相对论重离子对撞机上
奇异夸克物质实验研究进展

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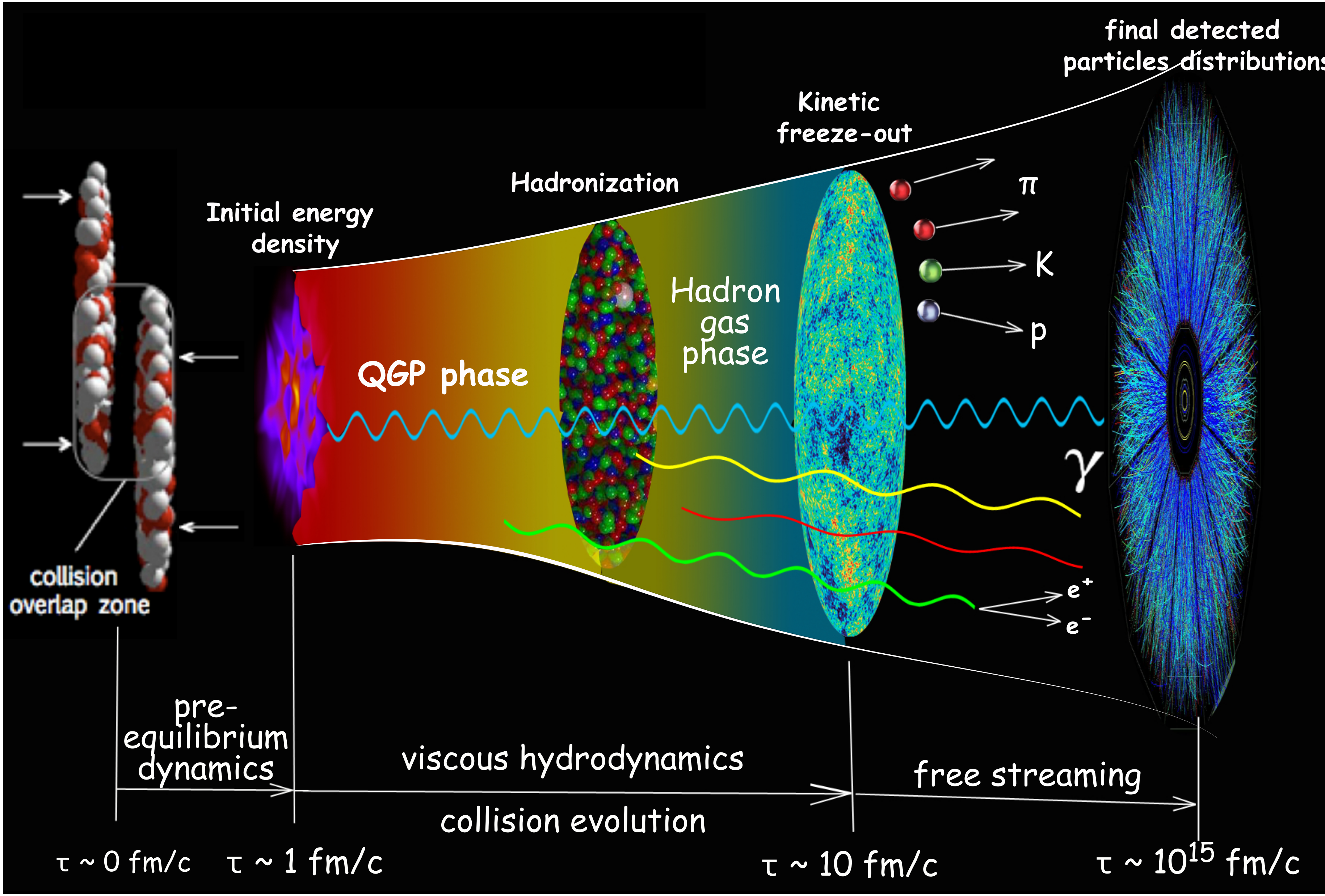
Outline

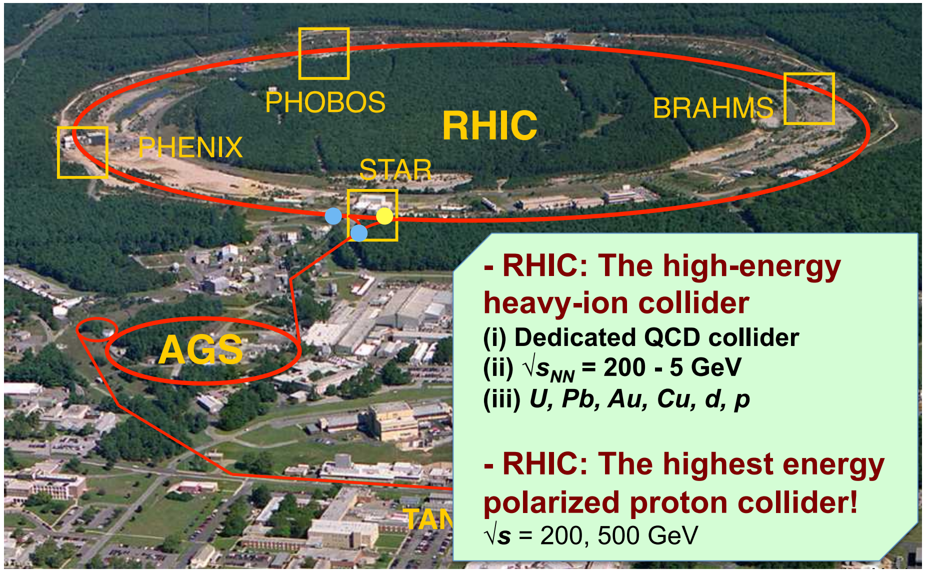
- ☑ Introduction
- ☑ Selected results
  - Strange hadron production at BES-I
  - Strange baryon interaction measurement
  - Hyper-baryon cluster measurement
- ☑ Summary and Outlook

Relativistic Heavy-Ion Collisions

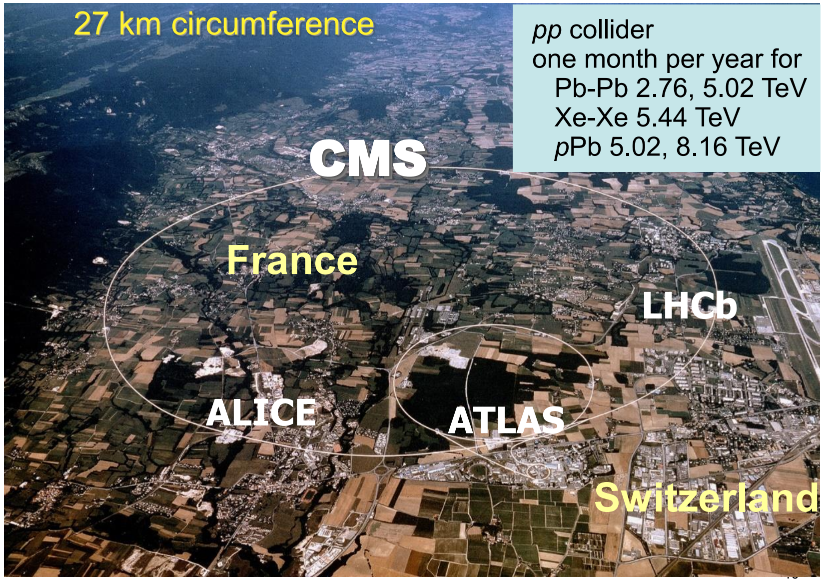


The facility and physics of RHIC

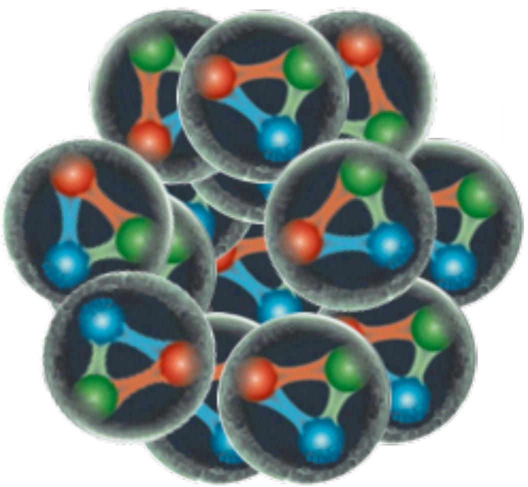
BNL-RHIC

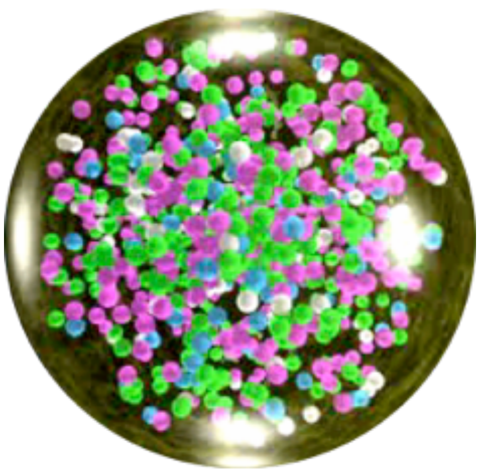


CERN-LHC



原子核　　高能重离子对撞　　夸克胶子等离子体





Study of QGP at RHIC

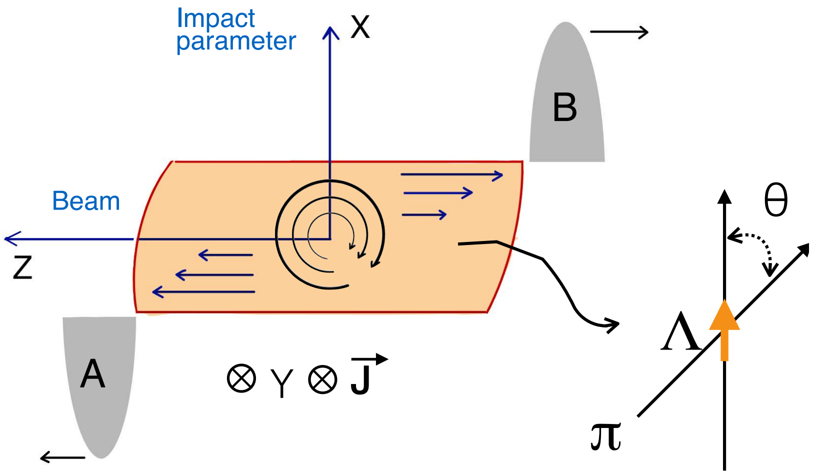
☑ Early days of RHIC discoveries and the topics that continue
- Jet quenching
- Flow

☑ And hot topics nowadays:
- Global/local polarization
- CME/CMW
- QCD phase diagram
- …

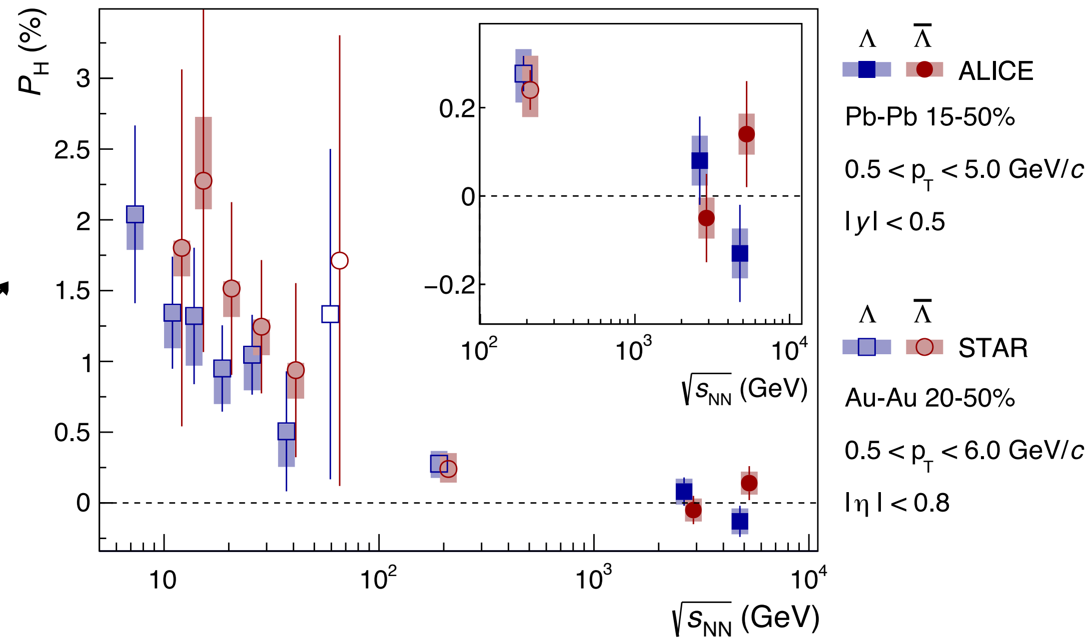
Strong evidences pointing to a "dense, opaque, low-viscous, pre-hadronic liquid state of matter not anticipated before RHIC"

RHIC white paper: Nucl. Phys. A 757 (2005)

Status of Global polarization-hyperon measurement



ALICE Col. Phys. Rev. C 101, 044611 (2020)
STAR Col. Nature 548, 62 (2017); Phy. Rev. C 98, 014910 (2018)

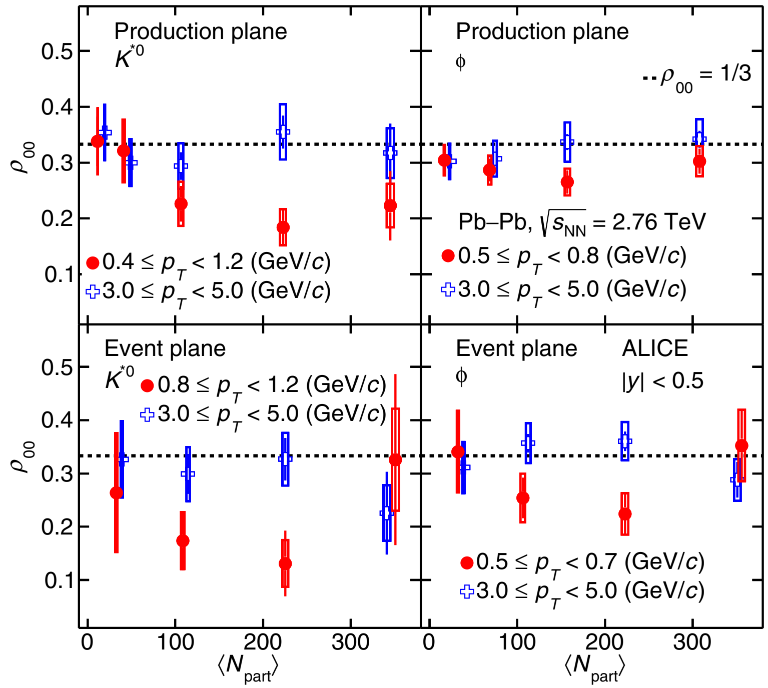


- ☑ How OAM is transferred to quark P_H so fast?
- ☑ How quark P_H is transferred to hadron P_H?
- ☑ Does anything other than OAM contribute to the P_H?
- ☑ What is the space-time dependence of vorticity?

- ☑ Currently we focus on differential measurements in p_T, eta, go to even lower energies, and with different particles

Status of Global polarization-vector meson measurement

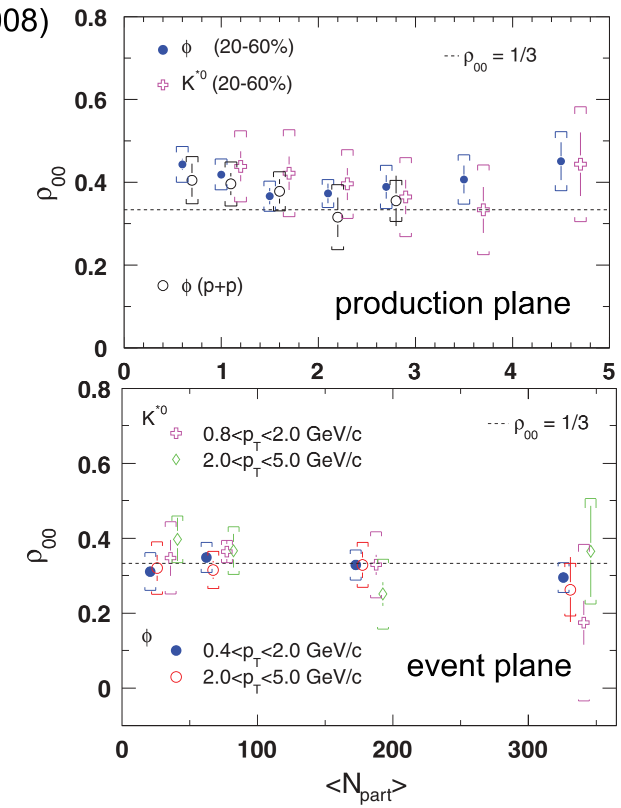
ALICE Col. PRL 125, 012301 (2020); STAR Col. Phys. Rev. C 77, 061902® (2008)



local

vs.

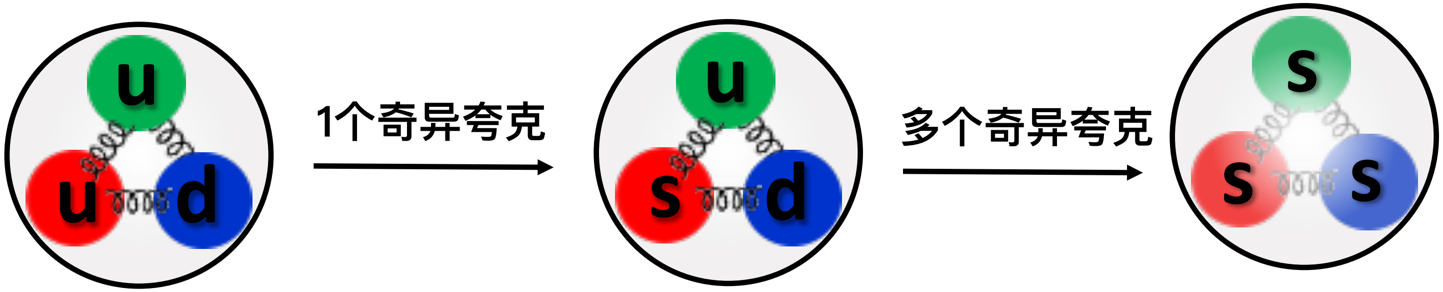
global



- STAR preliminary data on high stats. event at top RHIC energy and BES dependence present signal on phi and kstar, with the former >1/3, the latter < 1/3
  - The magnitude is too large? The difference between phi and kstar is also large?
  - In additional to \theta* term, \phi* term is non-vanishing   Xia,Li,Huang,Huang 2010.01474
  - Vector meson field may contribute to the phi-meson signal, kstar doesn't subject to

    Sheng,Oliva,Wang 1910.13684

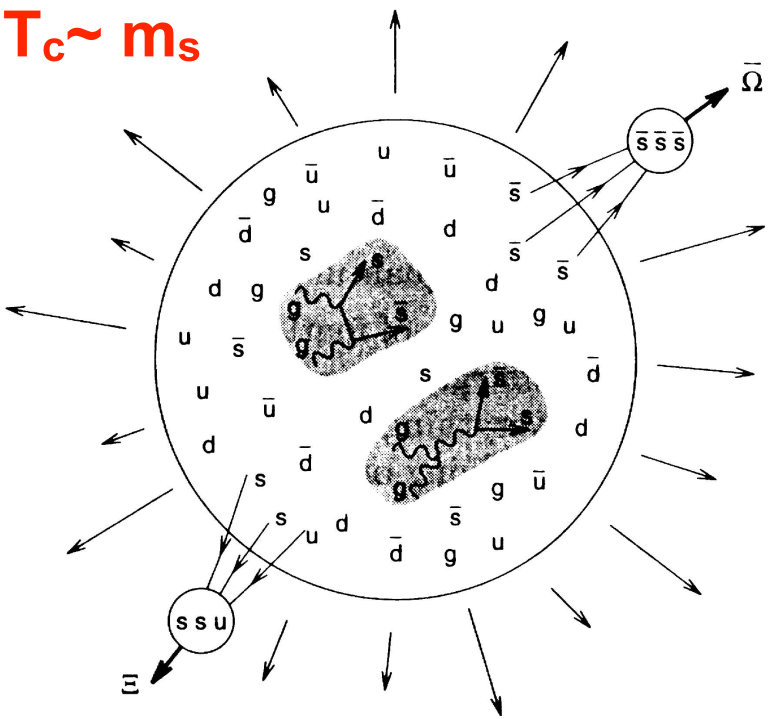
Selected results on strangeness production



Strangeness in Quark-Gluon Plasma

"Strangeness Production in the Quark-Gluon Plasma", J. Rafelski and B. Muller, PRL 48 (1982) 1066
"Strangeness in relativistic heavy ion collisions", P. Koch, B. Muller and J. Rafelski, Phys. Rept. 142 (1986) 167

$T_c \sim m_s$



$$dn_s/dt \approx A\{1-[n_s(t)/n_s(\infty)]^2\},$$

$$n_s(t) = n_s(\infty)\tanh(t/\tau), \quad \tau = n_s(\infty)/A.$$

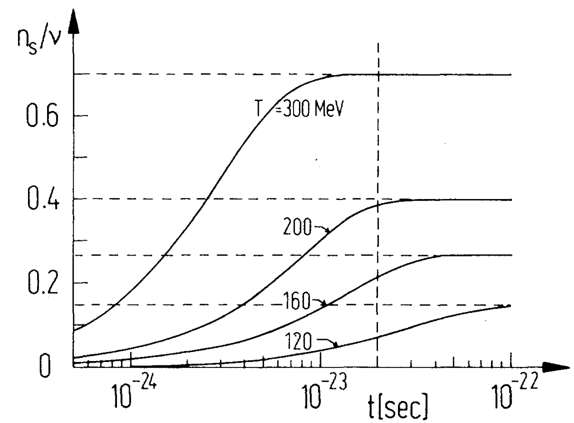


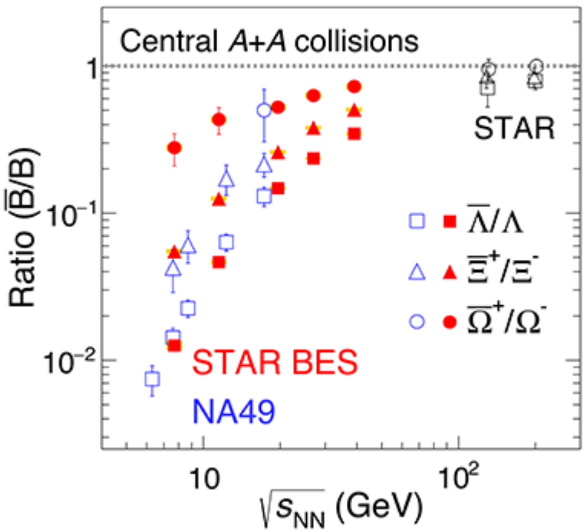
FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various temperatures (M = 150 MeV, α_s = 0.6).

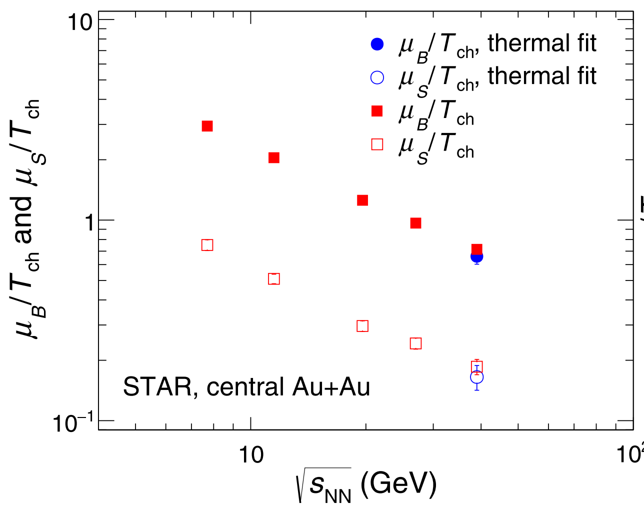
"Strangeness abundance saturates in sufficiently excited QGP (T > 160 MeV, E> 1 GeV/fm^3), allowing to utilize enhanced abundances of rare, strange hadrons as indicators for the formation of the plasma state in nuclear collisions."

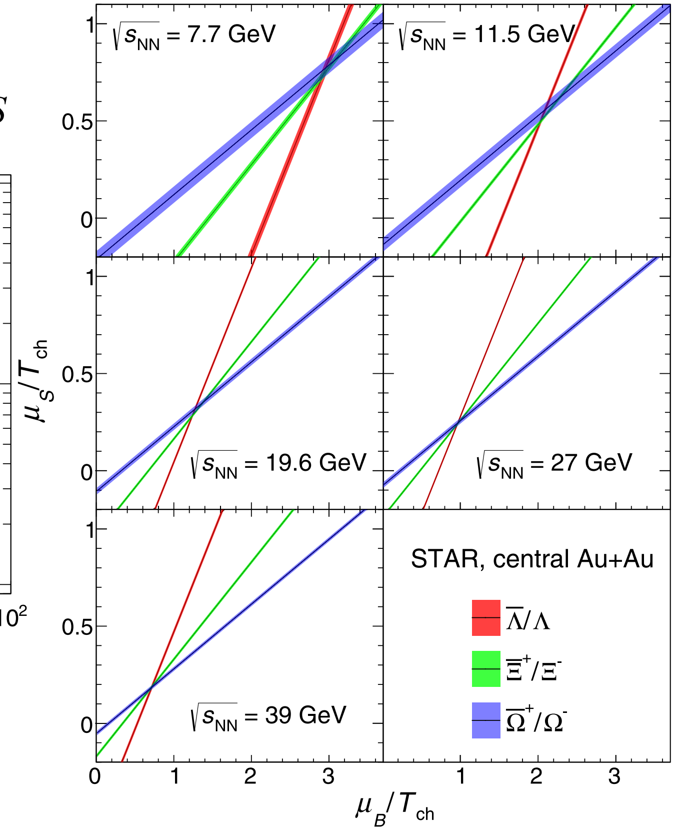
Strange hadron production in RHIC-BES I

STAR Col. Phys. Rev. C 102, 034909 (2020); 93, 021903® (2016)

$$\ln(\overline{\mathrm{B}}/\mathrm{B}) = -2\mu_B/T_{\mathrm{ch}} + \mu_S/T_{\mathrm{ch}}\Delta S$$



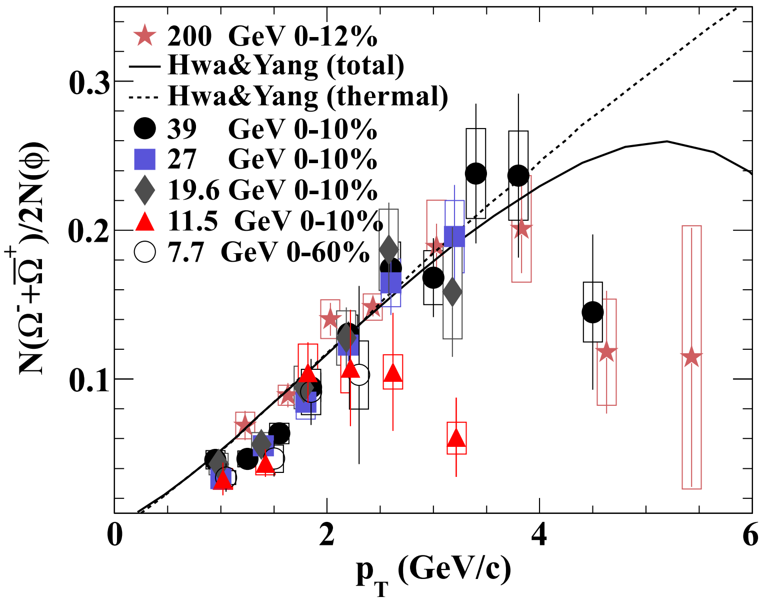




- ☑ Precision measurements of the abundances and p_T distributions for 8 species of strange mesons and baryons, as functions of centrality during a Au+Au beam-energy scan at RHIC.
- ☑ Test the thermal model parameter with different antibaryon-to-baryon ratios of different strangeness content, good agreement with results from light flavor hadron fit.

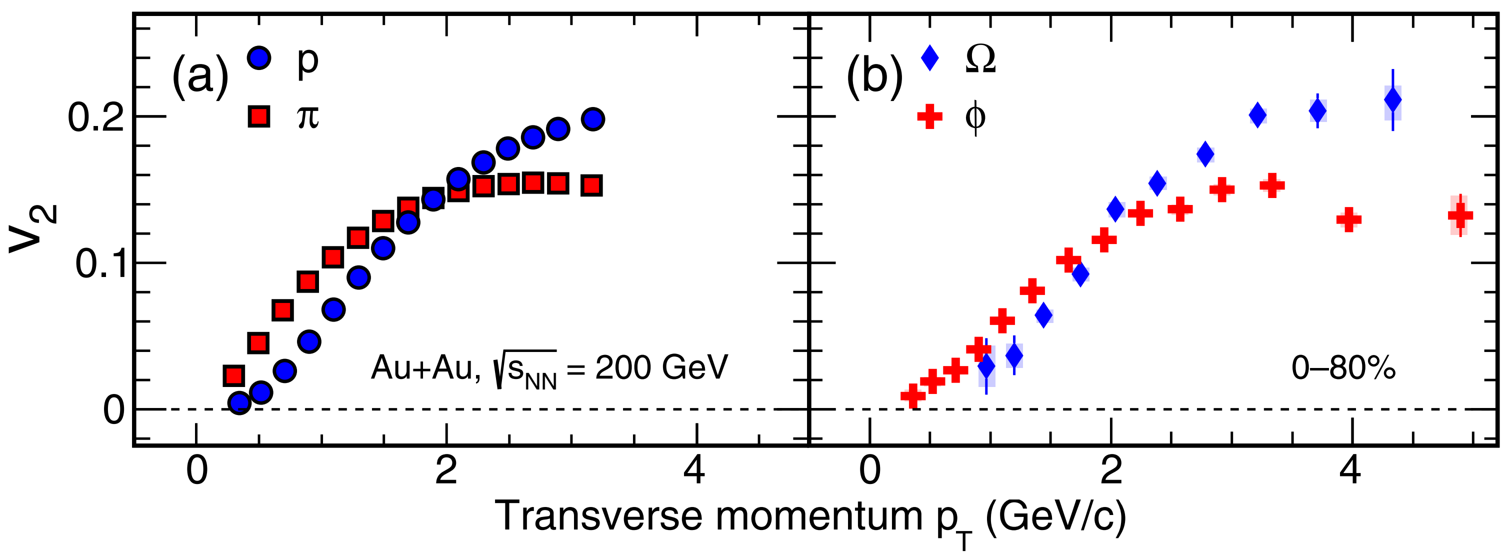
Multistrange hadron ratio and flow

STAR Col. Phys. Rev. C 93, 021903® (2016); PRL 116, 062301 (2016)



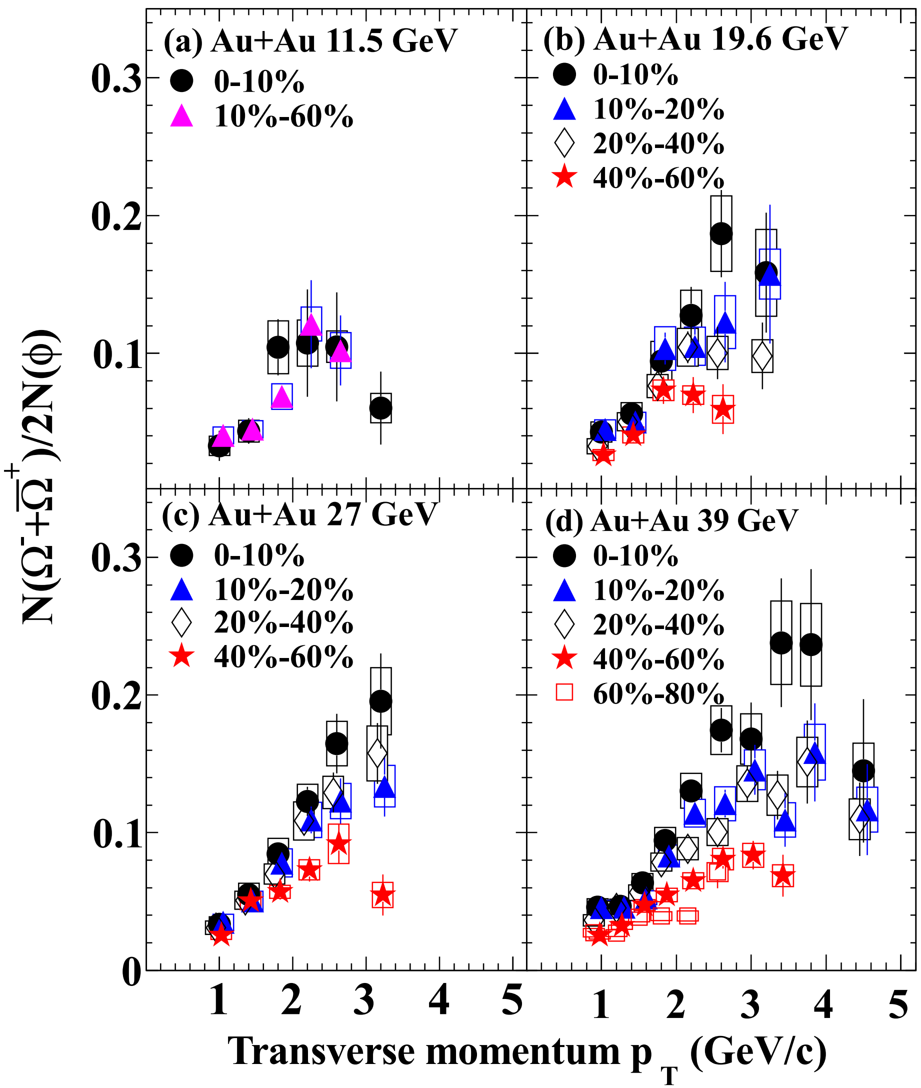
- ☑ Yield ratios are consistent with thermal parton coalescence calculation
- ☑ Anisotropic flow: multistrange hadron flow as strong as light flavor hadron, partonic collectivity in light/strange quarks

(charm quarks: Yifei/Xin)

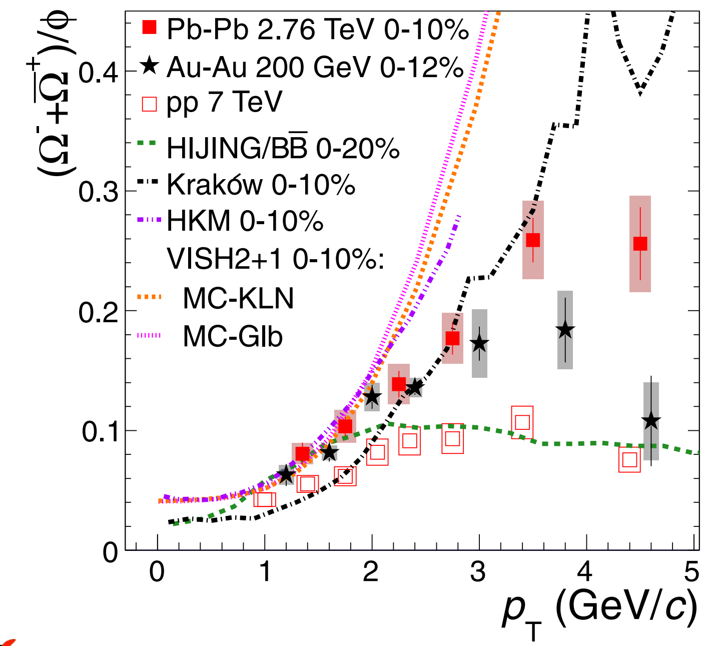


Yield ratio vs. centrality/energy

STAR Col. Phys. Rev. C 93, 021903® (2016)



ALICE Col. Phys. Rev. C 91, 024609 (2015)



- ☑ Difference between peripheral collisions to central collisions, between pp to AA is seen
- ☑ The ratios from 40-60% at 27 GeV are similar in magnitude to the ratios at 11.5 GeV
  - A possible change in strange-hadron production dynamics (<20 GeV)
- ☑ The results significantly improve the exp. knowledge in the energy range where key features of the QCD phase diagram are nowadays being studied.

SH production associated with fluctuation

☑ COAL-SH with quark density fluctuations

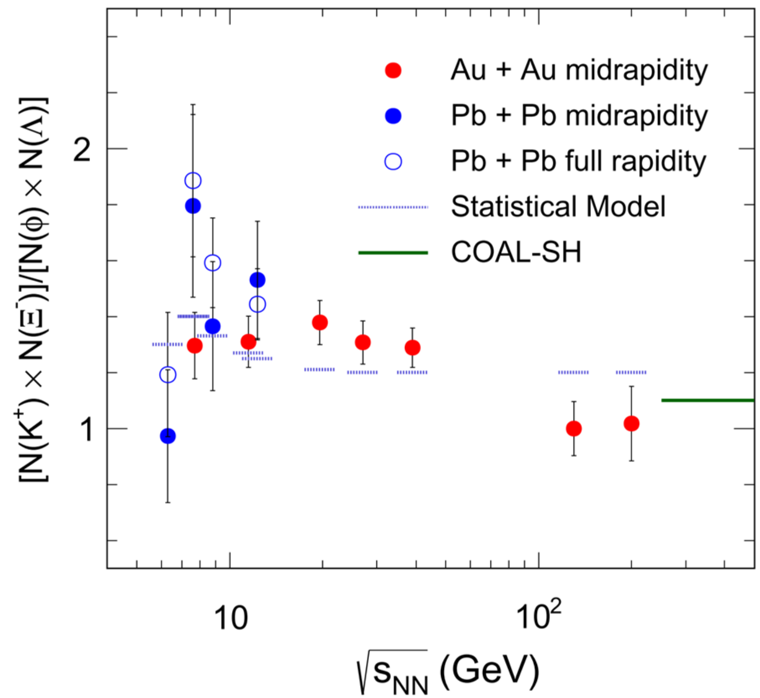
$$N_{K^+} = g_{K^+}\frac{(2\pi/T_C)^{3/2}}{1+\omega/(2T_C)}V_C\langle\bar{s}\rangle\langle u\rangle(1+\alpha_{\bar{s}u})$$

$$N_{\Xi^-} = g_{\Xi^-}\frac{(2\pi/T_C)^{3}}{[1+\omega/(2T_C)]^2}V_C\langle s\rangle^2\langle d\rangle(1+\Delta s+2\alpha_{sd})$$

$$N_{\phi} = g_{\phi}\frac{(2\pi/T_C)^{3/2}}{1+\omega/(2T_C)}V_C\langle s\rangle\langle\bar{s}\rangle(1+\alpha_{s\bar{s}})$$

$$N_{\Lambda} = g_{\Lambda}\frac{(2\pi/T_C)^{3}}{[1+\omega/(2T_C)]^2}V_C\langle s\rangle\langle u\rangle\langle d\rangle(1+\alpha_{sd}+\alpha_{su}+\alpha_{ud})$$

$$\frac{N(K^+)N(\Xi^-)}{N(\phi)N(\Lambda)} \approx g(1+\Delta s)$$



Shao, Chen, Ko, Sun, Phys. Lett. B 801 (2020) 135177

Table 2
Same as Table 1 for midrapidity strange hadrons except the last two columns, which give the yield ratio $\mathcal{O}_{K\text{-}\Xi\text{-}\phi\text{-}\Lambda}$ from the statistical model [50] and the coalescence model using the hadronization temperature T_C. For the statistical model, the percentage of contributions from different decay channels is taken from that calculated at $\sqrt{s_{NN}} = 200$ GeV.

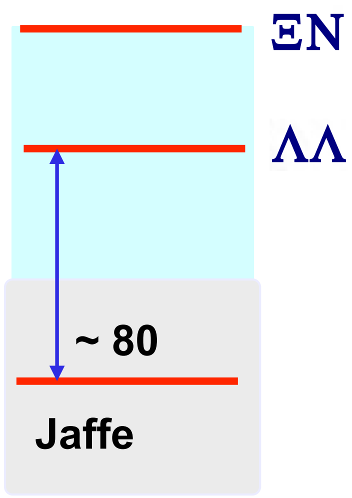
E	$\sqrt{s_{NN}}$	Ξ^-	K^+	Λ	ϕ	$\mathcal{O}_{K\text{-}\Xi\text{-}\phi\text{-}\Lambda}$	T_C	Δs	stat. model	COAL-SH
20	6.3	0.93±0.13	16.4±0.6	13.4±0.1	1.17±0.23	0.97±0.24	131.3	$0^{+0.10}$	1.30	1.10
30	7.6	1.17±0.13	21.2±0.8	14.7±0.2	0.94±0.13	1.79±0.33	140.1	0.63 ± 0.30	1.40	1.10
40	8.8	1.15±0.11	20.1±0.3	14.6±0.2	1.16±0.16	1.36±0.23	146.1	0.24 ± 0.21	1.33	1.10
80	12.3	1.22±0.14	24.6±0.2	12.9±0.2	1.52±0.11	1.53±0.21	153.5	0.39 ± 0.19	1.23	1.10

Selected results on strange hadron interaction

The long history of H particle problem

- In 1977, Jaffe predicted that double strange dibaryon made of six quark (*uuddss*) may be deeply bound below the Lambda-Lambda threshold due to strong attraction from color magnetic interaction based on the bag model calculation

Phys. Rev. D **15**, 267 (1977);
Phys. Rev. D **15**, 281 (1977)
PRL **38**,195 (1977); **38**, 617(E)(1977)



- Properties : $J^P = 0^+$, mass : (1.9-2.8) GeV/c^2

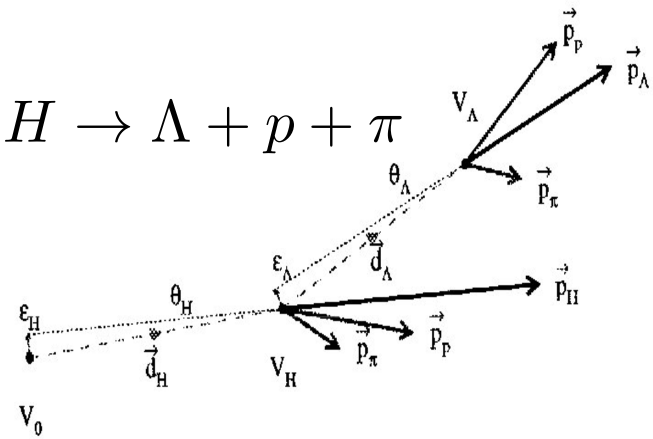
$$\psi(\mathrm{H}) = \sqrt{\frac{1}{8}}\psi(\Lambda\Lambda) + \sqrt{\frac{4}{8}}\psi(N\Xi) - \sqrt{\frac{3}{8}}\psi(\Sigma\Sigma)$$

- Since prediction, dedicated measurements have been performed to look for the H dibaryon signal, but its existence remains an open question

The latest measurement in HIC

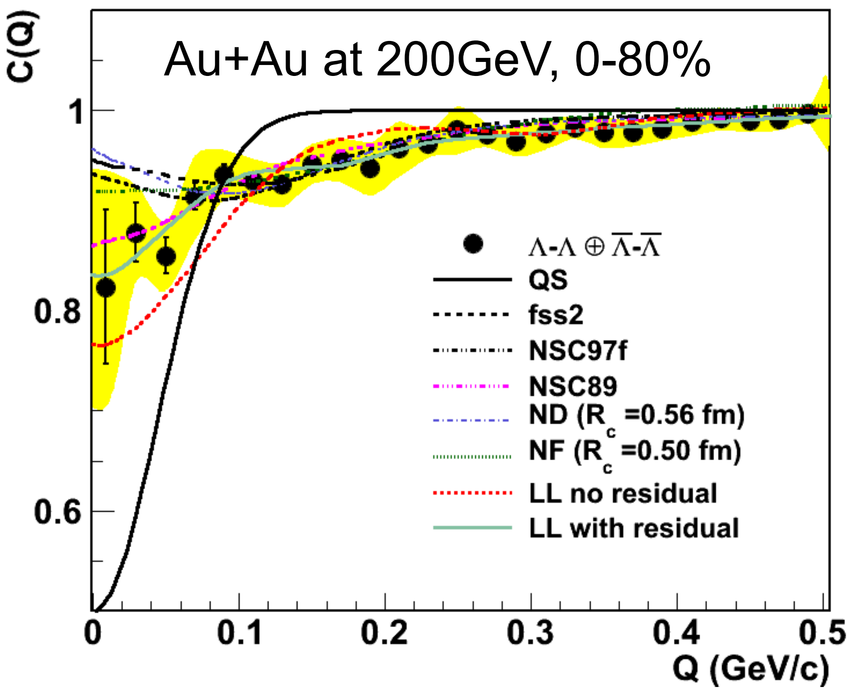
- ☑ Topological reconstruction didn't see a signal

$$H \rightarrow \Lambda + p + \pi$$

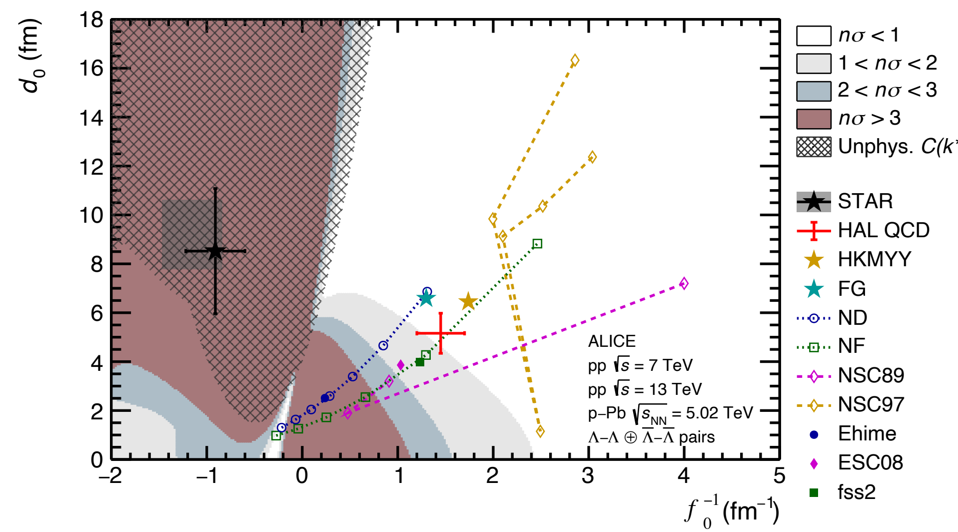


- ☑ Two particle correlation measurements suggest a rather weak interaction

STAR Col. PRL 114, 022301 (2015)



ALICE run1: limited stats.
Phys. Lett. B 797,134822 (2019)



- ☑ Physical point LQCD calculation: weakly attractive, not enough strong to produce bound or resonance dihyperon

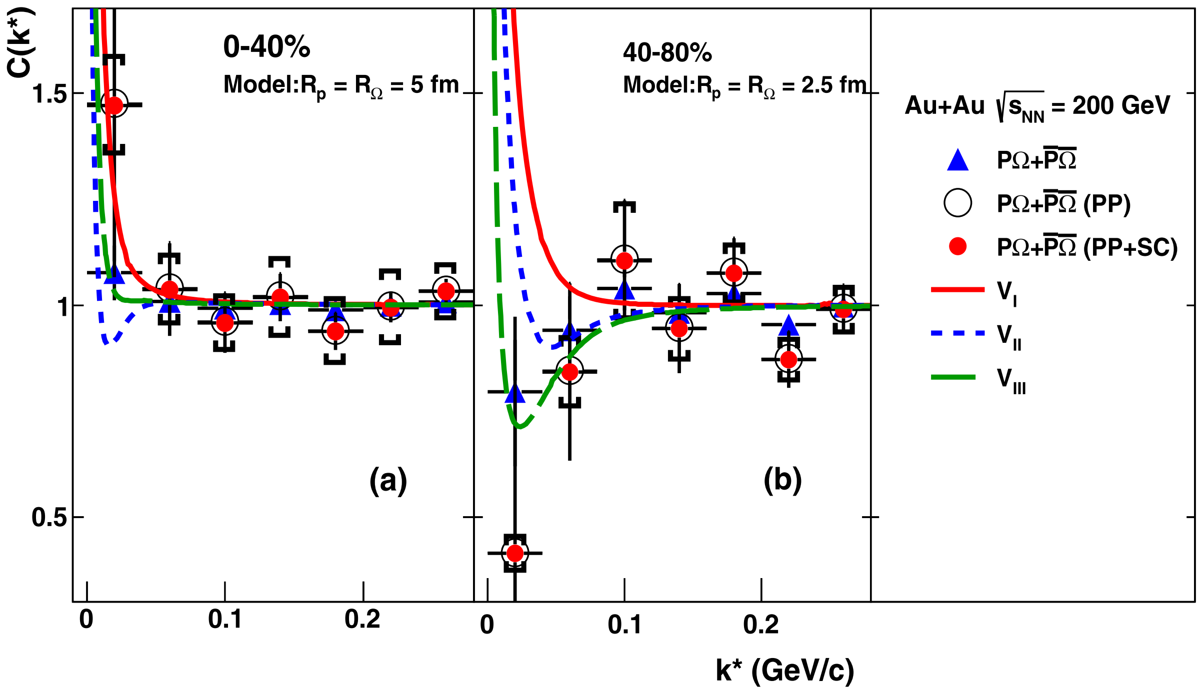
Nucl. Phys. A 998, 121737 (2020)

The p-Omega correlations (I) : Au+Au collisions

- Physical point LQCD calculation: the NΞ interaction has relatively strong attraction in isospin-singlet, spin-singlet channel
- ALICE see the signal

  PRL 123, 112002 (2019)

- the S=-3 sector?



STAR Col. Phys. Lett. B 790, 490 (2019)

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65

Morita, Ohnishi etc., Phys. Rev. C 94, 031901 (2016); 101,015201 (2020)

- Comparison of measured p-Omega CF from 0-40% and 40-80% centrality Au+Au collisions with the predictions for p-Omega interaction potentials V_I,V_{II},V_{III}

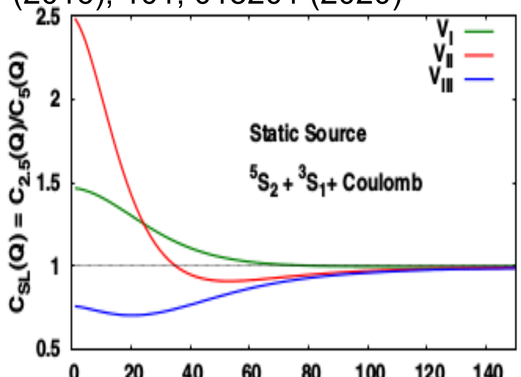
Take the ratio: the p-Omega correlation

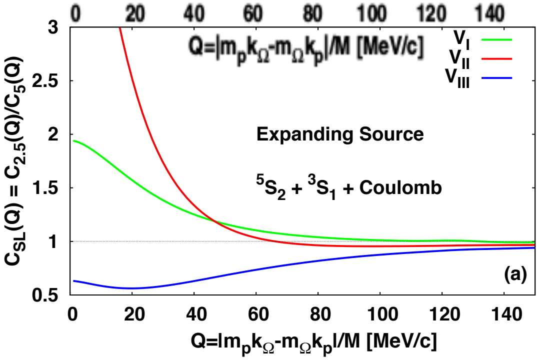
STAR Col. Phys. Lett. B 790, 490 (2019)

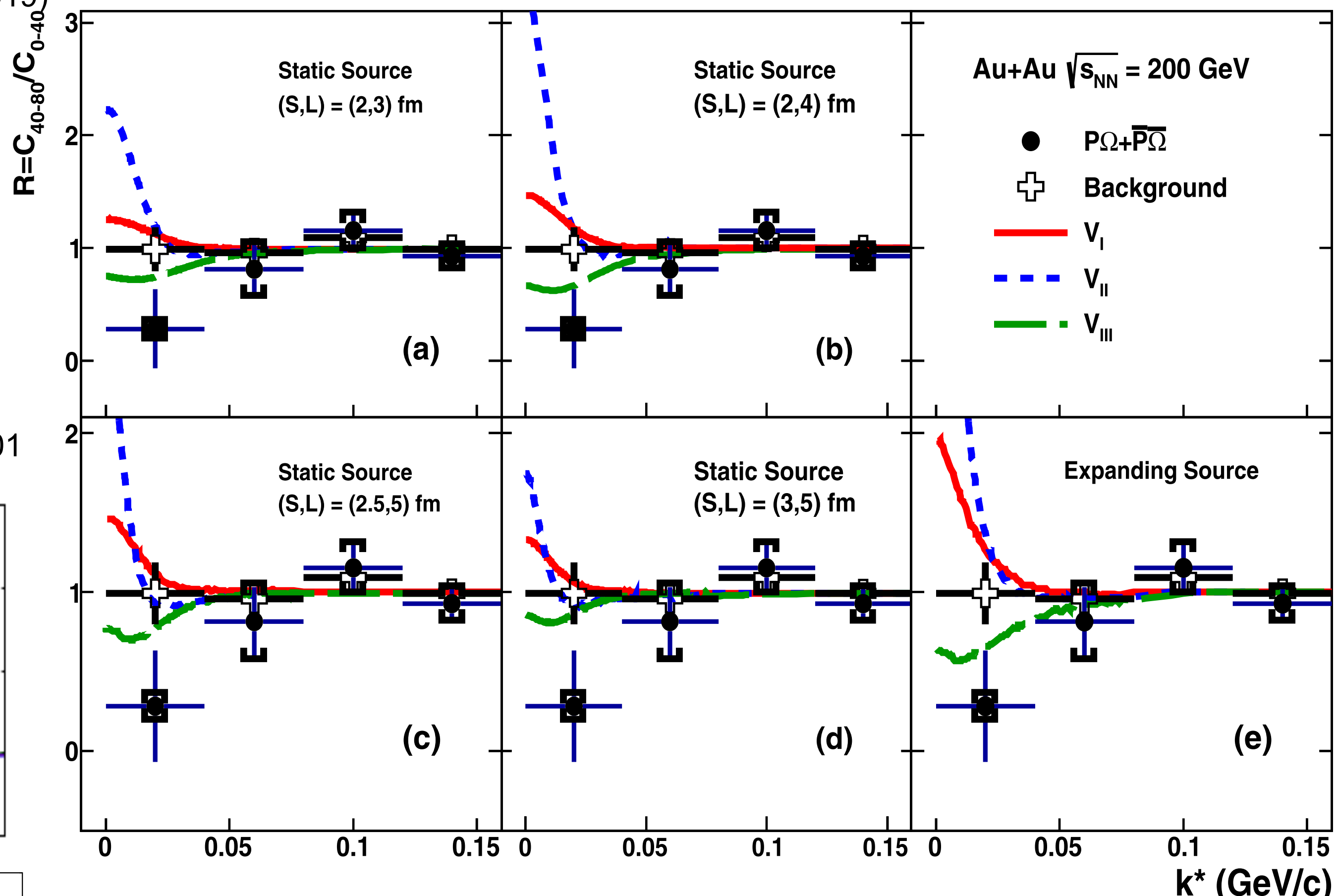
- The ratio at low k*
  – <1.0 for data
  – close to 1.0 for bg

  – Compared with LQCD calculation favors V_{III} potential scenario

Morita, Ohnishi etc.:PRC 94, 031901 (2016); 101, 015201 (2020)

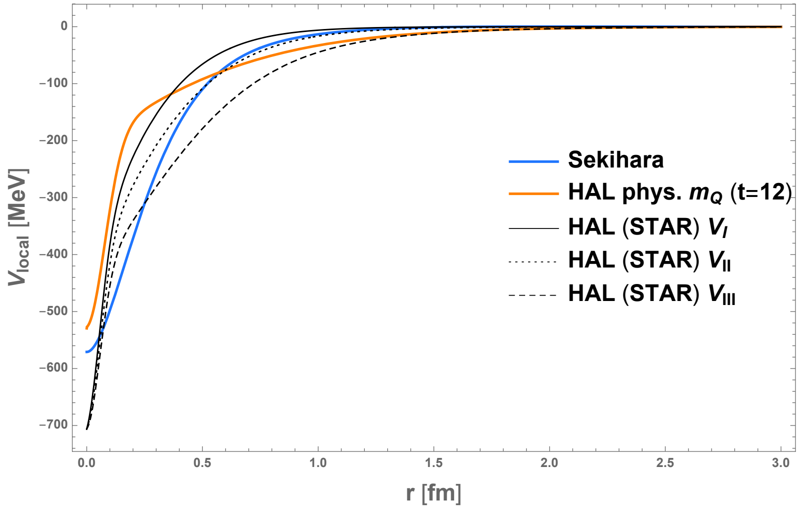






k* (GeV/c)	R	Background
0.20	$0.28\pm0.35_{stat}\pm0.03_{sys}$	$0.96\pm0.13_{stat}$
0.60	$0.81\pm0.22_{stat}\pm0.08_{sys}$	$0.97\pm0.05_{stat}$

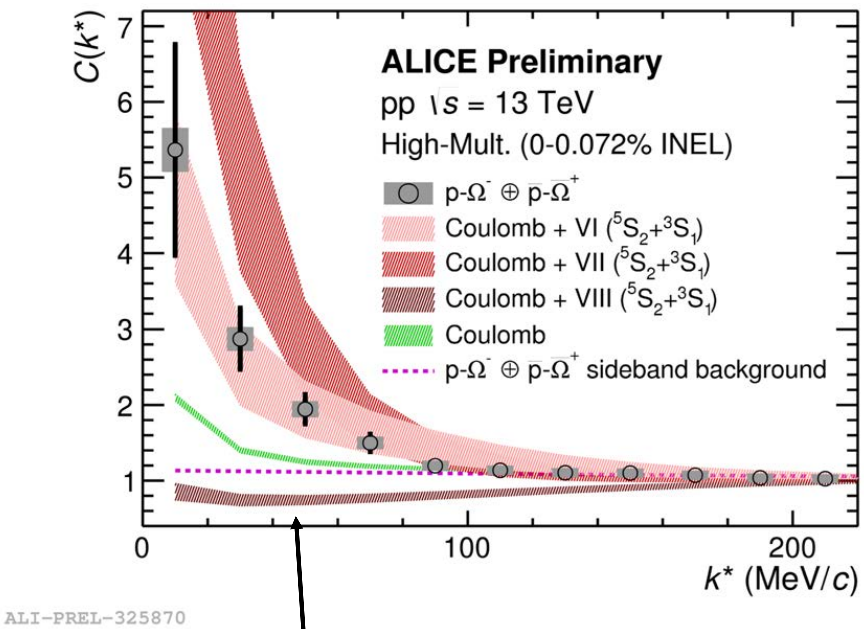
The p-Omega correlations (II) : pp collisions



Model	pΩ⁻ binding energy (strong interaction only)
HAL (STAR) VI	-
HAL (STAR) VII	6.3 MeV
HAL (STAR) VIII	24.8 MeV
HAL-QCD	1.54 MeV
Sekihara	0.1 MeV

PLB 792,284 (2019)

PRC 98,015201 (2018)



a_0 (pΩ) ~ 3.4 fm

R(ALICE pp)~ 0.85 fm, R(STAR Au+Au)~ 2.5 -5 fm

- ☑ HAL-QCD potential with physical quark mass give a small binding energy, meson-exchange model even smaller
- ☑ Preliminary data from ALICE suggests more attractive than p-Xi, and is not compatible with a large binding energy scenario
- ☑ p-Omega is very sensitive to the source size

Extend the strange hadron to hypernuclei

The lightest, s-shell, Lambda hypernuclei

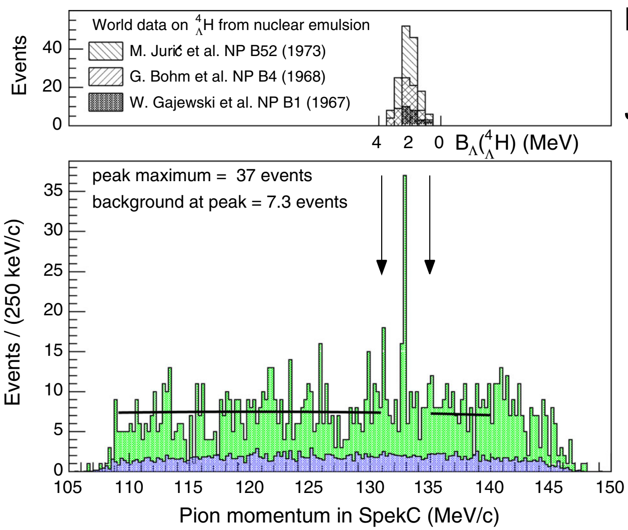
☑ The overbinding problem in s-shell

(MeV)	$B_\Lambda(^3_\Lambda\mathrm{H})$	$B_\Lambda(^4_\Lambda\mathrm{H}_{\mathrm{g.s.}})$	$E_x(^4_\Lambda\mathrm{H}_{\mathrm{exc.}})$	$B_\Lambda(^5_\Lambda\mathrm{He})$
Exp.	0.13(5)	2.16(8)	1.09(2)	3.12(2)
Dalitz	0.10	2.24	0.36	≥5.16
NSC97f(S)	0.18	2.16	1.53	2.10
AFDMC(I)	–	1.97(11)	–	5.1(1)
AFDMC(II)	−1.2(2)	1.07(8)	–	3.22(14)
LOχEFT(600)	0.11(1)	2.31(3)	0.95(15)	5.82(2)
LOχEFT(700)	–	2.13(3)	1.39(15)	4.43(2)

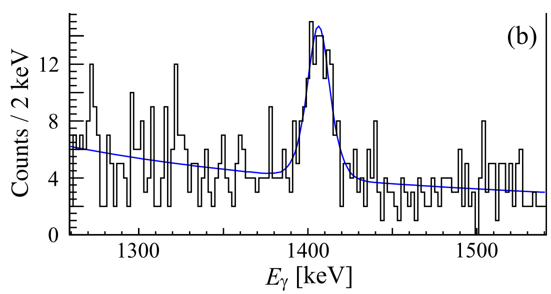
"Resolving the Lambda Hypernuclear Overbinding Problem in Pionless Effective Field Theory"
L. Contessi, N. Barnea, A. Gal,
PRL 121, 102502 (2018)

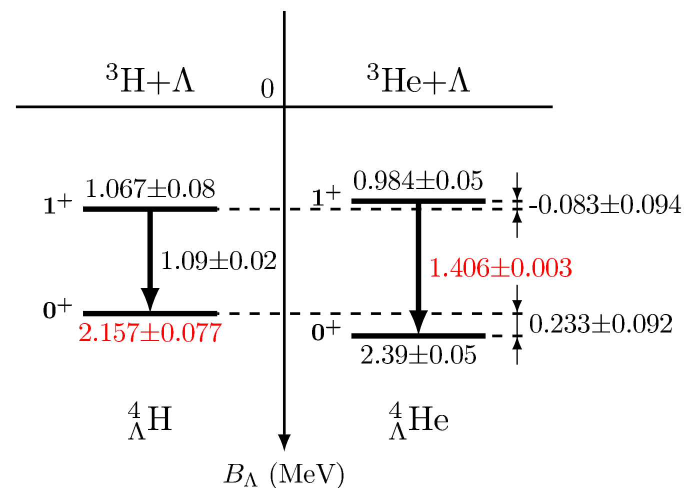
λ (fm^{-1})	Alexander[B]	NSC97f	χLO	χNLO
4	2.59(3)	2.32(3)	2.99(3)	2.40(3)
$\to\infty$	3.01(10)	2.74(11)	3.96(08)	3.01(06)

☑ The CSB problem in A = 4

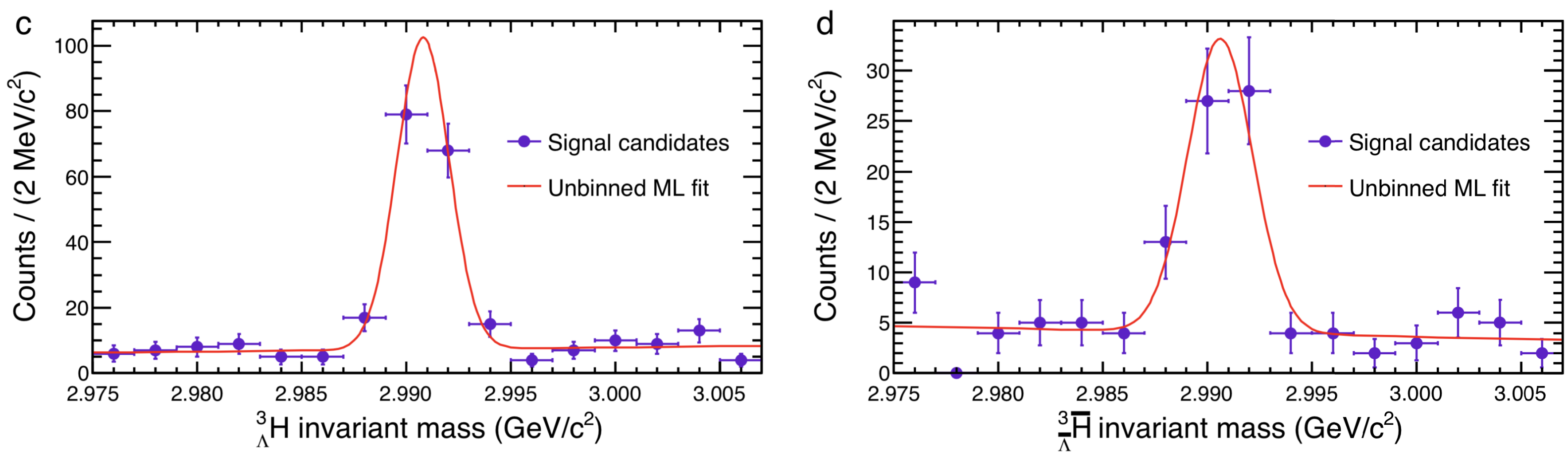


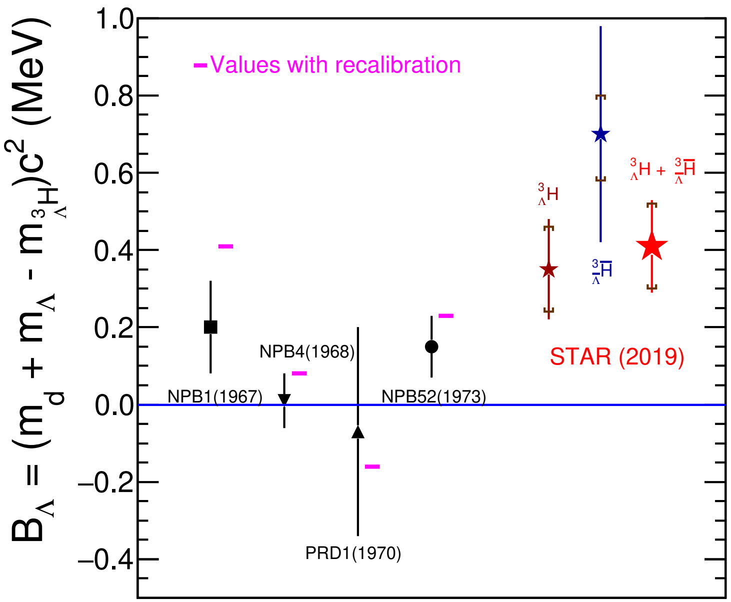
MAMI A1 Col.,
PRL 114, 232501 (2015)
J-PARK E13 Col.,
PRL 115, 222501 (2015)





Access the binding energy with HIC data





STAR Col. Nature Phys. 16, 409 (2020)

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

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

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

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

Recalibration details: Liu, Chen, Keane, Xu, Ma, Chin. Phys. C 43, 124001 (2019)

New data : stronger YNN interaction?

☑ Three-body hypernuclei from pionless EFT Hildenbrand, Hammer, Phys. Rev. C 100, 034002 (2019)

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

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

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

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

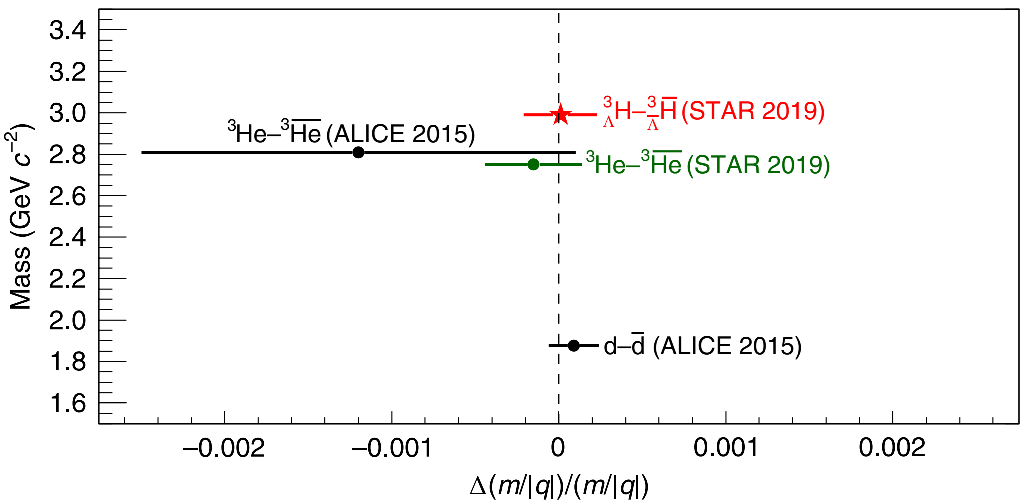
☑ Updated calculation on YN interaction within Chiral EFT: the in-medium interaction of the Lambda predicted by the new potential is now considerably more attractive and becomes repulsive at much higher nuclear densities

YN interaction	$^{3}_{\Lambda}$H
NLO13(650) w/ Σ	0.087
NLO13(650) w/o Σ	0.095
NLO19(650) w/ Σ	0.095
NLO19(650) w/o Σ	0.100
Jülich'04 w/ Σ	0.046
Jülich'04 w/o Σ	0.162
NSC97f w/ Σ	0.099
NSC97f w/o Σ	0.062

Haidenbauer, Meibner, Nogaa, Phys. Lett. B 801, 135189; Eur. Phys. J.A 56, 3 (2020)

"For a significantly larger BE, the excellent description of the LambdaN and SigmaN data can be maintained, by an approximate re-adjustment of the potential strengths in the LambdaN $^1S_0$ and $^3S_1$ partial waves - though at the expense of giving up the strict SU(3) constraints on the LECs between the LambdaN and SigmaN channels."

CPT test in nuclei sector with strangeness



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

ALICE (A = 3, S = 0)

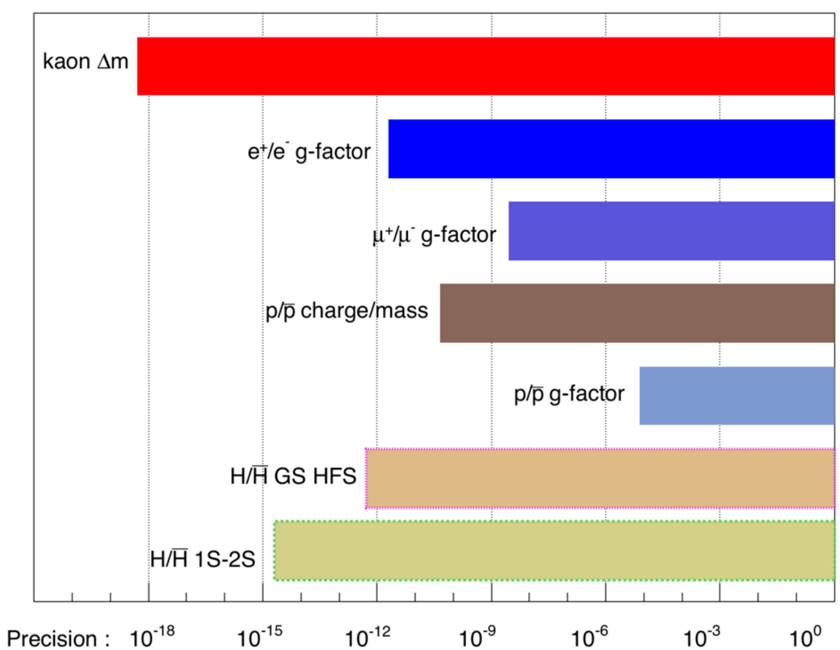
$(-1.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-3}$

STAR (A = 3, S = -1)

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

$[\,0.1 \pm 2.0(\text{stat.}) \pm 1.0(\text{syst.})] \times 10^{-4}$

STAR Col. Nature Phys. 16, 409 (2020)



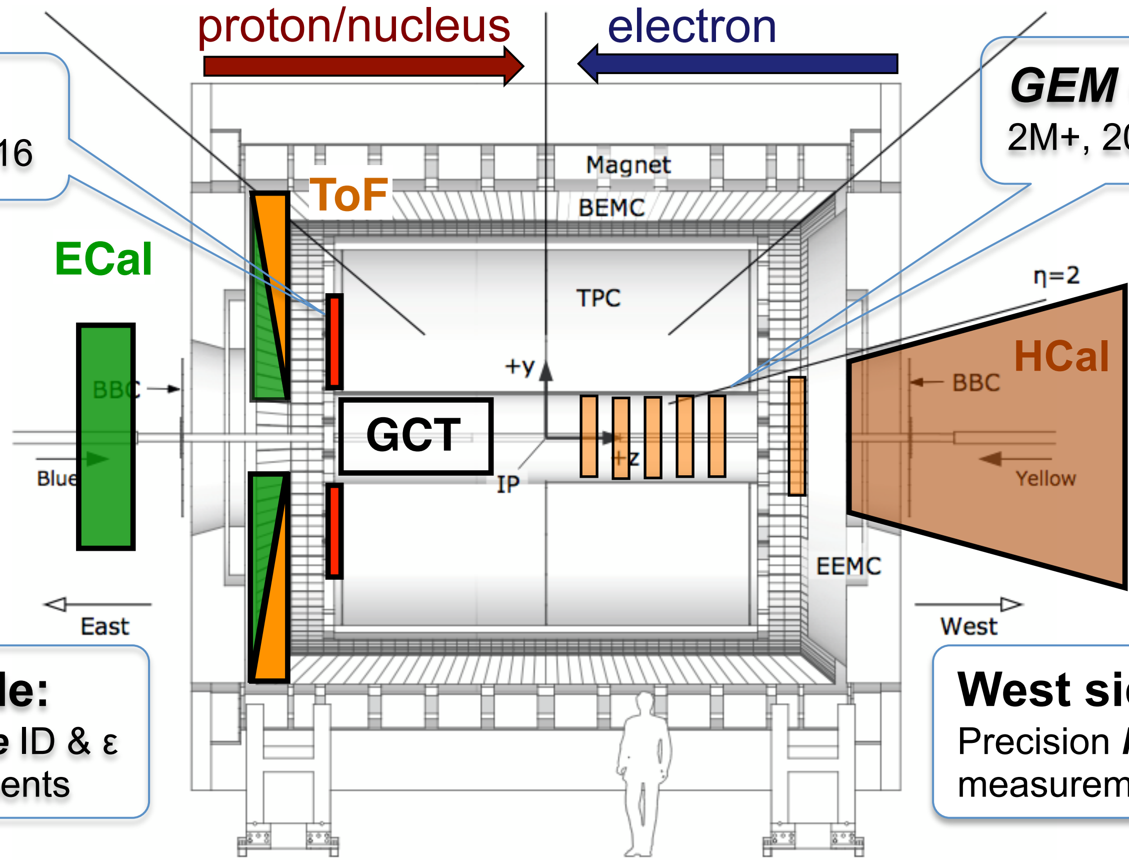
- An especially precise test is provided by the magnitude of the mass difference between Kaons. Many other tests present no CPT violations

Fig. taken from “Chen et al./Phys. Rept. 760, 1 (2018)”

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

Summary and Outlook

- ☑ Many other important physics have not been discussed…
- ☑ STAR China team contributes significantly to the experiment



East side:
Precision ***e*** ID & ε measurements

West side:
Precision ***h*** ID & ε measurements

Small-x cold nuclear matter properties in ep, eA, pA collisions (eSTAR)

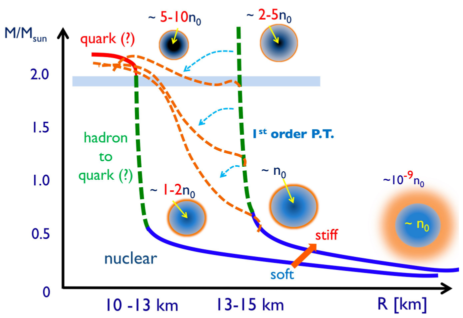
Discussions

☑ It is believed that massive neutron stars have sizable quark-matter cores

Annala, Gorda, Kurkela, Nattila, Vuorinen, Nature Phys. 16, 907 (2020);
Lonardoni et al., PRL114 (2015); Wirth and Roth, PRL 117 (2016)

☑ How to understand the 'hyperon puzzle' in NS?

– Measure the 3-body nucleon interaction with a hyperon?



Kojo, arXiv:2011.10940

☑ Where is the onset of Ξ stability?

– KEK-E373 (Ξ-^{14}N) event suggests attractive interaction between ΞN, but on the existence of hypernuclei, the interpretation is not conclusive

Nakazawa et al., Prog. Theor. Exp. Phys. 22 (2015)

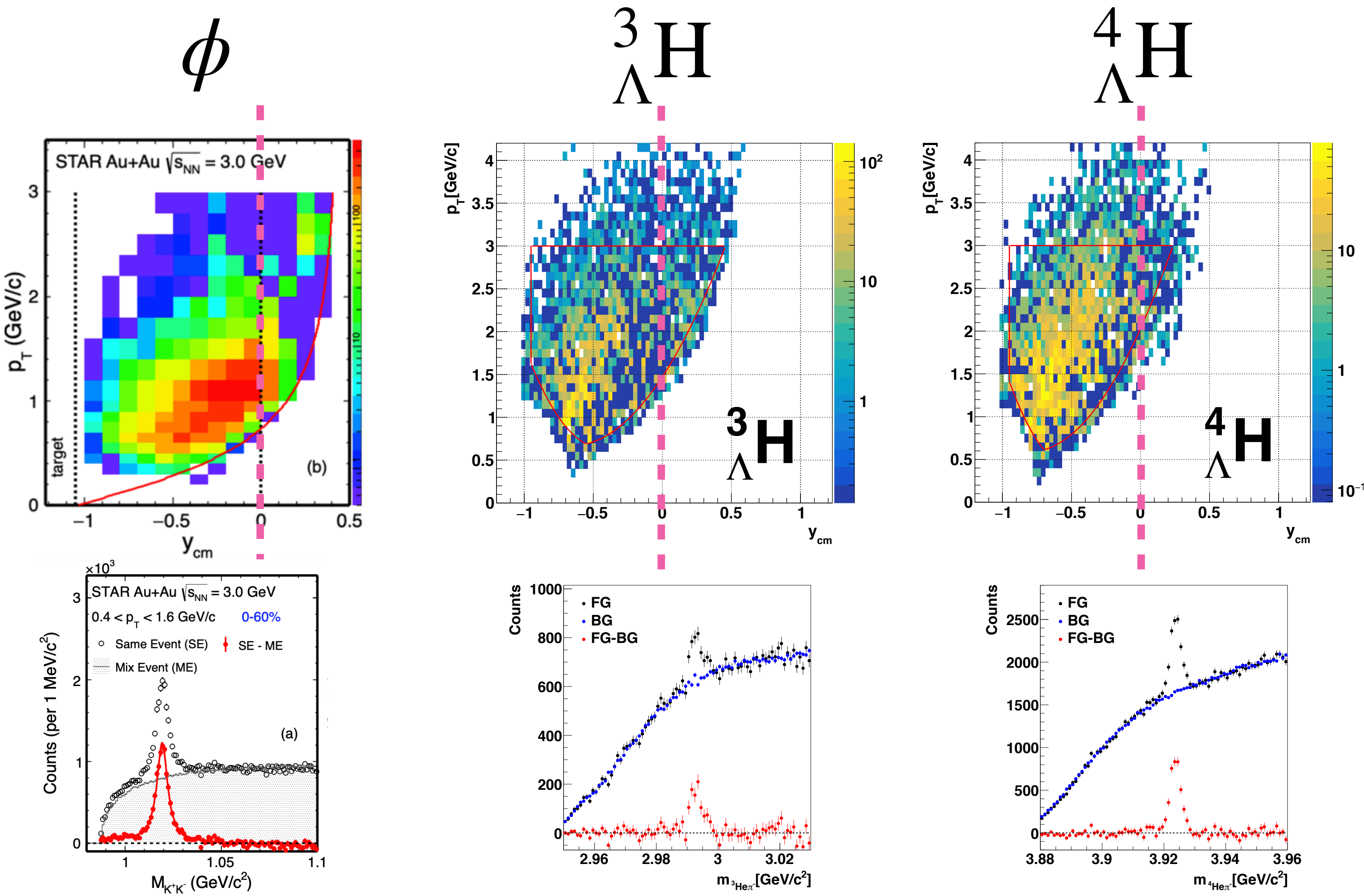
– Do Ξ bind in nuclei? A=6 or 7?

Gal, Hungerford, Millener, Rev. Mod. Phys. 88, 035004 (2016)

– A=4 system, a good candidate for the lightest Ξ hypernuclei

Hiyama et al., PRL 124, 092501 (2020)

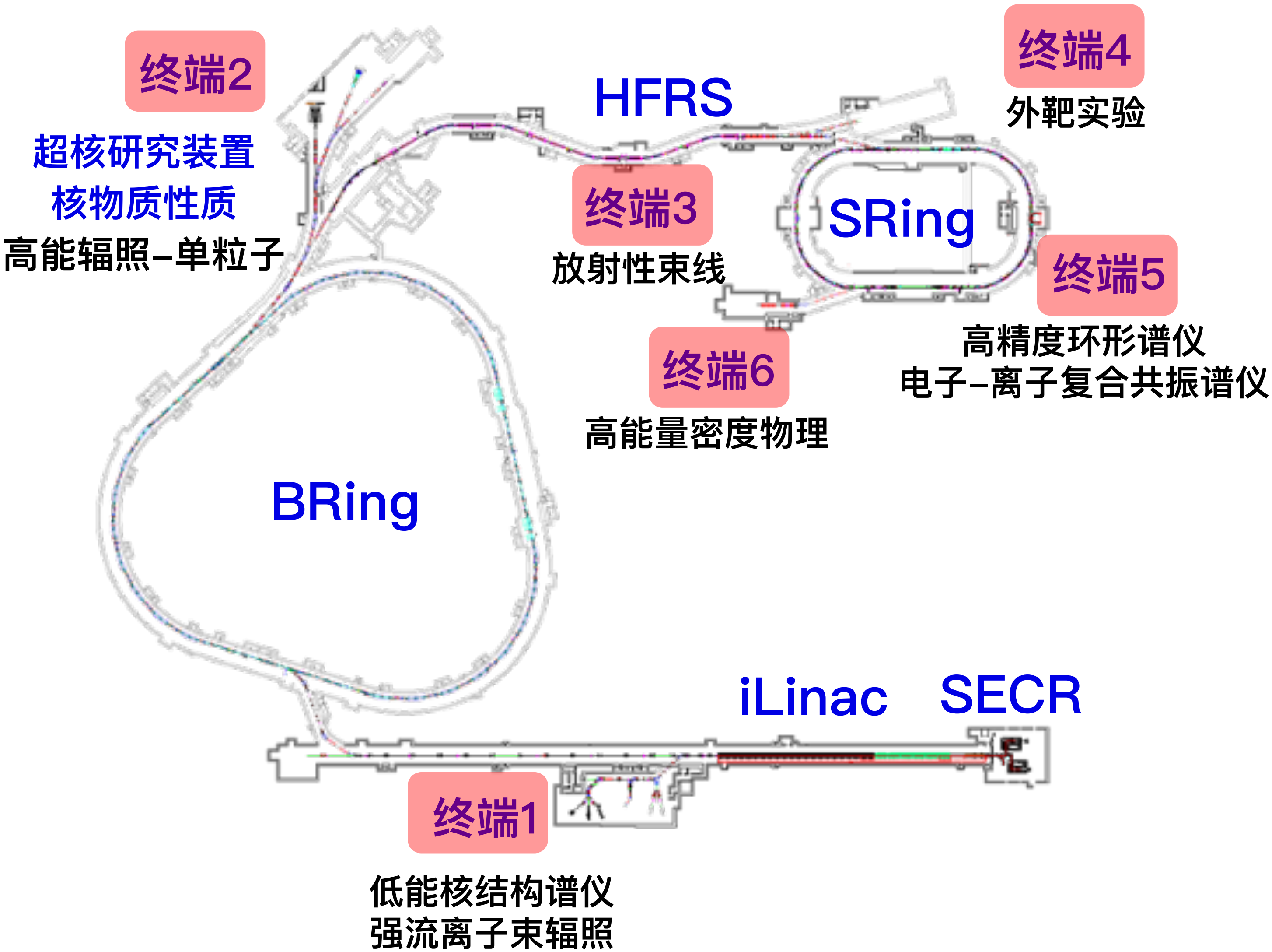
BES-II and FTX data are progressing well



Quantitative understanding of QCD matter in the high baryon density region

HIC is promising to describe QCD with a bright future

“十二五”国家重大基础设施:强流重离子加速器装置HIAF



感谢大家的聆听，敬请批评指正！