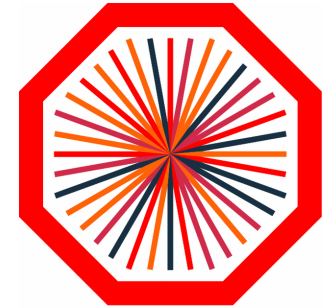
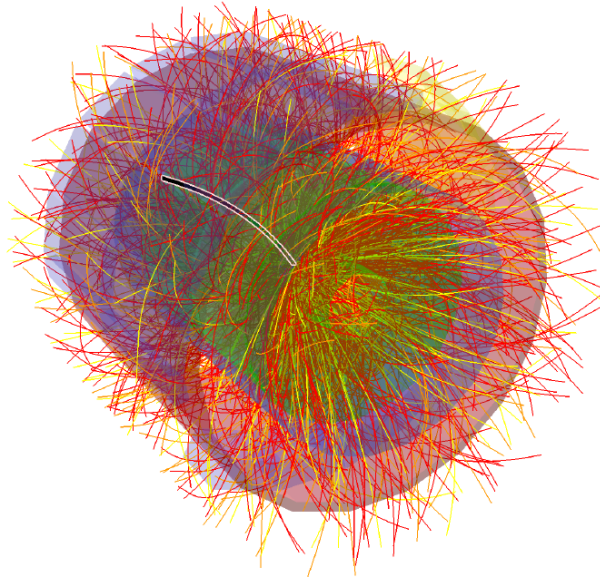


Production of (Anti-)(Hyper-)Nuclei, Exotica and Resonances with ALICE at the LHC



ALICE

17.10.2018

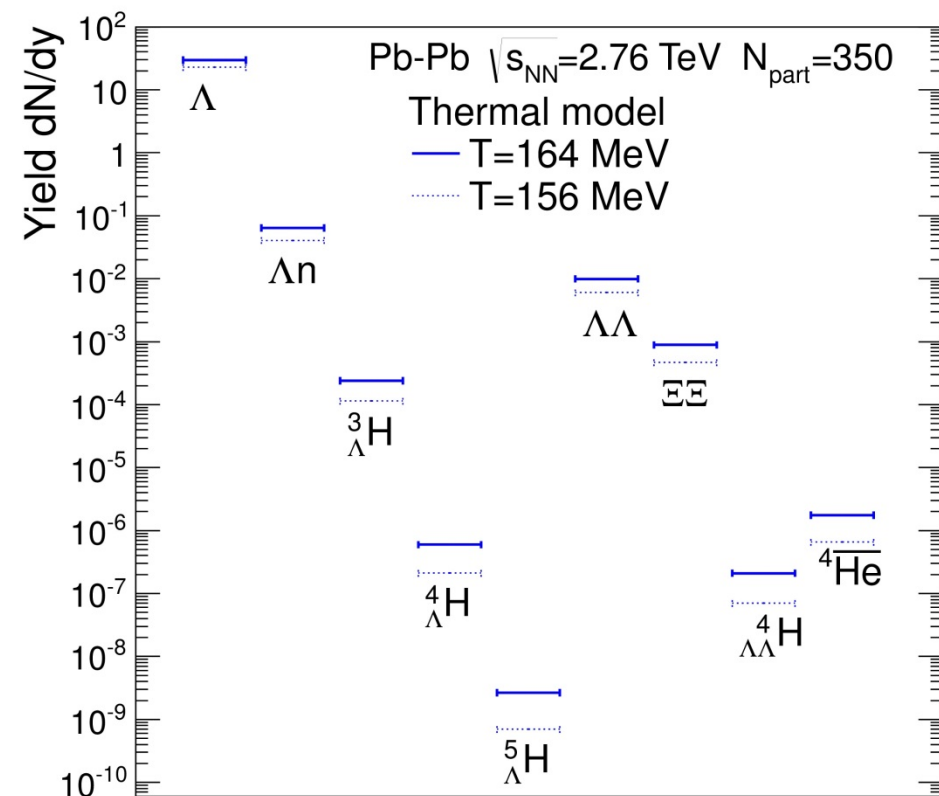
**ECT* Workshop: Observables of Hadronization
and the QCD Phase Diagram in the Cross-over Domain**

Content



- Introduction
- ALICE
- (Anti-)nuclei
- Exotica
- Resonances
- Summary/Conclusion

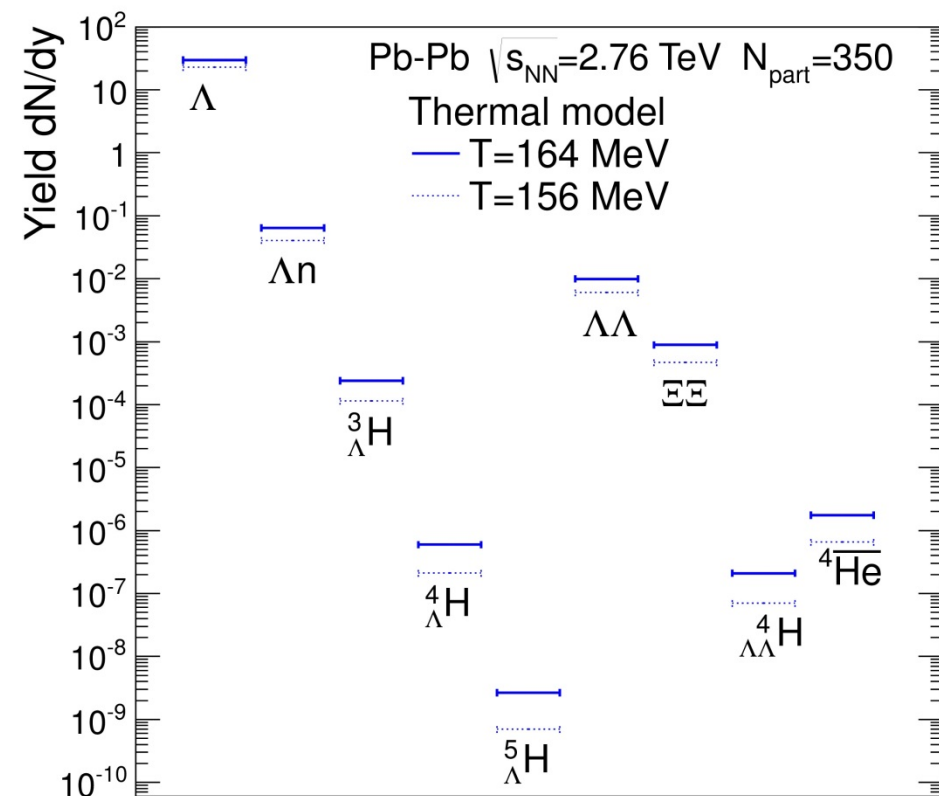
Motivation



- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
 - Search for rarely produced anti- and hyper-matter
 - Test model predictions, e.g. thermal and coalescence
- Understand production mechanisms

A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

Motivation

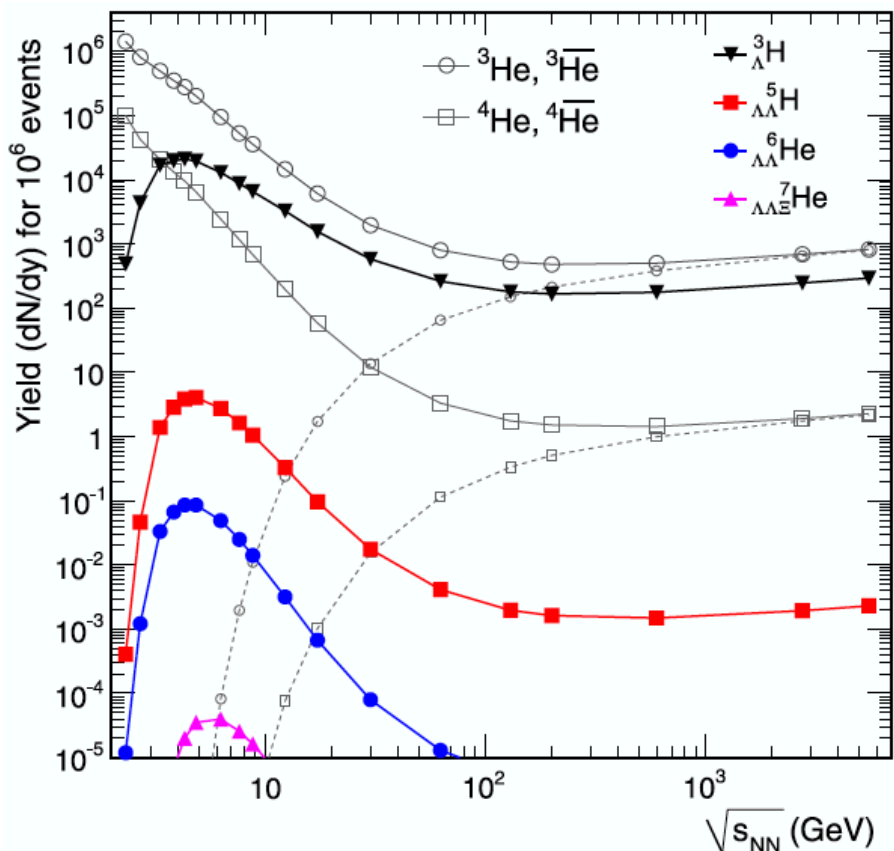


- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
 - Search for rarely produced anti- and hyper-matter
 - Test model predictions, e.g. thermal and coalescence
- Understand production mechanisms

→ Basis are light (anti-)nuclei

A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

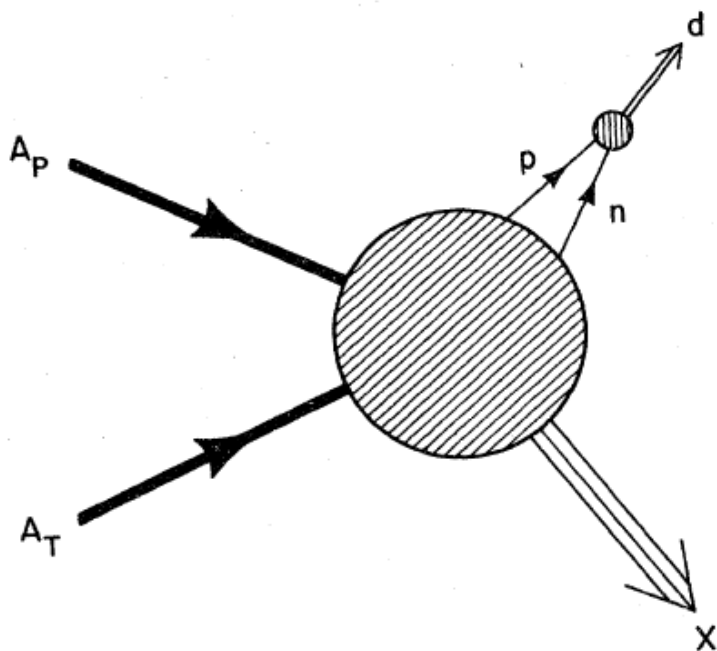
Thermal model



A. Andronic et al., PLB 697, 203 (2011)

- Key parameter at LHC energies:
 - chemical freeze-out temperature T_{ch}
 - Strong sensitivity of abundance of nuclei to choice of T_{ch} due to:
 1. large mass m
 2. exponential dependence of the yield $\sim \exp(-m/T_{\text{ch}})$
- Binding energies small compared to T_{ch}

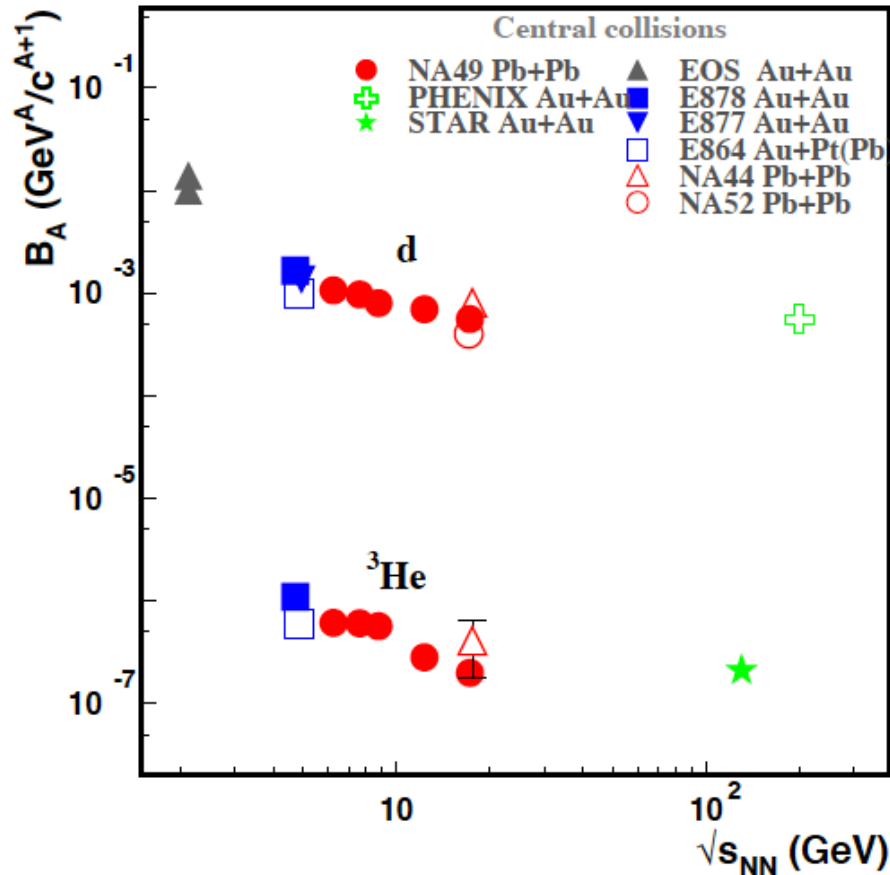
Coalescence (I)



J. I. Kapusta, PRC 21, 1301 (1980)

- Nuclei are formed by protons and neutrons which are nearby in space and have similar velocities (after kinetic freeze-out)
- Produced nuclei
→ can break apart
→ created again by final-state coalescence

Coalescence (II)



*T. Anticic et al. (NA49 Collaboration)
PRC 94, 044906 (2016)*

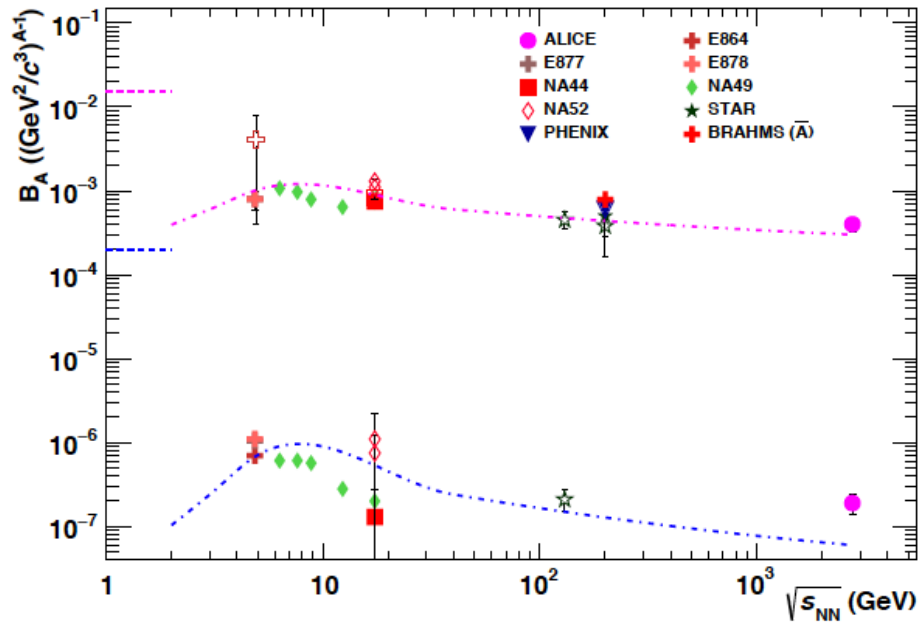
- Production probability of nuclei is usually quantified through a coalescence parameter B_A using

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

- B_A often connected to the coalescence volume (in momentum space p_0)

$$B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{A-1} \frac{M}{m^A}$$

Coalescence (III)



*P. Braun-Munzinger, bd, Invited review
NPA, arXiv:1809.04681*

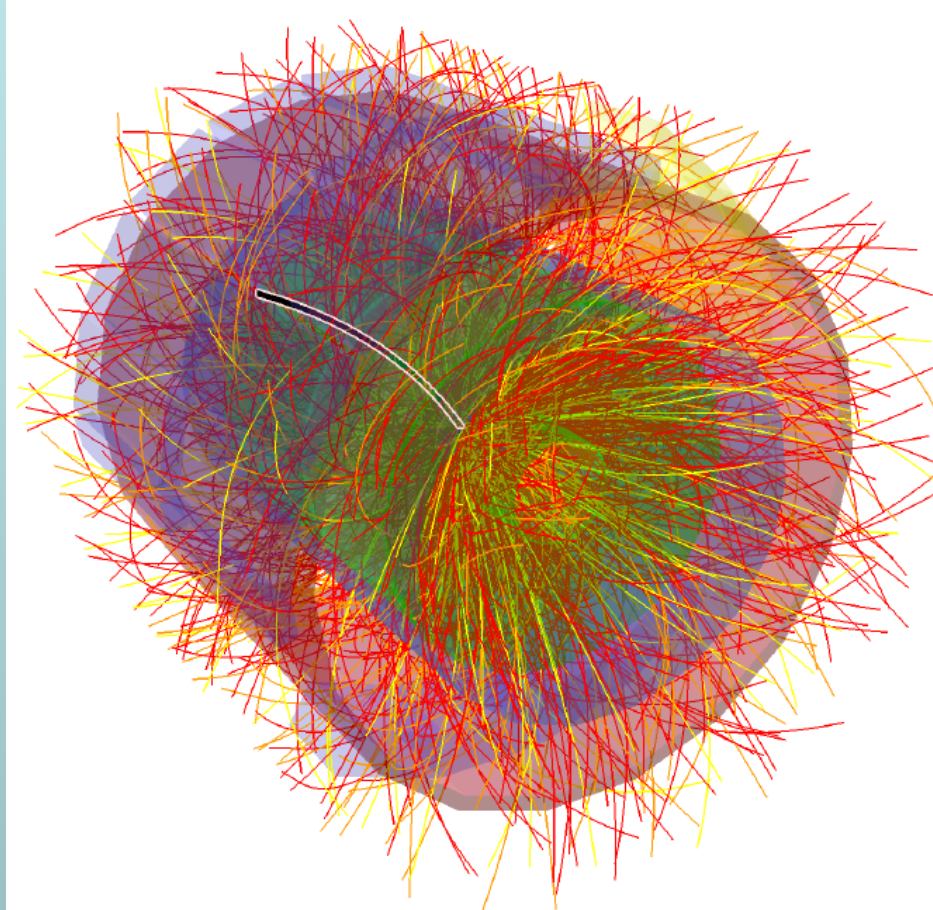
- Production probability of nuclei is usually quantified through a coalescence parameter B_A using

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

- In particular in HICs B_A described by replacing coalescence volume by HBT „volume“

$$B_A \propto \left(\frac{1}{V} \right)^{(A-1)}$$

ALICE



Large Hadron Collider at CERN



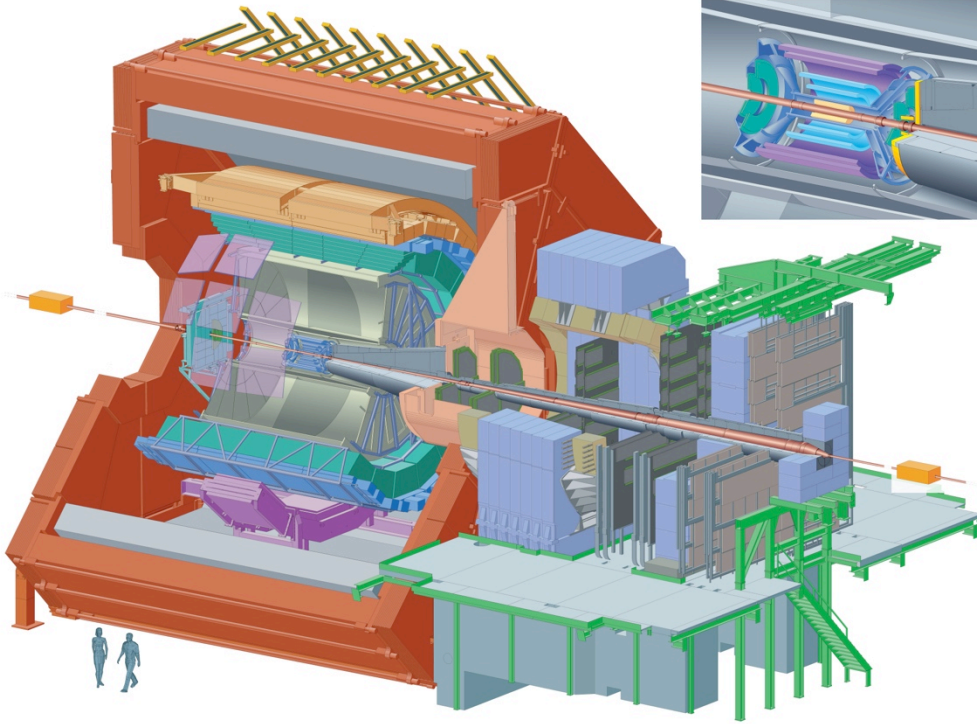
Large Hadron Collider at CERN



ALICE

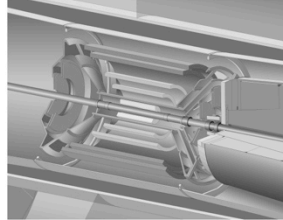
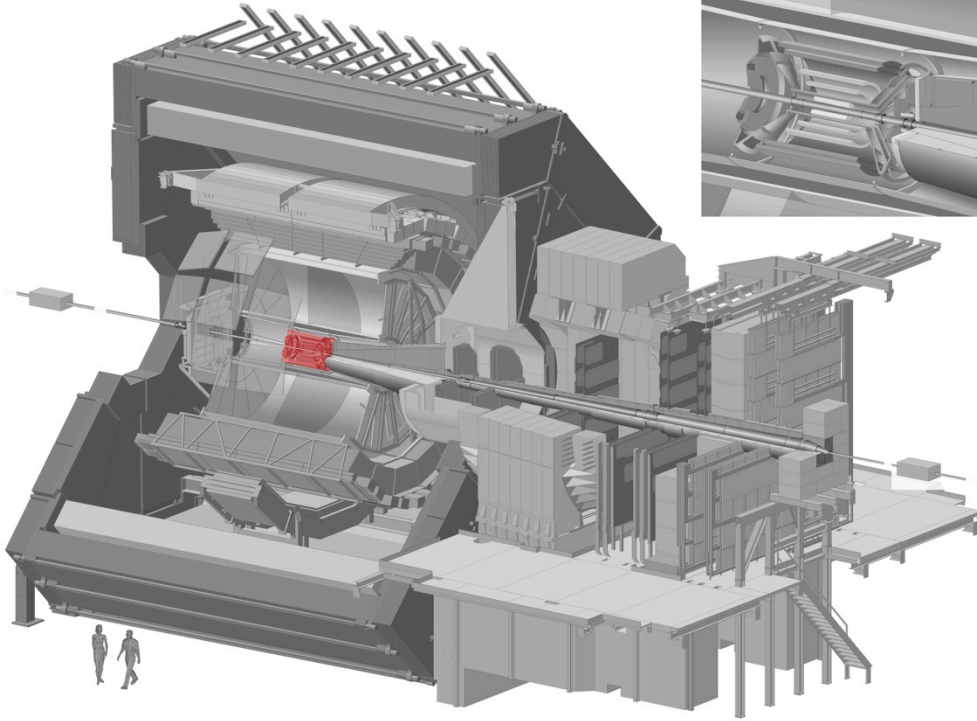


ALICE experiment



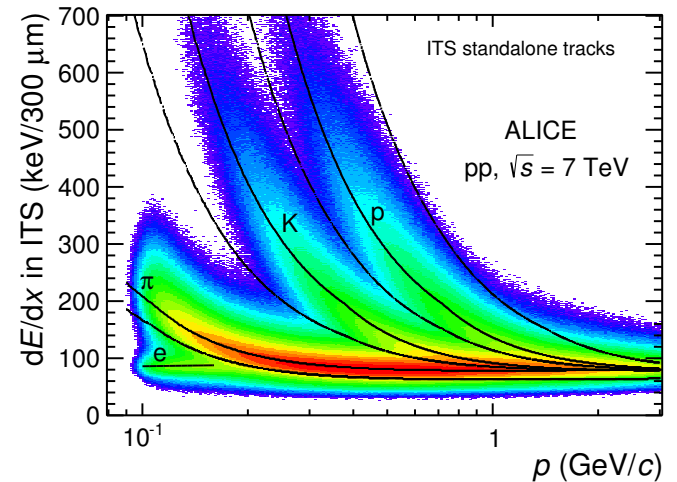
Specificity: low-momentum
tracking and particle
identification in a high-
multiplicity environment

ALICE experiment



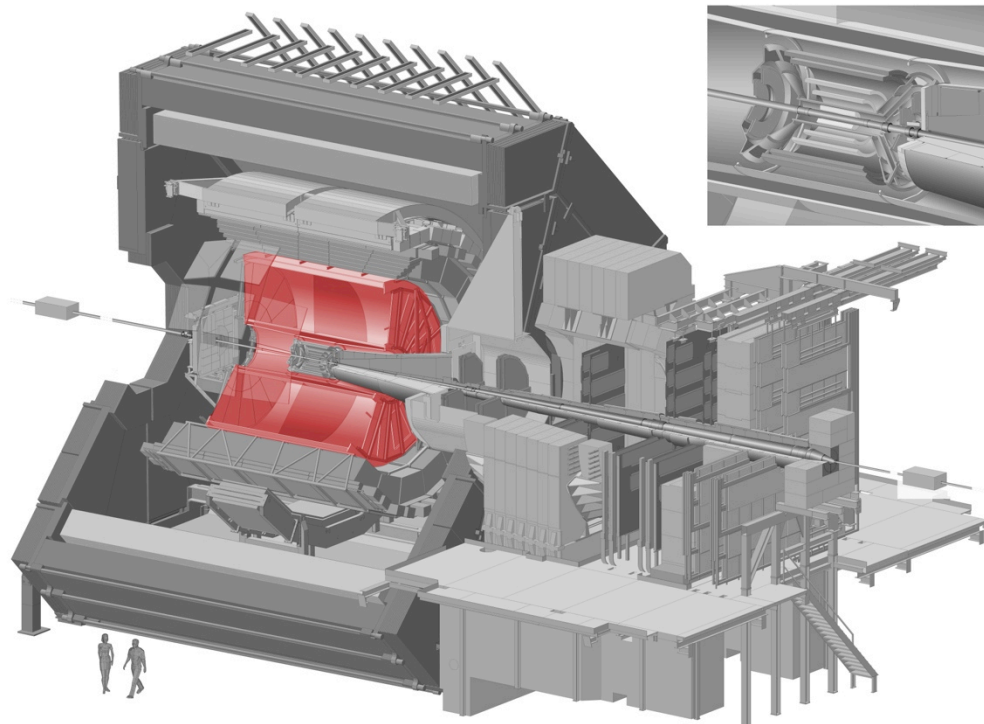
ITS ($|\eta| < 0.9$)

- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)



ITS dE/dx

ALICE experiment

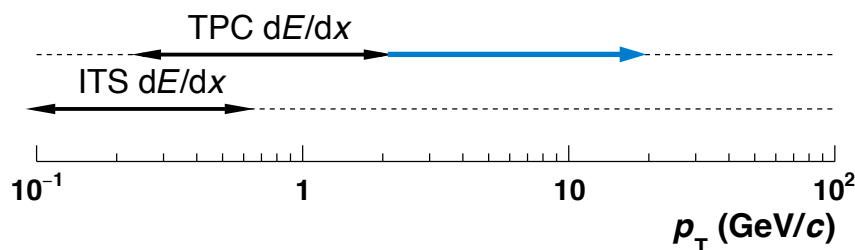
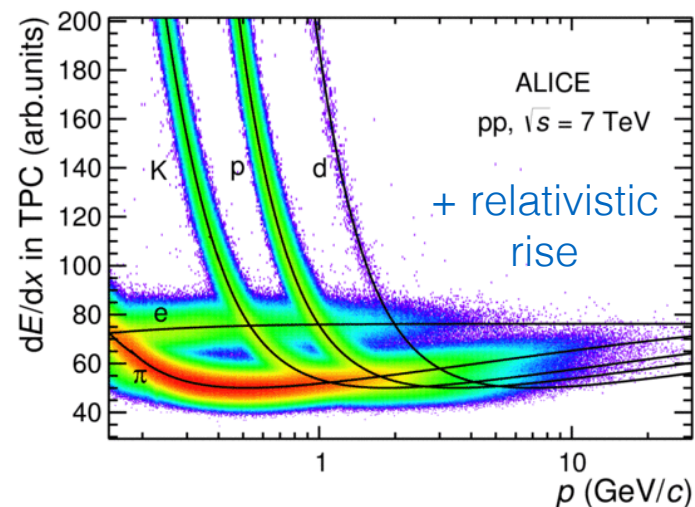


ITS ($|\eta| < 0.9$)

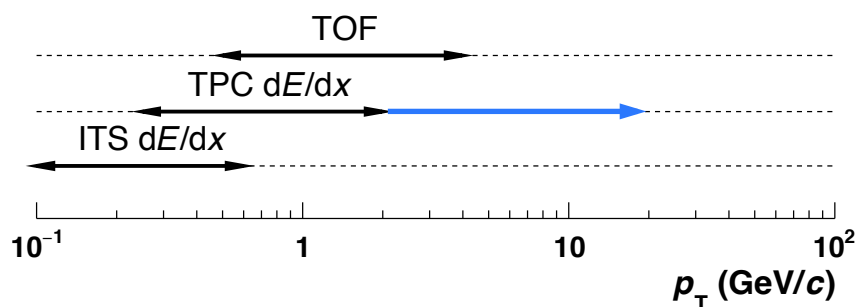
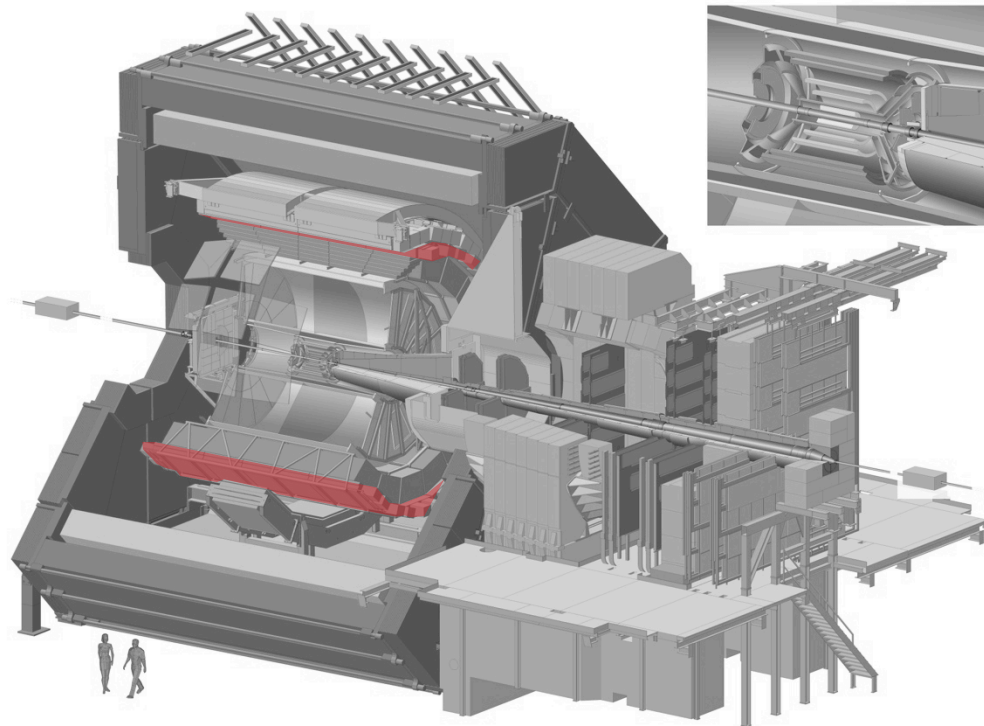
- 6 Layers of silicon detectors
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TPC ($|\eta| < 0.9$)

- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)



ALICE experiment



ITS ($|\eta| < 0.9$)

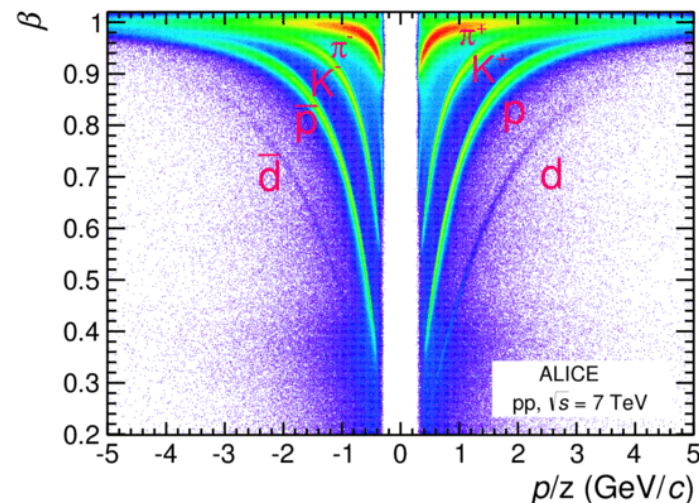
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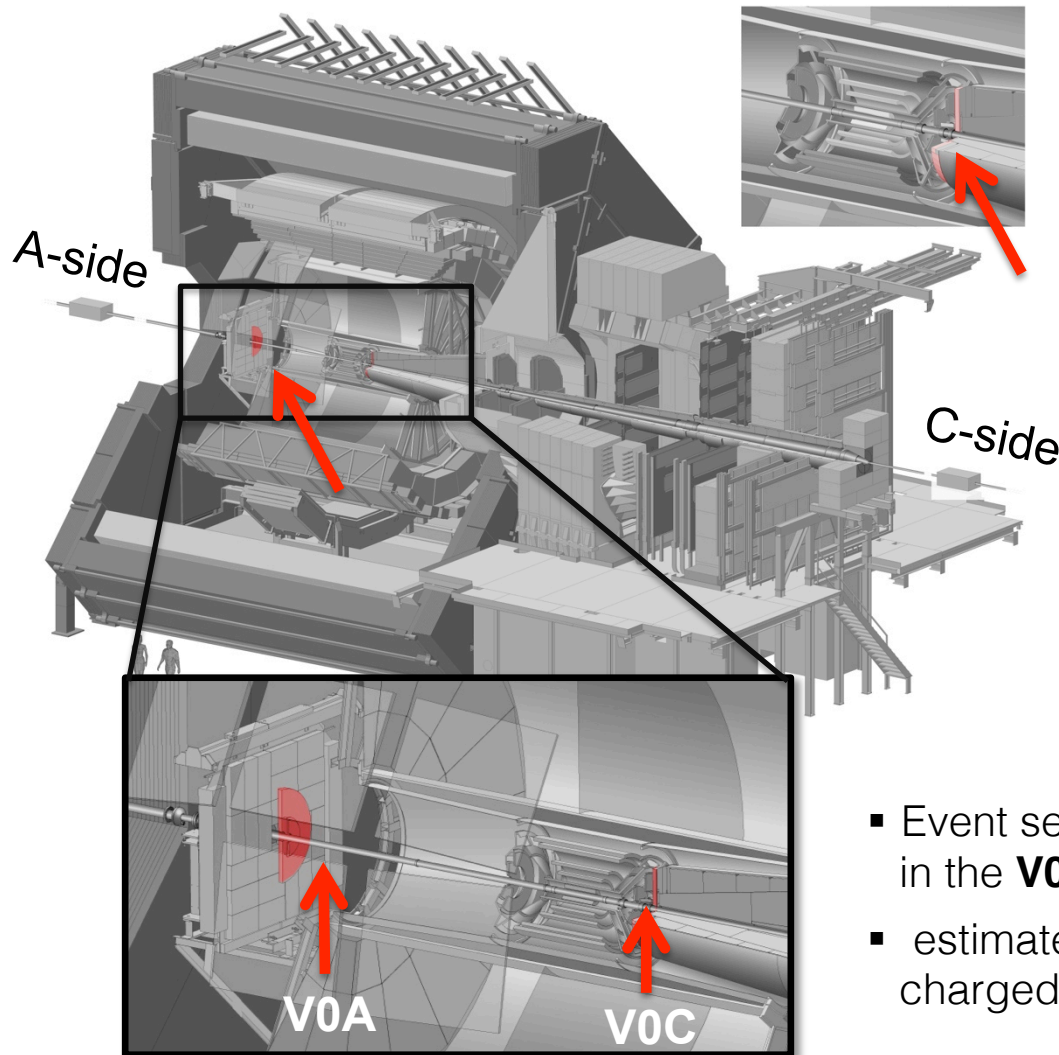
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)
- Weak decay reconstruction (topological)

TOF ($|\eta| < 0.9$)

- Multi-gap resistive plate chambers
- PID via velocity determination



ALICE experiment



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- 6 Layers of silicon detectors
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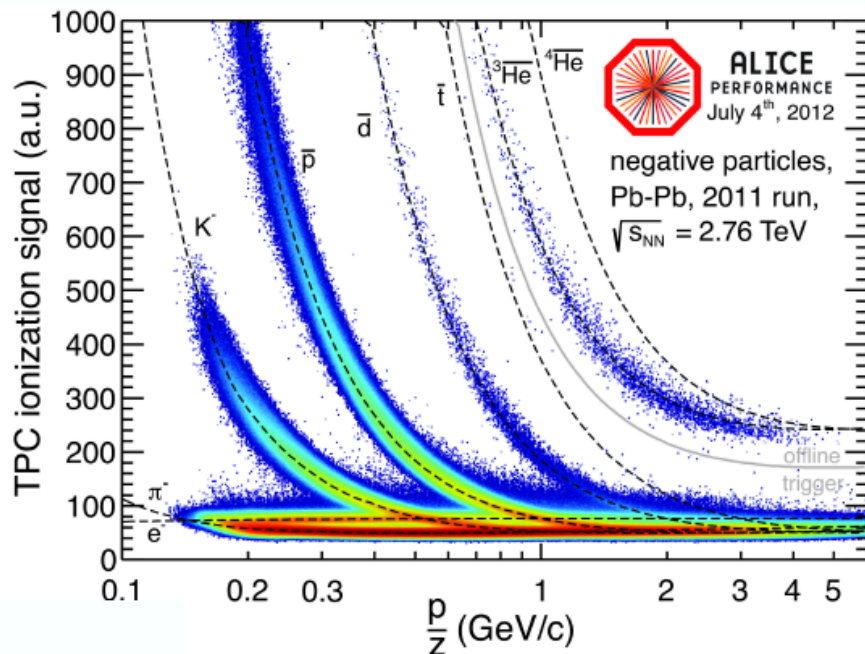
- Multi-gap resistive plate chambers
- PID via velocity determination

V0 [V0A ($2.8 < \eta < 5.1$) & V0C ($-3.7 < \eta < -1.7$)]

- Forward arrays of scintillators
- Trigger, beam gas rejection
- Multiplicity estimator:

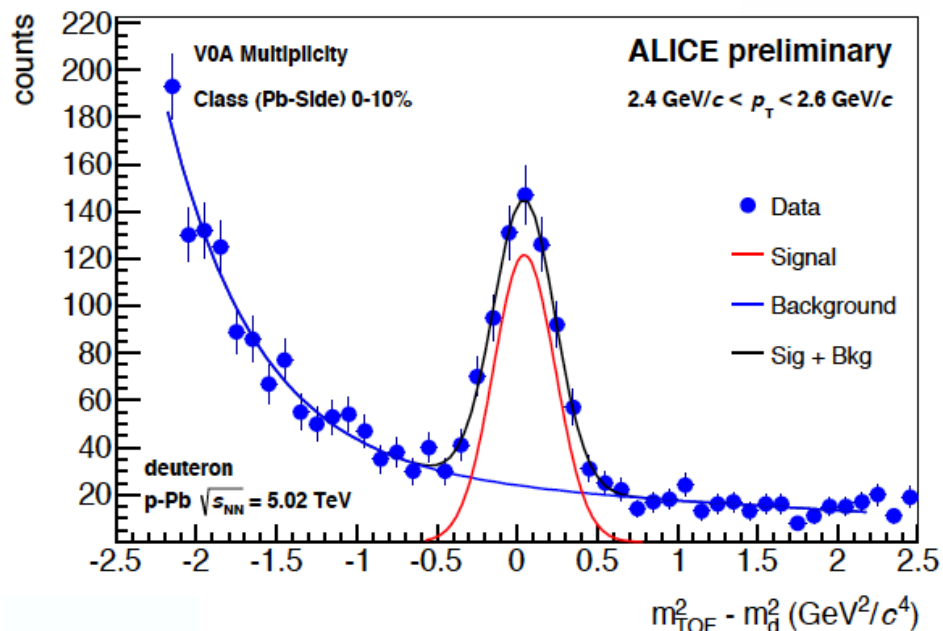
- Event selection based on total charge deposited in the **V0A** and **V0C** detectors ("V0M")
- estimated as the average number of primary charged tracks in $|\eta| < 0.5$

Particle Identification



Low momenta:

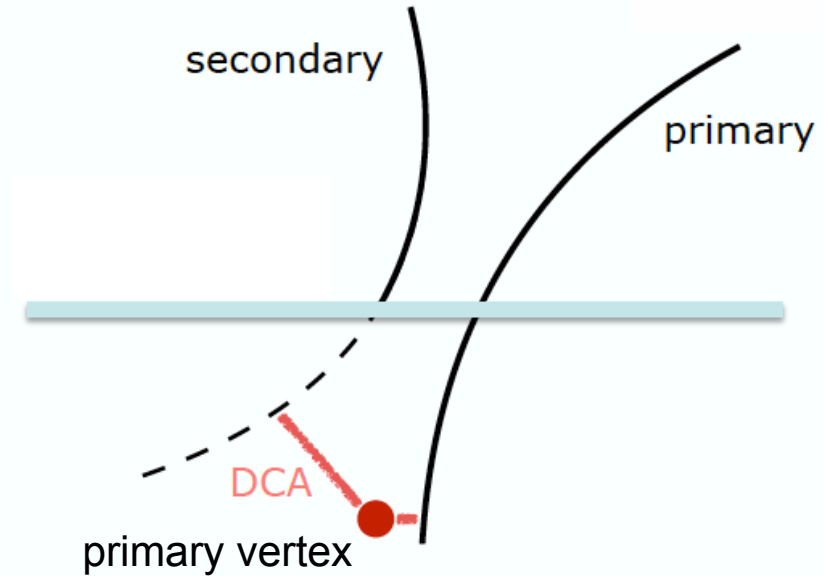
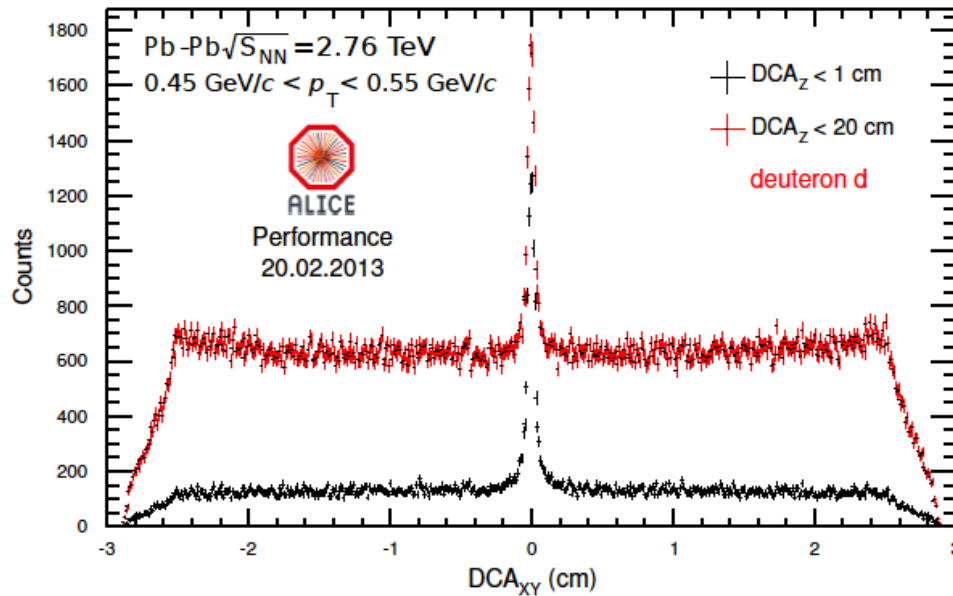
Nuclei are identified using the dE/dx measurement in the Time Projection Chamber (TPC)



Higher momenta:

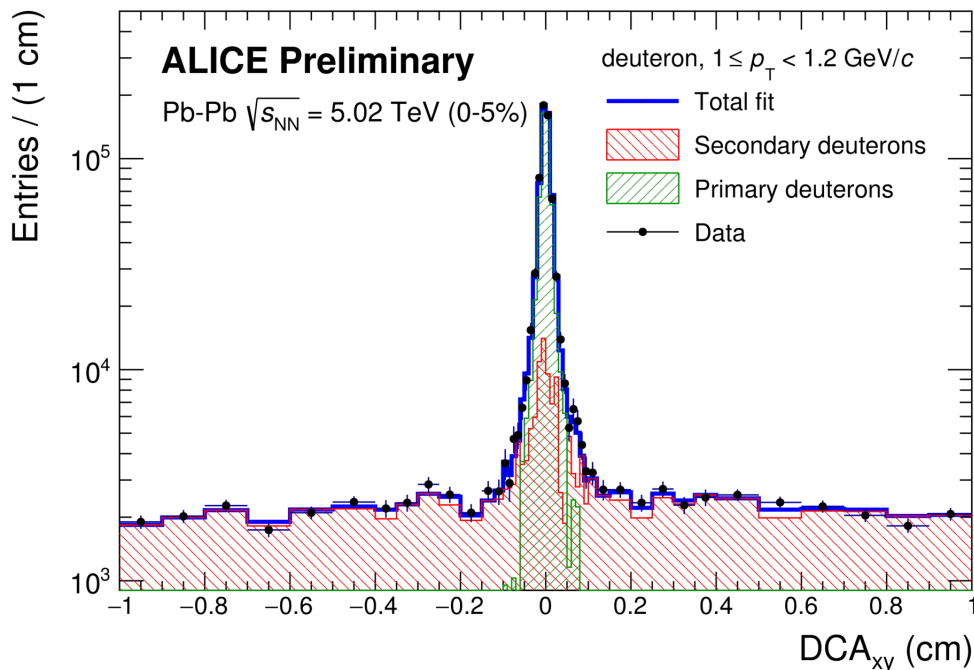
Velocity measurement with the Time-of-Flight (TOF) detector is used to calculate the m^2 distribution

Secondary contamination



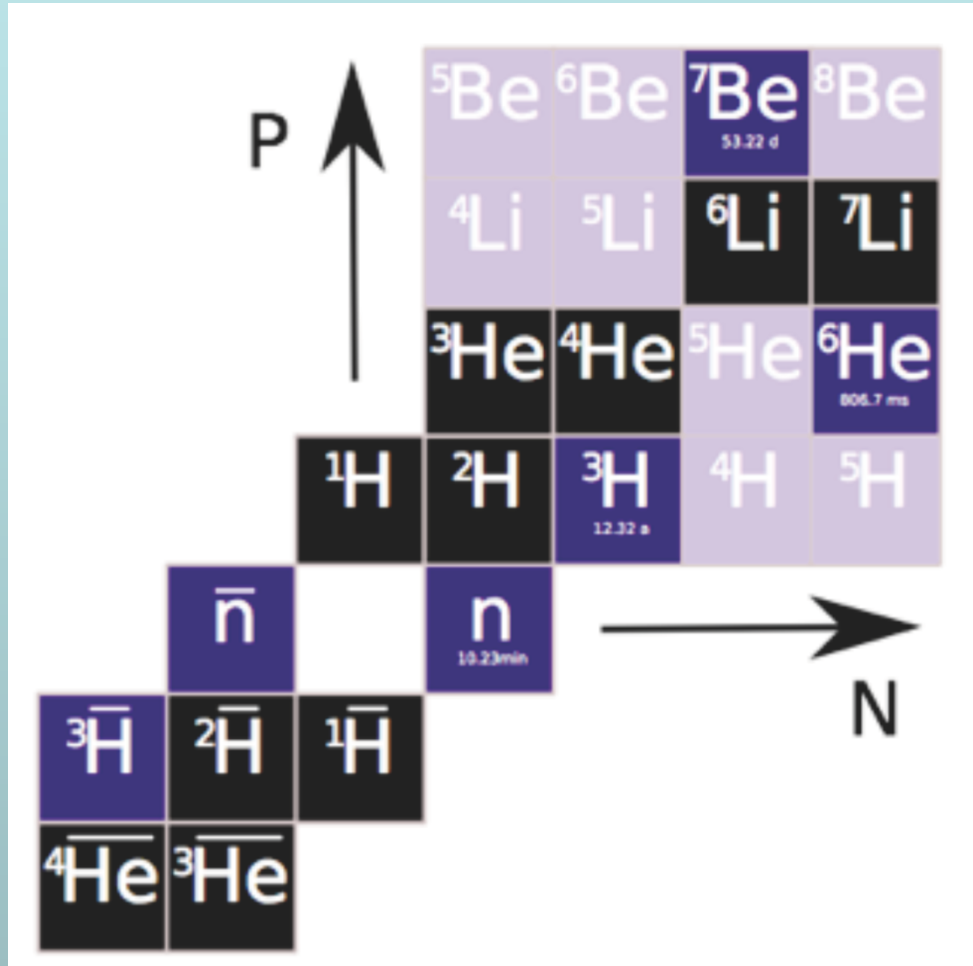
- Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material, e.g. beam pipe)
- Knock-out is a significant problem at low p_T , but only for nuclei not for anti-nuclei

Secondary contamination



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(Anti-)Nuclei

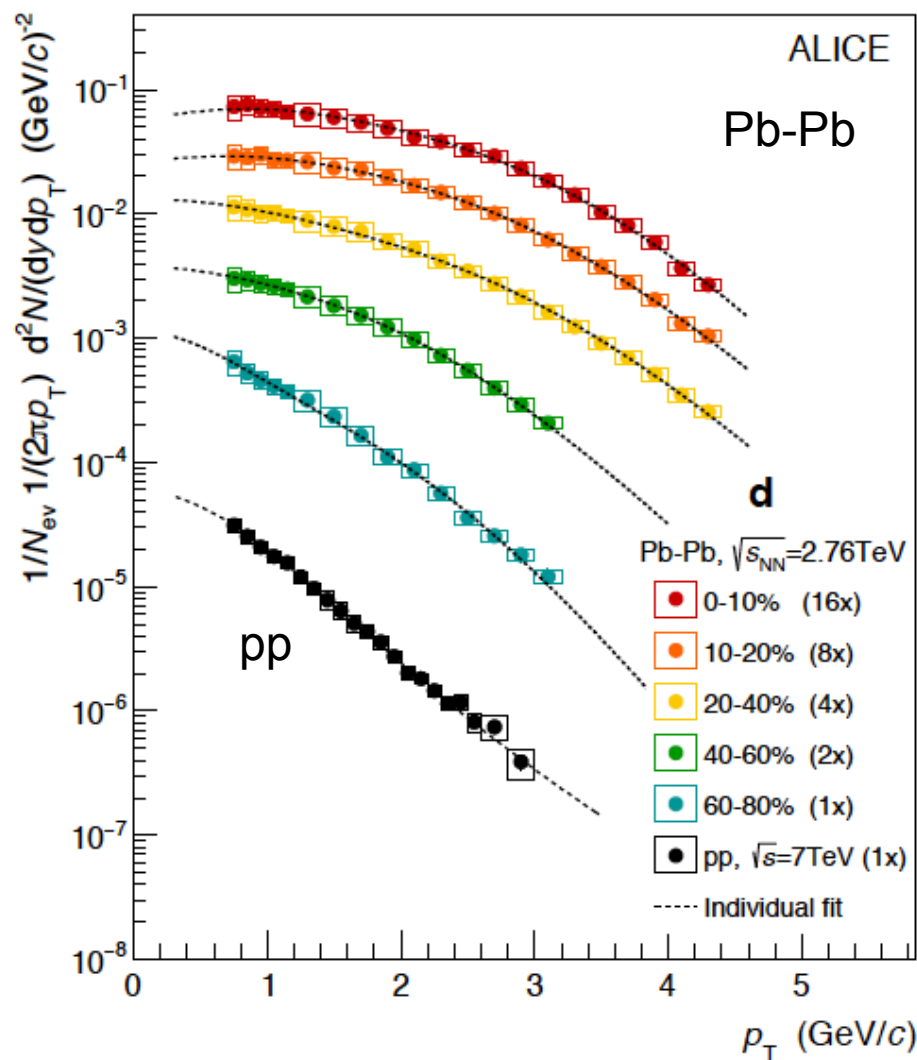
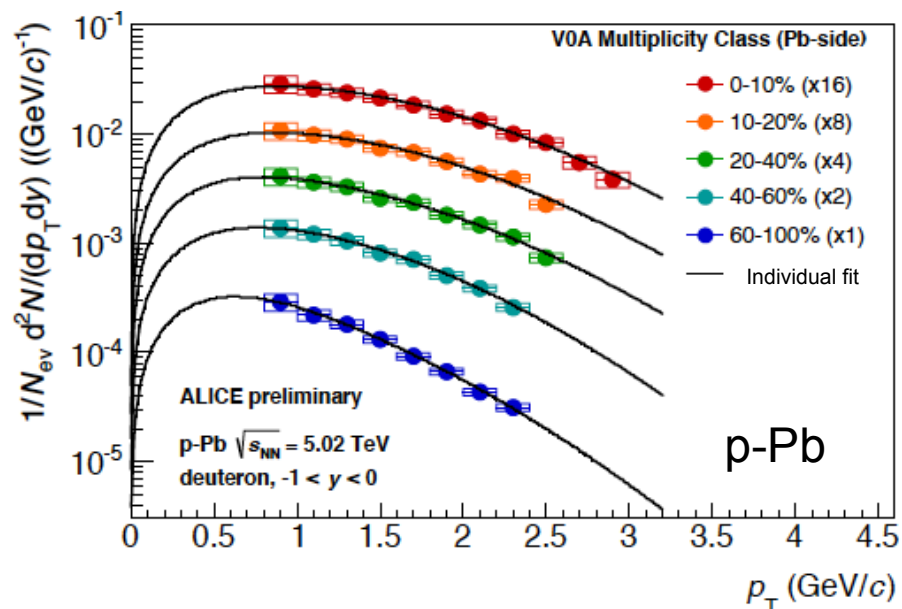


Deuterons



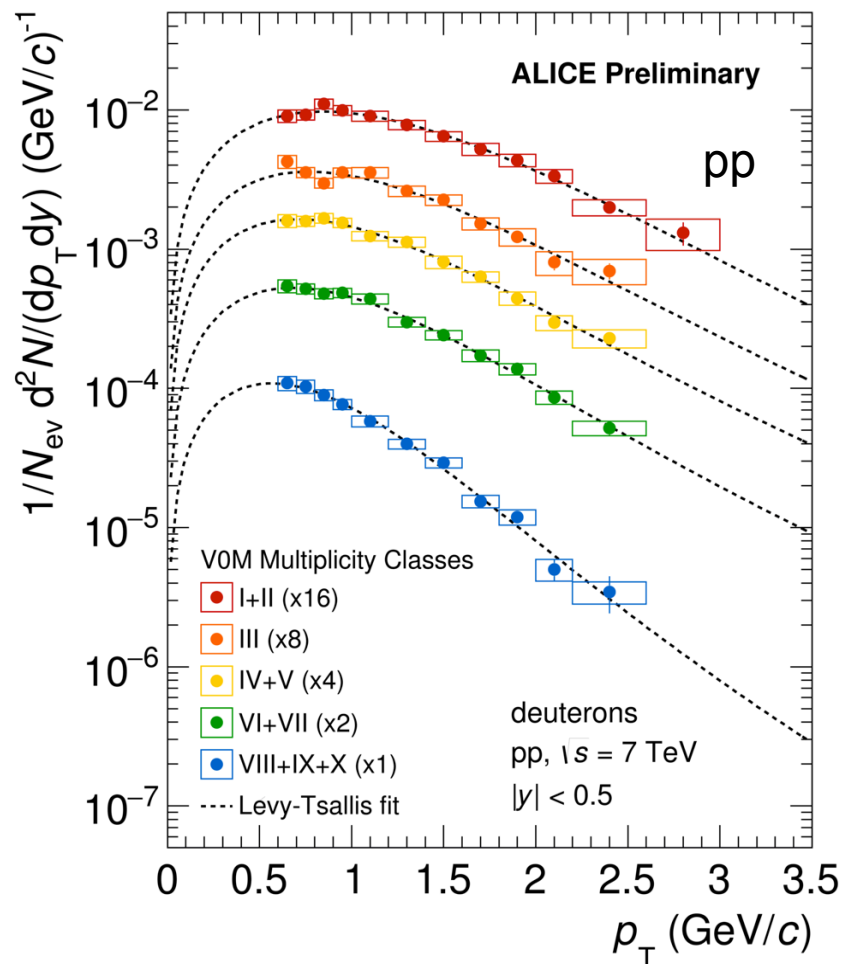
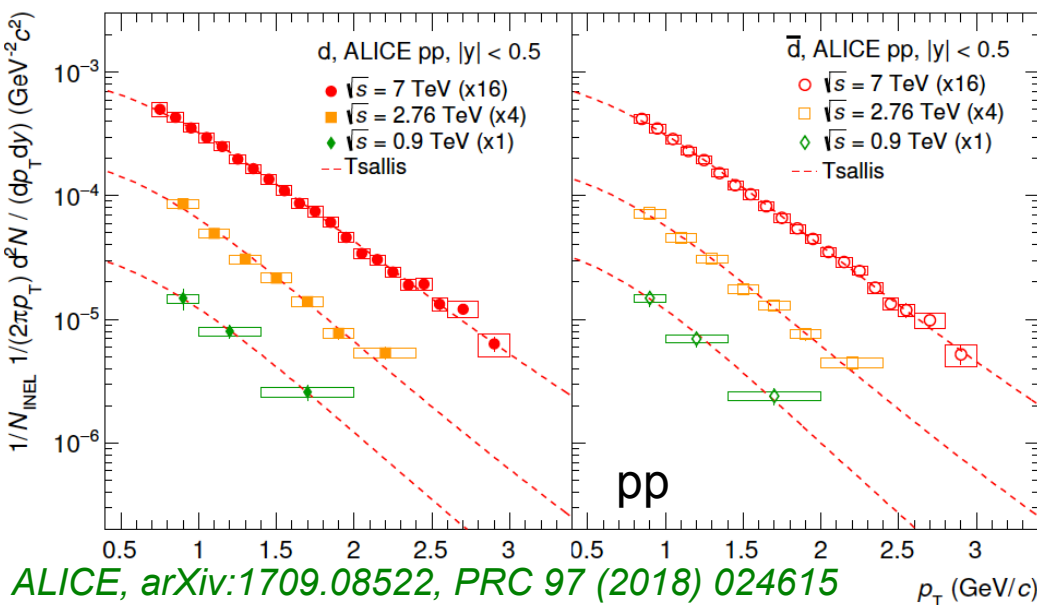
ALICE

- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp spectrum shows no sign of radial flow



Deuterons

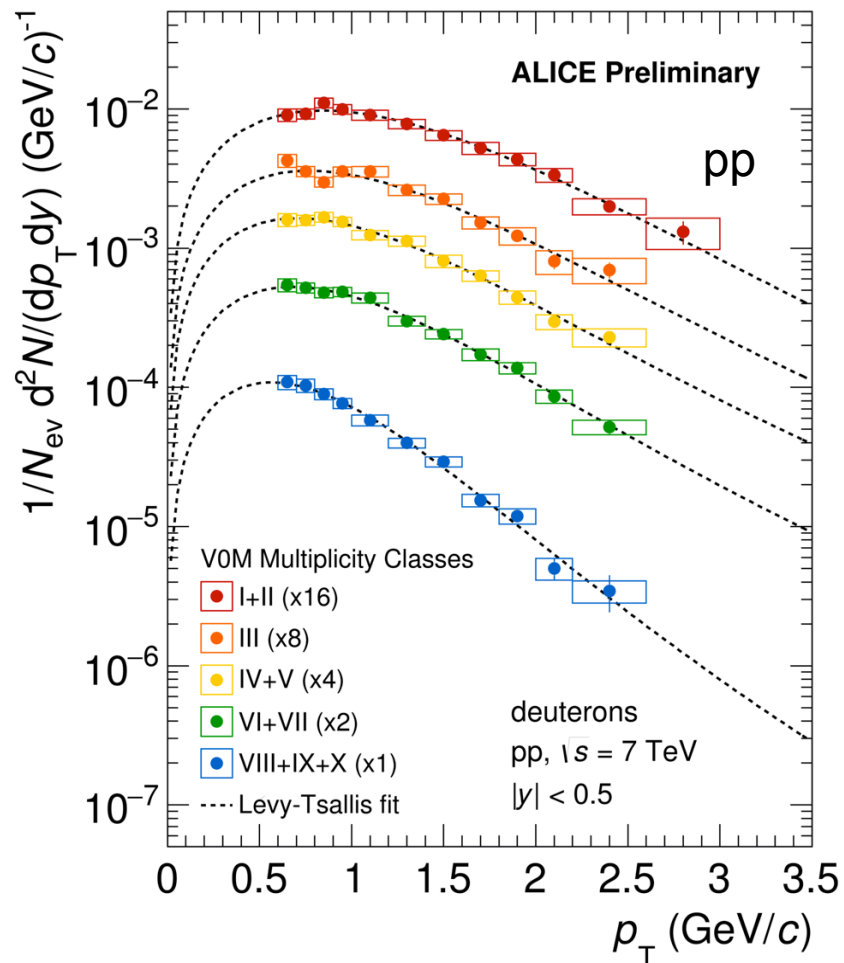
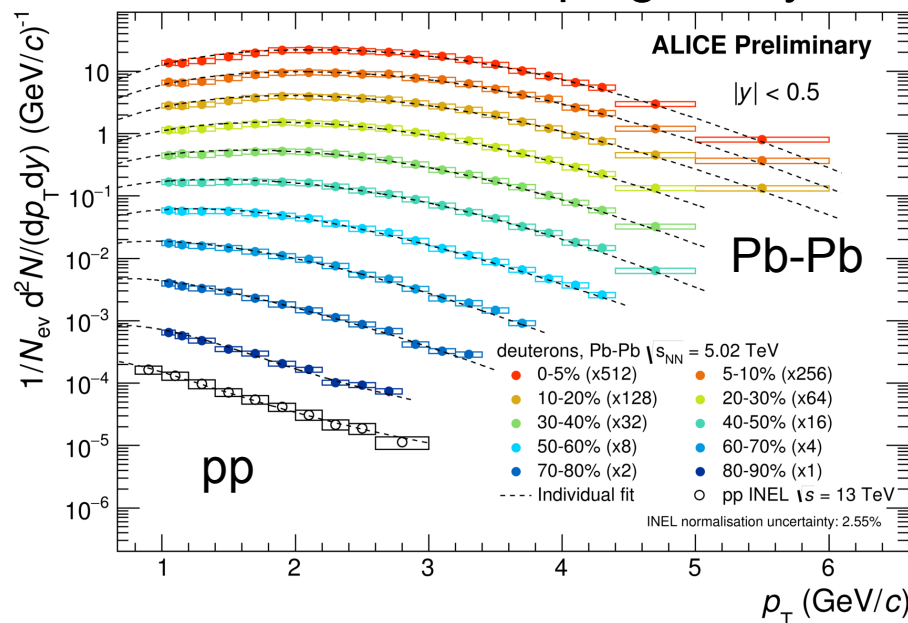
- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- MB pp spectrum shows no sign of radial flow $\rightarrow$ multiplicity bins show hardening



ALICE, arXiv:1709.08522, PRC 97 (2018) 024615

Deuterons

- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
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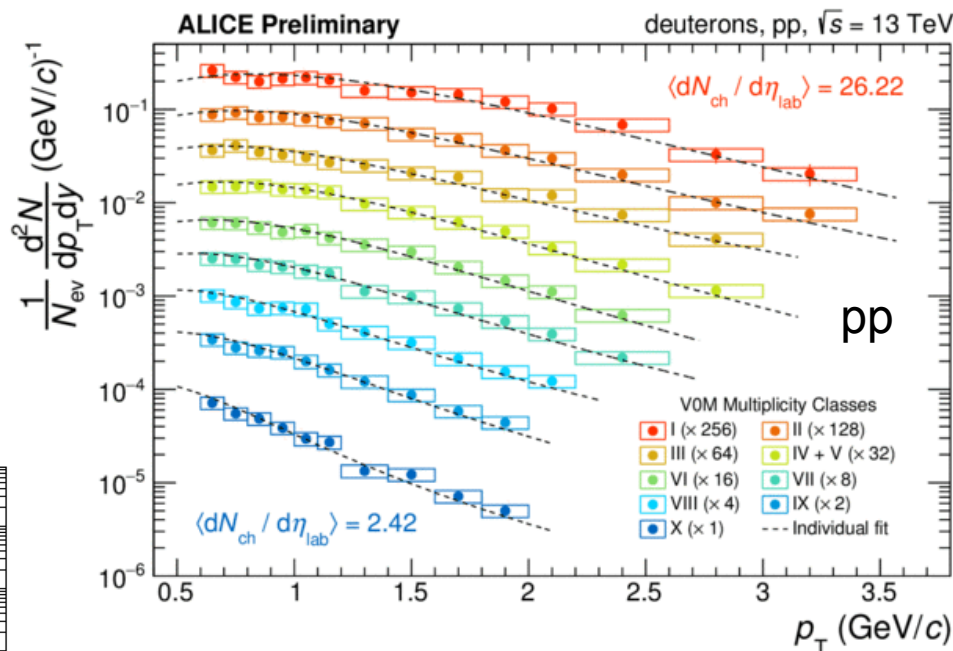
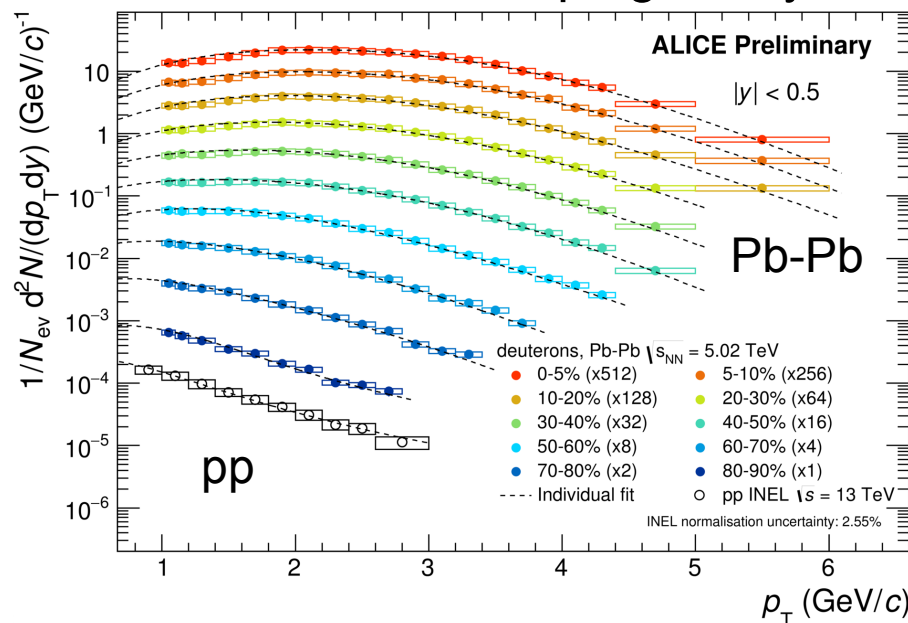


Deuterons



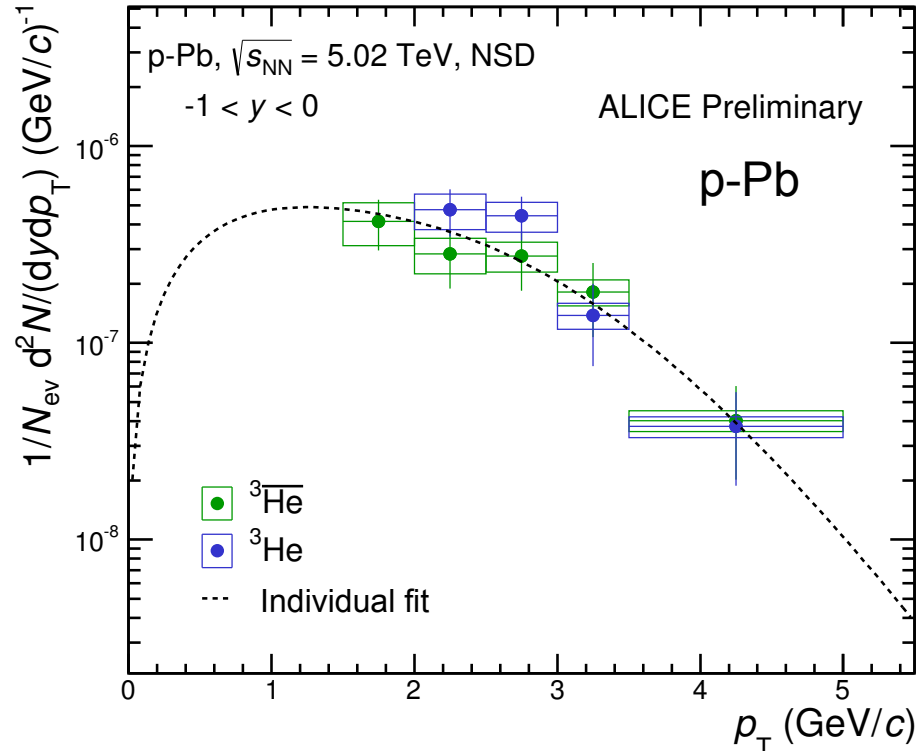
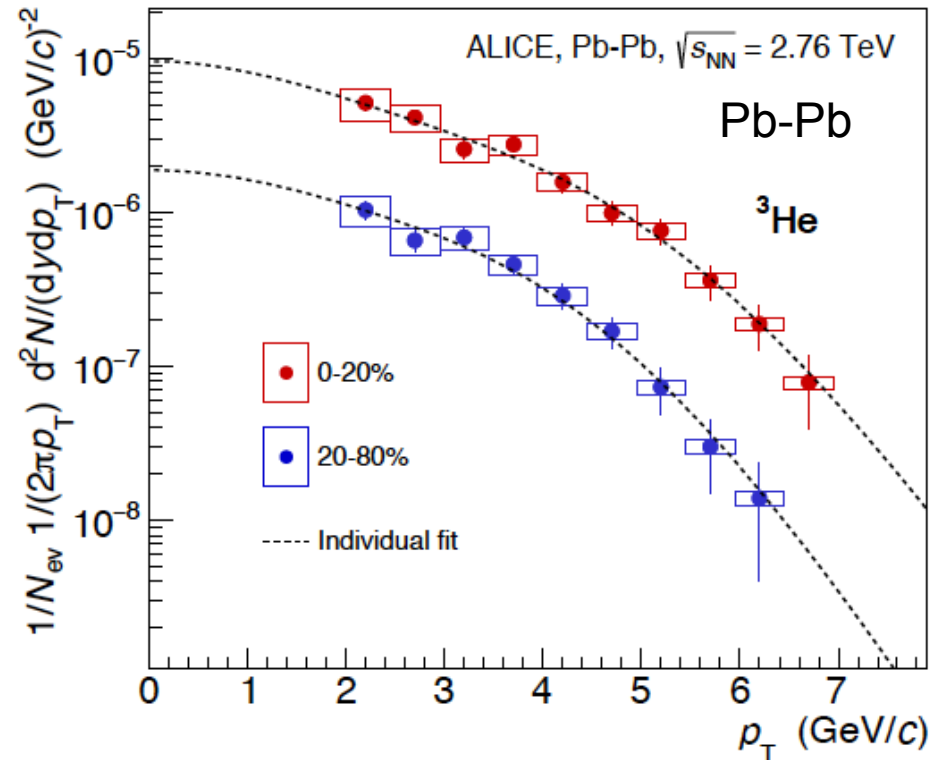
ALICE

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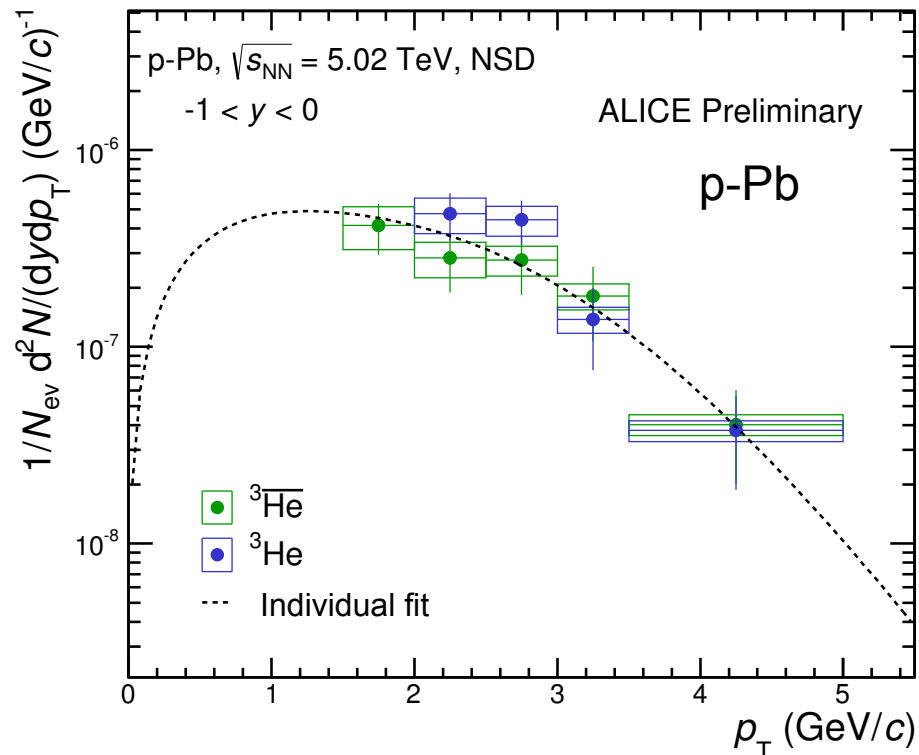
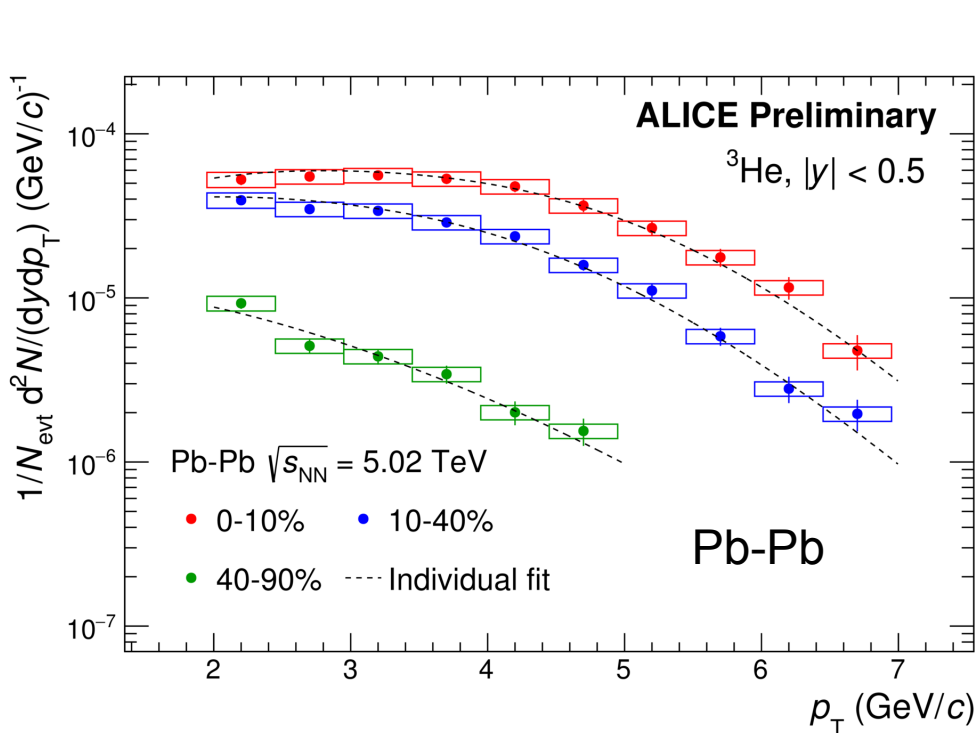
^3He

ALICE Collaboration: PRC 93, 024917 (2016)



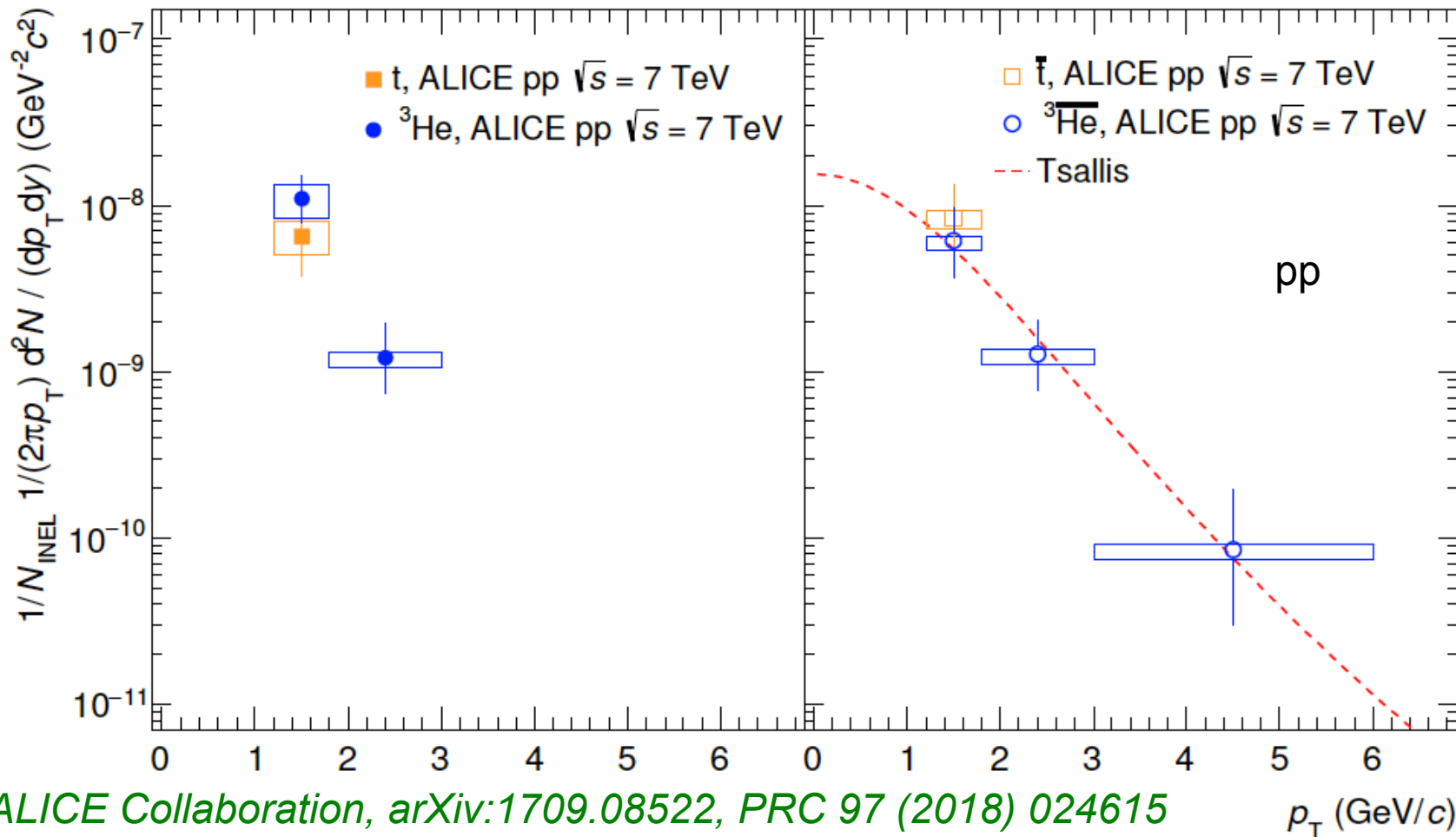
- Dashed curves represent individual Blast-Wave fits
- Spectrum obtained in 2 centrality classes in Pb-Pb and for NSD collisions in p-Pb

^3He



- Dashed curves represent individual Blast-Wave fits
- Spectrum obtained in 3 centrality classes in Pb-Pb and for NSD collisions in p-Pb

^3He and t



ALICE Collaboration, [arXiv:1709.08522](https://arxiv.org/abs/1709.08522), PRC 97 (2018) 024615

- First „spectrum“ measured in pp collisions at 7 TeV for ^3He and anti- ^3He
- t and anti- t measurement difficult, (anti-) t /(anti-) ^3He agrees with unity

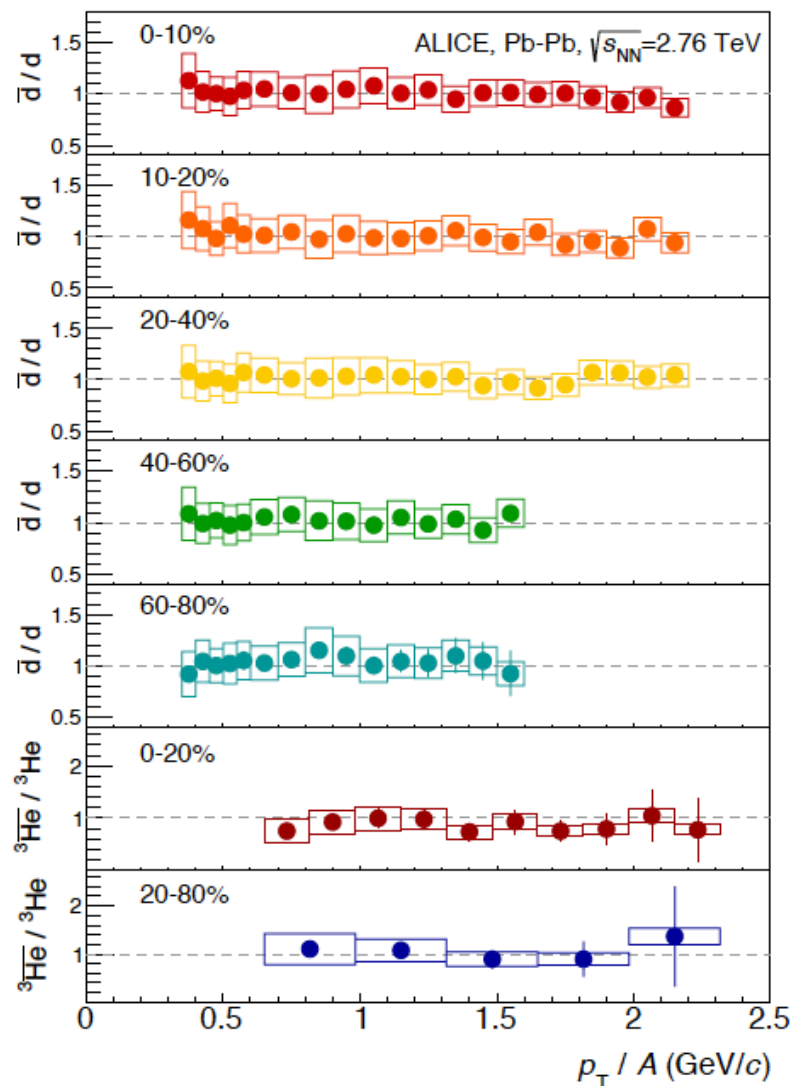


LHC: factory for anti-matter and matter



ALICE

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light particle species)
- Ratios exhibit constant behavior as a function of p_T and centrality
- Ratios are in agreement with the coalescence and thermal model expectations

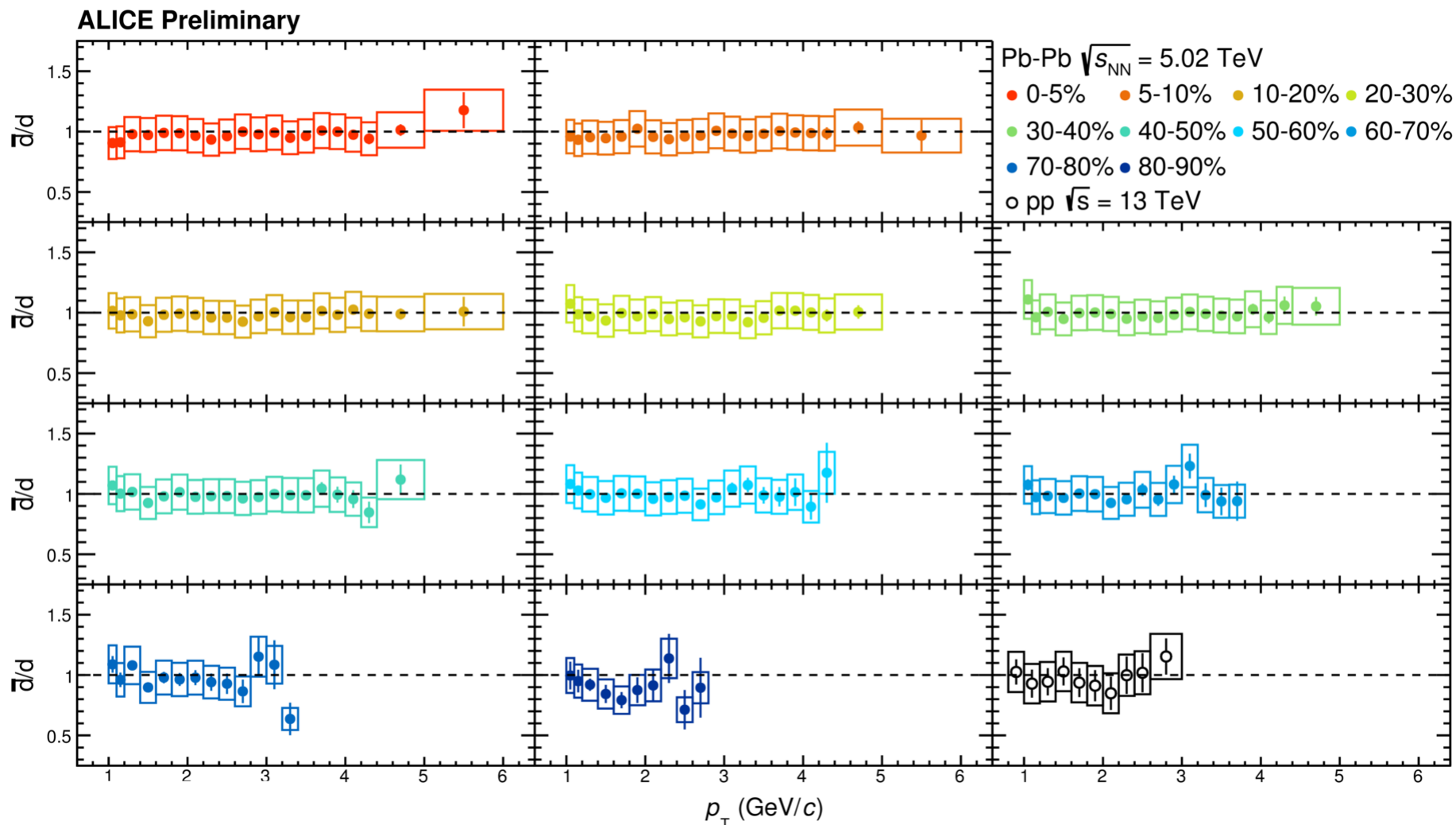


ALICE Collaboration: PRC 93, 024917 (2016)

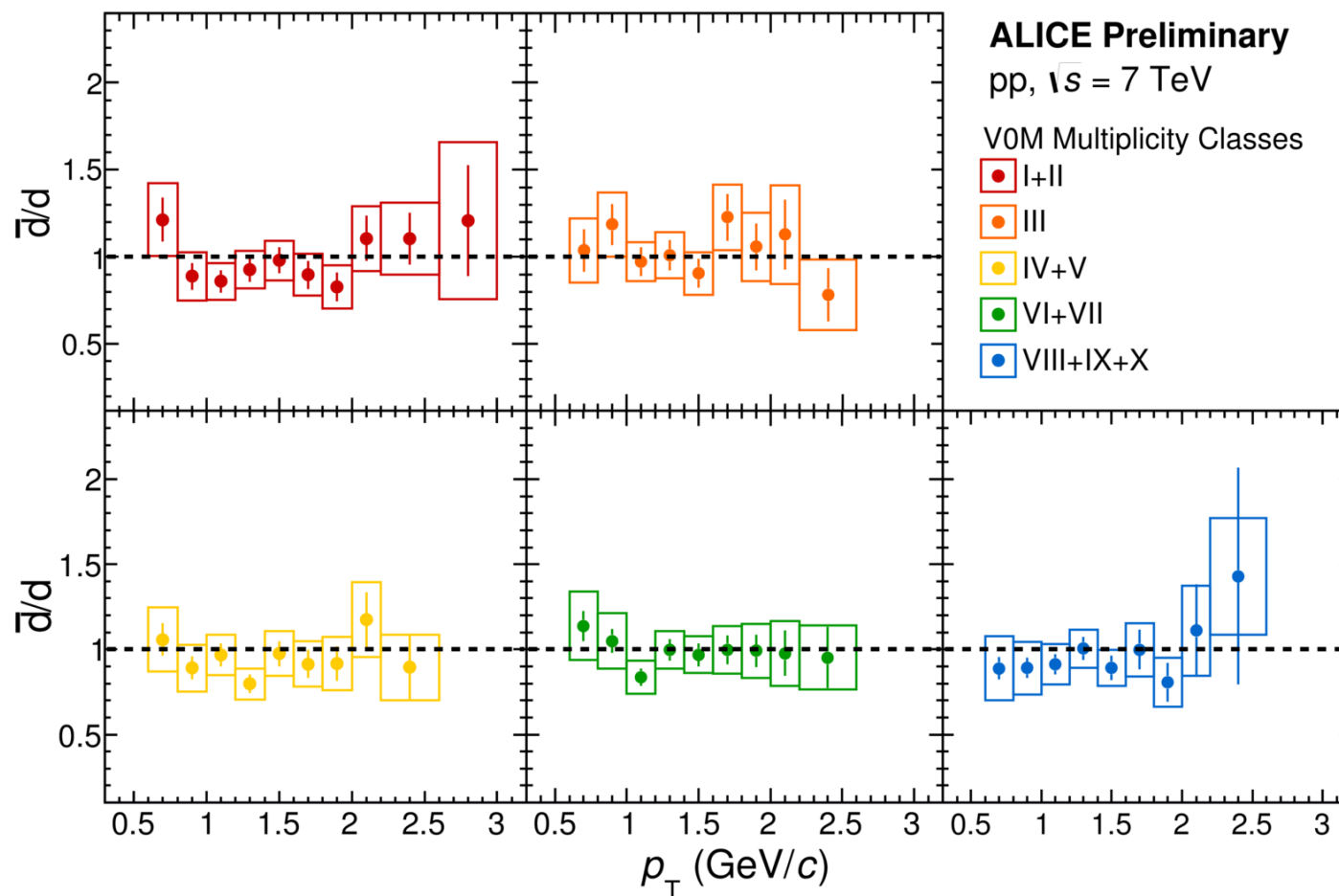
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ALICE

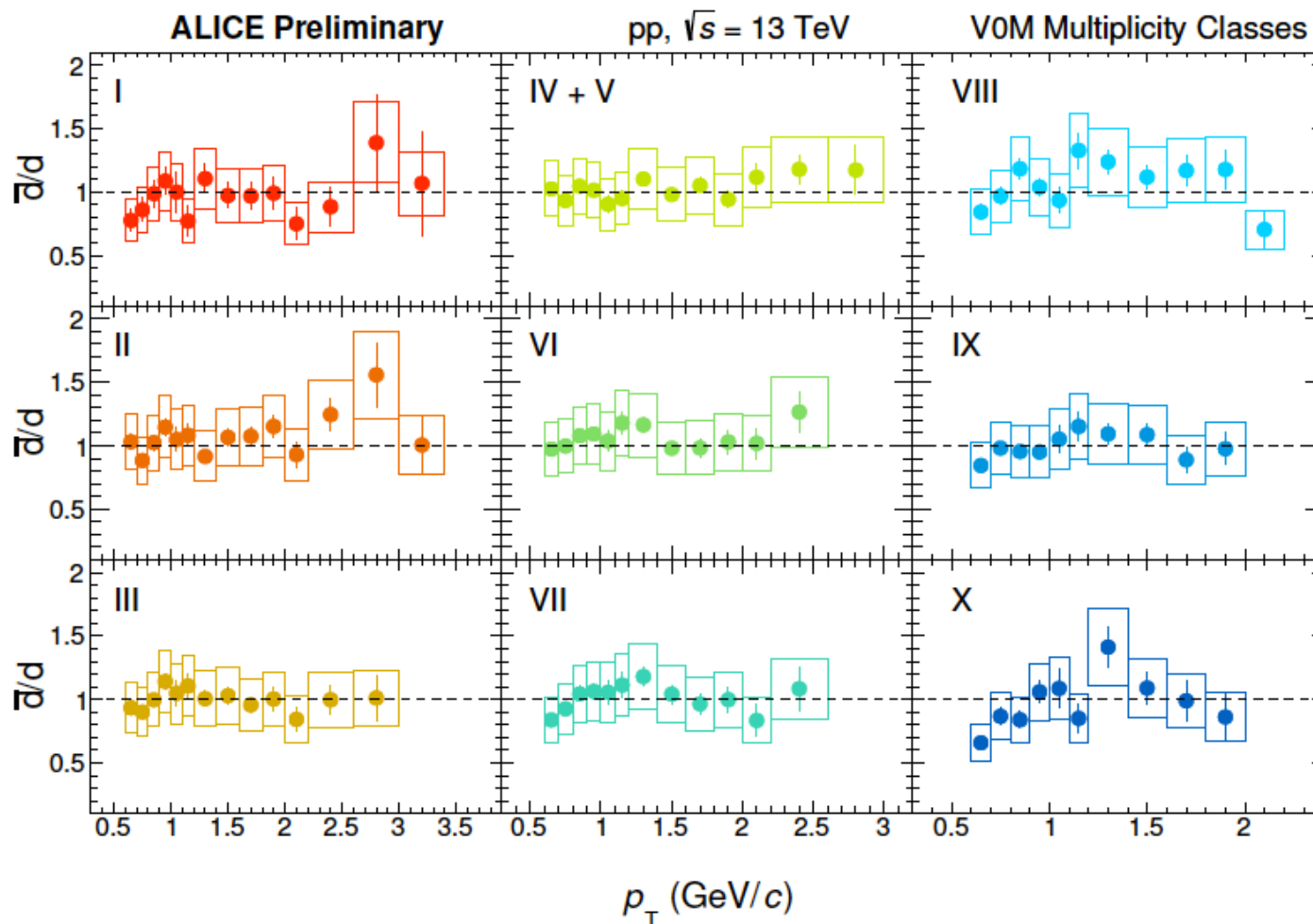


LHC: factory for anti-matter and matter



Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally

LHC: factory for anti-matter and matter



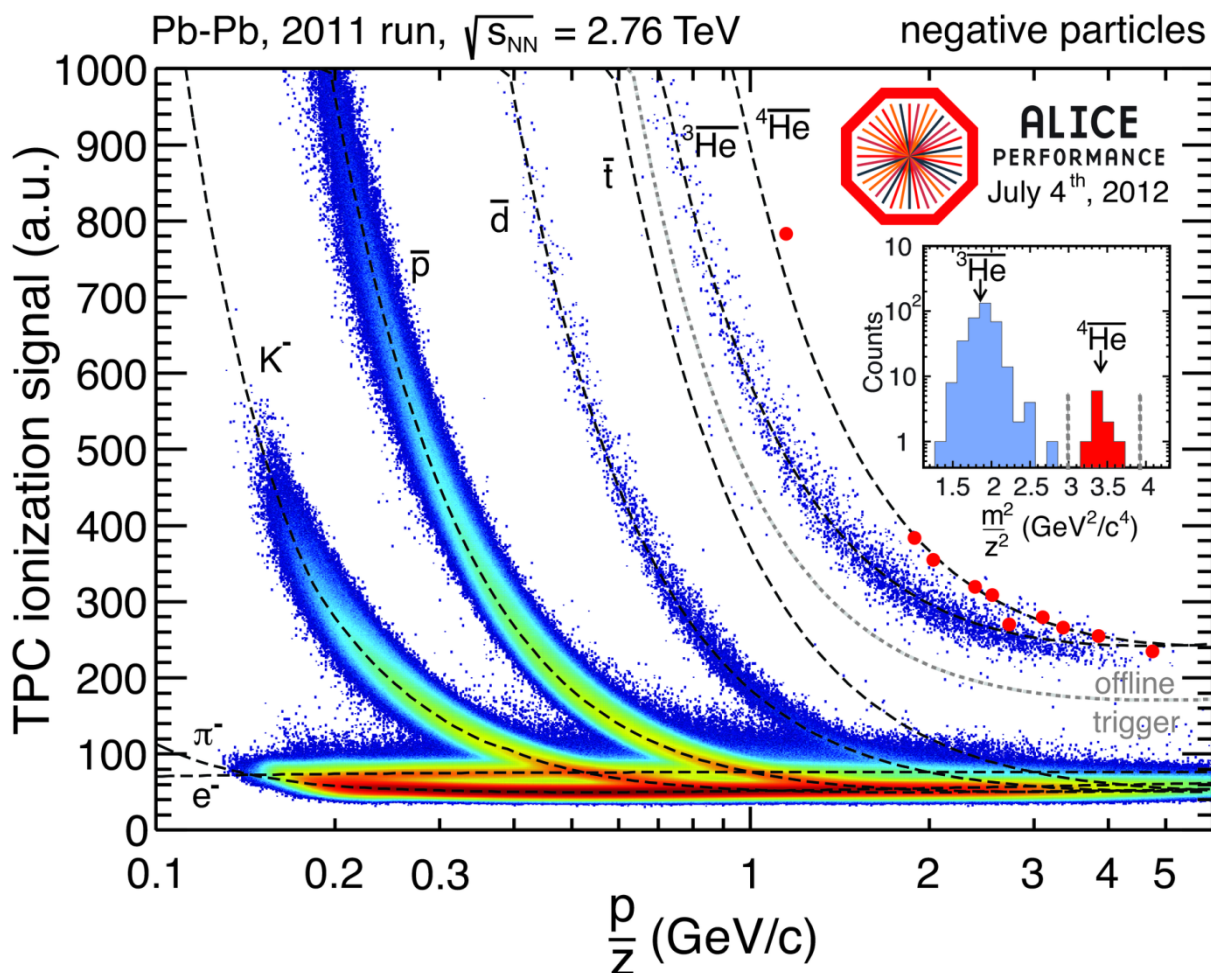
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Anti-Alpha

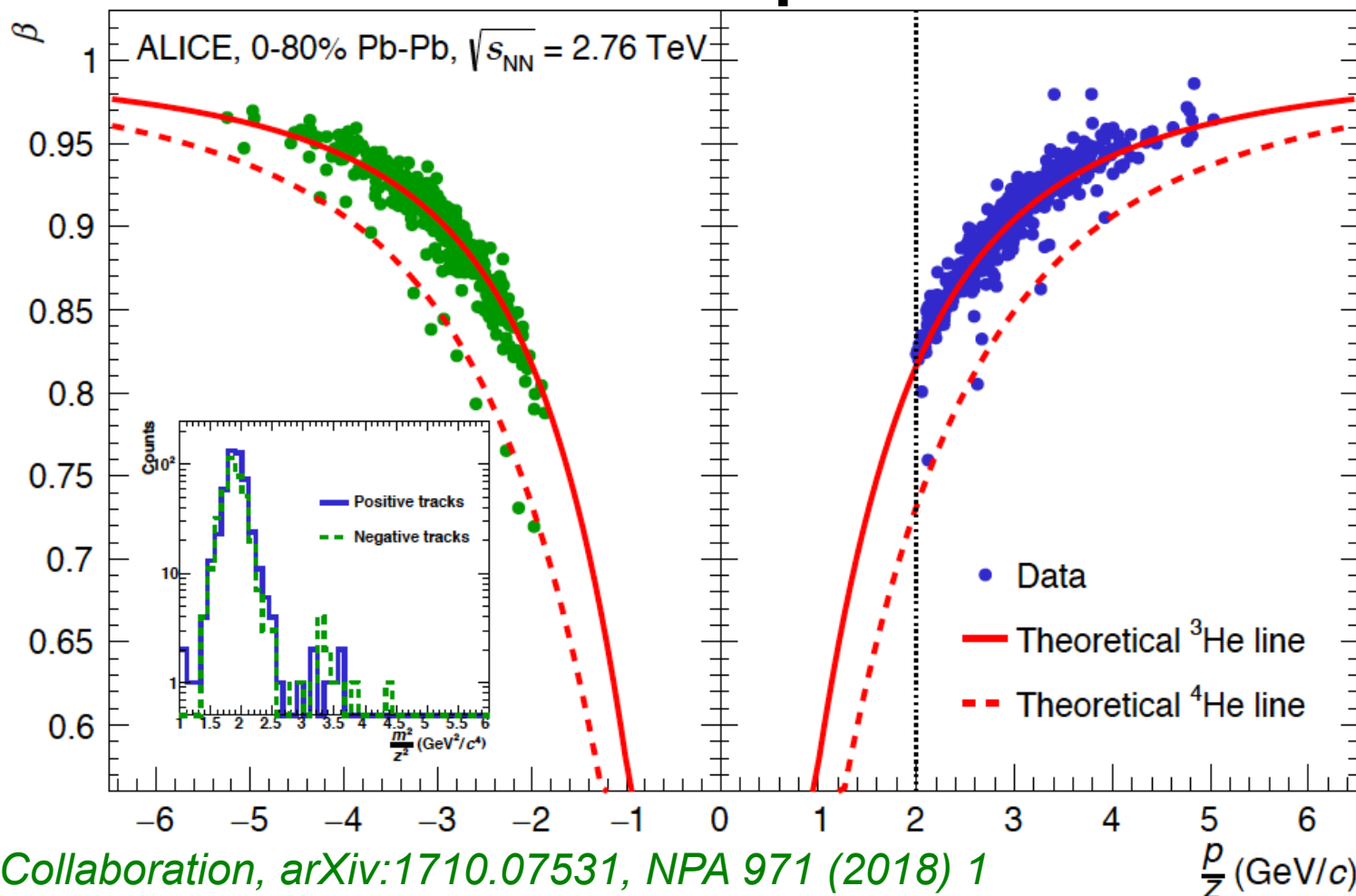
For the full statistics
of 2011 ALICE
identified 10 Anti-
Alphas using
TPC and TOF

STAR observed the
Anti-Alpha in 2010:

Nature 473, 353 (2011)



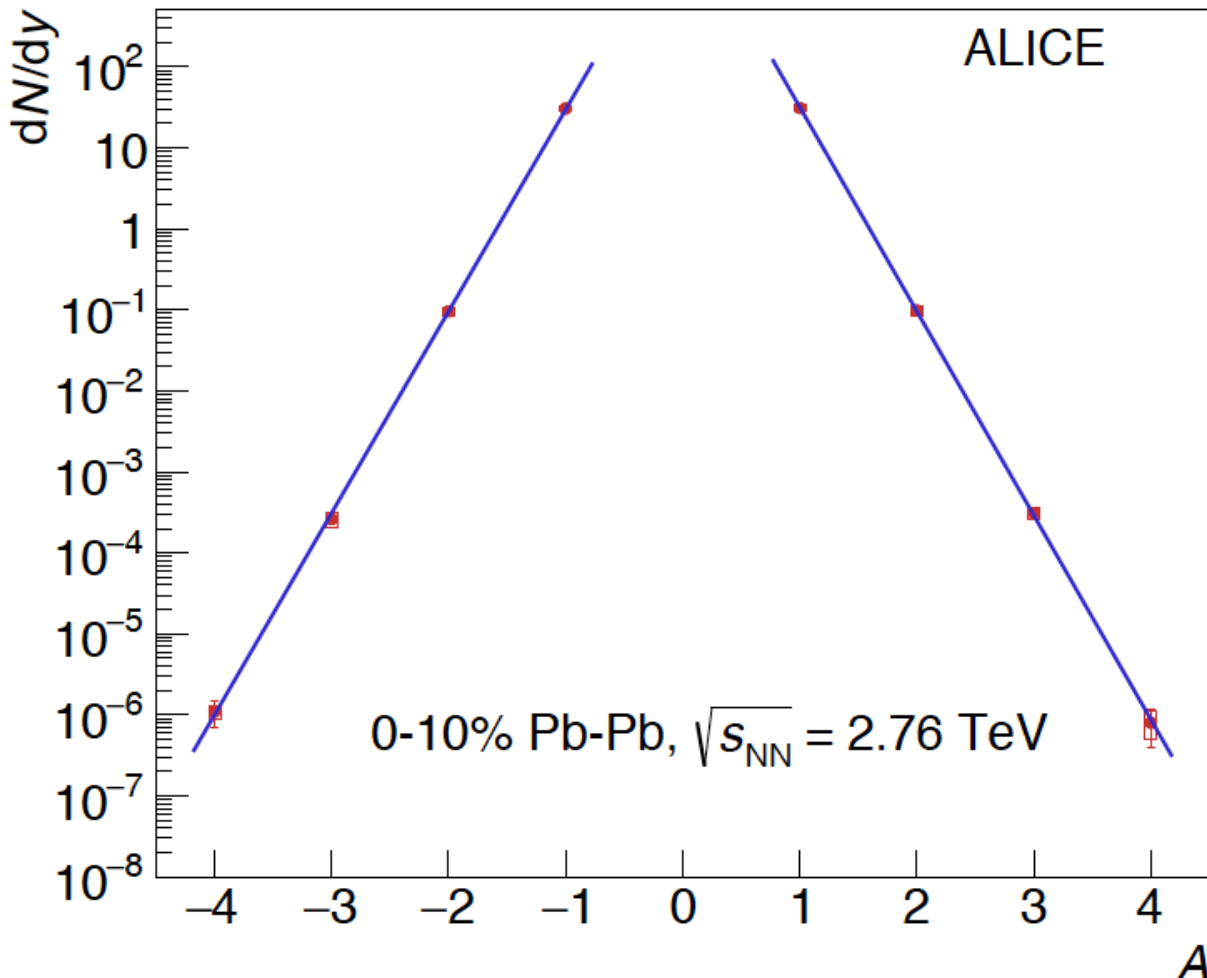
Anti-Alpha



ALICE Collaboration, [arXiv:1710.07531](https://arxiv.org/abs/1710.07531), NPA 971 (2018) 1

TOF β vs p/z after pre-selection of 3σ in TPC shows clear separation $\rightarrow$ Cut on Alpha needed to suppress contamination

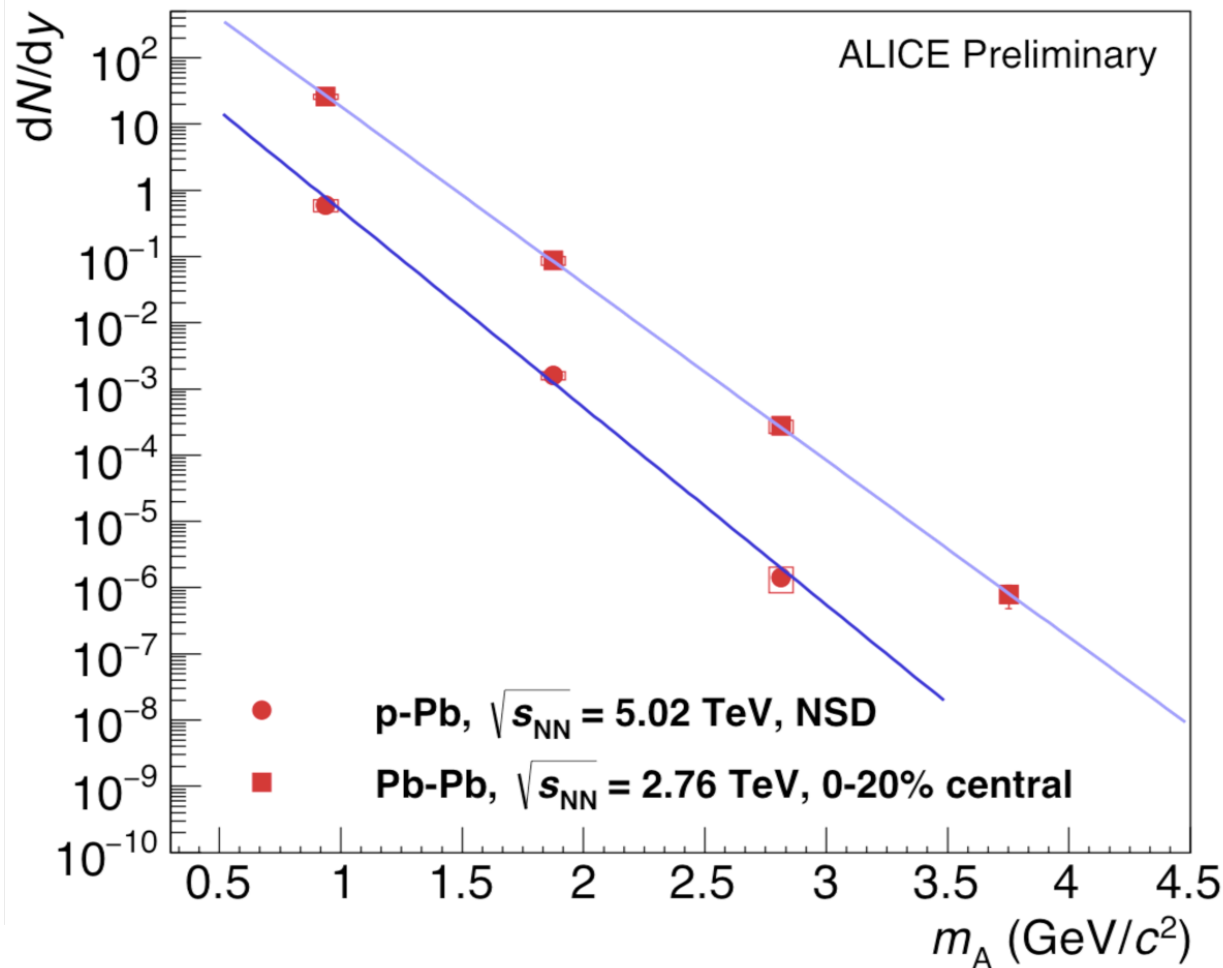
Mass dependence



- Nuclei production yields follow an **exponential** decrease with mass as predicted by the thermal model
- In Pb-Pb the penalty factor for adding one baryon is ~ 300 (for particles and antiparticles)

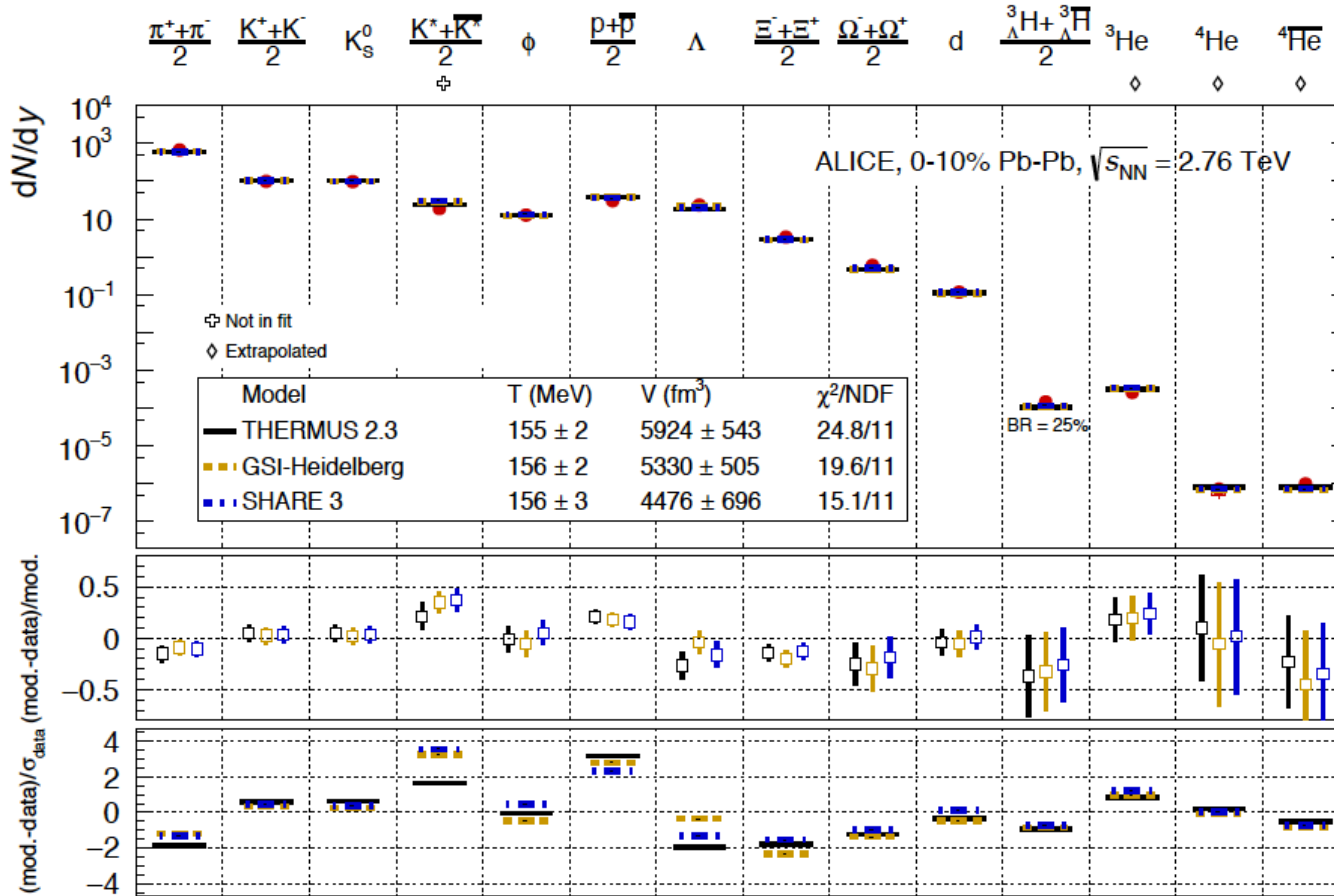
ALICE Collaboration, [arXiv:1710.07531](https://arxiv.org/abs/1710.07531), NPA 971, 1 (2018)

Mass dependence



- Nuclei production yields follow an **exponential** decrease with mass as predicted by the thermal model
- In Pb-Pb the penalty factor for adding one baryon is ~300 and in p-Pb is ~600

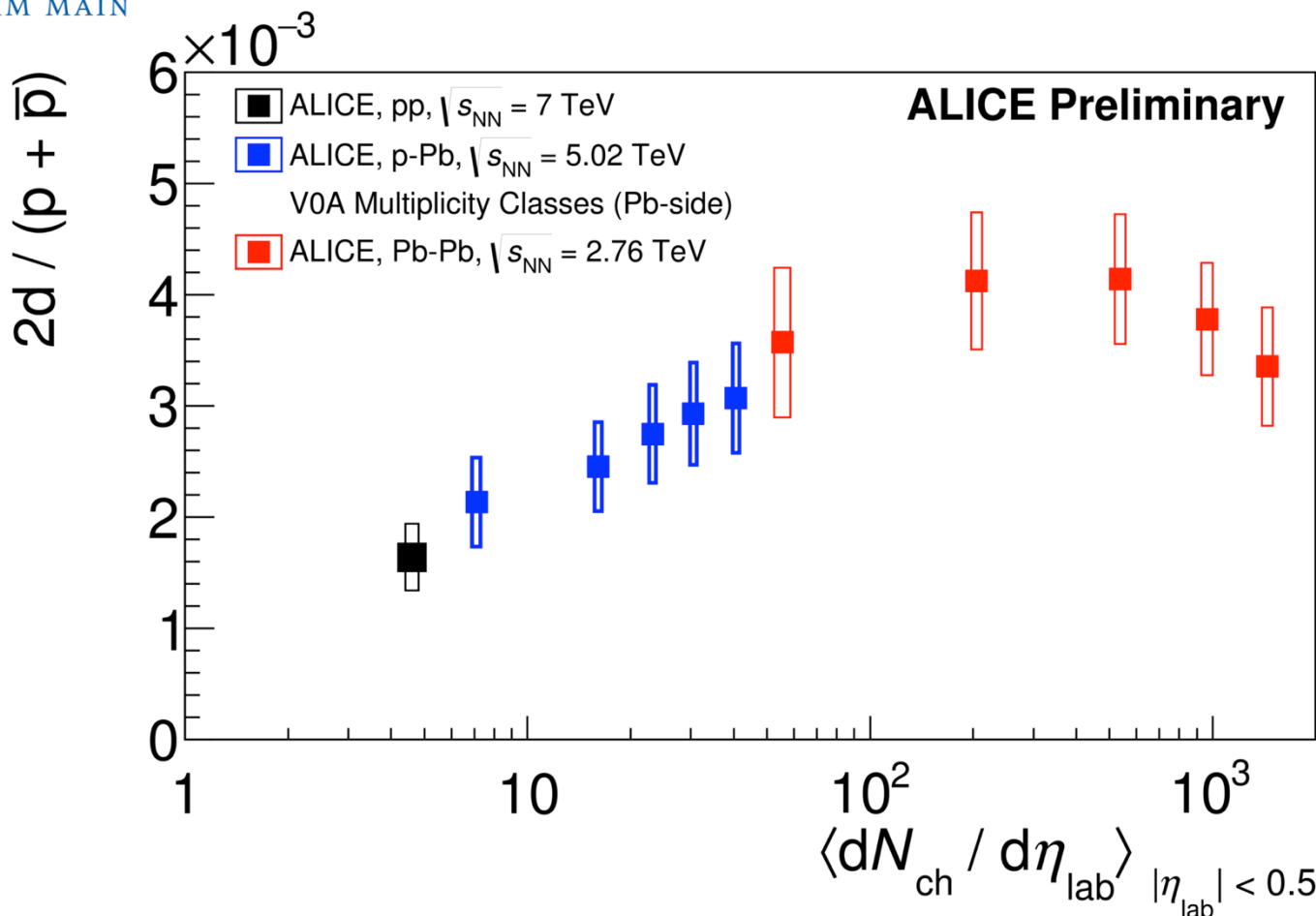
Thermal model fits



- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- Including nuclei in the fit causes no significant change in T_{ch}

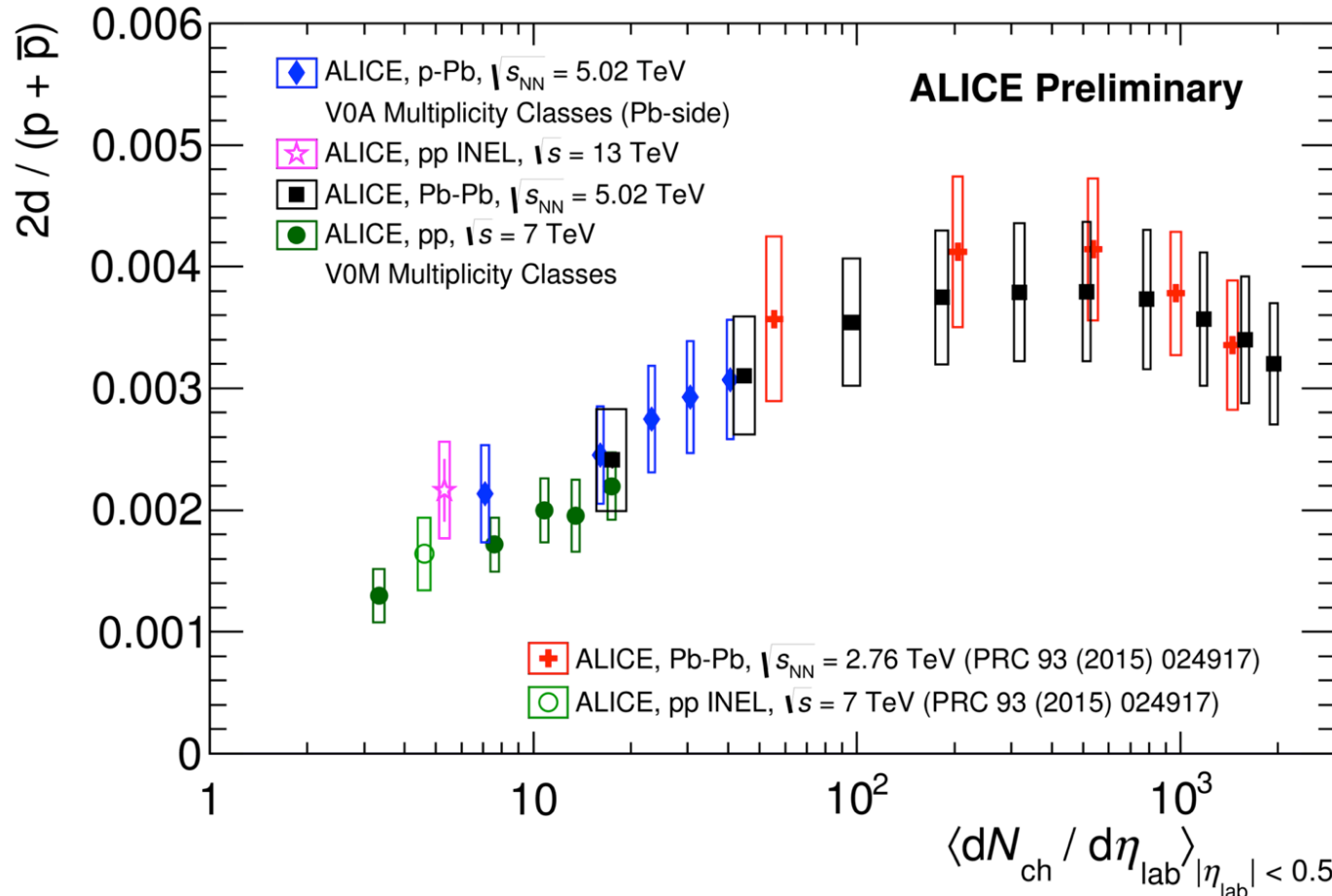
ALICE Collaboration, arXiv:1710.07531,
NPA 971, 1 (2018)

d/p vs. multiplicity



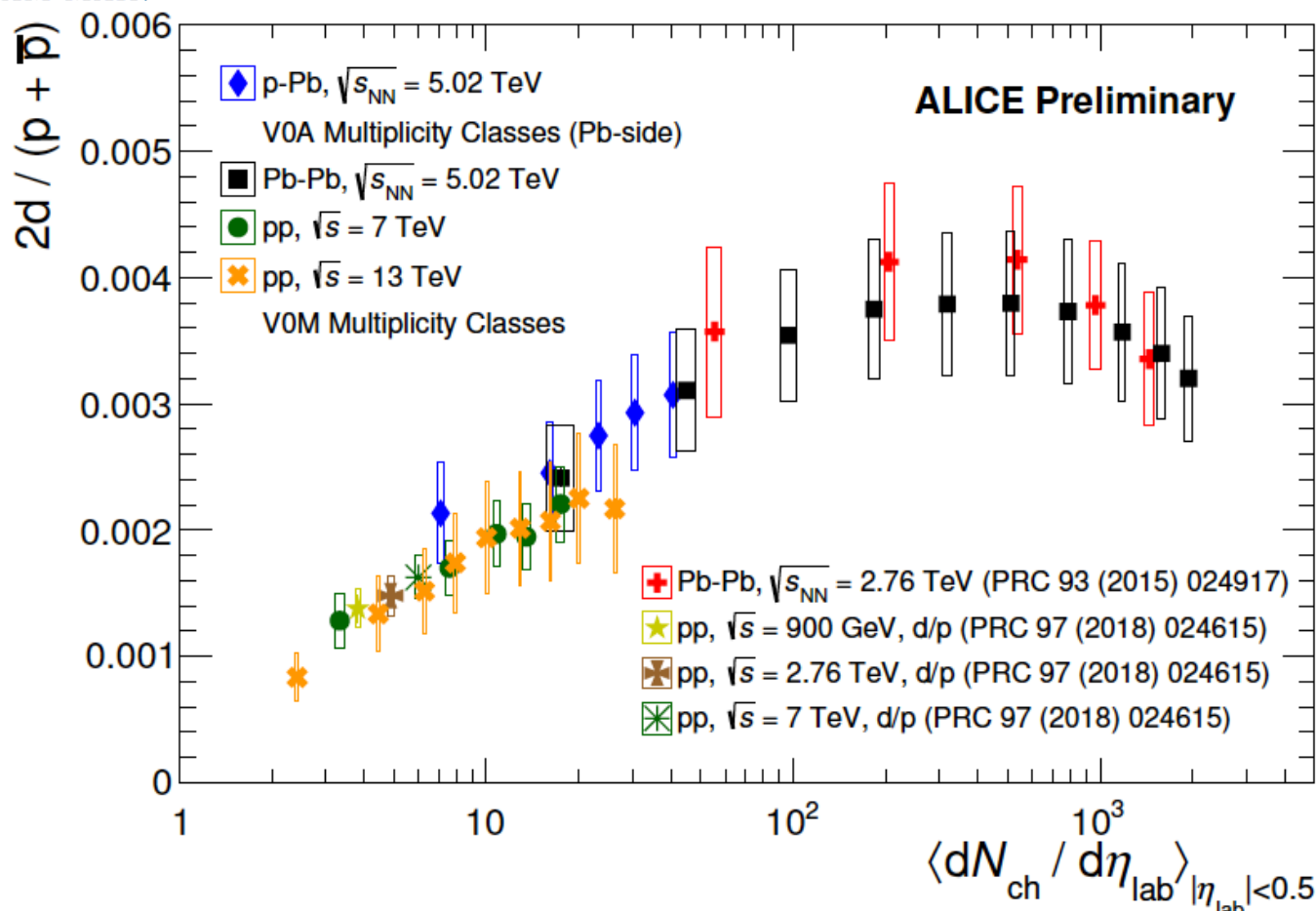
d/p ratio increases when going from pp to p-Pb, until it reaches the grand canonical thermal model value ($d/p=3 \times 10^{-3}$ at $T_{ch} = 156$ MeV)

d/p vs. multiplicity



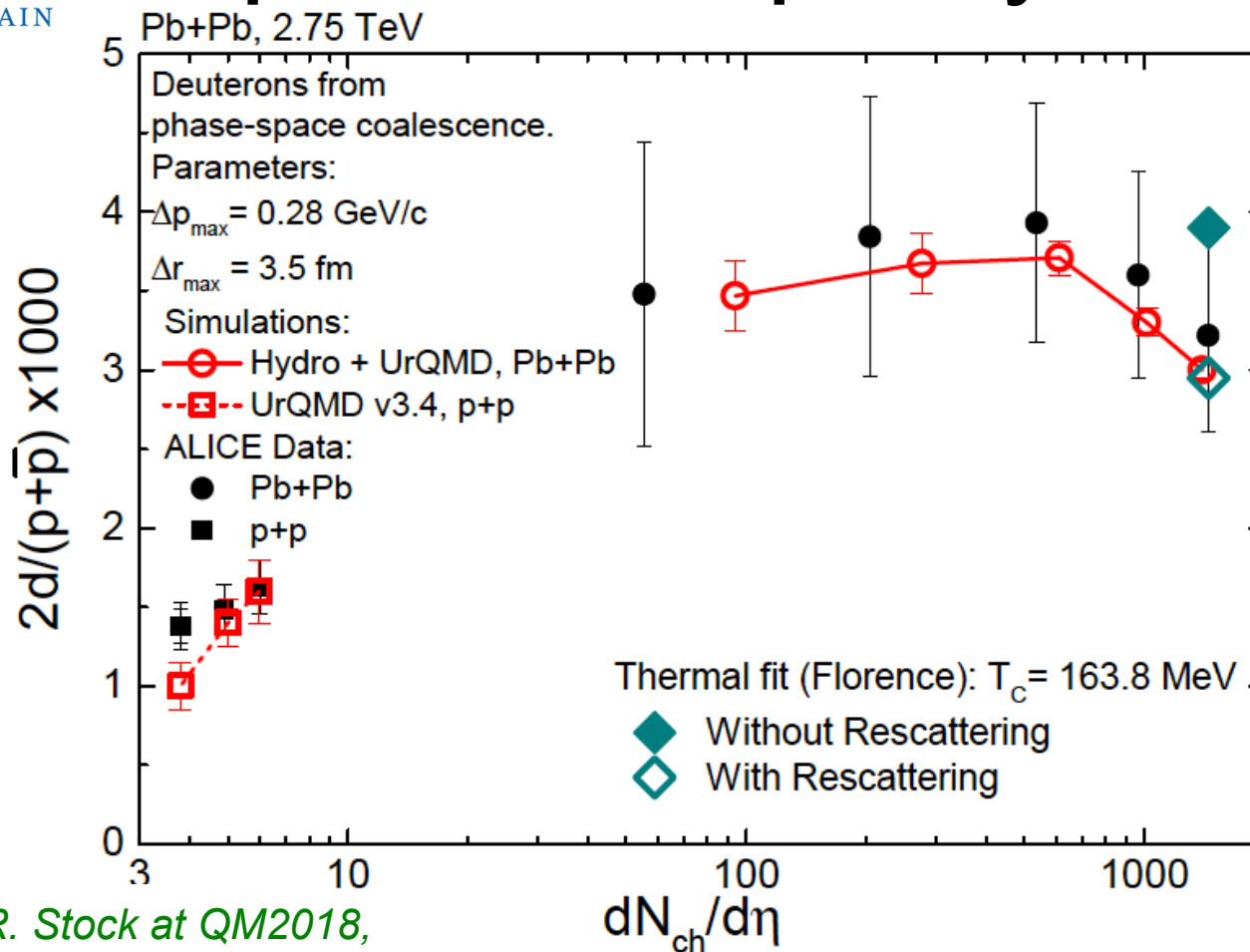
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d/p vs. multiplicity



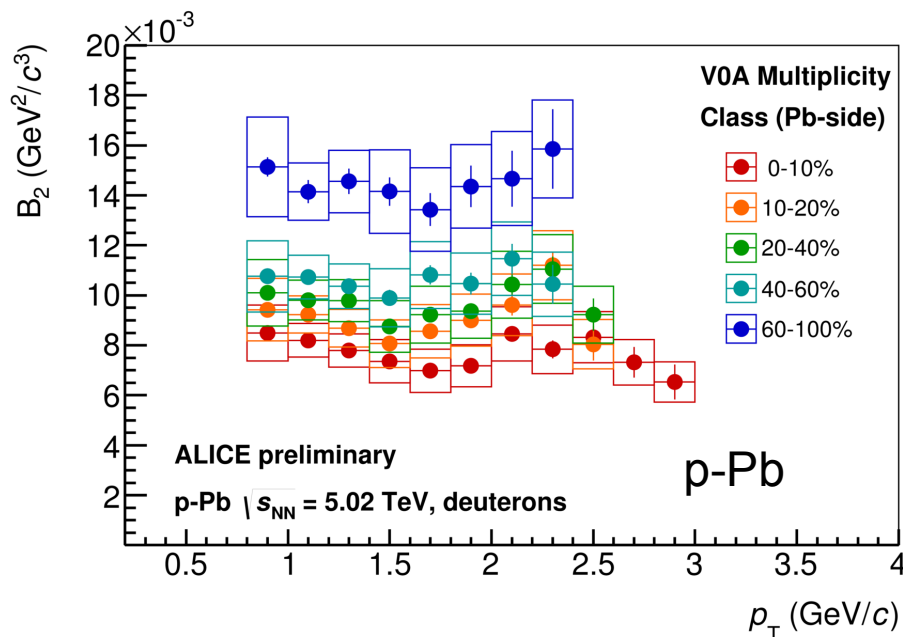
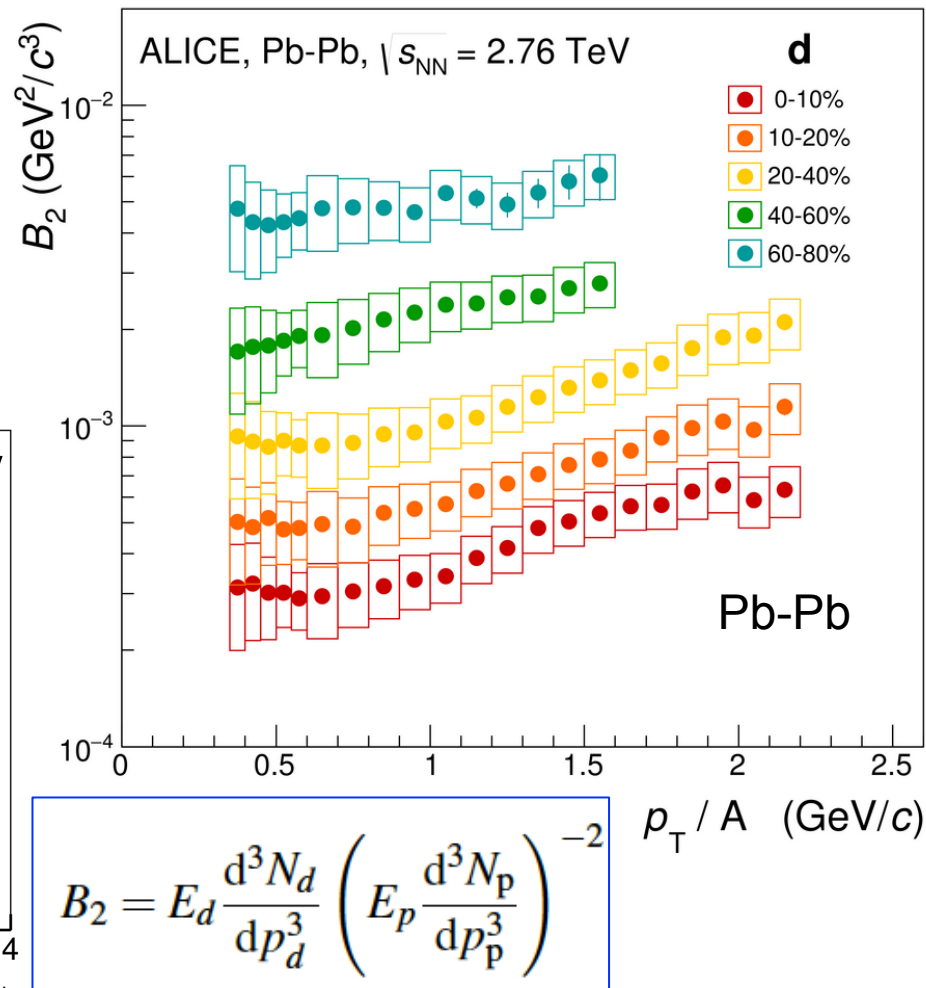
As shown by R. Stock at QM2018,
meanwhile coalescence on [arXiv:1805.11509](https://arxiv.org/abs/1805.11509)

d/p ratio described by applying afterburner on Hybrid
UrQMD simulations – similar results for thermal approach

Coalescence parameter B_2

ALICE Collaboration: PRC 93, 024917 (2016)

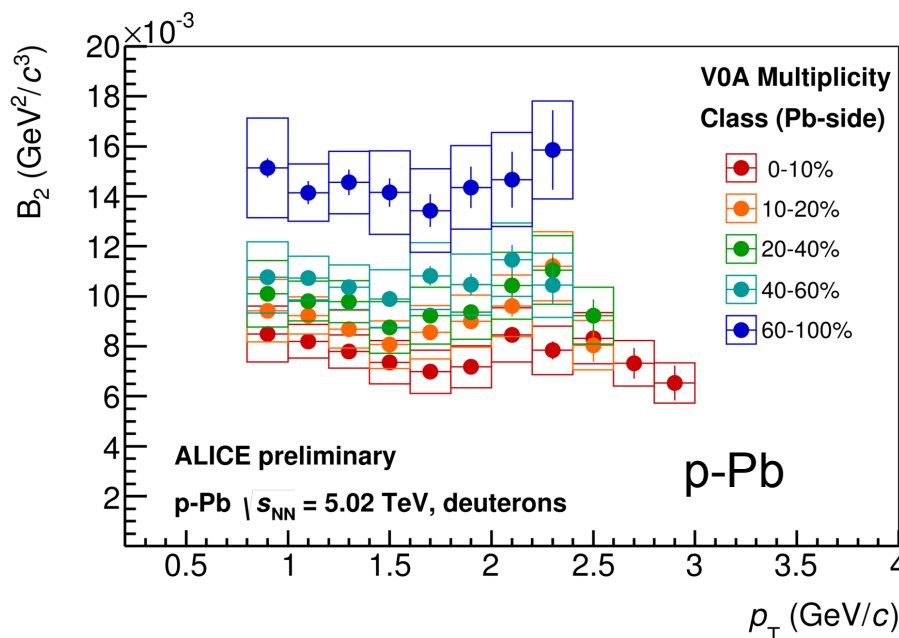
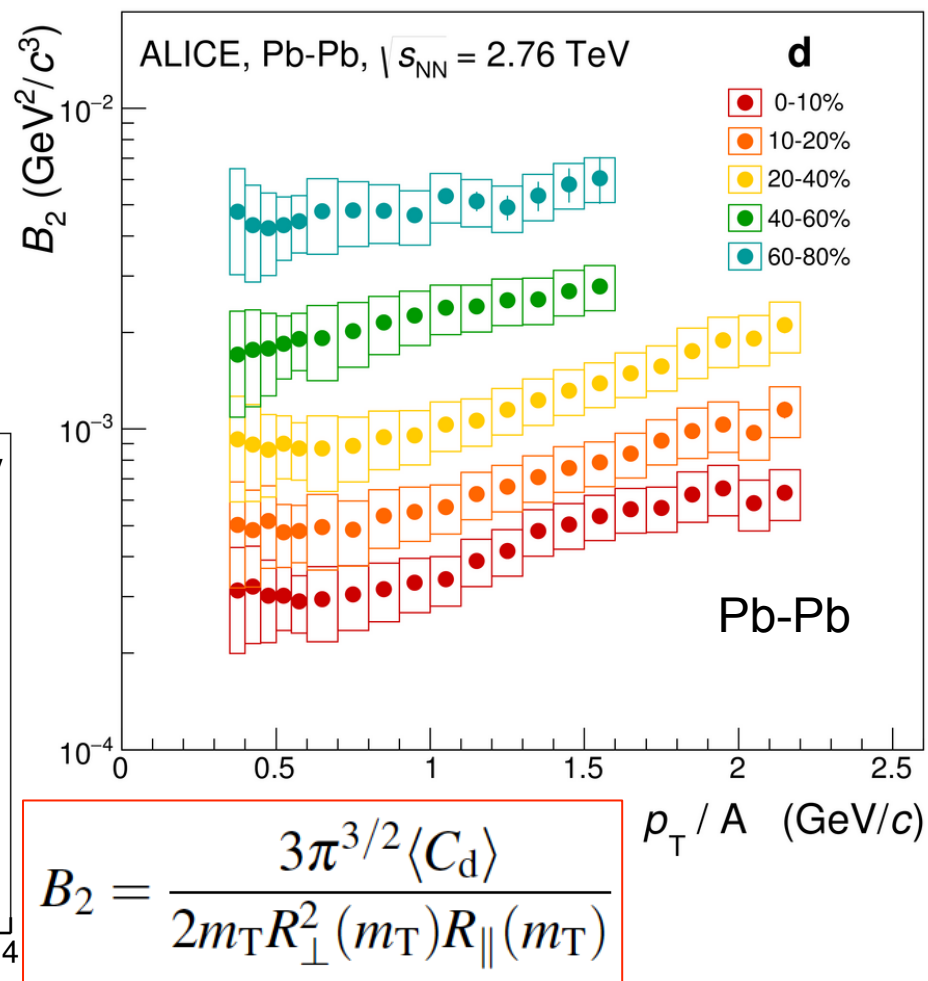
- Coalescence parameter B_2 decreases with centrality in Pb-Pb
- Similar effect seen in p-Pb: decrease with multiplicity, but less pronounced
- Simple coalescence expects B_2 to be constant



Coalescence parameter B_2

ALICE Collaboration: PRC 93, 024917 (2016)

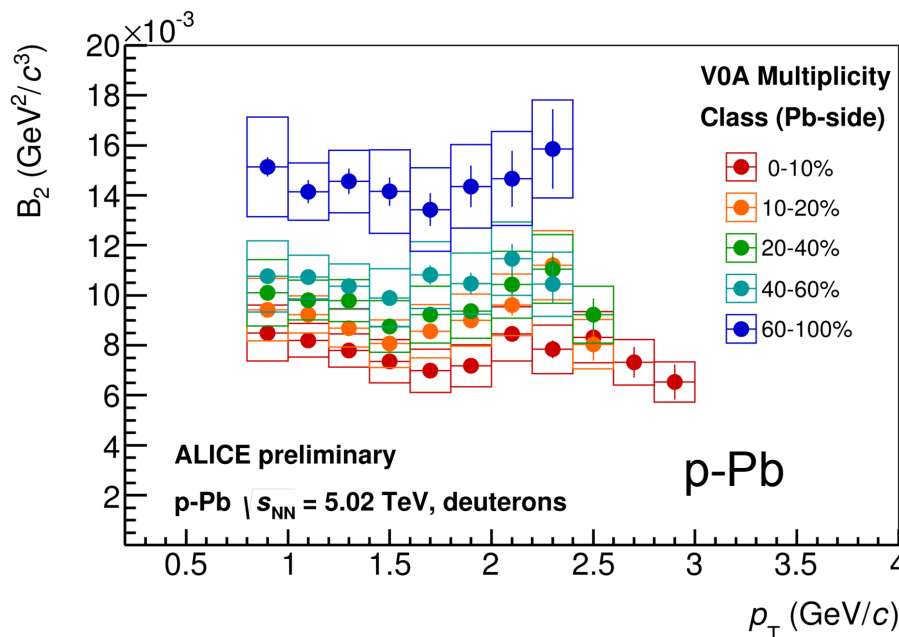
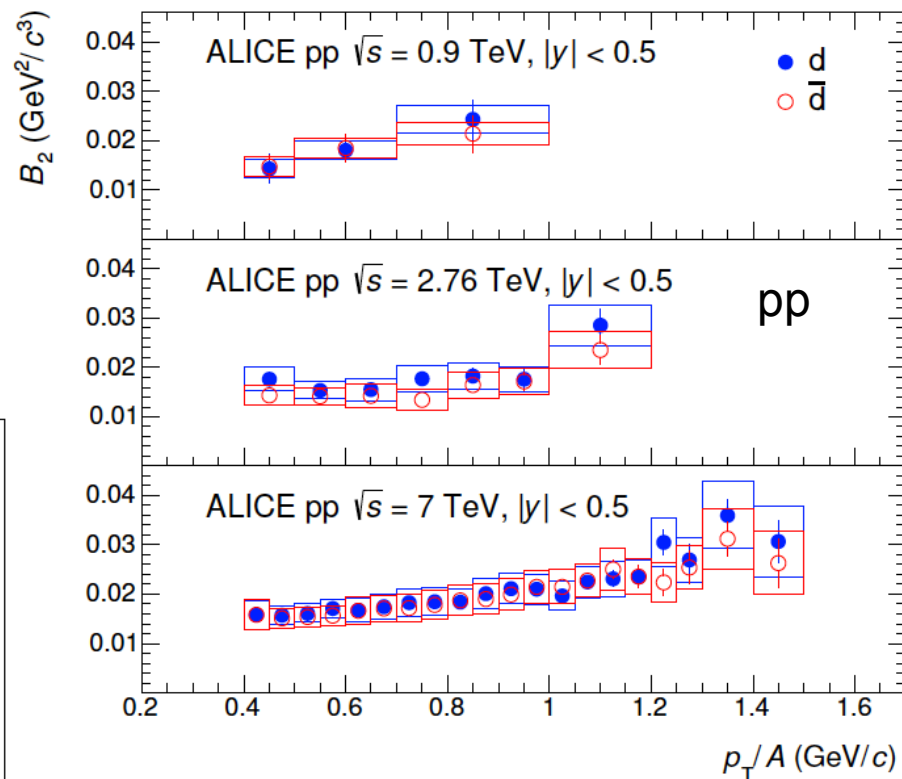
- Coalescence parameter B_2 decreases with centrality in Pb-Pb
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- B_2 scales like the HBT radii
 - Decrease with centrality in Pb-Pb is understood as an increase in the source volume



Coalescence parameter B_2

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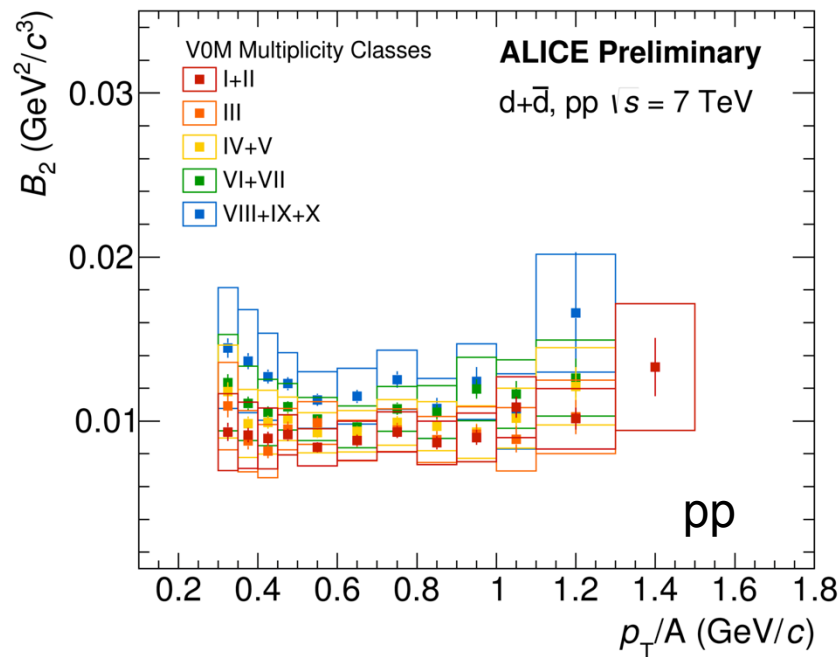
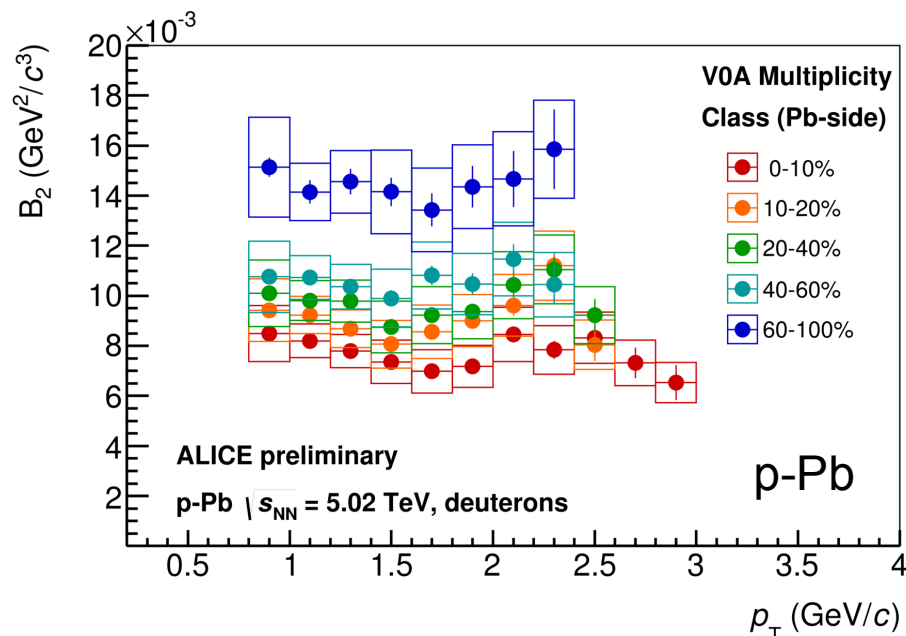
ALICE Collaboration, PRC 97 (2018) 024615



$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R_{\perp}^2(m_T) R_{\parallel}(m_T)}$$

Coalescence parameter B_2

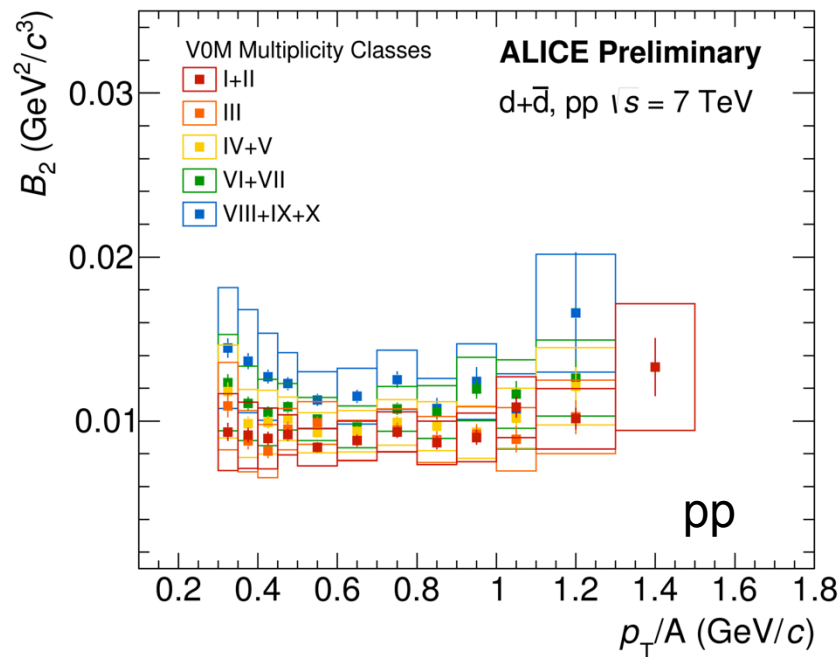
- Coalescence parameter B_2 decreases with centrality in Pb-Pb
- Similar effect seen in p-Pb: decrease with multiplicity, but less pronounced
- B_2 scales like the HBT radii
 - Decrease with centrality in Pb-Pb is understood as an increase in the source volume



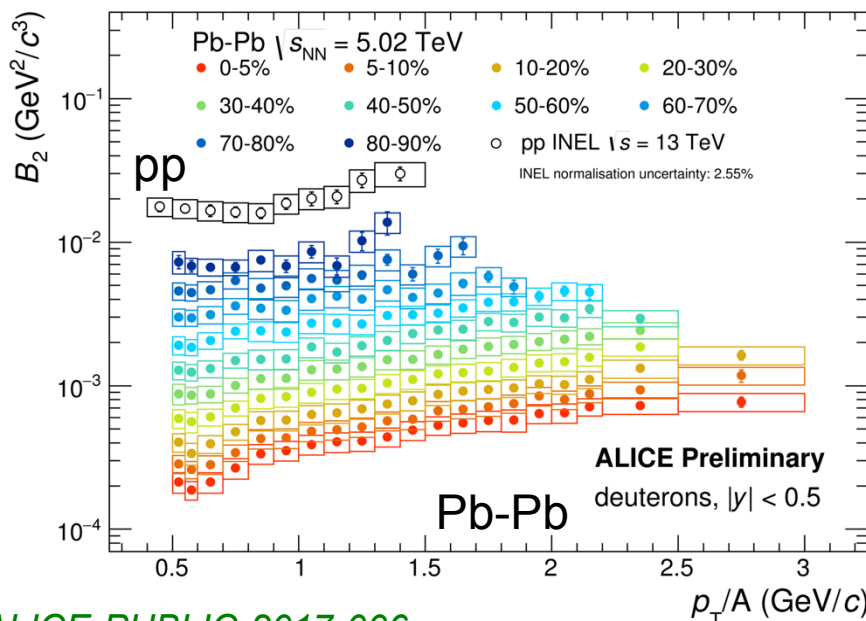
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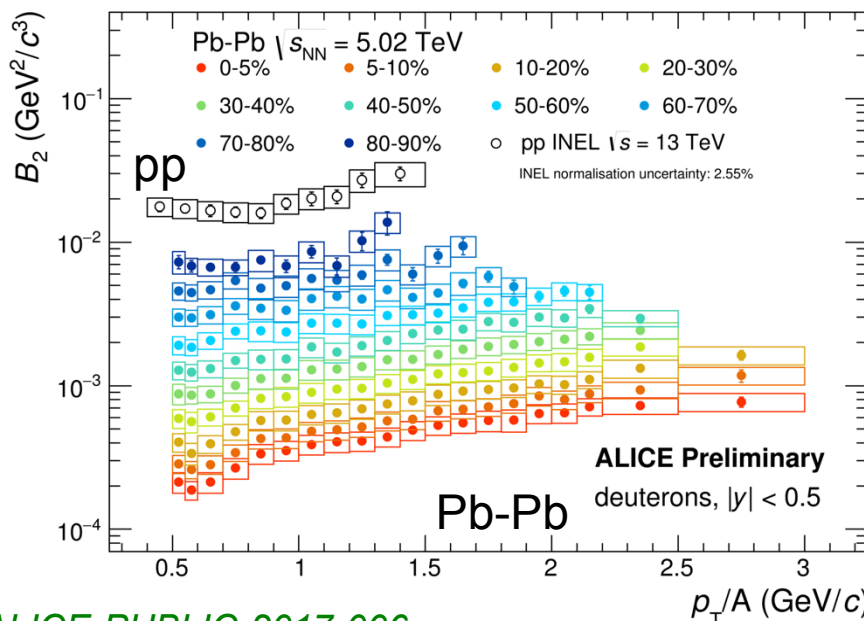
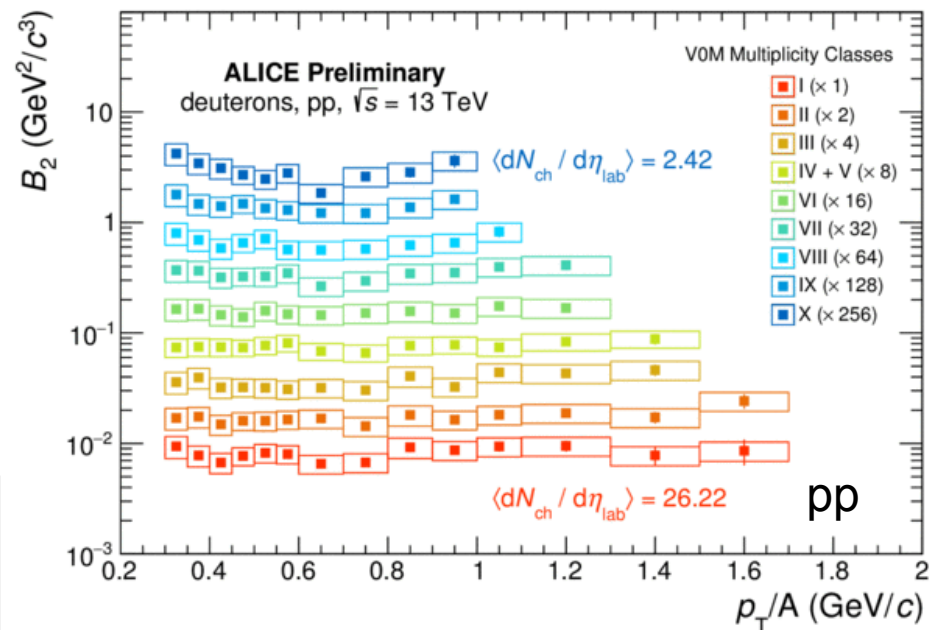


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Coalescence parameter B_2

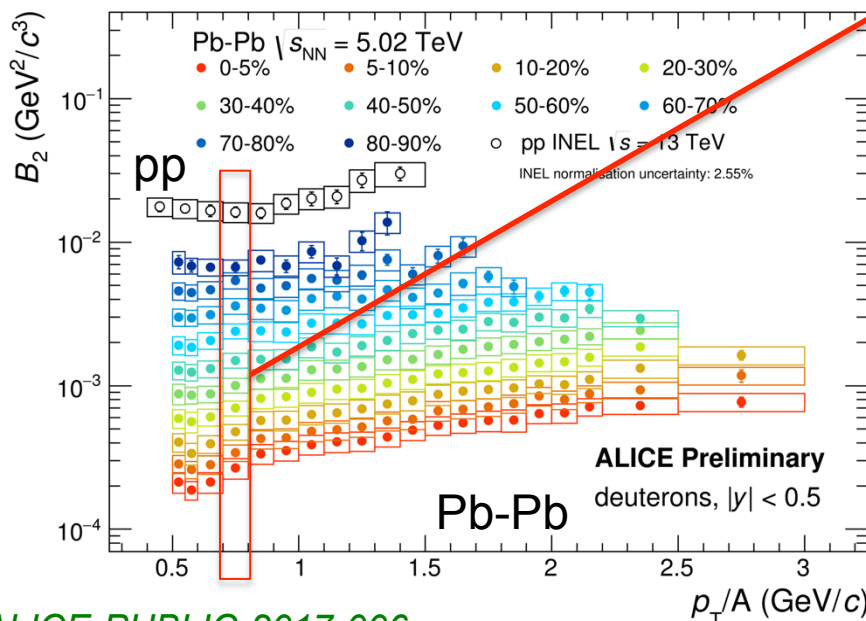
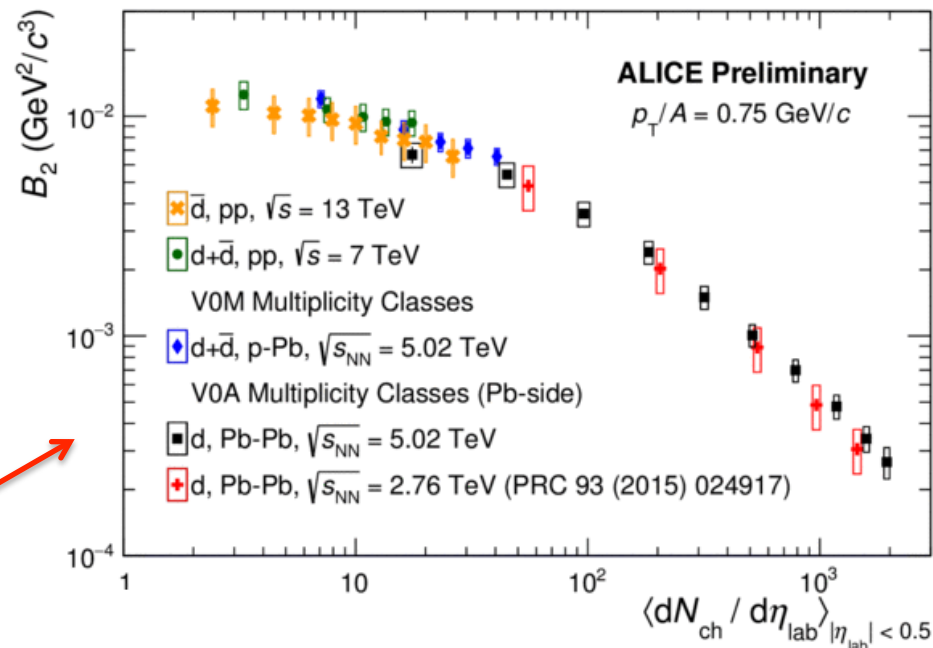
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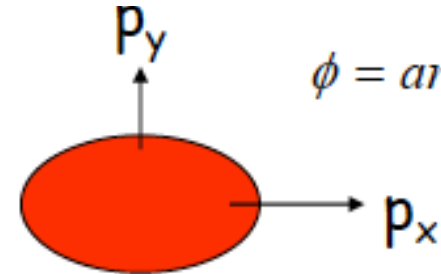
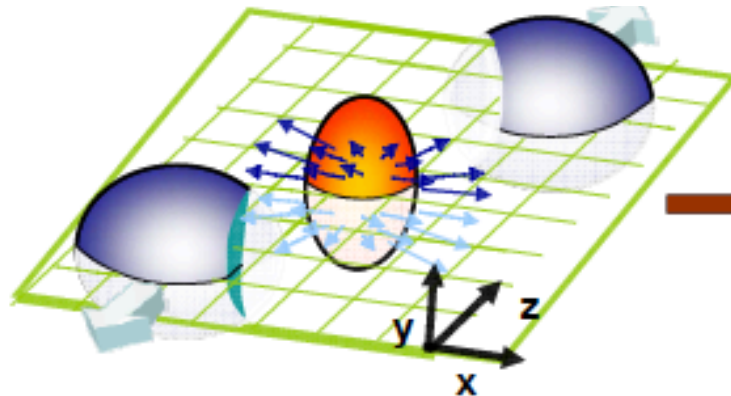
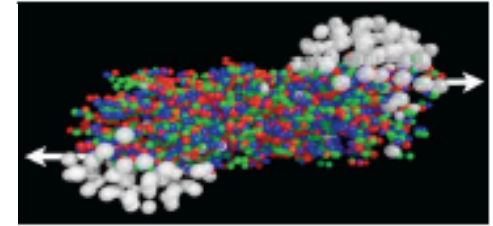
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$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R_\perp^2(m_T) R_\parallel(m_T)}$$

Elliptic flow



$$\phi = \arctan \frac{p_y}{p_x}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial coordinate-space anisotropy

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Final momentum-space anisotropy

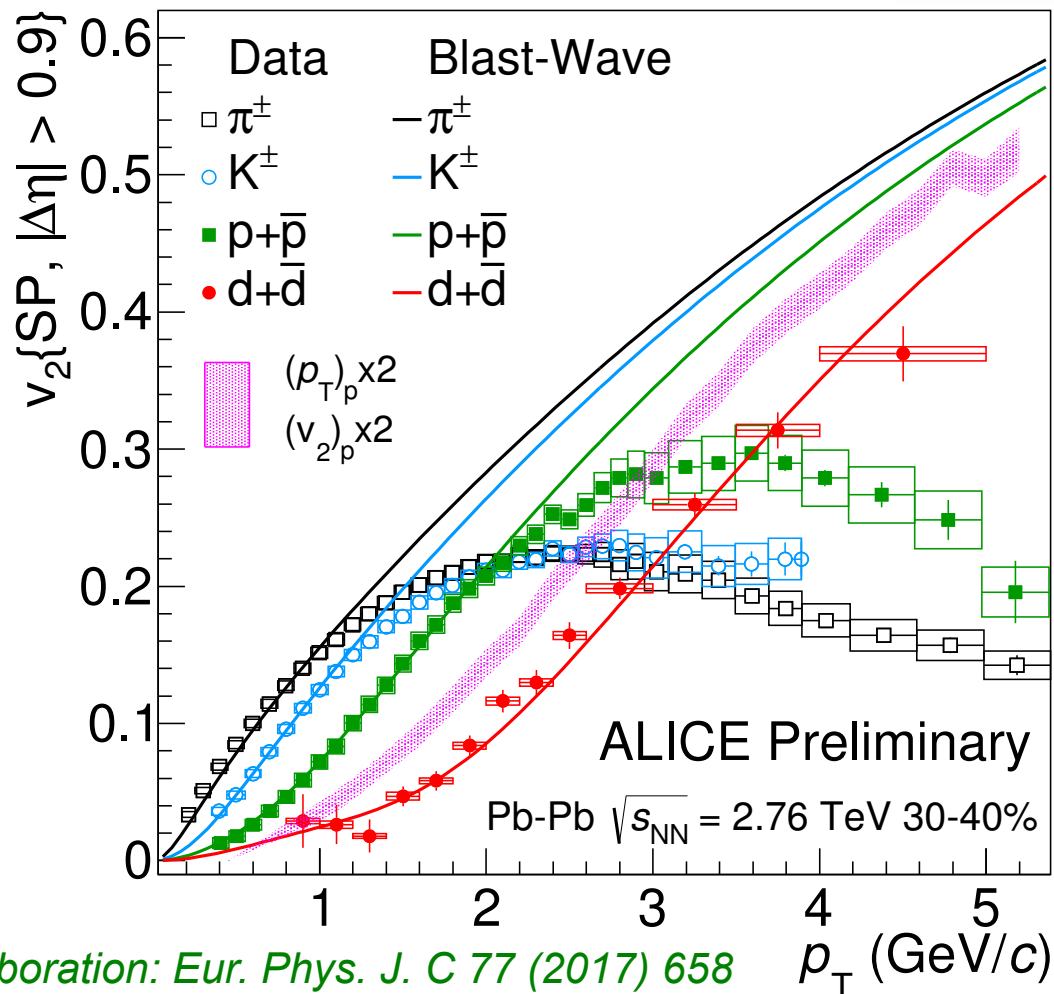
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)] + 2v_4 \cos[4(\phi - \Psi_R)] + \dots$$

Elliptic term

Anisotropy self-quenches, so
 v_2 is sensitive to early times

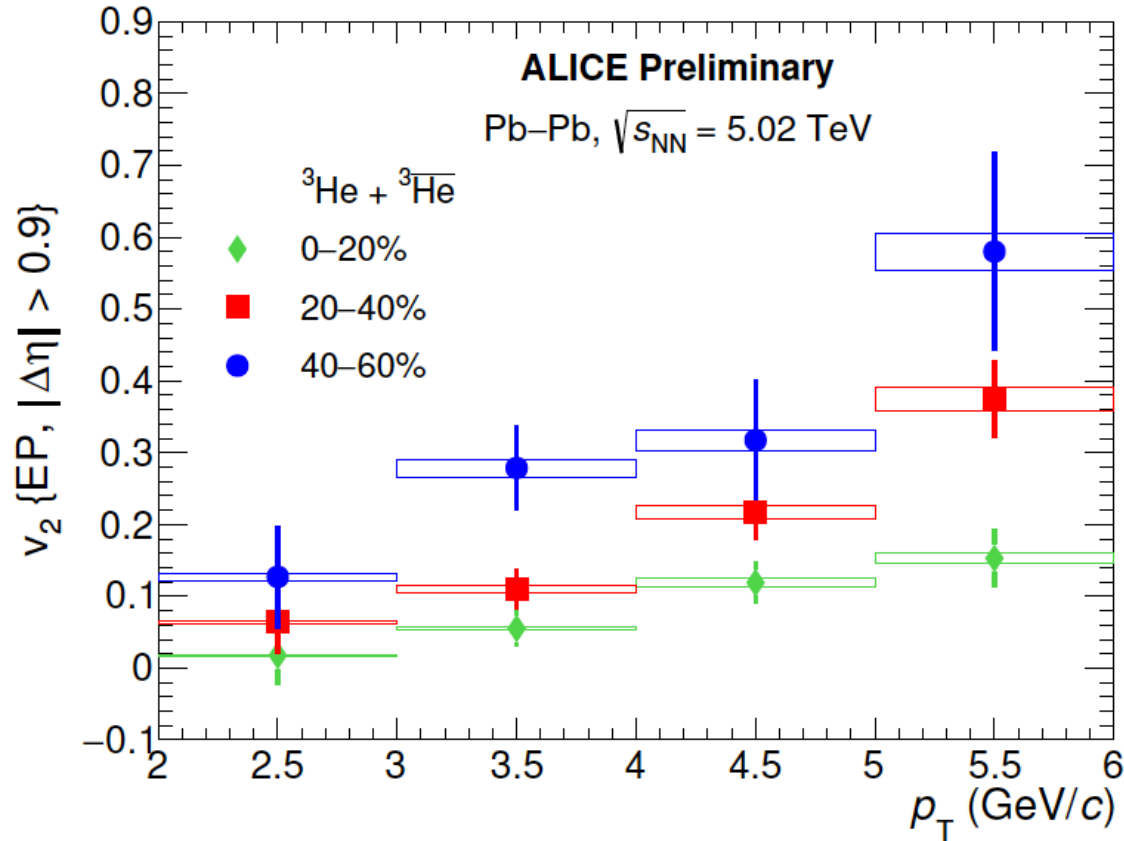
Deuteron flow

- Deuterons show a significant v_2
- Also the v_2 of deuterons follows the mass ordering expected from hydrodynamics
- A naive coalescence prediction is not able to reproduce the deuteron v_2
- A Blast-Wave prediction is able to describe the v_2 reasonably well



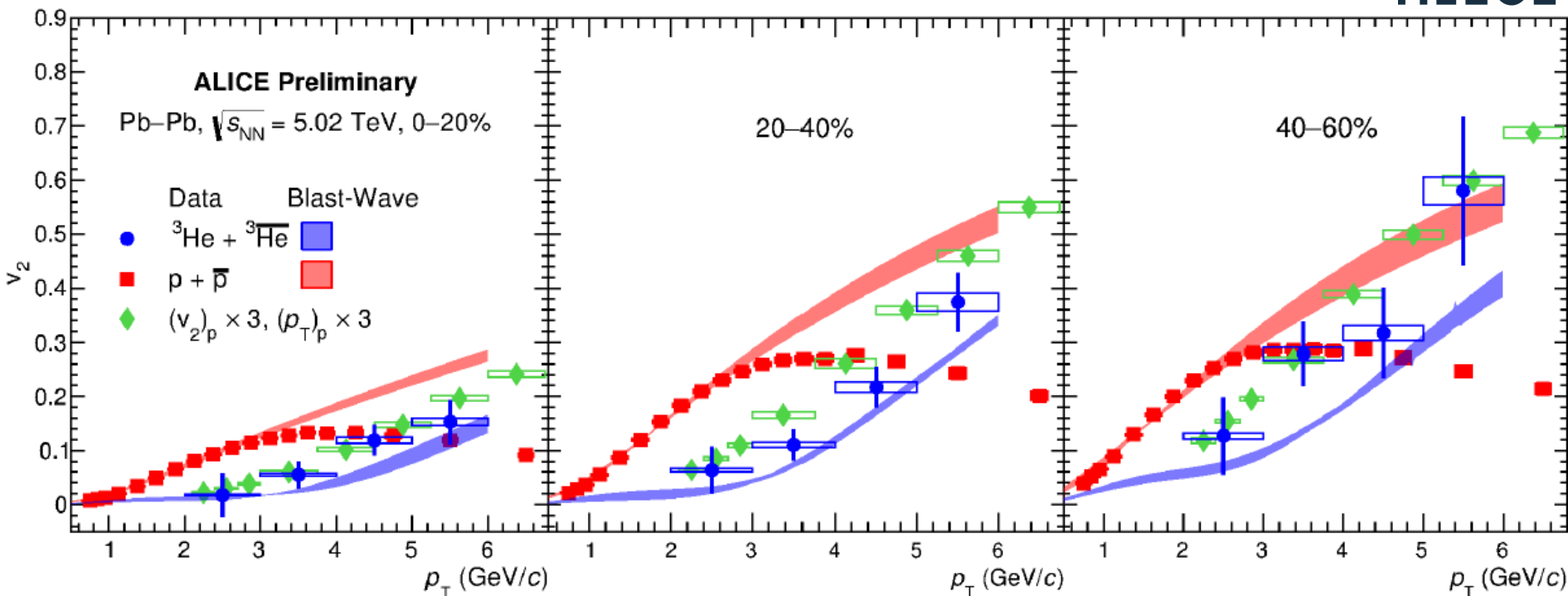
ALICE Collaboration: *Eur. Phys. J. C* 77 (2017) 658

^3He flow



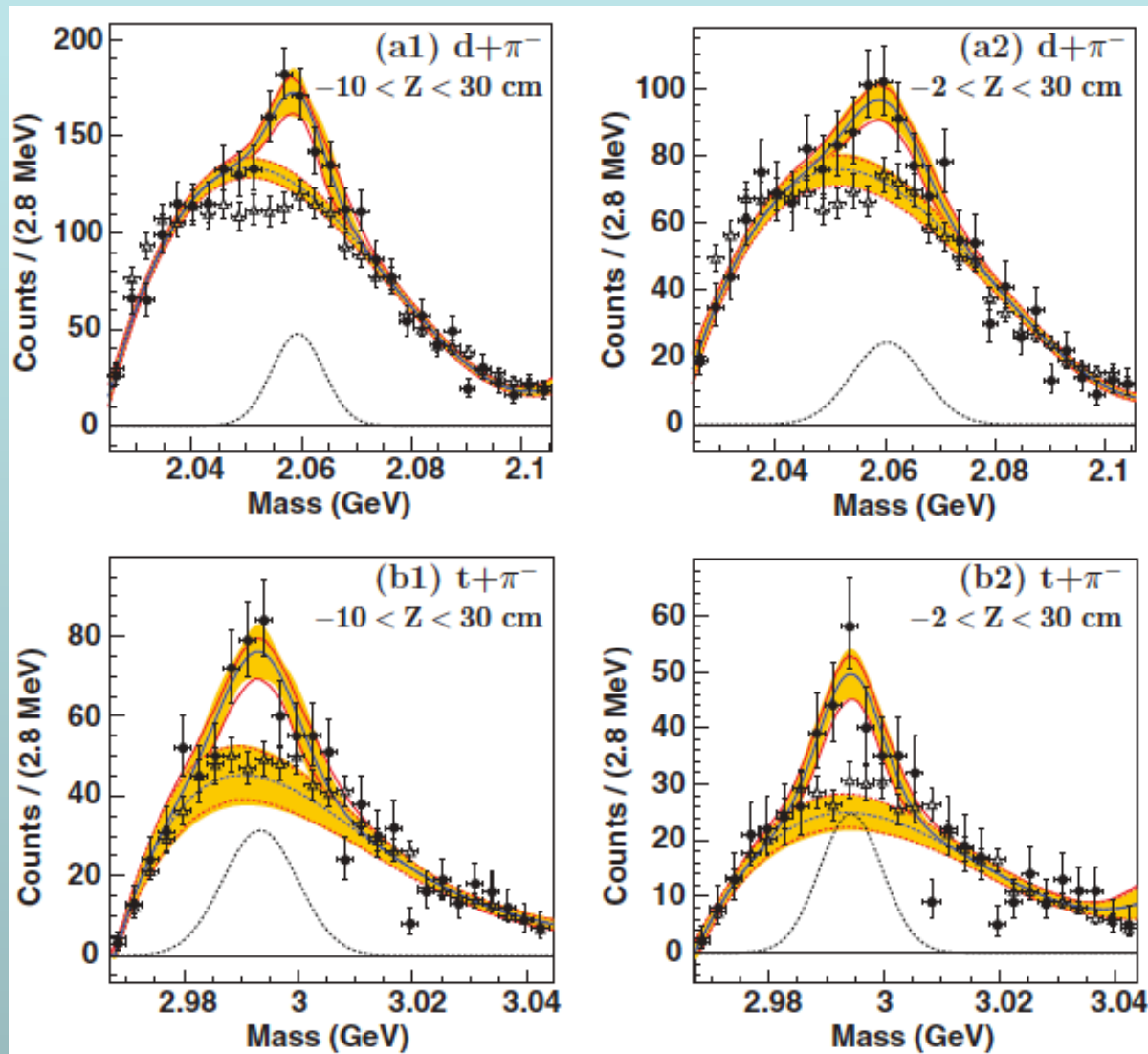
- ^3He also shows a significant v_2

^3He flow



- Also the v_2 of ^3He follows the mass ordering expected from hydrodynamics
- A naive coalescence prediction is not able to reproduce the ^3He v_2
- A Blast-Wave prediction has difficulties to describe the v_2 reasonably well

Exotica



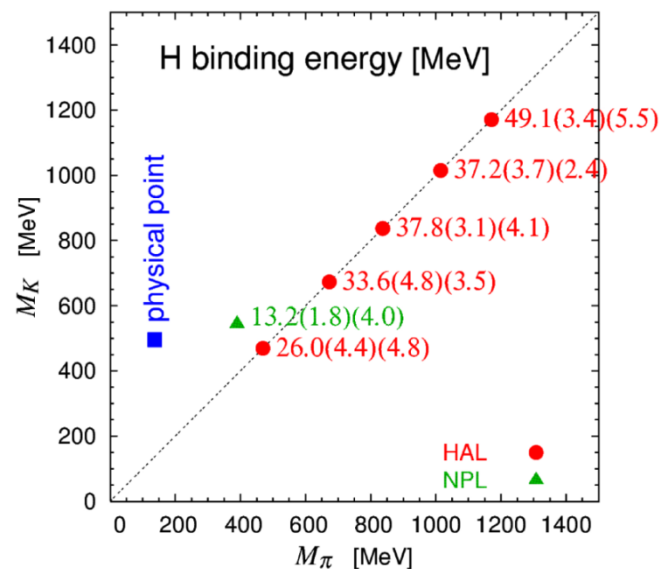
HypHI
Collaboration
observed signals
in the $t+\pi$ and $d+\pi$
invariant mass
distributions

C. Rappold et al.,
PRC 88, 041001 (2013)

H-Dibaryon

- Hypothetical bound state of $uuddss$ ($\Lambda\Lambda$)
- First predicted by Jaffe in a bag model calculation (*PRL 195, 38 +617 (1977)*)
- Recent lattice calculations suggest (*Inoue et al., PRL 106, 162001 (2011)* and *Beane et al., PRL 106, 162002 (2011)*) a bound state (20-50 MeV/c² or 13 MeV/c²)
- *Shanahan et al., PRL 107, 092004 (2011)* and *Haidenbauer, Meißner, PLB 706, 100 (2011)* made chiral extrapolation to a physical pion mass and got as result:
 - the H is unbound by 13 ± 14 MeV/c² or lies close to the Ξp threshold

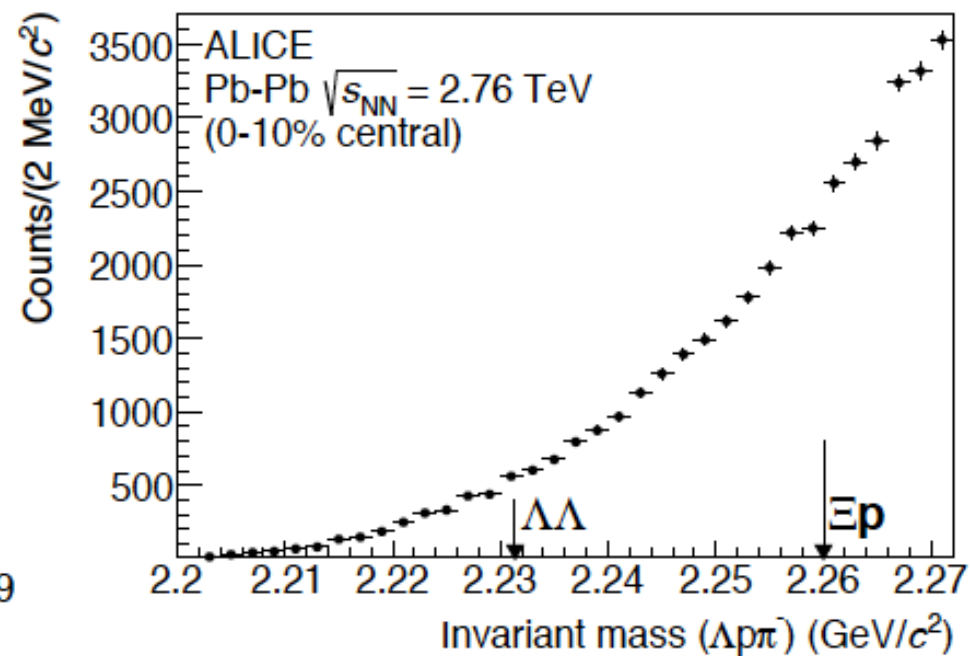
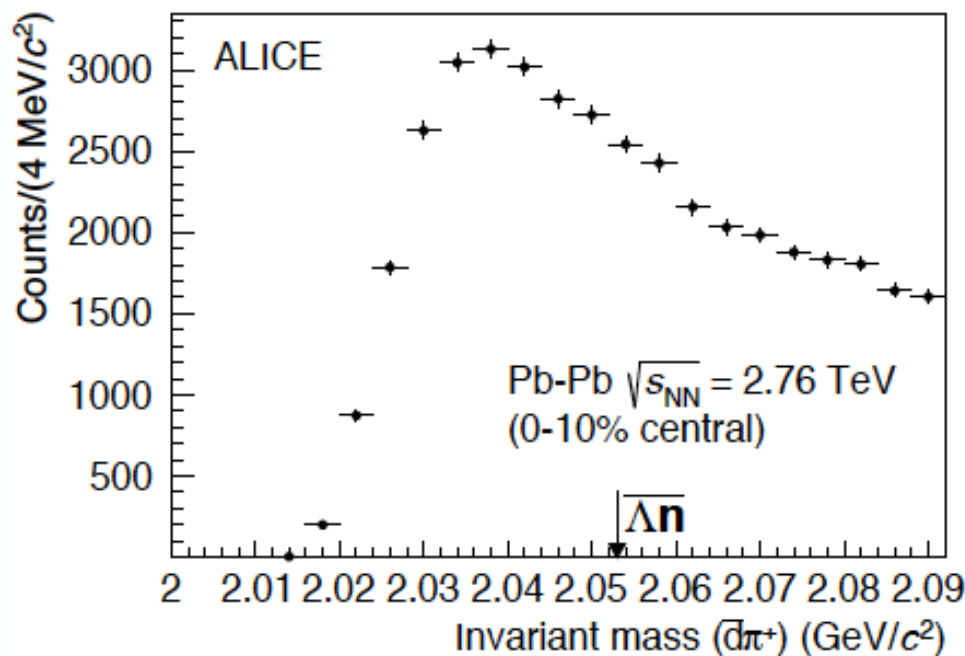
→ Renewed interest in experimental searches



T. Inoue, private communication

Searches for bound states

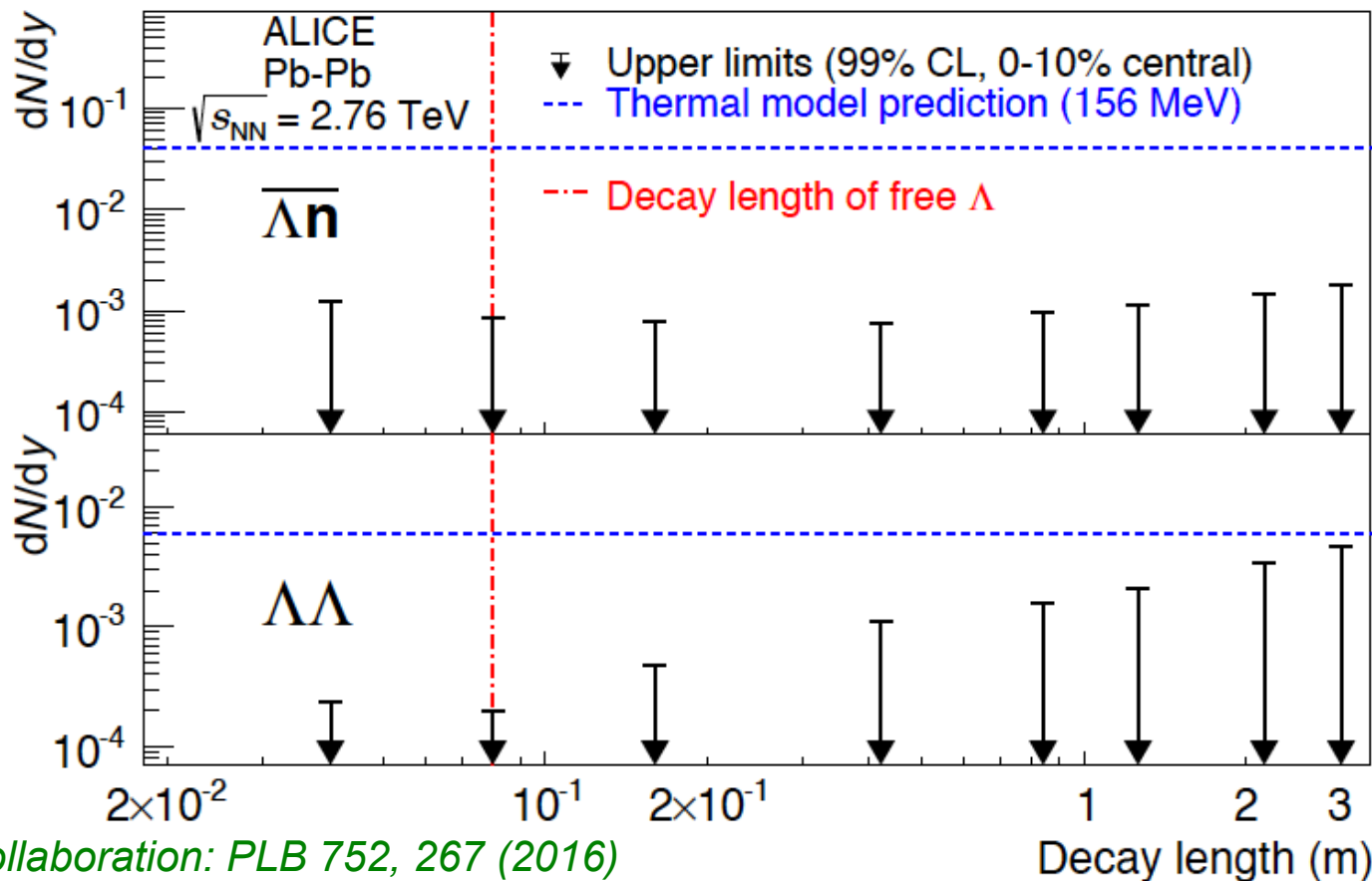
ALICE Collaboration: PLB 752, 267 (2016)



Invariant mass analyses of the two hypothetical particles lead to no visible signal → Upper limits set



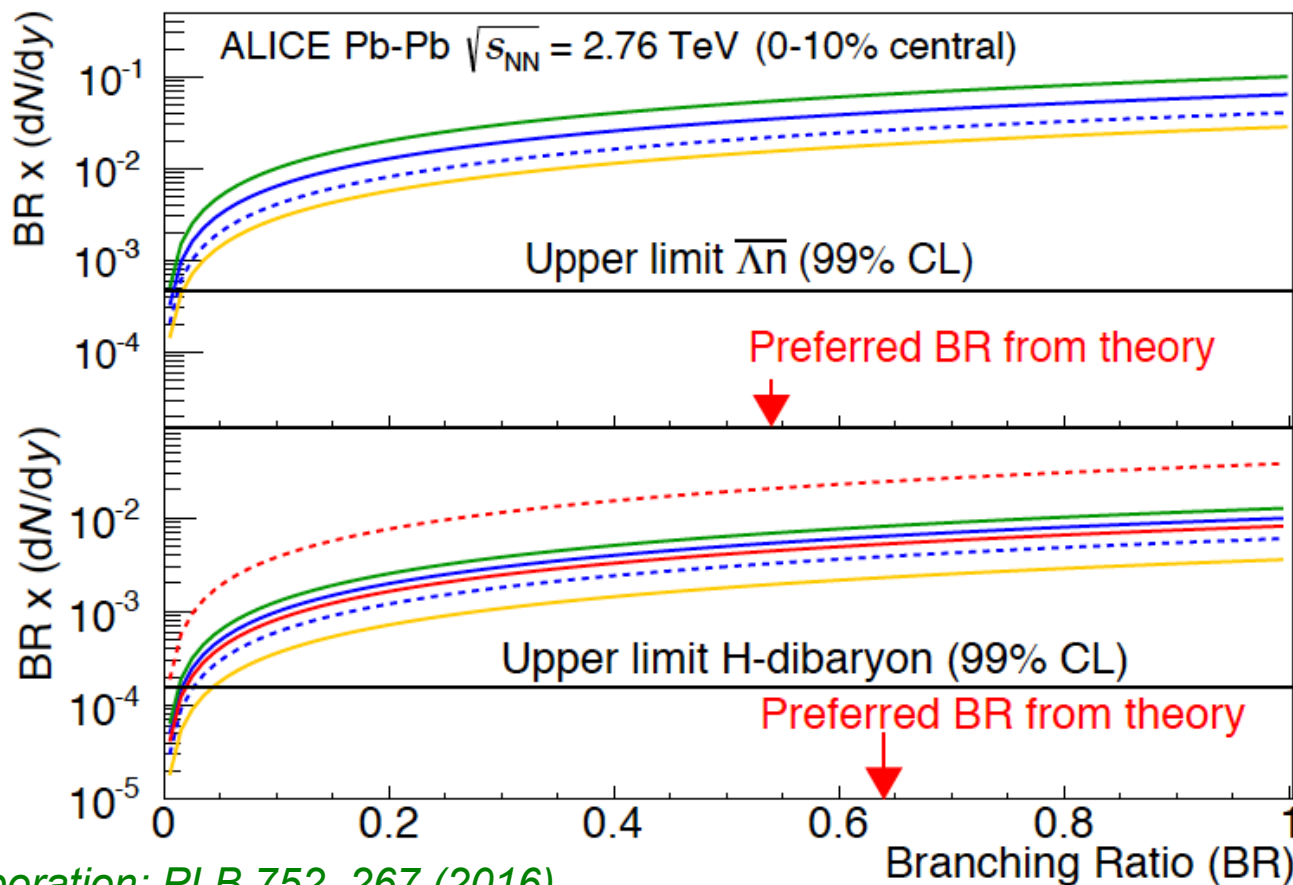
Decay length dependence



ALICE Collaboration: PLB 752, 267 (2016)

Search for a bound state of Λn and $\Lambda\Lambda$, shows no hint of signal
 → upper limits set (for different lifetimes assumed for the bound states)

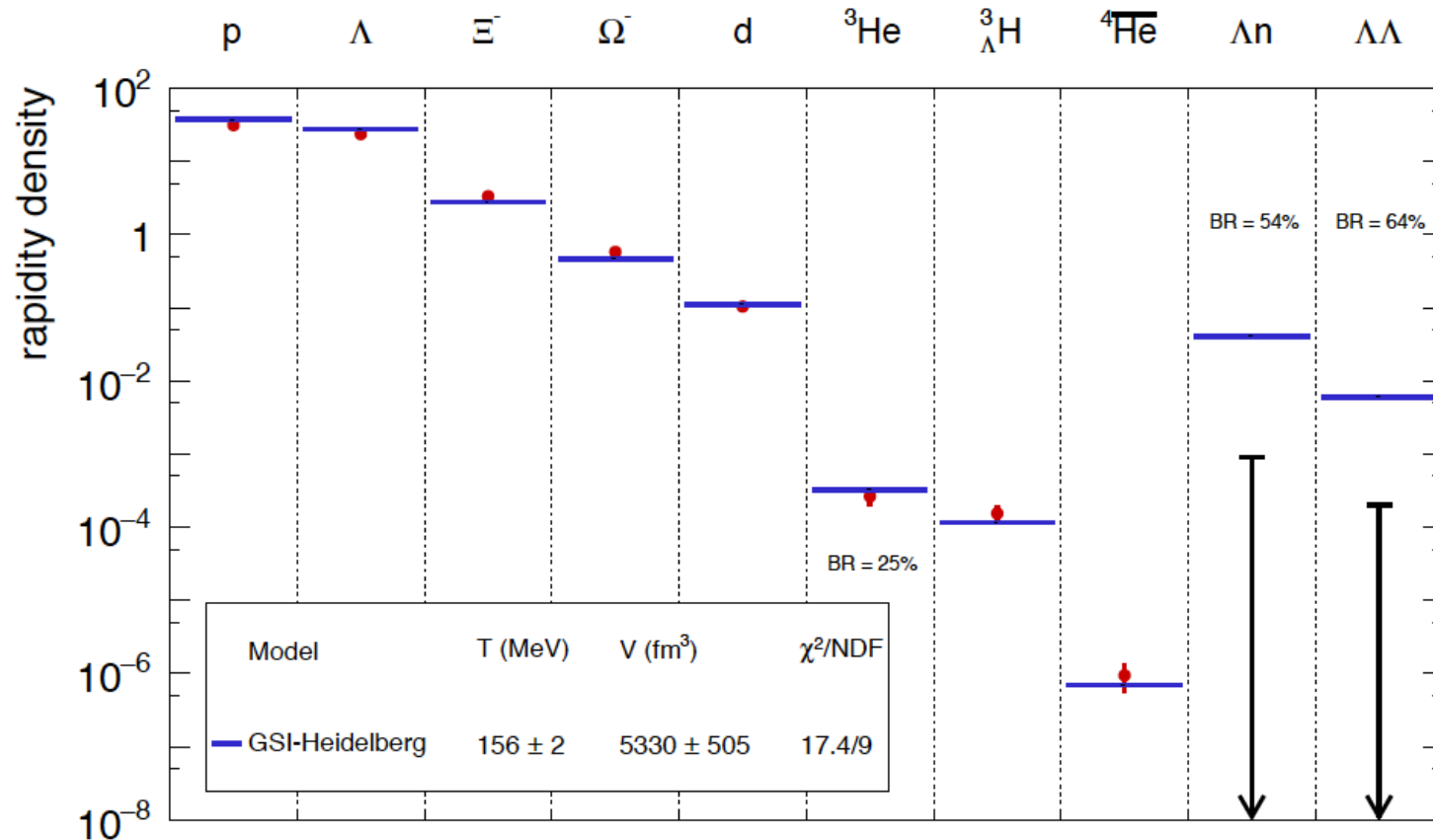
Dependence on BR



ALICE Collaboration: PLB 752, 267 (2016)

If the Λ lifetime is assumed, the upper limits are away from the expectations, as long as the branching ratio stays reasonable

Comparison with fit

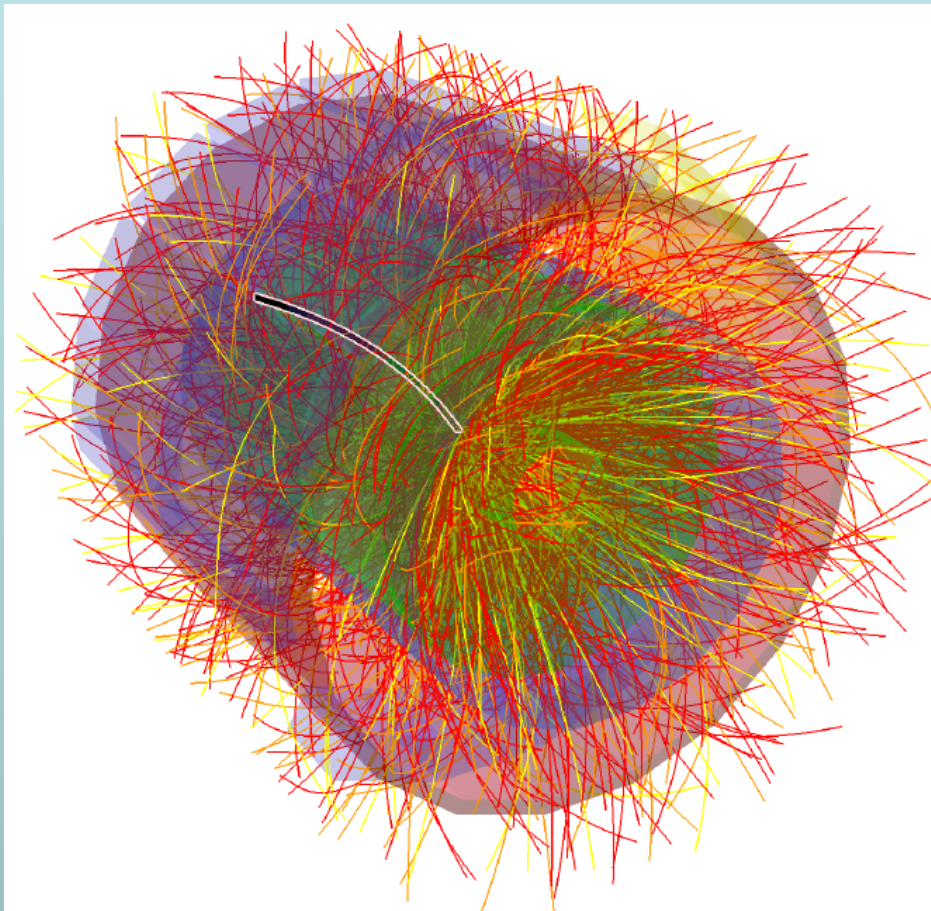


Simplified plot, CERN Courier (September 2015)

Hypertriton (B_Λ : 130 keV) and Anti-Alpha (B/A : 7 MeV) yields fit well with the thermal model expectations

→ Upper limits of $\Lambda\Lambda$ and Λn are factors of >25 below the model values

Resonances

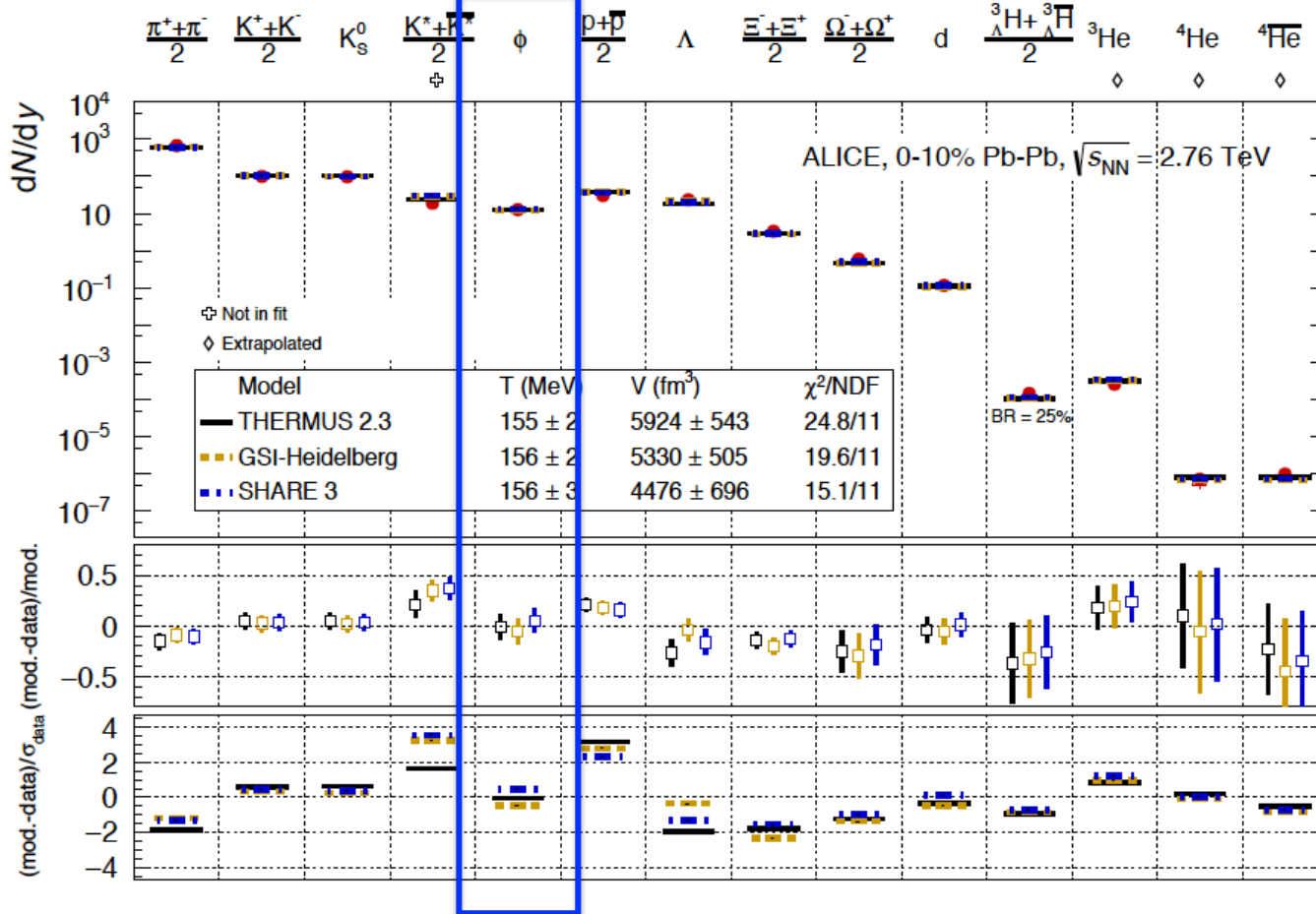




Resonances (can) deviate



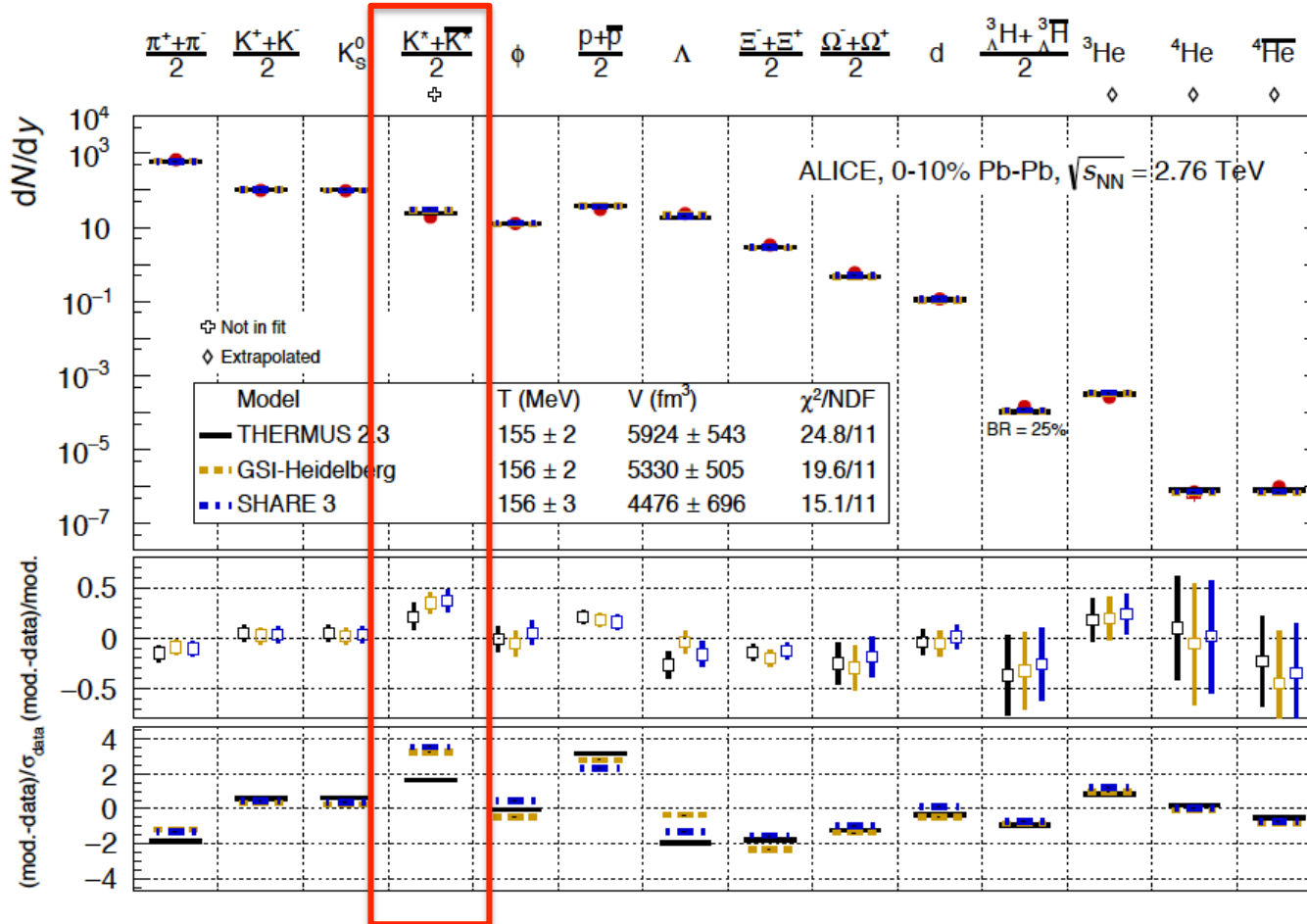
ALICE



- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- $\phi(1020)$ production also well described

ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

Resonances (can) deviate

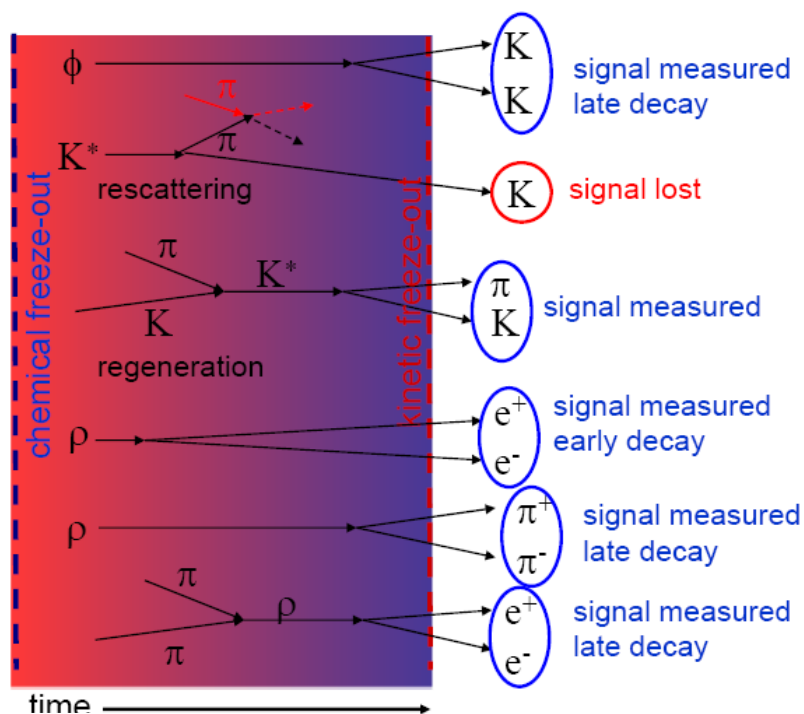


- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- **$K^*(892)$ production not described, but yield suppressed**

Resonances

PDG, Chin. Phys. C, 40, 100001 (2016)

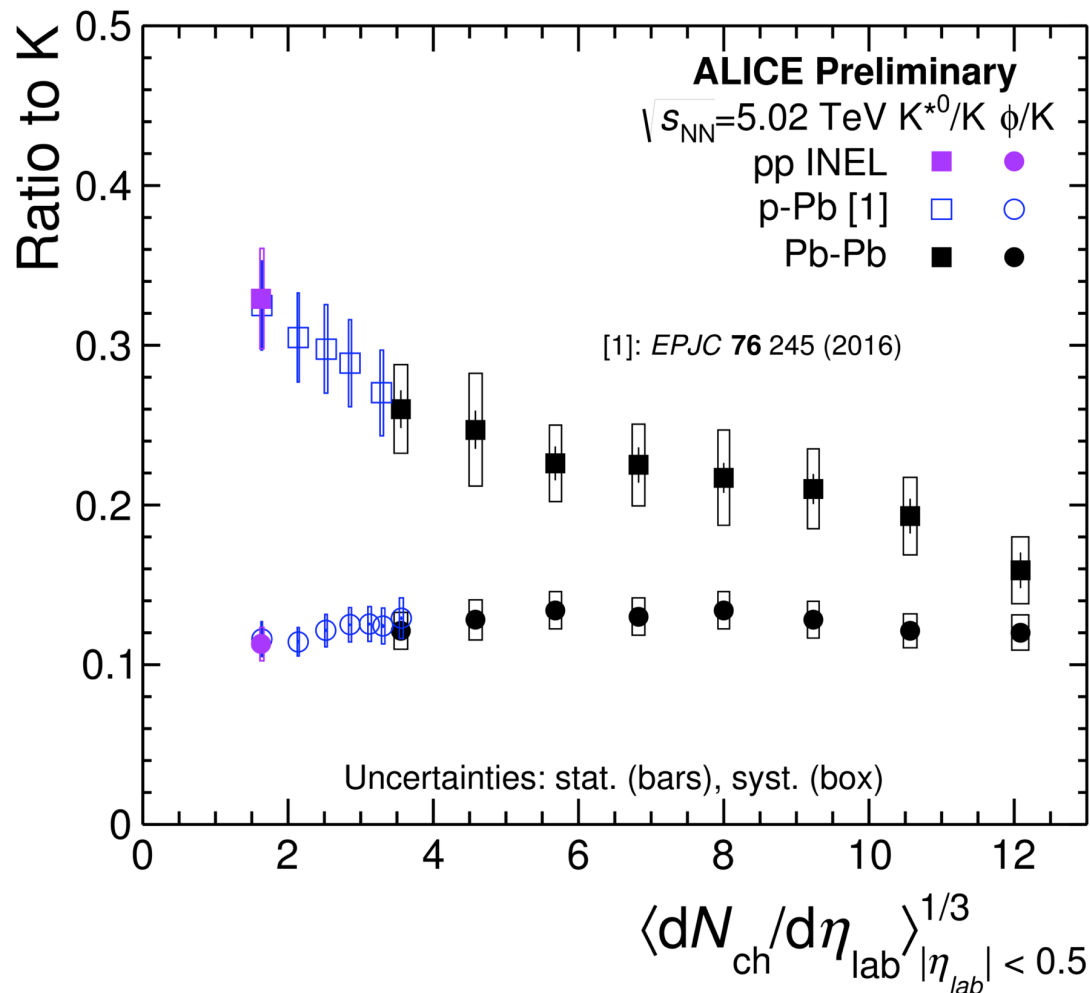
	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\Sigma(1385)^+$	$\Sigma(1385)^-$	$\Lambda(1520)$	$X(1530)^0$
$c\tau$ (fm/c)	1.3	4.2	46.2	5.01	5.51	12.6	21.7



- Lifetimes of many resonances within the lifetime of the fireball
- Resonances can decay in the fireball and re-scatter and/or regenerate
- Different lifetimes can help to study the hadronic phase of the fireball

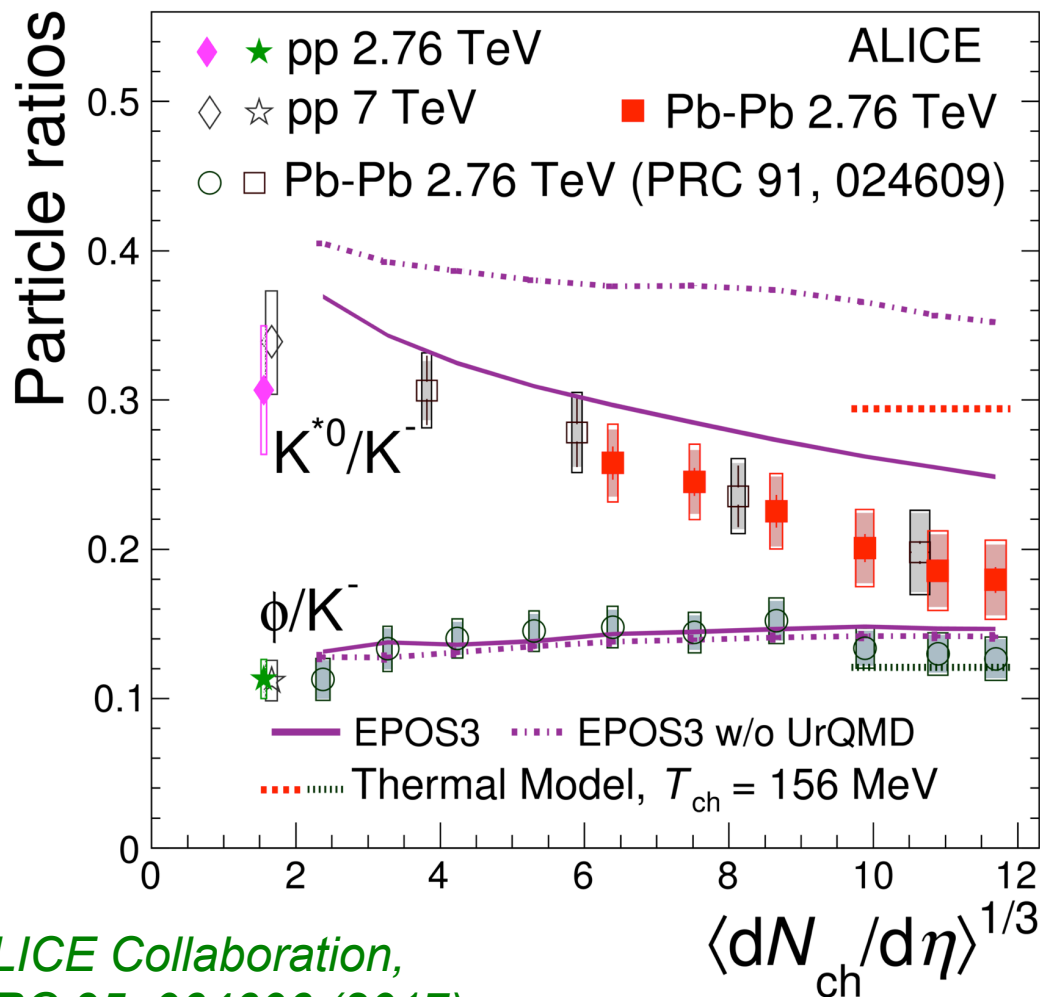
Courtesy of C. Markert

$\phi(1020)$ and $K^*(892)$



- $\phi(1020)/K$ ratio constant as function of multiplicity
 $\rightarrow$ independent of collision system (energy)
- $K^*(892)/K$ ratio decreases as function of multiplicity

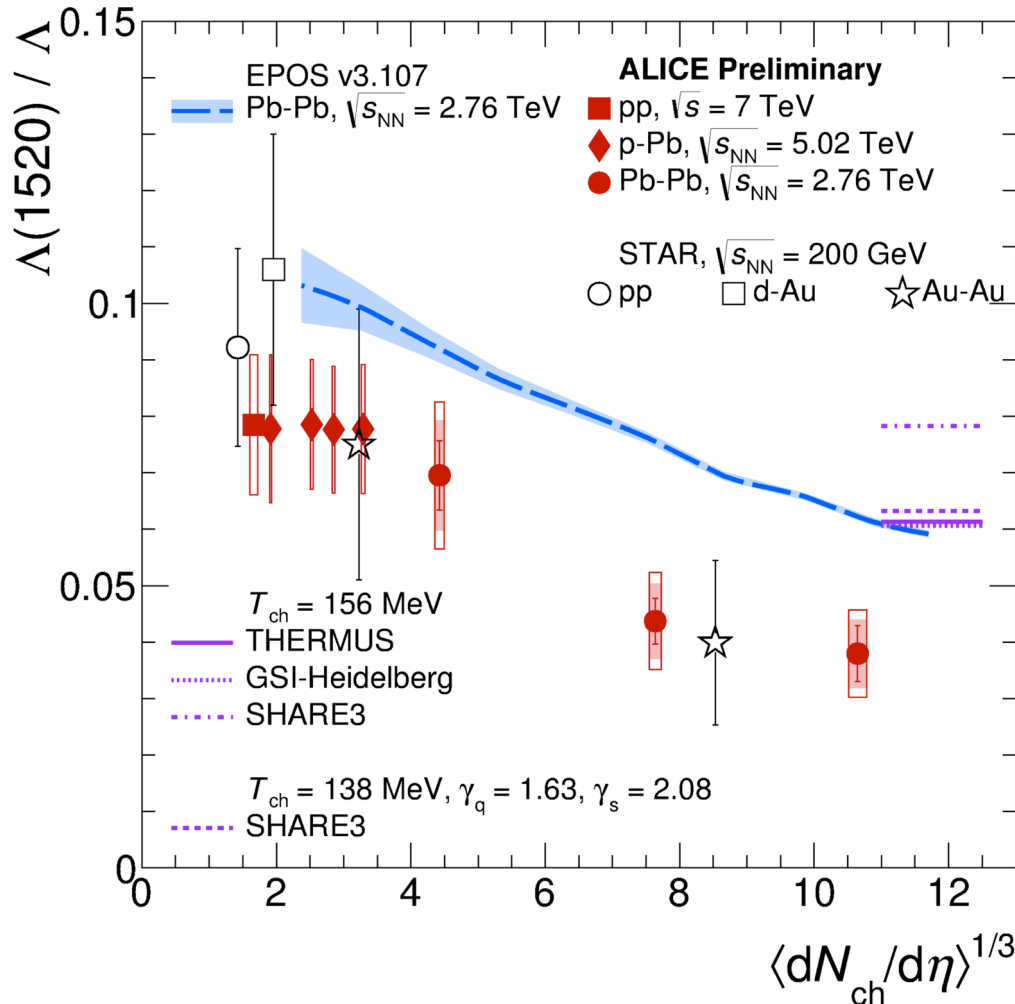
$\phi(1020)$ and $K^*(892)$



- $\phi(1020)/K$ ratio constant as function of multiplicity
→ independent of collision system (energy)
- $K^*(892)/K$ ratio decreases as function of multiplicity
- Trend of both can be described when EPOS is coupled to a UrQMD afterburner

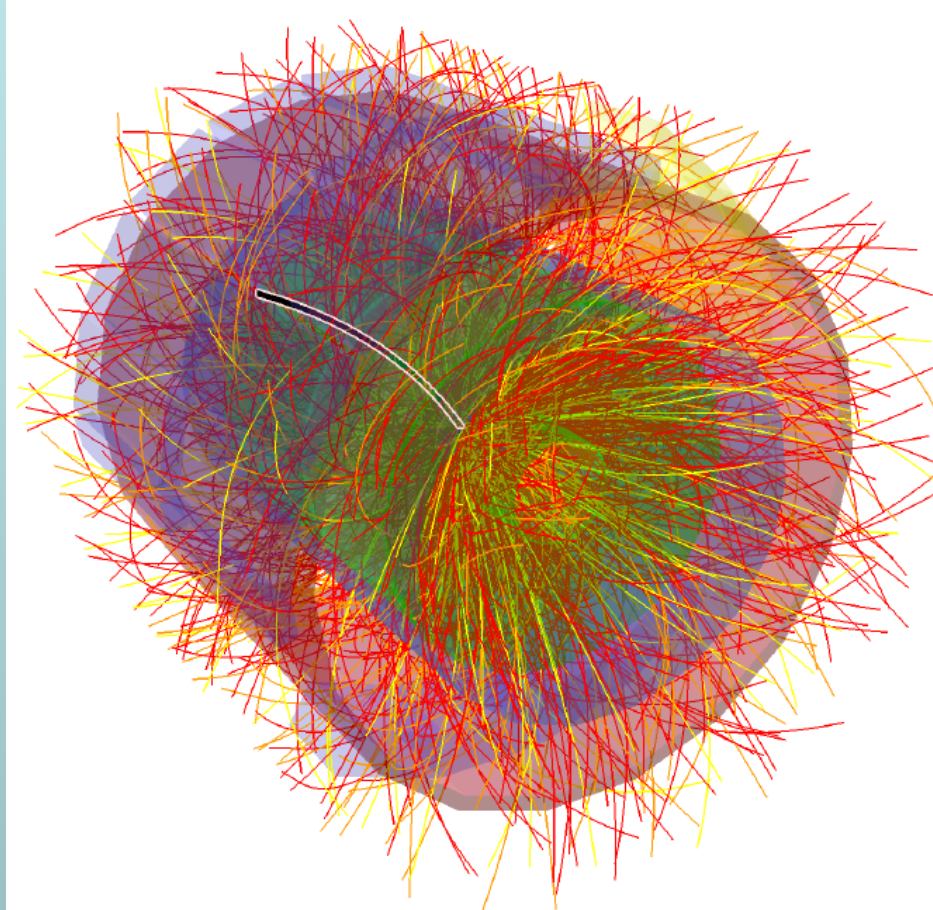
ALICE Collaboration,
PRC 95, 064606 (2017)

$\Lambda(1520)$



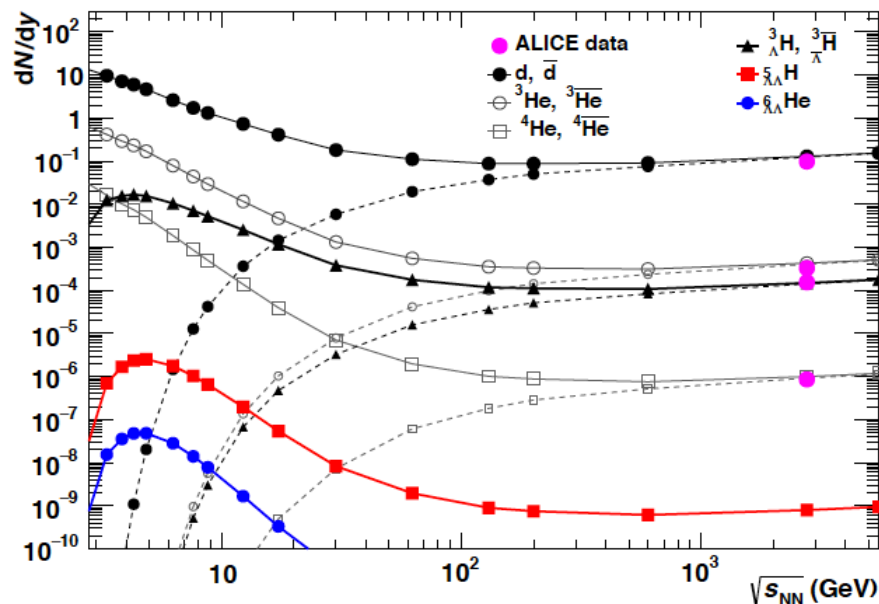
- $\Lambda(1520)/\Lambda$ ratio nearly constant in pp and p-Pb collisions
- $\Lambda(1520)/\Lambda$ ratio clearly decreases as function of multiplicity in Pb-Pb
- Trend can be described by EPOS
- Clear suppression compared to the thermal model predictions

Summary



Conclusion

- ALICE@LHC is well suited to study light (anti-)(hyper-)nuclei and perform searches for exotic bound states ($A < 5$)
- Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
- Thermal describe the (anti-)(hyper-)nuclei data rather well
- d/p ratio vs. multiplicity trend described by both models
- New and more precise data can be expected in the next years



P. Braun-Munzinger, bd, Invited review NPA, arXiv:1809.04681



Conclusion

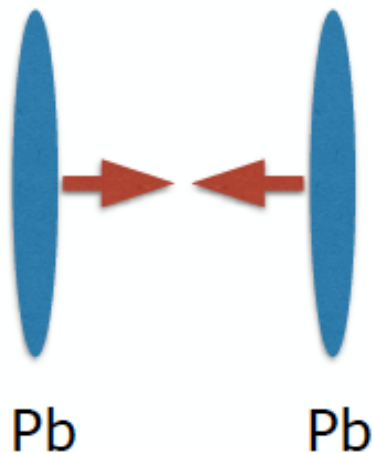


- ALICE@LHC is well suited to study light (anti-)(hyper-)nuclei, resonances and perform searches for exotic bound states ($A < 5$)
- Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
- Thermal and coalescence models describe the (anti-)(hyper-)nuclei data rather well
- d/p ratio shows increasing trend for pp and p-Pb collisions and seems to saturate for Pb-Pb multiplicities
- Resonances give clear indication of a hadronic phase which is slightly contradicting the findings for light nuclei
- New and more precise data can be expected from the LHC on the presented topics in the next years

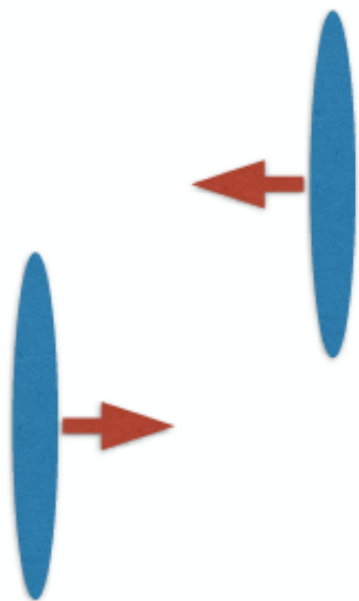
Backup



Interlude: Centrality



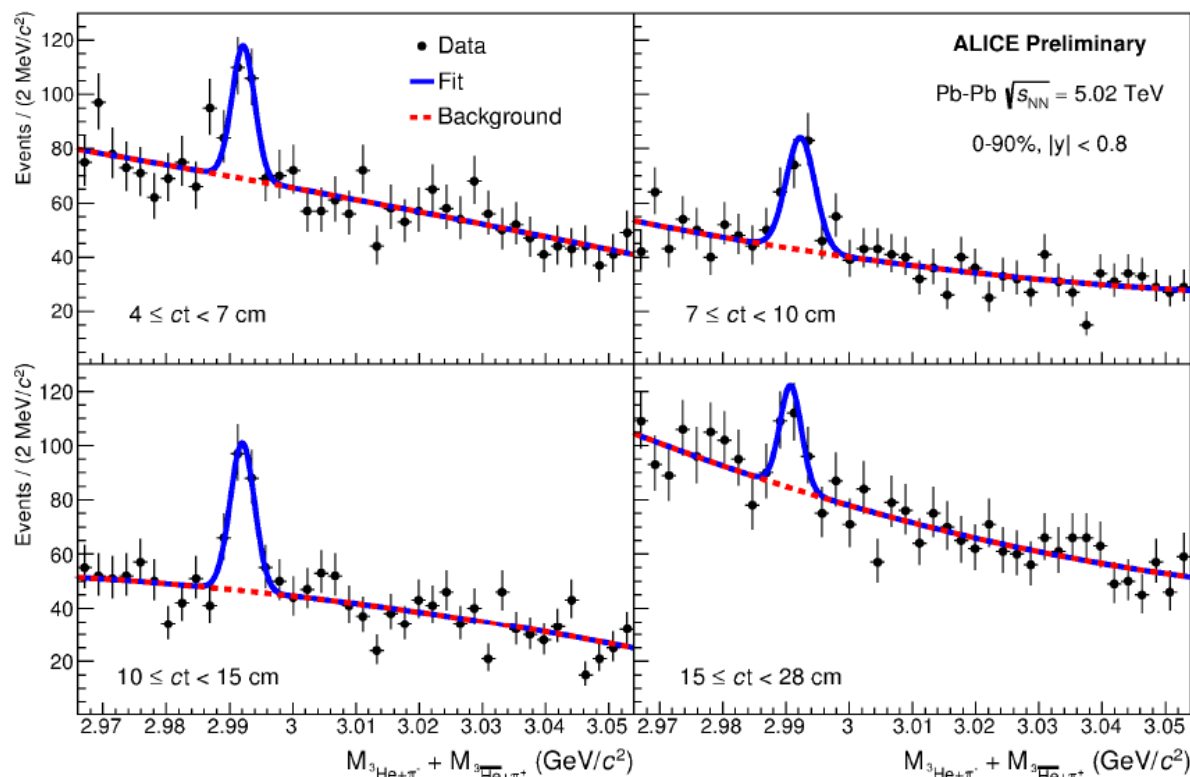
Central Pb-Pb collision:
High multiplicity = large $\langle dN/d\eta \rangle$
High number of tracks
(more than 2000 tracks in the detector)



Peripheral Pb-Pb collision:
Low multiplicity = small $\langle dN/d\eta \rangle$
Low number of tracks
(less than 100 tracks in the detector)

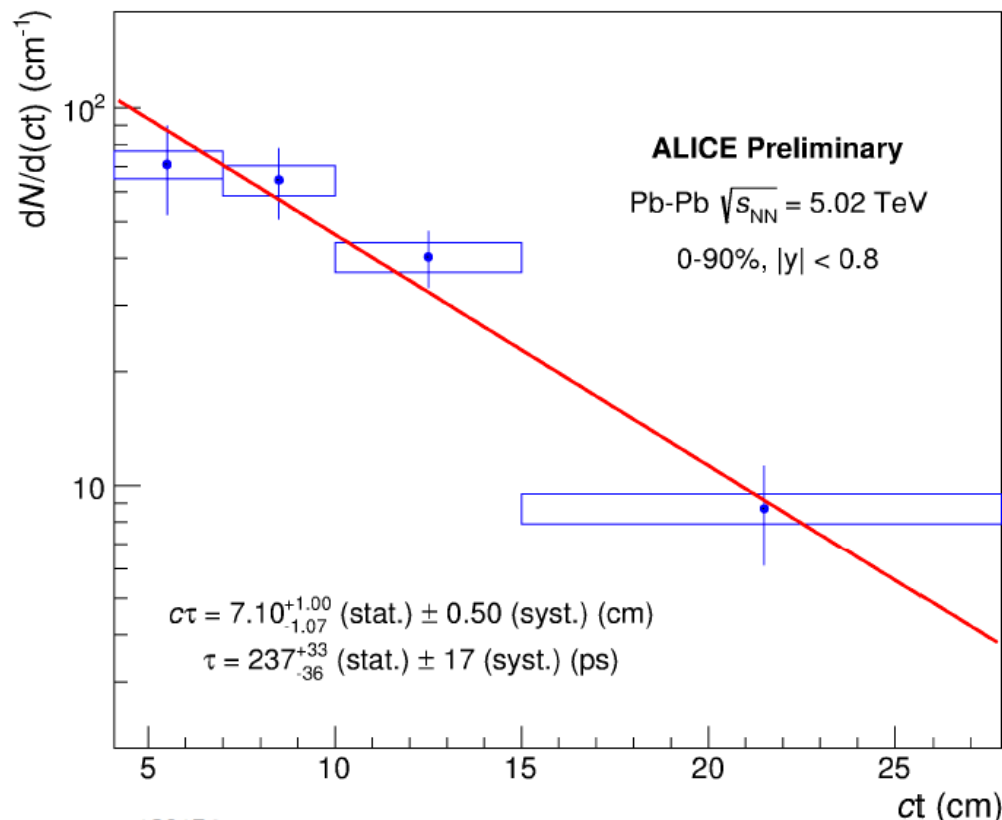
Hypertriton lifetime

- Recently extracted lifetimes significantly below the free Λ lifetime $\rightarrow$ new ALICE result agrees with world average and free Λ lifetime
- Two methods used which agree nicely:
1.) ct spectra (default)



Hypertriton lifetime

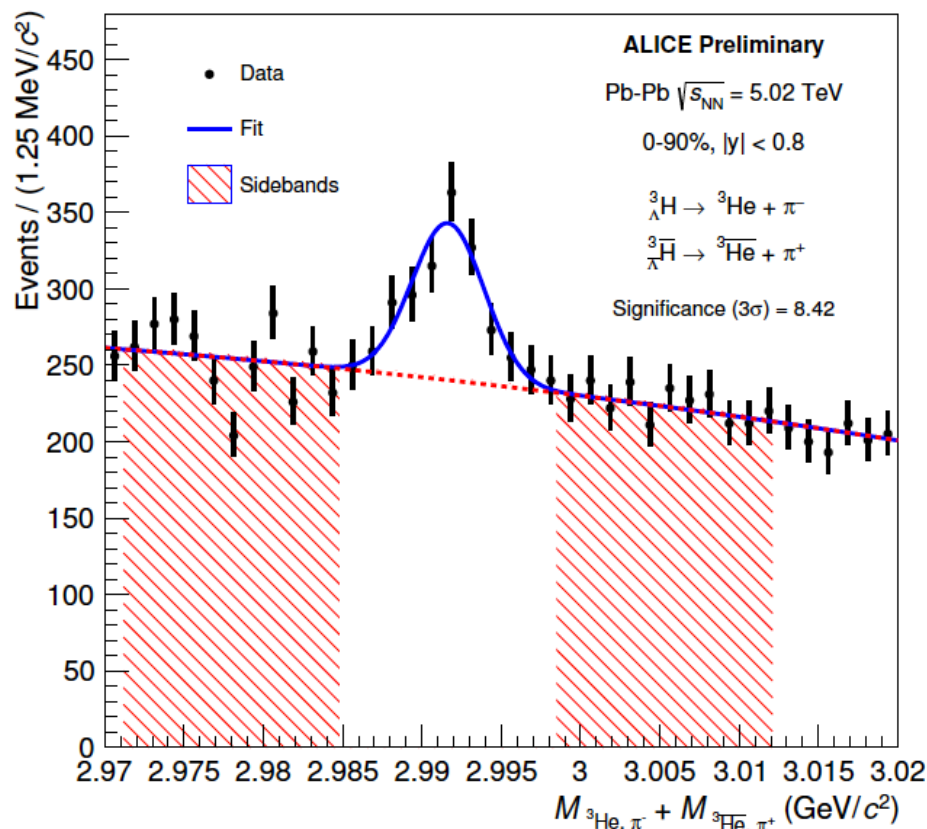
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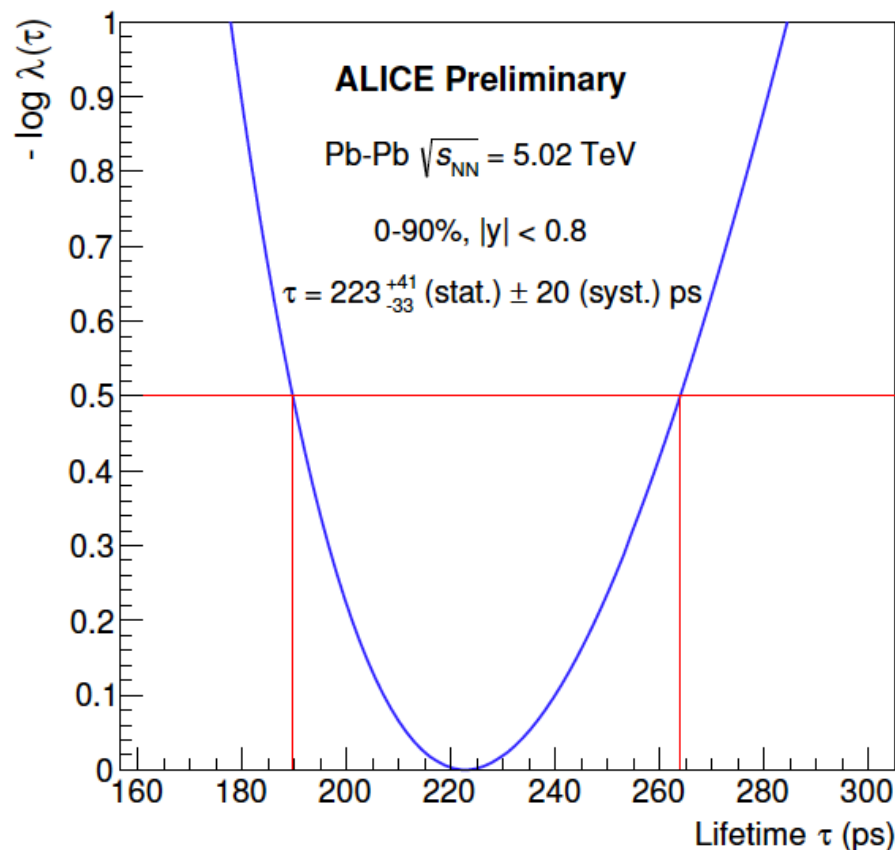




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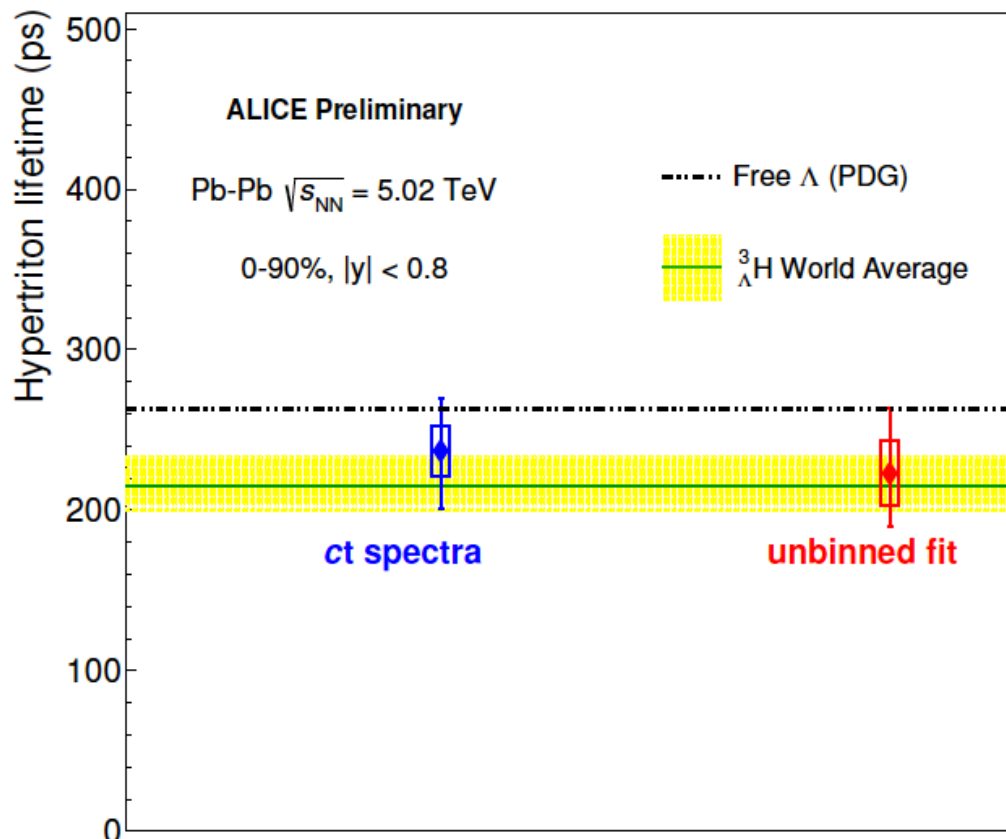
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Hypertriton lifetime

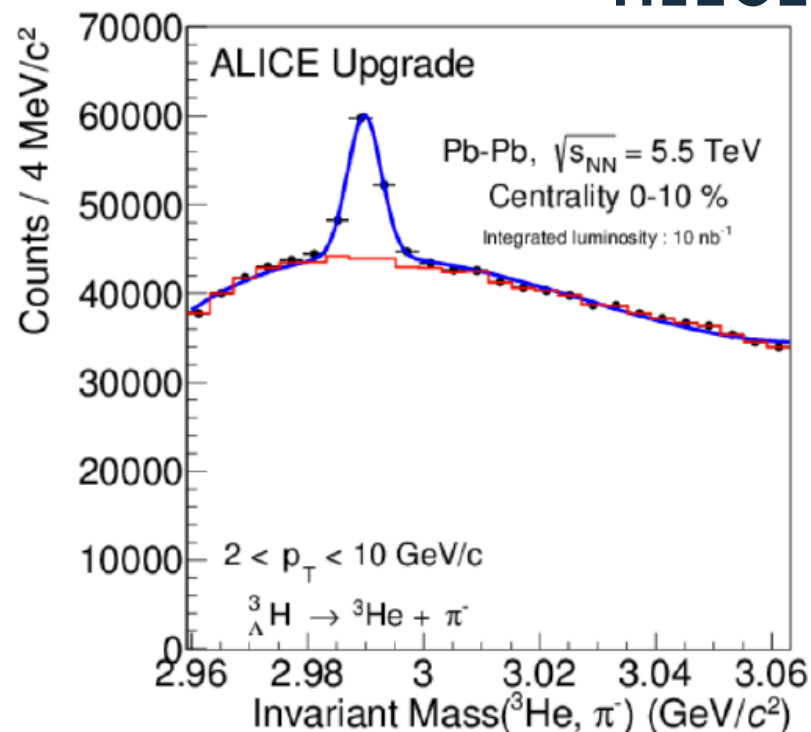
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Expectations

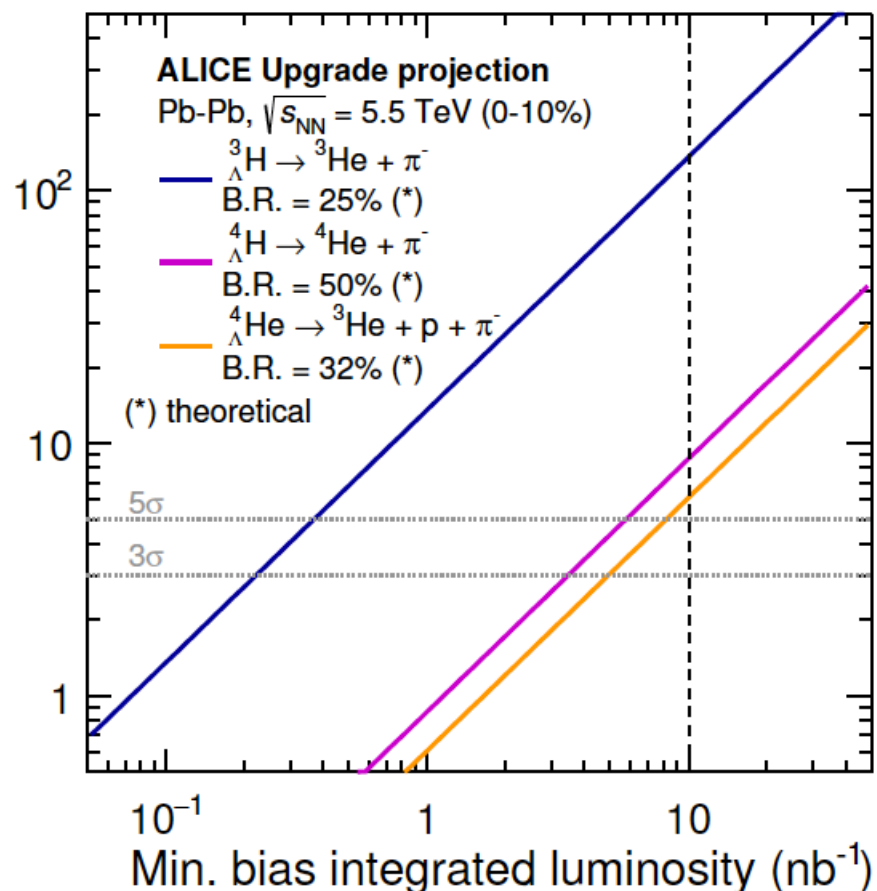
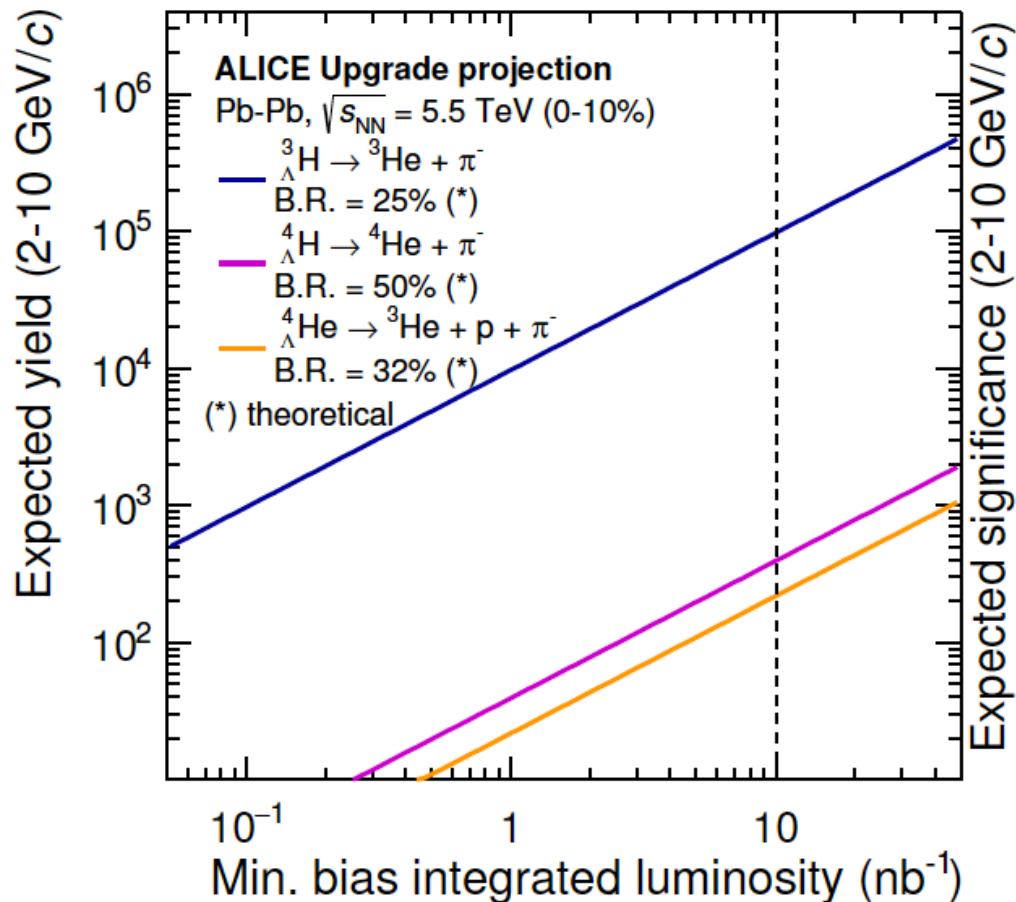
- Run 3 & Run 4 (2021 – 2029) of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continuous readout
- ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei
- Physics which is now done for $A = 2$ and $A = 3$ (hyper-)nuclei will be done for $A = 4$



ITS Upgrade TDR: J. Phys. G 41, 087002 (2014)

State	dN/dy	B.R.	$\langle \text{Acc} \times \epsilon \rangle$	Yield
${}^3_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
${}^4_{\Lambda}H$	2×10^{-7}	50%	7 %	110
${}^4_{\Lambda}He$	2×10^{-7}	32%	8 %	130

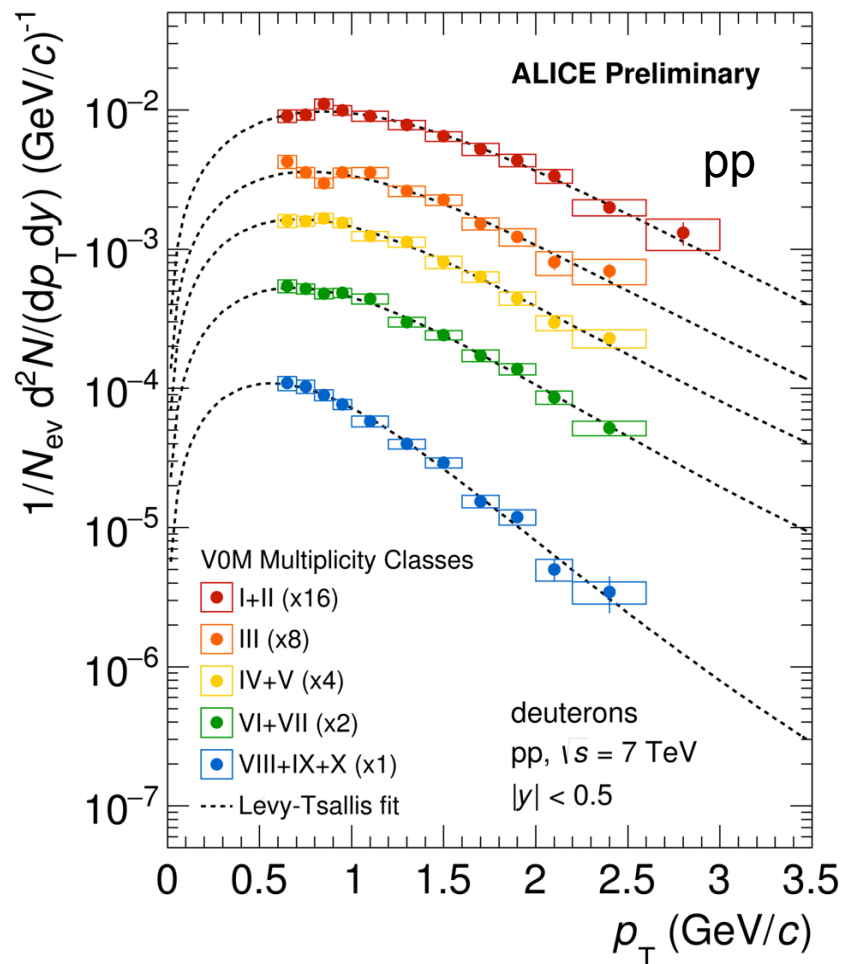
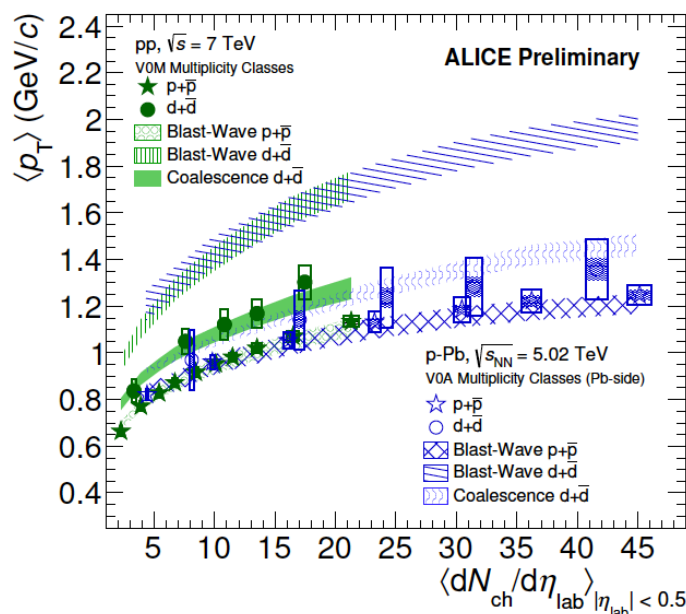
Expectations



Expected significance >5s for the full data set to be collected in Run 3 & 4

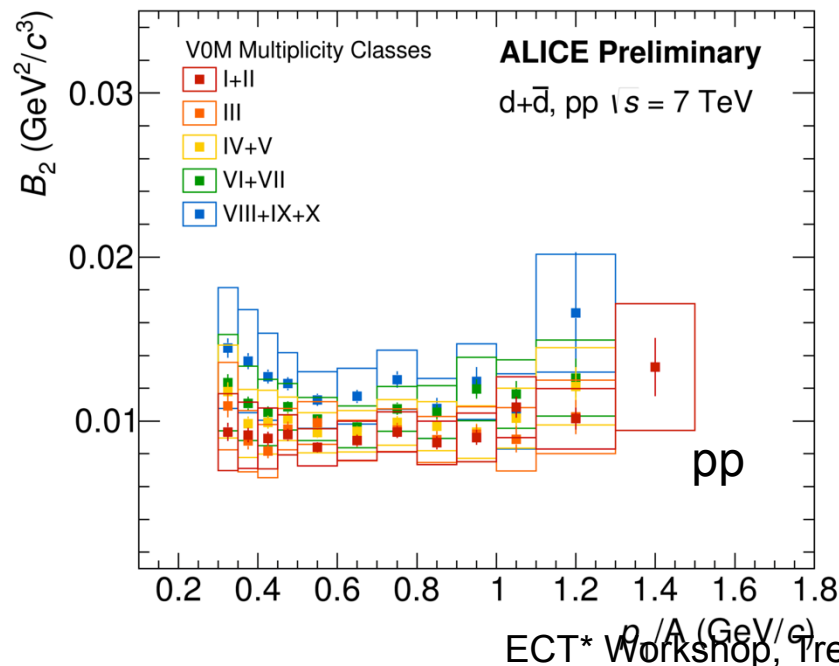
Deuterons

- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- MB pp spectrum shows no sign of radial flow $\rightarrow$ multiplicity bins show hardening

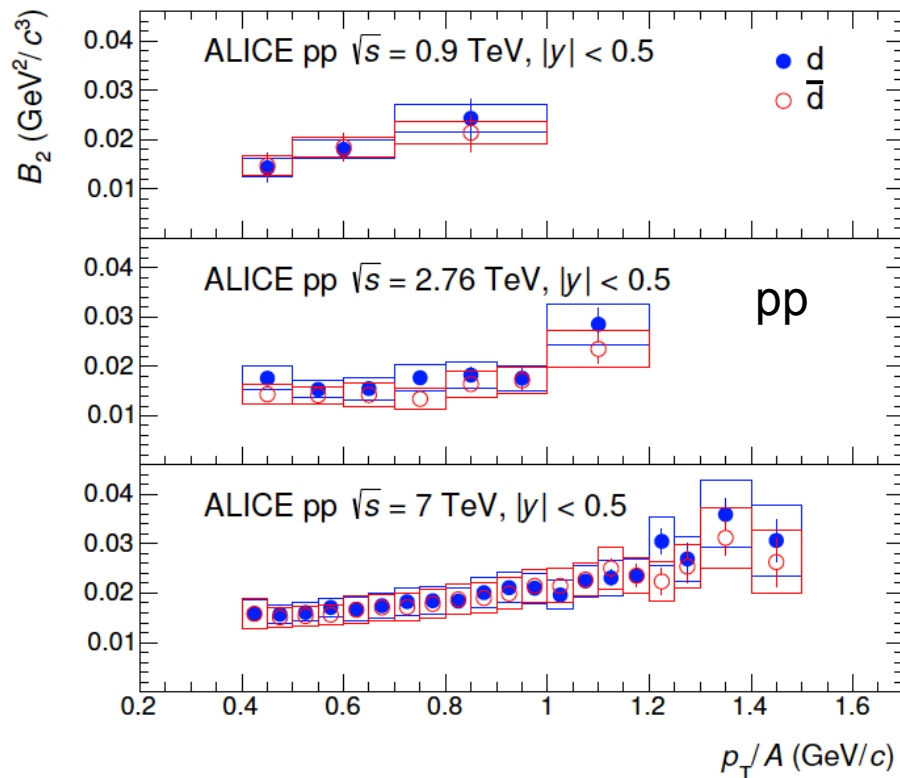


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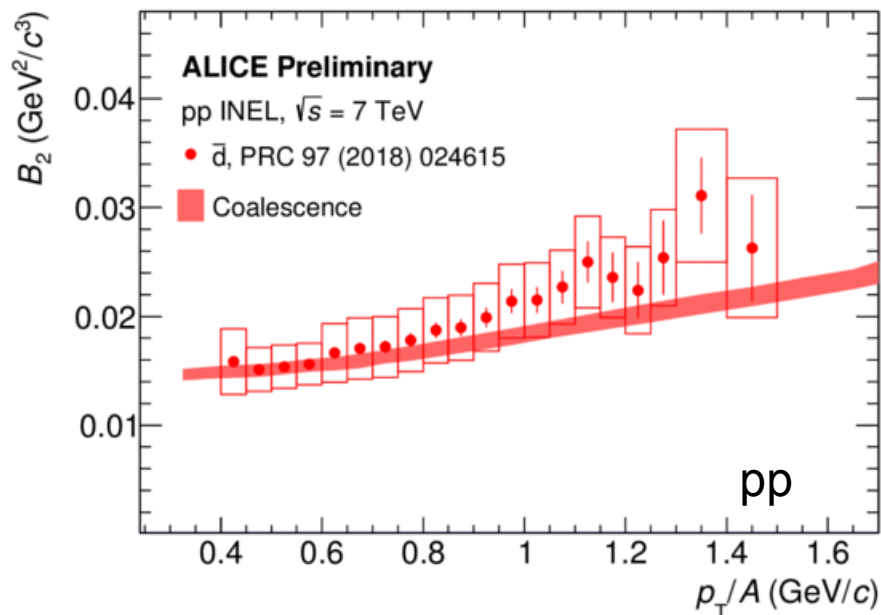
ALICE Collaboration, [arXiv:1709.08522](https://arxiv.org/abs/1709.08522)



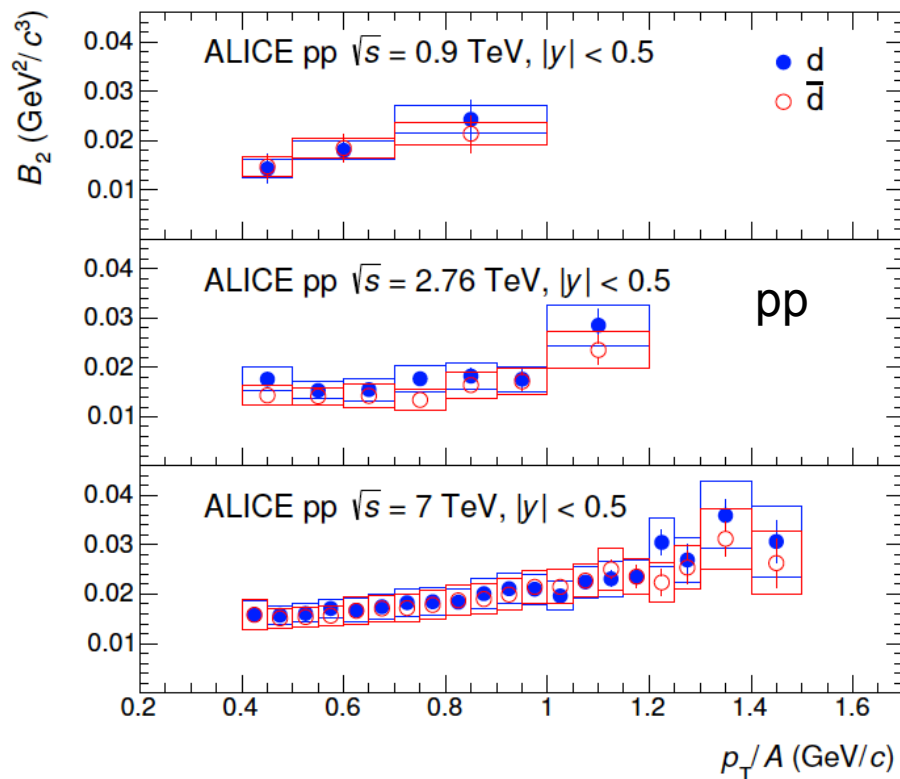
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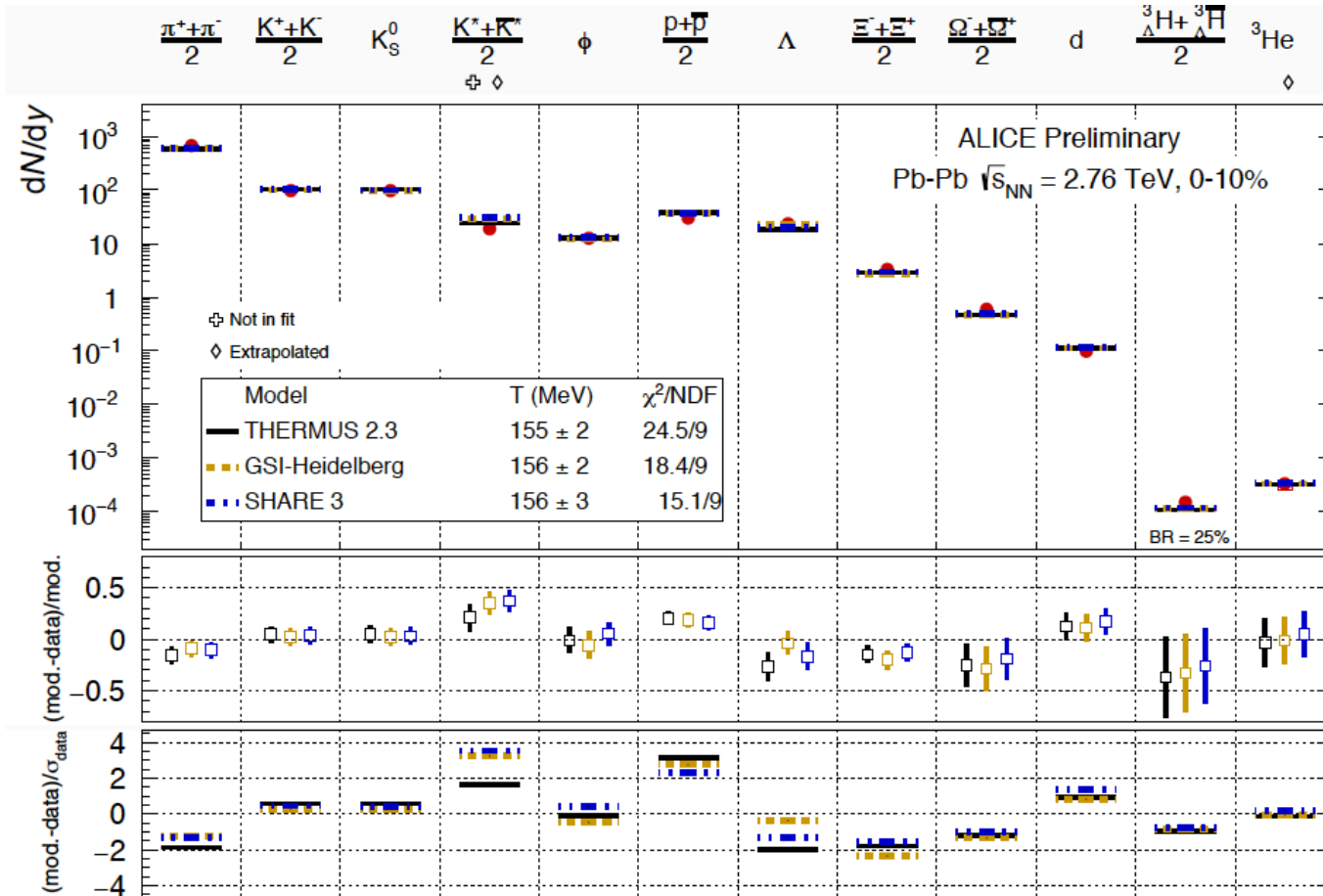


ALICE Collaboration, [arXiv:1709.08522](https://arxiv.org/abs/1709.08522)



$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R_{\perp}^2(m_T) R_{\parallel}(m_T)}$$

Thermal model fits



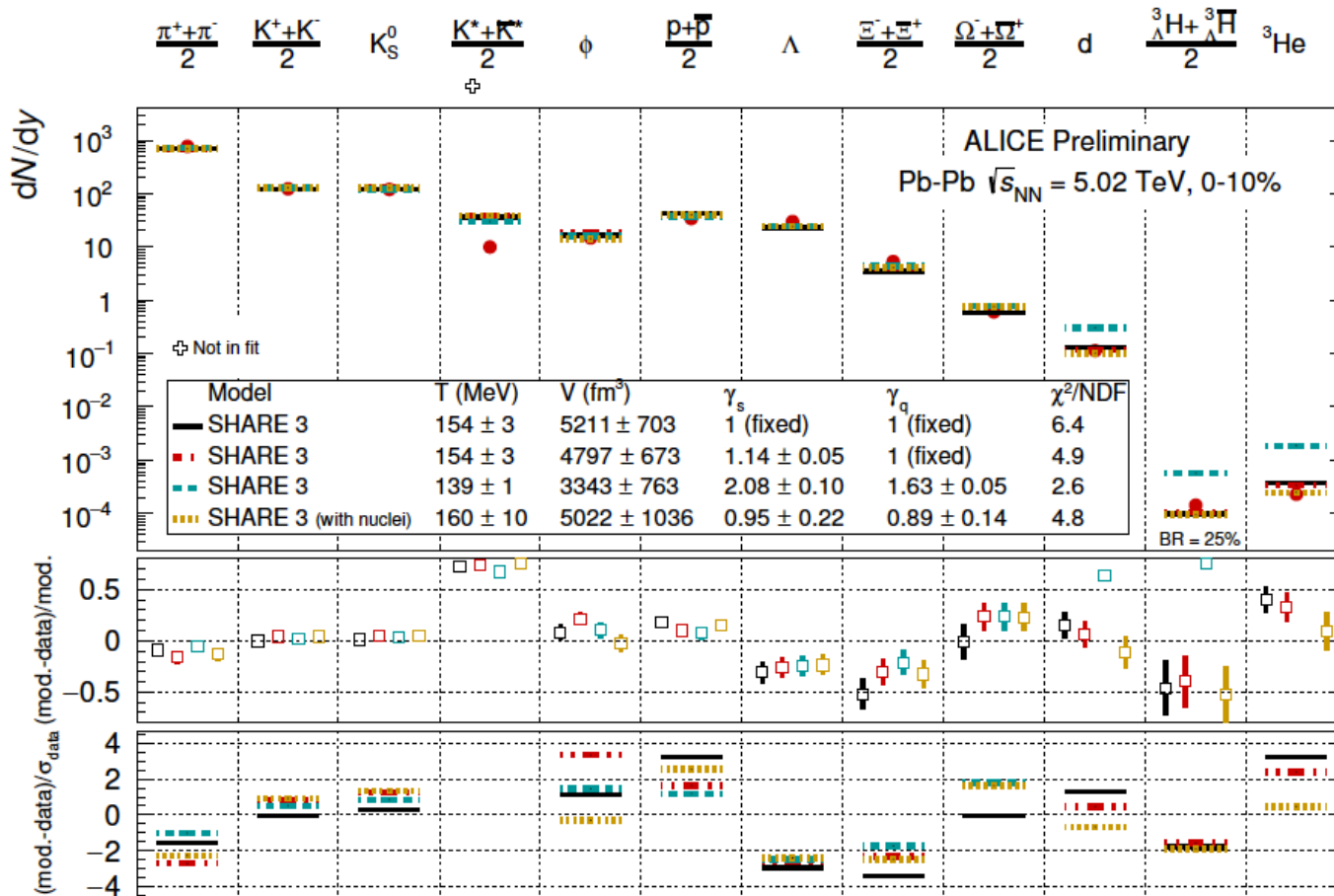
- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- Including nuclei in the fit causes no significant change in T_{ch}



Thermal model: SHARE

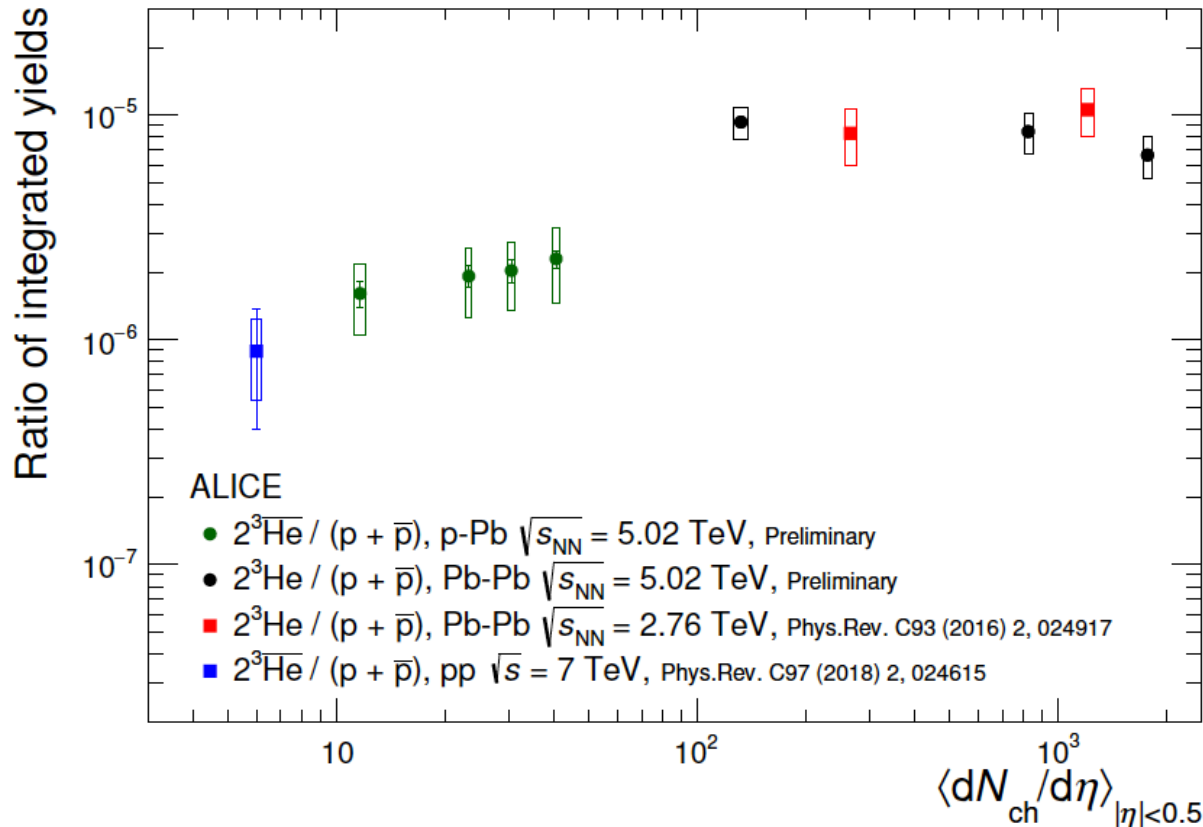


SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)



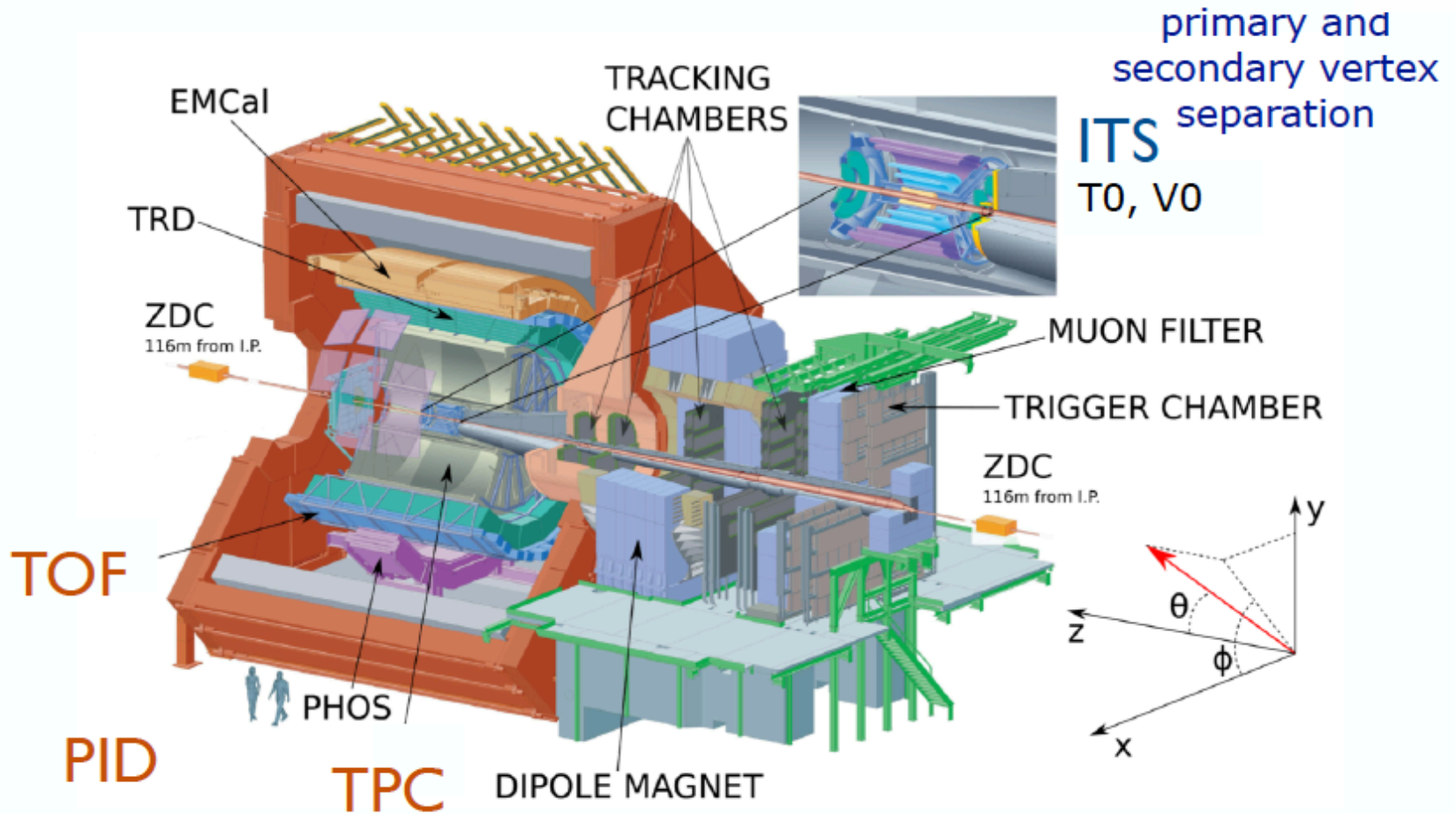
- Observations similar to QM2014 results
- Including nuclei drives a non-equilibrium fit towards the equilibrium values

$^3\text{He}/p$ vs. multiplicity



$^3\text{He}/p$ ratio increases also when going from pp to p-Pb, until it reaches the grand canonical thermal model value ($^3\text{He}/p=8 \times 10^{-6}$ at $T_{ch} = 156$ MeV)

Experiment: ALICE



Multiplicity classes: pp

- VOM Multiplicity Classes: $\left\{ \begin{array}{l} I \rightarrow \langle dN_{ch}/d\eta \rangle \approx 3.5 \times \langle dN_{ch}/d\eta \rangle^{INEL>0} \\ \vdots \\ X \rightarrow \langle dN_{ch}/d\eta \rangle \approx 0.4 \times \langle dN_{ch}/d\eta \rangle^{INEL>0} \end{array} \right.$
 $\left[\langle dN_{ch}/d\eta \rangle^{INEL>0} \approx 6.0 \right]$

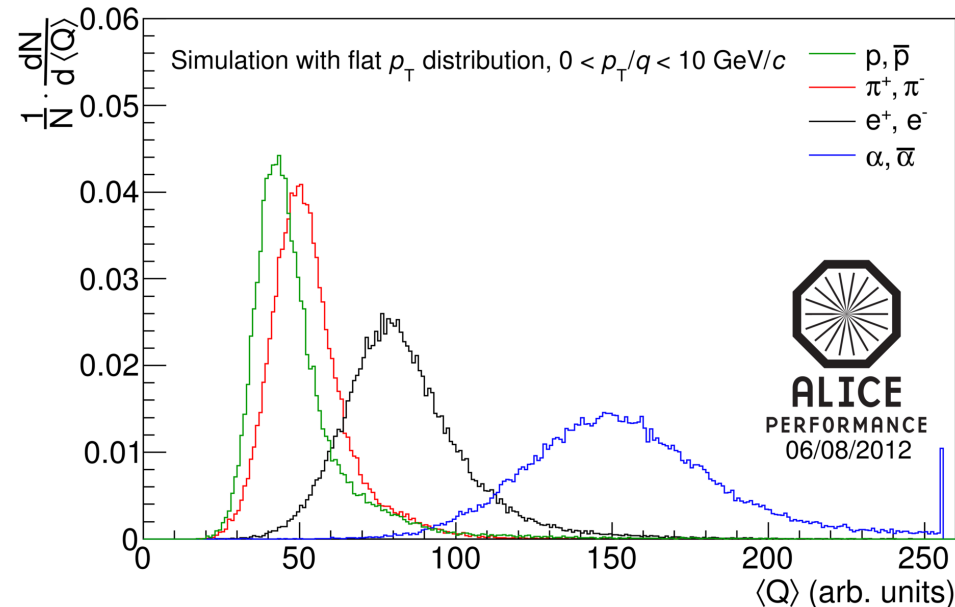
Table A.1: Event multiplicity classes, their corresponding fraction of the INEL>0 cross-section ($\sigma/\sigma_{INEL>0}$) and their corresponding $\langle dN_{ch}/d\eta \rangle$ at midrapidity ($|\eta| < 0.5$). The value of $\langle dN_{ch}/d\eta \rangle$ in the inclusive (INEL>0) class is 5.96 ± 0.23 . The uncertainties are the quadratic sum of statistical and systematic contributions and represent standard deviations.

Class name	I	II	III	IV	V	VI	VII	VIII	IX	X
$\sigma/\sigma_{INEL>0}$	0–0.95%	0.95–4.7%	4.7–9.5%	9.5–14%	14–19%	19–28%	28–38%	38–48%	48–68%	68–100%
$\langle dN_{ch}/d\eta \rangle$	21.3 ± 0.6	16.5 ± 0.5	13.5 ± 0.4	11.5 ± 0.3	10.1 ± 0.3	8.45 ± 0.25	6.72 ± 0.21	5.40 ± 0.17	3.90 ± 0.14	2.26 ± 0.12

ALICE Collaboration: J. Adam et al., Nature Physics 13 (2017) 535

TRD nuclei trigger

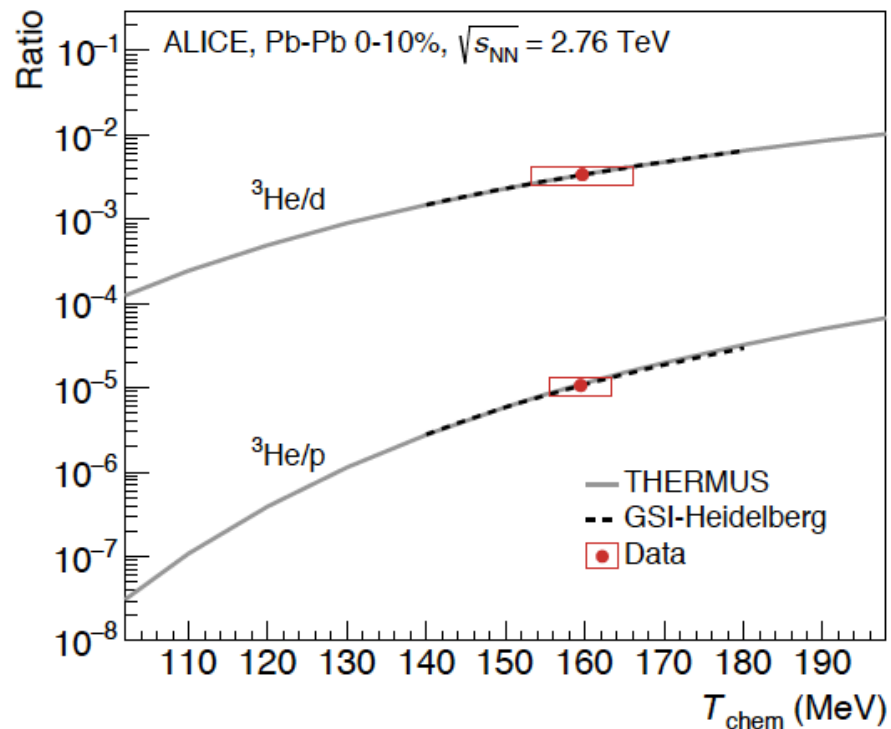
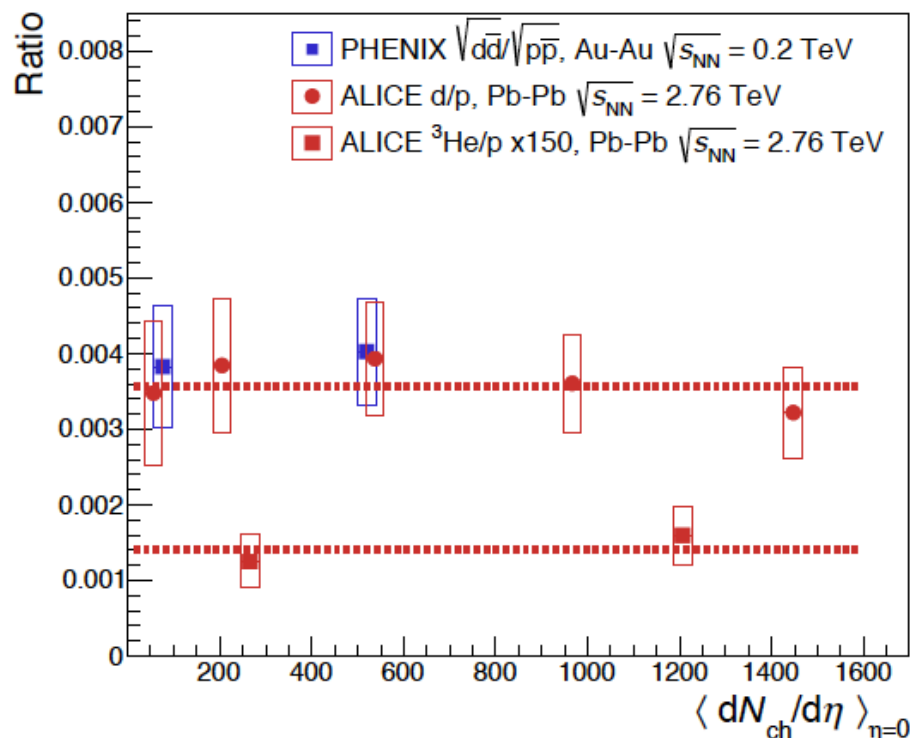
- A trigger on light (anti-)nuclei using the dependence of the ionisation on the charge number of the particle crossing the gas was studied intensively
- A first run in the p-Pb taking 2016
- Currently running in the standard trigger mix of ALICE in the pp data taking
- Expected enhancement mainly on $Z=2$ (anti-)nuclei, but possible reach up to (anti-)alpha even in pp is anticipated in 2017/2018 data taking campaign



Ratios between species

ALICE Collaboration: J. Adam et al., PRC 93, 024917 (2016)

Extracted ratios agree with the thermal model values



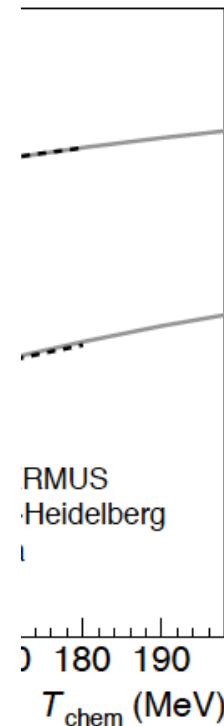
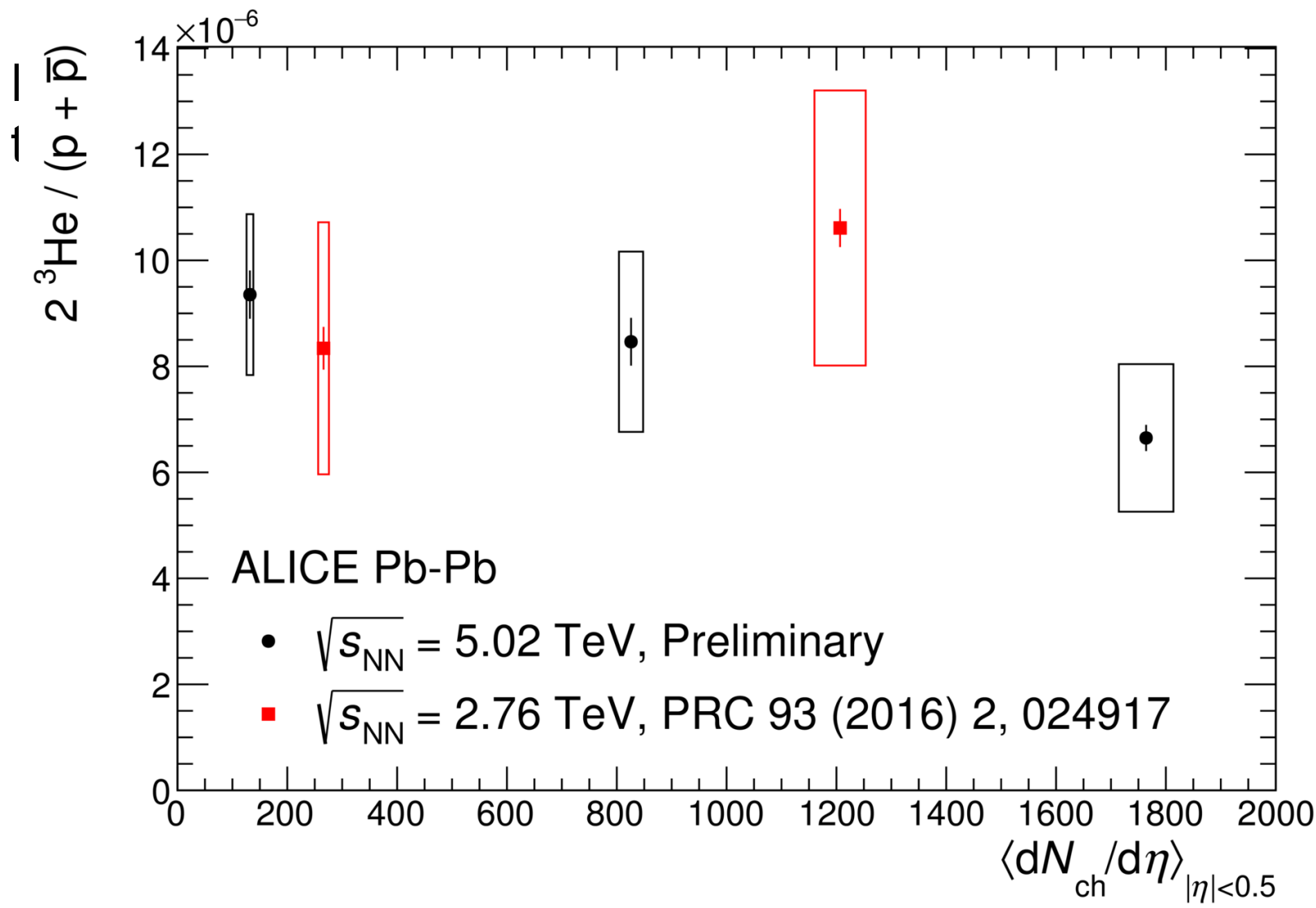
d/p ratio agrees well with the „averaged“ measurement at RHIC

Ratios between species



ALICE

917 (2016)



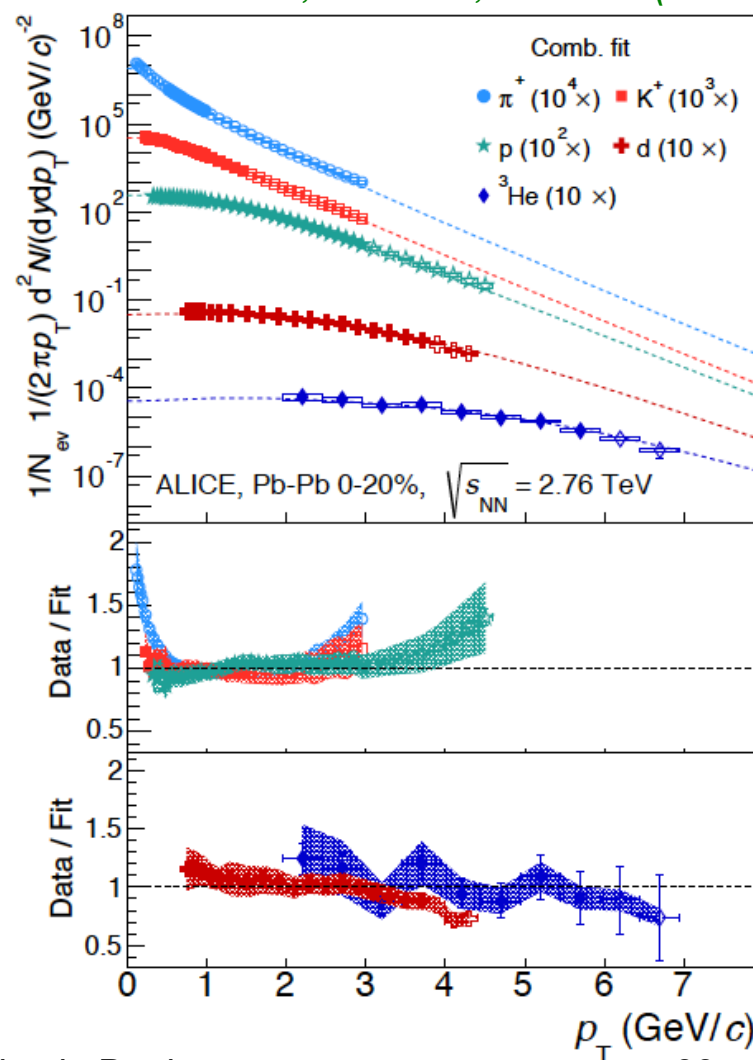
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Combined Blast-Wave fit

ALICE Collaboration: J. Adam et al., PRC 93, 024917 (2016)

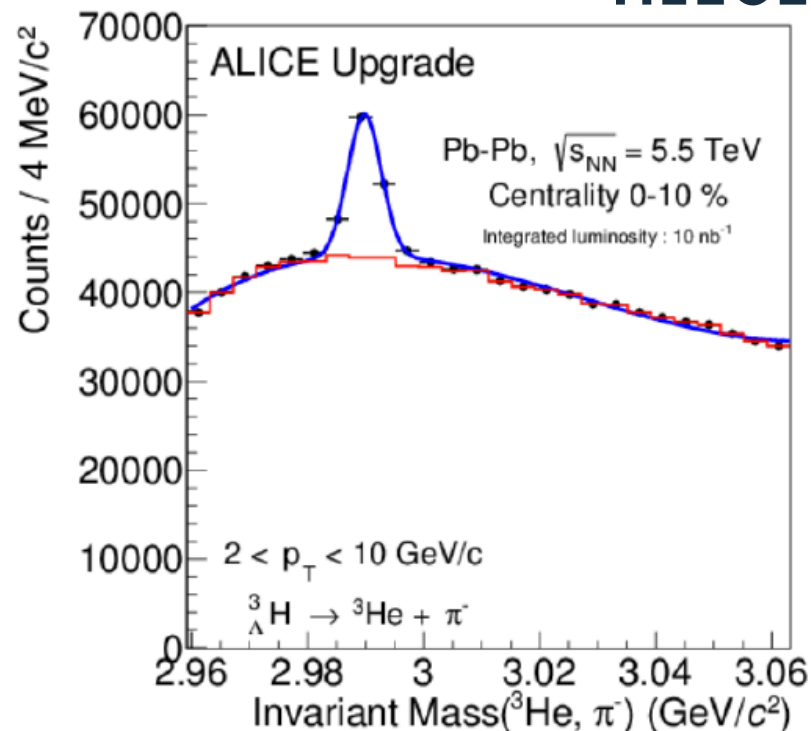
Simultaneous Blast-Wave fit of π^+ , K^+ , p, d and ^3He spectra for central Pb-Pb collisions leads to values for $\langle\beta\rangle$ and T_{kin} close to those obtained when only π, K, p are used

All particles are described rather well with this simultaneous fit



Expectations

- Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continuous readout
- ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei
- Physics which is now done for $A = 2$ and $A = 3$ (hyper-)nuclei will be done for $A = 4$



ITS Upgrade TDR: J. Phys. G 41, 087002 (2014)

State	dN/dy	B.R.	$\langle \text{Acc} \times \epsilon \rangle$	Yield
${}^3_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
${}^4_{\Lambda}H$	2×10^{-7}	50%	7 %	110
${}^4_{\Lambda}He$	2×10^{-7}	32%	8 %	130

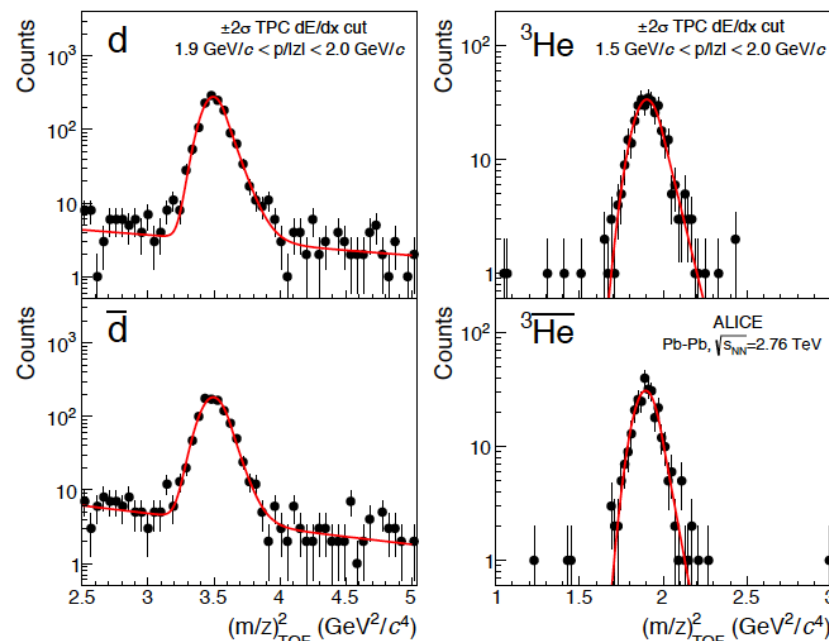
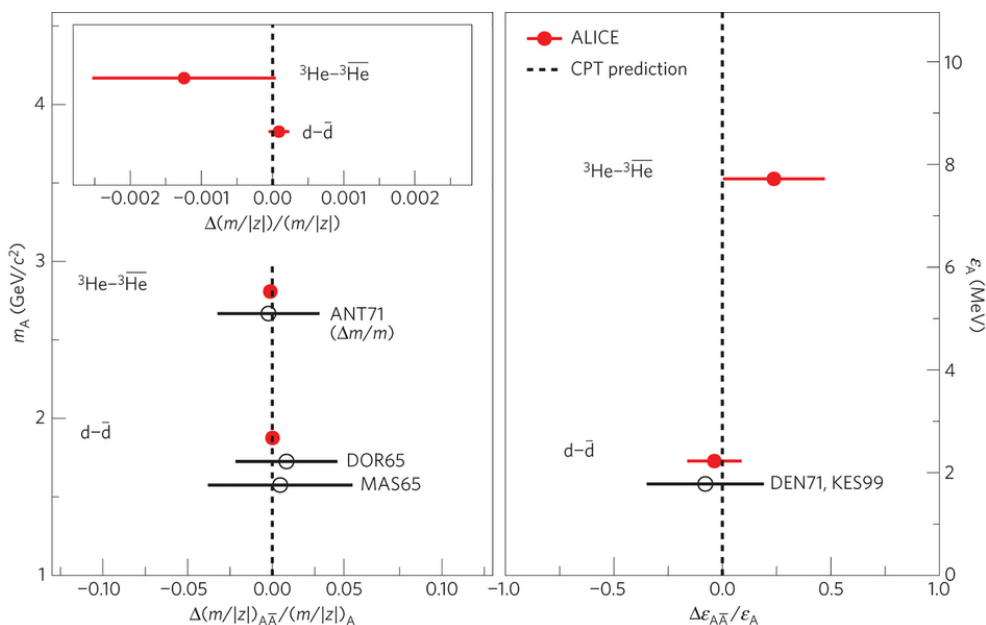
Precision mass measurement



ALICE Collaboration: *Nature Phys.* 11, 811 (2015)

- The precise measurement of (anti-)nuclei mass difference allows probing any difference in the interaction between nucleons and anti-nucleons

Performed test of the CPT invariance of residual QCD “nuclear force” by looking at the mass difference between nuclei and anti-nuclei

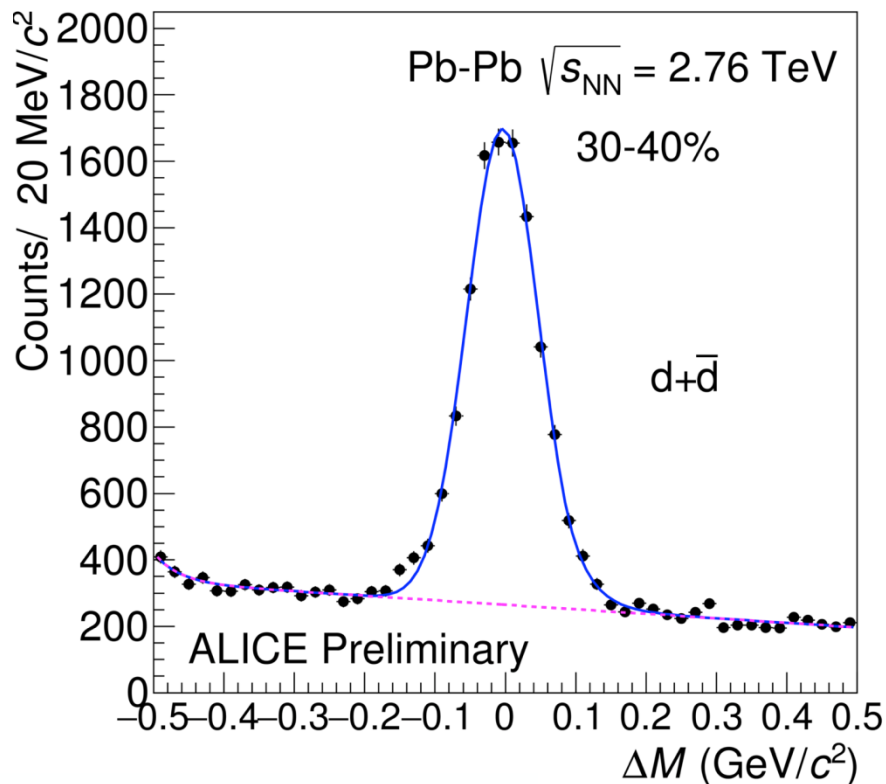


→ Mass and binding energies of nuclei and anti-nuclei are compatible within uncertainties

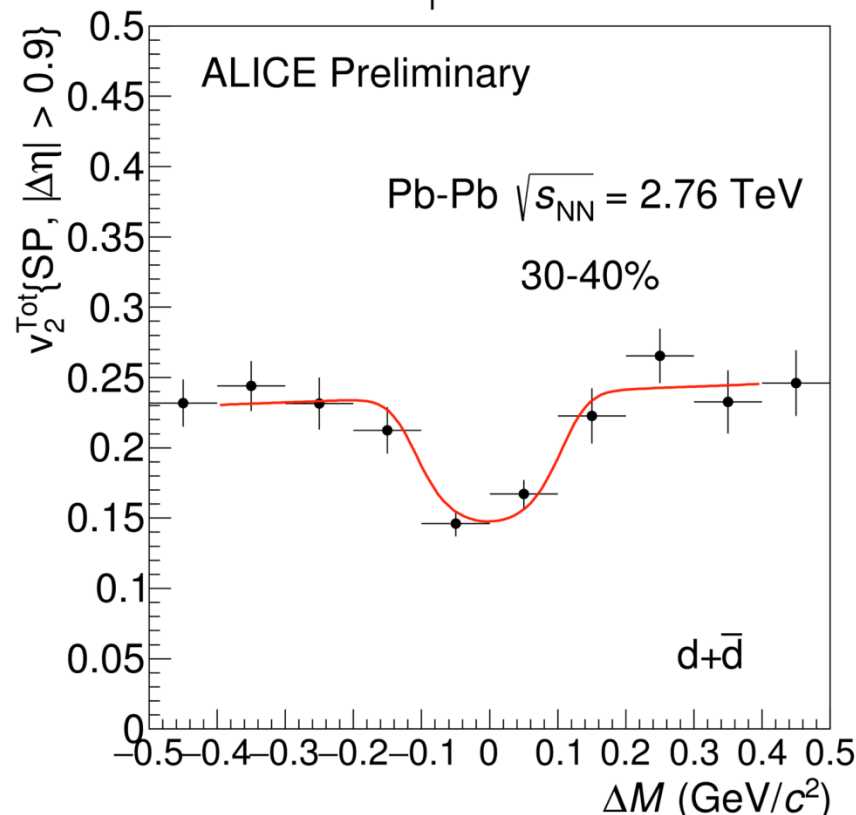
→ Measurement confirms the CPT invariance for light nuclei.

Elliptic flow

$2.20 < p_T < 2.40 \text{ GeV}/c$

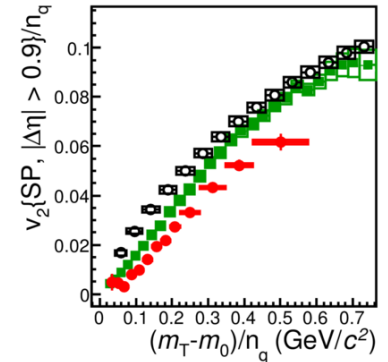
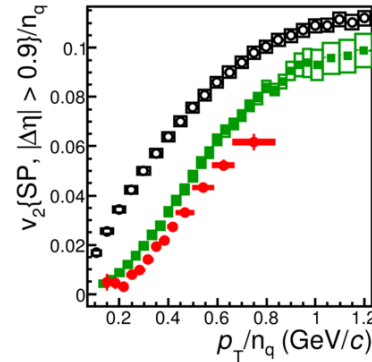
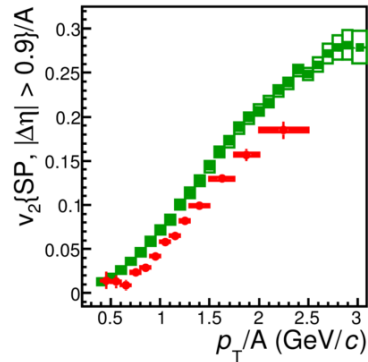
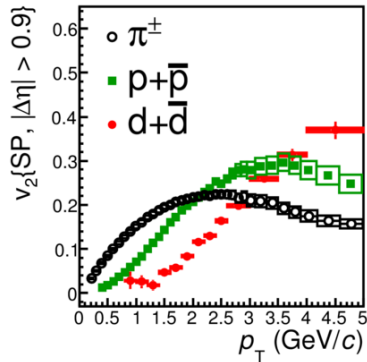


$2.20 < p_T < 2.40 \text{ GeV}/c$



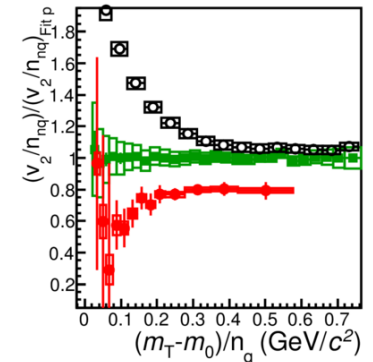
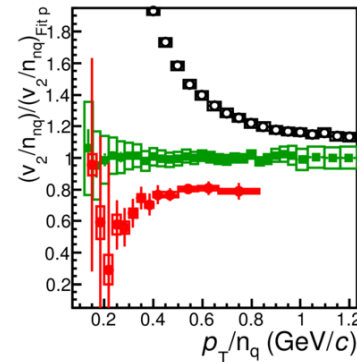
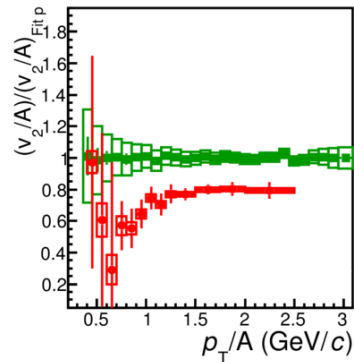
$$v_n\{SP\} = \frac{\langle u_{n,i}(p_T, \eta) \cdot \frac{Q_n^*}{M} \rangle}{\sqrt{\langle \frac{Q_{n,A}^*}{M_A} \cdot \frac{Q_{n,B}^*}{M_B} \rangle}}$$

Elliptic flow

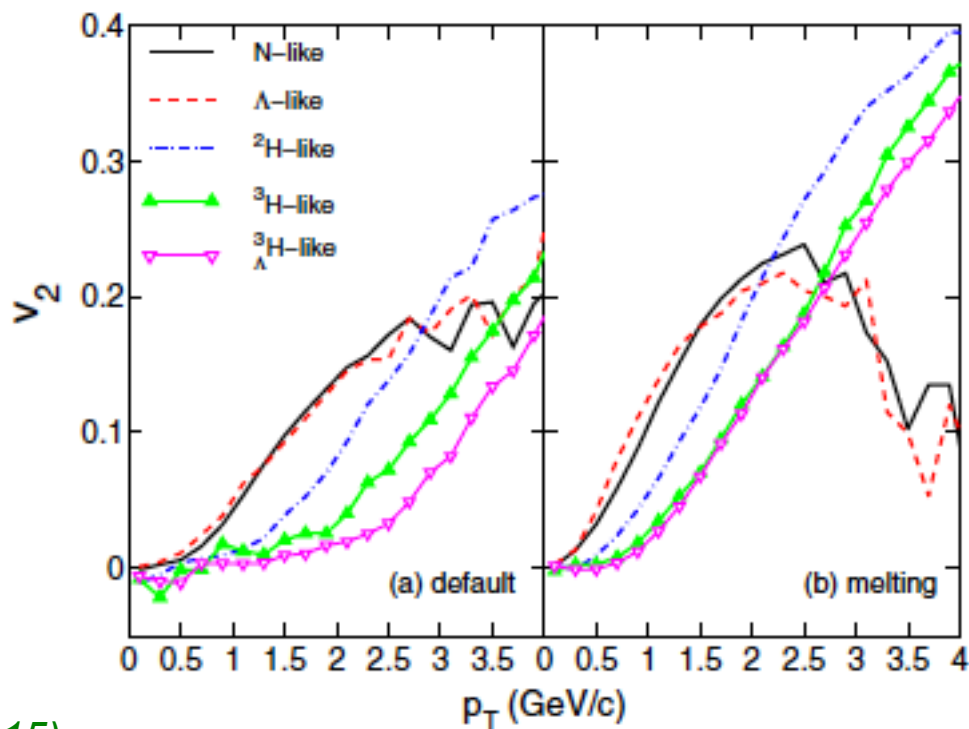
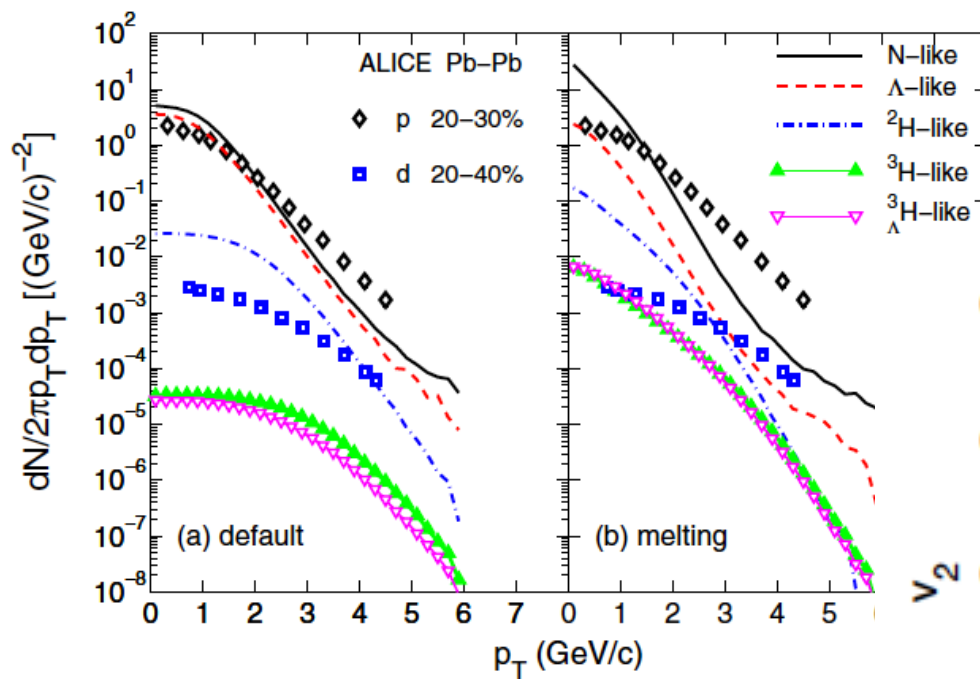


ALICE Preliminary

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV 30-40%

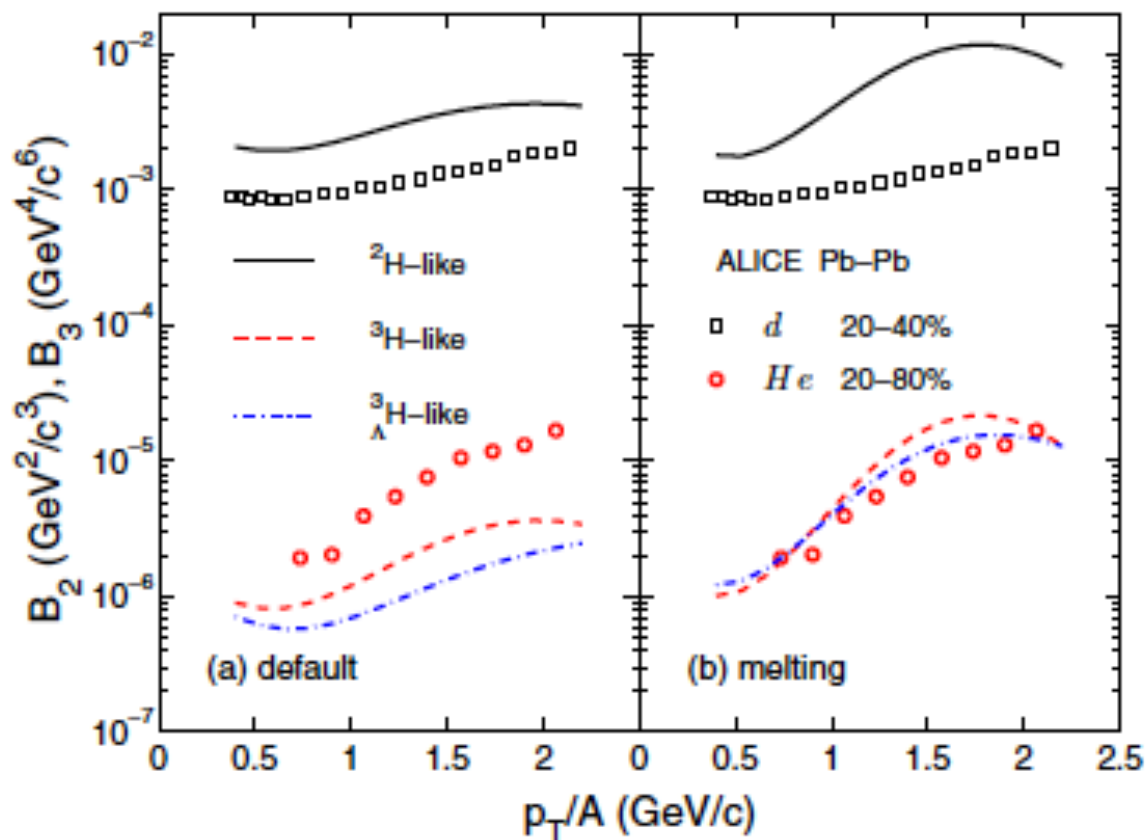


Elliptic flow



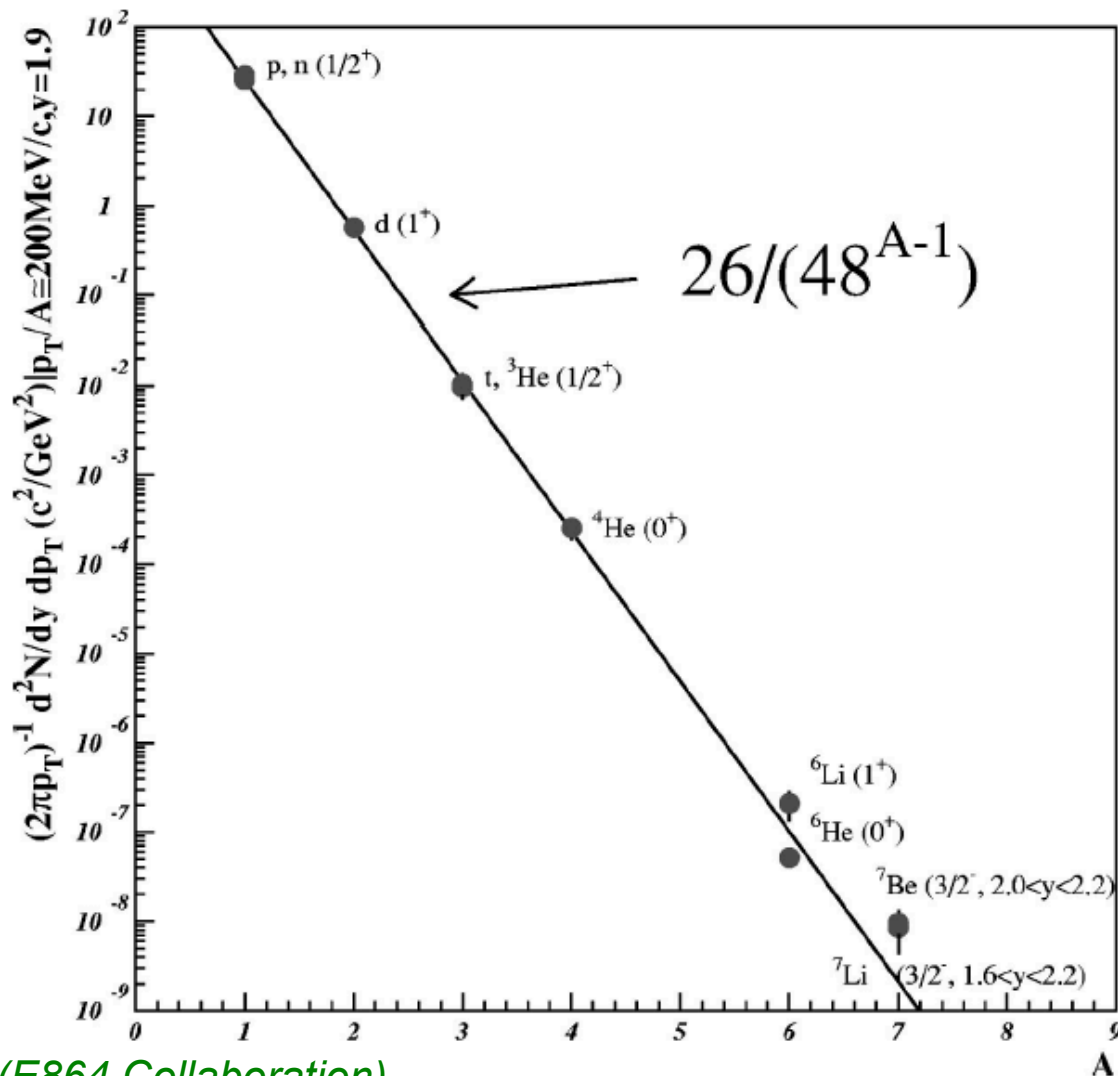
L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

Elliptic flow



L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

E864 nuclei result

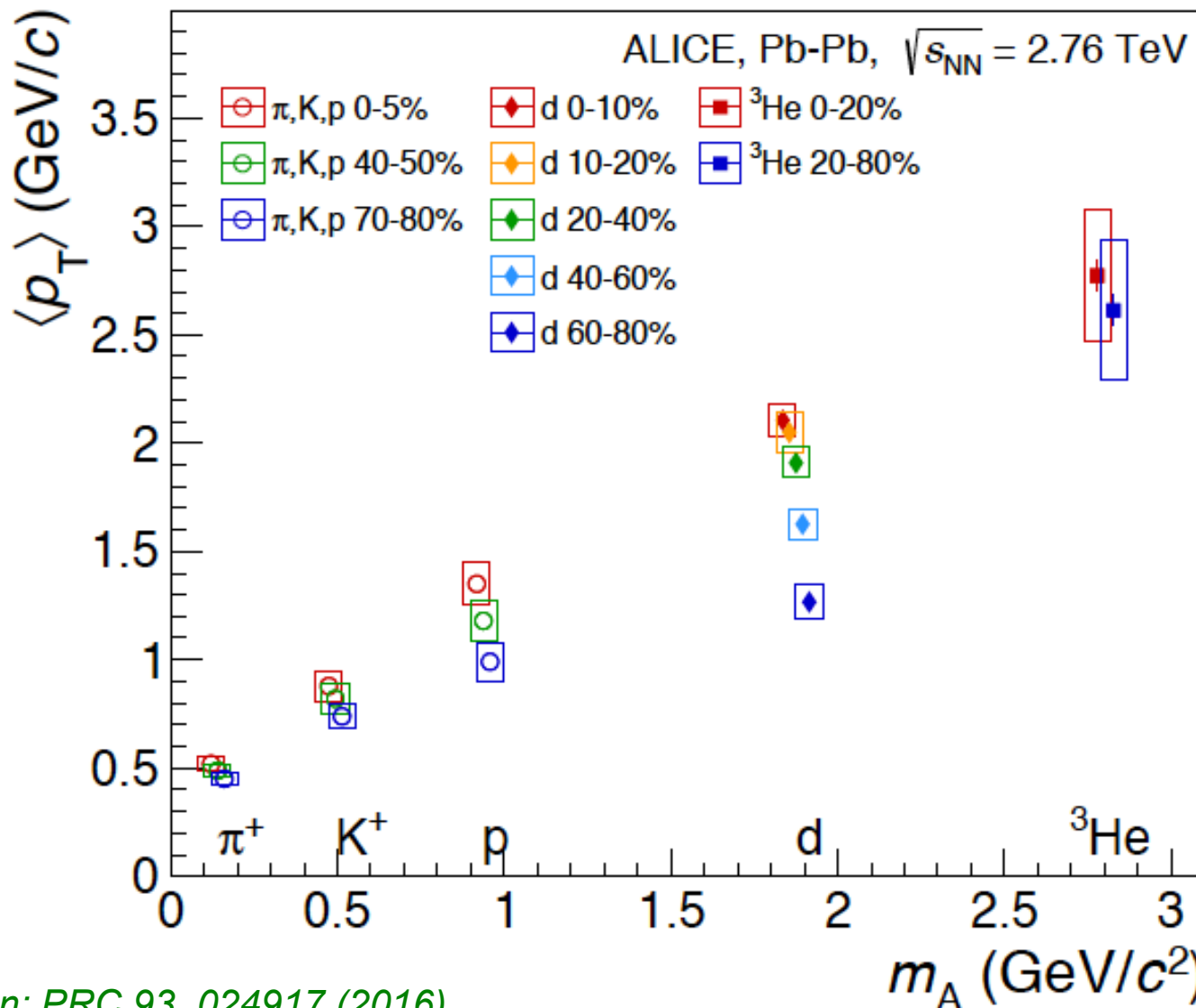


*T.A. Armstrong et al. (E864 Collaboration),
Phys. Rev. C 61 (2000) 064908*

Mean p_T



CE

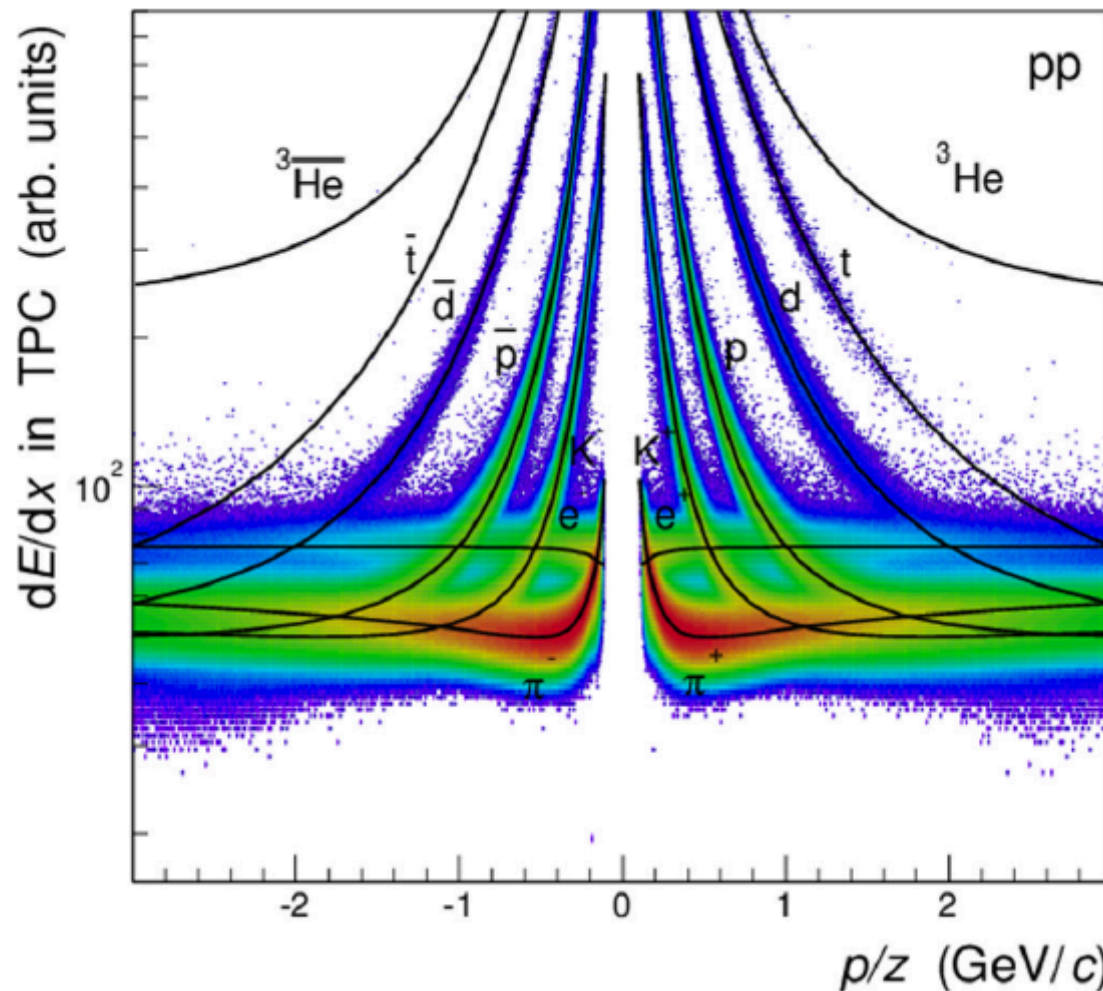


ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in pp

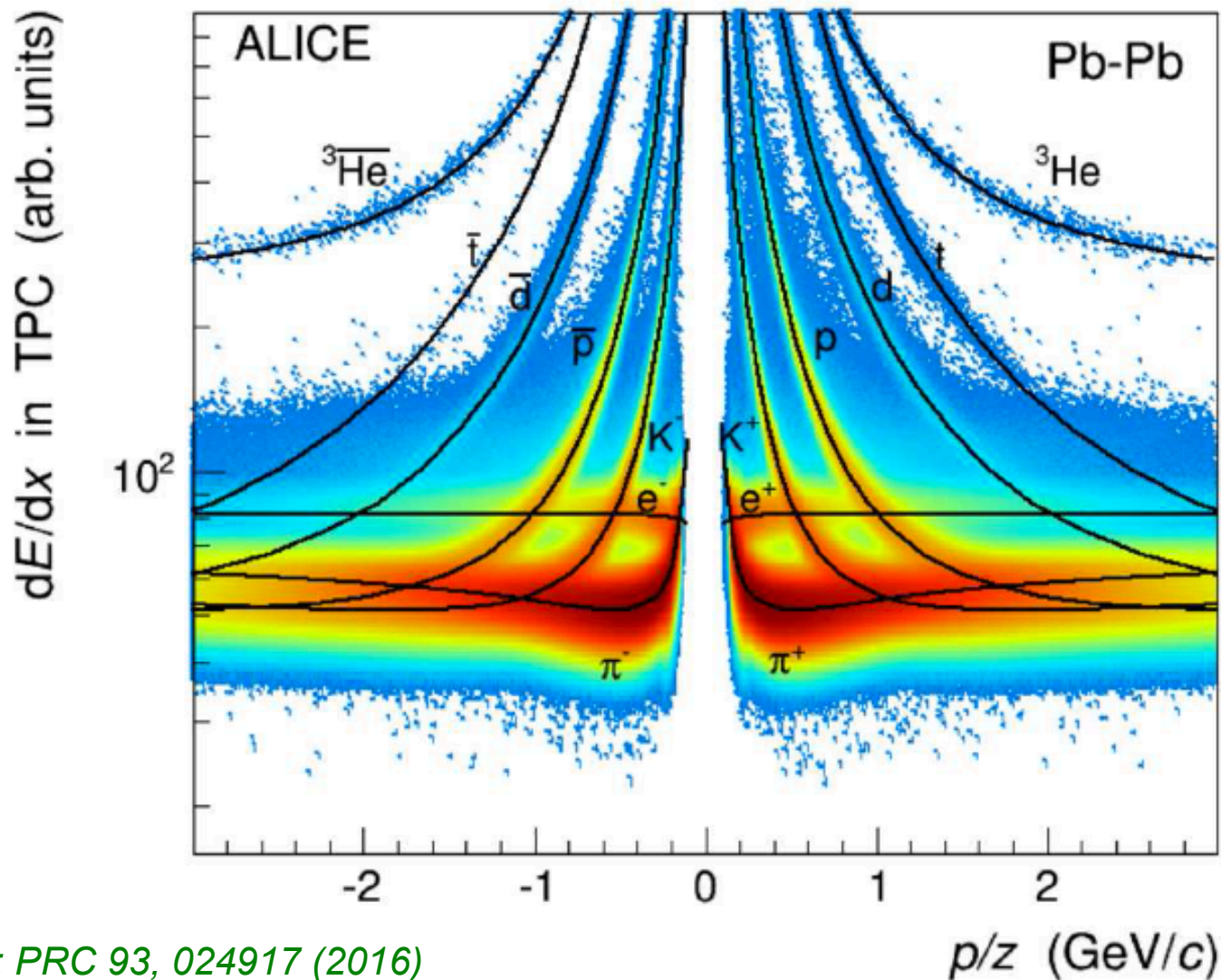


ALICE



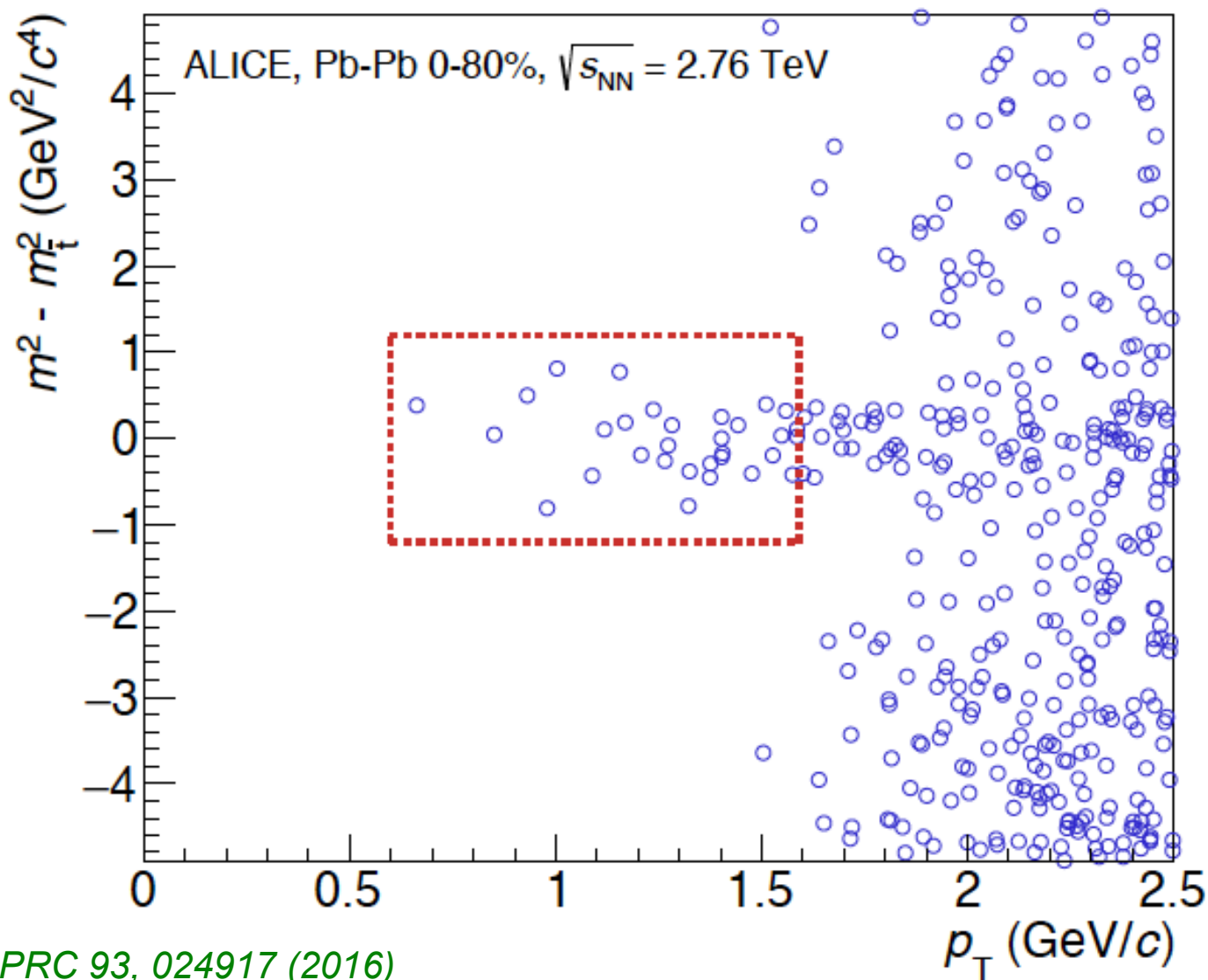
ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in Pb-Pb



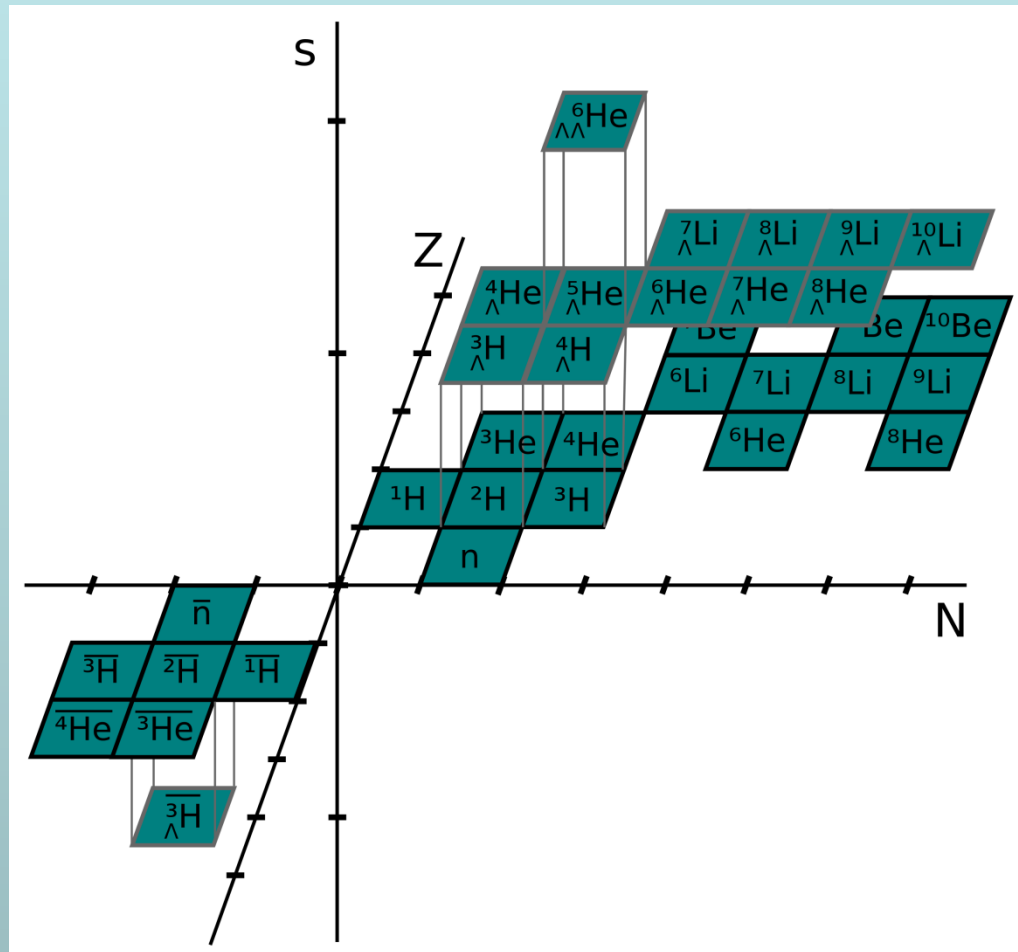
ALICE Collaboration: PRC 93, 024917 (2016)

Anti-tritons



ALICE Collaboration: PRC 93, 024917 (2016)

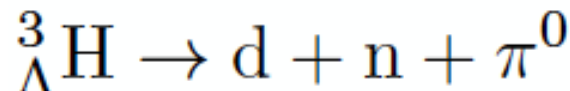
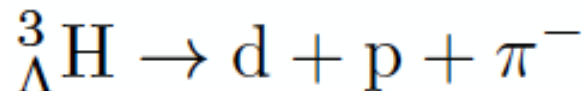
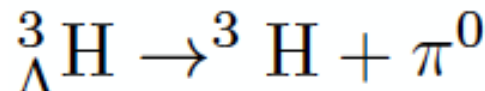
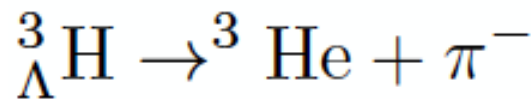
Hypernuclei



Hypertriton identification

Bound state of Λ , p, n
 $m = 2.991 \text{ GeV}/c^2$ ($B_\Lambda = 130 \text{ keV}$)
 $\rightarrow$ rms radius: 10.3 fm

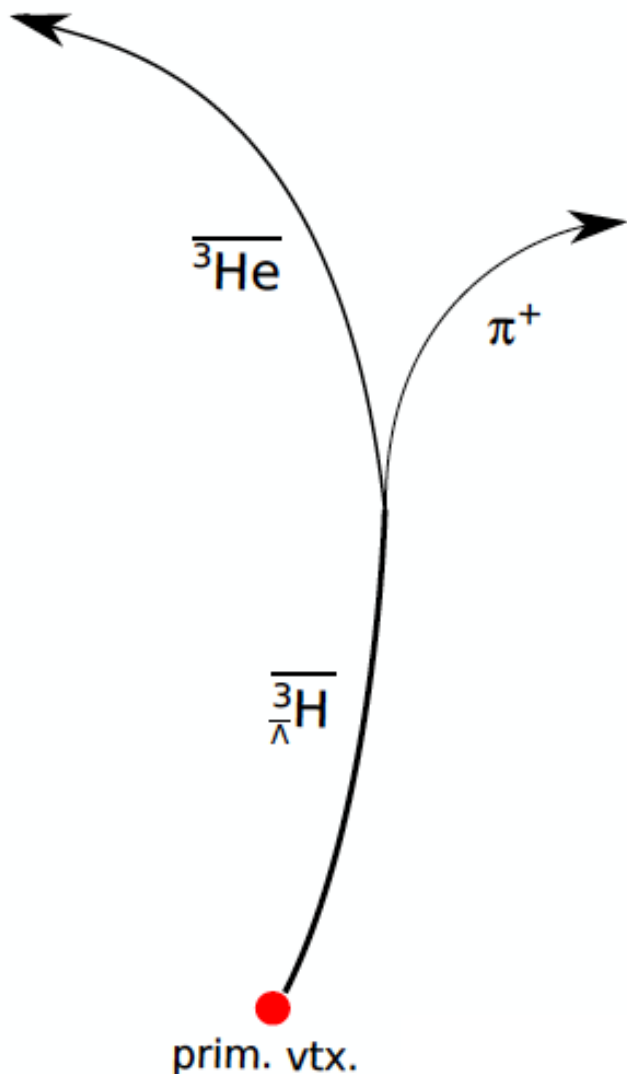
Decay modes:



+ anti-particles

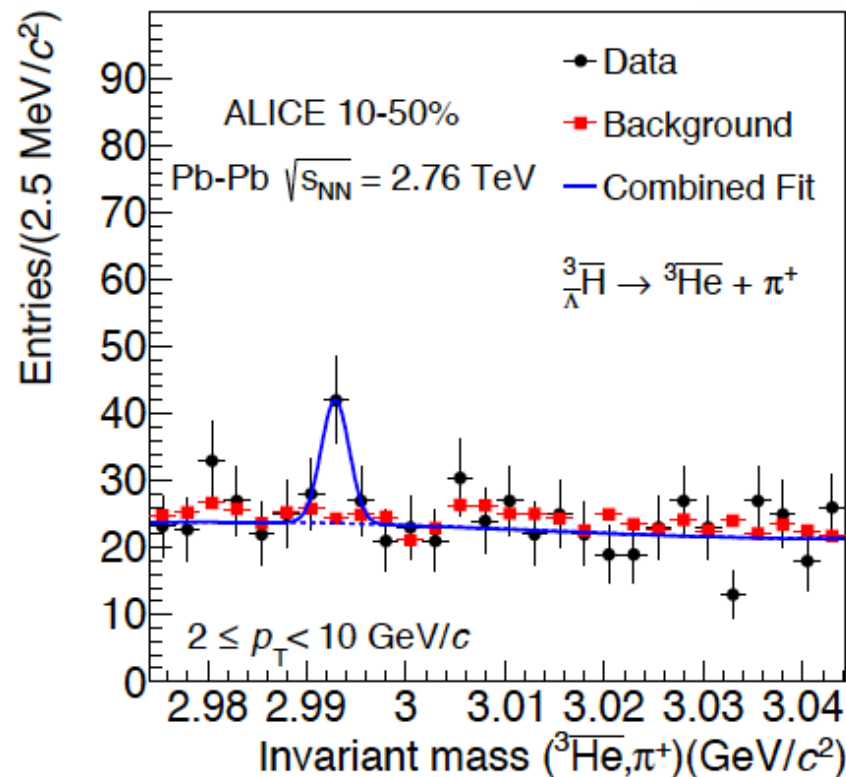
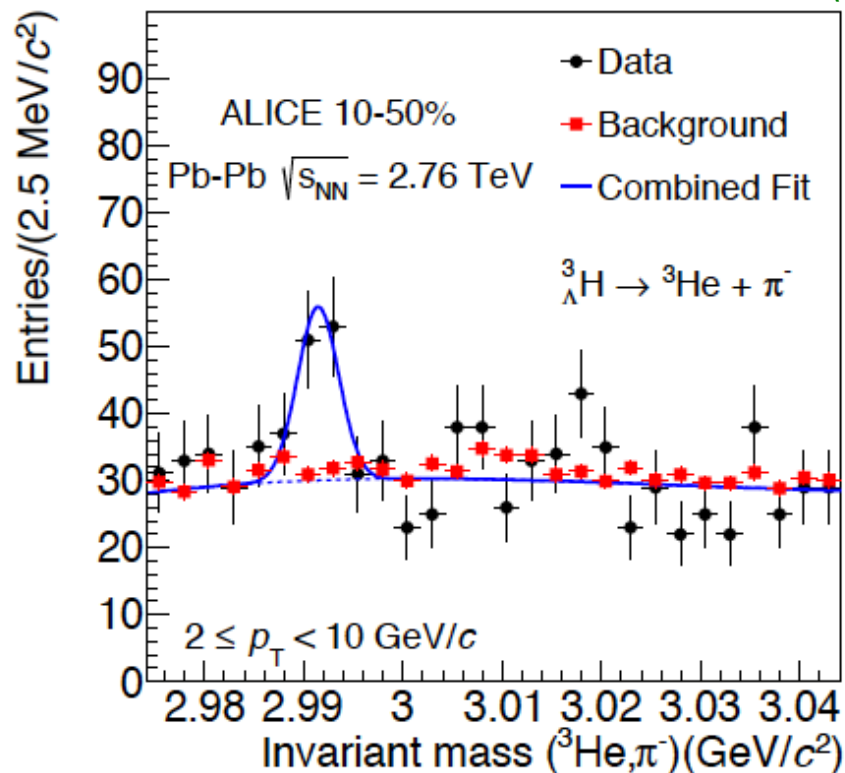
$\rightarrow$ Anti-hypertriton was first observed
 by the STAR Collaboration:

Science 328,58 (2010)



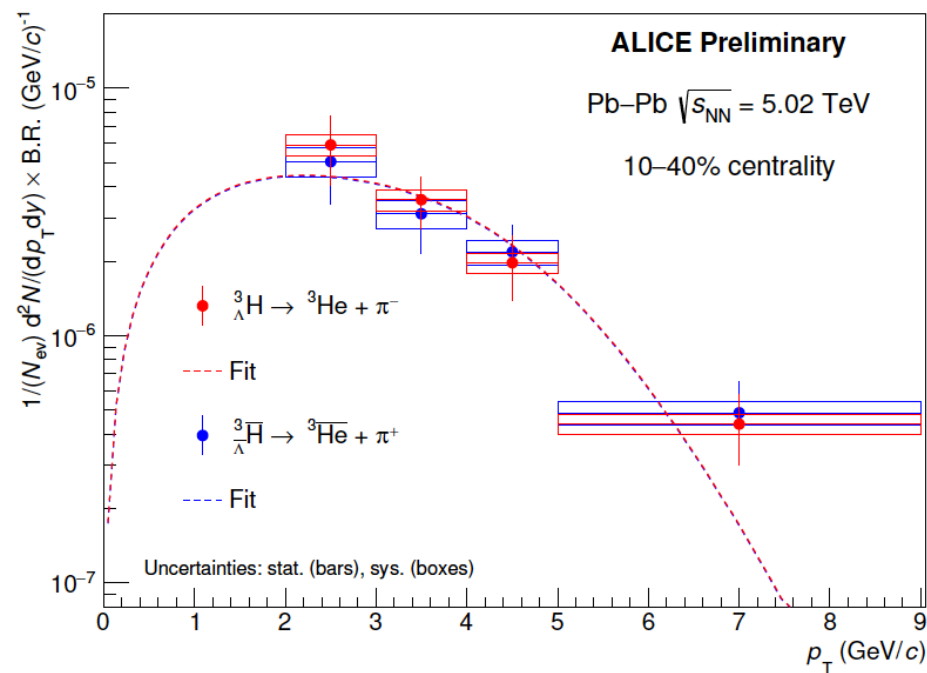
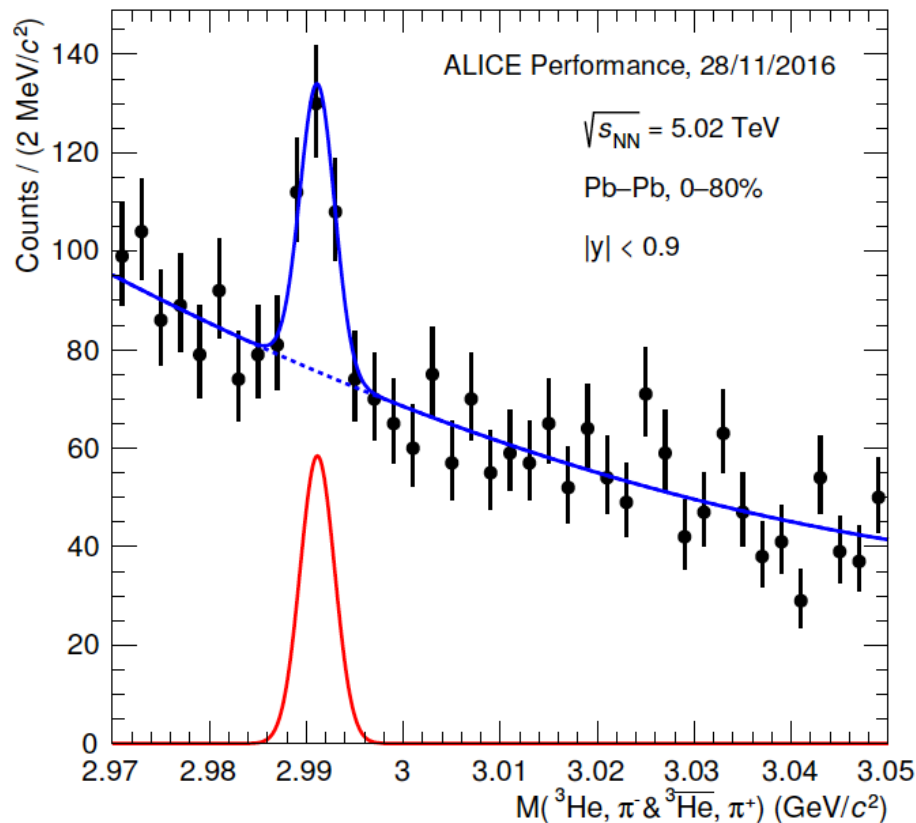
Hypertriton signal

ALICE Collaboration: PLB 754, 360 (2016)



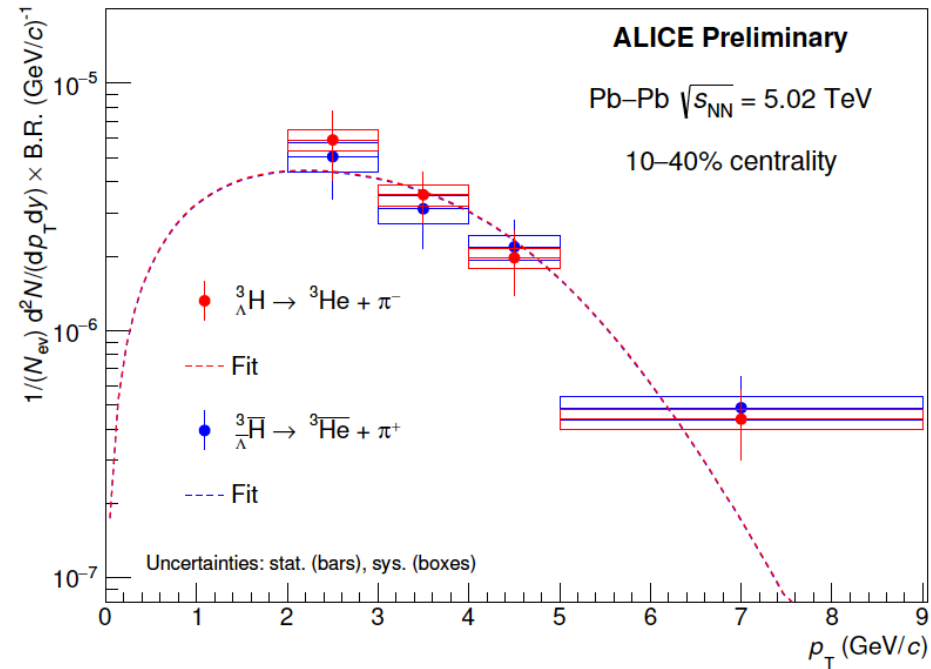
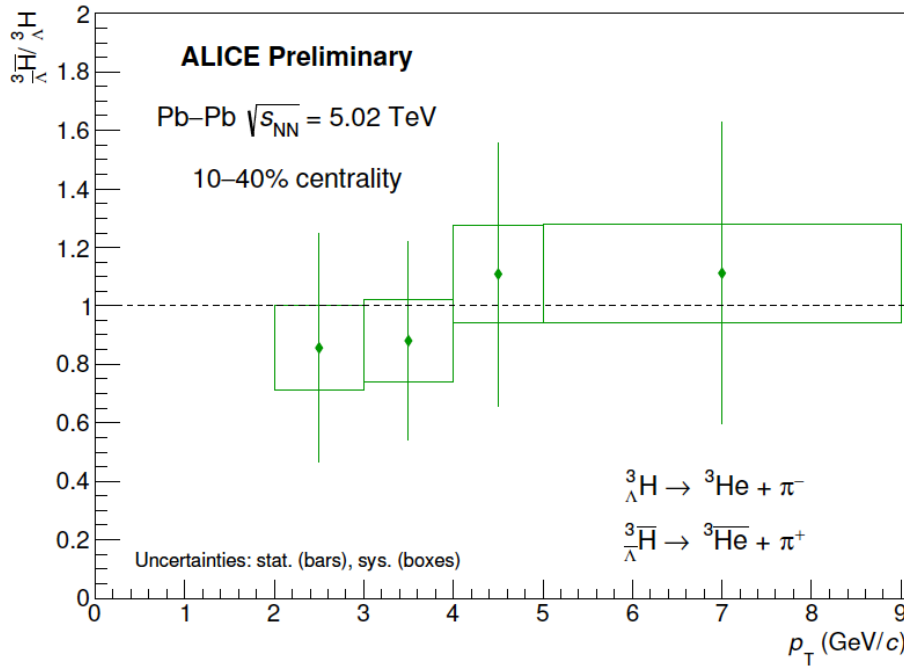
- Peaks are clearly visible for particle and anti-particle
→ Extracted yields in 3 p_T bins and 2 centrality classes

Hypertriton signal



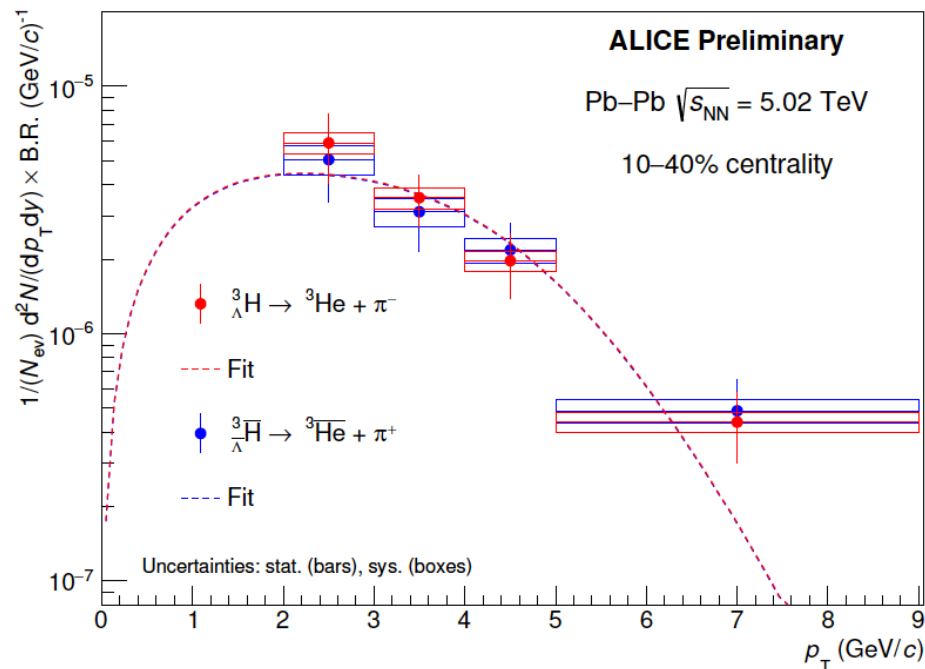
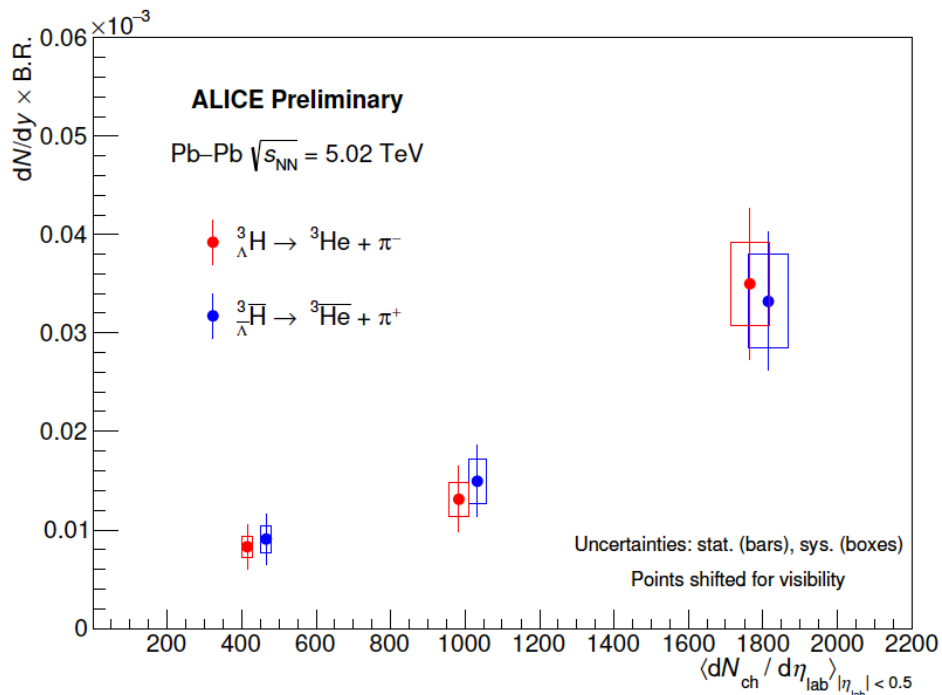
- Peaks are also clearly visible for particle and anti-particle
→ Extracted yields in 4 p_T bins and 3 centrality classes

Hypertriton spectra



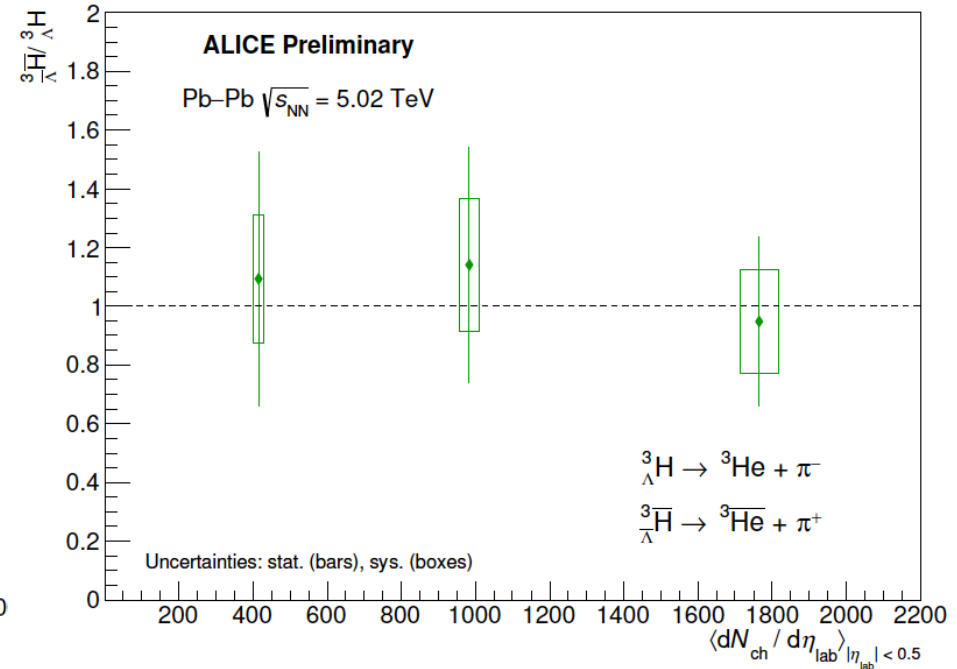
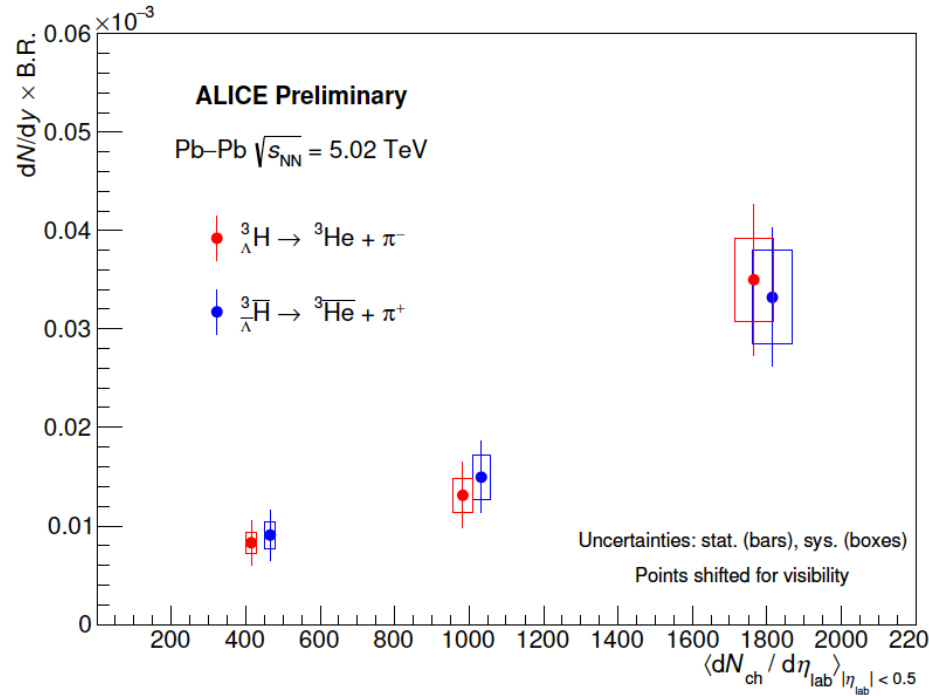
- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

Hypertriton yield



- Production in 3 centrality classes shows increase of production probability with increasing multiplicity

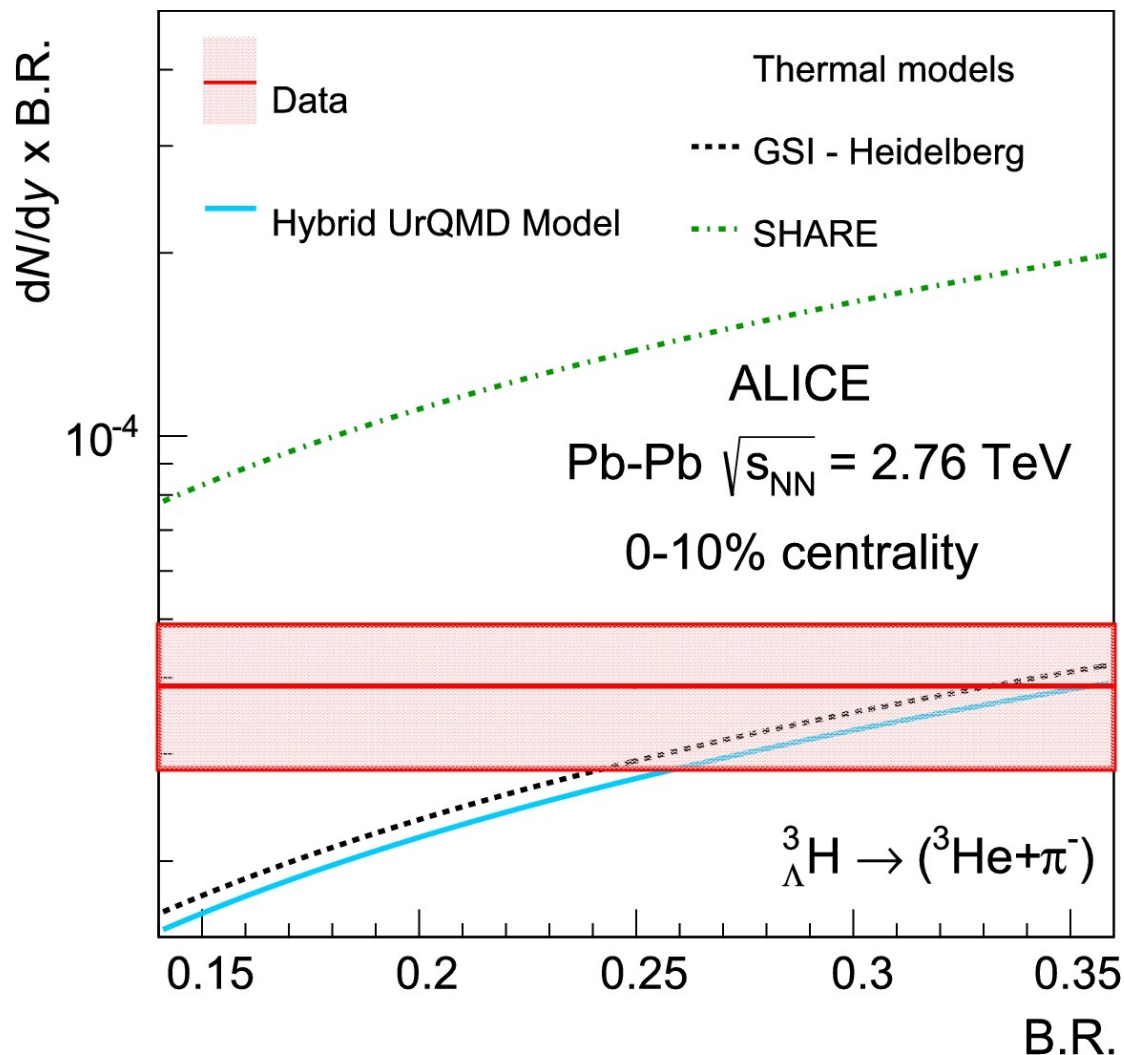
Hypertriton yield



- Production in 3 centrality classes shows increase of production probability with increasing multiplicity
- Ratio between anti-hypertriton-to-hypertriton unity for all centralities

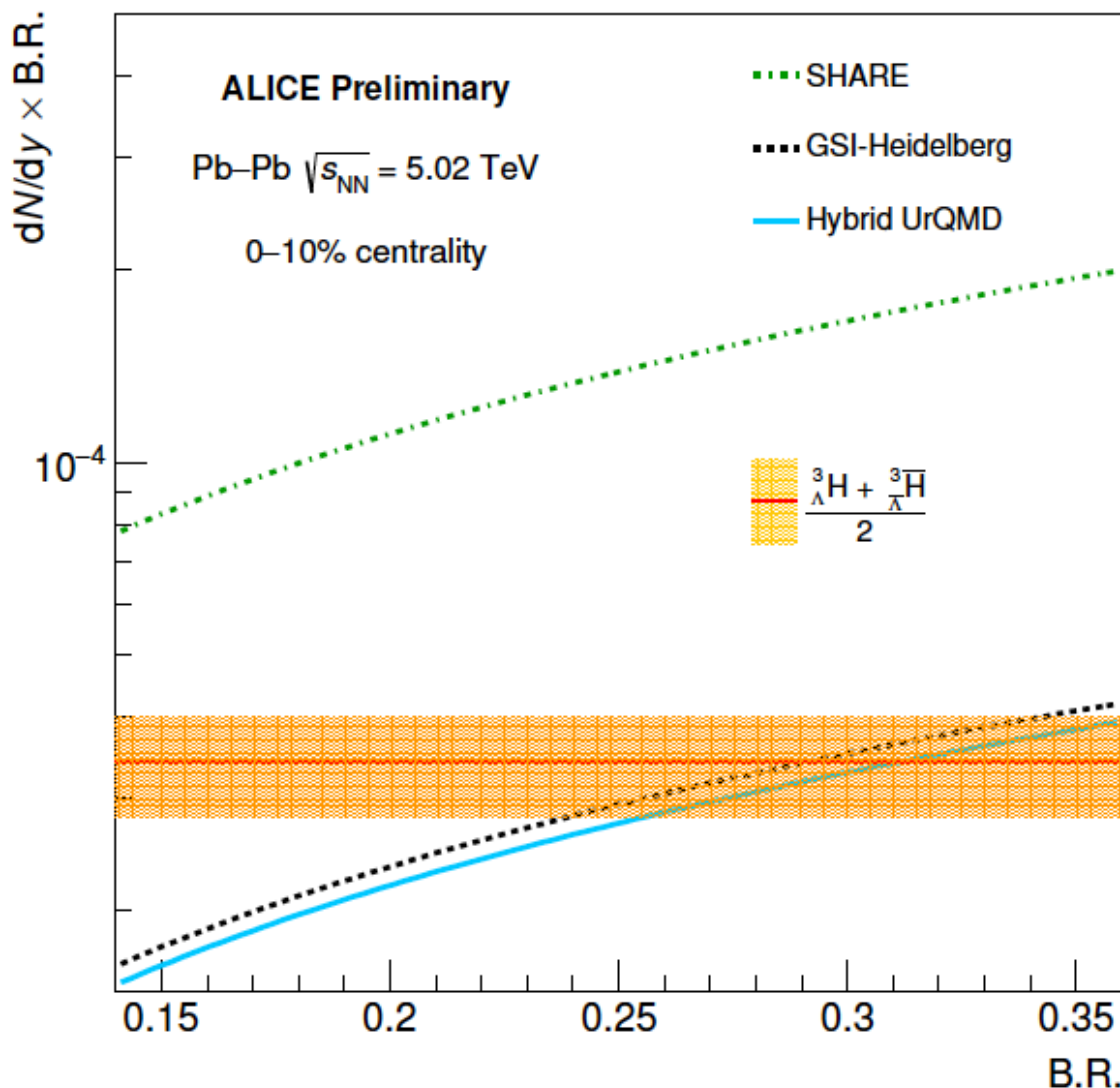
Hypertriton yield vs. B.R.

ALICE Collaboration: PLB 754, 360 (2016)



- The hypertriton branching ratio is not well known, only constrained by the ratio between all charged channels containing a pion
- Theory which prefers a value of around 25% gives a lifetime of the hypertriton close to the one of the free Λ

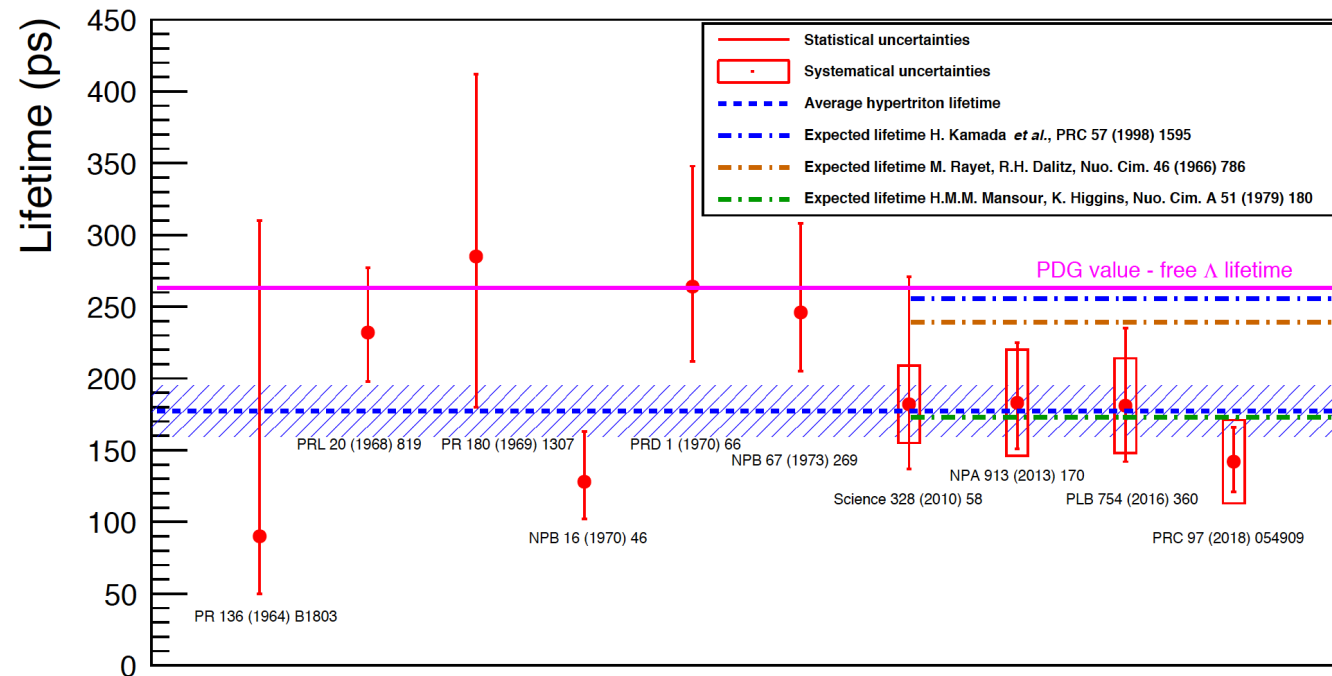
Hypertriton yield vs. B.R.



- The hypertriton branching ratio is not well known, only constrained by the ratio between all charged channels containing a pion
- Theory which prefers a value of around 25% gives a lifetime of the hypertriton close to the one of the free Λ

Hypertriton „puzzle“

- Recently extracted lifetimes significantly below the free Λ lifetime
- Not expected from theory!
- Data before 2010 from emulsions
- Currently most precise data coming from heavy-ion collisions
- Better precision expected from larger data samples to be collected



P. Braun-Munzinger, bd, Invited review NPA in preparation

Hypertriton „puzzle“

- Recently extracted lifetimes significantly below the free Λ lifetime $\rightarrow$ new ALICE result agrees with world average and free Λ lifetime

