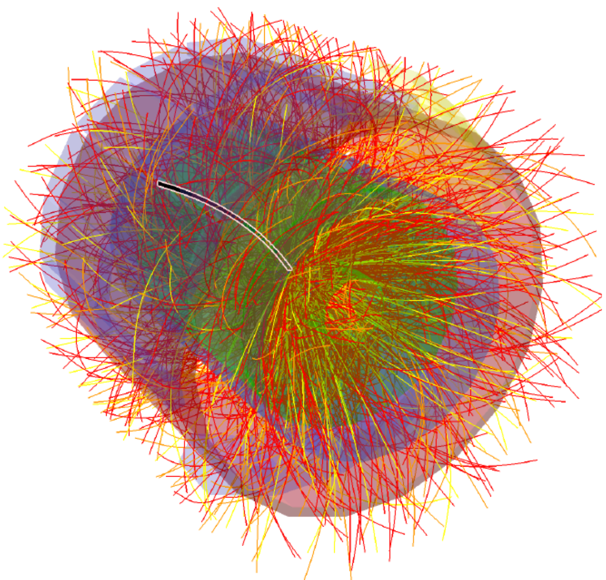
Highlights on the production of (Anti-)(Hyper-)Nuclei with STAR and ALICE



05.09.2019

ECT* Workshop: Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics

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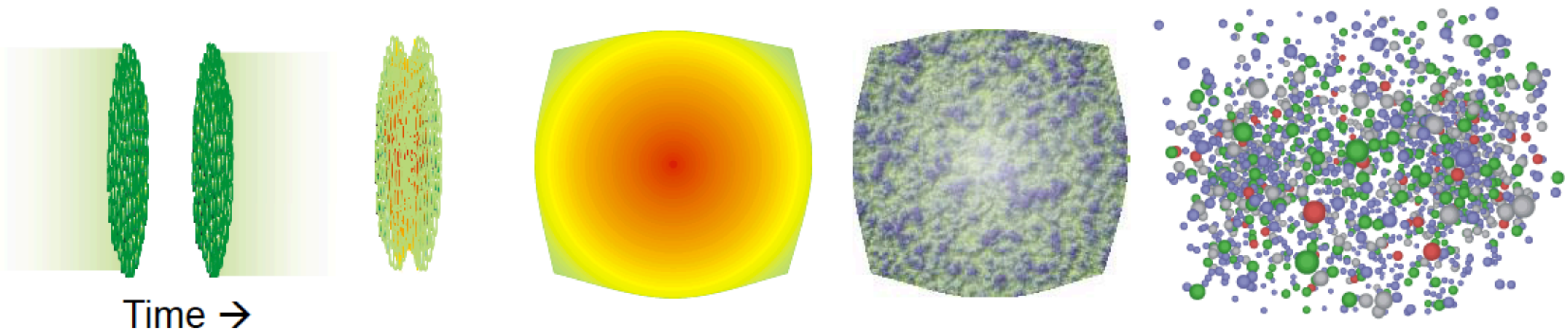
- Introduction
- ALICE
- (Anti-)nuclei
- (Anti-)hypernuclei
- Summary/Conclusion

Introduction



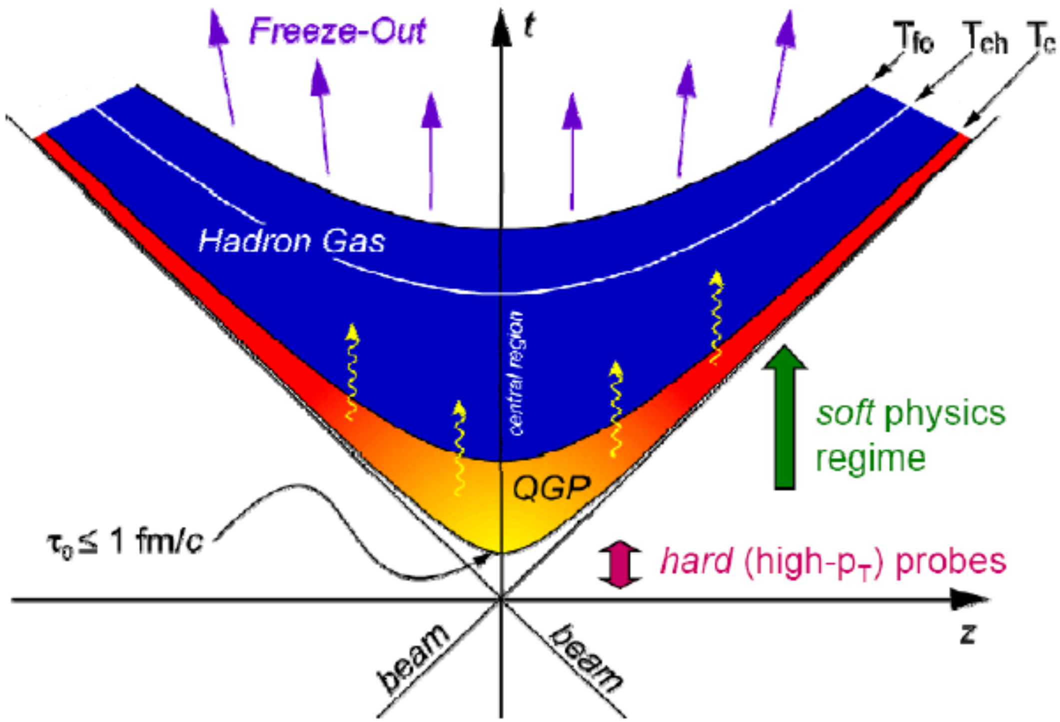
Cartoon of a Ultra-relativistic heavy-ion collision

Left to right:

- the two Lorentz contracted nuclei approach,
- collide,
- form a Quark-Gluon Plasma (QGP),
- the QGP expands and hadronizes,
- finally hadrons rescatter and freeze

Plot by S. Bass, Duke University; http://www.phy.duke.edu/research/NPTheory/QGP/transport/evo.jpg

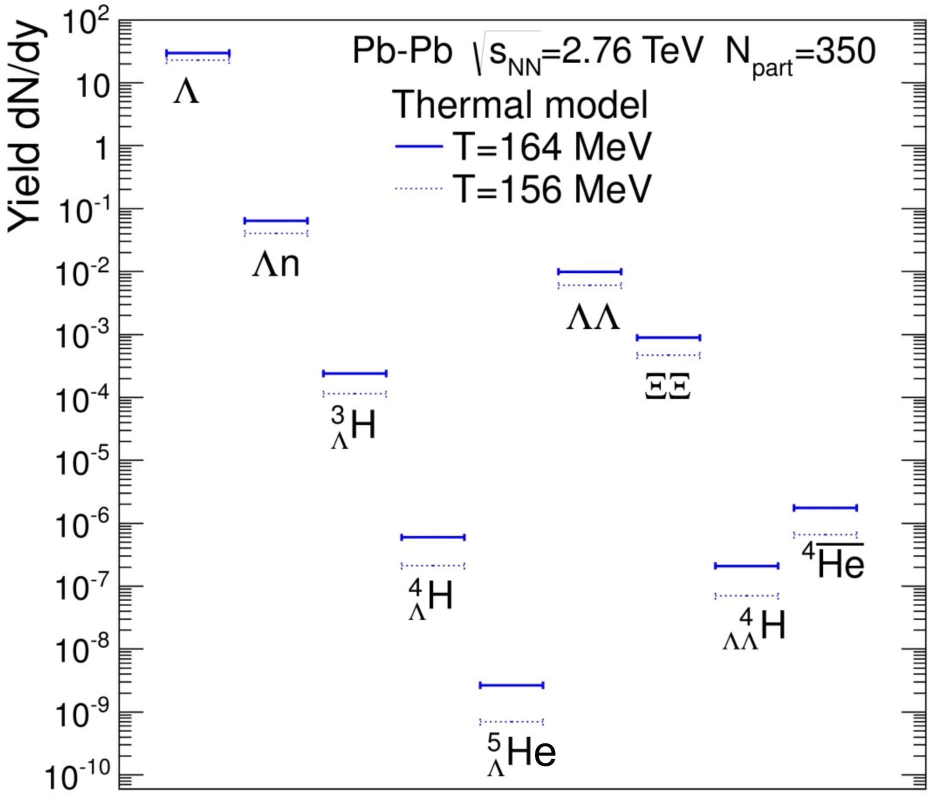
Introduction



The fireball evolution:

- Starts with a “pre-equilibrium state”
- Forms a Quark-Gluon Plasma phase (if T is larger than T_c)
- At *chemical freeze-out,* T_{ch}, *hadrons stop being produced*
- At *kinetic freeze-out,* T_{fo}, *hadrons stop scattering*

Motivation

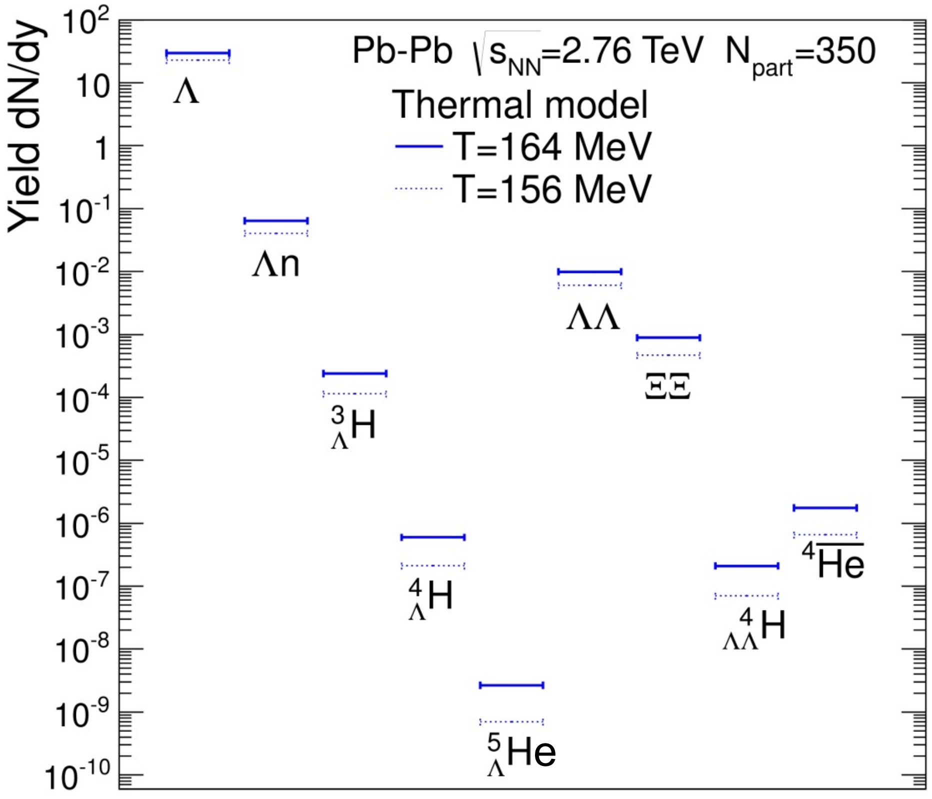


A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

- 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



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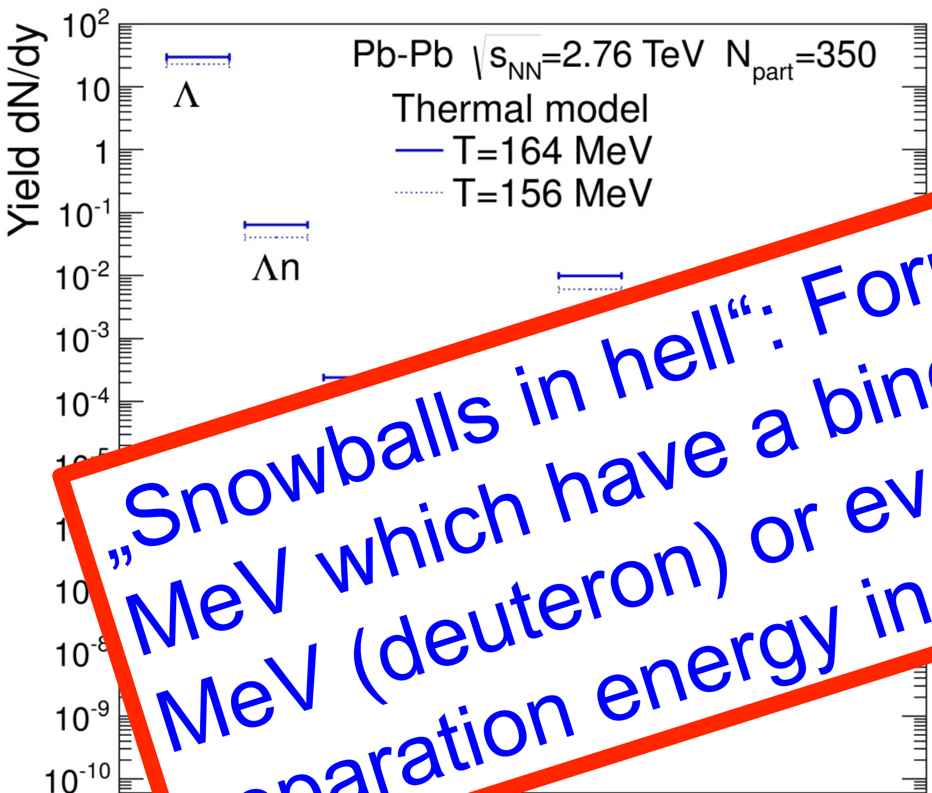
→ Basis are light (anti-)nuclei

Motivation



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

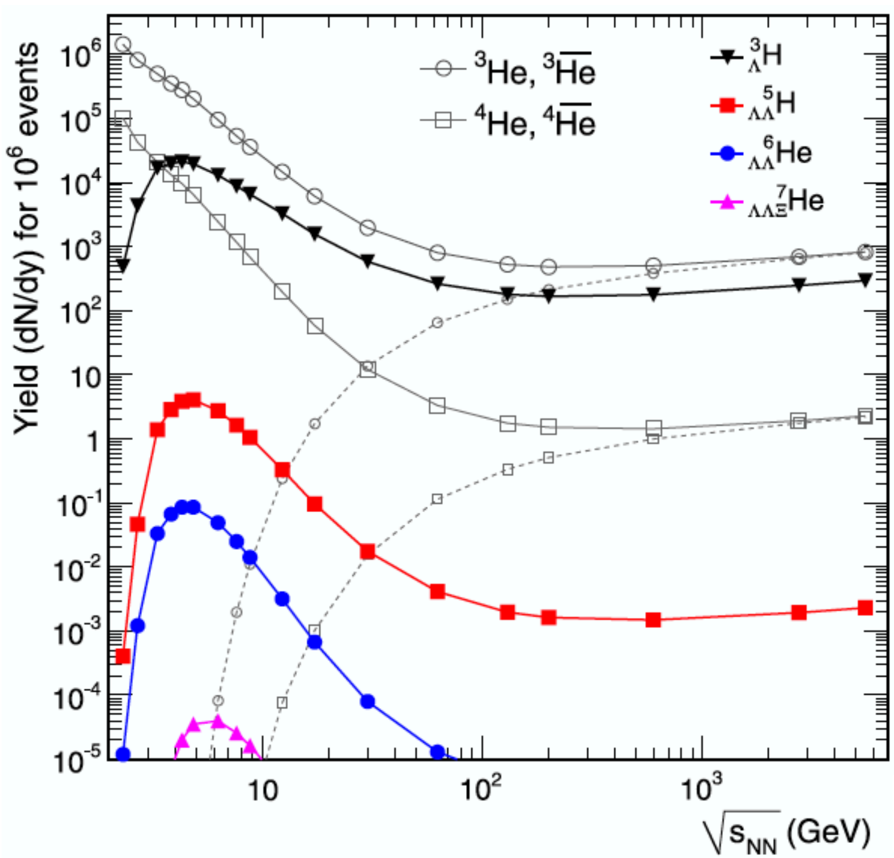
„Snowballs in hell": Forming objects at 150 MeV which have a binding energy of only 2.2 MeV (deuteron) or even only 130 keV (Λ separation energy in the hypertriton)

- Explore QCD ... inspi...
- ...atter
- ...del predictions, e.g. thermal and coalescence

→ Understand production mechanisms

→ Basis are light (anti-)nuclei

Thermal model

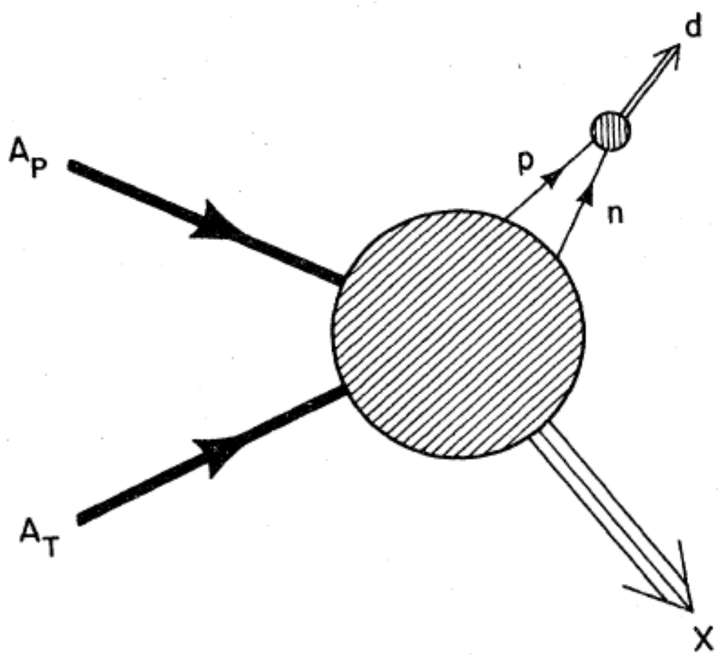


A. Andronic et al., PLB 697, 203 (2011)

- 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)

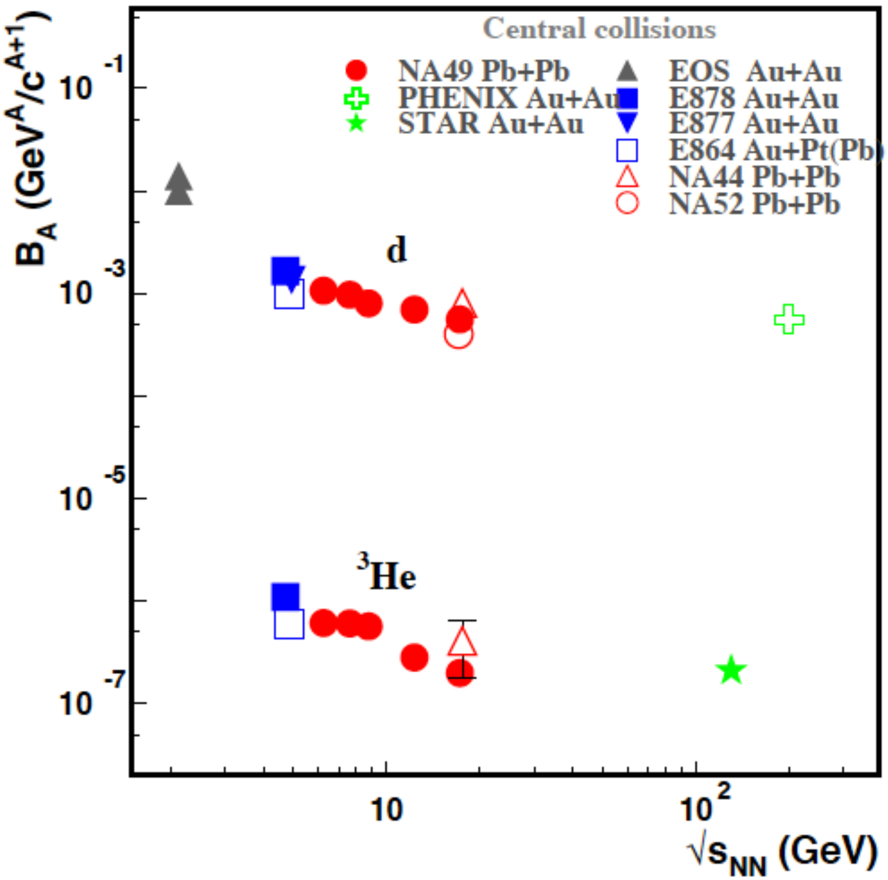
- Nuclei are formed by protons and neutrons which are nearby in space and have similar velocities (after kinetic freeze-out)

- Produced nuclei

➜ can break apart

➜ created again by final-state coalescence

Coalescence (II)



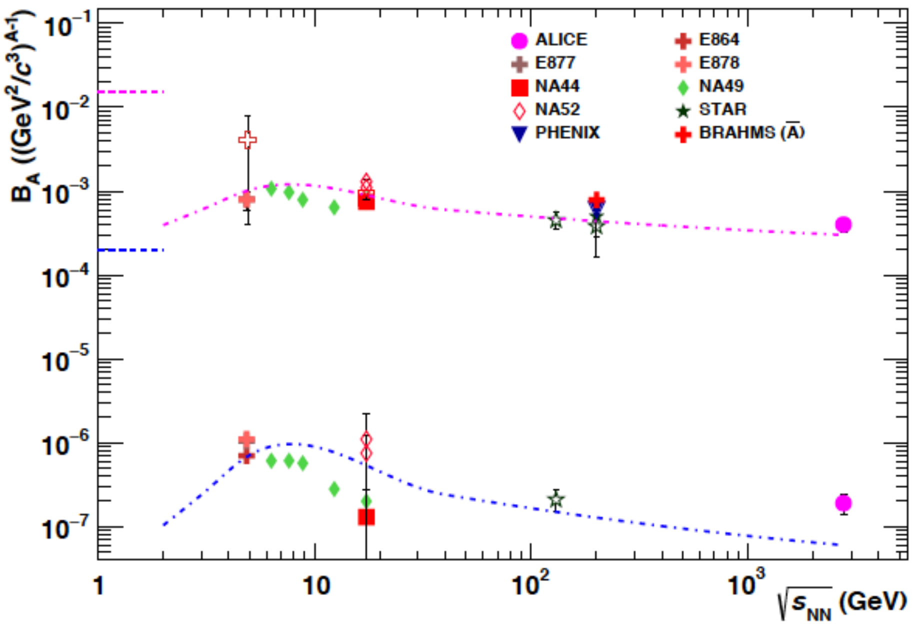
T. Anticic et al. (NA49 Collaboration)
PRC 94, 044906 (2016)

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

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

- 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)

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

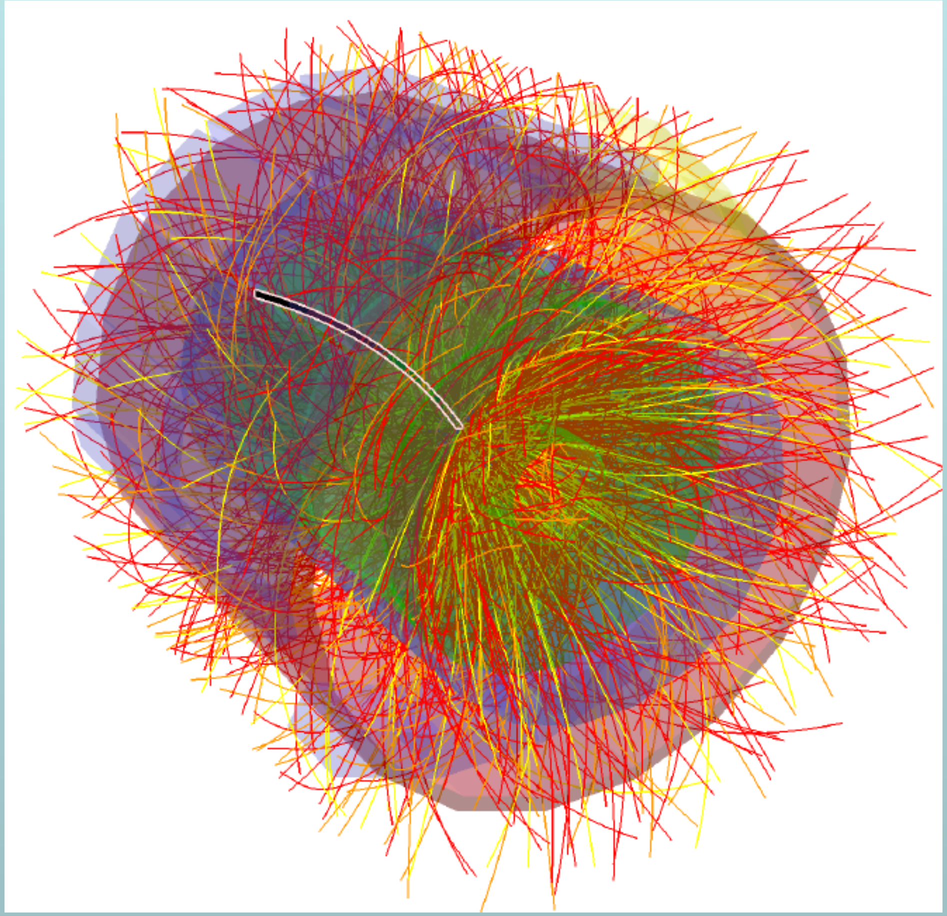
$$E_i \frac{d^3N_i}{dp_i^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A$$

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

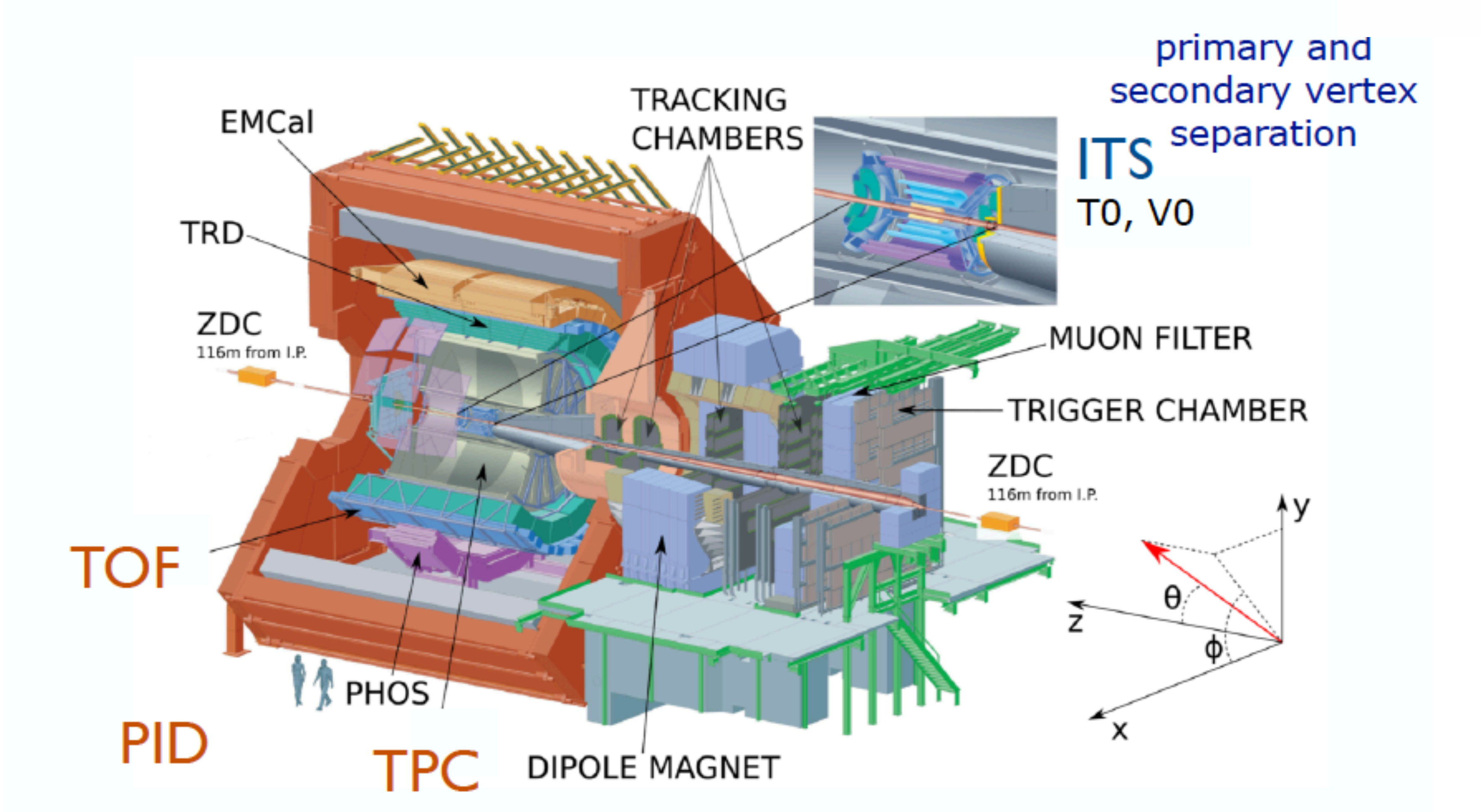
$$B_A \propto \left(\frac{1}{V} \right)^{(A-1)}$$

P. Braun-Munzinger, bd, invited review, NPA 987, 144 (2019), arXiv:1809.04681

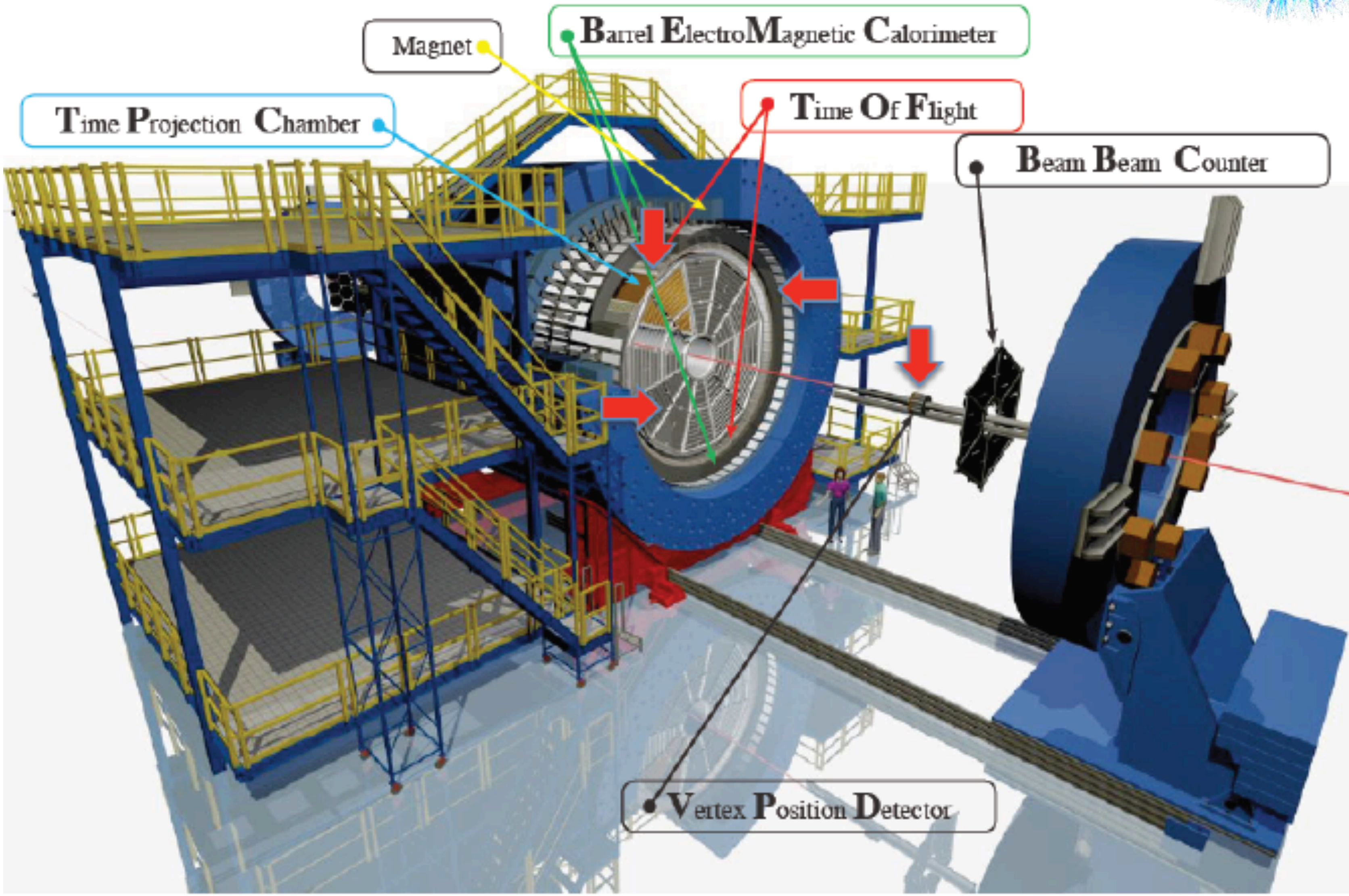
Detectors



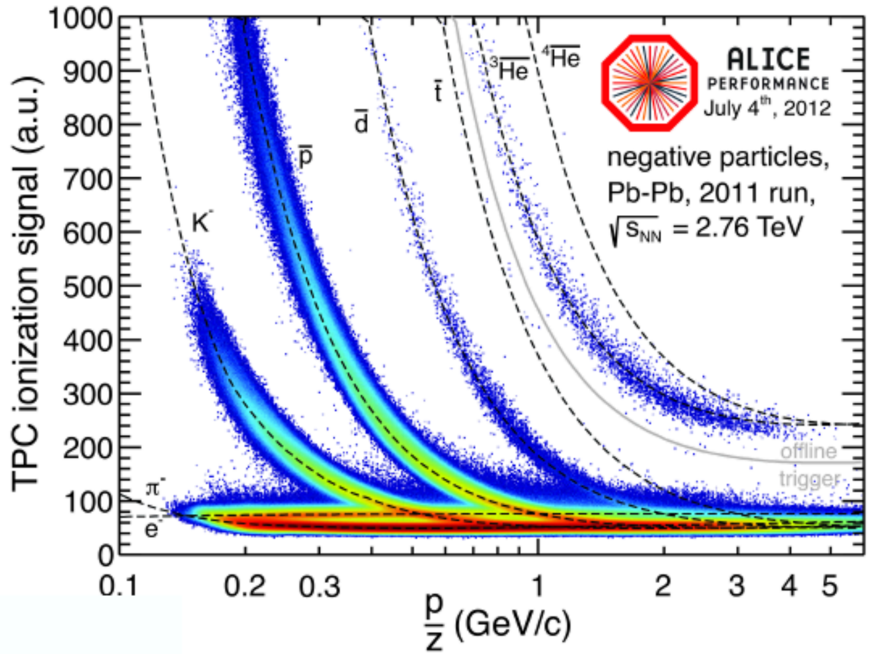
Experiments: ALICE

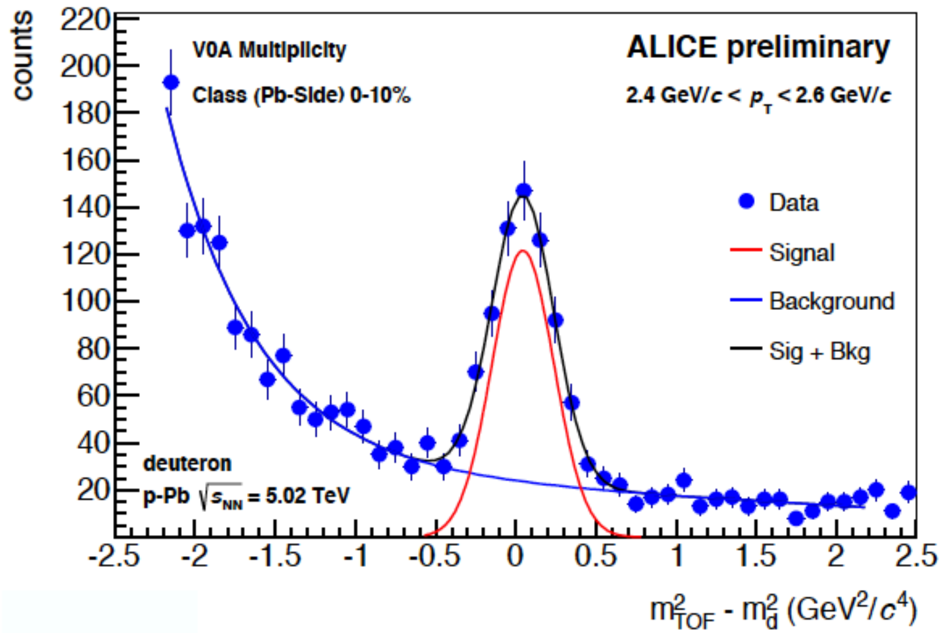


Experiments: STAR



Particle Identification





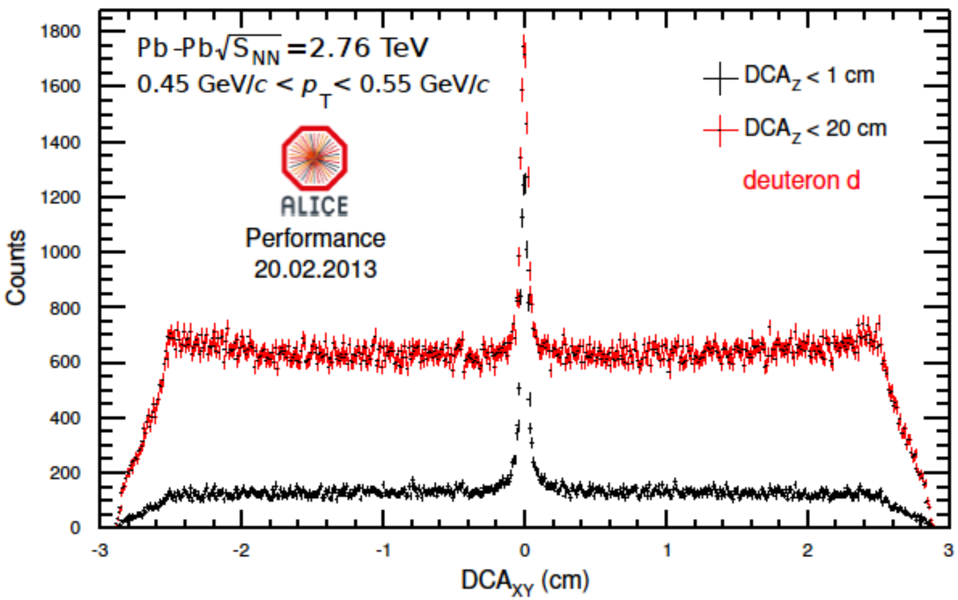
Low momenta:

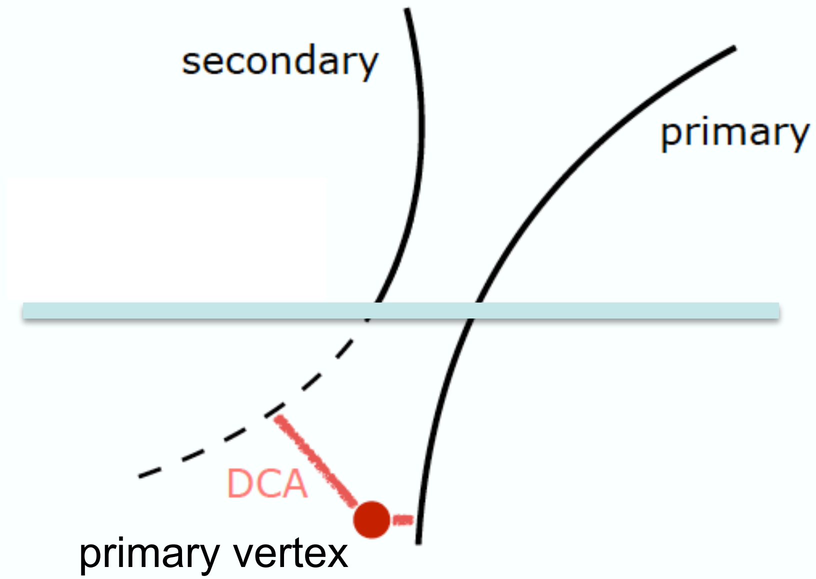
Nuclei are identified using the d*E*/d*x* measurement in the Time Projection Chamber (TPC)

Higher momenta:

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

Secondary contamination

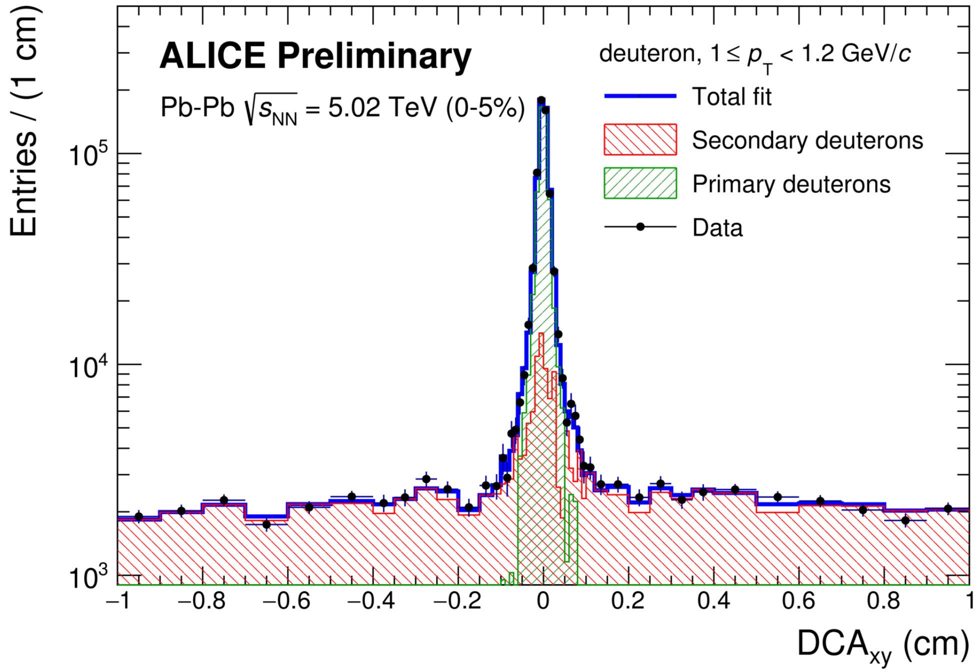




➜ Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material, e.g. beam pipe)

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

Secondary contamination



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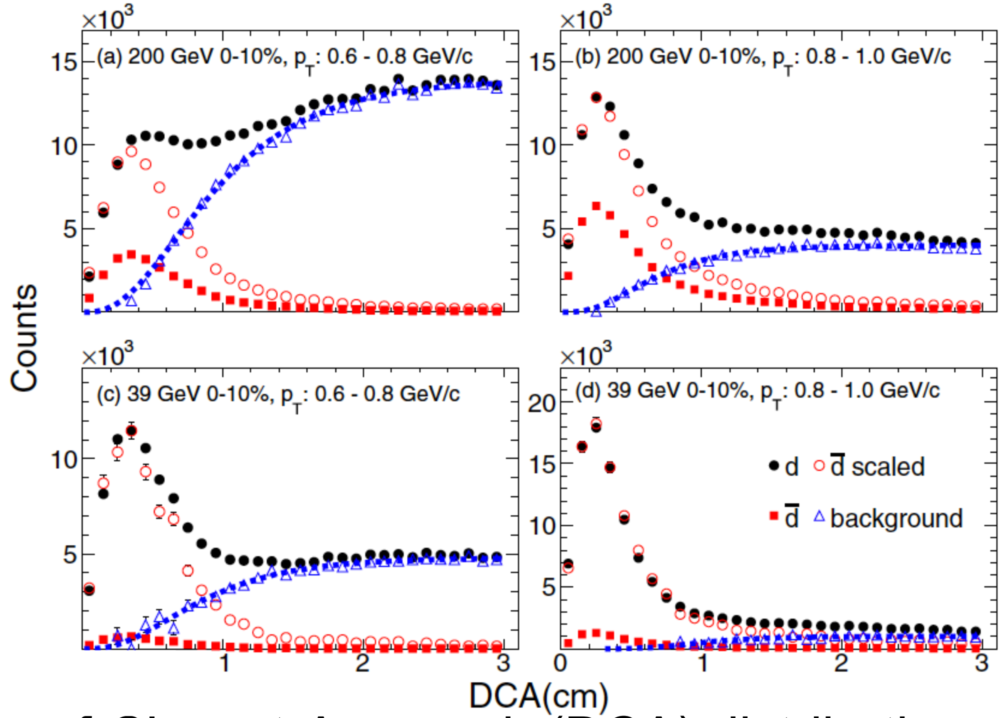
Second. contamination



STAR Collaboration: PRC 99, 064905 (2019)

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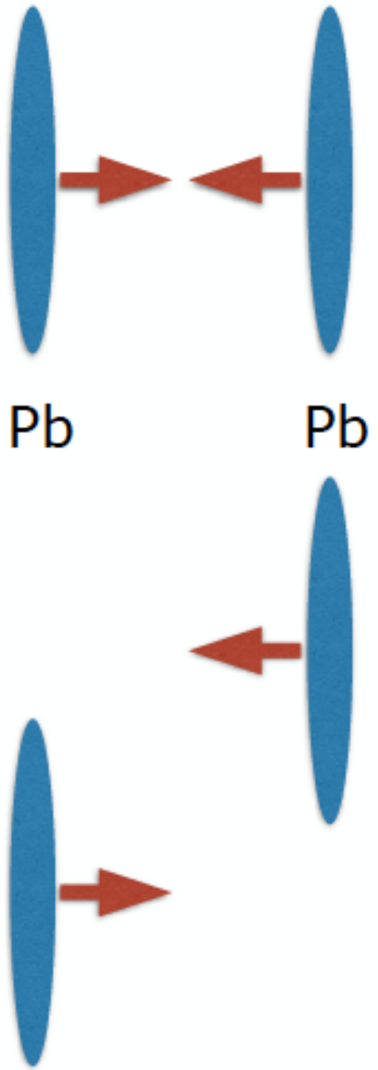
Interlude: Centrality



Central Pb-Pb collision:

High multiplicity = large $\langle dN/d\eta \rangle$

High number of tracks

(more than 2000 tracks in the detector)

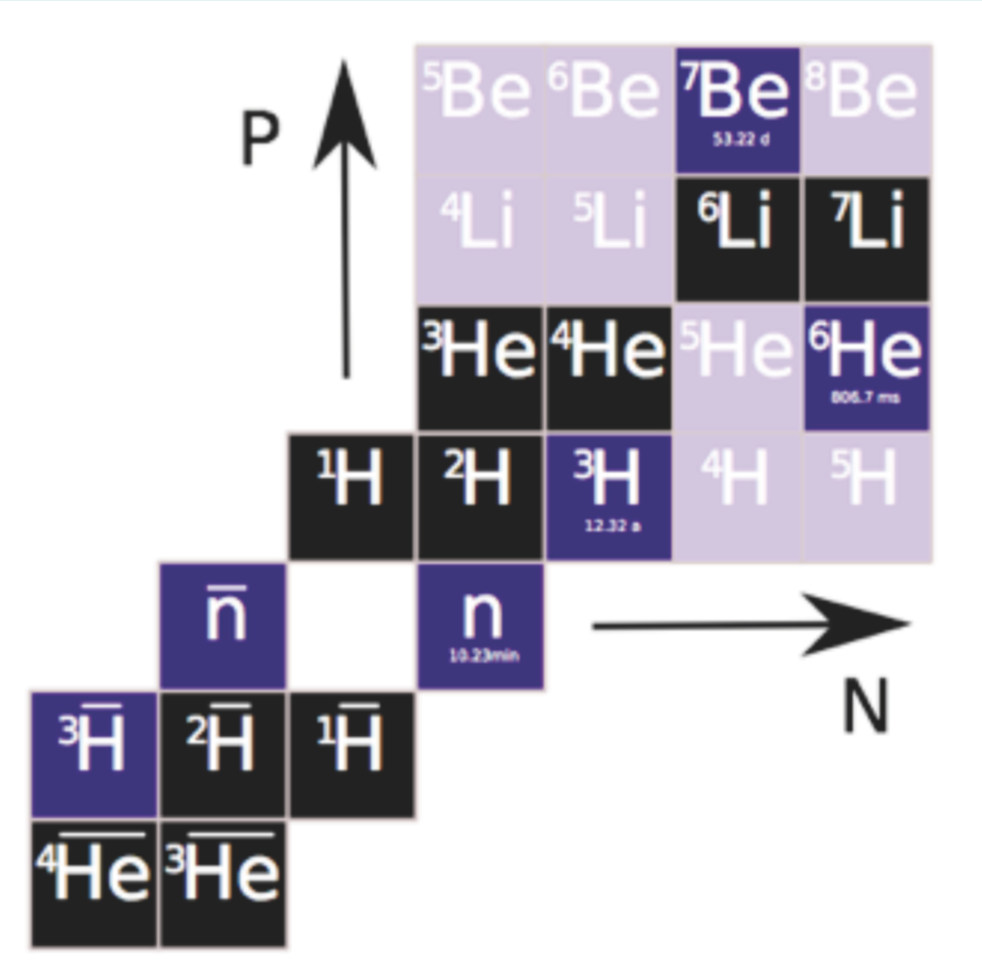
Peripheral Pb-Pb collision:

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

Low number of tracks

(less than 100 tracks in the detector)

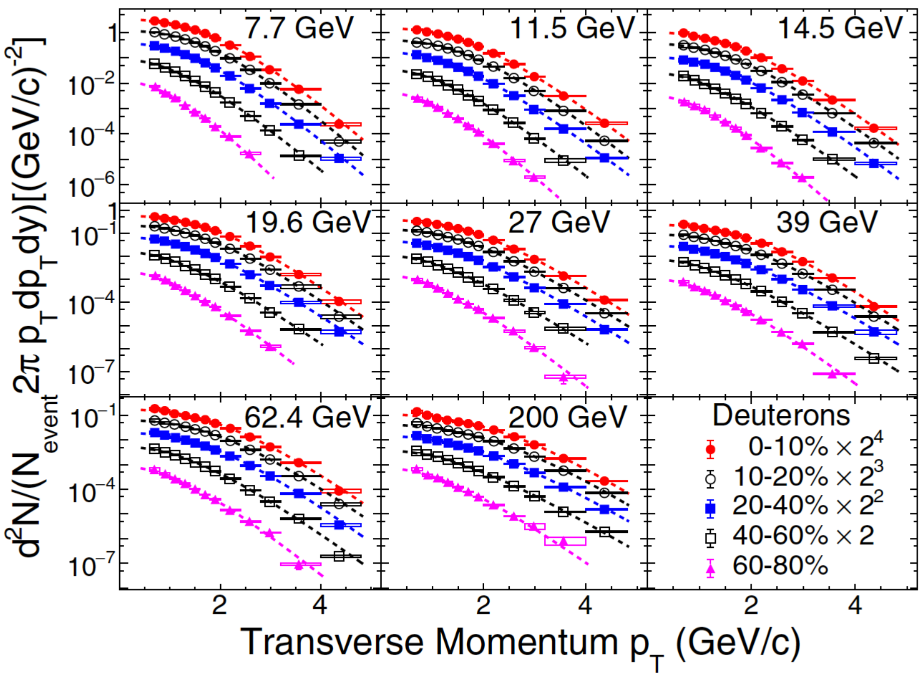
(Anti-)Nuclei

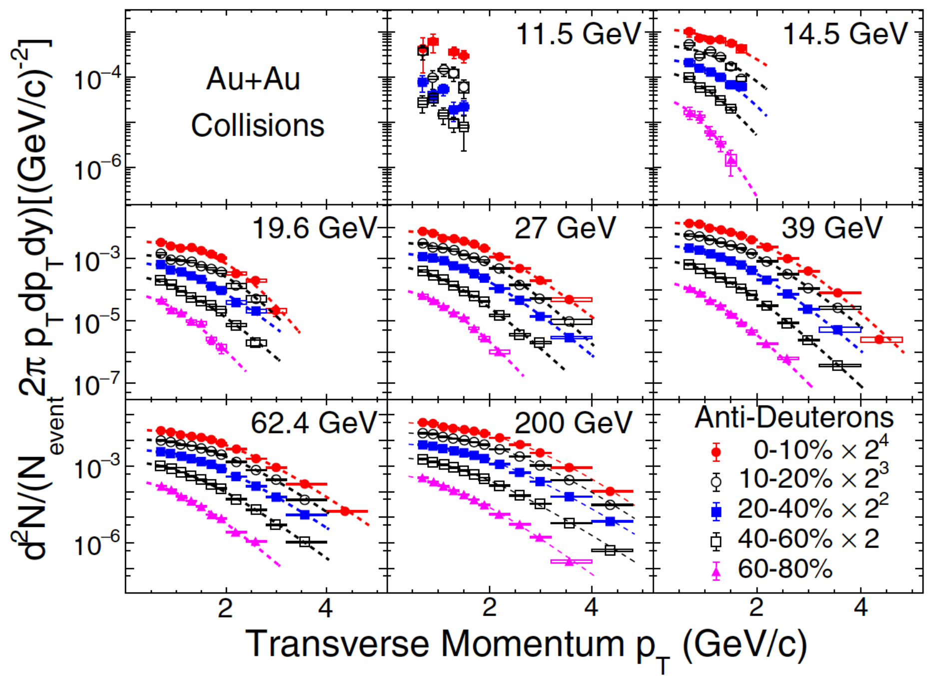


P
N
⁵Be
⁶Be
⁷Be
53.22 d
⁸Be
⁴Li
⁵Li
⁶Li
⁷Li
³He
⁴He
⁵He
⁶He
806.7 ms
¹H
²H
³H
12.32 a
⁴H
⁵H
n̄
n
10.23min
³H̄
²H̄
¹H̄
⁴He̅
³He̅

Deuterons

STAR Collaboration: PRC 99, 064905 (2019)

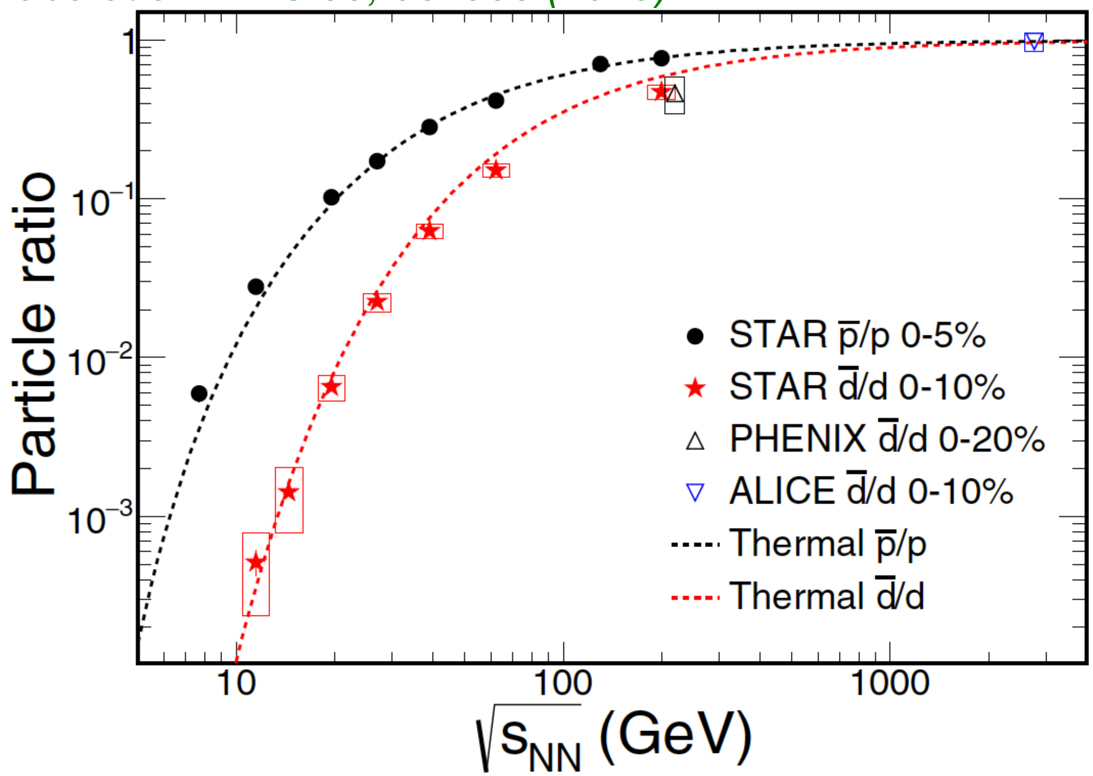




- STAR has measured the (anti-)deuteron production in several centralities in the Beam Energy Scan program at RHIC

Deuterons

STAR Collaboration: PRC 99, 064905 (2019)



$$\frac{n_{\bar{p}}}{n_p} = \exp(-2\mu_B/T)$$

$$\frac{n_{\bar{d}}}{n_d} = \exp(-4\mu_B/T)$$

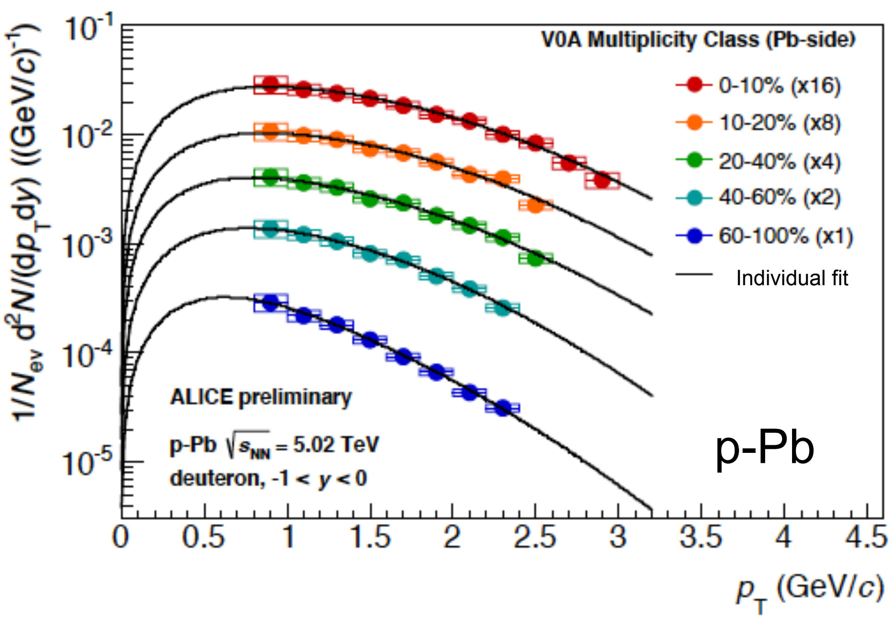
J. Cleymans et al.: PRC 84, 054916 (2011)

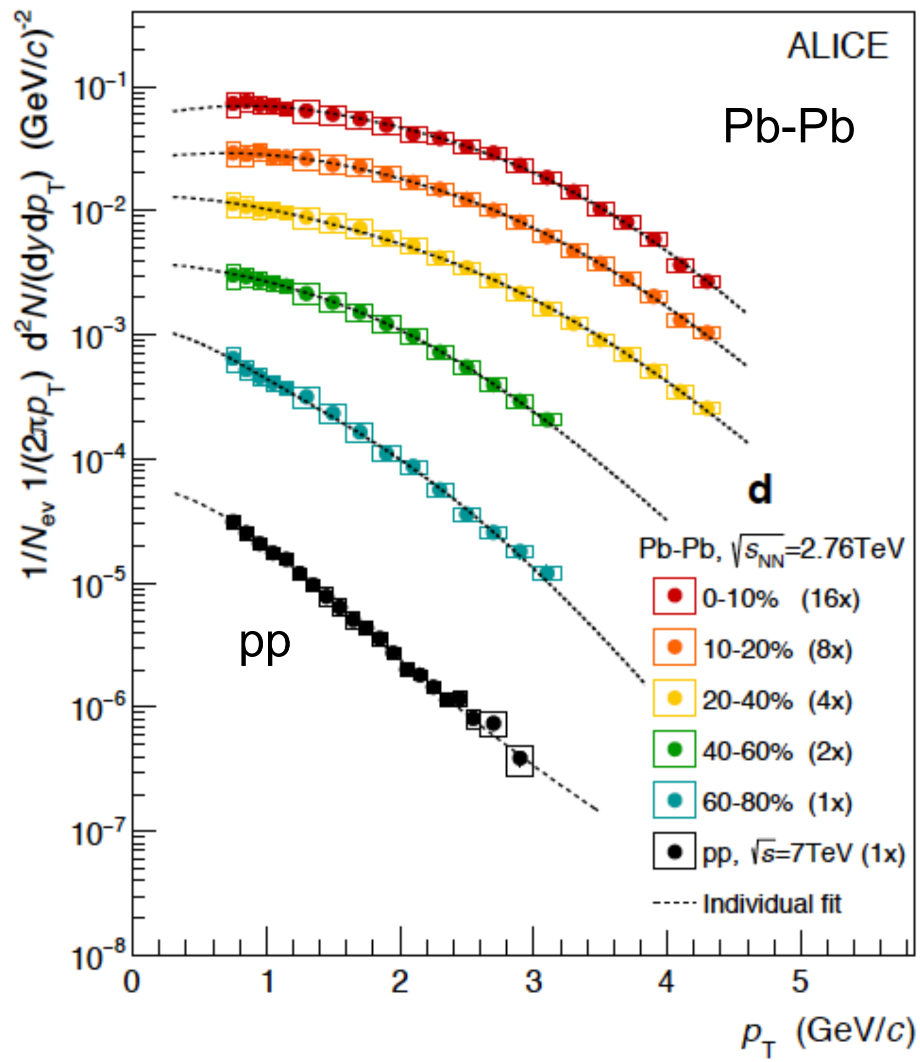
- STAR has measured the (anti-)deuteron production in several centralities in the Beam Energy Scan (BES) program at RHIC
- Trend as a function of centre-of-mass energy for anti-particle to particle ratios can be nicely described by the thermal model

Deuterons

ALICE Collaboration: PRC 93, 024917 (2016)

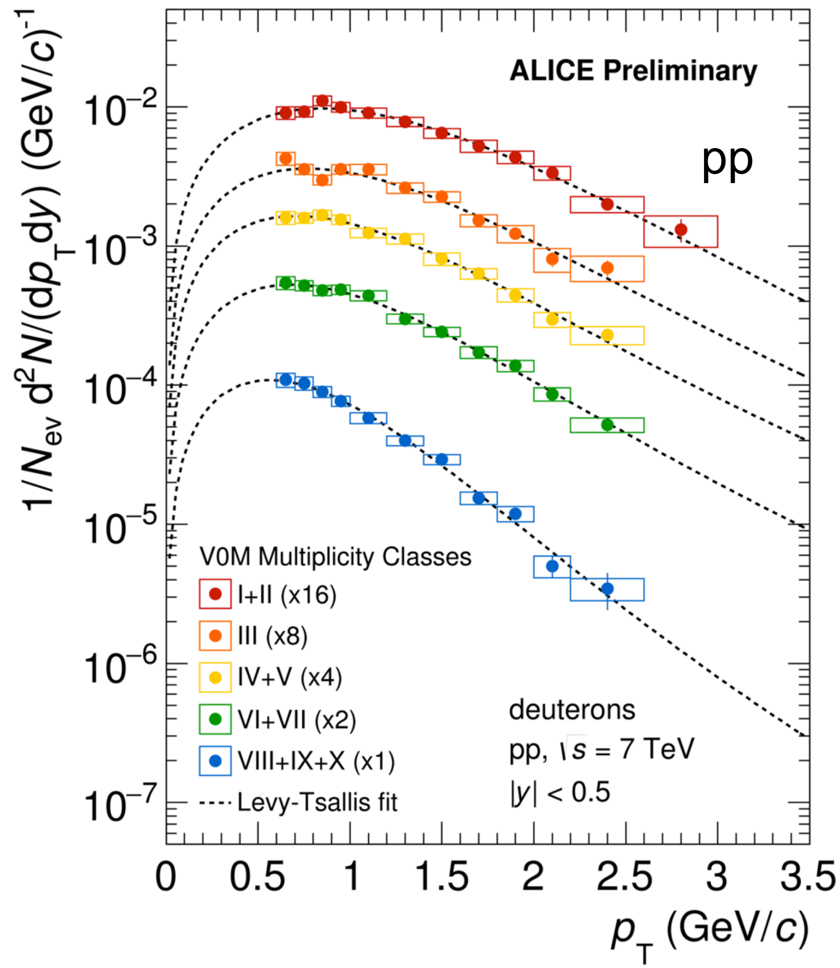
- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp spectrum shows no sign of radial flow

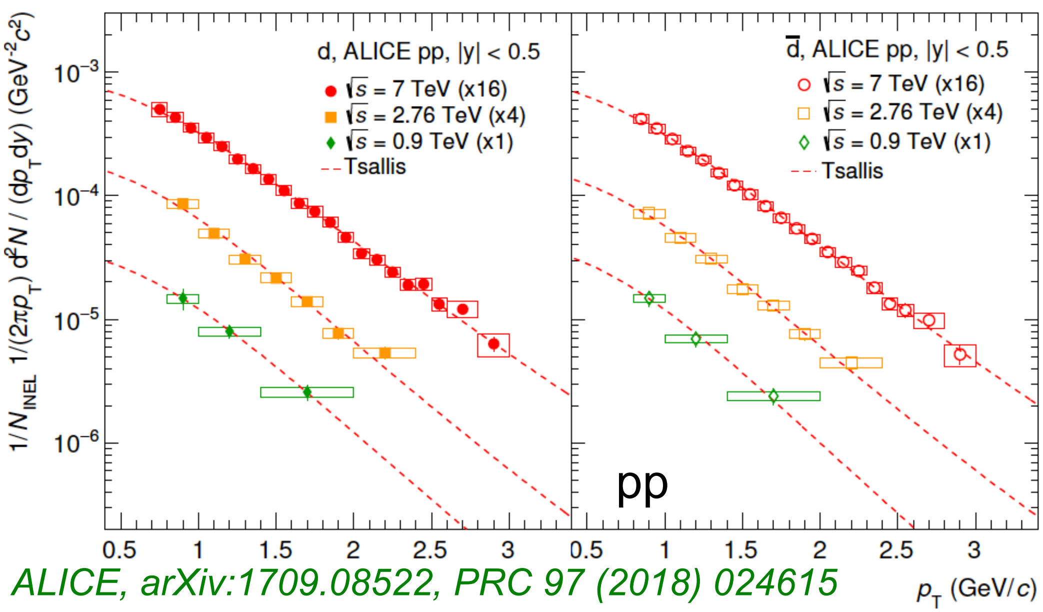




Deuterons

- 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

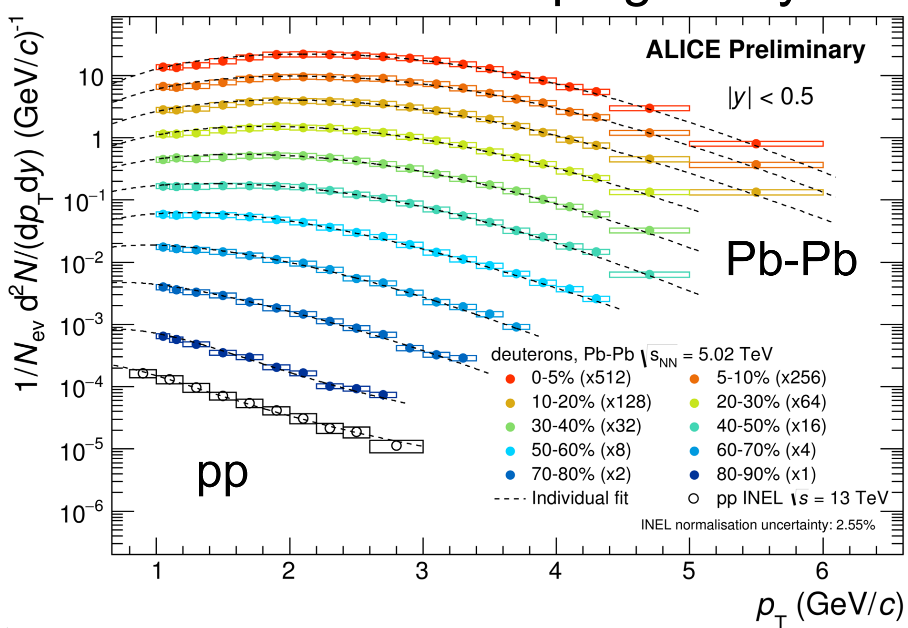


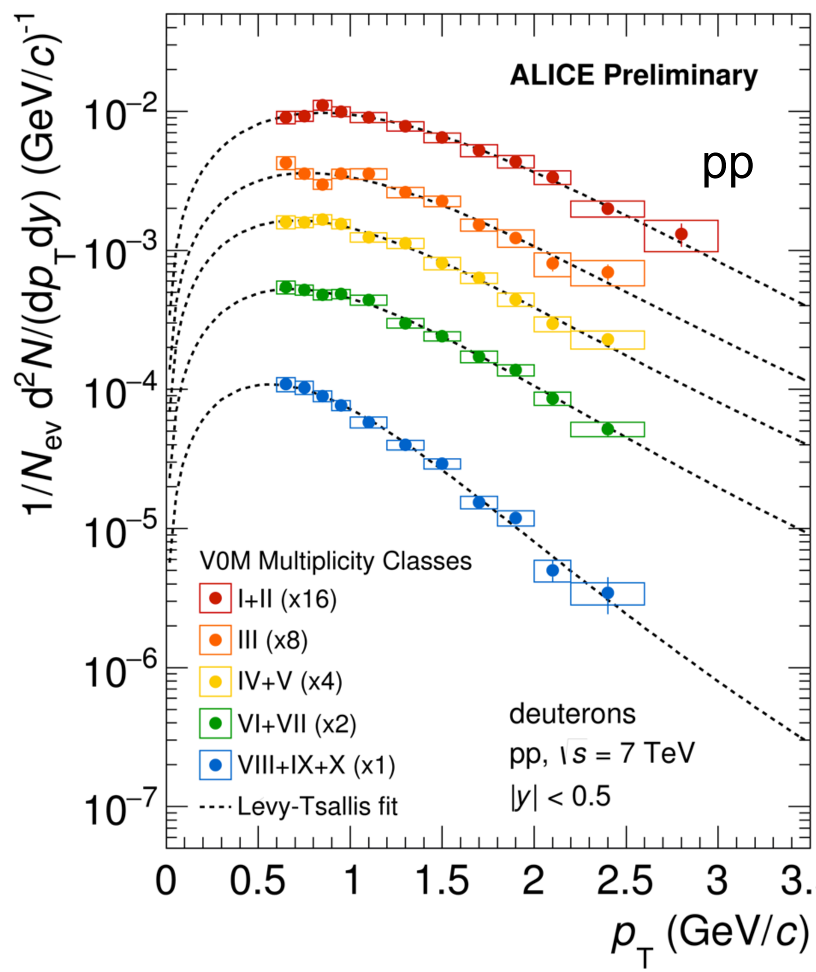


ALICE, arXiv:1709.08522, PRC 97 (2018) 024615

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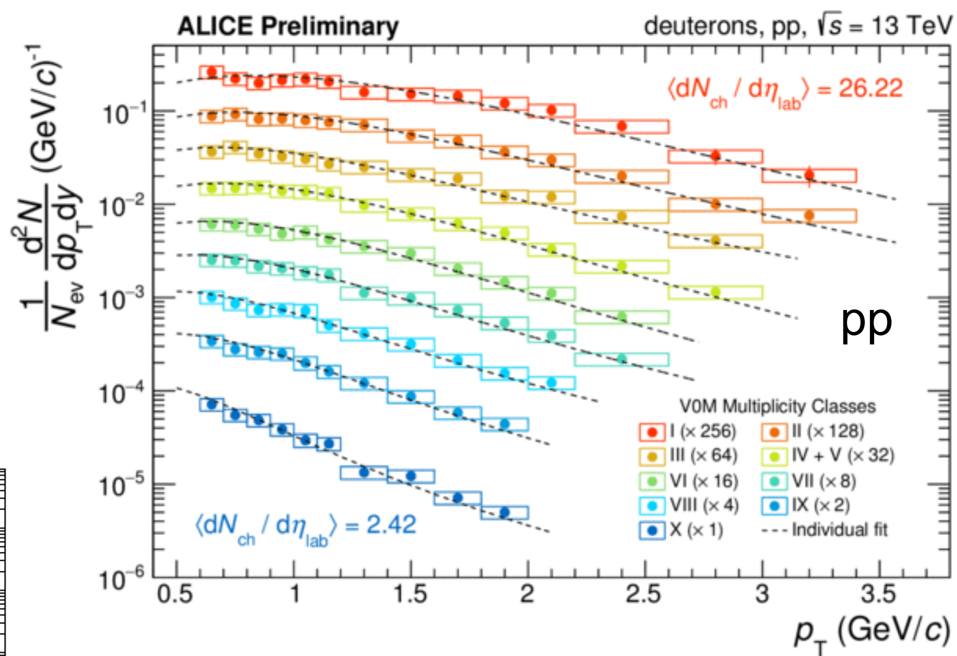
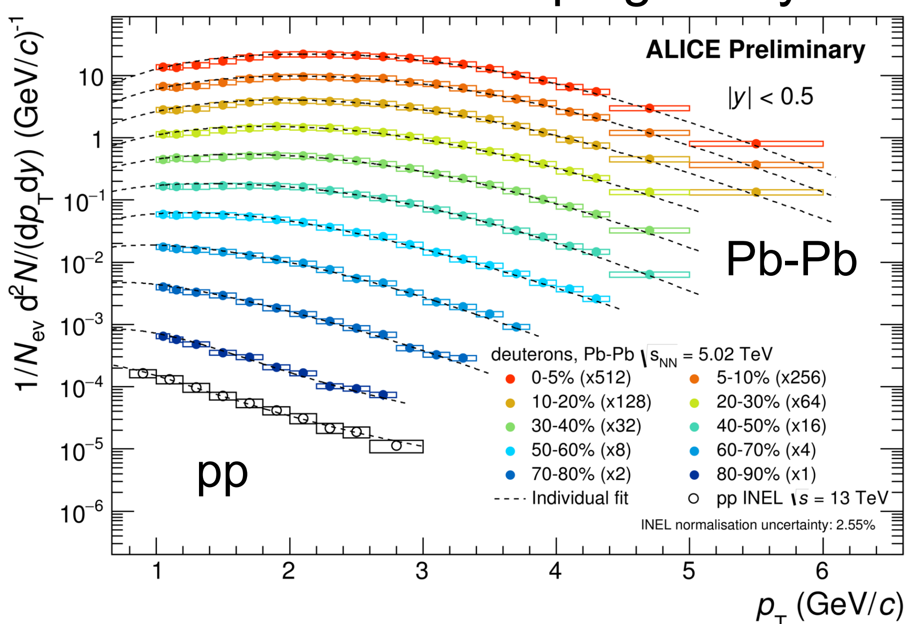
- MB pp spectrum shows no sign of radial flow → developing nicely

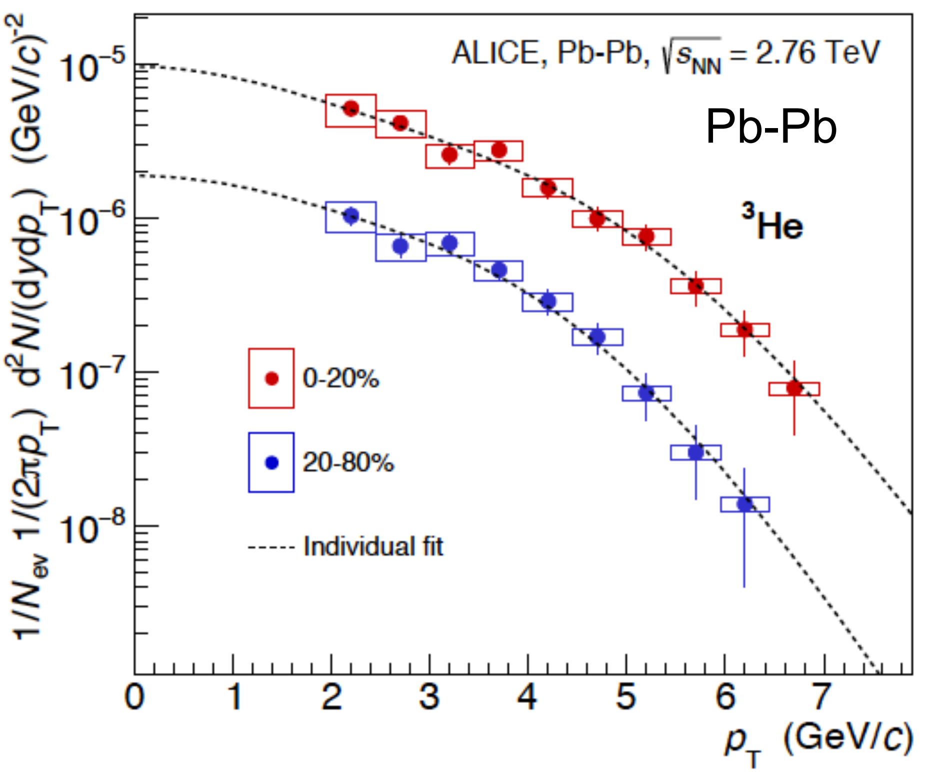


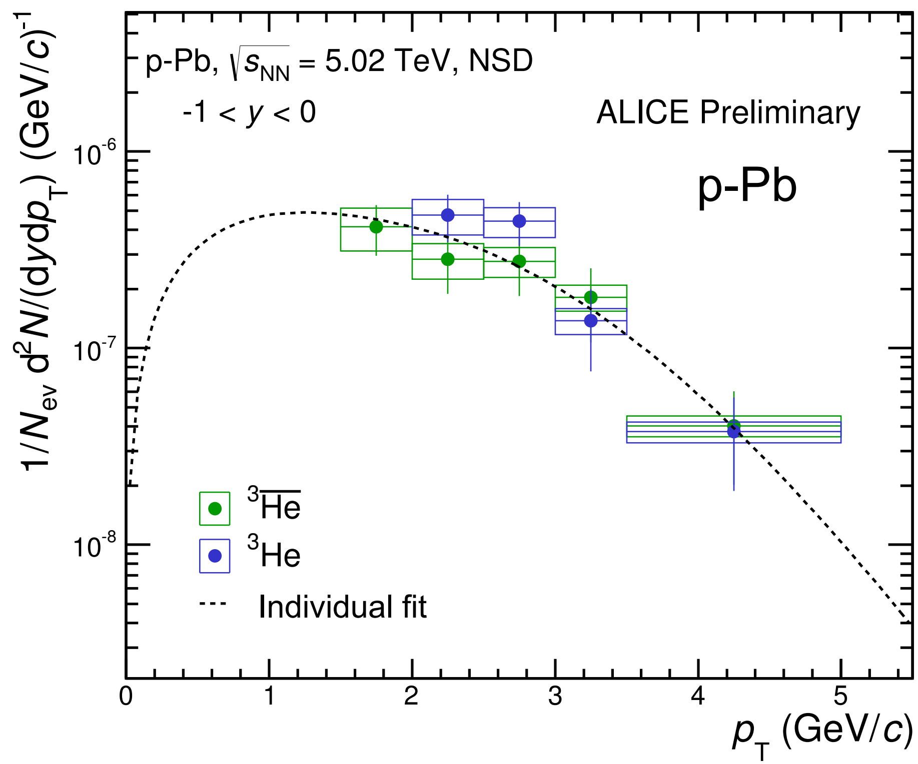


ALICE-PUBLIC-2017-006

^{3}He

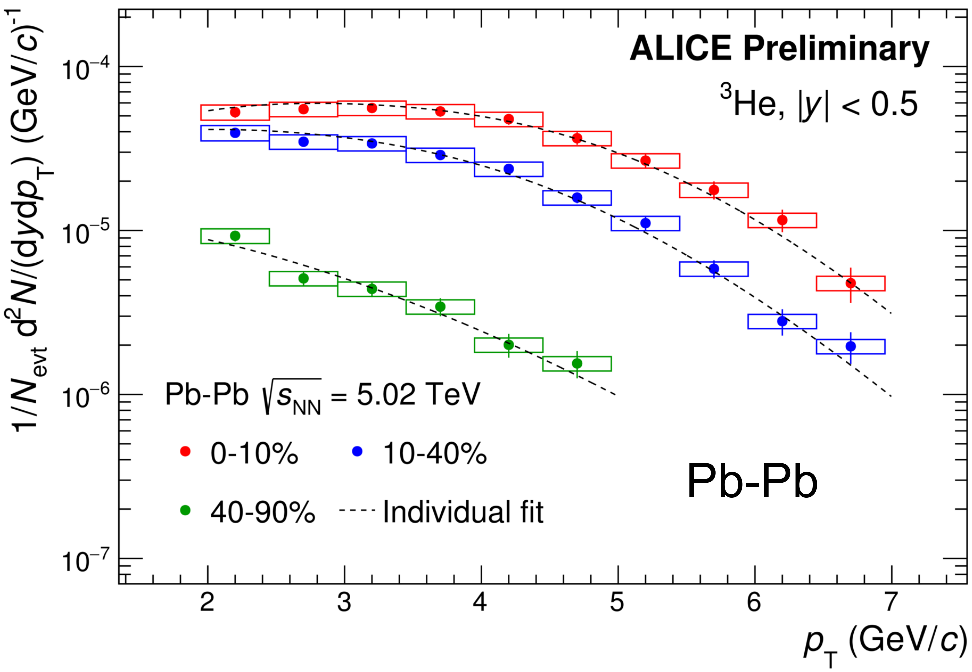
ALICE Collaboration: PRC 93, 024917 (2016)

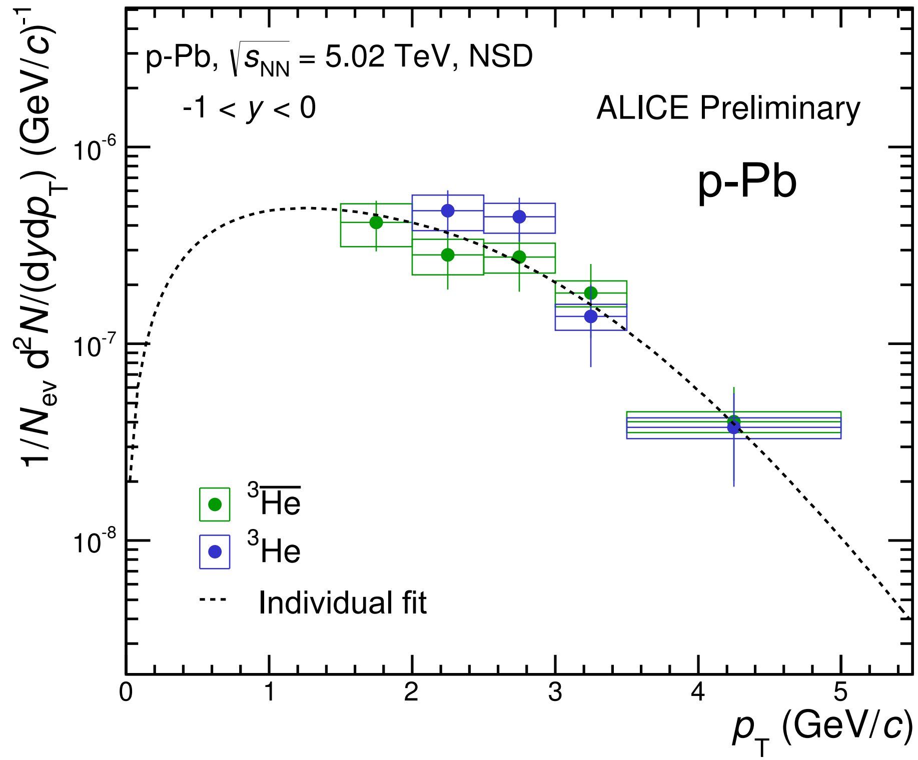




- Dashed curves represent individual Blast-Wave fits
- Spectrum obtained in 2 centrality classes in Pb-Pb and for NSD collisions in p-Pb

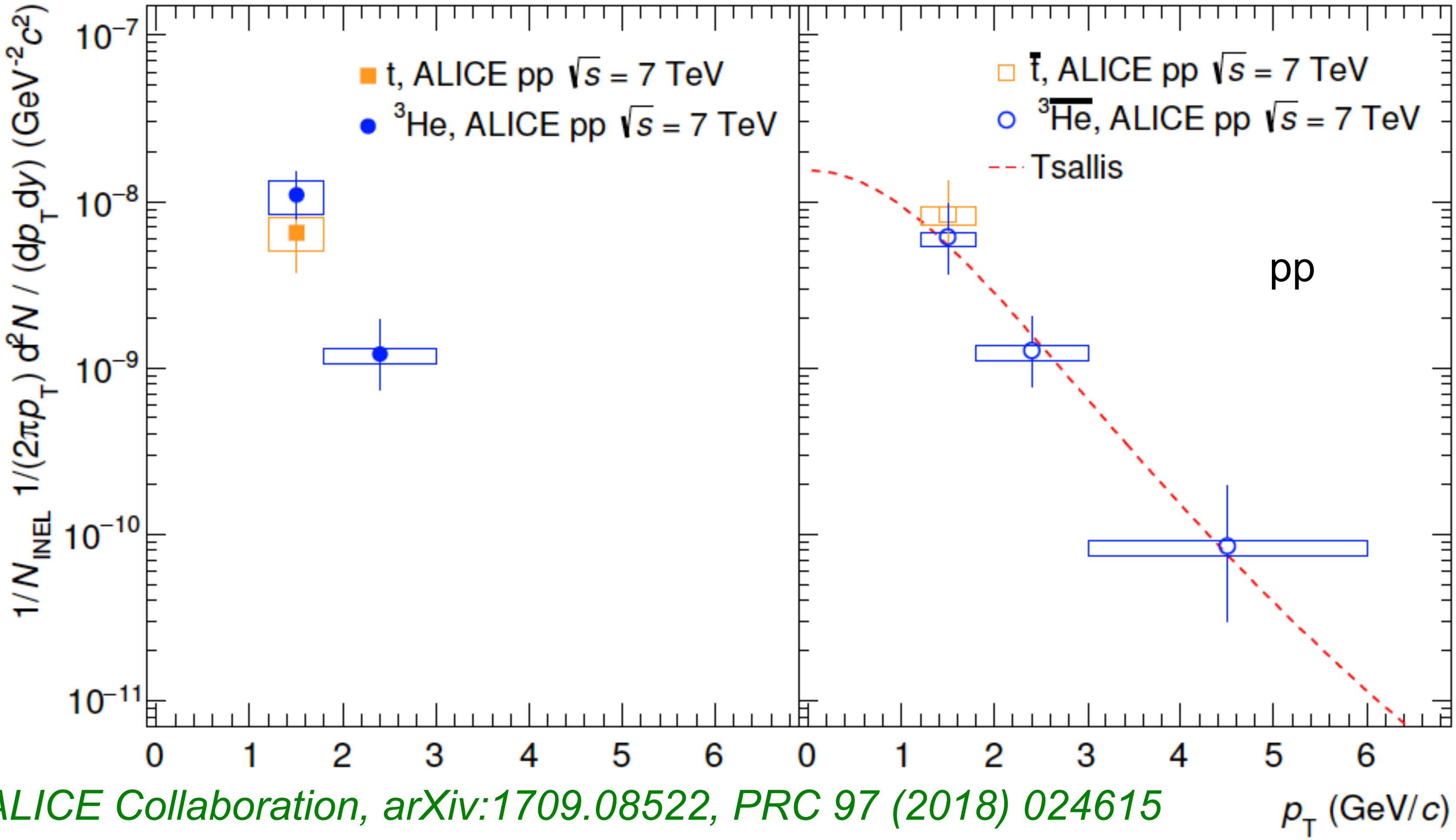
^{3}He





- 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 and t

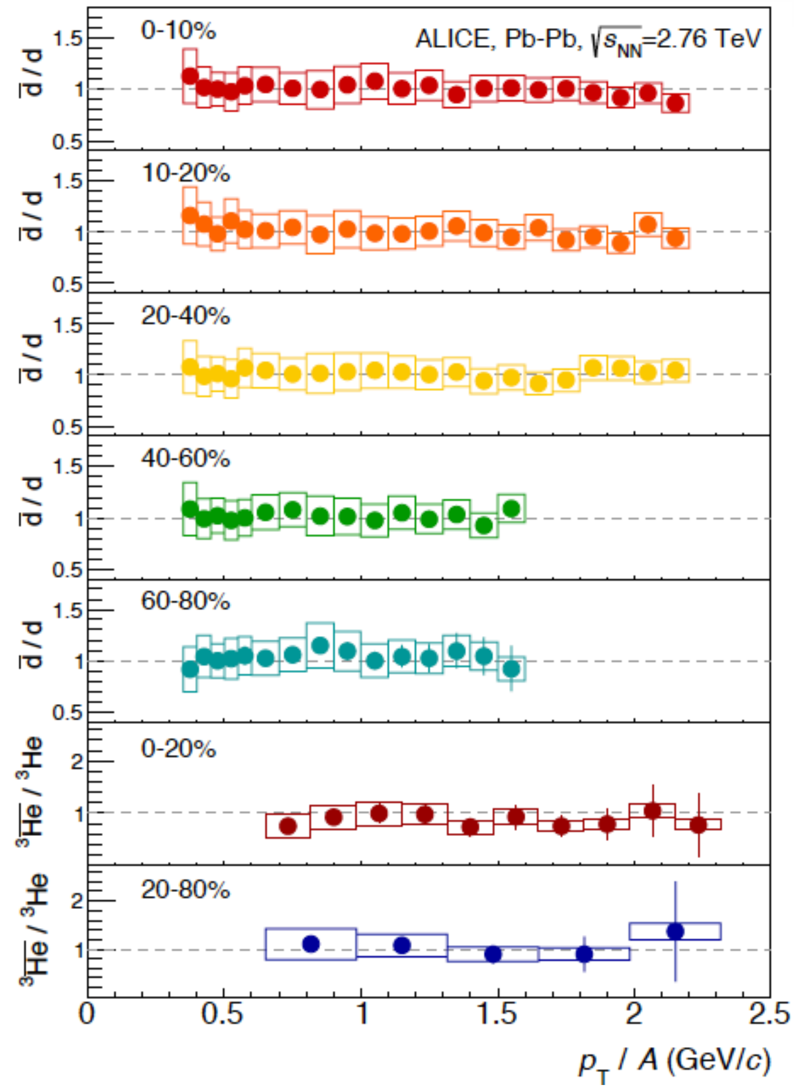


ALICE Collaboration, arXiv:1709.08522, PRC 97 (2018) 024615

- 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

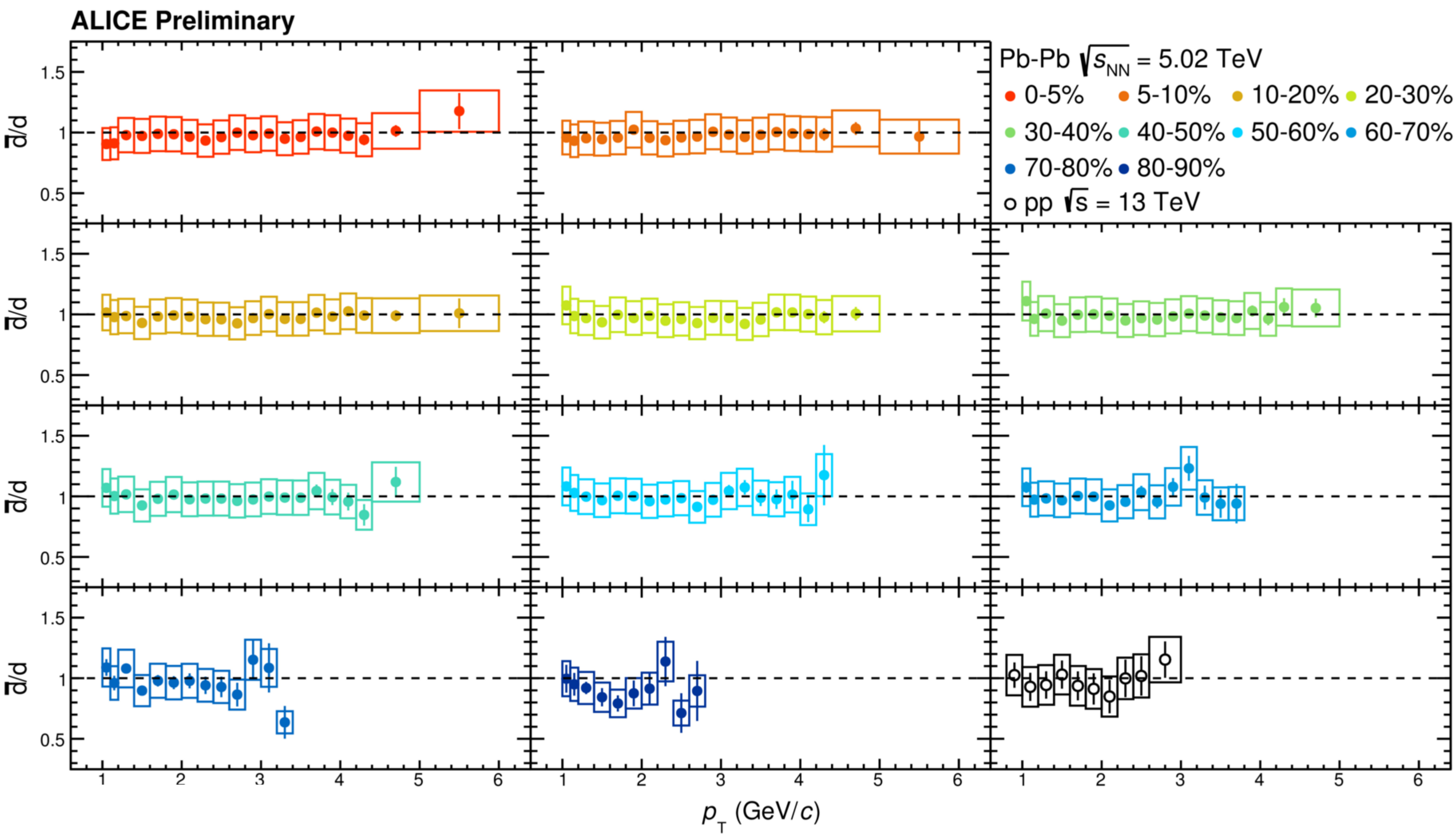
LHC: factory for anti-matter and matter

- 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

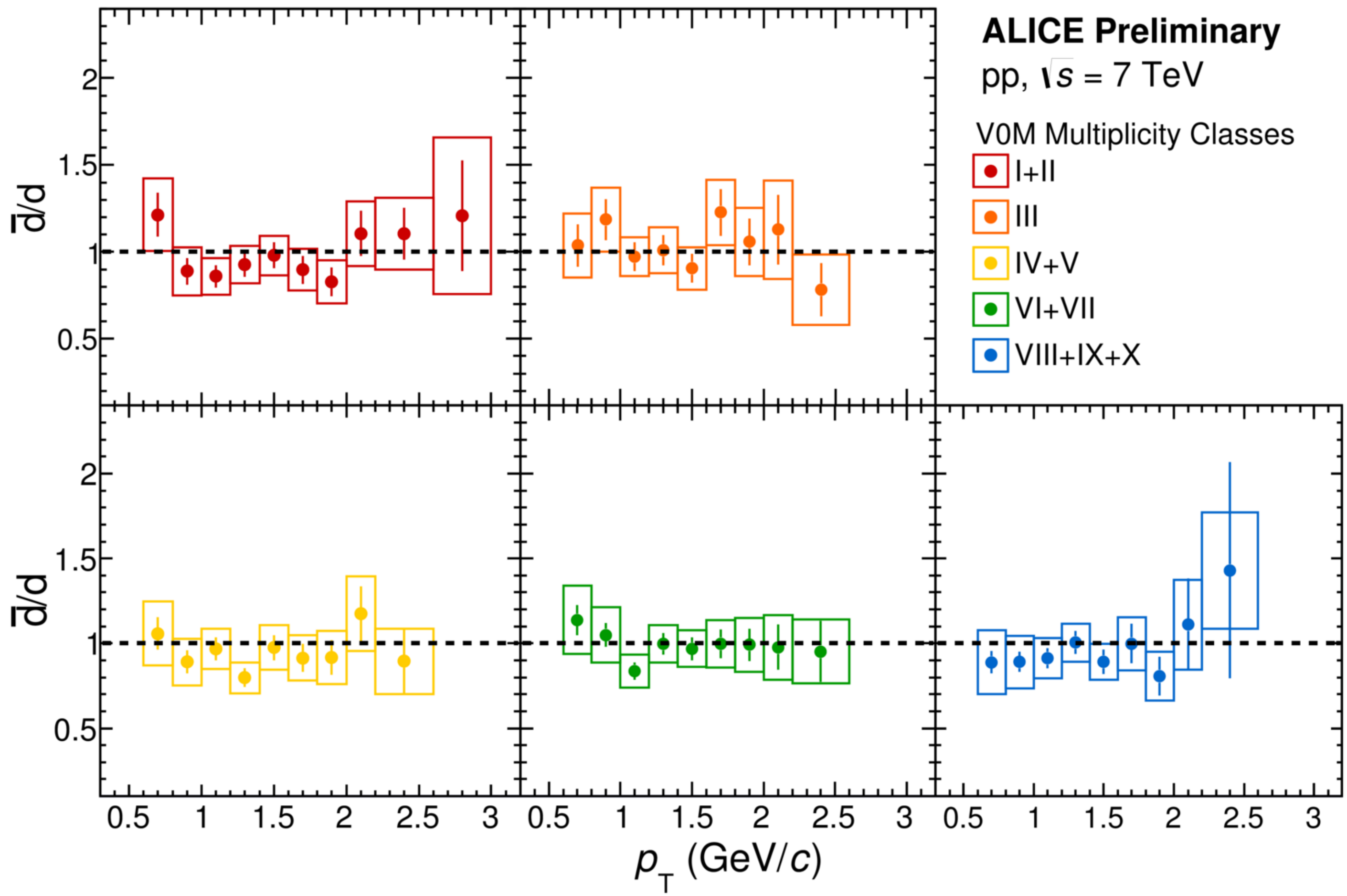


ALICE Collaboration: PRC 93, 024917 (2016)

LHC: factory for anti-matter and matter

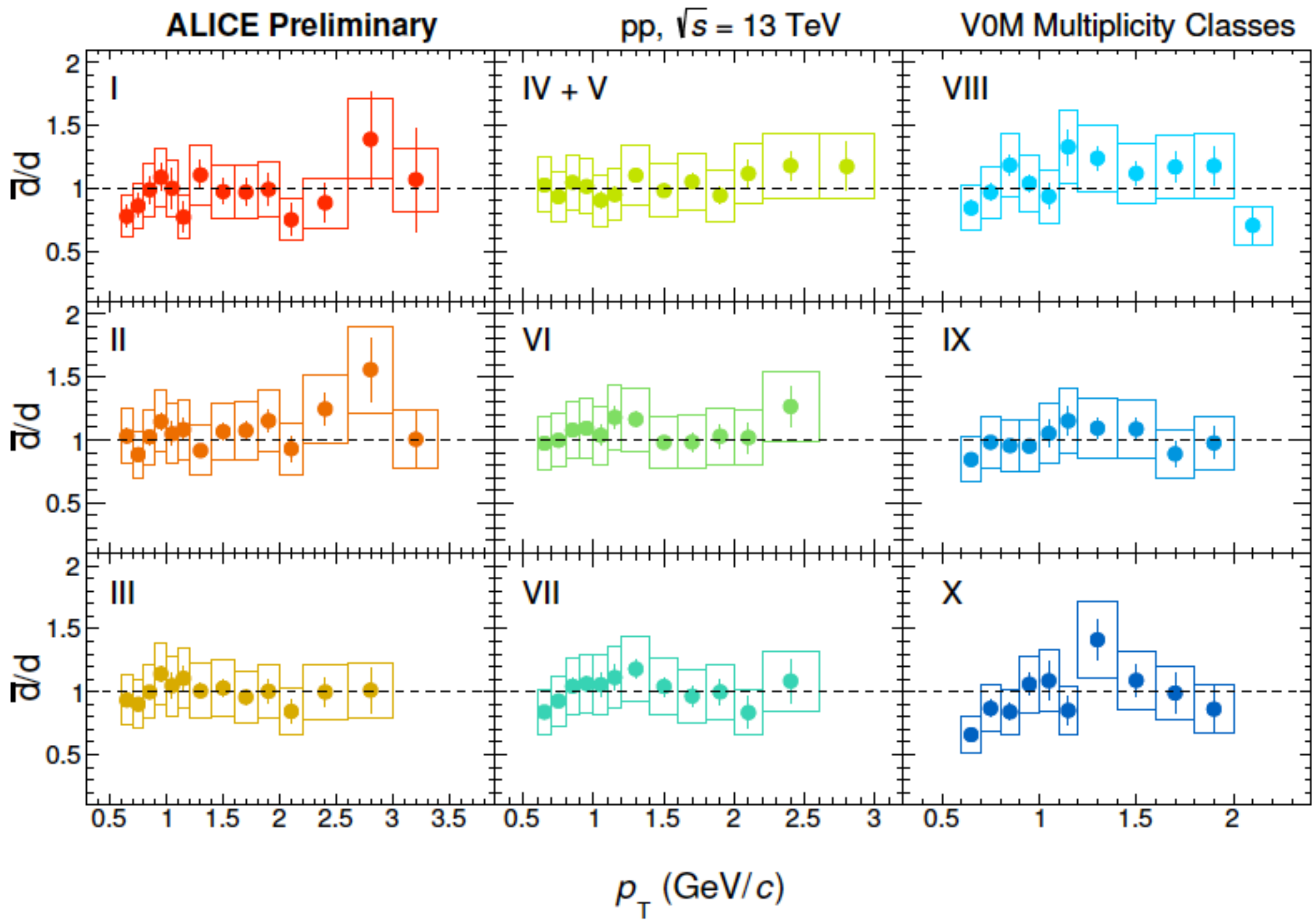


LHC: factory for anti-matter and matter



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

LHC: factory for anti-matter and matter



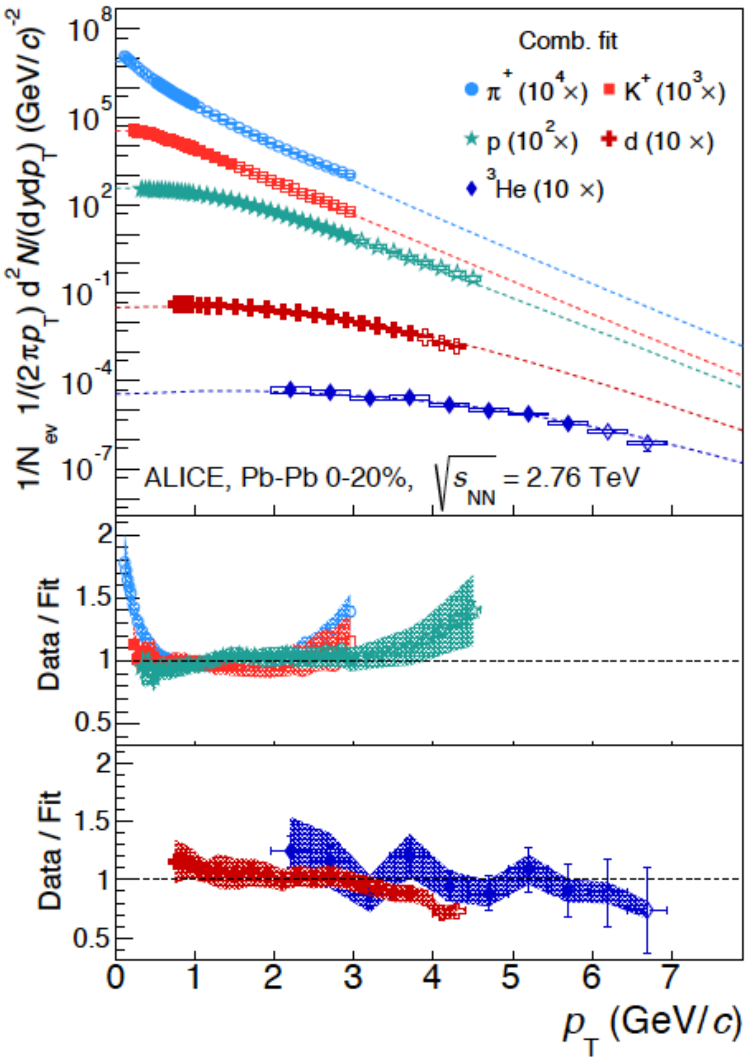
Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally

Combined Blast-Wave fit

ALICE Collaboration: PRC 93, 024917 (2016)

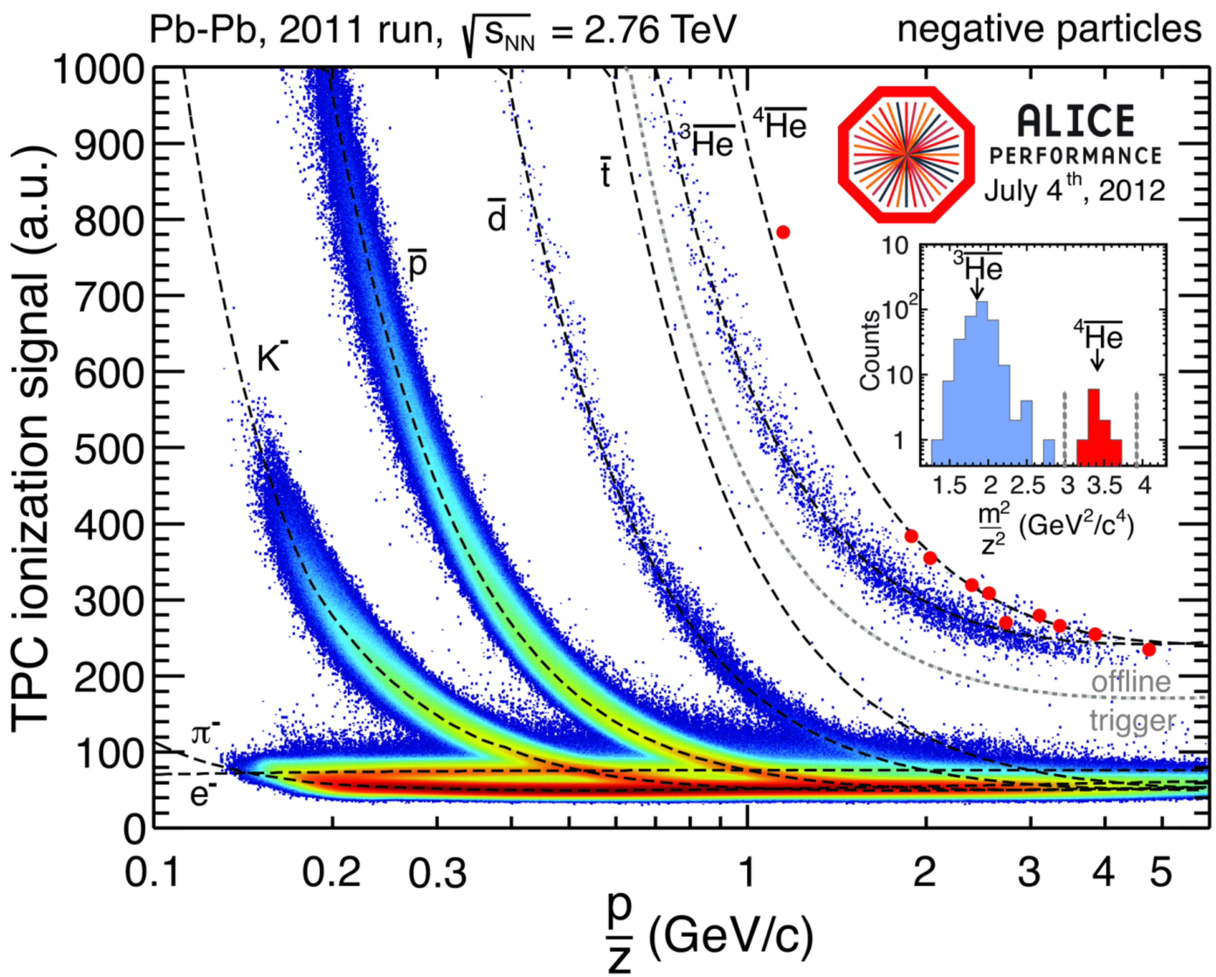
Simultaneous Blast-Wave fit of π^+, K^+, p, d and ^{3}He spectra for central Pb-Pb collisions leads to values for $<\beta>$ and T_{kin} close to the ones obtained when only π,K,p are used

All particles are described rather well with this simultaneous fit



Anti-Alpha

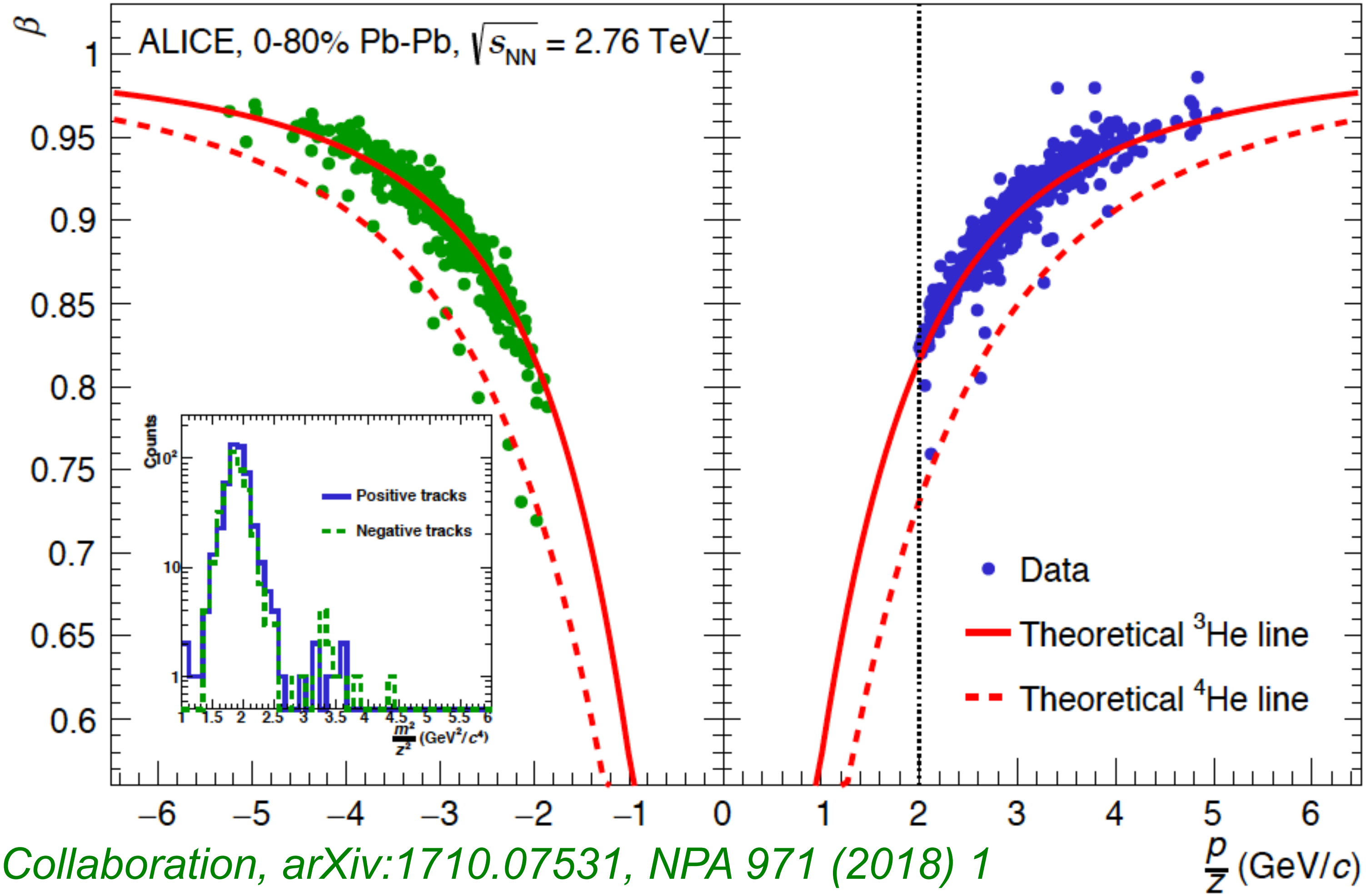
For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF



STAR observed the Anti-Alpha in 2010:

Nature 473, 353 (2011)

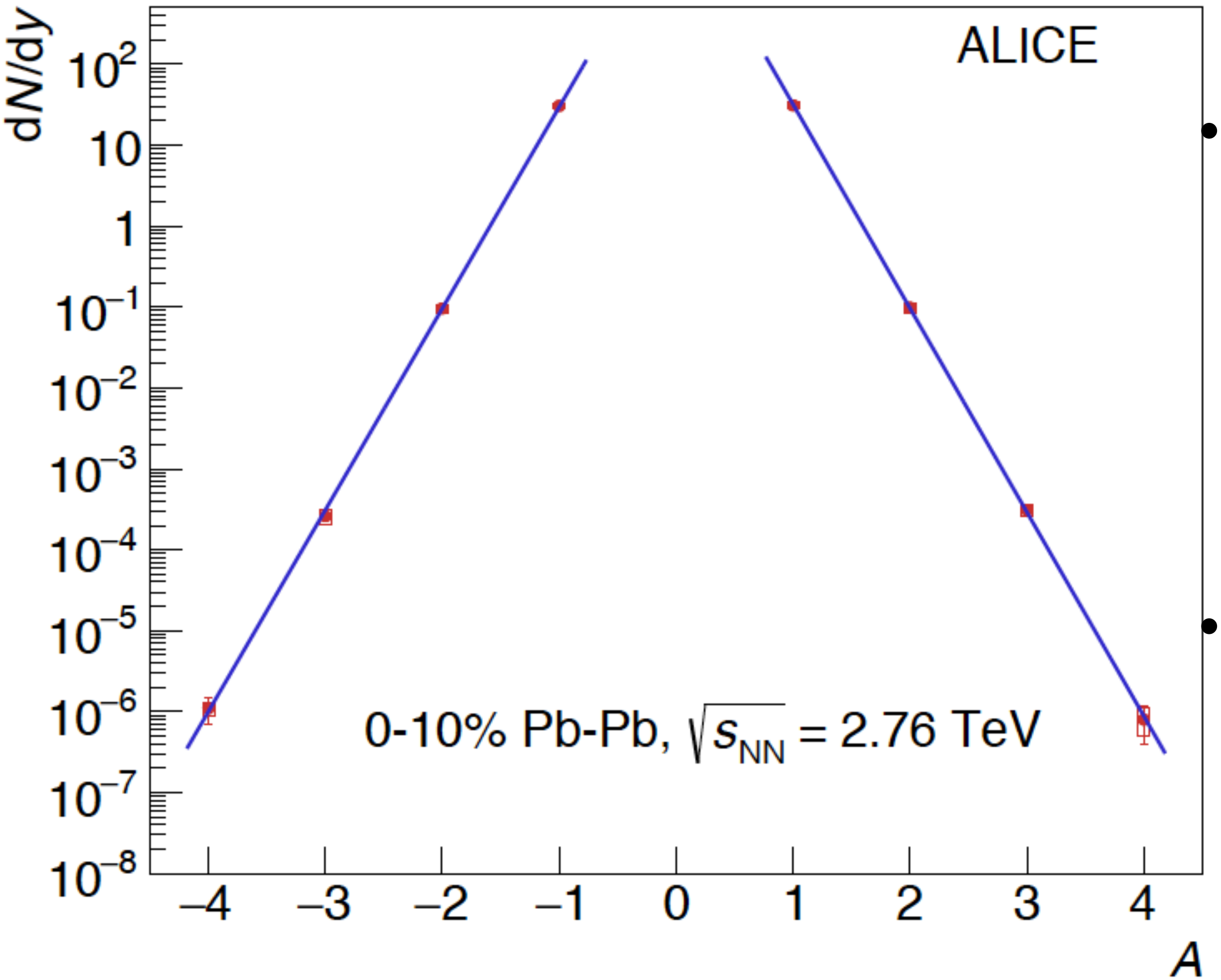
Anti-Alpha



ALICE Collaboration, arXiv:1710.07531, 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

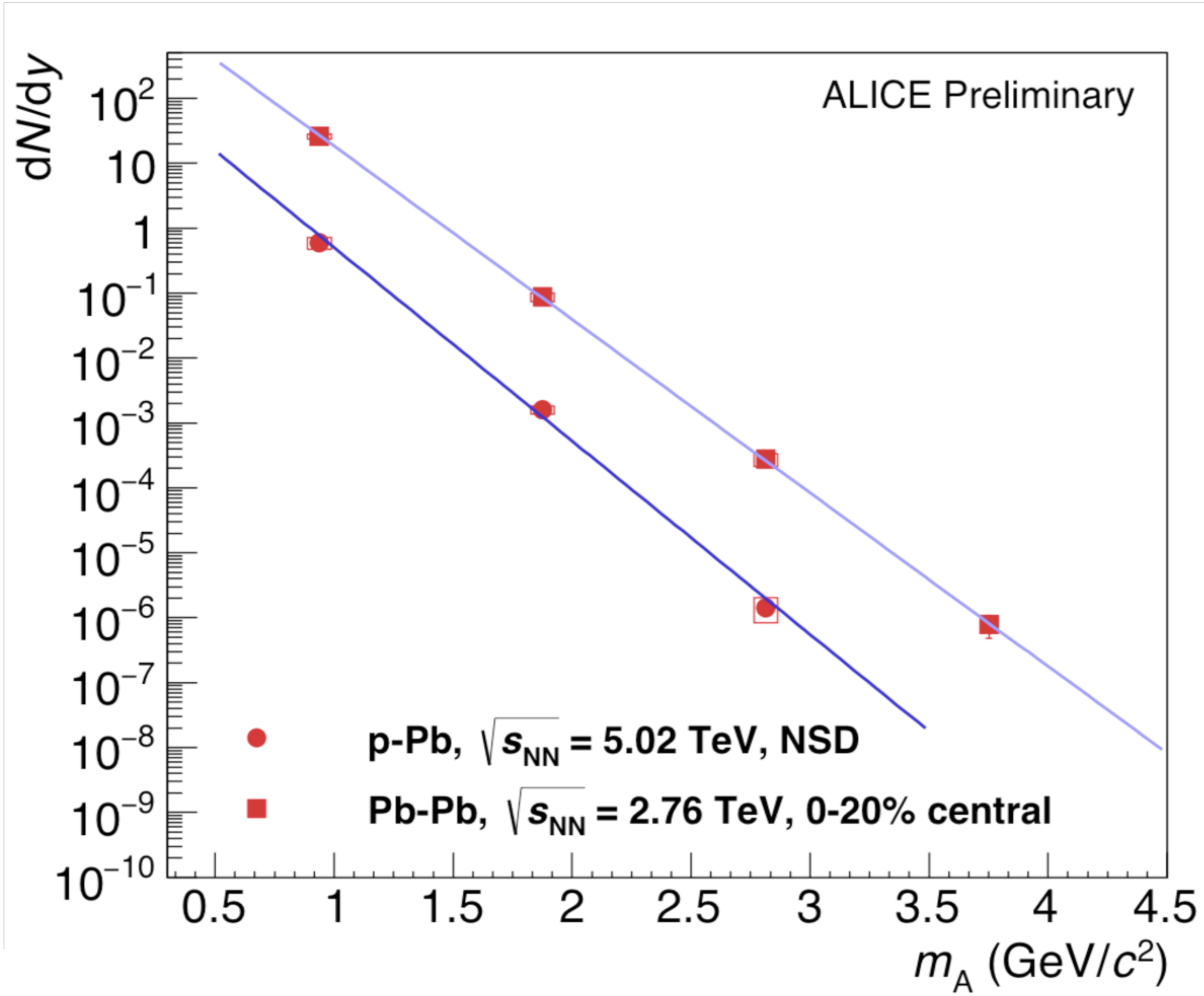
Mass dependence



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

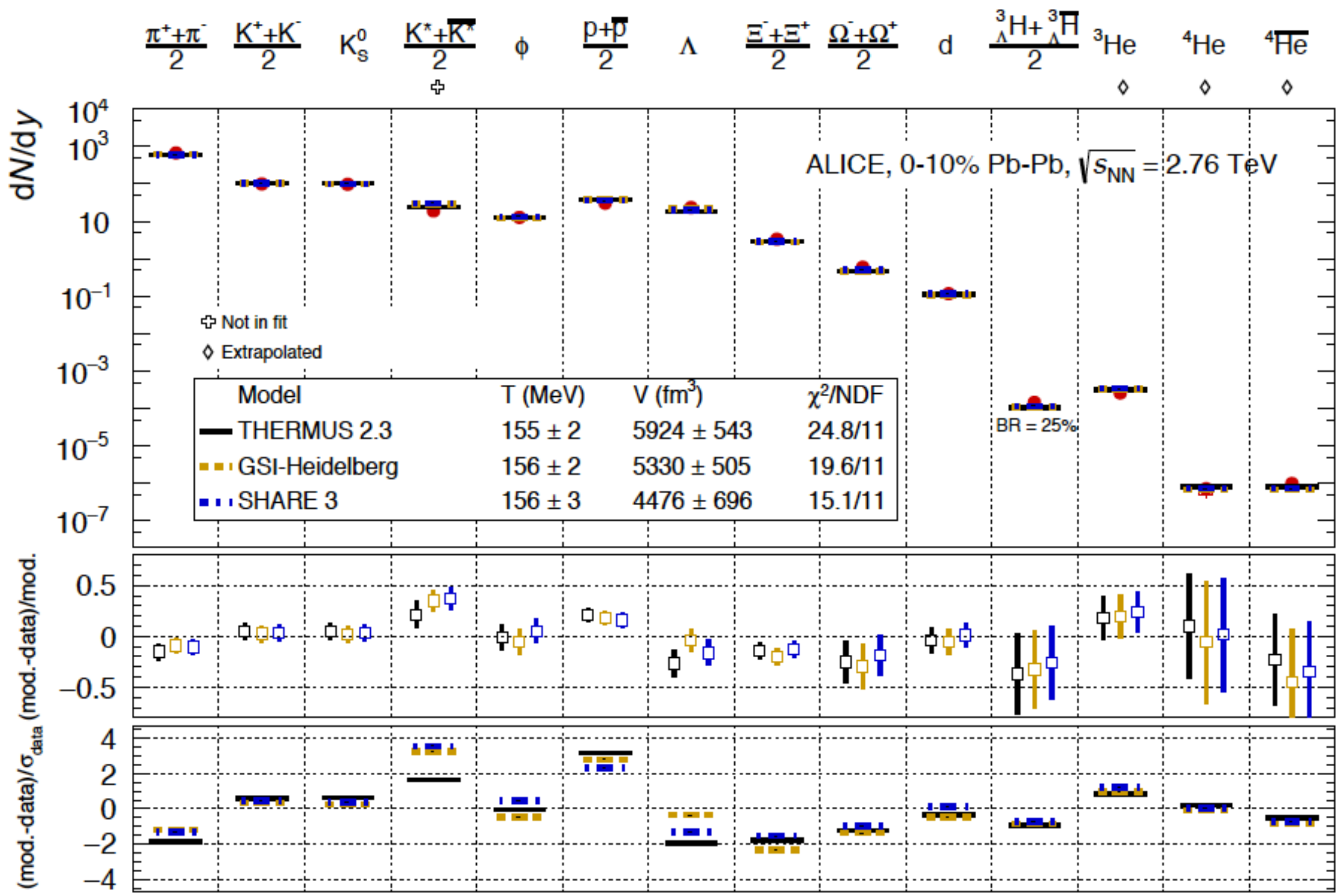
- Nuclei production yields follow an exponential decrease with mass as predicted by the thermal model
- In Pb-Pb the penalty factor for adding one baryon is ~300 (for particles and antiparticles)

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

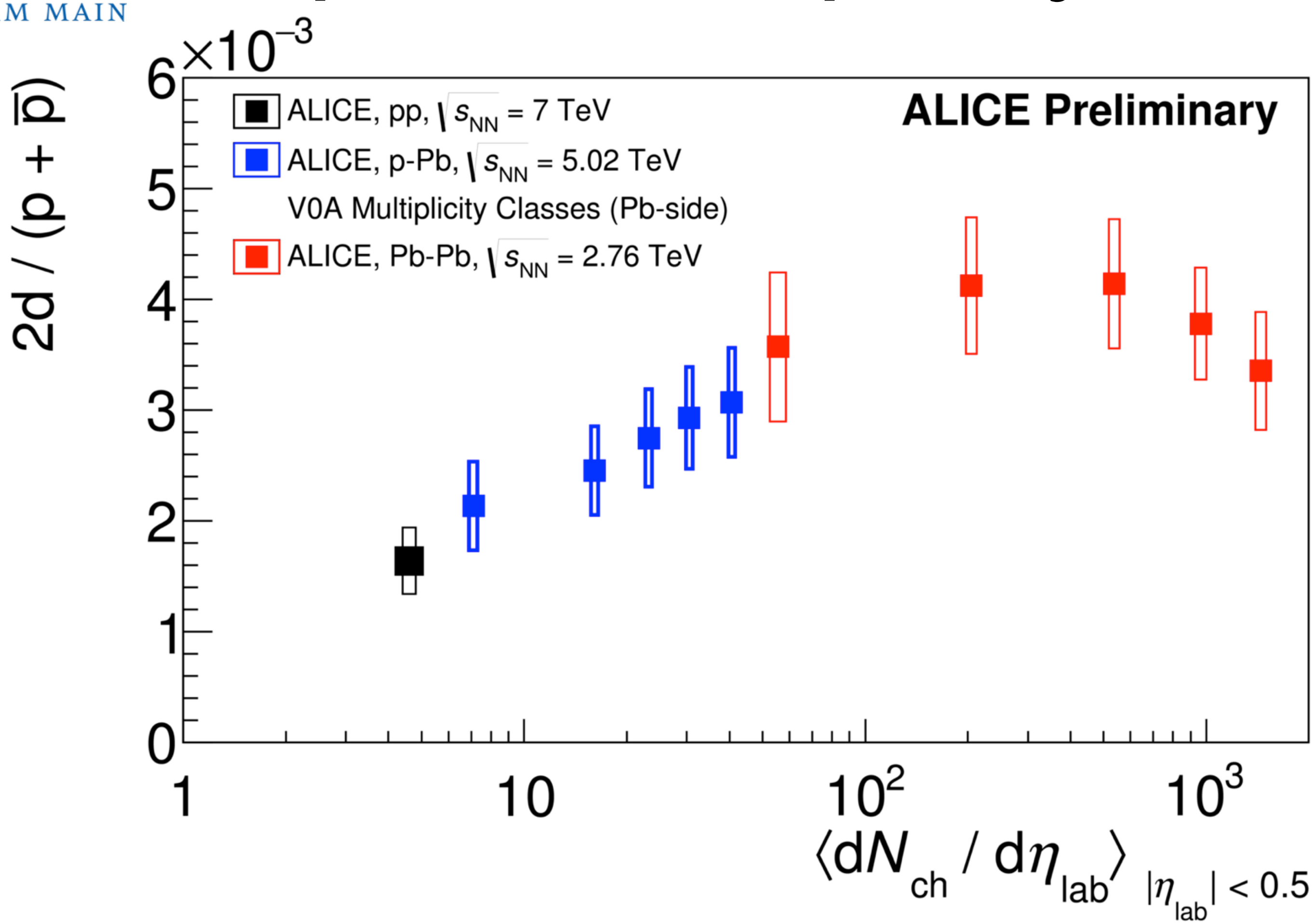


THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

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}

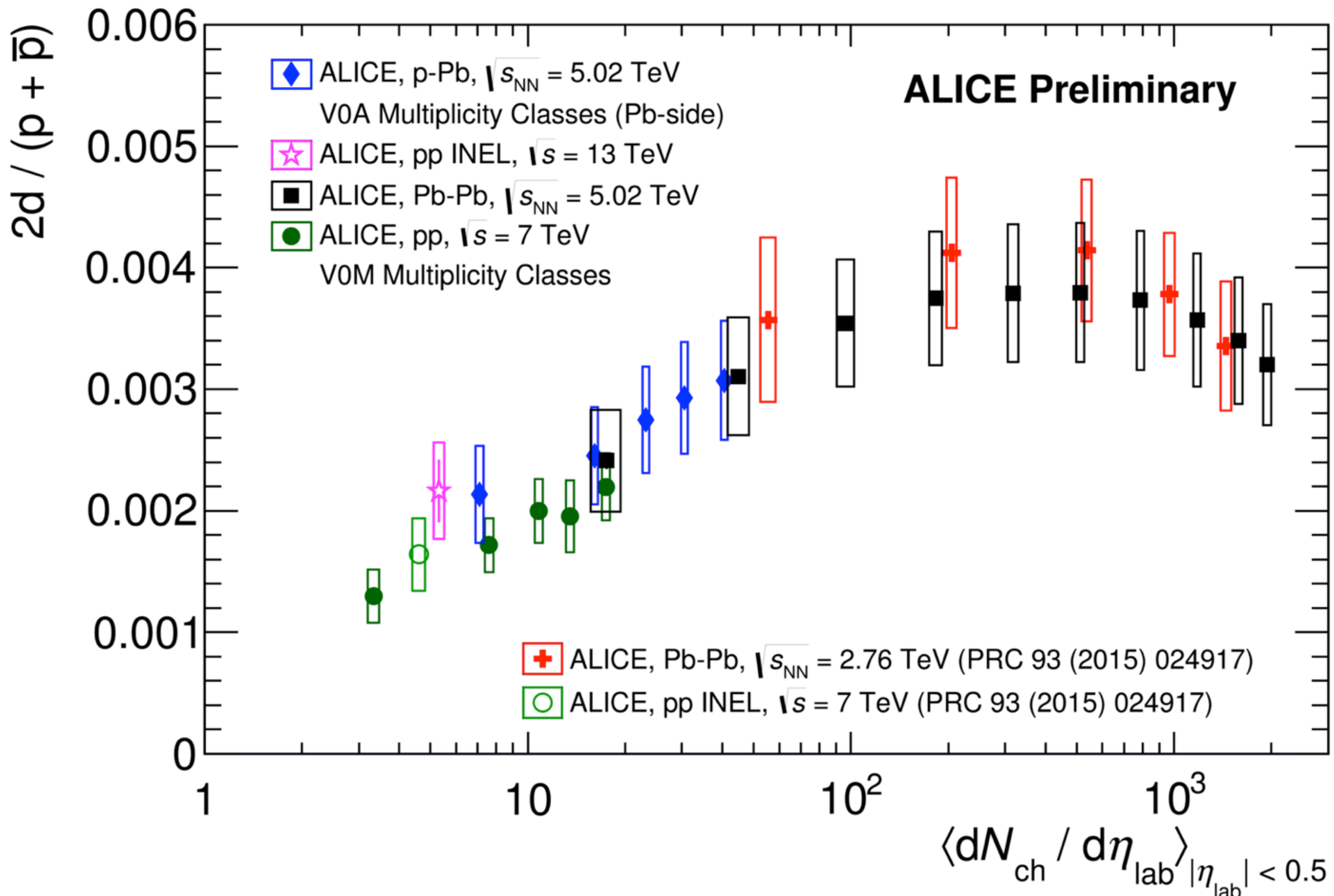
d/p vs. multiplicity



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

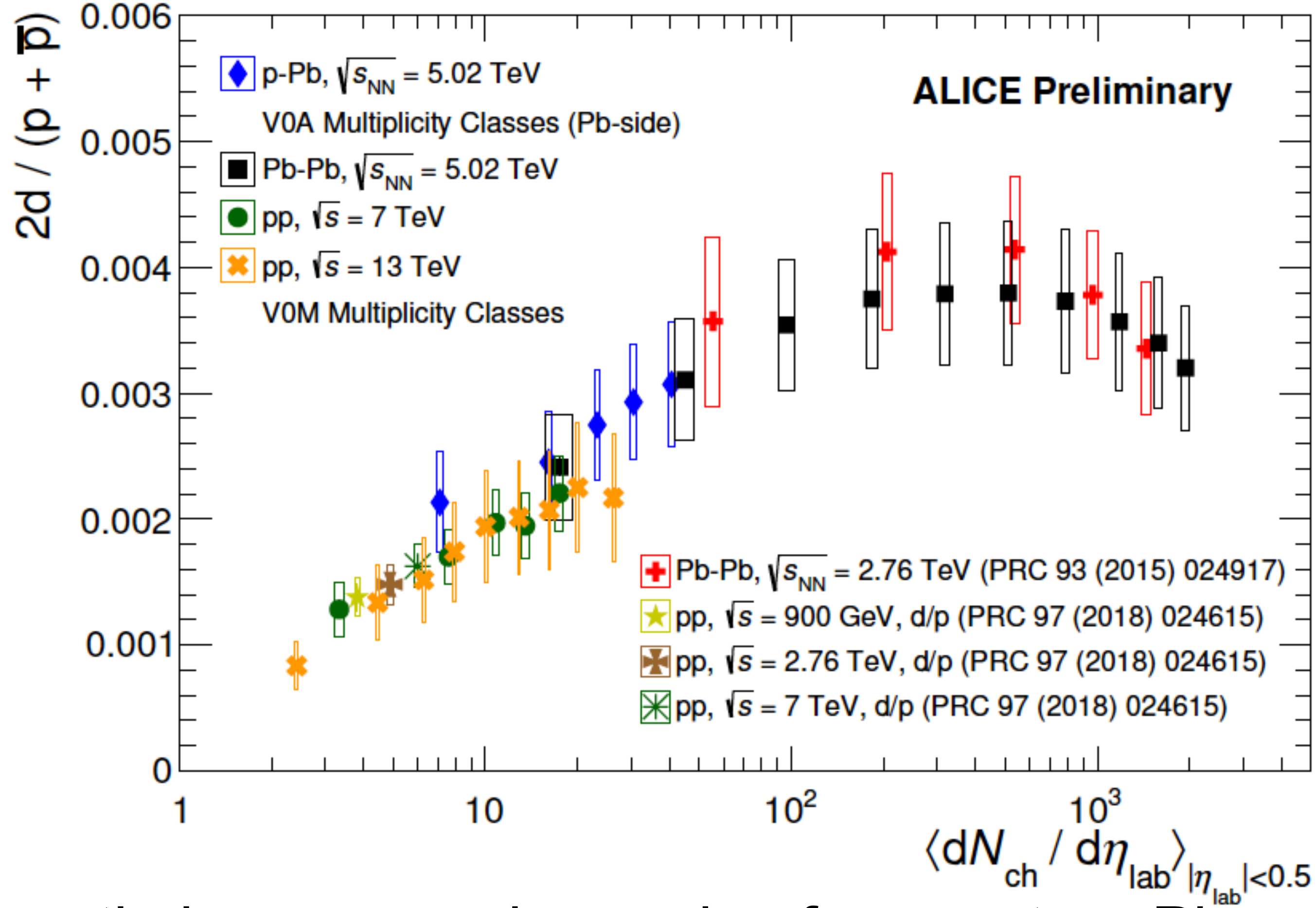
(d/p=3x10^{-3} at T_{ch}= 156 MeV)

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



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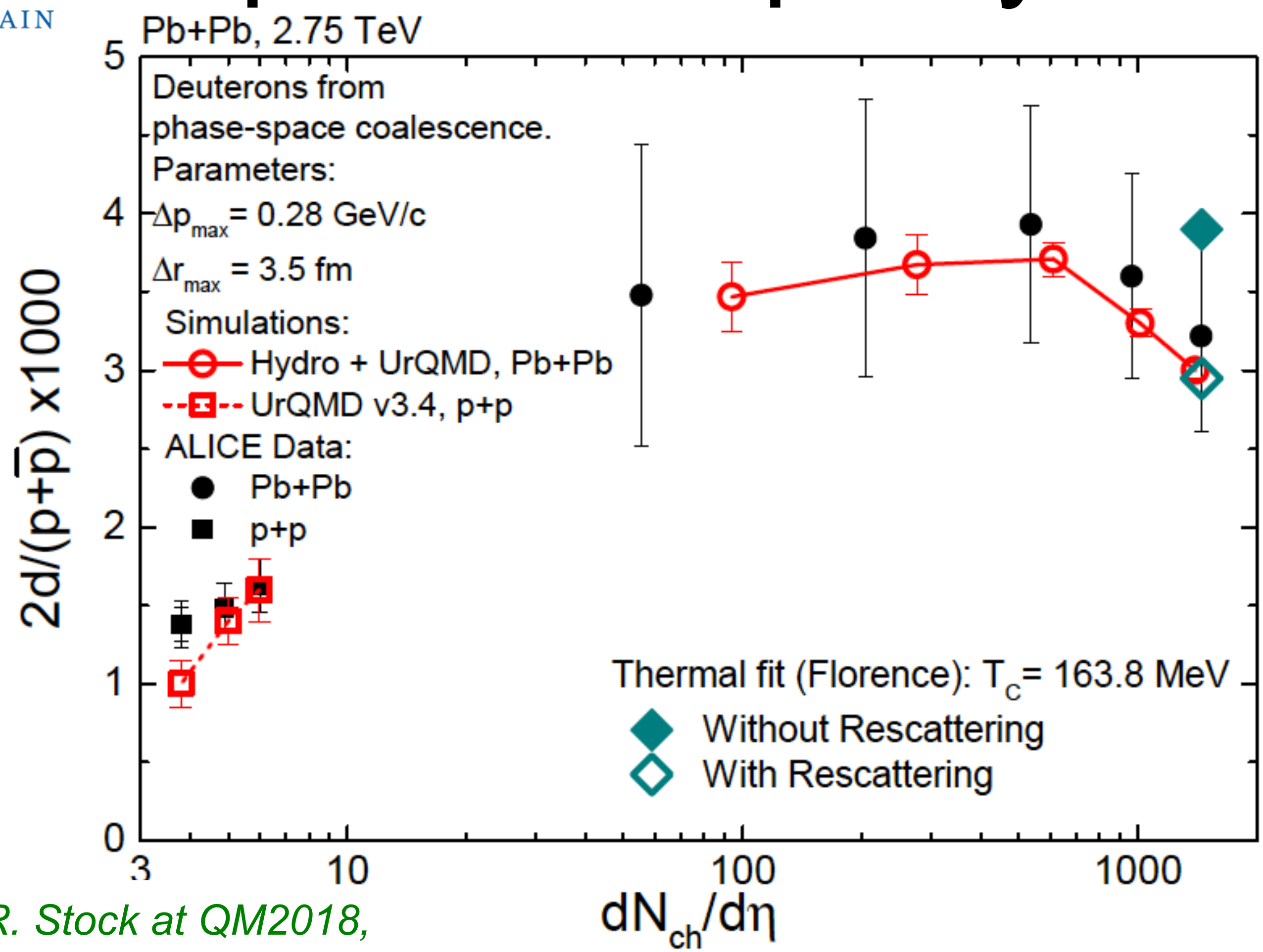
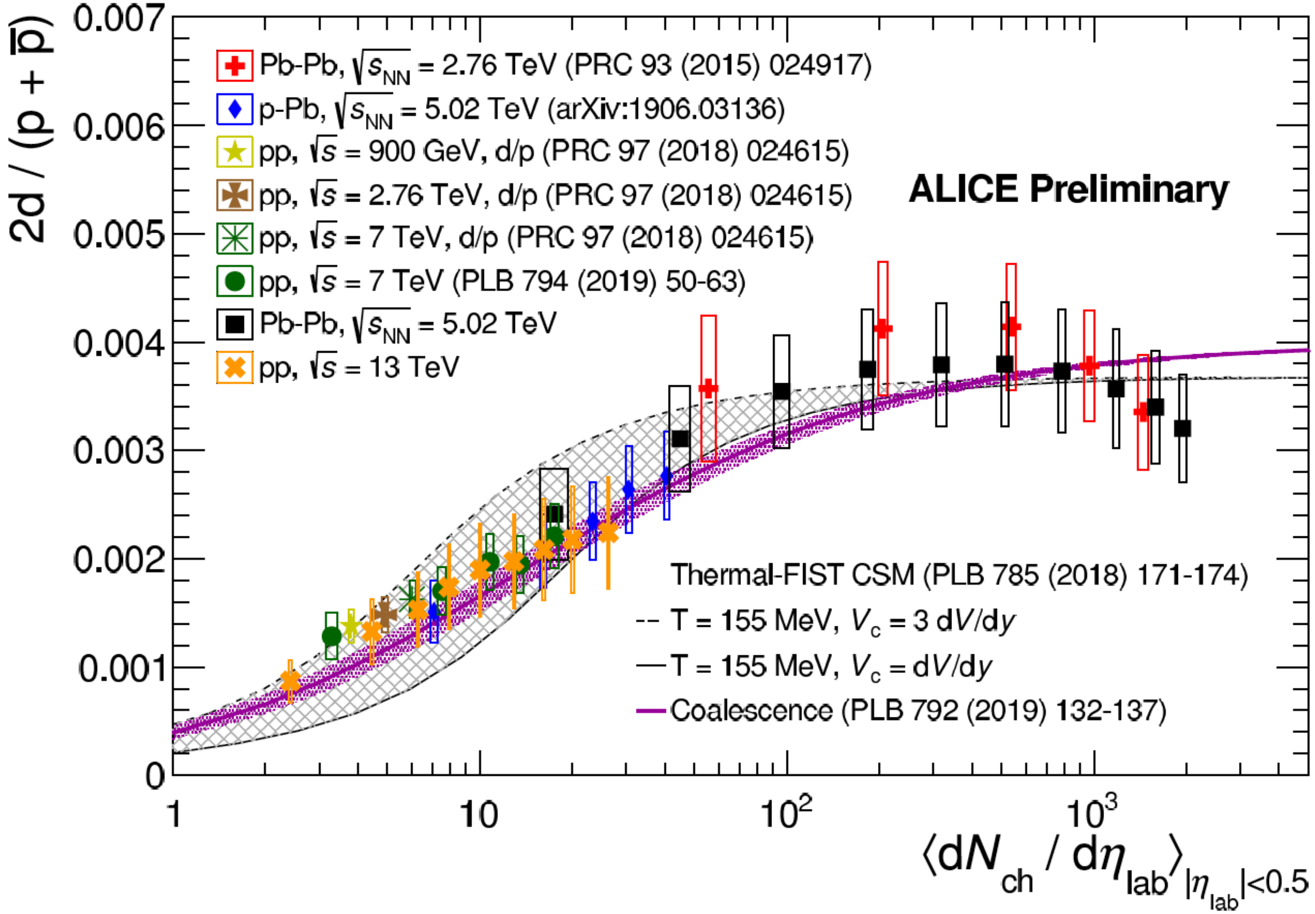


As shown by R. Stock at QM2018, meanwhile coalsecence on arXiv:1805.11509

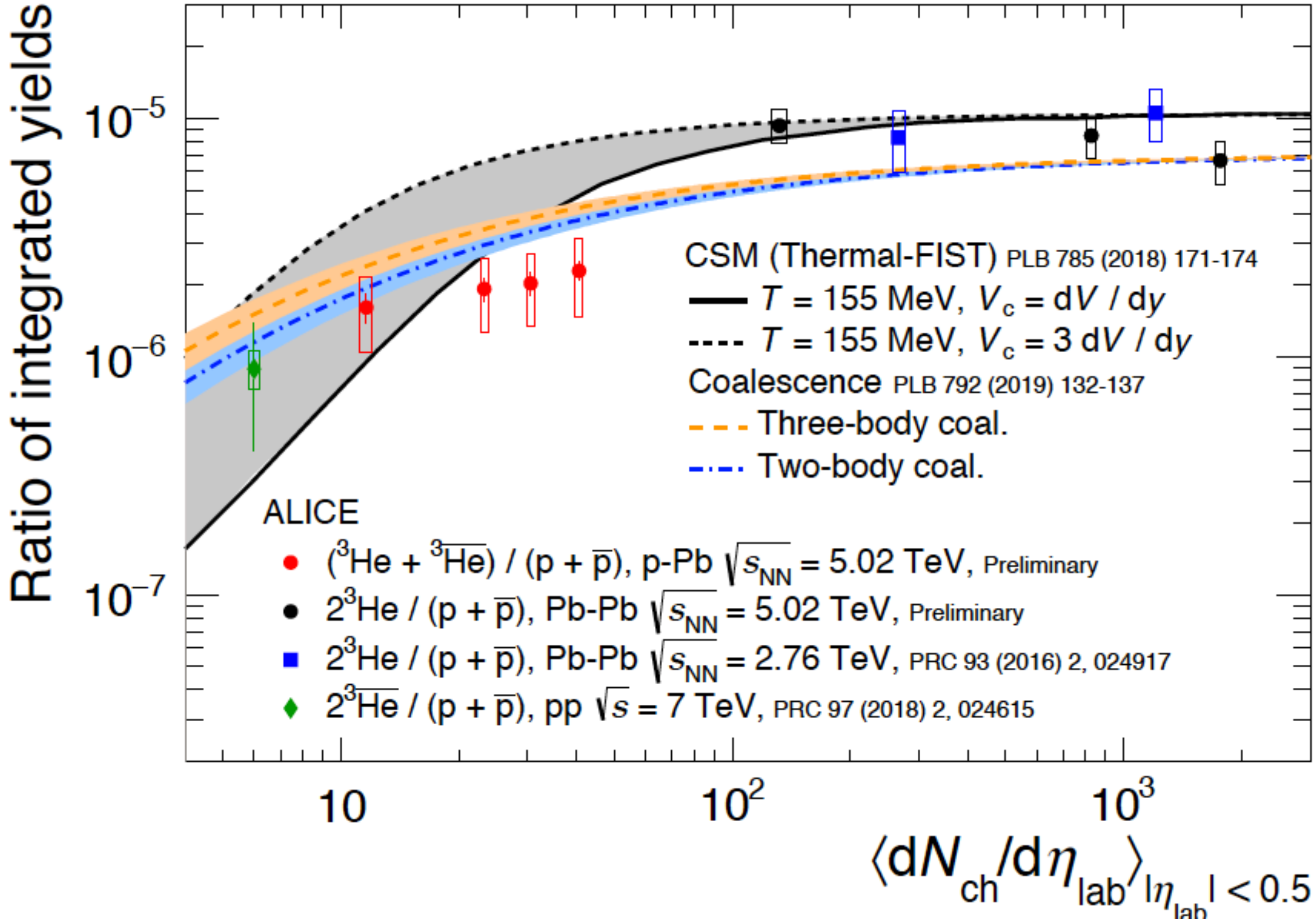
d/p ratio described by applying afterburner on Hybrid UrQMD simulations – similar results for thermal approach

d/p vs. multiplicity



d/p ratio rather well described by using a coalescence approach, from an analytical coalsecence formula or a canonical treatment

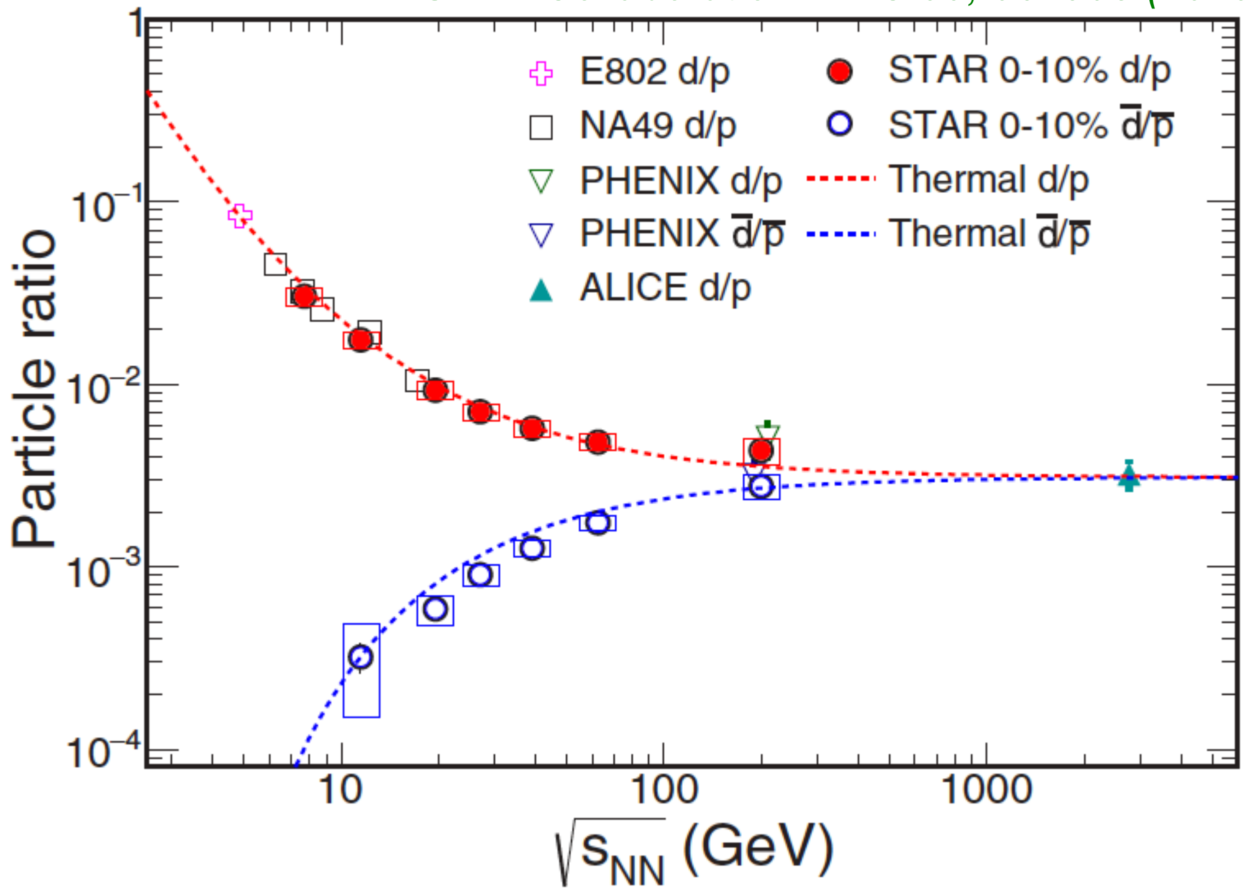
^{3}He/p vs. multiplicity



^{3}He/p ratio rather well described by using a coalescence approach, from an analytical coalsecence formula or a canonical treatment in the thermal model

d/p vs. cms energy

STAR Collaboration: PRC 99, 064905 (2019)

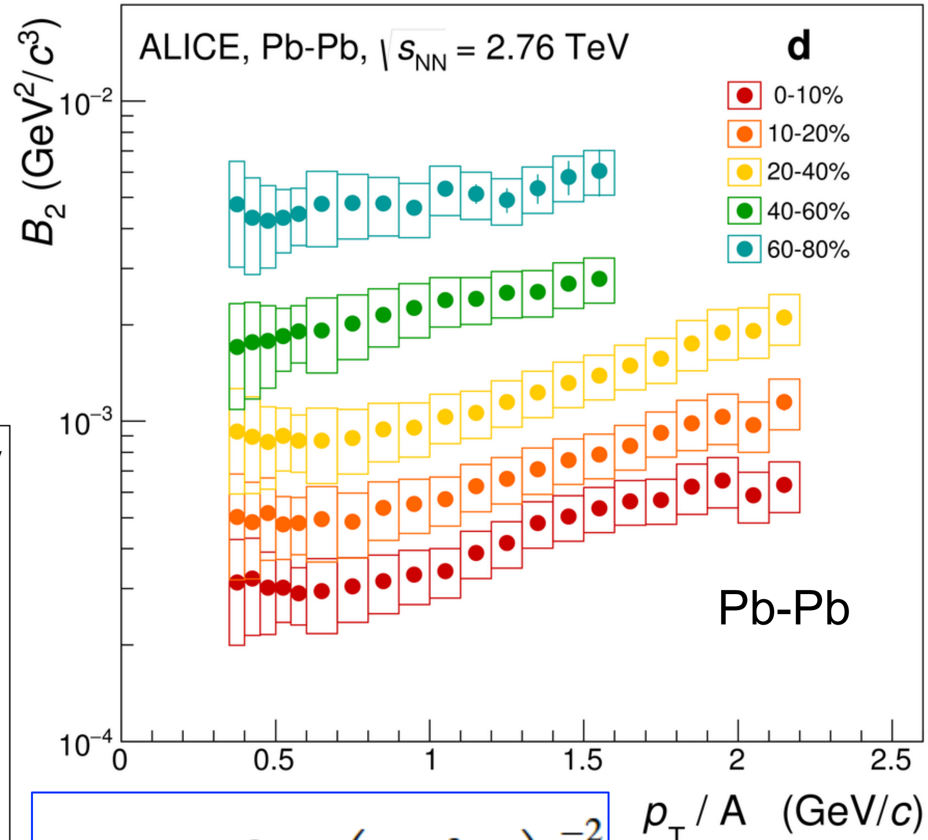


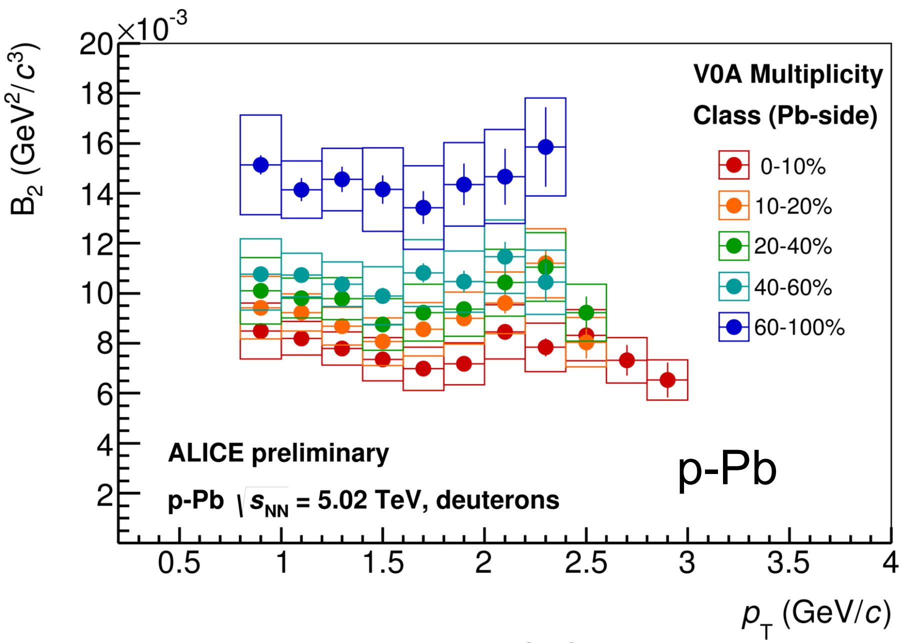
- d/p vs. collision energy ratio rather well described by thermal model approach

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





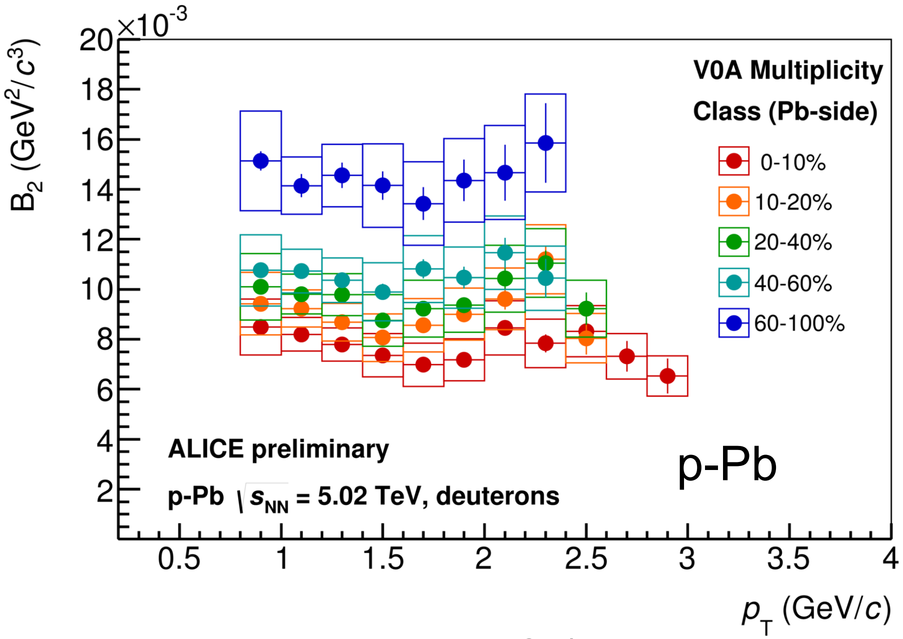
$$B_2 = E_d \frac{d^3 N_d}{dp_d^3} \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^{-2}$$

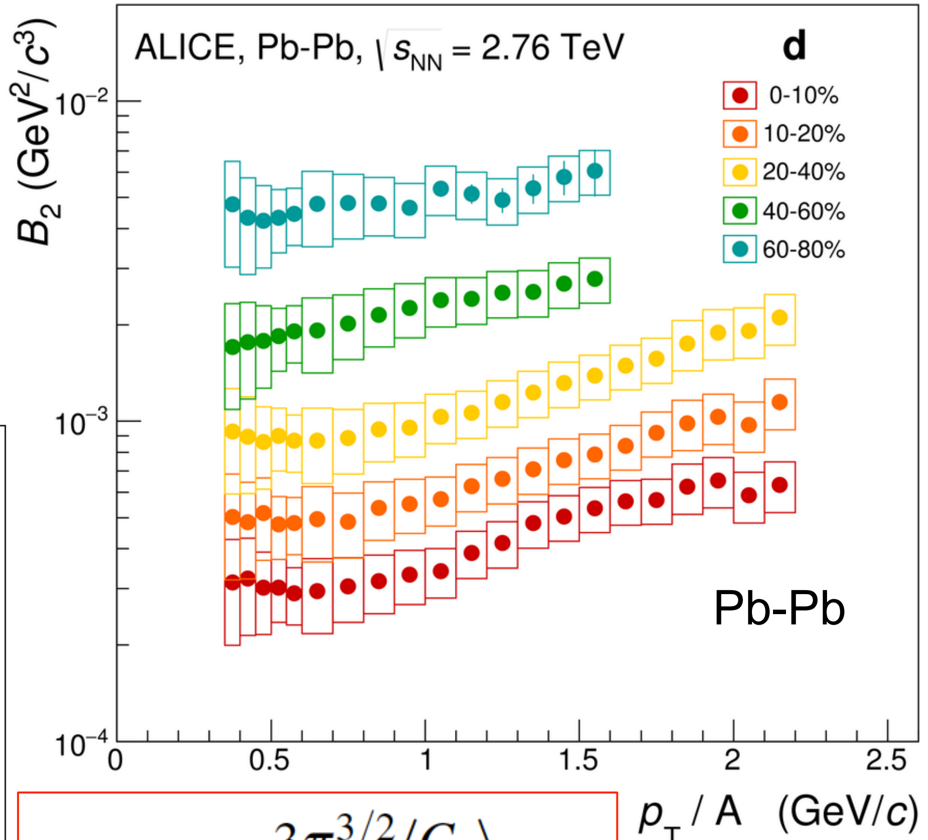
Coalescence parameter B_2

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





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

Coalescence parameter B_2

ALICE Collaboration, PRC 97 (2018) 024615

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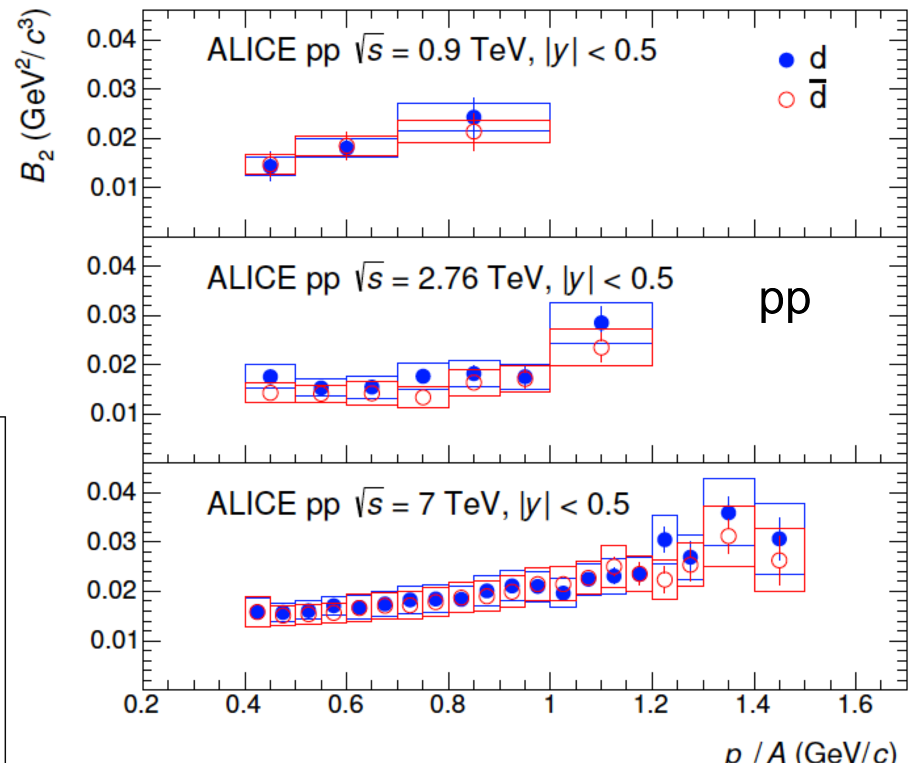

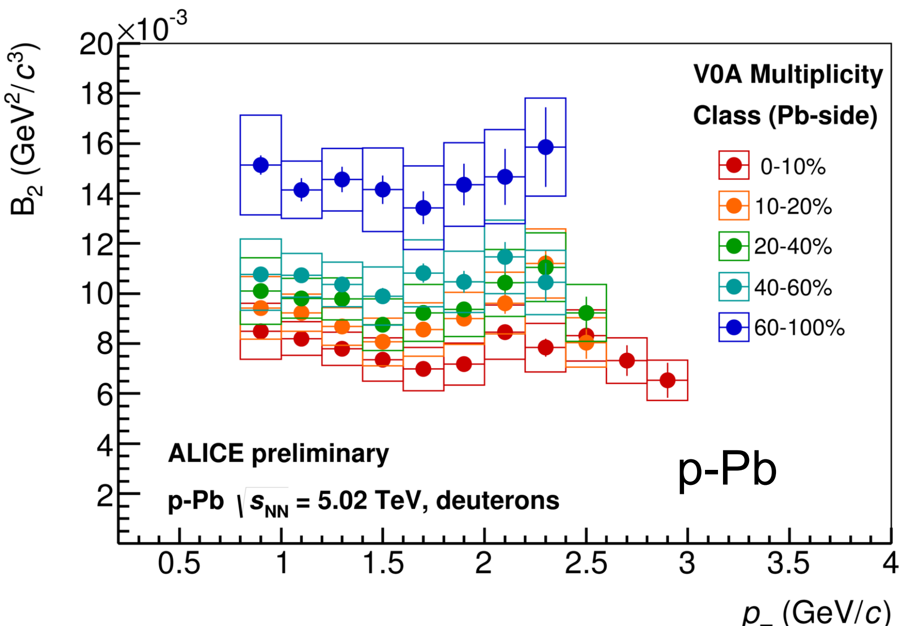

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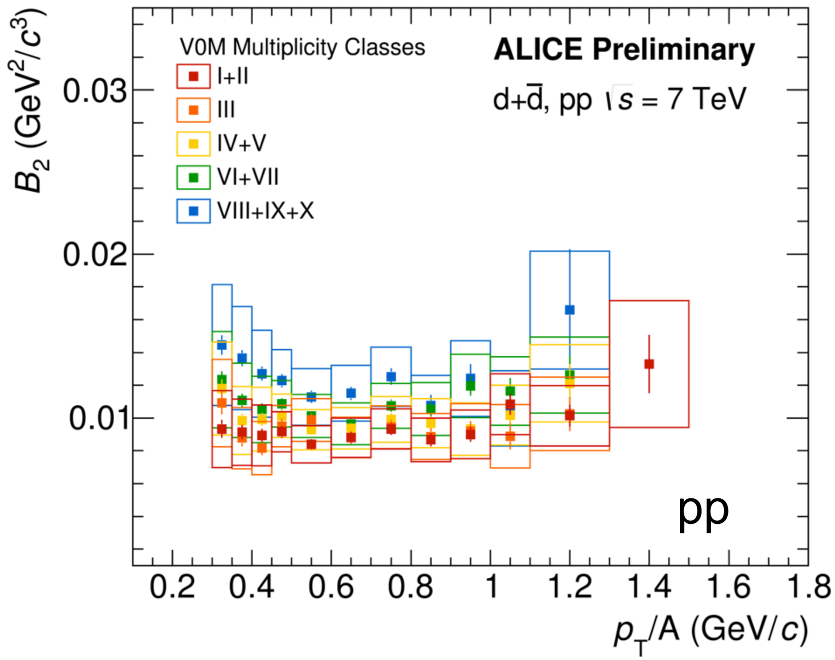

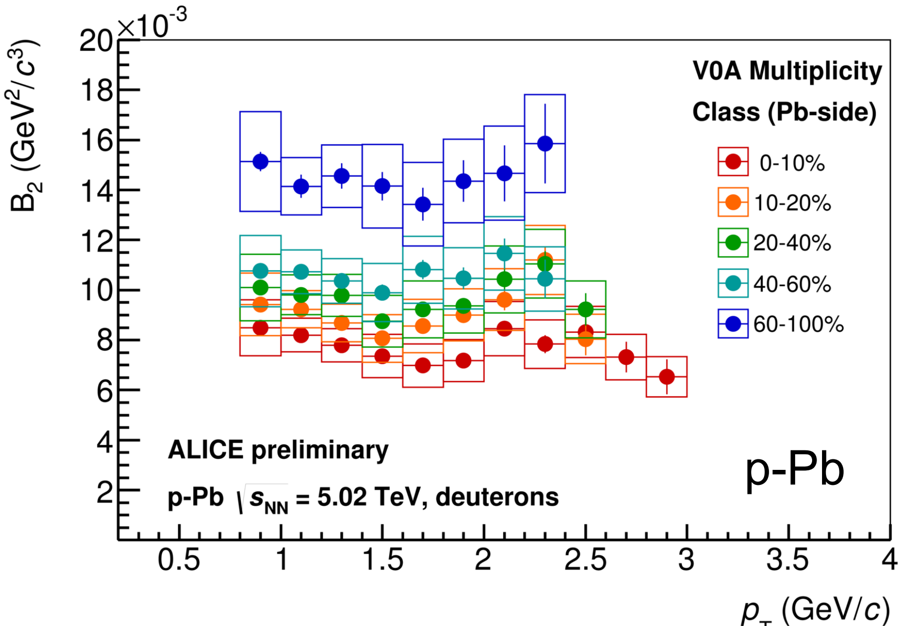

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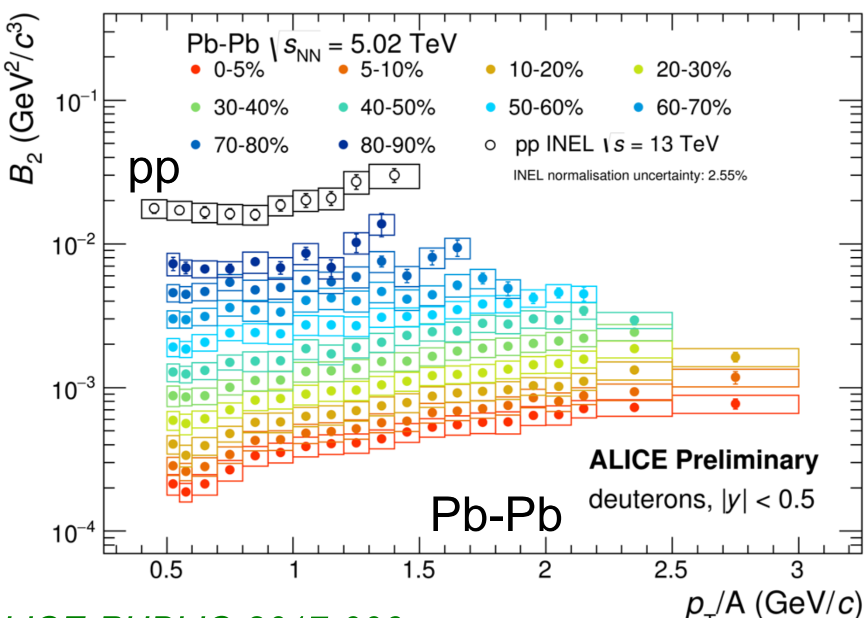

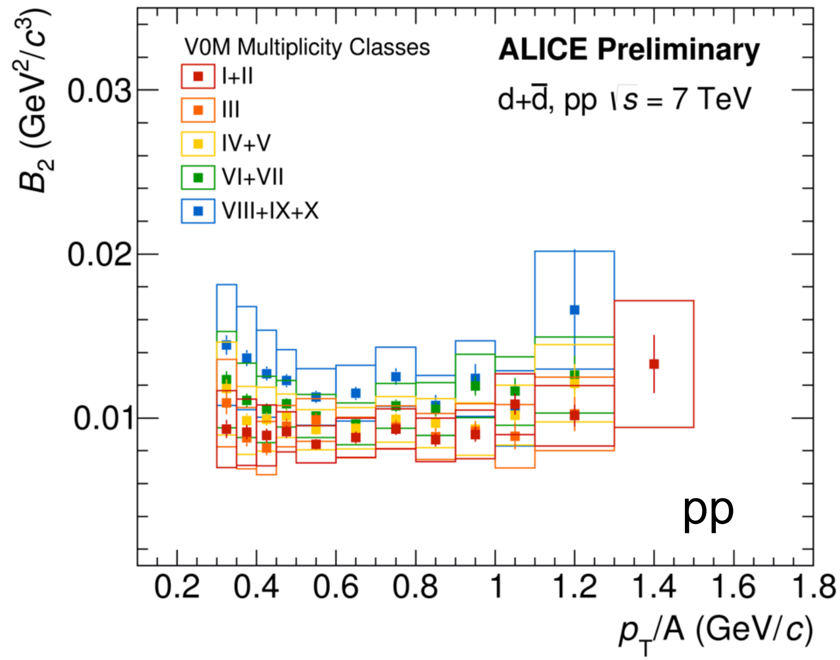

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ALICE-PUBLIC-2017-006

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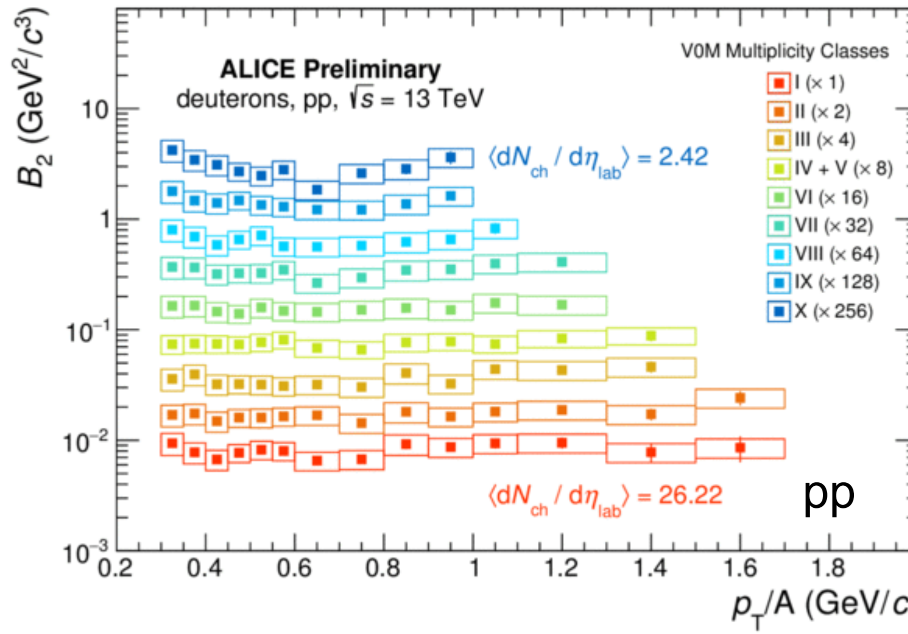

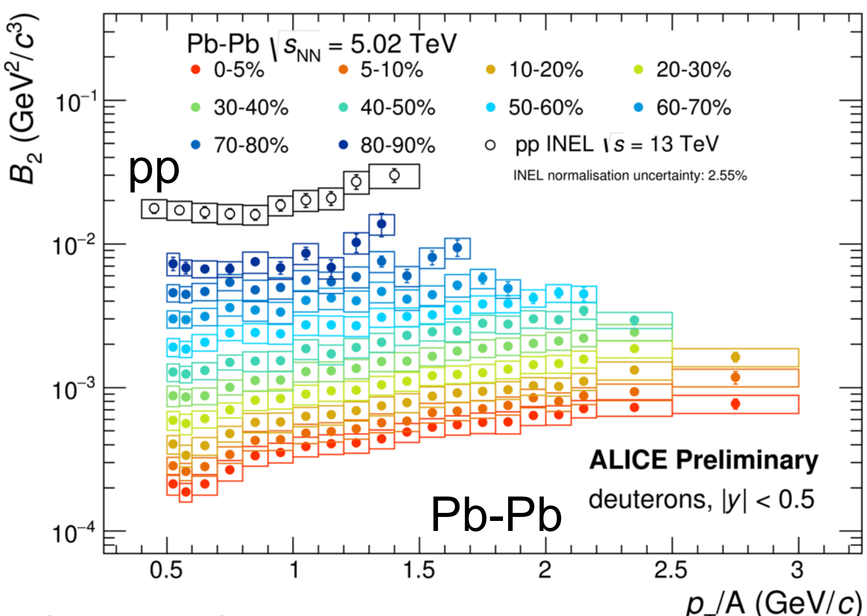

$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

ALICE-PUBLIC-2017-006

Coalescence parameter B_2

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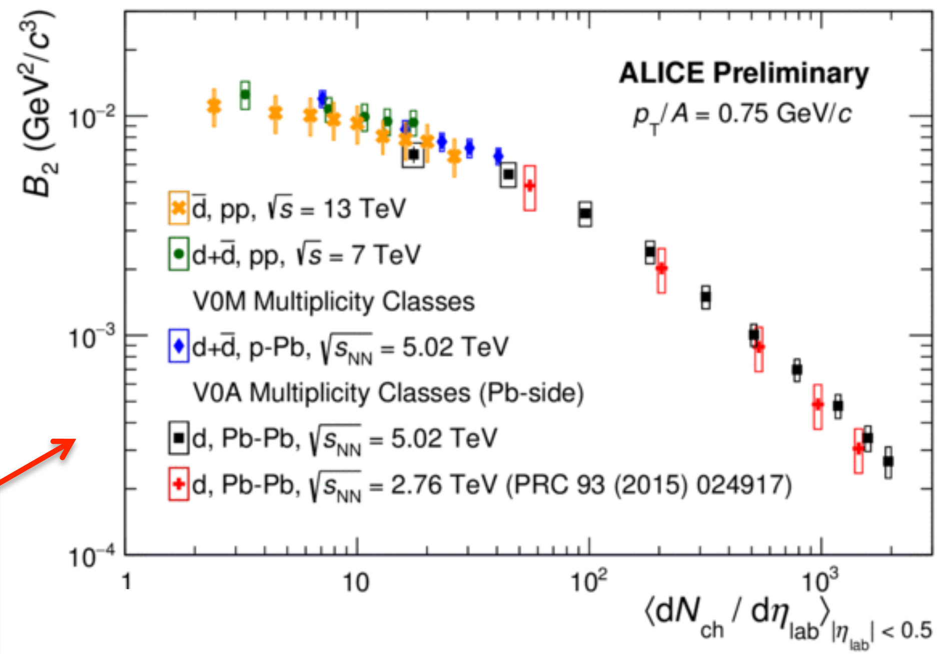

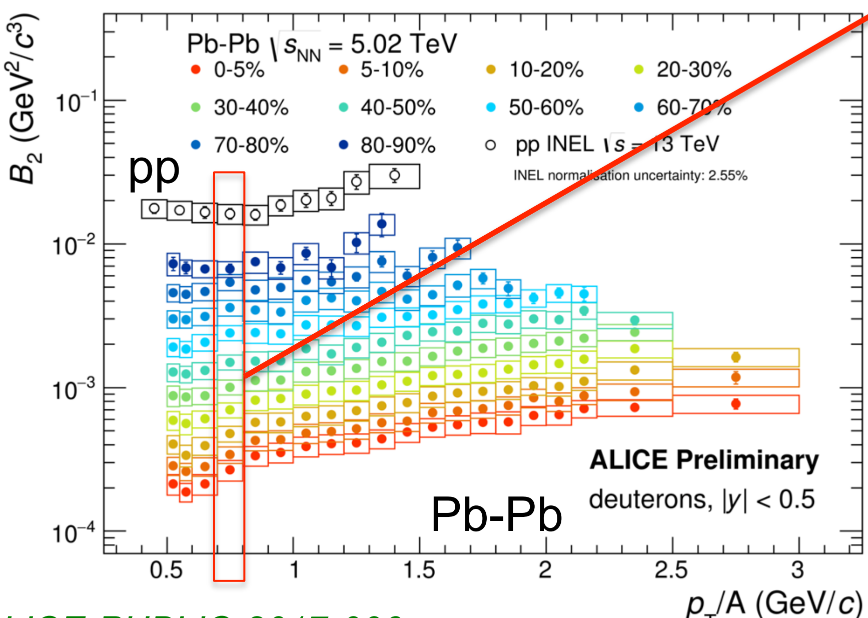

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ALICE-PUBLIC-2017-006

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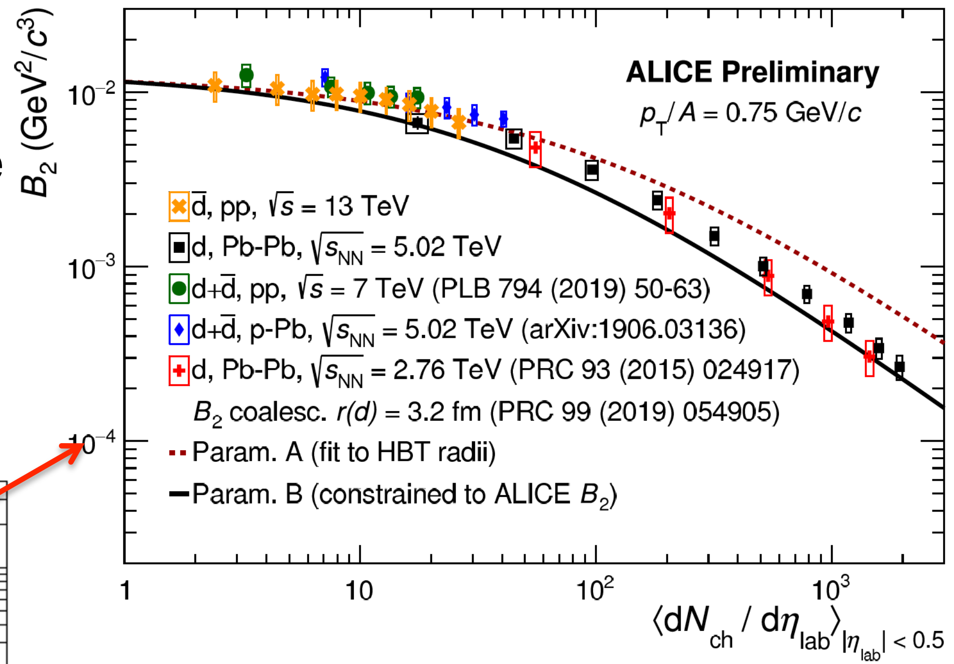

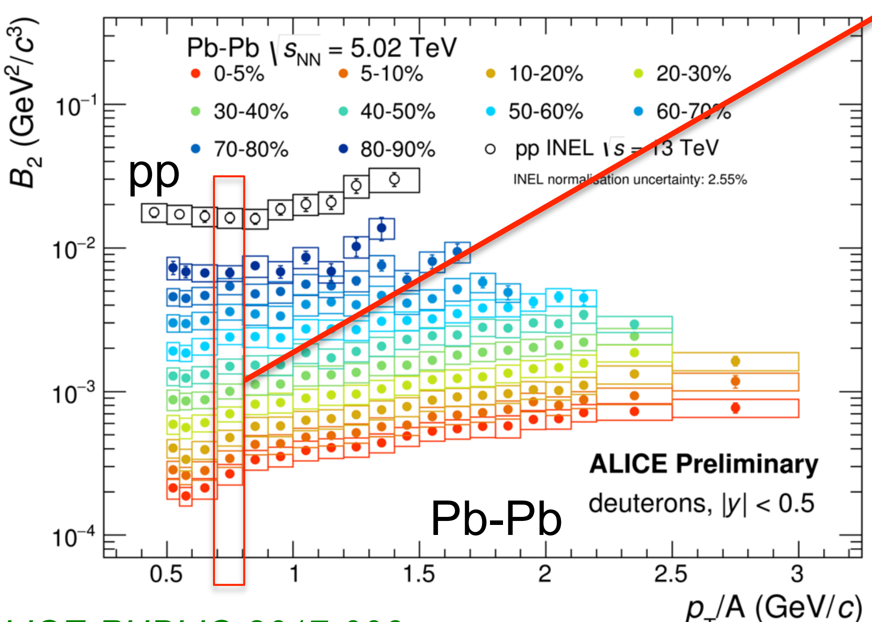

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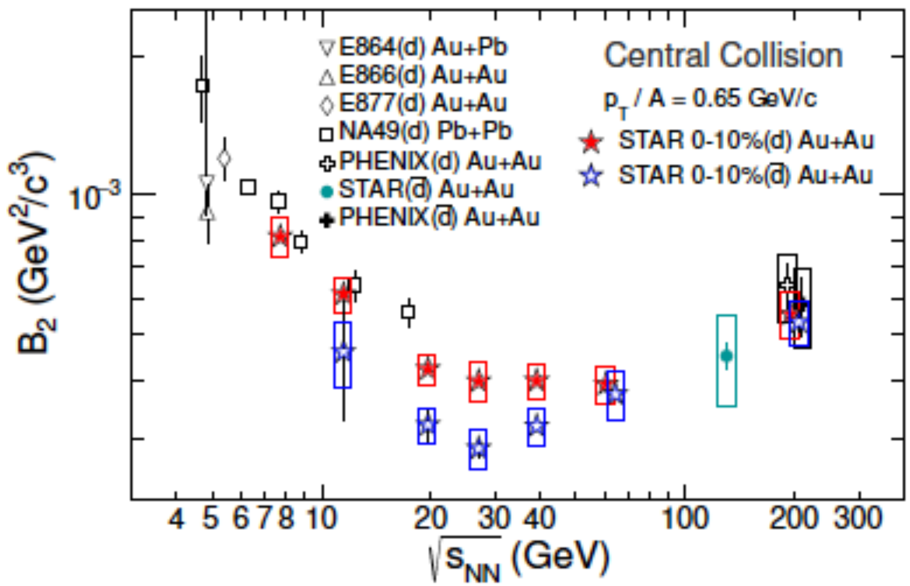
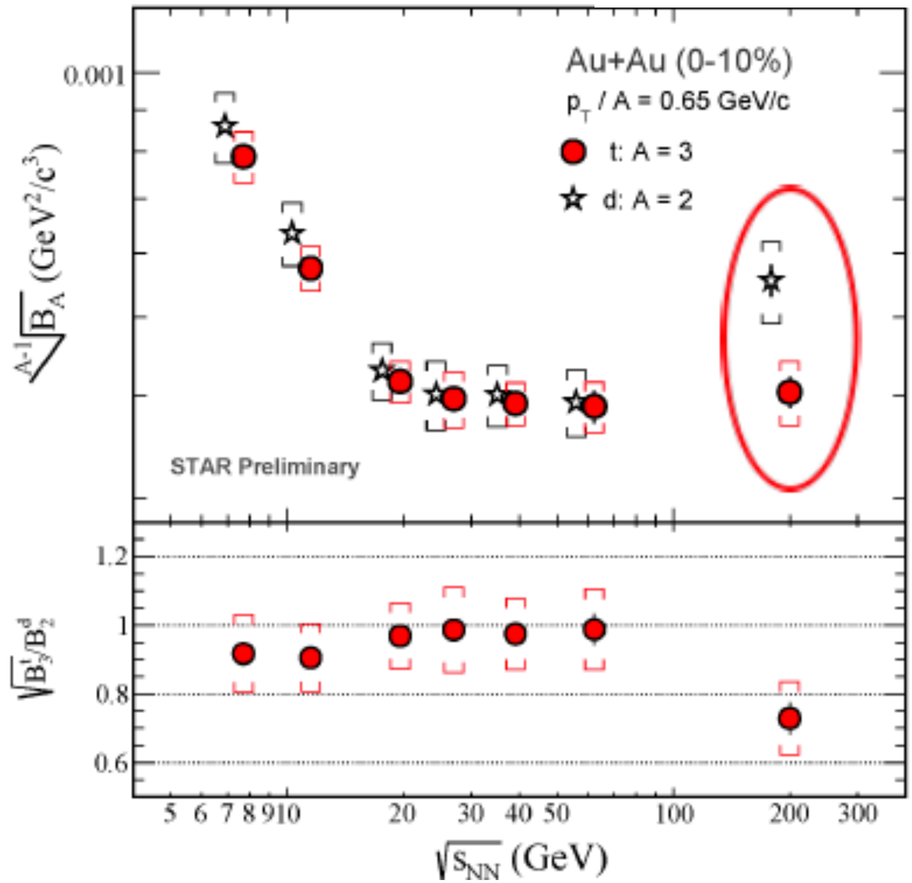
ALICE-PUBLIC-2017-006

B_2 and B_3

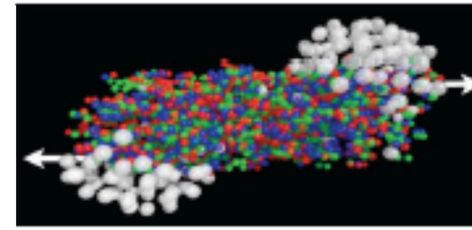
STAR Collaboration: PRC 99, 064905 (2019)

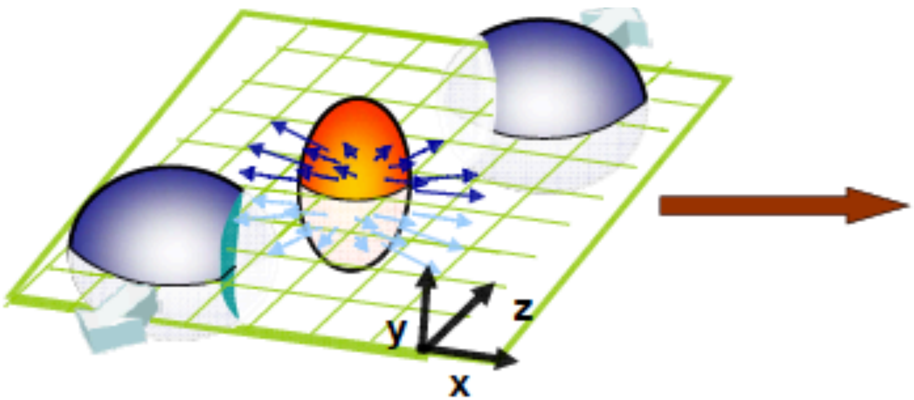


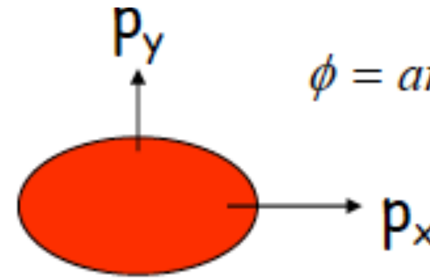


- B_2(anti-d) smaller than B_2(d) indicates different freeze-out volumes for baryons and anti-baryons
- B_2(d) and sqrt(B_3(d)) agree well except for 200 GeV

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

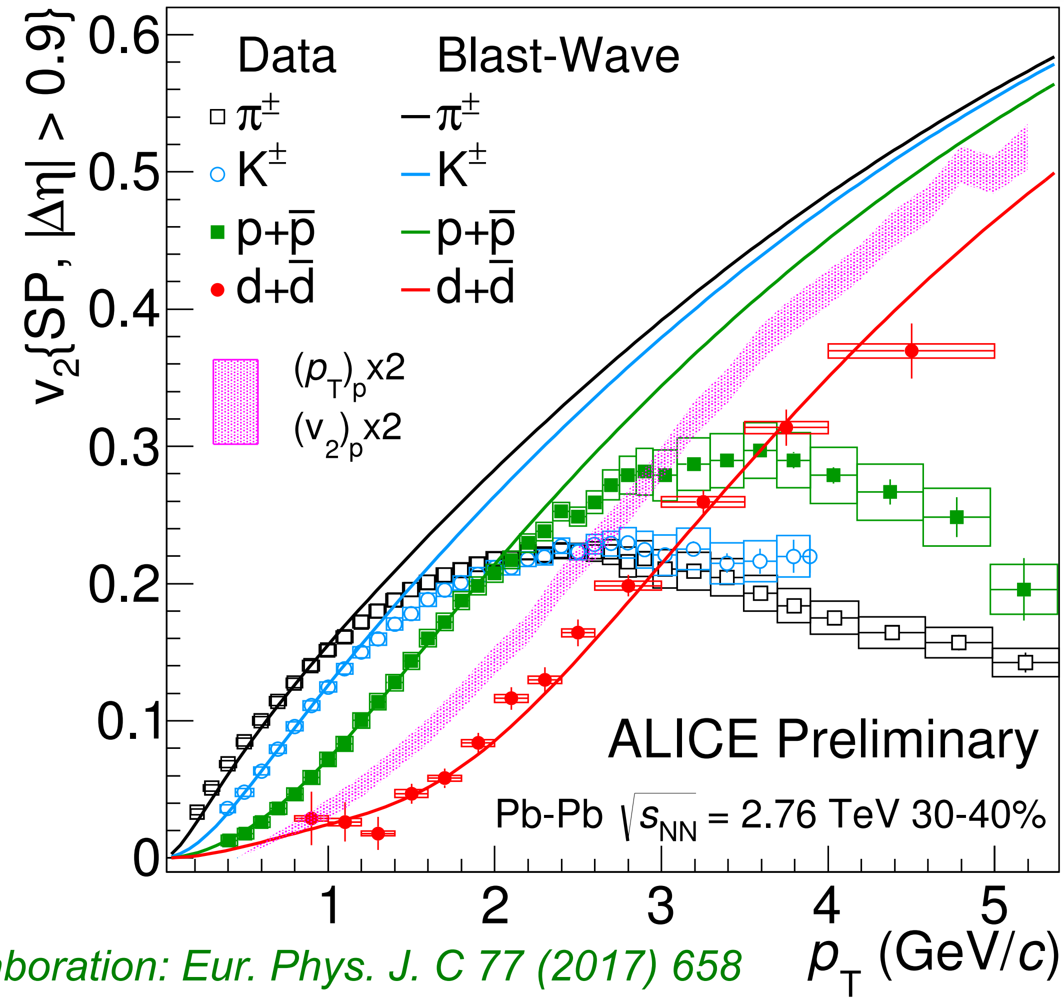
$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos[2(\phi-\Psi_R)] + 2v_4\cos[4(\phi-\Psi_R)] + \ldots$$

Elliptic term

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

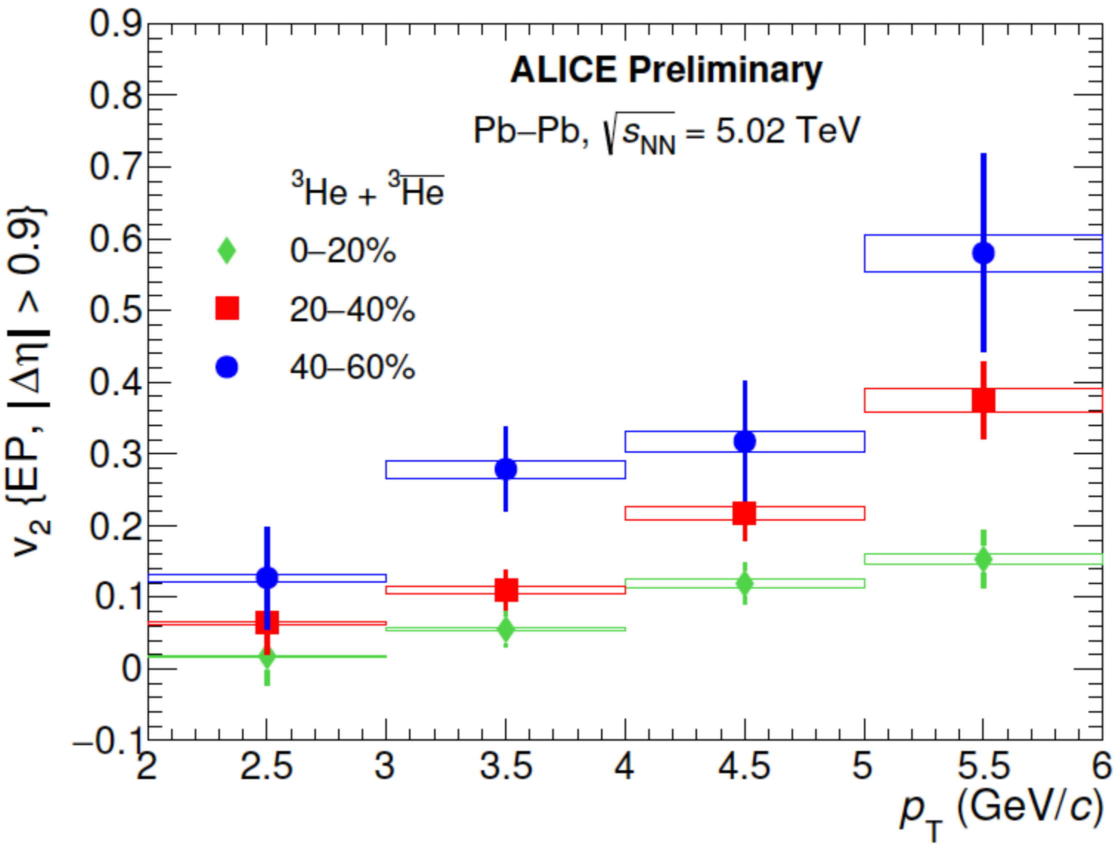
Deuteron flow

- 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



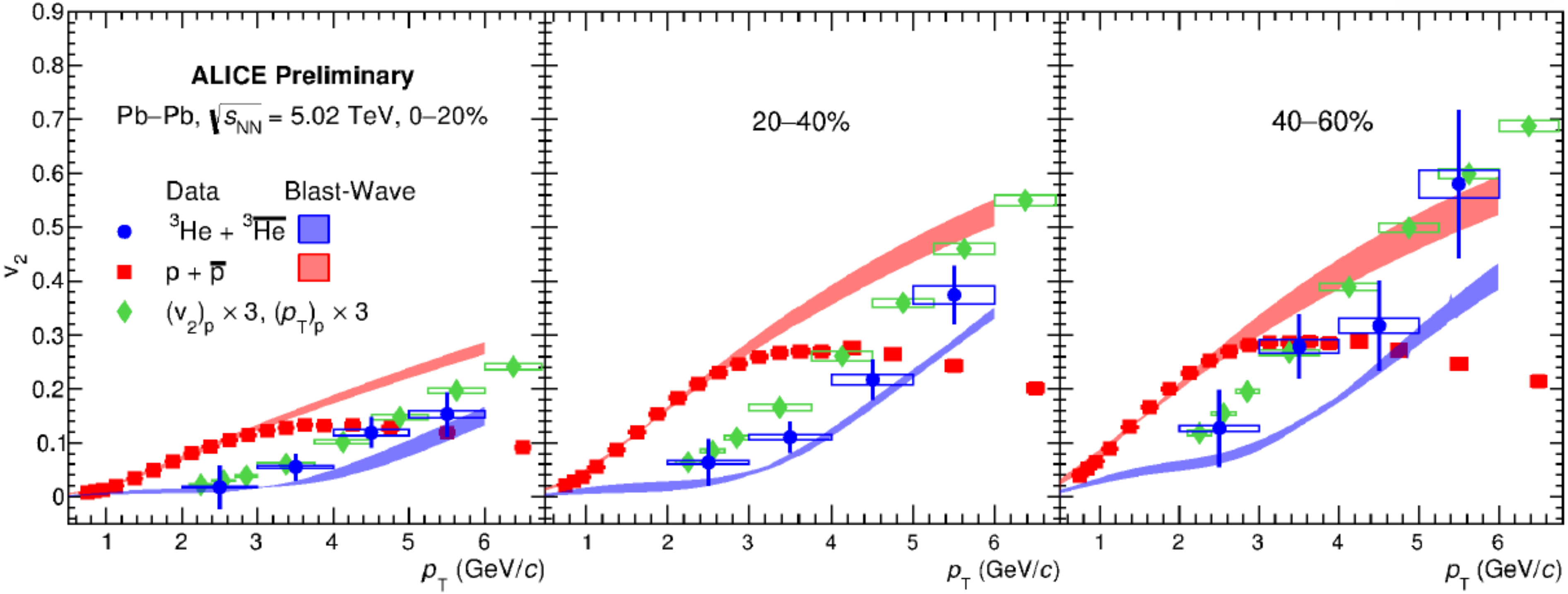
ALICE Collaboration: Eur. Phys. J. C 77 (2017) 658

^{3}He flow



- ^{3}He also shows a significant v_2

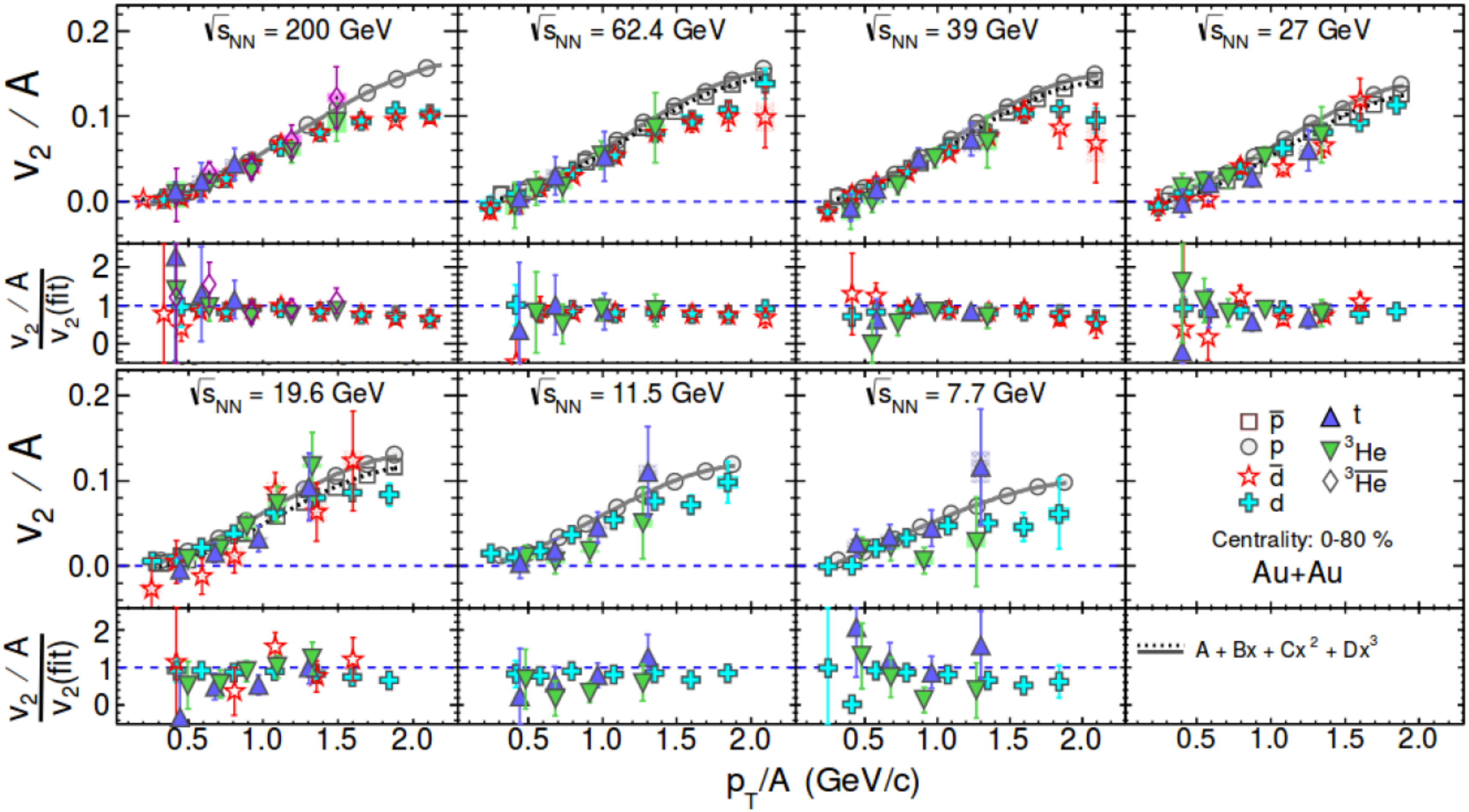
^{3}He flow



- 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

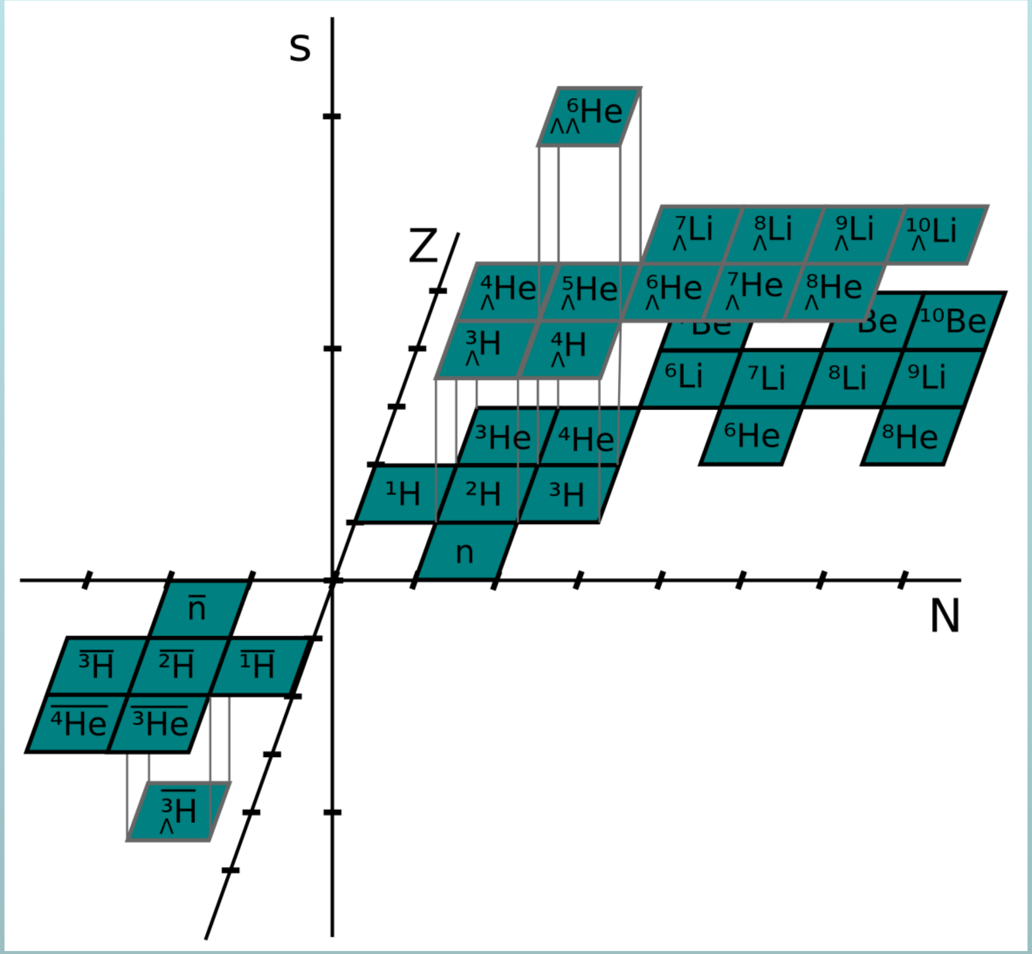
^{3}He flow

STAR Collaboration: PRC 94, 034908 (2016)



- Scaling the v_2 and p_T of particles works rather well for all nuclei at RHIC

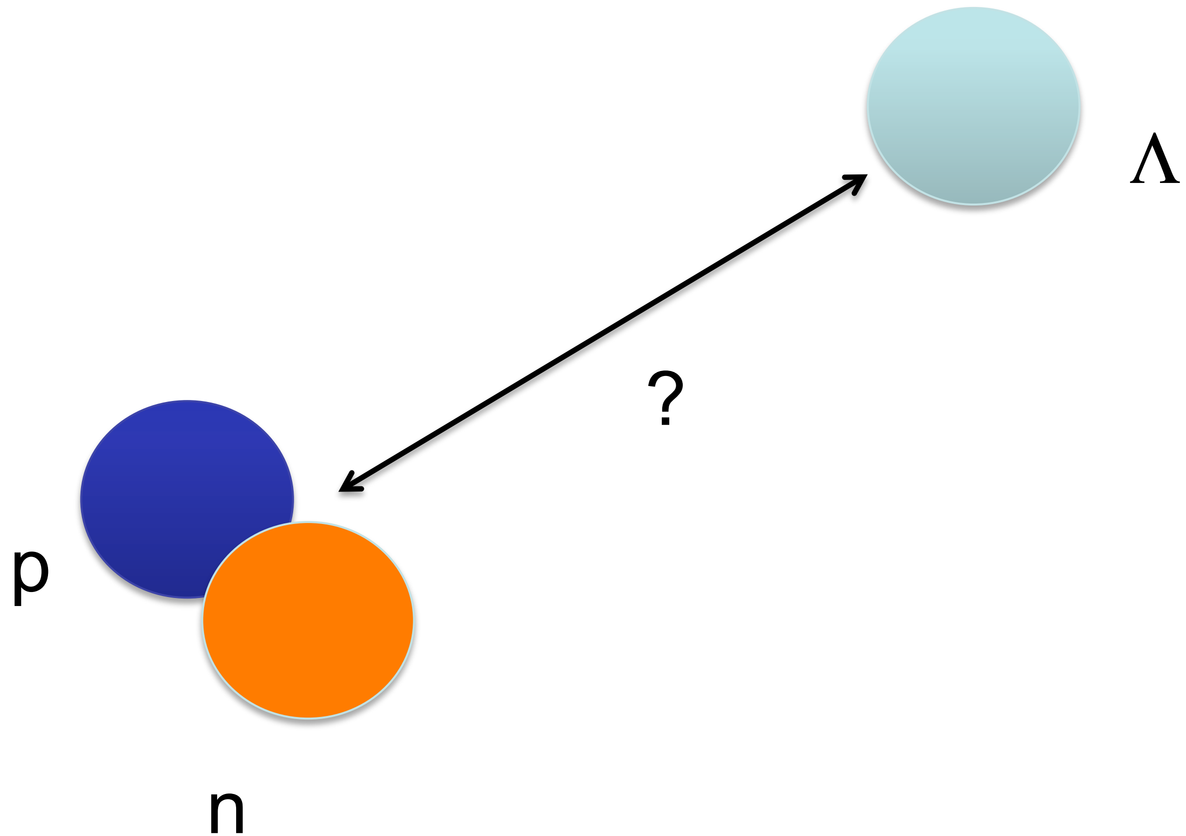
Hypernuclei



Hypertriton

Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)



Hypertriton

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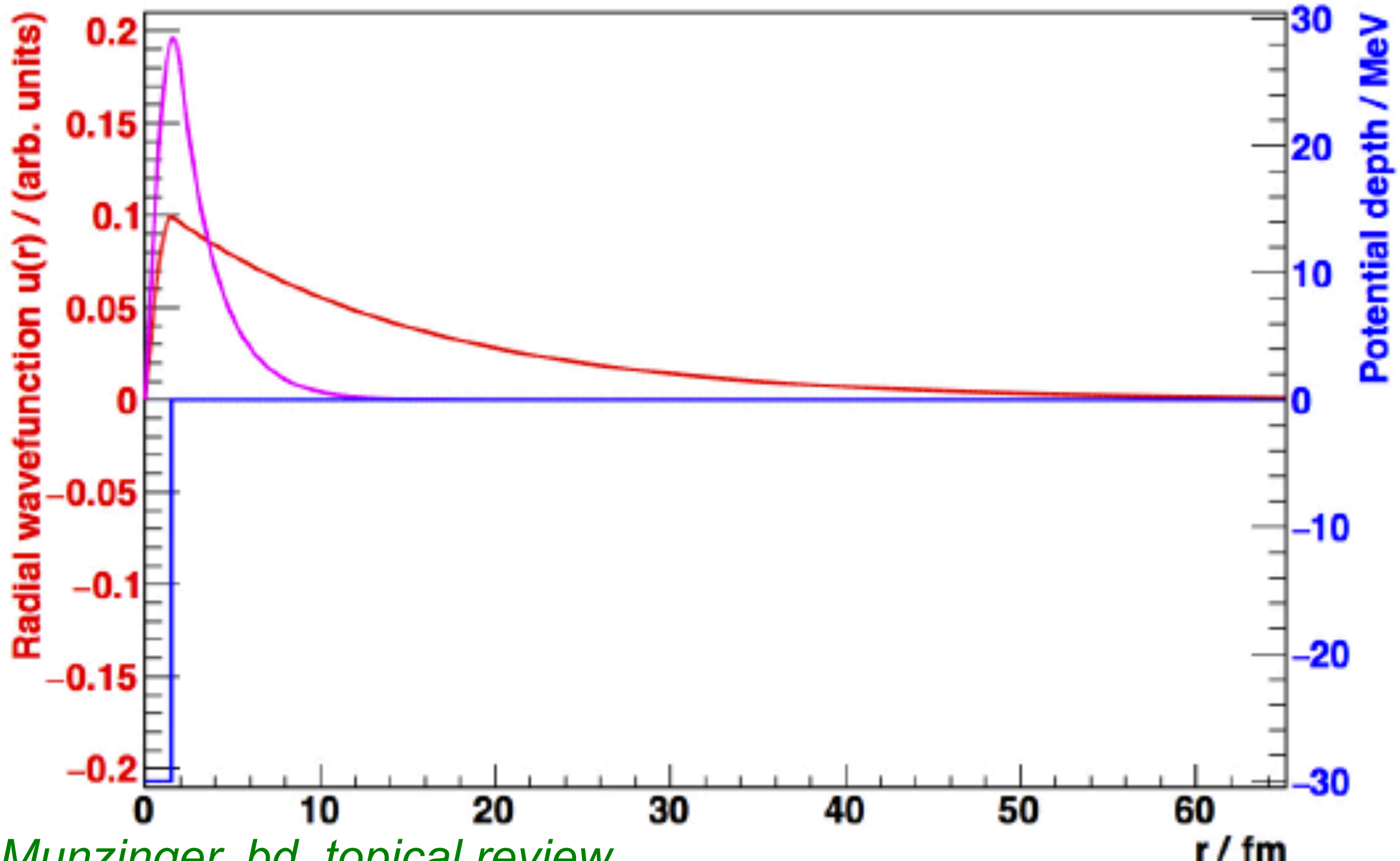

P. Braun-Munzinger, bd, topical review, NPA 987, 144 (2019), arXiv:1809.04681

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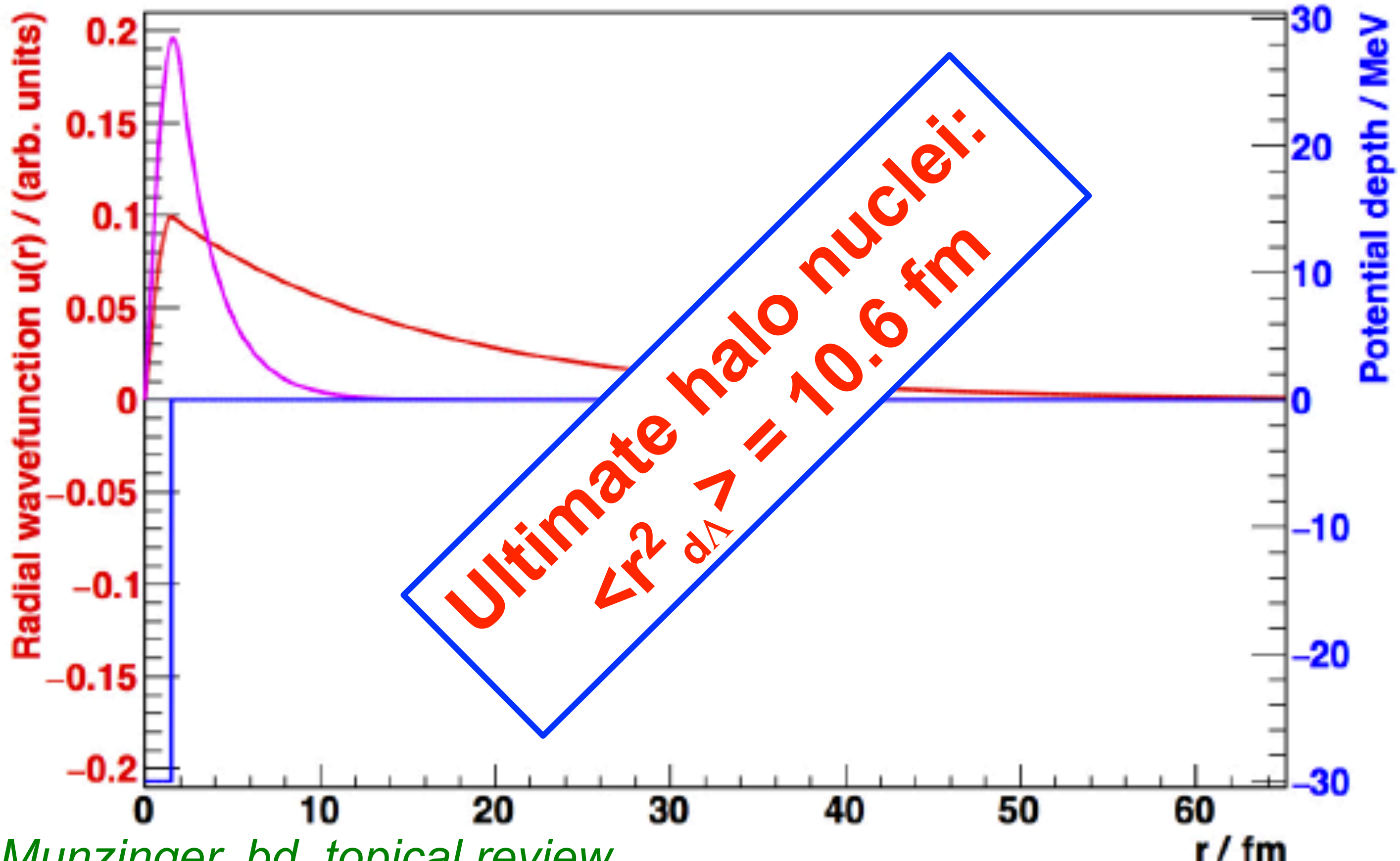
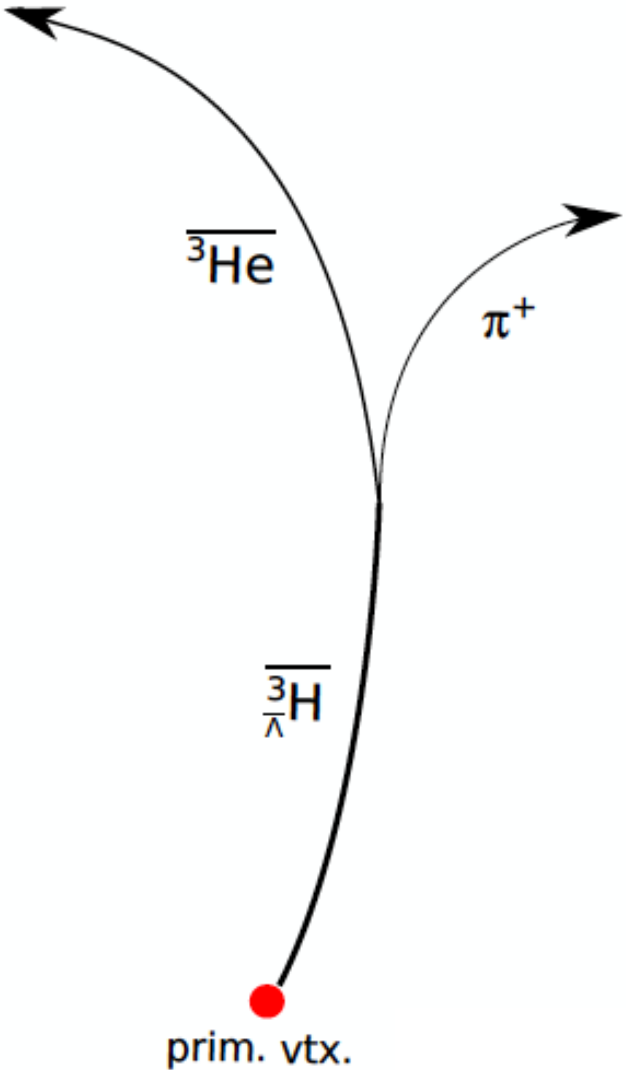


P. Braun-Munzinger, bd, topical review,
NPA 987, 144 (2019), arXiv:1809.04681

Hypertriton identification



Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

→ rms radius ($<r^2_{d\Lambda}>$): 10.6 fm

Decay modes:

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

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

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

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

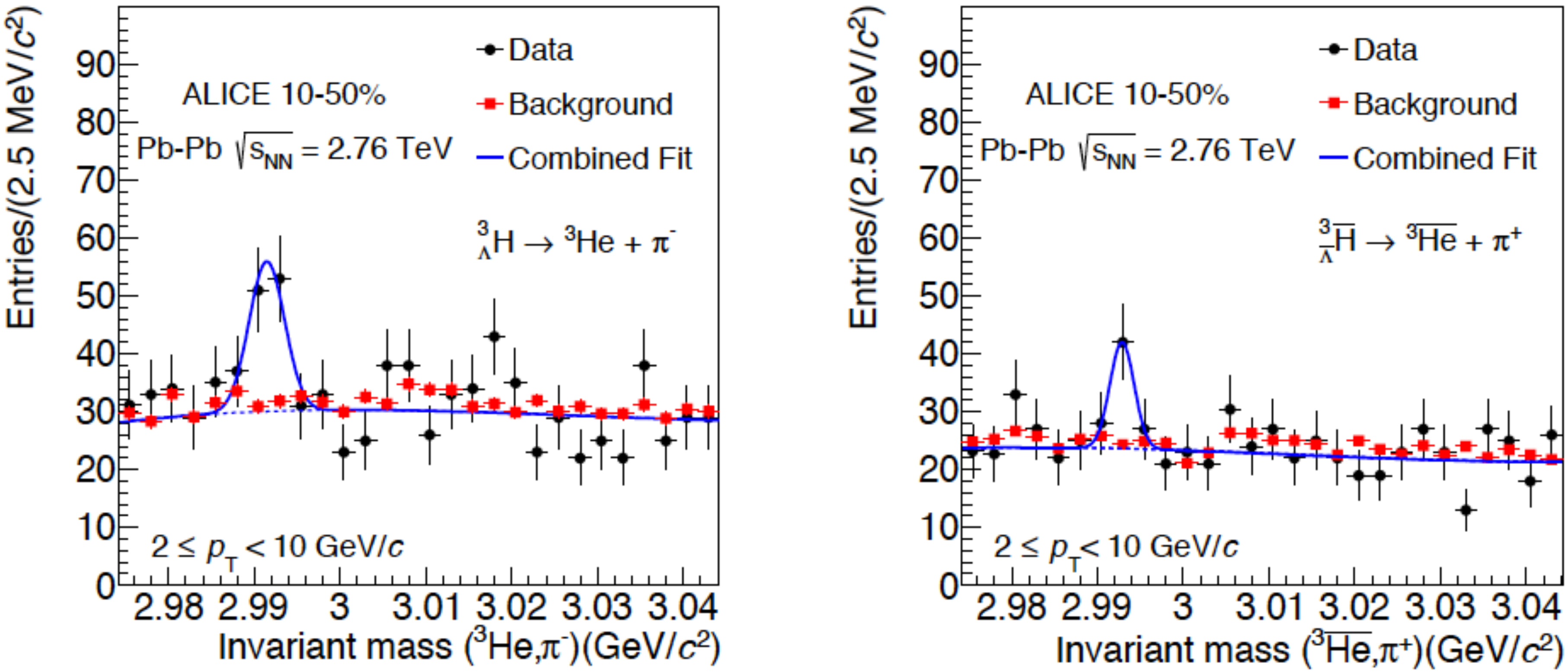
+ anti-particles

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

Science 328,58 (2010)

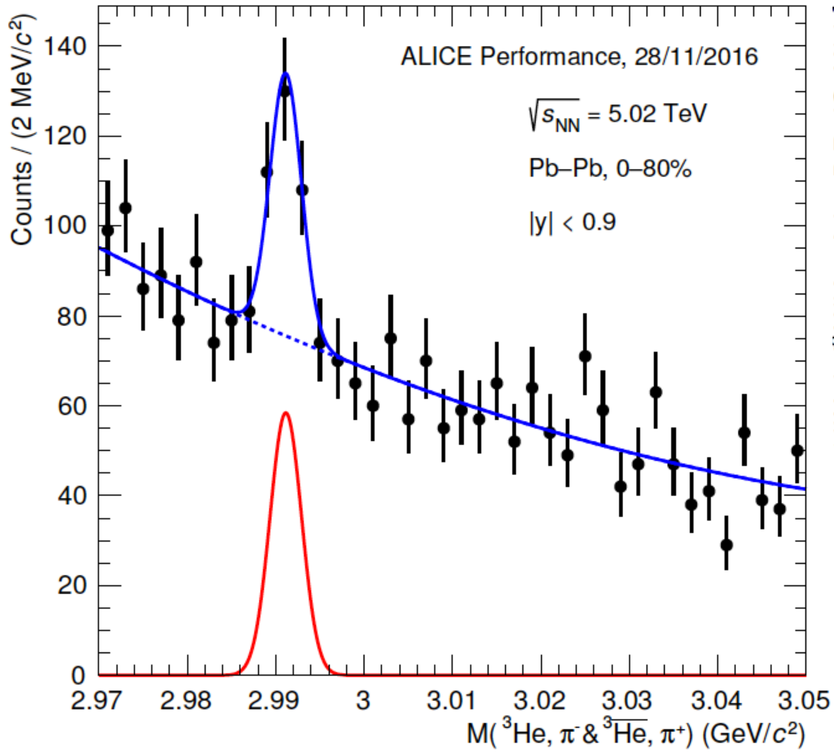
Hypertriton signal

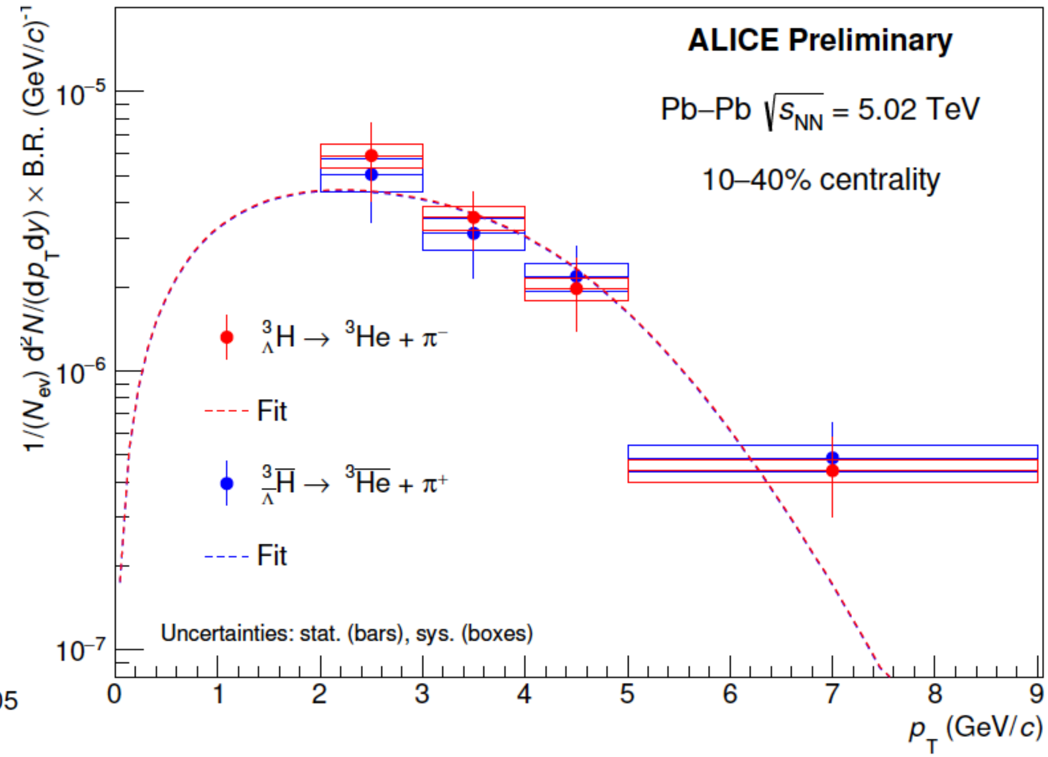
ALICE Collaboration: PLB 754, 360 (2016), arXiv:1506.08453



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

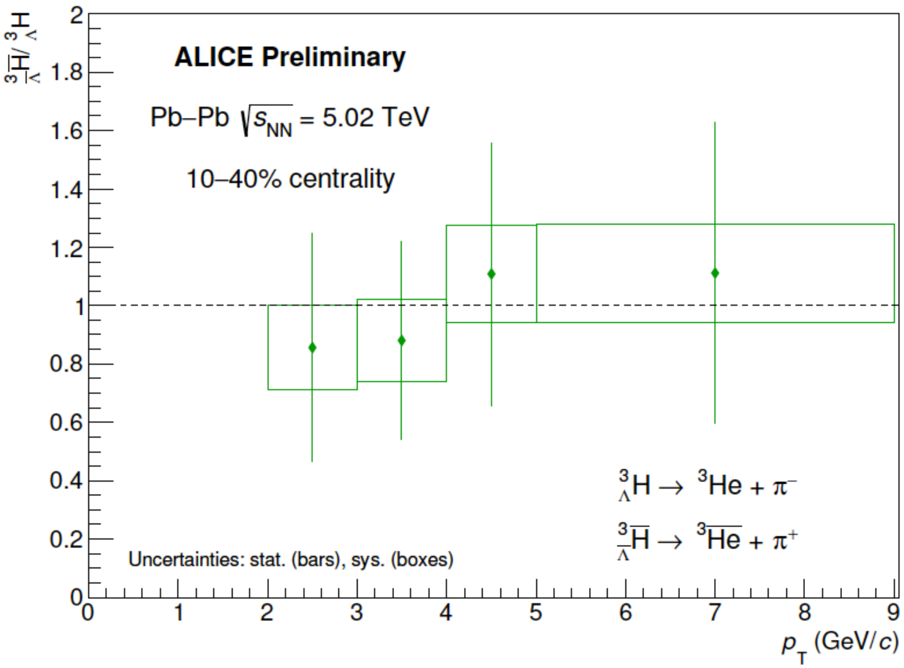
Hypertriton signal

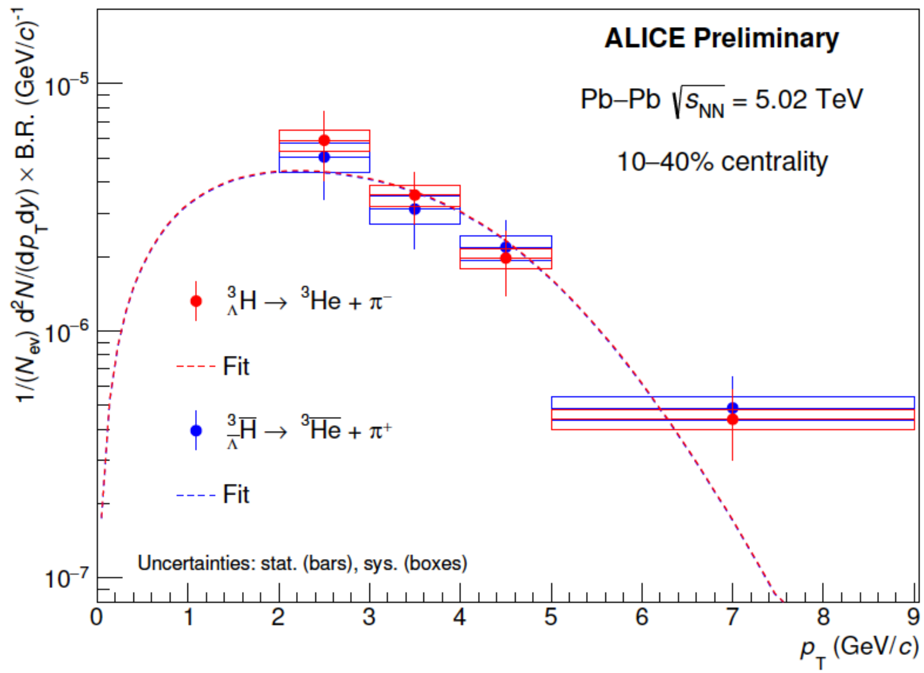




- Peaks are also clearly visible for particle and anti-particle
  - → Extracted yields in 4 p_T bins and 3 centrality classes

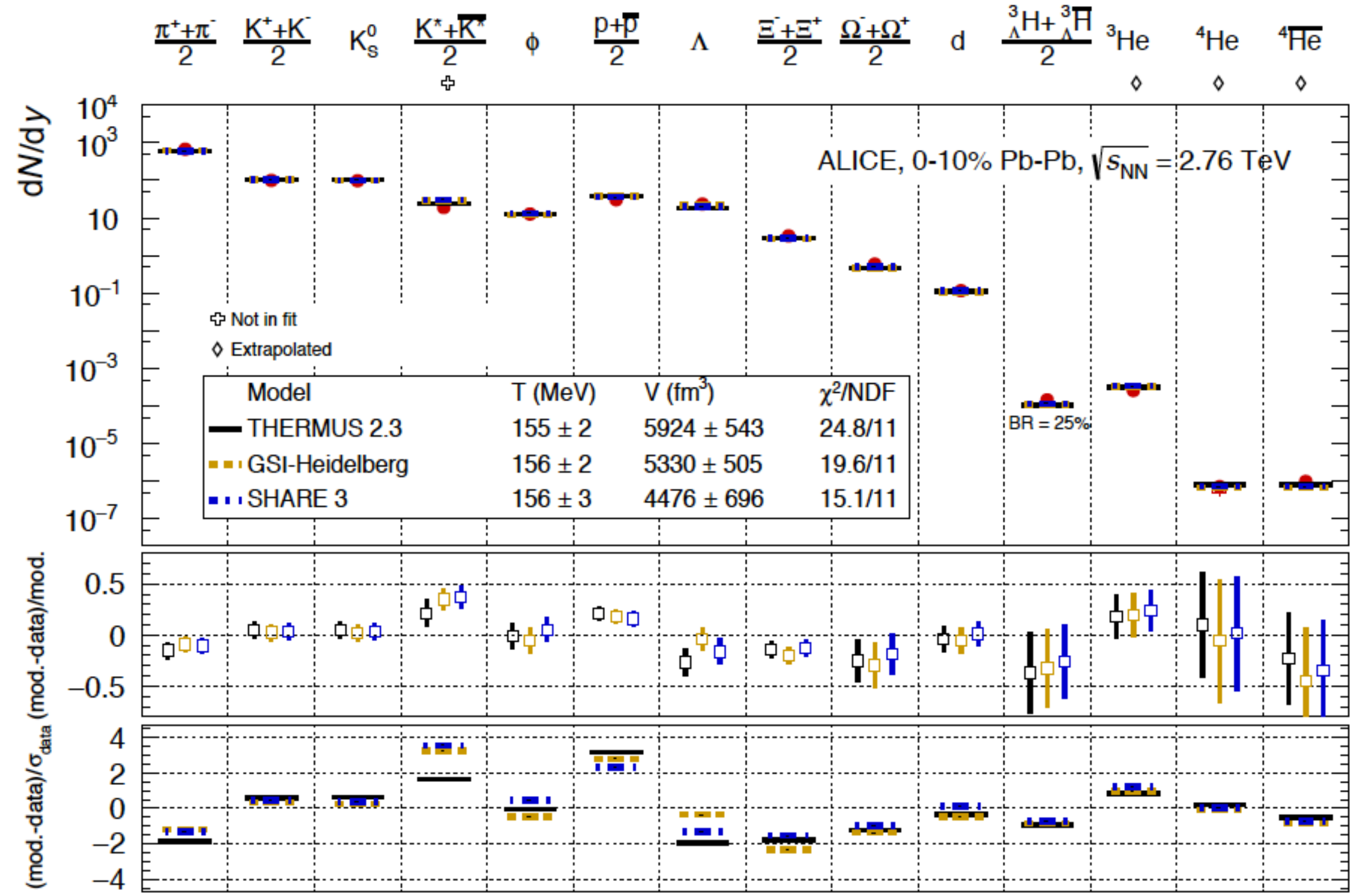
Hypertriton spectra





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

Thermal model fits



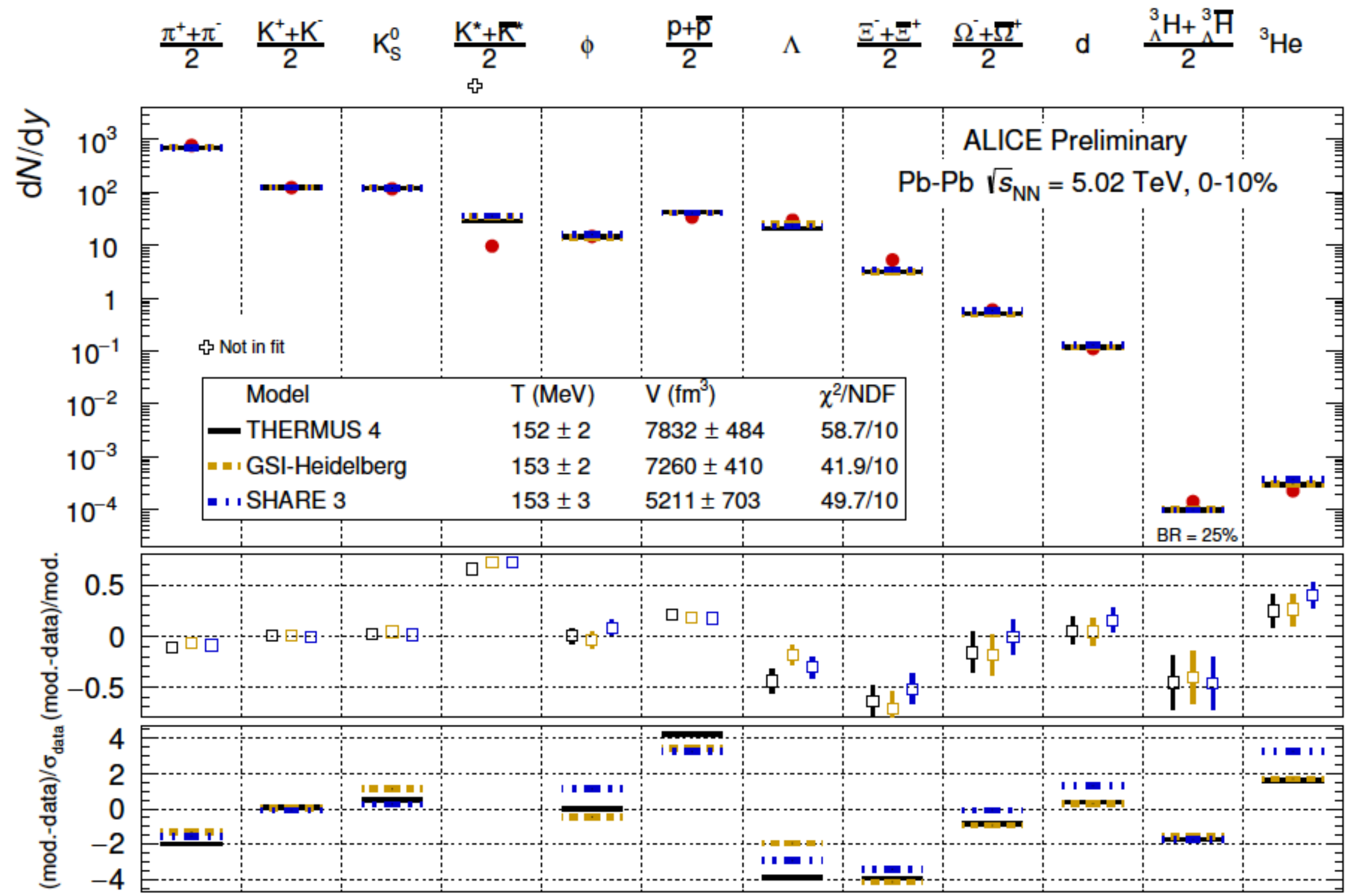
Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11

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



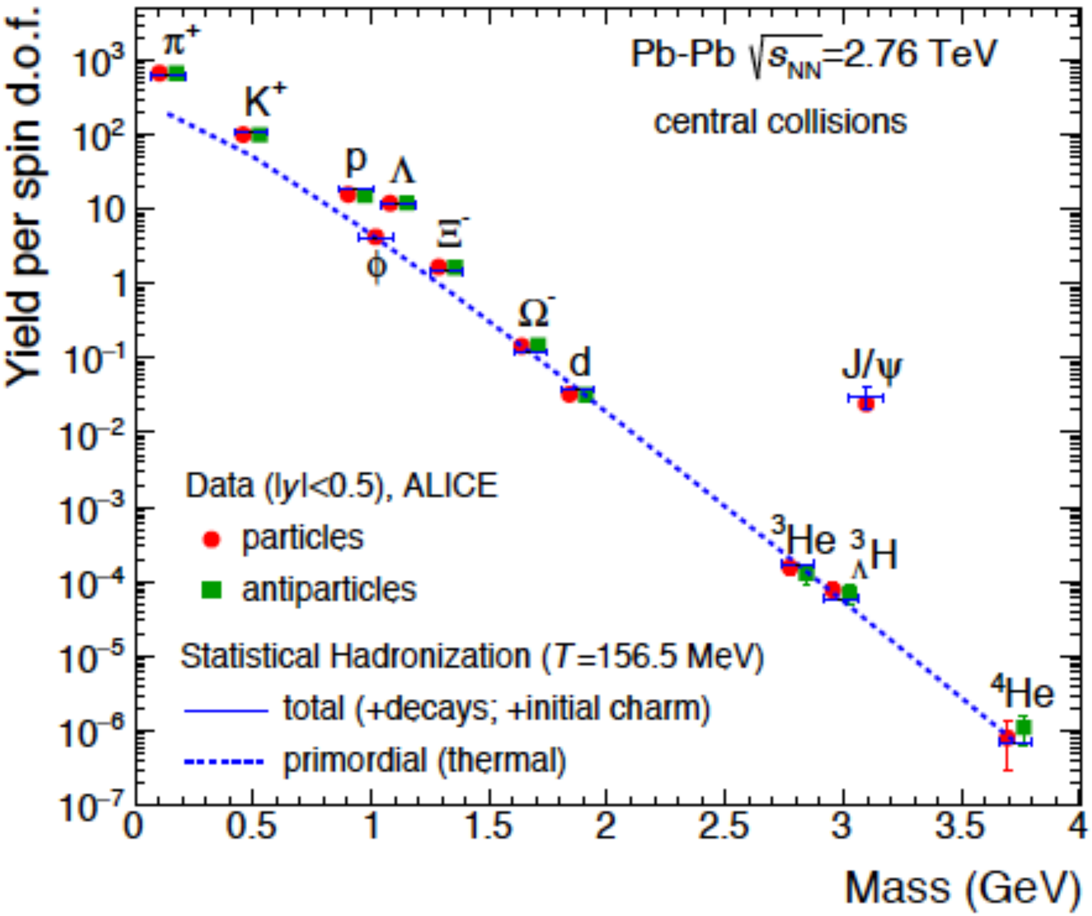
Model	T (MeV)	V (fm³)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

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}

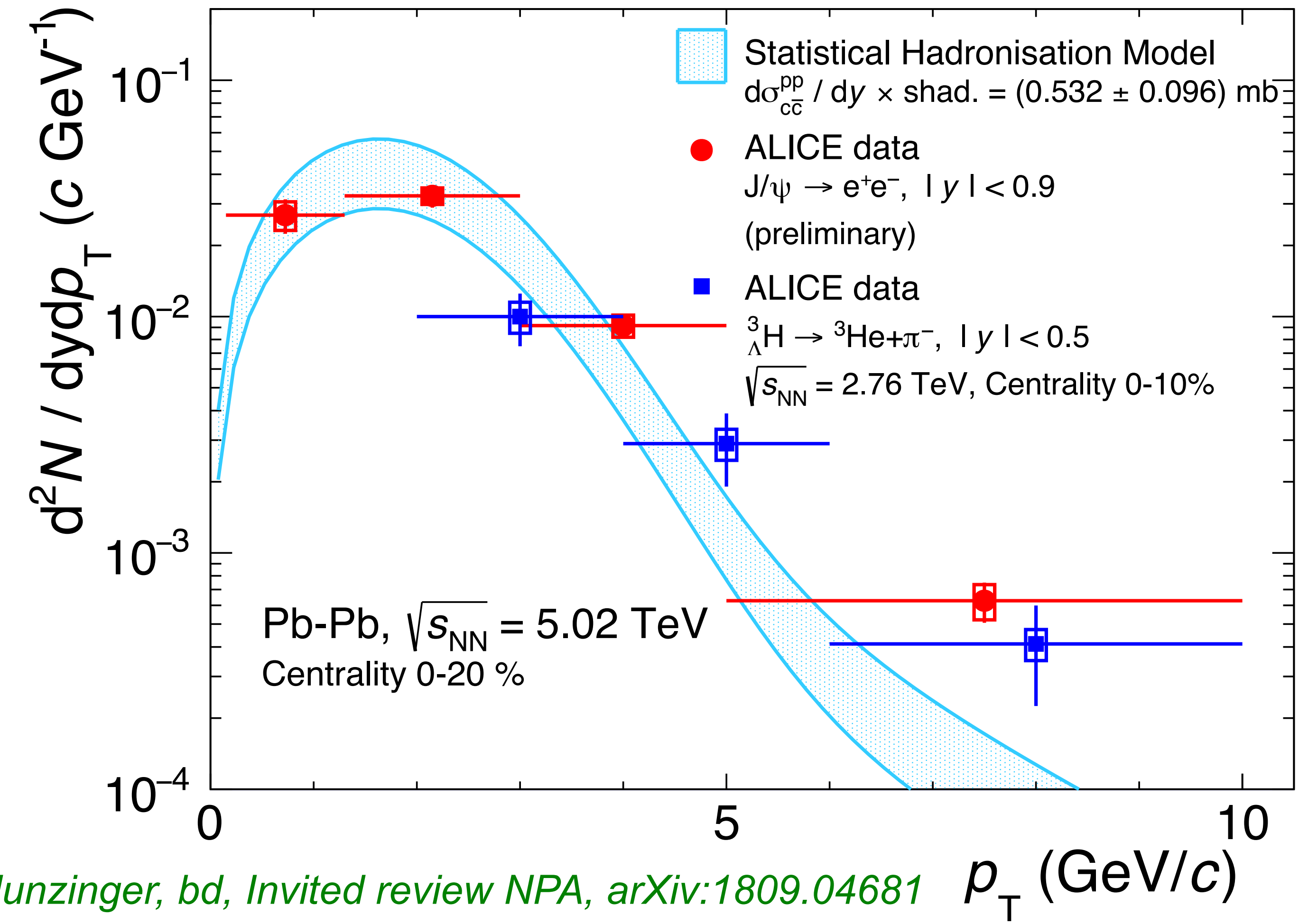
Fits: different view

A. Andronic et al., arXiv:1901.09200



- Excellent agreement over 9 orders of magnitude
- Fit of nuclei (d, ^{3}He, ^{4}He): T_{ch}=159 ± 5 MeV
- No feed-down for (anti-)(hyper-)nuclei
- charm quarks, out of chemical equilibrium, undergo statistical hadronization
  → only input: number of ccbar pairs

Hypertriton - J/ψ comparison

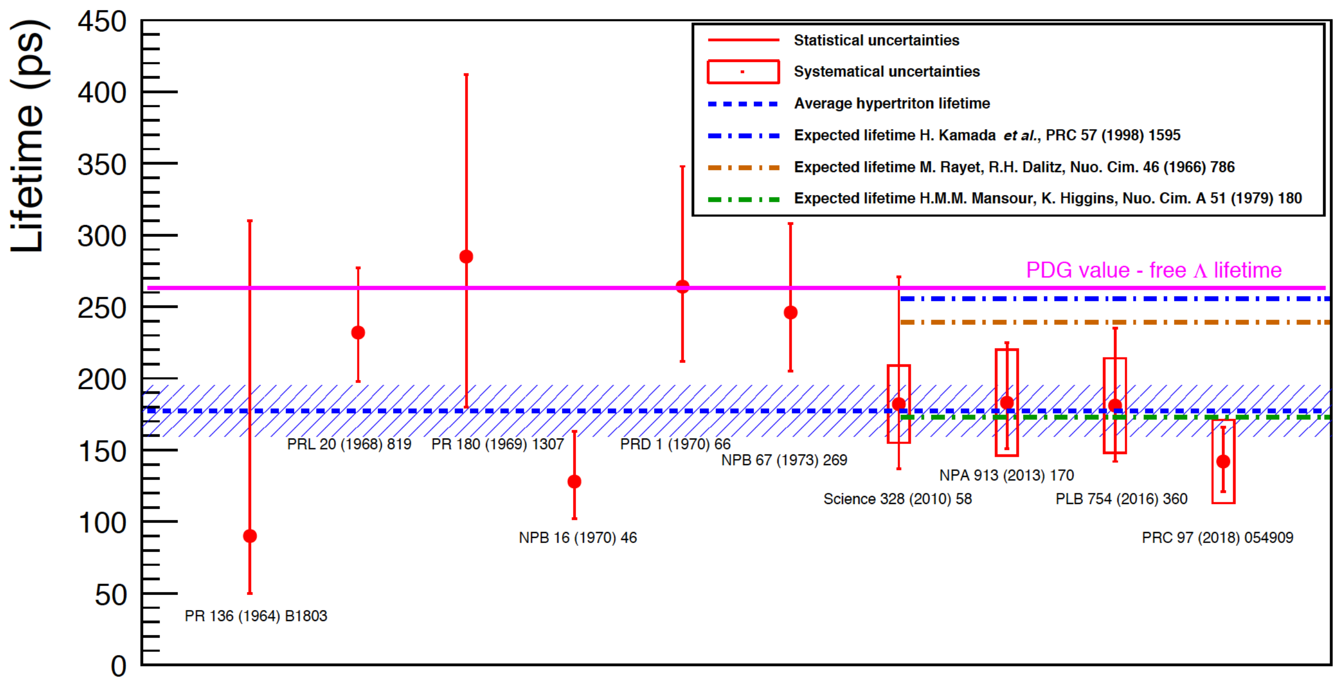


P. Braun-Munzinger, bd, Invited review NPA, arXiv:1809.04681

- Shape of the p_T spectra of J/ψ and hypertriton agree very well, despite the binding energy of the hypertriton is 2.35 MeV and of the J/ψ 600 MeV

Hypertriton „puzzle“

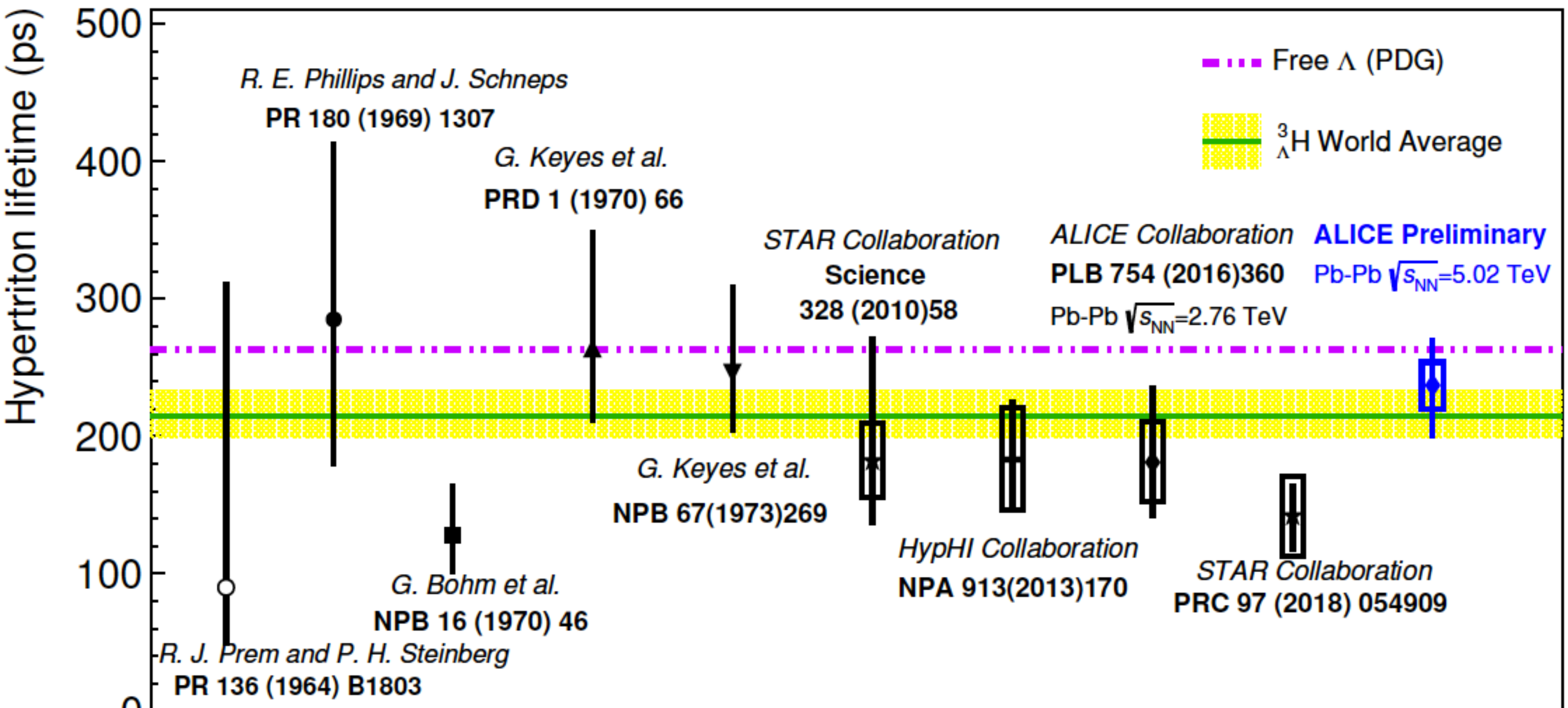
- Recently extracted lifetimes significantly below the free Λ lifetime
  - Not expected from theory!
  - Data before 2010 from visualization techniques
  - Currently most precise data coming from heavy-ion collisions
  - Better precision expected from larger data samples to be collected



P. Braun-Munzinger, bd, Invited review, NPA 987, 144 (2019), arXiv:1809.04681

Hypertriton „puzzle“

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



Hypertriton „puzzle“

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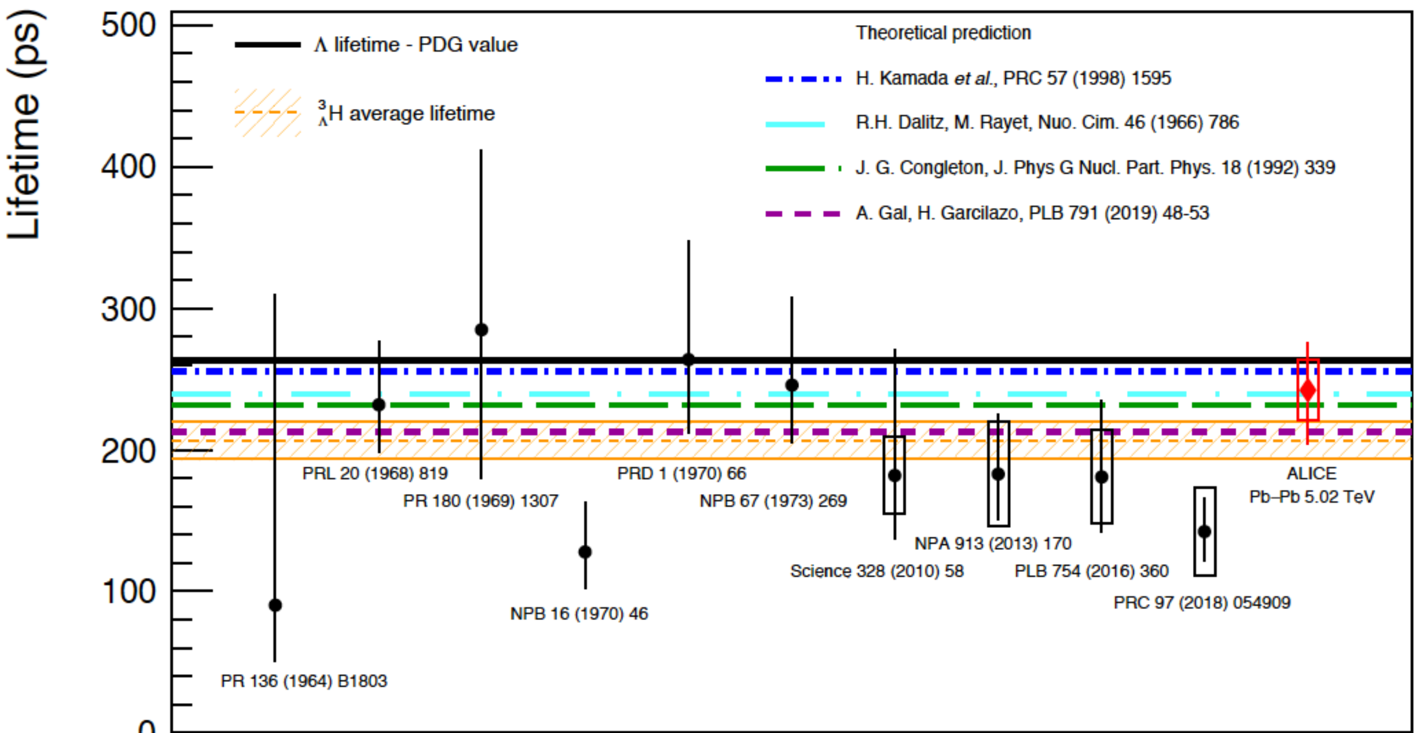
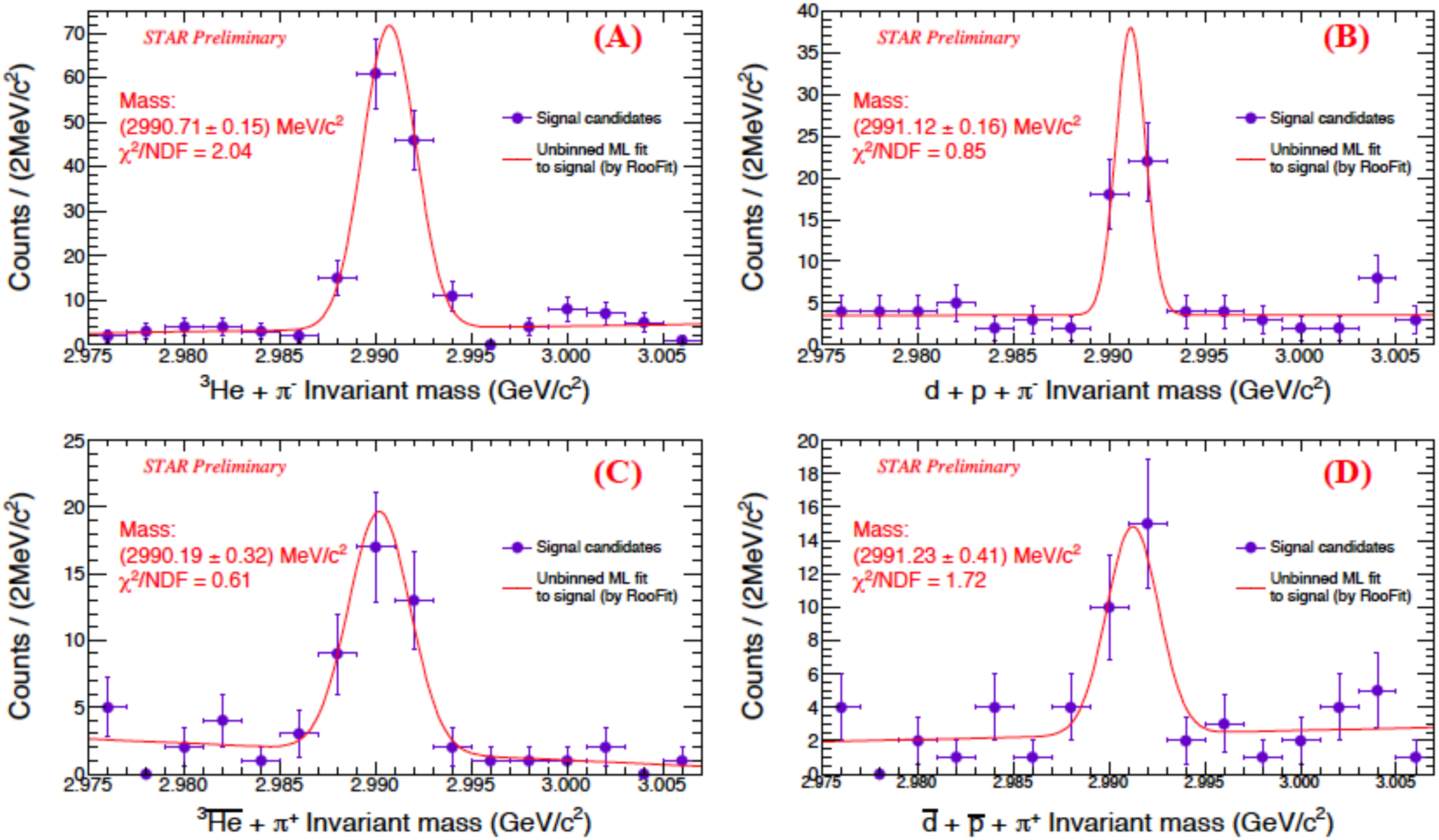
- Most recent calculation agrees with the observed trend



ALICE Collaboration: accepted by PLB, arXiv:1907.06906

Hypertriton „puzzle“



- Solution might be connected to the data from emulsions

→ re-measuring the Λ separation energy

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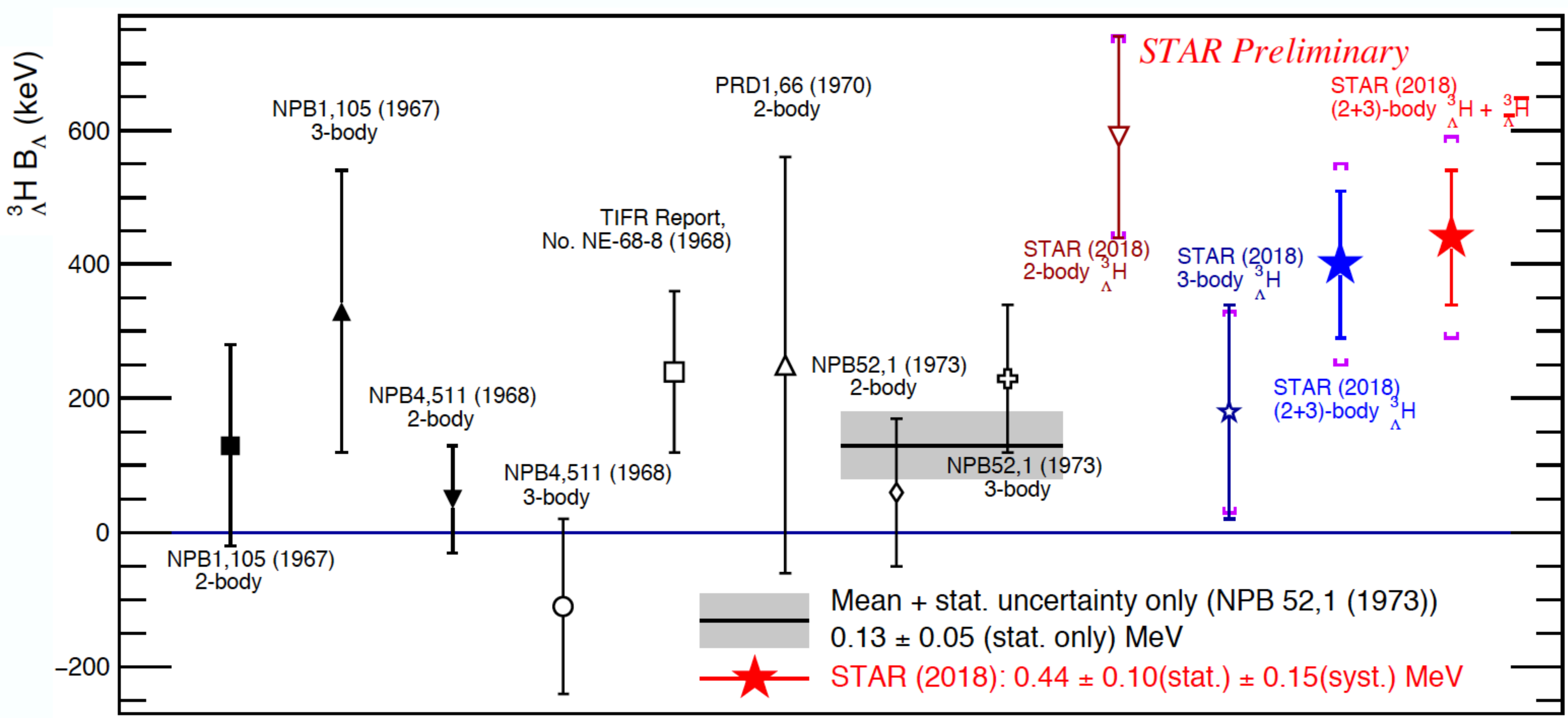

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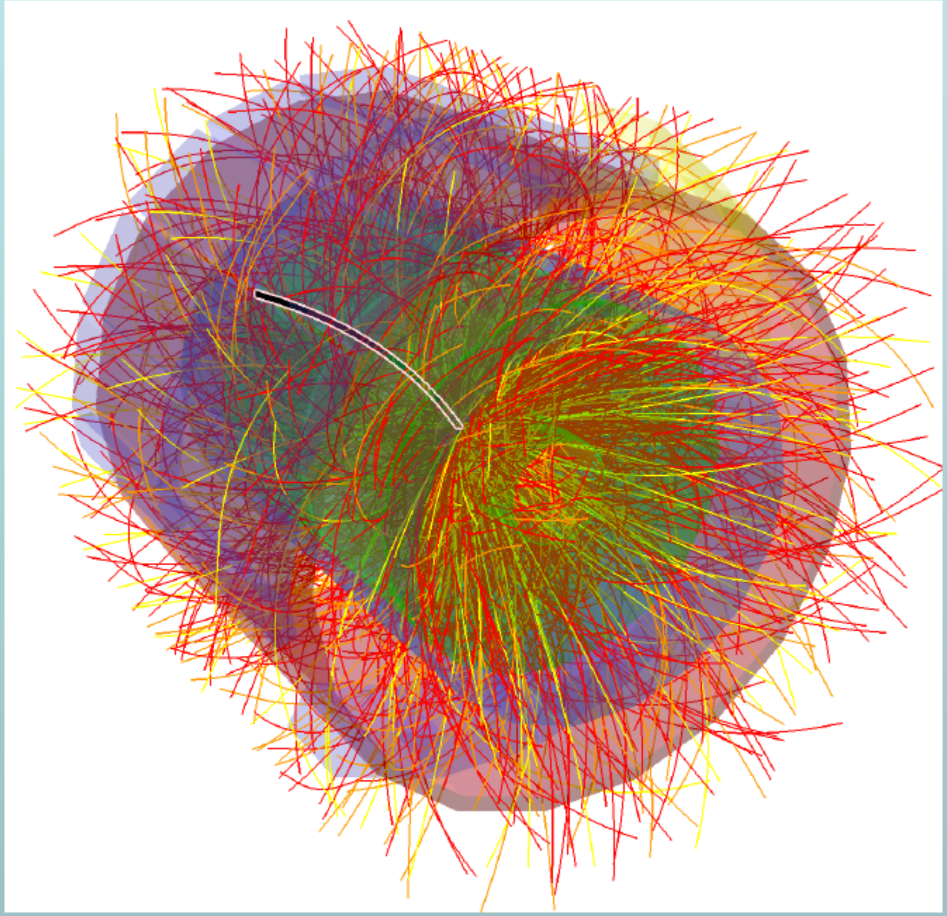
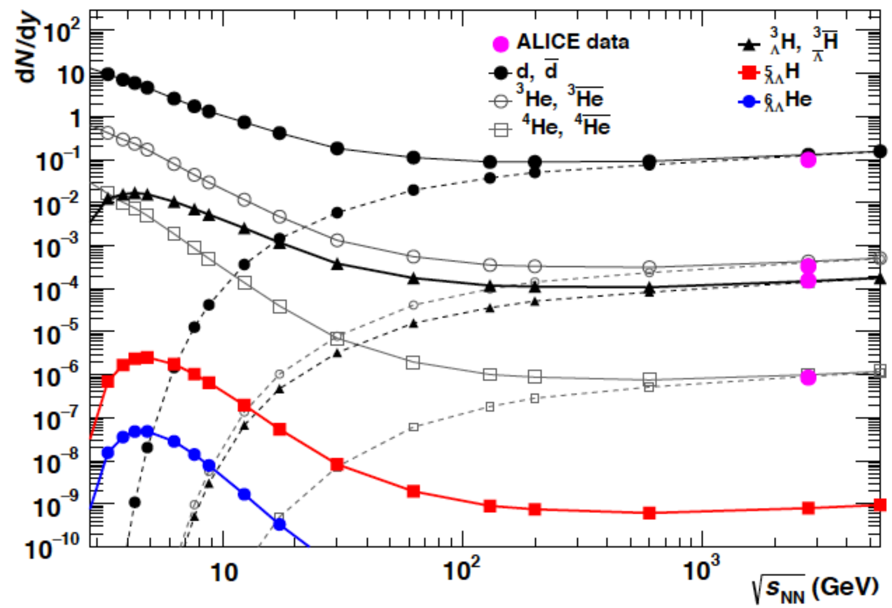
Summary



Conclusion

- ALICE@LHC and STAR@RHIC are 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
- Models describe the (anti-)(hyper-)nuclei data rather well
- Ratios 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 987, 144 (2019), arXiv:1809.04681

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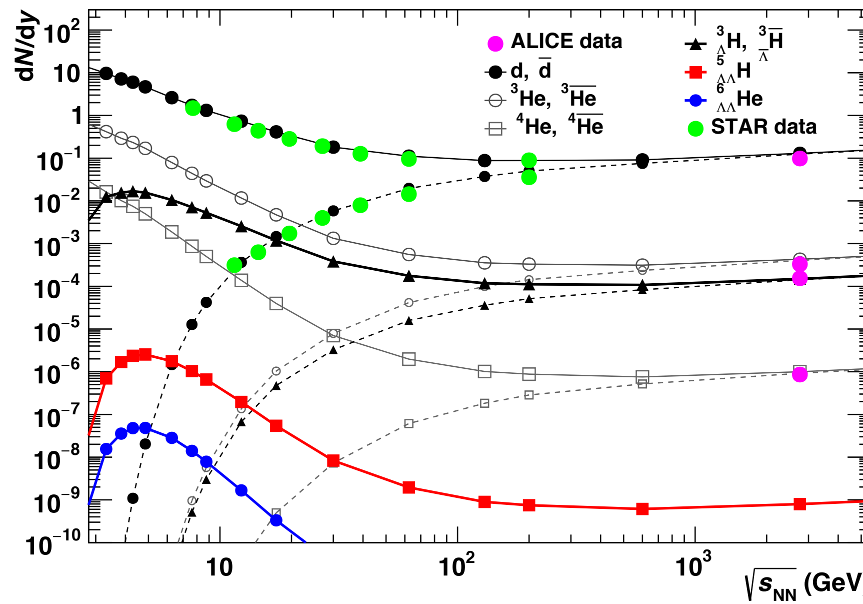
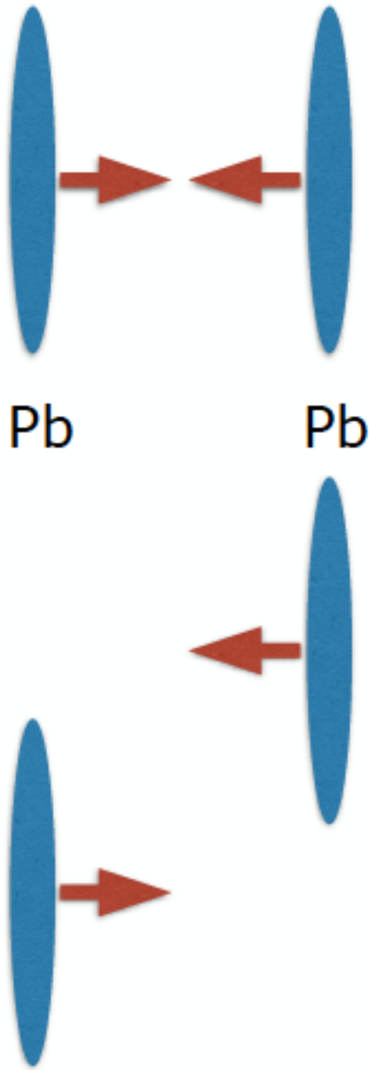


Backup

Interlude: Centrality



Central Pb-Pb collision:

High multiplicity = large $\langle \mathrm{d}N/\mathrm{d}\eta \rangle$

High number of tracks

(more than 2000 tracks in the detector)

Peripheral Pb-Pb collision:

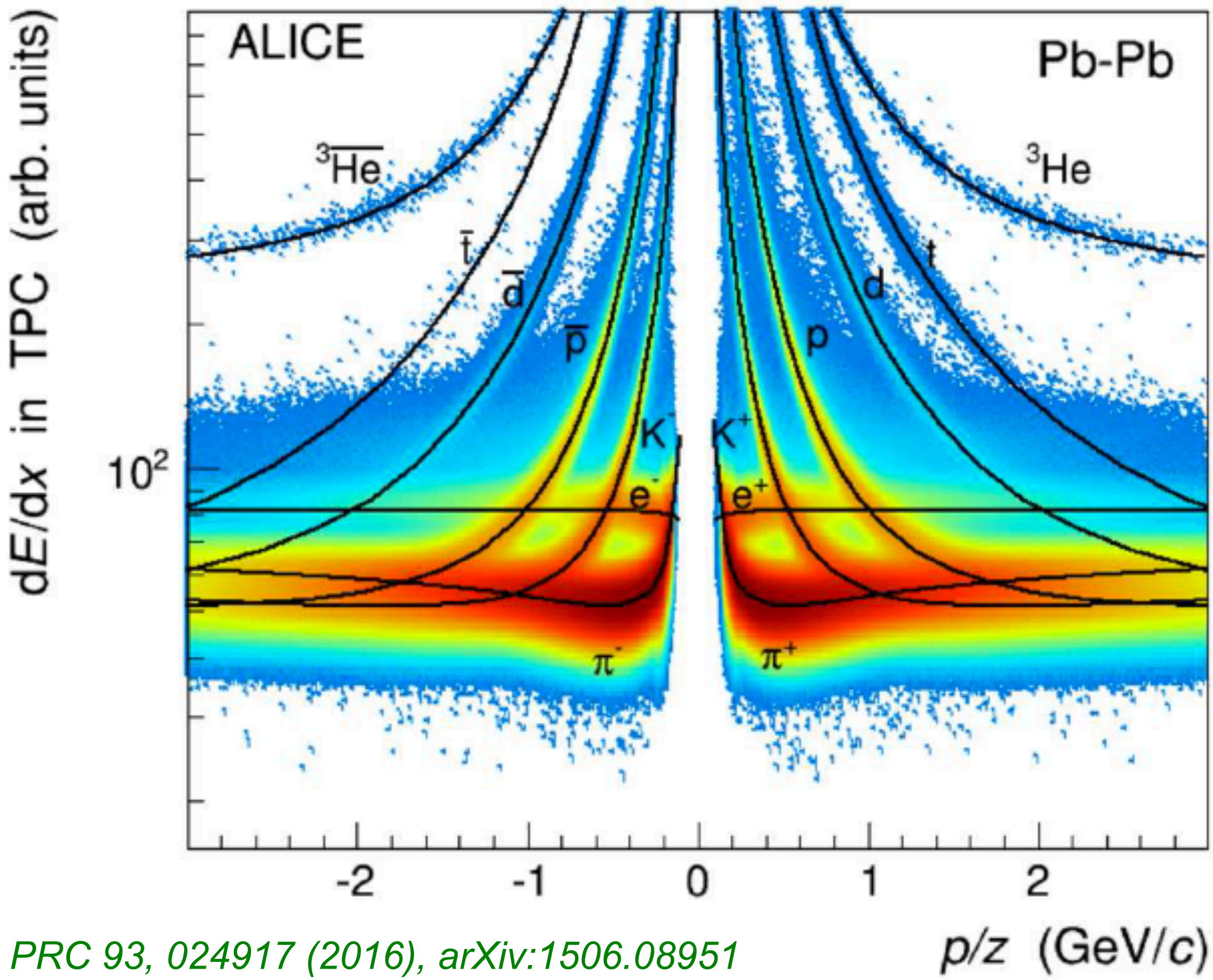
Low multiplicity = small $\langle \mathrm{d}N/\mathrm{d}\eta \rangle$

Low number of tracks

(less than 100 tracks in the detector)

TPC PID in Pb-Pb

- As shown by Silvia Masciocchi in the second heavy-ion lecture



ALICE Collaboration: PRC 93, 024917 (2016), arXiv:1506.08951

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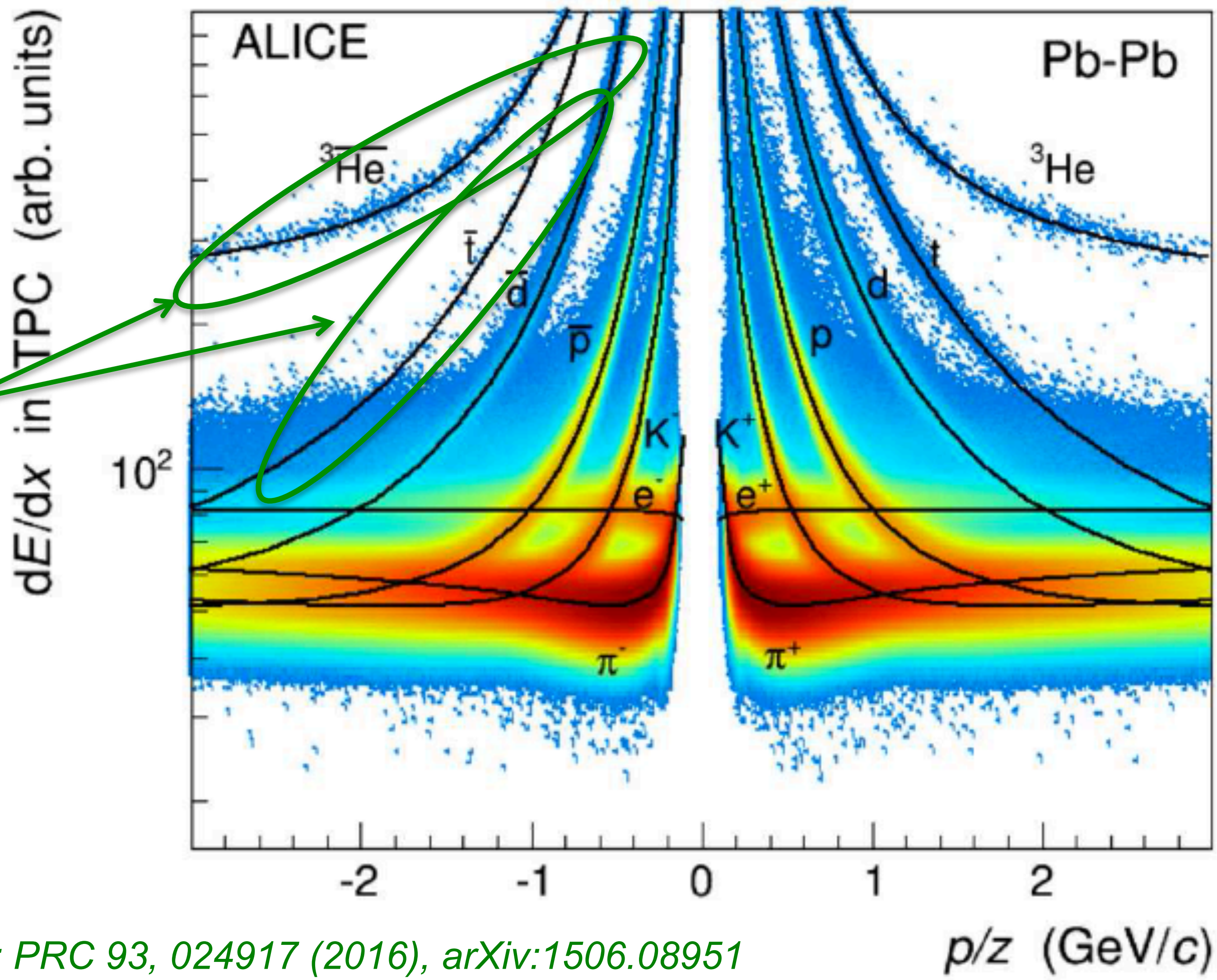

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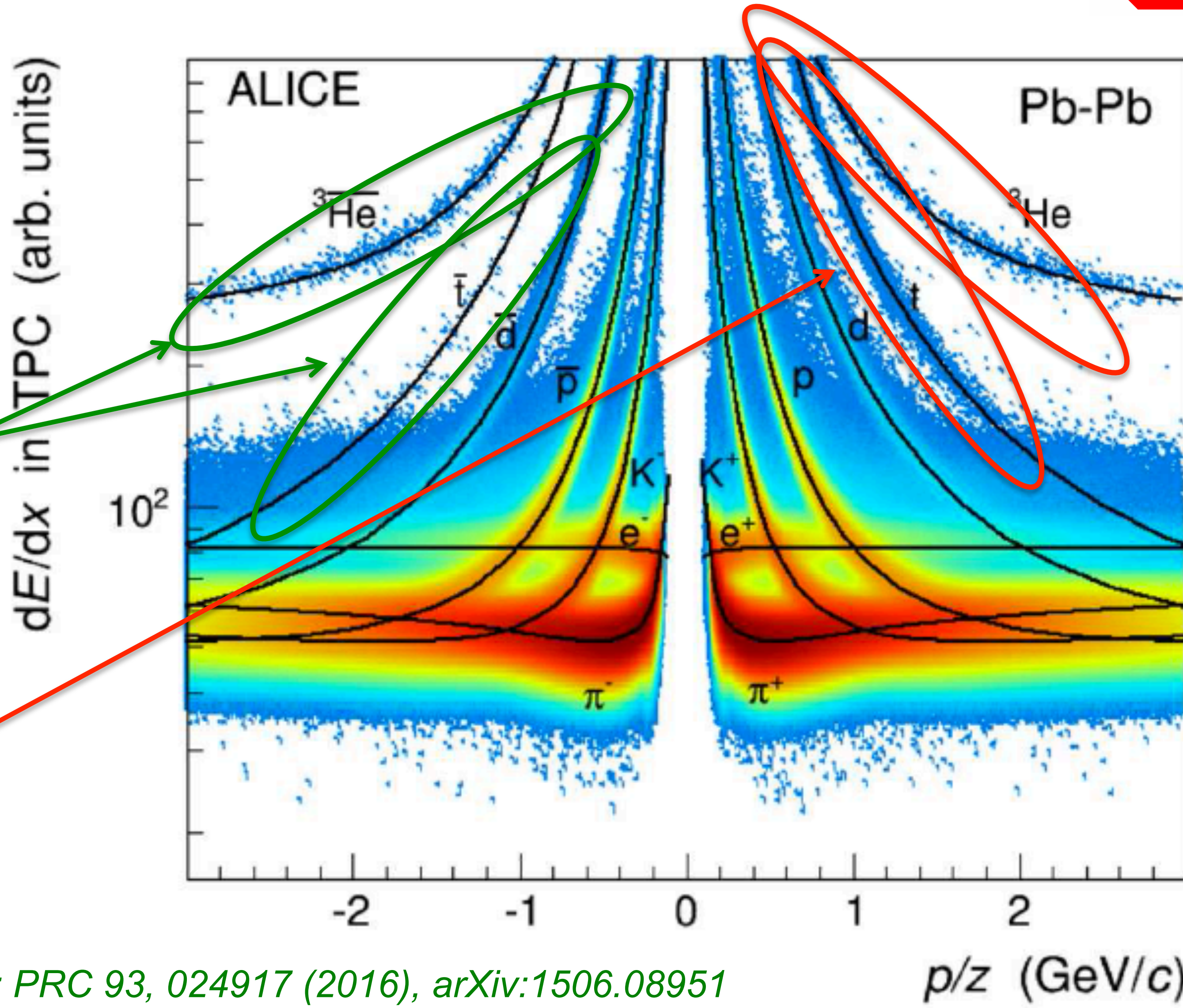

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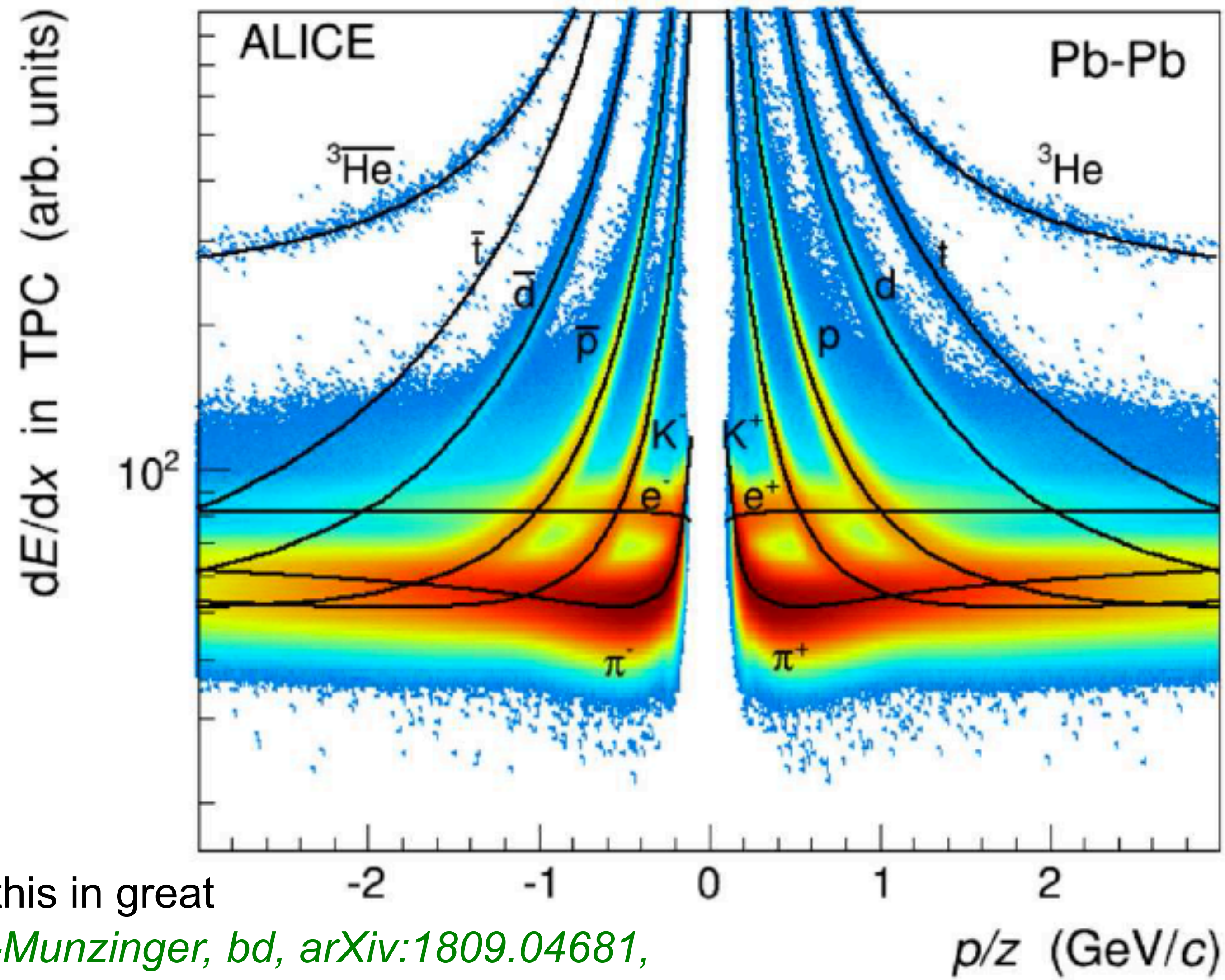
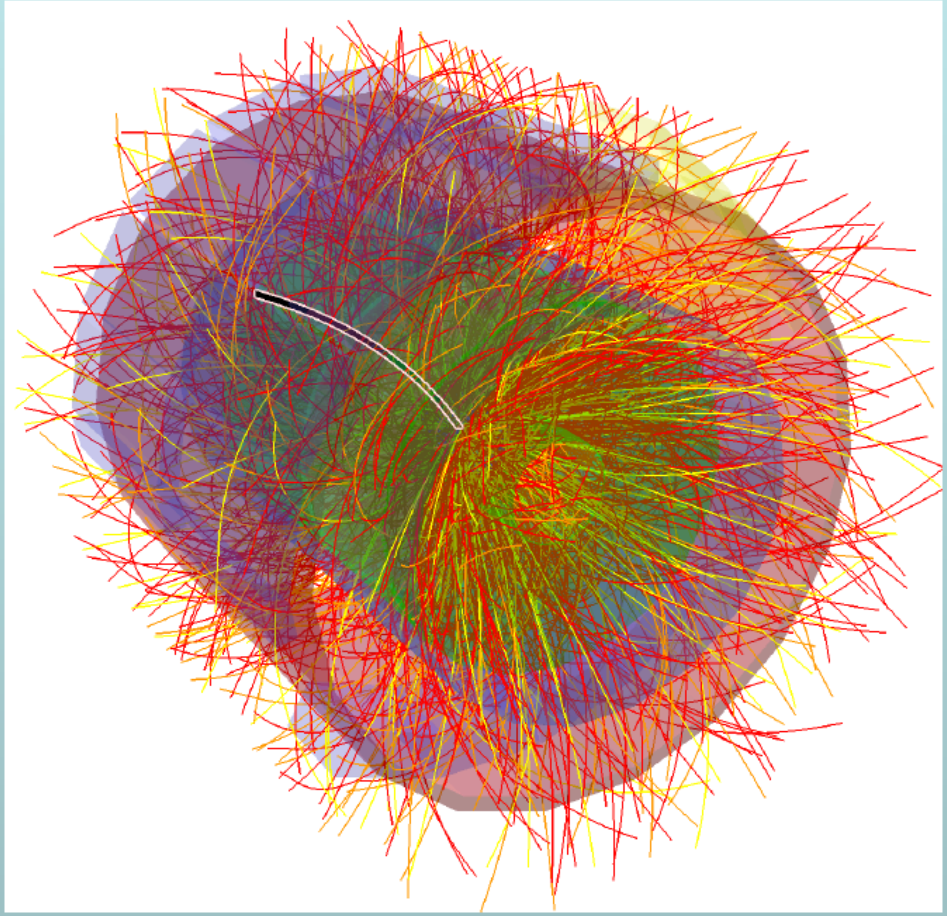


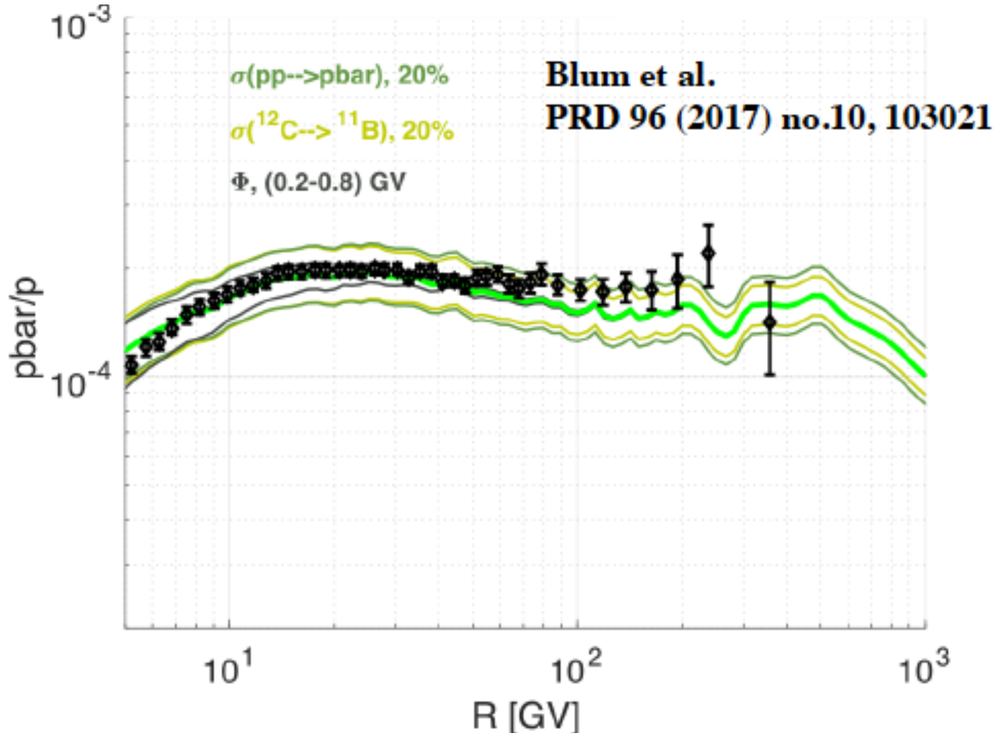
- We try to explain this in great detail in: *P. Braun-Munzinger, bd, arXiv:1809.04681, accepted by NPA*

Input for Cosmic Ray Dark Matter Searches



Coalescence@work

- AMS measures anti-nuclei in space, since it was proposed as a possible sign of dark matter (annihilation)
- ALICE anti-nuclei measurments can be used to predict the anti-nuclei production in the universe by usual production mechanism
- Simple assumption lead currently to the conclusion that matter matches expectations using a coalescence approach to describe the production sees in the AMS data



K. Blum et al. PRD 96, 103021 (2017)

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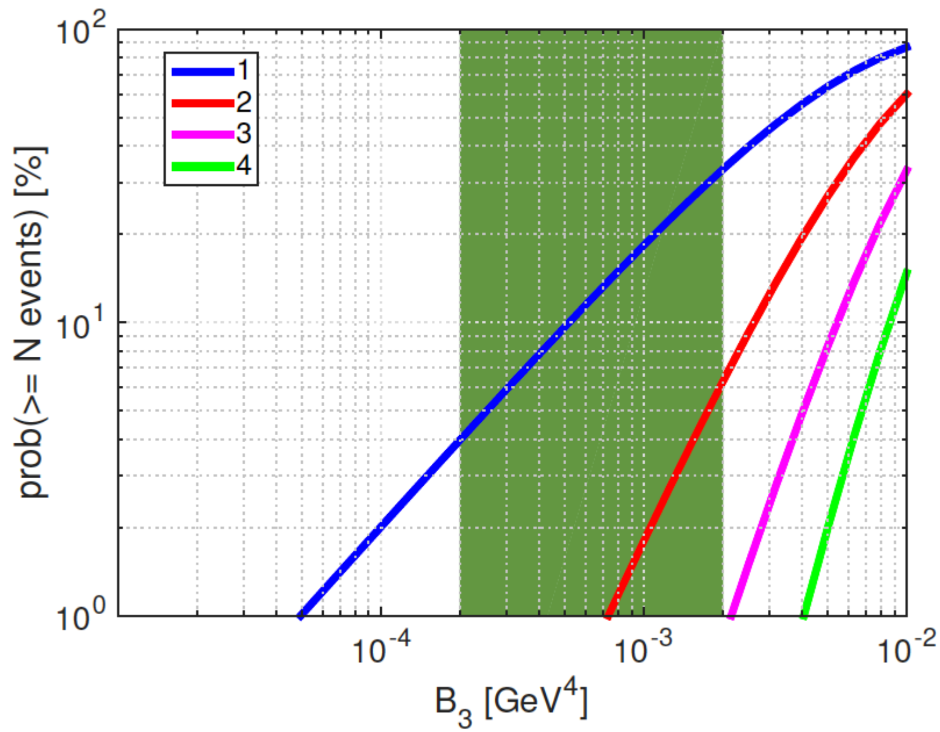

FIG. 5: Poisson probability for detecting $N \geq 1, 2, 3, 4$ $\overline{^3\mathrm{He}}$ events in a 5-yr analysis of AMS02, assuming the same exposure as in the $\bar{p}$ analysis [28]. Eq. (14) shown as green band.

K. Blum et al. PRD 96, 103021 (2017)

Expectations

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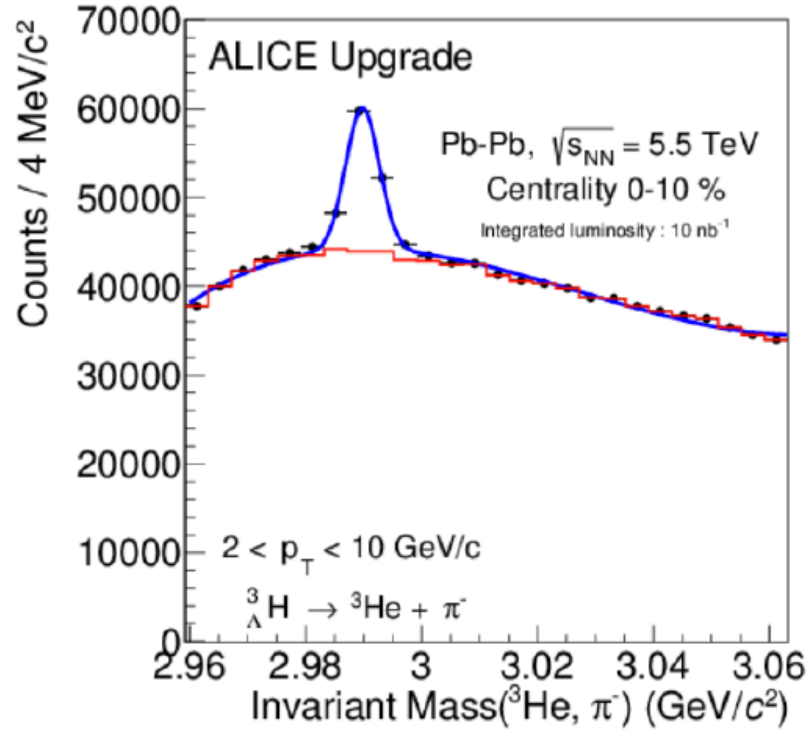

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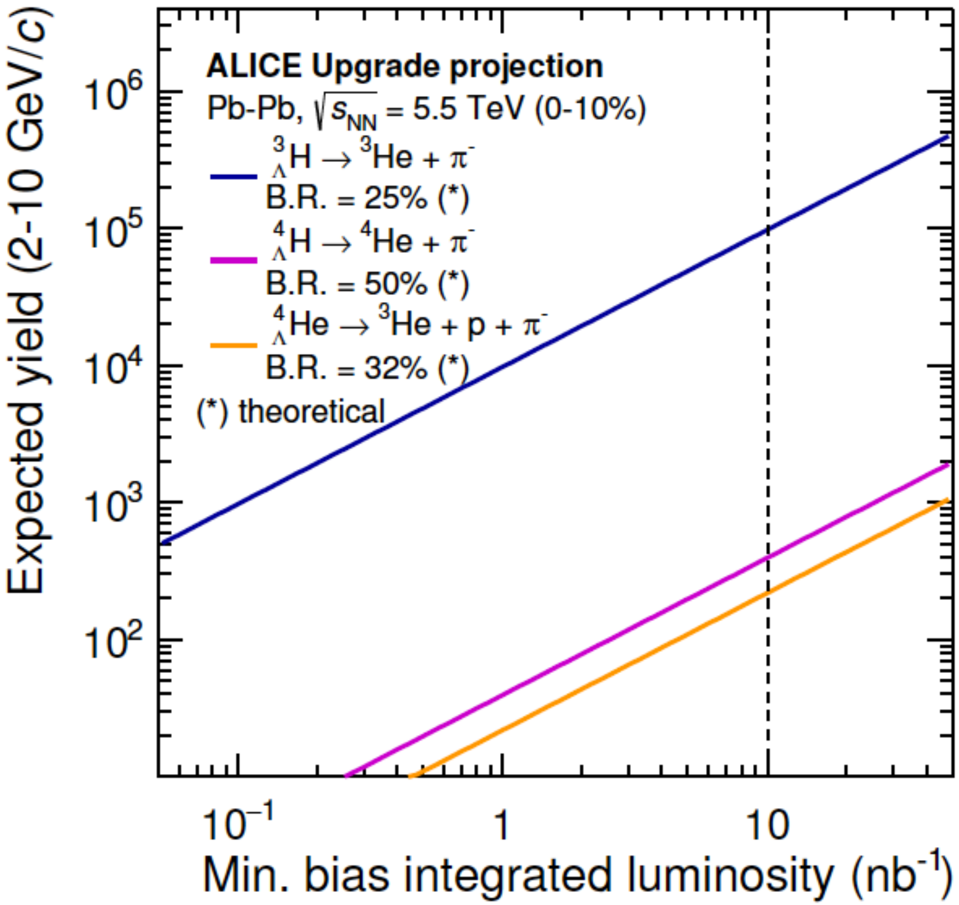

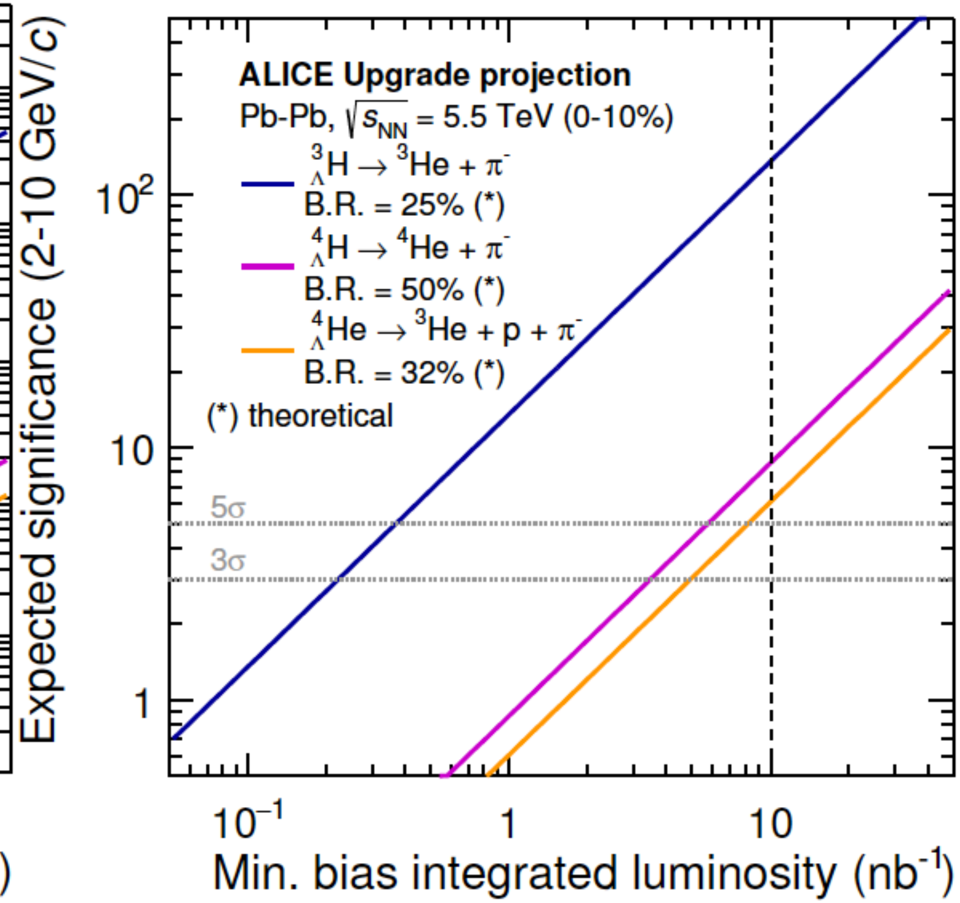

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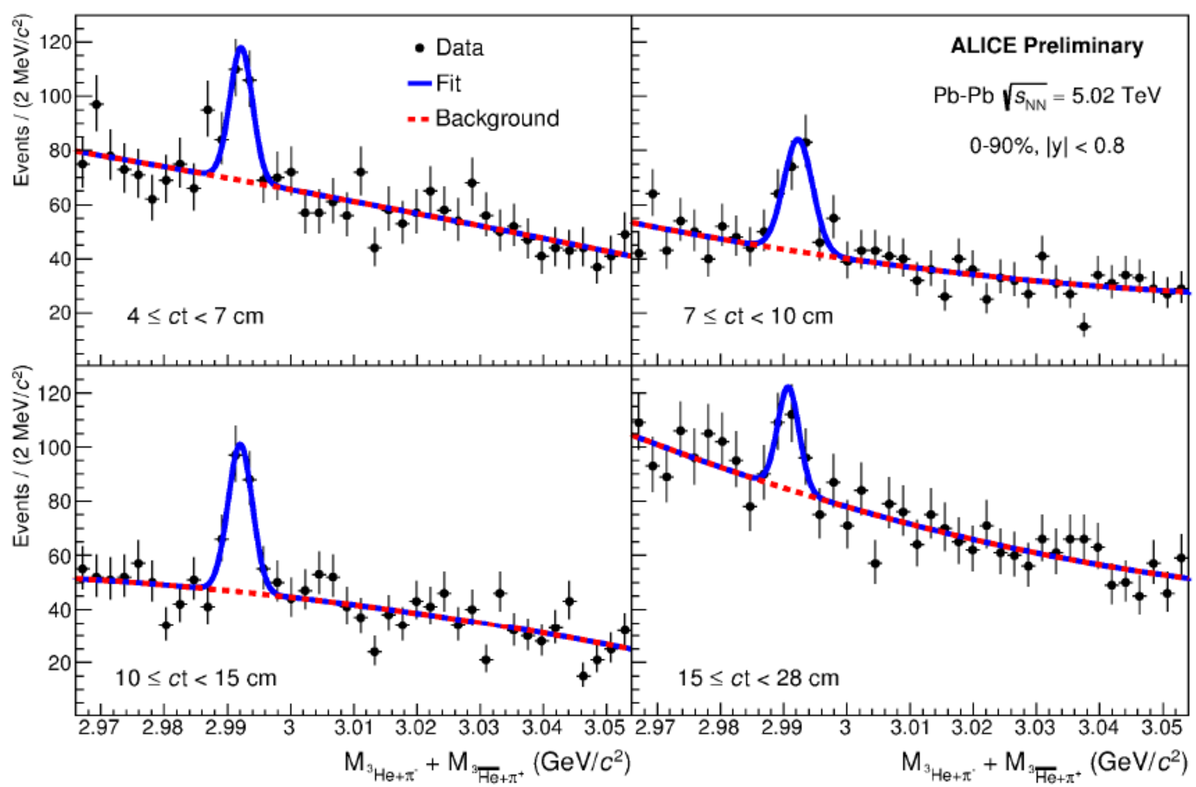
- Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
- Thermal and coalescence models describe the (anti-)(hyper-)nuclei data rather well
- d/p ratio shows increasing trend for pp and p-Pb collisions and seems to saturate for Pb-Pb multiplicities
- Resonances 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

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)



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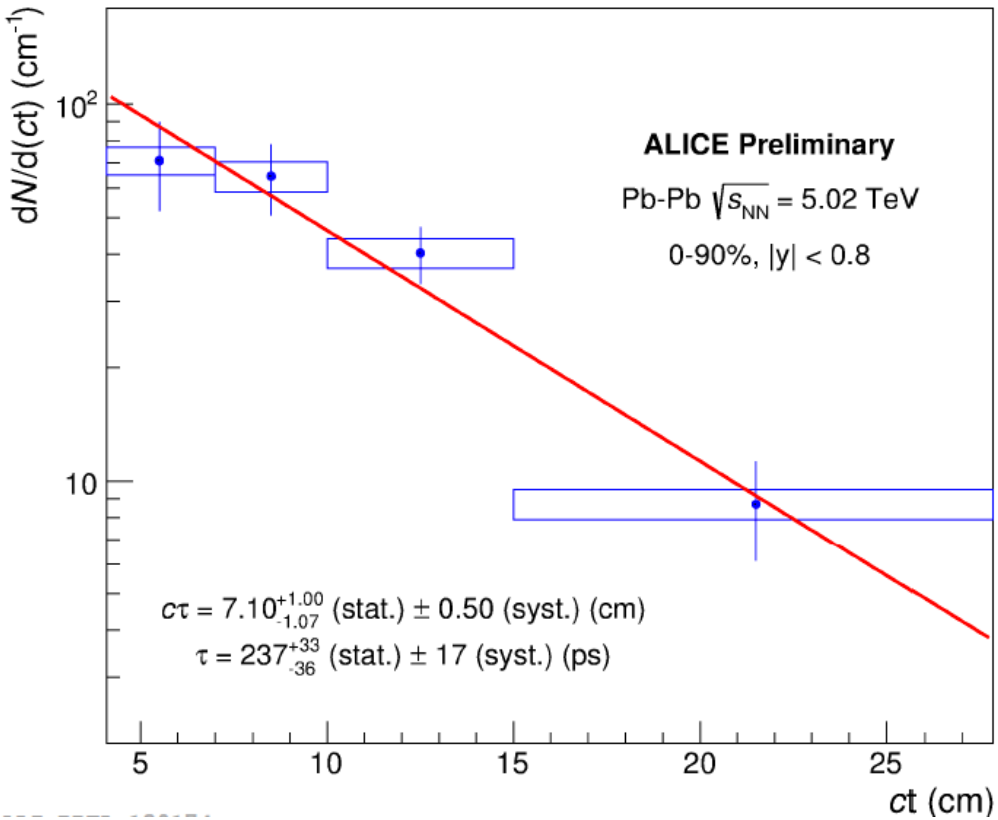

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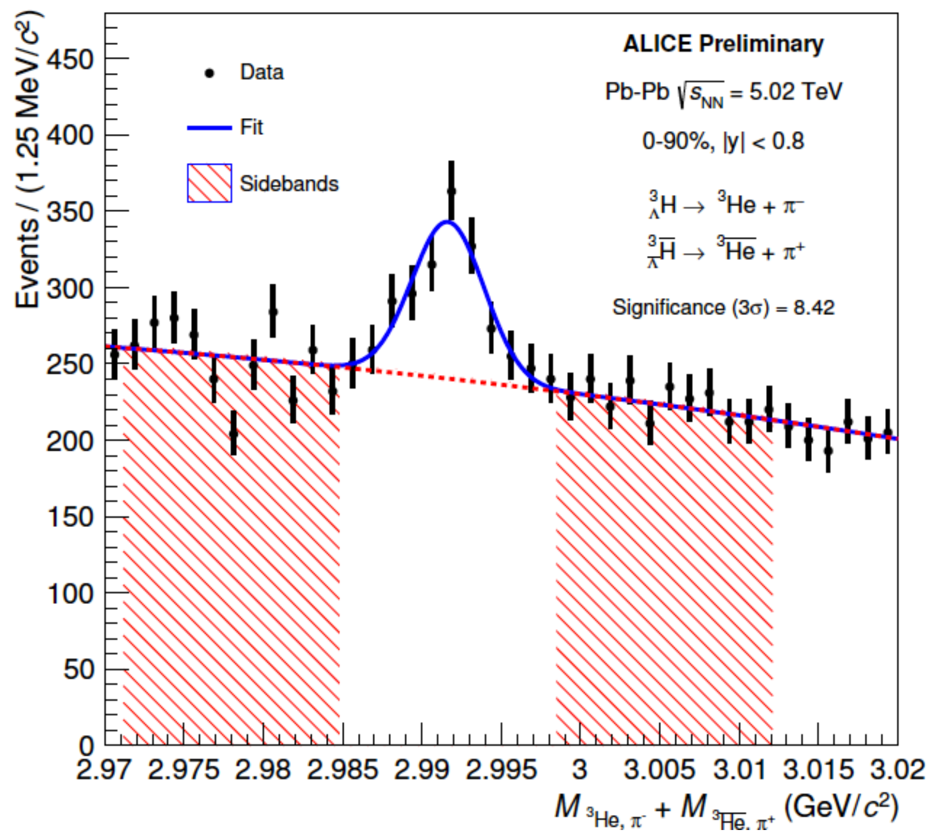

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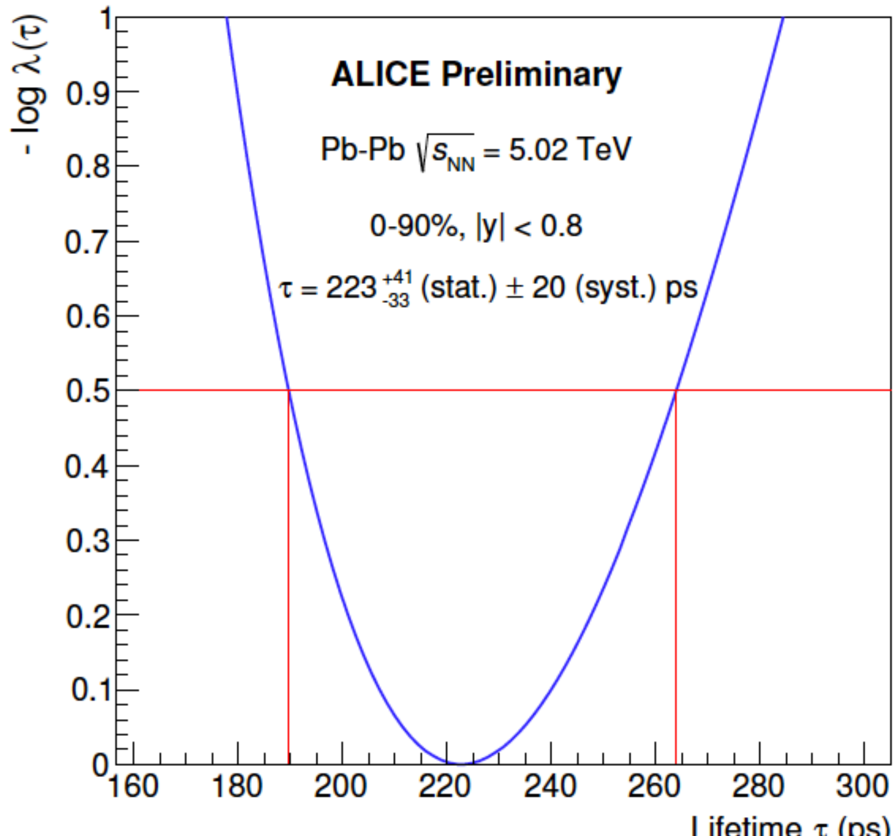

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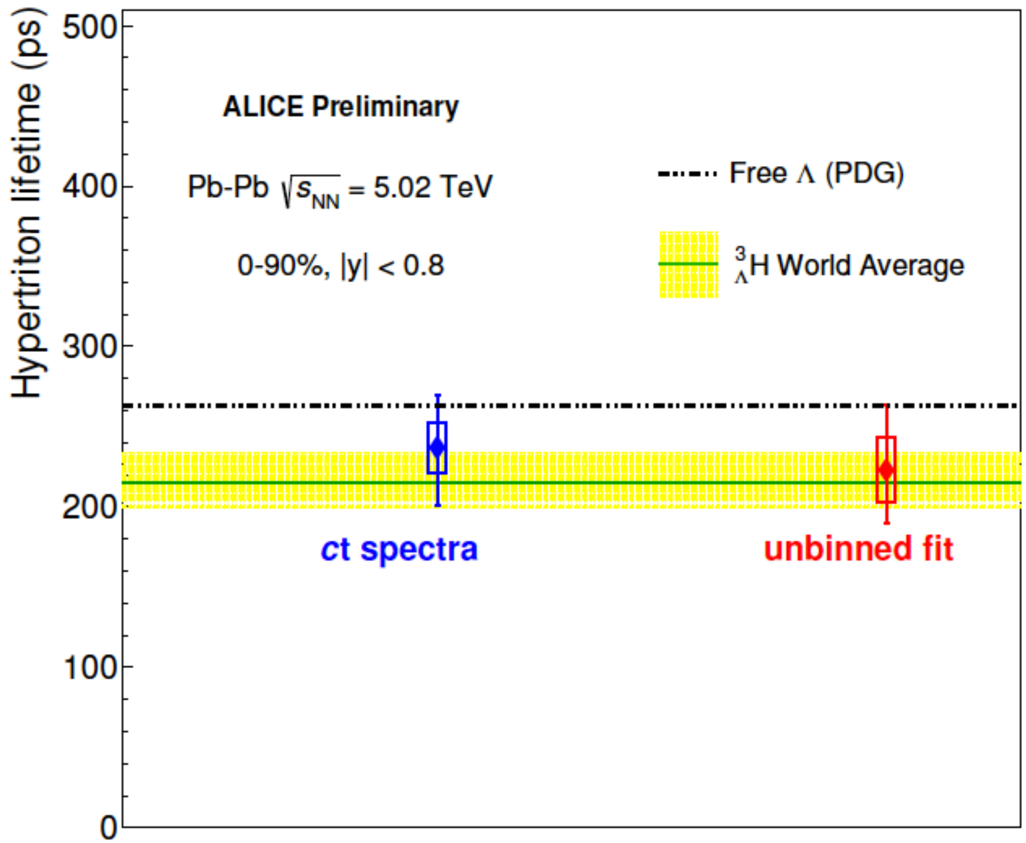

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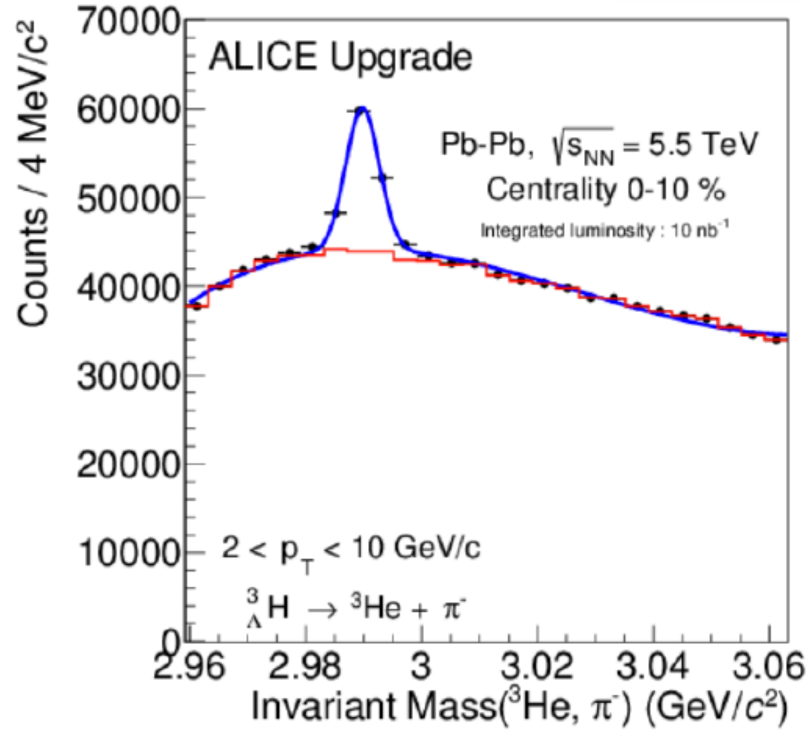

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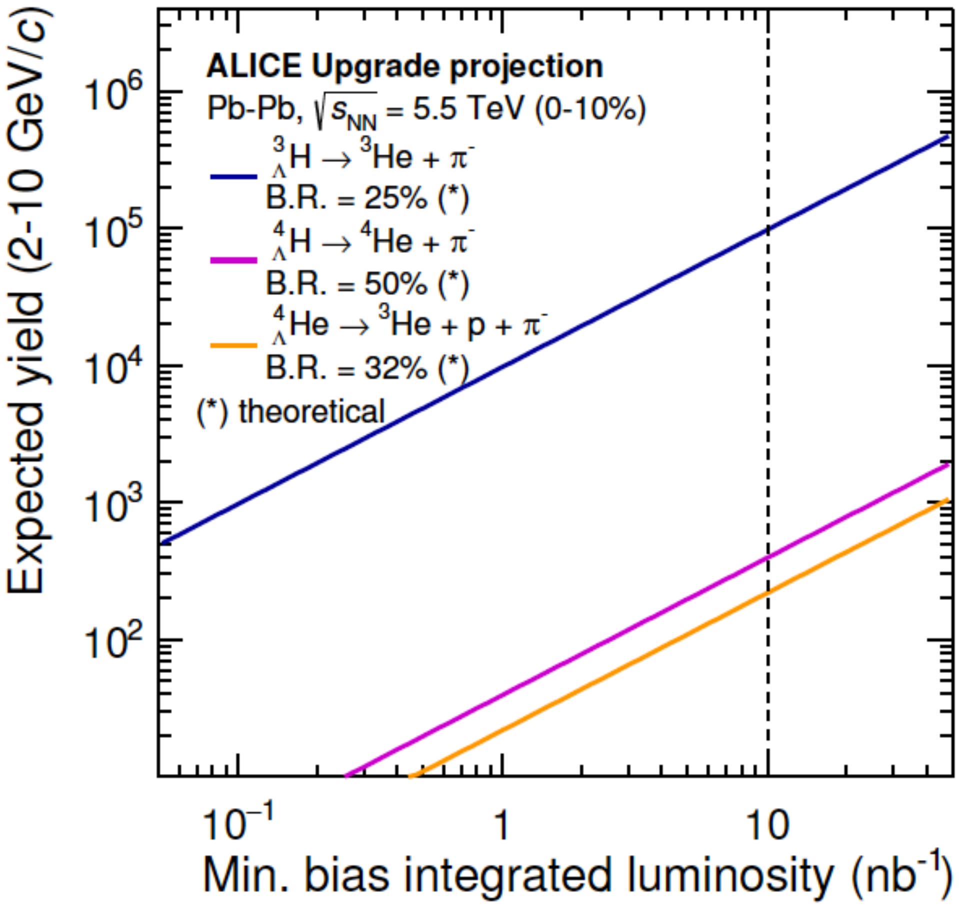

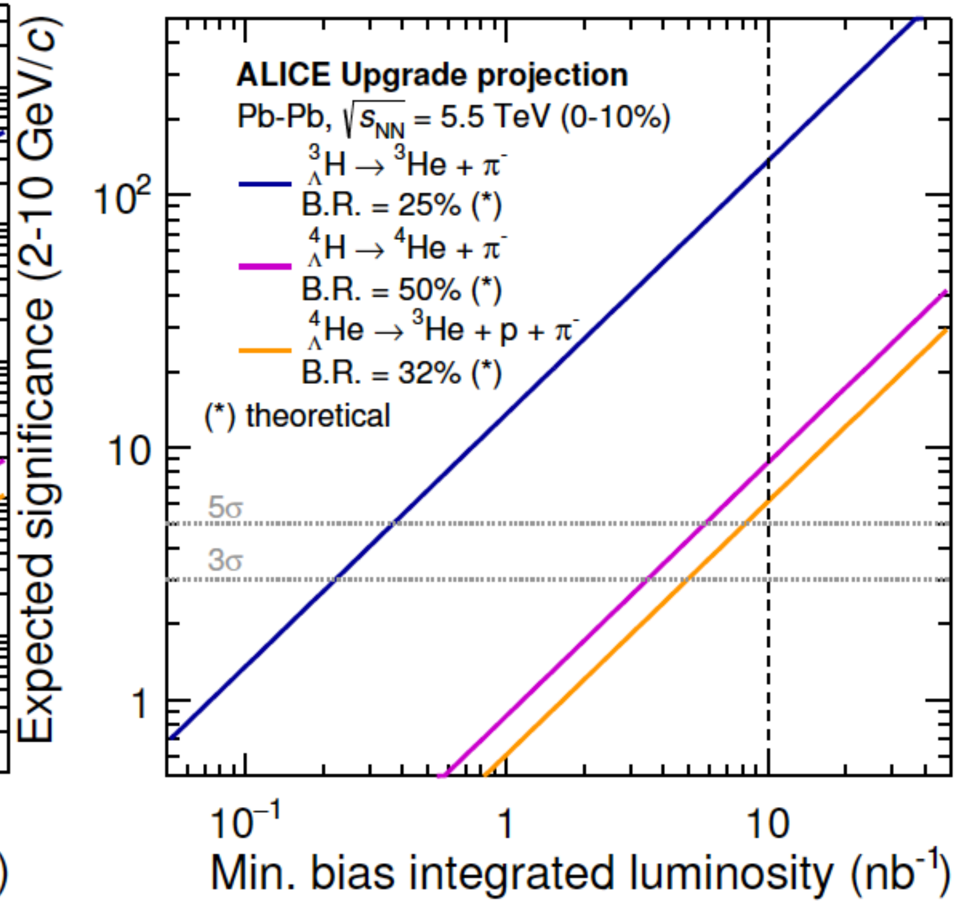

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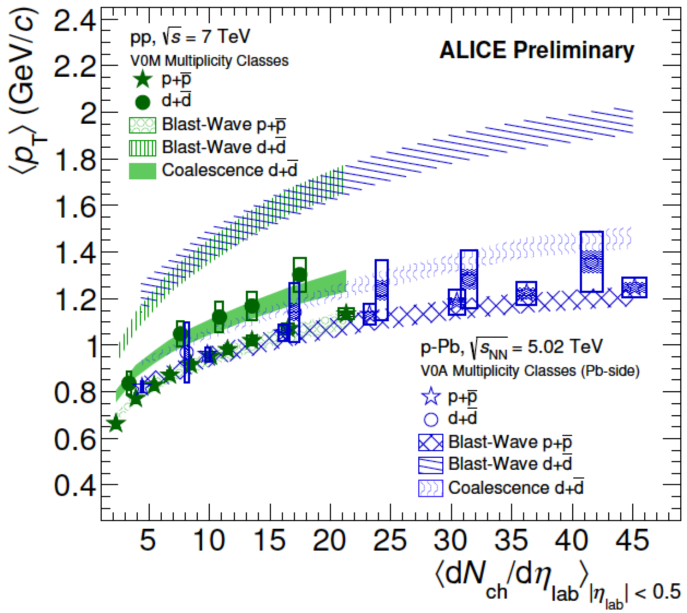
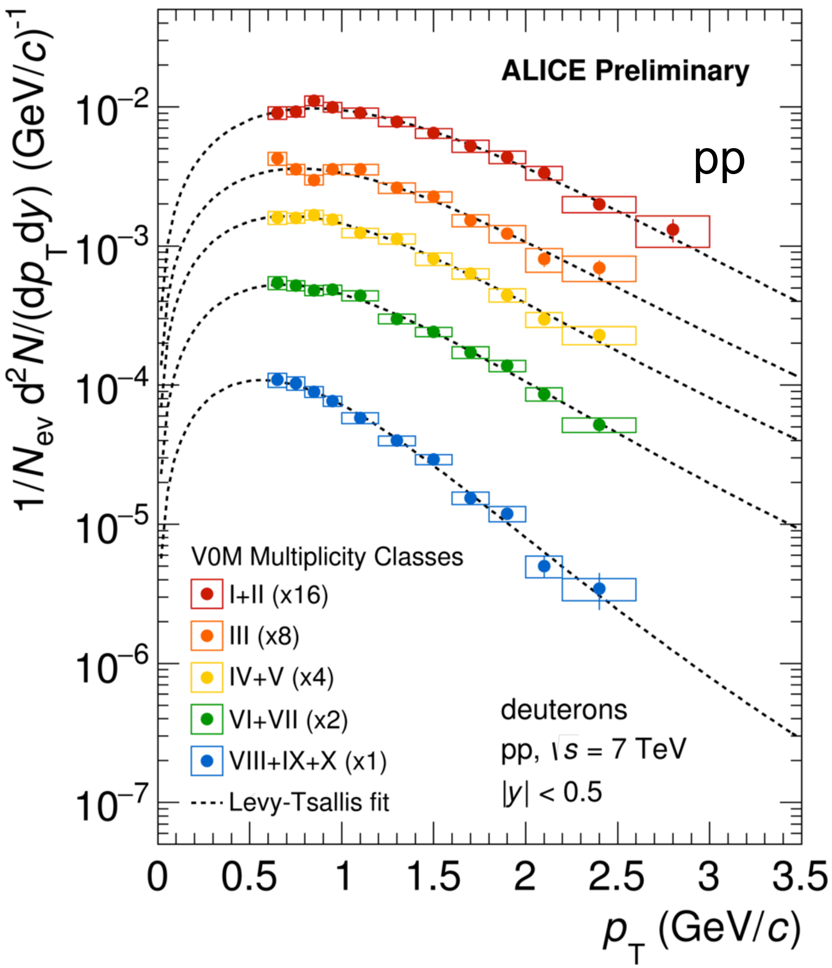
Deuterons

- 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



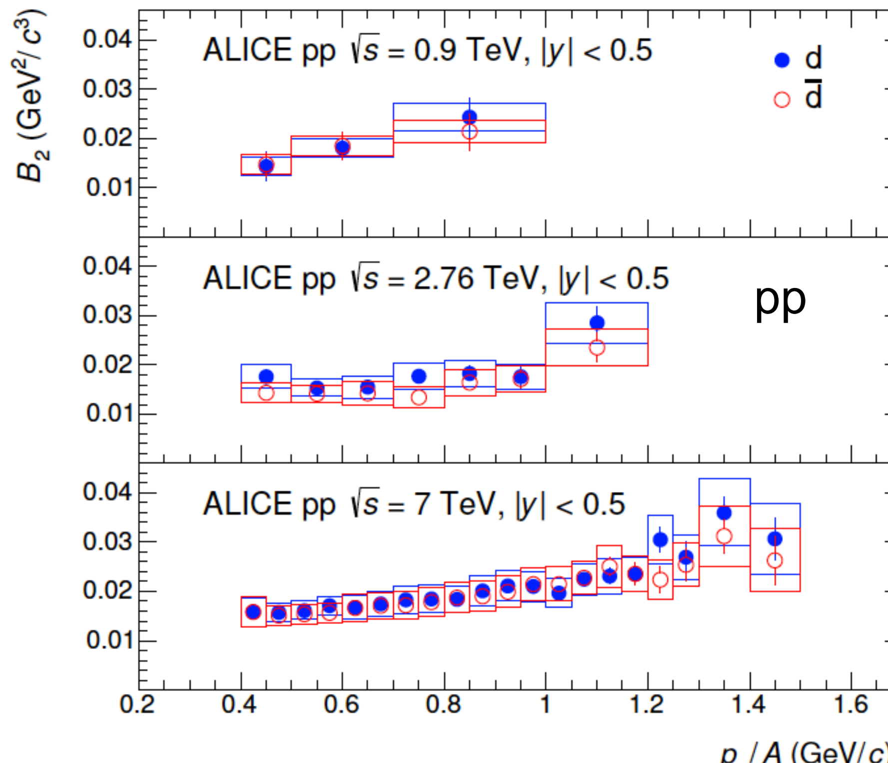


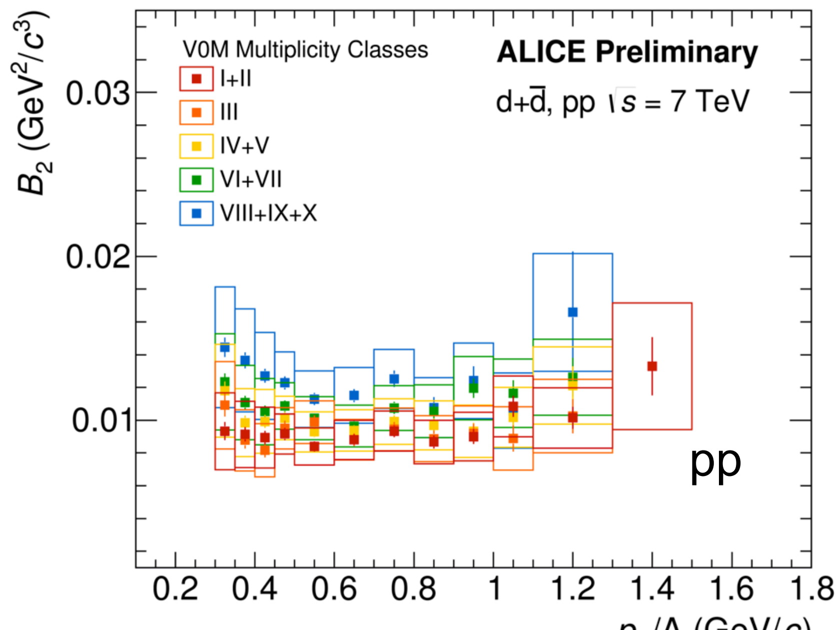
Coalescence parameter B_2

- 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





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

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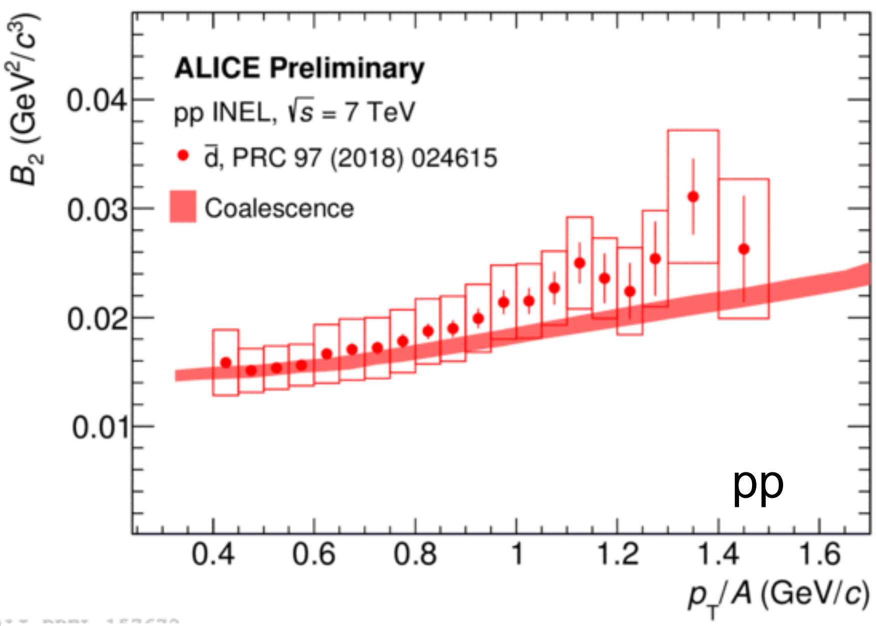

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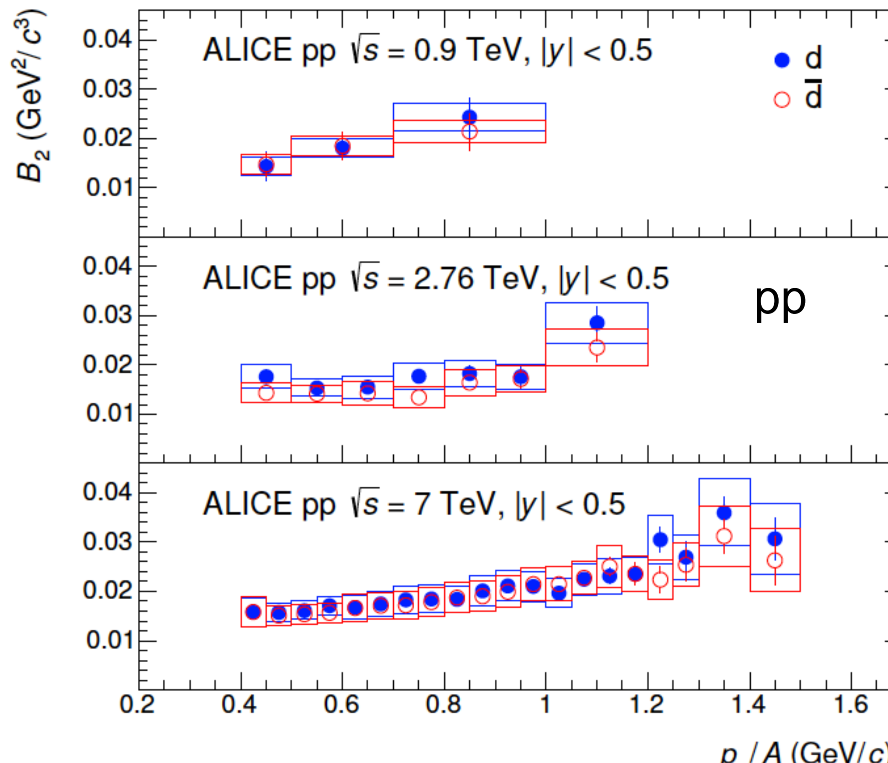

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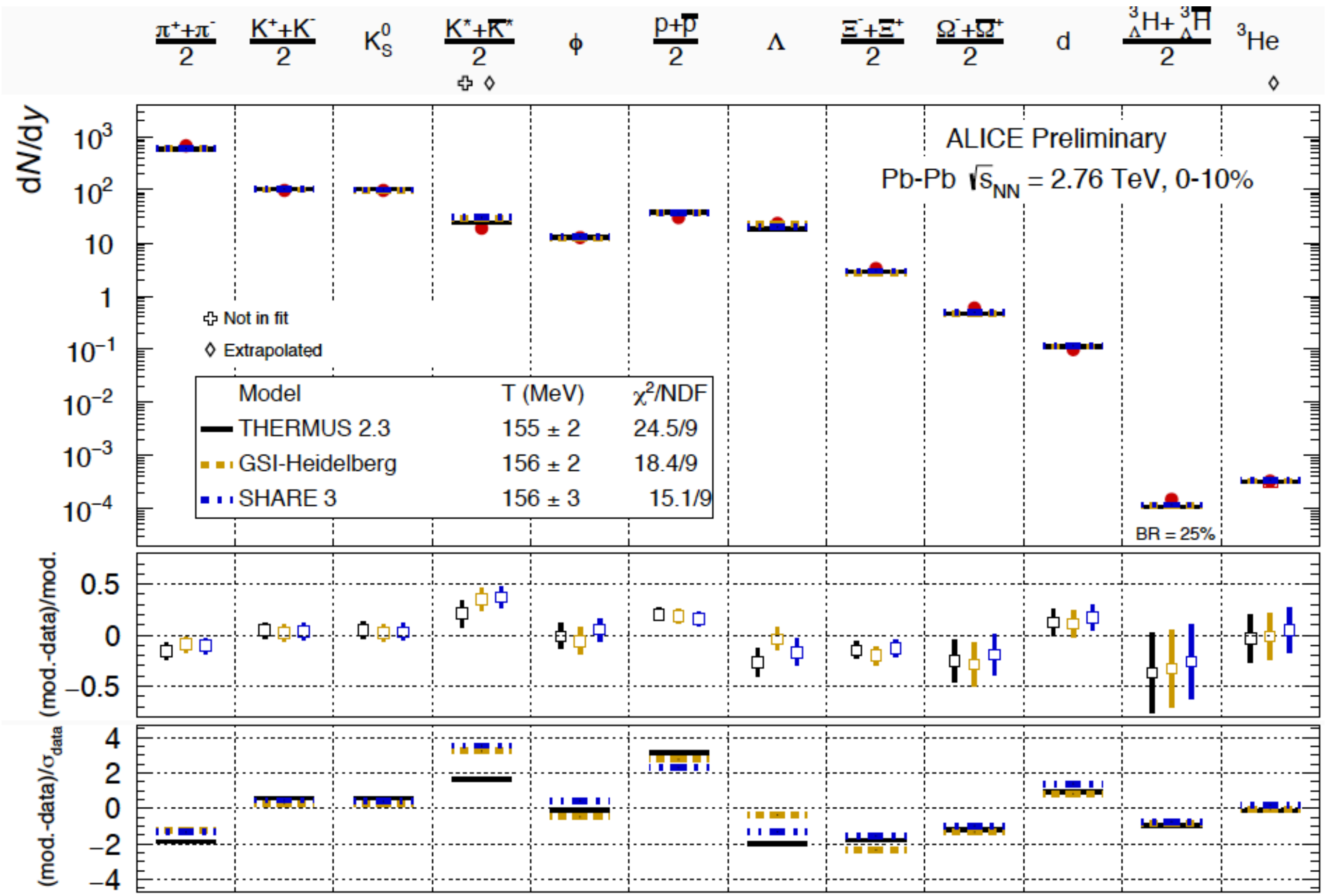
Thermal model fits

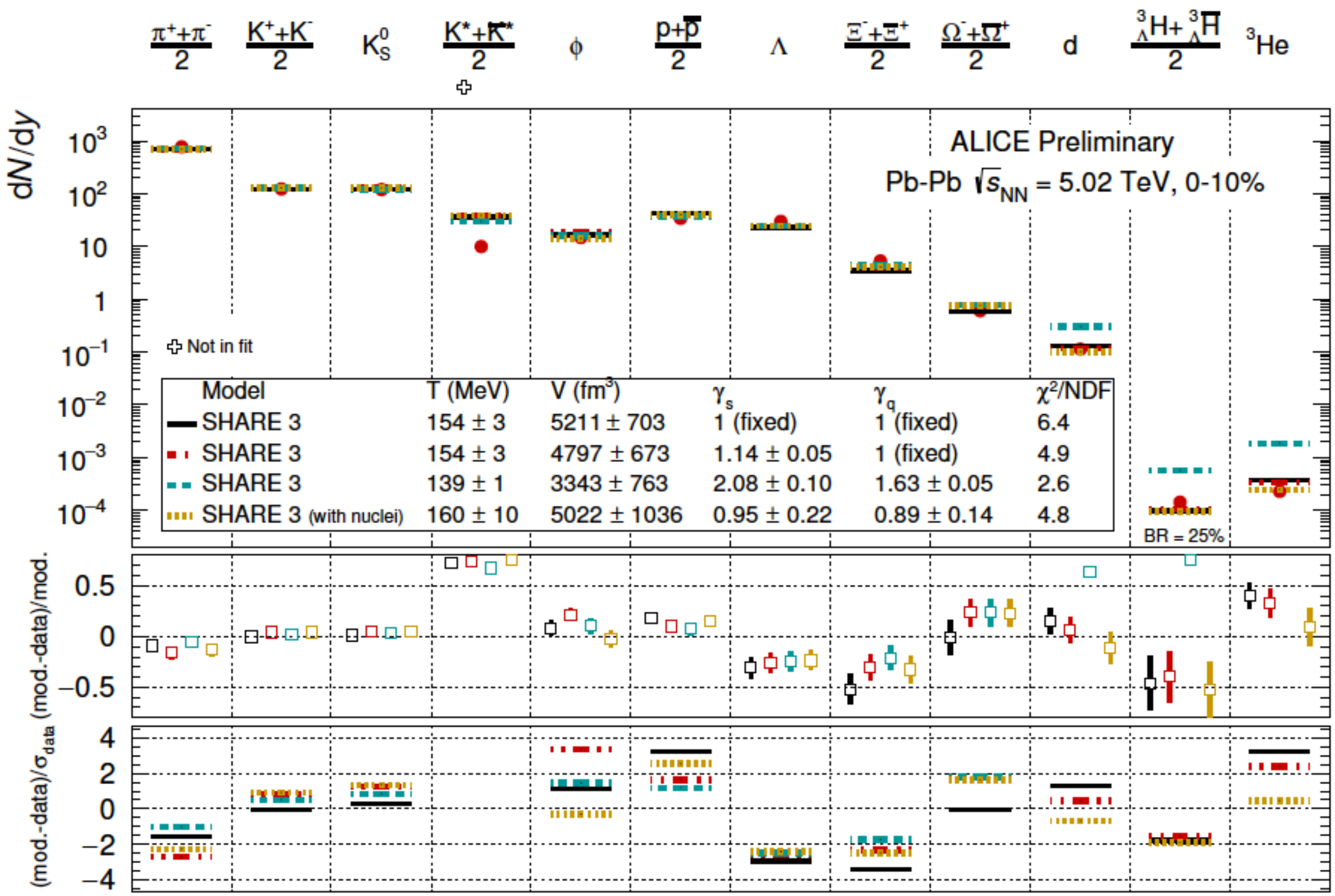
THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)



- 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}

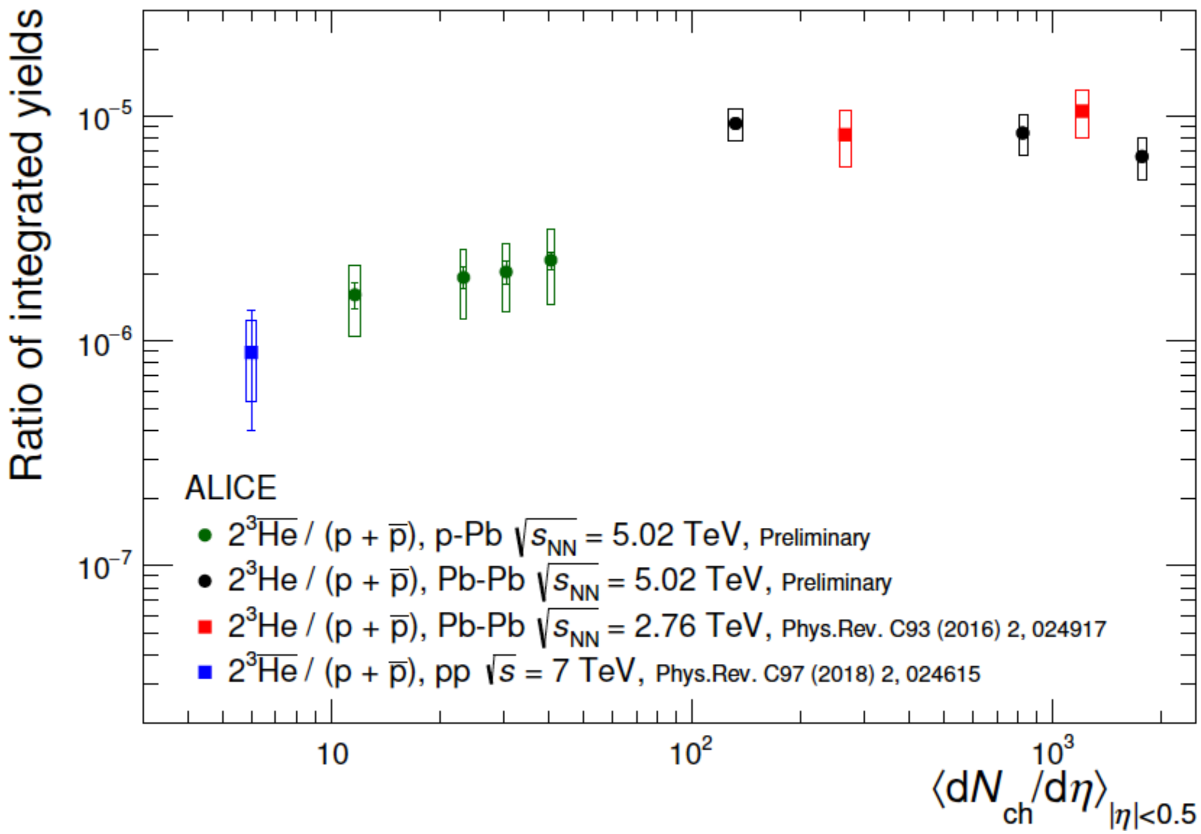
Thermal model: SHARE

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



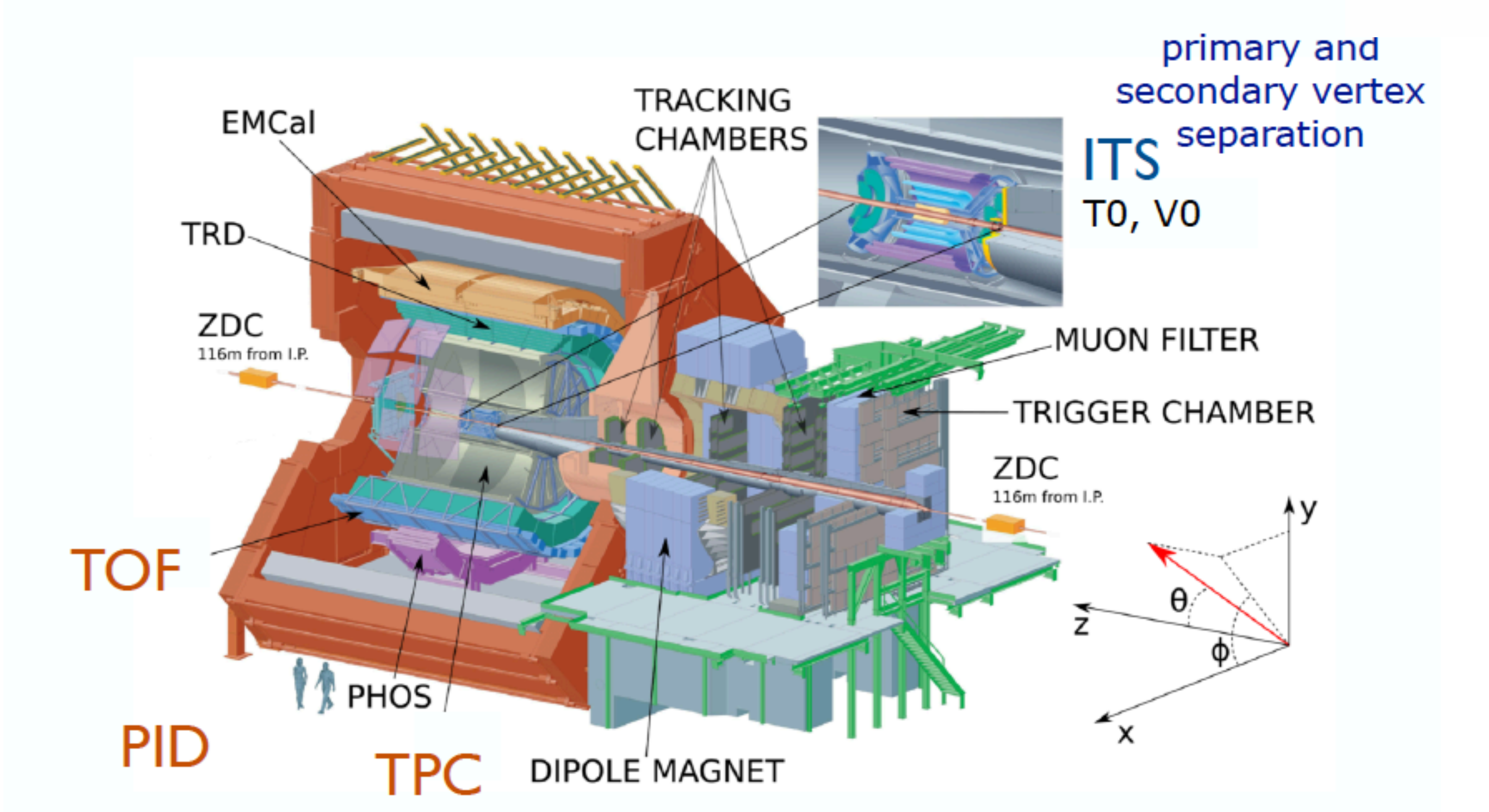
- Observations similar to QM2014 results
- Including nuclei drives a non-equilibrium fit towards the equilibrium values

^{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)

Experiment: ALICE



Multiplicity classes: pp

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

$\left[\langle dN_{ch}/d\eta \rangle^{INEL>0} \approx 6.0 \right]$

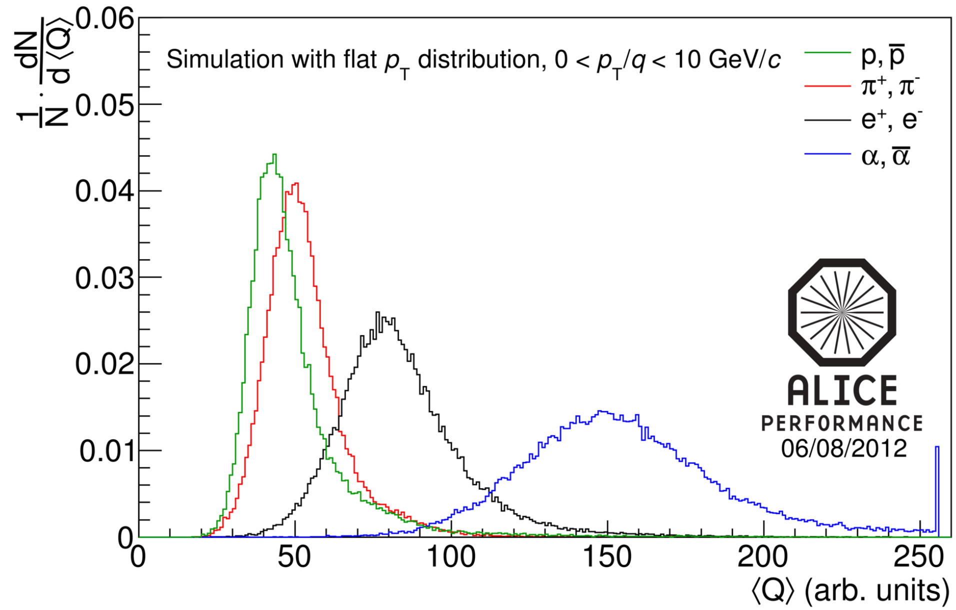
Table A.1: Event multiplicity classes, their corresponding fraction of the INEL>0 cross-section ($\sigma/\sigma_{INEL>0}$) and their corresponding $\langle dN_{ch}/d\eta \rangle$ at midrapidity ($|\eta| < 0.5$). The value of $\langle dN_{ch}/d\eta \rangle$ in the inclusive (INEL>0) class is 5.96 ± 0.23.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

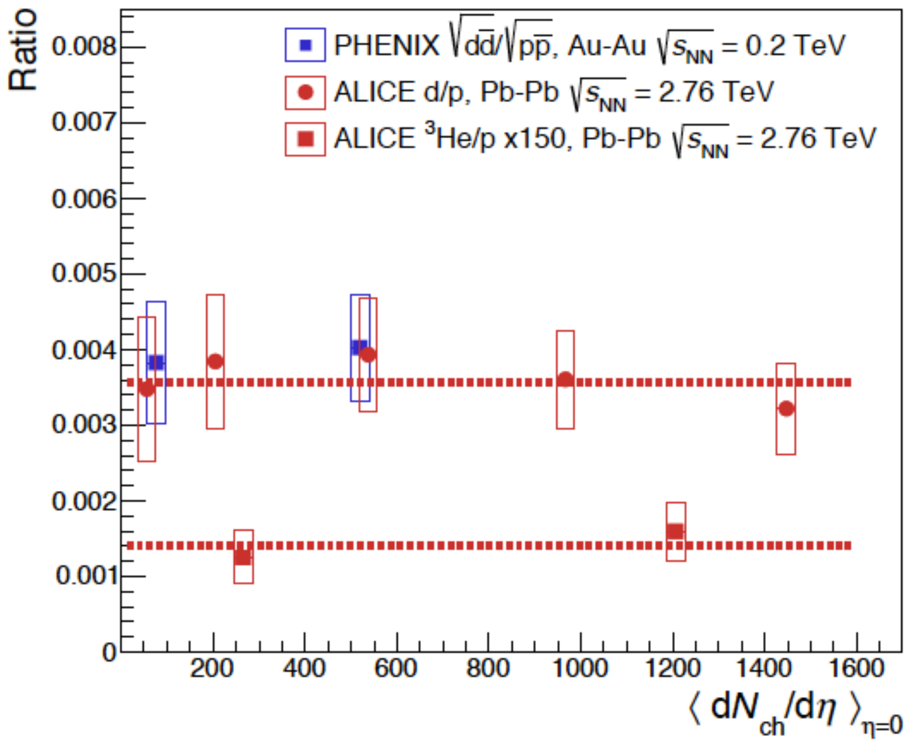
- A trigger on light (anti-)nuclei using the dependence of the ionisation on the charge number of the particle crossing the gas was studied intensively
- A first run in the p-Pb taking 2016
- Currently running in the standard trigger mix of ALICE in the pp data taking
- Expected enhancement mainly on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

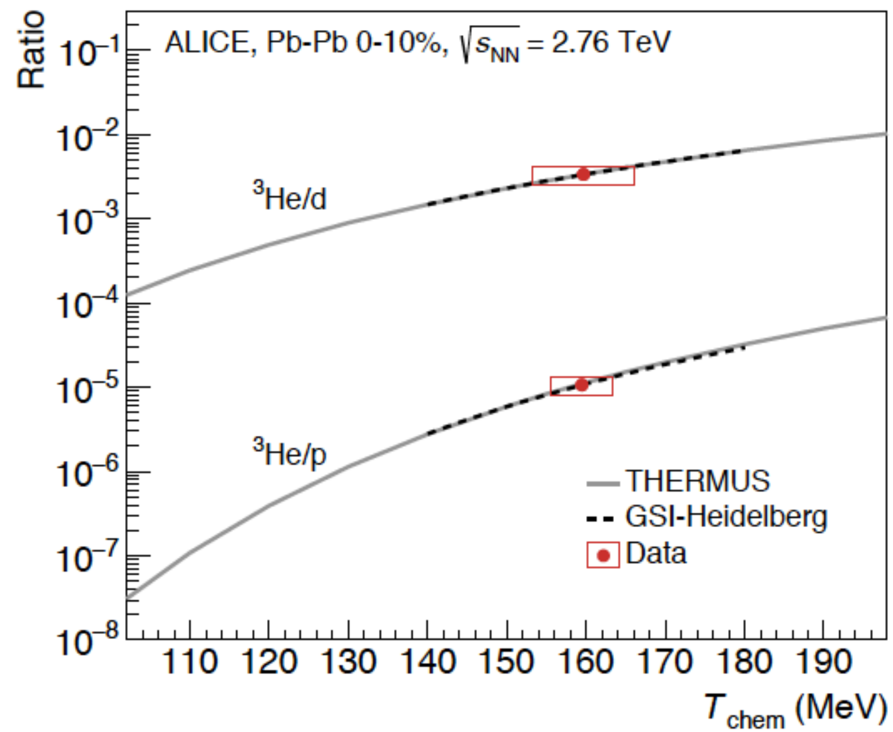


Ratios between species

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

Extracted ratios agree with the thermal model values

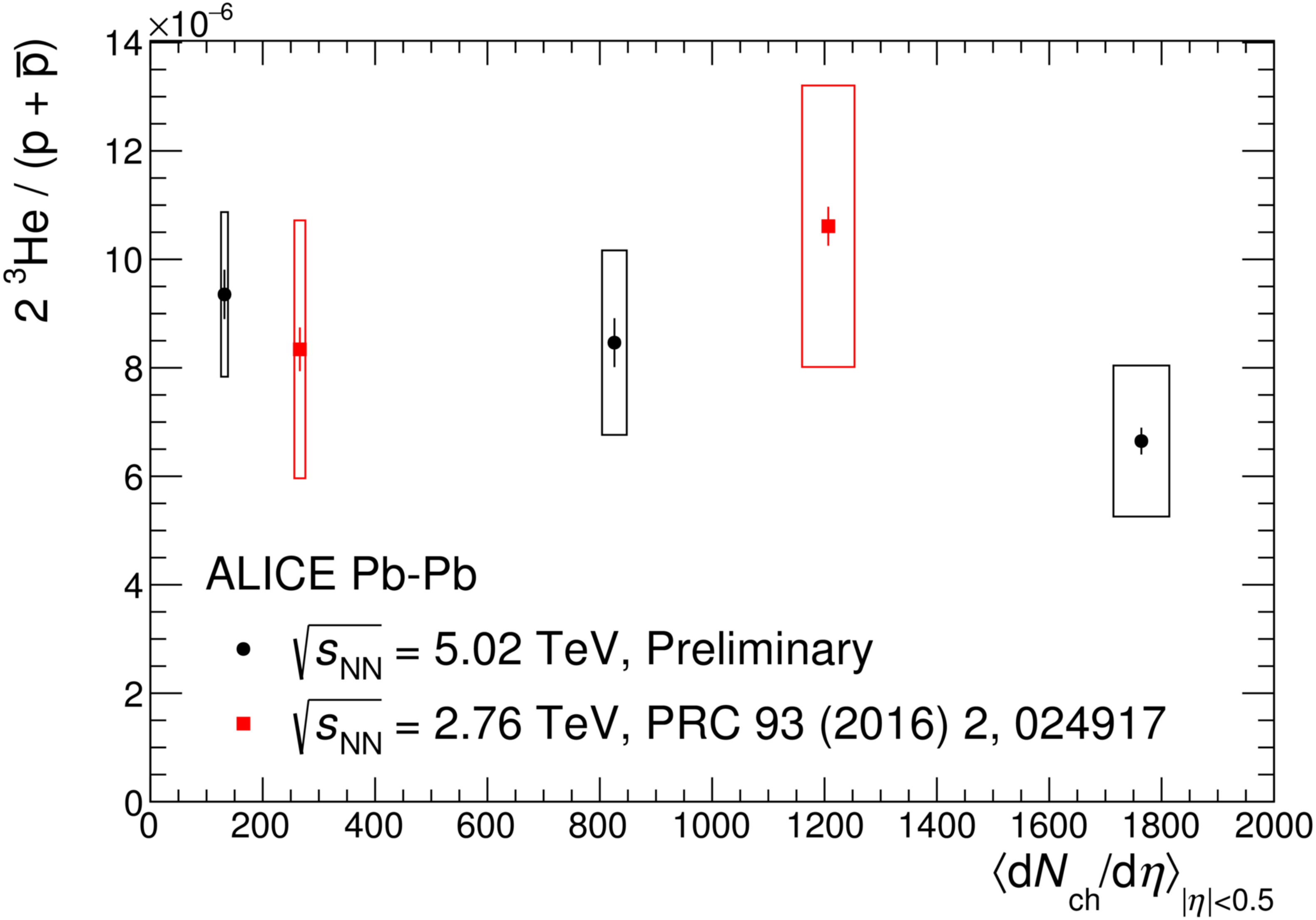


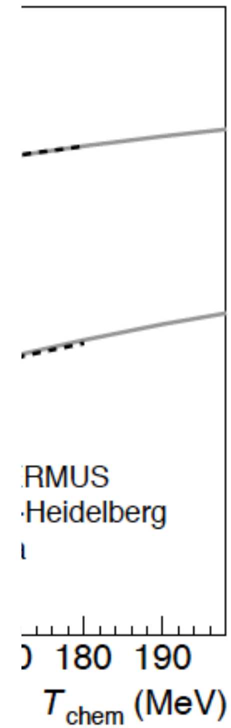


d/p ratio agrees well with the „averaged“ measurement at RHIC

Ratios between species

917 (2016)





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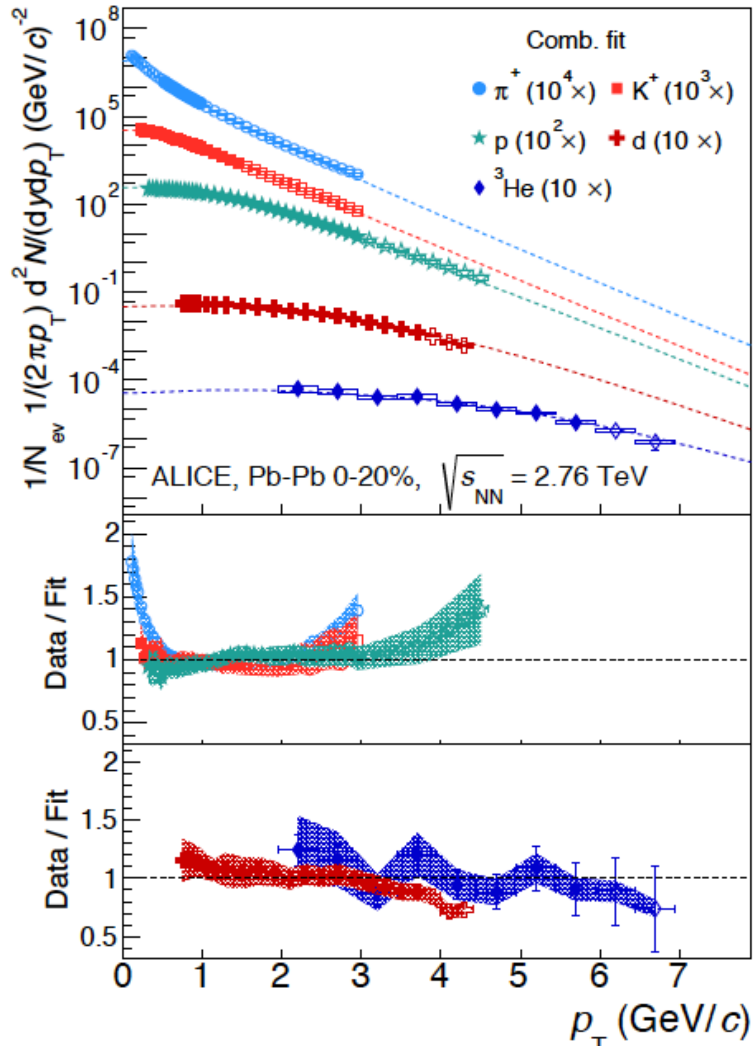
Combined Blast-Wave fit

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

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



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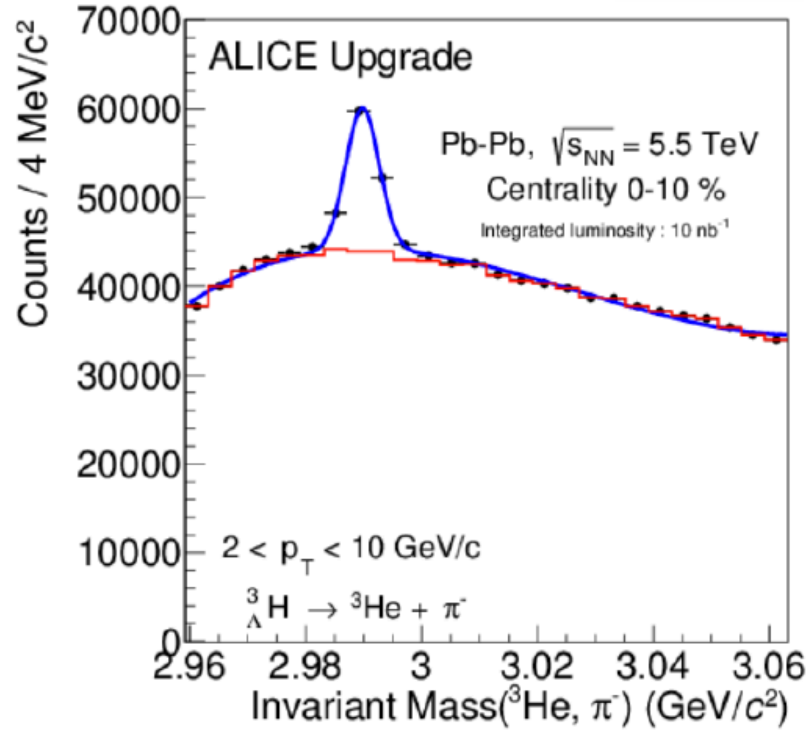

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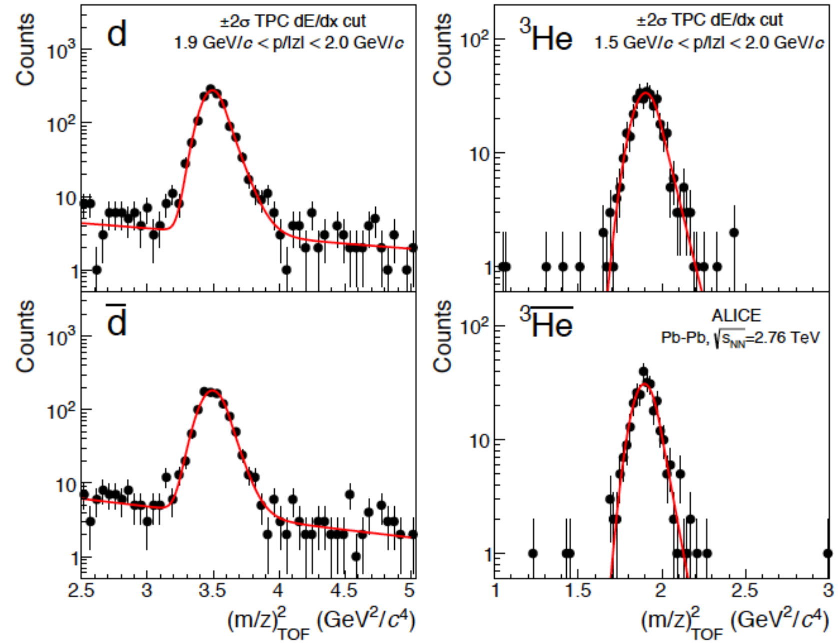
$^4_\Lambda He$	2×10^{-7}	32%	8 %	130

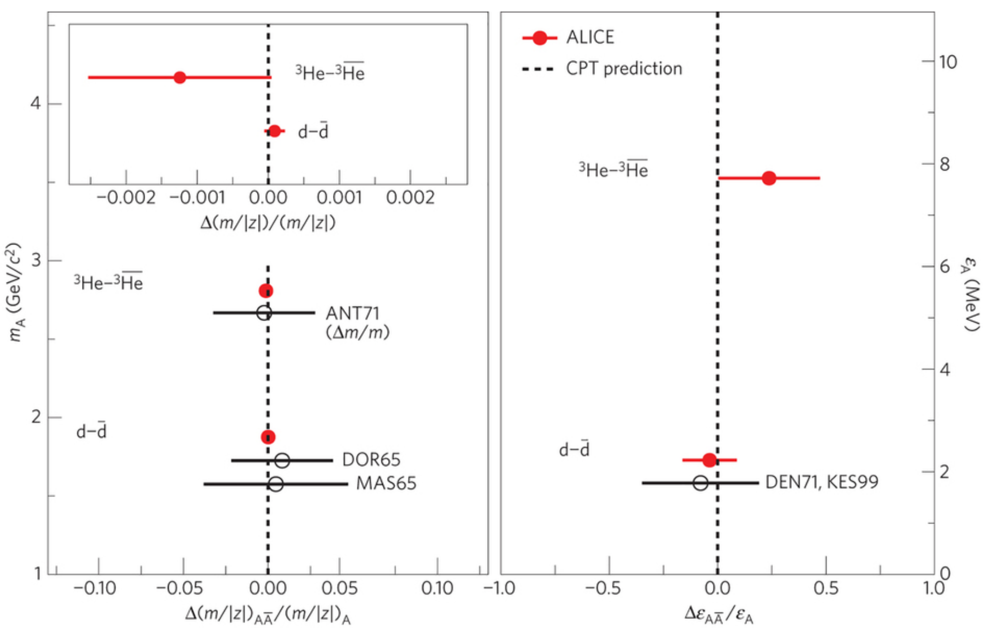
Precision mass measurement

- 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

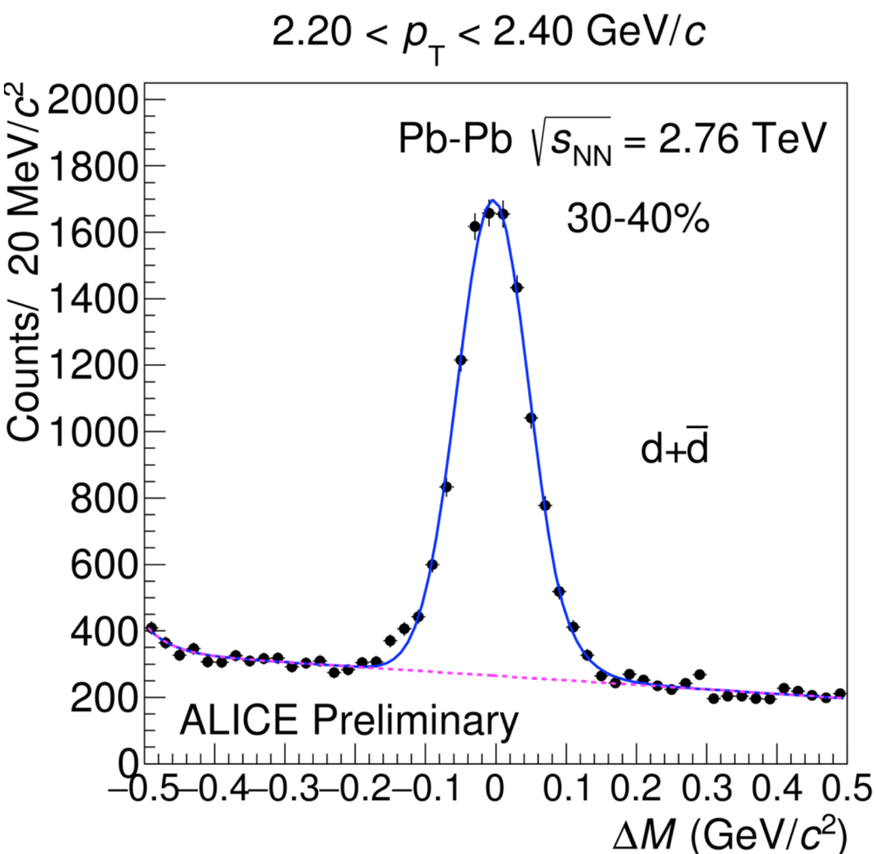
ALICE Collaboration: Nature Phys. 11, 811 (2015)

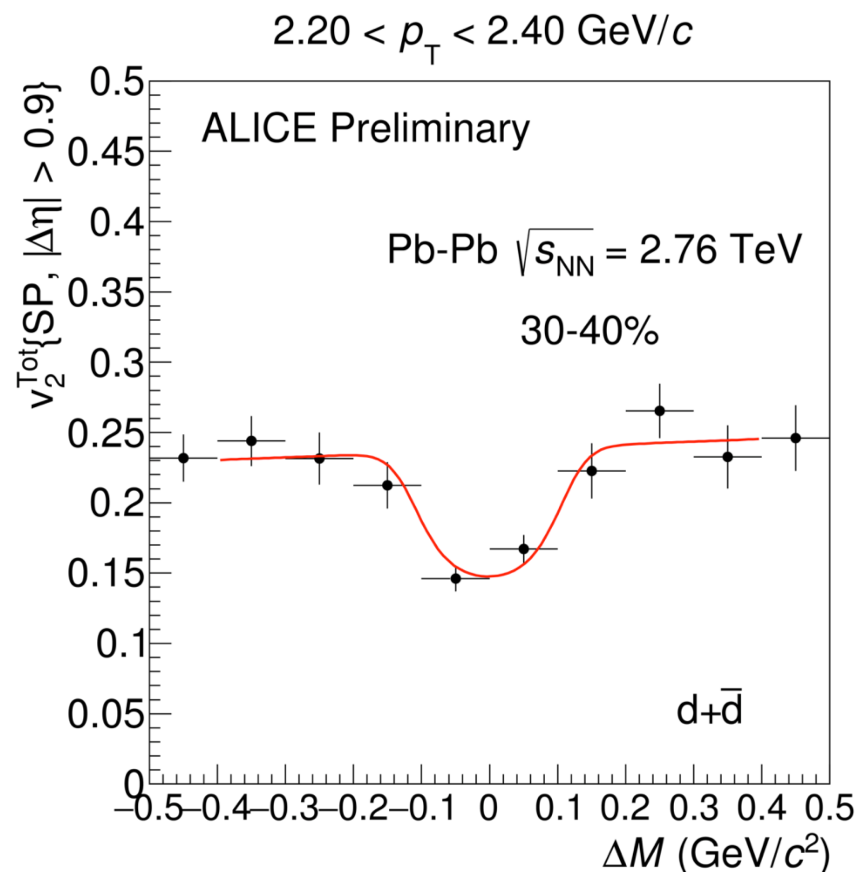




➜ Mass and binding energies of nuclei and anti-nuclei are compatible within uncertainties
➜ Measurement confirms the CPT invariance for light nuclei.

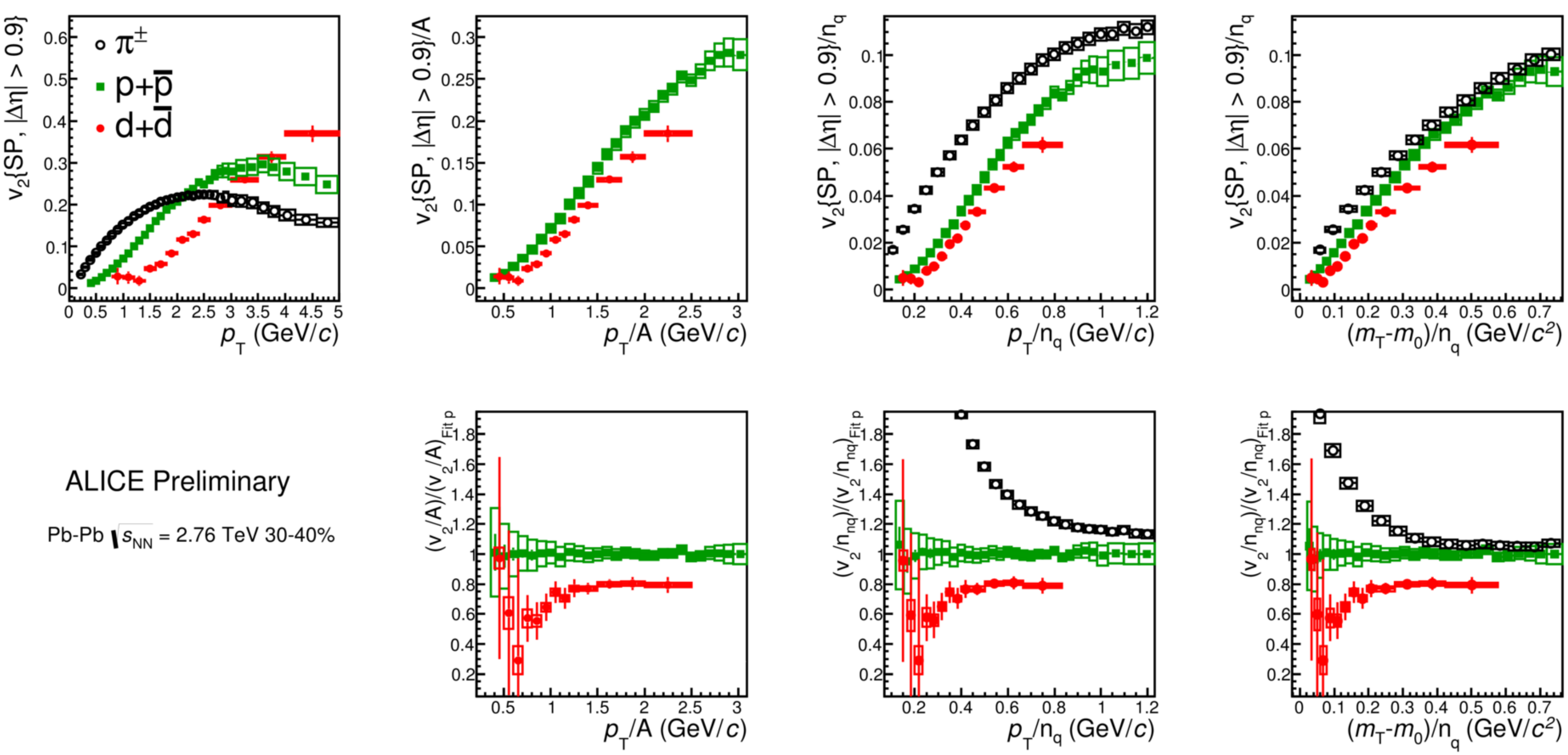
Elliptic flow



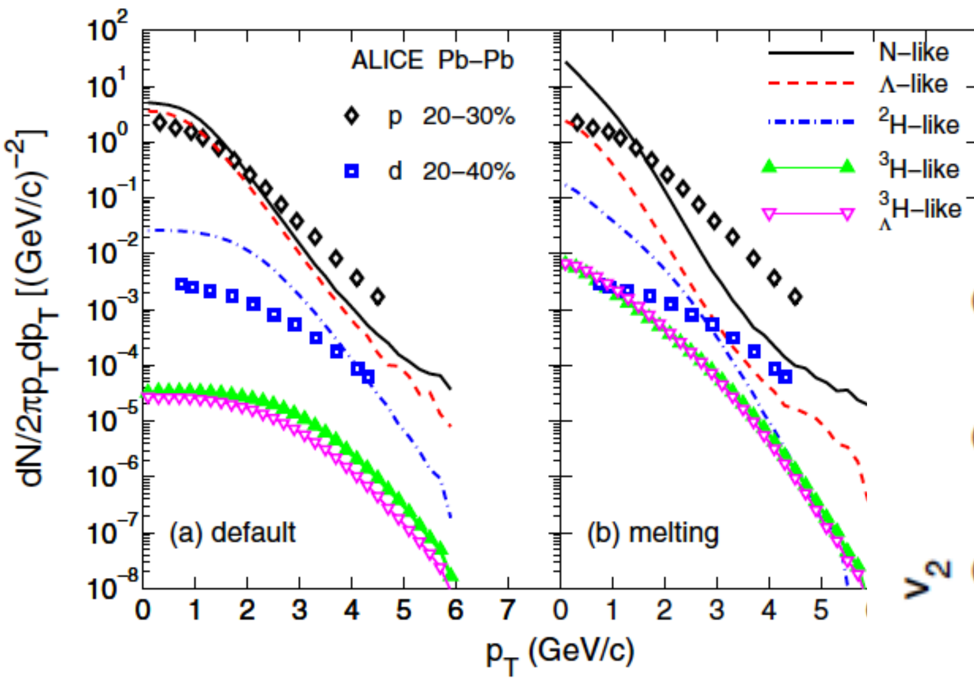


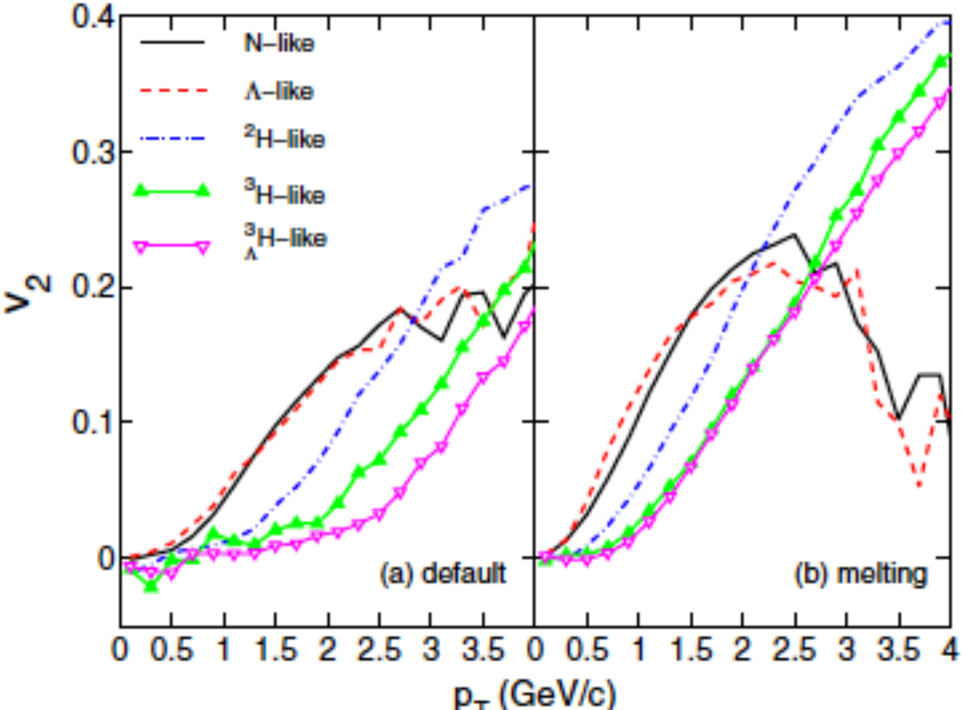
$$v_n\{SP\} = \frac{\langle u_{n,i}(p_T,\eta)\cdot \frac{Q_n^*}{M}\rangle}{\sqrt{\langle \frac{Q^*_{n,A}}{M_A}\cdot\frac{Q^*_{n,B}}{M_B}\rangle}}$$

Elliptic flow



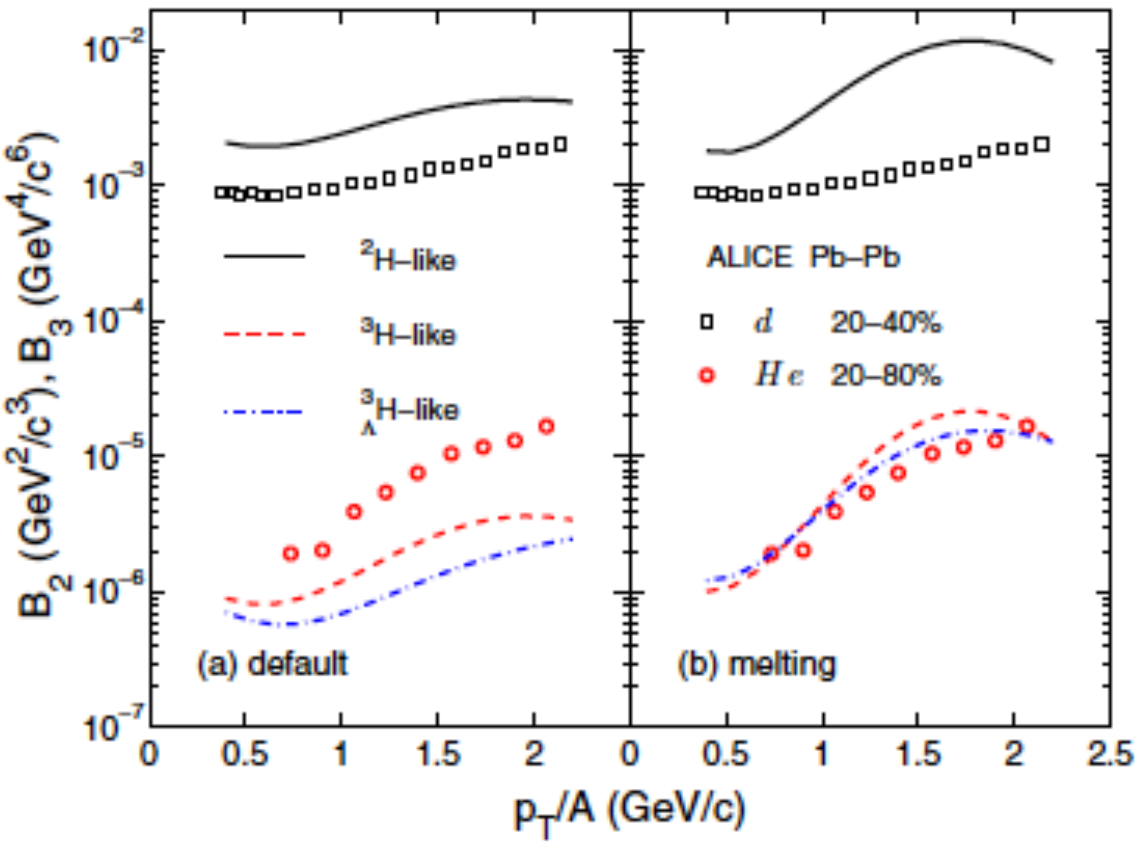
Elliptic flow





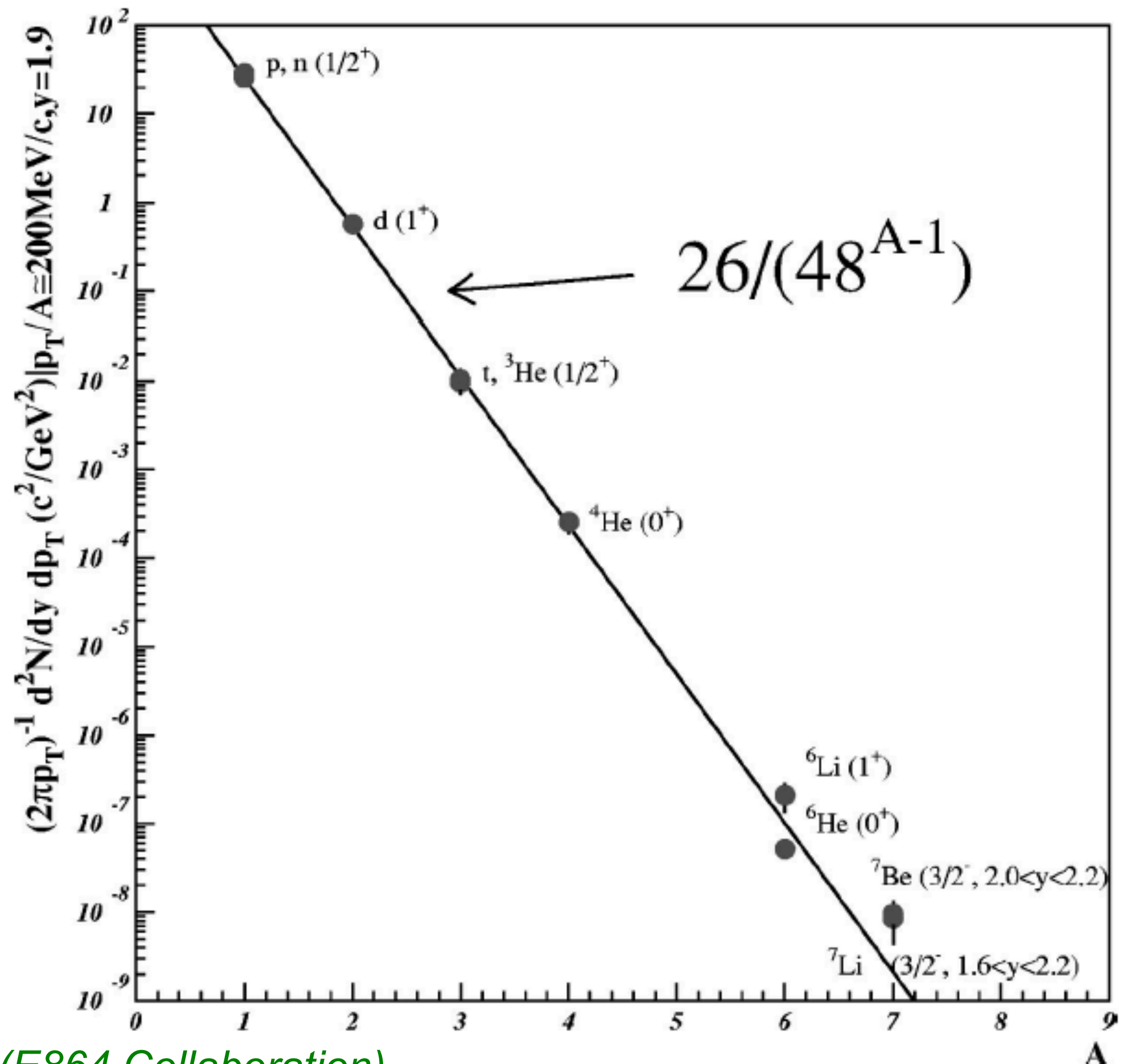
L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

Elliptic flow



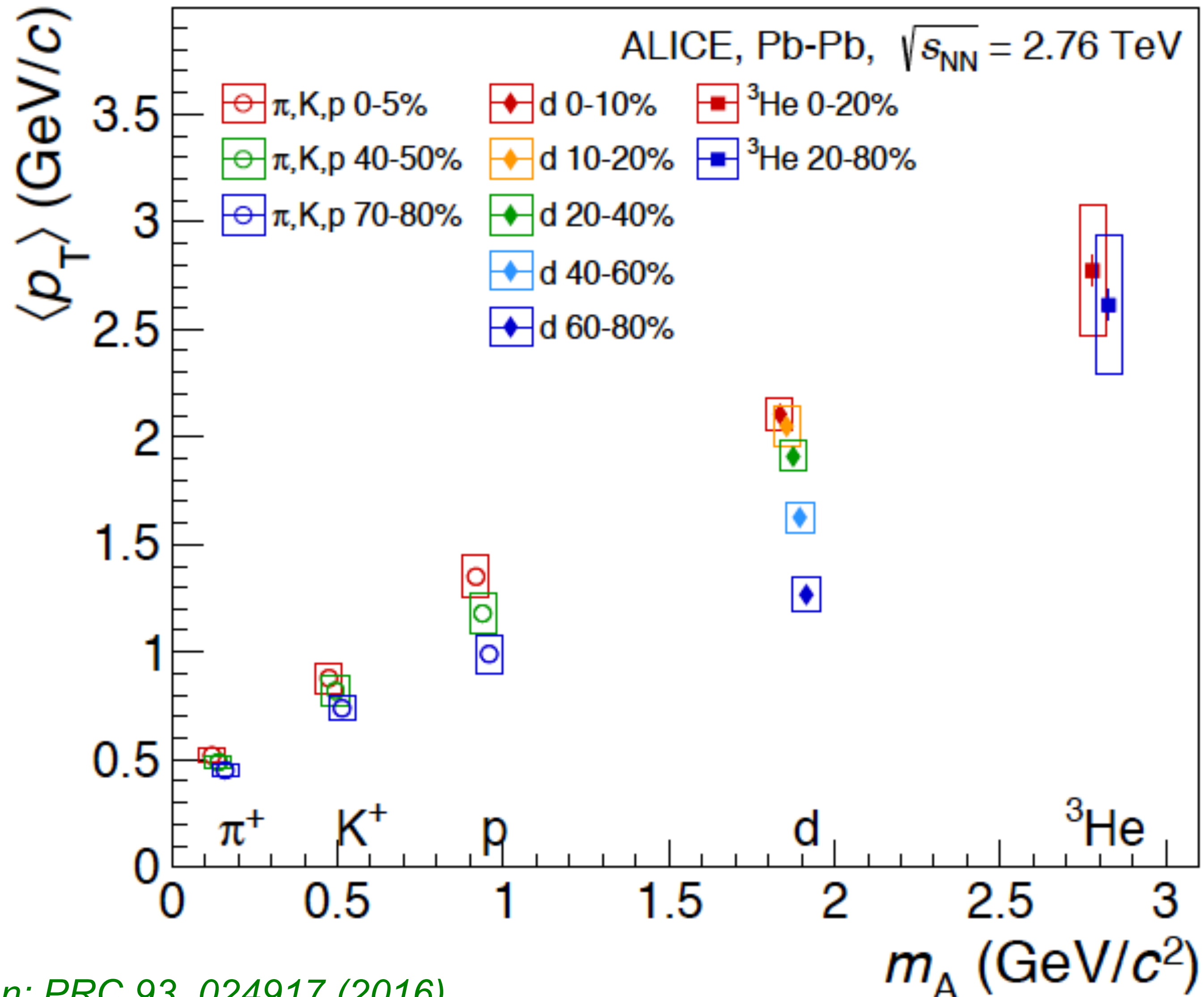
L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

E864 nuclei result



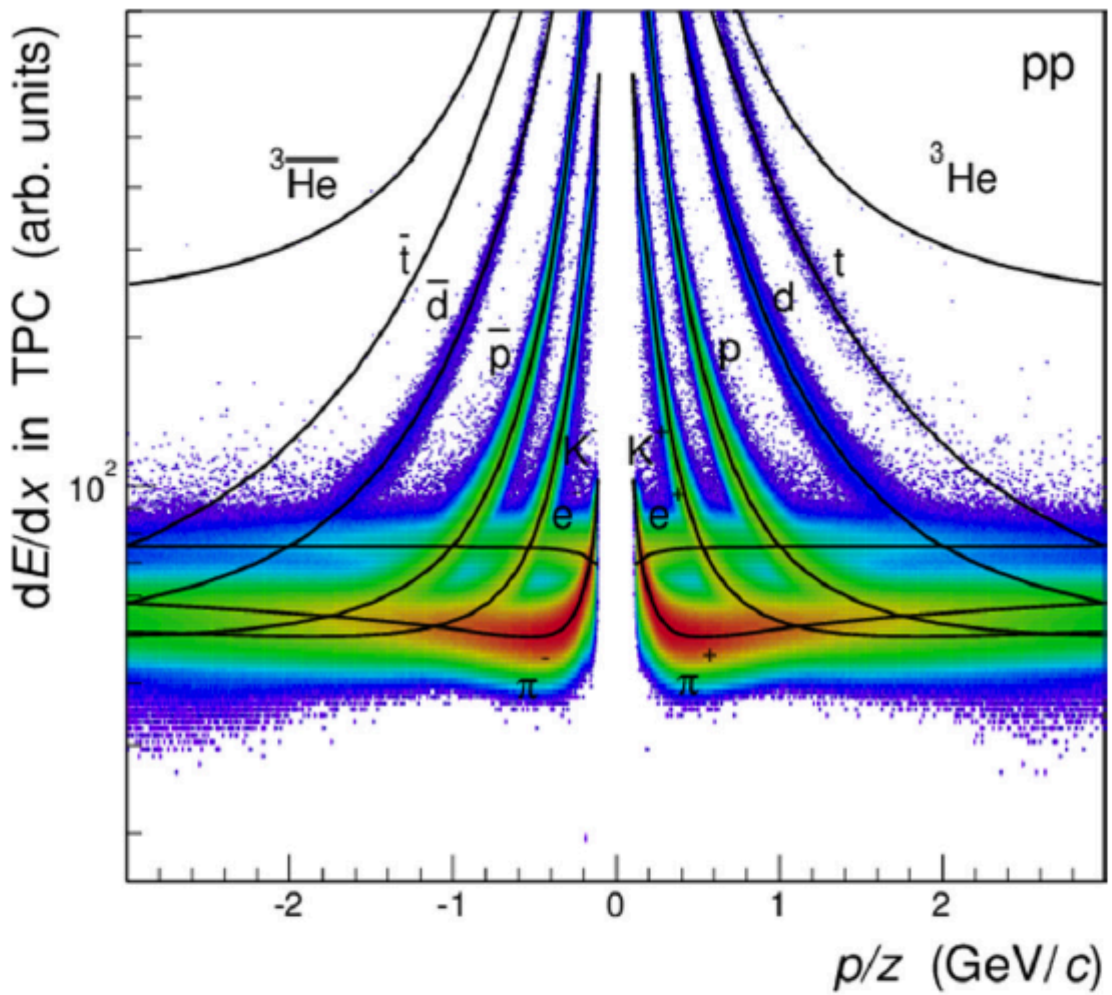
T.A. Armstrong et al. (E864 Collaboration), Phys. Rev. C 61 (2000) 064908

Mean p_T



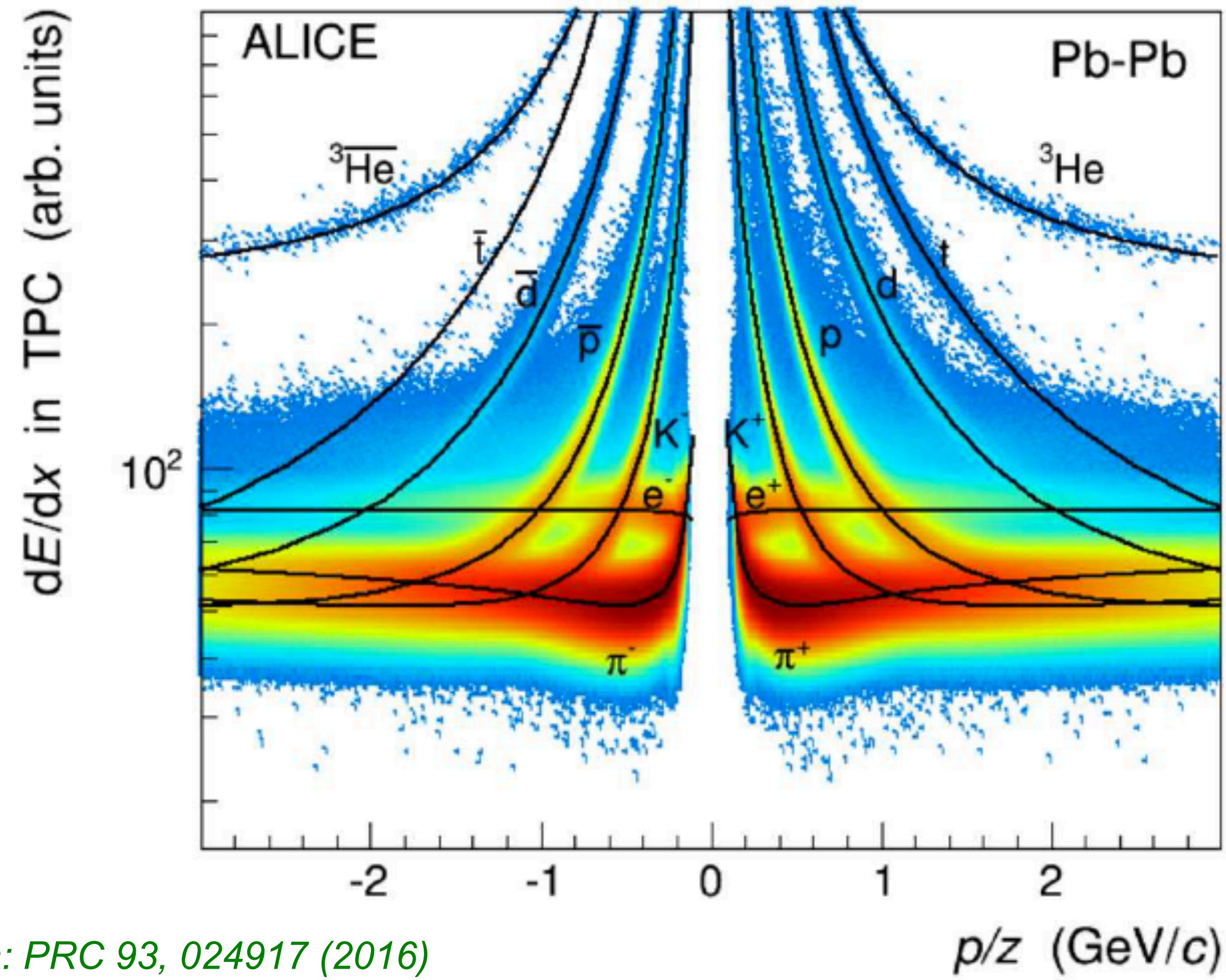
ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in pp



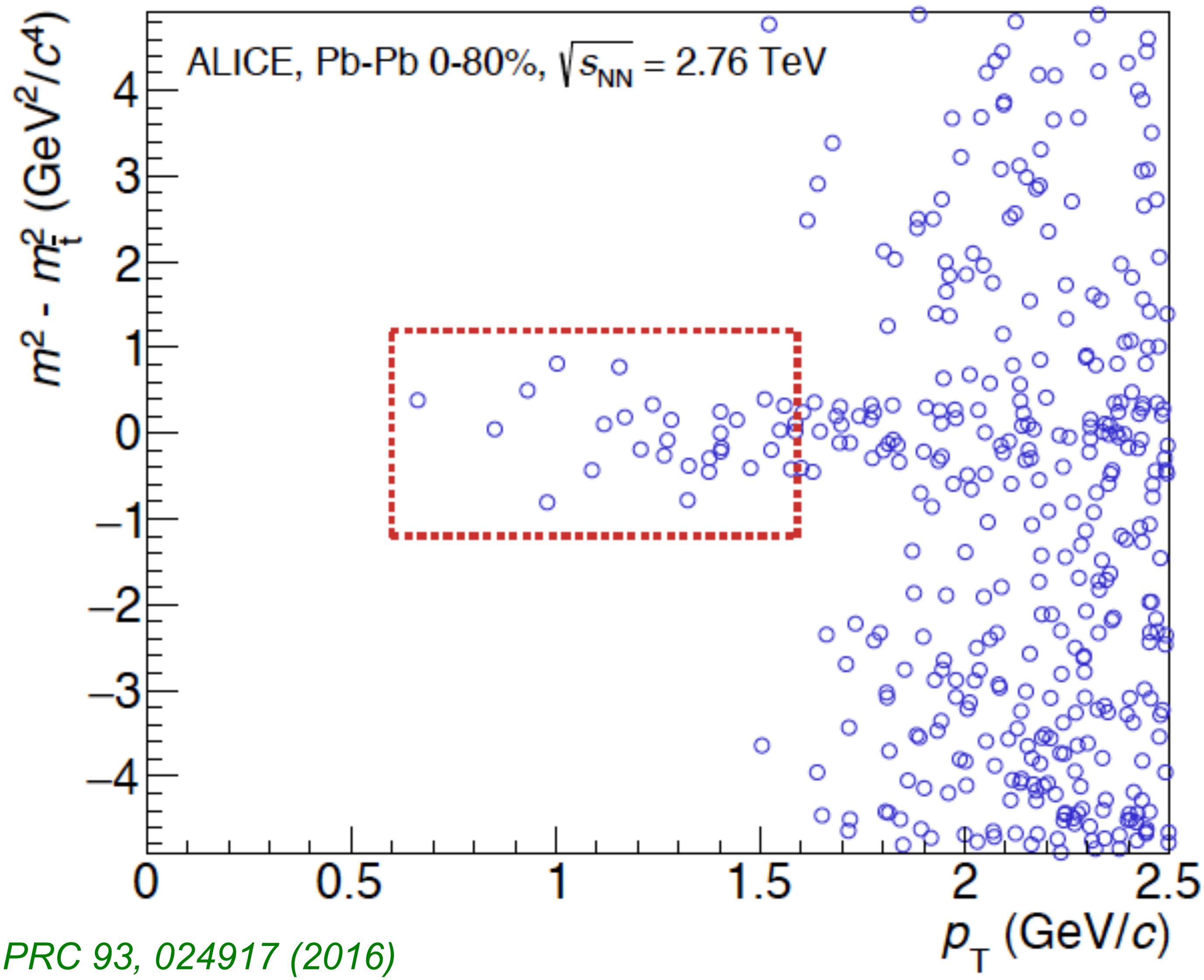
ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in Pb-Pb



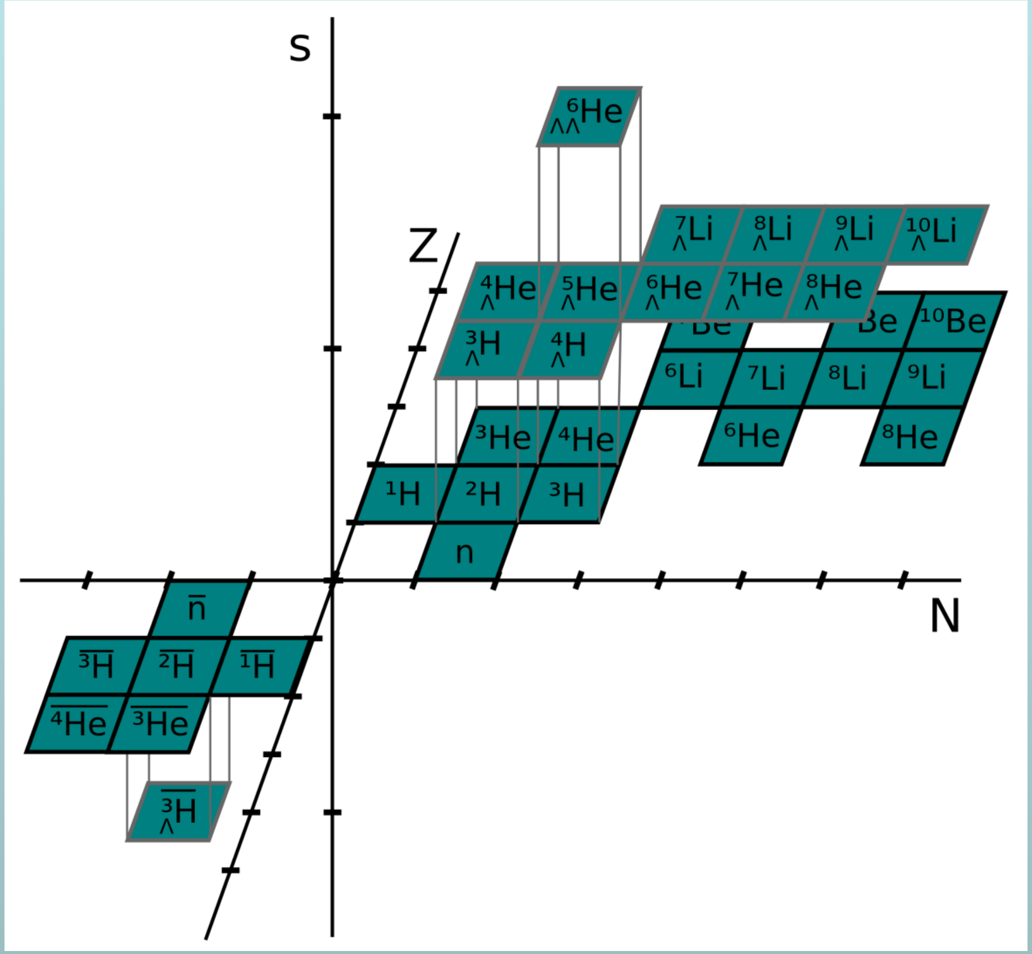
ALICE Collaboration: PRC 93, 024917 (2016)

Anti-tritons

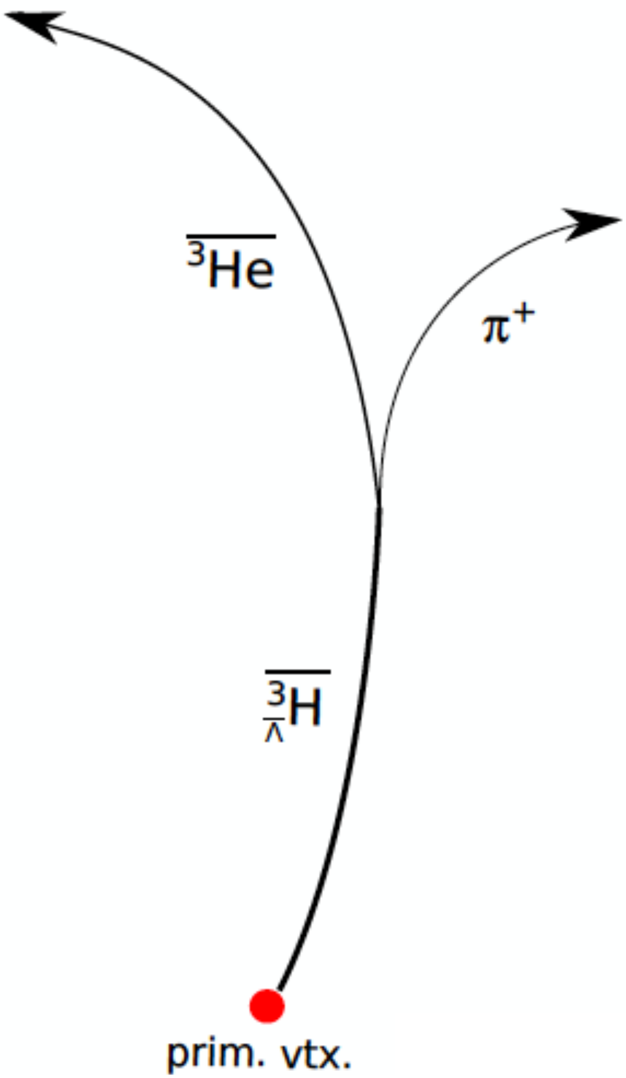


ALICE Collaboration: PRC 93, 024917 (2016)

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:

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

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

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

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

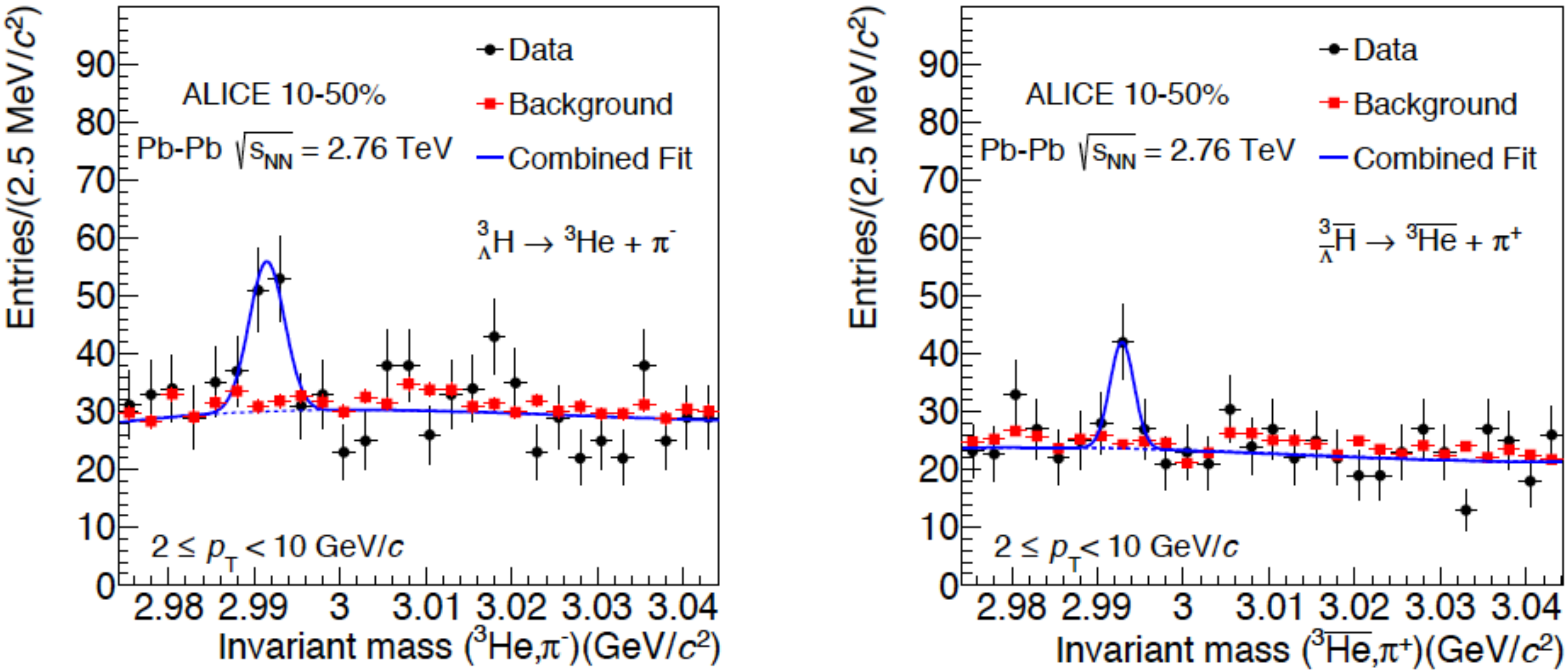
+ anti-particles

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

Science 328,58 (2010)

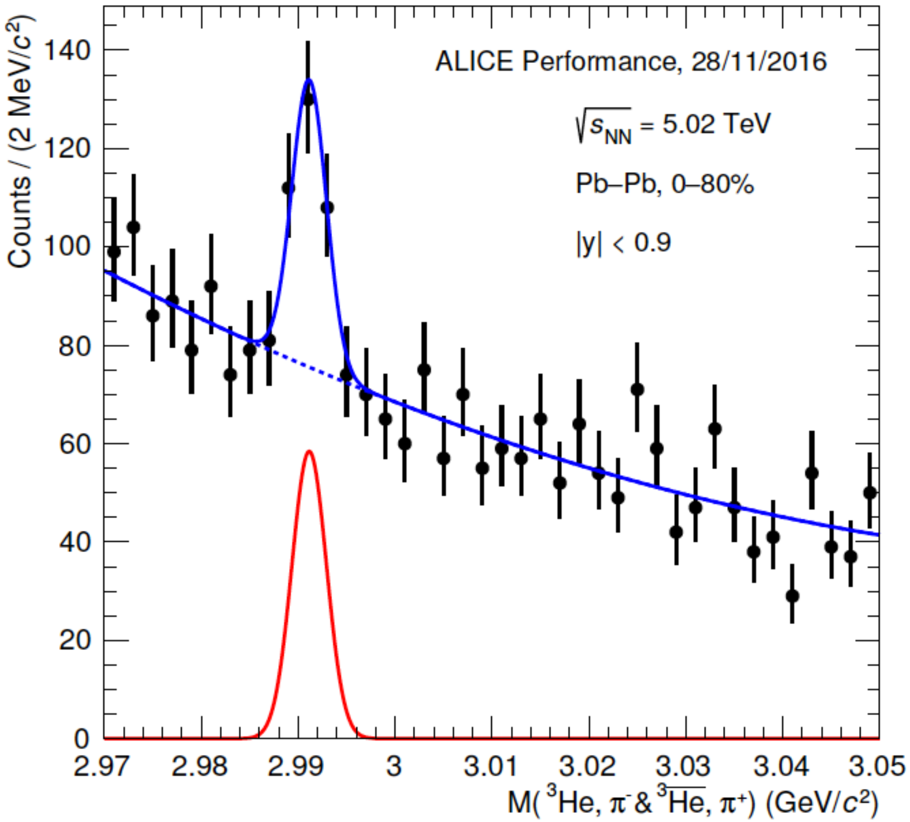
Hypertriton signal

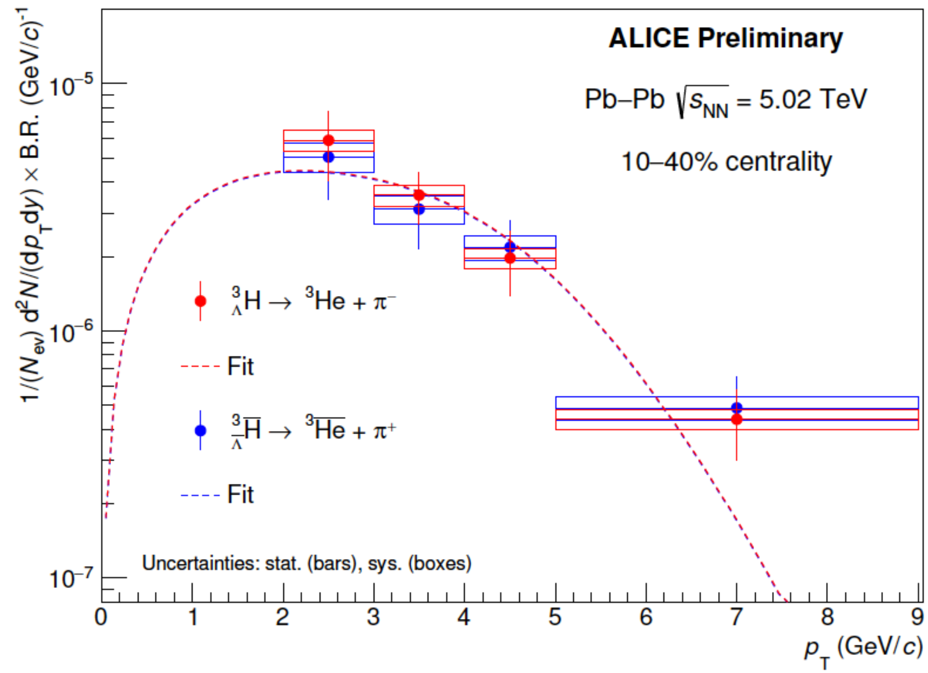
ALICE Collaboration: PLB 754, 360 (2016)



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

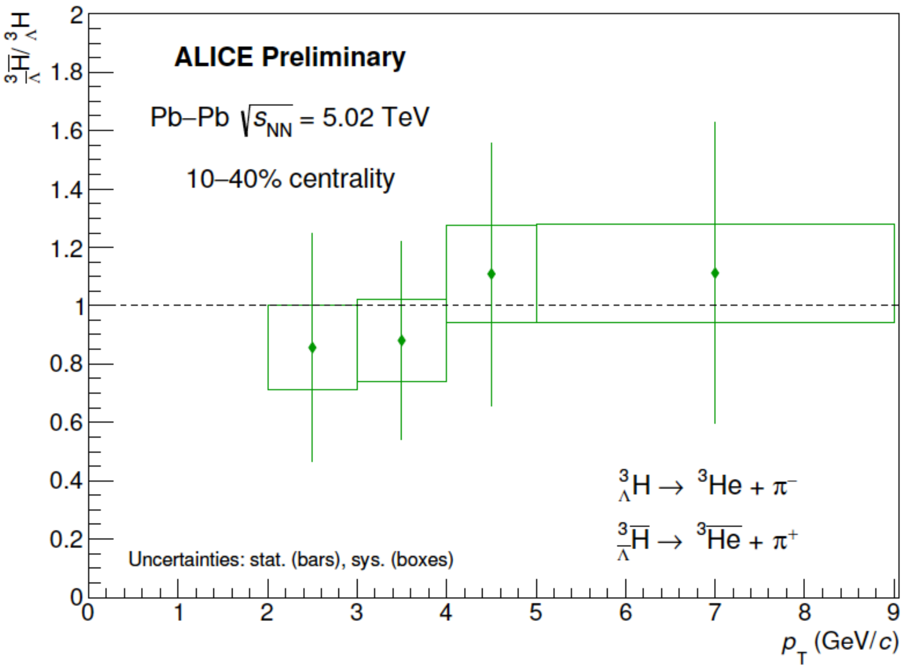
Hypertriton signal

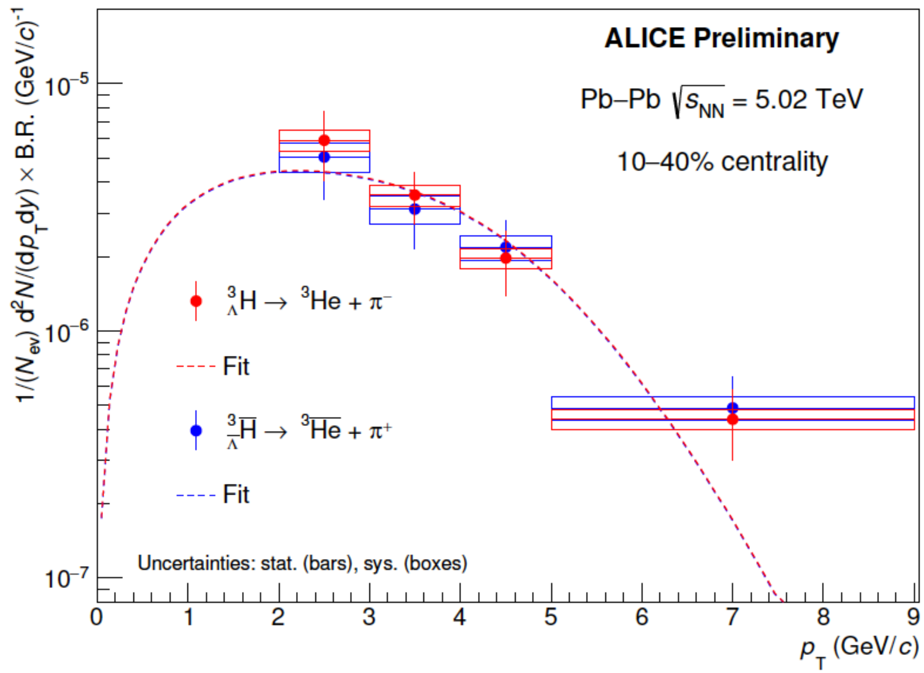




- Peaks are also clearly visible for particle and anti-particle
  - → Extracted yields in 4 p_T bins and 3 centrality classes

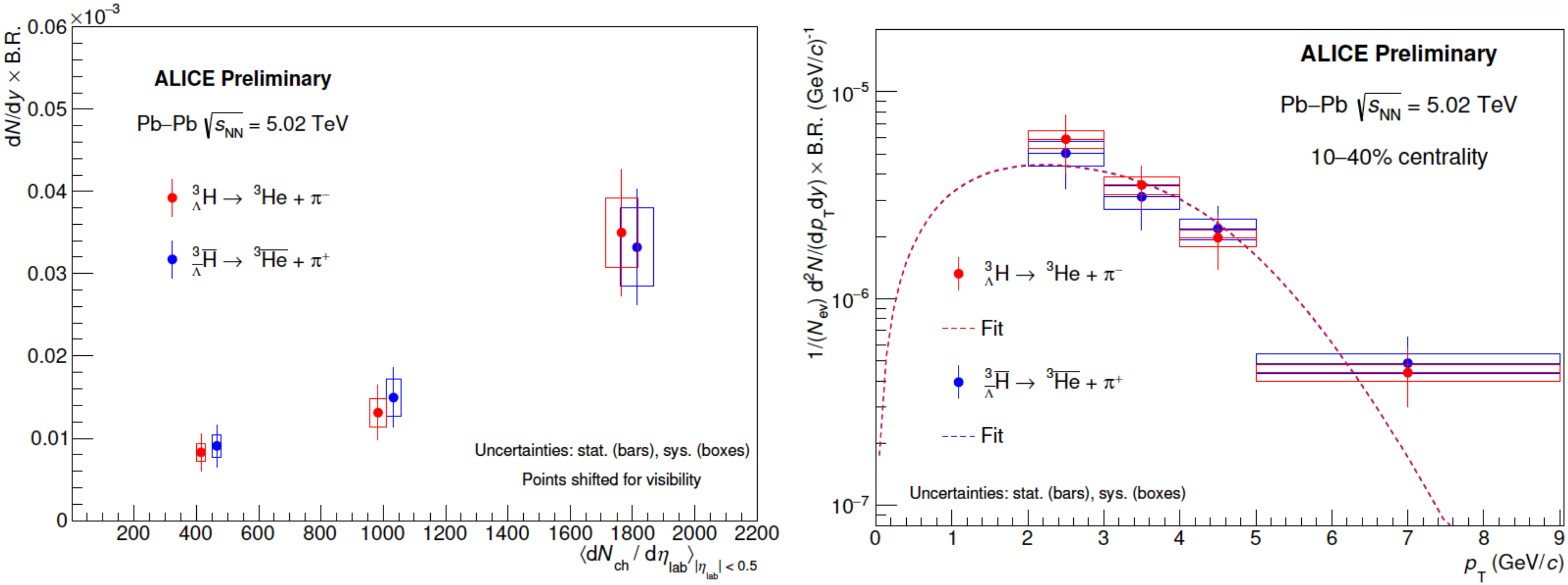
Hypertriton spectra





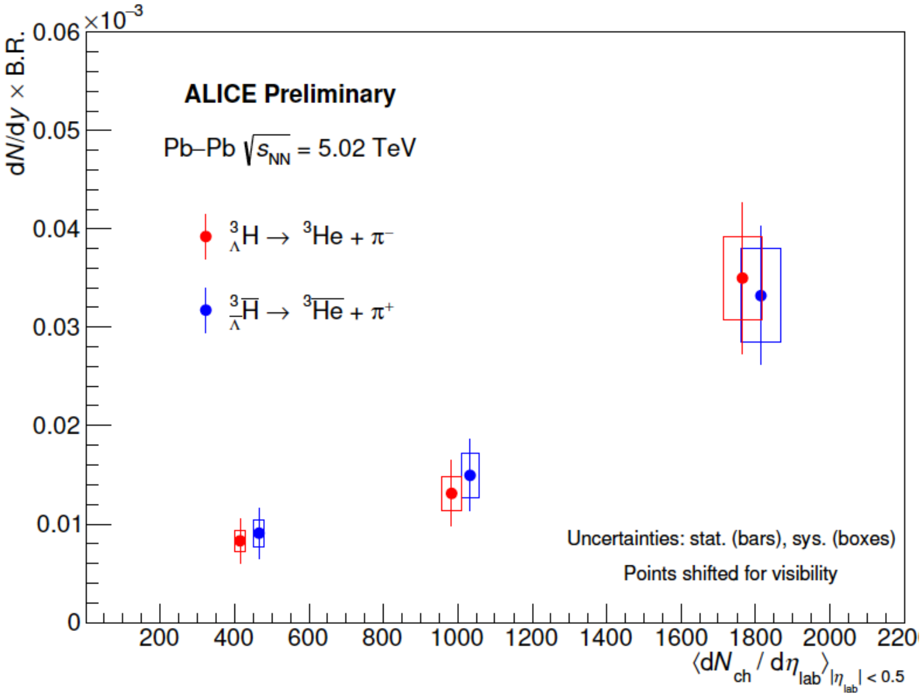
- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

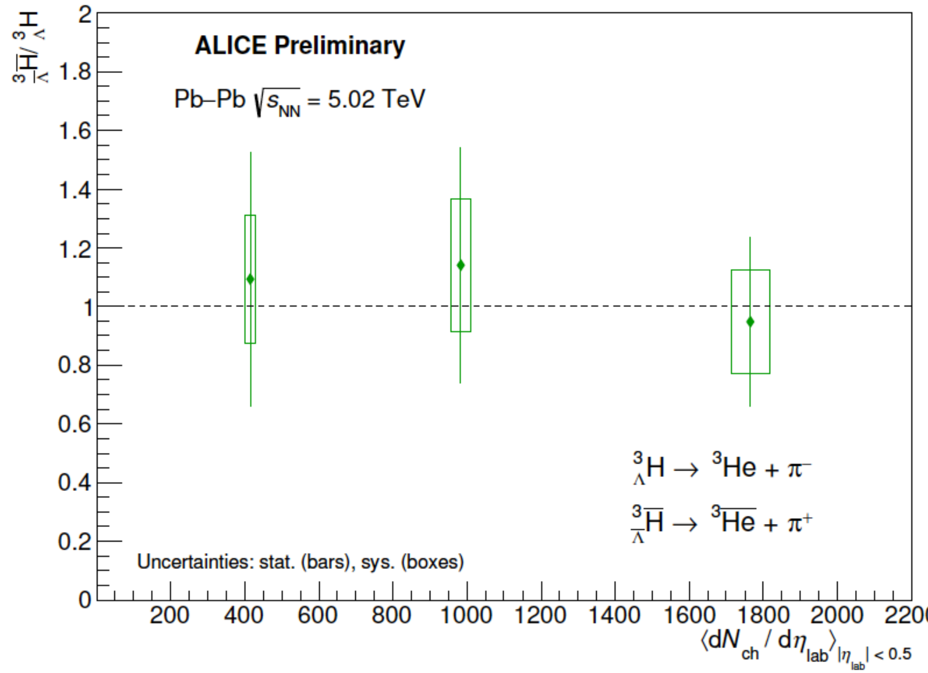
Hypertriton yield



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

Hypertriton yield

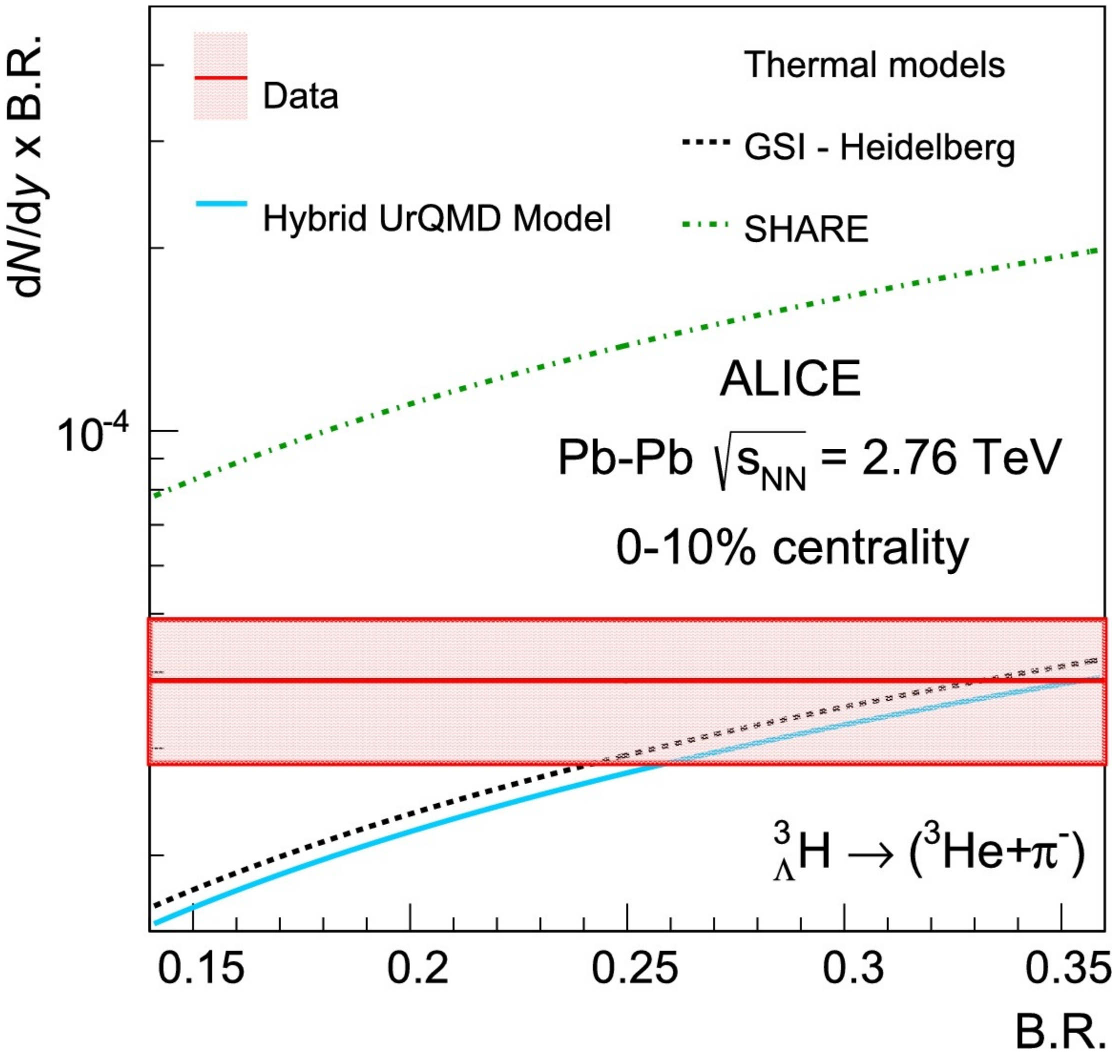




- Production in 3 centrality classes shows increase of prodcution probability with increasing multiplicity
- Ratio between anti-hypertriton-to-hypertriton unity for all centralities

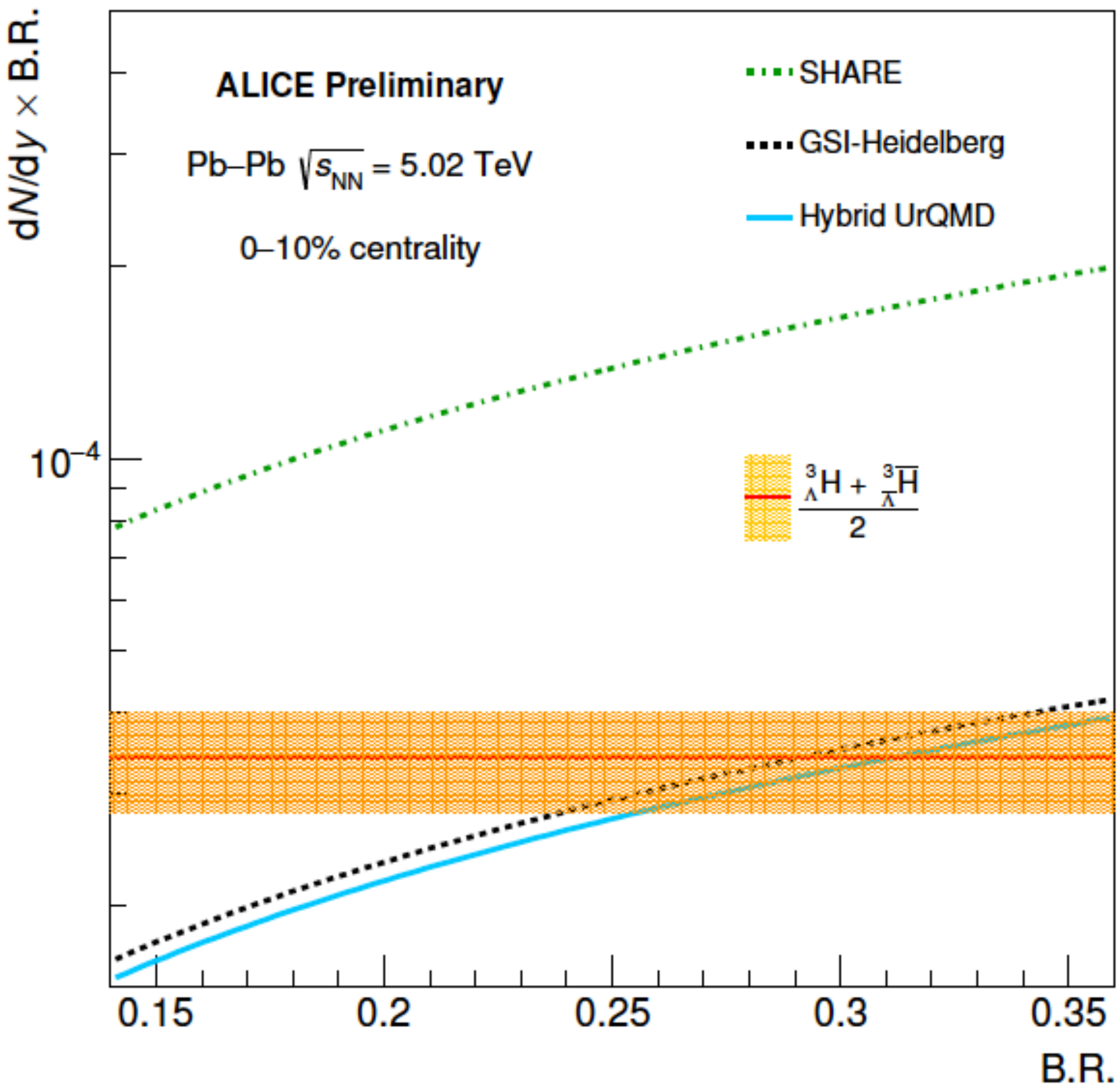
Hypertriton yield vs. B.R.

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.

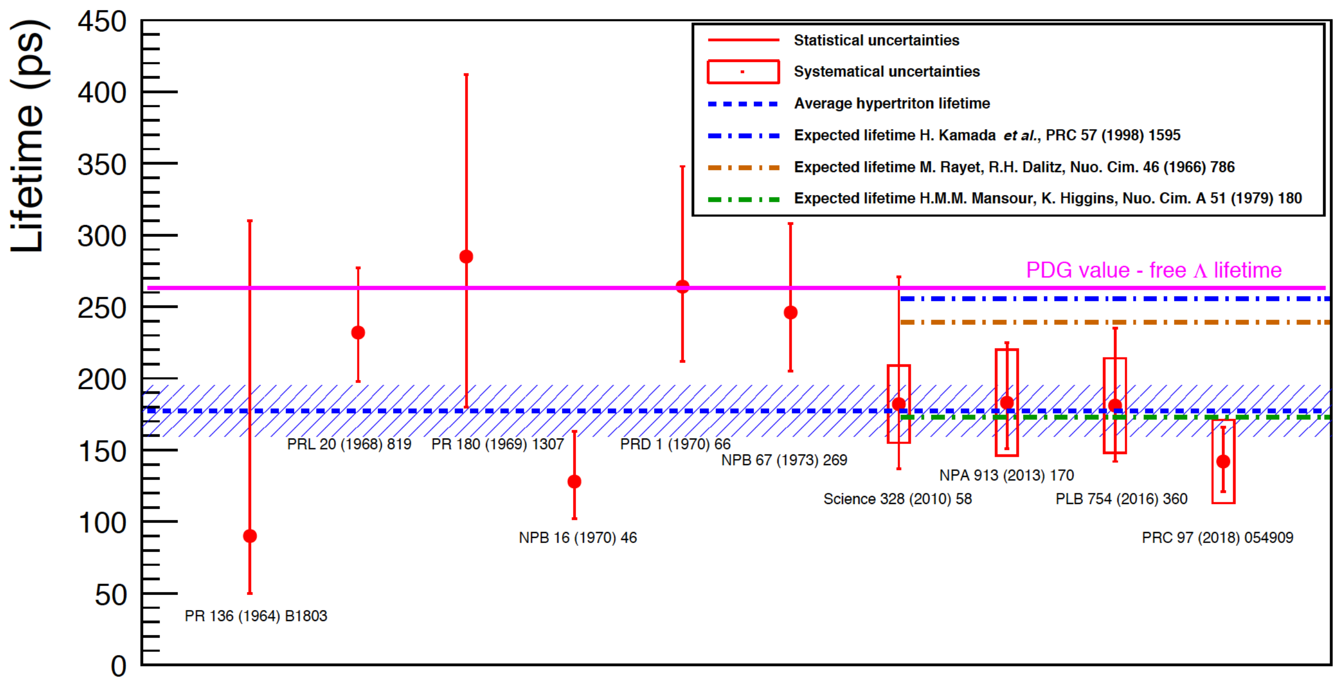


- The hypertriton branching ratio is not well known, only constrained by the ratio between all charged channels containing a pion
- Theory which prefers a value of around 25% gives a lifetime of the hypertriton close to the one of the free Λ

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