# Hyper nucleus production in heavy ion collision experiments

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Strangeness in Quark Matter 2015
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# Outline

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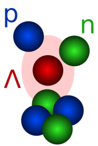
# What and Why Hypernucleus ?

Classic example in Nuclear Physics: Neutron Star

- Core of neutron star $\rightarrow$ strangeness ?
- EoS of hyper-matter : Potential of hyperons
  - No direct study of hyperon-nucleon interaction

Yet hypernucleus can also be a probe to phase transition : QGP, Hadron gaz.



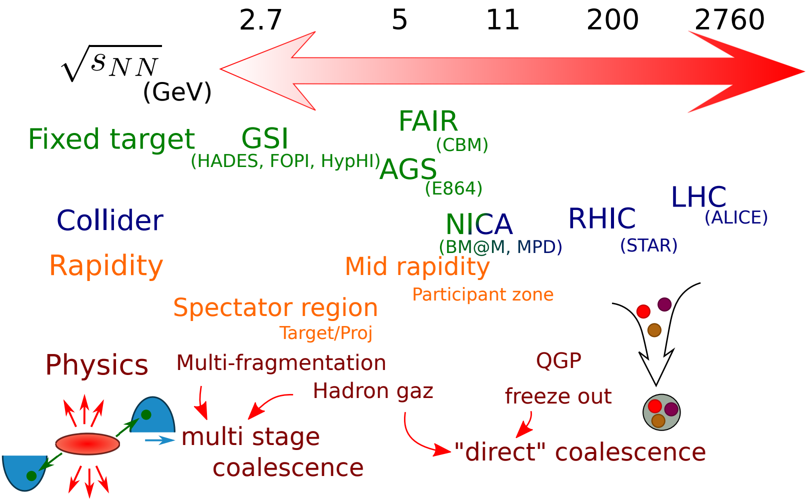

But, what is an hypernucleus ?

- Bound state of p,n and hyperon (Λ, Ξ, Σ) : ${}^{A}_{Y}Z$

And How ?

- Common way : pion, kaon, $e^-$ beam on fixed target.
- More recent : with heavy ion beam !

# hypernuclei with ion beam



# Observables on hypernuclear production in ion collisions

First "Classic" observables :

- Yields, Cross section, Multiplicity of the observed hypernuclei
- Absolute Or within Acceptance, also differential ($y0$, $Pt$)
  - $\rightarrow$ Useful to compare QMD models (dynamics of the reaction)
- Yield ratios : to Λ yield, to nuclear yield.
  - More sensitive to the dynamics than cross section.
  - Can be easier to extract from data (sometime eff. correction cancels out)

One special ratio : "Strangeness Population Factor" : Double ratio $\mathrm{S_3} = {}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He} \cdot \mathrm{p}/\Lambda$

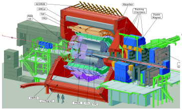
- Introduce by AGS (E864)
- With STAR, found out: nice probe to the phase transition and the QGP formation.
  - Theoretical calculation demonstration

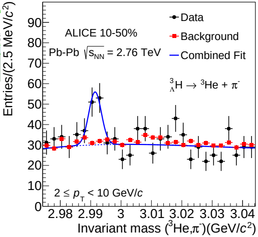
    [S. Zhang et al., Phys. Lett. B 684, 224 (2010)]

# Outline

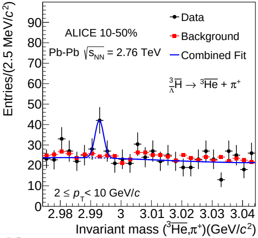
# Mid-rapidity, freeze out : ALICE results

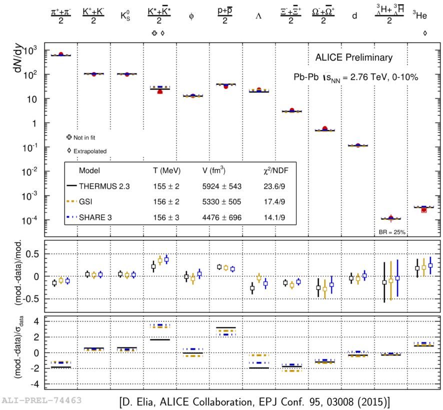
## Collider, Reaction : Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV





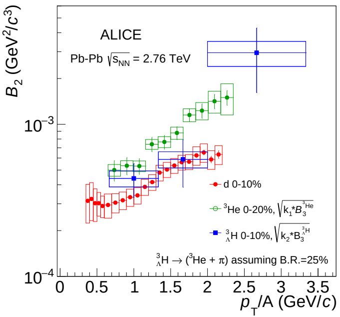

[ ALICE Collaboration, arXiv:1506.08453 (2015)]



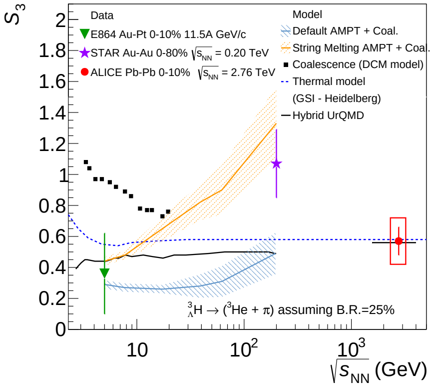




[D. Elia, ALICE Collaboration, EPJ Conf. 95, 03008 (2015)]

# Mid-rapidity, freeze out : ALICE results




[ ALICE Collaboration, arXiv:1506.08453 (2015)]




[ ALICE Collaboration, arXiv:1506.08453 (2015)]

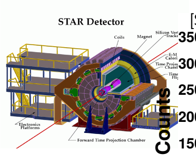
$$B_A = E_A \frac{d^3 N_A}{d^3 p_A} / (E_P \frac{d^3 N_P}{d^3 p_P})^A$$

- Not as simple as expected !

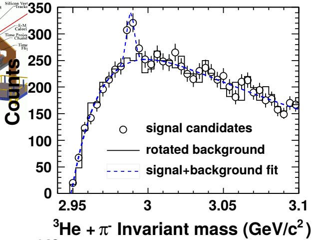
AMPT + Coal. : S. Zhang et al., Phys.Lett.B684 (2010) 224.
DCM model : J. Steinheimer et al., Phys.Lett.B714 (2012) 85.
Thermal model : A. Andronic et al., Phys.Lett.B697 (2011) 203.
Hybrid UrQMD : J. Steinheimer et al., Phys.Lett.B714 (2012) 85

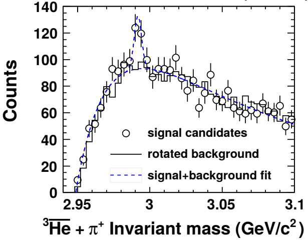
# Mid-rapidity, freeze out : STAR results

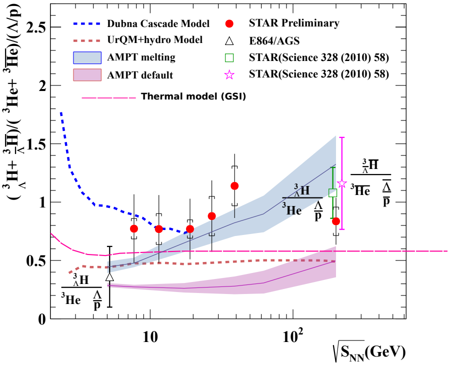
Collider, Reaction : Au+Au @ $\sqrt{s_{NN}} = 200$ GeV




[STAR Collaboration, Science 328, 58 (2010)]



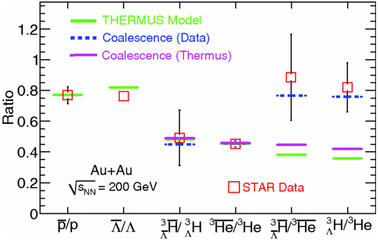



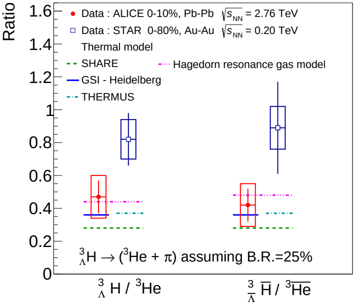

[Y.G. Ma, STAR collaboration, EPJ Conf. 66, 04020 (2014)]
modified version !

# Mid-rapidity, freeze out : STAR results

Coalescence or not coalescence ?




[J. Cleymans et al., Phys.Rev. C84, 054916 (2011).]




[ALICE collaboration, arXiv:1506.08453 (2015)]

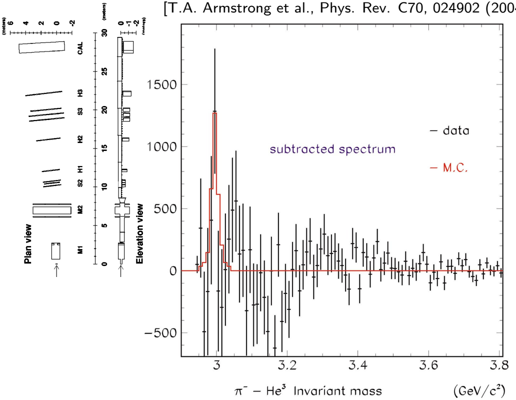
- Coalescence: not clear anymore.
- Hadronization at the freeze-out.

# Outline

# Mid-rapidity, freeze out : AGS E864 results

Fixed target, Reaction: Au+Pt @ 11.5 $A$GeV/c or $\sqrt{s_{NN}} = 4.84$ GeV

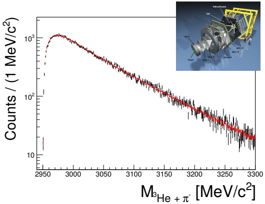
[T.A. Armstrong et al., Phys. Rev. C70, 024902 (2004)]




- $^3_\Lambda$H signal : $2\sigma$ in rapidity range :[1.6, 2.6] ($y_{cm} \sim 2.3$)
- $^4_\Lambda$H : upper limit.
- First to use the ratio $S_3 = {}^3_\Lambda\mathrm{H}/{}^3\mathrm{He}\cdot\mathrm{p}/\Lambda$ and $S_4 = {}^4_\Lambda\mathrm{H}/{}^4\mathrm{He}\cdot\mathrm{p}/\Lambda$
- $S_3 = 0.36 \pm 0.26$
- $S_4(upperLimit) < 0.225$

# Spectator region (target) : FOPI & HADES results :

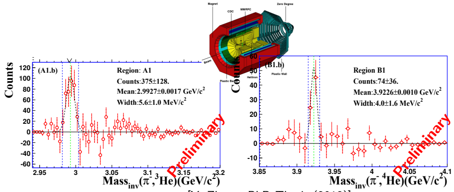
HADES: Ar+KCl @ 1.76$A$GeV or $\sqrt{s_{NN}} = 2.61$ GeV




[HADES Collaboration, Eur.Phys. J. A 49 (2013) 146]

- rapidity: [-0.7, 0.1] ($y_{cm} = 0.86$)
  - Upper limit : ${}^3_\Lambda H/\Lambda = 2.5 \pm 0.3 \cdot 10^{-2}$

FOPI : Ni+Ni @ 1.91 $A$GeV or $\sqrt{s_{NN}} = 2.67$ GeV

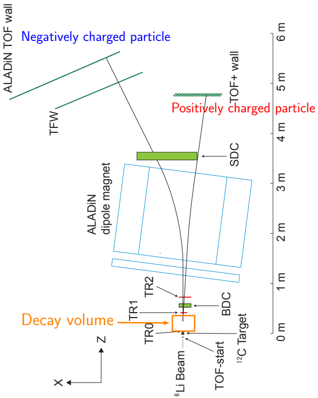


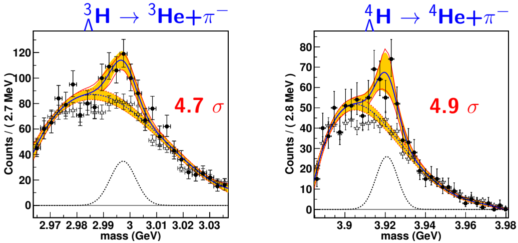

[Y. Zhang, PhD Thesis (2013)]

- Rapidity : [0.2, 0.4] ($y_{cm} = 0.9$) & Pt/m [0.2, 0.4]
  - ${}^3_\Lambda H/\Lambda = 0.52 \pm 0.04$
- Rapidity : [0.15, 0.4] ($y_{cm} = 0.9$) & Pt/m [0.15, 0.35]
  - ${}^4_\Lambda H/\Lambda \sim 0.09$

# Spectator region (projectile) : HypHI results

Fixed target, Reaction : $^{6}$Li+$^{12}$C @ 2 $A$GeV or $\sqrt{s_{NN}} = 2.7$ GeV



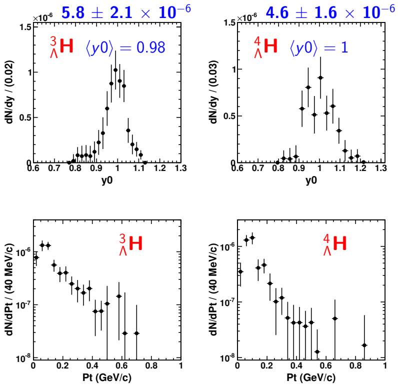

[ C. Rappold *et al.*, Nucl. Phys. A. **913**, 170 (2013) ]

- Before in proj. region :
  - At LBNL Bevatron
    $^{16}$O+polyethylene @ 2.1$A$GeV
    [K. Nield et al., Phys.Rev. C13, 1263 (1976)]
  - At JINR Dubna, $^{4}$He @ 3.7 $A$GeV & $^{7}$Li @ 3.0 $A$GeV + polyethylene
    [A. U. Abdurakhimov et al., N.Cimento A102, 645 (1989)]

# Spectator region (projectile) : HypHI results

Production cross section & multiplicity :

| | CS |
|---|---|
| $\Lambda$ | $1.7 \pm 0.8$ mb |
| ${}^{3}_{\Lambda}\mathrm{H}$ | $3.9 \pm 1.4$ μb |
| ${}^{4}_{\Lambda}\mathrm{H}$ | $3.1 \pm 1.0$ μb |
| ${}^{3}_{\Lambda}\mathrm{H}/{}^{4}_{\Lambda}\mathrm{H}$ | $1.4 \pm 0.8$ |
| ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ | $2.6 \pm 1.4 \times 10^{-3}$ |
| ${}^{4}_{\Lambda}\mathrm{H}/\Lambda$ | $2.1 \pm 1.1 \times 10^{-3}$ |
| ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}\cdot\mathrm{p}/\Lambda$ | $0.28 \pm 0.14$ |
| ${}^{4}_{\Lambda}\mathrm{H}/{}^{4}\mathrm{He}\cdot\mathrm{p}/\Lambda$ | $0.08 \pm 0.04$ |

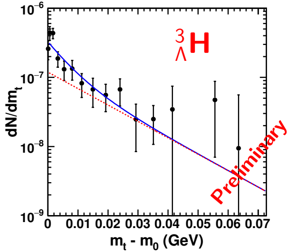


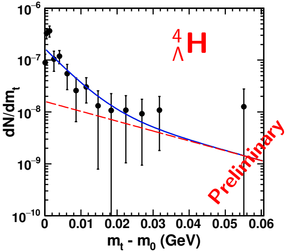

[C. Rappold *et al.*, Phys.Lett. B**747** (2015) 129]

# Spectator region : HypHI results

Inverse slope $T$, $m_t$ spectrum :

$$f(m_t - m_0) = K_1/T_1 \; e^{-(m_t - m_0)/T_1} + K_2/T_2 \; e^{-(m_t - m_0)/T_2}$$




- for $^{3}_{\Lambda}$H : $T_1 \sim 7 \pm 2$ MeV & $T_2 \sim 18 \pm 7$ MeV
- for $^{4}_{\Lambda}$H : $T_1 \sim 6 \pm 2$ MeV & $T_2 \sim 13 \pm 6$ MeV
- very similar to multi-fragmentation ALADIN results

  [T. Odeh et al., Phys. Rev. Lett. 84 (2000) 4557]
- and Goldhaber model :[A.S. Goldhaber, Phys. Lett. B 53 (1974) 306]

# Outline

# Conclusion

In ultra relativistic regime :

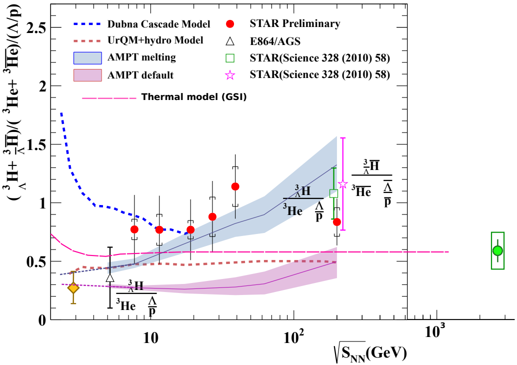
- From ALICE and STAR : similar tendency.
- yet sensitive observables give different conclusion on processes.
- Hadronization at the freeze-out vs coalescence
- Coalescence dependent to the volume and locality within QGP
- More precise measurements will be needed.

In relativistic regime :

- mid-rapidity: similar story: freeze-out.
- spectators: different production mechanism
  - coalescence of mid-rapidity $\Lambda$ with spectator fragments.
  - FOPI : $\sim$ target region / HypHI : spectator region
  - probe to what happen between the participants & spectator !
    - ex: Yield ratio sensitive to time interval of the interaction.

# Conclusion

Mock-up figure of $S_3$ factor with all available results:




[T.A. Armstrong et al., Phys. Rev. C70, 024902 (2004)]
[C. Rappold et al., Phys.Lett. B747, 129 (2015)]
[Y.G. Ma, STAR collaboration, EPJ Conf. 66, 04020 (2014)]
[STAR Collaboration, Science 328, 58 (2010)]
[ALICE collaboration, arXiv:1506.08453 (2015)]

# Conclusion

What next ?

- from ALICE & STAR :
  - Next hypernuclei, A=4 will be difficult to measure (penalty factor)
  - Might focus A=3 hypernuclei with different baryons.
- FOPI : work in progress for finalizing analysis.
- HypHI :
  - Second exp. performed $^{20}$Ne+$^{12}$C @ 2 $A$GeV
    - spectroscopy: $\Lambda$ analysis done ! $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H done !
    - $^{7}_{\Lambda}$Li and $^{6}_{\Lambda}$He analysis in progress.
    - reaction aspect: to be started.
  - Next exp. on proton rich hypernuclei.
- FAIR & NICA : excellent opportunities for the hypernuclear study !