Strangeness and Light Flavor Production with ALICE

D.D. Chinellato for the ALICE Collaboration

Strangeness in Quark Matter 2015

7th July 2015

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ALICE

Why Study Light Flavor Particle Production?

$\pi^{\pm}$	$K^{\pm}$	p	d	^{3}He	^{4}He	K_S^0	Λ	Ξ	Ω	$^{3}_{\Lambda}H$	K^*	ϕ

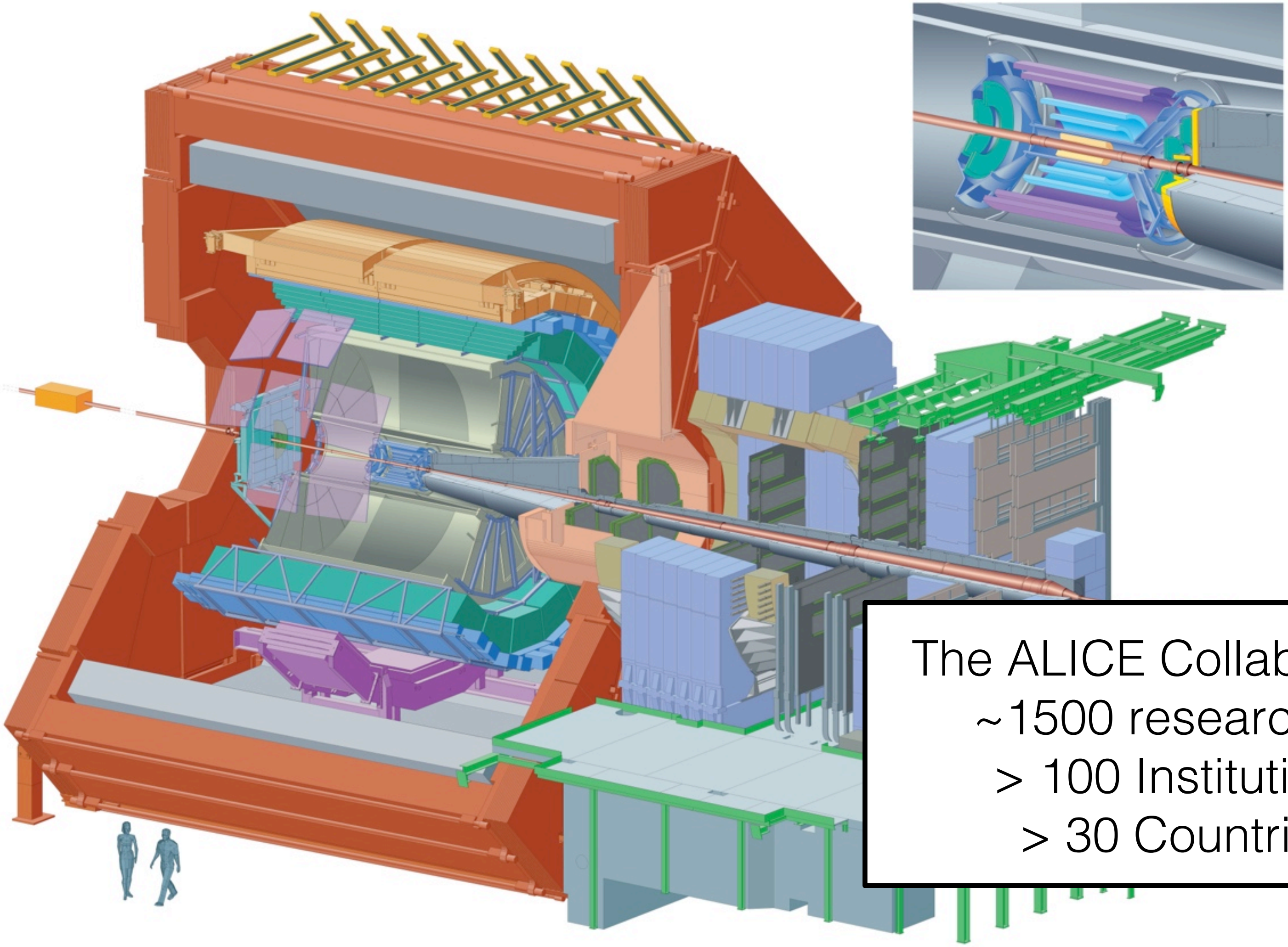
Why Study Light Flavor Particle Production?

$\pi^{\pm}$	$K^{\pm}$	p	d	^{3}He	^{4}He	K_S^0	Λ	Ξ	Ω	$^{3}_{\Lambda}H$	K^*	ϕ

1. Understanding collective behaviour
2. Hadrochemistry and strangeness enhancement
3. Particle production and thermal equilibration
4. Understanding of the late hadronic stage
5. Nuclei production and searches for exotica
6. Study of energy loss while traversing the medium

The ALICE Experiment

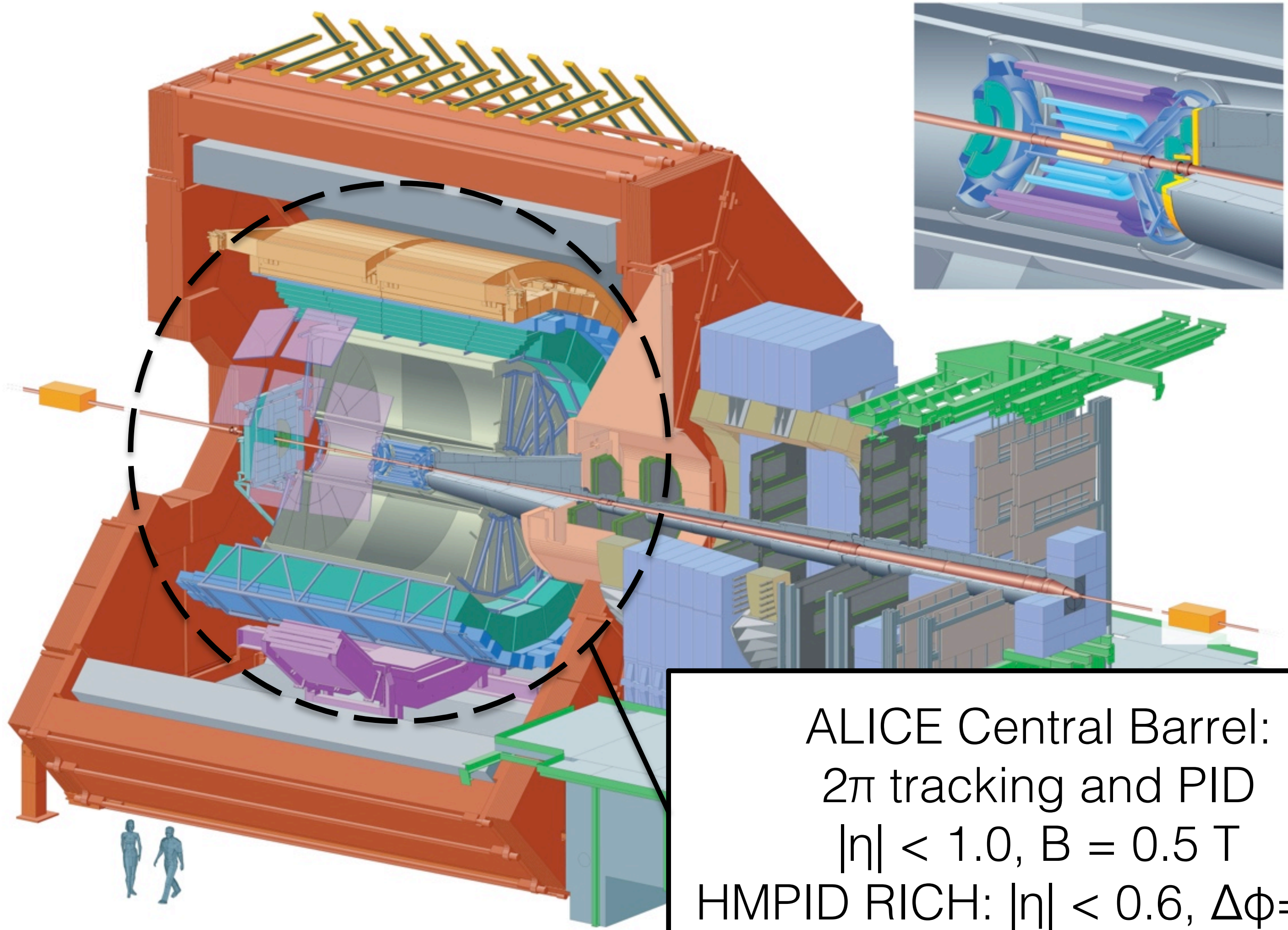
A dedicated heavy ion experiment



The ALICE Collaboration
~1500 researchers
> 100 Institutions
> 30 Countries

The ALICE Experiment

A dedicated heavy ion experiment

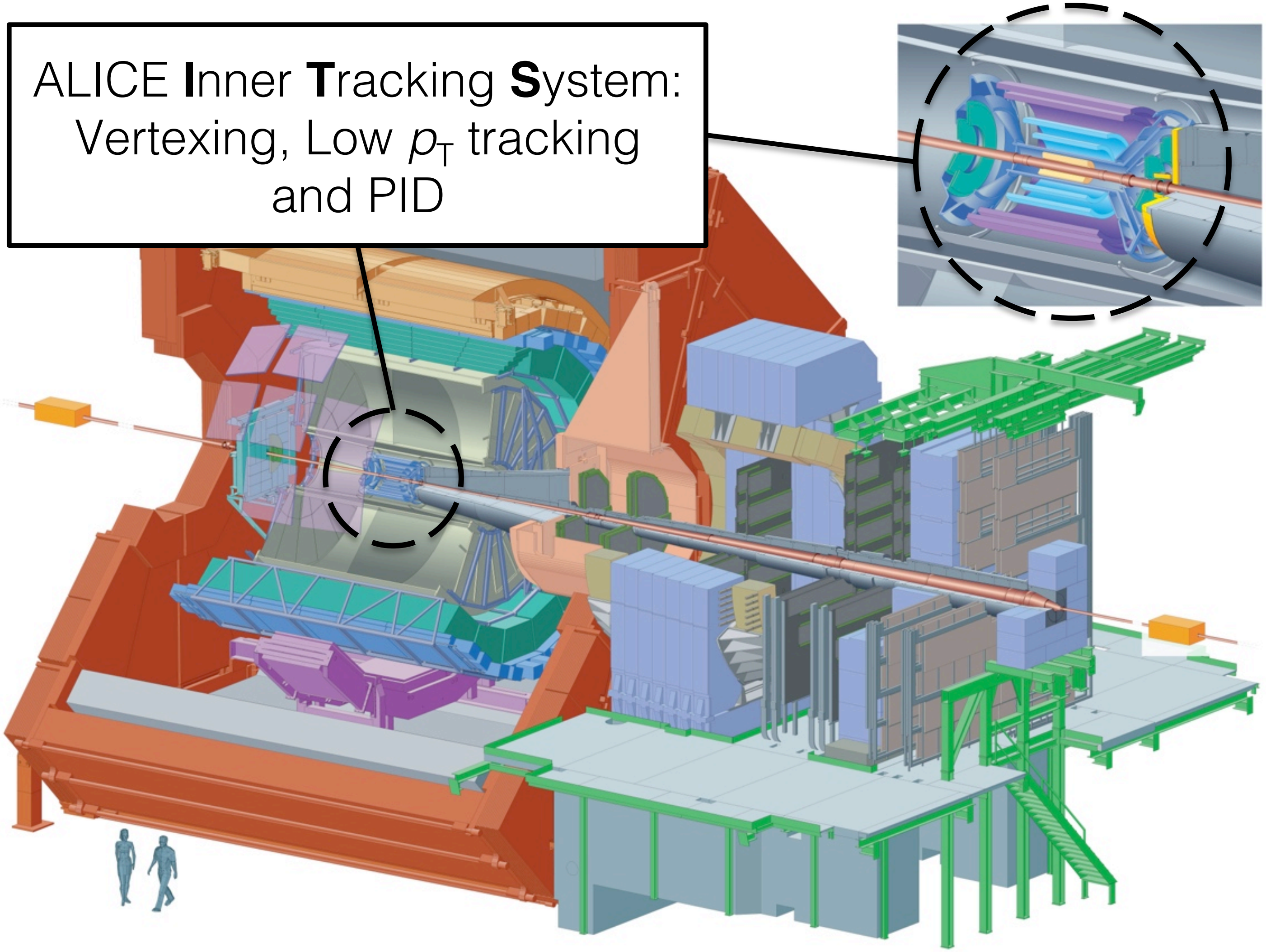


ALICE Central Barrel:
2π tracking and PID
$|\eta| < 1.0$, B = 0.5 T
HMPID RICH: $|\eta| < 0.6$, $\Delta\phi=57°$

The ALICE Experiment

A dedicated heavy ion experiment

ALICE **I**nner **T**racking **S**ystem: Vertexing, Low p_T tracking and PID



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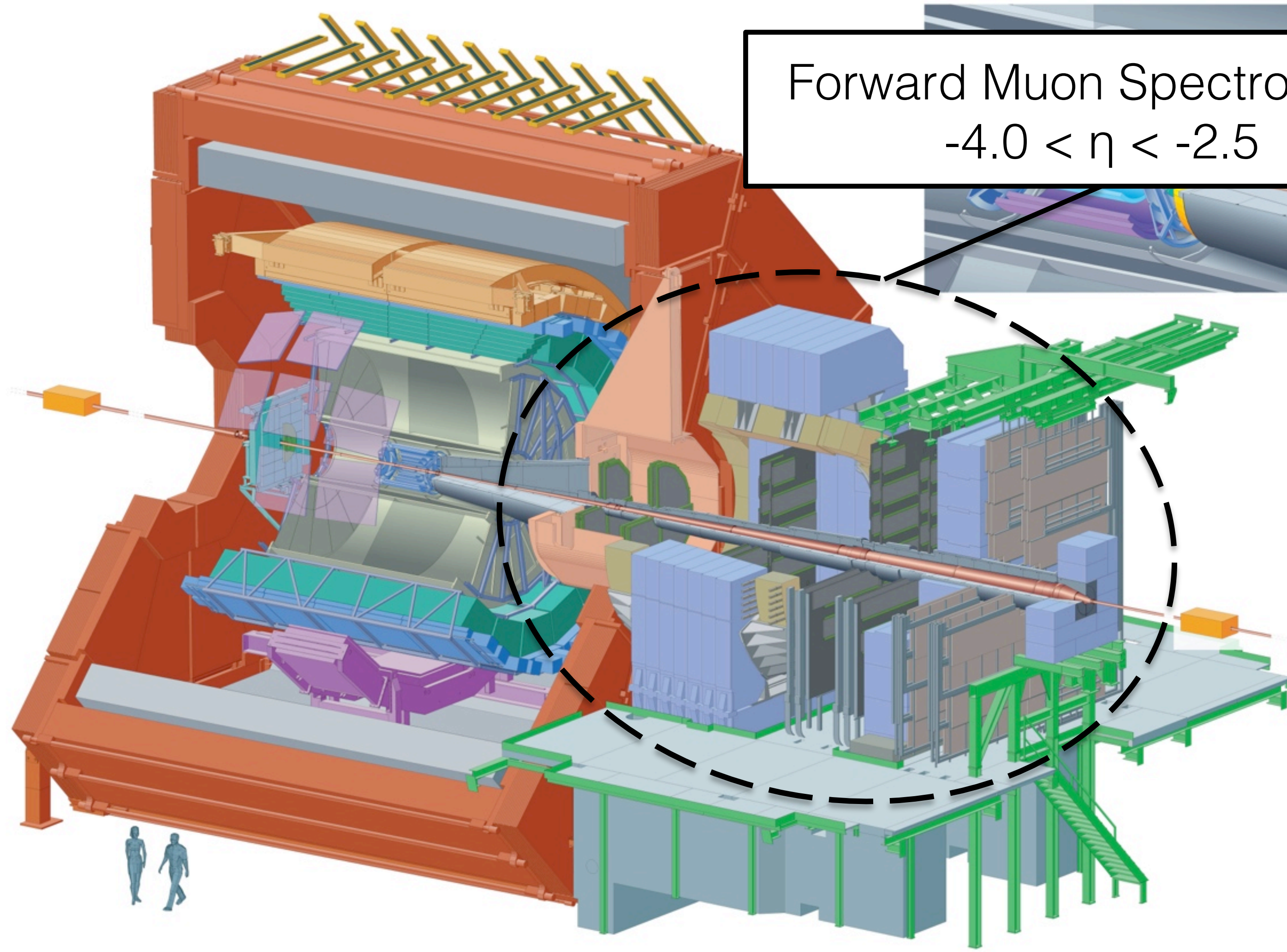

The ALICE Experiment

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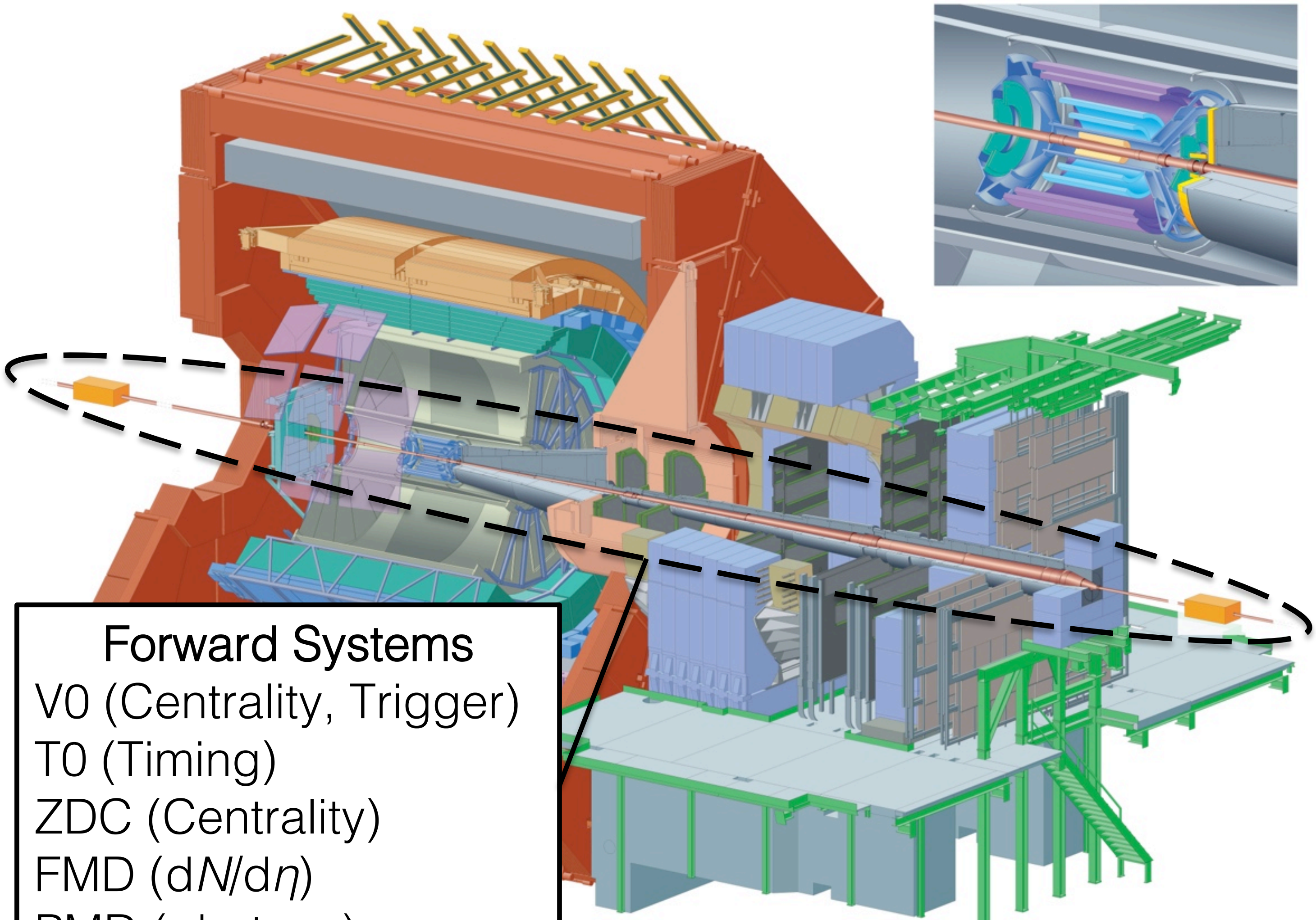
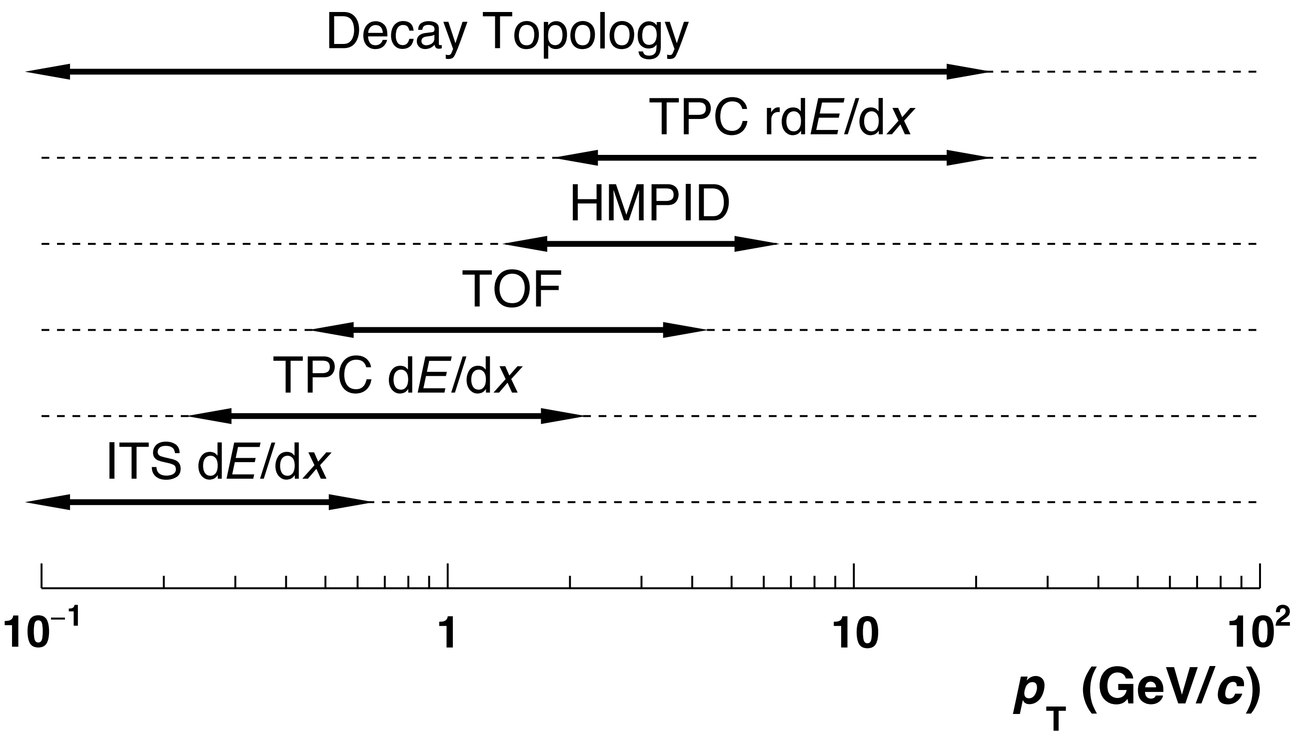
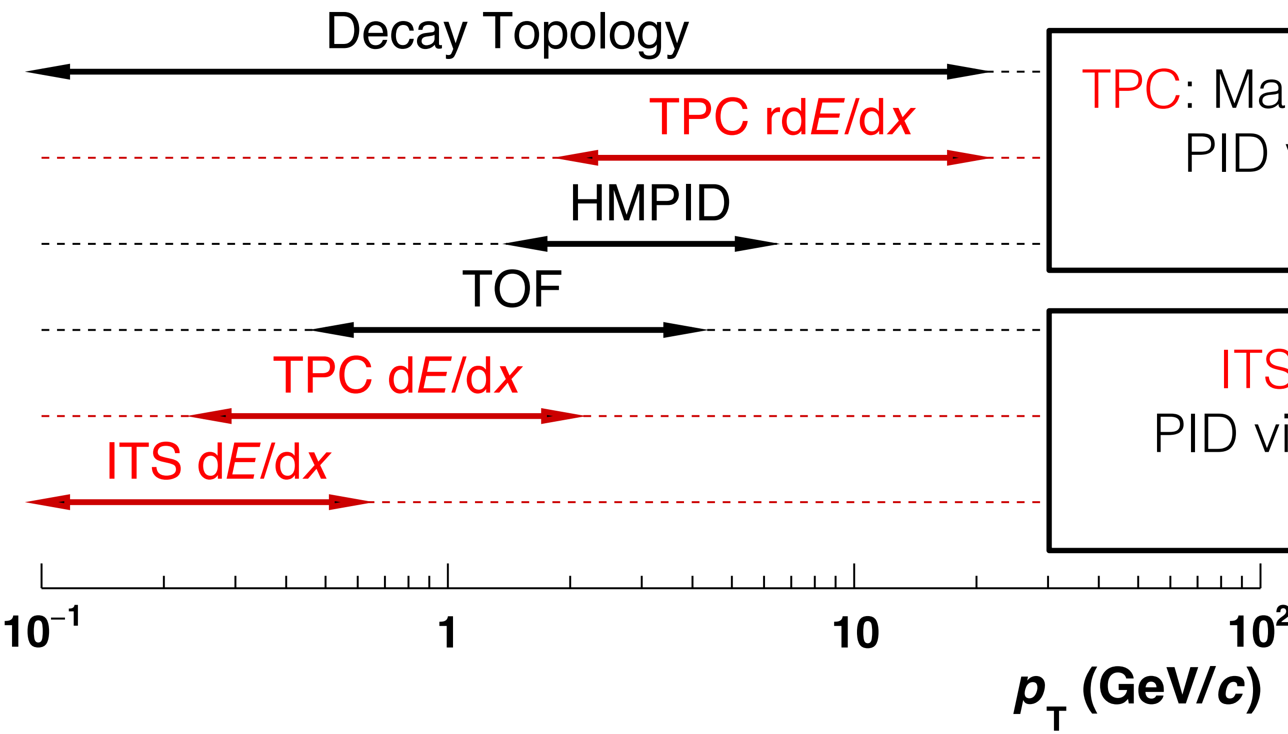


Particle IDentification in ALICE



ALICE has at its disposal practically all known particle identification techniques in a broad p_T range

Particle **ID**entification in ALICE



TPC: Main Tracking Detector
PID via dE/dx in gas
σ ~6%

ITS: PID at low p_T
PID via dE/dx in silicon
σ ~10-15%

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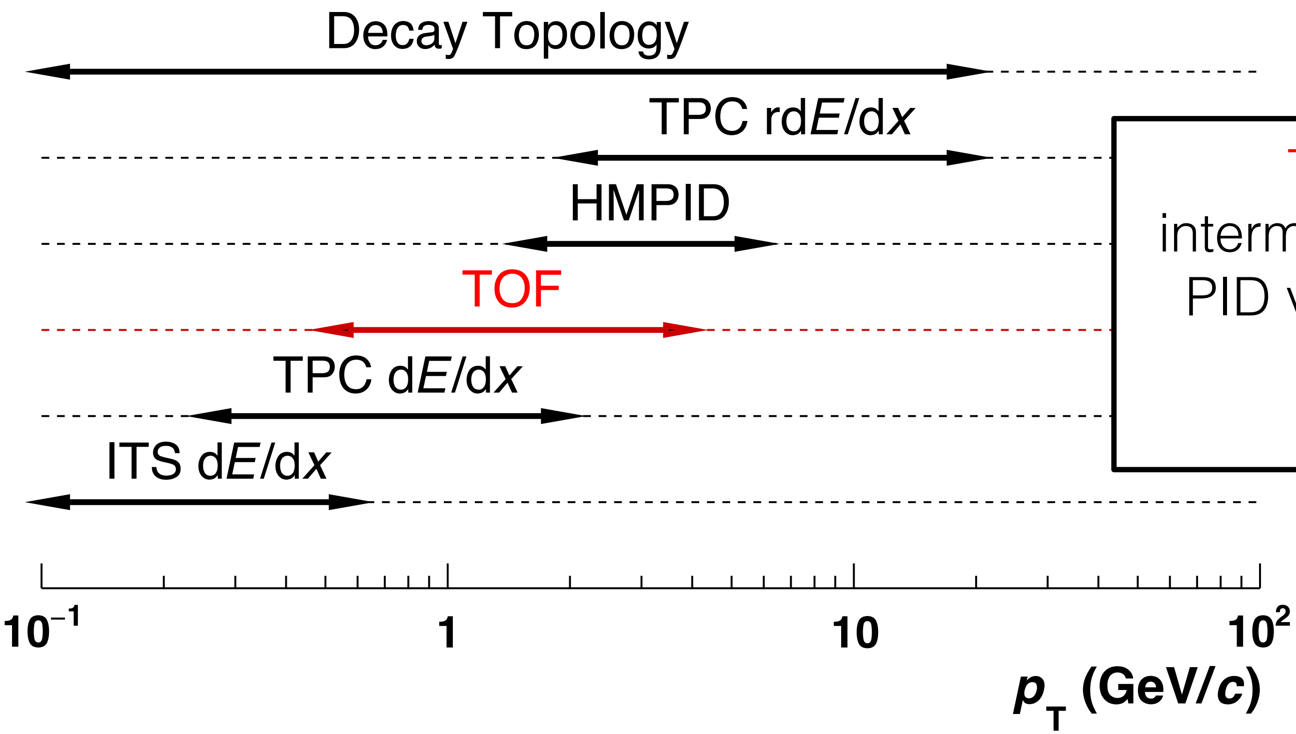
Particle **ID**entification in ALICE



TOF: PID at intermediate momenta
PID via time-of-flight technique
$\sigma < 100$ ps

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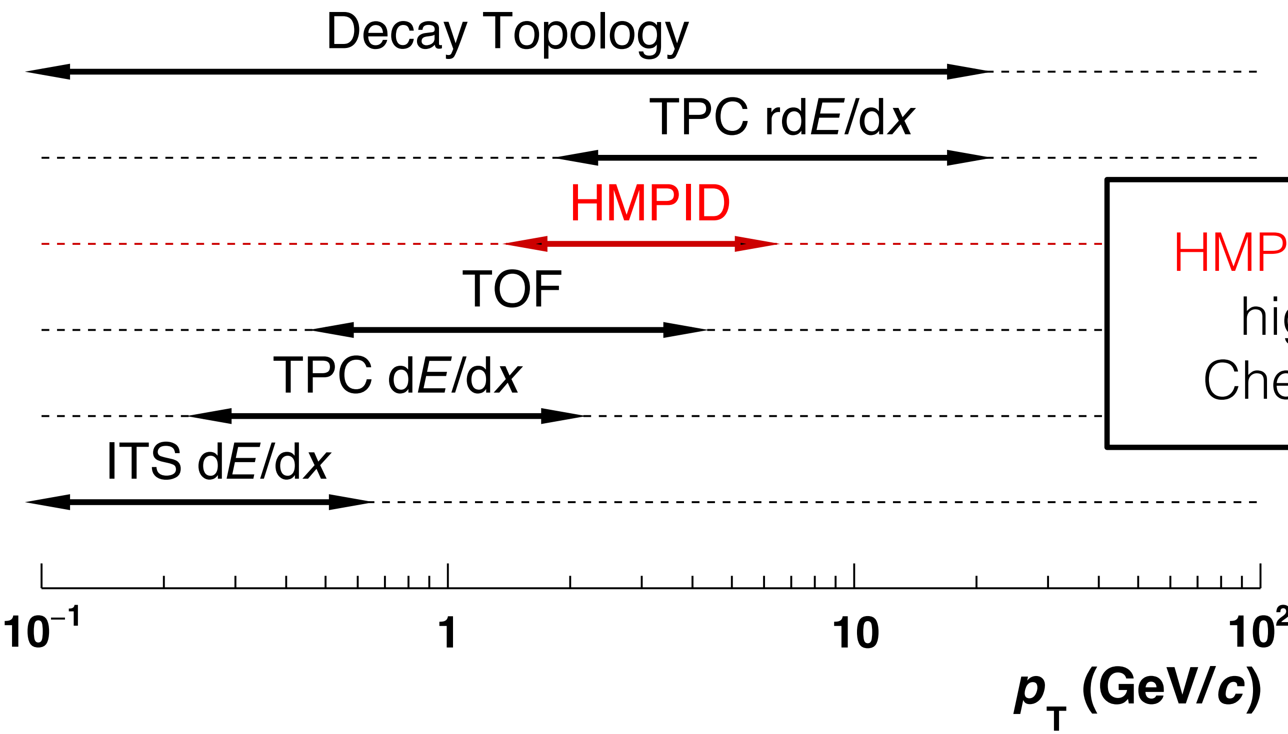
Particle IDentification in ALICE



HMPID: Extends PID to higher p_T; PID via Cherenkov angle θ_{ch}

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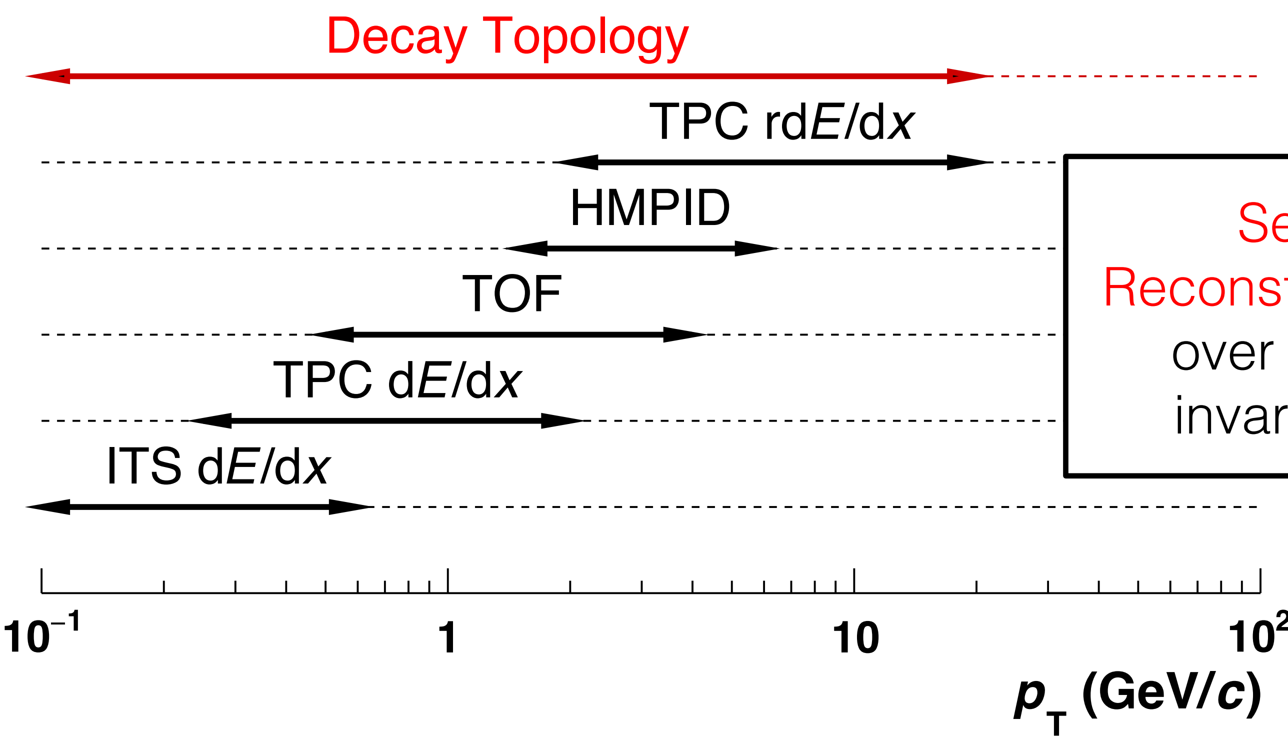
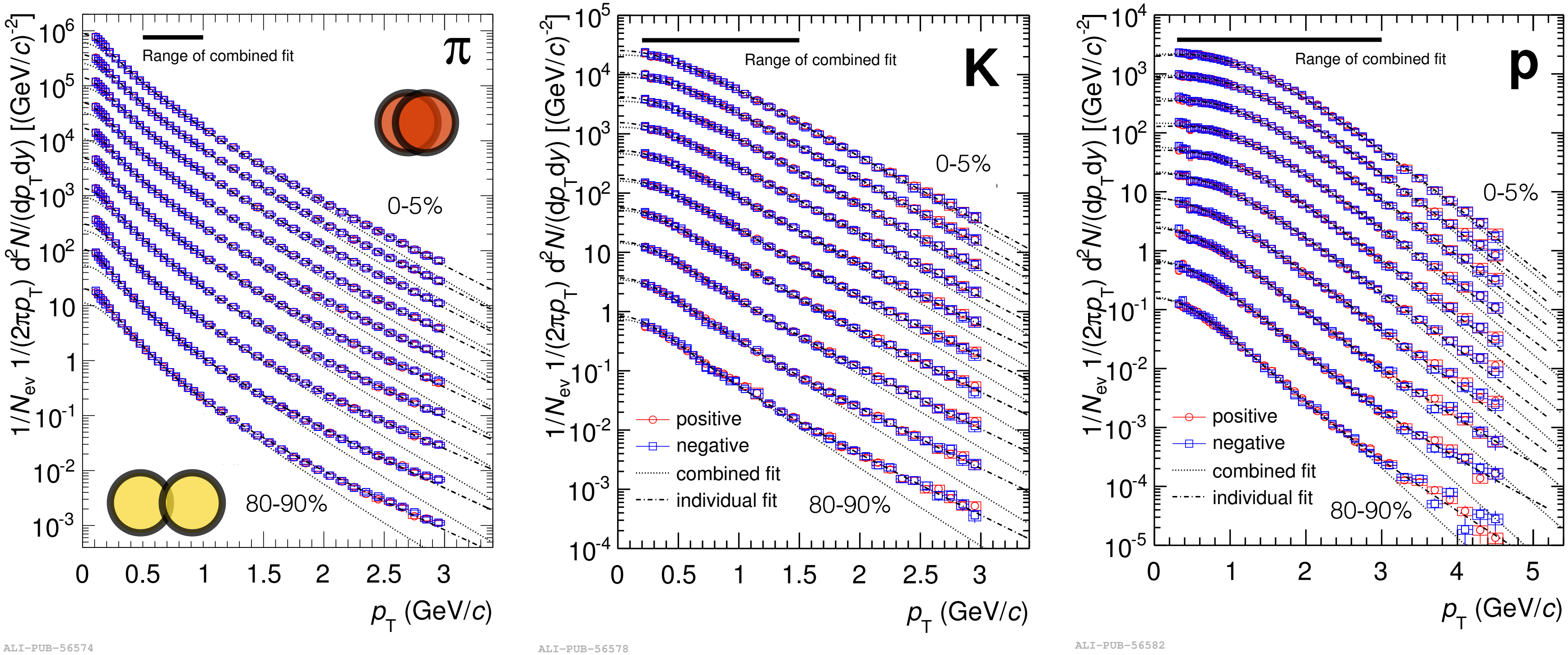
Particle IDentification in ALICE



Secondary Vertex Reconstruction: Identification over a large p_T range + invariant mass analysis

ALICE has at its disposal practically all known particle identification techniques in a broad p_T range

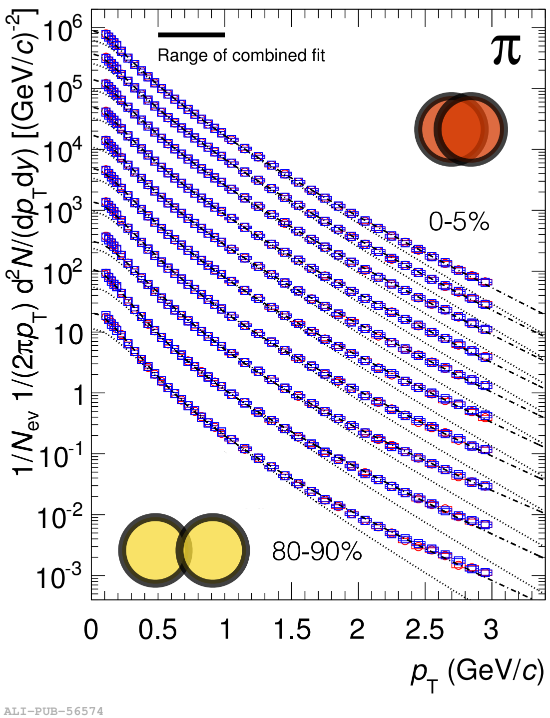
Pb-Pb: Identified Particle Spectra

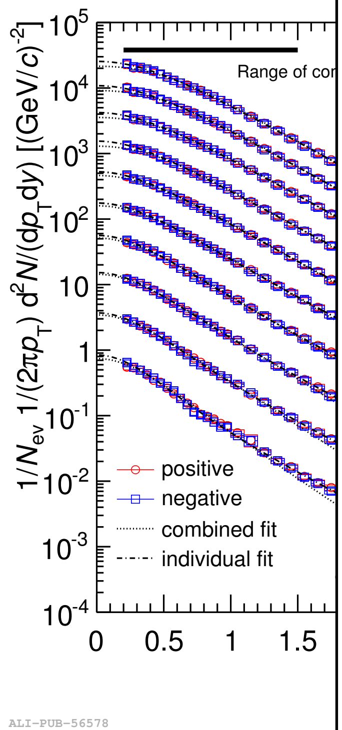


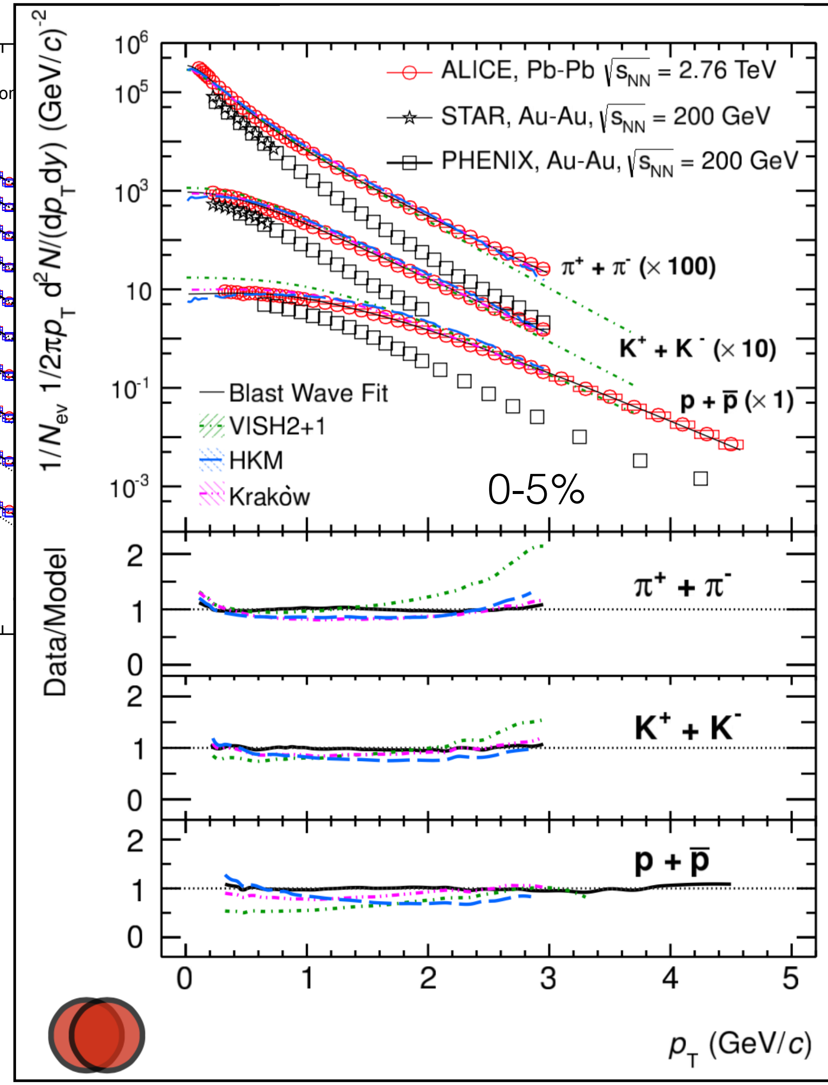
ALICE, PRC 88 (2013) 04910

- Spectra become harder with centrality in a mass-dependent way

Pb-Pb: Identified Particle Spectra





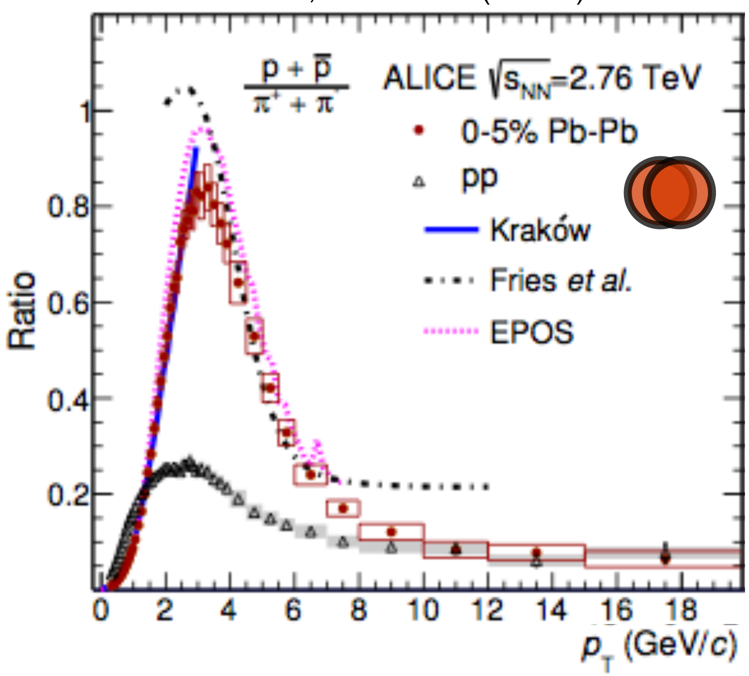


ALICE, PRL 109 (2012) 252301

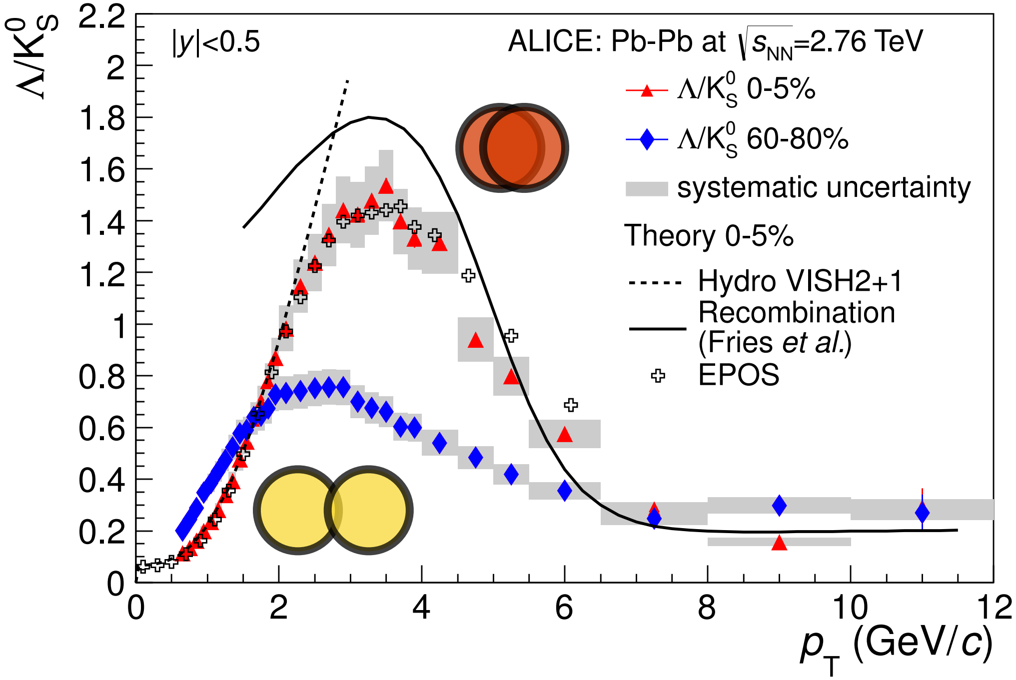
- Spectra become harder with centrality in a mass-dependent way
- Consistent with hydrodynamics expectations

Pb-Pb: Baryon to Meson Ratios (I)

ALICE, PLB 728 (2014) 25



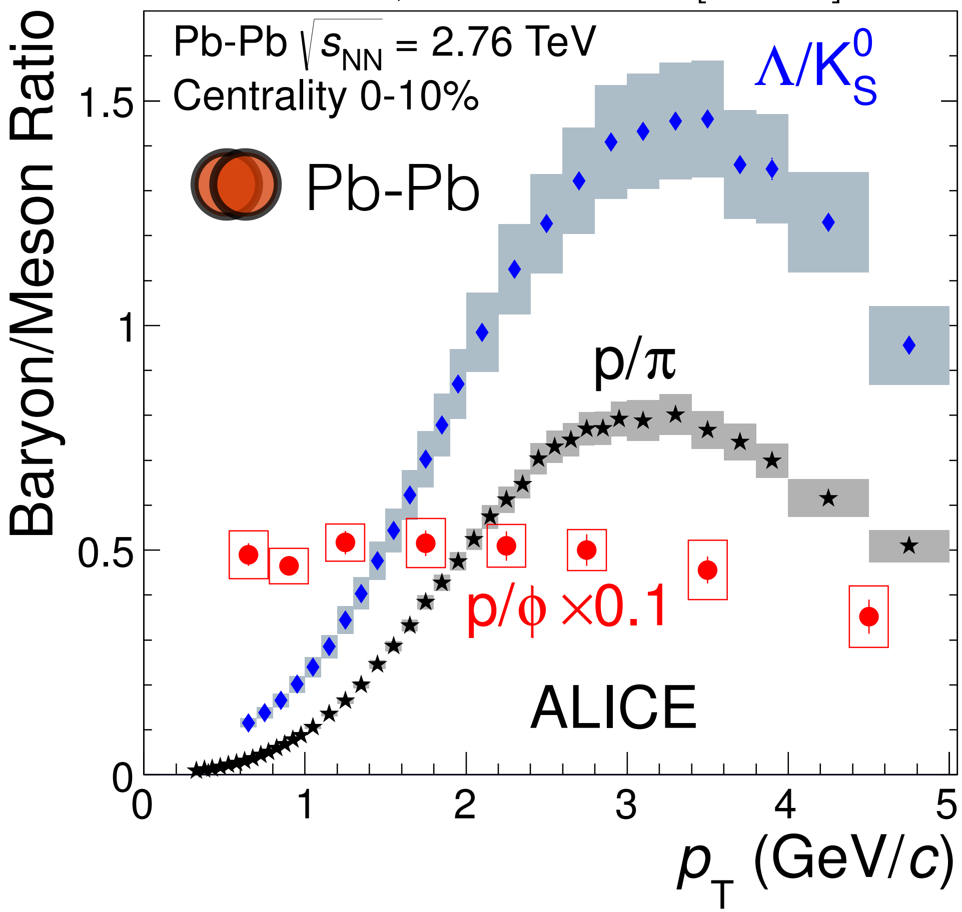
ALICE, PRL 111 (2013) 222301



- Hydro model explains data in $p_T < 2$ GeV/c
  - At higher p_T: no modification of baryon to meson ratios observed
- Recombination reproduces the shape qualitatively
- EPOS provides good description of data

Pb-Pb: Baryon to Meson Ratios (II)

ALICE, arXiv:1404.0495 [nucl-ex]



Is Mass the driving factor?

- p: 938 MeV/c^2
- ϕ: 1018 MeV/c^2

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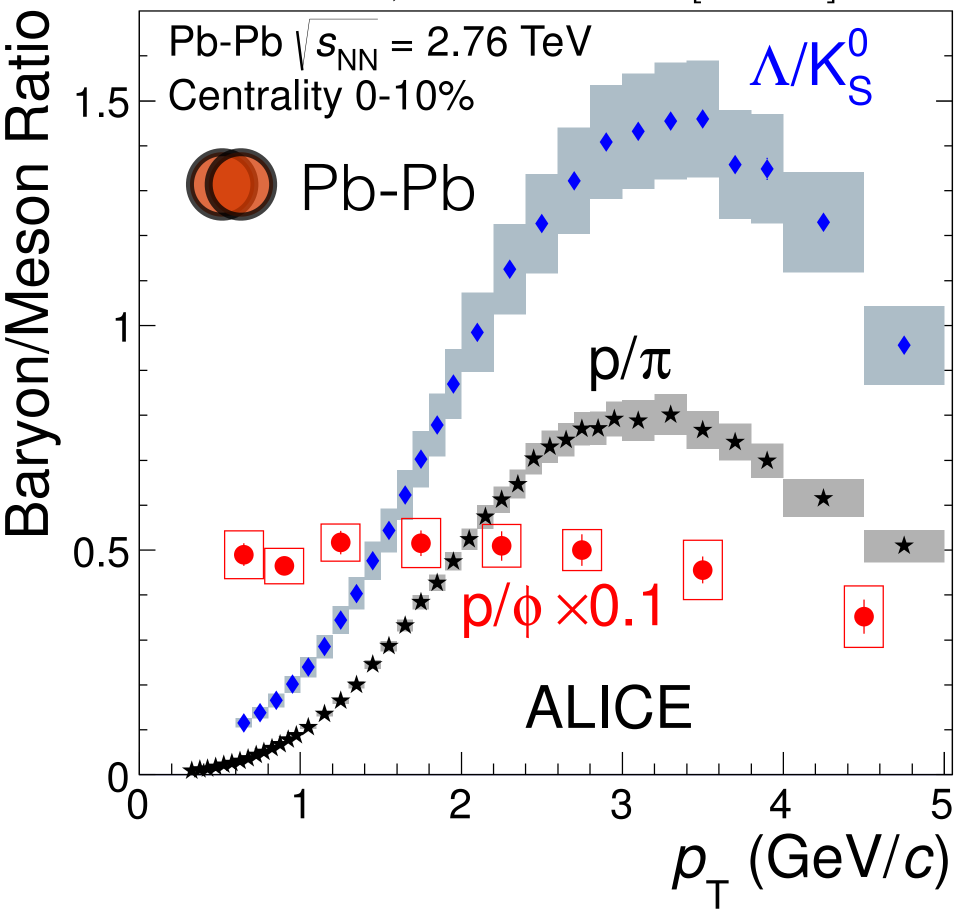


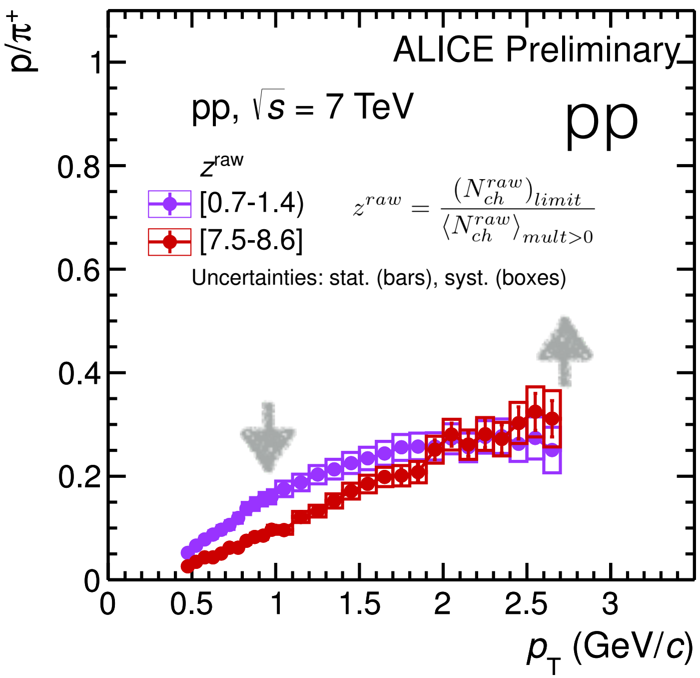
Is Mass the driving factor?

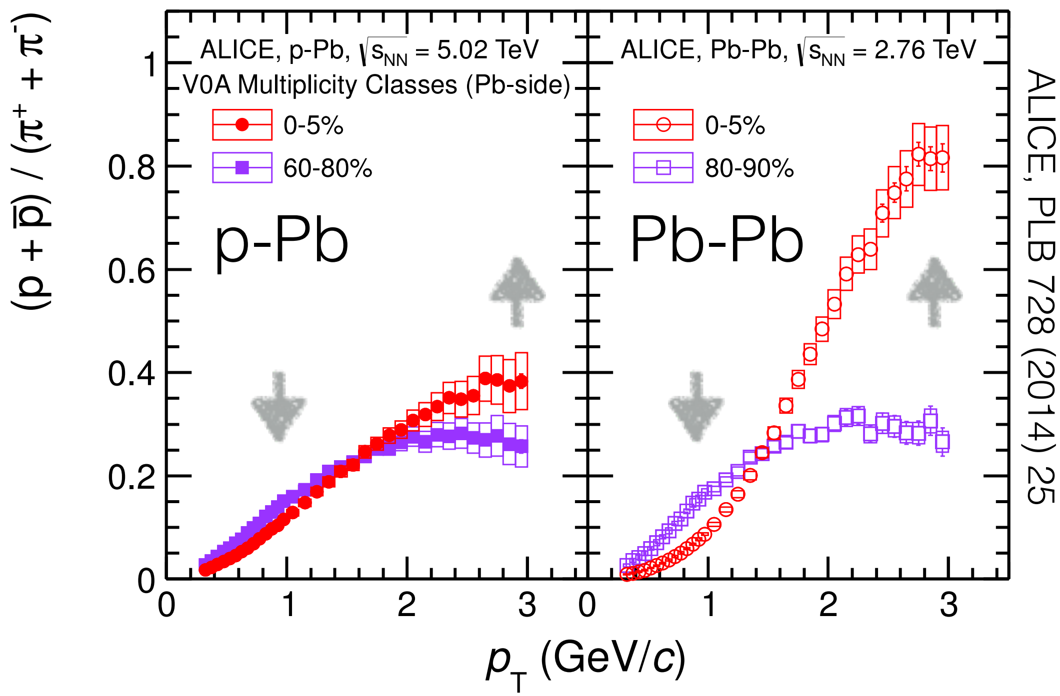
- p: 938 MeV/c^2
- ϕ: 1018 MeV/c^2

- Spectral shapes are the same for these two particles
- Mass is indeed the parameter driving momentum distributions

1. Measurement of collective behaviour in smaller systems (pp, p-Pb)?

Baryon to Meson Ratios in pp, p-Pb





- Looking at smaller systems as a function of multiplicity
  - Qualitatively Similar: depletion at low p_T, enhancement at mid p_T
  - Quantitatively rather different

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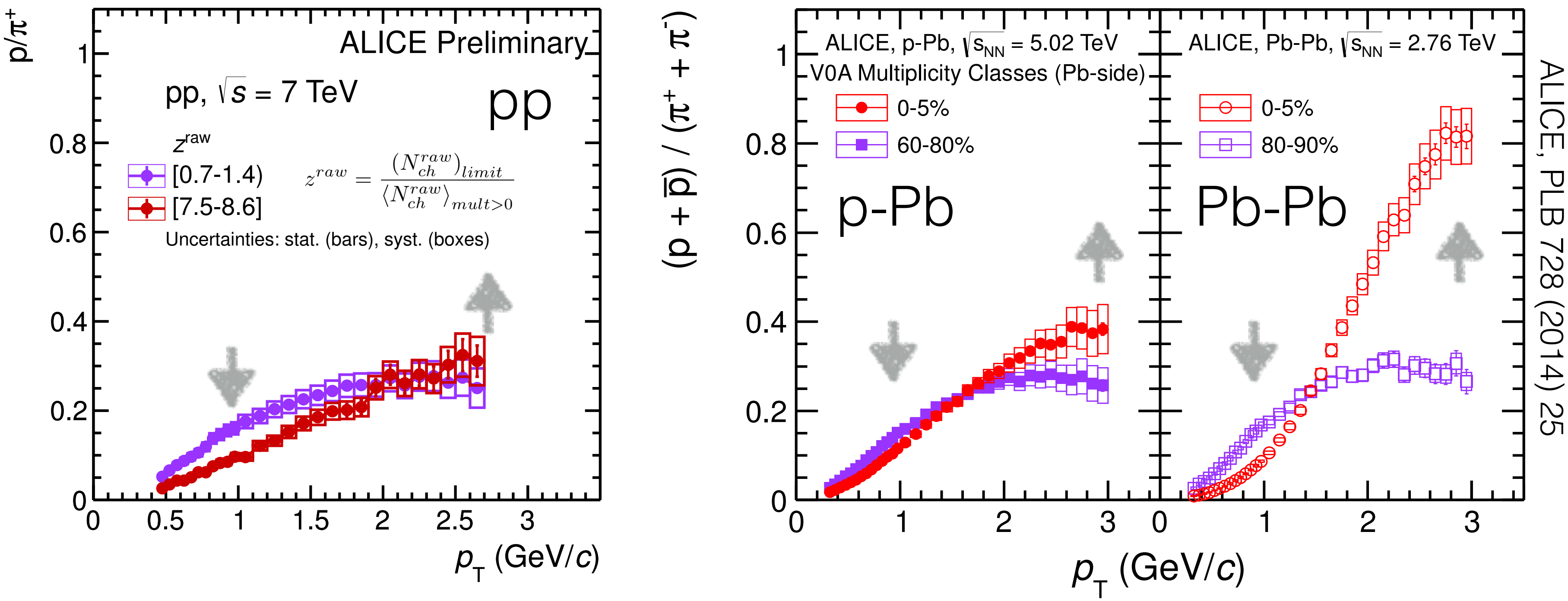
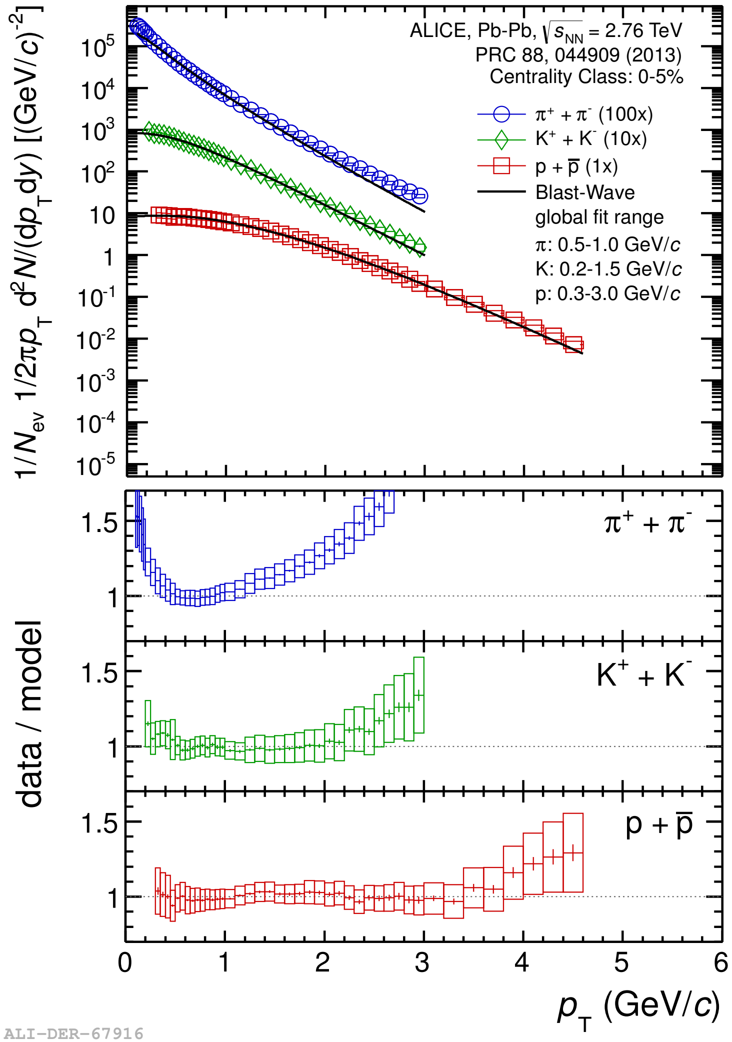


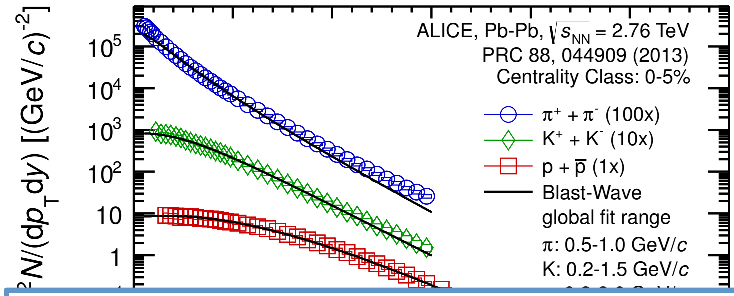
- Looking at smaller systems as a function of multiplicity
  - Qualitatively Similar: depletion at low p_T, enhancement at mid p_T
  - Quantitatively rather different
- Is there collectivity in smaller systems?

Spectral Shapes and the Blast Wave Model



- Simultaneous Blast wave fits to π, K, p with a set of parameters:
  - $<\beta_T>$: Radial Flow
  - T_{kin} : Freezeout Temperature
  - n : velocity profile

Spectral Shapes and the Blast Wave Model



- Qualitatively similar behaviour observed in p-Pb and Pb-Pb in parameter space

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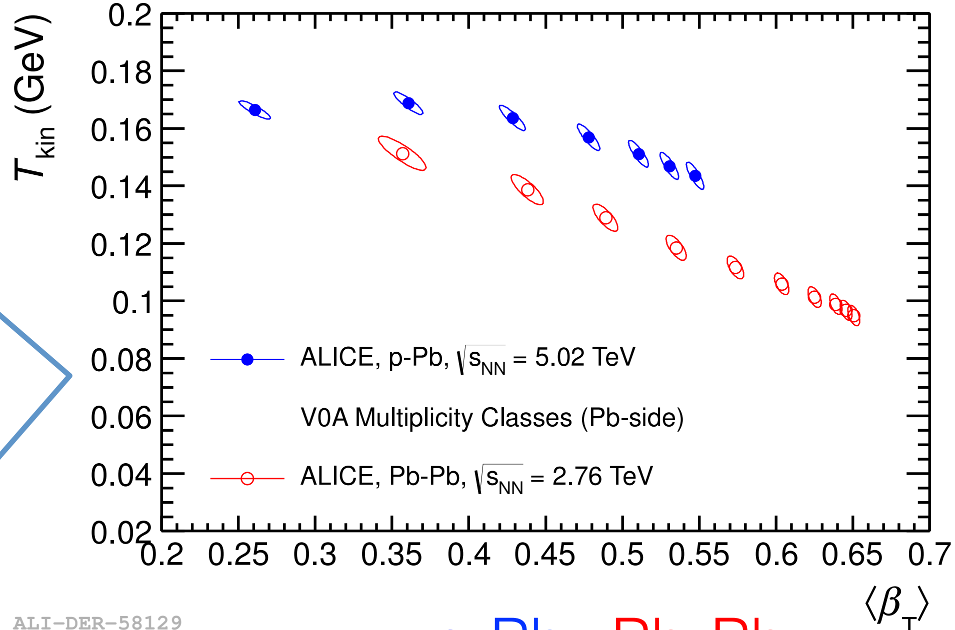

p-Pb Pb-Pb

1. Measurement of collective behaviour in smaller systems (pp, p-Pb)?

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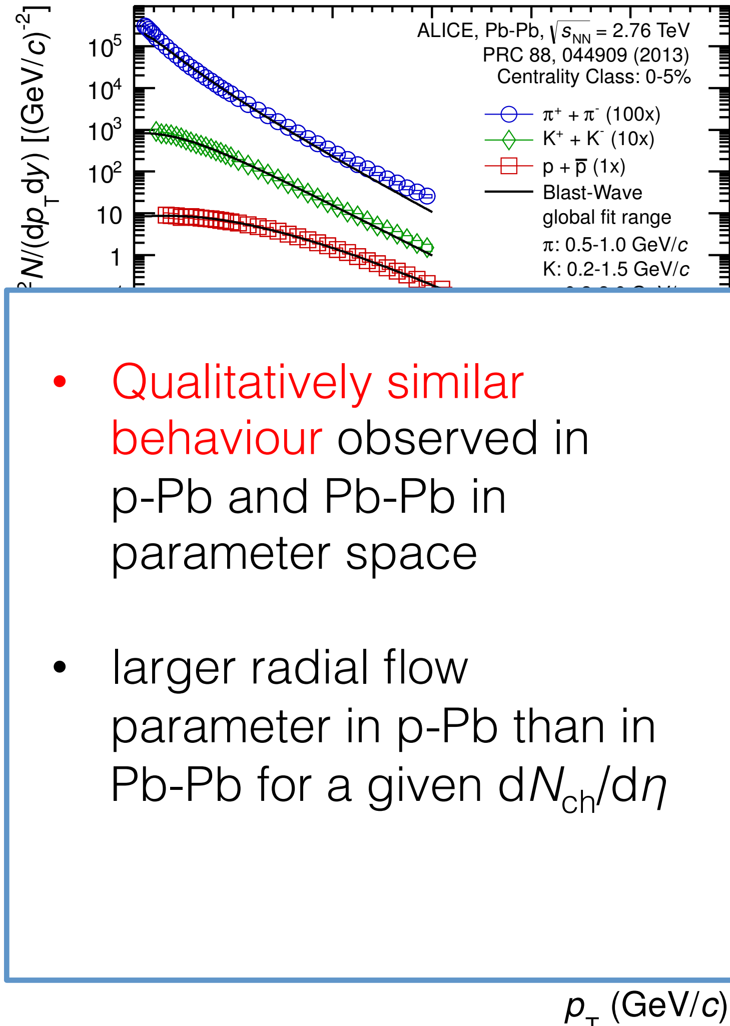

ALI-DER-67916

- Qualitatively similar behaviour observed in p-Pb and Pb-Pb in parameter space
- larger radial flow parameter in p-Pb than in Pb-Pb for a given $dN_{ch}/d\eta$

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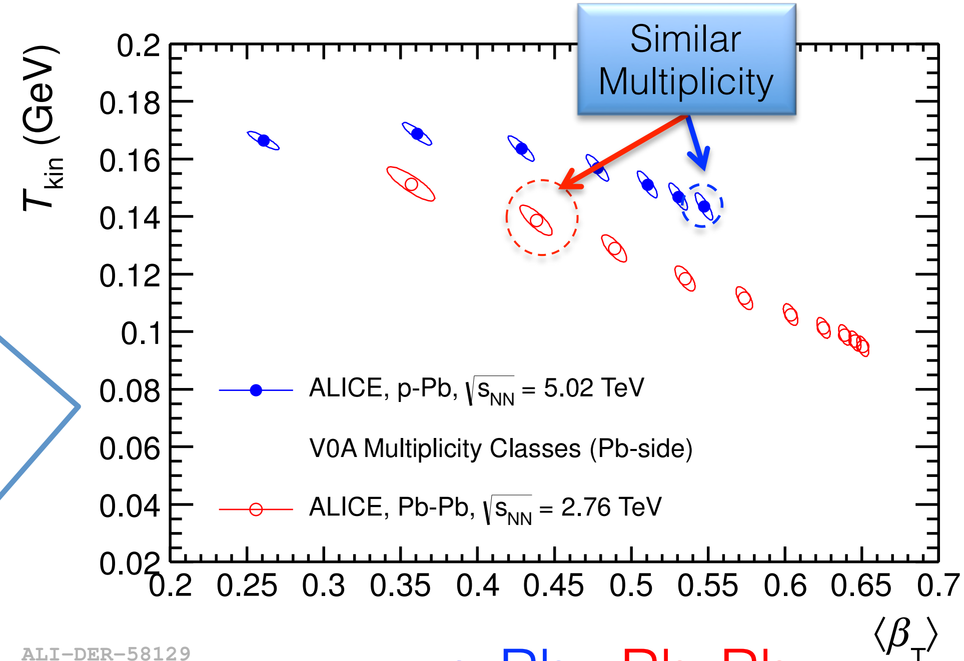
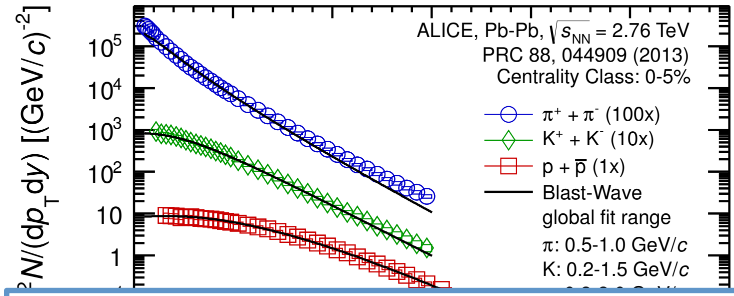


ALI-DER-58129

p-Pb Pb-Pb

Spectral Shapes and the Blast Wave Model



- Qualitatively similar behaviour observed in p-Pb and Pb-Pb in parameter space
- larger radial flow parameter in p-Pb than in Pb-Pb for a given $dN_{ch}/d\eta$
- What about pp ?

- Simultaneous Blast wave fits to π, K, p with a set of parameters:
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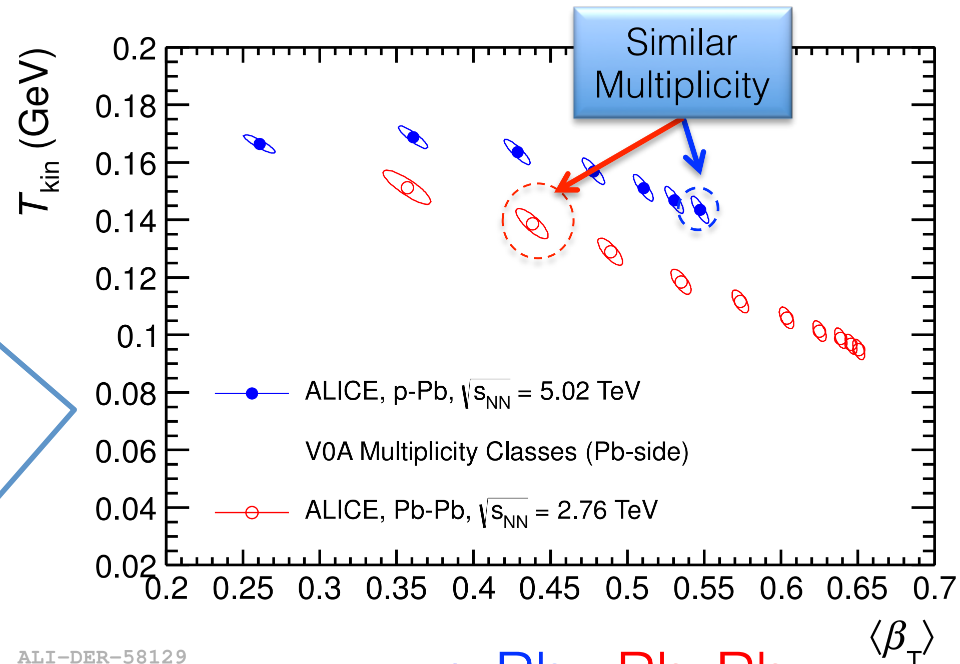

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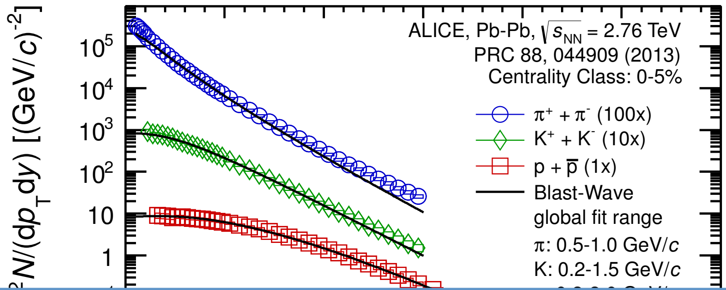

- Measurements versus event multiplicity in pp follow the same trends as in p-Pb

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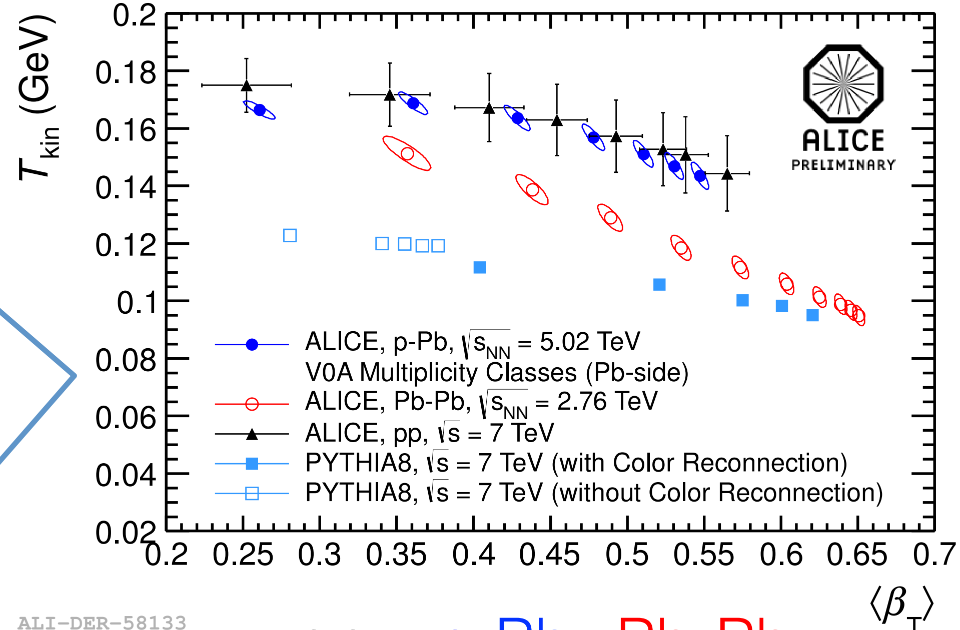

pp p-Pb Pb-Pb

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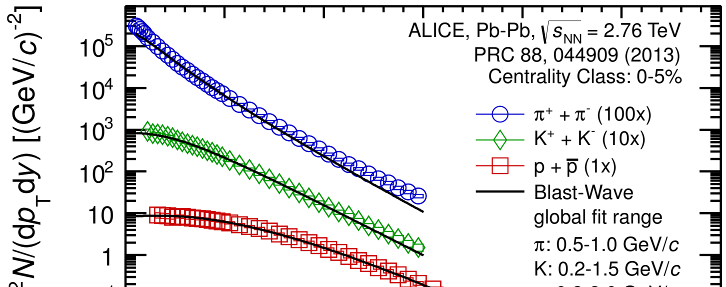
Spectral Shapes and the Blast Wave Model



- Measurements versus event multiplicity in pp follow the same trends as in p-Pb
- Comparisons to MC (PYTHIA) show that mechanisms such as Color Reconnection may introduce similar dynamics

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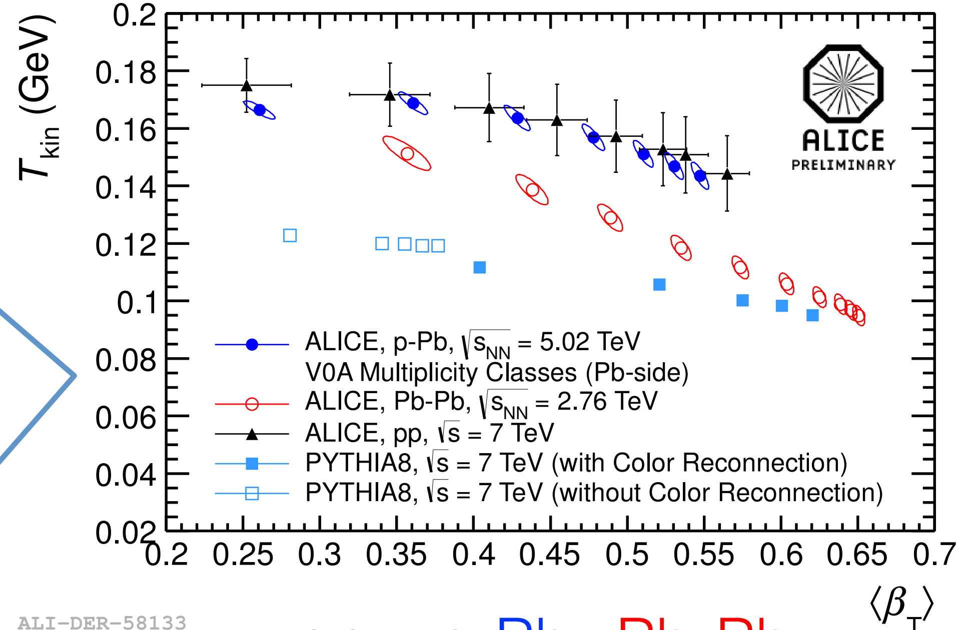

pp p-Pb Pb-Pb

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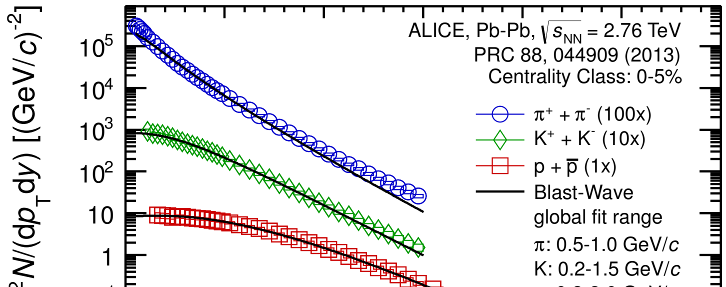

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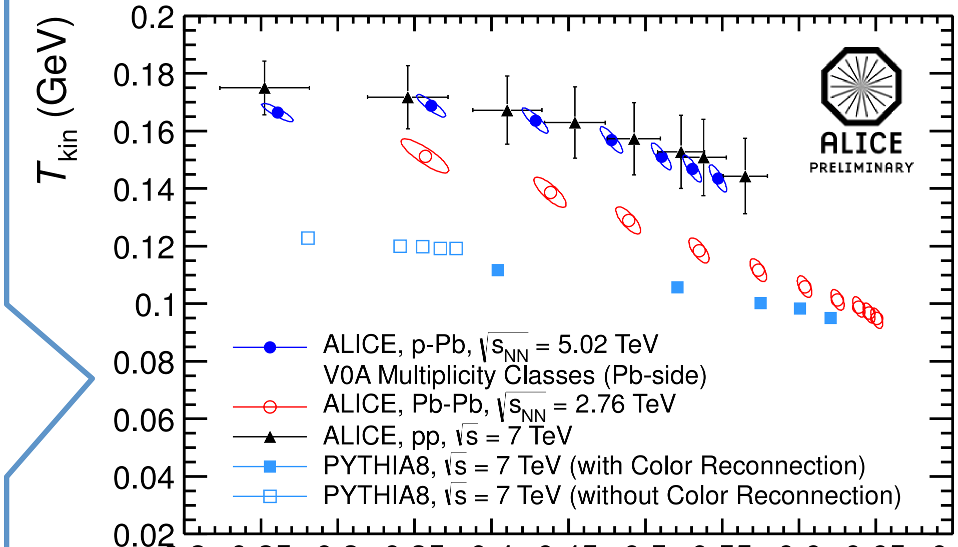

Talk by Barbara Guerzoni
Thursday at 16:00

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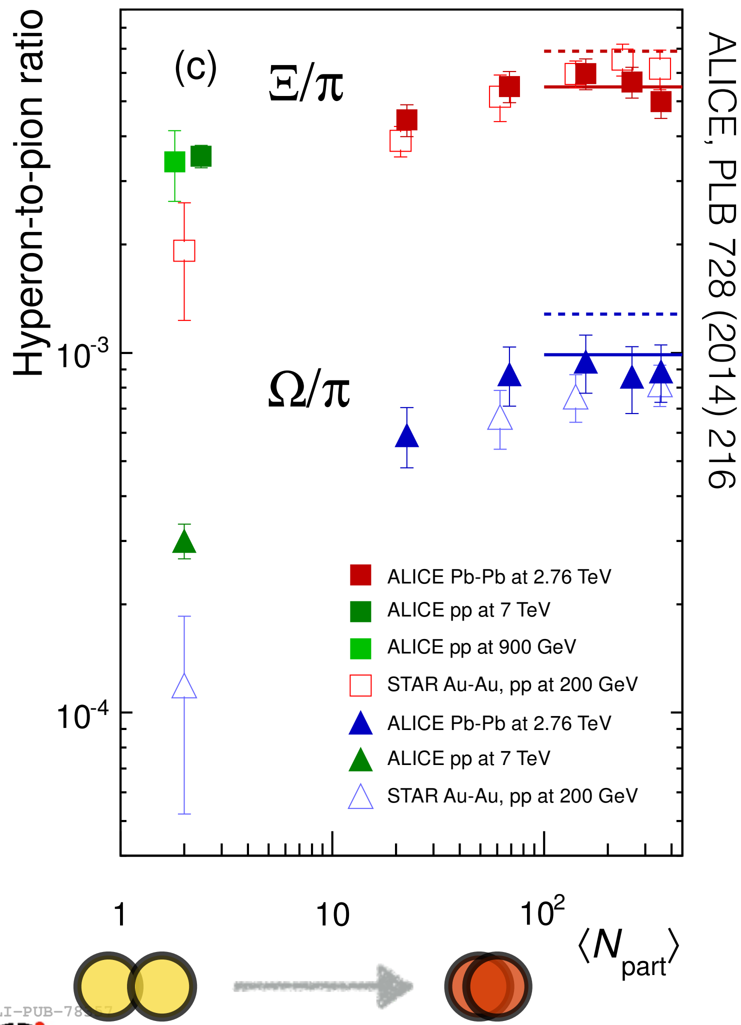
Ξ/π and Ω/π ratios in Pb-Pb



Strangeness enhancement:

One of the first proposed QGP signatures

Rafelski, PRL 48 (1982) 1066

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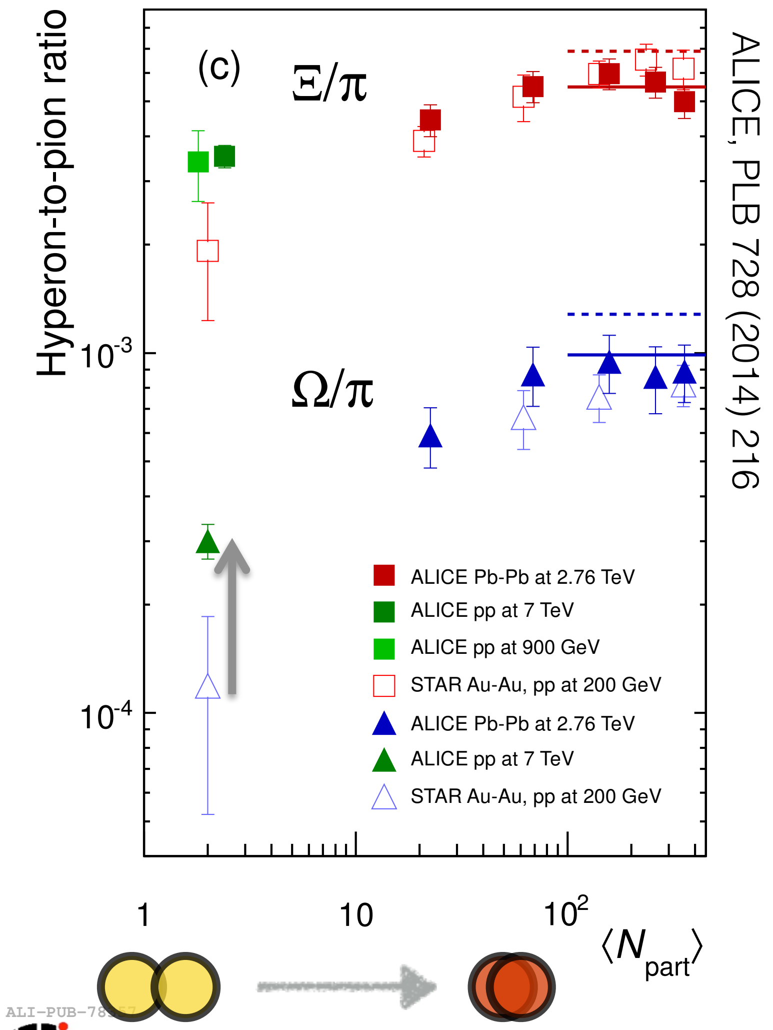

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- Production of strangeness relative to pions in pp collisions is larger at the LHC

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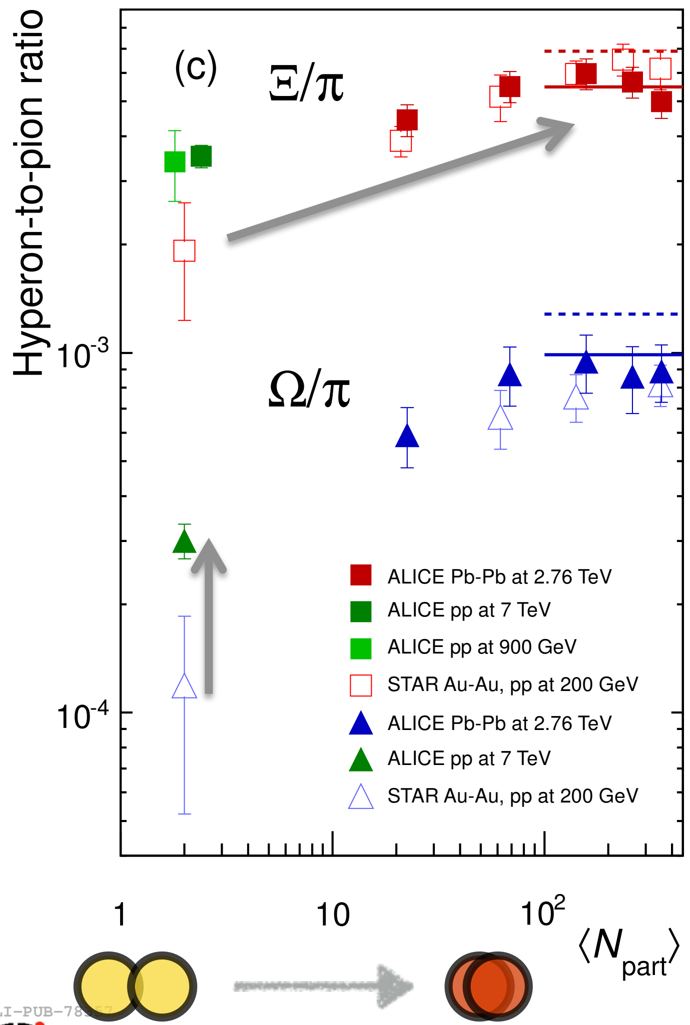

ALICE, PLB 728 (2014) 216

Strangeness enhancement:

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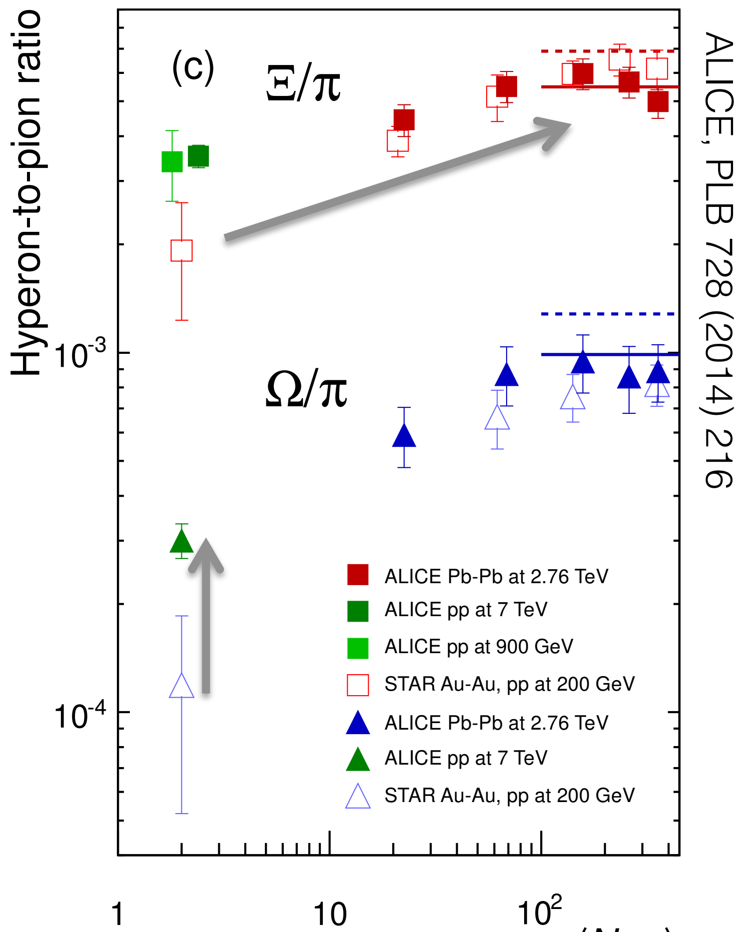
- Production of strangeness relative to pions in pp collisions is larger at the LHC
- Clear increase of strangeness production observed in Pb-Pb with respect to pp

Ξ/π and Ω/π ratios in Pb-Pb



Strangeness enhancement:

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- Production of strangeness relative to pions in pp collisions is larger at the LHC
- Clear increase of strangeness production observed in Pb-Pb with respect to pp
- Ratios saturate for $N_{part} > 150$
- Match predictions from thermal models utilizing Grand Canonical approaches:

GSI-Heidelberg: T_{ch} = 164 MeV

THERMUS: T_{ch} = 170 MeV

ALI-PUB-78357

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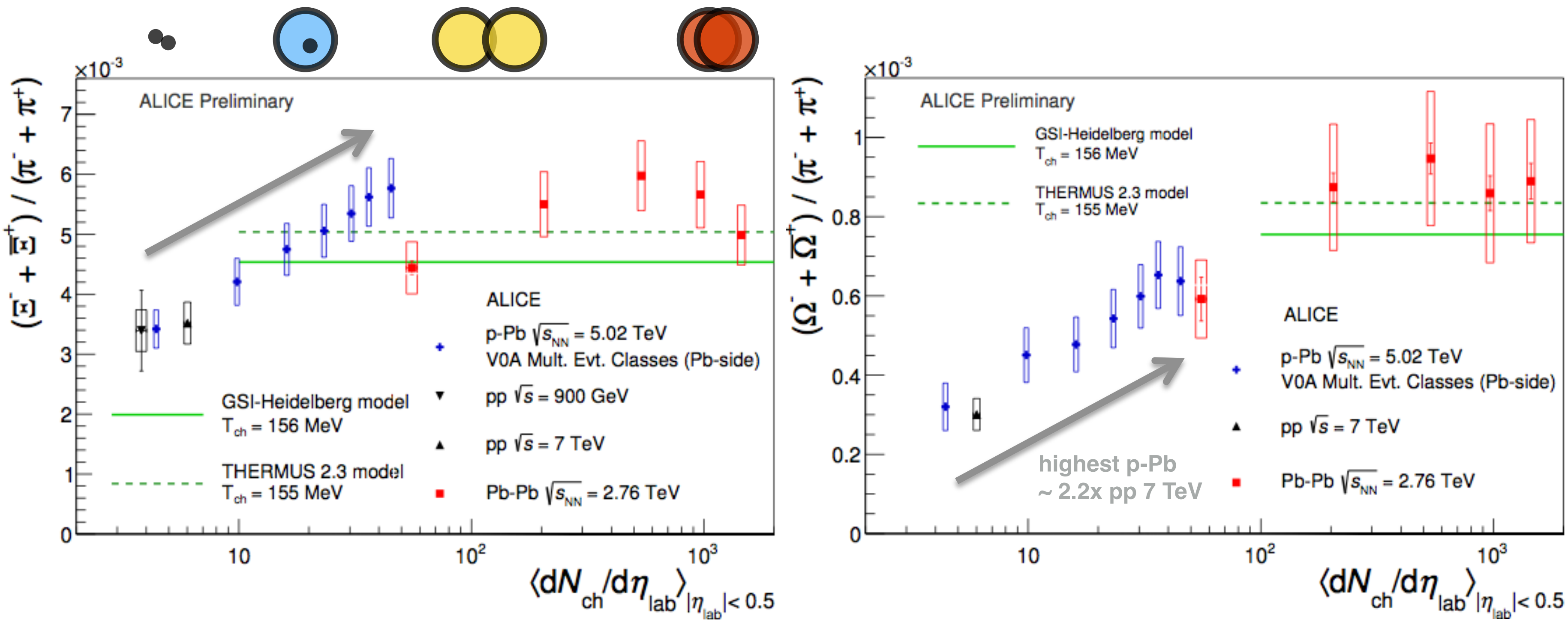
Ξ/π and Ω/π ratios in pp, p-Pb, Pb-Pb



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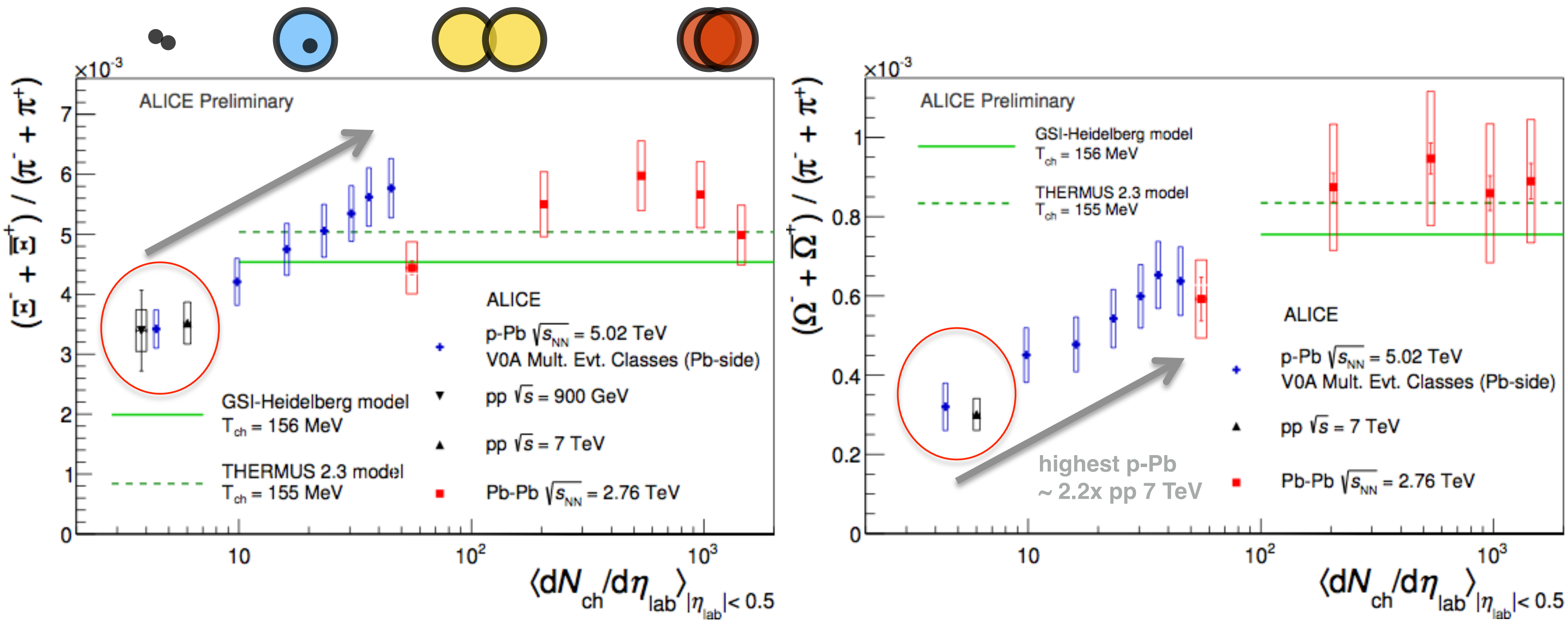
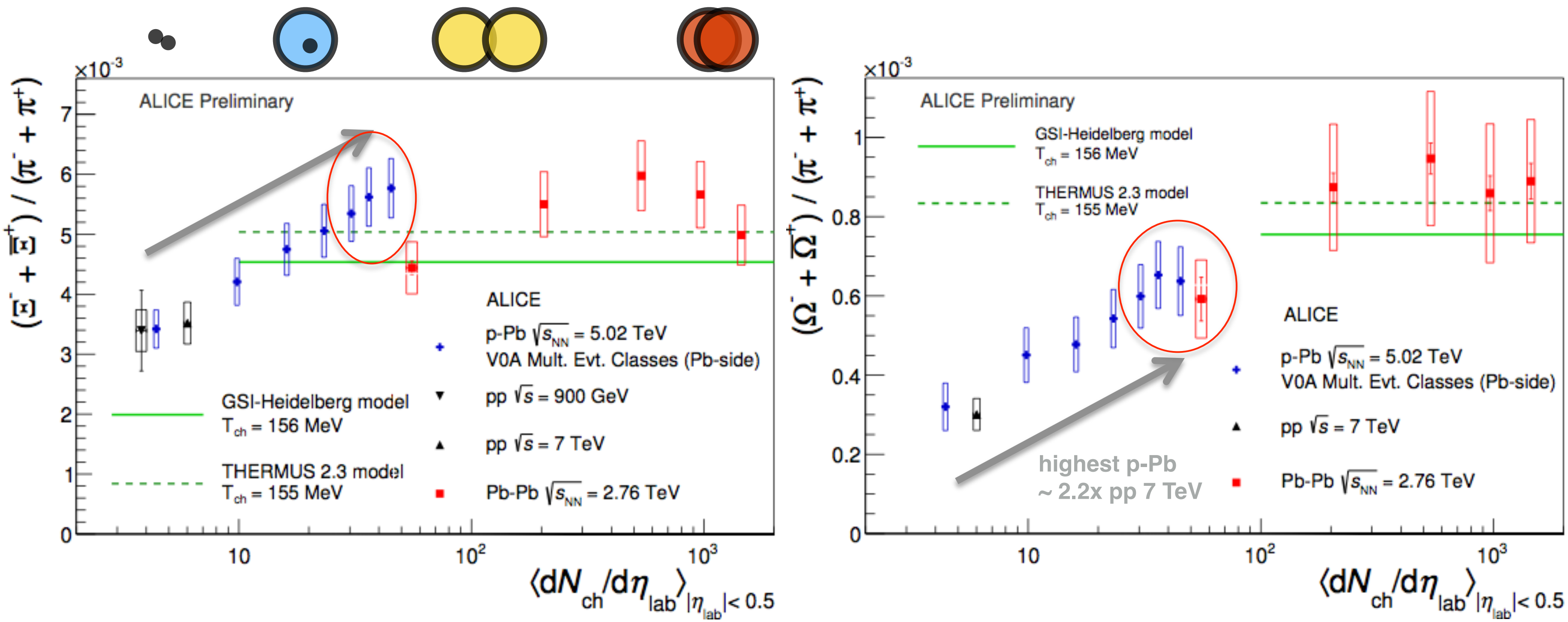
Ξ/π and Ω/π ratios in pp, p-Pb, Pb-Pb



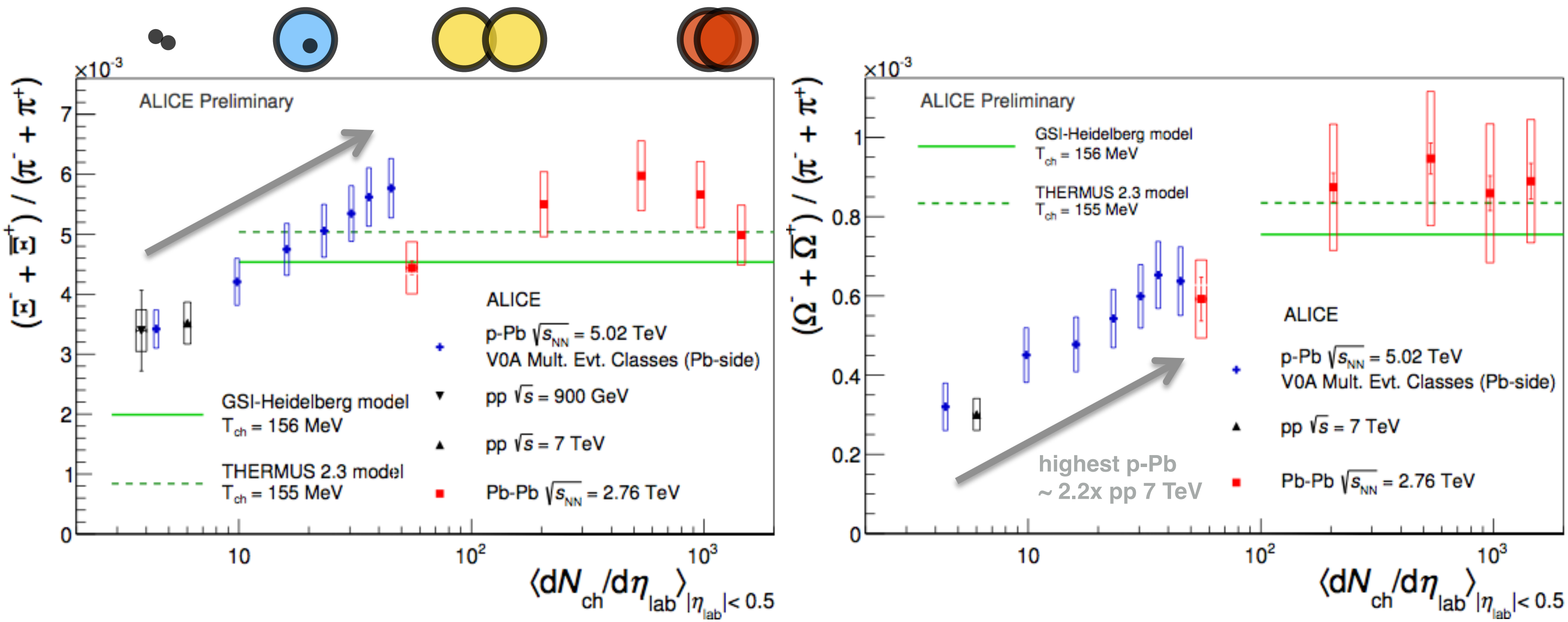
- Ξ/π and Ω/π ratios in p-Pb increase with increasing $\langle N_{ch} \rangle$
- Low Multiplicity: p-Pb consistent with pp measurements

Ξ/π and Ω/π ratios in pp, p-Pb, Pb-Pb



- Ξ/π and Ω/π ratios in p-Pb increase with increasing $\langle N_{ch} \rangle$
- Low Multiplicity: p-Pb consistent with pp measurements
- High Multiplicity:
  - Ξ/π in p-Pb consistent with central Pb-Pb
  - Ω/π in p-Pb consistent with peripheral Pb-Pb

Ξ/π and Ω/π ratios in pp, p-Pb, Pb-Pb



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  - Ω/π in p-Pb consistent with perip

Talk by Maria Nicassio
Friday at 17:20

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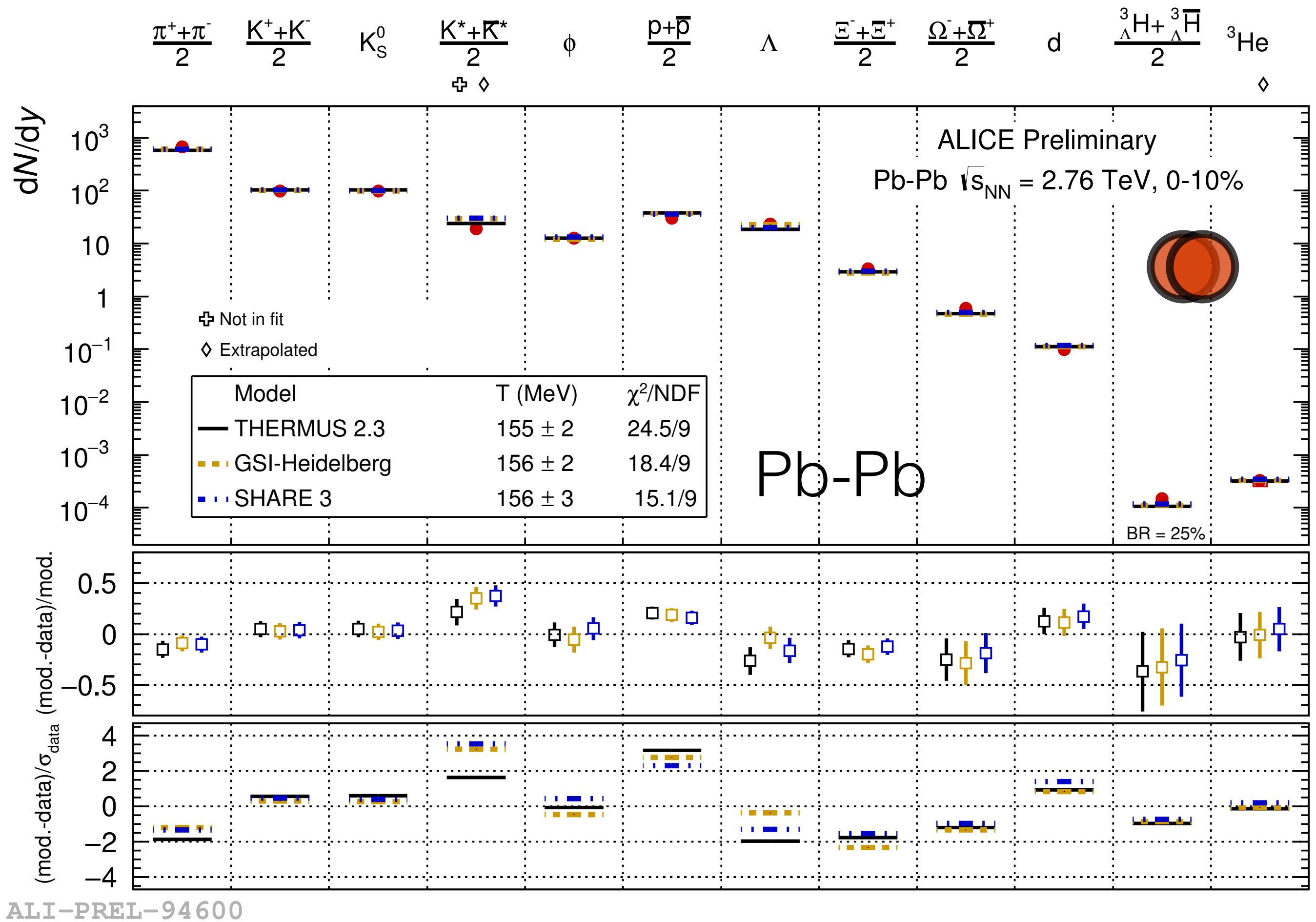
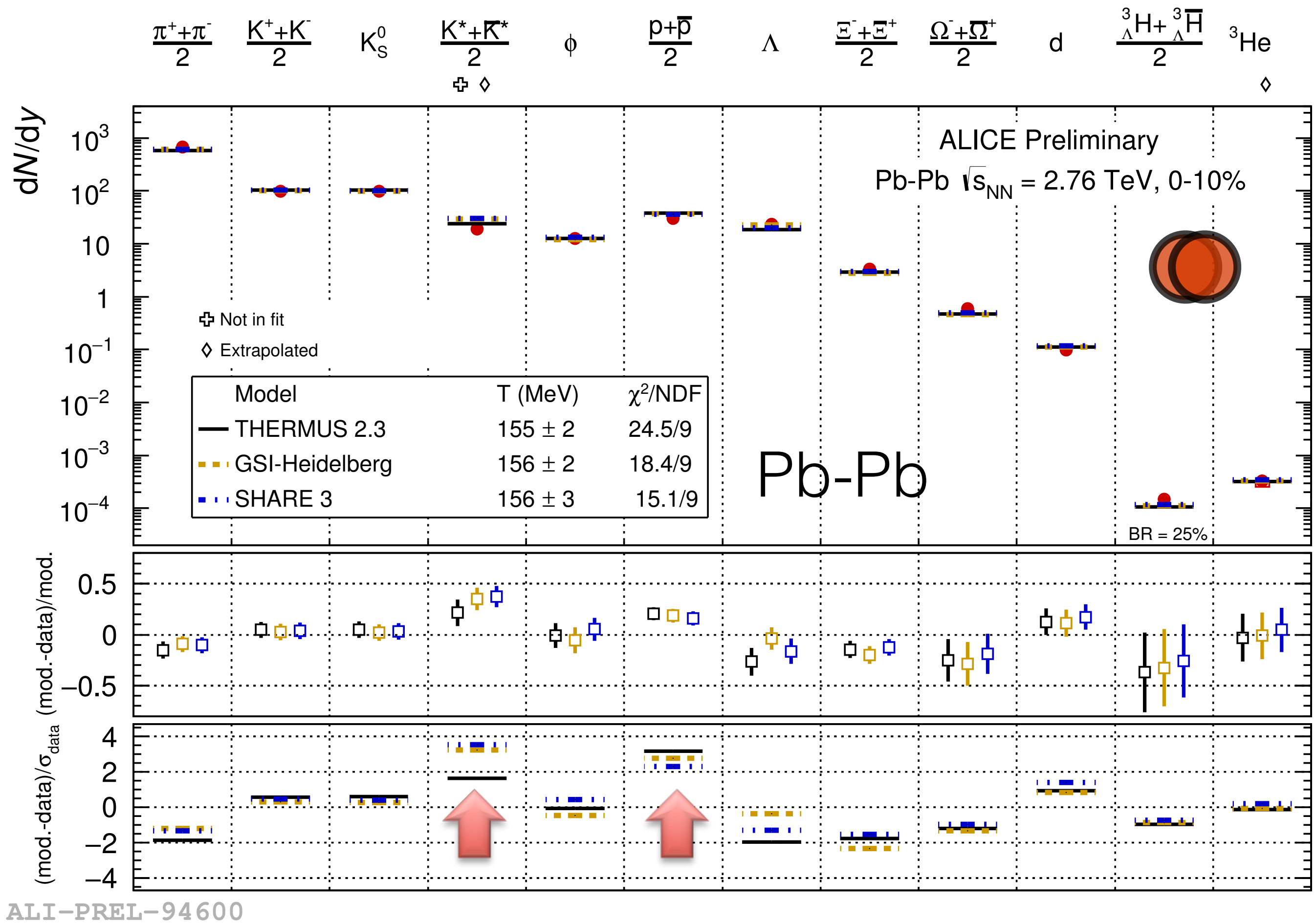
Thermal model of particle production



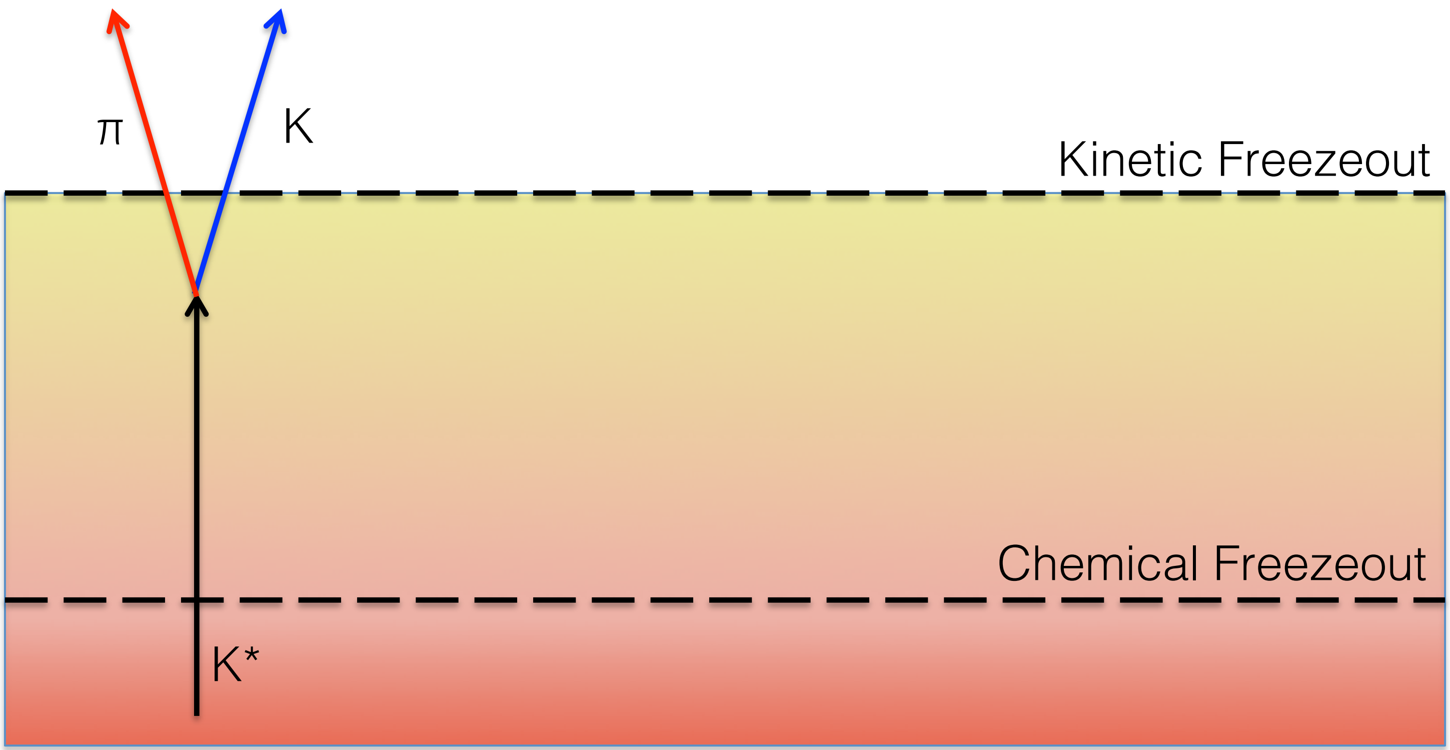
- Description of hadron yields in a thermally equilibrated regime: same conclusions from different implementations, T_{ch} ~156 MeV
- d*N*/d*y* of many species in Pb-Pb well described: χ^2/ndf ~2

Thermal model of particle production



Differences (p, K*) could hint at final-state interactions; other mechanisms under investigation (non-equilibrium, flavour hierarchy…)

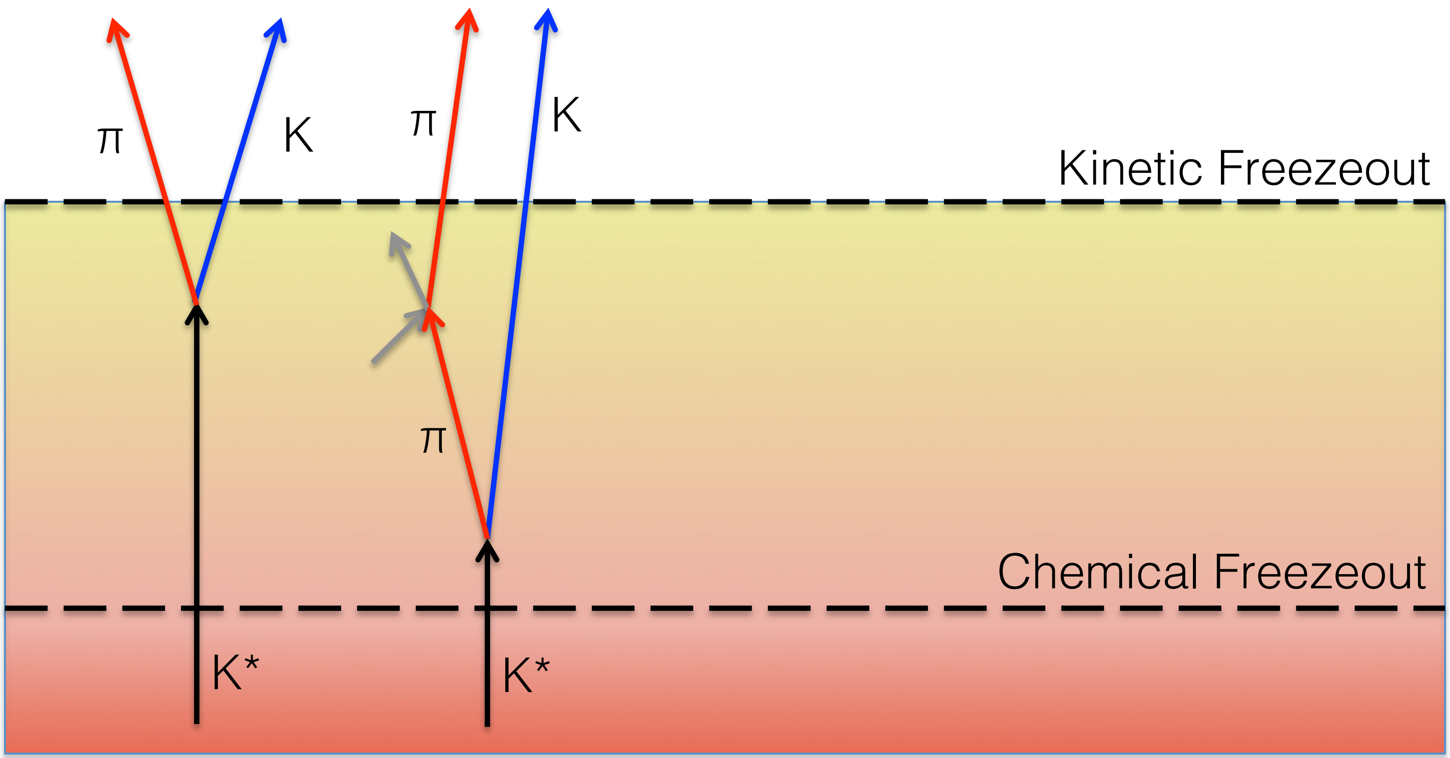
Resonances, Rescattering and Regeneration



- Consider the short-lived K* resonance (~4 fm/c)
  - Usual scenario: decay in the hadronic phase

4. Understanding of the late hadronic stage of the collision

Resonances, Rescattering and Regeneration



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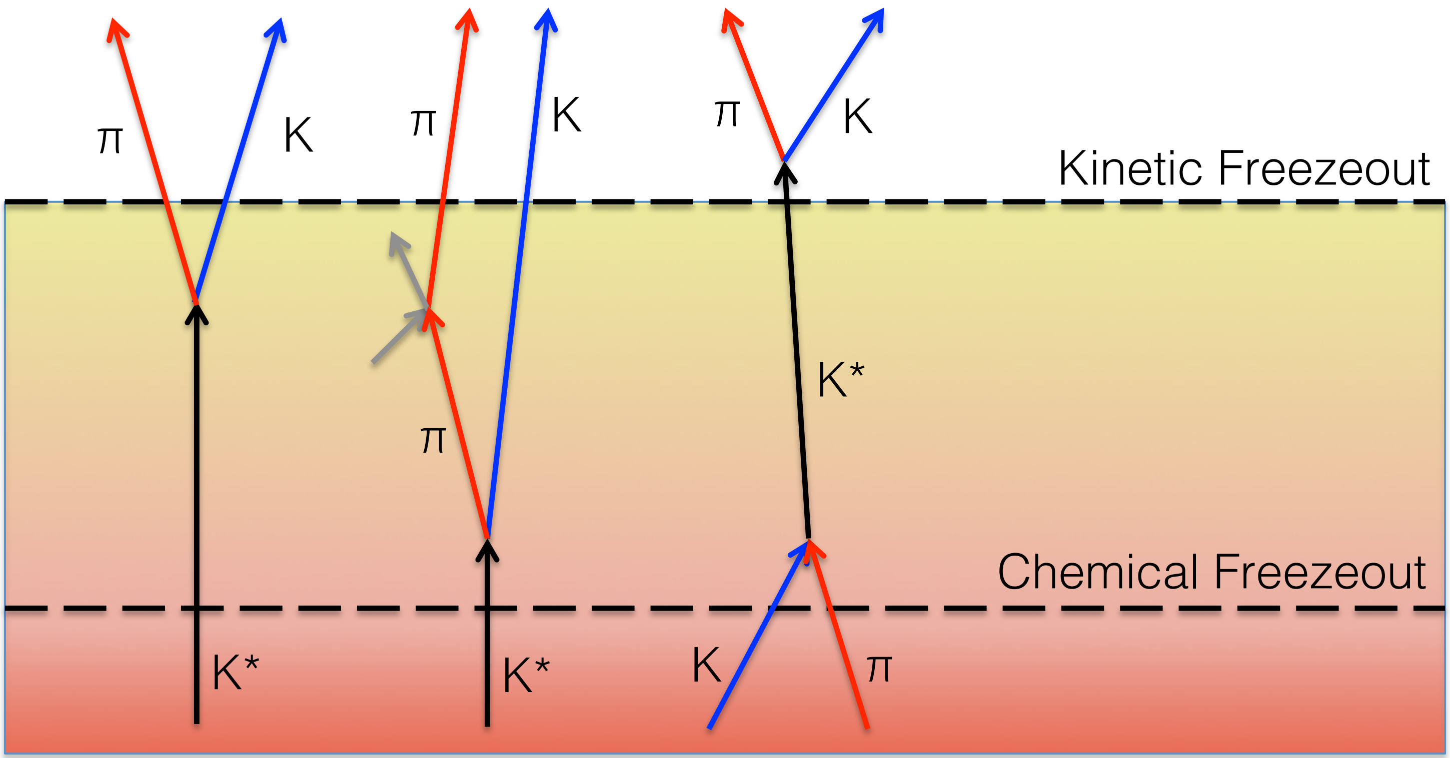

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  - Daughters may re-scatter and yield may not be visible
  - Regeneration (pseudo-elastic scattering) may recover part of the yield

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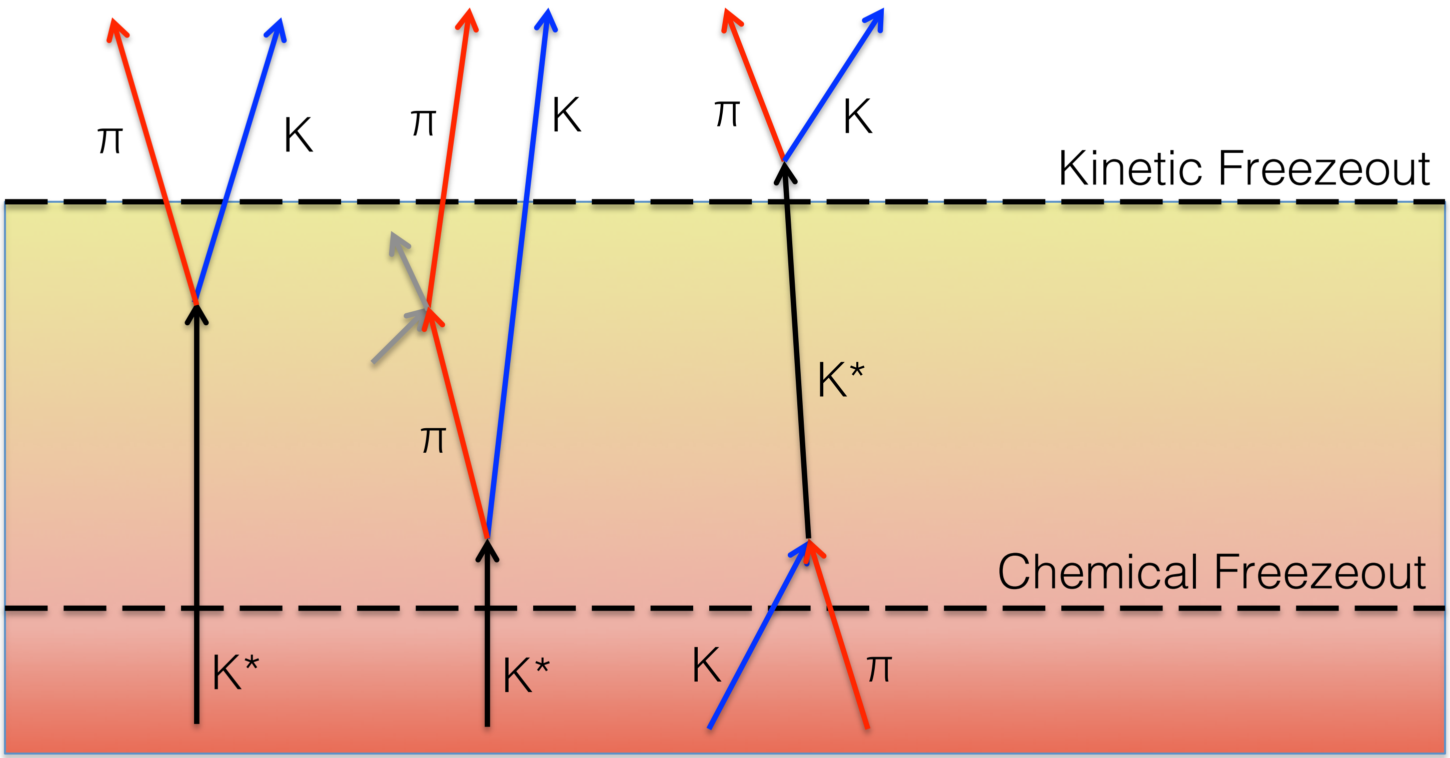

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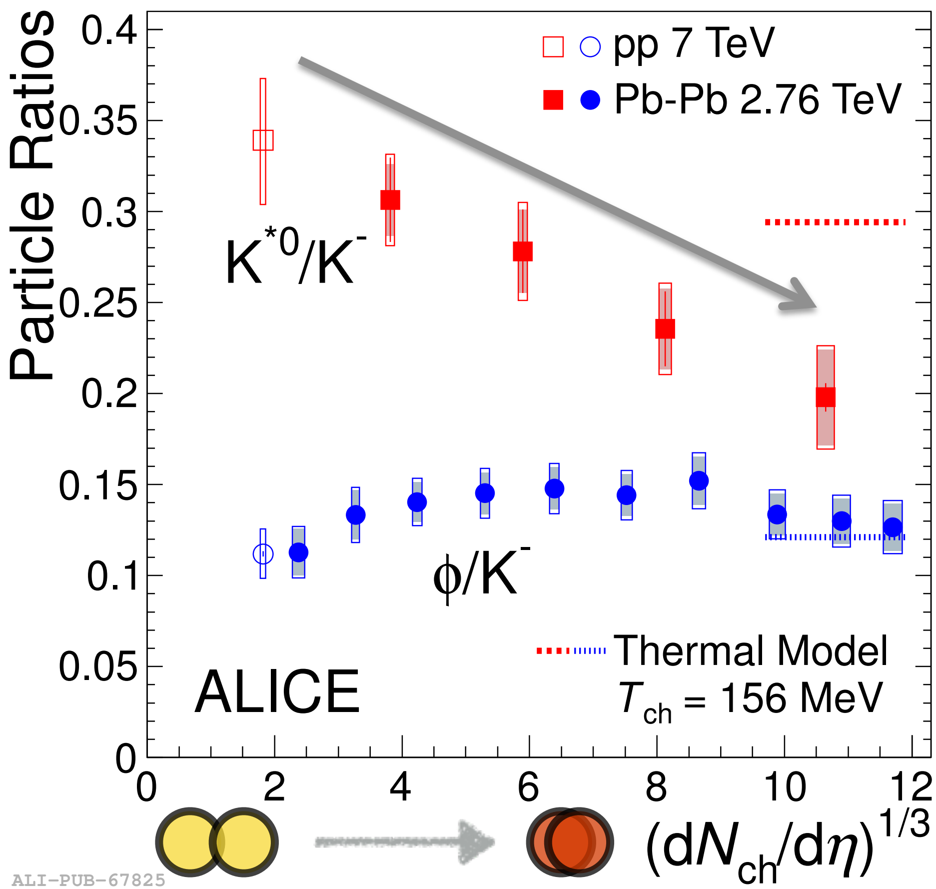
  - Usual scenario: decay in the hadronic phase
  - Daughters may re-scatter and yield may not be visible
  - Regeneration (pseudo-elastic scattering) may recover part of the yield

Resonances: probe (the duration of) the hadronic stage

K* and ϕ production rates in Pb-Pb

ALICE, arXiv:1404.0495 [nucl-ex]



- Clear suppression observed in K*/K- when going from pp to central Pb-Pb collisions
- Not observed for ϕ/K-
- Likely due to re-scattering of K* decay daughters with final-state hadronic medium

τ_{K^*} (~4 fm/c) ≪ τ_ϕ

K* and ϕ production rates in Pb-Pb

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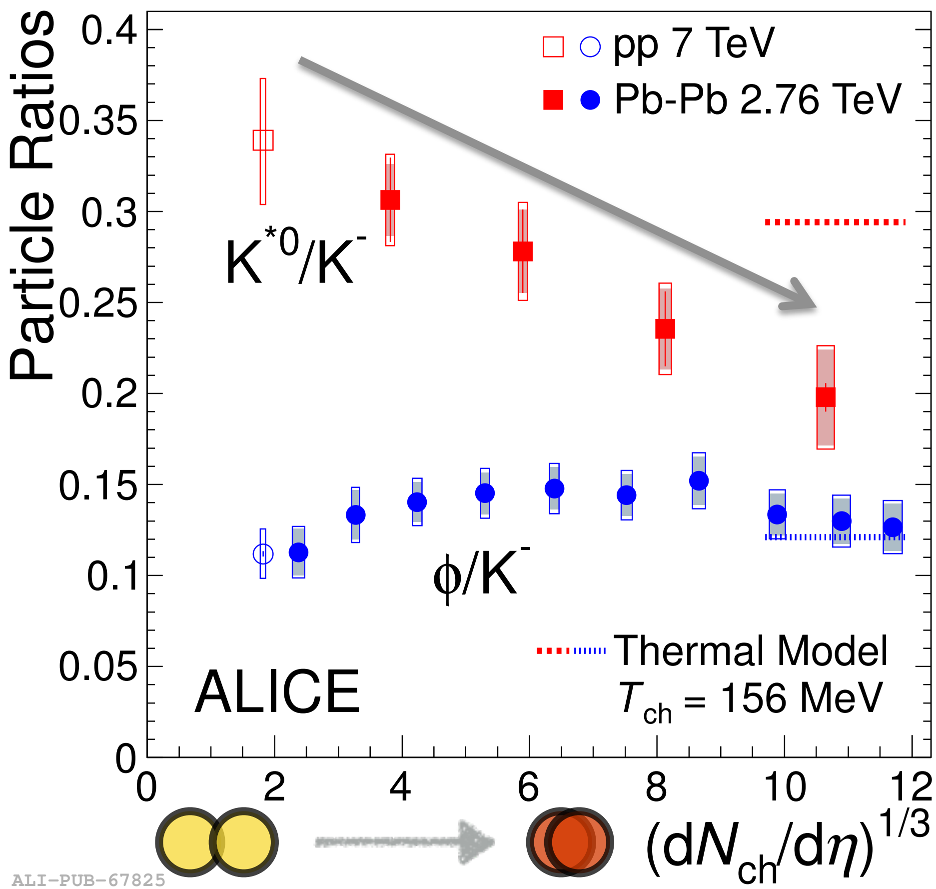
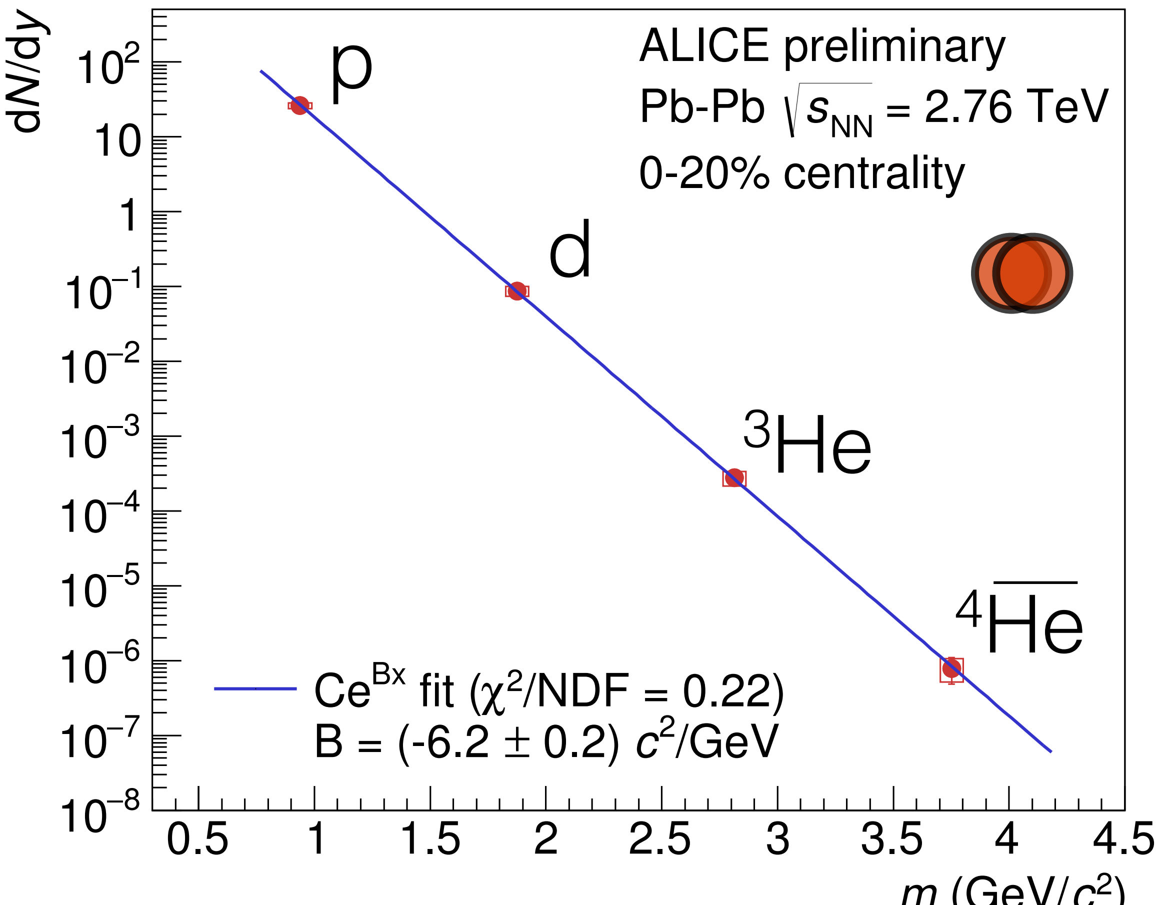


- Clear suppression observed in K^*/K^- when going from pp to central Pb-Pb collisions
- Not observed for ϕ/K^-
- Likely due to re-scattering of K* decay daughters with final-state hadronic medium

τ_{K^*} (~4 fm/c) ≪ τ_ϕ

Talk by Viktor Riabov
Friday at 18:00

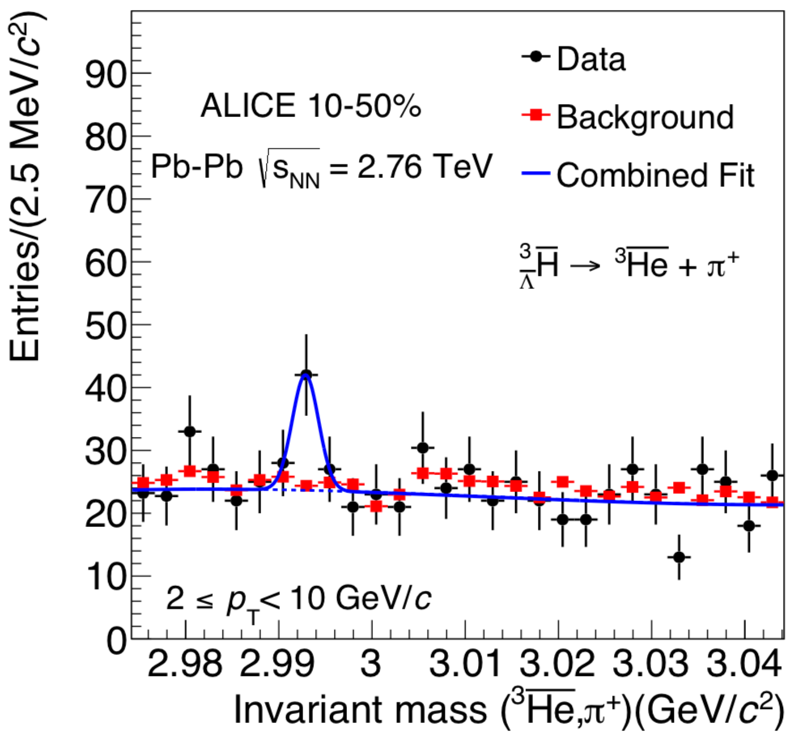
Anti-α production in Pb-Pb Collisions

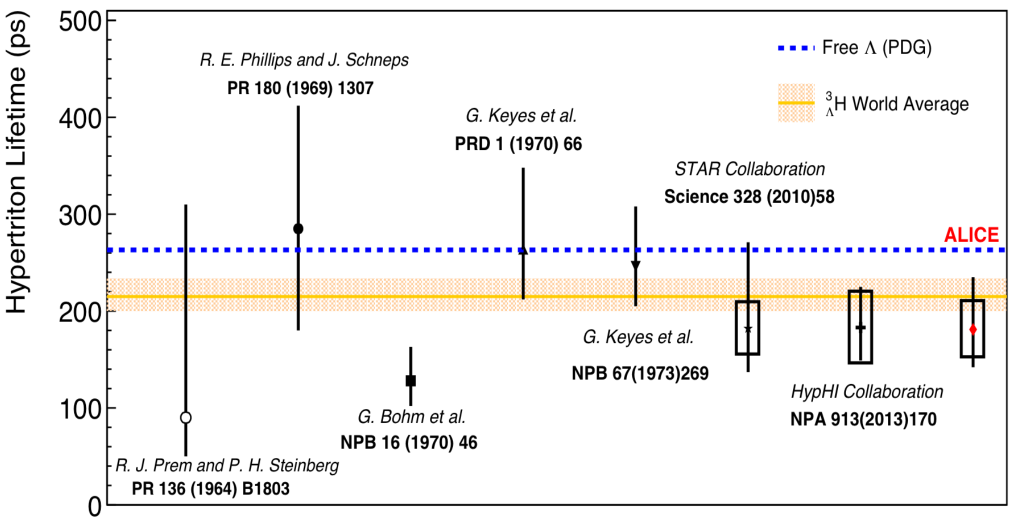


ALI-PREL-94596

- First observed at RHIC in heavy-ion collisions
- Production rates (dN/dy) follows expected exponential fall with mass
- Approximate 300x penalty factor for each added baryon
- Characteristic slope:
  - ~161 MeV/c^2

Hypertriton Production and Lifetime





ALICE, arXiv:1506.08453 [nucl-ex]

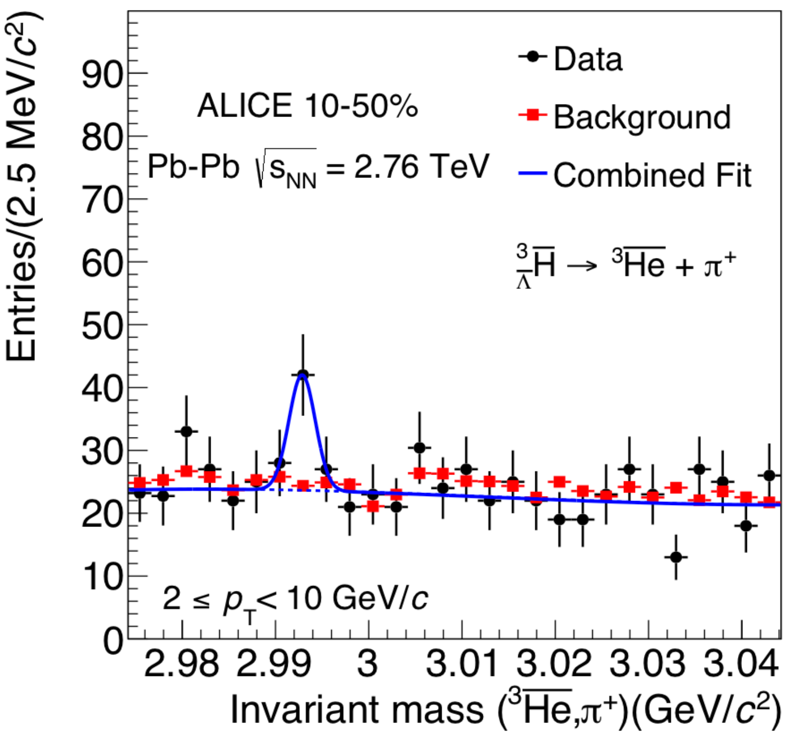
Weak decay of the lightest hypernucleus:

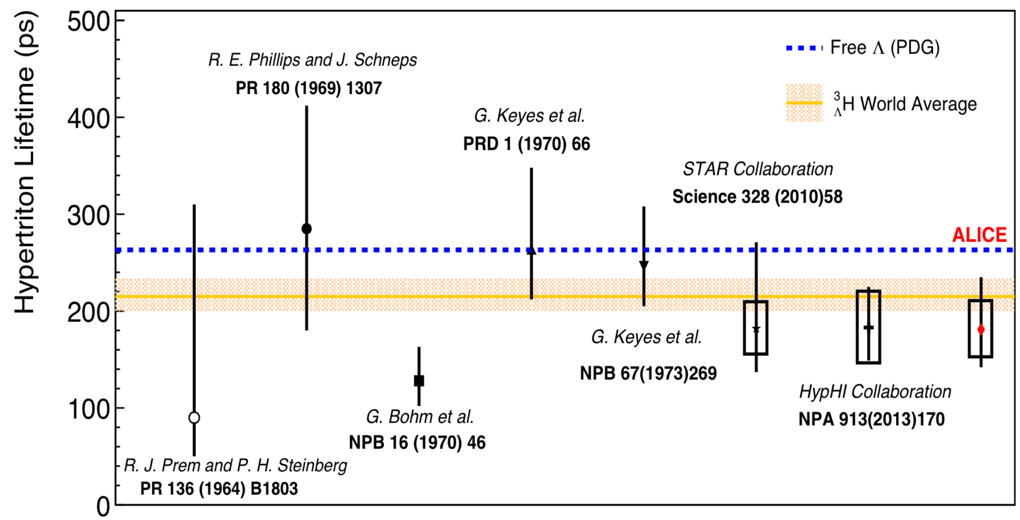
$^{3}{}_{\Lambda}H \rightarrow {}^{3}He\ \pi$

Reconstructed via decay topology + ^{3}He and π PID

5. Nuclei production and Searches for Exotica

Hypertriton Production and Lifetime





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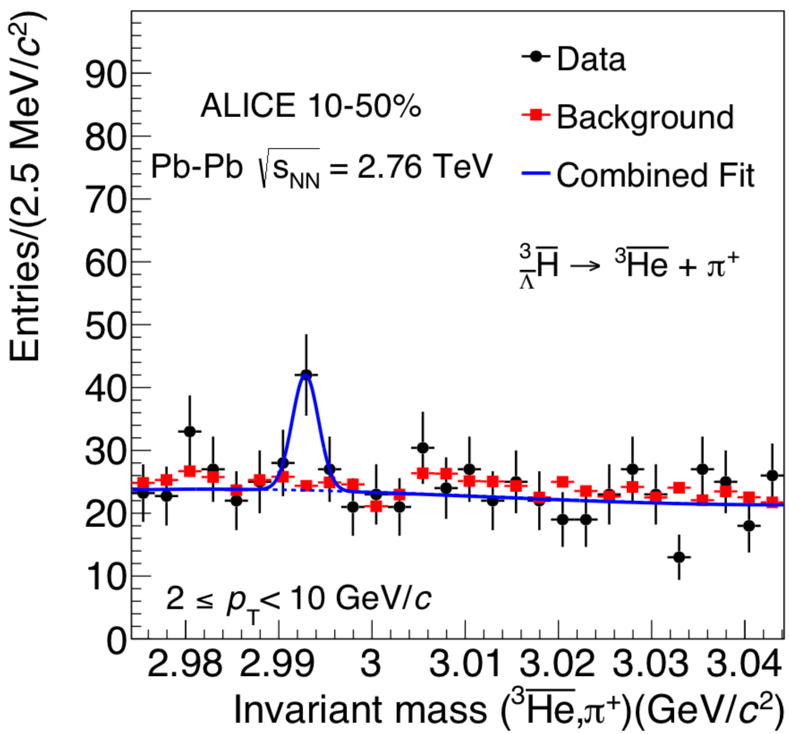
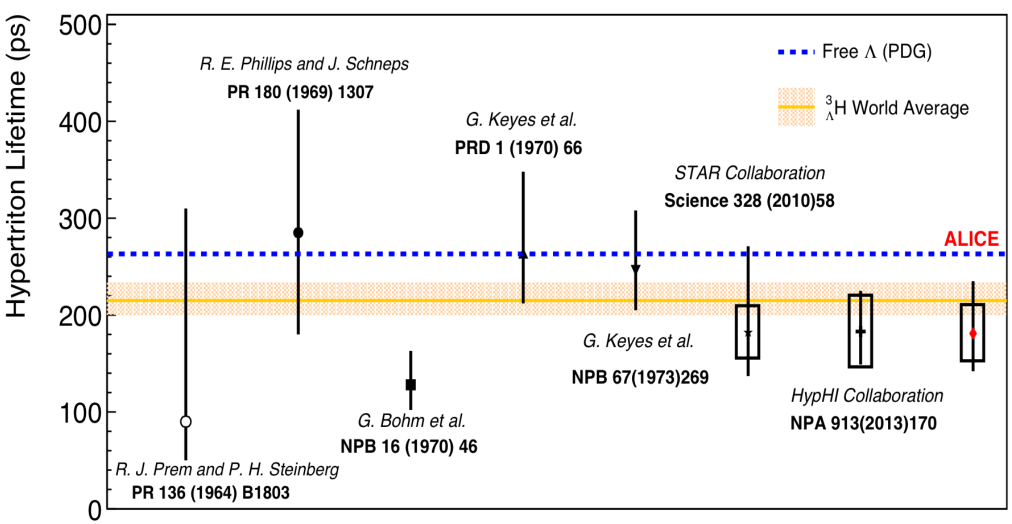
  - …despite very low binding energy of 0.13 MeV

Hypertriton Production and Lifetime





ALICE, arXiv:1506.08453 [nucl-ex]

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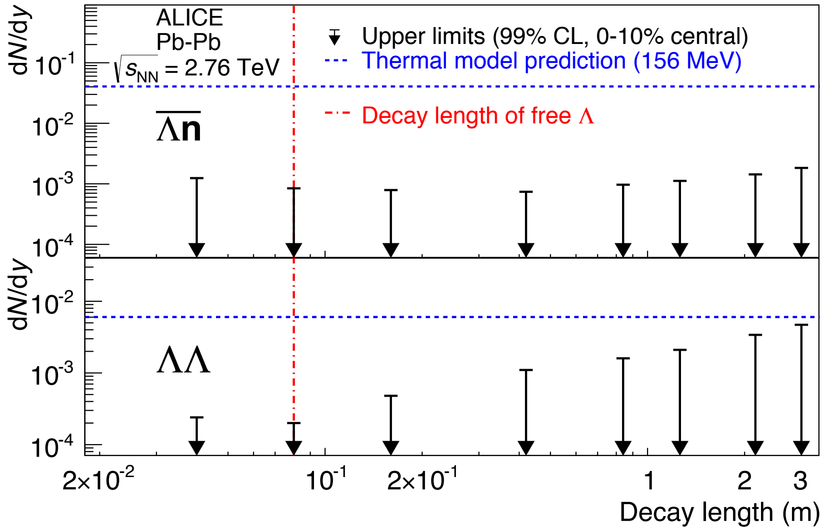
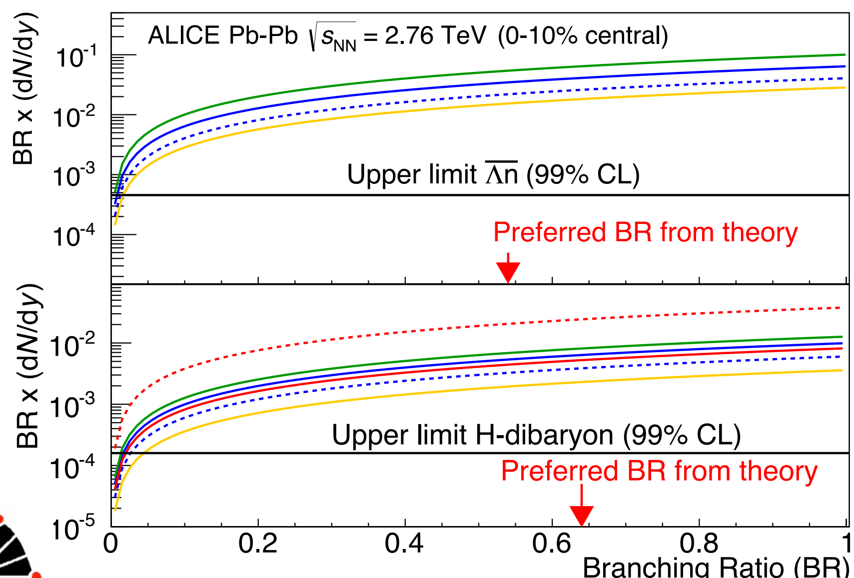
Reconstructed via decay topology + ^{3}He and π PID

- Production Rates consistent with thermal models, T_{ch} = 156 MeV
  - …despite very low binding energy of 0.13 MeV
- Lifetime measurement in line with that of other experiments

Searches for Exotica





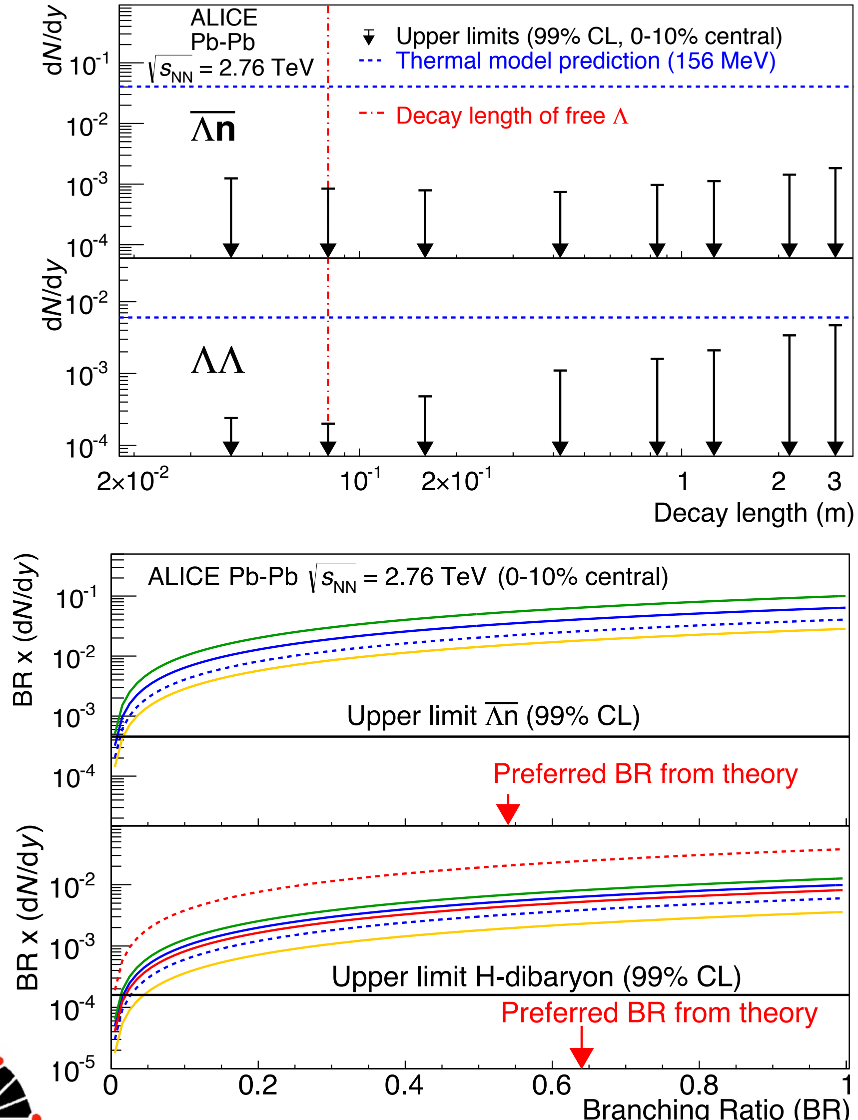
ALICE, arXiv:1506.07499 [nucl-ex]

- Searches for exotic particles such as dibaryons:

$$\overline{\Lambda n} \rightarrow d\,\pi$$
$$\Lambda\Lambda \rightarrow \Lambda\, p\, \pi$$

Searches for Exotica

ALICE, arXiv:1506.07499 [nucl-ex]



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- 99% confidence level limits are significantly below thermal model predictions

Searches for Exotica

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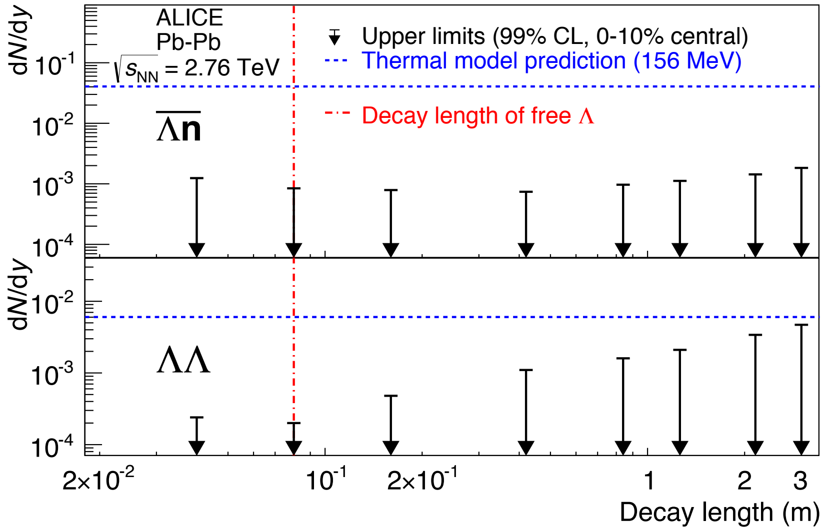

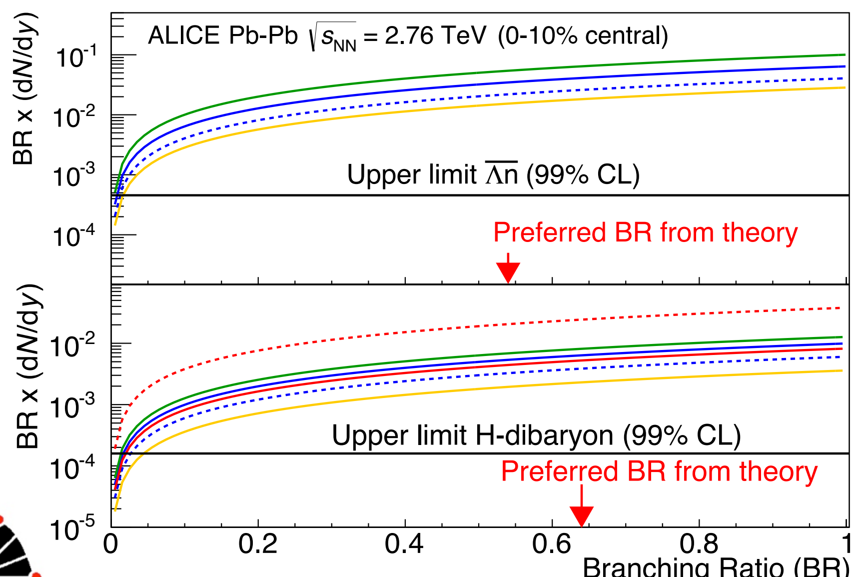

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Talk by Francesco Barile
Thursday at 17:40

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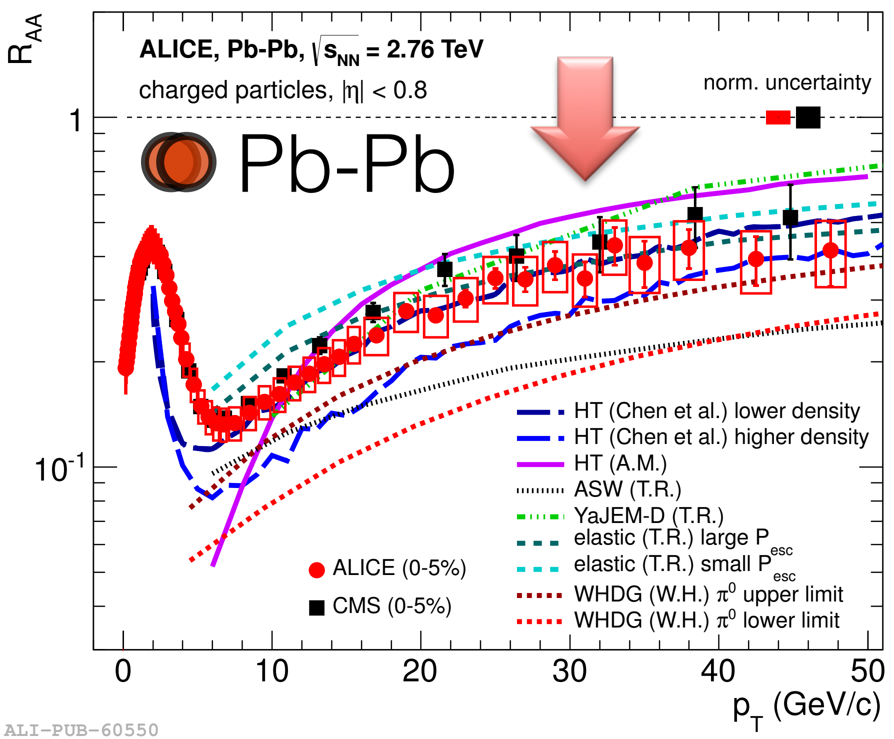
Nuclear Modification Factor

ALICE, PLB 720 (2013) 52



- partons produced in high Q^2 processes lose energy while traversing the medium
- Causes modification (suppression) of high-p_T production
- Quantified via calculation of the nuclear modification factor:

$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

R_{AA} = 1 for hard processes in absence of nuclear effects
(confirmed in Pb-Pb collisions at the LHC for direct γ, Z^0, $W^{\pm}$)

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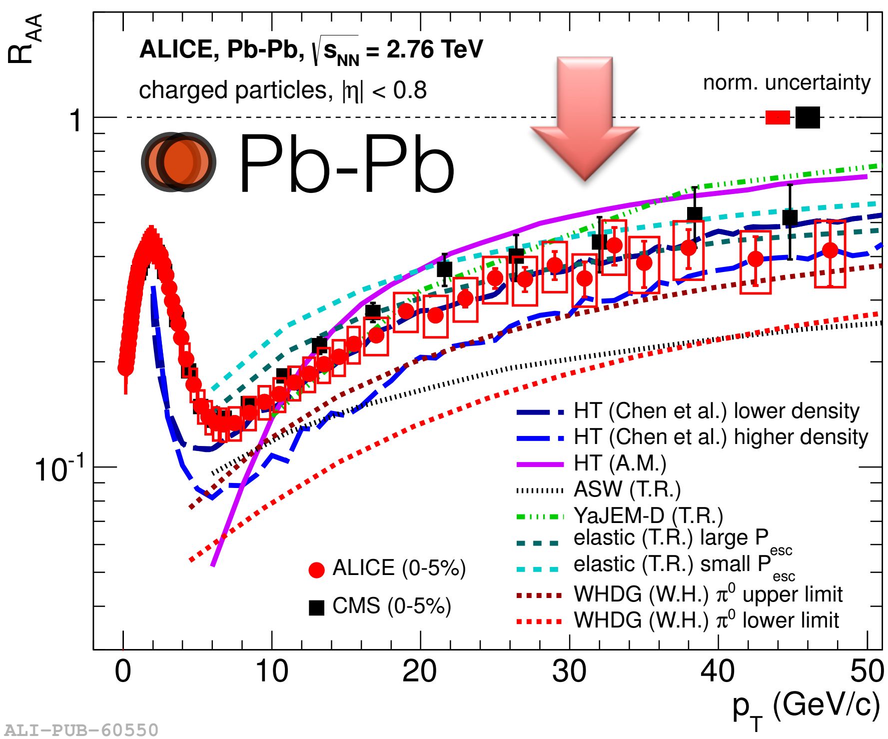
6. Study of energy loss while traversing the medium

Nuclear Modification Factor

ALICE, PLB 720 (2013) 52



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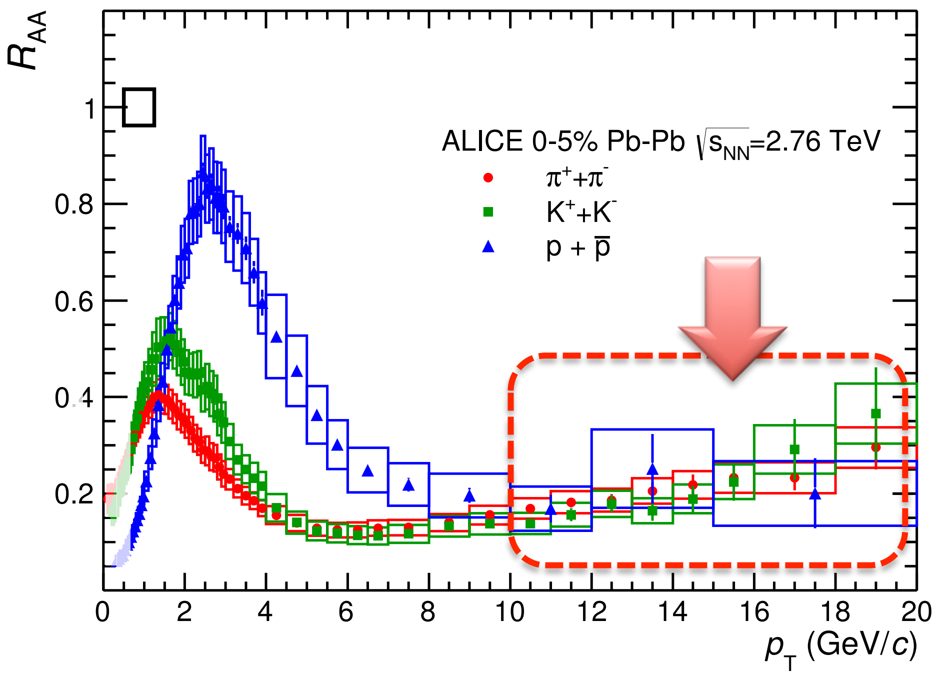
Spectra of charged particles are strongly suppressed over a wide transverse momentum range in Pb-Pb collisions

6. Study of energy loss while traversing the medium

Nuclear Modification Factor

arXiv:1506.07287v1



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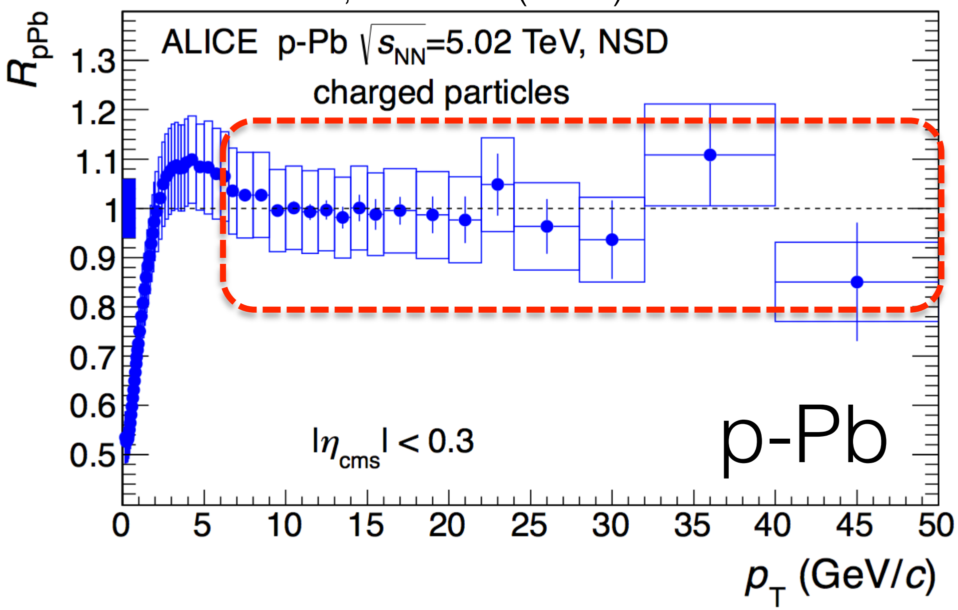
$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

….and the suppression factor is observed to be the same for different particle species at p_T > 10 GeV/c

Nuclear Modification Factor in p-Pb

ALICE, PRL 110 (2013) 082302
ALICE, EPJC 74 (2014) 3054



- p-Pb collisions can be used as a control experiment: hot nuclear matter is absent, disentanglement of cold nuclear matter and initial state effects from other phenomena
- No modification up to 50 GeV/*c*

Nuclear Modification Factor in p-Pb

ALICE, PRL 110 (2013) 082302
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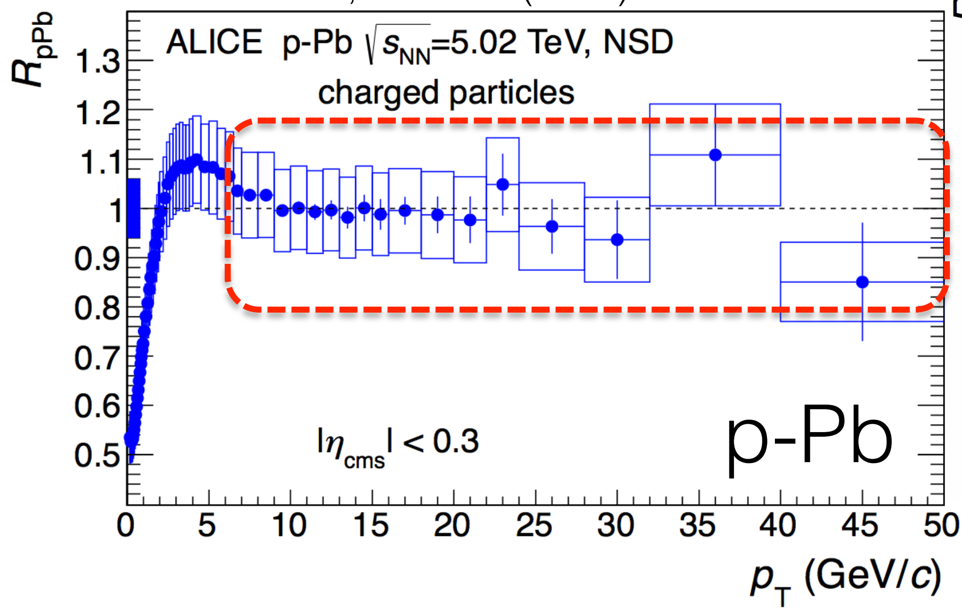

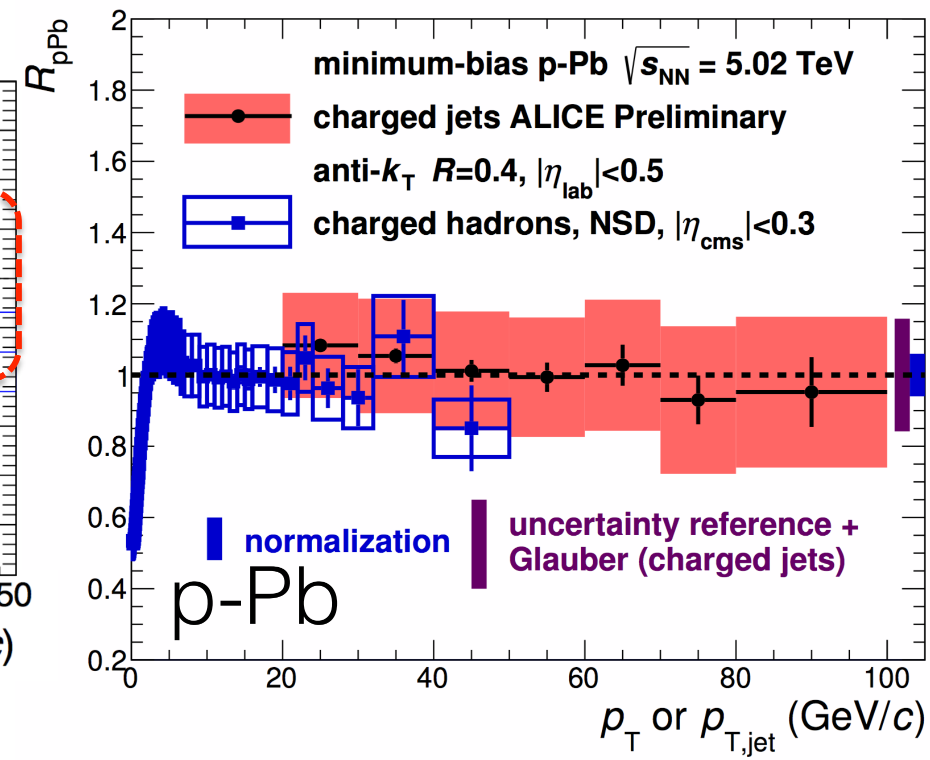

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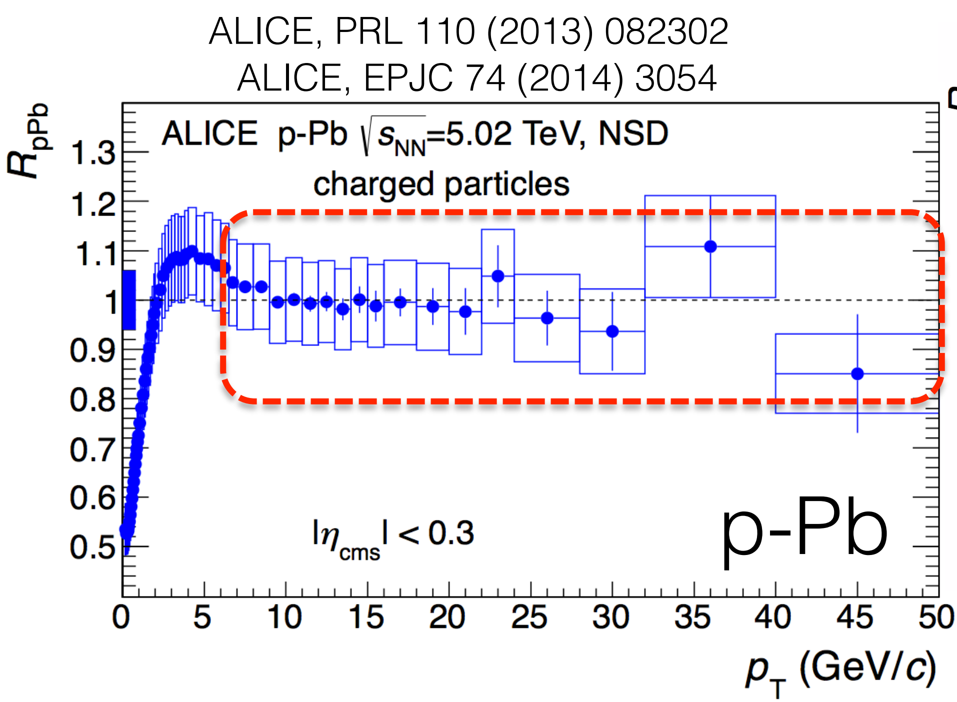
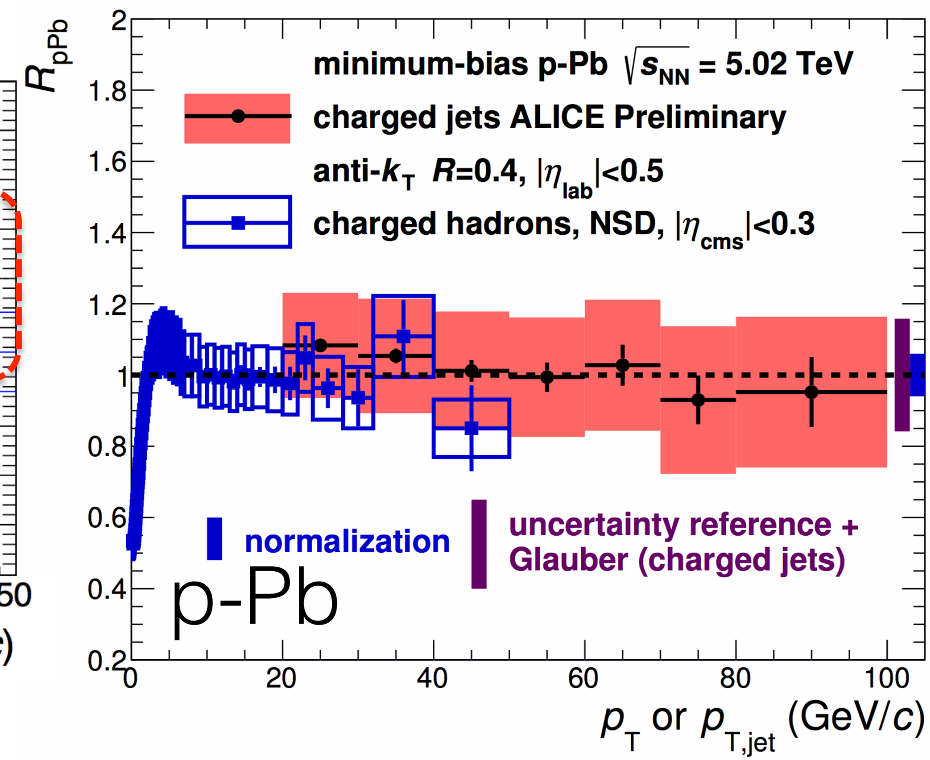
- No modification up to 50 GeV/c
- Jet measurements: no modification up to 100GeV/c

Nuclear Modification Factor in p-Pb





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- No modification up to 50 GeV/c
- Jet measurements: no modificati

Talk by Giacomo Volpe
Thursday at 15:40

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Summary (I)

1. Signatures of Collective Behaviour
   - In Pb-Pb, indicative of hydrodynamics evolution
   - Observed to a lesser degree in pp, p-Pb: Further studies warranted?

2. Strangeness Enhancement
   - Seen clearly in Pb-Pb, evolution of ratios observed in p-Pb
   - Measurement of interest: how does pp evolve with multiplicity?
     - Answer will come soon, also using Run II data at 13 TeV!

3. Thermally Equilibrated Particle Production
   - Observed to be a good description of Pb-Pb data
   - Where does the description fail? Clues on hadronic phase

4. Understanding the Late Hadronic Stage
   - Resonances as probes: lifetime(s) comparable of that of the fireball
   - Intermediate lifetime resonance measurements ongoing

Summary (II)

5. Nuclei and Exotica Measurements

- ^{3}He, ^{4}He, $^{3}_{\Lambda}$H in Pb-Pb: consistent with thermal model expectations
- Exotica Seaches: $\overline{\Lambda}$n and ΛΛ dibaryons unlikely to exist

6. Energy Loss in the Medium

- R_{AA} shows significant suppression in Pb-Pb up to very large p_T
- R_{pPb}: no suppression if no hot nuclear matter present

Stay tuned for results from Run II at larger energies!

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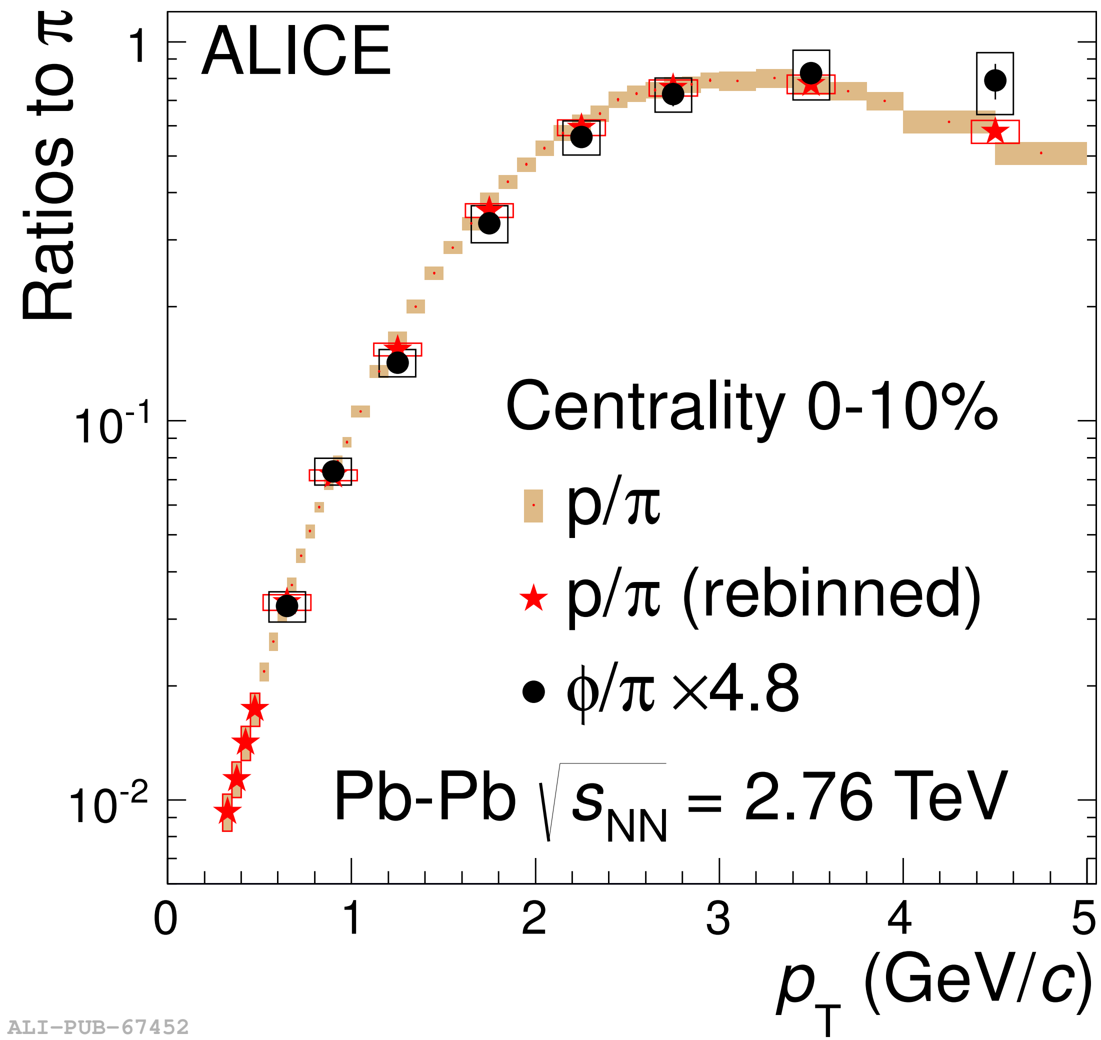
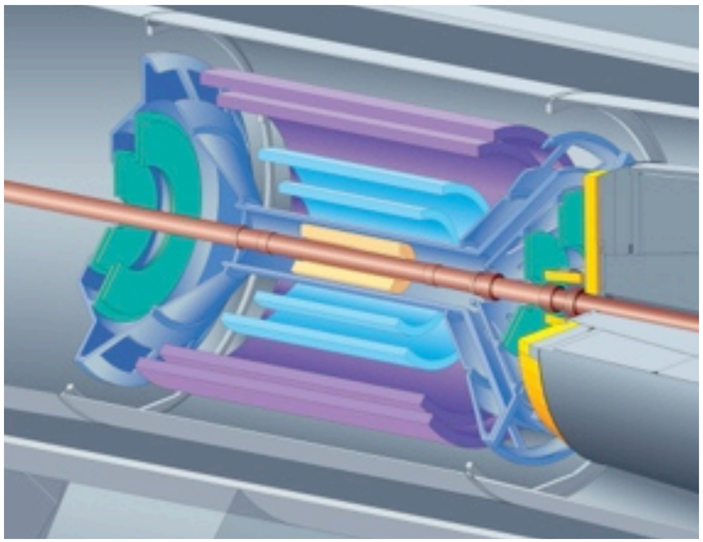
Thank you!

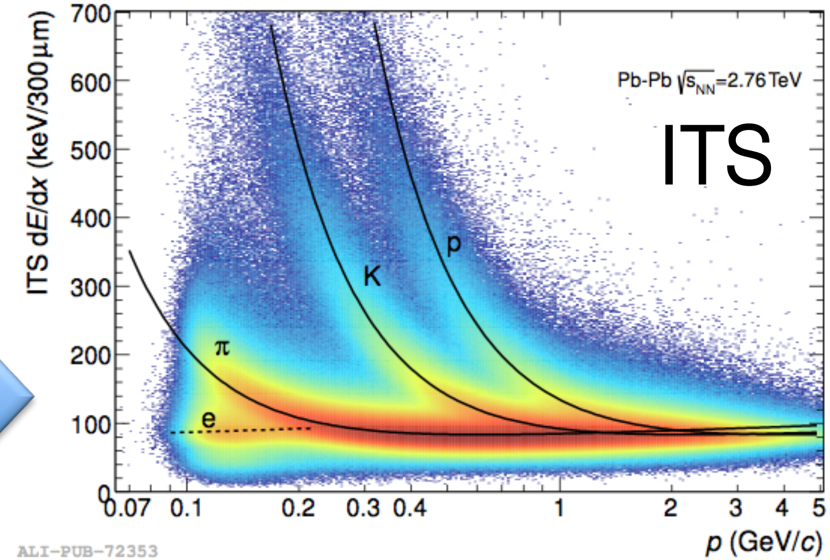
Backup

Baryon/Meson Ratios Compared



Particle Identification: ⟨dE/dx⟩

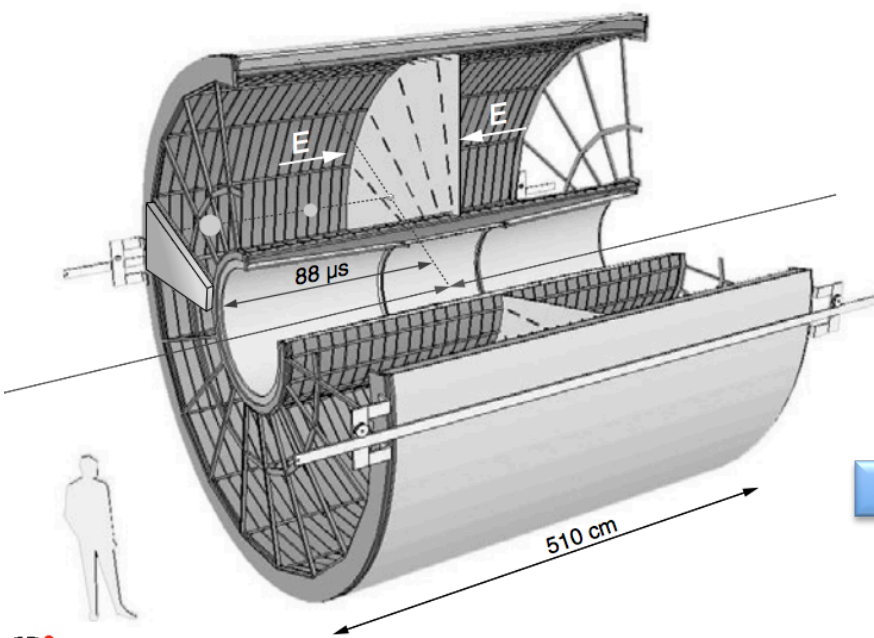


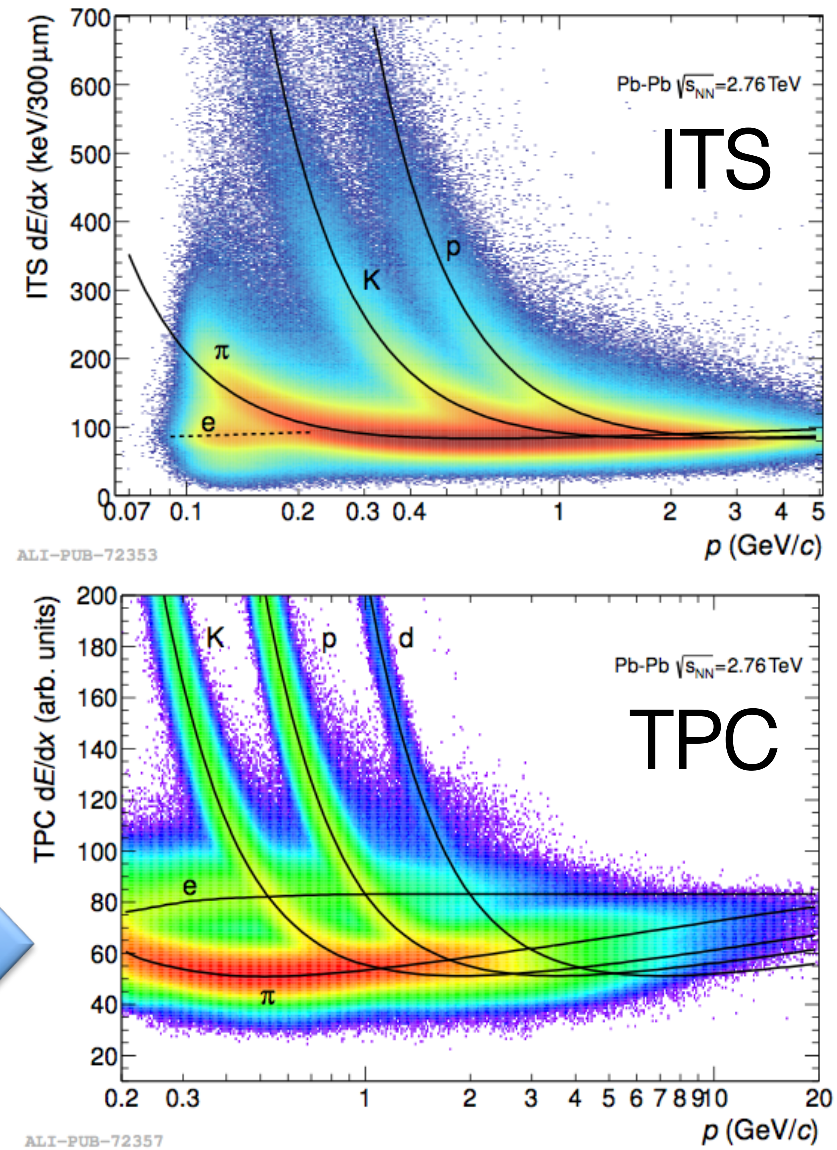


ITS: PID at low pT
PID via dE/dx in silicon
Up to 4 samples, σ ~10-15%

Particle Identification: ⟨d*E*/d*x*⟩

TPC: Main Tracking Detector
PID via d*E*/d*x* in gas
Up to 159 samples, σ ~6%





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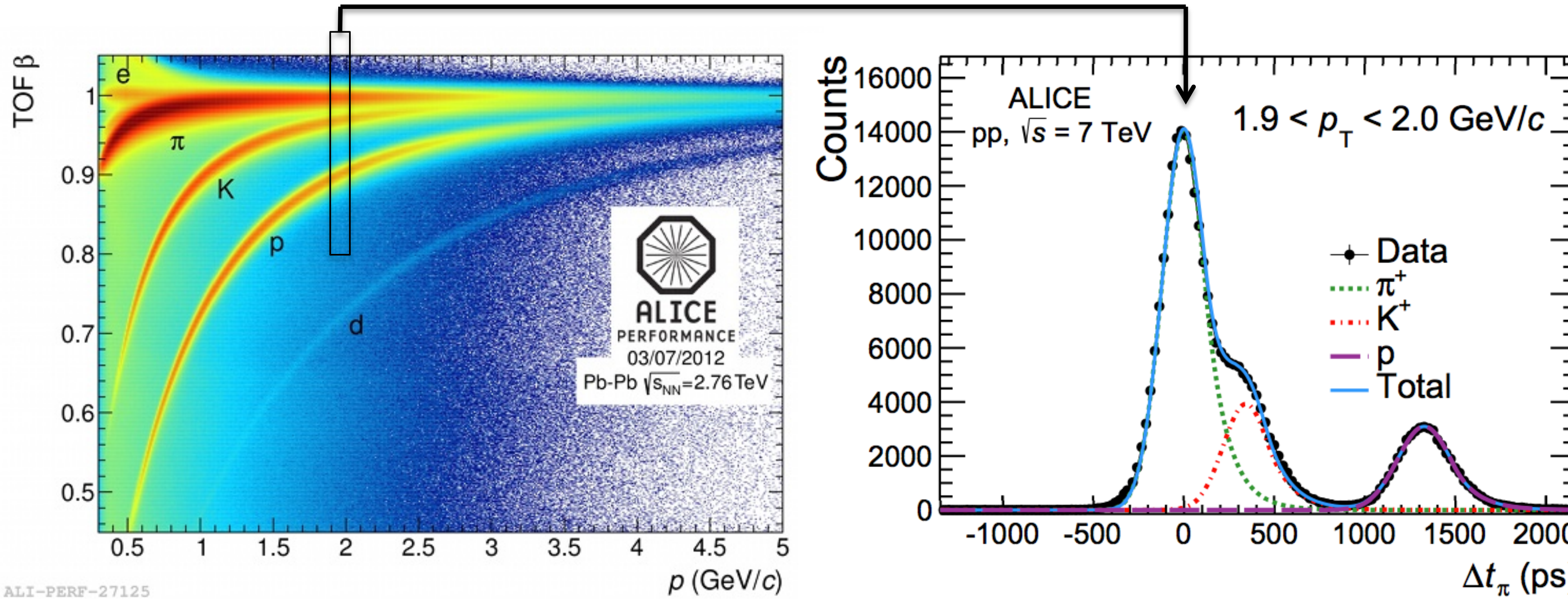
PID via **T**ime **O**f **F**light Measurement



TOF: PID at intermediate momenta
PID via time-of-flight technique
σ < 100 ps
3σ K/π separation up to 2.5 GeV/*c*
3σ p/π separation up to 3.0 GeV/*c*

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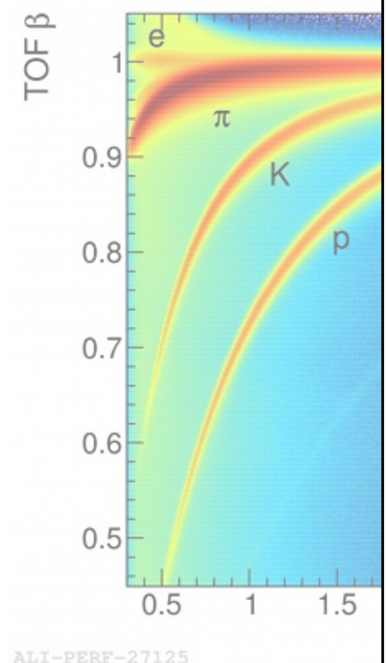
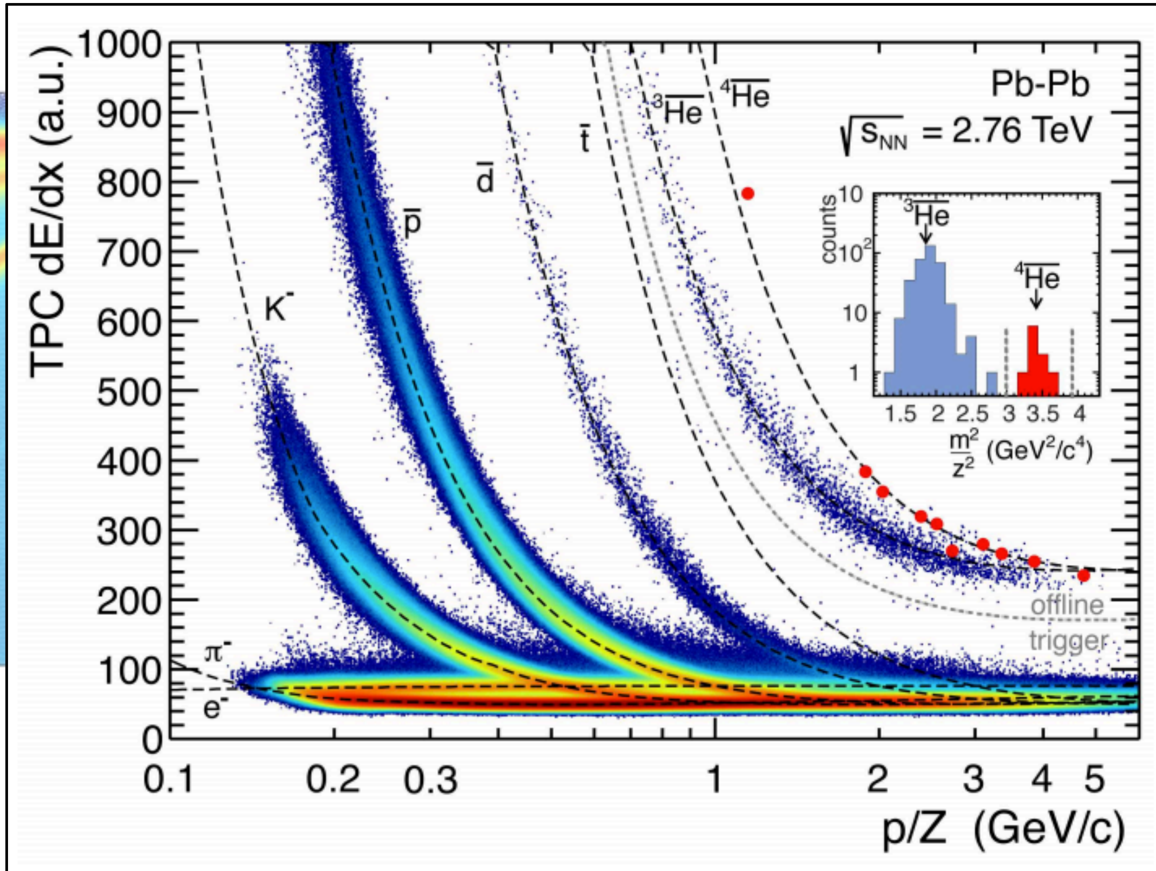
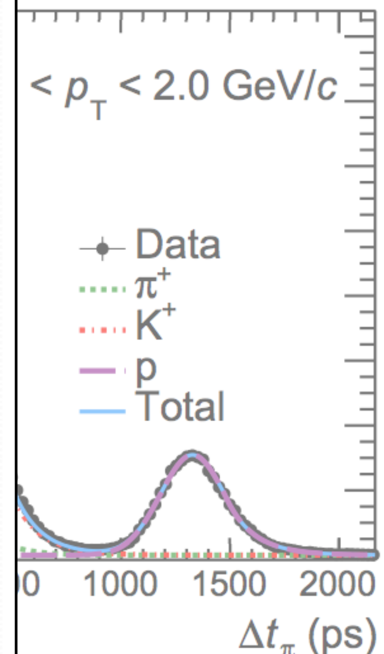
PID via **T**ime **O**f **F**light Measurement



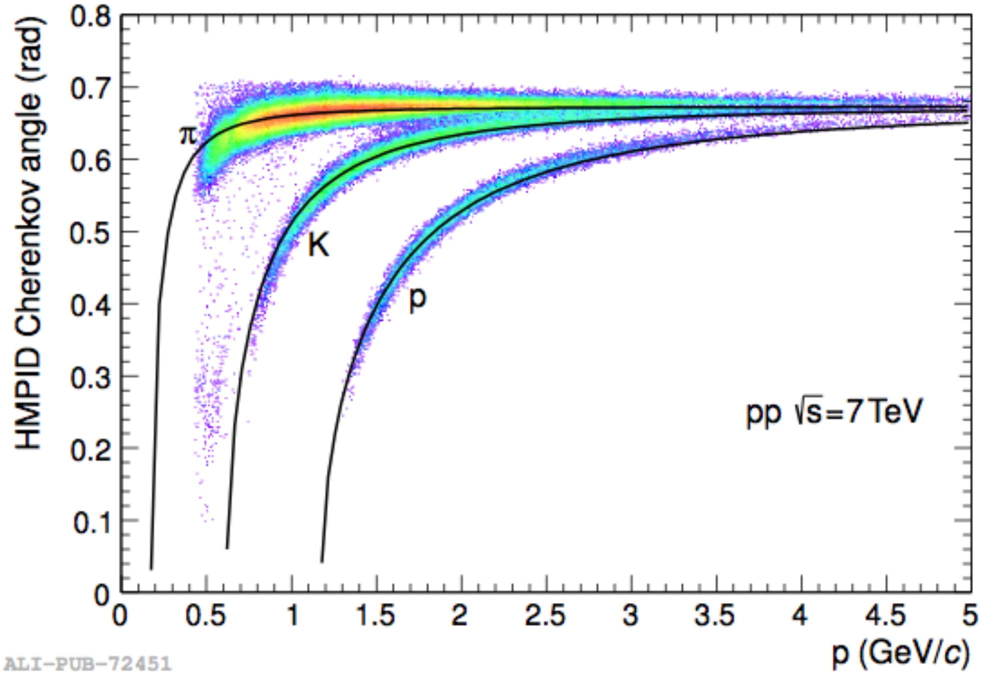


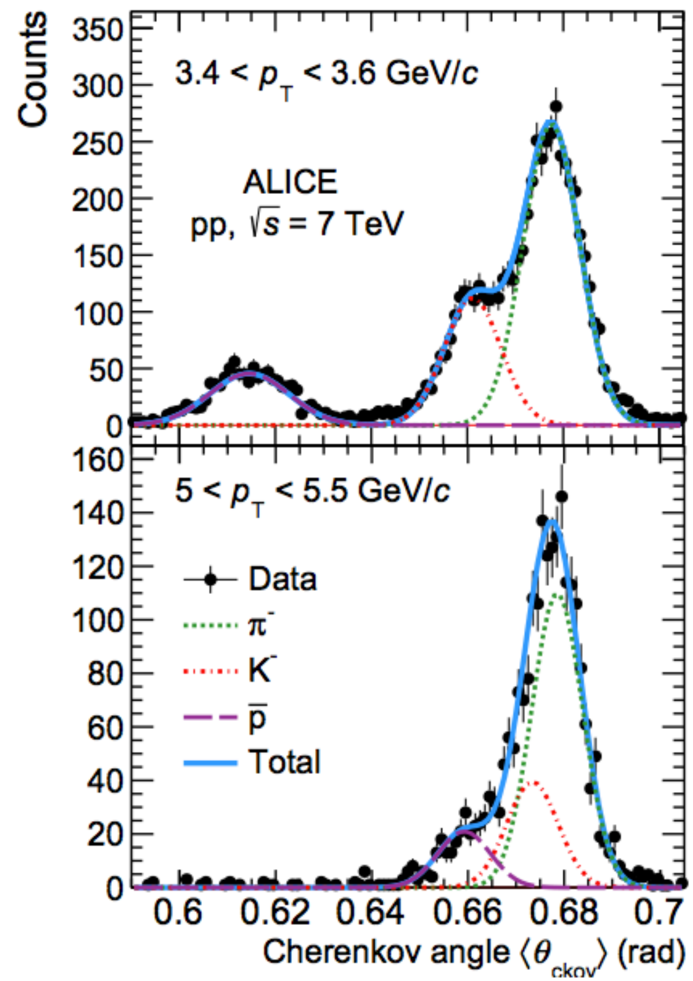


Combination of ⟨d*E*/d*x*⟩ in TPC and time of flight allows for further distinction of nuclei

PID via Cherenkov Radiation

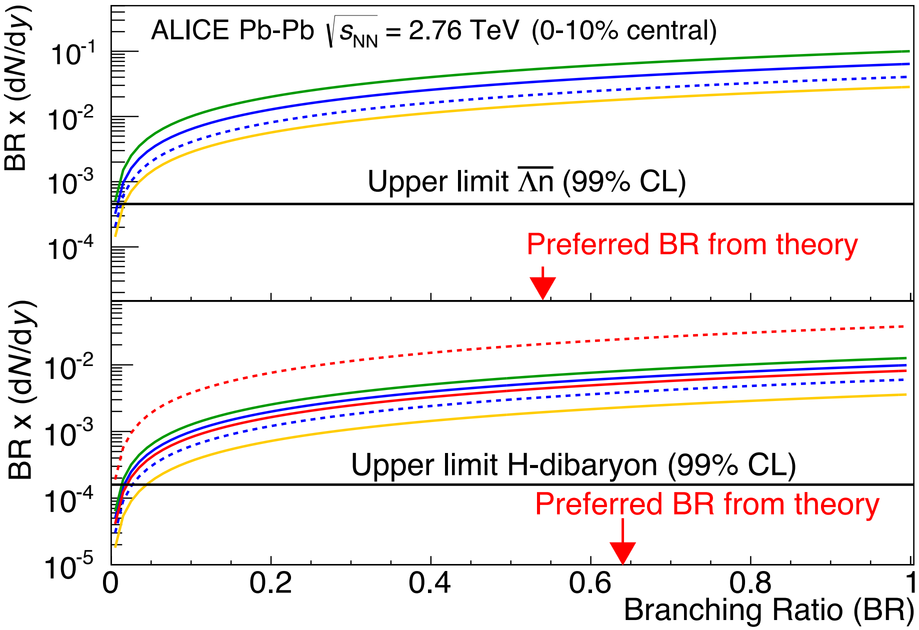
High **M**omentum **PID** Detector





HMPID: Extends PID to higher p_T
PID via Cherenkov angle θ_{ch}
Proximity-focus RICH Technique
3σ proton separation up to 5 GeV/*c*

Thermal model predictions for Exotica



- Blue: GSI-Heidelberg Model [1] for 156 MeV (dashed), 164 MeV (solid)
- Green: Non-equilibrium thermal model [2]
- Yellow: Hybrid UrQMD calculation [3]
- Red: Coalescence models, quark coalescence (solid) and hadron coalescence (dashed) [4]

[1] J. Stachel, A. Andronic, P. Braun-Munzinger, and K. Redlich, "Confronting LHC data with the statistical hadronization model," J. Phys.: Conf. Series 509 (2014) 012019.
[2] M. Petráň, calculation based [5] and [6], 2013
[3] J. Steinheimer, calculation based on [7], 2013.
[4] ExHIC Collaboration, S. Cho et al., "Exotic hadrons in heavy ion collisions," Phys. Rev. C 84 (2011) 064910.
[5] G. Torrieri, S. Steinke, W. Broniowski, W. Florkowski, J. Letessier, and J. Rafelski, "SHARE: Statistical hadronization with resonances," Comput. Phys. Commun. 167 (2005) 229.
[6] G. Torrieri, S. Jeon, J. Letessier, and J. Rafelski, "SHAREv2: fluctuations and a comprehensive treatment of decay feed-down," Comput. Phys. Commun. 175 (2006) 635.
[7] J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher, and H. Stocker, "Hypernuclei, ¨ dibaryon and antinuclei production in high energy heavy ion collisions: Thermal production vs. coalescence," Phys. Lett. B 714 (2012) 85.