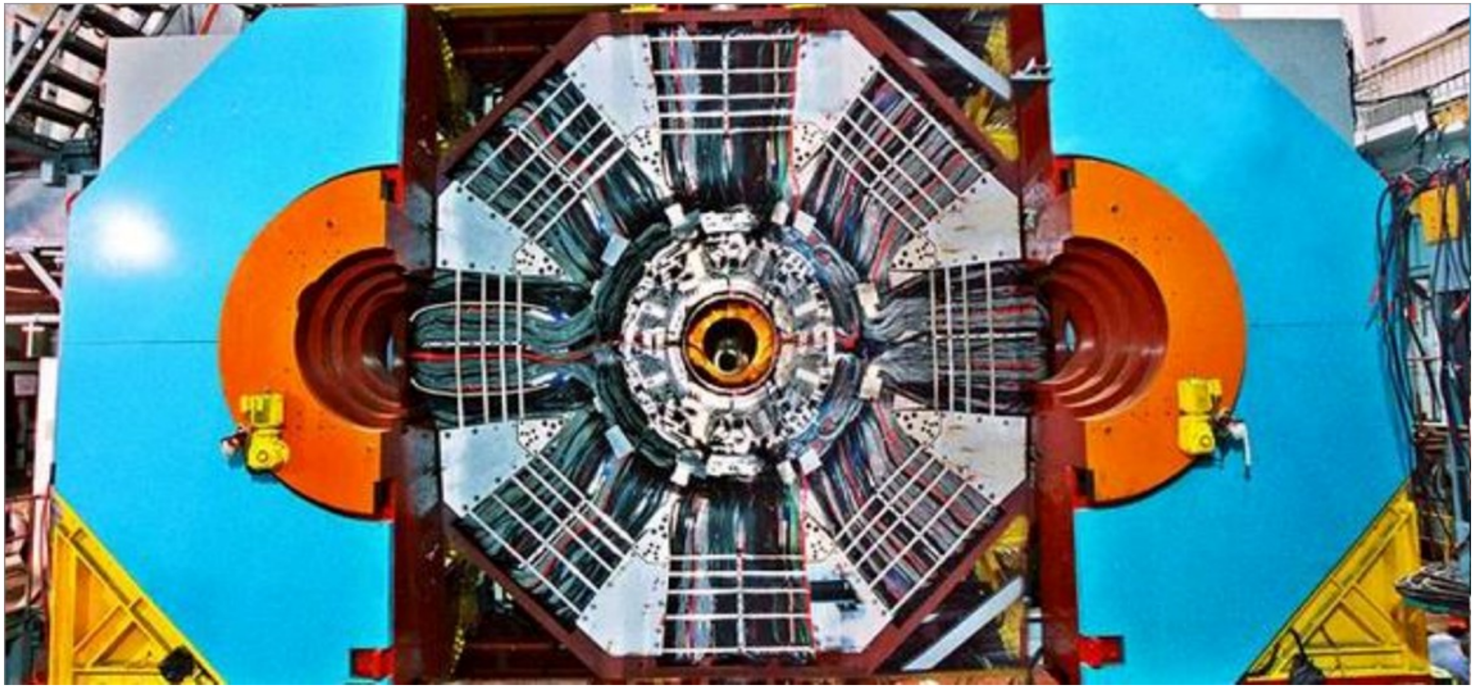


Recent results and future prospects on the BESIII experiment

Xiao-Rui Lyu (吕晓睿)

University of Chinese Academy of Sciences (UCAS)

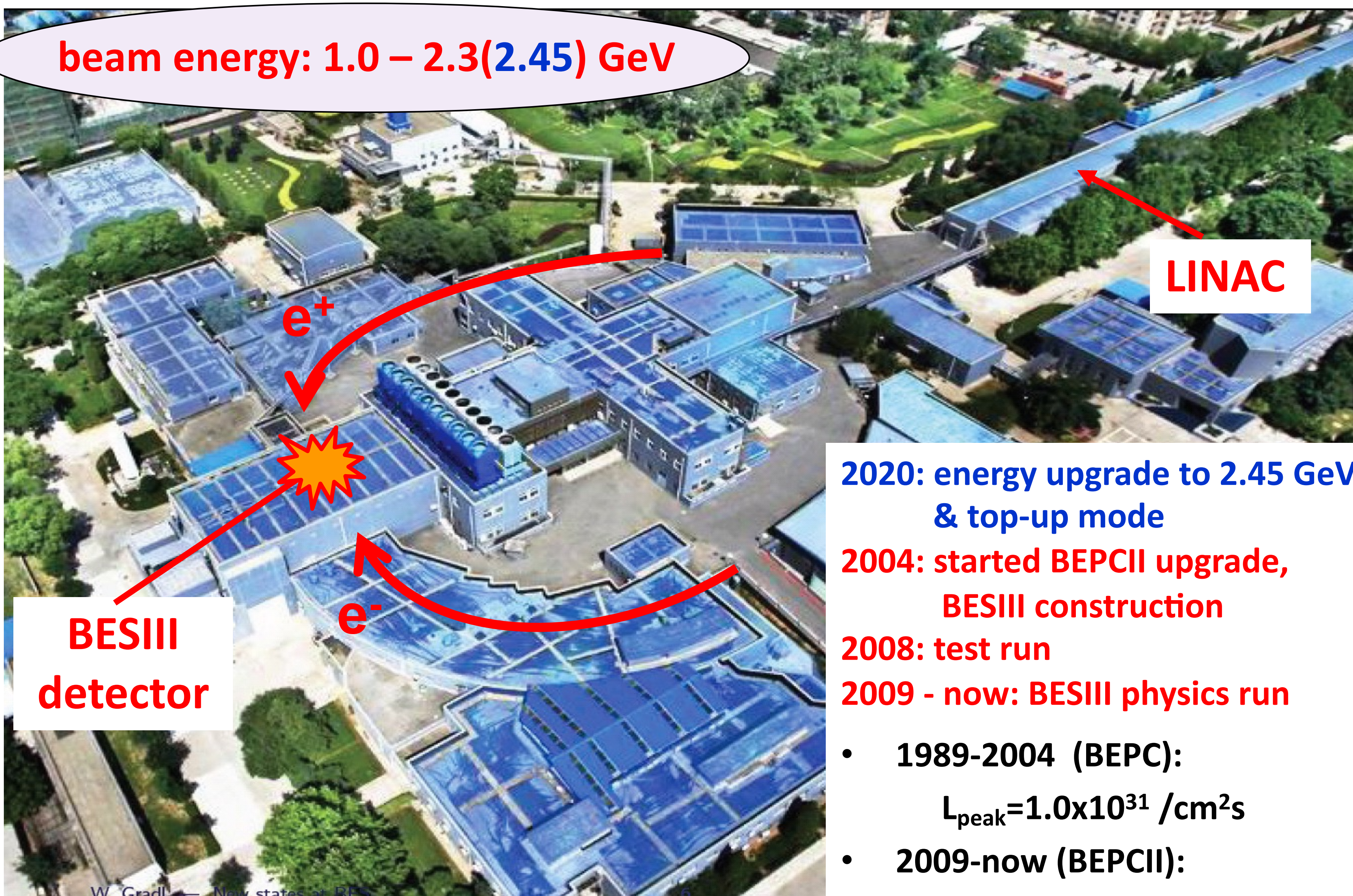
(On behalf of the BESIII collaboration)

Outline

- **Introduction**
- **Highlight on the recent results**
- **Prospects for the future**
- **Summary**

Disclaimer: selective overview, not comprehensive;
More results on new physics can be covered in different BESIII talks.

Beijing Electron Positron Collider (BEPCII)



2020: energy upgrade to 2.45 GeV & top-up mode

2004: started BEPCII upgrade, BESIII construction

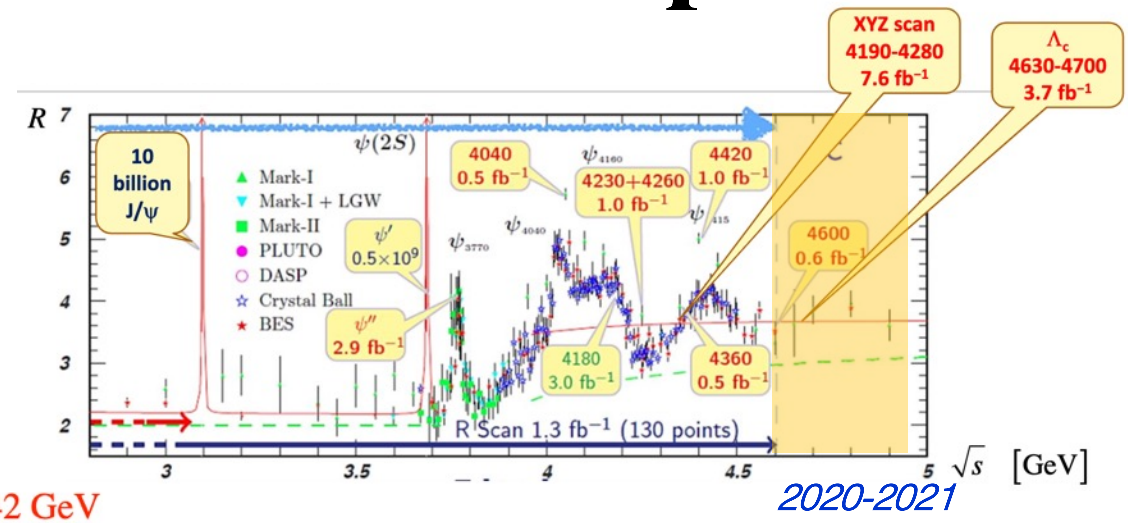
2008: test run

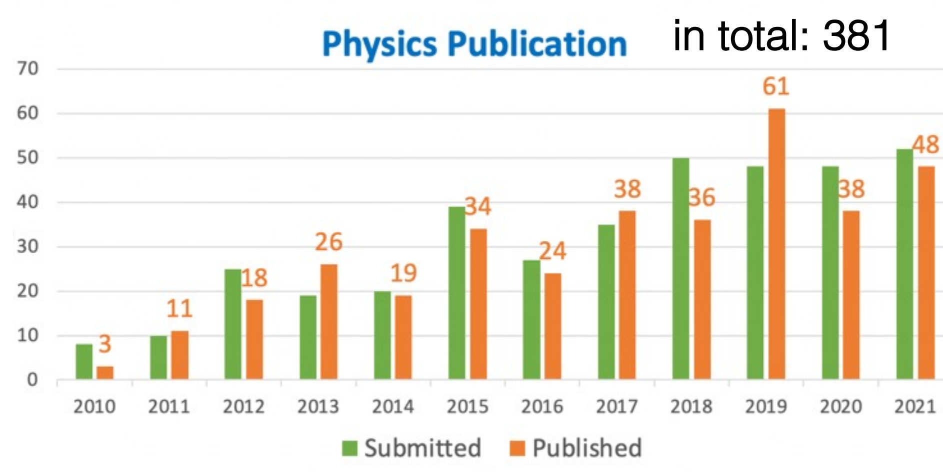
2009 - now: BESIII physics run

- 1989-2004 (BEPC): L_{peak}=1.0x10^{31} /cm^2s
- 2009-now (BEPCII): L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

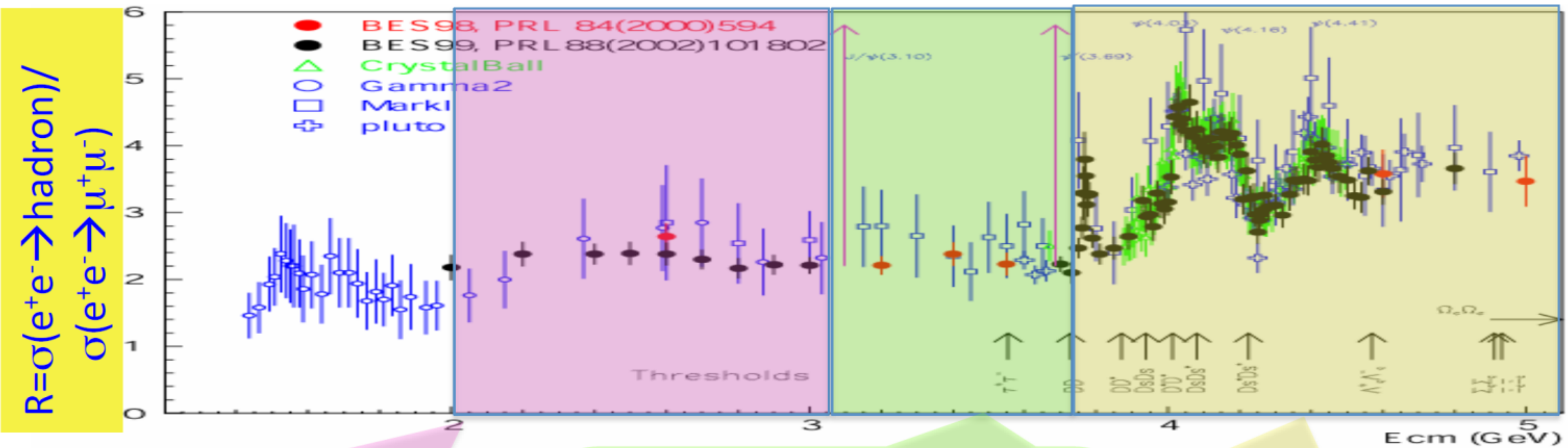
BESIII data sample

2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10×50 pb^{-1} scan 3.81 — 4.42 GeV
2014: 1029 pb^{-1} at 4.42 GeV
110 pb^{-1} at 4.47 GeV
110 pb^{-1} at 4.53 GeV
48 pb^{-1} at 4.575 GeV
567 pb^{-1} at 4.6 GeV
0.8 fb^{-1} R-scan 3.85 — 4.59 GeV
2015: R-scan 2 — 3 GeV + 2.175 GeV
2016: ~3fb^{-1} at 4.18 GeV (for D_s)
2017: 7×500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8×500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020：3.8 fb^{-1} scan **4.61-4.7 GeV**
2021：2 fb^{-1} scan **4.74-4.95 GeV**;
2.55B ψ(2S)





Physics at tau-charm Energy Region



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

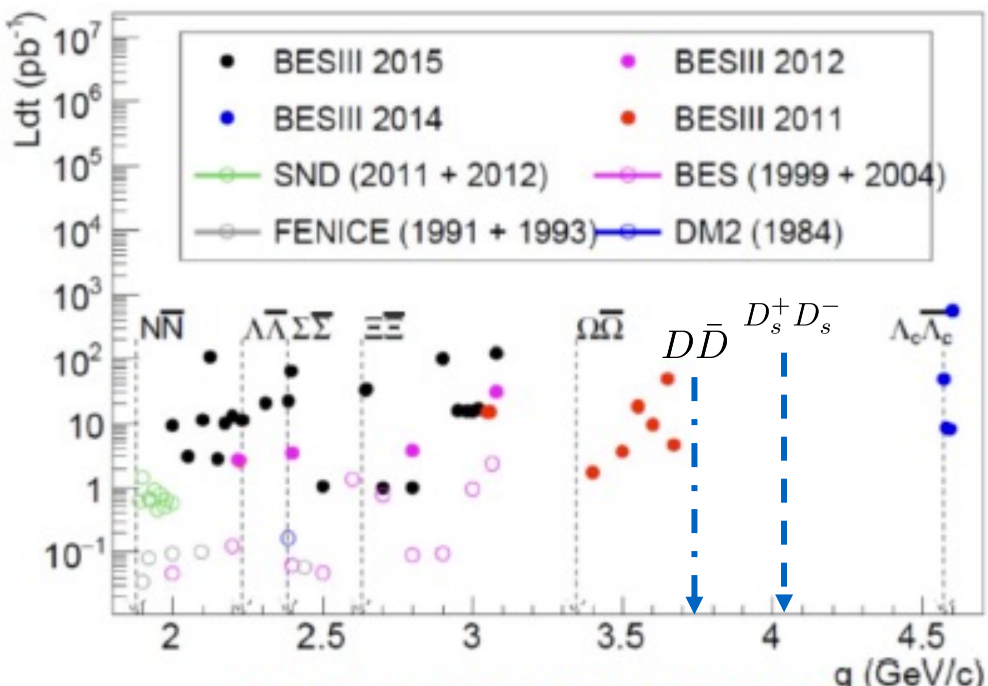
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

Unique data sets near thresholds

e^+e^- symmetric collision:
energy scan data sets at open charm thresholds

3.773 GeV, 2.93 fb^{-1}, $D\bar{D}$
4.008 GeV, 0.48 fb^{-1}, $D_s\bar{D}_s$
4.18-4.23 GeV, 6.32 fb^{-1}, $D_s\bar{D}_s^*$
4.6-4.7 GeV, 4.4 fb^{-1}, $\Lambda_c\bar{\Lambda}_c$



Energy scan in 2014-2015 at BESIII

- **Meson and Baryon pair-productions near thresholds:**
  form-factors in the time-like production, precision branching fractions, relative phase;
- **Quantum-entangled pair productions of charmed mesons**
- **Hyperon and charmed baryon spin polarization in quantum entangled productions;**

BESIII advantage: unique data near to the thresholds

Known initial 4-momentum

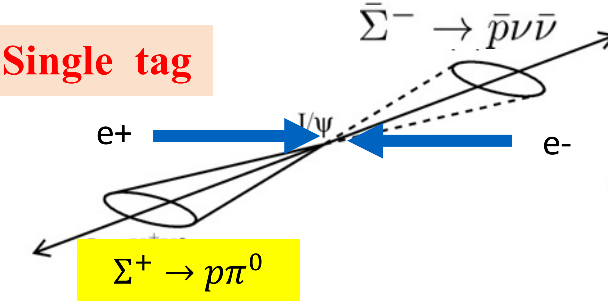
Known beam energy: pair productions

Decay with neutron & π^0

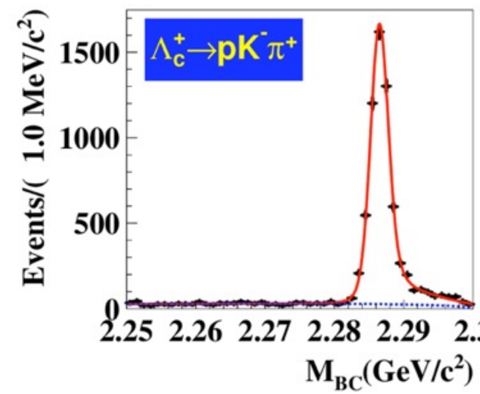
Decay with invisibles: neutrinos

Missing mass or missing energy

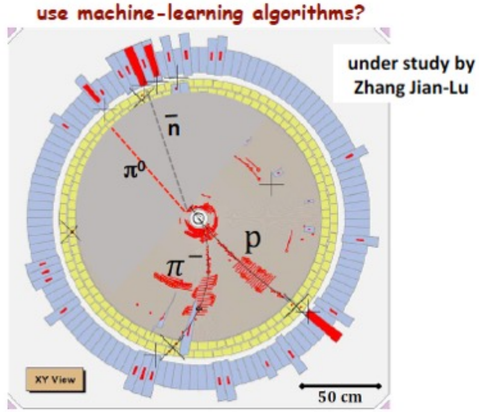
Single tag



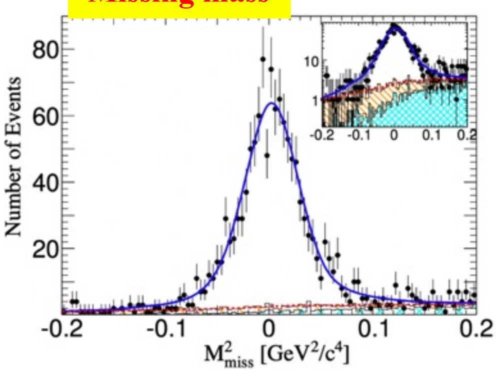
Excellent resolution
Beam-constraint Λ_c mass

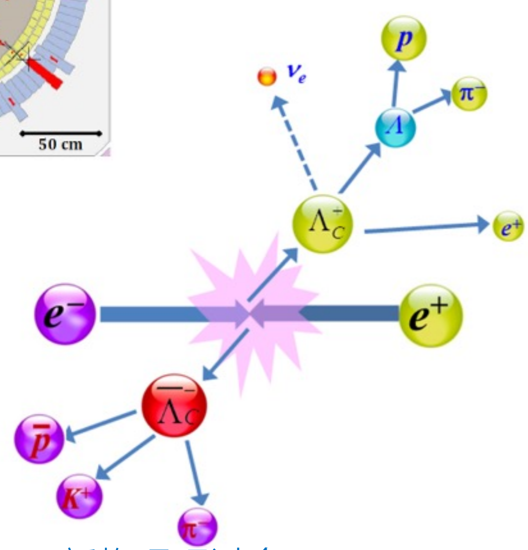


use machine-learning algorithms?



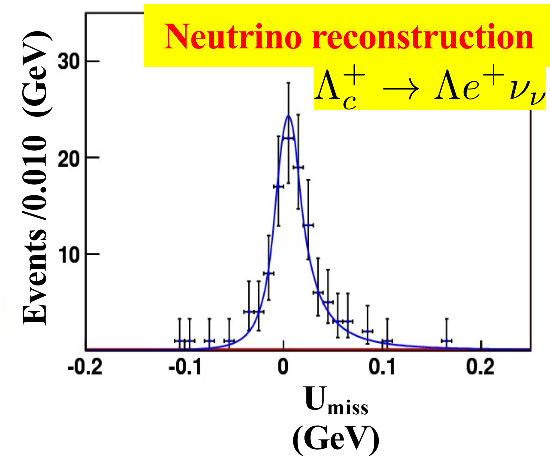
Missing mass



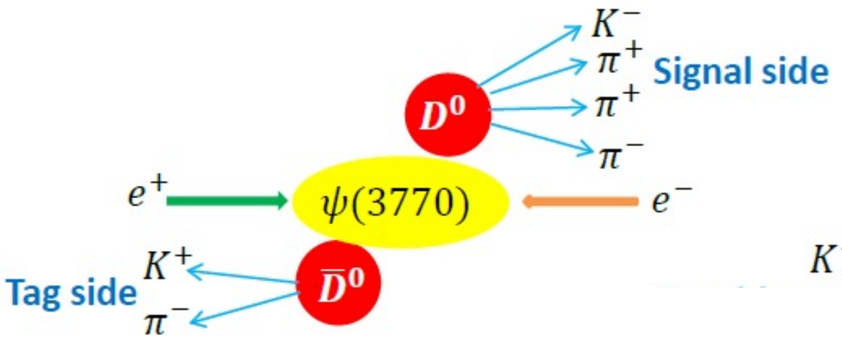


Neutrino reconstruction

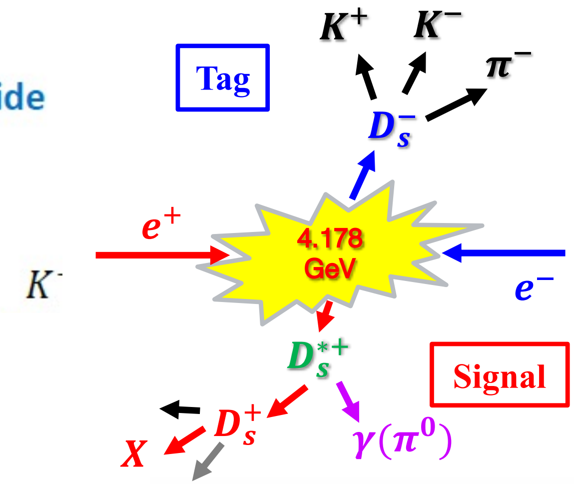
$\Lambda_c^+ \to \Lambda e^+ \nu_\nu$

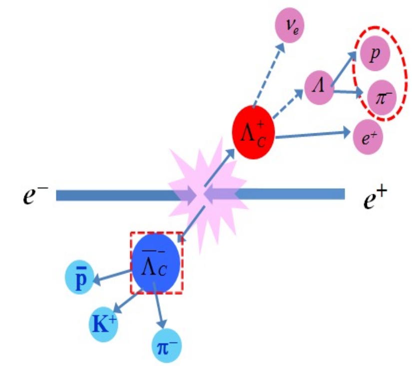


Charm hadron decays

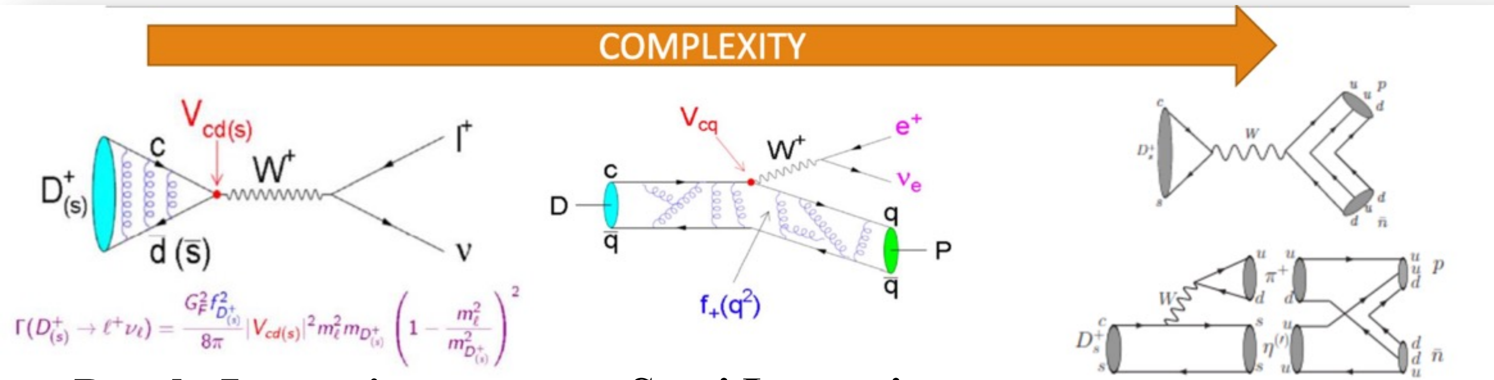


2.93/fb at $\psi(3770)$





0.567/fb at 4.6 GeV



Purely Leptonic	Semi Leptonic	Hadronic
Take V_{cx} from fits to CKM assuming unitarity and measure f Precise test of lattice QCD in charm and extrapolate to beauty	Similar to leptonic decay but now q (= four-momentum of W) dependent Test QCD models of the form factor	Models of hadronic decay • Isospin • SU(3) flavour • Different amplitudes T, P, A, E • Long and short distance effects

Precision measurement of CKM elements -- Test EW theory

CKM matrix elements are fundamental SM parameters that describe the mixing of quark fields due to weak interaction.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

BESIII + B factories + LQCD

Three generations of quark?

Unitary matrix?

Expected precision < 2% at BESIII

BESIII + B factories + LHCb + LQCD

- **Precision measurement of CKM matrix elements**
- **A precise test of SM model**
- **New physics beyond SM?**

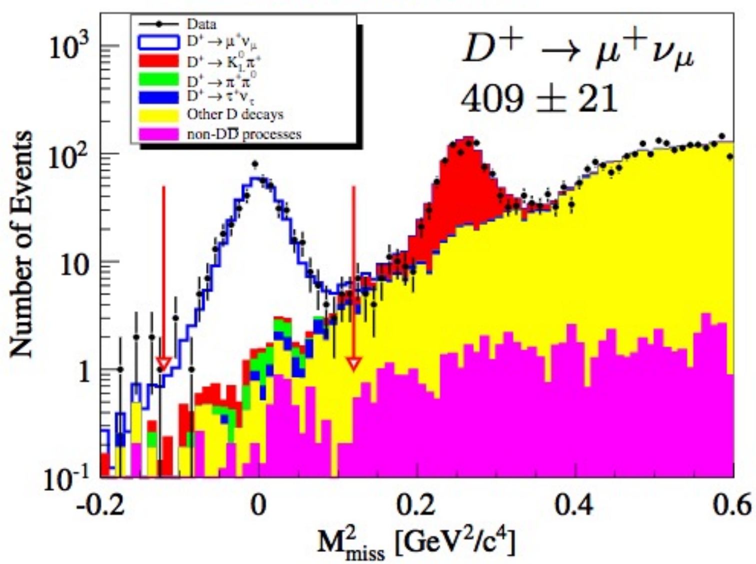
$D_{(S)}$ Leptonic decays

Purely Leptonic:

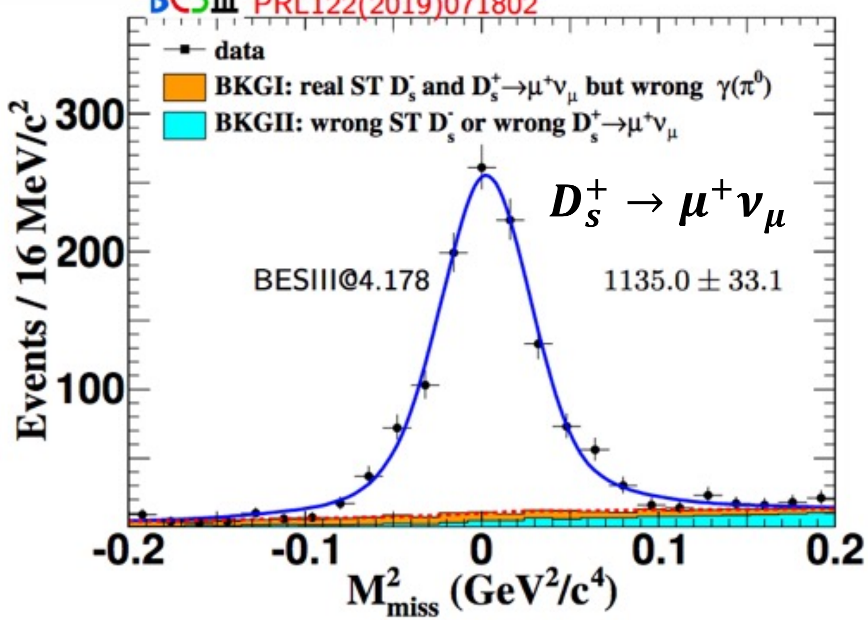
- Extract decay constant $f_{D(s)}$ incorporates the strong interaction effects (wave function at the origin)
- To validate Lattice QCD calculation of $f_{D(s)}$ and provide constrain of CKM-unitarity

$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} \mid V_{cd(s)} \mid^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

PRD89(2014)051104

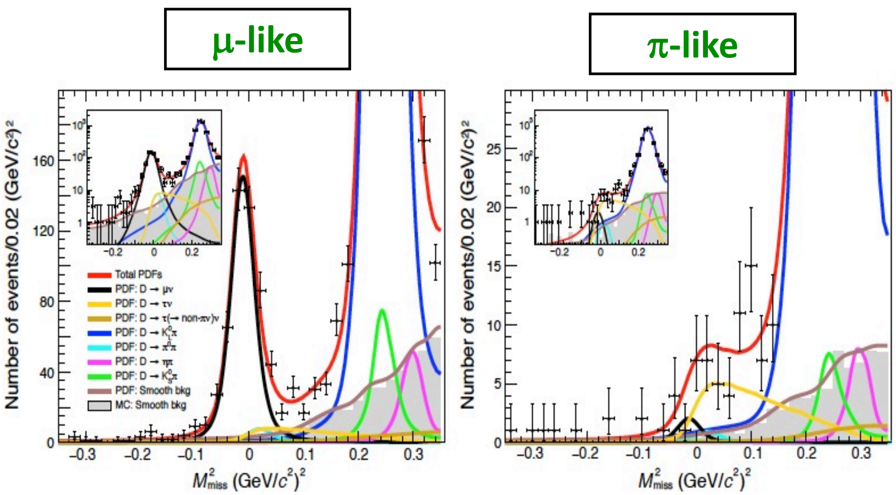


PRL122(2019)071802



$D^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$: first evidence (4σ) PRL123(2019)211802

$2.93\ \mathrm{fb}^{-1} @ E_{cm} = 3.773\mathrm{GeV}$



- 6 tagging modes
- Signal: $D^+ \to \tau^+ \nu_\tau$ extracted from MM^2.
- $D^+ \to \mu^+ \nu_\mu$ peaks at $MM^2=0$
- $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$ peaks near $MM^2=0$, as $M_D \sim M_\tau$
- Fit two MM^2 distributions simultaneously, MC based shape ⊕ Gaussian
- Fix $D \to \mu\nu$ component to the world average

Split data into two:

- μ-like: $E_{EMC} \leq 300$ MeV (mixture of $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$ and $D^+ \to \mu^+ \nu_\mu$)
- π-like: $E_{EMC} > 300$ MeV (mostly $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$).

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

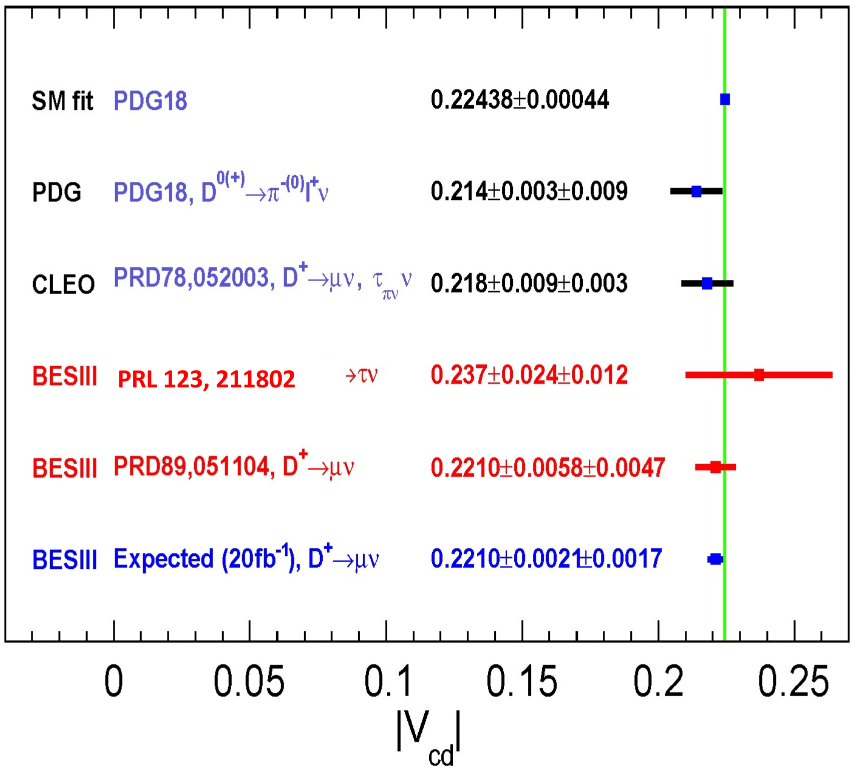
$$R_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm\ 0.64 \pm 0.43$$

Consistent with SM prediction，R = 2.65±0.01, within ~0.9σ

Extraction of $|V_{cd}|$ and f_{D^+}

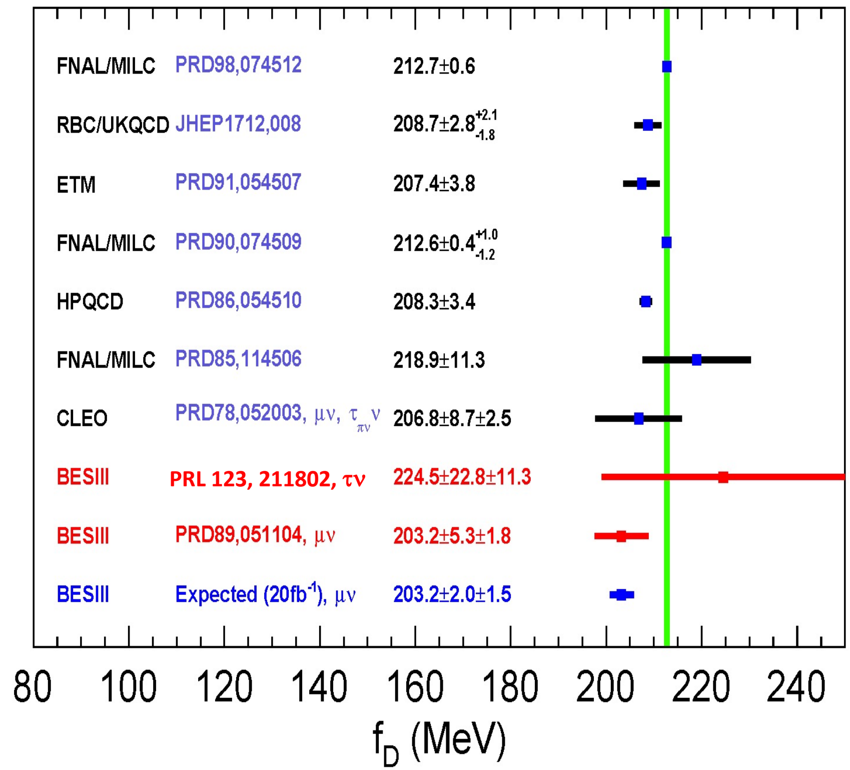
Take f_D^{LQCD} as input：

$|V_{cd}|$=(0.2210±0.0058±0.0047) ($\mu^+\nu$ mode)



Take $|V_{cd}|^{CKMfitter}$ as input：

f_{D+}=(203.2±5.3±1.8) MeV ($\mu^+\nu$ mode)



Most precise measurement

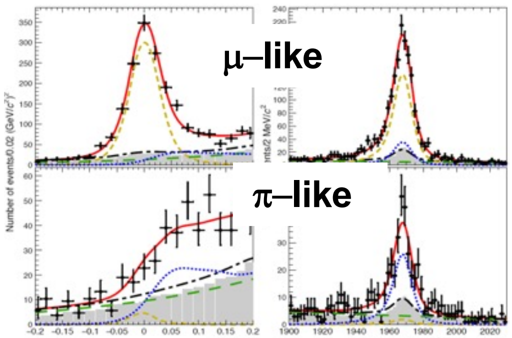
BESIII

$D_s^+ \to l^+ \nu_l$

$D_s^+ \to \mu^+ v + \tau^+(\pi^+ v)v$

6.3 fb^{-1}@4.18-4.23GeV

arXiv: 2102.11734



M_{miss}^2 Tag side inv. mass $M_{inv}(D_s^-)$

$B[D_s^+ \to \mu^+ v] = (5.35 \pm 0.13 \pm 0.16)\times 10^{-3}$

$B[D_s^+ \to \tau^+ v] = (5.22 \pm 0.25 \pm 0.17)\%$

$f_{D_s^+}|V_{cs}| = 243.1 \pm 3.0 \pm 3.7$ MeV$[\mu]$

$f_{D_s^+}|V_{cs}| = 243.0 \pm 5.8 \pm 4.0$ MeV$[\tau]$

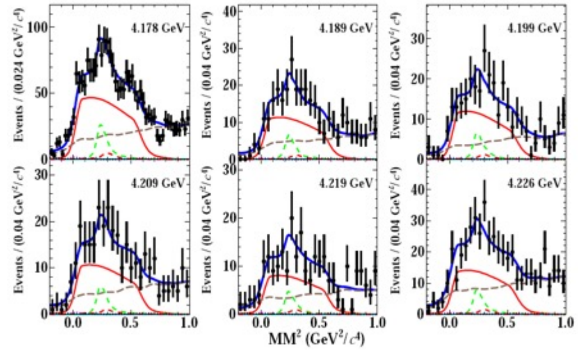
$A_{CP}[\mu v] = (-1.2 \pm 2.7)\%$

$A_{CP}[\tau v] = (2.9 \pm 4.9)\%$

$D_s^+ \to \tau^+(\rho^+ v)v$

6.3 fb^{-1}@4.18-4.23GeV

arXiv:2105.07178



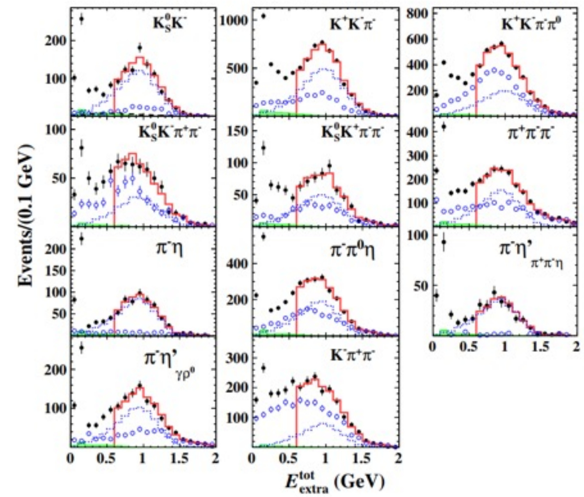
$B[D_s^+ \to \tau^+ v]$
$= (5.29 \pm 0.25 \pm 0.20)\%$

$f_{D_s^+}|V_{cs}| = 244.8 \pm 5.8 \pm 4.8$ MeV

$D_s^+ \to \tau^+(e^+ vv)v$

6.3 fb^{-1}@4.18-4.23GeV

arXiv: 2106.02218



$B[D_s^+ \to \tau^+ v]$
$= (5.27 \pm 0.10 \pm 0.12)\%$

$f_{D_s^+}|V_{cs}| = 244.4 \pm 2.3 \pm 2.9$ MeV

BESIII results

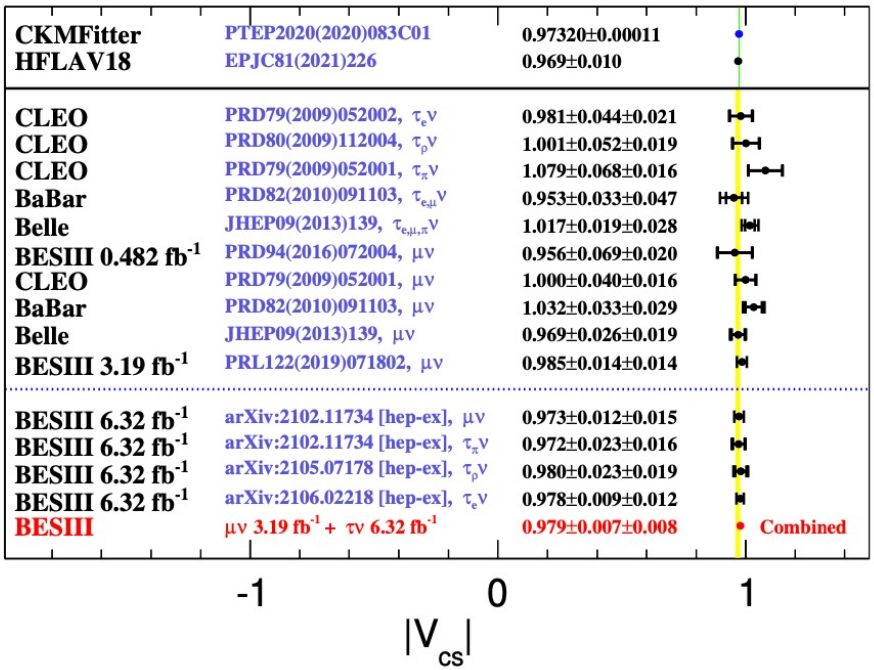
Mode	$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)$
$\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$	$(5.29 \pm 0.25 \pm 0.20)\%$
$\tau^+ \to \pi^+\bar{\nu}_\tau$	$(5.21 \pm 0.25 \pm 0.17)\%$
$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$	$(5.27 \pm 0.10 \pm 0.12)\%$
Average	$(5.26 \pm 0.09 \pm 0.09)\%$

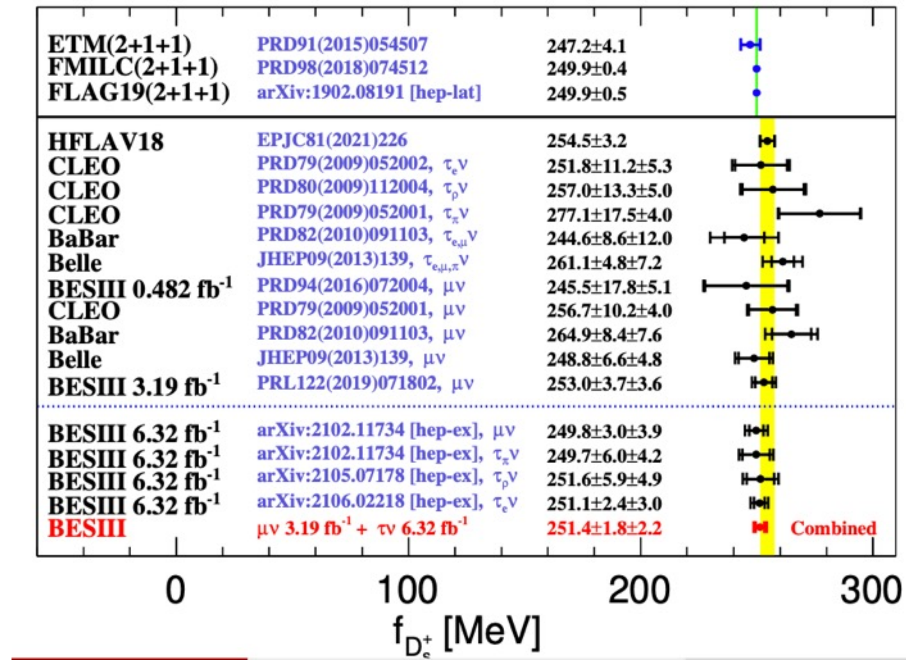
With the values of G_F, m_{D_s}, m_τ, and τ_{D_s} [PDG 2020],

$f_{D_s^+}|V_{cs}|^{4.178-4.226}_{\tau^+\nu_\tau} = (244.1 \pm 2.1 \pm 2.3)$ MeV $f_{D_s^+}|V_{cs}|^{4.178}_{\mu^+\nu_\mu} = (246.2 \pm 3.6 \pm 3.5)$ MeV

The averaged $f_{D_s^+}|V_{cs}|_{\mathrm{BESIII}} = (244.7 \pm 1.8 \pm 2.1)$ MeV

Extraction of $|V_{cs}|$ and $f_{D_s^+}$

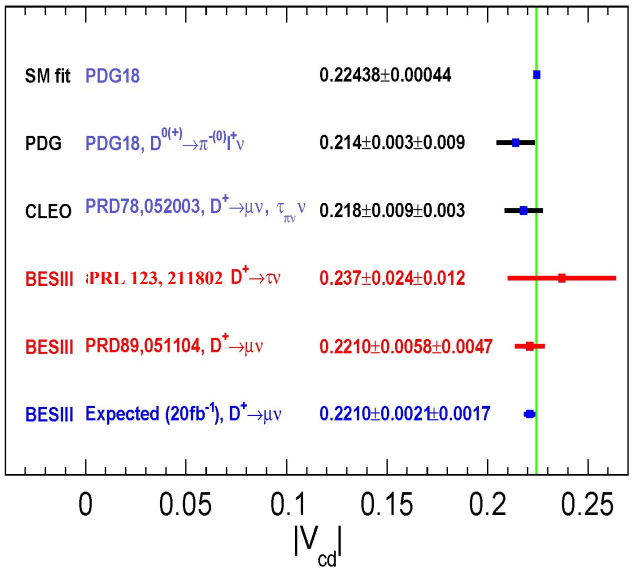




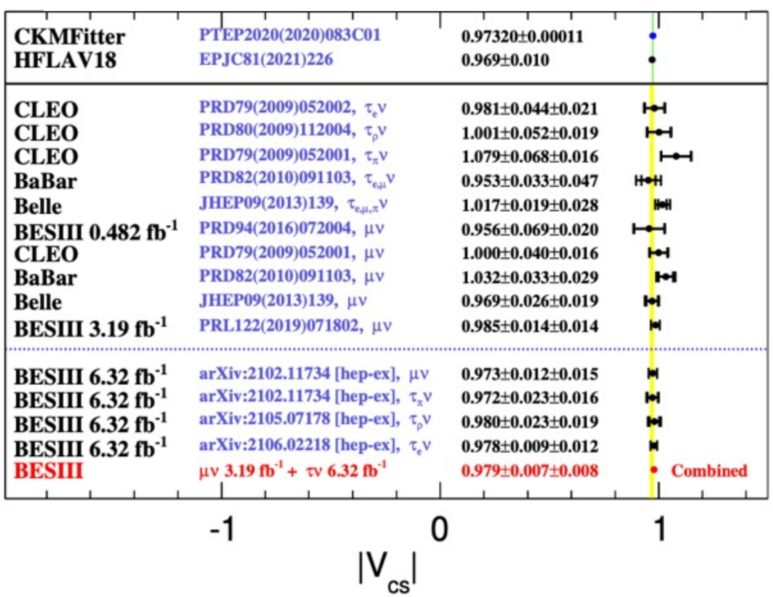
- **Input $f_{D_s^+} = 249.9 \pm 0.5$ MeV from LQCD calculations**
- **Input $|V_{cs}| = 0.97320 \pm 0.00011$ from CKM global fit**

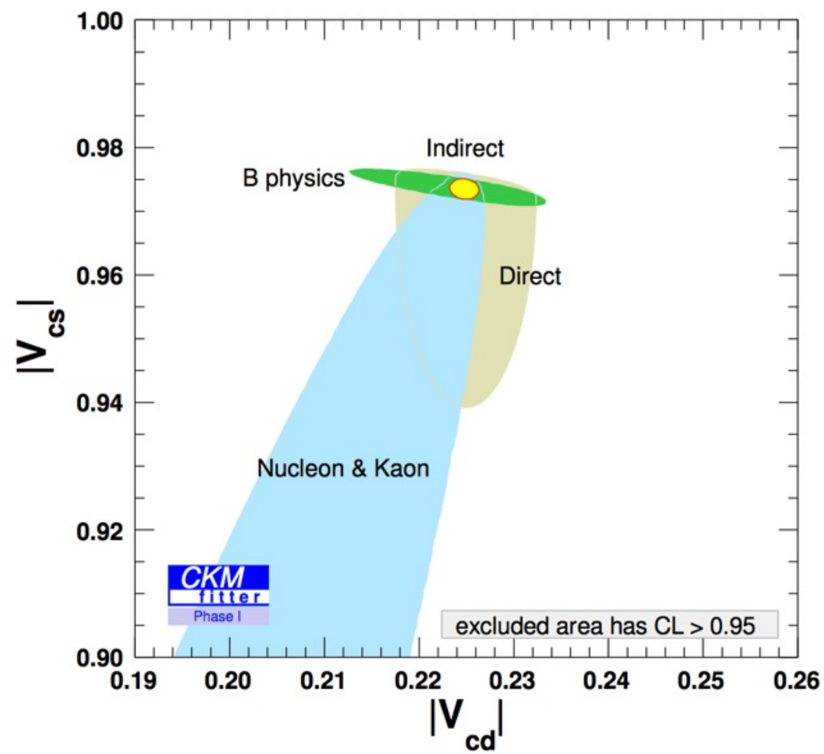
Most precise measurement

Direct measurement of Vcs and Vcd



BESIII: best precision and systematic dominant



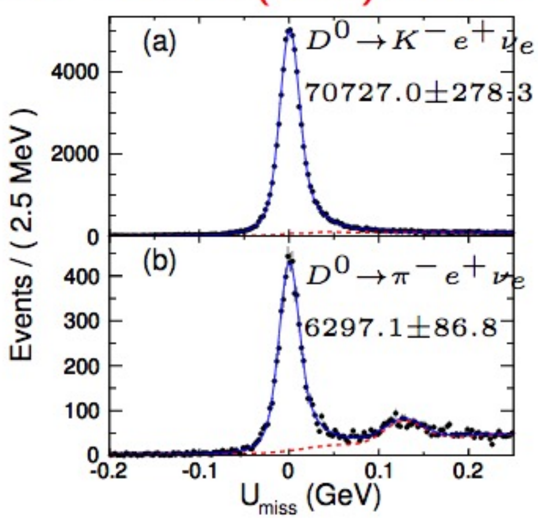


$D_{(S)}$ Semi-Leptonic decays: *e*-mode

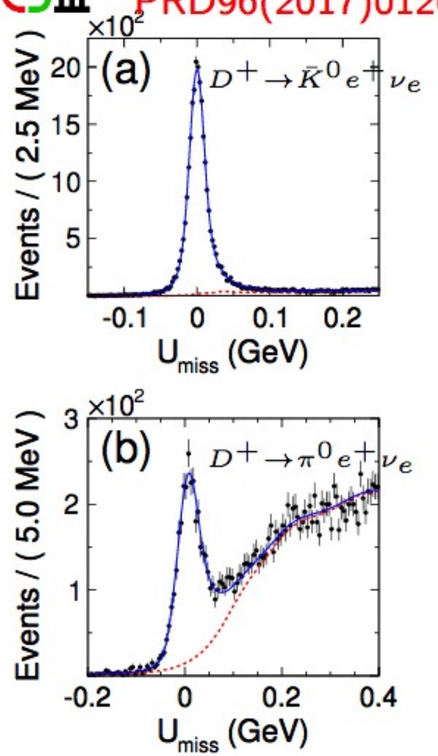
Semi-leptonic: form factor (FF)

- Measure $|V_{cx}|$ x FF
- Charm physics:
  - CKM-unitarity ⇒ $|V_{cx}|$, extract FF, test LQCD
  - Input LQCD FF to test CKM-unitarity

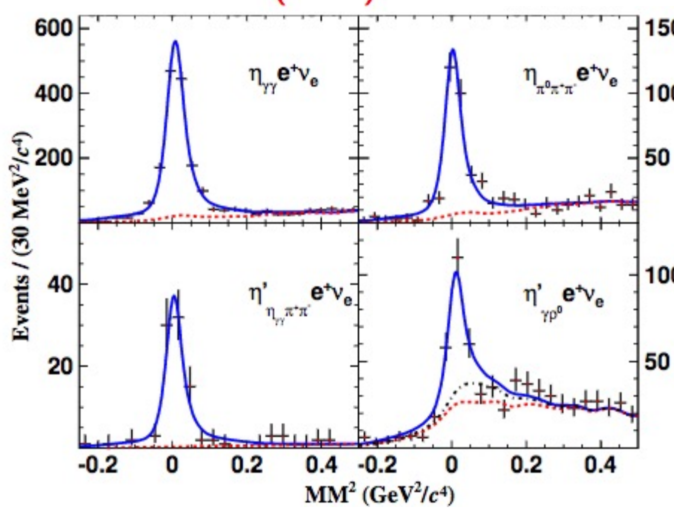
PRD92(2015)072012



PRD96(2017)012002



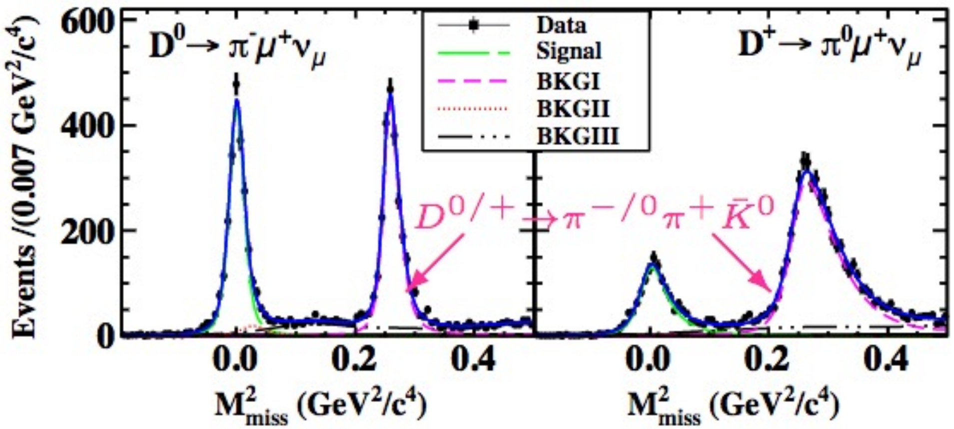
PRL122(2019)121801



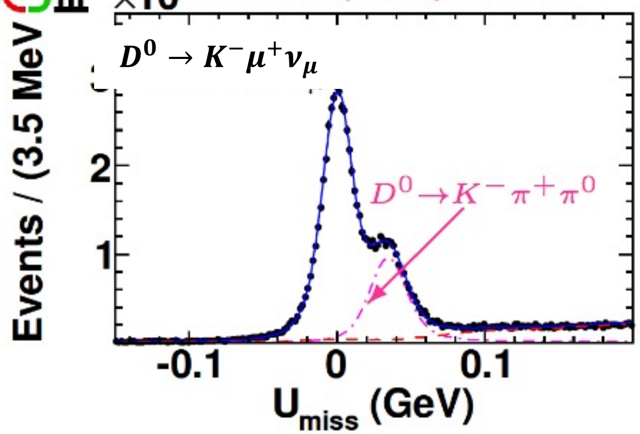
$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$

$D_{(S)}$ Semi-Leptonic decays: μ-mode

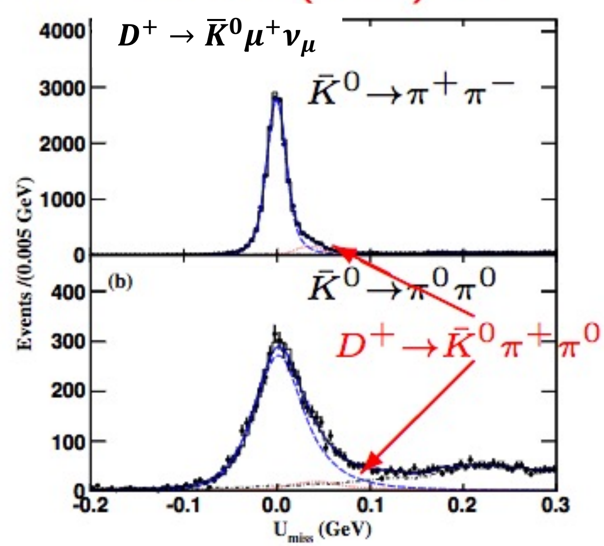
BESIII PRL121(2018)171803



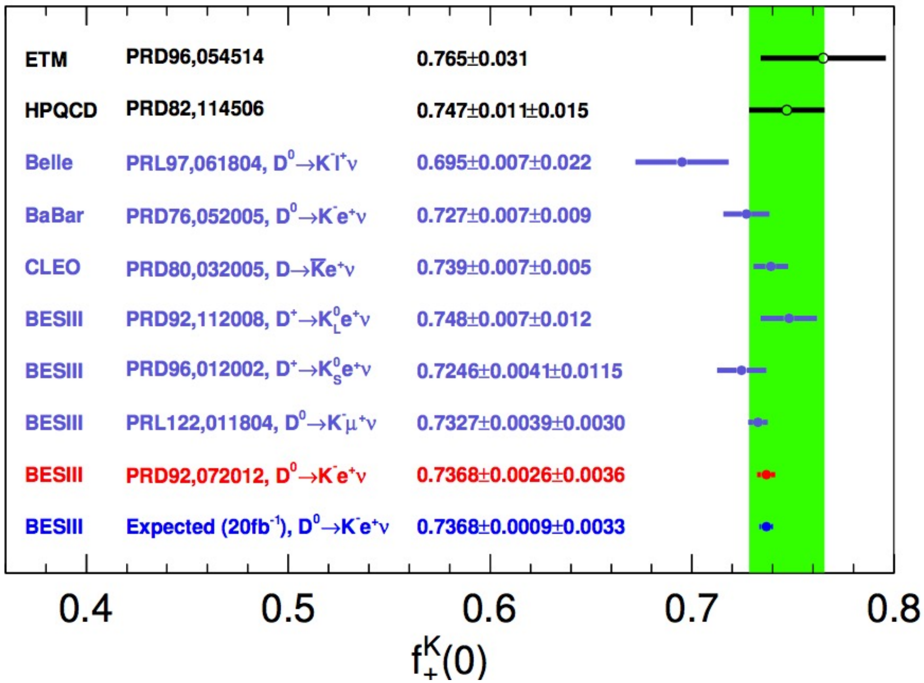
BESIII PRL122(2019)011804

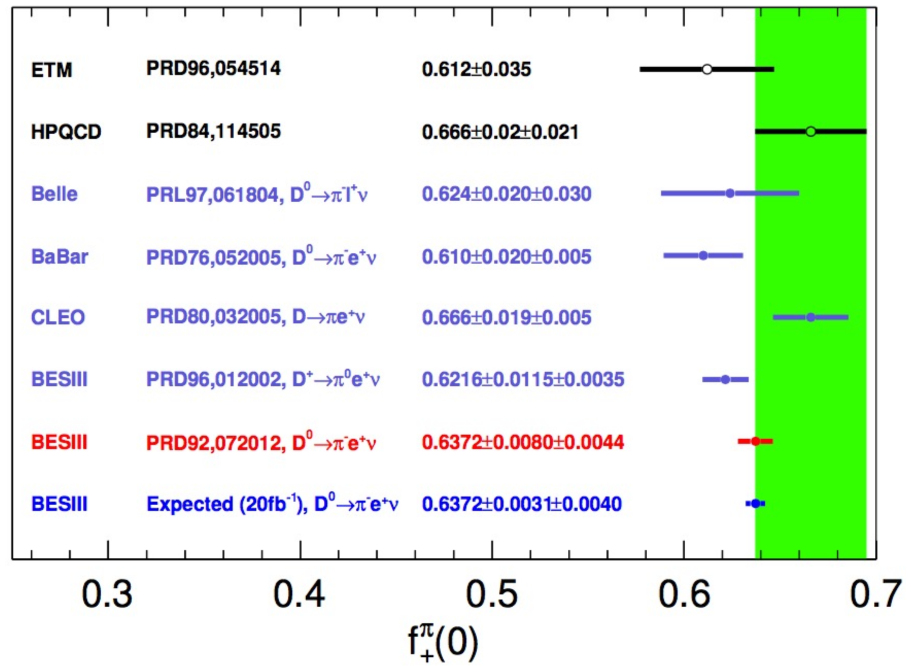


BESIII EPJC76(2016)369



Form factors $f_+^{D\to h}$





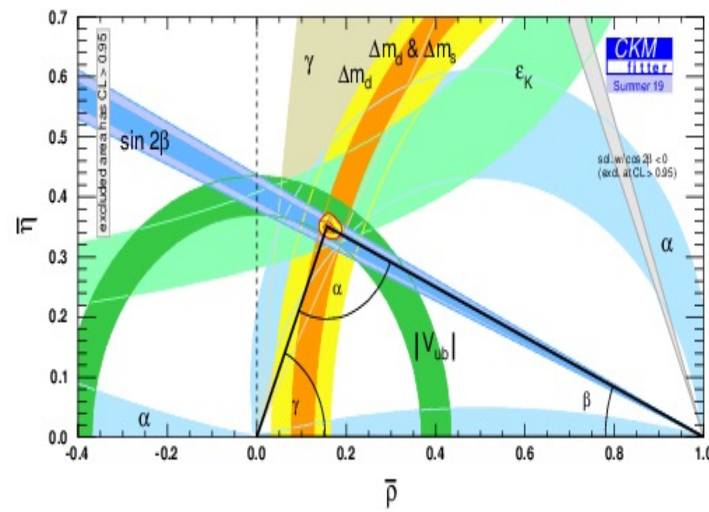
Precisions better than those of LQCD results

Hadronic decays of charm mesons

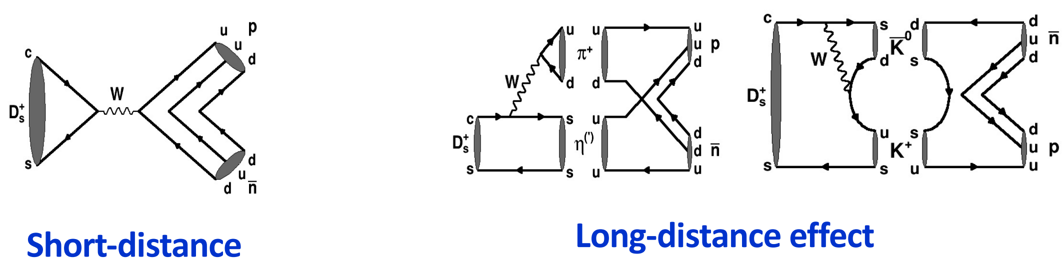
- **Strong phase measurement with quantum correlated $\psi(3770) \to D^0\bar{D}^0$ is crucial in the model-independent determinations of γ and charm mixing/direct CPV.**
  - γ is the least well known CKM constraint
  - γ status: Pre-LHCb: $\gamma = (73^{+22}_{-25})^\circ$

    Direct measurement $\gamma = (73.5\ ^{+4.2}_{-5.1})^\circ$,

    indirect measurement $\gamma = (65.8\ ^{+1.0}_{-1.7})^\circ$



- **Probe non-perturbative QCD**
  - Help to understand hadron spectroscopy
  - Study SU(3) flavor symmetry
  - Study short and long distance effects

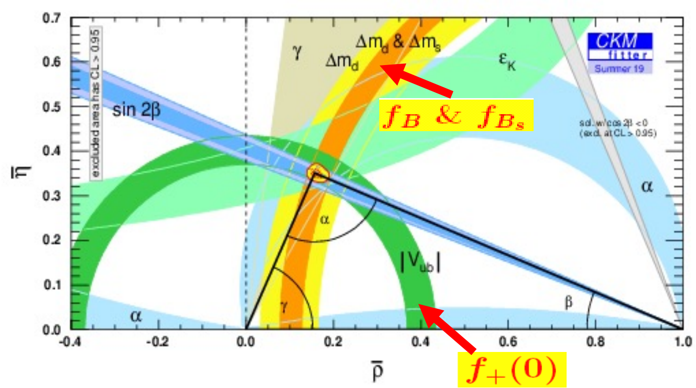


BESIII data @3770 MeV (2.93 fb^{-1} ➔ 20 fb^{-1})

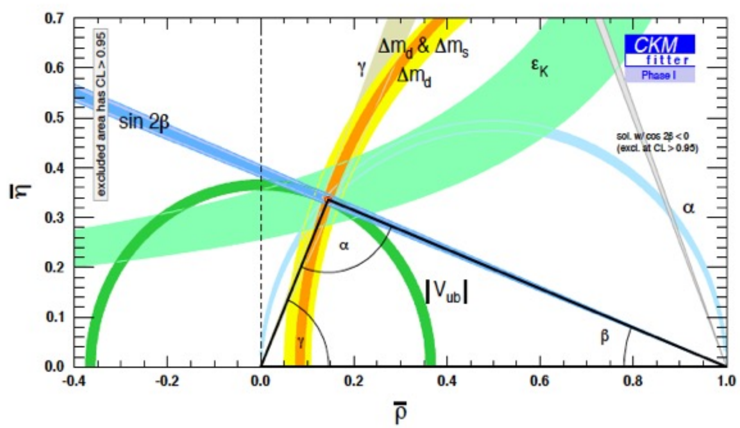
$\psi(3770) \rightarrow D^0\overline{D^0}$ quantum correlation➔strong phase parameters between D^0 and $\overline{D}^0$ decays

➔inputs to LHCb measurement of γ

Belle II (arXiv:1808.10567): 1.5^0 with 50 ab^{-1}
LHCb (arXiv:1808.08865v2): < 1^o, 50 fb^{-1}, phase-1 upgrade (2030),
< 0.4^o, 300 fb^{-1}, phase-2 upgrade (> 2035)



2019



>year of 2030 (BESIII 20 fb^{-1} data as inputs)

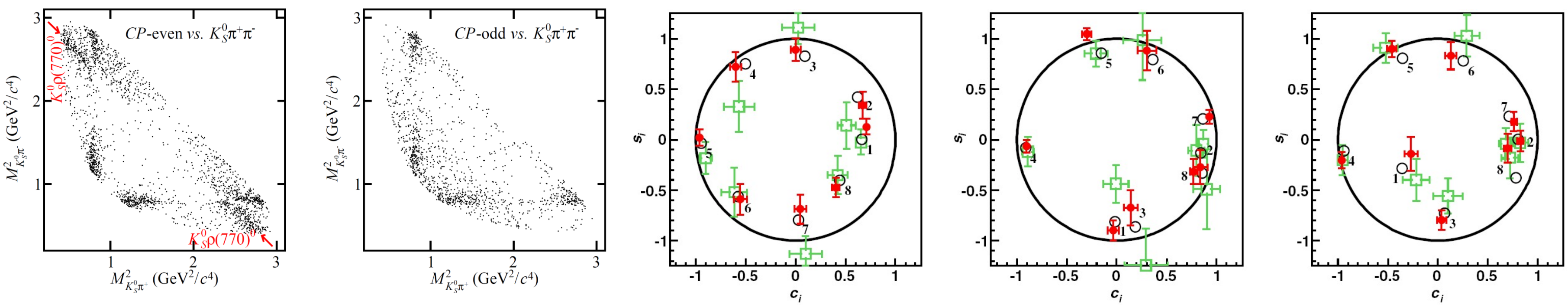
BESIII White Paper, Chinese Phys. C 44 (2020) 040001

Strong phase measurements

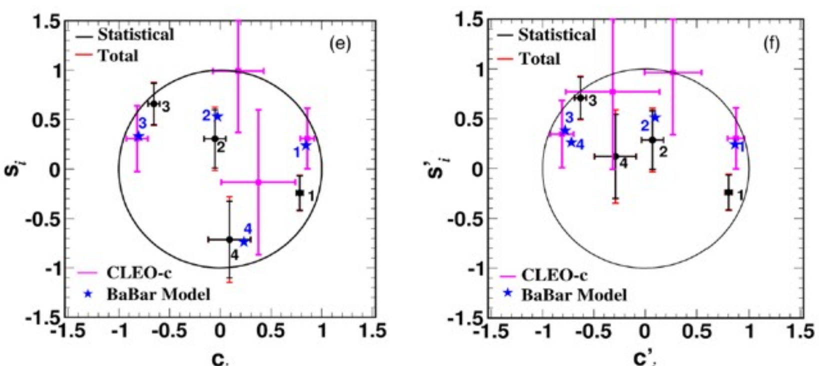
$2.93\ \text{fb}^{-1}@E_{cm} = 3.773\text{GeV}$
$e^+e^- \to \psi(3770) \to D\bar{D}$

■ $D \to K^0_{S/L}\pi^+\pi^-$ PRL 124 (2020)241802

Constraint on γ measurement ~ 0.9⁰



■ $D \to K^0_{S/L}K^+K^-$ PRD102(2020)052008



Constraint on γ measurement ~ 1.3⁰

■ $D \to K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$

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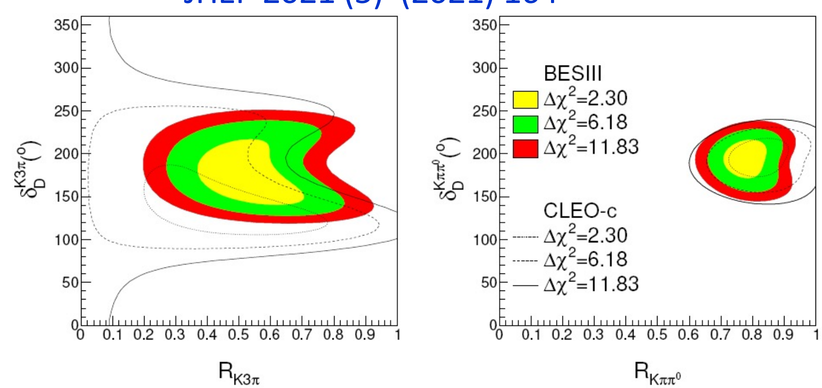
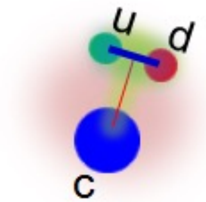
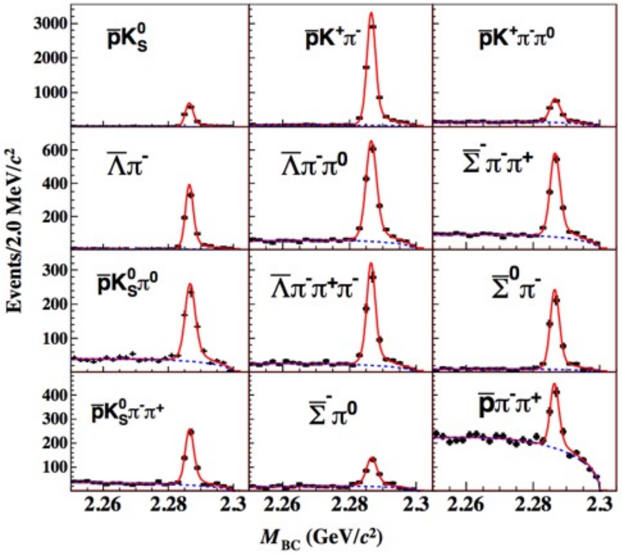


Constraint on γ measurement ~ 6⁰

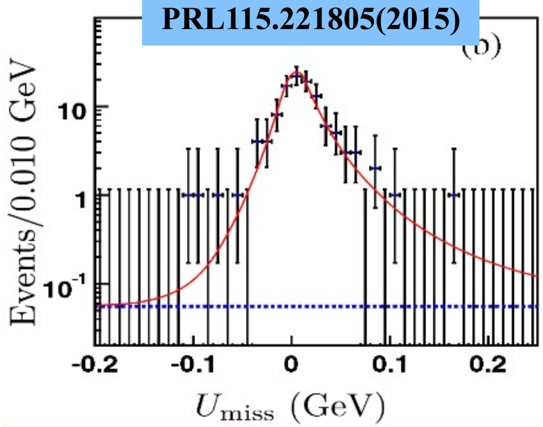
The Λ_c^+ decays



PRL116.052001(2016)



PRL115.221805(2015)



Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF modes	PRL 116, 052001 (2016)
$\Lambda_c^+ \to pK^+K^-$, $p\pi^+\pi^-$	PRL 117, 232002 (2016)
$\Lambda_c^+ \to nK_S\pi^+$	PRL 118, 12001 (2017)
$\Lambda_c^+ \to p\eta$, $p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB 772, 388 (2017)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD99, 032010 (2019)
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC43, 083002 (2019)
$\Lambda_c^+ \to$ BP decay asymmetries	PRD100, 072004 (2019)
$\Lambda_c^+ \to pK_S\eta$	arXiv: 2012.11106

Semi-leptonic decay

$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL 115, 221805(2015)
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB 767, 42 (2017)

Inclusive decay

$\Lambda_c^+ \to \Lambda X$	PRL121, 062003 (2018)
$\Lambda_c^+ \to e^+X$	PRL 121 251801(2018)
$\Lambda_c^+ \to K_S^0X$	EPJC 80, 935 (2020)

Production

$\Lambda_c^+\Lambda_c^-$ cross section	PRL 120,132001(2018)

BESIII

Impacts on Λ_c decay data

D_s^+ BRANCHING RATIOS

A number of older, now obsolete results have been omitted. They may be found in earlier editions.

Inclusive modes

$\Gamma(e^+\text{semileptonic})/\Gamma_{total}$ — Γ_1/Γ

This is the purely e^+ semileptonic branching fraction: the e^+ fraction from τ^+ decays has been subtracted off. The sum of our (non-… …actions — … $e^+\nu_e$ with an η, η', ϕ, K^0, or K^{*0} — is 5.99 ± 0.3… %.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
6.52±0.39±0.15	536 ± 29	[1] ASNER	10	CLEO	…$^+e^-$ at 37… MeV

[1] Using the D_s^+ and D^0 lifetimes, ASNER 10 fi…s that the rati… of the D_s^+ …nd D^0 semileptonic widths is 0.828 ± 0.051 ± 0.025.

$\Gamma(\pi^+\text{anything})/\Gamma_{total}$ — Γ_2/Γ

Events with two π^+'s count twice, etc. Bu… π^+'s from K_S^0 → $\pi^+\pi^-$ …re not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
119.3±1.2±0.7	DOBBS	…9	CLEO	e…e$^-$ at 4170 …eV

$\Gamma(\pi^-\text{anything})/\Gamma_{total}$ — Γ_3/Γ

Events with two π^-'s count twice, etc. Bu… π^-'s from K_S^0 → π^+… are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
43.2±0.9±0.3	DOBBS	…9	CLEO	e…e$^-$ at …170 MeV

$\Gamma(\pi^0\text{ anything})/\Gamma_{total}$ — Γ_4/Γ

Events with two π^0's count twice, etc. But π^0… from K_S^0 → … π^0 …re not i…cluded.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
123.4±3.8±5.3	DOBBS	…9	CLEO	e… at 4…0 …eV

$\Gamma(K^-\text{anything})/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
18.7±0.5±0.2	DOBBS	…9	CLEO	… at 4170 MeV

$\Gamma(K^+\text{anything})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
28.9±0.6±0.3	DOBBS	…9	CLE…	e…e$^-$ at 4170 MeV

$\Gamma(K_S^0\text{ anything})/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
19.0±1.0±0.4	DOBBS	…9	CLEO	e…e$^-$ at 4170 MeV

$\Gamma(\eta\text{ anything})/\Gamma_{total}$ — Γ_8/Γ

This ratio includes η particles from η' decays.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
29.9±2.2±1.7		DOBBS	09	CLEO	…$^+e^-$ at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
23.5±3.1±2.0	674 ± 91	HUANG	06B	CLEO	…ee DOBBS 09

$\Gamma(\omega\text{ anything})/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
6.1±1.4±0.3	DOBBS	…9	CLEO	e…e$^-$ at 4170 MeV

$\Gamma(\eta'\text{ anything})/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
10.3±1.4 OUR AVERAGE Error includes scale fact…r of 1.1.					
8.8±1.8±0.5	68	ABLIKIM	…5Z	BES3	4… pb^{-1}, 4009 MeV
11.7±1.7±0.7		DOBBS	…9	CLEO	e…e$^-$ at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.7±1.9±0.8	68	HUANG	…6B	CLEO	Se… DOBBS 09

$\Gamma(f_0(980)\text{ anything}, f_0 \to \pi^+\pi^-)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	DOBBS	…9	CLEO	e…e$^-$ at 4170 MeV

$\Gamma(\phi\text{ anything})/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
15.7±0.8±0.6		DOBBS	09	CLEO	…$^+e^-$ at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
16.1±1.2±1.1	398 ± 27	HUANG	06B	CLEO	…ee DOBBS 09

$\Gamma(K^+K^-\text{anything})/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
15.8±0.6±0.3	DOBBS	…9	CLEO	e…e$^-$ at 4170 MeV

CLEOc dominants the D_s Branching Fraction measurements. (Sys. Err. Dominates CF modes. Many SCS&DCS modes observed.)

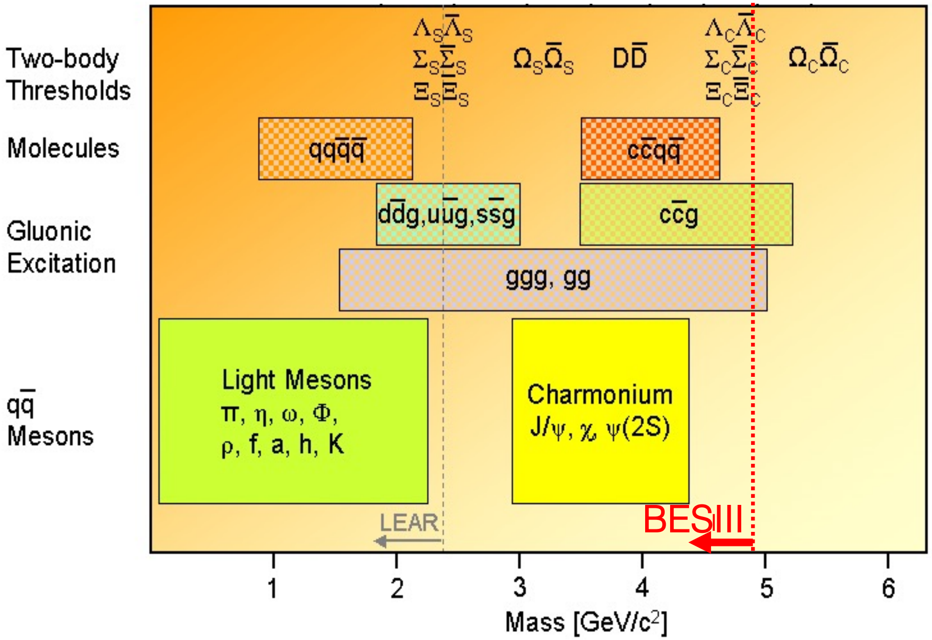
Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Λ_c^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1992 edition (Physical Review **D45**, 1 June, Part II) or in earlier editions.

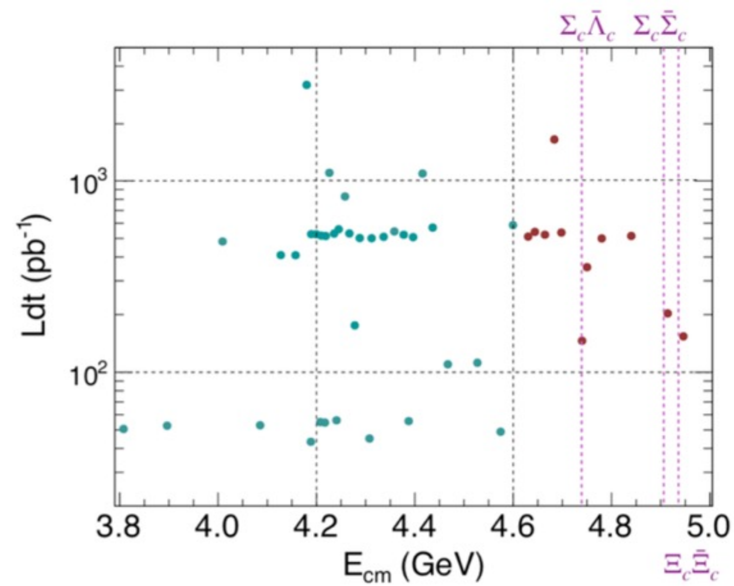
AAIJ	19AG	PR D100 032001	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	19AX	PR D100 072004	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	19X	CP C43 083002	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	19Y	PR D99 032010	M. Ablikim *et al.*	(BESIII Collab.) ★
AAIJ	18N	PR D97 091101	R. Aaij *et al.*	(LHCb Collab.)
AAIJ	18R	JHEP 1803 182	R. Aaij *et al.*	(LHCb Collab.)
AAIJ	18V	JHEP 1803 043	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	18AF	PRL 121 251801	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	18E	PRL 121 062003	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	18Y	PL B783 200	M. Ablikim *et al.*	(BESIII Collab.) ★
BERGER	18	PR D98 112006	M. Berger *et al.*	(BELLE Collab.)
ABLIKIM	17D	PL B767 42	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17H	PRL 118 112001	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17Q	PR D95 111102	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17Y	PL B772 388	M. Ablikim *et al.*	(BESIII Collab.) ★
PAL	17	PR D96 051102	B. Pal *et al.*	(BELLE Collab.)
ABLIKIM	16	PRL 116 052001	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	16U	PRL 117 232002	M. Ablikim *et al.*	(BESIII Collab.) ★
YANG	16	PRL 117 011801	S.B. Yang *et al.*	(BELLE Collab.)
ABLIKIM	15Y	PRL 115 221805	M. Ablikim *et al.*	(BESIII Collab.) ★
ZUPANC	14	PRL 113 042002	A. Zupanc *et al.*	(BELLE Collab.)
LEES	11G	PR D84 072006	J.P. Lees *et al.*	(BABAR Collab.)

Hadron Landscape



Hadron-physics challenges:

- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

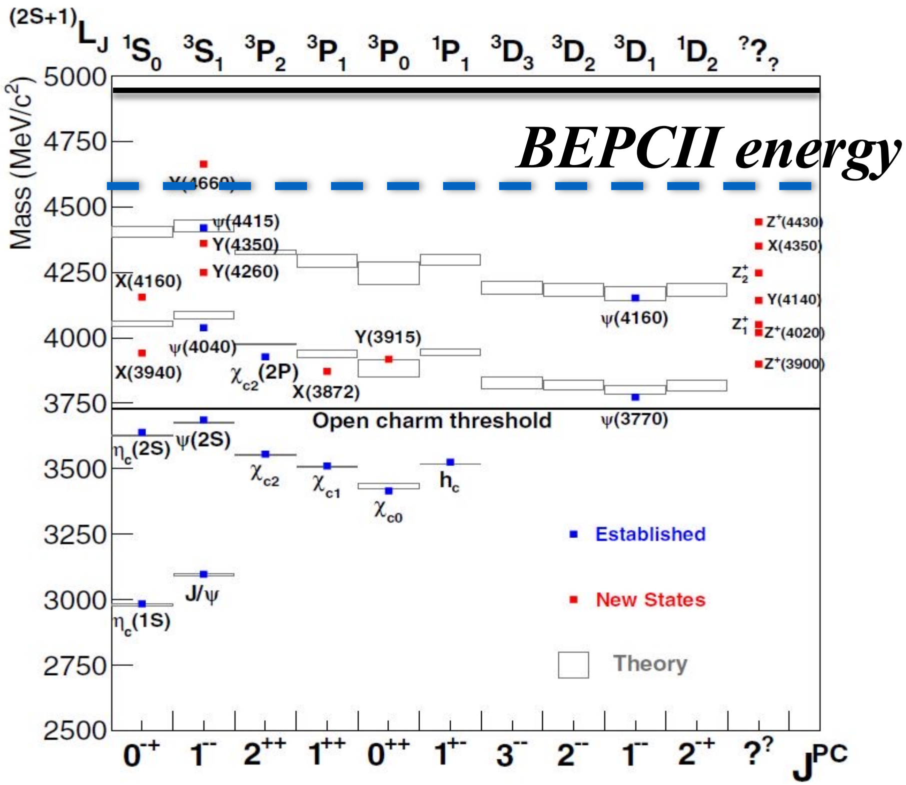


XYZ studies: about 23 /fb data above 3.8 GeV

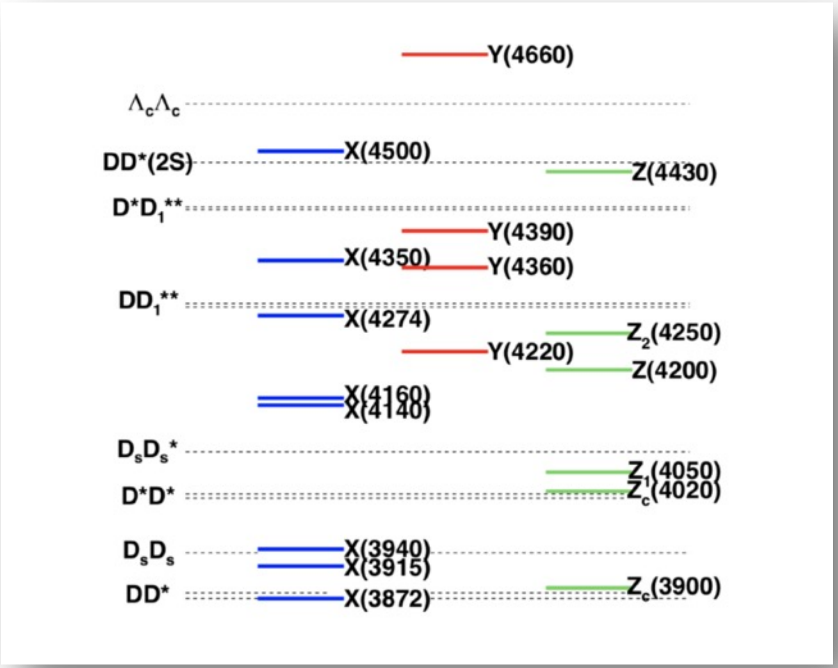
At BESIII, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

- Light hadrons: charmonium radiative decays (act as spin filter) (**10 B J/ψ and 3 B $\psi(2S)$**)
- Heavy hadrons: direct production, radiative and hadronic transitions (**data above 3.8 GeV**)

Overpopulated charmonium spectrum



arXiv:1511.01589, arXiv:1812.10947

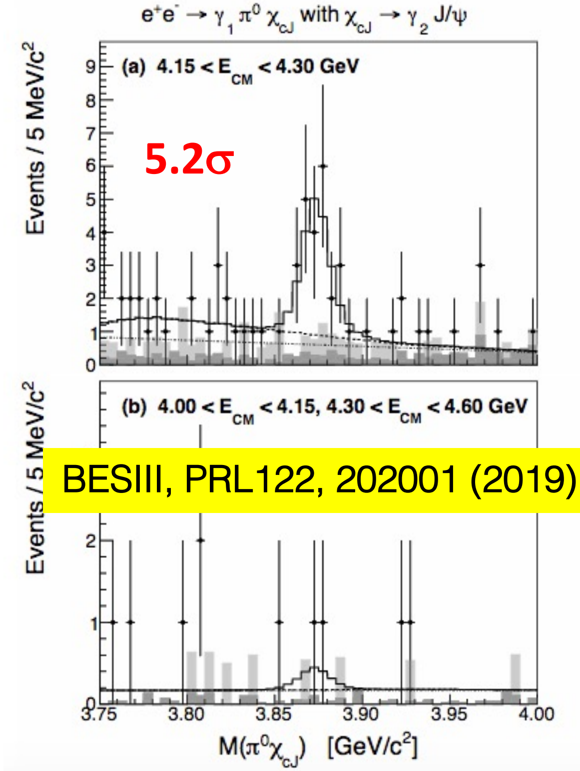


Overpopulated observed new charmonium-like states, i.e. "XYZ":

- Most of them are close to the mass thresholds of charmed meson pairs
- Some are not accommodated as conventional meson
  ==> candidate of exotic hadron states
- More efforts are needed to pin down their nature

More X(3872) decay information

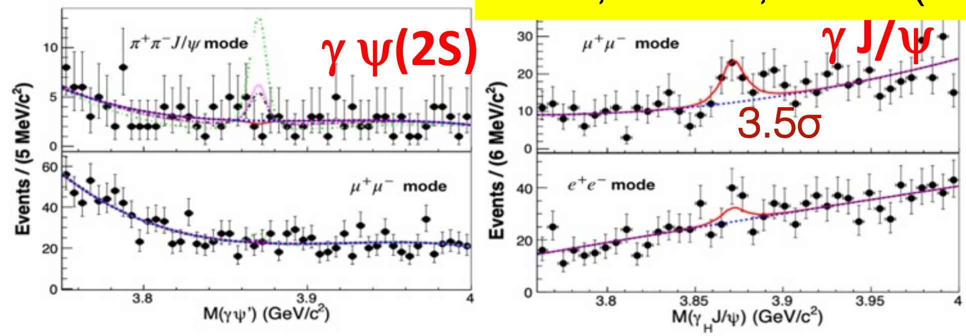
- Observation of X(3872) $\rightarrow \pi^0 \chi_{c1}$



BESIII, PRL122, 202001 (2019)

- Transition of $X(3872) \rightarrow \gamma J/\psi$, $\gamma\psi(2S)$

BESIII, PRL 124, 242001 (2020)



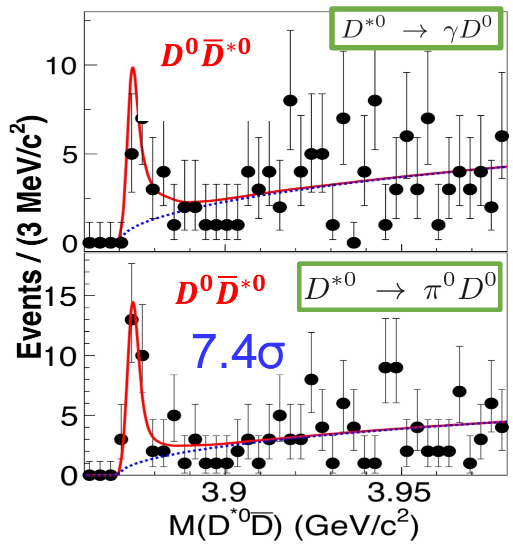
$R = \frac{BF(X(3872) \to \gamma\psi(2S))}{BF(X(3872) \to \gamma J/\psi)} < 0.59$ at 90% C.L. , agrees with Belle(<2.1), while challenges Babar(3.4±1.1) and LHCb results (2.46± 0.70)

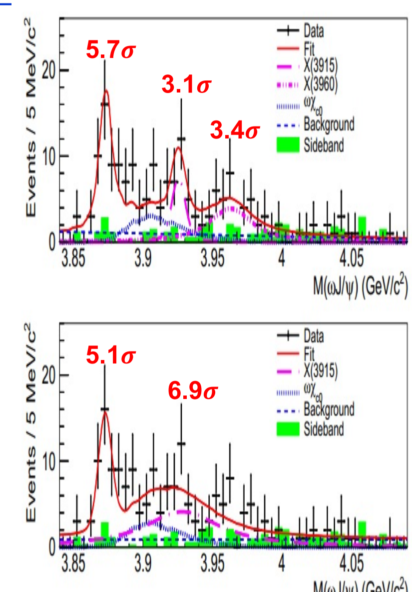
- Observation of X(3872) → ωJ/ψ

BESIII, PRL 122, 232002 (2019)

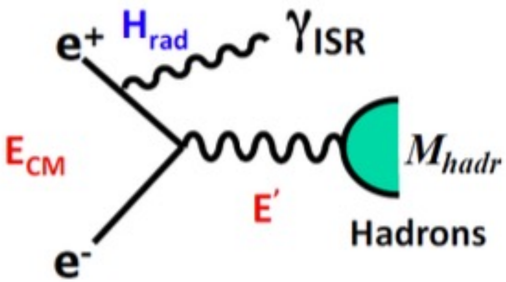
- Observation of X(3872) $\rightarrow D^0\bar{D}^{*0}$

BESIII, PRL 124, 242001 (2020)



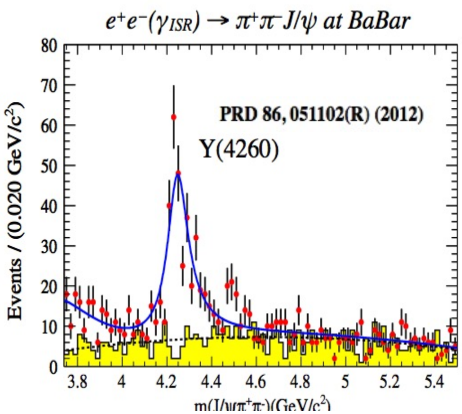


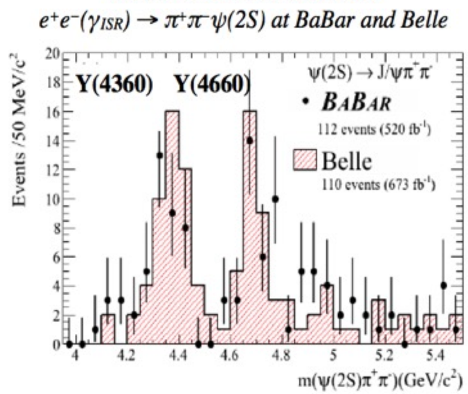
The Y states



Y states: charmonium-like states with $J^{PC}=1^{--}$;
Observed in direct e+e- annihilation or initial state radiation (ISR).

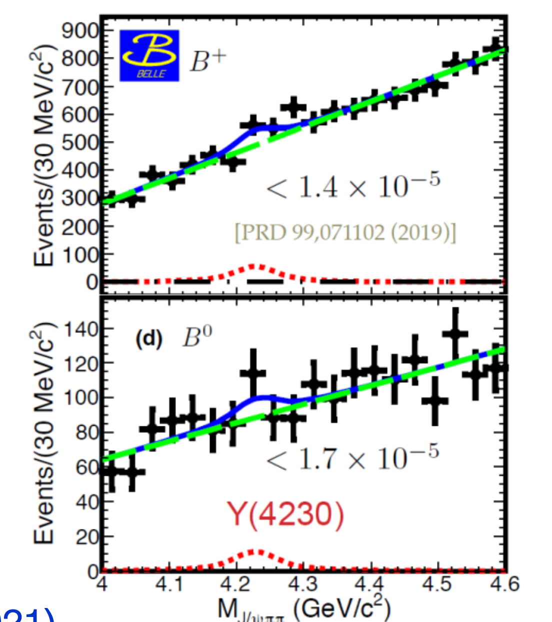
arXiv:1211.6271 and CHARM 2012



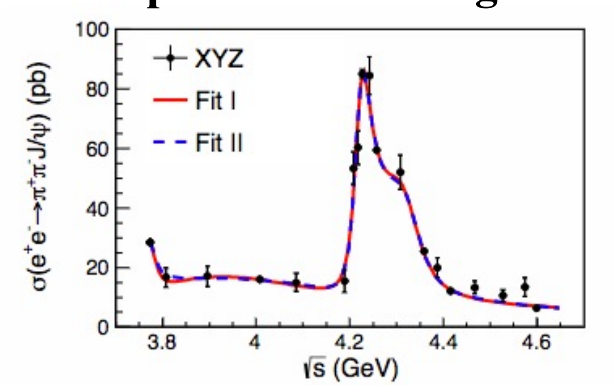


- **While not seen yet in B decays**

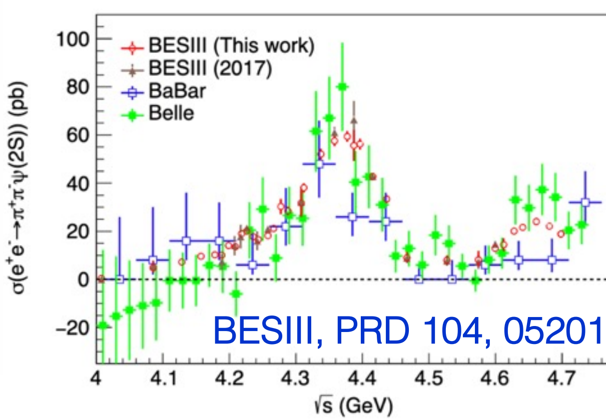
$$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$$



- **Improved knowledges from BESIII**

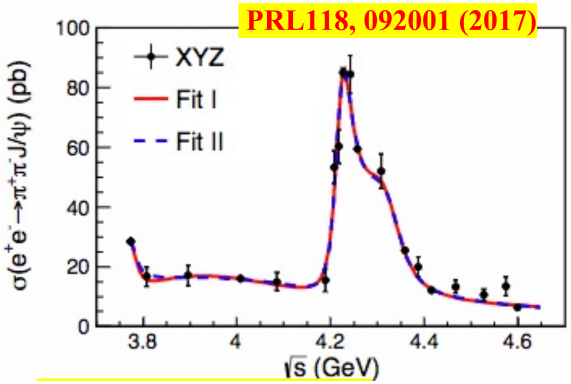


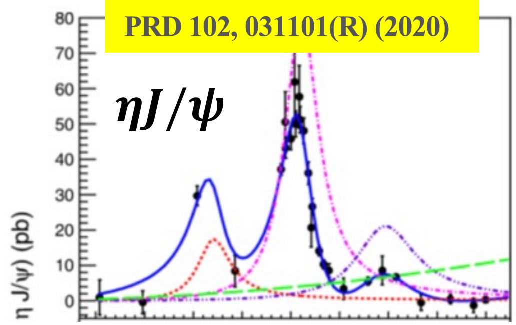
BESIII, PRL118, 092001 (2017)

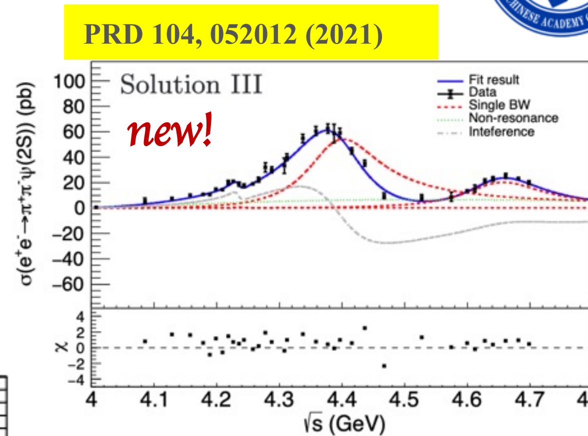


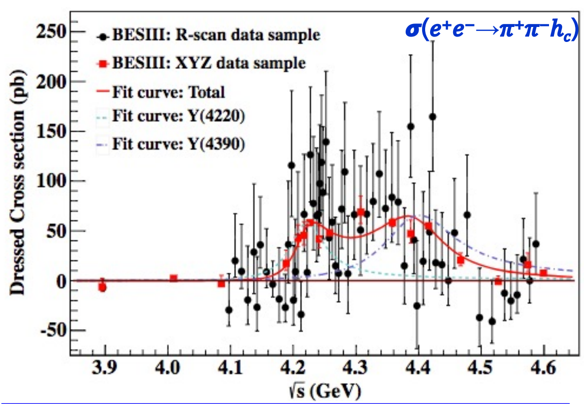
BESIII, PRD 104, 052012 (2021)

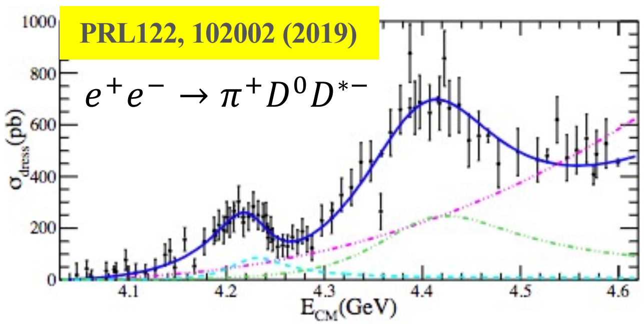
Y(4260) ➔ Y(4220) and new Y's

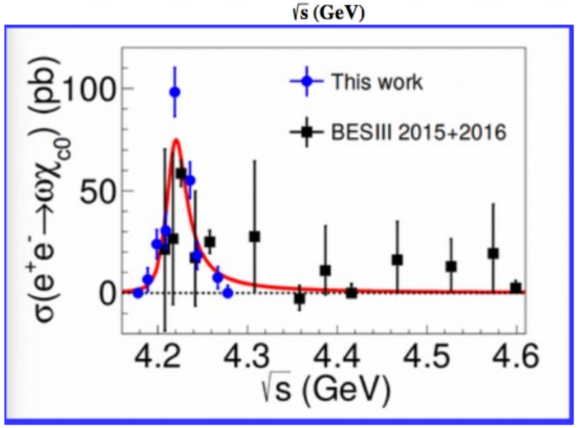


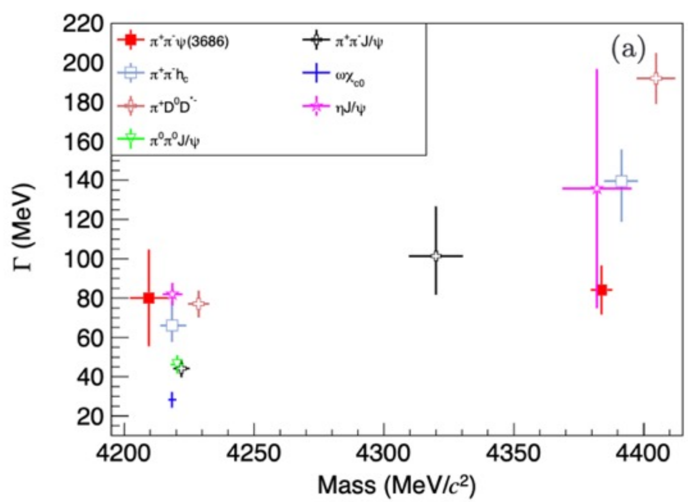






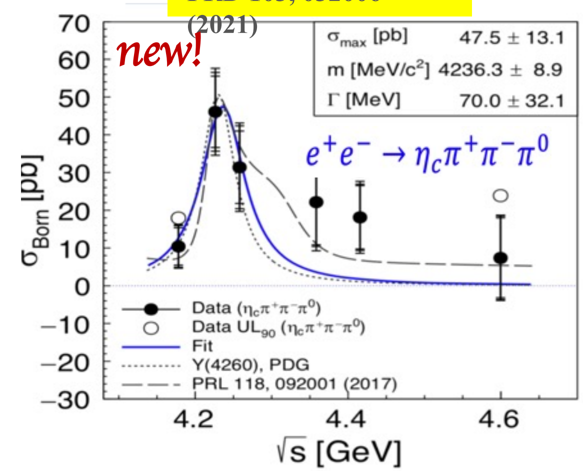






Evidence for Y(4220)→$\eta_c\pi^+\pi^-\pi^0$

PRD 103, 032006 (2021)

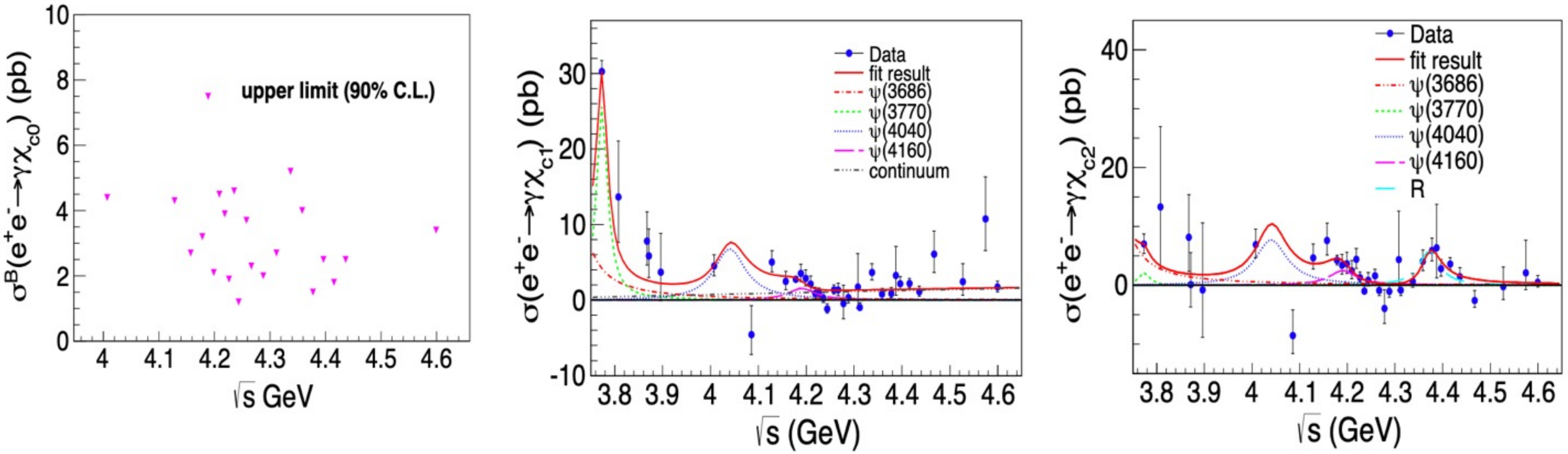


new!

$e^+e^- \to \gamma\chi_{cJ}$ at $\sqrt{s}$=3.8-4.6 GeV

arXiv:2107.03604

- No signals for $e^+e^- \to \gamma\chi_{c0}$
- Observations of $e^+e^- \to \gamma\chi_{c1,2}$



- $\gamma\chi_{c1}$: Well describe with conventional charmonium states
- $\gamma\chi_{c2}$: Along with conventional ones, an additional Y state is needed

$$M = 4371.7 \pm 7.5 \pm 1.8 \text{ MeV}/c^2 \;,\; \Gamma = 51.1 \pm 17.6 \pm 1.9 \text{ MeV}$$

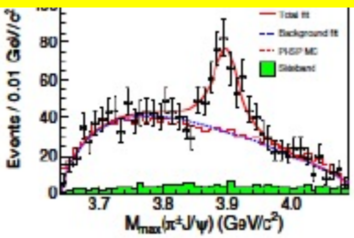
✓ statistical significance of 5.8 σ

✓ consistent with the Y(4360)/Y(4390)

The Zc Family at BESIII

Zc(3900)$^+$

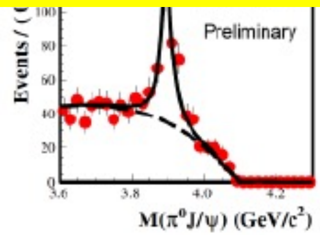
PRL 110, 252001 (2013)



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

Zc(3900)^0

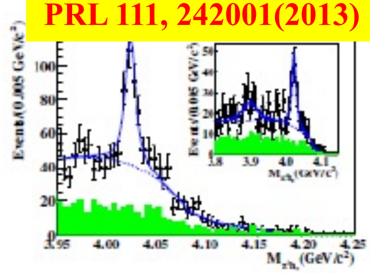
PRL 115, 112003 (2015)



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

Zc(4020)$^+$

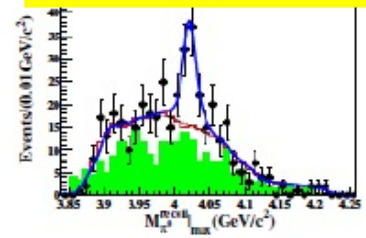
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+h_c$

Zc(4020)^0

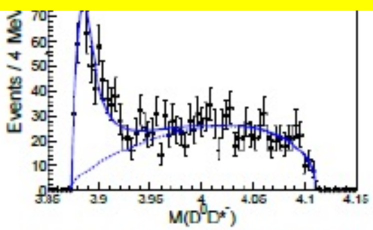
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0h_c$

Zc(3885)$^+$

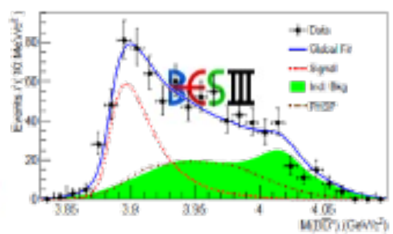
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3885)^0

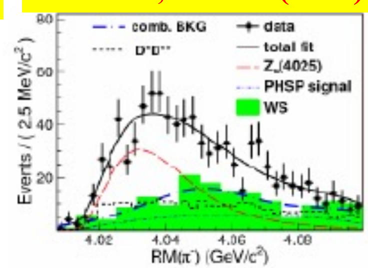
PRL 115, 222002 (2015)



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

Zc(4025)$^+$

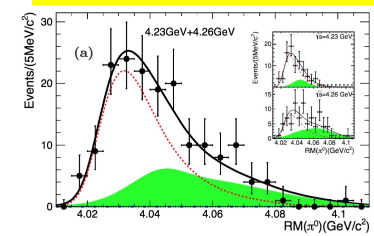
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

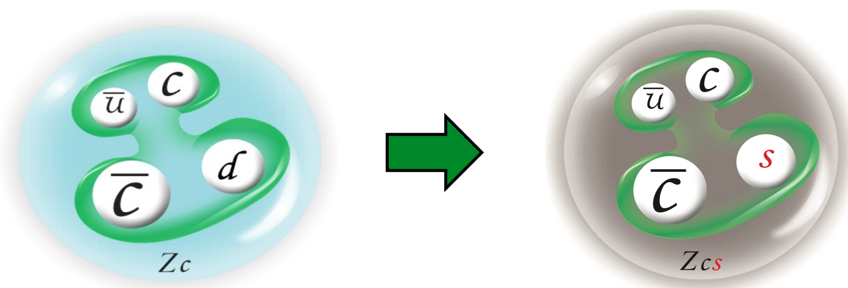
Zc(4025)^0

PRL115, 182002 (2015)



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

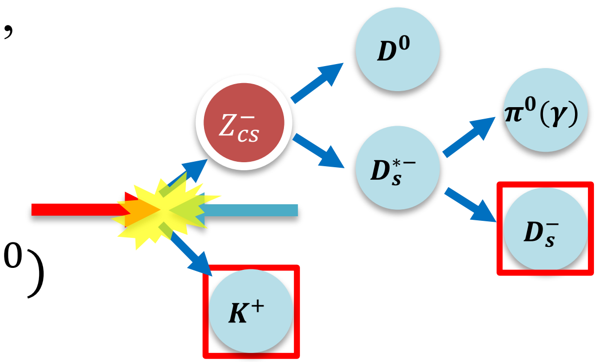
Which is the nature of these states?
If exists, there should be SU(3) counter-part Zcs state with strangeness



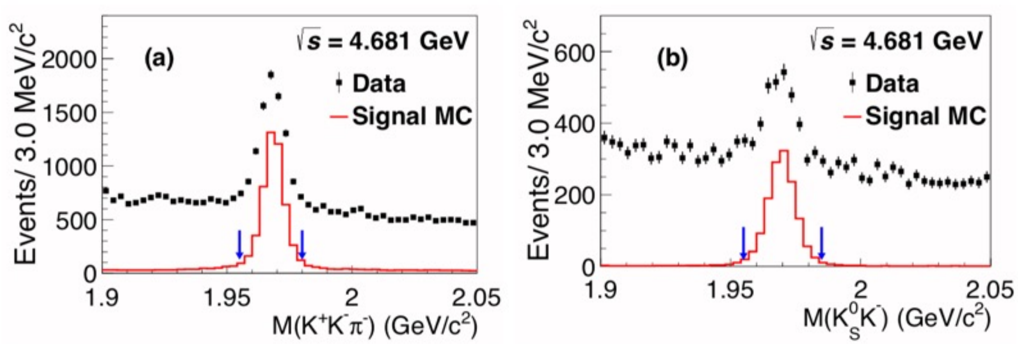
new! Observation of the $Z_{cs}(3985)^{\pm}$

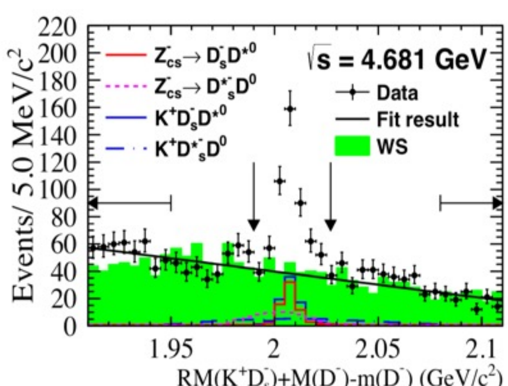
PRL126, 102001 (2021)

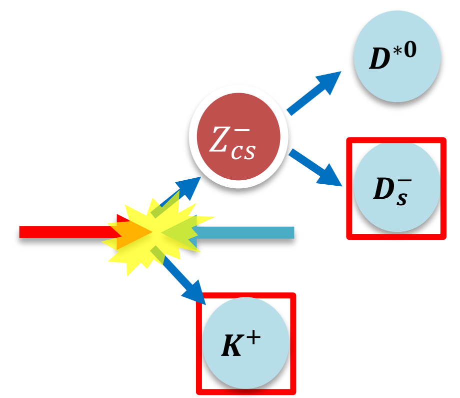
- We analyze 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- **Partial reconstruction of K^+ and D_s^-**
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



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





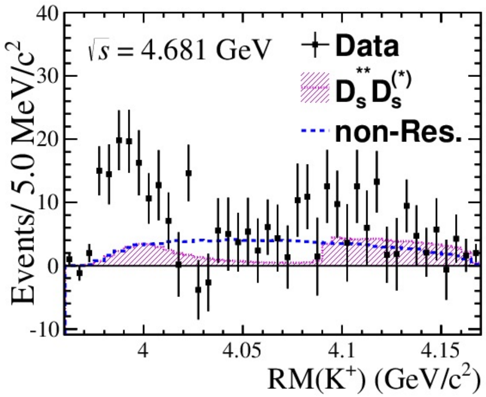


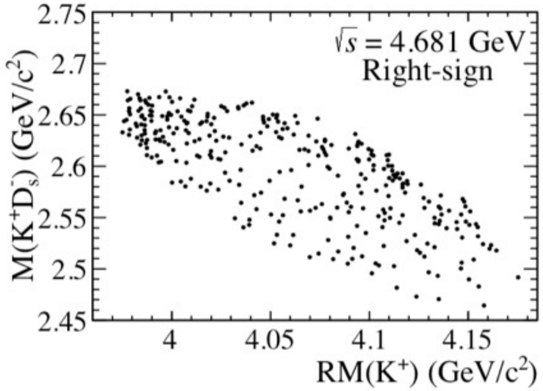
$e^+e^- \to K^+ D_s^- D^{*0}$

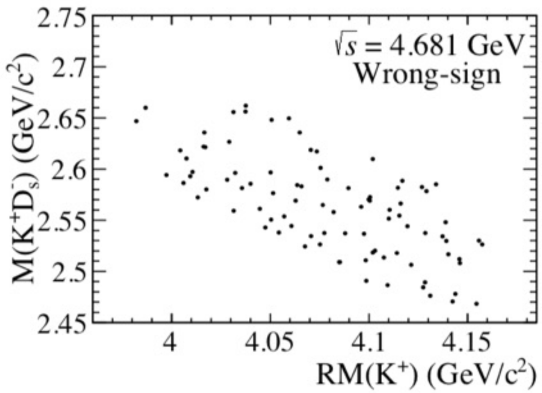
new! Observation of the $Z_{cs}(3985)^{\pm}$

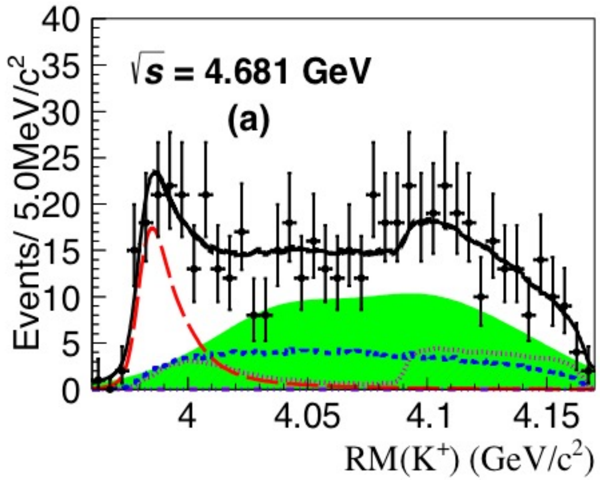
PRL126, 102001 (2021)

- Data driven background description: wrong Sign (WS) combination of D_s^- and K^-
- Conventional charmed mesons can not describe the enhancement below 4.0 GeV/c² at 4.681 GeV









- Assume the structure as a $D_s^- D^{*0}/D_s^{*-} D^0$ resonance, denoting it as the $Z_{cs}(3985)^-$.
- A fit of $J^P=1^+$ S-wave Breit-Wigner with mass dependent width returns:

$$\boldsymbol{m} = 3985.2^{+2.1}_{-2.0} \pm 1.7\ \mathrm{MeV/c^2}$$
$$\boldsymbol{\Gamma} = 13.8^{+8.1}_{-5.2} \pm 4.9\ \mathrm{MeV}$$

- Global significance: >5.3 $\boldsymbol{\sigma}$

First candidate of the hidden-charm tetraquark with strangeness

The Zcs $(3985)^{\pm}$ and Zc$(3885)^{\pm}$

1643/pb data @4.681 GeV — 525/pb data @4.26 GeV

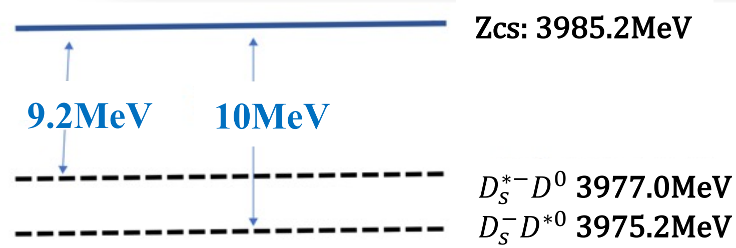
	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$	$Z_c(3885)^{\pm}$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	3899.0±3.6±4.9	3883.9±1.5±4.2
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	46±10±26	24.8±3.3±11.0
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0

~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

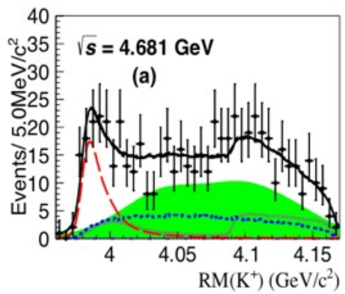
from Marek Karliner in Nov. 2020

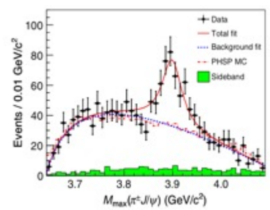
two general comments about
charm-tau factory program

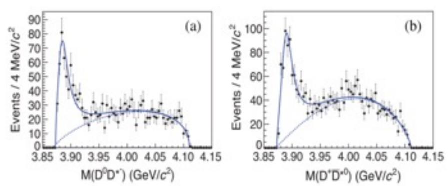
- $J/\psi\, K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism



SU(3) partner of Zc(3900)?







$Z_{cs}(3985)$

$K^-Z_{cs}^+$	$\bar{K}^0 Z_{cs}^0$	$K^0\bar{Z}_{cs}^0$	$K^+Z_{cs}^-$
1/4	1/4	1/4	1/4

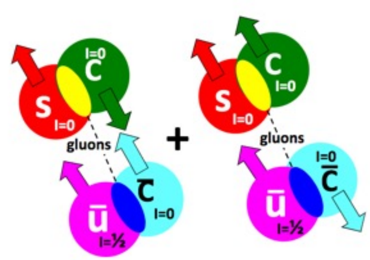
neutral/charged = 1

$Z_c(3900)$

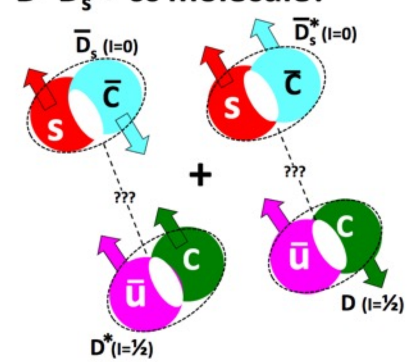
$\pi^- Z_c^+$	$\pi^0 Z_c^0$	$\pi^+ Z_c^-$
1/3	1/3	1/3

neutral/charged = 1/2

diquark-antidiquark?



$D^*\bar{D}_s$ + cc molecule?



Discussions on the nature of $Z_{cs}(3985)^{\pm}$

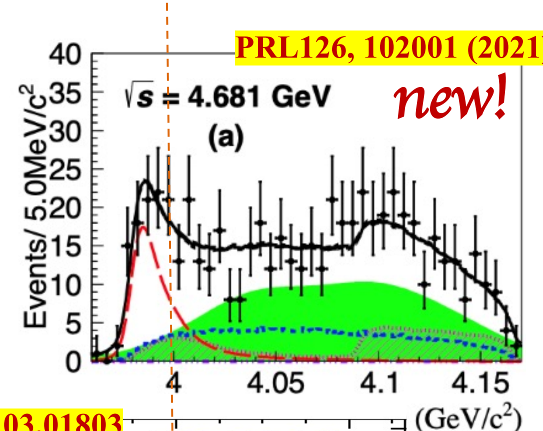
- Various interpretations are possible for the structure
  - Tetraquark state
  - Molecule
  - $D_{s2}^{*}(2573)^{+}D_{s}^{*-}$ threshold kinematic effects (Re-scattering , Reflection, Triangle singularity)
  - Mixture of molecular and tetraquark
  - …

$Z_{cs}(3985)$ from $e^{+}e^{-}$ annihilations and $Z_{cs}(4000)$ from B decays

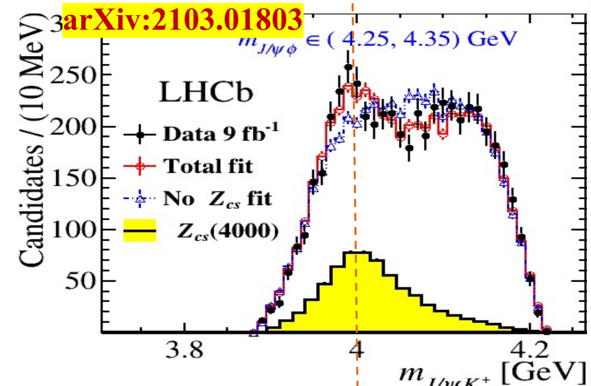
- their masses are close, but widths are different
- If they are same, why width so different?
- If they are not same, is there the corresponding wide Zc(3900)?
- Looking for more channels will be useful

PRL126, 102001 (2021)

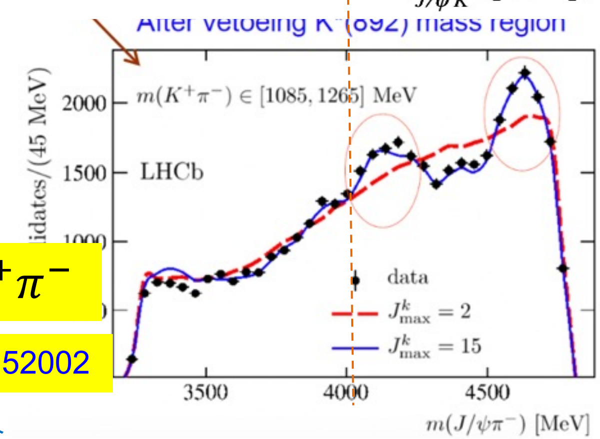
new!



arXiv:2103.01803



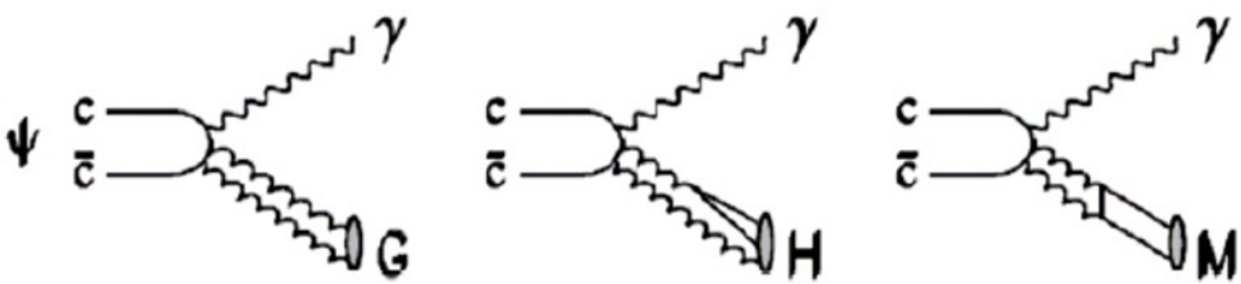
After vetoeing K*(892) mass region



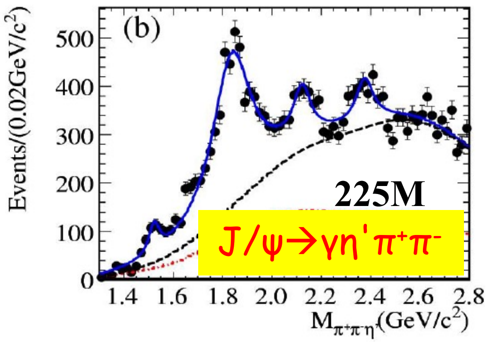
$B^{0} \to J/\psi K^{+}\pi^{-}$

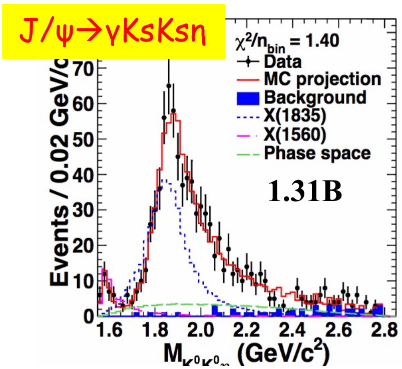
PRL 122 (2019) 152002

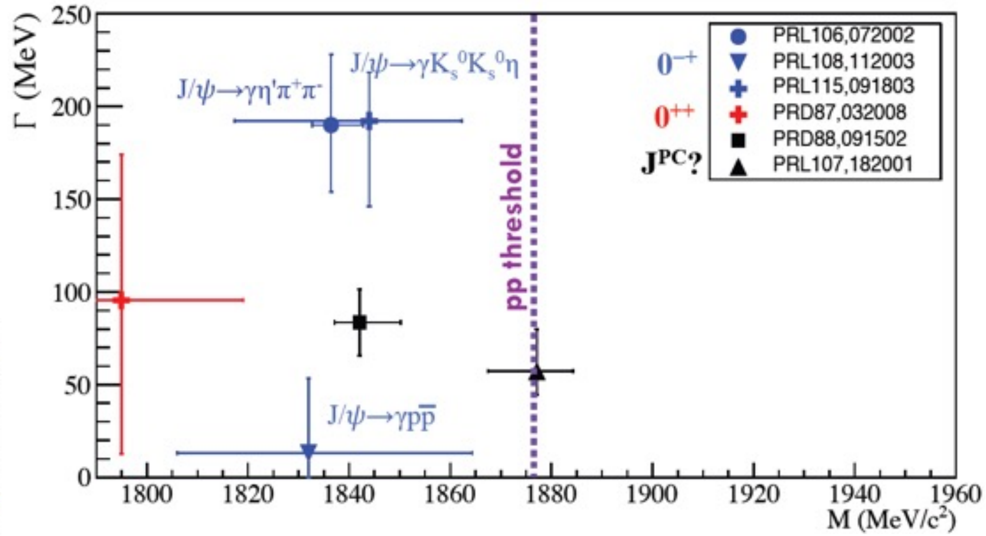
Light hadrons
(containing *u/d/s* quarks)

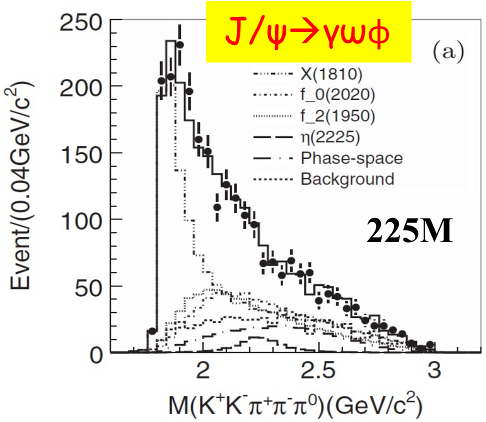


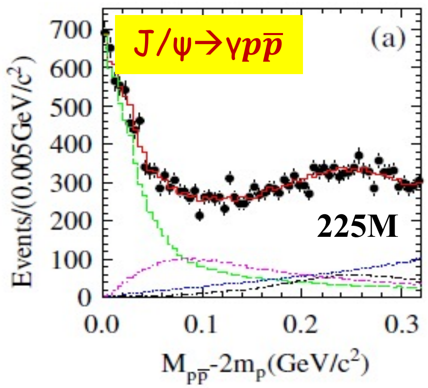
X($p\bar{p}$)/X(18??) from J/ψ radiative decays









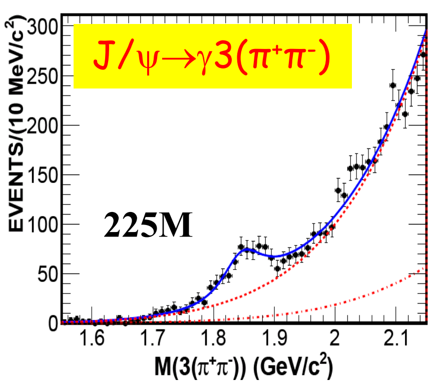


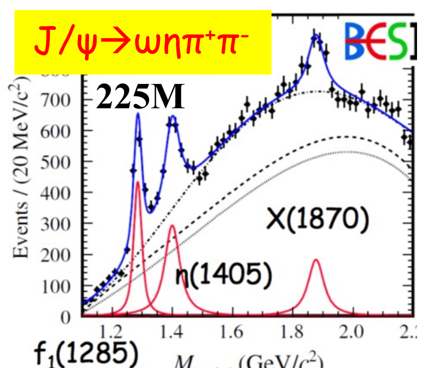
PRL117, 042002

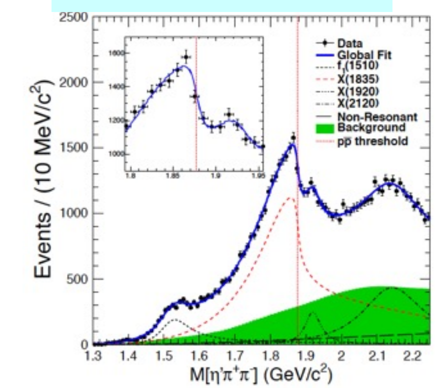
PRD97, 051101(R)(2018)

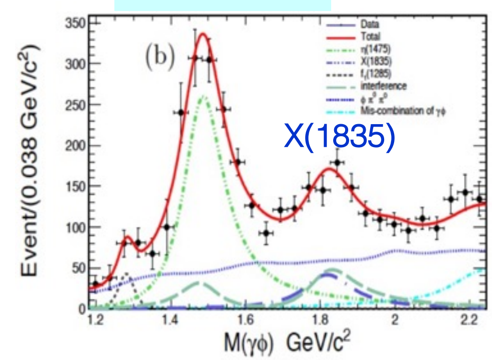
$J/\psi \to \gamma\eta'\pi^+\pi^-$

$J/\psi \to \gamma\gamma\phi$





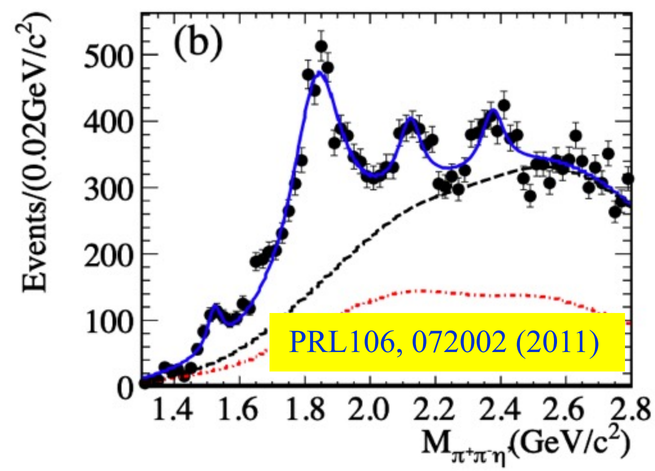




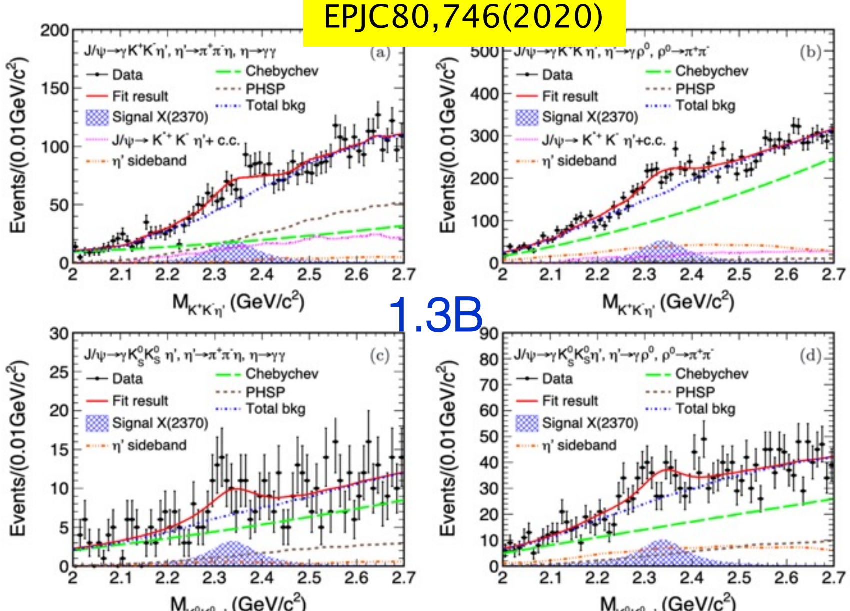
Are they the same state? It is crucial to understand their connections.

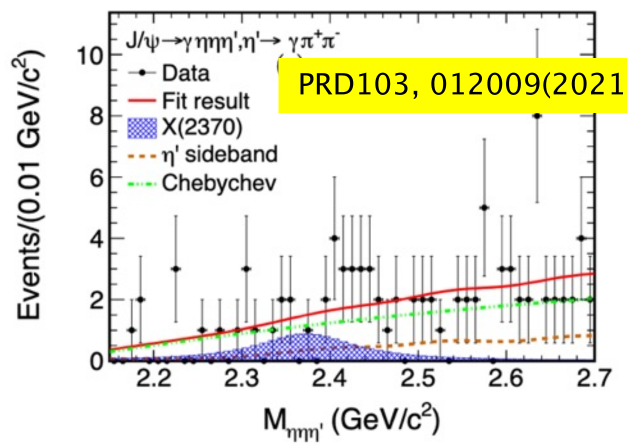
The X(2120) and X(2370) *new!*

- Observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$ at BESIII [PRL106, 072002 (2011)][PRL117, 042002(2016)]
- Candidates of glueball states
- Combined analysis of $J/\psi\to\gamma K^+K^-\eta'$ and $\gamma K_SK_S\eta'$
- Search for X(2370) in $J/\psi\to\gamma\eta\eta\eta'$



EPJC80,746(2020)





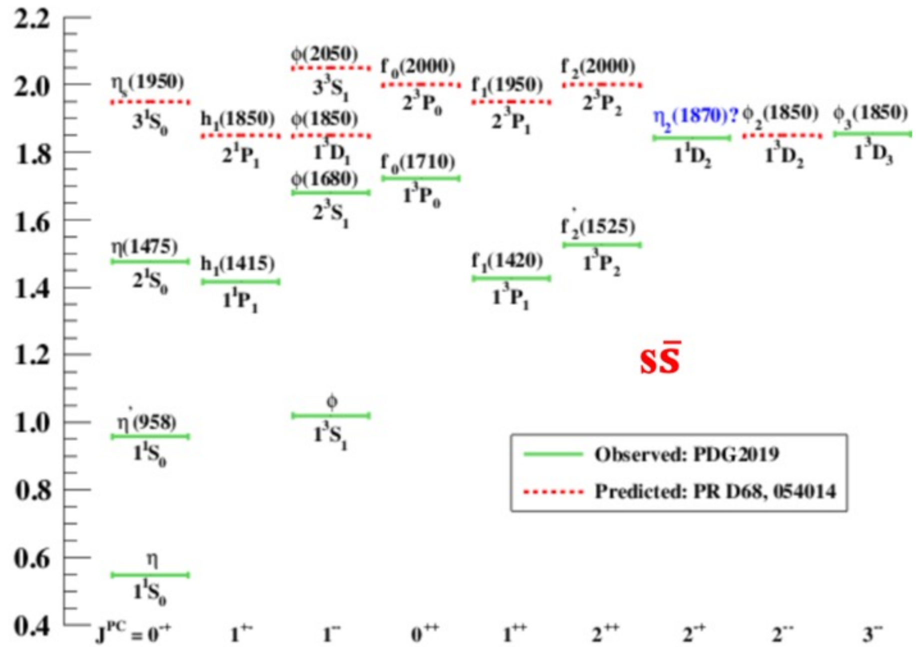
$$M_{X(2370)} = 2341.6 \pm 6.5(\text{stat.}) \pm 5.7(\text{syst.})\ \text{MeV}/c^2,$$
$$\Gamma_{X(2370)} = 117 \pm 10(\text{stat.}) \pm 8(\text{syst.})\ \text{MeV},$$

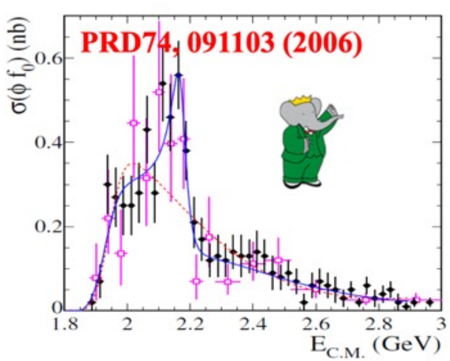
- Observation of $X(2370)\to K\bar{K}\eta'$ with stat. significance of 8.3σ
- No evidence of $X(2120)\to K\bar{K}\eta'$
- No evidence of $X(2370)\to\eta\eta\eta'$

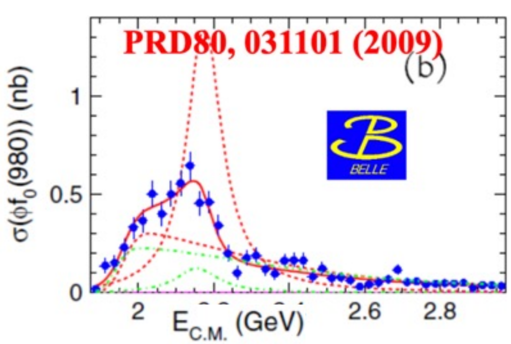
Studies on the ϕ(2170)/Y(2175)

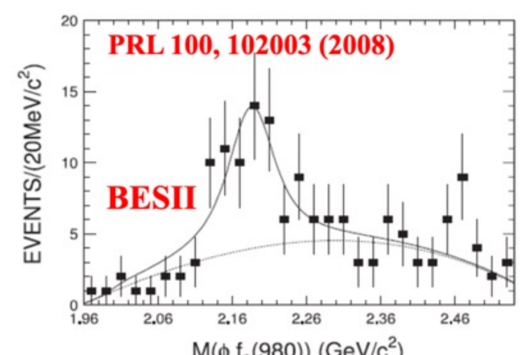
- A strangeonium(-like) state: *Y*-particle with strange quark

➢ **Theorists explain ϕ(2170) as**
- ✓ **$s\bar{s}g$ hybrid**
- ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
- ✓ **tetraquark**
- ✓ **Molecular state $\Lambda\bar{\Lambda}$**
- ✓ **$\phi f_0(980)$ resonance with FSI**
- ✓ **Three body system ϕKK**



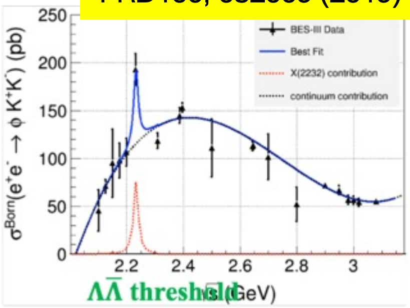




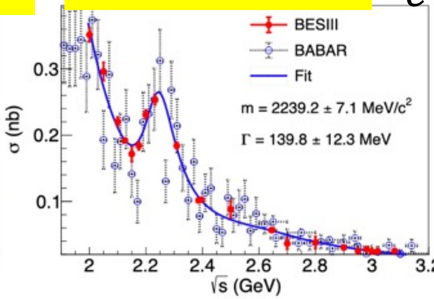


More results on the $\phi(2170)/Y(2175)$

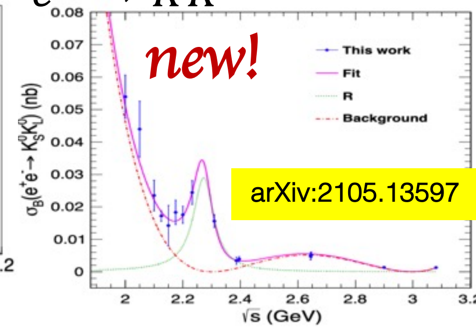
PRD100, 032009 (2019)



PRD99, 032001(2019)

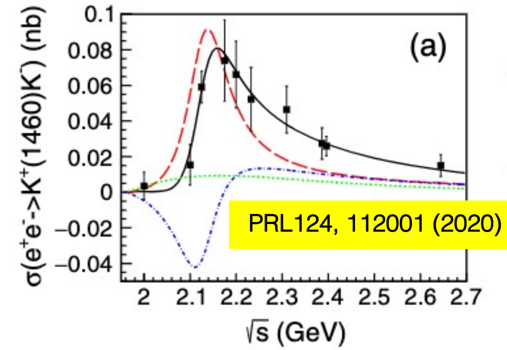


$e^+e^- \to K\bar{K}$

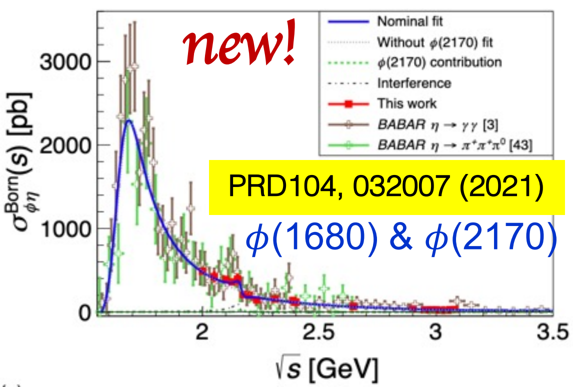


arXiv:2105.13597

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

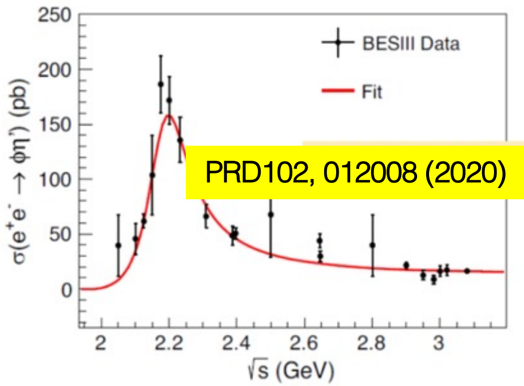


PRL124, 112001 (2020)

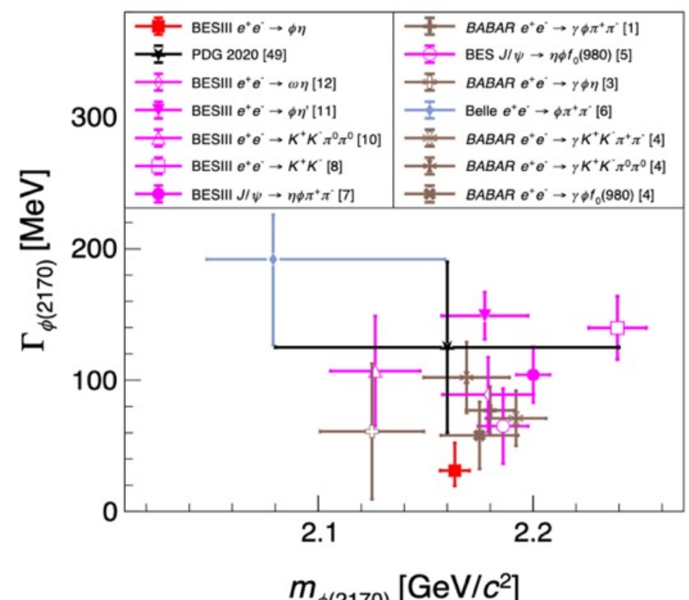


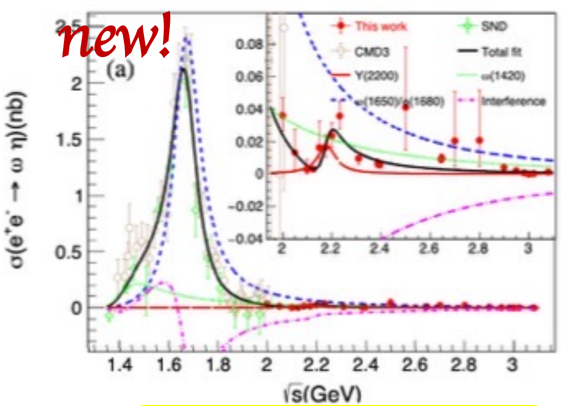
PRD104, 032007 (2021)

$\phi(1680)$ & $\phi(2170)$



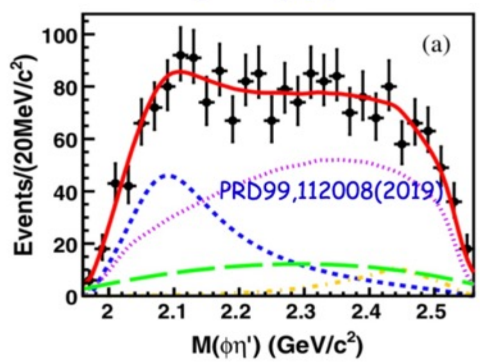
PRD102, 012008 (2020)





PLB 813, 136059 (2021)

$J/\psi \to \phi\eta\eta'$



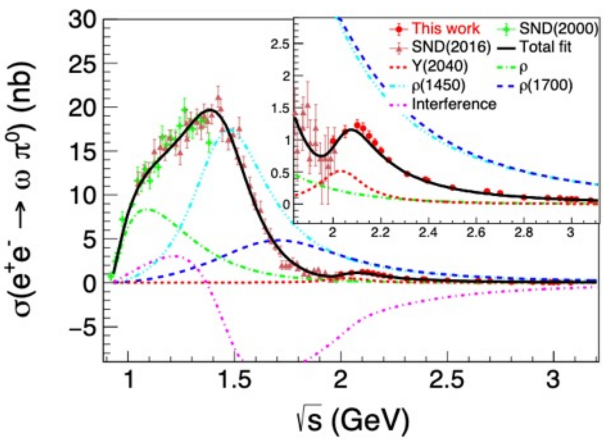
$\phi(2170)/Y(2175)$ is still a mystery

The isovector states

new!

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

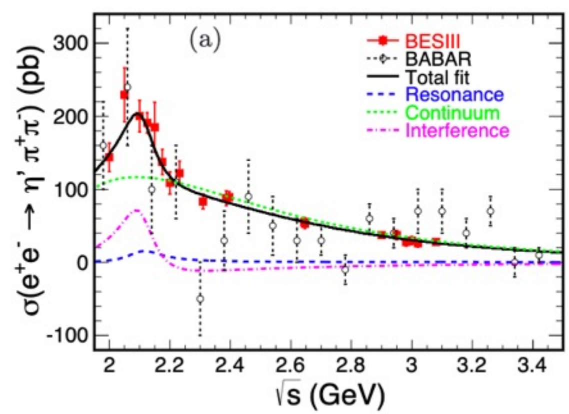
PLB 813, 136059 (2021)



- a structure Y(2040) with stat. significance $>10\sigma$
  $M = 2034 \pm 14 \pm 9\ \mathrm{MeV}/c^2$
  $\Gamma = 234 \pm 30 \pm 25\ \mathrm{MeV}$
- close to the isovector state $\rho(2000)$ or $\rho(2150)$

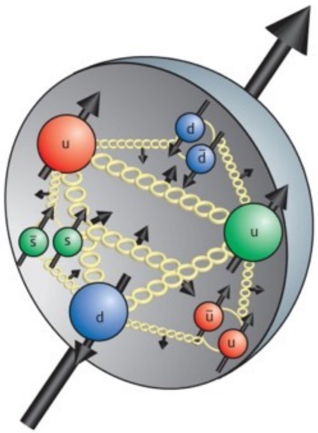
$e^+e^- \to \eta'\pi^+\pi^-$

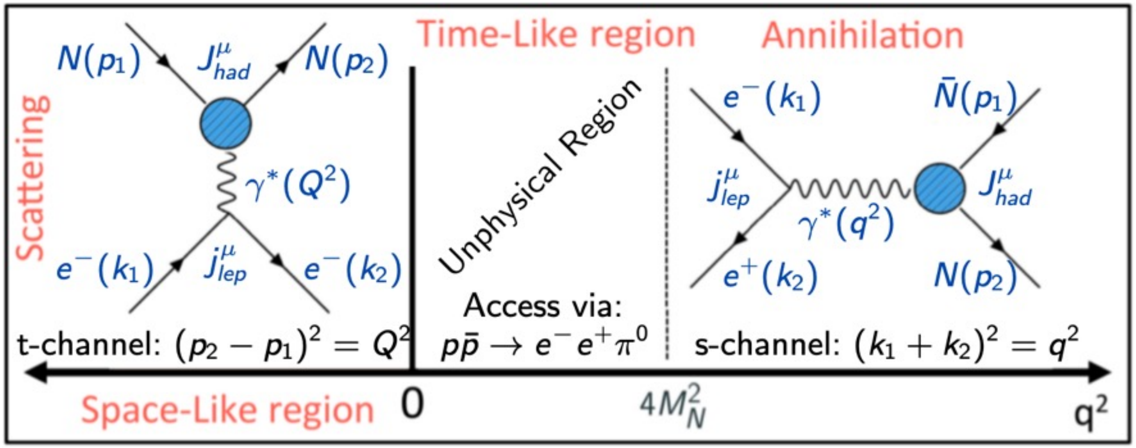
PRD 103, 072007 (2021)



- a structure around 2.1 GeV: stat. significance $>6.3\sigma$
  $M = 2111 \pm 43 \pm 25\ \mathrm{MeV}/c^2$
  $\Gamma = 135 \pm 34 \pm 30\ \mathrm{MeV}$
- consistent with the Y(2040) in $e^+e^- \to \omega\pi^0$

Form factors of baryons



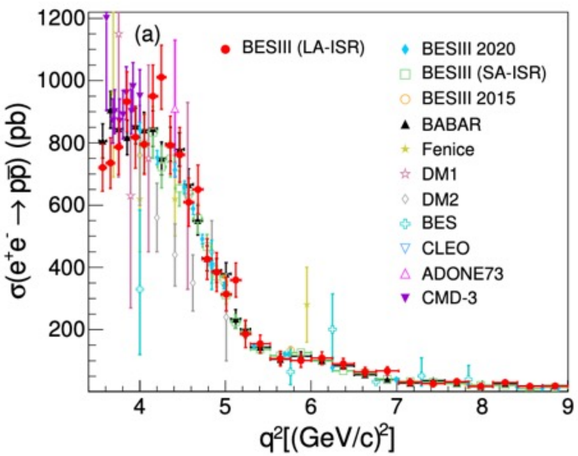


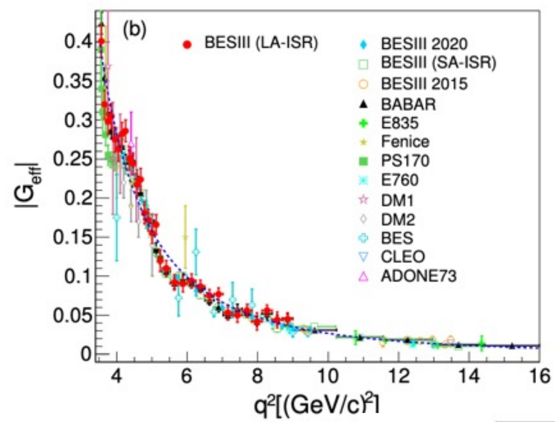
In the time-like region, access to the Electromagnetic Form Factors (EFF) of the baryons, which characterize the internal structure of the baryon

Threshold production of the nucleon

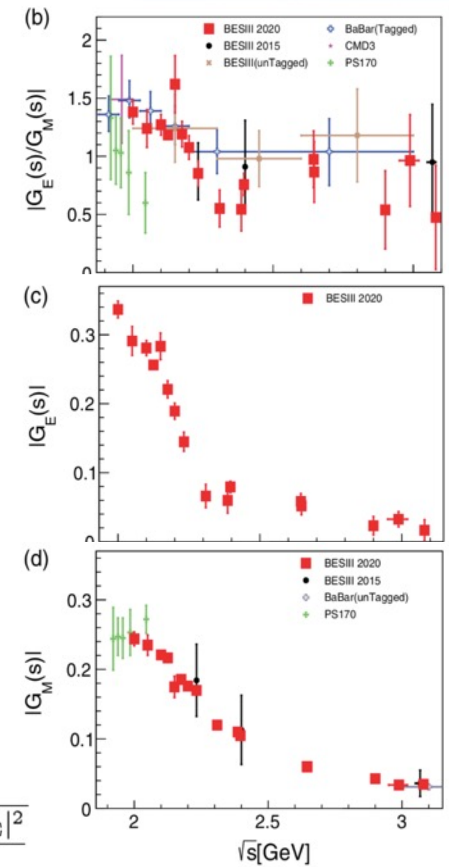
$$\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E(s)|^2\sin^2\theta\right]$$

BESIII tagged ISR: PLB 817, 136328 (2021)
BESIII 2020 energy scan: PRL124, 042001 (2020)
BESIII untagged ISR: PRD99, 092002 (2019)
BESIII 2015 energy scan: PRD91, 112004(2015)

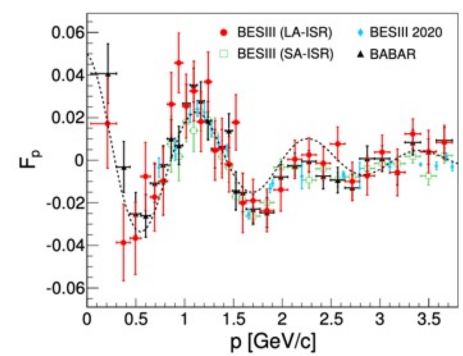




$$|G_{\rm eff}| = \sqrt{\frac{2\tau|G_{\rm M}|^2 + |G_{\rm E}|^2}{2\tau+1}}$$



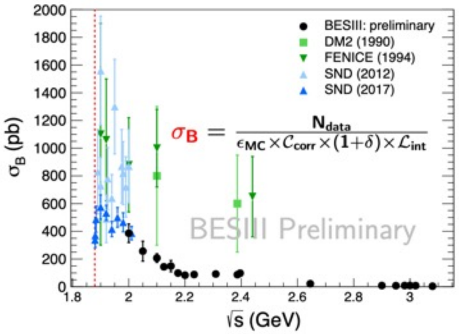
- BESIII provides best precisions: cross section threshold enhancement established
- Oscillating structures observed in the EFF after subtracted the modified dipole parameterization [PRL**114**, 232301 (2015)]
  - confirming the observation at BaBar

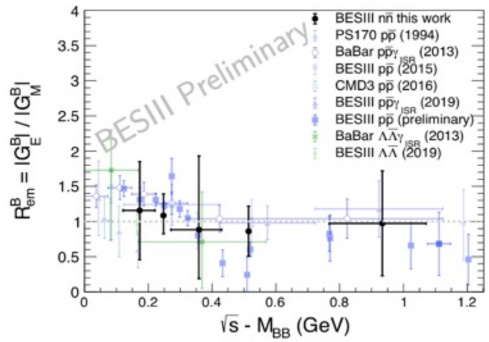


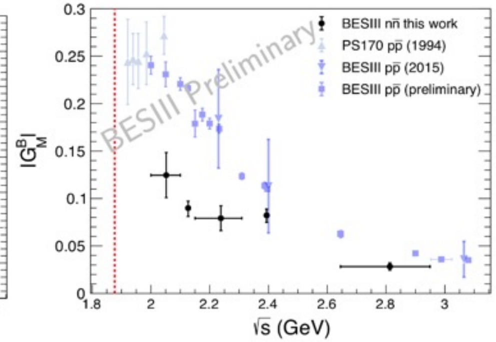
Threshold production of $e^+e^- \to n\bar{n}$

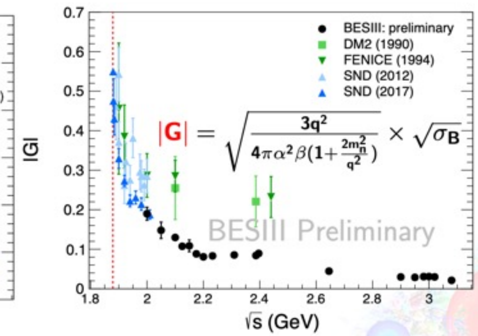
arXiv: 2103.12486
Accepted by Nature Physics

- Very challenging measurement due to pure neutron final states
- BESIII takes three approaches and provide validations among each other

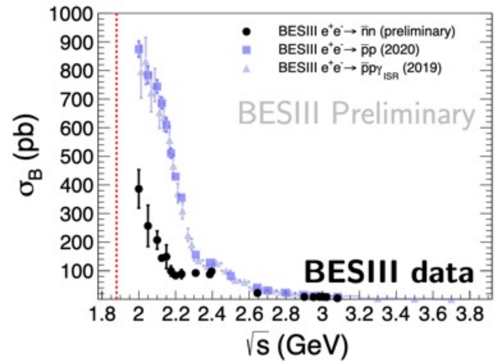


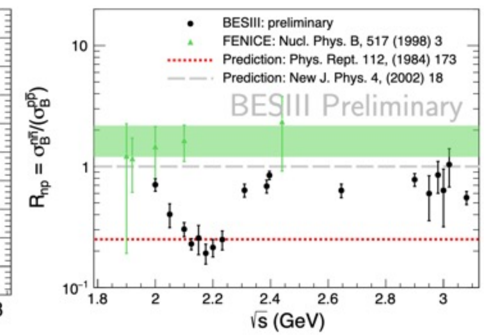


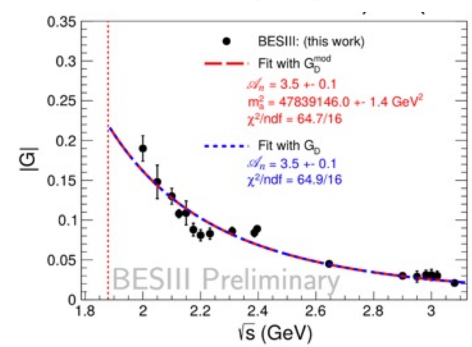


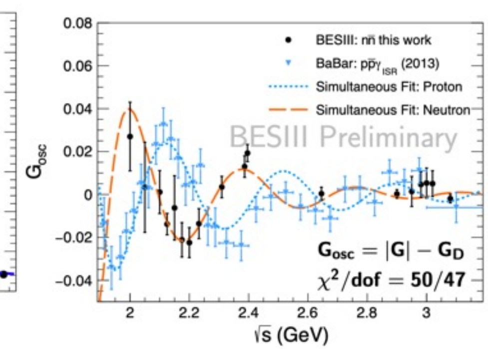


- XS measured in a wide range with unprecedented precision (~10%): confirming threshold enhancement
- EFF ratio R_{em} and G_M determined for the first time
- XS ratio between proton and neutron: do not support the FENICE conjecture, but are within the theoretical predictions
- Oscillation of EFF observed in neutron data: simultaneous fit of proton and neutron data gives shared frequency (5.55±0.28) GeV^{-1} with almost orthogonal phase difference of $(125\pm12)^{O}$



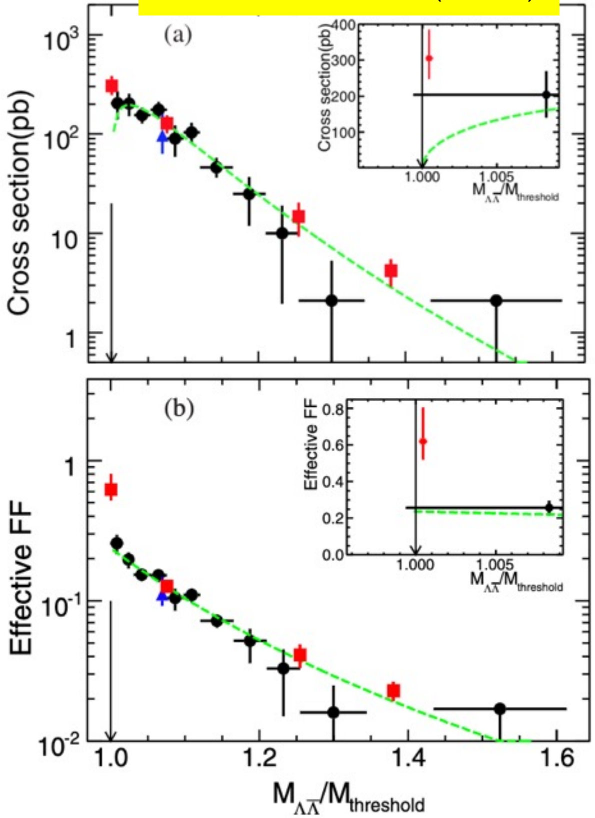




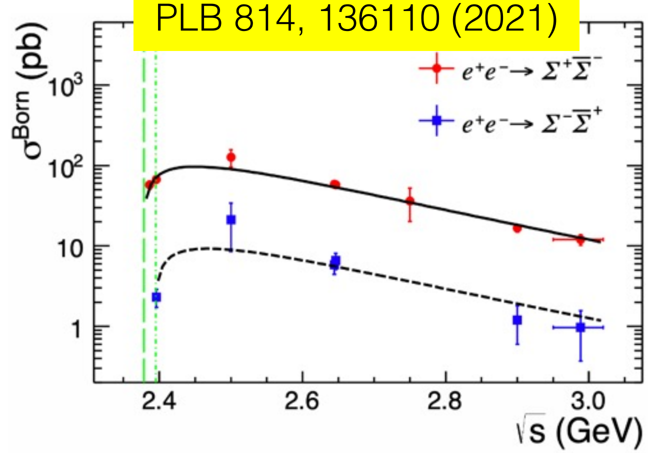


Hyperon production cross sections

PRD97, 032013 (2018)



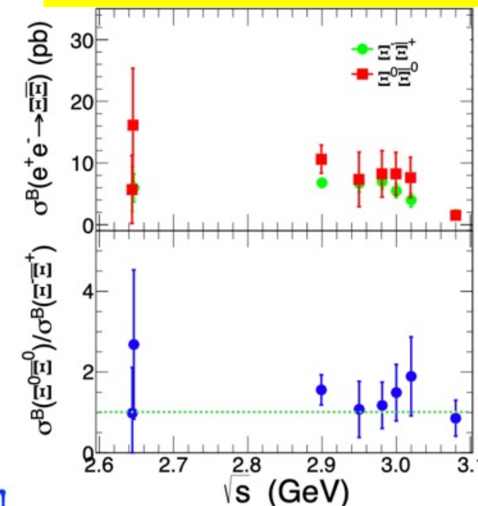
PLB 814, 136110 (2021)



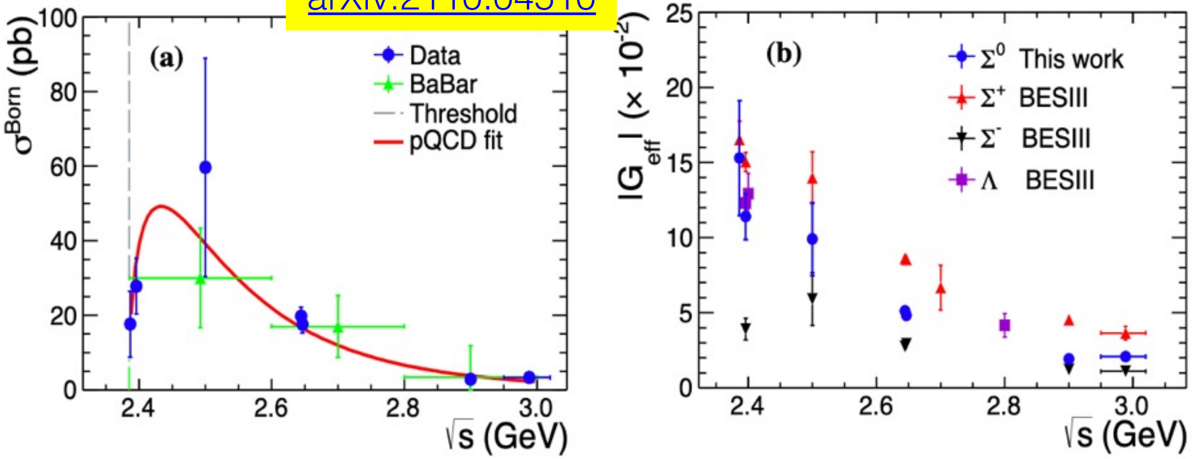
$$\frac{\sigma^{Born}(e^+e^- \to \Sigma^+\bar{\Sigma}^-)}{\sigma^{Born}(e^+e^- \to \Sigma^-\bar{\Sigma}^+)} = 9.7 \pm 1.3$$

consistent with the prediction of **Phys.Lett.B 799 (2019) 135041**

PRD103, 012005 (2021)
PLB 820, 136557 (2021)



arXiv:2110.04510



Threshold enhancement is observed for **Λ** pairs, while not for **Σ** pairs

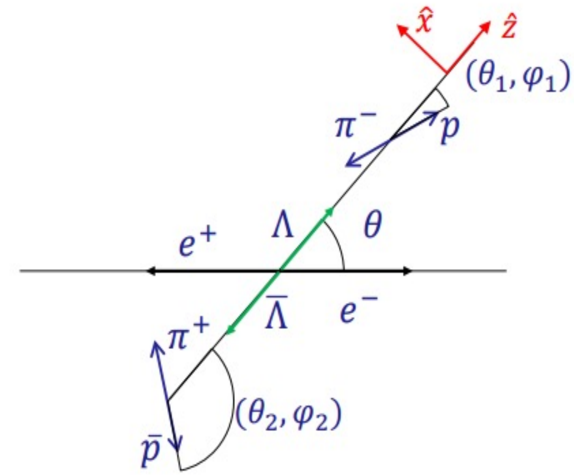
Relative phase of Λ Form Factors(FFs)

- Through the weak decay of hyperons, we could probe its polarization. Hence more information of the EFF can be studied
- $\Delta\phi$ is the phase angle difference of G_E and G_M: can be explored via angular analysis of the spin-coherent hyperon-pair weak decays

Unpolarized part — Polarized part — Spin correlated part

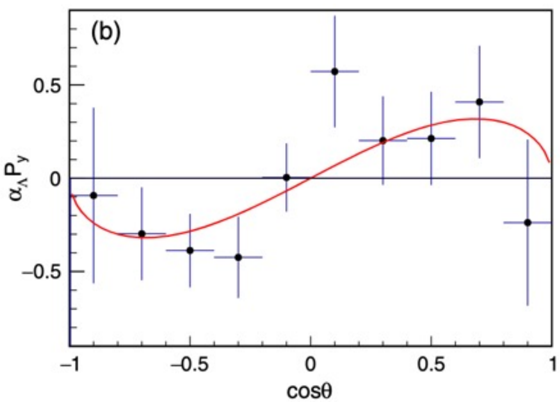
$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \alpha\bar{\alpha}\left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi)\right) + \sqrt{1-\eta^2}\sin(\Delta\Phi)(\alpha F_3(\xi) + \bar{\alpha} F_4(\xi))$$

$$R = |G_E/G_M|,\ \Delta\Phi = \Phi_E - \Phi_M,\ \eta = \frac{\tau - R^2}{\tau + R^2}$$



- First complete EFF measurement of the Λ at 2.396 GeV

PRL123,122003 (2019)



$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14(\text{stat.}) \pm 0.02(\text{sys.})$$

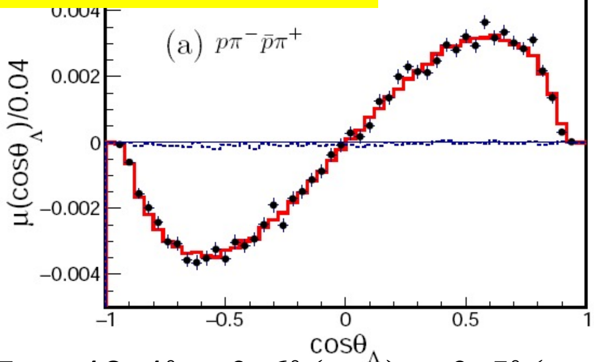
$$\Delta\Phi = 37^\circ \pm 12^\circ(\text{stat.}) \pm 6^\circ(\text{sys.})$$

Confirm the complex form of EMFFs !

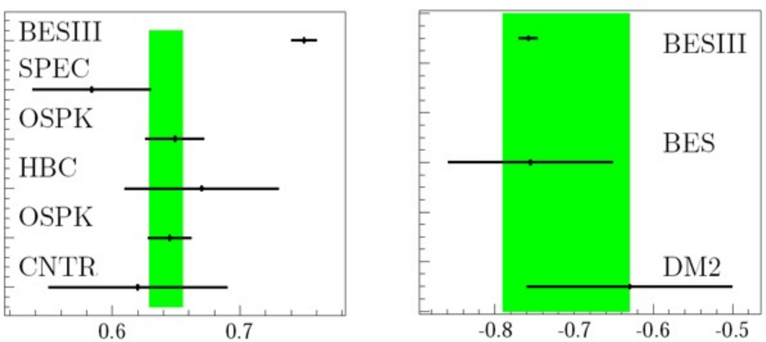
Hyperons produced at ψ peaks

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\bar{p}\pi^+\pi^-$

Nature Physics 15, 631 (2019)



$$\Delta\Phi = 42.4^\circ \pm 0.6^\circ(sta) \pm 0.5^\circ(sys.)$$

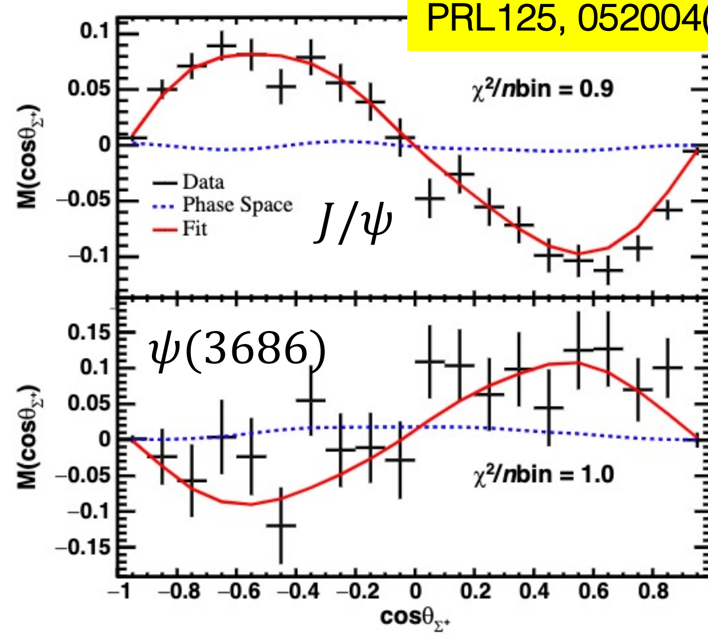


(a) α_- for $\Lambda \to p\pi^-$ (b) α_+ for $\bar{\Lambda} \to \bar{p}\pi^+$

- Very precise determination of hyperon decay asymmetry: ➔ CPV search
- Correct a long-history underestimation of Λ decay asymmetry

$e^+e^- \to \psi \to \Sigma^+\bar{\Sigma}^- \to p\bar{p}\pi^0\pi^0$

PRL125, 052004(2020)



Parameter	Measured value
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi'}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi'}$	$0.379 \pm 0.07 \pm 0.014$
α_0	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

CPV in $\Xi^- \to \Lambda\pi^-$ decay

BESIII: arXiv:2105.11155

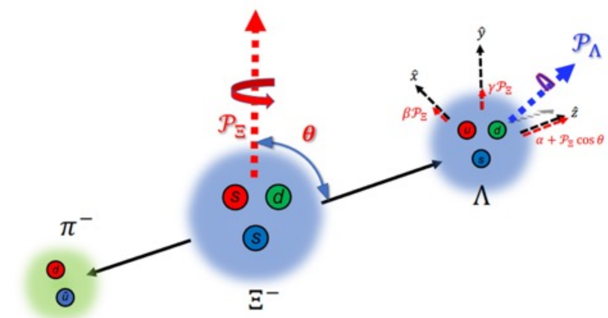
$$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$$

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	38
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad.	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	22
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad.	-0.037 ± 0.014 rad.	22
$\alpha_{\bar{\Xi}}$	$0.371 \pm 0.007 \pm 0.002$	–	
$\phi_{\bar{\Xi}}$	$-0.021 \pm 0.019 \pm 0.007$ rad.	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	3
$\alpha_{\bar{\Lambda}}$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	3
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad.	–	
$\delta_P - \delta_S$	$(-4.4 \pm 3.6 \pm 1.8) \times 10^{-2}$ rad.	$(8.7 \pm 3.3) \times 10^{-2}$ rad.	2
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad.	–	
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	3
$< \phi_\Xi >$	$0.016 \pm 0.014 \pm 0.007$ rad.		

HyperCP: $\phi_{\Xi,HyperCP} = -0.042 \pm 0.011 \pm 0.011$

BESIII: $<\phi_\Xi> = 0.016 \pm 0.014 \pm 0.007$

Based on 1.3 B J/ψ events (13% of total J/ψ events) 9-dimentional fit:



~73200 event candidates

Negligible background

First measurement of baryon weak phase difference

We obtain the same precision for ϕ as HyperCP with ***three orders of magnitude*** smaller data sample!

HyperCP: PRL 93(2004) 011802

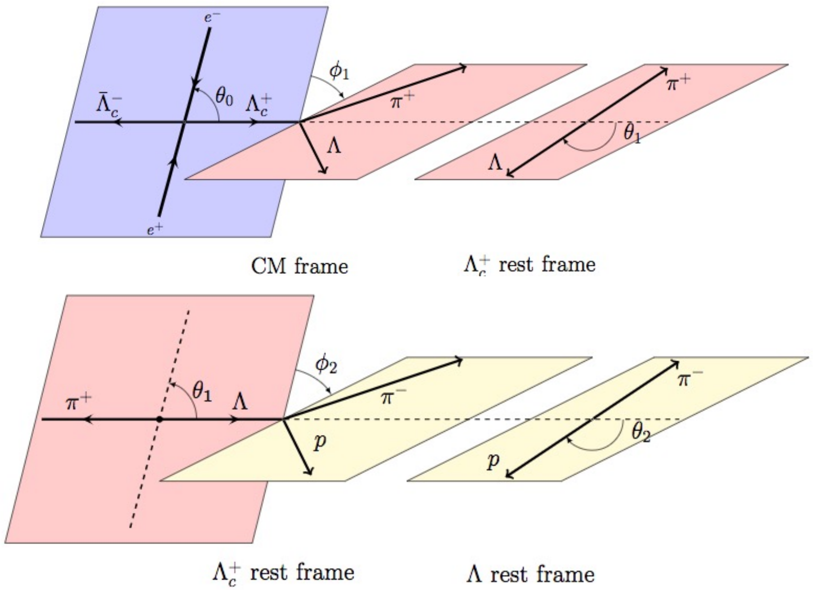
BESIII

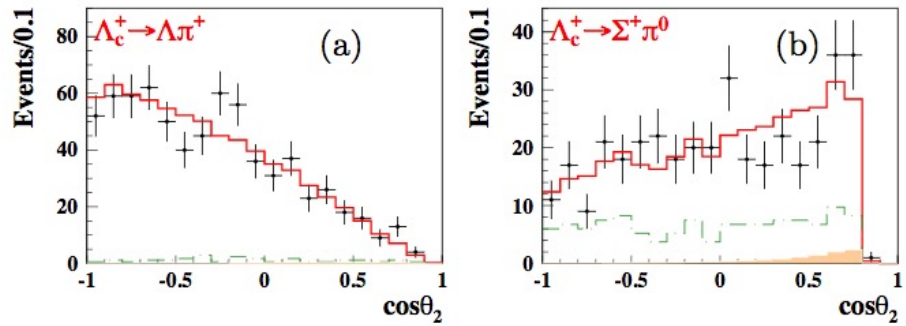
single tag method

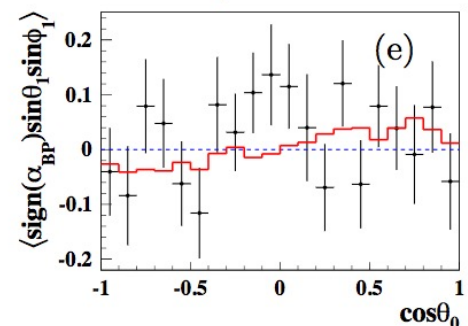
Λ_c decay asymmetries

PRD100, 072004 (2019)

- 4(6)-fold angular analysis of the cascade decays of $\Lambda_c \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$ based on 567/pb data



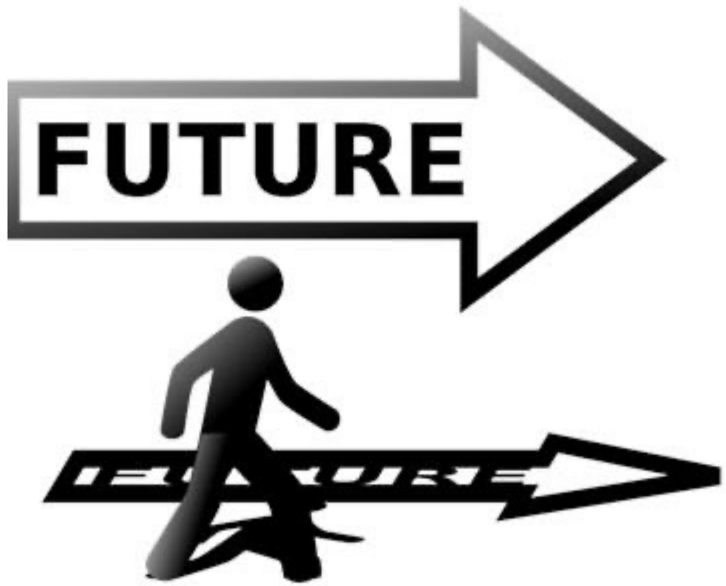




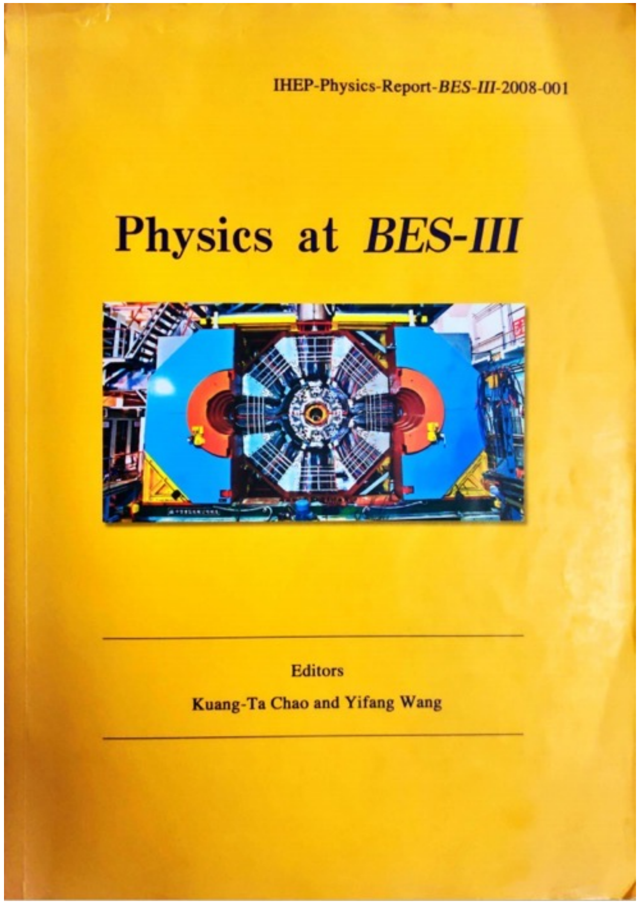
$\Lambda_c^+ \to$		pK_S^0	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
$\alpha_{BP}^{\Lambda_c^+}$	Predicted	-1.0 [16], 0.51 [11]	-0.70 [16], -0.67 [11]	0.71 [16], 0.92 [11]	0.70 [16], 0.92 [11]
		-0.49 [10], -0.90 [10]	-0.95 [10], -0.99 [10]	0.79 [10] -0.49 [10]	0.78 [10], -0.49 [10]
		-0.49 [17], -0.97 [18]	-0.96 [17], -0.95 [18]	0.83 [17], 0.43 [18]	0.83 [17], 0.43 [18]
		-0.66 [19], -0.90 [30]	-0.99 [19], -0.86 [30]	0.39 [19], -0.76 [30]	0.39 [19], -0.76 [30]
		-0.99 [20], -0.91 [31]	-0.99 [20], -0.94 [31]	-0.31 [20], -0.47 [31]	-0.31 [20], -0.47 [31]
	PDG [2]		-0.91 ± 0.15	-0.45 ± 0.32	
	This work	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$

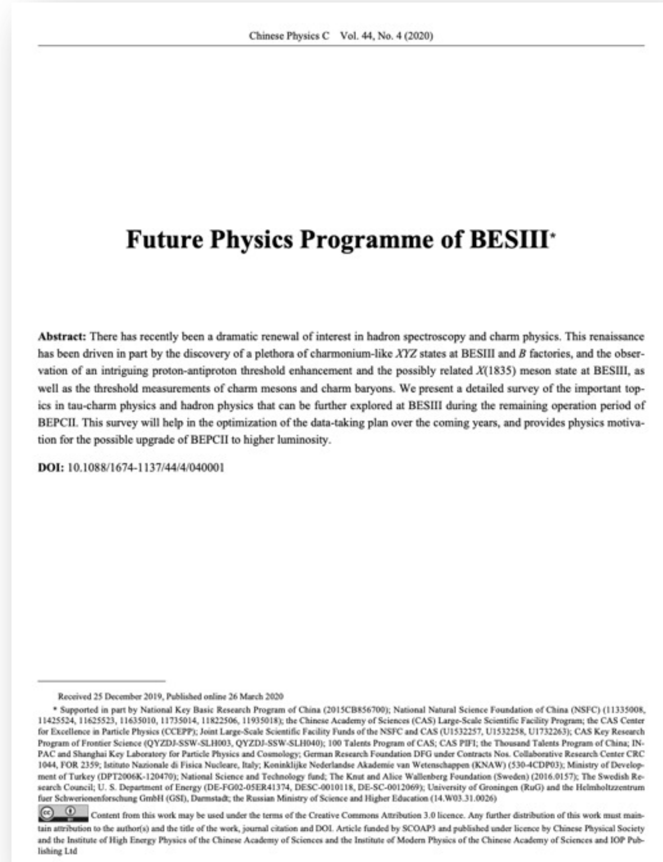
$\sin\Delta\phi = -0.28 \pm 0.13 \pm 0.03$

- Best precisions on the hadronic weak decay asymmetries
- The transverse polarization is firstly studied and found to be non-zero with 2.1σ


FUTURE

BESIII Physics




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

Future Physics Programme of BESIII*

Abstract: There has recently been a dramatic renewal of interest in hadron spectroscopy and charm physics. This renaissance has been driven in part by the discovery of a plethora of charmonium-like *XYZ* states at BESIII and *B* factories, and the observation of an intriguing proton-antiproton threshold enhancement and the possibly related *X*(1835) meson state at BESIII, as well as the threshold measurements of charm mesons and charm baryons. We present a detailed survey of the important topics in tau-charm physics and hadron physics that can be further explored at BESIII during the remaining operation period of BEPCII. This survey will help in the optimization of the data-taking plan over the coming years, and provides physics motivation for the possible upgrade of BEPCII to higher luminosity.

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Int. J. Mod. Phys. A 24, S1-794 (2009) [arXiv:0809.1869 [hep-ex]].

Chin. Phys. C 44, 040001 (2020) doi:10.1088/1674-1137/44/4/040001 [arXiv:1912.05983 [hep-ex]].

Planned future data set

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

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
✓ J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
✓ $\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	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	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

to be complete in 2022-23

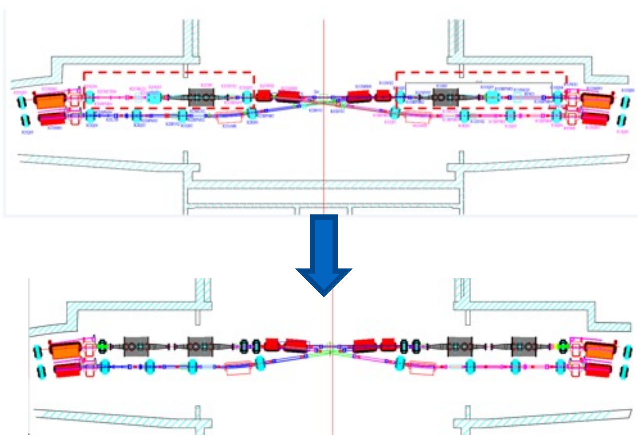
~55 fb^{-1}

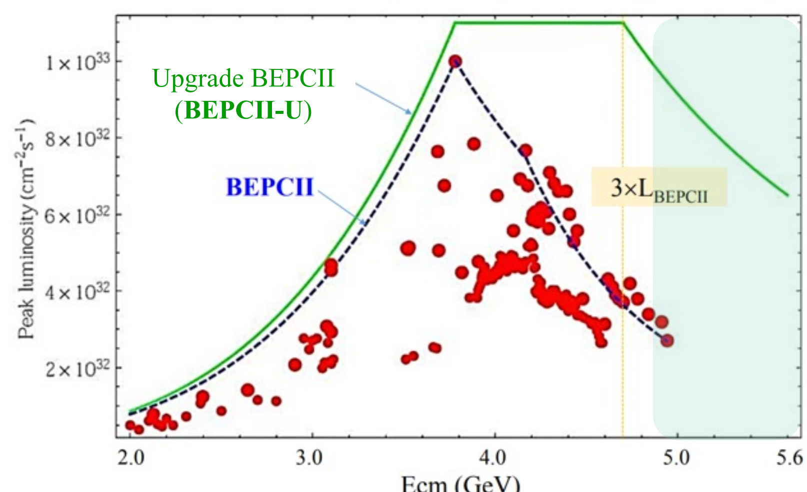
Proposal of the upgrade BEPCII

✓ 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

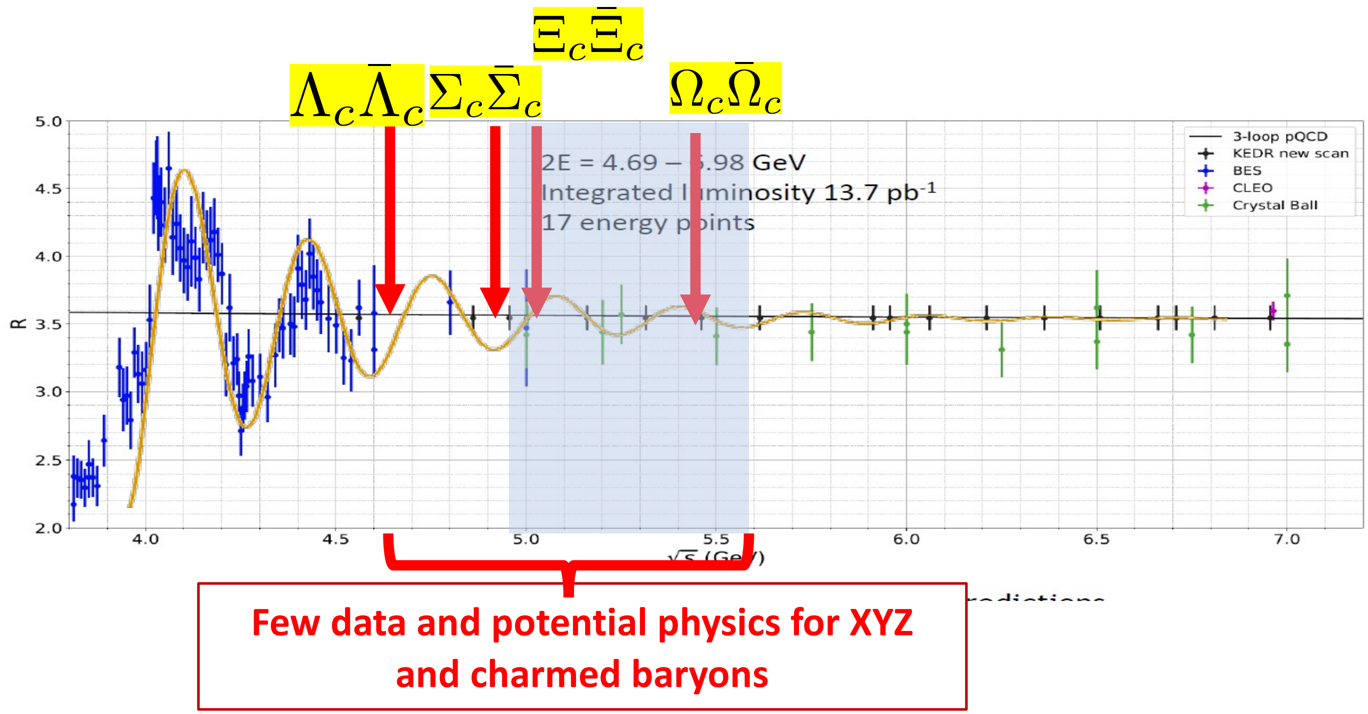
	BEPCII	BEPCII-U
Lum [$10^{32}cm^{-2}s^{-1}$]	3.5	11
β_y^* [cm]	1.5	1.35
Bunch Current [mA]	7.1	7.5
Bunch Num	56	120
SR Power [kW]	110	250
$\xi_{y,\mathrm{lum}}$	0.029	0.033
Emittance [nmrad]	147	152
Coupling [%]	0.53	0.35
Bucket Height	0.0069	0.011
$\sigma_{z,0}$ [cm]	1.54	1.07
σ_z [cm]	1.69	1.22
RF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





Potential physics with BEPCII-U

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



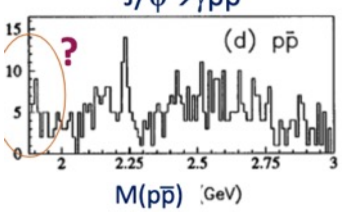
10 billon J/ψ events on tape!

from Stephen Olsen

you never have enough J/ψ events

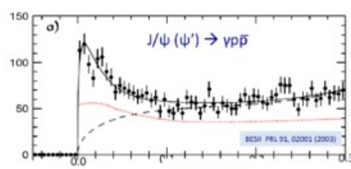
1996: 8 M J/ψ's

J/$\psi\to\gamma p\bar{p}$

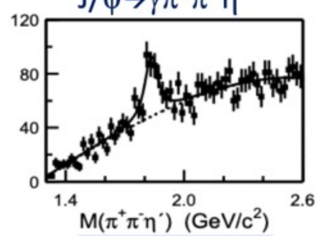


PRL 76, 3502

2002: 58 M J/ψ's

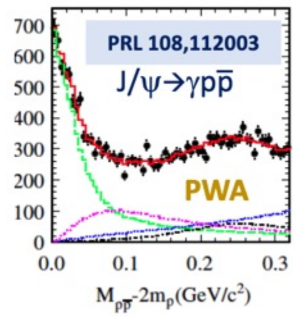


J/$\psi\to\gamma\pi^+\pi^-\eta'$

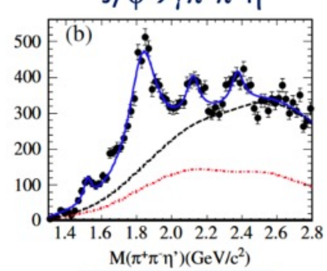


PRL 95,262001

2011: 225 M J/ψ's



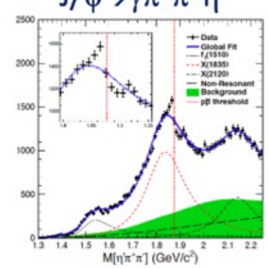
J/$\psi\to\gamma\pi^+\pi^-\eta'$



PRL 106,072002

2016: 1.3 B J/ψ's

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



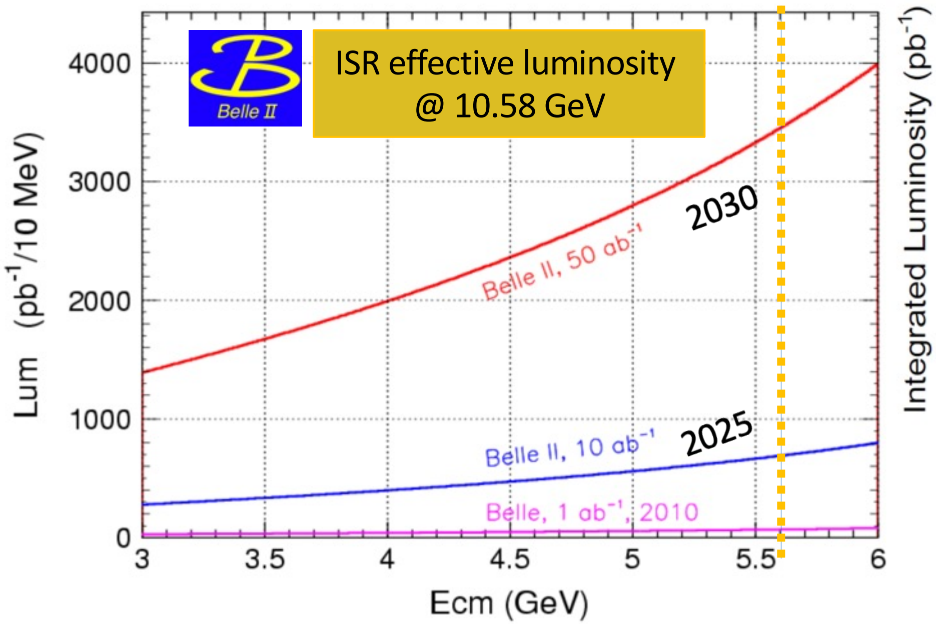
PRL 117,042002

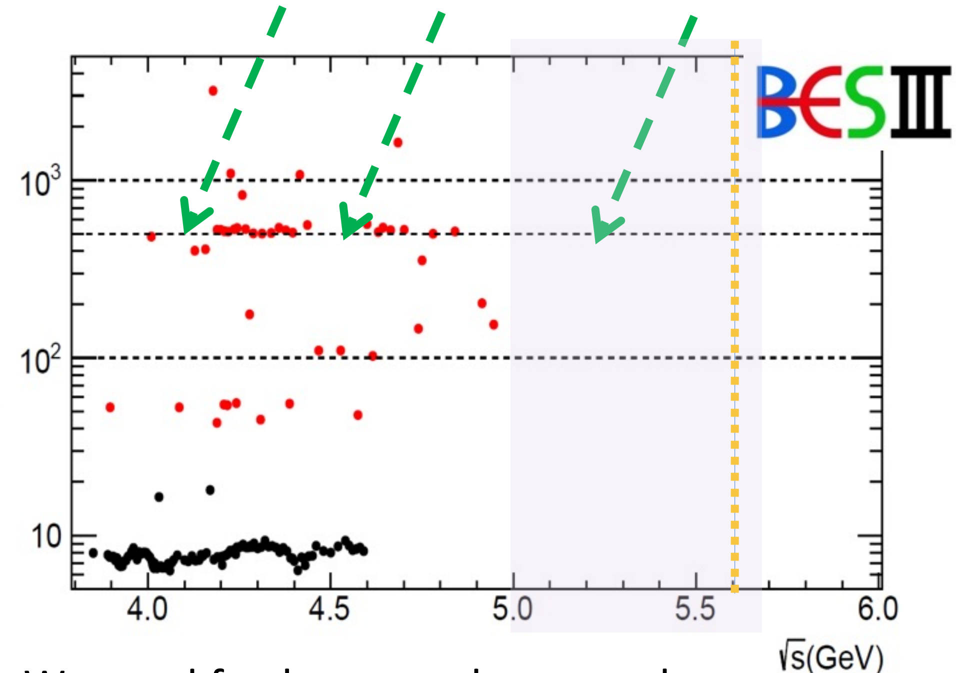
2019: 10 B J/ψ's

???

stay tuned

Some (personal) thoughts for future data taking





Competition with Belle II exists, and the scan energy points between 4.0 and 5.6 GeV need to be optimized

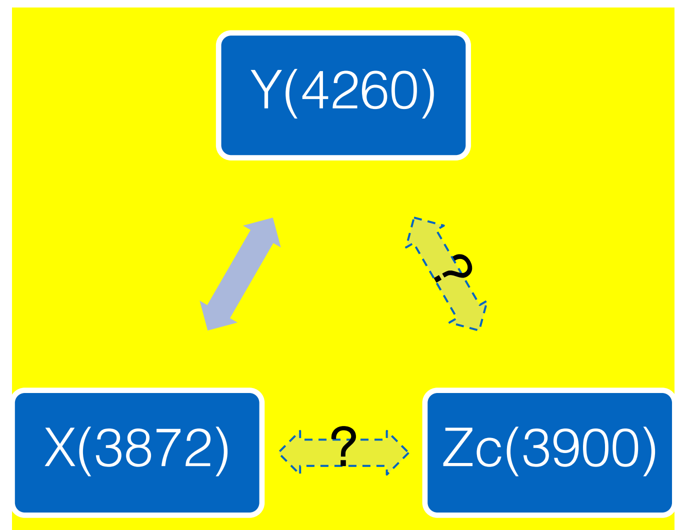
We need further scan data samples for Ecm=4.00-4.15, 4.43-4.59, 4.90-5.60 GeV, and some other energy points around charmed baryon threshold, such as

- ✓ 4.01 GeV: DsDs
- ✓ 4.6-4.7 GeV: $\Lambda_c \bar{\Lambda}_c$
- ✓ 4.95 -4.97GeV: $\Xi_c\ \bar{\Xi}_c$
  5.4 -5.6 GeV: $\Omega_c^0\bar{\Omega}_c^0$

Joint efforts among experiments and theories

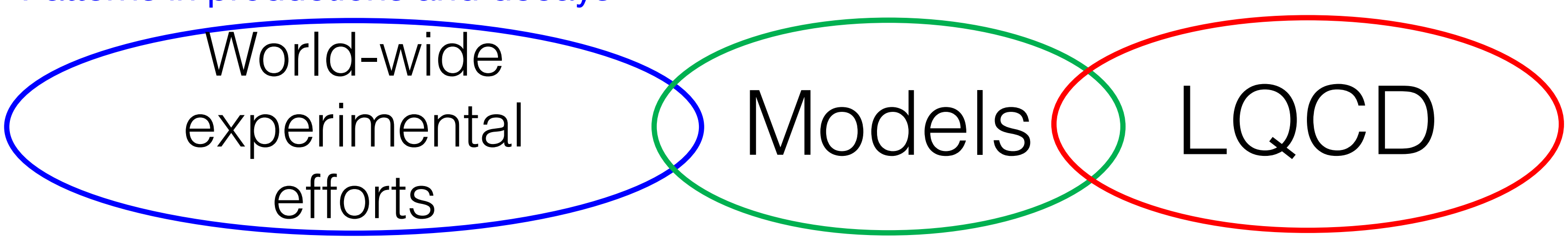
- It is crucial that different experiments, such as BESIII, LHCb and Belle II, exchange information in the efforts of amplitude analyses
  - ✓ Sharing the knowledge on analysis tools
    eg, **TF-PWA** (talks given inside BESIII and LHCb) https://github.com/jiangyi15/tf-pwa
  - ✓ Constraints on properties of the hadronic states
- A few cases:
  - Zc/Zcs productions (e^+e^- annihilations or b-hadron decays) and decays (to open or hidden charm states)

State	Decay modes	Seen by	
$Z_c(3900)^{\pm,0}$	$\pi^{\mp}J/\psi$, $(D^*\bar{D})^{\mp}$	BESIII, Belle CLEO	in $e^+e^- \to \pi^- Zc$
$Z_c(4020)^{\pm,0}$	$\pi^{\mp}h_c$, $(D^*\bar{D}^*)^{\mp}$	BESIII	in $e^+e^- \to \pi^- Zc$
$Z_c(4430)^{\pm}$	$\pi^{\mp}\psi(2S)$ $\pi^{\pm}J/\psi$	Belle, ~~BaBar,~~ LHCb	in $B \to KZc$



- Energy-dependence
- Patterns in productions and decays

Pole properties



Summary

- BESIII is successfully operating since 2008, and will continue to run for 5–10 years
  – collected large data samples in the energy range 2.0~5.6 GeV
- Many new results have been published regarding to spectroscopies
  - ✓ Charmed mesons and baryons
  - ✓ XYZ states and light hadron spectroscopy
  - ✓ Form factors of the nucleon and hyperons
  - ✓ Low-Q^2 QCD studies: R value, multi-meson production, fragmentation function, …
  - ✓ Rare decays and new physics search
  - ✓ …
- **Future goals:**
  50M D0, 50M D+, 15M Ds, 2M Λc , high-lumi. fine scan between 3.8 GeV and 5.6 GeV
  ➔ BEPCII-U: 3x upgrade on luminosity

Thank you!

谢谢！