

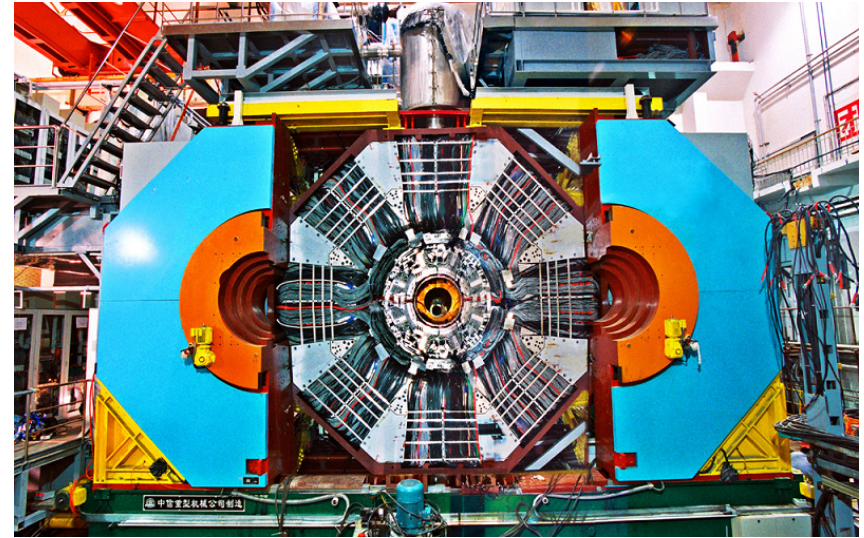
BESIII physics after 15 years: Retrospect, Recent results and Prospects

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July 13, 2023

目前国际上唯一运行在陶粲能区的大科学装置，在近阈值处产生大量的粲强子对和陶轻子对，引领国际陶粲物理研究



- First collision in 2008, physics run started in 2009
- energy upgrade & top-up mode
- Operation c.m. energy: 2.0-4.95 GeV
- BEPCII reached peak lumi of $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ @ 1.89 GeV in April 2016
- 2023 data-taking: $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Secured the running for another 5-10 years, with small (but critical) energy increase and lumi upgrade

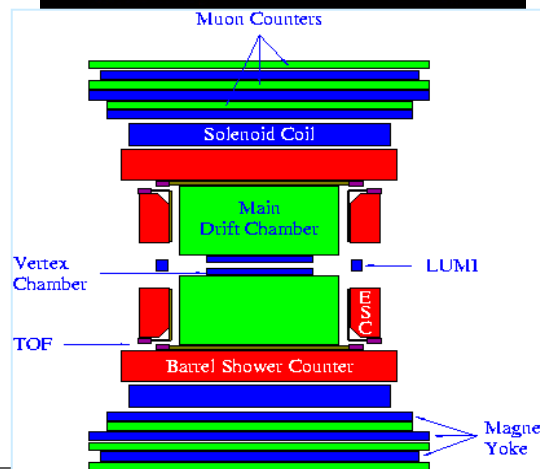
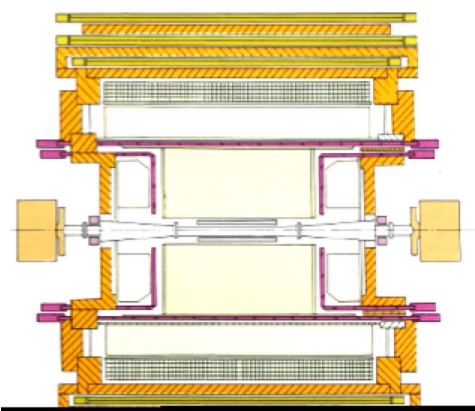
high lumi, large datasets,
hermetic detector with good
performance and clean
environment

- Retrospect: where were we from
- The uniqueness and strength
- Some selected recent results
- Prospects and potentials

- 1984 ground breaking
- 1988 1st collision
- 1989 data-taking began
- Updates in mid-90s: BESII

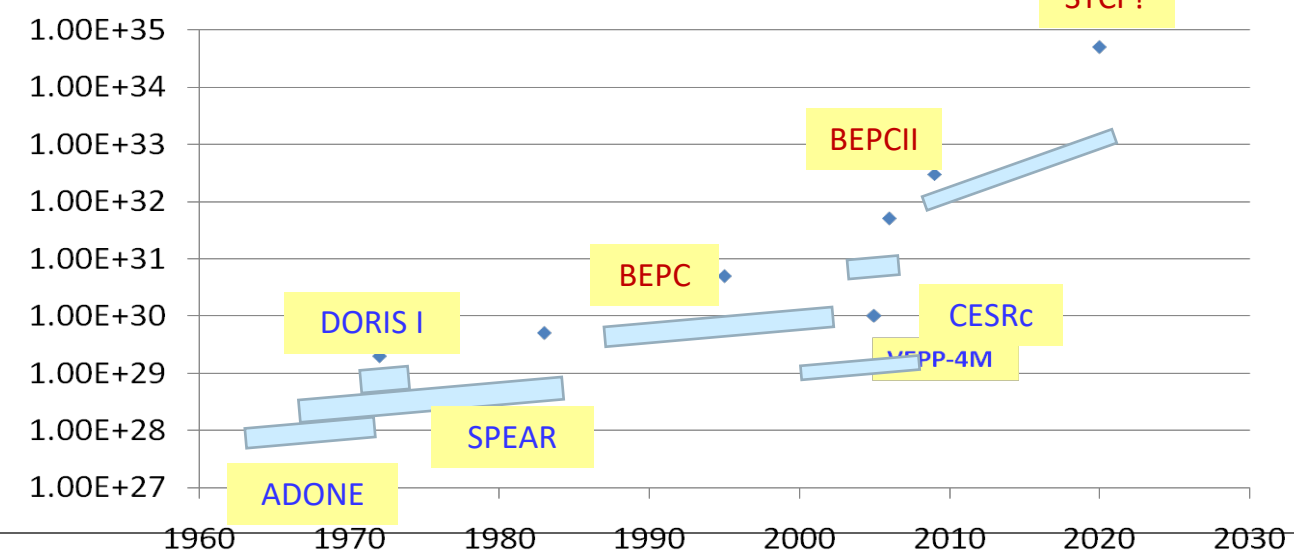


国家科技进步特等奖(1990)



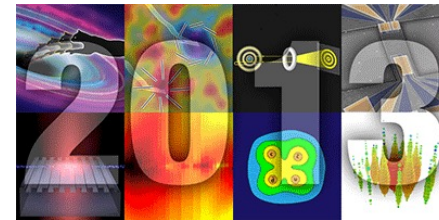
Flavor Physics Lecture
Side view of the BES detector

Luminosity($\text{cm}^{-2}\text{s}^{-1}$)



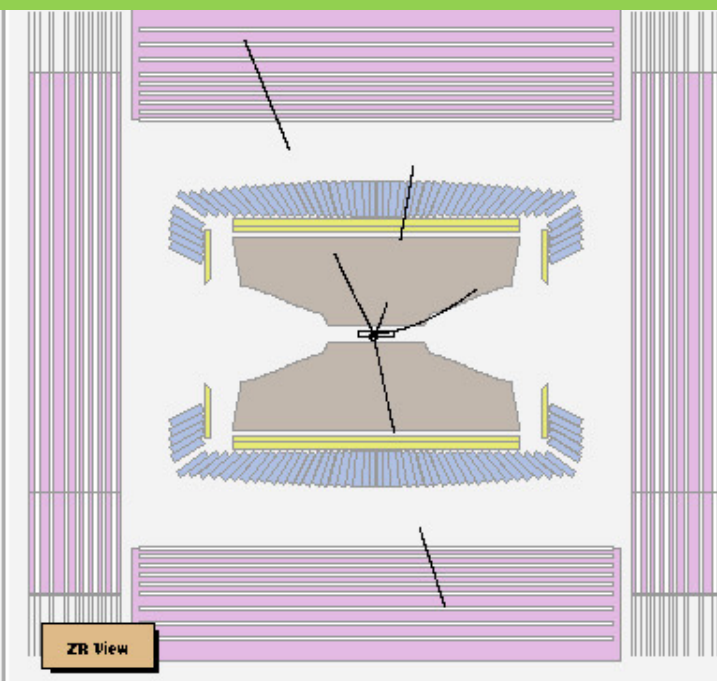
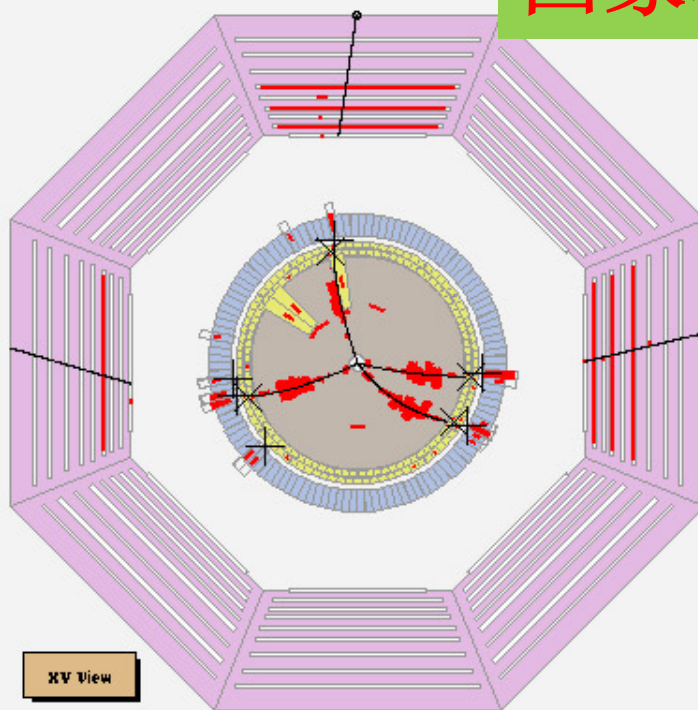
Dayong Wang

- **T mass** measurement (BES+BESIII)
 - 1995年国家自然科学二等奖
- **R value** measurement (BESII)
 - 2004年国家自然科学二等奖
- **Charmonium** physics
 - 2001年国家自然科学二等奖
- **Charm** physics (BESII+BESIII)
 - 2010年国家自然科学二等奖
- **Exotic hadrons** (BESII+BESIII)
 - 2013年国家自然科学二等奖



| | | | | |
|-------------------------|-------------|-----------------------|-----------------|----------------|
| Run 4530 | | <i>BesVis</i> | | |
| Event 100893 | | | | |
| <i>date: 2008-07-20</i> | | <i>time: 07:04:04</i> | | |
| MC=No | P= 3.116GeV | Pt= 2.903GeV | tofMin= 0.000ns | Ecal= 1.082GeV |
| MDC Track(GeV): | P1=0.945 | P2=0.702 | P3=0.421 | P4=1.048 |
| EMC Cluster(MeV): | E1=151.91 | E2=226.00 | E3=295.91 | E4=165.27 |
| E5=48.68 | E6=193.98 | | | |

国家科技进步一等奖 (2016)



It is 15th year since BEPCII/BESIII came online!

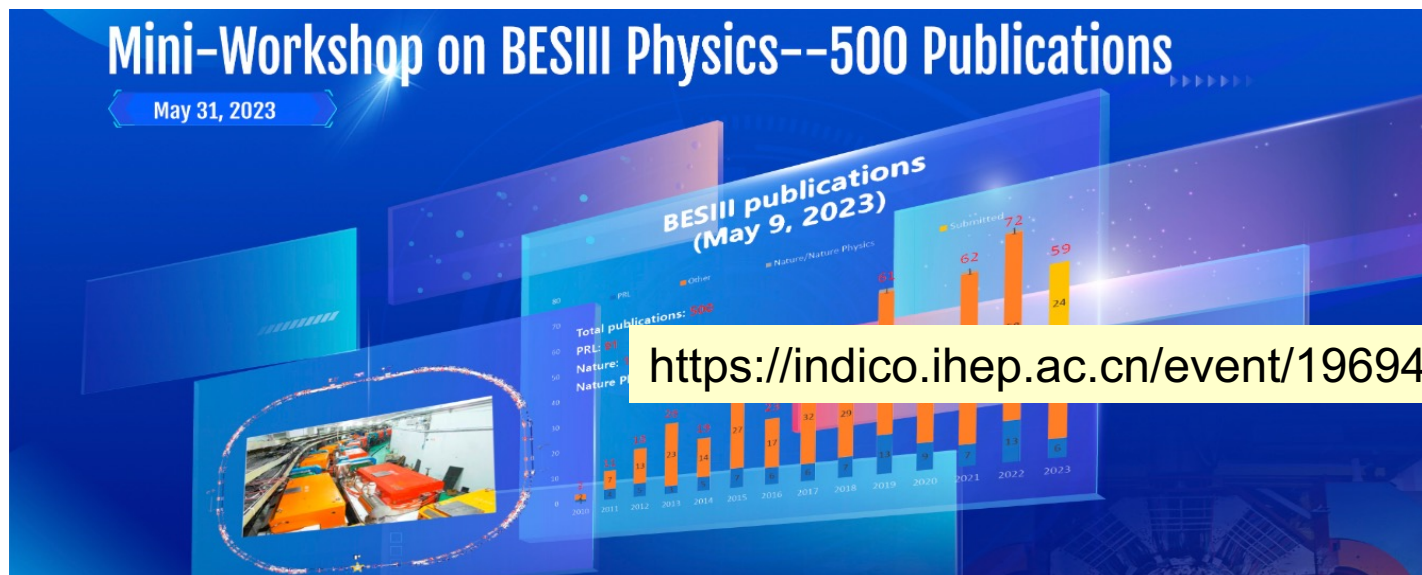
2023/01/07 18:18:47

Luminosity 10.50 E32/cm²/s

| | e+ | e- |
|-------------------|--------|--------|
| Energy [GeV] | 1.8935 | 1.8935 |
| Current [mA] | 885.64 | 843.00 |
| Lifetime [hr] | 1.61 | 1.94 |
| Inj.Rate [mA/min] | 0.00 | 0.00 |

We have reached 500 paper milestones
95 publications in PRL/Nature/Nat. Phys.

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



The collaboration size still growing: ~600 members from 86 institutions in 17 countries.

Some comments on the near-term/mid-term prospects

1

Unique energy
region and data
samples

2

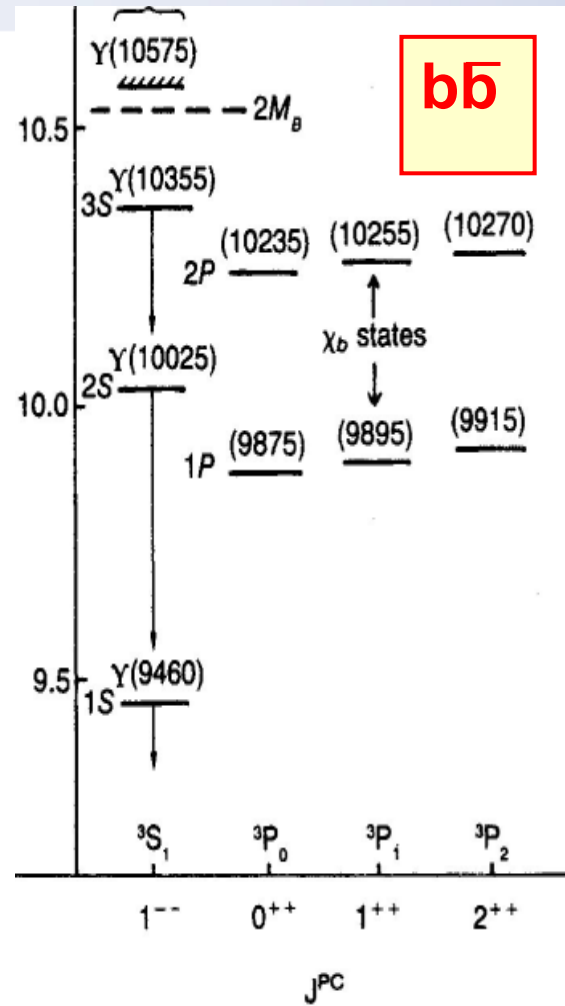
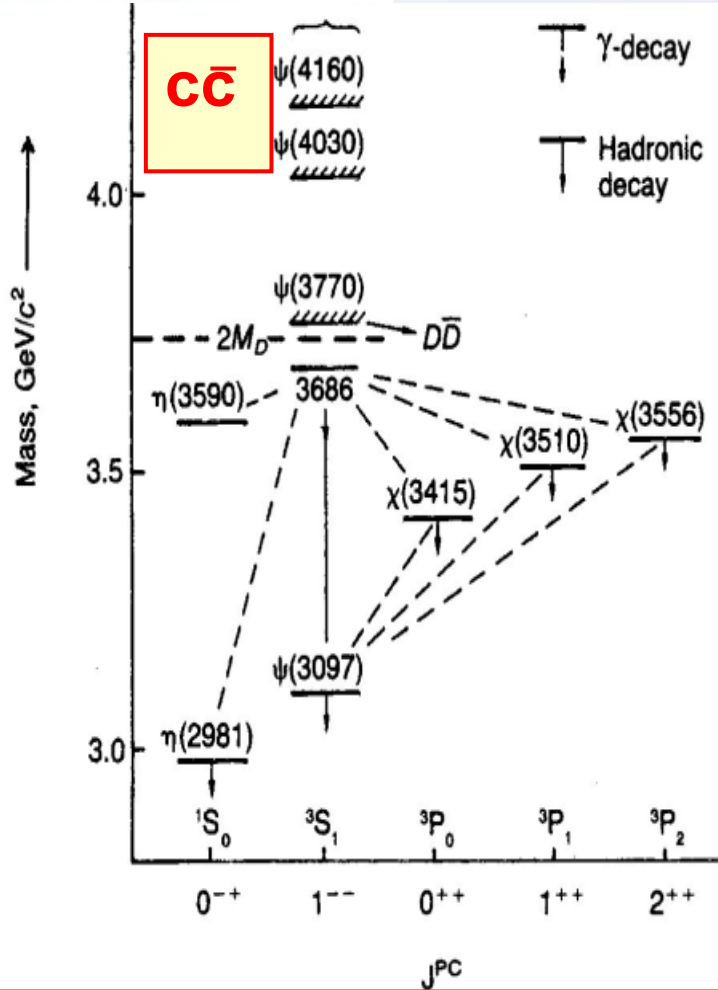
High statistics,
high quality
data

3

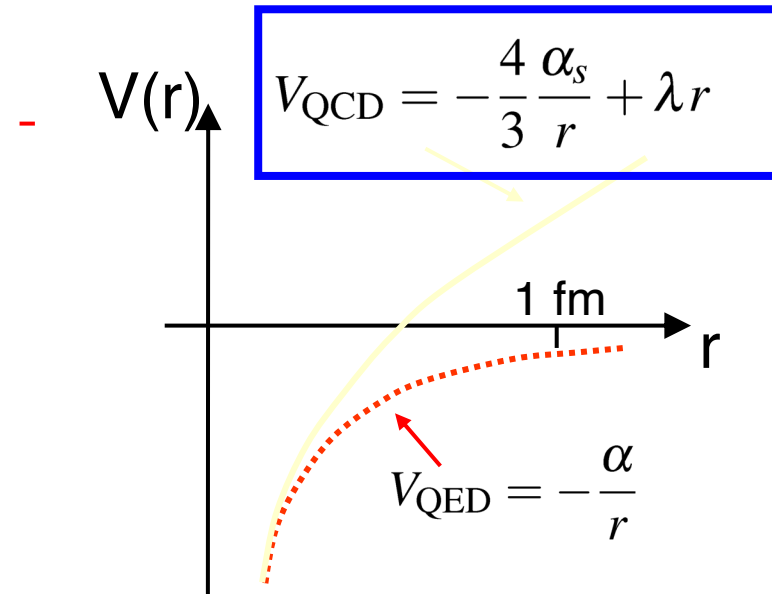
On-threshold
production;
correlated tags

4

Close collab of
theory and
experiment



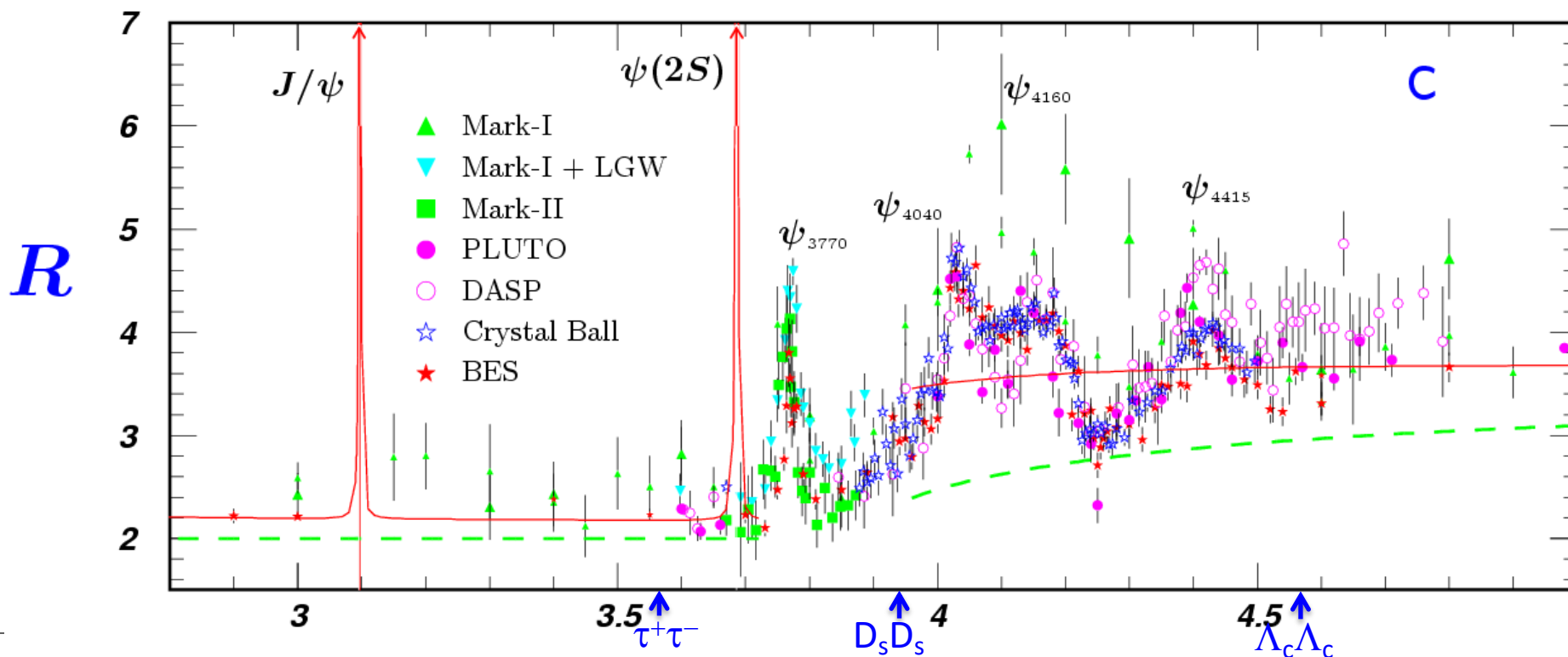
“Cornell” potential



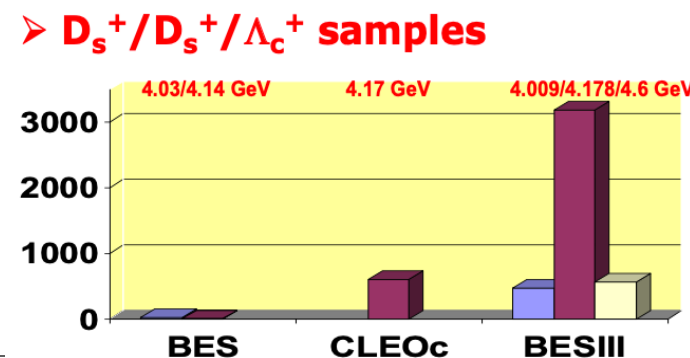
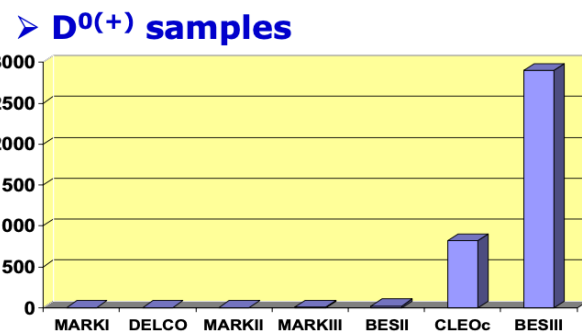
- **c, b** are heavy quarks
- approx. non-relativistic
- orbit close together
- probe $1/r$ part of V_{QCD}

Heavy Quarkonia: H atom of Strong Interaction

- Rich of **resonances**, charmonia and charmed mesons.
- **Threshold** characteristics (pairs of τ , D , D_s , charmed baryons...).
- **Transition** between perturbative and non-perturbative **QCD**.
- New **hadrons**: glueballs, hybrids, multi-quark states
- **New Physics**: rare decays; symmetry probes; BSM searches



- 1 Unique energy region and data samples
- 2 High statistics, high quality data
- 3 On-threshold production; correlated tags
- 4 Close collab of theory and experiment



huge sub-samples, such as $\eta, \eta', \omega, \phi, K_S^0$, hyperons ...

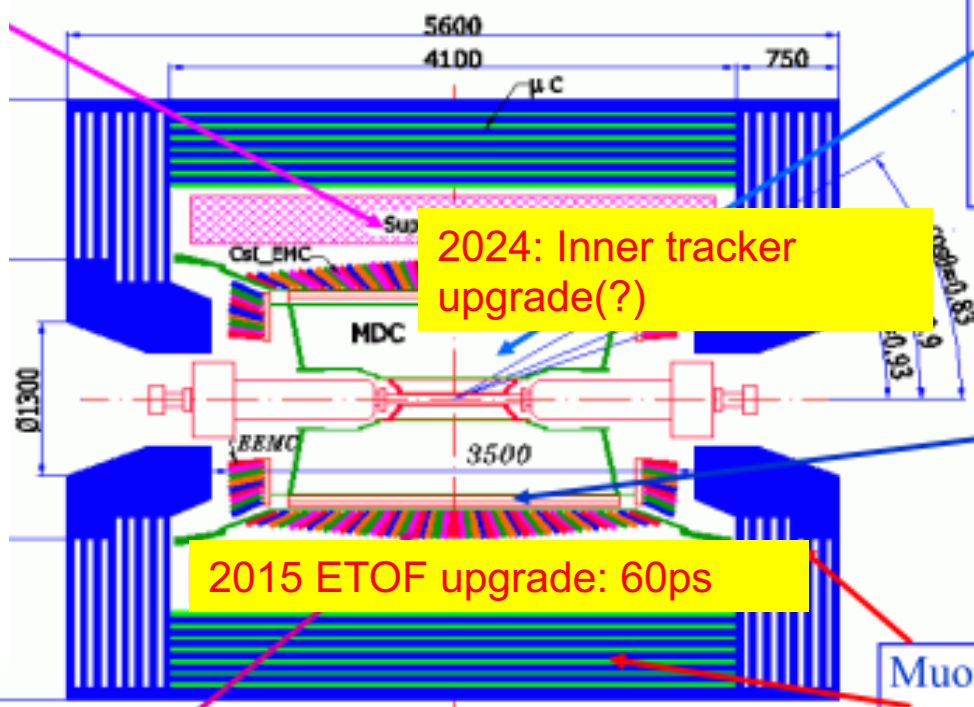
2009: 106M $\psi(2S)$
 225M J/ψ
 2010: 0.98 fb⁻¹ $\psi(3770)$ (for $D^{0(+)}$)
 2011: 2.93 fb⁻¹ $\psi(3770)$ (for $D^{0(+)}$, total)
 0.48 fb⁻¹ @4.01 GeV
 2012: 0.45B $\psi(2S)$ (total)
 1.30B J/ψ (total)
 2013: 1.09 fb⁻¹ @4.23 GeV
 0.83 fb⁻¹ @4.26 GeV
 0.54 fb⁻¹ @4.36 GeV
 10×0.05 fb⁻¹ XYZ scan@3.81-4.42 GeV
 2014: 1.03 fb⁻¹ @4.42 GeV
 0.11 fb⁻¹ @4.47 GeV
 0.11 fb⁻¹ @4.53 GeV
 0.05 fb⁻¹ @4.575 GeV
 0.57 fb⁻¹ @4.60 GeV (for Λ_c^+)
 0.80 fb⁻¹ R scan @3.85-4.59 GeV

2015: R-scan 2-3 GeV+2.175 GeV
 2016: 3.20 fb⁻¹ @4.178 GeV (for D_s^+)
 2017: 7×0.50 fb⁻¹ XYZ scan@4.19-4.27 GeV
 2018: More J/ψ +tuning new RF cavity
 2019: 10B J/ψ (total)
 8×0.50 fb⁻¹ XYZ scan@4.13, 4.16, 4.29-4.44 GeV
 2020: 3.8 fb⁻¹ @ 4.61-4.7 GeV (XYZ& Λ_c^+)
 2021: 2.0 fb⁻¹ @ 4.74-4.946 GeV
 2021: 2.7B $\psi(2S)$ (total)
 2022: 2×0.4 fb⁻¹@3.65, 3.682 GeV,
 5.1 fb⁻¹ $\psi(3770)$ (for $D^{0(+)}$, total)
 2023: ~8 fb⁻¹ at $\psi(3770)$

More than 47 fb⁻¹ of data taken between 2 and 4.95 GeV

Solenoid Magnet: 1 T Super conducting

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



2024: Inner tracker upgrade(?)

2015 ETOF upgrade: 60ps

MDC: small cell & He gas
 $\sigma_{xy} = 130 \mu\text{m}$
 $\delta p/p = 0.5\% @ 1\text{GeV}$
 $dE/dx = 6\%$

TOF:
 $\sigma_T = 90 \text{ ps}$ Barrel
 110 ps Endcap

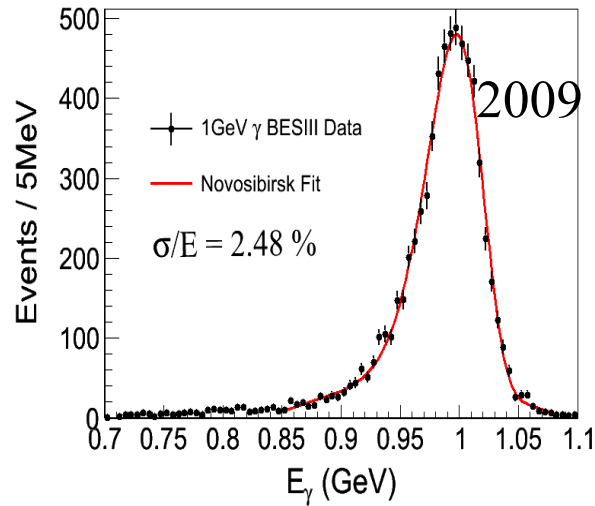
Muon ID: 8~9 layer RPC
 $\sigma_{R\Phi} = 1.4 \text{ cm} \sim 1.7 \text{ cm}$

EMCAL: CsI crystal
 $\Delta E/E = 2.5\% @ 1 \text{ GeV}$
 $\sigma_{\phi,z} = 0.5 \sim 0.7 \text{ cm}/\sqrt{E}$

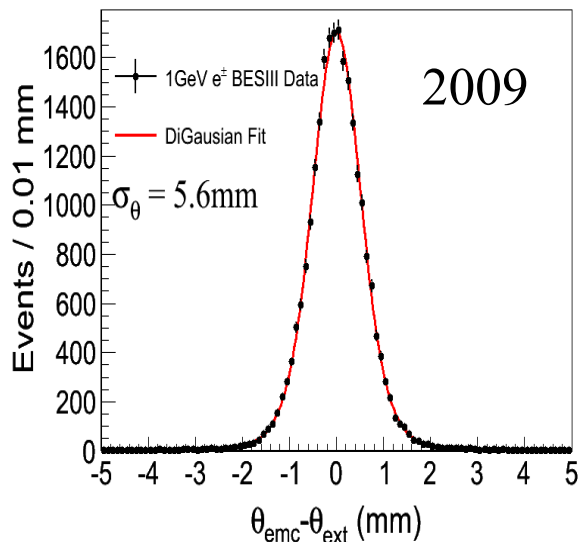
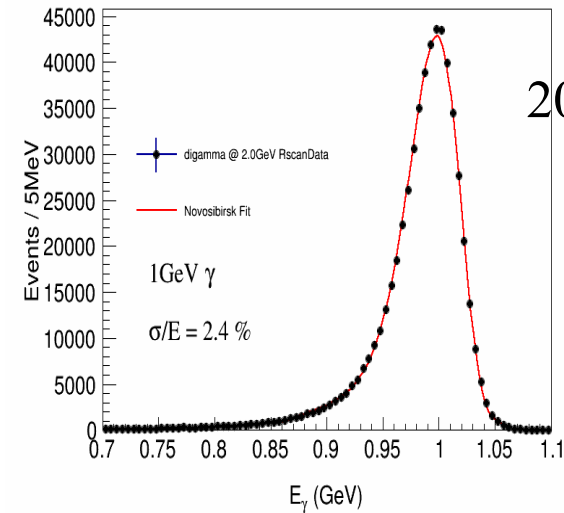
Data Acquisition:
 Event rate = 3 kHz
 Throughput $\sim 50 \text{ MB/s}$

Trigger: Tracks & Showers
 Pipelined; Latency = 6.4 μs

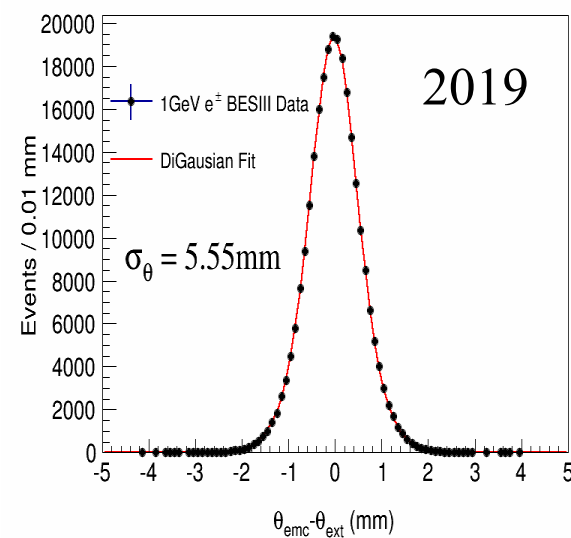
competitive in channels with low energy electron/photons, neutrons, pi0's



Energy Resol.



Angular Resol.



1

Unique energy region and data samples

2

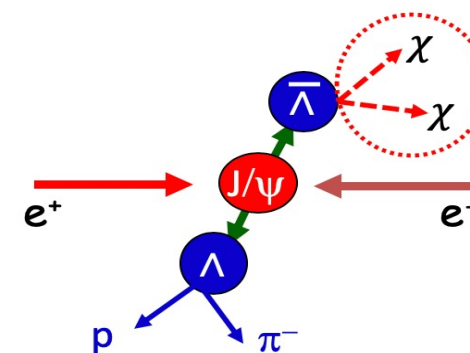
High statistics, high quality data

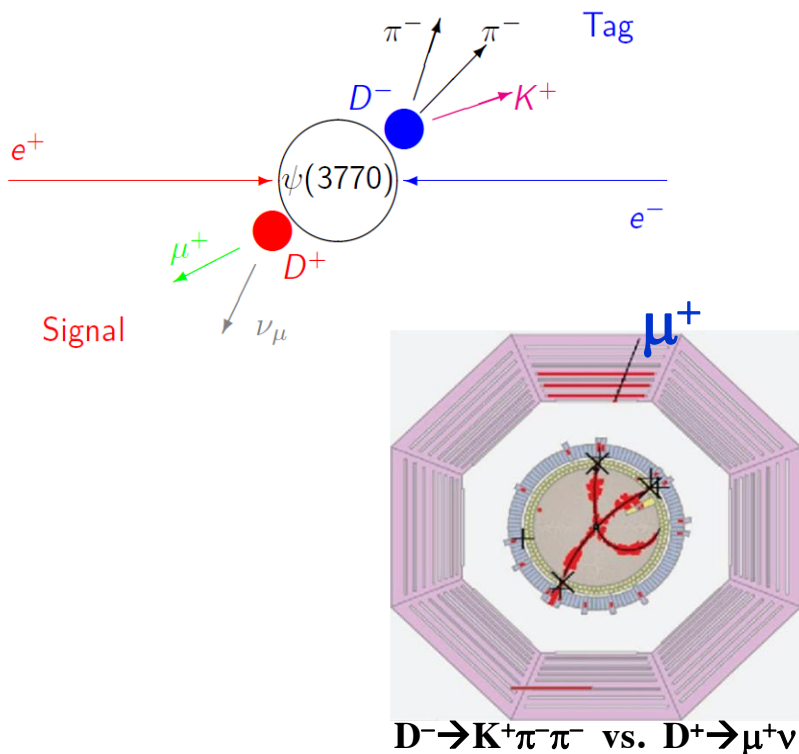
3

On-threshold production; correlated tags

4

Close collab of theory and experiment





- $e^+e^- \rightarrow D\bar{D}$ ($\Lambda_c^+\Lambda_c^-$), near Thrs.

- Double tag analysis

- ✓ Tagging D^- (\bar{D}^0), Λ_c^- from hadronic decay modes

$$M_{BC} = \sqrt{E_{\text{beam}}^2 - p_{D_{\text{tag}}}^2}$$

- ✓ (semi-)leptonic decay event can be well reconstructed in the recoil side of the tagged \bar{D} (Λ_c^-)

$$M_{\text{missing}}^2 = E_{\text{miss}}^2 - p_{\text{miss}}^2 \sim 0$$

$$U_{\text{miss}} \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}| \sim 0$$

Charmed hadrons:

- Produced in pair
- Quantum correlated $D^0\bar{D}^0$

- Event is very clean
- High tagging efficiency
- Most systematic uncertainties can be cancelled
- Could measure absolute BFs

2.93 \rightarrow 8 fb⁻¹@3.773 GeV $\rightarrow D^0\bar{D}^0$ and D^+D^-
 0.48 fb⁻¹@4.009 GeV $\rightarrow D_s^+D_s^-$
 7.33 fb⁻¹@4.13-4.23 GeV $\rightarrow D_s^*\bar{D}_s$
 4.5 fb⁻¹@4.6-4.7 GeV $\rightarrow \Lambda_c^+\bar{\Lambda}_c^-$



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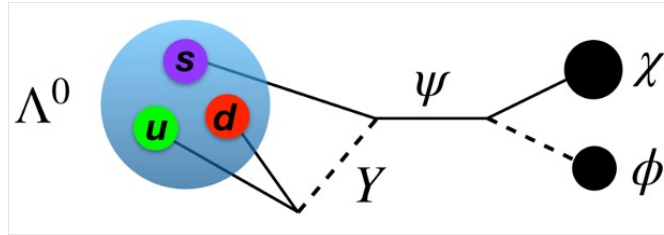
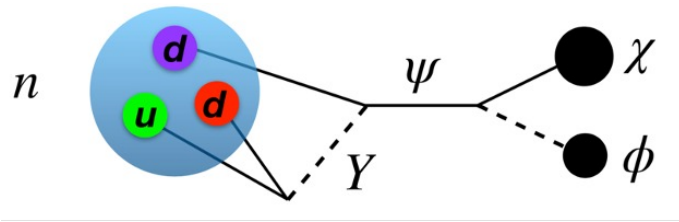
4

Close collab of
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experiment

➤ Some models predict baryon invisible decays:

PRD105, L071102 (2022)

Phys. Rev.D 99(2019) 3, 035031



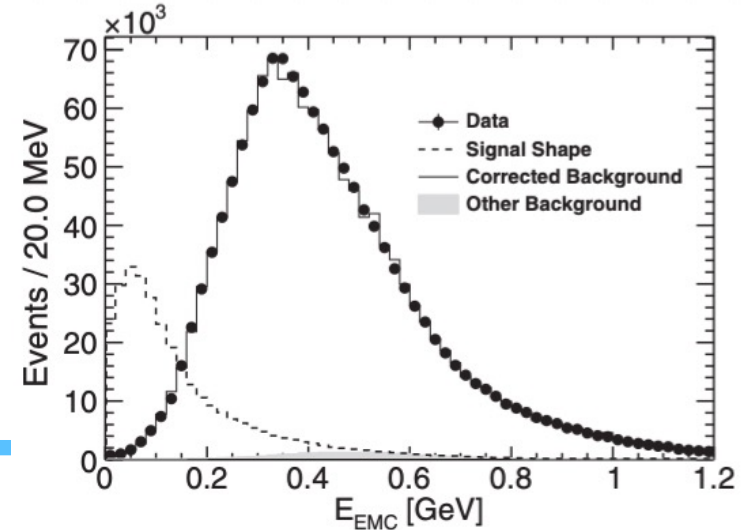
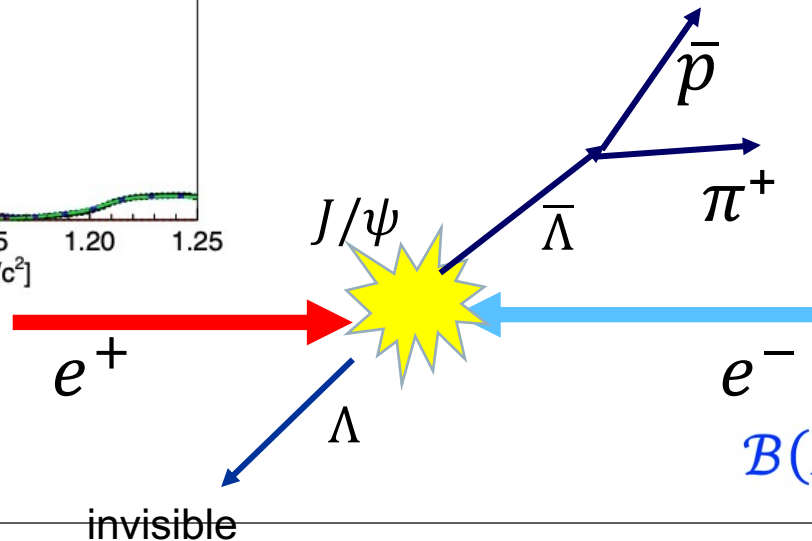
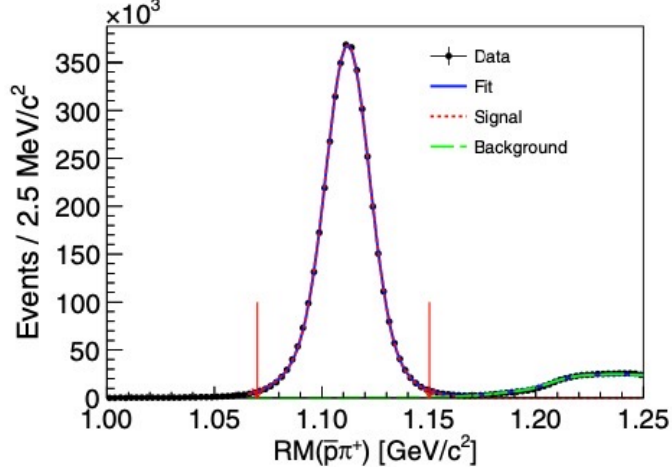
Phys. Lett. B 745 (2015), 79

Phys. Rev. Lett. 111, 222501 (2013)

➤ May also relate to neutron lifetime puzzle:

$$\tau_n^{beam} = \frac{\tau_n}{B(n \rightarrow p + X)} > \tau_n^{bottle}$$

$$B(n \rightarrow p + X) \approx 99\%$$

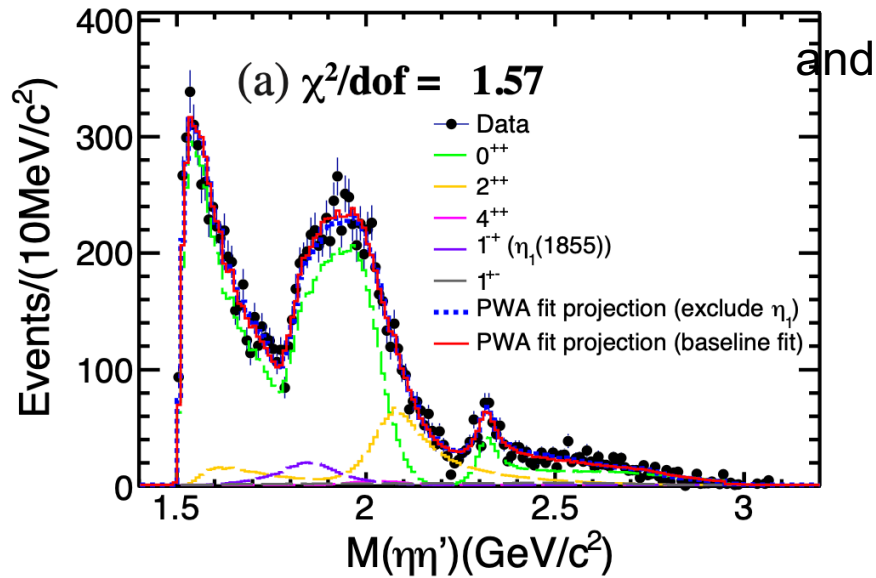


$$B(\Lambda \rightarrow \text{invisible}) < 7.4 \times 10^{-5}$$

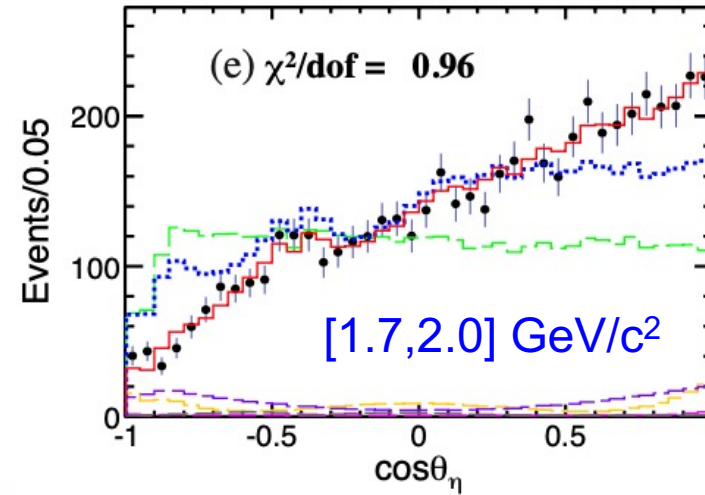
Light hadron Physics: Spectroscopy and decay properties

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

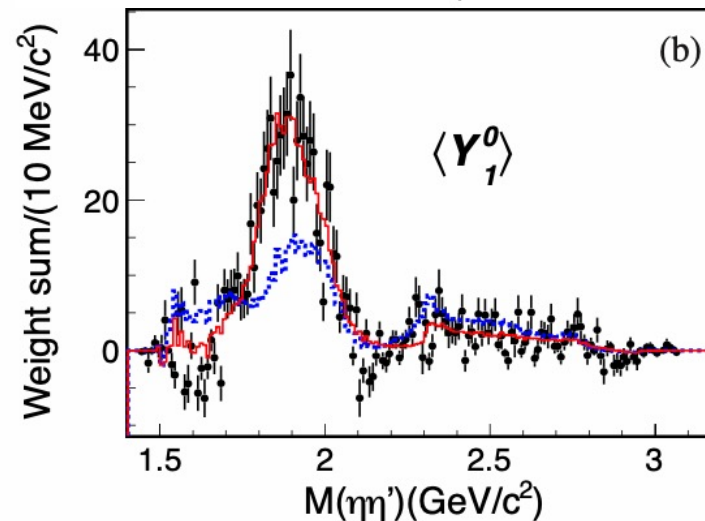
Phys. Rev. Lett. 129, 192002 (2022), Erratum: Phys. Rev. Lett. 130, 159901(2023)
 Phys. Rev. D 106, 072012 (2022), Eratum: Phys. Rev. D 107, 079901(2023)



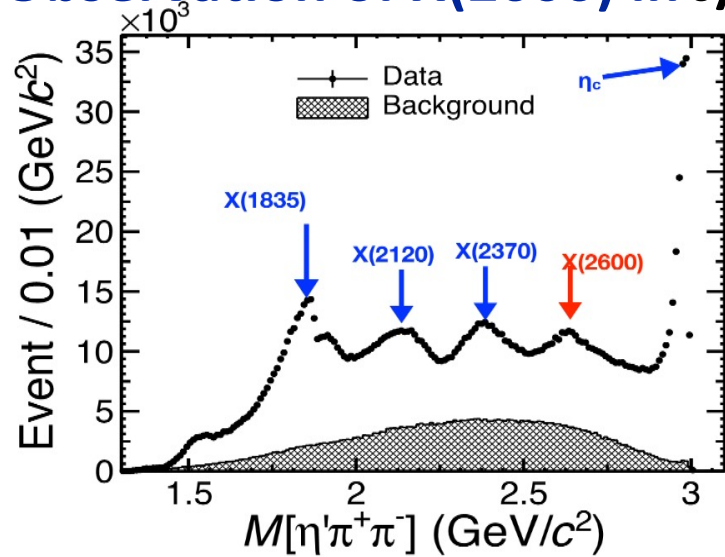
and



- critical to establish the 1^{-+} hybrid nonet.
- supporting $f_0(1710)$ overlap with glueball



Observation of $X(2600)$ in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$



PRL129(2022)042001

J^{PC} : unknown

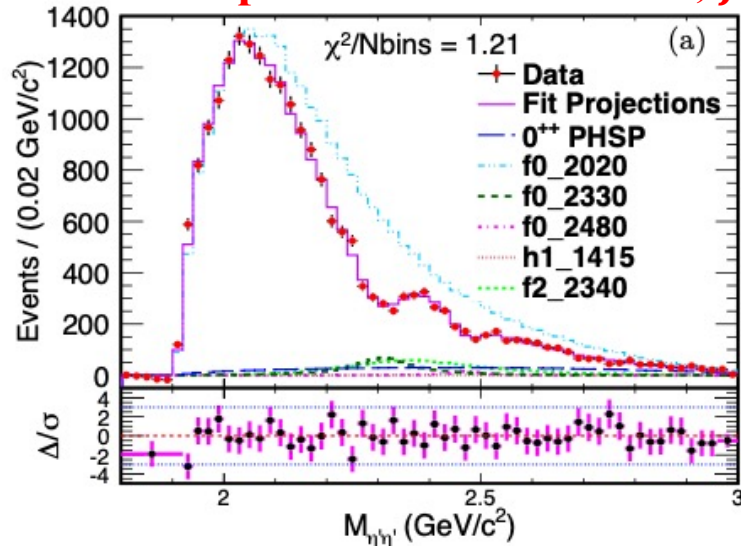
$M = 2618.3 \pm 2.0^{+16.3}_{-1.4} \text{ MeV}/c^2$

$\Gamma = 195 \pm 5^{+26}_{-17} \text{ MeV}$

η radial excitation or exotic hadron?

Observed a possible new 0^{++} state, $f_0(2480)$

PRD105(2022)072002

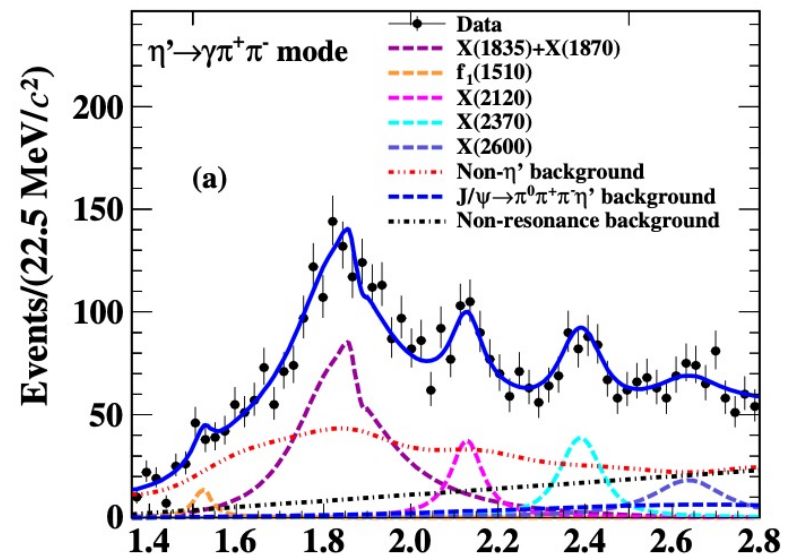


$J/\psi \rightarrow \gamma \eta' \eta'$

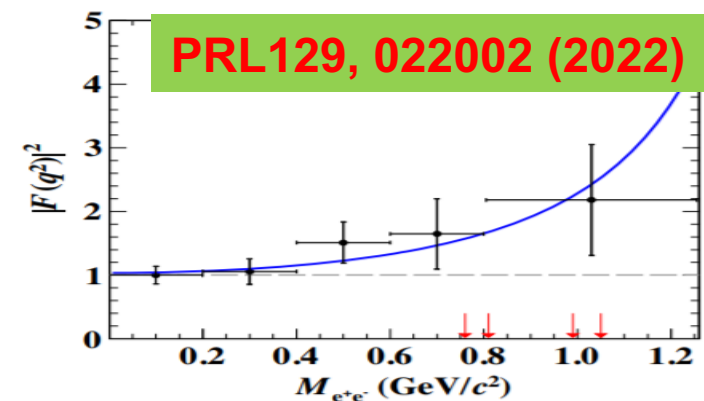
| Resonance | $M(\text{MeV}/c^2)$ | $\Gamma(\text{MeV})$ | B.F. | Sig. (σ) |
|---------------|-------------------------|--------------------------|--|-------------------|
| $f_0(2020)$ | $1982 \pm 3^{+54}_{-0}$ | $436 \pm 4^{+46}_{-49}$ | $(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$ | $\gg 25$ |
| $f_0(2330)$ | $2312 \pm 2^{+10}_{-0}$ | $134 \pm 5^{+30}_{-9}$ | $(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$ | 16.3 |
| $f_0(2480)$ | $2470 \pm 4^{+4}_{-6}$ | $75 \pm 9^{+11}_{-8}$ | $(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$ | 5.2 |
| $h_1(1415)$ | $1384 \pm 6^{+9}_{-0}$ | $66 \pm 10^{+12}_{-10}$ | $(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$ | 5.3 |
| $f_2(2340)$ | $2346 \pm 8^{+22}_{-6}$ | $332 \pm 14^{+26}_{-12}$ | $(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$ | 16.1 |
| 0^{++} PHSP | ... | ... | $(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$ | 15.7 |

The large production rate of $f_0(2020)$ in radiative J/ψ decay suggests that it has a large overlap with scalar glueball. But, its mass is lower than LQCD calculation

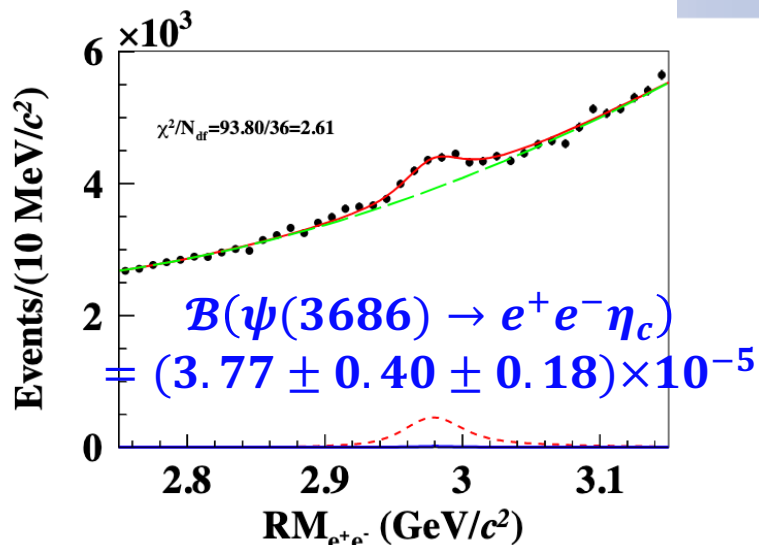
X(1835) in $J/\psi \rightarrow e^+e^- \eta' \pi^+ \pi^-$



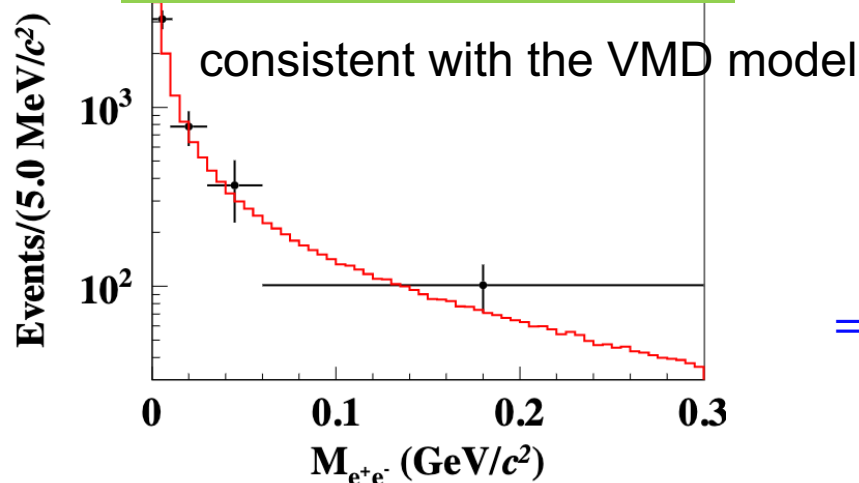
PRD129, 022002 (2022)



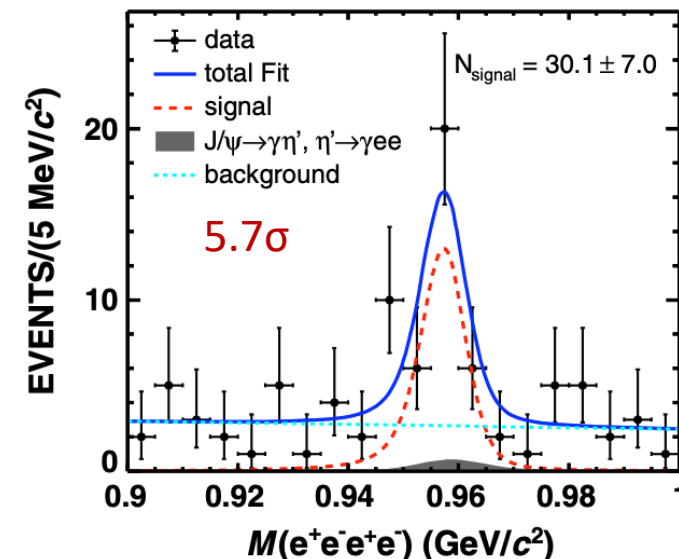
$$\Lambda = [1.75 \pm 0.29(\text{stat}) \pm 0.05(\text{syst})] \text{ GeV}/c^2$$



PRD106, 112002 (2022)



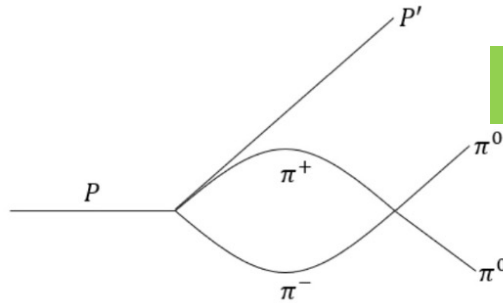
Observation of double Dalitz decay



PRD105, 112010 (2022)

$$\mathcal{B}(\eta' \rightarrow e^+e^-e^+e^-) = (4.5 \pm 1.0 \pm 0.5) \times 10^{-6}$$

Open many new possibilities

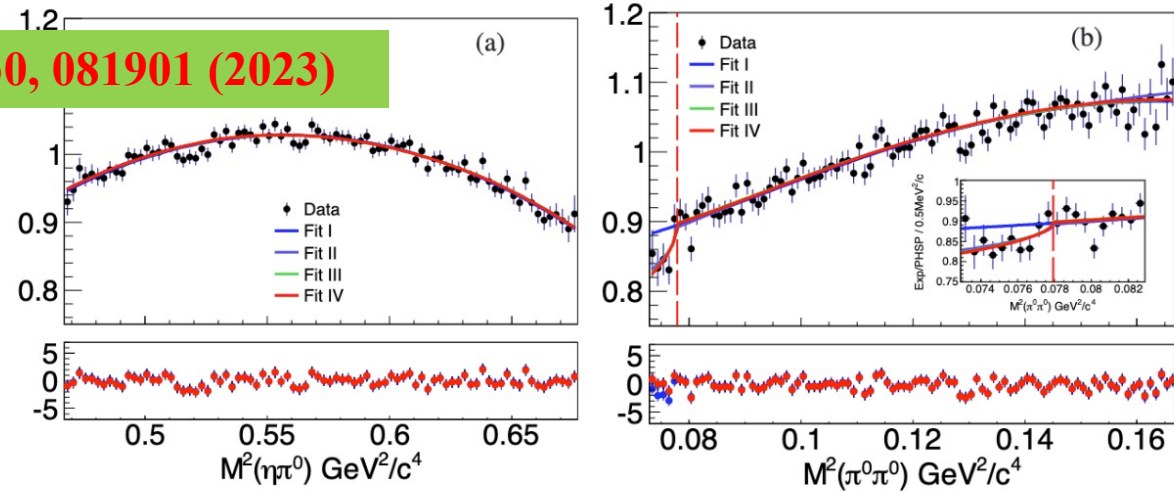


$$C_{00} = \frac{16\pi}{3}(a_0 + 2a_2)(1 - \xi),$$

$$C_x = \frac{16\pi}{3}(a_2 - a_0)(1 + \frac{\xi}{3}),$$

$$C_{+-} = \frac{8\pi}{3}(2a_0 + a_2)(1 + \xi).$$

PRL130, 081901 (2023)

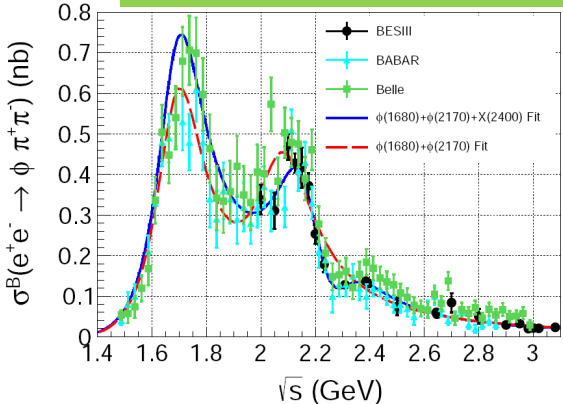


- Evidence for the cusp effect with significance 3.5σ , consistent with NREFT
- Scattering length combination in good agreement with theoretical calculation

| Decay Mode | $\mathcal{B}(\times 10^{-4})$ [5] | η/η' events | η decay mode | physics highlight | η' mode | physics highlight |
|----------------------------------|-----------------------------------|---------------------|------------------------------------|------------------------|-------------------------------------|--------------------------|
| $J/\psi \rightarrow \gamma\eta'$ | 51.5 ± 1.6 | 5.2×10^7 | $\eta \rightarrow \pi^0 2\gamma$ | ChPT | $\eta' \rightarrow \pi\pi$ | CPV |
| $J/\psi \rightarrow \gamma\eta$ | 11.04 ± 0.34 | 1.1×10^7 | $\eta \rightarrow \gamma B$ | leptophobic dark boson | $\eta' \rightarrow 2\gamma$ | chiral anomaly |
| $J/\psi \rightarrow \phi\eta'$ | 7.5 ± 0.8 | 7.5×10^6 | $\eta \rightarrow 3\pi^0$ | $m_u - m_d$ | $\eta' \rightarrow \gamma\pi\pi$ | box anomaly, form factor |
| $J/\psi \rightarrow \phi\eta$ | 4.5 ± 0.5 | 4.5×10^6 | $\eta \rightarrow \pi^+\pi^-\pi^0$ | $m_u - m_d, CV$ | $\eta' \rightarrow \pi^+\pi^-\pi^0$ | $m_u - m_d, CV$ |
| $J/\psi \rightarrow \omega\eta$ | 17.4 ± 2.0 | 1.7×10^7 | $\eta \rightarrow 3\gamma$ | CPV | $\eta' \rightarrow \pi^0\pi^0\eta$ | cusp effect [83] |
| $J/\psi \rightarrow \omega\eta'$ | 1.82 ± 0.21 | 1.8×10^6 | | | | |

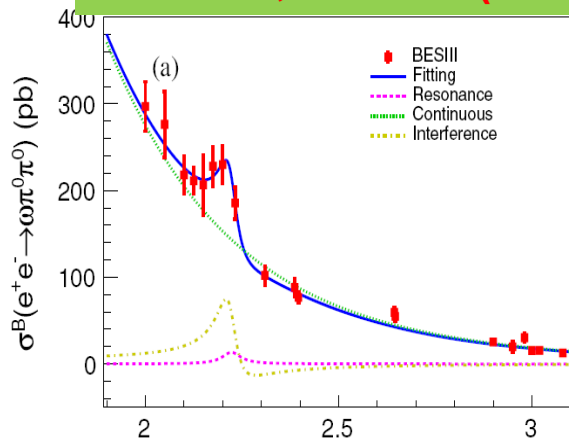
$$e^+e^- \rightarrow \phi\pi^+\pi^-$$

arXiv:2112.23219



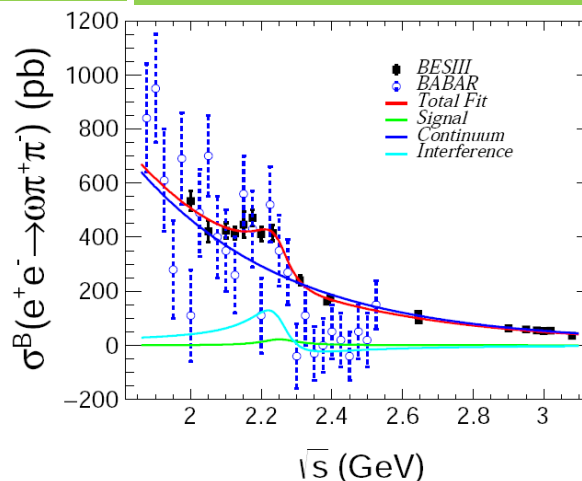
$$e^+e^- \rightarrow \omega\pi^0\pi^0$$

PRD105, 032005 (2022)



$$e^+e^- \rightarrow \omega\pi^+\pi^-$$

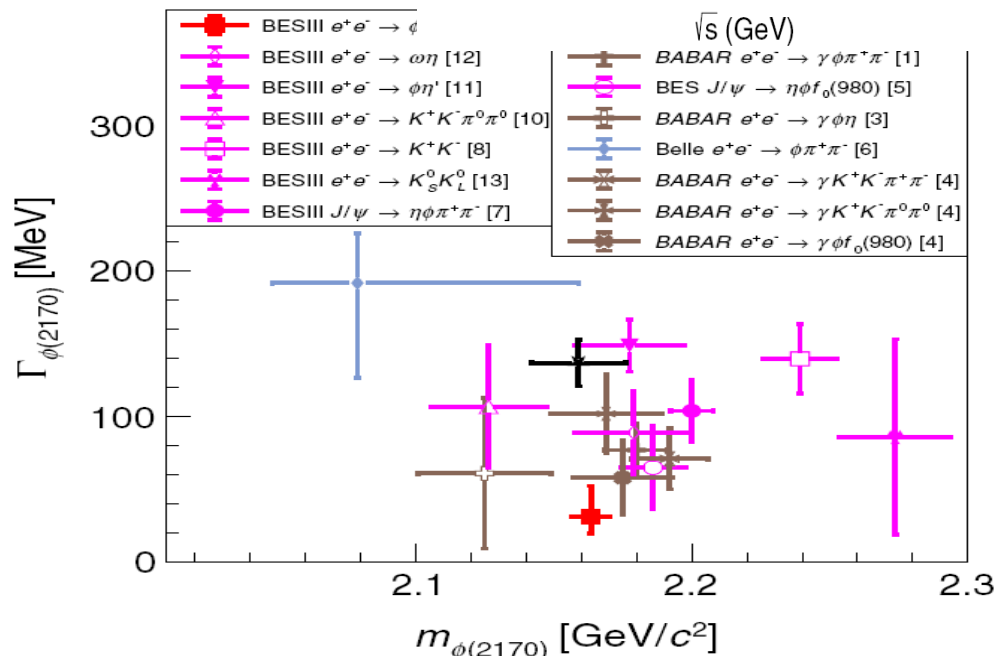
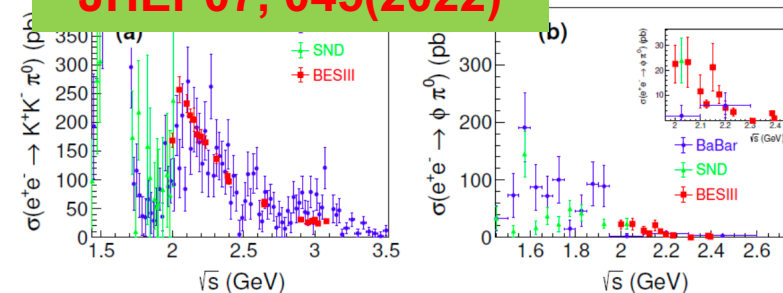
JHEP 01 (2023)111



$$e^+e^- \rightarrow K^+K^-\pi^0$$

- $M=2190\pm 19\pm 37$ MeV/ c^2 , $\Gamma=191\pm 28\pm 60$ MeV from PWA of $K^*(892)K$ and $K_2^*(1430)K$;

JHEP07, 045(2022)



- Different masses and widths
- Limited decay modes
- Nature is mysterious
- More studies are desirable

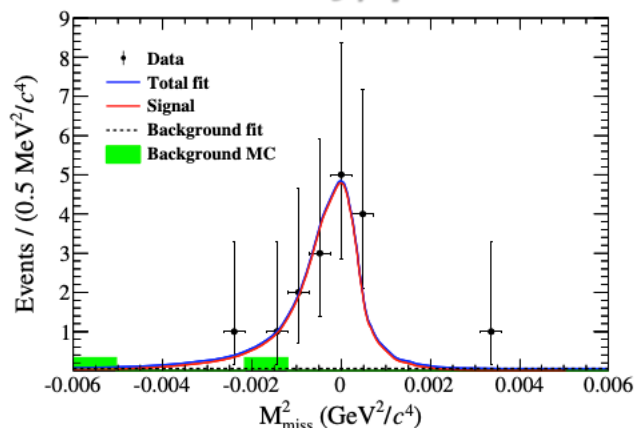
- More channels
- PWA with many Ecm points
- Joint analysis

More data samples in critical regions

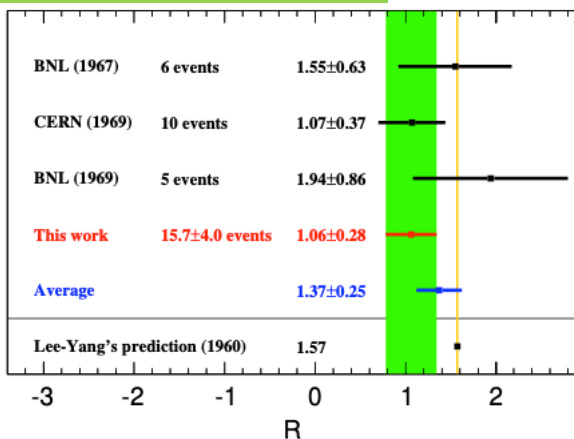
With world largest J/ψ sample, BESIII is also a hyperon factory!

PRL130, 211901(2023)

$\Sigma^+ \rightarrow \Lambda e^- \nu$ via $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$

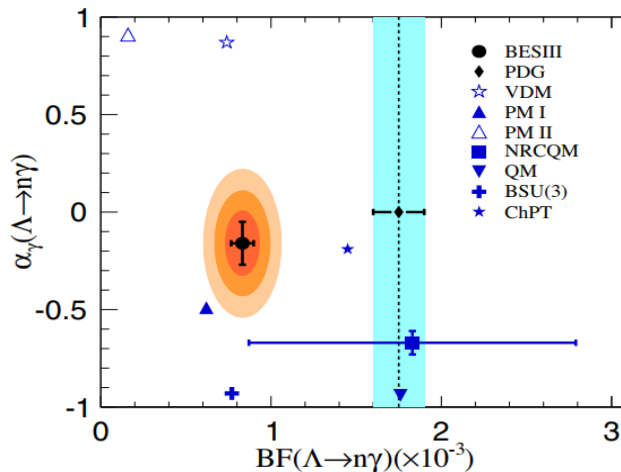
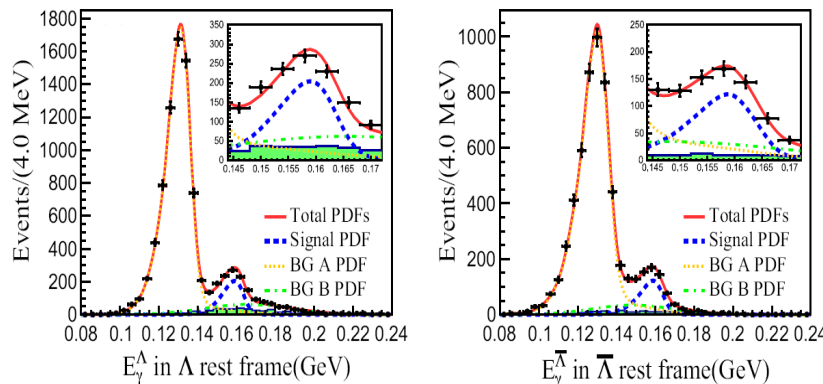


PRD107,072010(2023)



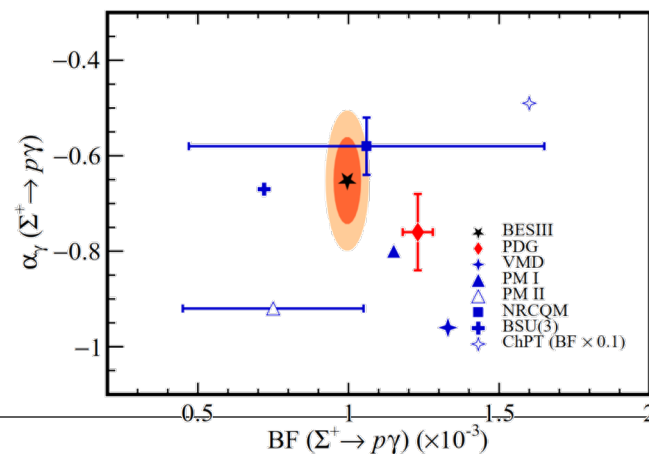
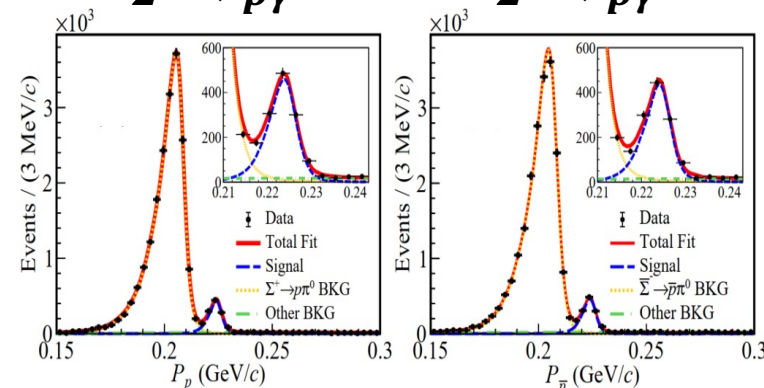
$\Lambda \rightarrow n \gamma$ via $J/\psi \rightarrow \Lambda \bar{\Lambda}$

PRL129, 122002(2022)



$\Sigma^+ \rightarrow p \gamma$ via $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$

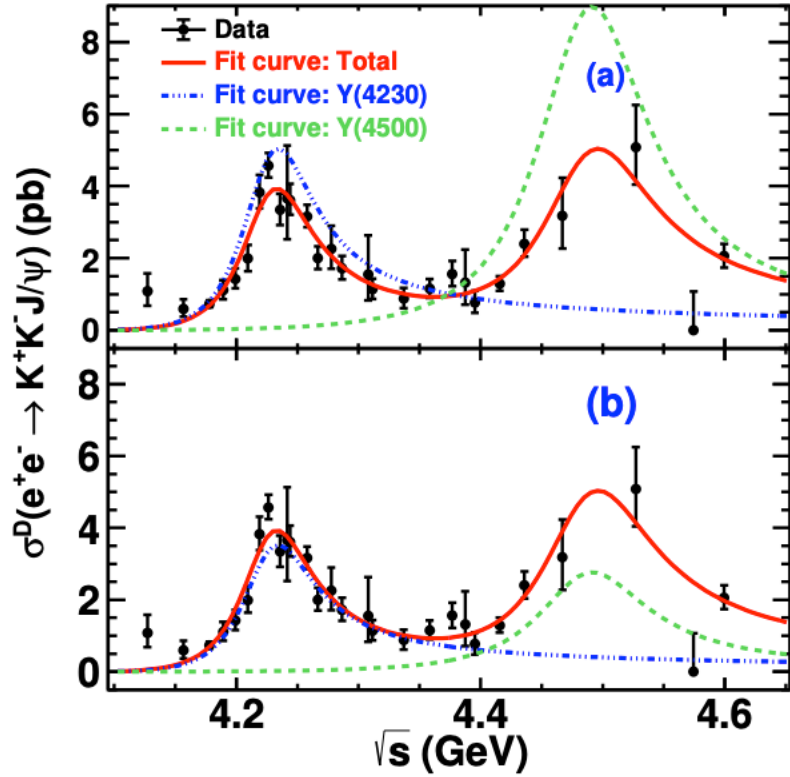
$\Sigma^+ \rightarrow p \gamma$ and $\bar{\Sigma}^- \rightarrow \bar{p} \gamma$



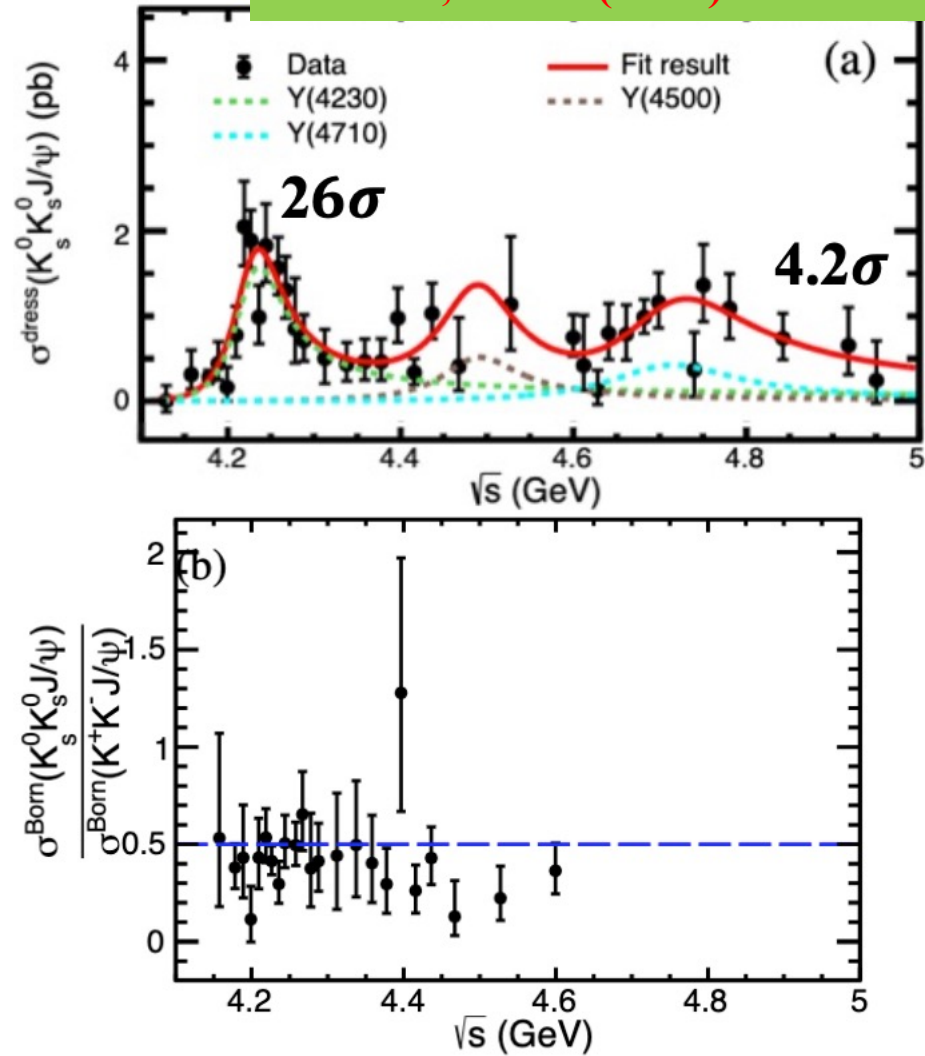
Charmonium Physics

"traditional" and XYZs

PRD107,092005(2023)

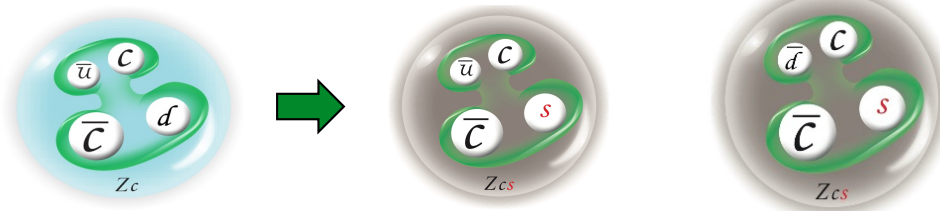
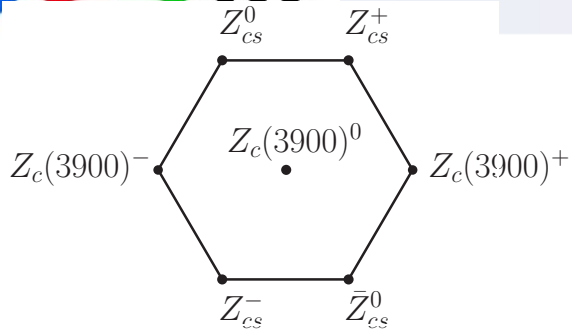


CPC 46, 111002(2022)



SU(3) partner Z_{cc} state with strangeness

“Tetra”-Octet?

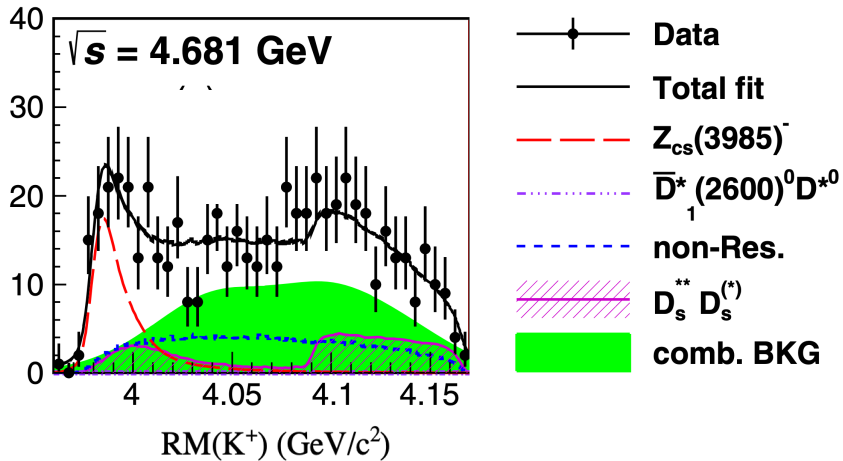


$$e^+e^- \rightarrow K^+(D_s^- D^{*0} + D_s^{*-} D^0)$$

$$e^+e^- \rightarrow K_s^0(D_s^+ D^{*-} + D_s^{*+} D^-)$$

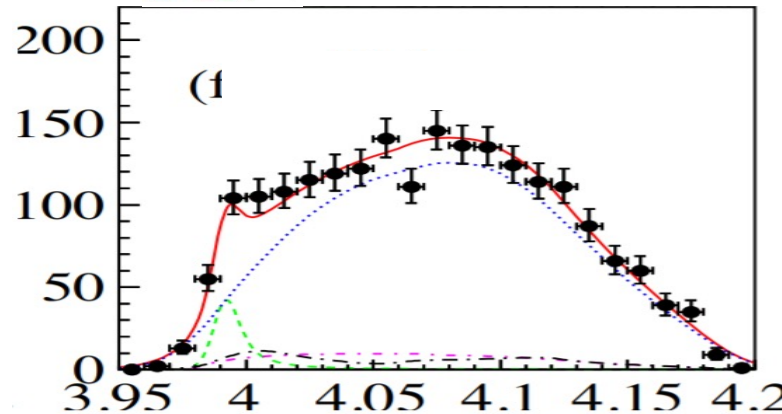
$$e^+e^- \rightarrow K^+(D_s^{*-} D^{*0})$$

PRL126(2021)102001



- $M = (3985.2_{-2.0}^{+2.1} \pm 1.7) \text{ MeV}/c^2$
- $\Gamma = (13.8_{-5.2}^{+8.1} \pm 4.9) \text{ MeV}$
- Open charm final state

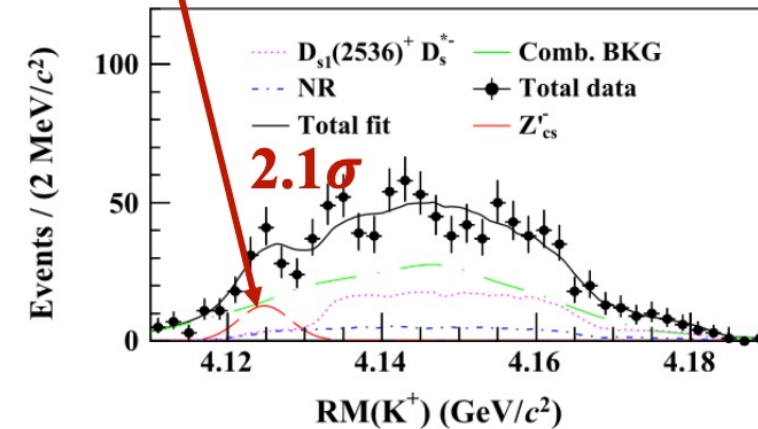
PRL129(2022)112003



- $M = 3992.2 \pm 1.7 \pm 1.6 \text{ MeV}/c^2$
- $\Gamma = (7.7_{-3.8}^{+4.1} \pm 4.3) \text{ MeV}$
- Open charm final state

CPC47, 033001 (2023)

$(4123.5 \pm 0.7_{\text{stat.}} \pm 4.7_{\text{syst.}}) \text{ MeV}/c^2$



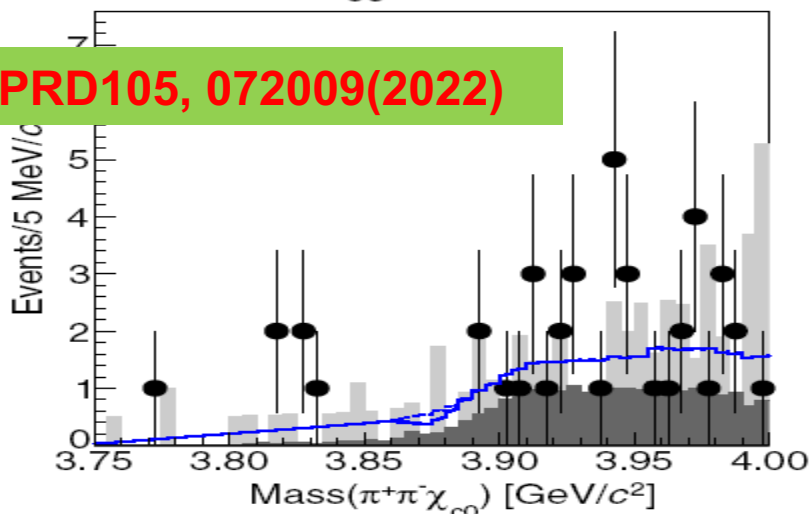
- X(3872) Main production channel: $e^+e^- \rightarrow \gamma X(3872)$

X(3872) $\rightarrow \pi^0 \chi_{c0}$ and $\pi\pi \chi_{c0}$
 $\chi_{c0} \rightarrow \pi^+ \pi^-$

• More channels

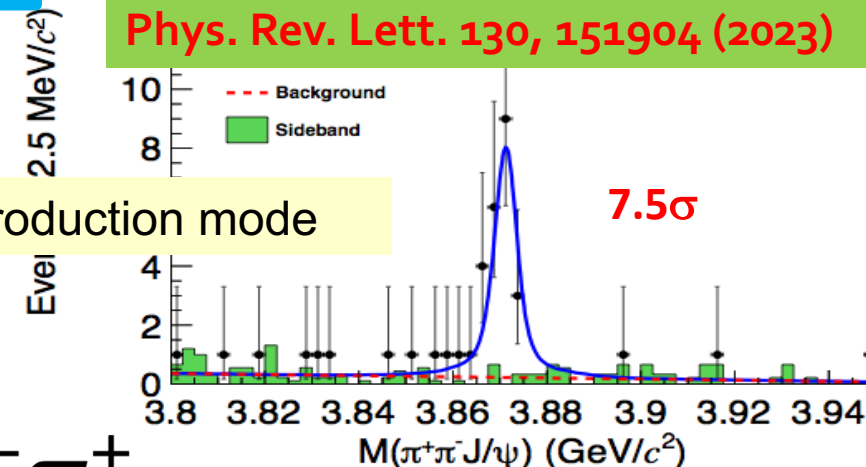
• More data samples

PRD105, 072009(2022)



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

Phys. Rev. Lett. 130, 151904 (2023)

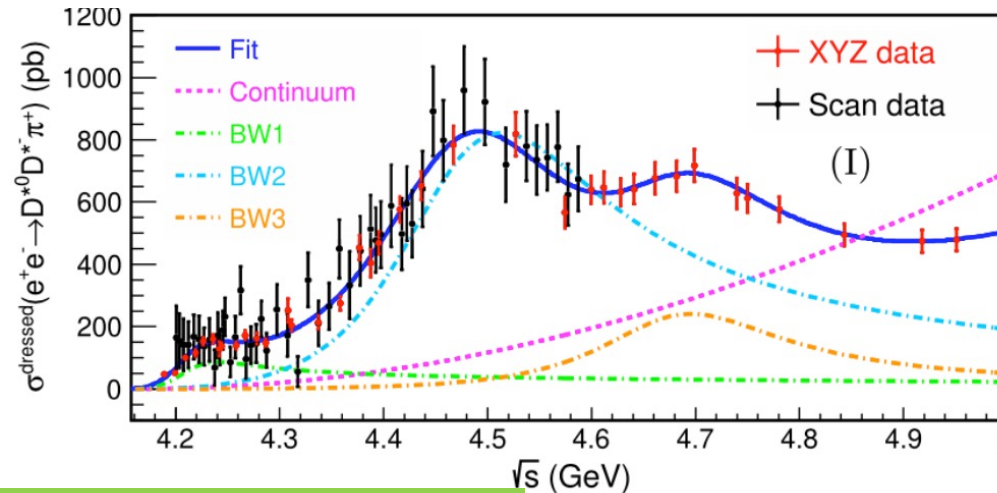
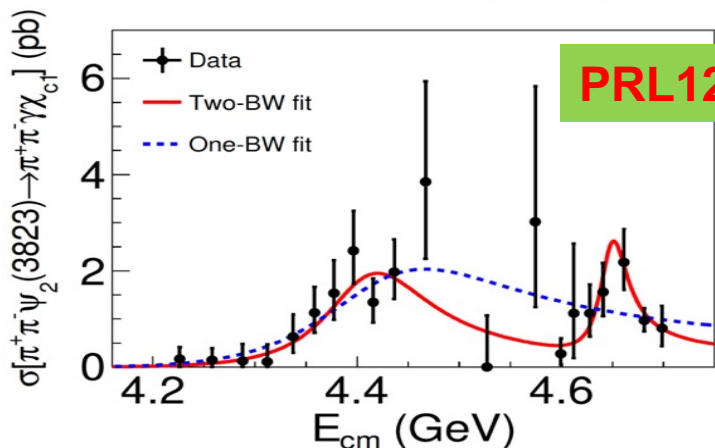


A new production mode

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

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

PRL129, 102003(2022)

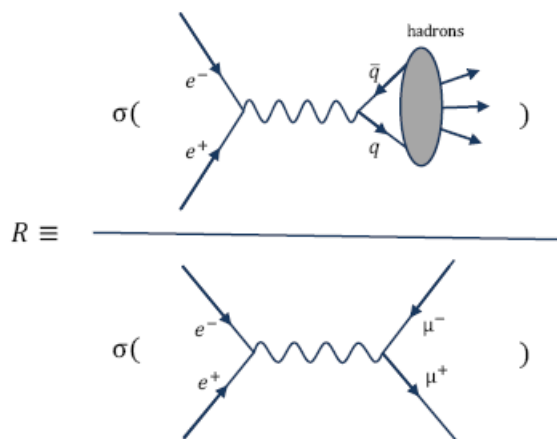


PRL130, 121901 (2023)

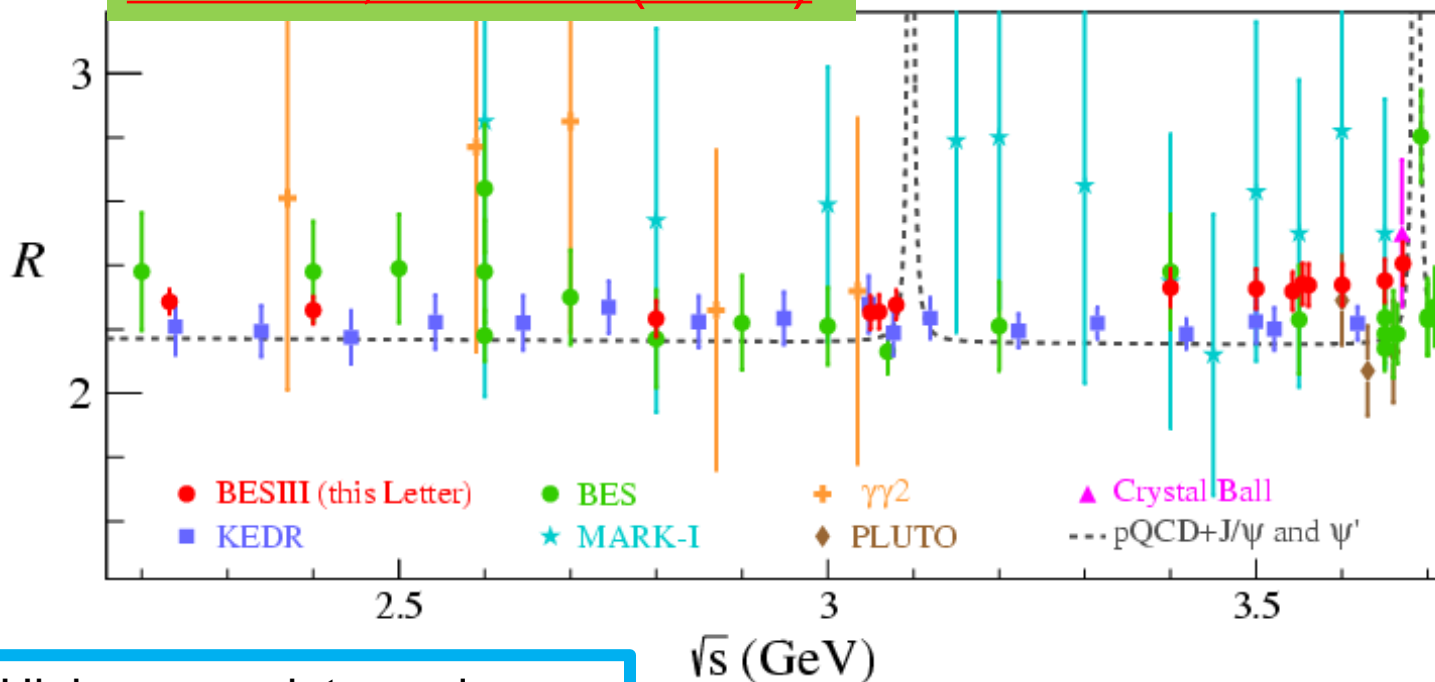
R value and QCD studies

- Measurement of R values in 14 energy points of 2.23-3.67 GeV
- Precision is < 2.6%(<3.0GeV)/3% and twofold better than previous best measurement
- Crucial input parameters to calculate the running coupling constant
- Help to constrain the muon g-2

$$R \equiv \frac{\sigma^0(e^+e^- \rightarrow \text{hadrons})}{\sigma^0(e^+e^- \rightarrow \mu^+\mu^-)} \equiv \frac{\sigma_{\text{had}}^0}{\sigma_{\mu\mu}^0}$$



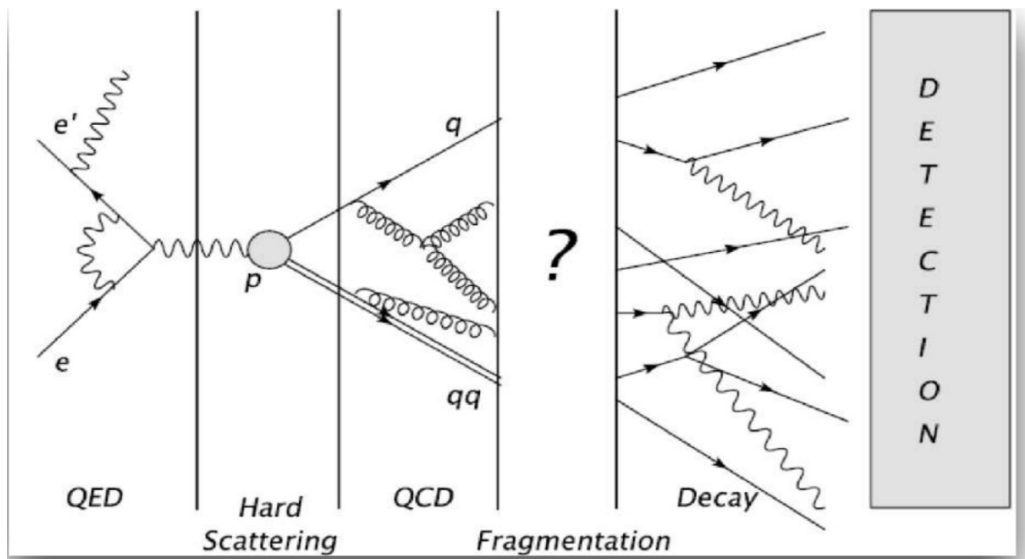
[PRL 128, 062004 \(2022\)](#)



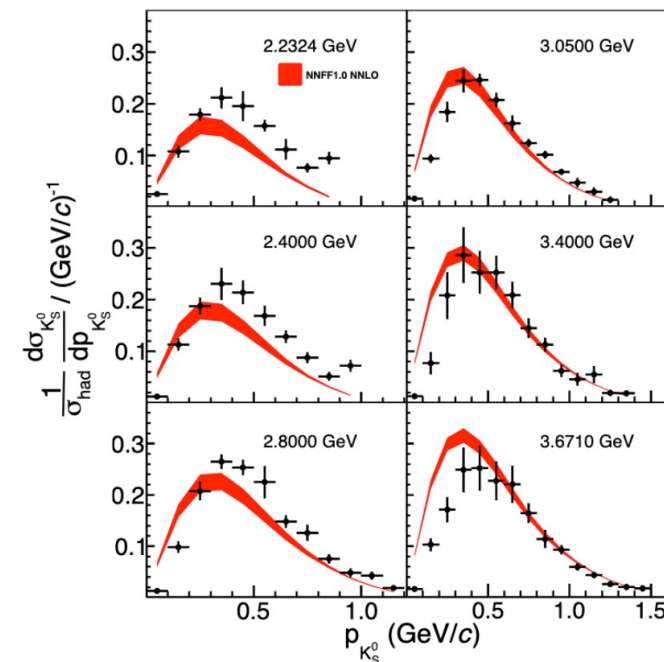
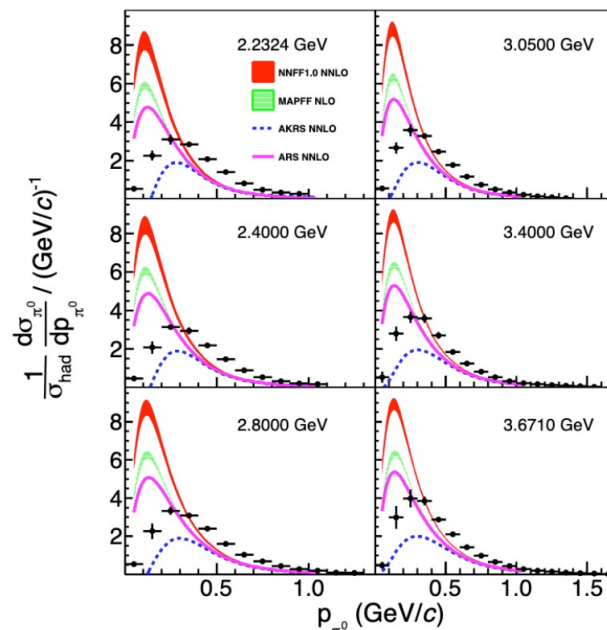
- High energy data analyses
- Exclusive measurement

- More data samples at low energy

PRL130, 231901(2023)



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



- Inclusive π^0 and K_s production in $e^+ e^-$ collision at 2.2324, 2.400, 2.800, 3.050, 3.400, 3.671 GeV.
- broad z_h coverage from 0.1 to 0.9, best precision
- provide brand new inputs in low-energy region to global fits of fragmentation function
- Studies of eta, charged K/pi is in progress

• More channels

Separated E/M FFs of the neutron in time-like region

PRL130, 151905(2023)



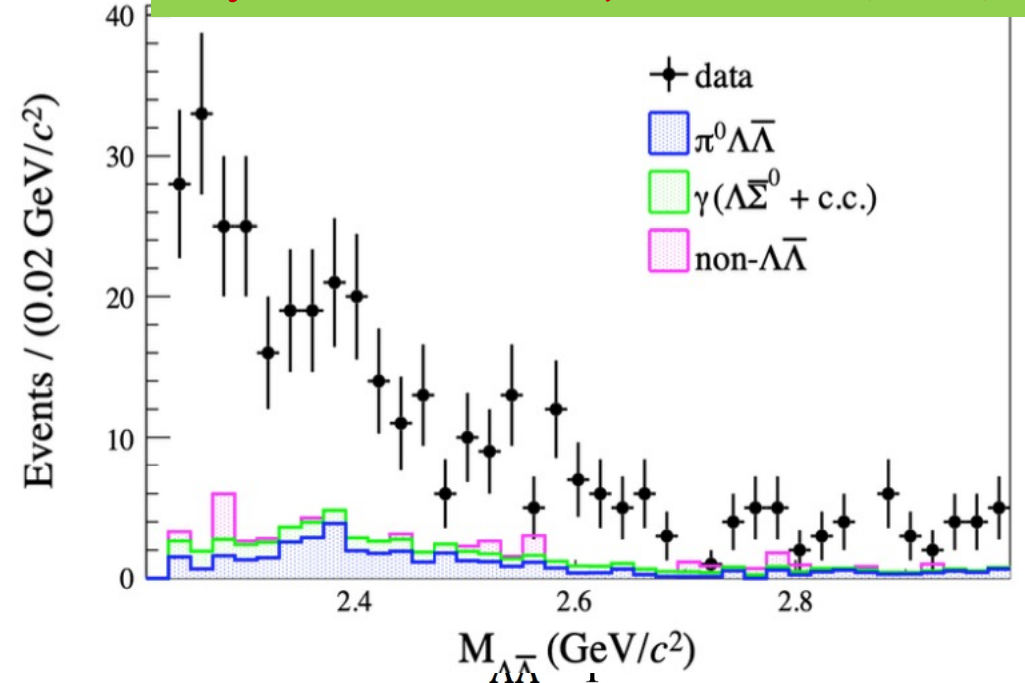
- G_M : lower than FENICE results
- G_E and G_M : agree more with Dispersion Relations (DR)
- TL vs SL: no sign of $R \rightarrow 1$ ($|q^2| \rightarrow \text{infinity}$)

• More analyses with ISR method

More data samples in critical regions

$e^+e^- \rightarrow \Lambda \bar{\Lambda}$ via Initial State Radiation

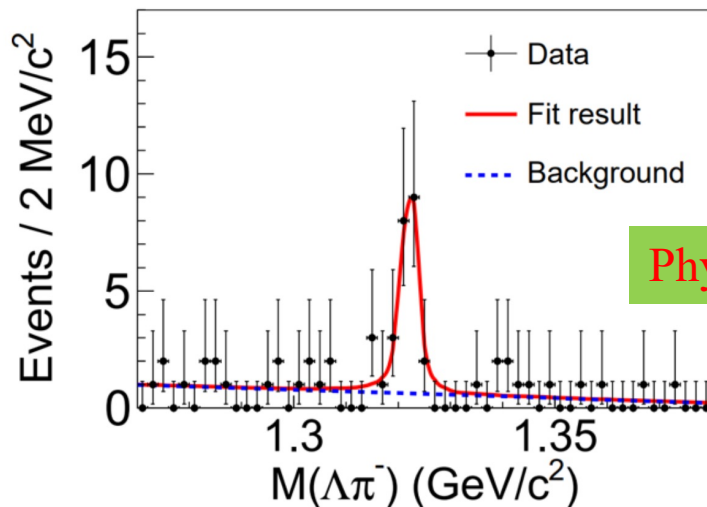
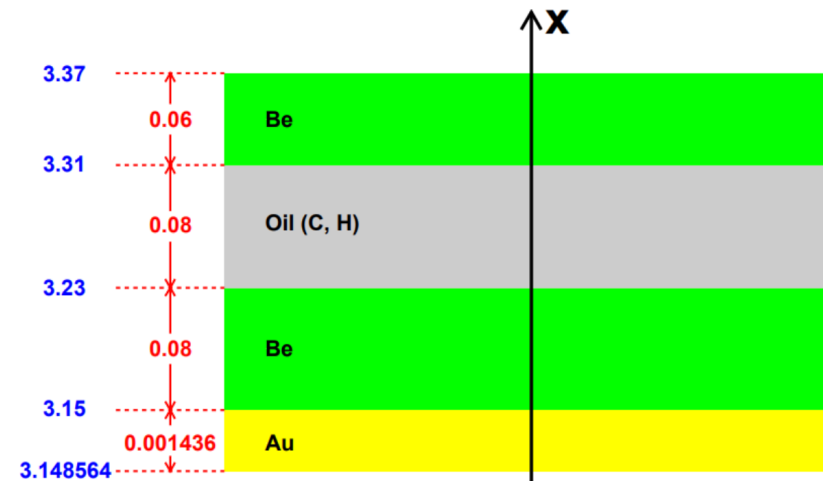
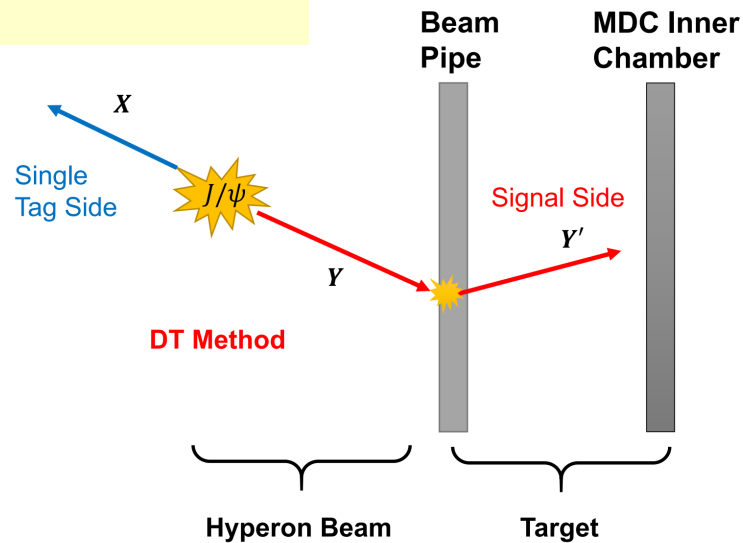
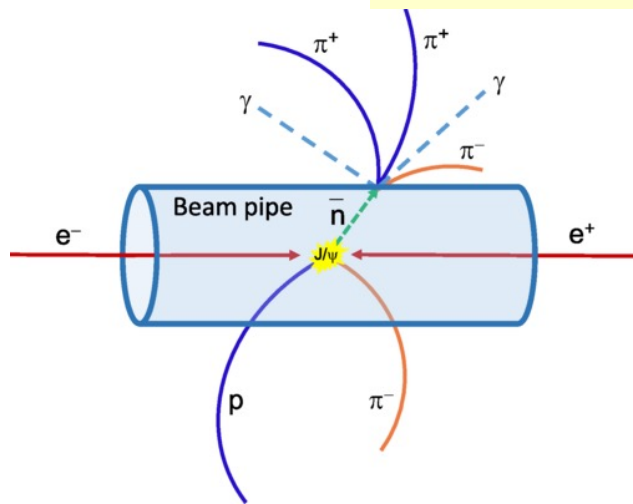
Phys. Rev. D 107, 072005 (2023)



$$\sigma_B(\Lambda\bar{\Lambda}) = \frac{(dN_{sig}/dM(\Lambda\bar{\Lambda}))_{corr}}{\varepsilon \cdot Br^2(\Lambda \rightarrow p\pi) \cdot d\mathcal{L}_{int}/dM(\Lambda\bar{\Lambda})}$$

$$\frac{d\mathcal{L}_{int}}{dM(\Lambda\bar{\Lambda})} = W(s, x) \cdot \mathcal{L}_{int}$$

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



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

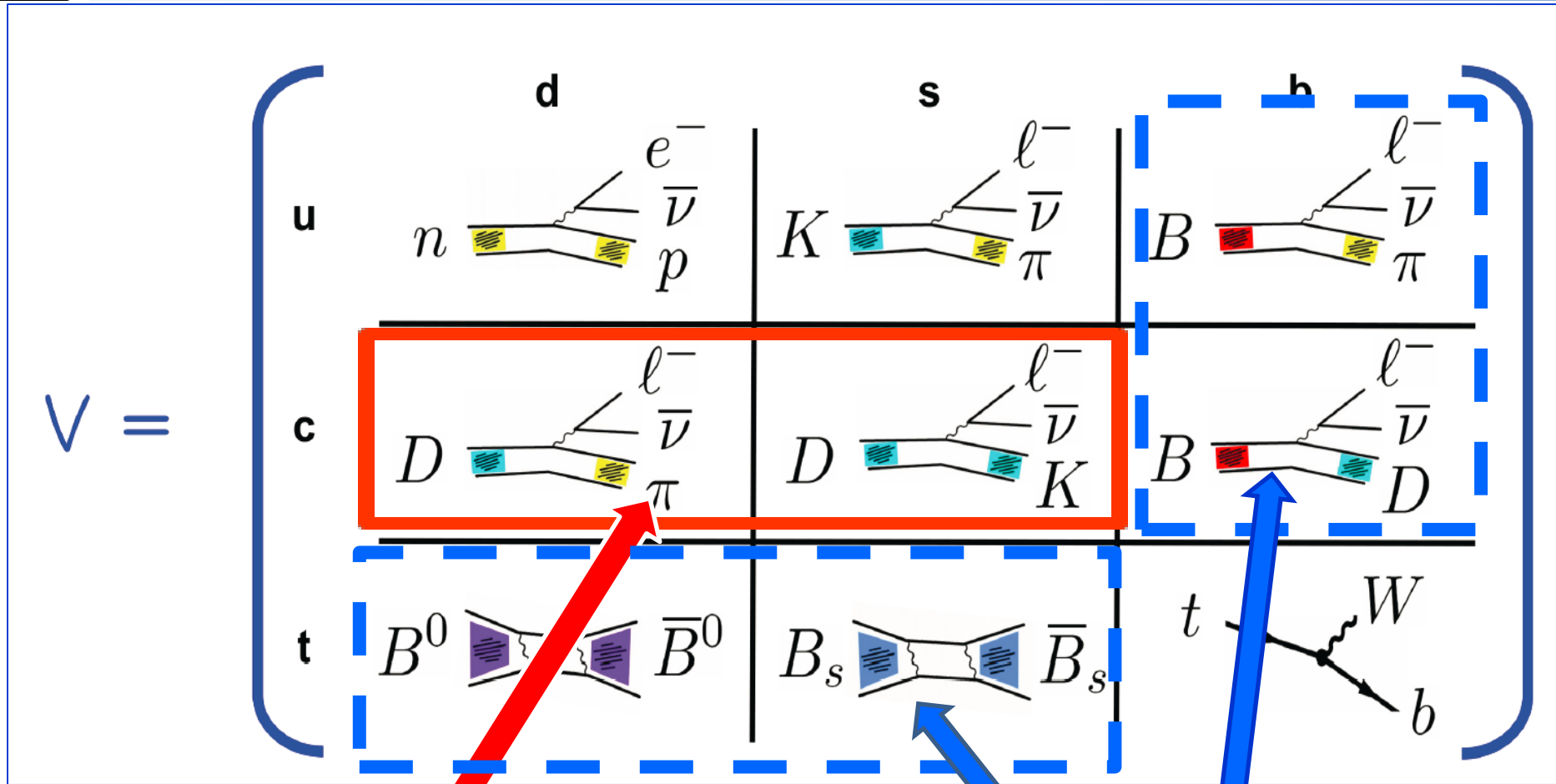
Phys. Rev. Lett. 130, 251902 (2023)



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

Charm Physics

mesons and baryons

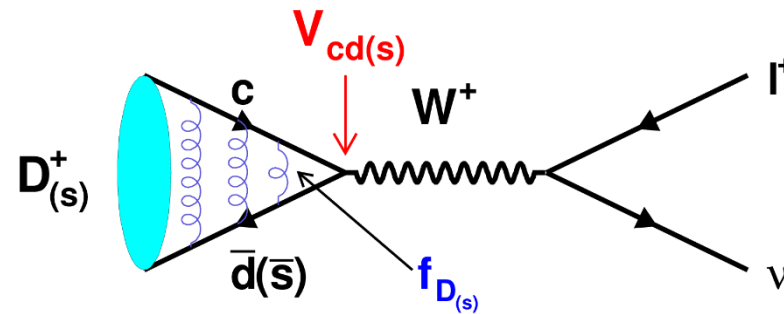


Charm decays + LQCD

Expected precision < 2% at BESIII

Charm decays + B decays + LQCD

- Extract decay constant $f_{D(s)}$ incorporates the strong interaction effects (wave function at the origin)
- To validate Lattice QCD calculation of $f_{D(s)}$ and provide constrain of CKM- unitarity



$$\text{Decay rate (Exp.)} \rightarrow \Gamma(D_{(s)} \rightarrow \ell\nu) = |V_{cd(s)}|^2 \times \underbrace{f_{D(s)}^2}_{\text{Decay constant (LQCD)}} \times \frac{G_F^2}{8\pi} m_\ell^2 m_{D(s)} (1 - m_\ell^2/m_{D(s)}^2)^2$$

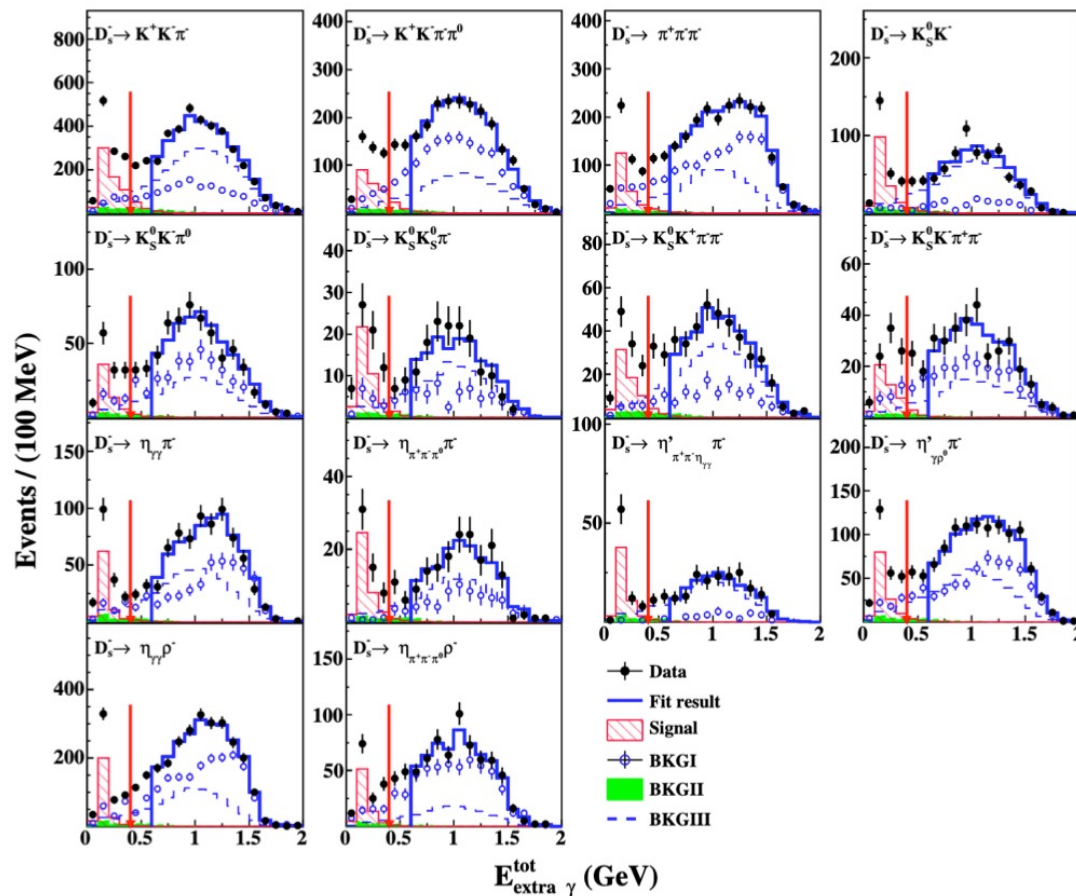
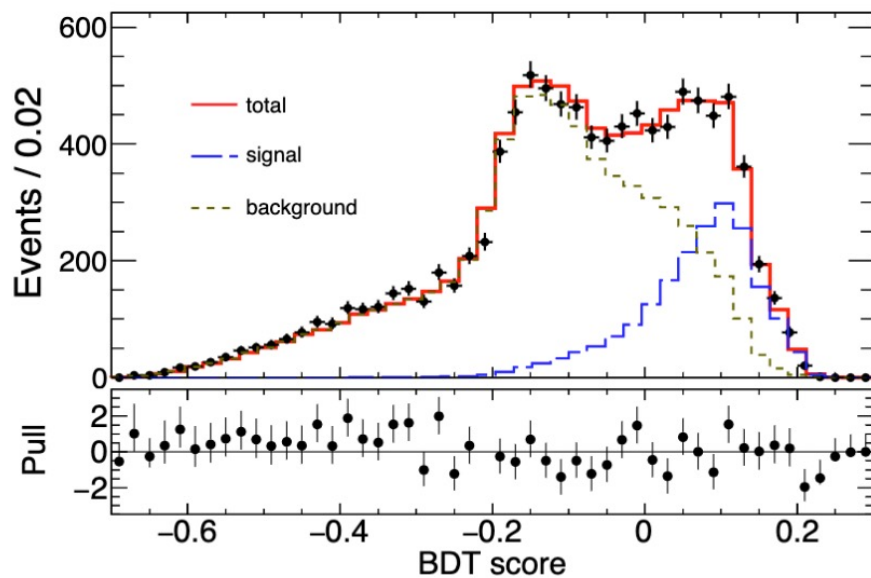
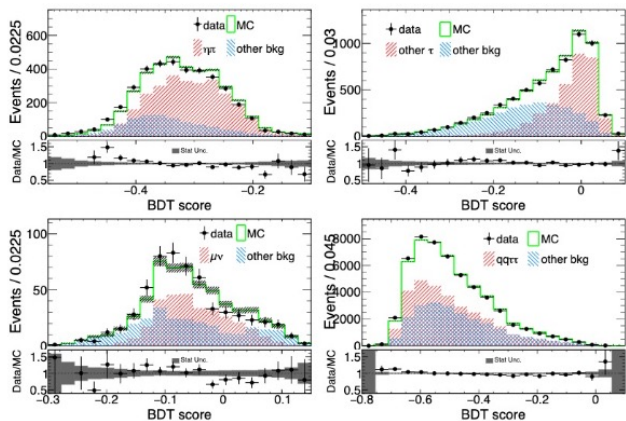
→ CKM matrix element

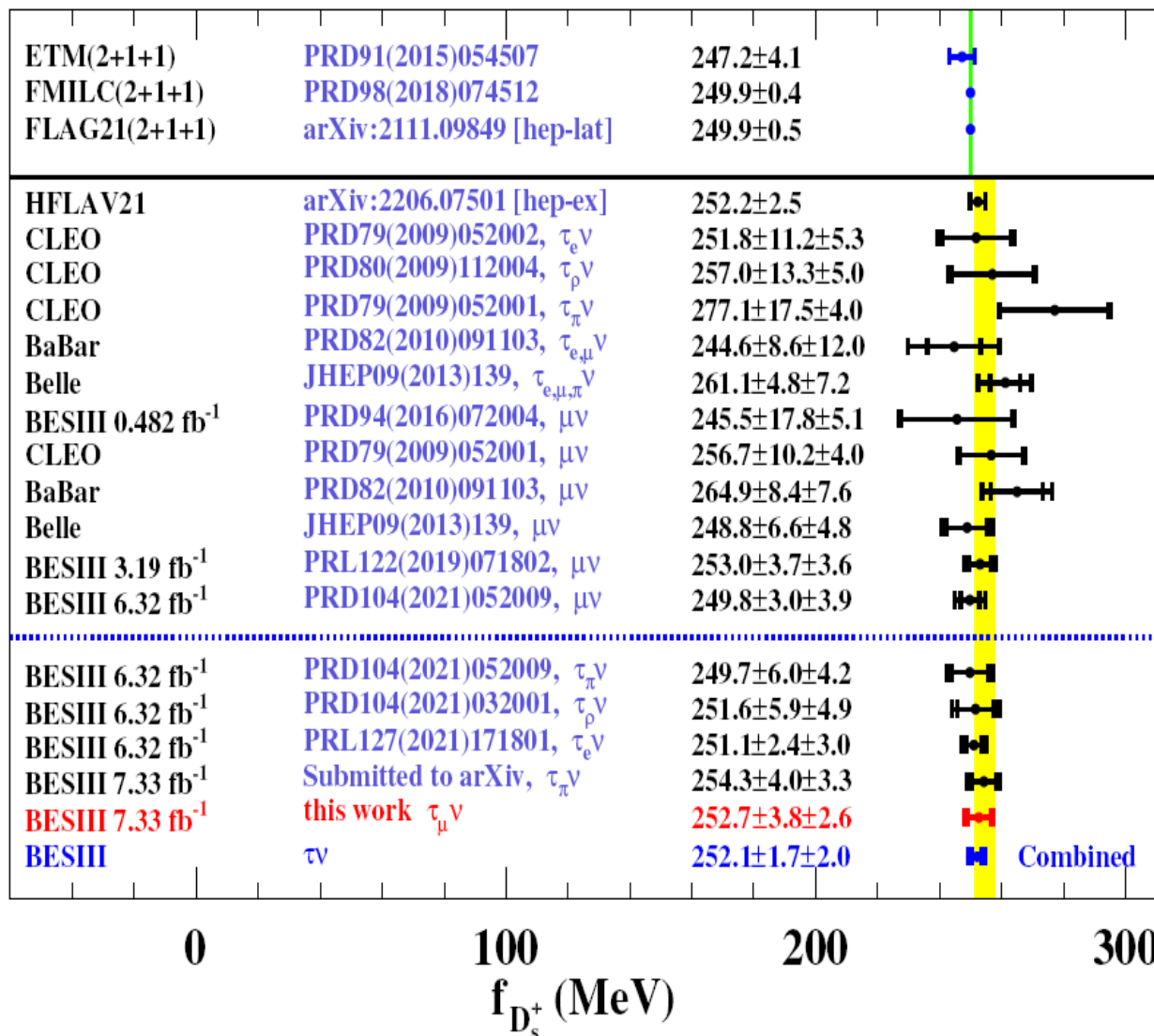
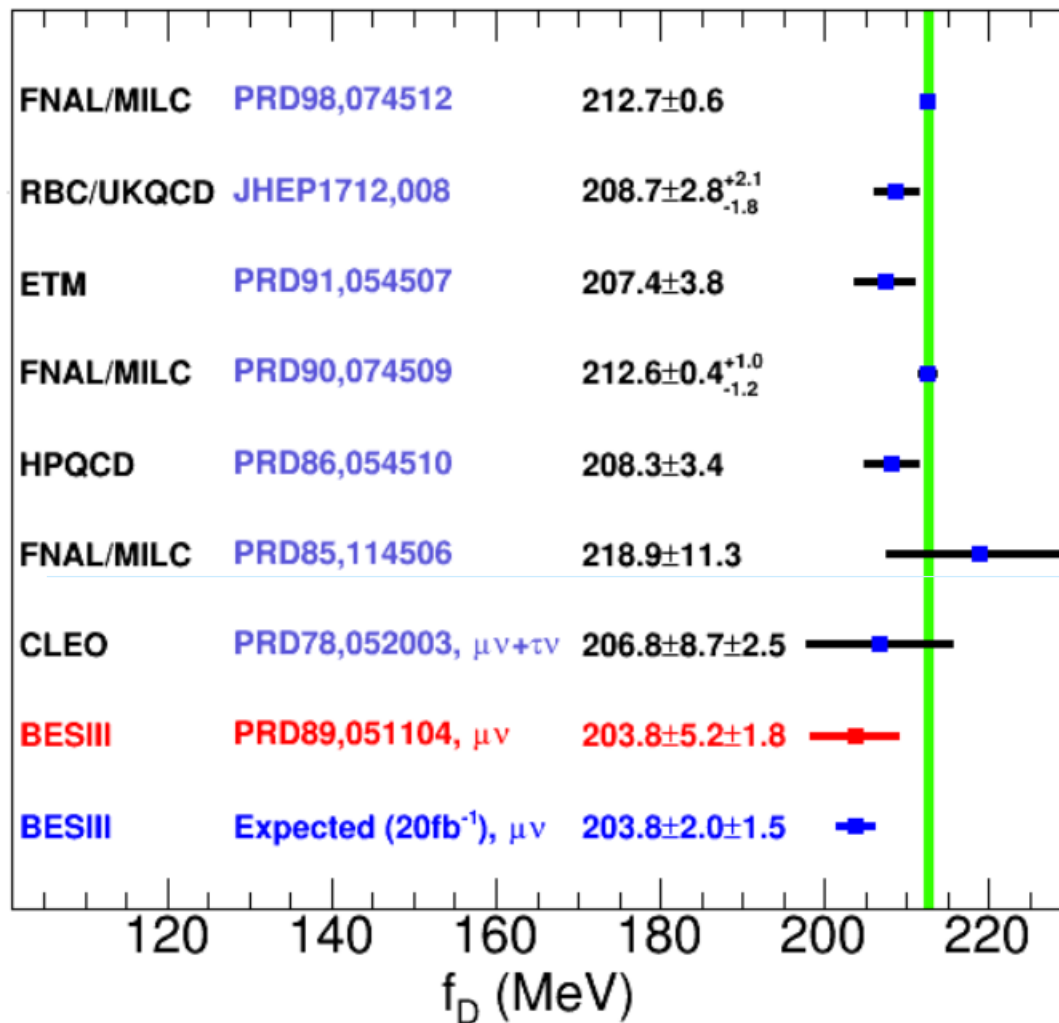
7.33 fb⁻¹ data from 4.128 GeV to 4.226 GeV

$$D_s^+ \rightarrow \tau^+ \nu_\tau, \tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$

$$D_s^+ \rightarrow \tau^+ \nu_\tau, \tau^+ \rightarrow \pi^+ \bar{\nu}_\tau \quad \text{arXiv:2303.12600}$$

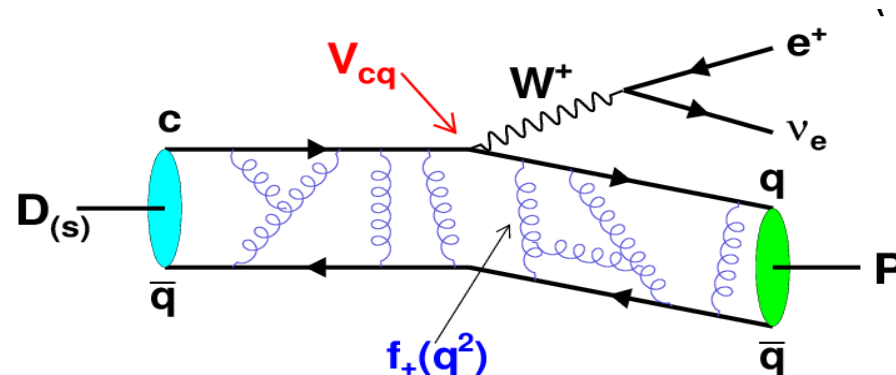
arXiv:2303.12468





■ **form factor (FF)**

- ◆ Measure $|V_{cq}| \times \text{FF}$
- ◆ CKM-unitarity $\Rightarrow |V_{cq}|$, extract FF, test LQCD
- ◆ Input LQCD FF to test CKM-unitarity

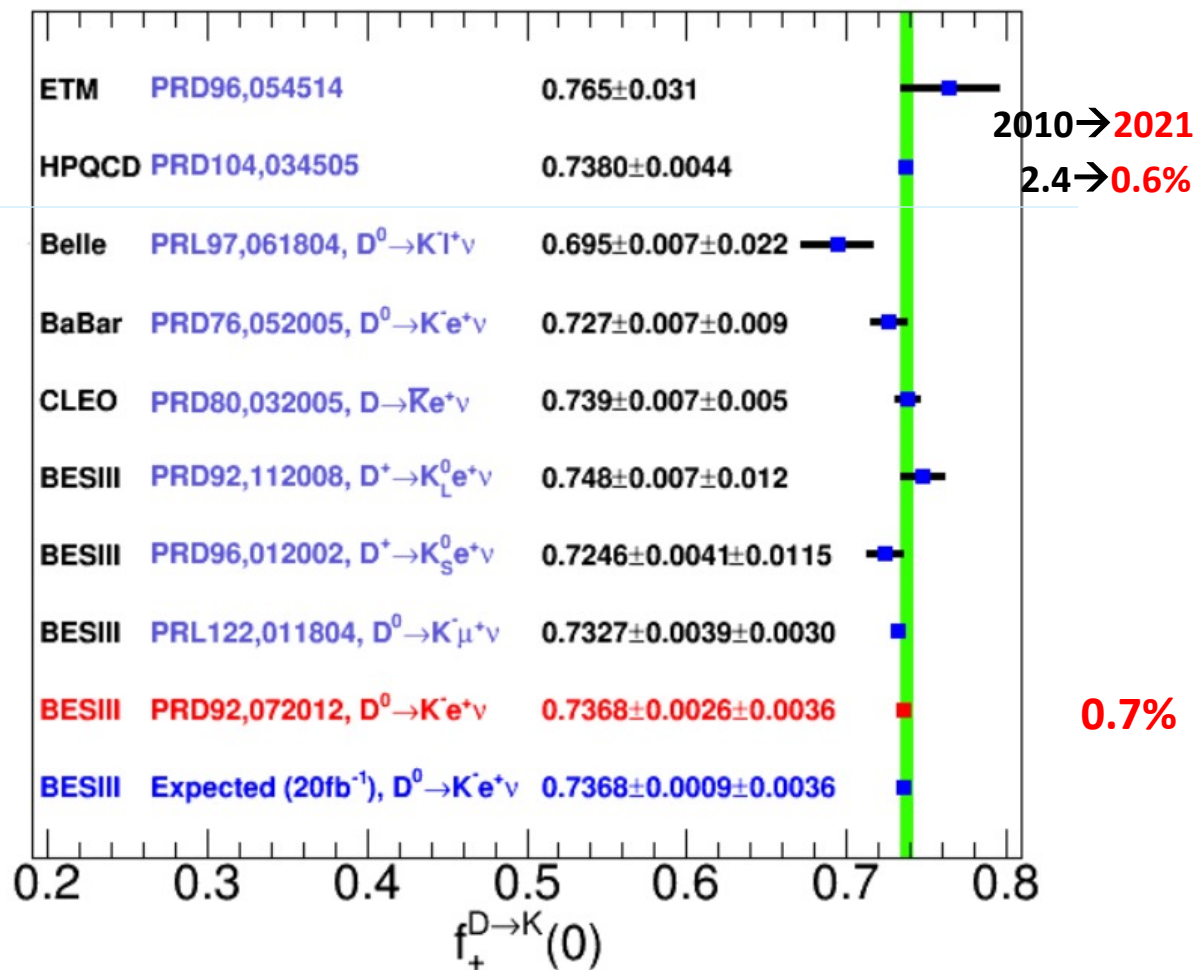


At zero positron mass limit:

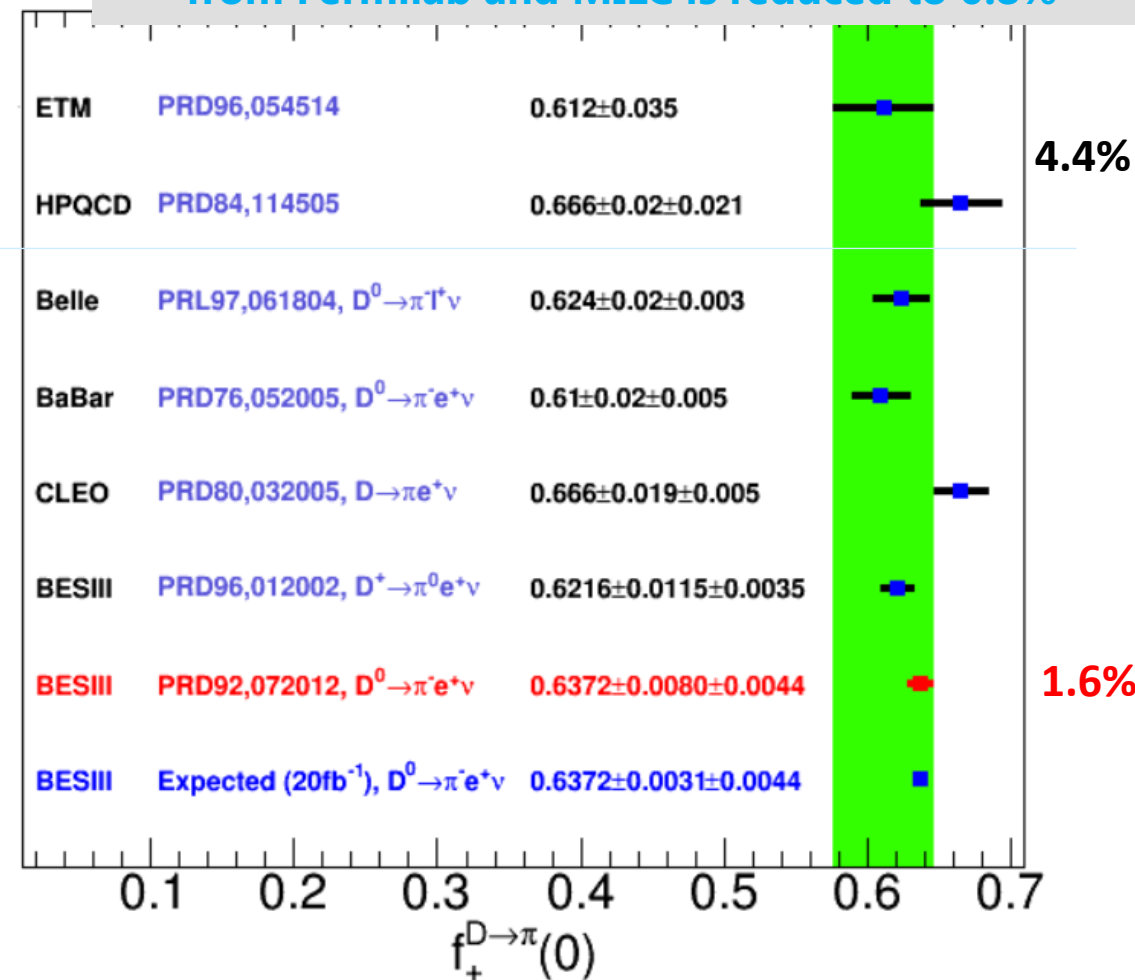
$$\text{Differential rate (Exp.)} \leftarrow \frac{d\Gamma(D_{(s)} \rightarrow K(\pi) l\nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2 P_{K(\pi)}^3}{24\pi^3} |f_+(q^2)|^2$$

CKM matrix element
Form factor (LQCD)

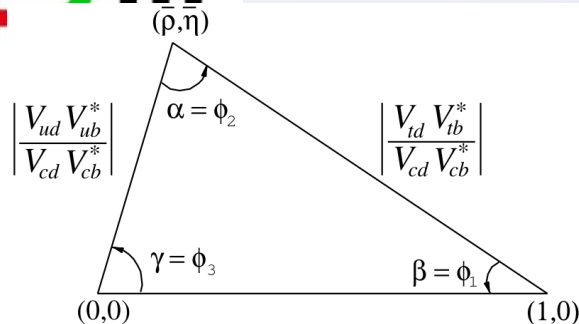
In arXiv:2212.12648, relative error on $f_+^{D \rightarrow \pi}(0)$ from Fermilab and MILC is reduced to 0.8%



Experimental precision of $f_+^{D \rightarrow K}(0)$ is comparable to the latest LQCD precision



Experimental precision of $f_+^{D \rightarrow \pi}(0)$ is still dominated by statistical uncertainties



In B physics, precision measurements of CP violation phase angles α , β and γ offer powerful tests on the EW theories. Among them, the γ precision is the most urgent

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

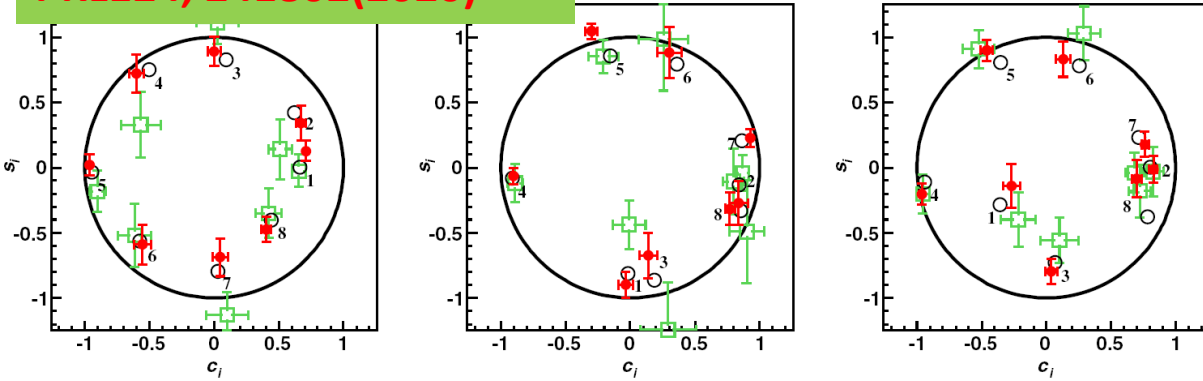
Quantum-correlated $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ pairs offer an ideal opportunity to extract the strong phase differences between D^0 and \bar{D}^0

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

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

$$D \rightarrow K_{S/L}^0 \pi^+ \pi^-$$

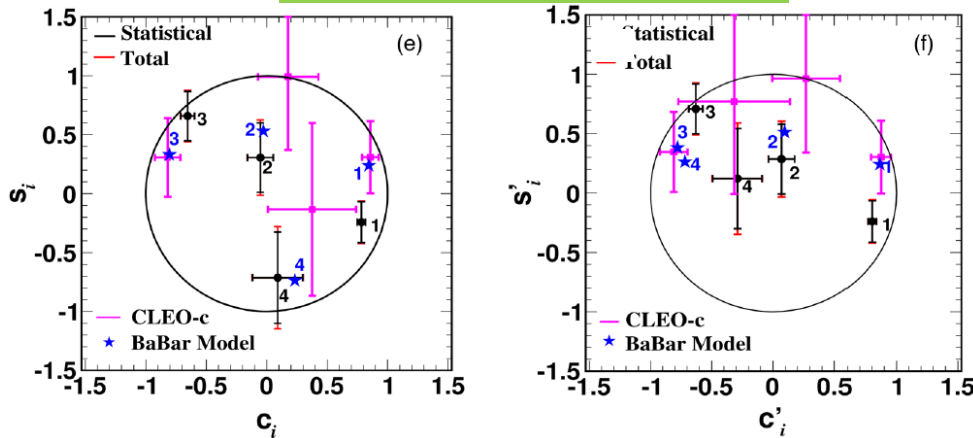
PRL124, 241802(2020)



Constraint on γ measurement

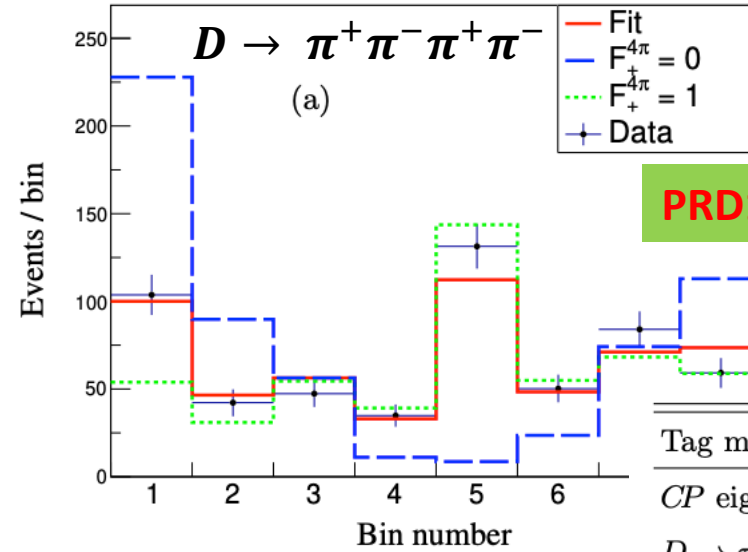
$$D \rightarrow K_{S/L}^0 K^+ K^-$$

PRD102, 052008(2020)



Constraint on γ measurement $\sim 1.3^\circ$

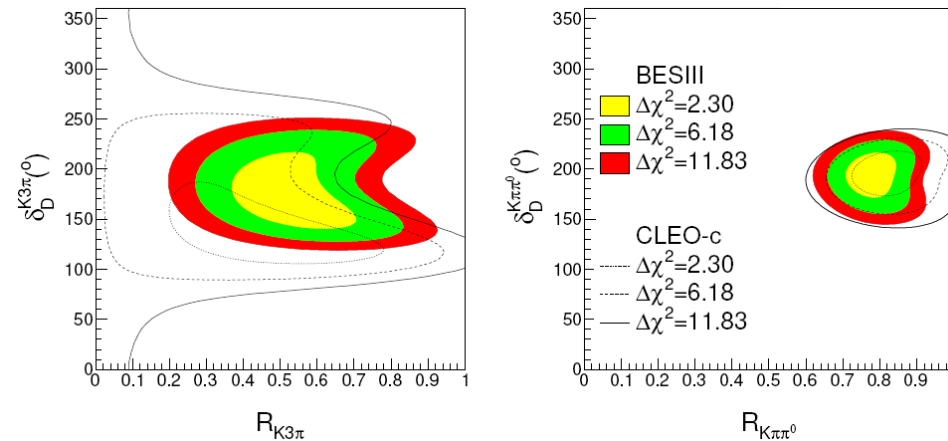
$$D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$$



PRD106, 092004(2022)

| Tag modes | $F_+^{4\pi}$ |
|---------------------------------------|-----------------------------|
| CP eigenstates | $0.721 \pm 0.019 \pm 0.007$ |
| $D \rightarrow \pi^+ \pi^- \pi^0$ | $0.753 \pm 0.028 \pm 0.010$ |
| $D \rightarrow K_{S,L}^0 \pi^+ \pi^-$ | $0.754 \pm 0.031 \pm 0.009$ |
| Combination | $0.735 \pm 0.015 \pm 0.005$ |

$$D \rightarrow K^- \pi^+ \pi^+ \pi^- \text{ and } K^- \pi^+ \pi^0$$



JHEP05, 164(2021)

Constraint on γ measurement $\sim 6^\circ$

| Analysis | Resonance | |
|---|----------------------------------|------------------------------|
| $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^- \pi^+$ | $a_1(1260)^+$ | JHEP07(2022)051 |
| $D_s^+ \rightarrow K_S^0 K_S^0 \pi^+$ | $a_0(1710)^0, f_0(1710)$ | PRD105(2022) L051103 |
| $D_s^+ \rightarrow K_S^0 K^+ \pi^0$ | $a_0(1817)^+$ | <u>PRL129, 182001 (2022)</u> |
| $D_s^+ \rightarrow K^+ \pi^+ \pi^-$ | $f_0(500), f_0(980), f_0(1370)$ | JHEP08(2022)196 |
| $D_s^+ \rightarrow \pi^+ \pi^0 \pi^0$ | $f_0(980), f_0(1370), f_2(1270)$ | JHEP01(2022)052 |

Charge conjugate channels are included.

[PRL129, 182001 \(2022\)](#)

- Amplitude analysis, $N_{\text{tot}} = 1050$ with a signal purity of $(94.7 \pm 0.7)\%$
- Observed $a_0(1817)^+ (\rightarrow K_S^0 K^+)$: isovector partner of $f_0(1710)$?

$$M = (1.817 \pm 0.008_{\text{stat.}} \pm 0.020_{\text{syst.}}) \text{ GeV}/c^2$$

$$\Gamma = (0.097 \pm 0.022_{\text{stat.}} \pm 0.015_{\text{syst.}}) \text{ GeV}$$

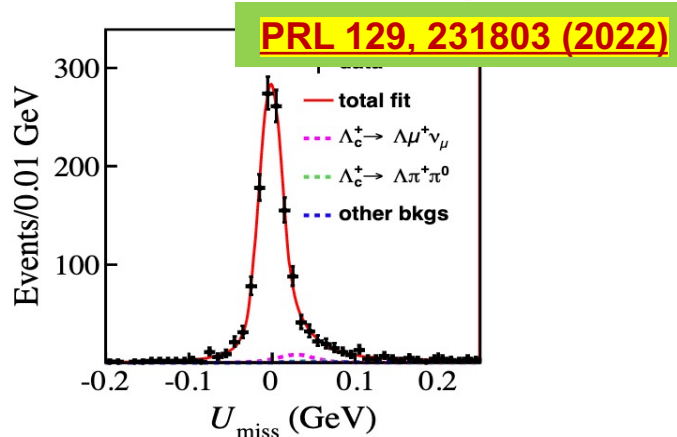
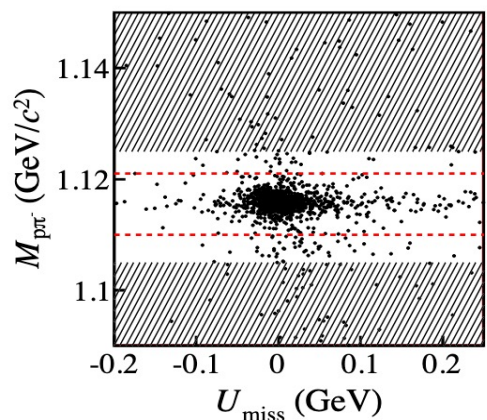
- The measured ratio for $a_0(980)^+$:

$$\frac{B[a_0(980)^+ \rightarrow \bar{K}^0 K^+]}{B[a_0(980)^+ \rightarrow \pi^+ \eta]} = (13.7 \pm 3.6_{\text{stat.}} \pm 4.2_{\text{syst.}})\%$$

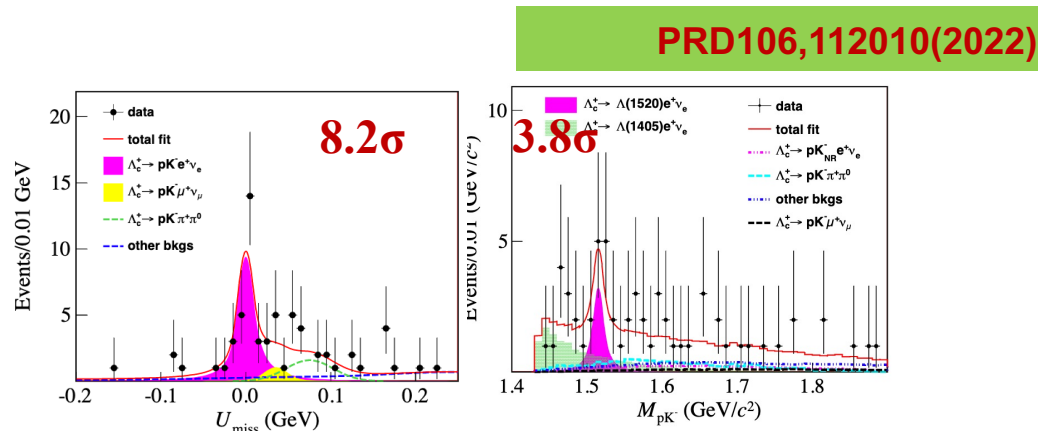
A key experimental input for the calculation of the coupling constants of the $a_0(980)$, and helps to determine its quark composition



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

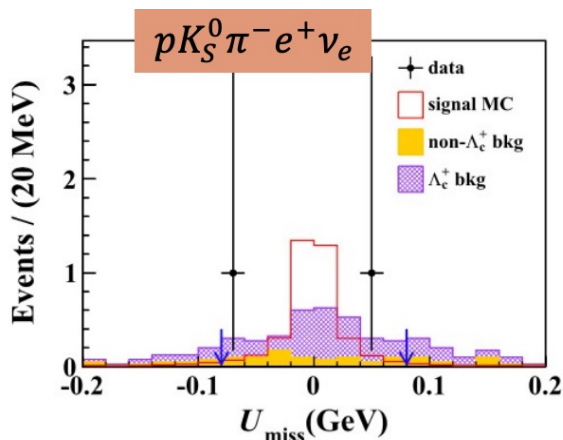
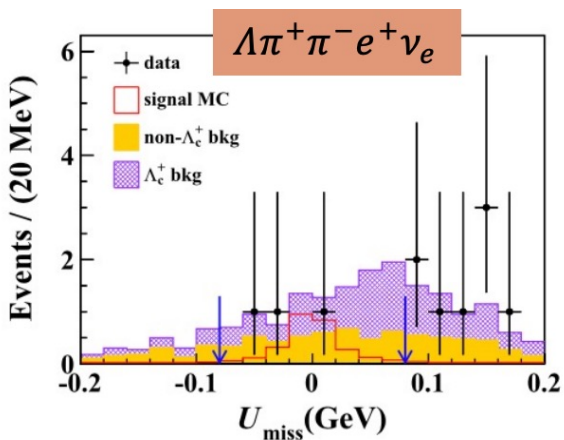
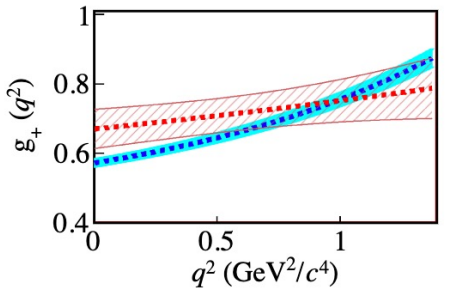
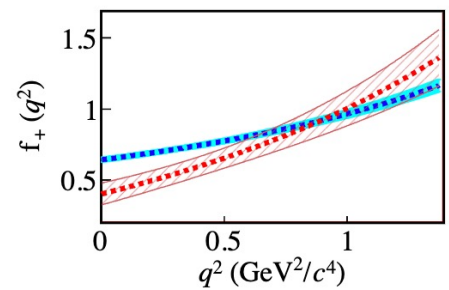
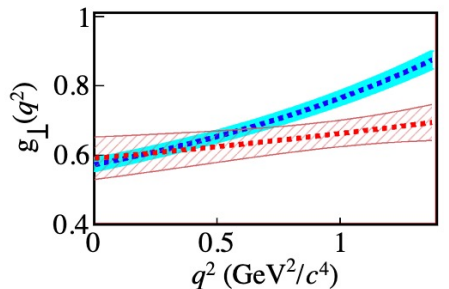
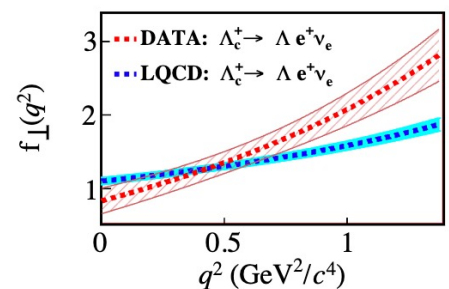


Observation of $\Lambda_c^+ \rightarrow pK^- e^+ \nu$



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

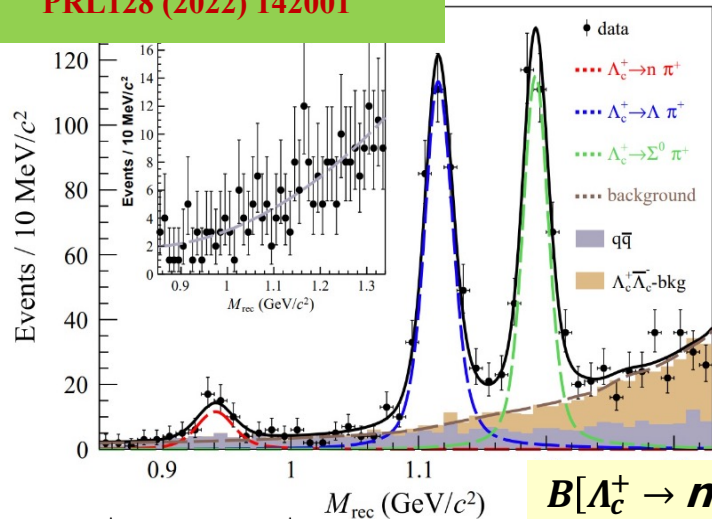
- Second leptonic decay of Λ_c^+ is observed!
- Good channel to study Λ excited states, such as $\Lambda(1405)$, $\Lambda(1520)$



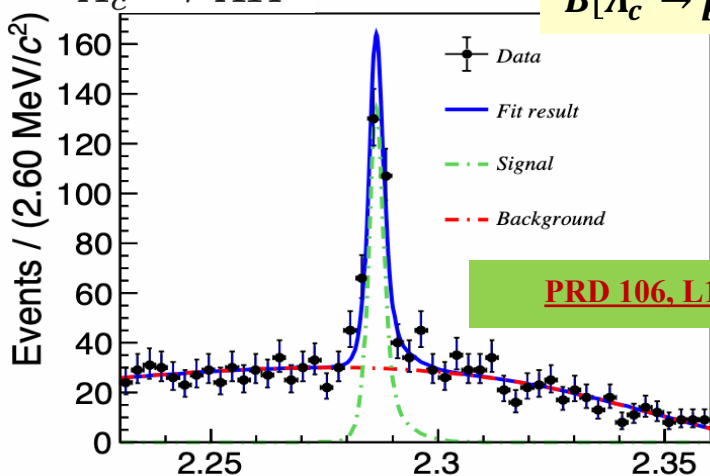
PLB843,137993(2023)

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

PRL128 (2022) 142001



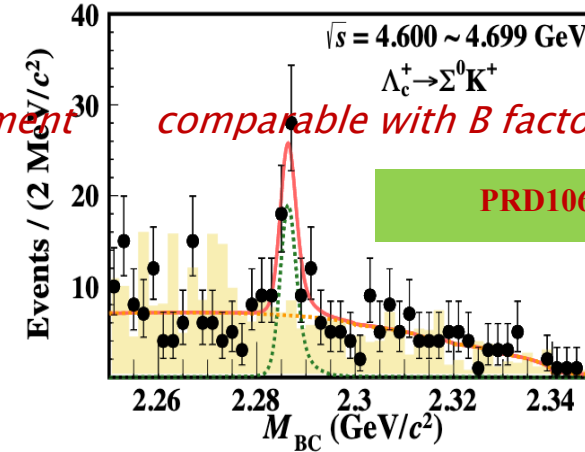
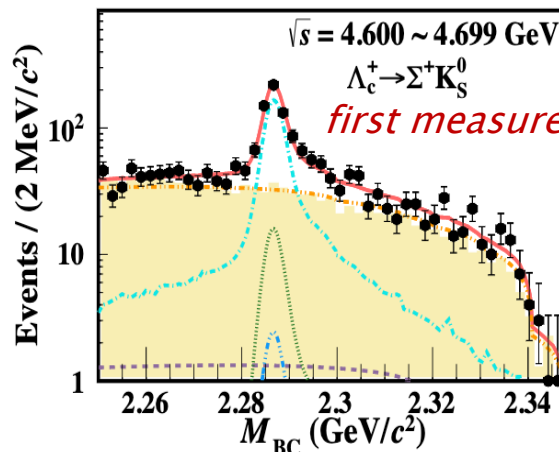
$$\frac{B[\Lambda_c^+ \rightarrow n\pi^+]}{B[\Lambda_c^+ \rightarrow p\pi^0]} > 7.2$$



PRD 106, L111101 (2022)

Many CS modes are explored.

Determination of the BF for $\Lambda_c^+ \rightarrow \Sigma^+ K_S$ and $\Sigma^0 K^+$

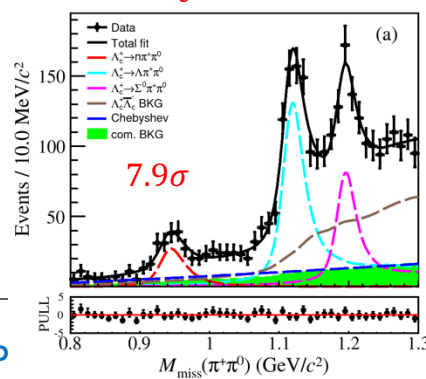


PRD106, 052003 (2022)

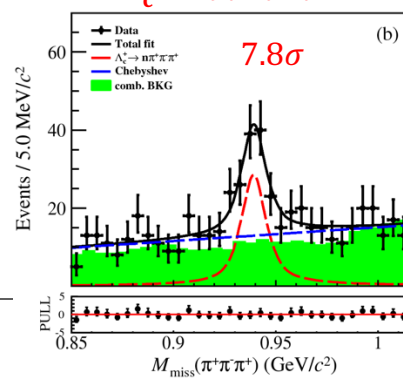
Arxiv:2304.09405

| Decay mode | RBF (This work) | RBF (Belle) | BF (This work) | BF (PDG) |
|-----------------------------------|--------------------------|-----------------------|---------------------------------------|-----------------|
| $\Sigma^+ K^+ K^-$ | $8.38 \pm 0.93 \pm 0.41$ | $7.6 \pm 0.7 \pm 0.9$ | $0.377 \pm 0.042 \pm 0.018 \pm 0.021$ | 0.35 ± 0.04 |
| $\Sigma^+ K^+ \pi^-$ | $4.44 \pm 0.52 \pm 0.23$ | $4.7 \pm 1.1 \pm 0.8$ | $0.200 \pm 0.023 \pm 0.010 \pm 0.011$ | 0.21 ± 0.06 |
| $\Sigma^+ K^+ \pi^- \pi^0$ | < 2.4 | - | < 0.11 | - |
| $\Sigma^+ \phi$ | $9.2 \pm 1.8 \pm 0.6$ | $8.5 \pm 1.2 \pm 1.2$ | $0.414 \pm 0.080 \pm 0.029 \pm 0.023$ | 0.39 ± 0.06 |
| $\Sigma^+ K^+ K^-$ (non- ϕ) | $4.38 \pm 0.79 \pm 0.19$ | - | $0.197 \pm 0.036 \pm 0.008 \pm 0.011$ | - |

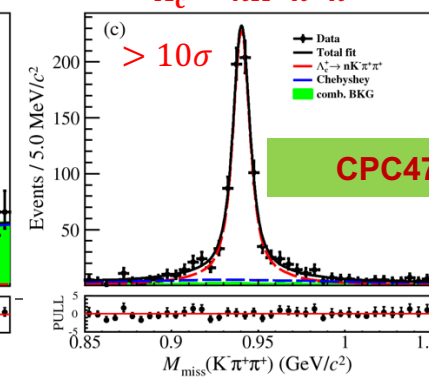
$\Lambda_c^+ \rightarrow n\pi^+\pi^0$



$\Lambda_c^+ \rightarrow n\pi^+\pi^-\pi^+$



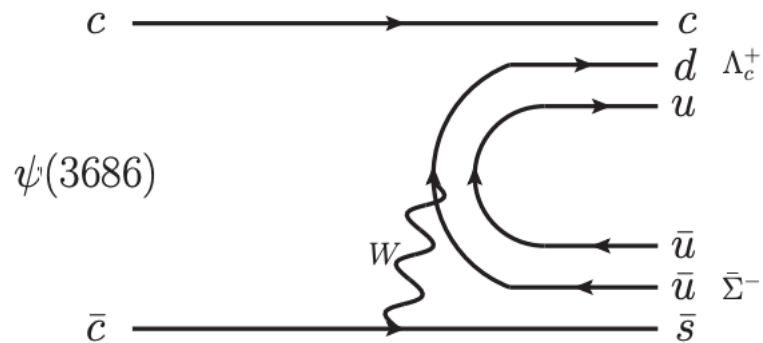
$\Lambda_c^+ \rightarrow nK^-\pi^+\pi^+$



CPC47, 023001(2023)

Exotic Decays and New Physics

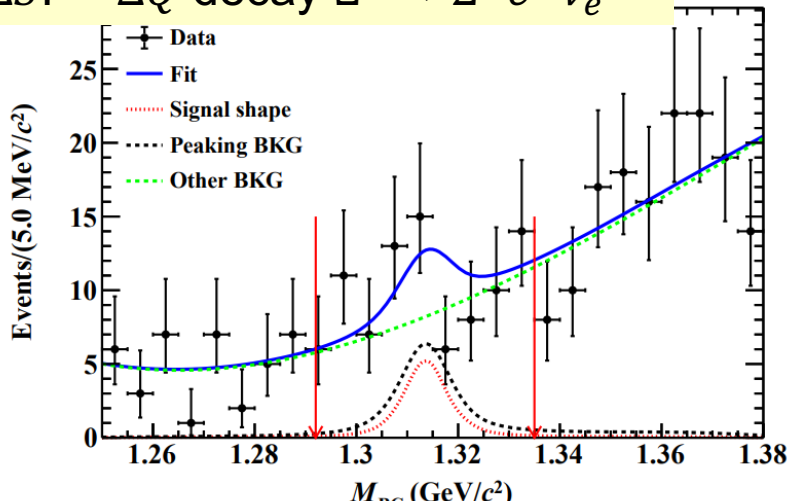
- More ideas (with theorists)
- More channels
- More exploitation of existing data



$B(\psi(3686) \rightarrow \Lambda_c^+ \text{ anti-}\Sigma^-) < 1.4 \times 10^{-5}$.

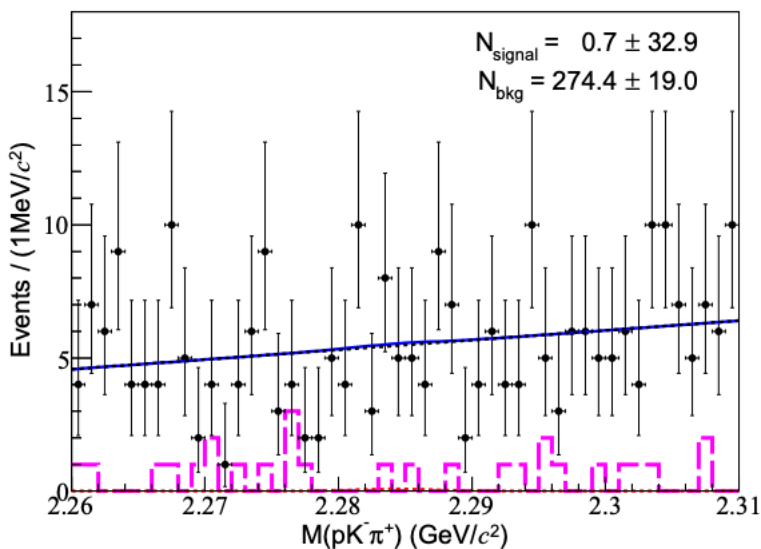
Chin. Phys. C 47, 013002 (2022)

$\Delta S! = \Delta Q$ decay $\Xi^0 \rightarrow \Sigma^- e^+ \nu_e$



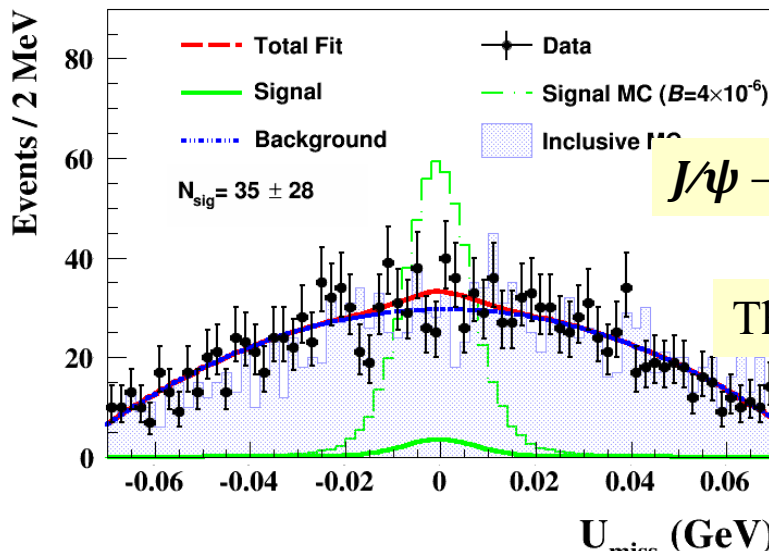
Phys. Rev. D 107, 012002 (2023)

$BF < 1.6 \times 10^{-4}$ @ 90% C.L.
One order of magnitude improvement over PDG



2023/7/13

Flavor Physics Lecture



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

Arxiv:2307.02165

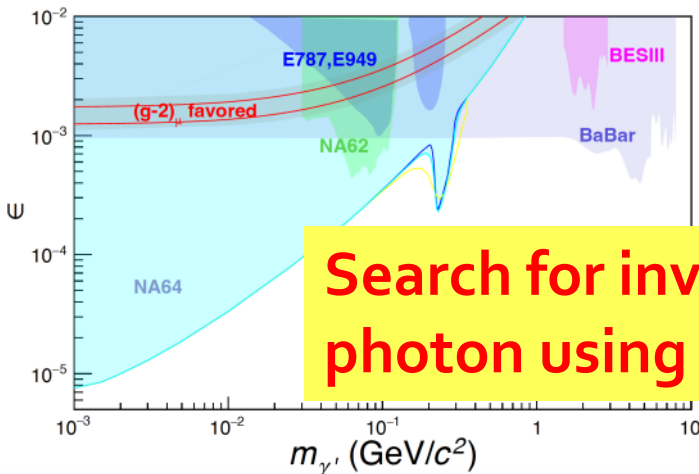
The 1st search for semi-muonic decay

JHEP 06 (2021) 157

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

| Data | Source | Mode | $ \Delta(B - L) $ | UL on BF @ 90% CL |
|---|------------------------|---|---|---------------------------|
| $\sqrt{s} = 3.773 \text{ GeV } 2.93 \text{ fb}^{-1}$ $N_{D^+D^-}^{\text{tot}} = (8,296 \pm 31 \pm 64) \times 10^3$ $N_{D^0\bar{D}^0}^{\text{tot}} = (10,597 \pm 28 \pm 98) \times 10^3$ | D mesons | $D^+ \rightarrow \bar{\Lambda} e^+$ | 0 | 6.5×10^{-7} |
| | | $D^+ \rightarrow \bar{\Sigma}^0 e^+$ | 0 | 1.3×10^{-6} |
| | | $D^+ \rightarrow \Lambda e^+$ | 2 | 1.1×10^{-6} |
| | | $D^+ \rightarrow \Sigma^0 e^+$ | 2 | 1.7×10^{-6} |
| | | $D^0 \rightarrow \bar{p} e^+$ PRD 105, 032006 (2022) | 2 | $1.2(2.2) \times 10^{-6}$ |
| | | $D^+ \rightarrow \bar{n} e^+$ PRD 106, 112009 (2022) | 0/2 | $1.4(2.5) \times 10^{-5}$ |
| | | $D^0 \rightarrow K^- \pi^+ e^+ e^+$ | 2 | 2.8×10^{-6} |
| | | $D^+ \rightarrow K_S^0 \pi^- e^+ e^+$ | 2 | 3.3×10^{-6} |
| | | $D^+ \rightarrow K^- \pi^0 e^+ e^+$ | 2 | 8.5×10^{-6} |
| $\sqrt{s} = 3.097 \text{ GeV}$ $N_{J/\psi}^{\text{tot}} = (1,310.6 \pm 7.0) \times 10^6$ | J/ψ meson | $J/\psi \rightarrow \Lambda_c^+ e^-$ | 0 | 6.9×10^{-8} |
| | | $J/\psi \rightarrow p K^- \bar{\Lambda} \rightarrow p K^- \Lambda$ 2305.04568 | 2 [BF ratio $P(\Lambda) < 4.4 \times 10^{-6}$] | |
| | Σ ⁻ hyperon | $\Sigma^- \rightarrow p e^- e^-$ | 2 | 6.7×10^{-5} |
| $\Sigma^- \rightarrow \Sigma^+ X$ | | 2 | 1.4×10^{-4} | |
| 10B Jpsi events | Ξ ⁰ hyperon | $\Xi^0 \rightarrow K^\pm e^\mp + cc.$ 2305.07231, PRD | 2 | $3.6(1.9) \times 10^{-6}$ |

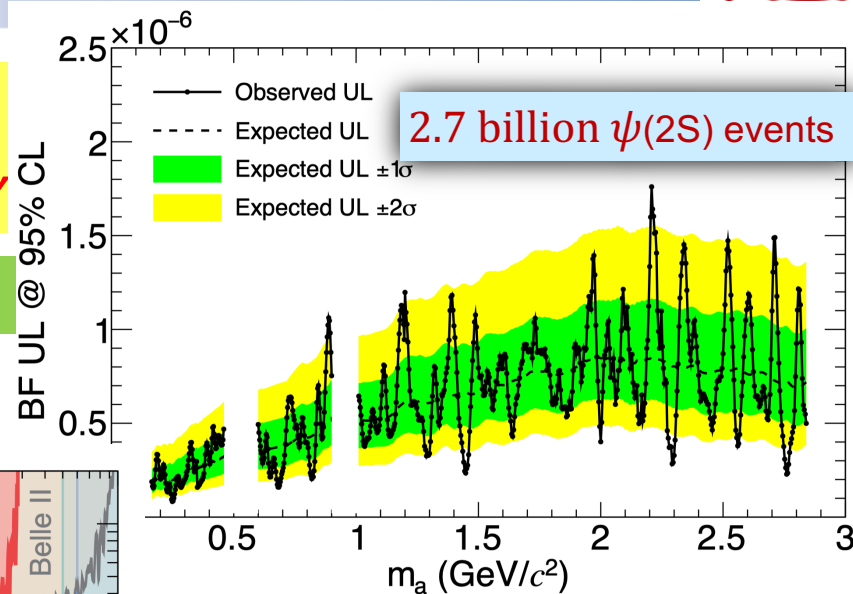
Phys. Lett. B 839 (2023)137785



Search for invisible dark photon using ISR

Search for a ALP in $J/\psi \rightarrow \gamma a, a \rightarrow \gamma\gamma$

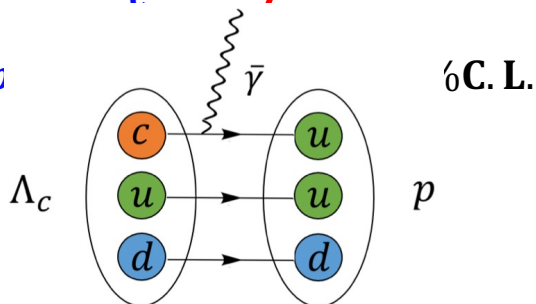
Phys. Lett. B 838 (2023)137698



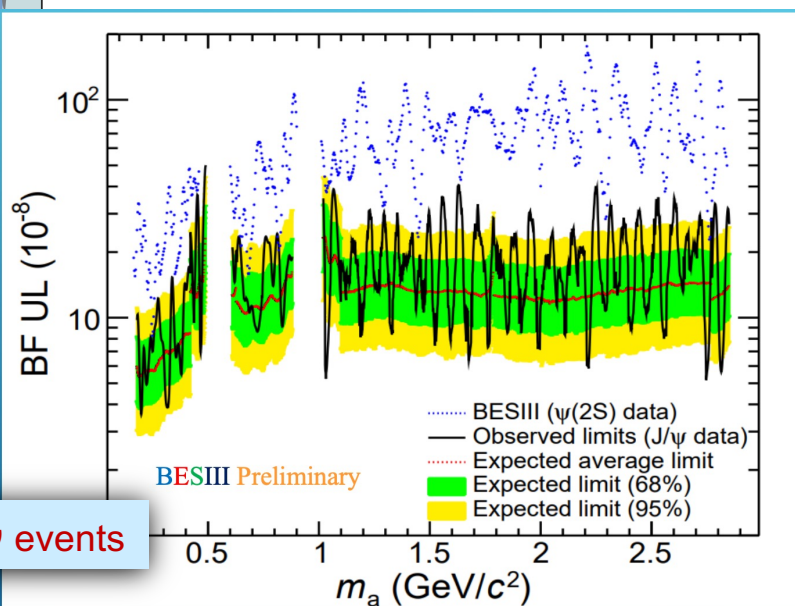
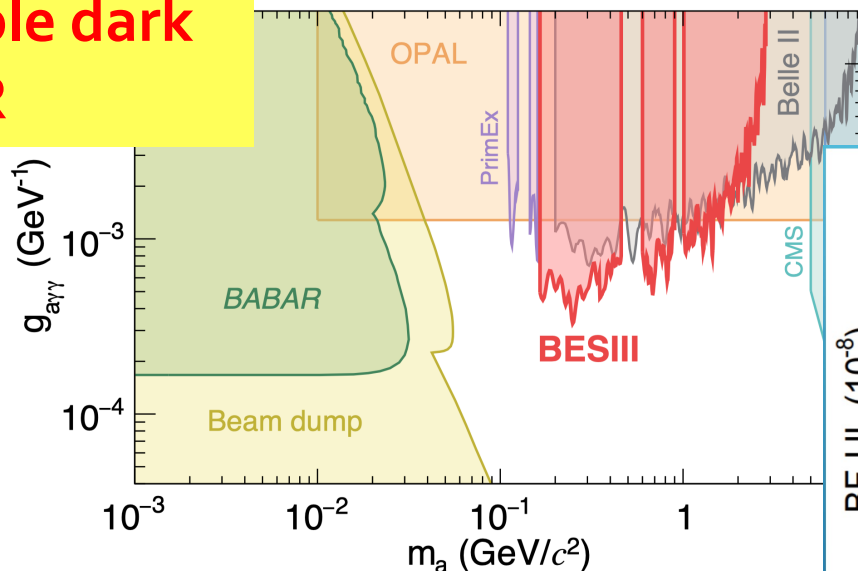
2.7 billion $\psi(2S)$ events

Search for massless dark photon in Λ_c decay

$$B(\Lambda_c^+ \rightarrow p \gamma)$$



68% C.L.



10 billion J/ψ events

Phys. Rev. D 106, 072008 (2022)

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

| Energy | Physics motivations | Current data | Expected final data | T_C / T_U |
|---------------------|---|--|--|---------------|
| 1.8 - 2.0 GeV | R values Nucleon cross-sections | N/A | 0.1 fb ⁻¹ (fine scan) | 60/50 days |
| 2.0 - 3.1 GeV | R values Cross-sections | Fine scan (20 energy points) | Complete scan (additional points) | 250/180 days |
| ✓ J/ψ peak | Light hadron & Glueball J/ψ decays | 3.2 fb ⁻¹ (10 billion) | ~16fb-1 taken, finish in 2024 | |
| ✓ $\psi(3686)$ peak | Light hadron & Glueball Charmonium decays | 0.67 fb ⁻¹ (0.45 billion) | 4.5 fb ⁻¹ (3.0 billion) | 150/90 days |
| $\psi(3770)$ peak | D^0/D^\pm decays | 2.9 fb ⁻¹ | 20.0 fb ⁻¹ | 610/360 days |
| 3.8 - 4.6 GeV | R values XYZ /Open charm | Fine scan (105 energy points) | No requirement | N/A |
| 4.180 GeV | D_s decay XYZ /Open charm | 3.2 fb ⁻¹ | 6 fb ⁻¹ | 140/50 days |
| 4.0 - 4.6 GeV | XYZ /Open charm Higher charmonia cross-sections | 16.0 fb ⁻¹ at different \sqrt{s} | 30 fb ⁻¹ at different \sqrt{s} | 770/310 days |
| 4.6 - 4.9 GeV | Charmed baryon/ XYZ cross-sections | 0.56 fb ⁻¹ at 4.6 GeV | 15 fb ⁻¹ at different \sqrt{s} | 1490/600 days |
| 4.74 GeV | $\Sigma_c^+ \Lambda_c^-$ cross-section | N/A | 1.0 fb ⁻¹ | 100/40 days |
| 4.91 GeV | $\Sigma_c \Sigma_c$ cross-section | N/A | 1.0 fb ⁻¹ | 120/50 days |
| 4.95 GeV | Ξ_c decays | N/A | 1.0 fb ⁻¹ | 130/50 days |

~55 fb⁻¹



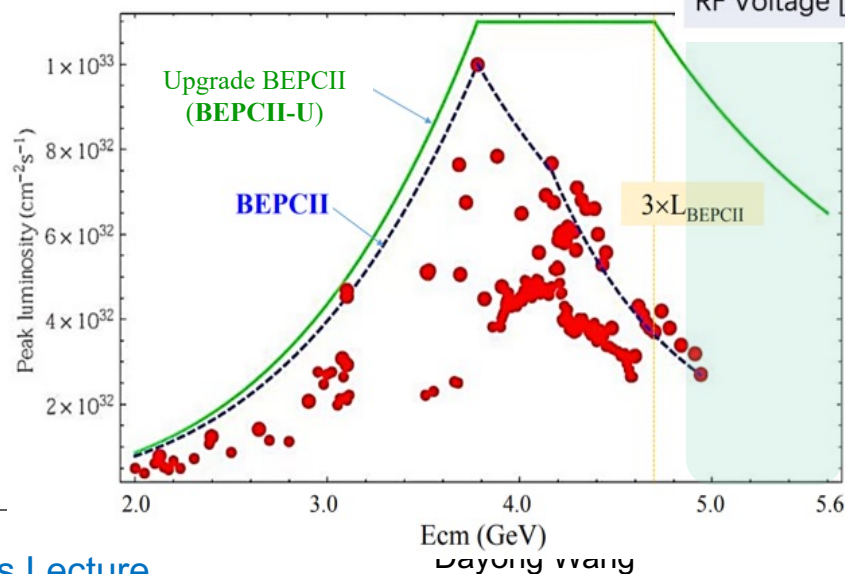
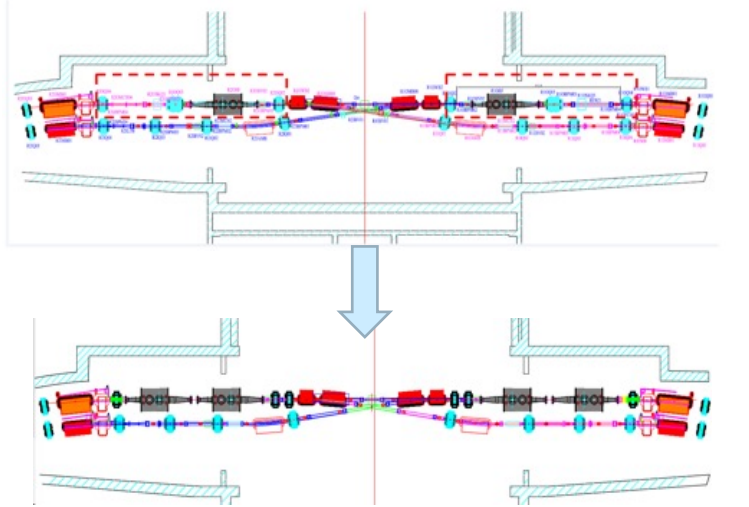
Future Physics Programme of BESIII (white book)

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

✓ An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021:
the optimized energy is 2.35 GeV with luminosity 3 times higher than current BEPCII and extend the maximum energy to 5.6 GeV

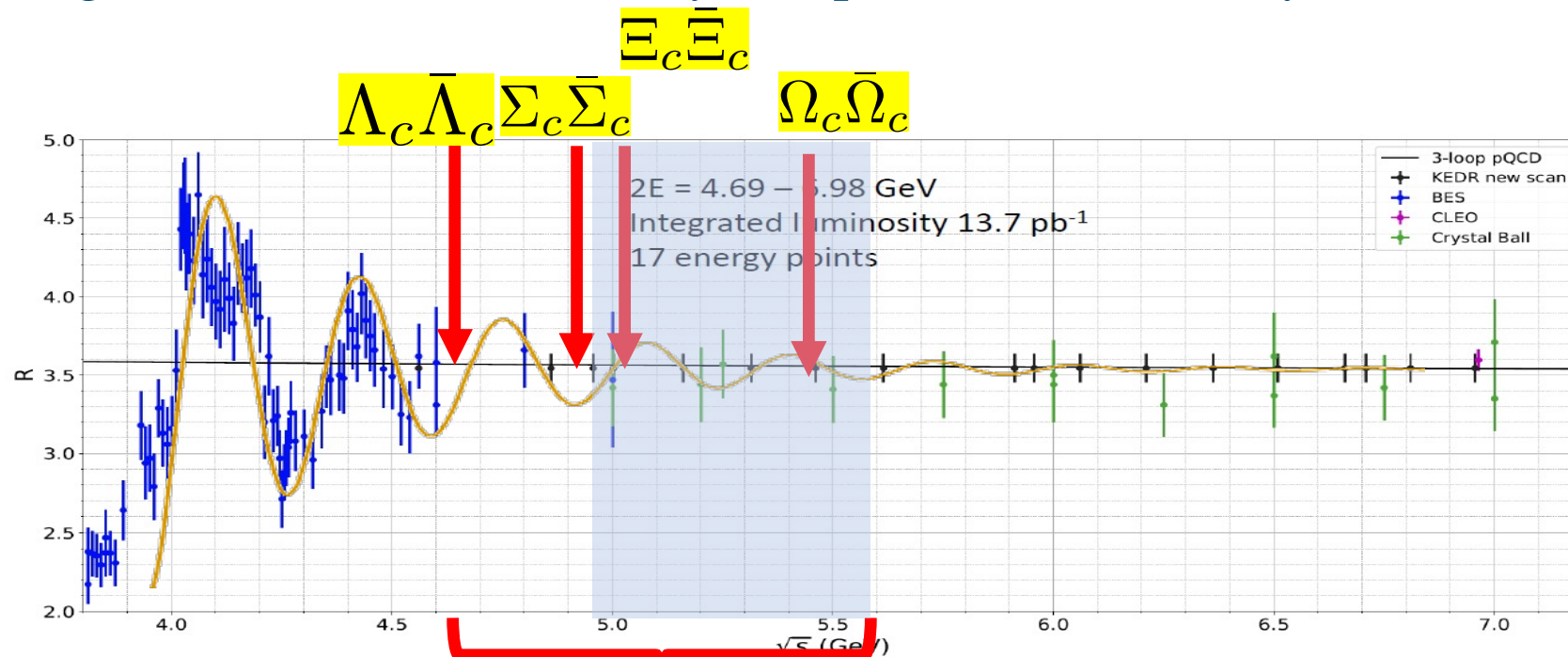
- Add another cavity per beam to improve the RF power
- Change optics slightly, increase number of bunches
- Challenges: high beam intensities, backgrounds and aging effect in the detector
- Small risk: can continue running with better performance than BEPCII
- Timescale: 2.5 years construction + 0.5 year installation
- Installation: July – December 2024 and the upgraded machine ready in Jan. 2025

| | BEPCII | BEPCII-U |
|--|--------------|--------------|
| Lum [$10^{32}\text{cm}^{-2}\text{s}^{-1}$] | 3.5 | 11 |
| β_y^* [cm] | 1.5 | 1.35 |
| Bunch Current [mA] | 7.1 | 7.5 |
| Bunch Num | 56 | 120 |
| SR Power [kW] | 110 | 250 |
| $\xi_{y,\text{lum}}$ | 0.029 | 0.033 |
| Emittance [nmrad] | 147 | 152 |
| Coupling [%] | 0.53 | 0.35 |
| Bucket Height | 0.0069 | 0.011 |
| $\sigma_{z,0}$ [cm] | 1.54 | 1.07 |
| σ_z [cm] | 1.69 | 1.22 |
| RF Voltage [MV] | 1.6 | 3.3 |



BESIII Detector: There is a **potential** upgrade of inner tracker, but **No** big change of performance foreseen

- ✓ Detailed studies of the known $Z_{c(s)}$ states and search for more exotic states in the higher energy region within a considerable amount of data sets.
- ✓ Cover all the ground-state charmed baryons: production & decays, CPV search



**Few data and potential physics for XYZ
and charmed baryons**

- **BESIII is operating with good performance after 15 years**
 - collect large data samples in the energy range 2.0~5.6 GeV
- **BESIII has performed wide range of physics studies**
 - ◆ Light hadron spectroscopy and decays
 - ◆ Charmonia transitions and XYZ
 - ◆ R value and QCD studies
 - ◆ Charmed meson and charmed baryon
 - ◆ Rare decays and new physics search
- **BESIII has great potential with unique datasets and analysis techniques. Operation for another 5-10 years foreseen**
 - BEPCII-U: 3x upgrade on luminosity, with energy to 5.6GeV
 - ...More to come!