

利用“超子工厂”理解中子星“超子疑难”

苑长征

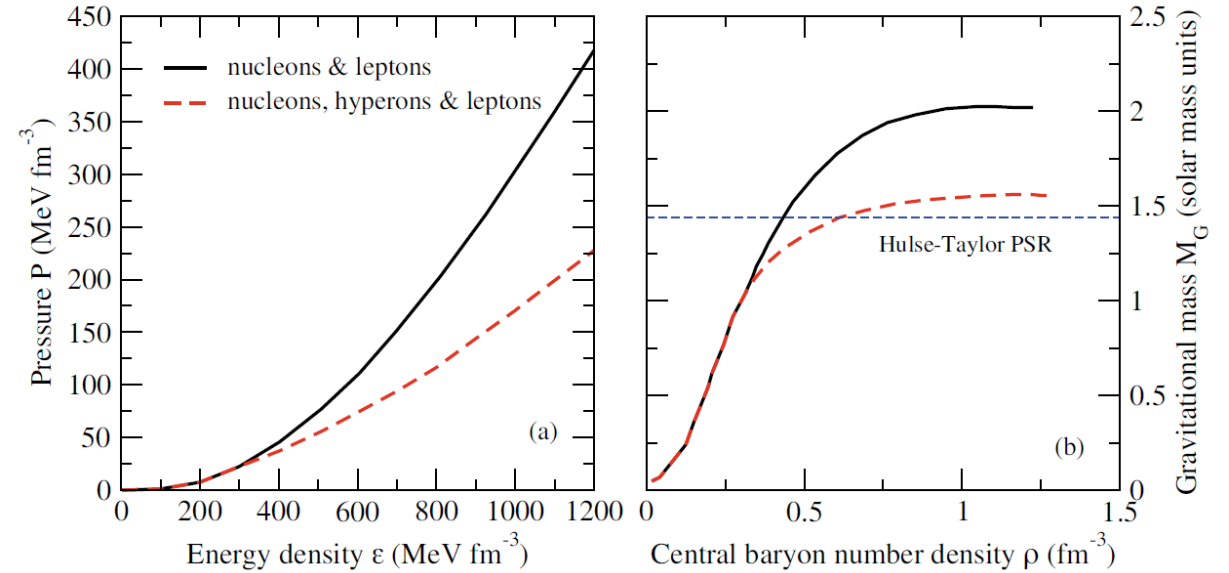
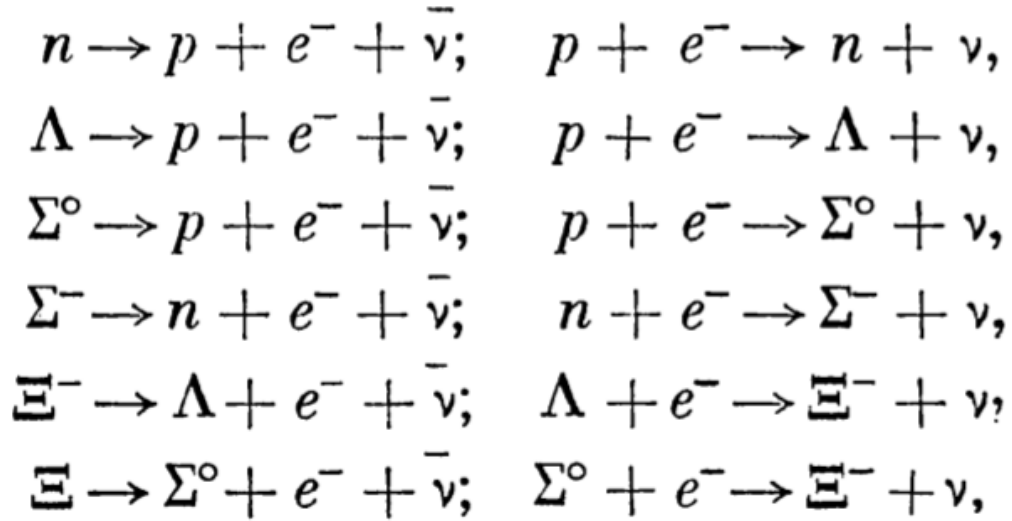
中国科学院高能物理研究所

2026年5月16日，高能与低能核物理交叉学术研讨会

- CZY & M. Karliner, PRL 127, 012003 ([2021](#)) [arXiv:2103.06658]
- 宋维民、苑长征, *物理* 51, 255 ([2022](#)): 超级J/ ψ 工厂里的“子弹”
- Z.L. Zhang, X. Gao, W.M. Song, & CZY, arXiv:[2603.16075v1](#) [hep-ex]
- CZY & M. Karliner, arXiv:[2604.16028v1](#) [nucl-ex]

Size of neutron stars & hyperon puzzle

For a review, see Chatterjee & Vidana, Eur. Phys. J. A (2016) **52**: 29



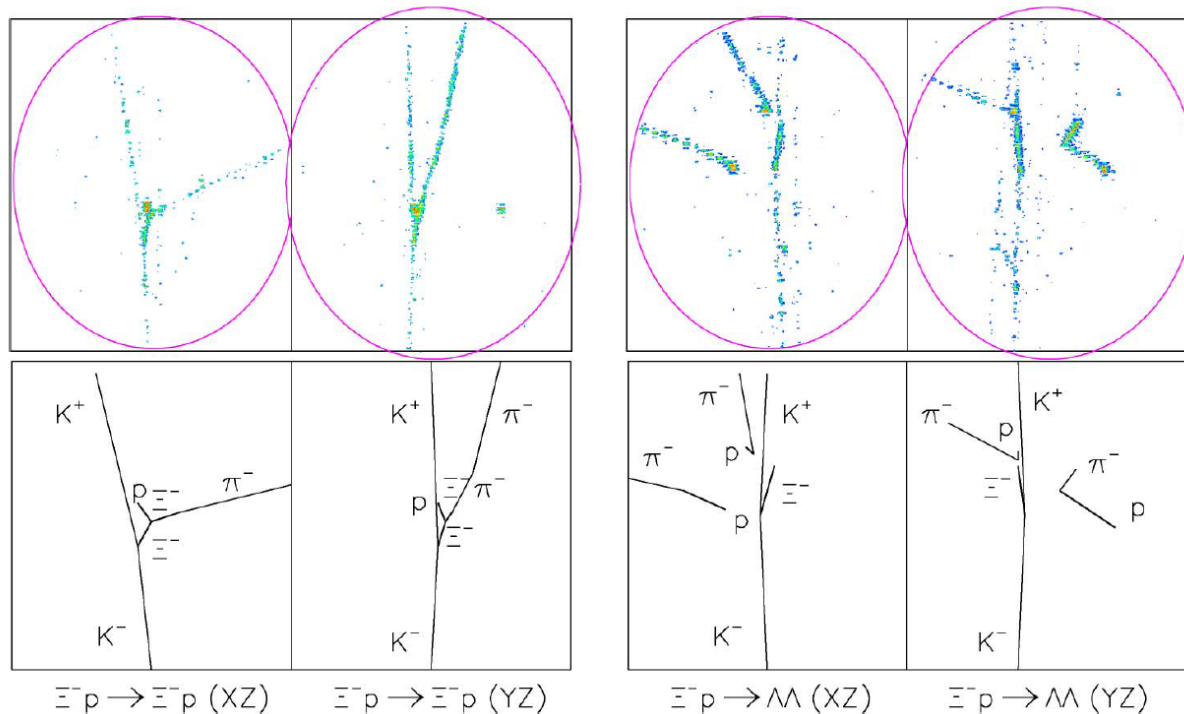
A conclusive observation of multiply strange nuclear systems is absolutely necessary for a better understanding of the role of strangeness in neutron stars. The theories for the description of strangeness in massive neutron stars cannot be answered without the improved knowledge of $\Lambda\Lambda$ interaction, for which one requires careful high precision series of investigations of such an interaction.

There are several new facilities planned or under construction such as in GSI in Germany, JLAB in USA and J-PARC in Japan. These facilities will hopefully provide much more precise updates on the properties of hyperon-nucleon and hyperon-hyperon interactions. Experimental hypernuclear physics is still an extremely active field of research.

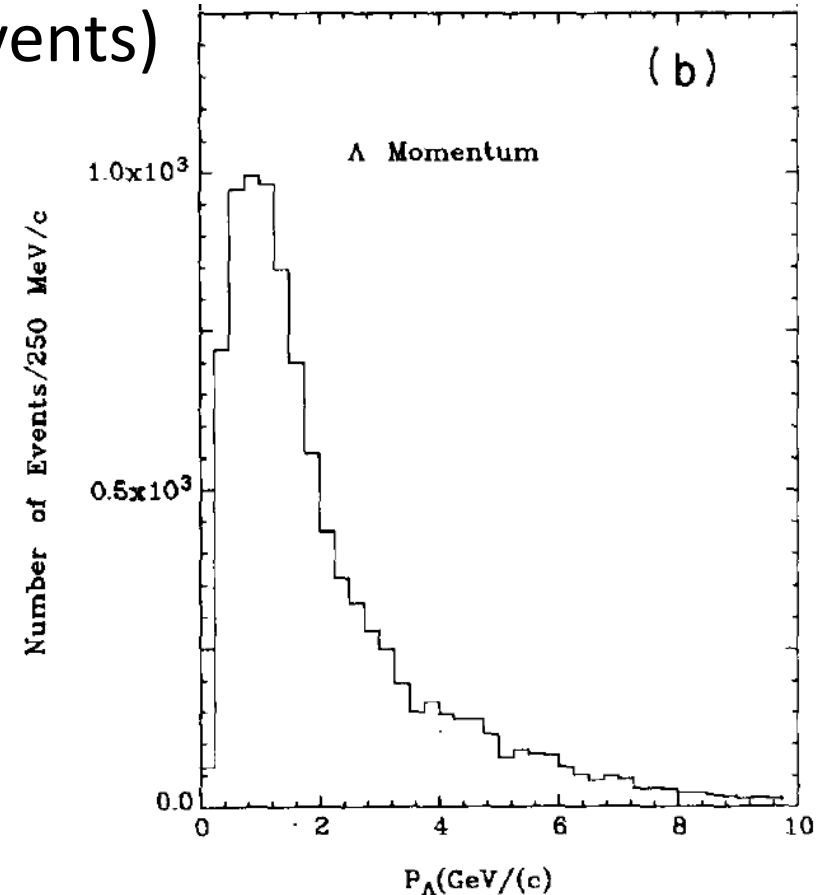
Sources of Λ & other hyperons are rare

- Bubble chamber experiments with hyperons from K^- +target
- Emulsion experiments with K^- +target $\rightarrow K^+ + X, K^+ + K^+ + X, \dots$
- A few to $\sim 10^4$ events (typical $O(100)$ tagged events)

J.K. Ahn et al. / Physics Letters B 633 (2006) 214–218



KEK, $K^- + \text{SCIFI} \rightarrow \Xi^- X$

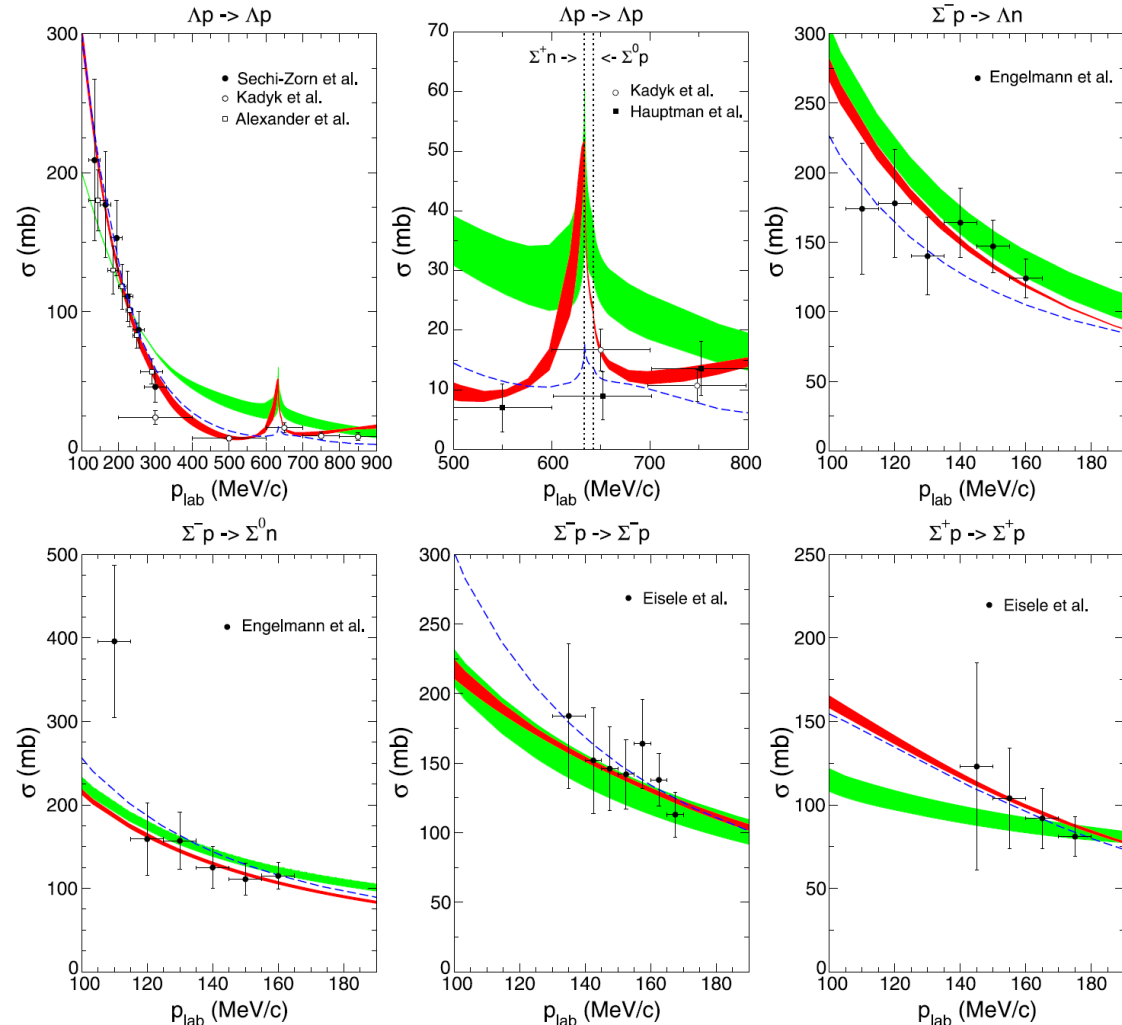


SLAC HBC, NPB125 (1977) 29-51

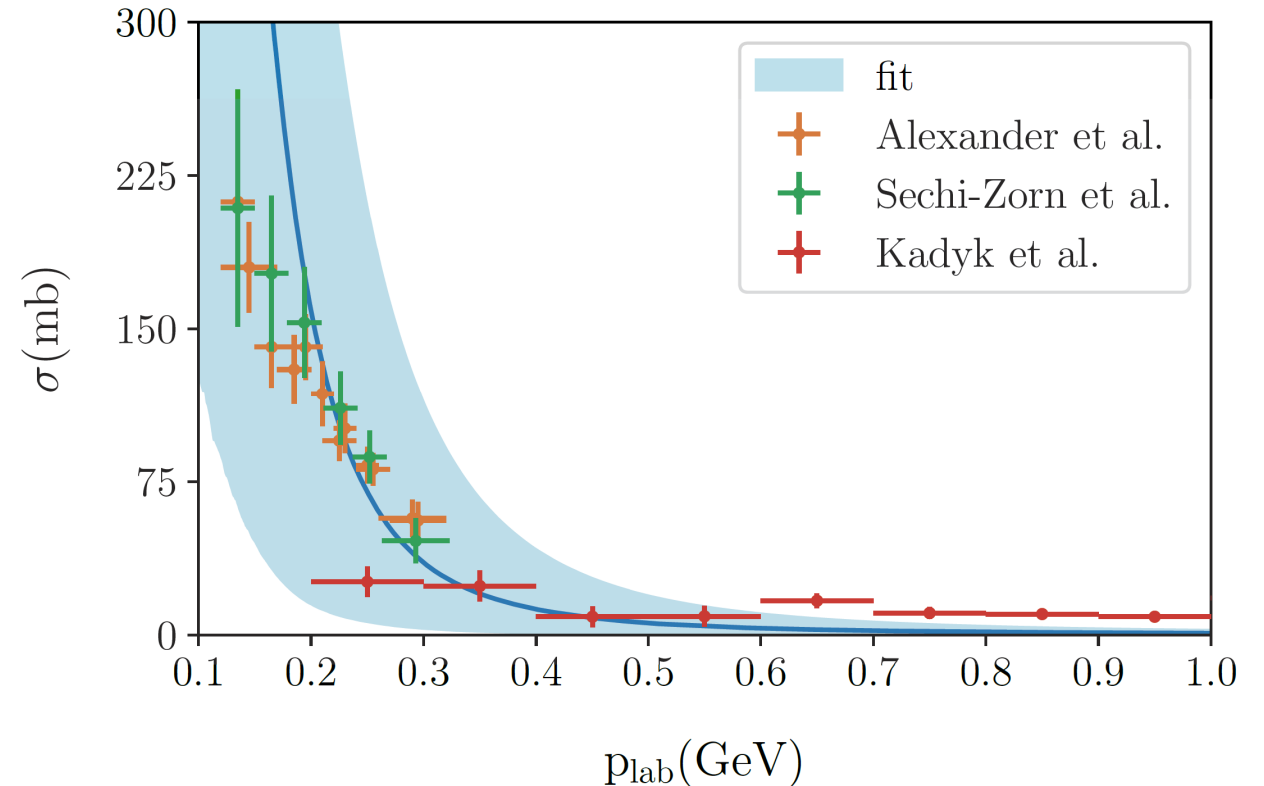
hyperon puzzle & YN interactions: Precision data needed!

36

J. Haidenbauer et al. / Nuclear Physics A 915 (2013) 24–58

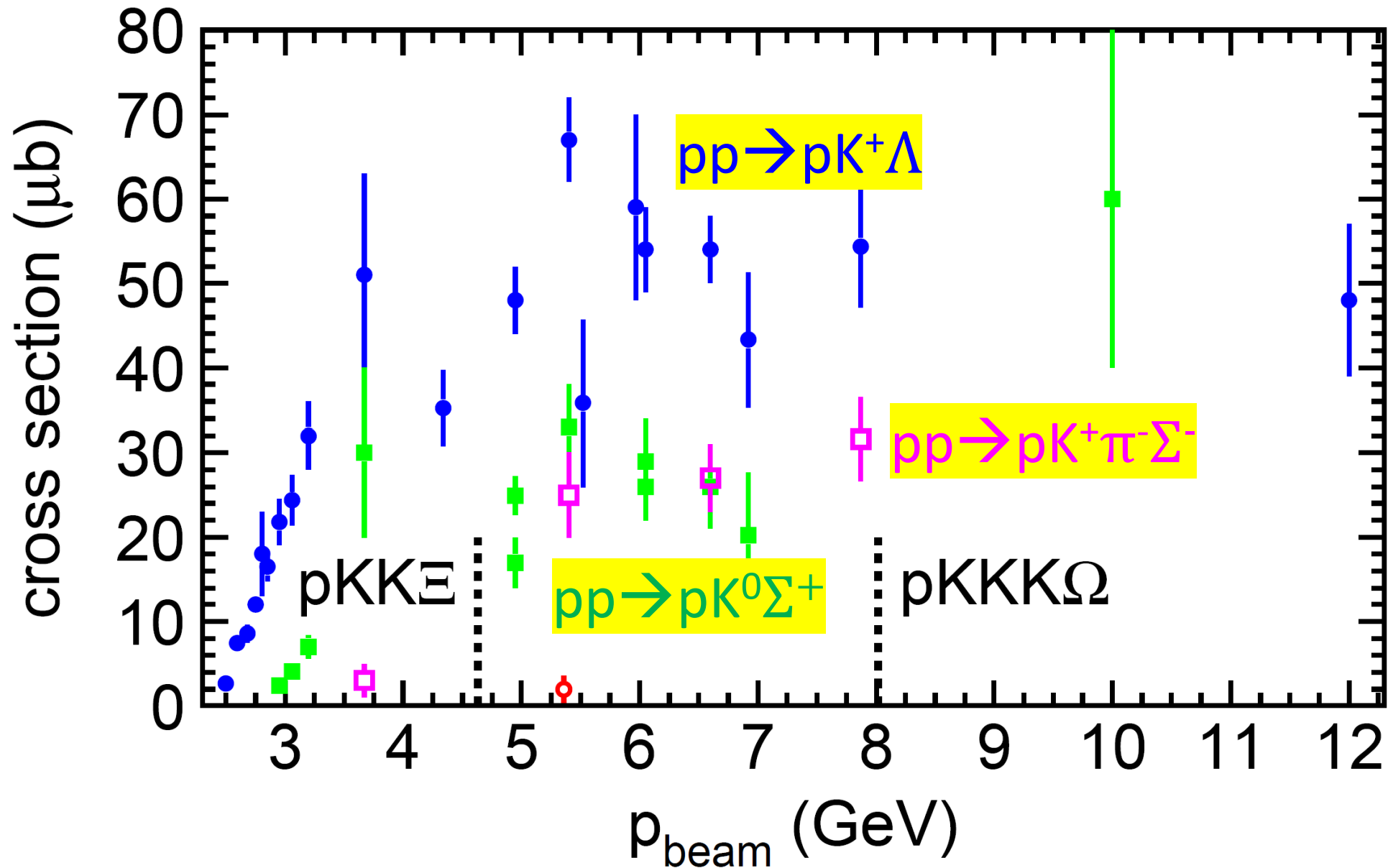


Hang Liu, Liuming Liu, Jin-Xin Tan, Wei Wang, Haobo Yan, Qian-Teng Zhu, [arXiv:2603.05854](https://arxiv.org/abs/2603.05854)
A Lattice QCD study of $p - \Lambda$ scattering in continuum and chiral limits



These can be studied @ hyperon factories: pp (FAIR, HIAF), e^+e^- (STCF, BEPCII-CW)

$pp \rightarrow$ 超子产生截面 $\sim O(10\mu b)$ ，如何用作粒子源？



$e^+e^- \rightarrow J/\psi \rightarrow$ 超子截面 $\sim O(\text{nb})$ ，如何用作粒子源？

$$\sigma_{Born}(s) = \frac{12\pi\Gamma_{ee}\Gamma_f}{(s - M^2)^2 + \Gamma_t^2 M^2}$$

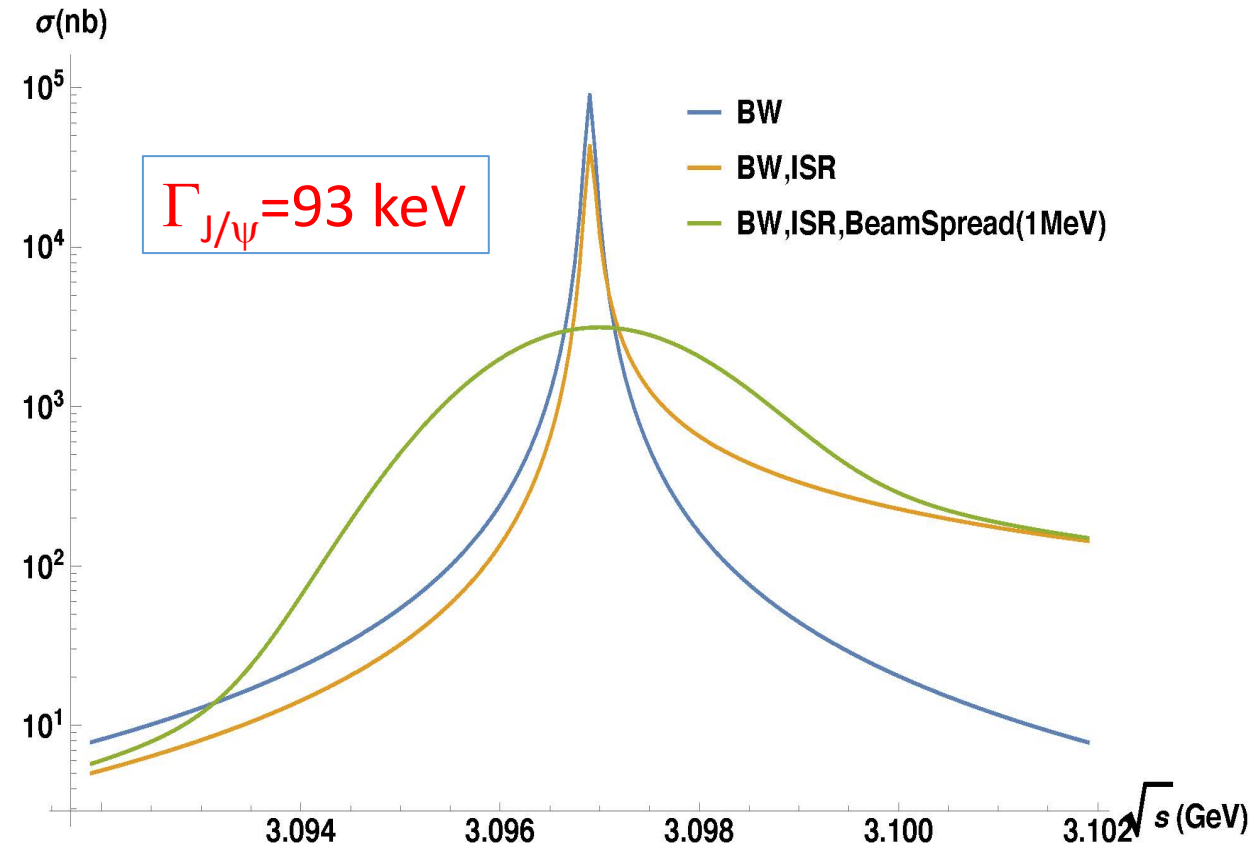
$$\sigma_{r.c.}(s) = \int_0^{x_m} dx F(x, s) \frac{\sigma_{Born}(s(1-x))}{|1 - \Pi(s(1-x))|^2}$$

$$\sigma_{exp}(W) = \int_0^\infty dW' \sigma_{r.c.}(W') G(W', W)$$

$$G(W, W') = \frac{1}{\sqrt{2\pi}\Delta} e^{-\frac{(W-W')^2}{2\Delta^2}}$$

Formulas from PLB 557 (2003) 192

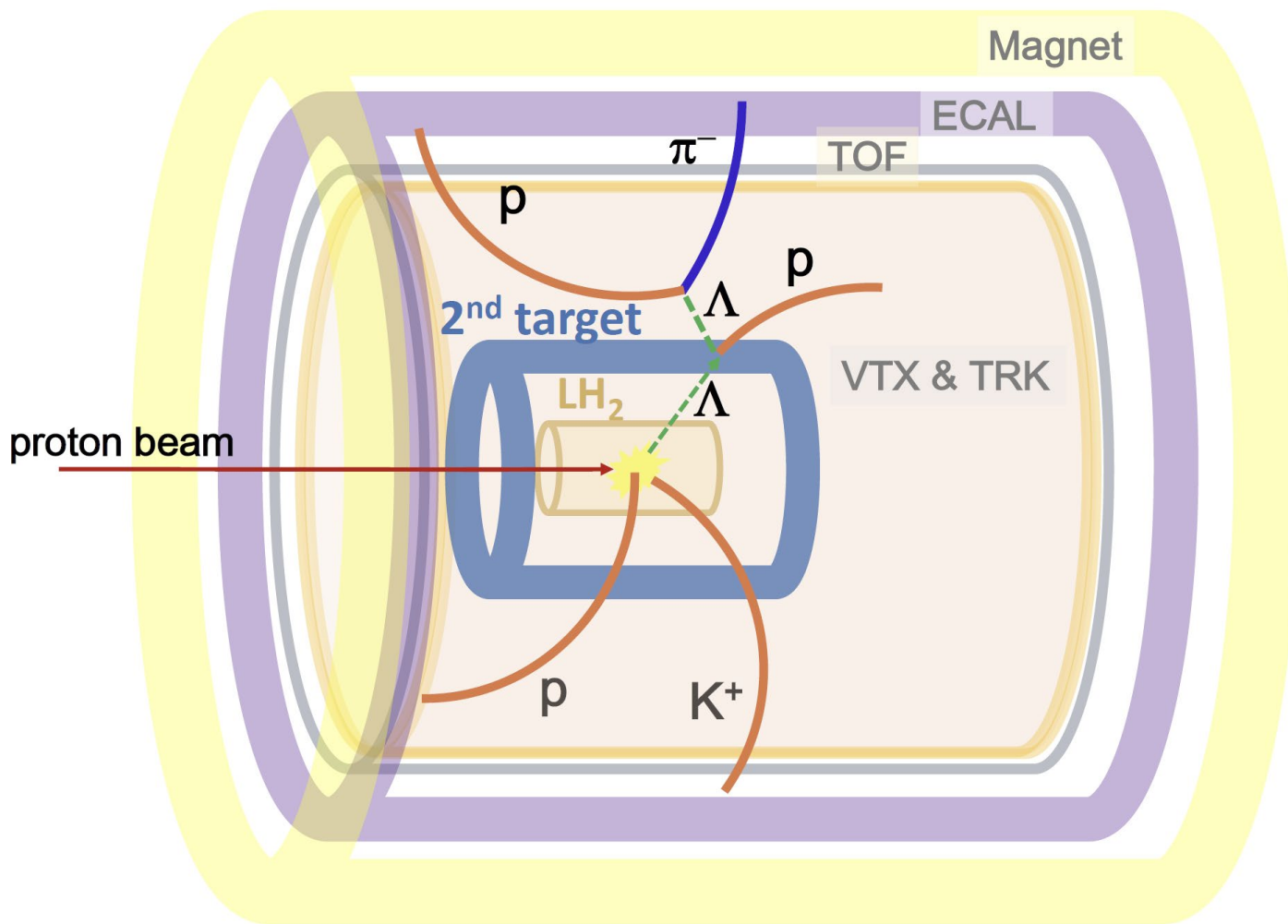
Numbers & plot from Yuping Guo



at J/ψ peak	Born	ISR	$\Delta=1$ MeV
σ (nb)	9.1×10^4	4.4×10^4	3,100

$\mathcal{L} = 0.5 \text{ nb}^{-1}\text{s}^{-1}$ @ BEPCII

常规质子打靶，加入第二个靶，成为“超子工厂”！



- LH₂, LD₂, or solid targets
- VTX&TRKer, TOF, ECAL in a magnet
- $pp \rightarrow pK^+\Lambda$, $pK\Sigma$, $pK\pi\Sigma$, $pKK\Xi$, $pKKK\Omega$
- Example: $pp \rightarrow pK^+\Lambda$
 - pK^+ to tag Λ
 - Reconstruct scattered $\Lambda \rightarrow p\pi$
 - With known Λ momentum & flux, measure (differential) cross section
- Proton flux= $10^{12}/s$, 5 cm thick target
➔ Luminosity $\sim 200 \text{ nb}^{-1}/s^{-1}$
- In one-month beam time
 - 10^7 observed Λp & Σp interactions
 - 10^6 observed Ξp interactions
 - 10^4 observed Ωp interactions
- HADES, CBM@FAIR; H-NS, HHaS@HIAF

Hyperon-Nucleon Spectrometer (H-NS)

梁羽铁 @ H-NS

Mag. Field: 1.5 Tesla

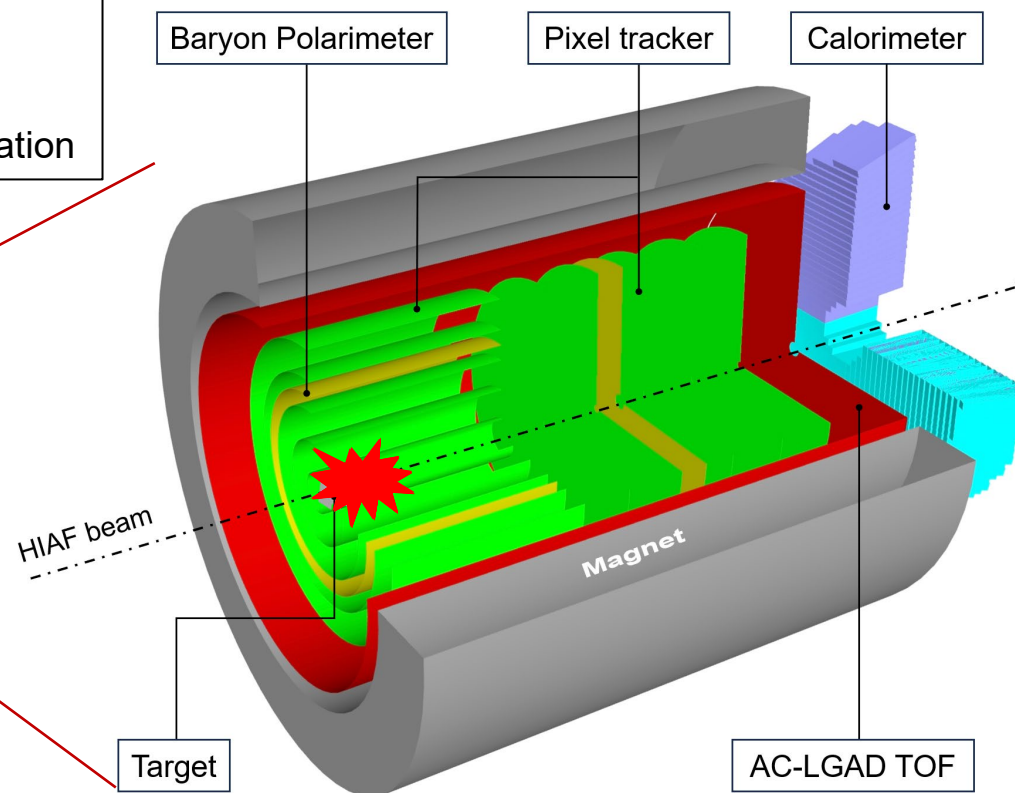
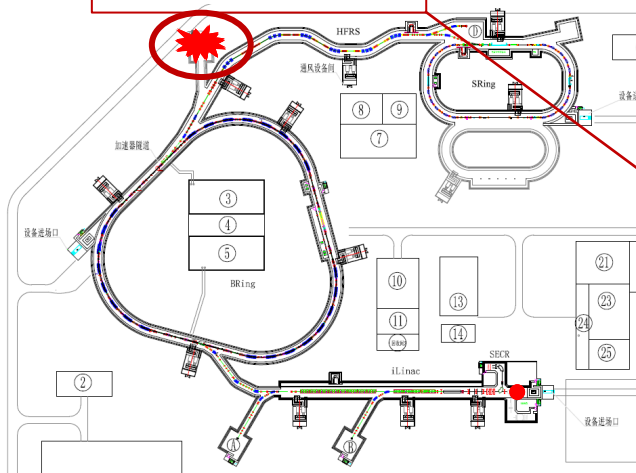
Tracker: MIC6, $30 \times 30 \mu\text{m}^2$, $0.35\% X/X_0$

LGAD: $\sigma_t \sim 30 \text{ ps}$, $300 \times 300 \mu\text{m}^2$

Calorimeter: $\sigma_E \sim 3\%$ @ 1 GeV

Polarimeter: nucleon and photon polarization

High Energy
Nuclear Physics
Terminal



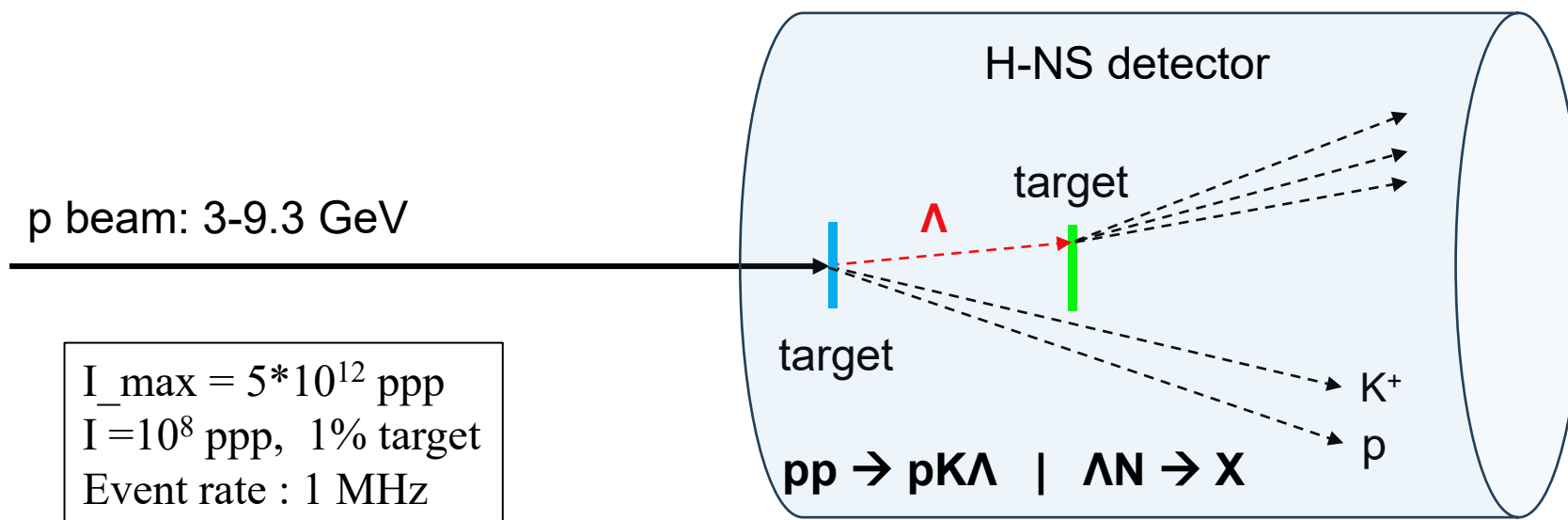
- Fix target experiment at HIAF
- pp, pA, AA of few GeV

Main physics:

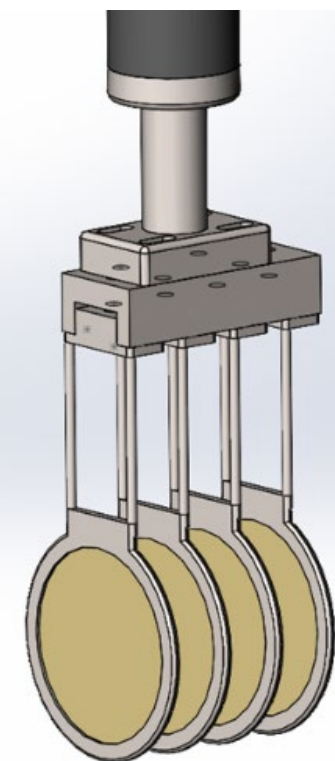
- Origin of Λ/p polarization
- **Baryon Spin structure**
- **QCD phase structure**
- Hadron spectroscopy
- **Y-N interaction**
- ...

YN interaction—hyperon beam at H-NS

梁羽铁 @ H-NS



参考CEE 4层靶设计



H-NS设计事例率1MHz；其中 $pp \rightarrow pK\Lambda$ 比例约0.1% $\rightarrow$ 1 kHz

第二层靶与初级靶距离1 cm，大部分 Λ 未衰变。

Λ 在衰变之前与后续靶材相互作用，假定后续靶材为 LH_2 靶，反应概率0.1%-1%

$\rightarrow \Lambda p$ 反应事例率为： 1-10 Hz

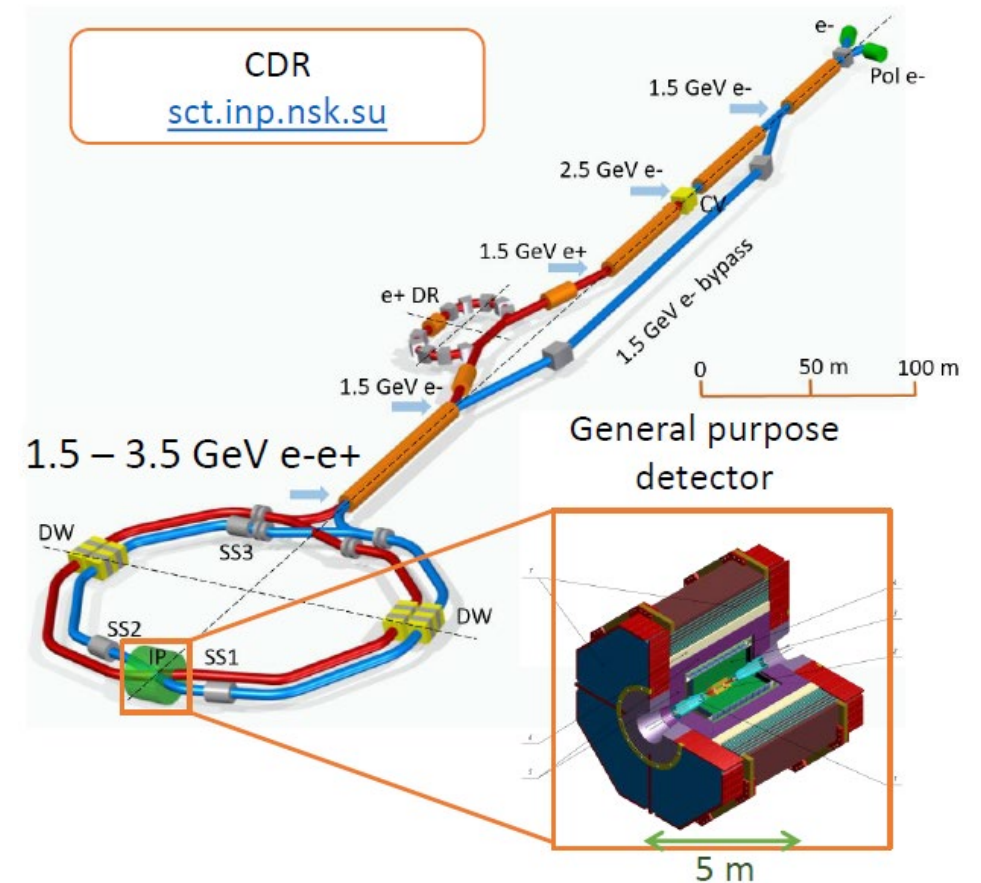
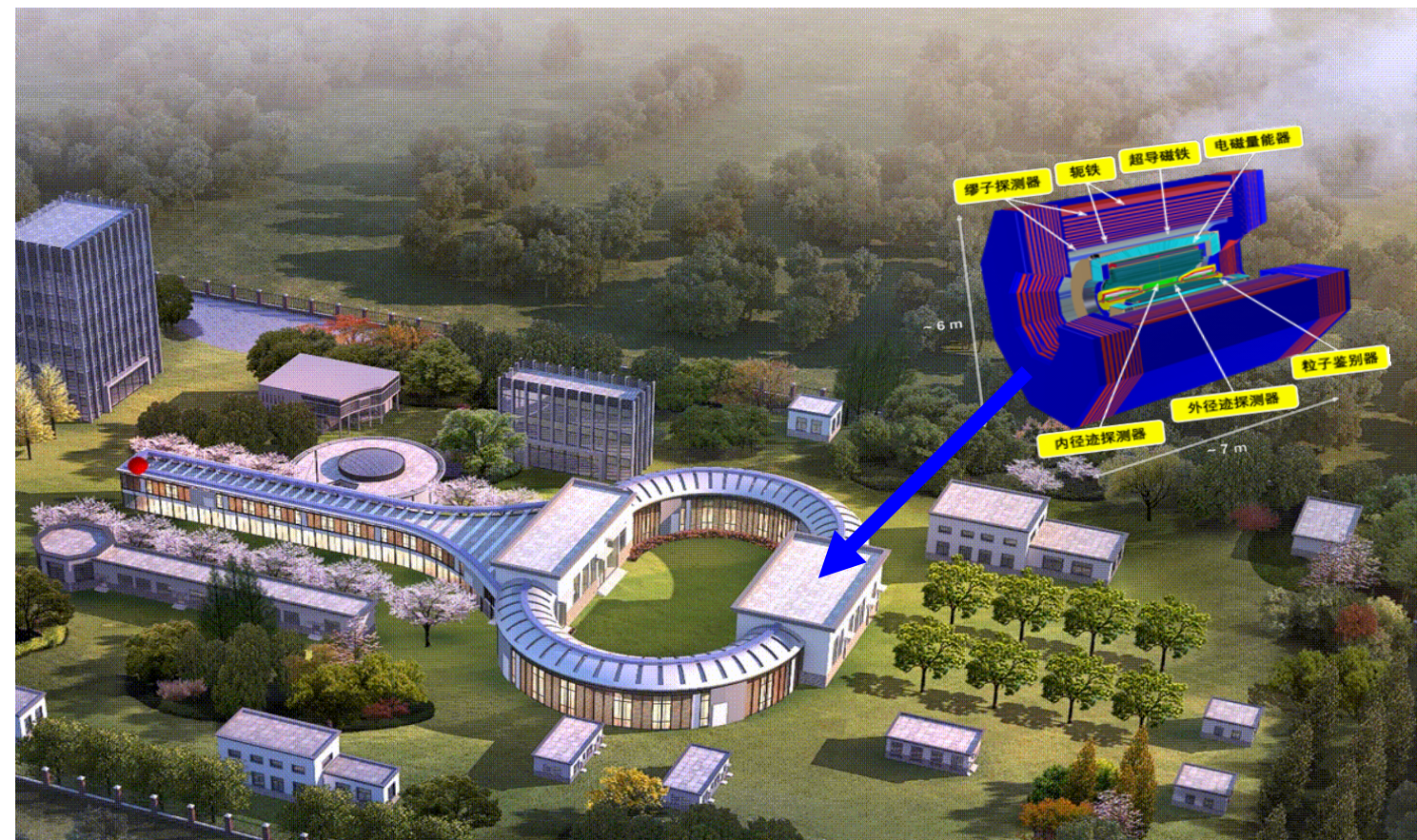
3个月运行预期： $N^{\text{prod}} \sim 10^7 - 10^8$; $N^{\text{obs}} \sim 10^6 - 10^7$ (效率 $\sim$ 10%)

HHaS上也可以加入靶物质进行类似研究

超级陶粲工厂，加入第二个靶，成为“超子工厂”！

中国合肥

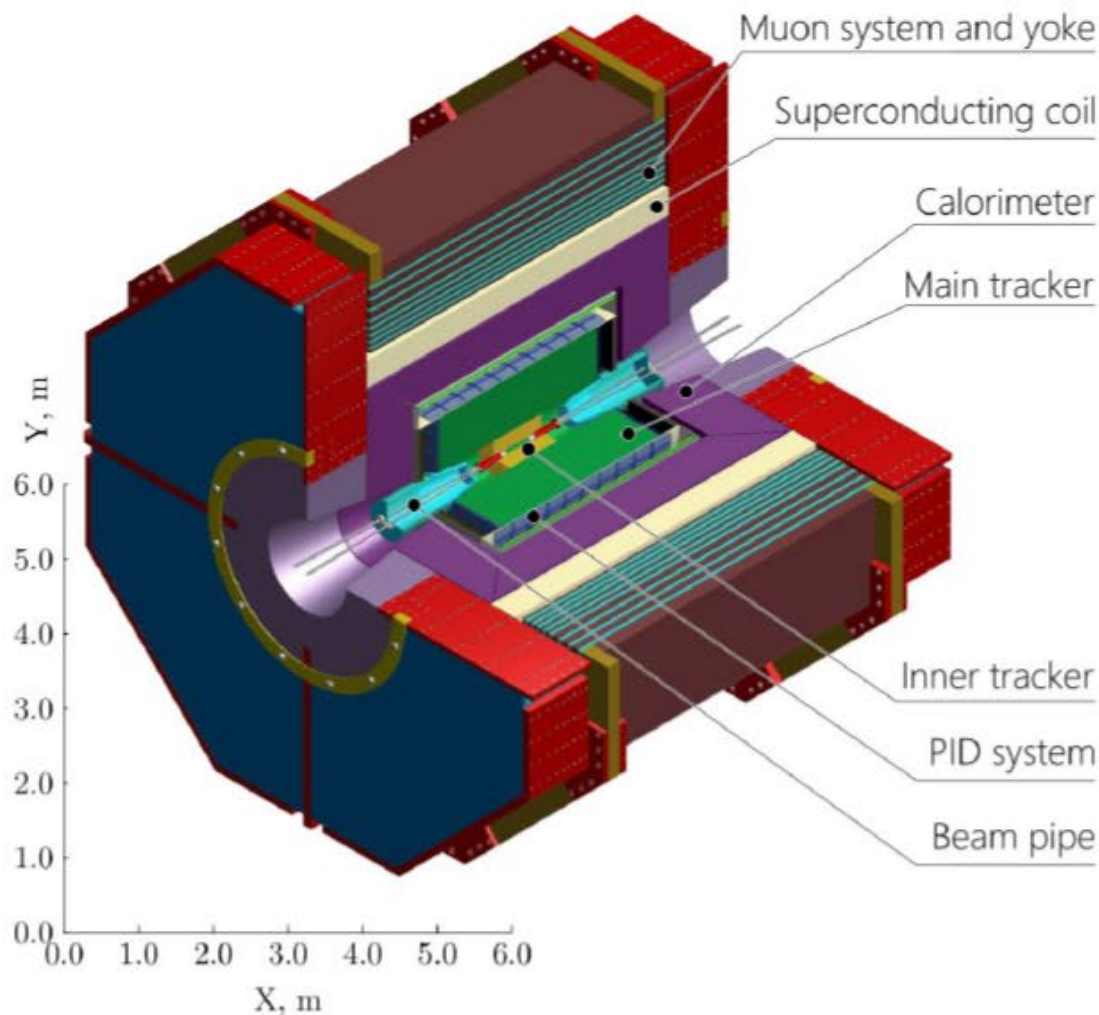
Sarov, Russia



中国合肥+俄罗斯 Sarov:

- CM Energy : **2-7 GeV**
- Peaking $\mathcal{L}$: **(5 ~ 10) $\times 10^{34}$ cm⁻² s⁻¹**

Detector concept



Momentum resolution $\sigma_p/p \leq 0.4\%$ at 1 GeV

Very symmetric and hermetic

Able to detect soft tracks ($p_t \geq 50 \text{ MeV}/c$)

- Inner tracker should be able to handle 10^4 tracks/cm²s

Very good particle identification: $e/\mu/\pi/K$

- π/K in the whole energy range, e.g. for $D\bar{D}$ mixing
- μ/π up to 1.5 GeV, e.g. for $\tau \rightarrow \mu\gamma$ search
- dE/dx better than 7%

Able to detect γ from 10 MeV to 3.5 GeV, good π^0/γ separation

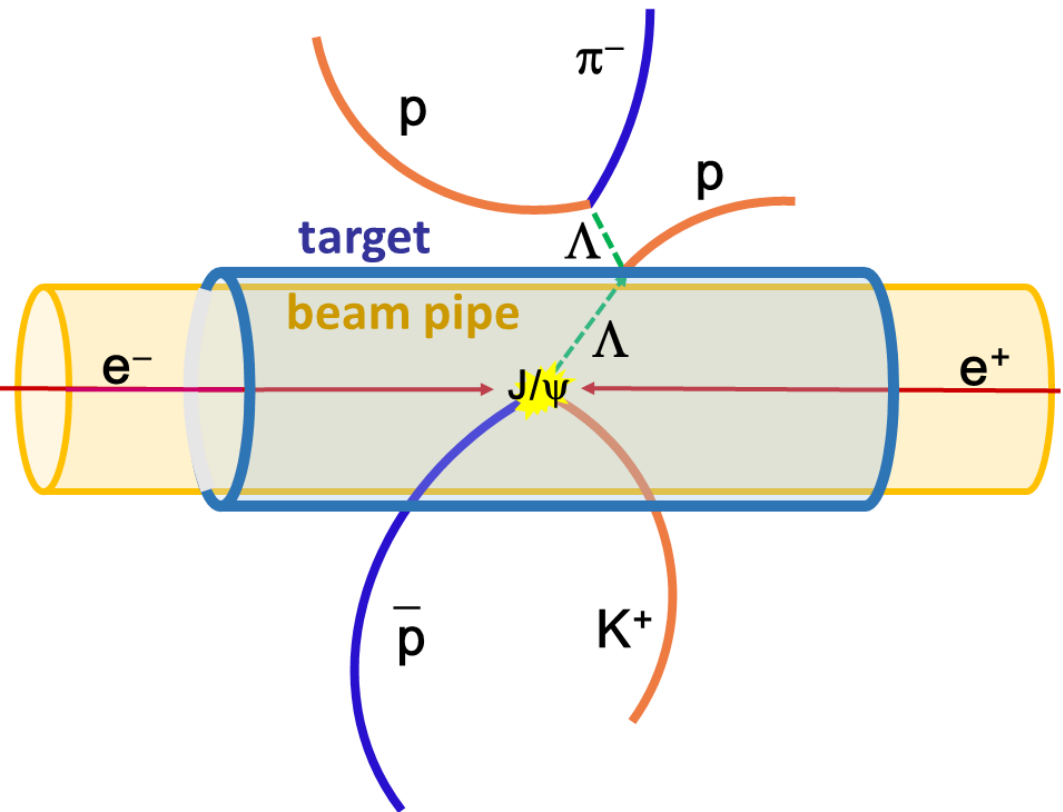
- Calorimeter energy resolution $\sigma_E/E \leq 1.8\%$ at 1 GeV
- Calorimeter time resolution $\sigma_t \leq 1 \text{ ns}$

Efficient “soft” trigger

Ability to operate at high luminosity, up to 300 kHz at J/ψ

束流管外加入 LH_2 、 LD_2 或含氢固体靶 $(\text{CH}_2)_n$ 等

detector



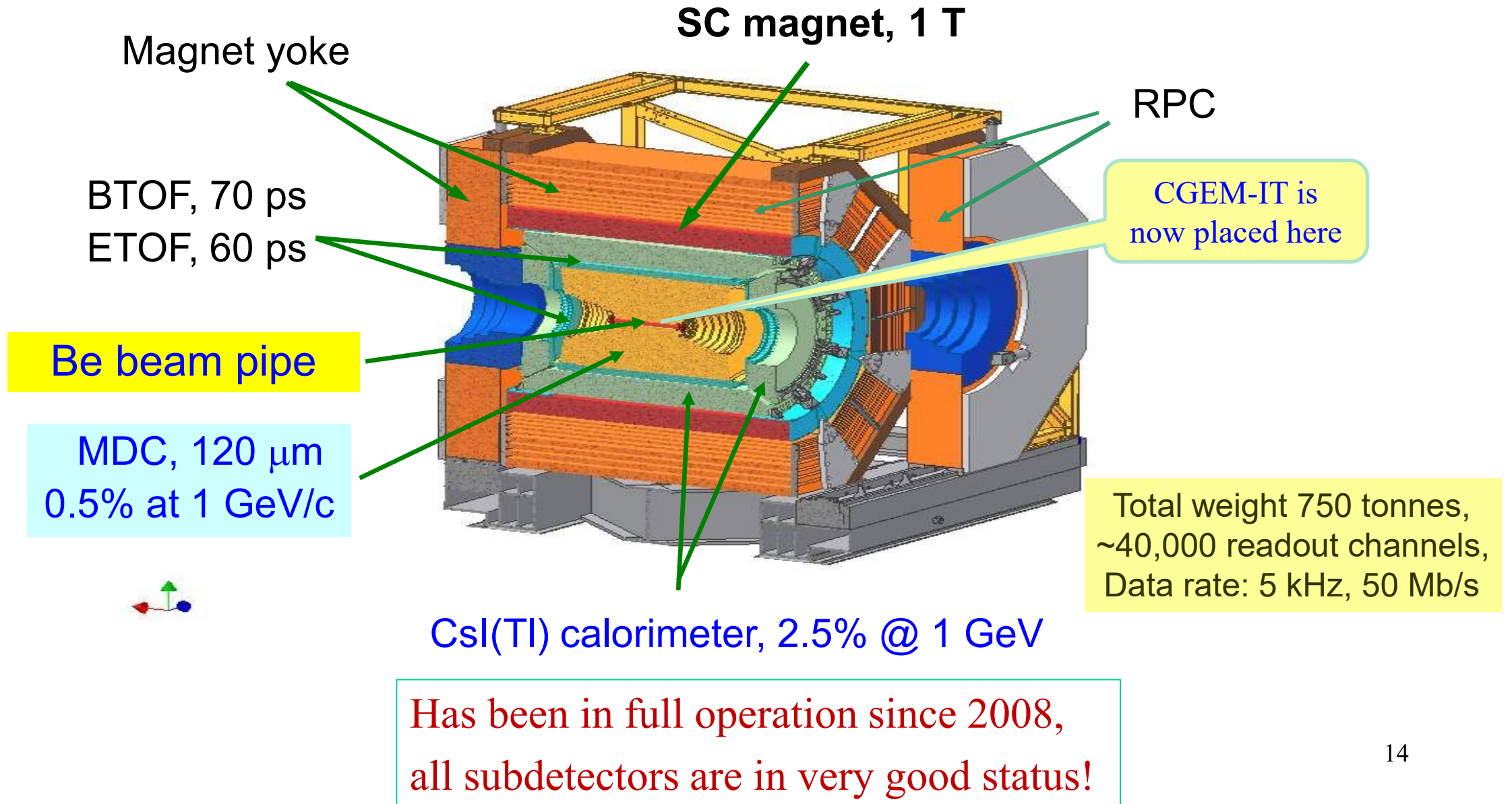
- Super J/ψ factory
 - e^+e^- annihilation @ 3.097 GeV
 - $O(10^{12})$ or more J/ψ events/year
- J/ψ decays into final states with nucleons or hyperons and their antiparticles
 - Branching Fraction $\sim 10^{-3}$
 - Tag efficiency $\sim (10-50)\%$
- High quality sources of (anti-)nucleon and long lived (anti-)hyperons
 - $O(10^8)$ tagged source particles per year
 - Well known momentum and direction
- Use variety of custom removable targets
- State of the art detector
- No need to share beam time
- $NN, \bar{N}N, YN, \bar{Y}N, \text{hypernuclei}, \dots$

Hyperons at STCF

重子	$c\tau/\text{cm}$	衰变模式	$B_{\text{tag}}/\%$	$\mathcal{E}_{\text{tag}}/\%$	$f_{1\text{cm}}^B/\%$	$f_{2\text{cm}}^B/\%$	$N_{1\text{cm}}^B/(\times 10^6)$	$N_{2\text{cm}}^B/(\times 10^6)$
Λ	7.89	$J/\psi \rightarrow \bar{\Lambda}\Lambda$	64	40	76	65	370	310
		$J/\psi \rightarrow \bar{p}K^+\Lambda$	100		70	55	240	190
Σ^+	2.40	$J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+$	52	40	49	27	150	84
		$J/\psi \rightarrow \bar{\Lambda}\pi^-\Sigma^+$	64		38	17	81	36
Σ^-	4.43	$J/\psi \rightarrow \bar{\Lambda}\pi^+\Sigma^-$	64	40	56	35	—	—
Ξ^0	8.71	$J/\psi \rightarrow \bar{\Xi}^0\Xi^0$	64	20	72	57	110	85
		$J/\psi \rightarrow \bar{\Xi}^+\pi^-\Xi^0$	64		66	49	—	—
Ξ^-	4.91	$J/\psi \rightarrow \bar{\Xi}^+\Xi^-$	64	20	60	40	74	50
		$J/\psi \rightarrow \bar{\Xi}^0\pi^+\Xi^-$	64		52	30	—	—
Ω^-	2.46	$\psi(2S) \rightarrow \bar{\Omega}^+\Omega^-$	44	20	31	11	1.4	0.5
		$\psi(2S) \rightarrow \bar{\Xi}^0K^+\Omega^-$	64		18	4	—	—

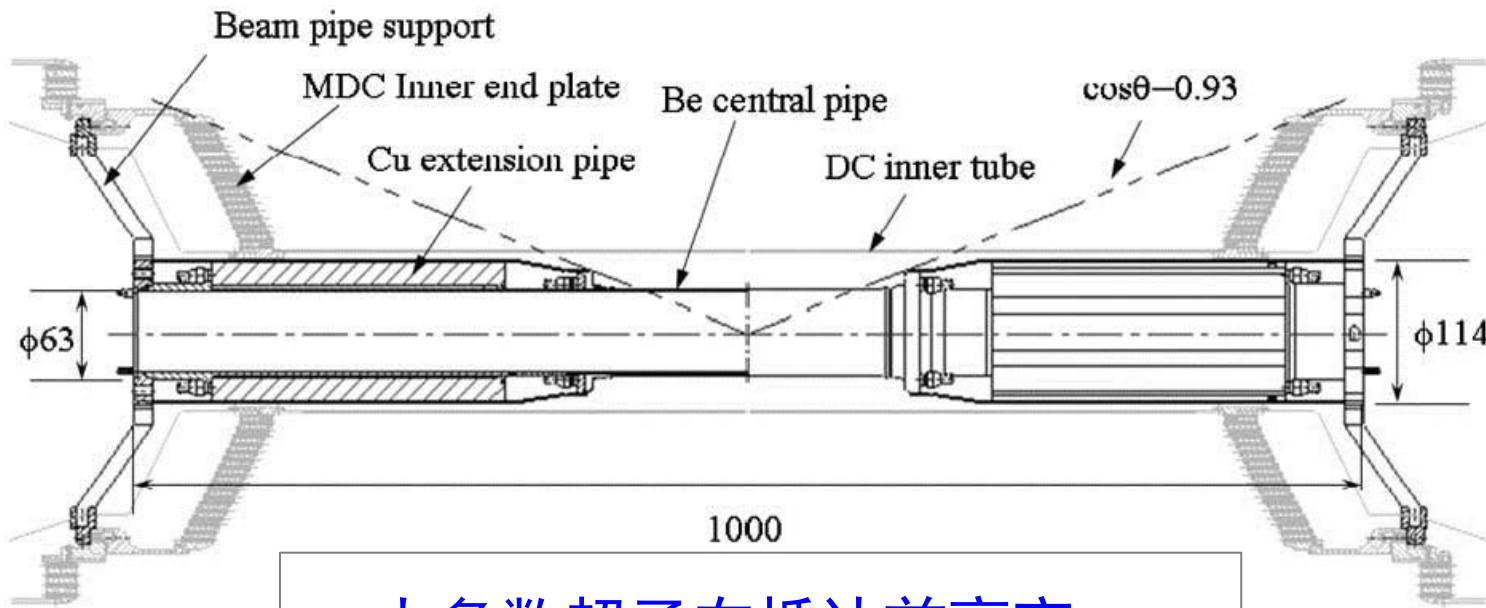
10^{12} J/ψ or $\psi(2S)$ events per year, target at 1 cm or 2 cm.

Proof of concept: study @ BESIII experiment

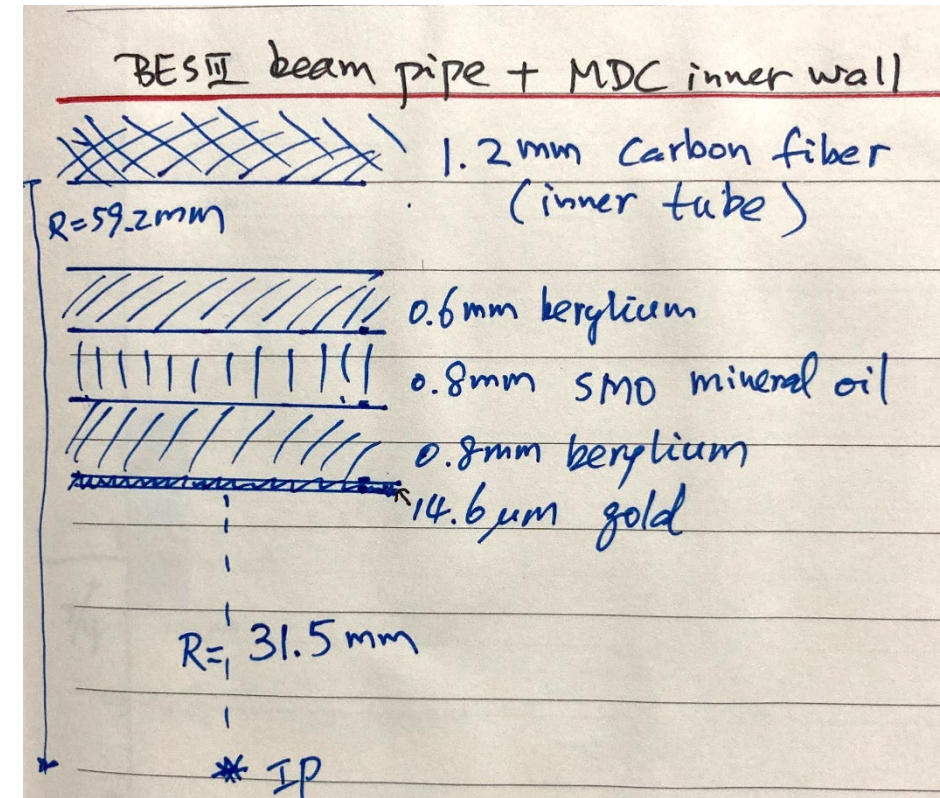


Proof of concept: study @ BESIII experiment

10 billion J/ψ data sample has been collected already, the detector material close to the interaction point in the inner detector serves as an effective target.



- 大多数超子在抵达前衰变
- 自由质子很少



BESIII可以研究超子与束流管中的质子以及其它原子核的碰撞！

Hyperons and anti-hyperons at BESIII (10B J/ψ)

Baryon	$c\tau$ (cm)	decay mode	$\mathcal{B} (\times 10^{-3})$	$p_{\max}$ (MeV/c)	$n_{\text{BP}}^B (\times 10^5)$
$\bar{n}$	2.6×10^{13}	$J/\psi \rightarrow p\pi^-\bar{n}$	2.12	1174	80
Λ	7.89	$J/\psi \rightarrow \bar{\Lambda}\Lambda$	1.89	1074	26
		$J/\psi \rightarrow \bar{p}K^+\Lambda$	0.87	876	9
Σ^+	2.40	$J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+$	1.50	992	4
		$J/\psi \rightarrow \bar{\Lambda}\pi^-\Sigma^+$	0.83	950	1
Σ^-	4.43	$J/\psi \rightarrow \bar{\Lambda}\pi^+\Sigma^-$	—	945	—
Ξ^0	8.71	$J/\psi \rightarrow \bar{\Xi}^0\Xi^0$	1.17	818	7
		$J/\psi \rightarrow \bar{\Xi}^+\pi^-\Xi^0$	—	685	—
Ξ^-	4.91	$J/\psi \rightarrow \bar{\Xi}^+\Xi^-$	0.97	807	3
		$J/\psi \rightarrow \bar{\Xi}^0\pi^+\Xi^-$	—	686	—
Ω^-	2.46	$\psi(2S) \rightarrow \bar{\Omega}^+\Omega^-$	0.05	774	0.05
		$\psi(2S) \rightarrow \bar{\Xi}^0K^+\Omega^-$	—	606	—

reference

The Ω hyperons are produced from 3 billion $\psi(2S)$ event sample.
All these particles can also be produced in decays of other charmonia.

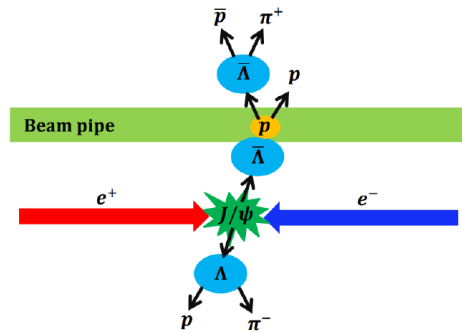
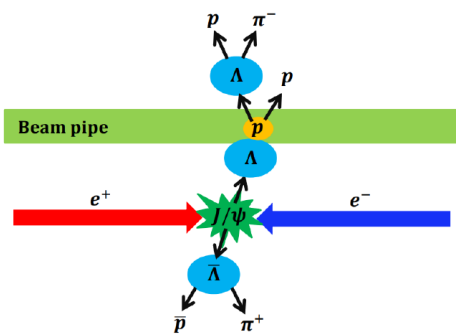
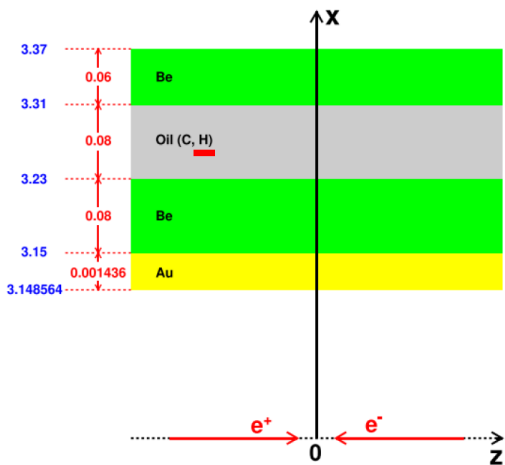
Proof of concept: study @ BESIII

Study of $\Lambda p \rightarrow \Lambda p$ and $\bar{\Lambda} p \rightarrow \bar{\Lambda} p$

PRL 132, 231902 (2024)

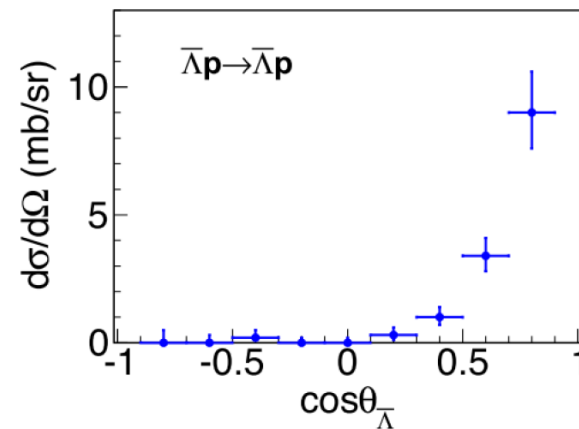
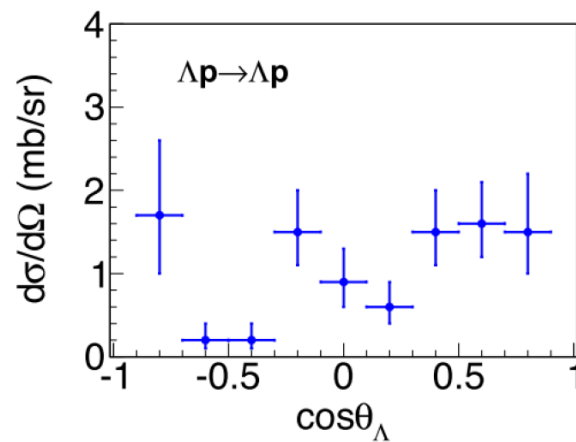
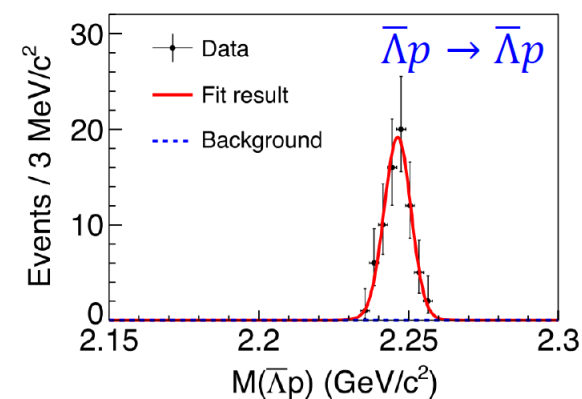
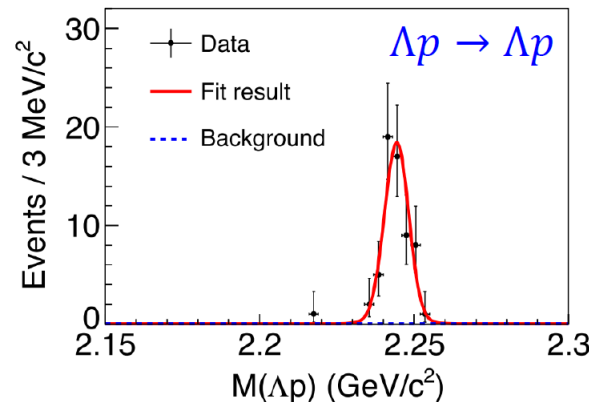
Taking the hydrogen in the cooling oil of the beam pipe as target material, the information on the hyperon-proton scattering can be extracted directly.

Two-body decay, $P_{\Lambda/\bar{\Lambda}} \approx 1.074 \text{ GeV}/c$



$J/\psi \rightarrow \bar{p} K \Lambda$ 可提供低动量超子

The center-of-mass energy for the incident $\Lambda/\bar{\Lambda}$ and a static p is about $2.243 \text{ GeV}/c^2$.



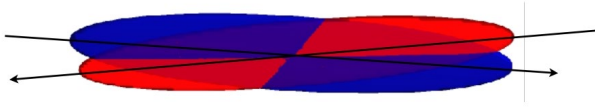
$$\sigma_t(\Lambda p \rightarrow \Lambda p) = (14.2 \pm 1.8_{\text{stat}} \pm 1.3_{\text{sys}}) \text{ mb}$$

$$\sigma_t(\bar{\Lambda} p \rightarrow \bar{\Lambda} p) = (27.4 \pm 3.2_{\text{stat}} \pm 2.5_{\text{sys}}) \text{ mb}$$

BEPCII crab waist scheme

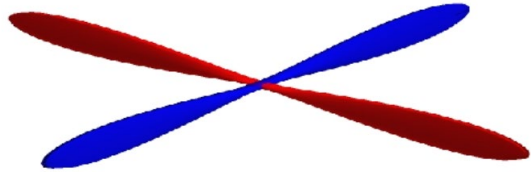
王逗 @ BEPCII

BEPCII/U



Design study supported by IHEP
Innovation funding since 2025.

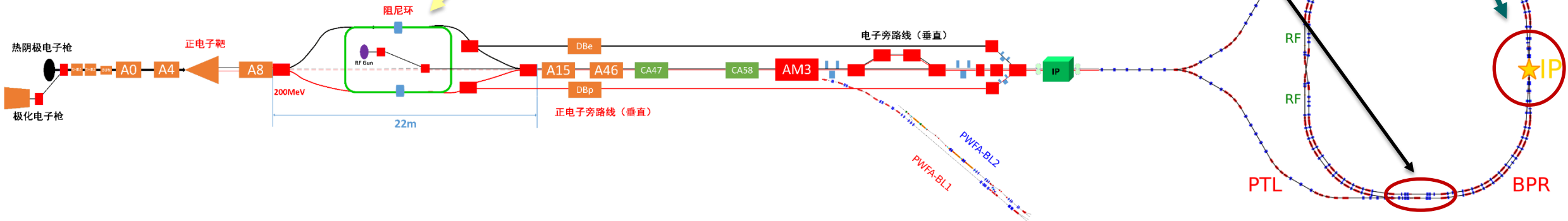
BEPCII crab waist



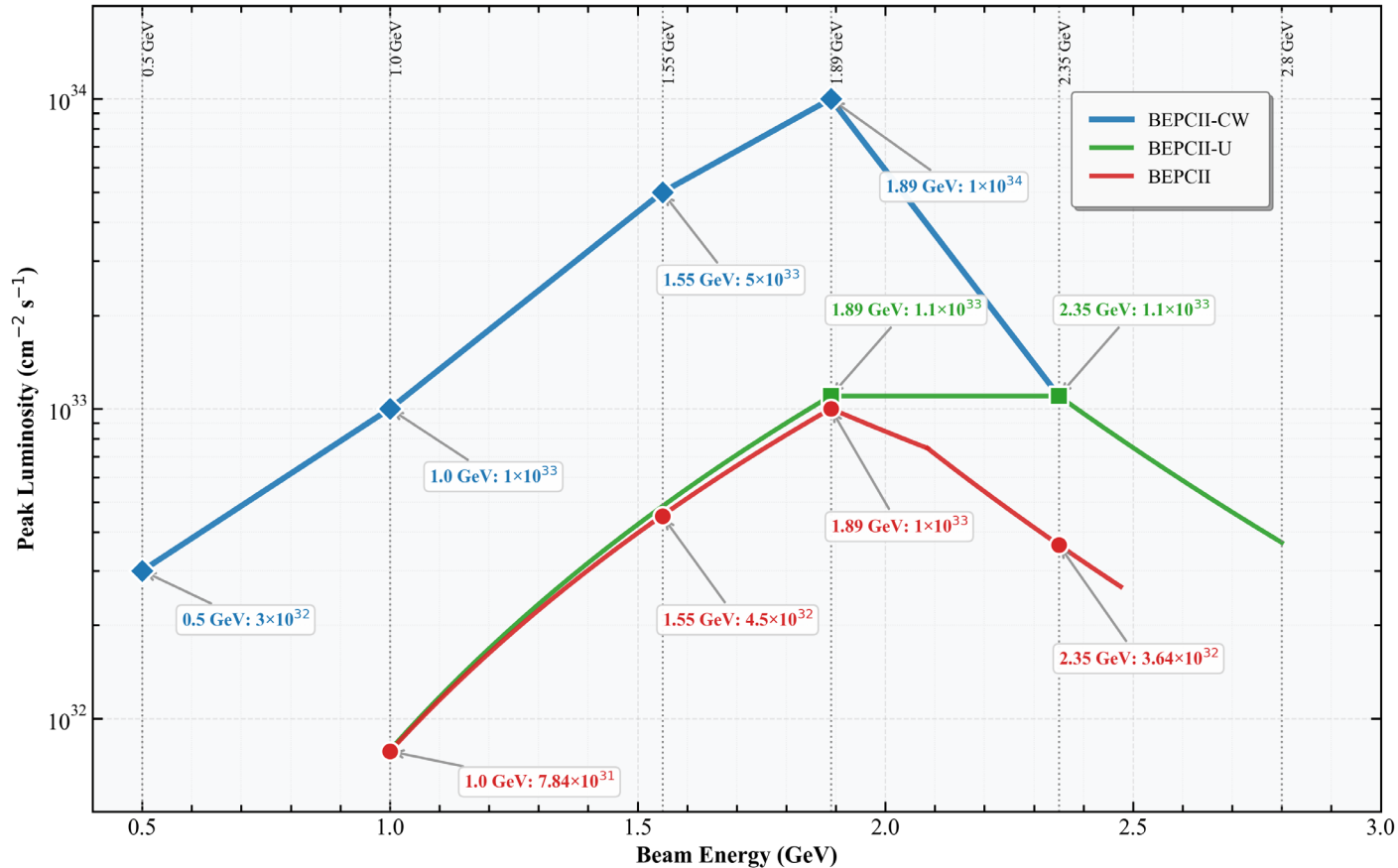
3. Linac: Compact
damping ring

2. Inner ring Inj. region:
insert wigglers

1. IR: crab waist collision



BEPCII-CW Luminosity vs BEPCII-U & BEPCII



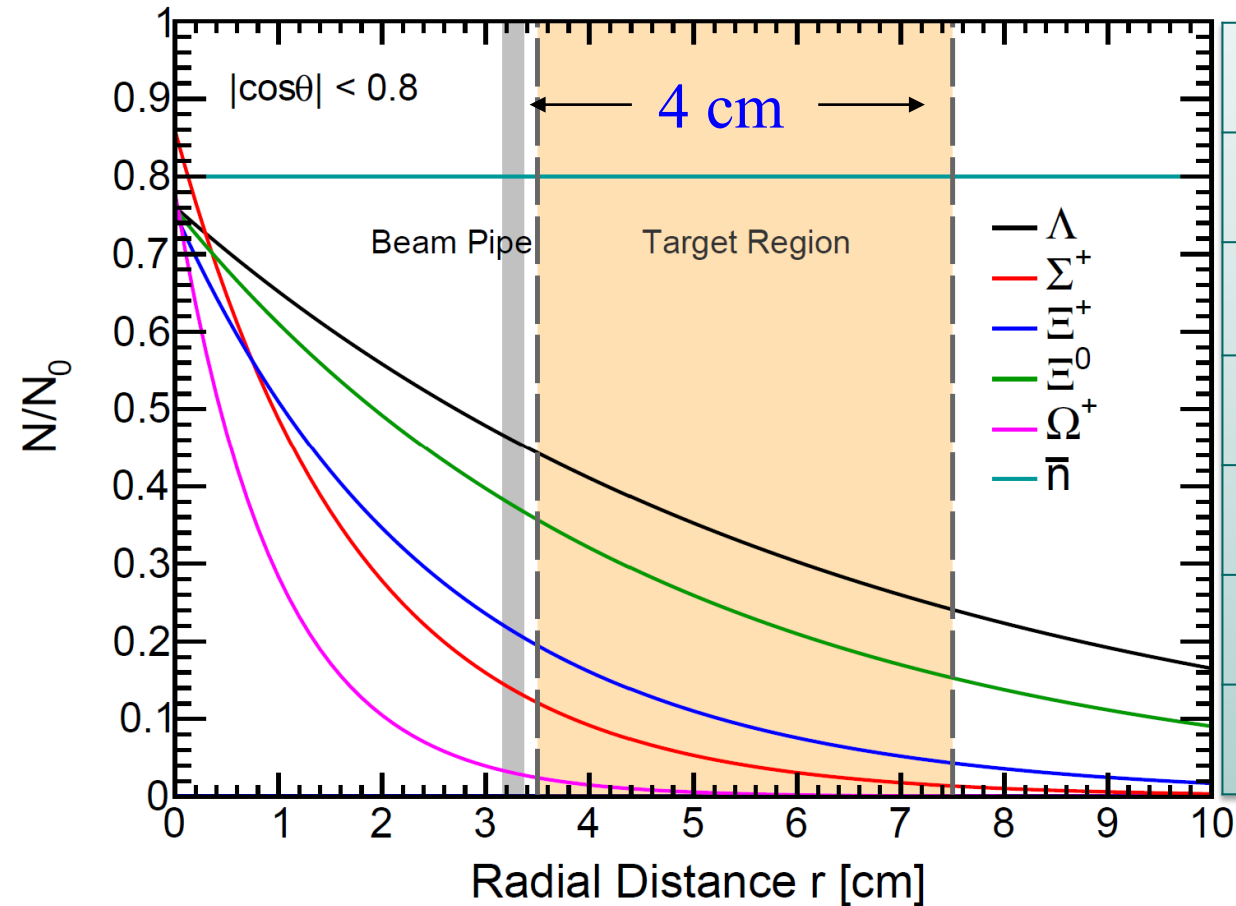
- The specifications at each energy are very preliminary.
- Parameters and lattice design need to be carefully optimized for each energy.
- Accelerator design is focusing on 1.89 GeV firstly.

- 100 billion J/ψ events in 1 year
- 30 billion $\psi(2S)$ in 1 year
- Lots hyperons can be accumulated!

- Luminosity may increase by $\times 10$ below 1.89 GeV
- Operation below 1 GeV is enabled
- May even reach 0.3 GeV

BESIII束流管和内层探测器直接加入LH₂靶?

显著增加YN相互作用事例



10B J/ ψ
p in BP

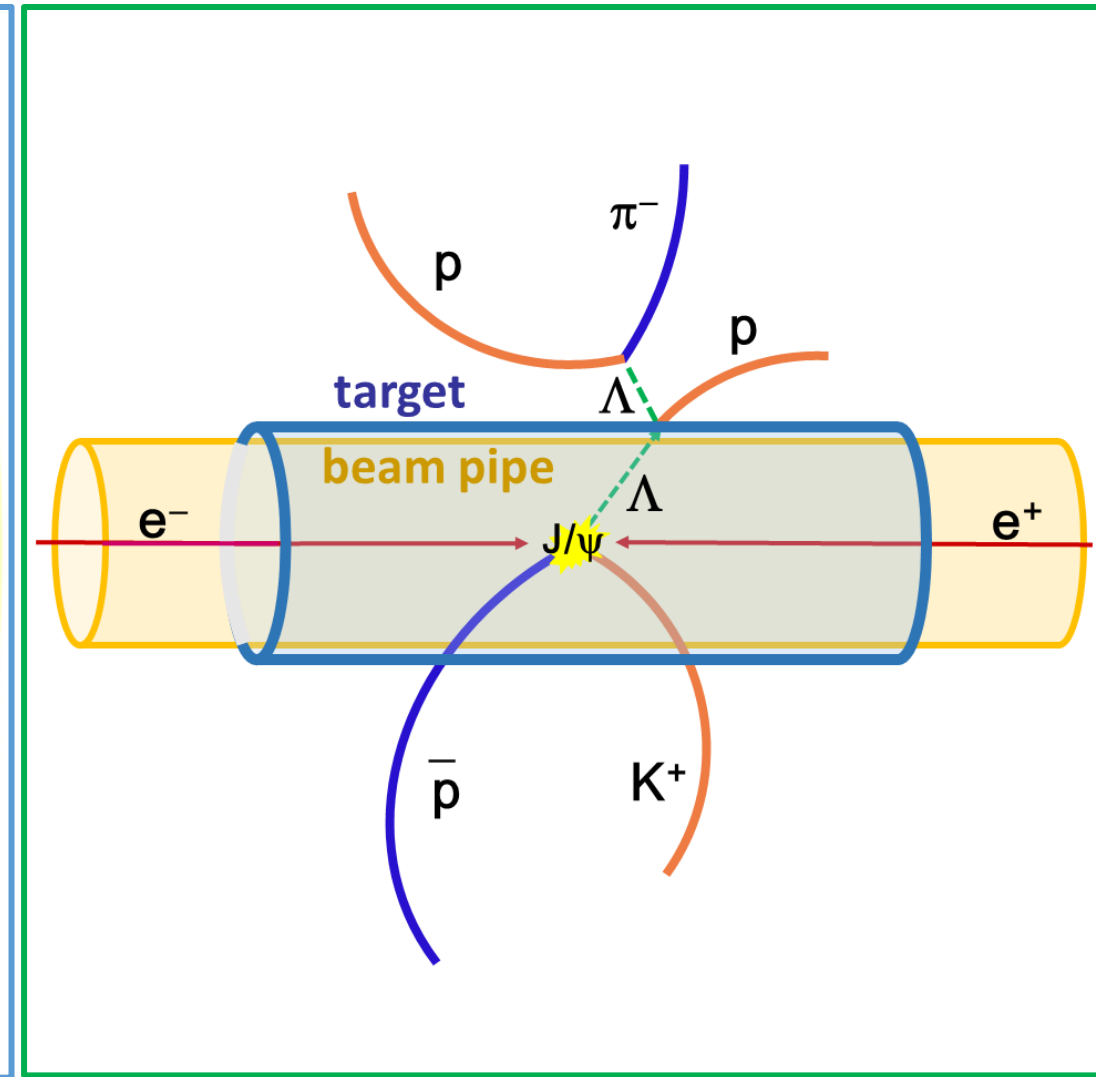
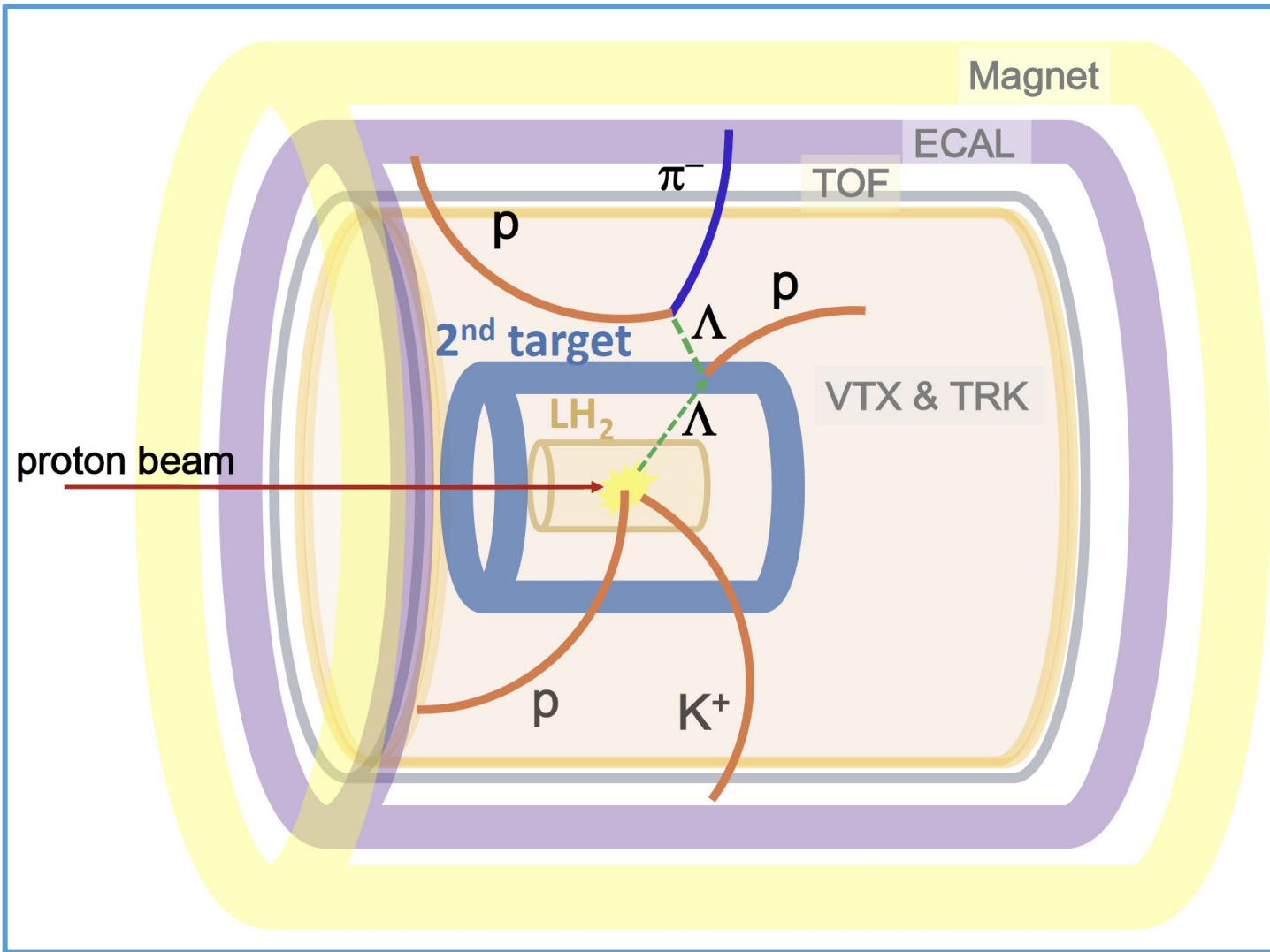
100B J/ ψ
with LH₂

Process*	N ^{obs} (BESIII)	σ (mb)	N ^{obs} (LH ₂)
$\Lambda + p \rightarrow \Lambda + p$	60.9 ± 7.8	$12.2 \pm 1.6 \pm 1.1$	~12,000
$\bar{\Lambda} + p \rightarrow \bar{\Lambda} + p$	72.0 ± 8.5	$27.4 \pm 3.2 \pm 2.5$	~14,000
$\Lambda + p \rightarrow \Sigma^+ + X$	795 ± 101	$19.3 \pm 2.4 \pm 1.8$	~8,000
$\Sigma^+ + n \rightarrow \Lambda + p$	77.6 ± 20.8	$45.2 \pm 12.1 \pm 7.2$	~1,000
$\Sigma^+ + n \rightarrow \Sigma^0 + p$	48.6 ± 15.9	$29.8 \pm 9.7 \pm 6.9$	~600
$\Xi^0 + n \rightarrow \Xi^- + p$	22.9 ± 5.5	$22.1 \pm 5.3 \pm 4.5$	~550

*hyperons from pair production only

30 billion $\psi(2S)$ events = hyperons with broader momentum distribution

我们建造一个(两个?) “超子工厂” 吧!



谢谢!

谢谢！

Comments on the Λ and $\bar{\Lambda}$ sources

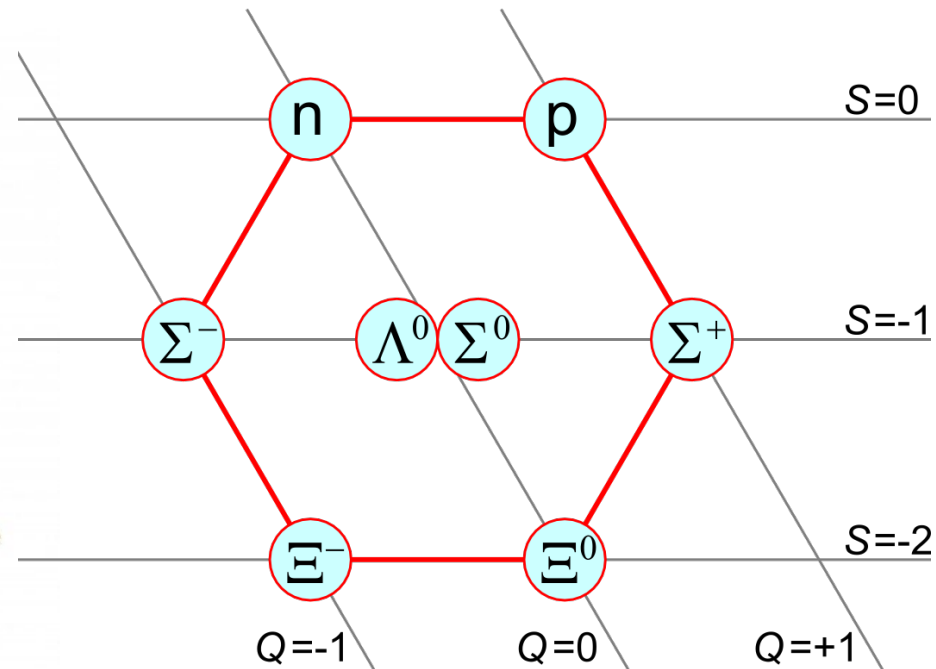
- Ground-state SU(3) octet hyperons (Λ , $\Sigma^\pm$, $\Xi^{0/-}$) and their antiparticles have relatively long lifetimes (with a typical $c\tau$ of a few centimeters) and are essential for investigating several important physics questions, including hyperon-nucleon interaction and the possible role of hyperons in neutron stars.
- The relevant experimental studies started in the 1960s and have lasted for more than half a century, using π or K beams shot into bubble chambers or scintillating fiber (SciFi) targets. The statistics of these experiments are low, with typically a few tens to a few hundreds of observed events.
- New ways of high efficiency hyperon production are essential.

Why particle sources are important

- Scattering experiments using many different kinds of beams are the mainstay of experiments investigating the fundamental interactions and structure of matter at the subatomic level.
- Beams of long-lived charged particles and of photons are easy to produce, and so many experiments using charged projectiles have been carried out during the more than 100 years since the trailblazing experiment shooting α particles into gold foil that enabled Rutherford to infer the existence of the atomic nucleus.
- Since then, e , μ , π , K , proton, antiproton, photon, and various heavy ion beams have been produced and have served as enablers of many scientific breakthroughs.
- Beams of some neutral particles, like neutrons and neutrinos, are relatively easy to produce but difficult to control; i.e., they have a large momentum spread.
- Beams of other neutral particles, such as antineutrons, K^0 and $\bar{K}^0$, long-lived hyperons (Λ , $\Sigma^\pm$, $\Xi^{0/-}$) and their antiparticles ($\bar{\Lambda}$, $\bar{\Sigma}^\pm$, $\bar{\Xi}^{0/+}$) have great physics potential, but they are typically much more difficult to produce and control.

PRL paper title:

- ① Cornucopia of antineutrons and hyperons
- ② from a super J/ψ factory
- ③ for next-generation nuclear and particle physics
- ④ high-precision experiments



+ their antiparticles

Why J/ψ decays: big $B(J/\psi \rightarrow \text{baryons})$

decay mode	$\mathcal{B} (\times 10^{-3})$	$p_{\text{max}} (\text{MeV}/c)$
$J/\psi \rightarrow p\pi^-\bar{n}$	2.12	1174
$J/\psi \rightarrow \bar{\Lambda}\Lambda$	1.89	1074
$J/\psi \rightarrow \bar{p}K^+\Lambda$	0.87	876
$J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+$	1.50	992
$J/\psi \rightarrow \bar{\Lambda}\pi^-\Sigma^+$	0.83	950
$J/\psi \rightarrow \bar{\Lambda}\pi^+\Sigma^-$	—	945
$J/\psi \rightarrow \bar{\Xi}^0\Xi^0$	1.17	818
$J/\psi \rightarrow \bar{\Xi}^+\pi^-\Xi^0$	—	685
$J/\psi \rightarrow \bar{\Xi}^+\Xi^-$	0.97	807
$J/\psi \rightarrow \bar{\Xi}^0\pi^+\Xi^-$	—	686
$\psi(2S) \rightarrow \bar{\Omega}^+\Omega^-$	0.05	774
$\psi(2S) \rightarrow \bar{\Xi}^0K^+\Omega^-$	—	606

Why J/ψ decays: high tag efficiency

	$\mathcal{B}_{\text{tag}}$	ε_{tag}
decay mode	(%)	(%)
$J/\psi \rightarrow p\pi^-\bar{n}$	100	50
$J/\psi \rightarrow \bar{\Lambda}\Lambda$	64	40
$J/\psi \rightarrow \bar{p}K^+\Lambda$	100	
$J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+$	52	40
$J/\psi \rightarrow \bar{\Lambda}\pi^-\Sigma^+$	64	
$J/\psi \rightarrow \bar{\Lambda}\pi^+\Sigma^-$	64	20
$J/\psi \rightarrow \bar{\Xi}^0\Xi^0$	64	20
$J/\psi \rightarrow \bar{\Xi}^+\pi^-\Xi^0$	64	
$J/\psi \rightarrow \bar{\Xi}^+\Xi^-$	64	20
$J/\psi \rightarrow \bar{\Xi}^0\pi^+\Xi^-$	64	
$\psi(2S) \rightarrow \bar{\Omega}^+\Omega^-$	44	20
$\psi(2S) \rightarrow \bar{\Xi}^0K^+\Omega^-$	64	