BESIII 实验研究进展

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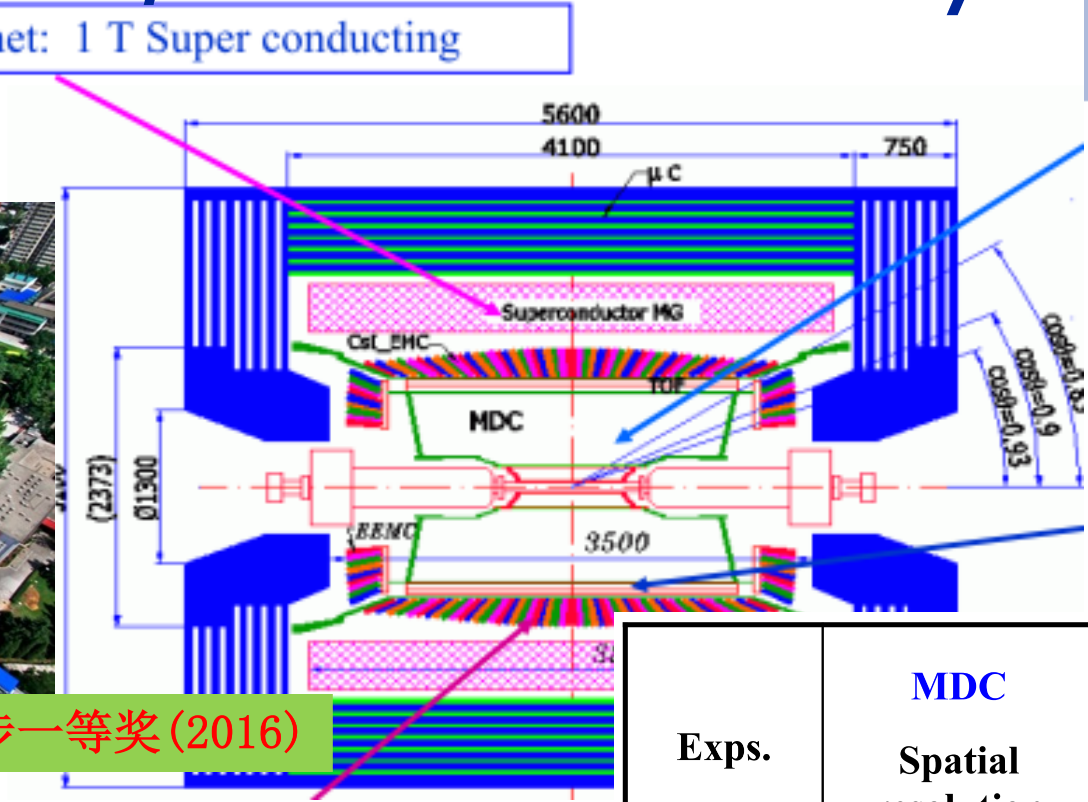
BEPCII/BESIII: a τ-c Factory



国家科技进步一等奖(2016)

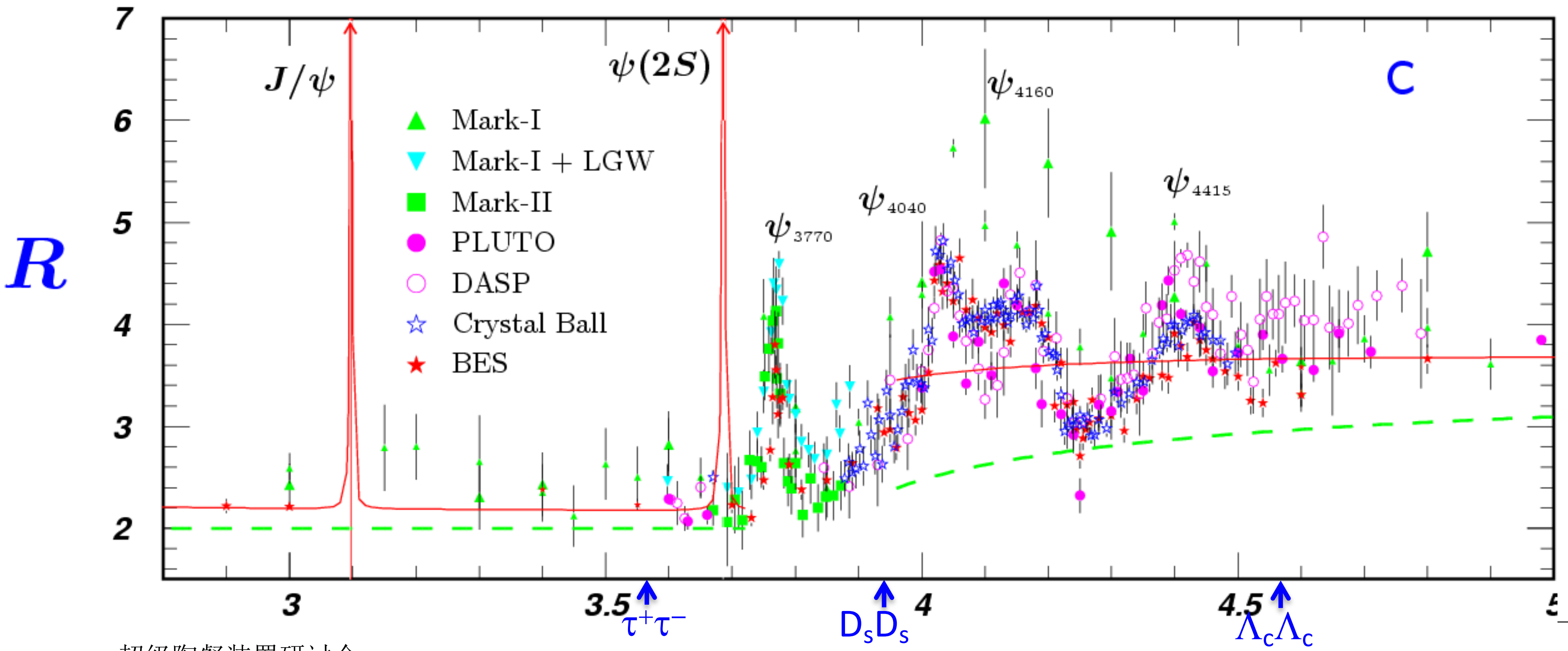
high lumi, large datasets, hermetic detector with good performance and clean environment

Exps.	MDC Spatial resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO-c	110 μm	5%	2.2-2.4 %
BaBar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII	115 μm	<5% (Bhabha)	2.4%

- First collision in 2008, physics run started in 2009
- Operation c.m. energy: 1.84-4.95GeV
- BEPCII continues to improve, energy upgrade & top-up reached peak lumi of $1.1\times10^{33}\,cm^{-2}s^{-1}$ @1.89GeV
- New in 2024: $20fb^{-1}$ psi" data achieved; low Ecm scan at 1.84-1.97 GeV; scan around psi" and chic2

BESIII physics: τ-c region features

- Rich of **resonances**, charmonia and charmed mesons.
- **Threshold** characteristics (pairs of τ, D, D_s, charmed baryons…).
- **Transition** between perturbative and non-perturbative **QCD**.
- New **hadrons**: glueballs, hybrids, multi-quark states
- **New Physics:** large datasets, hermetic detector, good performance



Data samples by BESIII

More than 52 fb^{-1}

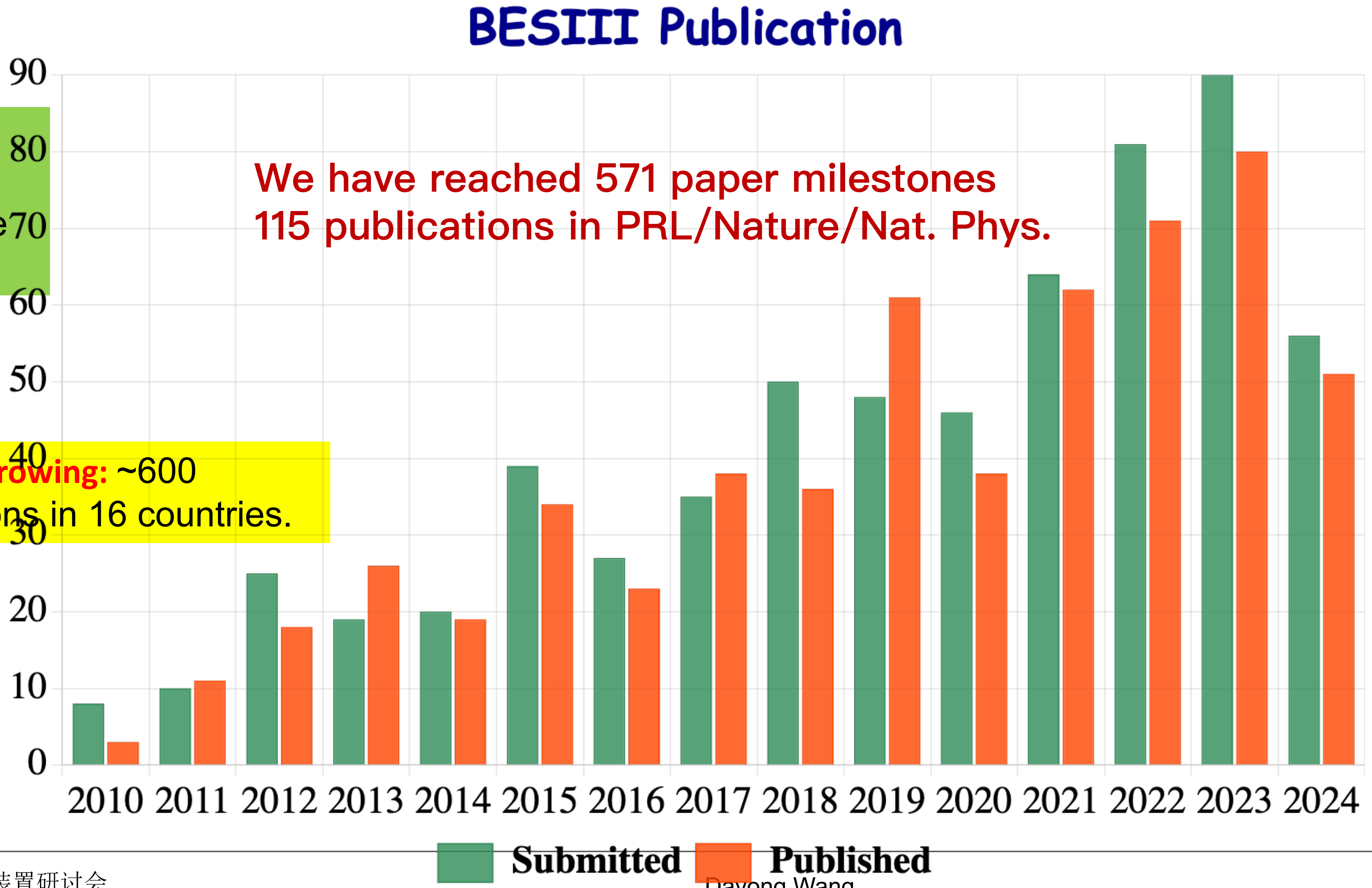
- 2009: 106M $\psi(2S)$
  - 225M J/ψ
- 2010: 0.98 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$)
- 2011: 2.93 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$, total)
  - 0.48 fb^{-1} @4.01 GeV
- 2012: 0.45B $\psi(2S)$ (total)
  - 1.30B J/ψ (total)
- 2013: 1.09 fb^{-1} @4.23 GeV
  - 0.83 fb^{-1} @4.26 GeV
  - 0.54 fb^{-1} @4.36 GeV
  - 10×0.05 fb^{-1} XYZ scan@3.81-4.42 GeV
- 2014: 1.03 fb^{-1} @4.42 GeV
  - 0.11 fb^{-1} @4.47 GeV
  - 0.11 fb^{-1} @4.53 GeV
  - 0.05 fb^{-1} @4.575 GeV
  - 0.57 fb^{-1} @4.60 GeV (for Λ_c^+)
  - 0.80 fb^{-1} R scan @3.85-4.59 GeV
- 2015: R-scan 2-3 GeV+2.175 GeV
- 2016: 3.20 fb^{-1} @4.178 GeV (for D_s^+)
- 2017: 7×0.50 fb^{-1} XYZ scan@4.19-4.27 GeV
- 2018: More J/ψ+tuning new RF cavity
- 2019: 10B J/ψ (total)
  - 8×0.50 fb^{-1} XYZ scan@4.13, 4.16, 4.29-4.44 GeV
- 2020: 3.8 fb^{-1} @ 4.61-4.7 GeV (XYZ&Λ_c^+)
- 2021: 2.0 fb^{-1} @ 4.74-4.946 GeV
- 2021: 2.7B $\psi(2S)$ (total)
- 2022: 2×0.4 fb^{-1}@3.65, 3.682 GeV,
  - 5.1 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$, total)
- 2023: ~8 fb^{-1} at $\psi(3770)$

Latest data taken in 2024 runs:

Dataset	E_{cm} / GeV	$\mathcal{L}_{int}$ / fb^{-1}	days
$\psi(3770)$	3.773	4.2	119
ψ'' scan	3.780	0.41	9
scan	3.800–3.885	0.14 in 14 points	6
ψ'' scan	3.768	0.41	10
χ_{c2}	3.554	0.13	4
< 2 GeV	1.80 – 2.00	0.025 in 13 points	64

BESIII is in very good state in all aspects

New lumi and Ecm record
Very stable data-taking
Good detector performance
Aging effects under control

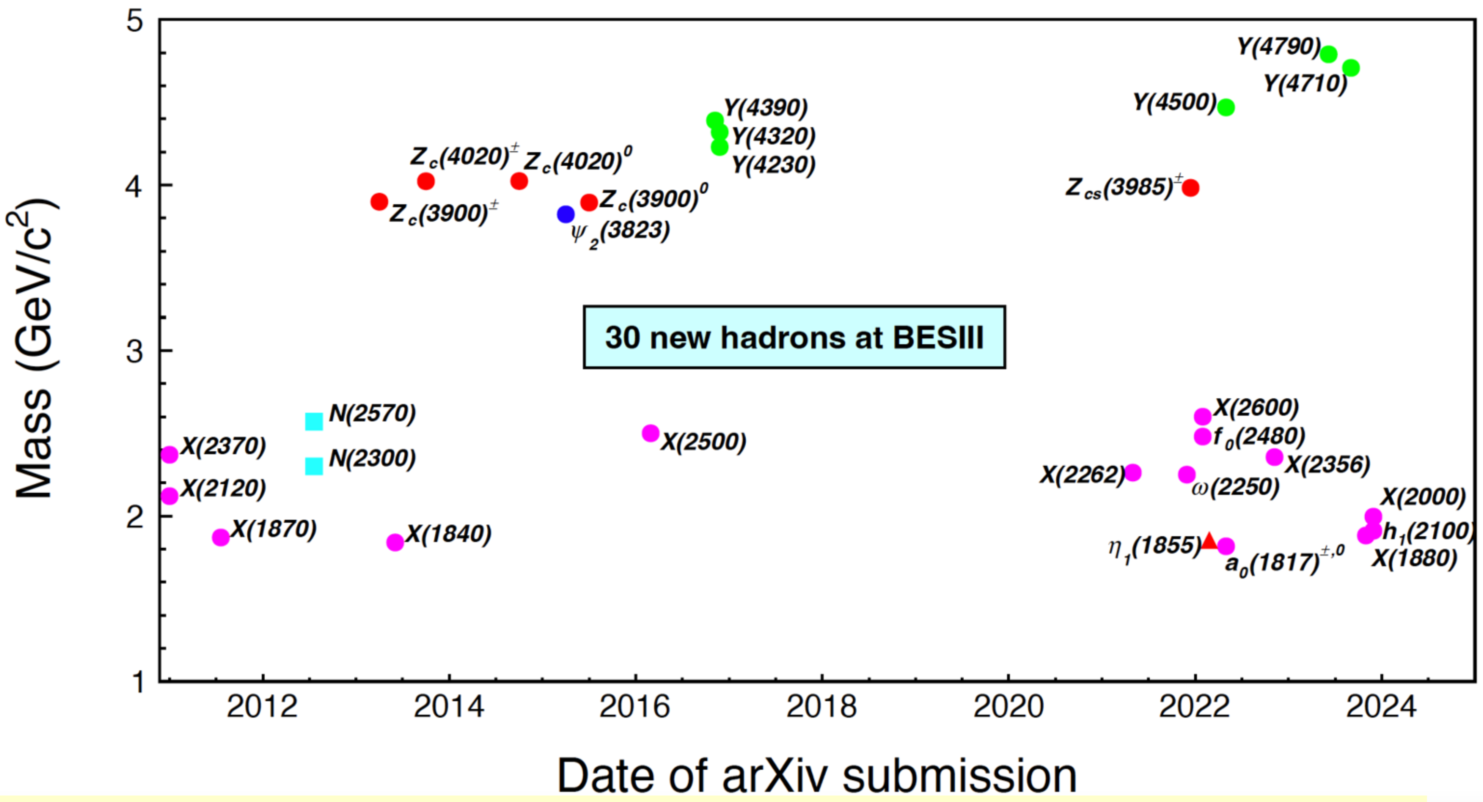


We have reached 571 paper milestones
115 publications in PRL/Nature/Nat. Phys.

The collaboration size still growing: ~600 members from 82 institutions in 16 countries.

物理研究成果丰富

- “四夸克物质Zc（3900）的发现”荣获2023年度 国家自然科学奖二等奖
  - （苑长征、朱科军、刘智青、李卫东、平荣刚等）
- BES上第6个国家自然科学奖二等奖 （1995, 2001, 2004, 2010, 2013, 2023)

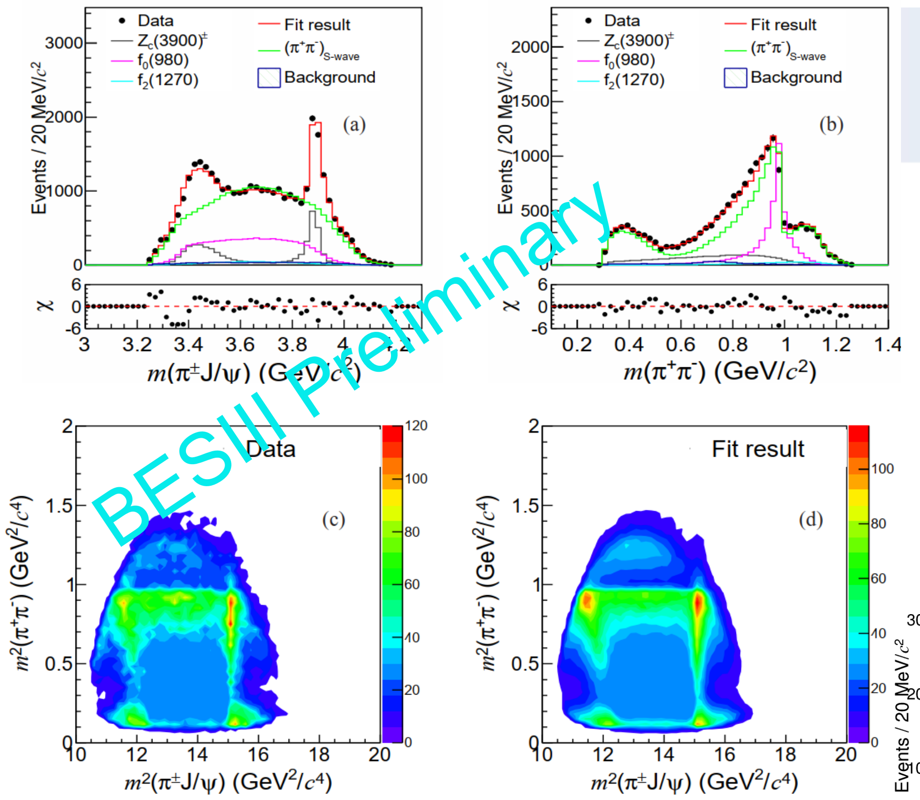


新思想
新方法
新测量
新精度

更多结果详细信息参见 BESIII Journal Publication Page:
http://english.ihep.cas.cn/bes/re/pu/pjp/

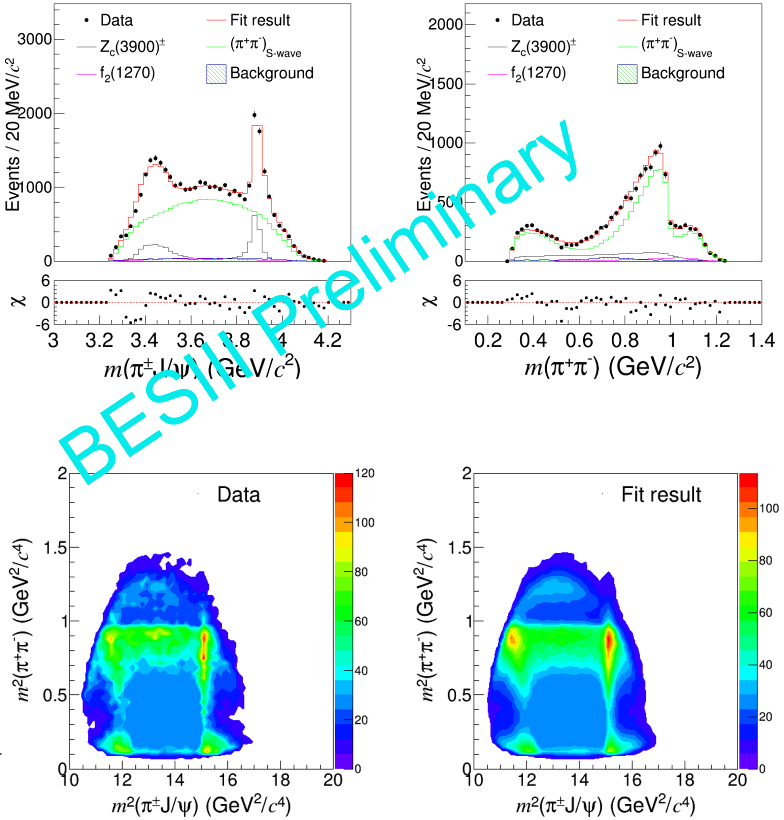
Charmonium Physics
with focus on “XYZ”s

PWA of $e^+e^- \to \pi^+\pi^- J/\psi$ 4.1271 to 4.3583 GeV

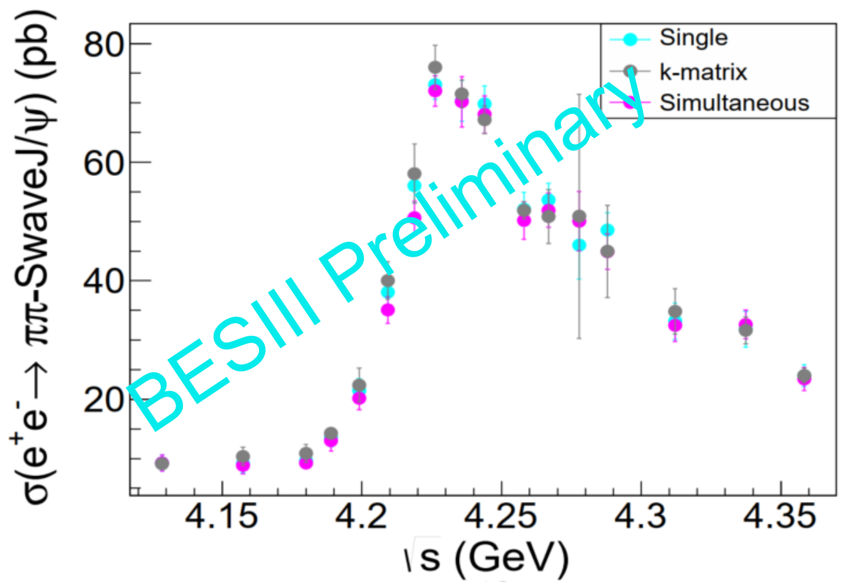


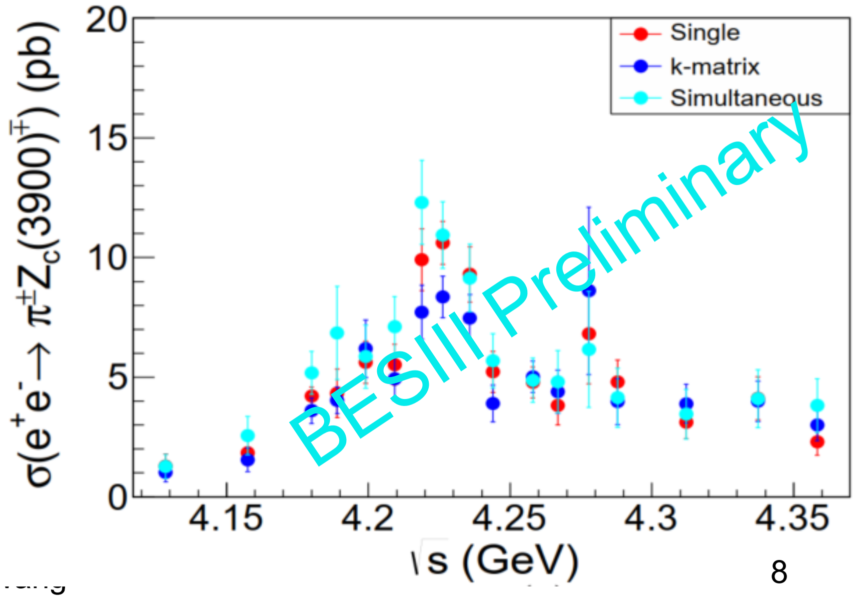
BW method

Tips: the $\pi\pi - Swave$ includes $f_0(500), f_0(980)$, and $f_0(1370)$.

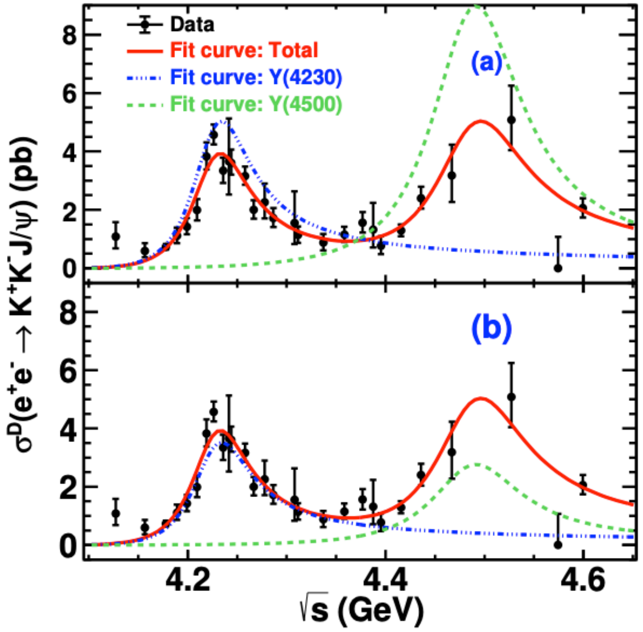


K-matrix method

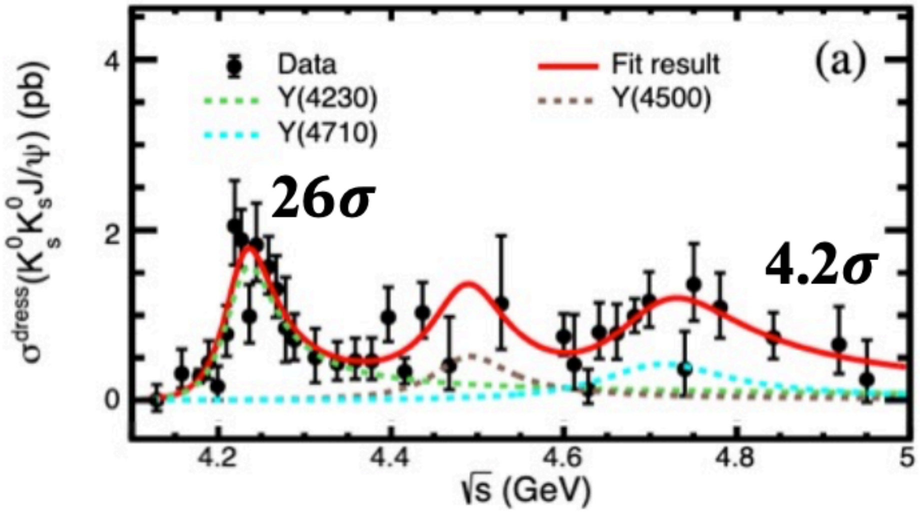


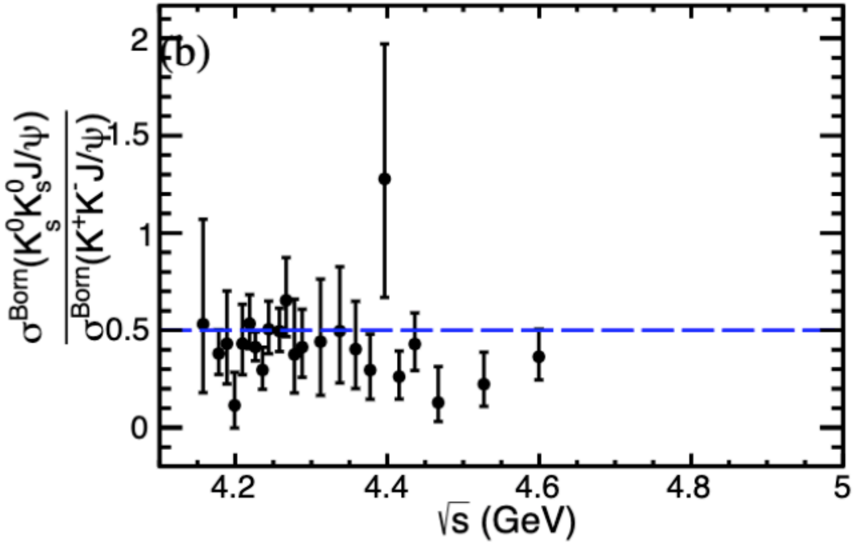


Studies of e+ e-→K K-bar J/Ψ

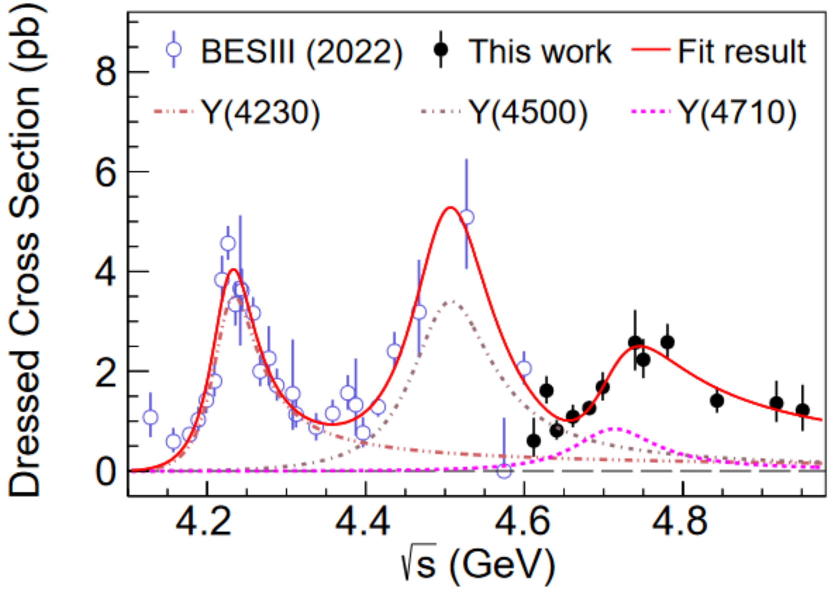


CPC 46, 111002(2022)

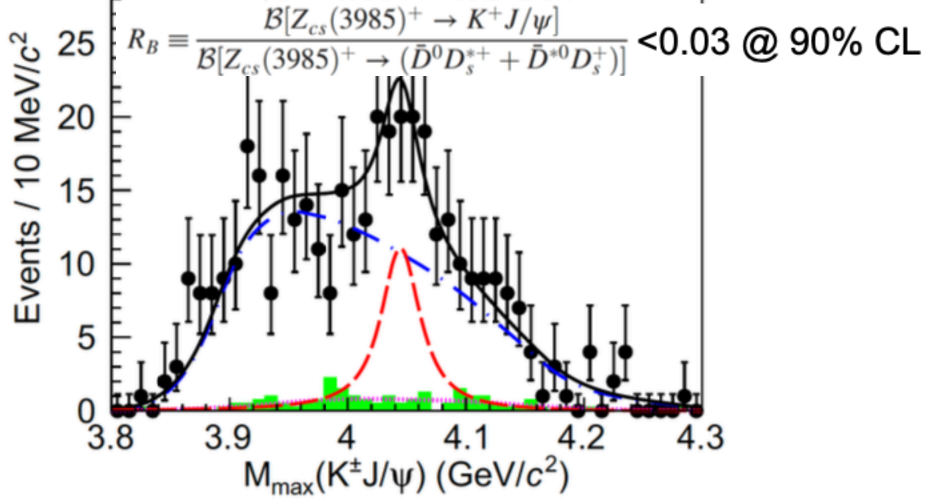




PRD107,092005(2023)

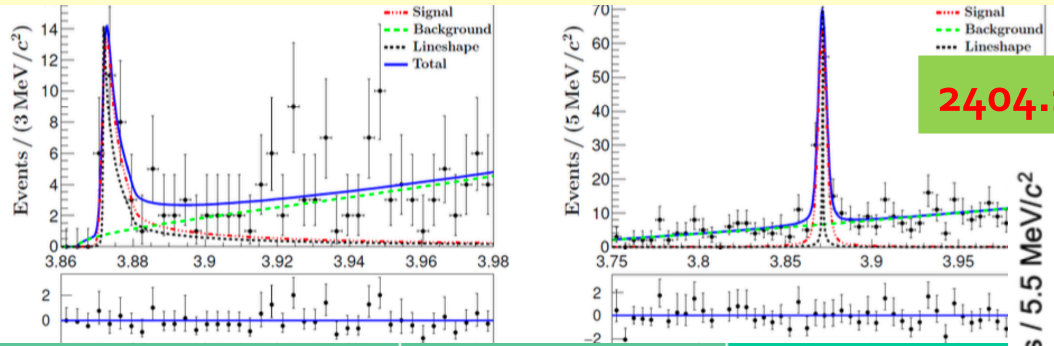


Phys. Rev. Lett. 131, 211902(2023)

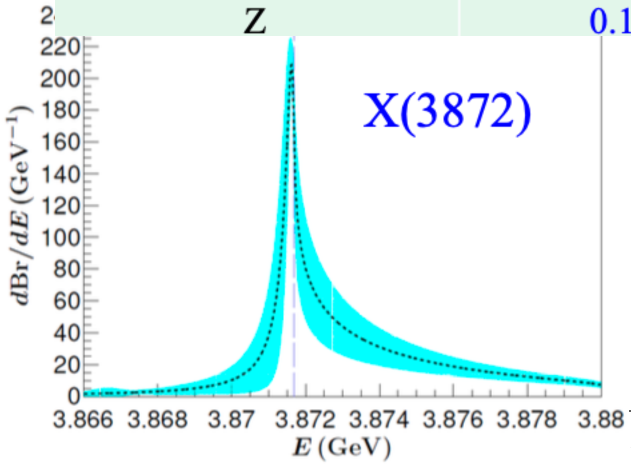


X(3872) recent results

coupled channel analysis of the X(3872) line shape



Parameters	BESIII	LHCb
g	$0.16 \pm 0.10^{+1.12}_{-0.11}$	$0.108 \pm 0.003^{+0.}_{-0.}$
$Re[E_I]$ [MeV]	$7.04 \pm 0.15^{+0.07}_{-0.08}$	7.10
$Im[E_I]$ [MeV]	$-0.19 \pm 0.08^{+0.14}_{-0.19}$	-0.13
$\Gamma(\pi^+\pi^- J/\psi)/\Gamma(D^0\bar{D}^{*0})$	$0.05 \pm 0.01^{+0.01}_{-0.02}$	0.11 ± 0.03
FWHM (MeV)	$0.44^{+0.13}_{-0.35}{}^{+0.38}_{-0.25}$	$0.22^{+0.06}_{-0.08}{}^{+0.25}_{-0.17}$
Z	0.18	0.15



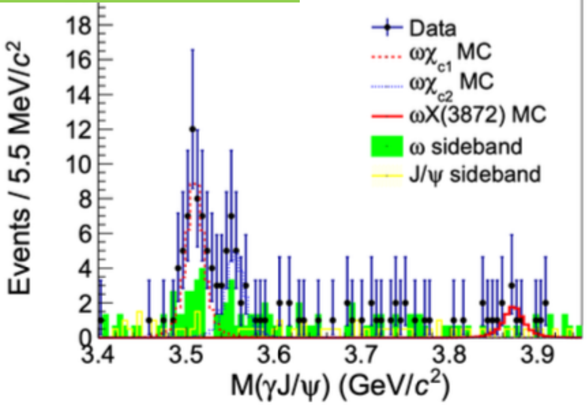
Weinberg's compositeness:
Z = 1: pure elementary state;
Z = 0: pure bound (composite) state.

PRL132, 151903(2024)

Production>4.6GeV

2404.13840, PRD

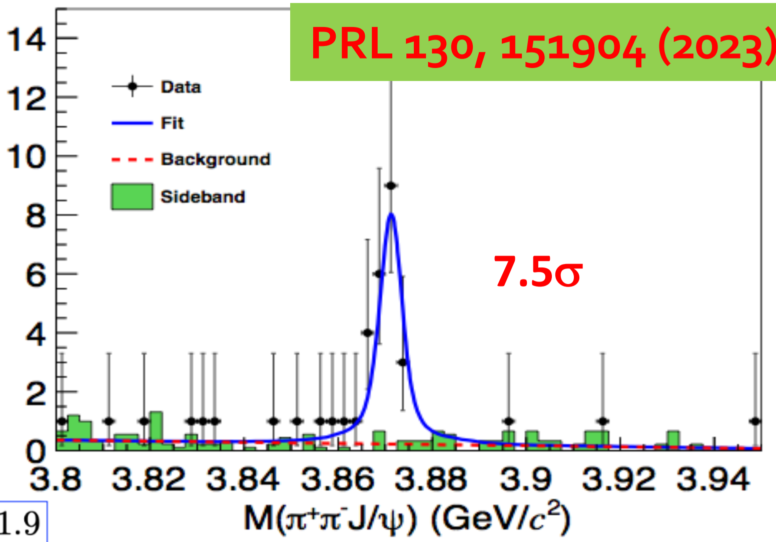
e+e-→ωX→ωγJ/ψ



$\sigma_{\omega X(3872)}/\sigma_{\omega\chi_{c1}}$	=	$5.2 \pm 1.0 \pm 1.9$
$\sigma_{\omega X(3872)}/\sigma_{\omega\chi_{c2}}$	=	$5.5 \pm 1.1 \pm 2.4$

$e^+e^- \to \omega X(3872) \to \omega\pi^+\pi^- J/\psi$

PRL 130, 151904 (2023)

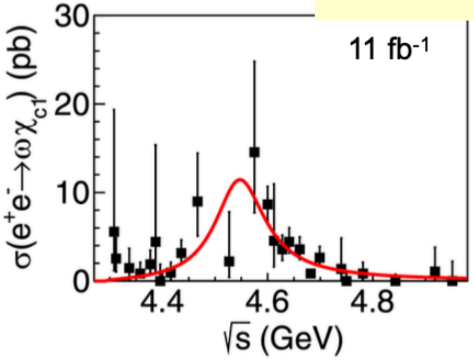


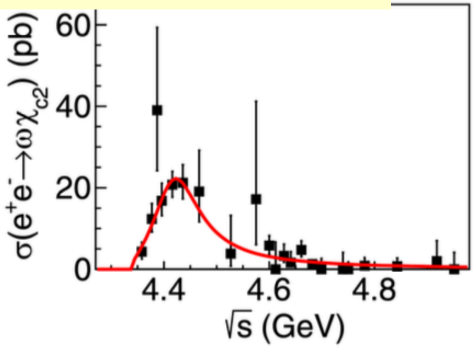
Decays

- X→$\pi^+\pi^-\chi_{c1}$ *PRD(L) 109, 071101 (2024)*
- X→$\pi^+\pi^-\eta$ *PRD(L) 109, 011102 (2024)*
- X→γJ/ψ via e^+e^-→ ωX(3872), *arXiv:2404.13840*
- X→γX(3823) *arXiv:2405.07741*

More XYZ results

4.308~4.951 GeV, 11 fb^{-1}

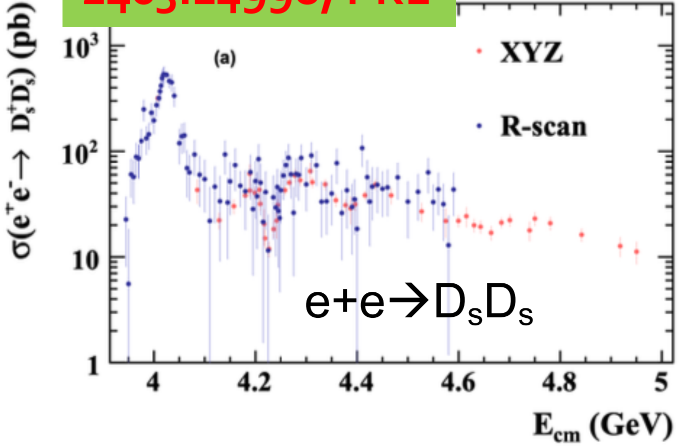




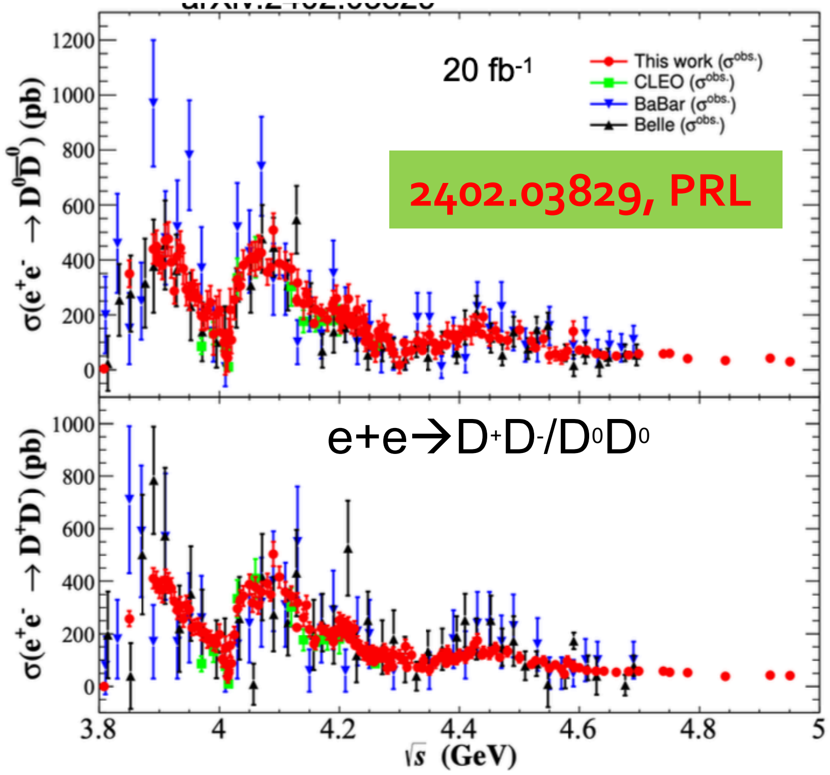
$$\sigma(\sqrt{s}) = \frac{12\pi\Gamma_{ee}\mathcal{B}(\omega\chi_{cJ})\Gamma}{(s-M^2)^2+M^2\Gamma^2} \times \frac{\Phi(\sqrt{s})}{\Phi(M)}$$

PRL 132, 161901 (2024)

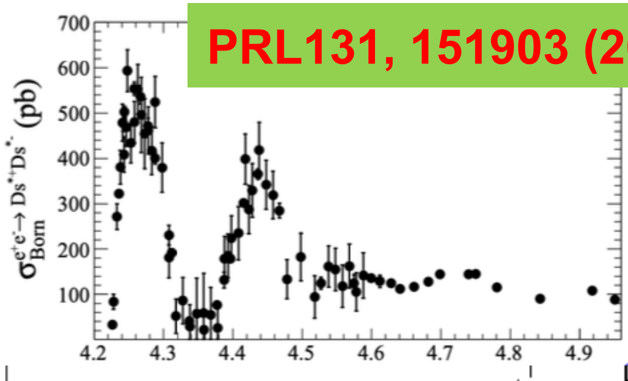
2403.14998, PRL



2402.03829, PRL

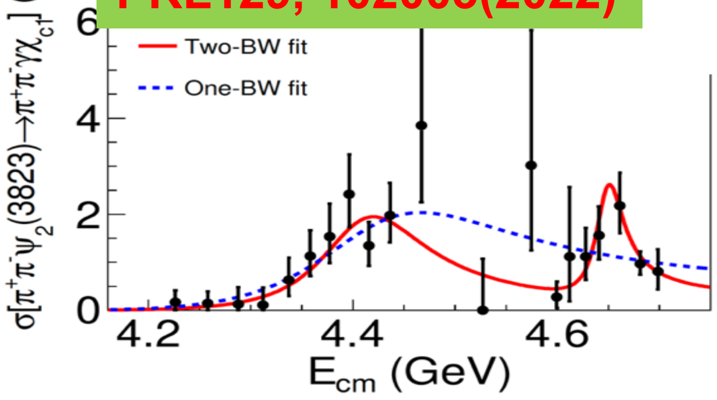


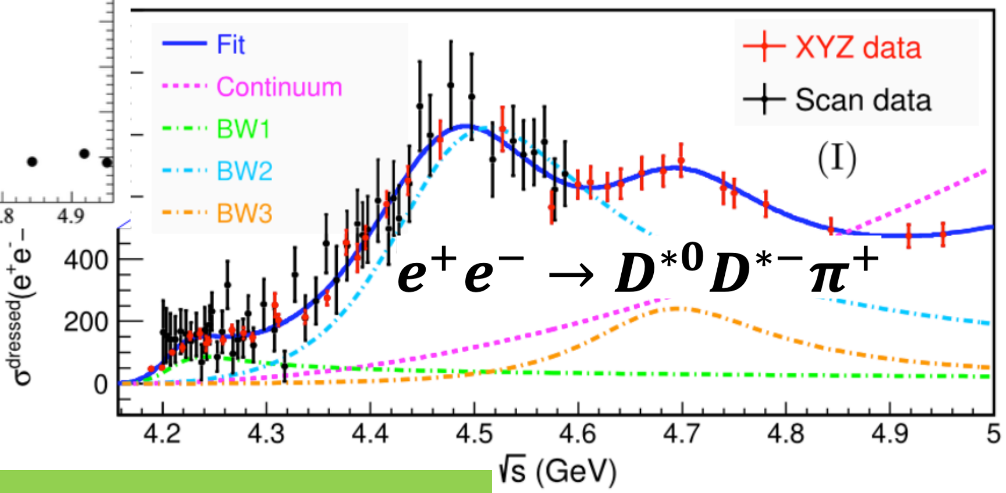
PRL131, 151903 (2023)



$e^+e^- \to \pi^+\pi^-\psi_2(3823)$

PRL129, 102003(2022)





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

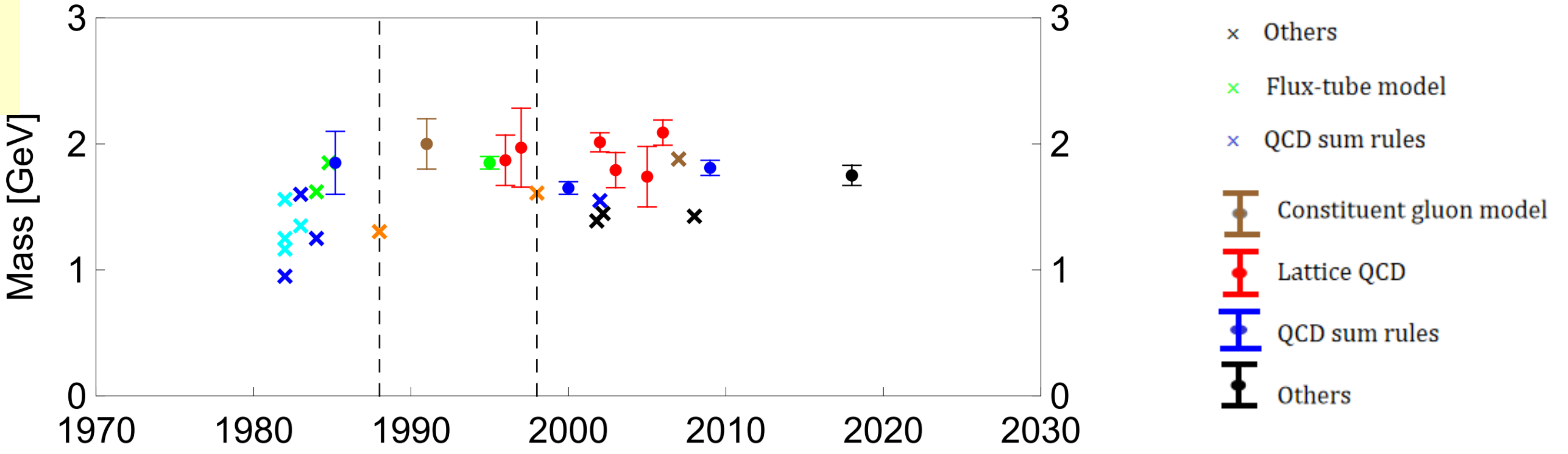
PRL130, 121901 (2023)

Light hadron Physics:
Spectroscopy and decay properties

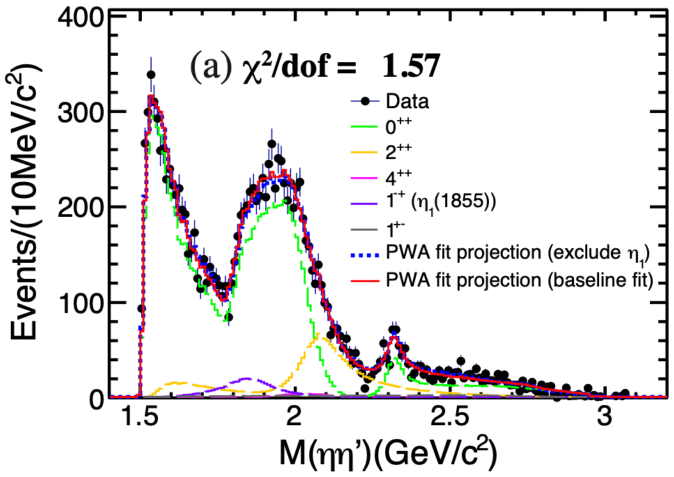
Light hadrons with exotic quantum numbers

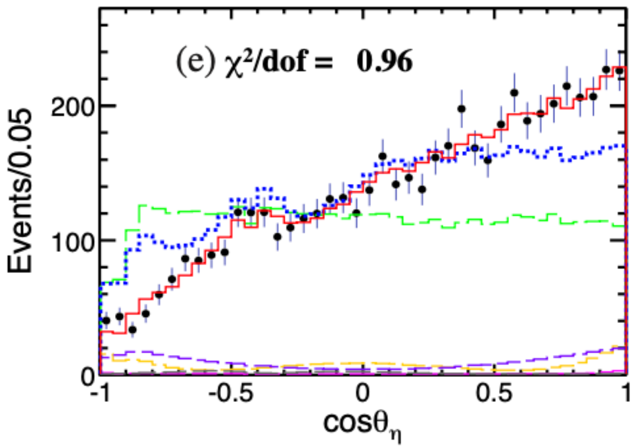
Theoretical predictions of the $J^{PC} = 1^{-+}$ hybrid meson mass

Rept.Prog.Phys. 86 (2023) 026201



Partial wave analysis of $J/\psi \to \gamma\eta\eta'$





PRL 129, 192002 (2022),
PRL 130, 159901(2023)
PRD 106, 072012 (2022),
PRD 107, 079901(2023)

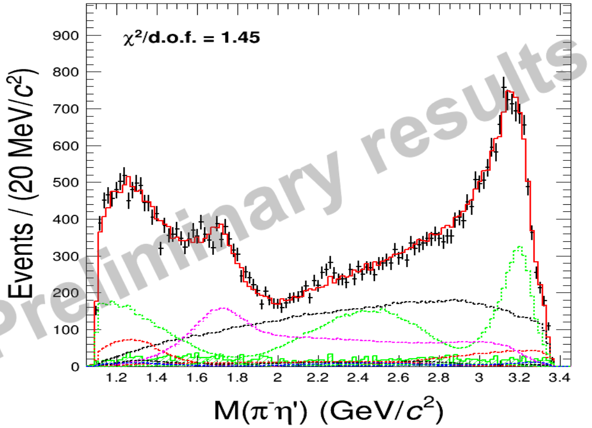
- Observation of isoscalar 1^{-+} $\eta_1(1855)$
- critical to establish the 1^{-+} hybrid nonet.
- supportring $f_0(1710)$ overlap with glueball

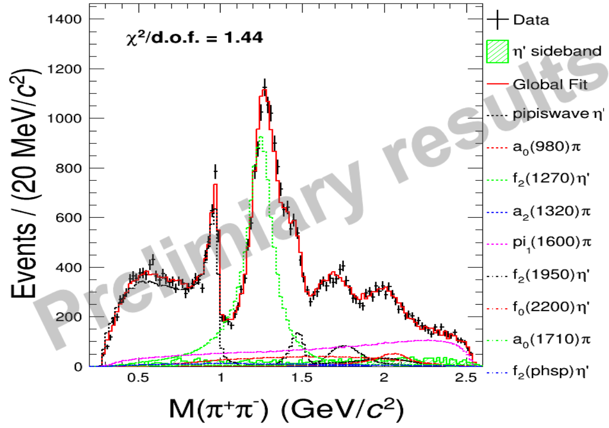
Observation of the $\pi_1(1600)$ in $\psi' \to \gamma\chi_{c1}, \chi_{c1} \to \pi^+\pi^-\eta'$

- **Spin-parity of the $\pi_1(1600)$**
  - 1^{-+} assignment fit is better than that for 0^{++}, 2^{++} or 4^{++} assignments with significances well over 10σ
- **Significance of the Breit-Wigner phase motion**
  - Replace the resonant $\pi_1(1600)$ with a non-resonant $\pi\eta'$ P-wave described by the Breit-Wigner function without phase motion
    - $f = \frac{1}{\sqrt{(m^2-s)^2+m^2\Gamma^2}}$
  - The fit yields that: $\Delta M = +6.9\ \text{MeV}/c^2$, $\Delta\Gamma = -96.4\ \text{MeV}$
  - We observed significant phase motion with a statistical significance greater than 10σ

Nominal PWA solution

state	J^{PC}	Decay mode	Significance
$\pi_1(1600)$	1^{-+}	$\pi^\pm\eta'$	$>> 10\sigma$
$(\pi\pi)_{S-wave}$	0^{++}	$\pi^\pm\eta'$	$>> 10\sigma$
$a_0(980)$	0^{++}	$\pi^\pm\eta'$	$> 10\sigma$
$f_2(1270)$	2^{++}	$\pi^+\pi^-$	$>> 10\sigma$
$a_2(1320)$	2^{++}	$\pi^\pm\eta'$	$> 5\sigma$
$f_2(1950)$	2^{++}	$\pi^+\pi^-$	$> 10\sigma$
$f_0(2200)$	0^{++}	$\pi^+\pi^-$	$> 10\sigma$
$a_0(1710)$	0^{++}	$\pi^\pm\eta'$	$> 10\sigma$
$f_2(PHSP)$	2^{++}	$\pi^+\pi^-$	$> 5\sigma$



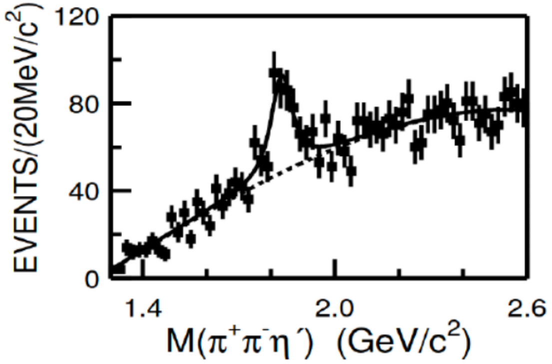


Light hadron spectrum: X families

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

58 M J/ψ

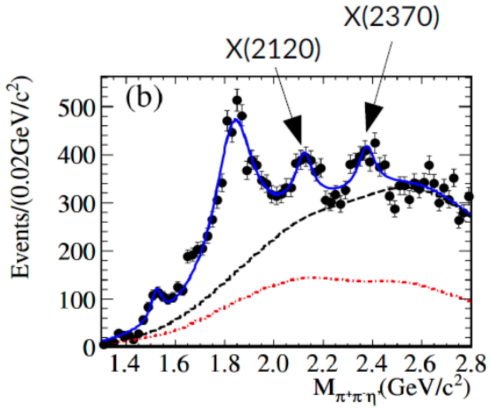
PRL 95 262001(2005)



Observation of X(1835)

225M J/ψ

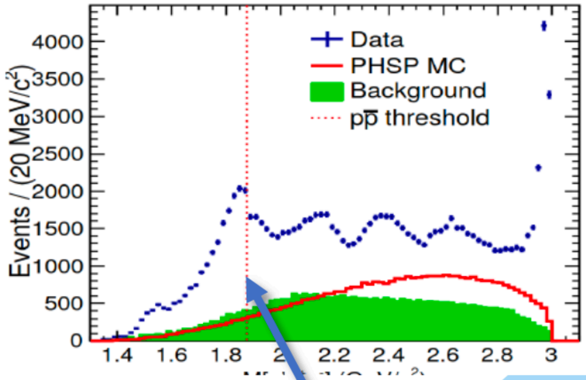
PRL 106 072002(2011)



Observation of X(2120), X(2370)

1.3B J/ψ

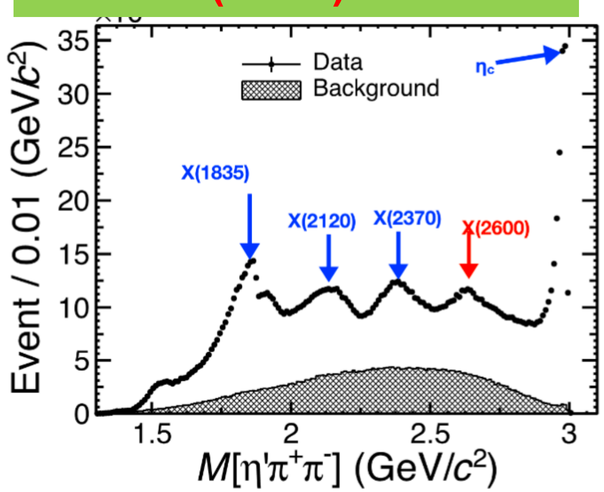
PRL 117 042002(2016)



Observation of anomalous line shape

10B J/ψ

PRL129(2022)042001

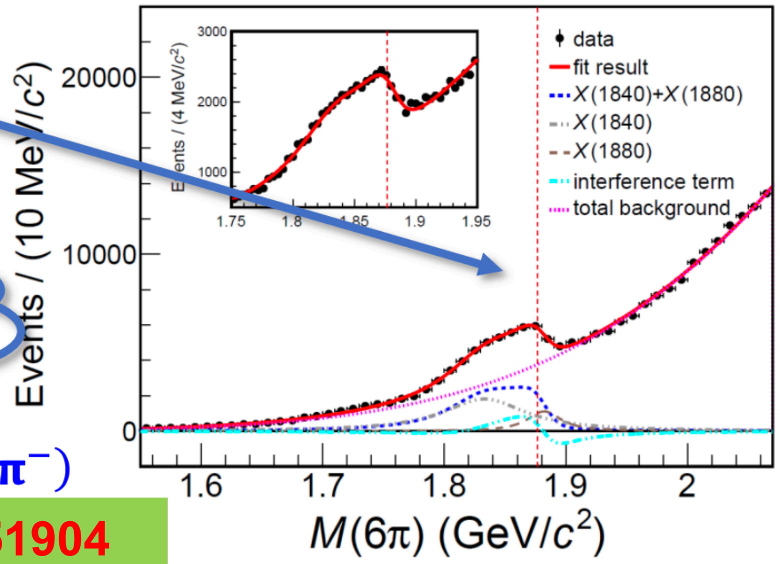


Observation of X(2600)

Indicating a ppbar bound state

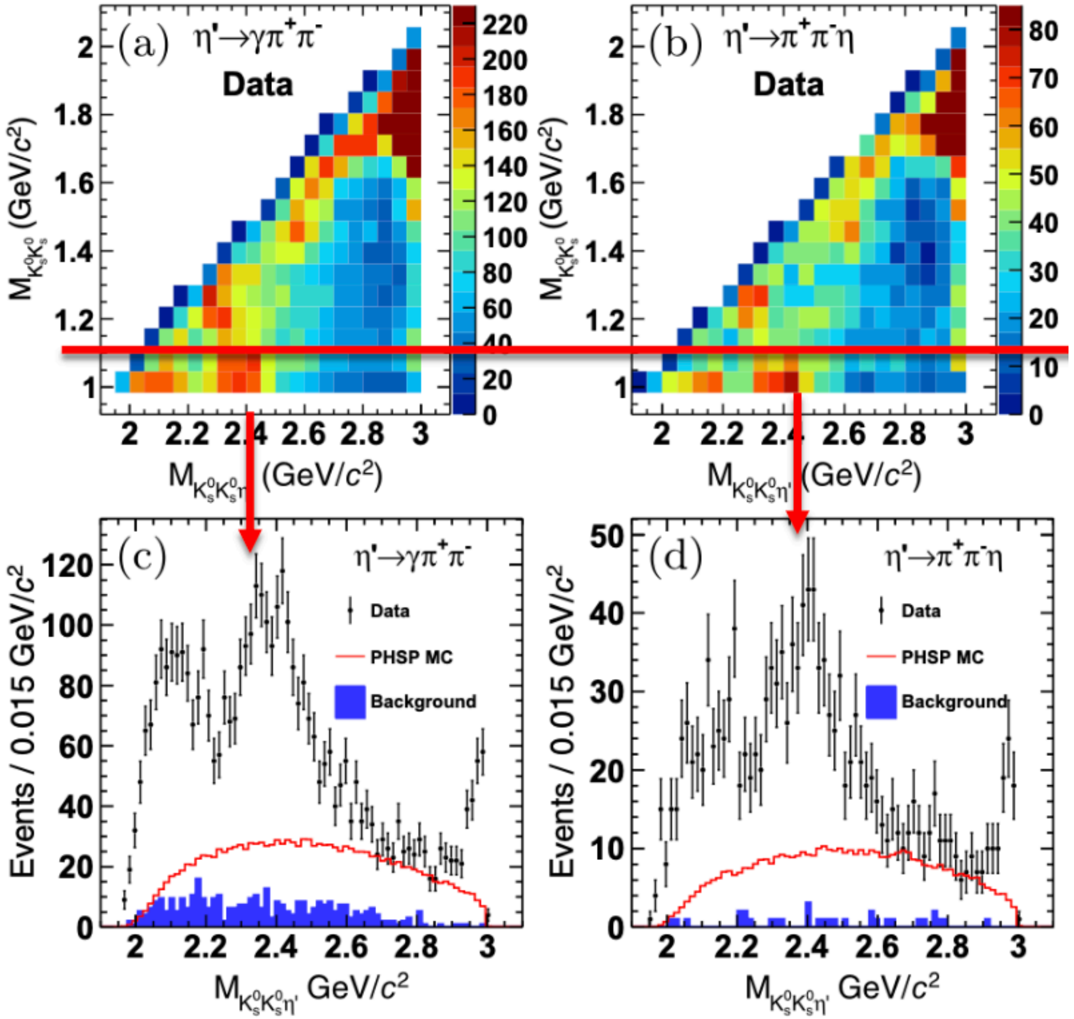
$J/\psi \to \gamma 3(\pi^+\pi^-)$

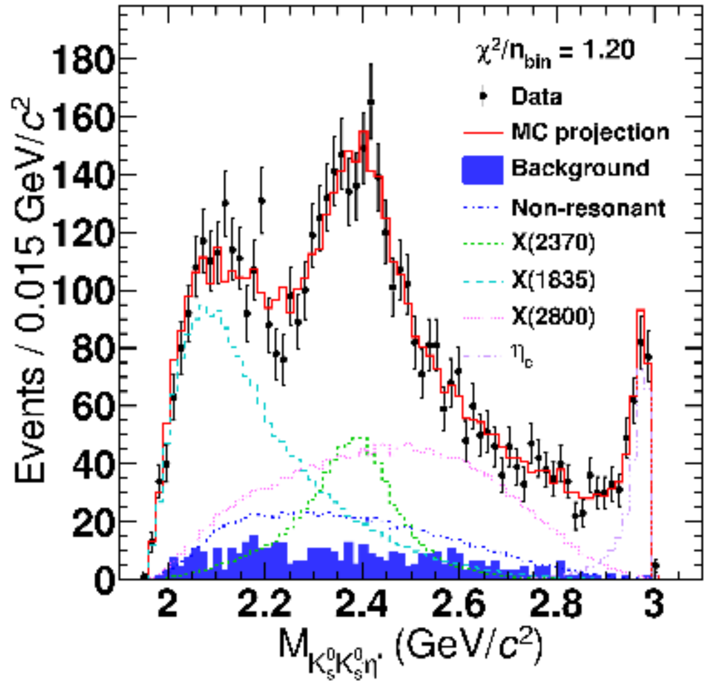
PRL132(2024) 151904

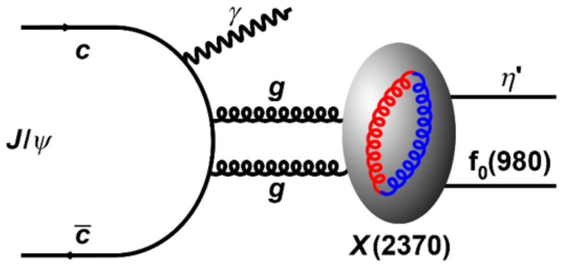


PWA of $J/\psi \to \gamma K_S K_S \eta'$

PRL 132, 181901 (2024)







Good agreement with LQCD prediction of lightest pseudoscalar glueball

$J^{PC} = 0^{-+}$ with significance >9.8σ

$M = 2395 \pm 11^{+26}_{-94}$ MeV

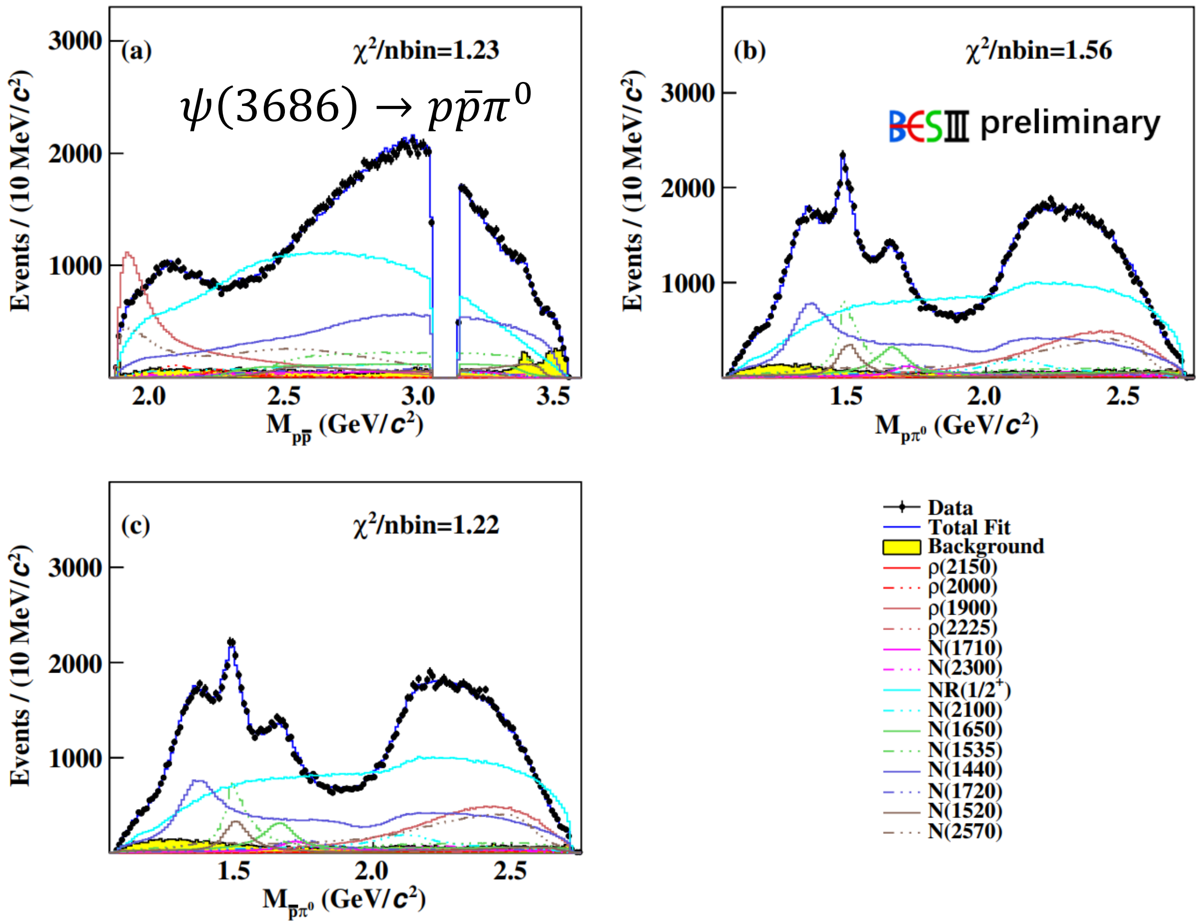
$\Gamma = 188^{+18}_{-17}{}^{+124}_{-33}$ MeV

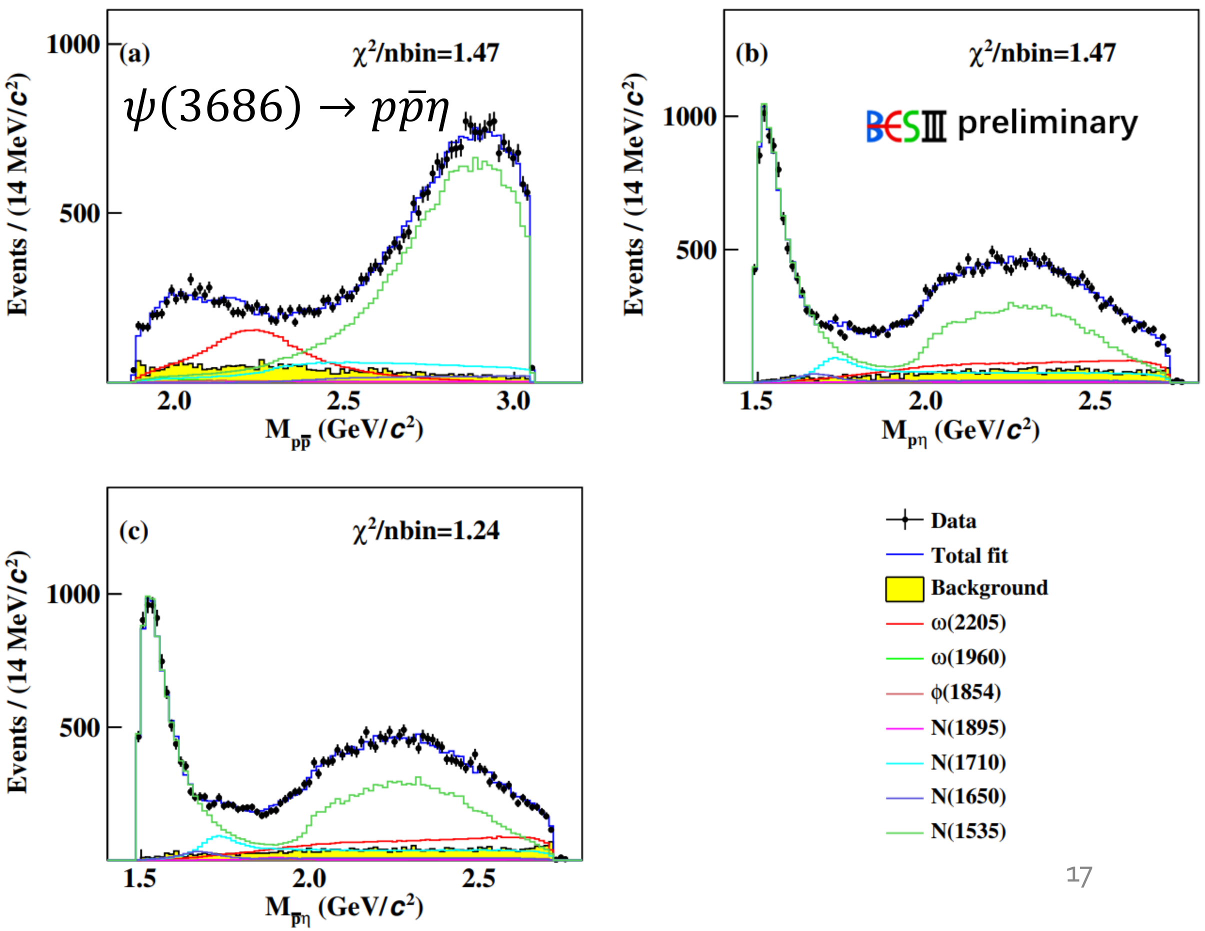
$B(J/\psi \to \gamma X(2370))B(X(2370) \to f_0(980)\eta')B(f_0(980) \to K^0_S K^0_S)$

$= 1.31 \pm 0.22^{+2.85}_{-0.84} \times 10^{-5}$

PWA of $\psi(3686) \to p\bar{p}\pi^0/\eta$

- ✓ Data can be well described with Several N^*& $\rho^*/\omega^*/\phi^*$ states.
- ✓ Three lowest lying N^* is described with KSU model: $\Gamma(\sqrt{s}) = \Gamma_0 \times \sum r_i \times \frac{\rho_i(\sqrt{s})}{\rho_i(m_0)}$
- ✓ **$\Gamma_{N\eta}/\Gamma_{N\pi}$ is determined to be $0.99 \pm 0.05_{sta.} \pm 0.17_{sys.}$**





PWA of $\psi(3686) \to p\bar{p}\pi^0/\eta$

✓ The continuum background is subtracted based on PWA result @3.773 GeV

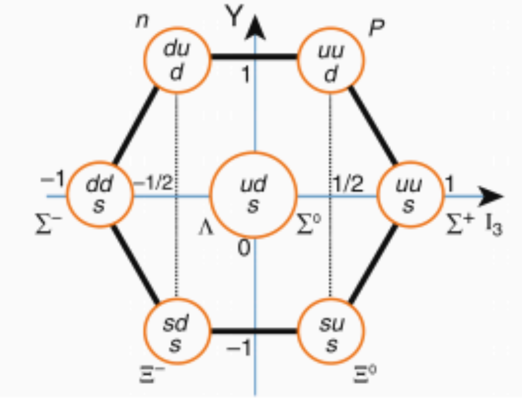
Resonance state	N_{sig}	N_{con}	N_{net}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-6}$)
NR($\frac{1}{2}^+$)	122215 ± 3266	656 ± 164	121188 ± 3276	39.71	$113.9 \pm 3.1 \pm 11.0$
$N(1440)$	57118 ± 1383	953 ± 147	55627 ± 1402	38.34	$54.2 \pm 1.4 \pm 13.2$
$N(1520)$	8109 ± 428	870 ± 81	6749 ± 446	38.43	$6.6 \pm 0.4 \pm 1.8$
$N(1535)$	18894 ± 778	240 ± 77	18519 ± 787	39.61	$17.5 \pm 0.7 \pm 3.4$
$N(1650)$	11146 ± 794	278 ± 79	10712 ± 804	43.75	$9.1 \pm 0.7 \pm 2.4$
$N(1710)$	5043 ± 472	369 ± 100	4466 ± 497	39.73	$4.2 \pm 0.5 \pm 3.8$
$N(1720)$	6983 ± 523	217 ± 33	6644 ± 539	39.93	$6.2 \pm 0.5 \pm 1.9$
$N(2100)$	11107 ± 1033	551 ± 161	10245 ± 1063	44.90	$8.5 \pm 0.9 \pm 3.8$
$N(2300)$	5633 ± 566	894 ± 222	4235 ± 664	43.75	$3.6 \pm 0.6 \pm 2.9$
$N(2570)$	27716 ± 1041	2349 ± 187	24043 ± 1082	46.14	$19.5 \pm 0.9 \pm 13.8$

Resonance state	N_{sig}	N_{con}	N_{net}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-6}$)
$N(1535)$	20411 ± 460	570 ± 115	19486 ± 486	36.17	$50.5 \pm 1.3 \pm 7.0$
$N(1650)$	809 ± 310	388 ± 88	180 ± 341	—	—
$N(1710)$	3351 ± 273	63 ± 63	3250 ± 292	38.81	$7.8 \pm 0.7 \pm 1.8$
$N(1895)$	198 ± 50	71 ± 32	83 ± 72	—	—

Also hyperons…

详见：BESIII实验和STCF上的超子精细测量 by 严亮

- Hyperons are the strange siblings of the proton and neutron



- ▸ **Half lifes:** $\tau_Y \sim 10^{-10}$ s
  - ★ Sensitivity loss $\sim 10^3$ w.r.t. to K^+, K_L
- ▸ **Rich phenomenology:**
  - ★ Spin → sensitivity to various NP structures
  - ★ $SU(3)$-relations to nucleon-structure

Testing of P and CP Symmetries,
X.G. He & J.P. Ma, *Phys.Lett.B* 839 (2023) 137834

New Physics Searches at Kaon and Hyperon Factories

Editors: Evgueni Goudzovski[1], Diego Redigolo[2,3], Kohsaku Tobioka[4,5], Jure Zupan[6]

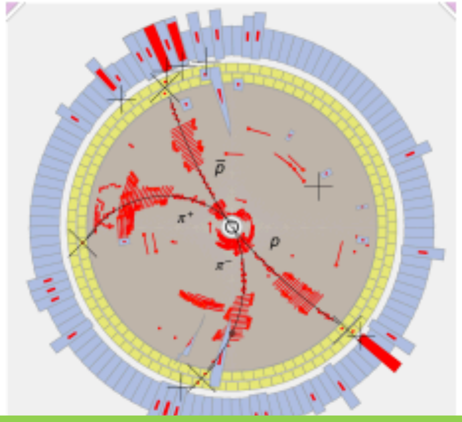
Authors: Gonzalo Alonso-Álvarez[7], Daniele S. M. Alves[8], Saurabh Bansal[6], Martin Bauer[9], Joachi… Brod[6], Veronika Chobanova[10], Giancarlo D'Ambrosio[11], Alakabha Datta[12], Avital Dery[13], France… Dettori[14], Bogdan A. Dobrescu[15], Babette Döbrich[16], Daniel Egana-Ugrinovic[17], Gilly Elor[18], Mi… Escudero[19], Marco Fabbrichesi[20], Bartosz Fornal[21], Patrick J. Fox[15], Emidio Gabrielli[20,22,23], Li-Sh… Yuva… Kelly… Kvedaraitė[6], Gaia Lanfranchi[41], Danny Marfatia[42], Jorge Martin Camalich[43,44], Diego Martínez Santos[10], Karim Massri[16], Patrick Meade[45], Matthew Moulson[41], Hajime Nanjo[46], Matthias Neube… Maxim Pospelov[31,32], Sophie Renner[2], Stefan Schacht[47], Marvin Schnubel[18], Rui-Xiang Shi[25,48], B… Shuve[49], Tommaso Spadaro[41], Yotam Soreq[50], Emmanuel Stamou[51], Olcyr Sumensari[52], Michele Tammaro[53], Jorge Terol-Calvo[43,44], Andrea Thamm[54], Yu-Chen Tung[55], Dayong Wang[56], Kei Yamamoto[57], Robert Ziegler[58]

Rept.Prog.Phys. 86 (2023) 1, 016201

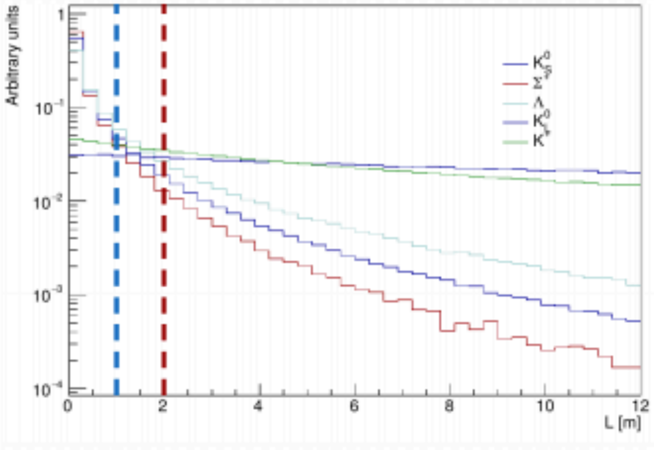
- Recent experimental "revolution" after 40^+ yrs …

▸ **Polarized-hyperon factories (BESIII&SCTF)**

▸ **LHCb:** 10^{2-3} more hyps than B's



Snowmass2021 workshop



Alves Junior *et al.* JHEP 05 (2019) 048

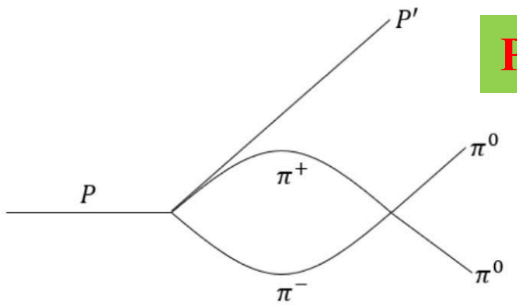
- More channels
- More complex analysis

More data samples in critical regions

Rich program with eta/eta' decays

Decay Mode	$\mathcal{B}(\times 10^{-4})$ [5]	η/η' events
$J/\psi \to \gamma\eta'$	51.5 ± 1.6	5.2×10^7
$J/\psi \to \gamma\eta$	11.04 ± 0.34	1.1×10^7
$J/\psi \to \phi\eta'$	7.5 ± 0.8	7.5×10^6
$J/\psi \to \phi\eta$	4.5 ± 0.5	4.5×10^6
$J/\psi \to \omega\eta$	17.4 ± 2.0	1.7×10^7
$J/\psi \to \omega\eta'$	1.82 ± 0.21	1.8×10^6

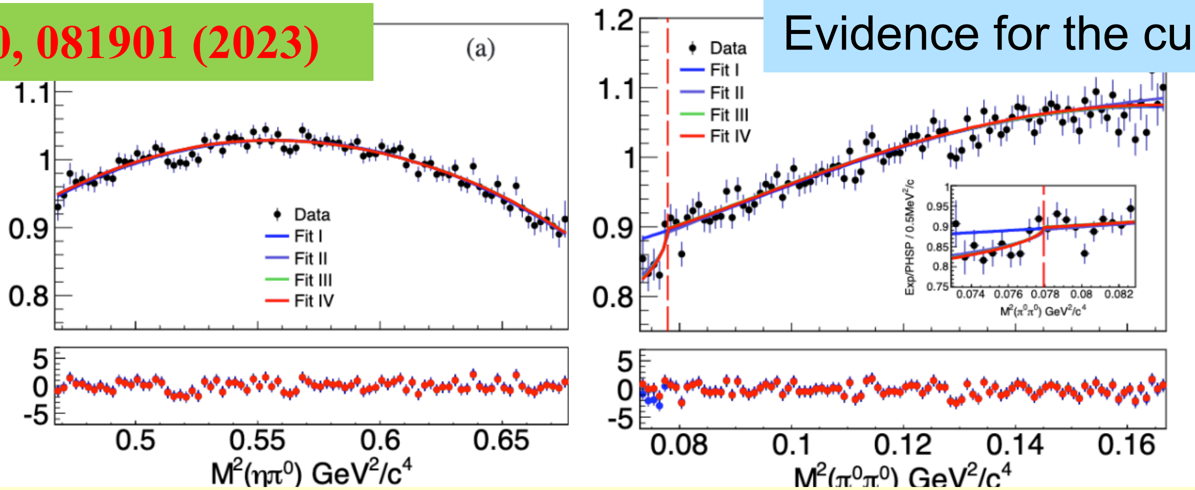
η decay mode	physics highlight	η' mode	physics highlight
$\eta \to \pi^0 2\gamma$	ChPT	$\eta' \to \pi\pi$	CPV
$\eta \to \gamma B$	leptophobic dark boson	$\eta' \to 2\gamma$	chiral anomaly
$\eta \to 3\pi^0$	$m_u - m_d$	$\eta' \to \gamma\pi\pi$	box anomaly, form factor
$\eta \to \pi^+\pi^-\pi^0$	$m_u - m_d$, CV	$\eta' \to \pi^+\pi^-\pi^0$	$m_u - m_d$, CV
$\eta \to 3\gamma$	CPV	$\eta' \to \pi^0\pi^0\eta$	cusp effect [83]



$$C_{00} = \frac{16\pi}{3}(a_0 + 2a_2)(1 - \xi),$$
$$C_x = \frac{16\pi}{3}(a_2 - a_0)(1 + \frac{\xi}{3}),$$
$$C_{+-} = \frac{8\pi}{3}(2a_0 + a_2)(1 + \xi),$$
$$\xi = \frac{M_{\pi^\pm}^2 - M_{\pi^0}^2}{M_{\pi^\pm}^2}.$$

PRL130, 081901 (2023)

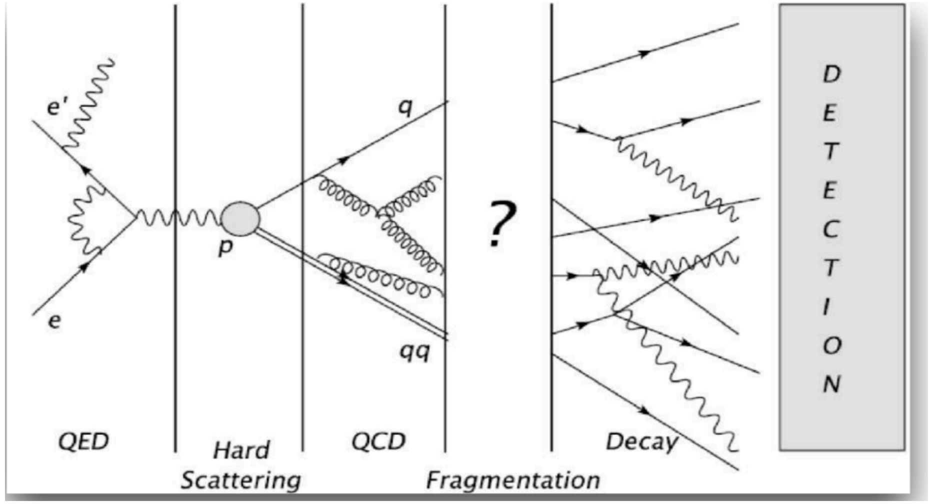
Evidence for the cusp effect in η'→η π^0 π^0



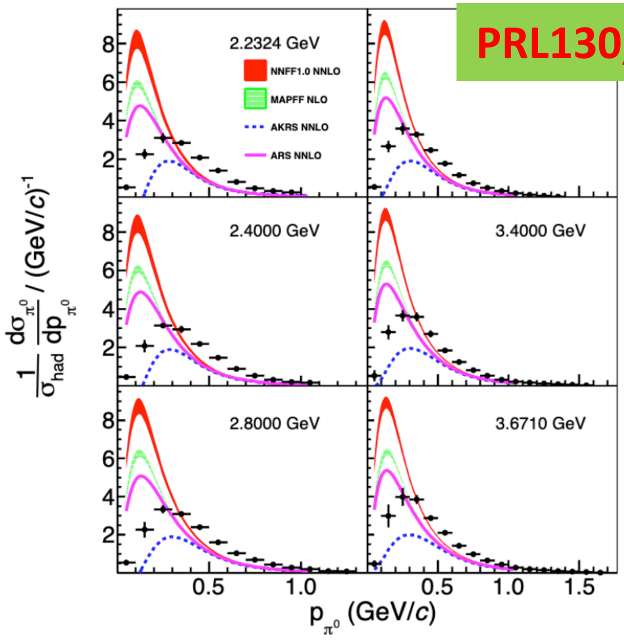
- Evidence for the cusp effect with 3.5σ, consistent with NREFT
- Scattering length combination in good agreement with calculation

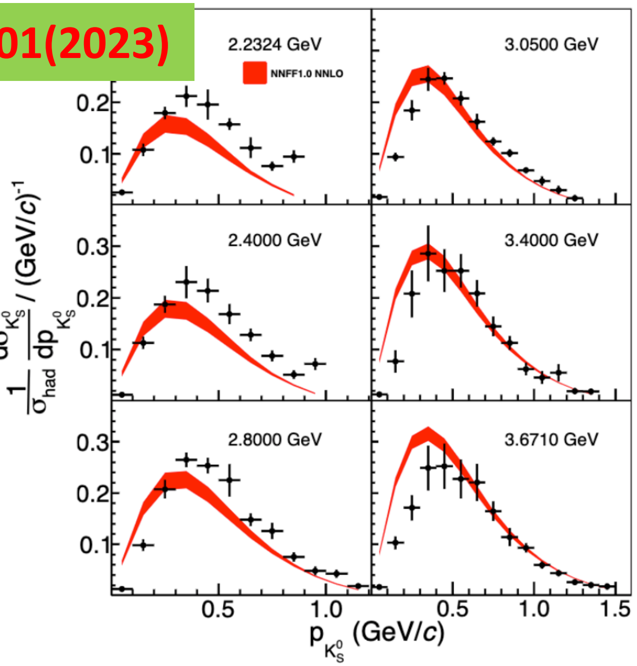
R value and QCD studies

Fragmentation function measurement



PRL130, 231901(2023)

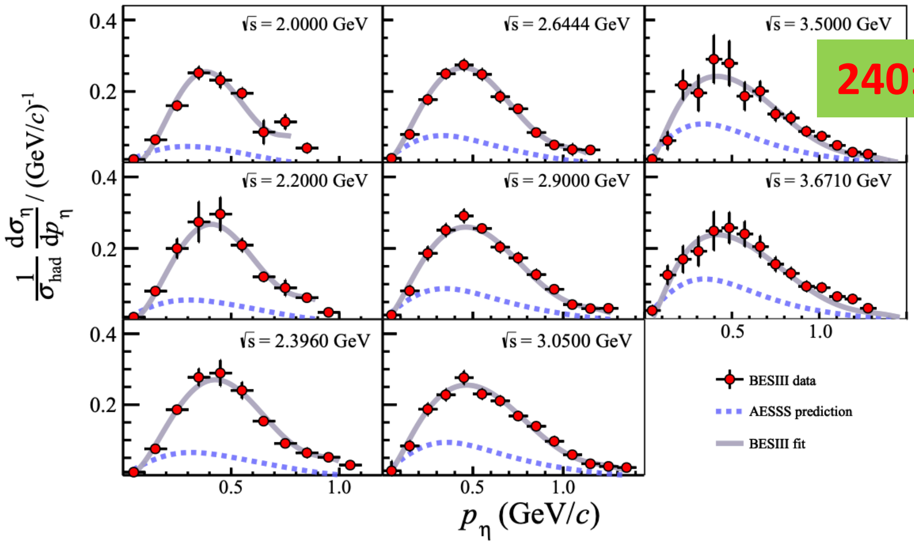




$$\frac{1}{\sigma_{tot}}\frac{d\sigma(h+X)}{dx} = \sum_i \int_x^1 \frac{dz}{z} C_i(z,\alpha_s(s),\frac{s}{\mu^2})\, D_i^h(\frac{x}{z},\mu^2)$$

- **Inclusive π^0 /Ks/eta production in e+ e- collision at 2.2324, 2.400, 2.800, 3.050, 3.400,3.671 GeV.**
- broad z_h coverage from 0.1 to 0.9, best precision
- provide brand new inputs in low-energy region to global fits of fragmentation function

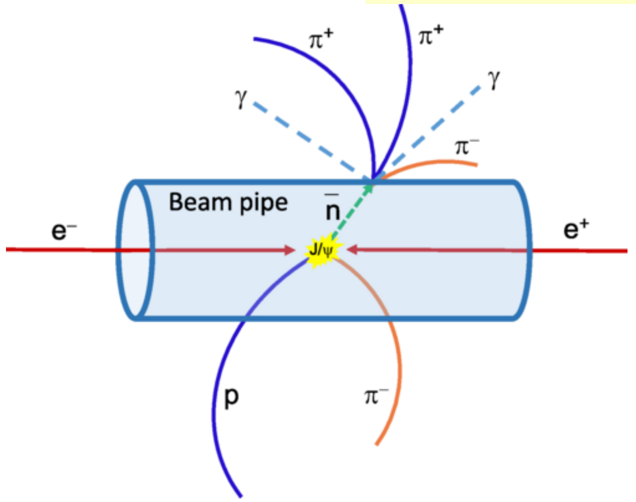
2401.17873, PRL (2024)

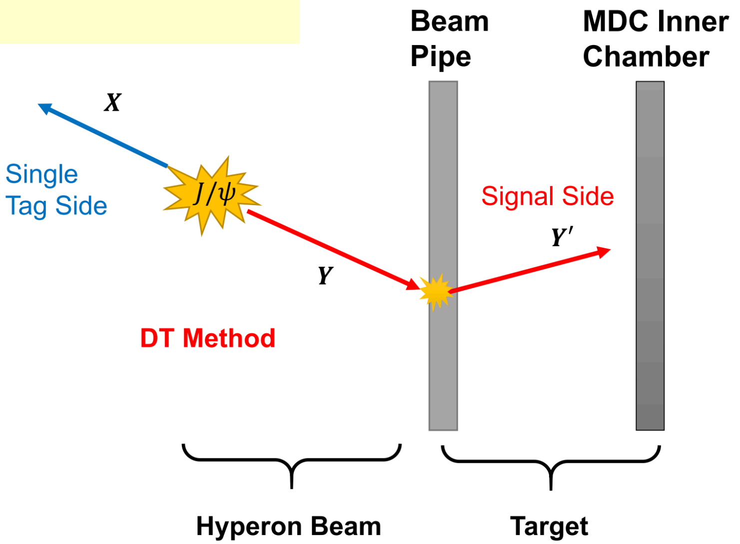


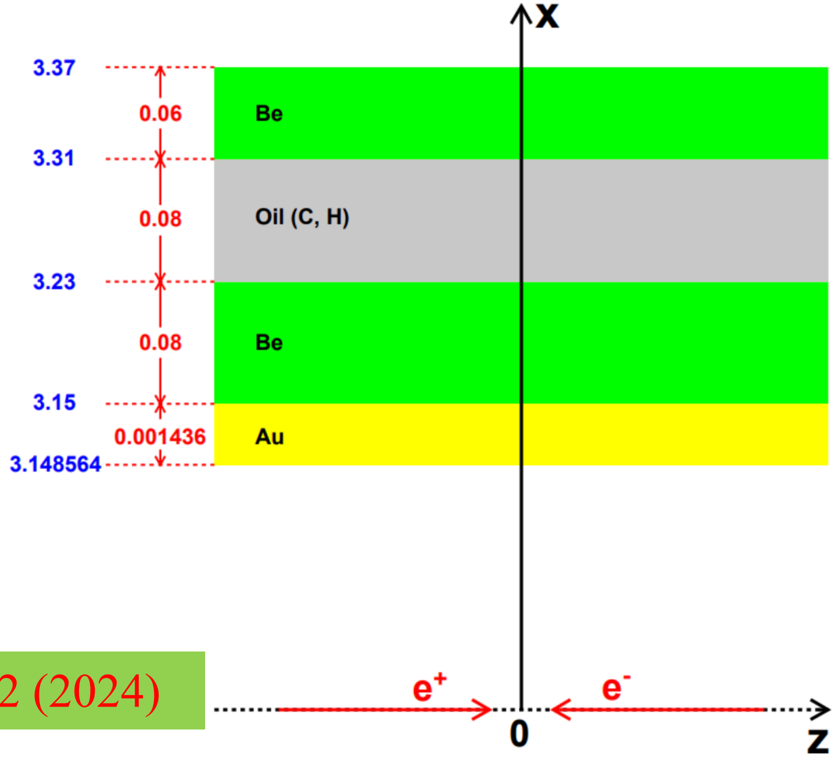
- More channels in progress

Study of hyperon/nbar-nucleon reactions

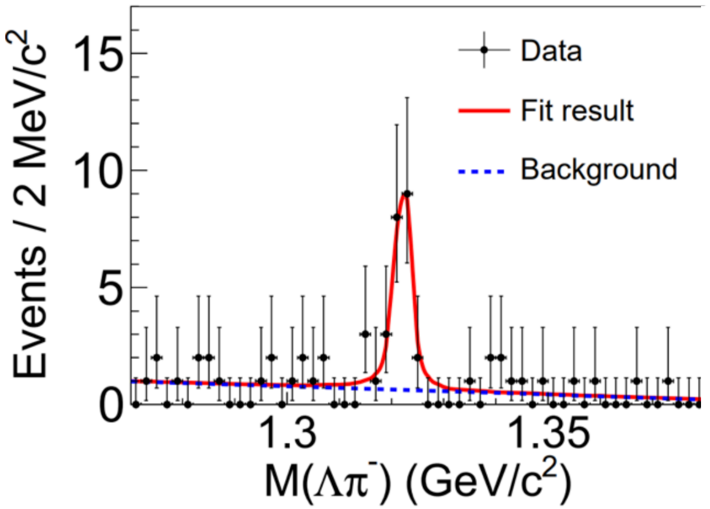
- ✓ Phys. Rev. Lett. 127, 012003 (2021).
- ✓ arXiv:2209.1260





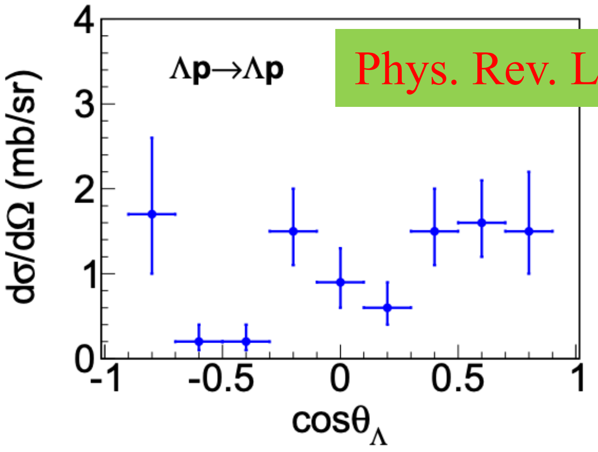


Study of $\Xi^0 n \to \Xi^- p$

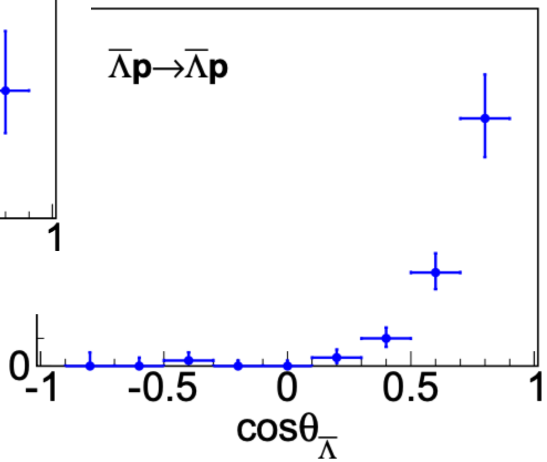


Phys. Rev. Lett. 130, 251902 (2023)

$\bar{\Lambda} p \to \bar{\Lambda} p$ and $\Lambda p \to \Lambda p$



Phys. Rev. Lett. 132, 231902 (2024)



- More channels with different beams, elastic/inelastic …
- Differential measurements

Charm Physics
mesons and baryons

Charm meson studies: Measuring CKM matrix

--- test SM EW theory

At zero positron mass limit:

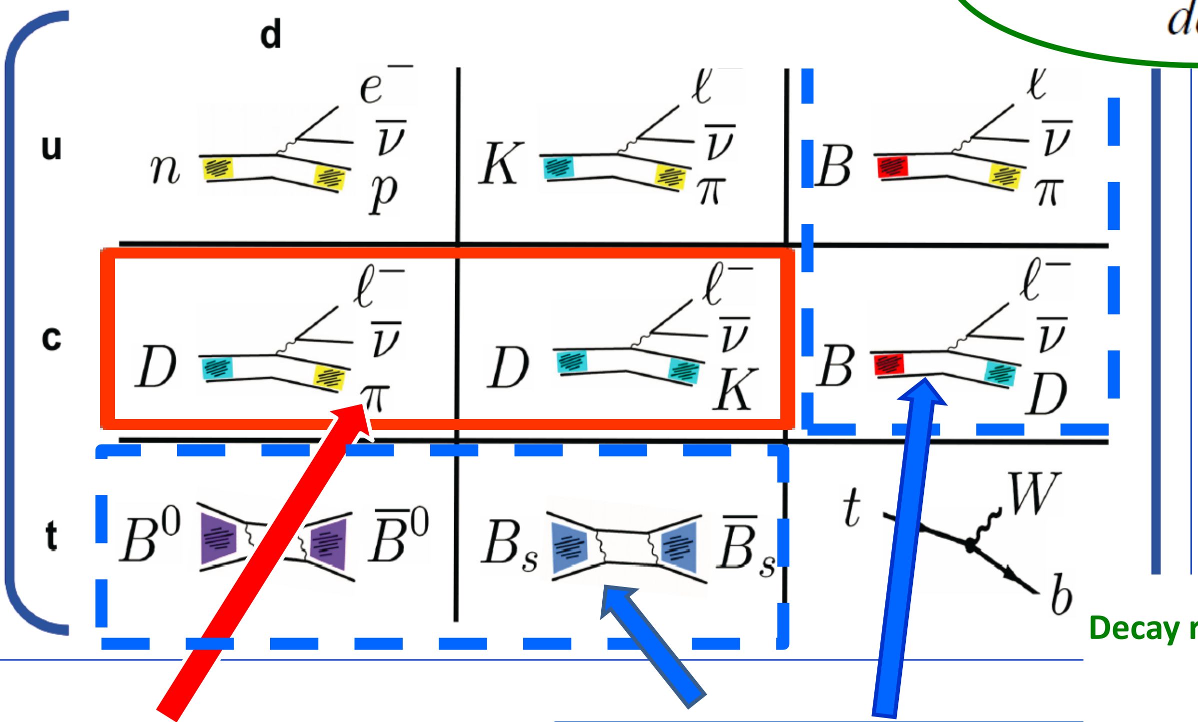
Differential rate (Exp.)

$$\frac{d\Gamma(D_{(s)}\to K(\pi)\ l\nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2 P_{K(\pi)}^3}{24\pi^3} |f_+(q^2)|^2$$

CKM matrix element

Form factor (LQCD)

V =



Charm decays + LQCD

Charm decays + B decays + LQCD

- extend analyses to 20fb-1 data
- More advanced analysis techniques

Decay rate (Exp.)

$$\Gamma(D_{(s)}\to \ell\nu) = |V_{cd(s)}|^2 \times f_{D_{(s)}}^2 \times \frac{G_F^2}{8\pi} m_\ell^2 m_{D_{(s)}} (1 - m_\ell^2/m_{D_{(s)}}^2)^2$$

Decay constant (LQCD)

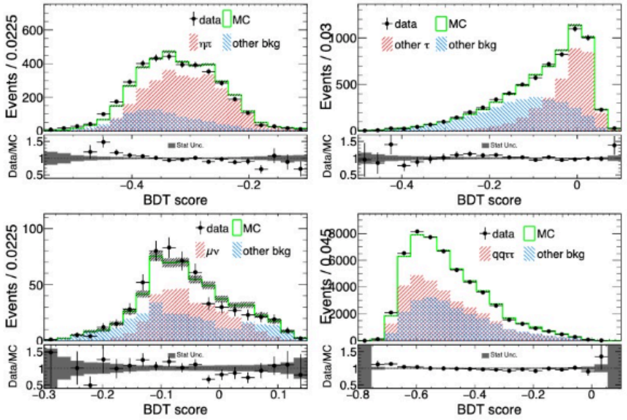
CKM matrix element

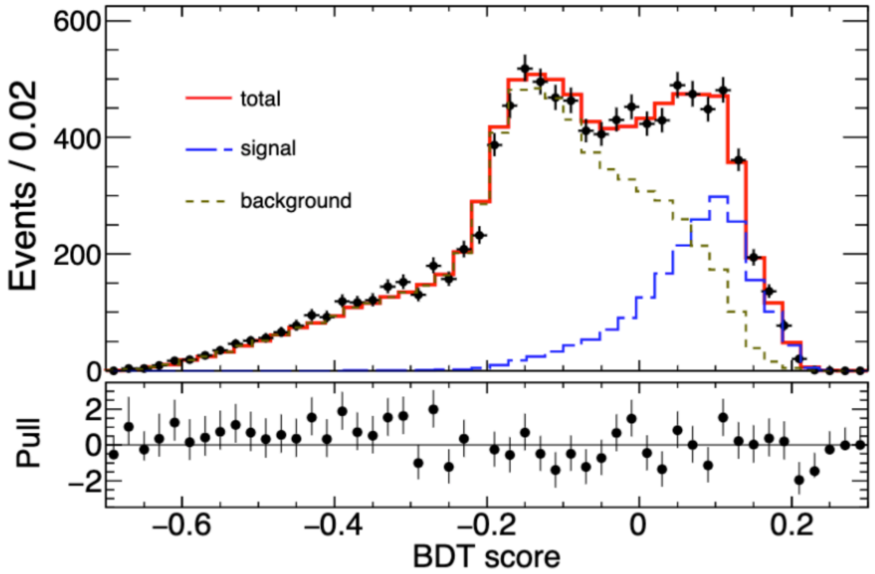
Expected precision < 2% at BESIII

Latest updates of $D_s \to \tau\nu$

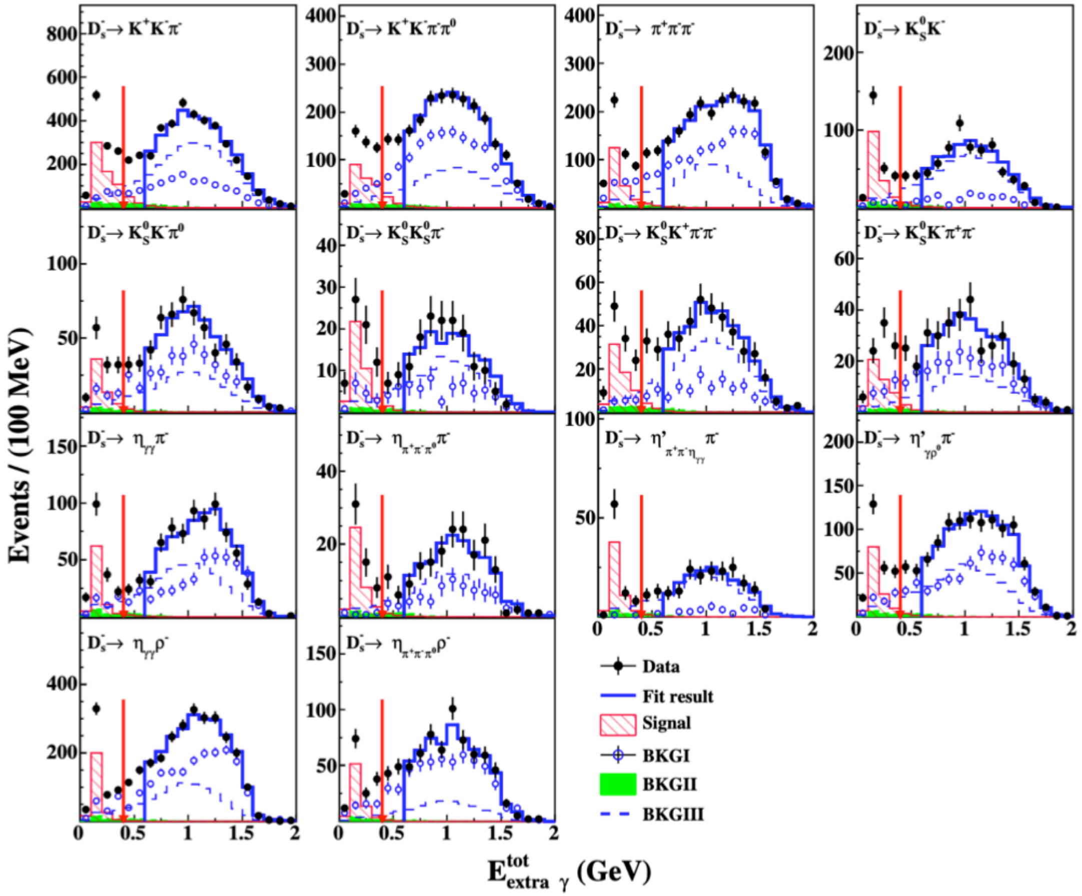
7.33 fb^{-1} data from 4.128 GeV to 4.226 GeV

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$ PRD108,092014(2023)

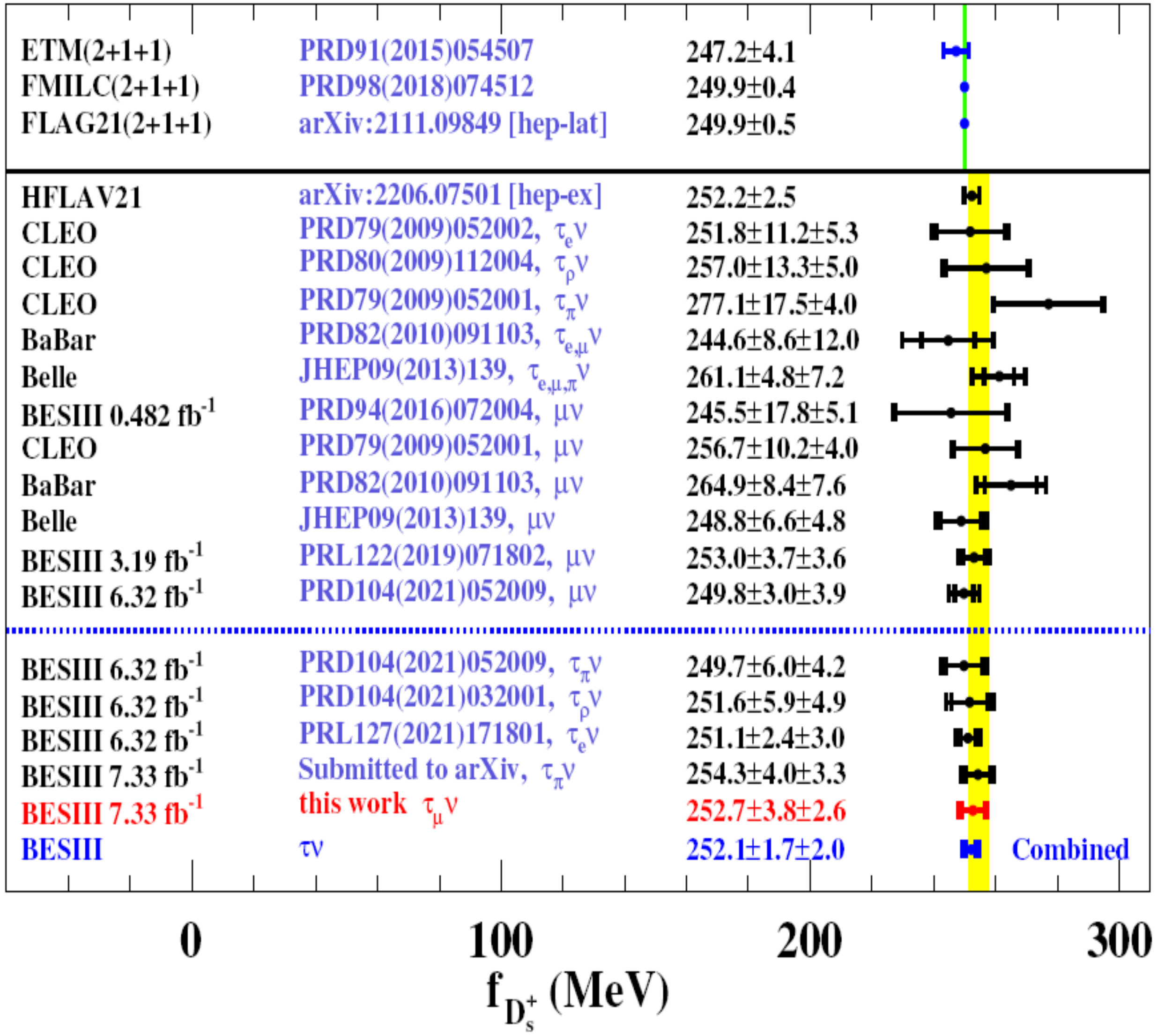


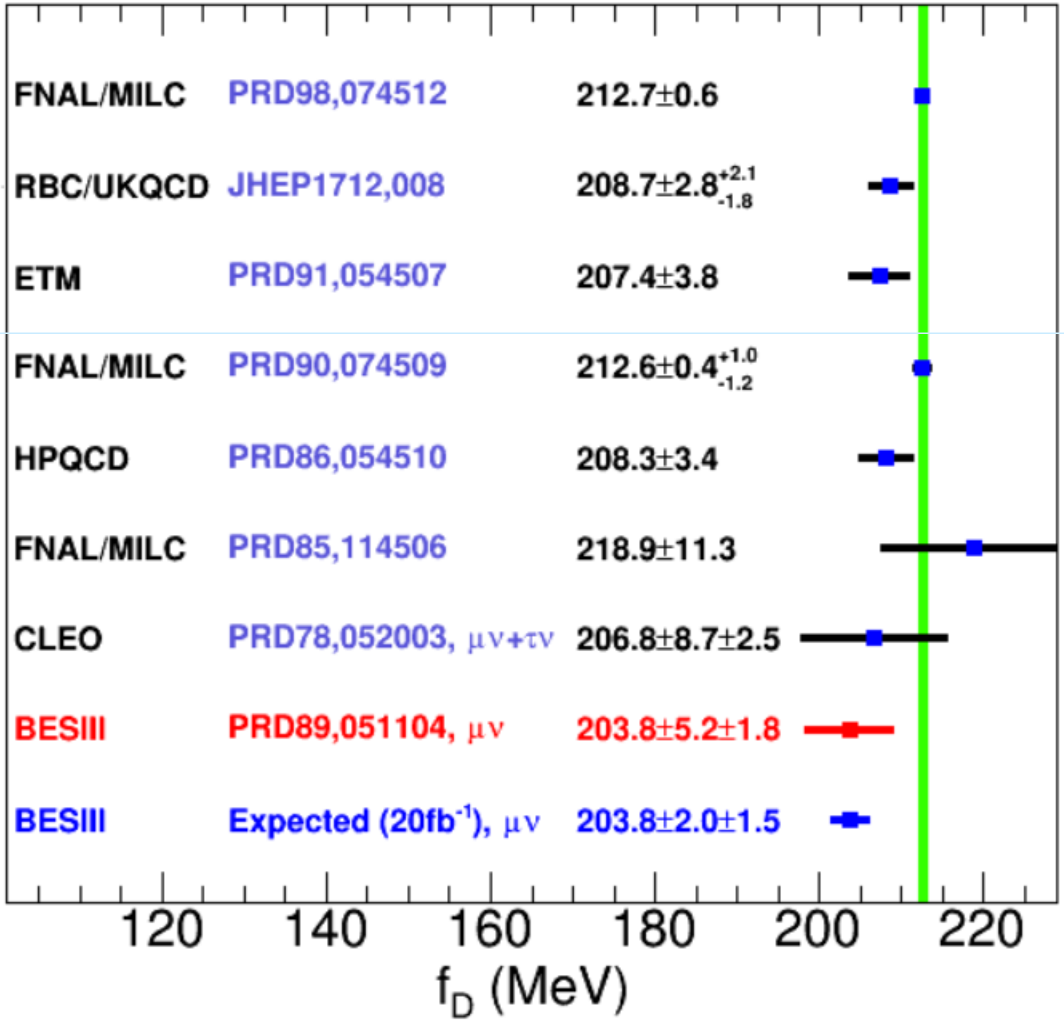


$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ JHEP09(2023)124



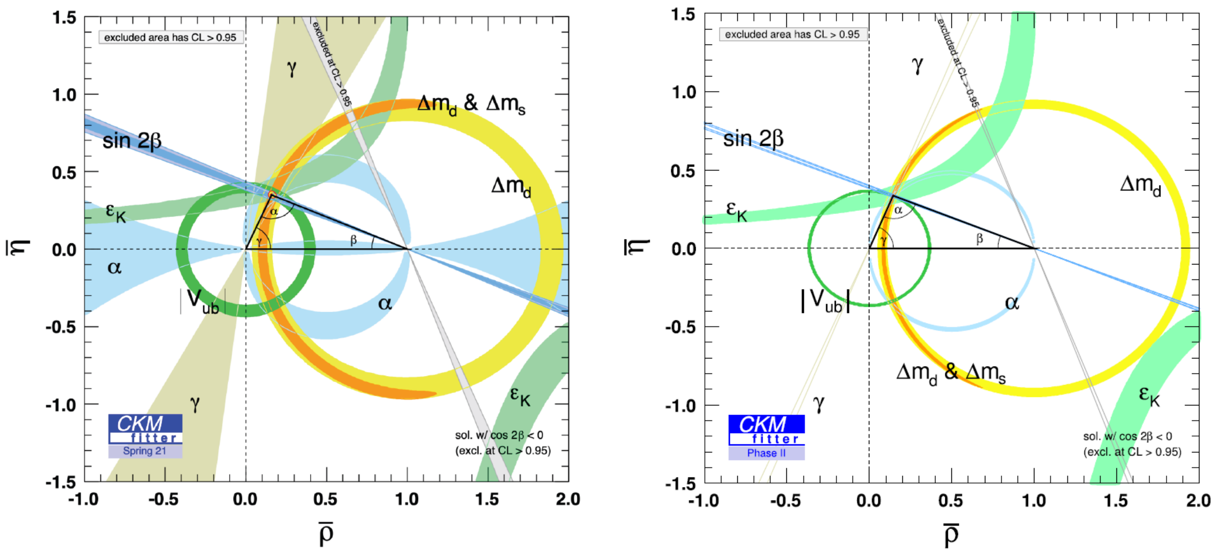
Comparisons of f_{D^+} and $f_{D_s^+}$





Strong phase diff b/w hadronic D^0 / $\bar{D}^0$ decays

Precision measurements of γ at LHCb and Belle II need input the strong phase differences of neutral D decays



Quantum-correlated $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ pairs at BESIII offer an ideal opportunity to extract the strong phase differences between D^0 and $\bar{D}^0$

In the future 10-15 years, the statistical uncertainties of the γ measurements will reach at ~1.5° and 0.4° at Belle II and LHCb upgrade

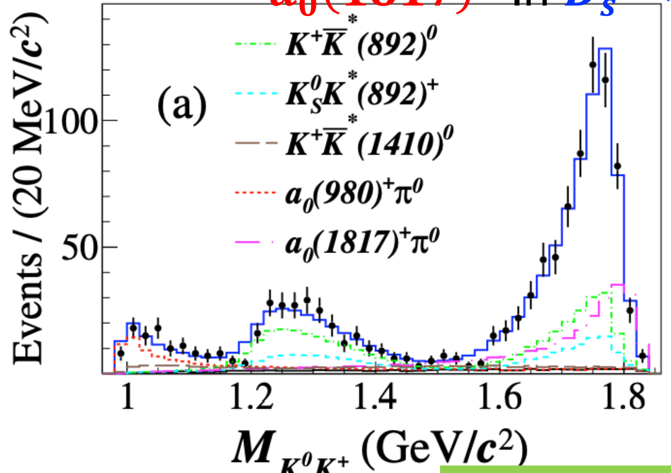
The constraint on the γ measurement before BESIII is only 2°. Improved measurements of strong phase differences are highly desirable

Hadronic D_s^+ decays: Amplitude analyses

$D_s^\pm$ Amplitude analyses

$D_s^+ \to K^+K^-\pi^+$ partial wave analyses	Phys. Rev. D **104** (2021) 012016
$D_s^+ \to K^+K_S\pi^0$ partial wave analyses	Phys. Rev. Lett. **129** (2022) 182001
$D_s^+ \to 2\pi^+\pi^-$ partial wave analyses	Phys. Rev. D **106** (2022) 112006
$D_s^+ \to 2\pi^+\pi^-\eta$ partial wave analyses	Phys. Rev. D **104** (2021) L071101
$D_s^+ \to \pi^+\pi^0\eta'$ partial wave analyses.	**JHEP 04** (2022) 058
$D_s^+ \to \pi^+2\pi^0$ partial wave analyses.	**JHEP 01** (2022) 052
$D_s^+ \to K^+\pi^+\pi^-$ partial wave analyses	**JHEP 08** (2022) 196
$D_s^+ \to K^+\pi^+\pi^-\pi^0$ partial wave analyses	**JHEP 09** (2022) 242
$D_s^+ \to 2K_S^0\pi^+$ partial wave analyses	Phys. Rev. D **105** (2022) L051103
$D_s^+ \to K_S^0K^-2\pi^+$ partial wave analyses	Phys. Rev. D **103** (2021) 092006
$D_s^+ \to K^-K^+\pi^+\pi^0$ partial wave analyses	Phys. Rev. D **104** (2021) 032011
$D_s^+ \to K^-K^+2\pi^+\pi^-$ partial wave analyses	**JHEP 07** (2022) 051
Amplitude analysis of $D_s^+ \to K_S^0\pi^+\pi^0$	**JHEP 06** (2021) 181
Amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta$	Phys. Rev. Lett. **123** (2019) 112001

$a_0(1817)^+$ In $D_s^+ \to K_S^0K^+\pi^0$



PRL129, 182001 (2022)

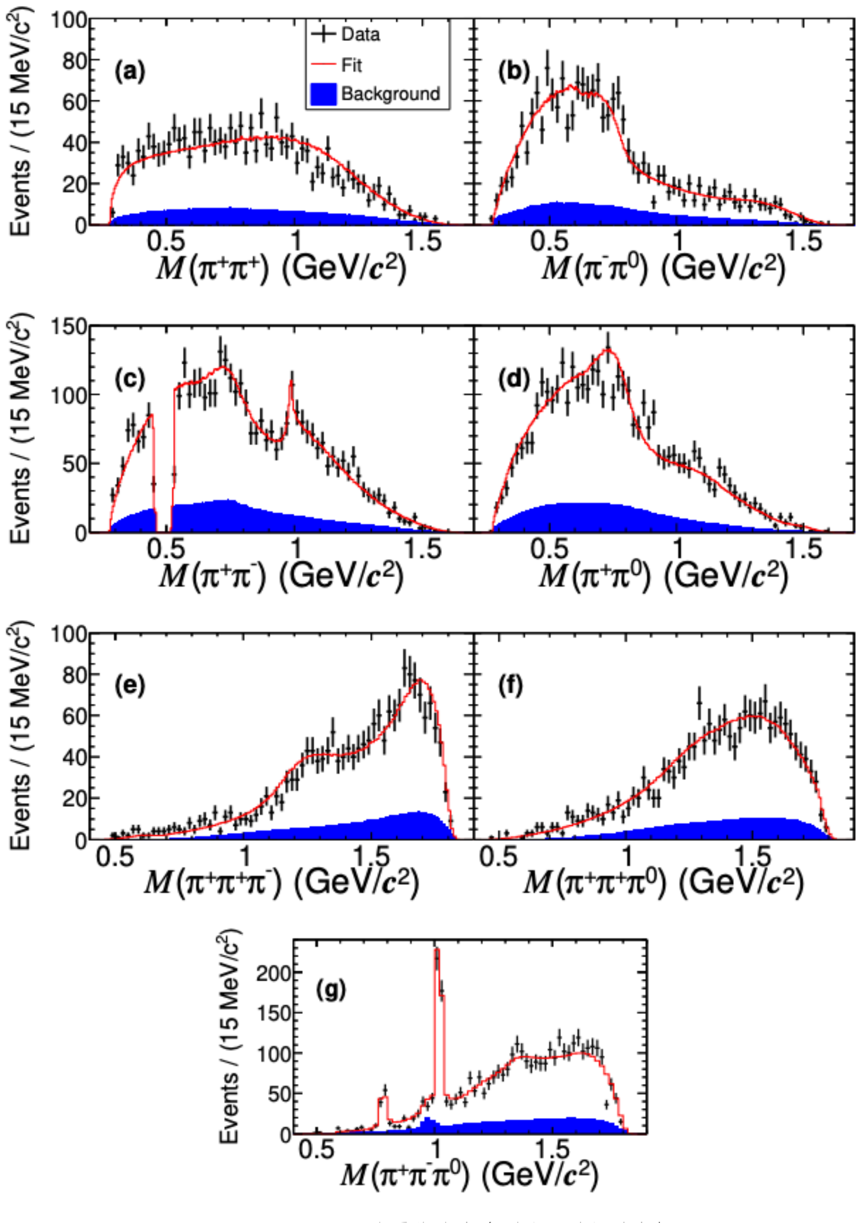
14 published results already in PDG
Many others are ongoing

$D_s^+ \to \pi^+\pi^+\pi^-\pi^0$
$D_s^+ \to \pi^+\pi^+\pi^-\pi^0\pi^0$
$D_s^+ \to \pi^+\pi^0\pi^0\eta$
$D_s^+ \to K_S^0K^+\pi^+\pi^-$

There are also many 3- and 4-body Amplitude analyses for D^+ and D^0

$D_s^+ \rightarrow \pi^+\pi^+\pi^-\pi^0$

Arxiv:2406.17452



10 sigma

Component	Phase (rad)	FF (%)	BF (10^{-3})
$f_0(1370)\rho^+$	0.0(fixed)	$24.9 \pm 3.8 \pm 2.1$	$5.08 \pm 0.80 \pm 0.43$
$f_0(980)\rho^+$	$3.99 \pm 0.13 \pm 0.07$	$12.6 \pm 2.1 \pm 1.0$	$2.57 \pm 0.44 \pm 0.20$
$f_2(1270)\rho^+$	$1.11 \pm 0.10 \pm 0.10$	$9.5 \pm 1.7 \pm 0.6$	$1.94 \pm 0.36 \pm 0.12$
$(\rho^+\rho^0)_S$	$1.10 \pm 0.18 \pm 0.10$	$3.5 \pm 1.2 \pm 0.6$	$0.71 \pm 0.25 \pm 0.12$
$(\rho(1450)^+\rho^0)_S$	$0.43 \pm 0.18 \pm 0.17$	$4.6 \pm 1.3 \pm 0.8$	$0.94 \pm 0.27 \pm 0.16$
$(\rho^+\rho(1450)^0)_P$	$4.58 \pm 0.16 \pm 0.09$	$8.6 \pm 1.3 \pm 0.4$	$1.75 \pm 0.27 \pm 0.08$
$\phi((\rho\pi) \rightarrow \pi^+\pi^-\pi^0)\pi^+$	$2.90 \pm 0.15 \pm 0.18$	$24.9 \pm 1.2 \pm 0.4$	$5.08 \pm 0.32 \pm 0.10$
$\omega((\rho\pi) \rightarrow \pi^+\pi^-\pi^0)\pi^+$	$3.22 \pm 0.21 \pm 0.09$	$6.9 \pm 0.8 \pm 0.3$	$1.41 \pm 0.17 \pm 0.06$
$a_1^+(\rho^0\pi^+)_S\pi^0$	$3.78 \pm 0.16 \pm 0.12$	$12.5 \pm 1.6 \pm 1.0$	$2.55 \pm 0.34 \pm 0.20$
$a_1^0((\rho\pi)_S \rightarrow \pi^+\pi^-\pi^0)\pi^+$	$4.82 \pm 0.15 \pm 0.12$	$6.3 \pm 1.9 \pm 1.2$	$1.29 \pm 0.39 \pm 0.24$
$\pi(1300)^0((\rho\pi)_P \rightarrow \pi^+\pi^-\pi^0)\pi^+$	$2.22 \pm 0.14 \pm 0.08$	$11.7 \pm 2.3 \pm 2.2$	$2.39 \pm 0.48 \pm 0.45$

$$\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^+\pi^-\pi^0|_{\text{non}-\eta}) = (2.04 \pm 0.08_{\text{stat.}} \pm 0.05_{\text{syst.}})\%$$

$$\mathcal{B}(D_s^+ \rightarrow \eta\pi^+) = (1.56 \pm 0.09_{\text{stat.}} \pm 0.04_{\text{syst.}})\%$$

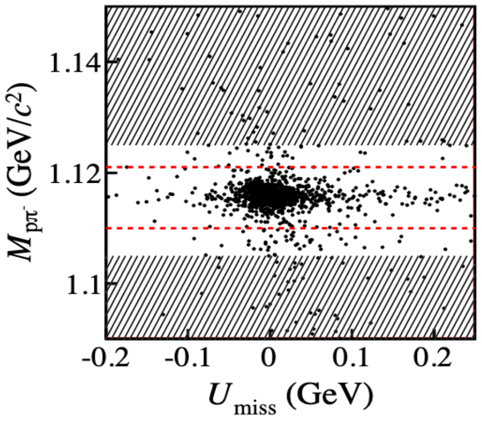
$$\frac{\mathcal{B}(\phi(1020)\rightarrow\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi(1020)\rightarrow K^+K^-)} = 0.230 \pm 0.014_{\text{stat.}} \pm 0.010_{\text{syst.}}$$

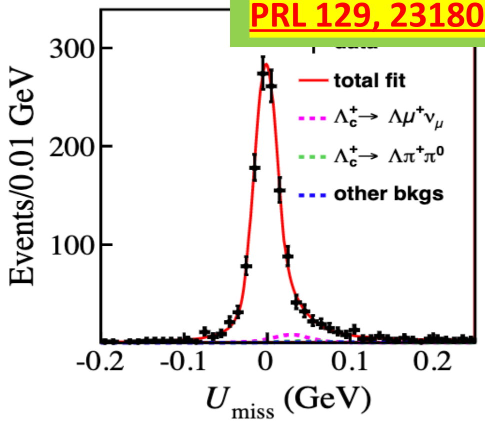
deviates from the world average value by more than 4σ

Studies on Λ_c^+ leptonic decays

Determination of form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

PRL 129, 231803 (2022)



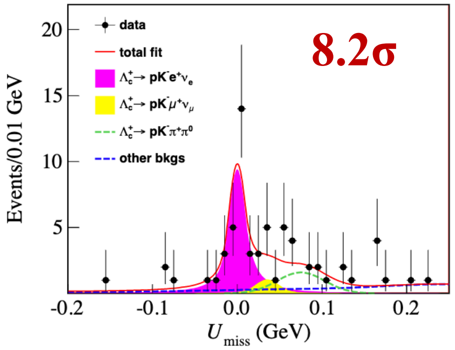


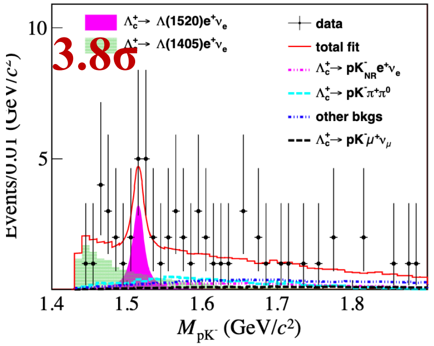
$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$

First direct comparisons on differential DRs and FFs with LQCD

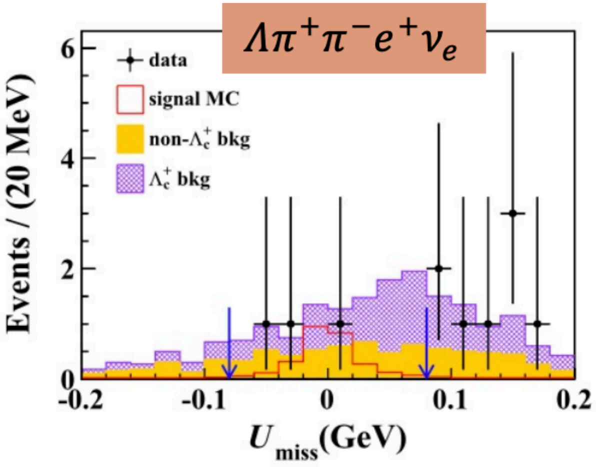
Observation of $\Lambda_c^+ \to p K^- e^+ \nu$

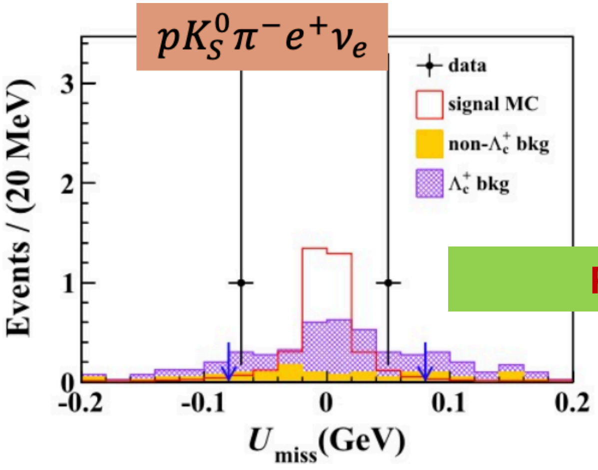
PRD106,112010(2022)





- Second leptonic decay of Λ_c^+ is observed!
- Good channel to study Λ excited states, Λ(1405), Λ(1520)





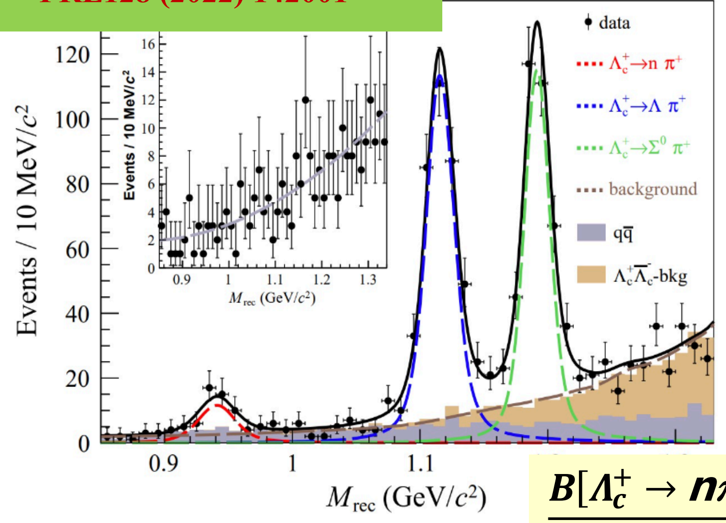
PLB843,137993(2023)

Studies on Λ_c hadronic decays

Many CS modes are explored.

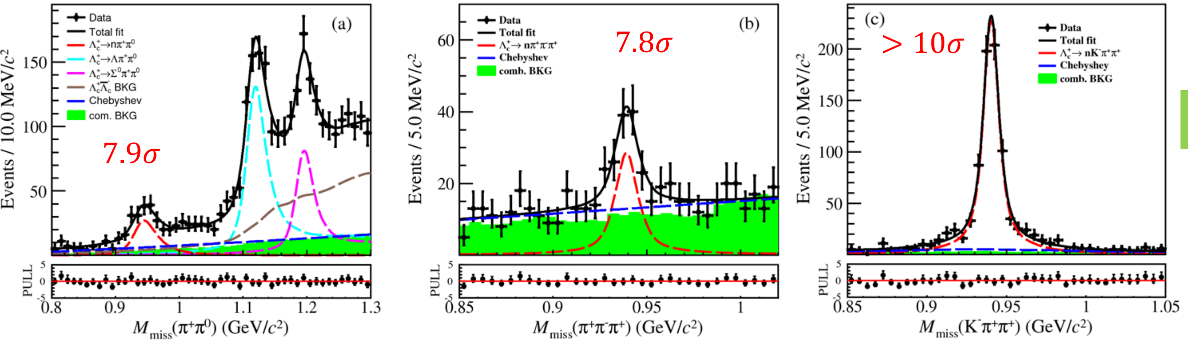
Observation of $\Lambda_c^+ \to n\pi^+$

PRL128 (2022) 142001

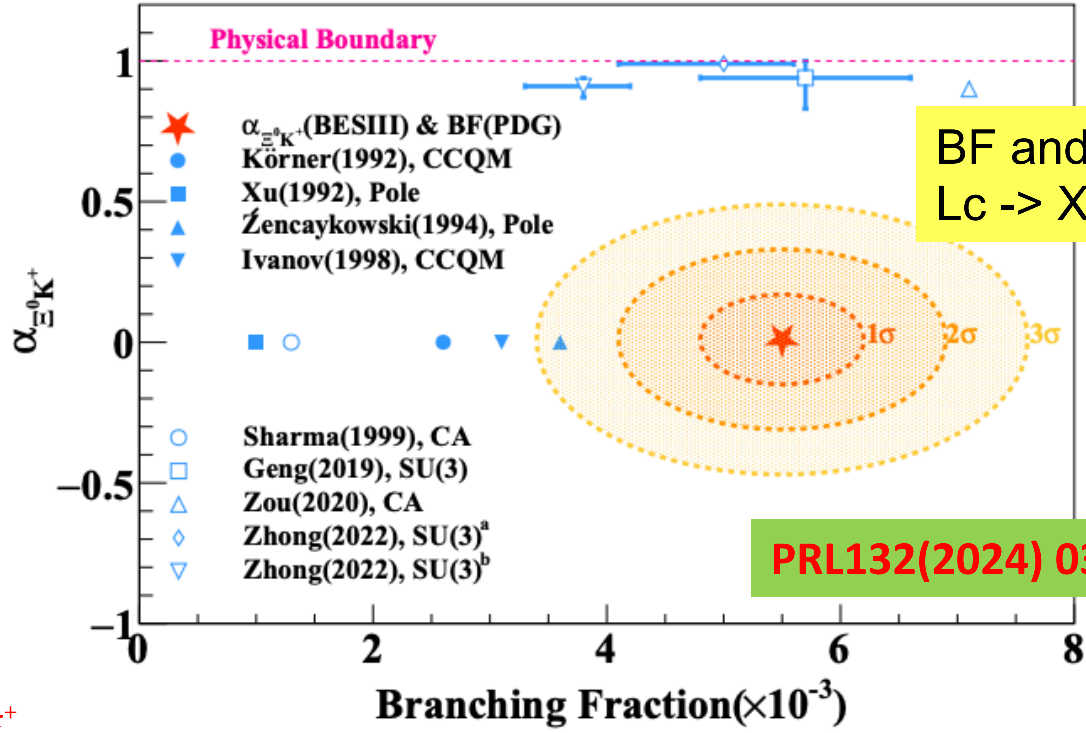


$$\frac{B[\Lambda_c^+ \to n\pi^+]}{B[\Lambda_c^+ \to p\pi^0]} > 7.2$$

$\Lambda_c^+ \to n\pi^+\pi^0$ $\Lambda_c^+ \to n\pi^+\pi^-\pi^+$ $\Lambda_c^+ \to nK^-\pi^+\pi^+$



CPC47, 023001(2023)



BF and decay asymmetry
Lc -> Xi0 K

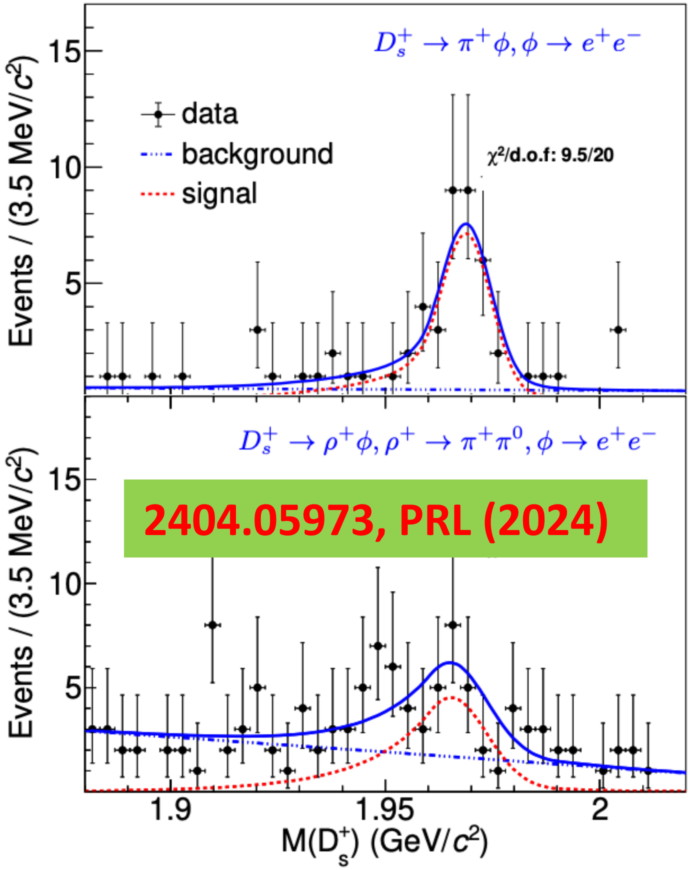
PRL132(2024) 031801

JHEP09（2023）125

	RBF (This work)	RBF (Belle)	BF (This work)
$\Sigma^+K^+K^-$	$8.38 \pm 0.93 \pm 0.41$	$7.6 \pm 0.7 \pm 0.9$	$0.377 \pm 0.042 \pm 0.018 \pm 0.021$
$\Sigma^+K^+\pi^-$	$4.44 \pm 0.52 \pm 0.23$	$4.7 \pm 1.1 \pm 0.8$	$0.200 \pm 0.023 \pm 0.010 \pm 0.011$
$\Sigma^+K^+\pi^-\pi^0$	< 2.4	-	<0.11
$\Sigma^+\phi$	$9.2 \pm 1.8 \pm 0.6$	$8.5 \pm 1.2 \pm 1.2$	$0.414 \pm 0.080 \pm 0.029 \pm 0.023$
$\Sigma^+K^+K^-$(non-ϕ)	$4.38 \pm 0.79 \pm 0.19$	-	$0.197 \pm 0.036 \pm 0.008 \pm 0.011$

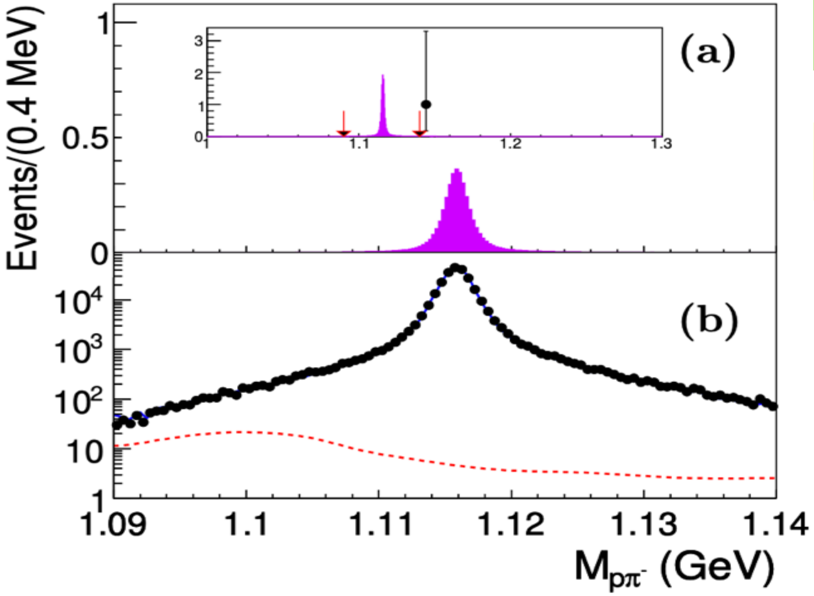
Exotic Decays and New Physics

Search for rare/forbidden phenomena



2404.05973, PRL (2024)

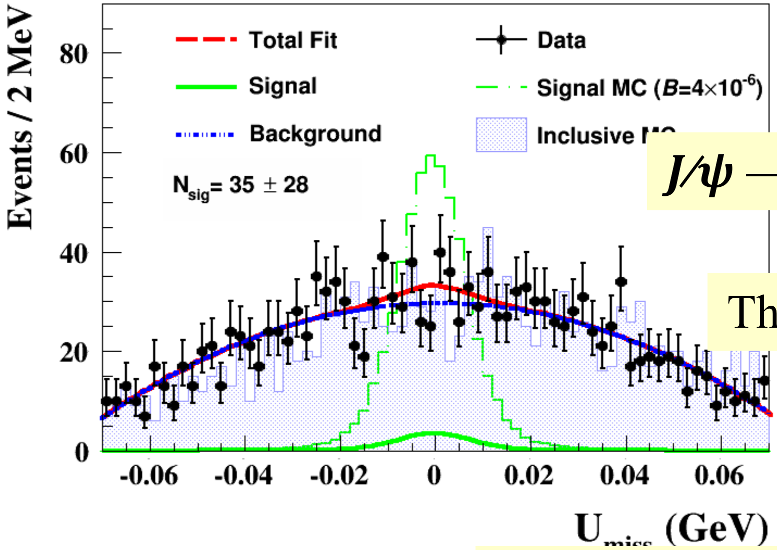
Decay	N_{sig}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0 e^+e^-$	...	7.4	< 7.0
$D_s^+ \to K^+\pi^0 e^+e^-$	...	5.3	< 7.1
$D_s^+ \to K_S^0\pi^+ e^+e^-$	...	6.7	< 8.1



Phys. Rev. Lett 131, 082101 (2023)

The 1st search of Lambda oscillation

- More ideas (with theorists)
- More channels
- More exploitation of existing data



$J/\psi \to D^-\mu^+\nu_e + c.c. < 5.6 \times 10^{-7}$ @ 90% CL

JHEP 01 (2024) 126

The 1st search for semi-muonic decay

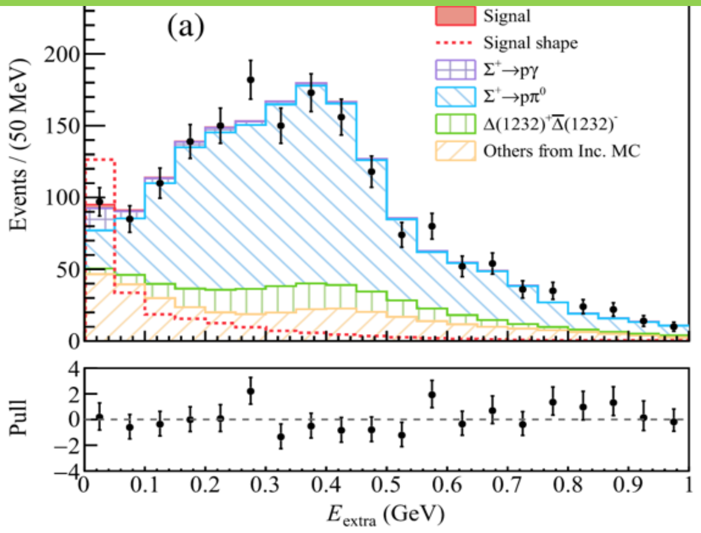
JHEP 06 (2021) 157

$J/\psi \to D^-e^+\nu_e + c.c. < 7.1 \times 10^{-8}$ @ 90% CL

BSM particle searches

Search for $\Sigma^+ \to p + \text{invisible} + c.c$

Phys. Lett. B 852 (2024)138614

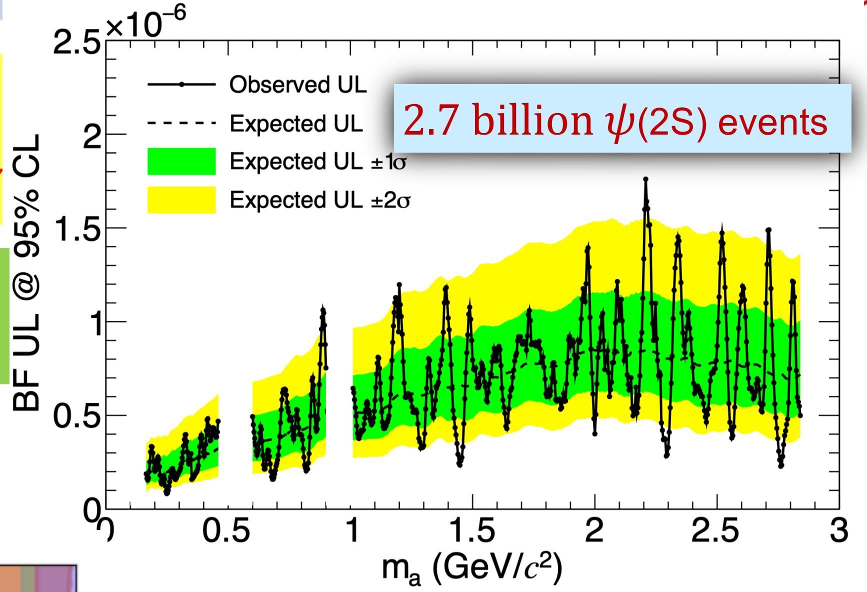


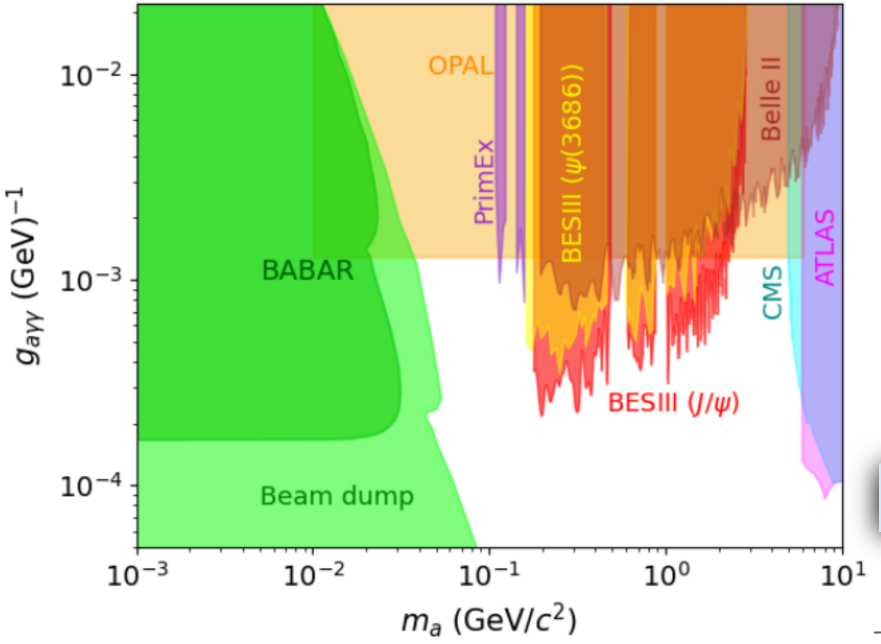
Search for a ALP in

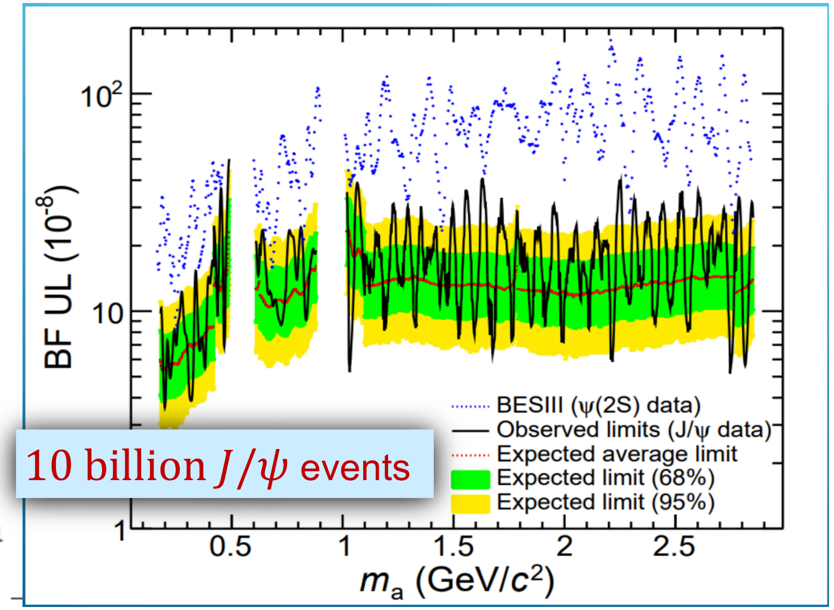
$$J/\psi \to \gamma a, \quad a \to \gamma\gamma$$

Phys. Lett. B 838 (2023)137698

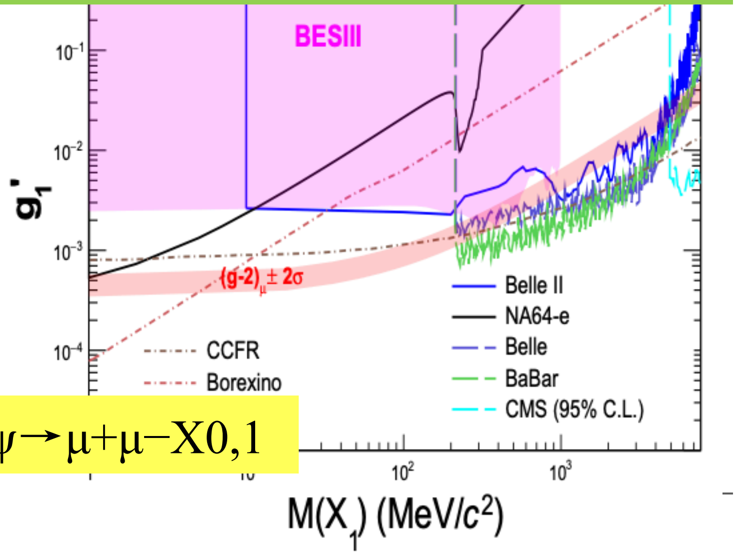
2404.04640, PRD(L)







Phys. Rev.D 109,L031102（2024）



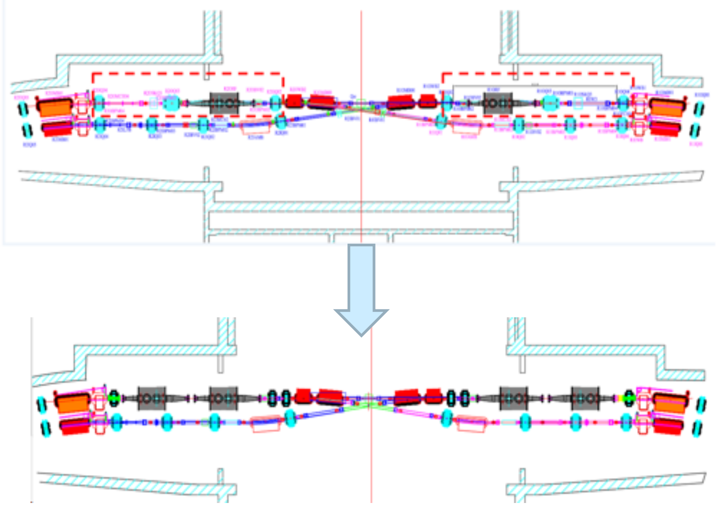
$J/\psi \to \mu^+\mu^- X_{0,1}$

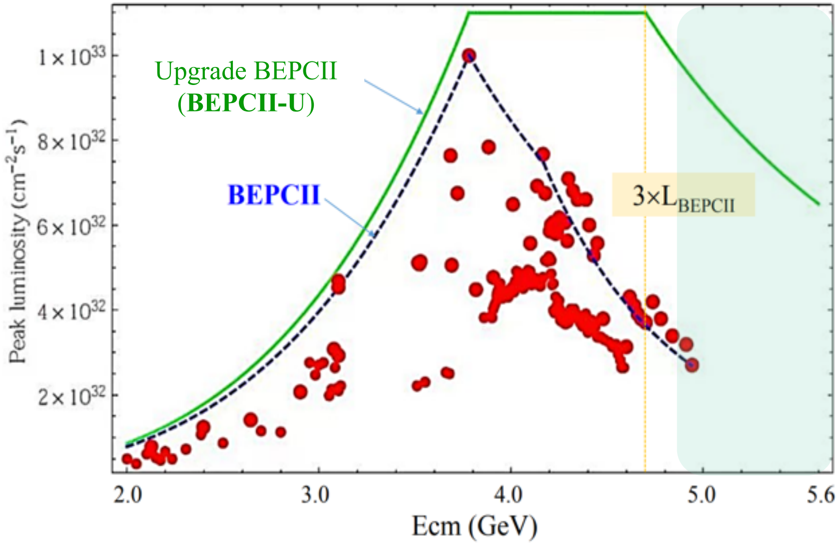
The upgrade: BEPCII-U

- ✓ An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021: **the optimized energy is 2.35 GeV with luminosity 3 times higher than current BEPCII and extend the maximum energy to 5.6 GeV**
- ✓ **With this critical energy increase and lumi upgrade, the operation is secured for another 5-10 years**
- ✓ BESIII Detector: inner tracker upgrade (CGEM), but No big change of performance foreseen

参见：

BEPCII-U进展 Yuan Zhang





Planned future data set

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)	[illegible] 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	$\Sigma_c^+\bar{\Lambda}_c^-$ 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

finished in 2024

~55 fb^{-1}

Chinese Physics C Vol. 44, No. 4 (2020)

Future Physics Programme of BESIII*

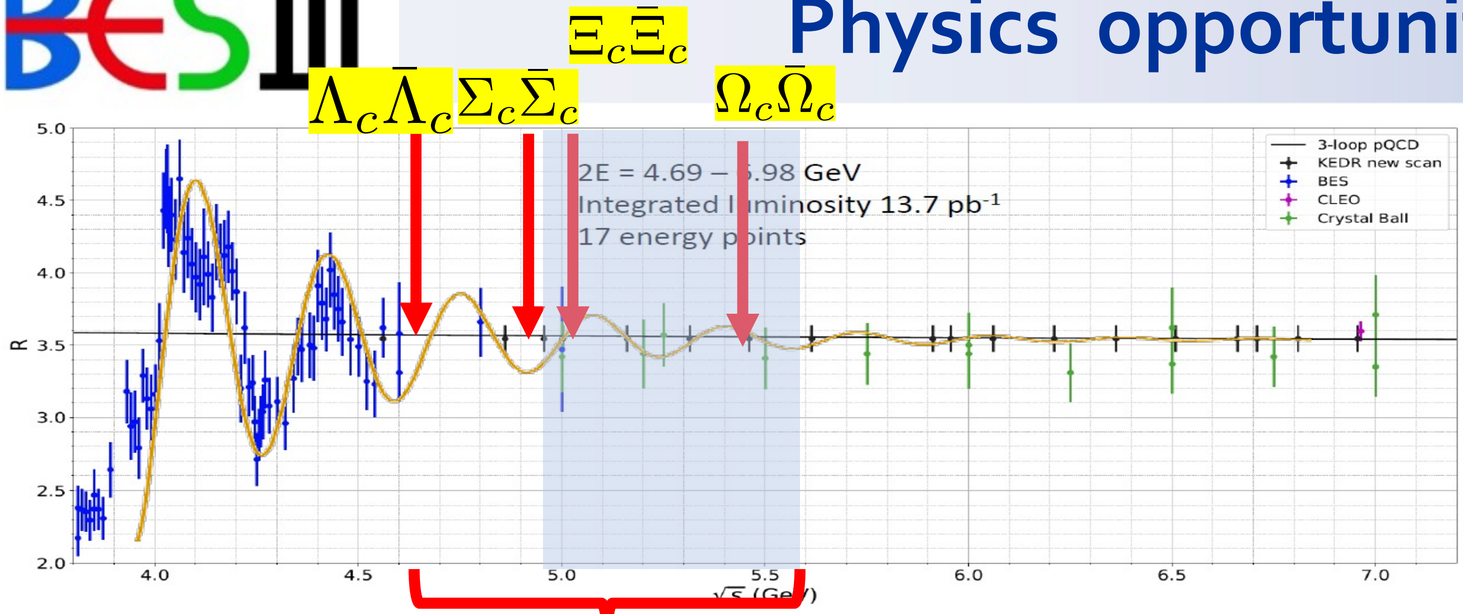
Abstract: There has recently been a dramatic renewal of interest in hadron spectroscopy and charm physics. This renaissance has been driven in part by the discovery of a plethora of charmonium-like XYZ states at BESIII and B factories, and the observation of an intriguing proton-antiproton threshold enhancement and the possibly related $X(1835)$ 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

Future Physics Programme of BESIII (white book)

Chin. Phys. C 44, 040001 (2020)
arXiv:1912.05983

Physics opportunities with BEPCII-U



Few data and potential physics for XYZ and charmed baryons

- **Cover all the ground-state charmed baryons:**
  - production
  - decays
  - CPV search
- Other possibilities to further explore

- **Detailed studies of known $Z_{c(s)}$ states and search for more exotic states in higher Ecm**
  - Identify vector charmonium(-like) states from 4.0 to 5.6 GeV
  - More Zc and Zcs for PWA
  - Search for Zc radiative transition to X(3872)
  - Search for penta-quark states

Summary

- BESIII is operating with good performance
  - collect large data samples of >52/fb in the energy range 1.84~4.95 GeV
- BESIII has performed wide range of physics studies
  - Light hadron spectroscopy and decays
  - Charmonia transitions and XYZ
  - R value and QCD studies
  - Charmed meson and charmed baryon
  - Rare decays and new physics search
- BESIII still has great potential
  - Near term: with unique datasets and analysis techniques.
  - Midterm: Operation for another 5-10 years foreseen
    - BEPCII-U: 3x upgrade on luminosity, with energy to 5.6GeV
- STCF is the natural further next step. Bright future is ahead !