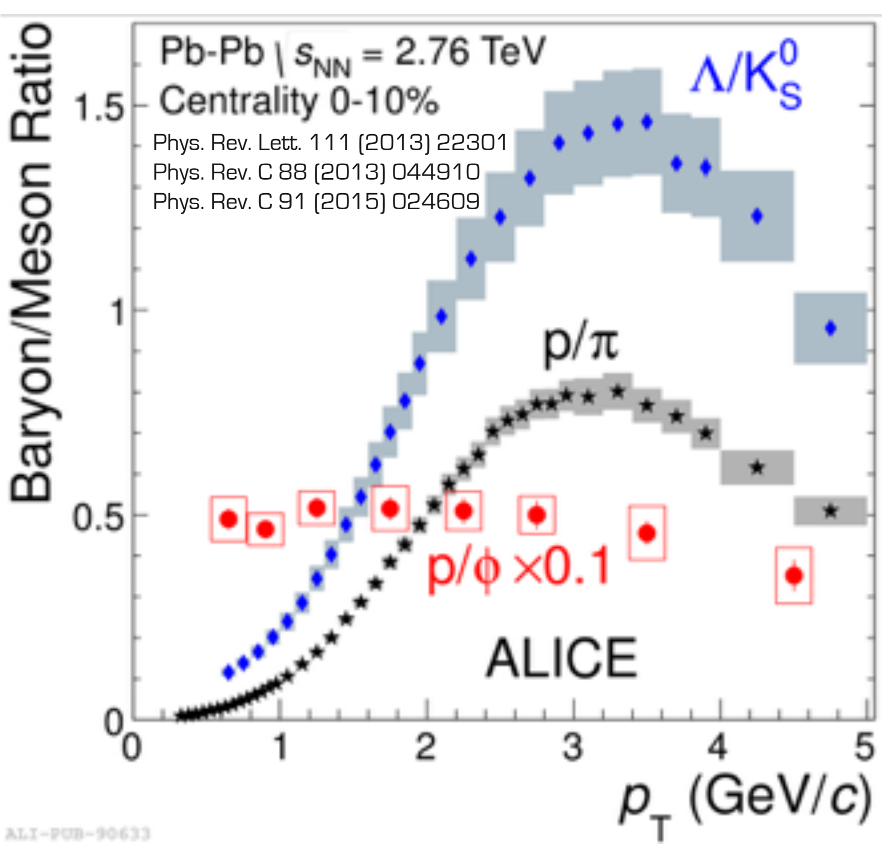
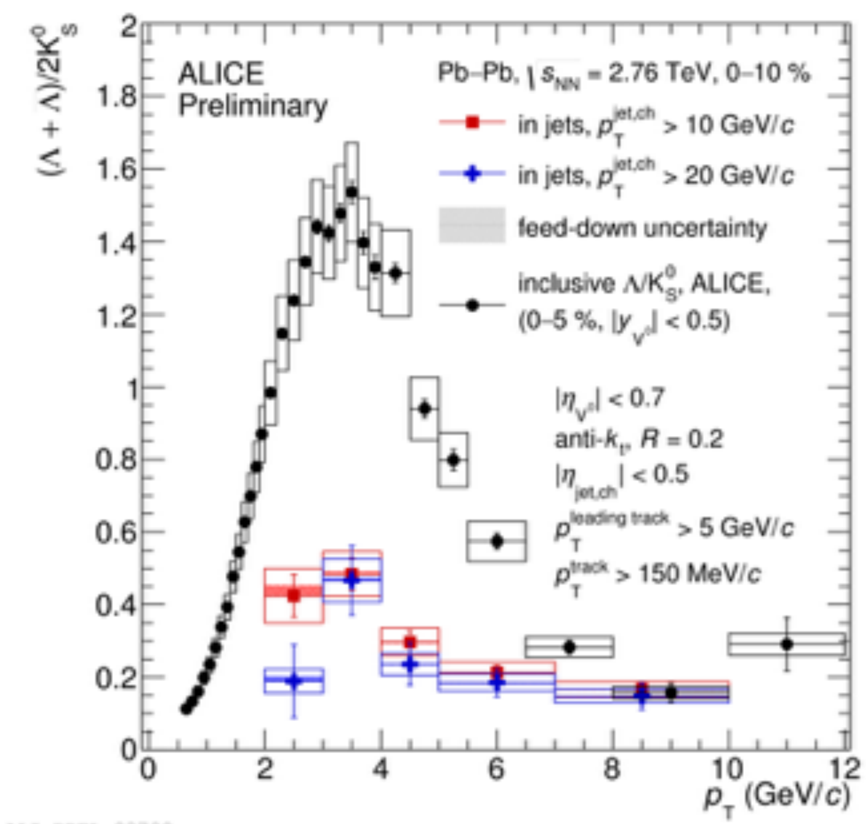
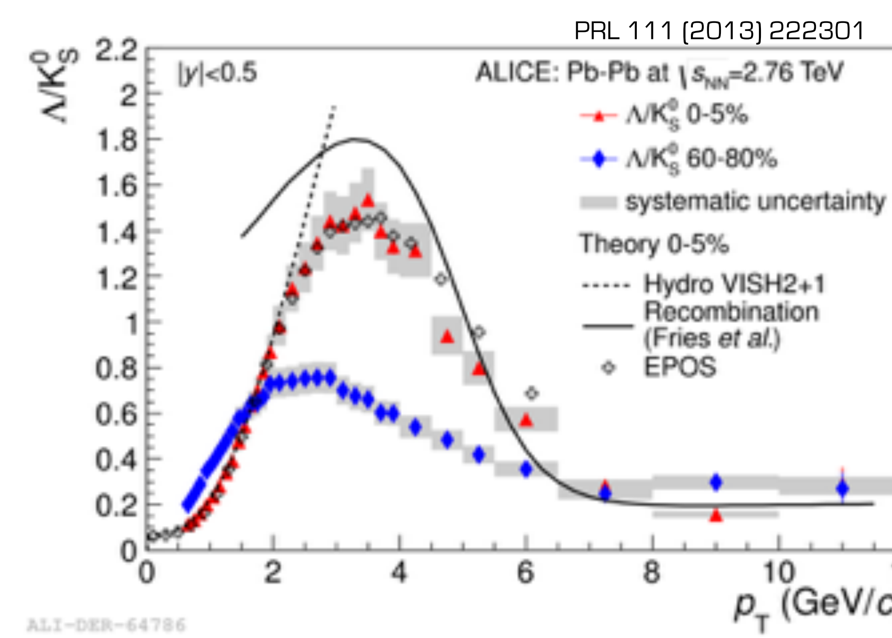
  - Hydro describes only the rise < 2 GeV/c
  - Recombination reproduces the effect at intermediate p_T but overestimates towards lower p_T
  - EPOS (with flow) gives good description
- ✓ p/ϕ independent of p_T → Similar mass drives similar spectral shape
  - Can be explained by models with recombination (Phys. Rev. C 92 (2015) 054904)







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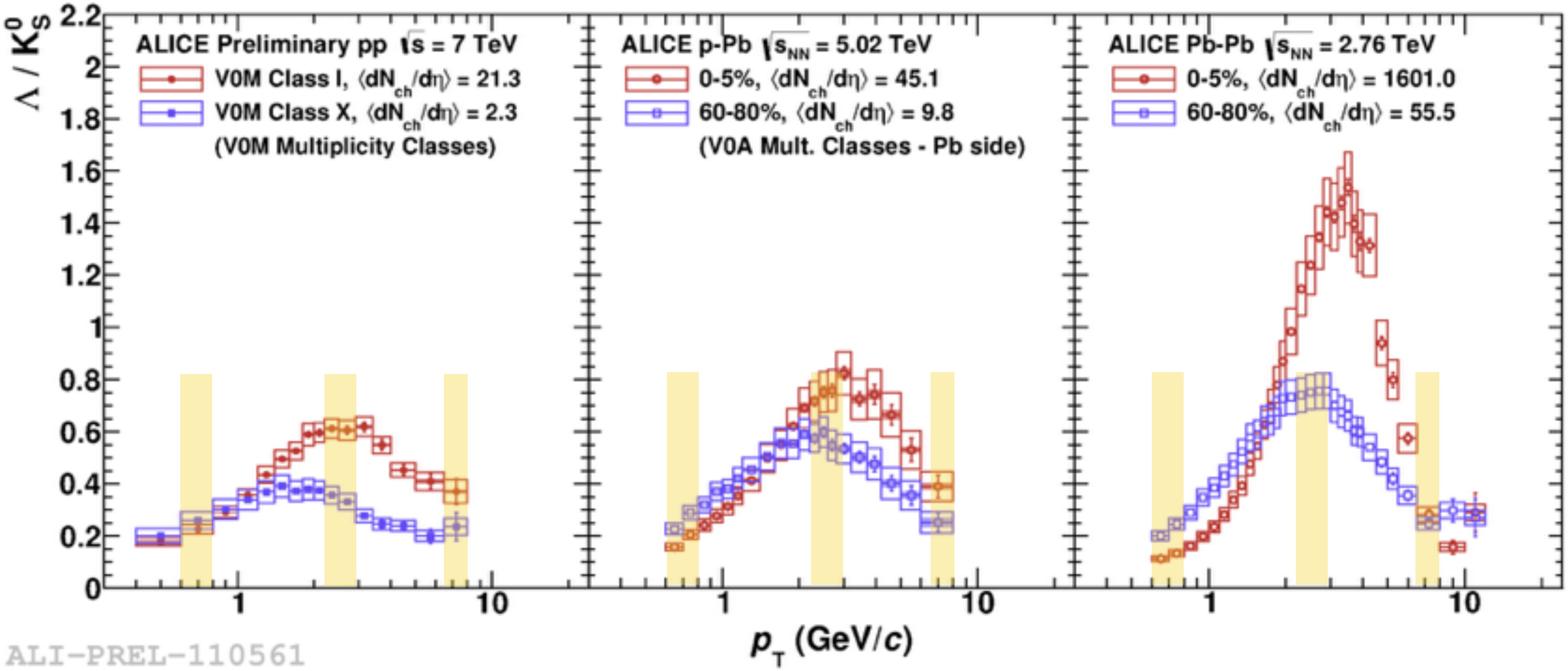

» Across the three systems Λ / K^0 evolves

✓ with multiplicity in qualitative way: depletion at low p_T and enhancement at intermediate p_T

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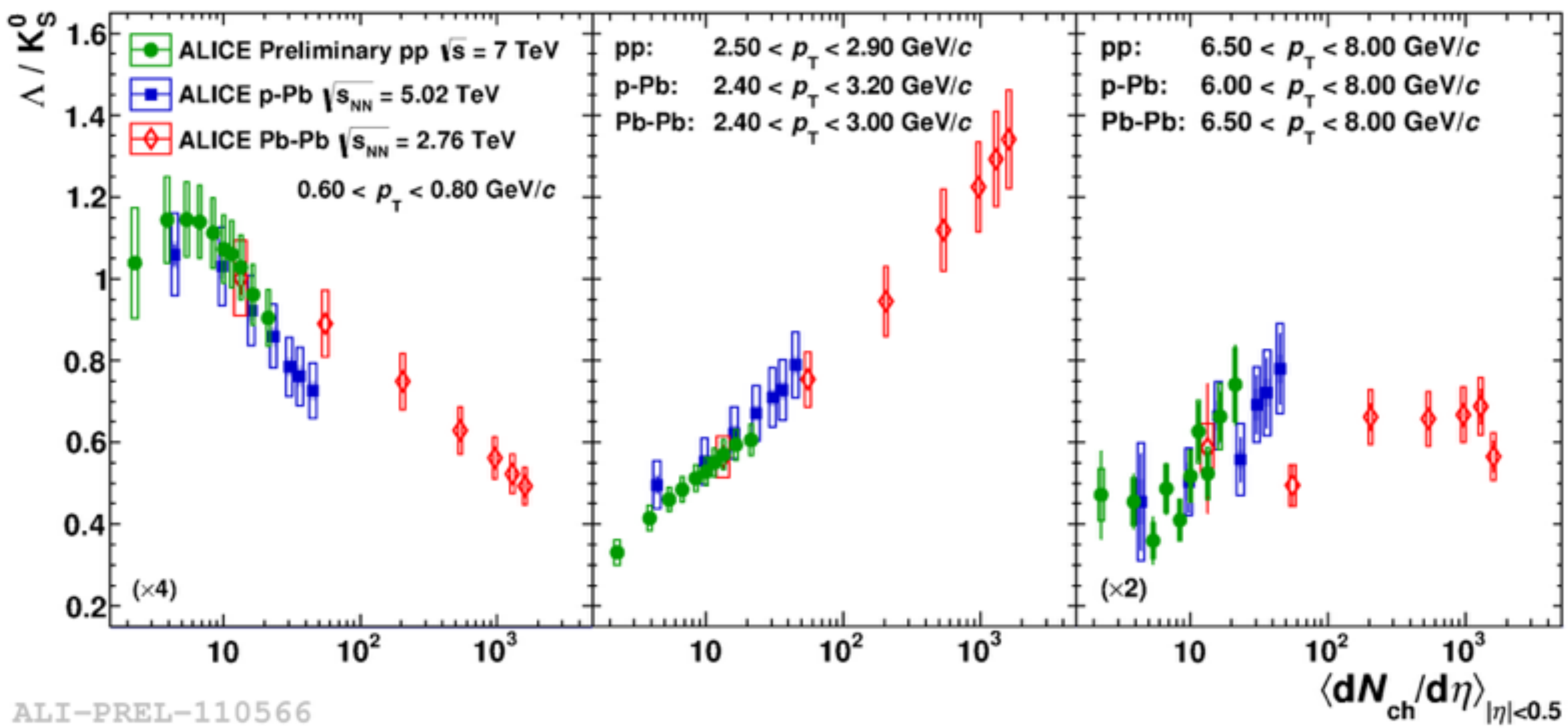


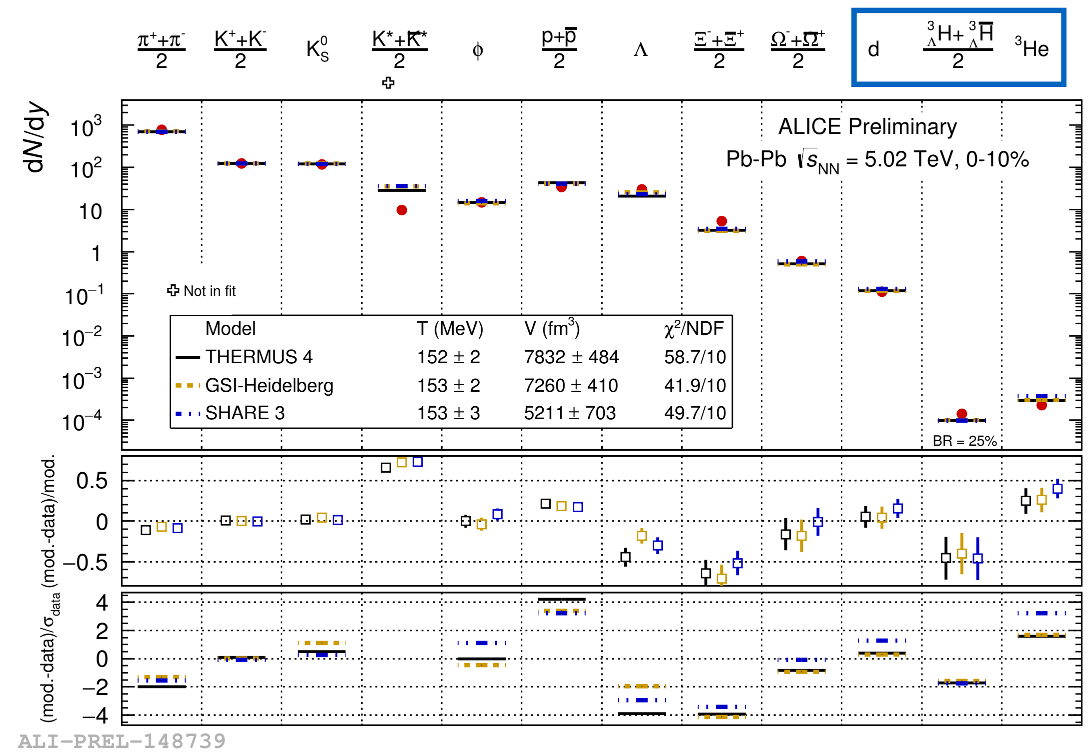
» Across the three systems Λ / K^0 evolves

- ✓ with multiplicity in qualitative way: depletion at low p_T and enhancement at intermediate p_T
- ✓ rather smoothly for given p_T intervals

Points toward one common driving mechanism in all systems

⑤ Light nuclei production

» Light (anti-)nuclei significantly produced at the LHC in pp, p-Pb and Pb-Pb collisions
» The production mechanisms in high-energy physics still not completely understood
 ✓ Low binding energy (E_B ~ 1 MeV) w.r.t. the kinetic freeze-out temperature (T_{fo} ~ 100 MeV)



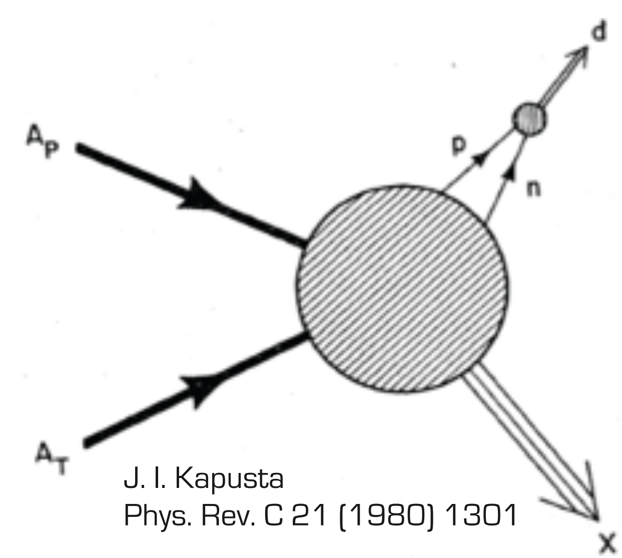
» Two classes of models are available:

✓ The **statistical-thermal model**
- Predicted yield $dN/dy \propto \exp(-m/T_{ch})$ strongly dependent on T_{ch} for nuclei given large m
- Yield well predicted for d, ^{3}He and $^3_\Lambda$H

✓ The **coalescence model**
- Nucleons that are close in phase-space at the freeze-out can form a nucleus via coalescence
- Main parameter is B_A, related to the probability to form a nucleus :

$$B_A = \frac{E_A \frac{d^3N_A}{dp_A^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A}$$

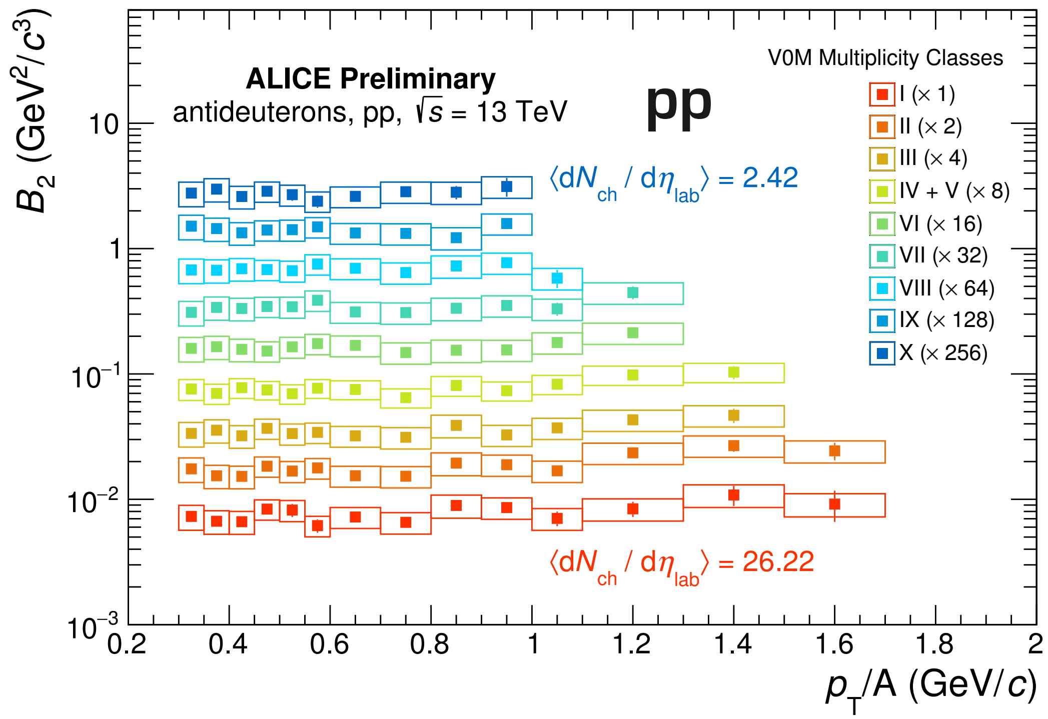
- A is the mass number of the nucleus
- $p_p = p_A/A$



J. I. Kapusta
Phys. Rev. C 21 (1980) 1301

⑤ Light nuclei production

» Simple coalescence → B_A flat in p_T
- ✓ Behaviour in Pb-Pb → NOT described
- ✓ From high to low multiplicity → rise in p_T becomes milder
- ✓ In pp collisions B_2 flat in p_T



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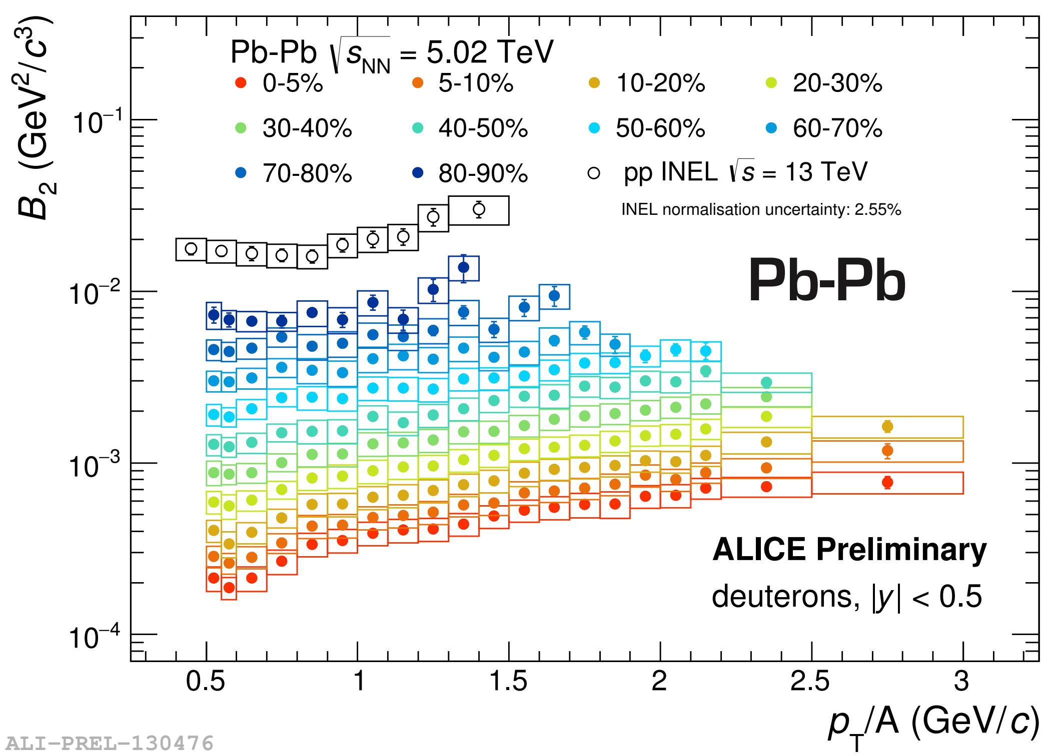

ALI-PREL-130476

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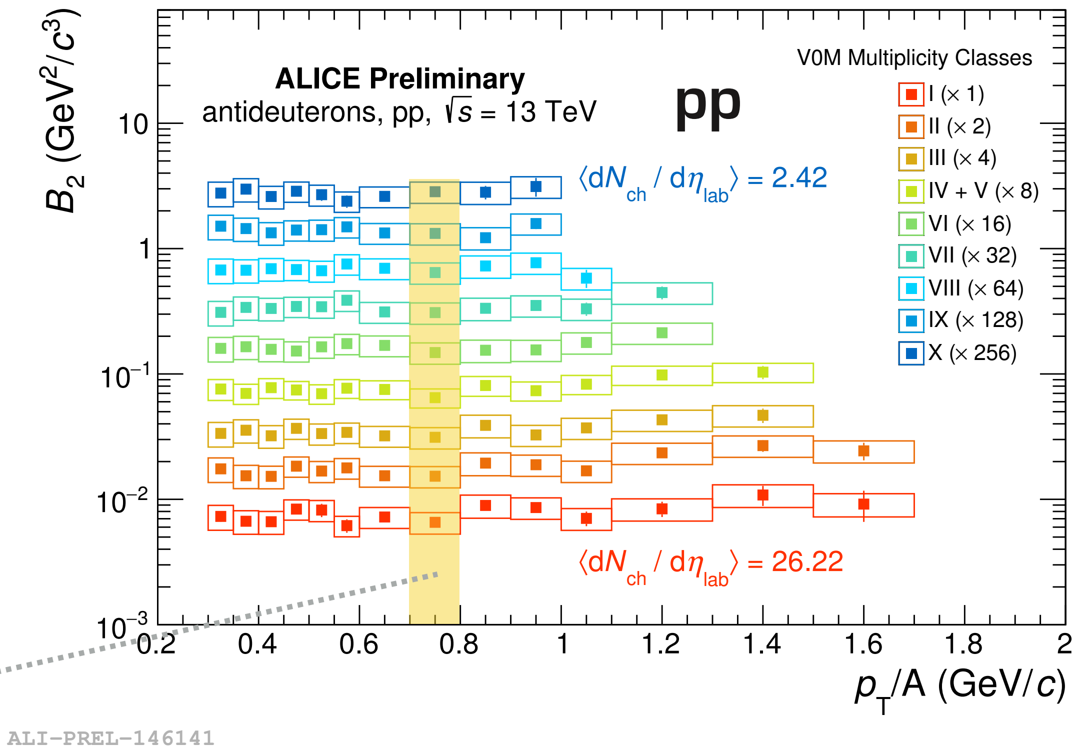
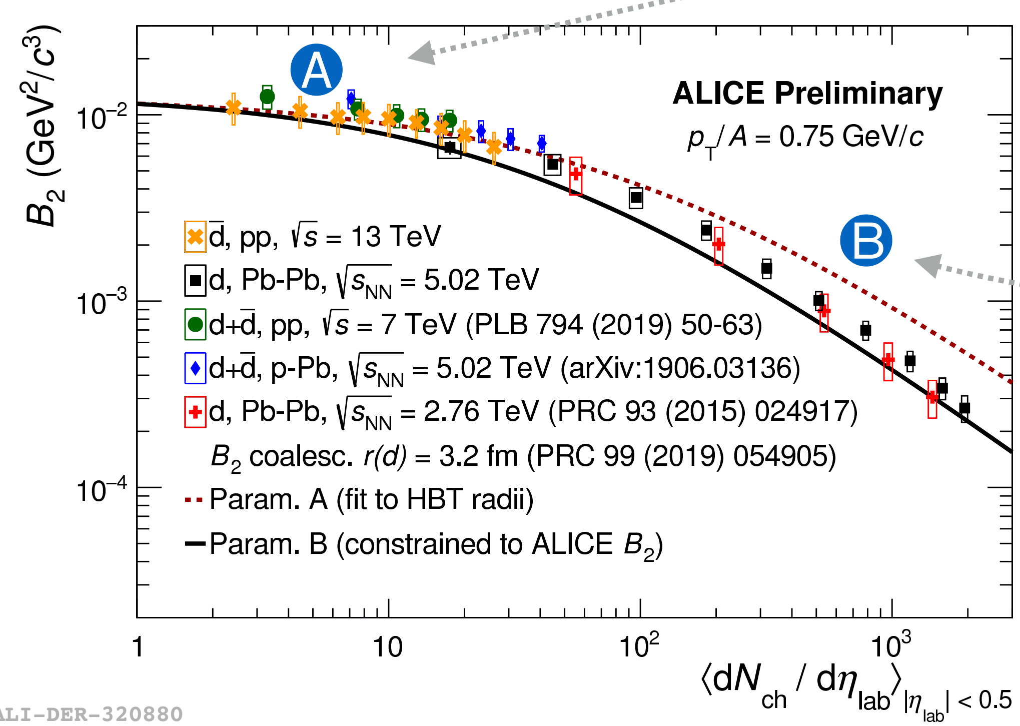
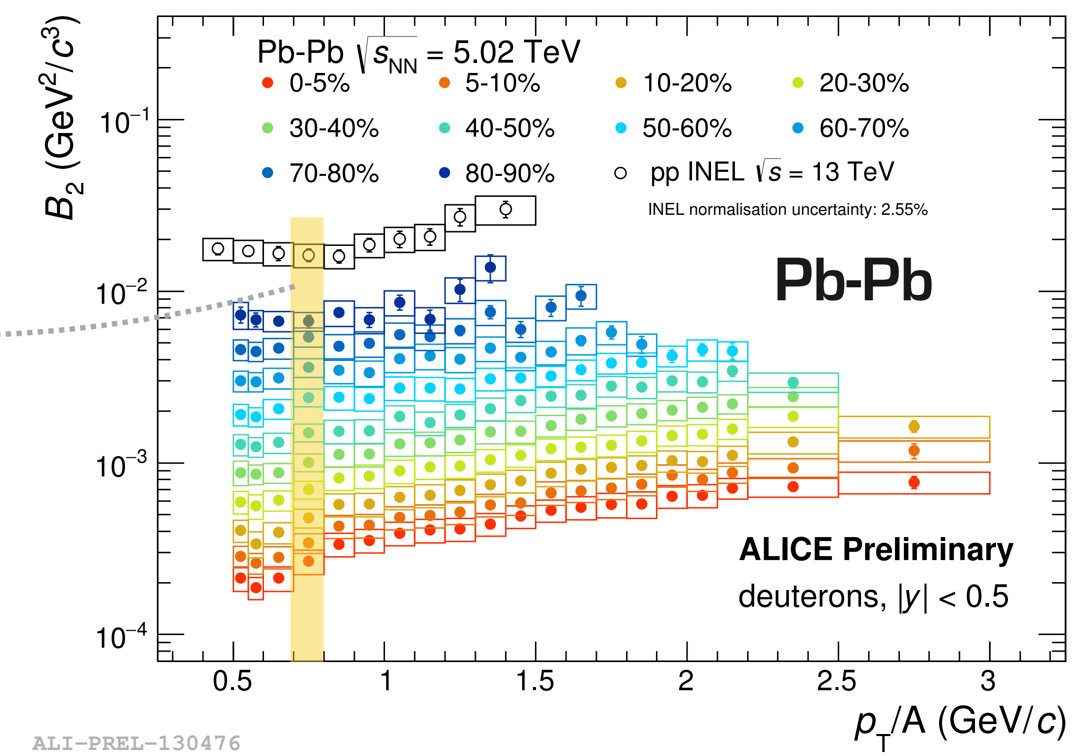
- ✓ Behaviour in Pb-Pb → NOT described
- ✓ From high to low multiplicity → rise in p_T becomes milder
- ✓ In pp collisions B_2 flat in p_T

» B_2 does not show discontinuity between different colliding systems and different energies
- ✓ Unique production mechanism depending on the system size
- ✓ Two regimes observed
  - A. **flat**: system size smaller than deuteron size
  - B. **decreasing**: system size larger than deuteron size



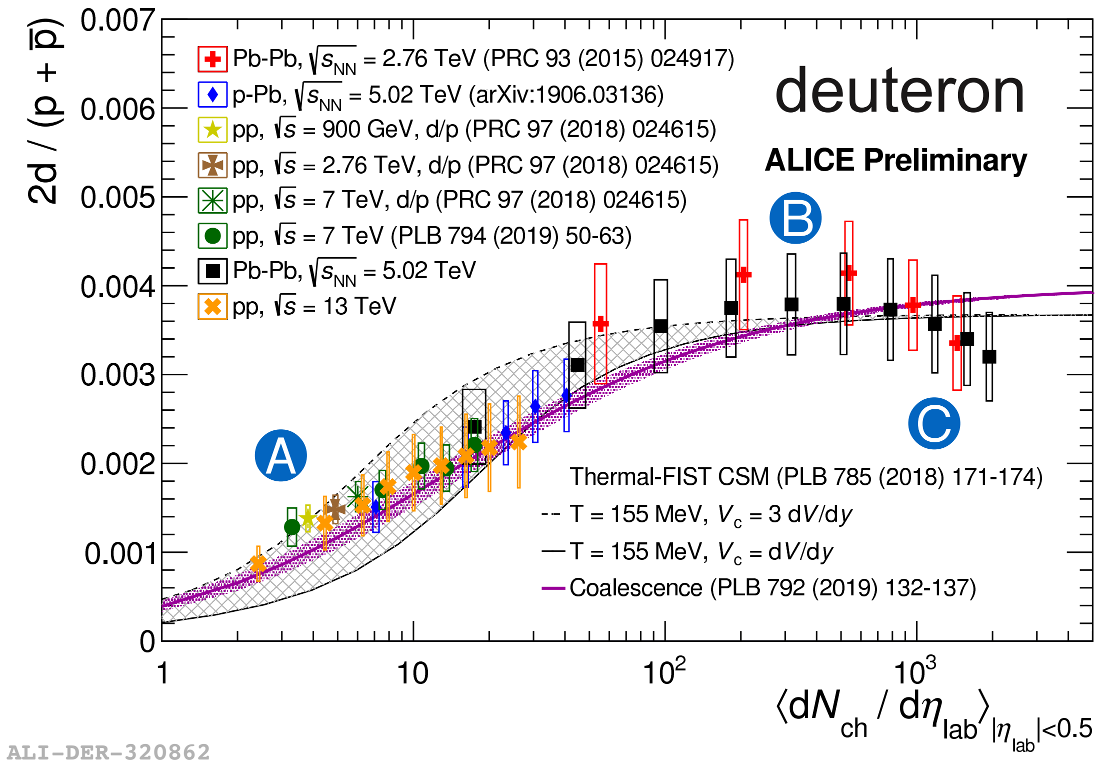




⑤ Light nuclei production

» Deuteron/proton ratio does not show discontinuity between different colliding systems and different energies

- ✓ Unique production mechanism depending only on the system size
- ✓ Two different regimes (or three)
  - A. **increasing**: thermal model → canonical suppression, coalescence → small phase space
  - B. **flat**: no dependence multiplicity, in agreement withe thermal model and coalescence
  - C. **suppression (?)**: too large uncertainties for a conclusion



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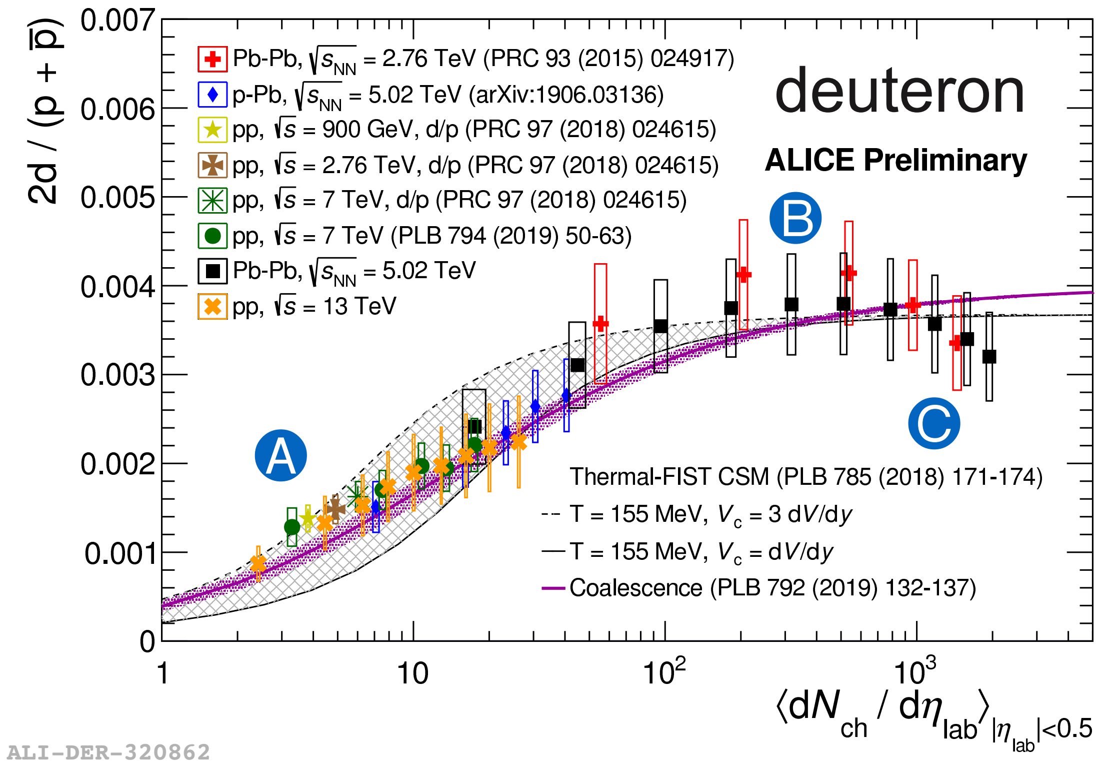
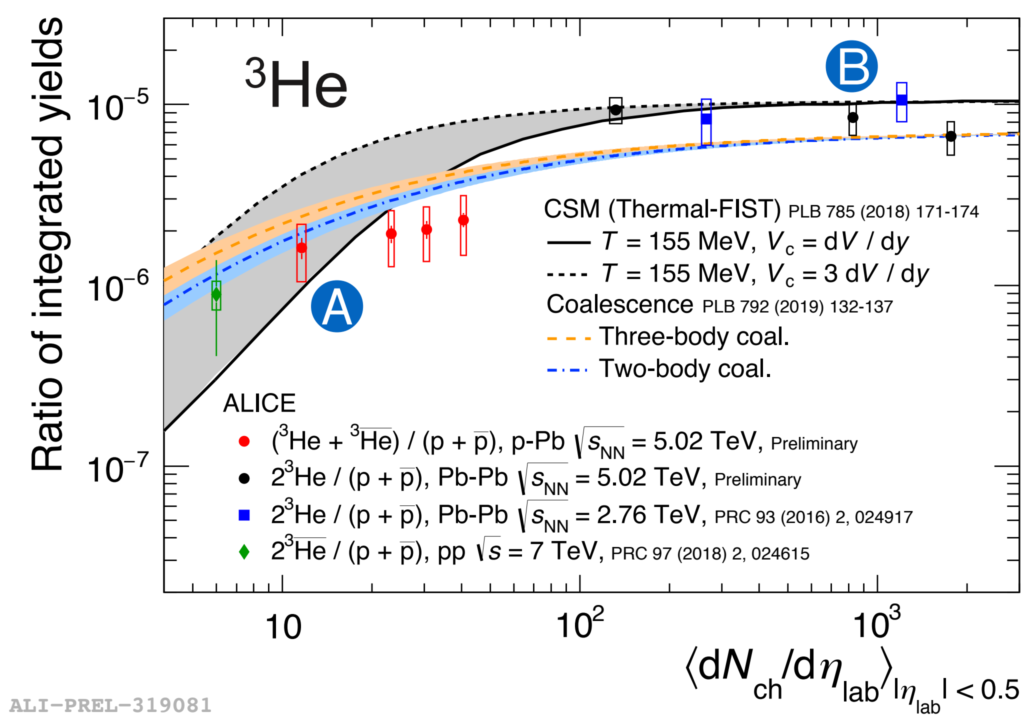
» Similar smooth transition vs multiplicity and regimes observed also for ^{3}He → More data needed to cover the multiplicity gap





Conclusions

- ➡ Hadron ch. driven by final state multiplicity (no $\sqrt{s}$ dependency) at the LHC
- ➡ Thermal description fairly good in large systems
  - ✓ tension for proton and multi-strange
  - ✓ resonances suppression
  - ✓ canonical approach successful in small systems (but ϕ)
- ➡ Yield smooth evolution with multiplicity suggest common production mechanism
  - ✓ d and ^{3}He: coalescence in small systems → thermal production & hydro in large systems
- ➡ Flow-like effect qualitatively similar in large and small systems smoothly evolving with multiplicity → common production mechanism
  - ✓ Effect also explained in recombination models
- ➡ ϕ yields evolve as an open strangeness particle

Backup

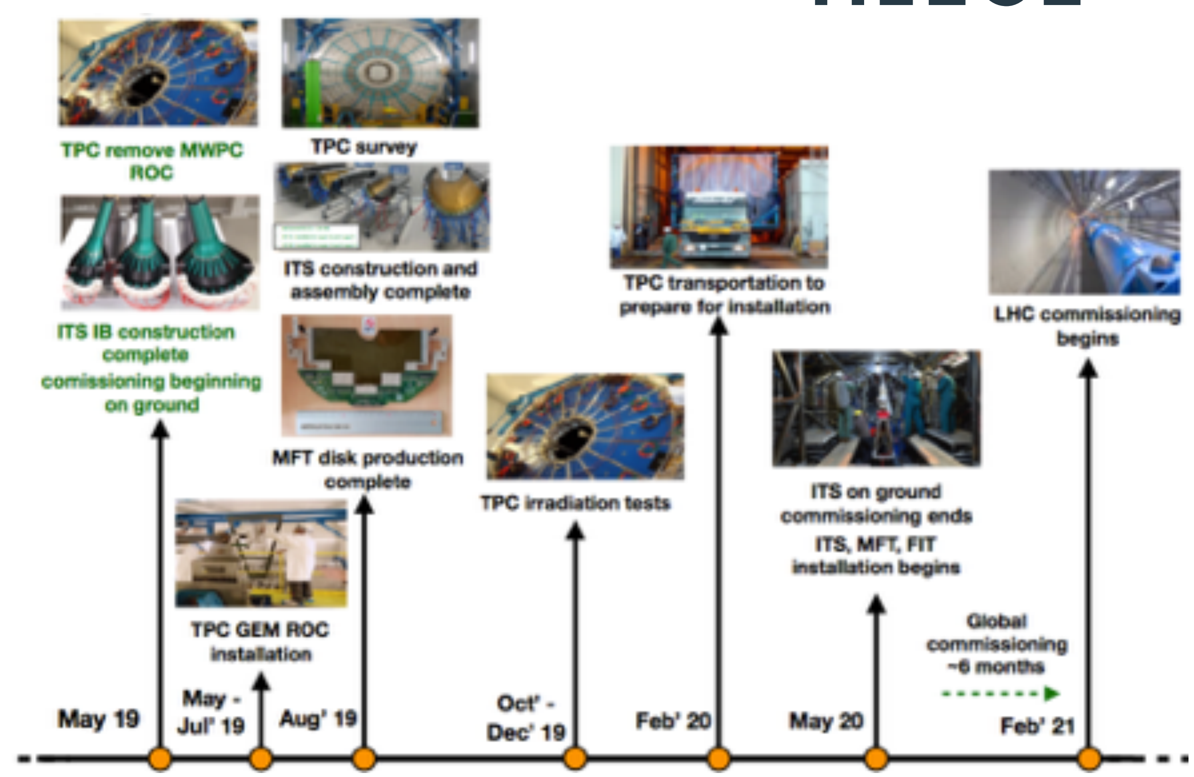
Backup

LHC Run3/4 program and ALICE Upgrade strategy

ALICE

4 key objectives identified by HL/HE-LHC working group 5 for high-density QCD at LHC after LS2

1. Characterising the microscopic long-wavelength QGP properties with unprecedented precision
2. Accessing the microscopic parton dynamics underlying QGP properties
3. Developing a unified picture of partial production from small (pp) to larger (p-A and A-A) systems
4. Probing parton densities in nuclei in a broad (x, Q2) kinematic range and searching for possible onset of parton saturation



Proposed run schedule for Run 3/4

System	$\sqrt{s}$, $\sqrt{s_{NN}}$	L_{int}	Note
Pb-Pb	5.5 TeV	13 nb^{-1}	3 nb^{-1} low B-field
p-Pb	8.8 TeV	1.2 pb^{-1}	
pp	14 TeV	200 pb^{-1}	High-multiplicity triggered
	8.8 TeV	3 pb^{-1}	
	5.5 TeV	6 pb^{-1}	
O-O	7 TeV	500 μb^{-1}	pilot run
p-O	9.9 TeV	200 μb^{-1}	

ALICE Upgrade strategy

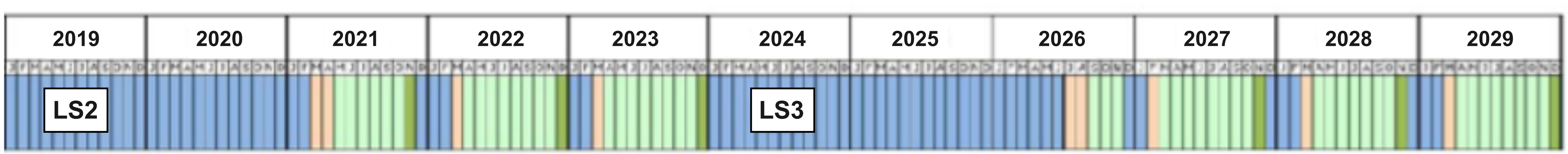
» New silicon trackers: ITS (mid-rapidity), MFT (forward rapidity)

» New TPC read-out chambers (GEMs) and electronics

» New Fast Interaction Trigger (FIT)

» New Read-out of other detectors (TOF, TRD, Muon arm, ZDC,...)

» Upgrade of Online and Offline systems (O^2 project)



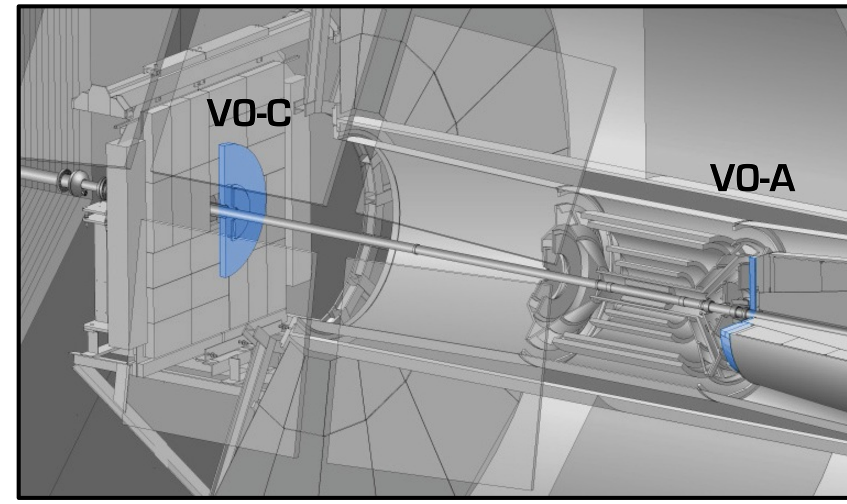
Run 3: $L_{Pb\text{-}Pb} = 6.0\ nb^{-1}$

Run 4: $L_{Pb\text{-}Pb} = 7.0\ nb^{-1}$

Backup

Centrality/Multiplicity determination

- The centrality/multiplicity classes requires the following steps:
  - ✓ the V0 amplitude distribution is fitted with Glauber MC
  - ✓ absolute scale is defined, through the definition of anchor point, as the amplitude of the V0 equivalent to 90% of hadronic cross-section
  - ✓ data are divided into several percentiles selecting on signal amplitude measured in the V0
- V0 amplitude distribution
  - ✓ **Pb–Pb and pp:** sum of amplitudes in the two V0 scintillators, V0-A&V0-C ("V0M")
  - ✓ **p–Pb:** amplitude by V0-A (placed on the outgoing Pb side)
- $\langle dN_{ch}/dh \rangle$ is measured in $|h| < 0.5$ to avoid "auto-biases" in multiplicity determination



The V0 detector is composed of a pair of forward scintillator hodoscopes placed at $2.8 < \eta < 5.1$ (V0-A) and $-3.7 < \eta < -1.7$ (V0-C)

$\langle dN_{ch}/d\eta \rangle$			
Centrality/Multiplicity class (Pb–Pb/p–Pb/pp)	Colliding system		
	Pb–Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)	p–Pb ($\sqrt{s_{NN}}$ = 5.02 TeV)	pp ($\sqrt{s}$ = 7 TeV)
0-5%/0-5%/0-0.95%	1601±60	45±1	21.3±0.6
70-80%/60-80%/48-68%	35±2	9.8±0.2	3.90±0.14

PRC 88 (2013) 044909