Study of multi-strange dibaryon at the LHC energy

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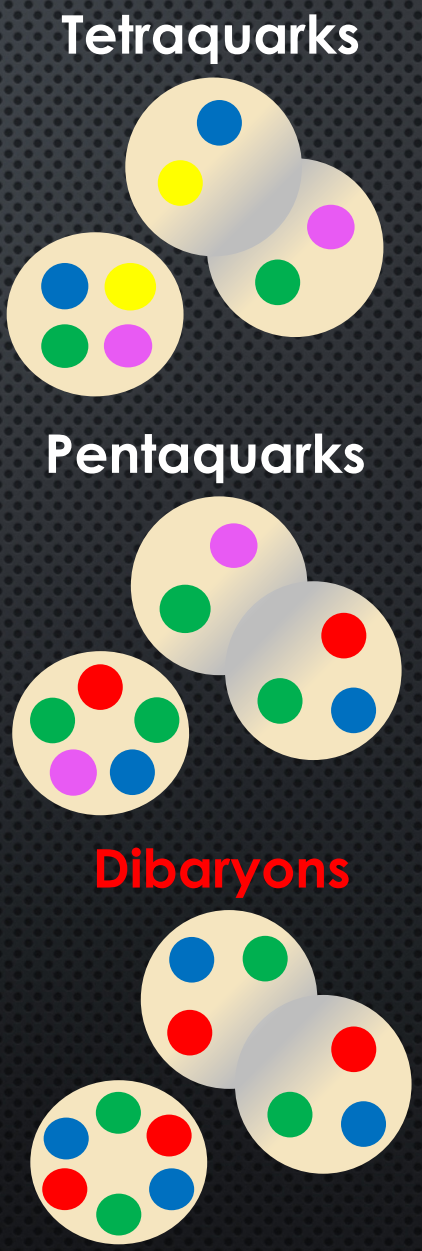
Multi-strange dibaryons

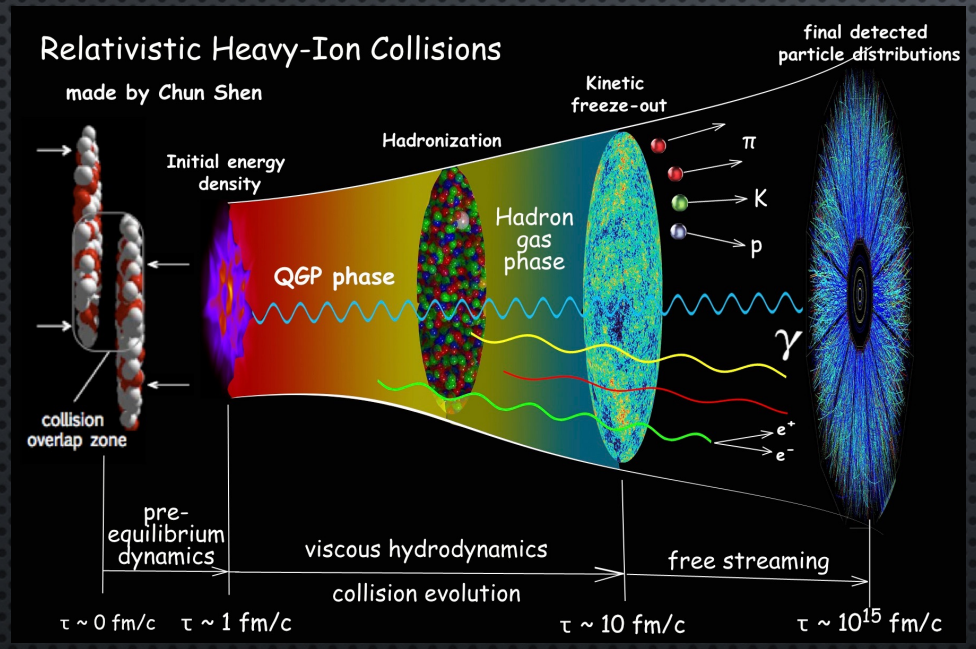
- Long-standing challenge in hadron physics
  - ✓ Multi-quark state other than mesons & baryons
    - Famous H dibaryon as six quark state of $uuddss$
  - ✓ Recent discoveries of exotic hadron candidates with heavy quarks

- Possible multi-strange dibaryons predicted by HAL QCD
  - ✓ Important to study fundamental hadron interactions in flavor SU(3)
  - ✓ Systems with $|S| > 2$ are of particular interest
    - $N\Omega\ (J = 2)$, $\Omega\Omega\ (J = 0)$
  - → Heavy Ion collisions as unique playground for multi-strange systems



Heavy Ion Collisions

- Dynamic space-time evolution of the collisions through phase transition from partonic phase (QGP) to hadronic phase



1. Initial collisions
2. QGP formation in $\tau < 1\mathrm{fm}/c$
3. Cross-over transition to Hadron phase at $T_c \sim 150\mathrm{MeV}$ ($\tau \sim a\ few\ 10\mathrm{fm}/c$)
4. chemical freeze-out happens after the transition
5. Evolution ends at kinetic freeze-out

- Coalescence as a main particle production process
  - ✓ Unique in Heavy ion collisions

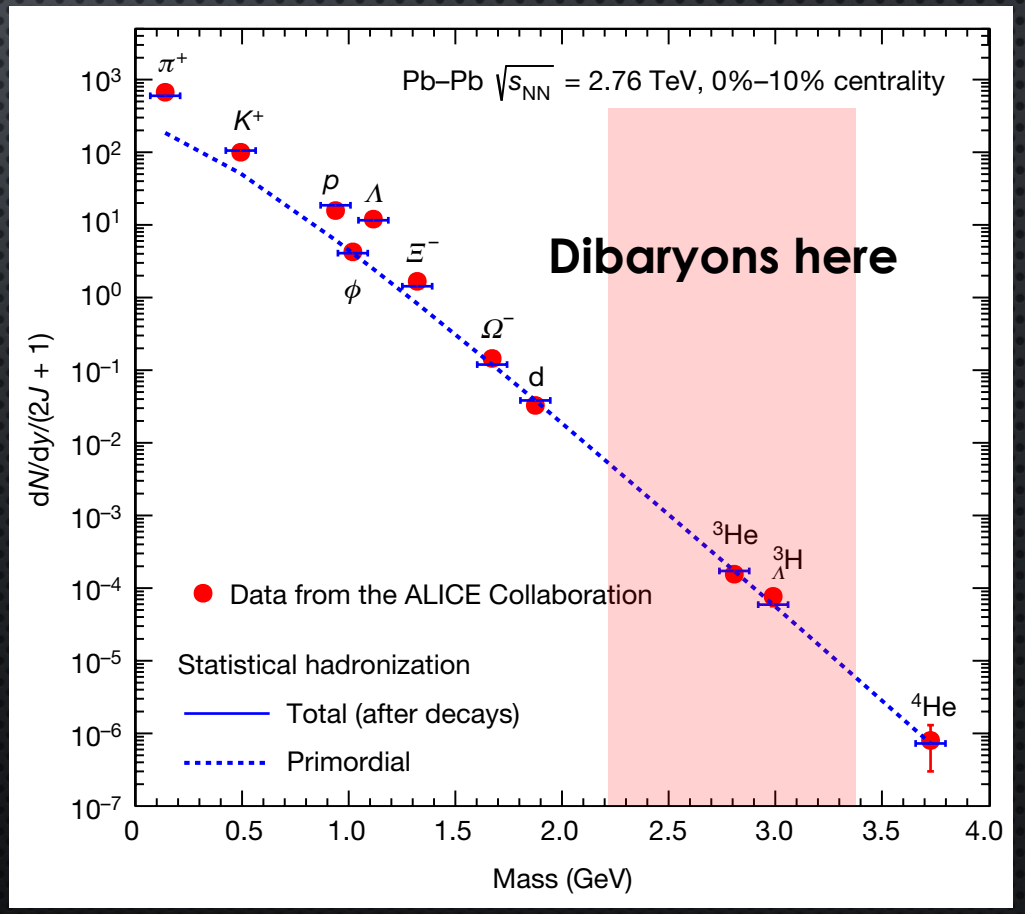
Estimation of dibaryon yields

- Hadron yields well-described by Statistical Hadronization model
  - ✓ Global fit with T_{ch}, μ_B, volume as free parameters
  - ✓ Works even for loosely bound particles **A.Andronic et al., Nature 561, 321-330 (2018)**
- Clear mass dependence of the yield

Rough estimation of dibaryon yields in Pb-Pb 0-10% at ALICE

	RUN-1 (2009-12)	RUN-2 (2015-18)
H	~$10^{4\text{-}5}$	~10^{6}
$N\Omega$	~10^{4}	~10^{5}
$\Omega\Omega$	~10^{2}	~10^{3}

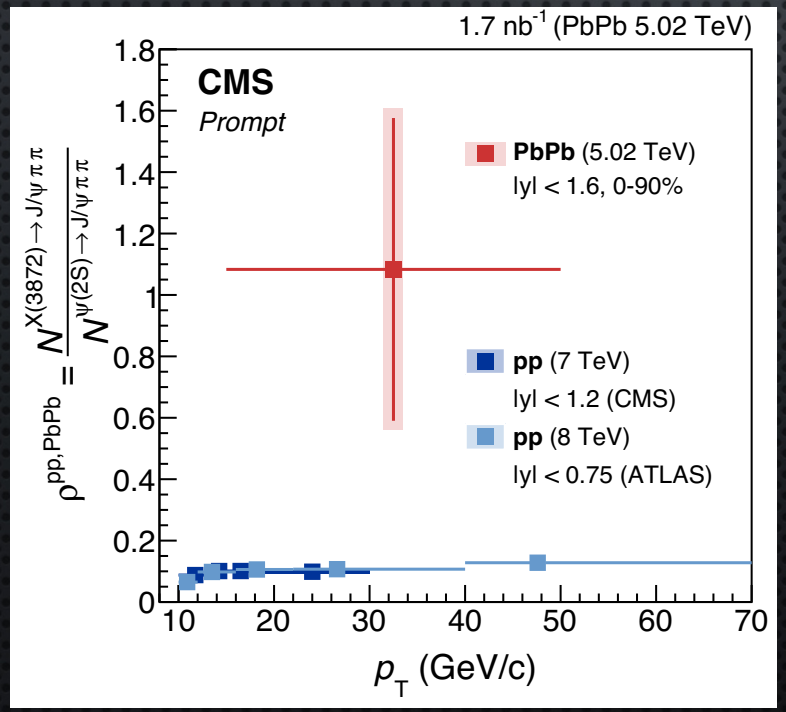
→ Searches for H & $N\Omega$ dibaryons in HIC
  - ✓ Less statistics in pp High Multi. and p-Pb, but better S/N than Pb-Pb

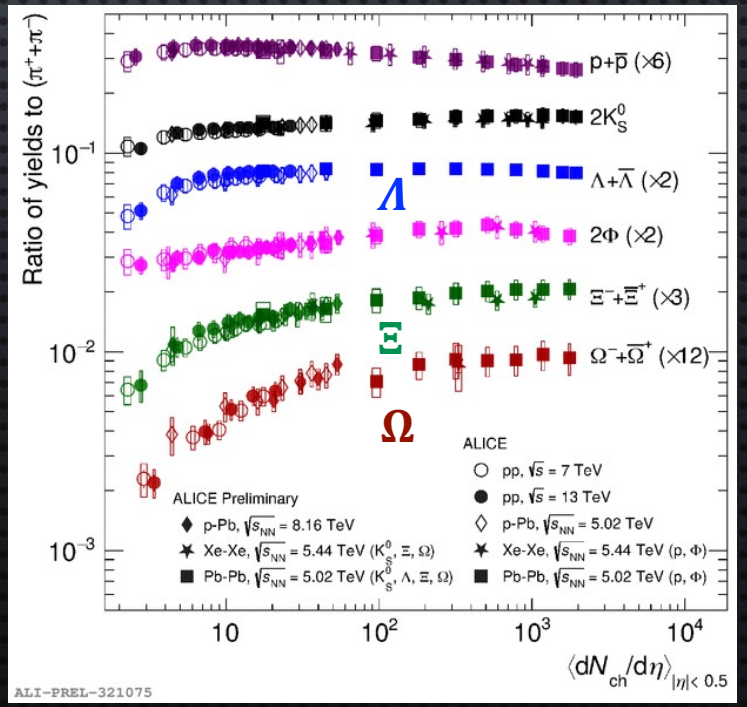


Advantages of Heavy Ion Collisions

- Possible enhancement of exotic hadrons by coalescence
  - ✓ Much larger yield of $X(3872)$ in Pb-Pb than pp
- Enhanced hyperon productions
  - ✓ Increasing at higher multiplicity even in pp/p-Pb collisions

CMS, PRL 128, 032001 (2022)





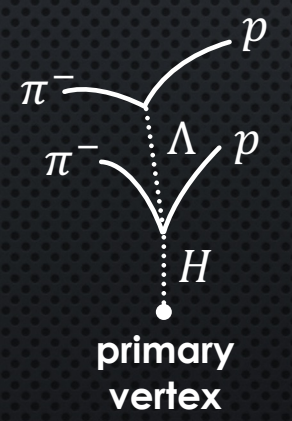
How to search for dibaryons

Measurements with possible daughter particles

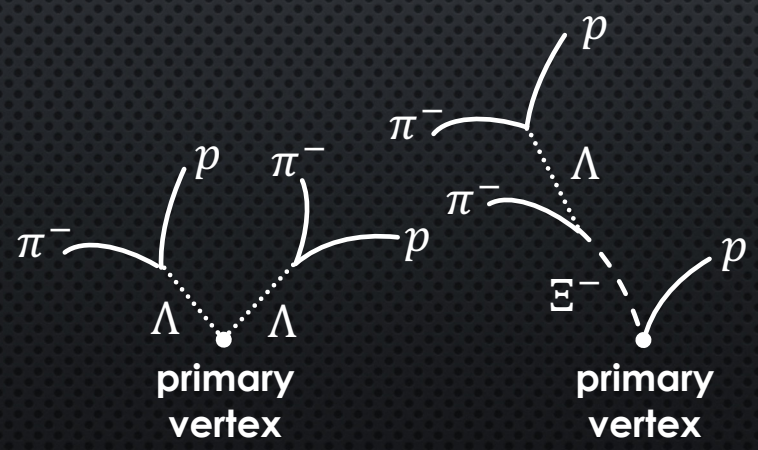
1. Invariant mass reconstruction
   - ✓ Only if the signal width is sufficiently small
2. Two-particle correlation

H dibaryon

a. $H \to p + \pi^- + \Lambda$

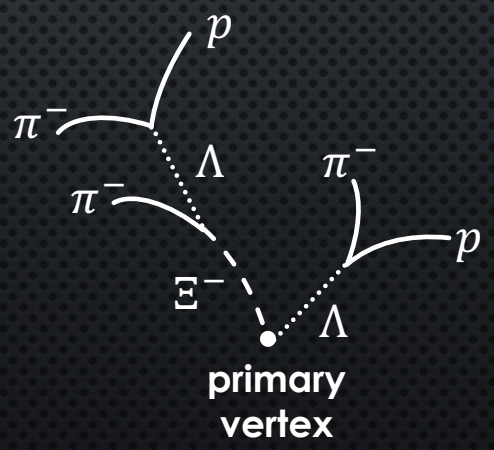


b. $H \to \Lambda + \Lambda/p + \Xi^-$

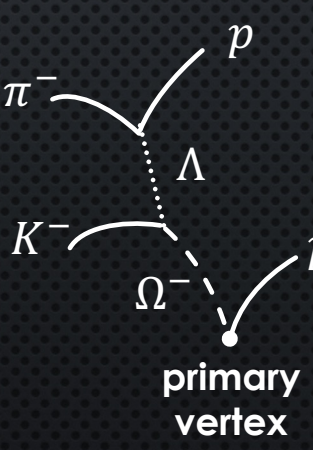


$N\Omega$ dibaryon

c. $n\Omega \to \Lambda + \Xi^-$

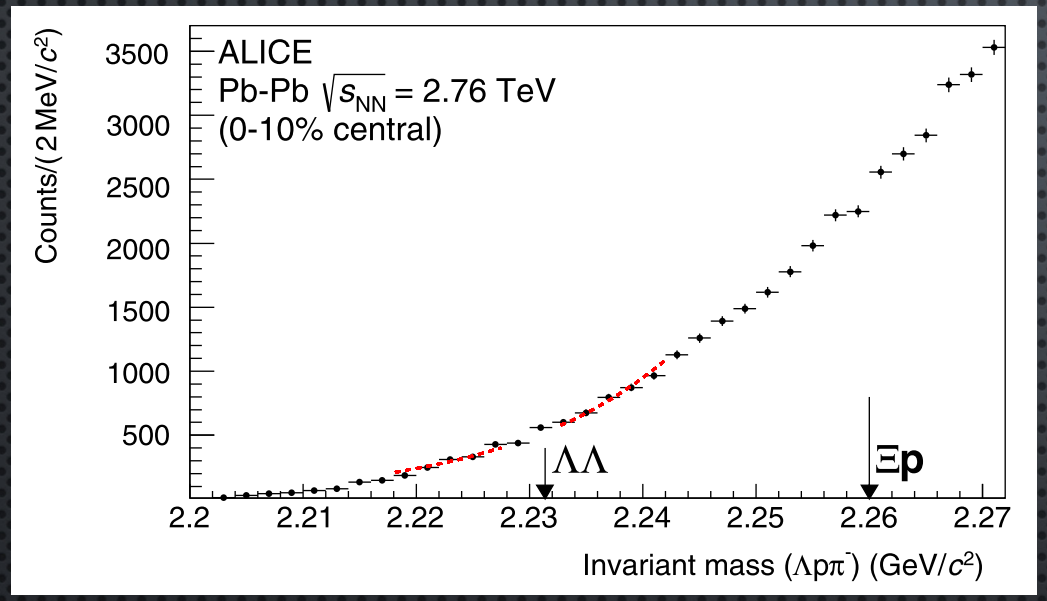


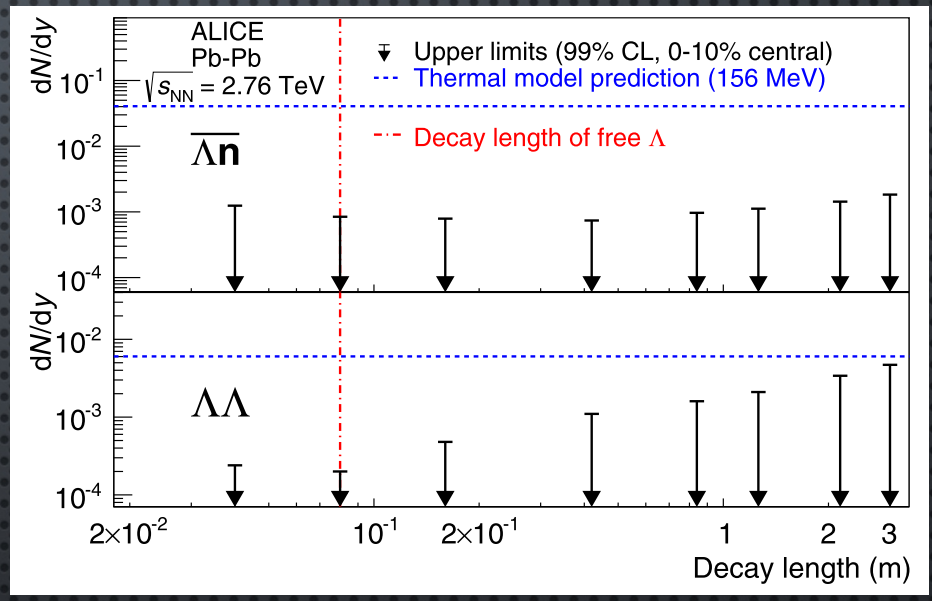
d. $p\Omega \to p + \Omega^-$



$\Lambda\Lambda$ bound state ($H \rightarrow p + \pi + \Lambda$)

ALICE, PLB 752, 267-277 (2016)





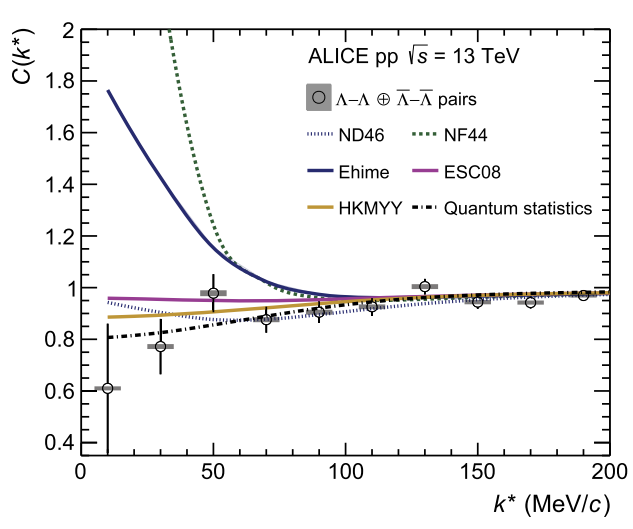
- Search for $\Lambda\Lambda$ bound state as H dibaryon with RUN-1 Pb-Pb data
  - ✓ Invariant mass reconstruction at secondary vertex
    - Search for $\overline{\Lambda n}$ bound state as well by $\bar{d} + \pi^+$ combination

→ No peak was found.

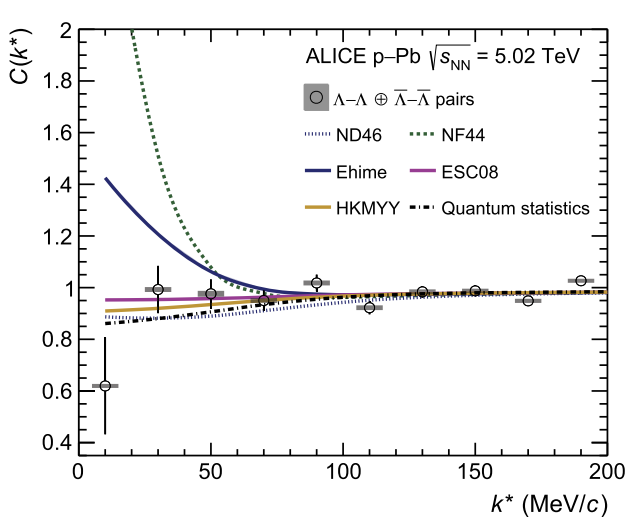
- ✓ Upper limits of the yield below 10^{-1} of model prediction
- ✓ Assumed to be long-lived as long as a free Λ

ΛΛ correlation in pp & p-Pb

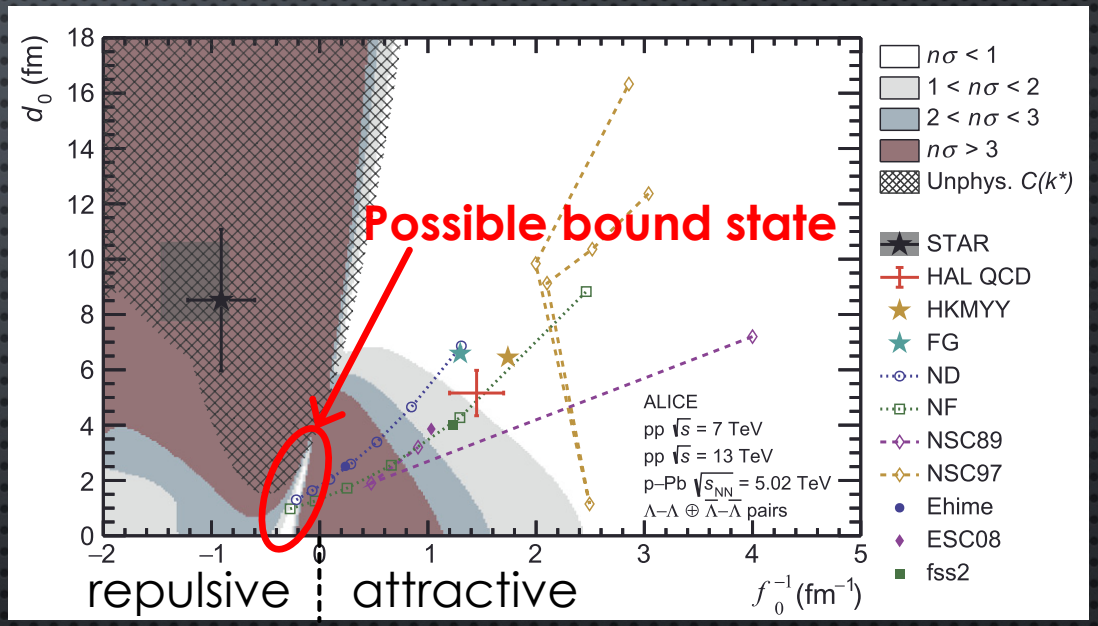
pp, 13TeV



p-Pb, 5.02TeV



ALICE, PLB 797, 134822 (2019)



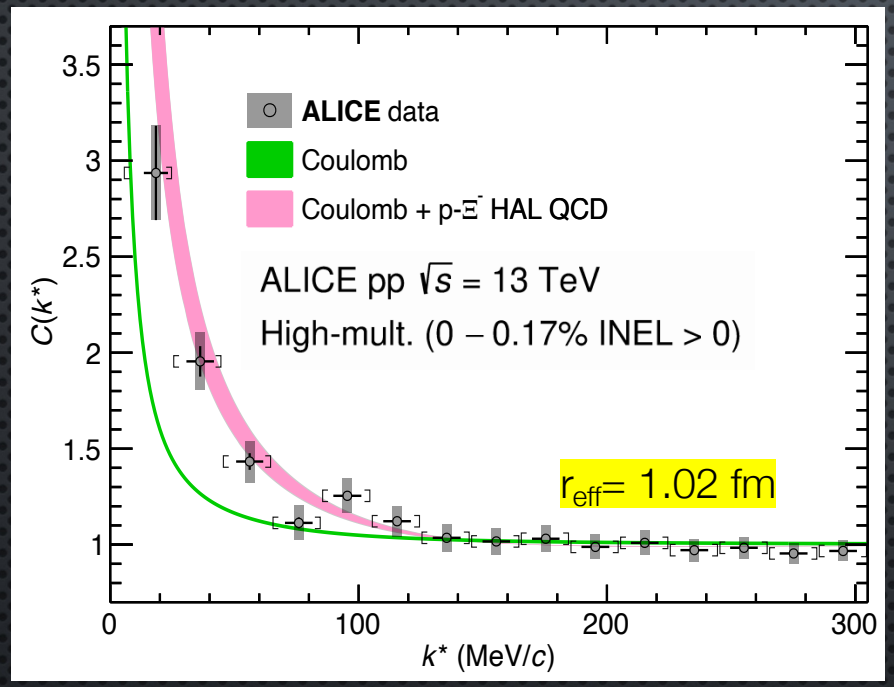
- ΛΛ correlation measured in pp & p-Pb collisions
  - ✓ Flat correlation allowing a large parameter space

→ Almost excluded a possibility of existence of bound state

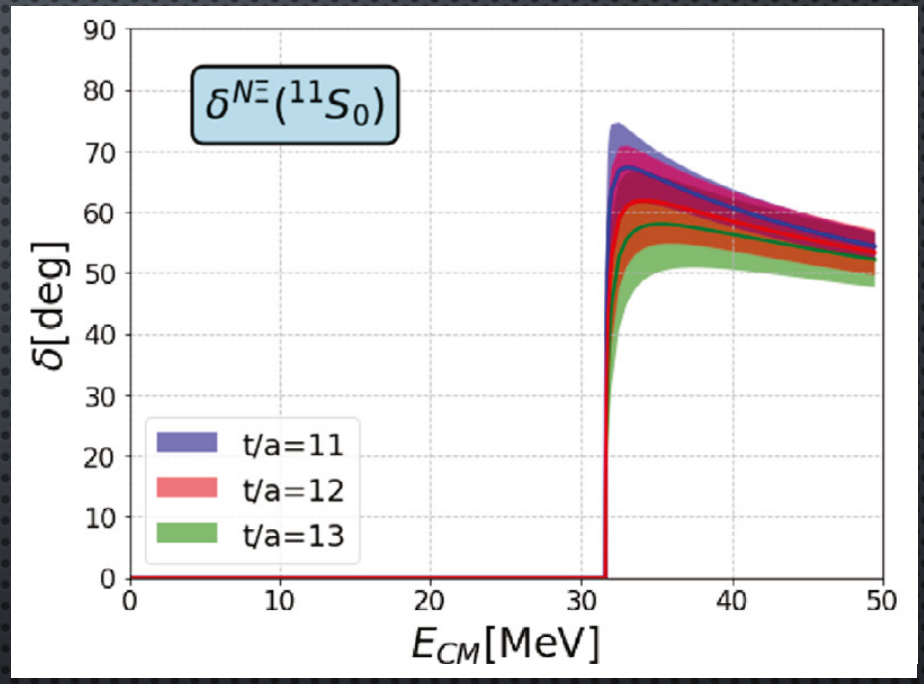
  - ✓ Non-existence of bound state supported by HAL QCD calculations with nearly physical point

H as resonance state ?

ALICE, Nature 588, 232-240 (2020)



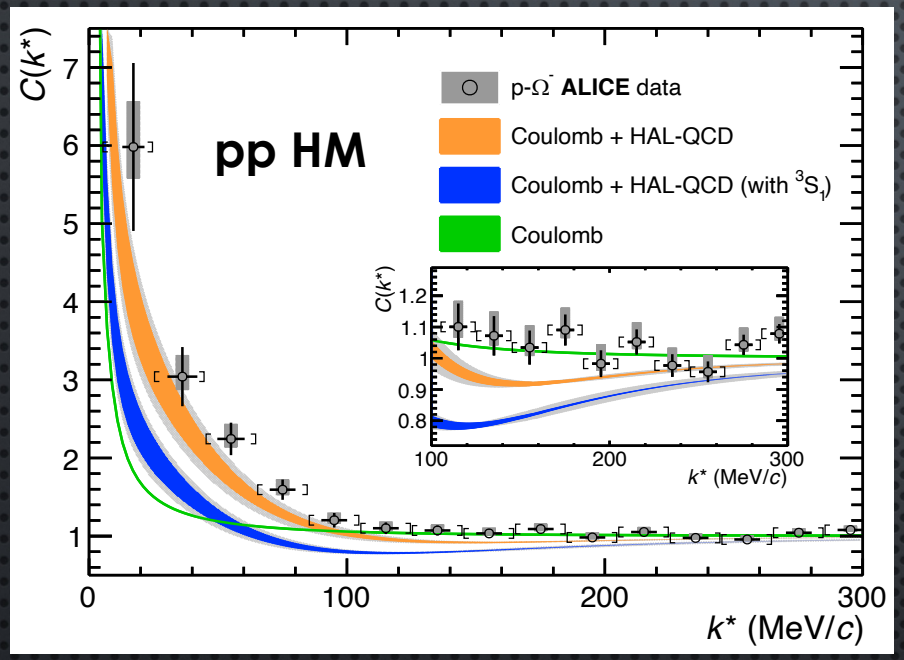
K.Sasaki et al., Nucl. Phys. A 998, 121737 (2020)



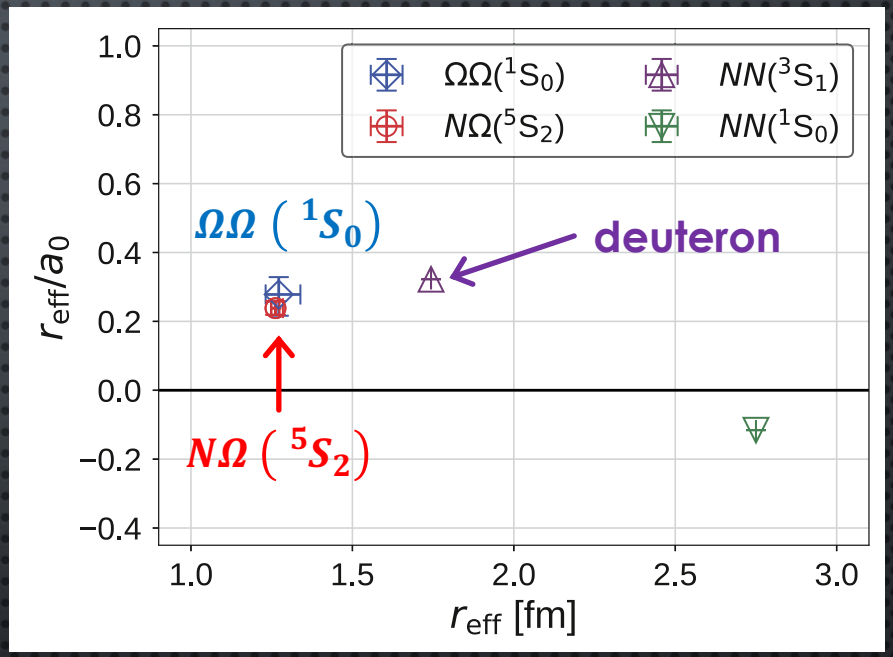
- Attractive $p\Xi^-$ interaction by strong interaction
  - ✓ Quantitative agreement with HAL QCD
  - ✓ Possible resonance state at $N\Xi$ threshold
  - → Looking for a possible peak around $N\Xi$ threshold by reconstructing invariant mass of $\Lambda\Lambda$ & $p\Xi^-$ from primary vertex

$N\Omega$ system

ALICE, Nature 588, 232-240 (2020)



T.Iritani et al., PLB 792, 284-289 (2019)

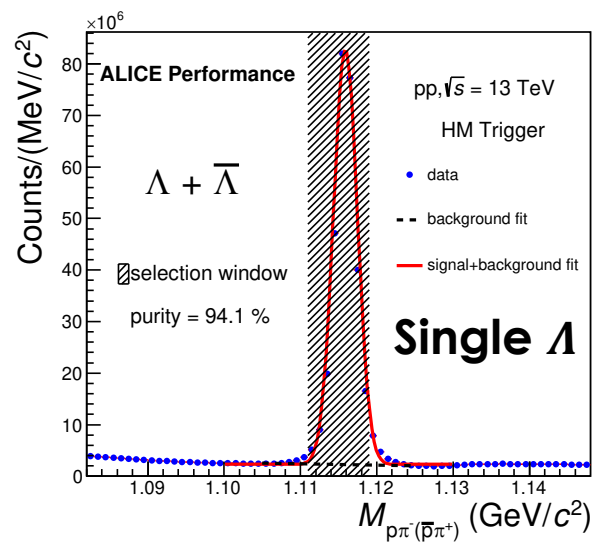


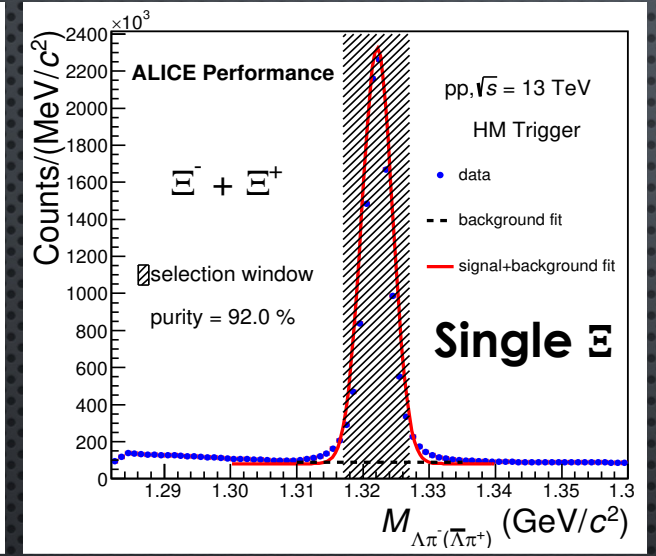
- Attractive $p\Omega^-$ interaction by strong interaction
  - ✓ More attractive than $p\Xi^-$
  - ✓ Consistent with HAL QCD
  - ✓ Possible quasi-bound state ($J = 2$) similar to deuteron
    - No Pauli blocking & assist by Coulomb attraction for $p\Omega$

→ Looking for a possible signal for $n\Omega$ quasi-bound state

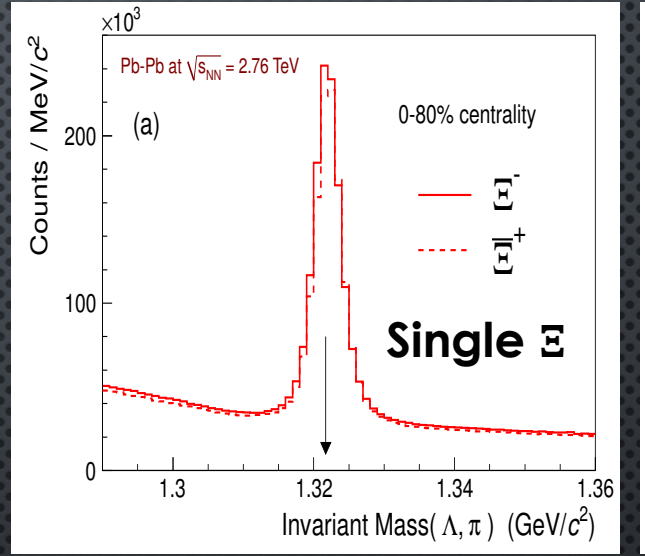
Single Λ, Ξ, Ω reconstruction

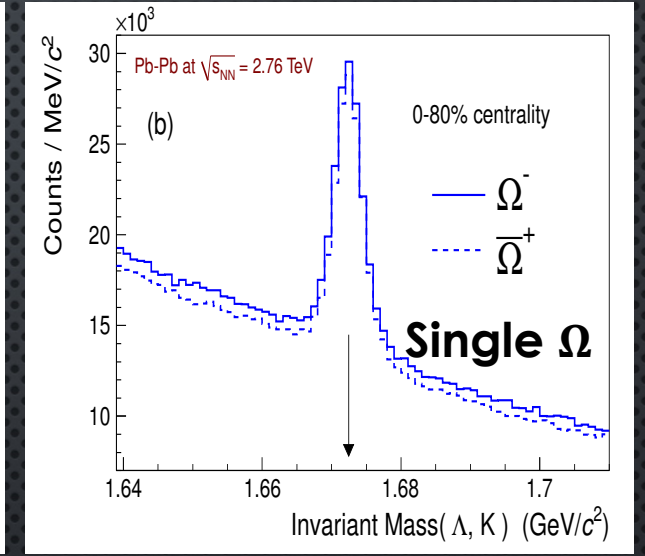
ALICE, PLB 728, 216 (2014)





pp 13TeV, High Mult.

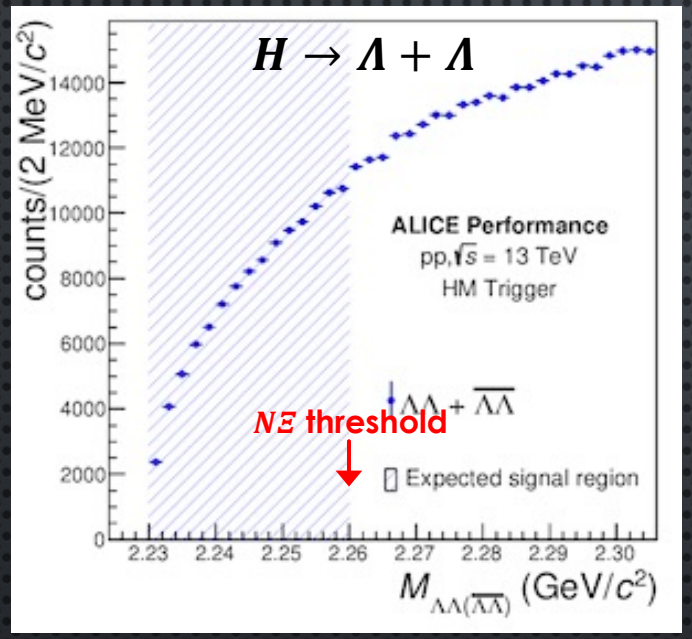


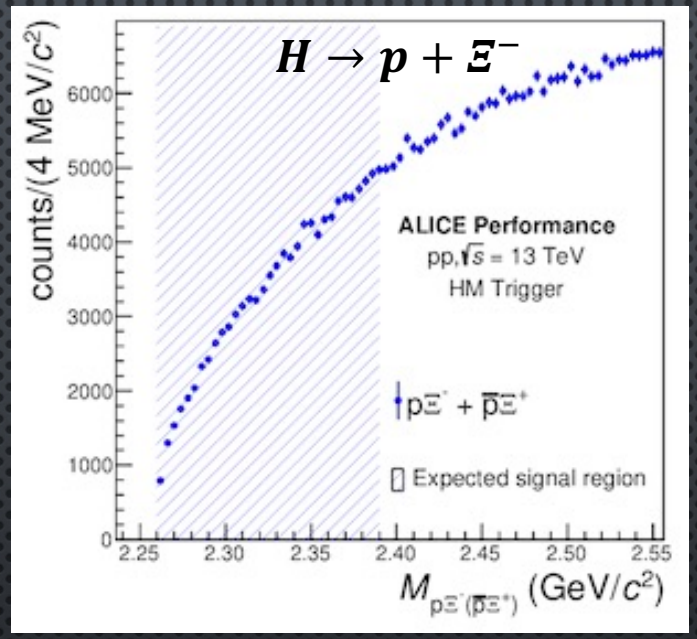


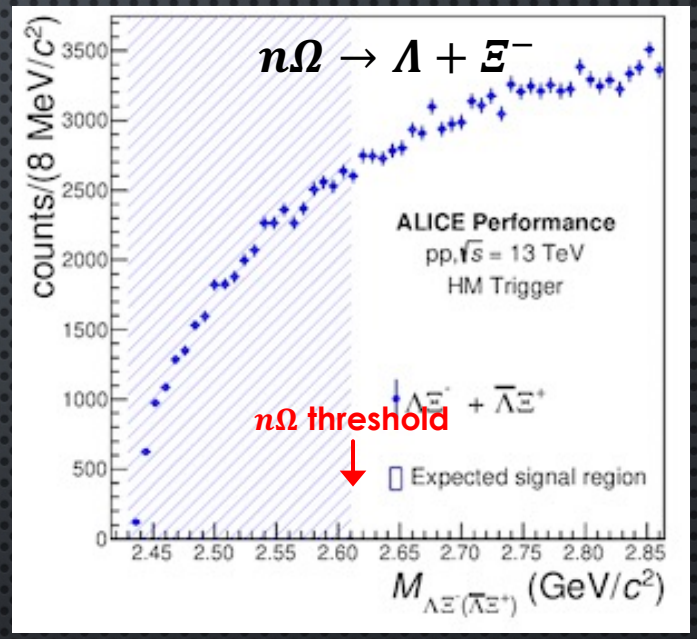
Pb-Pb 2.76TeV (Run-1)

- Successful reconstruction for Λ, Ξ, Ω in pp HM, p-Pb, Pb-Pb
  - ✓ pp HM & p-Pb: Good purity for single hyperon reconstruction
    - Λ: 94%, Ξ: 92% in pp HM
  - ✓ Pb-Pb: increase of combinatorial background
    - → Ongoing efforts to improve hyperon purities in Pb-Pb

Dibaryon mass reconstruction in small systems



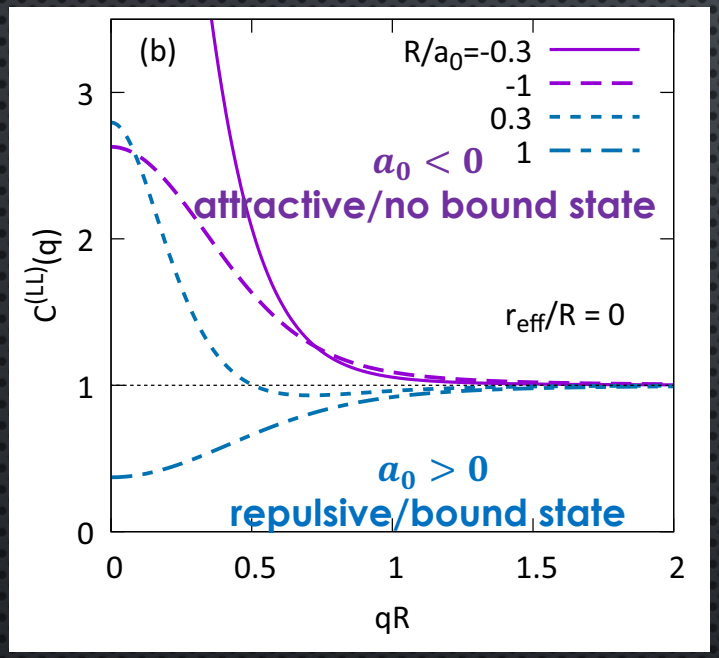




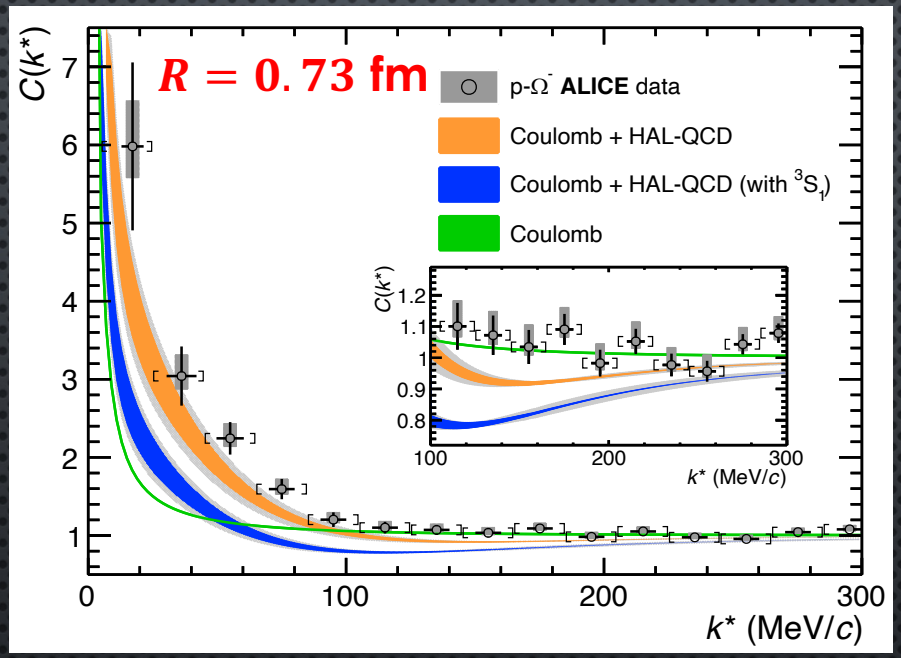
- Initial attempts with pp HM & p-Pb
  - ✓ Analyzed events: 1B (pp HM), 0.6B (p-Pb MB) events
  - ✓ No significant peak so far
    - $p\Omega \to p + \Omega^-$ analysis is ongoing
    - $N\Omega$: Statistically suffering with finer mass-bin
      → More statistics from ongoing Pb-Pb data analysis

$p\Omega$ correlation in Pb-Pb

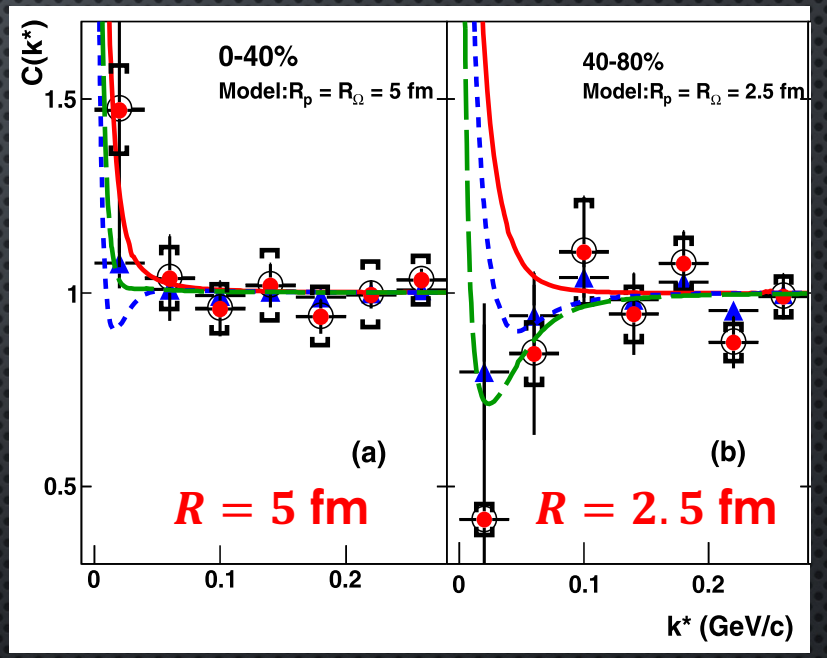
K.Morita et al., PRC 101, 015201 (2020)



ALICE, Nature 588, 232-240 (2020)



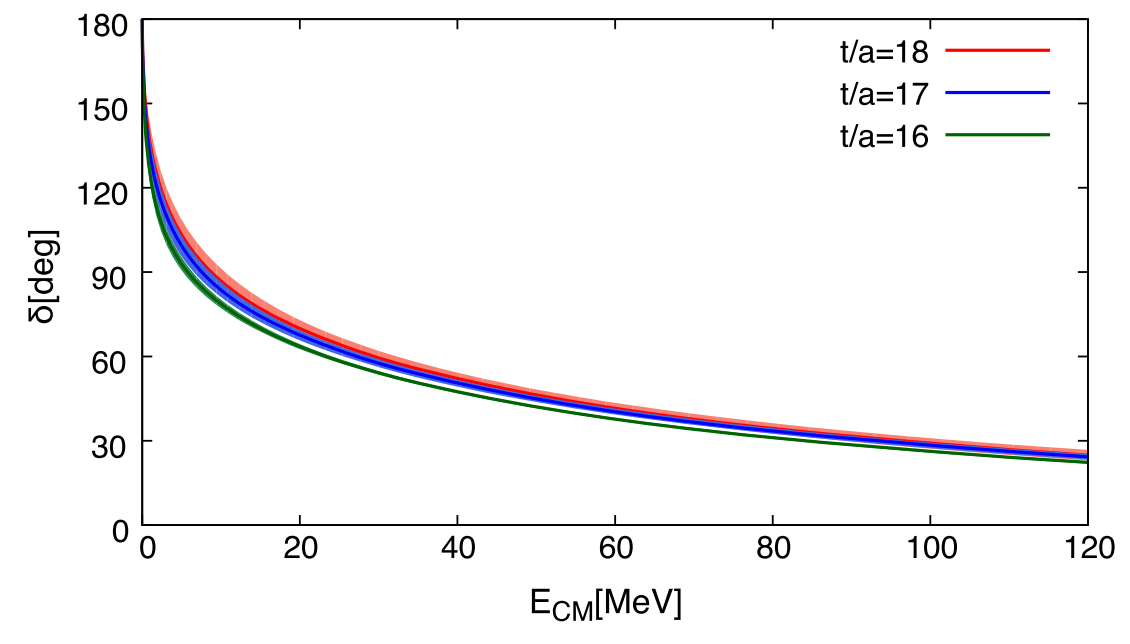
STAR, PLB 790, 490-497 (2019)



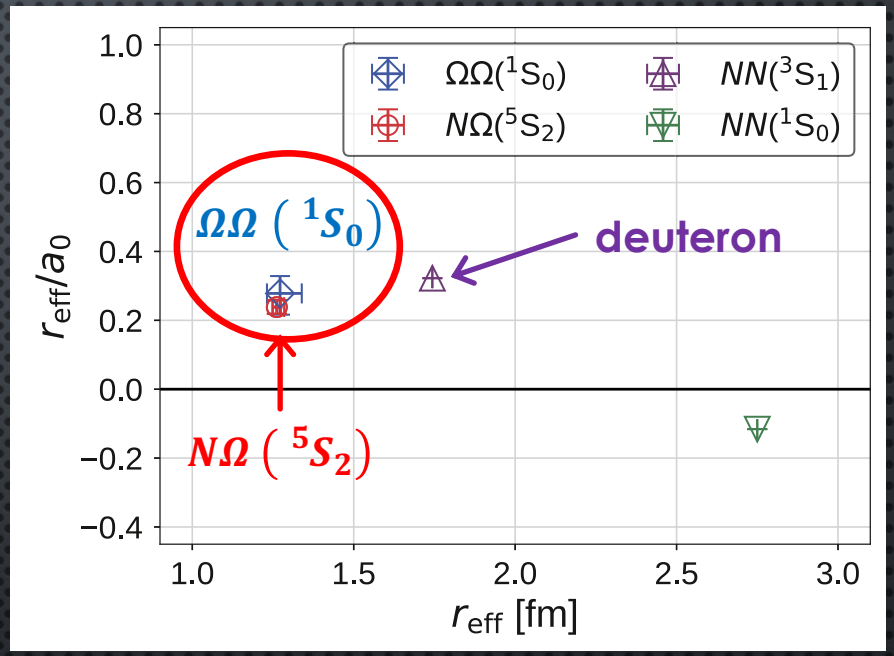
- Crucial to study source size dependence of correlation function
  - ✓ $p\Omega^-$ correlation: a sign of a_0 is unknown due to a large statistical error
  - → Working on improvement of single Ω purity & low p_T reach
    - Purity ~ 50% for p_T>1.2GeV/c with conventional selection

ΩΩ system

S.Gongyo et al., PRL 120, 212001 (2018)



T.Iritani et al., PLB 792, 284-289 (2019)



- Possible ΩΩ bound state for $J = 0$ predicted by HAL QCD calculation
  - ✓ Interesting to see with LHC RUN-3&4 data
    - 100 times more MB events at ALICE with detector upgrade
    - Both mass reconstruction via $\Omega\Omega \rightarrow \Omega + \Lambda + K$ & ΩΩ correlation function in Pb-Pb

Summary

- Making efforts to search for multi-strange dibaryons at LHC energy
  - ✓ Possible (quasi-)bound states for $N\Omega$ & $\Omega\Omega$ systems predicted by HAL QCD calculations
  - ✓ Invariant mass reconstruction & 2 particle correlation with daughter particles
- Current status:
  - ✓ Almost excluded $\Lambda\Lambda$ bound state by initial searches in RUN-1
  - ✓ No significant peaks for $H \rightarrow \Lambda + \Lambda/p + \Xi$ & $n\Omega \rightarrow \Lambda + \Xi$ in small systems so far
- Ongoing analysis & plans
  - ✓ Analysis with RUN-2 Pb-Pb data with more statistics
    - Working on improvement of purity for single Hyperons
  - ✓ 2 particle correlation measurements in Pb-Pb
    - Source size dependence of correlation function