# (Anti-)Nuclei production and survival, hyper-triton puzzle : Future Directions

Light-up 2018 Workshop – CERN

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of behalf of the ALICE Collaboration

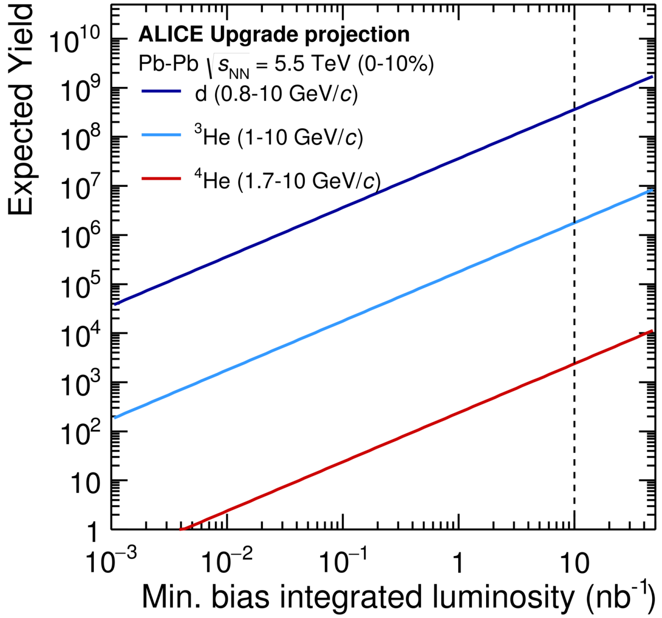
# (Anti)(Hyper)nuclei after the ALICE upgrade

- After the LS2 ALICE will be able to collect data with better performance at higher luminosity
- Expected integrated luminosity: ~10 $nb^{-1}$ ( ~ $8x10^9$ collisions in the 0-10% centrality class)
- New ITS: less material budget and more precise tracking for the identification of hyper-nuclei

- Studies on precise projections of the production yield of light (anti)(hyper)nuclei have been and are subject of several studies:
  - ALICE Upgrade LoI: CERN-LHCC-2012-012
  - ALICE ITS Upgrade TDR: CERN-LHCC-2013-024
  - CERN Yellow Report (in preparation)

# Nuclei yield reach in Run 3+4

- Accessible candidates assuming:
  - Thermal production (validated by Run1+2 results) at $T_{ch}$ = 156 MeV
  - Run 2 efficiencies in $|\eta| < 0.9$ (TPC+TOF)
- With upgraded detector
  - ALICE-GEM TPC tracking performance similar to MWPC TPC (distortion calibration to restore momentum resolution)
  - impact of upgraded ITS detector: geometry and material to be assessed



ALI-SIMUL-140342

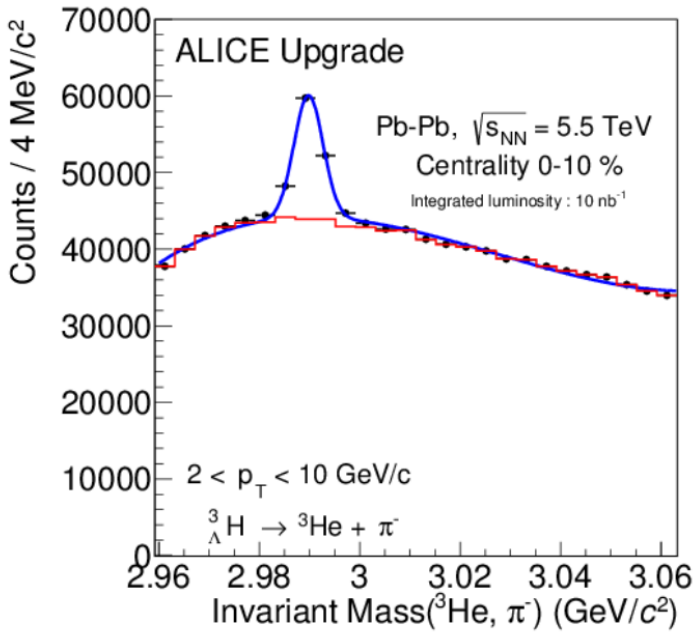
- What we will reach:
  - as many d as p in Run 1+2
  - What is now measured for A = 2 and A = 3 will be accessible for A = 4

# Hyper-Nuclei yield reach in Run 3+4

- High statistics sample of minimum bias Pb-Pb collisions
- Improved tracking resolution from the ALICE ITS upgrade
- ${}^{3}_{\Lambda}H$ reconstruction feasible in 2-body and 3-body decay with charged products
- For all the studied hypernuclei the B.R. is not well known [1,2]
- Precise evaluation of absorption cross section of anti(hyper)nuclei is needed

| | Mass (GeV/c²) | Decay Channel | B.R. | dN/dy (SHM) |
|---|---|---|---|---|
| **${}^{3}_{\Lambda}H$** | 2,991 | ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$<br>${}^{3}_{\Lambda}H \rightarrow d+p+\pi^{-}$ | 25%[1]<br>41%[1] | $1x10^{-4}$ |
| **${}^{4}_{\Lambda}H$** | 3,931 | ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$ | 50%[2] | $2x10^{-7}$ |
| **${}^{4}_{\Lambda}He$** | 3,929 | ${}^{4}_{\Lambda}He \rightarrow {}^{3}He+p+\pi^{-}$ | 32%[2] | $2x10^{-7}$ |

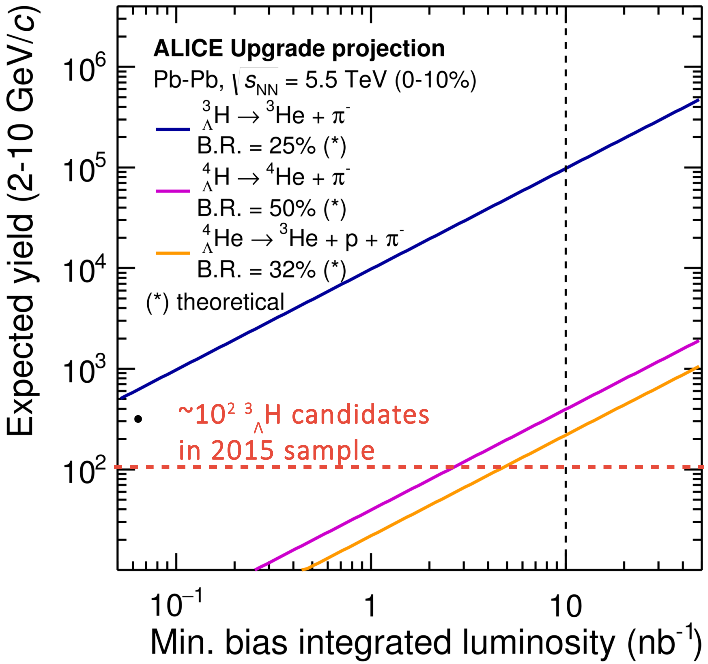
ALICE ITS upgrade TDR, : CERN-LHCC-2013-024



Expected invariant mass distribution for ${}^{3}_{\Lambda}H$ (plus antiparticle) reconstruction in Pb-Pb collisions (0-10% centrality class), corresponding to $L_{int}$= 10 nb$^{-1}$.

[1] H. Kamada et al., PRC 57, 1595 (1998),
[2]H. Outa et al., NPA 639 (1998) 251-260

# Hyper-Nuclei yield reach in Run 3+4



- ~$10^{2}$ $^{3}_{\Lambda}H$ candidates in 2015 sample

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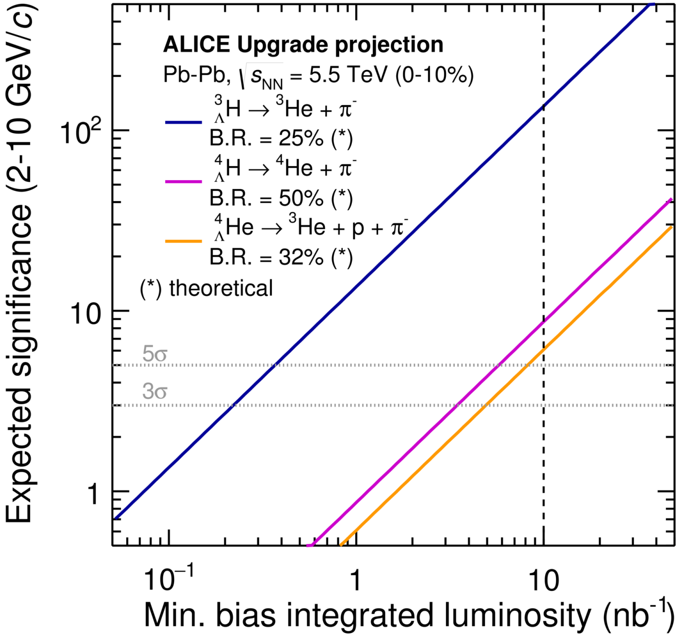

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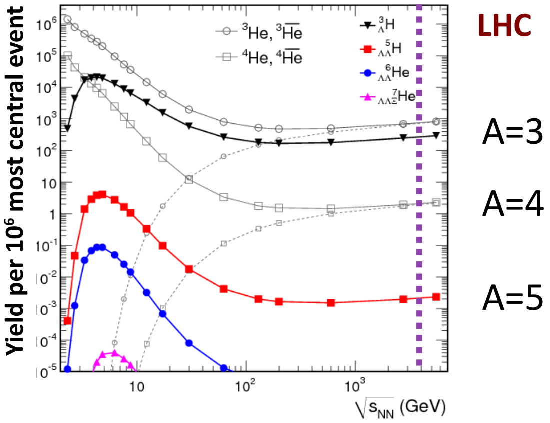
- With the expected 10 nb$^{-1}$ anti-$^{4}_{\Lambda}$H, anti-$^{4}_{\Lambda}$He “discovery” in reach

# Distinguish among production mechanisms

# Production models

## Statistical thermal model

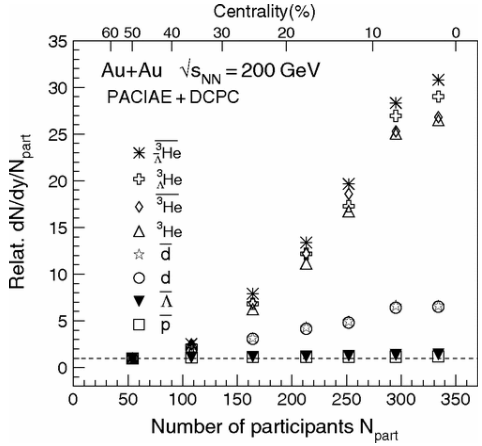
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out ($T_{chem}$) : (hyper)nuclei are very sensitive to $T_{chem}$ because of their large mass (M)
  - Exponential dependence of the yield: $dN/dy \propto e^{(-m/T_{chem})}$



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

## Coalescence

- 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 and be created again by final-state coalescence



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

# Can we distinguish coalescence vs thermal model?

- Can we understand if the models are in contrast and up to which extent?
- For which system(s) do they provide a valid description?
- Can they describe all the particles in their scope of validity?

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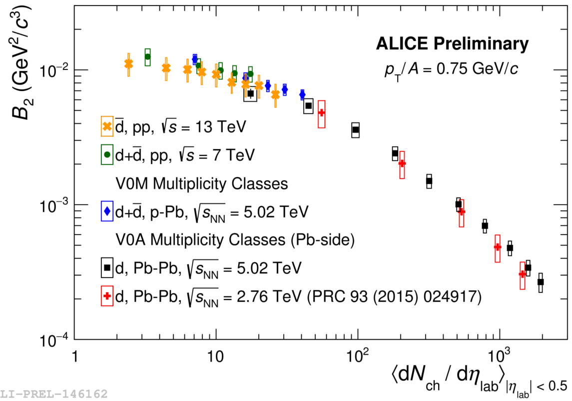
- For which system(s) do they provide a valid description?
- Can they describe all the particles in their scope of validity?
  - Recently, it has been proposed to address these questions by looking at the coalescence parameters (*$B_2$*, *$B_3$*, *$B_{3,\Lambda}$*) as the key observables, studied as a function of the source radius.



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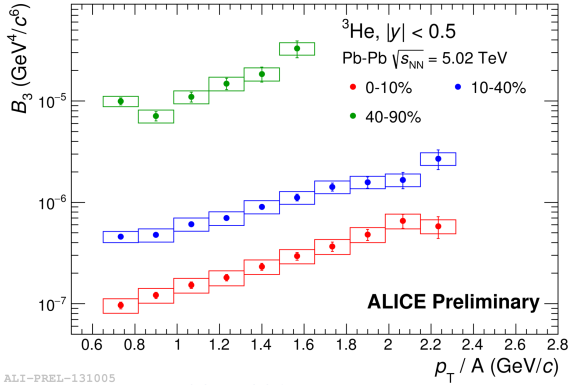

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ALICE-PUBLIC-2017-006

# Advanced coalescence model

- 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
- Since in “small” colliding systems the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space

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

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

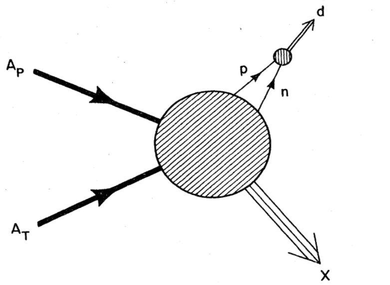

FIG. 1. Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.

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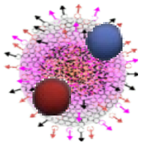
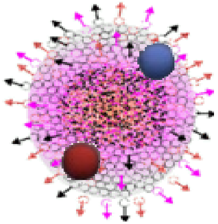
- For “large” systems, the size of the emitting volume ( $V_{\text{eff}}$) has to be taken into account: the larger the distance between the protons and neutrons which are created in the collision, the less likely it is that they coalesce



(small fireball)



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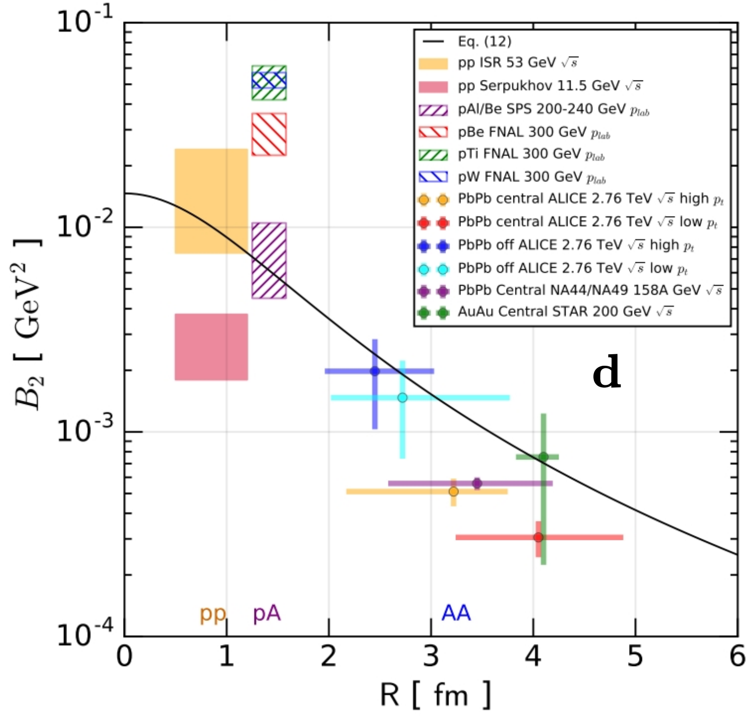
- The source can be parameterized as rapidly expanding under radial flow (hydro)
- The coalescence process is governed by the same correlation volume ("length of homogeneity") which can be extracted from HBT interferometry
- The source radius enters in the $B_{\mathrm{A}}$ and in the quantum-mechanical correction $\langle C_{\mathrm{A}} \rangle$ factor that accounts for the size of the object being produced (d, $^{3}$He, …)

$$B_A = \frac{2J_A+1}{2^A} A \langle \mathcal{C}_A \rangle \frac{V_{\mathrm{eff}}(A, M_t)}{V_{\mathrm{eff}}(1, m_t)} \left( \frac{(2\pi)^3}{m_t V_{\mathrm{eff}}(1, m_t)} \right)^{A-1}$$

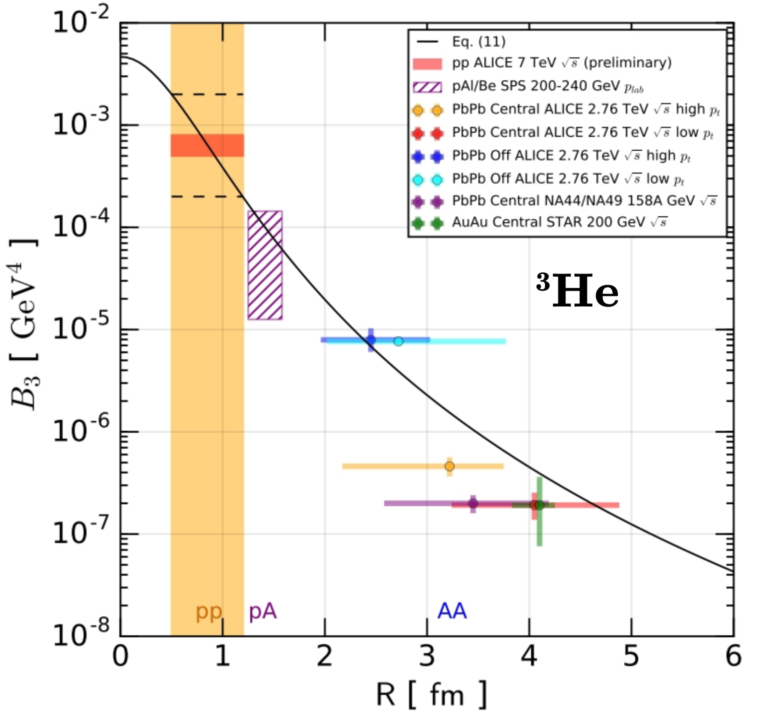
R. Scheibl, U. Heinz, PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

# $B_2$, $B_3$ from advanced coalescence

$$\frac{B_2}{\mathrm{GeV}^2} \approx 0.068 \left( \left( \frac{R(p_t)}{1\ \mathrm{fm}} \right)^2 + 2.6 \left( \frac{b_2}{3.2\ \mathrm{fm}} \right)^2 \right)^{-\frac{3}{2}} \quad [1]$$



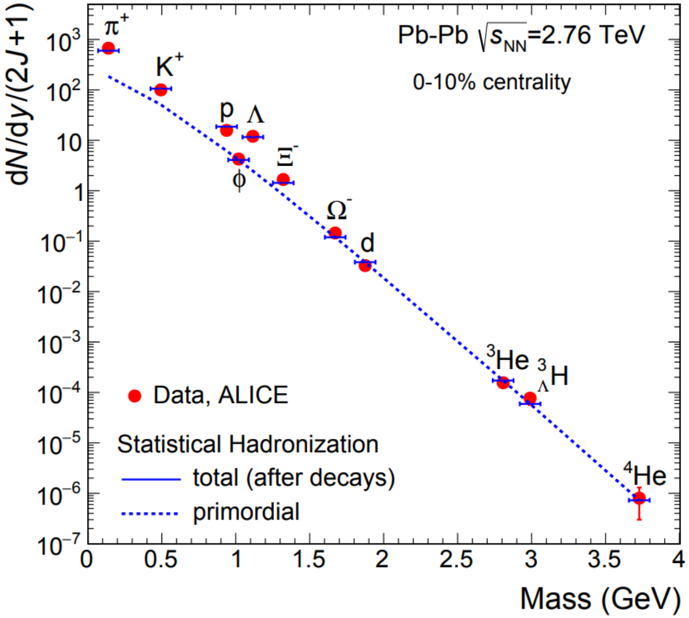
$$\frac{B_3}{\mathrm{GeV}^4} \approx 0.0024 \left( \left( \frac{R(p_t)}{1\ \mathrm{fm}} \right)^2 + 0.8 \left( \frac{b_3}{1.75\ \mathrm{fm}} \right)^2 \right)^{-3} \quad [1]$$



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

# $B_A$ from thermal model + blast-wave

- Statistical thermal models provide the yield of nuclei very precisely



A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel arXiv:1710.09425

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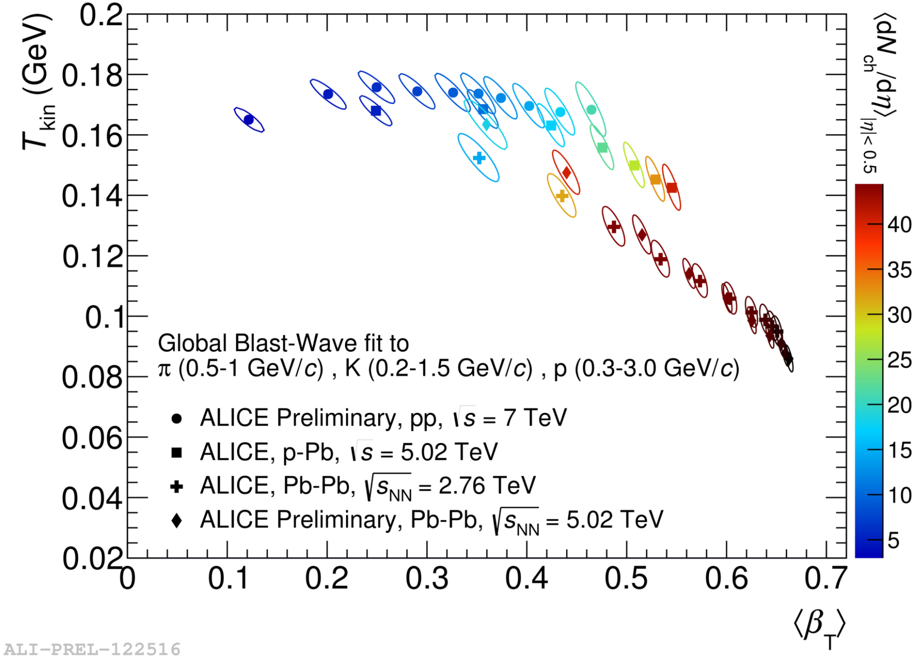
- To evaluate the $B_A$, the $p_T$ spectra have been modeled with a Blast-Wave parametrization, with parameters fixed by fit to π,K,p



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- The normalization for $^3_\Lambda$H is extracted from the $^3$He and the $S_3$ predicted by thermal model

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- Coalescence parameters $B_A$ are extracted from using

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

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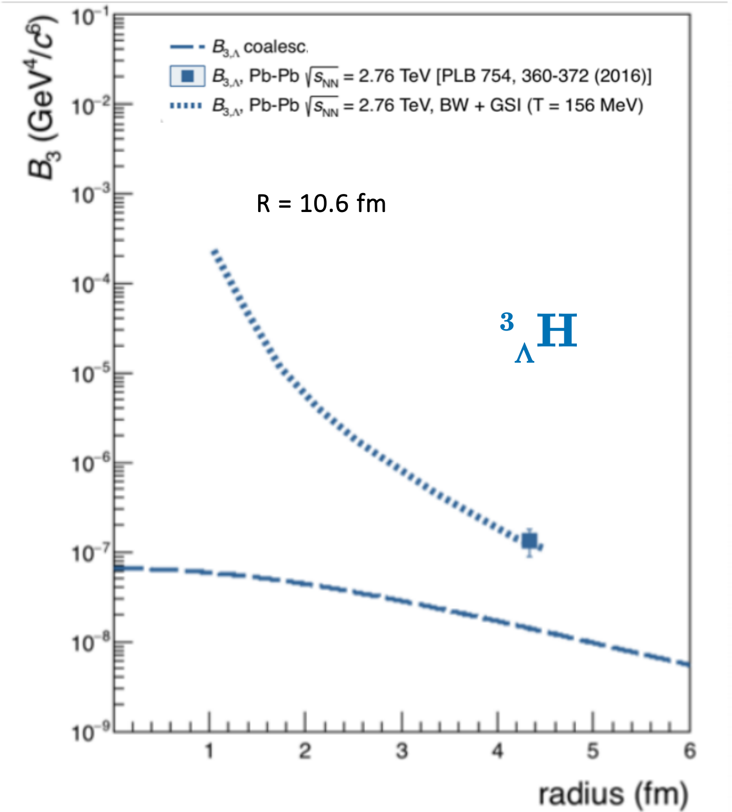
Nucleus $p_T$ spectra

Proton $p_T$ spectra

# Sensitivity to the radius of the object: the $B_{3,\Lambda}$ case



F.Bellini, A.Kalweit Private Communication
Based on PRD 96 (2017) 103021

- $^3_\Lambda$H is a very loosely bound state (→ large radius)
- Predictions of $B_{3,\Lambda}$ from advanced coalescence and SHM+Blast vary a lot when different $^3_\Lambda$H radii are considered
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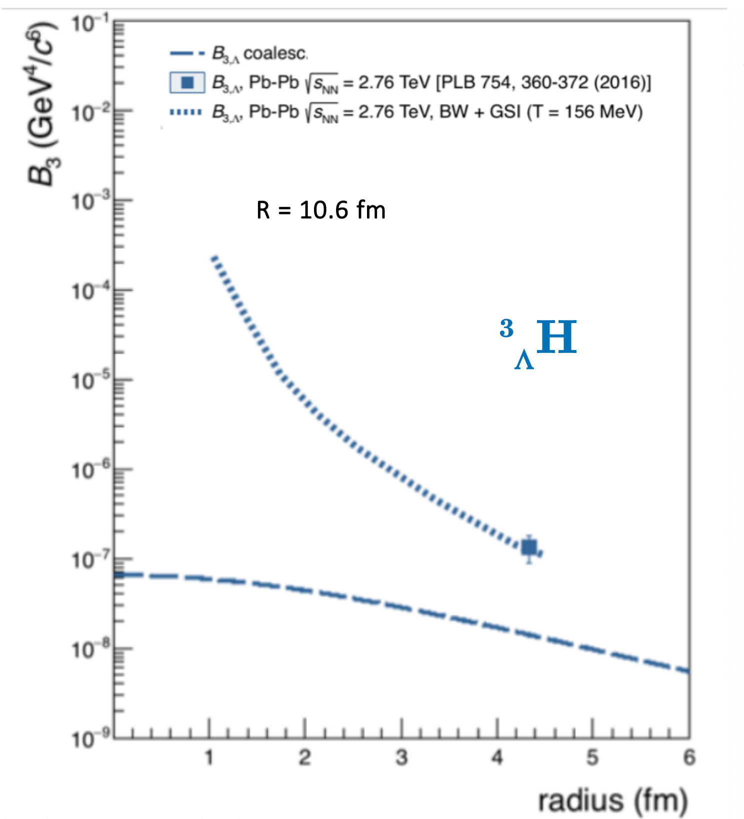

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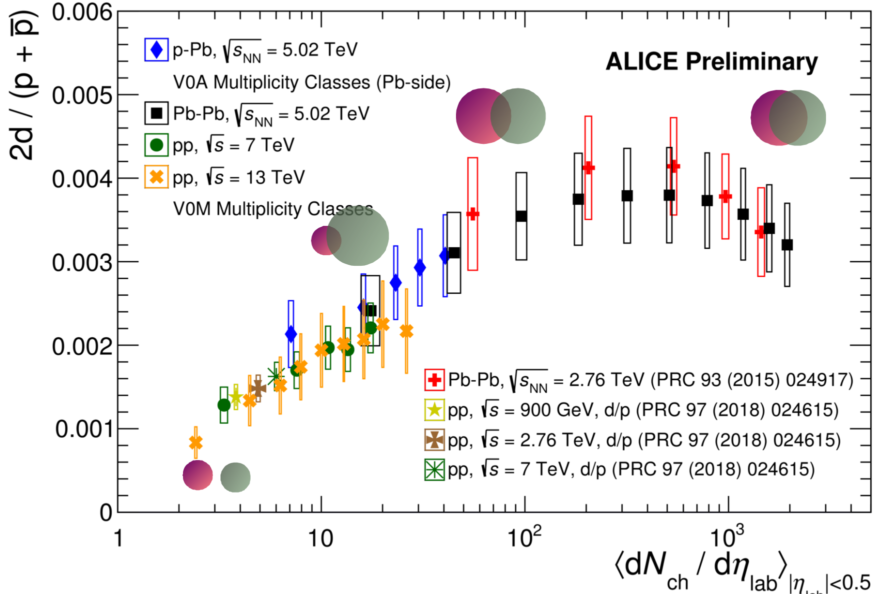
    - This measurement is fundamental to understand hyper-nuclei production mechanism in Pb-Pb collisions
- **Questions to be addressed in Run 3 and 4**
    - What is the centrality dependence of the hypertriton production in Pb-Pb?
    - Can we produce at all the hypertriton in pp collisions?

# Particle ratios: Coalescence vs Thermal model



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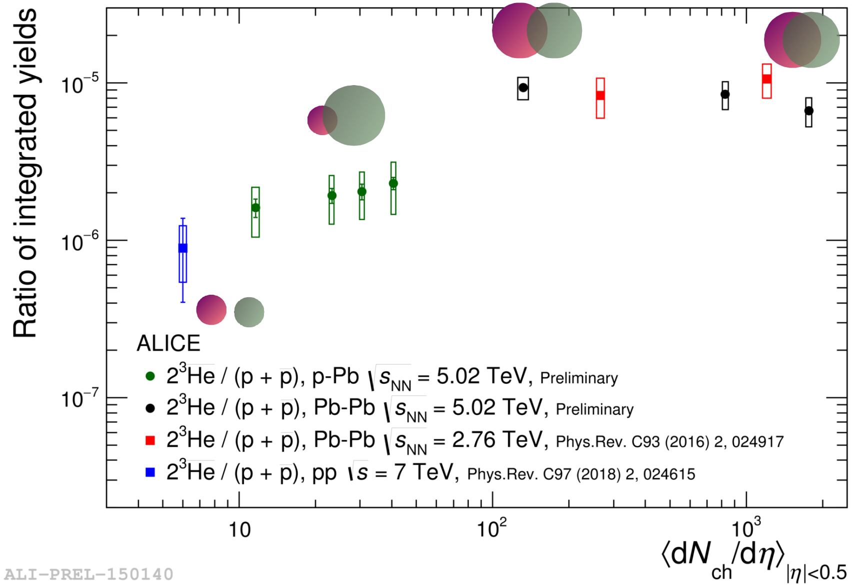
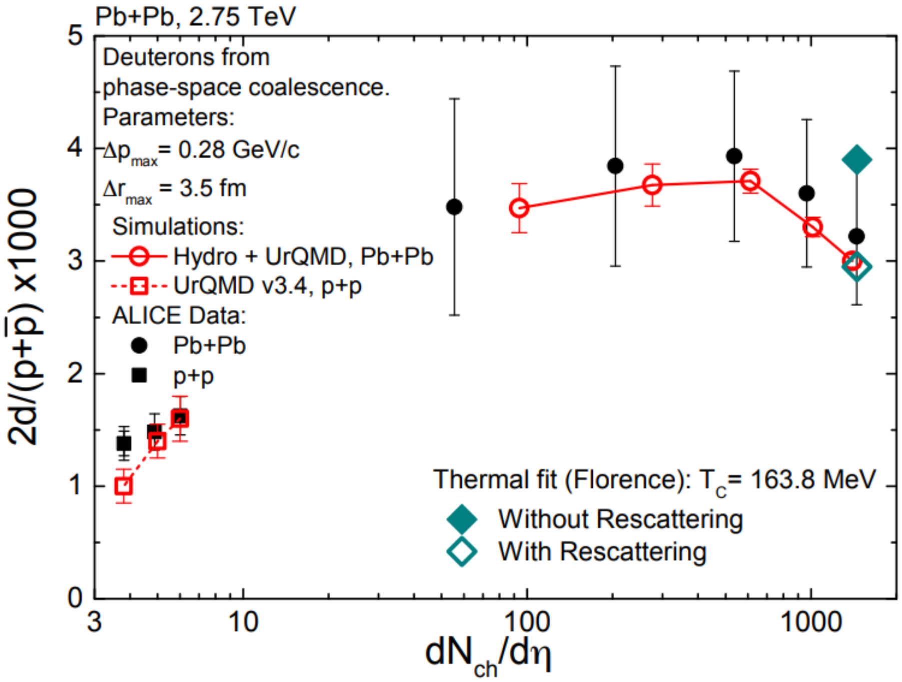


ALI-PREL-150140

- Simple coalescence works in small systems while thermal models describe better the Pb-Pb data
- Hint of deuteron suppression in central collisions (not significant with the current uncertainties)
- $^3$He/p: a factor 5 is seen going from small systems to Pb-Pb. If this will be confirmed by studies on larger data samples, a unified description will be more challenging

# Coalescence in UrQMD

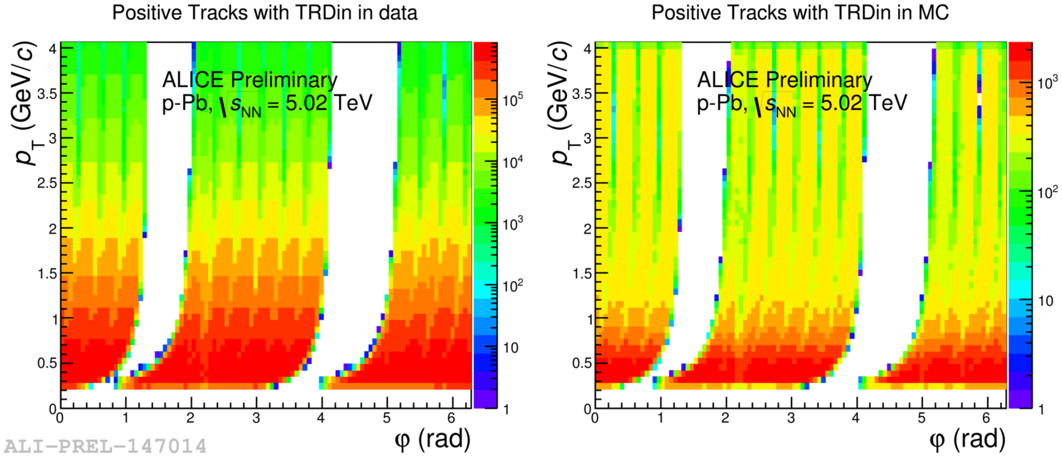


- Models with rescattering provide a significant difference for the d/p in central collisions
- At the moment our data are consistent with both the predictions.

  → The reduction of systematic uncertainties is mandatory for future measurements

Reinhard Stock (QM2018) https://indico.cern.ch/event/656452/contributions/2869985/attachments/1645416/2629552/Stock_QM2018-2.pdf

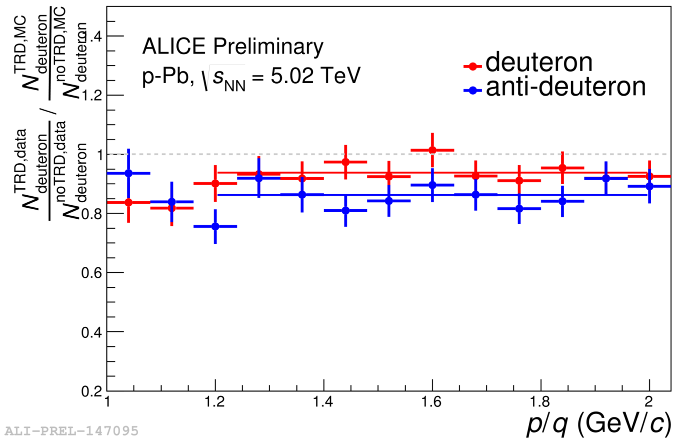
# Improving the anti-nuclei production systematics



Positive Tracks with TRDin in data

Positive Tracks with TRDin in MC

ALI-PREL-147014

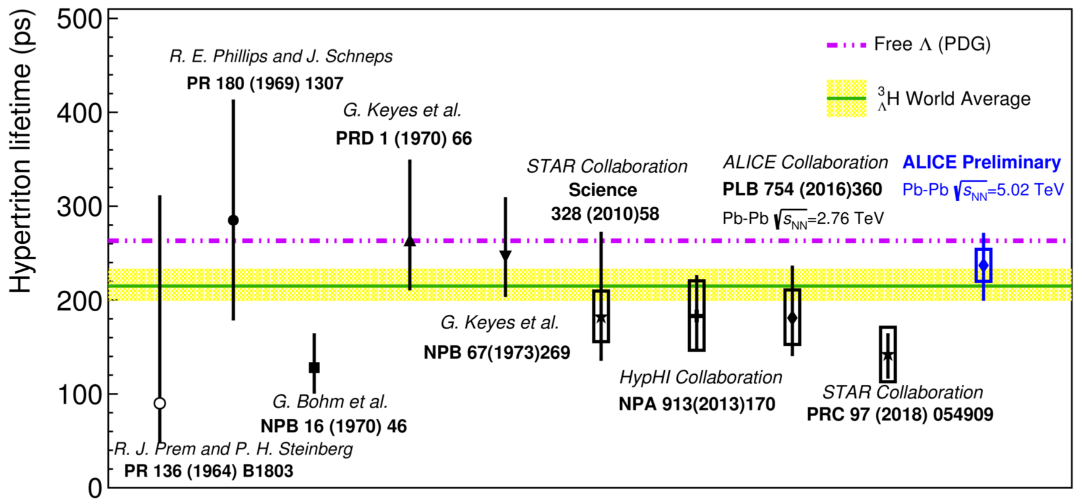


ALI-PREL-147095

- Knowing precisely the interaction of nuclei with the detector is fundamental for precise measurements
- At present, efficiencies are evaluated on MC using GEANT3 + empirical model for absorption of anti-nuclei and Geant4: results are quite different (O(10%))
- ALICE is now studying the discrepancies between data and MC using the TRD detector as a “target” for (anti-)nuclei projectiles
- First studies show that the current uncertainty can be reduced by applying a better data driven correction to our measurements.

# Precise measurements of $^{3}_{\Lambda}$H lifetime

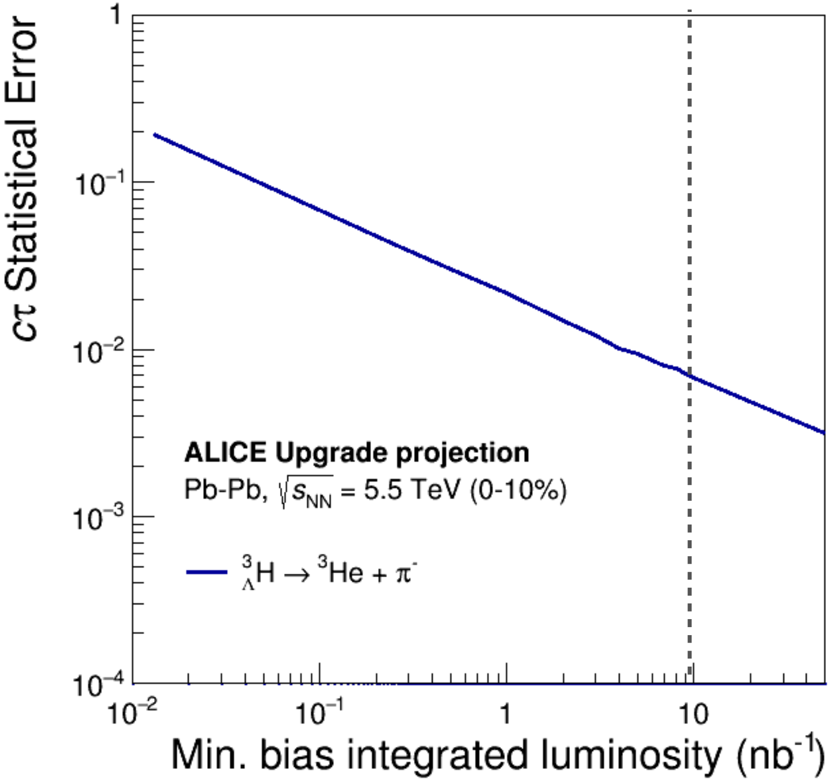
# ${}^{3}_{\Lambda}$H lifetime determination



ALI-DER-161043

- ALICE can be used also for hypernuclear physics measurements:
  - the present data provide one of the most precise measurement of ${}^{3}_{\Lambda}$H life
- How much will increase our precision on the measurement?

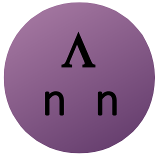
# ${}^{3}_{\Lambda}$H lifetime determination



- ALICE can be used also for hypernuclear physics measurements:
  - ➢ the present data provide one of the most precise measurement of ${}^{3}_{\Lambda}$H life
  - How much will increase our precision on the measurement?
    - With 13μb$^{-1}$ (2015 run) a statistical uncertainty of ~14% has been measured
    - With 10nb$^{-1}$ (Run 3 and 4)a statistical uncertainty of ~0.7% is foreseen
    - The increase of the measured statistics will reduce also the systematics uncertainties → the final evaluation is work in progress

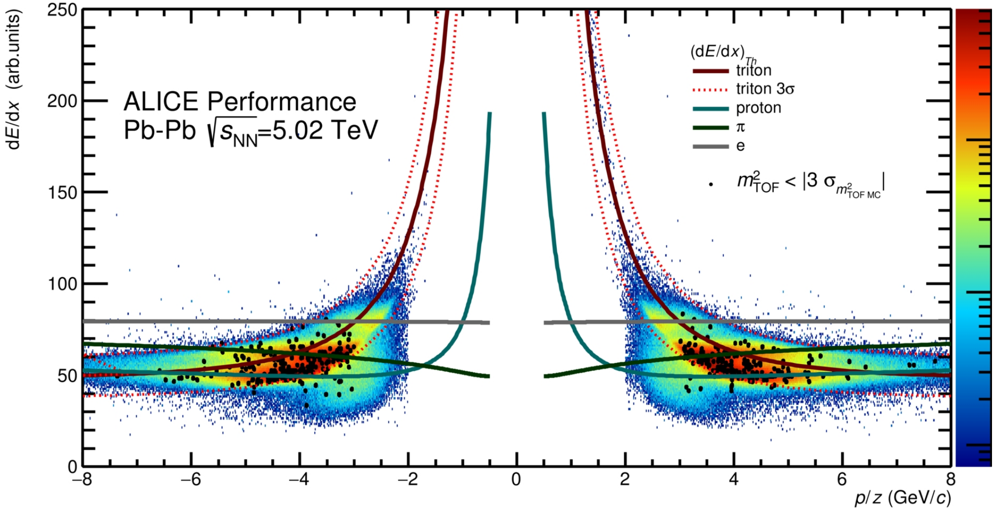
# Searches for exotic bound states

# Λnn bound state



Bound state of Λnn? HypHI experiment at GSI sees evidence of a new state: Λnn → t+ $\pi^-$

C. Rappold et al. (HypHI collaboration), Phys. Rev. C88, 041001(R) (2013)



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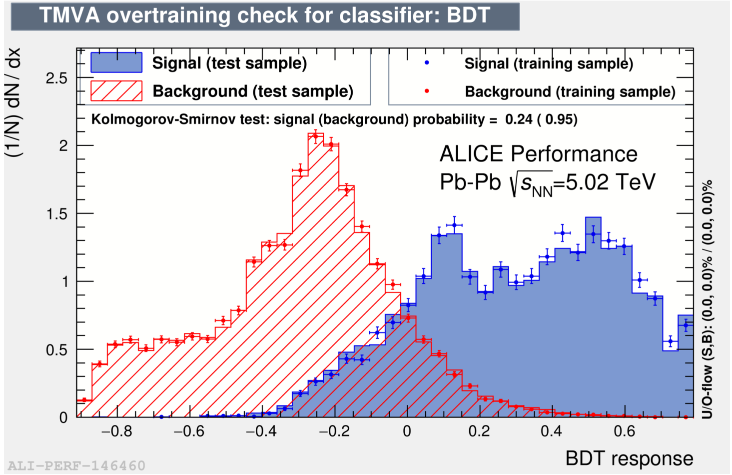


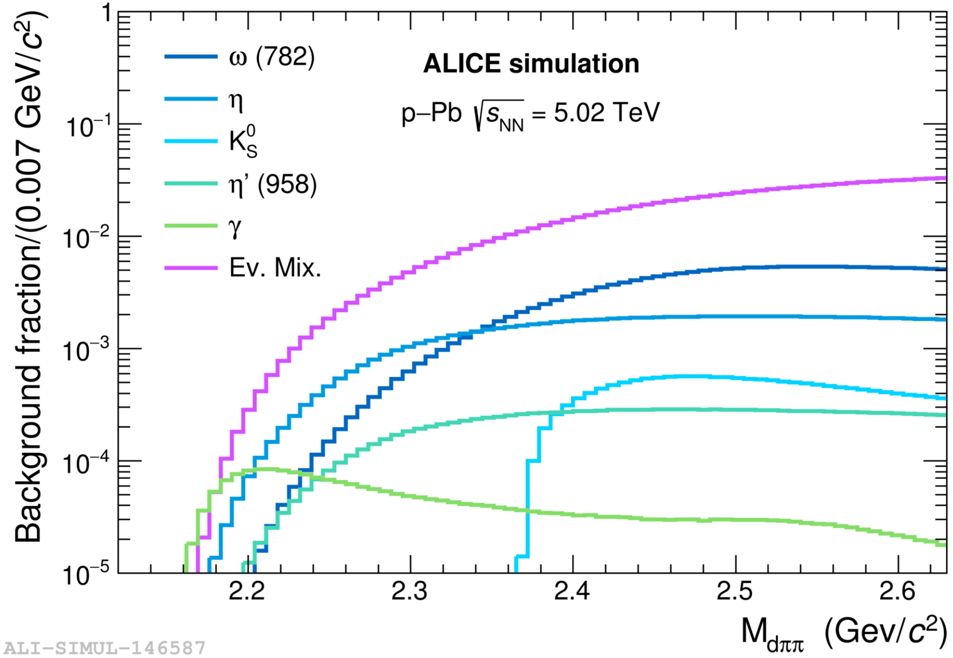
ALI-PERF-146460

- The main challenge of this analysis is that the signal is not only rare, but it may not even exist.
- Machine learning (ML) approach has been used to consider all the features of the signal.
- This study is not (yet) conclusive but will serve as a baseline for the search of other “exotic” particles

# Search for d*

**d***

In 2011 the WASA-at-COSY Collaboration reported the observation of a resonance compatible with the predicted d* in all relevant two pion decay channels as well as in np scattering. P. Adlarson, et al., Phys. Rev. Lett. 106 (2011) 242302



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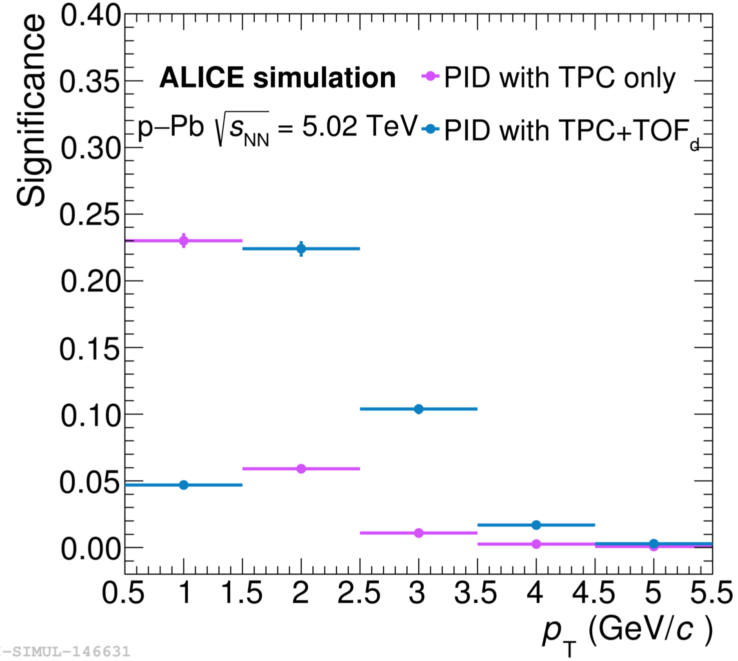
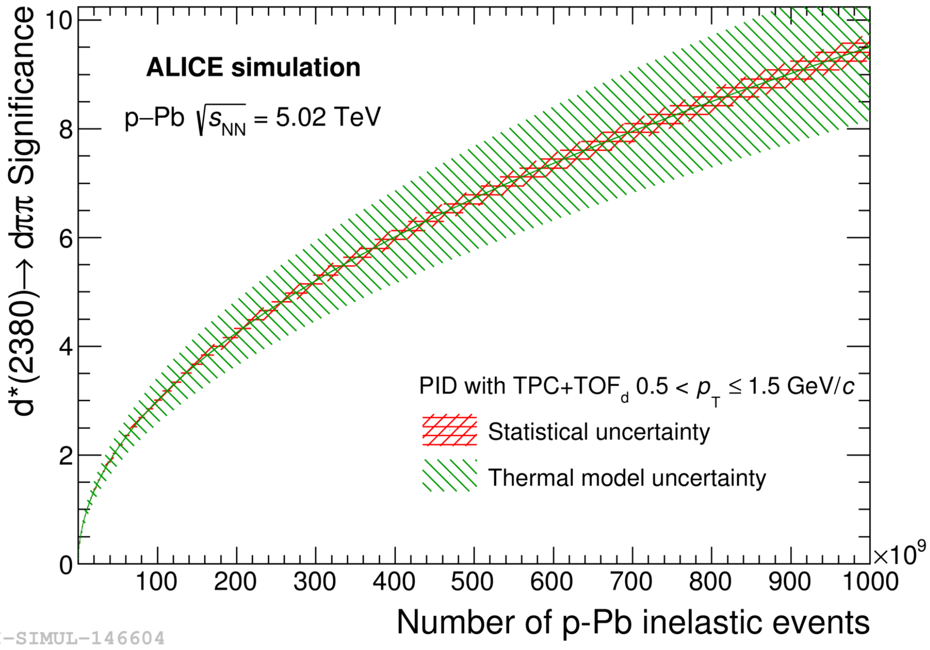


ALI-SIMUL-146631

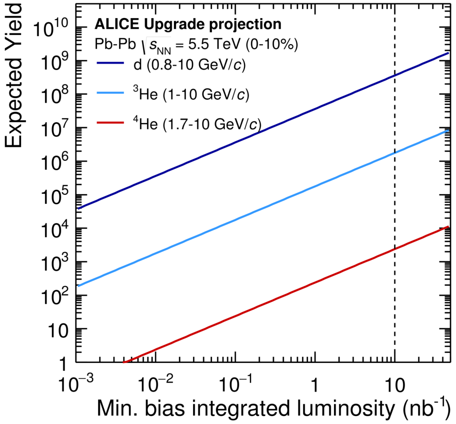
# Search for d*



- The significance of the d*(2380) signal measurement is low due to the huge background and to the low reconstruction efficiency at the production peak.
- Two methods to increase the significance:
  - Reducing background → Optimization of rejection criteria
  - Increasing data sample :
    - ~ 3 x $10^{11}$ events needed to reach 5σ
      - p-Pb integrated luminosity end of Run 4: ~100 $nb^{-1}$ → ~2x$10^{11}$ events
      - Very challenging measurement, but feasible at the end of Run4

# Conclusions

- After the LS2 ALICE will be able to collect data with better performance at higher luminosity
- All the physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4:
  - Differential measurements of A=3 (hyper)nuclei
  - Potential for discovery for A = 4 (anti)hypernuclei
  - Measurements of $B_4$ for $^{4}$He, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He



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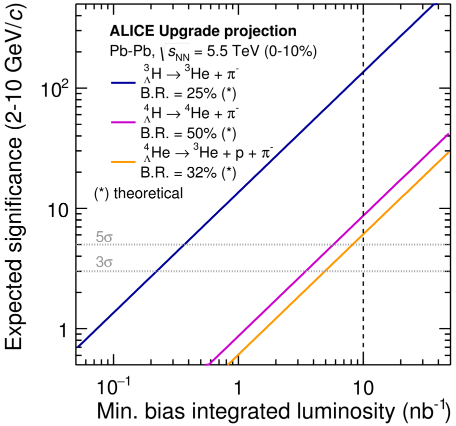

ALI-SIMUL-140350

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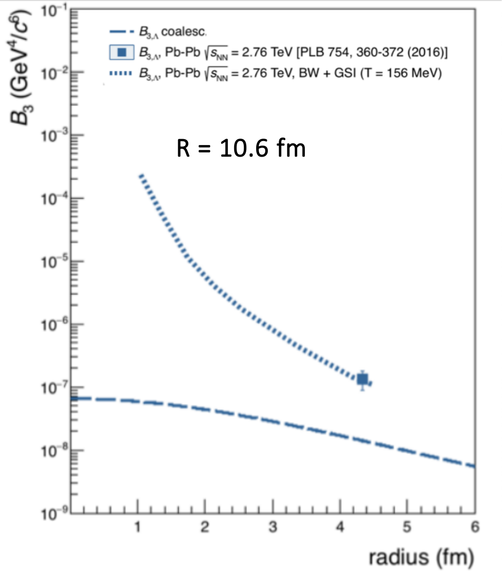
- The precise measurement of $B_A$ will shed light on the understanding of nuclei production mechanism



R = 10.6 fm

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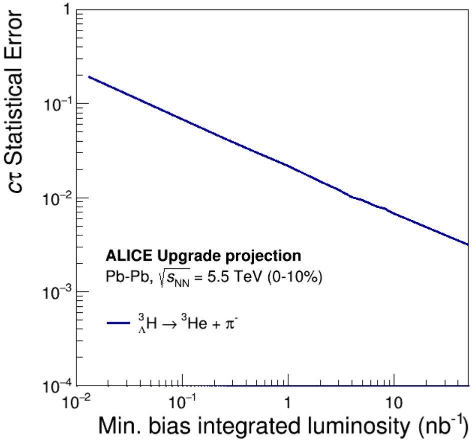
- All the physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4:
  - Differential measurements of A=3 (hyper)nuclei
  - Potential for discovery for A = 4 (anti)hypernuclei
  - Measurements of $B_4$ for $^4$He, $^4_\Lambda$H and $^4_\Lambda$He
- The precise measurement of $B_A$ will shed light on the understanding of nuclei production mechanism
- The $^3_\Lambda$H lifetime measurements will reach a statistical precision < 1%



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- The search for exotic bound systems will profit from the large statistics
- The reduction of systematics uncertainties will be mandatory

# Backup

# Mapping $\langle \mathrm{dN}/\mathrm{d}\eta \rangle$ into system radius

- ALICE measured spectra and yields in V0M (or V0A for p-Pb) multiplicity bins and we do not have HBT radii measurements with this estimator in all cases.
- The following assumptions have been done:
    - the radii defining the volume of the source are equal ($R_{side} = R_{long} = R_{out} \equiv R$)
    - R = 4.5 fm from the π HBT radii at the highest $\langle \mathbf{k}_{\mathrm{T}} \rangle$ in central Pb-Pb
    - for pp, $R \approx R_p \sim 0.8$ fm [PRD 96 (2017) 103021]
    - linear dependence of the $\langle d\mathrm{N}/\mathrm{d}\eta \rangle^{1/3}$ vs radius across collision systems
- Mapping of $\langle d\mathrm{N}/\mathrm{d}\eta \rangle \rightarrow$ R applied to ALICE data and Thermal + Blast-wave predictions.

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