(Anti)(hyper)matter production in high energy heavy-ion collisions

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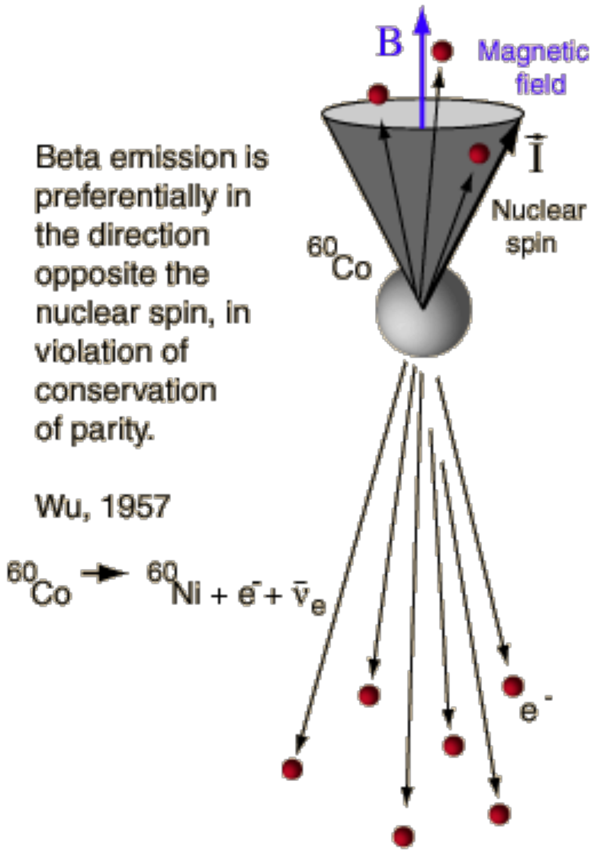
Matter-antimatter symmetry : CPT tests

Symmetry is fundamental in describing the world. Looking for any violation yield new physics



- P- violation : proposed by Lee and Yang. Confirmed by Wu in 1956

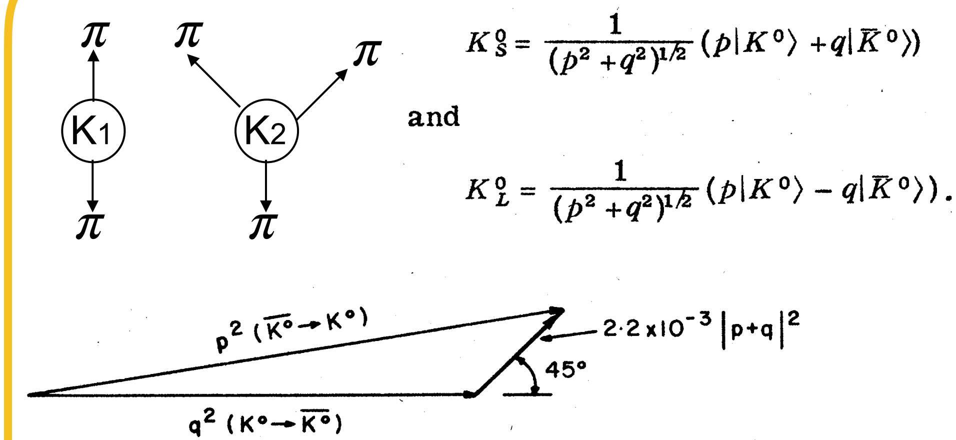


FIG. 4. Vector diagram showing schematically the difference in the amplitudes for $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$.

Cronin and Fitch, Rev. Mod. Phys. 53 (1981)

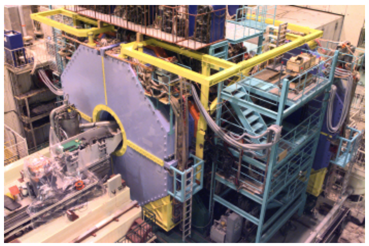
"In total 22700 K_2 decays, 45 two charged pions decay are observed, a decay mode forbidden by CP symmetry"

J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Lett. 13 (1964) 138

- CP- violation : Cronin and Fitch, 1964

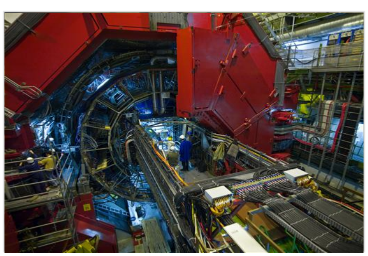
CPT is still a hot topic of interest

BaBar (SLAC):
CPT violation in B meson system.



Belle (KEK):
CPT violation in decays of B meson.

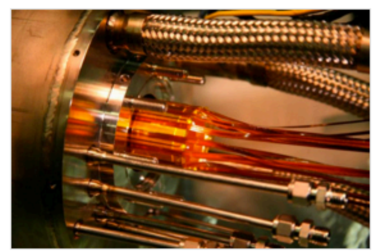
CPLEAR (CERN):
CPT violation in neutral kaon system.



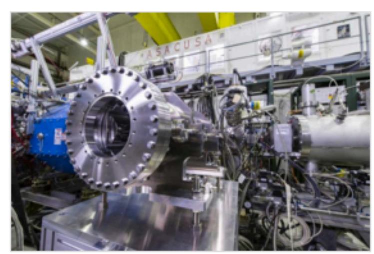
ALICE (CERN):
Antinuclei mass.
Nature physics 11 811 (2015)

AEGIS (CERN):
antimatter gravity.

ATRAP (CERN):
antimatter magnetic moment etc.



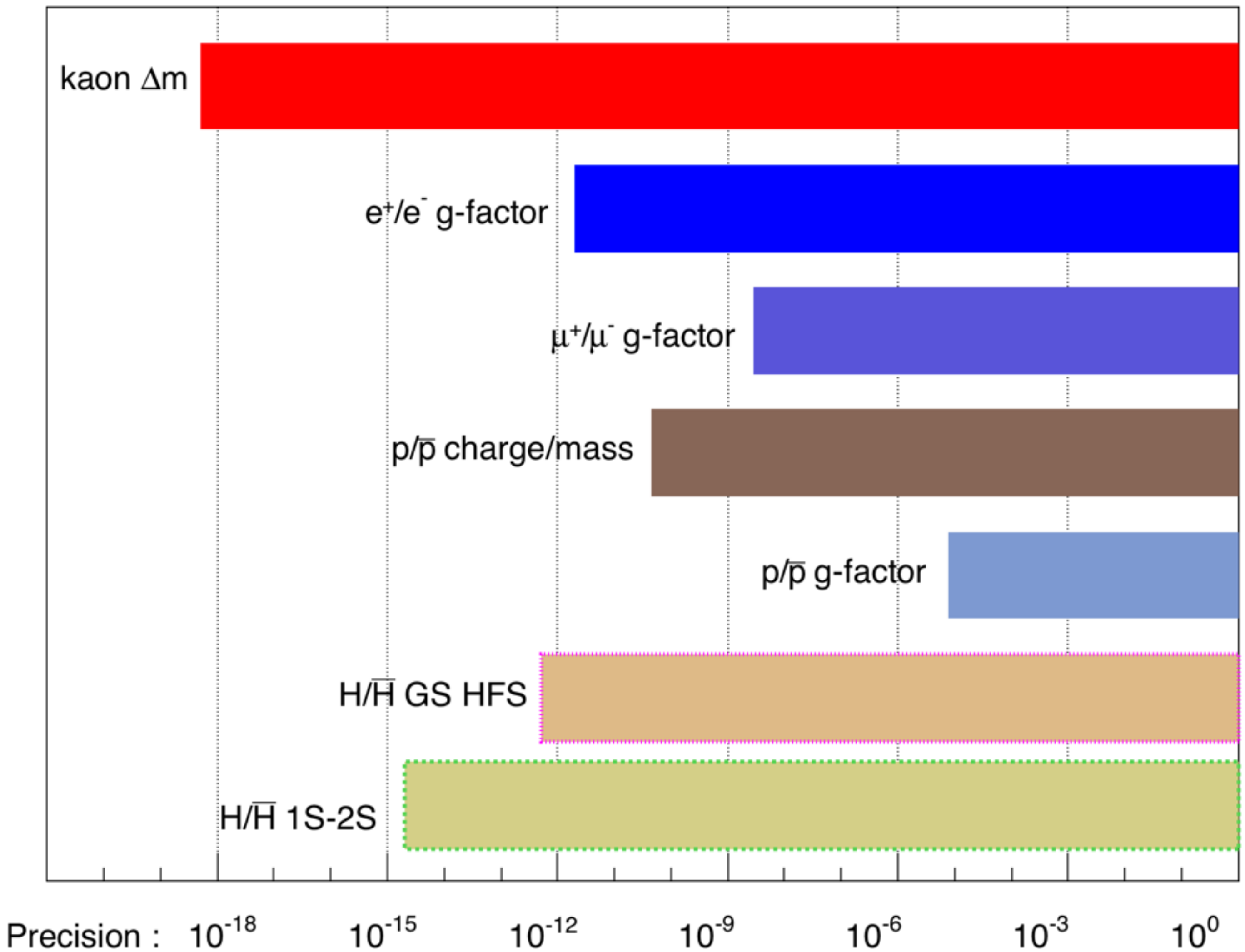
ALPHA (CERN):
antimatter gravity, charge, etc.



ASACUSA (CERN):
antimatter mass to charge ratio, hyperfine structure.

A subset of CPT test

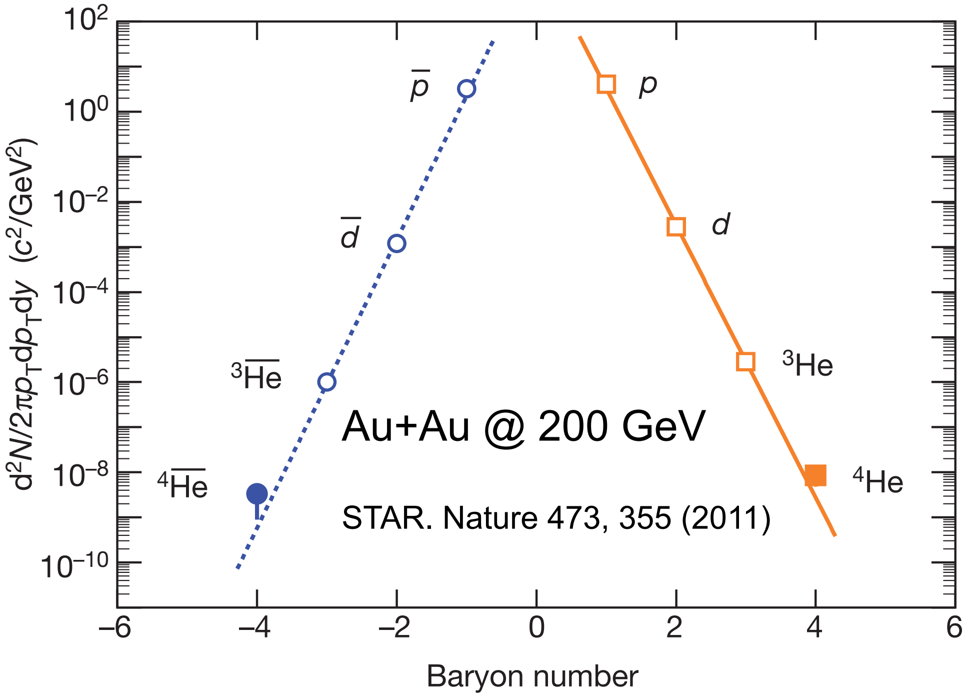
Fig. taken from "J. Chen et al./Phys. Rept. 760 (2018) 1"

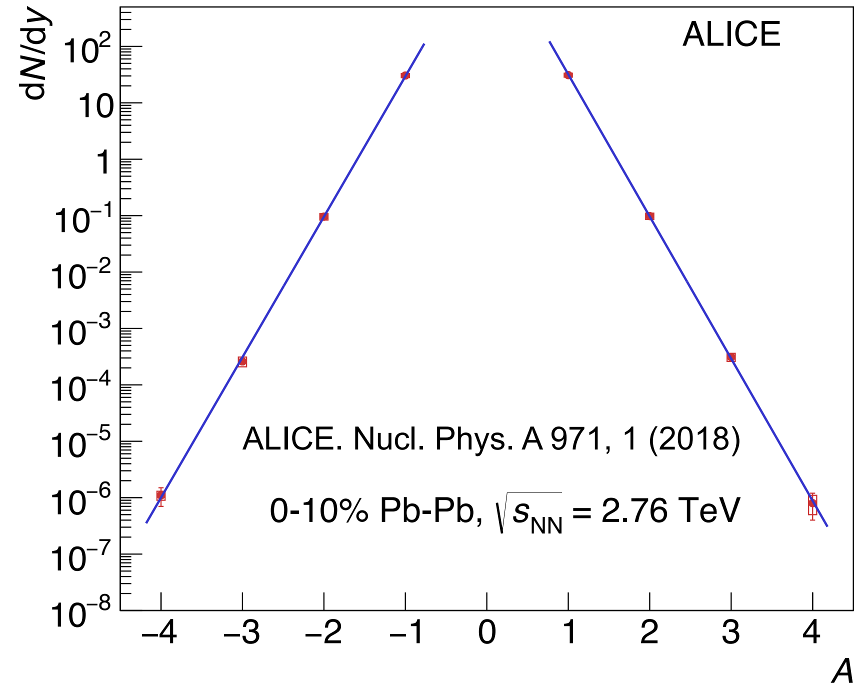


Data table, c.f.
V.A. Kostelecky and N. Russell,
Rev. Mod. Phys. 83 (2011) 11

☑ An especially precise test is provided by the magnitude of the mass difference between Kaons. Many other tests present no CPT violations

(Anti)(hyper)nuclei production in HIC



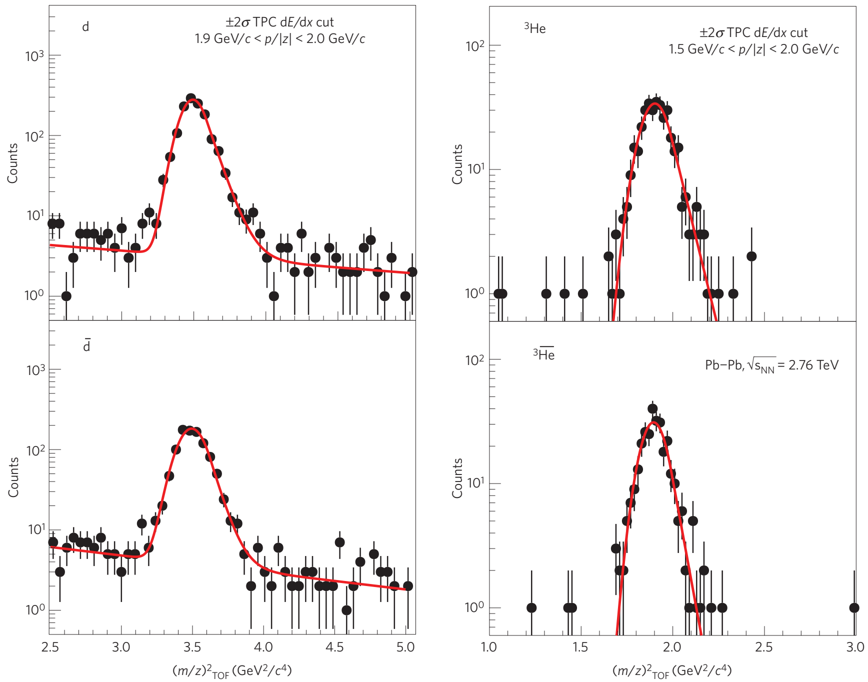


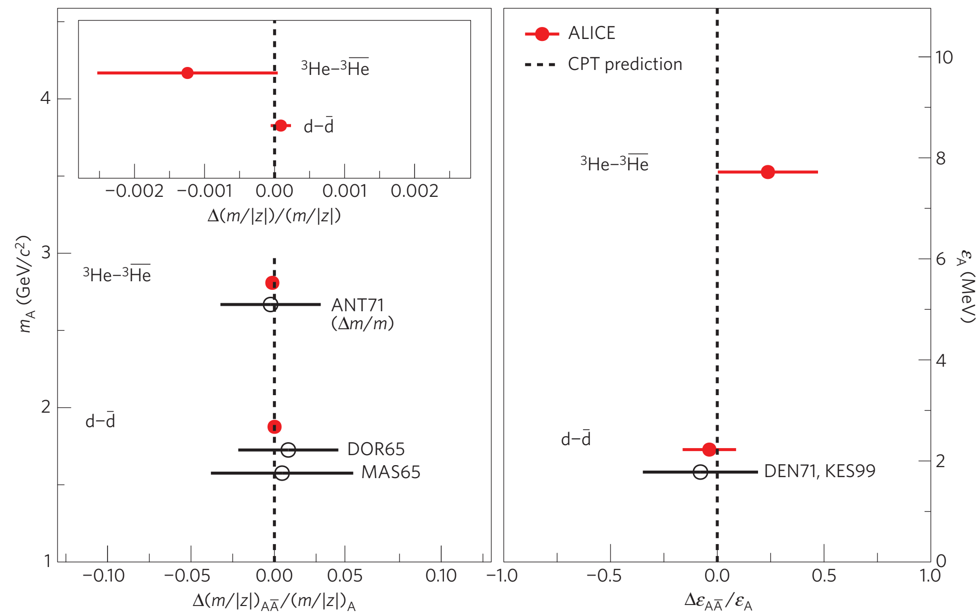
STAR. Science 328, 58 (2010)

Particle type	Ratio
$^3_{\bar{\Lambda}}\overline{H}/^3_{\Lambda}H$	$0.49 \pm 0.18 \pm 0.07$
$^3\overline{He}/^3He$	$0.45 \pm 0.02 \pm 0.04$
$^3_{\bar{\Lambda}}\overline{H}/^3\overline{He}$	$0.89 \pm 0.28 \pm 0.13$
$^3_{\Lambda}H/^3He$	$0.82 \pm 0.16 \pm 0.12$

- ☑ With abundantly produced antinucleons, RHIC and LHC are ideal machine for antimatter production
- ☑ The production reduction factor is up to 10^3 at RHIC and 300 at LHC, limited to A<4 system

ALICE measurements





ALICE Col. Nat.Phys. 11 (2015) 811

$$\frac{\Delta\mu_{d\bar{d}}}{\mu_d} = (0.9 \pm 0.5(\mathrm{stat.}) \pm 1.4(\mathrm{syst.})) \times 10^{-4}$$

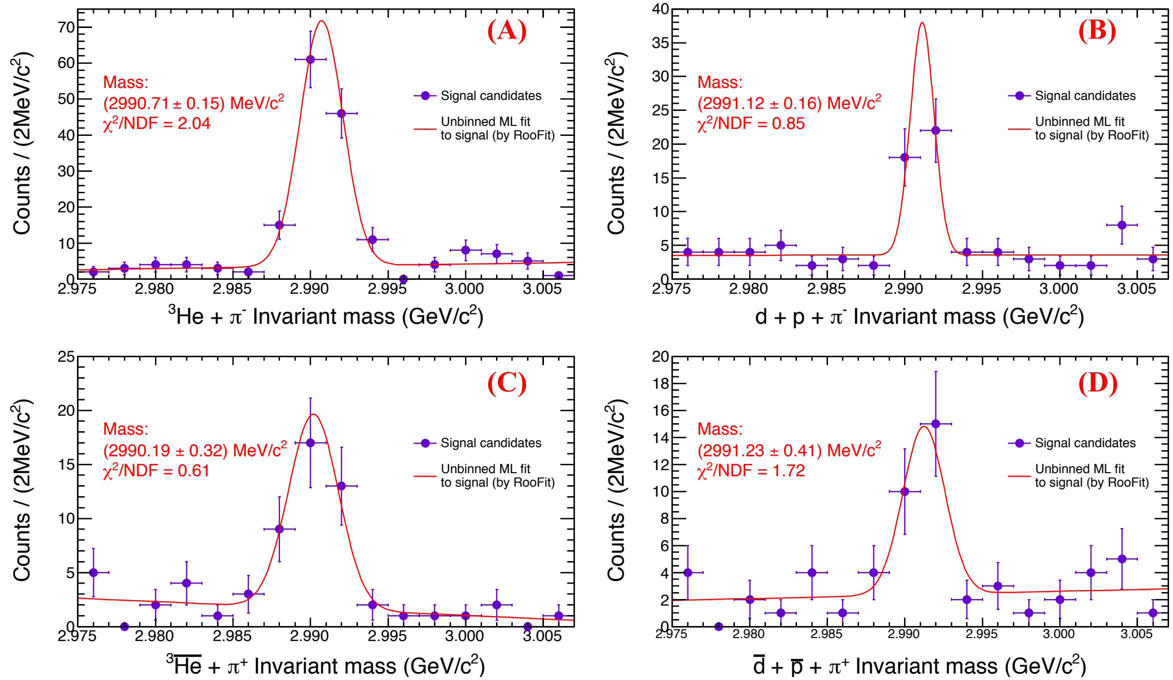
$$\frac{\Delta\varepsilon_{d\bar{d}}}{\varepsilon_d} = -0.04 \pm 0.05\ (\mathrm{stat.}) \pm 0.12\ (\mathrm{syst.})$$

$$\frac{\Delta\mu_{^3\mathrm{He}^3\overline{\mathrm{He}}}}{\mu_{^3\mathrm{He}}} = (-1.2 \pm 0.9(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})) \times 10^{-3}$$

$$\frac{\Delta\varepsilon_{^3\mathrm{He}^3\overline{\mathrm{He}}}}{\varepsilon_{^3\mathrm{He}}} = 0.24 \pm 0.16\ (\mathrm{stat.}) \pm 0.18\ (\mathrm{syst.})$$

☑ The high precision data with one to two orders of magnitude improvements, are compatible with zero and represent a CPT invariance test in systems bound by nuclear forces.

Extend the nuclei sector with strangeness



- ☑ Almost bg free with STAR HFT/TPC
  - 156 HT and 57 AHT from high stat. Run14 + Run16 data

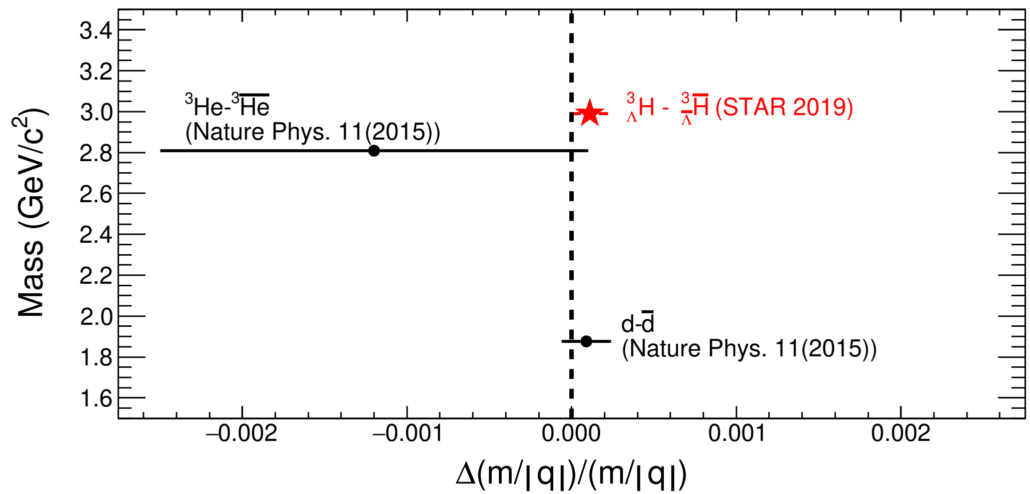
* The STAR measurement is related to the knowledge of masses of its decay daughter and is carried out with the CPT assumption for decay daughters

STAR Col. arXiv:1904.10520

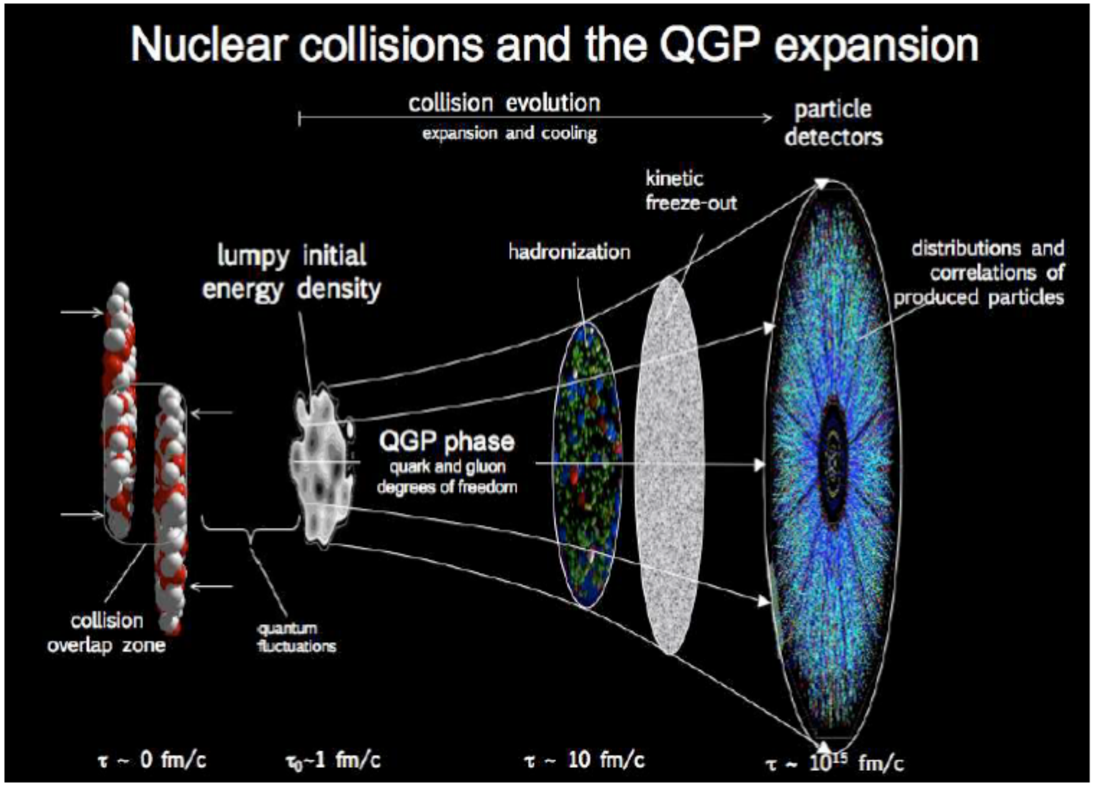
☑ The relative mass-over-charge ratio with A=3 system

$$(-1.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-3}$$

$$[\,1.1 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.})] \times 10^{-4}$$



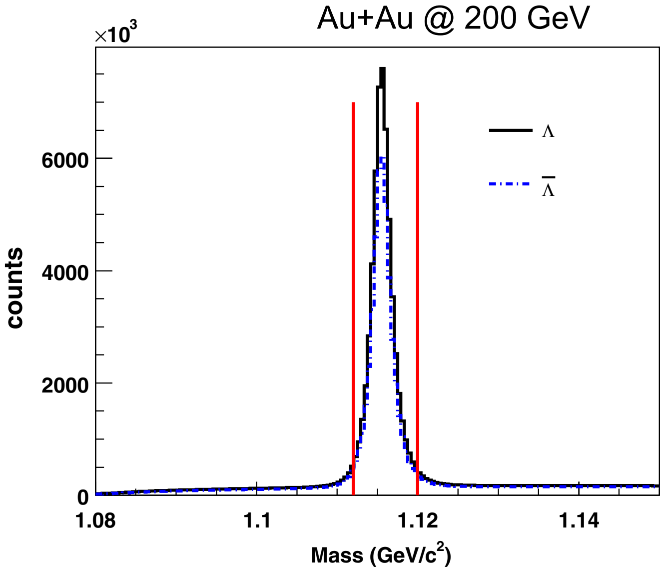
Heavy ion collider as a hyperon factory



- ☑ Hyperon rate is high at RHIC and LHC, lab. for Y-N interaction
- ☑ Excellent secondary vertex reconstruction in STAR and ALICE

0-5% central collisions, Au+Au @ 200 GeV, Pb-Pb @ 2.76 TeV

$$\left.\frac{dN_Y}{dy}\right|_{y=0} \simeq \begin{cases} 16.7, & 26, & \Lambda \text{ (S=-1)} \\ 2.2, & 3.3, & \Xi \text{ (S=-2)} \\ 0.3, & 0.6, & \Omega \text{ (S=-3)} \end{cases}$$

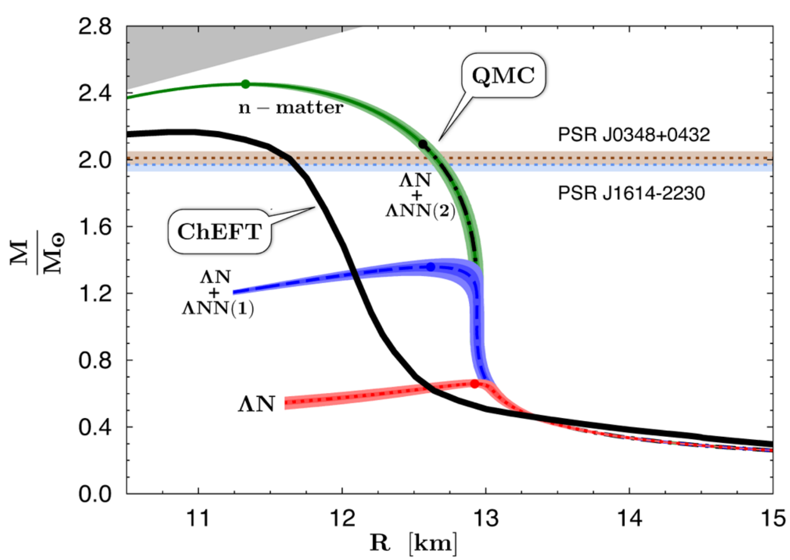


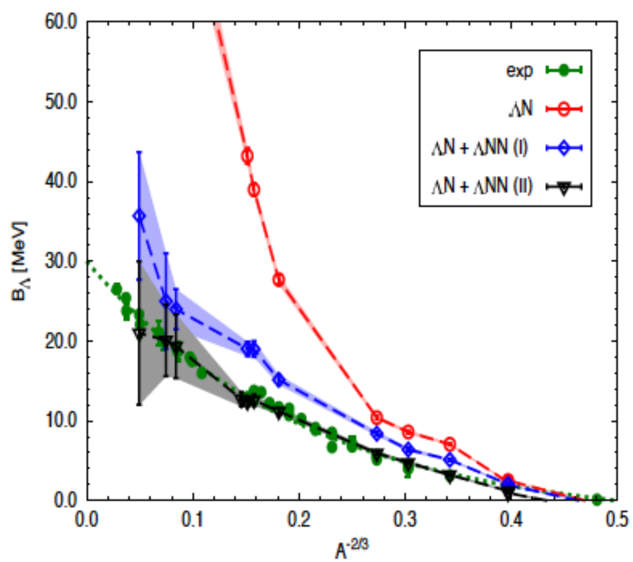
Hyperons in neutron stars

☑ Hyperon puzzle

- Hyperons are predicted to exist inside neutron stars at densities exceeding 2-3ρ_0
- The inner core of NS is so dense, Pauli blocking prevents hyperons from decaying by limiting the phase space available to nucleons
- The presence of hyperon reduces the maximum mass of neutron stars ~0.5-1.2M_0
- However, new observation for large mass of NS!

P. Demorest et al., Nature 467 (2010) 1081; Antoniadis et al., Science 340 (2013) 448





- Rijken and Schulze: inclusion of YY interactions add 0.3M to Mmax of NS
- Lonardoni: adding YNN stiffens EoS of NS, and increase the mass; solution to overbinding in s-shell hypernuclei?

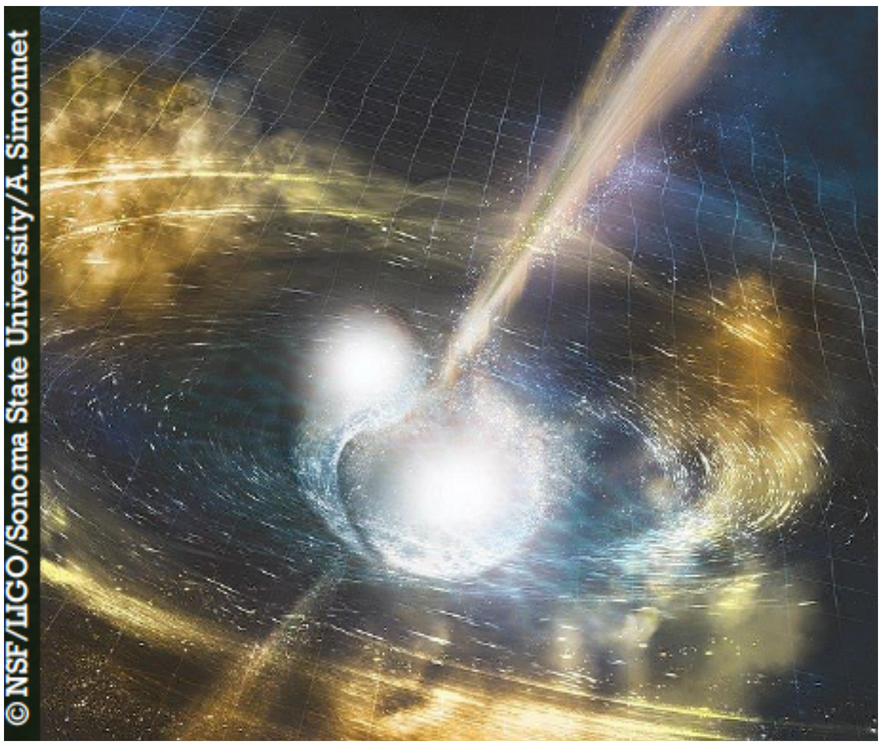
From hypernuclei to neutron stars

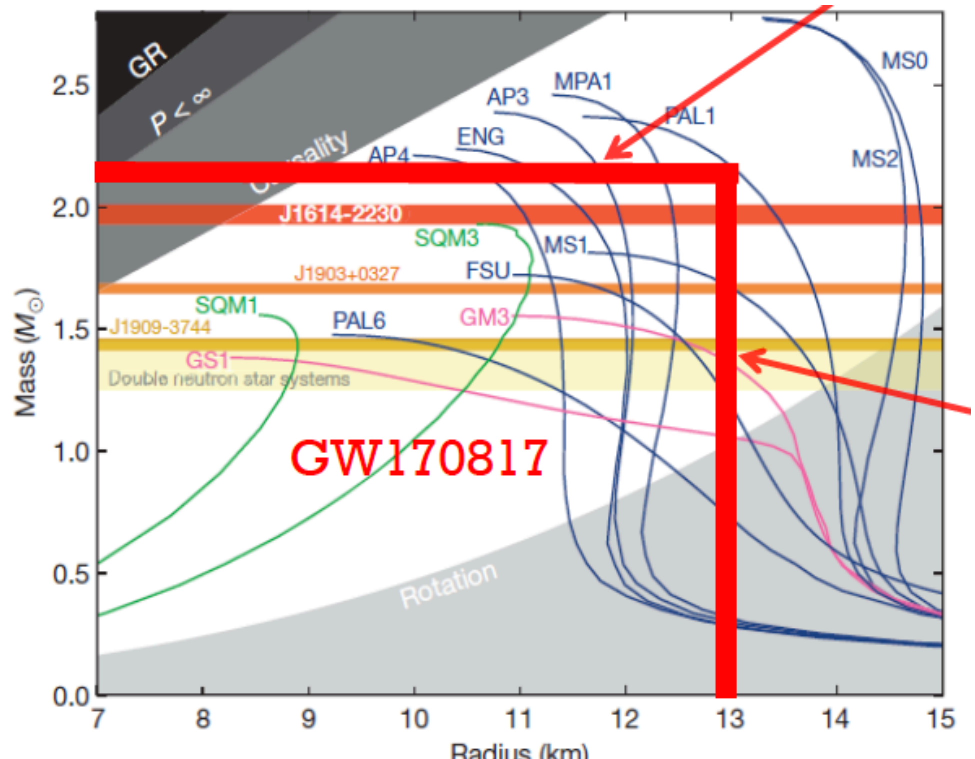
- ☑ GW from NS merger, provides new information on NS EoS, and new constrains on radius and mass

The LIGO and Virgo Col., Phys. Rev. Lett. 119, 161101 (2017); Phys. Rev. Lett. 121, 161101 (2018)

$1.97\ M_\odot \quad R_1 = 11.9^{+1.4}_{-1.4}$ km $\quad R_2 = 11.9^{+1.4}_{-1.4}$ km

Rezzolla et al., Astro. J. Lett. 852 (2018) $M \leq 2.16\ M_\odot$





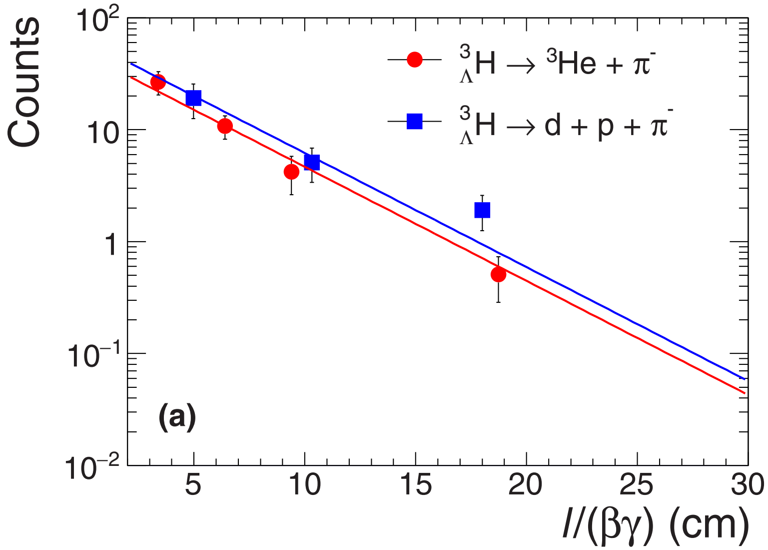
Raithel et al., Astro. J. Lett. 857 (2018) $R \leq 13\ km$

- ☑ Study on YNN interaction on-lab will provide constrains on EoS of NS

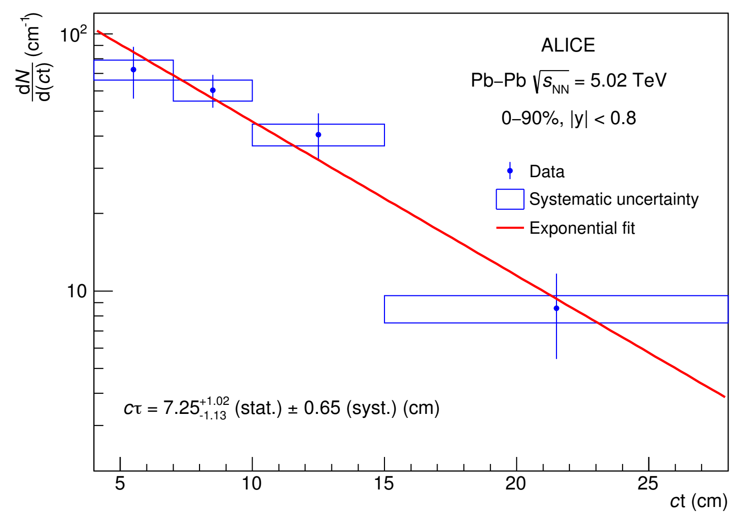
Lonardoni et al., Phys. Rev. Lett. 114 (2015); Wirth and Roth, Phys. Rev. Lett. 117 (2016)

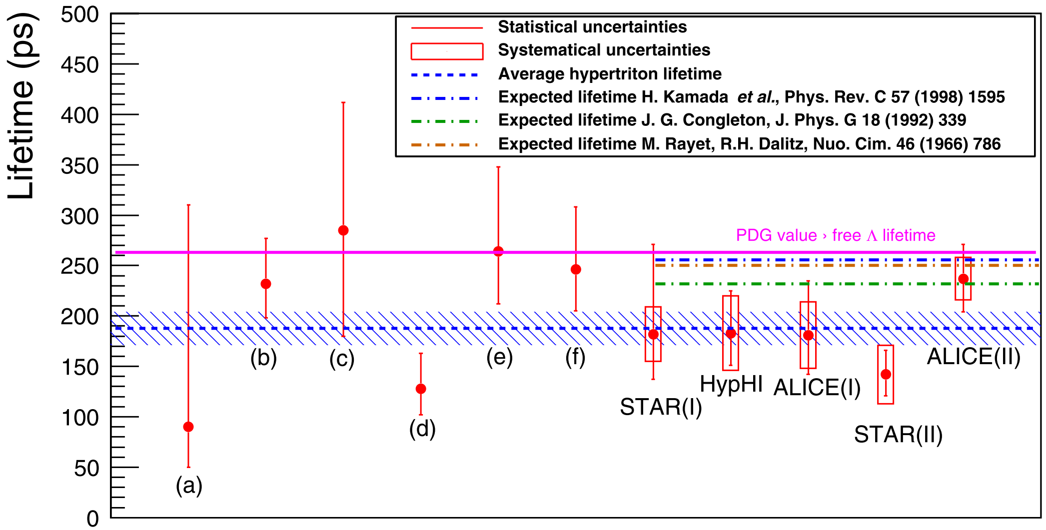
Recent results on lifetime measurement

STAR Phys. Rev. C 97 (2018)



ALICE runII





"Toward resolving the hyper triton lifetime puzzle"
Phys. Lett. B 791 (2019)

☑ A new evaluation by Gal with early popular theoretical framework, suggest 10% shorter than the free Lambda's, including pion FSI attraction effect give another 10% shorter than the free Lambda's

Binding energy: an answer to Dalitz's question?

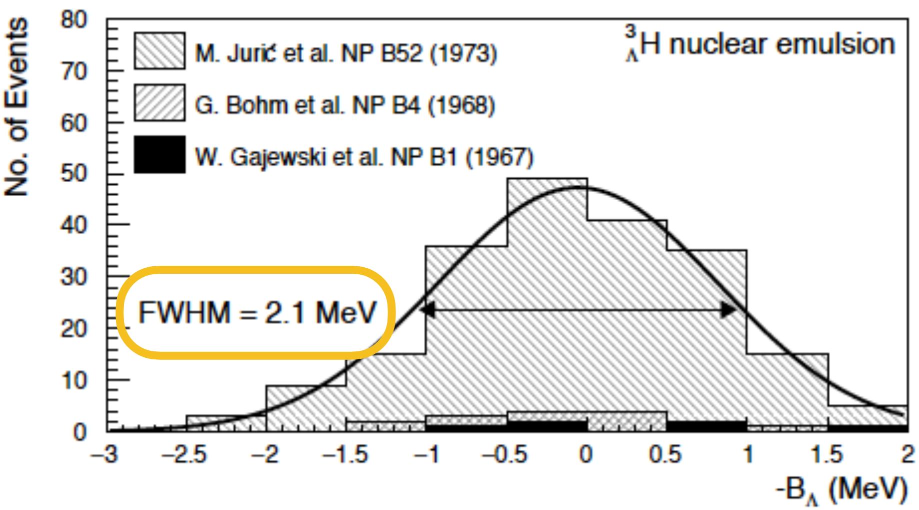
☑ The early data suffers from large statistical uncertainty!

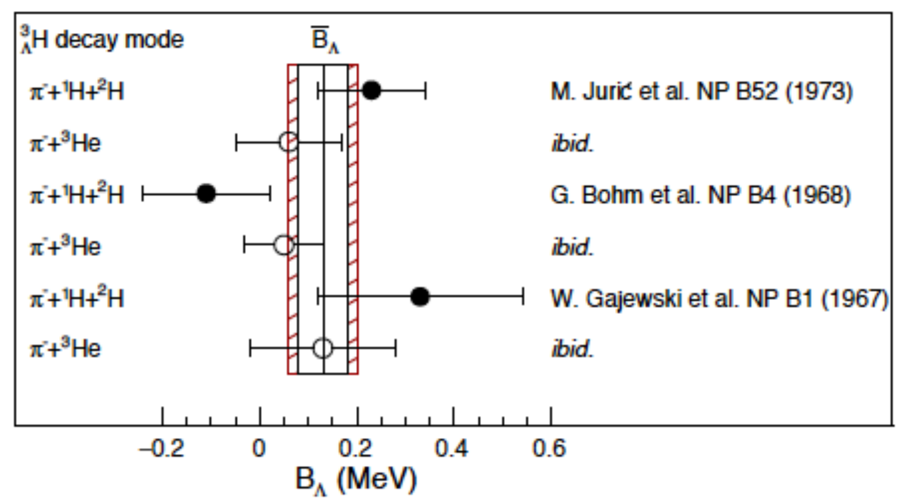
	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)		δB_Λ (MeV)
	Bohm et al.[a]	This work	
${}^3_\Lambda H$	0.01 ± 0.07	0.15 ± 0.08	0.14 ± 0.11

a) G. Bohm et al., Nucl. Phys. B4, 511 (1968)
b) This work : M. Juric, G. Bohm et al., Nucl. Phys. B52,1 (1973)

$$B_\Lambda = 0.13 \pm 0.05 \text{MeV}$$

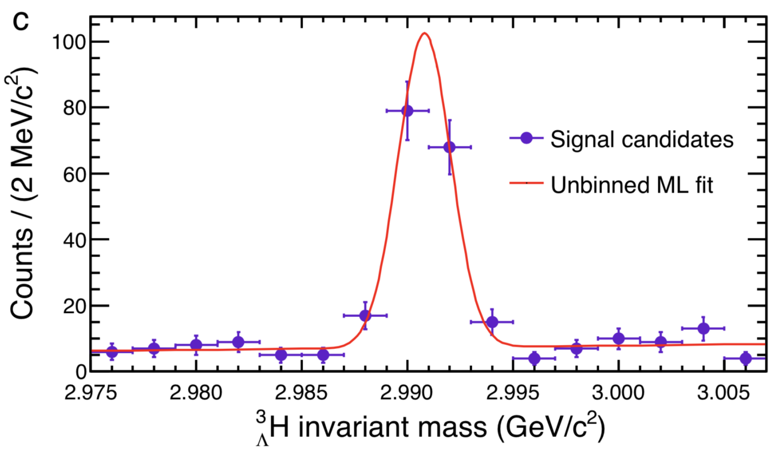
P. Achenbach, PoS (Hadron 2017) 207

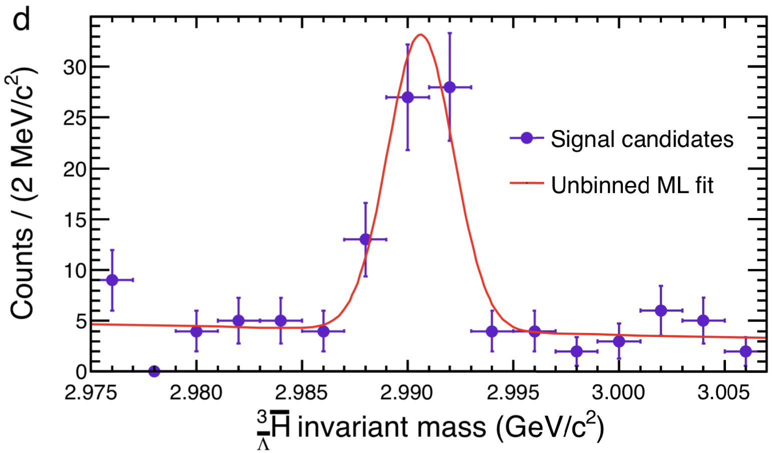


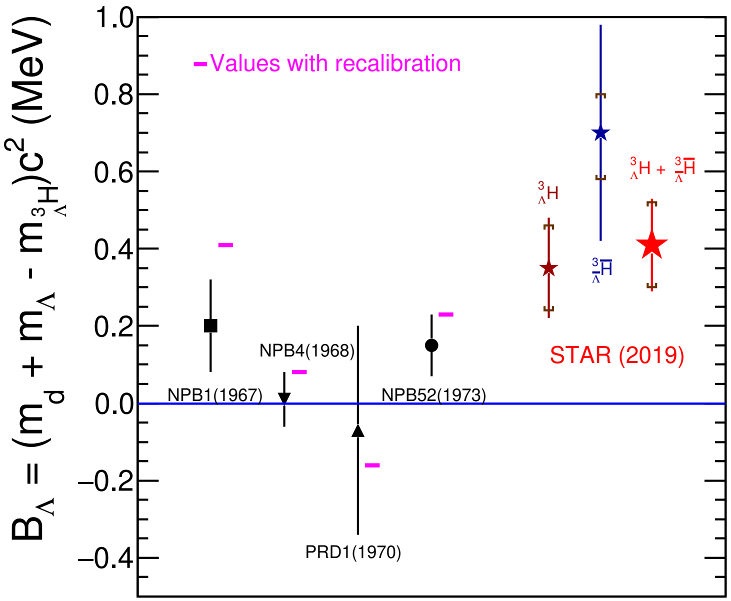


"I feel that we are far from seeing the end of this road. A good deal of theoretical work on this 3-body system would still be well justified." R.H. Dalitz Nucl. Phys. A 754, 14 (2005)

Our measurements with modern technology







$$B_\Lambda = 0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}$$

STAR Col. arXiv 1904.10520

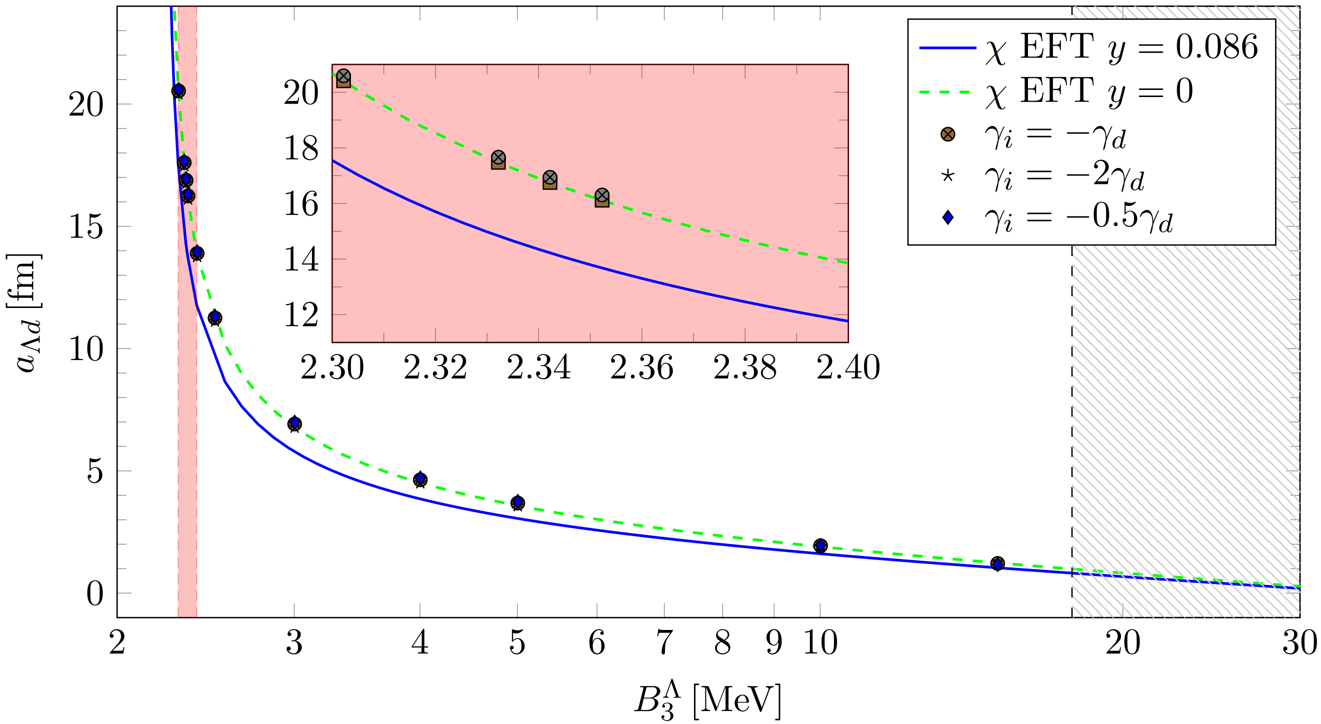
$$m_{^3_\Lambda H} = 2990.95 \pm 0.13(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}/c^2$$

$$m_{^3_{\bar{\Lambda}}\bar{H}} = 2990.60 \pm 0.28(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}/c^2$$

- ☑ STAR data differs from zero and larger than the prior measurements from 1973
- ☑ Strong Y-N interaction in hypernucleus system

New data yield stronger YNN interaction?

F. Hildenbrand and H.-W. Hammer, arXiv: 1904.05818



$B_\Lambda = 0.13 \pm 0.05 \text{MeV}$

$$a_{\Lambda d}^{y=0.086} = 13.80^{+3.75}_{-2.03} \text{ fm}$$

- ☑ The d-Lambda scattering length and hyper triton radius is strongly depend on the binding energy. At fixed cutoff an increase in the binding energy will require a more attractive three-body force

- ☑ Our data require higher-order correction to the effective d-Lambda assumption

Summary

- Production of (anti)(hyper)nuclei in ultra relativistic heavy ion collisions represents a unique opportunity to test the CPT invariance of nucleon-nucleon interaction using light (hyper)nuclei

- New measurements from STAR exp. open the (anti)(hyper)nuclei window. The latest results is:

$$[\,1.1 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.})] \times 10^{-4}$$

- High precision (anti)(hyper)nuclei data yield a conclusive measurement of hyper triton binding E:

$$0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}$$

- The increase in luminosity and detector upgrade allow the sensitivity of current measurement to be pushed forward, i.e., the (anti)4He