Physics of Hadronic Structure and QCD Phase Structure at HIAF

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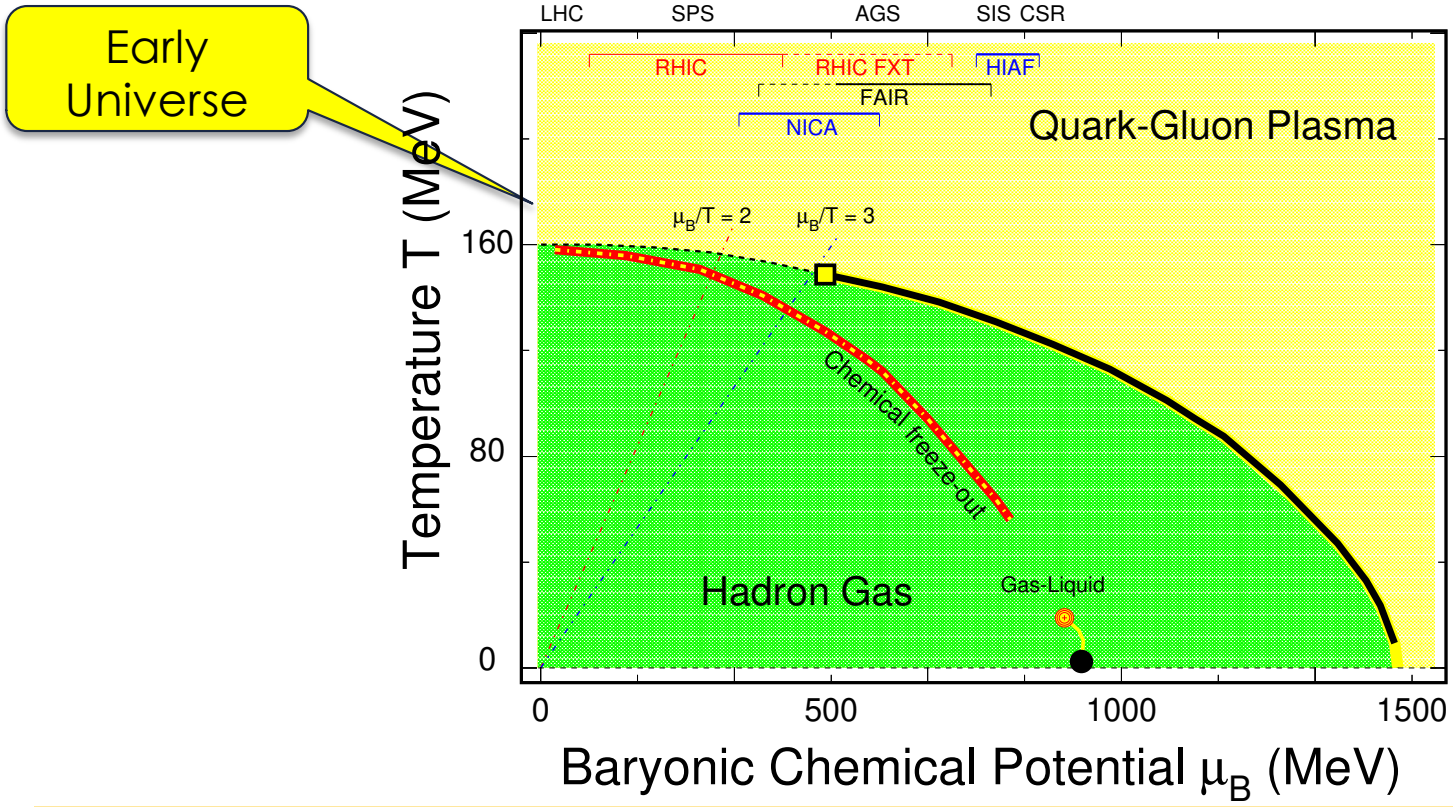
Outline

1) Introduction
   - Recent results from STAR

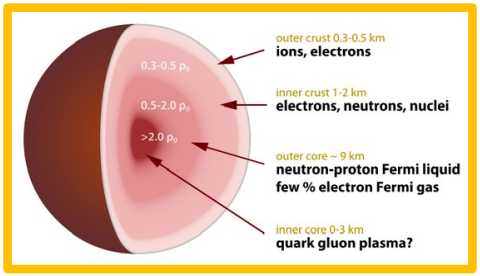
2) HIAF - High Intensity Heavy-ion Accelerator Facility

3) Polarization Measurements with H-NS

Nuclear Collisions and QCD Phase Diagram

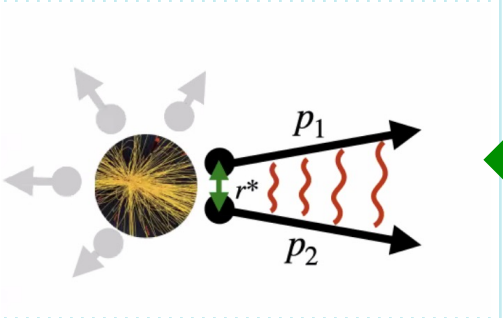


High baryon density: Inner structure of compact stars

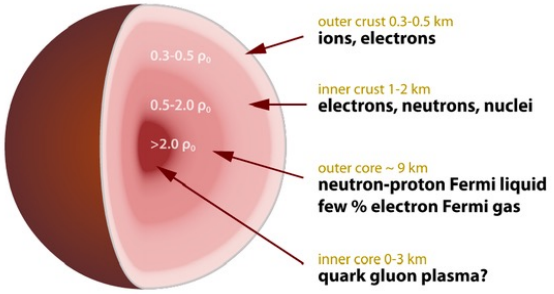


1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N-N$, $\Upsilon-N$) and EOS at high baryon density

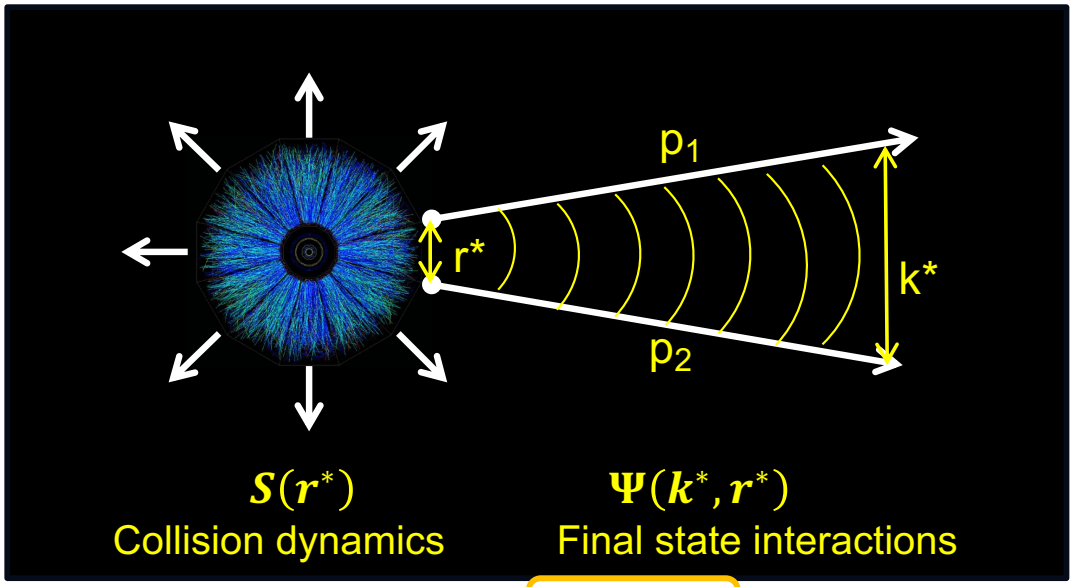
Baryon Correlations



FSI



Baryon Correlation Functions



STAR:

(1) Meson HBT: $\pi - \pi$, $K - K$;

(2) **Baryon Correlations:**

$p - p$	reference	
$p - \Lambda$,	$p - \Xi^-$, $\boldsymbol{p - \Omega}$	*Y-N*
	$p - \phi$	
	$\Lambda - \Lambda$	*Y-Y*
$\boldsymbol{p - d}$,	$\boldsymbol{d - d}$	*N-N-N*
$\boldsymbol{d - \Lambda}$		*Y-N-N*

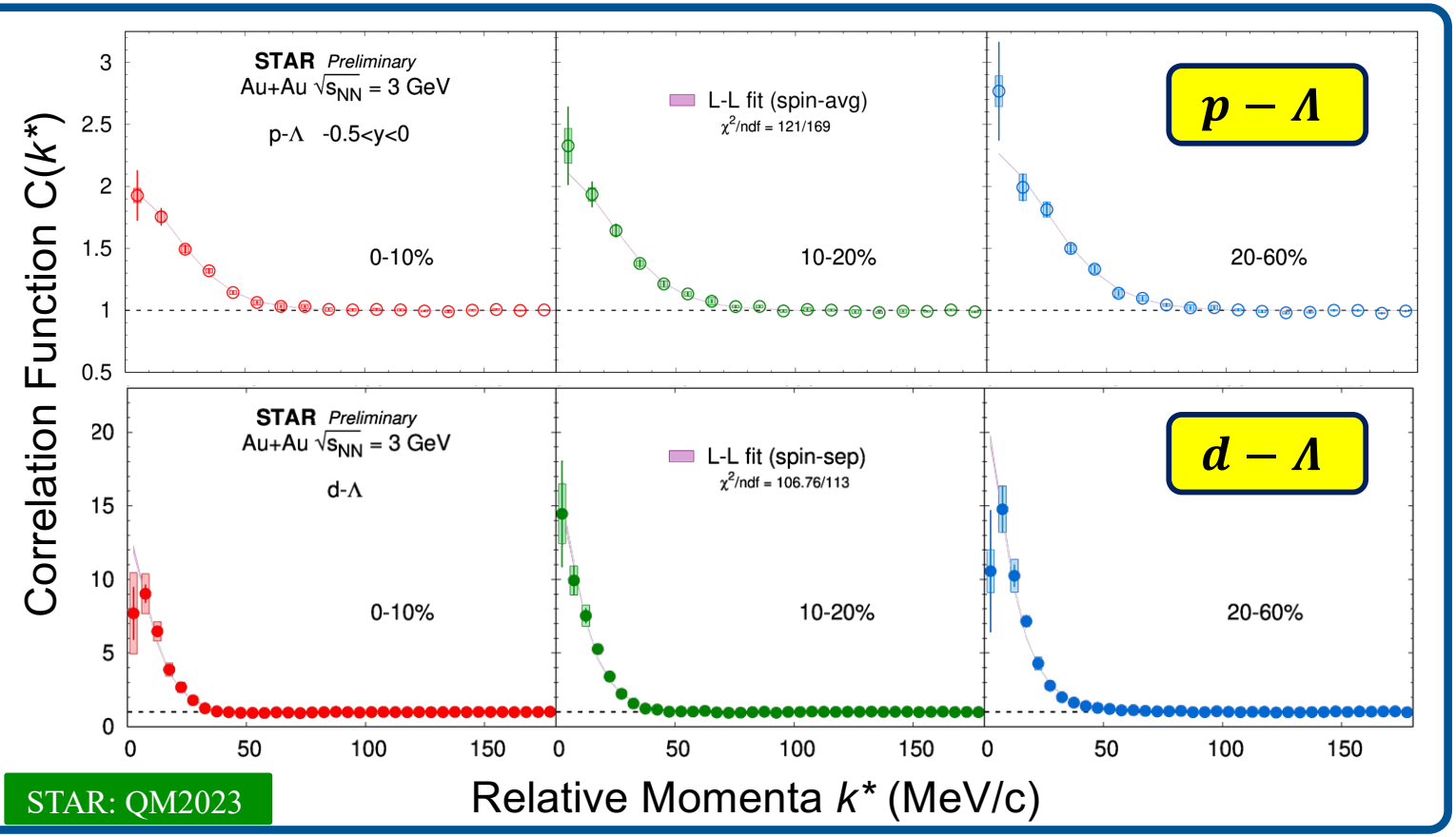
Source

$$C_{the}(k^*) = \frac{1}{4\pi} \int \mathrm{d}^3 r^* S(r^*) |\Psi(r^*, k^*)|^2$$

$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1, p_2)}{N(p_1) N(p_2)}$$

Final State Interactions:
(1) Quantum statistics; (2) Coulomb; (3) Strong interaction

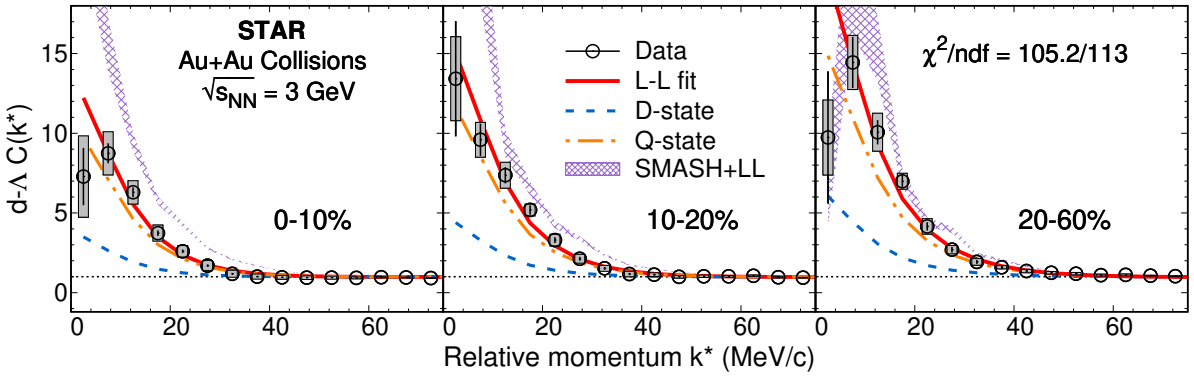
$p-\Lambda$, $d-\Lambda$ Correlation Functions

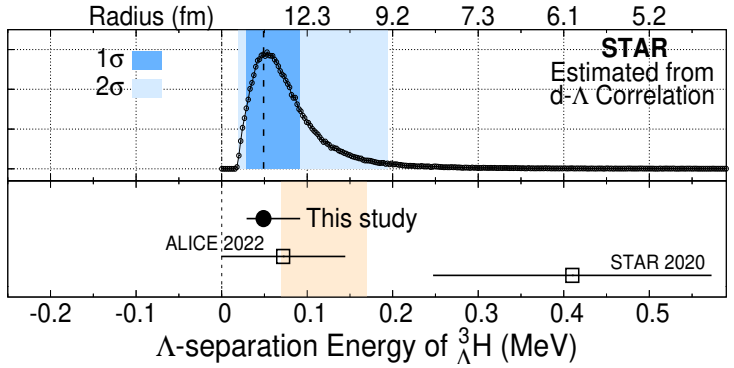


Corrections:
1) Track merging;
2) Track splitting;
3) Resonance decays;
4) Purity;
5) Momentum smearing;
6) Contribution of ${}^{3}_{\Lambda}H$

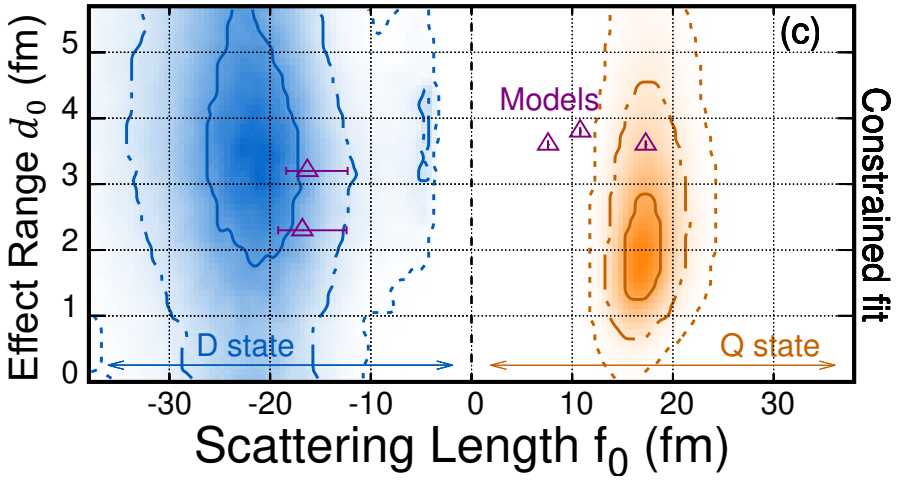
Acceptance:
- All: 0.5< y<0;
- **p**: 0.25< p_T < 2 (GeV/c);
- **d**: 0.25< p_T < 3 (GeV/c);
- Λ: 0.25< p_T < 2 (GeV/c)

$d - \Lambda$ Correlation Functions





STAR: CPOD2024, QM2024



1) Centrality dependence of the $d - \Lambda$ correlation functions from 3.0 GeV Au+Au collisions;

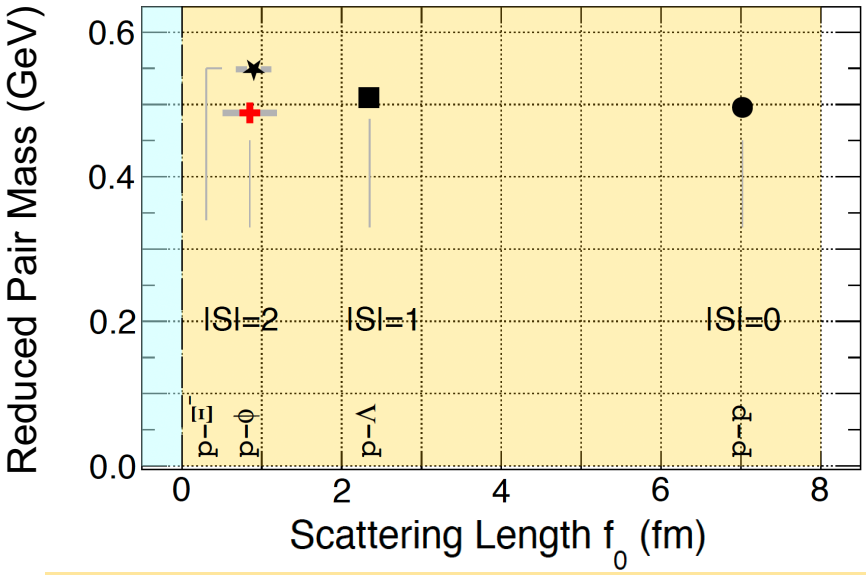
2) For the first time, spin dependent states, *D and Q*, identified experimentally!

→ **May help for studying 3-body interactions in the laboratory**

References:

(1) J.M. Lattimer and M. Prakash, Science **304**, 536 (2004);
(2) M. Kohno and H. Kamada, arXiv:2406.13899;
(3) H. W. Hammer, Nucl. Phys. **A705**,173 (2002)

NN, NY, YY Interactions

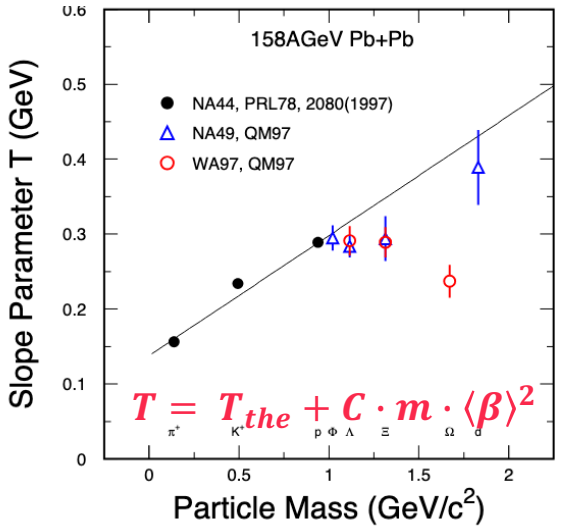


H. van Hecke, H. Sorge, NX, Phy.Rev.Lett. **81**, 5764(1998):

"Evidence of early multi-strange hadron freeze-out in high energy nuclear collisions"

→ Rescatterings lead to collectivity

→ Collectivity is reduced as the strangeness content is increased

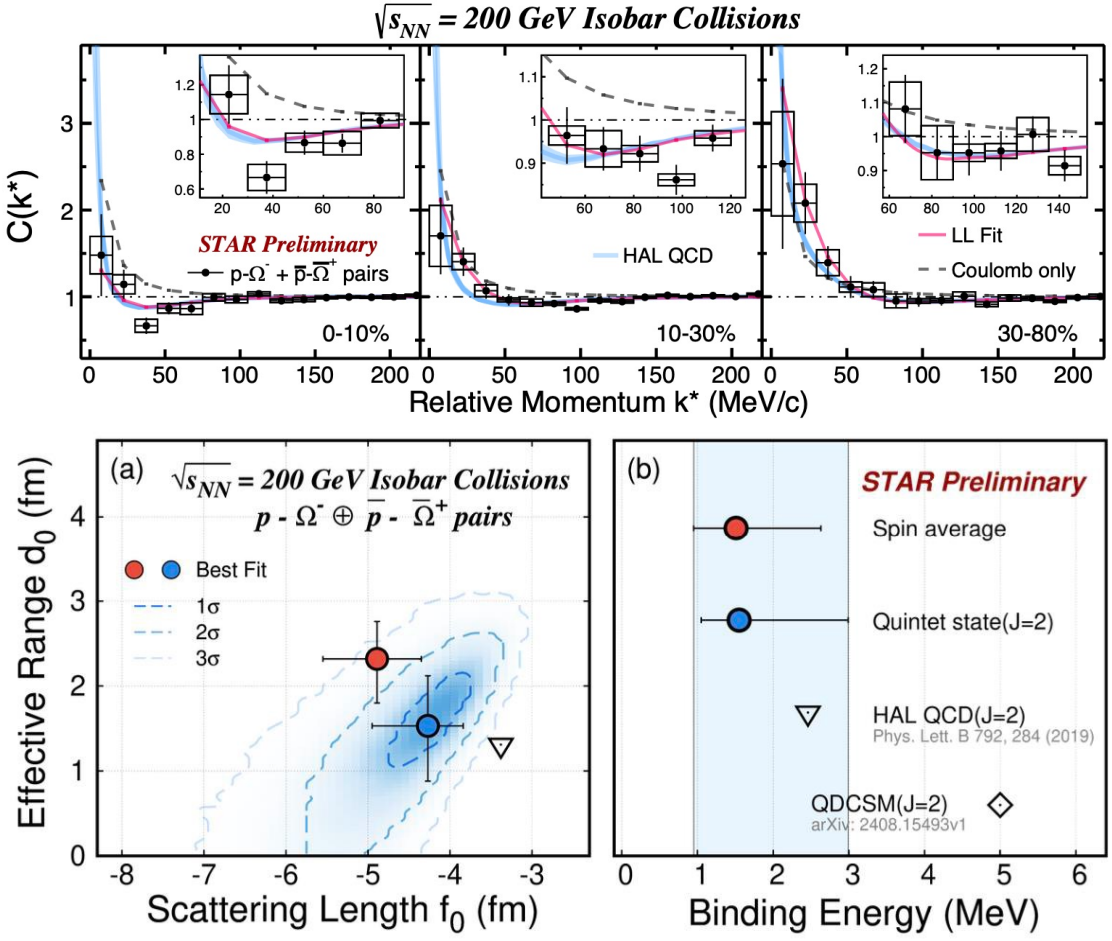


Hierarchy of strangeness content:

$$f_0(|s|=0) > f_0(|s|=1) > f_0(|s|=2) > 0, \quad f_0^2 \propto \sigma_{interaction}$$

- Interaction cross section is proportional to f_0^2. This observation implies that the *strength of the interaction depends on strangeness contents*;
- Understand the strangeness hierarchy in QCD?

Evidence of Strange Dibaryon

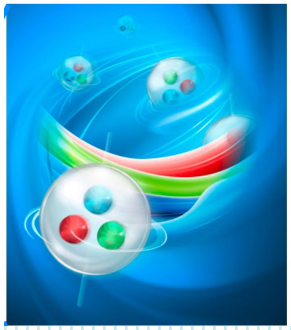


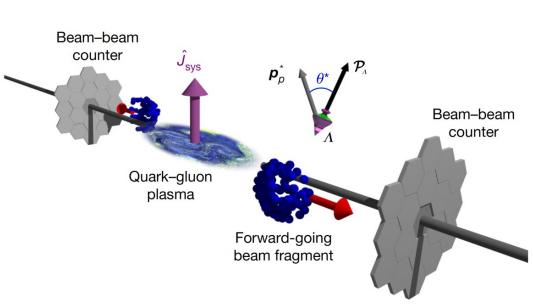
1) STAR results of the $p-\Omega$ **correlation functions** in 200GeV isobar collisions;
2) Extracted negative f_0 ($|f_0| > 2d_0$) by spin average method and Quintet (J=2) methods. **BE** $= 1.5^{+1.1}_{-0.6}$ **MeV**, consistent with HAL-QCD prediction;
3) First experimental evidence of the **Strange Dibaryon!**

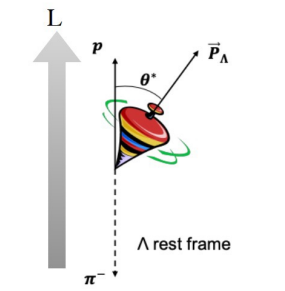
	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

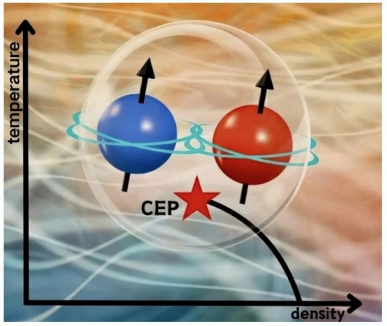
STAR: QM2025 et al., Phys. Rev. C 101, 015201 (2020)

Polarizations

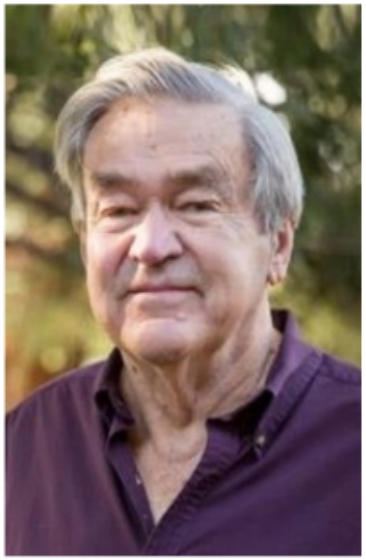








Spin and Strong Interactions



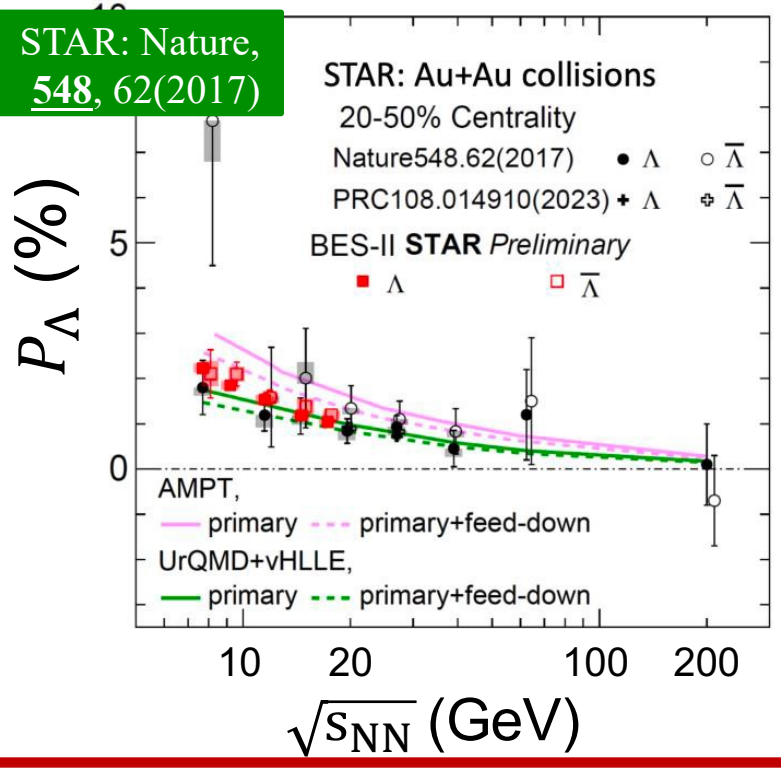
"Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they would ban all experiments involving spin."

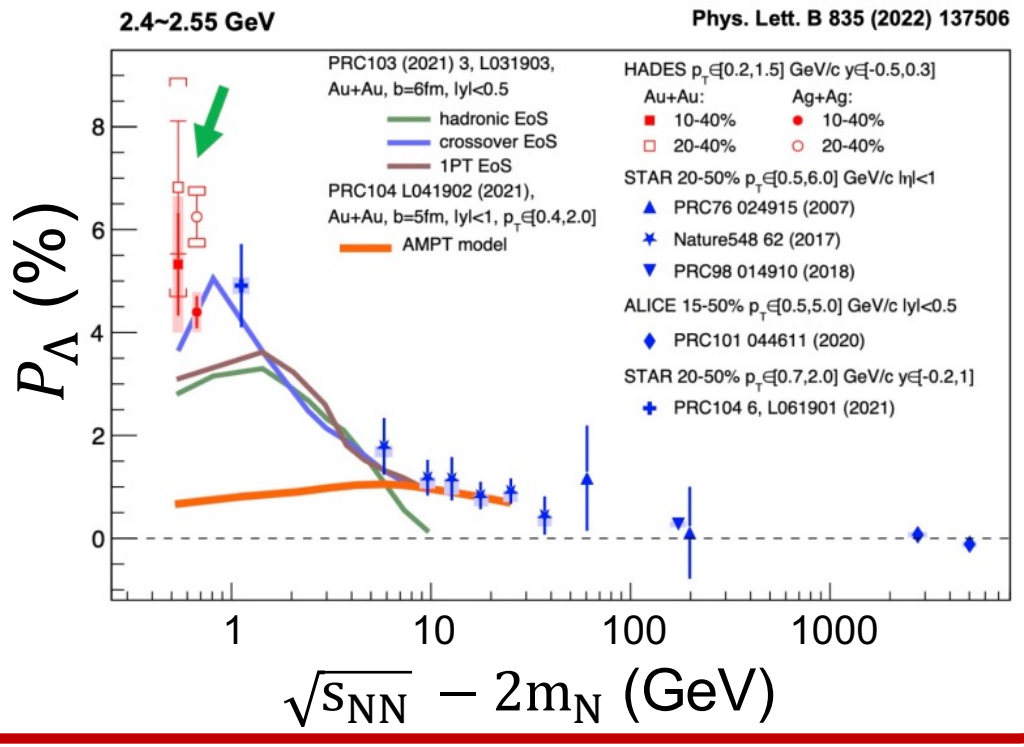
James D. Bjorken

Proc. Adv. Res. Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987)

Results on Λ-Global Polarizations

STAR: Nature, **548**, 62(2017)

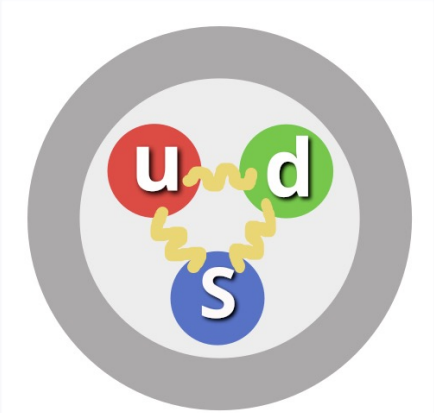




1) Observed Λ-global polarization: along the direction of the total angular momentum and increased as collision energy decreases!
2) No theory explain these data!

$\langle w \rangle \approx (9 \pm 1) \cdot 10^{21}/\text{sec}$ "The most vortical fluid"

Lambda baryon



Quark structure of the lambda baryon.

Composition	Λ^0: uds Λ_c^+: udc Λ_b^0: udb
Statistics	Fermionic
Family	Baryons
Interactions	Strong, weak, electromagnetic, and gravity
Types	3
Mass	Λ^0: 1 115.683 ± 0.006 MeV/c^2[1] Λ_c^+: 2 286.46 ± 0.14 MeV/c^2 Λ_b^0: 5 619.60 ± 0.17 MeV/c^2
Spin	½
Isospin	0

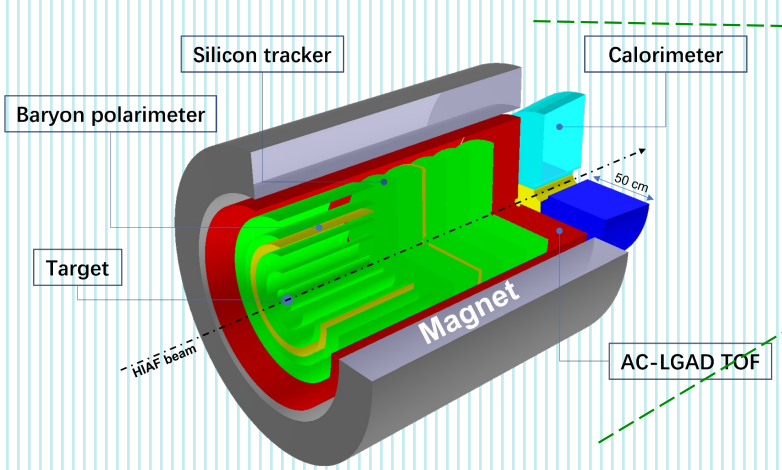
Spin and Strong Interactions

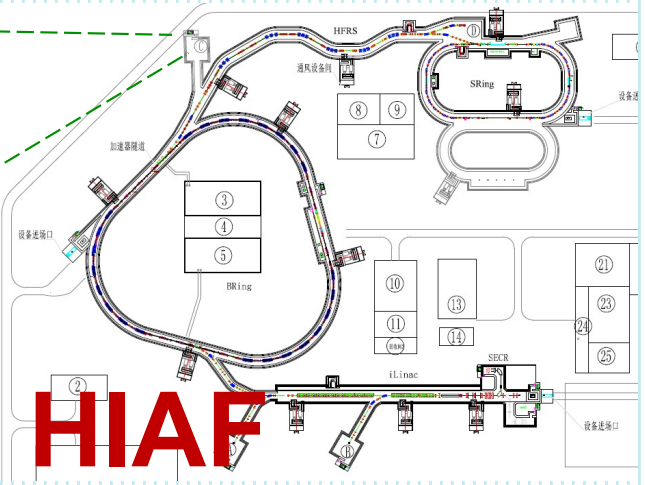
Chirality is the basic building block in strong interaction theory QCD. Experimental observables with spin, an intrinsic quantum number of any elementary particle, offer an important manifestation of chirality.

- Λ polarization and its spin structure?
- Polarization of other hadrons, *p*?
- The relation between Λ-local, global polarizations and its spin?
- …

Future Experimental Opportunities

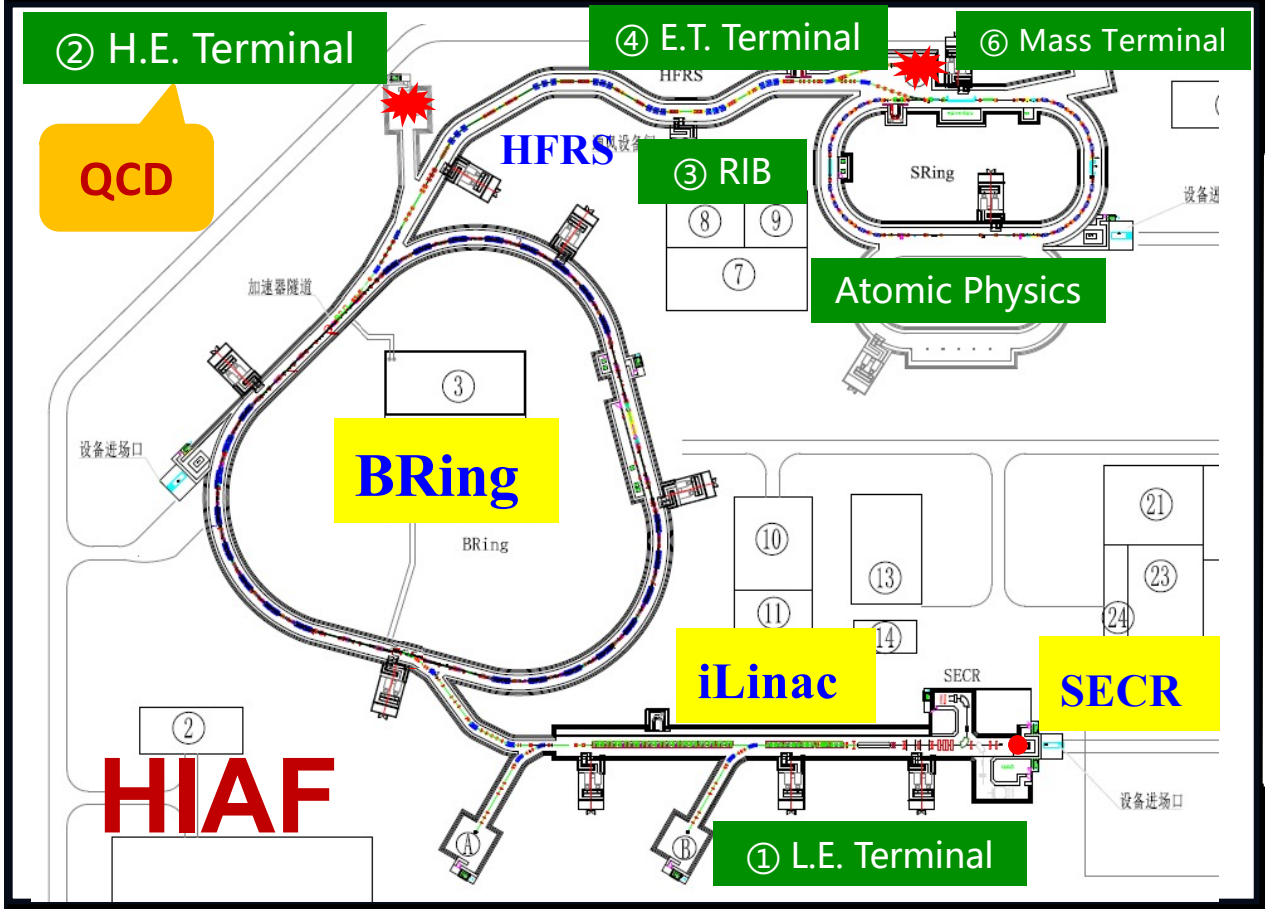
H-NS@HIAF





High Intensity heavy-ion Accelerator Facility

(HIAF, Huizhou, China)



HIAF Physics：

(i) Atomic physics;
(ii) Nuclear physics;
(iii) Applied research in biology and material science etc.

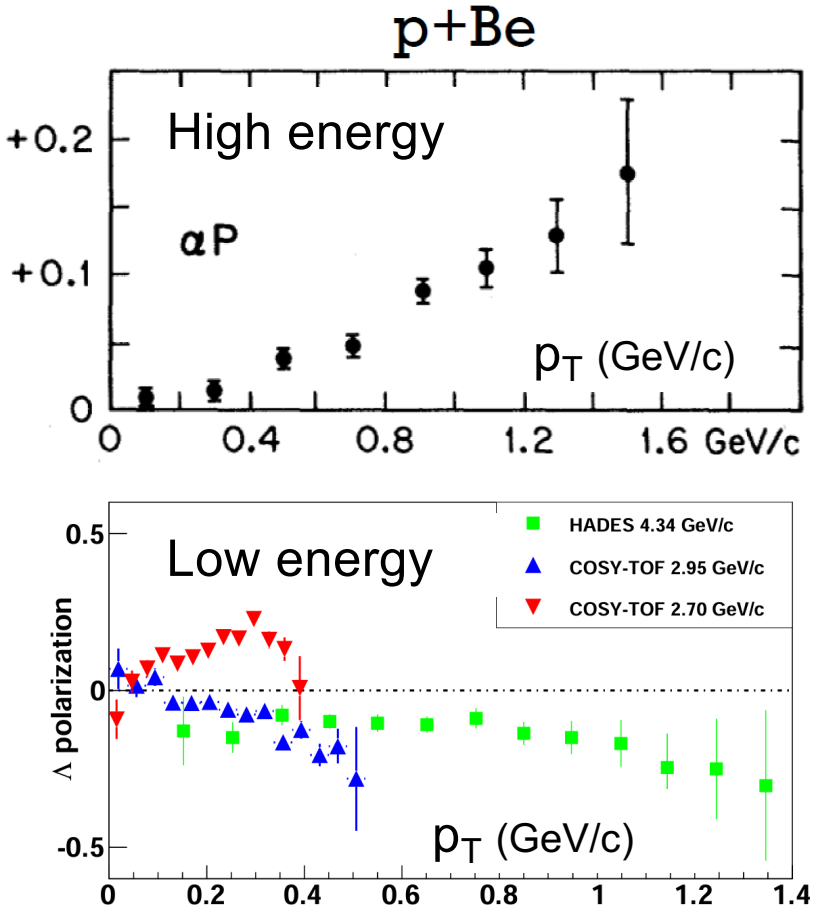
HIAF Commission will start in December of 2025

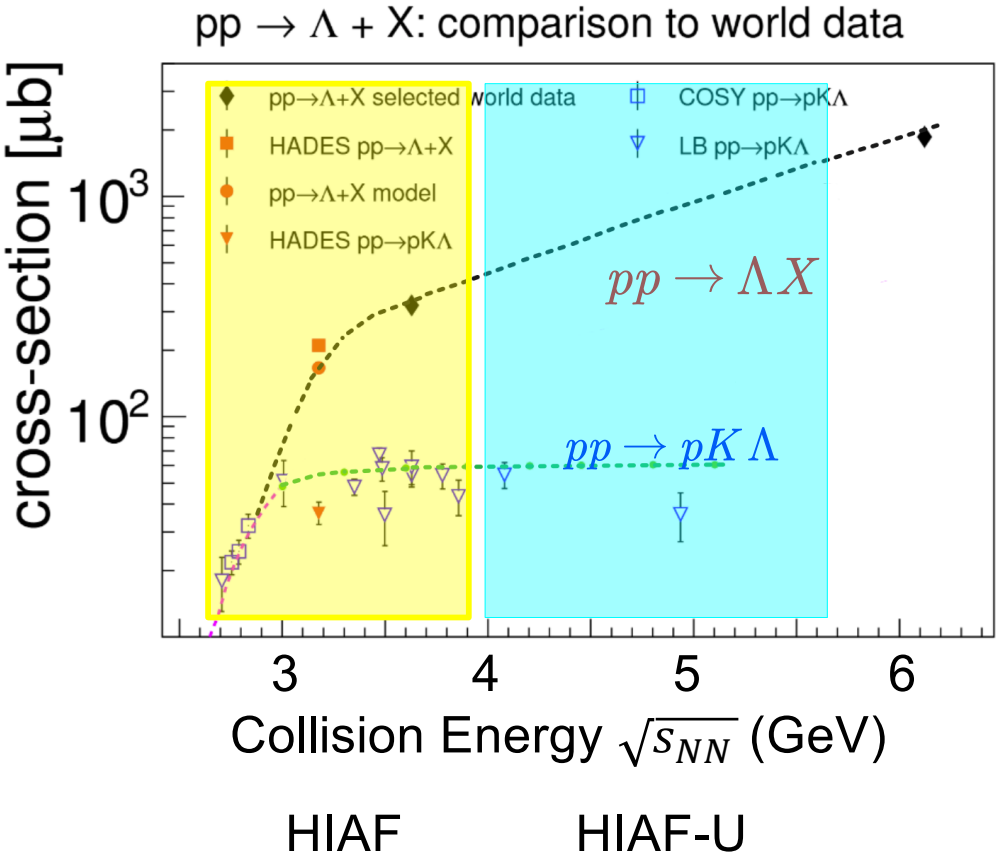
- 低能综合研究终端
- 电子-离子复合共振谱仪
- 高精度环谱仪(SRing)
- 配套设施
  - 公共配套设施
  - 通用设施及其他
  - 土建工程

HIAF Beam Parameters

Ion	Intensity (ppp)	Kinetic Energy
$^{238}U^{35+}$	2.0×10^{11}	0.84 (GeV/u)
$^{238}U^{76+}$	5.0×10^{10}	2.5 (GeV/u)
$^{129}Xe^{27+}$	3.6×10^{11}	1.4 (GeV/u)
$^{78}Kr^{19+}$	5.0×10^{11}	1.7 (GeV/u)
$^{40}Ar^{12+}$	7.0×10^{11}	2.3 (GeV/u)
$^{18}O^{6+}$	8.0×10^{11}	2.6 (GeV/u)
protons	5.0×10^{12}	9.3 (GeV/u)
	4.0×10^{14} (HIAF-U, EicC)	32 (GeV/u)

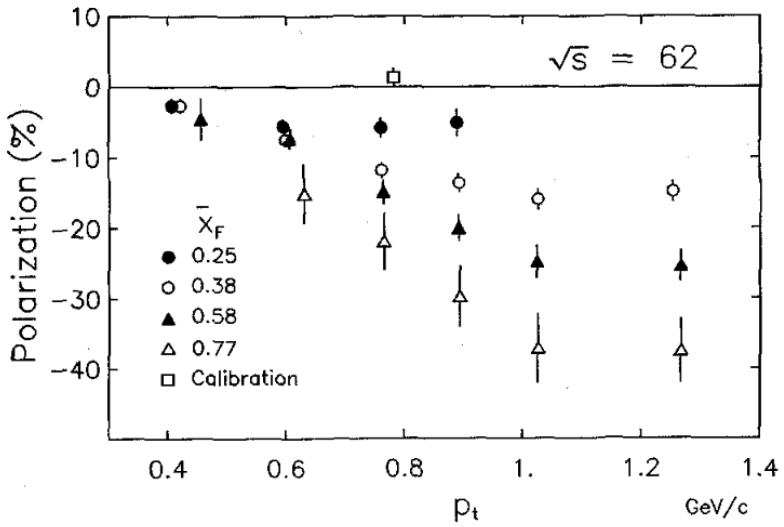
Λ Production and Polarization



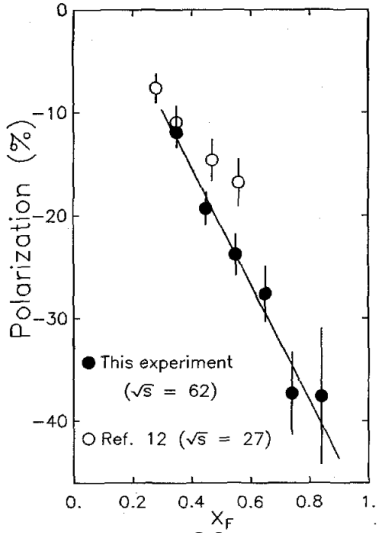


Λ –Polarization: x_f- anf p_T-scaling (?)

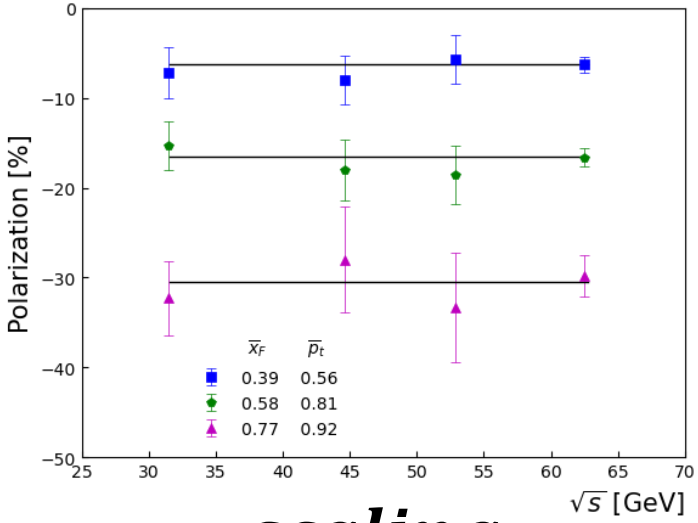
R608: 10.1016/0370-2693(87)91556-5



p_T



x_f

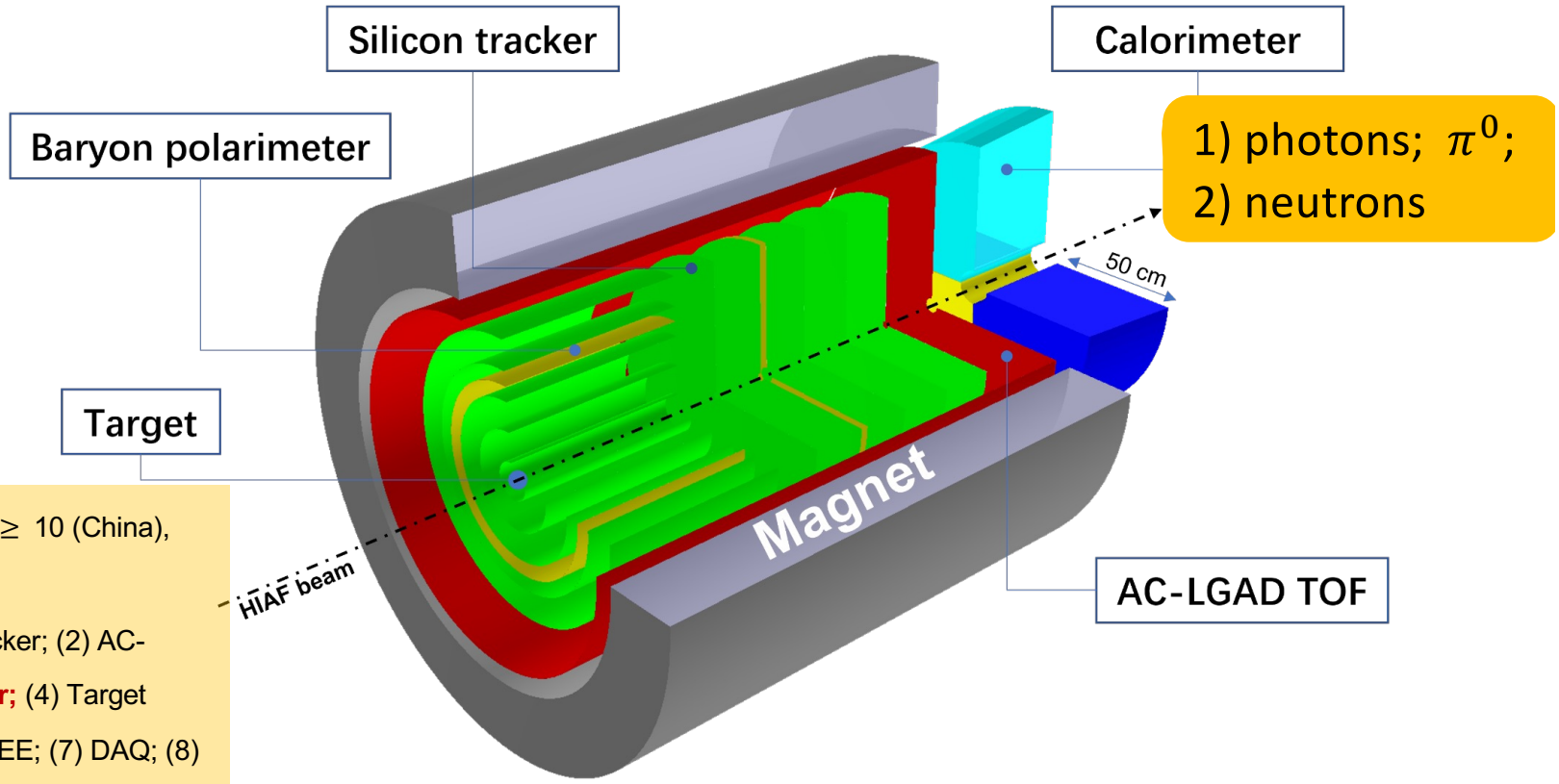


$scaling$

Questions:

1) Origin of the Λ polarization: **Collision dynamics? Intrinsic spin structure?**
2) In p+A and A+A collisions, Λ –global polarization, Λ –local polarization have been observed. What is the relation between those and Λ polarization?

Hyperon-Nucleon Spectrometer Concept



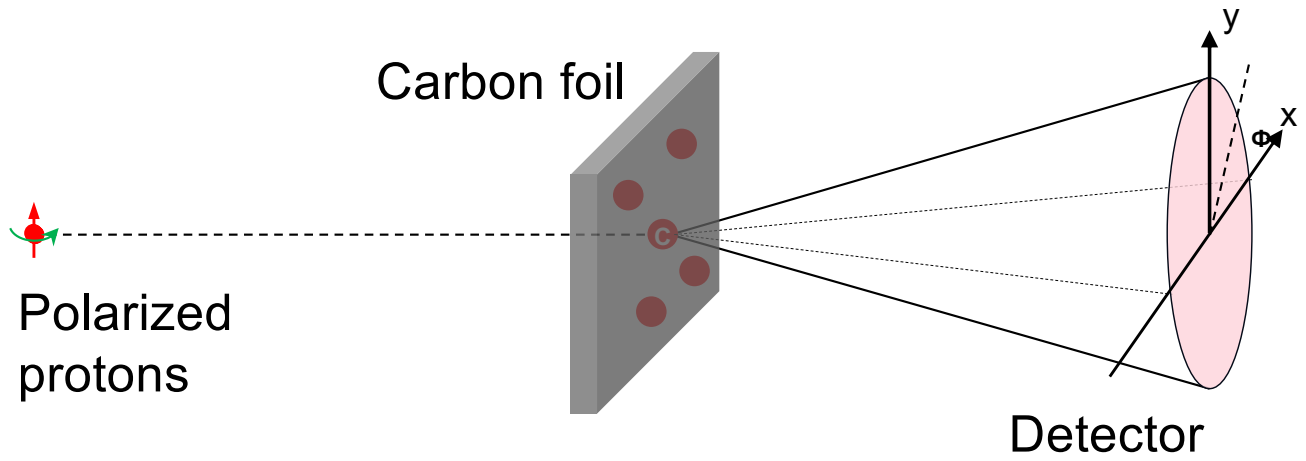
Participating Institutes: ≥ 10 (China), more are welcome!

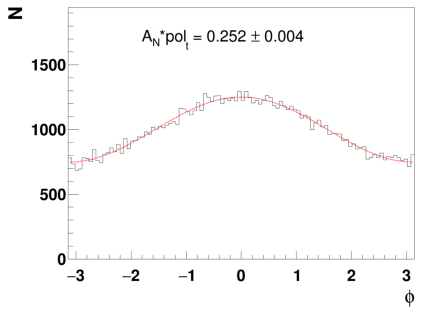
R&D Efforts: (1) Pixel tracker; (2) AC-LGAD; (3) **Baryon Polarimeter;** (4) Target systems; (5) Calorimeter; (6) FEE; (7) DAQ; (8) Magnet; (9) Beam line; (10) Mechanical structure design

Proton Polarimeter

Spin-dependent cross-section of p + p/C scattering:

$$\frac{d\sigma}{d\phi d\cos\theta} = \frac{1}{2\pi}\frac{d\sigma_0}{d\cos\theta}\left[1 + P_y A_N(\theta)\cos\phi\right]$$



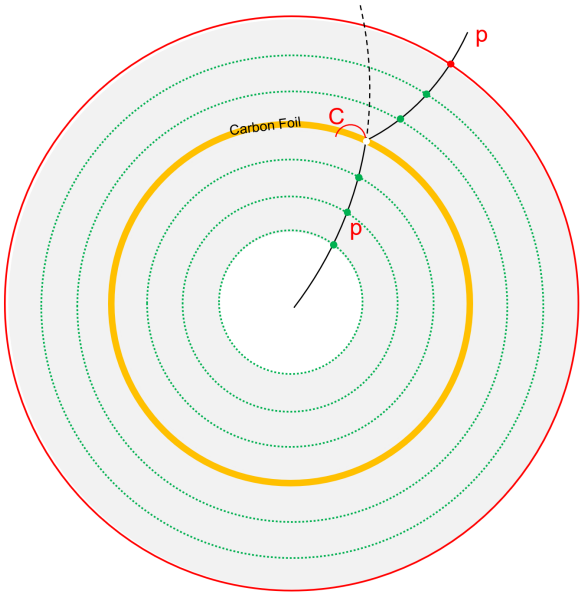


More protons to the left:
Left-right asymmetry

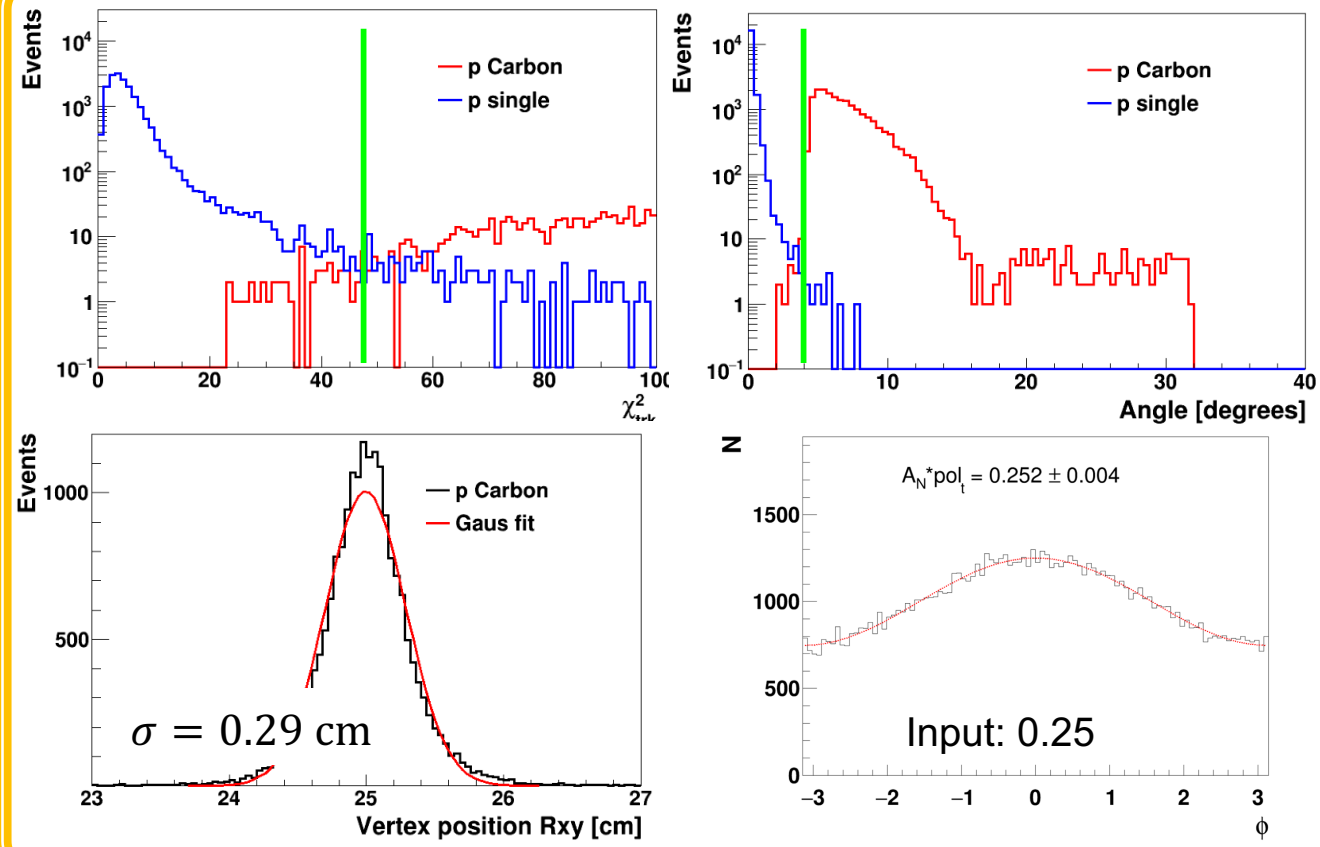
Widely used to measure polarized proton beam (PSI, TRIMUF, LAMPF, COSY, SATURNE, ZGS, KEK-PS, AGS, RHIC …)

Proton Polarimeter:
Yutie Liang: PRD**112**, L031502(2025)

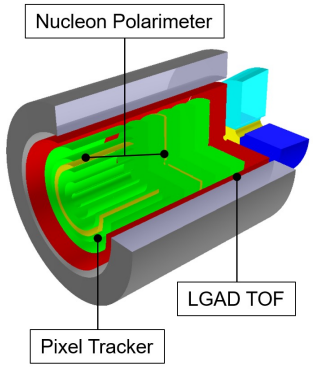
Simulations: Proton Polarization



- Tracking efficiency: > 70%
- Fake track rate: ~ 4x10^{-6}
- Low contamination!



Polarization Observable at H-NS



H-NS

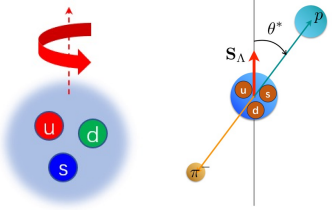
Reaction: p+p

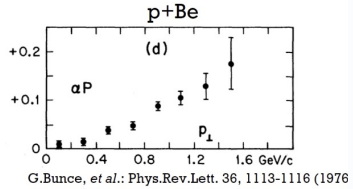
Event rate:1MHz

Time: 3 months

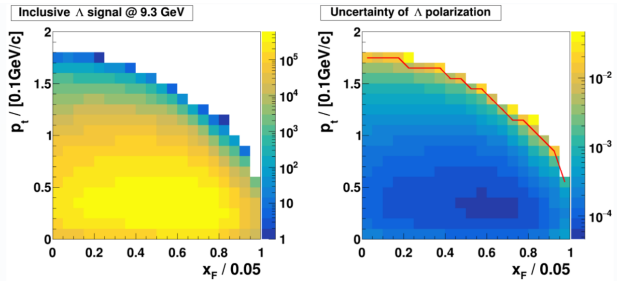
- pp → Λ+X N ~ 10^{11}
- pp → p+X N ~ 10^{13}
- pp → pKΛ N ~ 10^{10}

p p → Λ + X $\sigma_{stat.} < 0.01$ 2D:400 bins





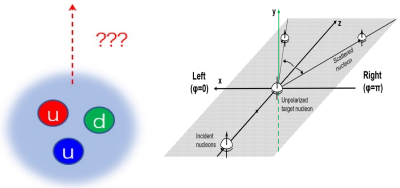
Λ polarization

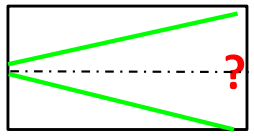


Projection @ H-NS

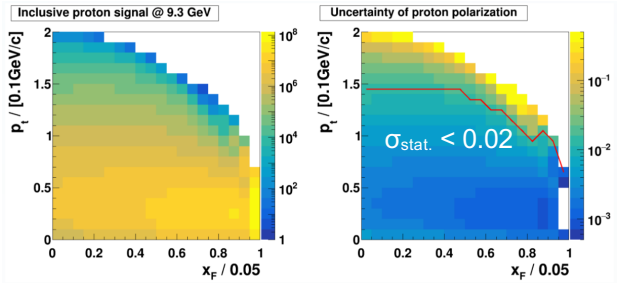
p p → p + X $\sigma_{stat.} < 0.02$ 2D:400 bins

pC scattering ~ 10^{13}*4*10^{-4} = 4*10^9



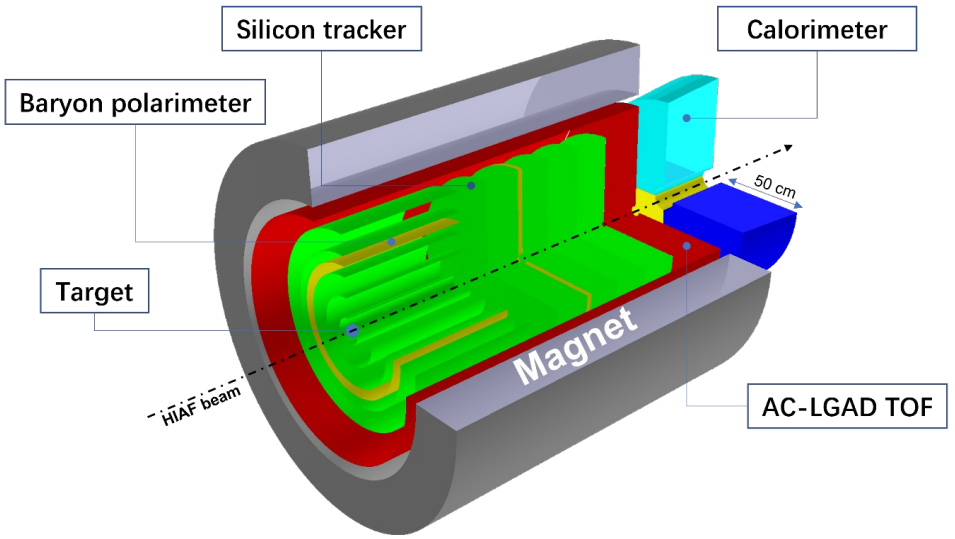


proton polarization



Projection @ H-NS

Hyperon-Nucleon Spectrometer (H-NS)



Participating Institute： 近代物理研究所、清华大学、山东大学、北京航空航天大学、复旦大学、国科大、华中师范大学、华南师范大学、北京师范大学、香港中文大学（深圳）、中科大、 中国原子能研究院、湖师、 …

Subsystems： Silicon tracker, AC-LGAD, Target, Baryon polarimeter, Calorimeter, Electronics, DAQ, Magnet, Beamline, Mechanics + Engineering

I. Physics：

- Λ production and polarization (*p*+*p*)
  - Medium effect (*p*+*A*)
  - Global polarization of Λ hyperon (*A*+*A*)
- Hadron physics via *p*+*p*

II. Community：

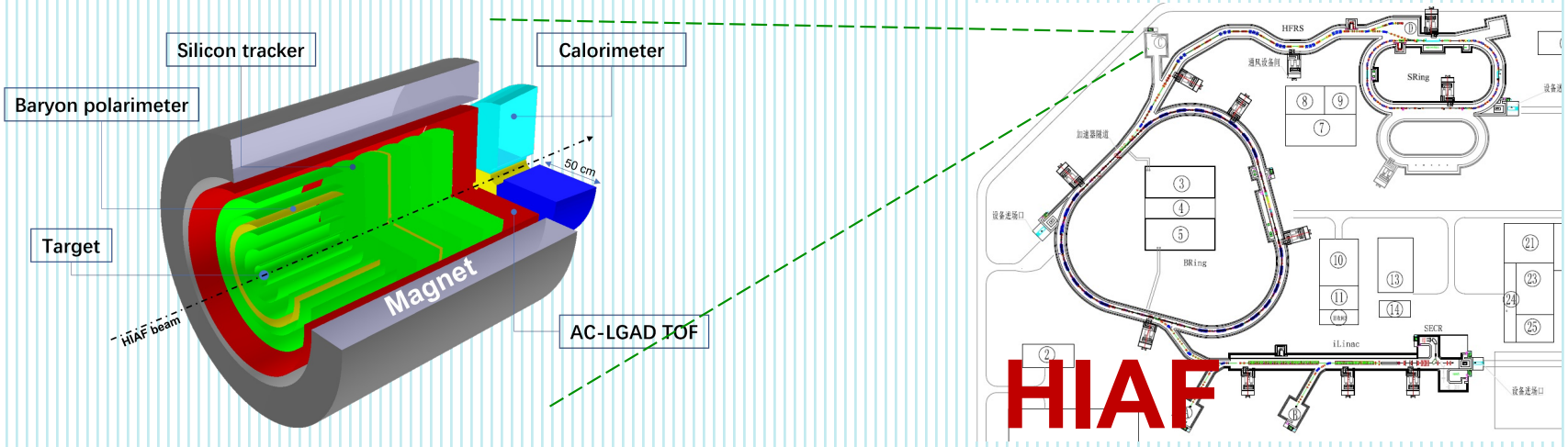
- Supports both communities of hadron structure and heavy-ion physics
- International participations are welcome!

III. Detector R&D

- Many parts are similar for CEPC, H-NS, EicC, and STCF. Save resources!
- H-NS: a detector R&D platform for EicC(½ EicC)

H-NS@HIAF:

1) **H-NS:** Large acceptance with full azimuthal coverage, High efficiency, Fast DAQ (~1M Hz). Energy scan within 3 – 9.3 GeV/u …
2) **p+p and p+A collisions:** Λ (p) polarization, Hadron spectra, Spin structure, Spin-spin correlations, Hyper-nuclei, …;
3) **A+A collisions:** High μ_B properties: QCD critical point, Global polarizations, …



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// BLUE: Theory // **RED**: Exp. //

Thank you for your attention!