PRODUCTION OF BARYONS, BOUND BARYON SYSTEMS AND EXOTICA WITH ALICE AT THE LHC

Stefano Piano on behalf of ALICE Collaboration
INFN sez. Trieste

MOTIVATION

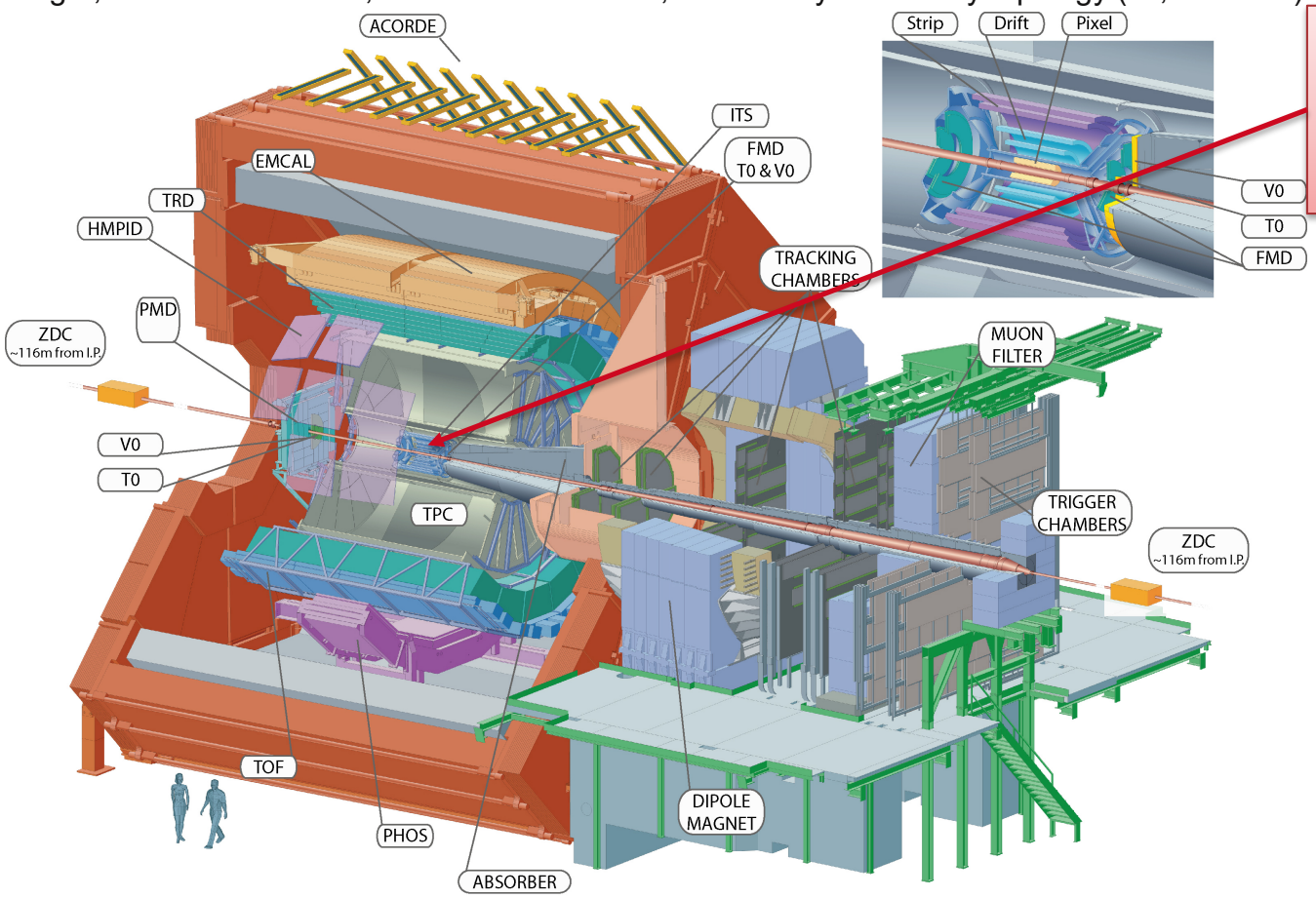
- **LF baryon production is a probe of hadronization and test of non-pertubative QCD models**
- **(anti-)(hyper-)nuclei are good probes of the coalescence mechanism**
- **(anti-)(hyper-)nuclei yields are sensitive to the freeze-out temperature in heavy-ion collision** due to their large mass (e.g. in the thermal model yield scales roughly $\propto e^{(-M/T_{chem})}$)
- light (anti-)(hyper-)nuclei have small binding energies and small Λ separation energies,

  e.g. $B_\Lambda(^3_\Lambda H) = 0.13 \pm 0.05$ MeV [H. Bando et al., Int. J. Mod. Phys. A 5 4021 (1990)] :
  - **they should dissociate in a medium with high T_{chem}** (~156 MeV) and be suppressed
  - if their yields equal to thermal model prediction ⇒ sign for **adiabatic (isentropic) expansion** in the hadronic phase
- Anti-nuclei in nature:
  - **matter–antimatter asymmetry**

    [J.Adam et al. (ALICE Collaboration), Nature Phys. 11, no.10, 811 (2015)]
  - light nuclei measurements in high-energy physics can be used in dark matter searches to estimate the background coming from the secondary anti-nuclei [K. Blum et al., Phys. Rev. D 96(2017)103021]
- Femtoscopy: analyses of two-baryon correlations allow to probe the strong interaction
  - Test of theoretical models and direct implications for neutron stars

A LARGE ION COLLIDER EXPERIMENT

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: d*E*/d*x*, time-of-flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V^0, cascade)



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

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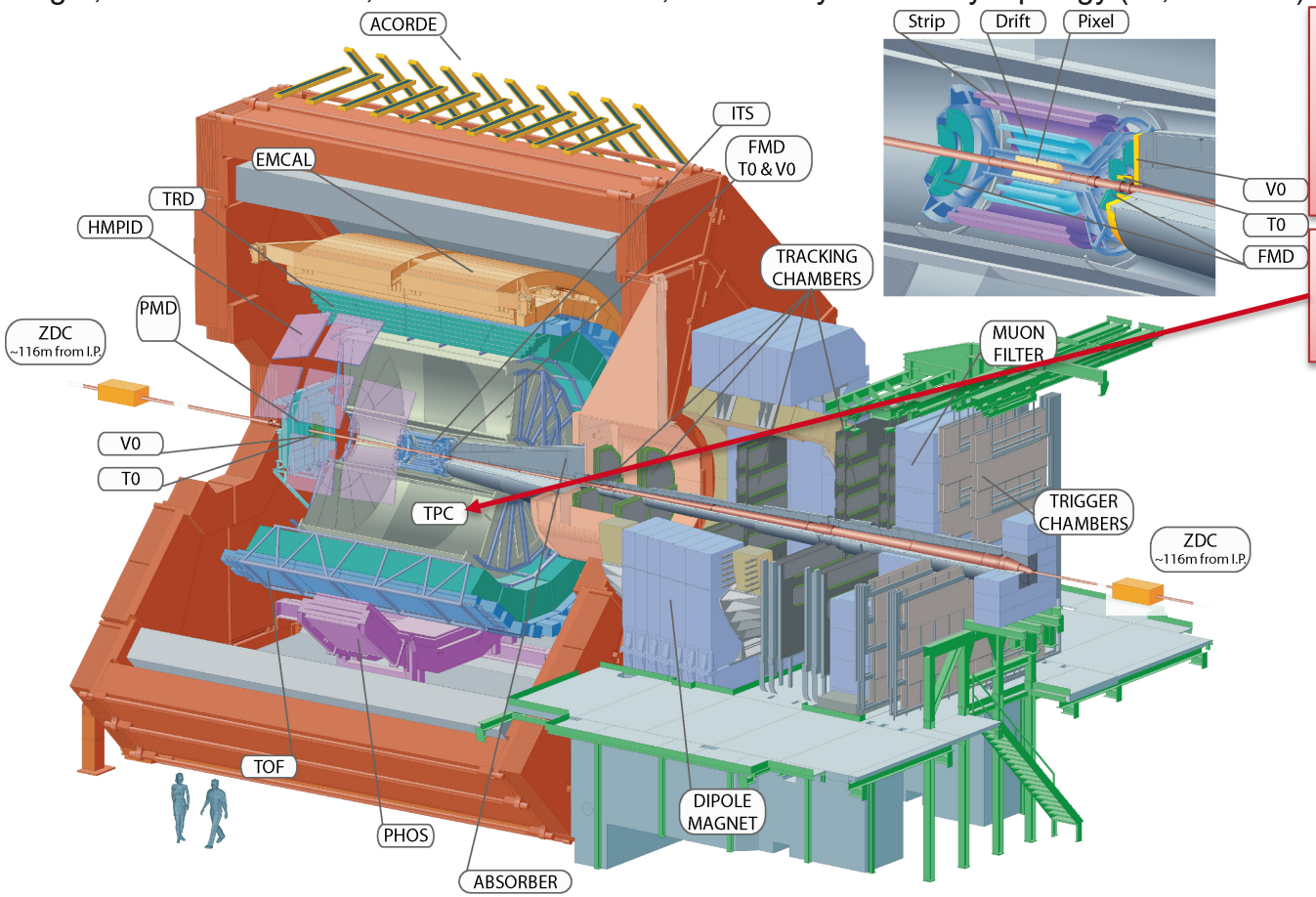

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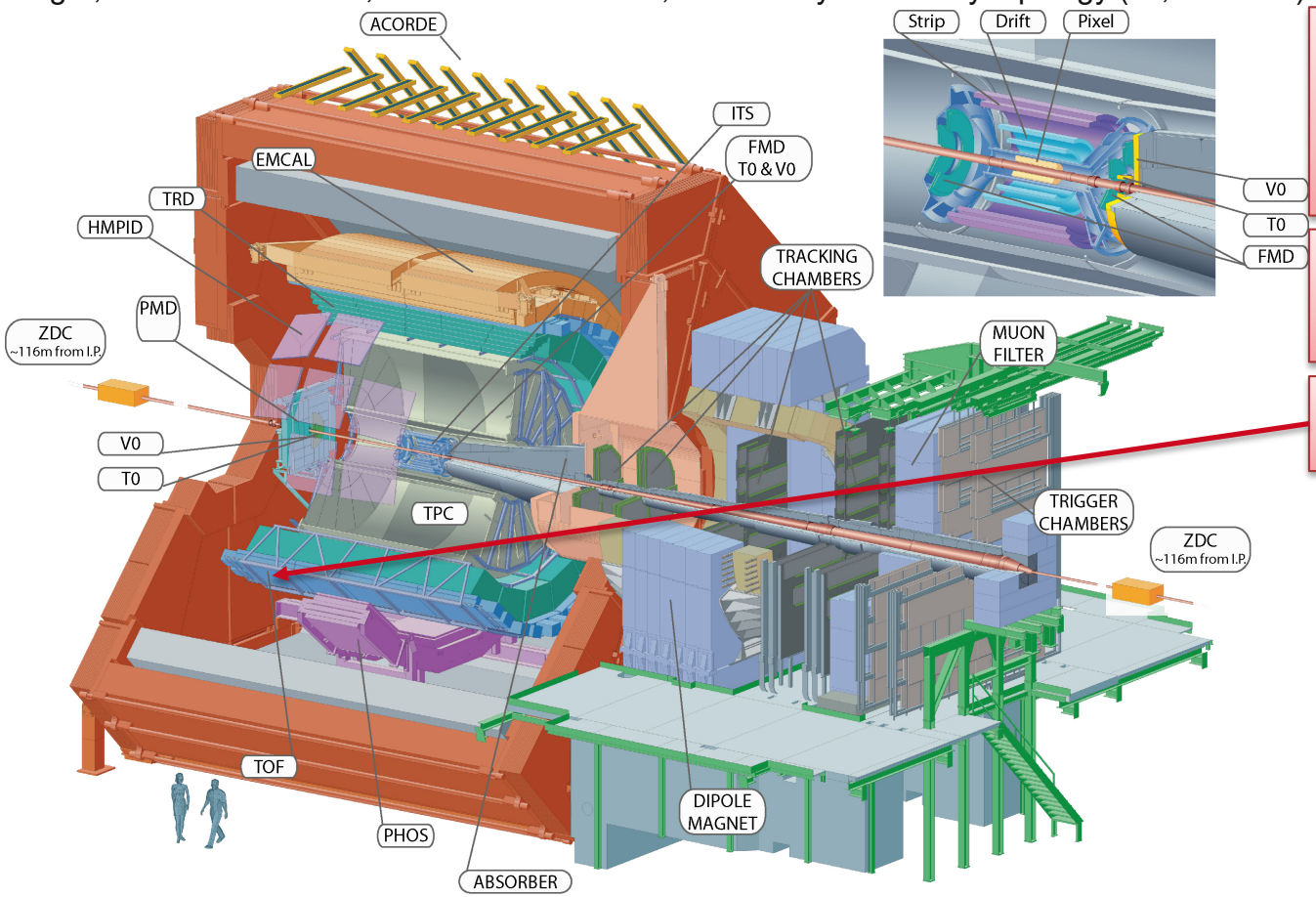

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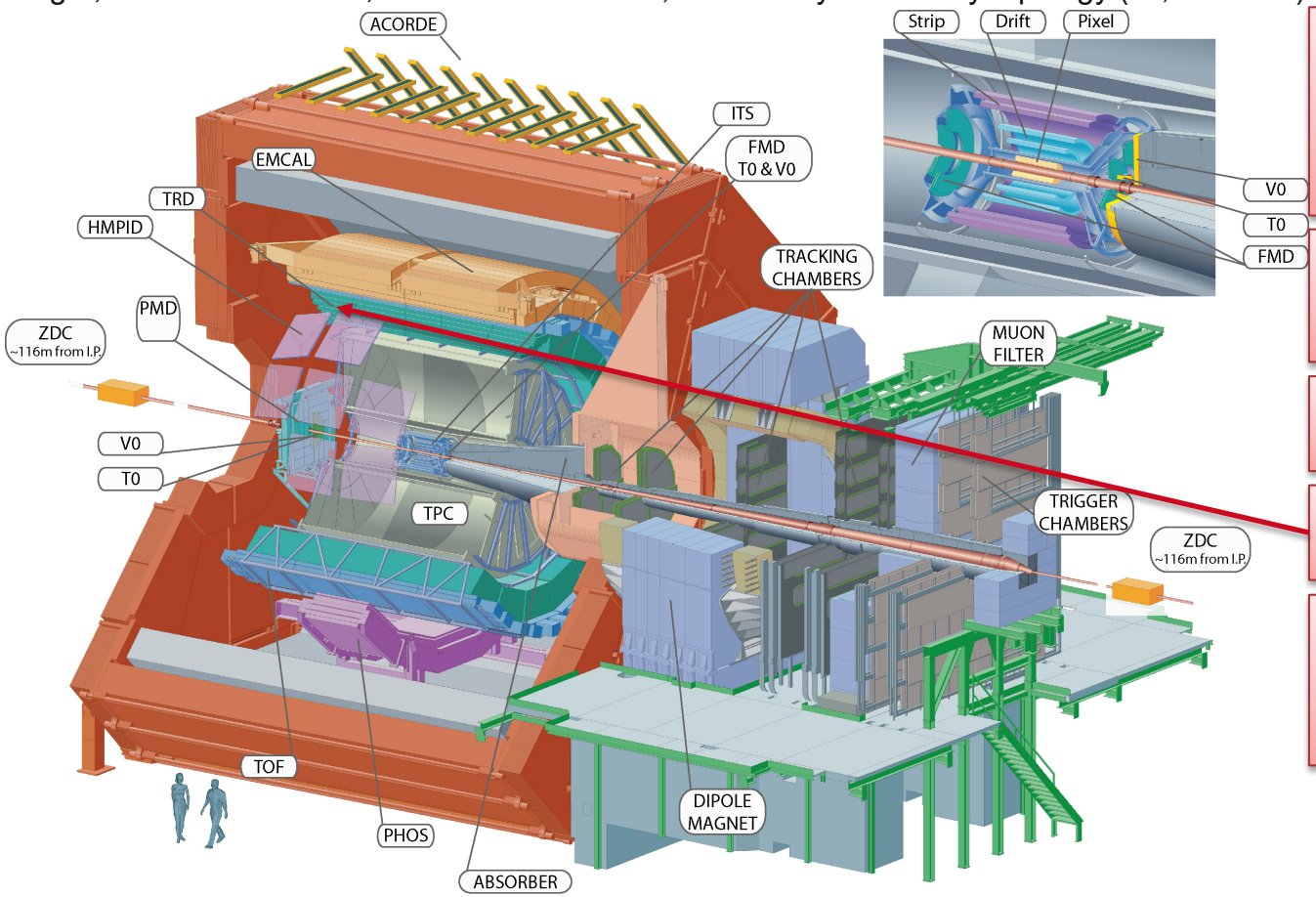

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ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment

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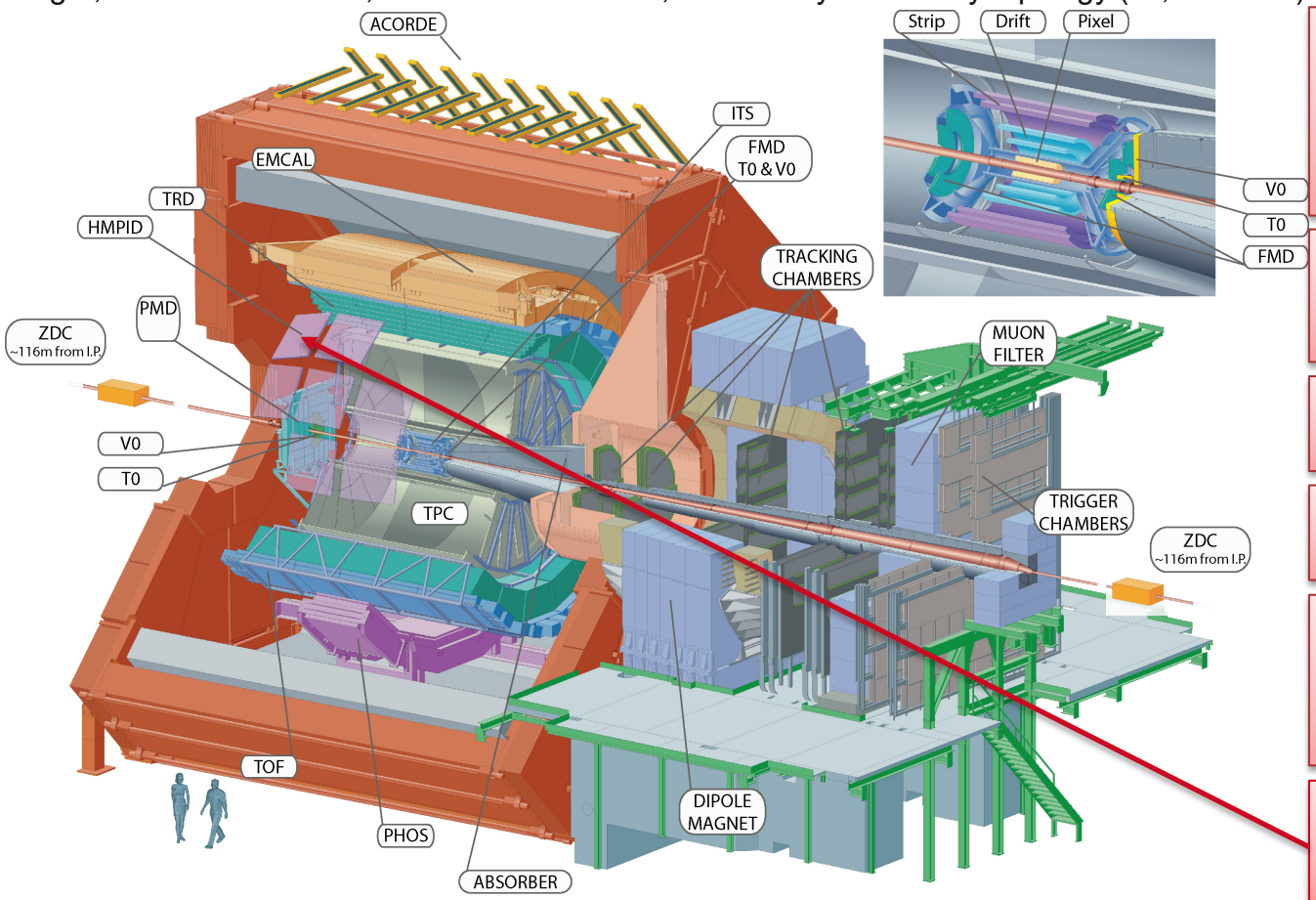

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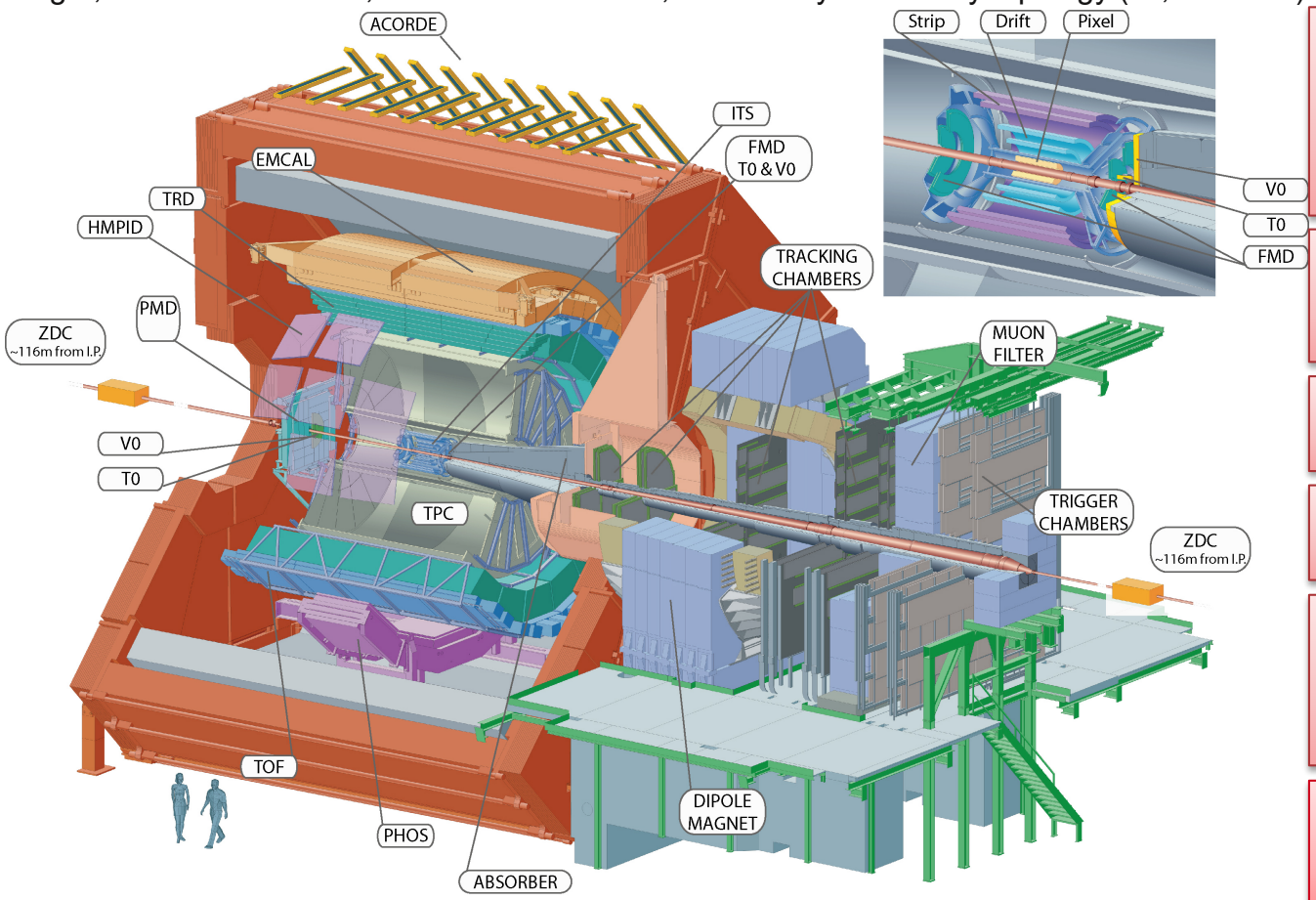

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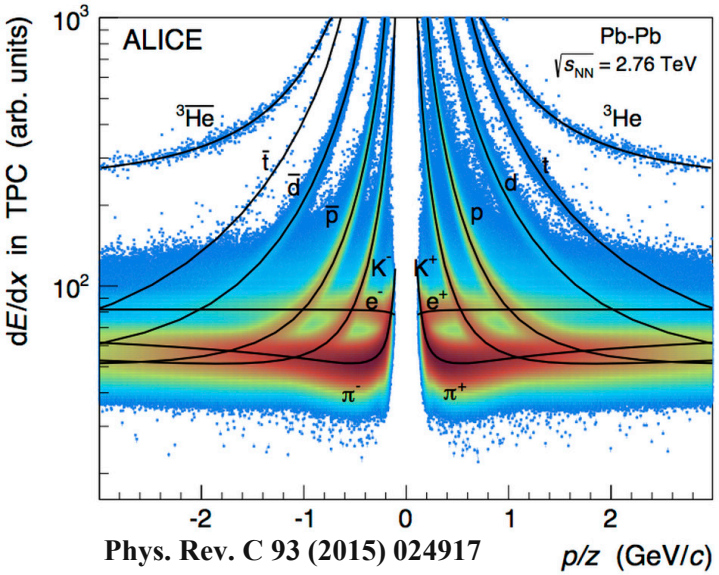
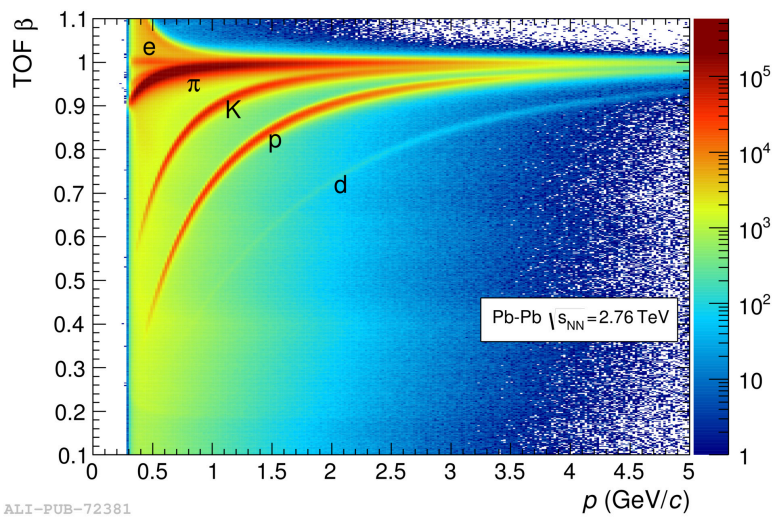
ALICE is ideally suited for the identification of (anti-) baryons and light (anti-)(hyper)nuclei

PARTICLES AND NUCLEI IDENTIFICATION



Phys. Rev. C 93 (2015) 024917



Low momenta

Identification via d*E*/d*x* measurement in the TPC:

- d*E*/d*x* resolution in central Pb-Pb collisions: ~6.5%
- Excellent separation of (anti-)nuclei from other particles over a wide momentum range
- About **10 anti-alpha candidates** identified out of 23×10^6 events by combining TPC and TOF particle identification

Higher momenta

Excellent TOF performance:

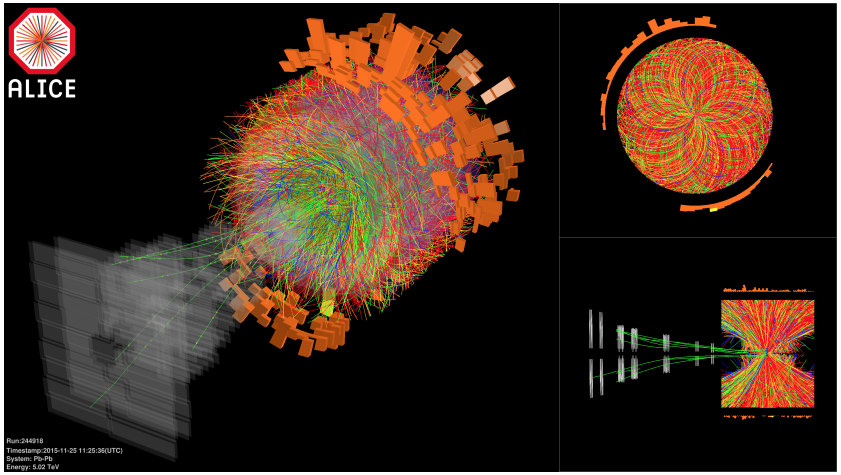
- $\sigma_{TOF} \approx 85$ ps in Pb-Pb collisions allows identification of light nuclei over a wide momentum range
- Velocity measurement with the TOF detector is used to evaluate the m^2 distribution and to subtract background from the signal in each p_T-bin by fitting the m^2 distribution

ALICE AT WORK SINCE 2009

pp, p-Pb, Pb-Pb and Xe-Xe collisions

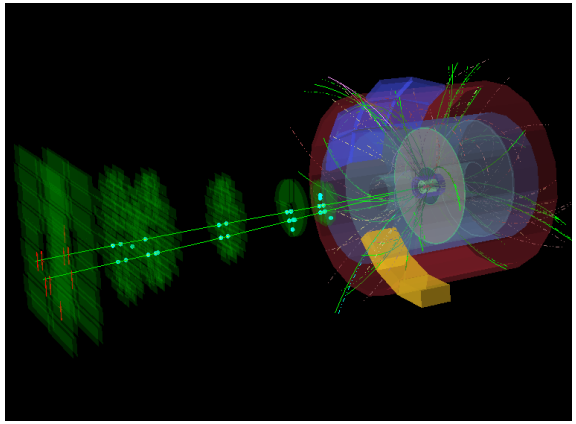
Energy and system dependence studies of particle production

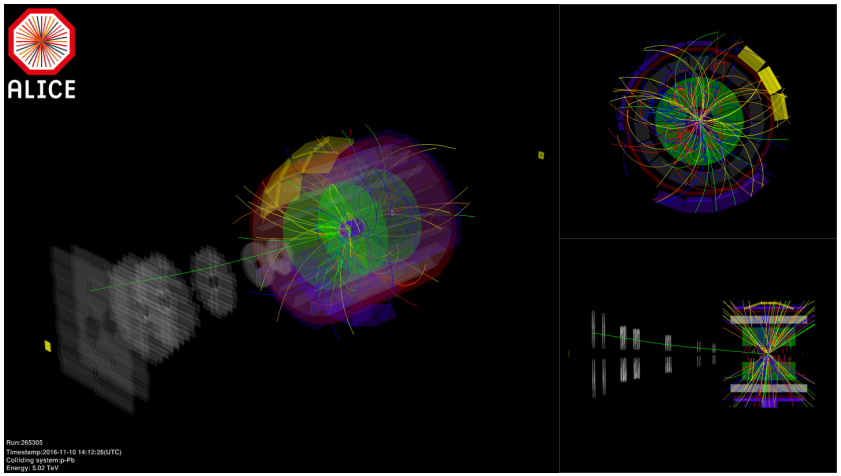
System	Year	√sNN (TeV)	L_{int}
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} ~1 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} , ~25 pb^{-1}



Large statistics of pp, p-Pb and Pb-Pb collisions at the same $\sqrt{s_{NN}}$

precise comparison studies



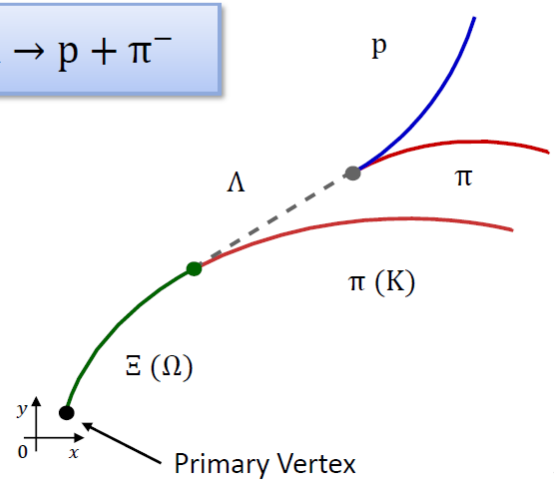


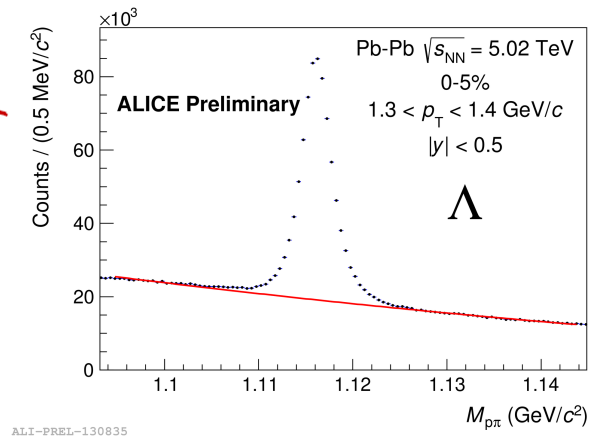
STRANGE BARYON PRODUCTION

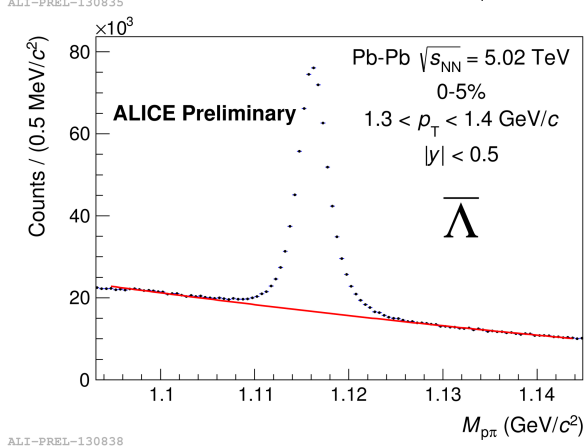
$\Xi^- \rightarrow \Lambda + \pi^-$

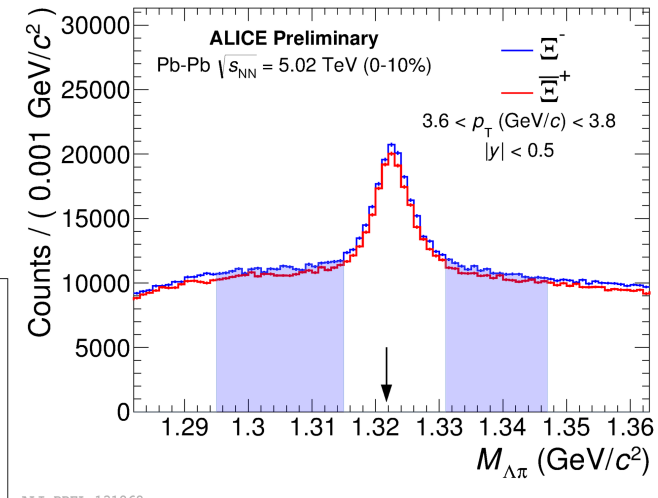
$\Omega^- \rightarrow \Lambda + K^-$

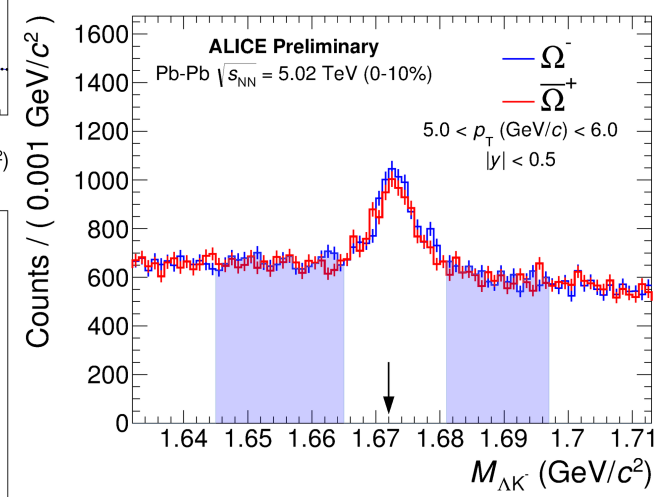
$\Lambda \rightarrow p + \pi^-$









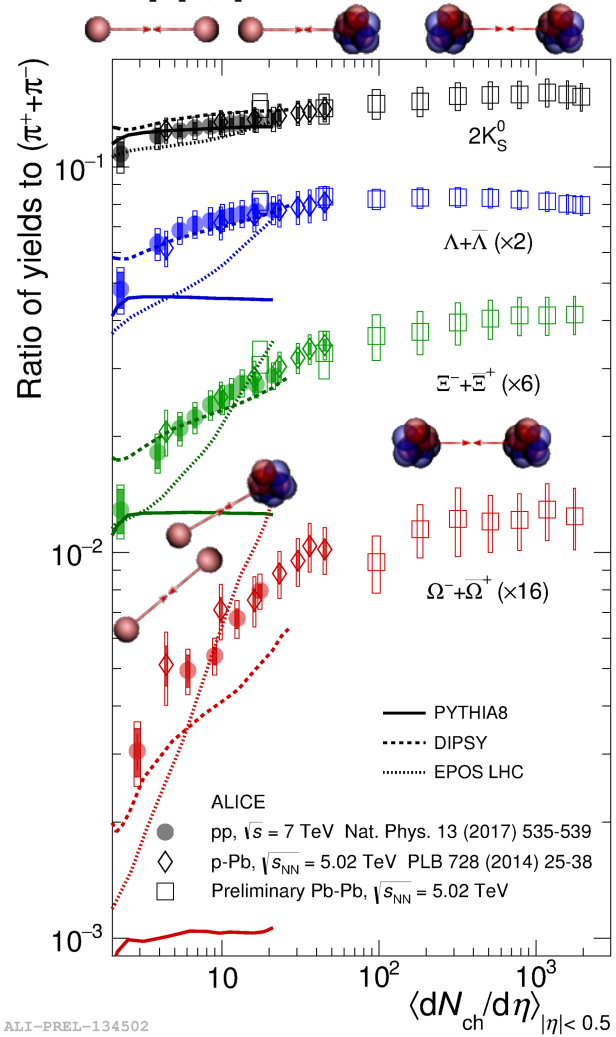


The antiparticle/particle production yields are identical within uncertainities, consistent with a vanishing baryochemical potential μ_B at LHC energies ⇒ possible to study particle and anti-particles together

Statistics allow to study the p_T and multiplicity dependence of baryon production

RELATIVE STRANGENESS PRODUCTION

in pp, p-Pb and Pb-Pb



Historically a signature of the Quark-Gluon Plasma

(Rafelski & Mueller, PRL 48 (1982) 1066)

- Smooth evolution from pp to Pb-Pb
- Enhancement observed in A-A which increases with strangeness content
- Enhancement also seen in the smaller systems pp and p-Pb
- No significant energy and system dependence is observed at similar multiplicity
- Traditional soft-QCD models based on Multiple Parton Interactions (MPI), e.g. PYTHIA, are not able to reproduce the observed trends:
  - Breaks concept of universality and factorization of fragmentation [JHEP01(2017)140]
- MPI based models that embed also effects from densely packed strings (DIPSY) or core-corona hadronization mechanisms (EPOS) reproduce qualitatively the observed increasing trends for strange particles
- Further tuning needed to reproduce all ratios simultaneously (DIPSY overestimates p/π) (not shown)

PYTHIA 8: Comput. Phys. Commun. 178 (2008) 852867
EPOS LHC: PRC92 (2015) 034906
DIPSY: PRD92 (2015) 094010

ALICE, Nature Physics 13 (2017) 535

RELATIVE STRANGENESS PRODUCTION

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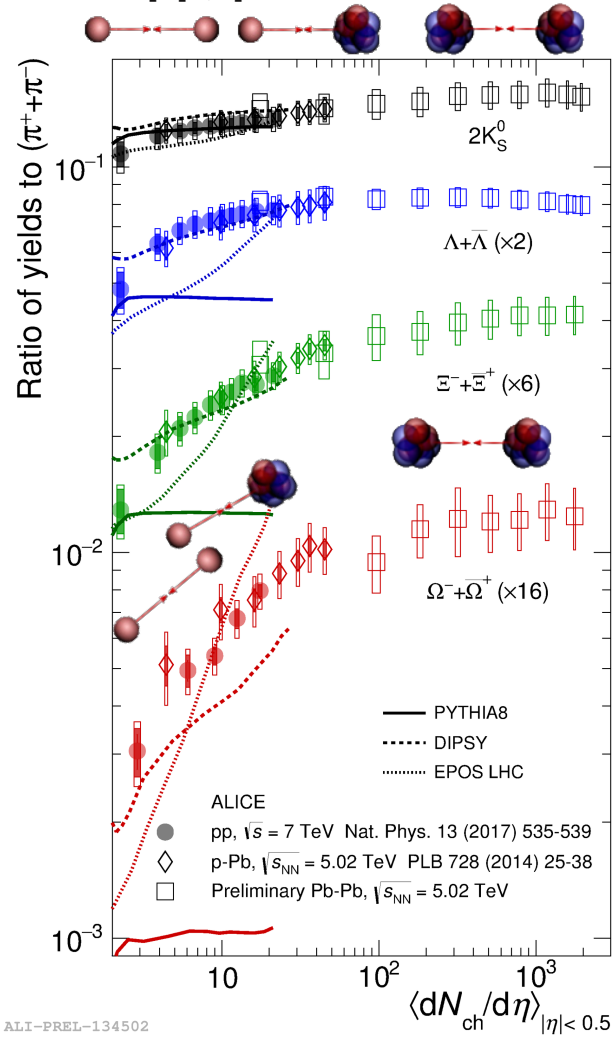
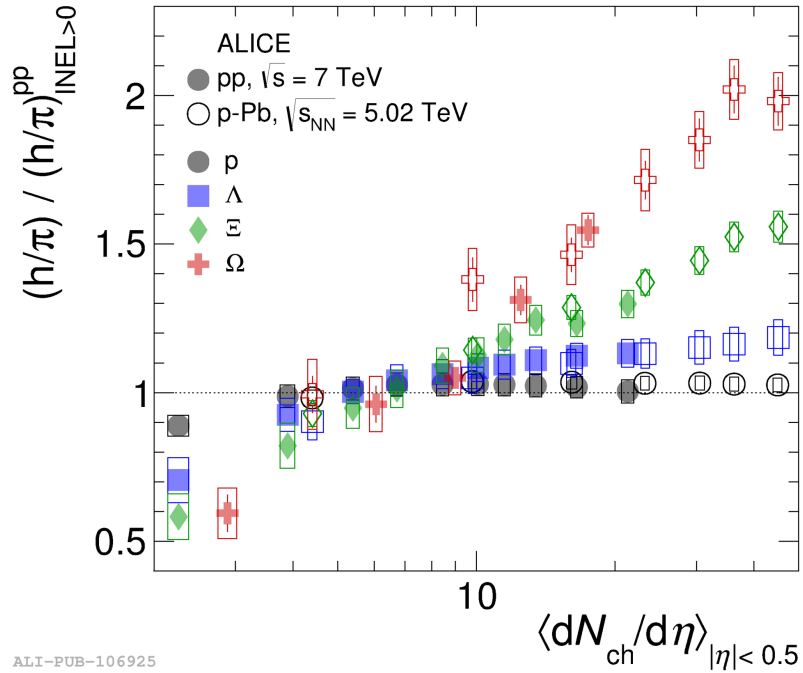




Hadrochemistry evolves smoothly with the final-state multiplicity of the collision.

Evolution is dramatic for strange particles:

the stranger, the steeper!

For proton (S=0) is consistent with unity up to highest $\langle dN_{ch}/d\eta \rangle$

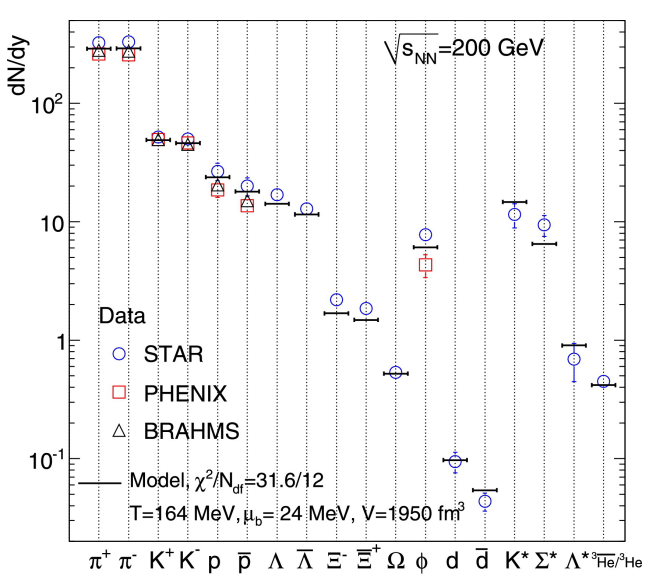
not a baryon effect !

ALICE, Nature Physics 13 (2017) 535

(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

Statistical Thermal model

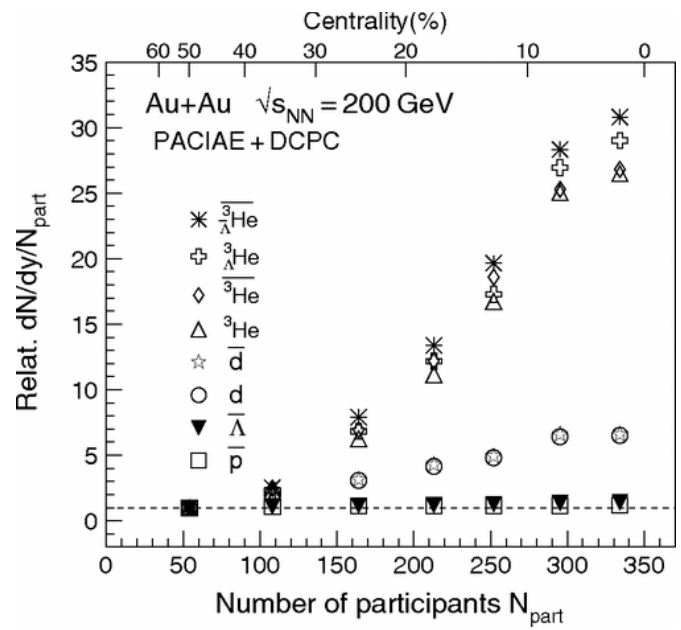
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem}) (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
- Exponential dependence of the yield $\propto e^{(-M/T_{chem})}$



A. Andronic et al., Phys. Lett. B 697, 203 (2011)

Coalescence

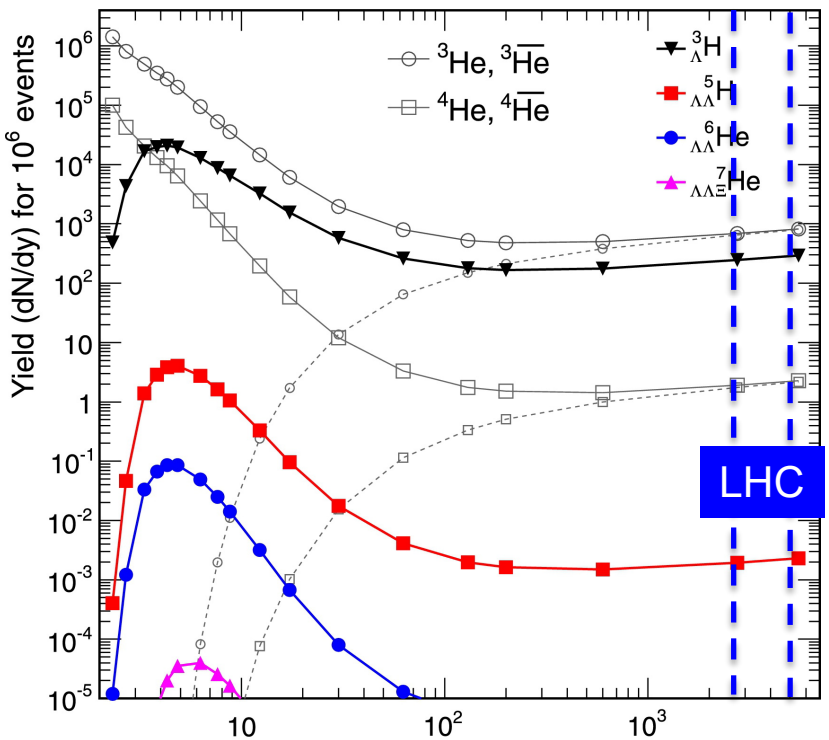
- If baryons at freeze-out are close enough in phase space an (anti-)(hyper-)nucleus can be formed
- (Hyper-)nuclei are formed by protons and neutrons (Λ) which have similar velocities after the freeze-out



G. Chen et al., Phys. Rev. C 88, 034908 (2013)

(ANTI-)(HYPER-)NUCLEI PRODUCTION AT LHC

Production yield estimate of (anti-)(hyper)nuclei in central heavy-ion collisions at LHC energy based on thermal model:



A. Andronic et al., Phys. Lett. B 697, 203 (2011)

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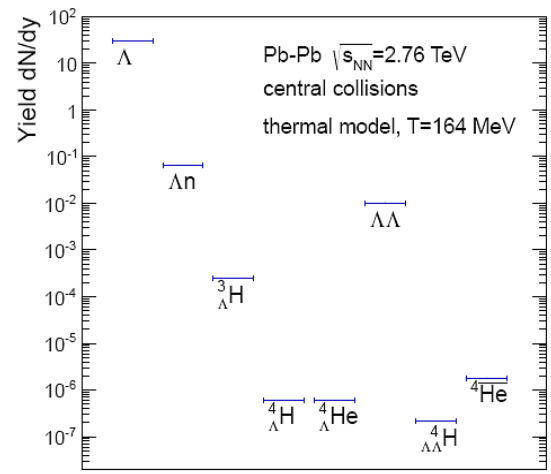
	Yield/event at mid-rapidity and central collisions
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

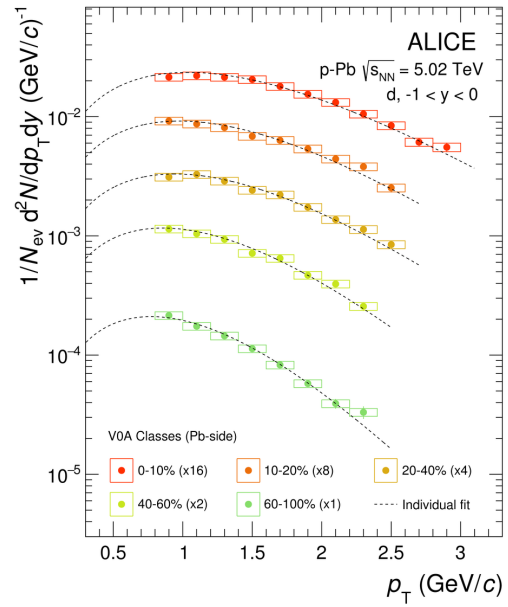
- ✓ Light nuclei
- ✓ Hypertriton
- ✓ Search for: Λn, ΛΛ dibaryons

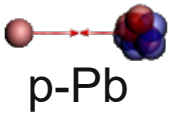


A. Andronic, private communication

DEUTERON p_T SPECTRA

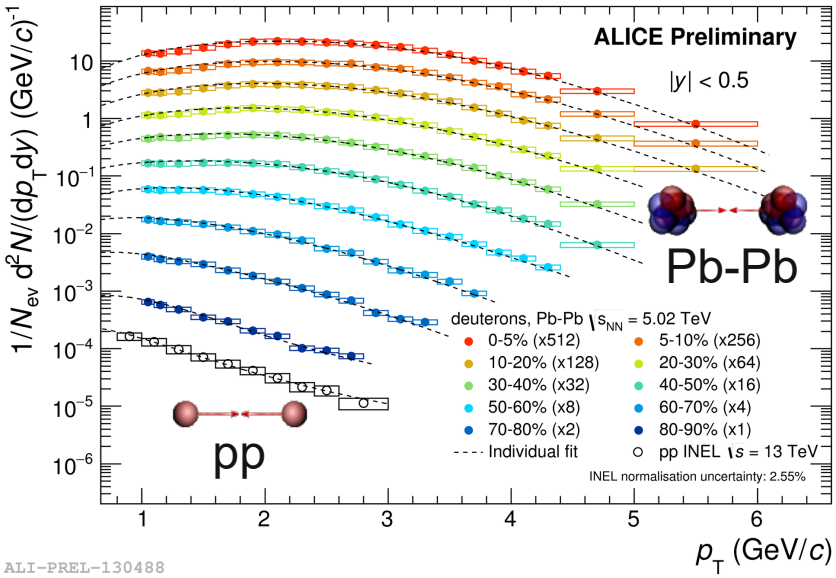
- Spectra become harder with increasing multiplicity in Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in Pb-Pb
- pp and p-Pb spectrum show no sign of radial flow





ALICE arXiv:1906.03136 [nucl-ex]

ALICE-PUBLIC-2017-006



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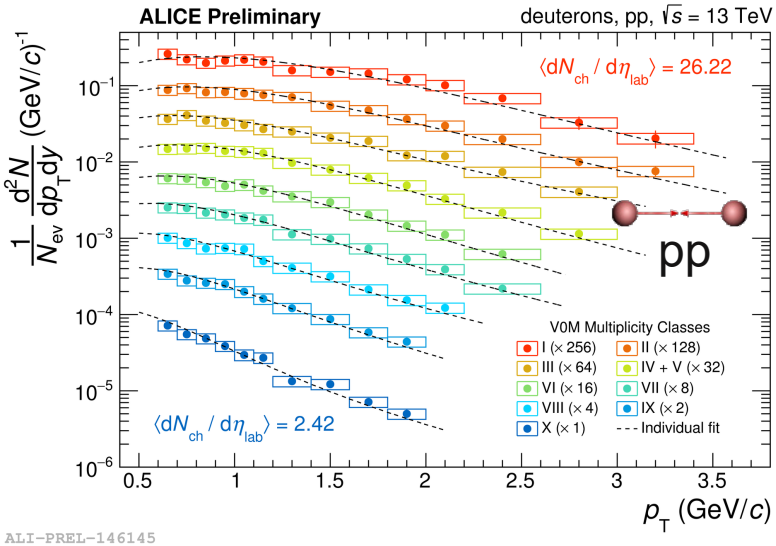
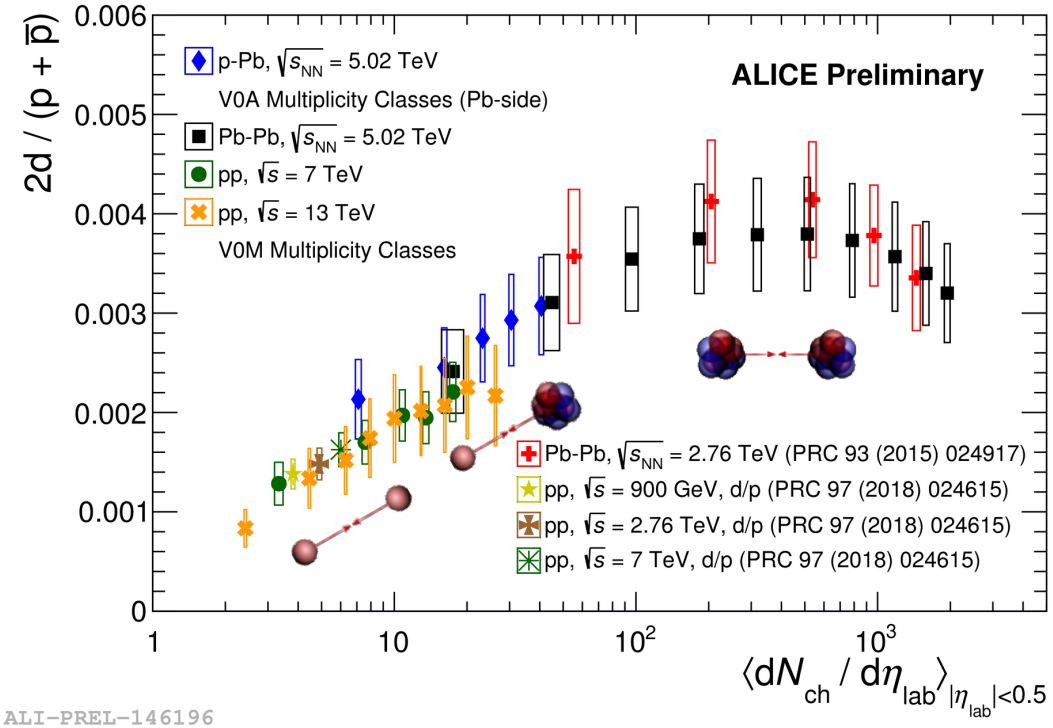


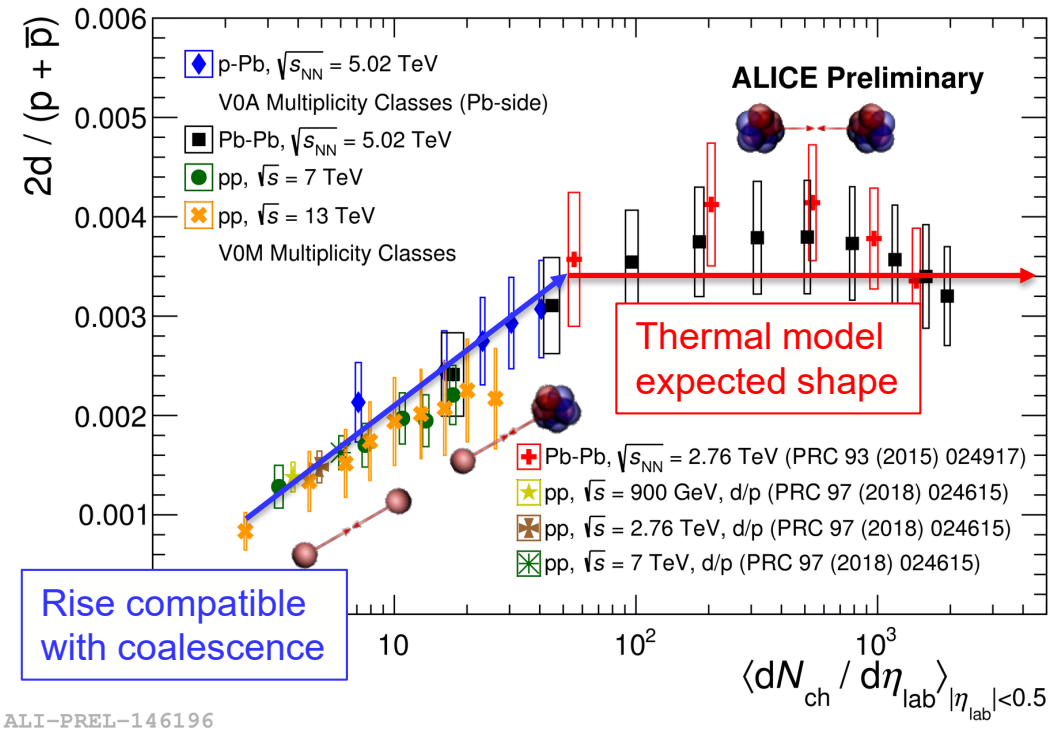
ALI-PREL-146145

DEUTERON TO PROTON RATIO



- No significant centrality dependence in Pb-Pb
- Ratio in pp collisions is a factor 2.5 lower than in Pb-Pb collisions
- d/p ratio increases when going from pp to p-Pb and peripheral Pb-Pb, until it reaches the grand canonical thermal model value (d/p ~ 3×10^{-3} at T_{ch}= 156 MeV)

DEUTERON TO PROTON RATIO



Simple coalescence works in small systems while thermal models describe better the Pb-Pb data

Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?

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COALESCENCE PARAMETER B_A

- If baryons at freeze-out are close enough in phase space (i.e. geometrically and in momentum) and match spin state, a (anti-)nucleus can be formed

- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space

- Assuming that p an n have the same mass and have the same p_T spectra:

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

- For A=2:

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

Measured deuteron p_T-spectra

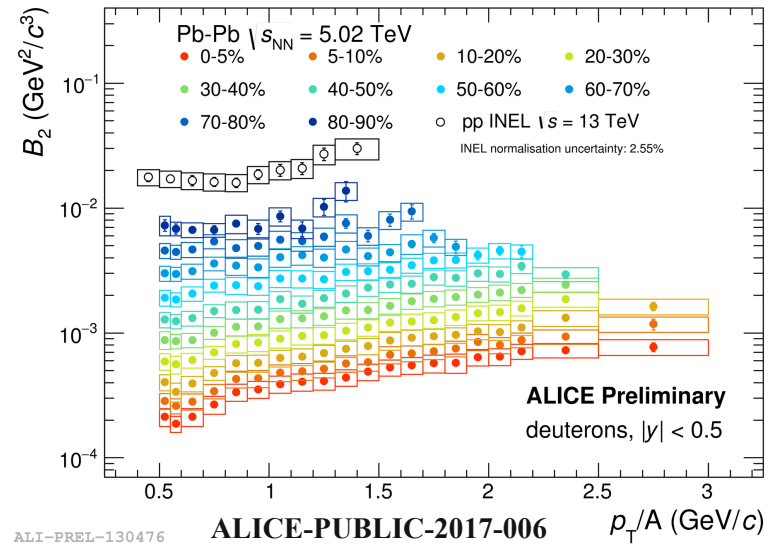
Measured proton p_T-spectra

COALESCENCE PARAMETER B_2

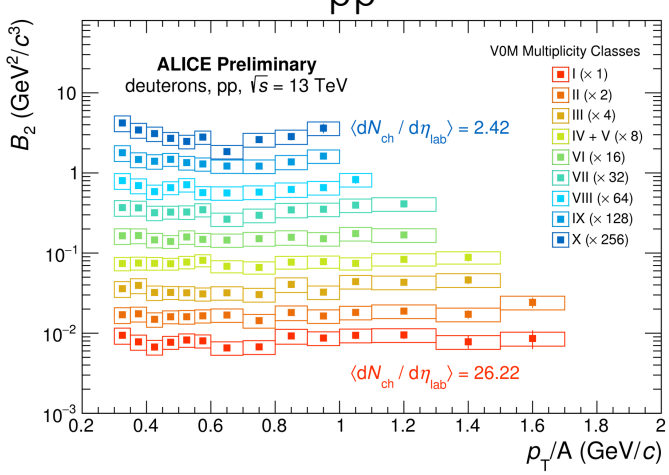
$$B_2 = E_d \frac{d^3N_d}{dp_d^3}\left(E_p \frac{d^3N_p}{dp_p^3}\right)^{-2}$$

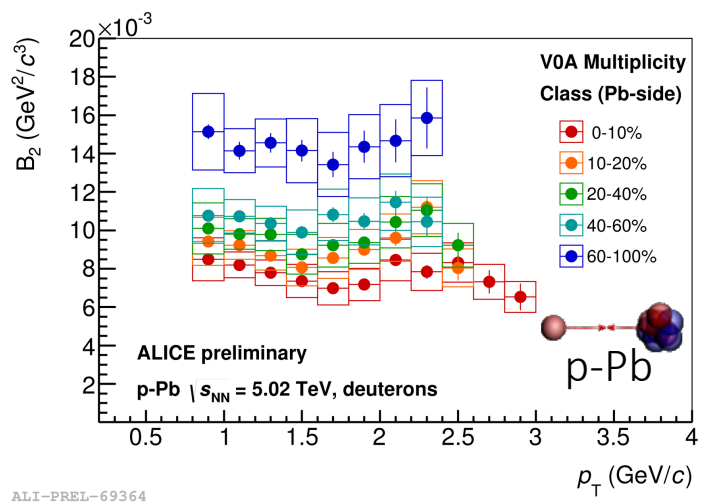
- Coalescence parameter B_2 decreases with centrality in Pb-Pb and increases with p_T
- Similar effect seen in p-Pb: decrease with multiplicity, but less pronounced
- Flat behavior for pp and no dependence on multiplicity

Pb-Pb



pp





p-Pb

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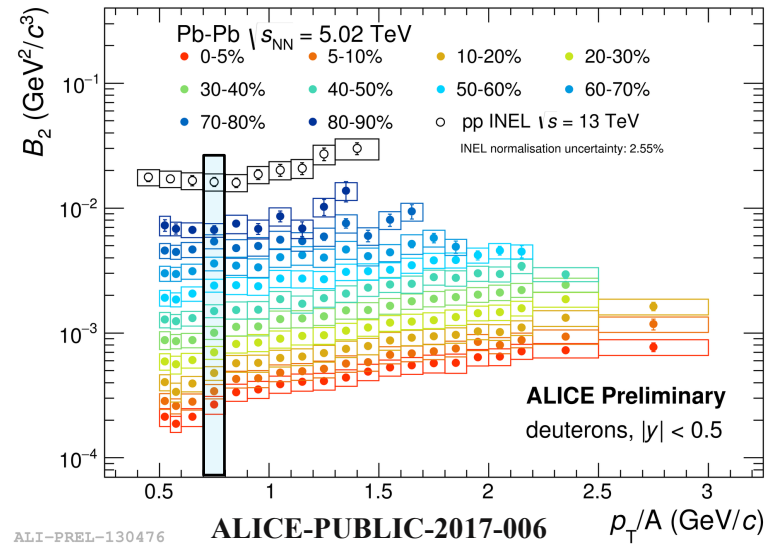
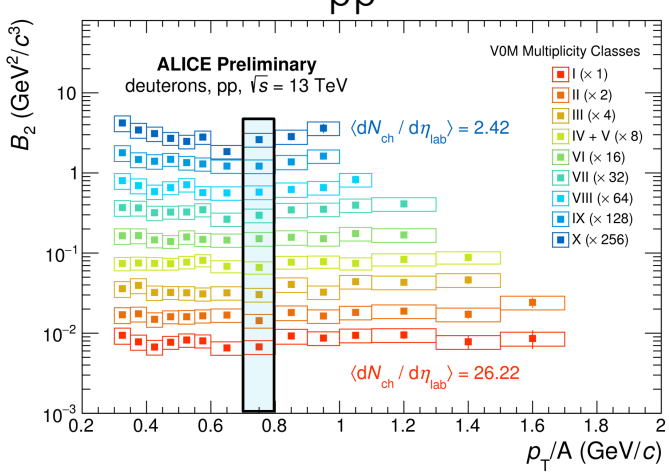
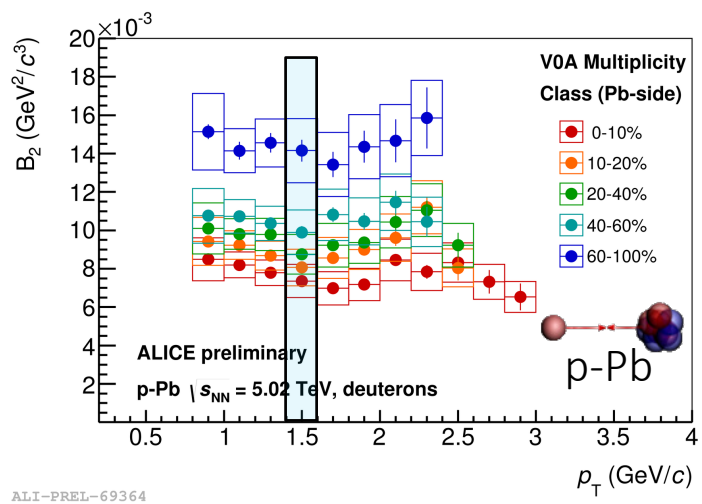


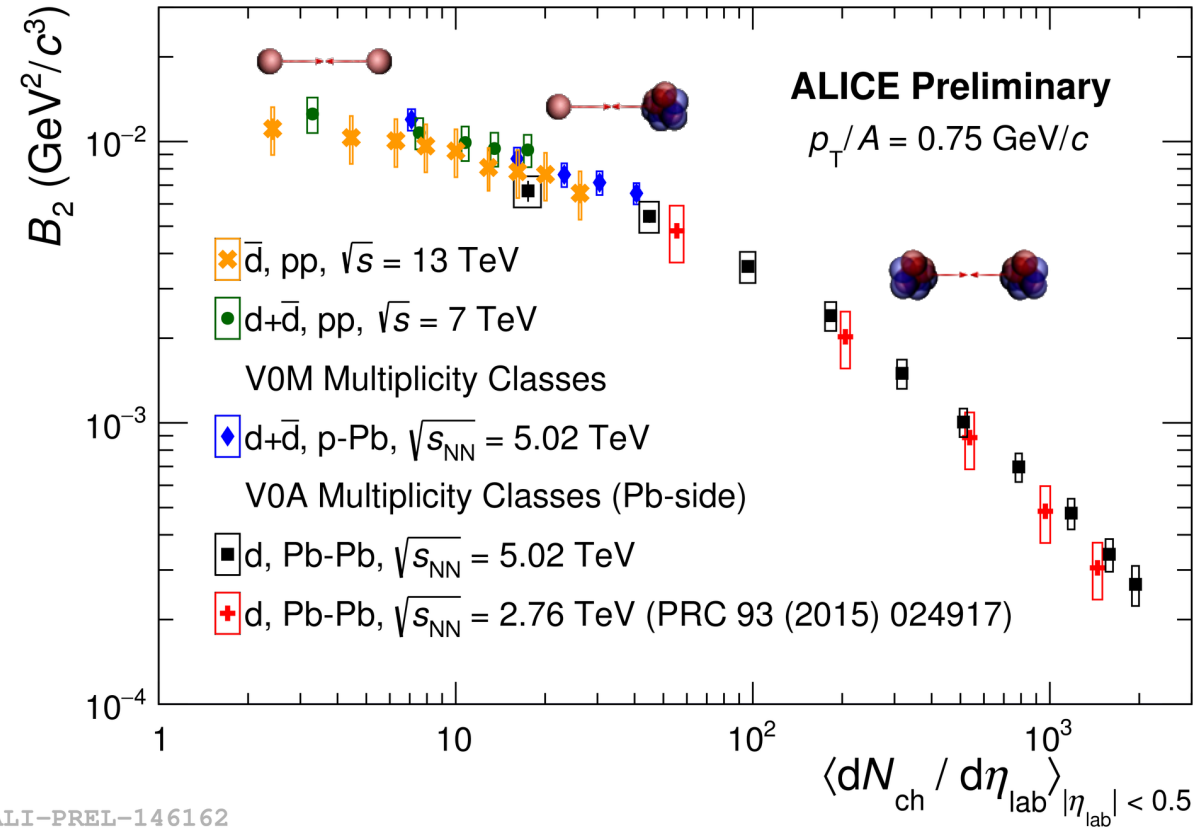
pp





$p_T/A = 0.75$ GeV/c

COALESCENCE PARAMETER B_2



The coalescence parameter evolves smoothly as a function of multiplicity with no discontinuity between different colliding systems

Simple coalescence model:

- Flat B_2 vs p_T and no dependence on multiplicity/centrality
- Observed "small systems": pp, p-Pb and peripheral Pb-Pb

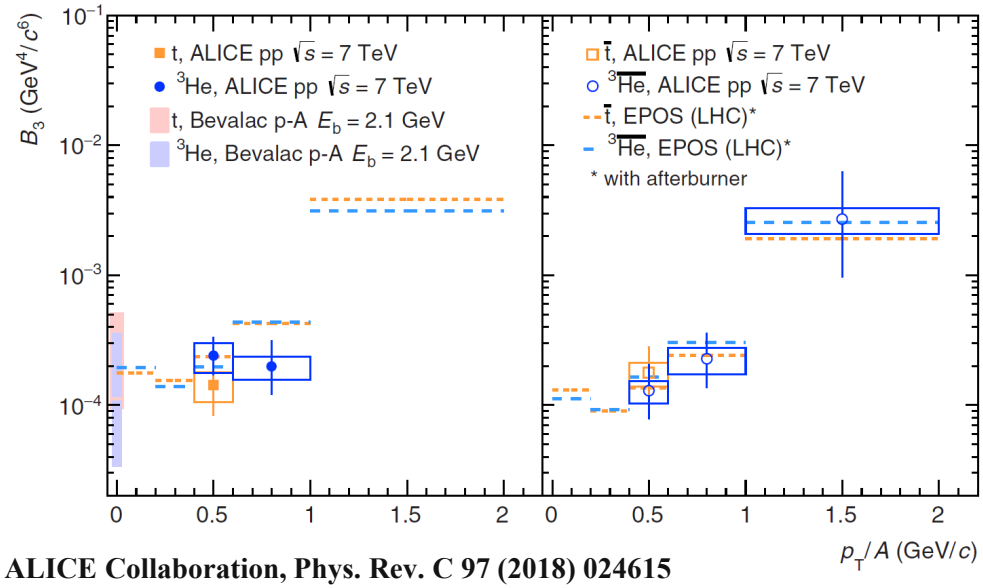
More elaborated coalescence model takes into account the volume of the source:

- B_2 scales like HBT radii (*)
- Decrease with centrality in Pb-Pb is explained as an increase in the source volume
- Increase with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume in HBT
- Qualitative agreement in central Pb-Pb collisions

(*) R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)

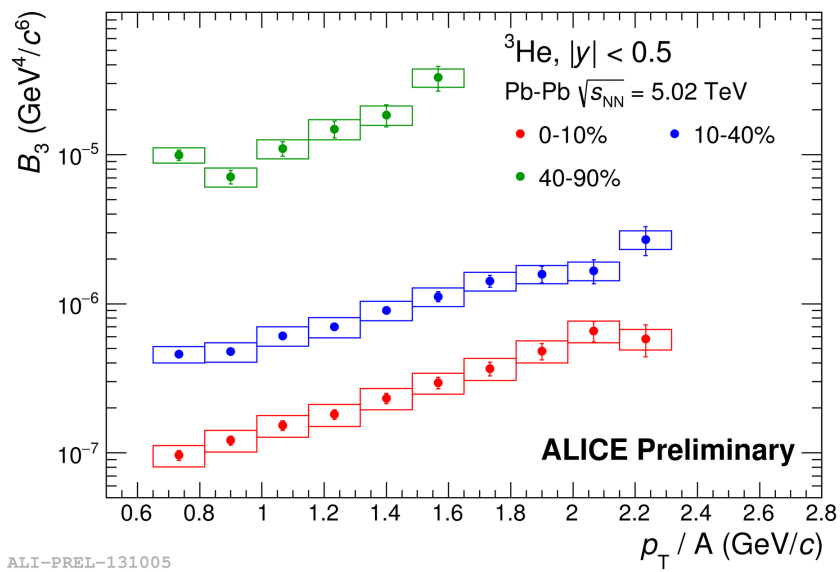
COALESCENCE PARAMETER B_3

pp



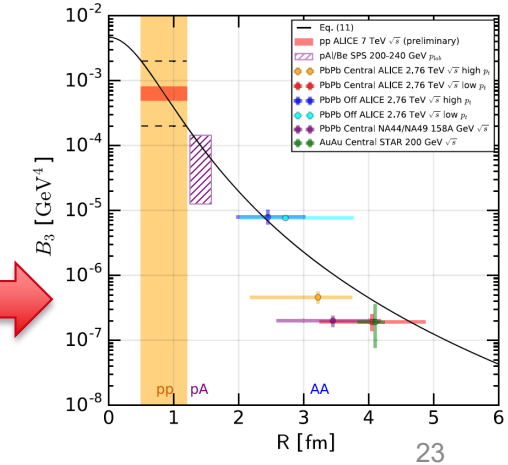
ALICE Collaboration, Phys. Rev. C 97 (2018) 024615

Pb-Pb



- B_3 of ($\bar{t}$)t and ($^3\overline{He}$)^{3}He measured in pp and Pb-Pb collisions
- First ever measurements of the B_3 of $\bar{t}$ and $^3\overline{He}$ in pp collisions
- Increasing trend with p_T and centrality observed in Pb-Pb collisions
- Present data allow to make a new estimate to assess the astrophysical secondary flux of antihelium

[K. Blum et al., Phys. Rev. D 96 (2017) 103021]



LOOKING TO THE SKY

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

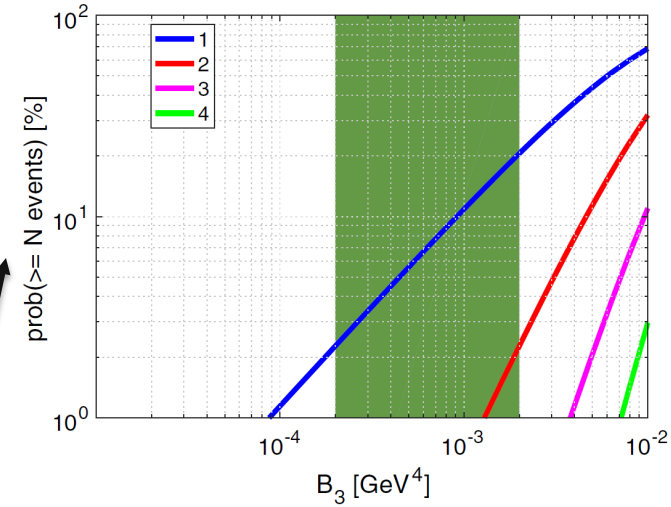
Cosmic Rays anti-deuterons and anti-^{3}He suggested as probe of DM annihilation, but anti-nuclei can be produced also by pp collisions with interstellar matter

***B_3 (B_2)* at LHC can constrain *secondary* anti-nuclei flux near Earth** induced by CRs interactions with interstellar matter (H, ^{3}He mainly)

Poisson probability for detecting N (1, 2, …) secondary $^3\overline{\text{He}}$ events in 5-yr analysis of AMS-02

Precise measurement of *B_3* (B_2) are essential for primordial anti-matter and Dark Matter searches !

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



B_3: pp→^{3}He no direct exp information

They estimate B_3 (green band) from: pp→d direct measurements plus coalescence calibrated with HBT correlations

LOOKING TO THE SKY

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

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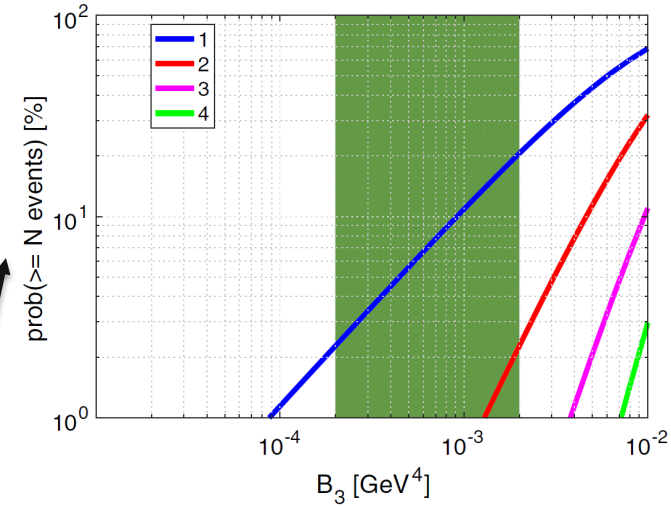
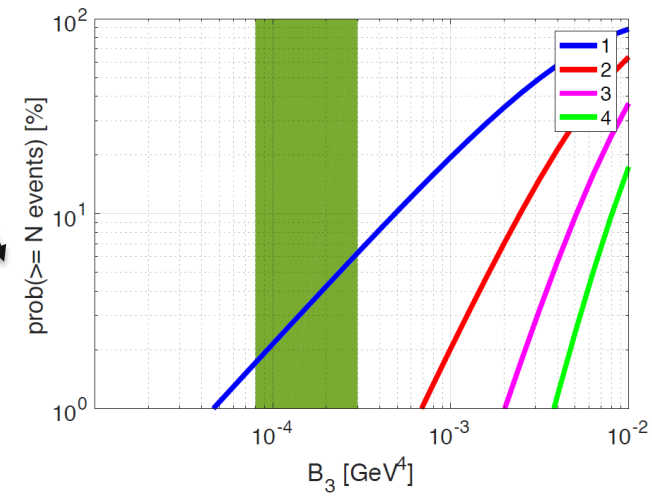
ALICE measurement of B_3 in pp

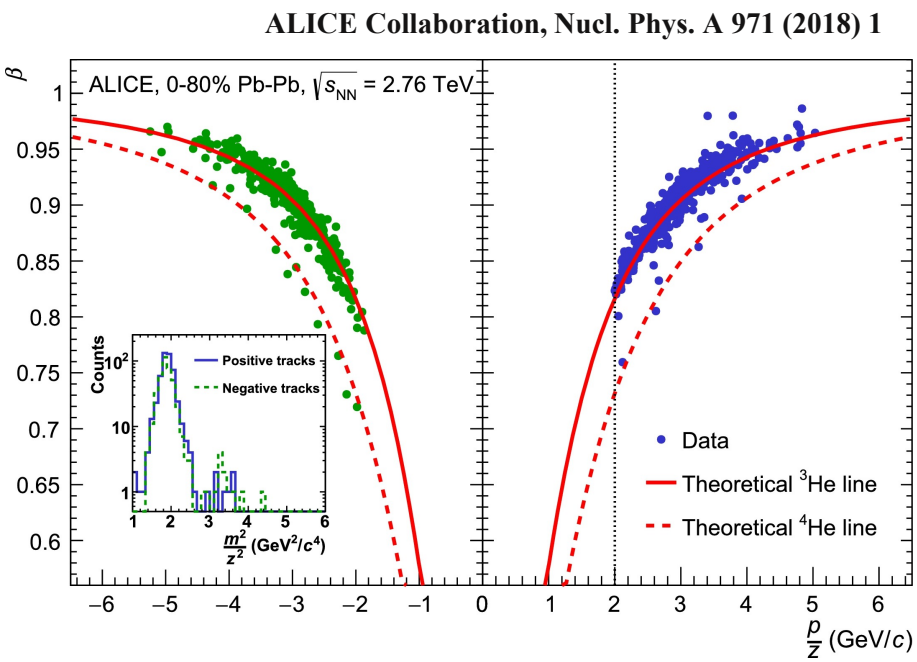
K. Blum et al., PRD 96 (2017) 103021

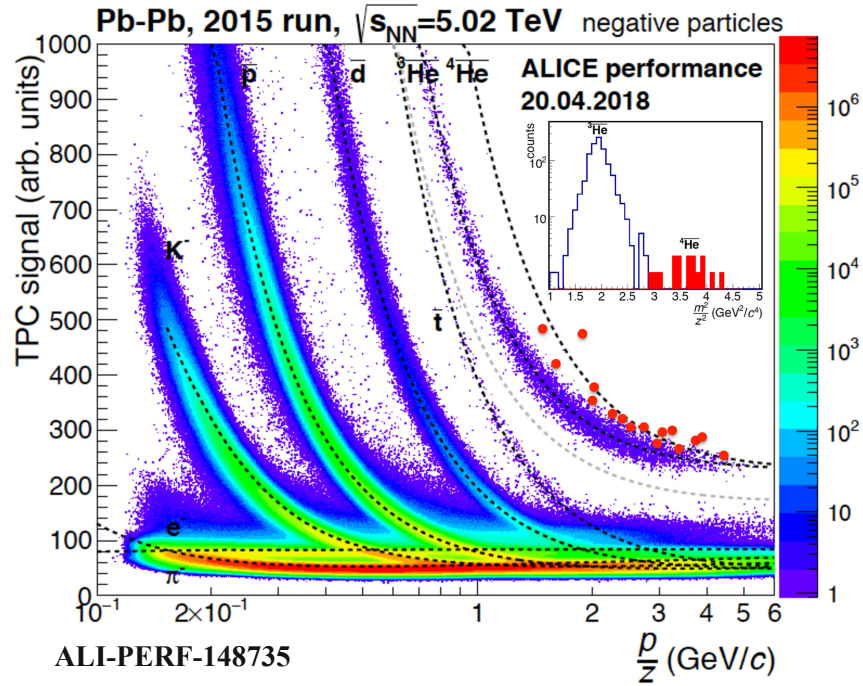


Blum
https://indico.gsi.de/event/6301/session/7/contribution/17



ANTI-ALPHA





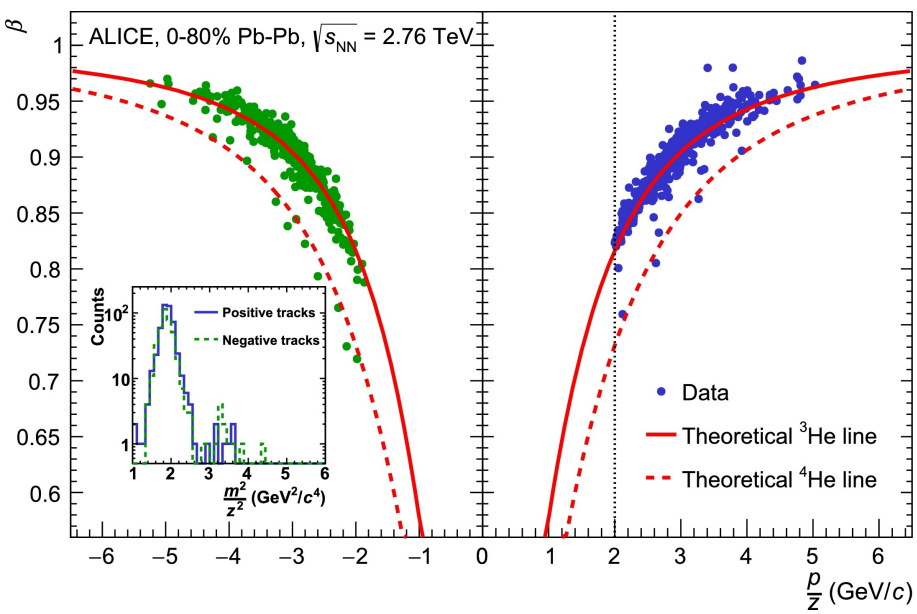
For the full statistics of 2011 (Pb-Pb@2.76 TeV) ALICE identified 10 Anti-Alphas using TPC and TOF

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

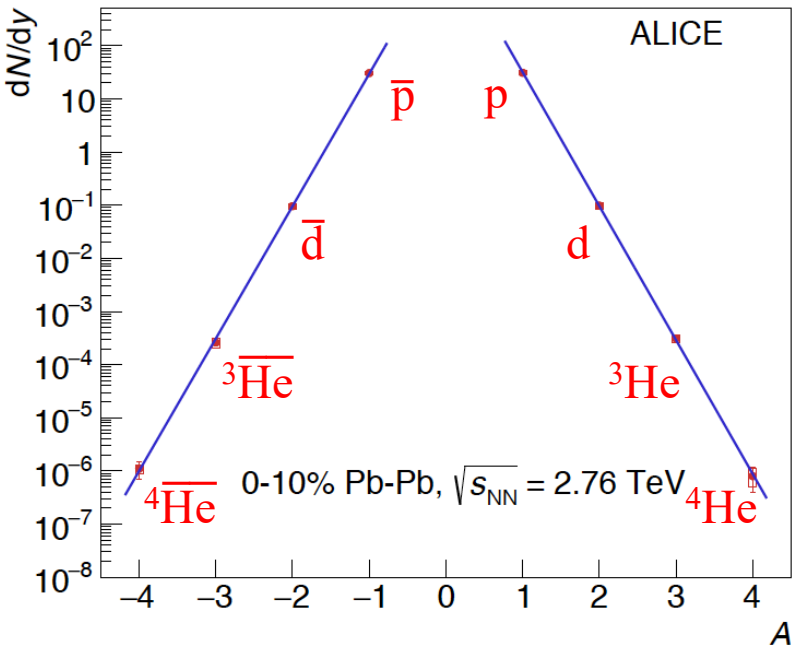
Anti-Alpha re-measured also in the new data sample Pb-Pb@5.02 TeV

NUCLEI PRODUCTION IN Pb-Pb

ALICE Collaboration, Nucl. Phys. A 971 (2018) 1



ALICE Collaboration, Nucl. Phys. A 971 (2018) 1



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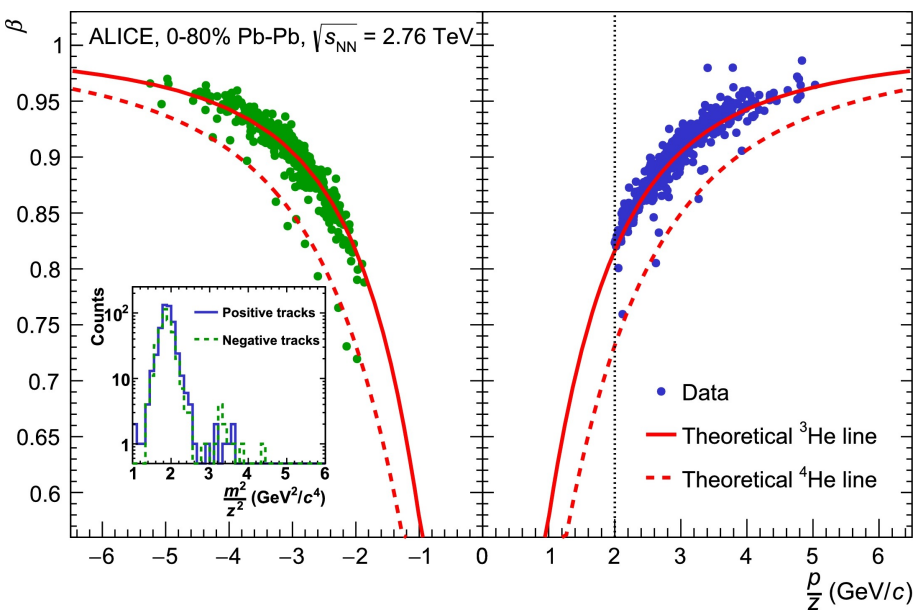
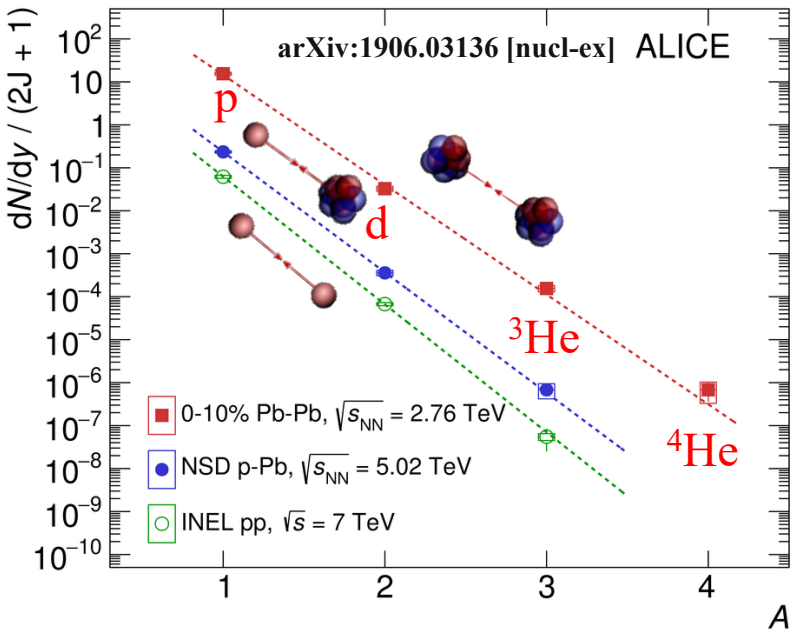
In **Pb-Pb** the penalty factor for adding one baryon is **~360** (for particles and antiparticles)

NUCLEI PRODUCTION IN Pb-Pb AND IN p-Pb

ALICE Collaboration, Nucl. Phys. A 971 (2018) 1





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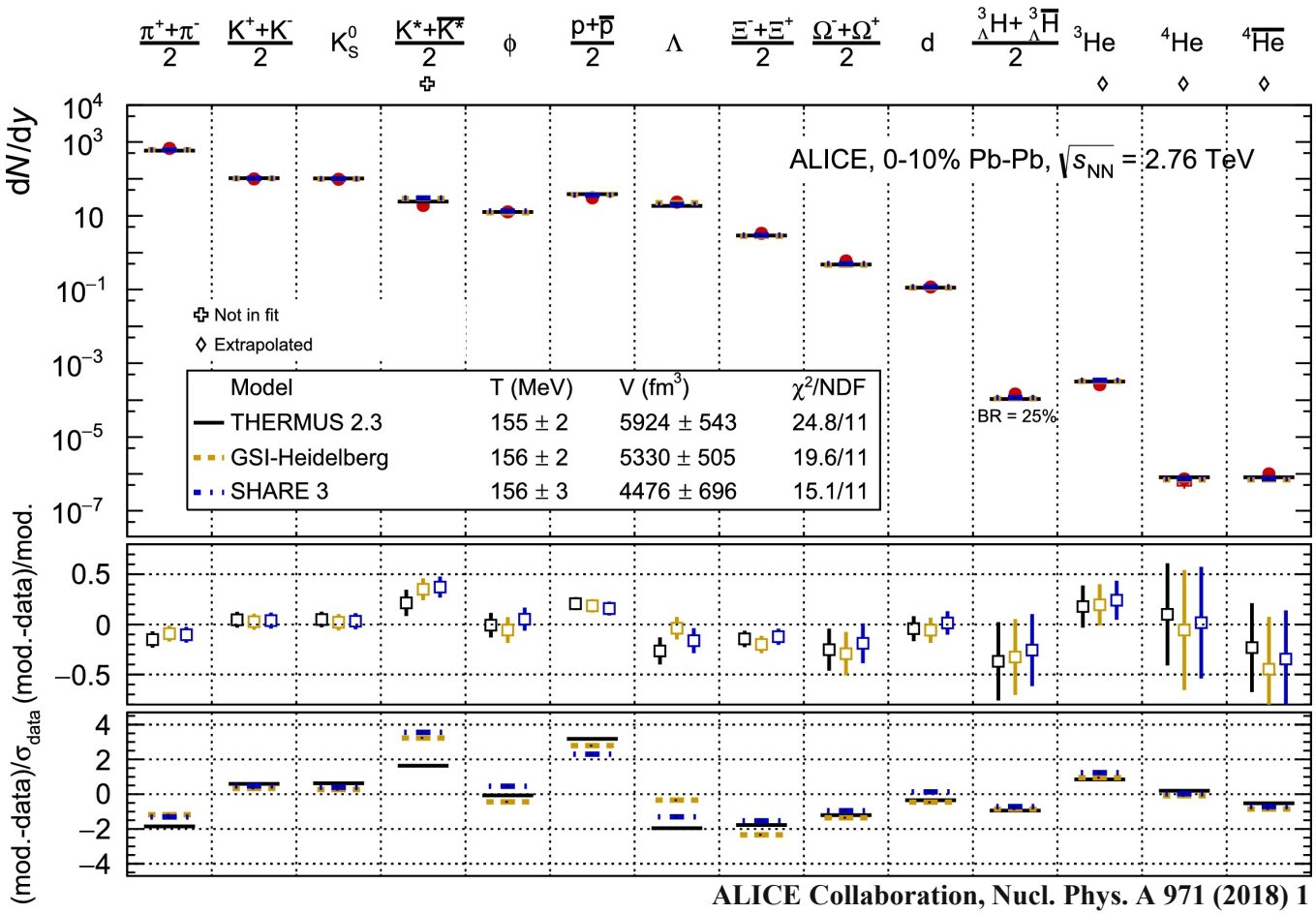
Nuclei yields follow an exponential decrease with mass as predicted by the thermal model

In **Pb-Pb** the penalty factor for adding one baryon is **~360** (for particles and antiparticles) **in p-Pb it is ~635 and in p-p ~940**

THERMAL MODEL FITS



ALICE Collaboration, Nucl. Phys. A 971 (2018) 1

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 with T_{ch} of about 156 MeV

Including nuclei in the fit causes no significant change in T_{ch}

Thermal model is very successful in reproducing the particle yields measured by ALICE in Pb-Pb collisions

Λn AND H-DIBARYON SEARCH

H-Dibaryon: hypothetical *udsuds* bound state

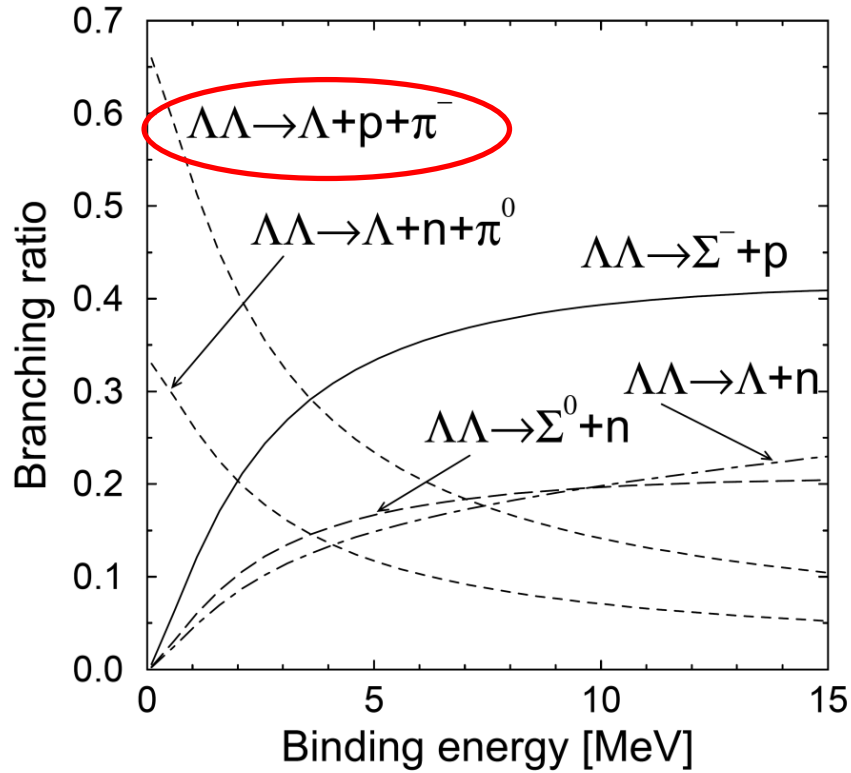
- First predicted by Jaffe [Jaffe, PRL 38, 195617 (1977)]
- Several predictions of bound and also resonant states.
- Recent Lattice models predict weakly bound states [Inoue et al., PRL 106, 162001 (2011), Beane et al., PRL 106, 162002 (2011)]

If H-Dibaryon is bound: m_H< ΛΛ threshold

- measurable channel H → Λpπ but BR depends on binding energy

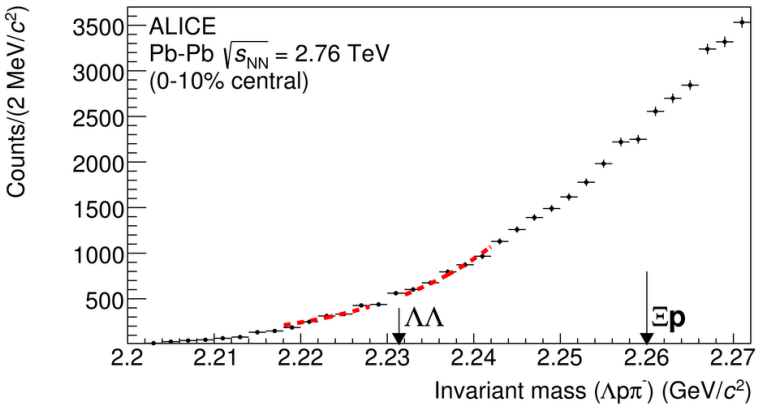
Bound state of **Λn** ?

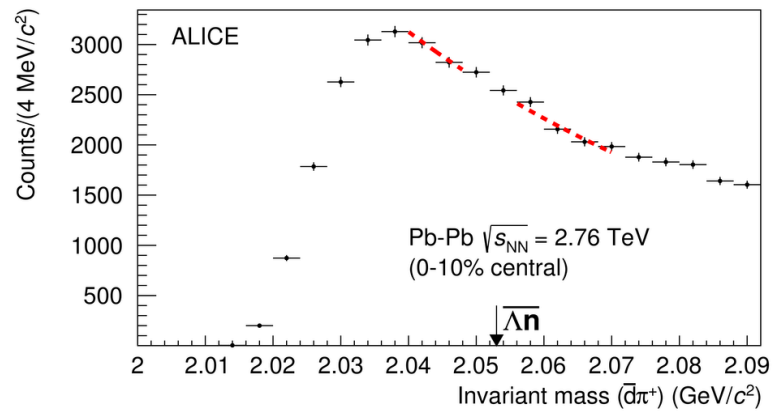
- HypHI experiment at GSI sees evidence of a new state: **Λn → d + π⁻** [C. Rappold et al. (HypHI collaboration), Phys. Rev. C88, 041001(R) (2013)]



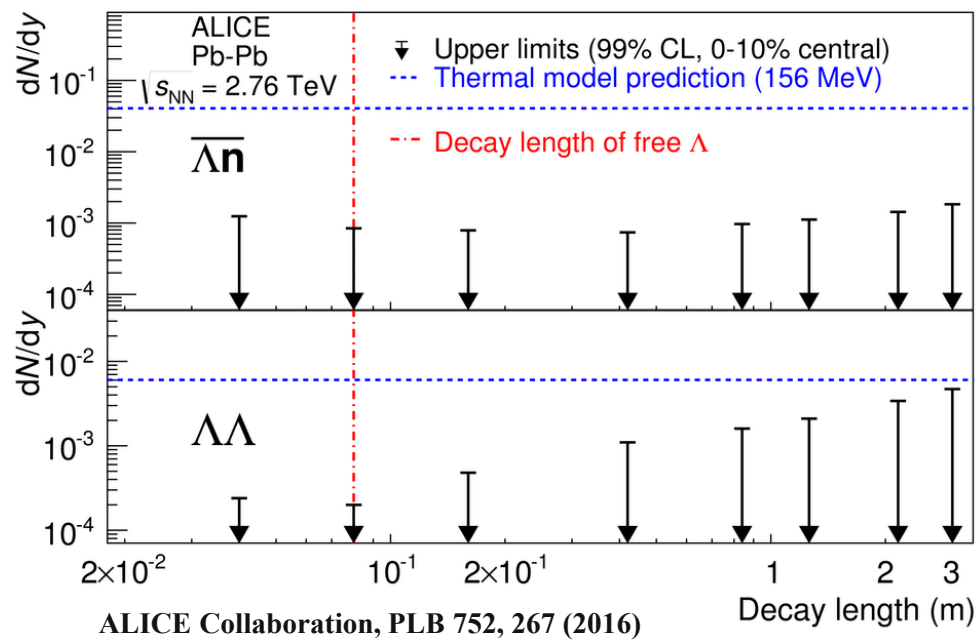
Schaffner-Bielich et al., PRL 84, 4305 (2000)

Λn AND H-DIBARYON SEARCH





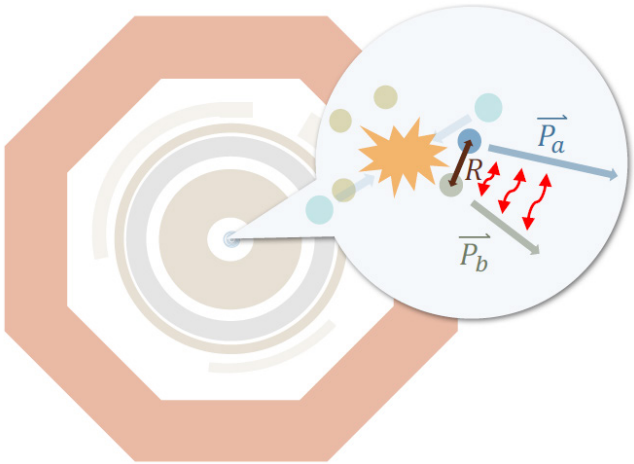
- No signal visible
- The upper limits for exotica are lower than the thermal model expectation by a factor of 20
- Thermal models with the same temperature describe precisely the production yield of deuterons, ^{3}He and $^3_\Lambda$H
- The existence of such states with the assumed B.R., mass and lifetime is questionable



ALICE Collaboration, PLB 752, 267 (2016)

A NEW GENERATION OF HADRON-HADRON INTERACTION MEASUREMENTS WITH ALICE

Femtoscopy: analyses of two-particle correlations allow to study the interactions



The correlation function:

$$C(k^*) = \frac{P(\boldsymbol{p}_a, \boldsymbol{p}_b)}{P(\boldsymbol{p}_a)P(\boldsymbol{p}_b)},$$

Experimentally obtained as:

$$C(k^*) = \mathcal{N}\frac{N_{Same}(k^*)}{N_{Mixed}(k^*)}$$

Given by:

$$C(k^*) = \int S(\boldsymbol{r}, k^*)|\psi(\boldsymbol{r}, k^*)|^2 \, d\vec{\boldsymbol{r}}$$

$$\xrightarrow{k^* \to \infty} 1$$

Source

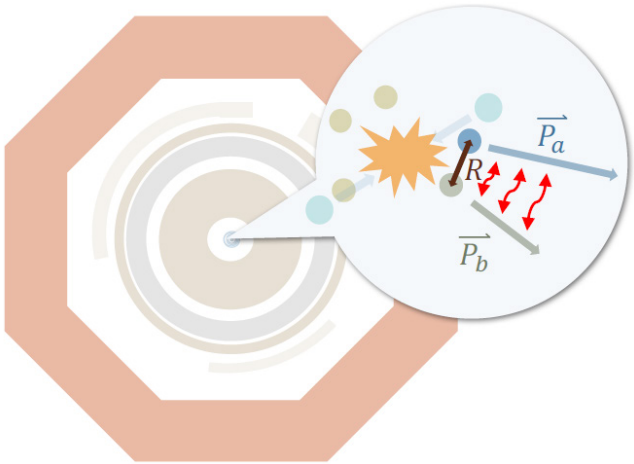
Relative Wave Function

$$k^* = \frac{|\boldsymbol{p}_a^* - \boldsymbol{p}_b^*|}{2} \text{and } \boldsymbol{p}_a^* + \boldsymbol{p}_b^* = 0$$

Pb-Pb collision: under the hypothesis that the interaction is known
⇒ possibile to study the emission region
e.g. applied to pions to characterize the source in heavy-ion collisions. i.e. the dimensions and profile of the fireball at thermal freeze-out

A NEW GENERATION OF HADRON-HADRON INTERACTION MEASUREMENTS WITH ALICE

Femtoscopy: analyses of two-particle correlations allow to study the interactions



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Source

Relative Wave Function

$$k^* = \frac{|\boldsymbol{p}_a^* - \boldsymbol{p}_b^*|}{2} \text{ and } \boldsymbol{p}_a^* + \boldsymbol{p}_b^* = 0$$

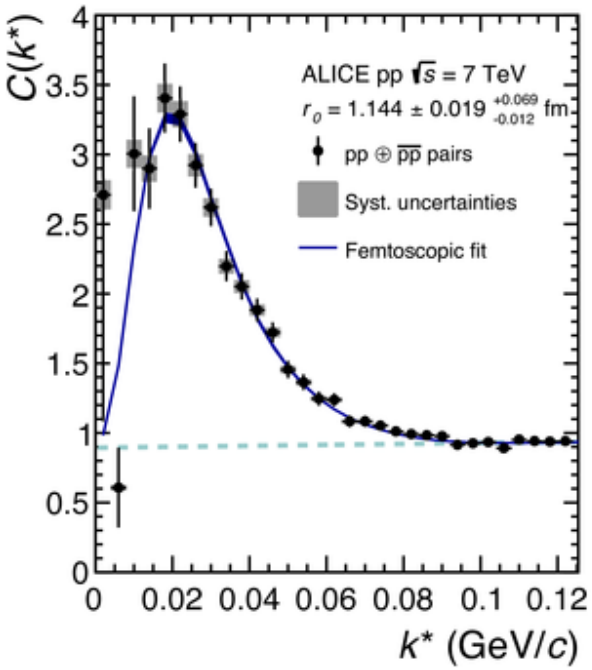
pp collision: the source is known (at least effectively modeled)
⇒ study the interaction

All detectable particle species can be studied:
already measured with ALICE **p-p**, **p-Λ**, **Λ-Λ**, **p-Ξ**, **p-K**
Assumption of a **common source** with **Gaussian shape** for the **p-p**, **p-Λ**, **p-Ξ**, Λ-Λ and p-K Correlation Function

FIT OF THE CORRELATION FUNCTION

p-p, Λ-p and Λ-Λ

p-p



ALICE Collaboration, PRC 99, 024001 (2019)

Interplay between the strong attractive and Coulomb repulsive interactions

Fit to the experimental with CATS (a femtoscopic correlation analysis tool using the Schrödinger equation) [1]:
Gaussian source and Argonne ν18 potential describes the p-p correlation function

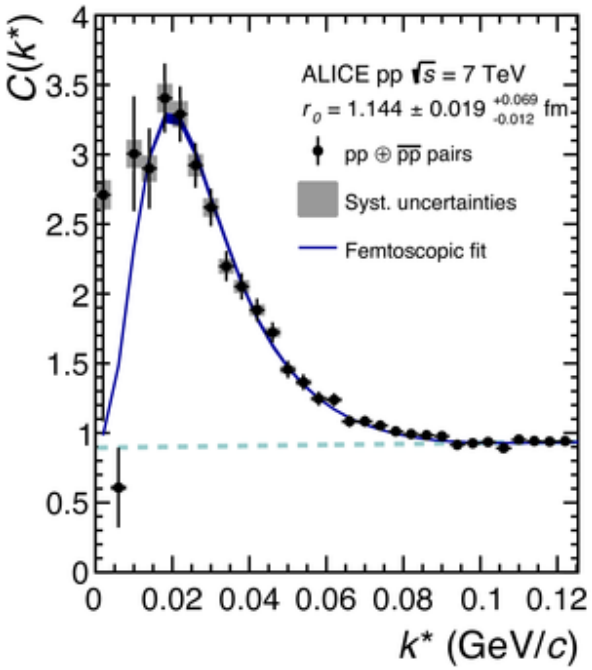
Source size of the **p-p (7 TeV)** system **r_0=1.14 fm**

[1] D.L.Mihaylov et al., Eur.Phys.J. C 78 (2018) no.5,394

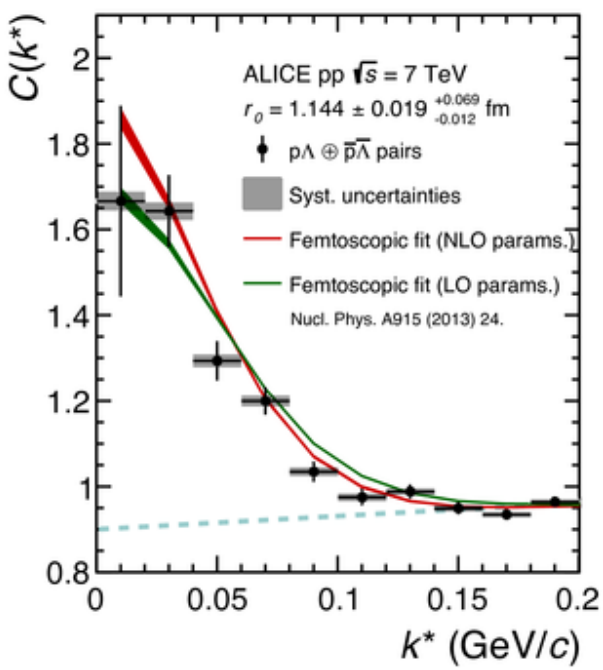
FIT OF THE CORRELATION FUNCTION

p-p, Λ-p and Λ-Λ

p-p



Λ-p



ALICE Collaboration, PRC 99, 024001 (2019)

Fixed the source size from **pp (7 TeV)** system **r_0=1.14 fm**

LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

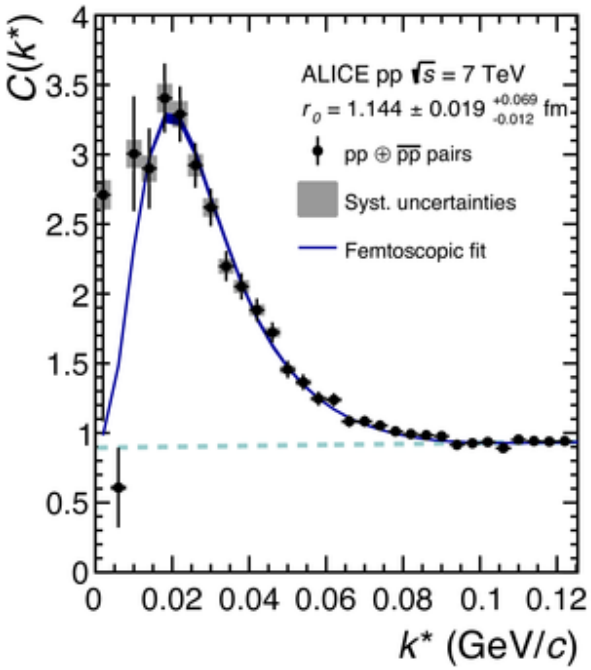
Combination of spin singlet and triplet

Statistics not sufficient to test different models

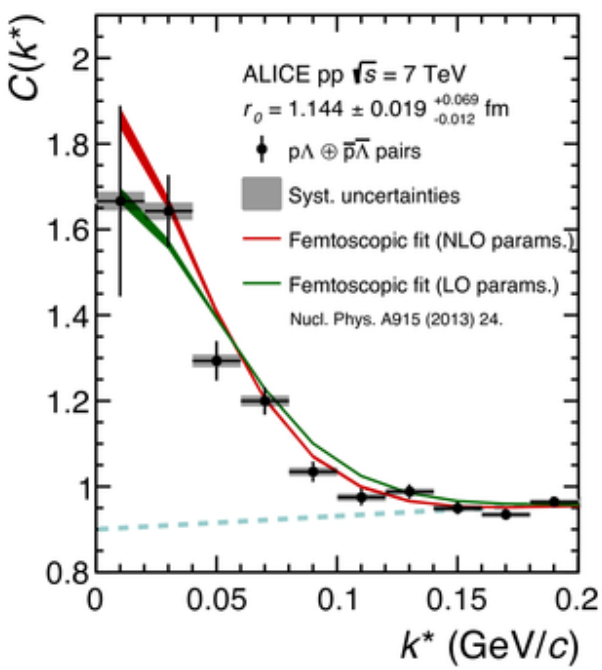
FIT OF THE CORRELATION FUNCTION

p-p, Λ-p and Λ-Λ

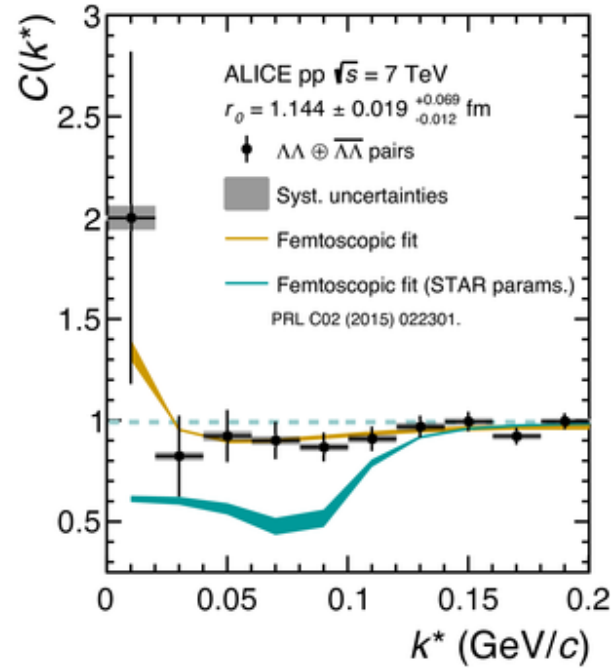
pp



Λp



ΛΛ



ALICE Collaboration, PRC 99, 024001 (2019)

pp 7 TeV RUN 1 ~ 2.5 10^8 events

Different baseline because of quantum statistics

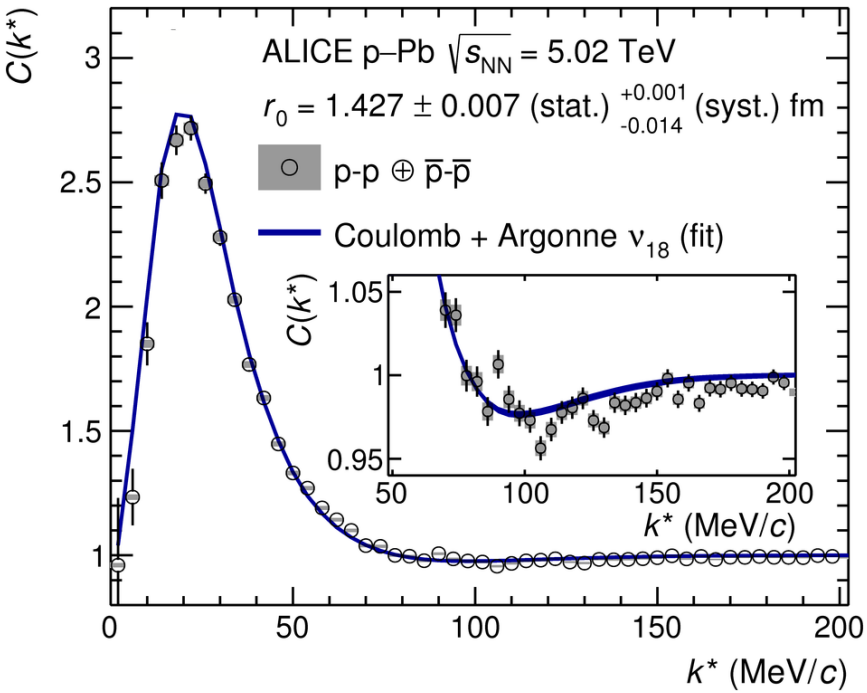
Lednicky [1] fit carried out on Λ-Λ

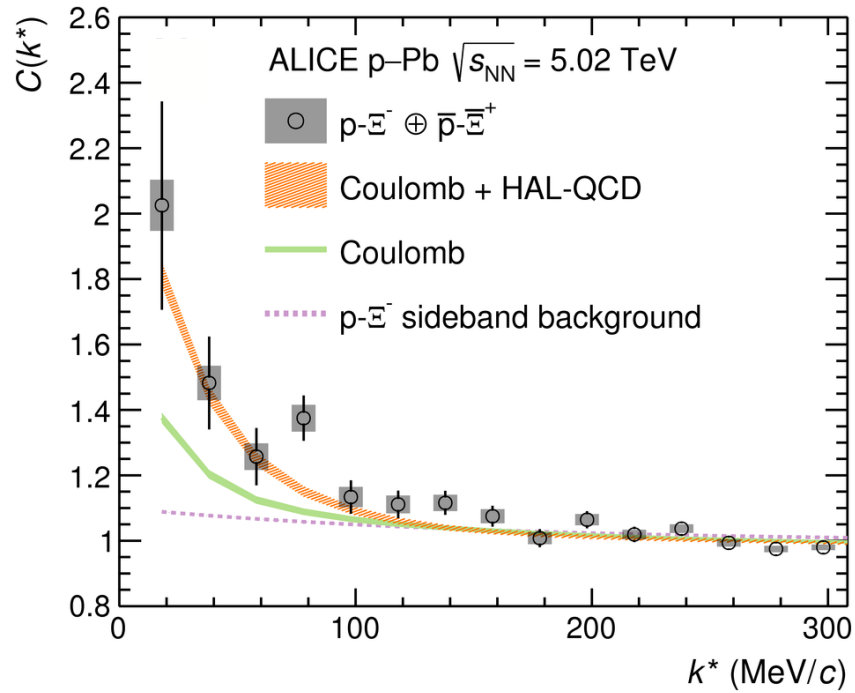
too large uncertainty yet on the scattering parameters

[1] M.A.Lisa et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 357

ANALYSIS IN p-Pb COLLISION SYSTEM

https://arxiv.org/pdf/1904.12198.pdf





Gaussian source
Argonne v18 strong interaction potential
Coulomb interaction & Quantum statistics
Size of source comparable to the typical range of strong potentials
Sensitivity to features of the potentials

First observation of strong attractive interaction in p-Ξ⁻
modeled with preliminary QCD strong potential by the HAL QCD collaboration
(Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)
Coulomb-only hypothesis excluded at ~3σ

ANALYSIS IN p-Pb COLLISION SYSTEM

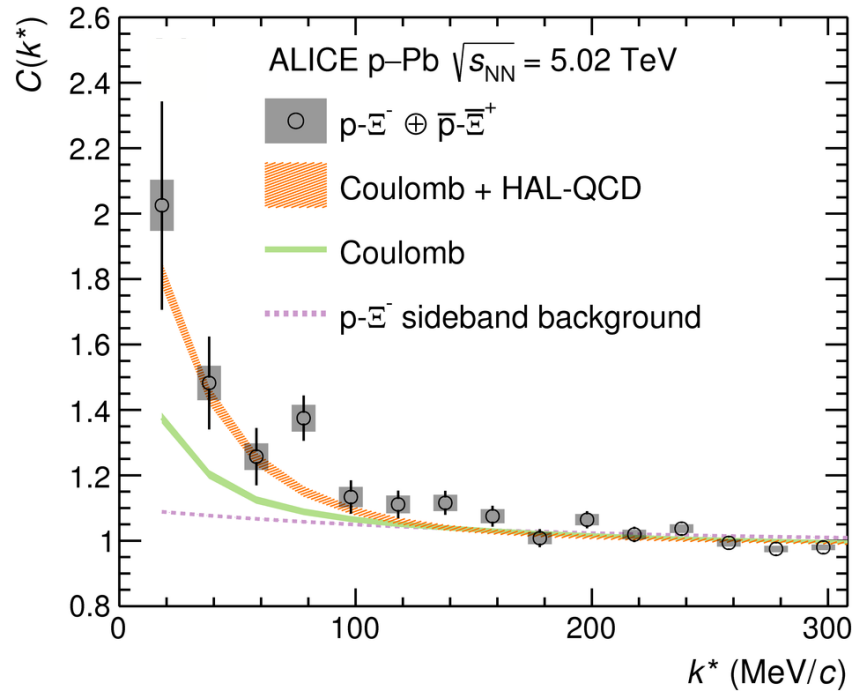
https://arxiv.org/pdf/1904.12198.pdf

The experimental p-Ξ^- correlation function shows a stronger enhancement than the Coulomb-only ⇒ **the total interaction is more attractive !**

Validated lattice predictions ⇒ **consequences for the Equation of State (EoS) of neutron stars**:

The Ξ^- single-particle potential in pure neutron matter at saturation density from HAL QCD:
Slightly repulsive U_{Ξ^-} ~ 6 MeV

⇒ stringent constraint with consequences for the EoS containing hyperons (stiffer EoS)



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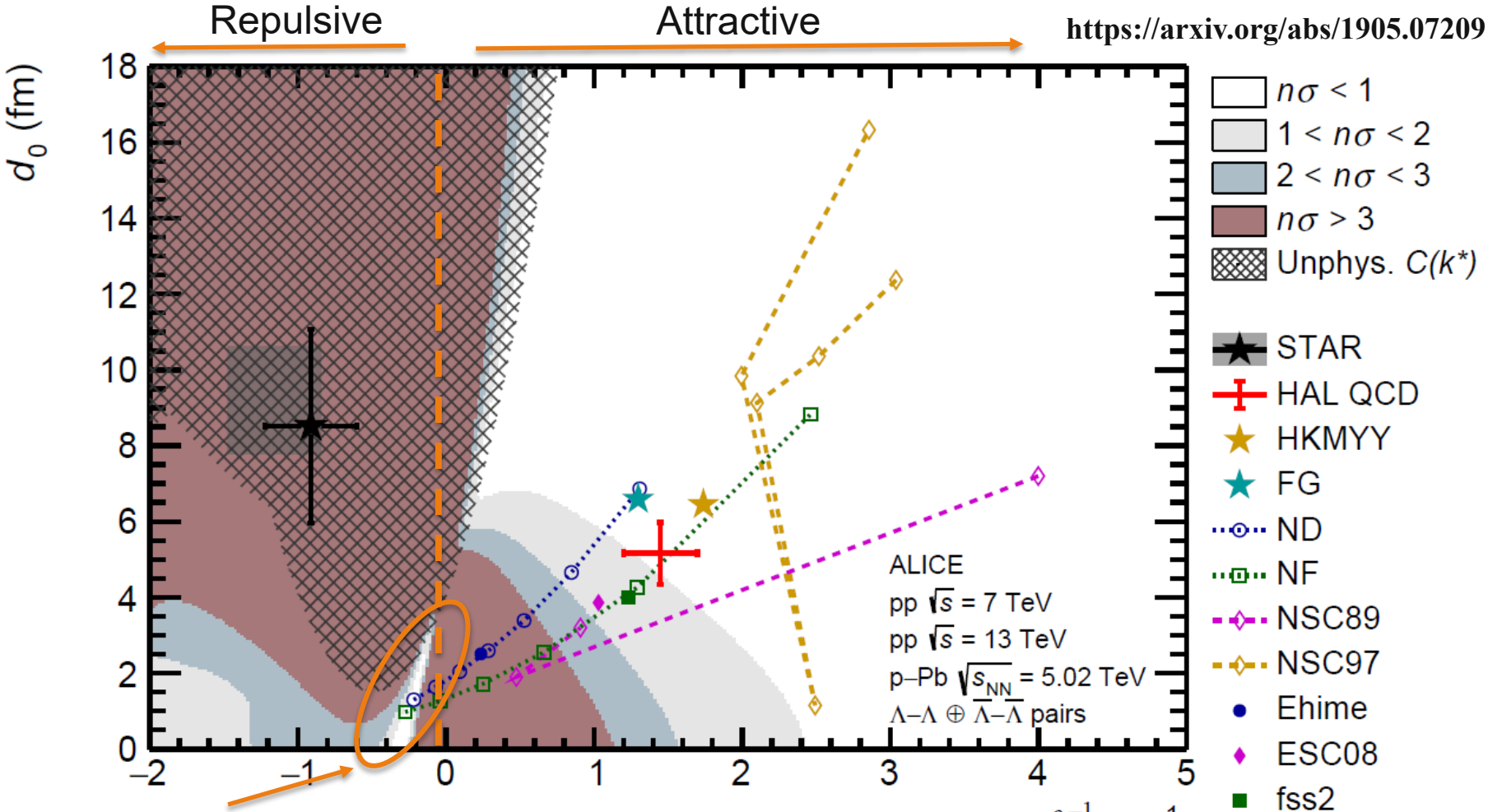
THE ΛΛ EXCLUSION PLOT

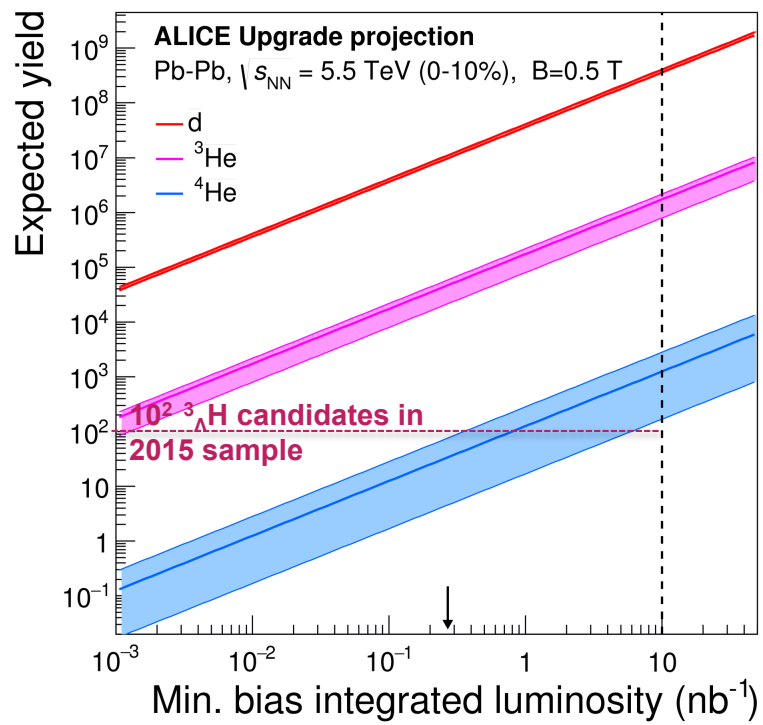


the available phase space for ΛΛ bound state is strongly constrained

OUTLOOK – ALICE UPGRADE

During the Long Shutdown 2 (2019-2020) upgrades of:

- **New Inner Tracking System (ITS)**
  - ✓ improved pointing precision
  - ✓ less material -> thinnest tracker at the LHC
- **Upgrade of Time Projection Chamber (TPC):**
  - ✓ new GEM technology for readout chambers
  - ✓ continuous readout
  - ✓ faster readout electronics
- **ALICE Online-Offline computing system (O2):**
  - ✓ new architecture
  - ✓ on line tracking & data compression
  - ✓ 50kHz Pb-Pb event rate



At the end of RUN 4 (2029):
the expected Integrated Luminosity: ~10 nb^{-1} (~8x10^9 collisions in the 0-10% centrality class)

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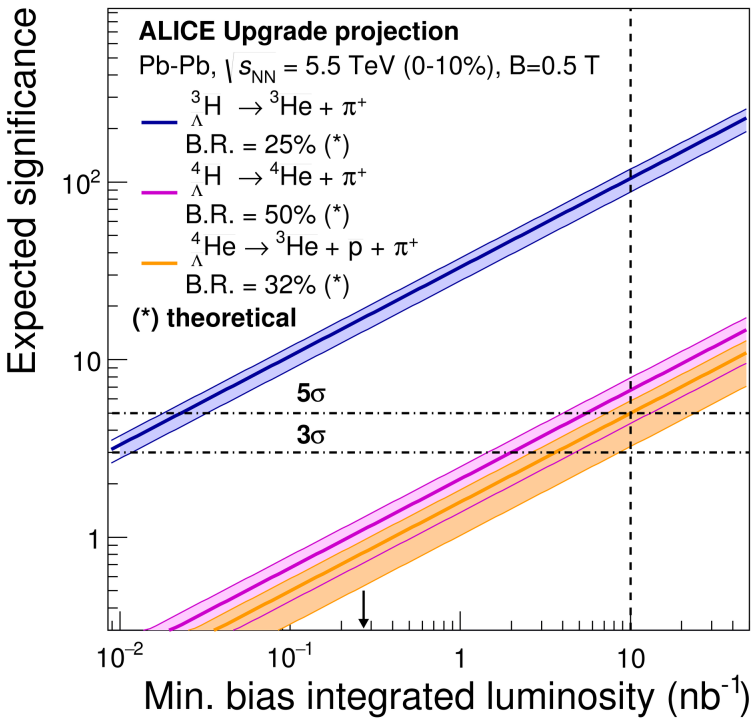


ALI-SIMUL-312332

At the end of RUN 4 (2029):
the expected Integrated Luminosity: ~10 nb^{-1} (~8x10^{9} collisions in the 0-10% centrality class)

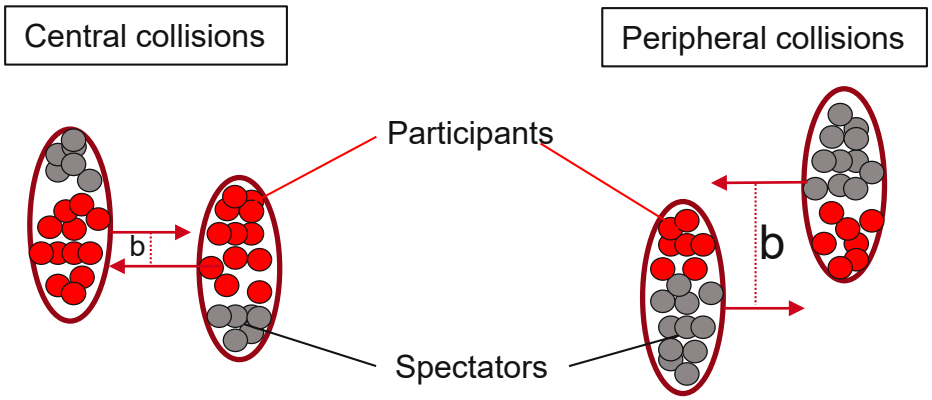
All the physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4

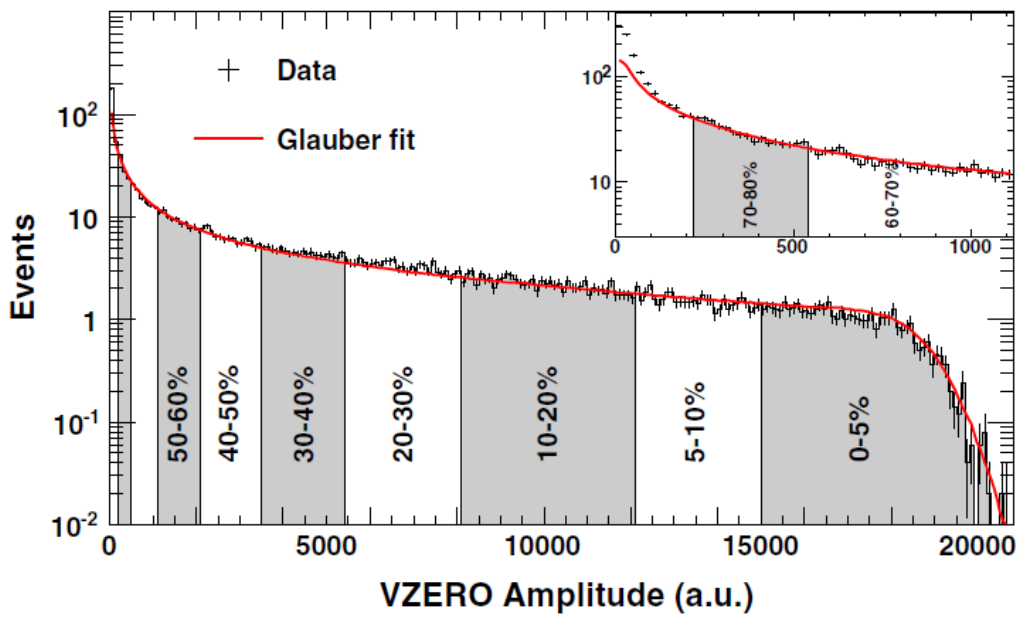
CONCLUSIONS

- Excellent **ALICE** performance allows for **detection of (anti-)baryons, light (anti-)nuclei and (anti-)hypernuclei**

- ALICE (anti-)baryons and (anti-)(hyper-)nuclei production measurements challenge the production models (QCD, thermal and coalescence models)
  - ✓ Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
  - ✓ B_2 coalescence parameter evolves smoothly as a function of multiplicity with no discontinuity between different colliding system
  - ✓ Valuable **inputs** (B_2 and B_3) **for Astroparticle Physics provided**
  - ✓ **The upper limits for exotica are lower than the thermal model expectation by a factor of 20**
- Femtoscopic measurements sensitive to differences in potentials
  - ✓ Already measured with ALICE p-p, p-Λ, Λ-Λ, p-Ξ, p-K
  - ✓ First time direct observation of an attractive p-Ξ^- interaction
- **Future LHC runs**, RUN 3 and RUN 4, and ALICE upgrades will **allow for precise study** of **(anti-)(hyper-)nuclei** production yield (and lifetime)
  - ✓ New and more precise data are expected from the LHC in the next years !

COLLISION GEOMETRY





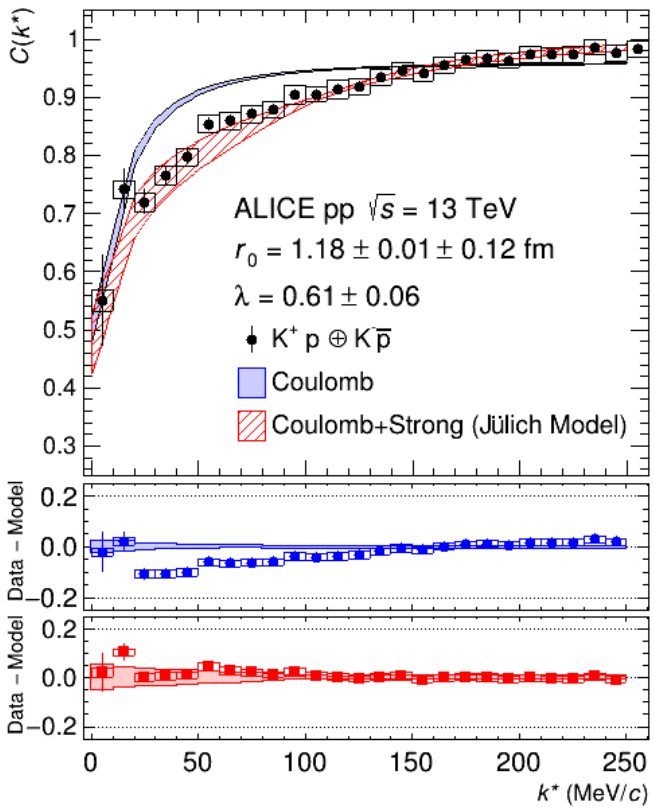
K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. 106, 032301 (2011)

- Nuclei are extended objects
- Geometry not directly measurable
- Centrality (percentage of the total cross section of the nuclear collision) connected to observables via Glauber model

- Data classified into centrality percentiles for which the average impact parameter, number of participants, and number of binary collisions can be determined

PROBING THE MESON-BARYON INTERACTION

K^+p and c.c.



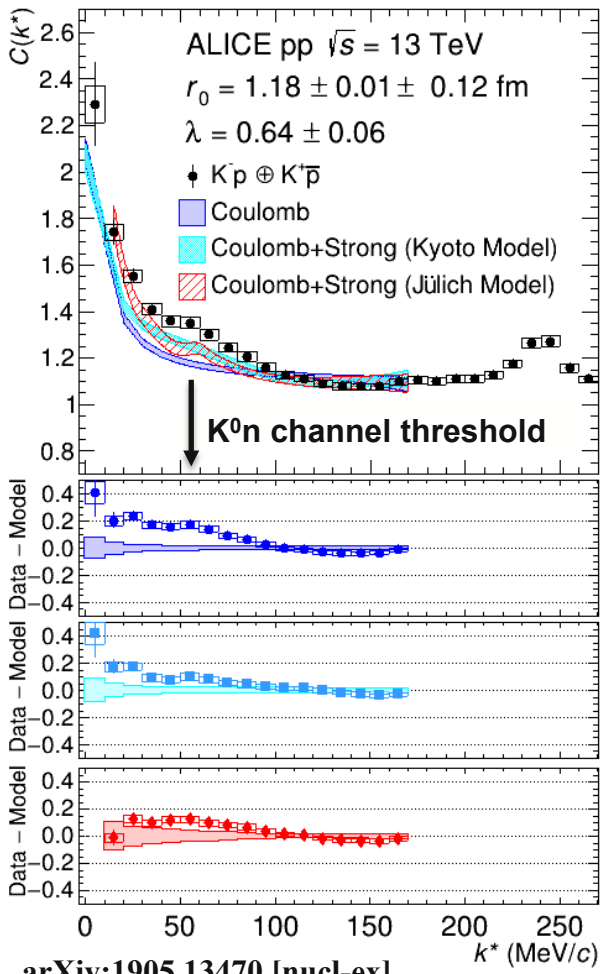
- The Coulomb-only (red band) and Coulomb+Strong (blue band) potentials have been used to fit the data
- The Coulomb-only potential is not able to fit data
- The Jülich model potential [1] is used to evaluate the strong component (the Coulomb interaction is included using Gamow factor): agreement between data and Coulomb+Strong potential
- The introduction of the strong potential is needed to fit the data: the measured correlation functions are sensitive to the strong interaction

arXiv:1905.13470 [nucl-ex]

[1] M. Hoffmann et al., Nucl.Phys. A593 (1995) 341-361
Partial wave function computed by Johann Haidenbauer

PROBING THE MESON-BARYON INTERACTION

K^-p and c.c.

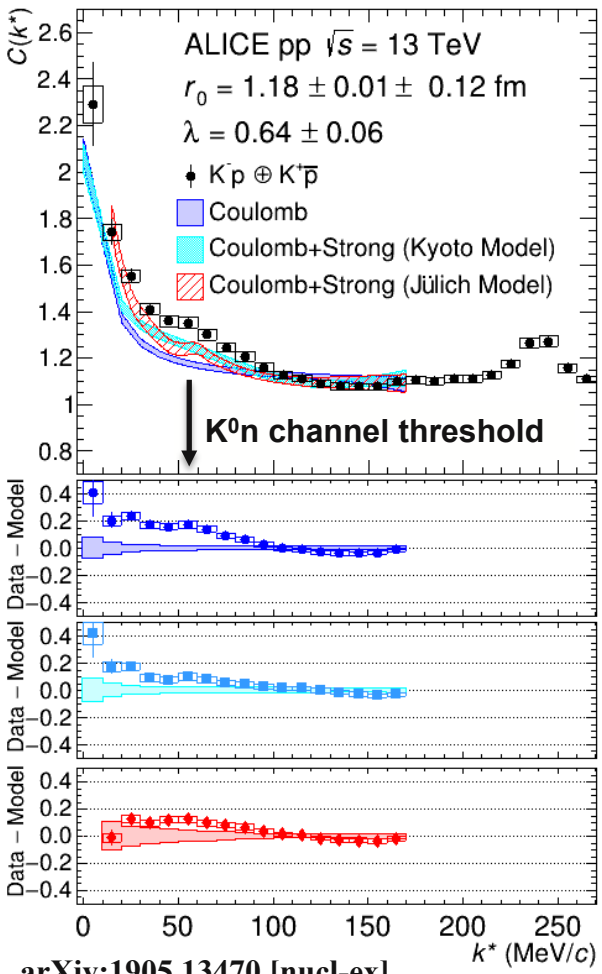


arXiv:1905.13470 [nucl-ex]

- Observation of a bump close to the K^0n threshold (89 MeV/c in the lab frame → 58 MeV/c in the CM frame)
- First experimental evidence of the opening of the K^0n ($\bar{K}^0\bar{n}$) isospin breaking channel → femtoscopy is a unique tool to study the Kp scattering, where the conventional scattering experiments at fixed target are difficult to perform.

PROBING THE MESON-BARYON INTERACTION

K^-p and c.c.



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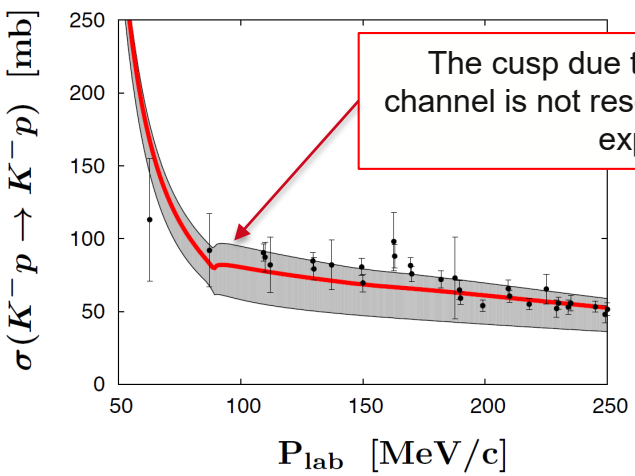
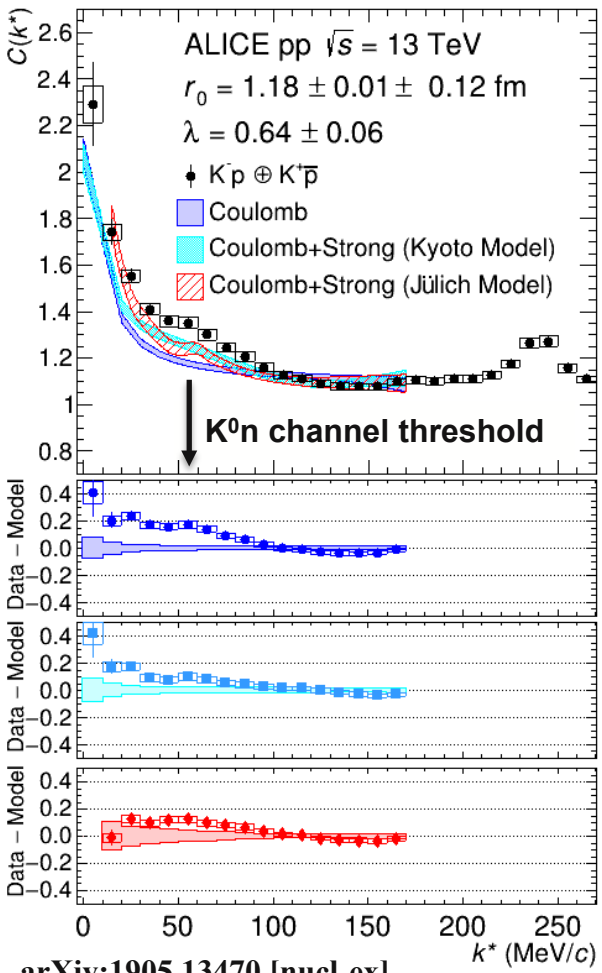


The cusp due to the opening of K^0n channel is not resolved by scattering data experiment

Y. Ikeda et al Nucl.Phys. A881 (2012) 98-114
see also
B. Borasoy et al Phys. Rev. C74 (2006) 055201

PROBING THE MESON-BARYON INTERACTION

K^-p and c.c.



arXiv:1905.13470 [nucl-ex]

- The Coulomb-only and Coulomb+Strong potentials have been used to fit the data
- Blue bands: Coulomb potential only
- Light blue bands: chiral Kyoto model [1-5] with approximate boundary conditions:
  - $K^- – K^0$ mass difference not considered (isospin averaged masses)
- Σπ and Λπ coupled channels neglected (dozen of resonances)
- Red bands: the Jülich strong potential, recently been updated to reproduce the SIDDHARTA results [6]:
  - includes the $K^- – K^0$ mass difference
  - and coupled channels

[1] PRC 93 (2016) 015201
[2] PRC 95 (2017) 065202
[3] Prog.Part.Nucl.Phys. 95 (2017) 279
[4] PLB 706 (2011) 63
[5] NPA 881 (2012) 98
[6] NPA 981 (2019) 1

(ANTI-)HYPERTRITON IDENTIFICATION

Decay Channels

$$\boxed{{}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-} \qquad {}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+}}$$

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

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

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

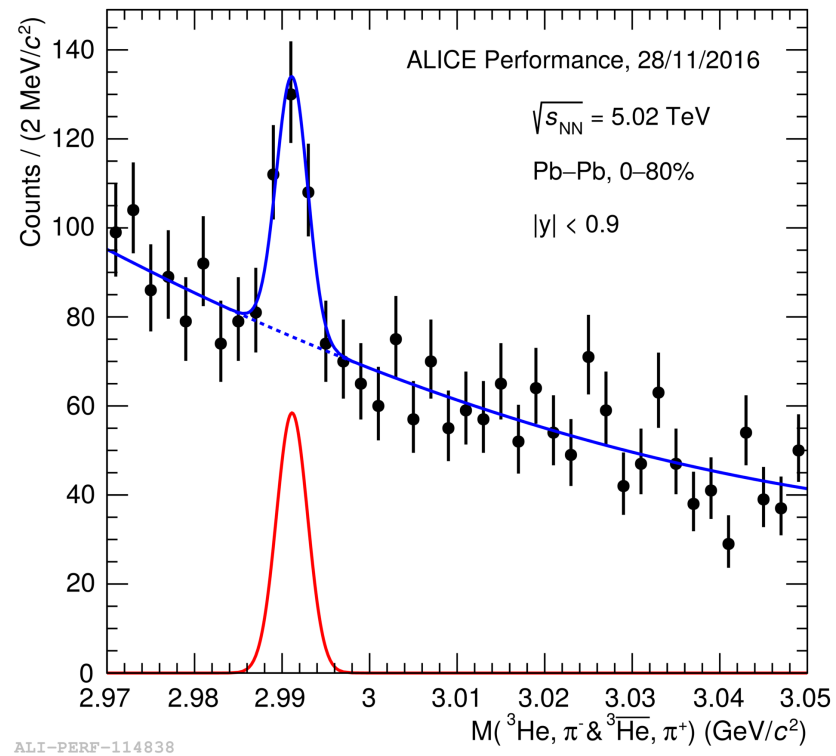
${}^{3}_{\Lambda}$H search via two-body decays into charged particles:

- Two body decay: lower combinatorial background
- Charged particles: ALICE acceptance and reconstruction efficiency for charged particles higher than for neutrals

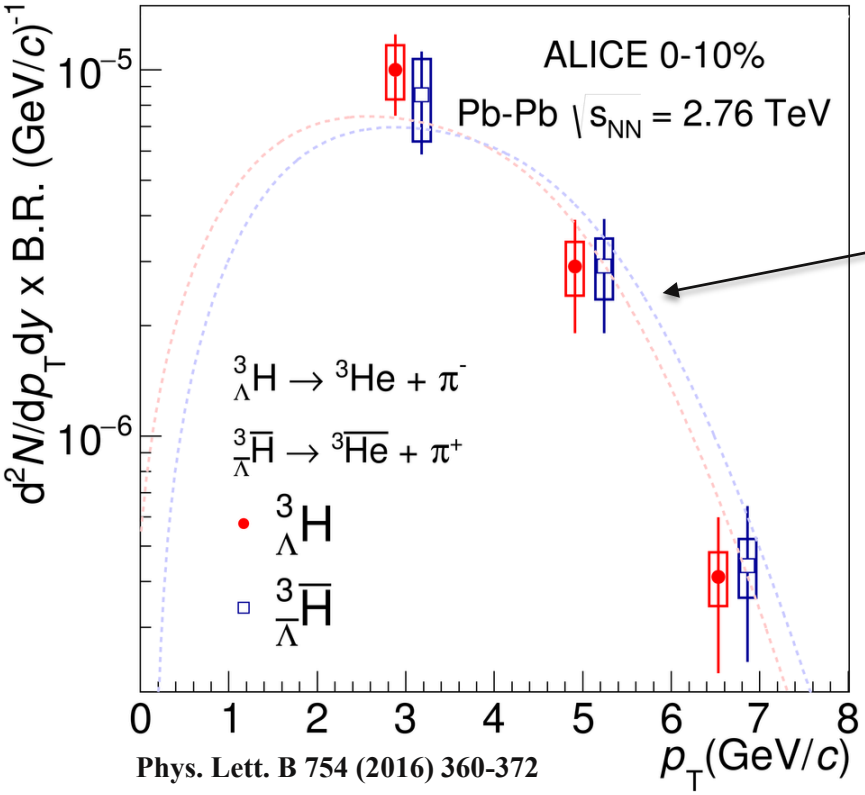
Signal extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - isolate secondary decay vertex and
  - reduce combinatorial background

Preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV

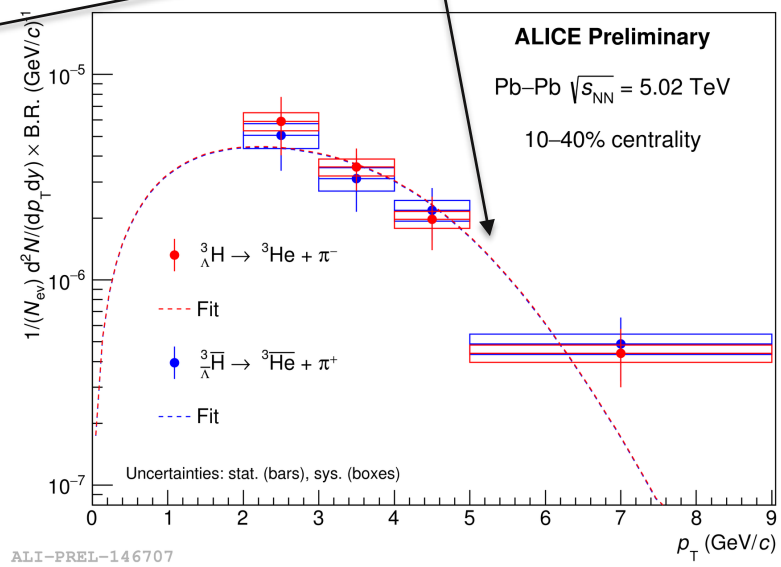


(ANTI-)HYPERTRITON YIELDS



Phys. Lett. B 754 (2016) 360-372

The dashed lines are the blast-wave curves used to extract the particle yields integrated over the full p_T range



Pb-Pb@2.76TeV:

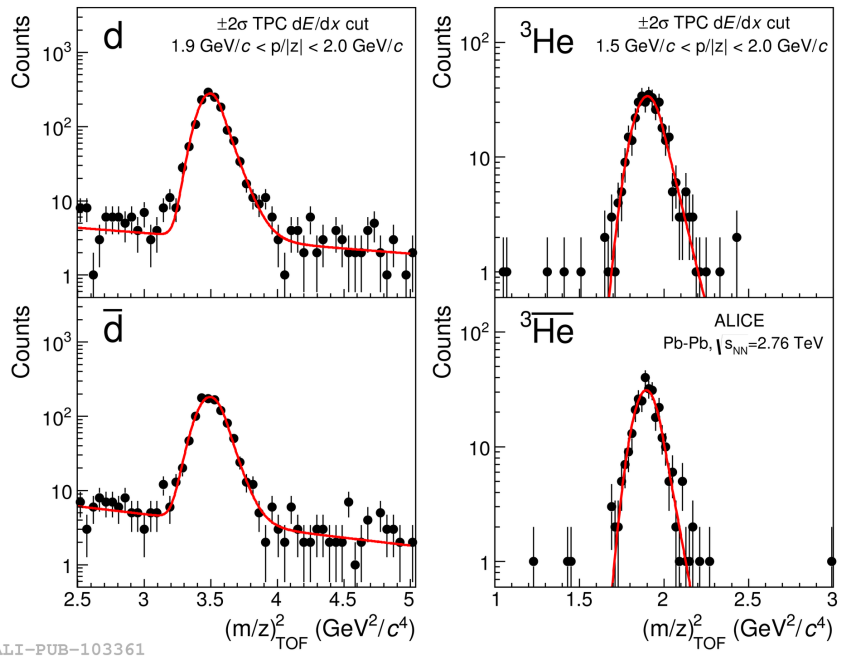
dN/dy x B.R. ($^3_\Lambda$H → ^{3}He π) yield extracted in three p_T bins for central (0-10%) events for $^3_\Lambda\overline{\mathrm{H}}$ and $^3_\Lambda$H separately

Pb-Pb@5.02TeV:

dN/dy x B.R. ($^3_\Lambda$H → ^{3}He π) yield extracted in four p_T bins for central (10-40%) events for $^3_\Lambda\overline{\mathrm{H}}$ and $^3_\Lambda$H separately

PRECISE MASS MEASUREMENT

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



- ✓ Masses and binding energies of nuclei and anti-nuclei are compatible within uncertainties
- ✓ Measurement confirms the CPT invariance for light nuclei

- ➢ The precise measurement of the mass difference between nuclei and their anti-counterparts allows one to probe any difference in the interaction between nucleons and anti-nucleons.
- ➢ Looking at the mass difference between nuclei and their anti-nuclei it is possible to test the CPT invariance of the residual QCD "nuclear force"