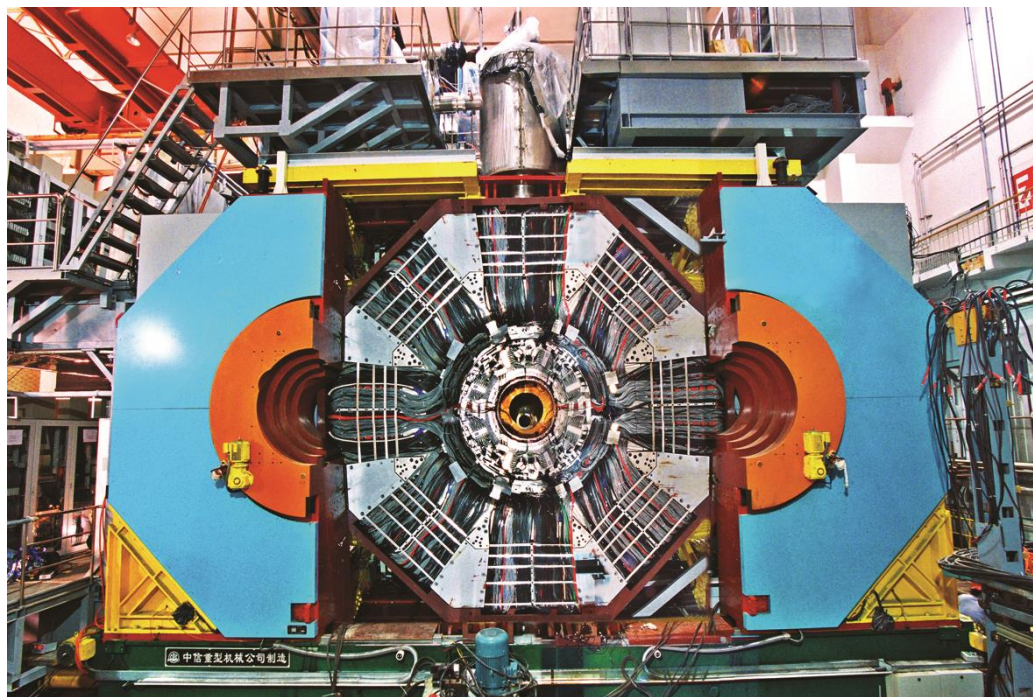


BESIII实验进展



Guangshun Huang(黄光顺)

(on behalf of the BESIII Collaboration)

University of Science and Technology of China

第五届中国格点量子色动力学研讨会

中国科学院近代物理研究所惠州研究部, 2025.10.11

Outline

- **Introduction**
- **Highlights on recent results**
 - **Hadron production and structure**
 - **Light hadron spectroscopy**
 - **Charmed meson and baryon**
 - **CPV in hyperon decays**
 - **Charmonium(-like) states**
- **Prospects for the future**
- **Summary**

Disclaimer: selected topics only, not possible to cover all.

Beijing Electron-Positron Collider II (BEPCII)

C.M. energy: 1.84~4.95 → 5.6 GeV

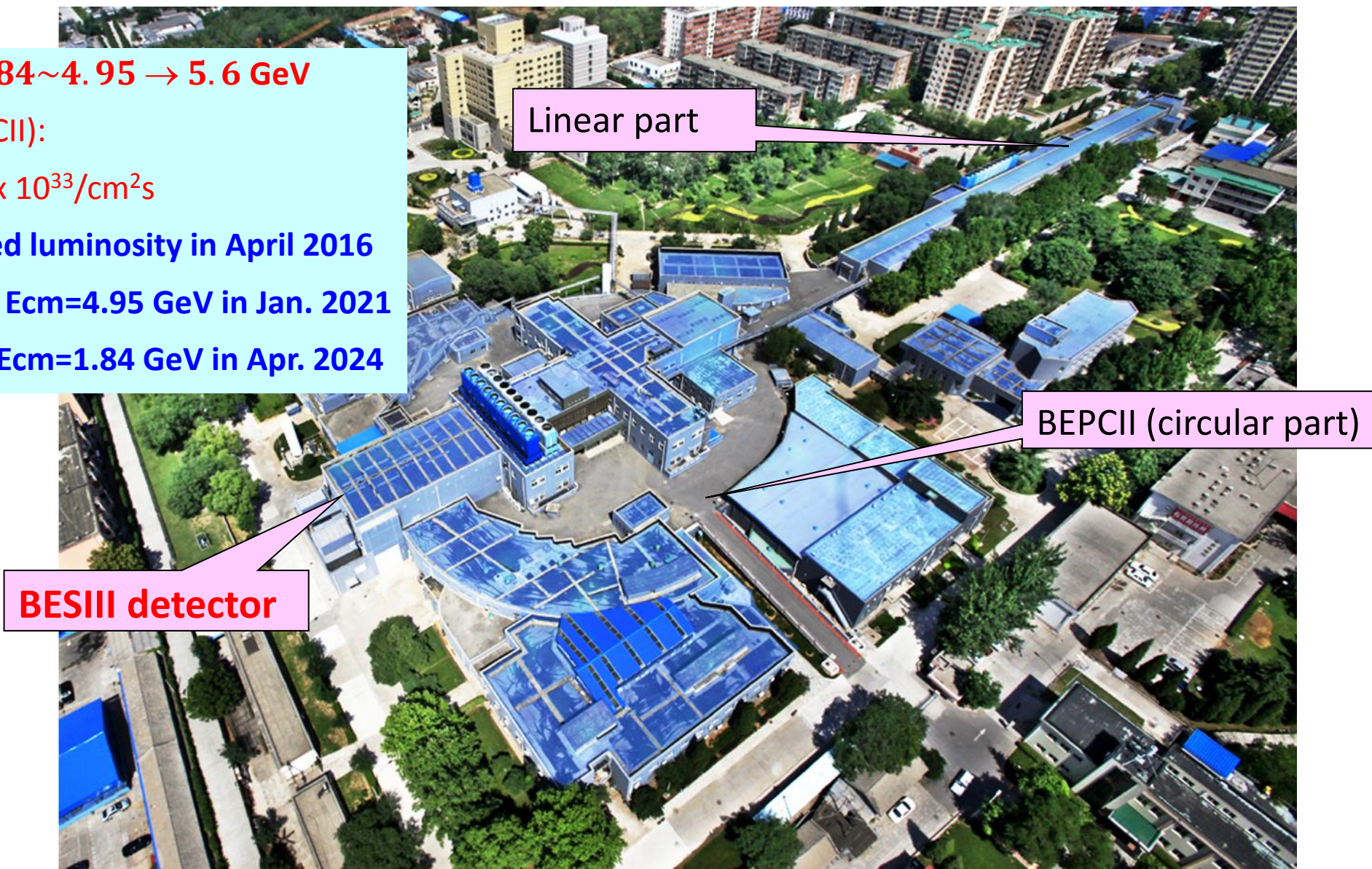
2008- **Now** (BEPCII):

$$L_{\text{peak}} = 1.0 \times 10^{33} / \text{cm}^2 \text{s}$$

Reached designed luminosity in April 2016

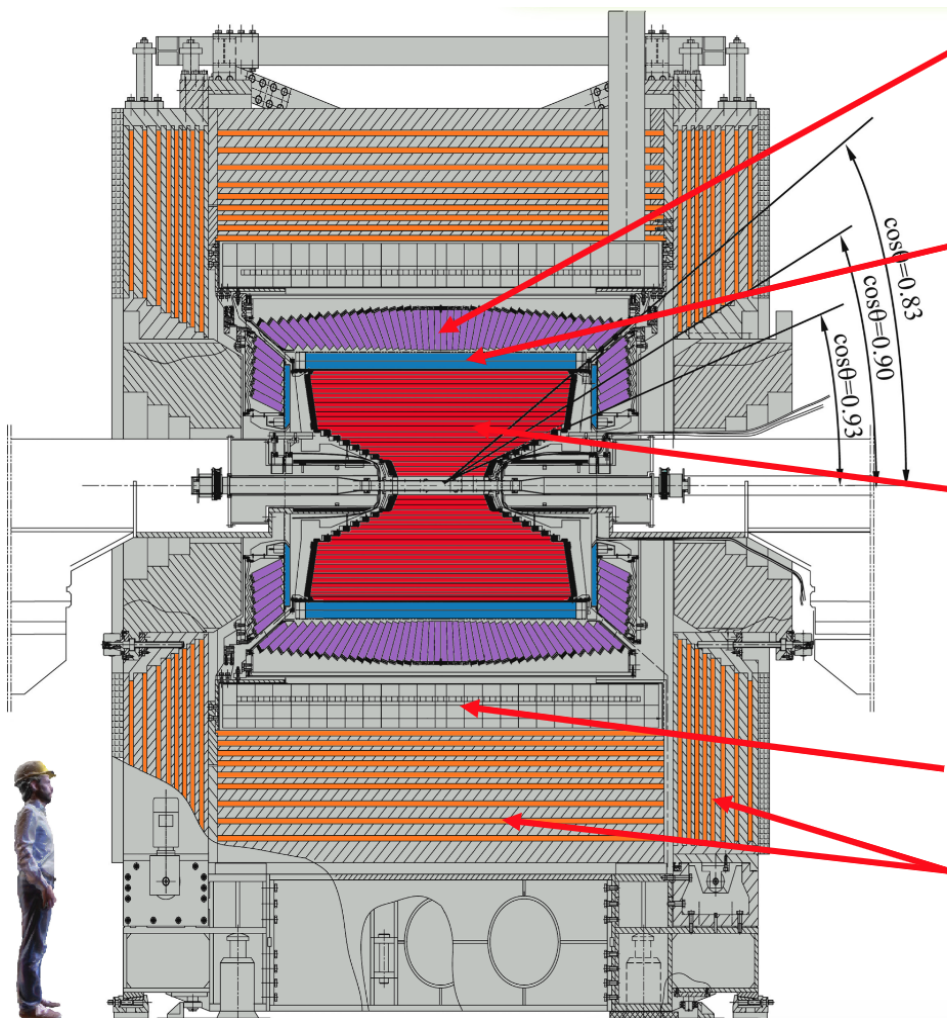
Reached highest $E_{\text{cm}}=4.95$ GeV in Jan. 2021

Reached lowest $E_{\text{cm}}=1.84$ GeV in Apr. 2024



BESIII detector

The detector is designed for neutral and charged particle with excellent resolution, PID, and large coverage.



EMC: CsI crystals

$\Delta E/E = 2.5\%$ @ 1 GeV - Barrel

$\Delta E/E = 5.0\%$ @ 1 GeV - Endcaps

TOF:

$\sigma_T = 80$ ps Barrel

$\sigma_T = 110$ (60) ps Endcap

MDC: small cell & He gas

$\sigma_{xy} = 130$ μm

$\sigma_p/p = 0.5\%$ @ 1 GeV

$dE/dx = 6\%$

Magnet: 1T Super conducting

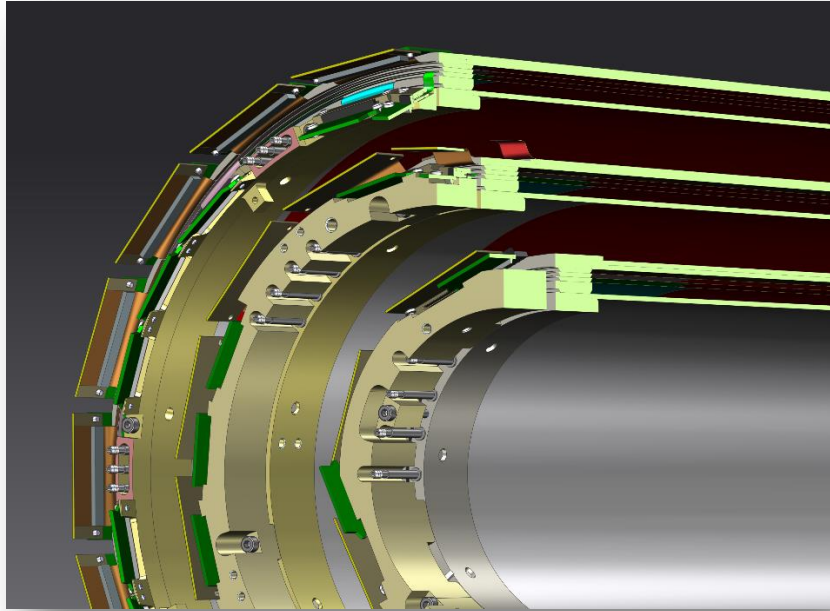
Muon ID: 9 layer RPC

Trigger: Tracks & Showers

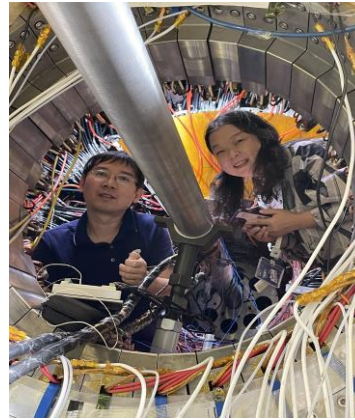
Total weight 730 ton,
~40,000 readout
channels, Data rate:
5kHz, 50Mb/s

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

BESIII Cylindrical Gas Electron Multiplier Inner Tracker (CGEM-IT)



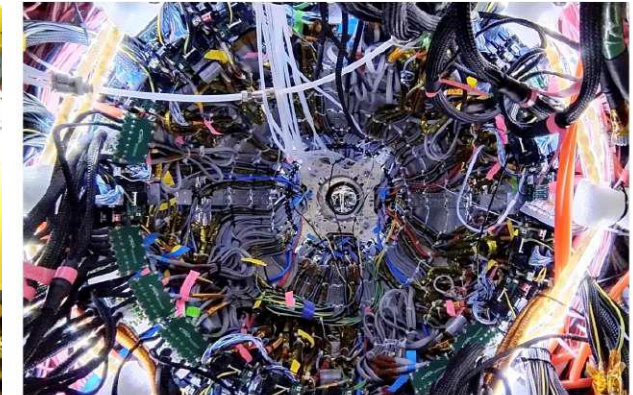
- Three layers of cylindrical triple GEM to replace the inner MDC
- Improve spatial resolution along the beam axis ($< 300 \mu\text{m}$), rate capability, and radiation hardness



Extraction of inner draft chamber on Sep. 14th

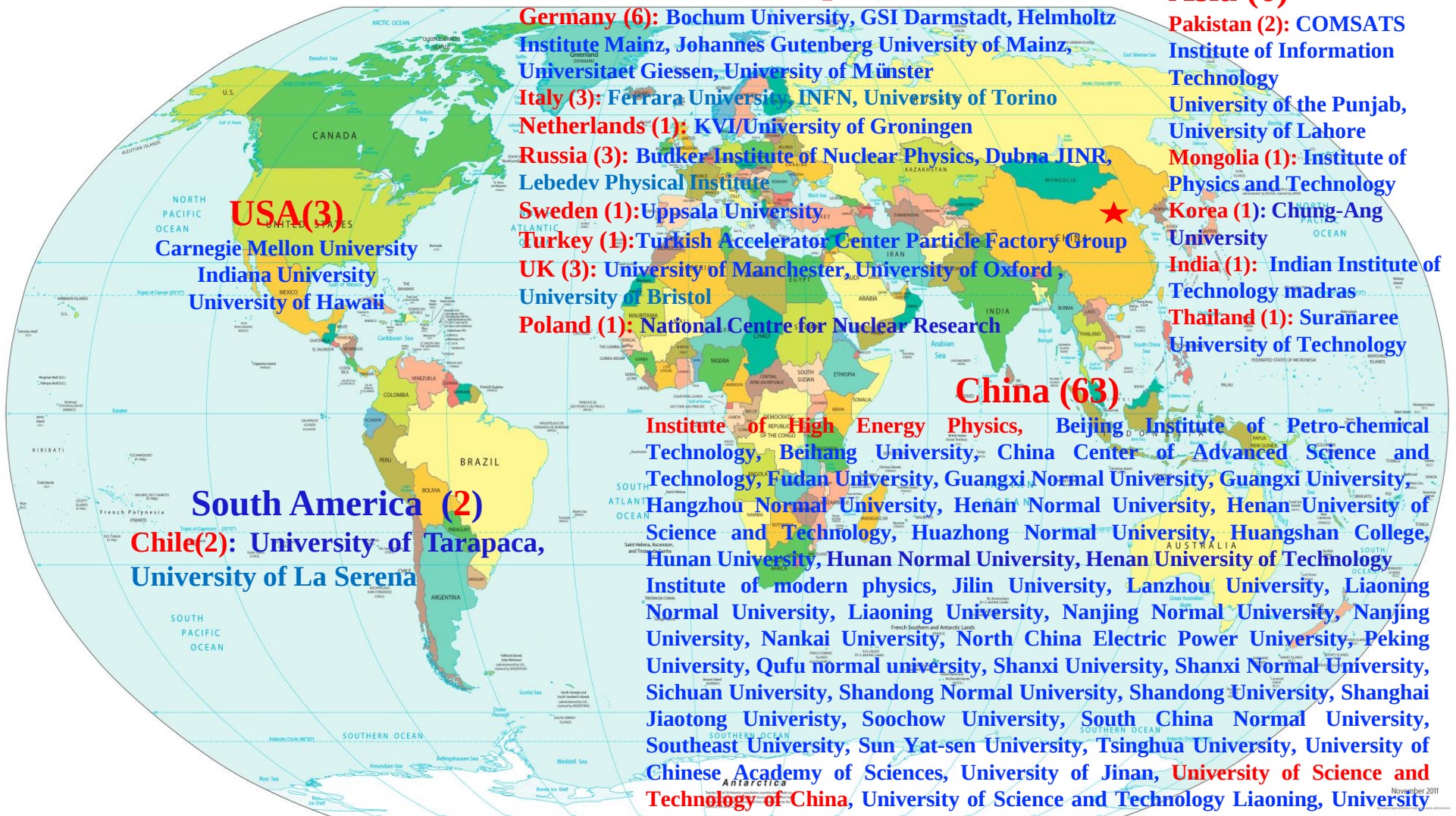
Status and timeline

- Software review on Dec. 1st, 2023
- Performance review on Feb. 20th 2024
- Overall assessments of Installation (March, 2024)
- Installation in October 2024 during the BEPCII-upgrade



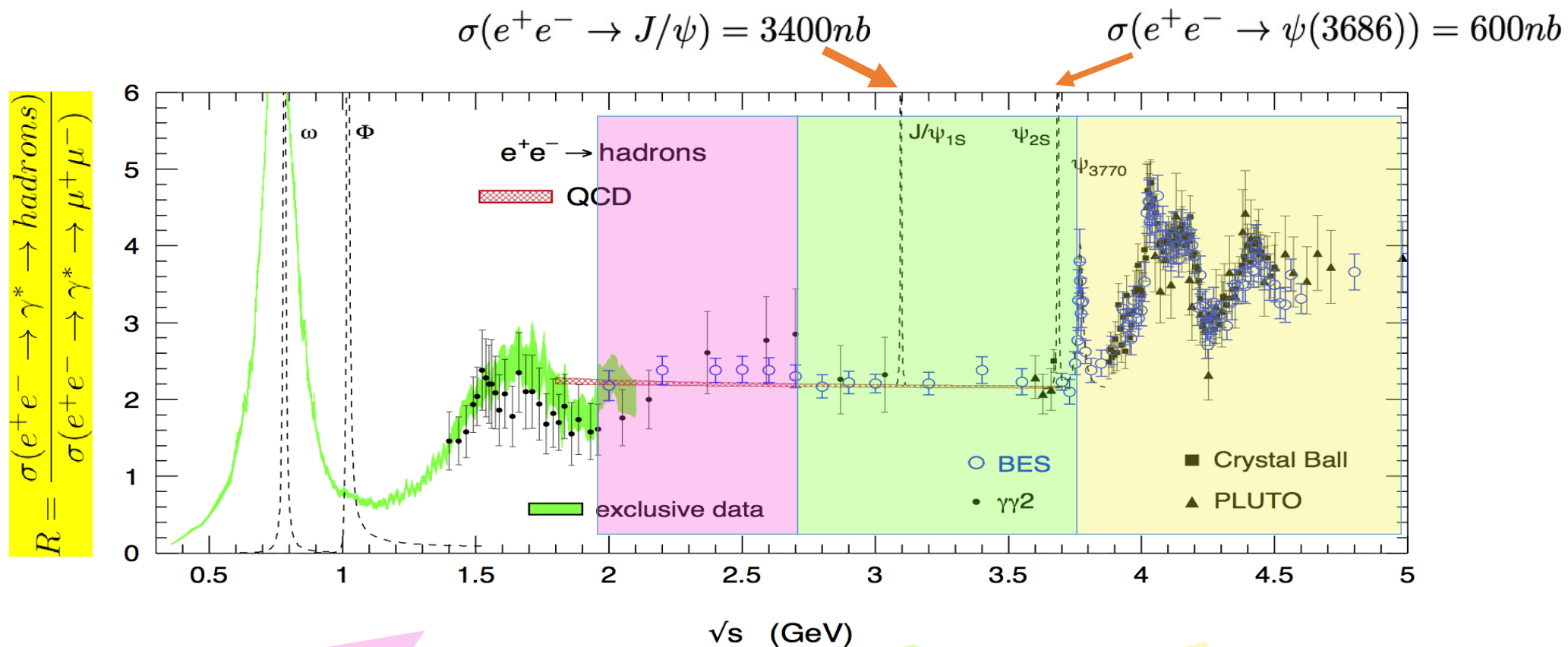
Ready for installation on Oct. 2nd

Completed on Oct 18th!



~700 members
From 93 institutions in 16 countries

Rich Physics at τ -charm Energy Region



- Hadron form factors
- R values and QCD

- Light hadron spectroscopy
- Gluonic and exotic states
- Physics with τ lepton

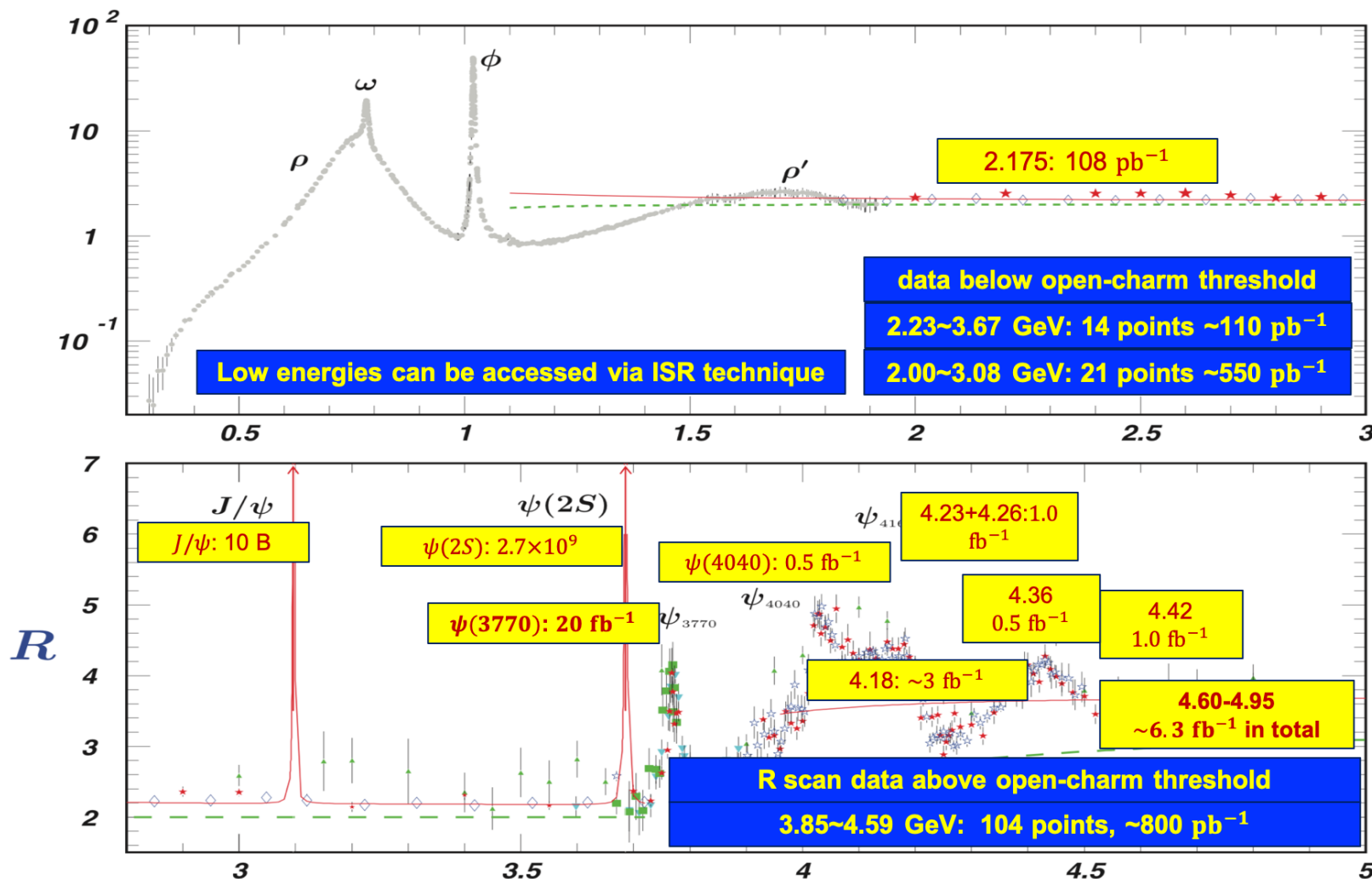
- XYZ particles
- Charm mesons
- Charm baryons

BESIII data samples: rich physics

Totally about 50 fb^{-1} integrated luminosity from 1.84-4.95 GeV

Data sets collected so far include

- 10×10^9 J/ψ events
- 2.7×10^9 $\psi(2S)$ events
- 20 fb^{-1} $\psi(3770)$
- Scan data between
 $1.84\text{--}1.97 \text{ GeV}$ (13 points, 25 pb^{-1})
 $2.0\text{--}3.08 \text{ GeV}$,
and above 3.74 GeV
- Large datasets for XYZ studies:
scan with $>500 \text{ pb}^{-1}$ per energy point
space $10\text{--}20 \text{ MeV}$ apart
- Entangled hadron pair-productions
near thresholds: form-factors,
relative phase, polarization and CP violation.

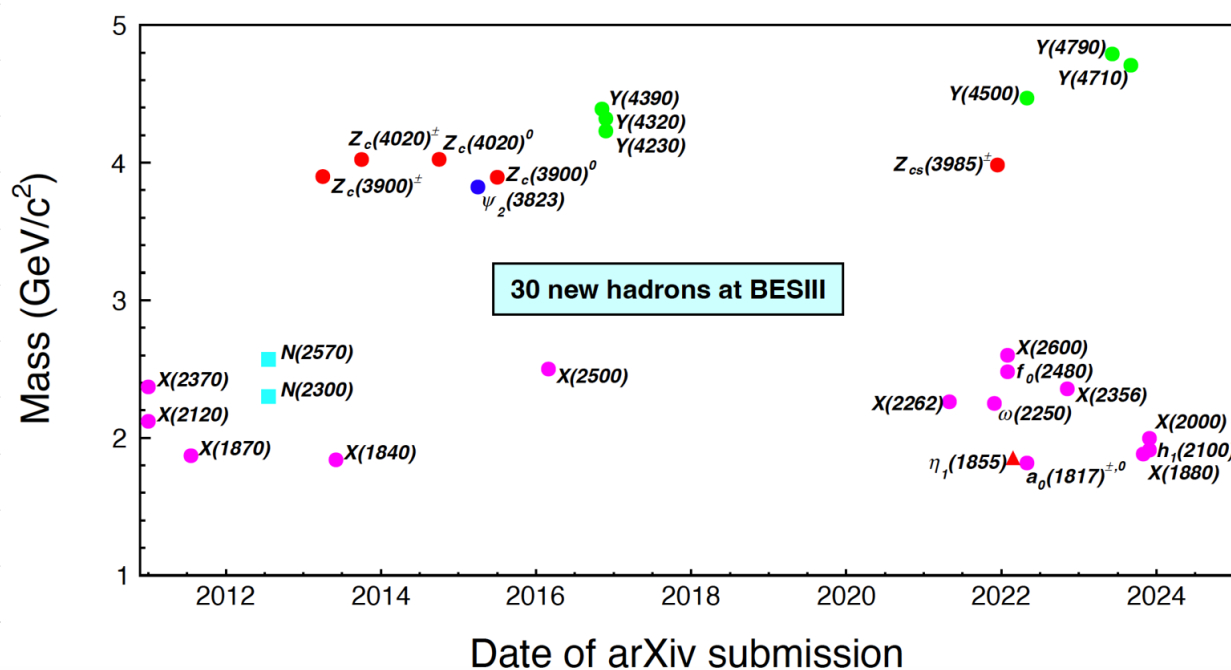


Hadron structure & dynamics in the non-perturbative QCD regime

Publications and achievements

707 published/752 submitted so far
 ~20% PRL + Nature (Phys./Commu.)
 110 papers published in 2024

BESIII Publication



Advantage: unique data near the thresholds

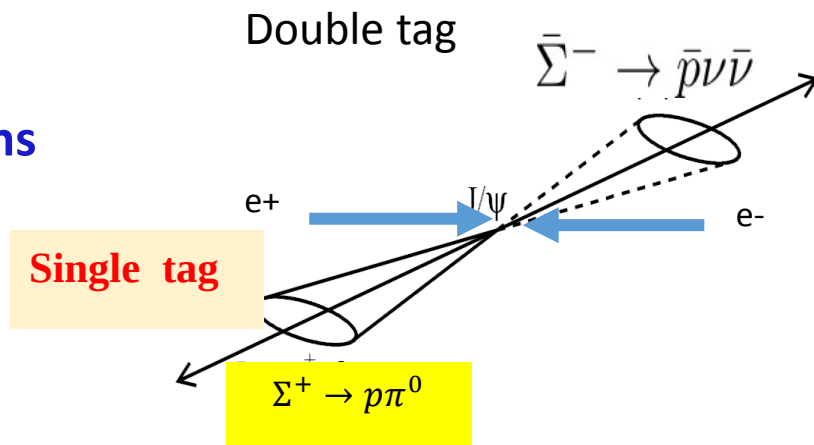
Known initial 4-momentum

Known beam energy: pair productions

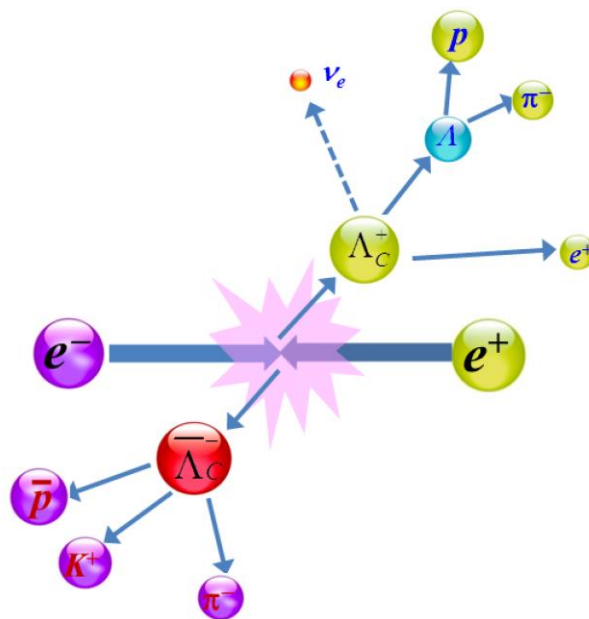
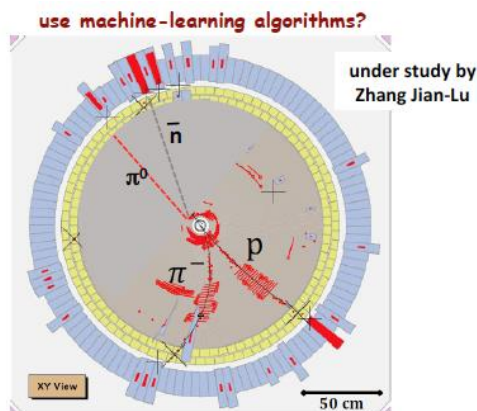
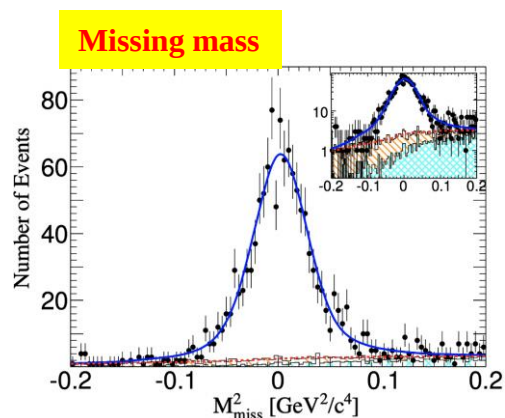
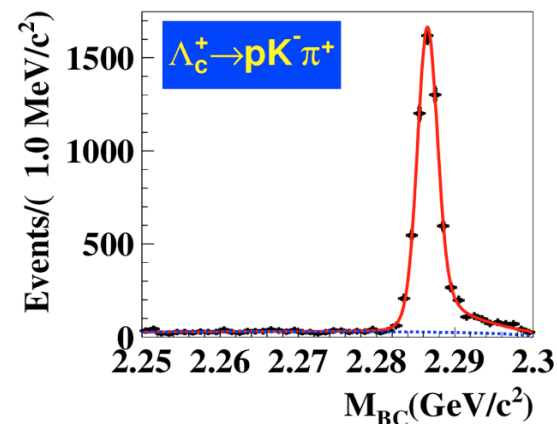
Decay with neutron & π^0

Decay with invisibles: neutrinos

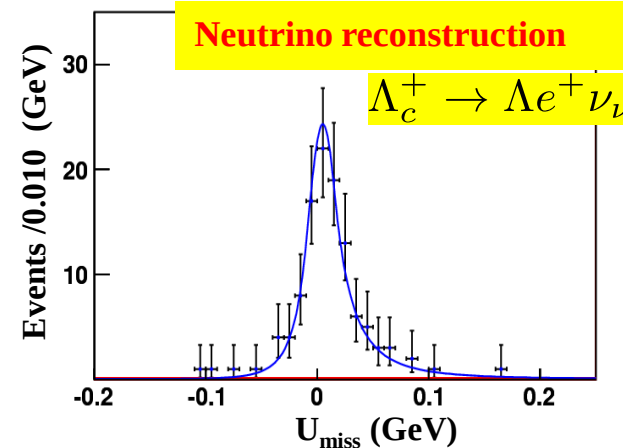
Missing mass or missing energy



Excellent resolution
Beam-constraint Λ_c mass

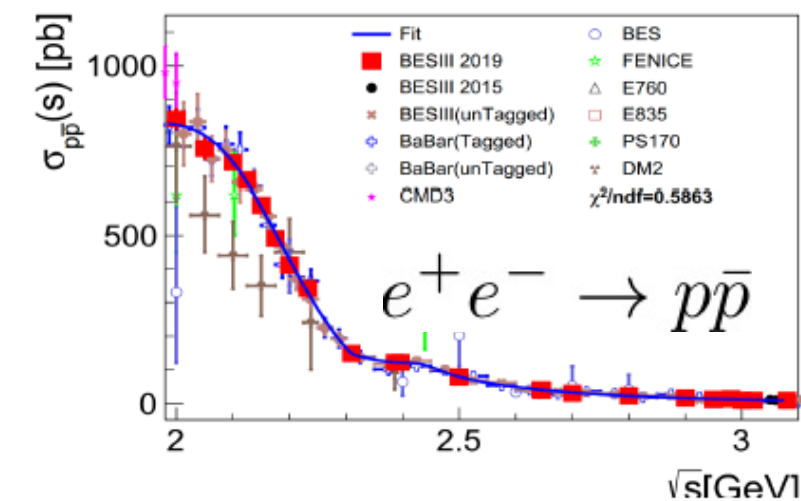
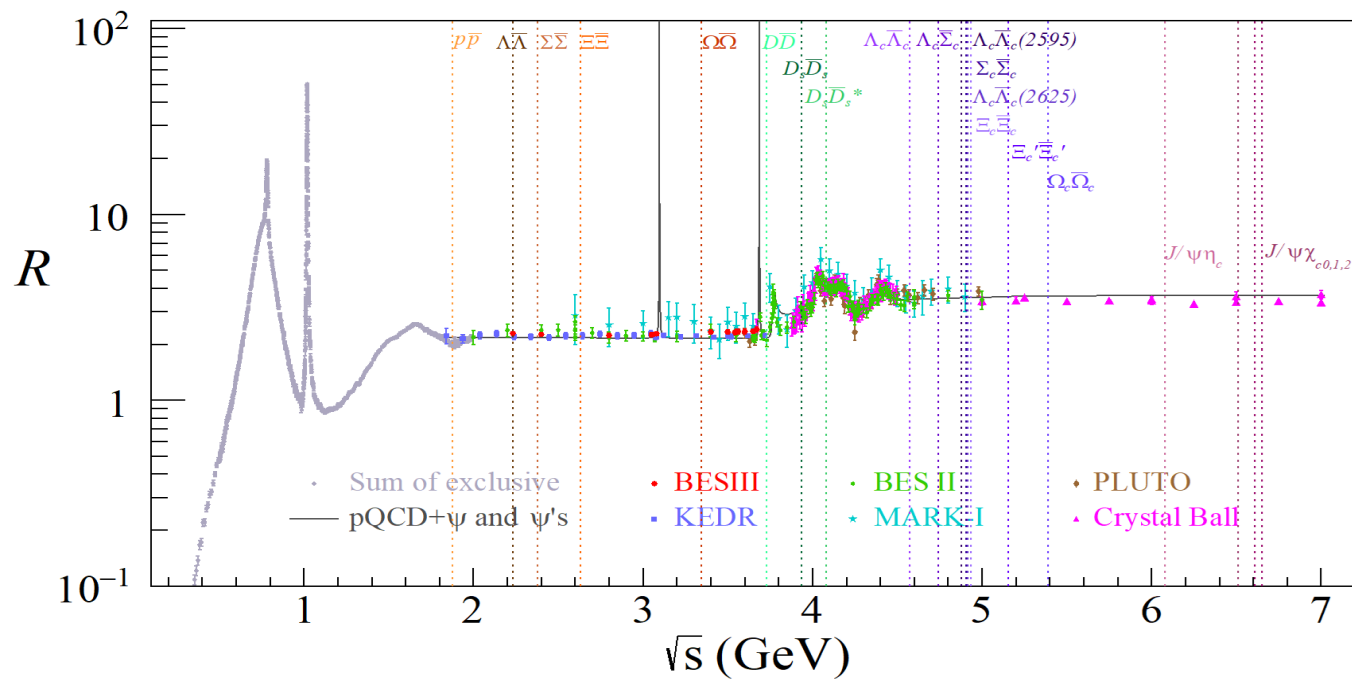


Neutrino reconstruction

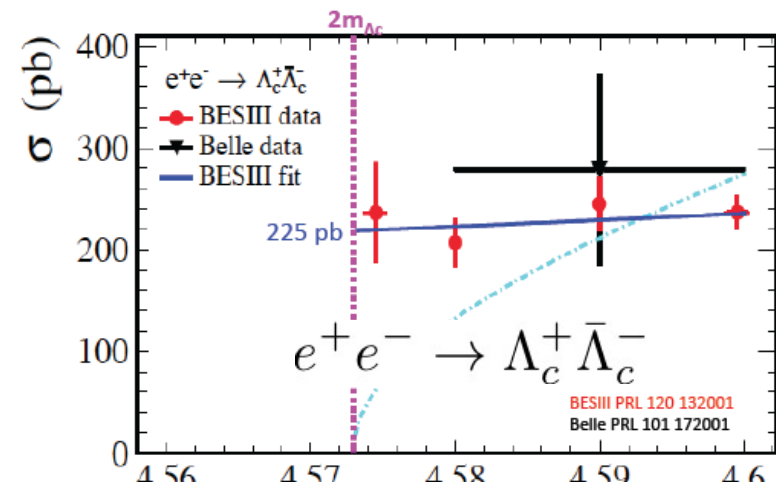
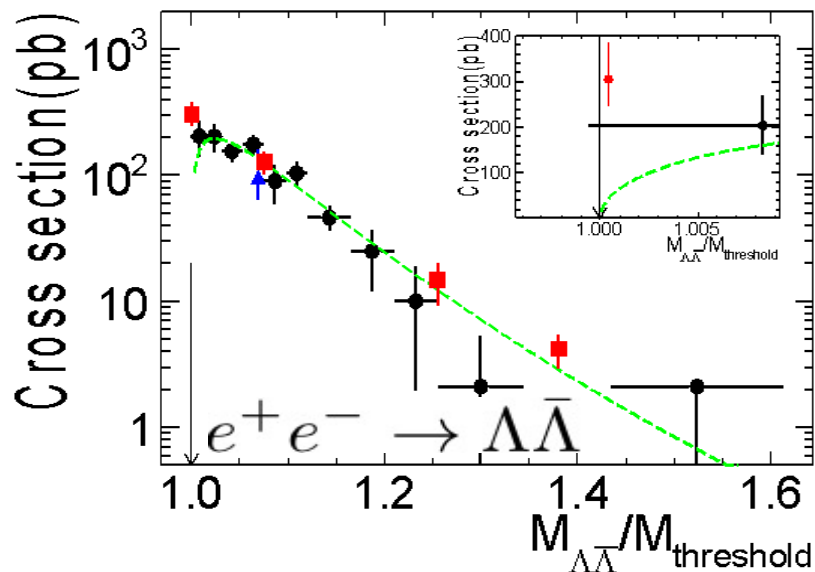


Advantage: data near to the thresholds

- Meson and Baryon pairs productions near thresholds: form-factors, relative phase;
- Hyperon and charmed baryon entangled
- Spin polarization;
- CP violation with quantum-entangled hadron pairs.



Best precision on σ : 3% (systematic dominant)



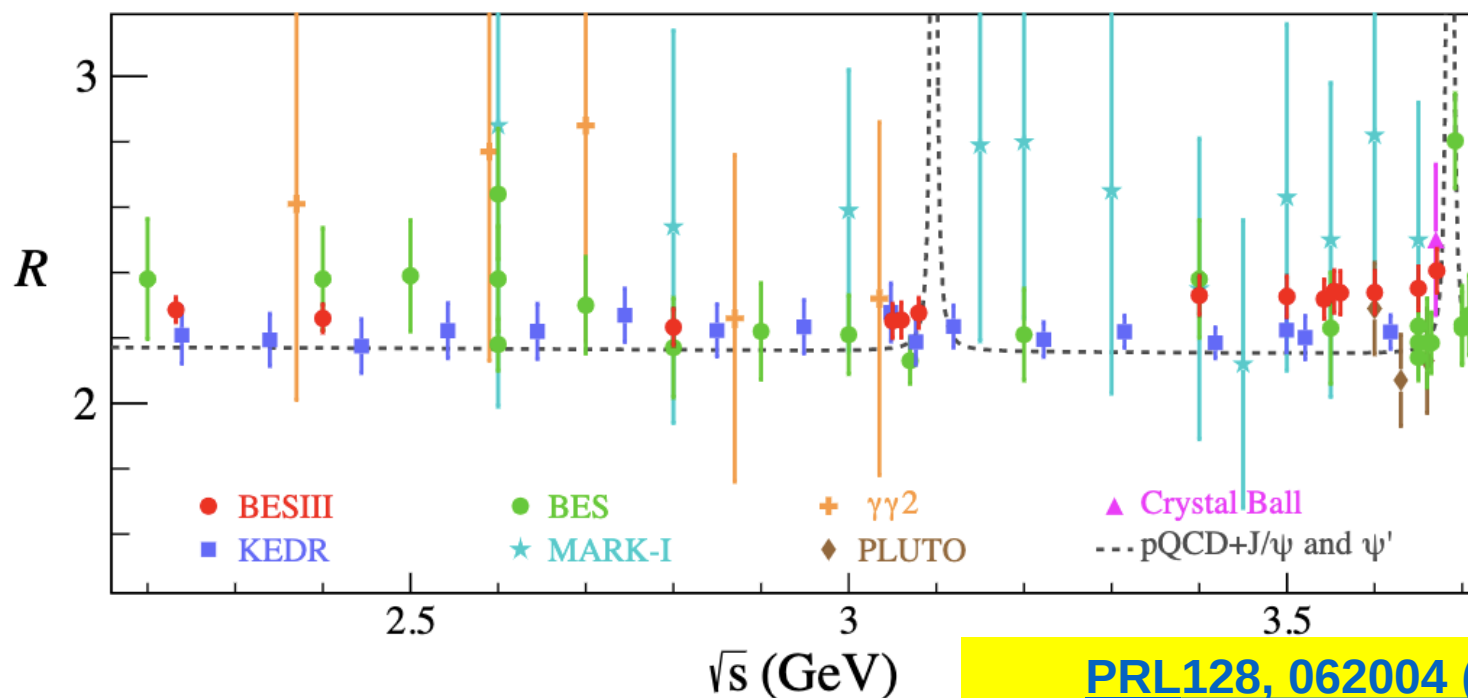
Updated R values at BESIII

- 14 fine-scan data points from 2.23-3.67 GeV
- Important inputs for SM-prediction of $g-2$

Comparing BESIII R values with previously published results:

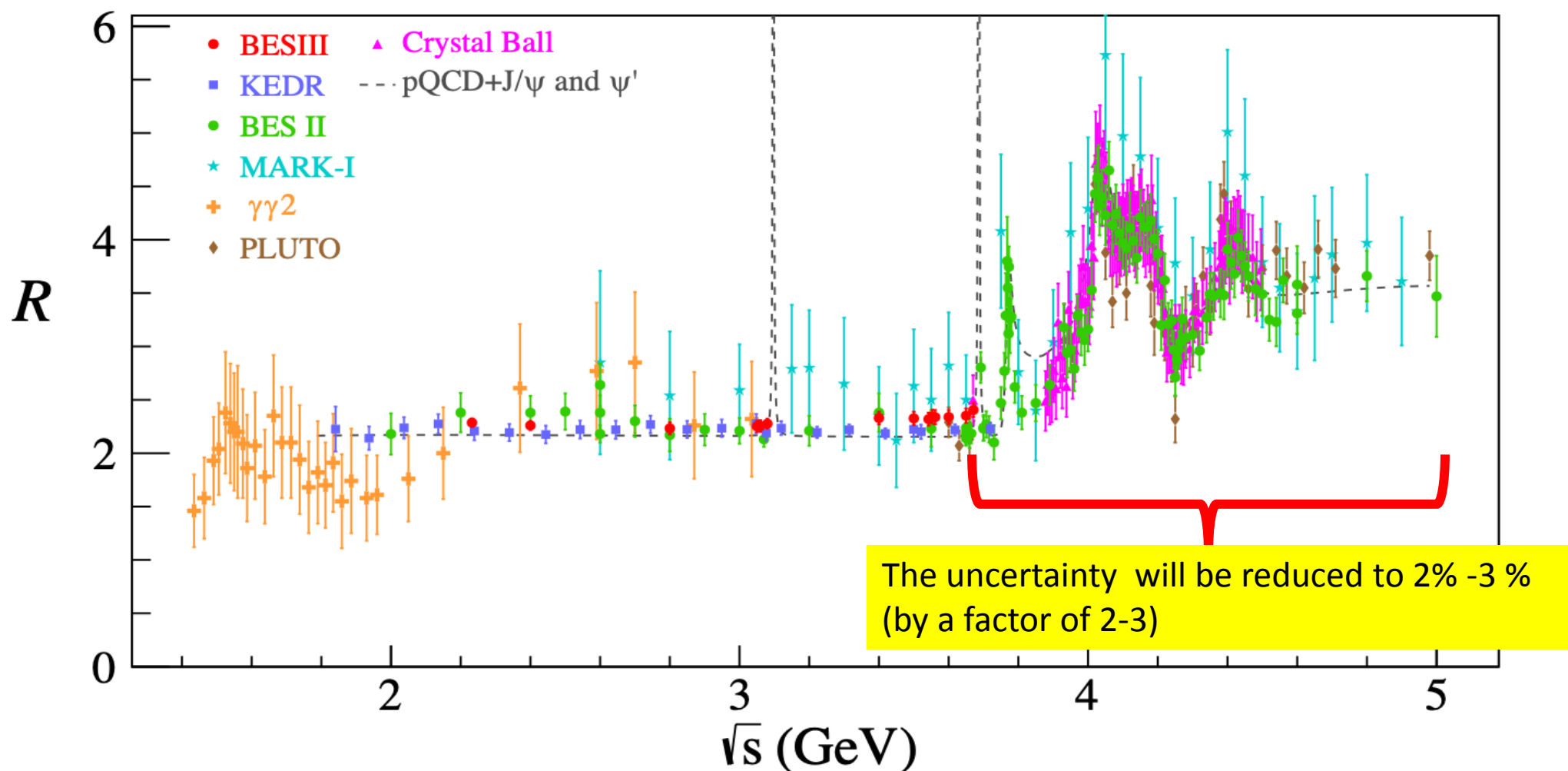
$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \sum_f Q_f^2$$

lowest order
flavor color



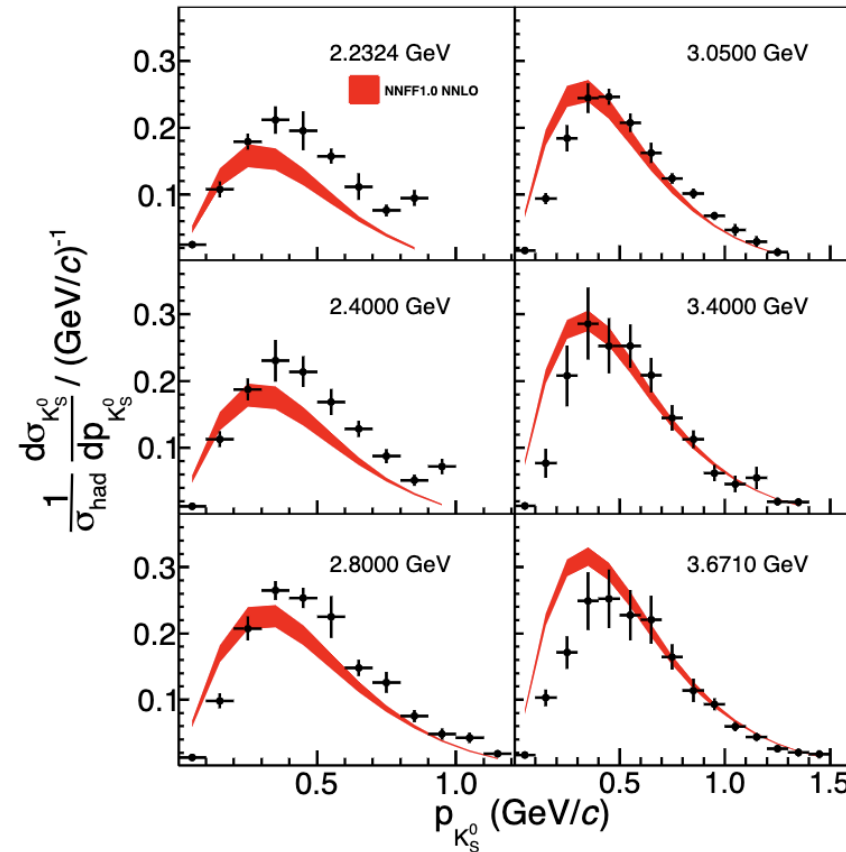
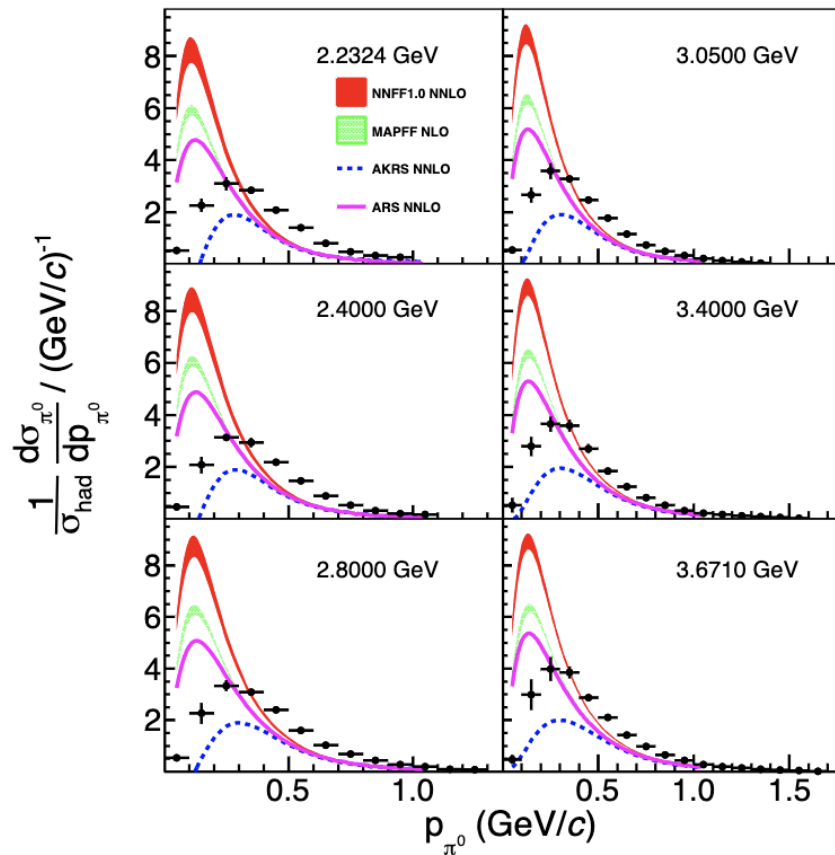
- The accuracy is better than 2.6% below 3.1 GeV and 3.0% above.
- Larger than the pQCD prediction by 2.7σ between 3.4 ~ 3.6 GeV.

The R program at BESIII



- R values in full range 1.84 - 4.95 GeV to come soon.

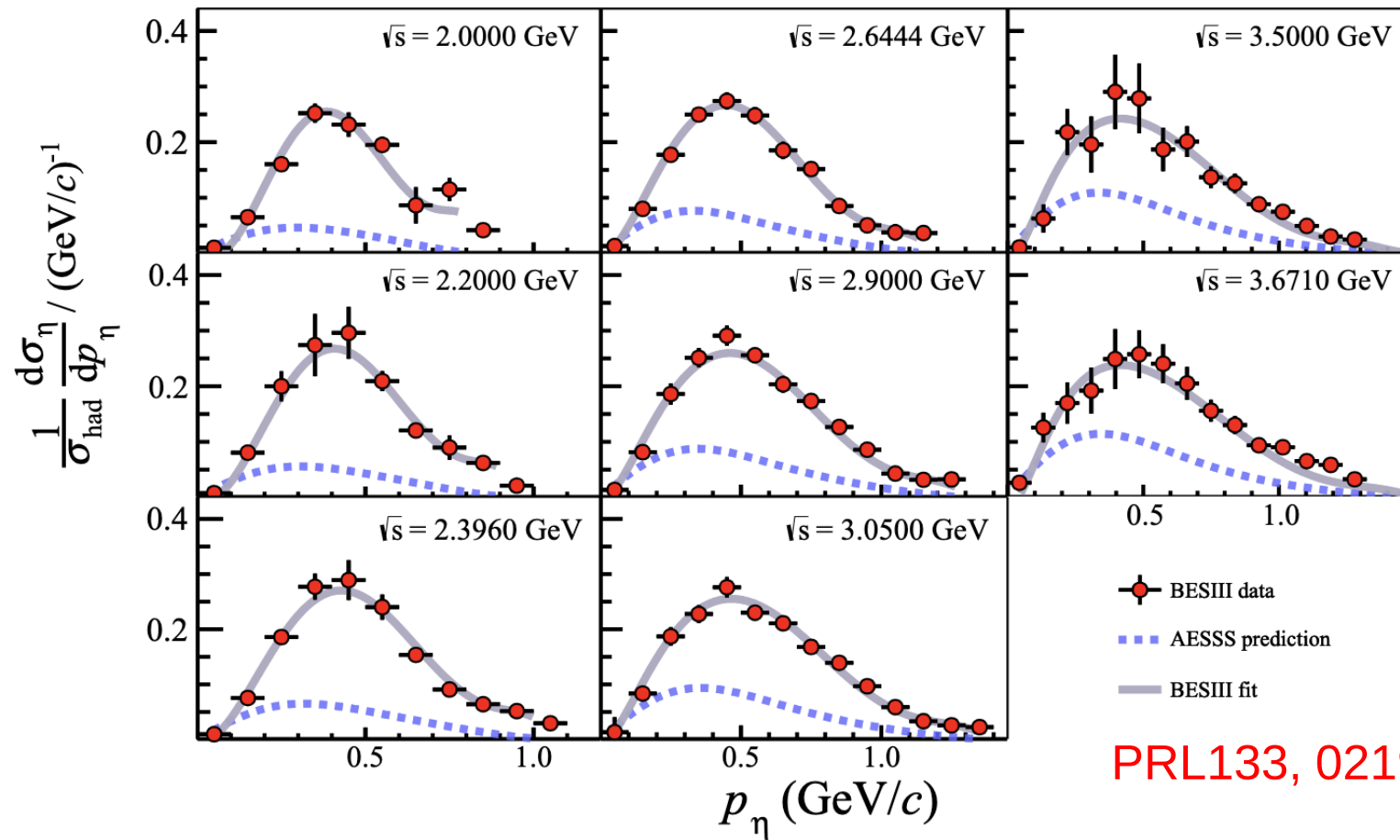
Inclusive π^0 and K_S productions in e^+e^- annihilations



PRL 130, 231901 (2023)

- Broad relative hadron energy range z_h from 0.1 to 0.9 with precision of around 3% at $z_h \sim 0.4$.
- Results significantly deviate from several theoretical calculations based on the existing FFs
- Provide brand new inputs in low-energy region to global fits of fragmentation function

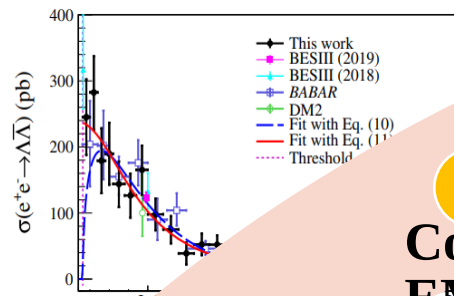
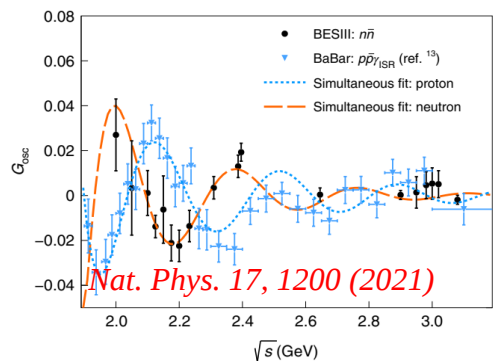
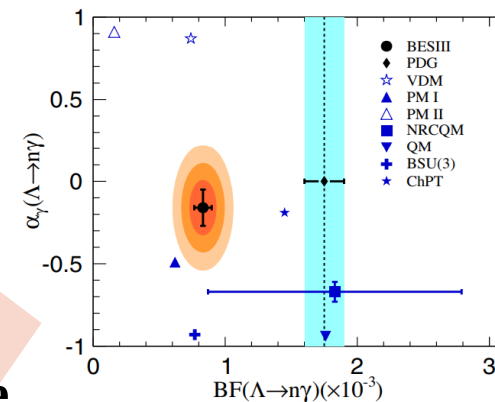
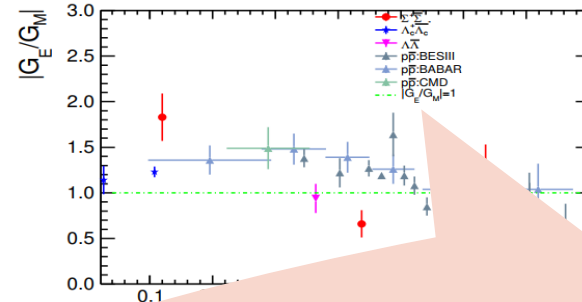
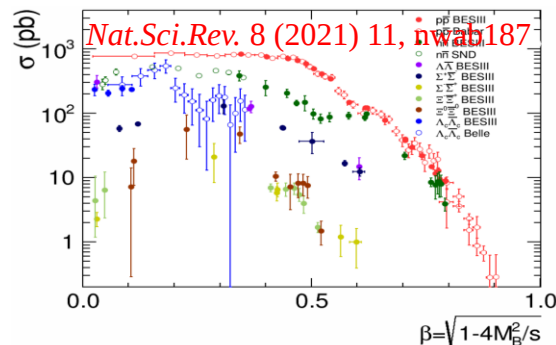
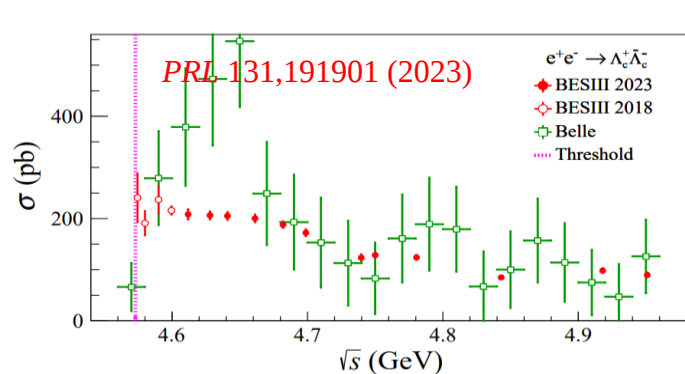
Inclusive η productions in e^+e^- annihilations



PRL133, 021901 (2024)

- Wide hadron energy fraction coverage $z_h \in (0.1, 0.9)$;
- Disagreement with theory prediction, especially at lower energy.

Baryon Electromagnetic form factors (EMFF)



Complete EMFF

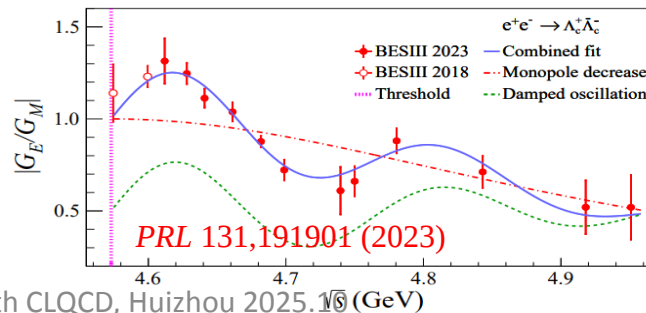
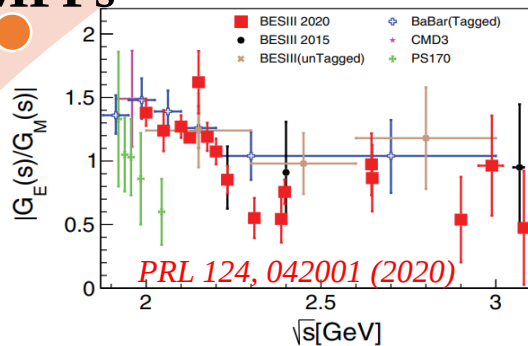
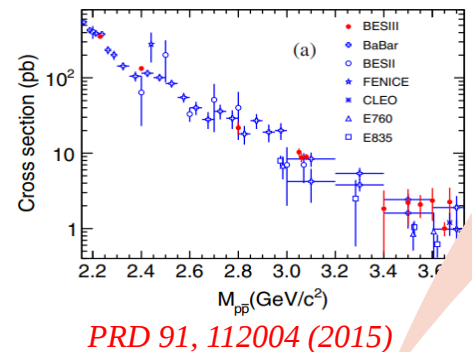
CP measurement

Weak radiative baryon decay

More precise results input to non-pQCD and SM!

Threshold effect

Baryon EMFFs

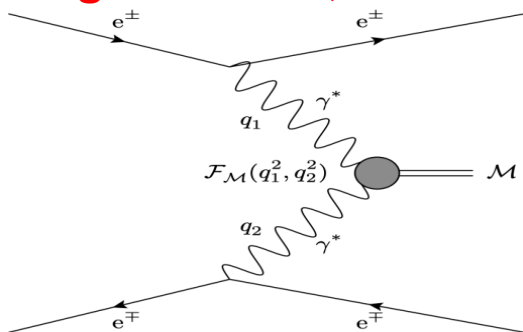


Highlight: light spectroscopy

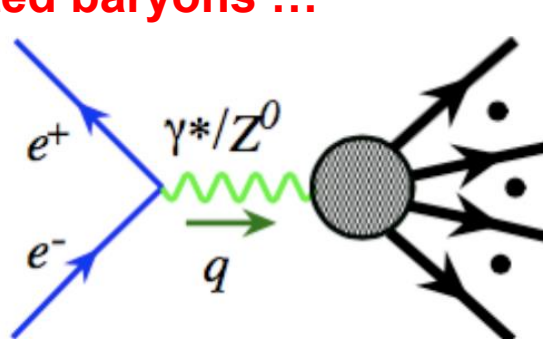
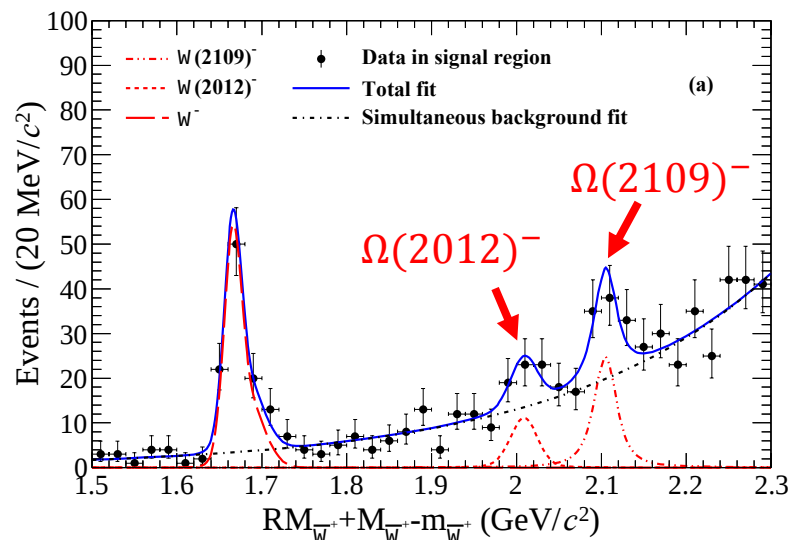
Light hadrons via Electron-positron annihilations, charmonium decays, charmed hadron decays, two-photon processes ...

It is crucial to search for light exotic states: glueball, hybrid, multi-quark states ...

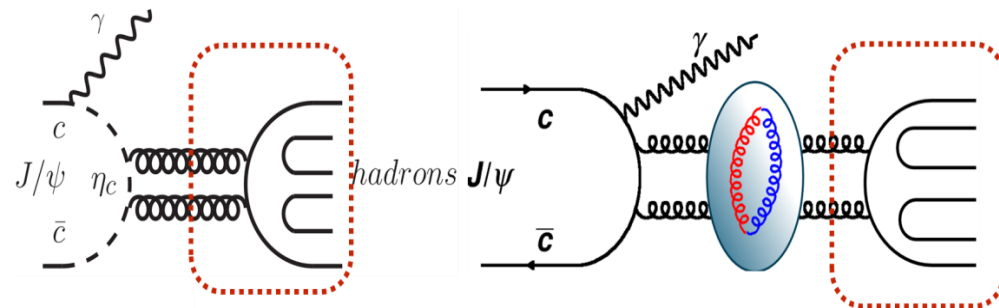
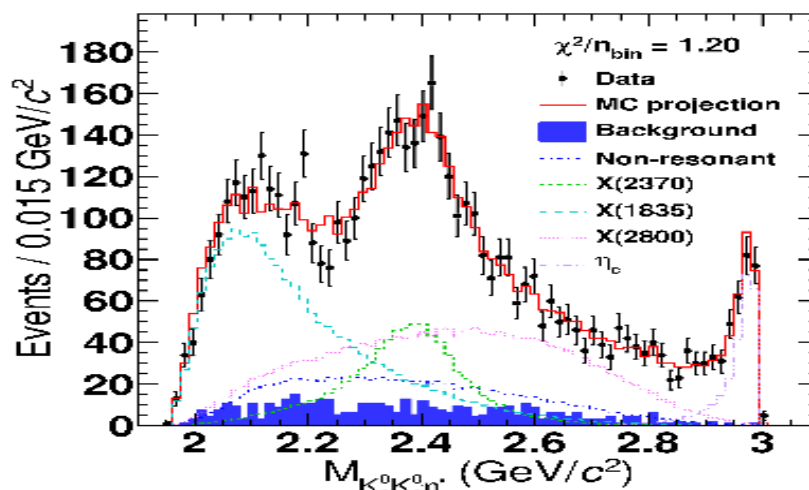
Rich light scalars, missed excited baryons ...



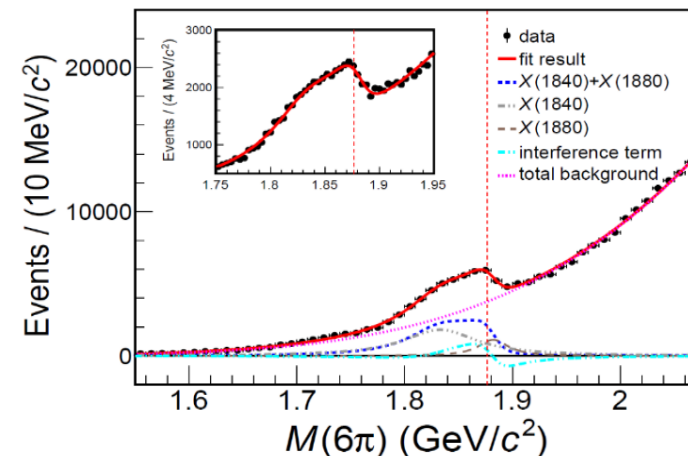
Evidence for Two Excited Ω^- Hyperons
PRL 134, 131903 (2025)



Discovered a Glueball-like Particle – X(2370)
PRL 132, 181901 (2024)



Discovery of fine structure near proton-
anti-proton threshold:: X(1840) and X(1880),
PRL132, 151901 (2024)



Hadron spectroscopy: high-statistics data

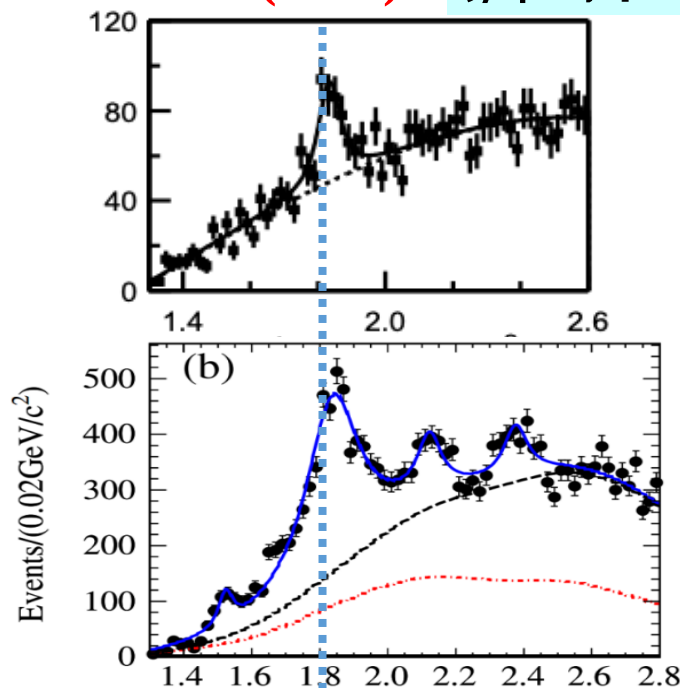
58 million

X(1835)

$J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

Structure

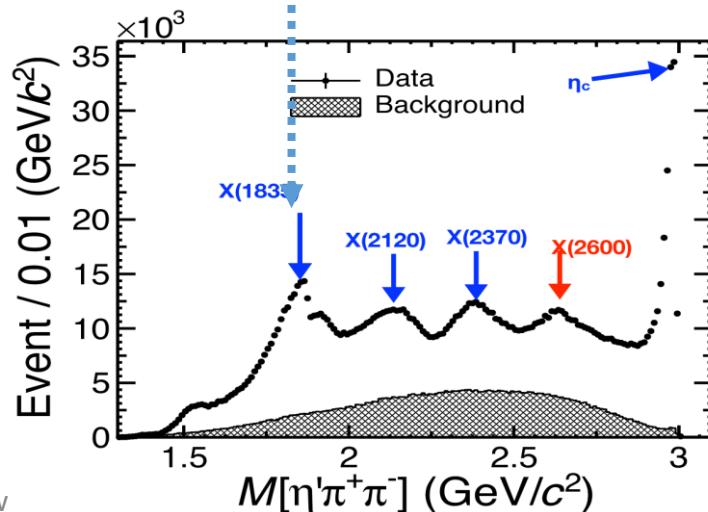
PRL 95, 262001 (2005)



More structures

PRL106, 072002 (2011)

225 million

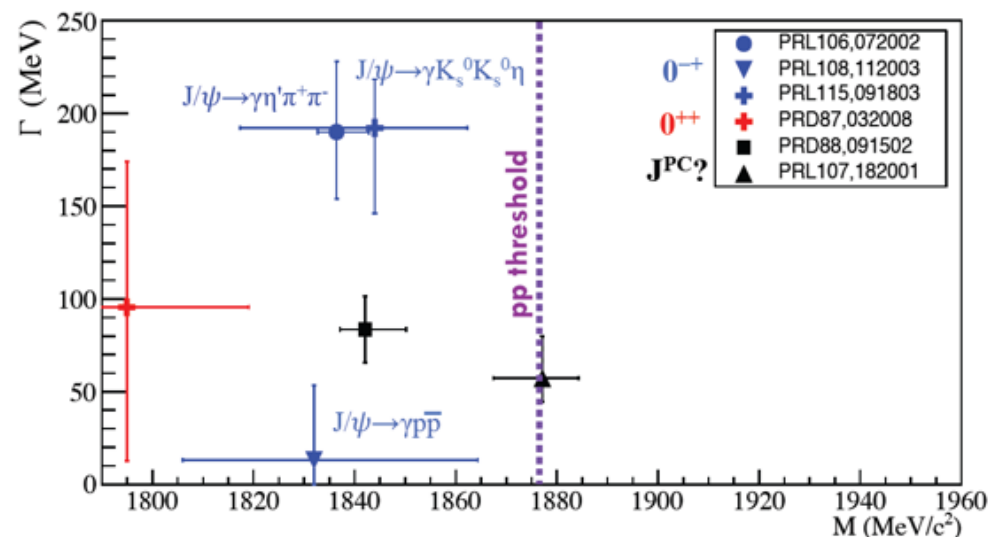


Fine structures

PRL129, 042001 (2022)

10 billion

Rich spectra



You never have enough J/ψ events

—The case for a J/ψ factory—

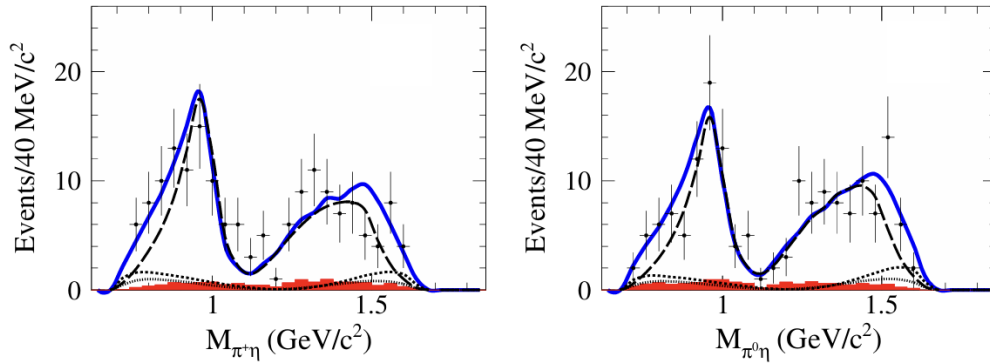
Stephen Lars Olsen

arXiv:2506.20975

BESIII Highlight: light hadron from charmed hadron decays

➤ $a_0(980)$ and $f_0(980)$: two-quark $q\bar{q}$ or tetraquark $q^2\bar{q}^2$?

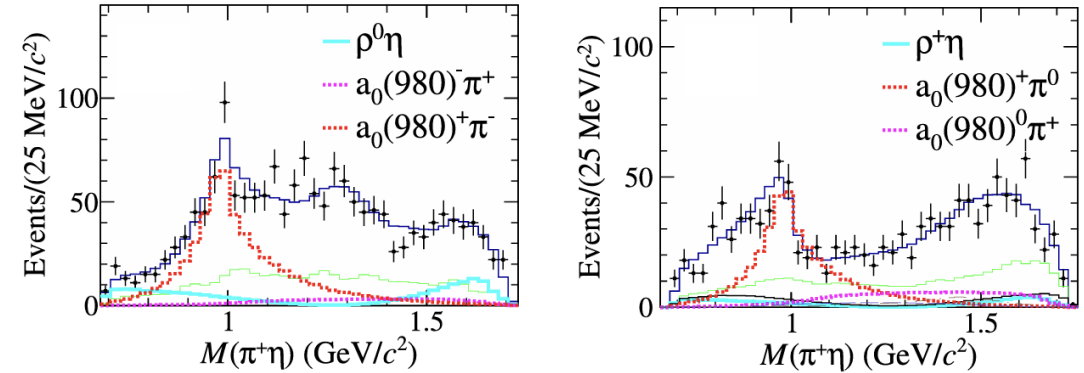
PRL 123, 112001 (2019)



W-Annihilation

$$B(D_S^+ \rightarrow a_0 \pi, a_0 \rightarrow \pi \eta) = (1.46 \pm 0.27)\%$$

PRD 110, L111102 (2024)

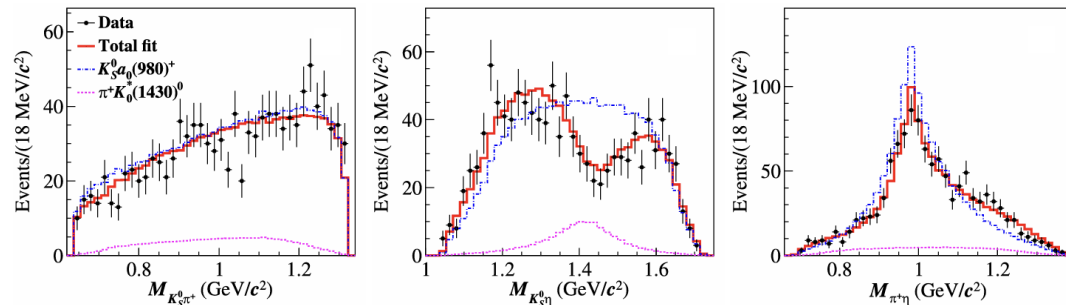


W-Emission & W-Exchange

$$B(D^+ \rightarrow a_0^0 \pi^+) = (3.7 \pm 1.1); (a_0^+ \pi^0) = (9.5 \pm 1.3) \times 10^{-4}$$

$$B(D^0 \rightarrow a_0^+ \pi^-) = (5.5 \pm 0.9); (a_0^- \pi^+) = (0.7 \pm 0.2) \times 10^{-4}, a_0 \rightarrow \pi \eta$$

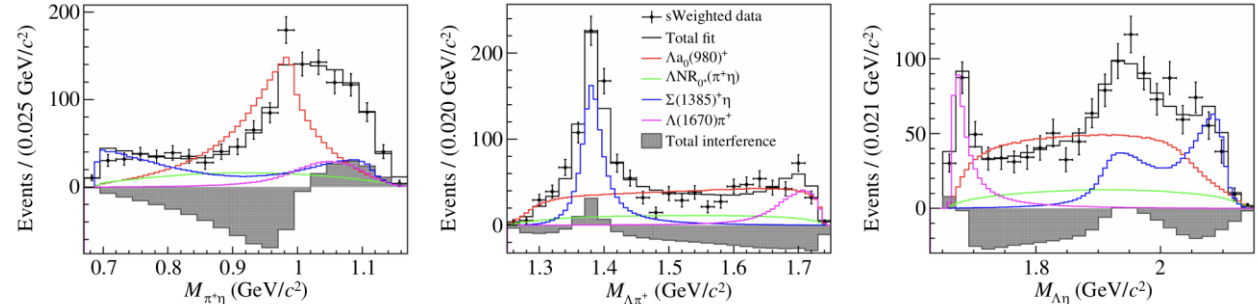
PRL 132, 131903 (2024)



W-Emission

$$B(D^+ \rightarrow a_0^+ K_S^0, a_0 \rightarrow \pi \eta) = (1.33 \pm 0.06)\%$$

PRL 134, 021901 (2025)



W-Emission & W-Exchange

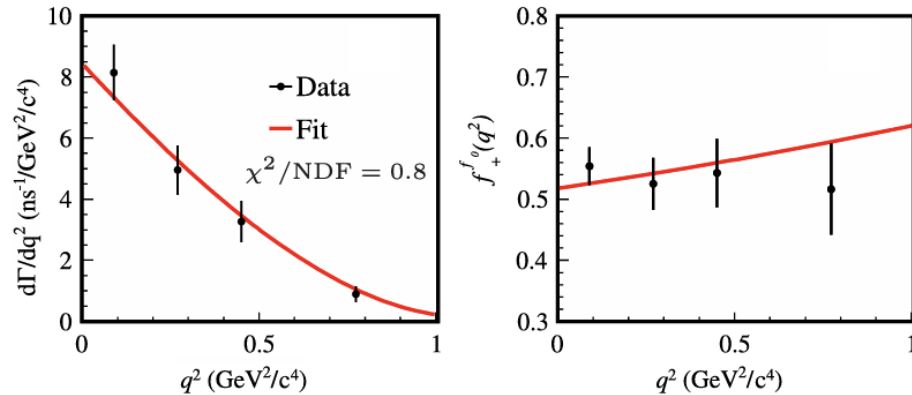
$$B(\Lambda_c^+ \rightarrow a_0^+ \Lambda, a_0 \rightarrow \pi \eta) = (1.05 \pm 0.18)\%$$

All of the measured branching fractions deviate from the predictions made by $q\bar{q}$ model $\Rightarrow q^2\bar{q}^2$ and Final State Interaction?

BESIII Highlight: light hadron from charmed hadron decays

➤ $\alpha_0(980)$ and $f_0(980)$: two-quark $q\bar{q}$ or tetraquark $q^2\bar{q}^2$?

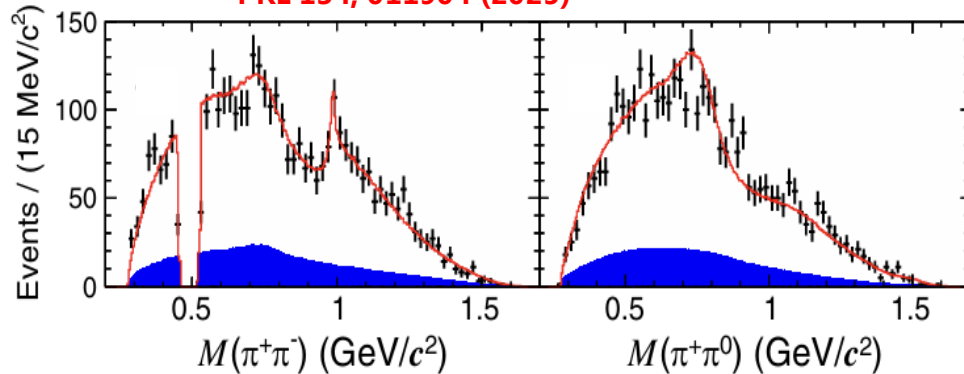
PRL 132, 141901 (2024)



$$B(D_s^+ \rightarrow f_0 e^+ \nu_e, f_0 \rightarrow \pi^+ \pi^-) = (1.72 \pm 0.16) \times 10^{-3}$$

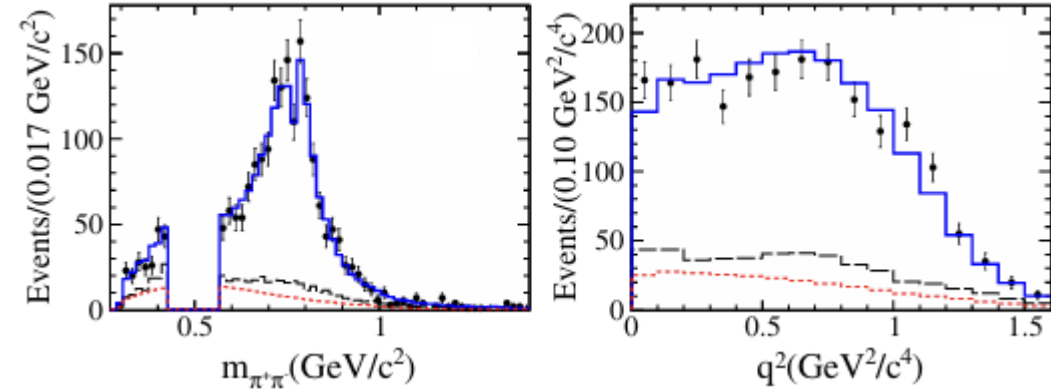
$$f_+^{f_0}(0) = 0.52 \pm 0.04$$

PRL 134, 011904 (2025)



$$B(D_s^+ \rightarrow f_0(980) \rho^+, f_0 \rightarrow \pi^+ \pi^-) = (2.57 \pm 0.48) \times 10^{-3}$$

PRL 122, 062001 (2019)



$$B(D^+ \rightarrow f_0 e^+ \nu_e, f_0 \rightarrow \pi^+ \pi^-) < 2.8 \times 10^{-5}$$

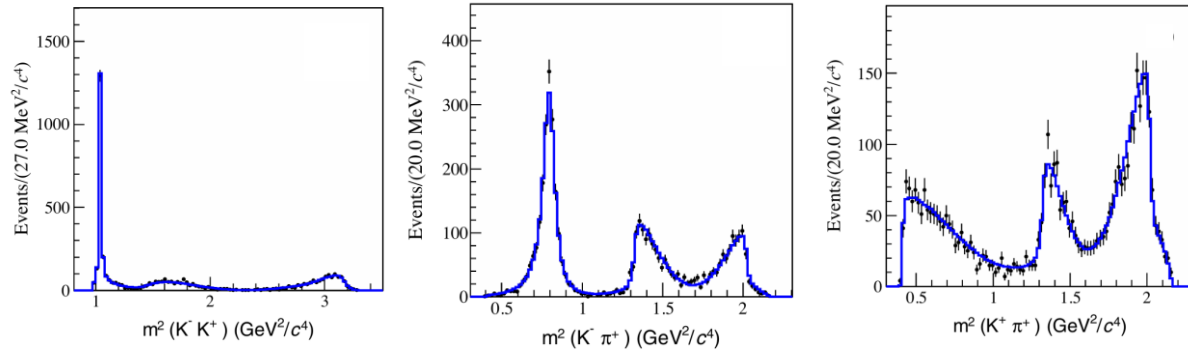
Theoretical predictions by JHEP12(2024)226	$q\bar{q}$	$q^2\bar{q}^2$
$f_+^{f_0}(0)$	0.52 ± 0.02	0.53 ± 0.02
$10^{-3} B(D_s^+ \rightarrow f_0 e^+ \nu_e)$	1.69 ± 1.39	1.72 ± 1.48
$10^{-5} B(D^+ \rightarrow f_0 e^+ \nu_e)$	1.3 ± 0.1	2.9 ± 0.7

Still being controversial!

BESIII Highlight: light hadron from charmed hadron decays

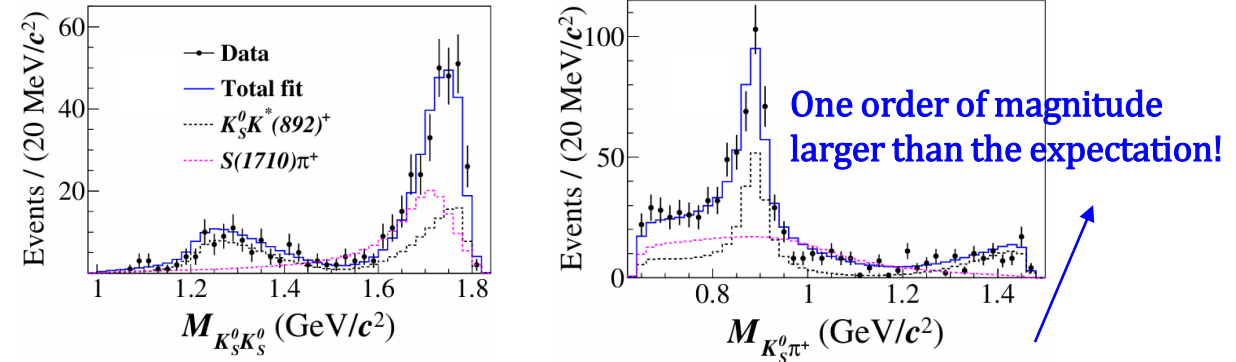
➤ $a_0(1817)$ and $f_0(1710)$

PRD 104, 012016 (2021)



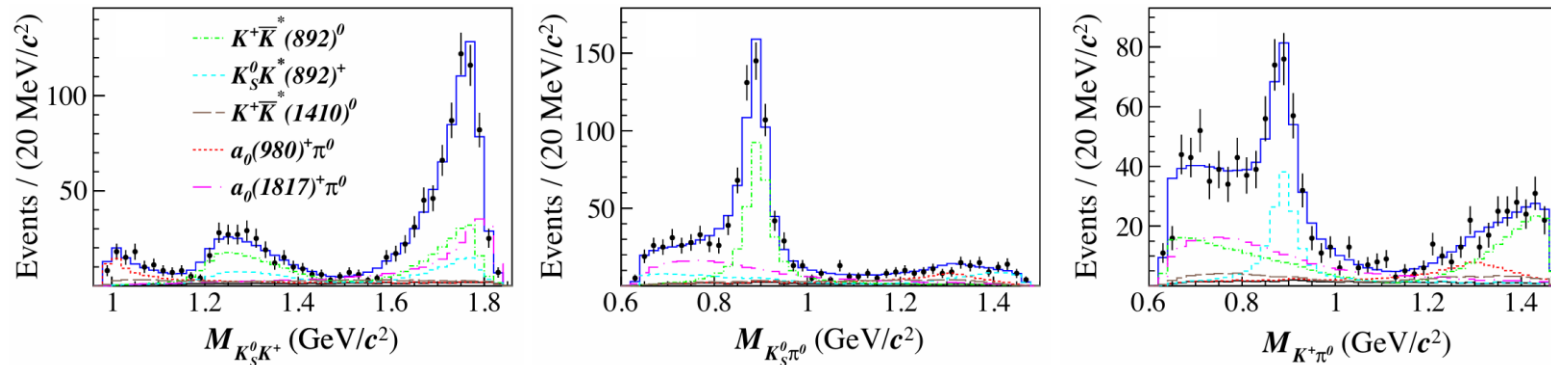
$$B(D_s^+ \rightarrow f_0(1710)\pi^+, f_0 \rightarrow K^+K^-) = (0.10 \pm 0.04)\%$$

PRD 105, L051103 (2022)



$$B(D_s^+ \rightarrow f_0(1710)\pi^+, f_0 \rightarrow K_S^0 K_S^0) = (0.31 \pm 0.03)\%$$

PRL 129, 182001 (2022)



Isospin-one partner of $f_0(1710)$ or $X(1812)$?

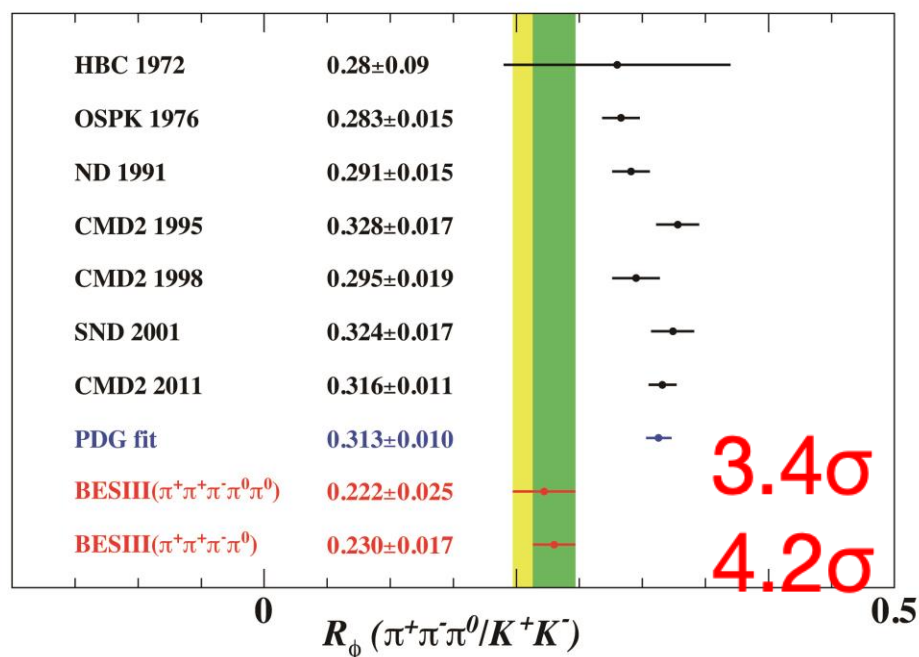
$$B(D_s^+ \rightarrow a_0(1817)^+\pi^0, a_0 \rightarrow K_S^0 K^+) = (3.44 \pm 0.61) \times 10^{-3}$$

$$\text{Mass: } (1.817 \pm 0.02)\text{GeV}/c^2 \quad \text{Width: } (0.097 \pm 0.027)\text{GeV}/c^2$$

Highlight: Puzzle of ϕ decays in charm

- In $D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0$, $D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0$ and $K_S^0 K_L^0 \pi^+$ decays, Relative Branching Fraction of ϕ meson deviate from PDG;
- More results are coming. New mechanism?

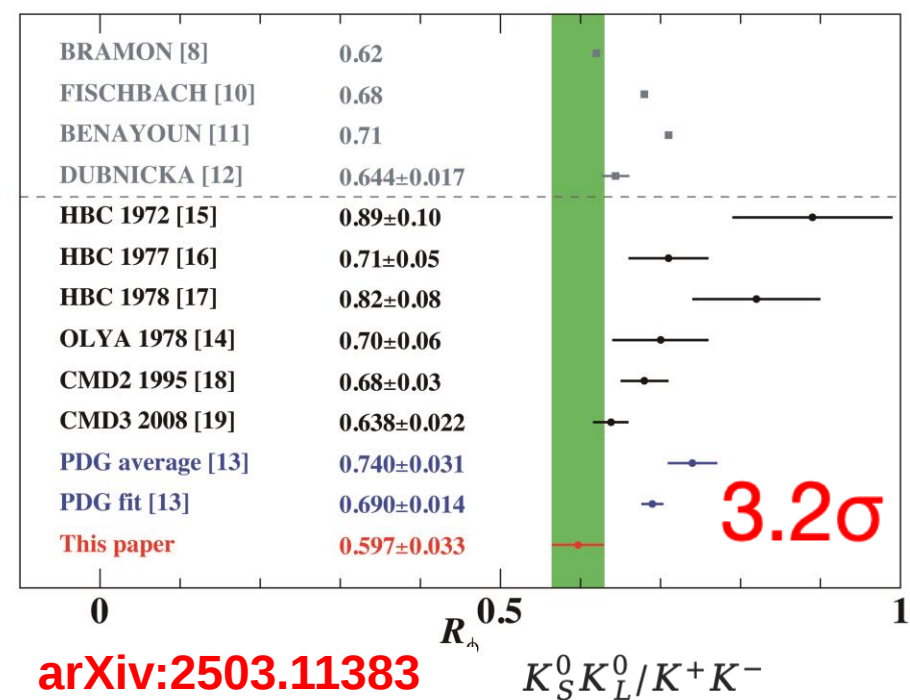
$$R_\phi = \frac{\mathcal{B}(\phi \rightarrow \pi^+ \pi^- \pi^0)}{\mathcal{B}(\phi \rightarrow K^+ K^-)}$$



arXiv:2501.04451

PRL 134, 011904 (2025)

$$R_\phi = \frac{\mathcal{B}(\phi \rightarrow K_S K_L)}{\mathcal{B}(\phi \rightarrow K^+ K^-)}$$



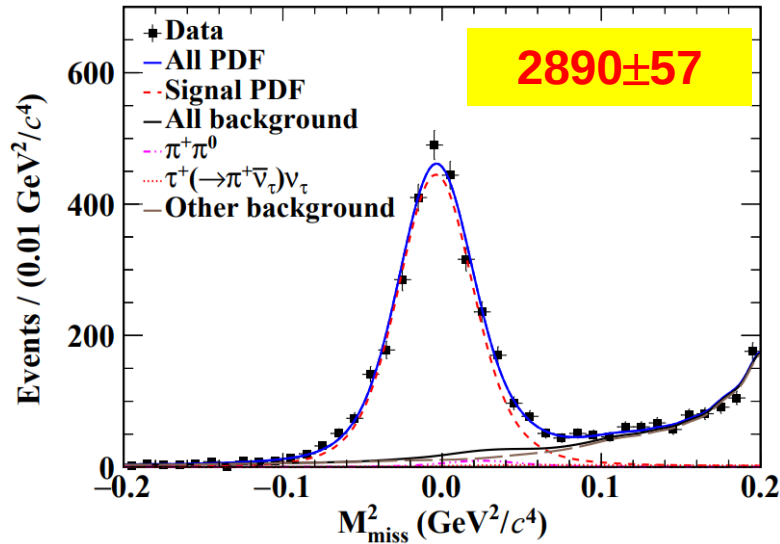
arXiv:2503.11383

Accepted by PRL

BESIII Highlights: The most precise measurement of $D^+ \rightarrow \mu^+ \nu_\mu$

The most precise measurement of $D^+ \rightarrow \mu^+ \nu_\mu$ with 20.3 fb^{-1} @ 3.773 GeV

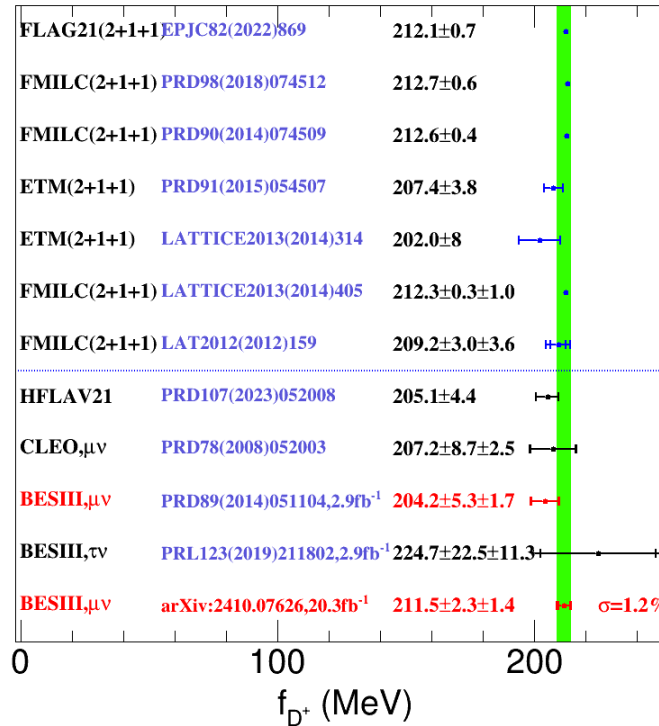
arXiv:2410.07626
PRL 135, 061801 (2025)



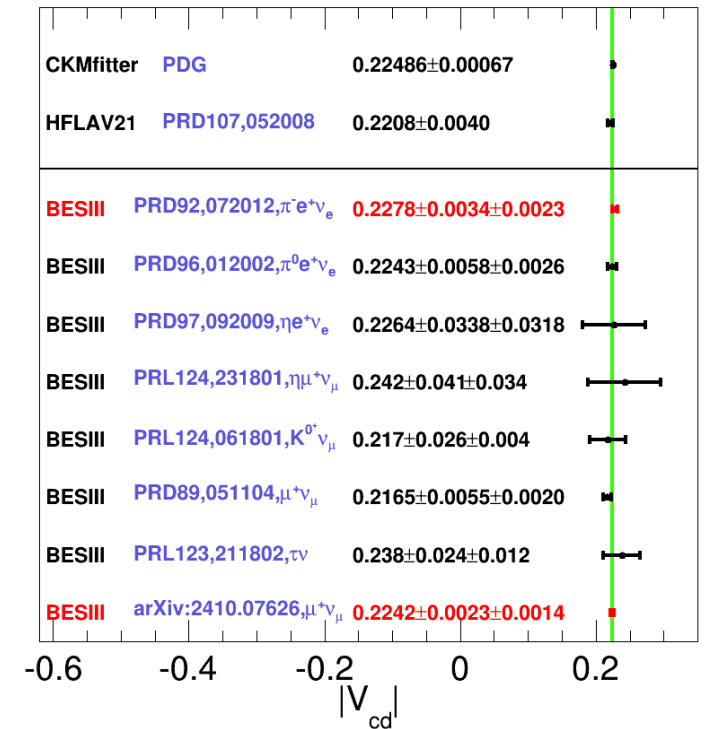
The most precise to date

$$B[D^+ \rightarrow \mu^+ \nu] = (3.98 \pm 0.08 \pm 0.04) \times 10^{-4}$$

$$f_{D^+} |V_{cd}| = 47.53 \pm 0.48 \pm 0.27 \text{ MeV}$$



The decay constant



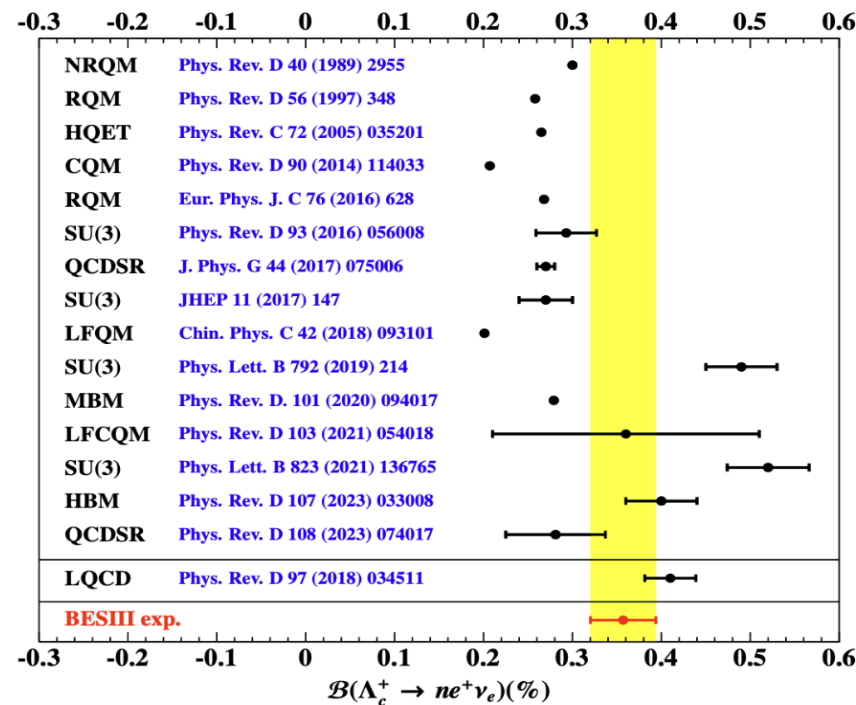
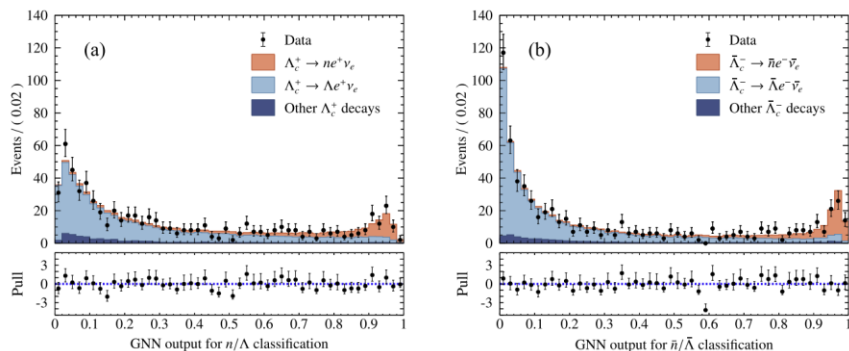
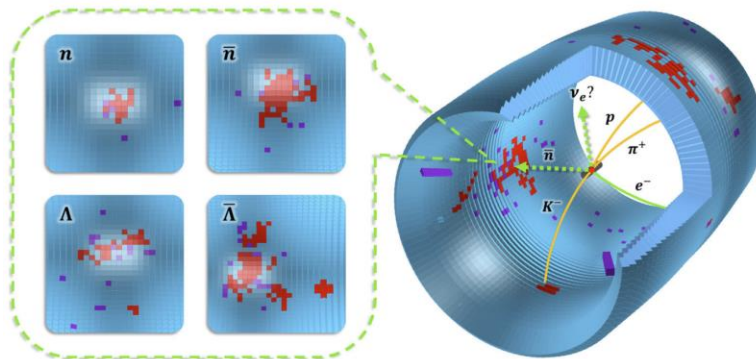
The value of V_{cd}

Precision $\sim$ 1.2%

Highlights : observation of $\Lambda_c^+ \rightarrow ne^+\nu_e$

Nature Commun. 16, 681 (2025)

- A novel Deep Learning is utilized to separate signals from dominant background.
- First observation of $\Lambda_c^+ \rightarrow ne^+\nu_e$
 - $\mathcal{B}(\Lambda_c^+ \rightarrow ne^+\nu_e) = (0.357 \pm 0.034_{\text{stat}} \pm 0.014_{\text{syst}})\% (> 10\sigma)$
 - $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.005_{\text{LQCD}} \pm 0.001_{\tau_{\Lambda_c^+}}$
- This measurement demonstrates a level of precision comparable to the LQCD prediction.
- The absence of HCAL restricted us to extract the form factors.
- Still, the BF provides significant insights, shedding light on the di-quark structure within the Λ_c^+ core and the $\pi - N$ clouds in the low Q^2



BESIII CPV in hyperon decays, #events do we need?

CPV in SM is small :

B meson : $O(1)$ discovered (2001)

10^3

Experiment

B factory

K meson : $O(10^{-3})$ discovered (1964)

10^6

Fix targets

D meson : $O(10^{-4})$ discovered (2019)

10^8

LHCb

Λ_b baryon: discovered (2025)

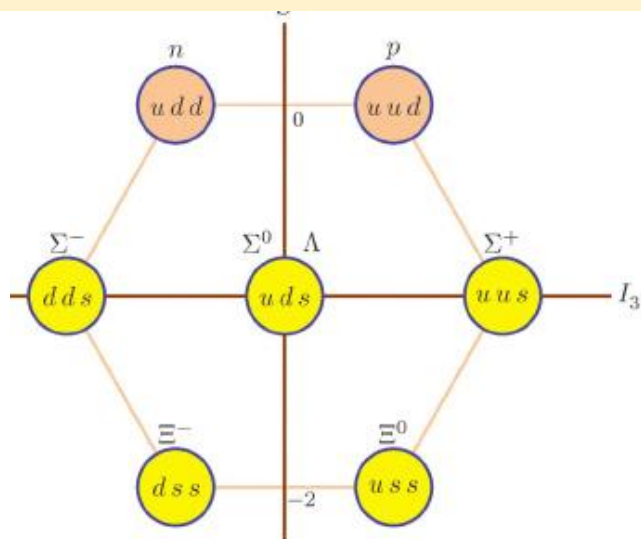
LHCb

Hyperon : $O(10^{-4})$ no evidence (10^{-2})

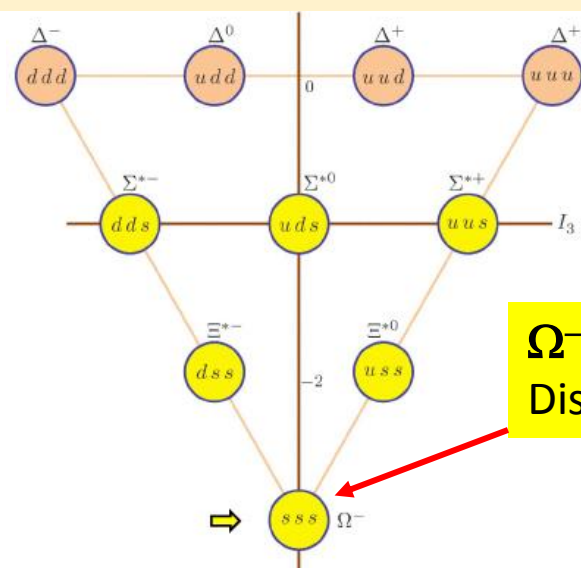
$O(10^8)$

Fix targets

→ BESIII, hyperon factory ?



Flavor-SU(3) Octet of spin $\frac{1}{2}$



Ω^- was predicted by quark model
Discovered in 1964 at BNL.

Flavor-SU(3) Decuplet of spin $\frac{3}{2}$

CP observables in hyperon decays



General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. LEE* AND C. N. YANG

Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

Phys. Rev. 108, 1645 (1957)

The amplitude of spin $\frac{1}{2}$ baryon B_i decay to a spin $\frac{1}{2}$ baryon B_f and π :

$$\mathcal{A} \sim S\sigma_0 + P\sigma \cdot \hat{n}$$

The decay parameters are defined as:

$$\alpha_Y = \frac{2 \operatorname{Re}(S^*P)}{|S|^2 + |P|^2}, \quad \beta_Y = \frac{2 \operatorname{Im}(S^*P)}{|S|^2 + |P|^2}, \quad \gamma_Y = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

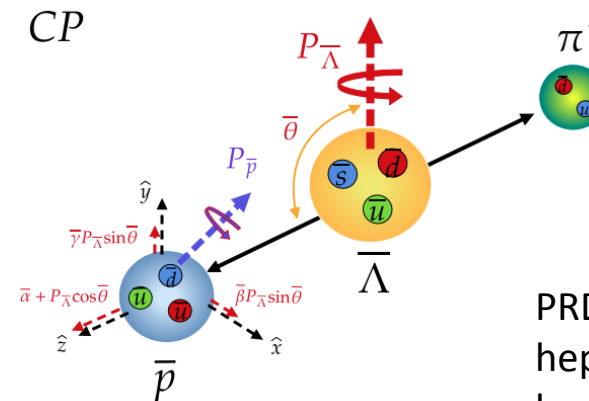
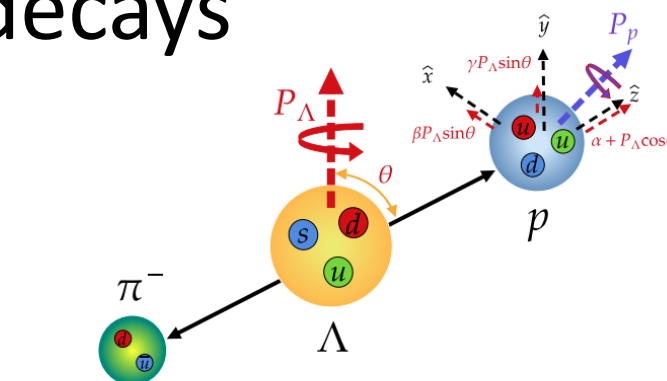
Two complex amplitudes: **ϕ weak phase, δ strong phase**

$$S = \sum^i S_i e^{i(\phi_i^S + \delta_i^S)}, \quad P = \sum^i P_i e^{i(\phi_i^P + \delta_i^P)}$$

Under CP transformation:

$$\bar{S} = -\sum^i S_i e^{i(-\phi_i^S + \delta_i^S)}, \quad \bar{P} = \sum^i P_i e^{i(-\phi_i^P + \delta_i^P)}$$

If CP conserved: $S \xrightarrow{CP} -S$ $\xrightarrow{\quad} \alpha \xrightarrow{CP} \bar{\alpha} = -\alpha$
 $P \xrightarrow{CP} P$ $\xrightarrow{\quad} \beta \xrightarrow{CP} \bar{\beta} = -\beta$



PRD 34, 833 (1986)
 hep-ph/991023
 hep-ph/0002210

CPV observables

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} + \Delta$$

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \approx \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} + \Delta$$

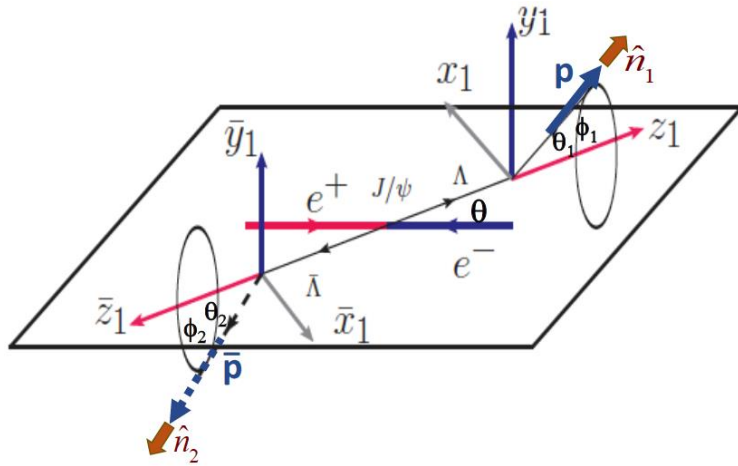
BESIII If $\Delta\Phi \neq 0$, Λ and $\bar{\Lambda}$ are transversely polarized

Correlated 5-dim. angular distribution $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$

$$\mathcal{W}(\xi; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+) = 1 + \alpha_\psi \cos^2 \theta_\Lambda$$

Unpolarized part

Entangled part



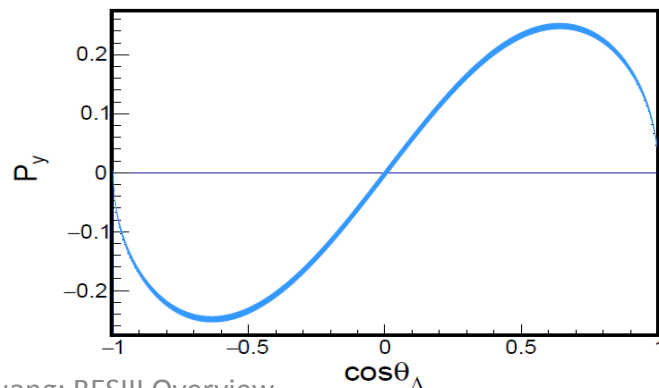
$$+ \alpha_- \alpha_+ [\sin^2 \theta_\Lambda (n_{1,x} n_{2,x} - \alpha_\psi n_{1,y} n_{2,y}) + (\cos^2 \theta_\Lambda + \alpha_\psi) n_{1,z} n_{2,z}]$$

$$+ \alpha_- \alpha_+ \sqrt{1 - \alpha_\psi^2} \cos(\Delta\Phi) \sin \theta_\Lambda \cos \theta_\Lambda (n_{1,x} n_{2,z} + n_{1,z} n_{2,x})$$

$$+ \sqrt{1 - \alpha_\psi^2} \sin(\Delta\Phi) \sin \theta_\Lambda \cos \theta_\Lambda (\alpha_- n_{1,y} + \alpha_+ n_{2,y}),$$

Polarized part

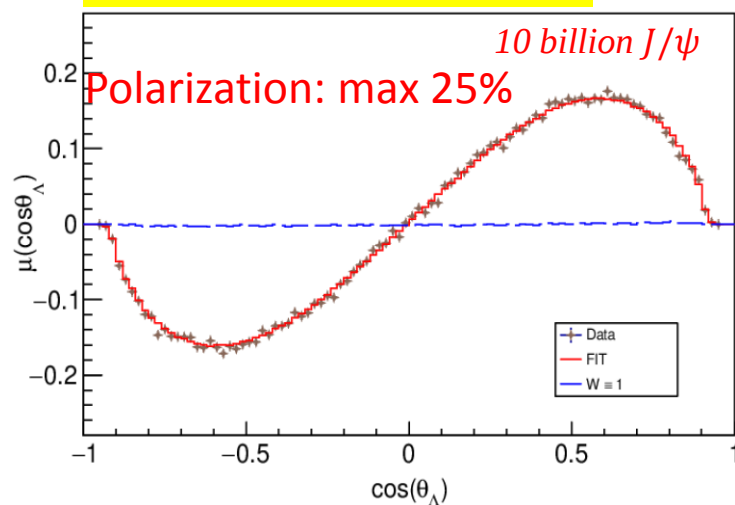
Polarization-term can be used to determine α_- and α_+ simultaneously



$$P_y(\cos \theta_\Lambda) = \frac{\sqrt{1 - \alpha_\psi^2} \sin(\Delta\Phi) \cos \theta_\Lambda \sin \theta_\Lambda}{1 + \alpha_\psi \cos^2 \theta_\Lambda}$$

The most precise CP test *in* Λ and $\bar{\Lambda}$ decay

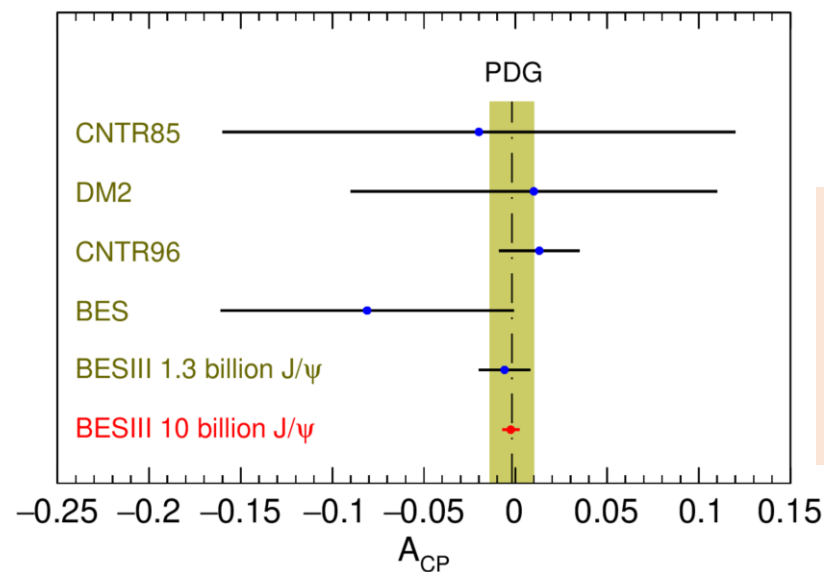
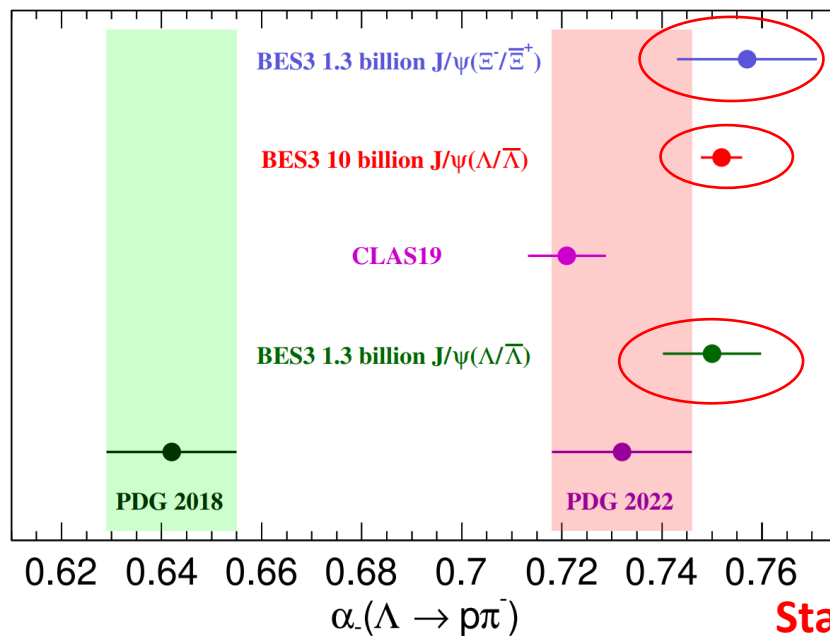
PRL 129, 131801 (2022)



Nat. Phys. 15, 631 (2019)

Paras.	This Work (10 billion J/ψ)	Previous Results (1.3 billion J/ψ)
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$-0.006 \pm 0.012 \pm 0.007$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0020$	—

More than 10 standard deviation shift from all previous measurements

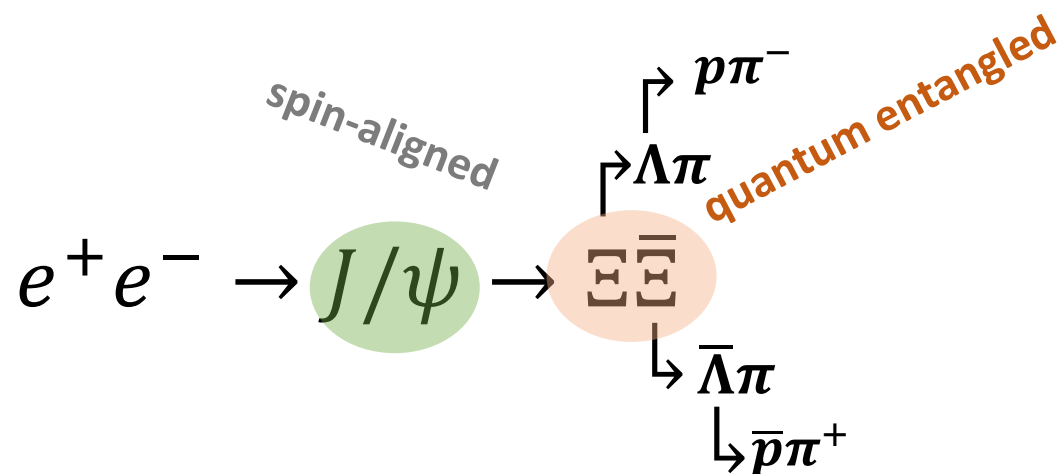


Sensitivity of A_{CP} : below 0.5% unprecedented precision

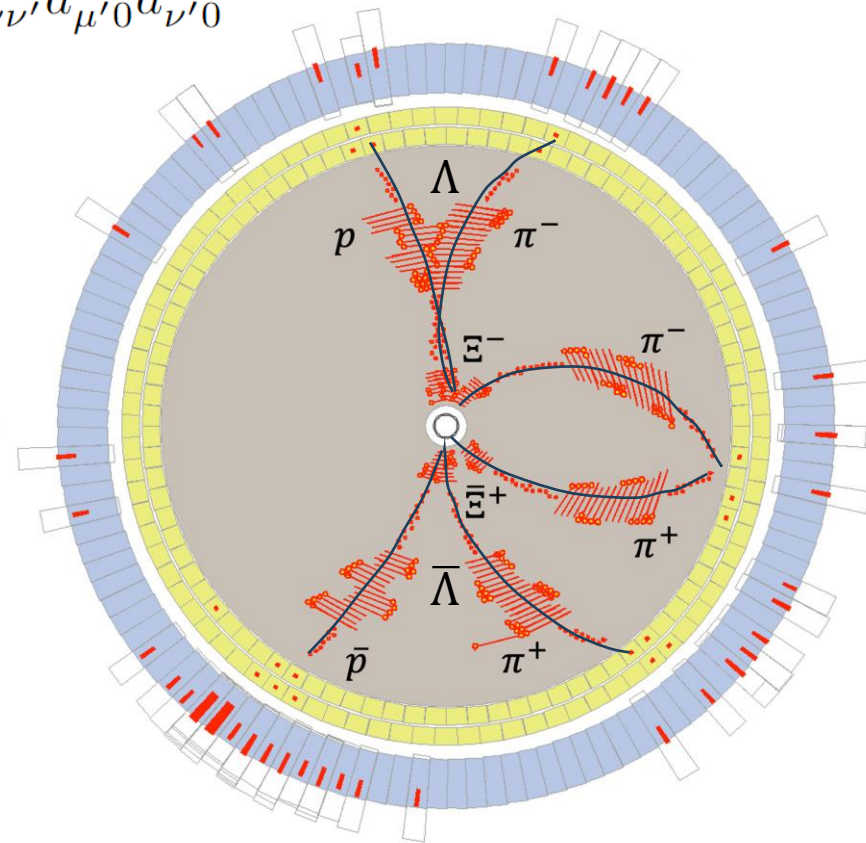
Standard model prediction : $A_{CP} \sim 10^{-4}$ (PRD 34, 833 (1986))

PLB 772, 16 (2017)

$$\mathcal{W}(\vec{\omega}, \vec{\zeta}) = \sum_{\mu, \nu=0}^3 C_{\mu\nu} \sum_{\mu'=0}^3 \sum_{\nu'=0}^3 a_{\mu\mu'}^{\Xi} a_{\nu\nu'}^{\bar{\Xi}} a_{\mu'0}^{\Lambda} a_{\nu'0}^{\bar{\Lambda}}$$



Through the **sequential decays of Ξ** , the CPV phase can be directly measured!



The *perfect* reaction for hyperon CPV searches!

Search for CPV in Ξ decay

The precision of our analysis (73K $\Xi^- \bar{\Xi}^+$) is comparable with the measurement from HyperCP (144M events), which means that the accuracy of a single event is more than 1000 times higher than HyperCP!

320K $\Xi^0 \bar{\Xi}^0$ pairs

10 billion J/ψ

Ξ^0

Ξ^-

1.3 billion J/ψ

Parameter	Nature 606 (2022) 64-69	Previous result
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016 \text{ rad}$	-
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009 \text{ rad}$	$-0.042 \pm 0.011 \pm 0.011$
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	HyperCP: PRL 93(2004) 011802
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007 \text{ rad}$	-
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2} \text{ rad}$	-
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2} \text{ rad}$	$(10.2 \pm 3.9) \times 10^{-2} \text{ rad}$
$A_{CP}^{\Xi^-}$	$(6 \pm 13 \pm 6) \times 10^{-3}$	-
$\Delta\phi_{CP}^{\Xi^-}$	$(-5 \pm 14 \pm 3) \times 10^{-3} \text{ rad}$	-
A_{CP}^{Λ}	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007 \text{ rad}$	-

Parameter	PRD 108, L031106 (2023)
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$
$\Delta\Phi(\text{rad})$	$1.168 \pm 0.019 \pm 0.018$
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$
$\phi_\Xi(\text{rad})$	$0.0051 \pm 0.0096 \pm 0.0018$
$\bar{\phi}_\Xi(\text{rad})$	$-0.0053 \pm 0.0097 \pm 0.0019$
α_Λ	$0.7551 \pm 0.0052 \pm 0.0023$
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$
$\xi_P - \xi_S(\text{rad})$	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$
$\delta_P - \delta_S(\text{rad})$	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$
$A_{CP}^{\Xi^-}$	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$
$\Delta\phi_{CP}^{\Xi^-}(\text{rad})$	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$
A_{CP}^{Λ}	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$
$\langle\phi_\Xi\rangle(\text{rad})$	$0.0052 \pm 0.0069 \pm 0.0016$
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$

First measurements of the weak (CPV) phase difference in Ξ^-/Ξ^0 decays

Three CP tests in Ξ^-/Ξ^0 decays

The results of 10B J/ψ is on the way!

PRD(L) Editor's Suggestion

$$e^+e^- \rightarrow J/\psi, \psi(3686) \rightarrow \Sigma^+\bar{\Sigma}^-, \Sigma^+ \rightarrow p\pi^0, \bar{\Lambda} \rightarrow \bar{p}\pi^0$$

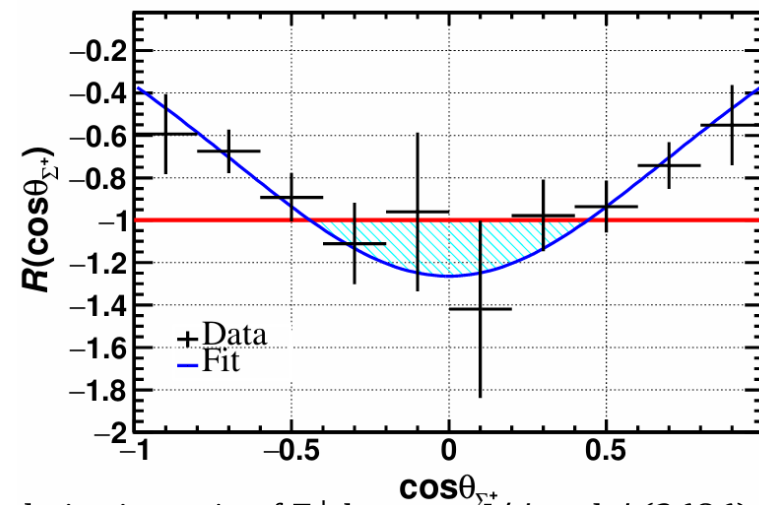
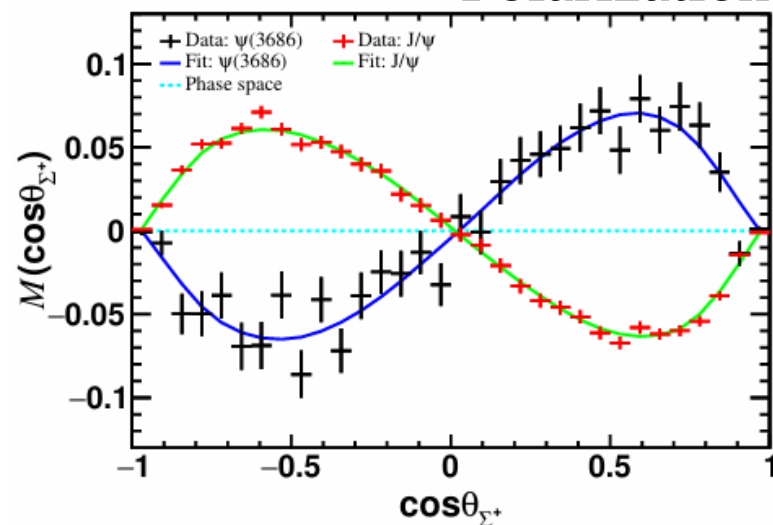
arXiv:2503.17165, PRL 135, 141804 (2025)

10B J/ψ and 2.7B $\psi(3686)$ 1.12 M $\Sigma^+\bar{\Sigma}^-$ pairs reconstructed

Parameter	This Letter	PRL 131, 191802 (2023)
$\alpha_{J/\psi}$	$-0.5047 \pm 0.0018 \pm 0.0010$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.2744 \pm 0.0033 \pm 0.0010$	$-0.270 \pm 0.012 \pm 0.009$
α_0	$-0.975 \pm 0.011 \pm 0.002$	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.999 \pm 0.011 \pm 0.004$	$0.990 \pm 0.037 \pm 0.011$
$\alpha_{\psi(3686)}$	$0.7133 \pm 0.0094 \pm 0.0065$	$0.682 \pm 0.030 \pm 0.011$
$\Delta\Phi_{\psi(3686)}$	$0.427 \pm 0.022 \pm 0.003$	$0.379 \pm 0.070 \pm 0.014$
$\langle\alpha_0\rangle$	$-0.9869 \pm 0.0011 \pm 0.0016$	$-0.994 \pm 0.004 \pm 0.002$
A_{CP}	$-0.0118 \pm 0.0083 \pm 0.0028$	$0.004 \pm 0.037 \pm 0.010$

- Opposite directions of the Σ^+ polarization in J/ψ and $\psi(3686)$ decays
- Most precise measurements of the Σ^+ decay parameters
- Most precise CP test in the decays of Σ^+

Polarizations of Σ^+



Polarization ratio of Σ^+ between J/ψ and $\psi(3686)$ decays

Search for Strong CPV in $\Sigma^0(\rightarrow \Lambda\gamma)$ decay

PRL 133, 101902 (2024)

PLB 788, 535 (2019)

The CPV sources in SM:

- Weak interaction, CKM (observed, but too small)
- Strong interaction, θ -term (Not yet observed)

10 B J/ψ and 2.7 B $\psi(3686)$

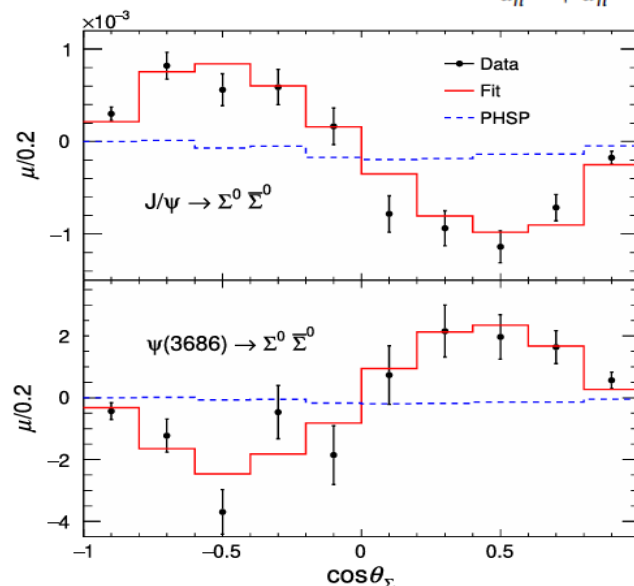
$e^+e^- \rightarrow J/\psi, \psi(3686) \rightarrow \Sigma^0(\rightarrow \Lambda\gamma)\bar{\Sigma}^0(\rightarrow \bar{\Lambda}\gamma), \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$

Parameter	PRL 133, 101902 (2024)
$\alpha_{J/\psi}$	$-0.4133 \pm 0.0035 \pm 0.0077$
$\Delta\Phi_{J/\psi}$ (rad)	$-0.0828 \pm 0.0068 \pm 0.0033$
$\alpha_{\psi(3686)}$	$0.814 \pm 0.028 \pm 0.028$
$\Delta\Phi_{\psi(3686)}$ (rad)	$0.512 \pm 0.085 \pm 0.034$
α_{Σ^0}	$-0.0017 \pm 0.0021 \pm 0.0018$
$\bar{\alpha}_{\Sigma^0}$	$0.0021 \pm 0.0020 \pm 0.0022$
α_{Λ}	$0.730 \pm 0.051 \pm 0.011$
$\bar{\alpha}_{\Lambda}$	$-0.776 \pm 0.054 \pm 0.010$
A_{CP}^{Σ}	$(0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$
A_{CP}^{Λ}	$(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$

The Transition EDM of $\Sigma^0(\rightarrow \Lambda\gamma)$

$$\frac{d_{\Sigma\Lambda}}{d_n} = \frac{d_{\Sigma\Lambda}^{\text{tree}} + d_{\Sigma\Lambda}^{\text{loop}}}{d_n^{\text{tree}} + d_n^{\text{loop}}} \approx -0.88$$

Neutron EDM



Polarizations of Σ^0

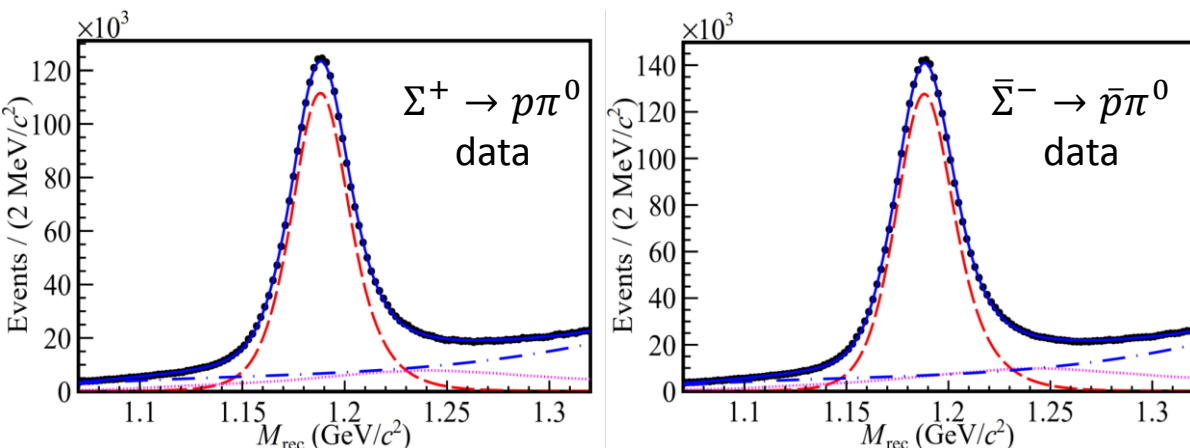
Similar behavior is observed in Σ^+ , but not in Λ or Ξ !

Opposite directions of the Σ^0 polarization

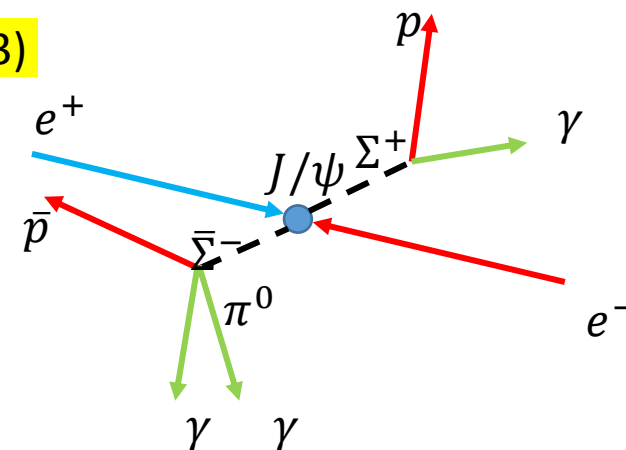
The first attempt to measure the P-violating decay parameter of $\Sigma \rightarrow \Lambda\gamma$.

The first strong-CP test in hyperon decays.

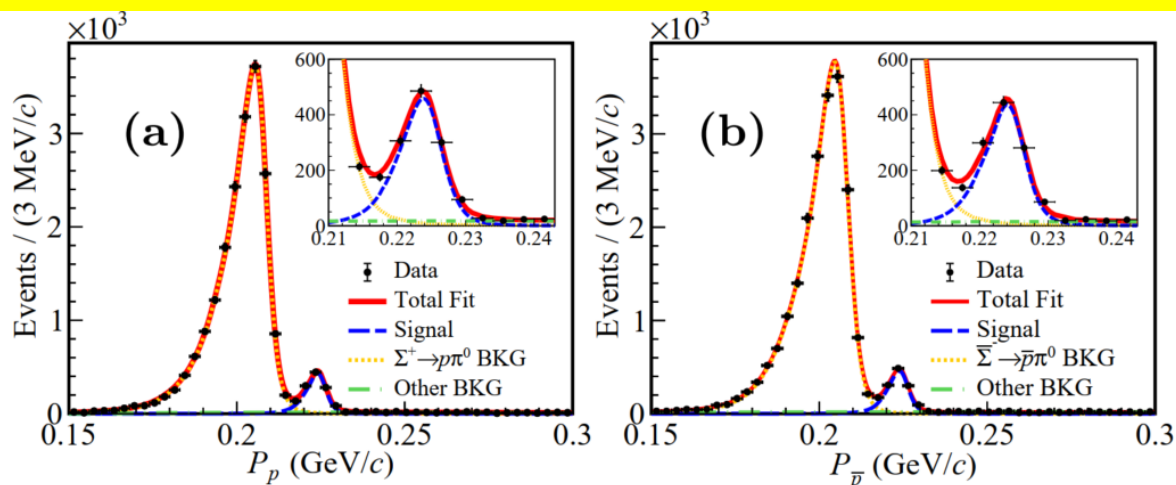
Radiative decay: $\Sigma^+ \rightarrow p\gamma$ in $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$



PRL130, 211901(2023)



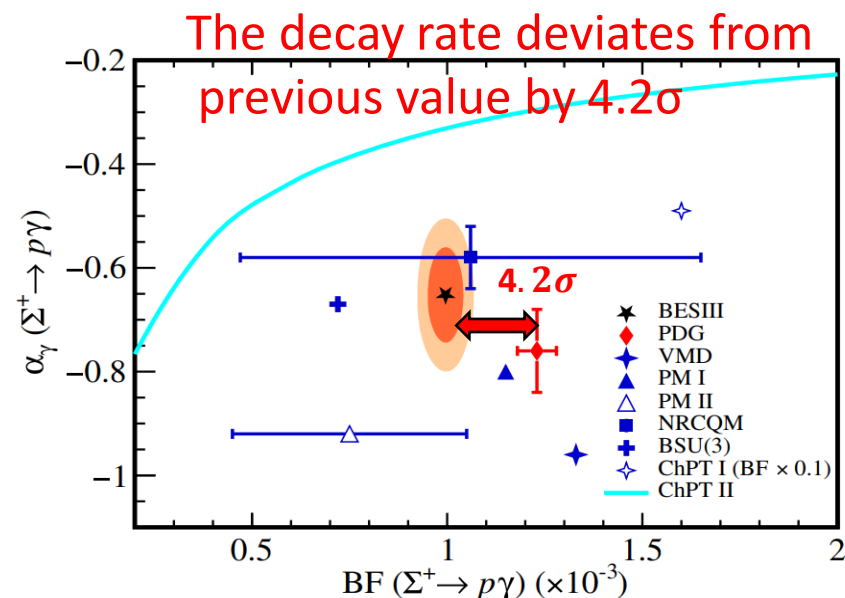
Signal side: momentum distributions of proton in the rest frame of Σ :



The CP asymmetry is calculated to be

$$A_{CP} = (\alpha_- + \alpha_+) / (\alpha_- - \alpha_+) = 0.095 \pm 0.087 \pm 0.022$$

$$\Delta_{CP} = (\mathcal{B}_+ - \mathcal{B}_-) / (\mathcal{B}_+ + \mathcal{B}_-) = 0.006 \pm 0.011 \pm 0.006$$

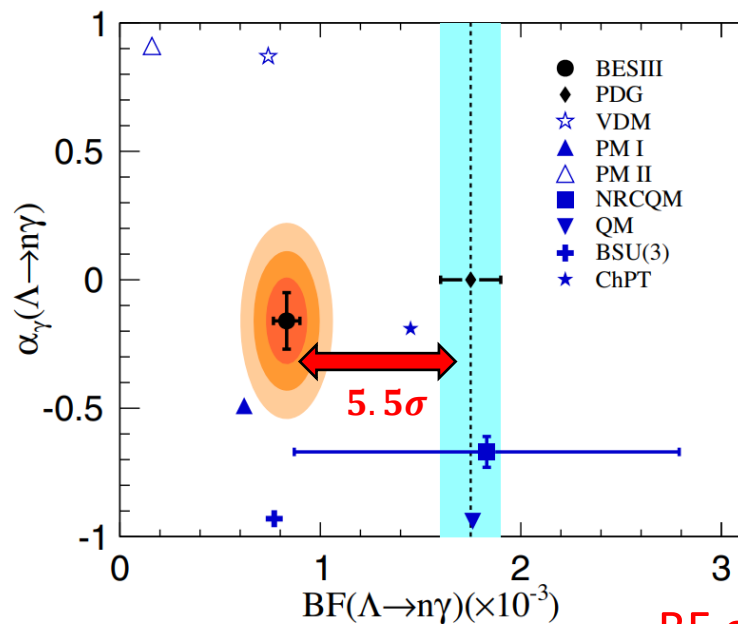
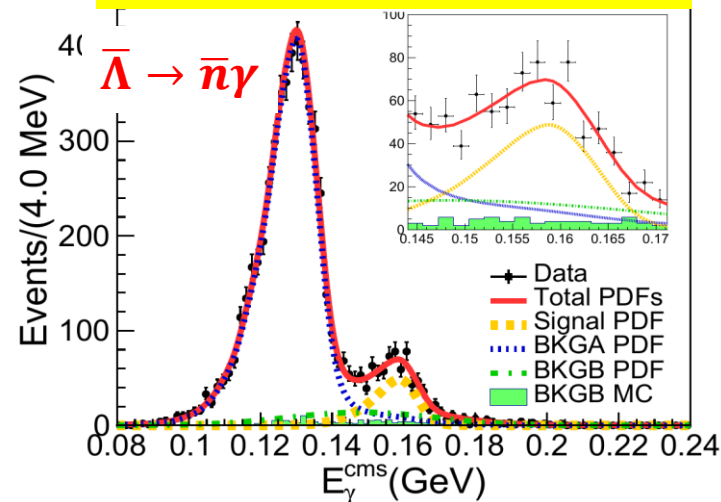
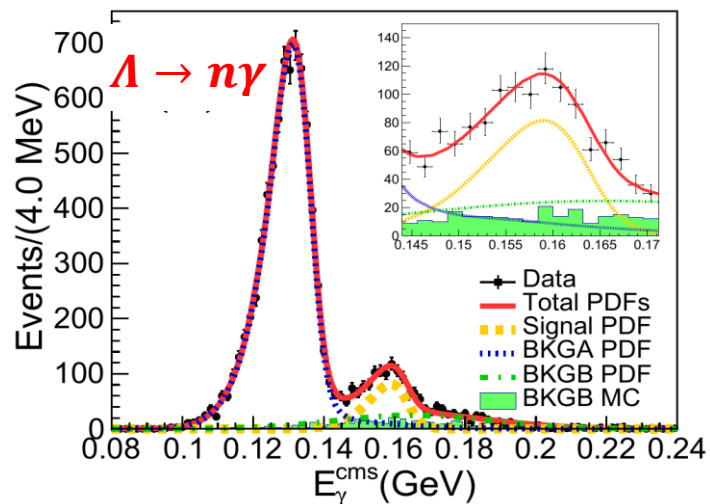


The decay rate $(0.996 \pm 0.022_{stat} \pm 0.017_{syst}) \times 10^{-3}$

The decay parameter: $-0.651 \pm 0.056_{stat} \pm 0.020_{syst}$

Radiative decay: $\Lambda \rightarrow n\gamma$ in $J/\psi \rightarrow \Lambda\bar{\Lambda}$

PRL 129, 212002 (2022)



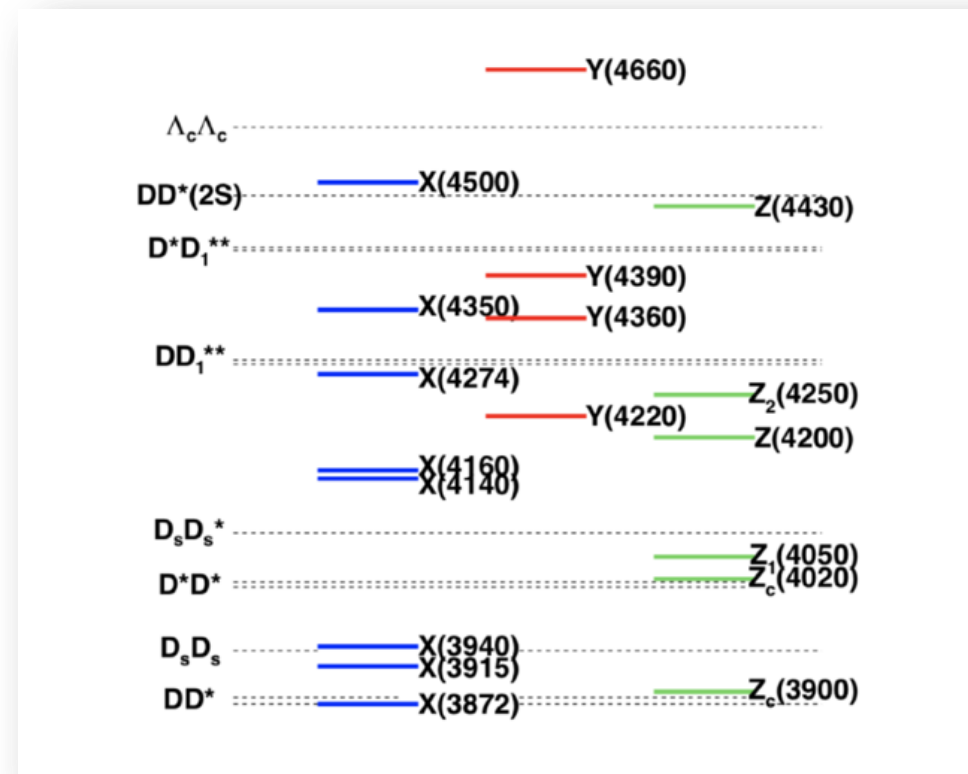
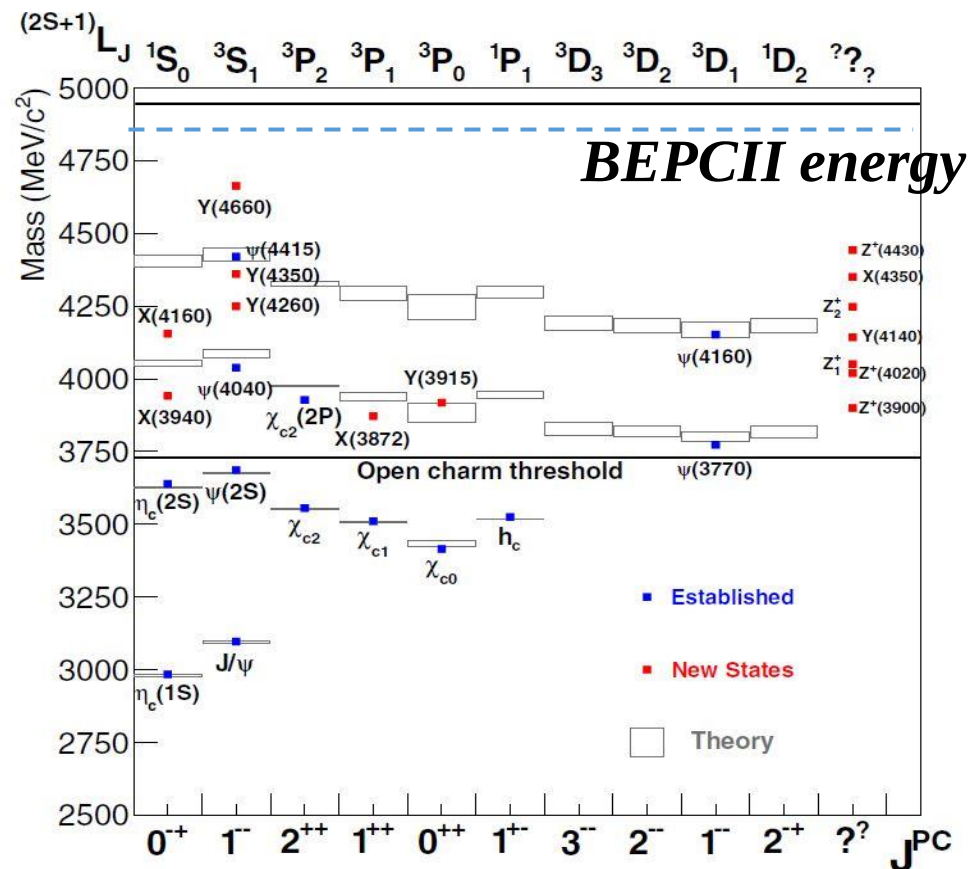
Variables	$\Lambda \rightarrow \gamma n$	$\bar{\Lambda} \rightarrow \gamma \bar{n}$
BF ($\times 10^3$)	$0.834 \pm 0.046 \pm 0.064$	$0.876 \pm 0.071 \pm 0.082$
α_γ	$-0.13 \pm 0.13 \pm 0.02$	$0.21 \pm 0.15 \pm 0.06$
Δ_{CP}	$-0.025 \pm 0.049 \pm 0.060$	
A_{CP}	$-0.25 \pm 0.61 \pm 0.15$	

Theoretical attentions: L.S. Geng, Q. Zhao, R.M. Wang et al.

BF of $\Lambda \rightarrow n\gamma$, with improved precision, smaller than PDG value by 5.5σ

Overpopulated charmonium spectrum

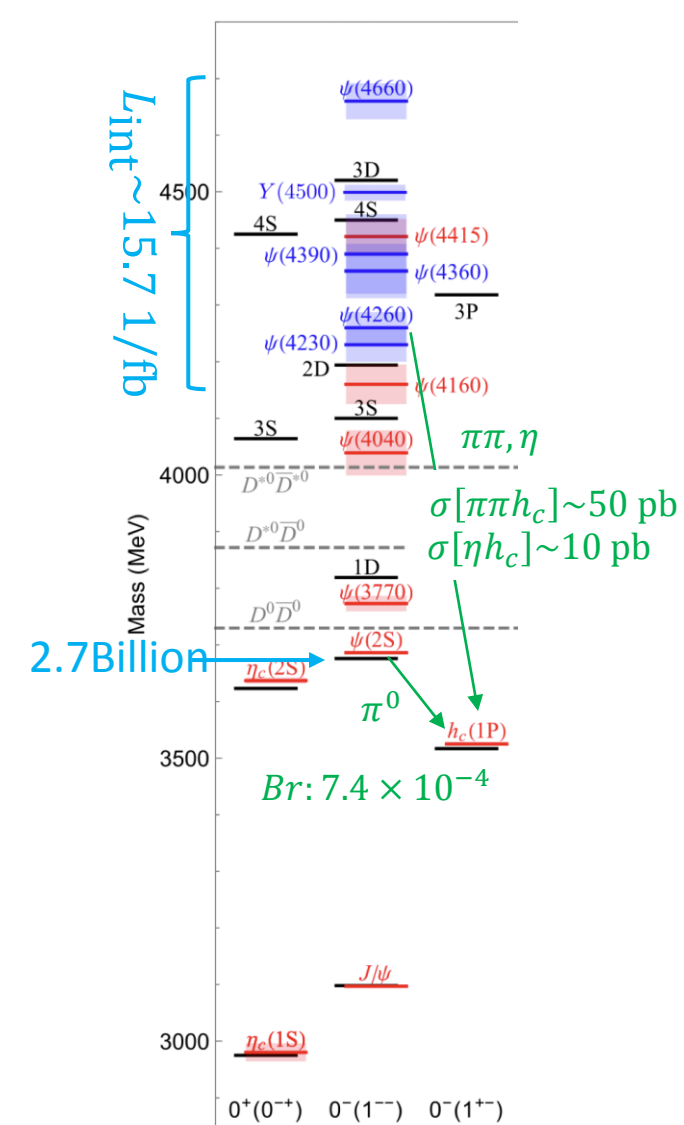
arXiv:1511.01589, arXiv:1812.10947



Overpopulated observed charmonium-like states, i.e. “XYZ”:

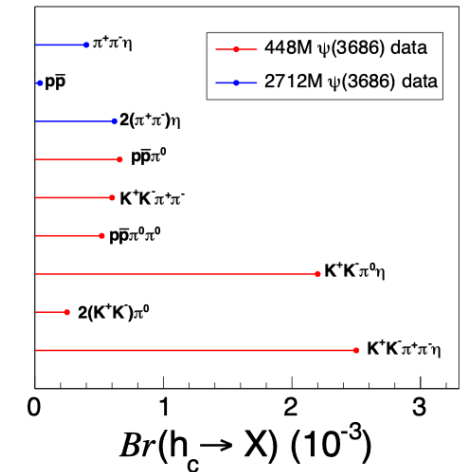
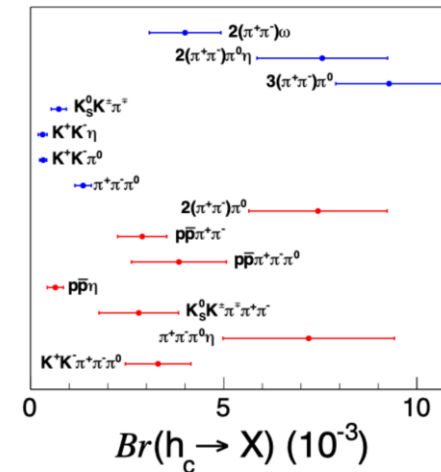
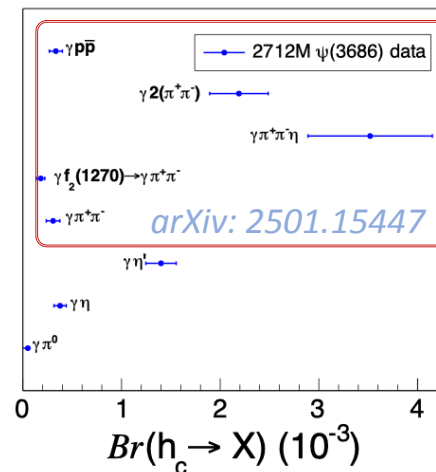
- Most of them are close to the mass thresholds of charmed meson pairs
- Some are not accommodated as conventional meson
==> candidate of exotic hadron states
- More efforts are needed to pin down their nature

BESIII Highlight: Production and decay properties of h_c



- P -wave singlet charmonium state, first observed by CLEO PRL95, 102003 (2005)
- First measurement of $B[\psi' \rightarrow \pi^0 h_c]$ by BESIII PRL104, 132002 (2010)
- 2M h_c particle in 2.7B ψ' events, possible to explore h_c decay mode with $Br \sim 10^{-4}$; 0.7M h_c particle from XYZ scan sample
- Decay of h_c :

- pQCD prediction: $h_c \rightarrow \gamma g g \sim 5.5\%$ PRD 66, 014012 (2002)
- pQCD and NRQCD predictions of $h_c \rightarrow \text{light hadrons}$: 48% and 8% PRD 65, 094024 (2002)

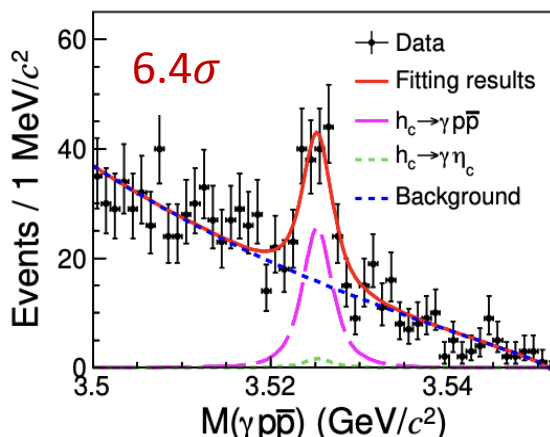
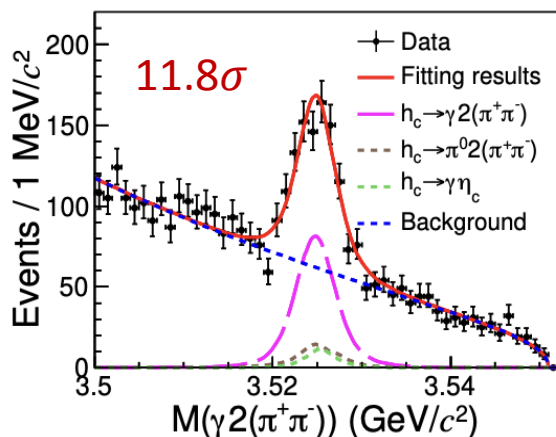
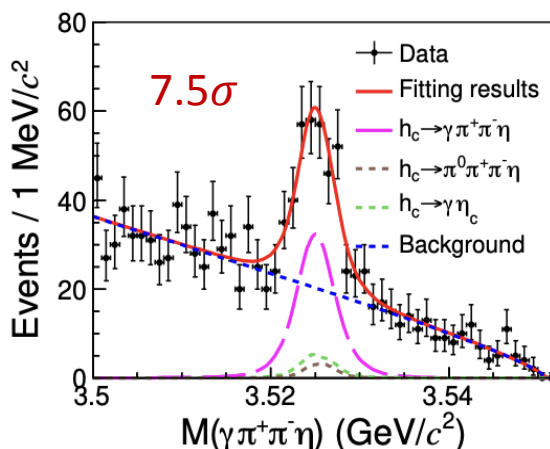
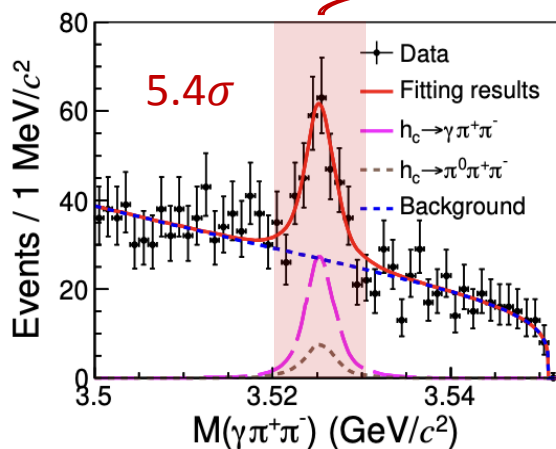


Highlight: Production and decay properties of h_c

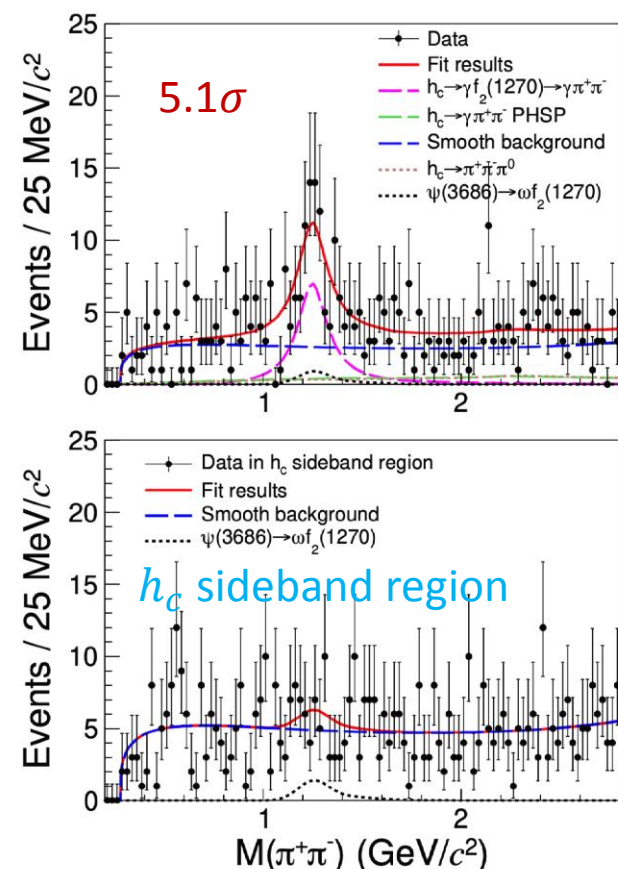
Observation of h_c radiative decays and $h_c \rightarrow \gamma f_2(1270)$

arXiv:2501.15447

PRL 134, 241902 (2025)



$h_c \rightarrow \gamma f_2(1270)$

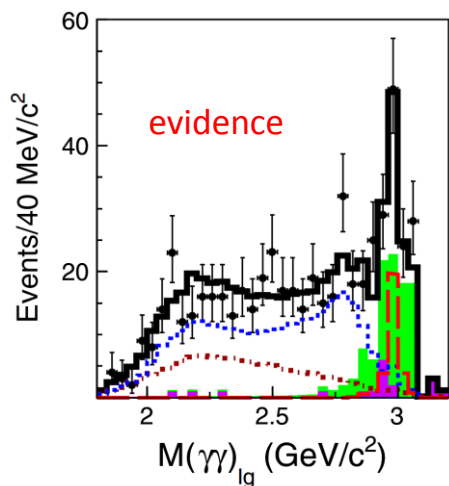
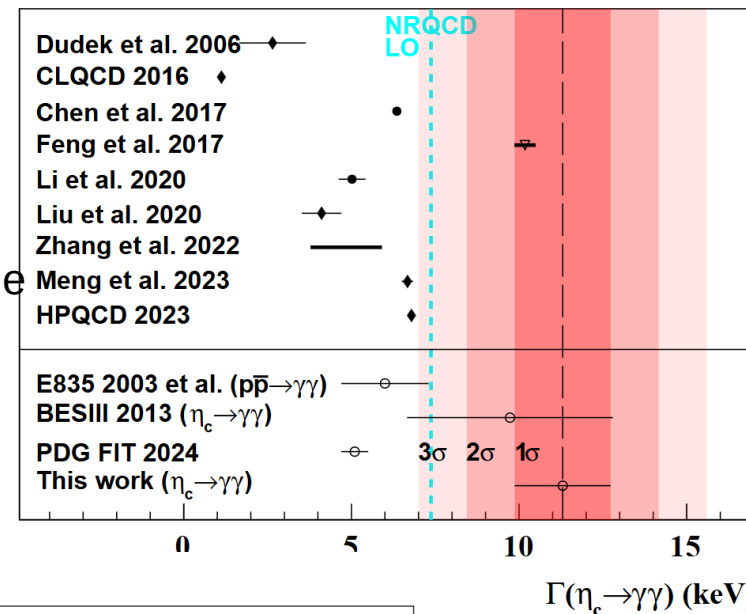


Highlight: measurements of $\eta_c \rightarrow \gamma\gamma$

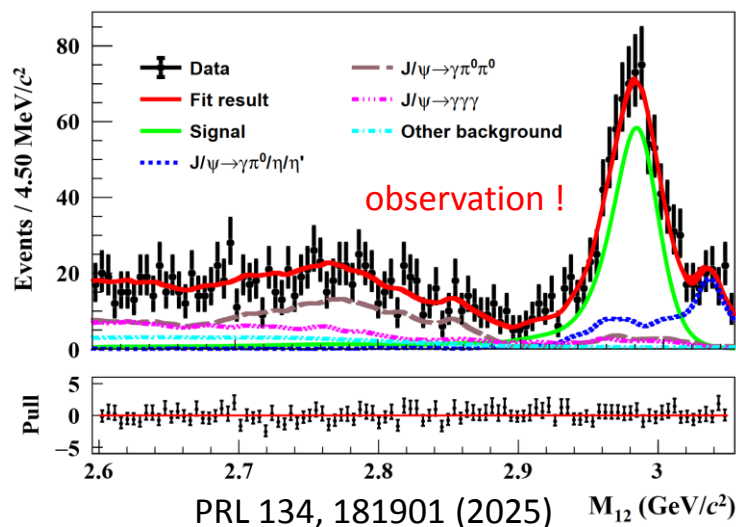
arXiv: 2412.12998
PRL 134, 181901 (2025)

- As the simplest decay of η_c , $\eta_c \rightarrow \gamma\gamma$ serves as a benchmark for QCD calculation.
- Most measurements come from the time reversal process $\gamma\gamma^{(*)} \rightarrow \eta_c$
- BESIII has the unique opportunity to directly measure $\eta_c \rightarrow \gamma\gamma$ via $J/\psi \rightarrow \gamma\eta_c$ (first observation) or $h_c \rightarrow \gamma\eta_c$ (absolute branching fraction, most precise).
- Measured $B(J/\psi \rightarrow \gamma\eta_c) \times B(\eta_c \rightarrow \gamma\gamma)$ is consistent with theoretical predictions, while the individual $\Gamma(\eta_c \rightarrow \gamma\gamma)$ deviates from the most recent LQCD prediction by more than 3σ .

$$\Gamma(\eta_c \rightarrow \gamma\gamma) = (11.30 \pm 0.56_{\text{stat.}} \pm 0.66_{\text{syst.}} \pm 1.14_{\text{ref.}}) \text{ keV}$$

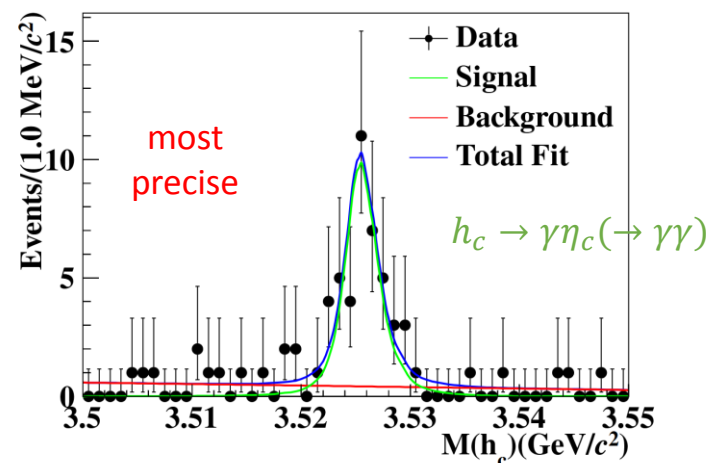


Phys. Rev. D 87, 032003 (2013)



PRL 134, 181901 (2025)

$J/\psi \rightarrow \gamma\eta_c(\rightarrow \gamma\gamma)$



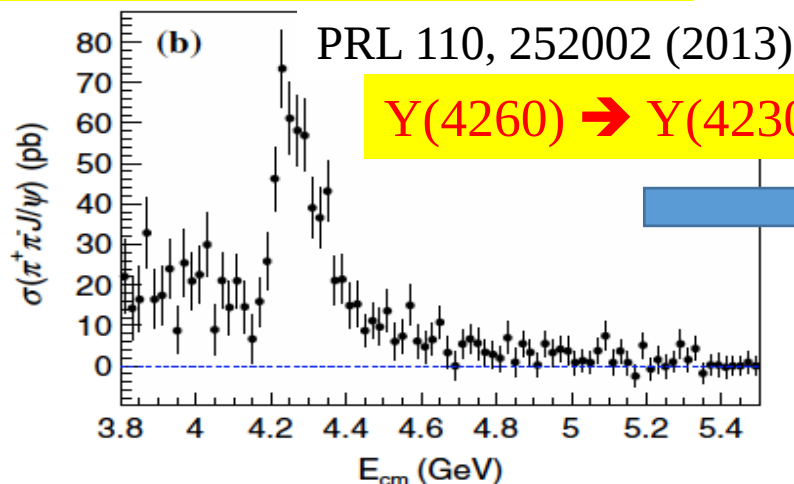
The first measurement of absolute branching fraction via $h_c \rightarrow \gamma\eta_c$ will provide a brand new reference

in preparation

Precise test of LQCD: hyperfine mass splitting

The vector Y states from scan data near open-charm thresholds

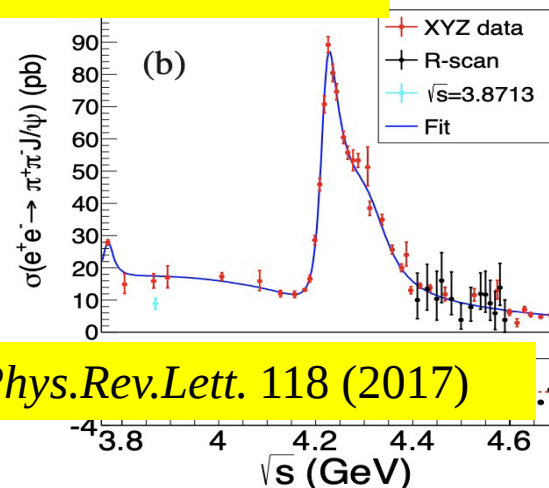
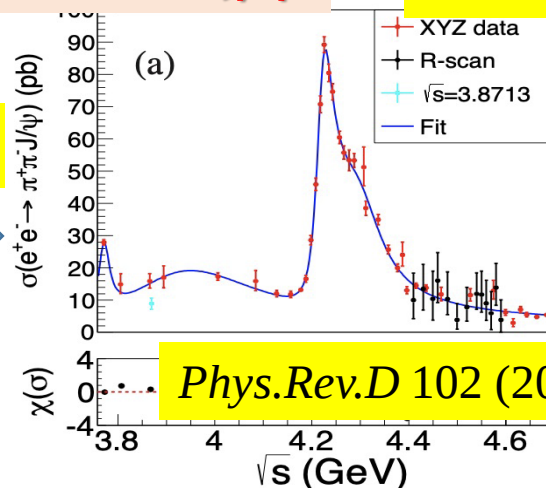
Belle Resolution: about 5-10 MeV



$Y(4260) \rightarrow Y(4230)$

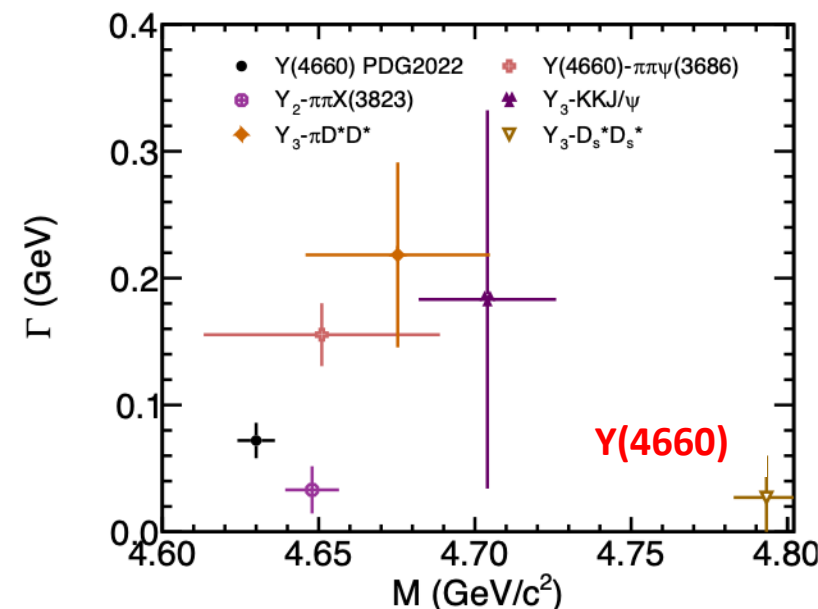
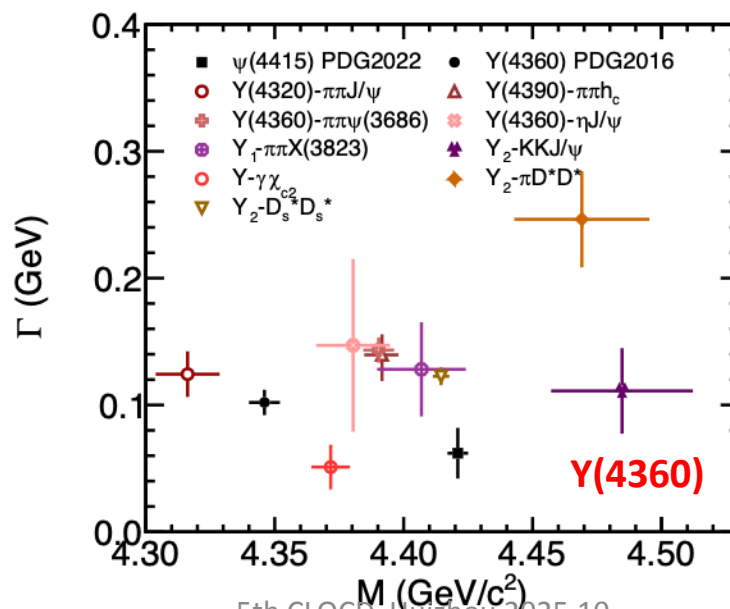
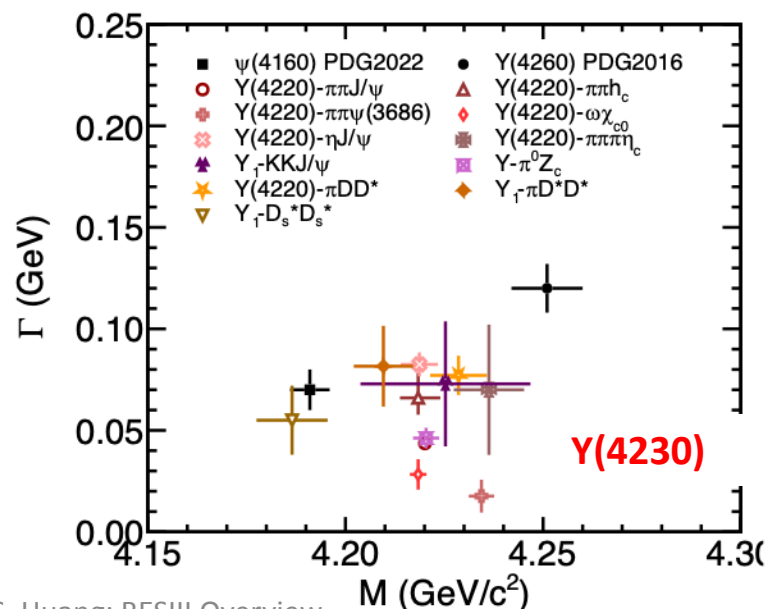
$e^+e^- \rightarrow \pi^+\pi^-J/\psi$

BESIII Resolution: 1 - 2 MeV



Phys.Rev.D 102 (2020) *Phys.Rev.Lett.* 118 (2017)

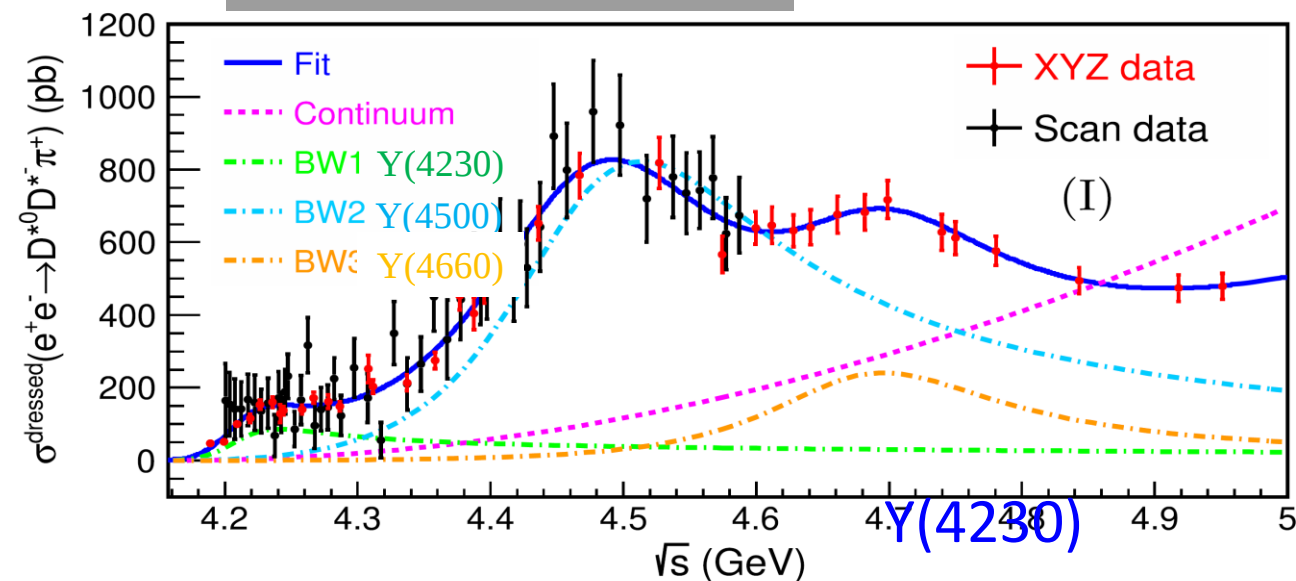
Fine structures of Charmonium-like states are seen at BESIII with scan data!



More Y states: Y(4500), Y(4710) and Y(4790)

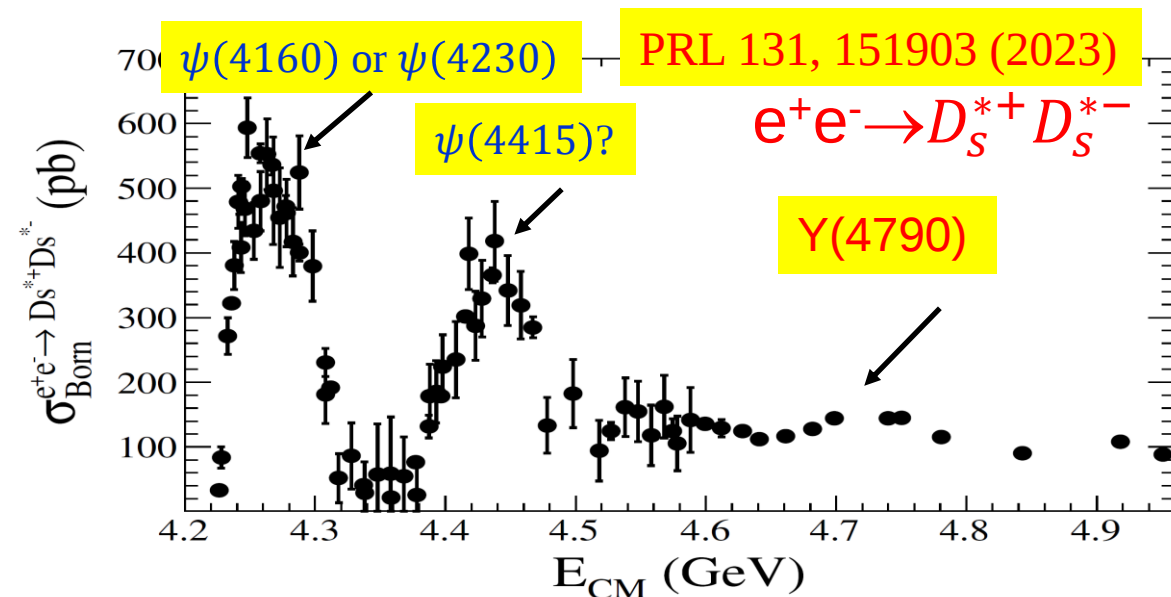
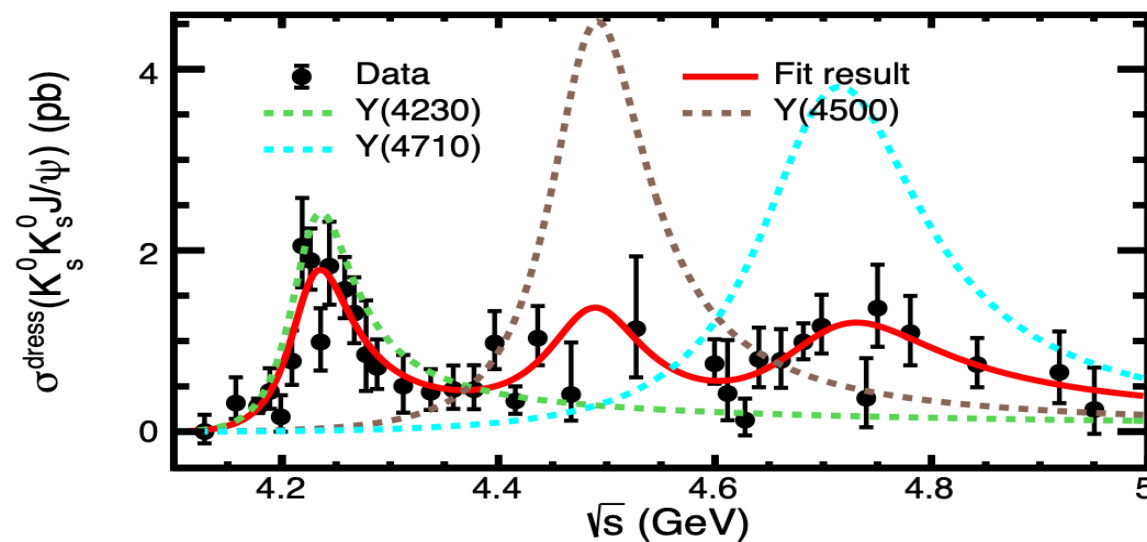
PRL 130, 121901 (2023)

$$e^+e^- \rightarrow D^{*0}D^{*-}\pi^+$$



PRD 107, 092005 (2023)

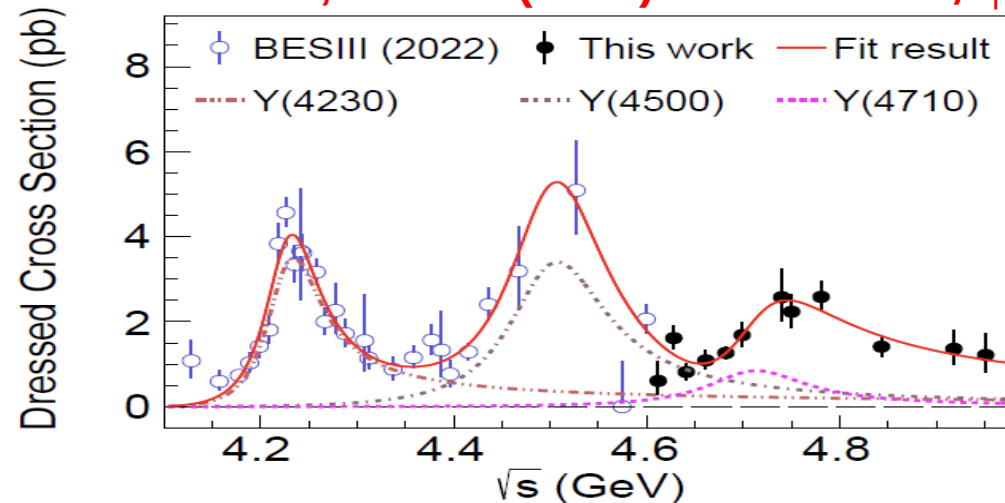
$$e^+e^- \rightarrow K_S K_S J/\psi$$



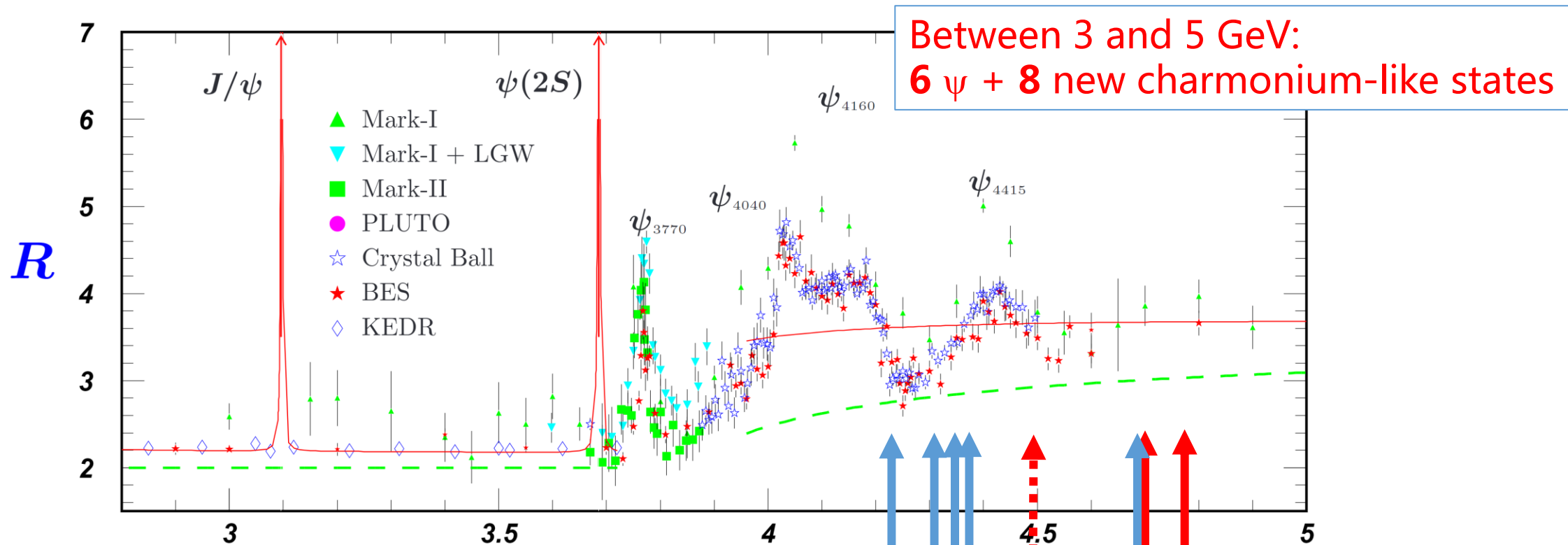
PRL 131, 151903 (2023)

$$e^+e^- \rightarrow D_s^{*+} D_s^{*-}$$

PRL 131, 211902 (2023)



How many vectors in charmonium energy region?



Besides vector charmonium ($c\bar{c}$) states, we also expect $c\bar{c}g$ hybrids, and $c\bar{c}q\bar{q}$ tetraquark states. Have they already been observed?

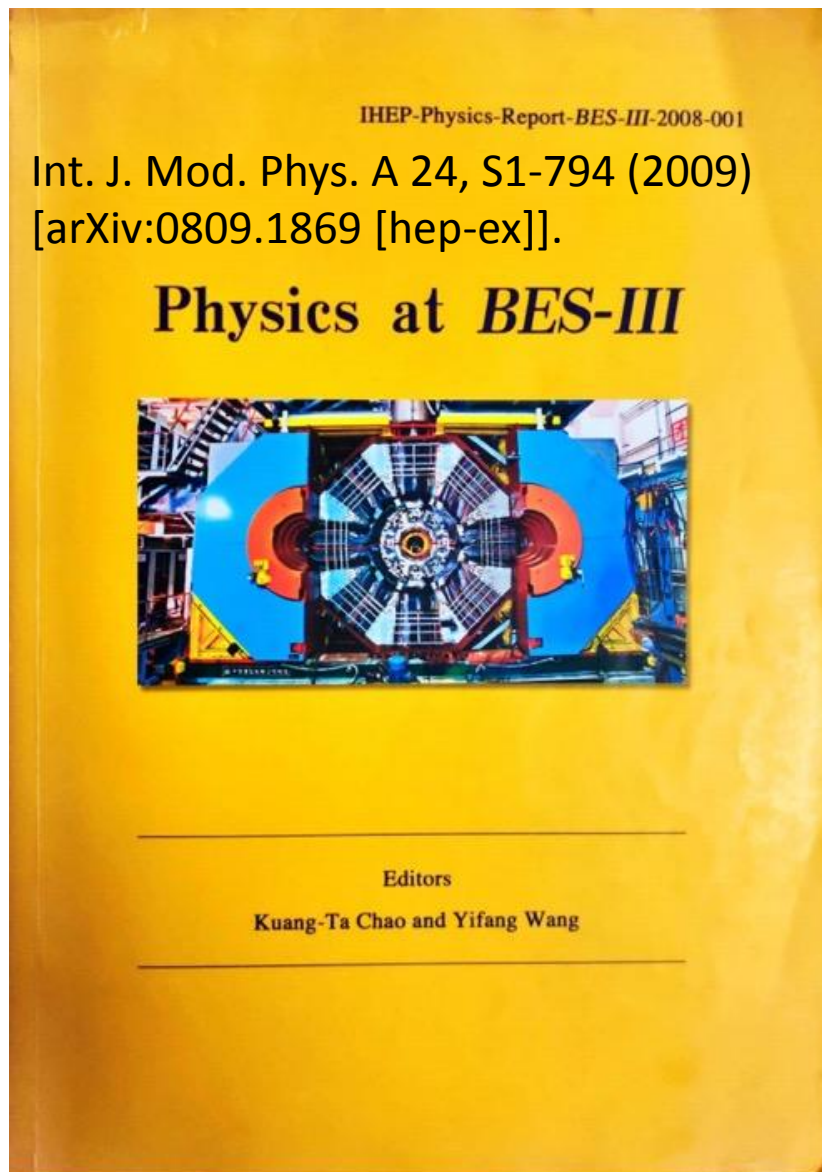
➔ More theoretical/experimental efforts necessary!

Y(4230), Y(4320),
Y(4360), Y(4390)

Y(4500)

Y(4660),
Y(4710), Y(4790)

BESIII Prospects



Yellow book



Chin. Phys. C 44, 040001 (2020)
[arXiv:1912.05983 [hep-ex]].

Future Physics Programme of BESIII*

Abstract: There has recently been a dramatic renewal of interest in hadron spectroscopy and charm physics. This renaissance has been driven in part by the discovery of a plethora of charmonium-like $X\Upsilon Z$ states at BESIII and B factories, and the observation of an intriguing proton-antiproton threshold enhancement and the possibly related $\Lambda(1835)$ meson state at BESIII, as well as the threshold measurements of charm mesons and charm baryons. We present a detailed survey of the important topics in tau-charm physics and hadron physics that can be further explored at BESIII during the remaining operation period of BEPCII. This survey will help in the optimization of the data-taking plan over the coming years, and provides physics motivation for the possible upgrade of BEPCII to higher luminosity.

DOI: 10.1088/1674-1137/44/4/040001

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White book

White book: planned future data

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb ⁻¹ (fine scan) ←	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
✓ J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb ⁻¹ (10 billion)	3.2 fb ⁻¹ (10 billion)	N/A
✓ $\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb ⁻¹ (0.45 billion)	4.5 fb ⁻¹ (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb ⁻¹	20.0 fb ⁻¹ ←	610/360 days
3.8 - 4.6 GeV	R values XYZ /Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ /Open charm	3.2 fb ⁻¹	6 fb ⁻¹	140/50 days
4.0 - 4.6 GeV	XYZ /Open charm Higher charmonia cross-sections	16.0 fb ⁻¹ at different $\sqrt{s}$	30 fb ⁻¹ at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/ XYZ cross-sections	0.56 fb ⁻¹ at 4.6 GeV	15 fb ⁻¹ at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+ \Lambda_c^-$ cross-section	N/A	1.0 fb ⁻¹	100/40 days
4.91 GeV	$\Sigma_c \bar{\Sigma}_c$ cross-section	N/A	1.0 fb ⁻¹	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb ⁻¹	130/50 days

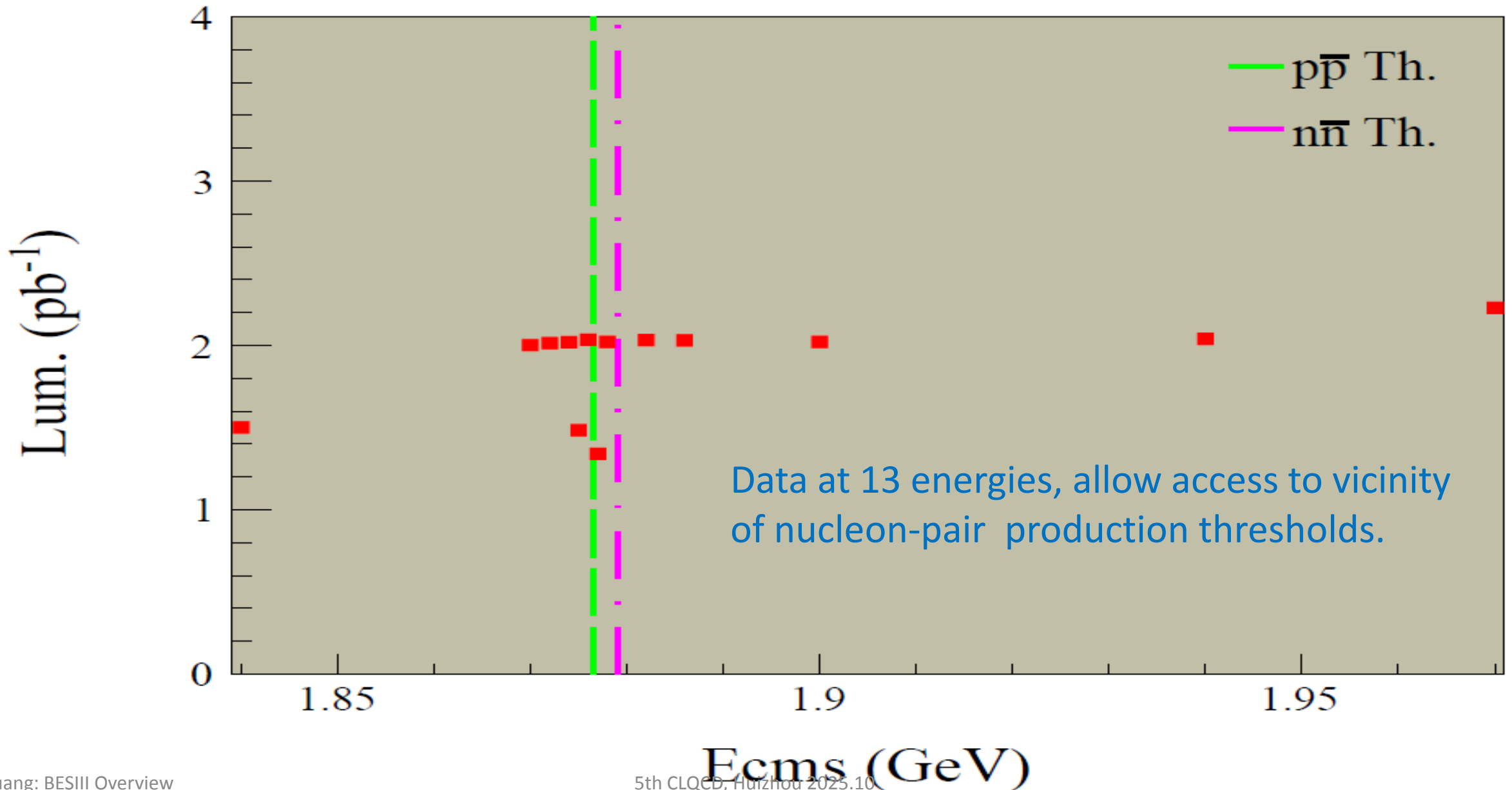
Only part 2024

Completed 2024

BEPCII-U

Another 6 years running to collect >60 fb⁻¹ data at different energies .

1.84-1.97 GeV: low extremes of BEPCII



BEPCh upgrades in 2024

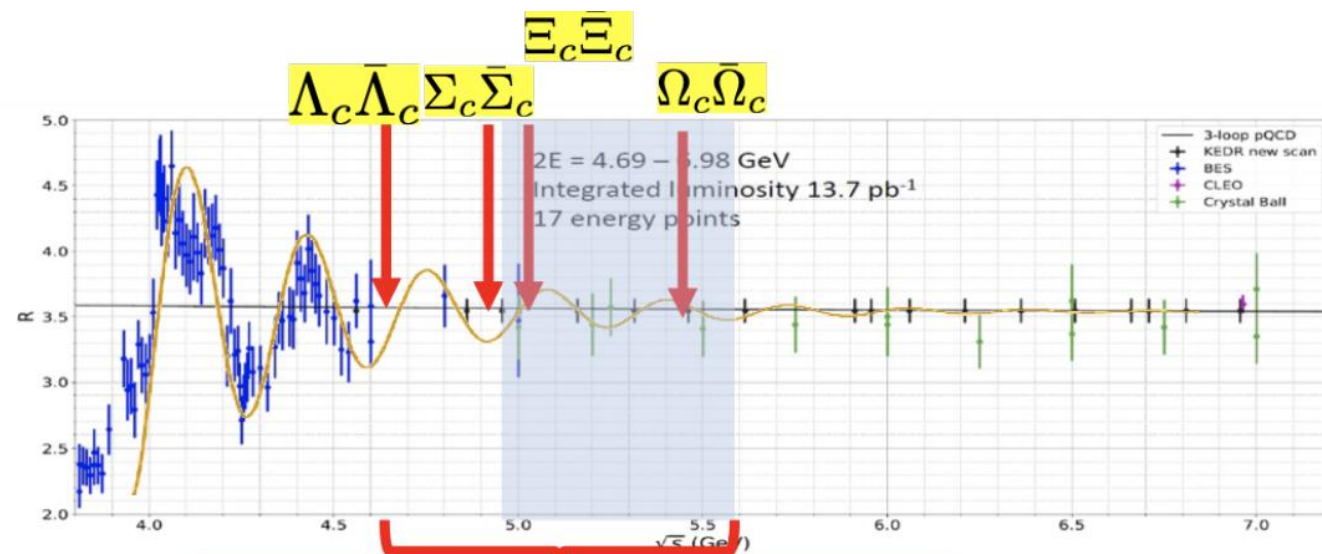
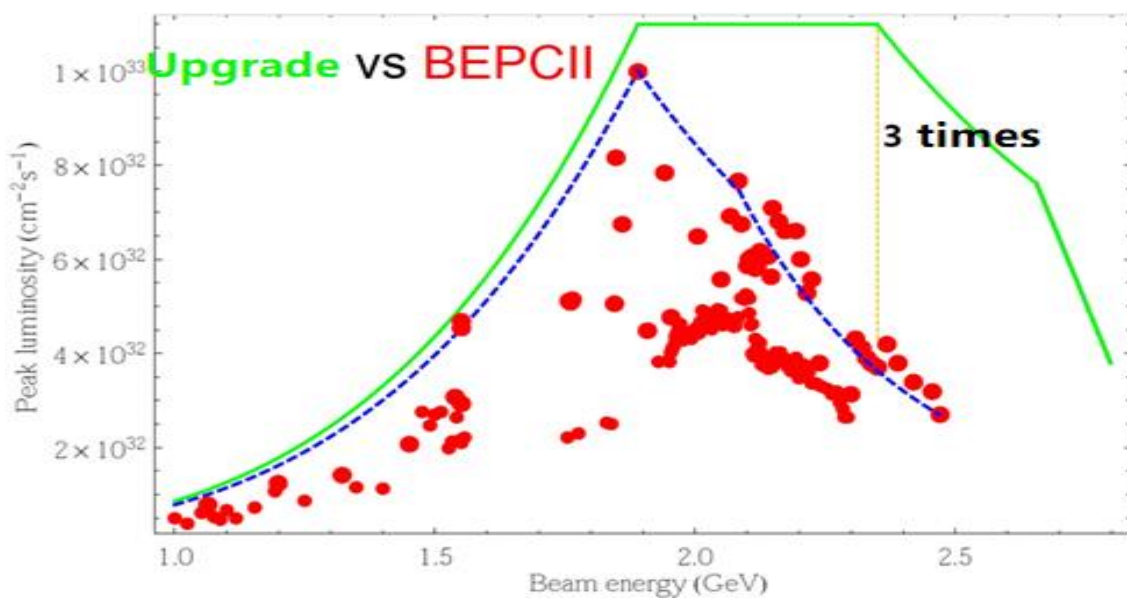
BEPCh upgrade (installation: 2024. 7- 2024. 12)

Highest beam energy: 2.8 GeV

Luminosity: $1.2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (4.0 ~ 5.0 GeV)
 $(0.4\text{-}0.7) \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (5.0 ~ 5.6 GeV)

BESIII will collect about **60 fb⁻¹** between 4.0 – 5.6 GeV, and to study potential physics:

- ✓ Cover energy up to 5.6 GeV
- ✓ Deeper studies of the XYZ states
- ✓ Study the ground-state charmed baryons
- ✓ Provide information on charm-quark fragmentation function



Few data and potential physics for XYZ and charmed baryons

Summary

- BESIII is running smoothly, and very productive now;
- BEPCII upgrades have been finished in 2024, more data taking above 4.0 GeV, up to 5.6 GeV to study: excited charmonium, charmonium-like states, XYZ particles, charmed baryon ...
- Advantages at BECPII/BESIII: scan data near thresholds, quantum-entangled meson and baryon pairs
- BESIII plays leading role in hadron physics, flavor physics (charmed hadron and strange hadron).

Charm is still needed for precise test of the SM!

