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

Weimin Song (宋维民)

Jilin University, Changchun

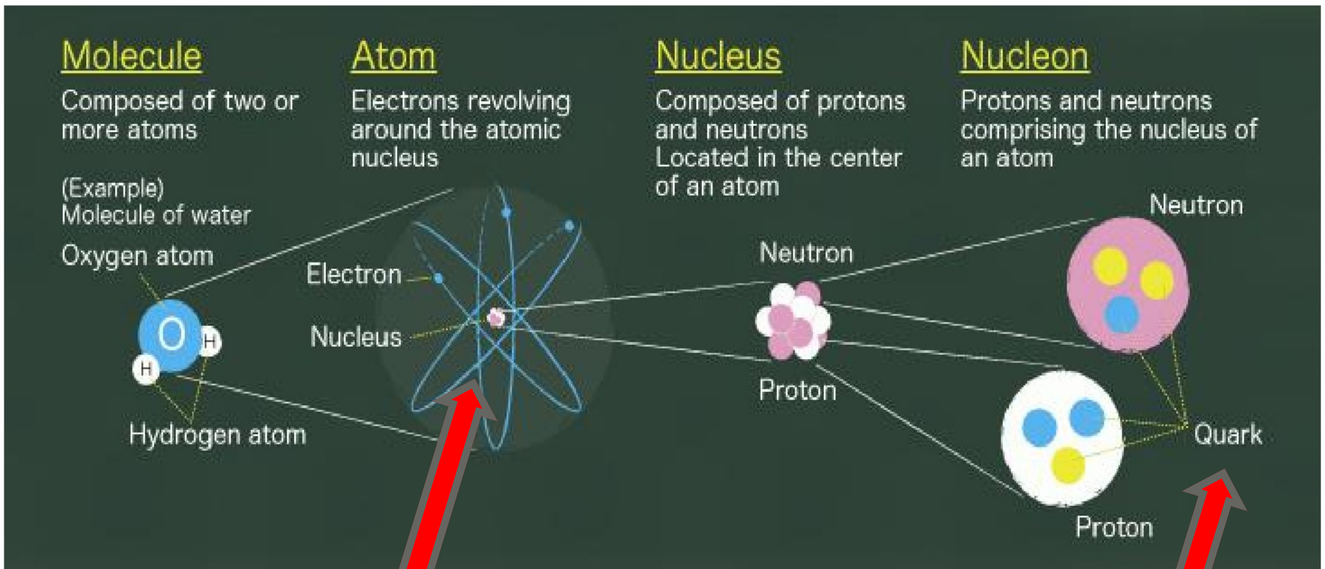
- C. Z. Yuan & M. Karliner, PRL 127, 012003 (2021) [arXiv:2103.06658]
  "Editors' suggestion" & "Featured in *Physics*"
- W. M. Song & C. Z. Yuan, Physics 51，255 (2022）

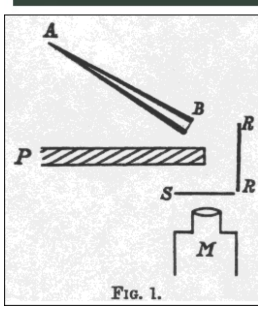
Exotic Hadron Spectroscopy April 19-21, 2023

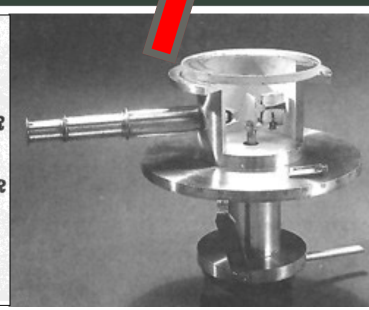
Outline

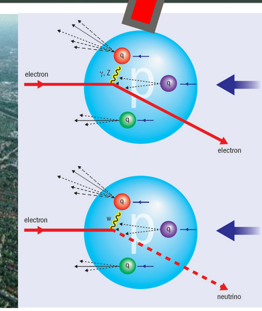
- ❖ **Status of antineutron and hyperon as particle source**
- ❖ **Why J/ψ factory could improve the status much**
- ❖ **Proof of concept at BESIII and prospect at STCF**
- ❖ **Summary**

Scattering experiments shed light on matter structure







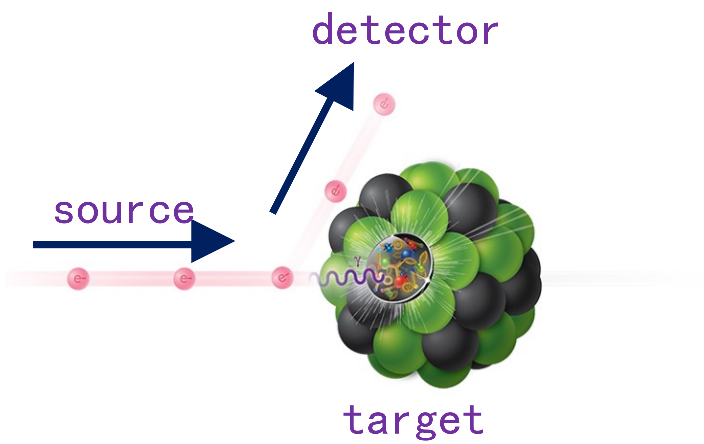


Rutherford experiment → **Nucleus**

Electon-nucleon DIS → **Quark**

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……

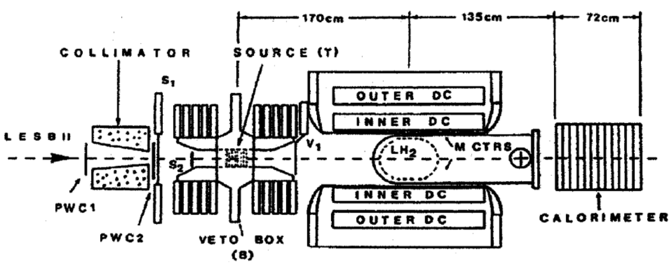
- **charged : electron/positron , muon , pion , kaon , proton , heavy ion**
- **neutral : photon , neutron , neutrino**

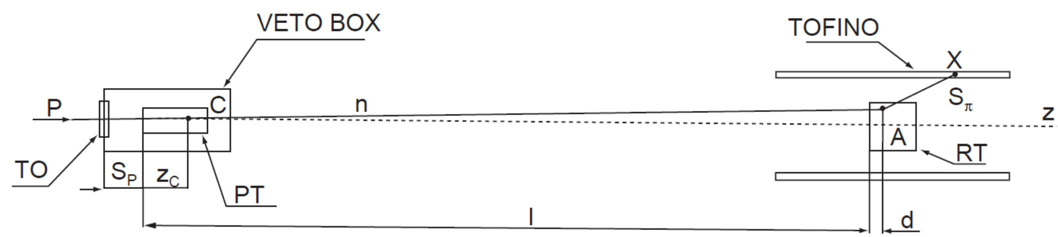
For more details: D.C. Faircloth, Particle Sources, 2103.13231 (Proceedings of the CERN–Accelerator–School: Introduction to Accelerator Physics)

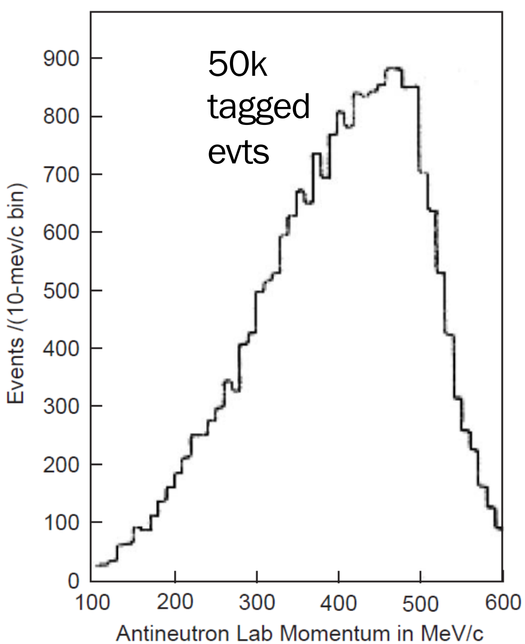
Beams of other neutral particles, such as antineutrons, K^0 and $\bar{K}^0$, long-lived hyperons (Λ, $\Sigma^{\pm}$, $\Xi^{0/-}$) and their antiparticles ($\bar{\Lambda}$, $\bar{\Sigma}^{\pm}$, $\bar{\Xi}^{0/+}$) have great physics potential, but they are typically much more difficult to produce and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

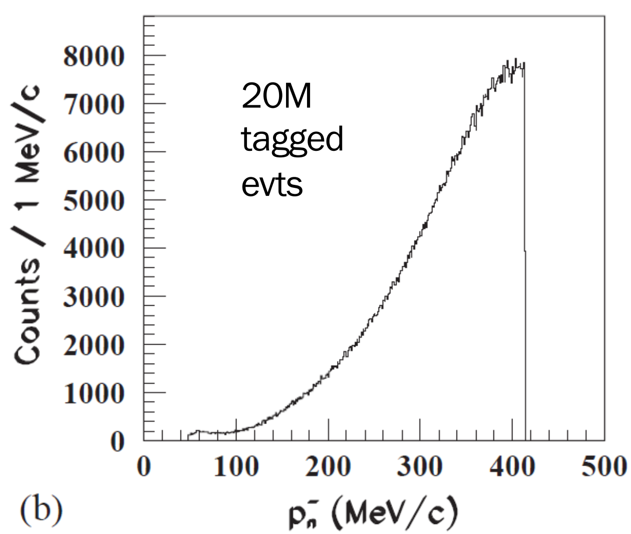
Antineutron in history

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









Limited statistics

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

[2x10^7 collected in 5 years]

Limited momentum range

Uncertainty in flux~7%

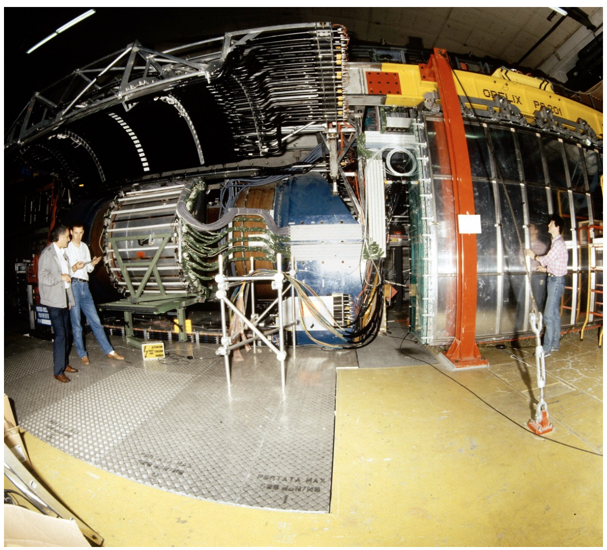
$\sigma p_{\bar{n}}$ = 3% @ 50 MeV/c

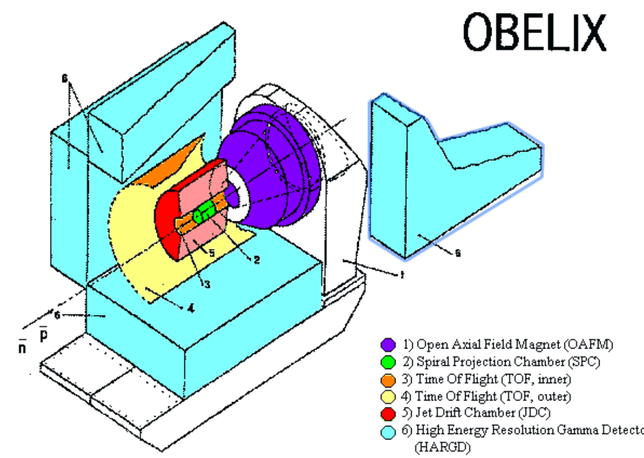
= 5% @ 400 MeV/c

Antineutron in history

Anti-entruon is neutral

Hard to control and select **VS** **No coulomb interaction, easy to get the physics amplitute**



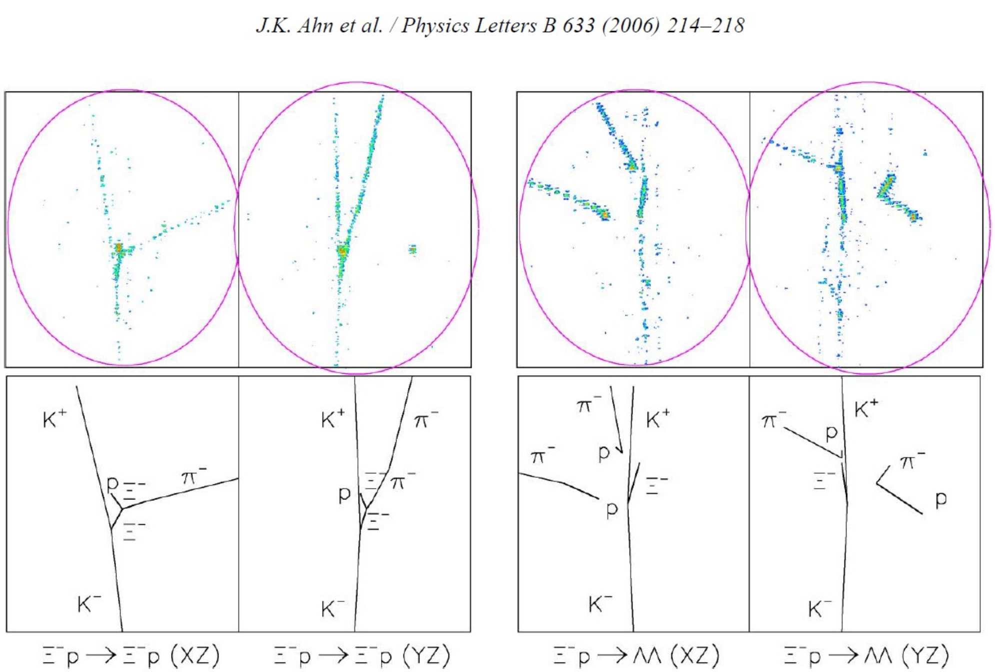


OBLIX experiment at CERN : $p\bar{p} \rightarrow n\bar{n}$

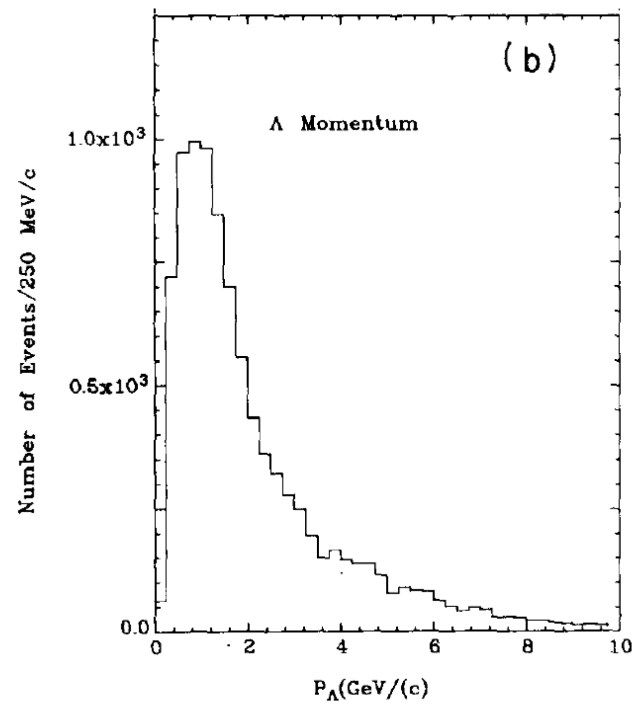
About 40 publications [Physics Report 383, 213-297]

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!

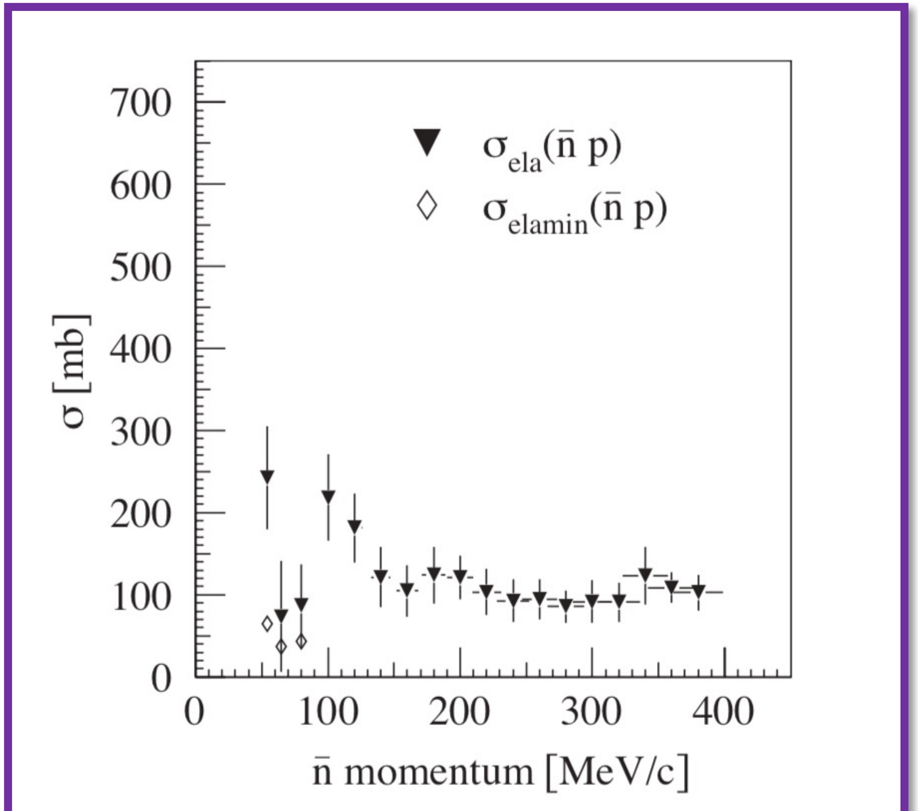


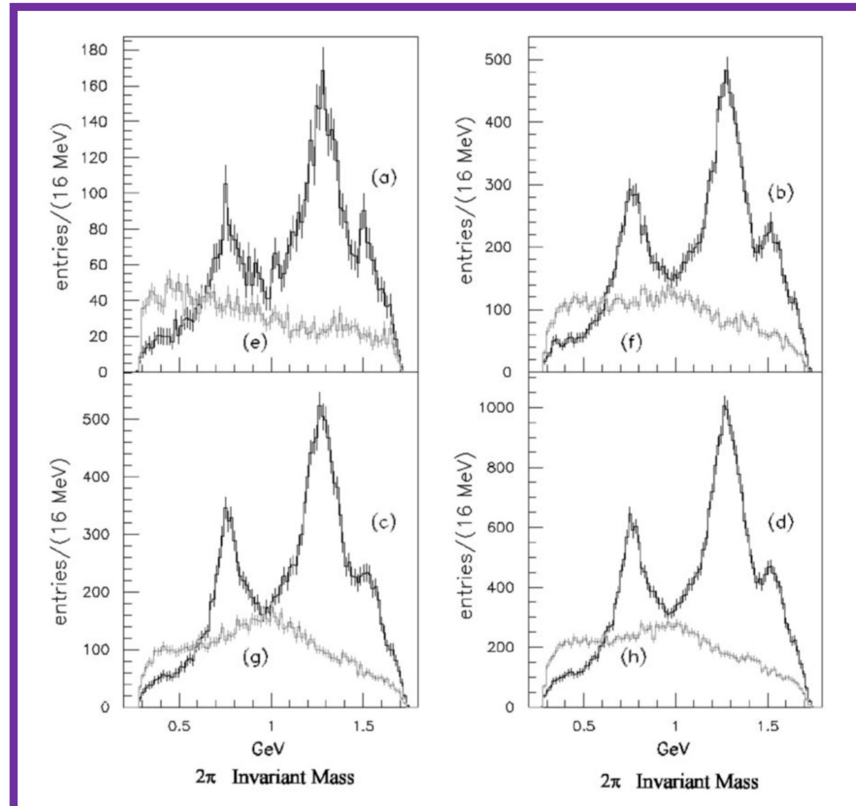
KEK, K^- + SCIFI → Ξ^- X



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

Many unsolved problems

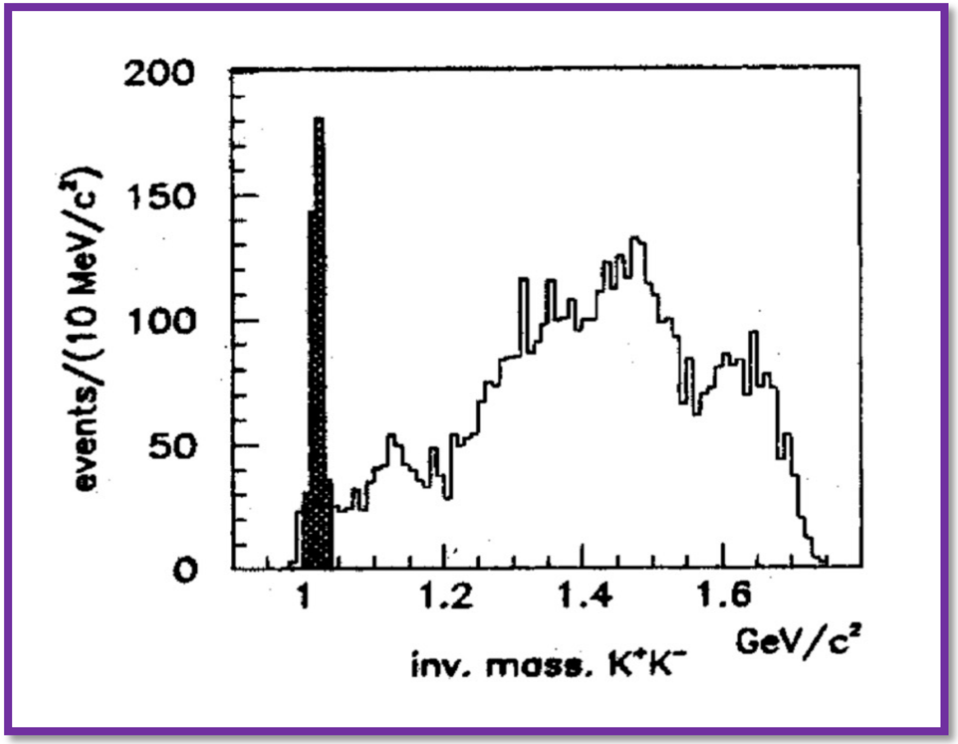


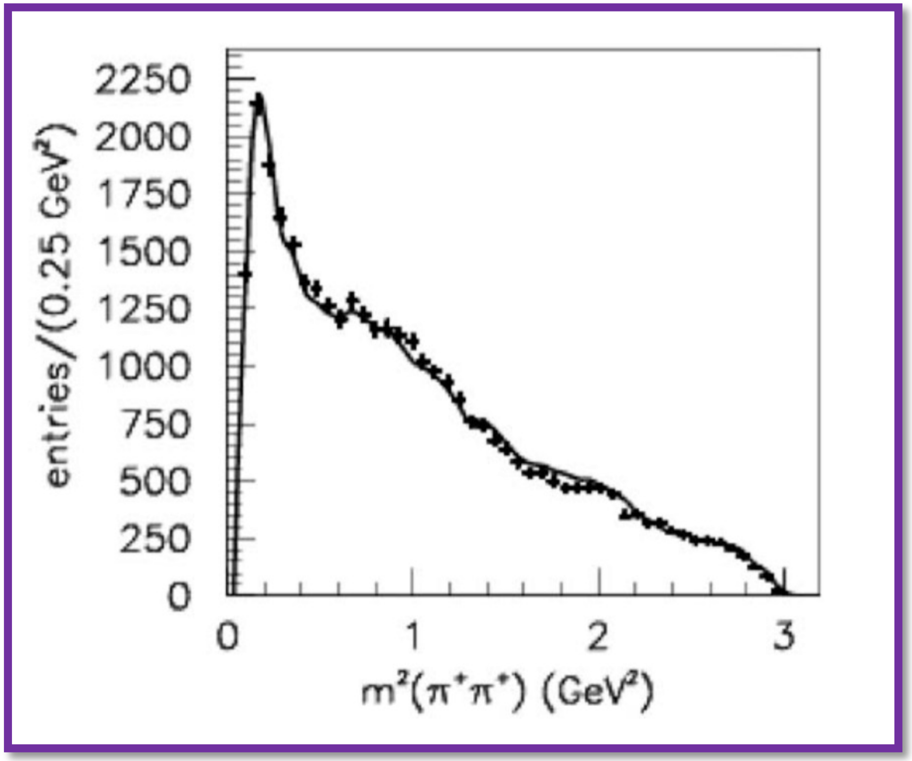


Dip on the cross section:
Initial-Final State Interaction?

$f_0(1500)$: glue ball?

Many unsolved problems





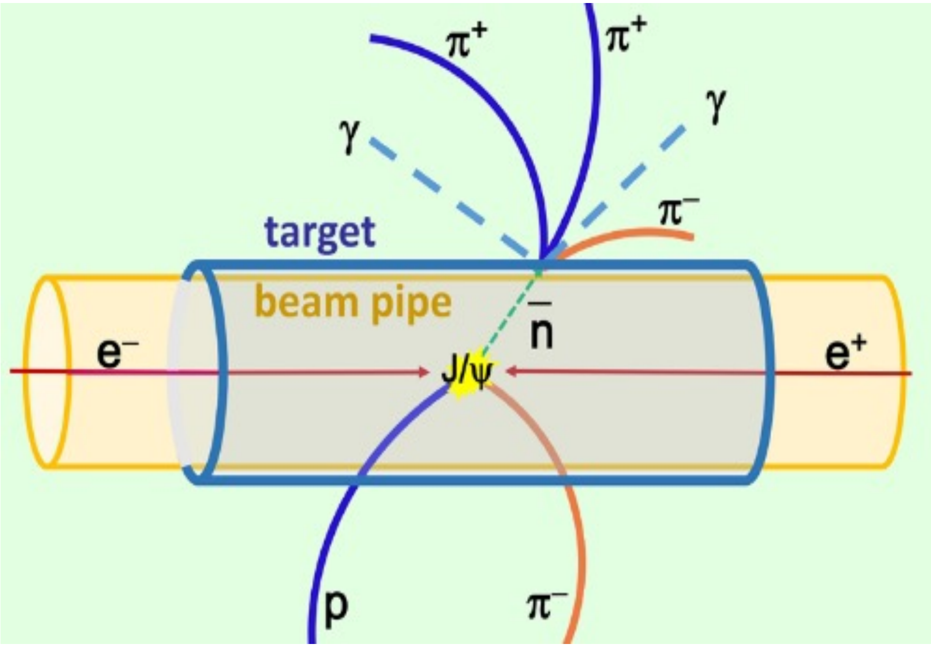
Large Kaon pair production: OZI Violation?

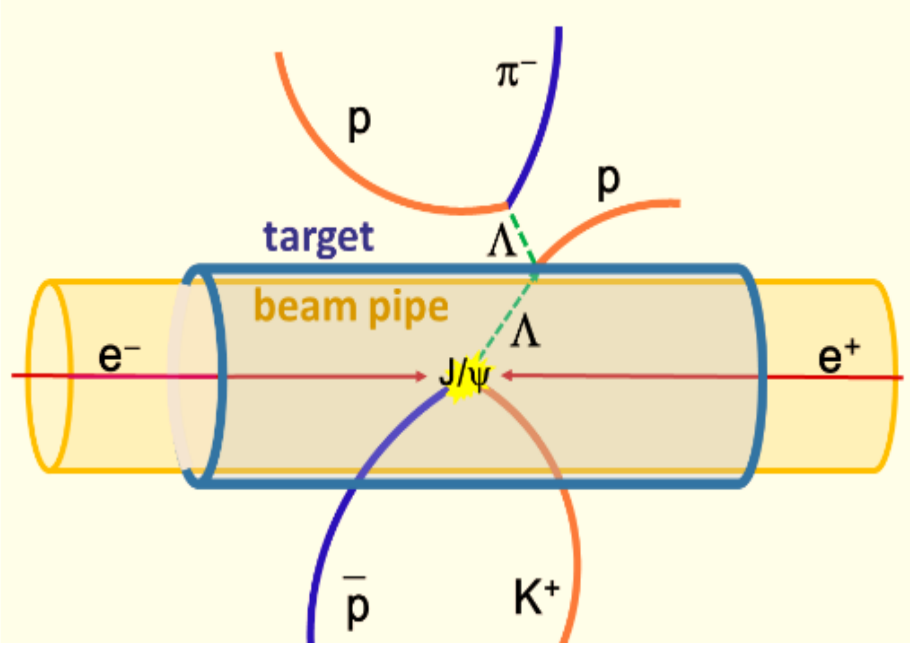
Paticle with Isospin=2?

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 $e^+e^- \rightarrow J/\psi$

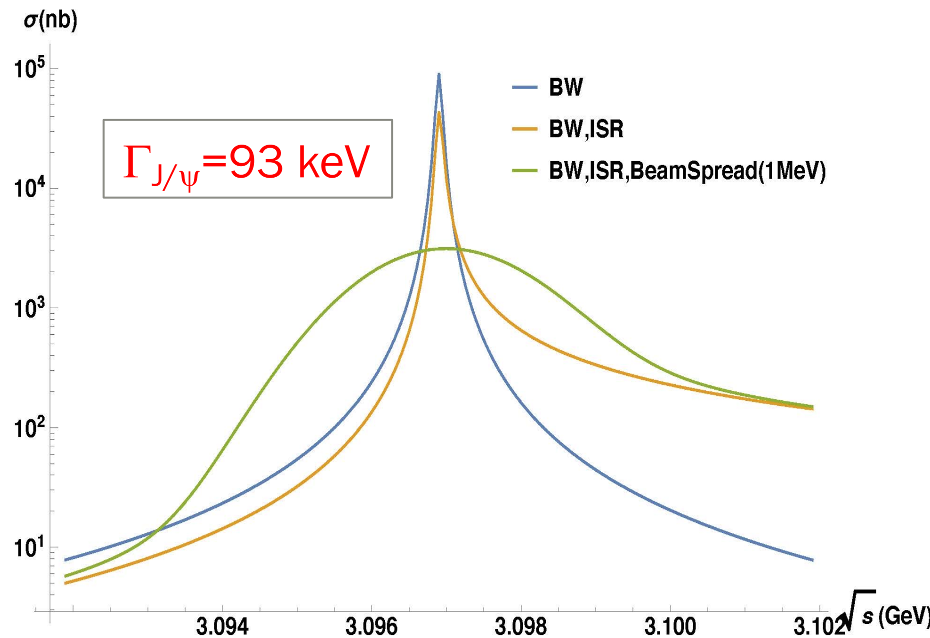
$$\sigma_{Born}(s) = \frac{12\pi\Gamma_{ee}\Gamma_f}{(s-M^2)^2+\Gamma_t^2 M^2}$$

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

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

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

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

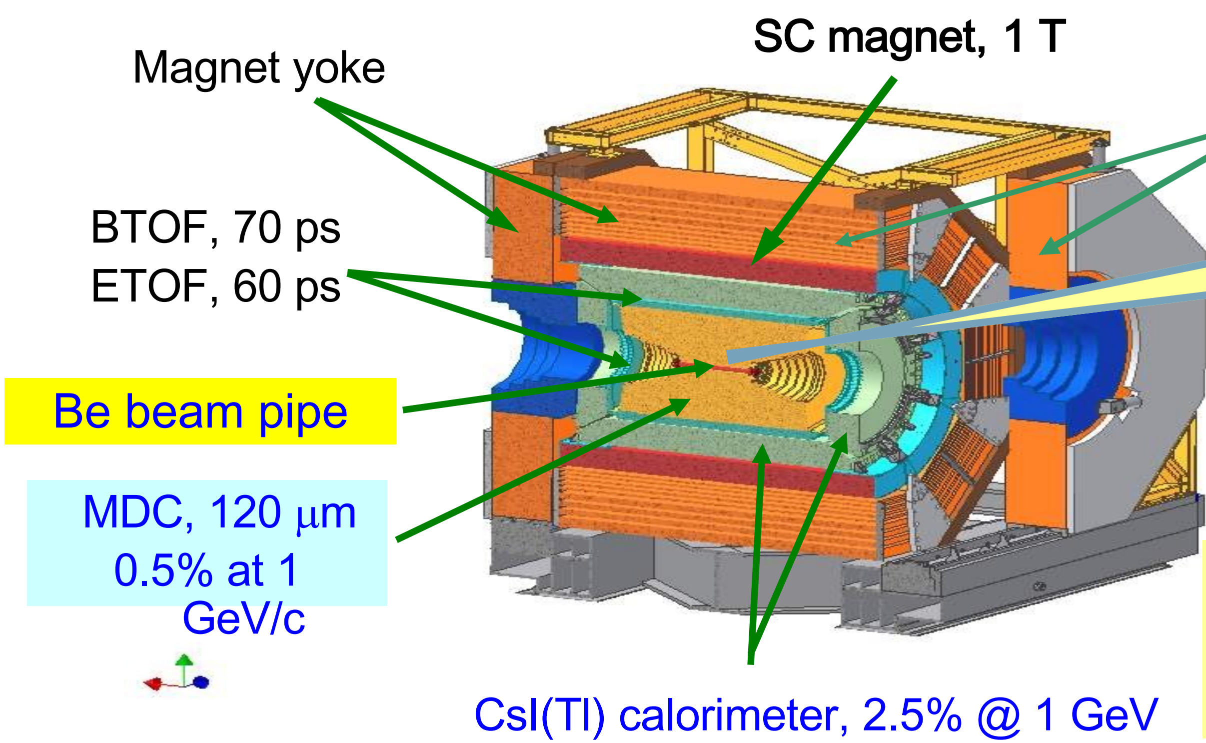
Why J/ψ decays: (2) big B(J/ψ→baryons)

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



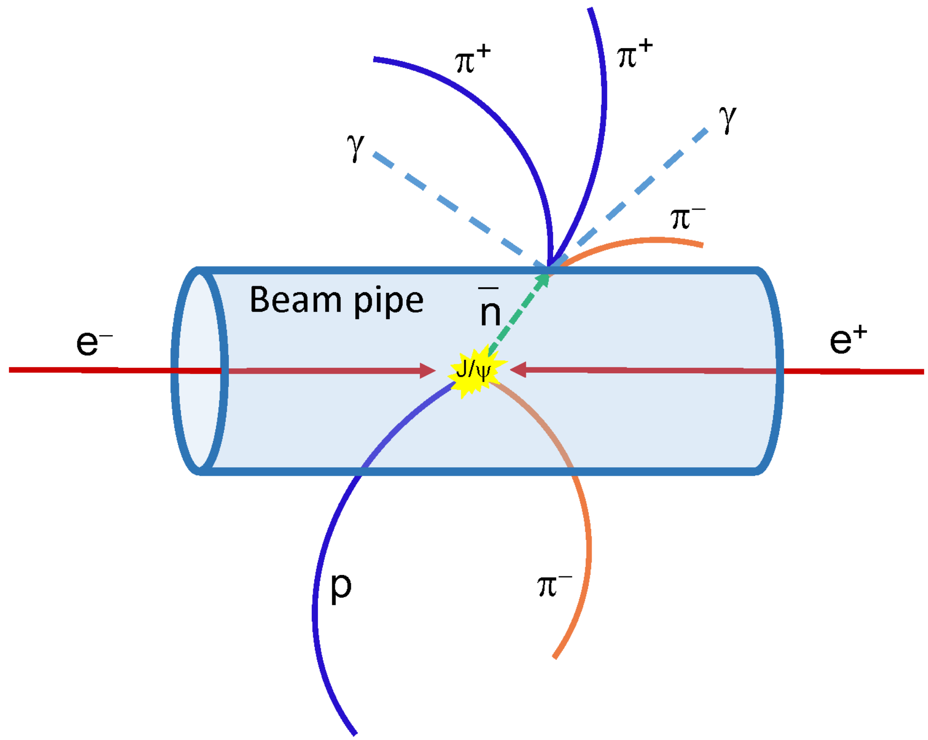
Total weight 750 tonnes, ~40,000 readout channels, Data rate: 5 kHz, 50 Mb/s

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

BESIII physics program

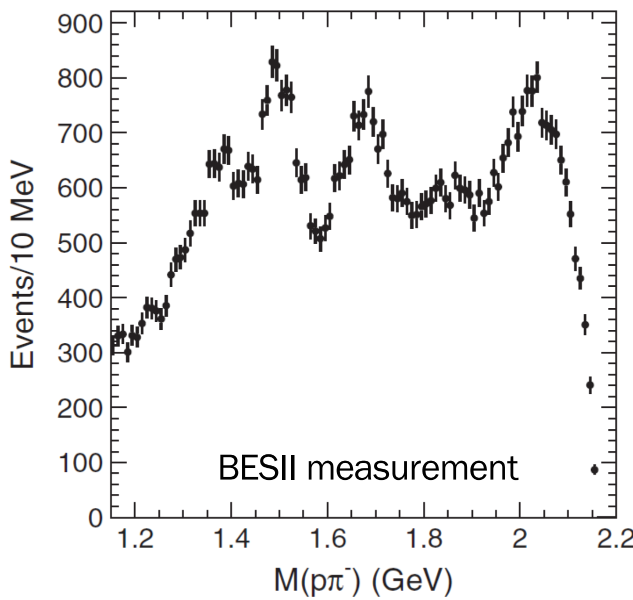
- **Light hadron physics: J/Ψ decays, glueball search** （10 billion J/ Ψ）
- **Charmonium physics: charmonium states decays/transitions, XYZ** (largest electron-positron collision dataset around 4 GeV)
- **Charm physics: charm meson/baryon decays**
- **Tau&R&QCD physics: R value, form factor measurement**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

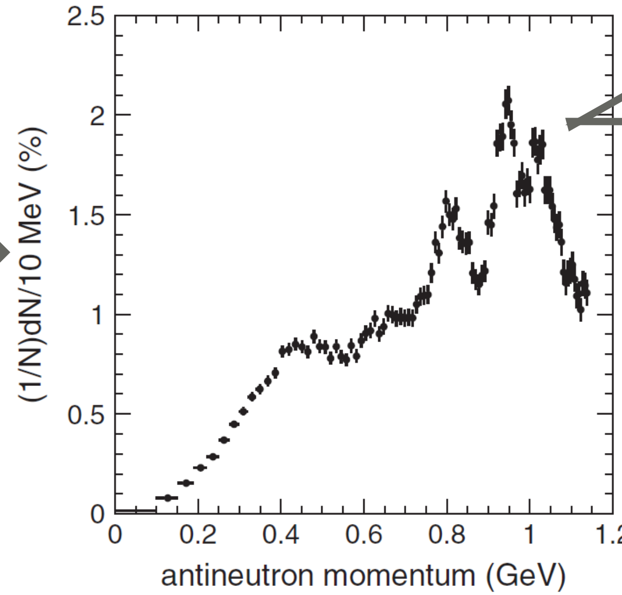
Proof of concept: study @ BESIII experiment



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

Proof of concept: study @ BESIII experiment





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

- $N(J/\psi) = 10^{10}$
- $B(J/\psi \to p\pi^-\bar{n}) = (2.12 \pm 0.09)\times10^{-3}$
- ε = 40%
- Tagged $\bar{n} = 10^{10}\times2.12\times10^{-3}\times40\%$ = 8 million!

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

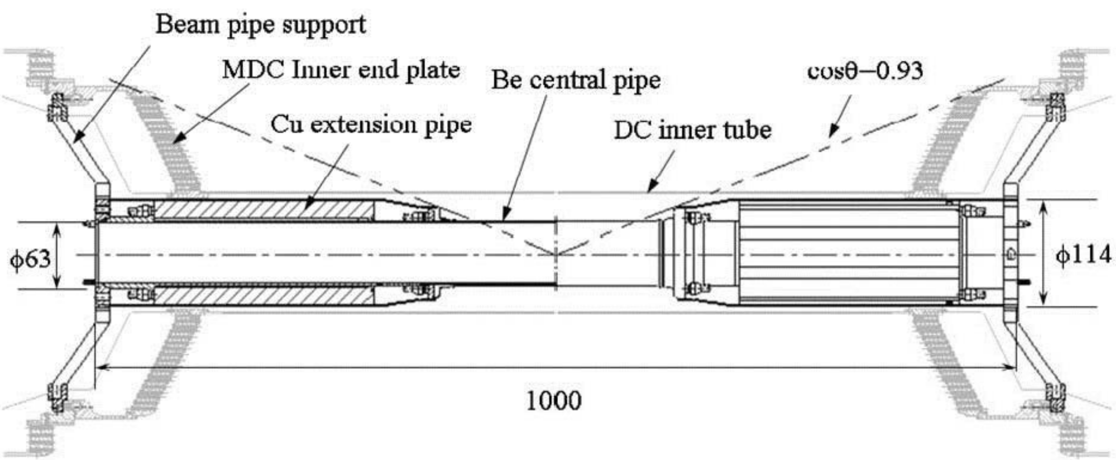
Hyperons and anti-hyperons at BESIII experiment

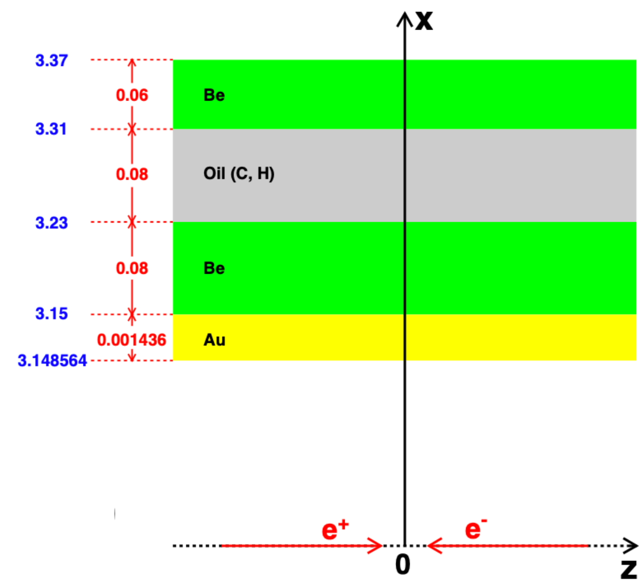
Baryon	$c\tau$ (cm)	decay mode	$\mathcal{B}$ ($\times 10^{-3}$)	$p_{\max}$ (MeV/c)	$n_{\rm BP}^{B}$ ($\times 10^{5}$)
$\bar{n}$	2.6×10^{13}	$J/\psi \to p\pi^{-}\bar{n}$	2.12	1174	80
Λ	7.89	$J/\psi \to \bar{\Lambda}\Lambda$	1.89	1074	26
		$J/\psi \to \bar{p}K^{+}\Lambda$	0.87	876	9
Σ^{+}	2.40	$J/\psi \to \bar{\Sigma}^{-}\Sigma^{+}$	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.

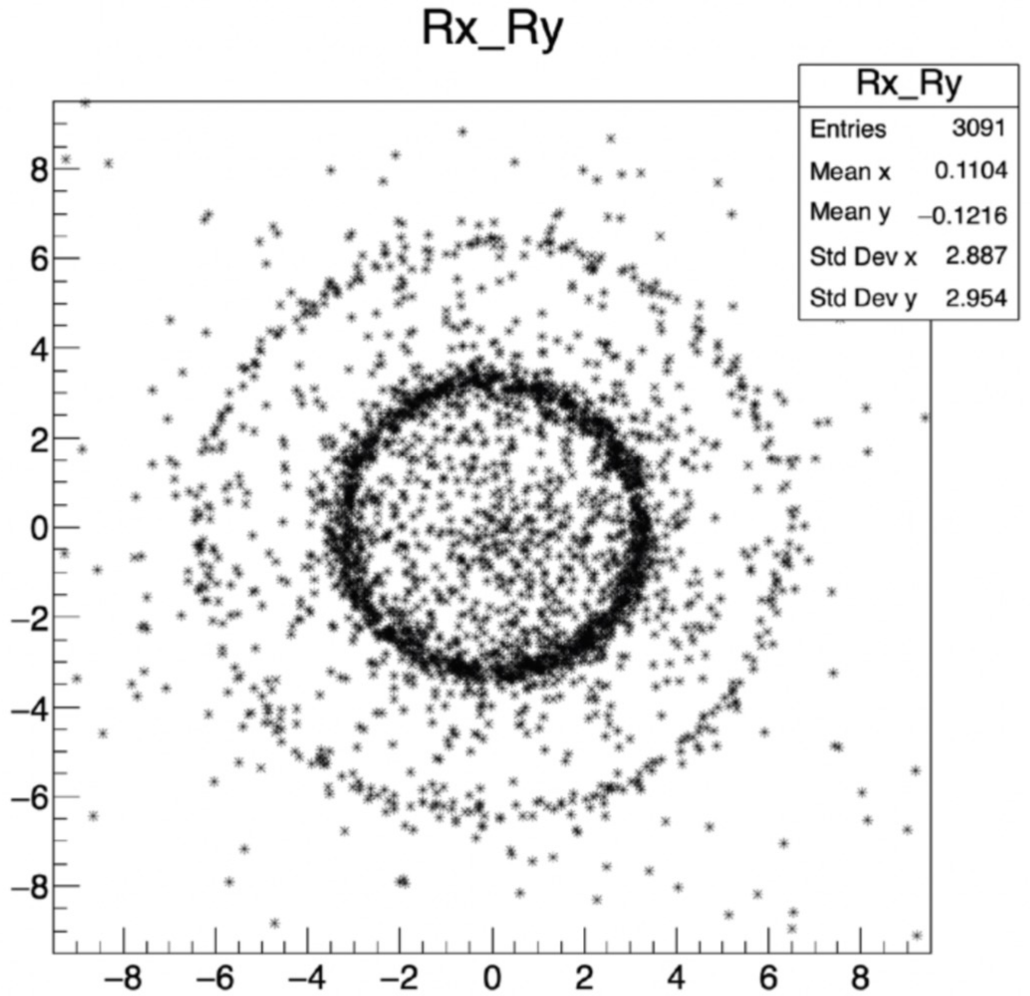




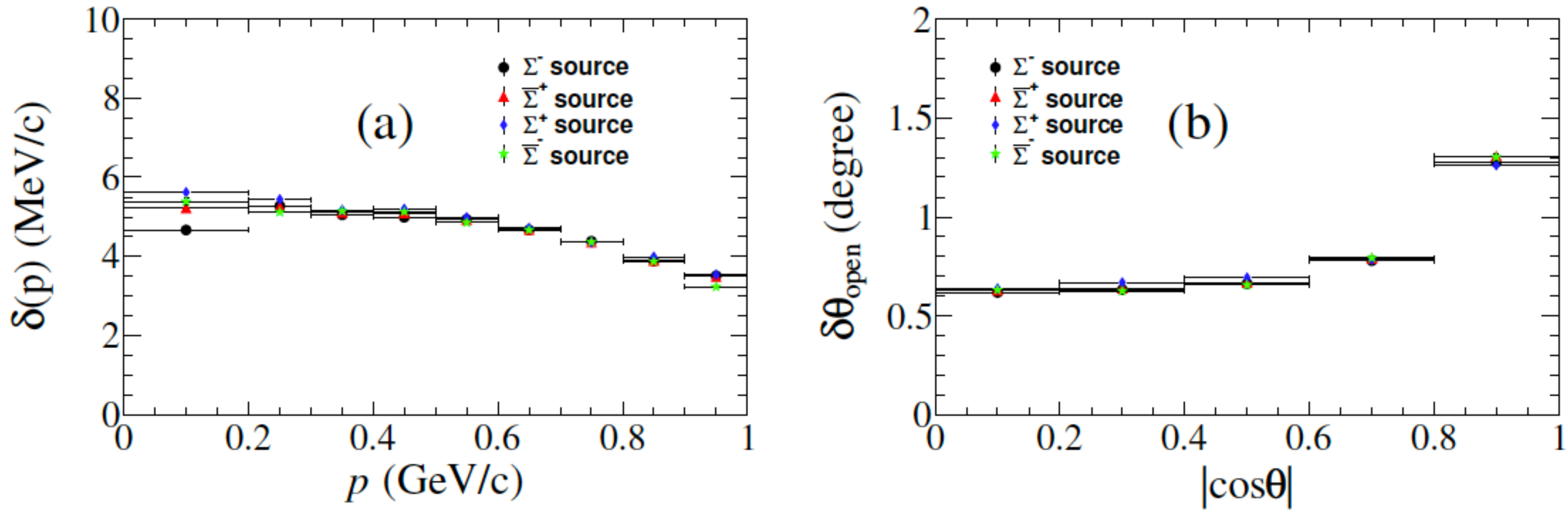
with $\sigma(\bar{n}p) \approx \sigma(\bar{n}n) \approx 100$ mb
expect 1–2% of tagged $\bar{n}$-s interact with Be & 1-2% with C fiber target

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

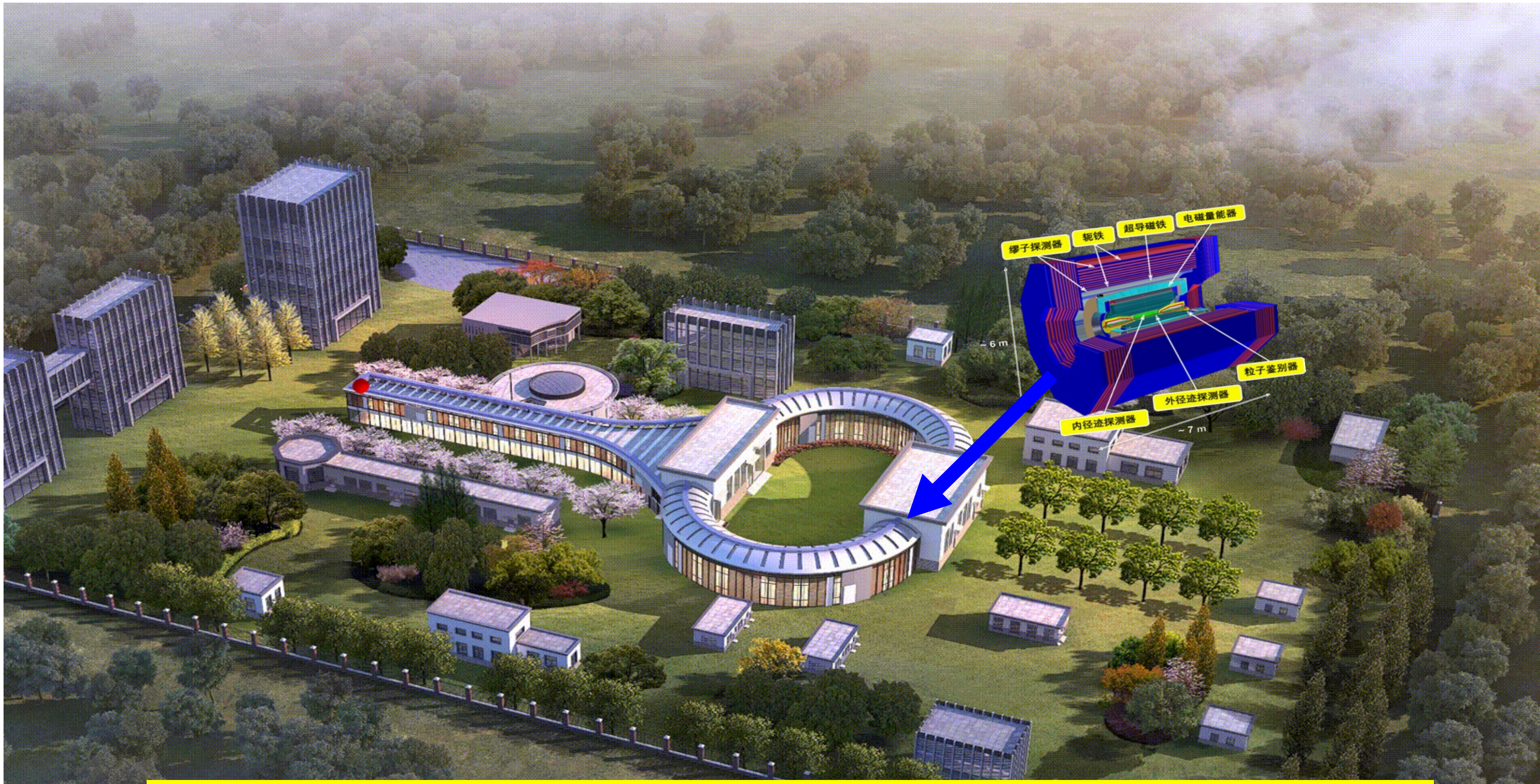


Momentum resolution (left)、angular resolution (right)

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), SCT (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, ...

STCF in China



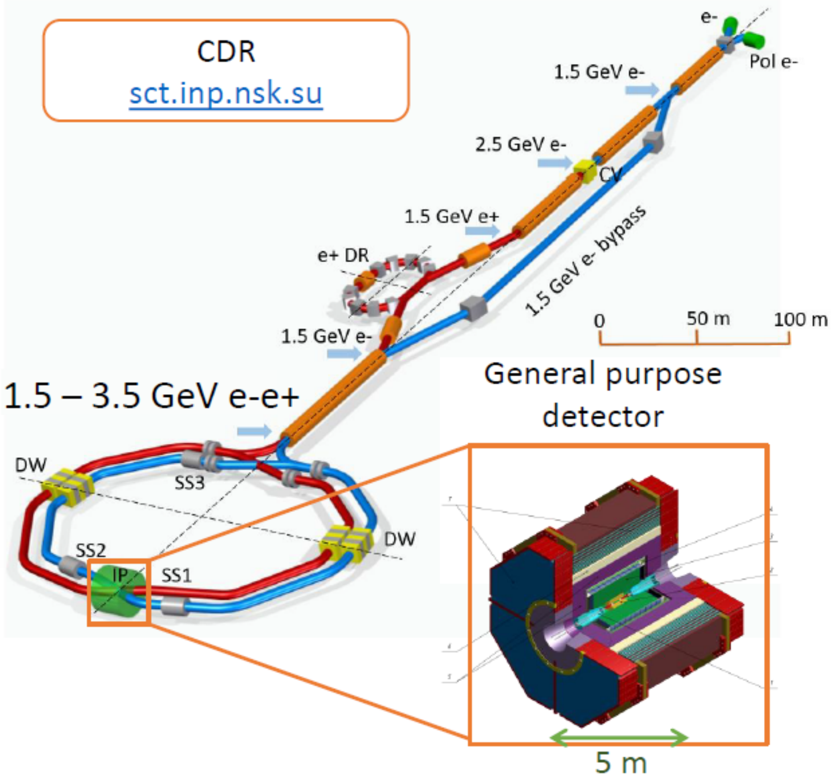
- CM Energy : 2-7 GeV
- Peaking $\mathcal{L}$: $>5\times10^{34}$ cm^{-2} s^{-1}
- Potential to further improve the $\mathcal{L}_{peak}$ and realize polarized beam
- Double storage ring : ~800 m , injection : ~ 300m
- BESIII-Like detector
- Cost 4.5B RMB

STCF workshop, Guangzhou, 2022

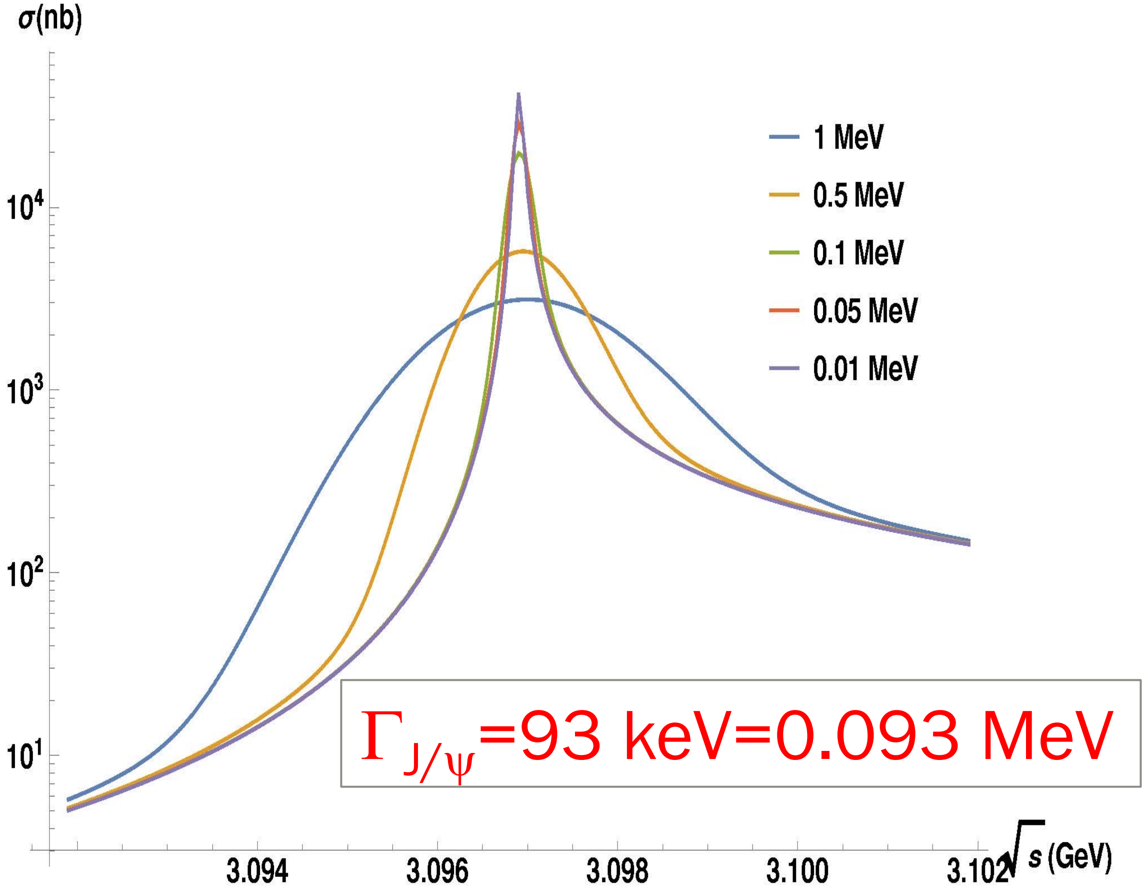
Ivan Logashenko (BINP)
PhiPsi2022

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:

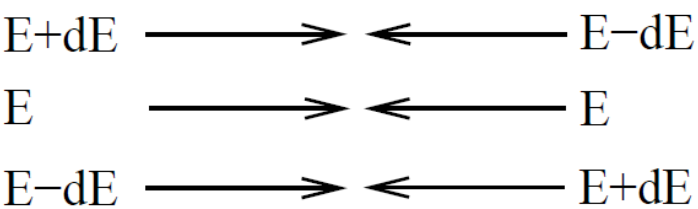
1. Increase luminosity
2. Reduce energy spread

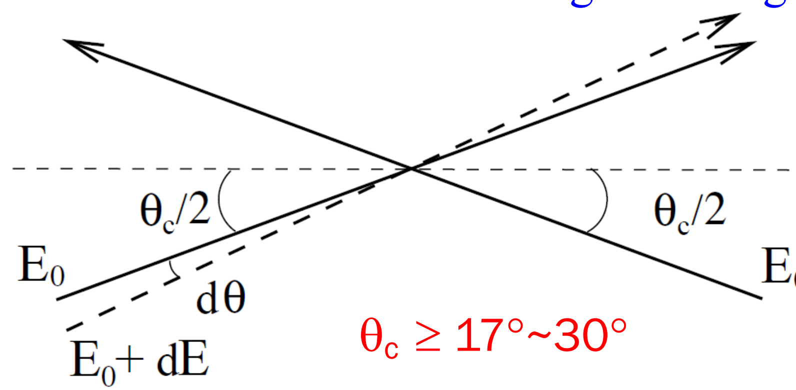
Energy spread (MeV)	Cross section (nb)
1	3,100
0.5	5,700
0.1	20,000
0.05	29,000
0.01	42,000

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





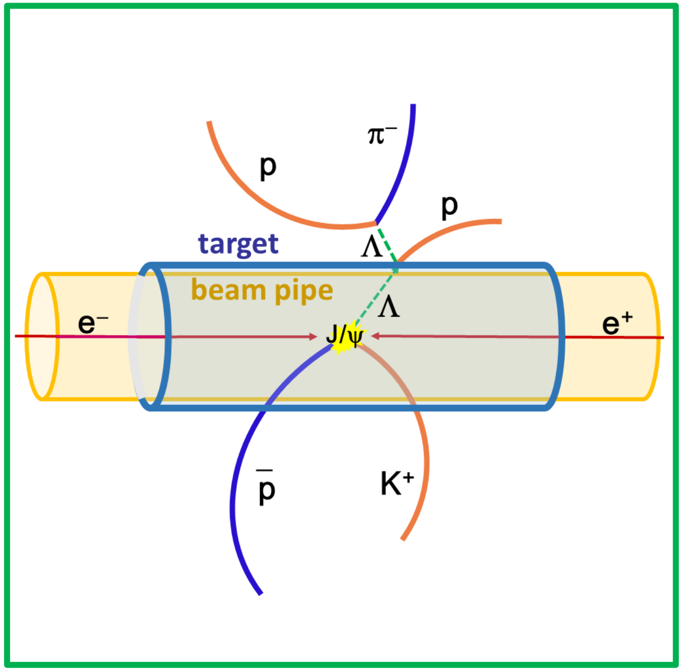
Existing monochromatization scheme for head-on collisions will reduce luminosity significantly

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.

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

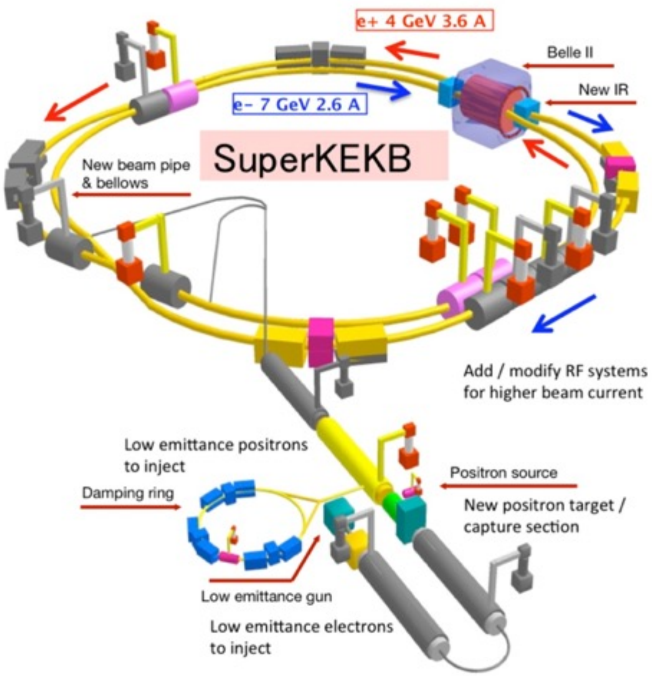
σW=10-15 keV @ J/ψ peak
and J/ψ is moving!

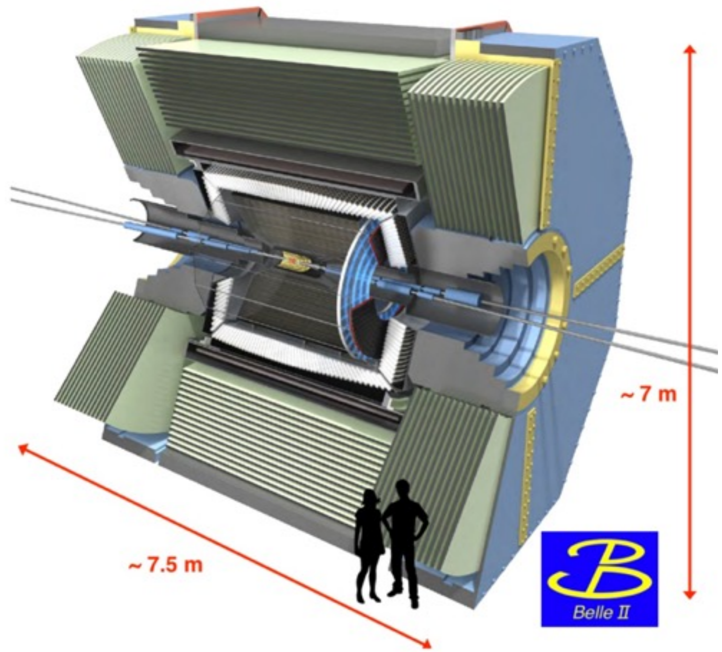
Summary: Do fixed target experiments @ a super J/ψ factory



- 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!