Highlights of BESIII experiment

房双世

(for BESIII Collaboration)

高能物理研究所

第三届强子与重味物理理论与实验联合研讨会

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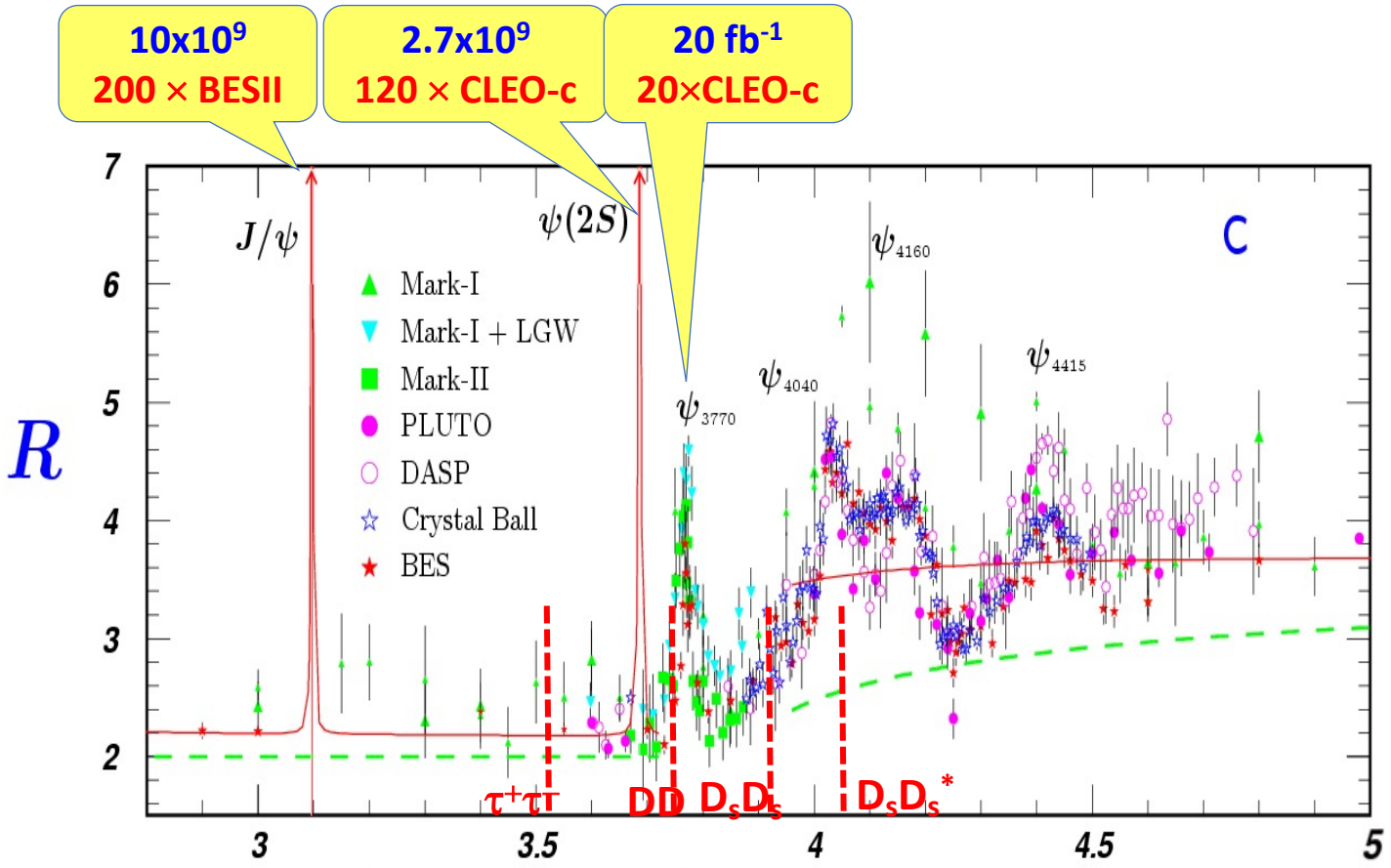
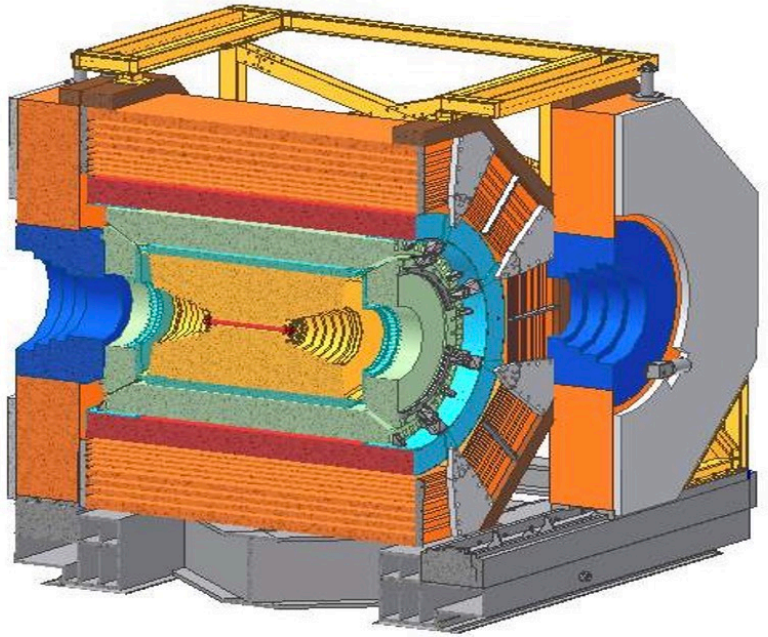
Outline

- Status of BEPCII/BESIII
- Recent Highlights
  - Hadron spectroscopy
  - Hadron structure
  - Symmetries tests
  - Hadron interactions
- Future prospects

BEPCII/BESIII : τ-charm factory





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

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

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

What/how can we learn from BESIII data?

Questions

Hadron structures

Hadron interactions

New Physics

Observables

Hadron spectroscopy

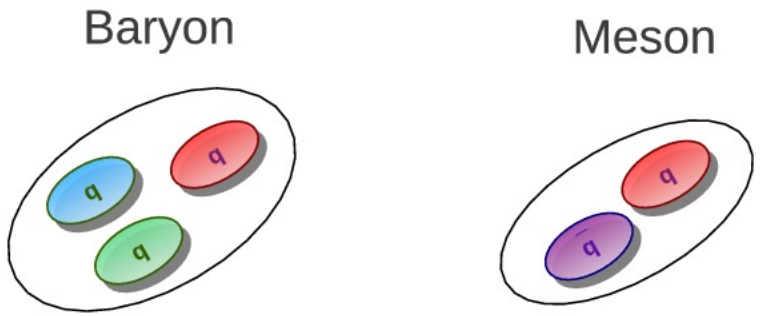
Form factors

Decays & productions

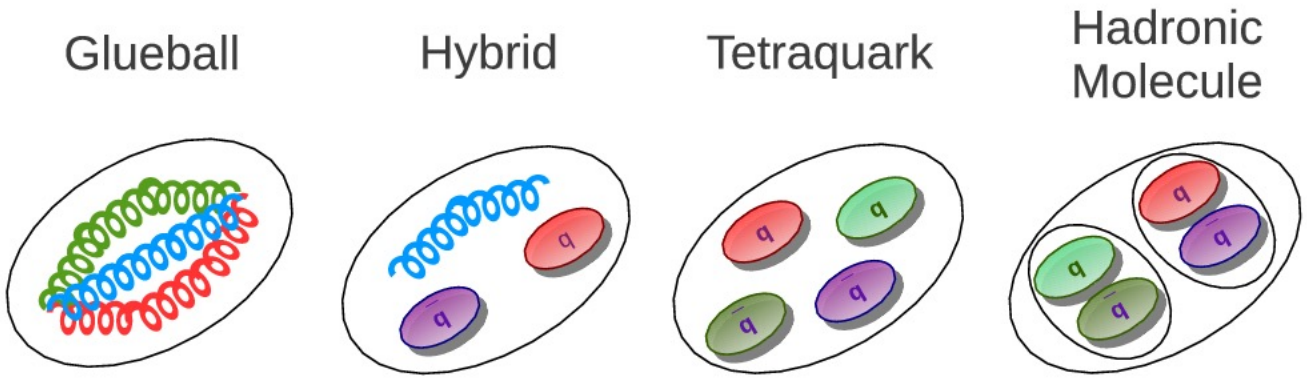
Symmetries test

Ordinary vs exotic matter

- Conventional hadrons

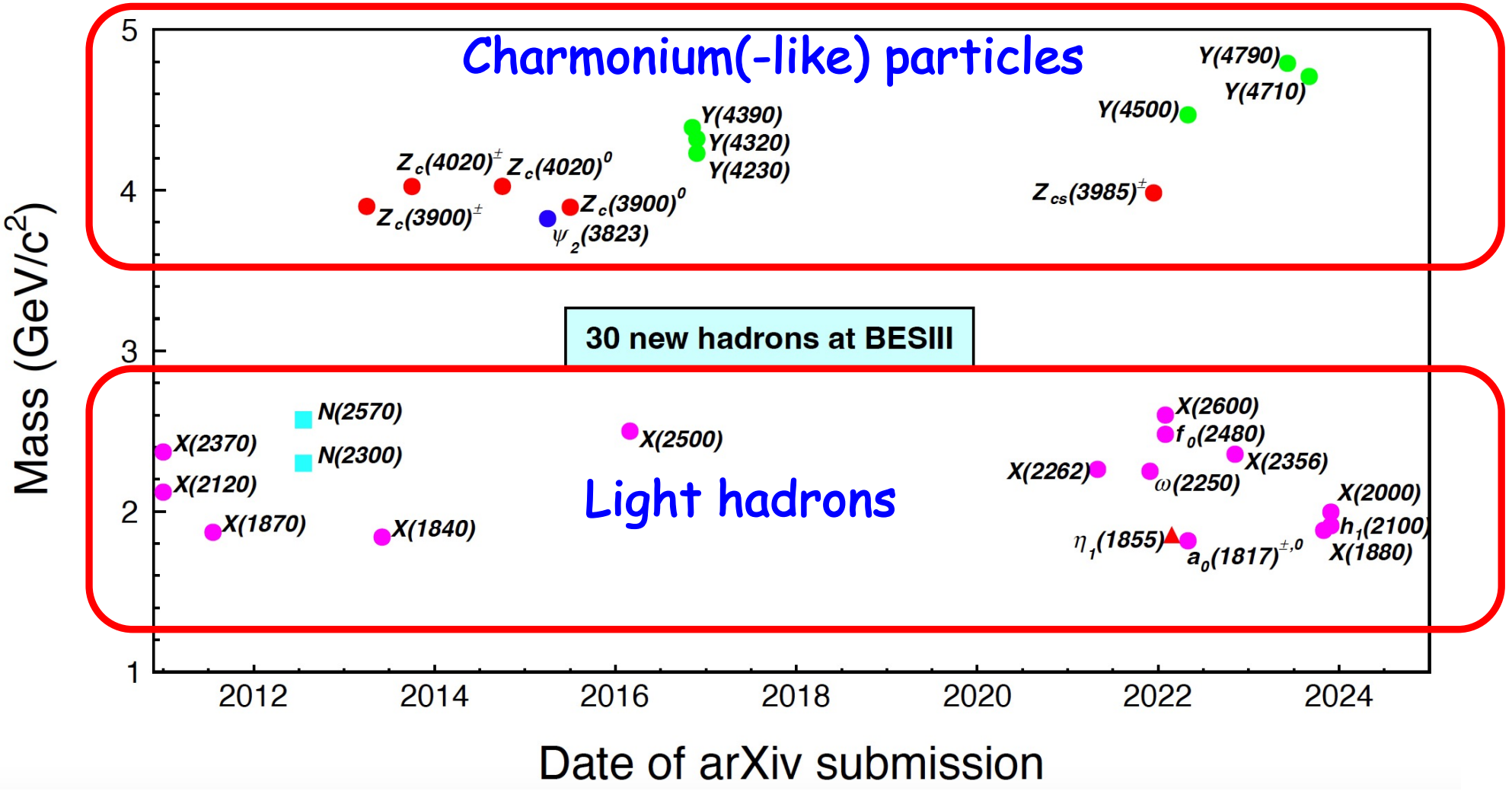


- QCD allows for "exotics"



- Searching for those states provides test of QCD

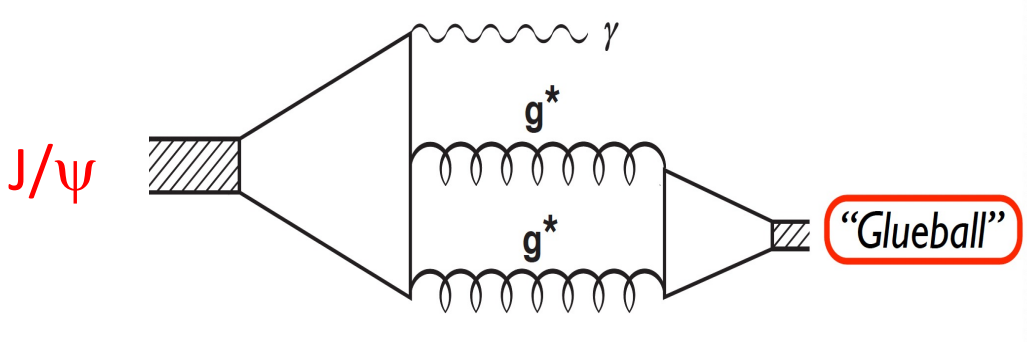
New resonant structures at BESIII

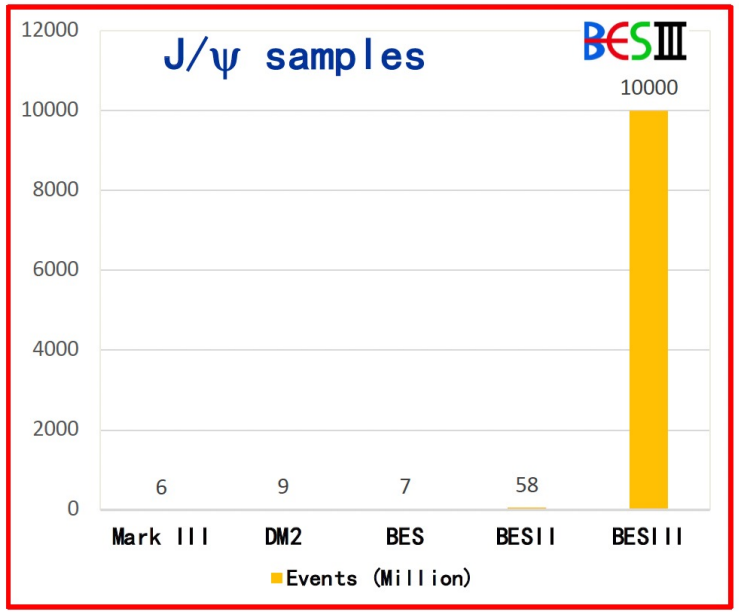


Glueball searches

Two big issues

- What is the production mechanism to utilize?
- What is the mixing with quark model mesons?





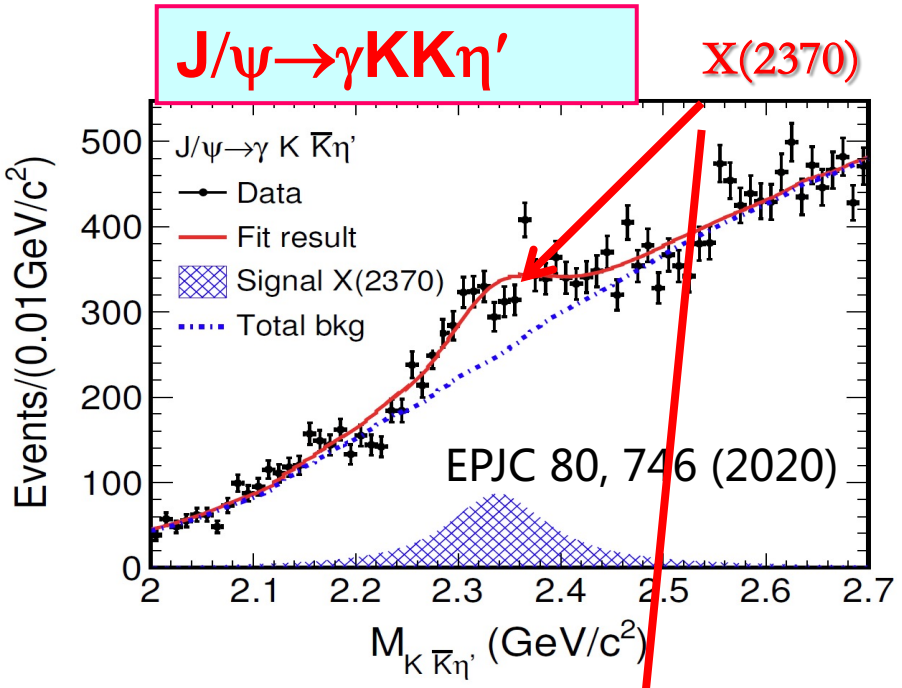
Production rate could be calculable in LQCD, but the manifestation of a "glueball" can be tricky!

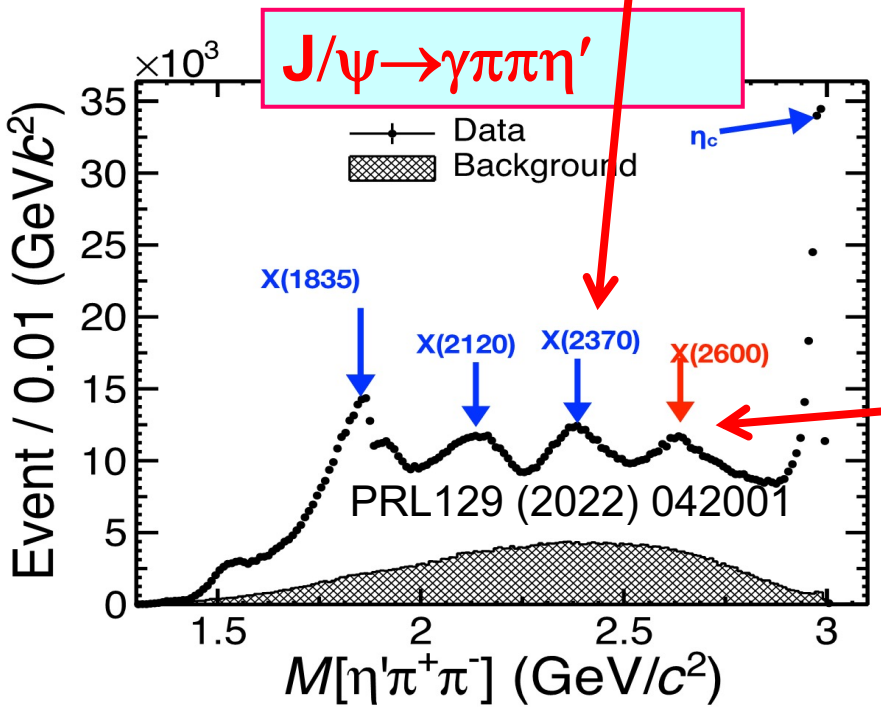
Chanowitz, Phys.Rev.Lett. 95(2005)172001

Systematic studies needed

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

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

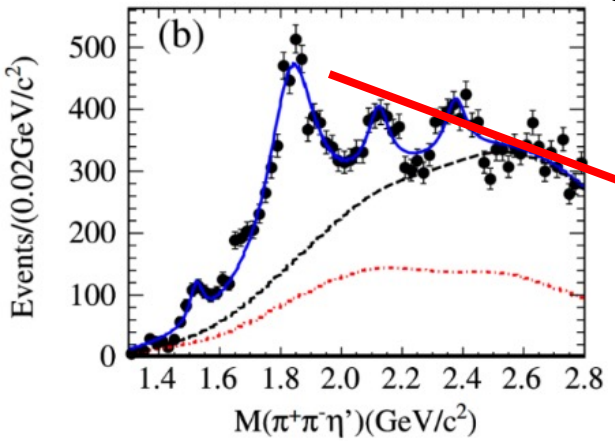
Motivated by the newly observed resonance $X(2600)$ by BESIII Collaboration, we examine the trigluon glueball interpretation for it in the framework of QCD sum rules. We evaluate the mass spectra of the trigluon glueballs with quantum numbers 0^{-+} and 2^{-+} up to dimension 8 condensate in the operator 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 $J/\psi \to \gamma\eta'\pi^+\pi^-$



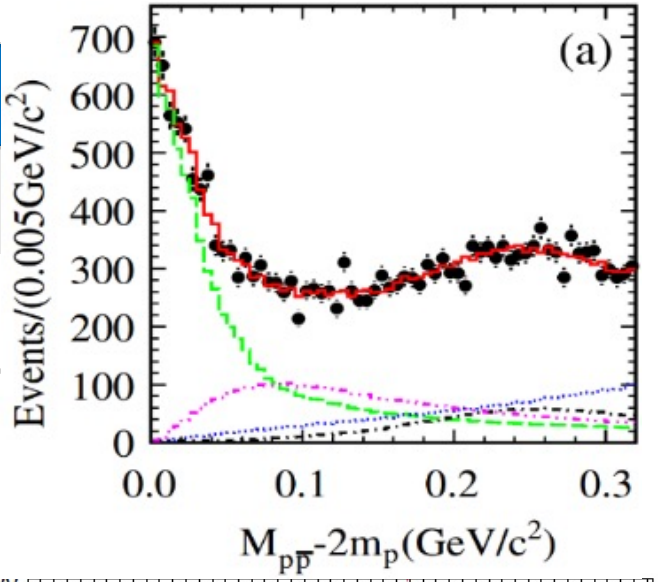
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

PRL 106, 072002 (2011)

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

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

PRL 108, 112003 (2012)

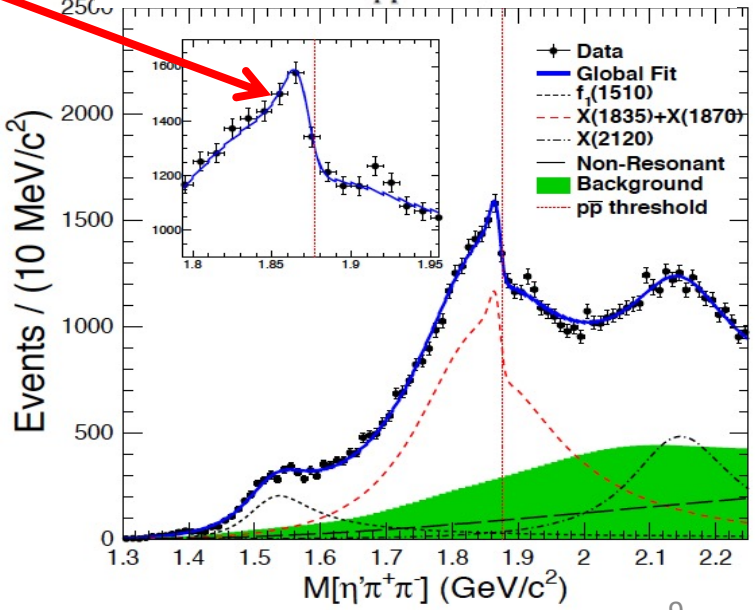


connection between X(1835) and X(p$\bar{p}$)

The anomalous line shape :

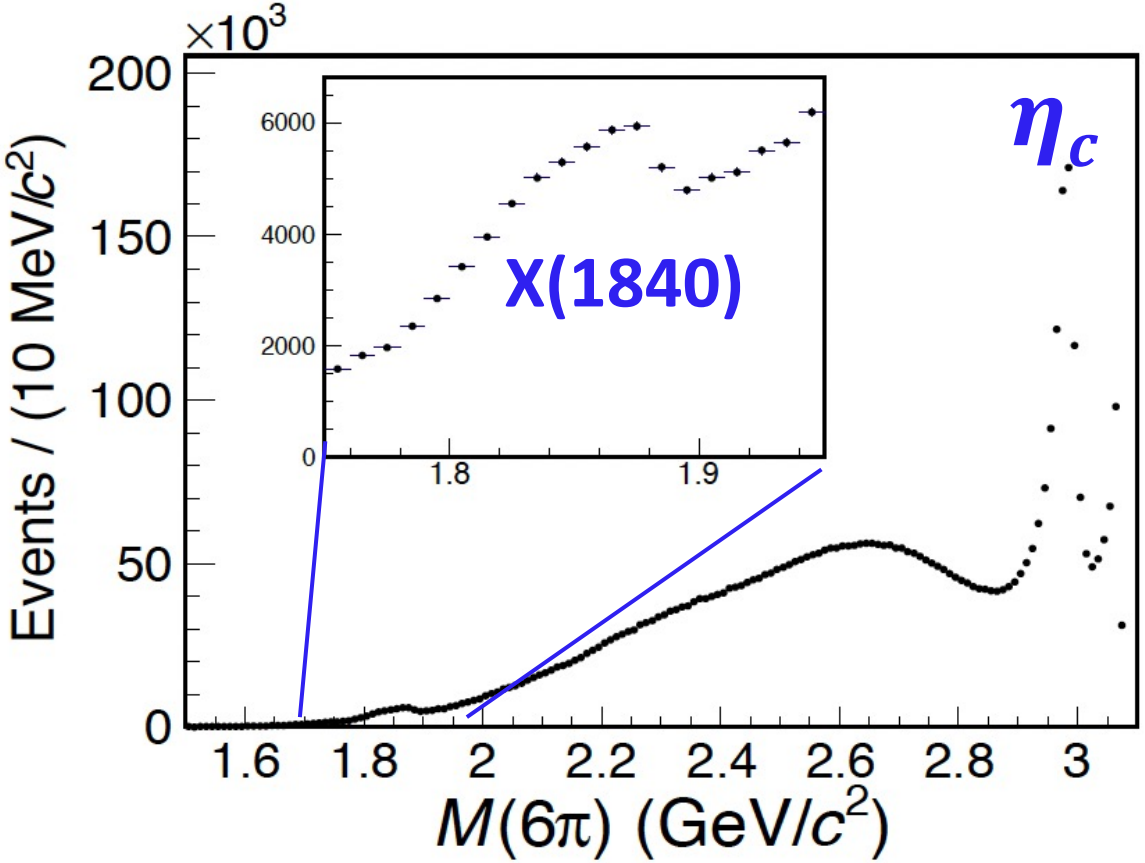
-- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold

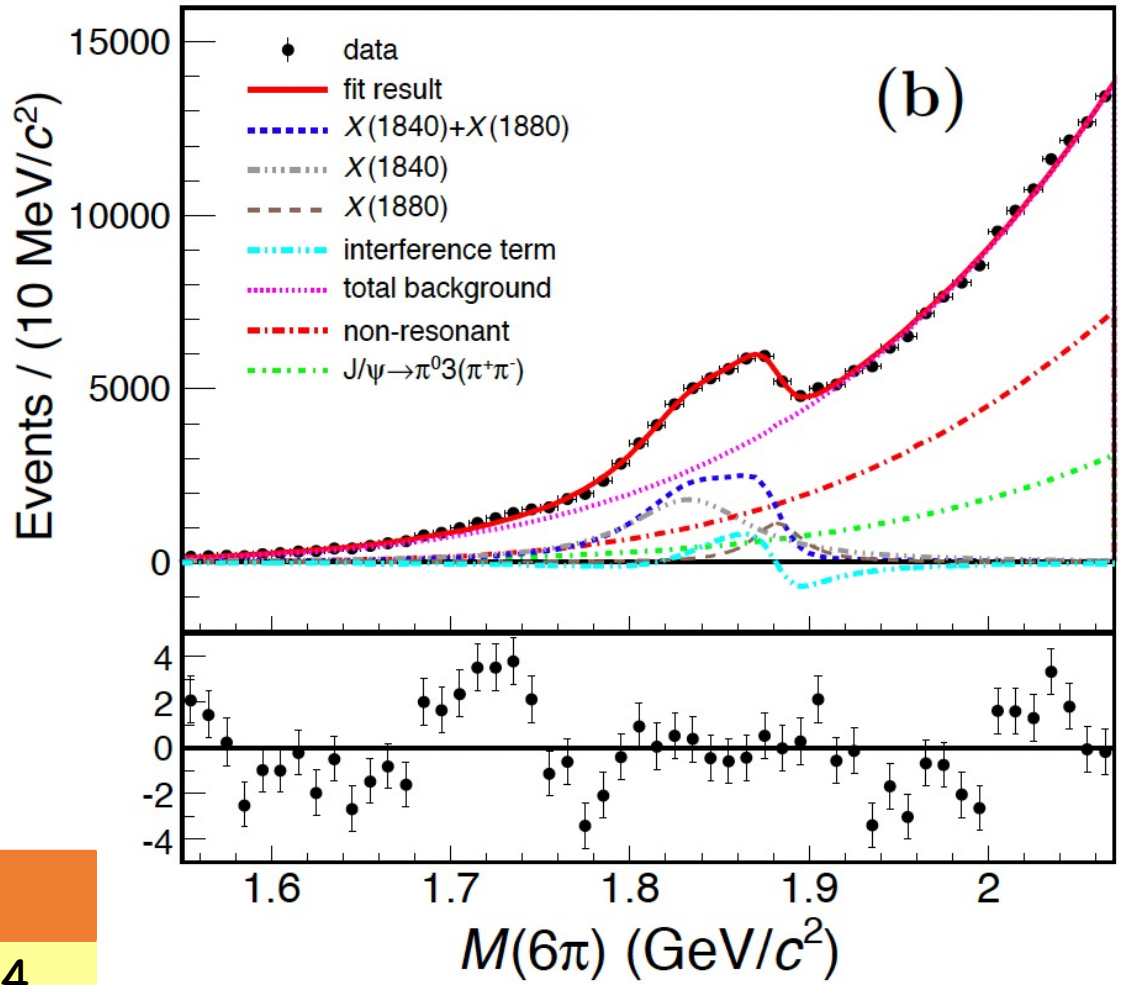
-- Support the existence of a $p\bar{p}$ molecule-like state or bound state



PRL 117, 042002 (2016)

A narrow state around $p\bar{p}$ threshold in $J/\psi \to \gamma 3(\pi^+\pi^-)$



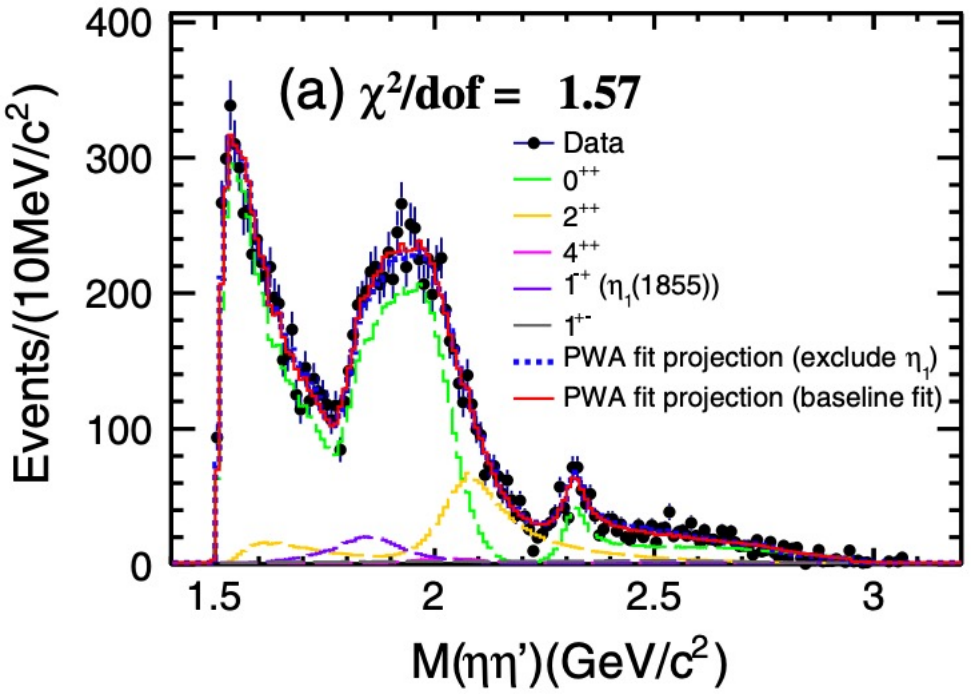


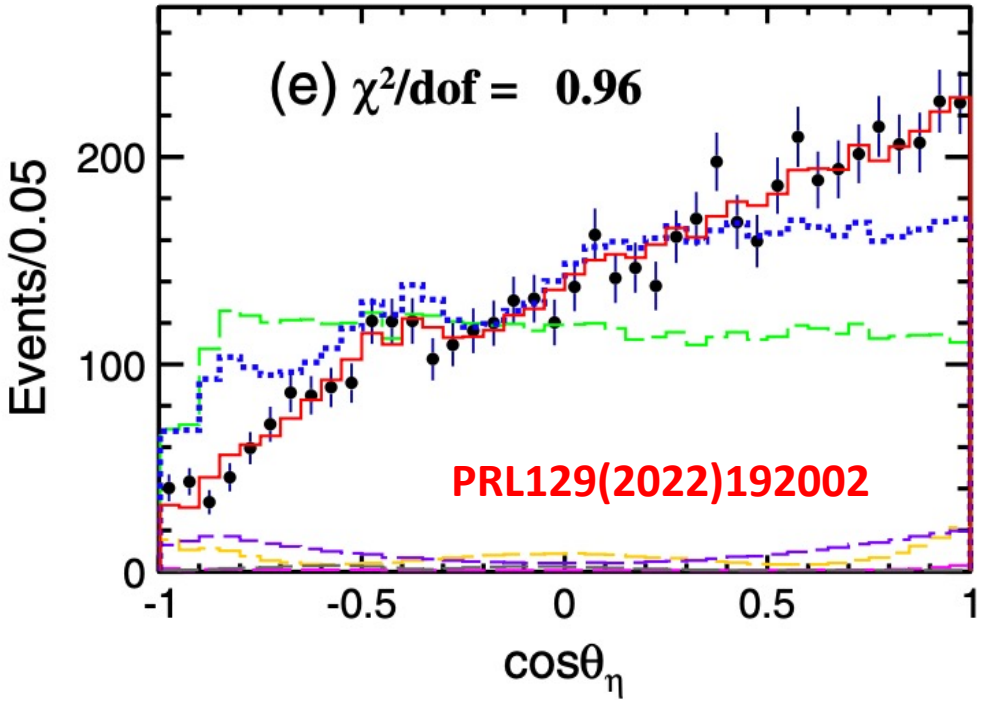
Resonance	M(MeV/c^2)	Γ(MeV/c^2)
X(1880)	1882.1±1.7±0.7	30.7±5.5±2.4
X(1840)	1832.5±3.1±2.5	80.7±5.2±7.7

arXiv:2310.17937, accepted by PRL

Support the existence of ppbar bound state !

Observation of 1^{-+} $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$





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

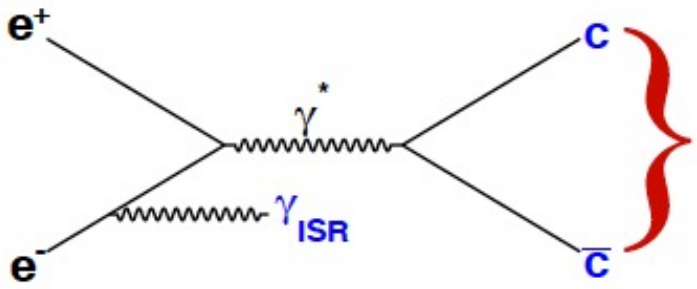
$M = 1855 \pm 9^{+6}_{-1}$ MeV/c^2

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

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

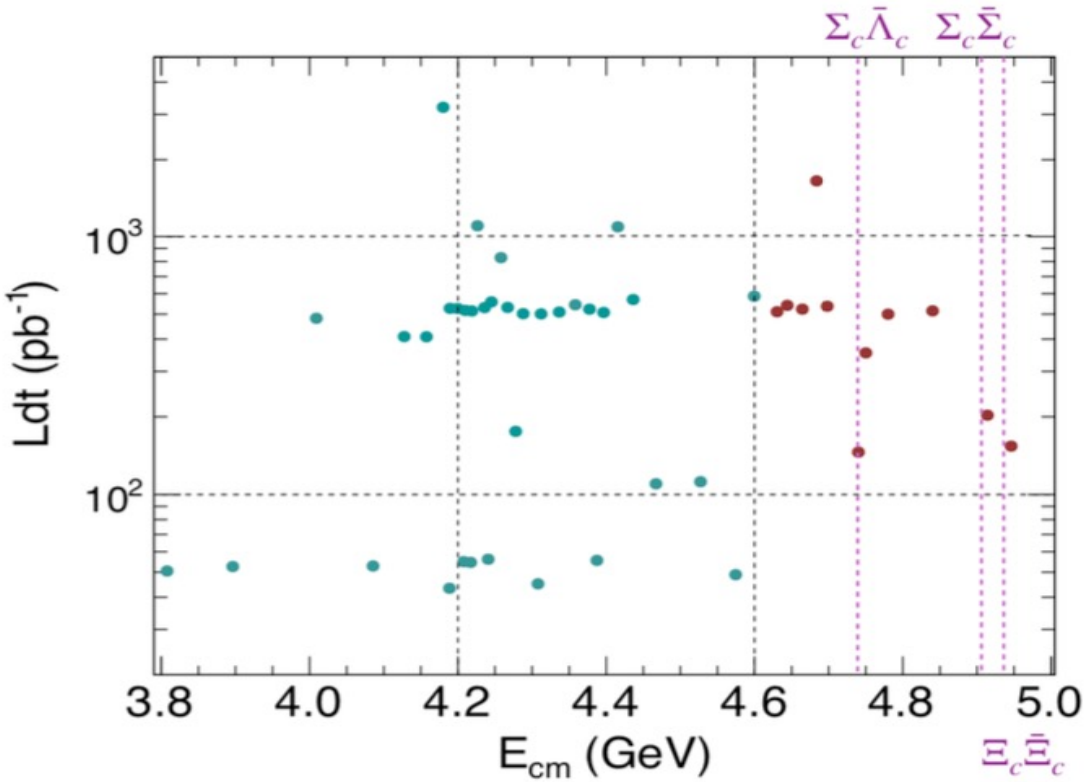
More works in progress for establishing the state with I=1

Charmonium(-like) states

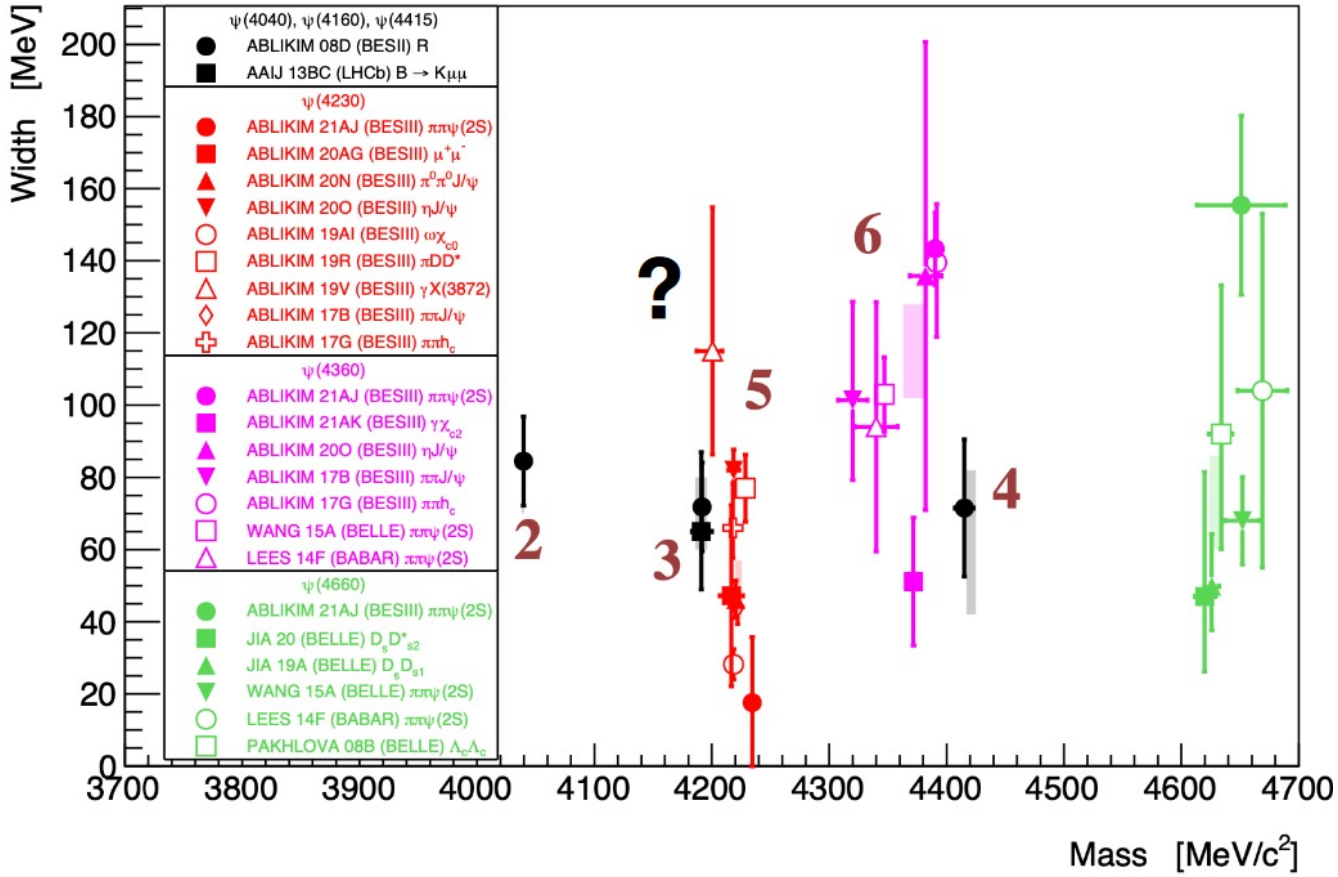


$J^{PC} = 1^{--}$

$\psi', \psi'', \Upsilon \ldots$



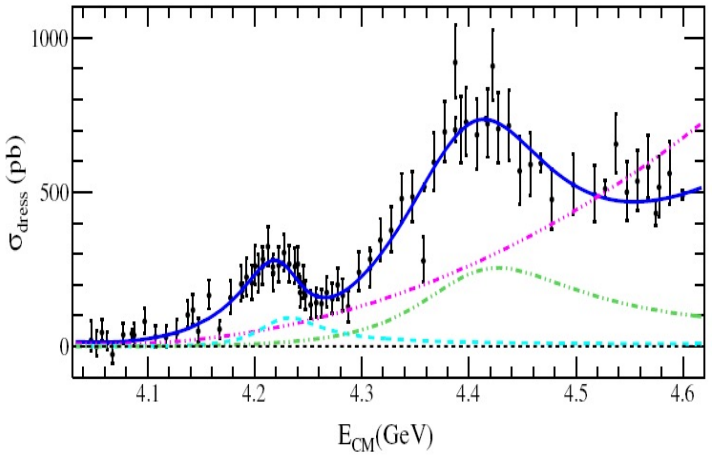
XYZ studies with ~25 fb^{-1} data above 3.8 GeV



Fine Structure of $Y(4260) \rightarrow Y(4220) + Y(4320)$?

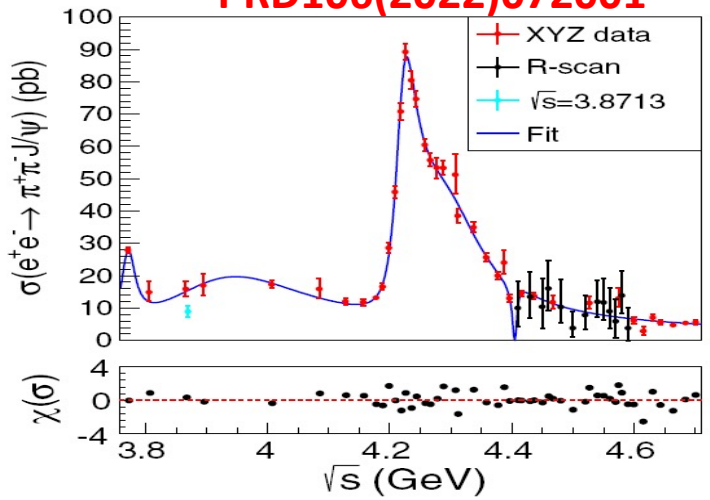
$e^+e^- \rightarrow \pi^+ D^0 D^{*-}$ +c.c.

PRL122(2019)102002



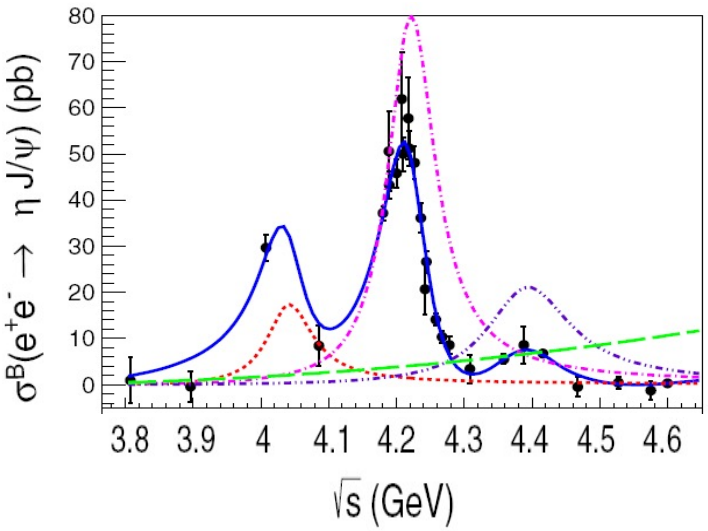
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$

PRD106(2022)072001



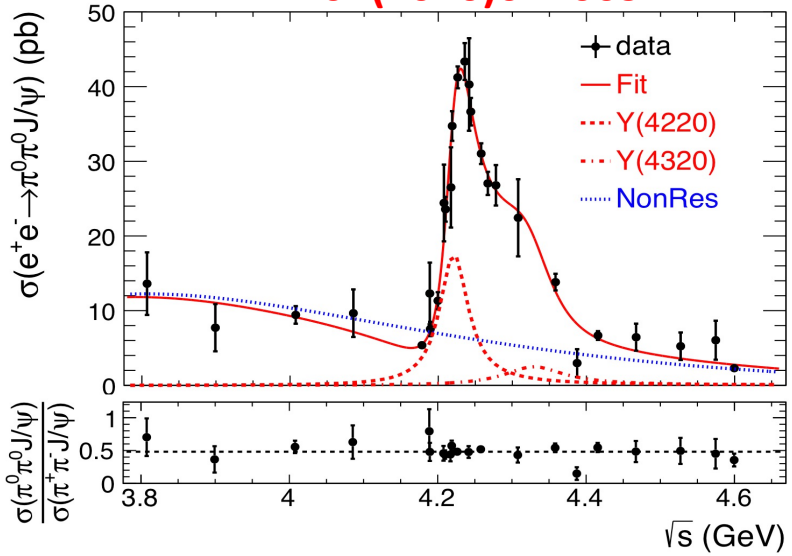
$e^+e^- \rightarrow \eta J/\psi$

PRD102(2020)031101(RC)

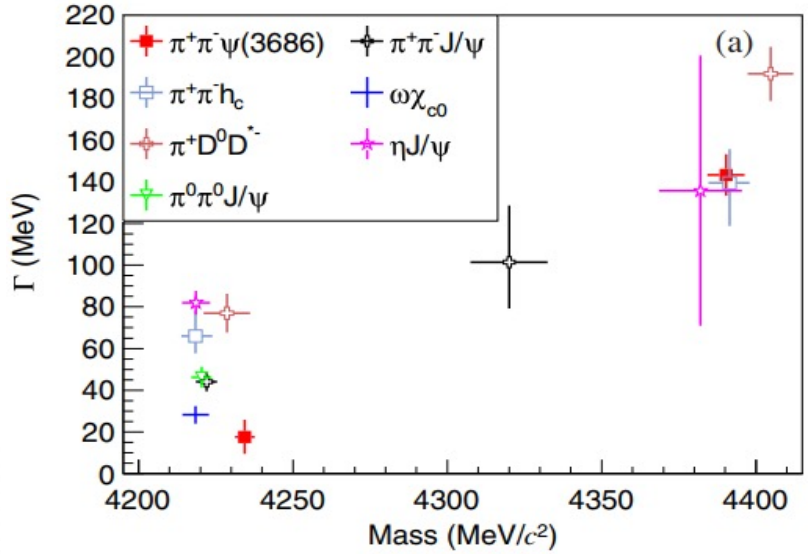


$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$

PRD102(2020)012009

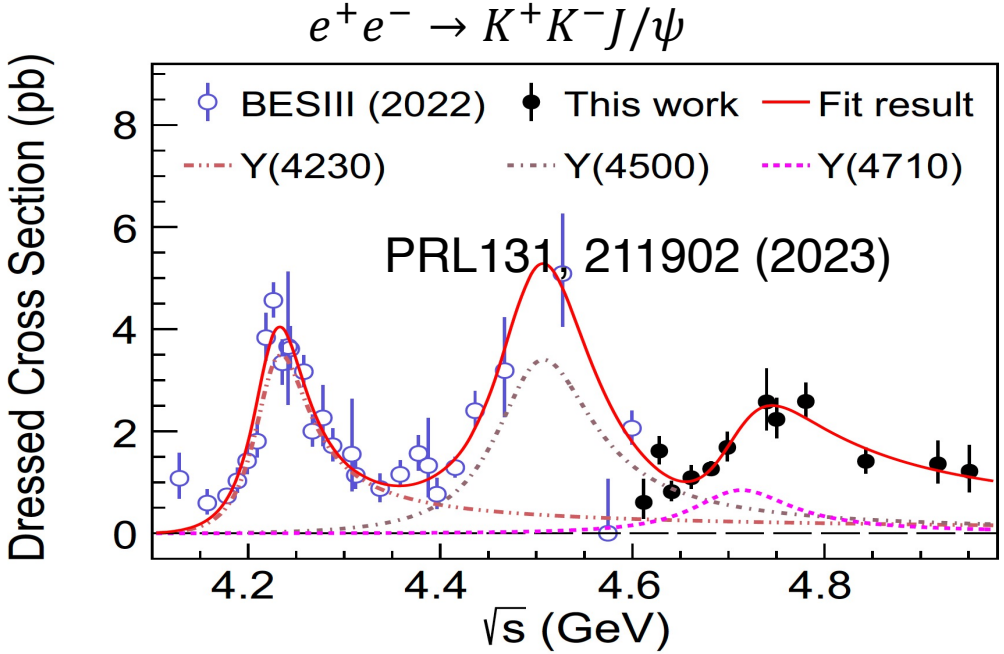


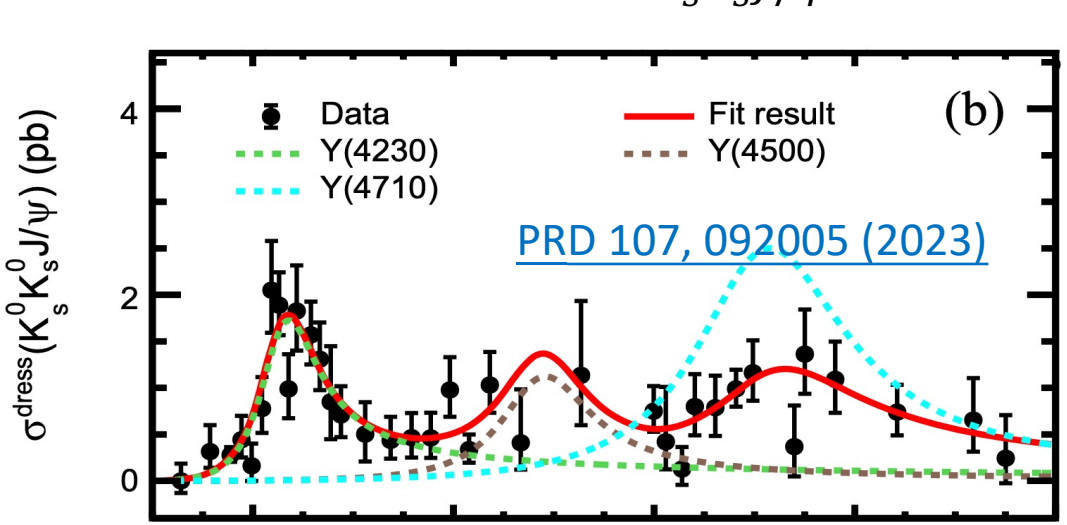
Different masses and widths in various processes

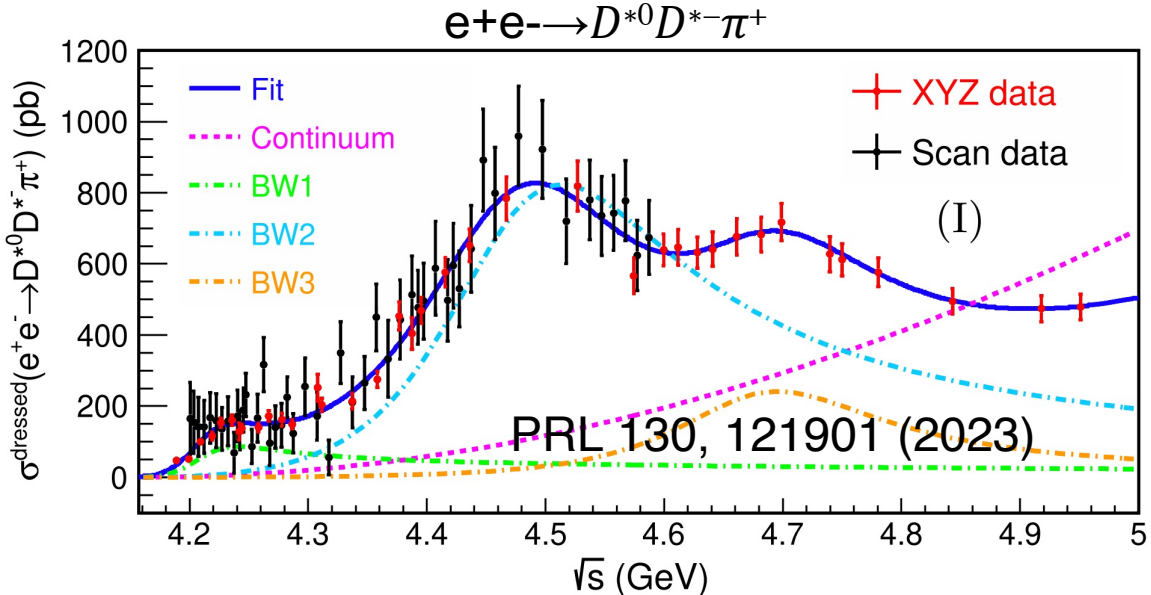


Mass~4220 MeV, width~ 50 MeV!

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



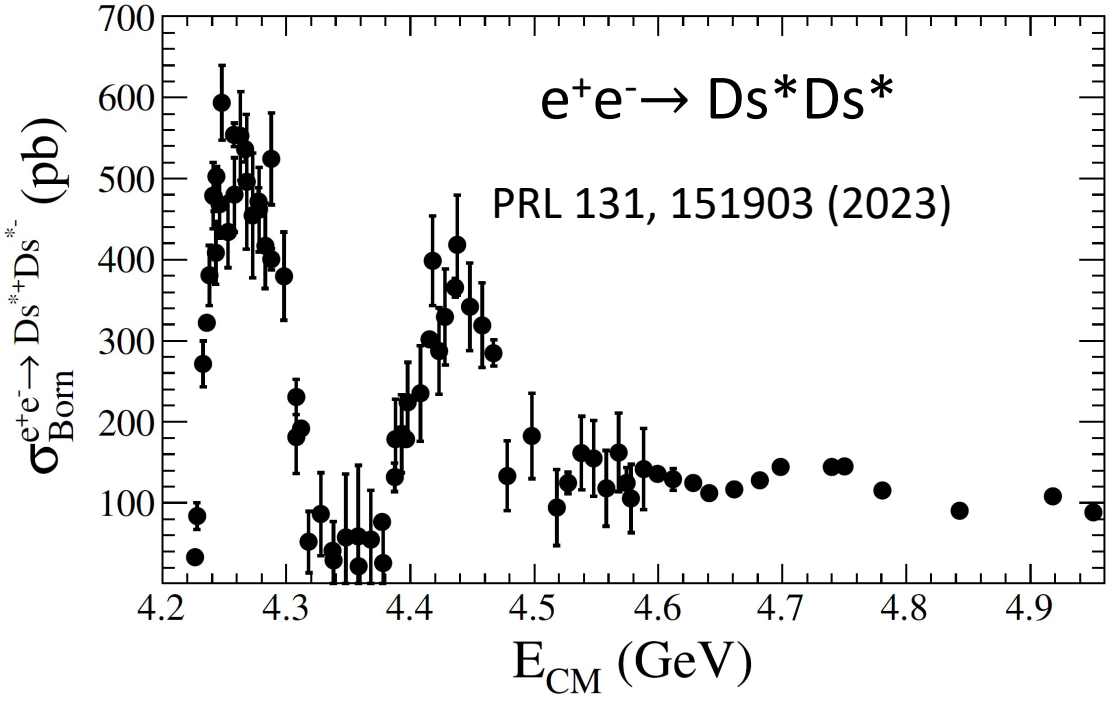




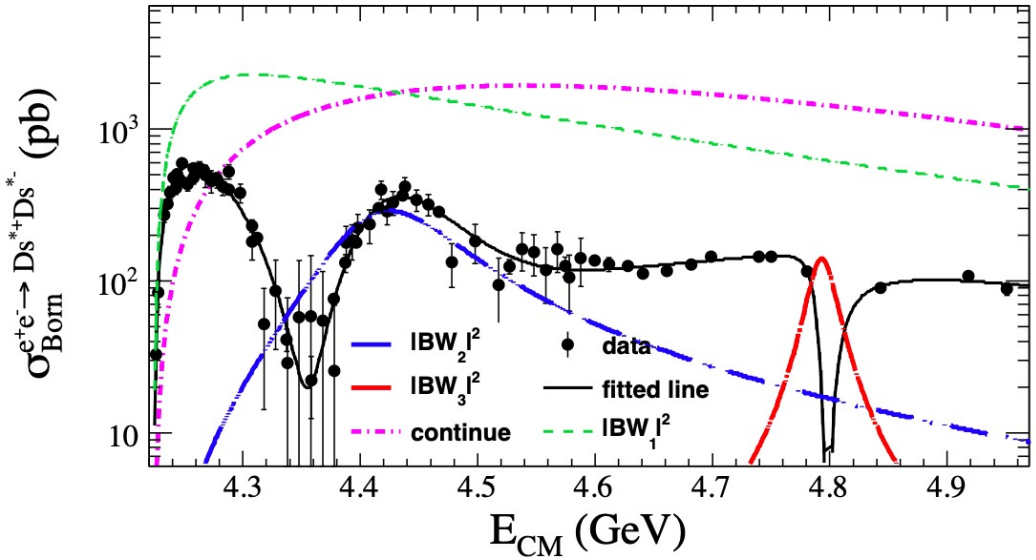
- New decay mode of Y(4230)
- Confirmation of Y(4500)
- Y(4710): one of the heaviest vector charmonium-like state, hybrid, 5S charmonium, 5S-4D/6S-5D mixing?

M~4710 MeV/c^2, Γ~ 180 MeV

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



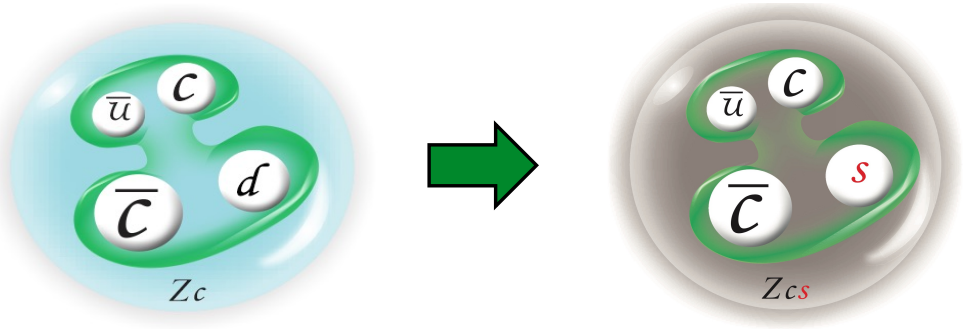
	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.5±9.0	4193.8±7.5	4195.3±7.5
Γ_1 (MeV)	55±17	61.2±9.0	61.8±9.0
M_2 (MeV/c^2)	4414.5±3.2	4412.8±3.2	4411.0±3.2
Γ_2 (MeV)	122.6±7.0	120.3±7.0	120.0±7.0
M_3 (MeV/c^2)	4793.3±7.5	4789.8±9.0	4786±10
Γ_3 (MeV)	27.1±7.0	41±39	60±35



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

Observation of $Z_{cs}(3985)$: SU(3) partner of Z_c

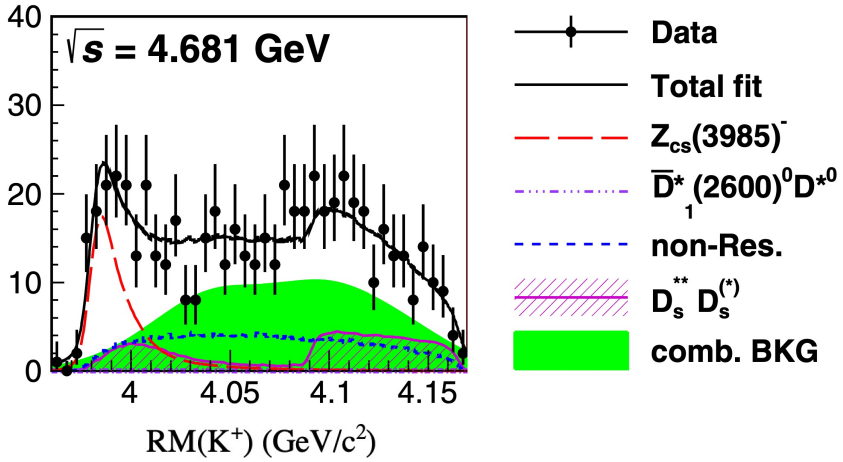
$e^+e^- \to K^+K^-J/\psi$



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

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

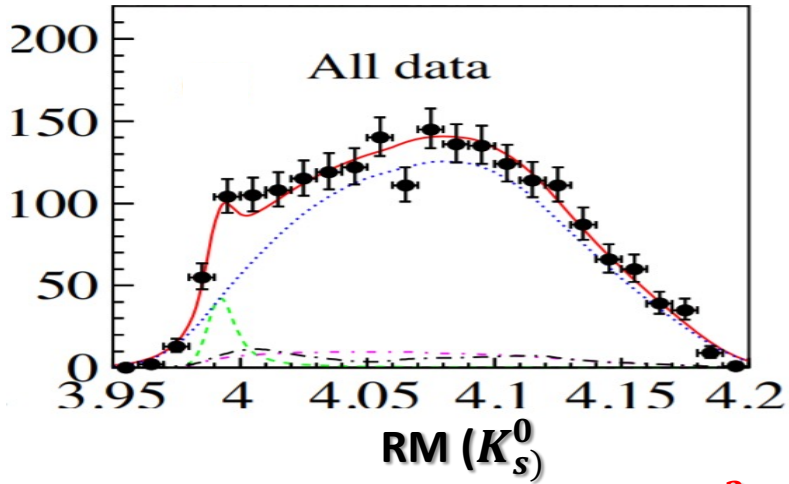
PRL126(2021)102001



- M=$(3985.2^{+2.1}_{-2.0}\pm1.7)$ MeV/c^2
- Γ =$(13.8^{+8.1}_{-5.2}\pm4.9)$ MeV

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

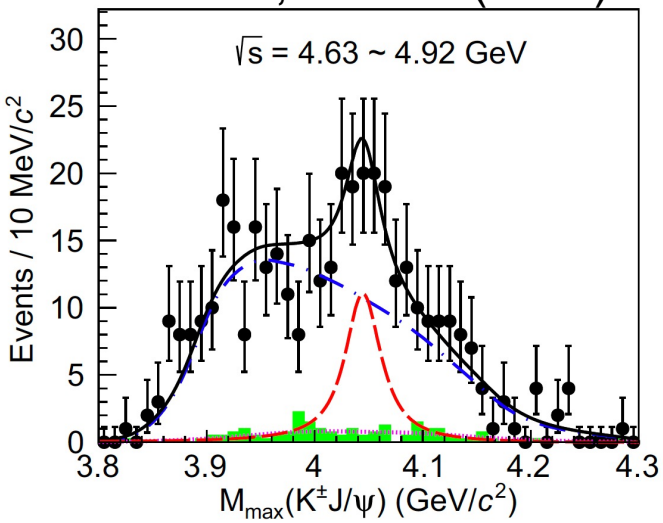
PRL129(2022)112003



- M=$3992.2 \pm 1.7 \pm 1.6)$ MeV/c^2
- Γ =$(7.7^{+4.1}_{-3.8}\pm4.3)$ MeV

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

PRL131, 211902 (2023)

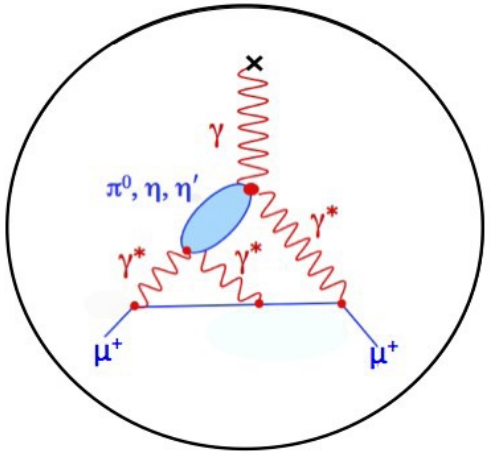


Not significant !

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

LHCb: PRL127, 082001 (2021)

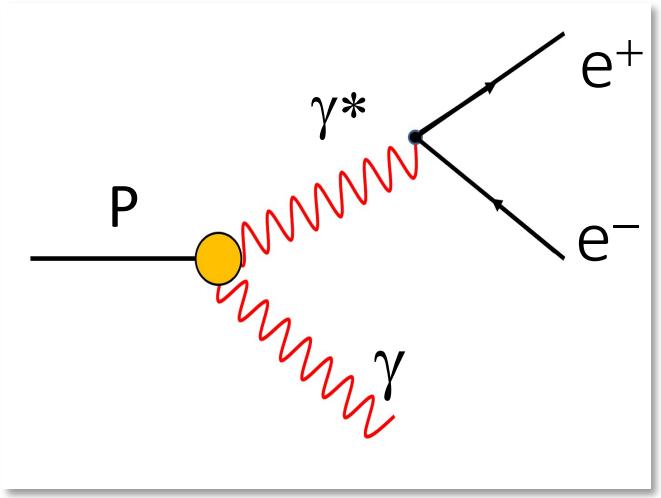
Pseudoscalar meson TFF



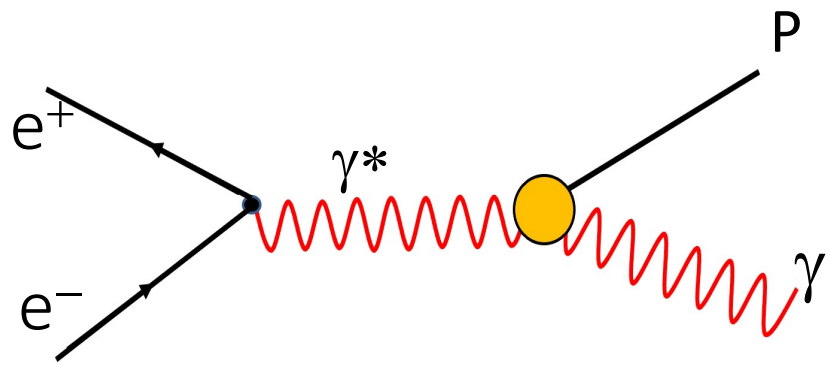
HLbL contributions

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

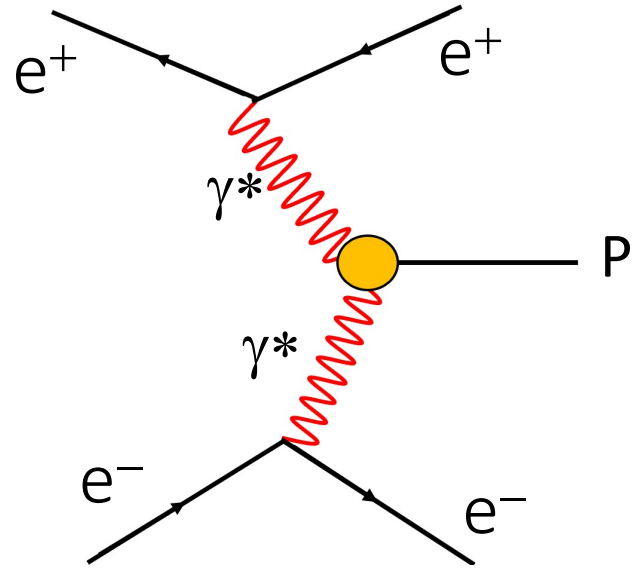
Pseudoscalar TFFs are experimentally accessible in three different processes



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



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

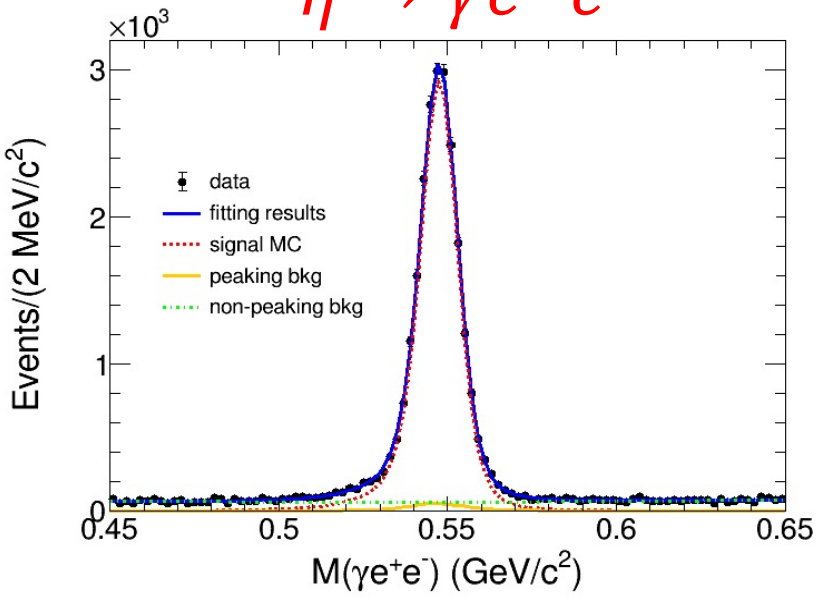


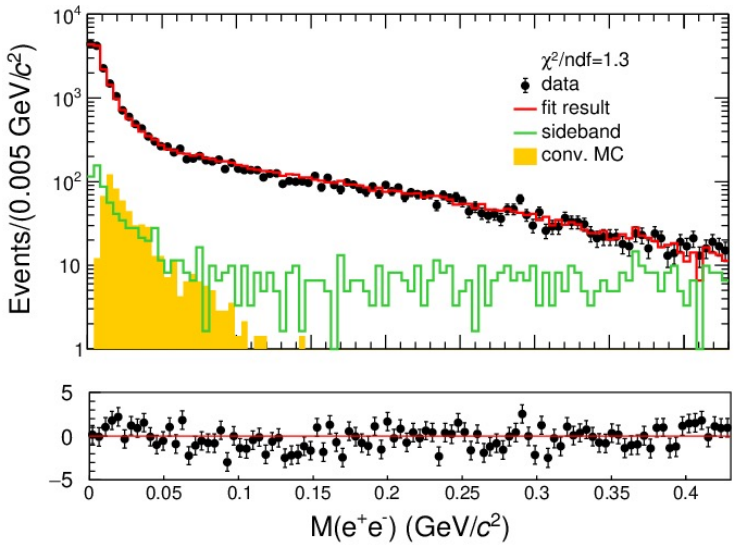
Two photon process

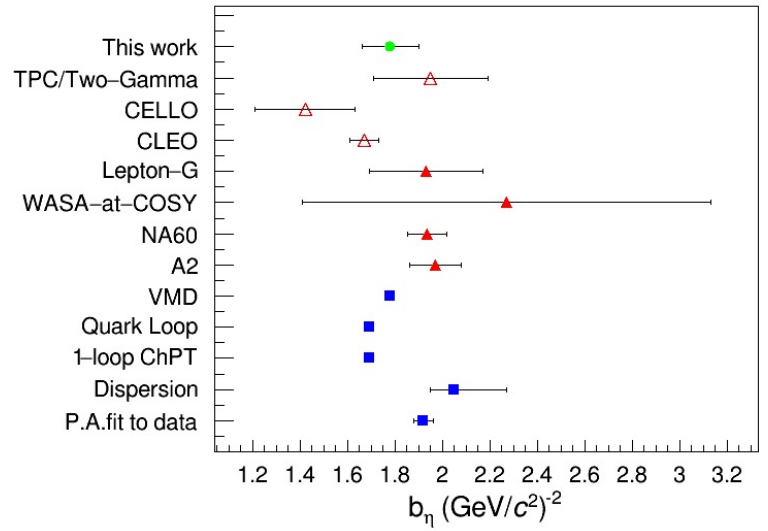
Single Dalitz decays $\eta/\eta' \to \gamma e^+e^-$

Phys. Rev. D109, 072001 (2024)

$\eta \to \gamma e^+ e^-$

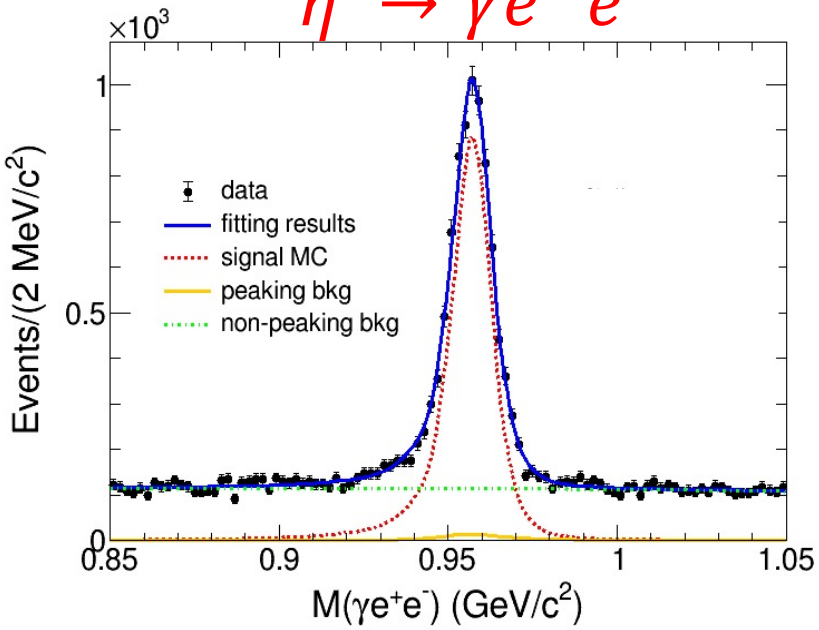


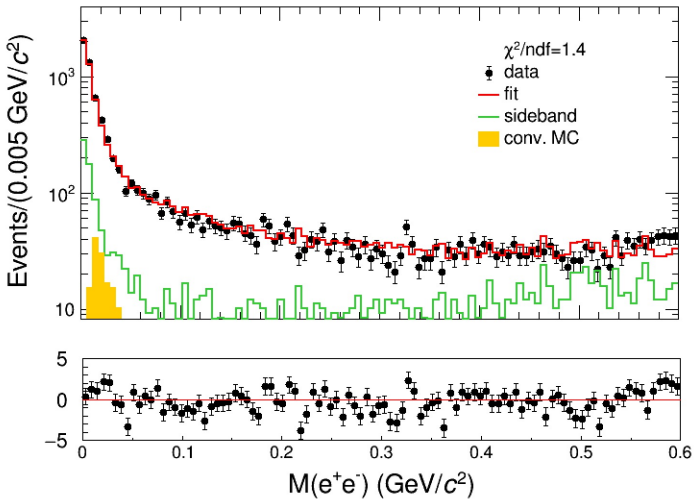


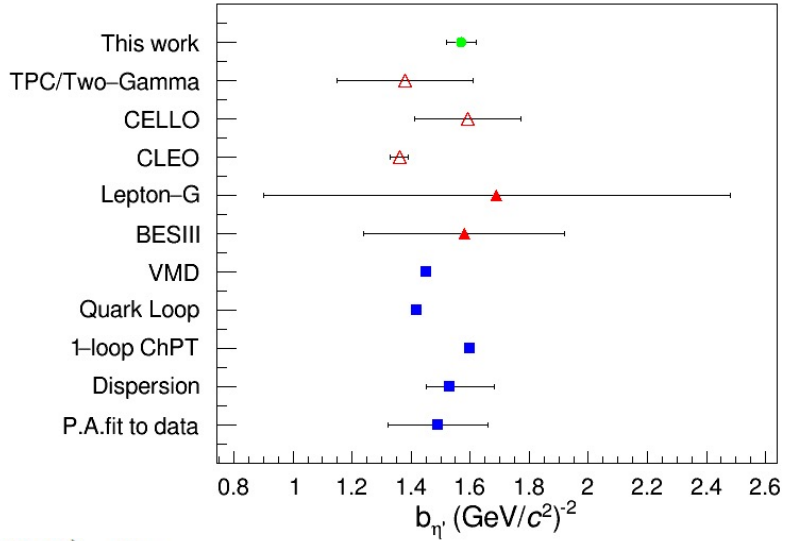


$$R_\eta = (0.645 \pm 0.023 \pm 0.007)\ \text{fm}$$

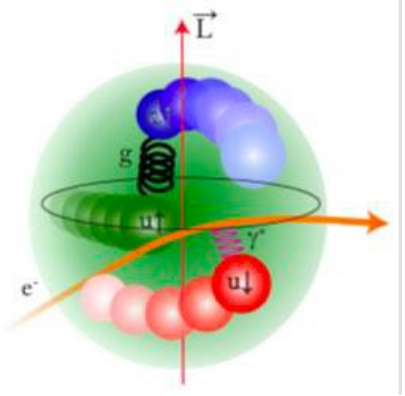
$\eta' \to \gamma e^+ e^-$







$$R_{\eta'} = (0.596 \pm 0.005 \pm 0.006)\ \text{fm}.$$



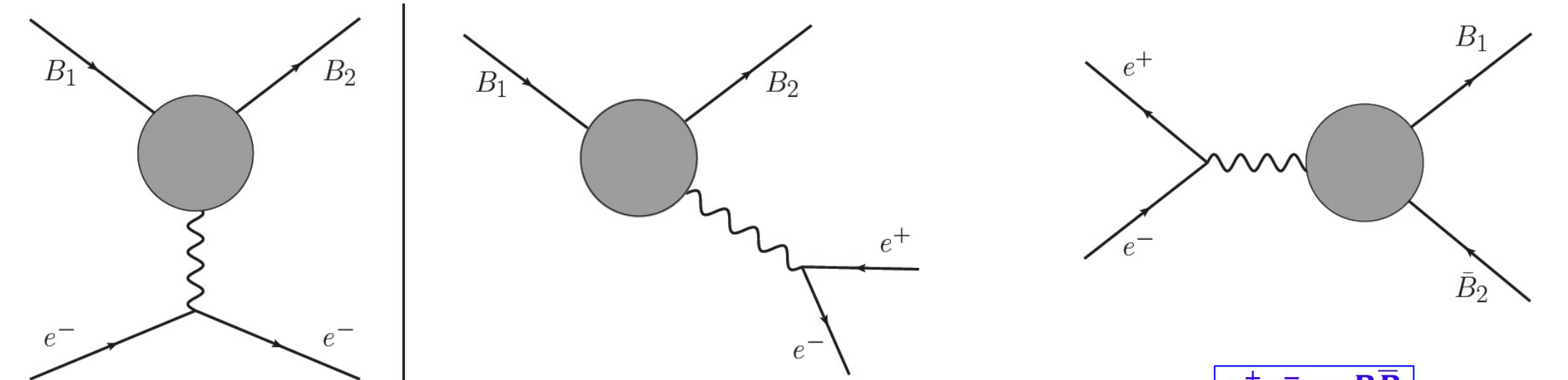
Baryon Form Factors

Space-like
$q^2 < 0$

Time-like
$q^2 > 0$

Low-q^2

High-q^2



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

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

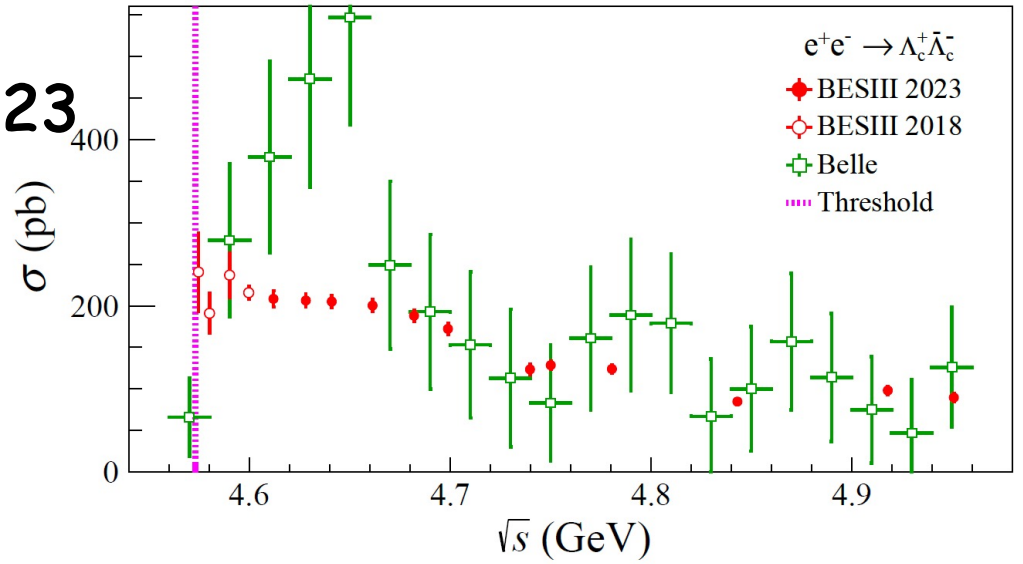
$e^+e^- \to B\bar{B}$
$\bar{B}B \to e^+e^-$
BES III
BELLE II
PANDA

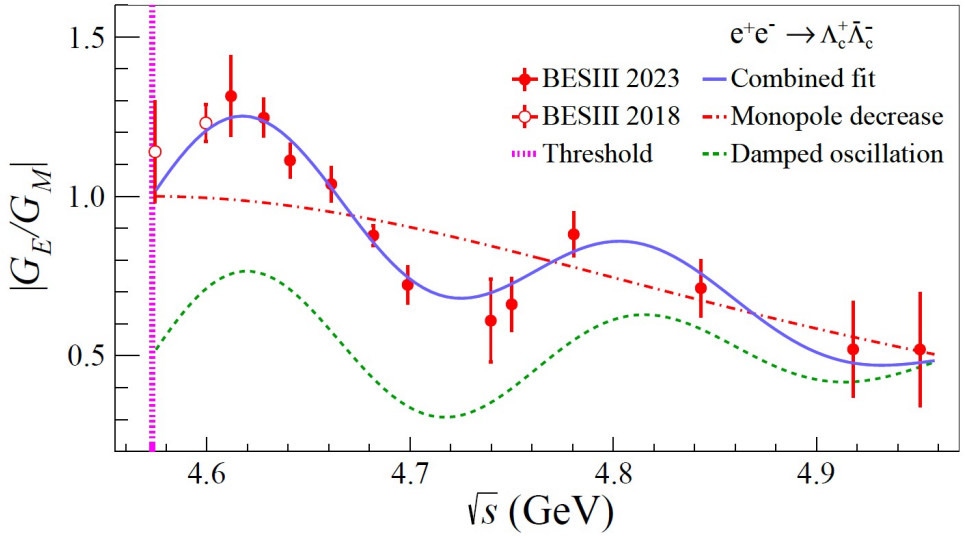
Oscillation of FF of Charm Λ_c

- 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





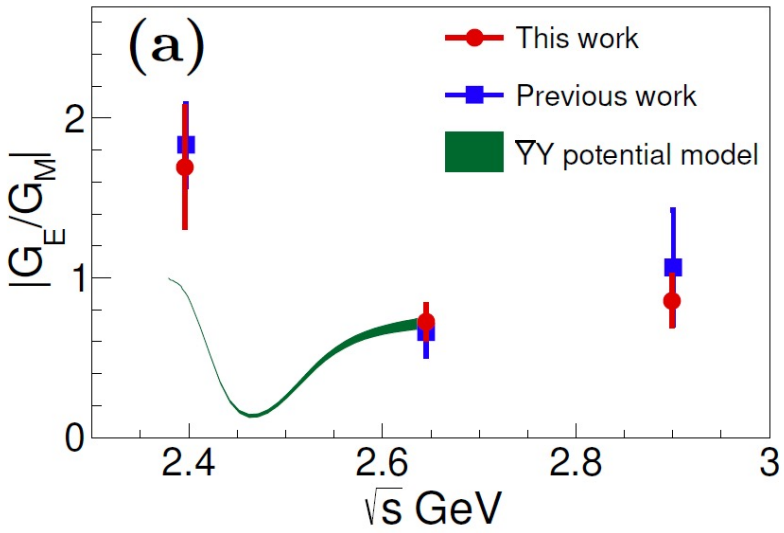
BESIII:
Phys. Rev. Lett. 120, 132001 (2018)
Phys. Rev. Lett. 131, 191901
Belle:
Phys. Rev. Lett. 101, 172001 (2008)

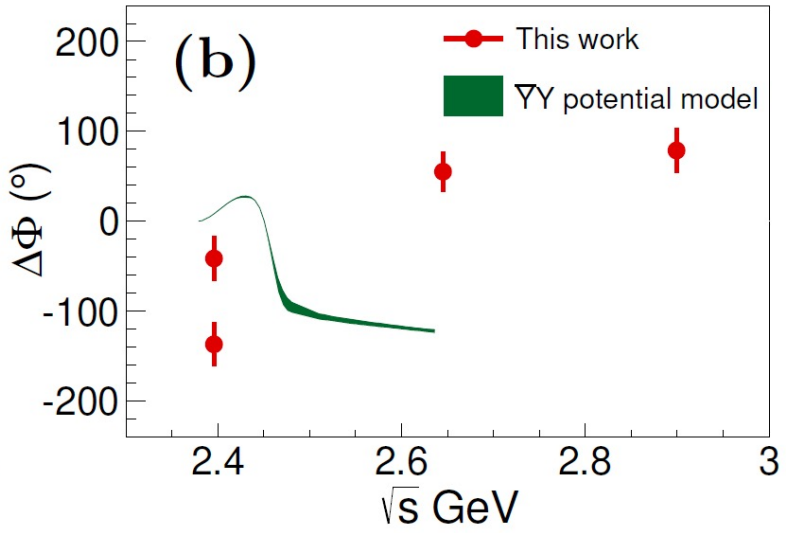
Σ^+ and Λ Form Factors

$e^+e^- \rightarrow \Sigma^+\Sigma^-$

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

e+e- → YY-bar:
Haidenbauer *et al.,* Phys. Rev. D103, 014028 (2021)

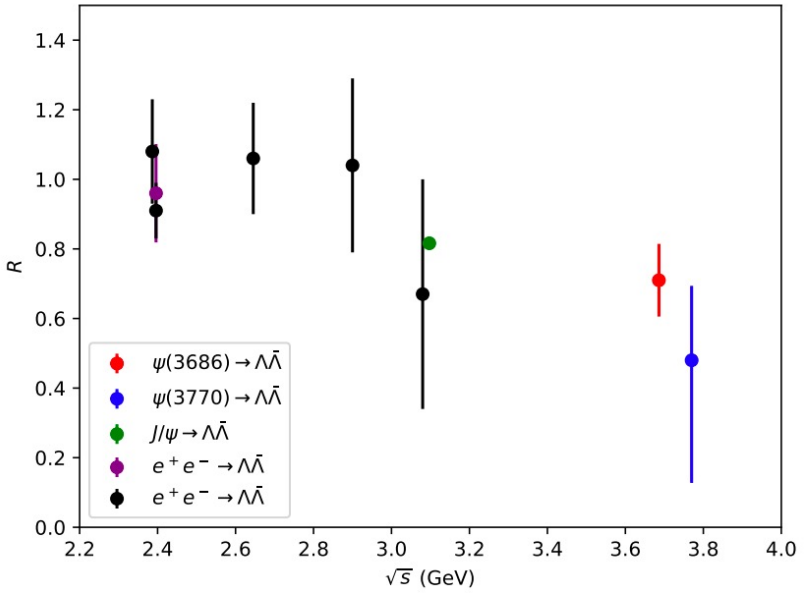


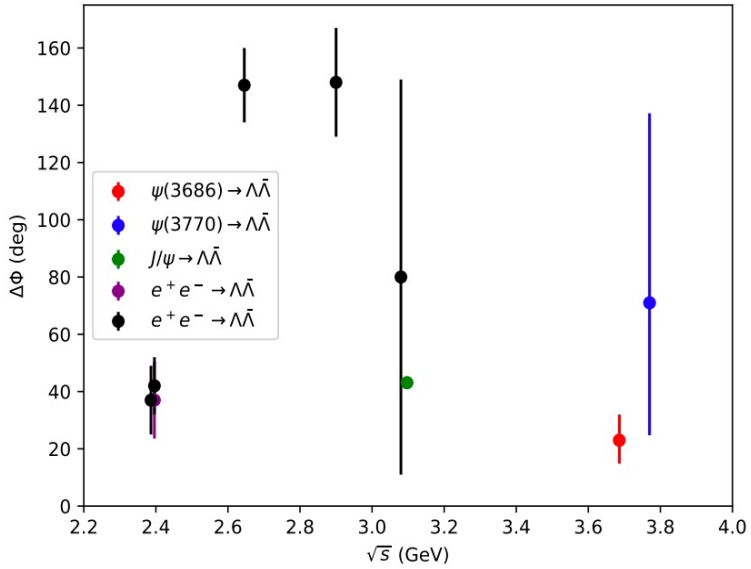


$e^+e^- \rightarrow \Lambda\ \bar{\Lambda}$

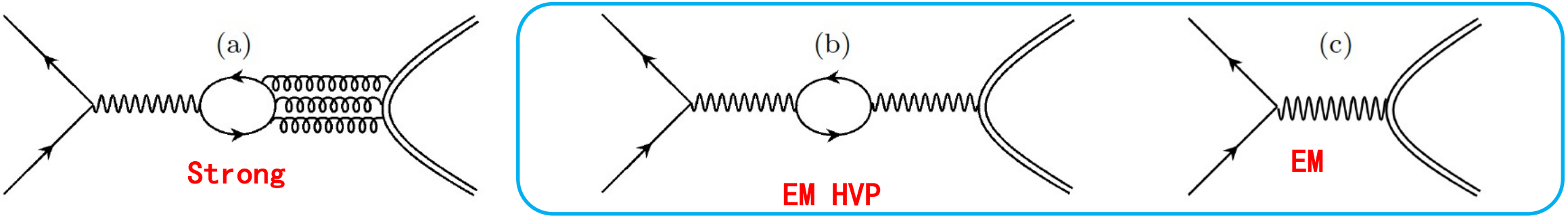
BESIII:
Phys. Rev. Lett. 123, 122003 (2019)
Nature Phys. **15**, p. 631-634 (2019)
JHEP10(2023)081
Phys. Rev. D 105, L011101 (2020)

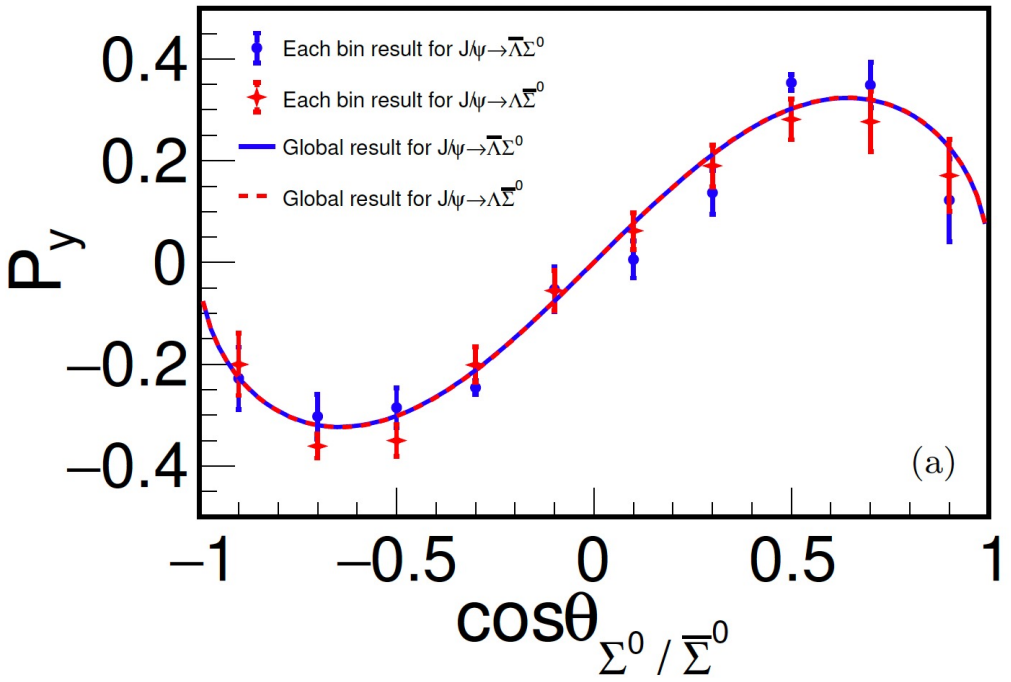
Picture credit Michael Papenbrock





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





First measurements:

$\Delta\phi_1 = 1.011 \pm 0.094 \pm 0.010$

$\Delta\phi_2 = 2.128 \pm 0.094 \pm 0.010$

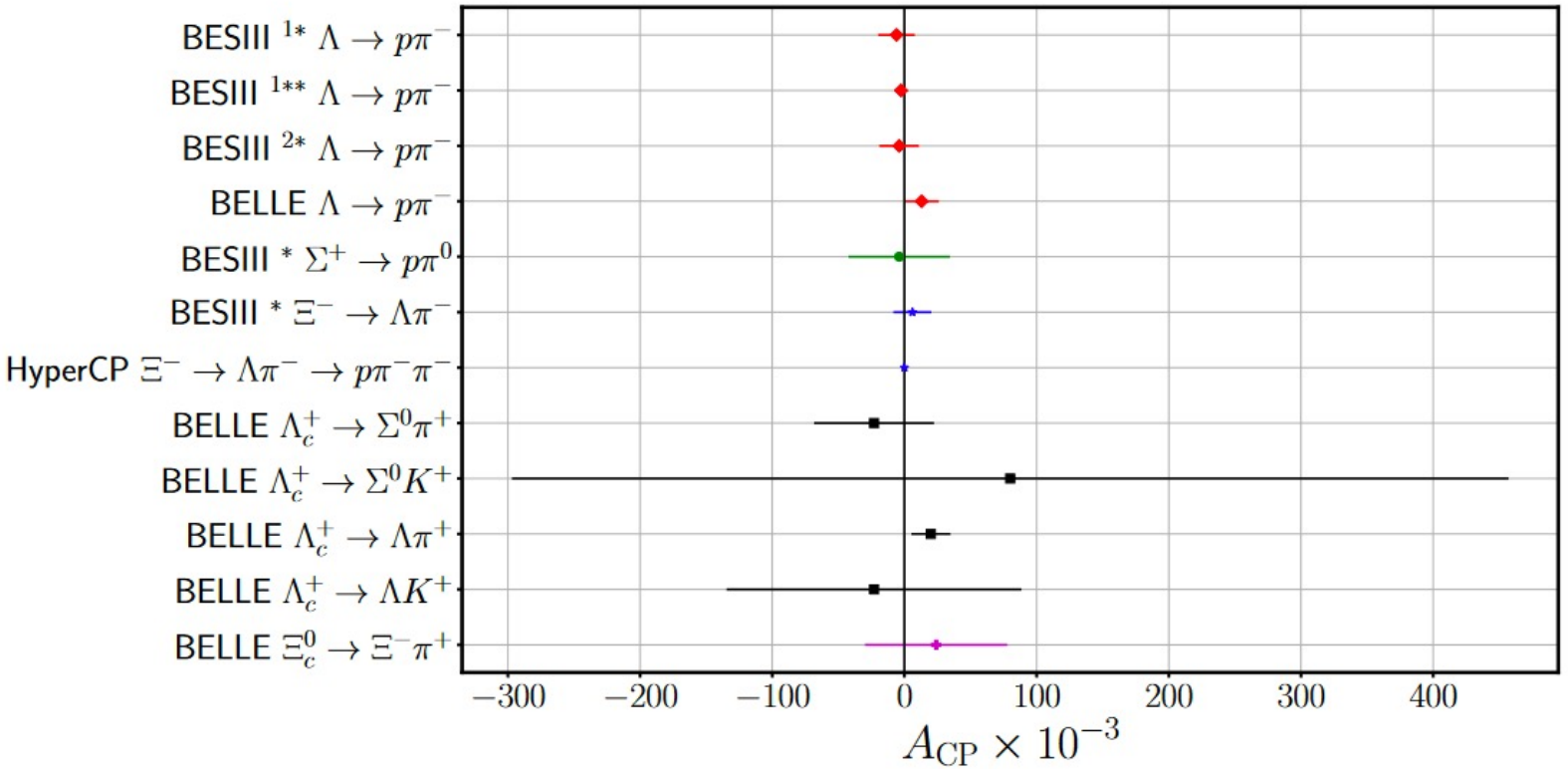
$|G_E/G_M| = 0.086 +- 0.029 +- 0.010$

$\Delta\phi_1 + \Delta\phi_2 = (3.139 \pm 0.133 \pm 0.014)$

arXiv:2309.04139, submitted to Nature Physics

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.

Search for baryon number violating $\Lambda\ \bar{\Lambda}$ oscillations

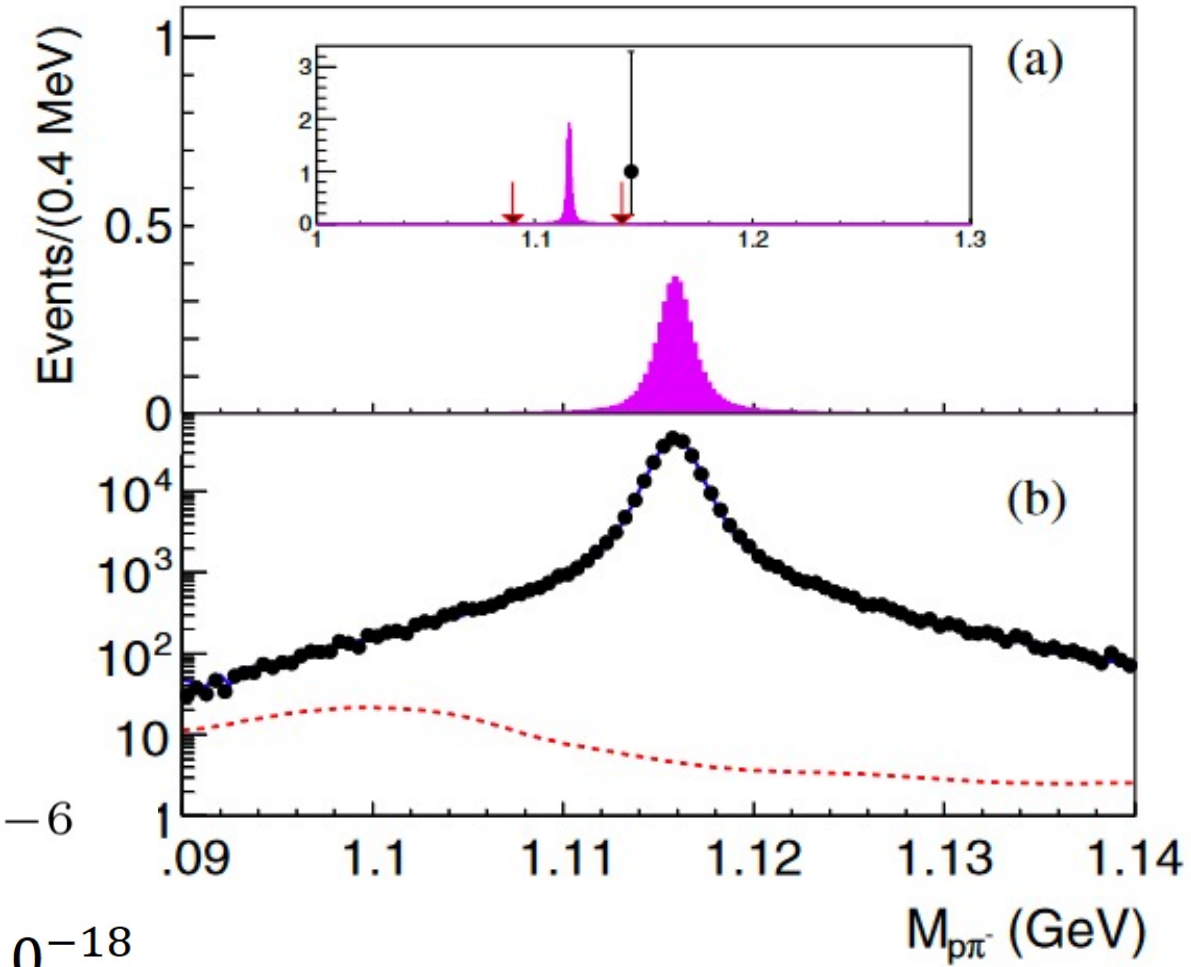
Origin of M-antiM asymmetry

Sakharov criteria:

violation of C) and symmetry;
violation of baryon number conservation;
deviation from thermal equilibrium

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

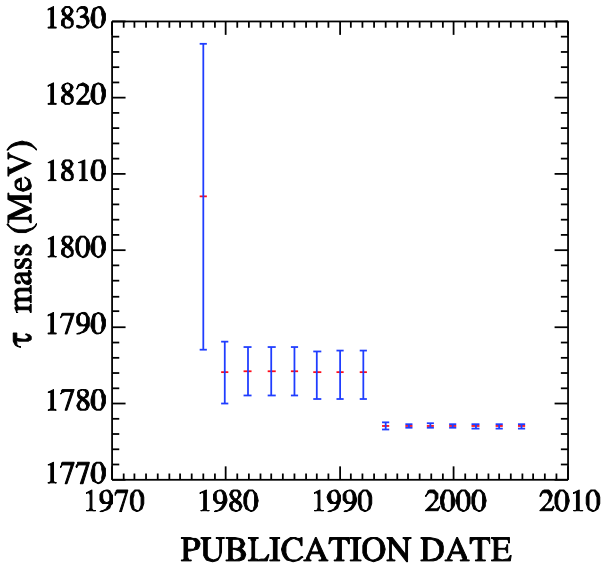
$$\rightarrow \text{oscillation parameter } \delta m_{\Lambda\bar{\Lambda}} < 3.8 \cdot 10^{-18}$$

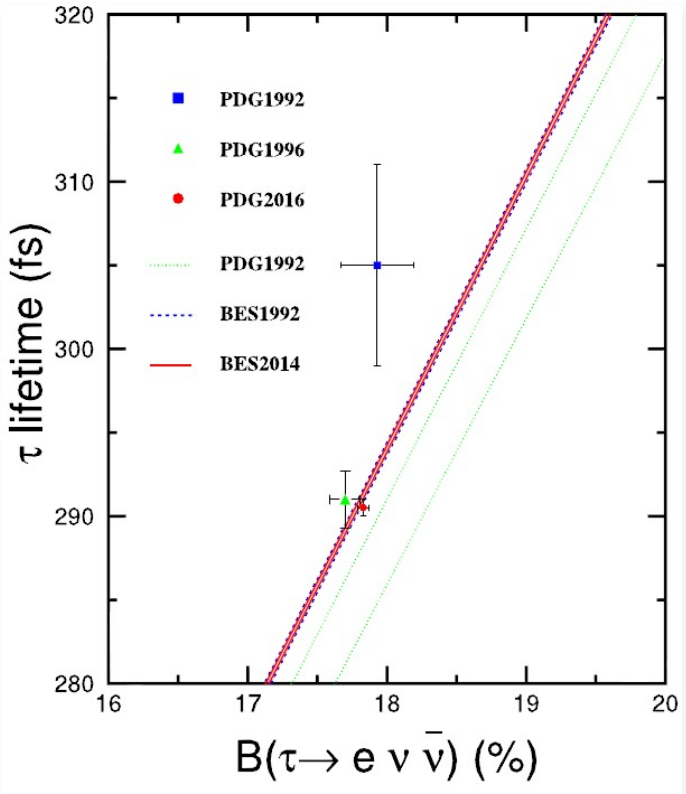


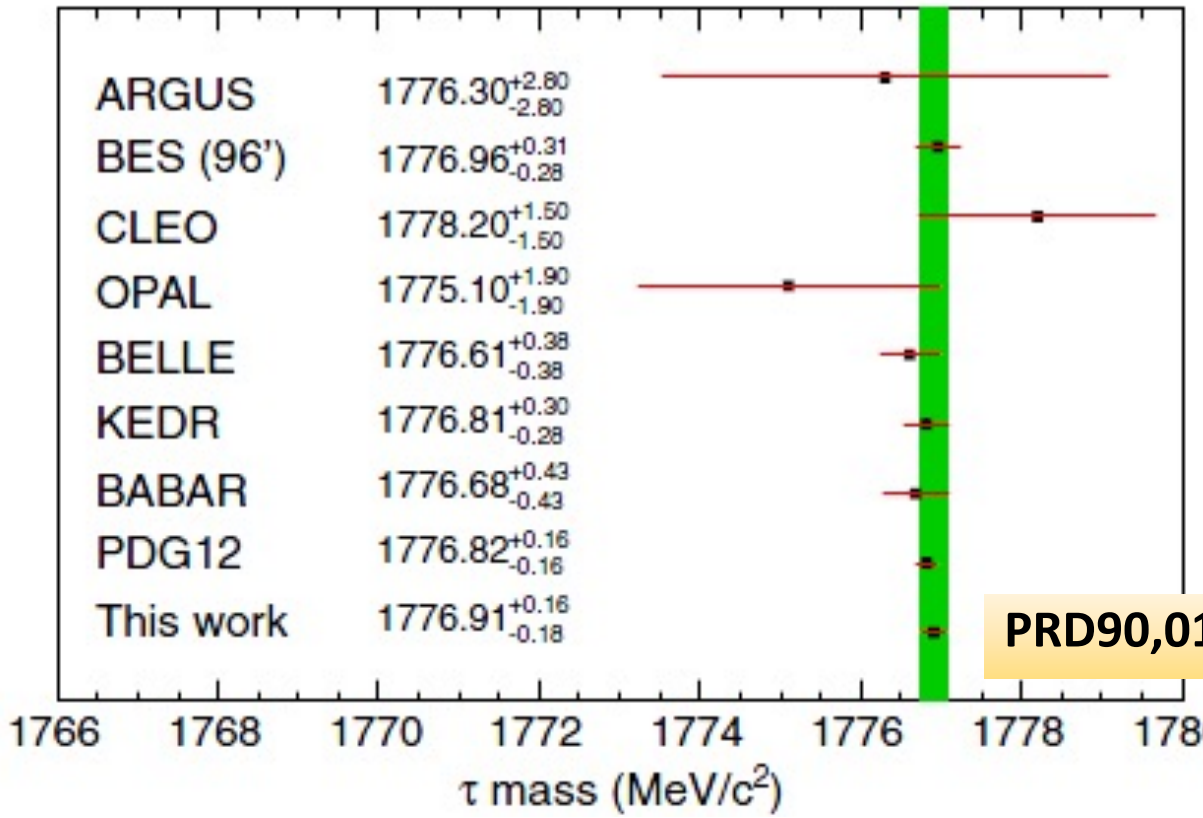
Phys. Rev. Lett. 131, 121801 (2023)

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

τ mass and LUT at BESIII







PRD90,012001(2014)

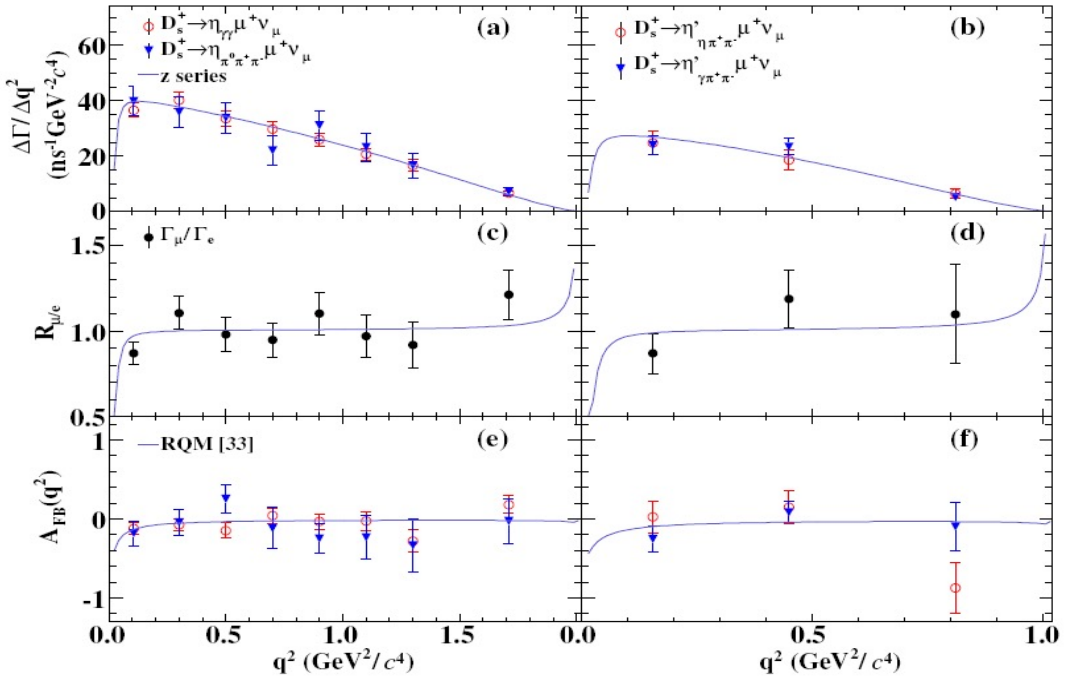
$$m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13}\ MeV$$

$$\frac{g_\tau}{g_\mu} = 1.0016 \pm 0.0042$$

- A fine scan was performed ~136pb^{-1}
- Expected to be < 0.1 MeV

LUT tests in Charm decays at BESIII

$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$ PRL132,091802(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

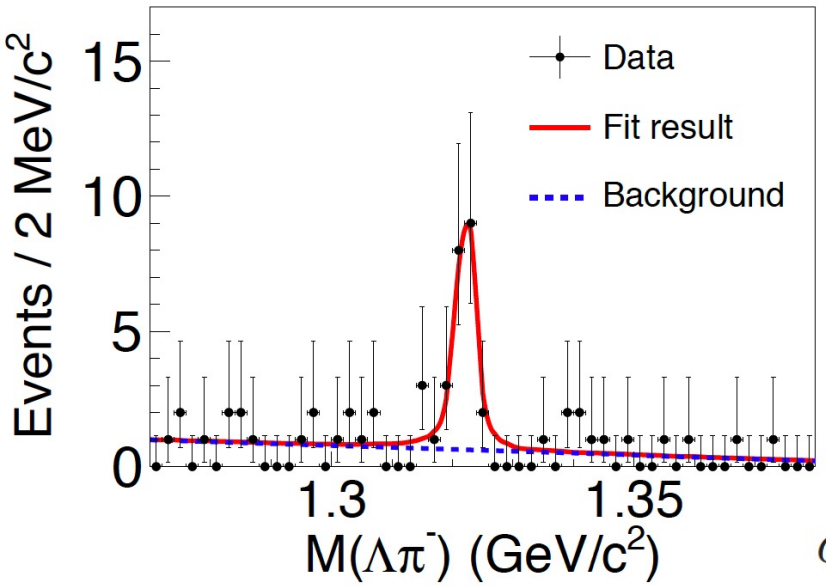
	BF ratios		References
μ/e	$D^0 \to K^-$	$0.978 \pm 0.007 \pm 0.012$	PRL122(2019)011804
	$D^0 \to \pi^-$	$0.922 \pm 0.030 \pm 0.022$	PRL121(2018)171803
	$D^0 \to \rho^-$	0.90 ± 0.11	PRD104(2021)L091003
	$D^+ \to \bar{K}^0$	1.00 ± 0.03	EPJC76(2016)369
	$D^+ \to \pi^0$	$0.964 \pm 0.037 \pm 0.026$	PRL121(2018)171803
	$D^+ \to \omega$	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

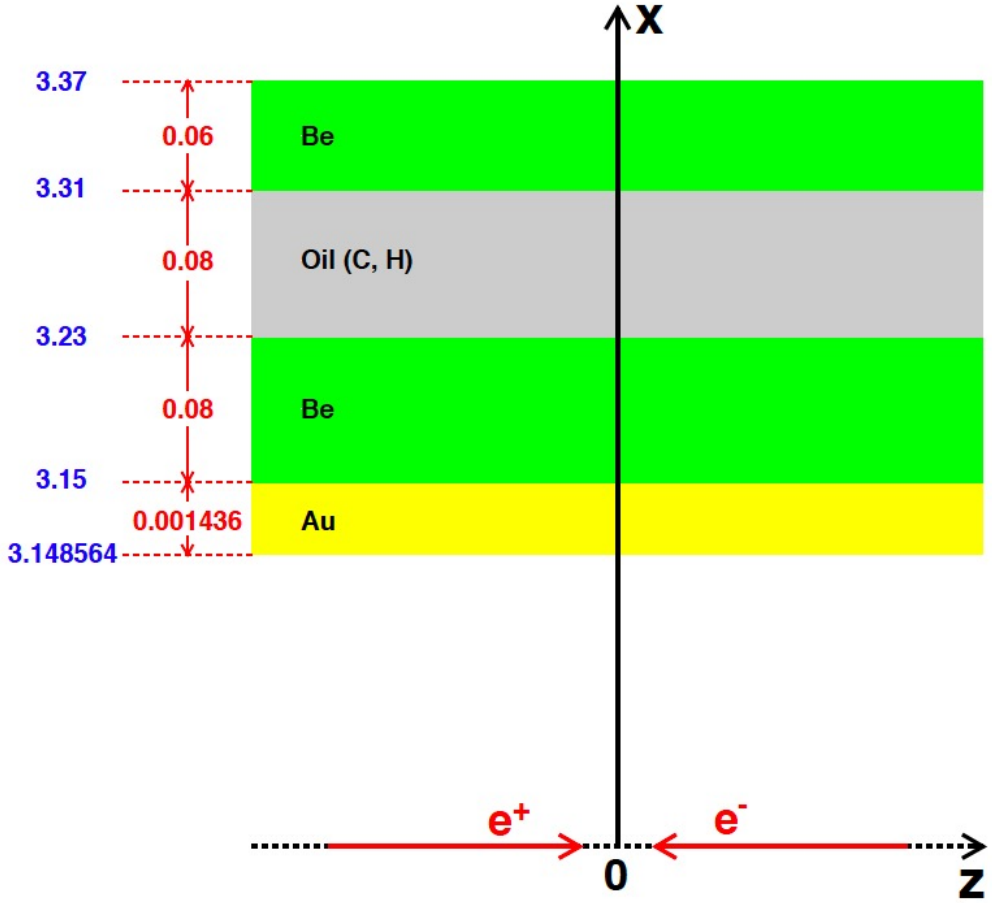
No clear deviation is found!

Hyperon-nucleon interactions

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

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



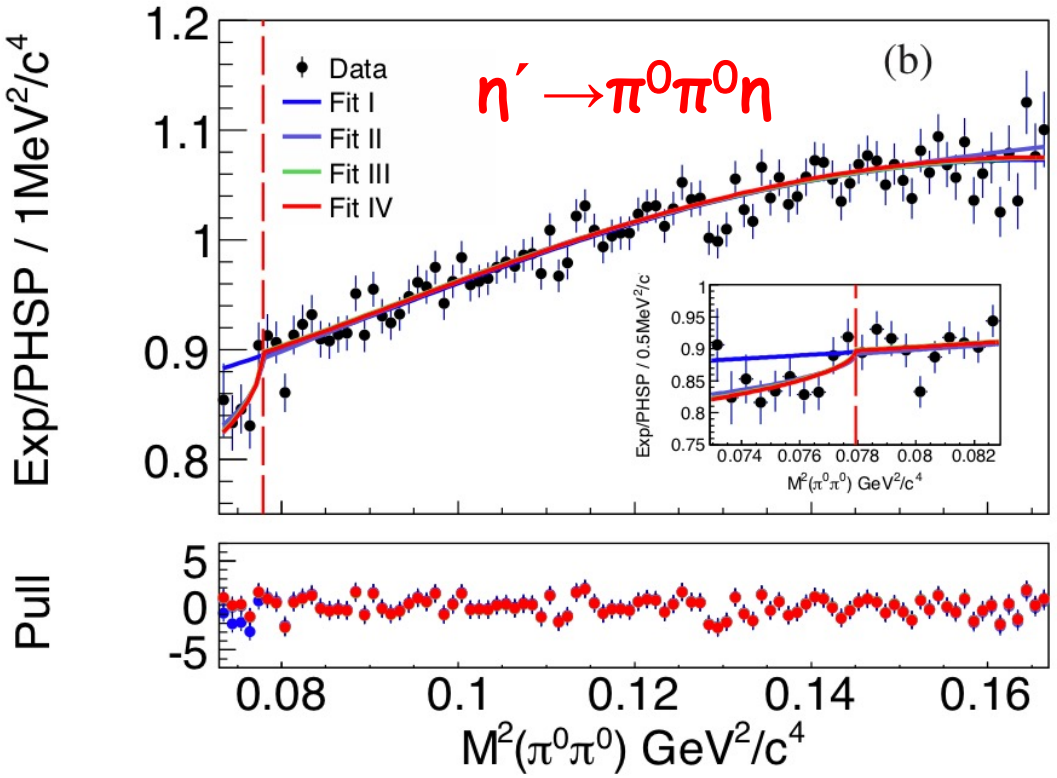


$$\sigma(\Xi^0 + {}^9\mathrm{Be} \rightarrow \Xi^- + p + {}^8\mathrm{Be}) = (22.1 \pm 5.3_{\mathrm{stat}} \pm 4.5_{\mathrm{sys}})\ \mathrm{mb}$$

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

PRL130,251902(2023)

Meson-meson interactions



- **Non-relativistic effective field theory**

  B. Kubis and S. P. Schneider, EPJC 62, 511 (2009)

  - Investigation on ππ and πη FI
  - Cusp effect is sizeable in this decay

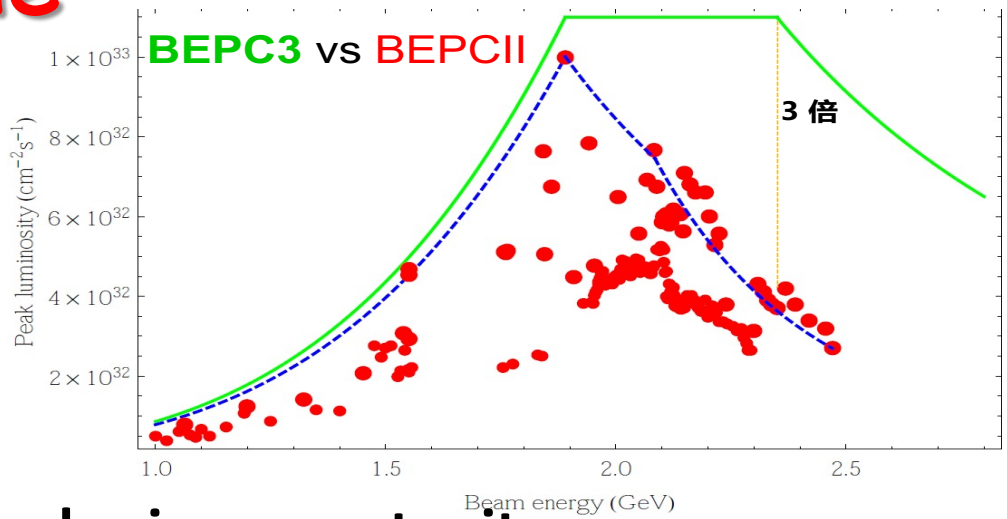
- **Evidence of the cusp effect @ 3.5σ !**

PRL130,081901(2023)

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

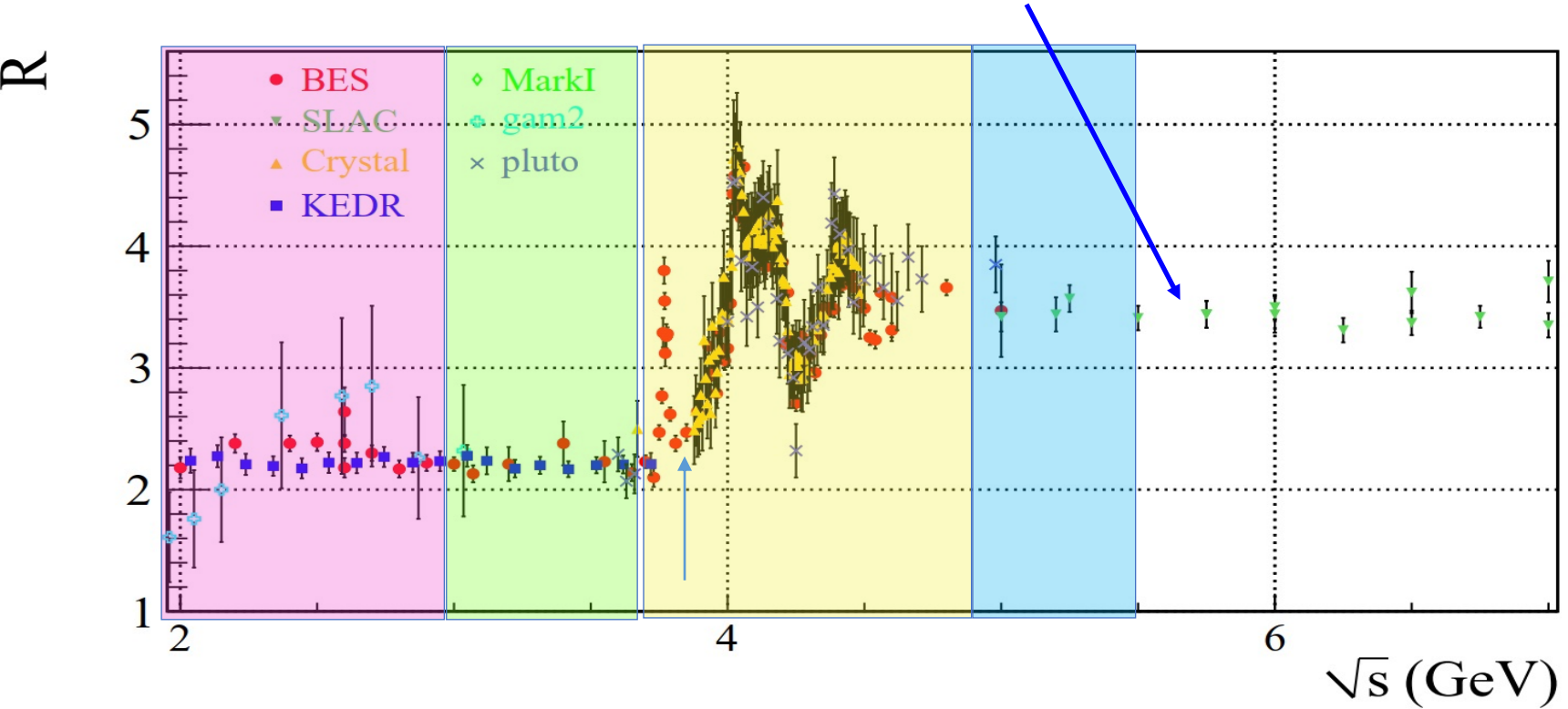
Plan of BEPCII/BESIII upgrade

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**

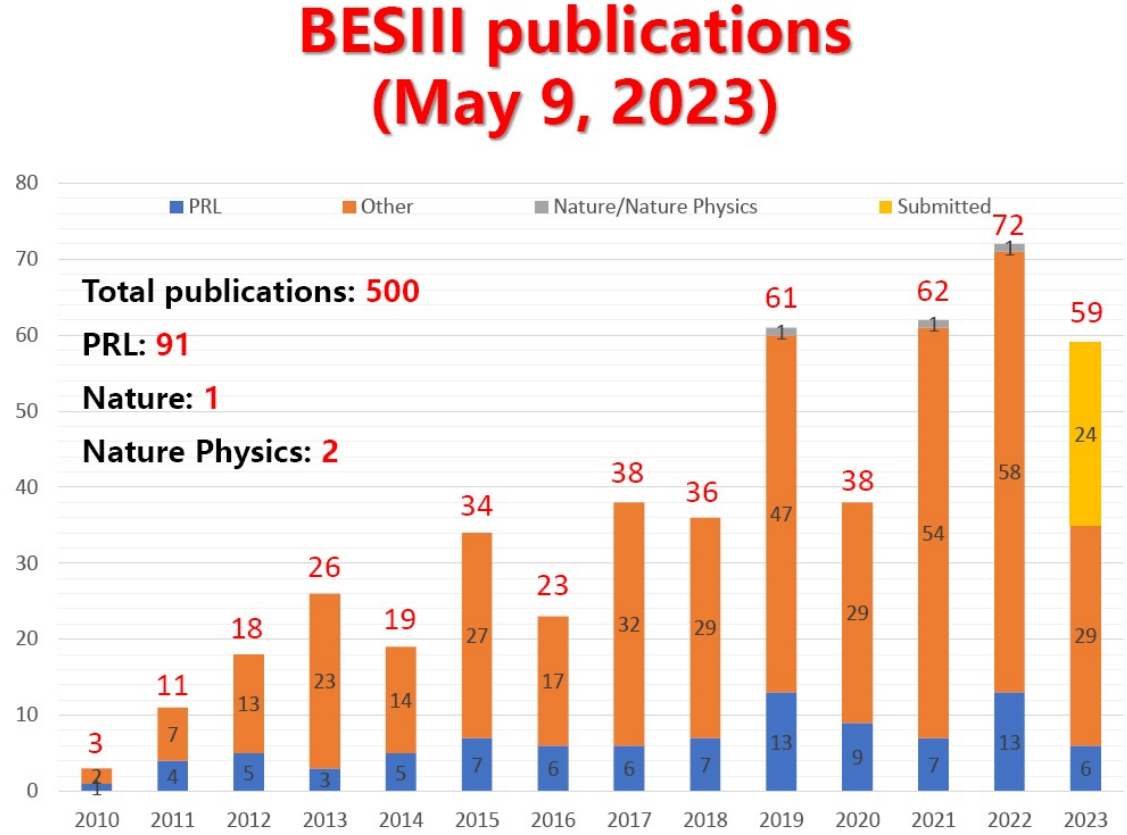
Extend the maximum E_{cm} up to 5.6 GeV → more physics opportunity



Nearly blank at 5-7GeV

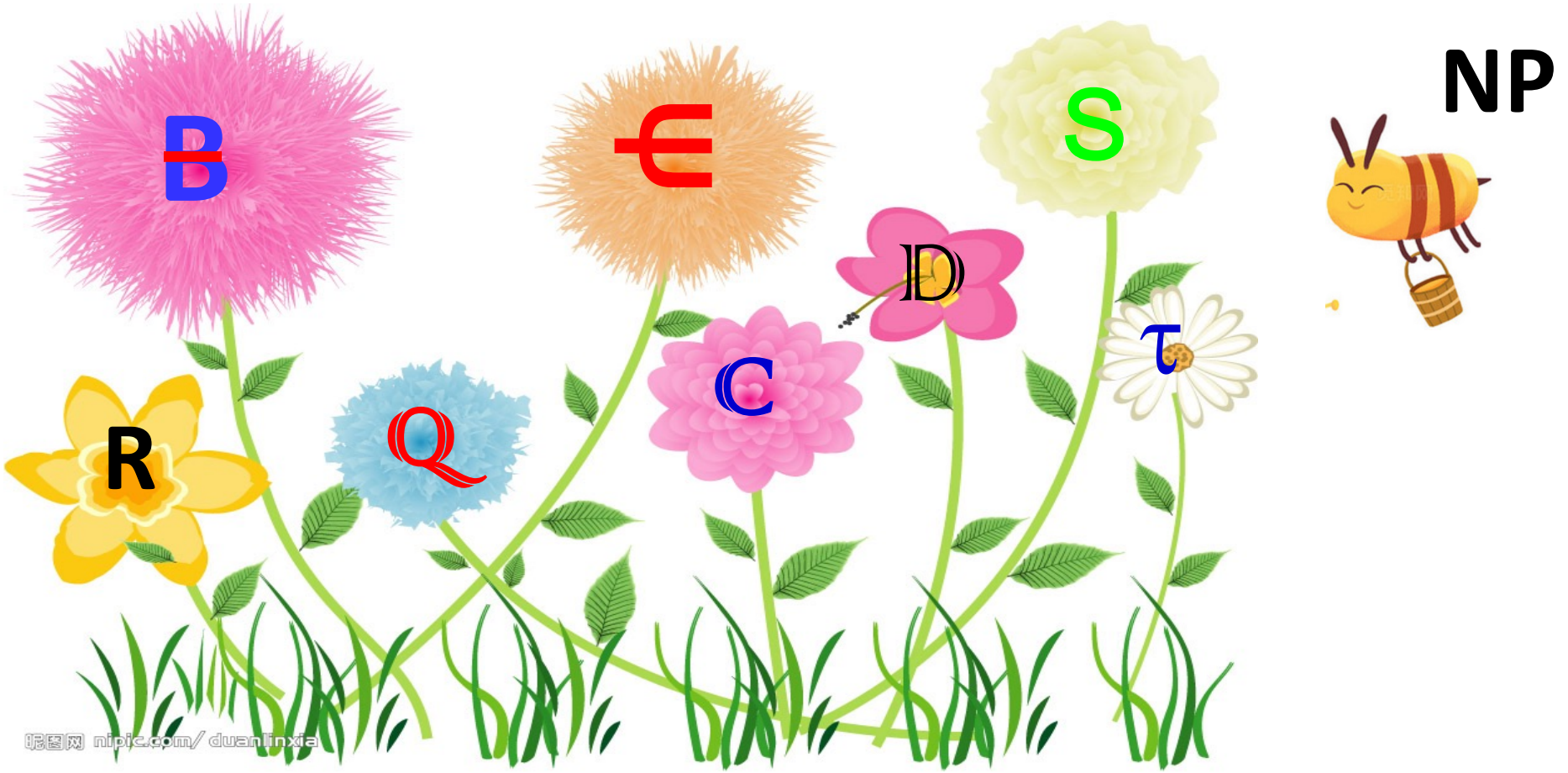
Summary & Outlook

- 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) !

More important results are expected from BESIII !



Many thanks for your attention !