Highlights of BESIII experiments

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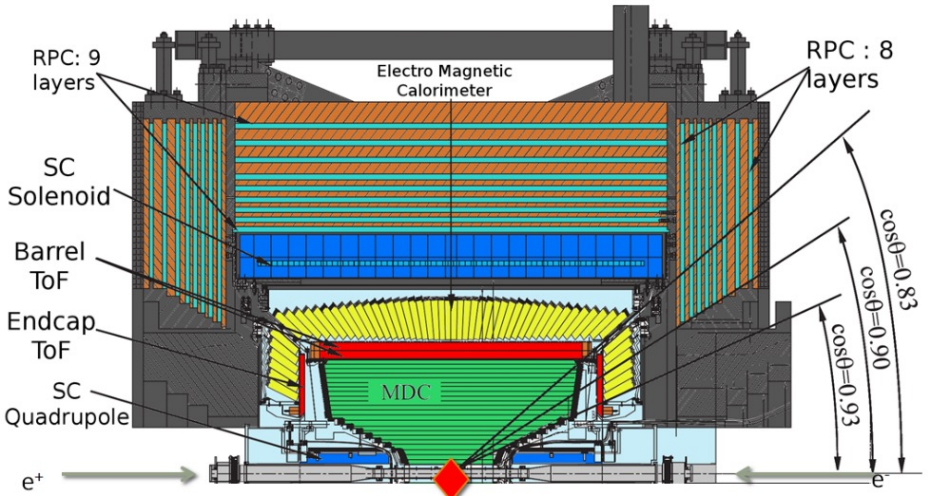
第七届强子谱和强子结构研讨会

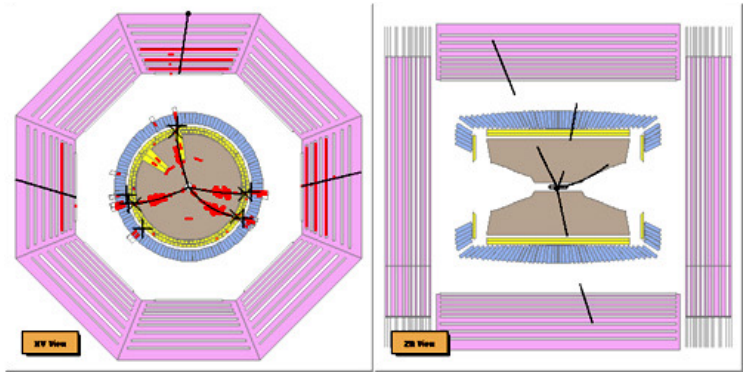
2024.04.27 成都

Outline

- BEPCII & BESIII
- Recent Highlights
  - Hadron spectroscopy
  - Hadron structure
  - Hadron interaction
  - Symmetry test
- Summary & Prospect

BEPCII & BESIII



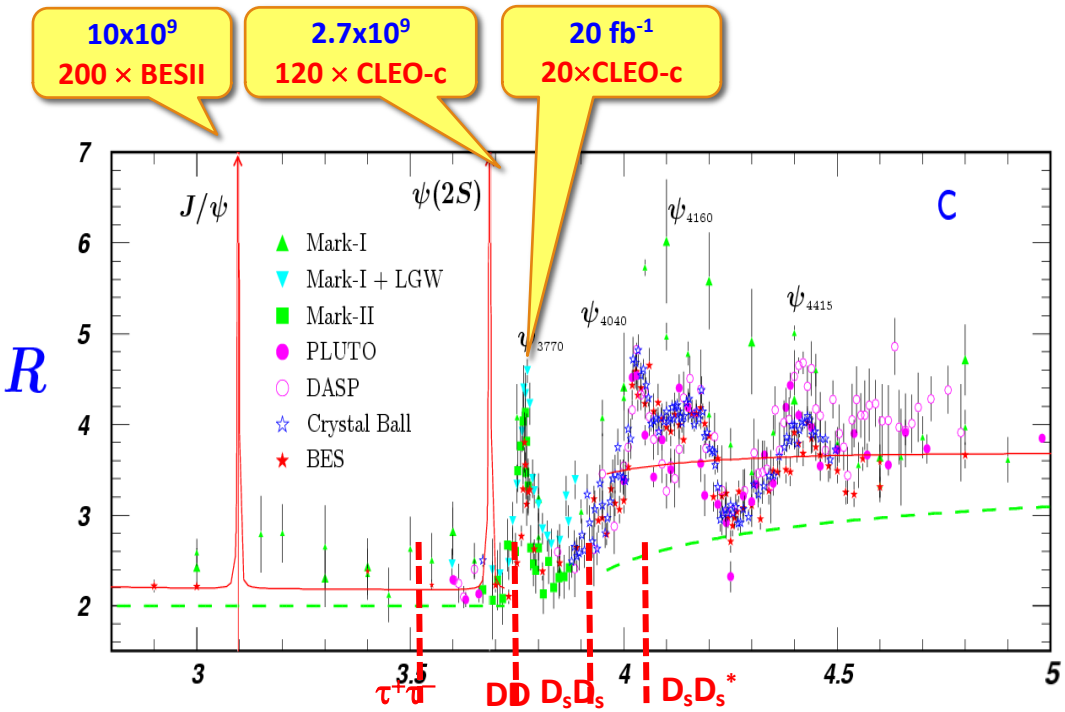


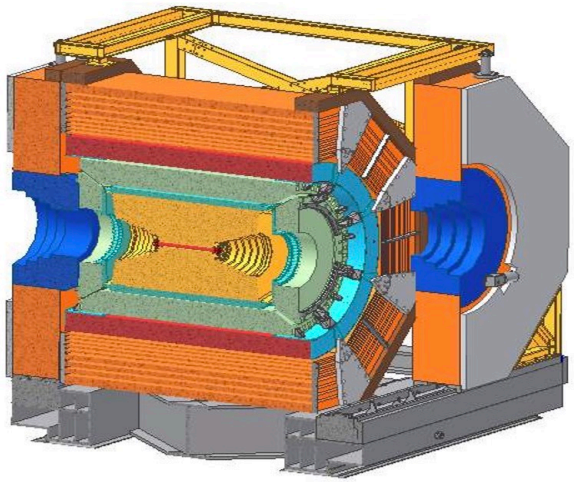
First HEP collider in China (1988)

c.m.s energy：2 ~ 4.95 GeV

Max luminosity：$1\times10^{33}cm^{-2}s^{-1}$

BESIII: τ-charm factory



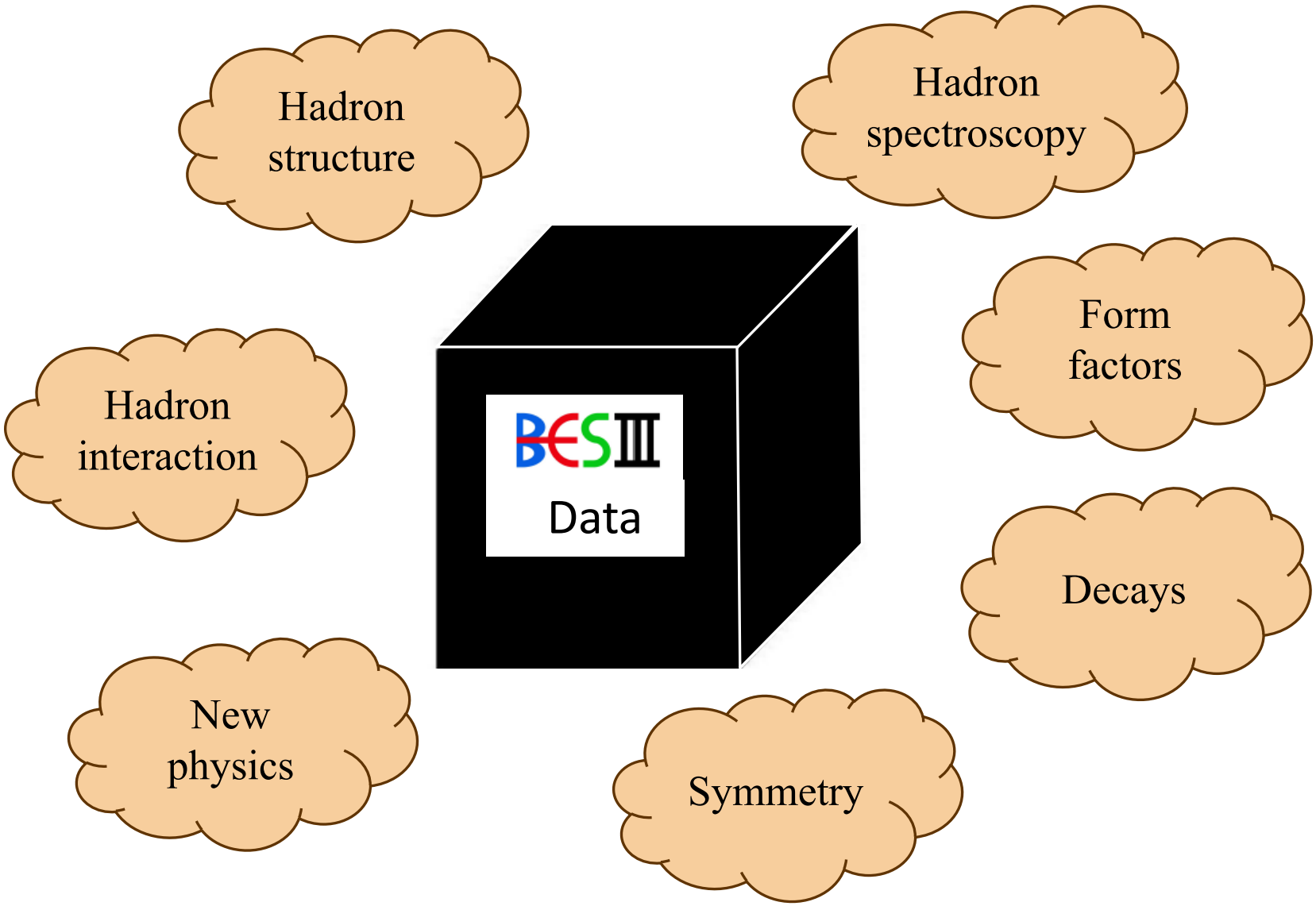


BESIII: ~55 fb^{-1} data in $E_{cm} = 2 \sim 4.95$ GeV

World largest data sample directly collected in the t-charm region

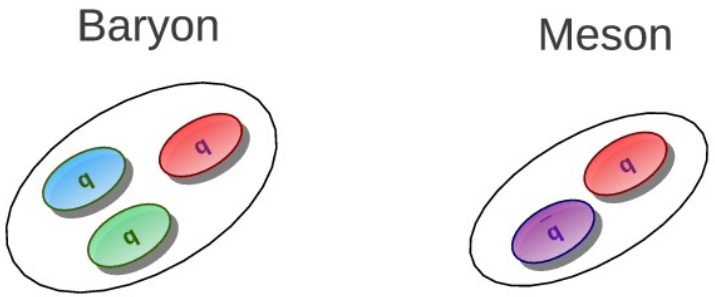
- **Charmonium physics**
- **Light hadron physics**
- **Charm physics**
- **R-QCD physics**
- **New physics**

BESIII physics

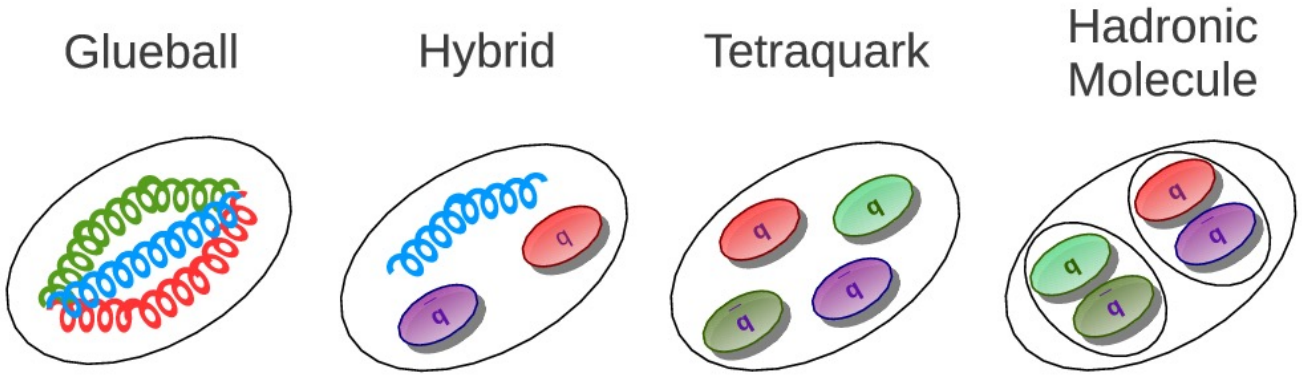


Ordinary vs exotic matter

- Conventional hadrons

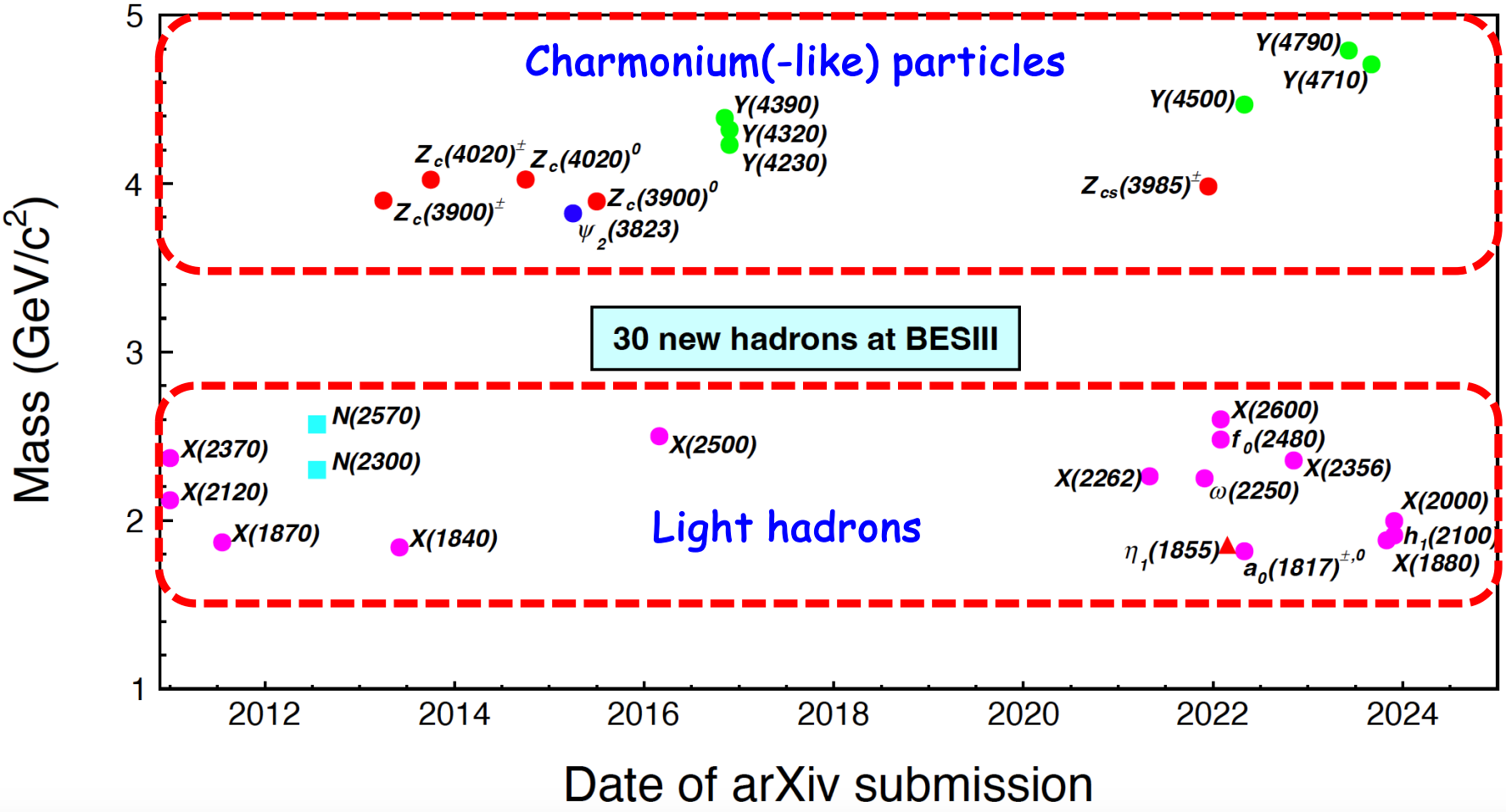


- QCD allows for “exotics”



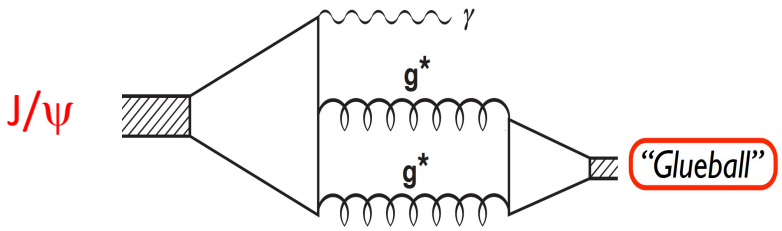
- Searching for those states provides test of QCD

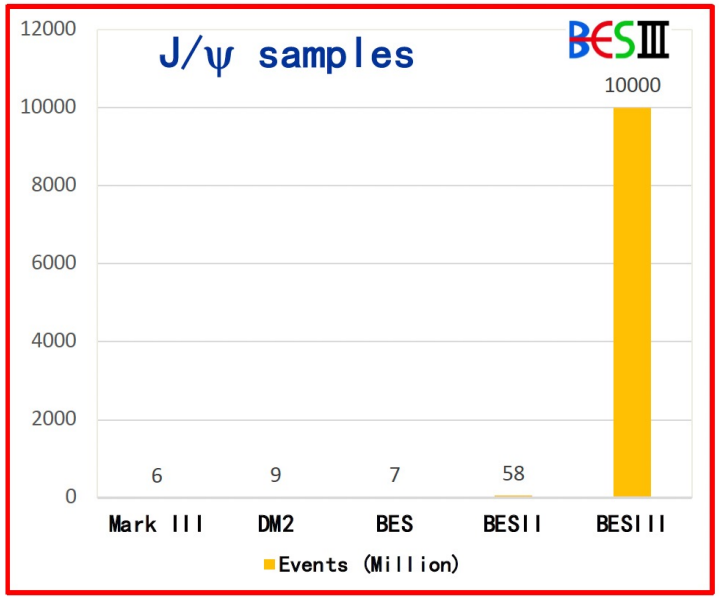
New resonant structures at BESIII



Glueball searches

- **Two big issues**
  - What is the production mechanism to utilize?
  - What is the mixing with quark model mesons?





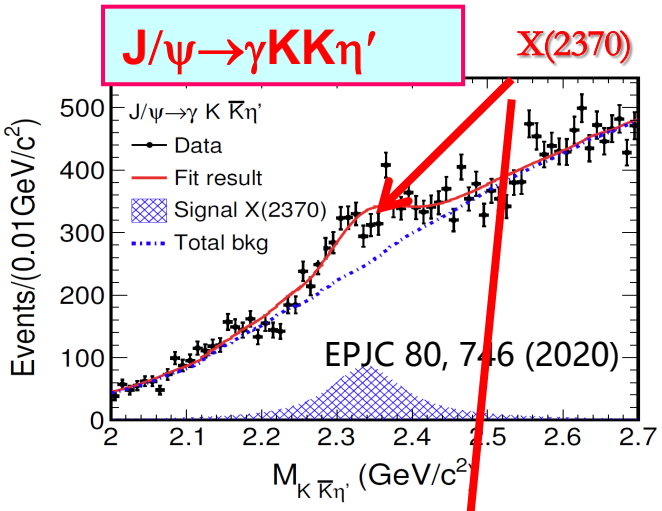
- Production rate could be calculable in LQCD, but the manifestation of a "glueball" can be tricky!

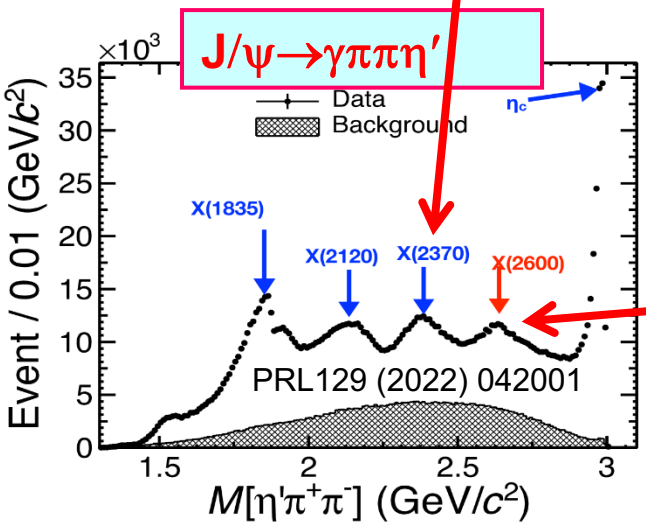
Chanowitz, Phys.Rev.Lett. 95(2005)172001

Systematic studies needed

- Outnumbering of conventional QM states
- Abnormal properties ? Eg., small production rate in two photon process

Glueball candidate





X(2370) and X(2600): new glueball candidate ?

An updated review of the new hadron states

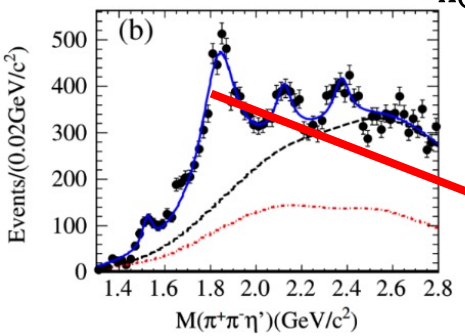
H.X.Chen, W Chen, X Liu, Y.R. Liu, S.L. Zhu Rept.Prog.Phys. 86 (2023) 2, 026201

Motivated by the newly observed resonance $X(2600)$ by BESIII Collaboration, we examine the trigluon glueball interpretation for it in the framework of QCD sum rules. We evaluate the mass spectra of the trigluon glueballs with quantum numbers 0^{-+} and 2^{-+} up to dimension 8 condensate in the operator product expansion. Our numerical results indicate that the mass of the 2^{-+} trigluon glueball is about 2.66 ± 0.06 GeV, which is consistent with the mass of the X(2600) within the uncertainties, while 0^{-+} has a mass of 2.61 ± 0.14 GeV. The possible decay channels of the 2^{-+} state are analyzed, which are crucial in decoding $X(2600)$'s internal structure and are hopefully measurable in BESIII, BEllEII, PANDA, and LHCb experiments.

QCD sum rules

S.Q. Zhang et al, PRD 106 (2022) 7, 074010

X($p\bar{p}$) : Baryonium state?



X(1835) observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$

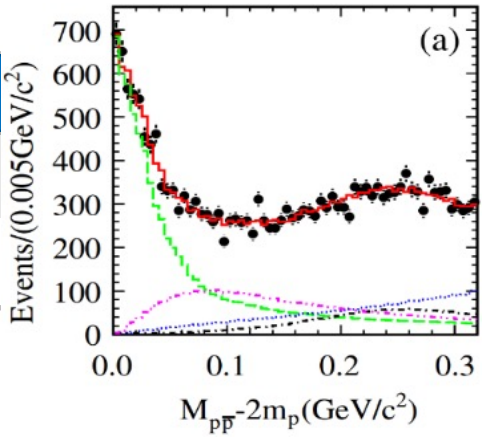
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

PRL 106, 072002 (2011)

X($p\bar{p}$) observed in $J/\psi\to\gamma p\bar{p}$

X($p\bar{p}$) $J^{PC}=0^{-+}$
$M = 1832^{+19\ +18}_{-5\ -17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)

PRL 108, 112003 (2012)

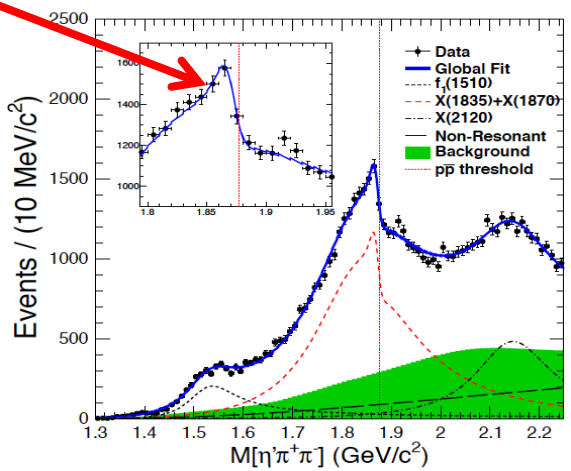


connection between X(1835) and X($p\bar{p}$)

The anomalous line shape :

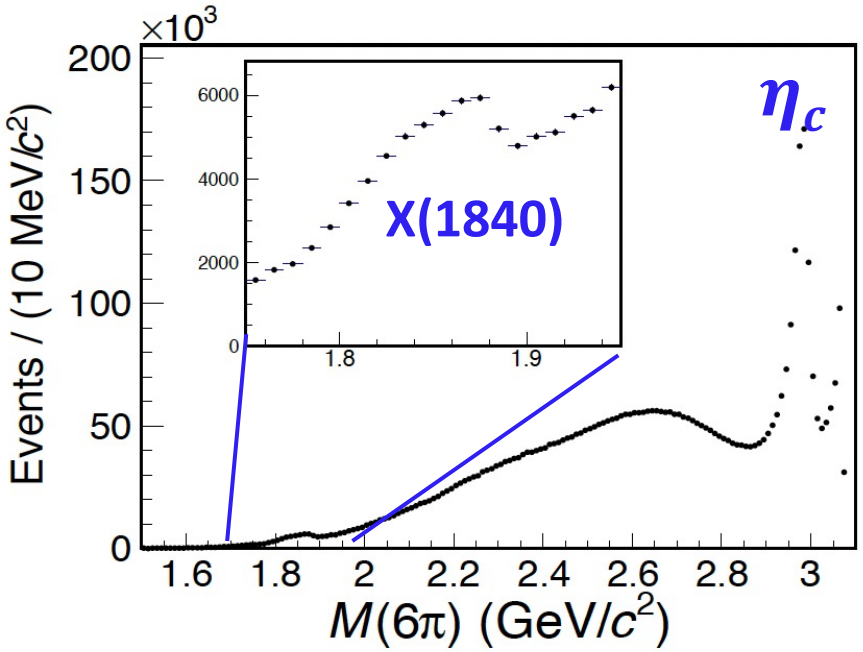
-- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold

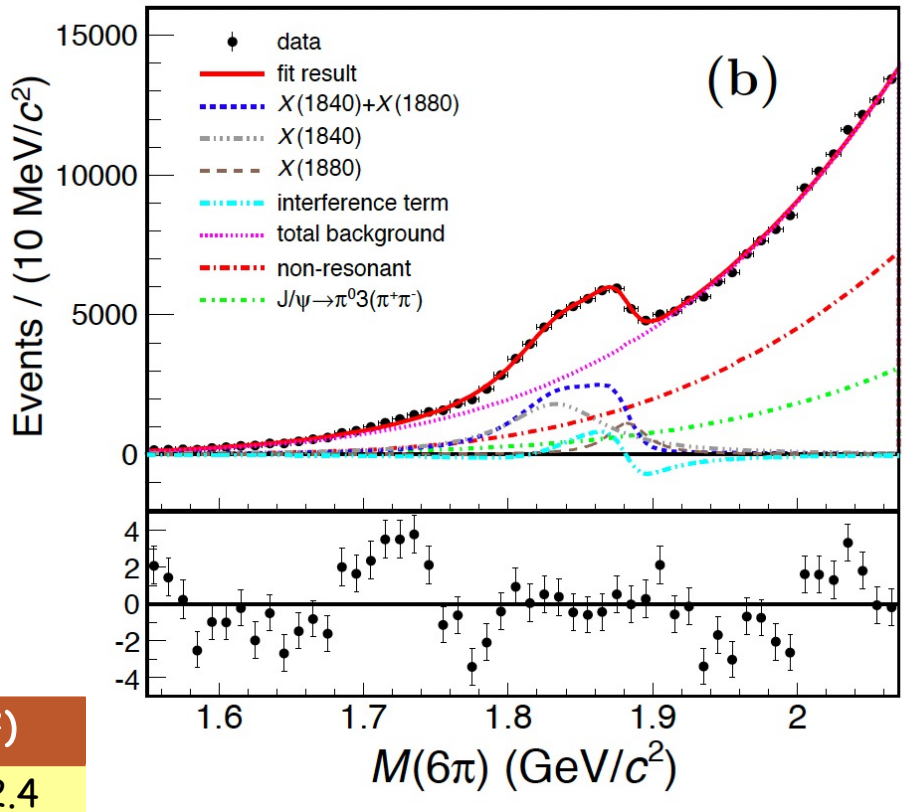
-- Support the existence of a $p\bar{p}$ molecule-like state or bound state



PRL 117, 042002 (2016)

A narrow state around $p\bar{p}$ threshold



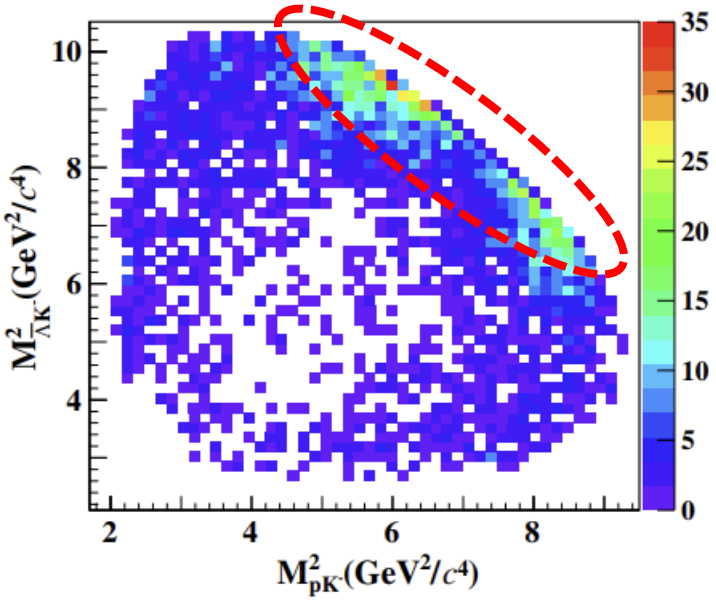


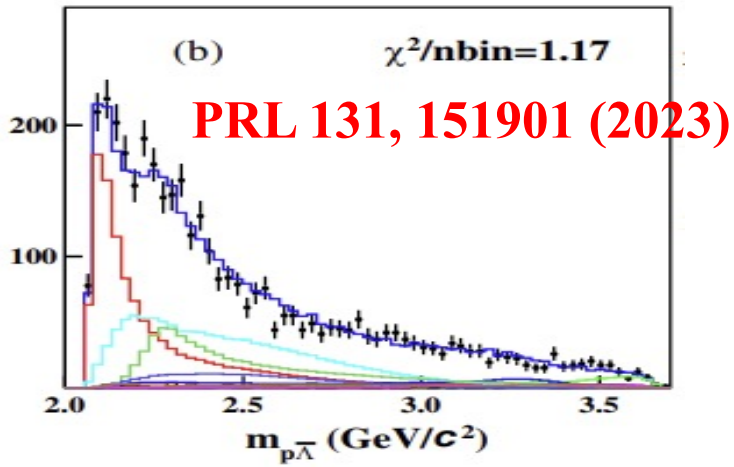
Resonance	M(MeV/c²)	Γ(MeV/c²)
X(1880)	1882.1±1.7±0.7	30.7±5.5±2.4
X(1840)	1832.5±3.1±2.5	80.7±5.2±7.7

PRL 132, 151904 (2024)

Support the existence of $p\bar{p}$ bound state !

A narrow state around $p\bar{\Lambda}$ threshold





PRL 131, 151901 (2023)

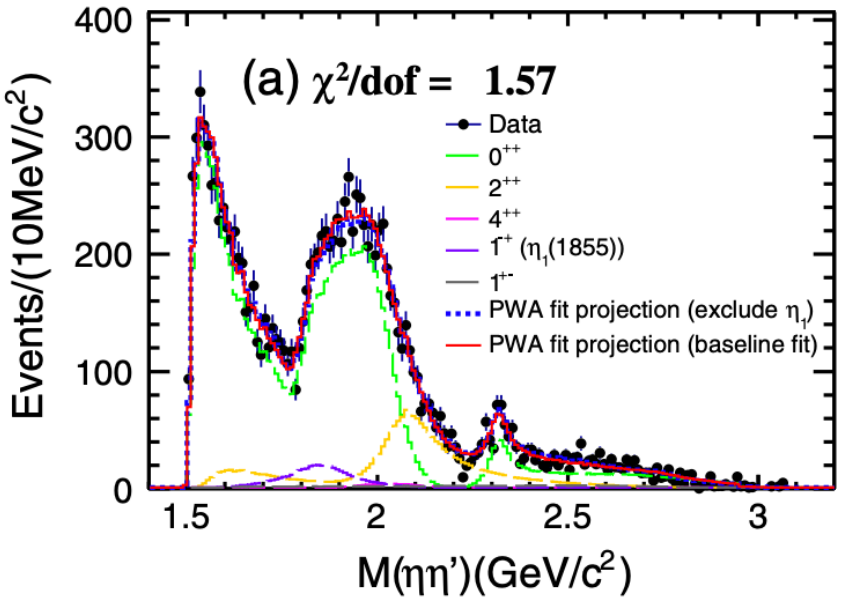
$\sqrt{s}$	$\mathcal{L}_{\rm int}$	$M_{\rm pole}$	$\Gamma_{\rm pole}$
4.008	482.0 ± 4.7	2082^{+13}_{-9}	56^{+15}_{-14}
4.178	3189.0 ± 31.9	2083^{+6}_{-4}	63^{+8}_{-7}
4.226	1100.9 ± 7.0	2086^{+11}_{-8}	71^{+15}_{-13}
4.258	828.4 ± 5.5	2081^{+9}_{-6}	52^{+10}_{-9}
4.416	1090.7 ± 7.2	2085^{+10}_{-7}	59^{+11}_{-9}
4.682	1669.3 ± 9.0	2090^{+9}_{-7}	55^{+8}_{-5}
Average	—	2084^{+4}_{-2}	58^{+4}_{-3}

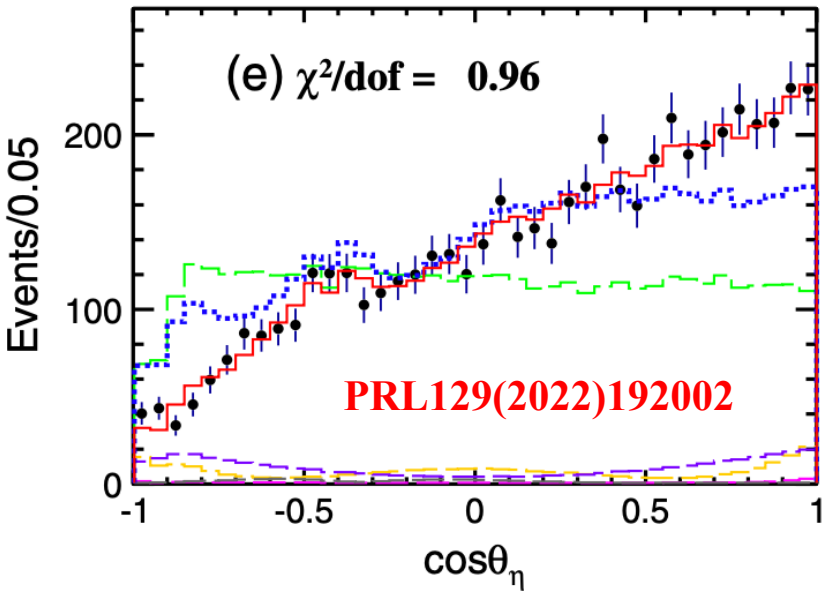
A narrow structure in the $p\bar{\Lambda}$ system, named as $X(2085)$, is observed with greater than 20σ, J^P is determined to be 1^+, pole position is:

$$M_{pole} = (2084^{+4}_{-2} \pm 9)\ \text{MeV/c}^2$$

$$\Gamma_{pole} = (58^{+4}_{-3} \pm 25)\ \text{MeV}$$

Observation of 1^{-+} $h_1(1855)$ in $J/\psi \to \gamma\eta\eta'$





Isoscalar state with exotic quantum numbers $J^{PC}=1^{-+}$

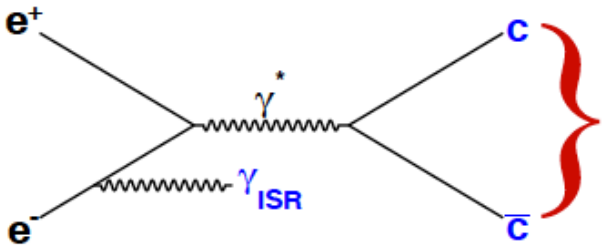
$M = 1855 \pm 9^{+6}_{-1}$ MeV/c²

$\Gamma = 188 \pm 18^{+3}_{-8}$ MeV

Critical to establish the 1^{-+} spectroscopy !

More works in progress for establishing the state with I=1

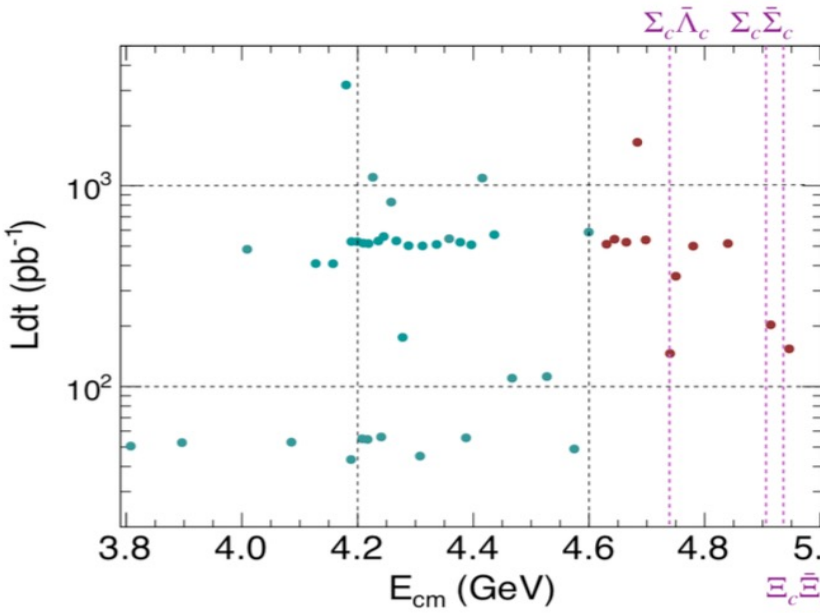
Charmonium(-like) states

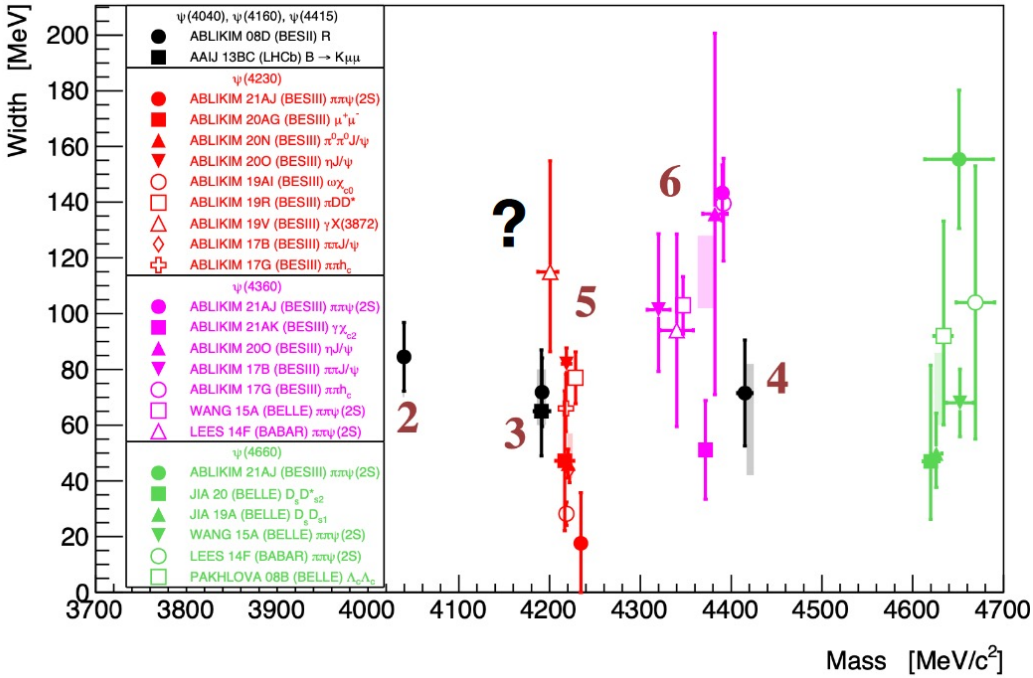


$J^{PC} = 1^{--}$

$\psi', \psi'', Y\ldots$

XYZ studies with ~25 fb^{-1} data above 3.8 GeV

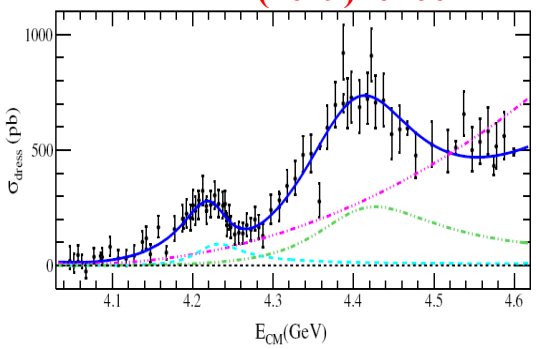




The structure of Y(4260)→Y(4220)+Y(4320)?

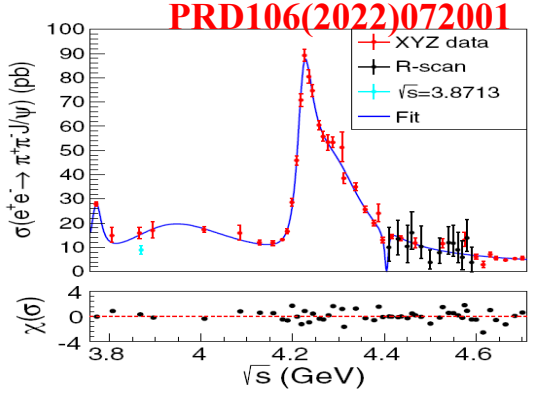
$e^+e^- \to \pi^+ D^0 D^{*-}$+c.c.

PRL122(2019)102002

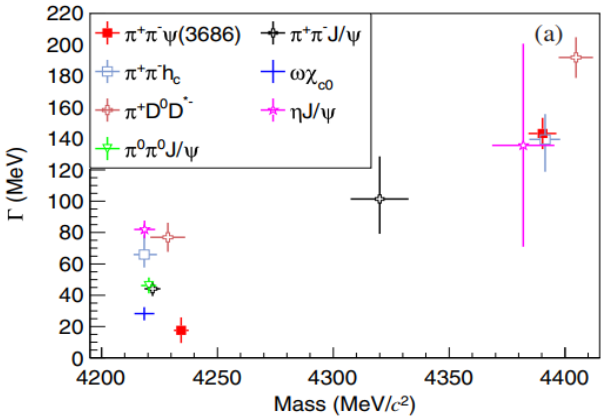


$e^+e^- \to \pi^+\pi^- J/\psi$

PRD106(2022)072001

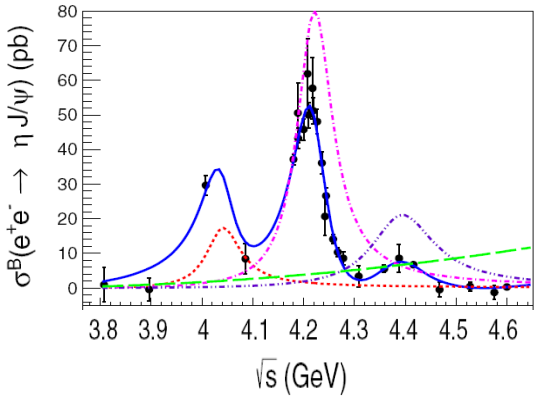


Different masses and widths in various processes



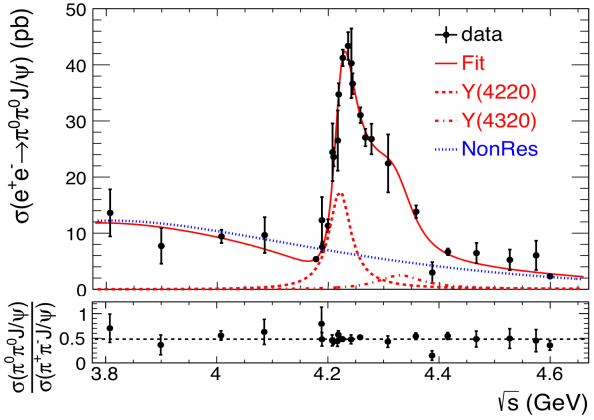
$e^+e^- \to \eta J/\psi$

PRD102(2020)031101(RC)



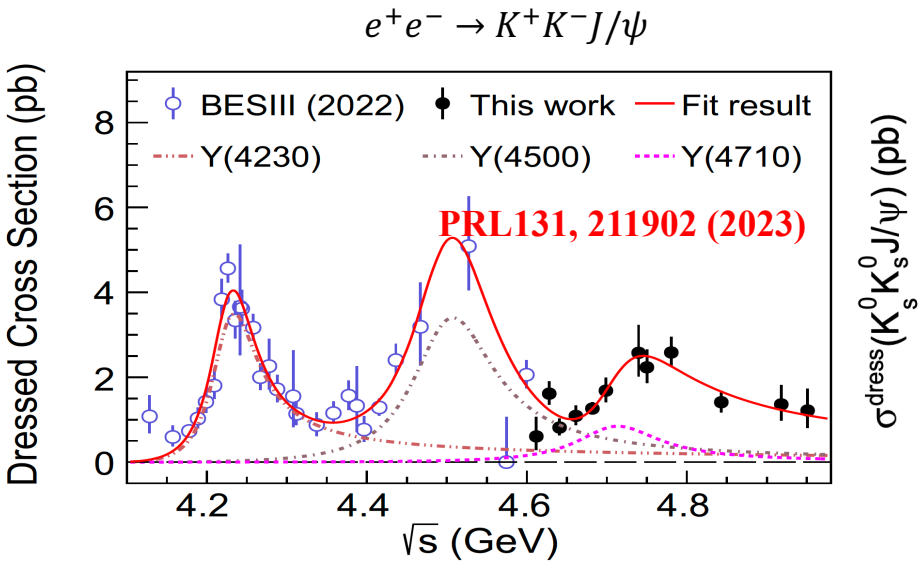
$e^+e^- \to \pi^0\pi^0 J/\psi$

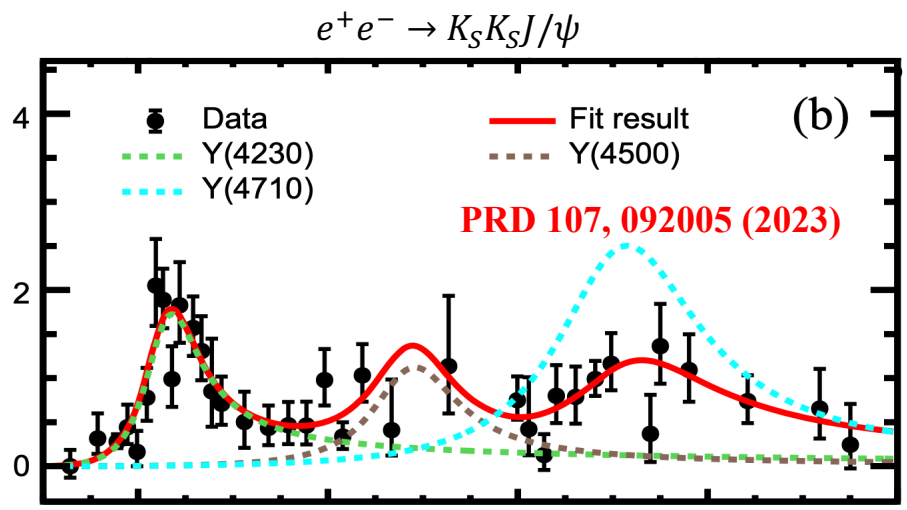
PRD102(2020)012009

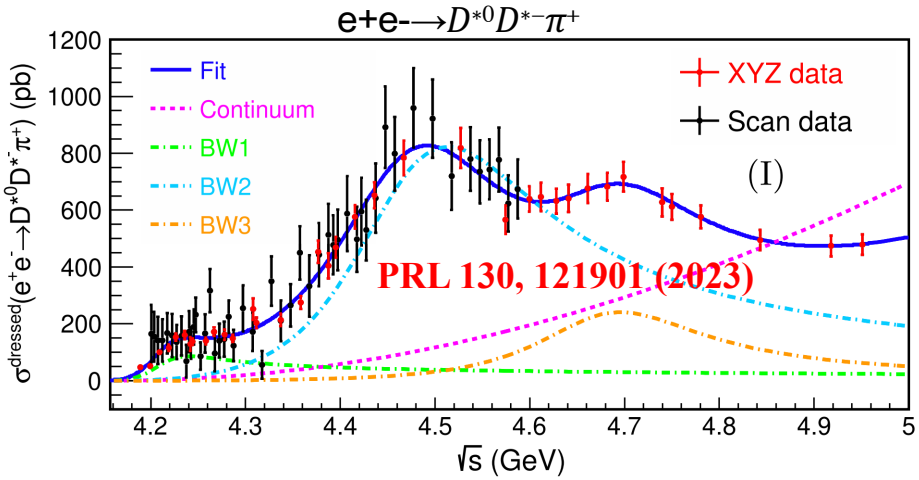


Mass ~ 4220 MeV/c^2
width ~ 50 MeV

Observations of Y(4230), Y(4500) and Y(4710)



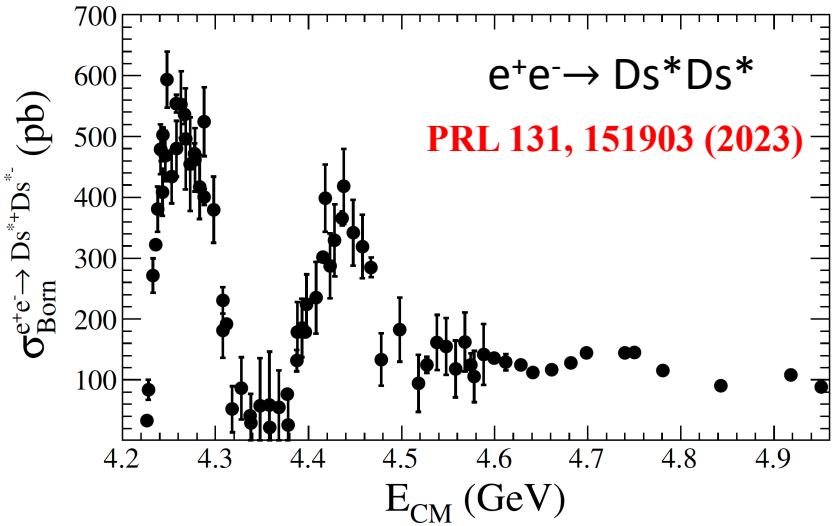


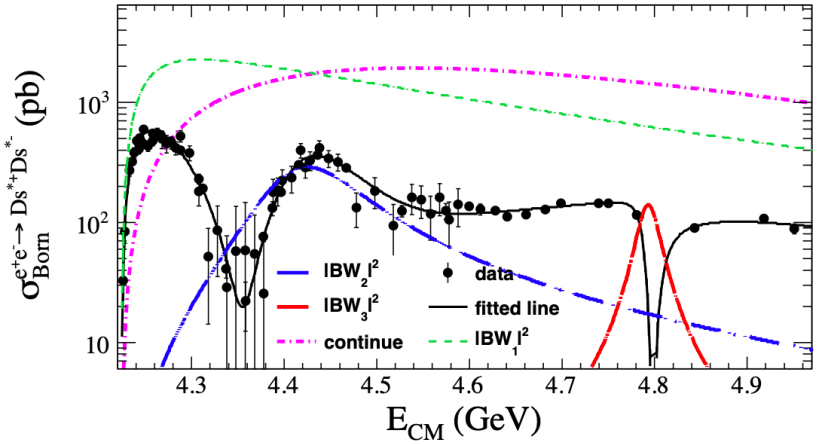


- New decay mode of Y(4230)
- Confirmation of Y(4500)
- Y(4710): one of the heaviest vector charmonium-like state, hybrid, 5S charmonium, 5S-4D/6S-5D mixing?

Mass ~ 4710 MeV/c^2, Width ~ 180 MeV

Observation of a new charmonium-like state Y(4790)

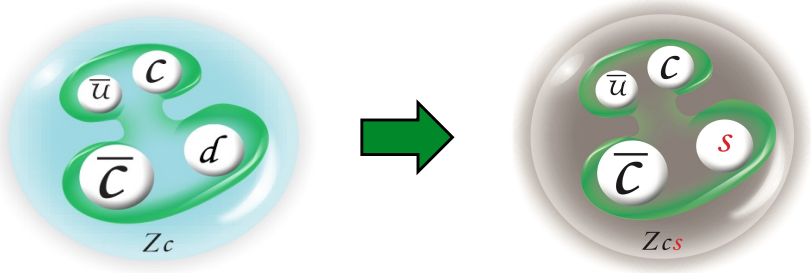




	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.5±9.0	4193.8±7.5	4195.3±7.5
Γ_1 (MeV)	55±17	61.2±9.0	61.8±9.0
M_2 (MeV/c^2)	4414.5±3.2	4412.8±3.2	4411.0±3.2
Γ_2 (MeV)	122.6±7.0	120.3±7.0	120.0±7.0
M_3 (MeV/c^2)	4793.3±7.5	4789.8±9.0	4786±10
Γ_3 (MeV)	27.1±7.0	41±39	60±35

- Y(4160) or Y(4260) [strong coupling to Ds*Ds*?]
- Consistent with Y(4415)
- Y(4790): necessary to improve fit quality (>6s)

Observation of $Z_{cs}(3985)$

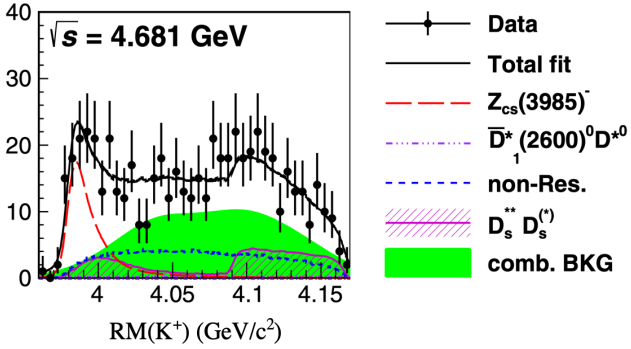


$e^+e^- \to K^+K^-J/\psi$

Given tetraquark state assumption, there should exist SU(3) partner **Z_{cs} state with strangeness**

$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$

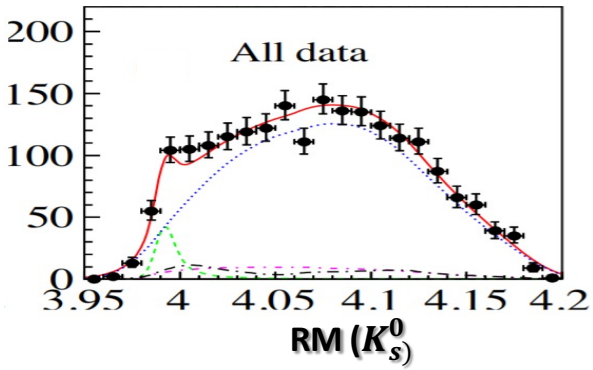
PRL126(2021)102001



- M=$(3985.2^{+2.1}_{-2.0}\pm1.7)$ MeV/c²
- Γ =$(13.8^{+8.1}_{-5.2}\pm4.9)$ MeV

$e^+e^- \to K_S^0(D_s^+D^{*-} + D_s^{*+}D^-)$

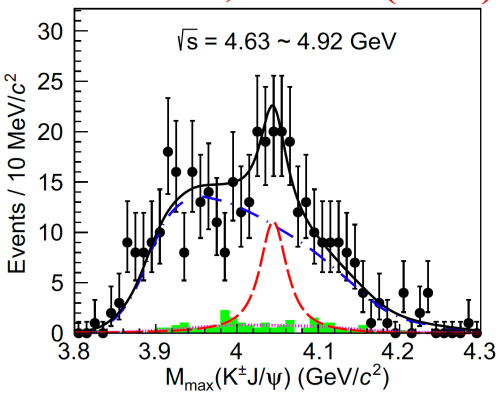
PRL129(2022)112003



- M=$3992.2 \pm 1.7 \pm 1.6$) MeV/c²
- Γ =$(7.7^{+4.1}_{-3.8}\pm4.3)$ MeV

$e^+e^- \to K^+K^-J/\Psi$

PRL131, 211902 (2023)

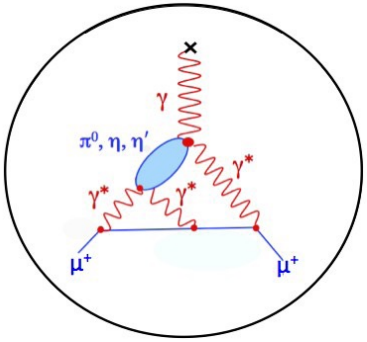


Not significant !

Close mass but very different widths for Zcs(4000) at LHCb !

LHCb: PRL127, 082001 (2021)

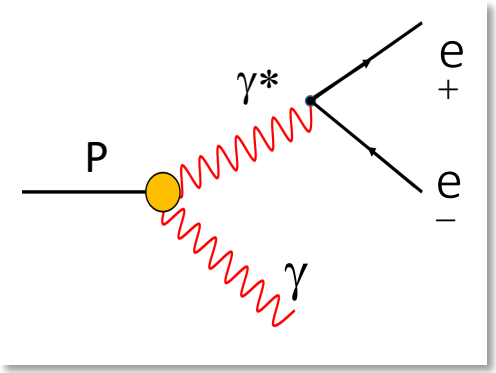
Pseudoscalar meson TFF



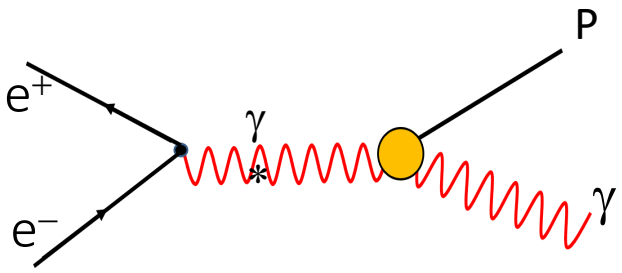
HLbL contributions

$$\frac{d\sigma}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\text{point}} |F(q^2)|^2 \qquad < r^2 > \approx -6\frac{\partial F(q^2)}{dq^2}|_{q^2\to 0}$$

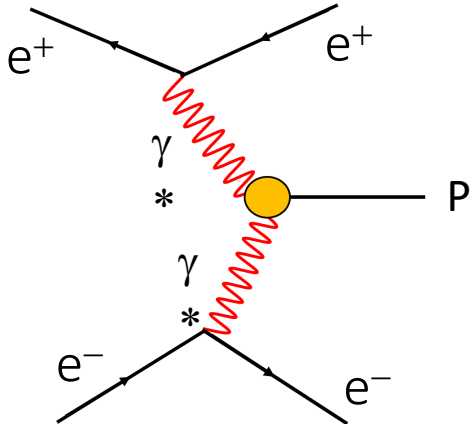
Pseudoscalar TFFs are experimentally accessible in three different processes



Dalitz decays $0 < q^2 < M^2$

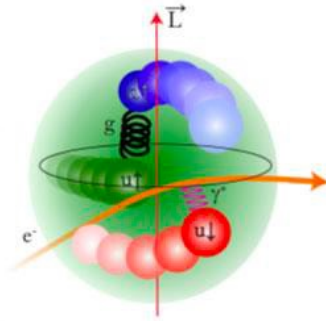


Annihilation process $q^2 = s > M^2$



Two photon process

Baryon Form Factors

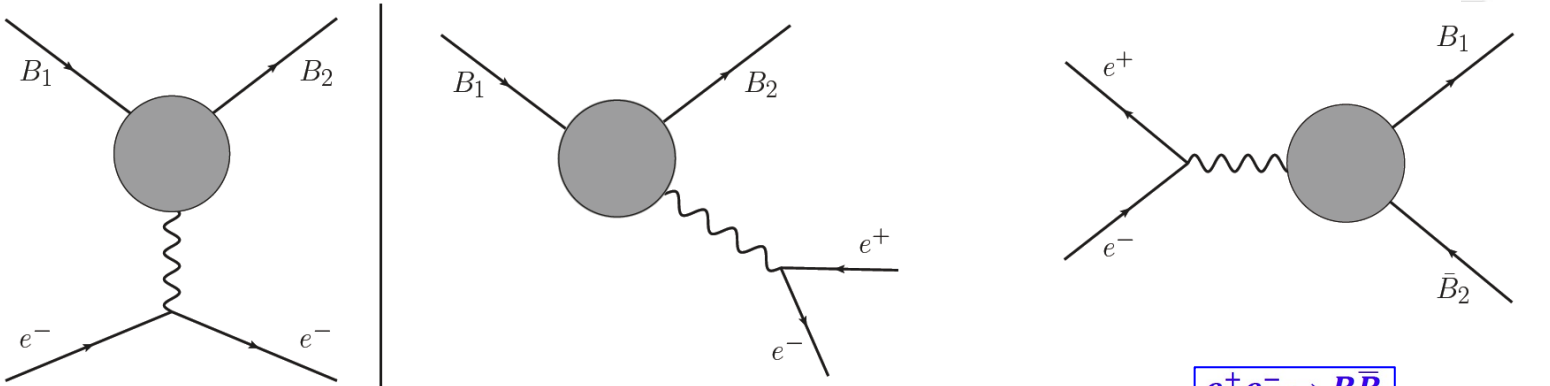


Space-like
$q^2 < 0$

Low-q^2

Time-like
$q^2 > 0$

High-q^2



$e^-B \to e^-B$
e.g. JLAB

0 $4m_e^2$

$B_1 \to B_2 e^+ e^-$
HADES
PANDA

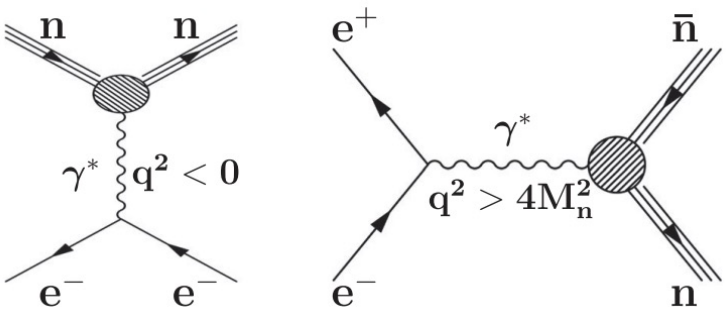
$(m_1 - m_2)^2$ $(m_1 + m_2)^2$

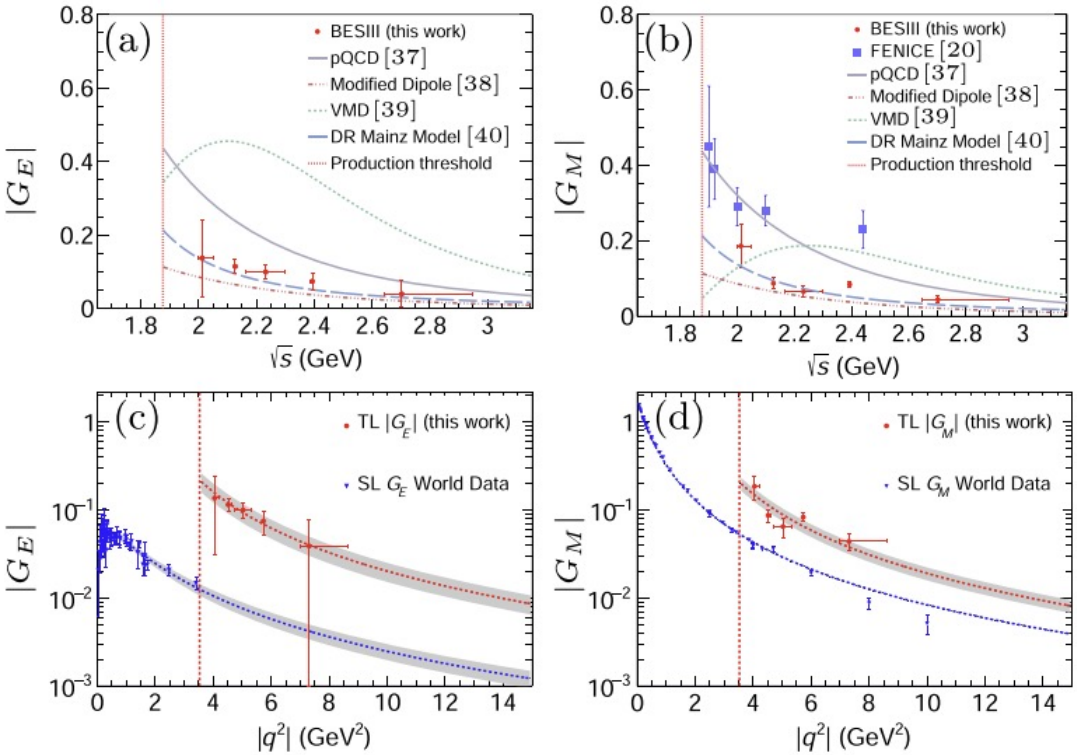
$e^+e^- \to B\bar{B}$
$\bar{B}B \to e^+e^-$
BES III
BELLE II
PANDA

q^2

EM Form Factors of Neutron

- First Measurement for EM Form Factor of $n\bar{n}$ in the time-like region (positive q^2).





PRL 130, 151905 (2023)

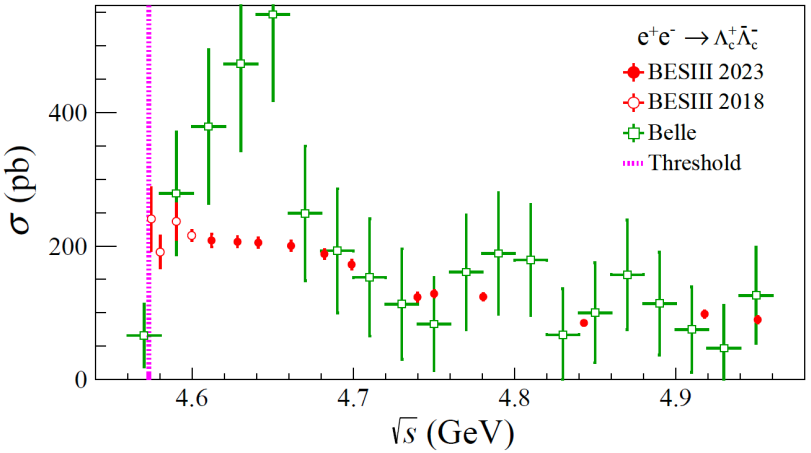
$\lvert G_E\rvert$		
...	TL ($q^2 > 4M_n^2$)	SL ($q^2 < 0$)
Formula	$[A/(1-q^2/0.71)^2]$	$[A\tau/(1+B\tau)][1/(1-q^2/0.71)^2]$
Parameters	$A = 3.39 \pm 0.43$	$A = 1.42 \pm 0.08$, $B = 2.17 \pm 0.39$
χ^2/ndf	0.4/4	25/36

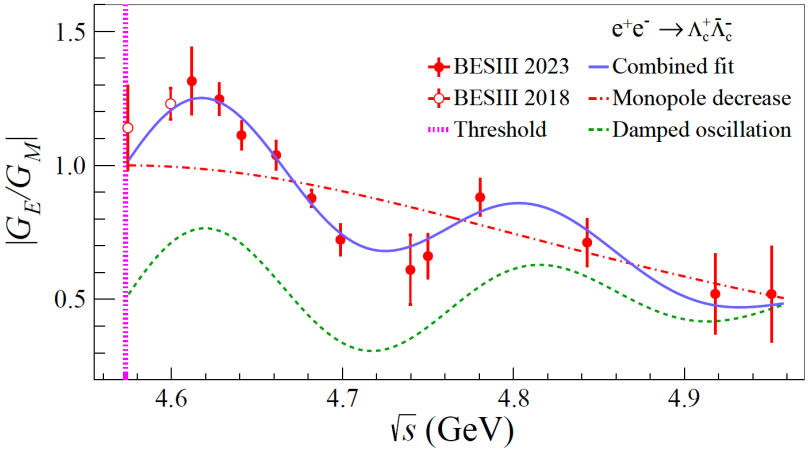
$\lvert G_M\rvert$		
...	TL ($q^2 > 4M_n^2$)	SL ($q^2 < 0$)
Formula	$[A/(1-q^2/0.71)^2]$	$[A/(1-q^2/0.71)^2]$
Parameters	$A = 3.27 \pm 0.28$	$A = 1.899 \pm 0.008$
χ^2/ndf	8.8/4	82/31

- Separate $|G_E|$ from $|G_M|$ for the neutron within a wide range of q^2 from 4 to 9 GeV/c^2 with relative uncertainty of around 12%.

Oscillation of FF of Charm Λ_c^+

- BESIII energy scans from 2018 and 2023
- Disagreement with Belle near 4.6 GeV
  - Energy dependence of R = $|G_E/G_M|$:
  - → Damped oscillations with frequency
  - ~3.5 times larger than for the proton





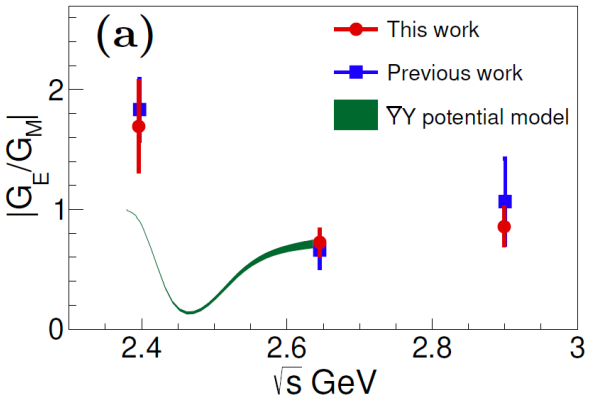
BESIII:
Phys. Rev. Lett. 120, 132001 (2018)
Phys. Rev. Lett. 131, 191901 (2023)

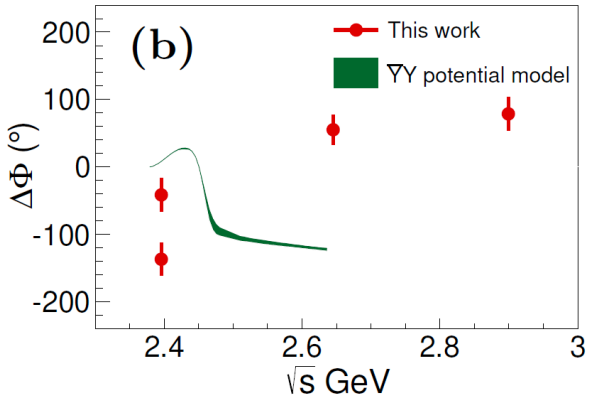
Belle:
Phys. Rev. Lett. 101, 172001 (2008)

Σ^+ and Λ Form Factors

$e^+e^- \to \Sigma^+\Sigma^-$

Phys. Rev. Lett.132, 081904(2024)





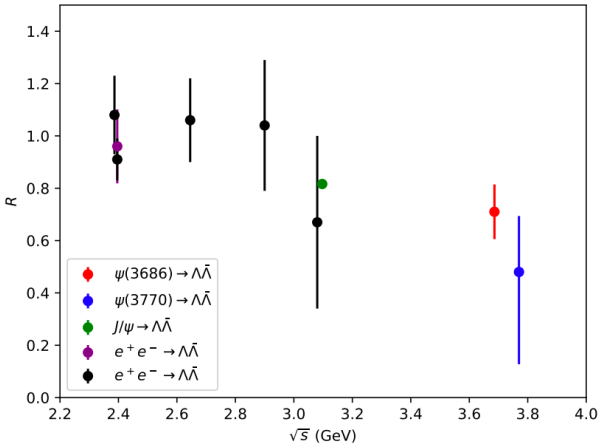
$e^+e^- \to \Lambda\ \bar{\Lambda}$

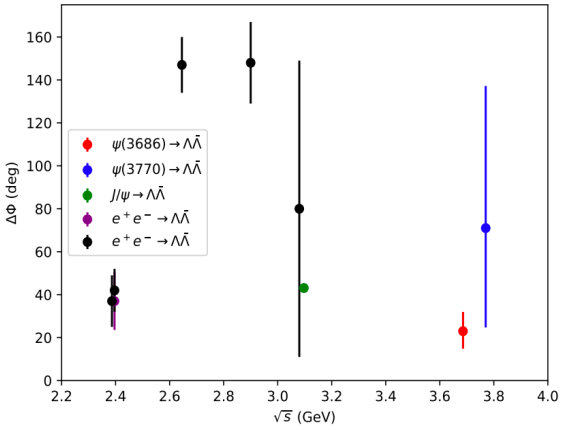
Phys. Rev. Lett. 123, 122003 (2019)

Nature Phys. 15, p. 631-634 (2019)

JHEP10(2023)081

Phys. Rev. D 105, L011101 (2020)

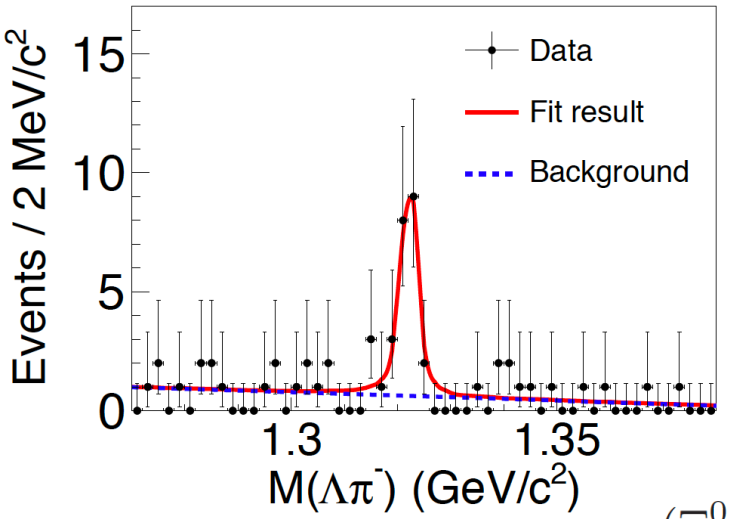


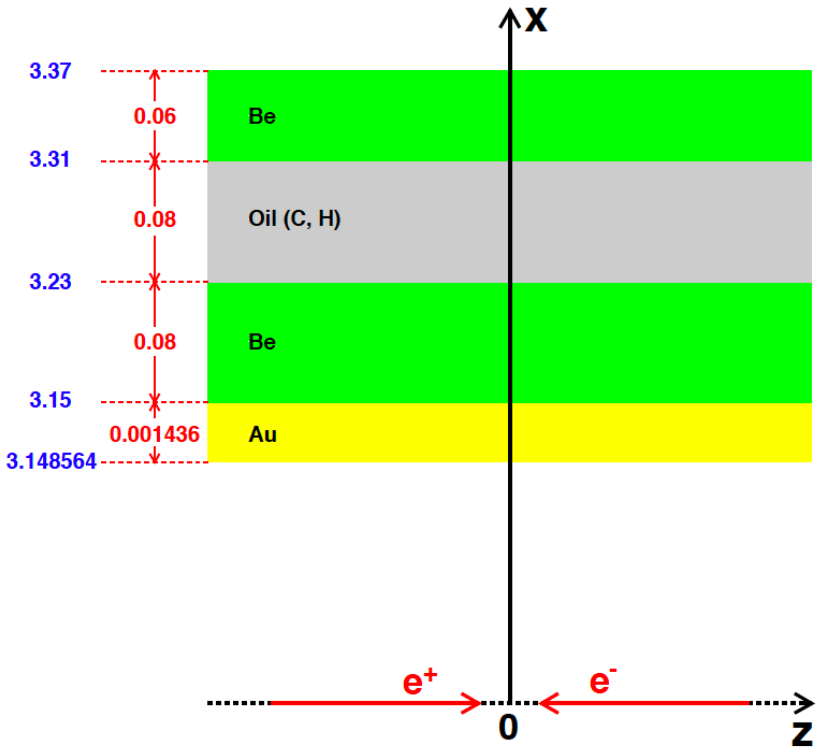


Hyperon-nucleon interactions

- Essential to check the theoretical models
- Experimental study is quite scarce

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





$$\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = (22.1 \pm 5.3_{\mathrm{stat}} \pm 4.5_{\mathrm{sys}})\ \mathrm{mb}$$

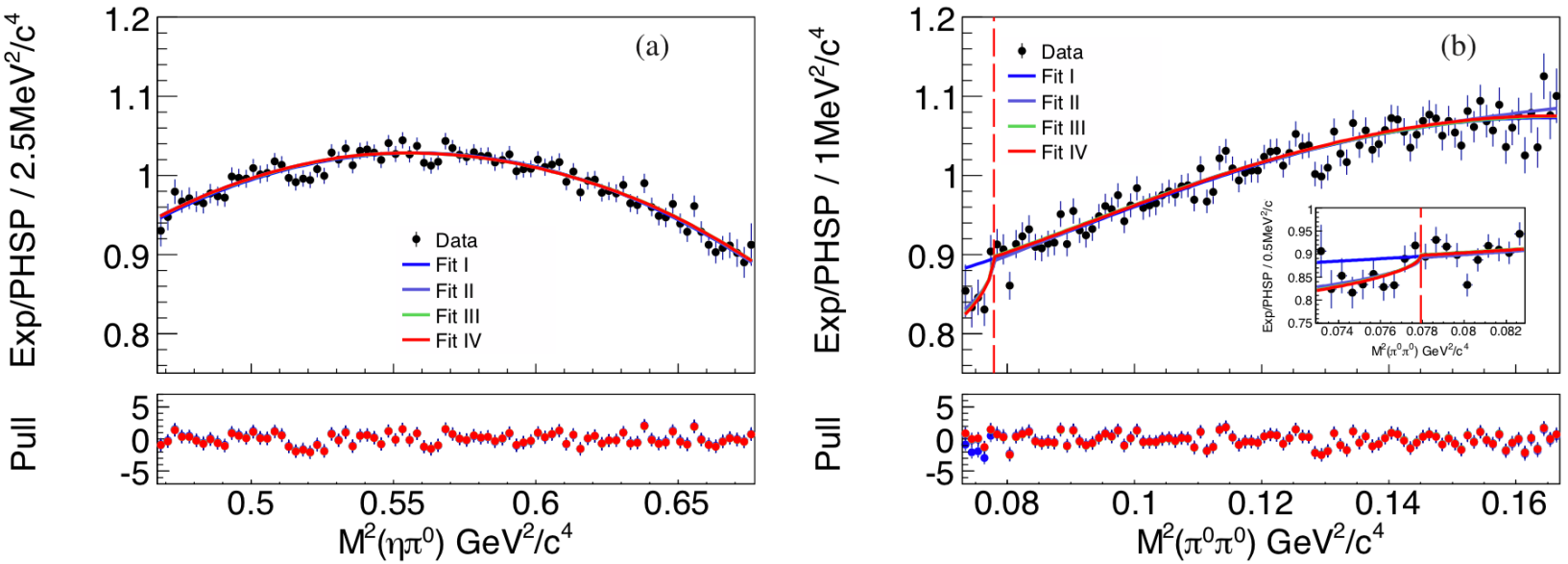
C. Z. Yuan and M. Karliner, Phys. Rev. Lett. 127,012003 (2021)
J. P. Dai, H. B. Li, H. Miao and J. Y. Zhang, arXiv:2209.12601

PRL 130, 251902(2023)

Meson-meson interactions

$\eta' \to \pi^0\pi^0\eta$

- Investigation on ππ and πη FI **PRL130,081901(2023)**
- Cusp effect is sizeable in this decay

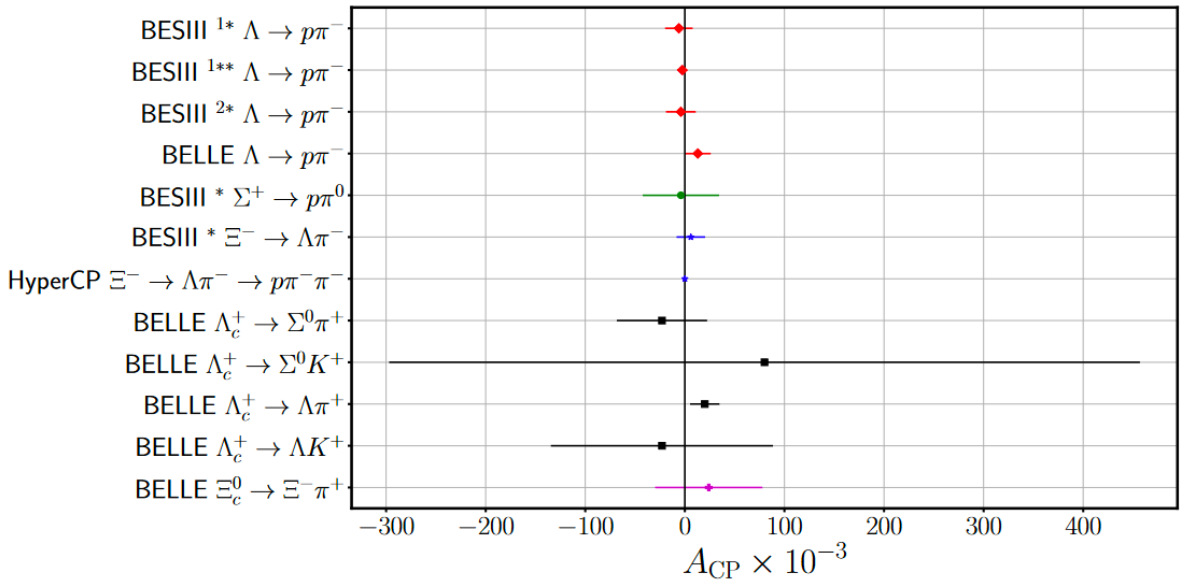


Parameters	Fit I	Fit II	Fit III	Fit IV
a	$-0.075 \pm 0.003 \pm 0.001$	-0.207 ± 0.013	-0.143 ± 0.010	$-0.077 \pm 0.003 \pm 0.001$
b	$-0.073 \pm 0.005 \pm 0.001$	-0.051 ± 0.014	-0.038 ± 0.006	$-0.066 \pm 0.006 \pm 0.001$
d	$-0.066 \pm 0.003 \pm 0.001$	-0.068 ± 0.004	-0.067 ± 0.003	$-0.068 \pm 0.004 \pm 0.001$
$a_0 - a_2$	-	0.174 ± 0.066	0.225 ± 0.062	$0.226 \pm 0.060 \pm 0.012$
a_0	-	0.497 ± 0.094	-	-
a_2	-	0.322 ± 0.129	-	-
Statistical Significance	-	3.4σ	3.7σ	3.6σ

- **Evidence of the cusp effect @ 3.5s !**

CP tests at BESIII & Belle

- SM predicts very small violations of charge conjugation and parity (CP) symmetry.
- Sizeable CP violations prerequisite for Baryogenesis
- Spin-carrying hyperons precision probe of CP symmetry.

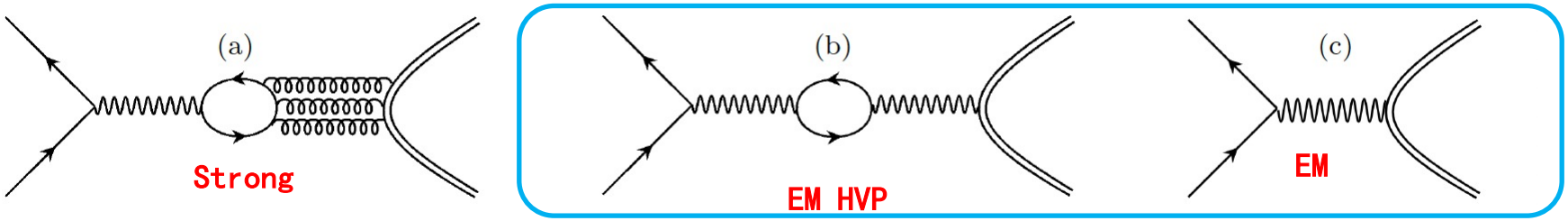


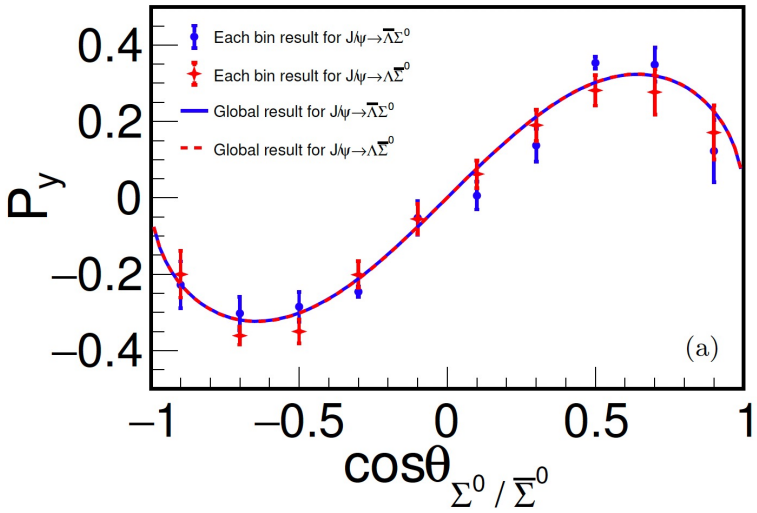
BESIII:
Nature Phys. 15, p 631-634 (2019)
Phys. Rev. Lett. 125, 052004 (2020)
Nature 606, 64-69 (2022)
Phys. Rev. Lett. 129, 131801 (2022)
Phys. Rev. D 108, L031106 (2023)

Belle:
Sci. Bull. 68, 583-592 (2023)

HyperCP:
Phys. Rev. Lett. 93, 262001, 2004.

CP test in $J/\psi \to \Lambda\bar{\Sigma}$





First measurements:

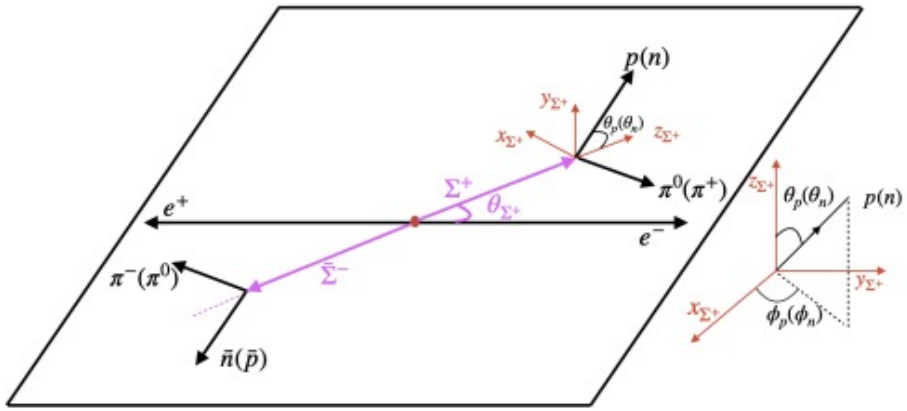
Df_1=1.011±0.094±0.010
Df_2=2.128±0.094±0.010
$|G_E/G_M|$=0.086±0.029±0.010

Df_1+Df_2=(3.139±0.133± 0.014)

arXiv:2309.04139, submitted to Nature Physics

CP test in $\Sigma^+ \to n\pi^+$

- Helicity frame definition:



Differential cross-section:

$$\mathcal{W}(\xi) = \mathcal{T}_0(\xi) + \alpha_{J/\psi}\mathcal{T}_5(\xi) + \alpha\bar{\alpha}\left(\mathcal{T}_1(\xi) + \sqrt{1-\alpha_{J/\psi}^2}\cos(\Delta\Phi)\mathcal{T}_2(\xi) + \alpha_{J/\psi}\mathcal{T}_6(\xi)\right) + \sqrt{1-\alpha_{J/\psi}^2}\sin(\Delta\Phi)(\alpha\mathcal{T}_3(\xi) + \bar{\alpha}\mathcal{T}_4(\xi)),$$

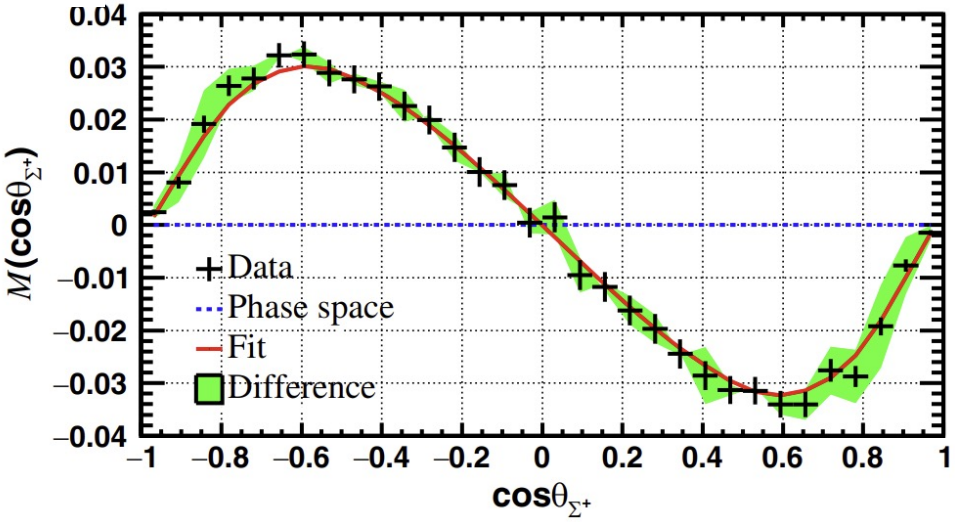
PRL 131, 191802 (2023)

The weak decay parameters are determined to be:

$$\alpha_+ = 0.0481 \pm 0.0031 \pm 0.0019$$

$$\alpha_- = -0.0565 \pm 0.0047 \pm 0.0022$$

$$A_{CP} = -0.080 \pm 0.052 \pm 0.028$$

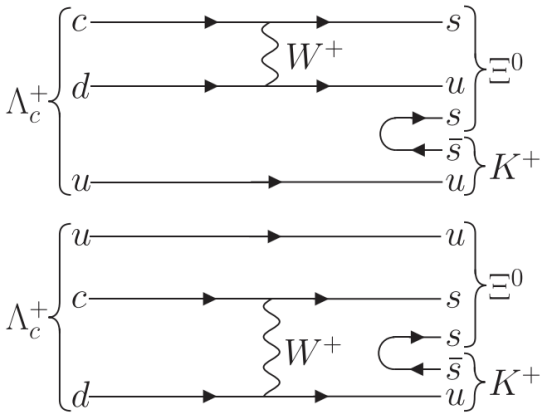


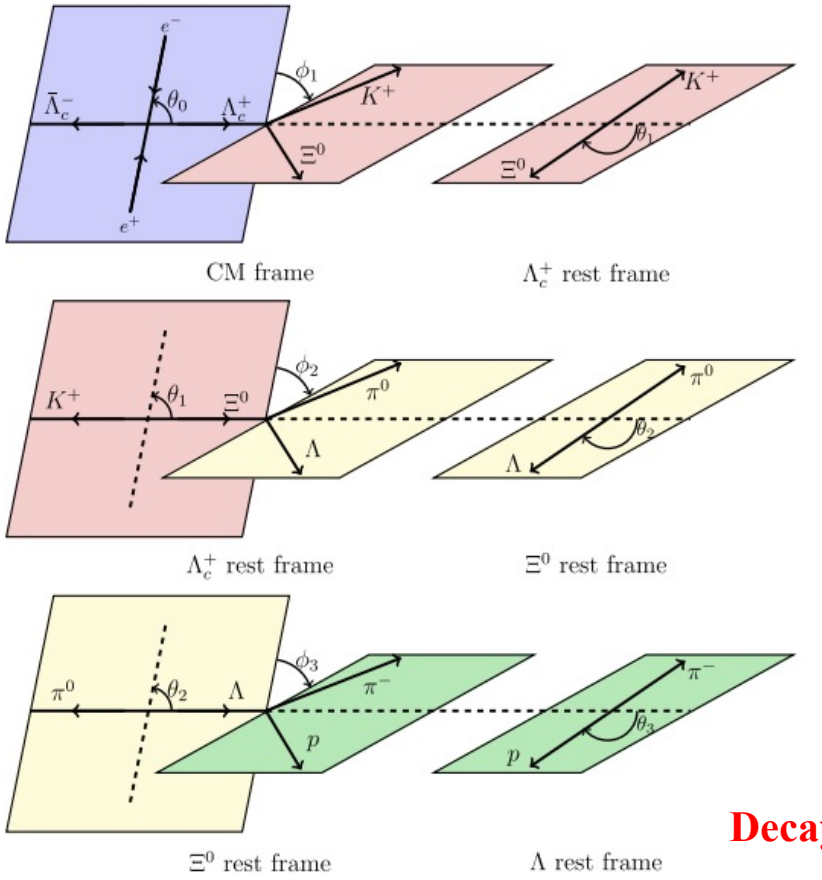
Decay asymmetry parameter in $\Lambda_c^+ \to \Xi^0 K^+$

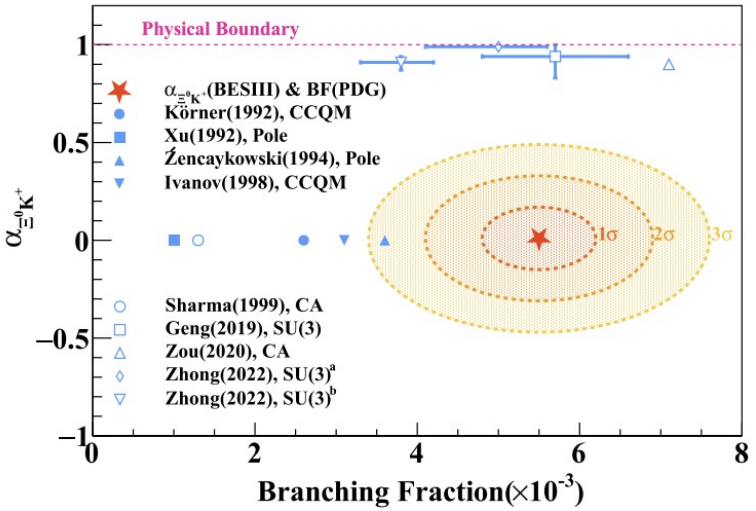
PRL 132, 031801 (2024)

- Helicity frame:

W-boson-exchange decay:







Decay asymmetry parameter: $\alpha = 0.01 \pm 0.16 \pm 0.03$

Phase between S and P wave: $\delta_P - \delta_S = -1.55 \pm 0.25 \pm 0.05, or\ 1.59 \pm 0.25 \pm 0.05$

Search for BNV in $\Lambda\bar{\Lambda}$ oscillations

Origin of Matter – anti Matter asymmetry.

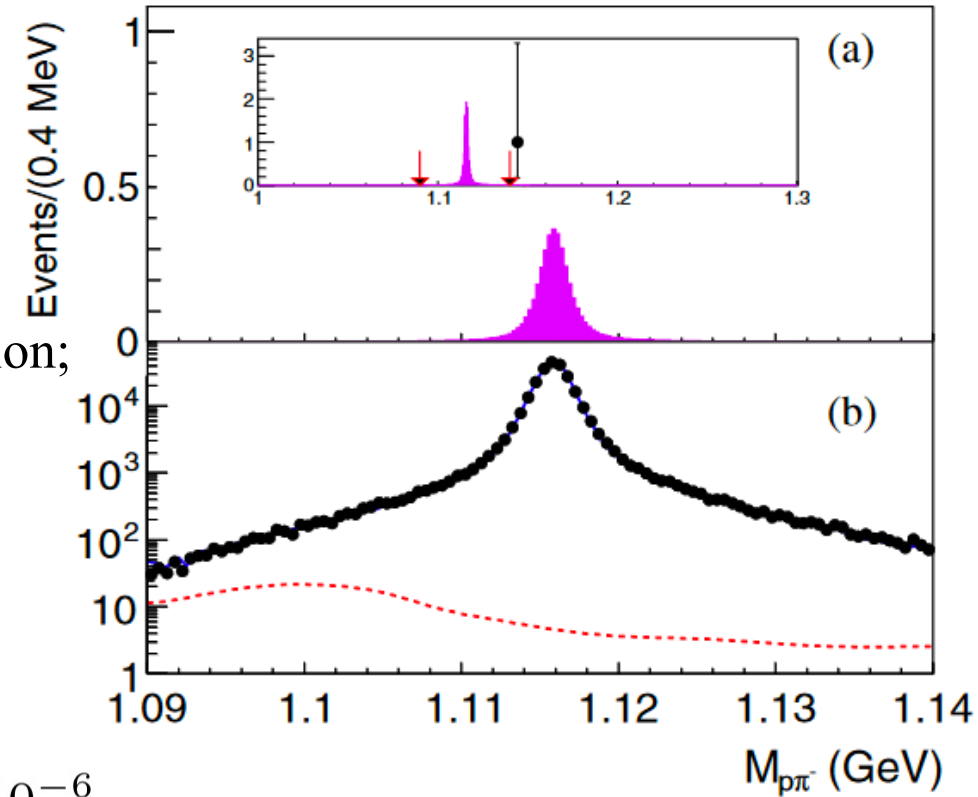
Sakharov criteria:

violation of C) and symmetry;

violation of baryon number conservation;

deviation from thermal equilibrium

D. Sakharov, JETP Lett. 5, 24 (1967).



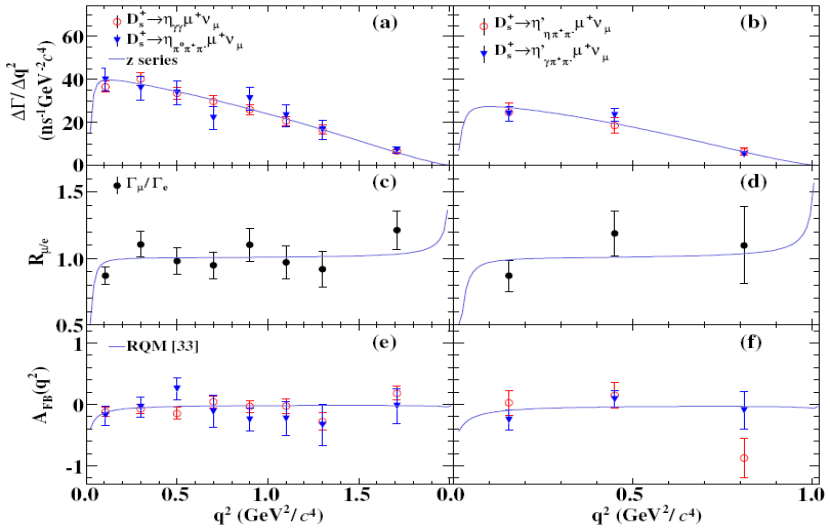
$$\mathcal{P}(\Lambda) = \frac{\mathcal{B}(J/\psi \to pK^-\Lambda + c.c.)}{\mathcal{B}(J/\psi \to pK^-\bar{\Lambda} + c.c.)} < 4.4 \times 10^{-6}$$

$\rightarrow$ oscillation parameter $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \cdot 10^{-18}$

Phys. Rev. Lett. 131, 121801 (2023)

LUT tests in Charm decays at BESIII

$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$ PRL 132,091802(2024)



$$R_{D_s^+\eta} = \frac{\Gamma[D_s^+ \to \eta\mu^+\nu]}{\Gamma[D_s^+ \to \eta e^+\nu]} = 0.984 \pm 0.032$$

$$R_{D_s^+\eta'} = \frac{\Gamma[D_s^+ \to \eta'\mu^+\nu]}{\Gamma[D_s^+ \to \eta' e^+\nu]} = 0.989 \pm 0.089$$

$D_s^+ \to \phi\mu^+\nu_\mu$ JHEP12(2023)072

$$R_{D_s^+\phi} = \frac{\Gamma[D_s^+ \to \phi\mu^+\nu]}{\Gamma[D_s^+ \to \phi e^+\nu]} = 0.94 \pm 0.08$$

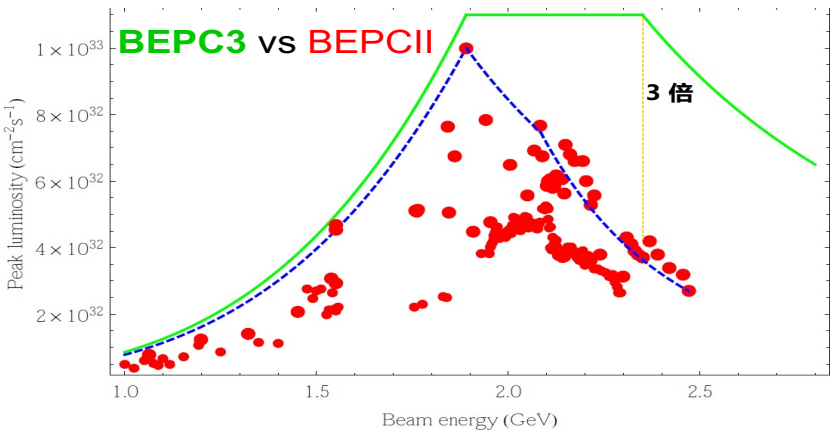
The $D^+ \to \tau^+\nu$ and seven semimuonic D decays are observed for the first time. Five semimuonic charm decays are measured with better precision

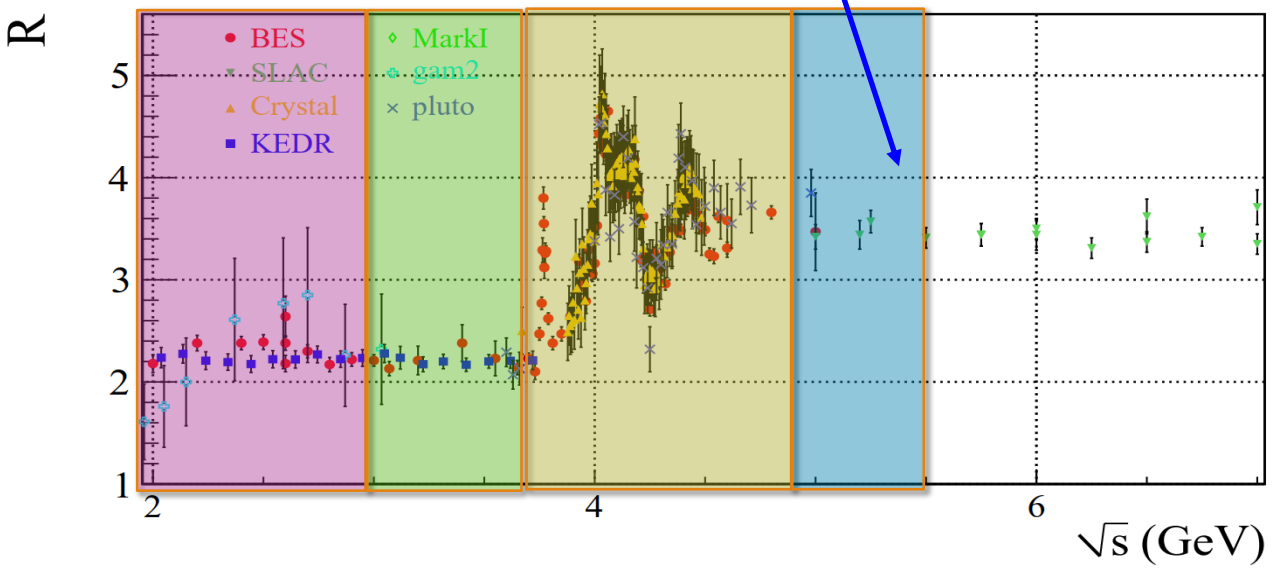
	BF ratios		References
μ/e	$D^0 \to K^-$	$0.978 \pm 0.007 \pm 0.012$	PRL122(2019)011804
	$D^0 \to \pi^-$	$0.922 \pm 0.030 \pm 0.022$	PRL121(2018)171803
	$D^0 \to \rho^-$	0.90 ± 0.11	PRD104(2021)L091003
	$D^+ \to \bar{K}^0$	1.00 ± 0.03	EPJC76(2016)369
	$D^+ \to \pi^0$	$0.964 \pm 0.037 \pm 0.026$	PRL121(2018)171803
	$D^+ \to \omega$	1.05 ± 0.14	PRD101(2020)072005
	$D^+ \to \eta$	0.91 ± 0.13	PRL124(2020)231801
	$D_s^+ \to \eta$	$0.984 \pm 0.028 \pm 0.016$	arXiv:2307.12852 accepted by PRL
	$D_s^+ \to \eta'$	$0.989 \pm 0.082 \pm 0.034$	
	$D_s^+ \to \phi$	0.94 ± 0.08	JHEP12(2023)072
	$\Lambda_c^+ \to \Lambda$	$0.98 \pm 0.05 \pm 0.03$	PRD108(2023)L031105
τ/μ	$D^+ \to t^+\nu$	$3.21 \pm 0.64 \pm 0.43$	PRL123(2019)211802
	$D_s^+ \to t^+\nu$	10.05 ± 0.35	PRL127(2021)171801

Plan of BEPCII/BESIII upgrade

Chin. Phys. C 44 (2020) 4, 040001

- Optimize E_{cm} at 4.7 GeV with luminosity 3 times higher than the current BEPCII
  → more effective data taking
- CGEM inner tracker
- Extend the maximum E_{cm} up to 5.6 GeV
  → more physics opportunity





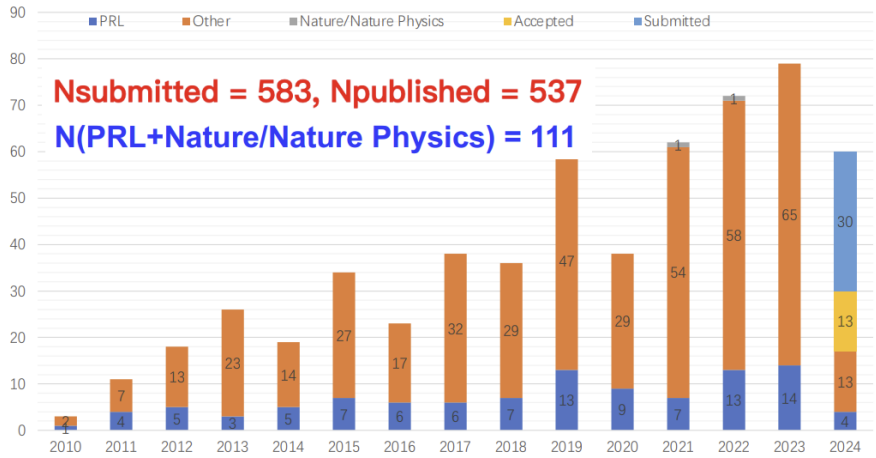
Nearly blank at 5-7GeV

Summary & Prospect

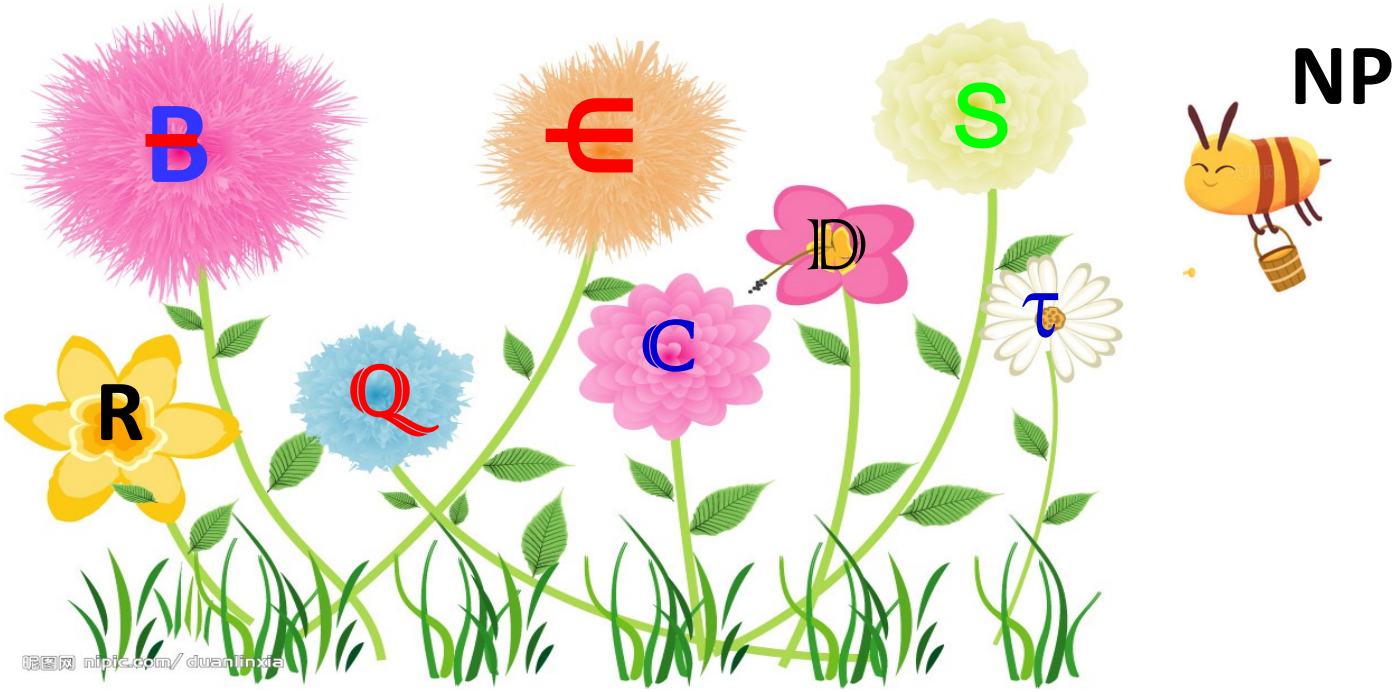
- World largest data samples at BESIII
  - An excellent laboratory to study a wide physics program
- Recent highlights of BESIII results are briefly overviewed
  - A personal selection of latest BESIII results
- Latest large data-sets under study
- BEPCII-U: 3x lum above 4 GeV &max energy to 5.6 GeV) !

March 2024

BESIII Publications



More important results are expected from BESIII !



Many thanks for your attention !