Study of antineutron and hyperon interact with nuclei at J/ψ factory

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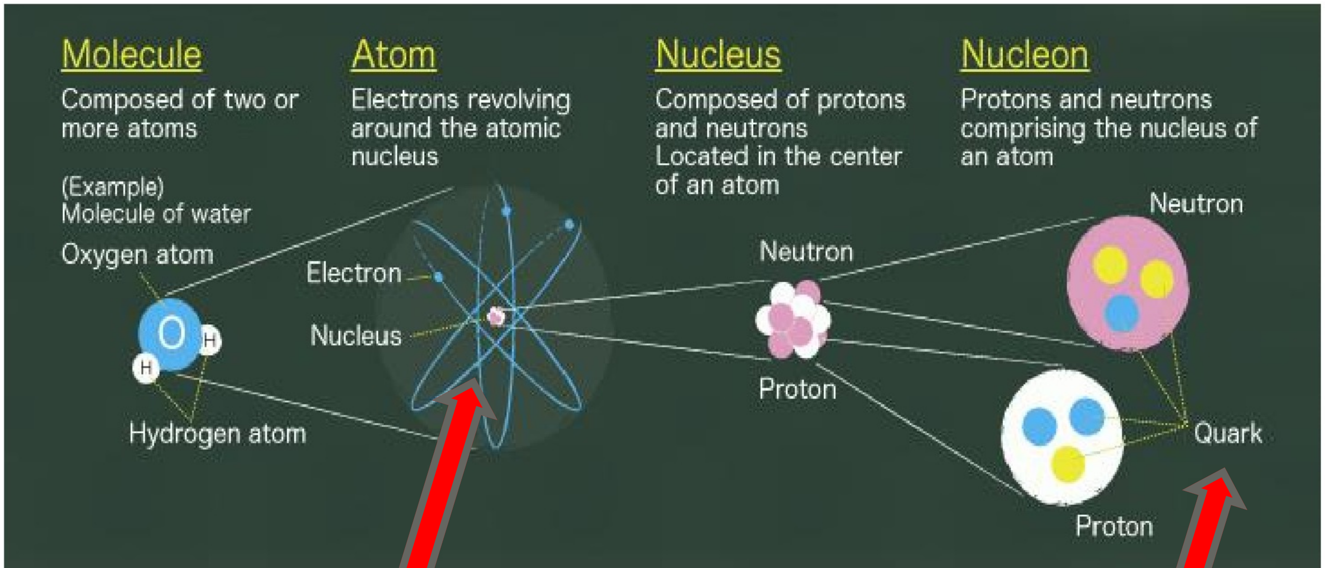
- C. Z. Yuan & M. Karliner, PRL 127, 012003 (2021) [arXiv:2103.06658]
  "Editors' suggestion" & "Featured in *Physics*"
- W. M. Song & C. Z. Yuan, Physics 51，255 (2022)

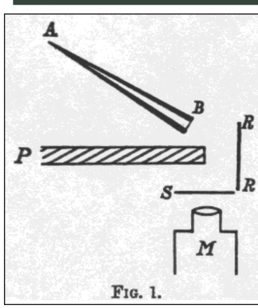
NSTAR2024, June 17-21, 2024 @ York

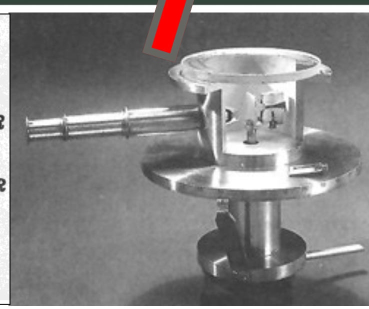
Outline

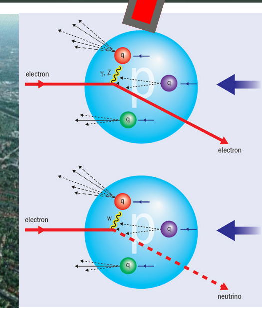
- **Status of antineutron and hyperon as particle source**
- **Why J/ψ factory could improve the status much**
- **Proof of concept at BESIII and prospect at STCF**
- **Summary**

Scattering experiments shed light on matter structure







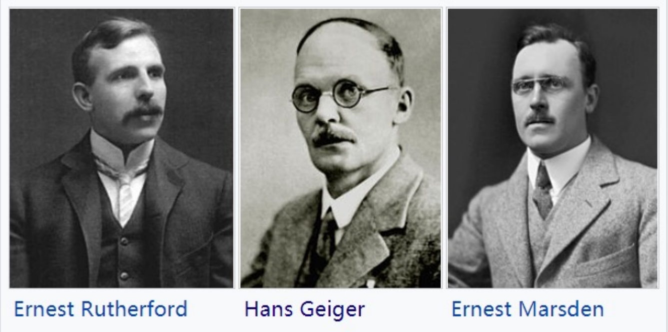


Rutherford experiment → **Nucleus**

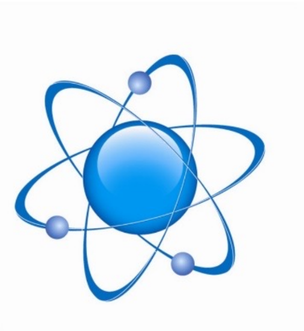
Electon-nucleon DIS → **Quark**

Geiger–Marsden experiment

(Rutherford gold foil experiment)



- AB： conical glass tube containing “radium emanation” (radon), “radium A” (actual radium), and “radium C” (bismuth-214); its open end sealed with mica [云母]
- P： lead plate
- S： fluorescent zinc sulfide screen
- R： metal foil
- M： microscope



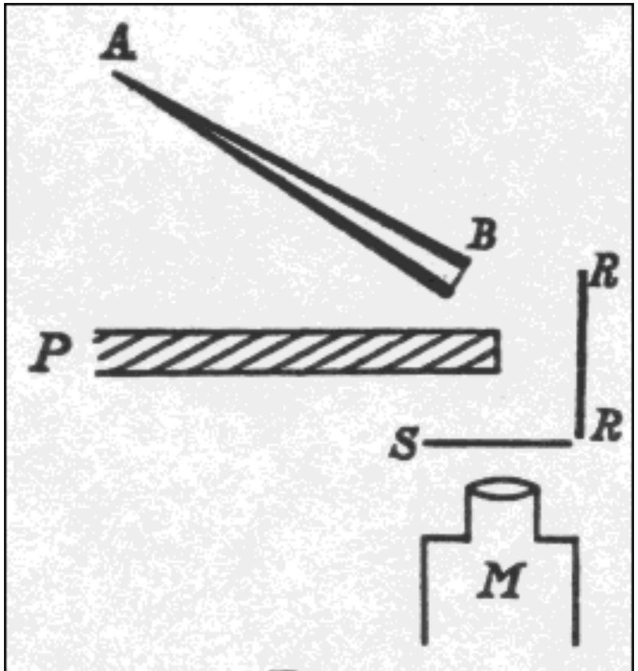
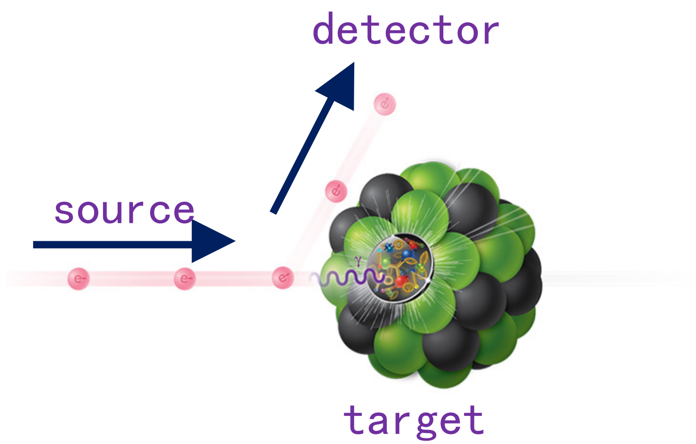


FIG. 1.

Geiger, Hans; Marsden, Ernest (1909). "On a Diffuse Reflection of the α-Particles". *Proceedings of the Royal Society of London A*. **82** (557): 495.

Particle sources

Three elements of scattering experiment : particle source, target, and detector



High quality particle source : long lifetime、easy to produce and control、low background、high intensity、good resolution……

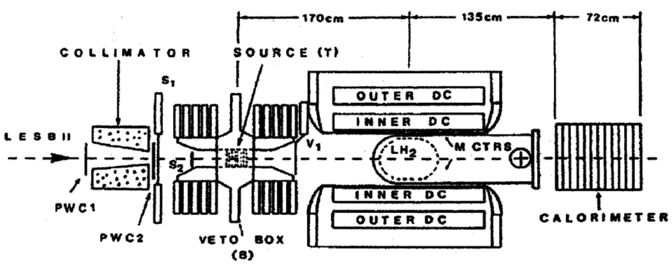
- **charged : electron/positron , muon , pion , kaon , proton , heavy ion**
- **neutral : photon , neutron , neutrino**

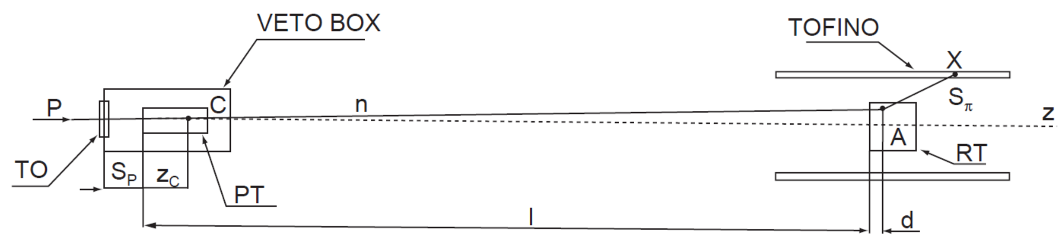
For more details: D.C. Faircloth, Particle Sources, 2103.13231 (Proceedings of the CERN–Accelerator–School: Introduction to Accelerator Physics)

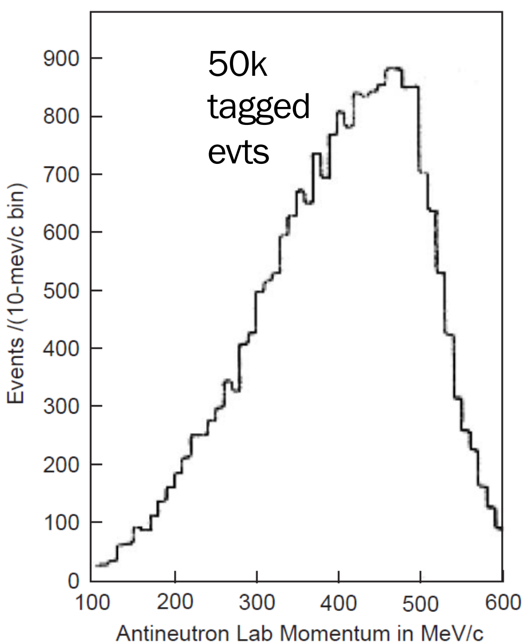
Beams of other neutral particles, such as antineutrons, K^0 and $\overline{K}^0$, long-lived hyperons (Λ, $\Sigma^{\pm}$, $\Xi^{0/-}$) and their antiparticles ($\overline{\Lambda}$, $\overline{\Sigma}^{\pm}$, $\overline{\Xi}^{0/+}$) have great physics potential, but they are typically much more difficult to produce and control.

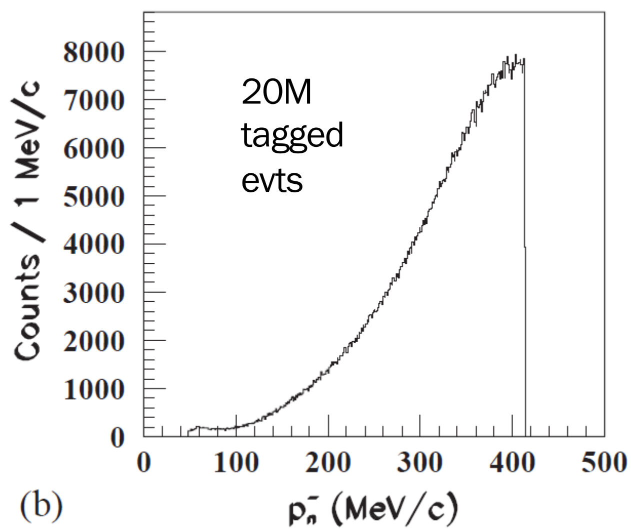
Antineutron in history

- $\bar{p}p \rightarrow \bar{n}n$ @ E-767@BNL & OBELIX@CERN









Limited statistics

36 $\bar{n}$ per 10^6 $\bar{p}$

[2×10^7 collected in 5 years]

Limited momentum range

Uncertainty in flux~7%

$\sigma p_{\bar{n}}$ = 3% @ 50 MeV/c

= 5% @ 400 MeV/c

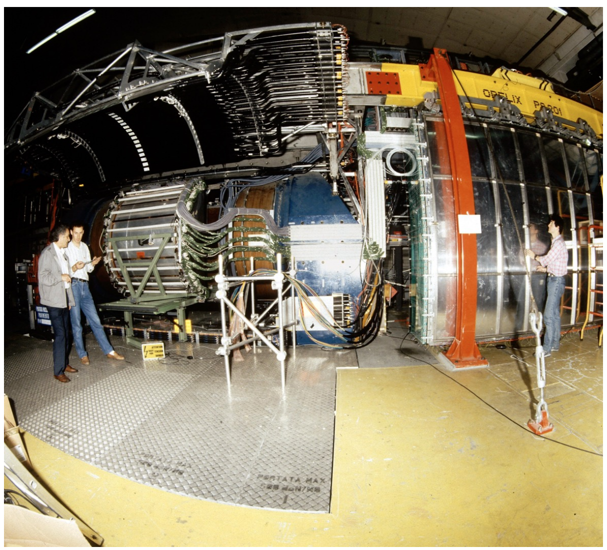
Antineutron in history

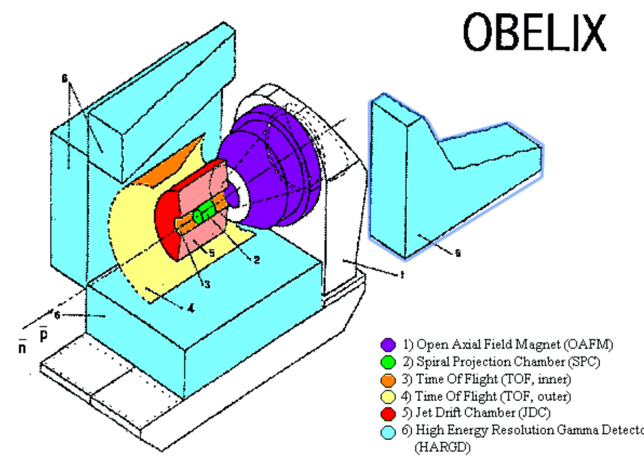
Anti-neutron is neutral

Hard to control and select

VS

No coulomb interaction, easy to get the physics amplitute





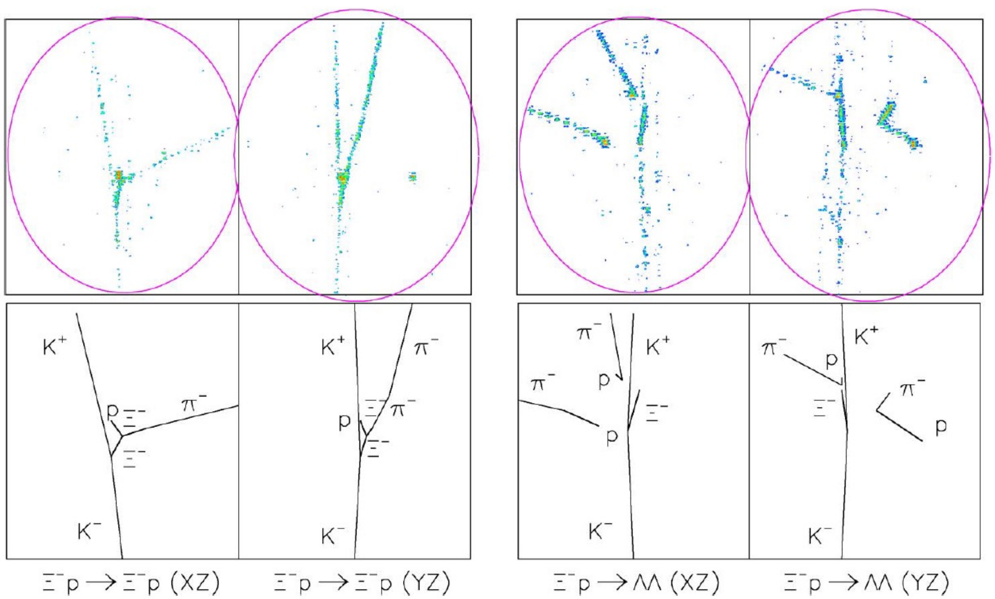
OBLIX experiment at CERN : $\mathrm{p}\bar{p} \rightarrow n\bar{n}$

About 40 publications [Physics Report 383, 213-297]

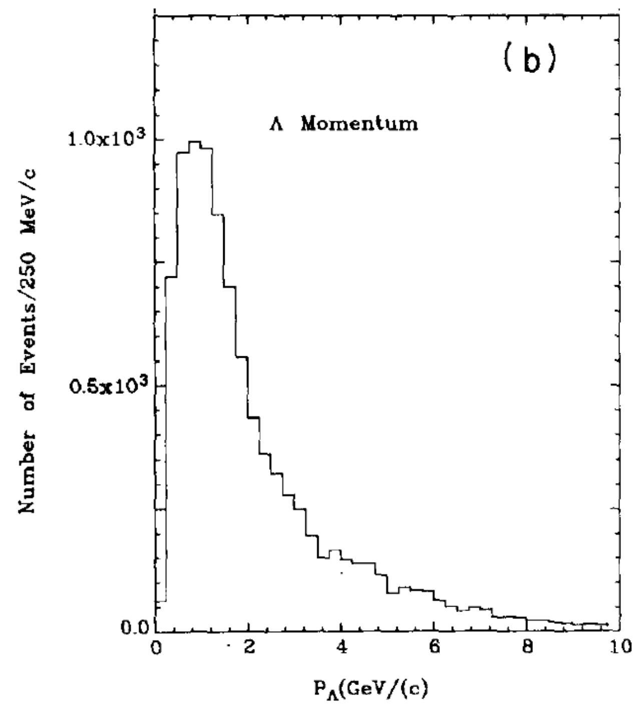
Sources of Λ & other hyperons

- Bubble chamber experiments with hyperons from K^-+target
- Emulsion experiments with K^-+target → K^++X, K^++K^++X, ...
- A few to about 10^4 events (typical O(100) tagged events)
- No anti-hyperon sources!

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

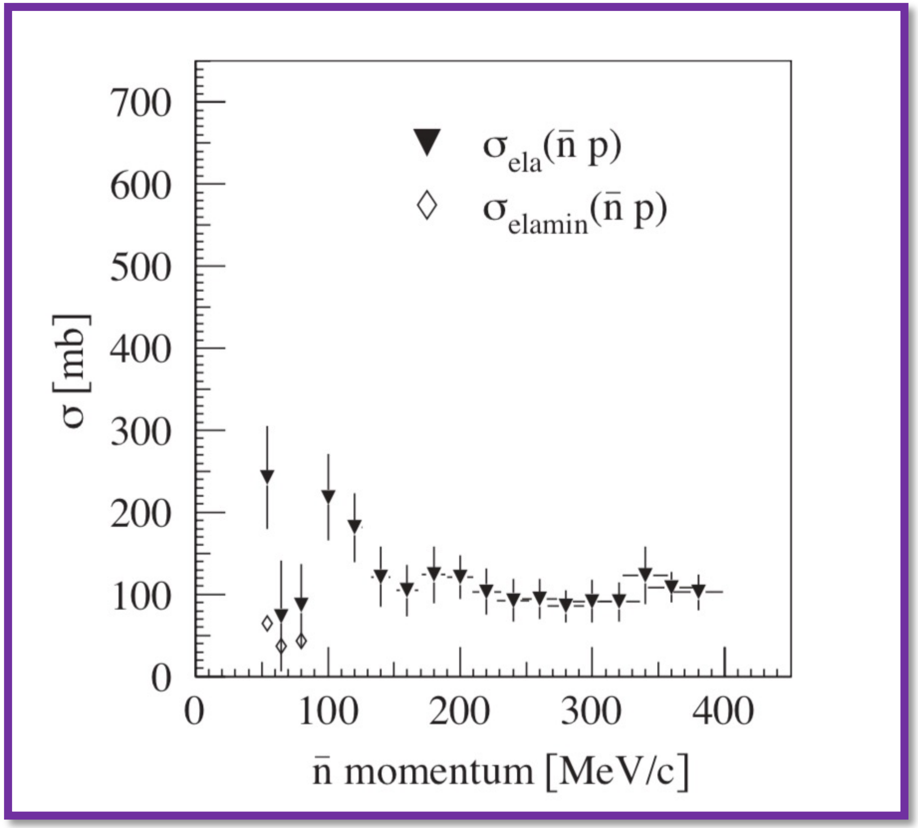


KEK, K^- + SCIFI → Ξ^- X

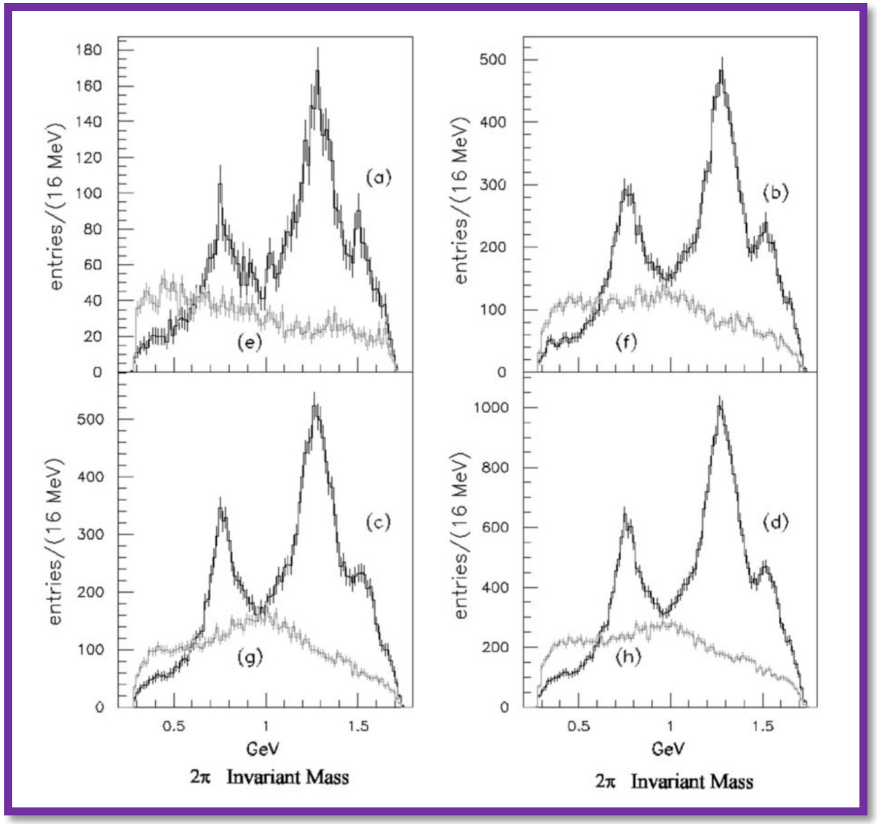


SLAC HBC, Nuclear Physics B125 (1977) 29-51

Many unsolved problems

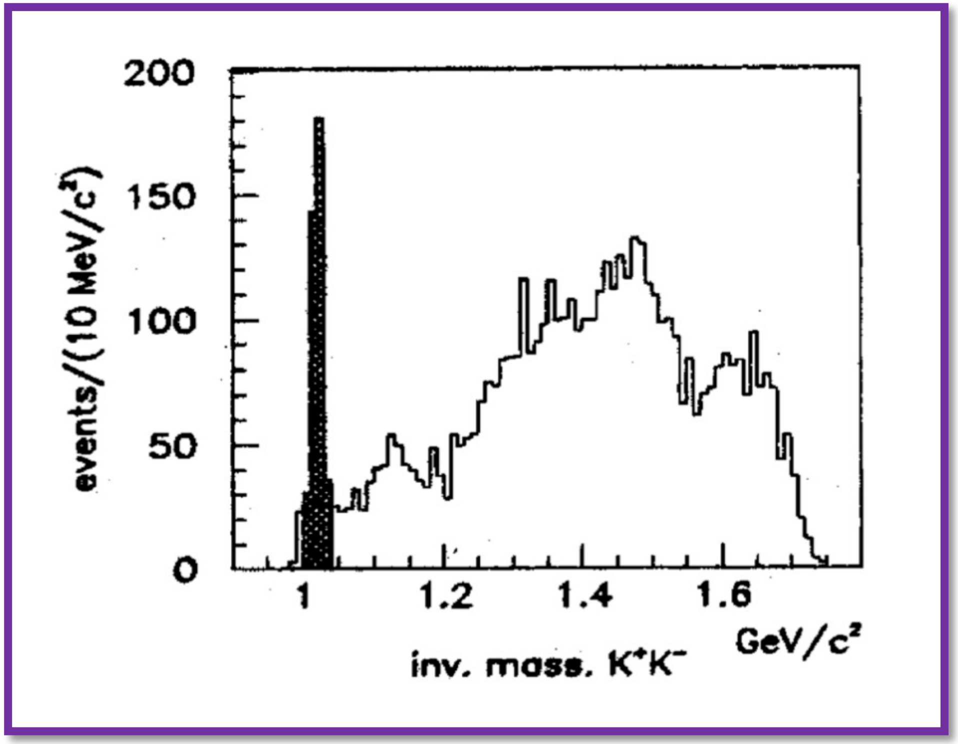


Dip on the cross section:
Initial-Final State Interaction?

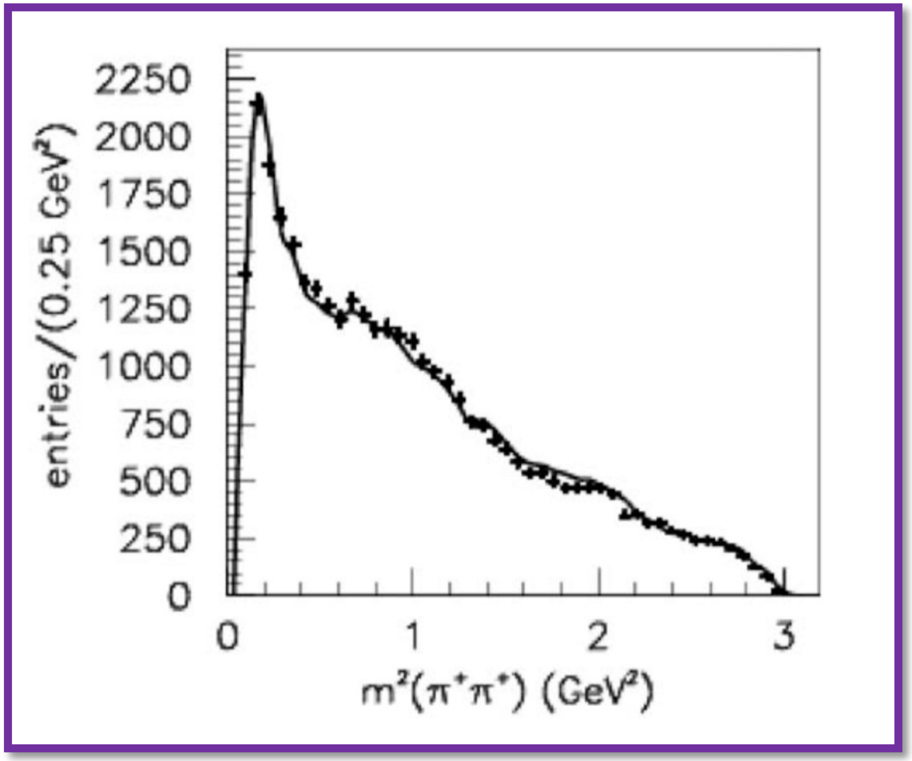


$f_0(1500)$: glue ball?

Many unsolved problems



Large Kaon pair production: OZI Violation?

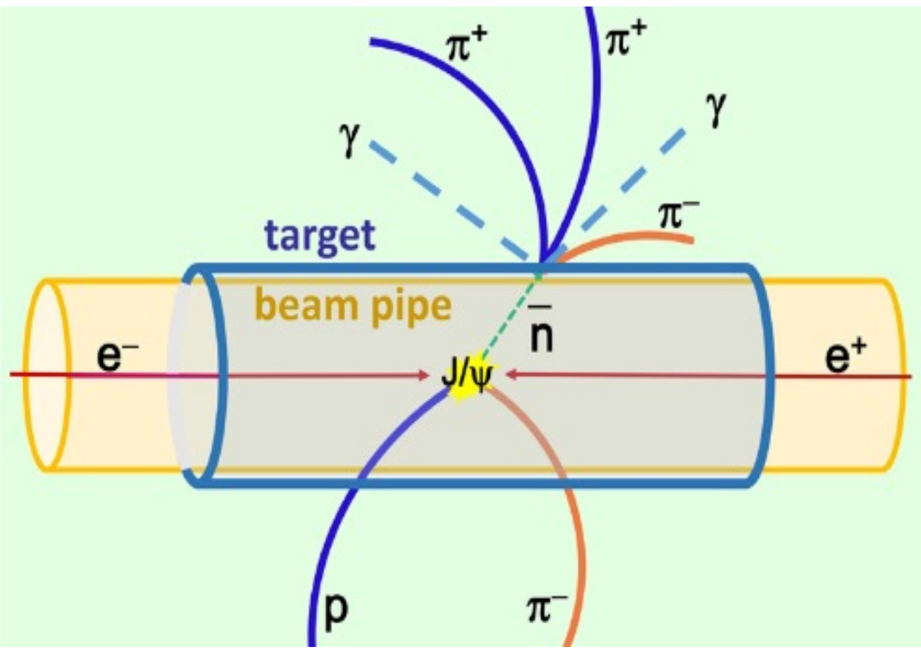


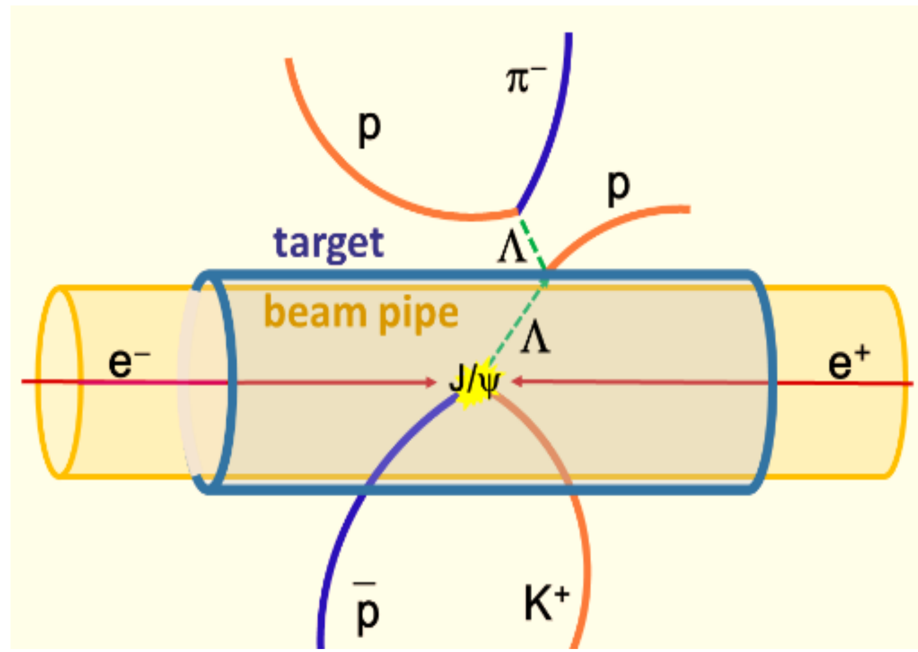
Paticle with Isospin=2?

How could we obtain antineutron/hyperson sources with better resolution, wider momentum range and lower cost?

The idea

Do fixed target experiments @ a super J/ψ factory





Why J/ψ decays: (1) huge cross section of $e^+e^- \rightarrow J/\psi$

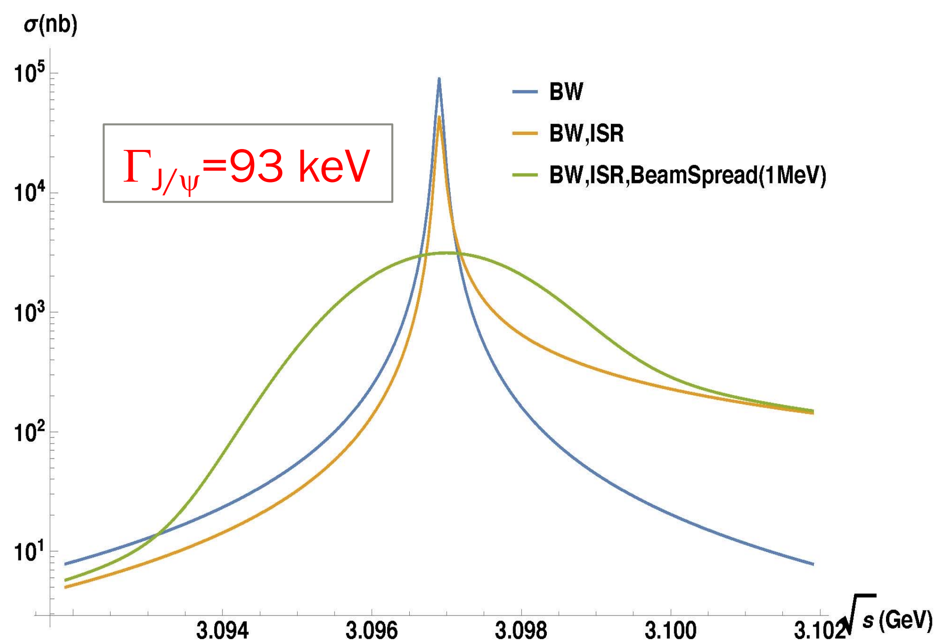
$$\sigma_{Born}(s) = \frac{12\pi\Gamma_{ee}\Gamma_f}{(s-M^2)^2+\Gamma_t^2 M^2}$$

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

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

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

Formulas from PLB 557 (2003) 192
Numbers & plot from Yuping Guo



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

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

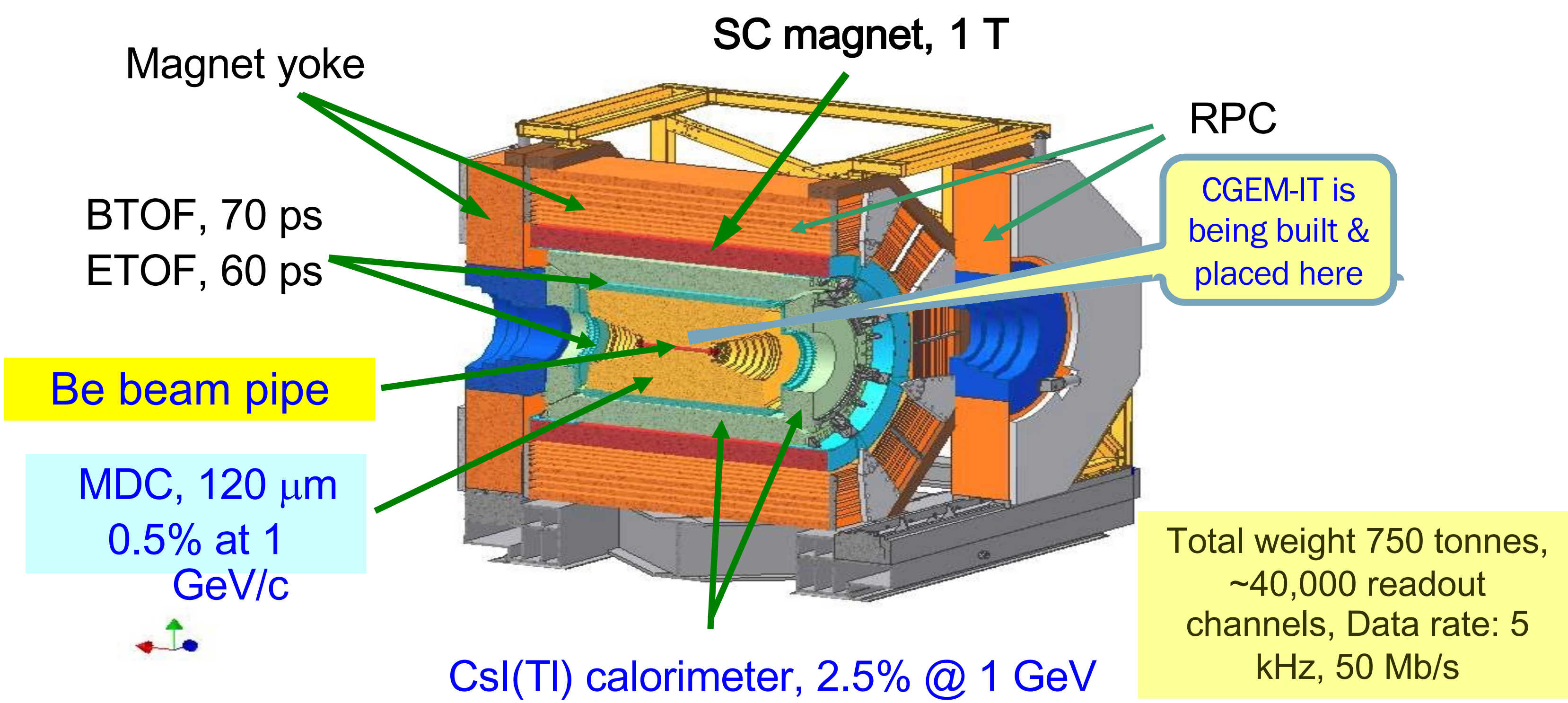
Why J/ψ decays: (2) big B(J/ψ→baryons)

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

Why J/ψ decays: (3) high tag efficiency

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

Proof of concept: study @ BESIII experiment



Has been in full operation since 2008, all subdetectors are in very good status!

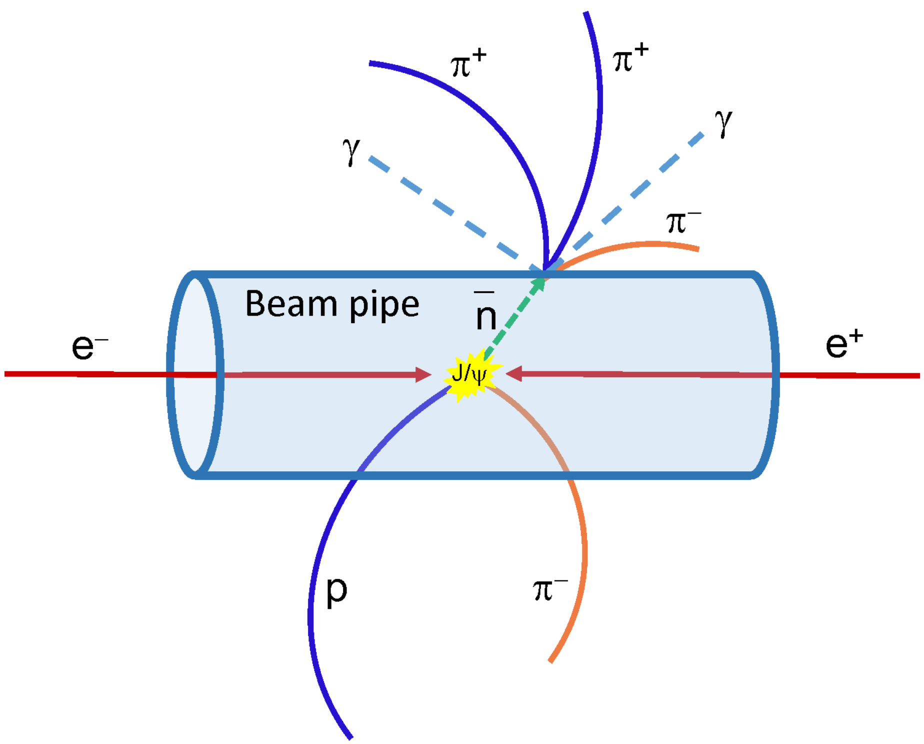
Already mentioned by Xiaoyan, Karin, and Xiaorong in this meeting.

BESIII physics program

- **Light hadron physics: J/Ψ decays, glueball search** (10 billion J/ Ψ)
- **Charmonium physics: charmonium states decays/transitions, XYZ** (largest electron-positron collision dataset around 4 GeV)
- **Charm physics: charm meson/baryon decays**
- **Tau&R&QCD physics: R value, form factor measurement**
- **New physics: dark photon search, BSM**

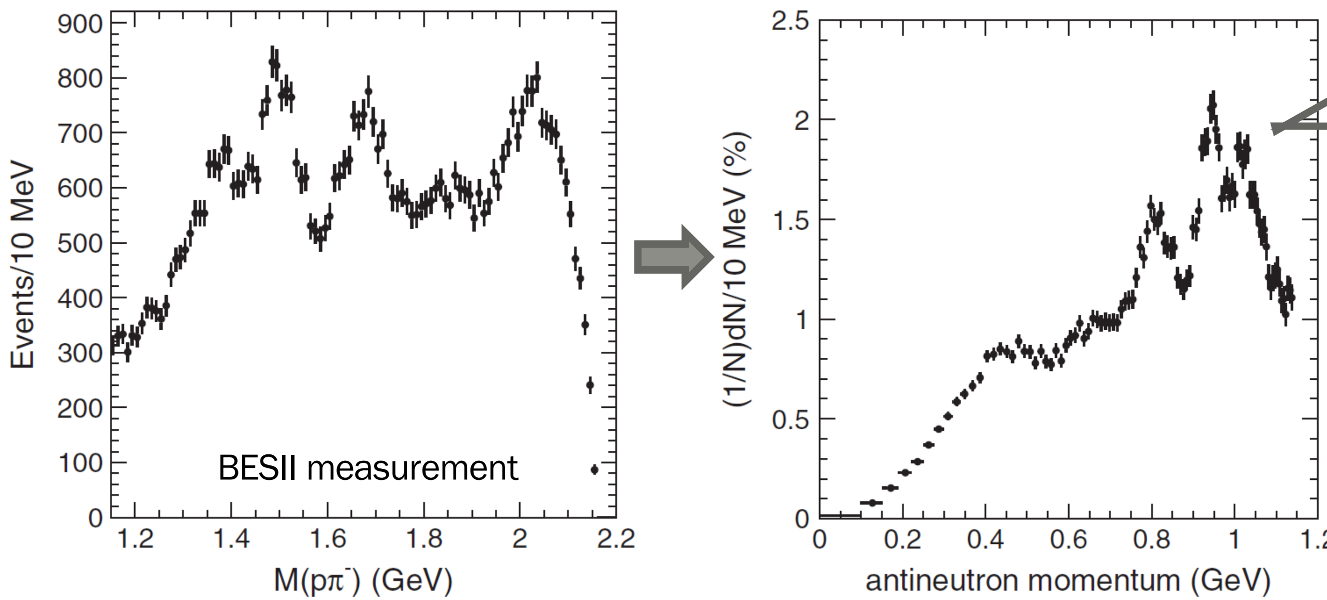
Already mentioned by Xiaoyan, Karin, and Xiaorong in this meeting.

Proof of concept: study @ BESIII experiment



$$e^+e^- \to J/\psi \to p\pi^-\bar{n}, \bar{n}p \to \pi^+\pi^-\pi^+\pi^0, \pi^0 \to \gamma\gamma$$

Proof of concept: study @ BESIII experiment



Unique high momentum $\bar{n}$ sample!

- $N(J/\psi) = 10^{10}$
- $B(J/\psi \rightarrow p\pi^-\bar{n}) = (2.12 \pm 0.09)\times10^{-3}$
- $\varepsilon = 40\%$
- Tagged $\bar{n} = 10^{10}\text{x}2.12\text{x}10^{-3}\text{x}40\% = 8$ million!

- $0<p_{\bar{n}}<1174$ MeV/c
- σp: ~7 MeV/c
- $\bar{n}$ direction: O(mrad)

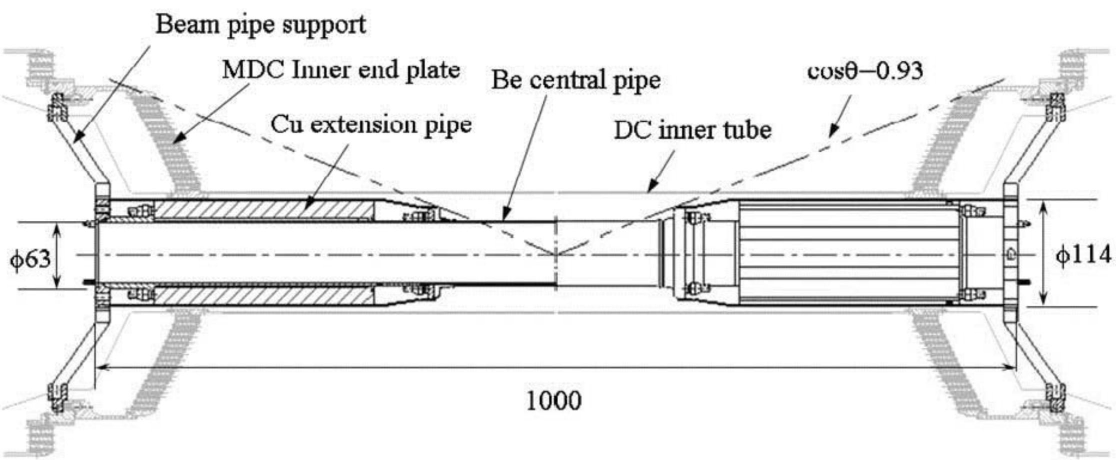
Hyperons and anti-hyperons at BESIII experiment

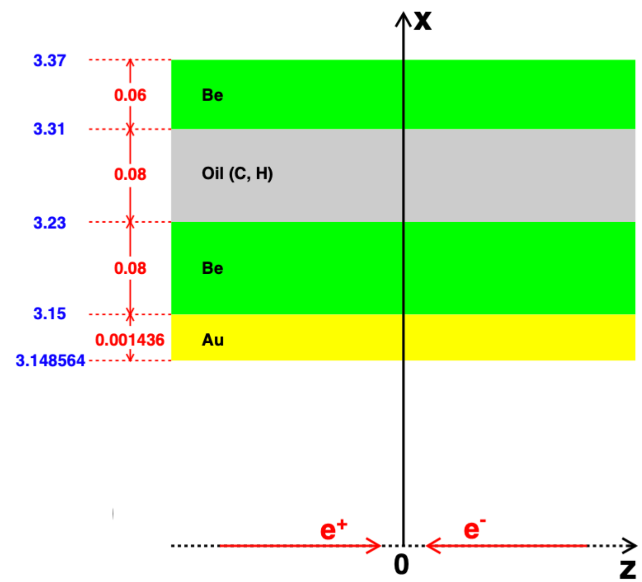
Baryon	$c\tau$ (cm)	decay mode	$\mathcal{B}$ ($\times 10^{-3}$)	$p_{\rm max}$ (MeV/c)	$n^{B}_{\rm BP}$ ($\times 10^5$)
$\bar{n}$	2.6×10^{13}	$J/\psi \to p\pi^- \bar{n}$	2.12	1174	80
Λ	7.89	$J/\psi \to \bar{\Lambda}\Lambda$	1.89	1074	26
		$J/\psi \to \bar{p}K^+\Lambda$	0.87	876	9
Σ^+	2.40	$J/\psi \to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

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

Proof of concept: study @ BESIII experiment

The BESIII 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.

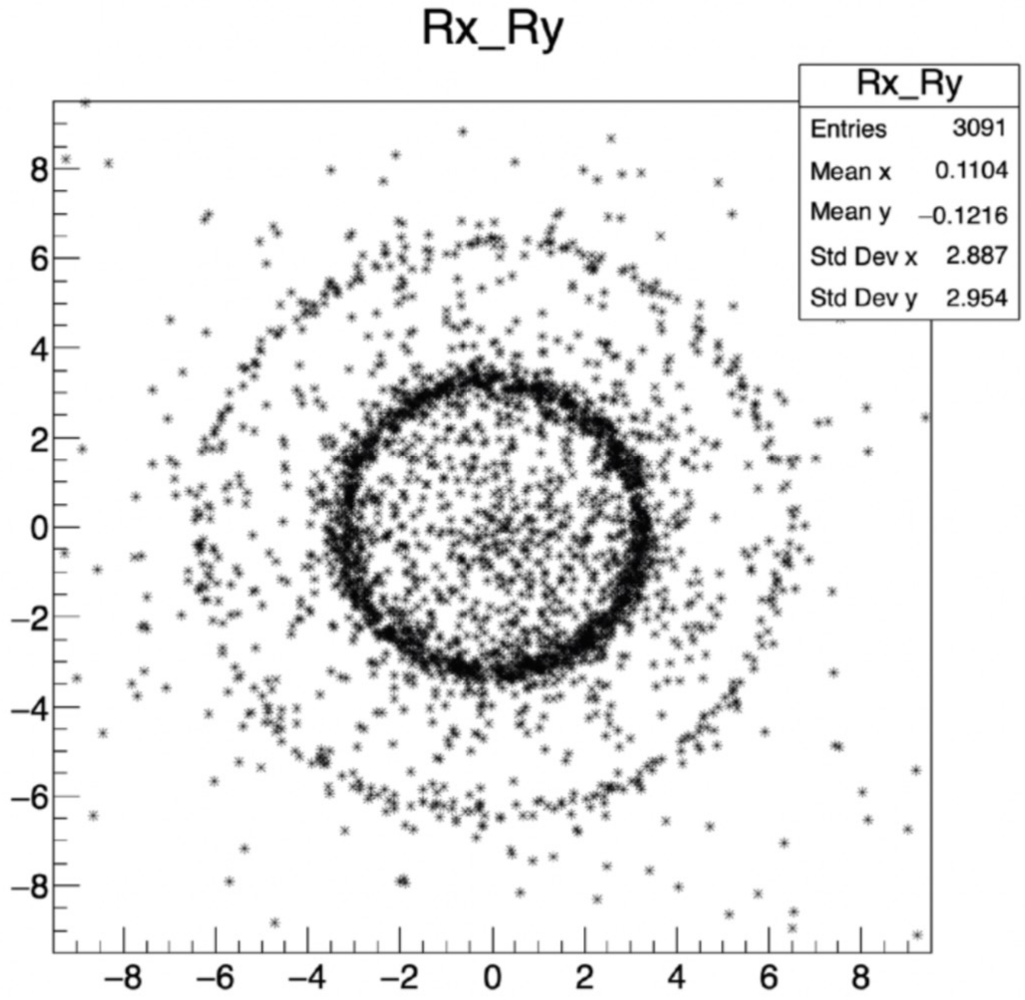




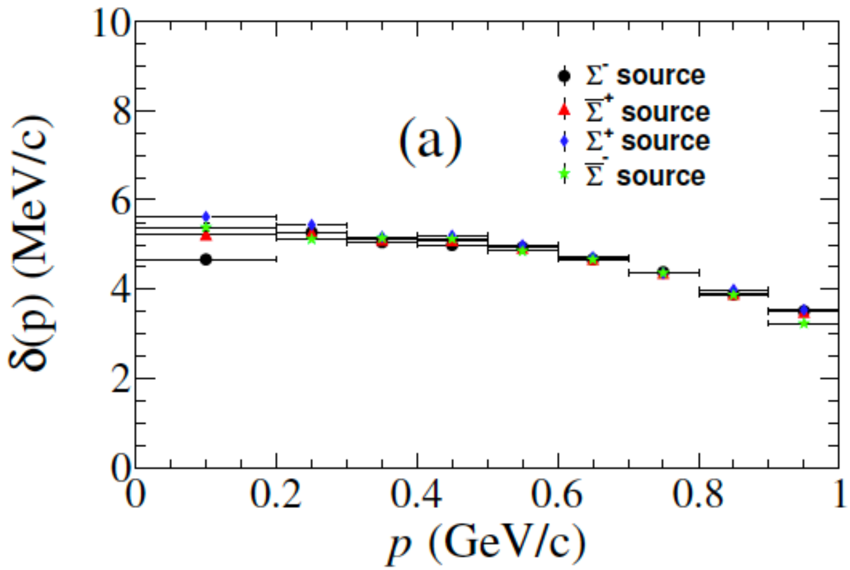
with $\sigma(\bar{n}p) \approx \sigma(\bar{n}n) \approx 100$ mb
expect 1–2% of tagged $\bar{n}$-s interact with Be & 1-2% with C fiber target

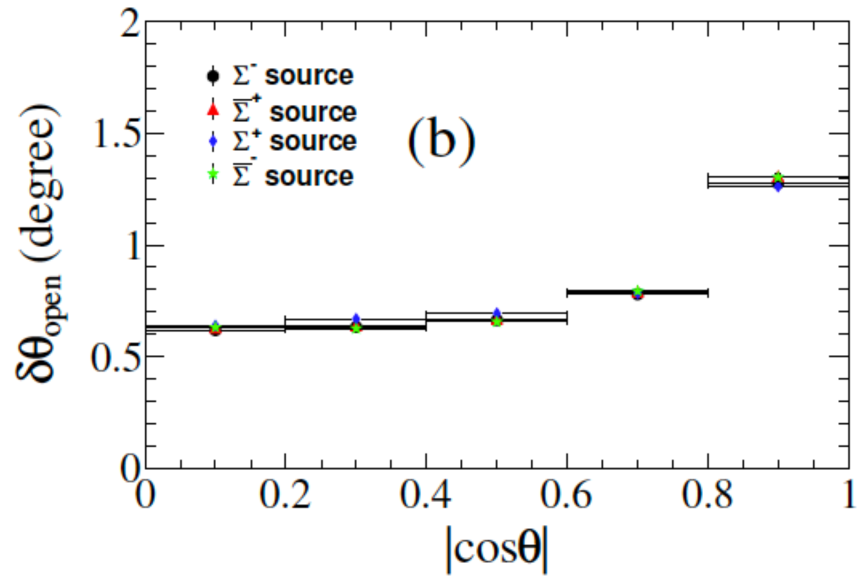
so $\sim$100, 000 $\bar{n}$ + Be events and $\sim$100, 000 $\bar{n}$ + C events

$J/\psi \to p\pi^{-}\bar{n}$ @ BESIII experiment



$J/\psi \rightarrow \Lambda\Sigma\pi$ @ BESIII experiment

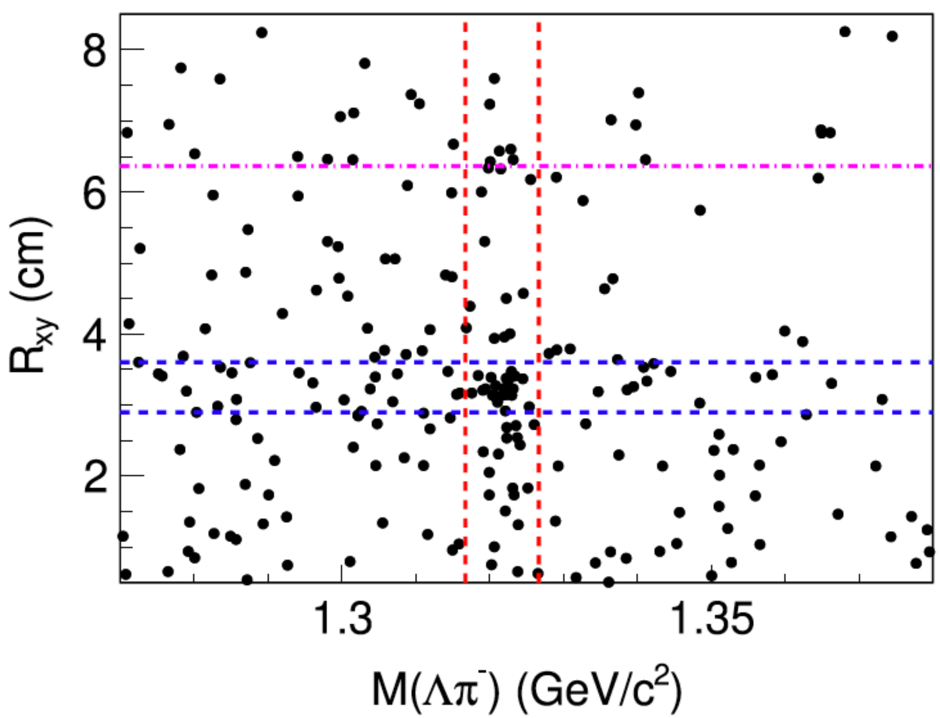




Momentum resolution (left)、angular resolution (right)

PRD 108, 112012 (2023)

First Study of Reaction $\Xi^0 n \to \Xi^- p$ Using Ξ^0-Nucleus Scattering at an Electron-Positron Collider



$\sigma(\Xi^0 \boldsymbol{n} \to \Xi^- \boldsymbol{p})$= (7.4 ± 1.8_{sta} ± 1.5_{sys}) mb

Consistent with calculations based on chiral effective field theory, and resonating-group method.

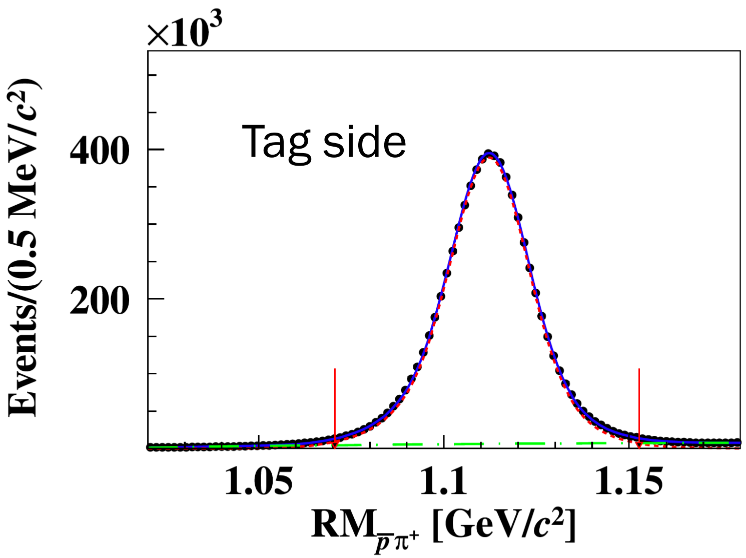
PHYSICAL REVIEW C **109**, L052201 (2024)

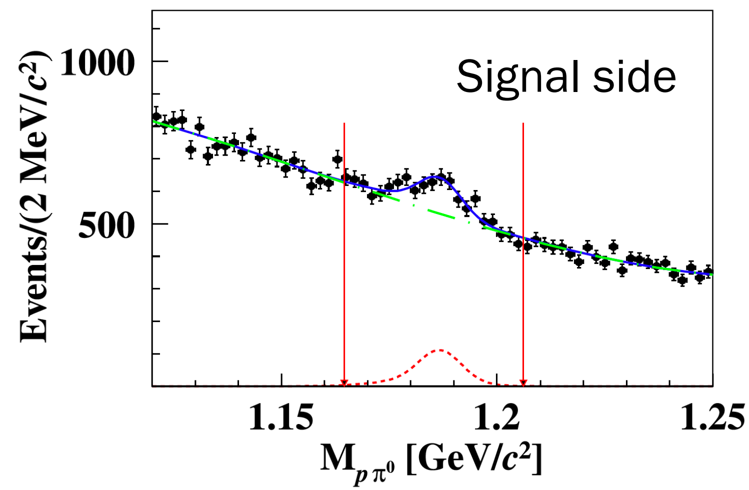
Letter

First measurement of ΛN inelastic scattering with Λ from $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

M. Ablikim *et al.**
(BESIII Collaboration)

(Received 10 October 2023; accepted 12 April 2024; published 14 May 2024)





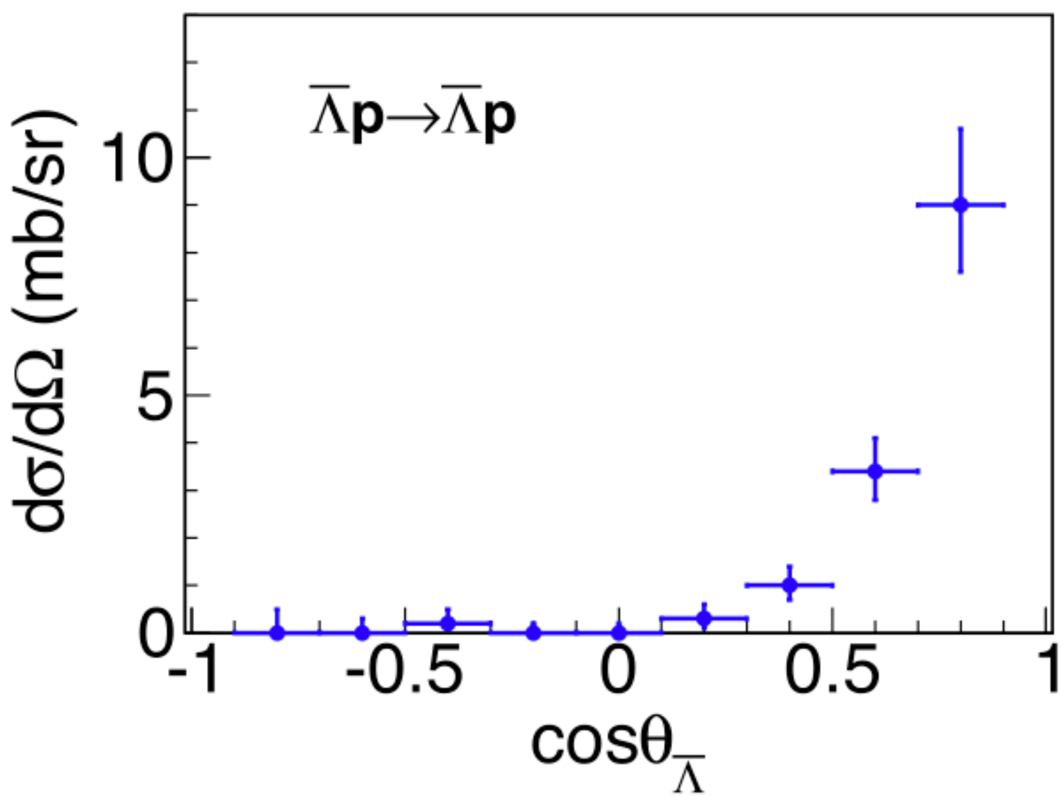
$\sigma(\Lambda + \boldsymbol{p} \to \Sigma^+ + X)$= ($19.3 \pm 2.4_{sta} \pm 1.8_{sys}$) mb

PHYSICAL REVIEW LETTERS **132,** 231902 (2024)

First Study of Antihyperon-Nucleon Scattering $\bar{\Lambda}p \to \bar{\Lambda}p$ and Measurement of $\Lambda p \to \Lambda p$ Cross Section

M. Ablikim *et al.*[*]
(BESIII Collaboration)

(Received 11 January 2024; revised 4 May 2024; accepted 7 May 2024; published 4 June 2024)



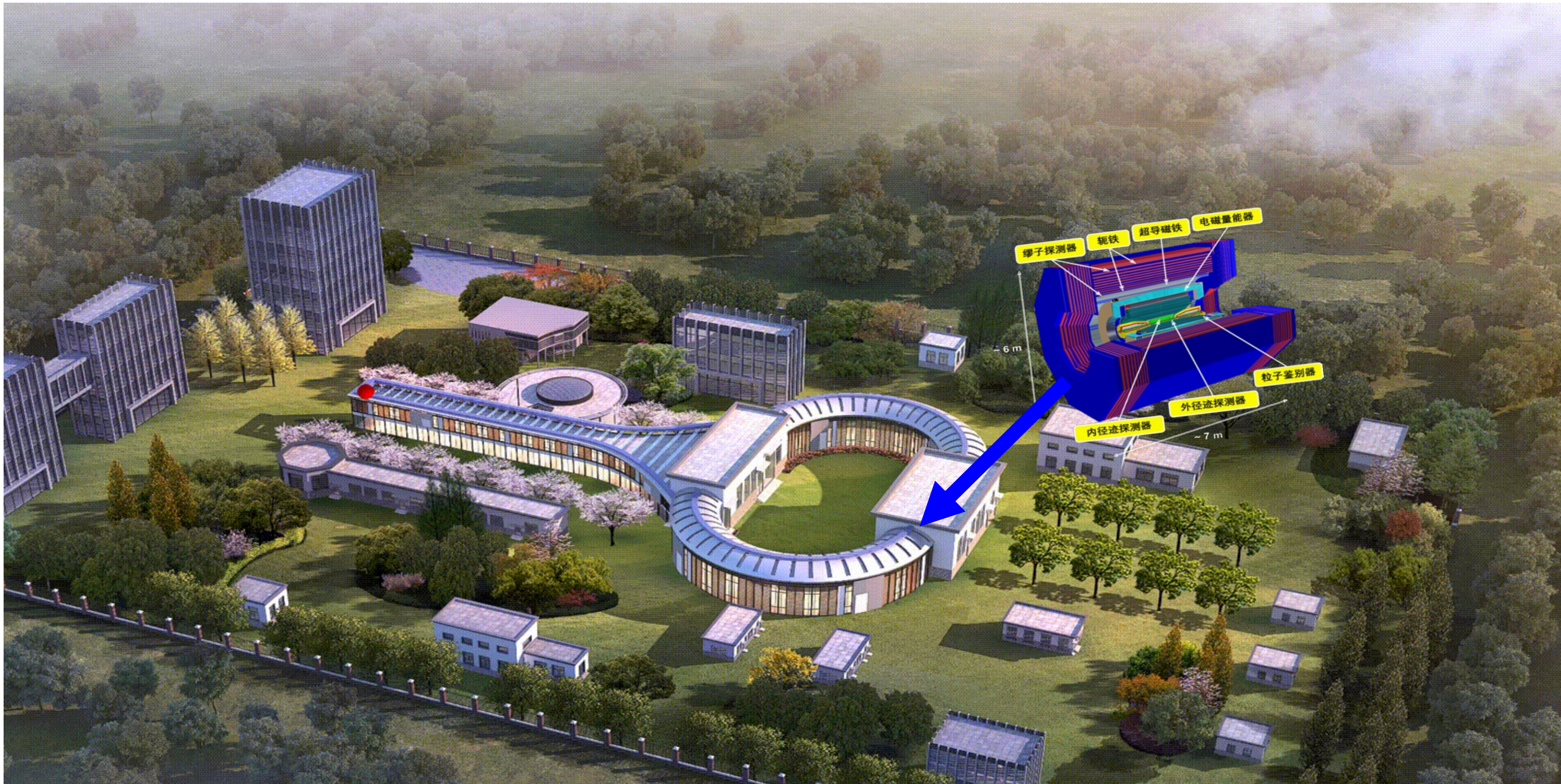
Favor the forward region.

A super J/ψ factory with 10^{12} J/ψ events per year

- Design luminosity = O(100) × $\mathscr{L}$@BESIII ~ 10^{35} $cm^{-2}s^{-1}$
  - ✓ Existing proposals: STCF (China), SCTF (Novosibirsk)
- Detector improvements vs. BESIII: tracking, PID, γ detection
- (1-3)×10^{12} J/ψ events/year = 100 × BESIII sample
- Further improvements to expand range of physics topics
  - ✓ Reduce the diameter of the beam pipe
  - ✓ Interchangeable custom targets inside the detector
  - ✓ Subdetector for specific final states, e.g. deuteron, triton, ...

More details will be mentioned by Xiaorong's talk on Friday.

STCF in China



- CM Energy : 2-7 GeV
- Peaking $\mathcal{L}$: >5×10^{34} cm^{-2} s^{-1}
- Potential to further improve the $\mathcal{L}_{peak}$ and realize polarized beam
- Double storage ring : ~800 m , injection : ~ 300m
- BESIII-Like detector
- Cost 4.5B RMB

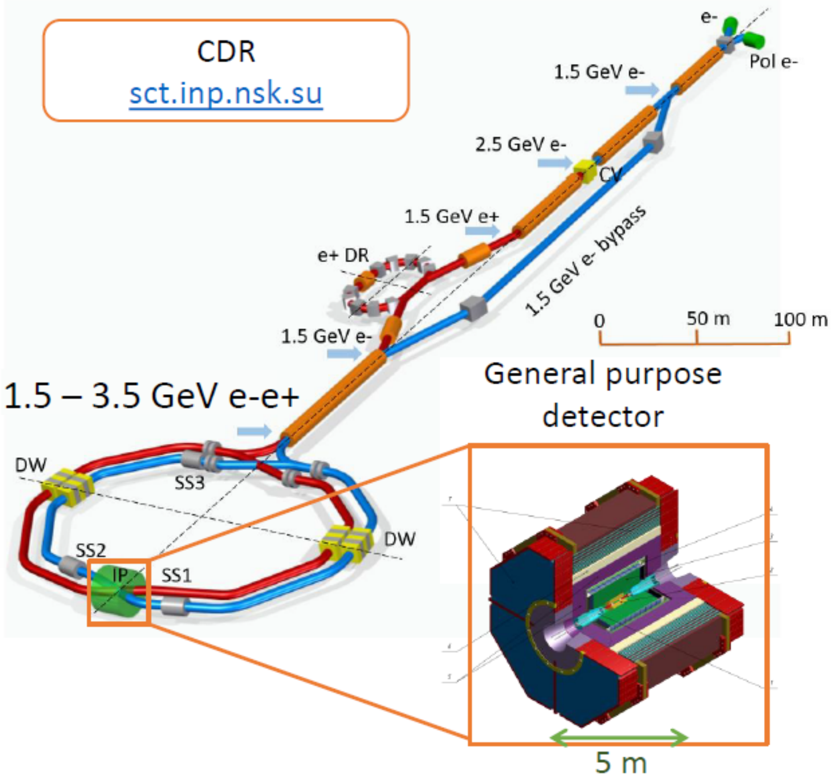
STCF workshop, Guangzhou, 2022

Sarov, Russia

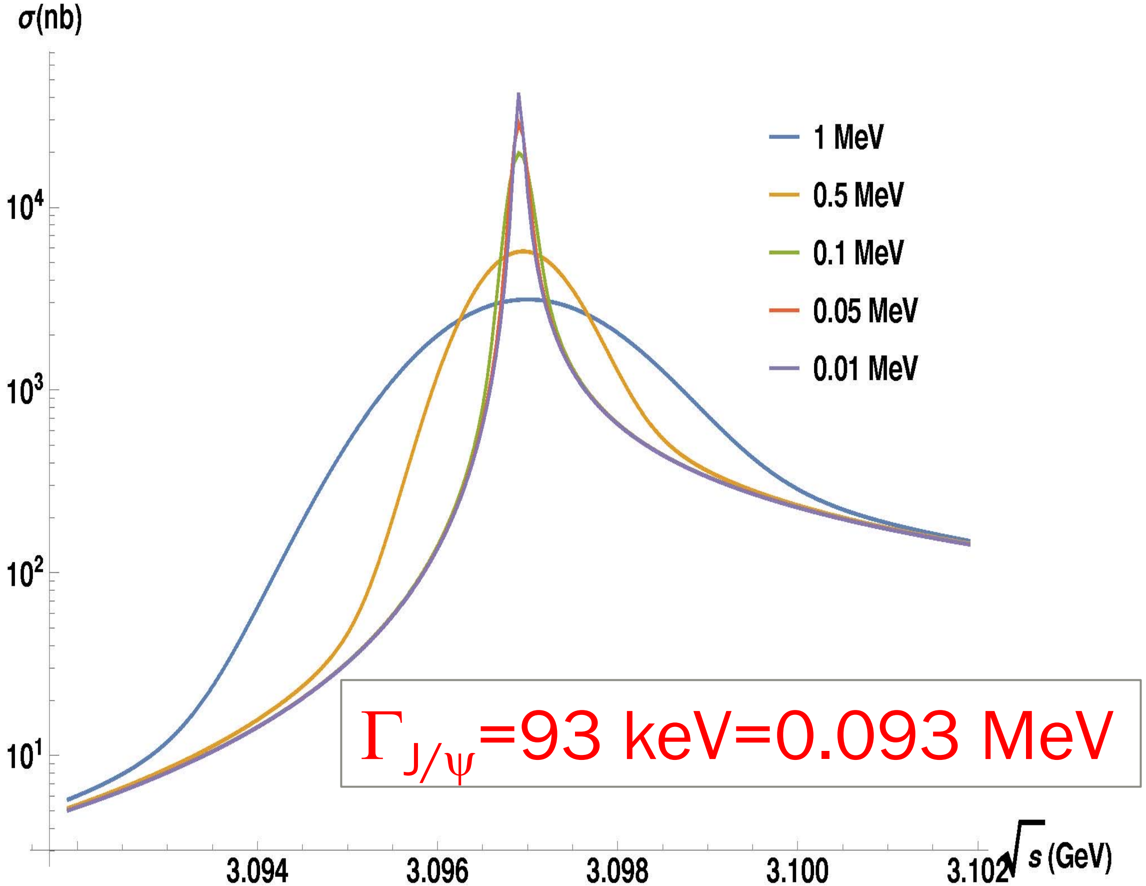
Ivan Logashenko (BINP)
PhiPsi2022

Super charm-tau factory

- Super charm-tau factory is e^+e^- collider, dedicated to precision study of properties of charm-quark, tau-lepton, study of strong interactions, search of BSM physics
  - Beam energy from 1.5 (1.0) to 3.5 GeV
  - Luminosity $\mathcal{L} = 10^{35}\ cm^{-2}c^{-1}$ @ 2 GeV
  - Longitudinally polarized electron beam
- Experiments will be conducted using state-of-the-art general purpose detector
  - Tracking (including low p_t)
  - Calorimetry (high resolution, fast, π^0/γ sep.)
  - Particle ID ($\mu/\pi/K/p$ up to 1.5 GeV/c)



A hyper J/ψ factory with 10^{13} J/ψ events?



Two ways of improving J/ψ production rate:

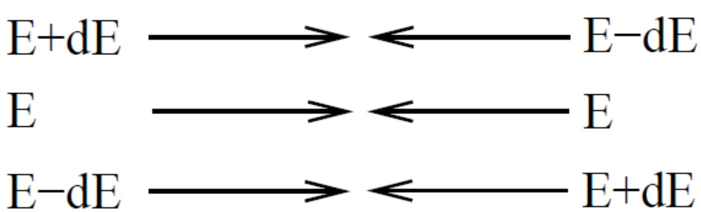
1. Increase luminosity
2. Reduce energy spread

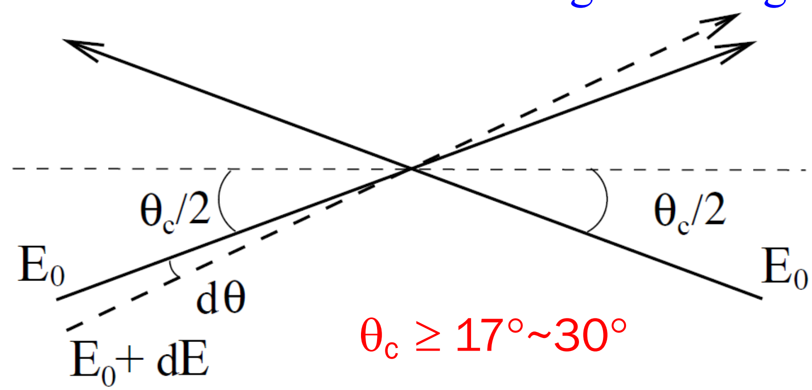
Energy spread (MeV)	Cross section (nb)
1	3,100
0.5	5,700
0.1	20,000
0.05	29,000
0.01	42,000

Numbers & plot from Yuping Guo

A new scheme of monochromatization?

V. I. Telnov, 2008.13668v3
Monochromatization of e^+e^- colliders with a large crossing angle





$\theta_c \geq 17°\sim30°$

Existing monochromatization scheme for head-on collisions will reduce luminosity significantly

New scheme: Provide the beams with an angular dispersion such that a beam particle arrives to the IP with a horizontal angle that depends on its energy.

$$\sigma_W/W \sim (3\text{–}5)\times 10^{-6}$$

σW=10-15 keV @ J/ψ peak
and J/ψ is moving!

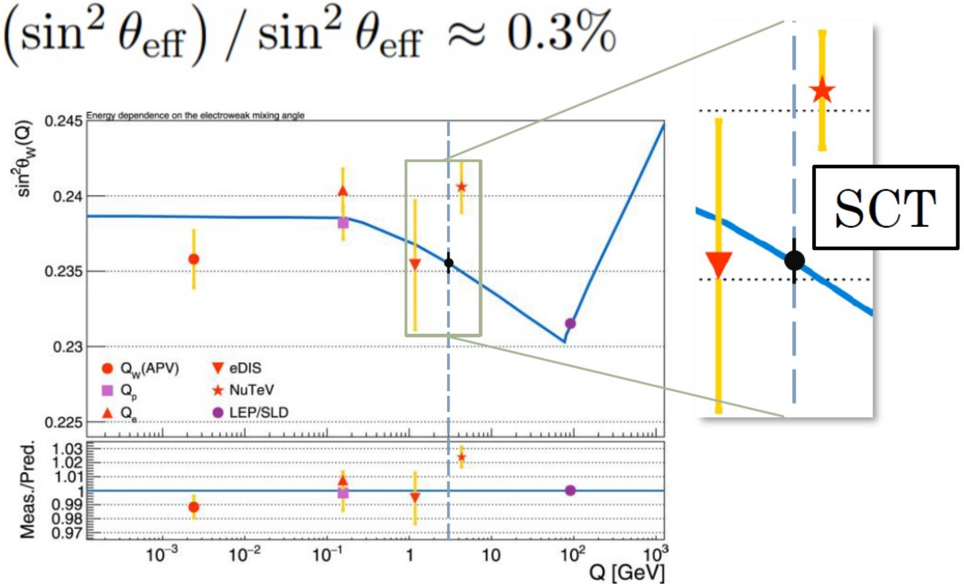
Potential physics studies

- antinucleon-nucleon interaction
- OZI violation
- nonvalence $\bar{s}s$ components of the nucleon
- (anti)hyperon-nucleon interaction
- (multi-strange) hypernuclei
- light hadron spectroscopy, including exotics and many others
- cross sections of antineutrons with material for the calibration of Monte Carlo simulation codes for particle physics and medical applications, such as FLUKA and GEANT4
- Hyperon puzzle and size of neutron stars
- Maybe more topics from nuclear physics community

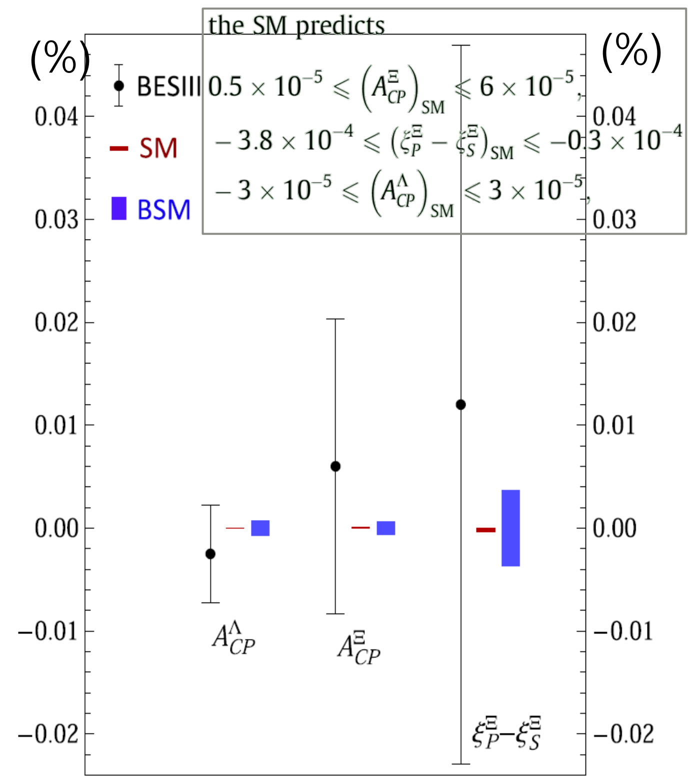
Potential physics with direct J/ψ decays

1. Precision measurement of Weinberg angle
2. CPV in hyperon decays
3. New physics searches with $10^{12\sim14}$ produced J/ψ events

$$\delta\left(\sin^2\theta_{\rm eff}\right)/\sin^2\theta_{\rm eff} \approx 0.3\%$$

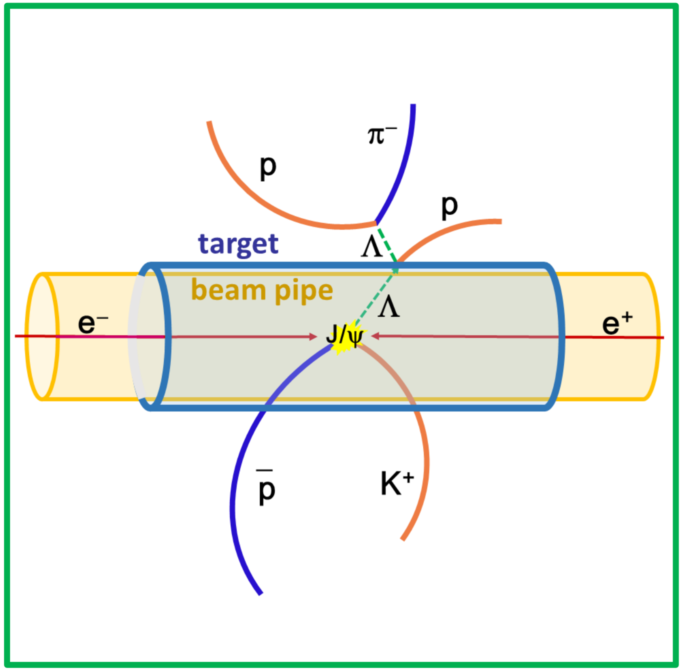


A. Bondar et al., JHEP 03 (2020) 76



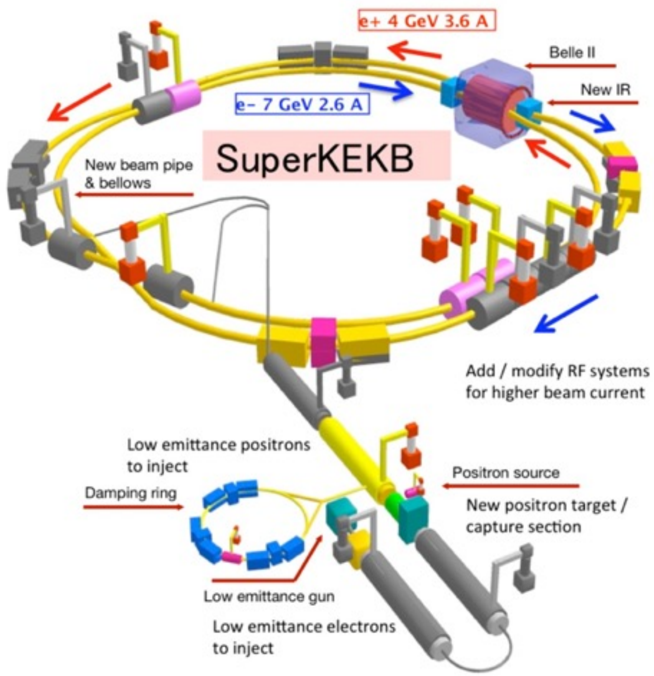
X. G. He et al., Science Bulletin, Volume 67, Issue 18, 2022

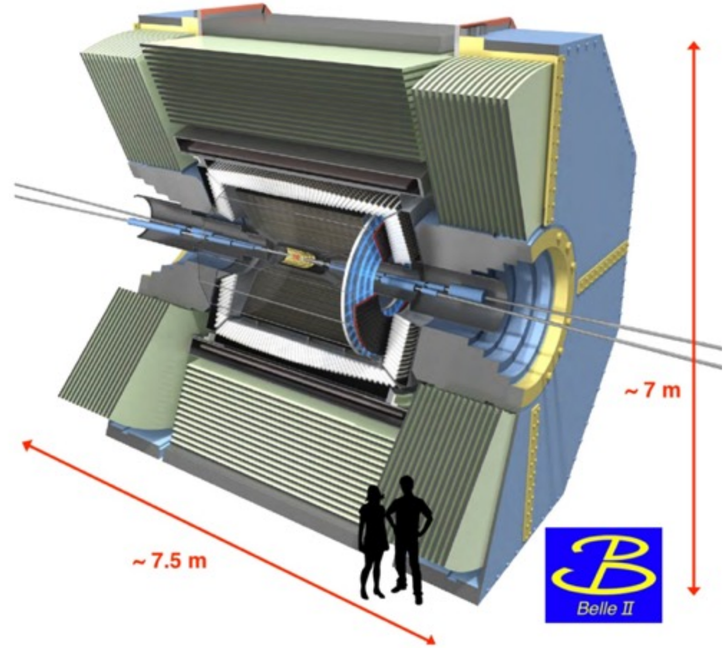
Summary: Do fixed target experiments @ a super J/ψ factory



- Super (or hyper) J/ψ factory
  - *e^+e^- annihilation @ 3.097 GeV; O($10^{12\text{-}13}$) J/ψ events/year*
  - *State of the art detector*
  - *Variety of custom removable targets*
  - *Smaller beam pipe*
- High quality sources of long lived (anti-)hyperons and $\bar{n}$ for many different kinds of experiments
- Same software, similar systematic effects
- No need to share beam time
- No need for additional resources, additional infrastructure, minimal further investments
- A variety of physics topics

The idea could be extended: Belle II, CEPC……





Belle II: Cross section of ee->baryon antibaryon via ISR or in the continuum, as well as in the B decays is about 10-100 pb; the reconstruction efficiency is about 20%; With 50 ab^{-1} data, there are 10^8 – 10^9 strange baryon.

CEPC: higher energy means stronger boost, and hyperons with shorter life time could reach the beam pipe.

Thanks very much!