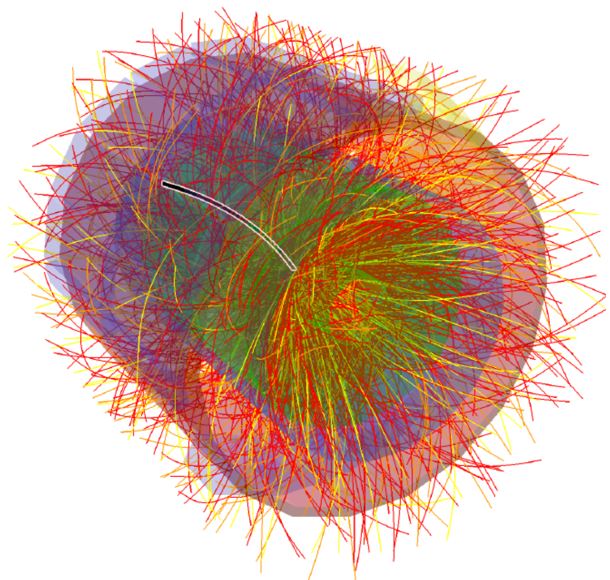
Highlights of the production of (anti-)(hyper-)nuclei and exotica with ALICE at the LHC



06/27/2018

HYP2018

Portsmouth, VA

Benjamin Dönigus

for the ALICE Collaboration

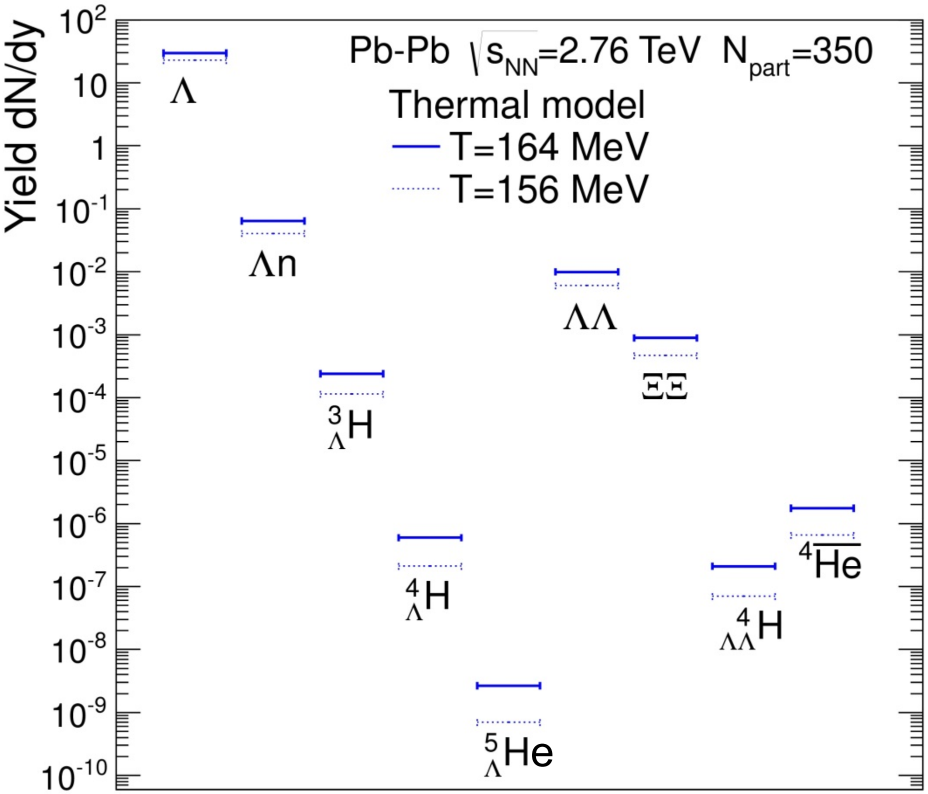
Institut für Kernphysik

Goethe Universität Frankfurt

Content

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

Motivation

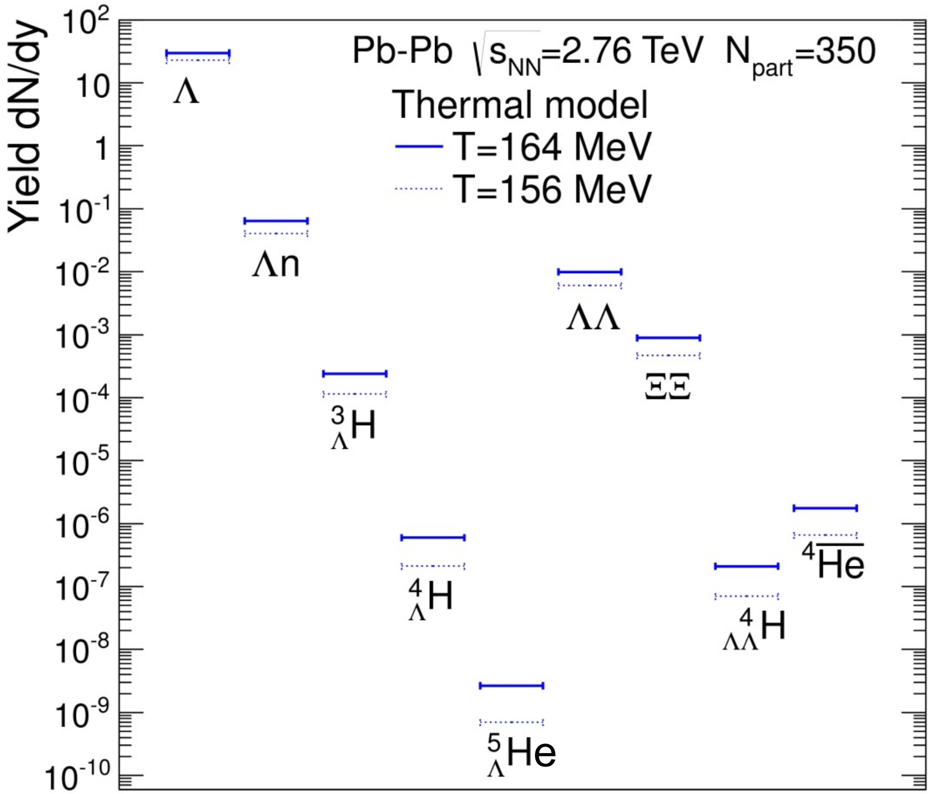


A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

- 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

Motivation



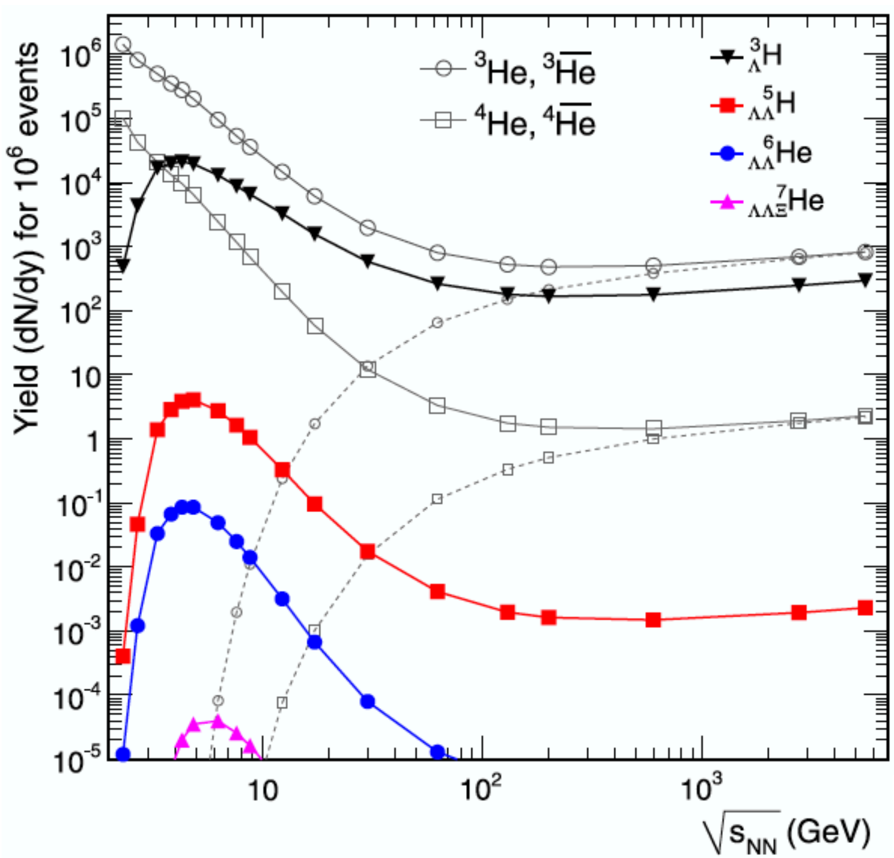
A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

- 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

Thermal model

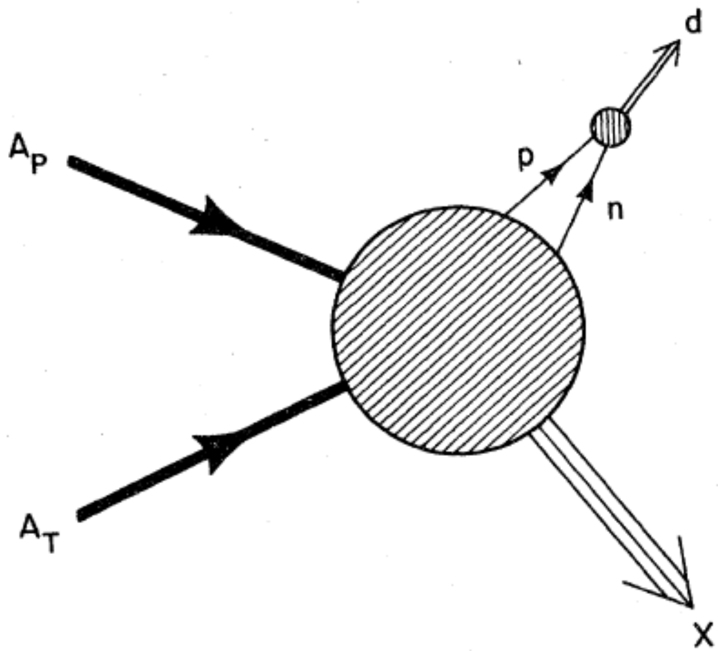


A. Andronic et al., PLB 697, 203 (2011)

- 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 ~ $\exp(-m/T_{ch})$

→ Binding energies small compared to T_{ch}

Coalescence (I)



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

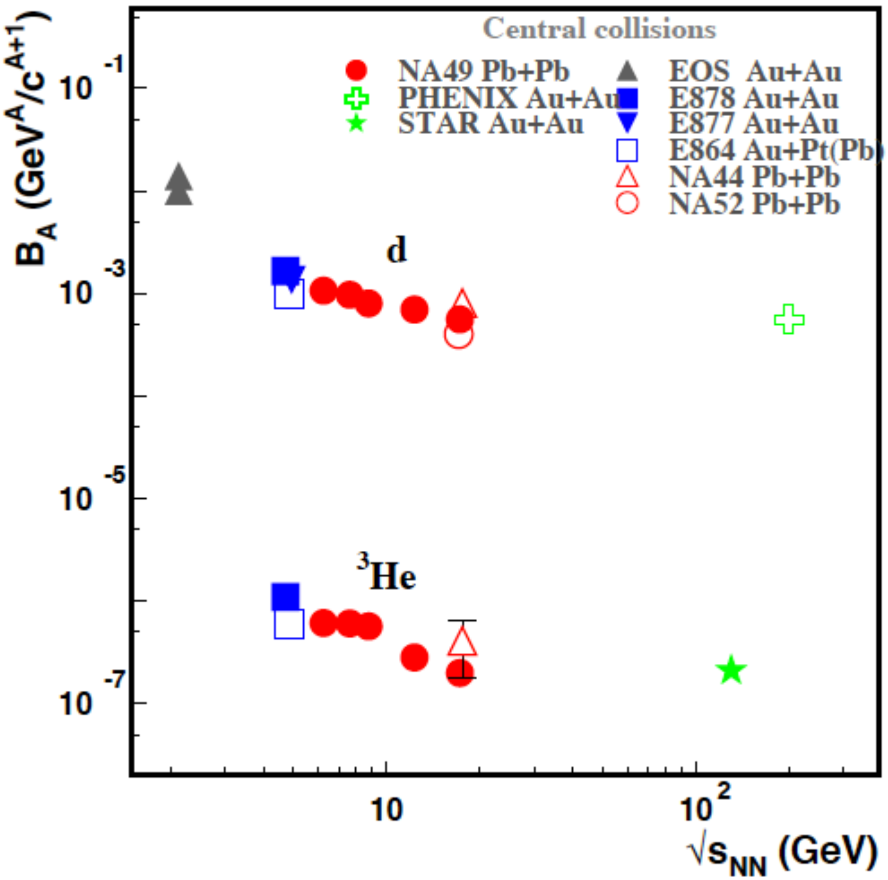
- Nuclei are formed by protons and neutrons which are nearby in space and have similar velocities (after kinetic freeze-out)

- Produced nuclei

➜ can break apart

➜ created again by final-state coalescence

Coalescence (II)



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

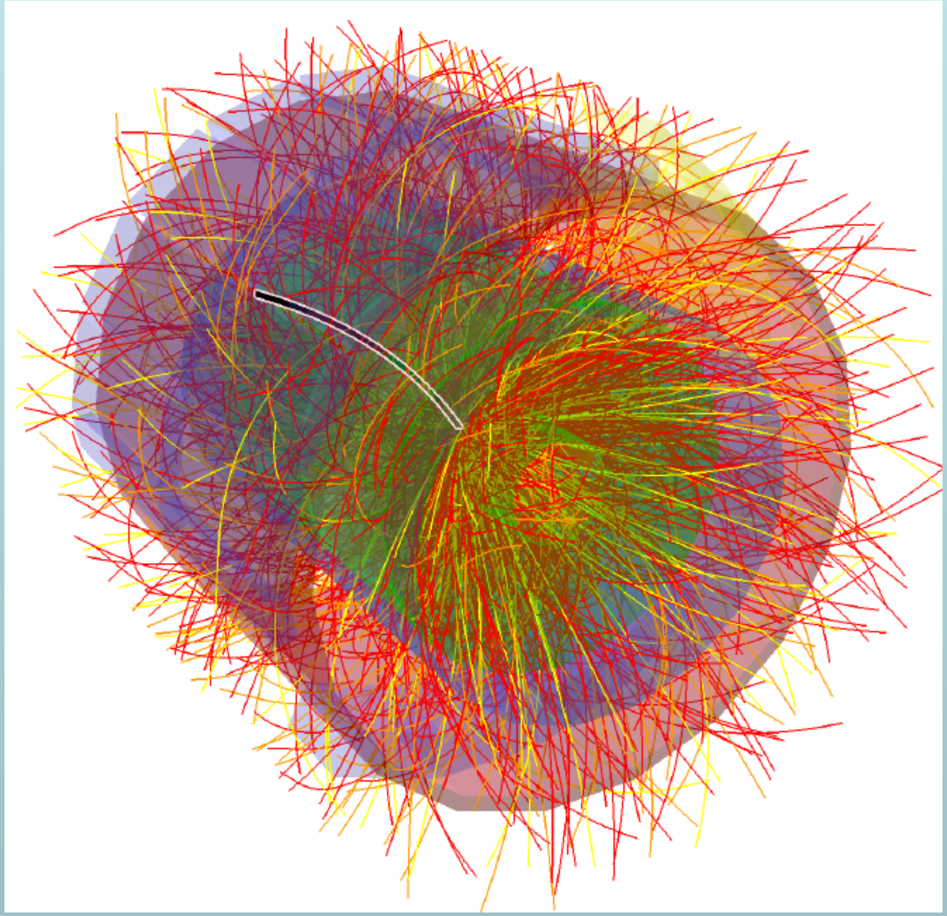
- Production probability of nuclei is usually quantified through a coalescence parameter B_A using

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

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

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

ALICE



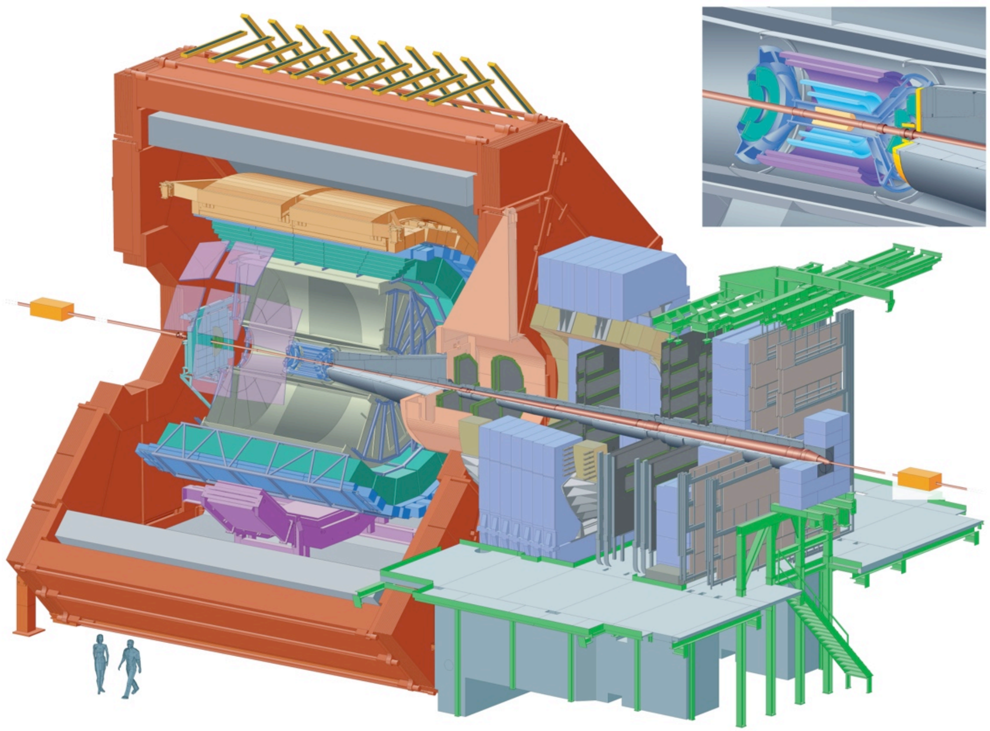
Large Hadron Collider at CERN

Large Hadron Collider at CERN

ALICE experiment

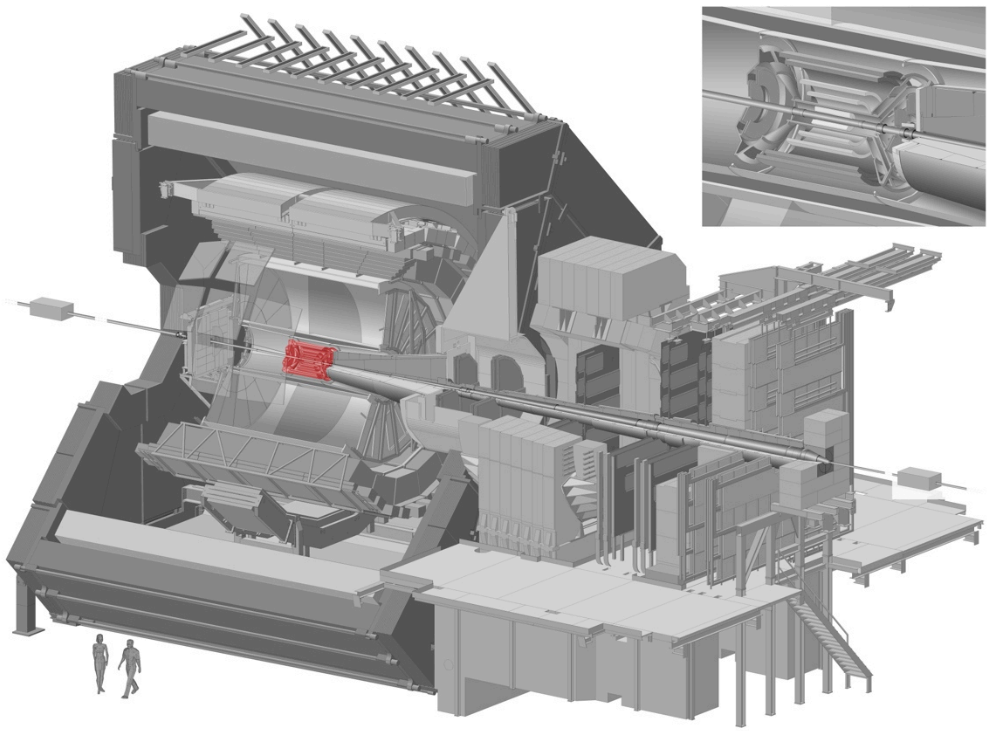
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

ALICE



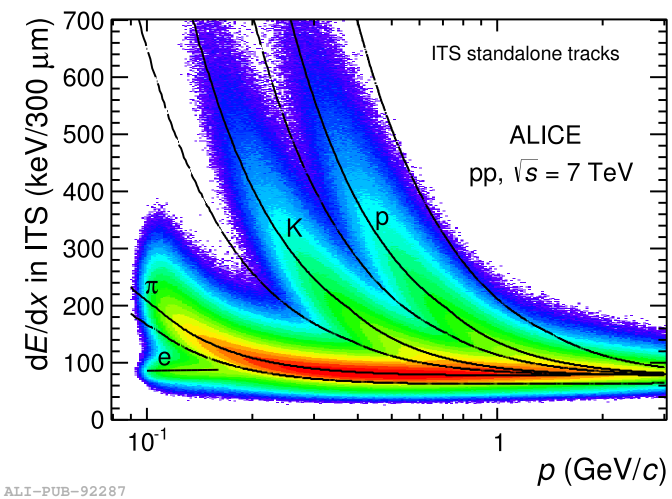
Specificity: low-momentum tracking and particle identification in a high-multiplicity environment

ALICE experiment



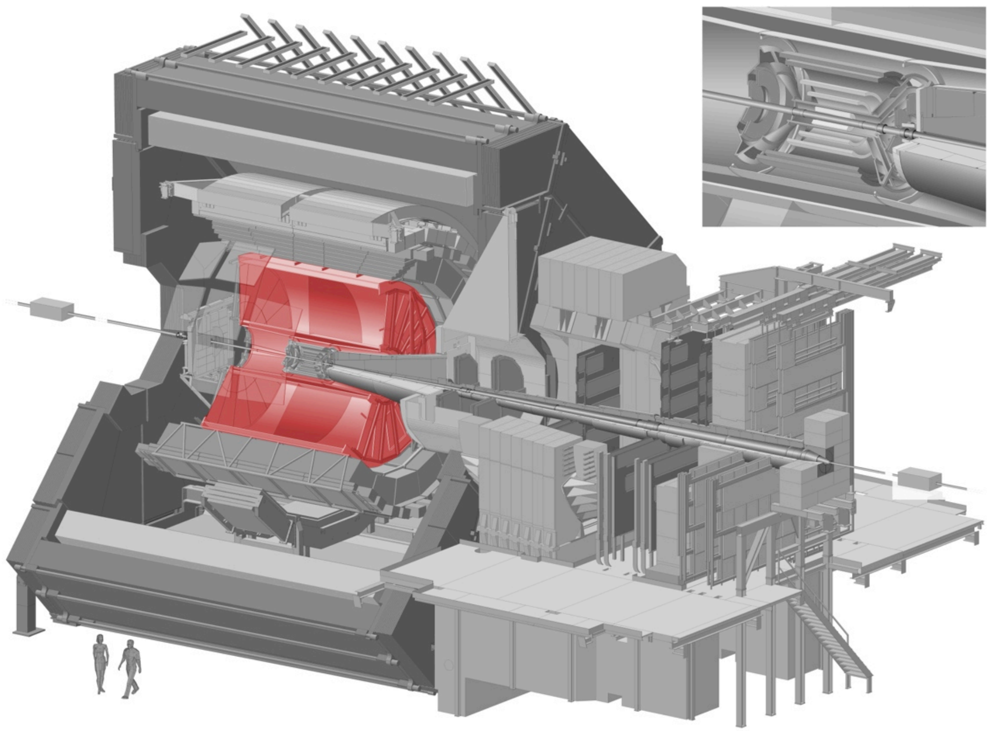
ITS (|η|<0.9)

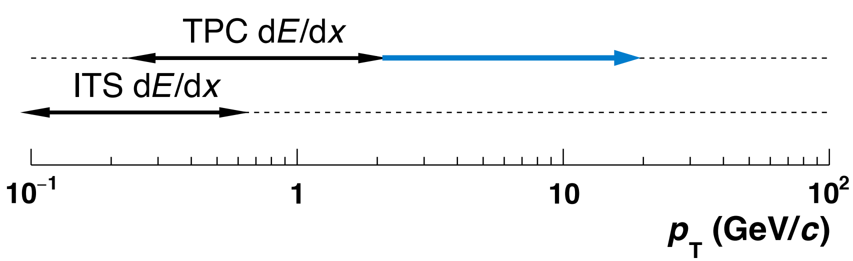
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)



ITS dE/dx

ALICE experiment



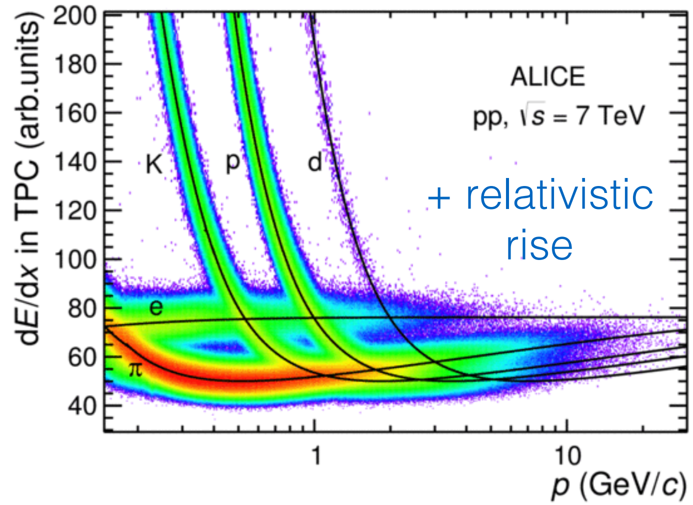


ITS ($|\eta|<0.9$)

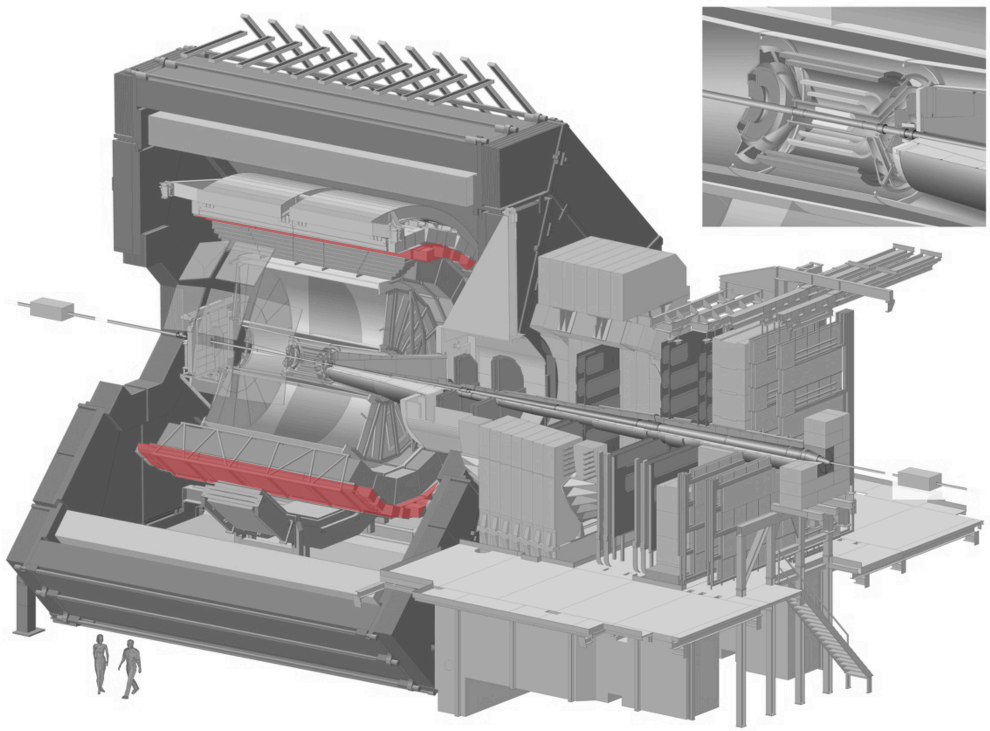
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)

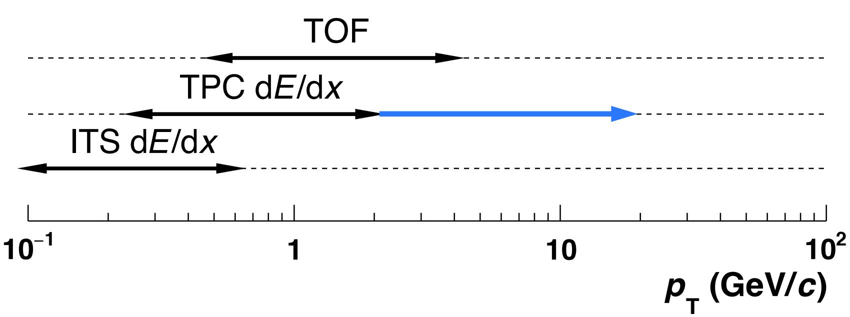
TPC ($|\eta|<0.9$)

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



ALICE experiment

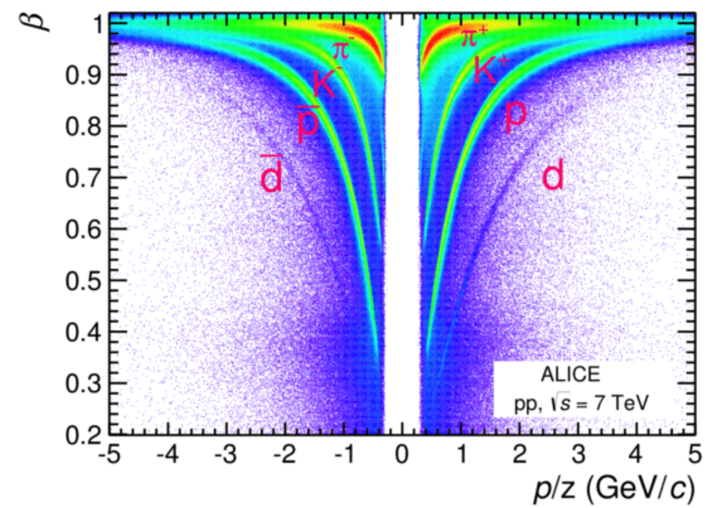




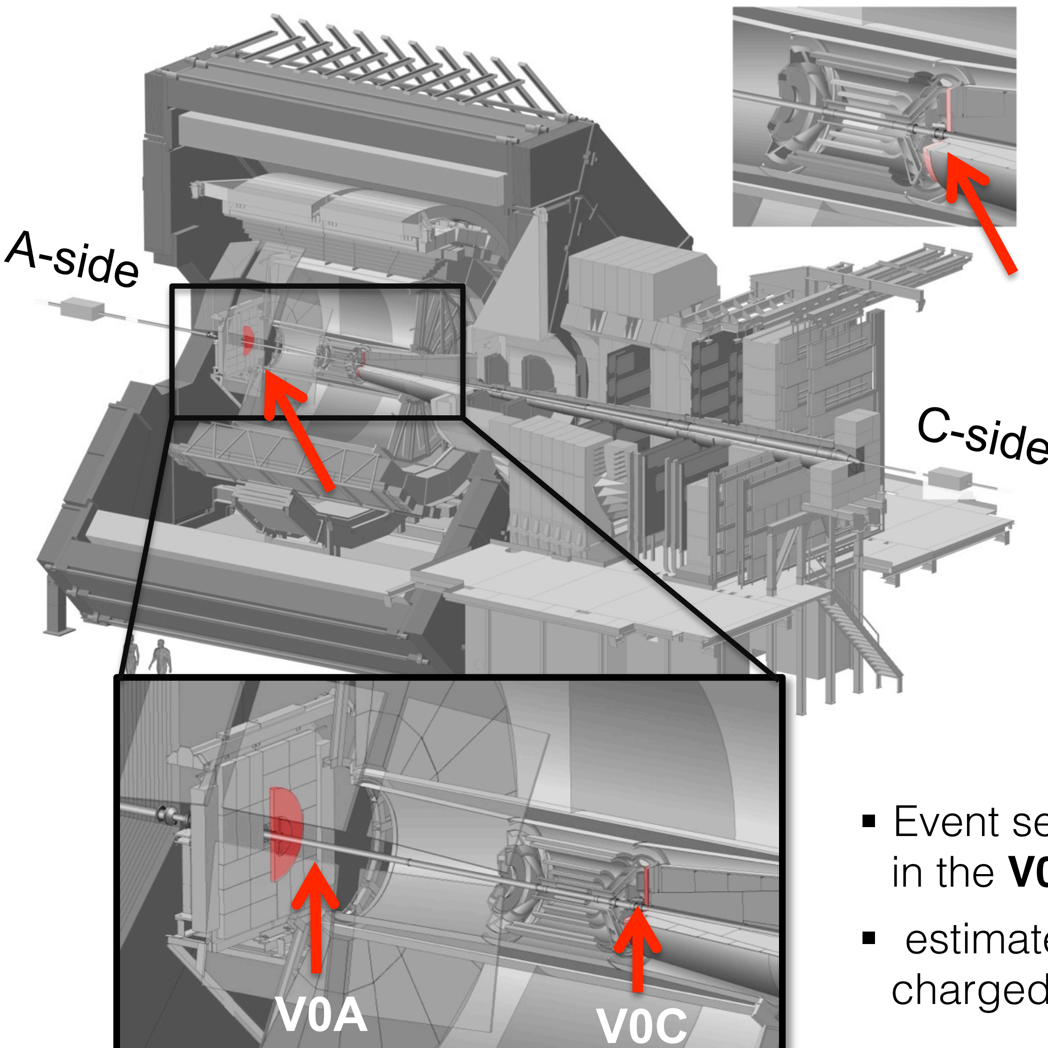
ITS (|η|<0.9)
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)

TPC (|η|<0.9)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)
- Weak decay reconstruction (topological)

TOF (|η|<0.9)
- Multi-gap resistive plate chambers
- PID via velocity determination



ALICE experiment



ITS ($|\eta|<0.9$)

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

TPC ($|\eta|<0.9$)

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

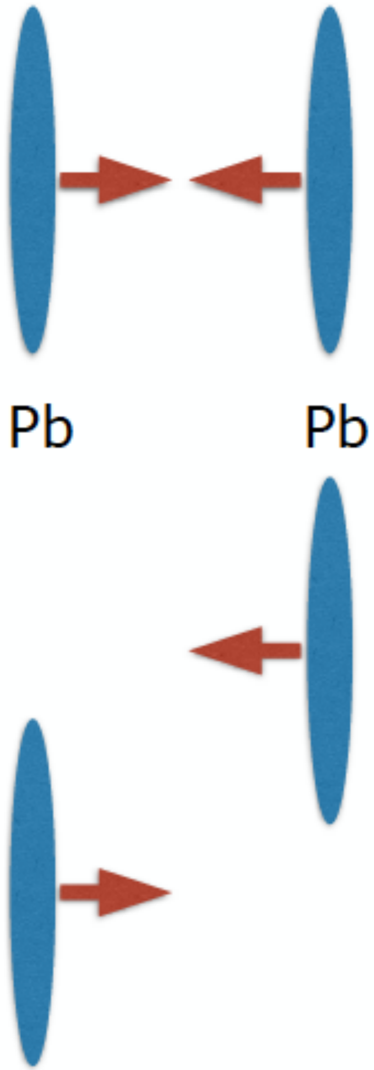
TOF ($|\eta|<0.9$)

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

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 $|\eta|<0.5$

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)

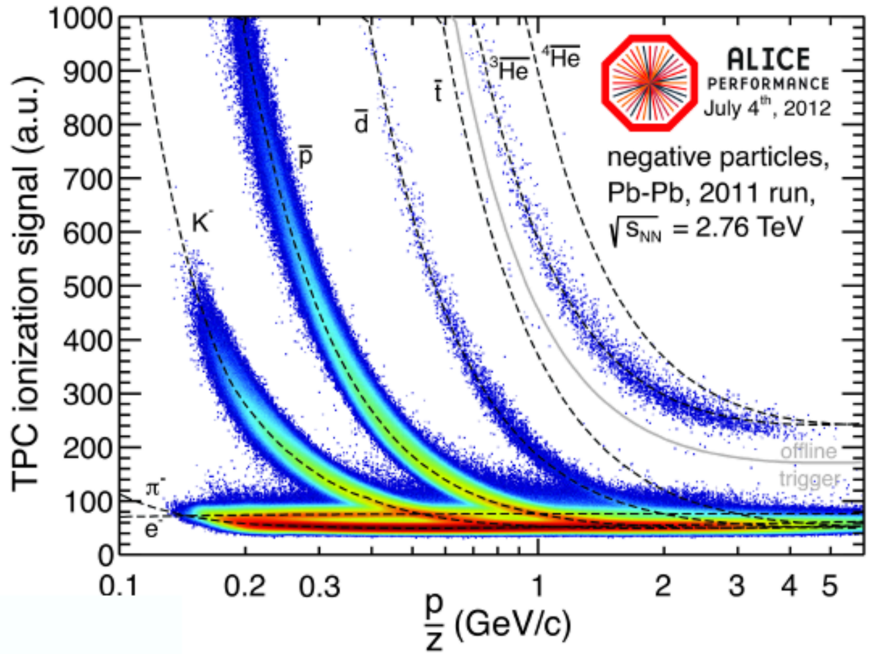
Peripheral Pb-Pb collision:

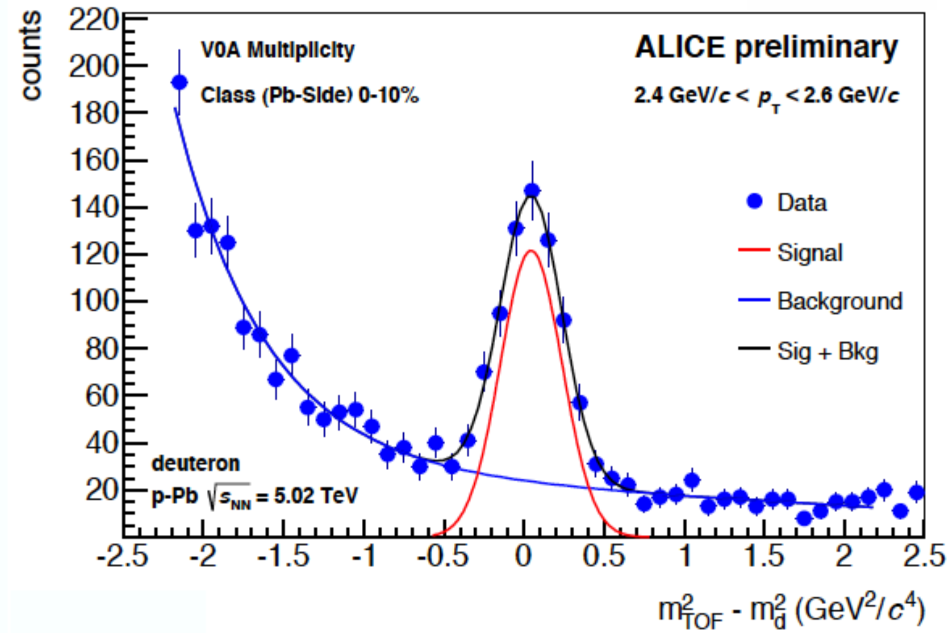
Low multiplicity = small $\langle dN/d\eta \rangle$

Low number of tracks

(less than 100 tracks in the detector)

Particle Identification





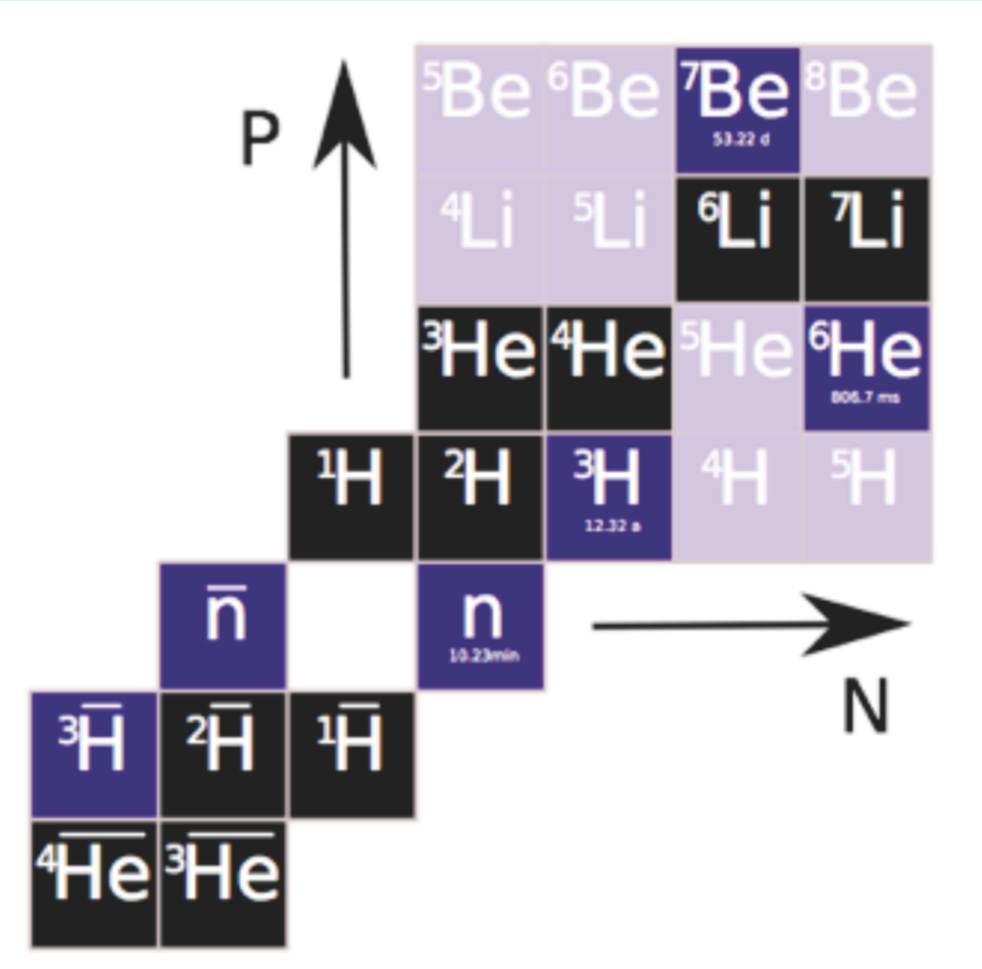
Low momenta:

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

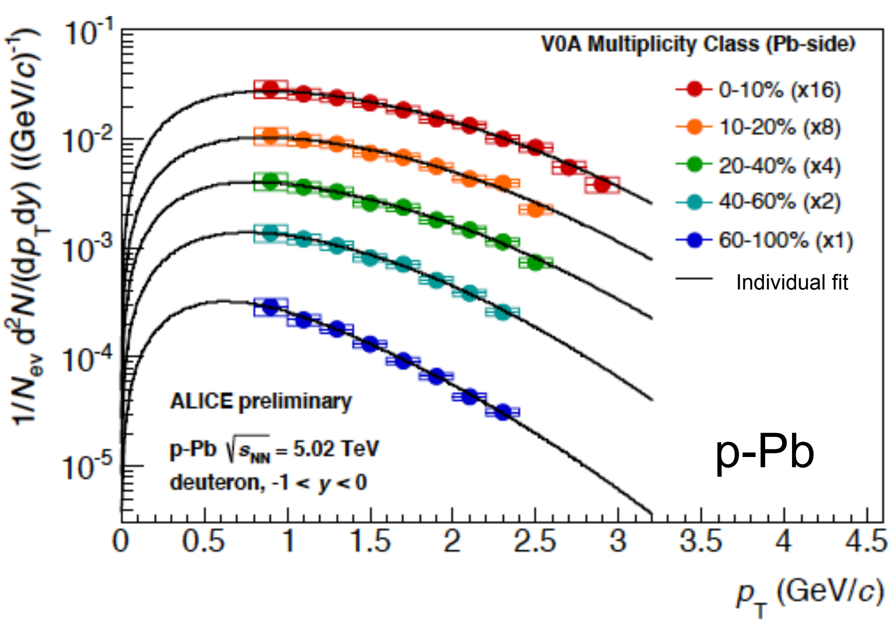
(Anti-)Nuclei

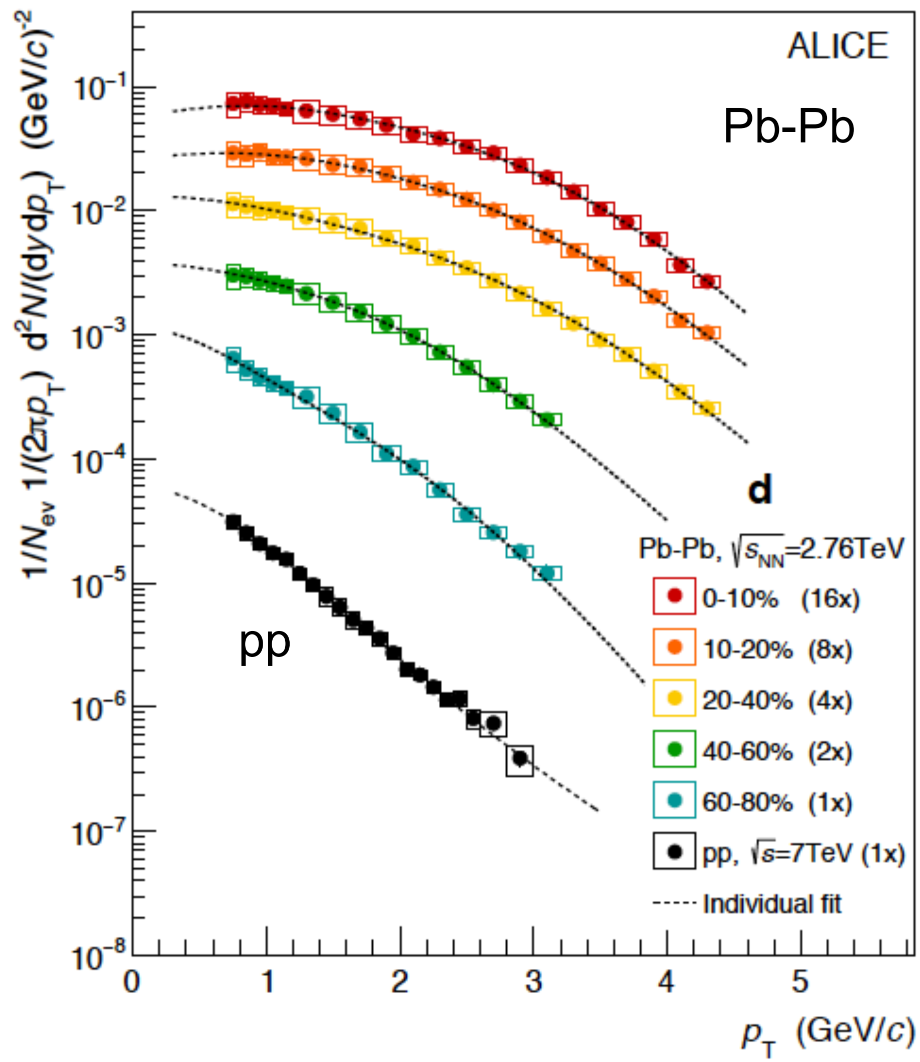

P
N
⁵Be ⁶Be ⁷Be ⁸Be
53.22 d
⁴Li ⁵Li ⁶Li ⁷Li
³He ⁴He ⁵He ⁶He
806.7 ms
¹H ²H ³H ⁴H ⁵H
12.32 a
n̄
n
10.23min
³H̄ ²H̄ ¹H̄
⁴He̅ ³He̅

Deuterons

ALICE Collaboration: PRC 93, 024917 (2016)

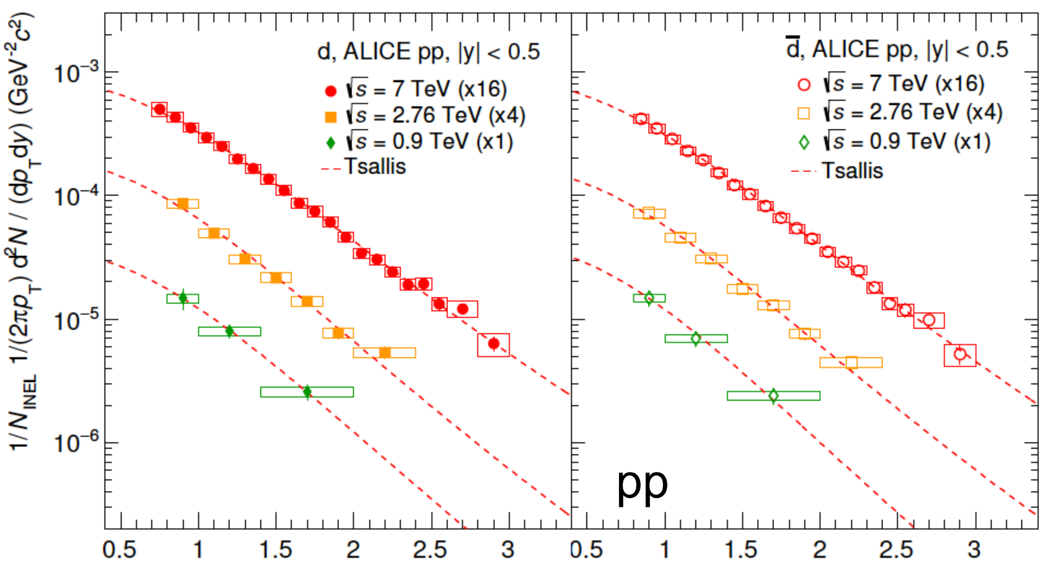
- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp spectrum shows no sign of radial flow



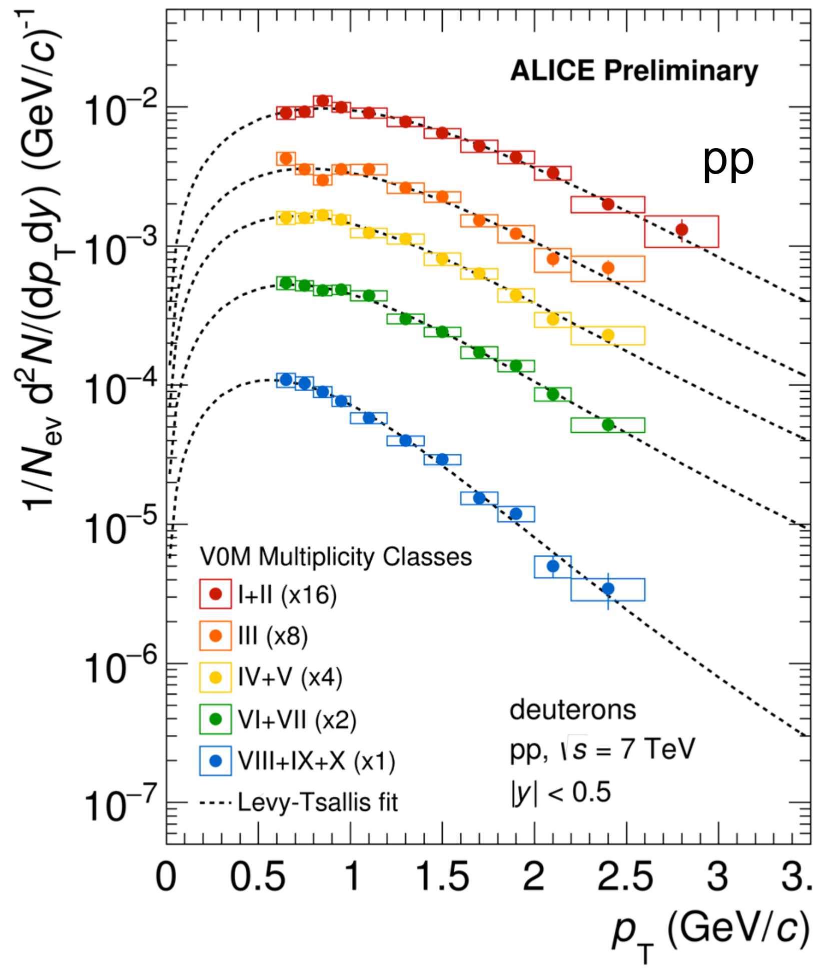


Deuterons

- 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 → multiplicity bins show hardening

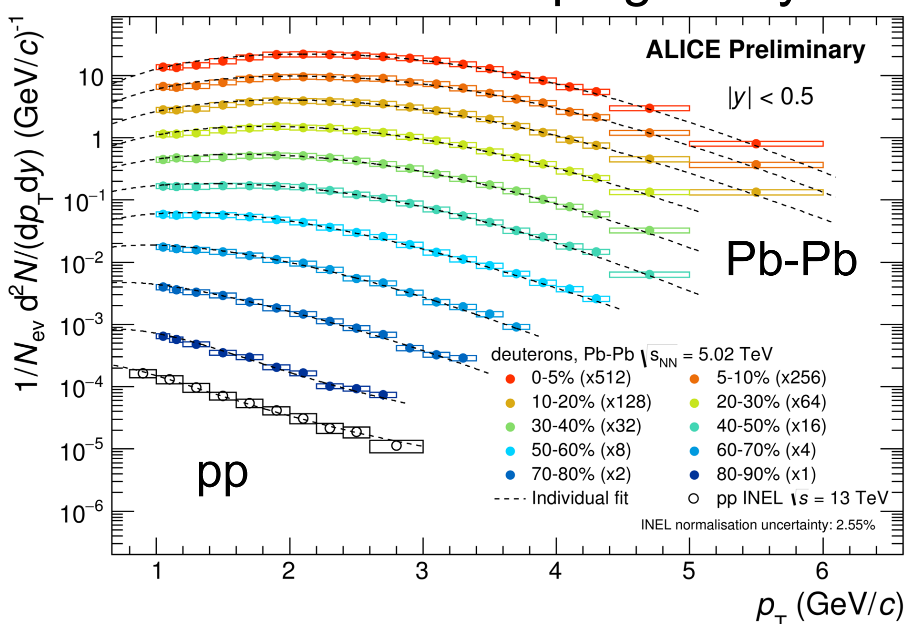


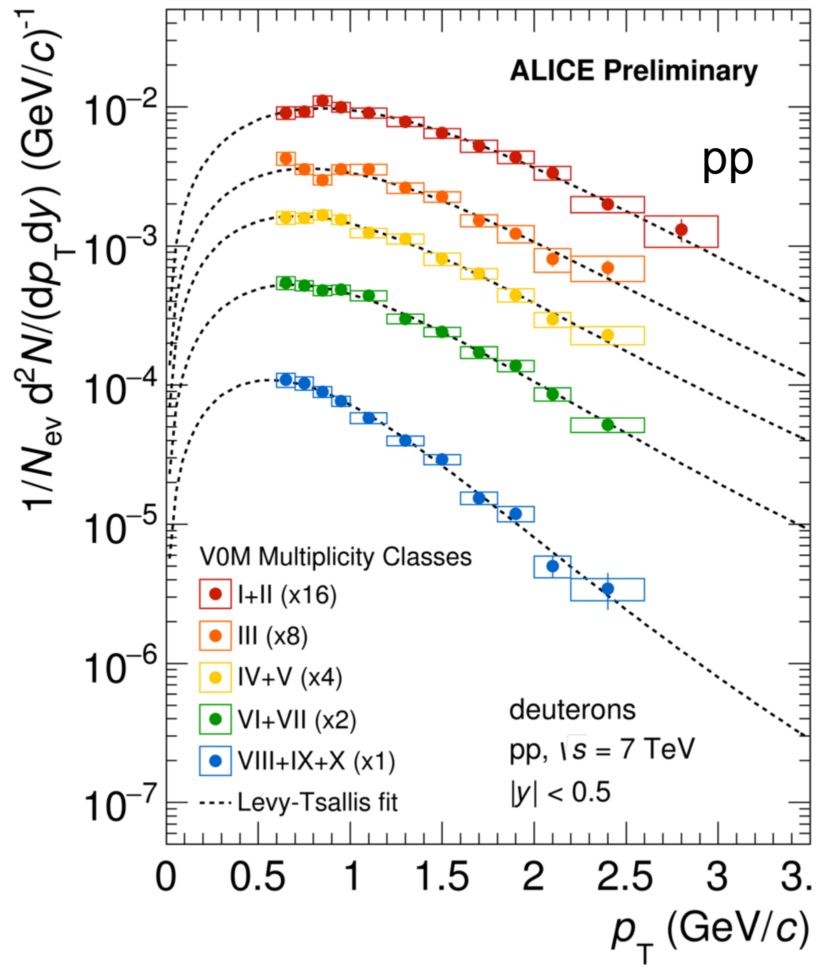
ALICE, arXiv:1709.08522, PRC 97 (2018) 024615



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
- MB pp spectrum shows no sign of radial flow → developing nicely

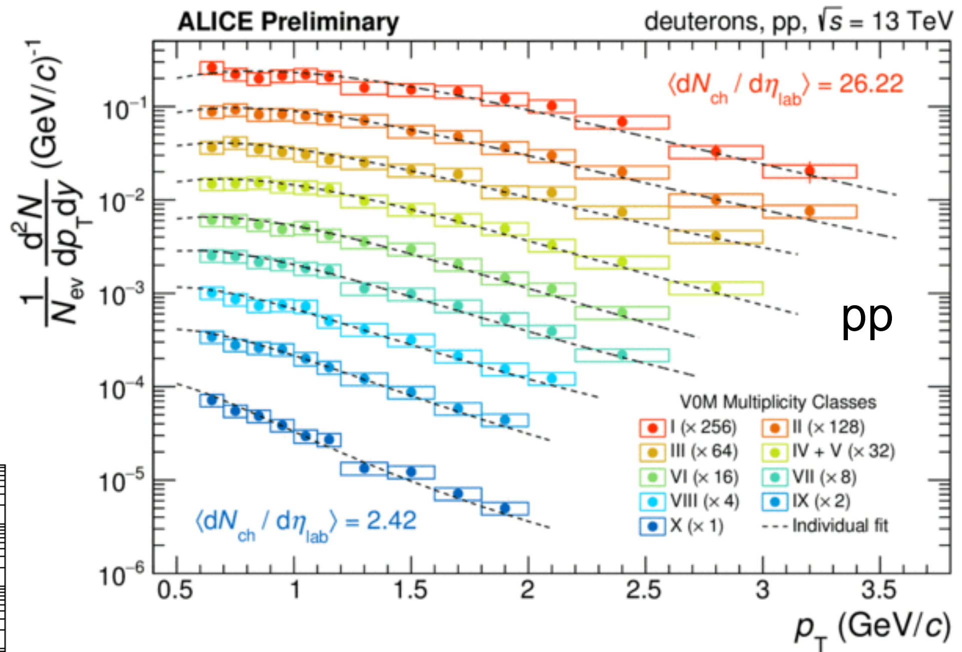


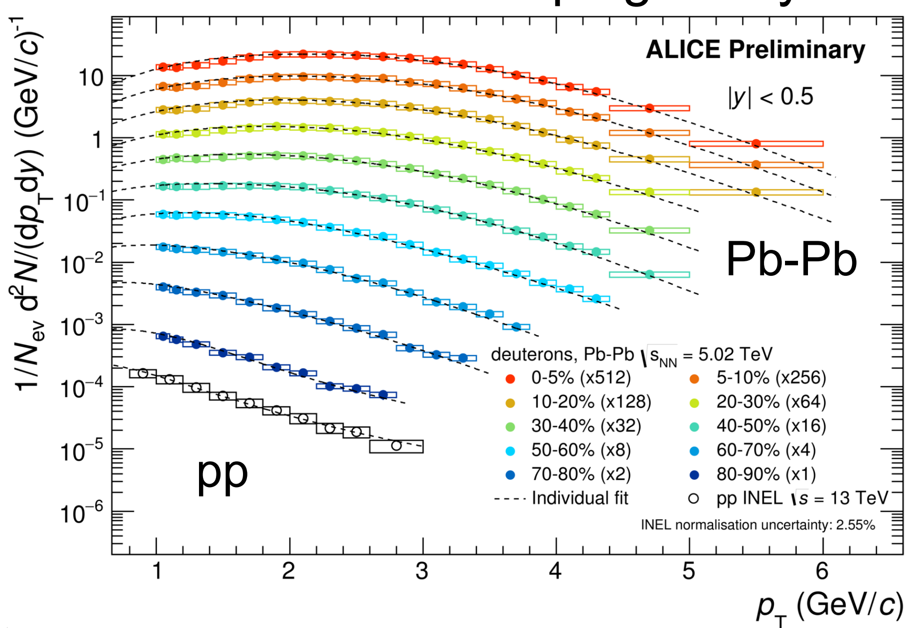


ALICE-PUBLIC-2017-006

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 → developing nicely

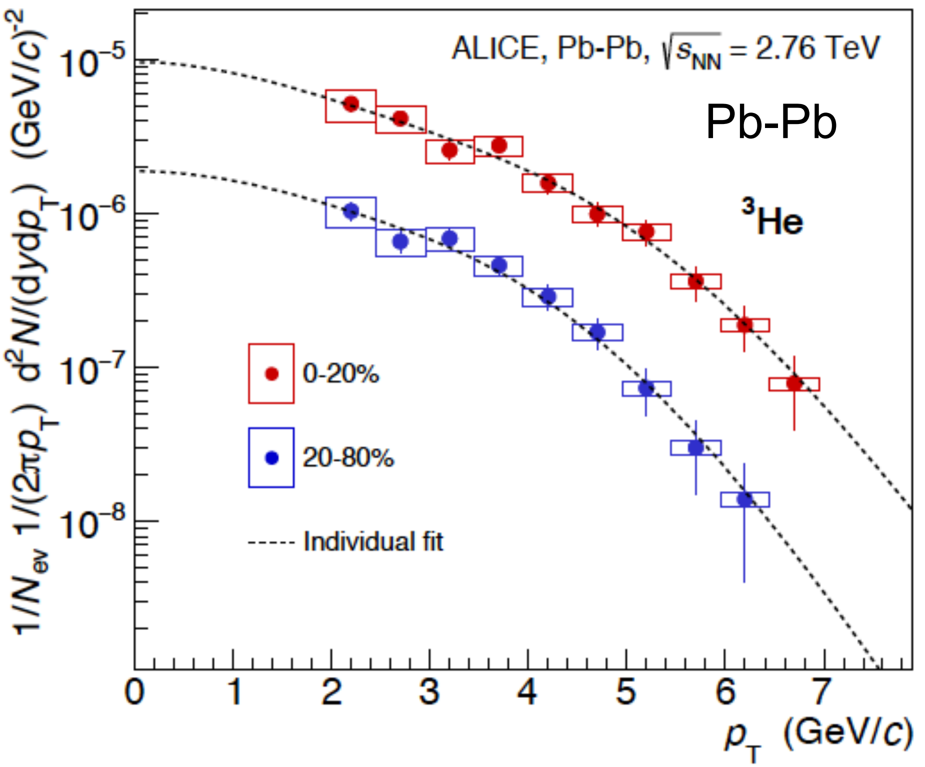


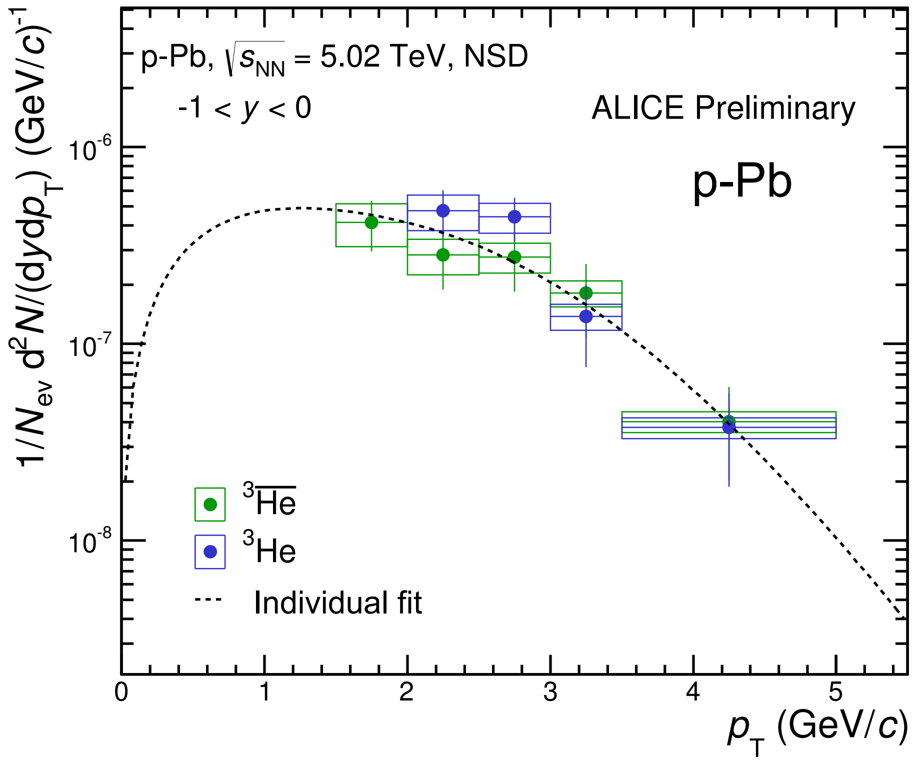


ALICE-PUBLIC-2017-006

^{3}He

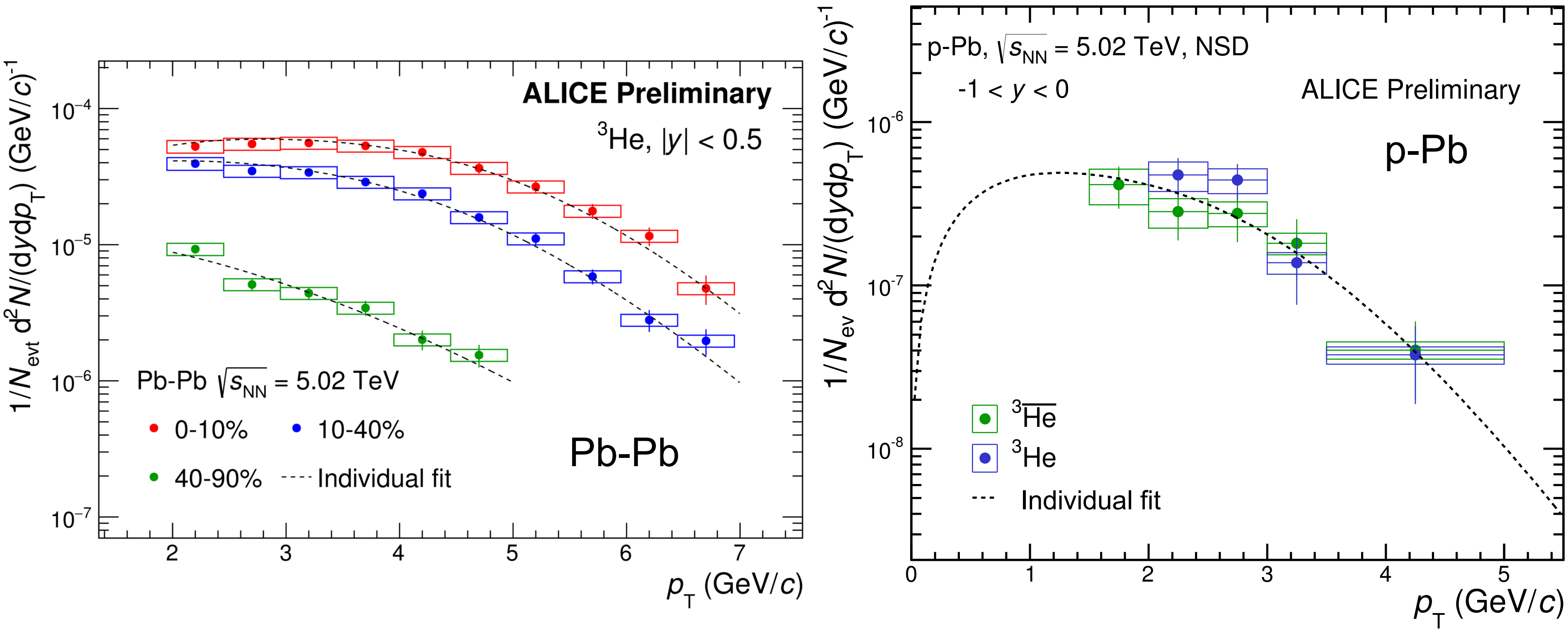
ALICE Collaboration: PRC 93, 024917 (2016)





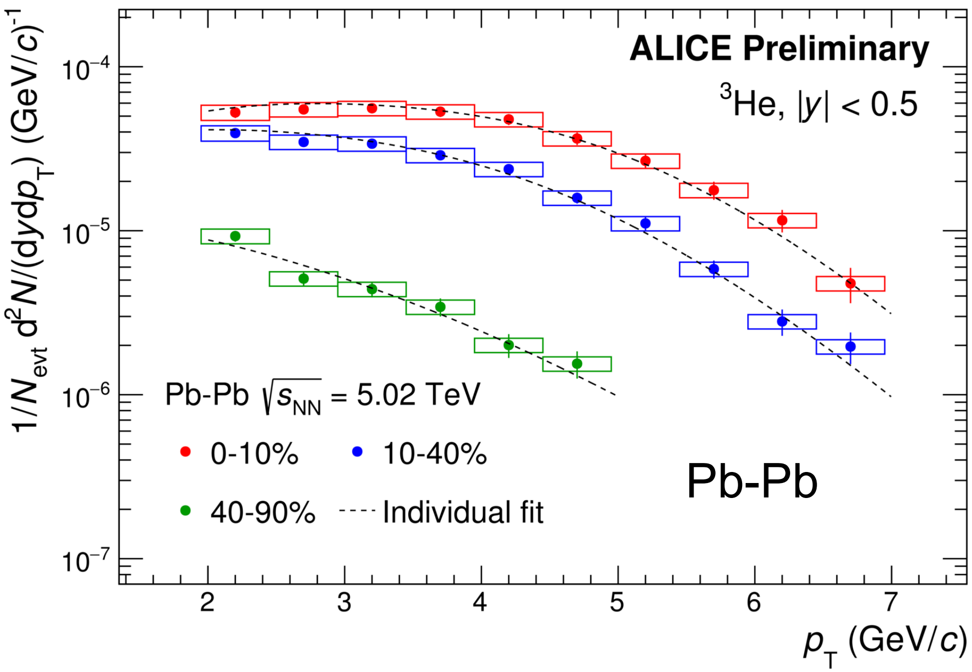
- Dashed curves represent individual Blast-Wave fits
- Spectrum obtained in 2 centrality classes in Pb-Pb and for NSD collisions in p-Pb

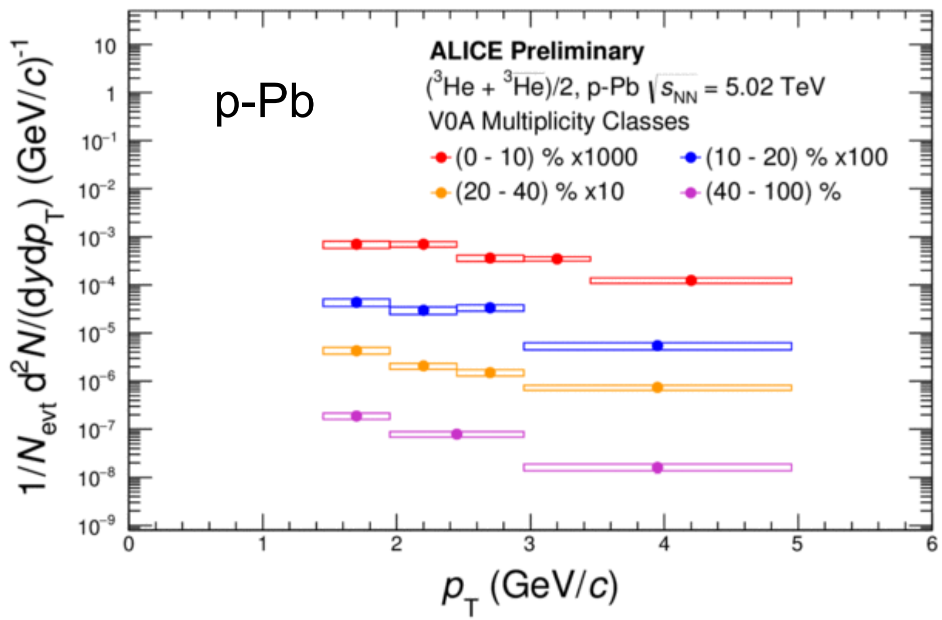
^{3}He



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

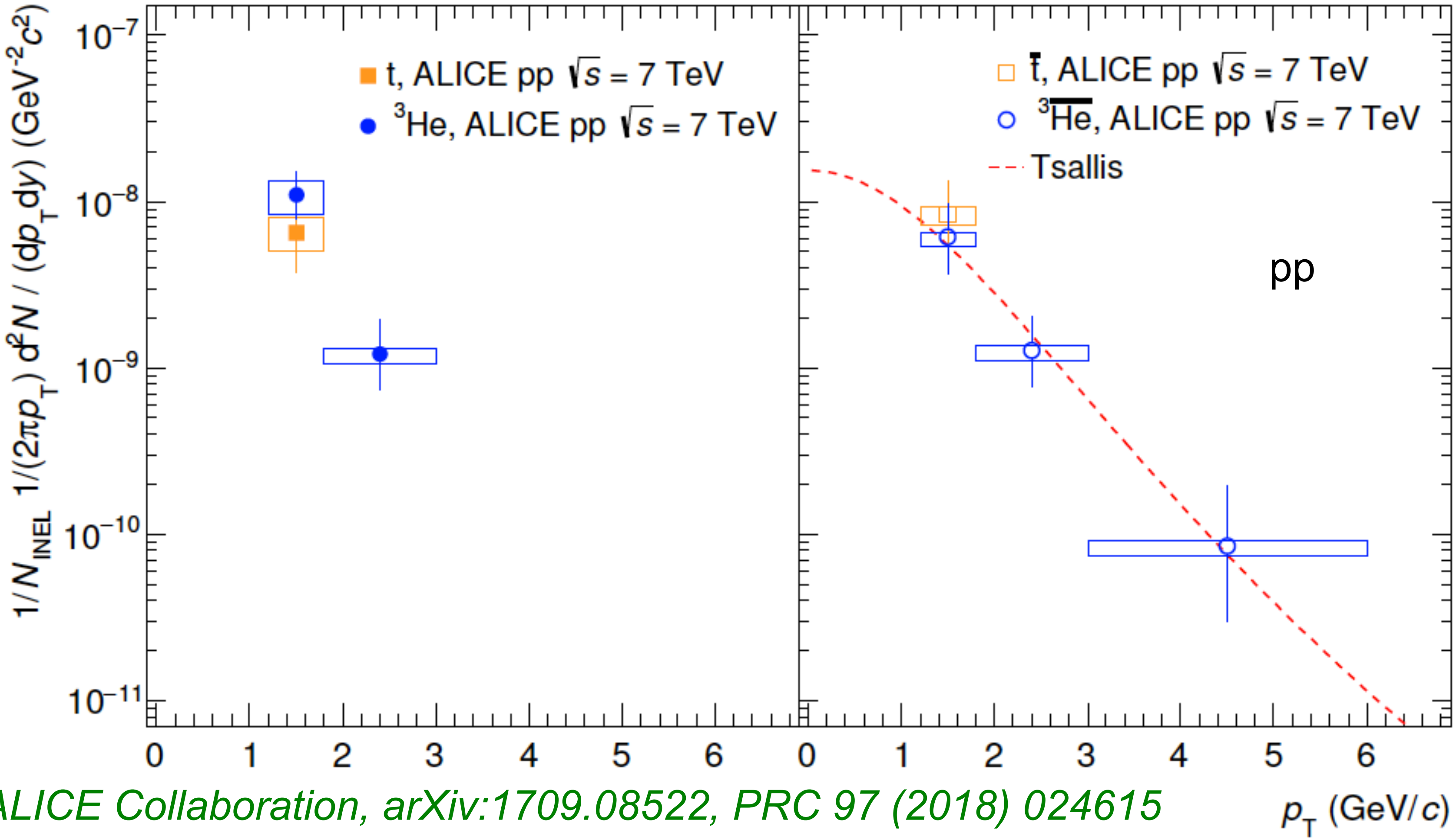
^{3}He





- Dashed curves represent individual Blast-Wave fits
- Spectrum obtained in 3 centrality classes in Pb-Pb and in 4 multiplicity classes in p-Pb

^{3}He and t

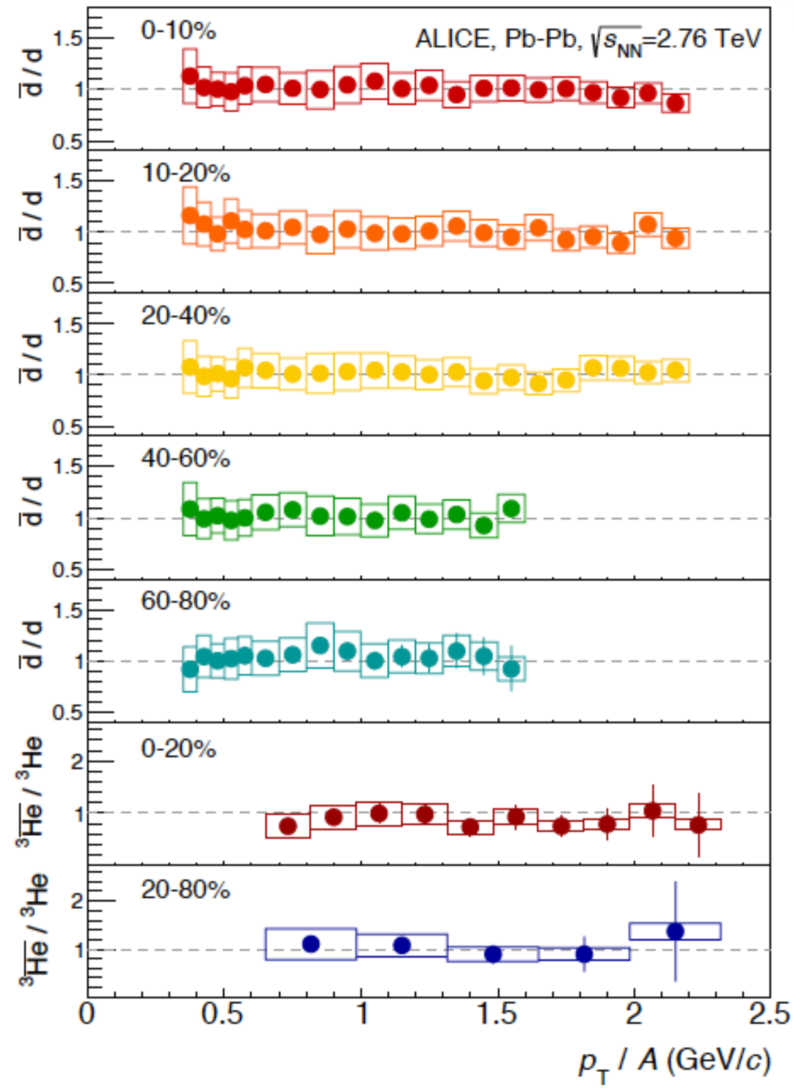


ALICE Collaboration, arXiv:1709.08522, PRC 97 (2018) 024615

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

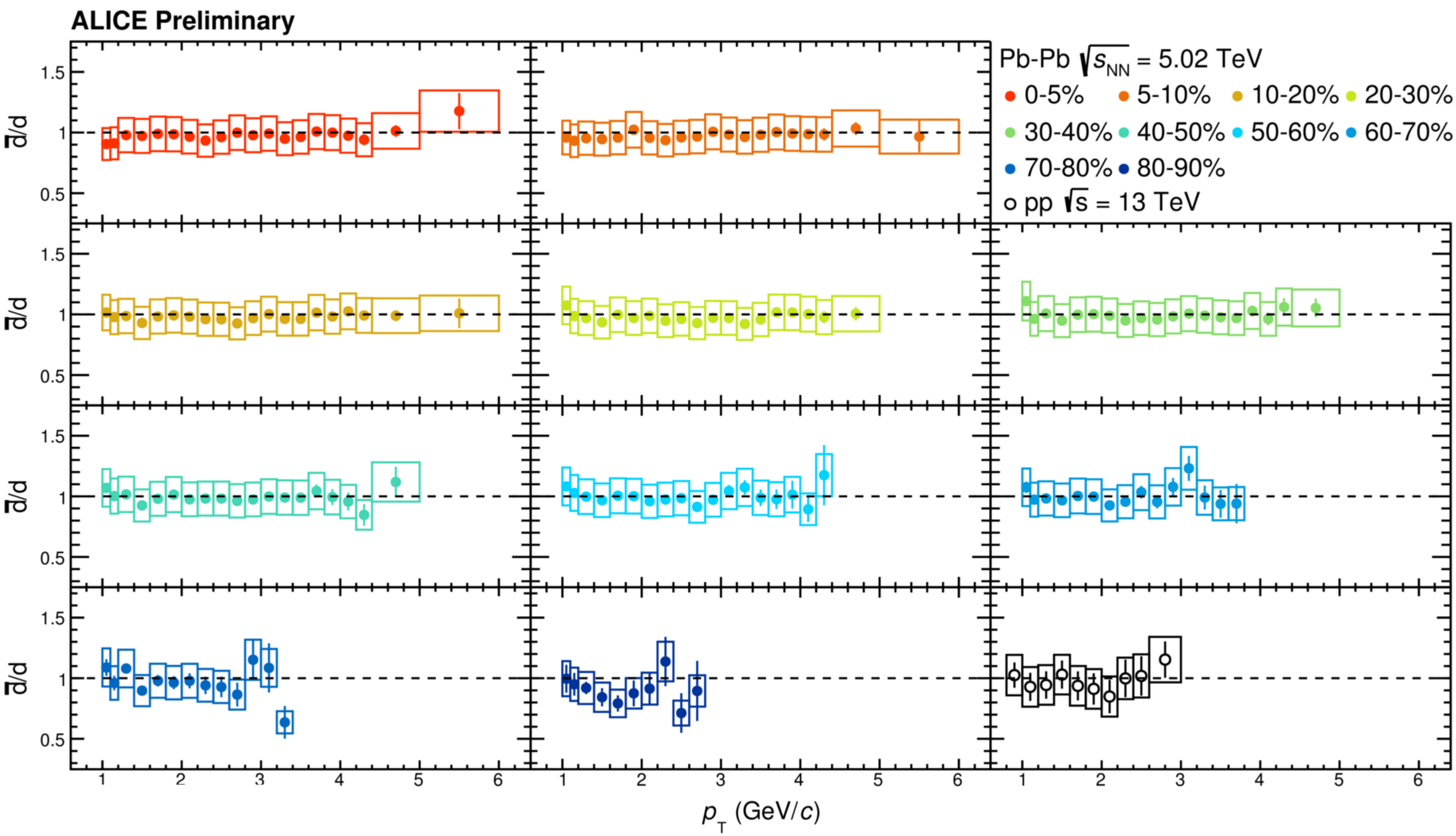
LHC: factory for anti-matter and matter

- 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

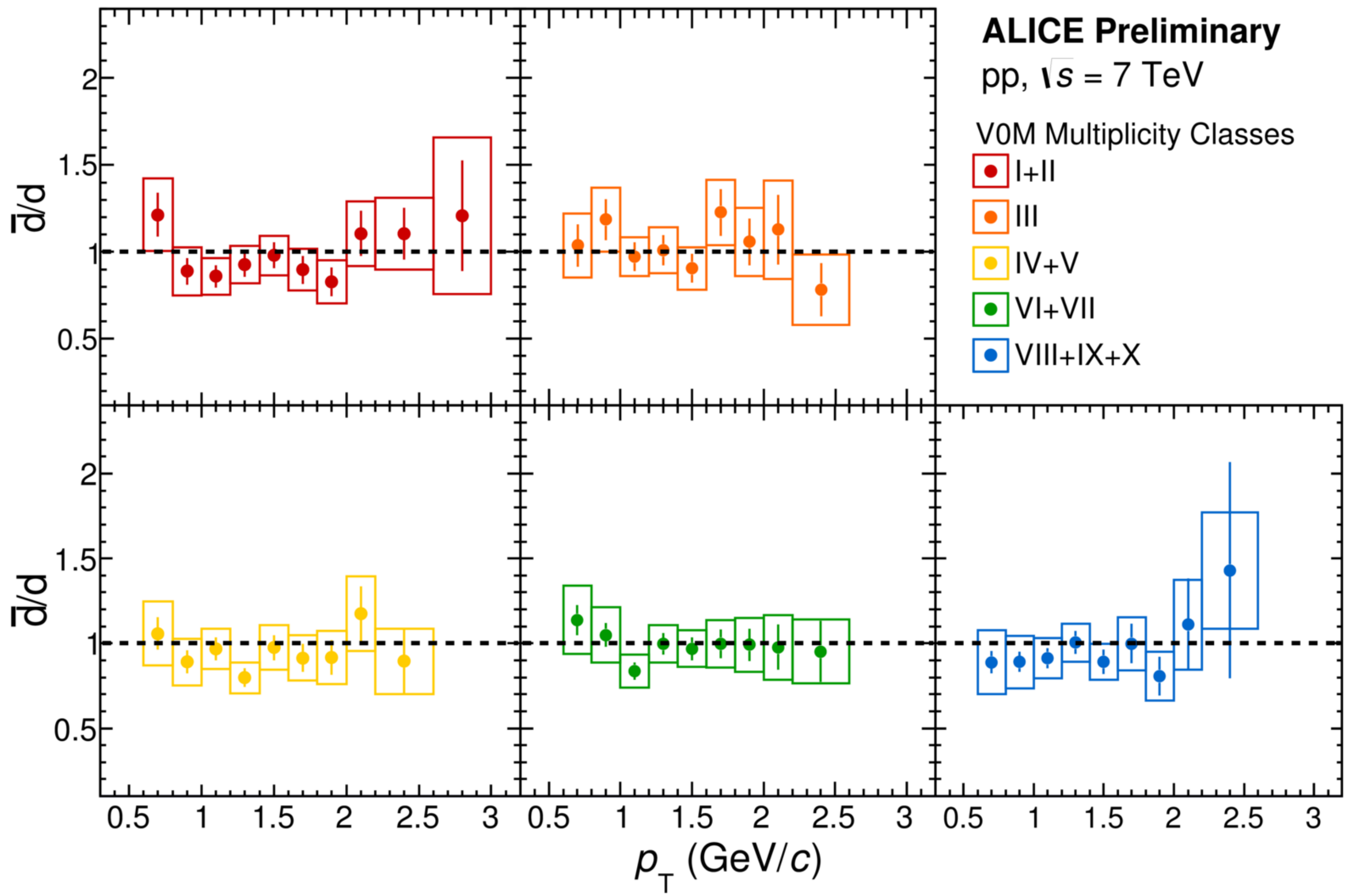


ALICE Collaboration: PRC 93, 024917 (2016)

LHC: factory for anti-matter and matter

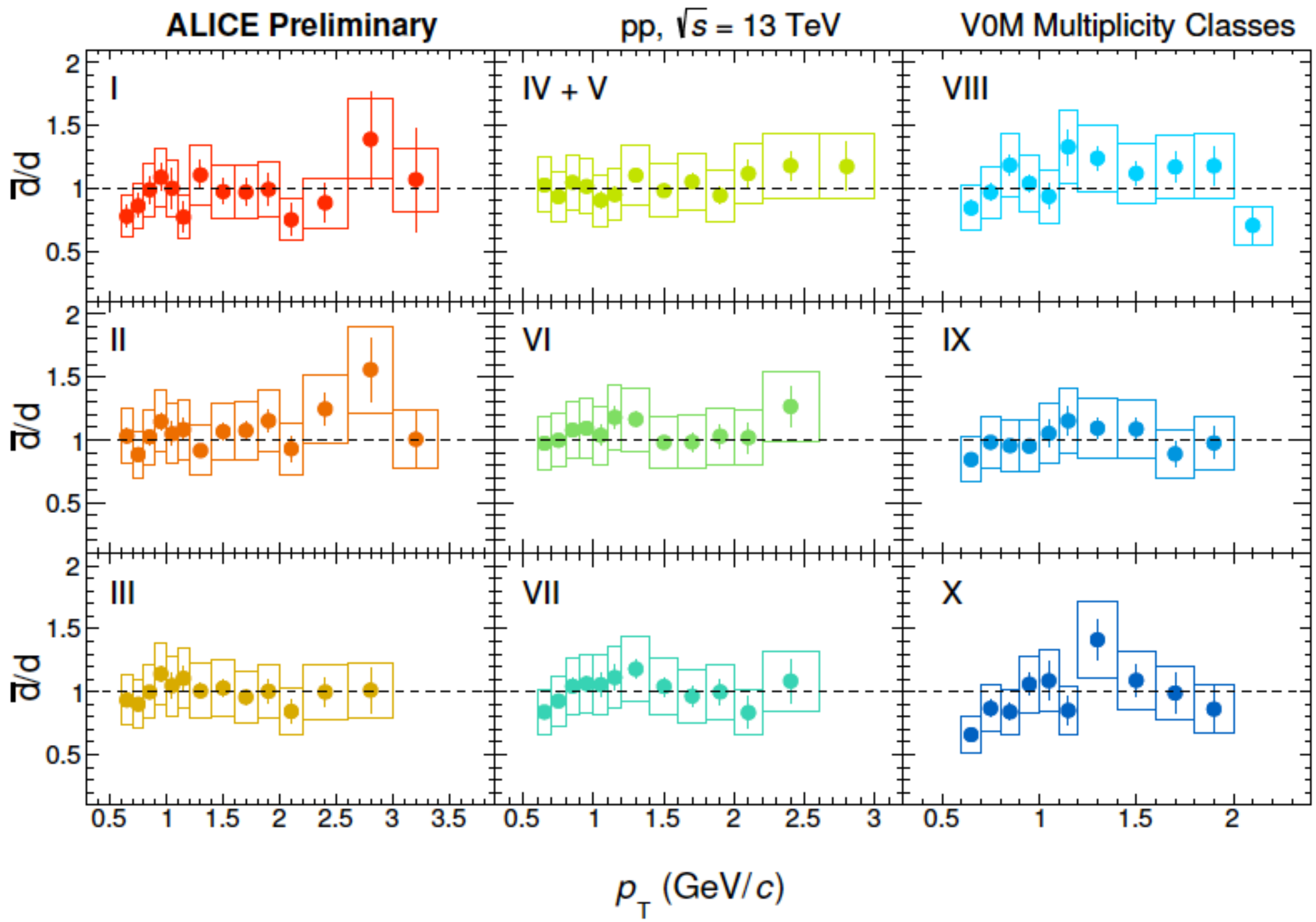


LHC: factory for anti-matter and matter



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

LHC: factory for anti-matter and matter



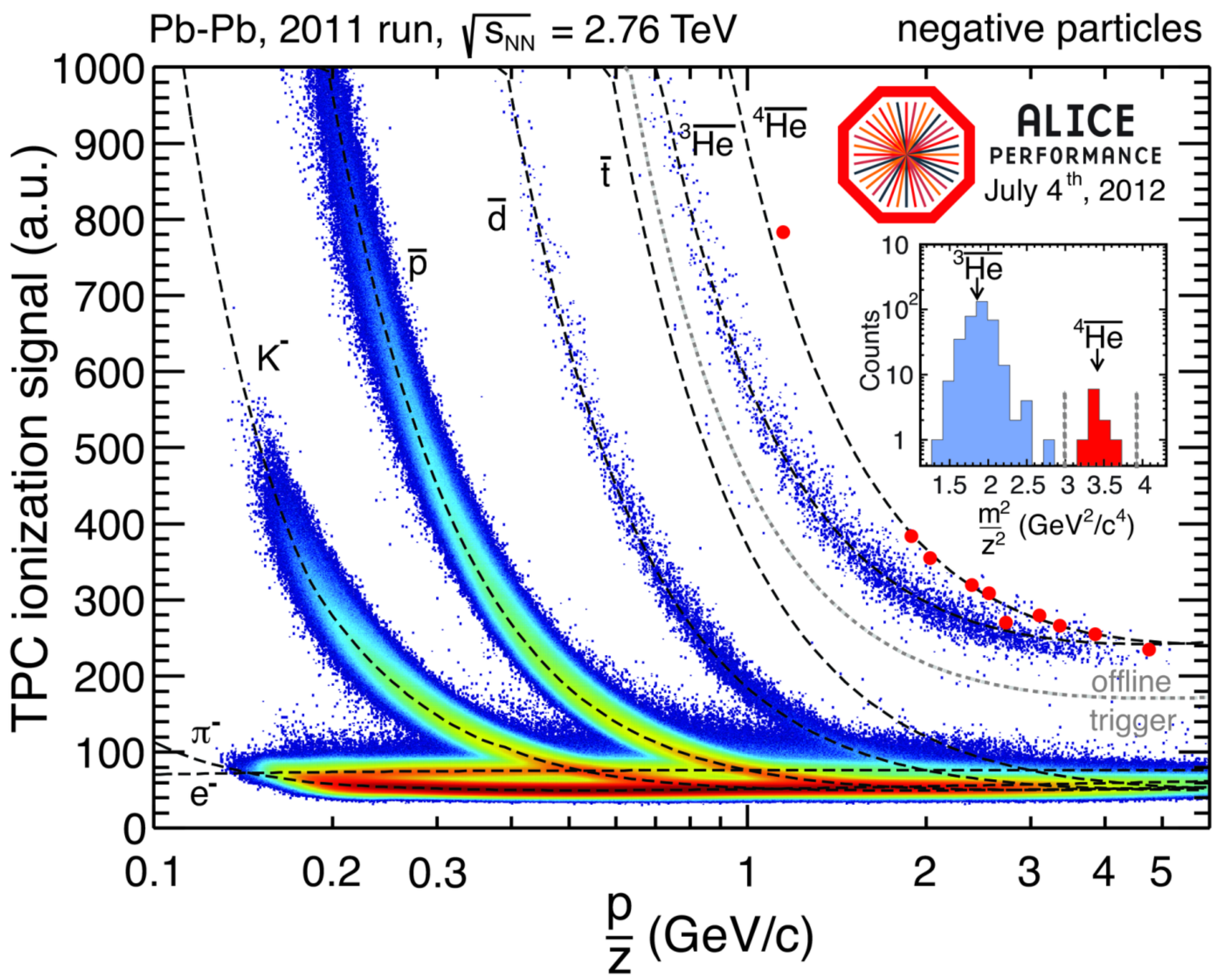
Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally

Anti-Alpha

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

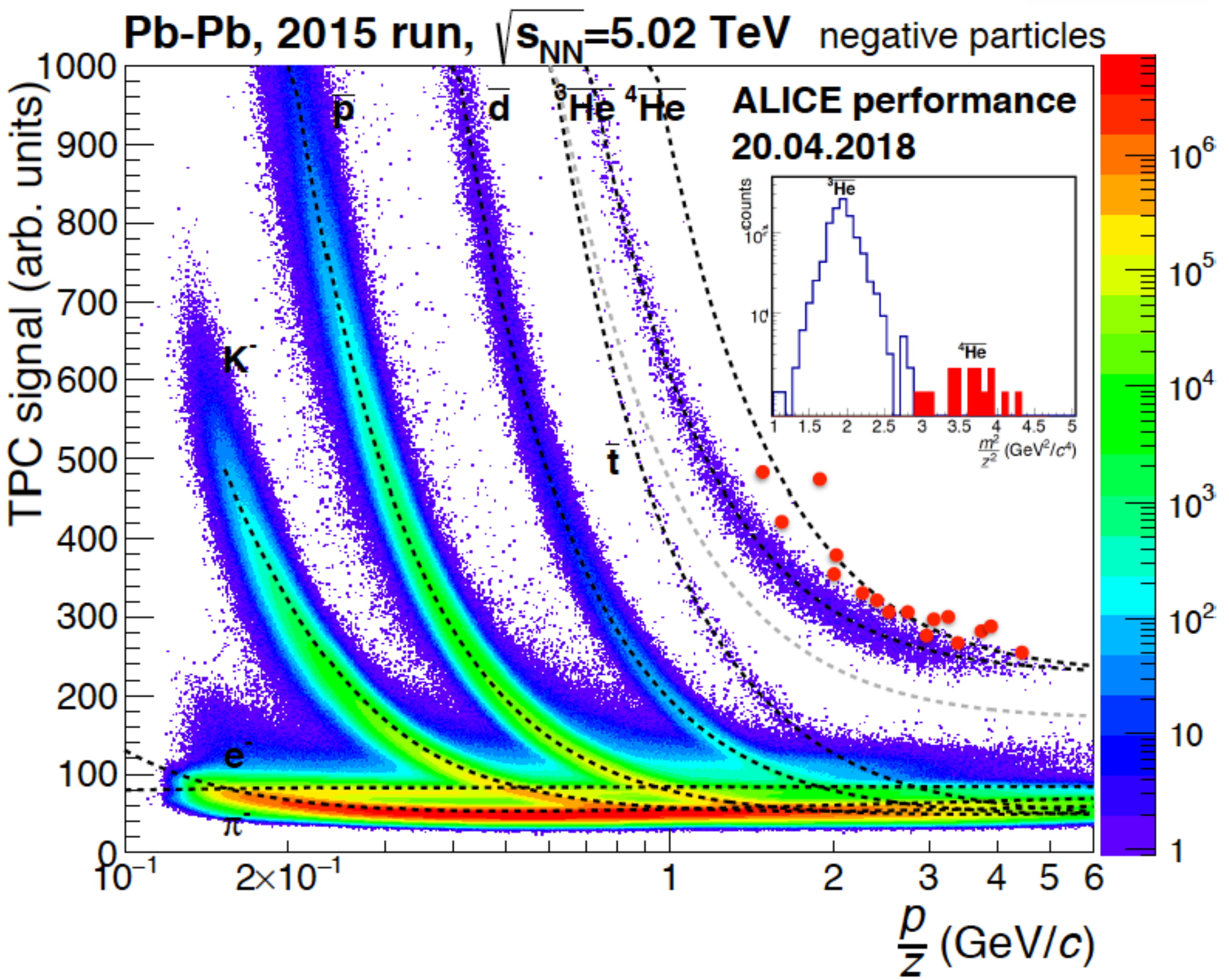
STAR observed the Anti-Alpha in 2010:

Nature 473, 353 (2011)



Anti-Alpha

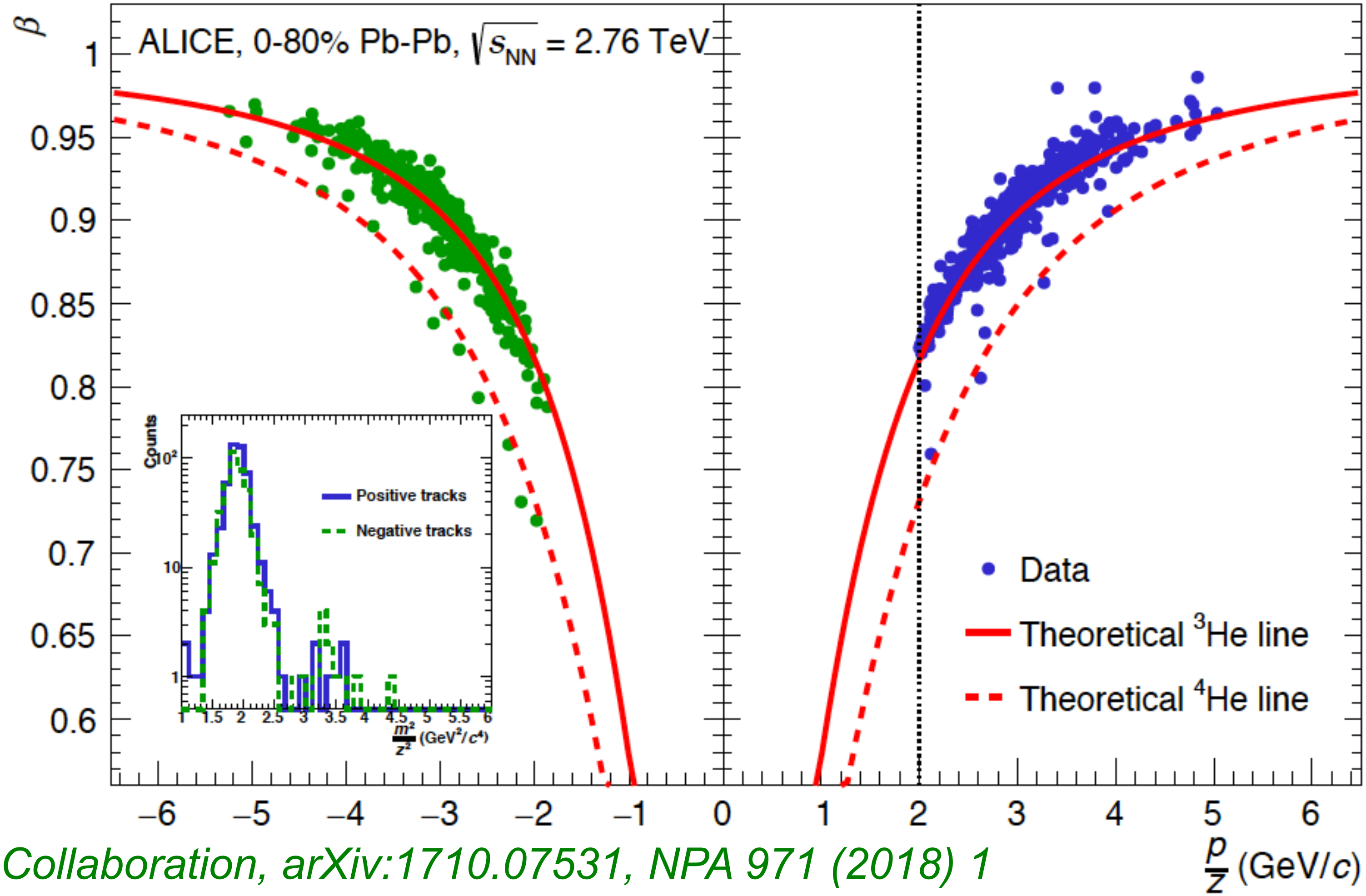
For the full statistics of 2015 ALICE identified 16 Anti-Alphas using TPC and TOF



STAR observed the Anti-Alpha in 2010:

Nature 473, 353 (2011)

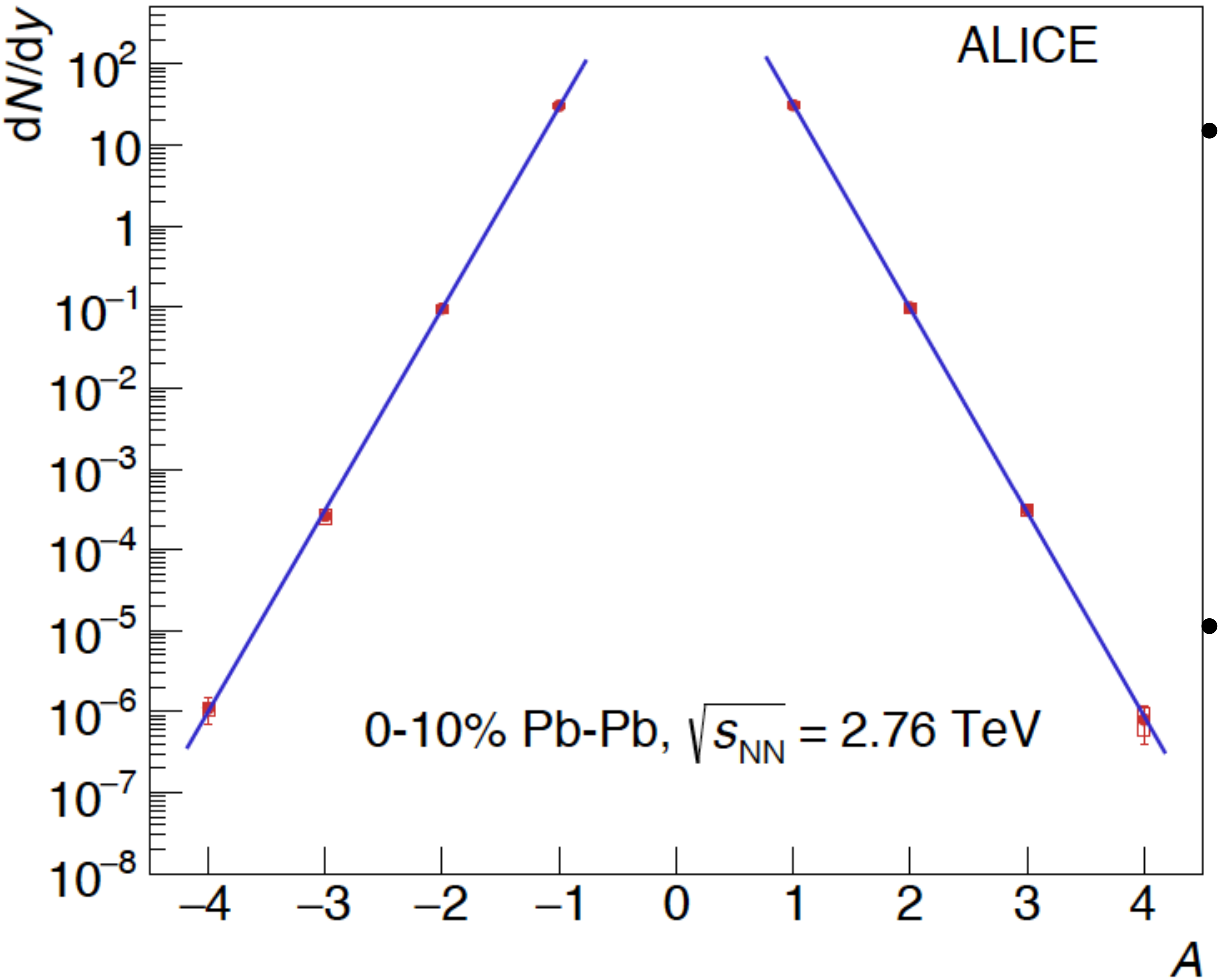
Anti-Alpha



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

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

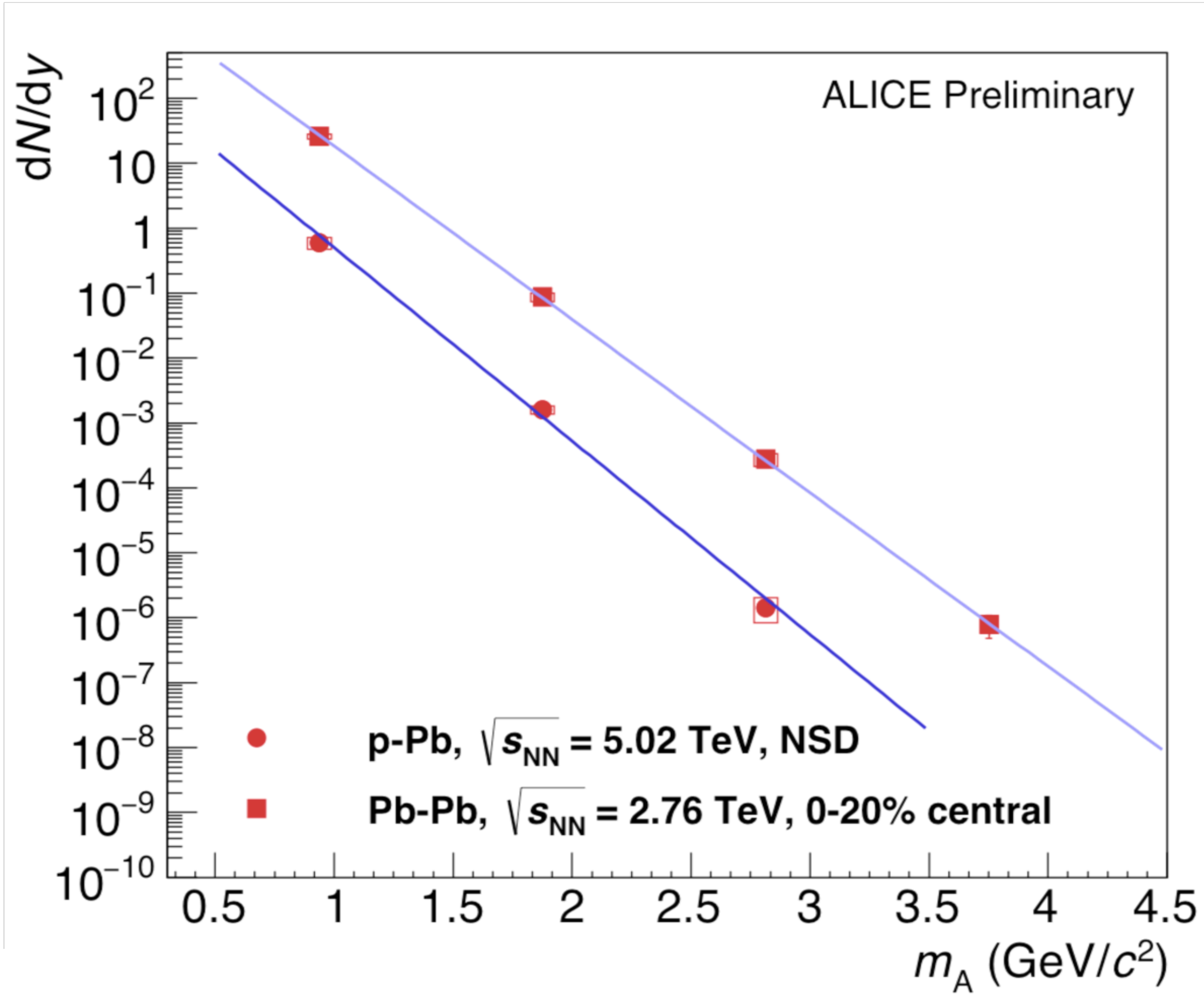
Mass dependence



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

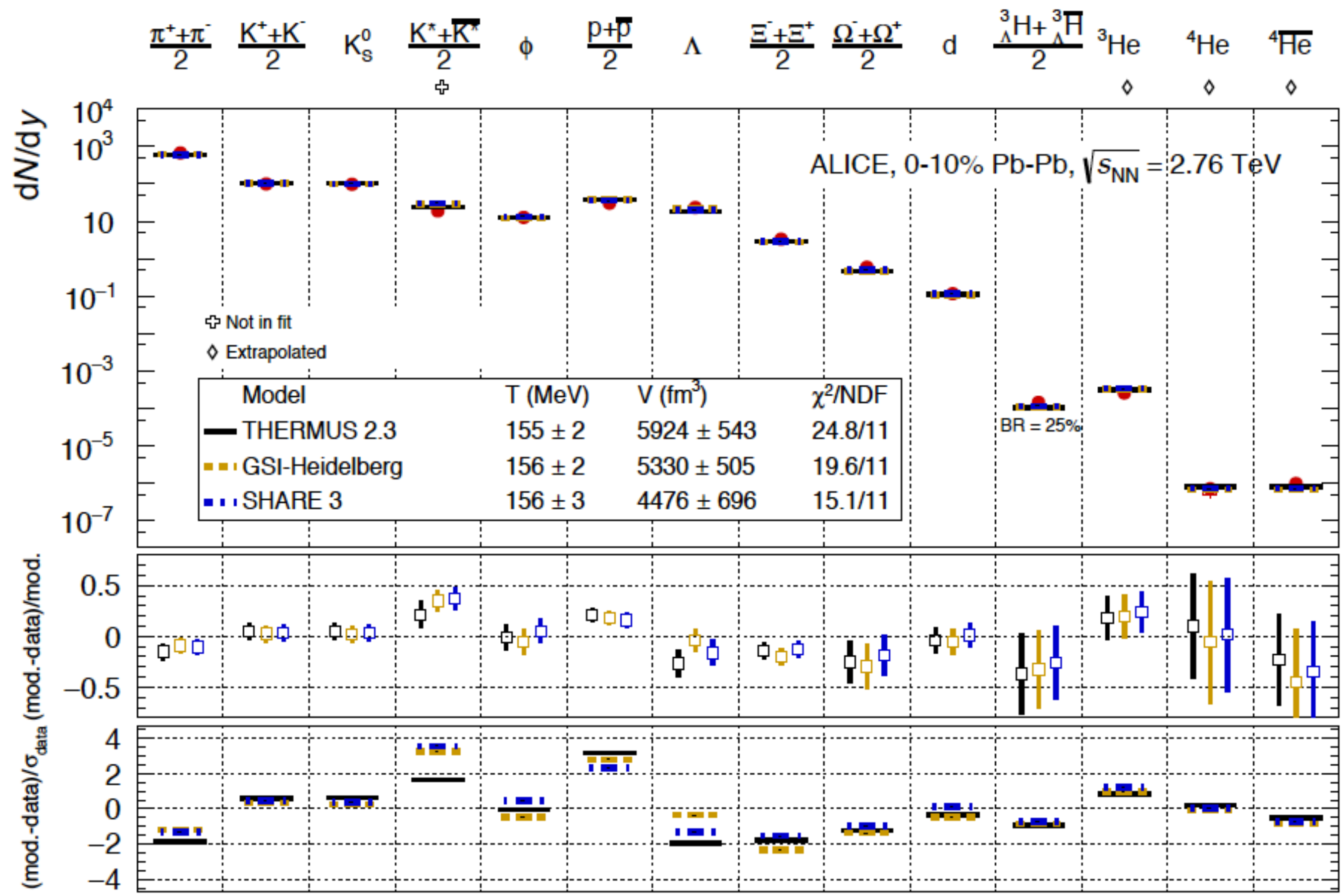
- Nuclei production yields follow an exponential decrease with mass as predicted by the thermal model
- In Pb-Pb the penalty factor for adding one baryon is ~300 (for particles and antiparticles)

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

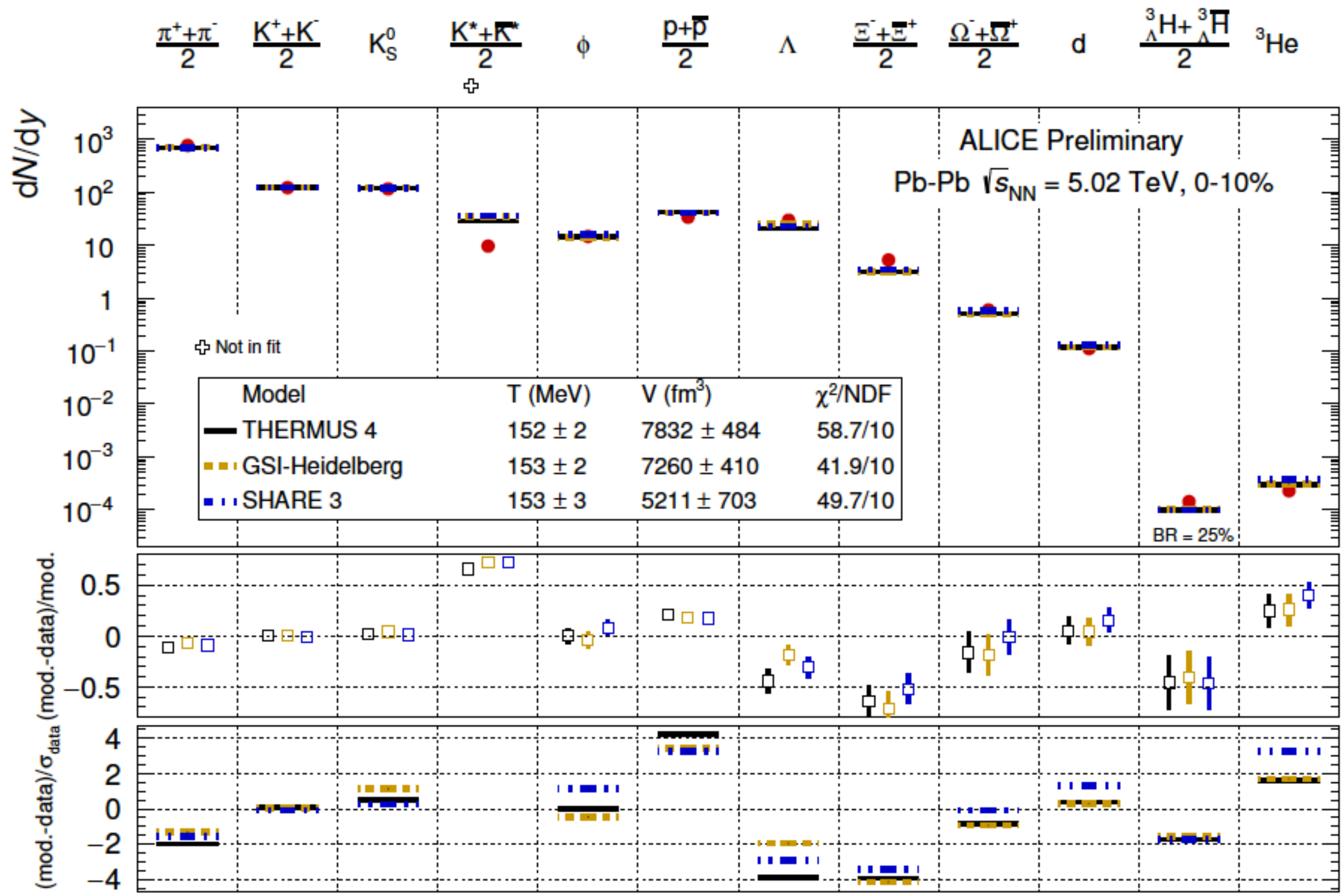


THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

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

- 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}

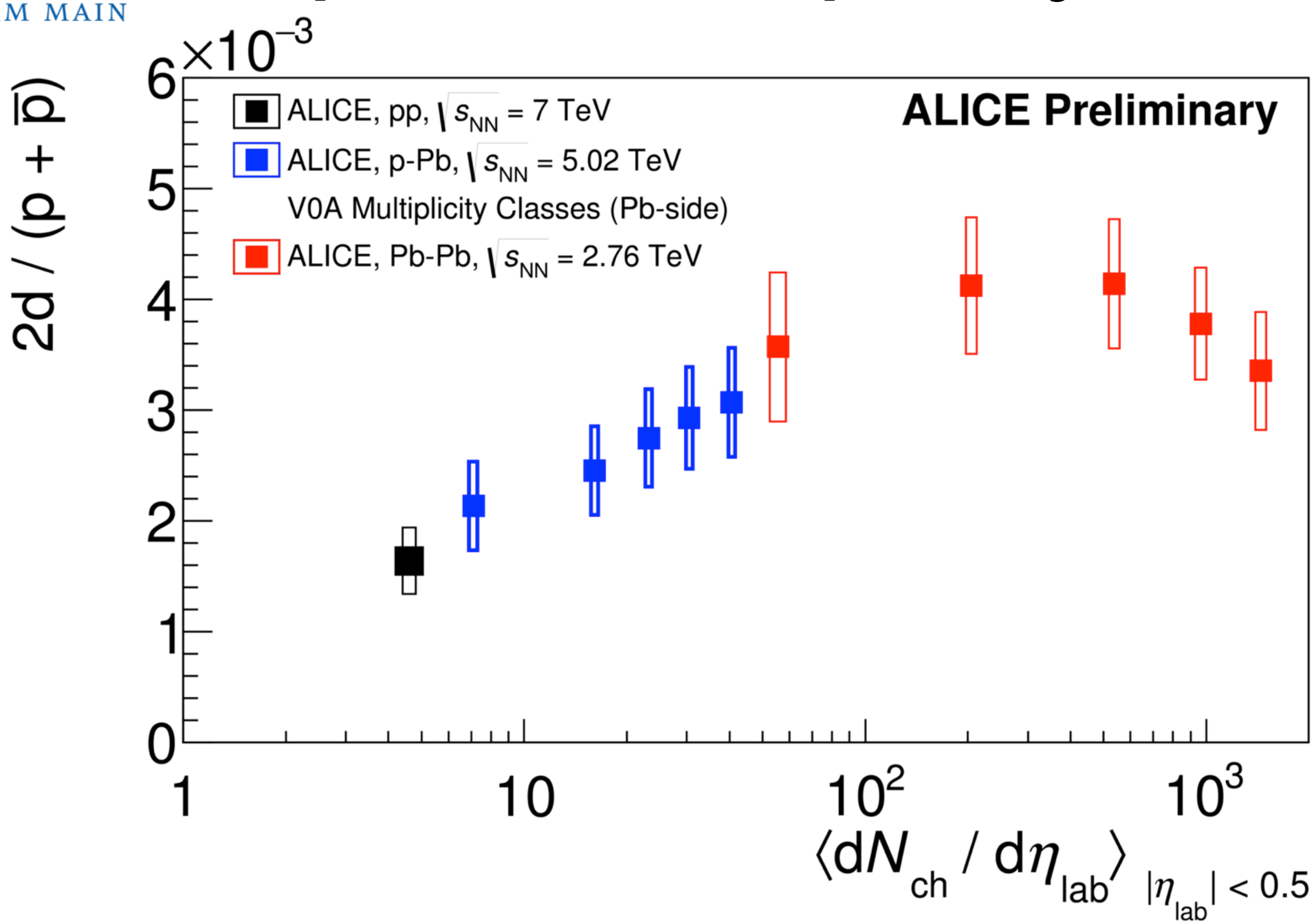
Thermal model fits



THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

- Different models describe particle yields including light (hyper-)nuclei slightly worse at higher collision energy with a T_{ch} of about 153 MeV
- Including nuclei in the fit causes no significant change in T_{ch}

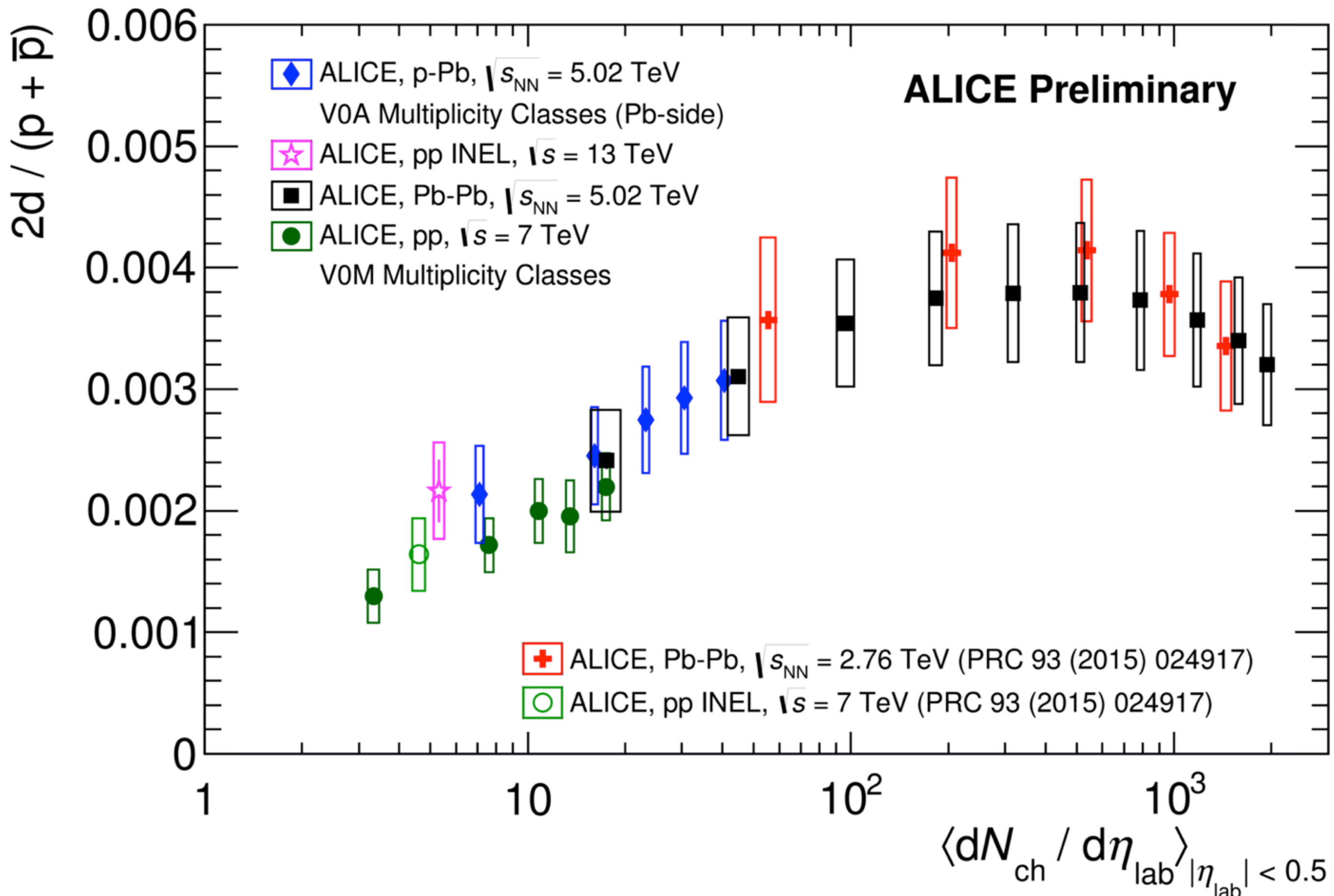
d/p vs. multiplicity



d/p ratio increases when going from pp to p-Pb, until it reaches the grand canonical thermal model value

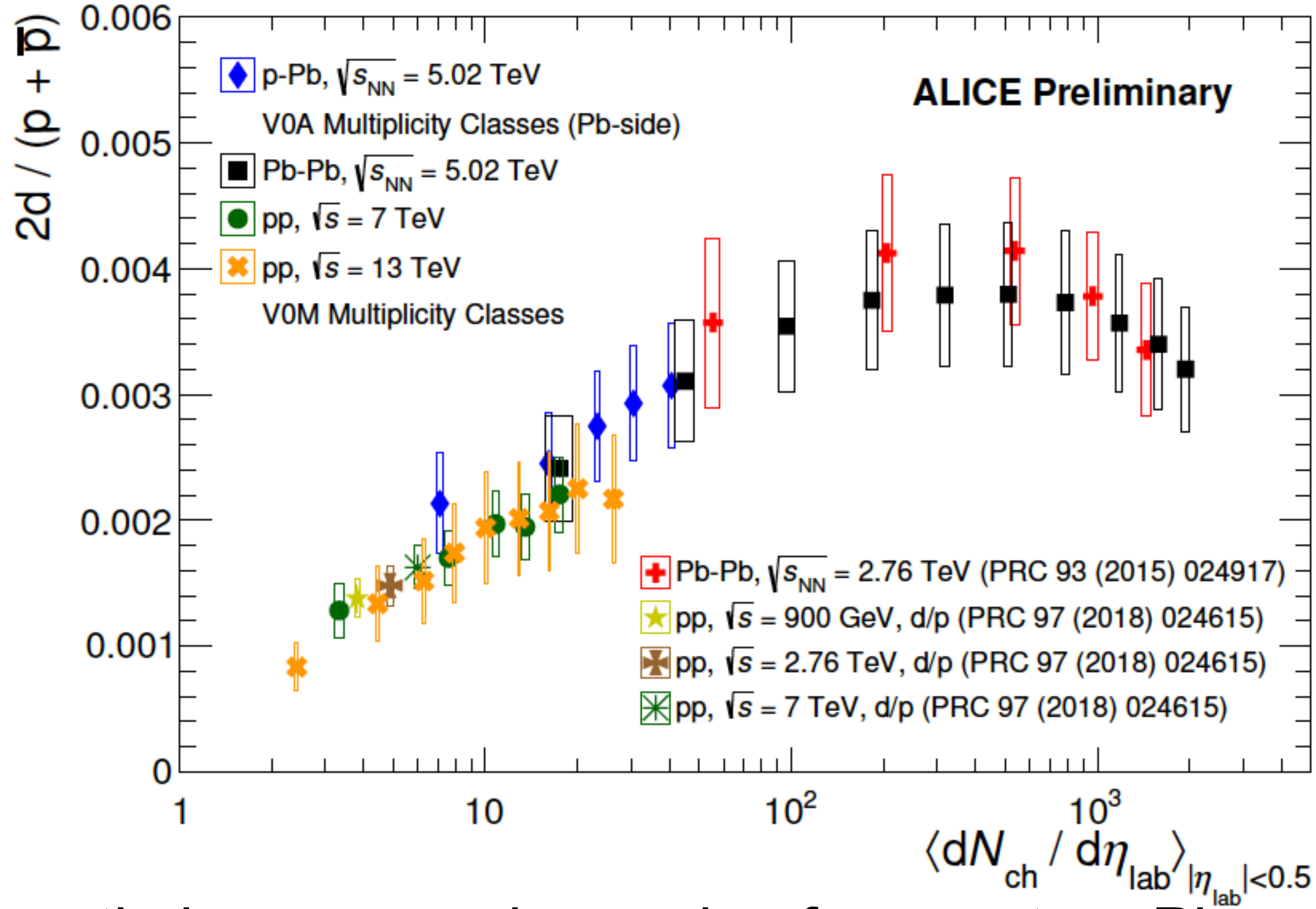
(d/p=3×10^{-3} at T_{ch}= 156 MeV)

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=3×10^{-3} at T_{ch}= 156 MeV)

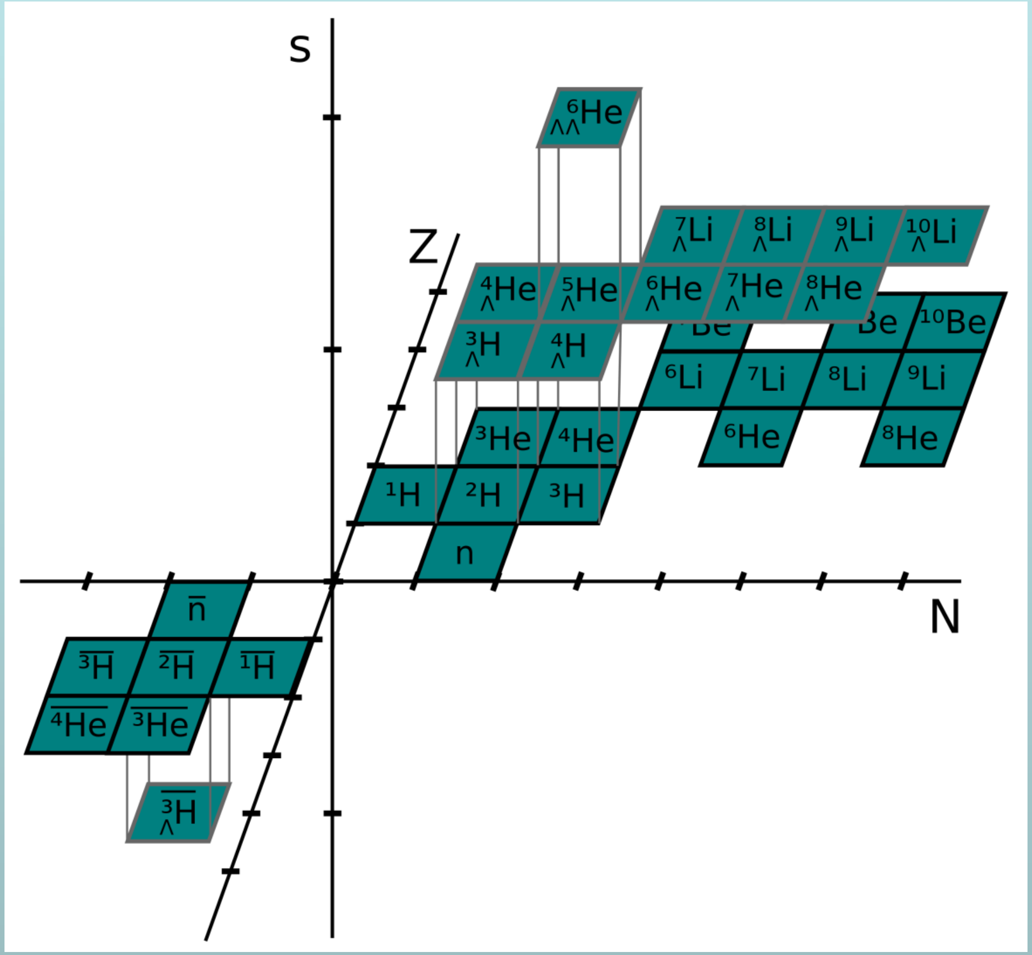
d/p vs. multiplicity



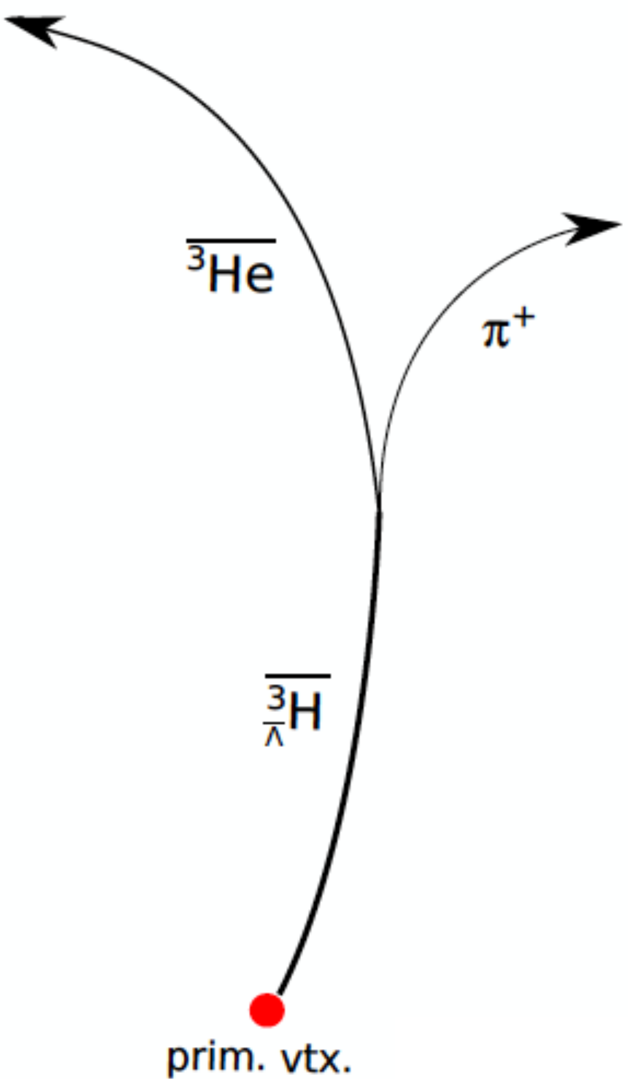
d/p ratio increases when going from pp to p-Pb, until it reaches the grand canonical thermal model value

(d/p=3x10^{-3} at T_{ch}= 156 MeV)

Hypernuclei



Hypertriton identification



Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

→ rms radius: 10.3 fm

Decay modes:

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

$$^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{H} + \pi^0$$

$$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$$

$$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^0$$

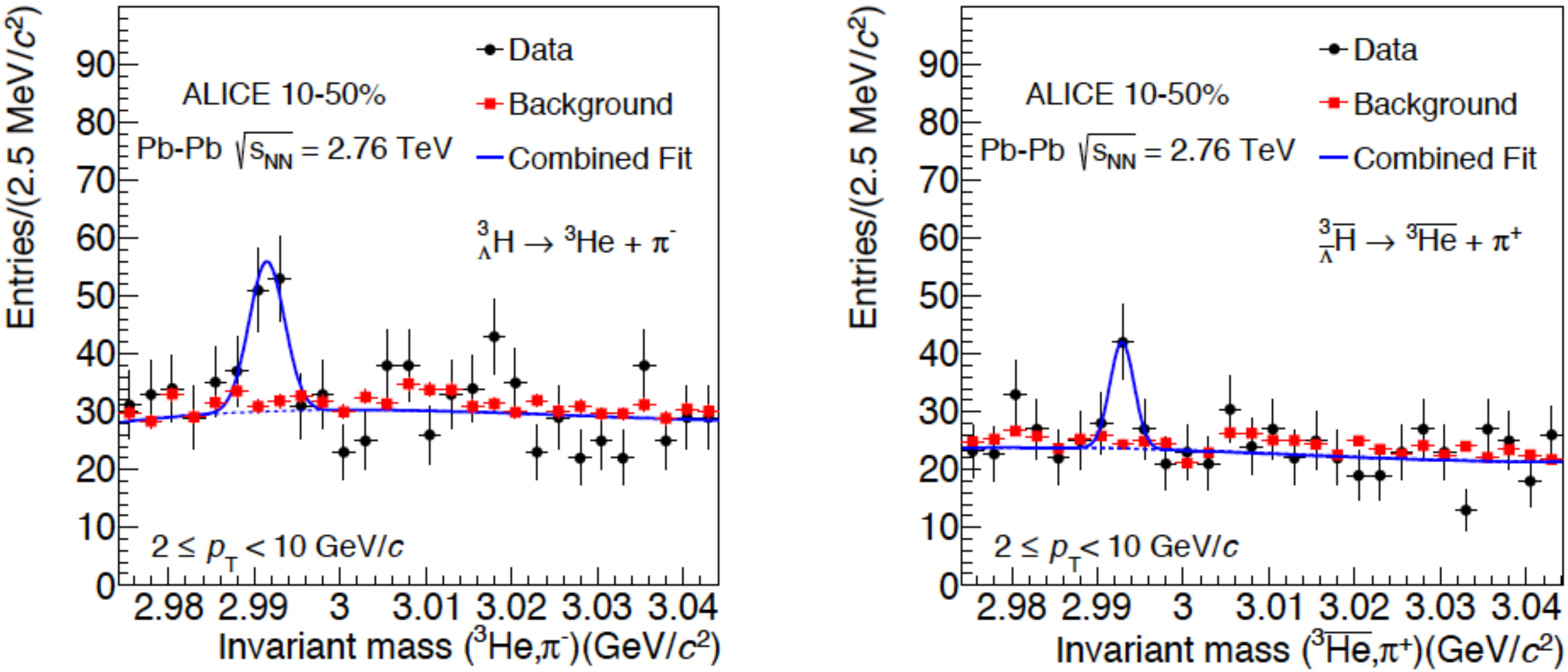
+ anti-particles

→ Anti-hypertriton was first observed by the STAR Collaboration:

Science 328,58 (2010)

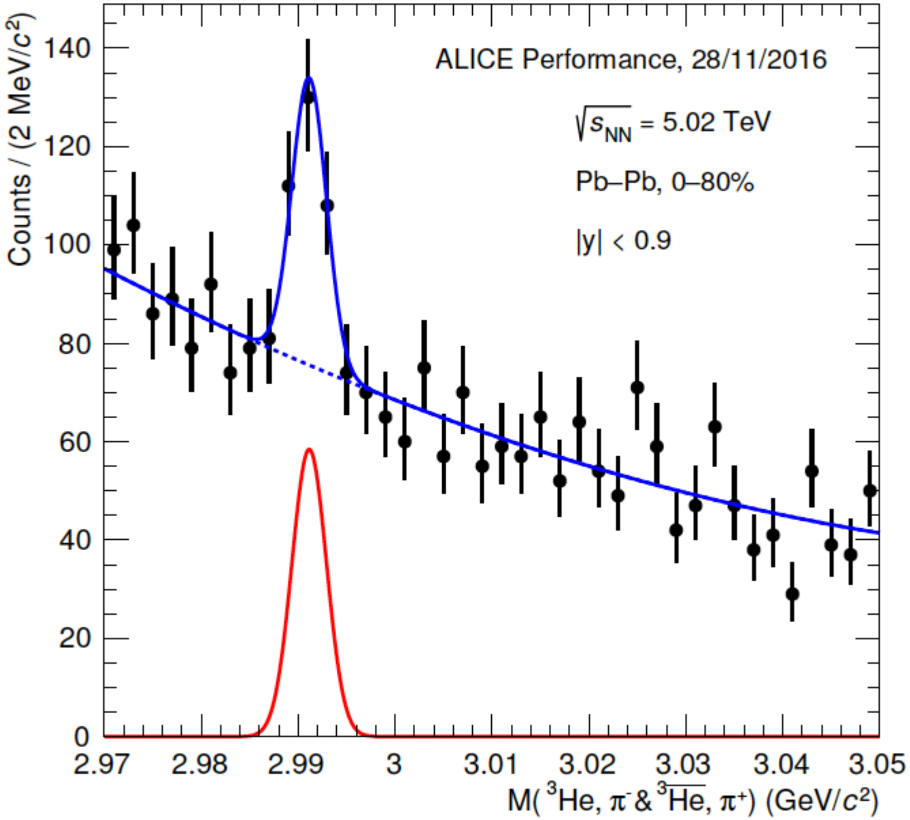
Hypertriton signal

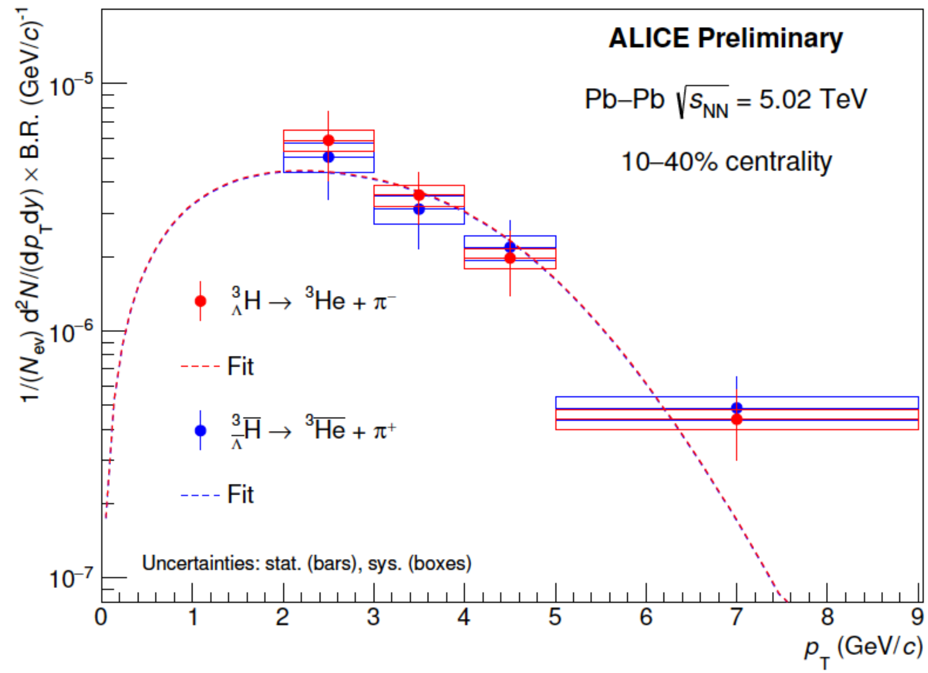
ALICE Collaboration: PLB 754, 360 (2016)



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

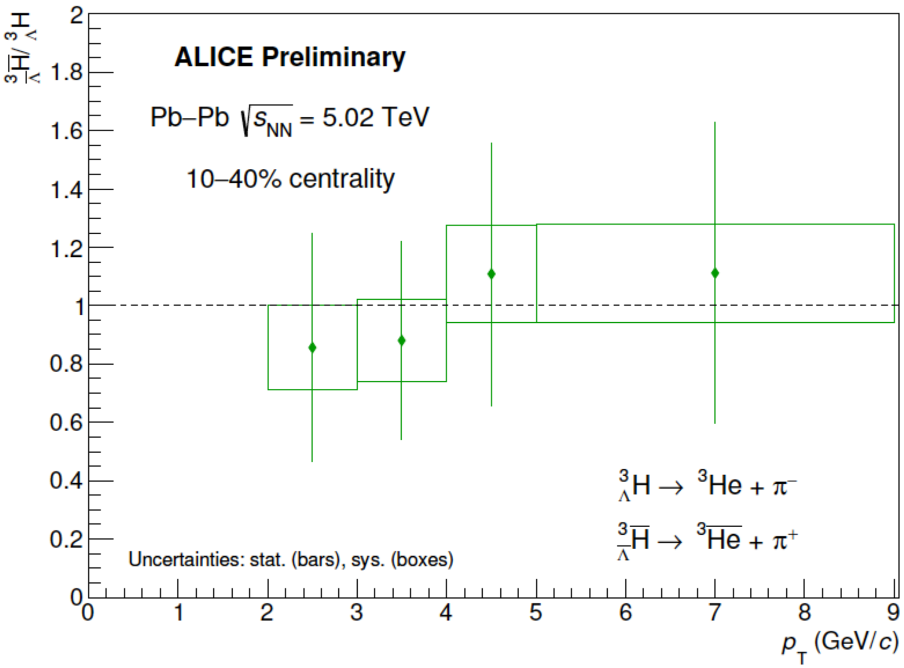
Hypertriton signal

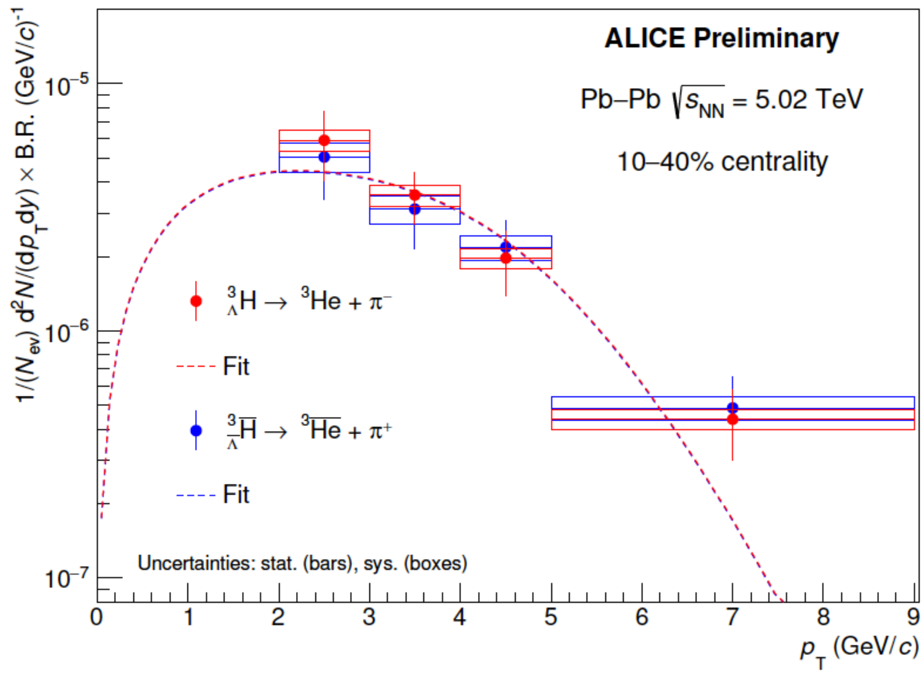




- Peaks are also clearly visible for particle and anti-particle
  - → Extracted yields in 4 p_T bins and 3 centrality classes

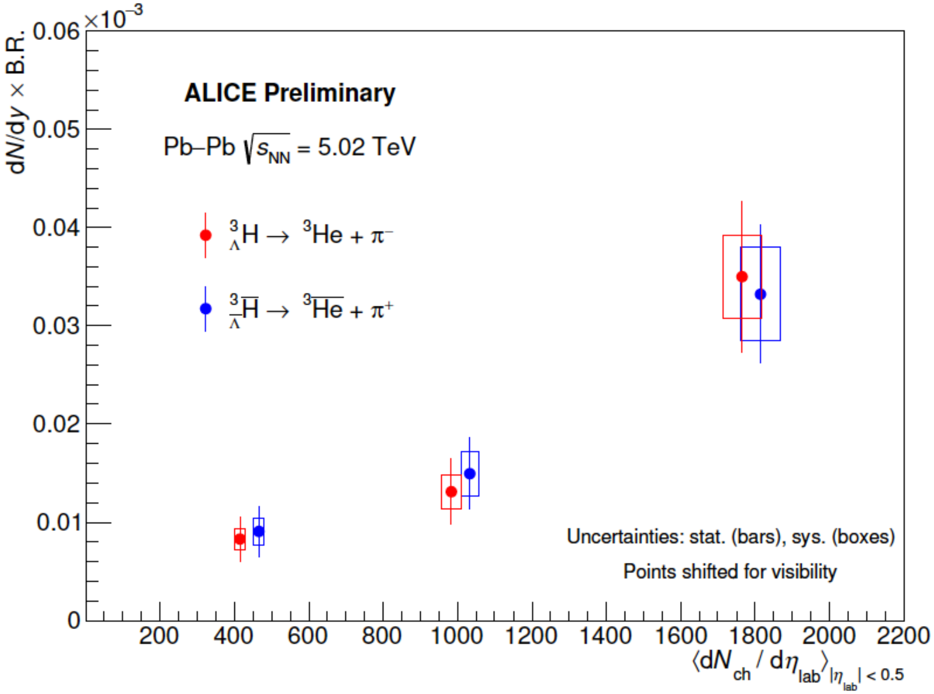
Hypertriton spectra

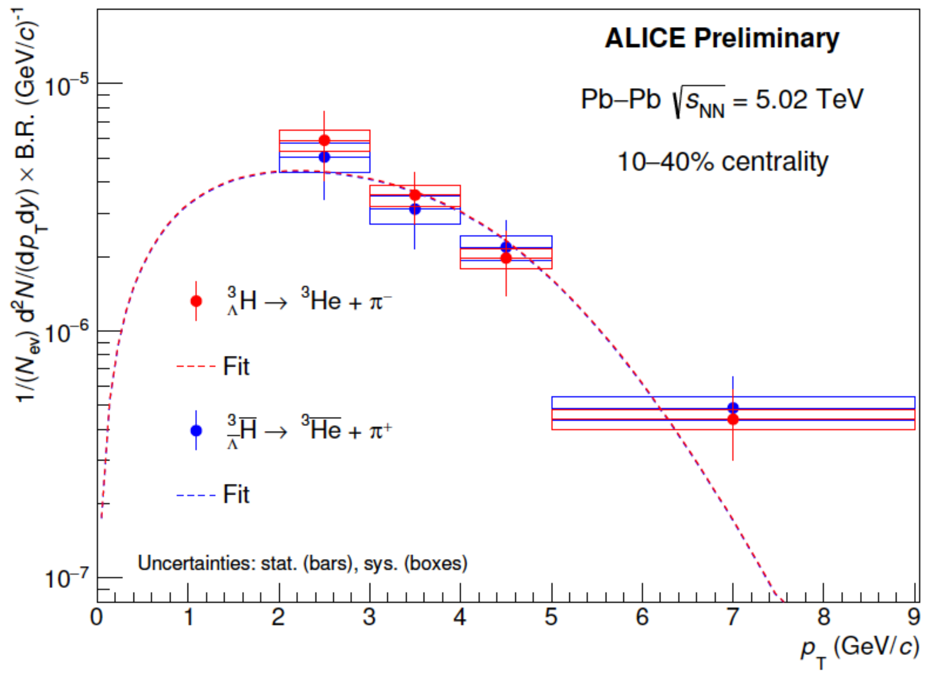




- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_{T}

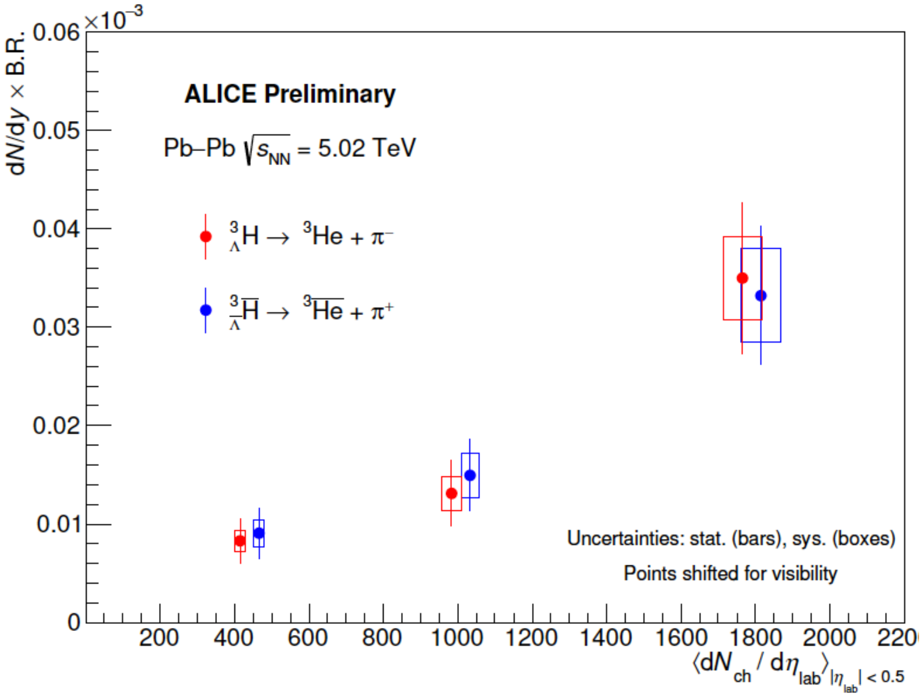
Hypertriton yield

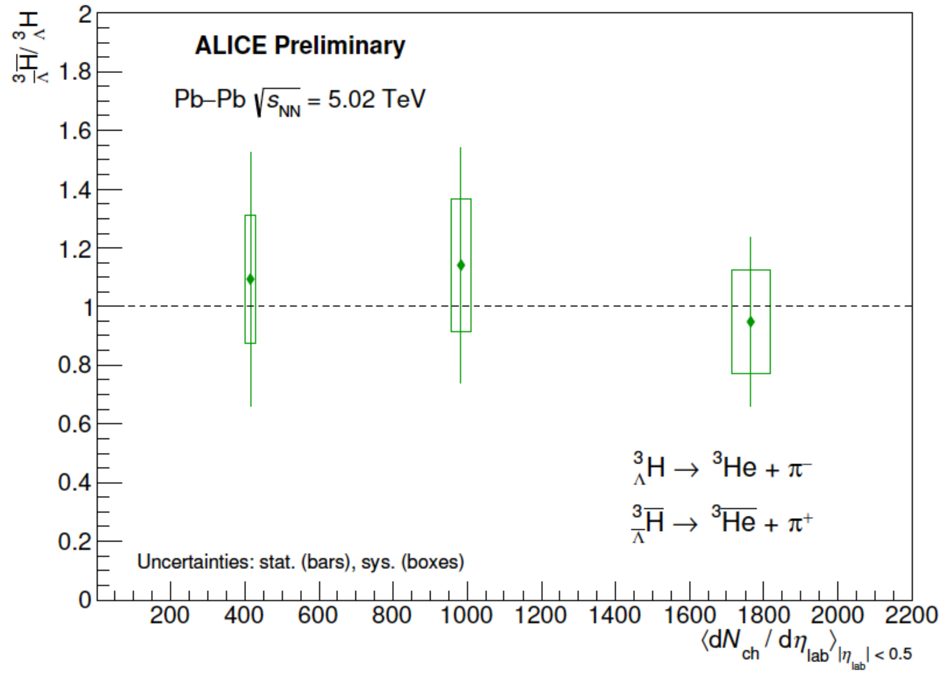




- Production in 3 centrality classes shows increase of prodcution probability with increasing multiplicity

Hypertriton yield

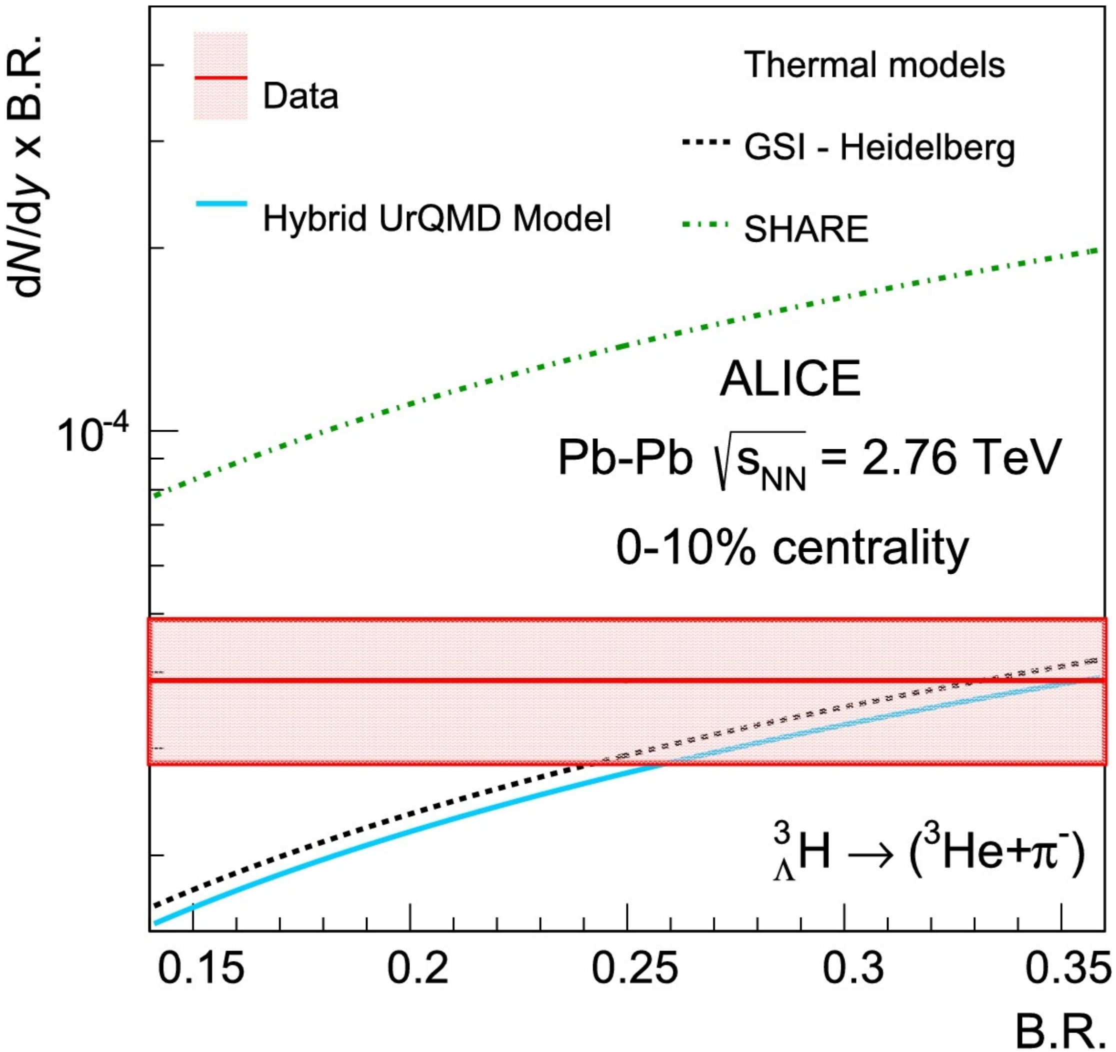




- Production in 3 centrality classes shows increase of prodcution probability with increasing multiplicity
- Ratio between anti-hypertriton-to-hypertriton unity for all centralities

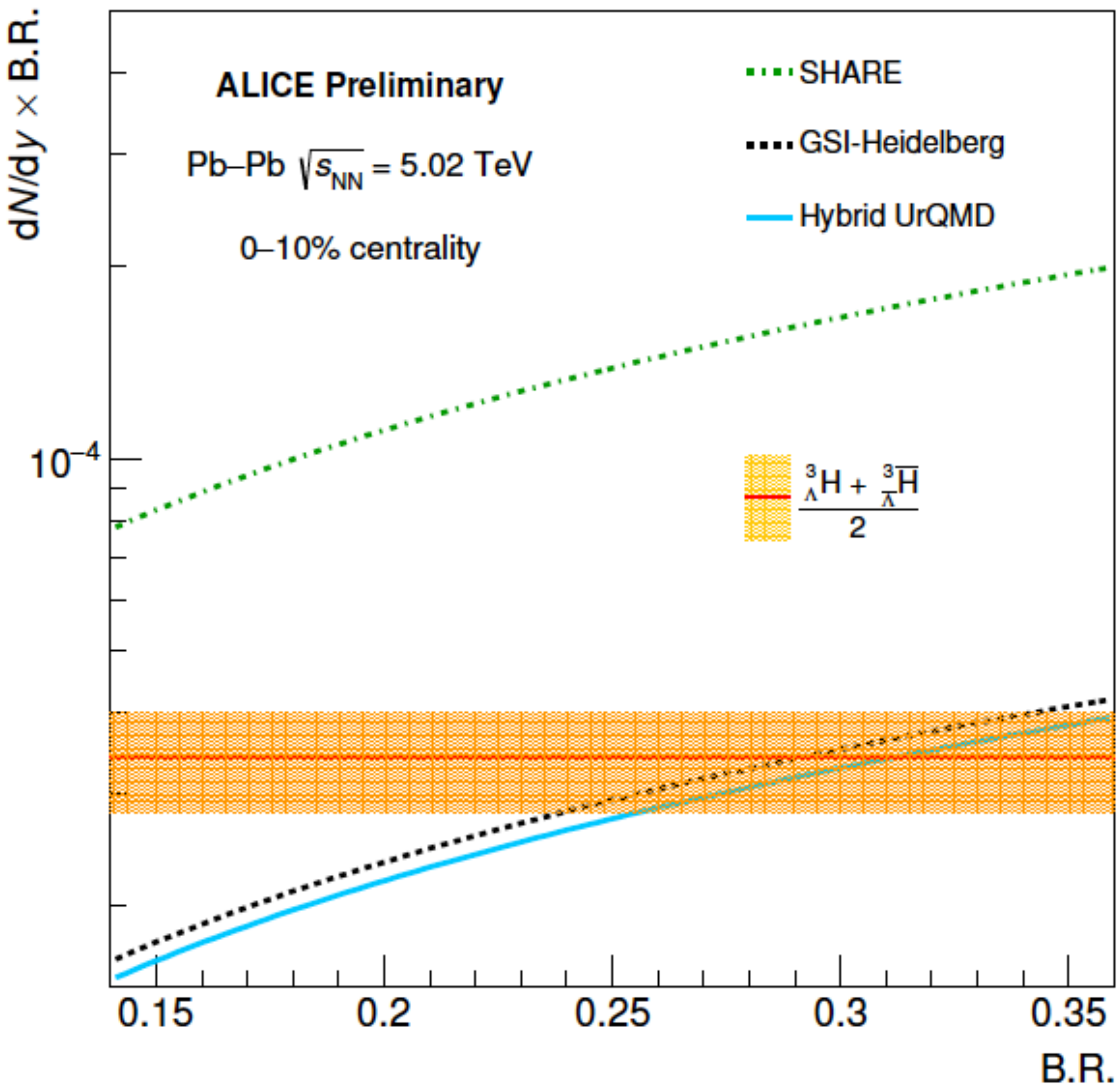
Hypertriton yield vs. B.R.

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.

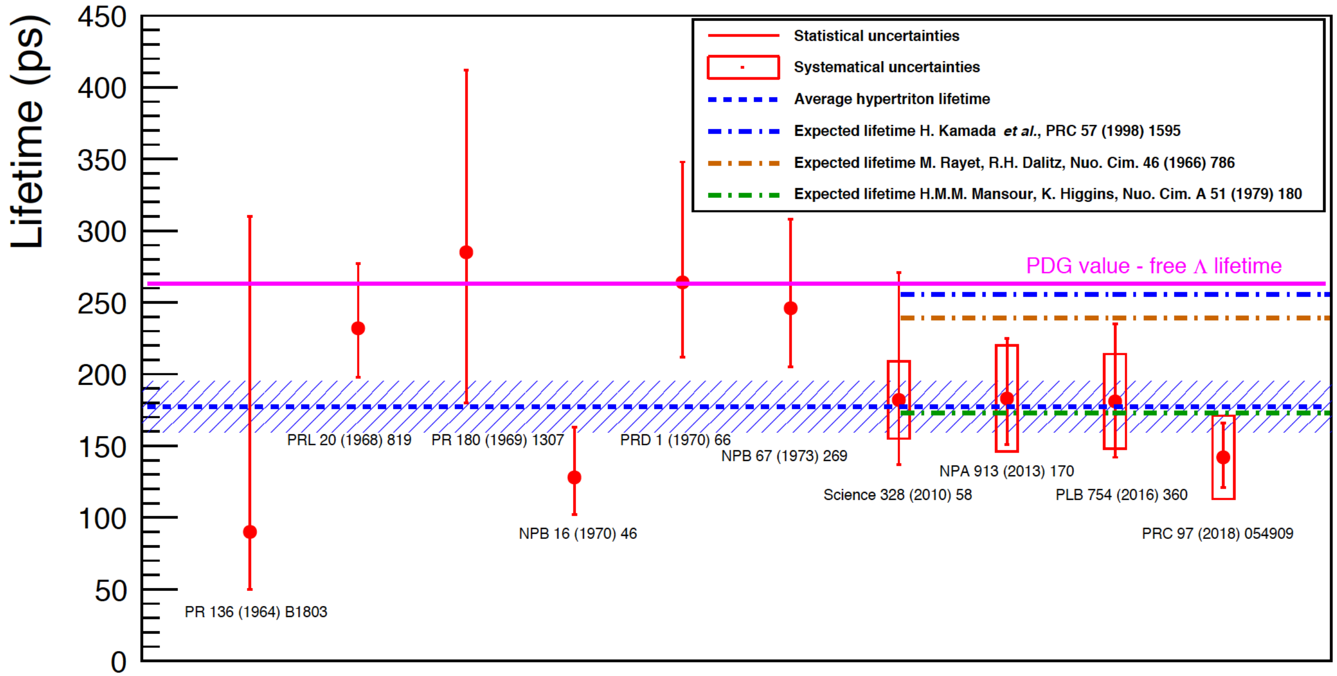


- The hypertriton branching ratio is not well known, only constrained by the ratio between all charged channels containing a pion
- Theory which prefers a value of around 25% gives a lifetime of the hypertriton close to the one of the free Λ

Hypertriton „puzzle"

- Recently extracted lifetimes significantly below the free Λ lifetime

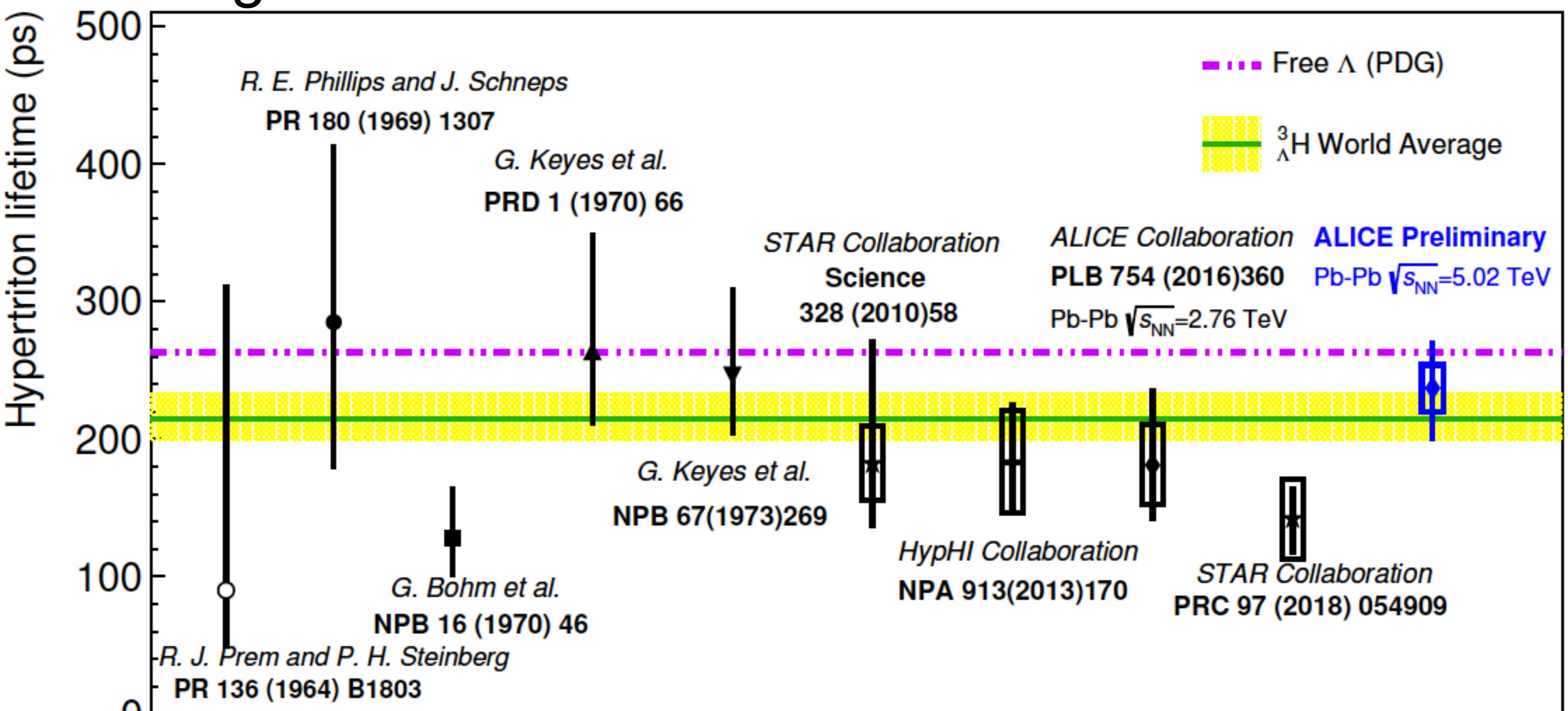
- Not expected from theory!
- Data before 2010 from emulsions
- Currently most precise data coming from heavy-ion collisions
- Better precision expected from larger data samples to be collected



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

Hypertriton „puzzle"

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

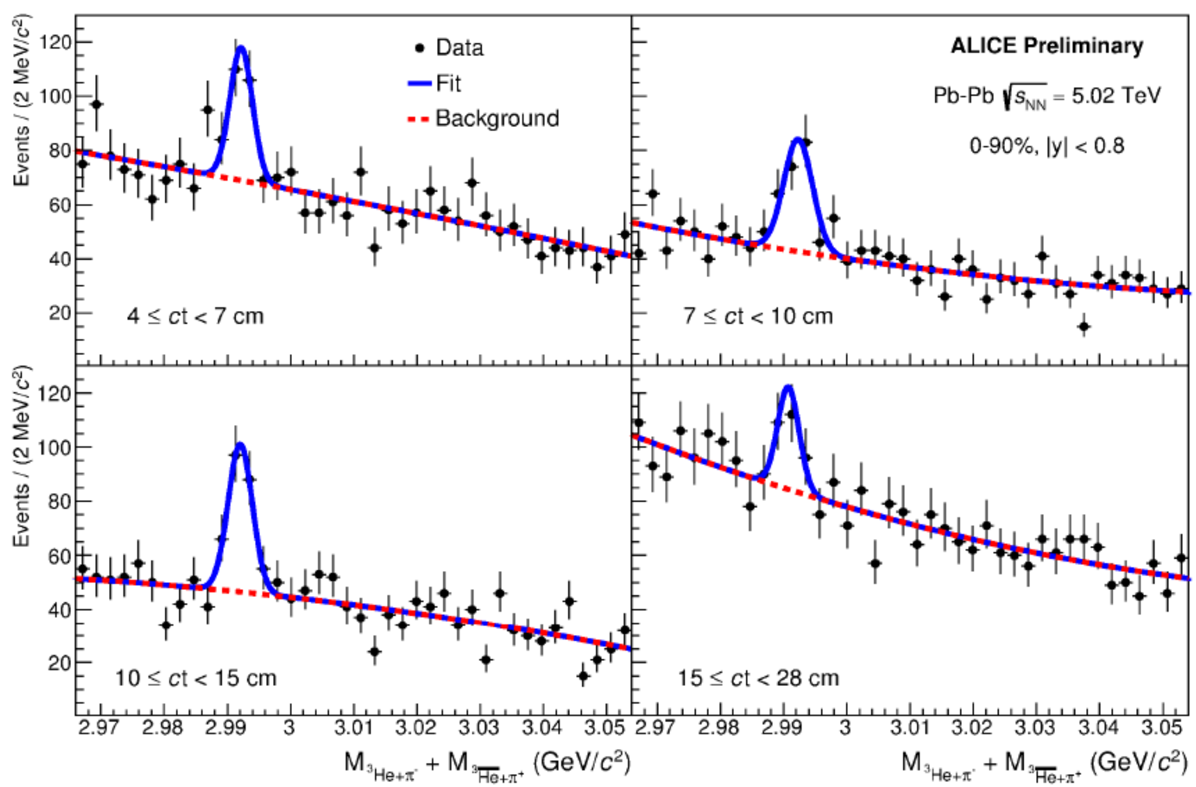


Hypertriton lifetime

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

- Two methods used which agree nicely:

1.) *ct* spectra (default)

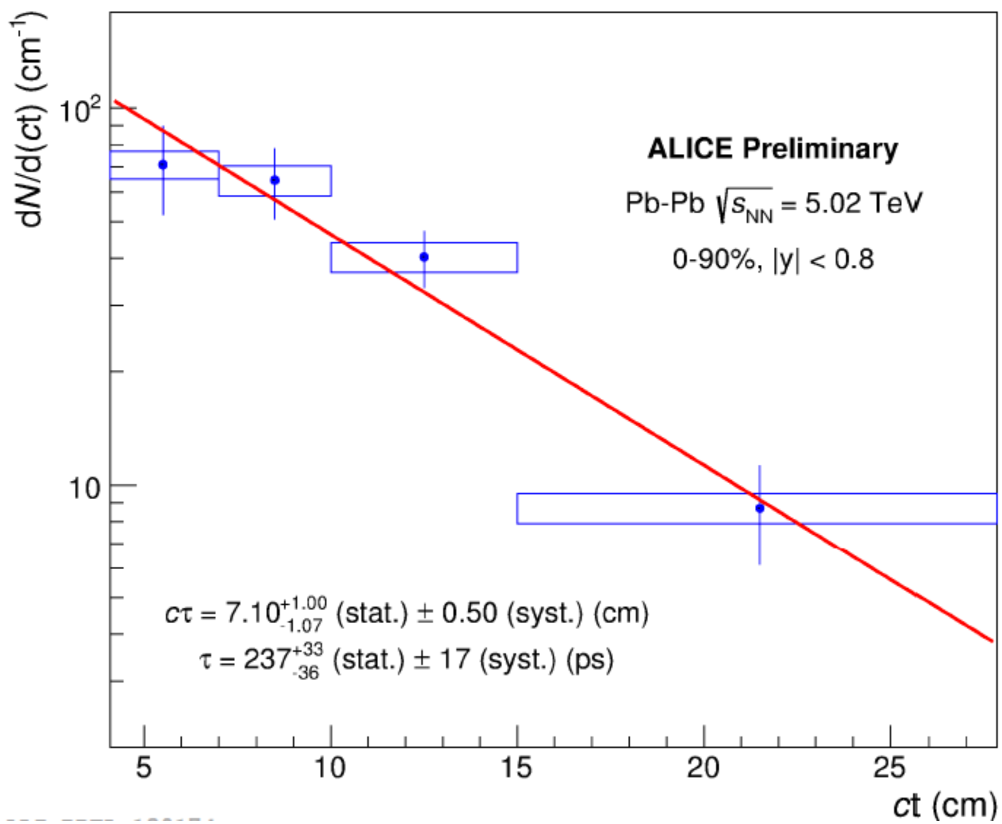


Hypertriton lifetime

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

- Two methods used which agree nicely:

1.) *ct* spectra (default)



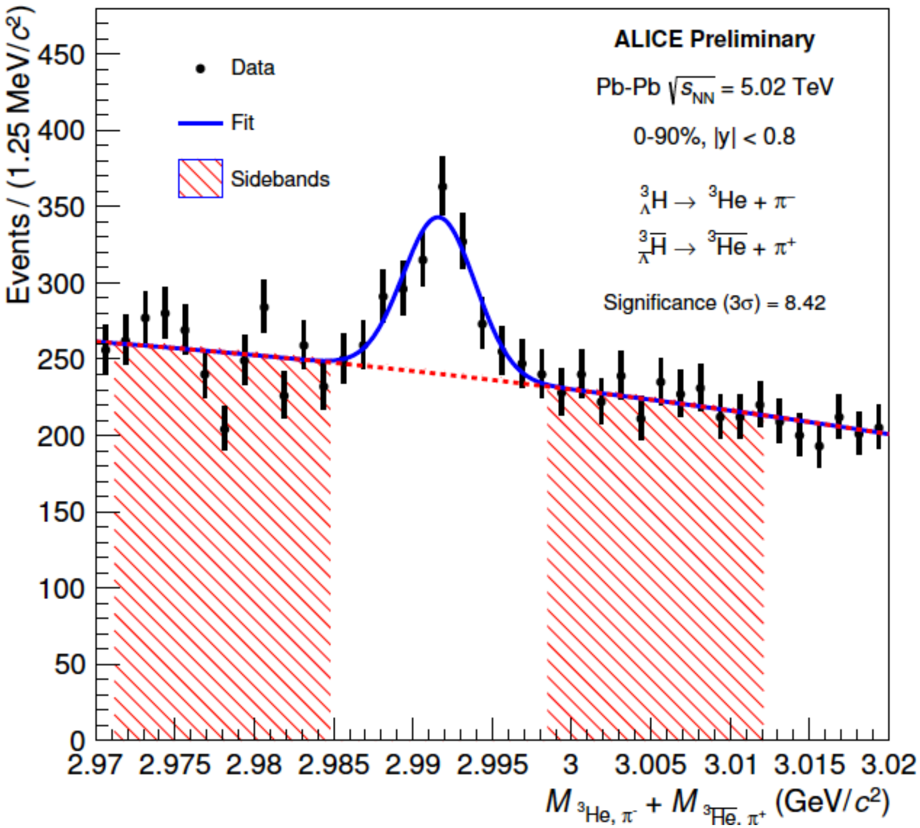
Hypertriton lifetime

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

- Two methods used which agree nicely:

1.) *ct* spectra (default)

2.) „unbinned“ method using sideband region for fitting the background and the signal region for extracting the lifetime of the hypertriton



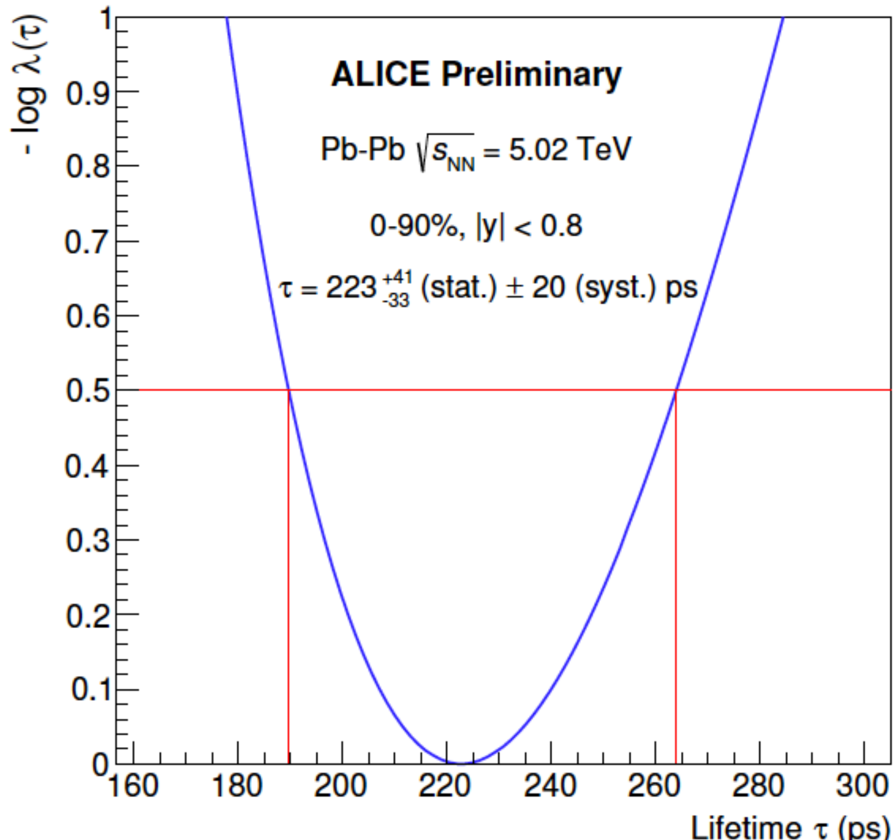
Hypertriton lifetime

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

- Two methods used which agree nicely:

1.) *c*t spectra (default)

2.) „unbinned“ method using sideband region for fitting the background and the signal region for extracting the lifetime of the hypertriton



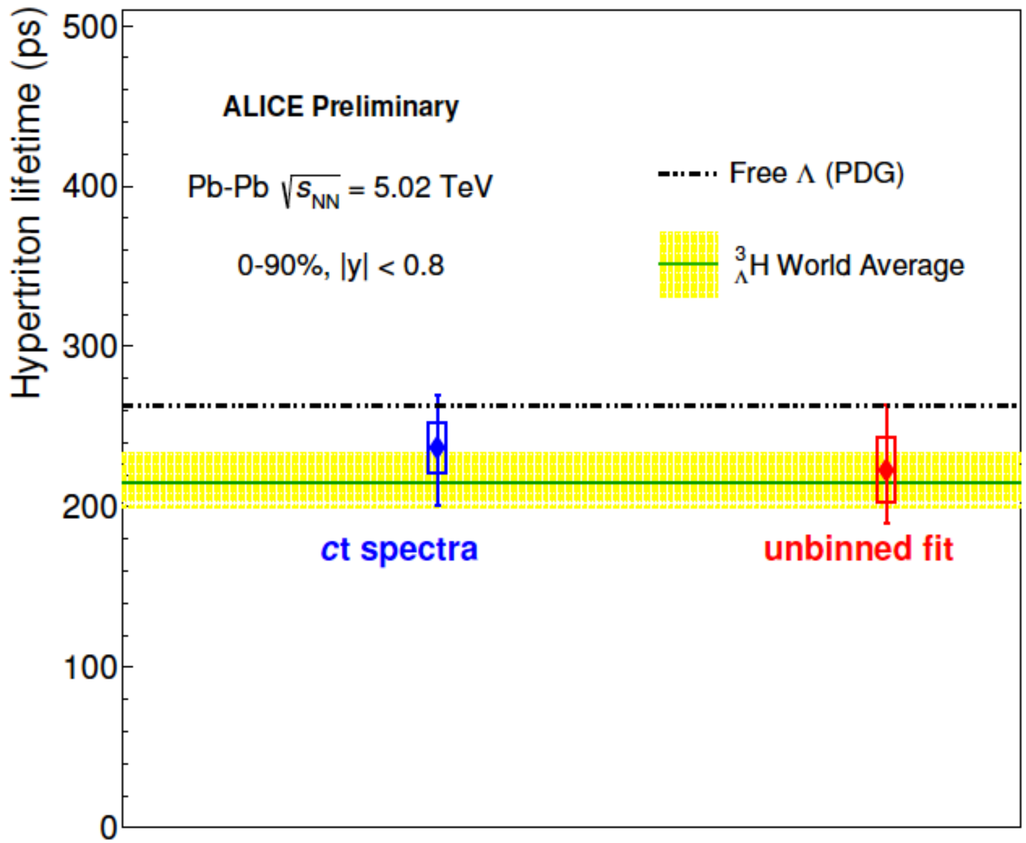
Hypertriton lifetime

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

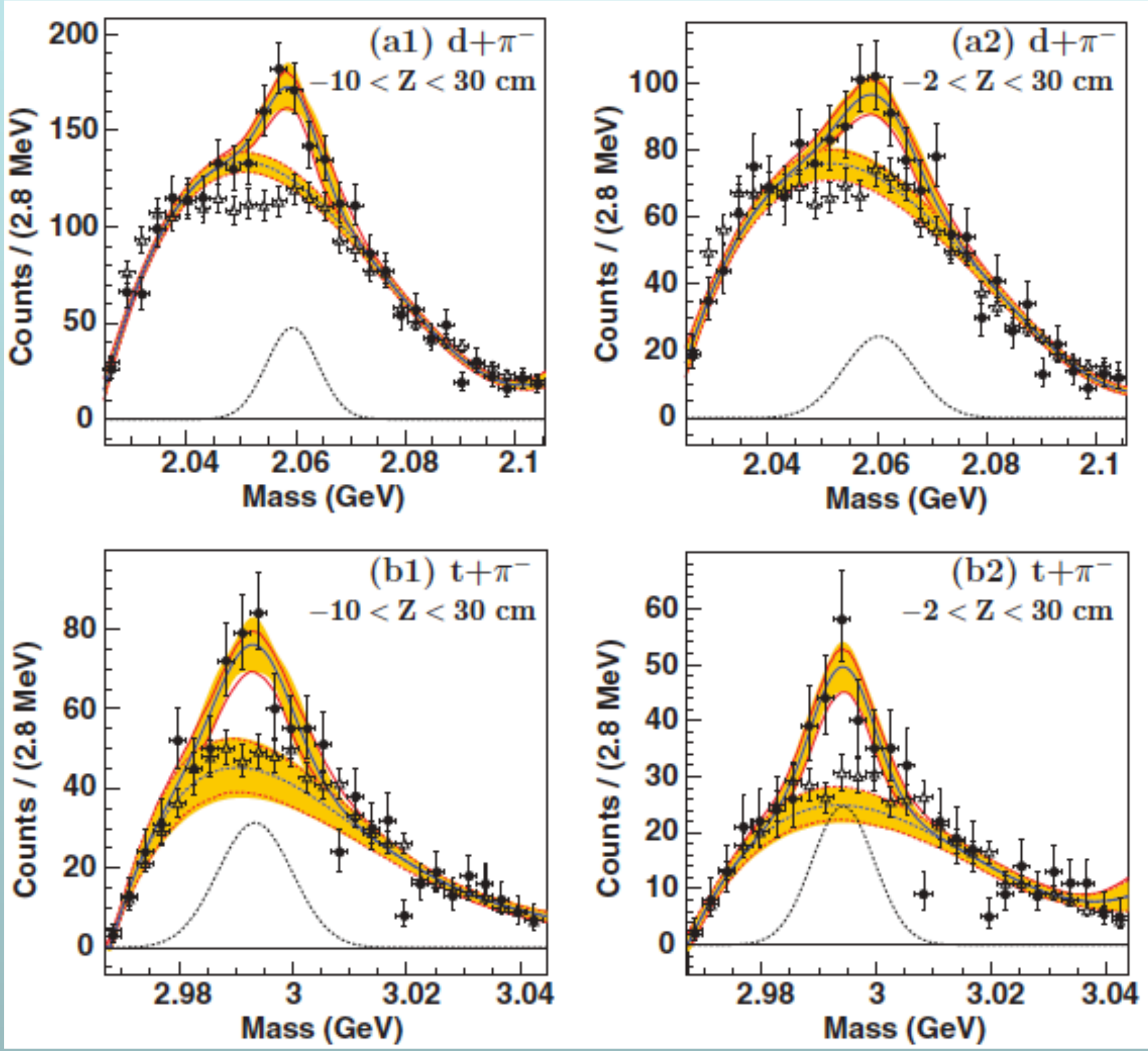
- Two methods used which agree nicely:

1.) *ct* spectra (default)

2.) „unbinned" method using sideband region for fitting the background and the signal region for extracting the lifetime of the hypertriton



Exotica

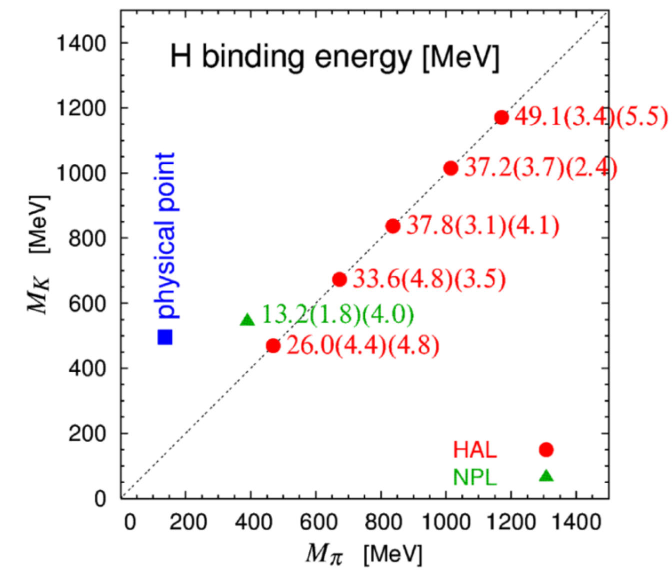


HypHI Collaboration observed signals in the t+π and d+π invariant mass distributions

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/c^2 or 13 MeV/c^2)
- *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/c^2 or lies close to the Ξp threshold

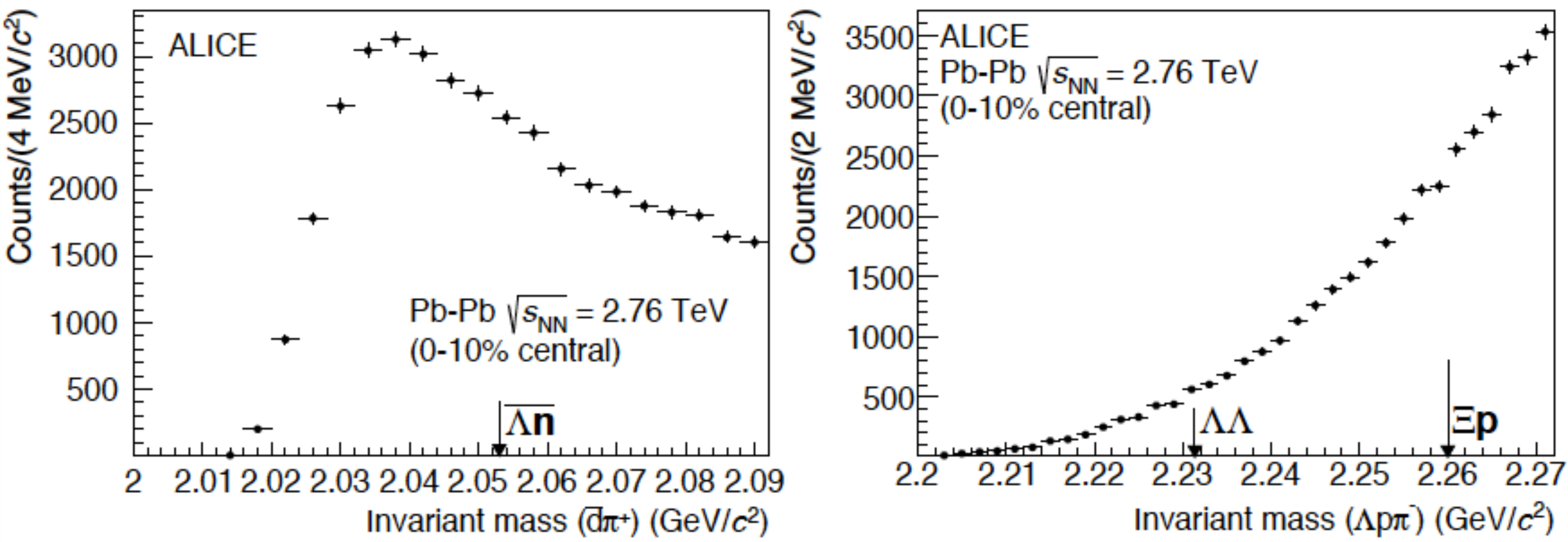


T. Inoue, private communication

→ Renewed interest in experimental searches

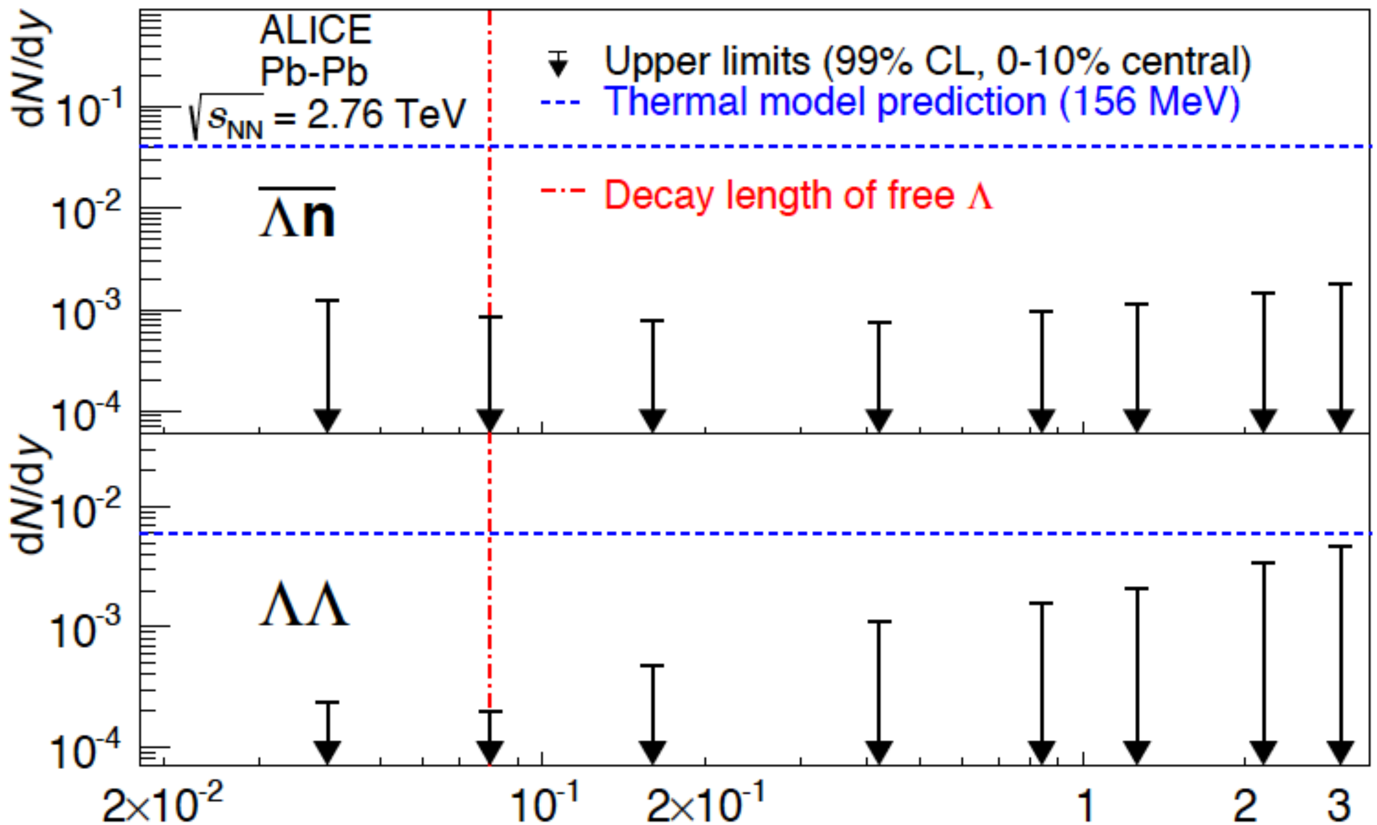
Searches for bound states

ALICE Collaboration: PLB 752, 267 (2016)



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

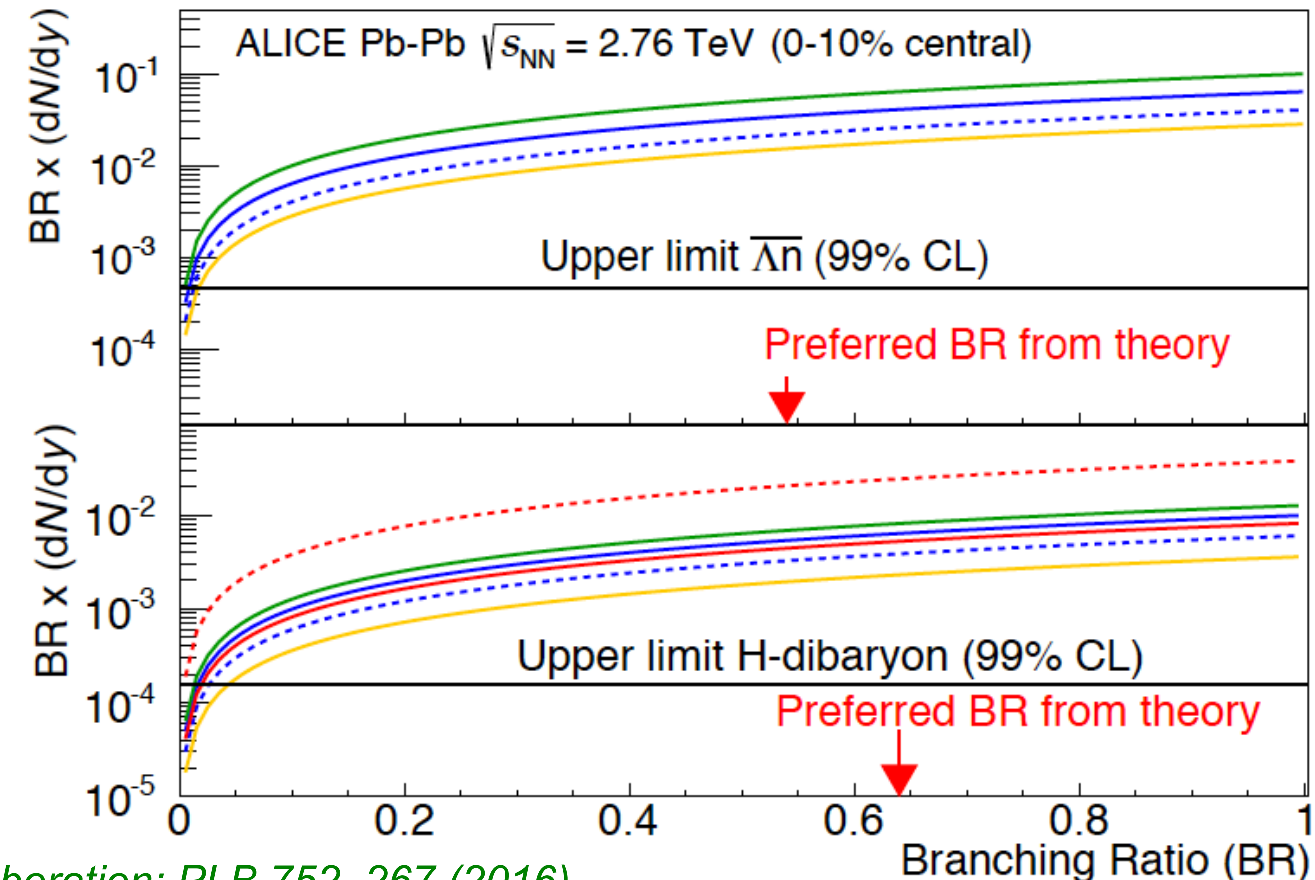
Decay length dependence



ALICE Collaboration: PLB 752, 267 (2016)

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

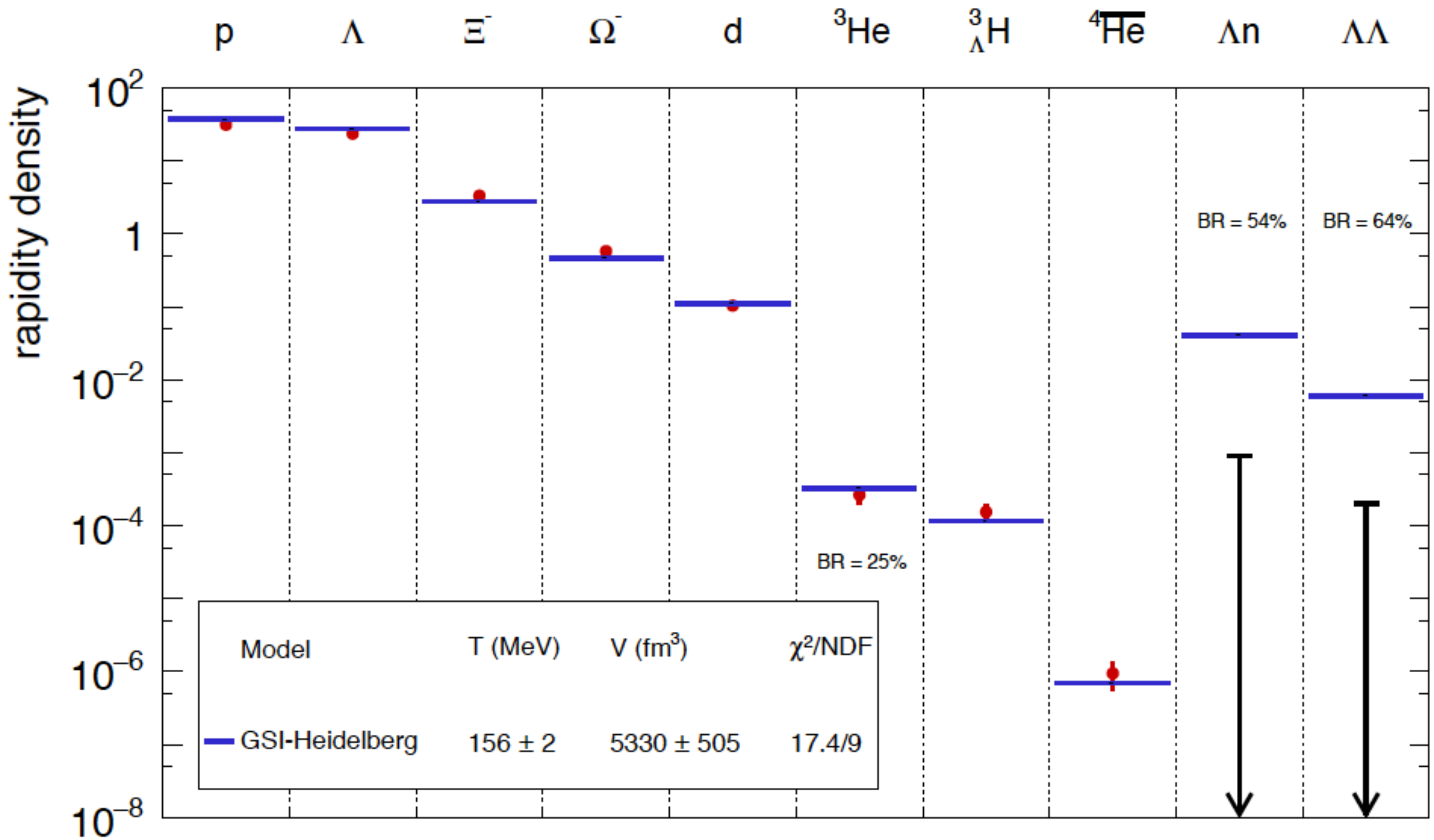
Dependence on BR



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

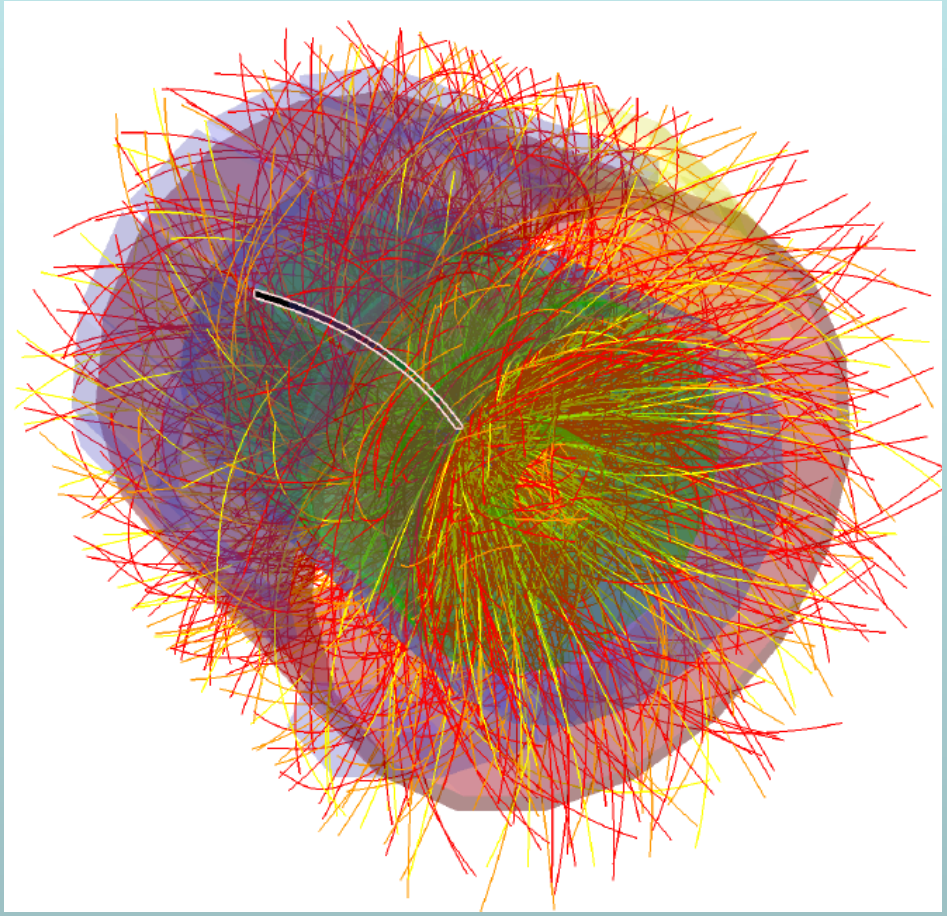


Simplified plot, CERN Courier (September 2015)

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

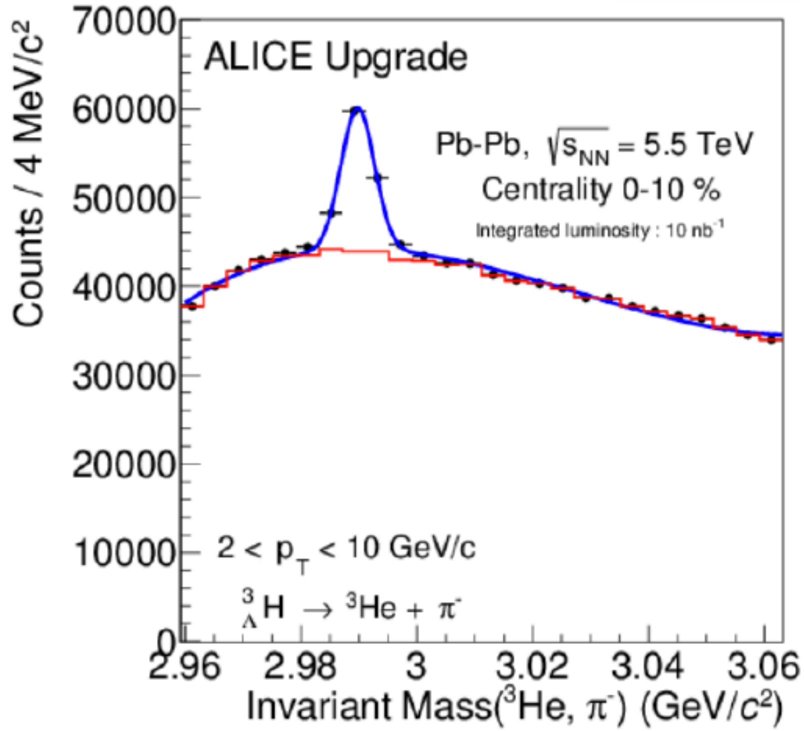
→ Upper limits of ΛΛ and Λn are factors of >25 below the model values

Oulook & Summary



Expectations

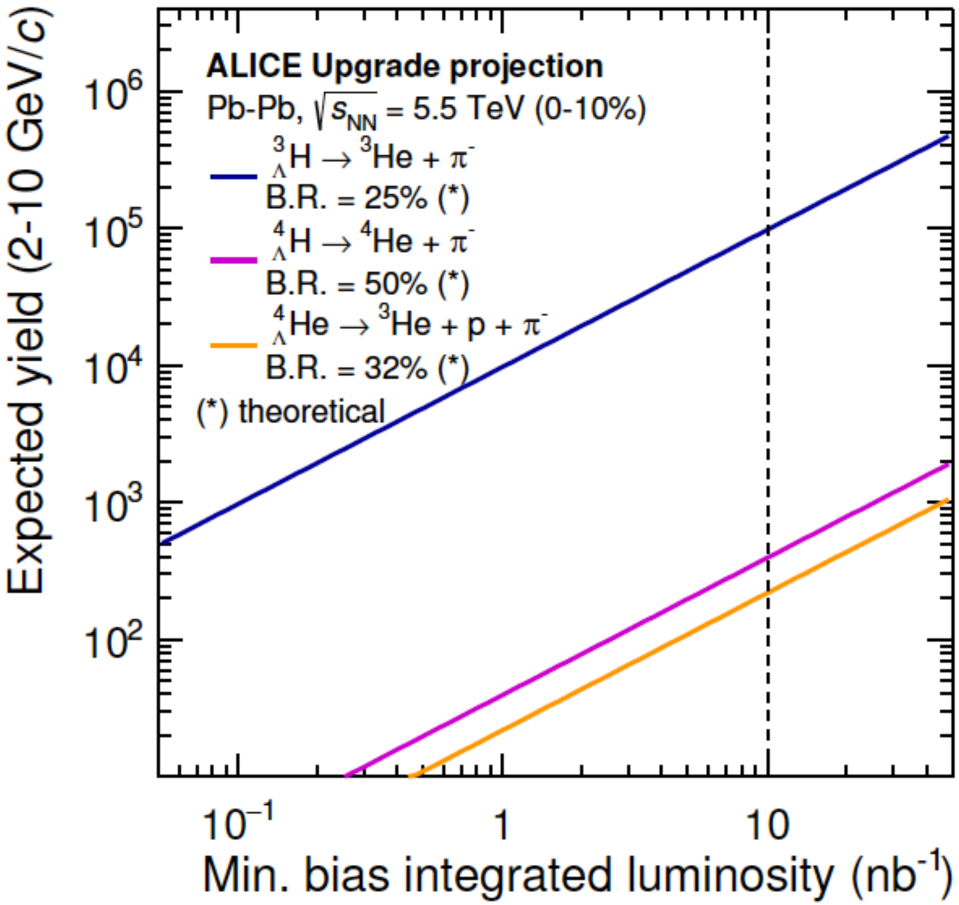
- Run 3 & Run 4 (2021 – 2029) of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continous readout
- ITS Upgrade: less material budget and more precise tracking for the identification of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

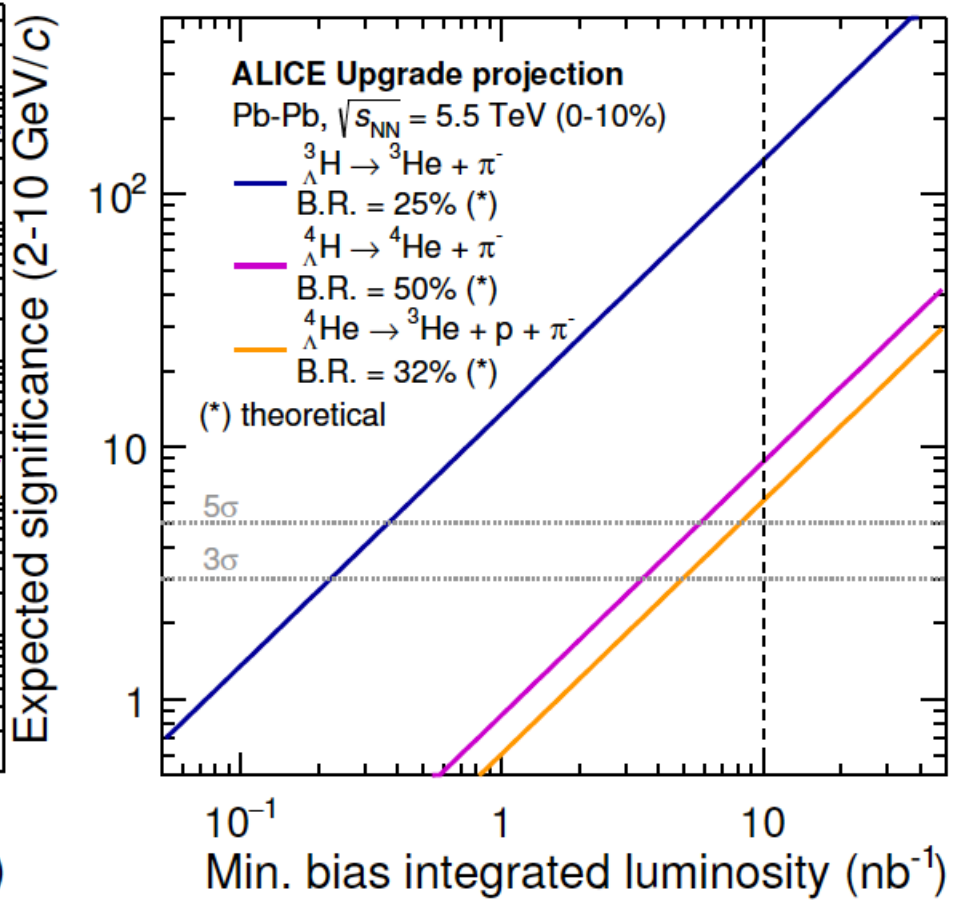


ITS Upgrade TDR: J. Phys. G 41, 087002 (2014)

State	dN/dy	B.R.	$\langle Acc \times \epsilon \rangle$	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

Conclusion

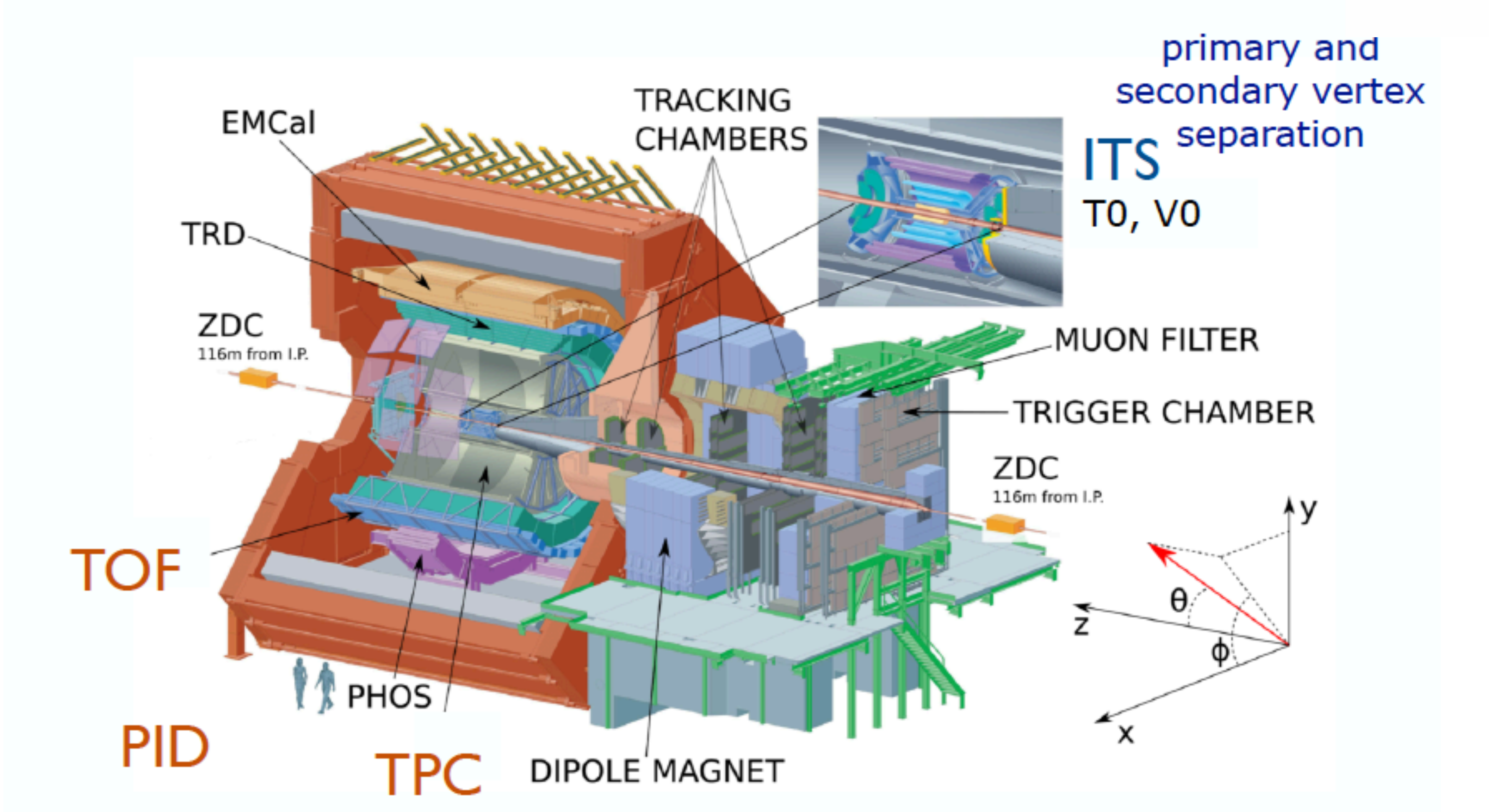
- ALICE@LHC is well suited to study light (anti-)(hyper-)nuclei and perform searches for exotic bound states (A<5)
- Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
- Thermal model describes the (anti-)(hyper-)nuclei data rather well
- d/p ratio shows increasing trend for pp and p-Pb collisions and seems to saturate for Pb-Pb multiplicities (increase: coalescence, saturation: thermal)
- Most recent measurement of the hypertriton lifetime is in agreement with the free Λ lifetime and the current world average

Conclusion

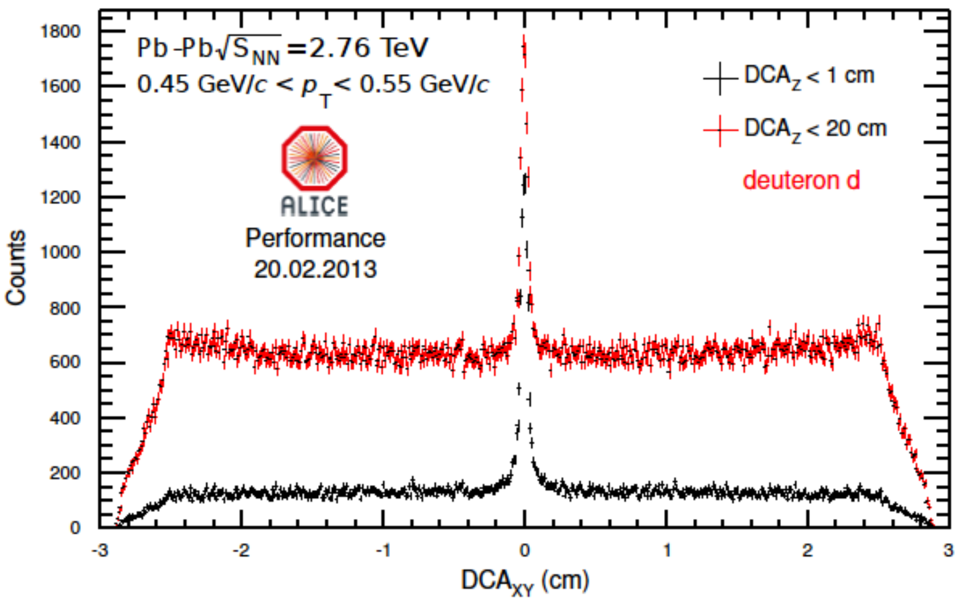
- Only a selection of results possible
- See also
  - L. Fabbietti: Femptoscopy in pp and pA collisions at GeV and TeV energies as a too to shed light on the hyperon puzzle (Mo 14:35)
  - D. Mihaylov: Baryon-baryon femptoscopy in pp and p-Pb collisions (Poster)
  - R. Lea: Studying the strong interaction for meson-baryon with femptoscopy in pp collisions with ALICE (Th 16:35 Session B2)

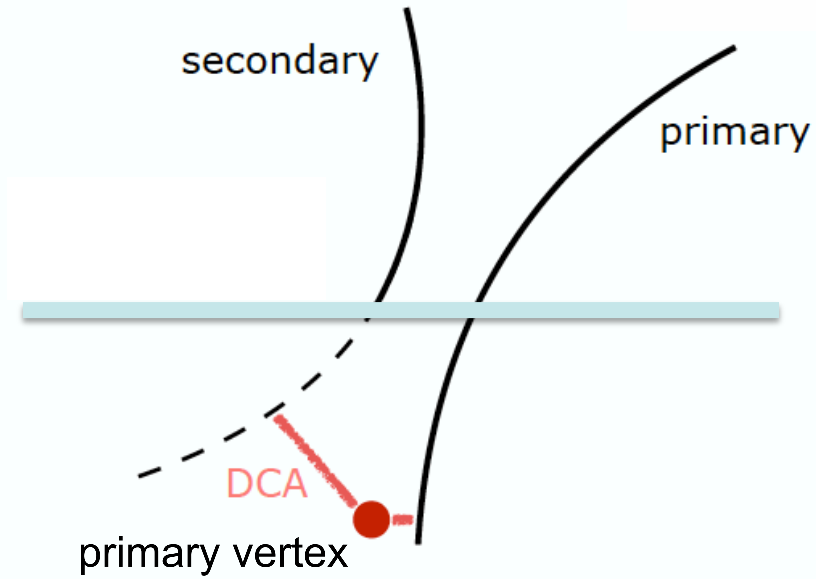
Backup

Experiment: ALICE



Secondary contamination

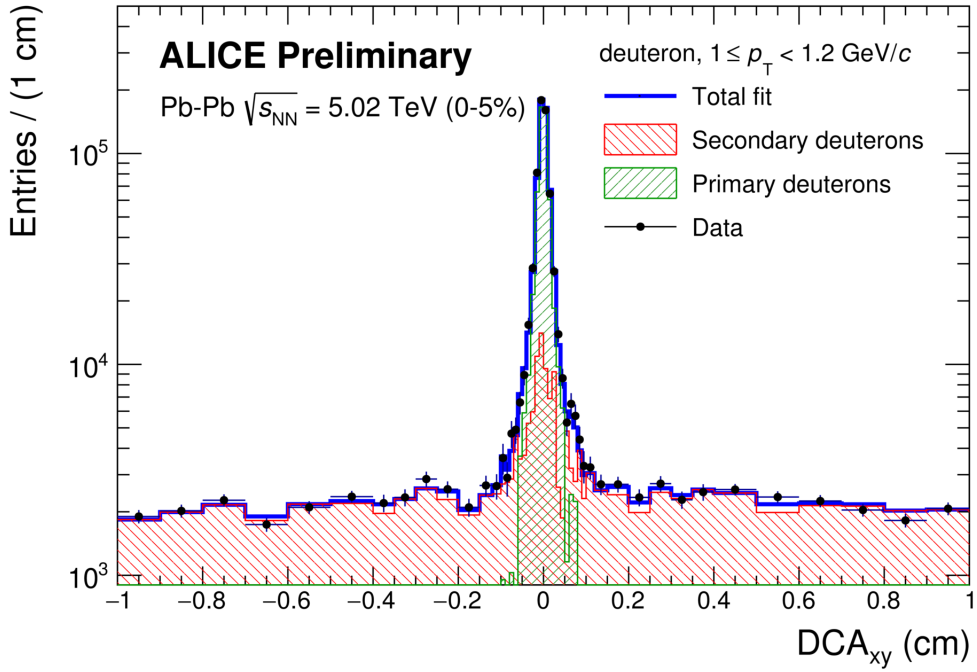




➜ Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material, e.g. beam pipe)

➜ Knock-out is a significant problem at low p_T, but only for nuclei not for anti-nuclei

Secondary contamination

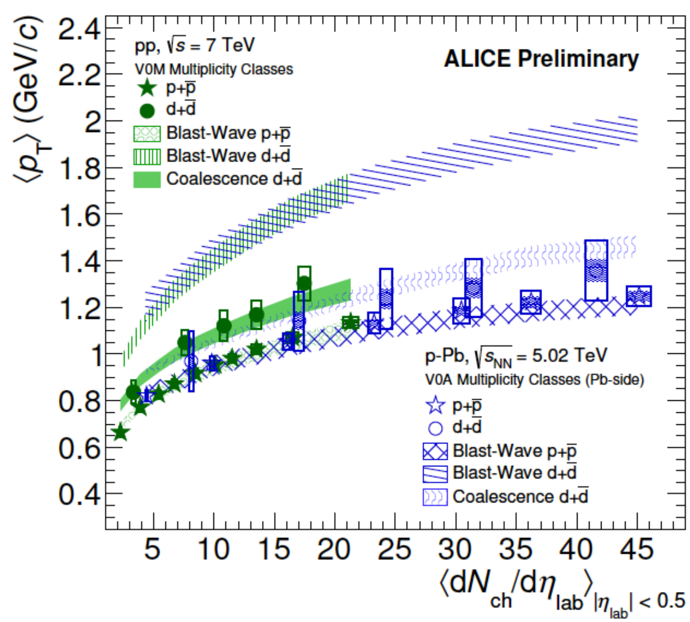


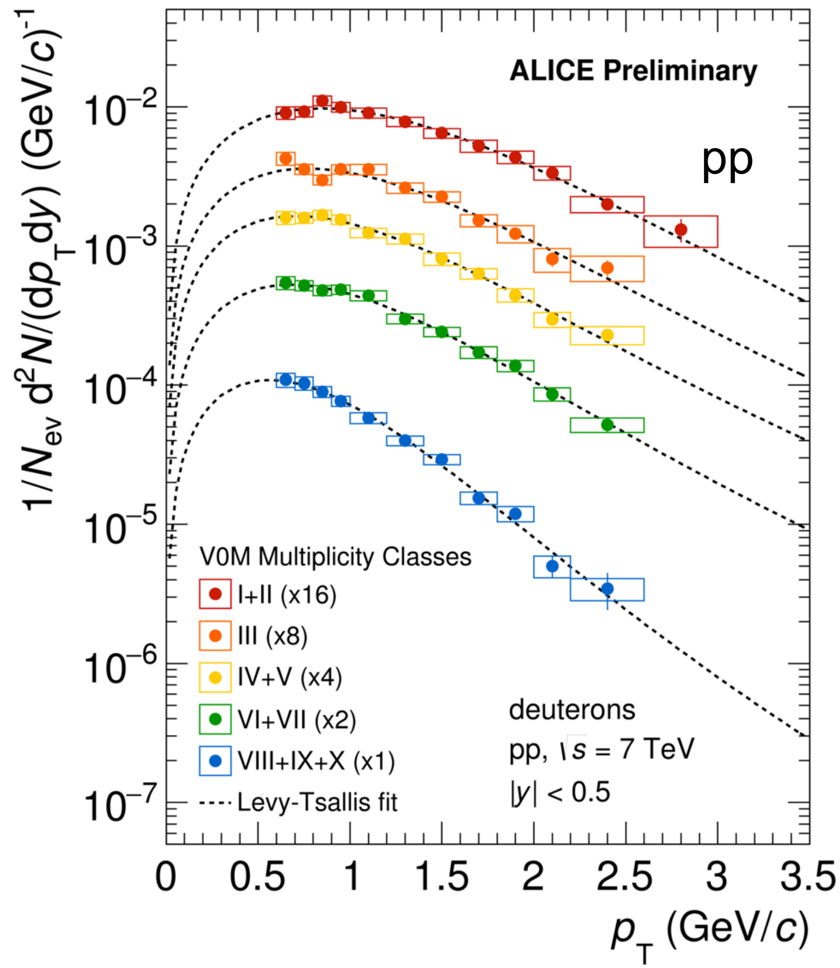
➜ Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material, e.g. beam pipe)

➜ Knock-out is a significant problem at low p_T, but only for nuclei not for anti-nuclei

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 → multiplicity bins show hardening





Multiplicity classes: pp

- **V0M Multiplicity Classes:** $\left[\langle dN_{ch}/d\eta \rangle^{INEL>0} \approx 6.0 \right]$
  $\begin{cases} I \rightarrow \langle dN_{ch}/d\eta \rangle \approx 3.5 \times \langle dN_{ch}/d\eta \rangle^{INEL>0} \\ \vdots \\ X \rightarrow \langle dN_{ch}/d\eta \rangle \approx 0.4 \times \langle dN_{ch}/d\eta \rangle^{INEL>0} \end{cases}$

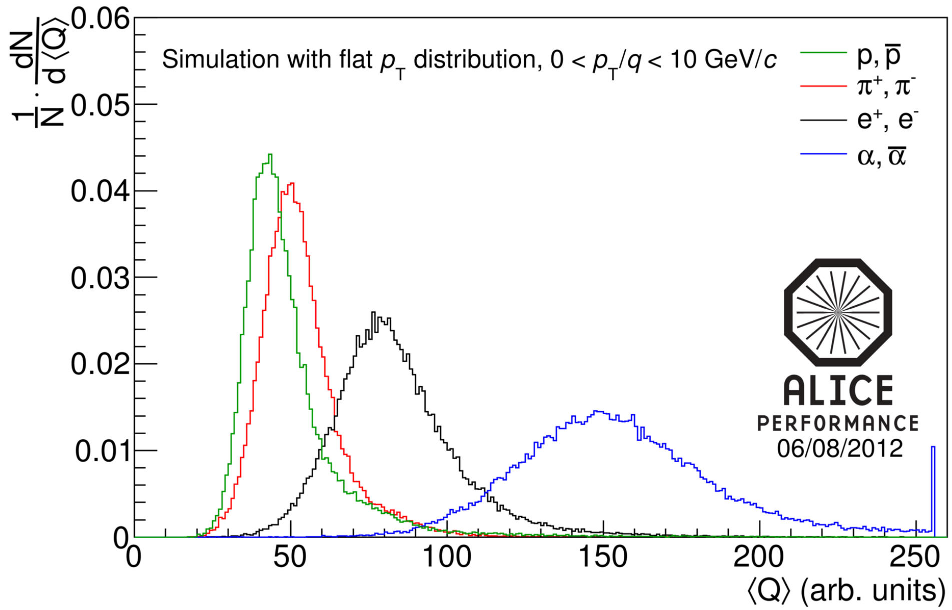
Table A.1: Event multiplicity classes, their corresponding fraction of the INEL>0 cross-section ($\sigma/\sigma_{INEL>0}$) and their corresponding $\langle dN_{ch}/d\eta \rangle$ at midrapidity ($|\eta| < 0.5$). The value of $\langle dN_{ch}/d\eta \rangle$ in the inclusive (INEL>0) class is 5.96 ± 0.23.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

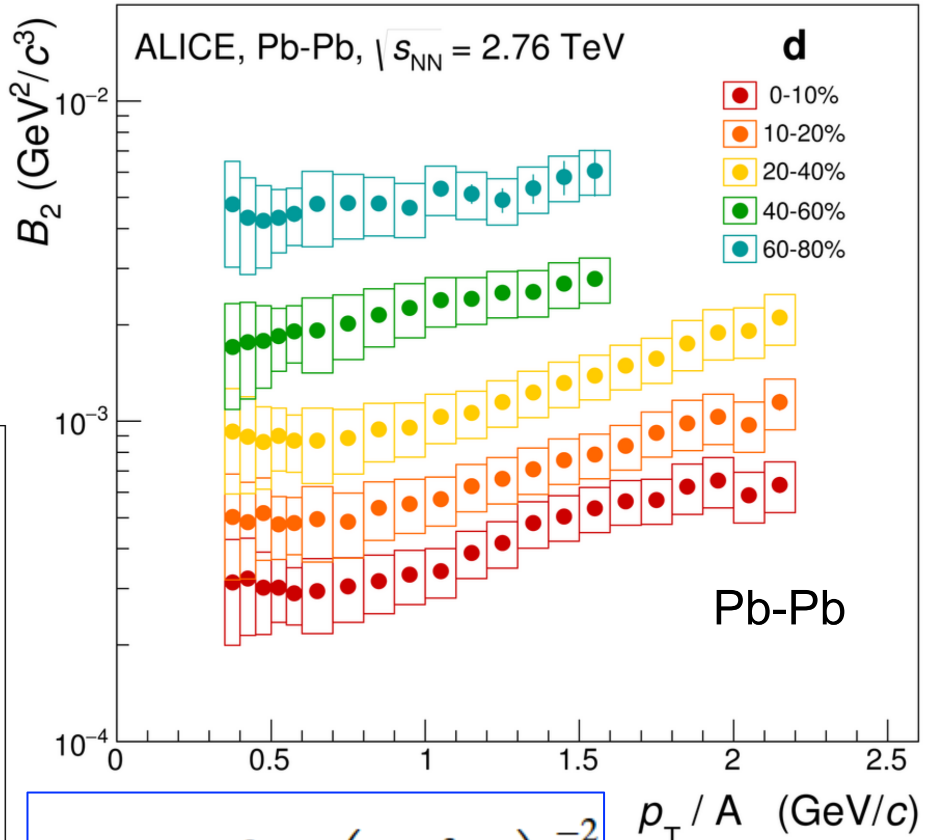
- A trigger on light (anti-)nuclei using the dependence of the ionisation on the charge number of the particle crossing the gas was studied intensively
- A first run in the p-Pb taking 2016
- Currently running in the standard trigger mix of ALICE in the pp data taking
- Expected enhancement mainly on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

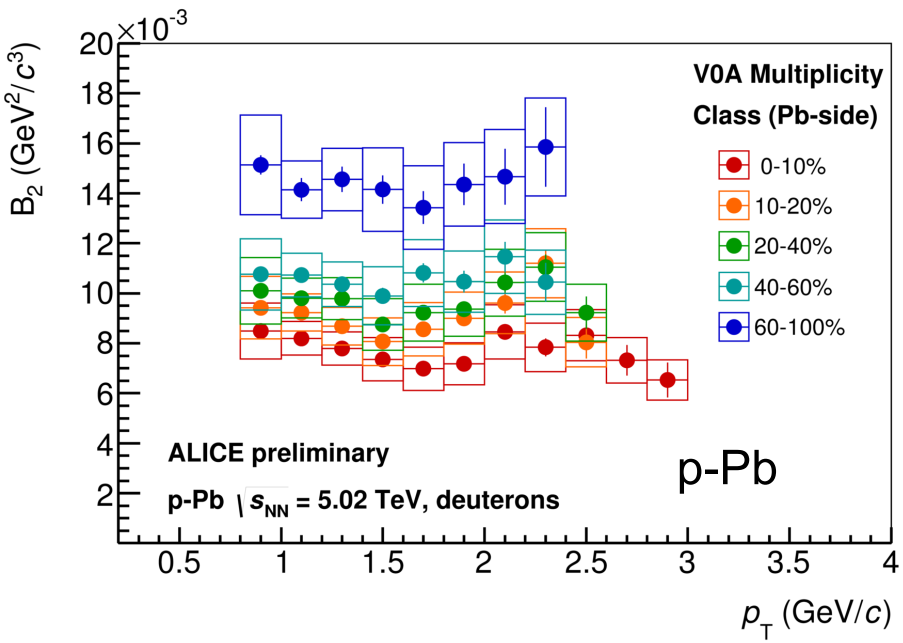


Coalescence parameter B_2

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





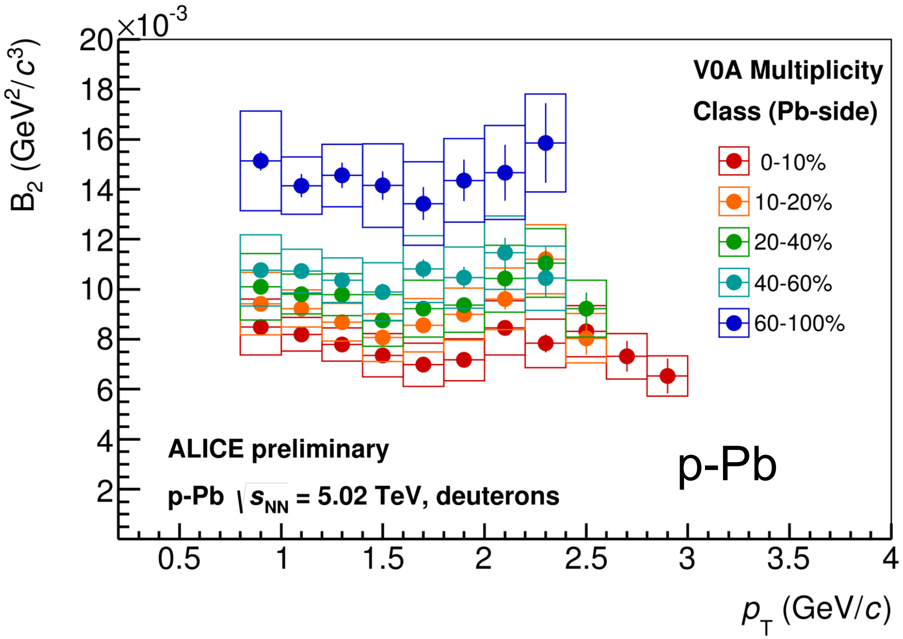
$$B_2 = E_d \frac{d^3N_d}{dp_d^3} \left(E_p \frac{d^3N_p}{dp_p^3} \right)^{-2}$$

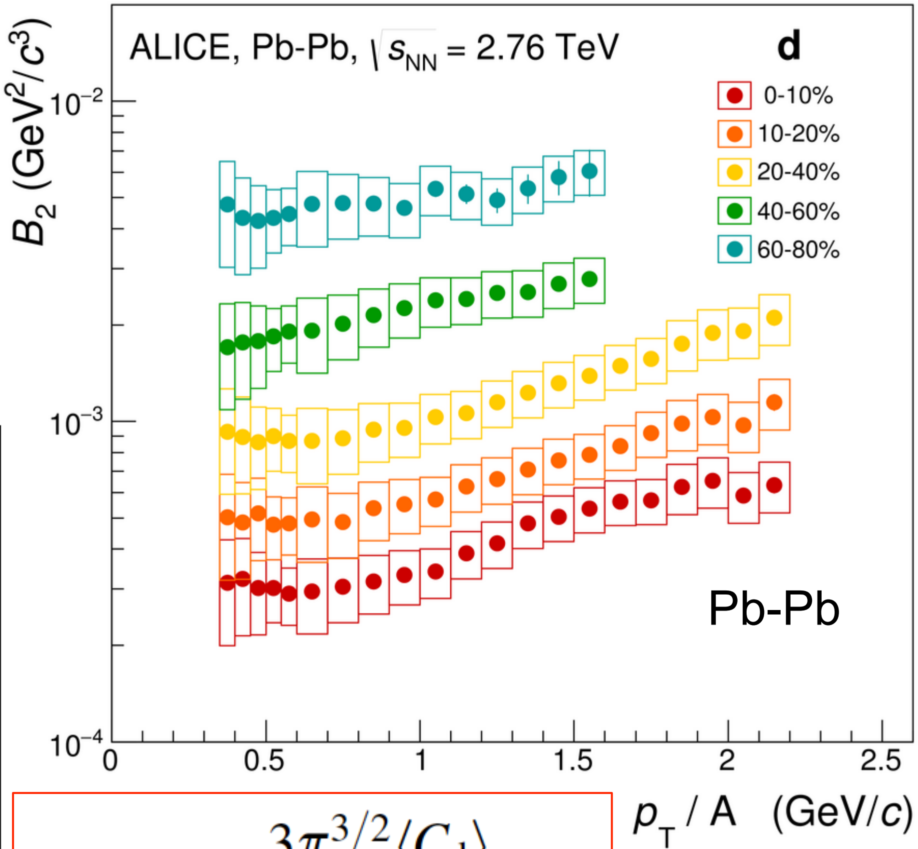
Coalescence parameter B_2

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
- B_2 scales like the HBT radii

  ➜ Decrease with centrality in Pb-Pb is understood as an increase in the source volume





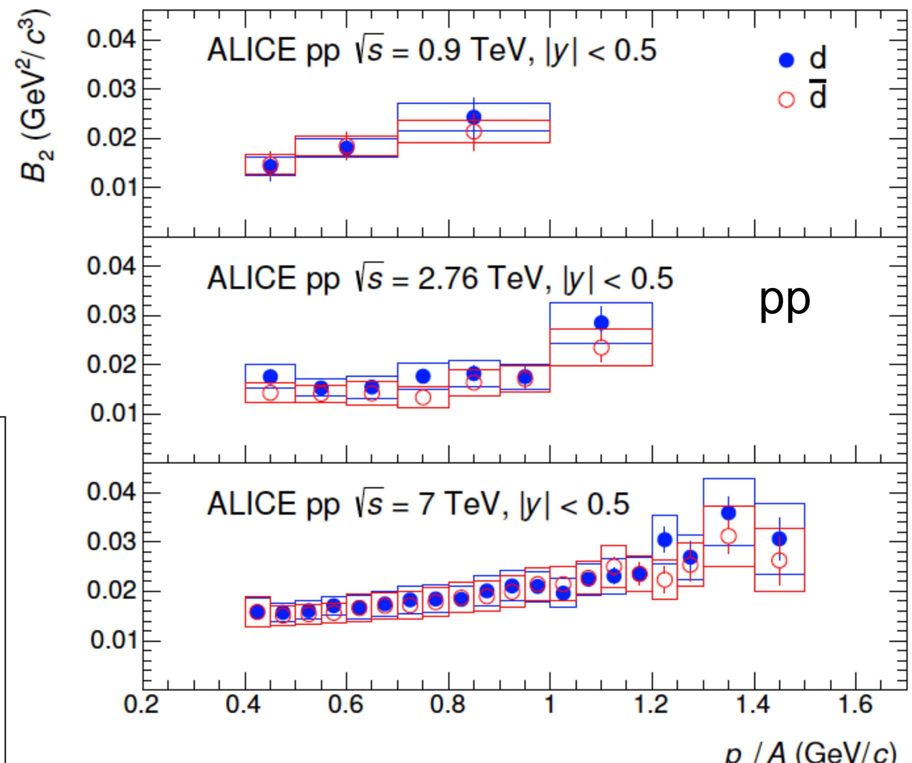
$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

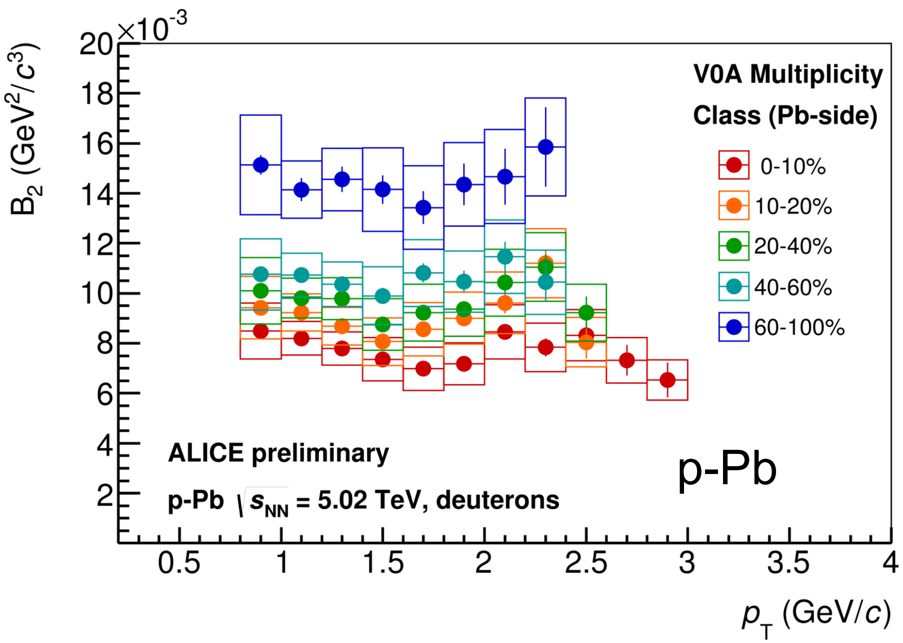
Coalescence parameter B_2

- 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

ALICE Collaboration, arXiv:1709.08522

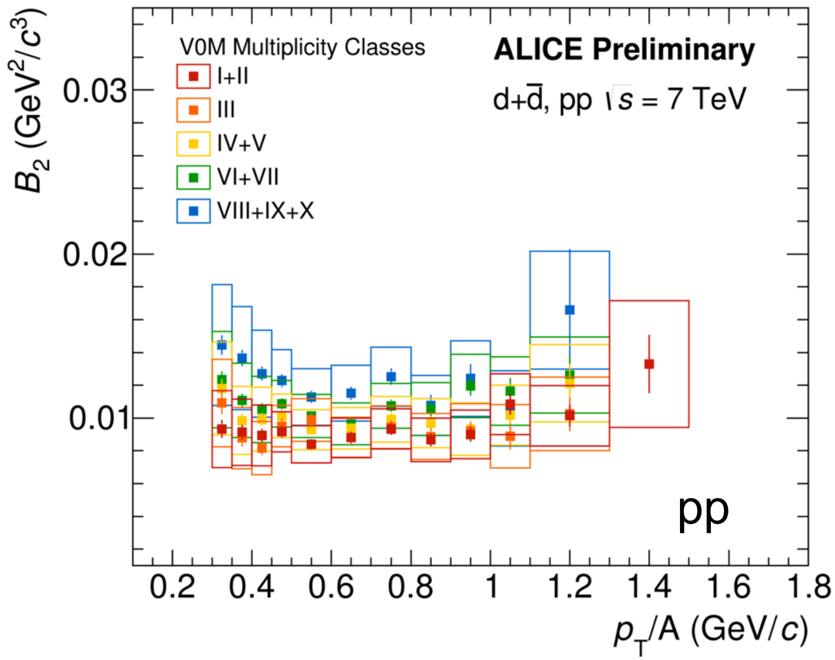


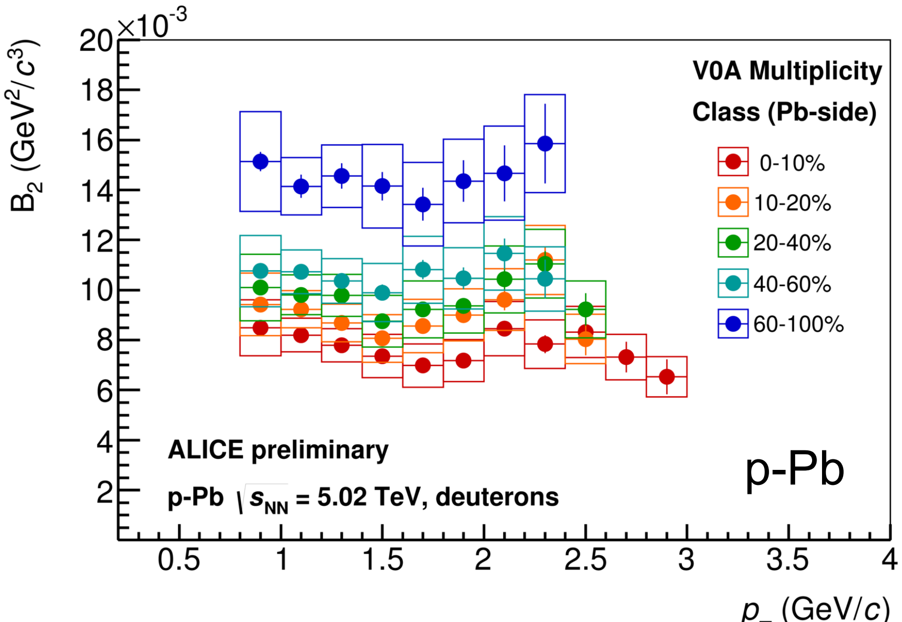


$$B_2 = \frac{3\pi^{3/2}\langle C_{\mathrm{d}}\rangle}{2m_{\mathrm{T}}R_{\perp}^2(m_{\mathrm{T}})R_{\parallel}(m_{\mathrm{T}})}$$

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



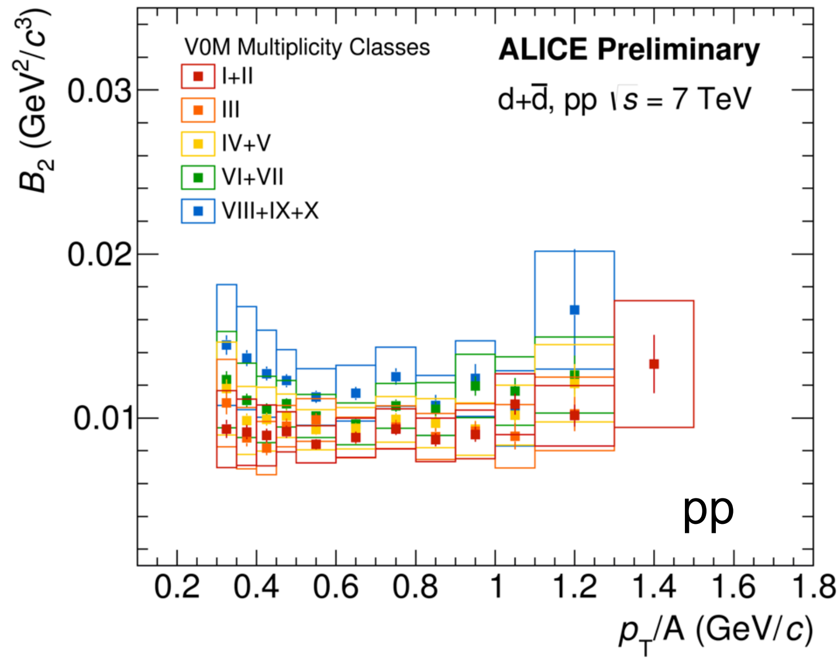


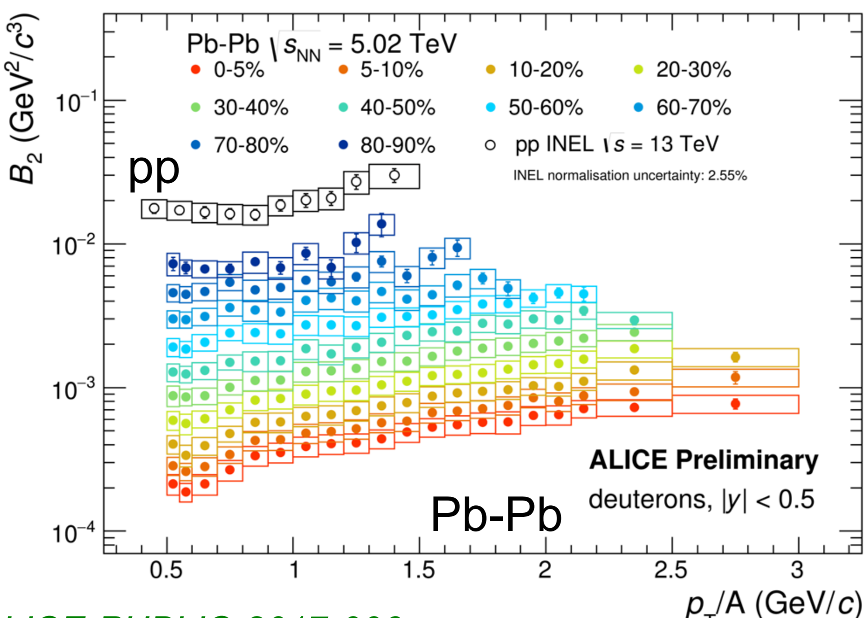
$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

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





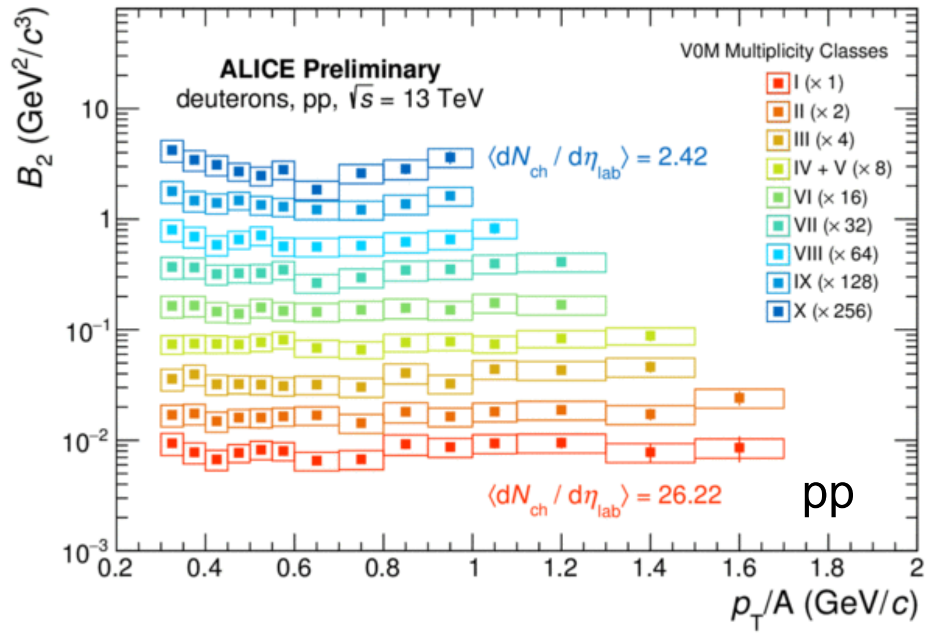
$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R_\perp^2(m_T) R_\parallel(m_T)}$$

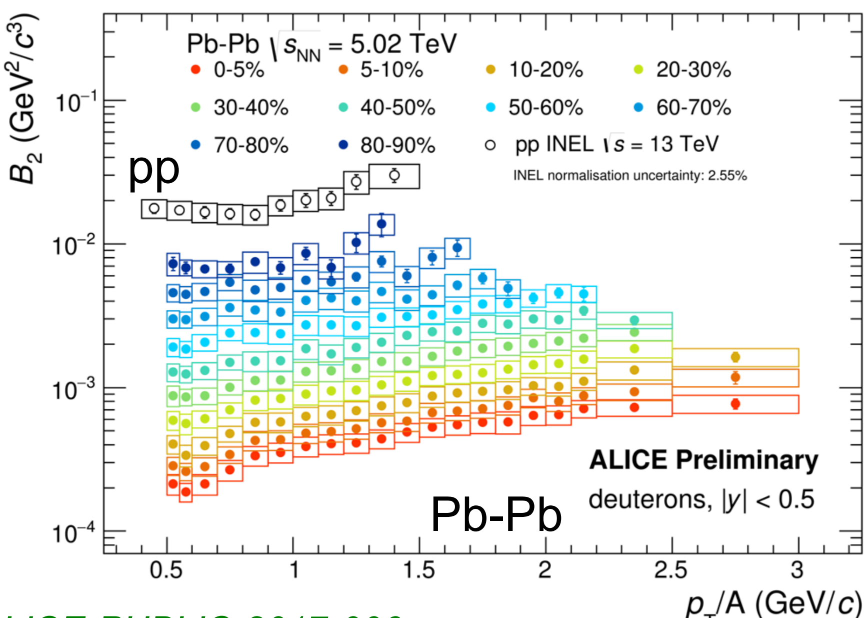
ALICE-PUBLIC-2017-006

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





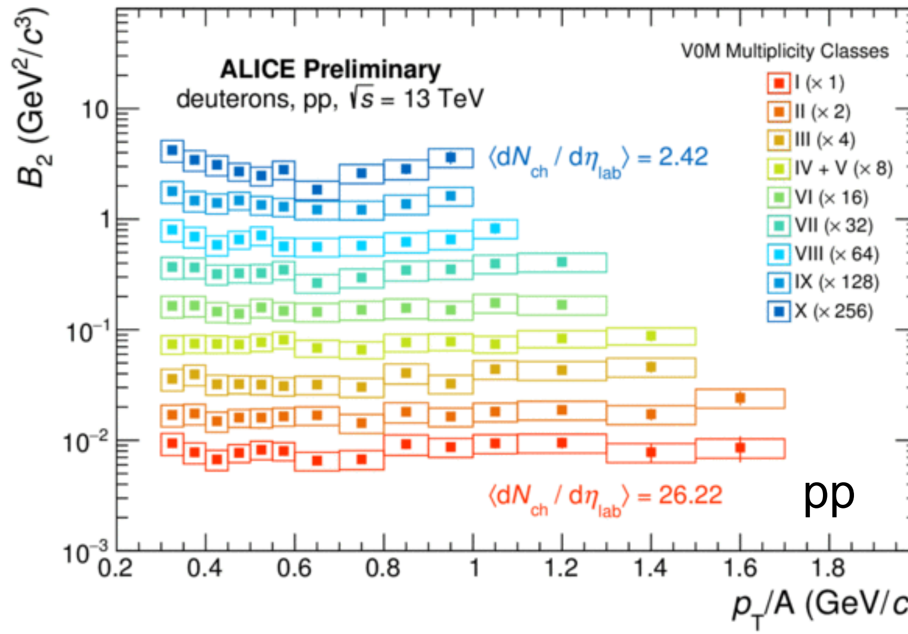
$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

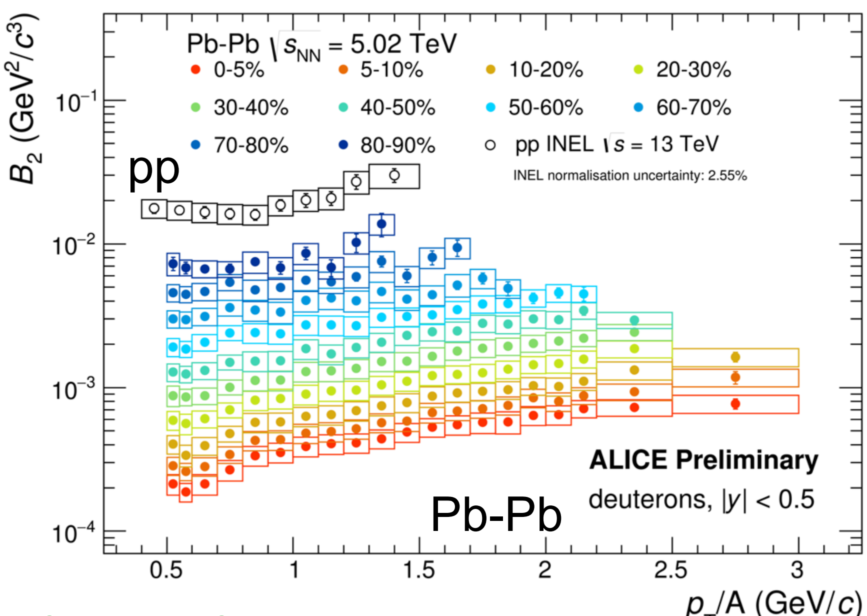
ALICE-PUBLIC-2017-006

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





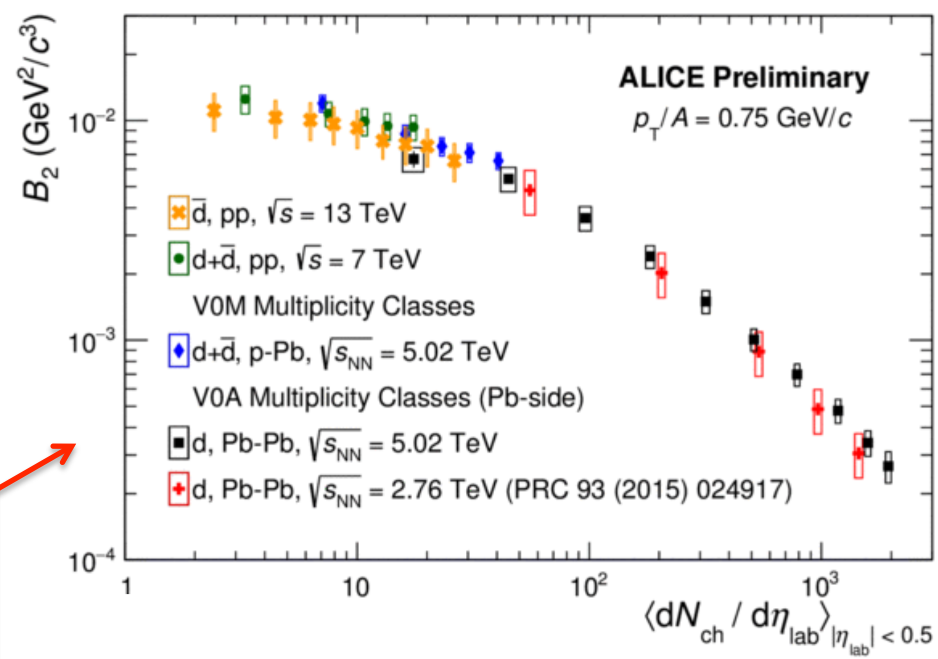
$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

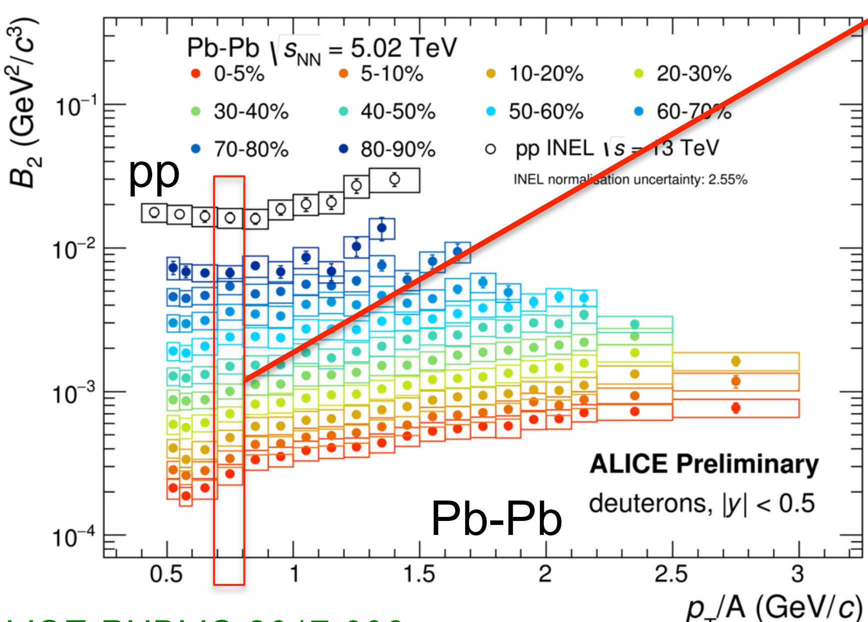
ALICE-PUBLIC-2017-006

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





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

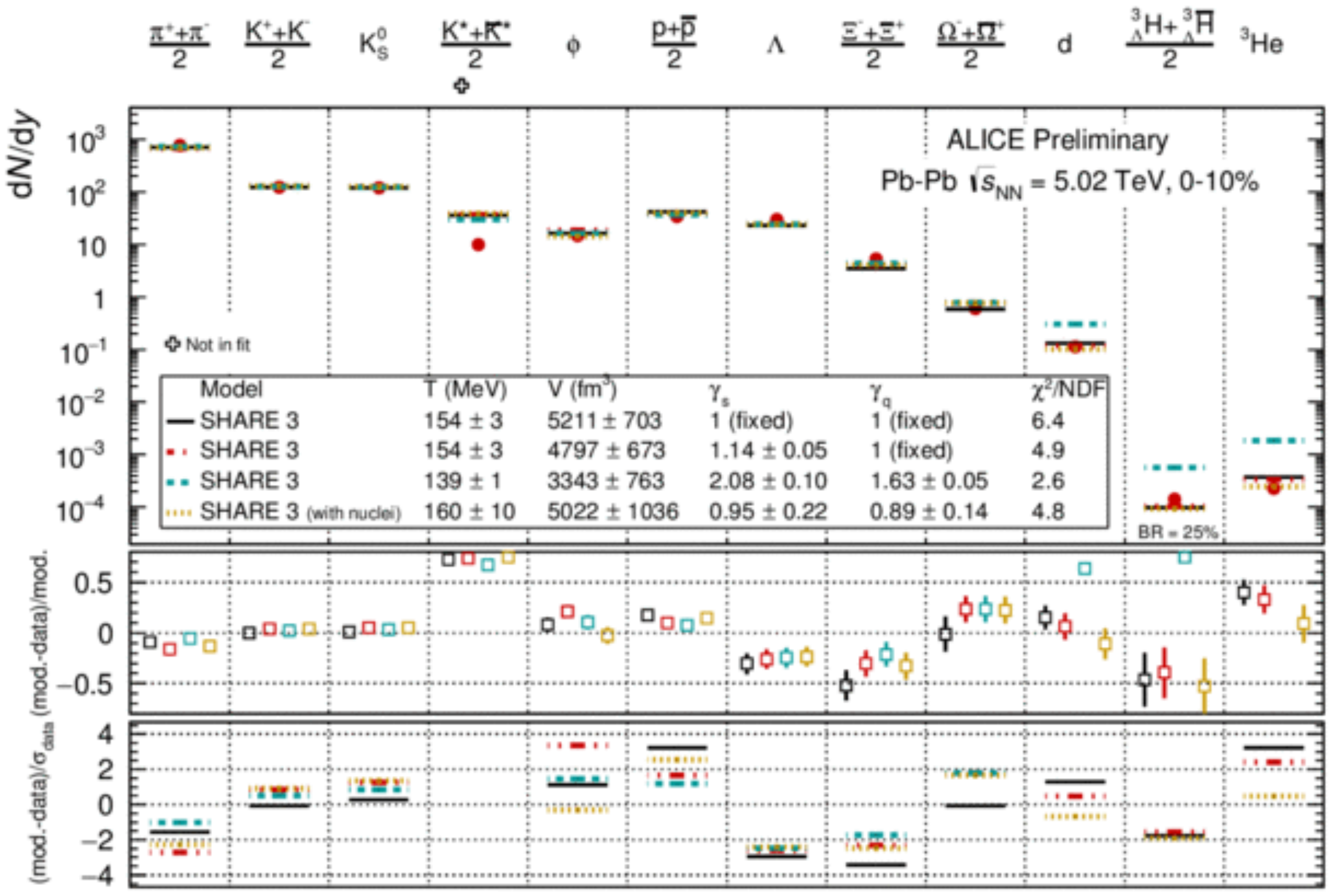
ALICE-PUBLIC-2017-006

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Thermal model fits

ALICE

THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

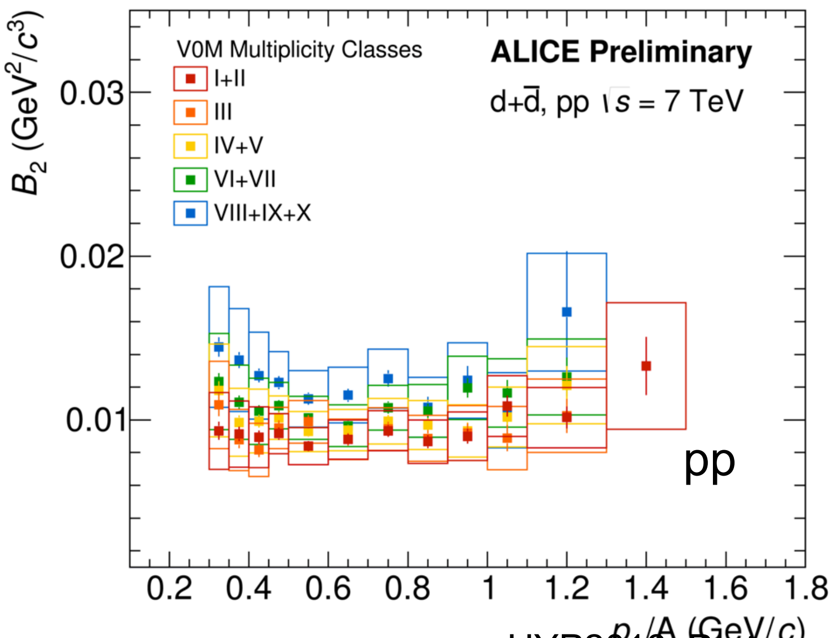


- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- Including nuclei in the fit causes no significant change in T_{ch}

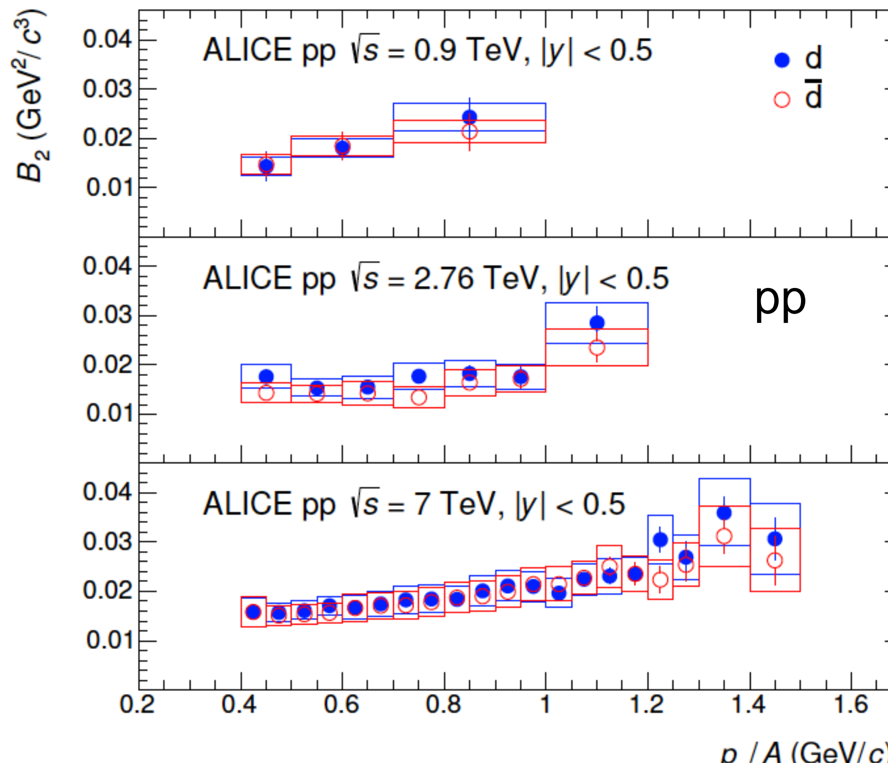
Coalescence parameter B_2

- 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



ALICE Collaboration, arXiv:1709.08522

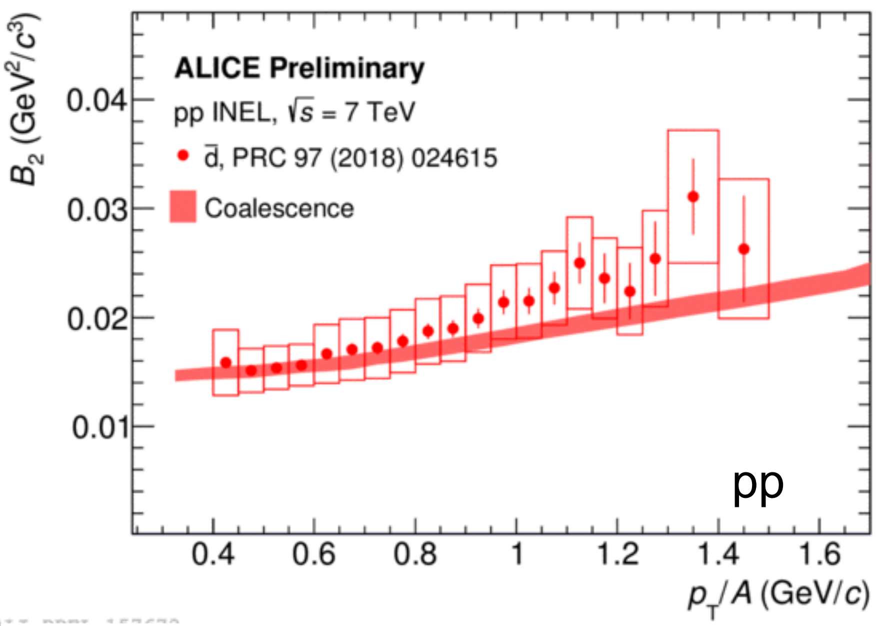


$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R_\perp^2(m_T) R_\parallel(m_T)}$$

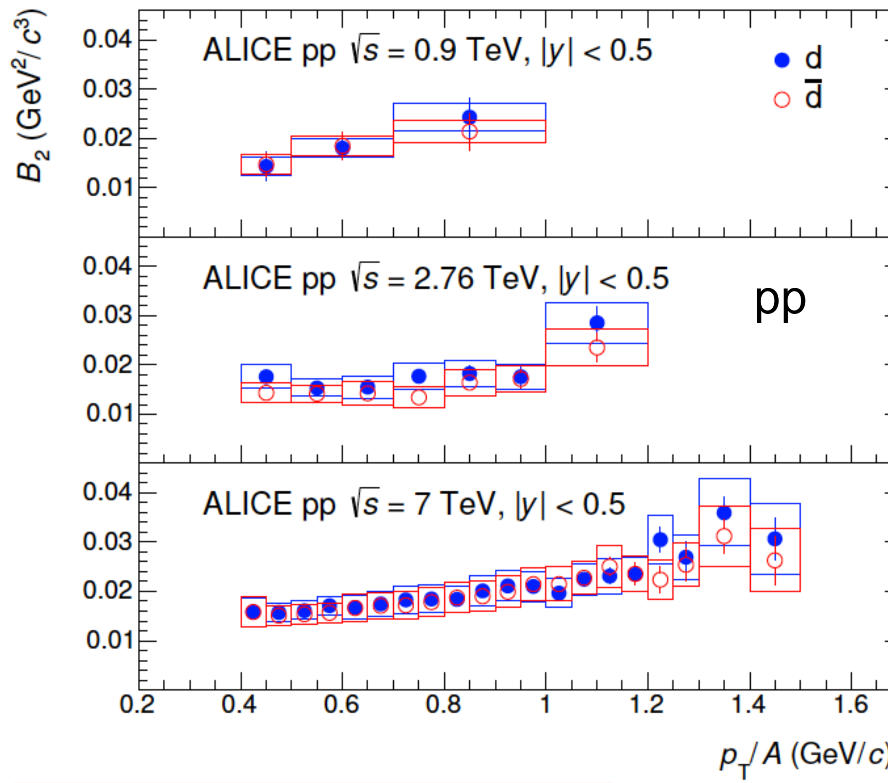
Coalescence parameter B_2

- 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



ALICE Collaboration, arXiv:1709.08522

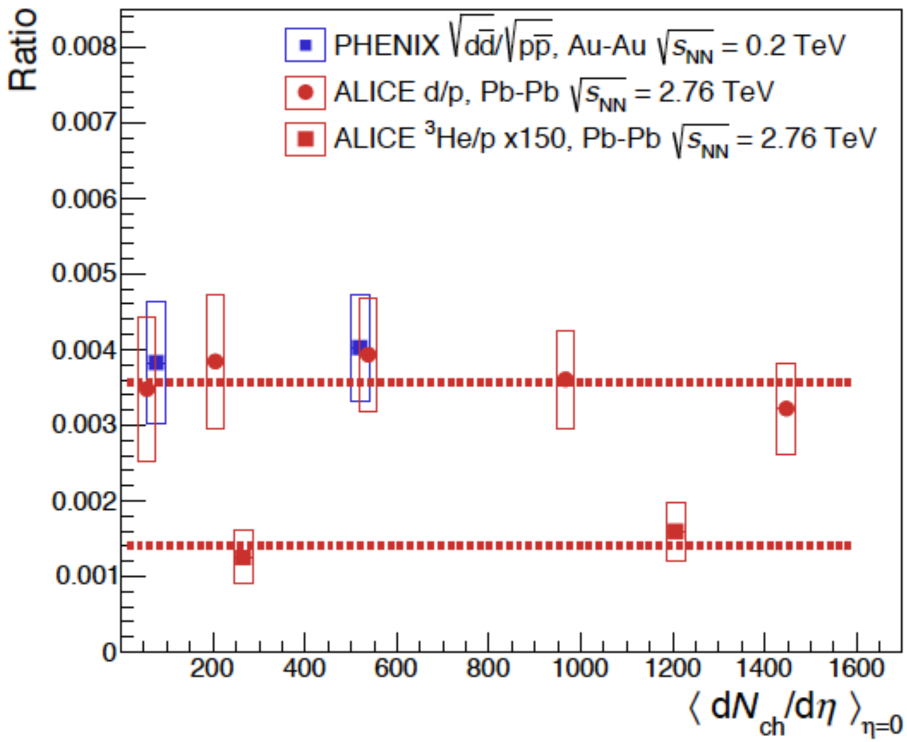


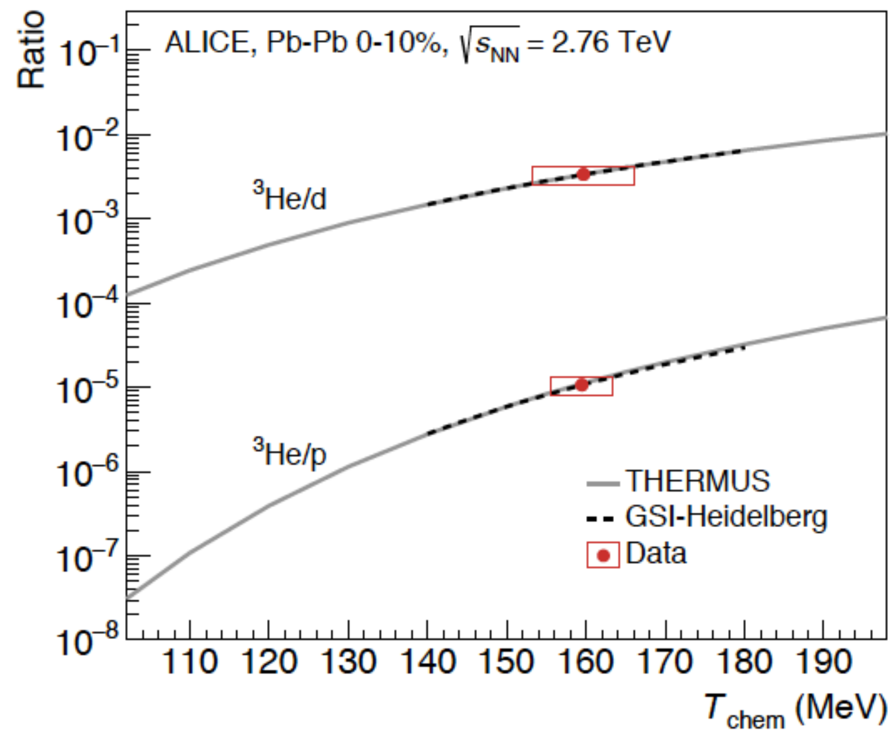
$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

Ratios between species

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

Extracted ratios agree with the thermal model values

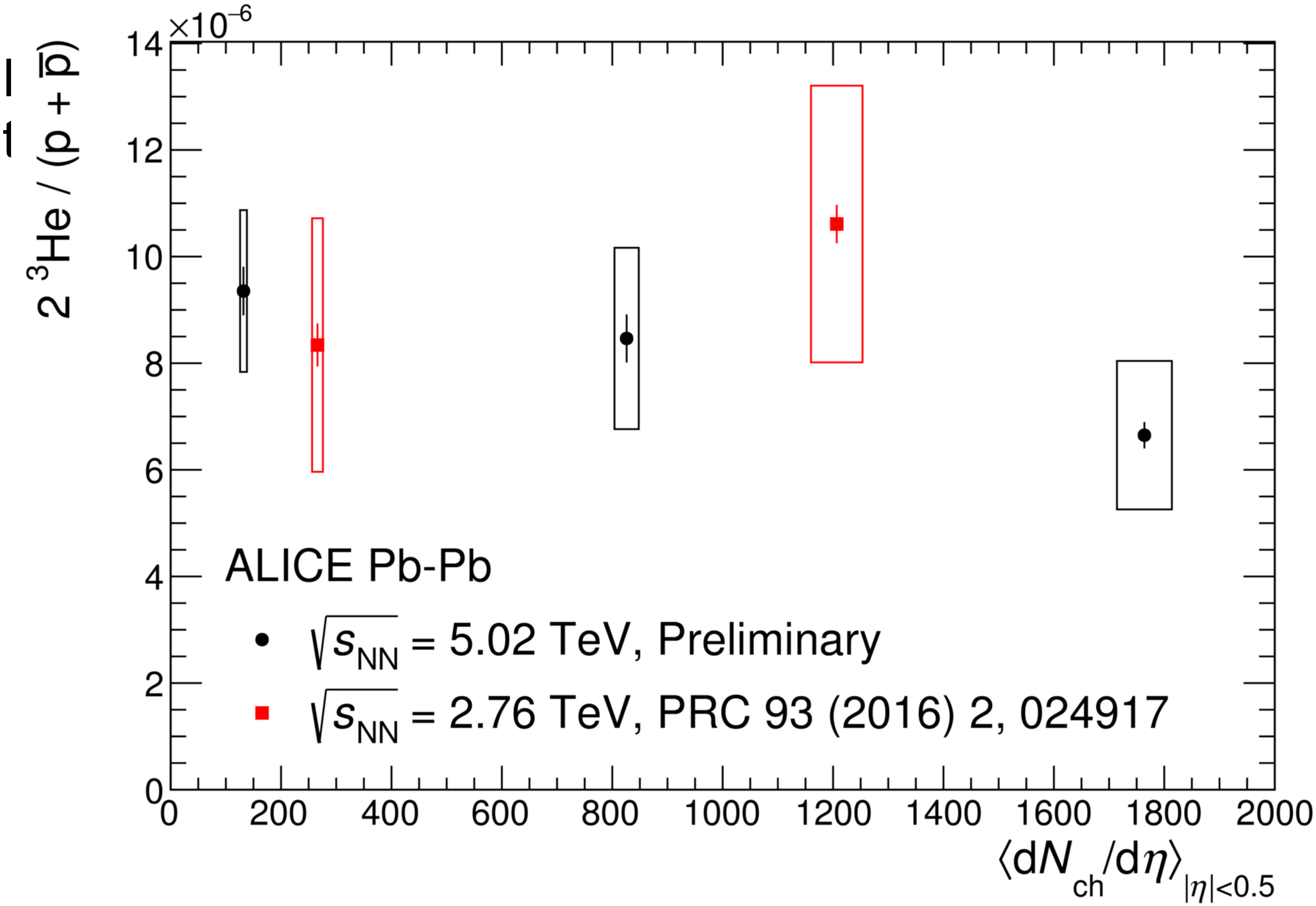


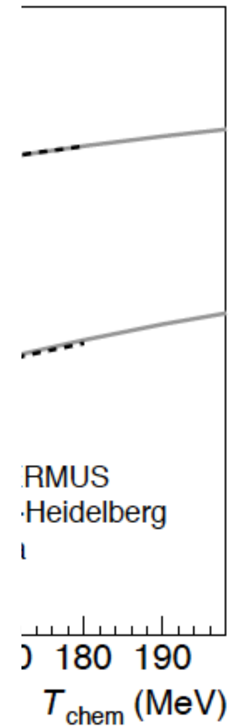


d/p ratio agrees well with the „averaged“ measurement at RHIC

Ratios between species

917 (2016)





th the

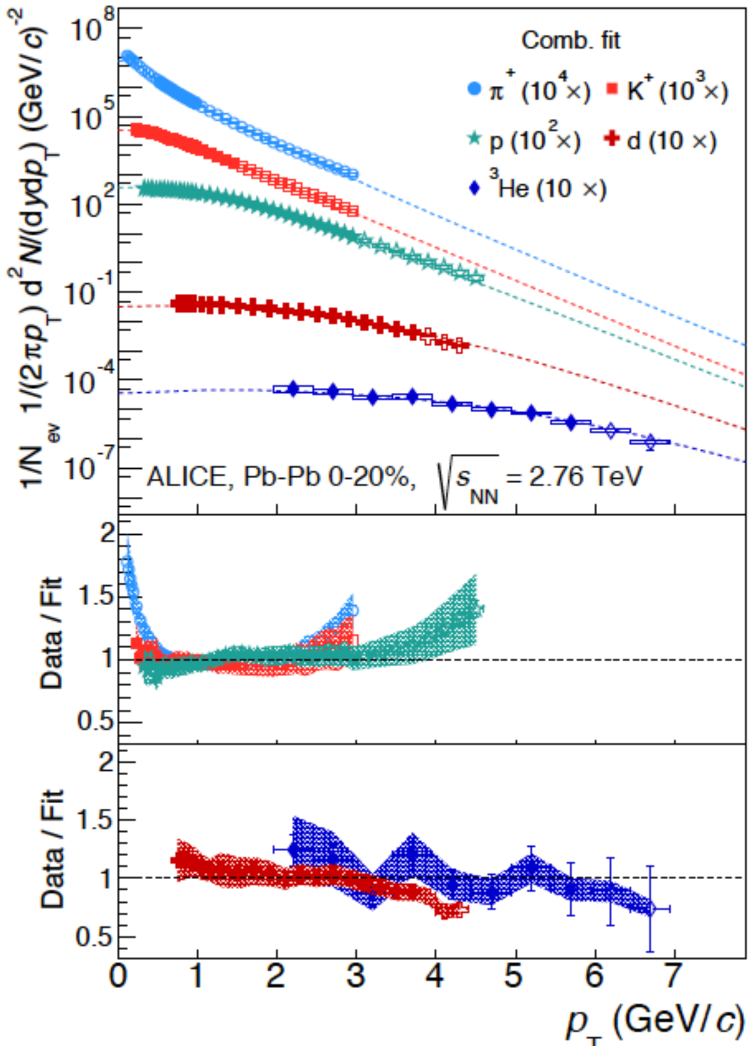
nt at

Combined Blast-Wave fit

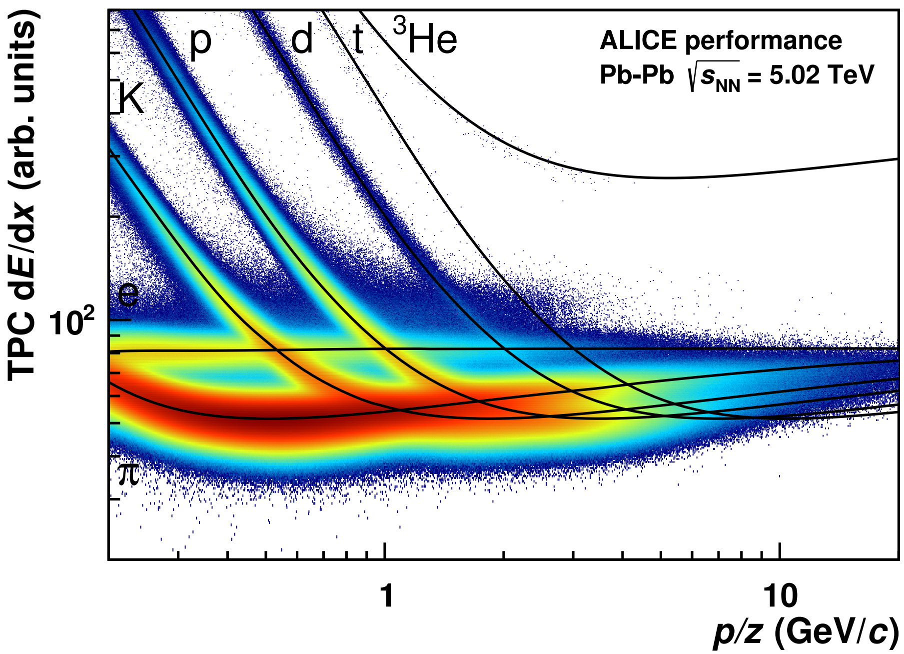
ALICE Collaboration: J. Adam et al., PRC 93, 024917 (2016)

Simultaneous Blast-Wave fit of π^+, K^+, p, d and ^{3}He 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

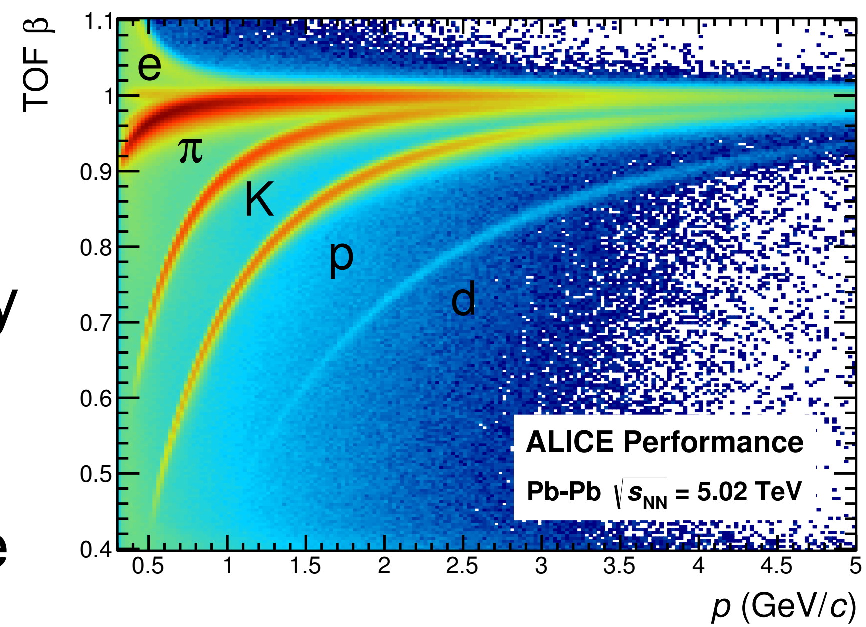
All particles are described rather well with this simultaneous fit



Outlook: Run 2



- Run 2 of the LHC has started in 2015 and for Pb-Pb collisions ~ factor 10 increase expected in statistics



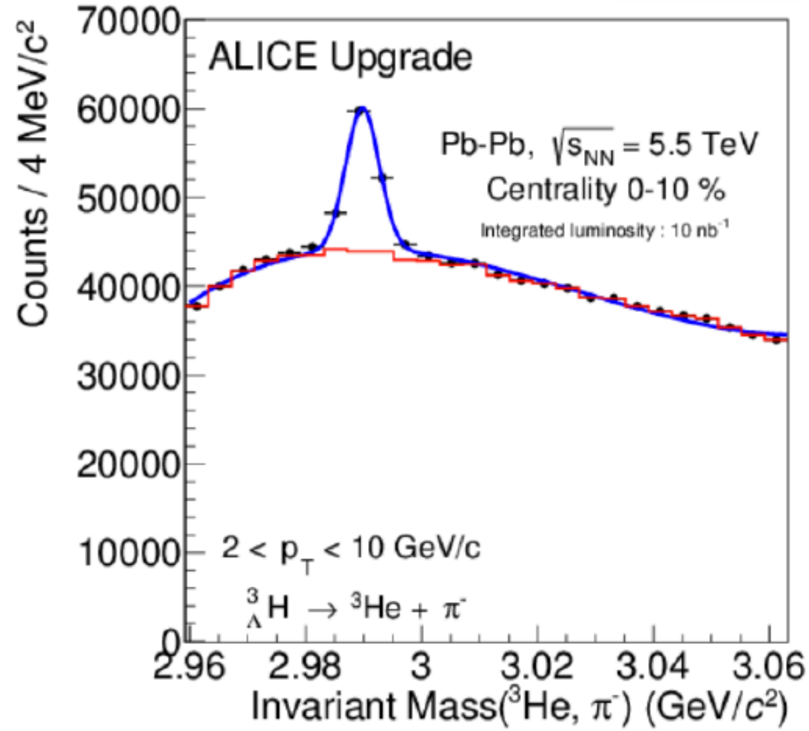
- Performance shown here only for a small fraction (~3M MB events)

→ Light nuclei are clearly visible

→ Interesting results ahead

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 continous 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)

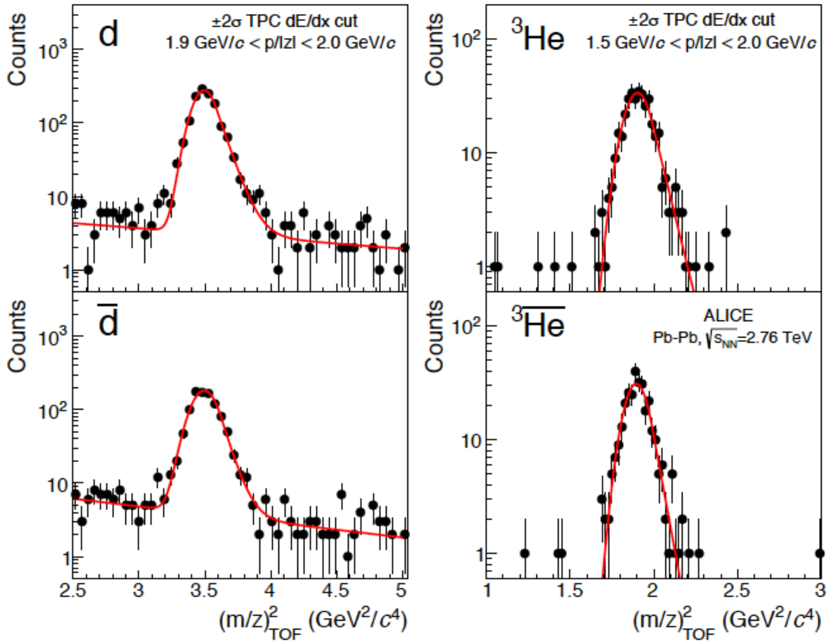
State	dN/dy	B.R.	$\langle Acc \times \epsilon \rangle$	Yield
$^{3}_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
$^{4}_{\Lambda}H$	2×10^{-7}	50%	7 %	110
$^{4}_{\Lambda}He$	2×10^{-7}	32%	8 %	130

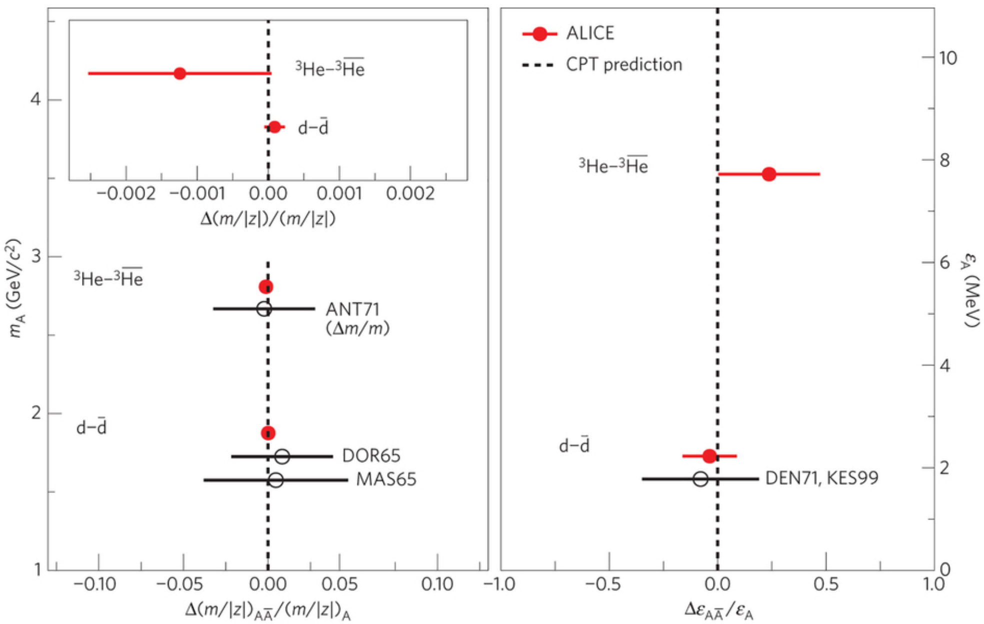
Precision mass measurement

- 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

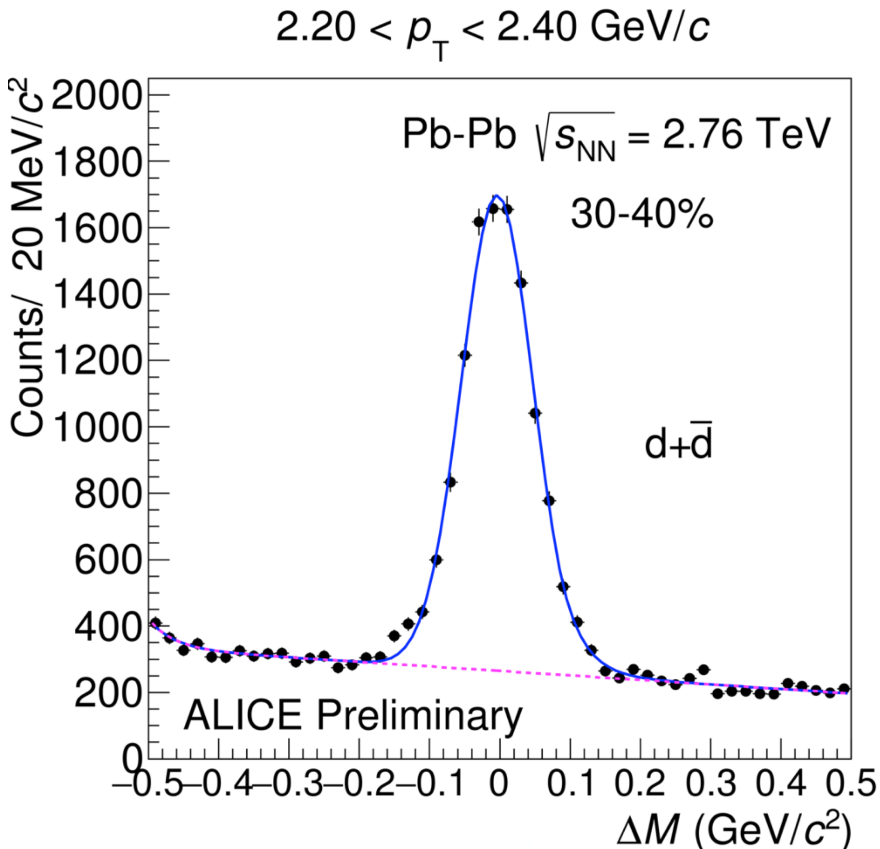
ALICE Collaboration: Nature Phys. 11, 811 (2015)

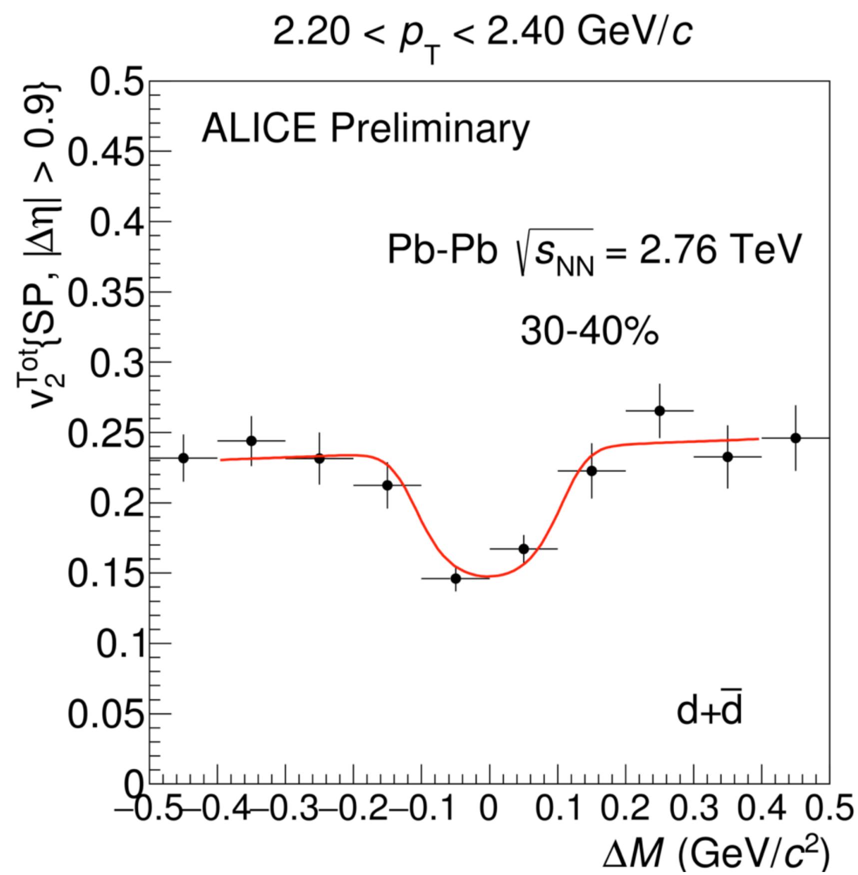




➜ Mass and binding energies of nuclei and anti-nuclei are compatible within uncertainties
➜ Measurement confirms the CPT invariance for light nuclei.

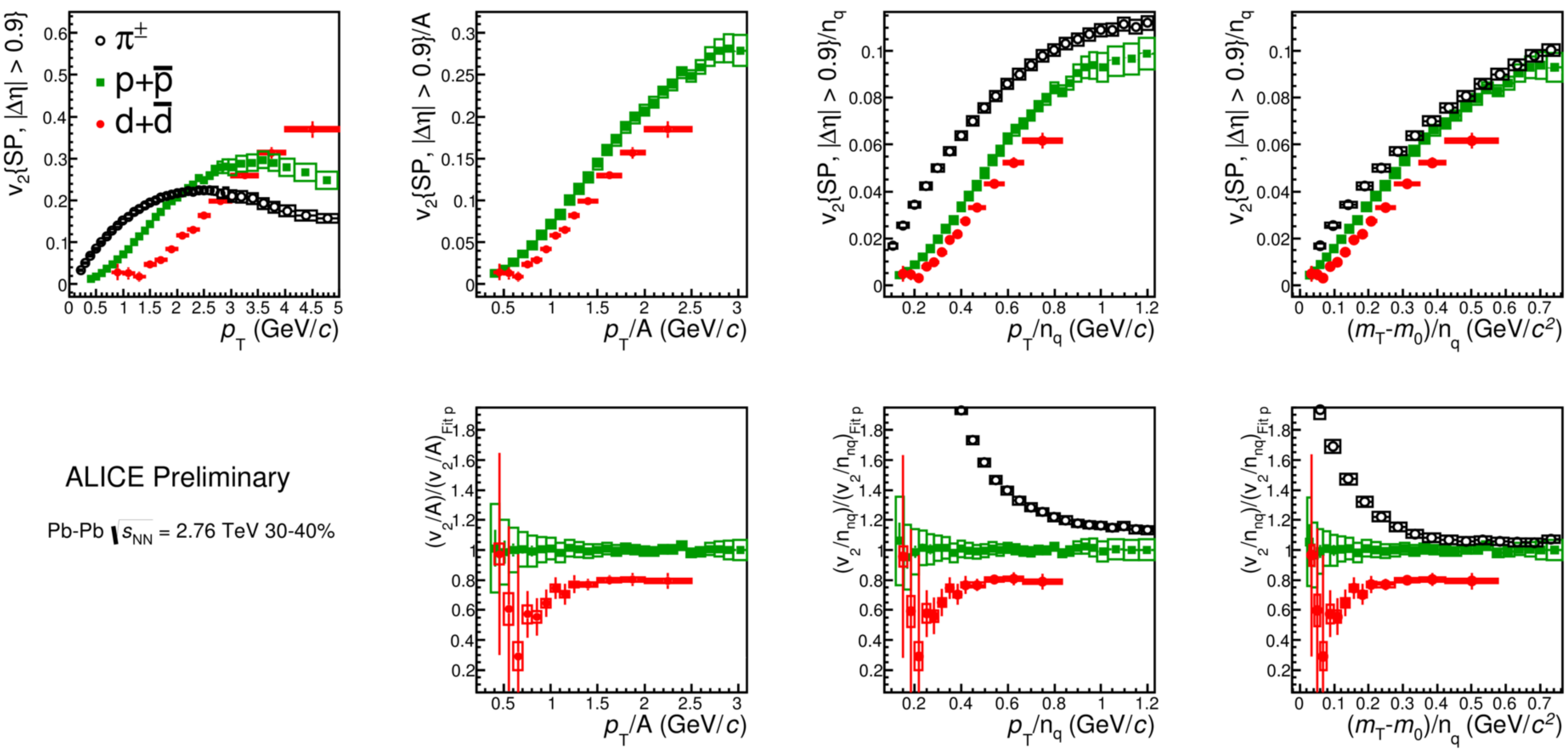
Elliptic flow



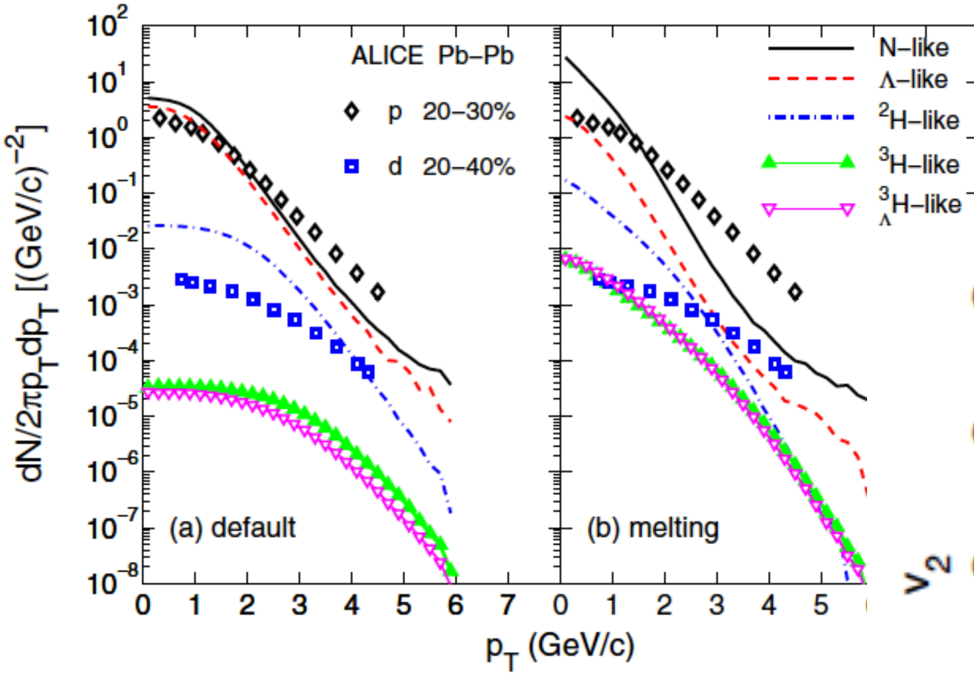


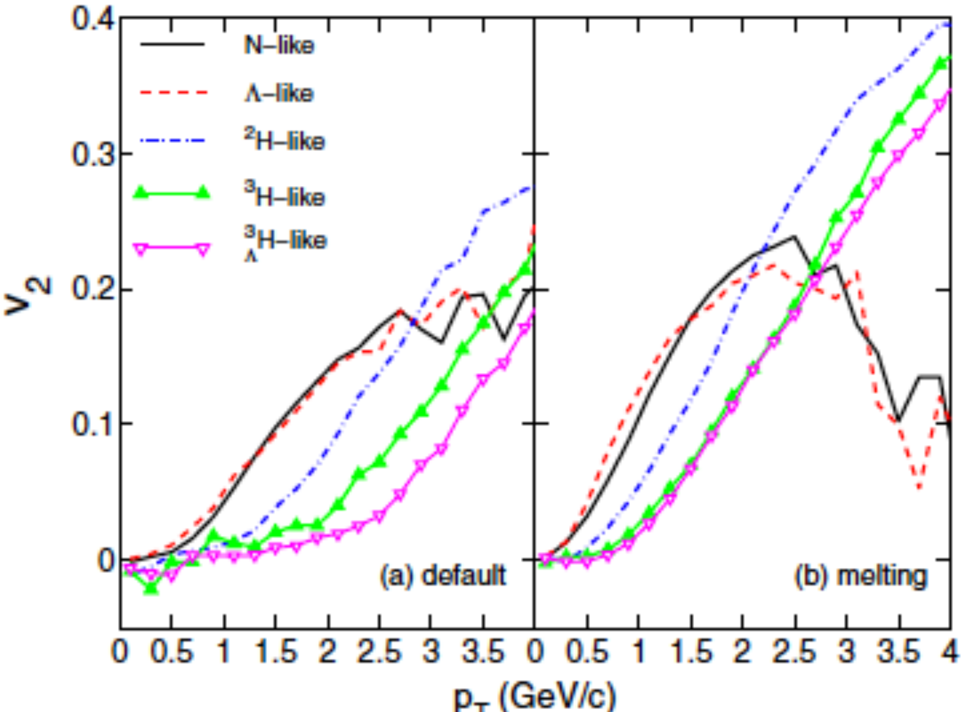
$$v_n\{SP\} = \frac{\langle u_{n,i}(p_T,\eta) \cdot \frac{Q_n^*}{M} \rangle}{\sqrt{\langle \frac{Q^*_{n,A}}{M_A} \cdot \frac{Q^*_{n,B}}{M_B} \rangle}}$$

Elliptic flow



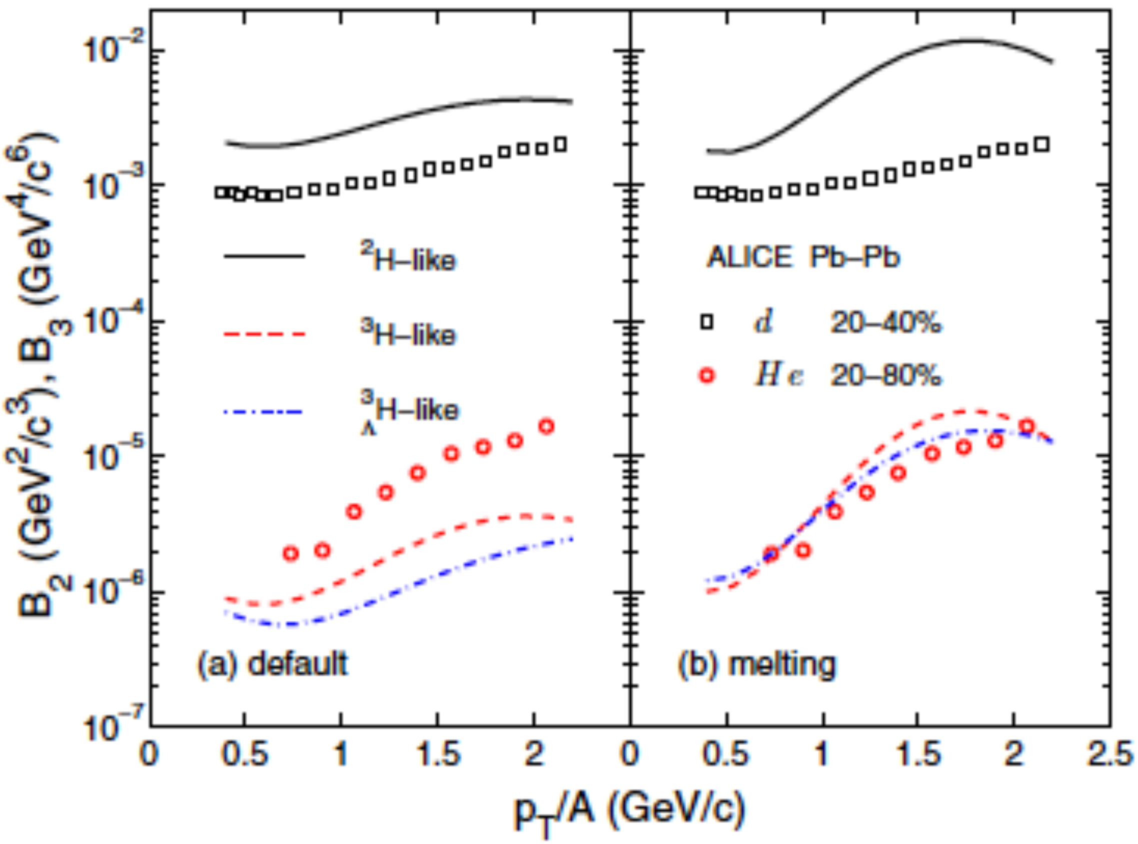
Elliptic flow





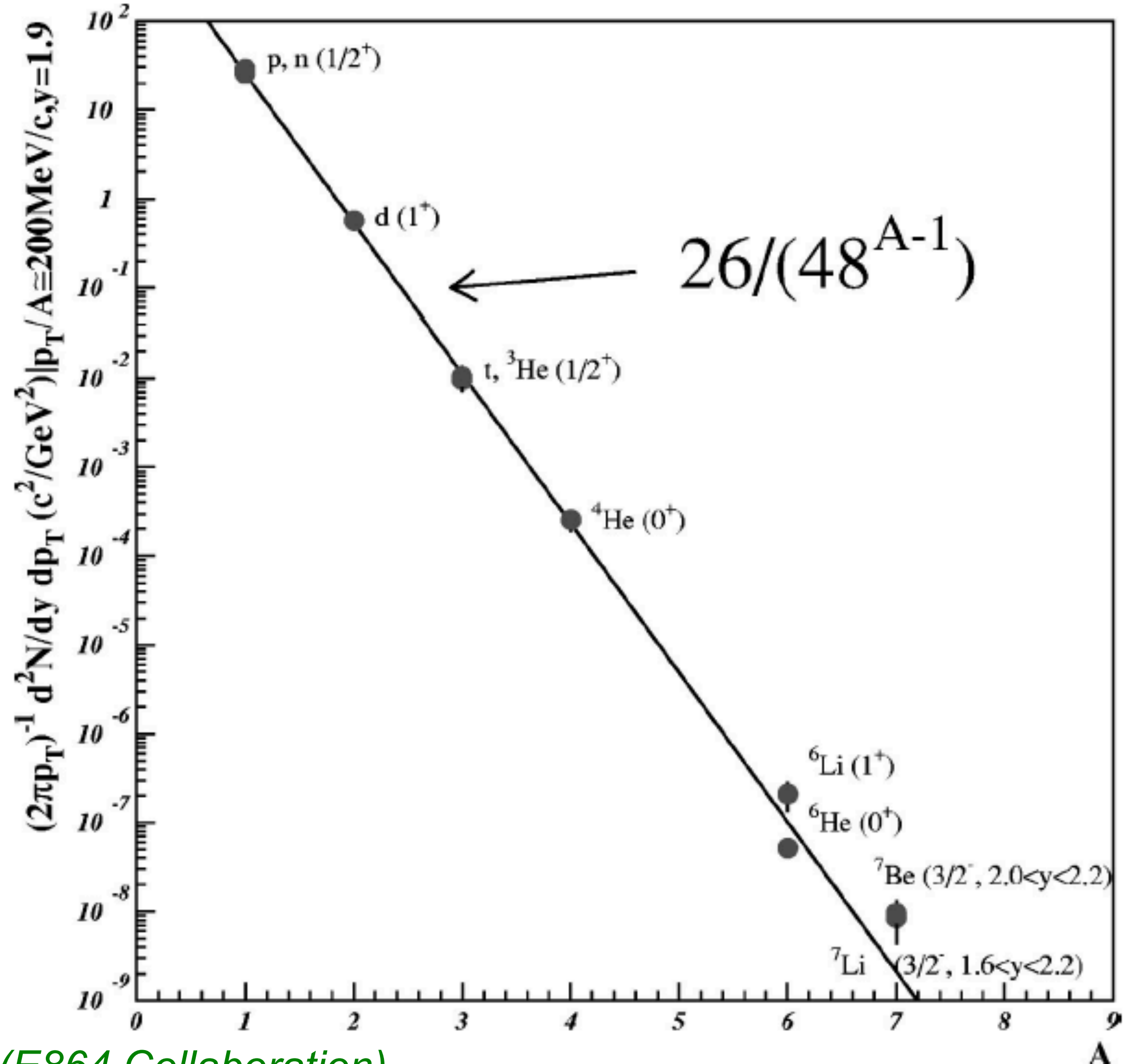
L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

Elliptic flow



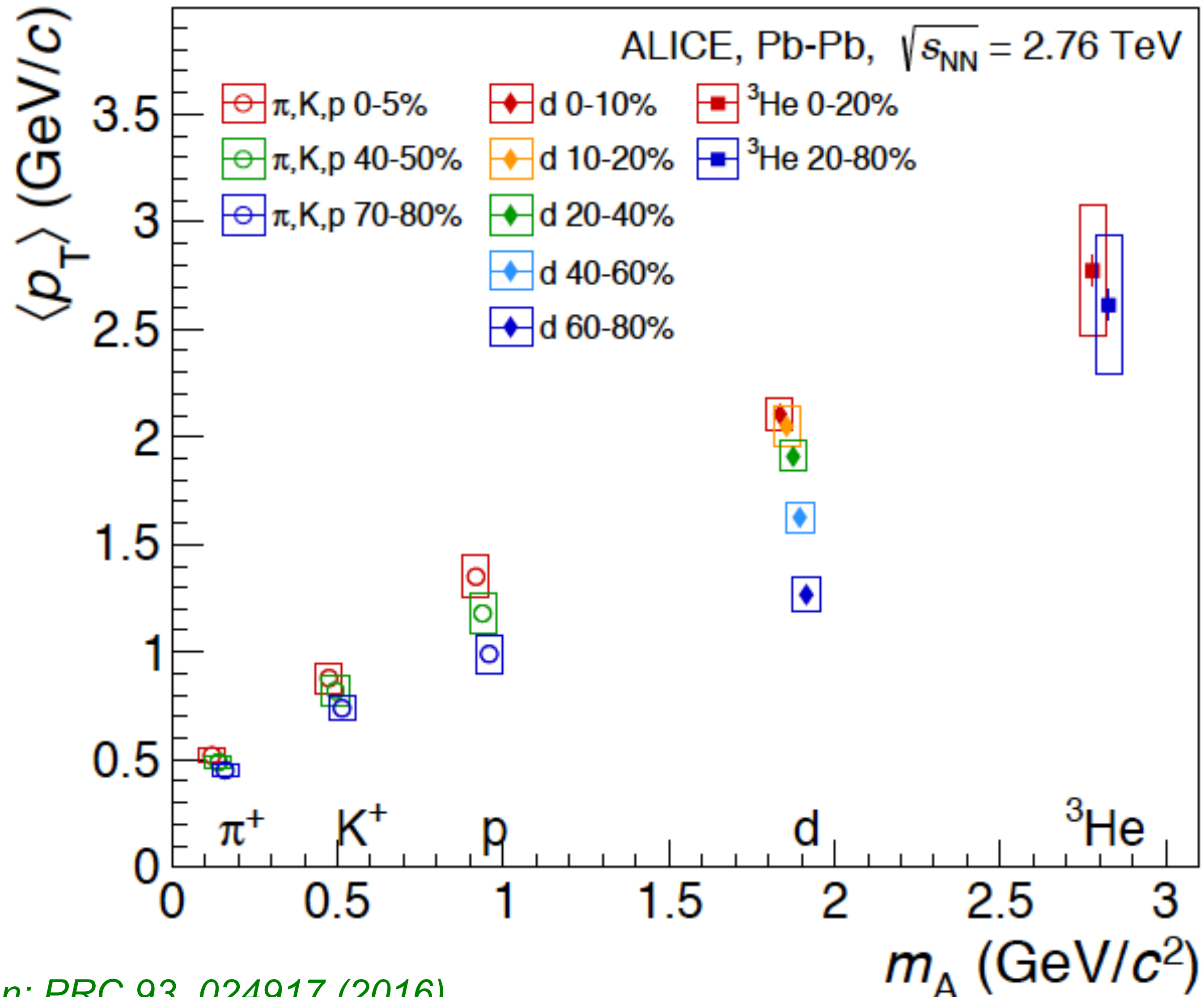
L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

E864 nuclei result



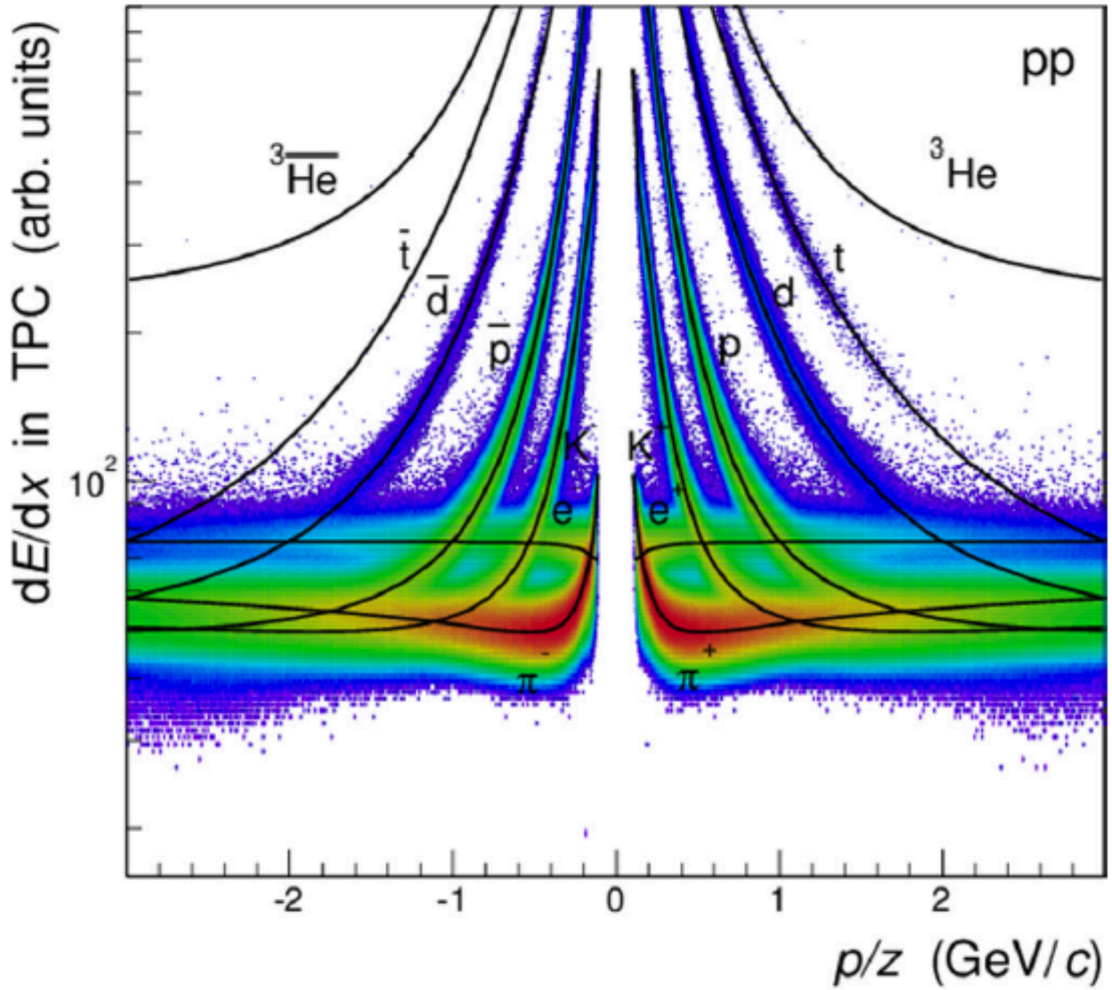
T.A. Armstrong et al. (E864 Collaboration), Phys. Rev. C 61 (2000) 064908

Mean p_T



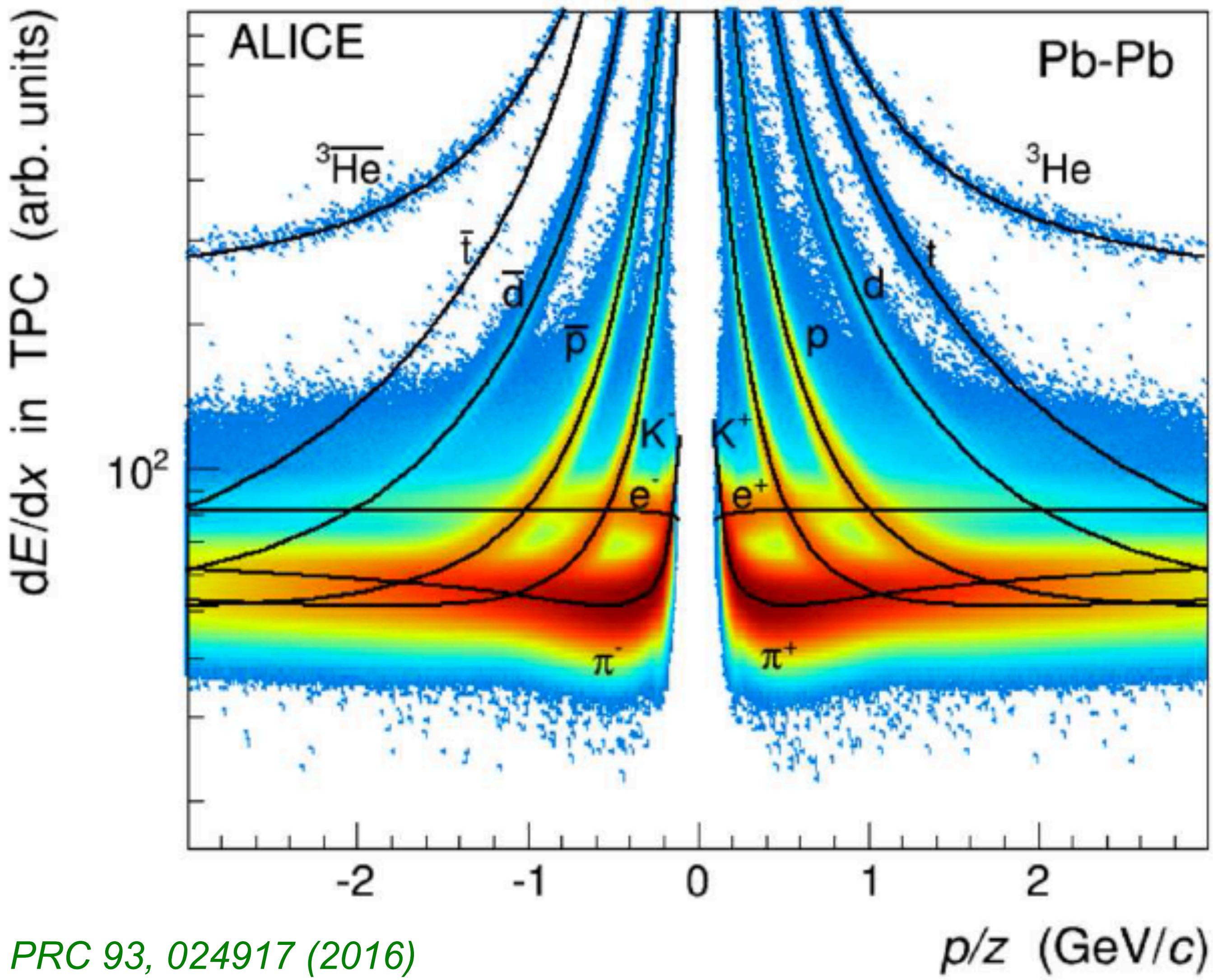
ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in pp



ALICE Collaboration: PRC 93, 024917 (2016)

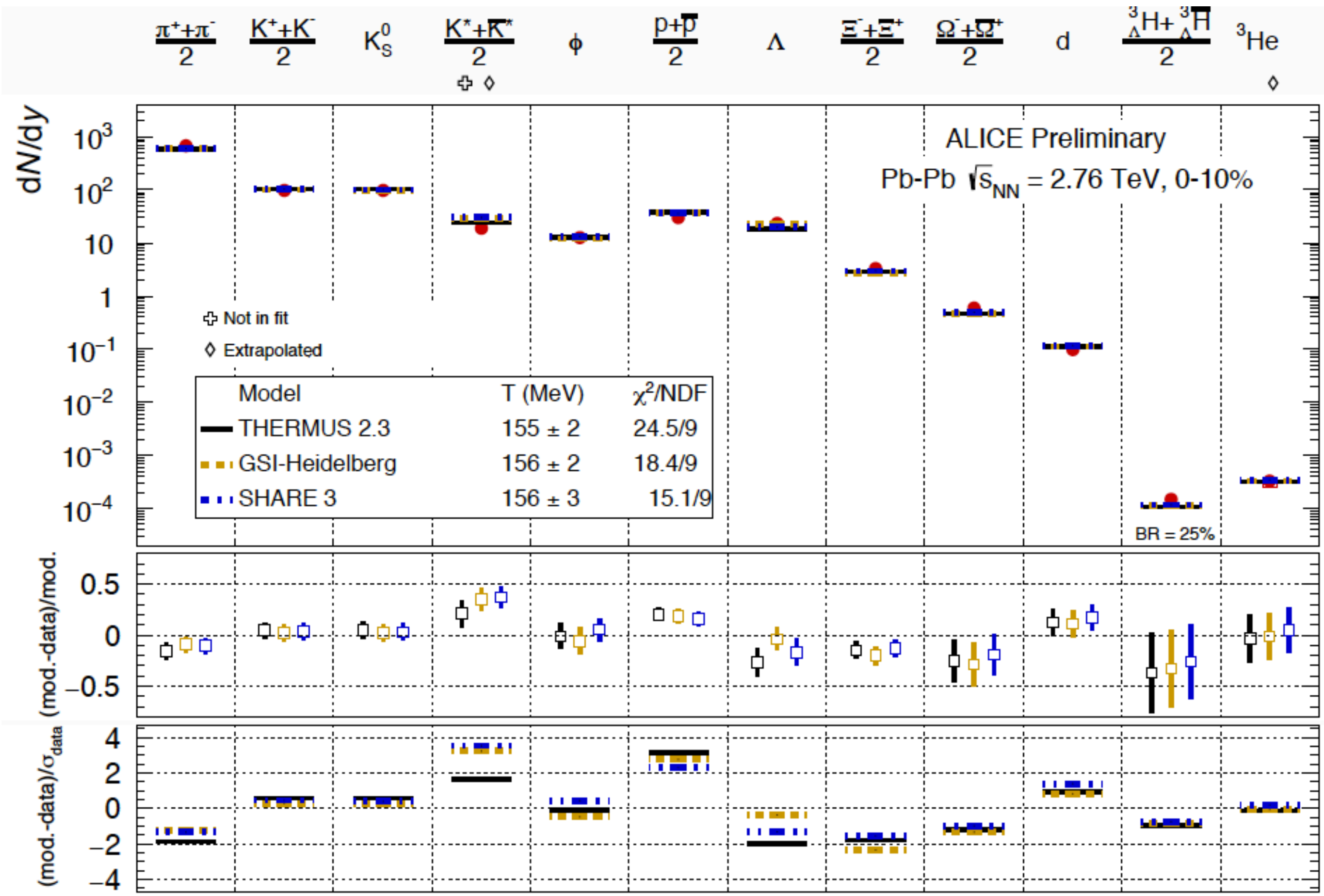
TPC PID in Pb-Pb



ALICE Collaboration: PRC 93, 024917 (2016)

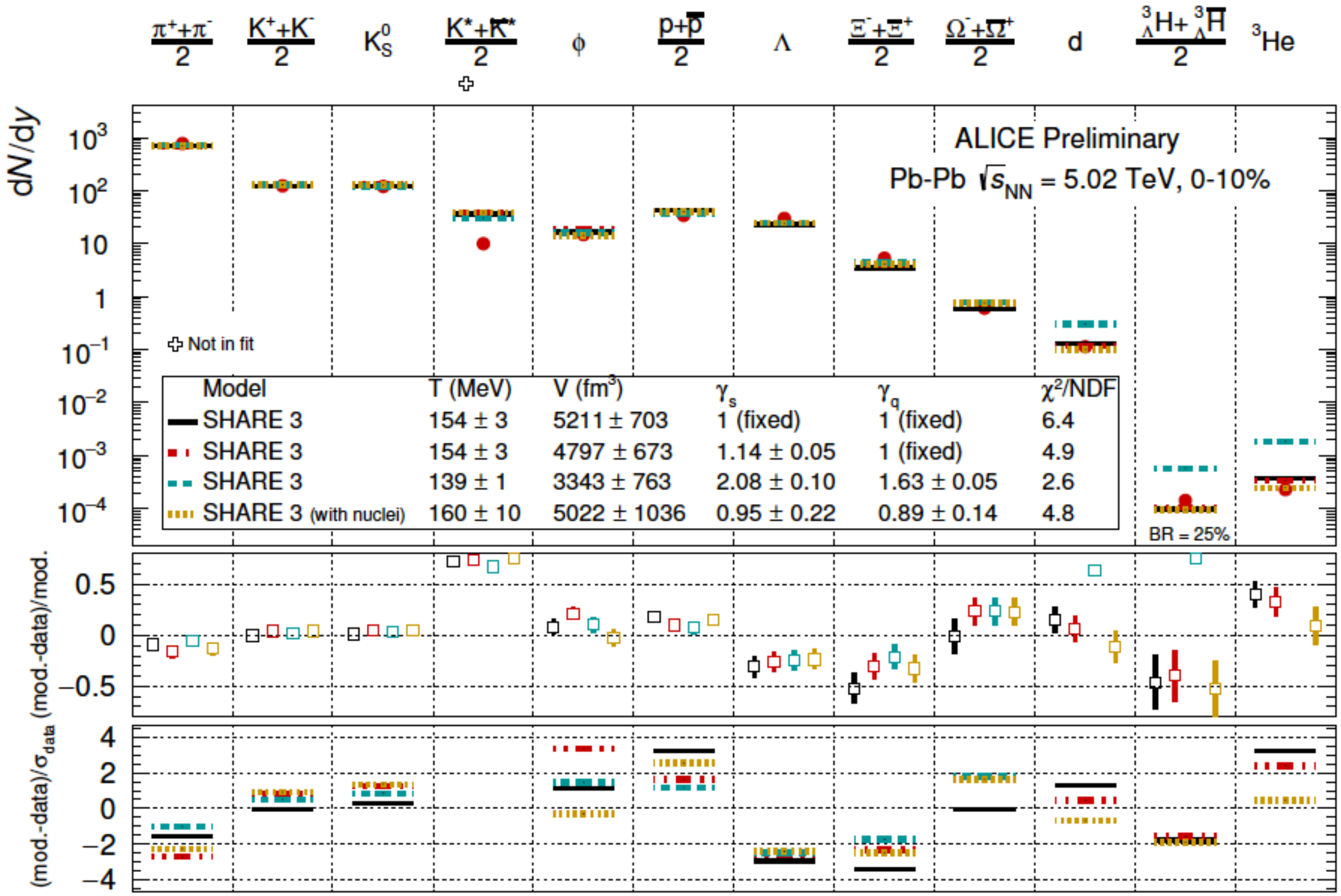
Thermal model fits

THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)



- 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}

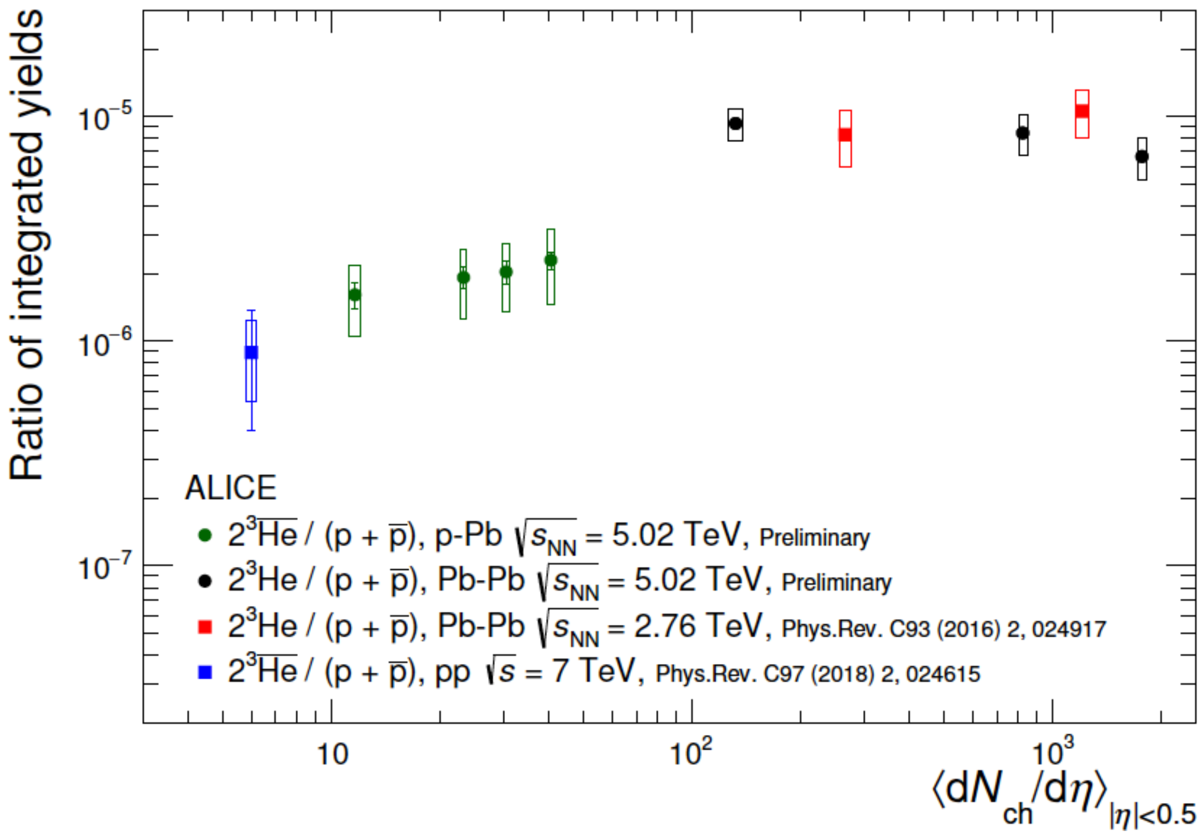
Thermal model: SHARE



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

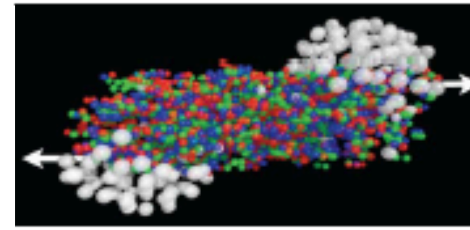
- Observations similar to QM2014 results
- Including nuclei drives a non-equilibrium fit towards the equilibrium values

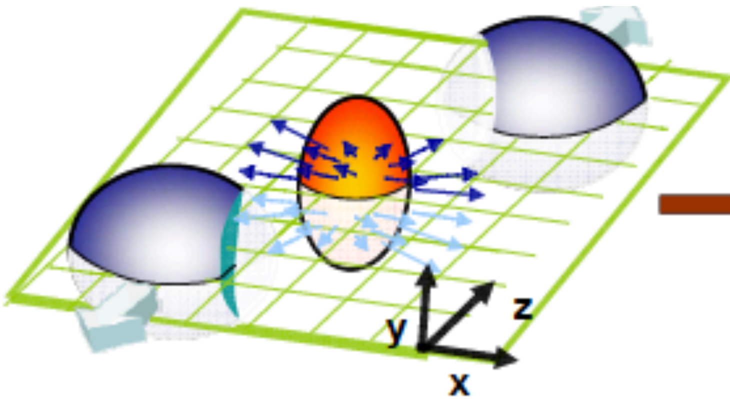
^{3}He/p vs. multiplicity

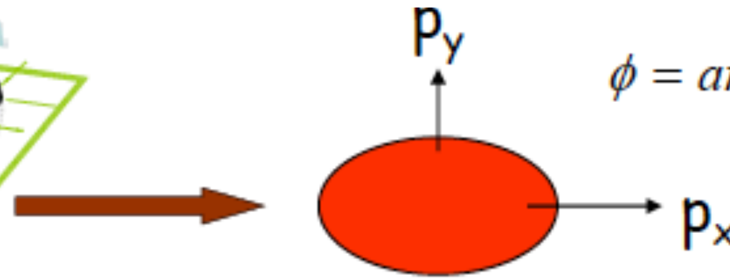


^{3}He/p ratio increases also when going from pp to p-Pb, until it reaches the grand canonical thermal model value (^{3}He/p=8x10^{-6} at T_{ch}= 156 MeV)

Elliptic flow







$$\phi = arc\tan\frac{p_y}{p_x}$$

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

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

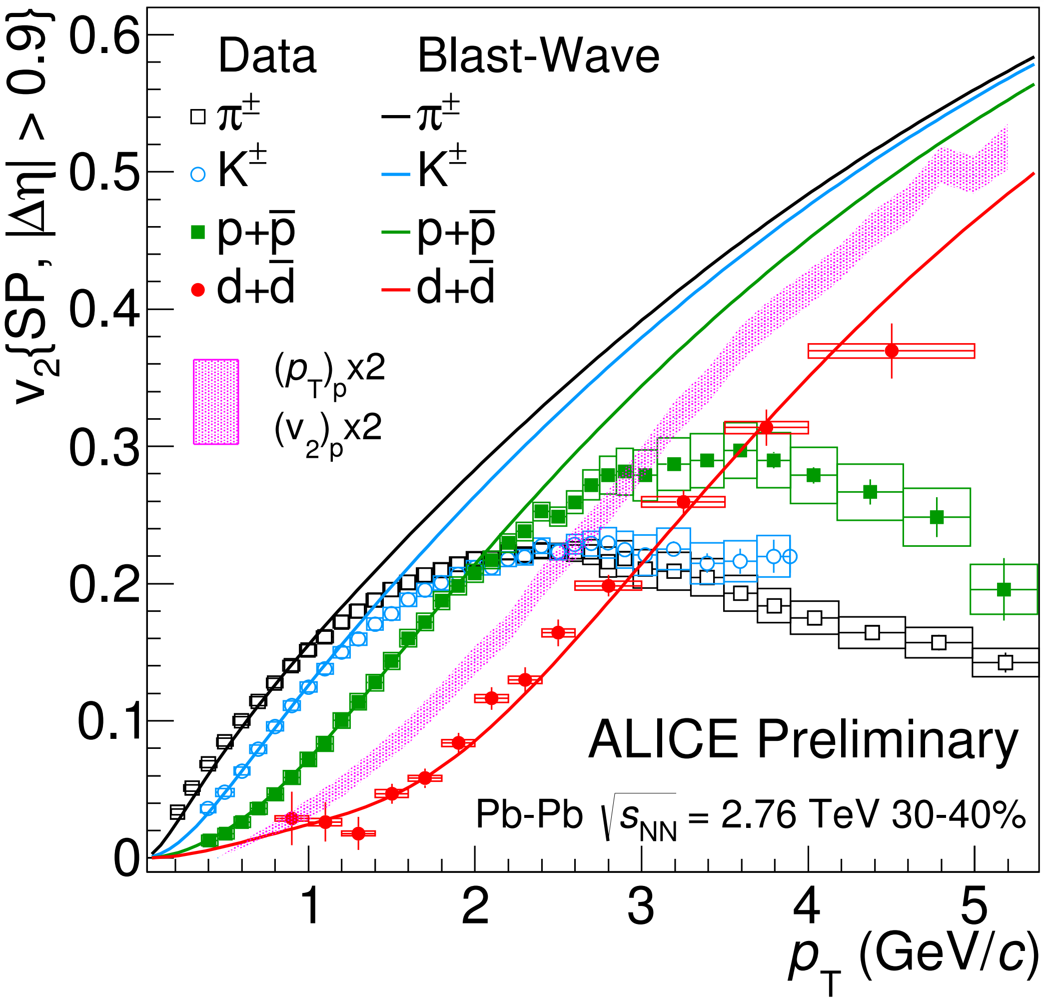
$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos[2(\phi - \Psi_R)] + 2v_4\cos[4(\phi - \Psi_R)] + \ldots$$

Elliptic term

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

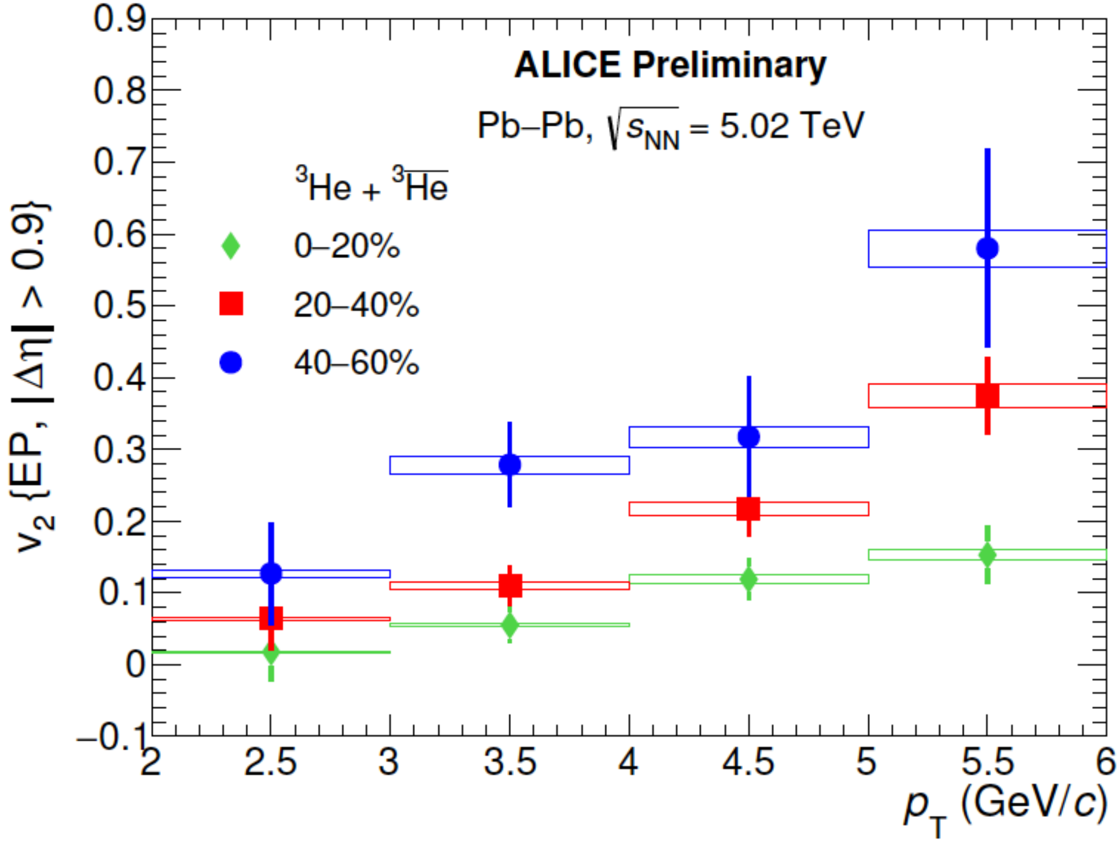
Deuteron flow

- 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

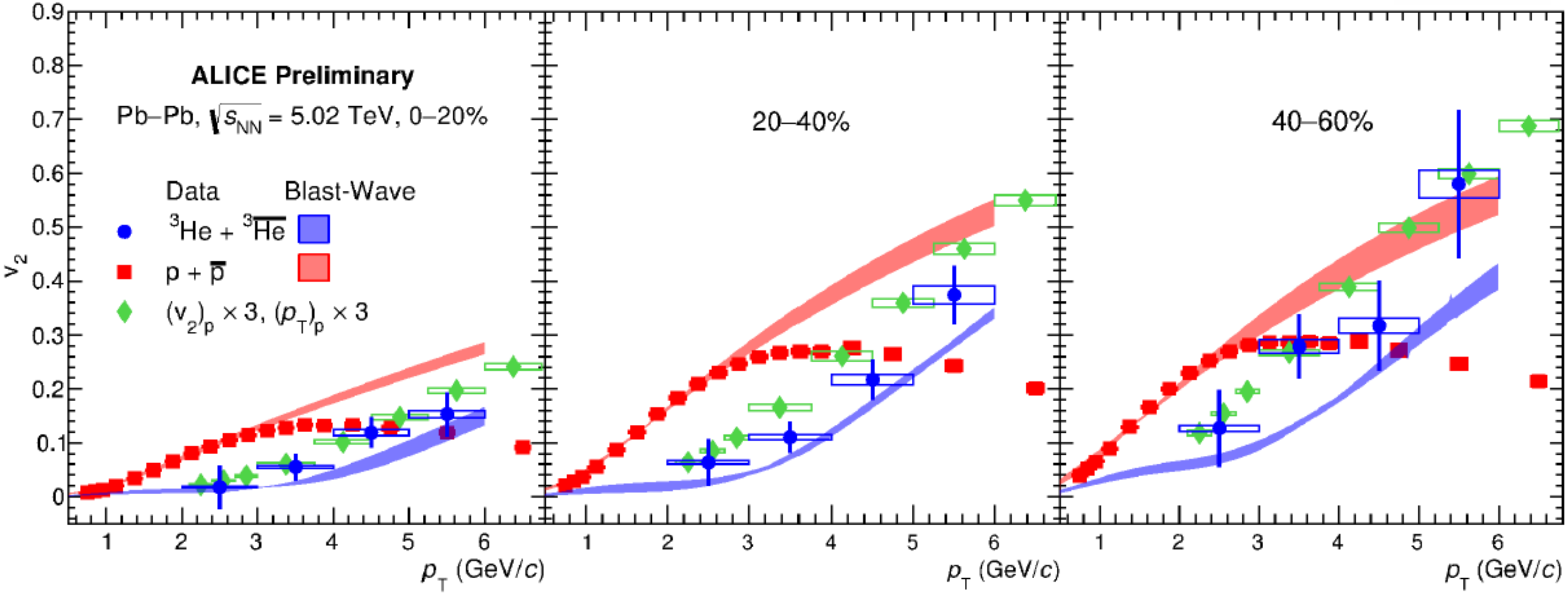


^{3}He flow

- ^{3}He also shows a significant v_2

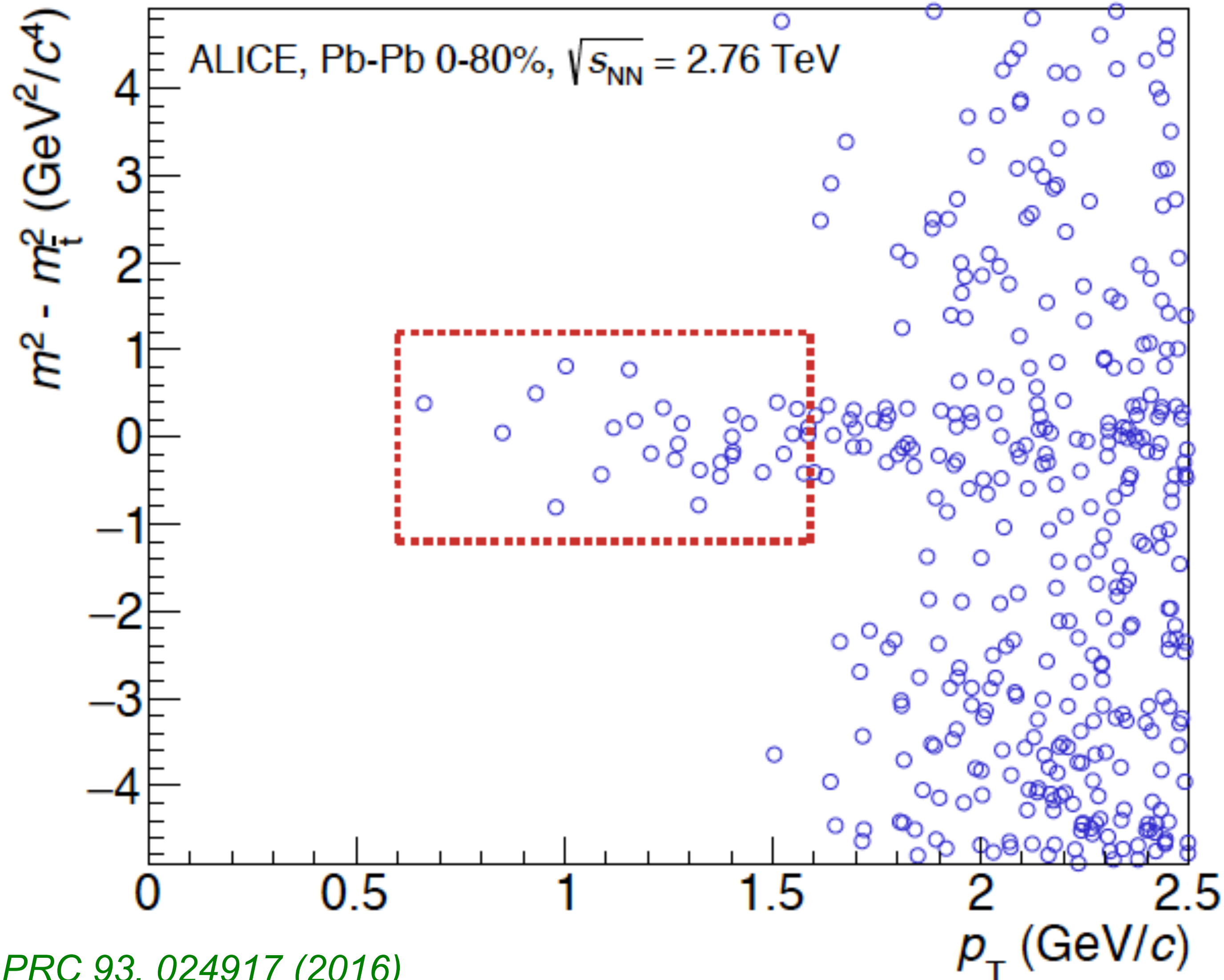


^{3}He flow



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

Anti-tritons



ALICE Collaboration: PRC 93, 024917 (2016)