Multi-strange dibaryon search at LHC-ALICE

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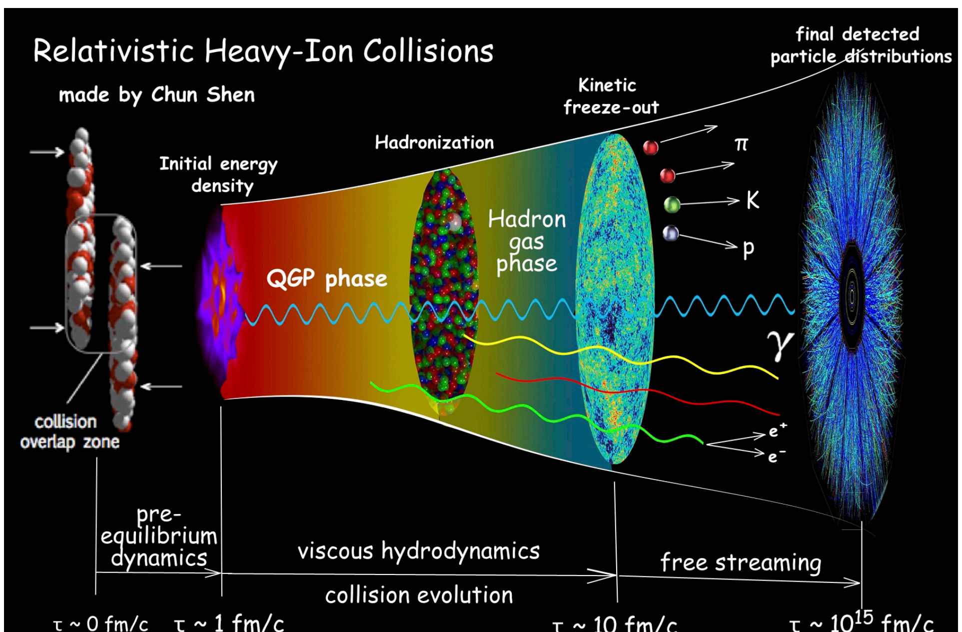
Dibaryons in flavor SU(3)

- Long-standing challenge in hadron physics
  - ✓ Important to study fundamental hadronic interactions (N-Y, Y-Y)
  - ✓ Famous H dibaryon: six quark state of uuddss predicted in 1977
    - ➢ Not found yet, while not theoretically prohibited.
- Recent impressive works by HALQCD
  - ✓ Lattice QCD calculation at nearly physical point
    - ➢ $m_\pi \approx 146\mathrm{MeV}, m_K \approx 525\mathrm{MeV}$
    - ➢ Two particle correlations & possible dibaryons for multi-strangeness systems

Heavy Ion collisions

- Study of Quark Gluon Plasma as the deconfined phase of quarks and gluons
  - ✓ LHC@CERN: Pb-Pb (5.5TeV), p-Pb, pp (14TeV)
- Dynamic space-time evolution of the collisions from initial collision to kinetic freeze-out

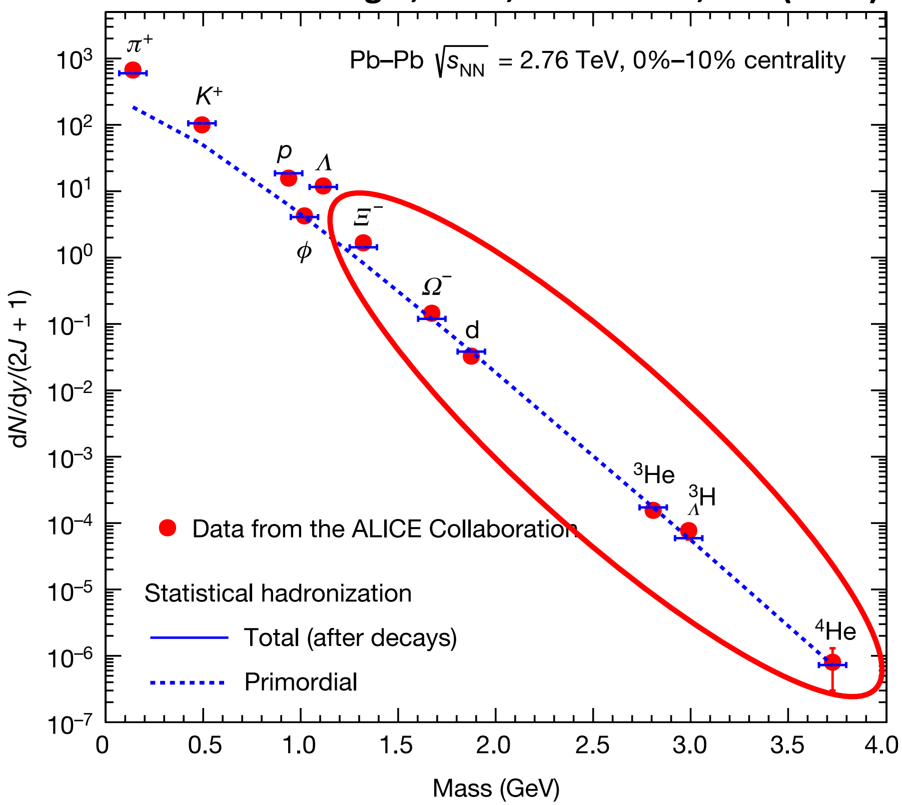


1. Initial collisions
2. QGP formation in $\tau < 1\mathrm{fm}/c$
3. Cross-over transition to Hadron phase at $T_c \sim 150\mathrm{MeV}$ $(\tau \sim a\ few\ 10\mathrm{fm}/c)$
4. chemical freeze-out happens just after the transition
5. Evolution ends at kinetic freeze-out

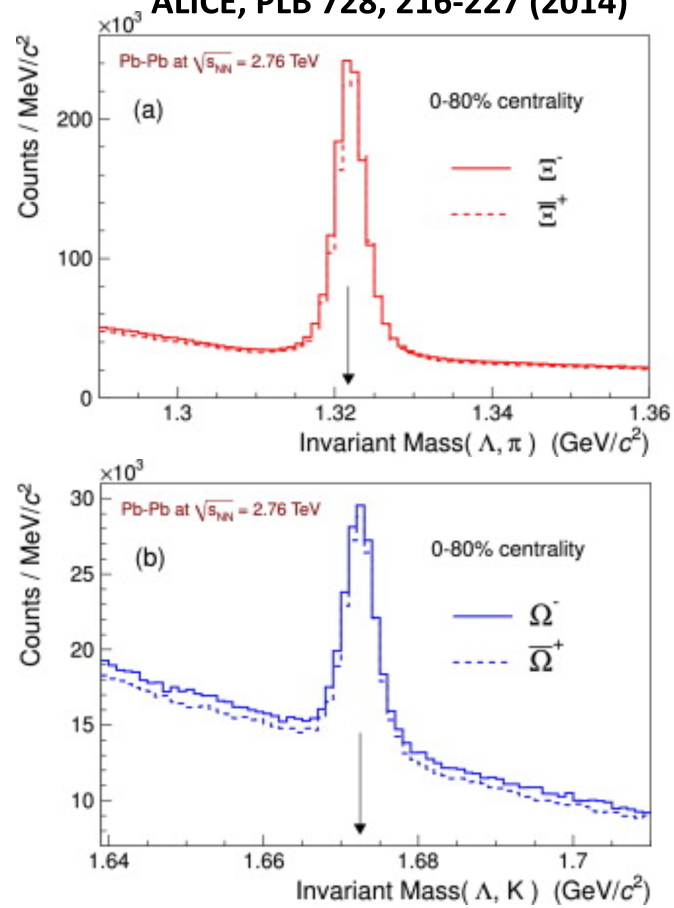
Multi-strange baryons at LHC

- Heavy Ion collisions as a new playground for dibaryon search and baryon-baryon interactions
  - ✓ Abundant multi-strange baryons as well as loose-bound nuclei

P. Braun-Munzinger, et al., Nature 561, 321 (2018)



ALICE, PLB 728, 216-227 (2014)

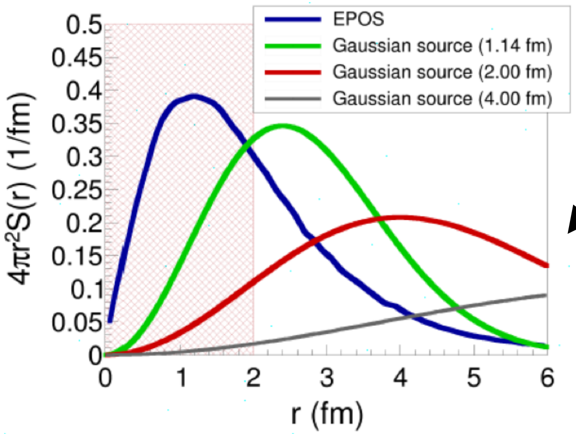


Measurement methods

- Mass reconstruction
  - ✓ Identify possible daughter particles
  - ✓ Peak finding of bound or resonance state
- Two particle correlation
  - ✓ Original idea: HBT interferometry to determine the Sirius angular diameter
    - ➢ Hanbury Brown & Twiss, Nature 10, 1047 (1956)
  - ✓ Pion emission source size measured by 2 pion correlation in $p\bar{p}$ annihilation
    - ➢ G.Goldhaber, S.Goldhaber, W.Lee, A.Pais, Phys. Rev. 120, 300 (1960)

  → Femtoscopy

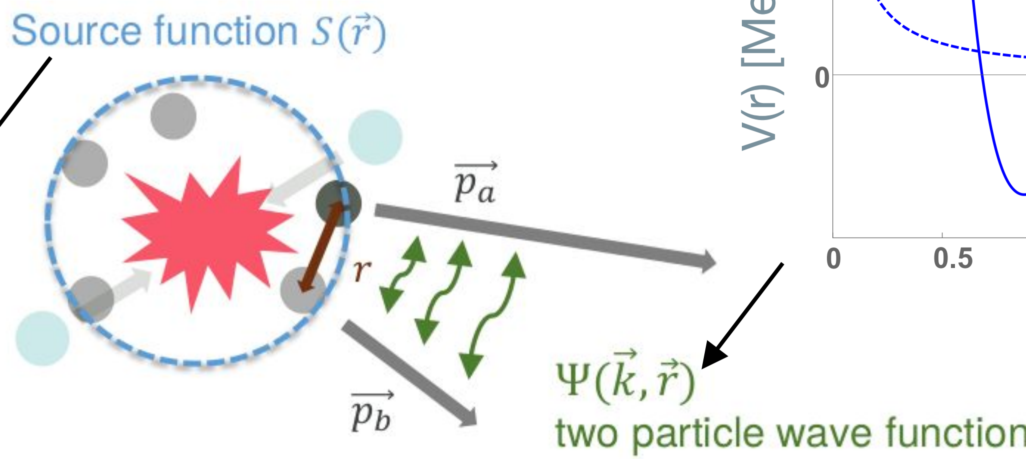
Two particle correlation

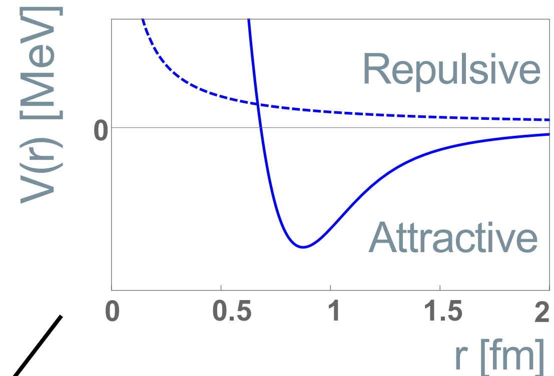


A-A: r ~ 4 fm

p-A: r ~ 2 fm

pp : r ~ 1 fm





Statistical definition ***Experimental definition*** ***Theoretical definition***

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\text{Same}}(k^*)}{N_{\text{Mixed}}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

Single-particle momenta

Normalization factor

Relative distance / reduced momentum in the rest frame of the pair

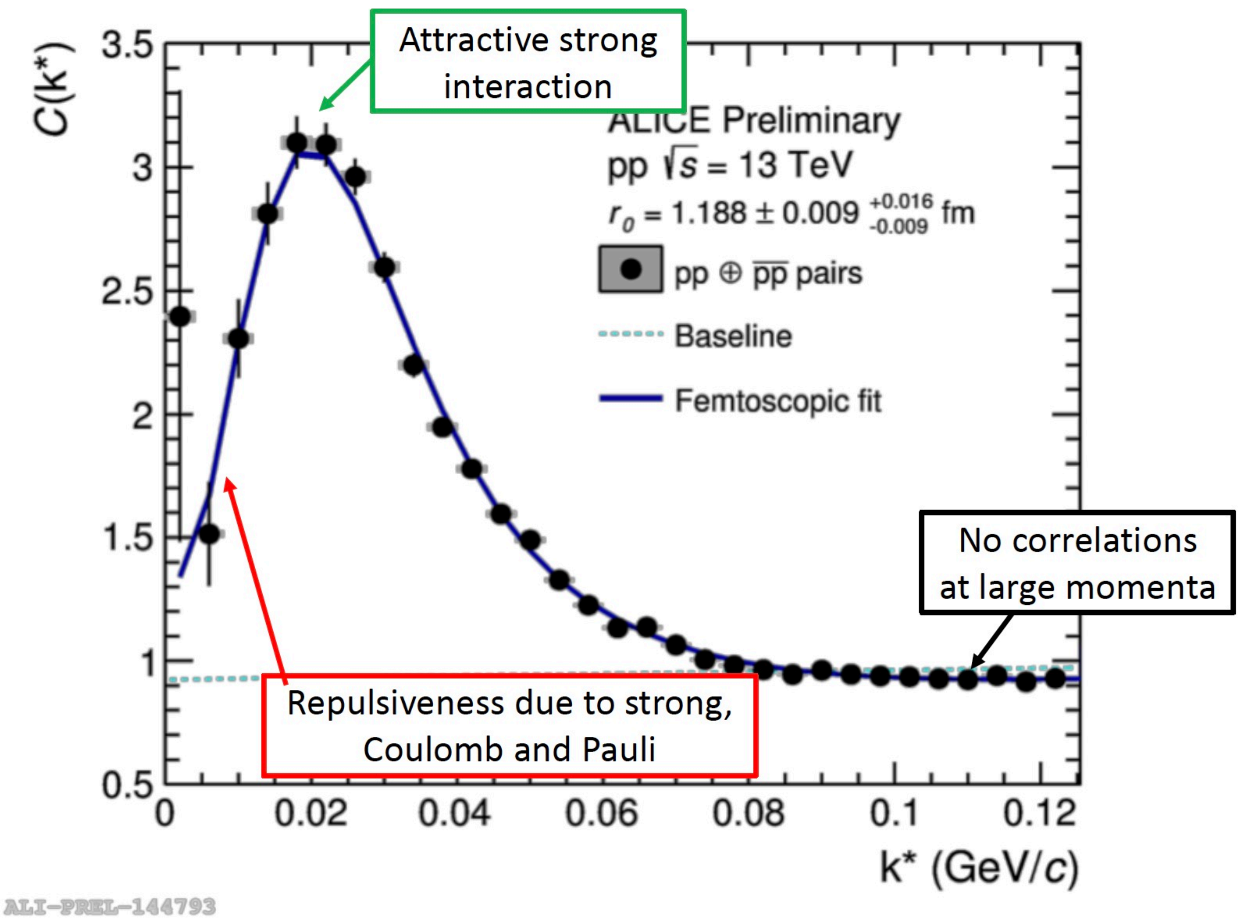
$$k^* = \frac{\left|\vec{p_a^*} - \vec{p_b^*}\right|}{2} \;\&\; \vec{p_a^*} + \vec{p_b^*} = 0$$

Correlation function

$$C(k^*) = \int S(\vec{r})\,\left|\Psi(\overrightarrow{k^*},\vec{r})\right|^2 d^3\vec{r}$$

$C(k^*) \longrightarrow$

- > 1 attraction
- $= 1$ no interaction
- < 1 repulsion

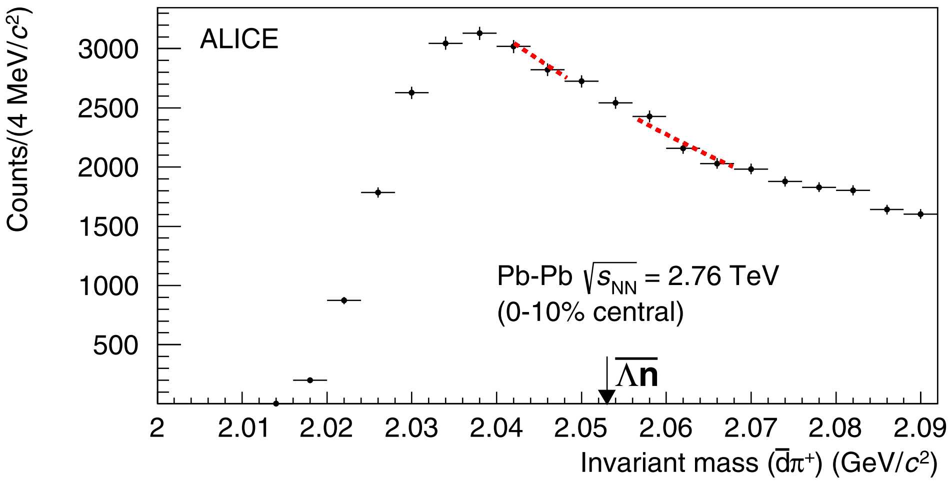


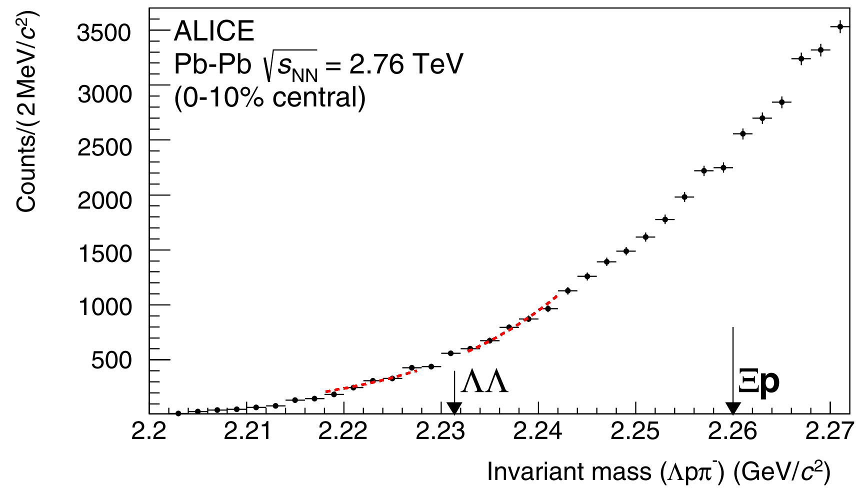
$\overline{\Lambda n}$ and $\Lambda\Lambda$ bound states

$\overline{\Lambda n} \rightarrow \bar{d} + \pi^+$

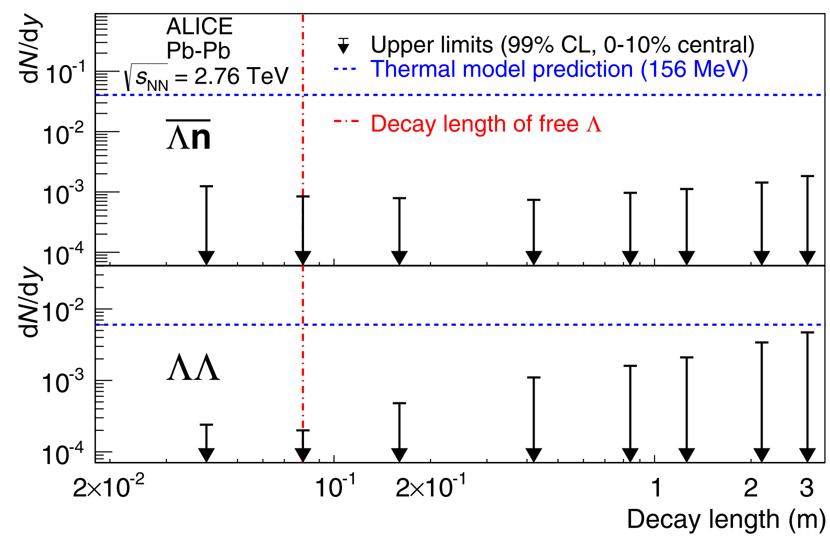
ALICE, PLB 752, 267-277 (2016)

$H(\Lambda\Lambda) \rightarrow \Lambda + p + \pi^-$



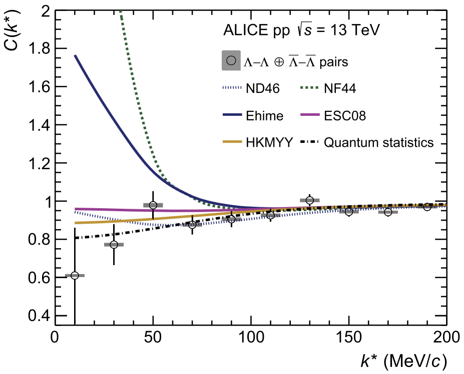


- No peak was found for both long-lived bound states
  - ✓ $\overline{\Lambda n}$: better S/N than Λn due to less production of anti-particles
  - ✓ $H(\Lambda\Lambda)$: assuming H has a long lifetime as same as a free Λ
    - ➢ Required Λ and p coming from secondary vertice

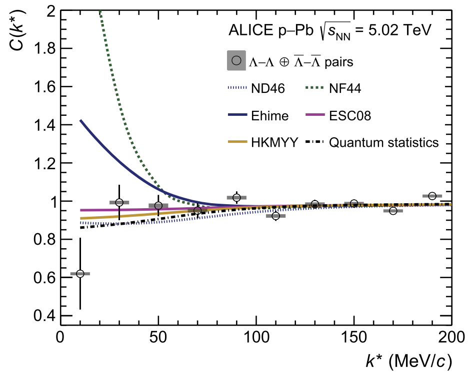


ΛΛ correlation in pp & p-Pb

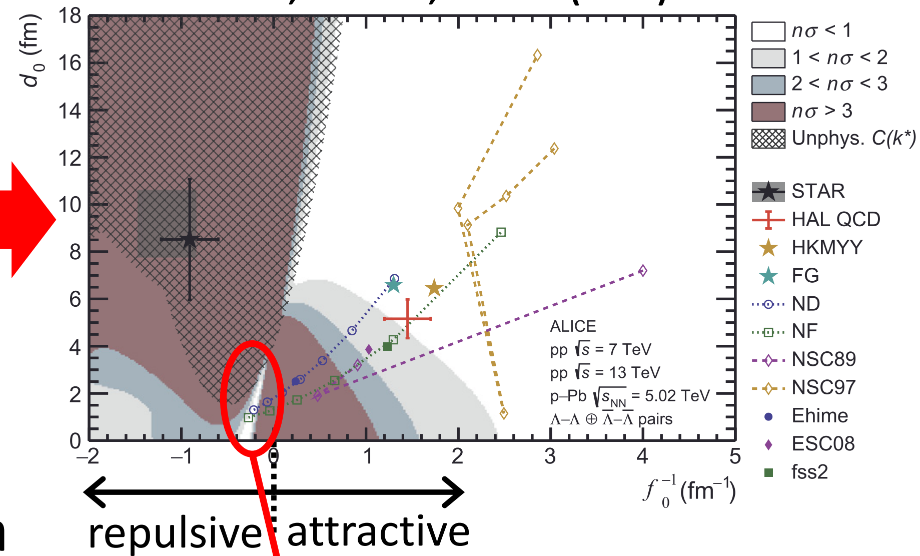
pp, 13TeV



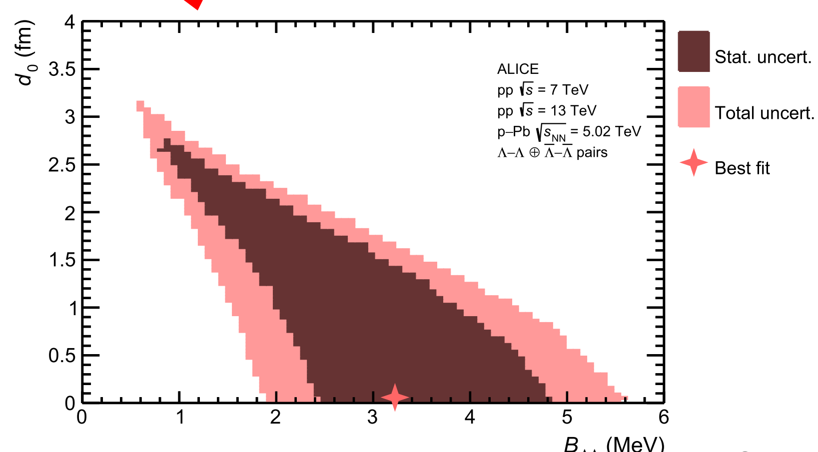
p-Pb, 5.02TeV



ALICE, PLB 797, 134822 (2019)



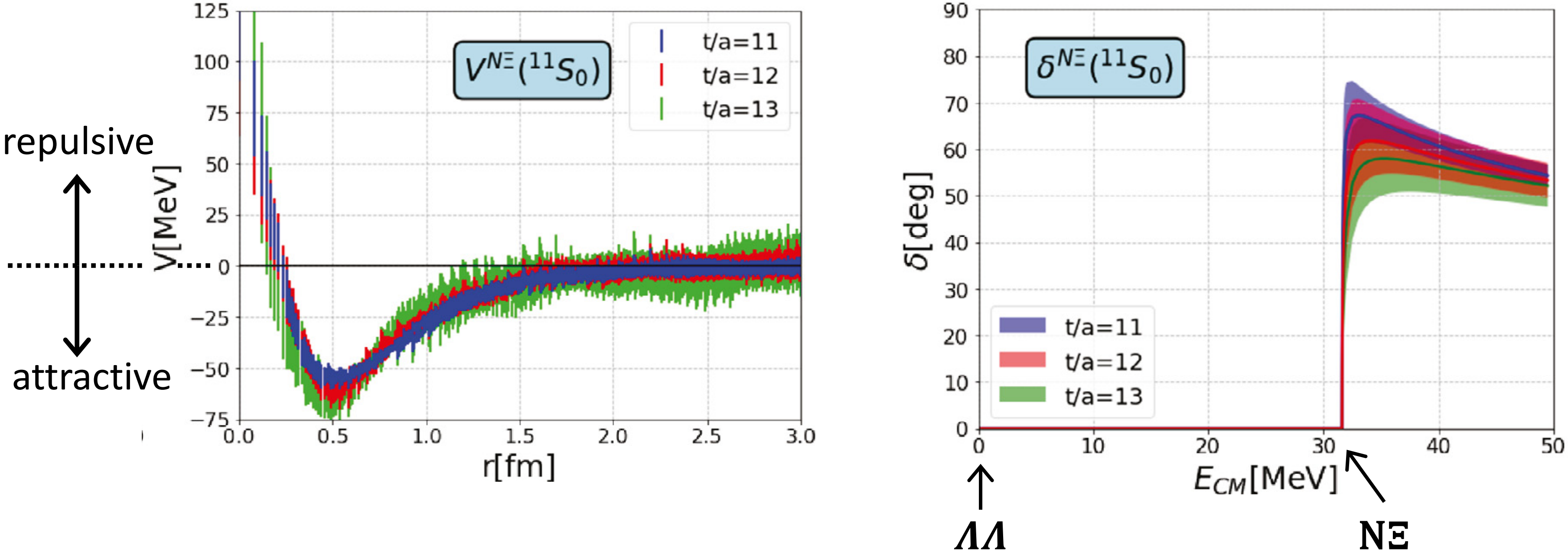
- Flat correlation function allowing a large parameter space of d_0 and f_0^{-1}, especially in $f_0^{-1} > 0$
  - ✓ d_0: effective range of ΛΛ
  - ✓ f_0: scattering length
- Small remaining region for possible bound state
  - ✓ $B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\text{stat.})^{+1.8}_{-1.0}(\text{syst.})\text{MeV}$



$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\left(1 - \sqrt{1 + 2 d_0 f_0^{-1}}\right)^2$$

H dibaryon from lattice QCD

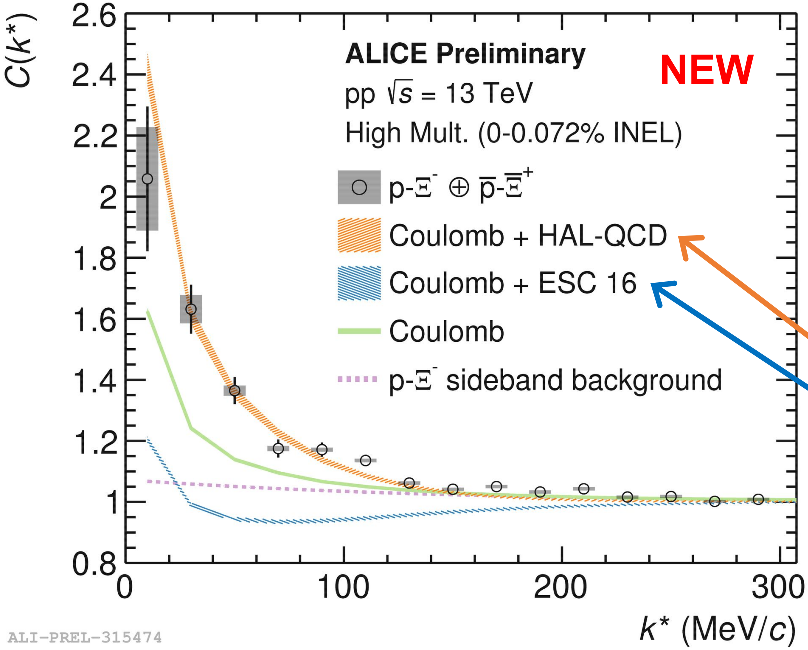
K.Sasaki, et al. (HALQCD), Nucl. Phys. A 998, 121737 (2020)



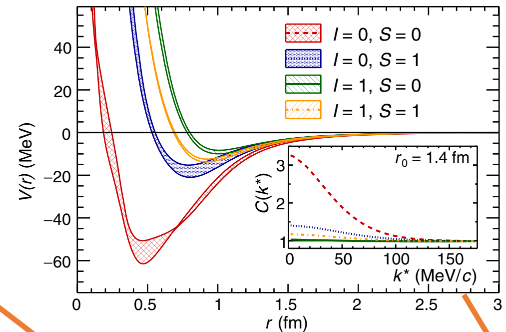
- H as ΛΛ and NΞ systems calculated by HALQCD
  - ✓ Consistent ΛΛ correlation with ALICE result
    → No bound state of ΛΛ
  - ✓ More attractive for NΞ
  - ✓ Sharp rise of phase shift around NΞ threshold
    → Resonance?

$p\Xi^-$ correlation in pp & p-Pb

ALICE, PRL 123, 112002 (2019) for p-Pb

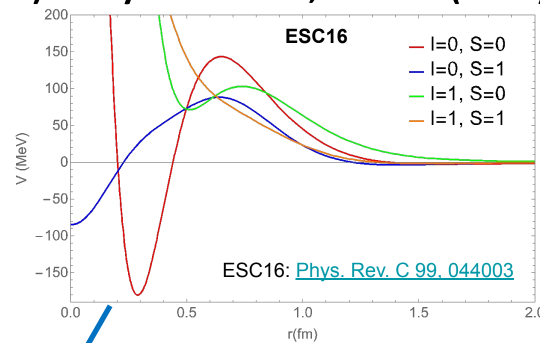


AIP conf. Proc. 2130, 020002 (2019)



HALQCD

Phys. Rev. C 99, 044003 (2019)



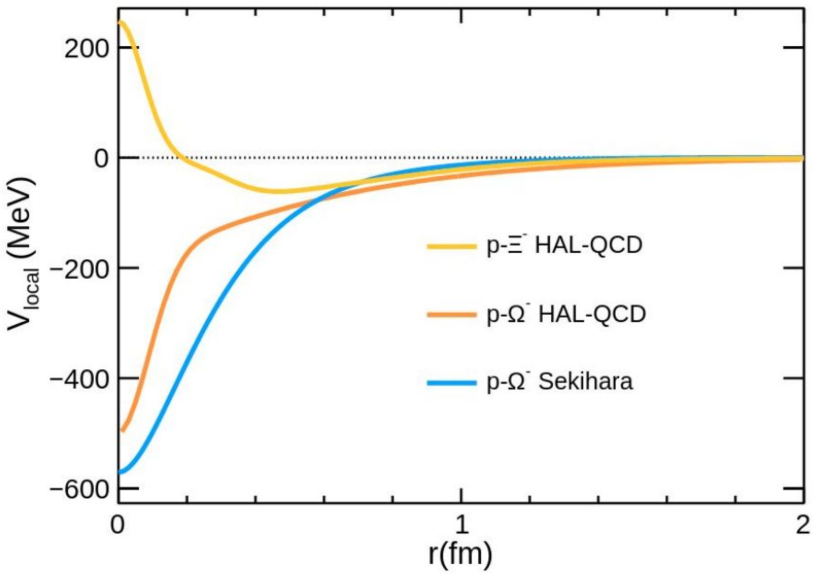
ESC16

$$C_{p\text{-}\Xi^-} = \frac{1}{8} C_{N\text{-}\Xi}(I=0, S=0) + \frac{3}{8} C_{N\text{-}\Xi}(I=0, S=1) + \frac{1}{8} C_{N\text{-}\Xi}(I=1, S=0) + \frac{3}{8} C_{N\text{-}\Xi}(I=1, S=1).$$

- First experimentally observed strong attraction in NΞ system
  - ✓ pp 13TeV: preliminary & p-Pb 5.02TeV: already published
  - ✓ Cannot be described by only Coulomb attraction
    - ➢ Good agreement with HALQCD + Coulomb
    - ➢ ESC16 is excluded

NΩ system

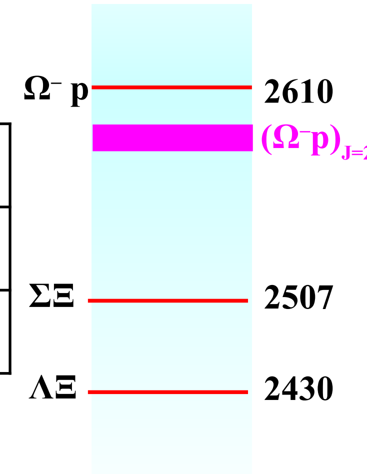
T.Iritani, et al. (HALQCD), PLB 792, 284-289 (2019)
T.Sekihara, et al., Phy. Rev. C 98, 015205, (2018)



NΩ bound state

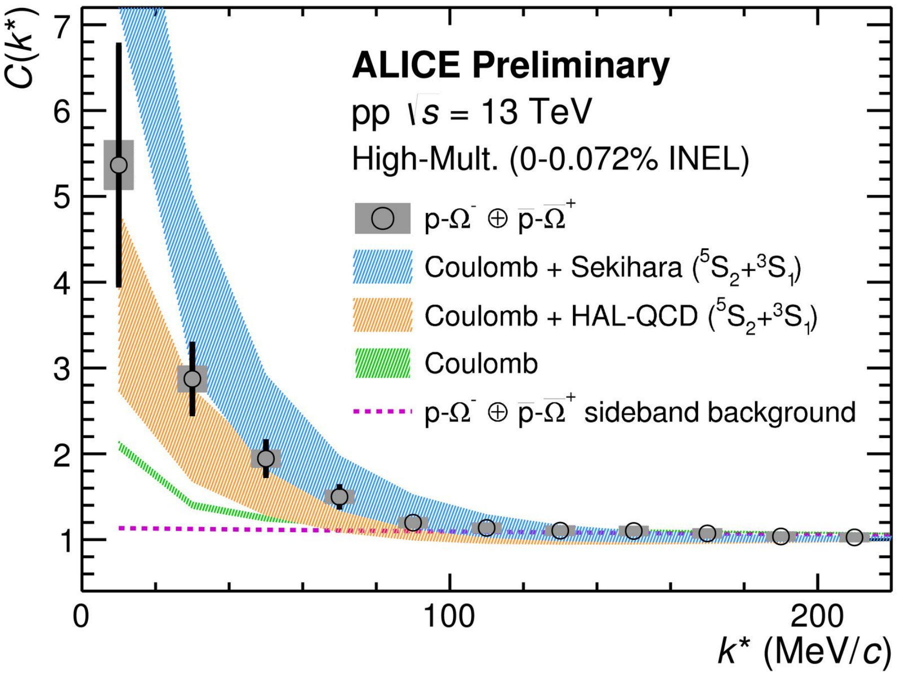
Model	$B_{N\Omega}$
HALQCD	1.54 MeV
Meson-exchange	0.1 MeV

+1MeV from Coulomb for $p\Omega^-$

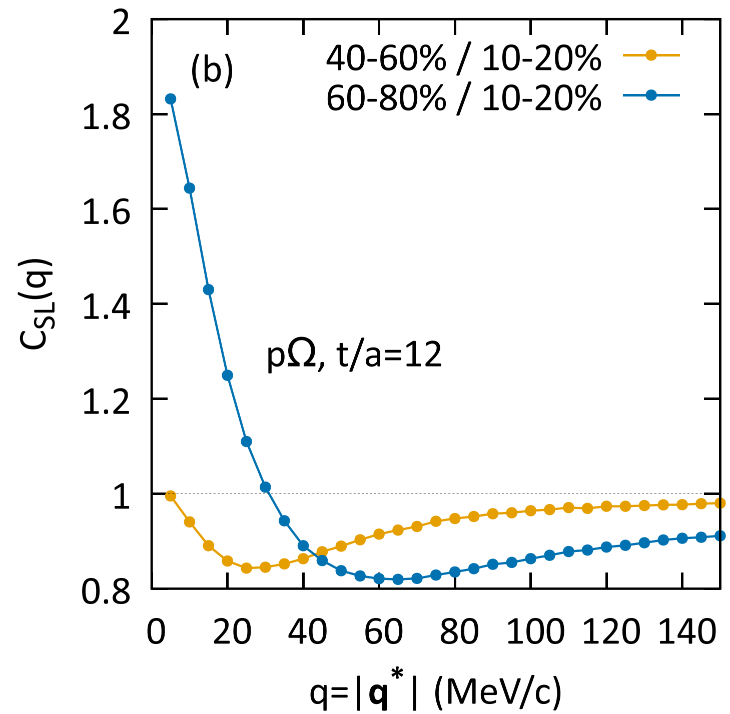


- Interesting characteristics of NΩ system
  - ✓ No Pauli blocking of constituent quarks
  - ✓ Additional Coulomb attraction for $p\Omega^-$
  - ✓ Attraction predicted by HALQCD & meson exchange model
    - ➢ Calculations for $^5S_2$ channel
  - → Possible bound state
    - ➢ Decay into ΣΞ or ΛΞ

$p\Omega^-$ correlation in pp



K.Morita, et al., Phy. Rev. C 101, 015201, (2020)



- $p\Omega^-$ correlation in high multiplicity pp events
  - ✓ Stronger attraction than $p\Xi^-$ ($C \approx 2@k^*\sim 0$)
  - ✓ Consistent with theory calculations predicting **bound state**

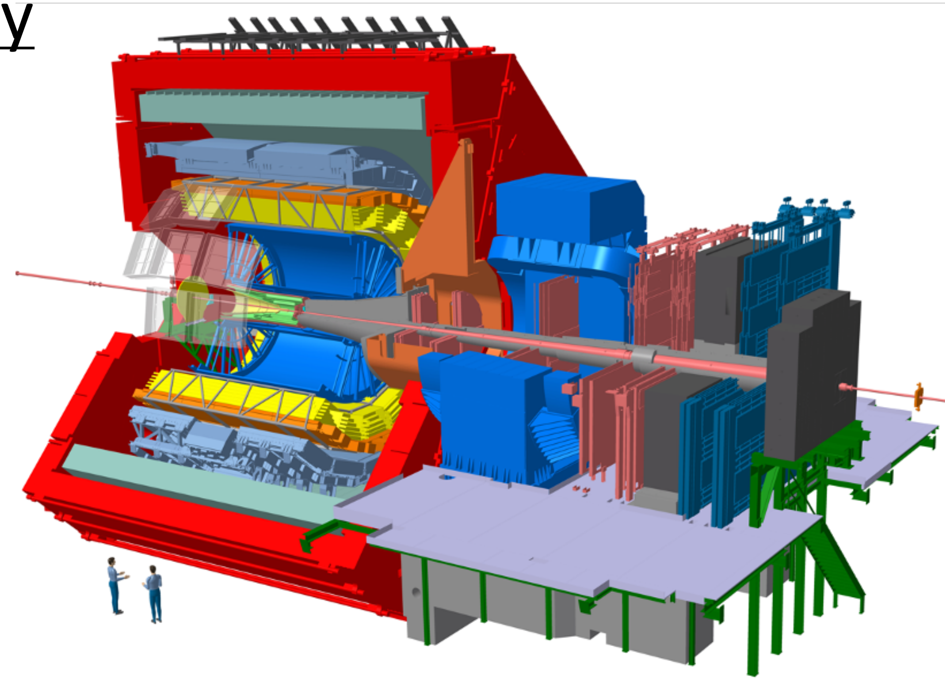
→ Interesting to make direct reconstruction

→ Small-to-Large ratio, $C_{SL} = C(peripheral)/C(central)$
  - ✓ Cancellation of Coulomb effect

ALICE upgrades for LHC-Run3

<u>Major upgrades in mid-rapidity</u>

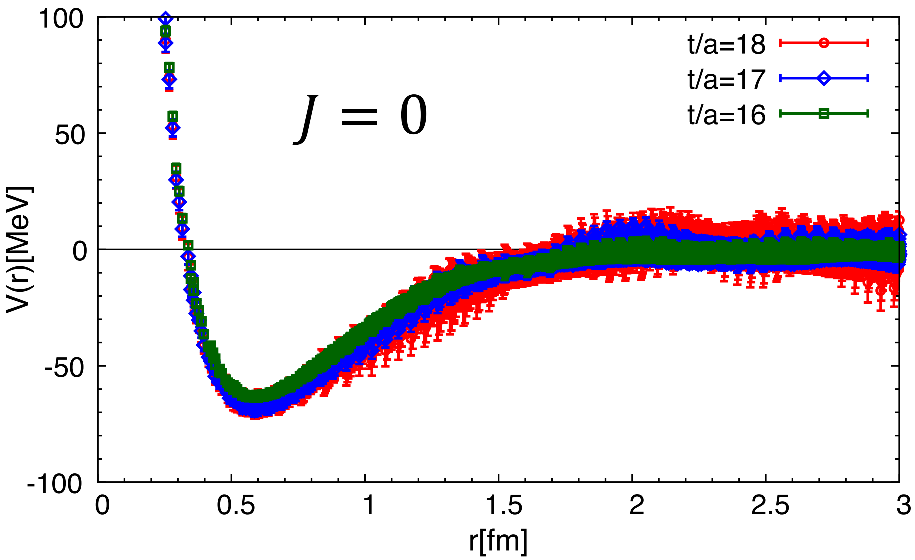
1. ITS upgrade
   - ✓ 6 layers (first 2 for pixel) → 7 layers (all pixel)
   - ✓ Thinner material
2. GEM-TPC upgrade
   - ✓ Readout: MWPC → GEM
   - ✓ Continuous readout
3. New computing system (O^2)



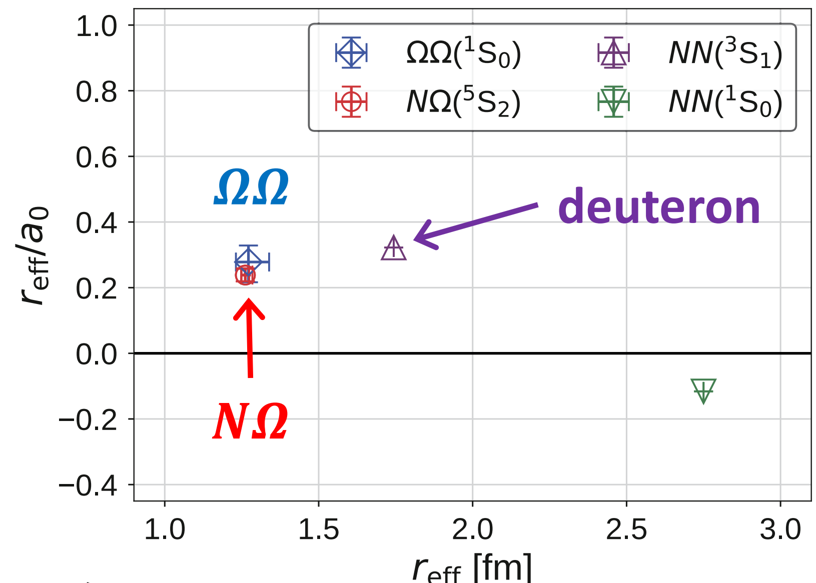
- LHC-Run3 will start in 2022
  - ✓ Data-taking with 50kHz Pb-Pb collisions
  - ✓ 10^{11} MB events in Run3&4 = 100 times higher statistics
  - → Possible to search for more strange dibaryon

ΩΩ from lattice QCD

S.Gongyo, et al. (HALQCD), Phys. Rev. Lett. 120, 212001 (2018)



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



- Most strange dibaryon = ΩΩ $(ssssss)$
  - ✓ Similar characteristics with NΩ system
    - ➢ No Pauli blocking of constituent quarks for $^1S_0$ $(J = 0)$
    - ➢ Strong attraction predicted by HALQCD
  - → Possible bound state as same as NΩ
    - ➢ $B_{\Omega\Omega} = 1.6(\mathrm{QCD}) - 0.9(\mathrm{Coulomb}) = 0.7\mathrm{MeV}$
    - ➢ Hope to access with the coming ALICE data

Summary

- Heavy ion collision is a new playground for dibaryon search & study of baryon interaction
  - ✓ Consistent results of $\Lambda\Lambda, p\Xi^-, p\Omega^-$ correlations with lattice QCD calculations
  - → Positive indication to discover H at $N\Xi$ threshold & $N\Omega$ bound state
- Promising to have much more exciting results with LHC-Run3 starting from 2022
  - ✓ 100 times higher statistics than present HI data, with ALICE upgrade & 50kHz Pb-Pb collisions
  - → Hope to reach $\Omega\Omega$