Recent results from BESIII Experiment
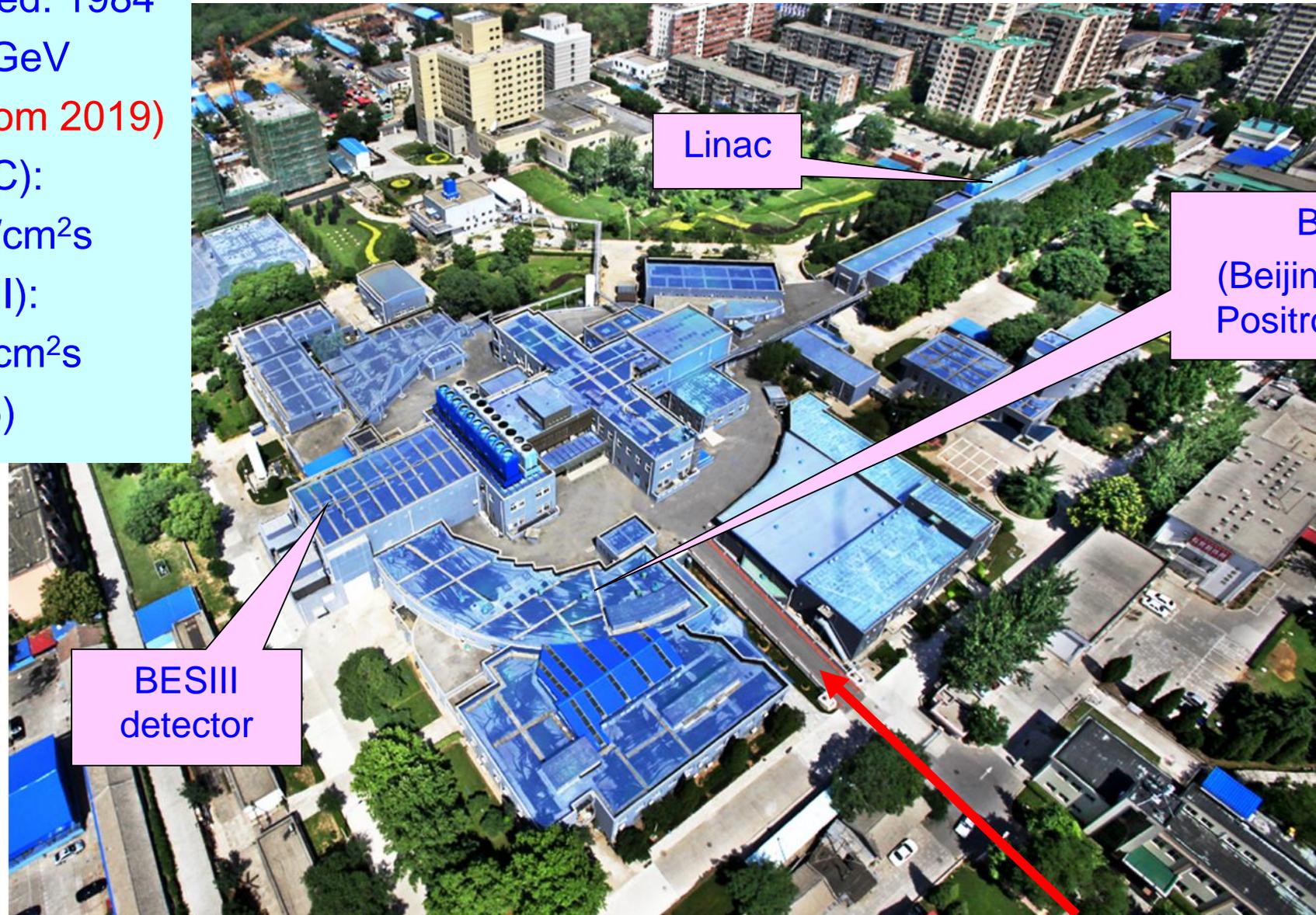
Chang-Zheng Yuan（苑长征）

IHEP, Beijing

（for the BESIII Collaboration）

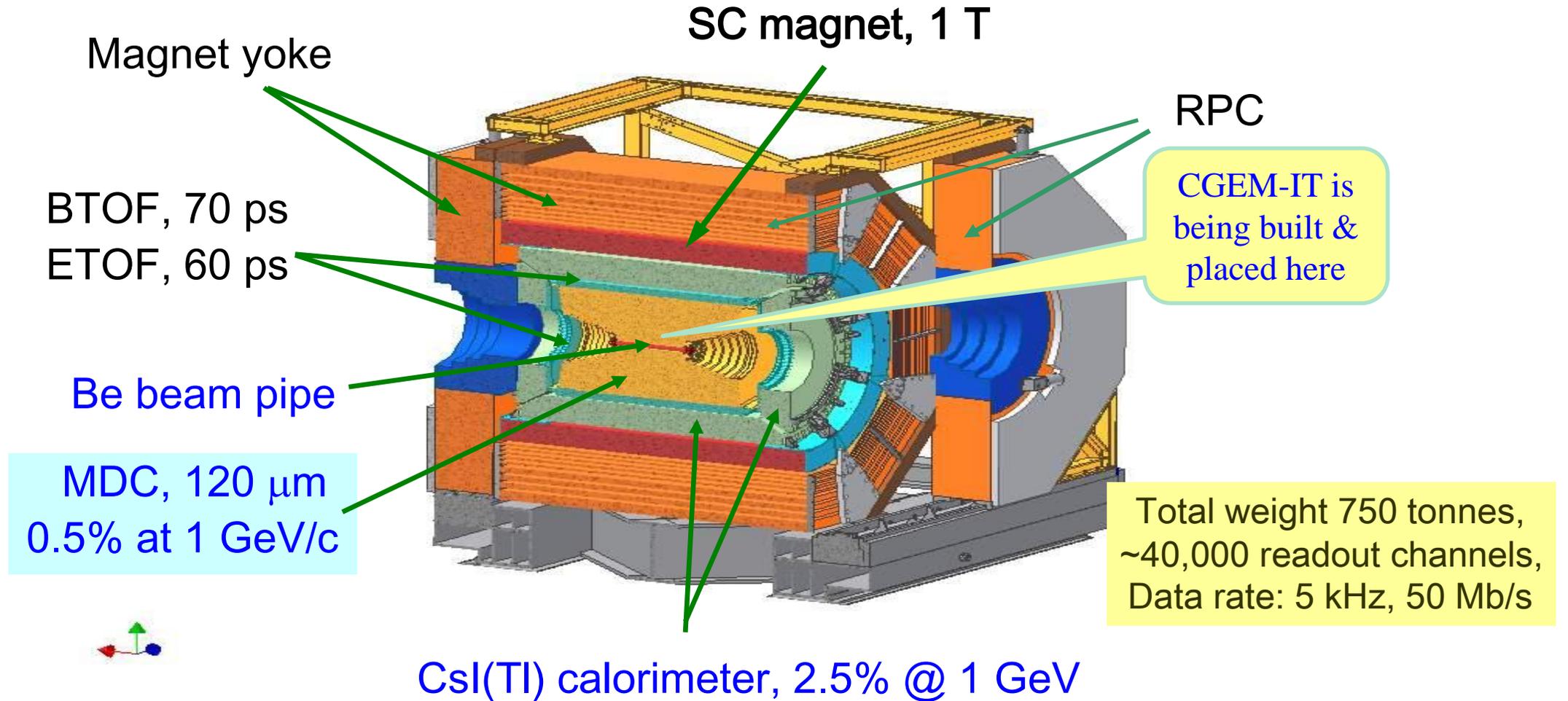Lattice 2019, Wuhan, June 16 - 22, 2019

Beijing Electron Positron Collider (BEPC)

- Construction started: 1984

  Ecm = 2.0-4.6 GeV

  (2.0-4.9 GeV from 2019)

- 1989-2005 (BEPC):

  $L_{peak}=1.0 \times 10^{31}$ /cm^{2}s

- 2008-now (BEPCII):

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

  (Apr. 5, 2016)

Linac

BEPCII
(Beijing Electron-Positron Collider)

BESIII
detector

IHEP campus
19B Yuquan Rd.
Beijing, China

BESIII detector

Magnet yoke

SC magnet, 1 T

RPC

BTOF, 70 ps
ETOF, 60 ps

CGEM-IT is being built & placed here

Be beam pipe

MDC, 120 μm
0.5% at 1 GeV/c

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

CsI(Tl) calorimeter, 2.5% @ 1 GeV

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

Can cover 0-4.9 GeV from direct annihilation or ISR

4130, 4160, 4190, 4200, 4210, 4220, 4236, 4245, 4270, 4280, 4290, 4315, 4340, 4380, 4400, 4440

7.7 fb^{-1}

PDG 2015

u, d, s

3 loop pQCD

Naive quark model

2175
0.1 fb^{-1}

Energy Scan 526 pb^{-1}

Inclusive measurements

J/ψ
10×10^9

4040
0.5 fb^{-1}

4230+4260
1.9 fb^{-1}

4420
1.0 fb^{-1}

ψ'
0.5×10^9

4600
0.6 fb^{-1}

ψ''
2.9 fb^{-1}

4180
3.0 fb^{-1}

4360
0.5 fb^{-1}

R Scan 1.3 fb^{-1} (130 points)

- ▲ Mark-I
- ▼ Mark-I + LGW
- ■ Mark-II
- ● PLUTO
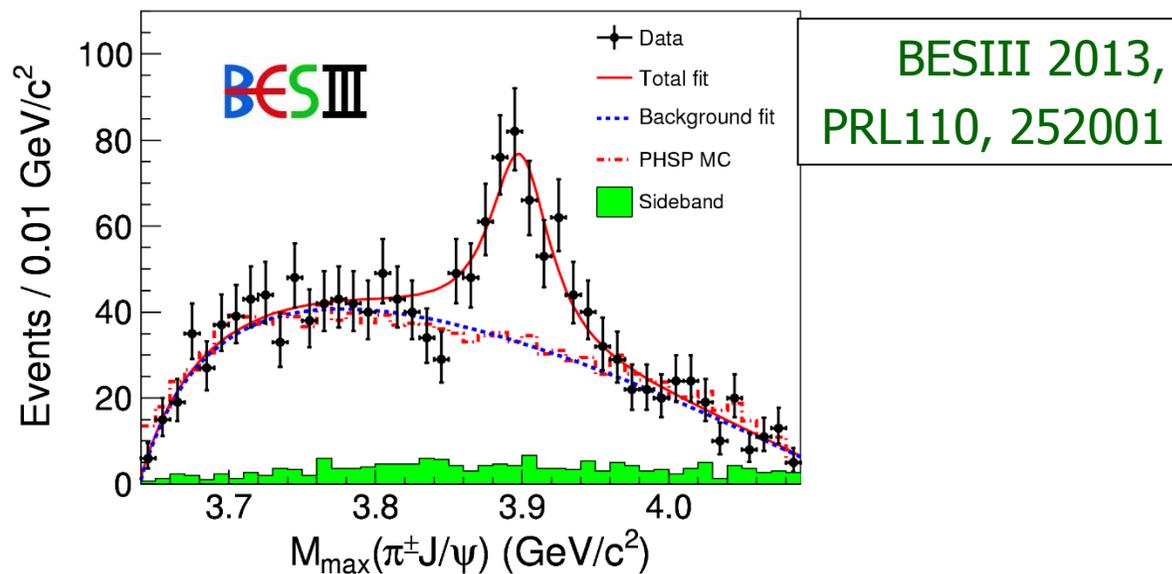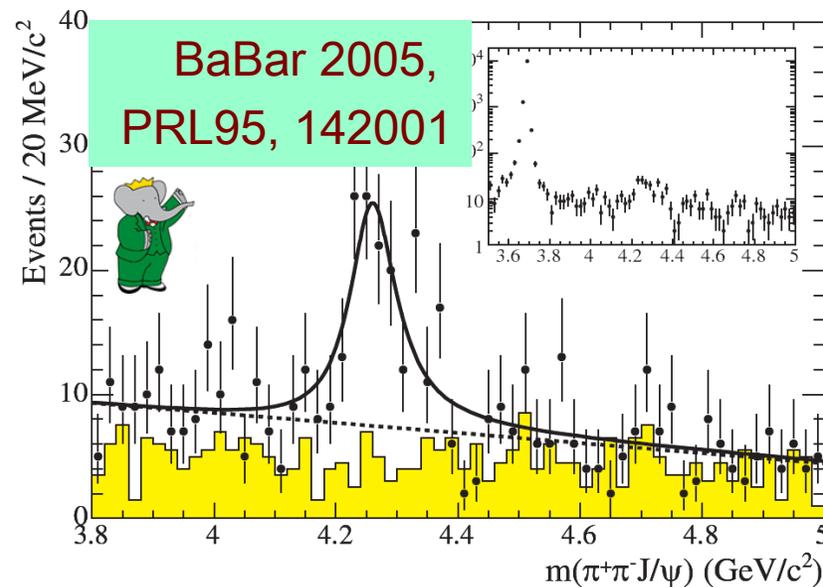- ○ DASP
- ☆ Crystal Ball
- ★ BES

$\sqrt{s}$ [GeV]

4

Selected topics

- XYZ particles: X(3872), Y(4260), Zc(3900)

- Light hadrons: glueballs & more

- Charm decays: CKM, decay constants, form factors, LFU
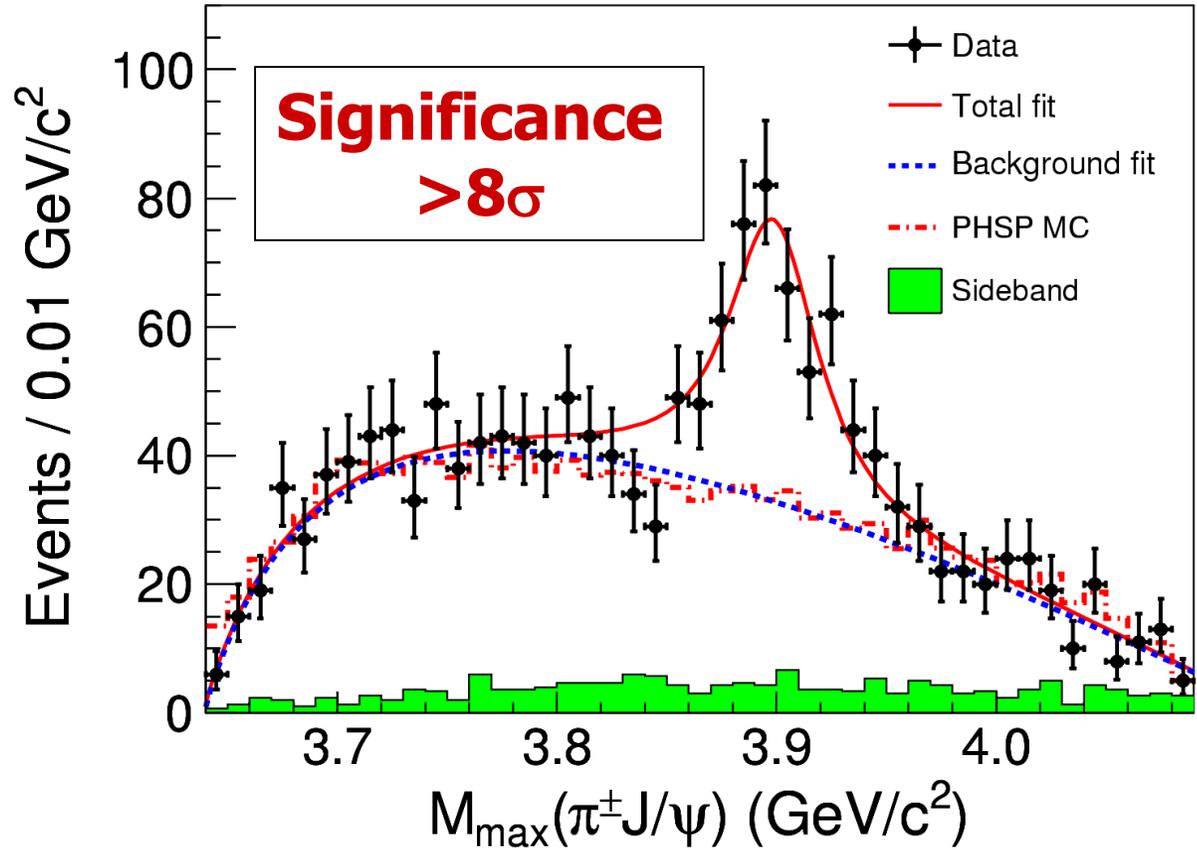
- Baryons: form factors & polarization

X(3872), Y(4260), & Z_c(3900)

Belle 2003,
PRL91, 262001

Events/0.010 GeV

M($\pi^+\pi^-l^+l^-$) − M(l^+l^-) (GeV)

BaBar 2005,
PRL95, 142001

Events / 20 MeV/c

m($\pi^+\pi^- J/\psi$) (GeV/c²)

BESIII 2013,
PRL110, 252001

Events / 0.01 GeV/c²

- Data
- Total fit
- Background fit
- PHSP MC
- Sideband

BESⅢ

$M_{max}(\pi^\pm J/\psi)$ (GeV/c²)
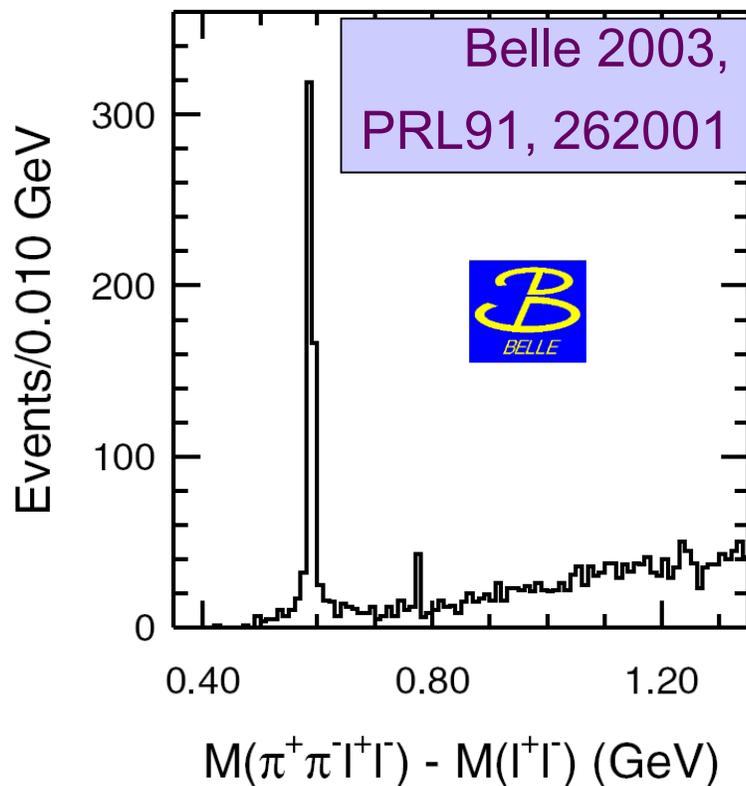
Most famous charmoniumlike states.
Good candidates for exotic states with
charm quarks.
BESIII supply crucial information!

Discovery of the $Z_c(3900)$

BES III

Significance >8σ

Data
— Total fit
---- Background fit
-·-· PHSP MC
■ Sideband

Events / 0.01 GeV/c^2

$M_{max}(\pi^\pm J/\psi)$ (GeV/c^2)

In $e^+e^- \to \pi^+\pi^- J/\psi$ events at 4.26 GeV, a particle decays into $\pi^\pm J/\psi$ is observed!

- Couples to $\bar{c}c$
- Has electric charge
- At least 4 quarks
- A tetraquark state?
  A $\overline{D}D^*$ molecule?

➢ Mass = (3899.0±3.6±4.9) MeV
➢ Width = (46±10±20) MeV
➢ Fraction = (21.5±3.3±7.5)%
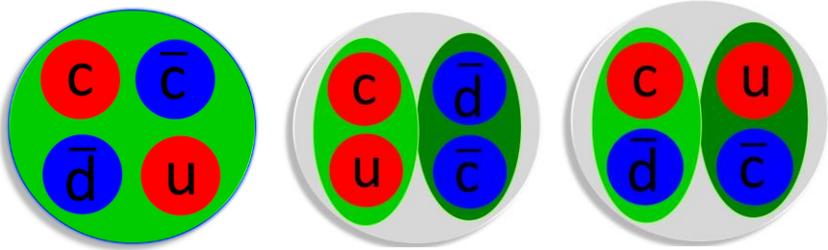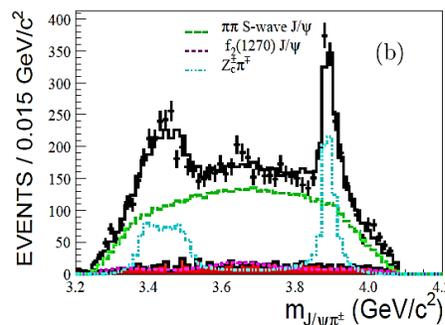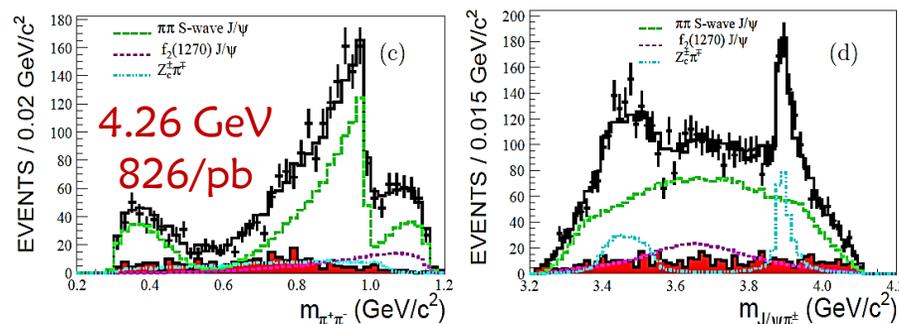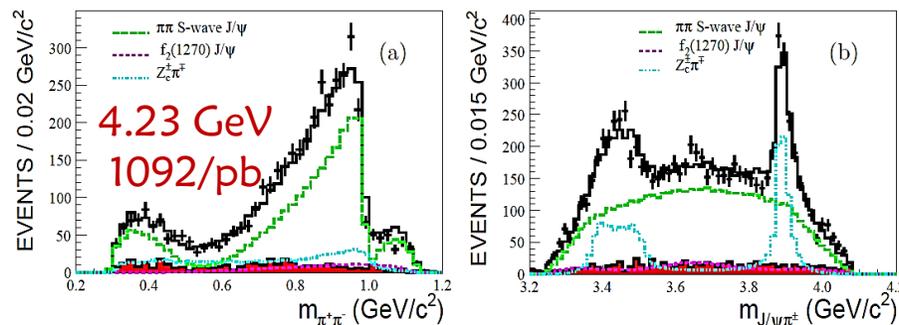
PRL110, 252001 (2013)

BES III

- $I^G = 1^+$
- $J^{PC} = 1^{+-}$
- Decay modes
  - ✓ $\pi J/\psi$
  - ✓ $\overline{D}D^*$
  - ✓ $\rho\eta_c$ (4.2σ)
  - ✓ πh_c (2.1σ)
  - ✓ Not to light hadrons
- Partner state: Z_c(4020)
  - ✓ $I^G = 1^+$; $J^{PC} = ?^{?-}$
  - ✓ Couples to πh_c and $\overline{D}^*D^*$
  - ✓ Couples possibly to $\pi\psi'$
  - ✓ M=4022.9±2.8 MeV
  - ✓ Γ=7.9±3.7 MeV
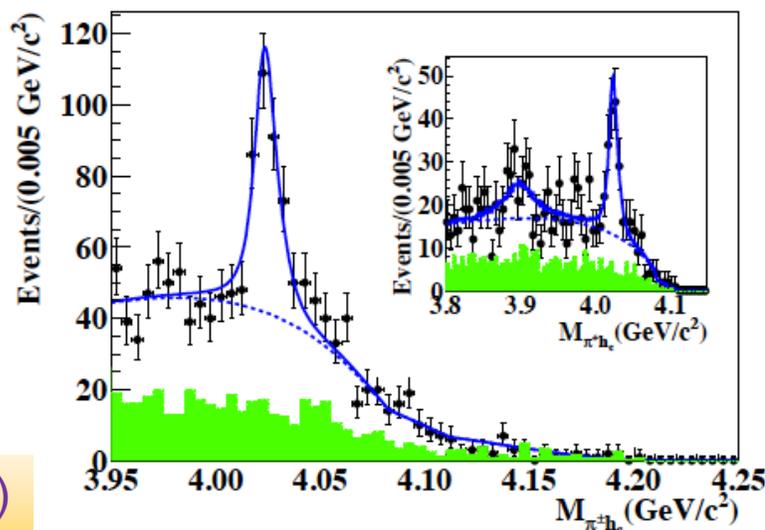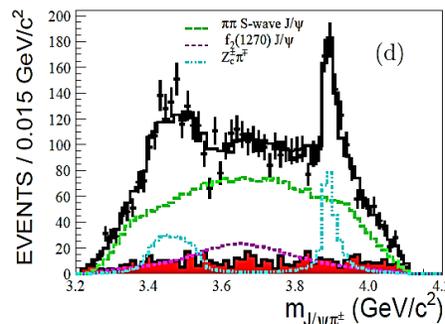
PWA of $e^+e^- \to \pi^+\pi^- J/\psi$

- Asymmetric line shape
- JP=1+ preferred over 0-, 1-, 2-, 2+ by at least 7σ.
- Significant f_0(980) contribution
- $\pi\pi$ D-wave fraction increases as E_{cm} increases

8

New

arXiv:1906.00831

- $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$
- $\eta_c \to 9$ hadronic decays

Decay mode	BR
$\eta_c \to p\bar{p}$	~0.13%
$\eta_c \to 2(K^+K^-)$	~0.15%
$\eta_c \to \pi^+\pi^-K^+K^-$	~1.50%
$\eta_c \to K^+K^-\pi^0$	~1.20%
$\eta_c \to p\bar{p}\pi^0$	~0.18%
$\eta_c \to K_S K\pi$	~1.80%
$\eta_c \to \pi^+\pi^-\eta$	~1.60%
$\eta_c \to K^+K^-\eta$	~0.57%
$\eta_c \to \pi^+\pi^-\pi^0\pi^0$	~2.40%

- Strong evidence of $e^+e^- \to \pi Z_c$, $Z_c \to \rho\eta_c$ at $\sqrt{s} = 4.23$, statistical significance is 4.2σ. (3.9σ including systematics)

- $e^+e^- \to \pi Z_c'$, $Z_c' \to \rho\eta_c$ not seen.
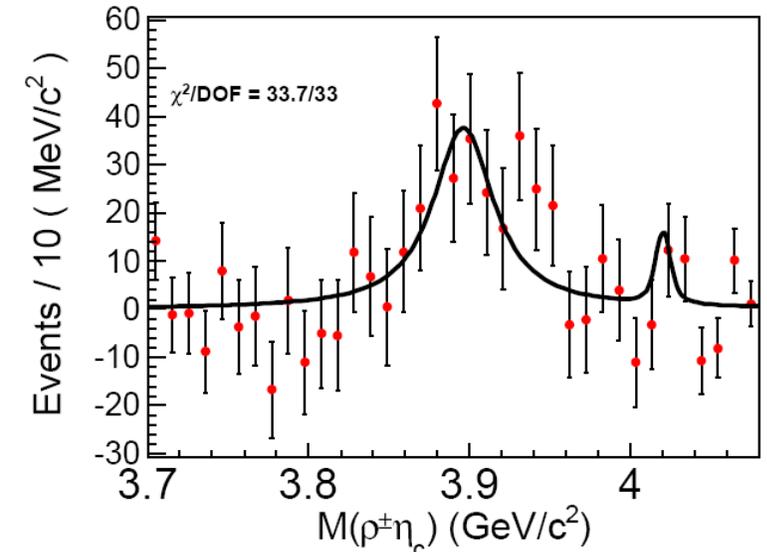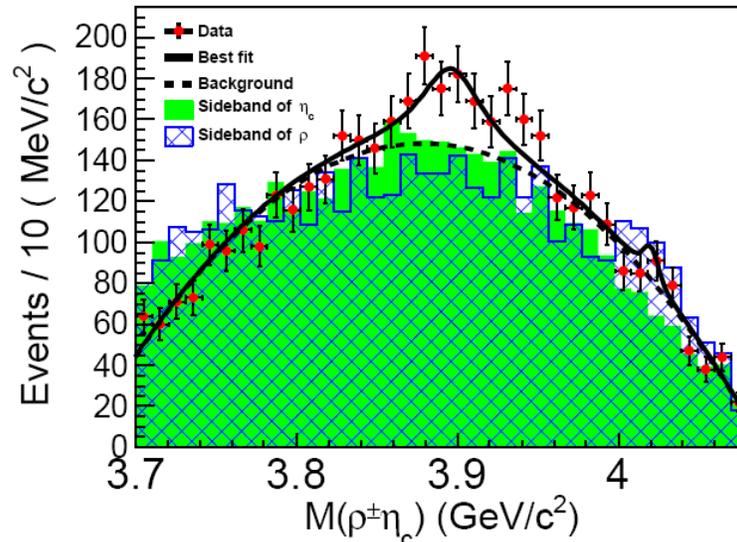
$e^+e^- \to \pi Z_c$, $Z_c \to \rho\eta_c$ @ 4.23 GeV

Evidence for $Z_c \to \rho\eta_c$
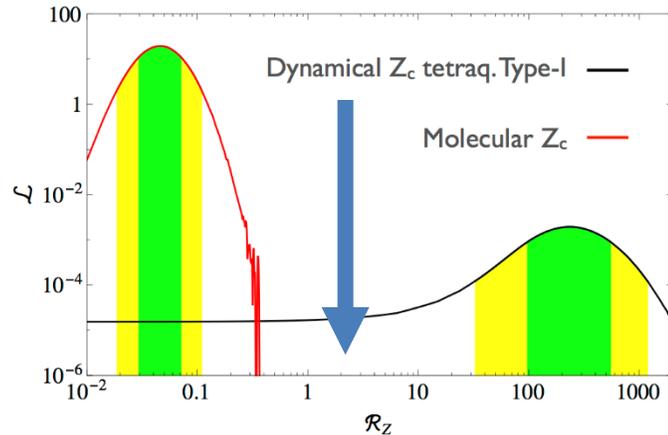
- **Measure Born cross section at 4.23 GeV:**

arXiv:1906.00831

$$\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46\,^{+12}_{-11} \pm 10)\ \text{pb}$$

$$\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c) = (48 \pm 11 \pm 11)\ \text{pb}$$

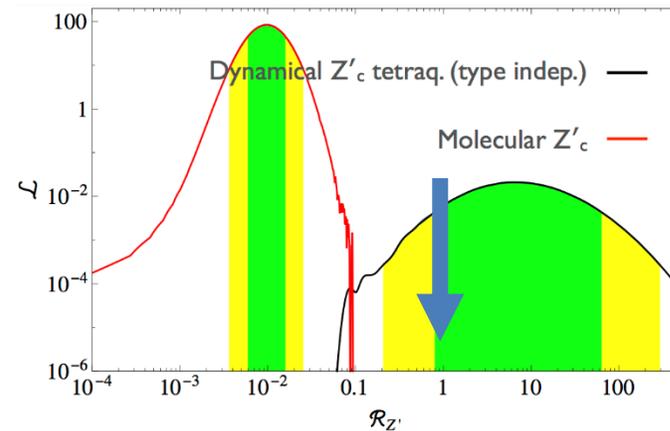|	$\sqrt{s} = 4.226\ \text{GeV}$	$\sqrt{s} = 4.258\ \text{GeV}$	$\sqrt{s} = 4.358\ \text{GeV}$	Type-I	Type-II	Molecule
$R_{Z_c(3900)}$	2.2 ± 0.9	< 5.6	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.6	< 0.9	< 1.4	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$

A.Esposito, A.L.Guerrieri, A.Pilloni, Phys. Lett. B 746, 194 (2015)

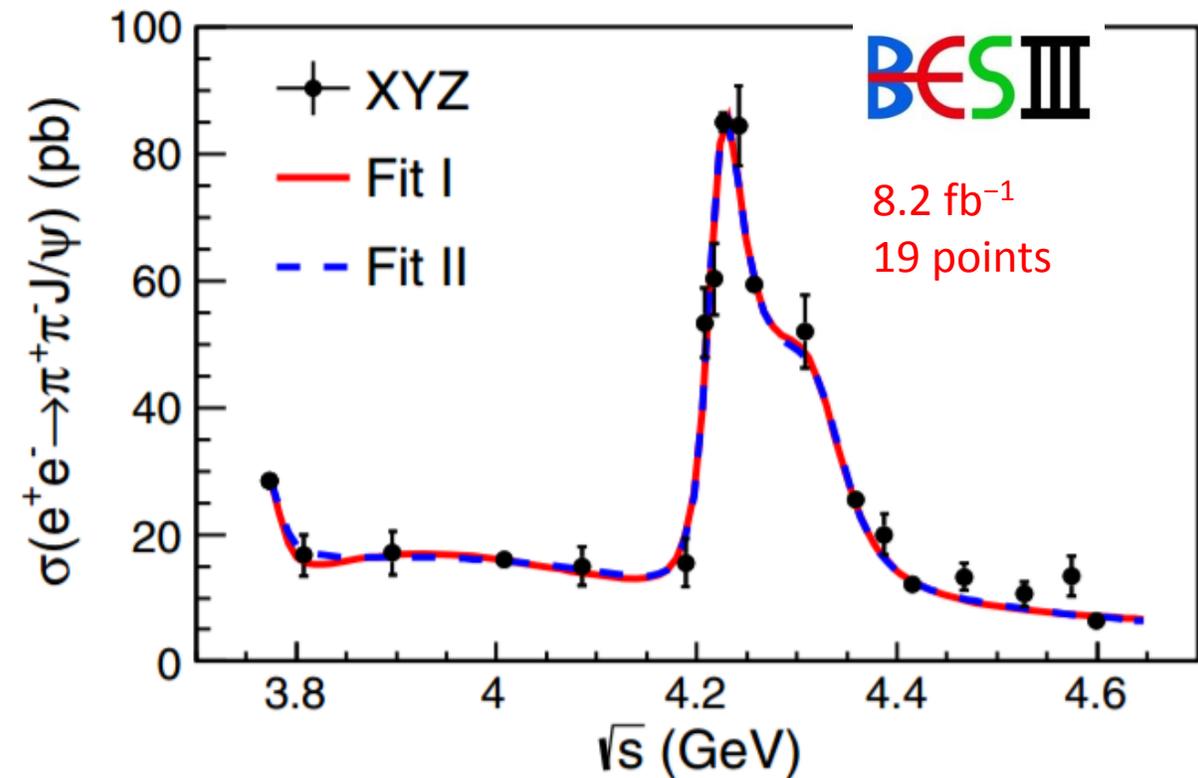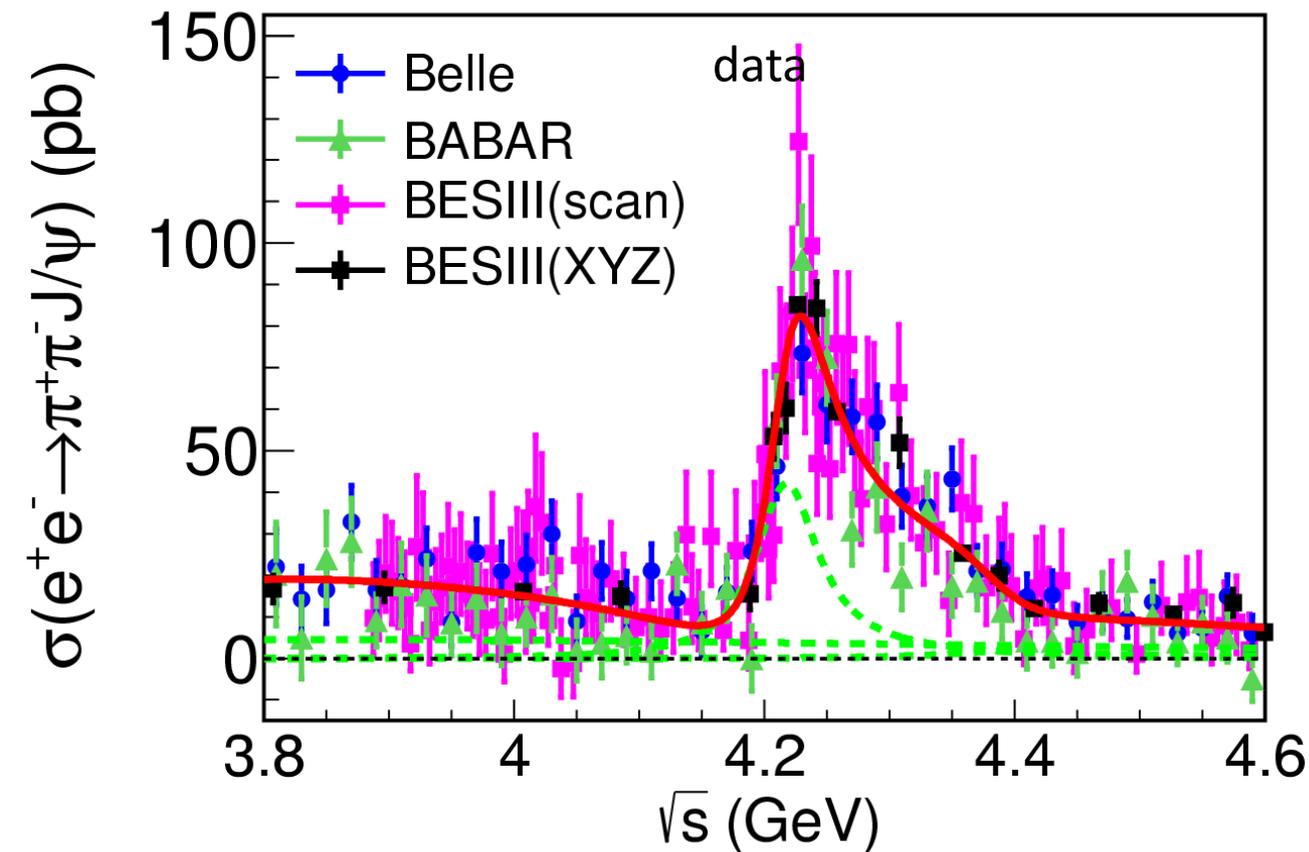$$R_z = \frac{B(Z_c \to \rho\eta_c)}{B(Z_c \to \pi J/\psi)}$$

$$R_{z'} = \frac{B(Z_c' \to \rho\eta_c)}{B(Z_c' \to \pi h_c)}$$

Z_c states have both tetraquark and molecule components?   **Refined calculations needed!**

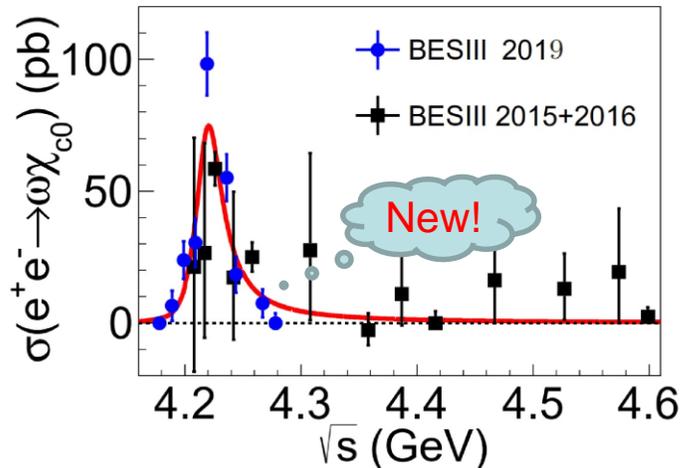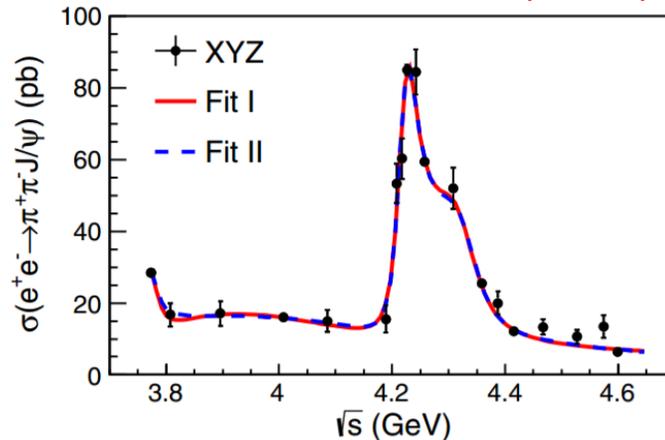# $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$: Y(4260) ➤ Y(4220)

- ➤ Most precise cross section measurment to date from BESIII
- ➤ <u>Y(4220)</u>: M = 4222.0±3.1±1.4 MeV (lower), Γ = 44.1±4.3±2.0 MeV (narrower)
- ➤ <u>Y(4320)</u>: M = 4320.0±10.4±7.0 MeV, Γ = 101.4$^{+25.3}_{-19.7}$±10.2 MeV
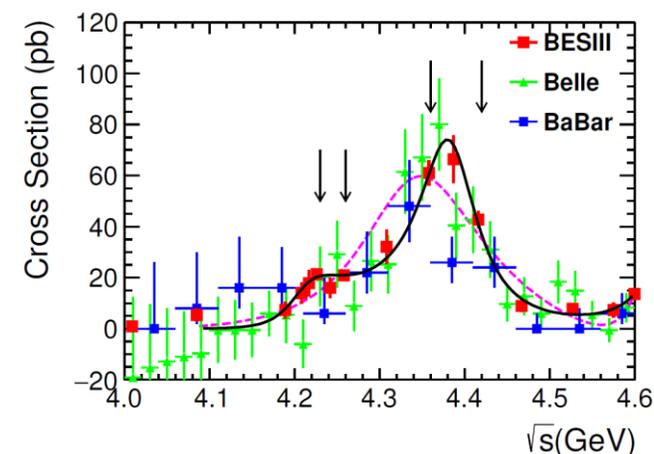
Y(4260)➜Y(4220): more modes
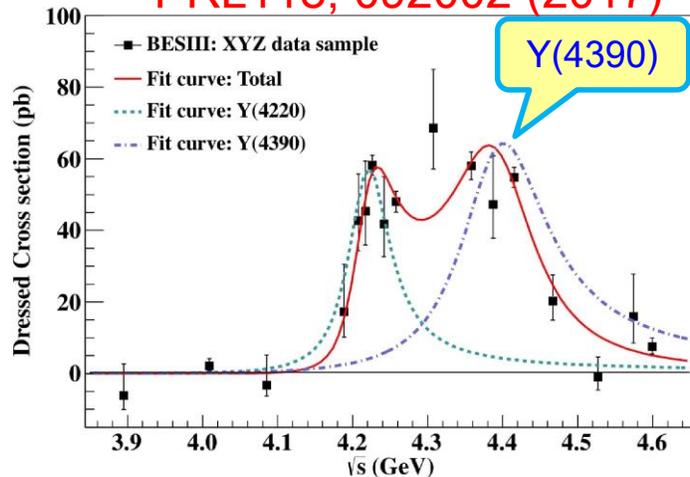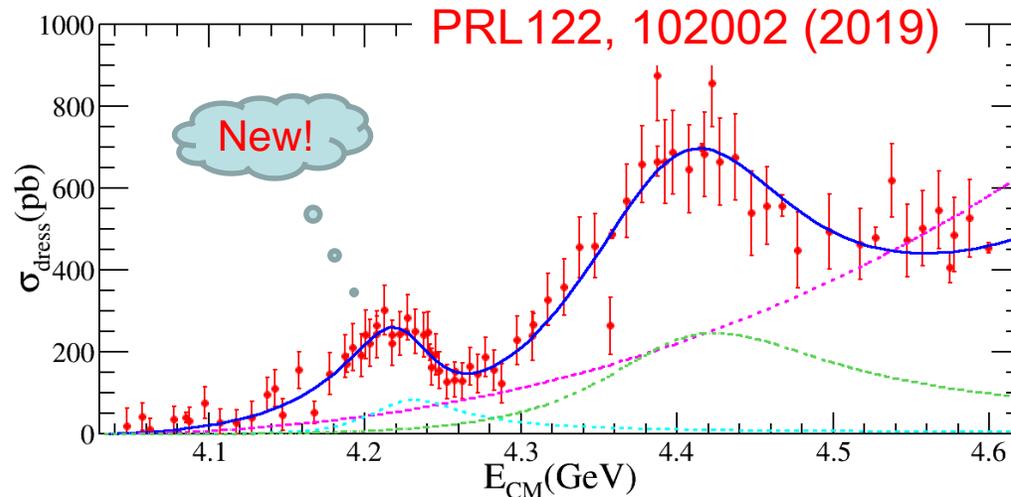
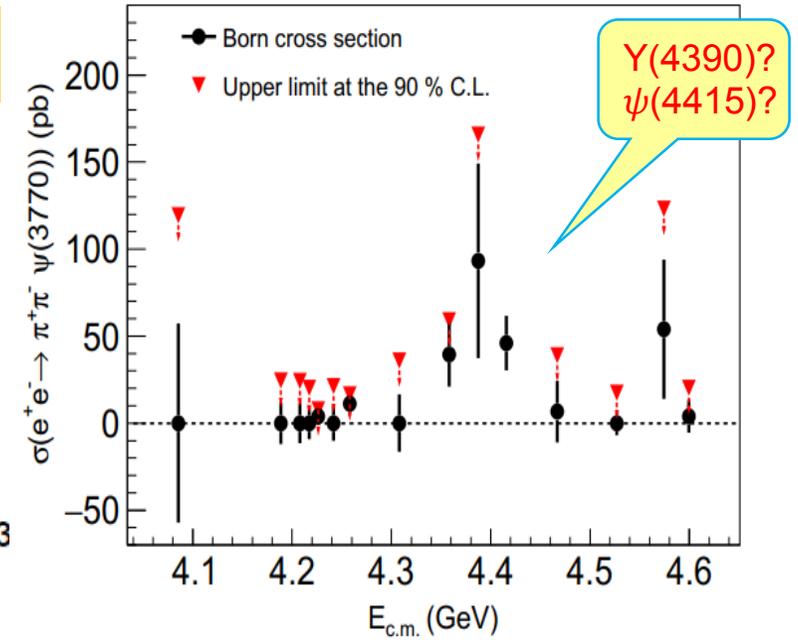$$Y(4220) \text{ appears in } \omega\chi_{c0}, \pi^+\pi^- J/\psi, \pi^+\pi^- \psi', \pi^+\pi^- h_c, D^0 D^{*-}\pi^+$$

Mass~4220 MeV, width~ 60 MeV!

$e^+e^- \to \pi^+\pi^-\psi(3770)$

■ Study $e^+e^- \to \pi^+\pi^- D^0\overline{D}^0$, $e^+e^- \to \pi^+\pi^- D^+D^-$

➢ $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^+\pi^-\pi^0$

➢ $D^+ \to K^-\pi^+\pi^+, K^-\pi^+\pi^+\pi^0, K_S^0\pi^+, K_S^0\pi^+\pi^0$, and $K_S^0\pi^+\pi^+\pi^-$
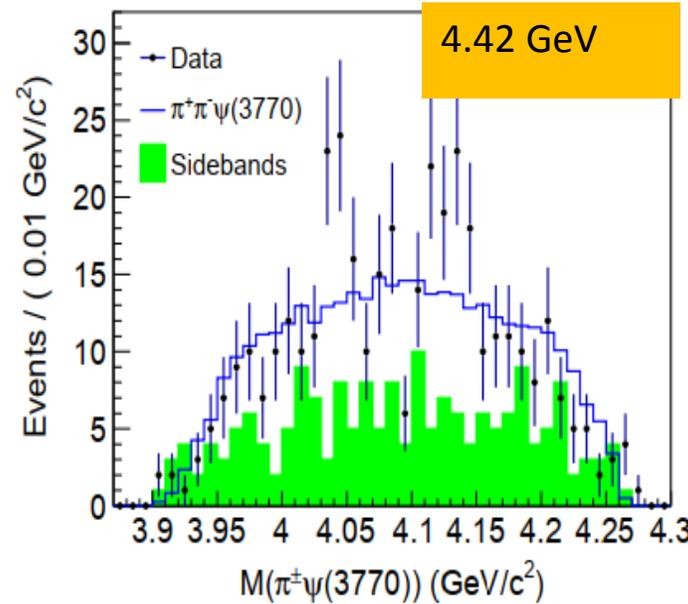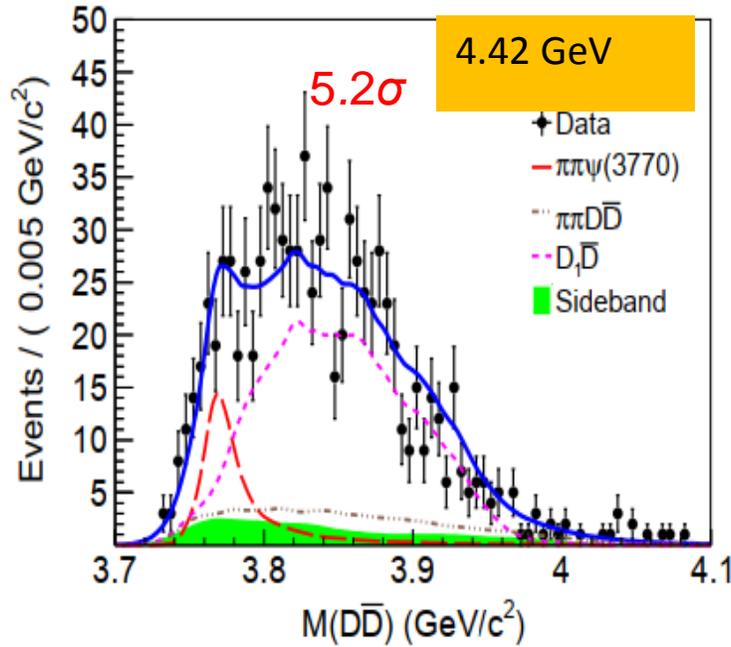
➢ $e^+e^- \to \pi^+\pi^-\psi(3770)$ is observed for the first time, no evidence for $\psi(1^3D_3)$

➢ Hints of Z_c in M($\pi^\pm\psi(3770)$) at 4.04 and 4.13 GeV in $\sqrt{s}$ = 4.42 GeV data

➢ Clear structure in line-shape of $\pi^+\pi^-\psi(3770)$

13
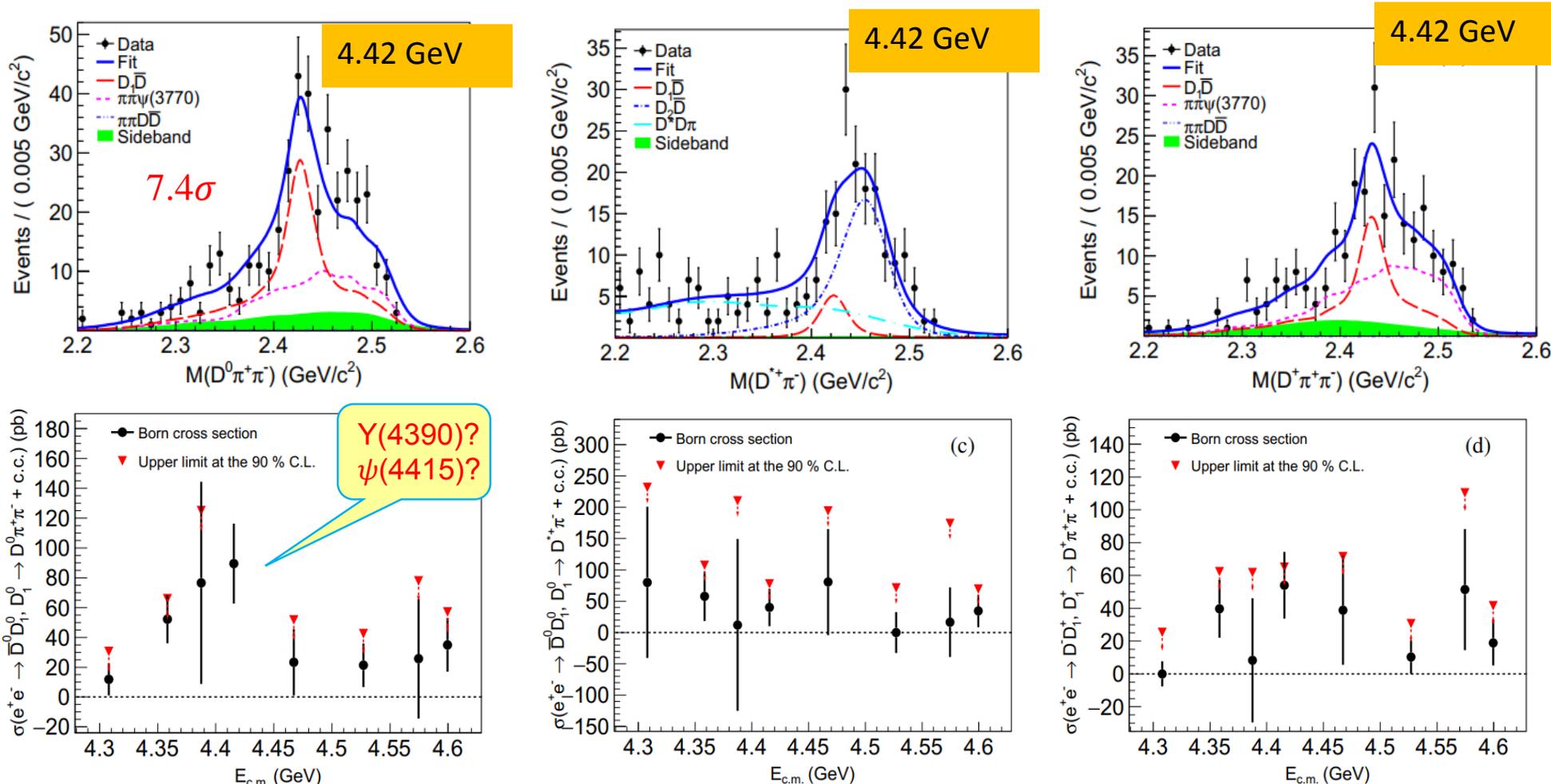
$e^+e^- \to D_1(2420)\bar{D} \to \pi^+\pi^- D\bar{D}$

Y(4260) $\neq$ $\overline{D}D_1$ molecule?

Y(4390)?
$\psi(4415)$?

- Three different decay channels ($D^0\pi^+\pi^-$, $D^{*+}\pi^-$, and $D^+\pi^+\pi^-$) are used to search for $D_1(2420)$
- Clear structure in the line-shape of $e^+e^- \to D_1(2420)\bar{D}$. No abnormal threshold effect seen.

Observation of e⁺e⁻ → γX(3872)

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

4.0 fb⁻¹, 20±5 evts

11.6 fb⁻¹, 79±9 evts

Observation of $X(3872) \to \omega J/\psi$
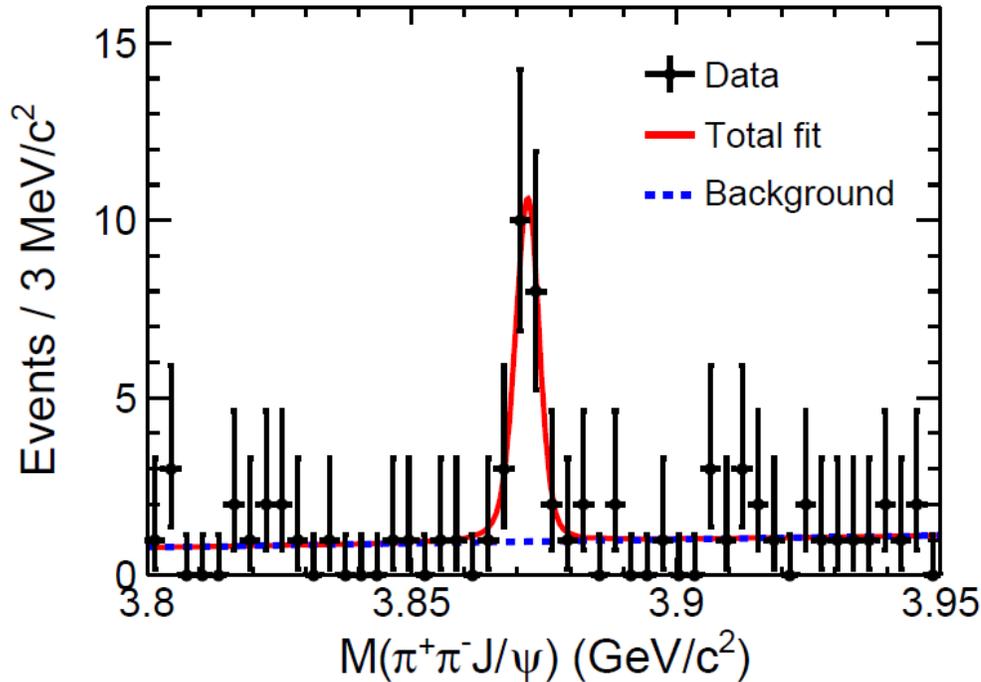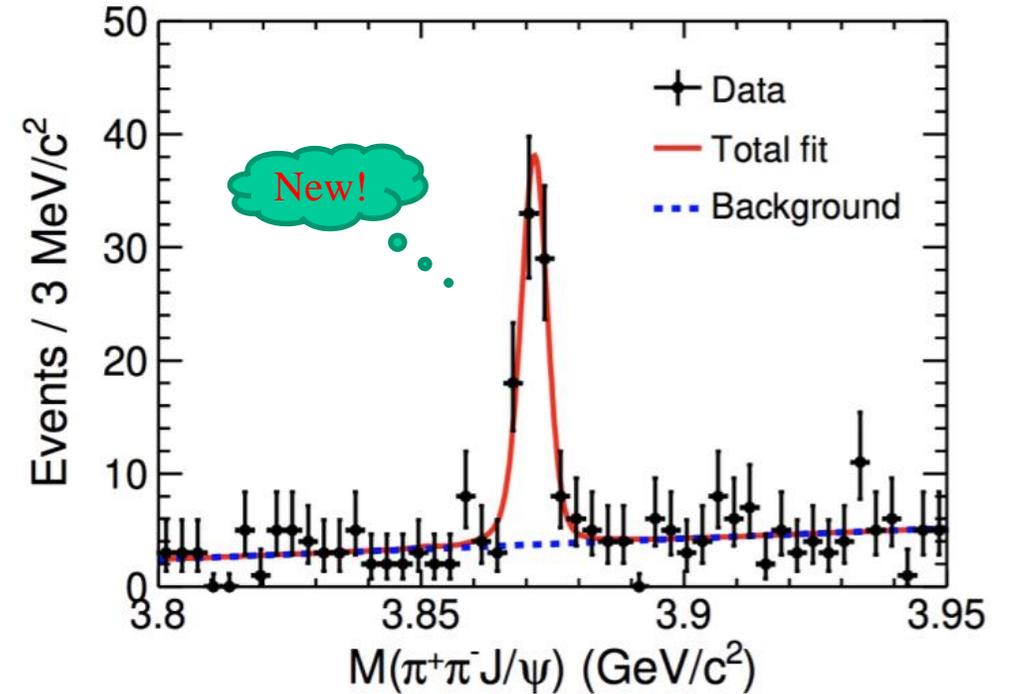
■ Signal process: $e^+e^- \to \gamma X \to \gamma \omega J/\psi$, with $\omega \to \pi^+\pi^-\pi^0$, $J/\psi \to l^+l^-$
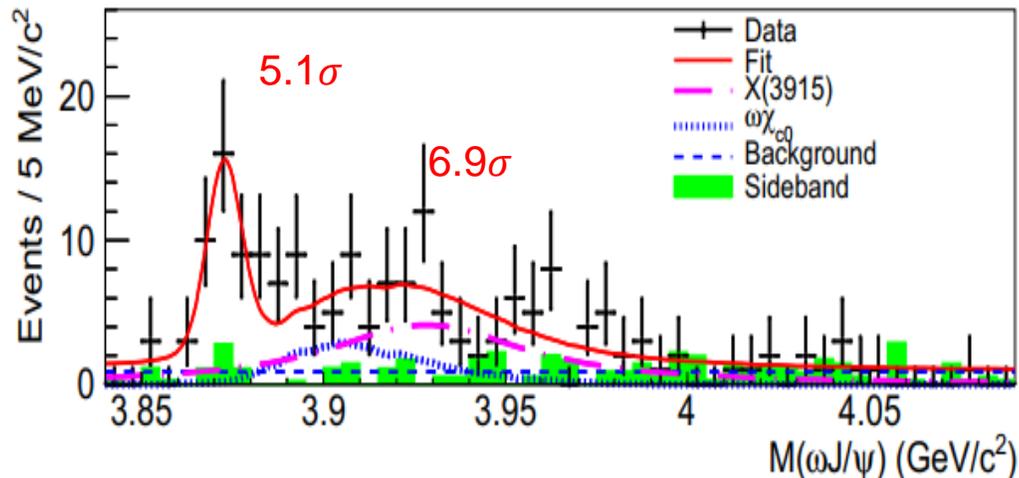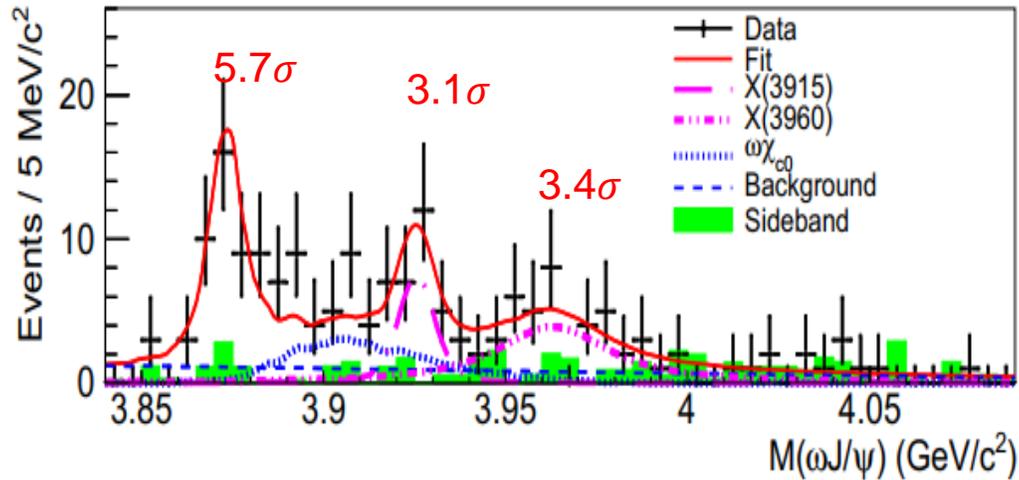
There were only evidence at Belle (4.3σ) and BaBar (4σ) experiments!

➤ Signal PDF:

✓ 3 resonances: (X(3872), X(3915) and X(3960))

$$N_{sig}(X(3872)) = 45 \pm 9 \pm 3$$

✓ Two resonances: (X(3872), X(3915))

$$N_{sig}(X(3872)) = 40 \pm 8 \pm 2$$

	Mass	Width
$X(3872)$	3873.3 ± 1.1 (3872.8 ± 1.2)	1.2 (1.2)
$X(3915)$	3926.4 ± 2.2 (3932.6 ± 8.7)	3.8 ± 7.5 (59.7 ± 15.5)
$X(3960)$	3963.7 ± 5.5	33.3 ± 34.2

Hard to distinguish the two hypotheses since only 2.5σ difference.

Observation of $X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$

$$e^+e^- \rightarrow \gamma X(3872), X(3872) \rightarrow \pi^0 \chi_{cJ} \text{ (with } \chi_{cJ} \rightarrow \gamma J/\psi, J/\psi \rightarrow l^+l^-)$$

$e^+e^- \rightarrow \gamma_1 \pi^0 \chi_{cJ}$ with $\chi_{cJ} \rightarrow \gamma_2 J/\psi$

(a) $4.15 < E_{CM} < 4.30$ GeV

(b) $4.00 < E_{CM} < 4.15, 4.30 < E_{CM} < 4.60$ GeV

$M(\pi^0 \chi_{cJ})$ [GeV/c^2]

$M(\gamma_{1,2} J/\psi)$ [GeV/c^2]
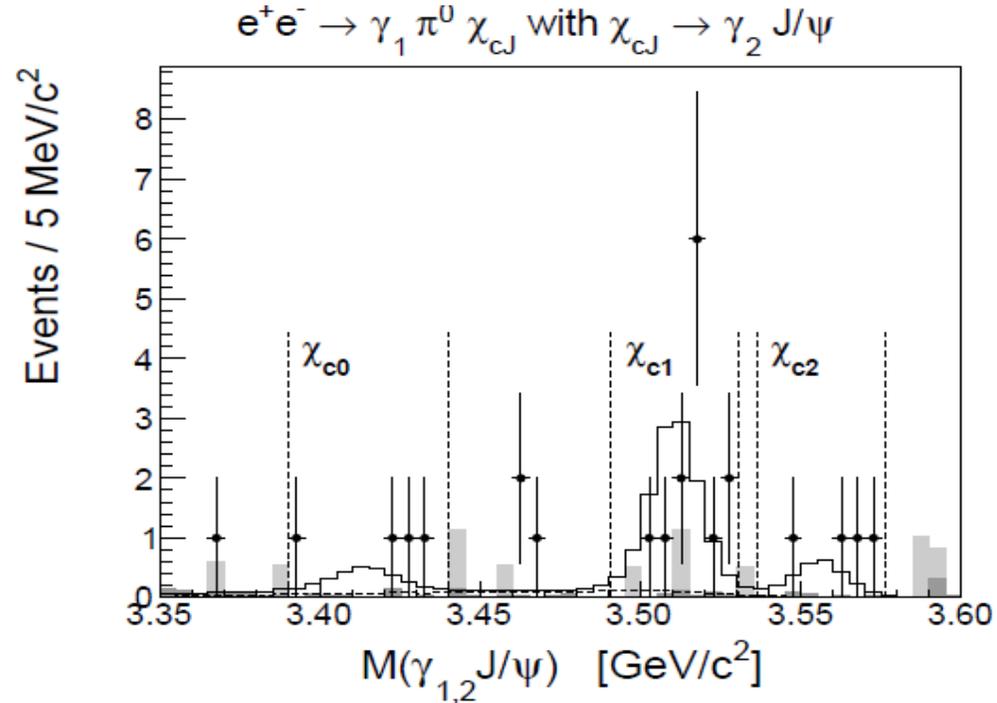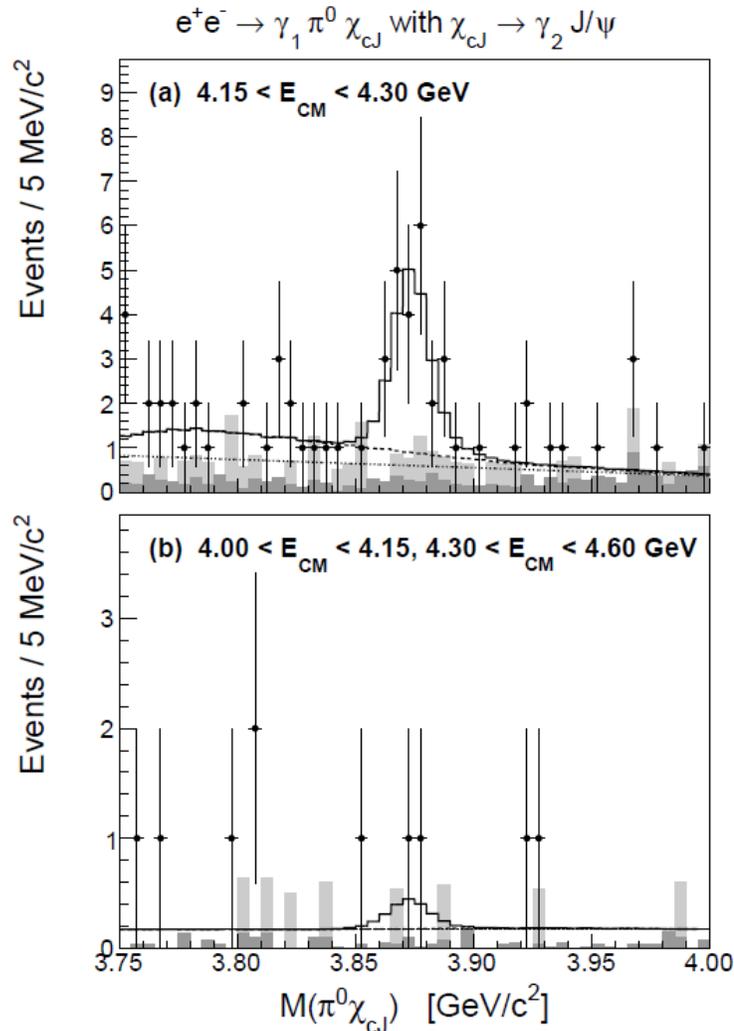
- Clear signal of $X(3872)$ in Y(4260) region, $N_{X(3872)} = 16.9^{+5.2}_{-4.9}$
- No $X(3872)$ events outside of $Y(4260)$
- Clear cluster of $\chi_{c1}(1P)$ events in X(3872) mass window
- First observation of $X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$ with significance >5σ.

Measurements of $X(3872) \to \gamma J/\psi, \gamma \psi(3686)$

New!

preliminary

$X(3872) \to \gamma J/\psi$

$J/\psi \to \mu\mu/ee$

Belle (4.9σ); BaBar (3.6σ); LHCb (>5σ)
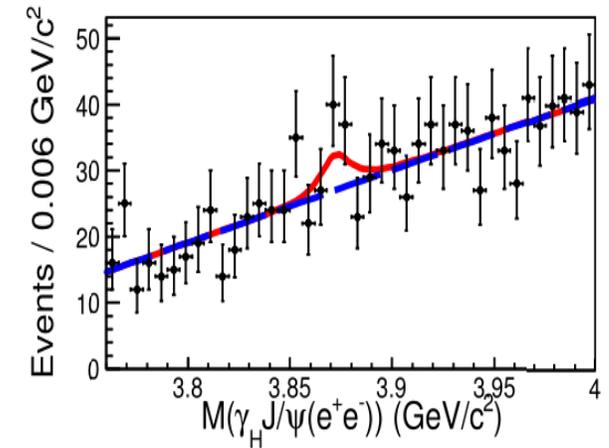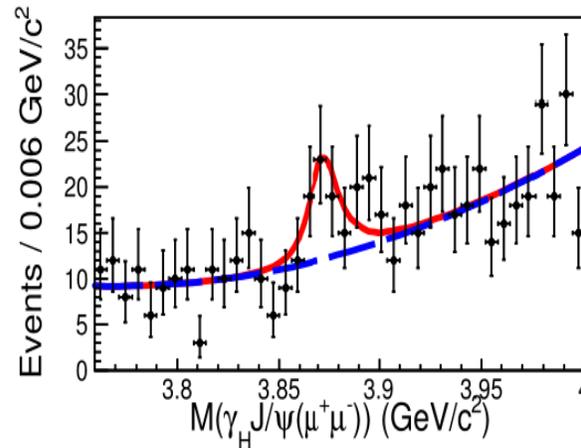
➢ Simultaneous fit; significance > 3.5σ

$X(3872) \to \gamma \psi(3686)$

$\psi(3686) \to \pi^+\pi^- J/\psi$

$\psi(3686) \to \mu\mu$

Belle (0.4σ); BaBar (3.5σ); LHCb (4.4σ)

$\dfrac{B[X(3872) \to \gamma \psi(3686)]}{B[X(3872) \to \gamma J/\psi]} < 0.59$ at 90% C.L.

➢ Simultaneous fit; NO evident signal!

Expectation strength

Measurements of $X(3872) \to D^0 \bar{D}^{*0}$, $\gamma D^+ D^-$
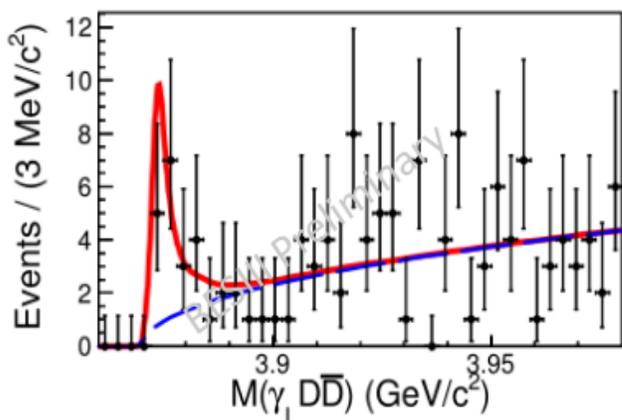
preliminary

$X(3872) \to D^0 \bar{D}^{*0} + c.c.$

$D^{*0} \to \gamma D^0, \pi^0 D^0$

$D^0 \to K\pi, K\pi\pi, K\pi\pi\pi$

$X(3872) \to \gamma D^+ D^-$

$D^{\pm} \to K\pi\pi, K\pi\pi\pi$

$N_{DD^*} = (25.5 \pm 4.4)$
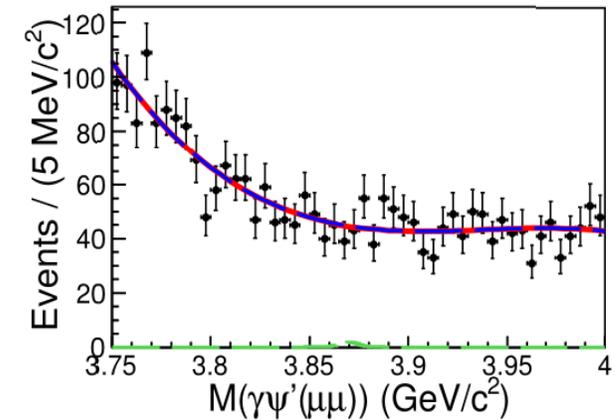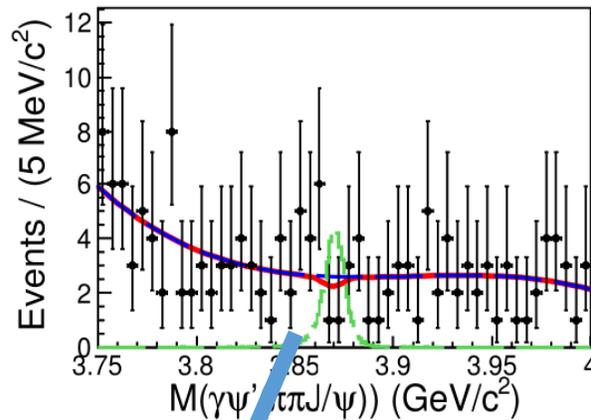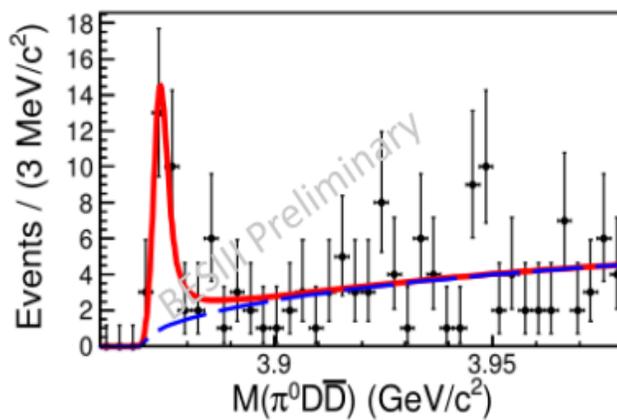
$N_{DD^*} = (32.5 \pm 5.5)$
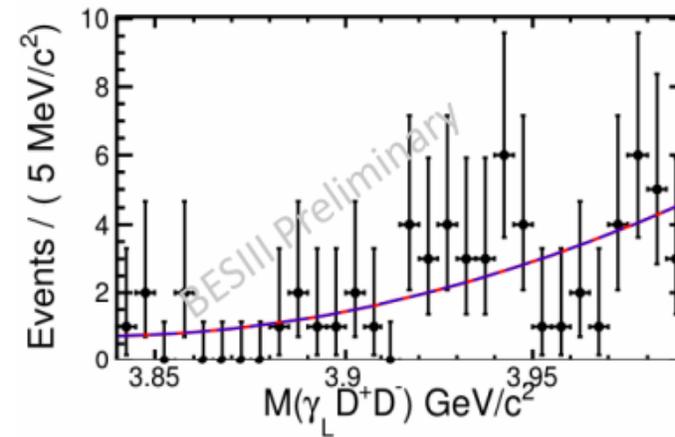
$N_{\gamma D^+ D^-} = 0.0^{+0.5}_{-0.0}$

➤ Simultaneous fit on $D^{*0} \to \gamma D^0$ and $\pi^0 D^0$
➤ Significance > 7.4σ

No evident signal for $\gamma D^+ D^-$

➤ Relative branching ratio compared with $X(3872) \to \pi^+ \pi^- J/\psi$

mode	$D^{*0}\bar{D}^0 + c.c.$	$\gamma J/\psi$	$\gamma\psi'$	$\gamma D^+ D^-$	$\omega J/\psi$	$\pi^0 \chi_{c1}$
ratio	14.81 ± 3.80	0.79 ± 0.28	< 0.42	< 0.99	$1.7^{+0.4}_{-0.3} \pm 0.2$ [27]	$0.88^{+0.33}_{-0.27} \pm 0.10$ [37]

X(3872) decay BRs

mode	$D^{*0}D^0 + c.c.$	$\gamma J/\psi$	$\gamma \psi'$	$\gamma D^+ D^-$	$\omega J/\psi$	$\pi^0 \chi_{c1}$
ratio	14.81 ± 3.80	0.79 ± 0.28	< 0.42	< 0.99	$1.7^{+0.4}_{-0.3} \pm 0.2$ [27]	$0.88^{+0.33}_{-0.27} \pm 0.10$ [37]

With recent $B(X(3872) \to \pi^+\pi^- J/\psi) = (4.1\pm1.3)\%$ from BaBar, one gets

B(known)=(1+14.81+0.79+1.7+0.88)*4.1% = 19.2x4.1% ~ (79$\pm$32)%!

Find more decay modes, and/or improve the precisions!

X、Y、Z particles are correlated!

What are they? Are they all molecules/tetraquarks/…?

Y(4260)

X(3872)   ? Z_c(3900)
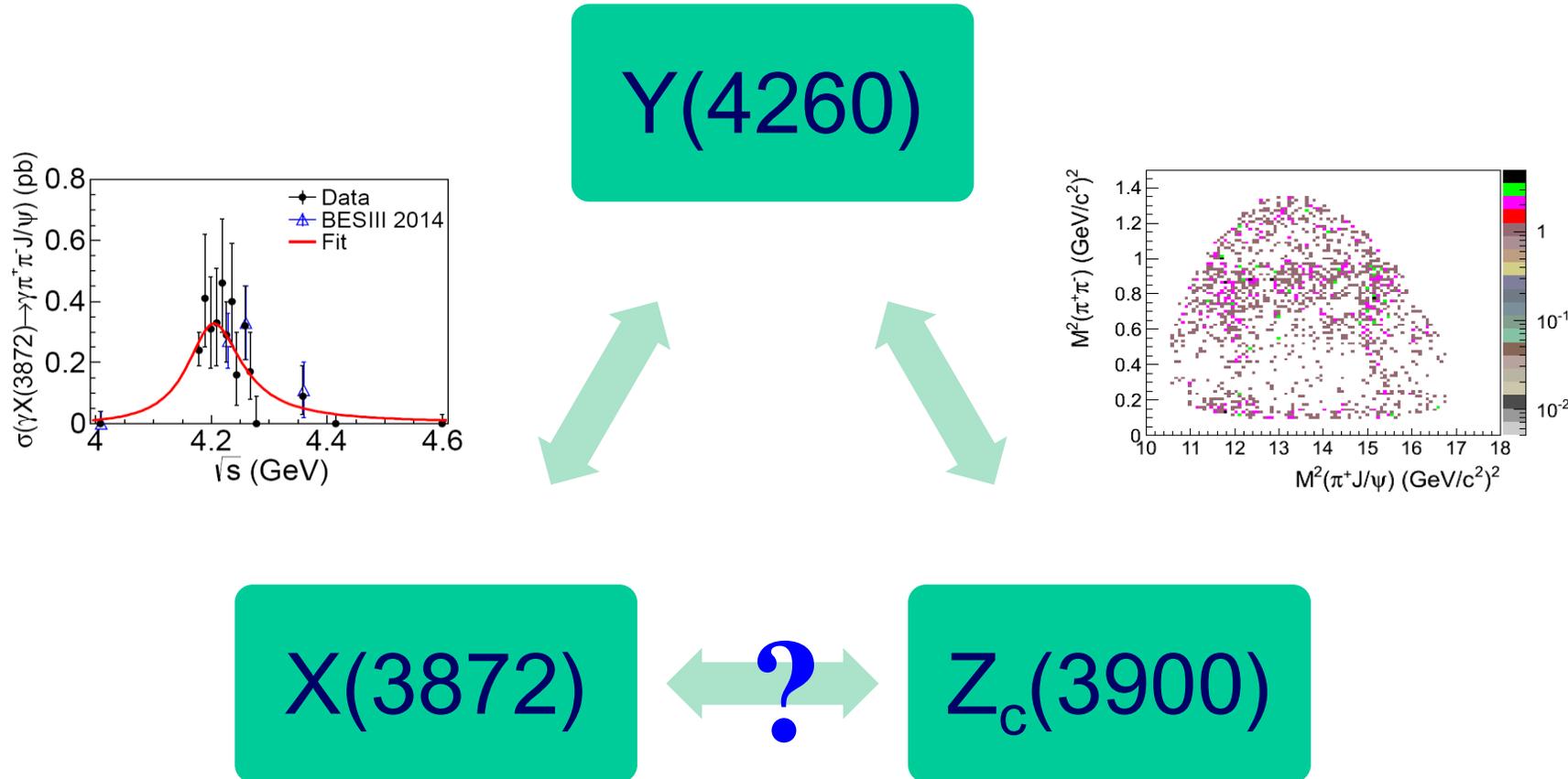
Light Hadron States

Glueball program at BESIII in a nutshell

	0^+	2^+	0^-
J/ψ→γPP	▨	▨	
J/ψ→γVV		▨	▨
J/ψ→γPPP			▨

- 0^+, 2^+ : Coupled channel analyses
  - J/ψ→γPP
  - J/ψ→ω/φ + X
- 0^- : trajectory, X(2370)
  - J/ψ→γPPP
  - J/ψ→γγ V

J/ψ→γη η /η′η′/η η′/$\pi^0\pi^0$/$K_S K_S$

J/ψ→γωφ/φφ/ωω

J/ψ→γ η′ππ /η′KK/ηππ/KKπ/ηKK/ π π π

- PWA published
- Published, PWA undone
- Ongoing

Flavor Filters：

J/ψ→γX →γ γ V   J/ψ→ω/φ + X

Anti filter:

23
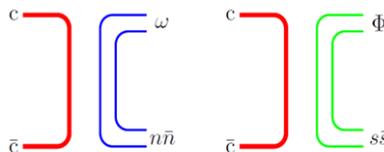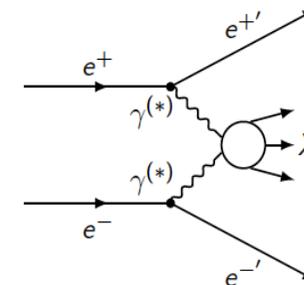
PWA of J/ψ→γηη/γK$_S^0$K$_S^0$

Phys. Rev. D 87, 092009 (2013)

$\chi^2/\text{nbin}=1.72$

PWA of J/ψ→γηη

Phys. Rev. D 98, 072003 (2018)

$\chi^2/\text{nbin}=1.45$

PWA of J/ψ→γK$_S^0$K$_S^0$
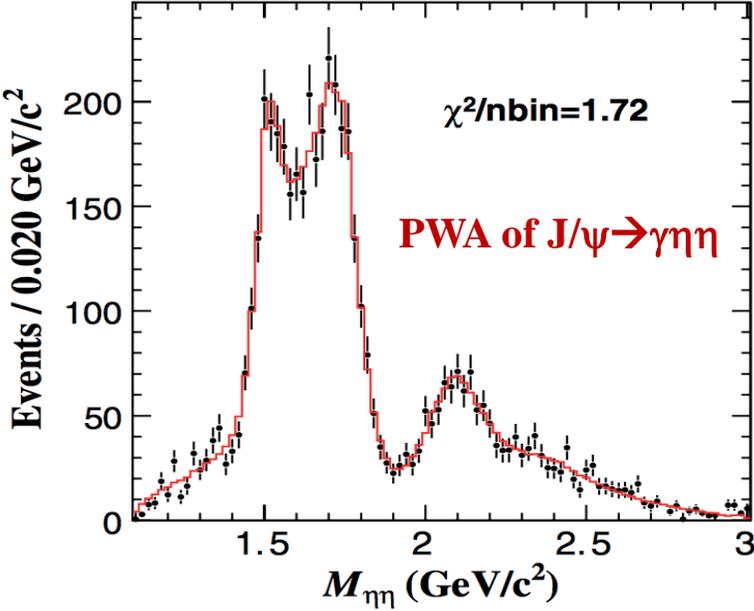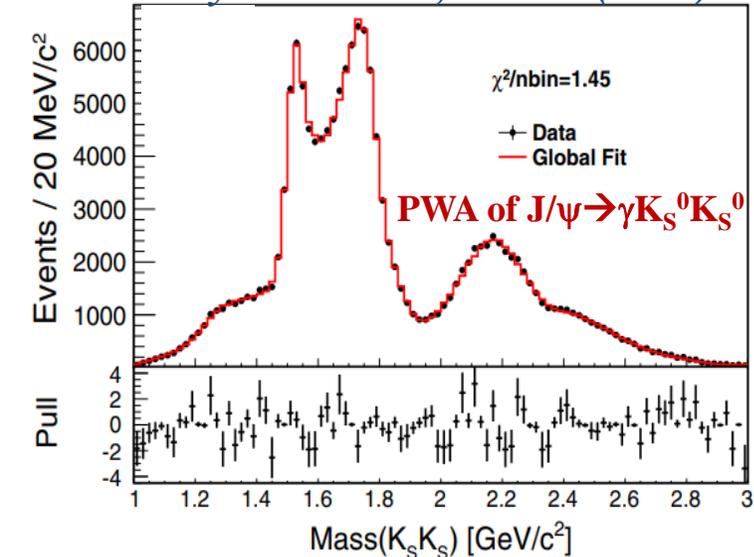
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$\cdots$	$146 \pm 14^{+7}_{-15}$	$\cdots$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$\cdots$	$349 \pm 18^{+23}_{-1}$	$\cdots$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

Scalar/tensor glueball candidate ($0^{++}/2^{++}$)

Decay rate of pure glueball from LQCD:

$$\Gamma(J/\psi \to \gamma G_{0+}) = \frac{4}{27}\alpha\frac{|p|}{M_{J/\psi}^2}|E_1(0)|^2 = 0.35(8)keV$$

$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9)\times 10^{-3}$$

CLQCD, Phys. Rev. Lett. 110, 021601 (2013)

$$\Gamma(J/\psi \to \gamma G_{2+}) = 1.01(22)keV$$

$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

Experimental results from J/ψ radiative decays to scalars or tensors:

➢ B(J/ψ → $\gamma f_0(1710)$ → $\gamma K\bar{K}$)=($8.5^{+1.2}_{-0.9}$) × 10^{-4}

➢ B(J/ψ → $\gamma f_0(1710)$ → $\gamma\pi\pi$)=(4.0 ± 1.0)× 10^{-4}

➢ B(J/ψ → $\gamma f_0(1710)$ → $\gamma\omega\omega$)=(3.1 ± 1.0)× 10^{-4}

➢ B(J/ψ → $\gamma f_0(1710)$ → $\gamma\eta\eta$)=($2.35^{+0.13+1.24}_{-0.11-0.74}$)× 10^{-4}

➢ B(J/ψ → $\gamma f_2(2340)$ → $\gamma\eta\eta$)=($5.60^{+0.62\ +2.37}_{-0.65\ -2.07}$)× 10^{-5}

➢ B(J/ψ → $\gamma f_2(2340)$ → $\gamma\phi\phi$)=($1.91 \pm 0.14^{+0.72}_{-0.73}$)× 10^{-4}

➢ B(J/ψ → $\gamma f_2(2340)$ → $\gamma K_S^0 K_S^0$)=($5.54^{+0.34\ +3.28}_{-0.40\ -1.49}$)× 10^{-5}
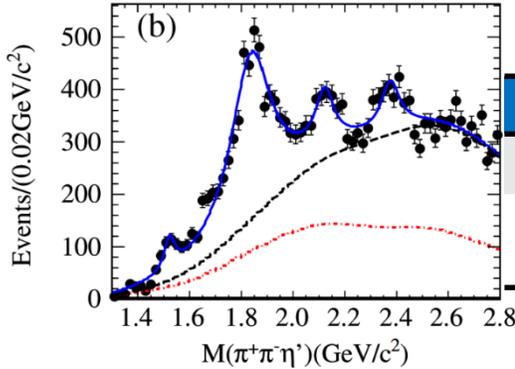
⟹   B(J/ψ → $\gamma f_0(1710)$) > 1.7×10^{-3}

$f_0(1710)$ / $f_2(2340)$: candidates of the scalar/ tensor glueballs ?

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

Phys. Rev. Lett. 106, 072002 (2011)

0.2B J/ψ evts

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

PRL 108, 112003 (2012); PRL 115, 091803 (2015)
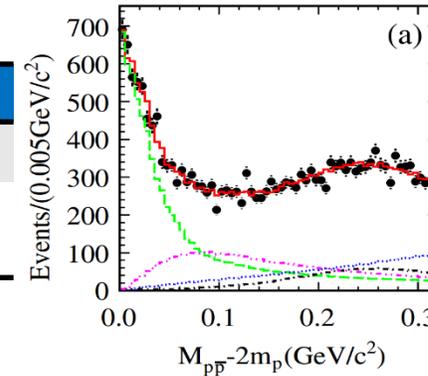
X(1835) $J^{PC}=0^{-+}$	X($p\bar{p}$) $J^{PC}=0^{-+}$
M = $1844 \pm 9^{+16}_{-25}$ MeV/c^2	M = $1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2	$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 **MeV/c²** @ 90% C.L.)

1.3B J/ψ evts

PRL 117, 042002 (2016)
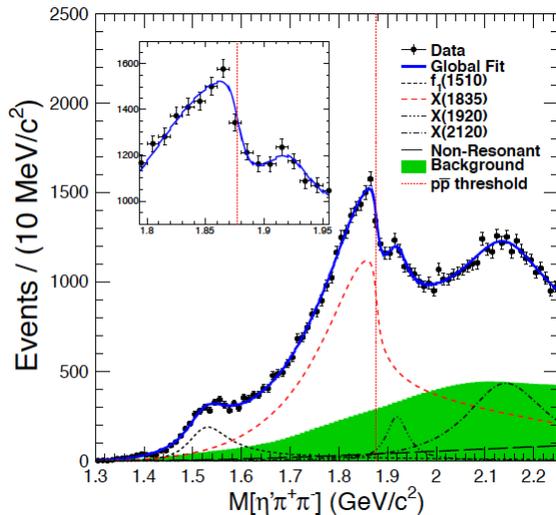
Model I:
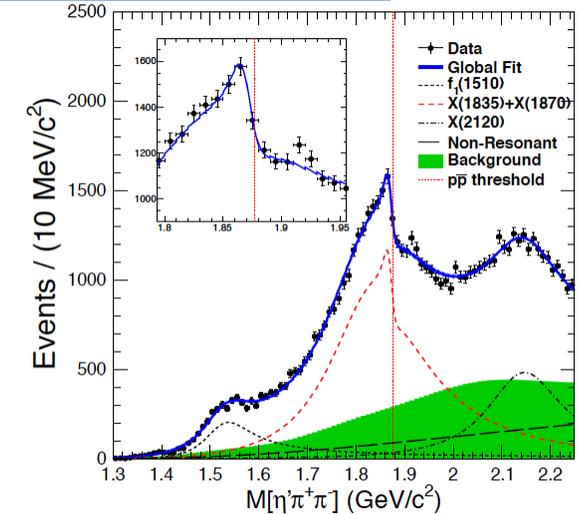Flatte line shape with strong coupling to $p\bar{p}$ and one additional narrow BW at ~ 1920 MeV

Model II:
Two coherent BW, X(1835) and one additional, narrow BW at ~ 1870 MeV significance > 7σ

- Existence of a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
- Existence of a $p\bar{p}$ molecule-like state or bound state?

26

Search for X(1835)'s other decay modes

J/ψ→γγφ:

✓ First observation of η(1475)/X(1835)→γφ.
✓ Angular distribution favor $J^{PC} = 0^{-+}$.

J/ψ→ωπ⁺π⁻η':
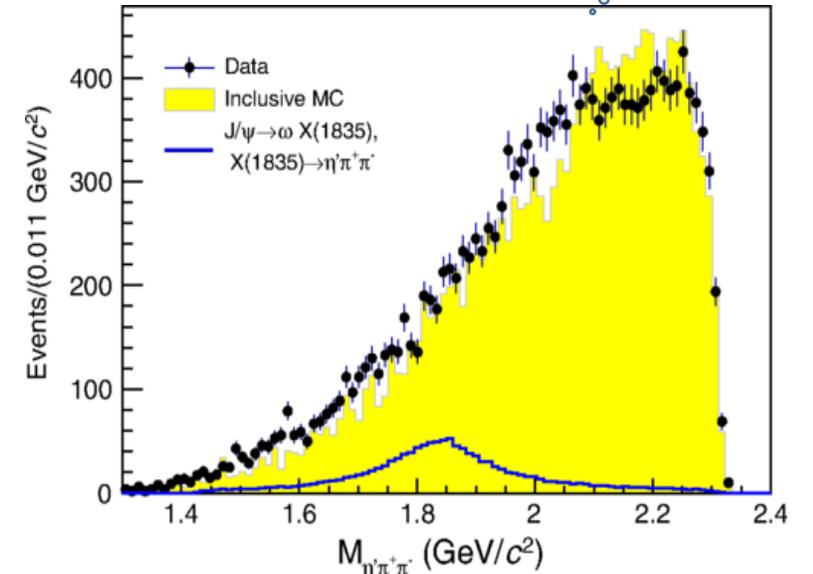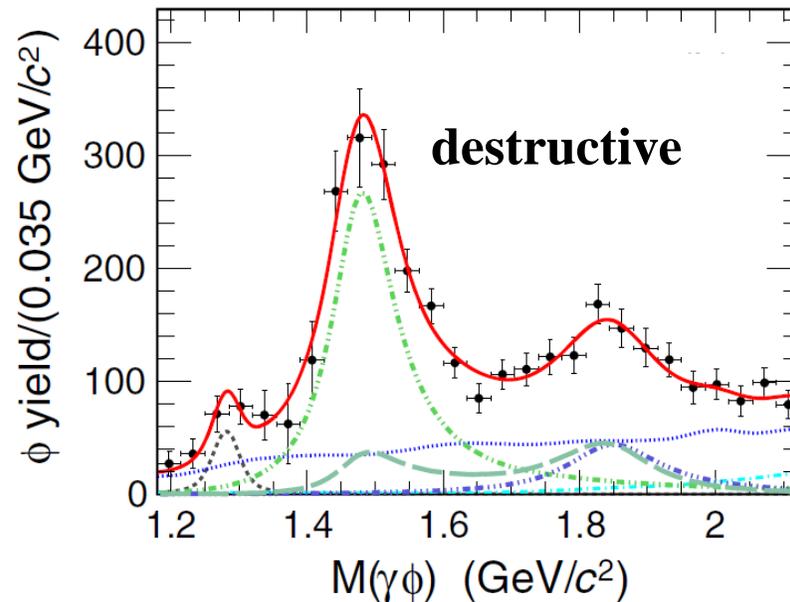
✓ No obvious signal of X(1835) is found.
✓ B.R.$< 6.2×10^{-5}$ @ 90% C. L.

Sizeable $s\bar{s}$ component in X(1835)
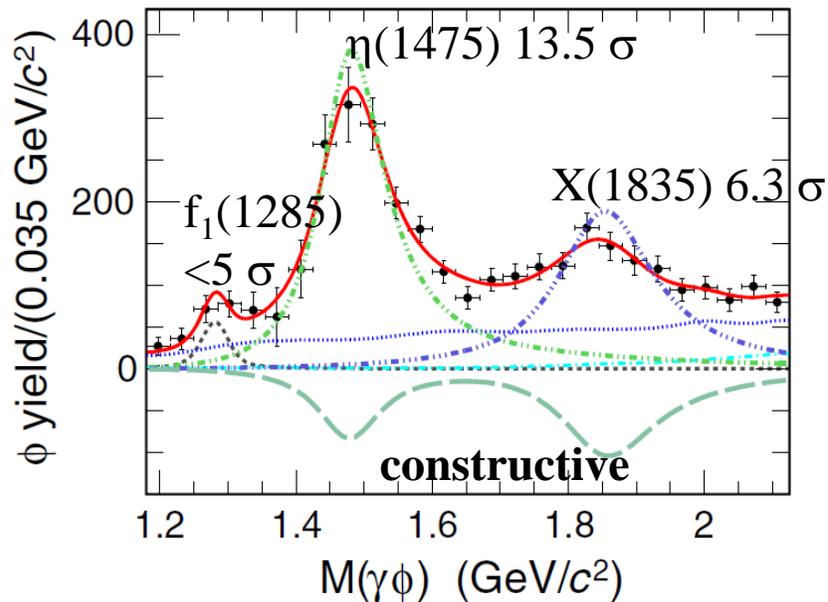
Phys. Rev. D 97, 051101(R) (2018)

Phys. Rev. D 99, 071101(R) (2019)

10 Billion J/ψ events by Feb. 2019

BESIII control room

BESIII amasses record J/ψ dataset
On 11 February, the BESIII experiment at the Beijing Electron Positron Collider in China finished accumulating a sample of 10 billion J/ψ events – the world's largest dataset produced directly from electron–positron annihilations. Decays of the J/ψ particle offer a clean laboratory for studying exotic hadrons composed of light quarks and gluons, including those composed of pure gluons. With 1.3 billion J/ψ events collected in 2009 and 2012, BESIII has reported many such studies. The record J/ψ–event data sample – which adds the 8.7 billion events collected in 2017, 2018 and 2019 – will improve the precision of such studies.

CERN courier

Unique sample for studying
light hadron spectroscopy
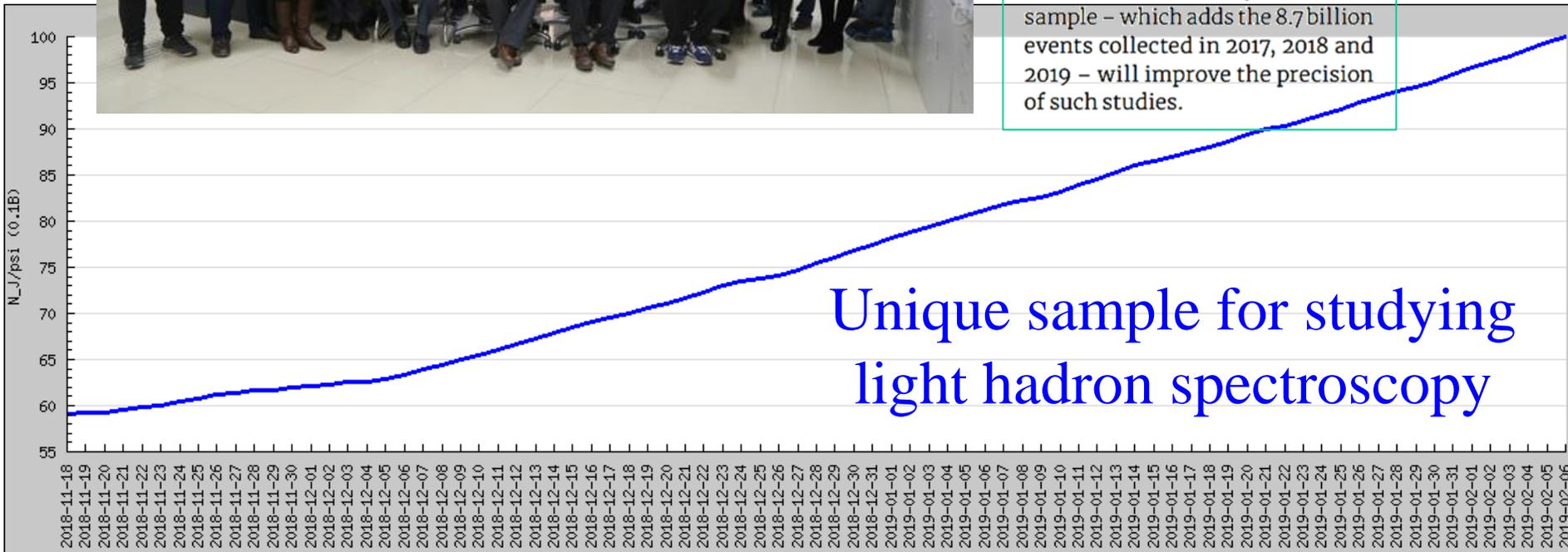
Charm Physics

Leptonic & semileptonic decays
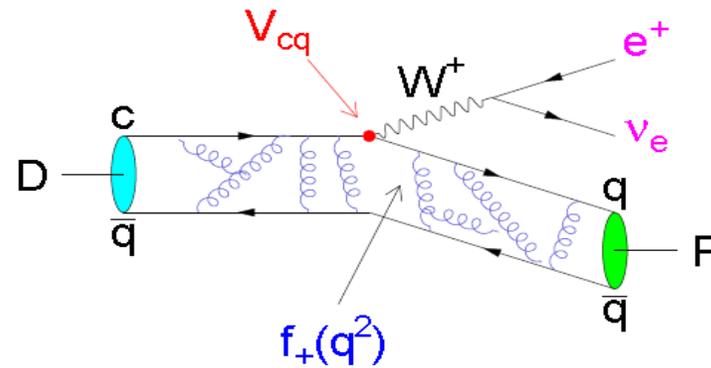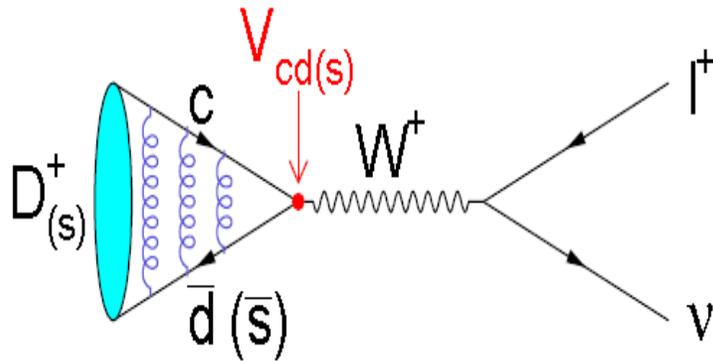
$$\Gamma(D_{(s)}^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$

$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

Leptonic and semileptonic decays of charmed hadrons (D^0, D^+, D_s^+, Λ_c^+) provide ideal testbeds to explore weak and strong interactions

1. **$|V_{cs(d)}|$: better test on CKM matrix unitarity**
2. **(Semi-)leptonic $D_{(s)}$ decays allow for LFU tests**
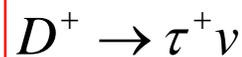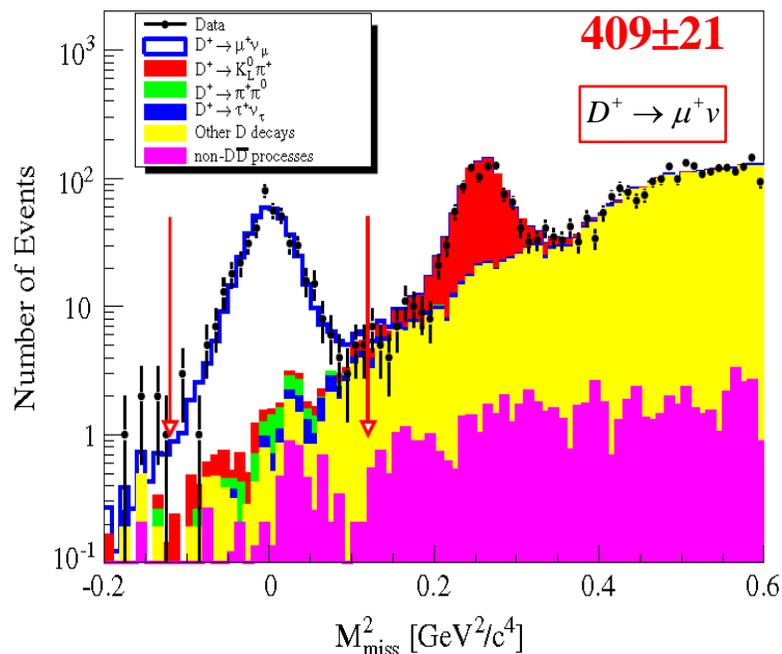3. **$f_{D(s)+}$, $f_+^{K(\pi)}(0)$: test of LQCD**

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$\mathbf{f_{D+}|V_{cd}|}$ from $\mathbf{D^+ \rightarrow l^+v}$

2.93 fb^{-1} data@ 3.773 GeV

PRD89, 051104 (2014)

$D^+ \rightarrow \tau^+v$

BESIII preliminary
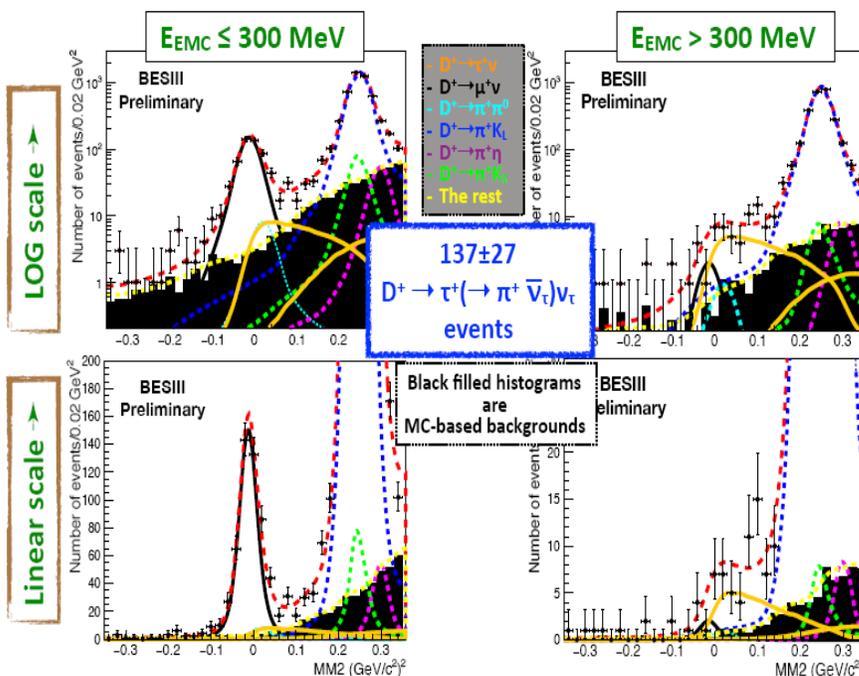
	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
m_{D^+}	1.86965(5) GeV
τ_{D^+}	1.040(7) ps
G_F	$1.1663787(6) \times 10^{-5}$ GeV^{-2}

409±21

$D^+ \rightarrow \mu^+v$

$E_{EMC} \leq 300$ MeV

$E_{EMC} > 300$ MeV

LOG scale →

Linear scale →

137±27
$D^+ \rightarrow \tau^+(\rightarrow \pi^+ \bar{v}_\tau)v_\tau$
events

Black filled histograms are MC-based backgrounds
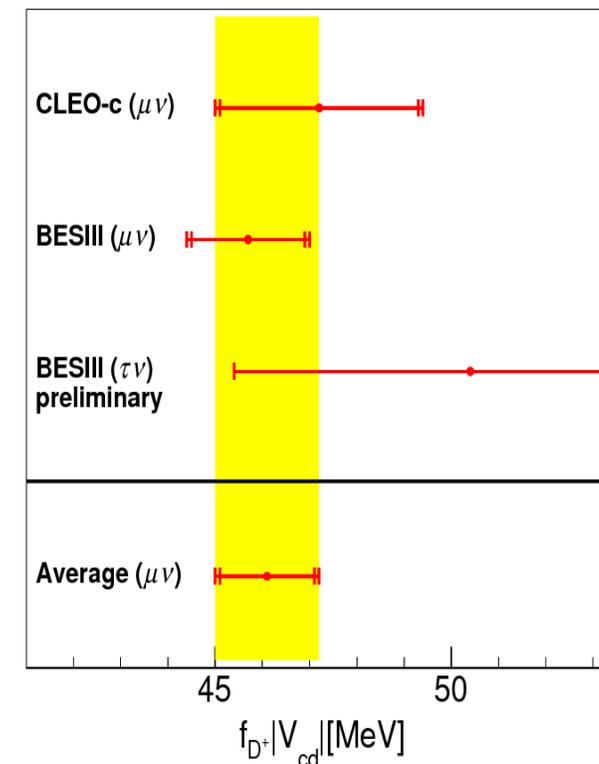
$B[D^+ \rightarrow \mu^+v] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

$B[D^+ \rightarrow \tau^+v] = (1.20 \pm 0.24_{stat}) \times 10^{-3}$

$f_{D^+}|V_{cd}| = 45.75 \pm 1.20 \pm 0.39$ MeV

$f_{D^+}|V_{cd}| = 50.4 \pm 5.0_{stat}$ MeV

statistical error dominant

CLEO-c (μv)

BESIII (μv)

BESIII (τv) preliminary

Average (μv)

$f_{D^+}|V_{cd}|$[MeV]

$f_{D_s^+}|V_{cs}|$ from $D_s^+ \to l^+v$

0.48 fb^{-1} data@4.01 GeV

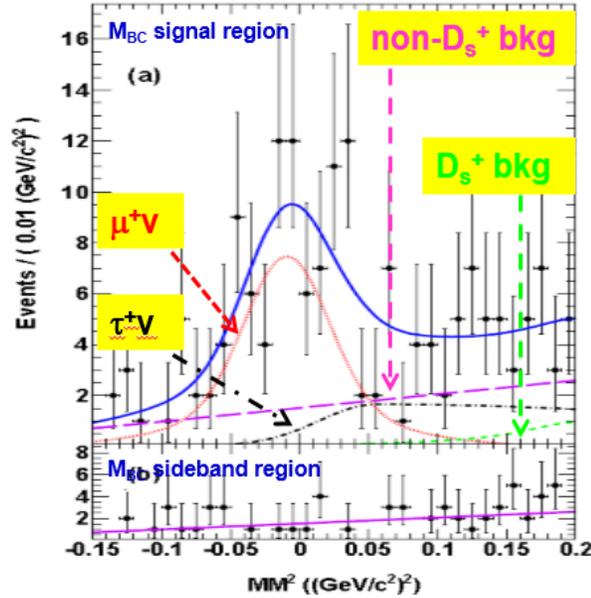**3.19 fb^{-1} data@4.178 GeV**

New inputs from PDG2018:

	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
$m_{D_s^+}$	1.96834(7) GeV
$\tau_{D_s^+}$	504(4) ps
G_F	1.1663787(6)$\times 10^{-5}$ GeV^{-2}

PRD94, 072004 (2016)

PRL122, 071802 (2019)
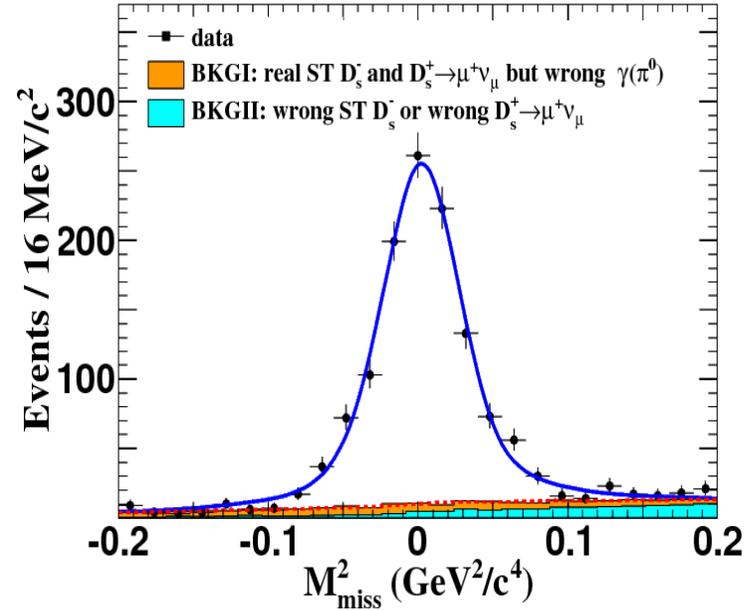
$B[D_s^+ \to \mu^+v] = (5.17 \pm 0.75 \pm 0.21) \times 10^{-3}$

$B[D_s^+ \to \tau^+v] = (3.28 \pm 1.83 \pm 0.37)\%$

$f_{D_s^+}|V_{cs}| = 239 \pm 17 \pm 5$ MeV [μ]

$f_{D_s^+}|V_{cs}| = 193 \pm 54 \pm 11$ MeV [τ]

$B[D_s^+ \to \mu^+v] = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$

$f_{D_s^+}|V_{cs}| = 246.2 \pm 3.6 \pm 3.5$ MeV

Comparisons of f_{D+}, f_{Ds+} and f_{D+}:f_{Ds+}

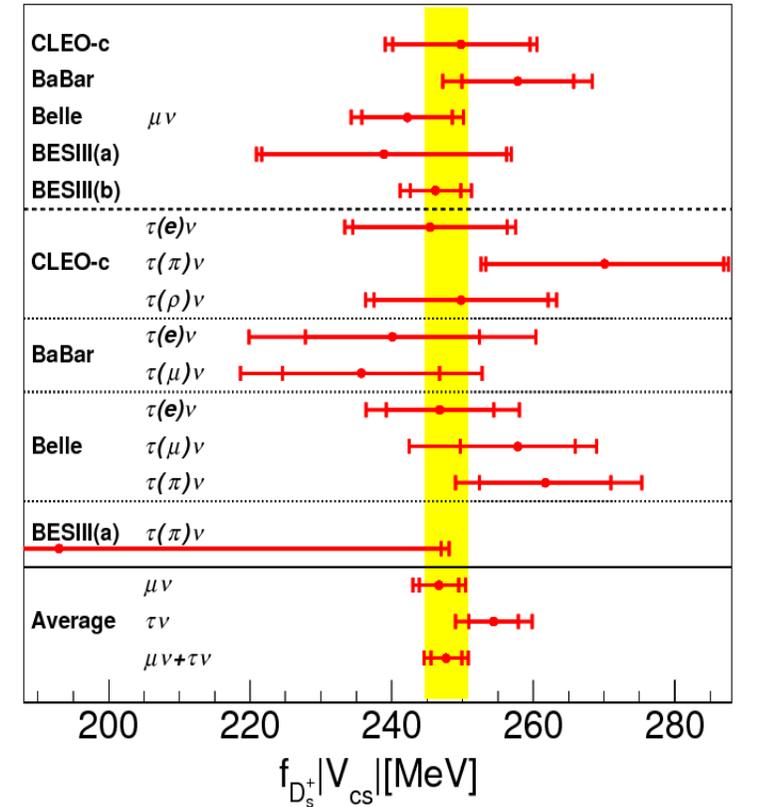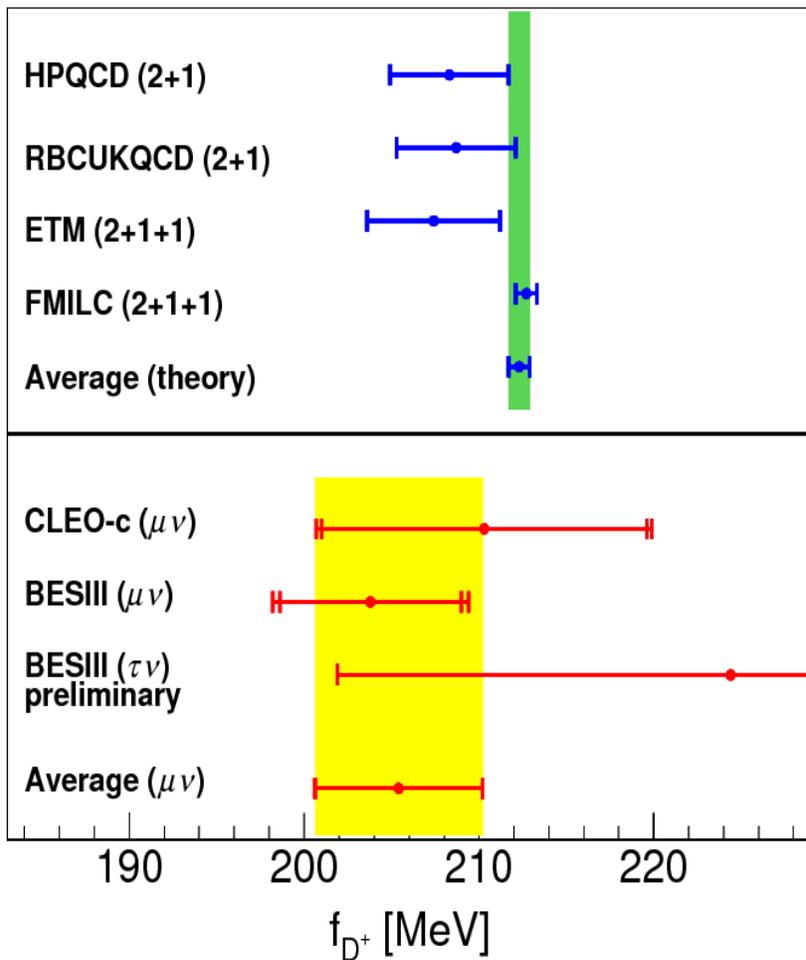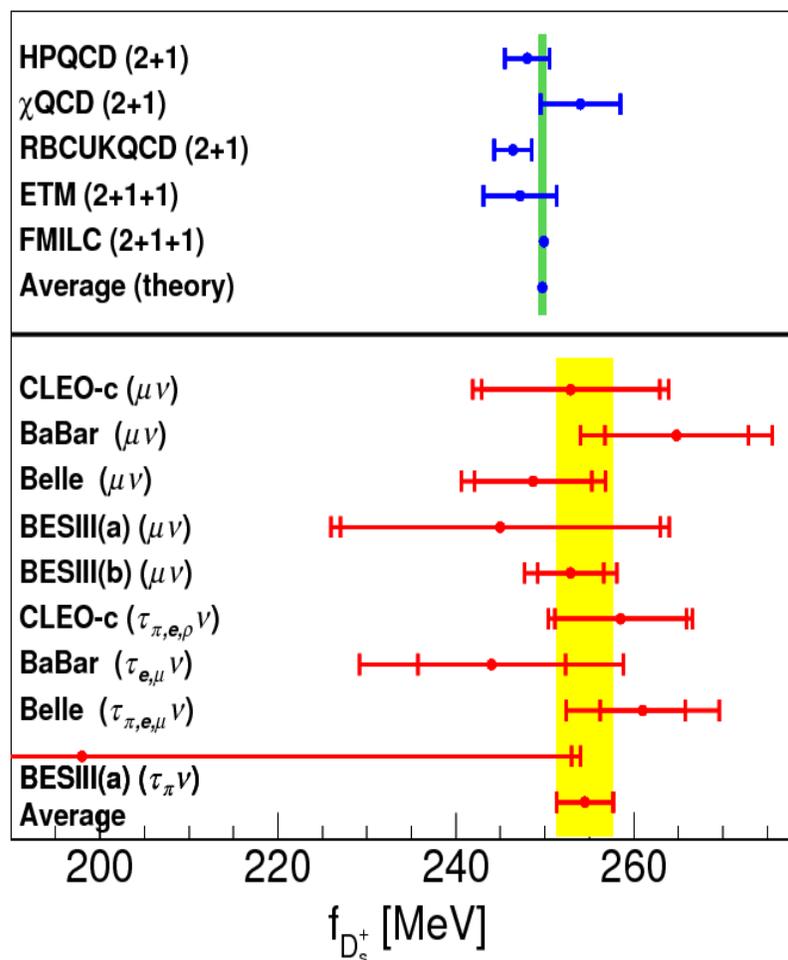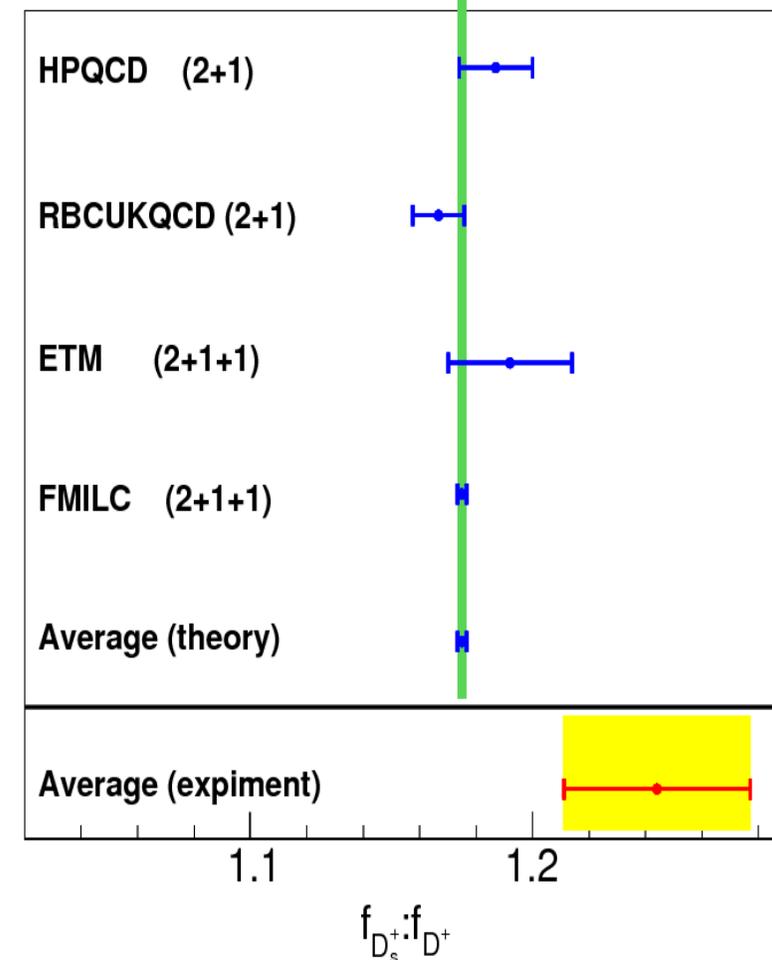**-1.4σ difference** **+1.5σ difference** **2σ difference**

➡ More discussion in Prof. Gottlieb's talk next session.

$f^K_+(0)|V_{cs}|$ from $D^0 \rightarrow K^-\mu^+\nu$

Differential partial widths

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{8\pi^3 m_D} |\vec{p}_K| |f^K_+(q^2)|^2 \left(\frac{W_0 - E_K}{F_0}\right)^2$$

$$\times [\frac{1}{3} m_D |\vec{p}_K|^2 + \frac{m_\ell^2}{8m_D}(m_D^2 + m_K^2 + 2m_D E_K)$$

$$+ \frac{1}{3} m_\ell^2 \frac{|\vec{p}_K|^2}{F_0} + \frac{1}{4} m_\ell^2 \frac{m_D^2 - m_K^2}{m_D} Re\left(\frac{f^K_-(q^2)}{f^K_+(q^2)}\right)$$

$$+ \frac{1}{4} m_\ell^2 F_0 |\frac{f^K_-(q^2)}{f^K_+(q^2)}|^2]$$

Assumed to be independent of q^2 following FOCUS's treatment (PLB607, 233 (2005))

$$q = p_\mu + p_\nu$$

$$W_0 = (m_D^2 + m_K^2 - m_\ell^2)/2m_D$$

$$F_0 = W_0 - E_K + m_\ell^2/2m_D$$

$\chi^2/\text{NDOF} = 15.8/15$

Series expansion parameterization for form factor (2nd order):

$f^K_+(0)|V_{cs}| = 0.7148(38)(29)$

34
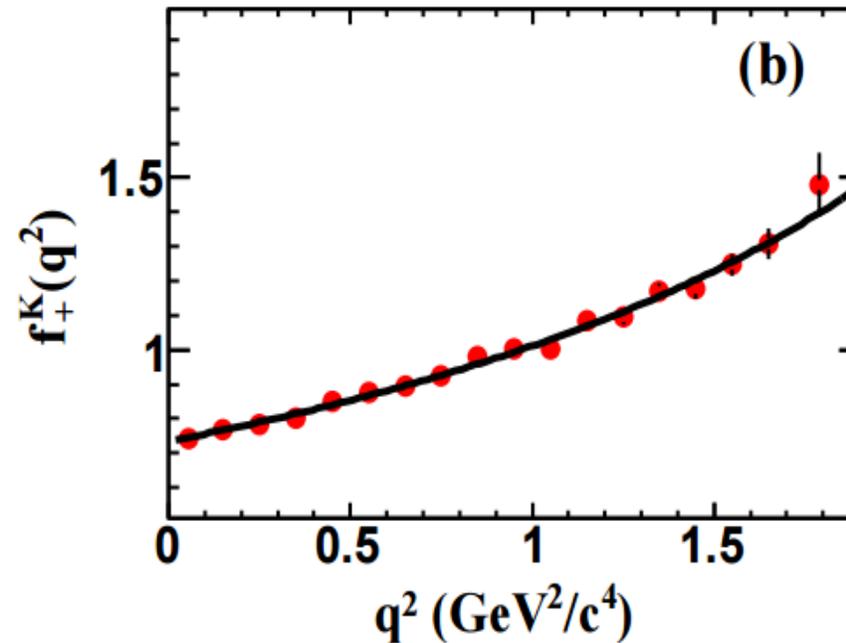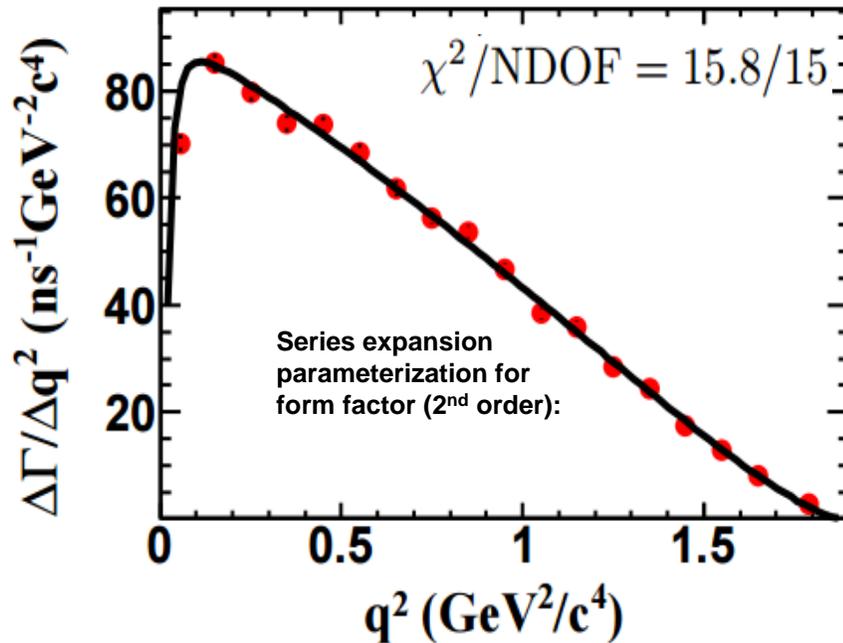
Comparisons of form factors $f_+^{K(\pi)}(0)$

HFLAV16 averages based on a combined analysis of all

D→K(π)lv measurements before 2016 using series expansion

$$f_+^K(0)\,|\,V_{cs}\,| = 0.7226(22)(26)$$

$$f_+^\pi(0)\,|\,V_{cd}\,| = 0.1426(17)(08)$$
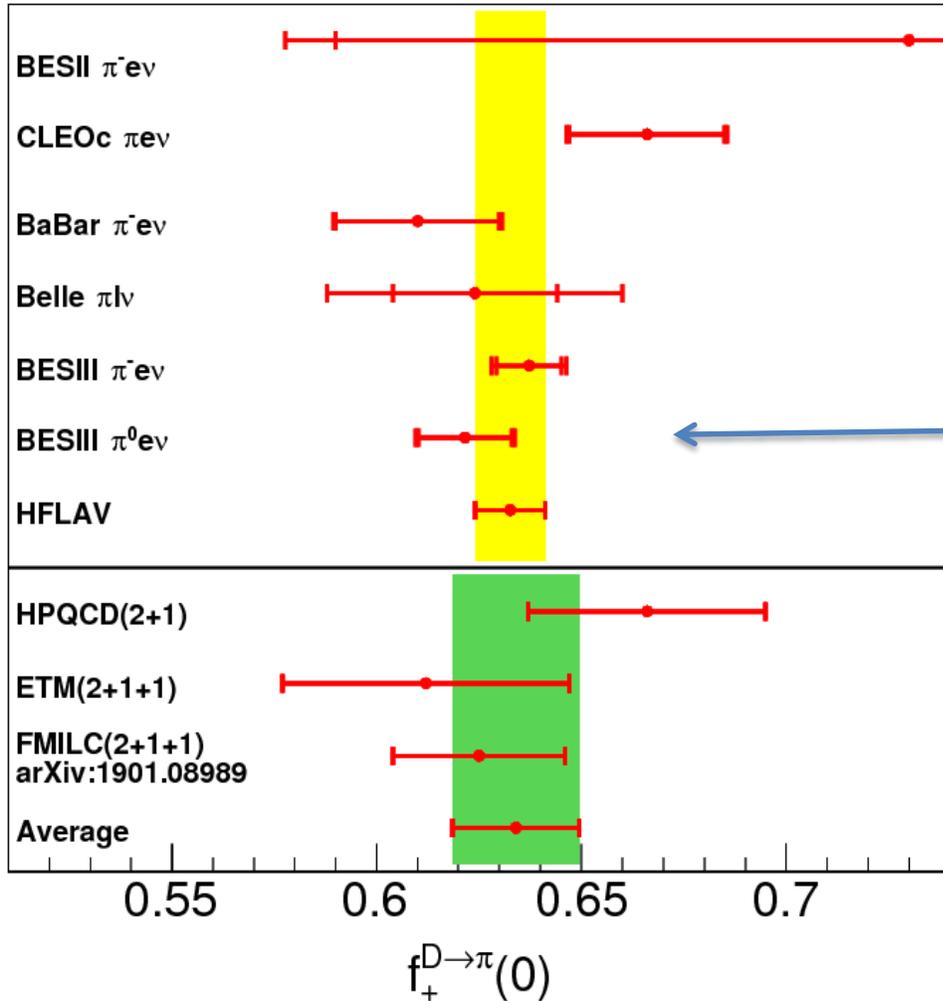
Not included for averages

Left panel axis label: $f_+^{D\to\pi}(0)$

Left panel entries: BESII π^-ev, CLEOc πev, BaBar π^-ev, Belle πlv, BESIII π^-ev, BESIII π^0ev, HFLAV, HPQCD(2+1), ETM(2+1+1), FMILC(2+1+1) arXiv:1901.08989, Average

Right panel axis label: $f_+^{D\to K}(0)$

Right panel entries: BESII K^-ev, CLEOc $\overline{K}$ev, BaBar K^-ev, Belle $\overline{K}$lv, BESIII K^-ev, BESIII K_L^0ev, BESIII K_S^0ev, BESIII $K^-\mu\nu$, HFLAV, HPQCD(2+1), ETM(2+1+1), FMILC(2+1+1) arXiv:1901.08989, Average
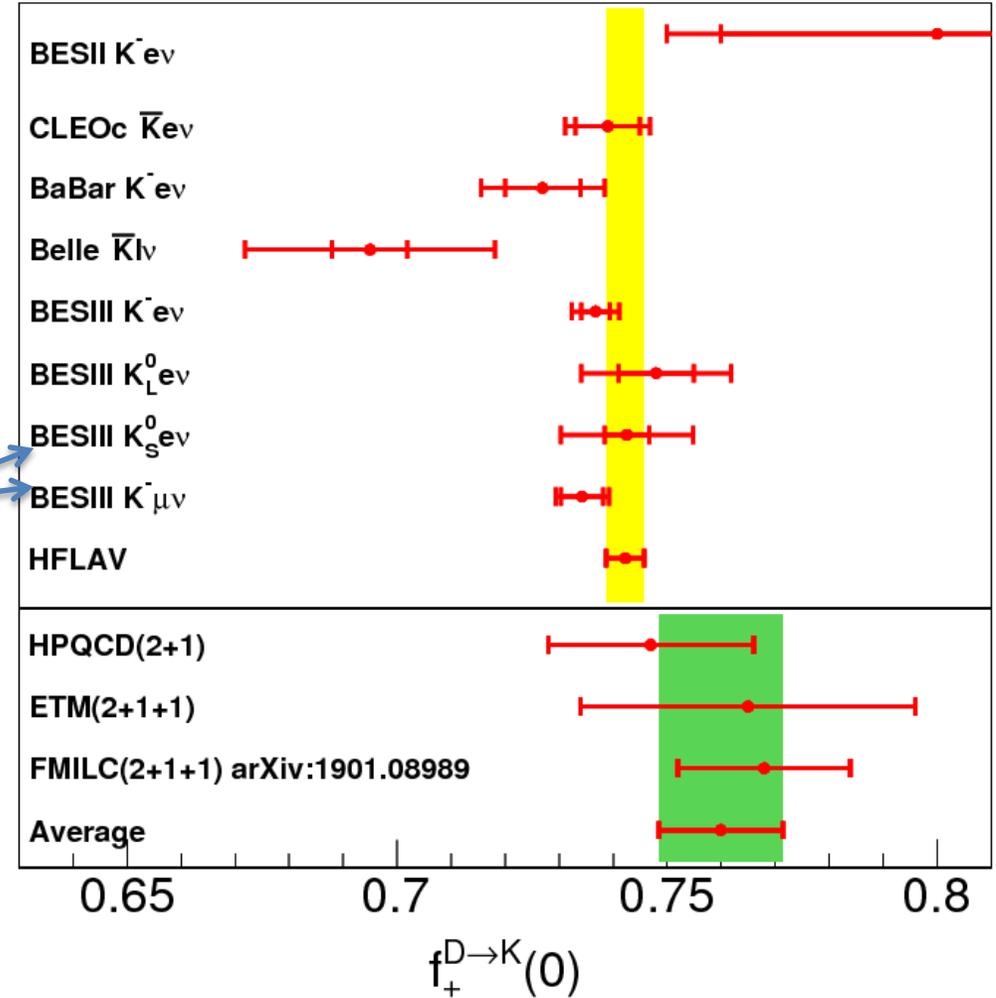
LFU test with semileptonic decays

Mode	D^0 decay BR (%)	D^+ decay BR (%)
$Ke\nu$	3.505 ± 0.035	8.60 ± 0.16
$K\mu\nu$	3.413 ± 0.040	8.72 ± 0.19
$\pi e\nu$	0.295 ± 0.005	0.363 ± 0.009
$\pi\mu\nu$	0.272 ± 0.010	0.350 ± 0.015

$$R_0^\pi = \frac{\Gamma(D^0 \to \pi^-\mu^+\nu)}{\Gamma(D^0 \to \pi^-e^+\nu)} = 0.922 \pm 0.037$$

$$R_+^\pi = \frac{\Gamma(D^+ \to \pi^0\mu^+\nu)}{\Gamma(D^+ \to \pi^0e^+\nu)} = 0.964 \pm 0.045$$

$$R_0^K = \frac{\Gamma(D^0 \to K^-\mu^+\nu)}{\Gamma(D^0 \to K^-e^+\nu)} = 0.974 \pm 0.014$$

$$R_+^K = \frac{\Gamma(D^+ \to \overline{K}^0\mu^+\nu)}{\Gamma(D^+ \to \overline{K}^0e^+\nu)} = 1.014 \pm 0.017$$

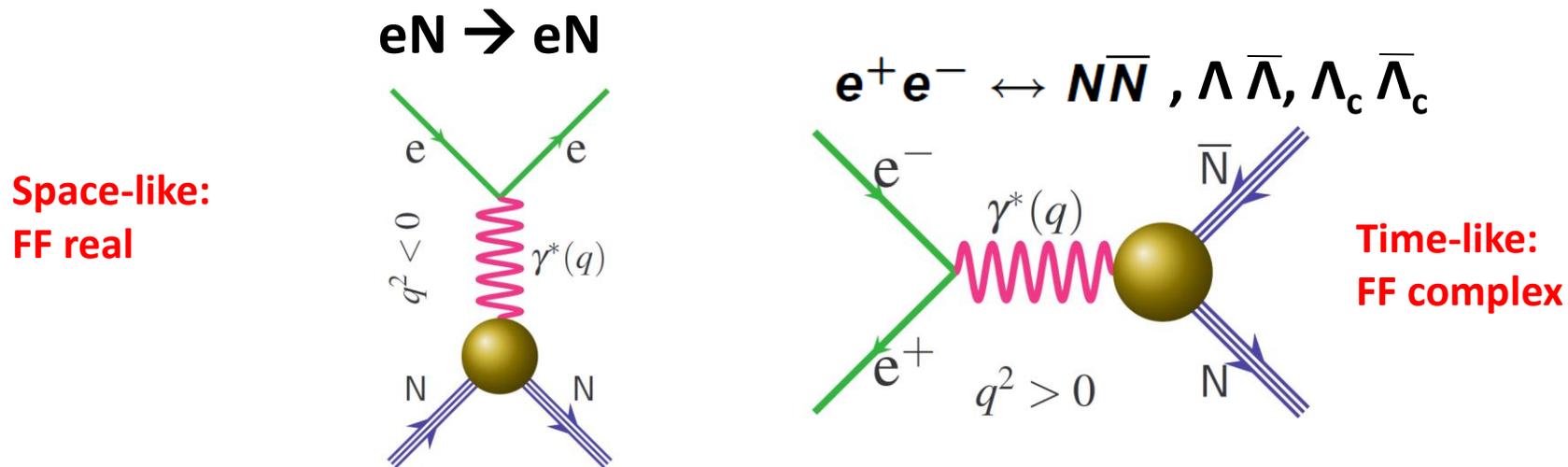Theoretical expectation:

$$R^\pi = 0.985 \pm 0.002$$

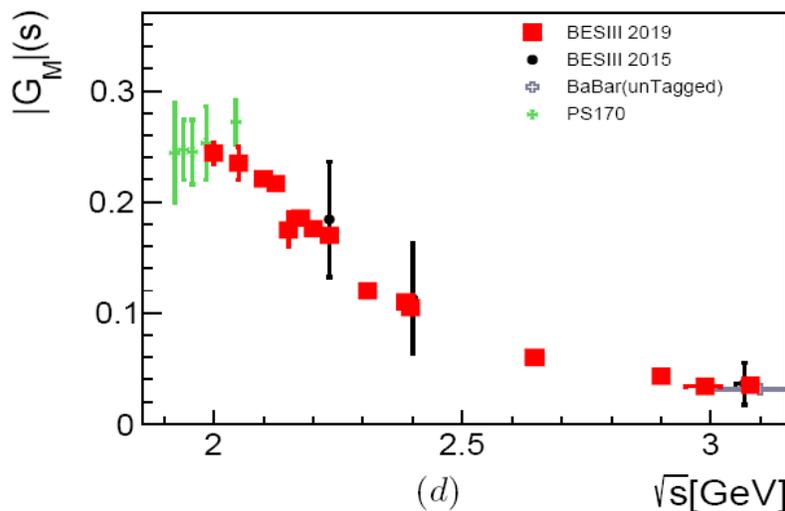$$R^K = 0.975 \pm 0.001$$

Lepton universality tested at % level!

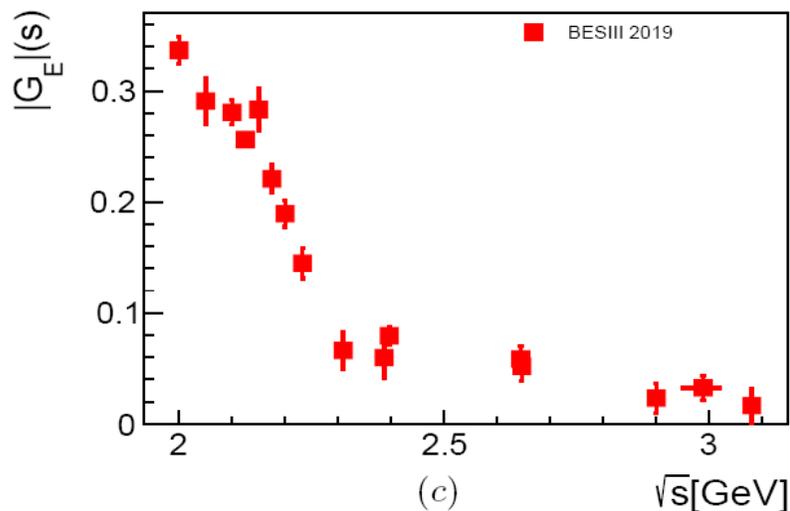# Baryon Form Factors

&

Polarization

Nucleon (and baryon) Form Factor

- **Fundamental properties of the nucleon**

  ➢ **Connected to charge, magnetization distribution**

  ➢ **Crucial testing ground for models of the nucleon internal structure**

  ➢ **Necessary input for experiments probing nuclear structure, or trying to understand modification of nucleon structure in nuclear medium**

- **Can be measured from space-like processes (eN) (precision 1%)**

  or time-like process (e⁺e⁻ annihilation) (precision 10%-30%)

eN → eN

$$e^+ e^- \leftrightarrow N\overline{N} , \Lambda \overline{\Lambda}, \Lambda_c \overline{\Lambda}_c$$

Space-like:
FF real

e e

$q^2 < 0$ $\gamma^*(q)$

N N

e^- $\overline{N}$

$\gamma^*(q)$

e^+ $q^2 > 0$ N

Time-like:
FF complex

BES III

New!

(a) $\sigma_{p\bar{p}}(s)$ [pb] vs $\sqrt{s}$[GeV]

Fit, BESIII 2019, BESIII 2015, BESIII(unTagged), BaBar(Tagged), BaBar(unTagged), CMD3, BES, FENICE, E760, E835, PS170, DM2, χ^2/ndf=0.5863

(b) $|G_E/G_M|(s)$ vs $\sqrt{s}$[GeV]

BESIII 2019, BESIII 2015, BESIII(unTagged), BaBar(Tagged), CMD3, PS170

(c) $|G_E|(s)$ vs $\sqrt{s}$[GeV] — BESIII 2019

(d) $|G_M|(s)$ vs $\sqrt{s}$[GeV] — BESIII 2019, BESIII 2015, BaBar(unTagged), PS170
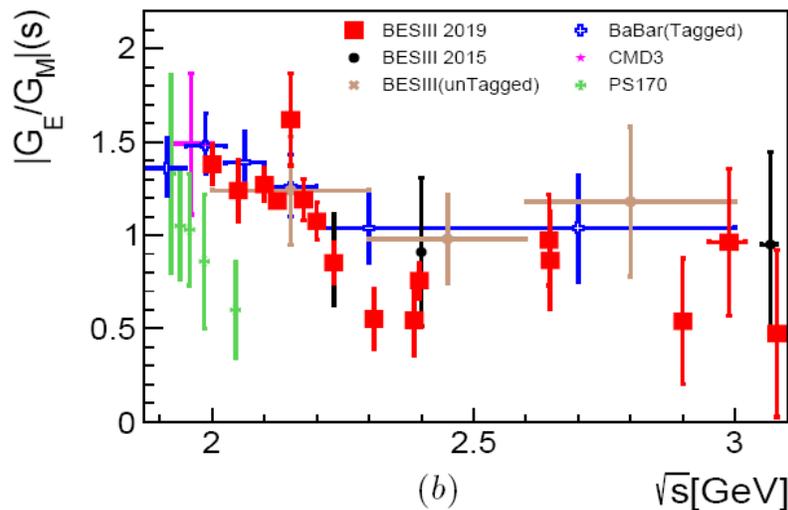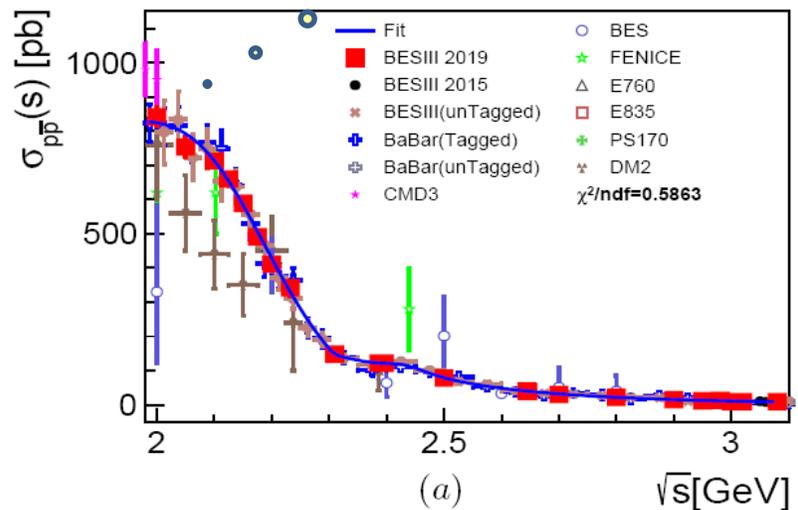
1905.09001, submitted to PRL
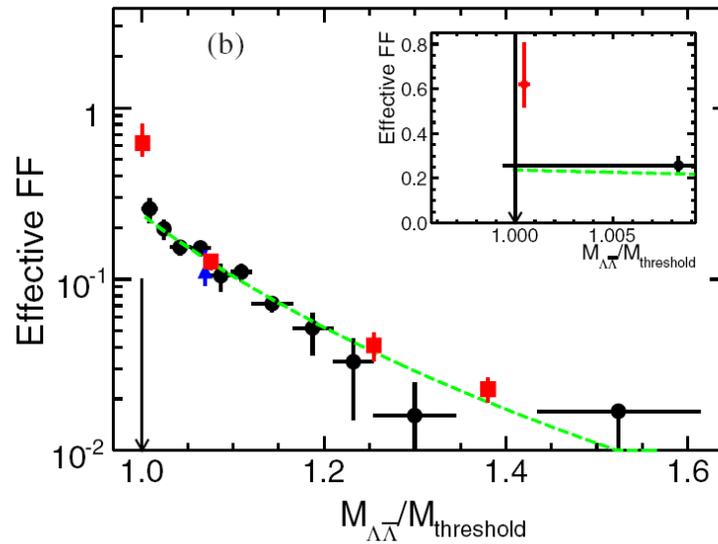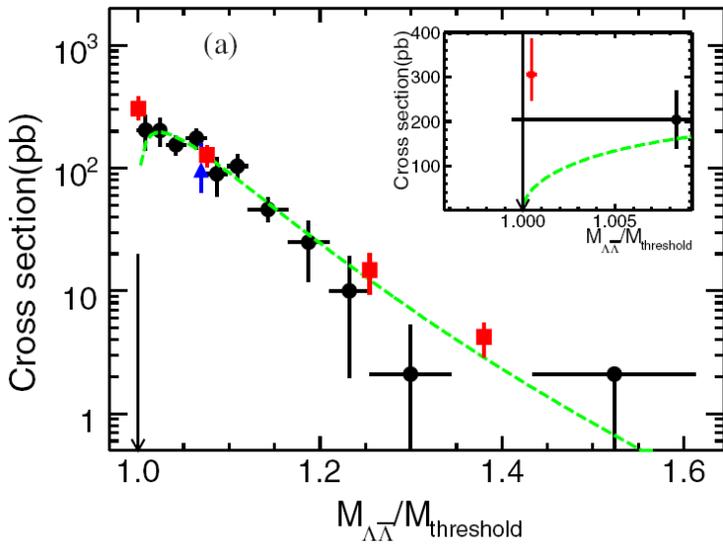+ PRD99, 092002 (2019)
+ PRD91, 112004 (2015)

A. D. Sakharov, Zh. Eksp. Teor. Fiz. 18, 631-635 (1948)

Coulomb interaction for point−like charged particles at threshold:

$$\Delta\sigma = \frac{\pi\alpha^3}{2m_B^2}$$

$\Delta\sigma$ = 0.85 nb for proton
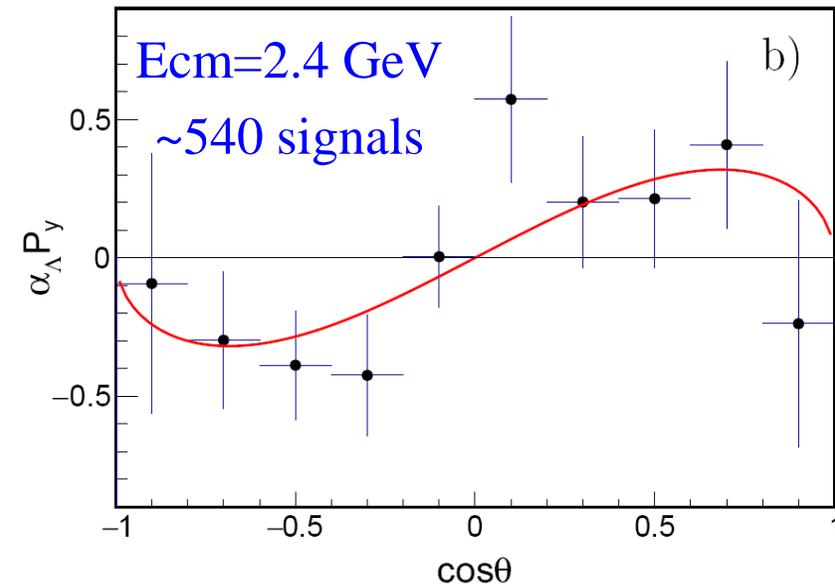
Agree well with data.

Coulomb interaction for point−like charged particles at threshold:

$$\Delta\sigma = \frac{\pi\alpha^3}{2m_B^2}$$

Ecm=2.4 GeV

~540 signals

Spin-correlation between Λ and $\overline{\Lambda}$ and the polarization allow a measurement of the relative phase between G_E and G_M!
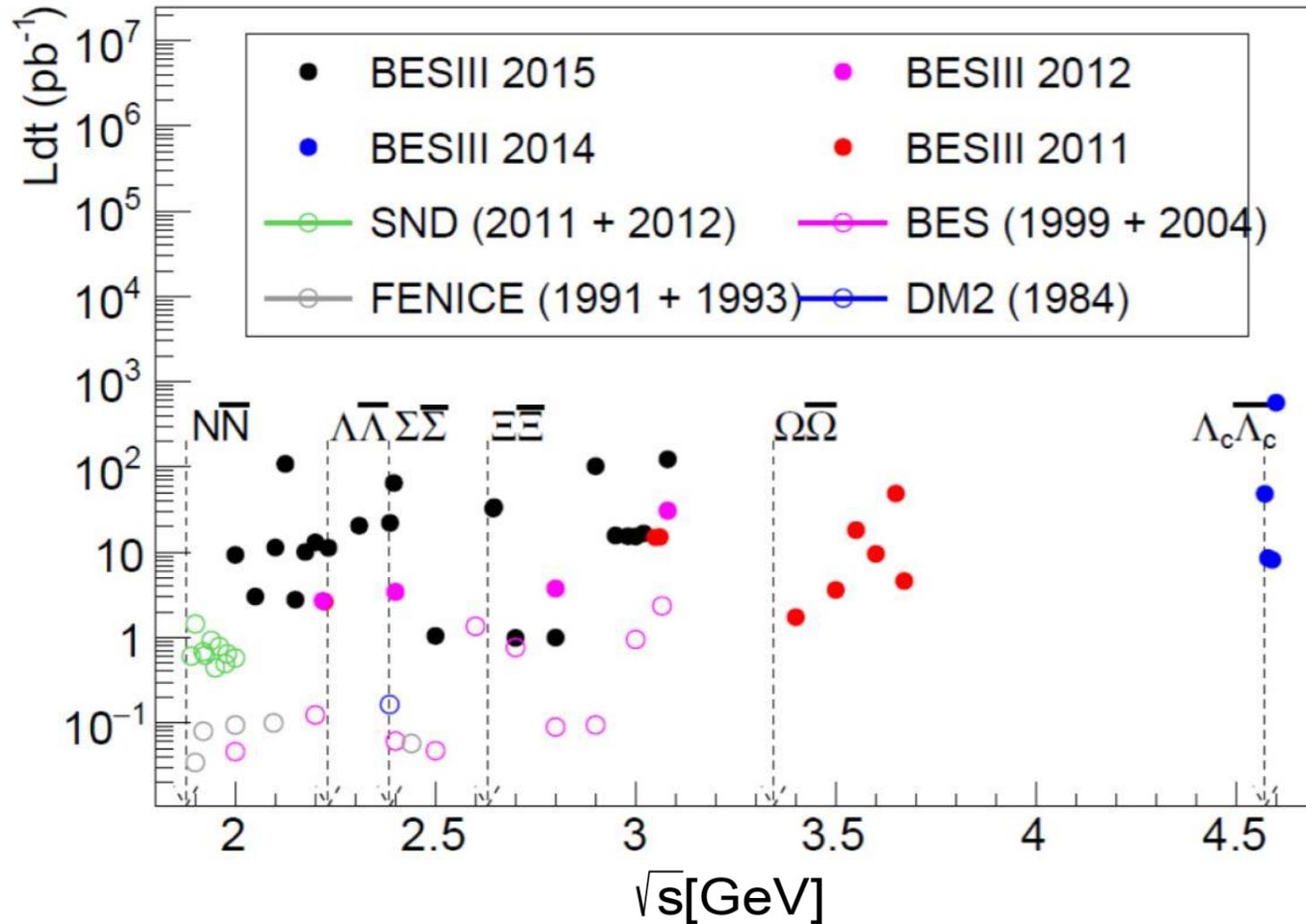
$$\Delta\Phi=(37\pm12\pm6)°$$

$\Delta\sigma$ = 0.305±0.058 nb in data!
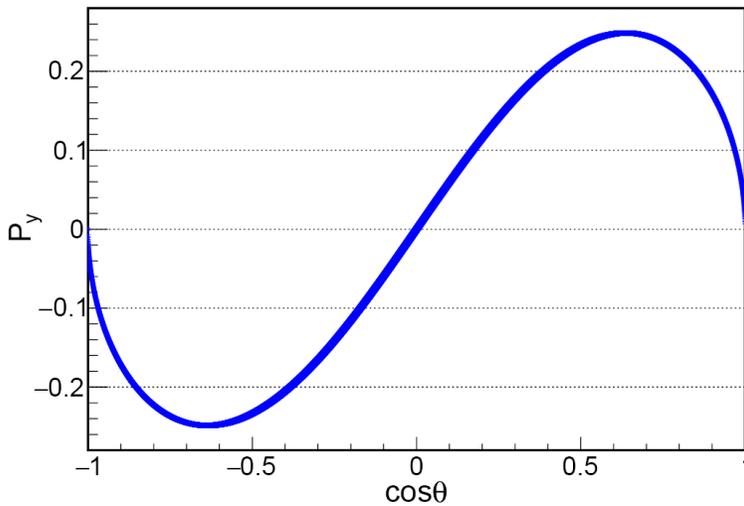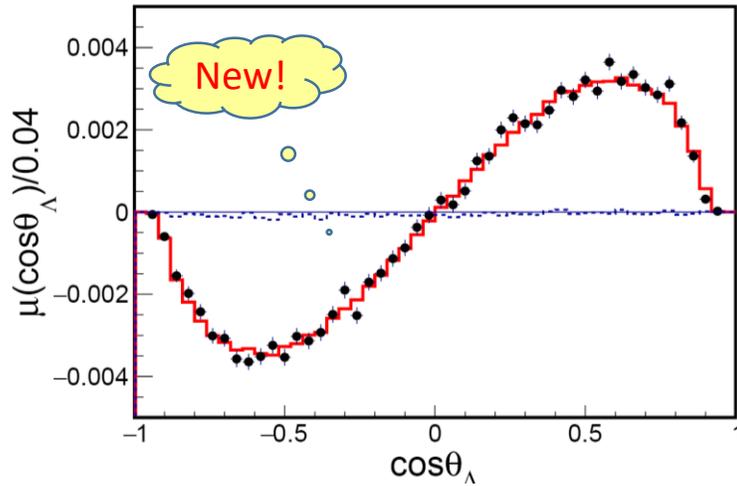
$\Delta\sigma$ = 0 for neutral particle!

$\Delta\sigma$ = 0.60 nb for charged particle with Λ mass.

More study with other baryons

Threshold behavior of different baryons; $|G_E|$, $|G_M|$, and $\Delta\Phi$ over large range of q^2.

More studies with polarized baryons ➜ decay parameters, CPV, …

New!

420K selected $J/\psi \to \Lambda \bar{\Lambda}$ in 1.3B J/ψ events.

First observation of Λ polarization!

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)°$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

Only measurement used in PDG 2019

2% level sensitivity for CPV test

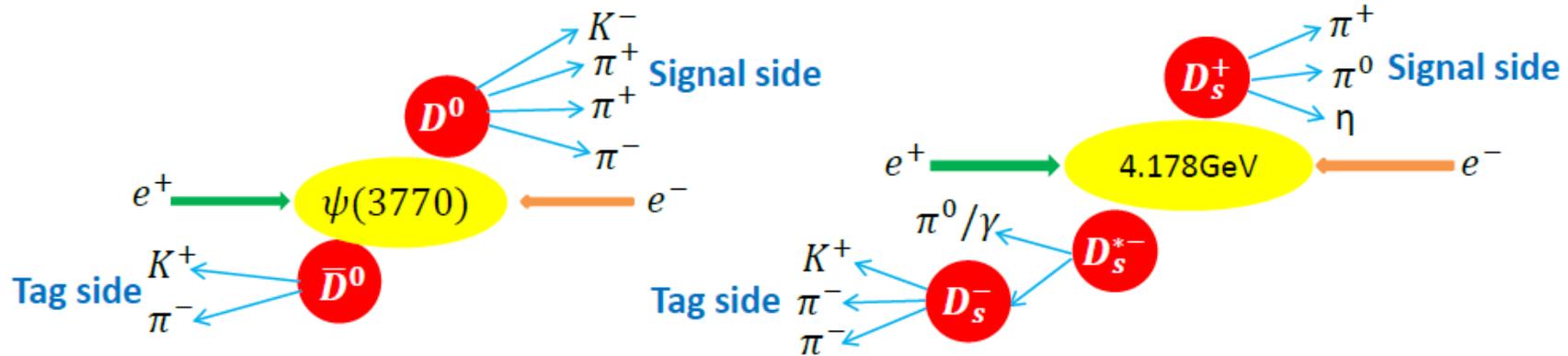Highest sensitivity test of CPV in baryon decays!

Summary

- BESIII achieved a lot in the experimental study of hadron physics and weak decays of charmed hadrons;

- BEPCII beam energy is upgraded from 2.3 to 2.45 GeV; topup injection increases luminosity by 30%; peak luminosity upgrade at high energy is under discussion;

- BESIII detector is in good status, inner detector upgrade in progress;

- BESIII will continue data taking for another 5-10 years and contribute more in these fields;

- LQCD calculations are essential to understand our data!

Thank you!

谢谢！

Charm Production at Threshold

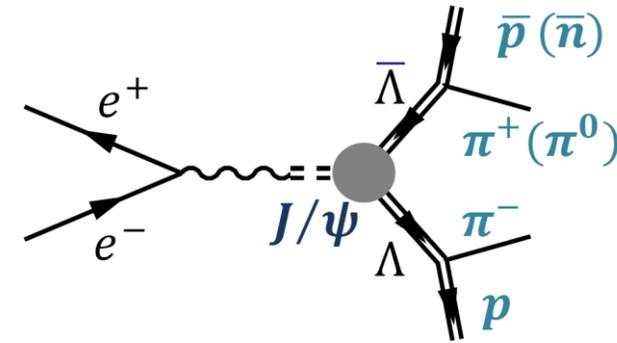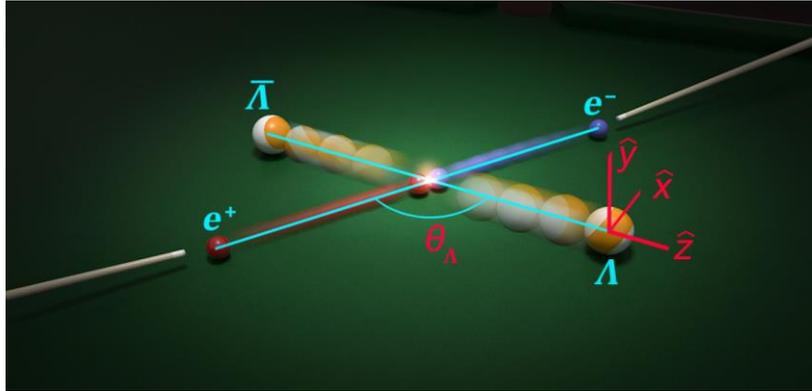- Single tag: fully reconstruct the signal $D_{(s)}$, Λ_c

- Double tag:

  - Fully reconstruct the tag $D_{(s)}$, Λ_c taking advantage of kinematic constrains

  - Search for the signal mode in the recoil system

  - Possible to measure absolute branching fraction or suppress background

$$\Delta E = E_D - E_{\text{Beam}}$$

$$M_{\text{BC}} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$$

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

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

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

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

A non-zero $\Delta\Phi$ results in Λ polarization and makes measuring α_+ and α_- simultaneously possible!

PWA of J/ψ→γφφ

- Besides η(2225), the pseudoscalars above 2 GeV are poorly understood.

- J/ψ→γφφ provides opportunity to study 0^{-+} & 2^{++} states above 2 GeV.

- Dominant contribution from 0^{-+} states
  - ✓ η(2225) is confirmed
  - ✓ Newly observed: η(2100) and X(2500)

- 2^{++} contibutions
  - ✓ $f_2(2010)$, $f_2(2300)$, $f_2(2340)$ from $\pi^- p \to \phi\phi n$ are observed.
  - ✓ Large production rate of $f_2(2340)$

- Model dependent PWA results are consistent with those from MIPWA.
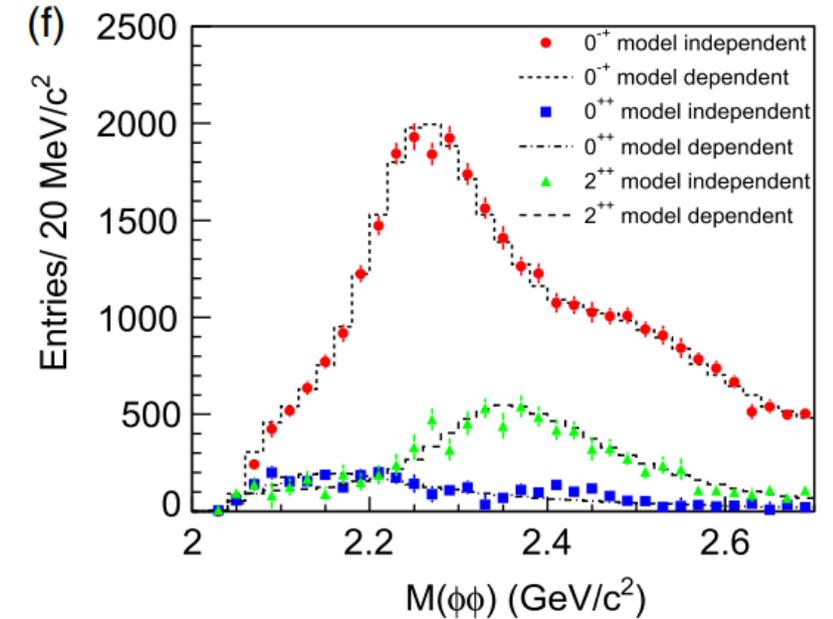
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ