Highlights on Flavor Physics at BESIII

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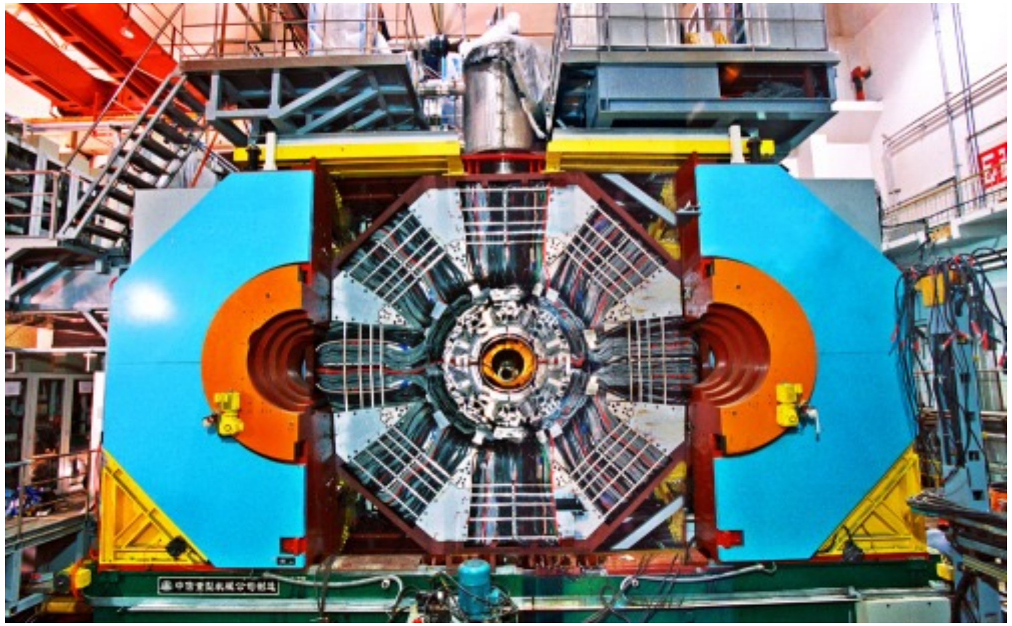
Outline

- BEPCII/BESIII
- Highlights of Physics accomplishments
- Future prospects

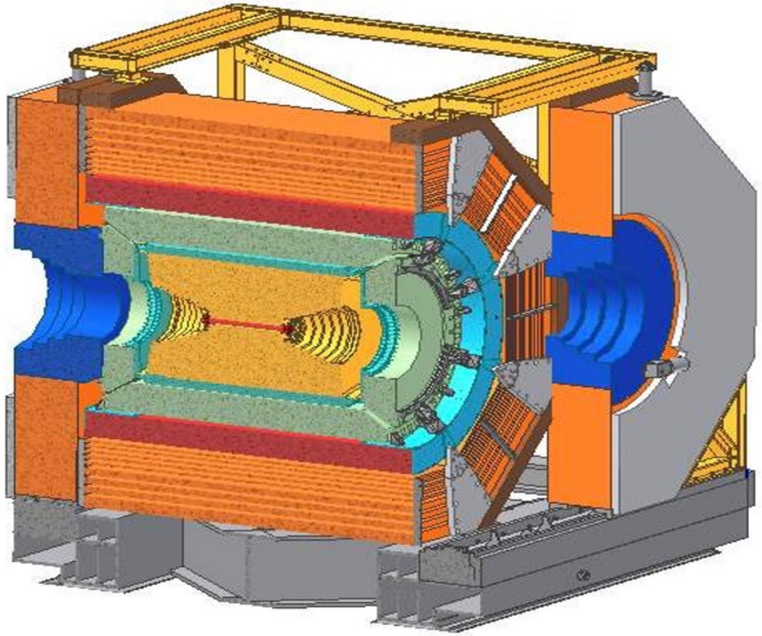
BEPCII/BESIII: τ-charm factory

- BEPC → BEPCII
  - Luminosity: 1.0×10^{31} → $1.0\times10^{33}\mathrm{cm^{-2}s^{-1}}$



Upgrade in 1996–1998
(BES→BESII)

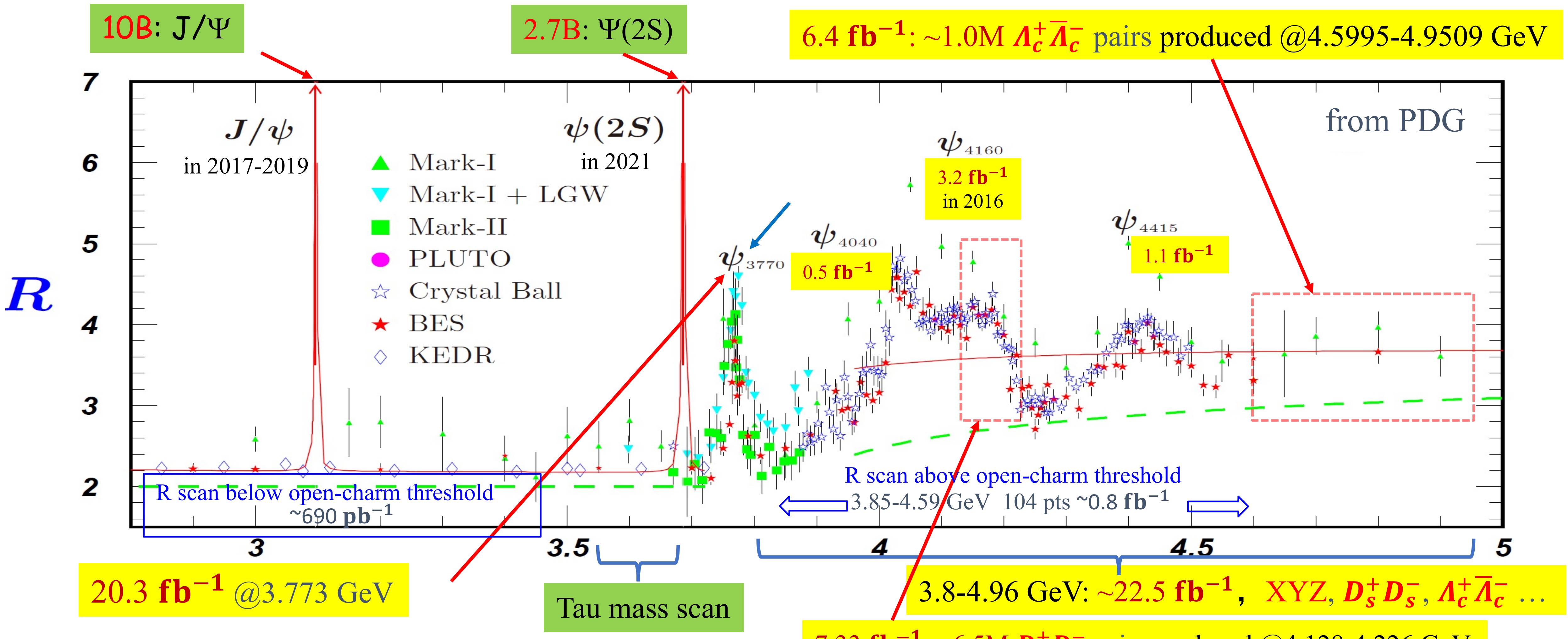
Upgrade in 2004–2008
(BESII→BESIII)



BESIII: a new spectrometer

- Very good energy resolution for photon
- Excellent momentum resolution for charged particles
- Good hadron identification capabilities

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

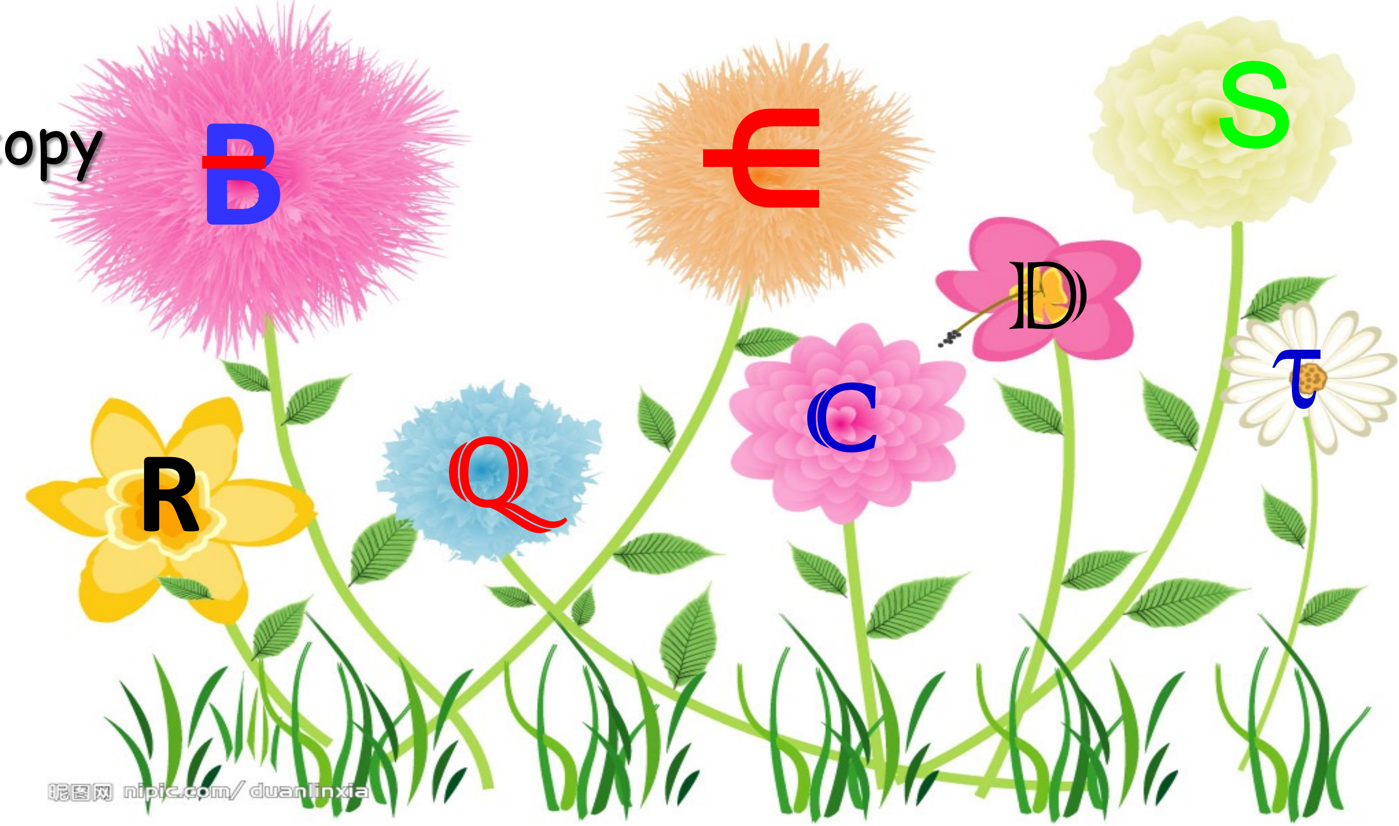


BESIII: ~55 fb^{-1} from 1.84 – 4.95 GeV

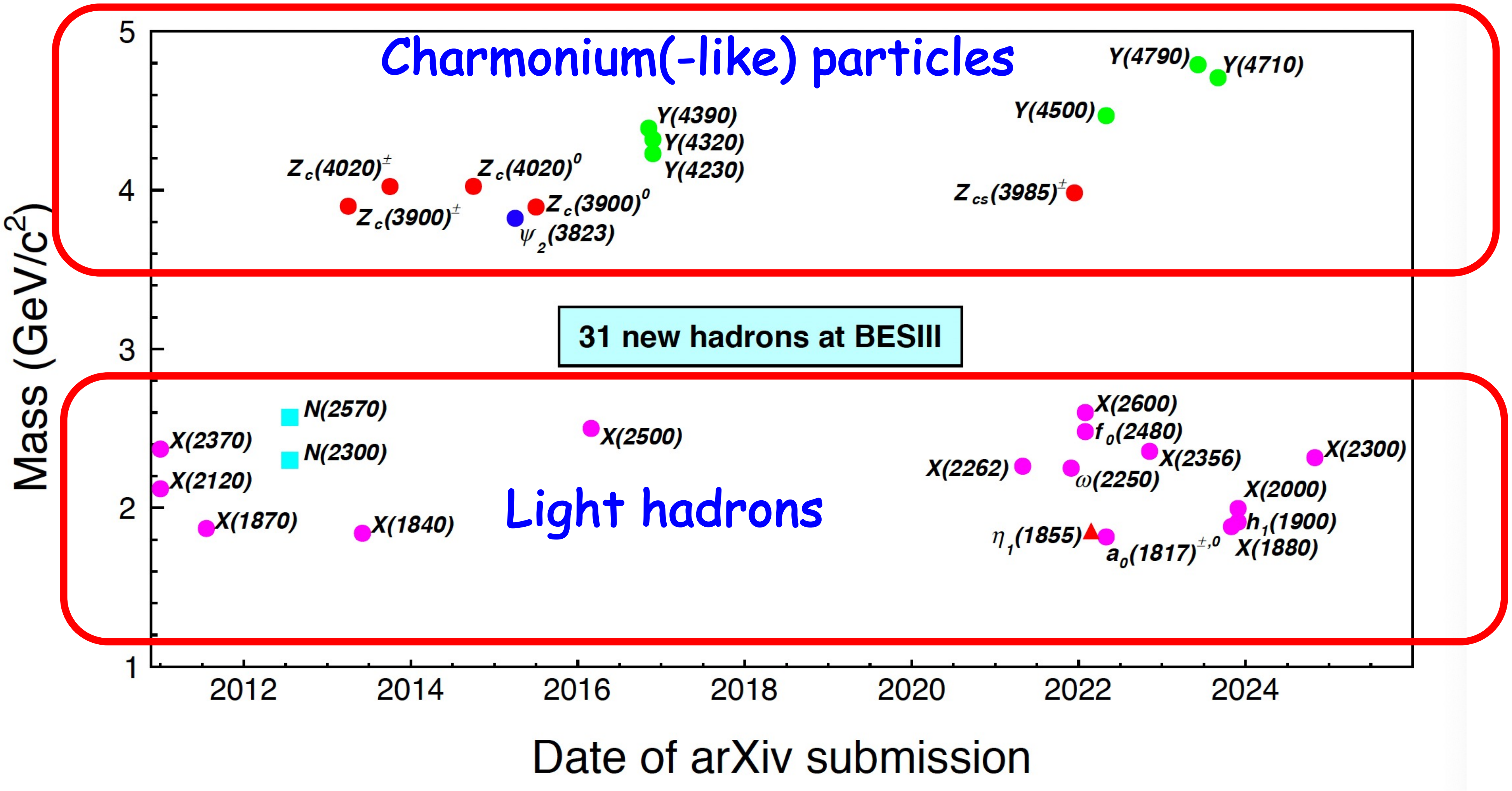
Physics at BESIII

NP

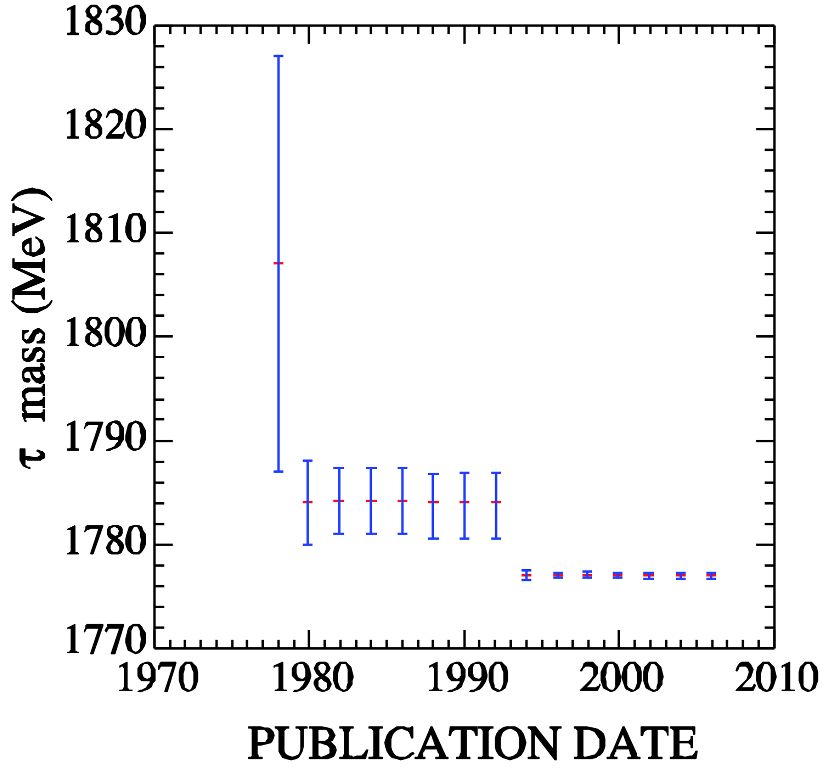
- Charmonium physics
- Light hadron Spectroscopy
- R-QCD physics
- New physics
- Charm physics



New resonant structures at BESIII



τ mass: BES

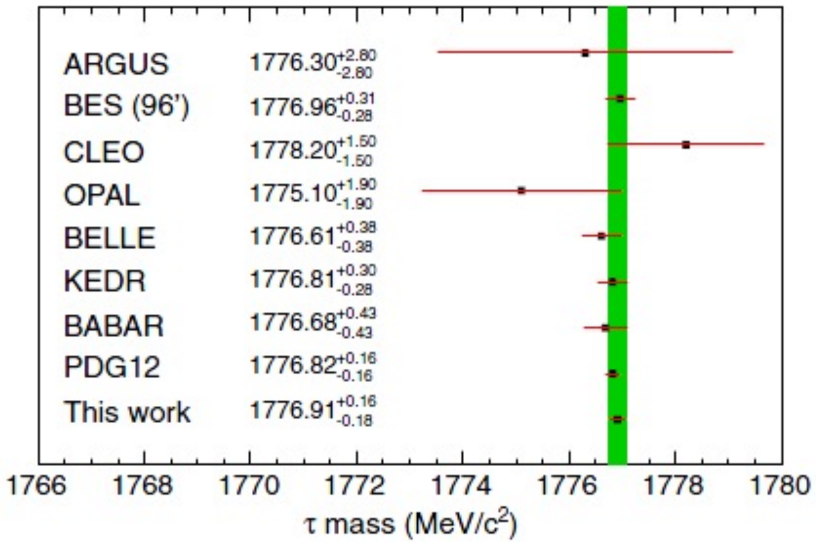


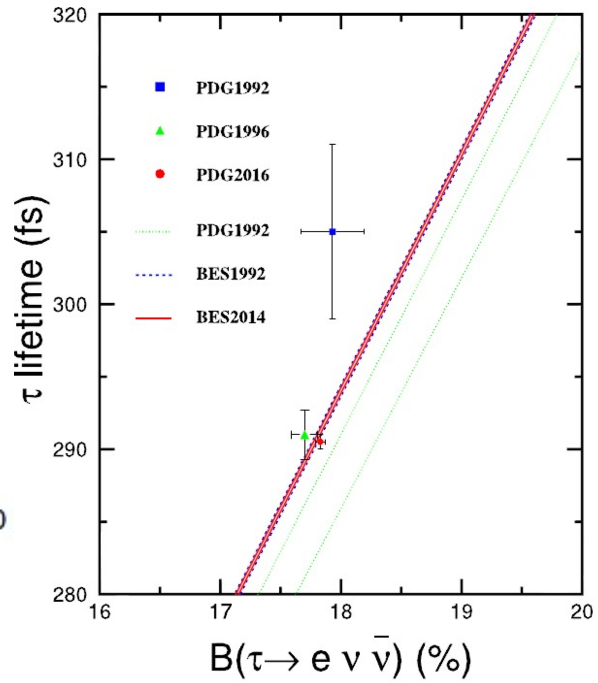
$$m_\tau = 1776.96^{+0.18+0.25}_{-0.21-0.17}\,MeV$$

$$\frac{g_\tau}{g_\mu} = 0.9886 \pm 0.0085$$

PRL69,3021(1992)

τ mass: BESIII





PRD90,012001(2014)

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

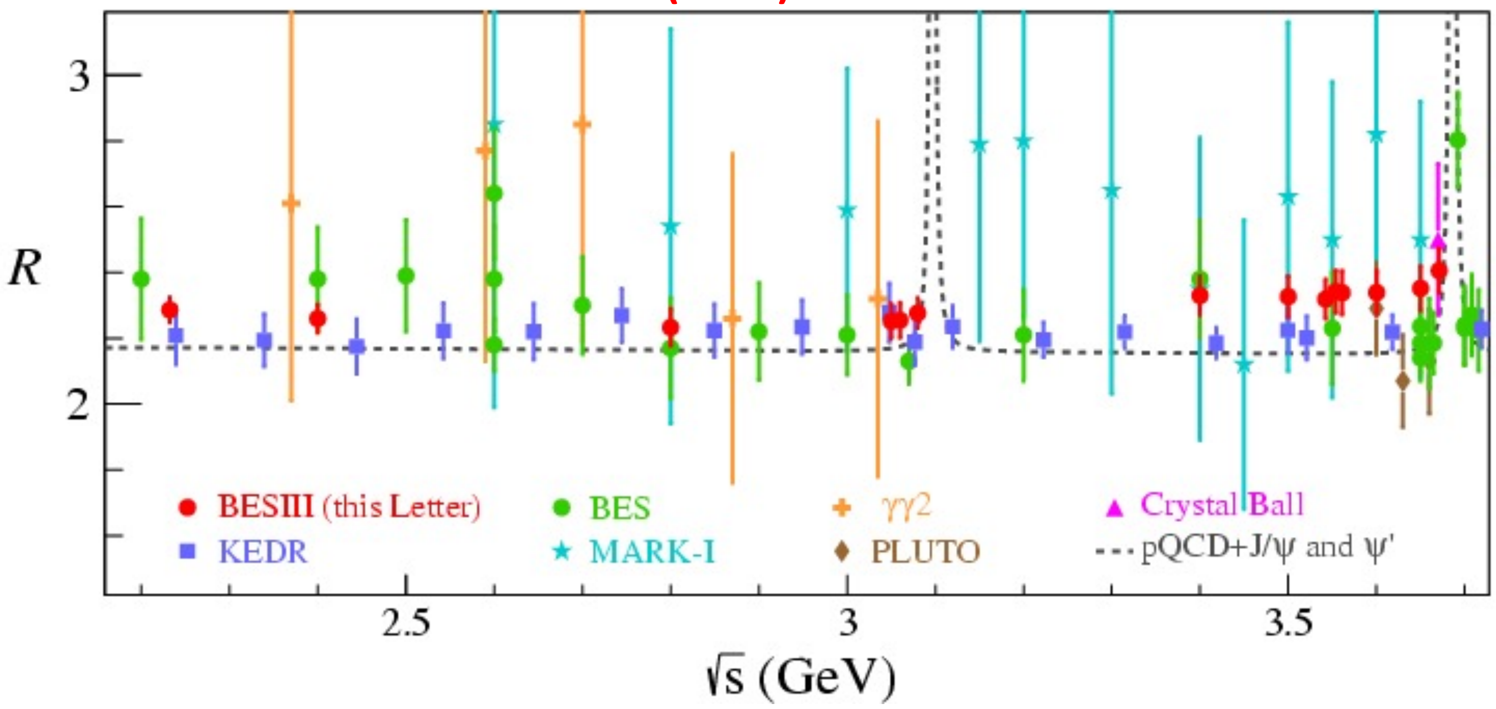
$$\frac{g_\tau}{g_\mu} = 1.0016 \pm 0.0042$$

Lepton universality !

R value measurement at BESIII

- R values :2.23-3.67 GeV
- Precision is better than 3%
- Constraints on (g-2)μ

PRL128(2022)062004



R scan above open-charm threshold
3.85-4.59 GeV 104 pts ~0.8 $\mathbf{fb}^{-1}$

- Full energy region in progress
- Exclusive hadron cross section
- Form factors of baryons and light mesons

Flavor physics at BESIII

- **Charm physics**
- **Hyperon physics**

Table 2 K^0_S and Λ statistics in the $Z\to q\bar{q}$ simulation sample (number of particles per event)

Particle	K^0_S	Λ
Total	1.022	0.1710
Flavor dependence		
$Z\to d\bar{d}$	0.802	0.1577
$Z\to u\bar{u}$	0.767	0.1563
$Z\to s\bar{s}$	1.172	0.2273
$Z\to c\bar{c}$	1.138	0.1705
$Z\to b\bar{b}$	1.200	0.1401
BR($K^0_S \to \pi^+\pi^-$)/BR($\Lambda\to p\pi^-$)	67.84%	61.8%

Ks, Λ production at CEPC
EPJ Plus 135 (2020) 3, 274

CEPC White paper on flavor physics, Chinese Phys. C 49 103003

Particle	BESIII	Belle II (50 ab^{-1} on $\Upsilon(4S)$)	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
D^0, $\bar{D}^0$	1.2×10^8	4.8×10^{10}	1.4×10^{15}	8.3×10^{11}
$D^\pm$	1.2×10^8	4.8×10^{10}	6×10^{14}	4.9×10^{11}
$D_s^\pm$	1×10^7	1.6×10^{10}	2×10^{14}	1.8×10^{11}
$\Lambda_c^\pm$	0.3×10^7	1.6×10^{10}	2×10^{14}	6.2×10^{10}
$\tau^+\tau^-$	3.6×10^8	4.5×10^{10}		1.2×10^{11}

CKM Matrix

- CKM matrix elements are fundamental parameters of the Standard Model (SM):

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Charm decays + LQCD
Expected precision < 1% at BESIII

B decays + LQCD

- 3x3 unitary complex matrix
- 4 parameters: 3 mixing angles and 1 phase
- Unitarity: $\sum_i V_{ij}V^*_{ik} = \delta_{jk}$ and $\sum_j V_{ij}V^*_{kj} = \delta_{ik}$

- Any deviation of V_{CKM} from unitarity indicates new physics

→ Measurements of CKM matrix elements [from PDG2024]

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9984 \pm 0.0009$ =1(SM)

$|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2 = 1.001 \pm 0.007$ =1(SM)

Precision: 0.7%

$|V_{cd}| = 0.221 \pm 0.004$

$|V_{cs}| = 0.975 \pm 0.006$

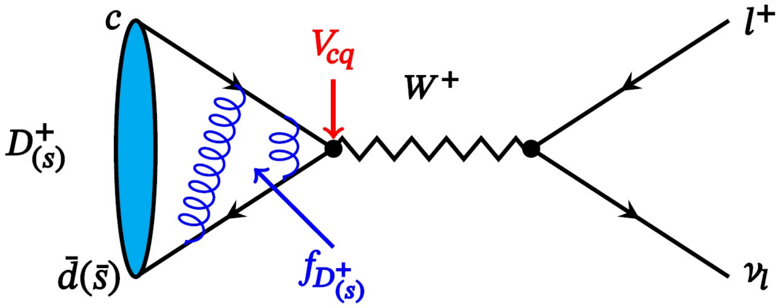
$|V_{cb}| = 0.0410 \pm 0.0012$

Precision: (0.6-1.8)%

- $\boldsymbol{D/D_s}$ (Semi-)leptonic decays provide direct measurements of $|V_{cs}|$ and $|V_{cd}|$

Charm leptonic decays $D^+_{(s)} \to l^+\nu_l$

$l = e, \mu, \tau$



Decay constant $f_{D_{(s)}}$ (LQCD)

Decay rate

CKM matrix element

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

- Charm leptonic decays involve weak and strong interactions

  Weak interaction: annihilation of the quark-antiquark pair via W^+ → $|V_{cd(s)}|$

  Strong interaction: glue exchanges between charm quark and light quark → $f_{D_{(s)}}$

- Exp. decay rate + $|V_{cd(s)}|^{\text{CKMfitter}}$ → $f_{D_{(s)}}$

  Calibrate LQCD @charm

  Extrapolate to Beauty

- Exp. decay rate + $\boxed{f_{D_{(s)}} \text{ of LQCD}}$

  → CKM matrix elements $|V_{cd(s)}|$

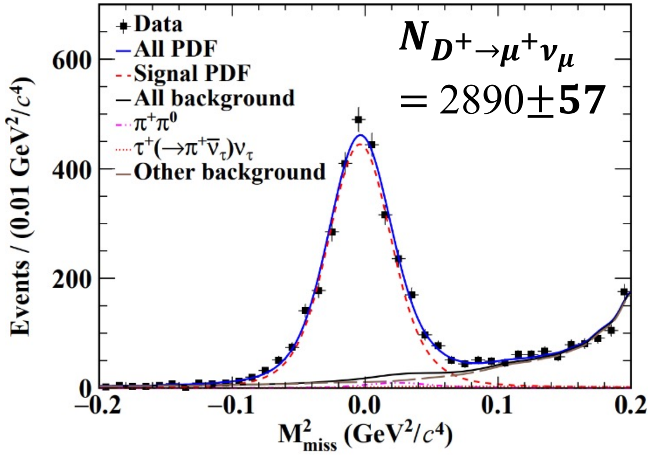
High precision: 0.2% - 0.33%
FLAG, PRD 107, 052008 (2023)

SM expected relative decay widths:

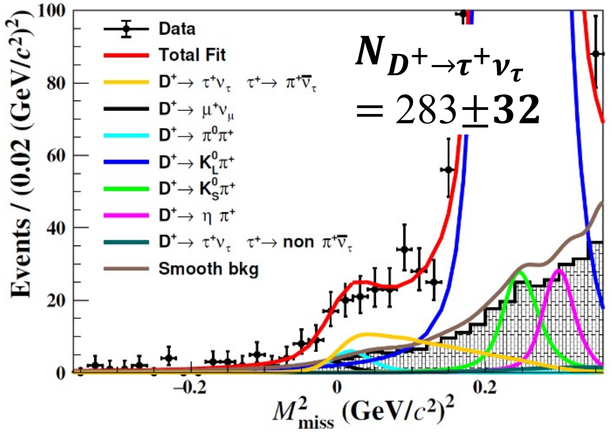
	$e^+\nu_e$	: $\mu^+\nu_\mu$	: $\tau^+\nu_\tau$
D^+	2.35×10^{-5}	: 1	: 2.67
D_s^+	2.35×10^{-5}	: 1	: 9.75

→ Test lepton flavor universality (LFU)

$|V_{cd}|$ from $D^+ \to \mu^+\nu_\mu$ and $D^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$



20.3 fb^{-1}@ 3.773 GeV
arXiv:2410:07626



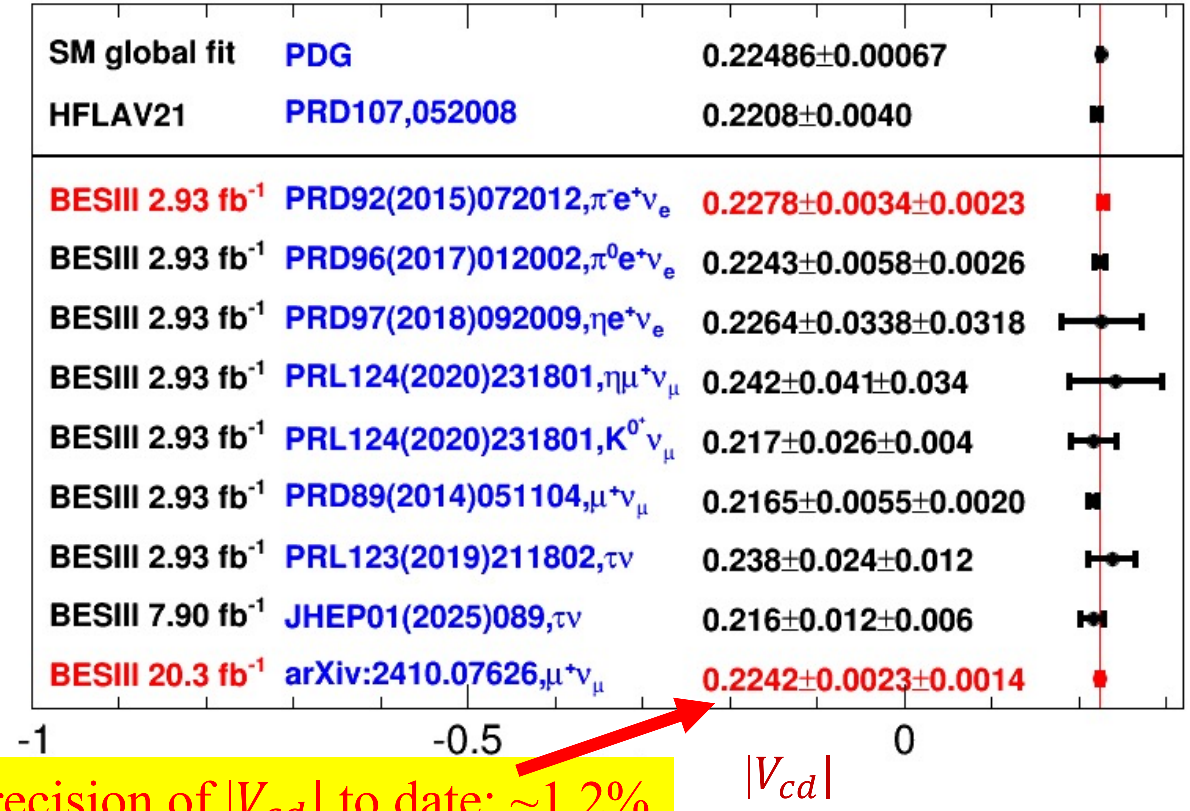
7.9 fb^{-1}@ 3.773 GeV
JHEP01(2025)089

$$\mathcal{B}_{D^+\to\mu^+\nu_\mu} = (3.98 \pm 0.08_{\rm stat.} \pm 0.04_{\rm syst.}) \times 10^{-4}$$

$$f_{D^+}|V_{cd}| = (47.53 \pm 0.48_{\rm stat} \pm 0.24_{\rm syst} \pm 0.12_{\rm input})\ \text{MeV}$$

$$f_{D^+} = (211.5 \pm 2.1_{\rm stat} \pm 1.1_{\rm syst} \pm 0.8_{\rm input})\ \text{MeV}$$

$$|V_{cd}| = 0.2242 \pm 0.0023_{\rm stat} \pm 0.0011_{\rm syst} \pm 0.0009_{\rm input}$$



$$\mathcal{B}_{D^+\to\tau^+\nu_\tau} = (9.9 \pm 1.1_{\rm stat.} \pm 0.5_{\rm syst.}) \times 10^{-4}$$

$$f_{D^+}|V_{cd}| = (45.9 \pm 2.5_{\rm stat} \pm 1.2_{\rm syst} \pm 0.1_{\rm input})\ \text{MeV}$$

$$|V_{cd}| = (0.216\pm0.012_{\rm stat}\pm0.006_{\rm syst}\pm0.001_{\rm input})$$

LFU test: $\mathcal{R}_{\tau/\mu} = \dfrac{\mathcal{B}_{D^+\to\tau^+\nu_\tau}}{\mathcal{B}_{D^+\to\mu^+\nu_\mu}} = 2.49 \pm 0.31$

SM=2.67

Highest precision of $|V_{cd}|$ to date: ~1.2%

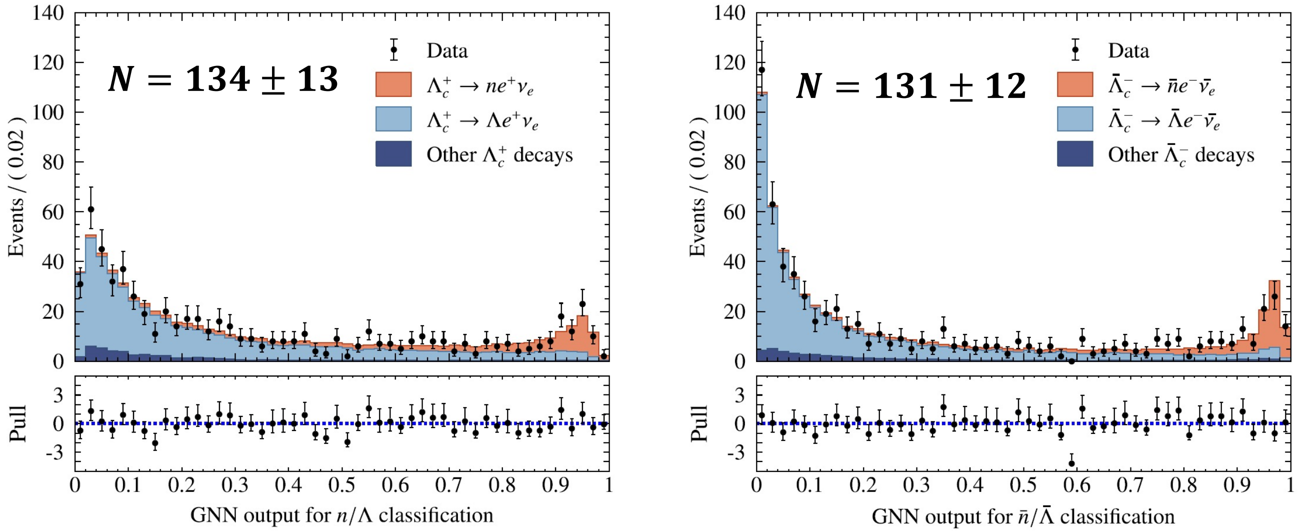
$|V_{cd}|$ from $\Lambda_c^+ \to n e^+ \nu_e$

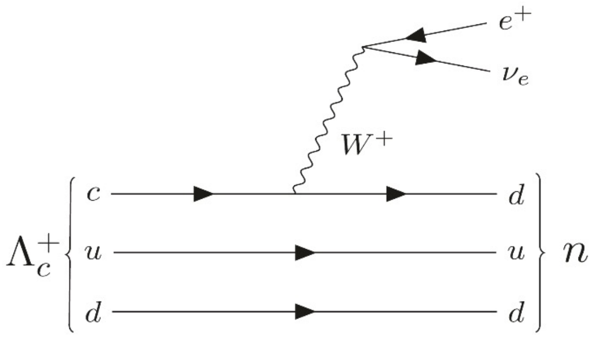
Nat Commun **16**, 681 (2025)

$4.5\ \text{fb}^{-1} @ E_{\text{cm}} = 4.60 - 4.699\text{GeV}$

Observation of a rare beta decay $\Lambda_c^+ \to n e^+ \nu_e$ with machine learning of Graph Neural Network

Machine learning → discriminate energy deposition patterns of neutrons from those of Λ in the EMC of BESIII detector





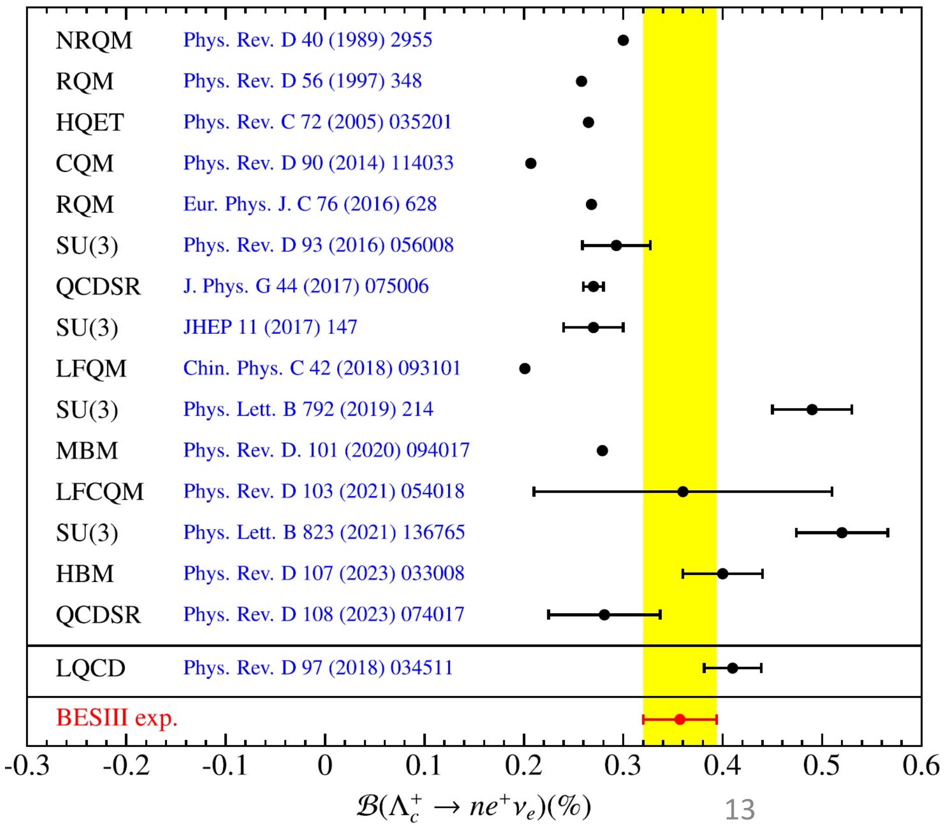
→ $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = \left(0.357 \pm 0.034_{\text{stat.}} \pm 0.014_{\text{syst.}}\right)\%$

Using $\Gamma(\Lambda_c^+ \to n e^+ \nu_e) = |V_{cd}|^2 (0.405 \pm 0.016 \pm 0.020)\ \text{ps}^{-1}$

[PRD97,034511(2018)]

→ $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.007_{\text{LQCD}} \pm 0.001_{\tau_{\Lambda_c^+}}$

First determination from charmed baryon decays

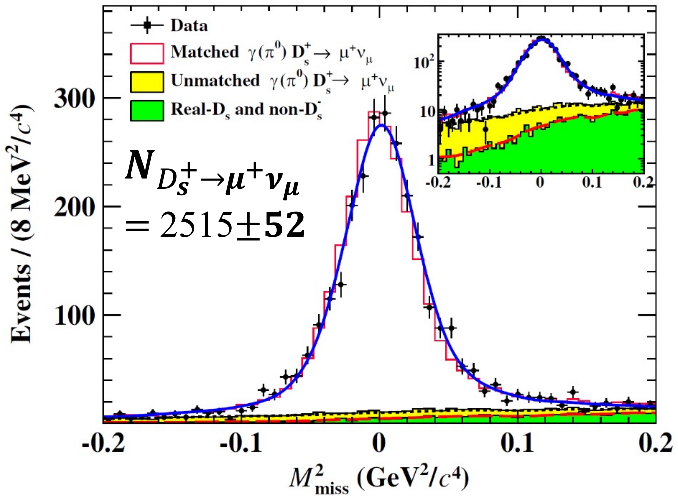


$|V_{cs}|$ from $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$

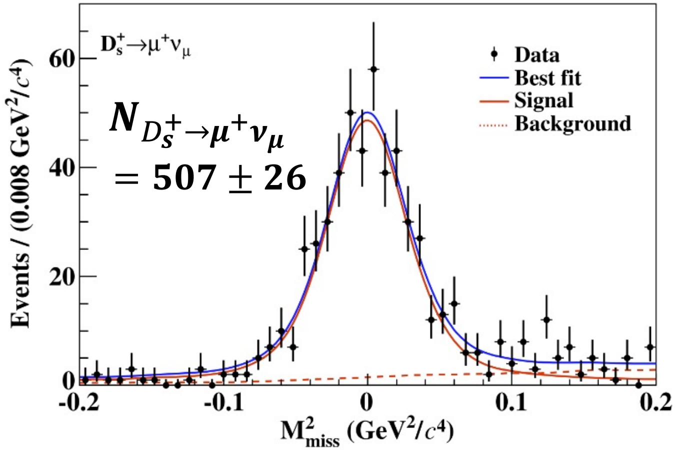
7.33 fb^{-1}@ 4.128-4.226 GeV
PRD 108, 112001 (2023)

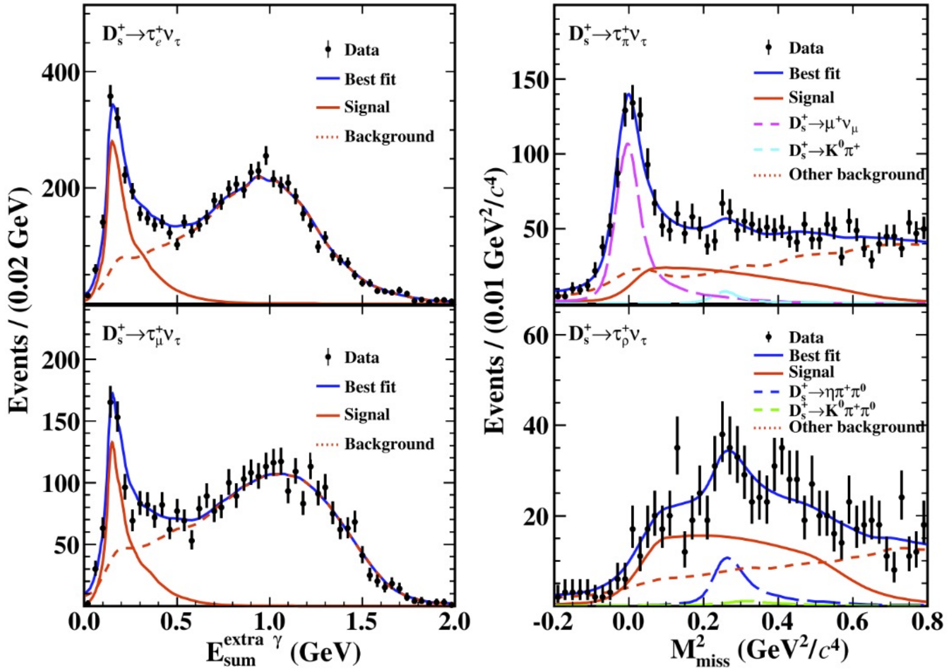
10.64 fb^{-1}@ 4.237-4.699 GeV， PRD 110, 052002 (2024)

via $e^+e^- \to D_s^{*\pm}D_s^{\mp}$



via $e^+e^- \to D_s^{*+}D_s^{*-}$





$N_{D^+\to\tau^+\nu_\tau} = 2845 \pm 83$

$$\mathcal{B}_{D_s^+\to\mu^+\nu_\mu} = (0.5294 \pm 0.0108_{\rm stat} \pm 0.0085_{\rm syst})\%$$

$$f_{D_s^+}|V_{cs}| = 241.8 \pm 2.5_{\rm stat} \pm 2.2_{\rm syst}\ \text{MeV}$$

$$f_{D_s^+} = 248.4 \pm 2.5_{\rm stat} \pm 2.2_{\rm syst}\ \text{MeV}$$

$$|V_{cs}| = 0.968 \pm 0.010_{\rm stat} \pm 0.009_{\rm syst}$$

Precision : ~1.4%

$$\mathcal{B}_{D_s^+\to\mu^+\nu_\mu} = (0.547 \pm 0.026_{\rm stat} \pm 0.016_{\rm syst})\%$$

$$f_{D_s^+} = (253.2 \pm 6.0_{\rm stat} \pm 3.7_{\rm syst} \pm 0.6_{\rm input})$$

$$|V_{cs}| = (0.986 \pm 0.023_{\rm stat} \pm 0.014_{\rm syst} \pm 0.003_{\rm input})$$

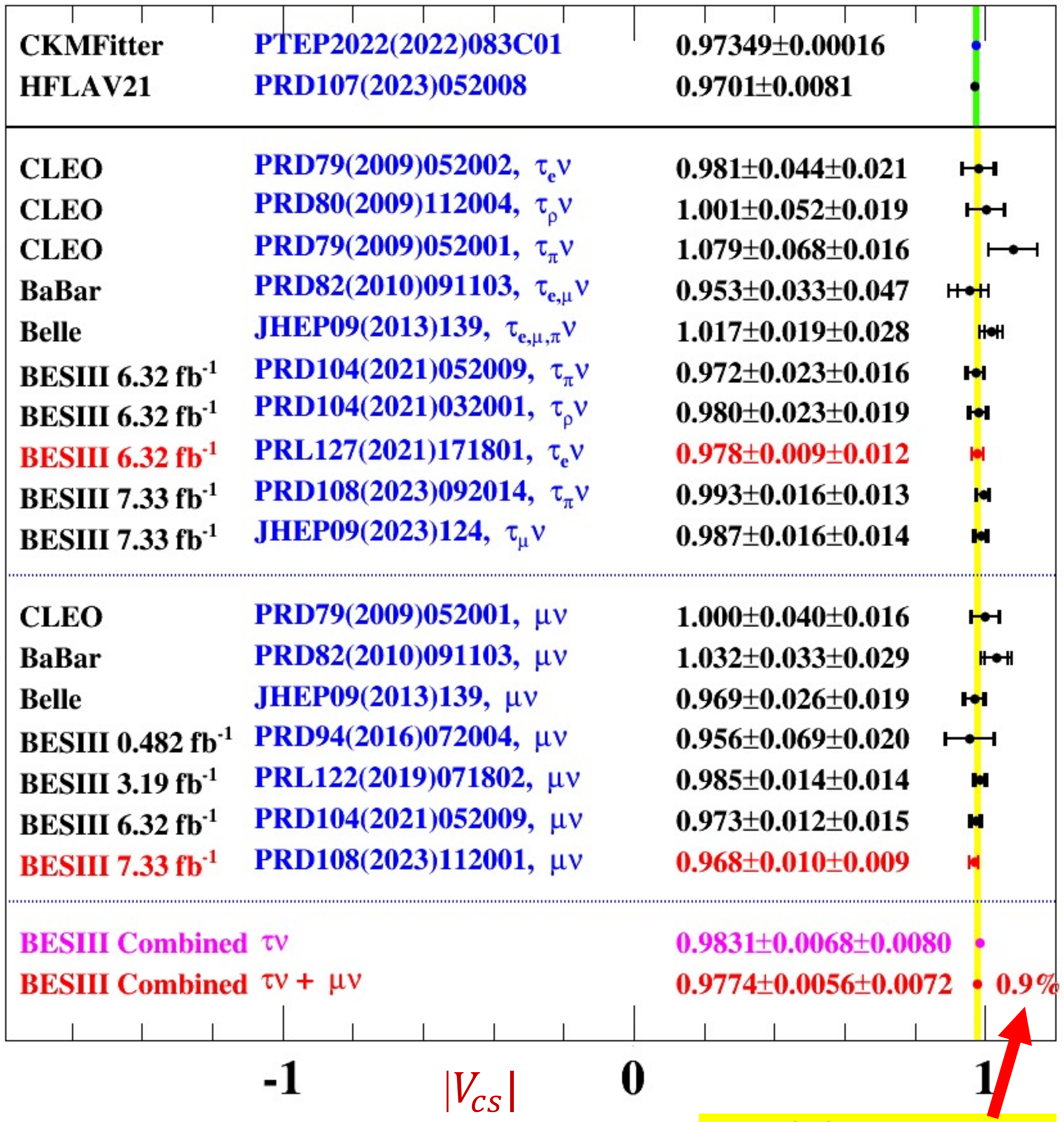
$$\mathcal{B}_{D_s^+\to\tau^+\nu_\tau} = (5.60 \pm 0.16_{\rm stat} \pm 0.20_{\rm syst})\%$$

$$f_{D_s^+} = (259.6 \pm 3.7_{\rm stat} \pm 4.6_{\rm syst} \pm 0.6_{\rm input})$$

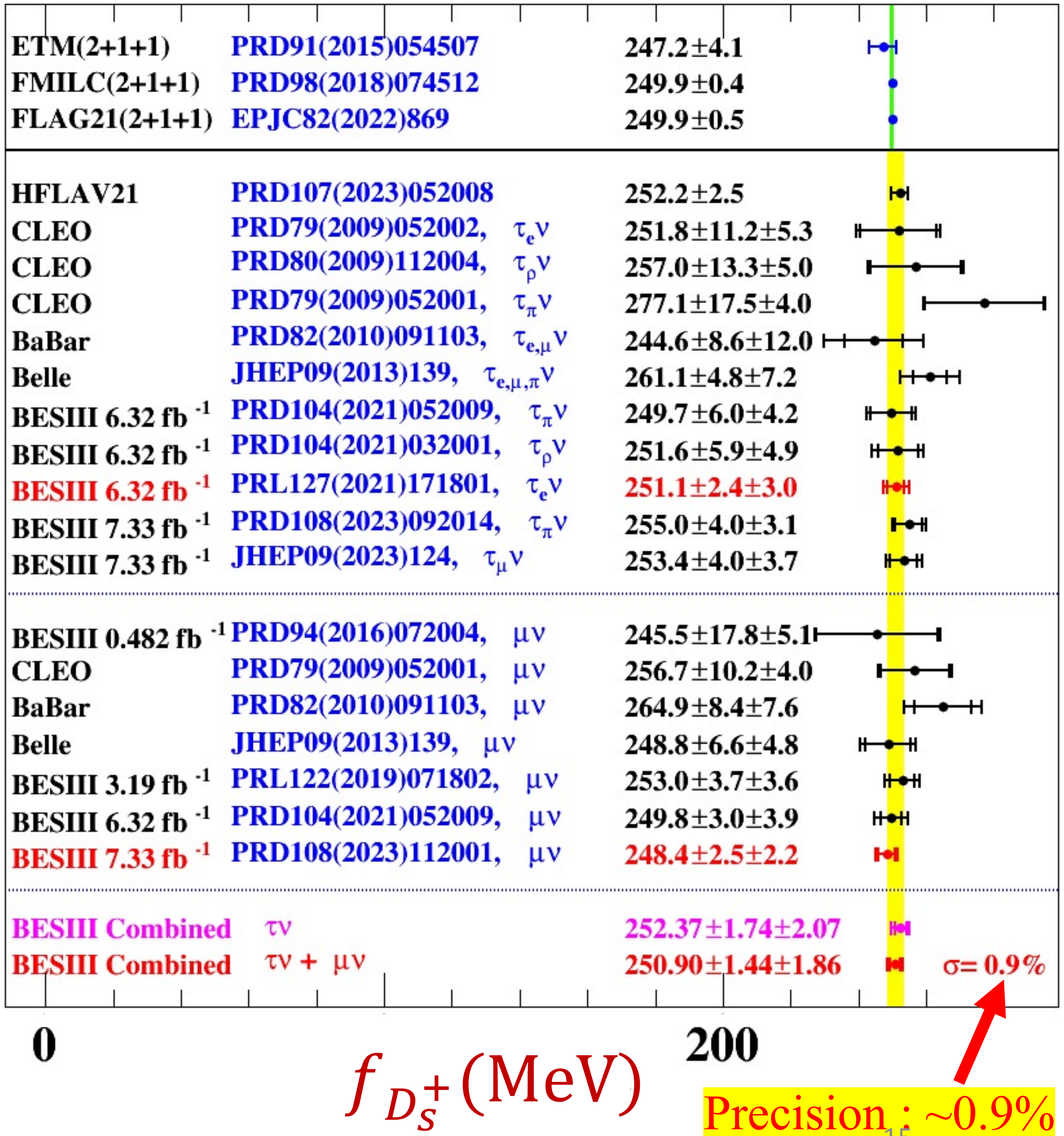
$$|V_{cs}| = (1.011 \pm 0.014_{\rm stat} \pm 0.018_{\rm syst} \pm 0.003_{\rm input})$$

LFU test: $\dfrac{\Gamma_{D_s^+\to\tau^+\nu_\tau}}{\Gamma_{D_s^+\to\mu^+\nu_\mu}} = 10.24 \pm 0.57$ SM=9.75

$|V_{cs}|$ and $f_{D_s^+}$ from $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$

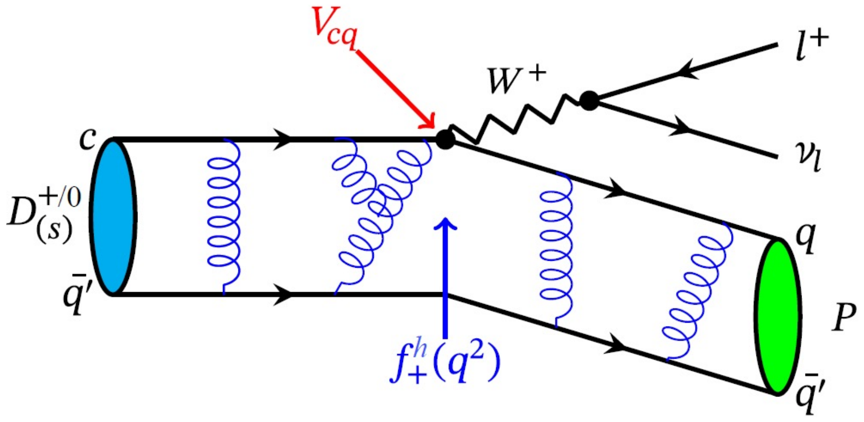


Precision : ~0.9%



Precision : ~0.9%

Charm semi-leptonic decays $D_{(s)}^{+} \to \pi(K) l^{+} \nu_l$



Partial decay rate

Form factor (LQCD)

CKM matrix element

$$\boxed{\frac{d\Gamma}{dq^2}} = X \frac{G_F^2}{24\pi^3} \boxed{|f_+^h(0)|}^2 \boxed{|V_{cq}|}^2 |\vec{p}_h|^3$$

(X = 1 for K^-, π^-, $\bar{K}^0$, $\eta^{(\prime)}$; $X = \frac{1}{2}$ for π^0)

- The weak and strong interactions can be separated:

  Weak interaction: CKM matrix elements $|V_{cd(s)}|$

  Form factors $f_+^h(0)$ describe strong interaction can be calculated in LQCD

- Exp. partial decay rate → q^2 dependence of $f_+^{\pi(K)}(q^2)$,

  → extract $f_+^{\pi(K)}(0)$ with $|V_{cd(s)}|^{\text{CKMfitter}}$ as input → calibrate QCD

- Exp. partial decay rate + $\boxed{\text{LQCD calculation of } f_+^{\pi(K)}(0)}$

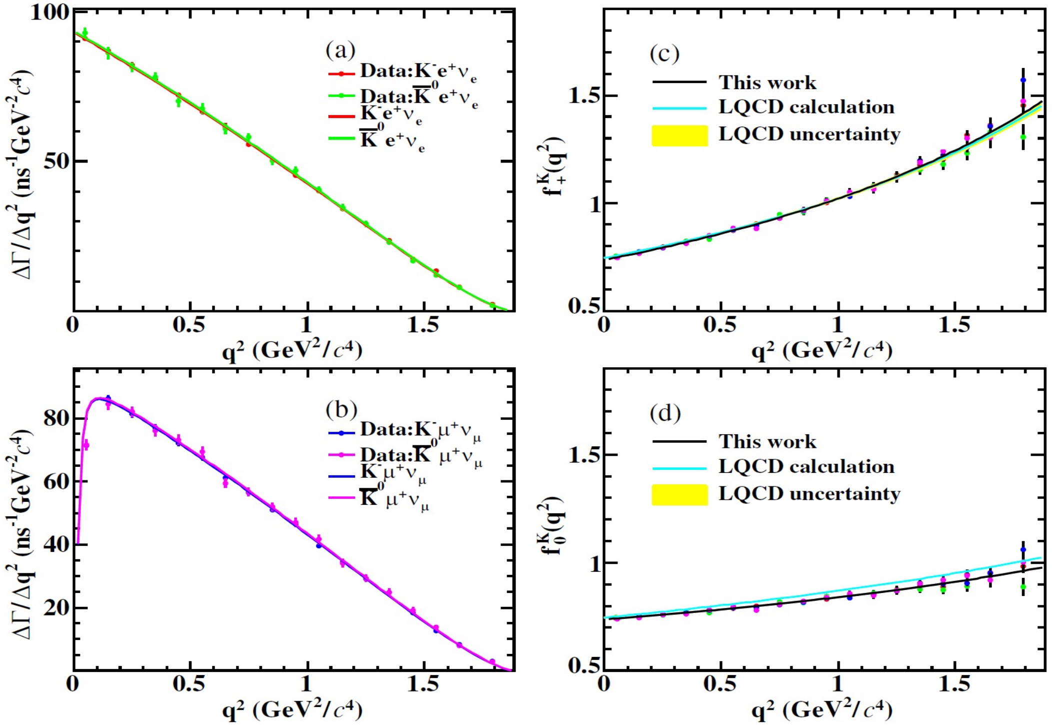
  → CKM matrix elements $|V_{cd(s)}|$

Low precision: >1.5%
FLAG, PRD 107, 052008 (2023)

$|V_{cs}|$, $f_+^K(0)$ from $D^0 \to K^- l^+ \nu_l$ and $D^+ \to \bar{K}^0 l^+ \nu_l$

Branching fractions:

Signal decay	N_{DT}	$\mathcal{B}_{sig}(\%)$
$D^0 \to K^- e^+ \nu_e$	190605 ± 471	$3.521 \pm 0.009 \pm 0.016$
$D^0 \to K^- \mu^+ \nu_\mu$	147596 ± 488	$3.419 \pm 0.011 \pm 0.016$
$D^+ \to \bar{K}^0 e^+ \nu_e$	57846 ± 256	$8.864 \pm 0.039 \pm 0.082$
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	47229 ± 248	$8.665 \pm 0.046 \pm 0.084$



Simultaneous fit to the partial decay rates

Extract $|V_{cs}|$

7.93 fb^{-1}@ 3.773 GeV, PRD 110, 112006 (2024)

$$|V_{cs}| = 0.9623 \pm 0.0015_{\rm stat} \pm 0.0017_{\rm syst} \pm 0.0040_{\rm LQCD}$$

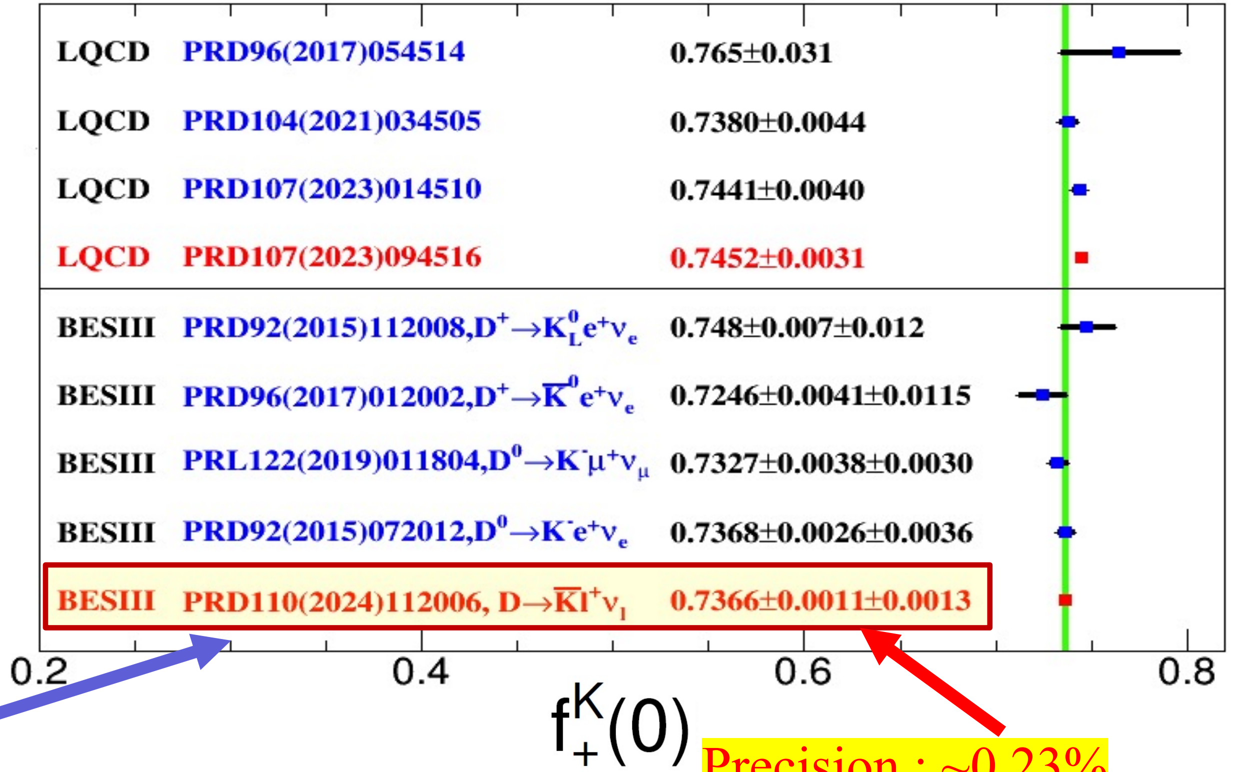
Precision: 0.4%

Test LFU:

$$\frac{\mathcal{B}_{D^+\to\bar{K}^0\mu^+\nu_\mu}}{\mathcal{B}_{D^+\to\bar{K}^0 e^+\nu_e}} = 0.978 \pm 0.007_{\rm stat} \pm 0.013_{\rm syst}$$

$$\frac{\mathcal{B}_{D^0\to K^-\mu^+\nu_\mu}}{\mathcal{B}_{D^0\to K^- e^+\nu_e}} = 0.971 \pm 0.004_{\rm stat} \pm 0.006_{\rm syst}$$

SM=9.75



Precision : ~0.23%

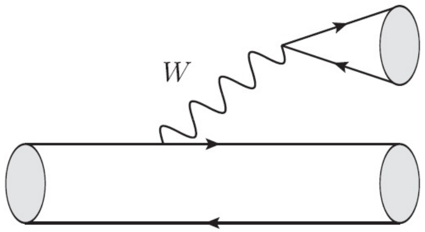
Charmed mesons hadronic decays

- Measurements of the BFs
  - → Probe and calibrate non-perturbative QCD
  - → Understand SU(3) flavor symmetry and its breaking effect
  - → Test theoretical calculations of BFs
- Amplitude analysis of multi-body decays
  - → Information of $D \to VP, PP, SP, SV, VV, AP, AV, TP$ ...
  - → Light hadron spectroscopy

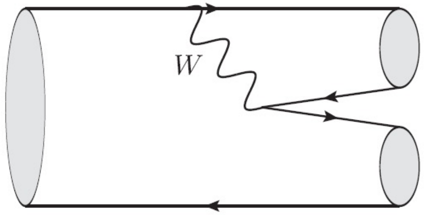
P: pseudo-scalar
V: vector
S: scalar
A: axial-vector
T: tensor

Topological Diagrammatic for D/D_s^+ decays:

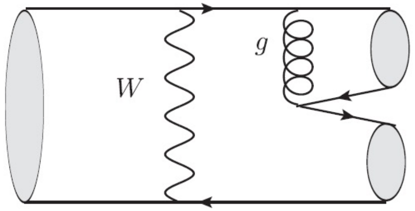
H.-Y. Cheng, *et al.* PRD 85, 034036



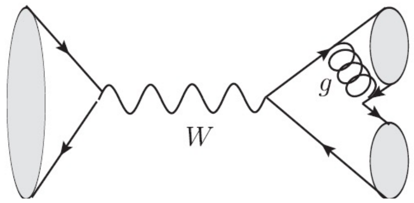
Color-allowed tree T



Color-suppressed tree C



W-exchange E



W-annihilation A

Calculation is not reliable, need exp. input

Amplitude analysis of $D_s^+ \to K_S^0 K_L^0 \pi^+$

7.33fb^{-1} @ $4.178 - 4.226$GeV, arXiv:2503.11383

2310 candidates with >78% purity

Measurement of $\phi \to K_S^0 K_L^0$

$$\mathcal{B}_{D_s^+ \to K_S^0 K_L^0 \pi^+} = (1.86 \pm 0.06_{\text{stat}} \pm 0.003_{\text{syst}})\%$$

Amplitude	Phase (rad)	BF (%)
$D_s^+ \to \phi\pi^+$	0.0(fixed)	$1.32 \pm 0.05 \pm 0.04$
$D_s^+ \to K_L^0 K^*(892)^+$	$0.68 \pm 0.17 \pm 0.21$	$0.42 \pm 0.03 \pm 0.03$
$D_s^+ \to K_S^0 K^*(892)^+$	$-2.40 \pm 0.18 \pm 0.31$	$0.31 \pm 0.02 \pm 0.02$

$$\frac{\mathcal{B}(\phi(1020) \to K_S^0 K_L^0)}{\mathcal{B}(\phi(1020) \to K^+ K^-)} = 0.597 \pm 0.023_{\text{stat}} \pm 0.018_{\text{syst}} \pm 0.016_{\text{PDG}}$$

Taking from PDG

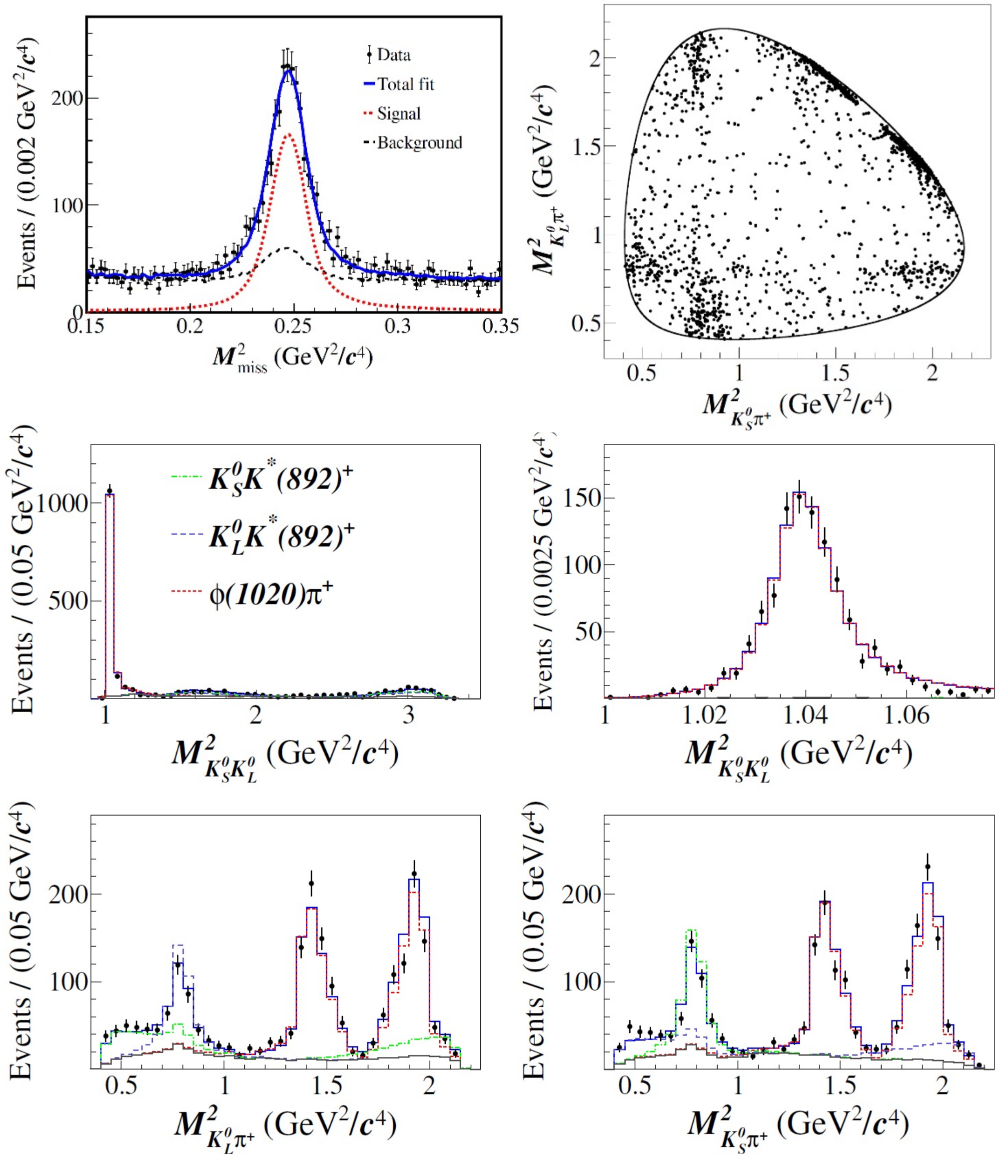
Deviates from PDG value (0.740 ± 0.031) by $>3\sigma$

First observation of $K_S^0 - K_L^0$ asymmetry

$$\frac{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) - \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)}{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) + \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)} = (-13.4 \pm 5.0_{\text{stat}} \pm 3.4_{\text{syst}})\%$$

Model	DAT(F4)	DAT(F1′)
$D_s^+ \to \bar{K}^0 K^{*+}$	-0.164 ± 0.032	-0.159 ± 0.028

Predictions by H.-Y. Cheng *et al.*, PRD109, 073008（2024）

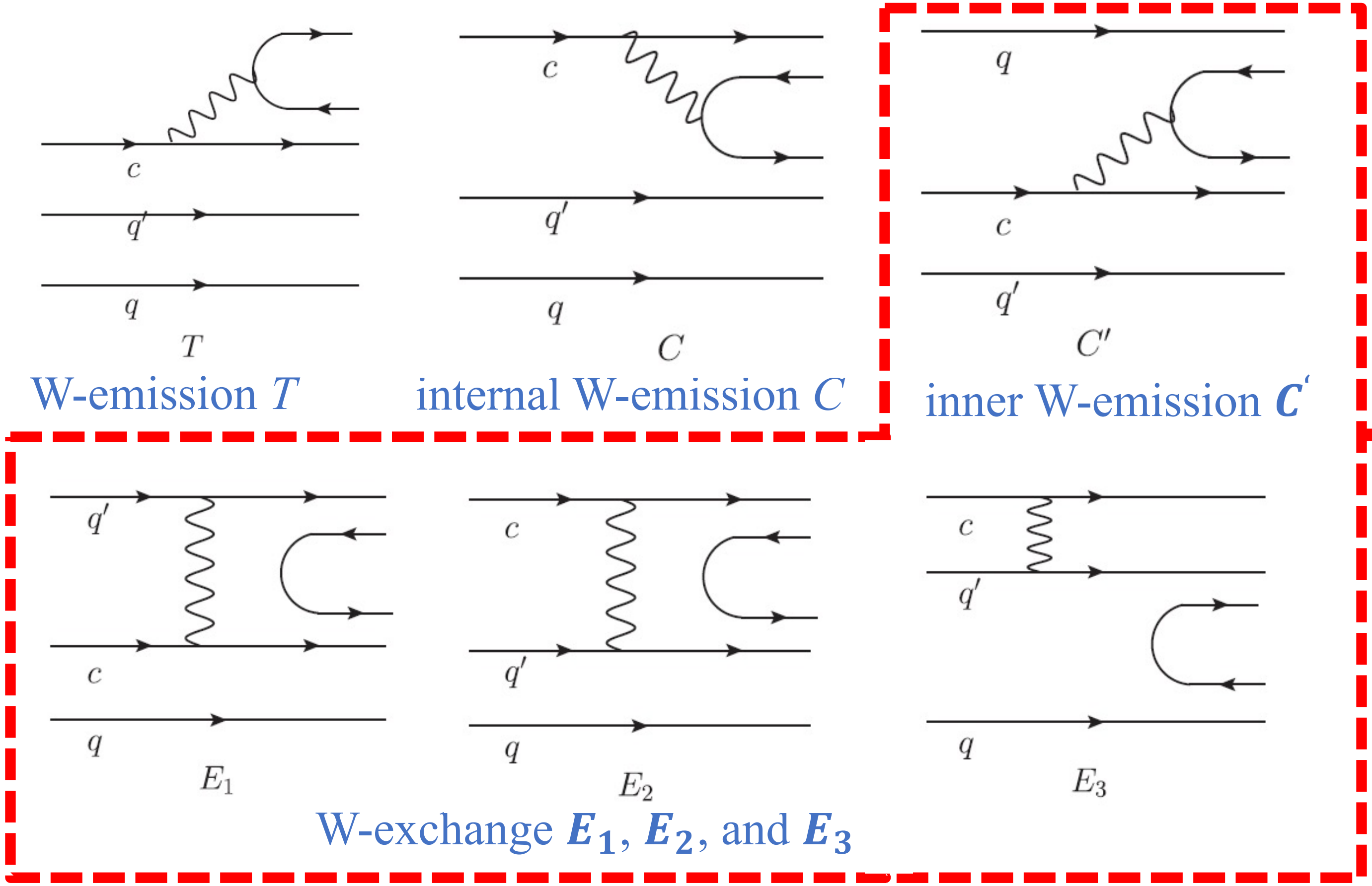


Charmed baryonic decays

- Λ_c^+ may reveal more information of strong- and weak-interactions in charm region, complementary to D/D_s

  → Most charmed baryons eventually decay to Λ_c^+

Topological Diagrams for $\boldsymbol{\Lambda_c^+}$ decays:



H.-Y. Cheng *et al.*, *Chinese Journal of Physics*, 78(2022) 324-362

Non-factorization amplitude → Calculation is not reliable, need exp. input

Recent studies on the Λ_c^+ measurments at BESIII

- Λ_c^+ leptonic decays
  - ☐ $\Lambda_c^+ \to \Lambda e^+\nu_e, \Lambda\mu^+\nu_\mu$: PRL 129.231803 (2022). PRD 108.L031105 (2023).
  - ☐ $\Lambda_c^+ \to pK^-e^+\nu_e$: PRD 106.112010 (2022).
  - ☐ $\Lambda_c^+ \to Xe^+\nu_e$: PRD 107.052005 (2023).
  - ☐ $\Lambda_c^+ \to ne^+\nu_e$: Nature Commun. 16, 681 (2025).

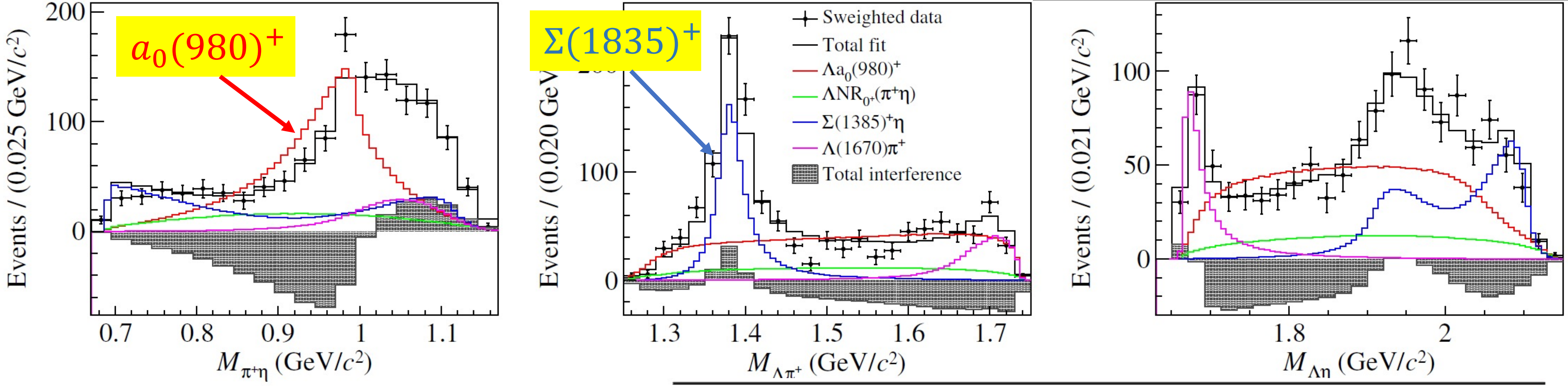
- Λ_c^+ hadronic decays(two body)
  - ☐ $\Lambda_c^+ \to n\pi^+$: PRL 128.142001 (2022).
  - ☐ $\Lambda_c^+ \to p\eta'$: PRD 106.072002 (2022).
  - ☐ $\Lambda_c^+ \to p\eta, p\omega$: JHEP 11.137 (2023).
  - ☐ $\Lambda_c^+ \to \Xi^0K^+$: PRL 132, 031801(2024).
  - ☐ $\Lambda_c^+ \to \Sigma^+\eta'$: arXiv 2505.18004 (JHEP accepted).
  - ☐ $\Lambda_c^+ \to p\pi^0$: PRD 111, L051101 (2025).
  - ☐ $\Lambda_c^+ \to pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+, \Sigma^+\pi^0$: arXiv 2508.11400.
- Λ_c^+ hadronic decays(multi-body)
  - ☐ $\bar{\Lambda}_c^- \to \bar{n}X$: PRD 108.L031101 (2023).
  - ☐ $\Lambda_c^+ \to K_S^0X$: JHEP 06.194 (2025).
  - ☐ $\Lambda_c^+ \to nK_S^0\pi^+\pi^0$: PRD 109, 053005 (2024).
  - ☐ $\Lambda_c^+ \to \Lambda\pi^+\eta$ ✓ : PRL 134, 021901 (2025).
  - ☐ $\Lambda_c^+ \to \Sigma^0K^+\pi^0, \Sigma^0K^+\pi^+\pi^-$: CPC 49, 073001 (2025).
  - ☐ $\Lambda_c^+ \to \Lambda K_S^0K^+, \Lambda K^*\ \Lambda K_S^0\pi^+$: PRD 111, 012014 (2025).

Observation $a_0(980)^+$ in $\Lambda_c^+ \to \Lambda\pi^+\eta$

$6.1\ \text{fb}^{-1}@E_{\text{cm}} = 4.600 - 4.843\text{GeV}$, PRL 134, 021901(2025)

Observation of $\Lambda_c^+ \to \Lambda a_0(980)^+$

1312 ± 45 signal events with 80% purity



$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\eta) =$
$(1.94 \pm 0.07_{\text{stat}} \pm 0.11_{\text{syst}})\%$

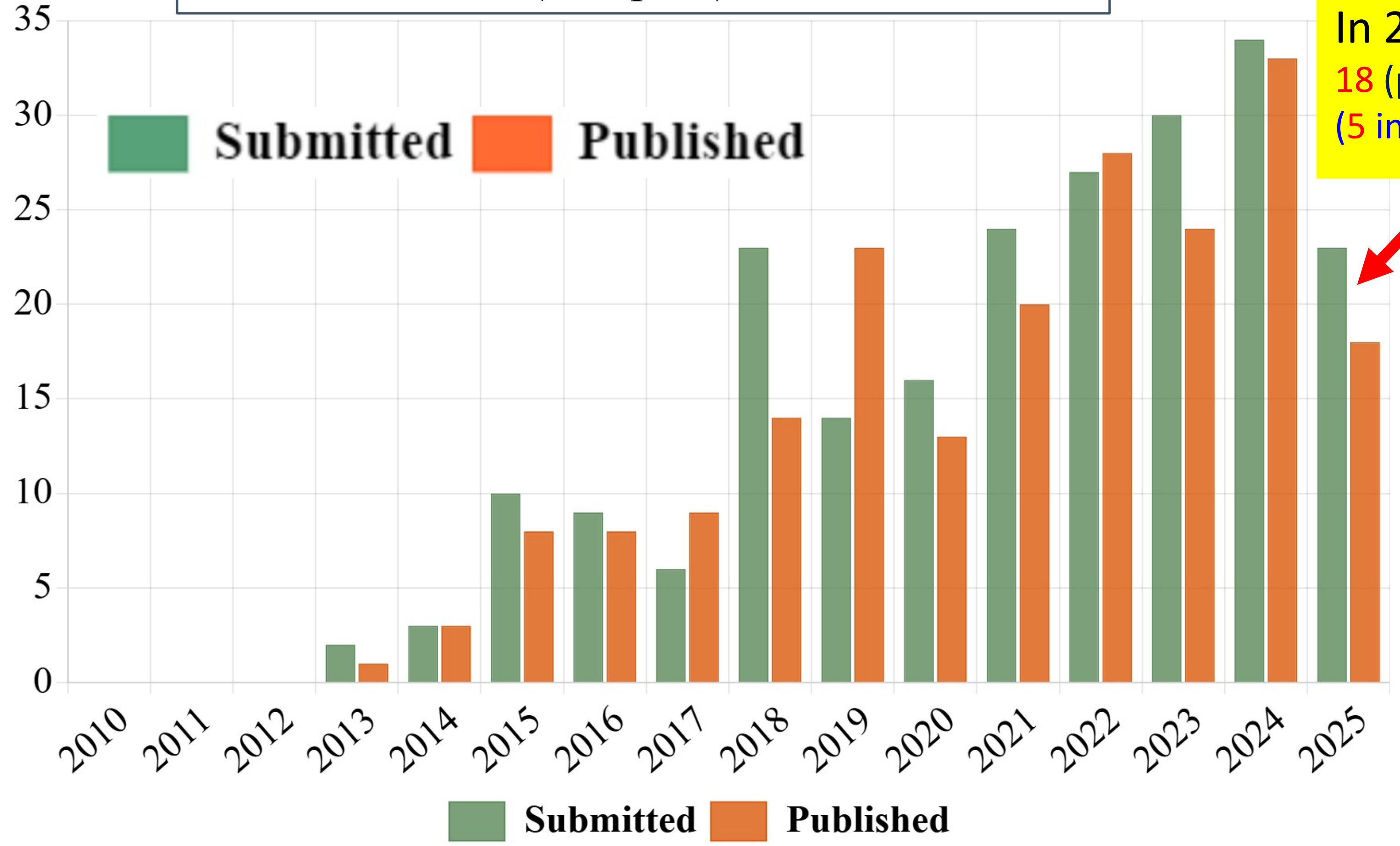
Process	FF (%)	significance	decay asymmetry α
$\Lambda a_0(980)^+$	$54.0 \pm 8.4 \pm 2.6$	13.1σ	$-0.91^{+0.18}_{-0.09} \pm 0.08$
$\Sigma(1385)^+\eta$	$30.4 \pm 2.6 \pm 0.7$	22.5σ	$-0.61 \pm 0.15 \pm 0.04$
$\Lambda(1670)\pi^+$	$14.1 \pm 2.8 \pm 1.2$	11.7σ	$0.21 \pm 0.27 \pm 0.33$
ΛNR_{0^+}	15.4 ± 5.3	6.7σ	$\cdots$

$\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.05 \pm 0.16_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.07_{\text{ext}})\%$

$\to$ $\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+) = (1.23 \pm 0.21)\%$ Larger than theoretical calculations by 1-2 orders.

Charm physics publications

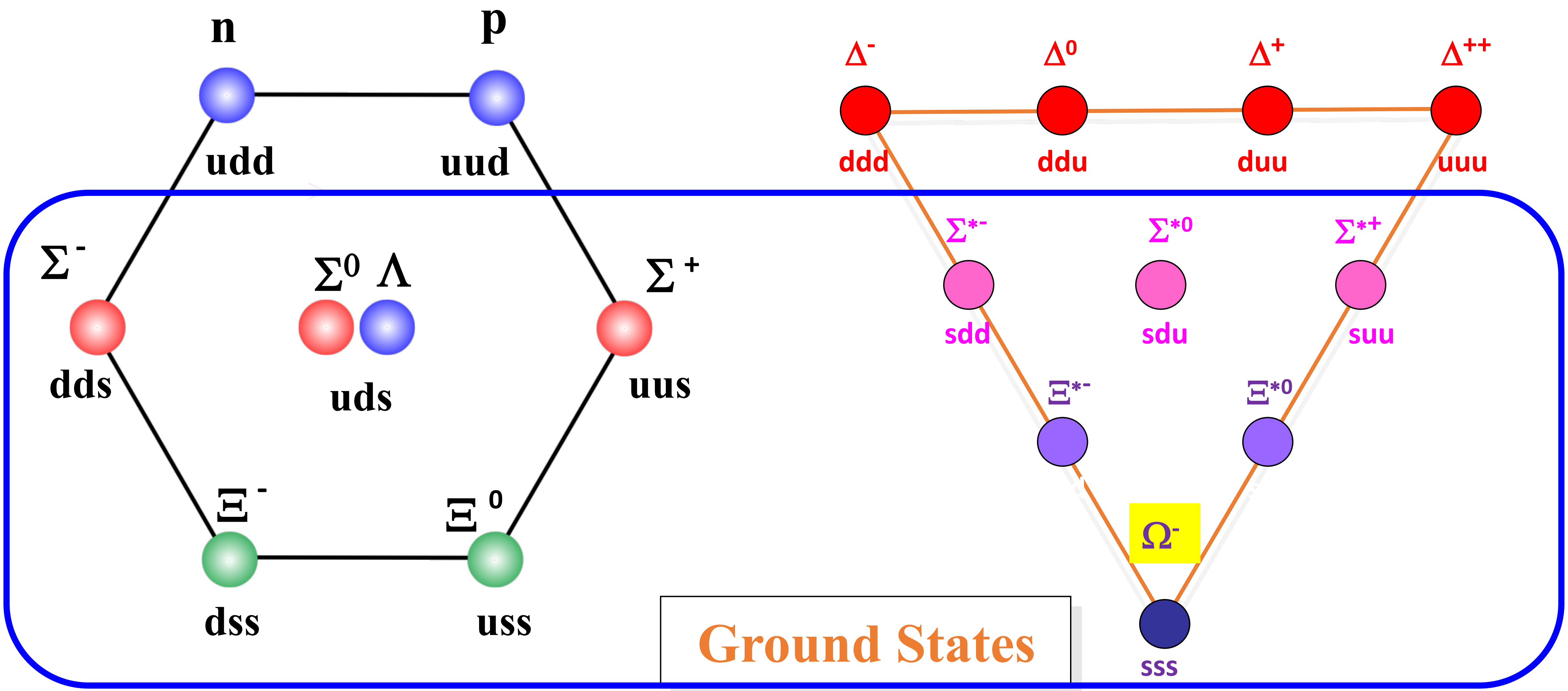
Published: 202 (PRL&Nature Commun. 39)
（by 2025-06-26） + 5 (accepted)



In 2025,
18 (published)+5(accepted)+14 （submitted）
(5 in PRL/Nature Commun.)

In this talk, a selection of latest results in charm physics from BESIII is presented.

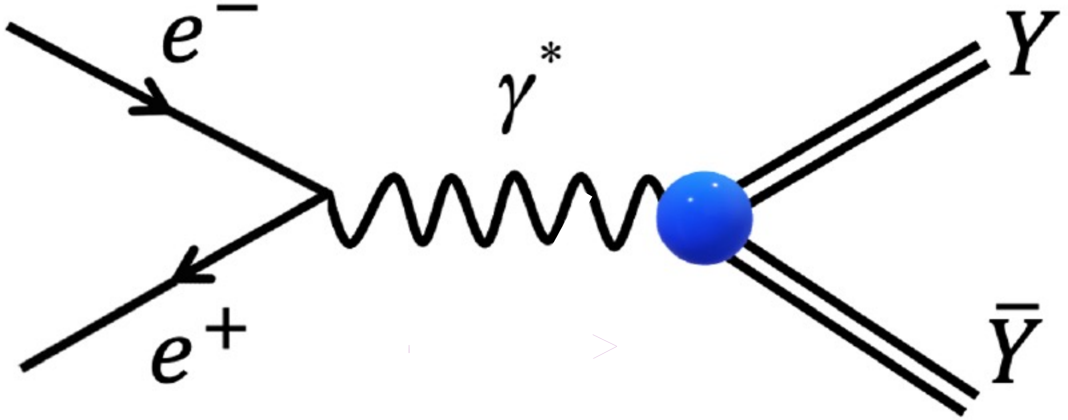
Hyperon: a unique role in particle physics

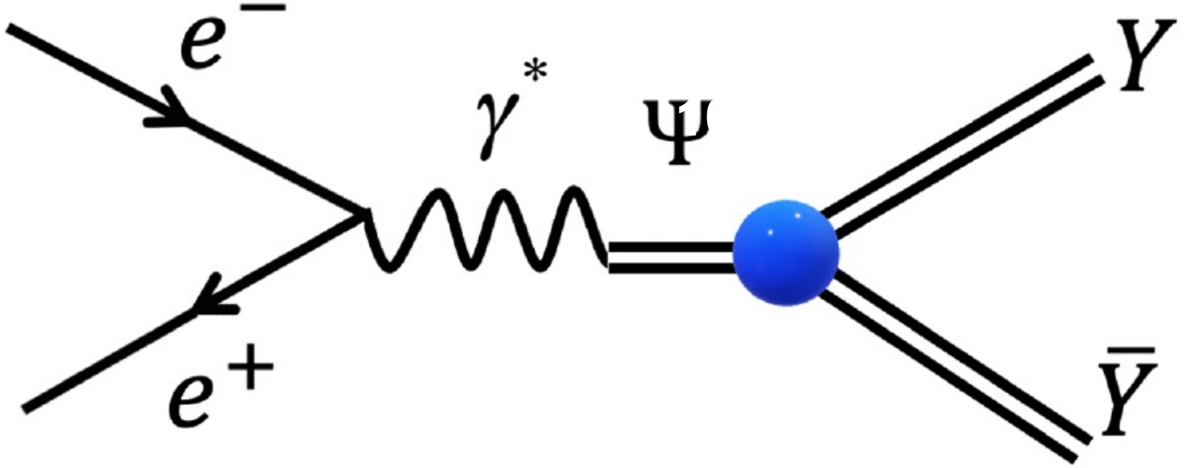


Octet $J^P = 1/2^+$

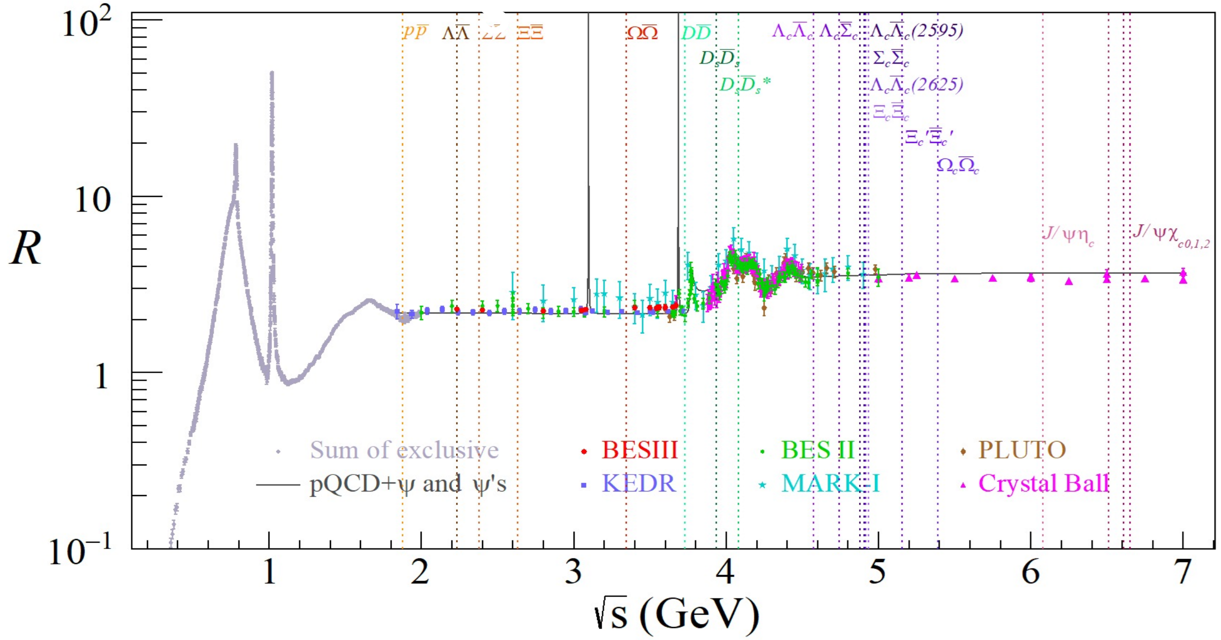
decuplet $J^P = 3/2^+$

Hyperons production at BESIII





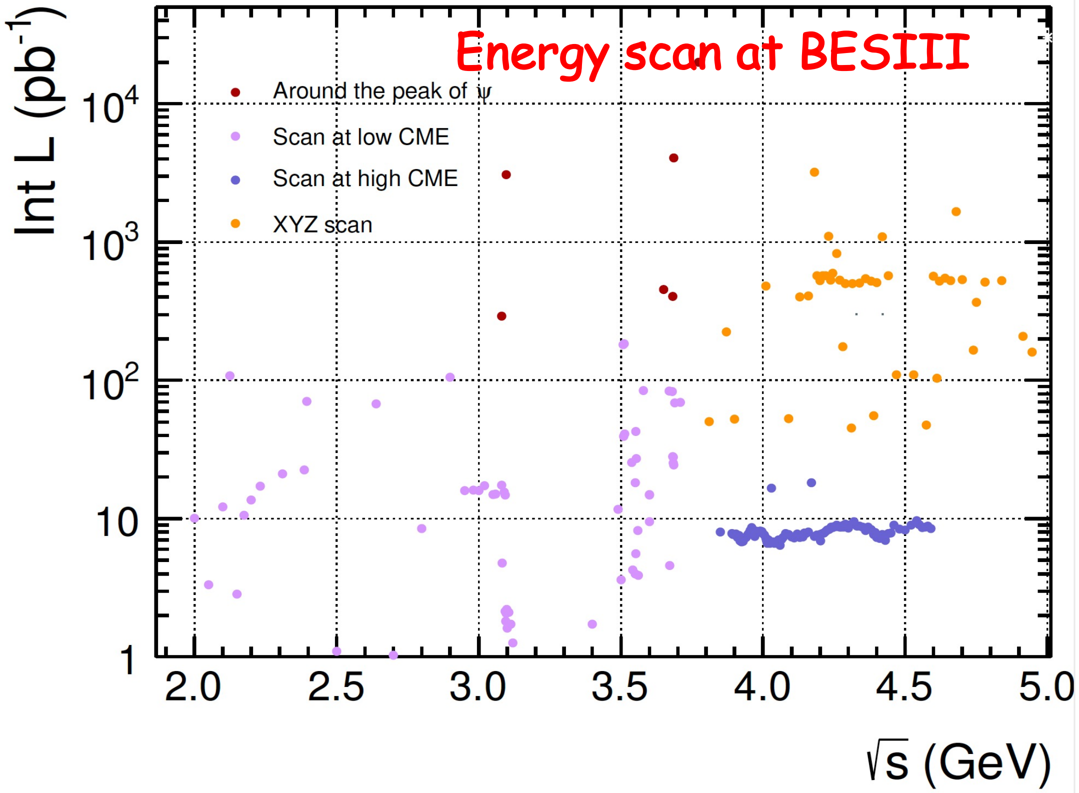
- Hyperon structure

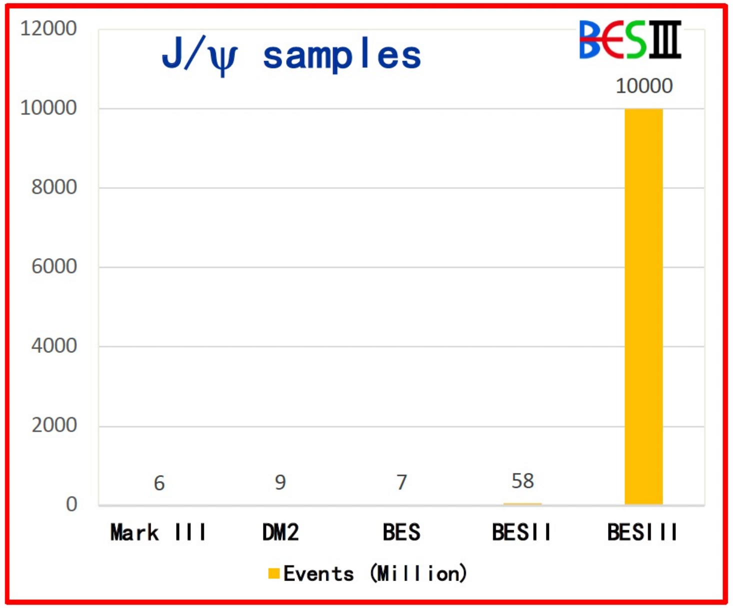


- Symmetries tests
- Hyperon decays
- Hyperon-nucleon interactions
- Hyperon spectroscopy

Advantage: data near to the thresholds

- Meson and Baryon pairs productions near thresholds: form-factors in the time-like production, precision branching fractions, relative phase
- High production in charmonium decays
- CP violation with quantum-entangled pair productions of hyperons





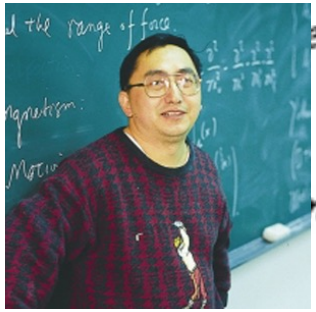
Decay mode	$\mathcal{B}$(units 10^{-4})	Detection efficiency	No. events expected at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	40%	3200×10^3
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	40%	650×10^3
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.65 ± 0.04	14%	670×10^3
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	2.73 ± 0.03	14%	160×10^3
$J/\psi \to \Xi^-\bar{\Xi}^+$	10.40 ± 0.06	19%	810×10^3
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	2.78 ± 0.05	19%	210×10^3

Classic paper

Phys. Rev. D34, 833 (1986)

Hyperon decays and *CP* nonconservation

John F. Donoghue



ent of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

Xiao-Gang He and Sandip Pakvasa

nent of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 9

(Received 7 March 1986)

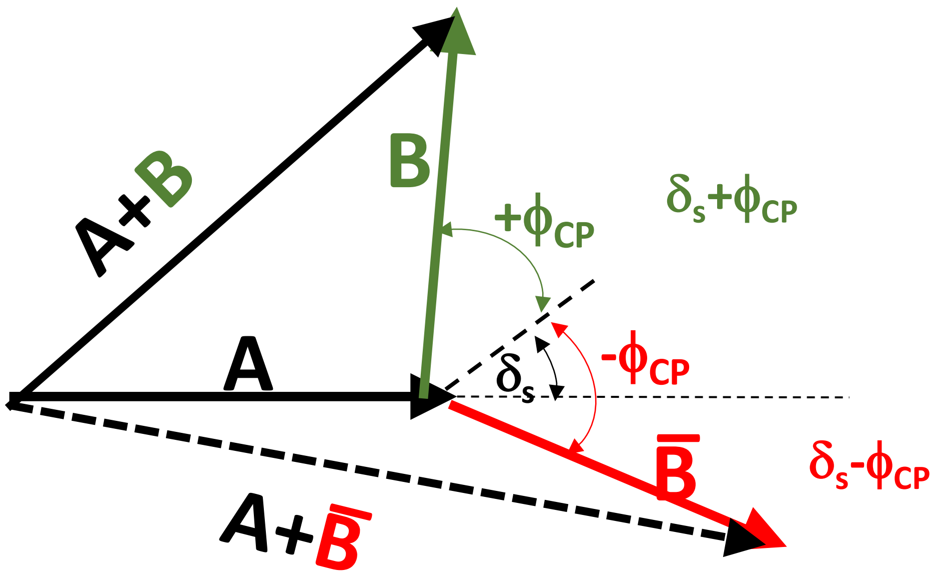
We study all modes of hyperon nonleptonic decay and consider the *CP*-odd observables which result. Explicit calculations are provided in the Kobayashi-Maskawa, Weinberg-Higgs, and left-right-symmetric models of *CP* nonconservation.

QM phase measurements require interference

A $\xrightarrow{CP}$ A

$B = |B| e^{i\delta_s + i\phi_{CP}}$ $\qquad$ $B = |B| e^{i\delta_s - i\phi_{CP}}$

A: non-CPV process to the same final state
δ_s; strong phase difference between **A** and **B**



$$\boxed{|A+B| - |A+\bar{B}| = 4|A||B|\sin\delta_s \sin\phi_{CP}}$$

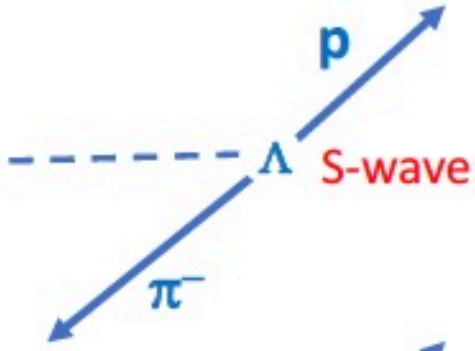
measureable CPV asymmetry requires:

1) non-zero ϕ_{CP}
2) interfering amplitude
3) non-zero δ_s

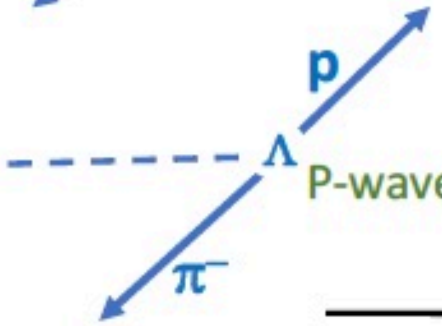
non-zero ϕ_{CP} is not enough!!

Example CPV in $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$)

-- assume CPV is in P-wave --



S-wave: $S\,e^{i\delta^S}$

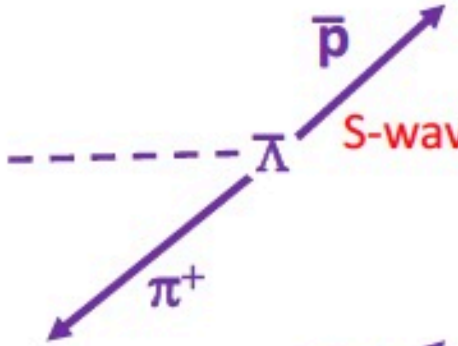


P-wave: $P\,e^{i\delta^P + i\phi_{CP}}$

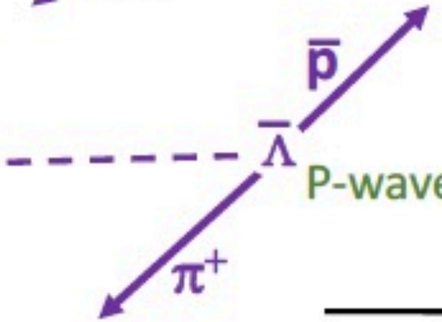
$$e^{-i\delta^S}\left(S + P\,e^{i(\delta^P - \delta^S) + i\phi_{CP}}\right)$$

or $(\Delta_s = \delta^P - \delta^S)$

$$e^{-i\delta^S}\left(S + P\,e^{i\Delta_s + i\phi_{CP}}\right)$$



S-wave: $S\,e^{i\delta^S}$



P-wave: $P\,e^{i\delta^P - i\phi_{CP}}$

$$e^{-i\delta^S}\left(S + P\,e^{i\Delta_s - i\phi_{CP}}\right)$$

α, β and γ parameters for hyperon decays

1957

Chen Ning Yang

Tsung-Dao Lee

Phys. Rev. 108 1645 (1957)

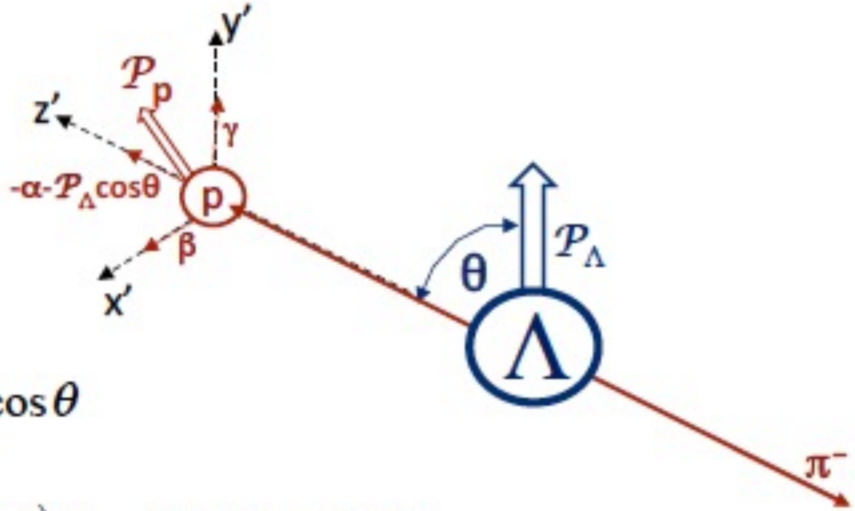
General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. Lee* and C. N. Yang
Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

$$\boxed{\Lambda \to p\pi^-, \quad \Sigma^+ \to p\pi^0}$$

$$\boxed{\begin{aligned} \bar{S} &= -\sum_i S_i e^{i(\delta_i^S - \phi_i^S)}, \\ \bar{P} &= \sum_i P_i e^{i(\delta_i^P - \phi_i^P)}. \end{aligned}}$$



$$\alpha = \frac{2\mathrm{Re}(S^* \cdot P)}{|S|^2 + |P|^2}$$

$$\beta = \frac{2\mathrm{Im}(S^* \cdot P)}{|S|^2 + |P|^2}$$

$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\vec{z}' + \beta P_\Lambda \vec{x}' + \gamma P_\Lambda \vec{y}'}{1 + \alpha P_\Lambda \cos\theta}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

CP asymmetry

$$\boxed{A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \quad B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}}.}$$

If $\Delta\Phi \neq 0$, Λ and $\bar{\Lambda}$ are transversely polarized

Correlated 5-dim. angular distribution $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

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

Unpolarized part

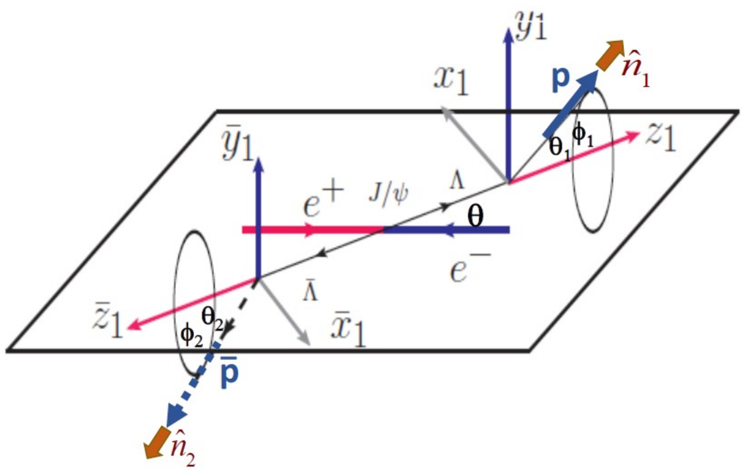
Entangled part

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

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

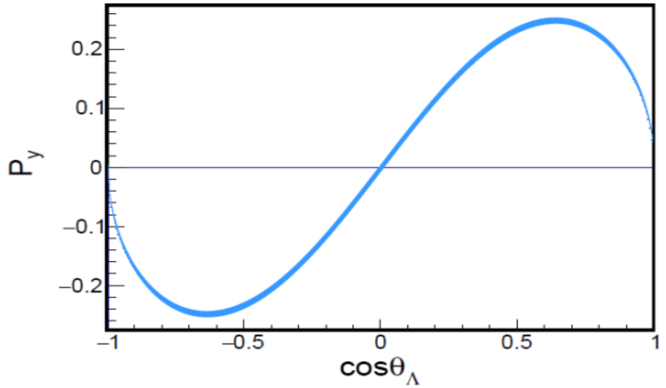
$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_- n_{1,y} + \alpha_+ n_{2,y}\right),$$

Polarized part



Polarization-term can be used to determine a_- and a_+ simultaneously

Λ

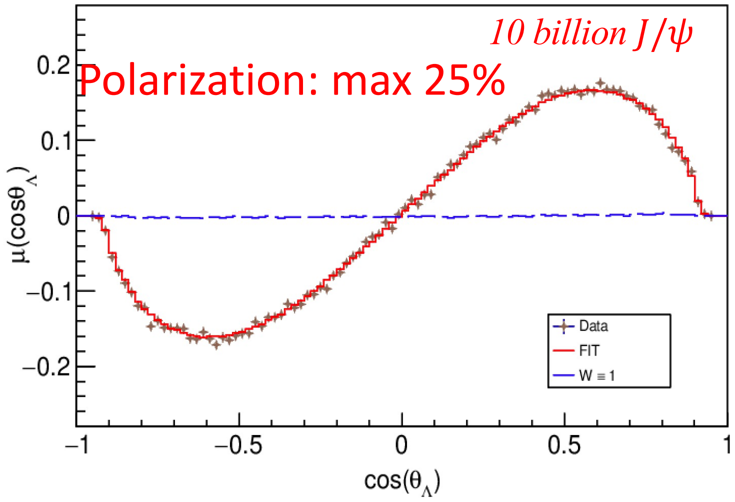


$$P_y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

The most precise CP test in Λ and $\bar{\Lambda}$ decay

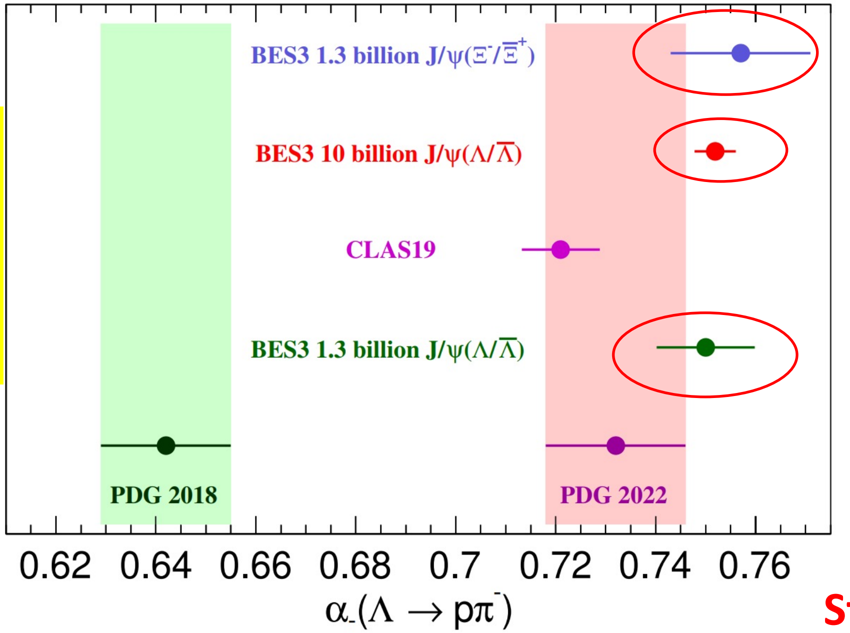
10 billion J/ψ (PRL. 129, 131801 (2022))

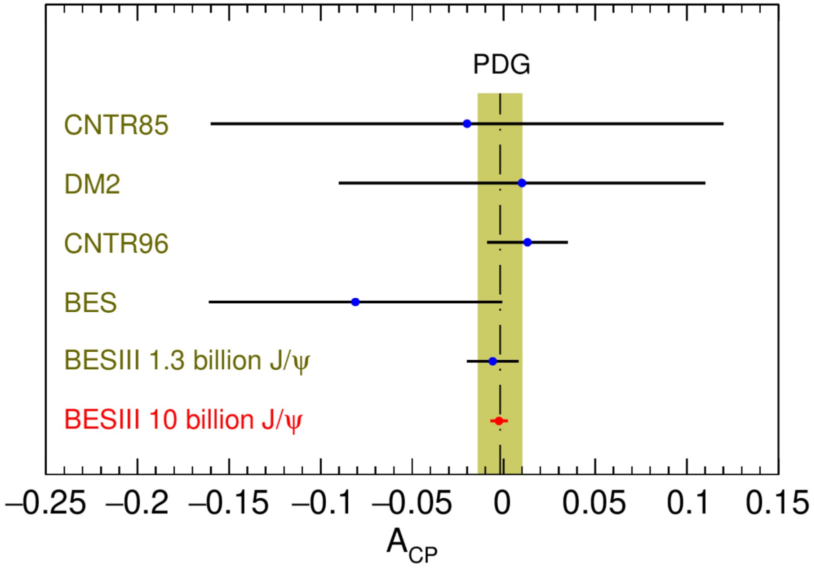
Nat. Phys. 15, 631 (2019)



Paras.	This Work (10 billion J/ψ)	Previous Results (1.3 billion J/ψ)
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$-0.006 \pm 0.012 \pm 0.007$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0020$	—

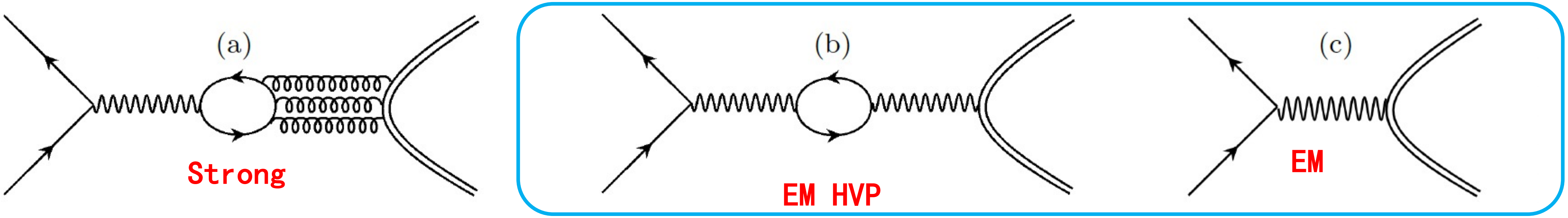
More than 10 standard deviation shift from all previous measurements

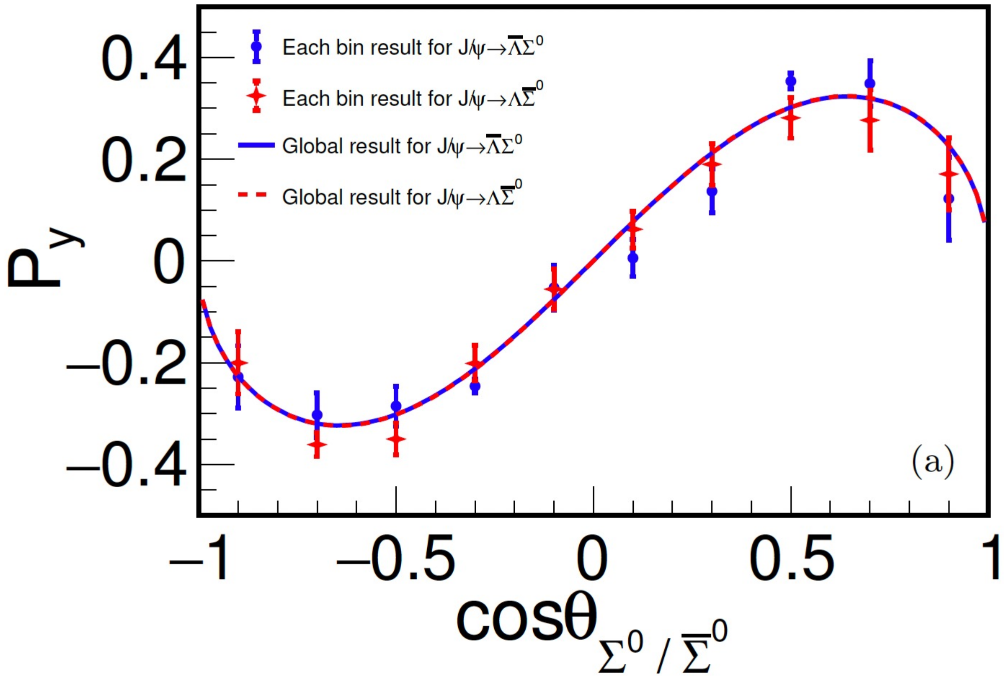




Standard mode prediction : A_{CP}~ 10^{-4} (PRD 34, 833 (1986))

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





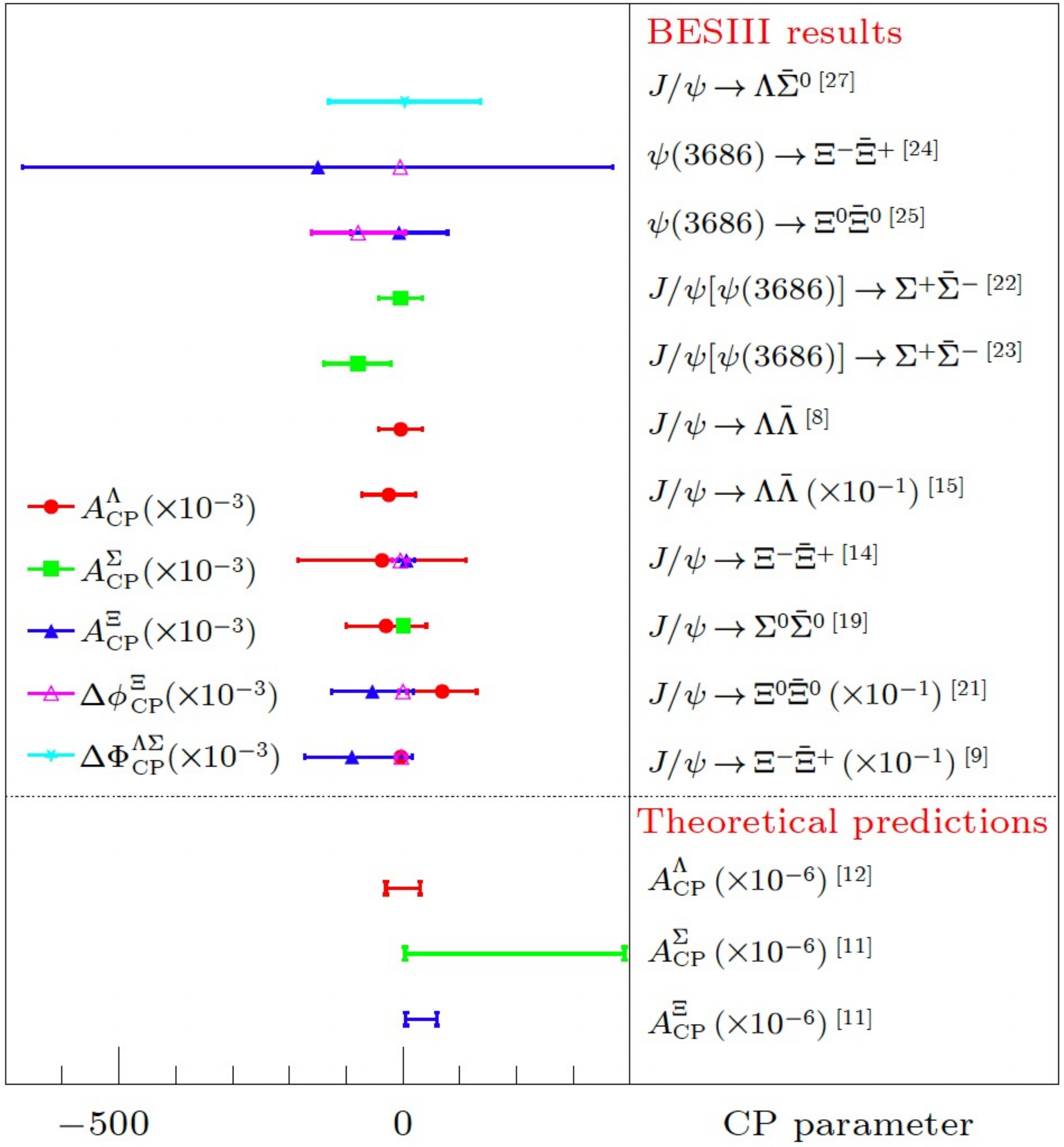
First measurements:

$\Delta\phi_1 = 1.011 \pm 0.094 \pm 0.010$
$\Delta\phi_2 = 2.128 \pm 0.094 \pm 0.010$
$|G_E/G_M| = 0.086 \pm 0.029 \pm 0.010$

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

Nat. Commun. 15, 8812 (2024)

CP tests at BESIII

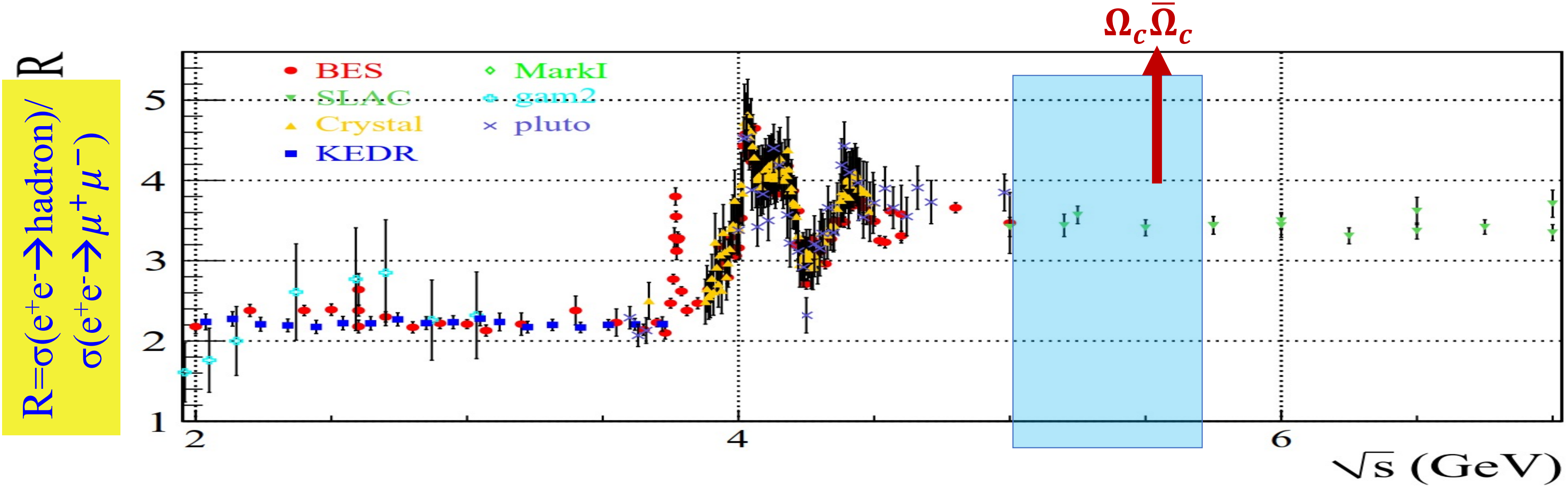


- SM predicts very small violations of CP symmetry.
- Sizeable CP violations prerequisite for *Baryogenesis*
- BESIII: 10 billion J/ψ events
- CPV at BESIII: ~ 10^{-3}
- More data strongly needed!

Theoretical preditions: X.G. He et al. Sci.Bull. 67 (2022) 1840-1843

Future prospects

- BEPCII/BESIII upgraded in 2024
- Optimization E_{cm} at 4.7 GeV with luminosity 3 times higher than the current BEPCII → more effective data taking
- Extend the maximum E_{cm} up to 5.6 GeV → more physics opportunity



Summary and Prospects

- BEPCII/BESIIIBESIII made significant contributions to charmed flavor physics
- Charm (semi-)leptonic decays are crucial for calibrating lattice QCD; determining CKM matrix elements; and testing lepton flavor universality.

  $f_{D^+}\sim 1.2\%$, $f_{D_s^+}\sim 0.9\%$, $|V_{cd}|\sim 1.2\%$, $|V_{cs}|\sim 0.9\%$, $f_+^K(0)\sim 0.23\%$
- Charm hadronic decays are key labs to understand non-perturbative QCD; study the properties of light hadron ($a_0(980)$, $f_0(980)$, $f_0(500)$...)
- Significant progresses on hyperon polarization and CP tests
- BESIII's Future prospects

  → More interesting results are coming using $20.3\ \mathrm{fb}^{-1}\ \psi(3770)$ data.

  → BEPCII-U continues to run till >2030

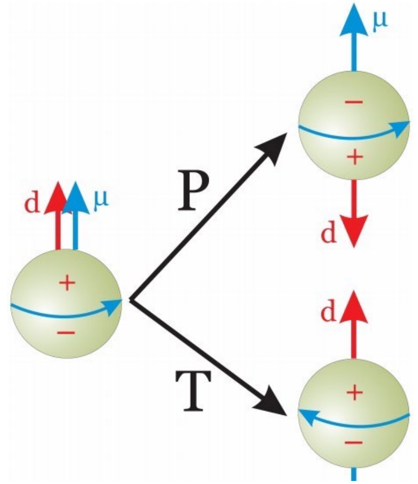
  3× luminosity above 4 GeV & max energy to 5.6 GeV

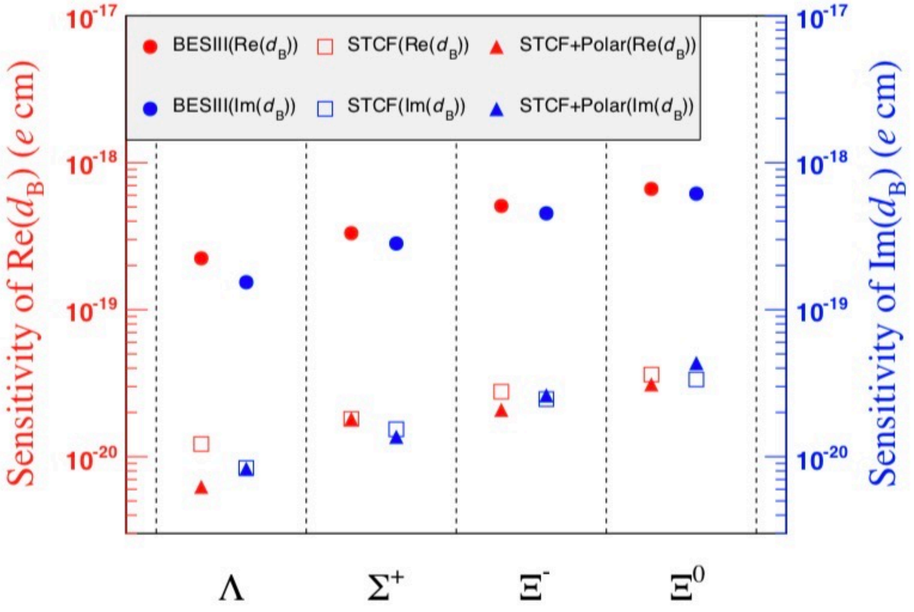
From BEPC to CEPC, the physics flavor is forever !

Many thanks！

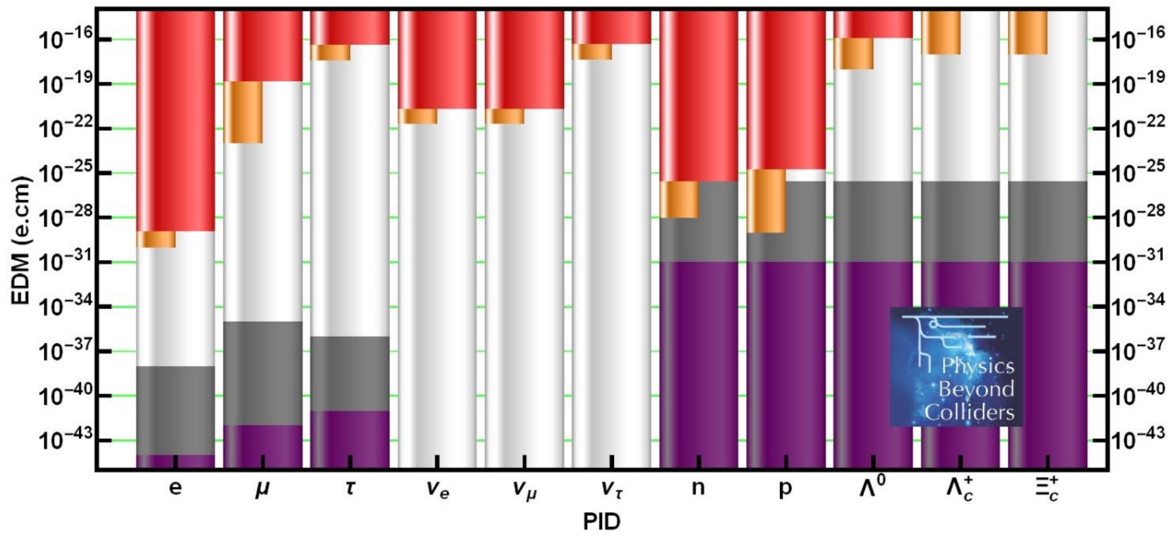
Search for Hyperon Electric Dipole Moments

Phys. Rev. D 108 (9), L091301 (2023)





(a) Sensitivity for $Re(d_B)$ and $Im(d_B)$



SM (CKM) SM ($\theta\theta$) < d (Current data) < d (Expectations)

J. Phys. G 47 (2020) 1, 010501

- A non-zero intrinsic EDM would violate both parity (P) and time-reversal (T) symmetries
- When CPT symmetry is conserved, T violation is equivalent to CP violation.