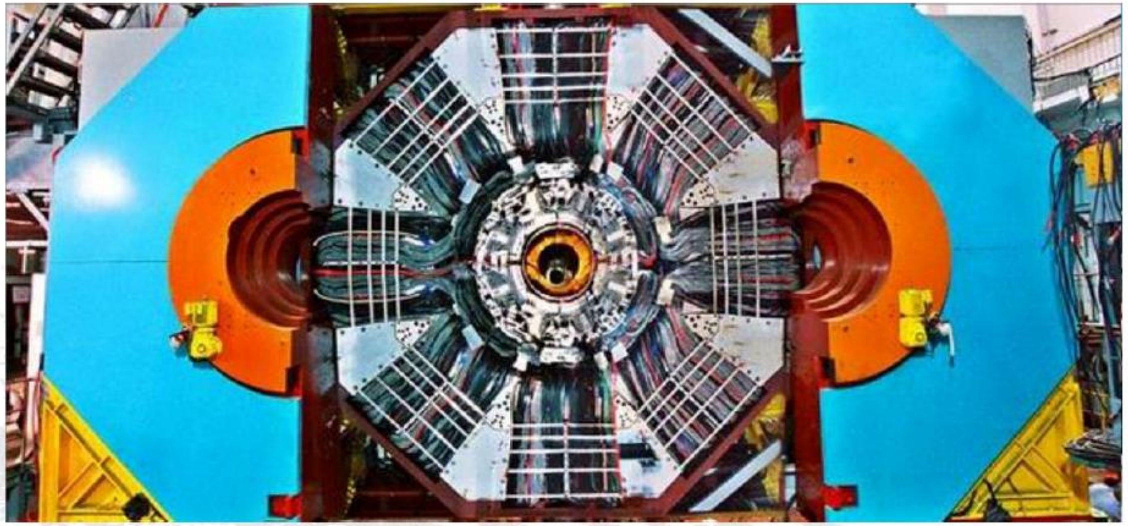
中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Physics at BESIII



Xiaoyan SHEN

On behalf of BESIII Collaboration

Institute of High Energy Physics, Chinese Academy of Sciences

Oct. 20, 2024, IHEP, Beijing

Outline

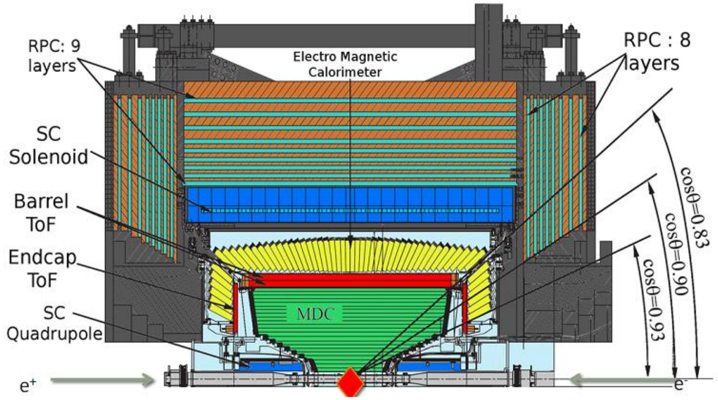
- Introduction
- Selected highlights of BESIII results

  The pseudoscalar glueball study will be covered by S. Jin.

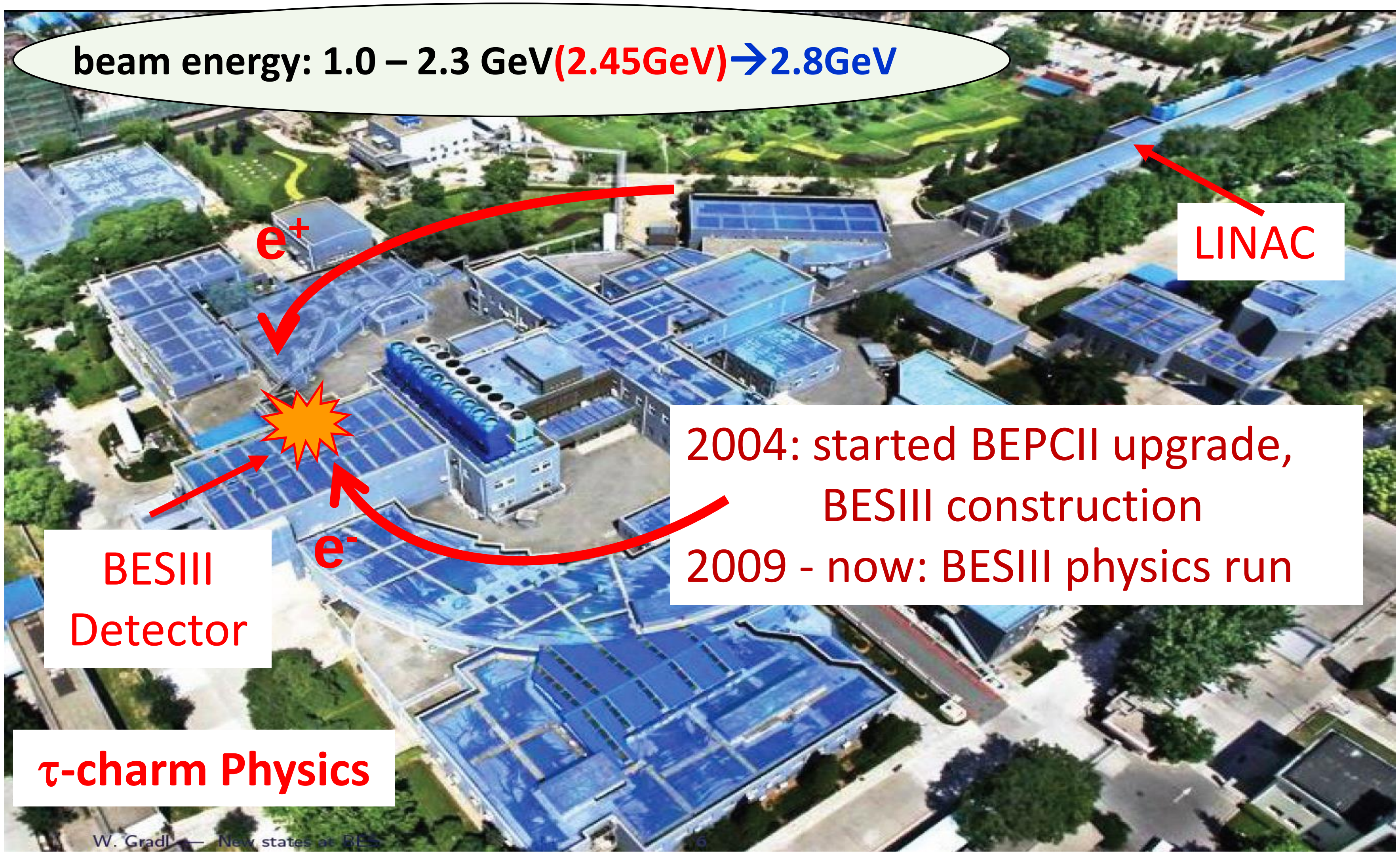
  XYZ's will be covered by C. Z. Yuan
- Summary

BESIII @ Beijing Electron Positron Collider (BEPCII) - A τ-Charm Facility

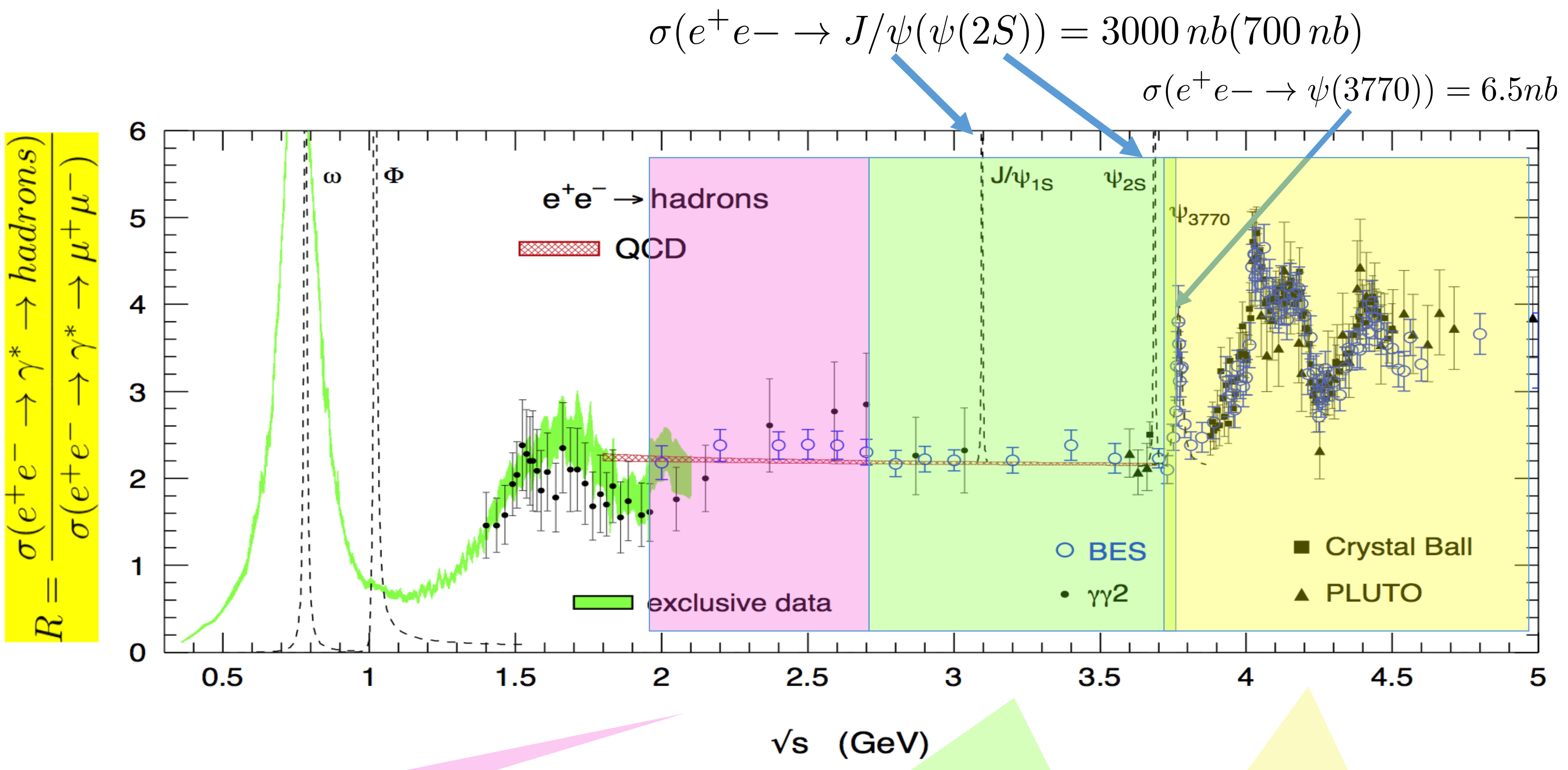
- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(2016)
  L_{peak}= 1.1 x10^{33}/cm^2(2023)



MDC: spatial reso. 115μm
dE/dx reso: 5%
EMC: energy reso.: 2.4%
BTOF: time reso.: 70 ps
ETOF: time reso.: 60 ps



Discovery of charm quark – BESIII rich physics program



- Hadron form factors
- R values and QCD

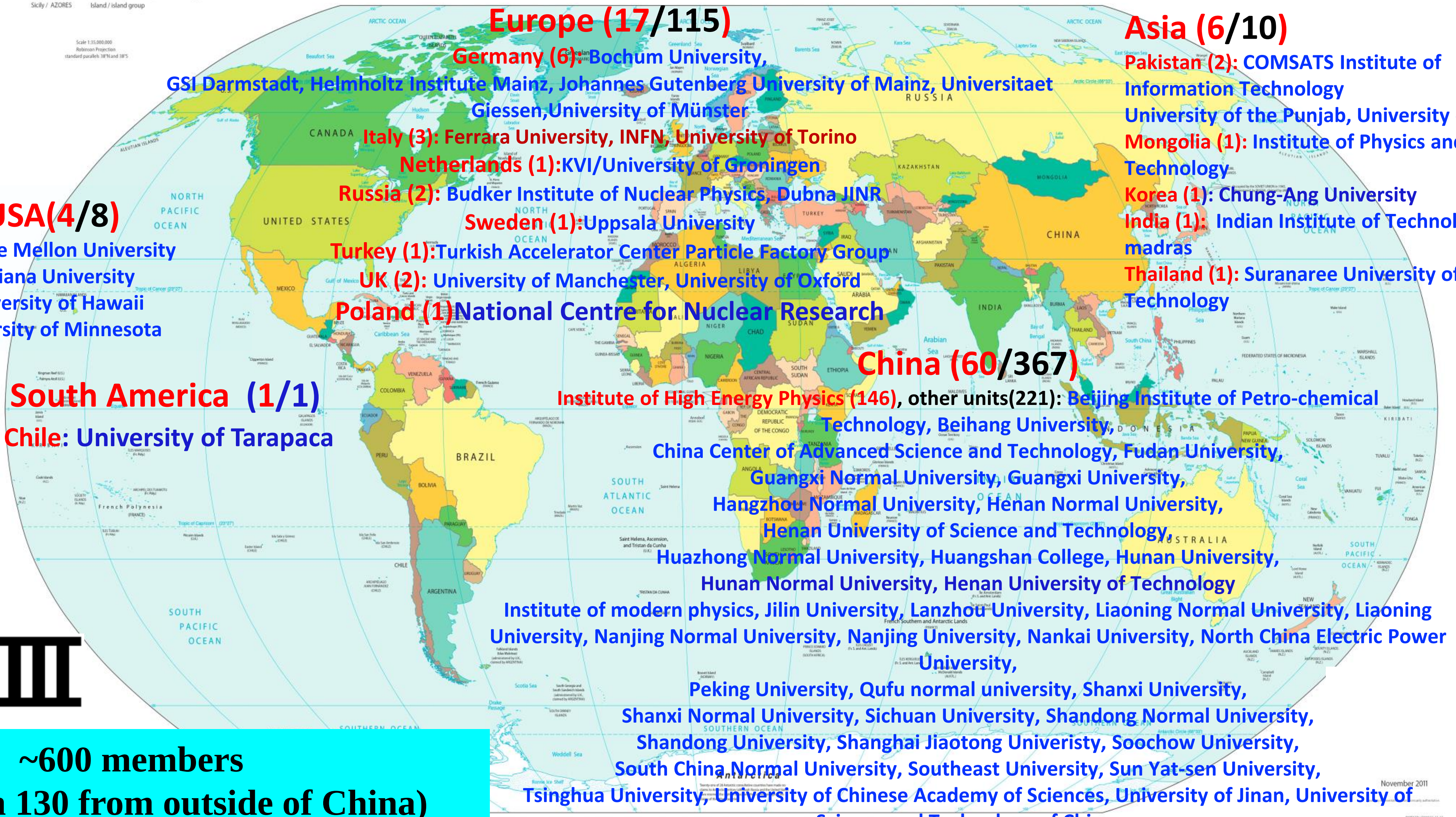
- Light hadron spectroscopy
- Gluonic and exotic states
- Physics with τ lepton

- XYZ particles
- Charm mesons
- Charm baryons

BEPCII Energy Region

- Rich of resonances: charmonia, charm mesons, charm baryons
- Transition between smooth and resonances, perturbative and non-perturbative QCD
- Energy location of the gluonic matters and XYZ's
- Threshold characteristics (pairs of τ, D, D_s, Λ_c…)
  Fixed initial and final states, low background

BESIII Collaboration



Europe (17/115)

Germany (6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

Italy (3): Ferrara University, INFN, University of Torino

Netherlands (1): KVI/University of Groningen

Russia (2): Budker Institute of Nuclear Physics, Dubna JINR

Sweden (1): Uppsala University

Turkey (1): Turkish Accelerator Center Particle Factory Group

UK (2): University of Manchester, University of Oxford

Poland (1) National Centre for Nuclear Research

Asia (6/10)

Pakistan (2): COMSATS Institute of Information Technology University of the Punjab, University of Lahore

Mongolia (1): Institute of Physics and Technology

Korea (1): Chung-Ang University

India (1): Indian Institute of Technology madras

Thailand (1): Suranaree University of Technology

USA(4/8)

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota

South America (1/1)

Chile: University of Tarapaca

China (60/367)

Institute of High Energy Physics (146), other units(221): Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Henan University of Technology Institute of modern physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu normal university, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiaotong Univeristy, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University,YunNan University , China University of Geosciences

BESIII

~600 members
(more than 130 from outside of China)
From 87 institutions in 16 countries

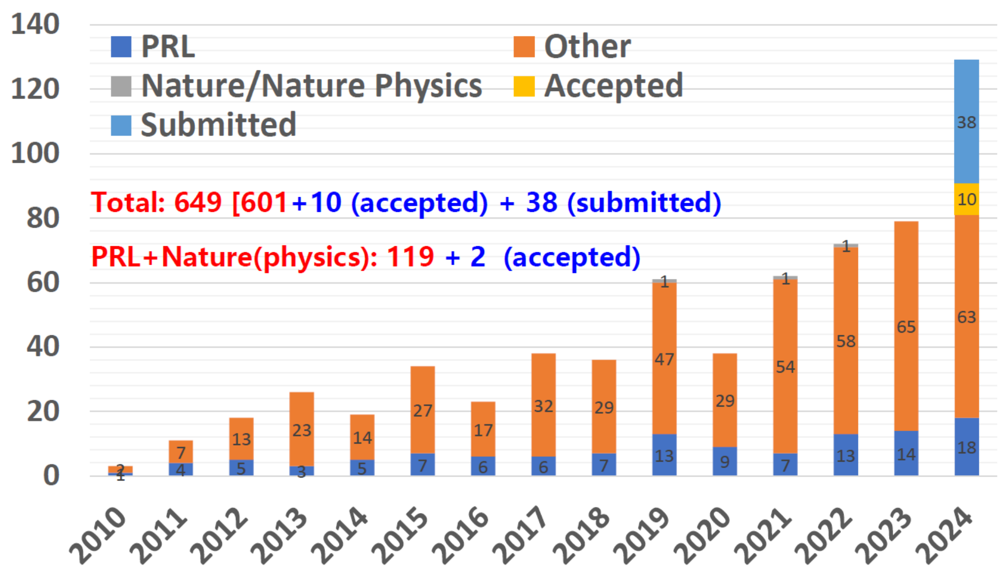
BESIII achievements

See also talks from and S. Jin and C. Z. Yuan

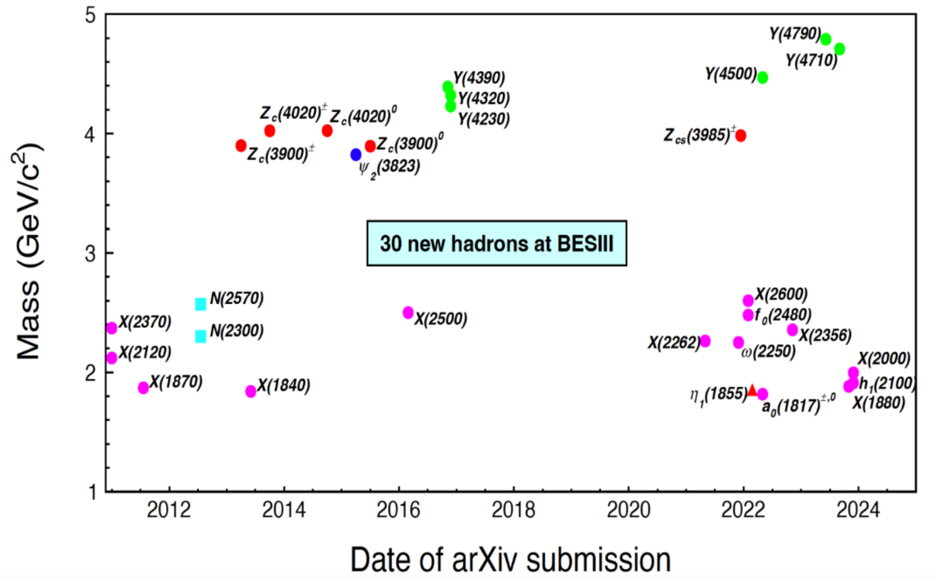
Data sets collected so far include: (50 fb^{-1})

- 10×10^9 J/ψ events， 2.7×10^9 ψ (2S) events， 20 fb^{-1} ψ(3770)
- 4.0-4.6 GeV: 22.5 fb^{-1} for XYZ and charm physics, 4.6-4.95 GeV: 6.3 fb^{-1} for XYZ and charmed baryons
- Scan data between 1.84-1.97 GeV， 2.0 and 3.08 GeV, and above 3.74 GeV

Publications as of Oct. 8, 2024



New Hadrons Observed



BESIII is playing an important role in charmed flavor and hadron physics

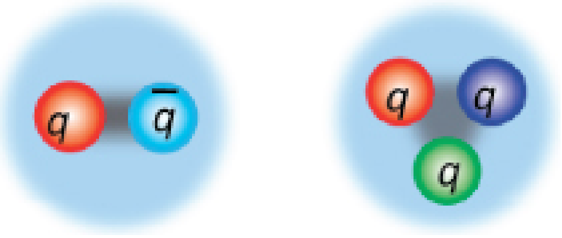
New forms of hadrons

See also talks from S. Jin and C. Z. Yuan

- Conventional hadrons consist of 2 or 3 quarks：

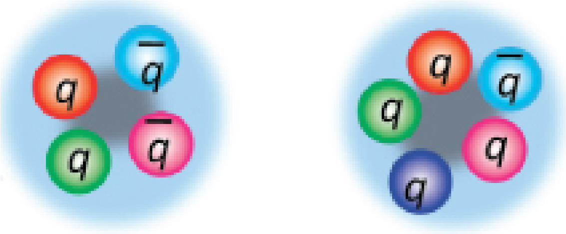
Naive Quark Model：

meson

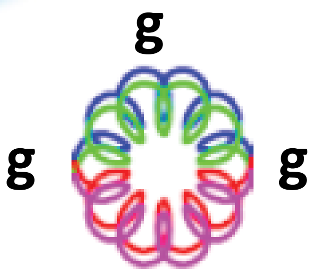


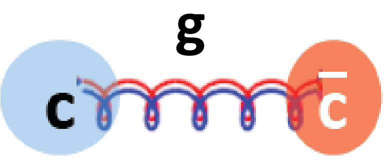
baryon

- QCD predicts the new forms of hadrons:
  - Multi-quark states ： Number of quarks >＝ 4



  - Hybrids ： qqg， qq$\bar{q}$g …
  - Glueballs ： gg， ggg …



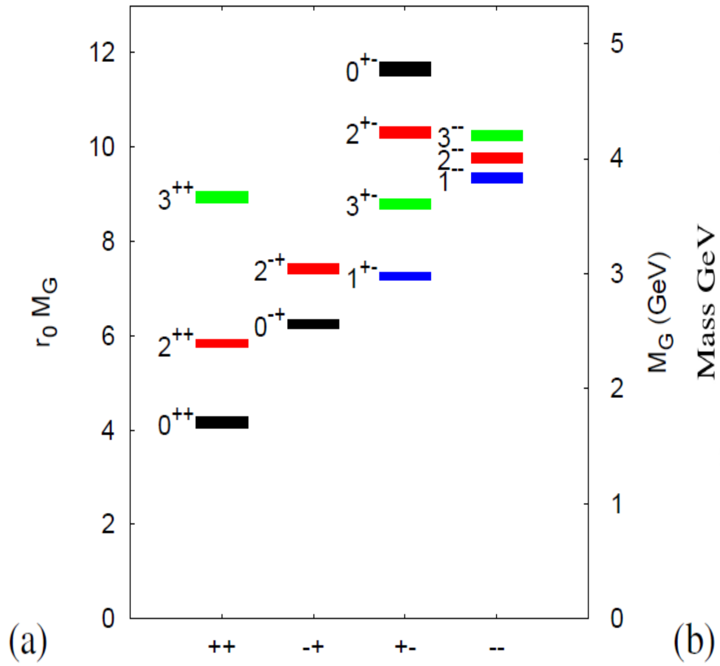


None of the new forms of hadrons is settled !

Glueball spectrum – Lattice QCD

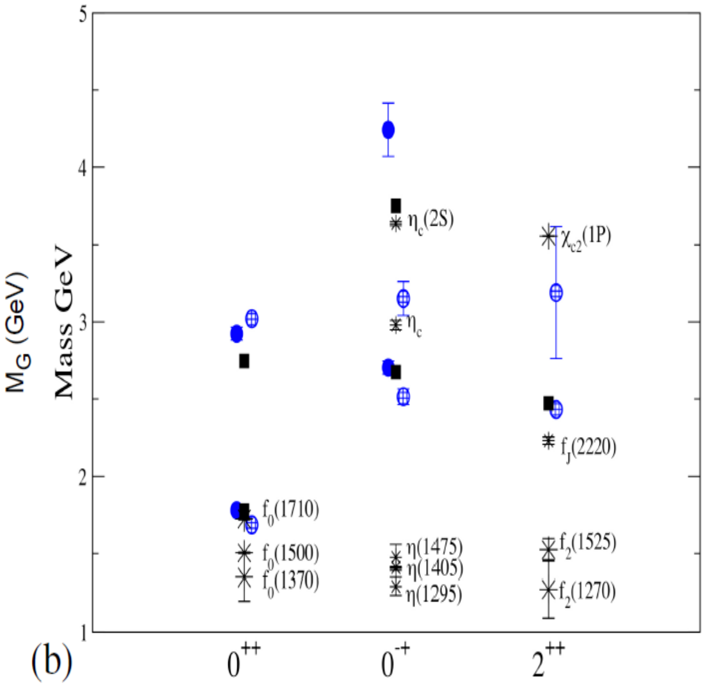
Quenched LQCD

Y. Chen et al.,
PRD 73 (2006) 014516



Unquenched LQCD

Morningstar CJ and Peardon MJ.
PRD, 1999;60:, PRD 60, 034509
Richards CM, Irving AC, Gregory EB
et al. PRD 82, 034501.



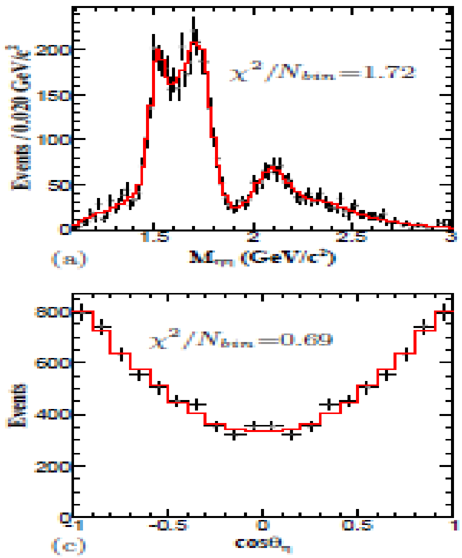
LQCD predicts:

- **The lowest glueball state is 0^{++}. The mass around 1.5 GeV – 1.7 GeV.**
- **The next lightest glueball is 2^{++}. The mass is around 2.4 GeV.**
- **The lightest 0^{-+} glueball mass is ~ 2.3 GeV**
- **Unquenched calculations obtain similar results for light glueballs.**

The mix of glueballs with ordinary $q\bar{q}$ mesons makes the situation more difficult.

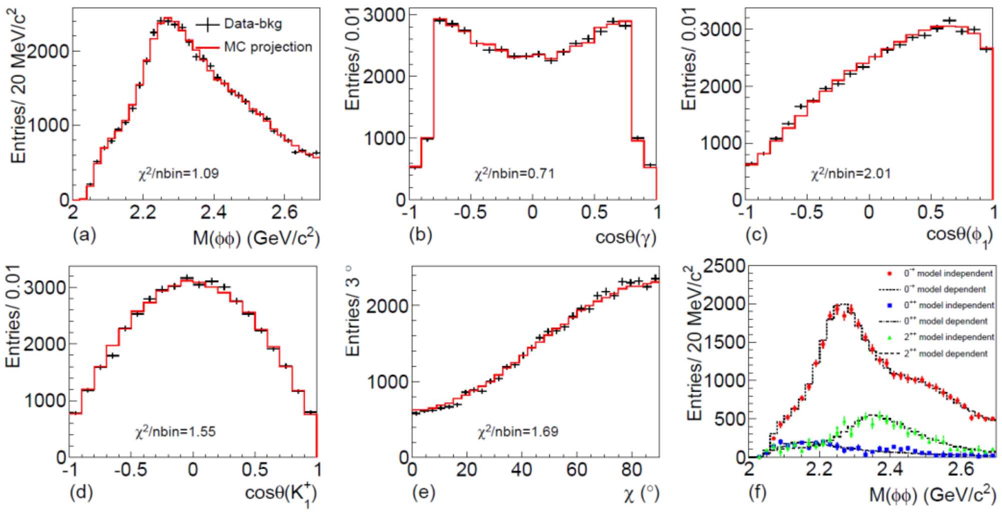
$J/\psi \to \gamma\eta\eta$ (225M J/ψ)

PRD87, 092009 (2013)



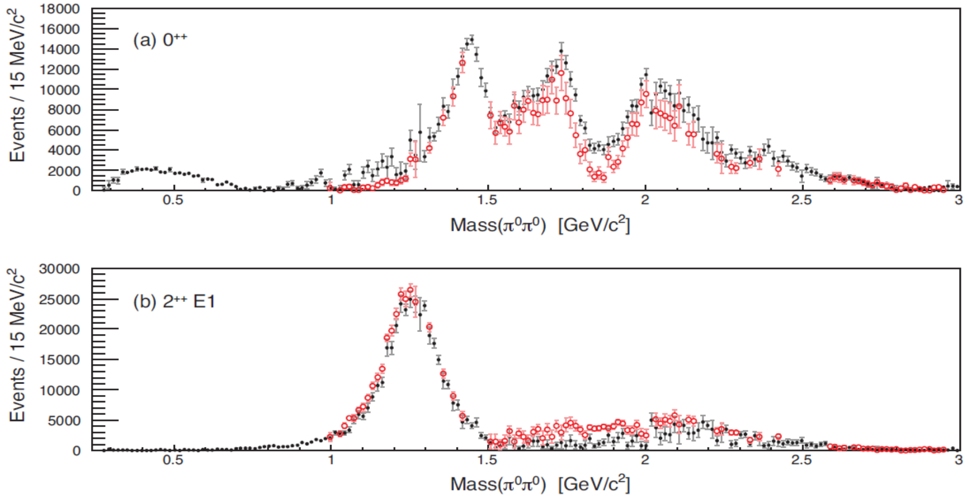
$J/\psi \to \gamma\phi\phi$ (225M J/ψ)

PRD 93, 112011(2016)



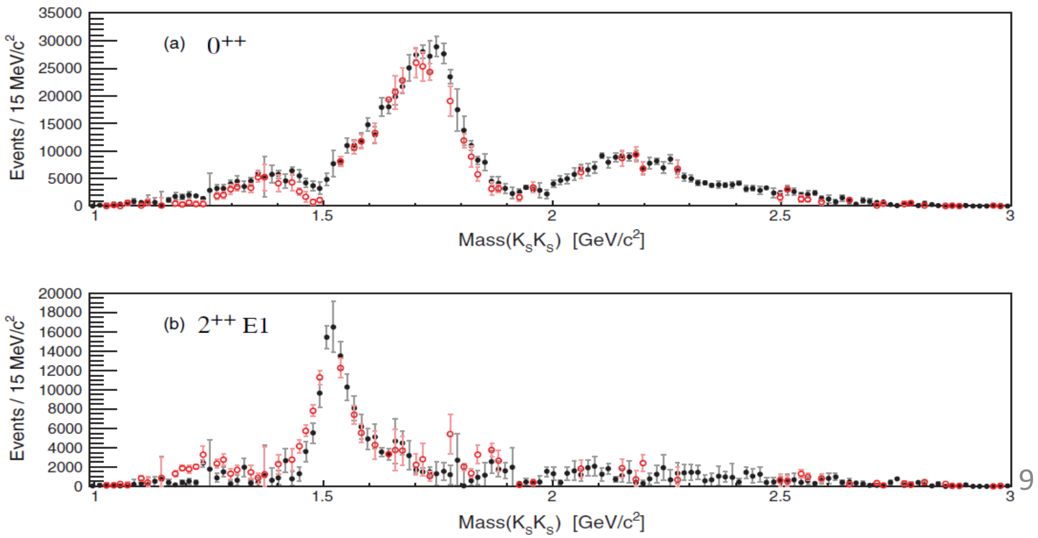
$J/\psi \to \gamma\pi^0\pi^0$ (1.3B J/ψ)

PRD92, 052003 (2015)



$J/\psi \to \gamma K_s K_s$ (1.3B J/ψ)

PRD98, 072003 (2018)



Current status for scalar glueball candidate (0^{++})

$J/\psi \to \gamma X \to \gamma\pi\pi$ BES, PLB(2006)441

$Br(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.01 \pm 1.0) \times 10^{-4}$

$Br(J/\psi \to \gamma f_0(1500) \to \gamma\pi\pi) = (1.01 \pm 0.34) \times 10^{-5}$

$J/\psi \to \gamma X \to \gamma\eta\eta$ BESIII, PRD87(2013)092009

$Br(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+1.27}_{-0.77}) \times 10^{-4}$

$Br(J/\psi \to \gamma f_0(1500) \to \gamma\eta\eta) = (1.65^{+0.57}_{-1.50}) \times 10^{-5}$

$J/\psi \to \gamma X \to \gamma K_s K_s$ BESIII，PRD 98, 072003 (2018)

$Br(J/\psi \to \gamma f_0(1710) \to \gamma K_s K_s) = (2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$

$Br(J/\psi \to \gamma f_0(1500) \to \gamma K_s K_s) = (1.59^{+0.16+0.18}_{-0.16-0.59}) \times 10^{-5}$

$J/\psi \to \gamma X \to \gamma\eta\eta'$ BESIII，PRL 129 192002(2022) , PRD 106 072012(2022

$\frac{Br(f_0(1500)\to\eta\eta')}{Br(f_0(1500)\to\pi\pi)} = (8.96^{+2.95}_{-2.88}) \times 10^{-2}$

$\frac{Br(f_0(1710)\to\eta\eta')}{Br(f_0(1710)\to\pi\pi)} < 1.61 \times 10^{-3}$ @ 90% C. L.

Theoretical calculation: $\frac{Br(f_0(1710)\to\eta\eta')}{Br(f_0(1710)\to\pi\pi)} < 0.04$

$\Rightarrow Br(J/\psi \to \gamma f_0(1500)) = 2.9 \times 10^{-4}$

$\Rightarrow Br(J/\psi \to \gamma f_0(1710)) > 1.9 \times 10^{-3}$

- $f_0(1710)$: mass consistent with LQCD
- $Br(J/\psi \to \gamma f_0(1710)) \sim 10 \times Br(J/\psi \to \gamma f_0(1500))$
- $f_0(1710) \to \eta\eta'$ suppressed
- $f_0(1710)$: Coupled-channel analyses based on BESIII data reveal large scalar glueball component.

PLB 816, 136227 (2021),
EPJC 82, 80 (2022),
PLB 826, 136906 (2022)

Current status for tensor glueball candidate (2^{++})

Lattice QCD: $\Gamma(J/\psi \to \gamma G_{2^+}) = \frac{4}{27}\alpha\frac{|p|}{M_{J/\psi}^2}[|E_1(0)|^2 + |M_2(0)|^2 + |E_3(0)|^2]$

Y.B. Yang ,et al .(CLQCD Collaboration)
PRL 111, 091601 (2013))

$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22)keV$
$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1(2) \times 10^{-2}$

$J/\psi \to \gamma X \to \gamma\eta\eta$ BESIII, PRD87(2013)092009

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$$

$J/\psi \to \gamma X \to \gamma\varphi\varphi$ BESIII, PRD93(2016)112011

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$

$J/\psi \to \gamma X \to \gamma K_s K_s$ BESIII，PRD 98, 072003 (2018)

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = (5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$$

$f_2(2340)$: consistent with LQCD's calculation for the mass of a tensor glueball.

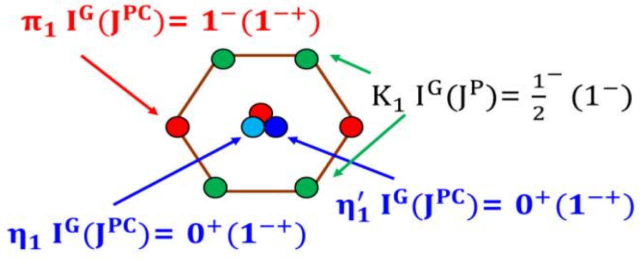
States with exotic quantum numbers

- $J^{PC} = 0^{--}$, even^{+-}, odd^{-+} are forbidden for $q\bar{q}$
- Light hadrons with exotic quantum numbers are unambiguously signatures of exotic states
- Three $1^-(1^{-+})$ isovector candidates:
  - ✓ $\pi_1(1400)$: seen in ηπ, ρπ
  - ✓ $\pi_1(1600)$: seen in ρπ, η'π, $b_1\pi$, $f_1\pi$
  - ✓ $\pi_1(2015)$ (needs confirmation): seen in $b_1\pi$, and $f_1\pi$

  $\pi_1(1400)$ and $\pi_1(1600)$ could be from one pole.

  PRL 122, 042002 (2019), EPJ C 81, 1056 (2021])

- Observation of I=0 η_1 exotic state is crucial

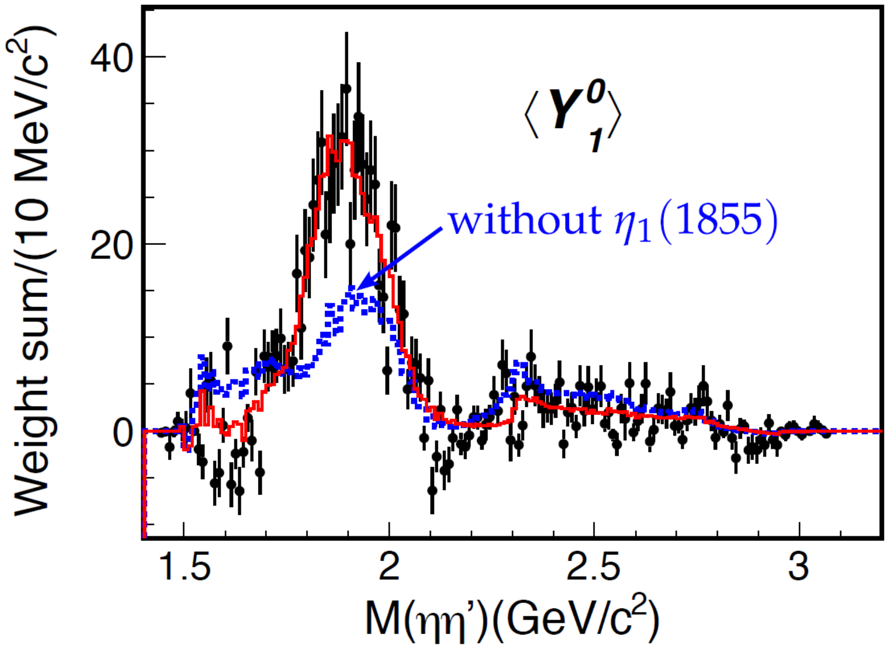


	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^-p \to \pi^-\eta p$ $\pi^-p \to \pi^0\eta n$ $\pi^-p \to \pi^-\eta p$ $\pi^-p \to \pi^0\eta n$ $\bar{p}n \to \pi^-\pi^0\eta$ $\bar{p}p \to \pi^0\pi^0\eta$	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p}p \to 2\pi^+2\pi^-$	Obelix
$\pi_1(1600)$	$\eta'\pi$	$\pi^-Be \to \eta'\pi^-\pi^0 Be$ $\pi^-p \to \pi^-\eta' p$	VES E852
	$b_1\pi$	$\pi^-Be \to \omega\pi^-\pi^0 Be$ $\bar{p}p \to \omega\pi^+\pi^-\pi^0$ $\pi^-p \to \omega\pi^-\pi^0 p$	VES CBAR E852
	$\rho\pi$	$\pi^-Pb \to \pi^+\pi^-\pi^- X$ $\pi^-p \to \pi^+\pi^-\pi^- p$	COMPASS E852
	$f_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$ $\pi^-A \to \eta\pi^+\pi^-\pi^- A$	E852 VES
$\pi_1(2015)$	$f_1\pi$	$\pi^-p \to \omega\pi^-\pi^0 p$	E852
	$b_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$	

Observation of $0^+(1^{-+})$ $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$ at BESIII

PRL 129 192002(2022) , PRD 106 072012(2022)

- **$J/\psi \to \gamma\eta\eta'$: 1^{-+} $\eta_1(1855)$, stat. sig. $>>10\sigma$**
  - $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2$, $\Gamma = (188 \pm 18^{+3}_{-8})\mathrm{MeV}$
  - $B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = \left(2.70 \pm 0.41^{+0.16}_{-0.35}\right) \times 10^{-6}$
- **The mass is consistent with LQCD expectation**
- **Stimulated theoretical discussions –**
  Hybrid/$K\bar{K}_1$ Molecule/Tetraquark
- **Statistical significance for an additional η_1 ~4.6σ at ~ 2.15 GeV**



CP violation in flavored hadrons

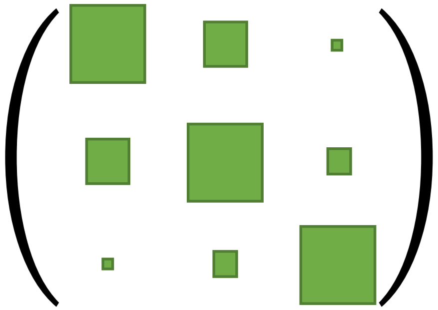
- In 1964, the first CPV was discovered in Kaon
- In 2001, CPV in B was established by two B-factories
- In 2019, CPV was discovered in D meson: 10^{-4}, with 10^{8} reconstructed D mesons (LHCb)
- All are consistent with CKM theory in the Standard model

1980

2008

CPV phase δ

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



δ_s strong phase ϕ_w weak phase

For decay $A = A_1 e^{i\delta_s^1} e^{i\phi_w^1} + A_2 e^{i\delta_s^2} e^{i\phi_w^2}$ $\xrightarrow{CP}$ $\bar{A} = A_1 e^{i\delta_s^1} e^{-i\phi_w^1} + A_2 e^{i\delta_s^2} e^{-i\phi_w^2}$

Make $r = A_2/A_1$, $\delta = \delta_s^2 - \delta_s^1$, $\phi = \phi_w^2 - \phi_w^1$

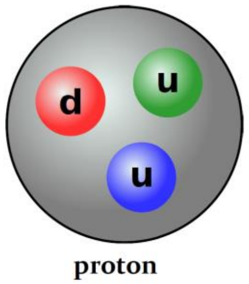
Thus $A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{|A_1|^2 |1+re^{i(\delta+\phi)}|^2 - |A_1|^2 |1+re^{i(\delta-\phi)}|^2}{|A_1|^2 |1+re^{i(\delta+\phi)}|^2 + |A_1|^2 |1+re^{i(\delta-\phi)}|^2}$

$= \frac{2r\cos(\delta+\phi) - 2r\cos(\delta-\phi)}{2(1+r^2+r\cos(\delta+\phi)+r\cos(\delta-\phi))} = \frac{2r\sin\delta\sin\phi}{1+r^2+2r\cos\delta\cos\phi} \neq 0$, (if $\delta \neq 0$ and $\phi \neq 0$)

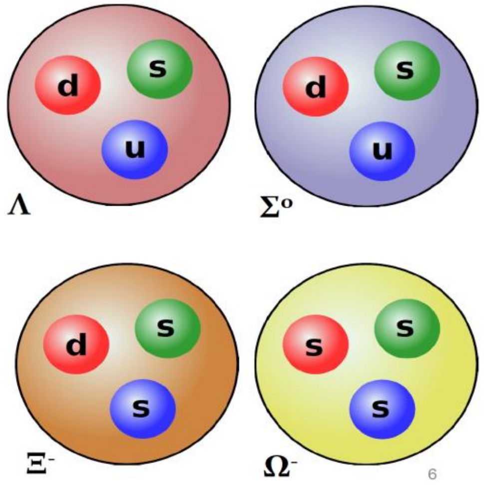
Baryon asymmetry of the universe means that there must be non-SM CPV source.

What we learn on hyperon physics from J/ψ decays ?

Hyperon is any baryon containing one or more *s* quarks, but no *c, b* or *t* quark.



Replace one or more light quark(s) in the proton
with one or more *s* quark(s)



☐ Hyperon decays

- ➢ Non-leptonic weak decay
  CP test
- ➢ Beta decay – semi-leptonic decays
  form factor or V_{us}, CP test, lepton flavor universality (LFU) test
- ➢ The weak radiative decays

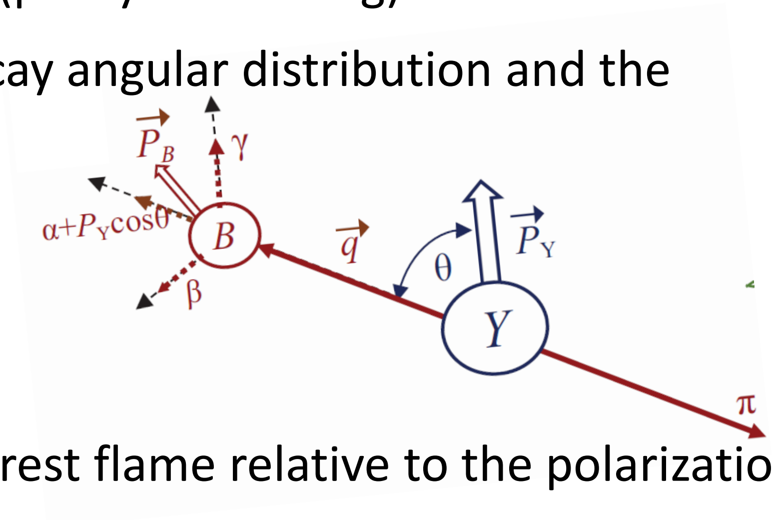
CP test in Hyperon non-leptonic weak decays

- Lee and Yang's prediction for parity violation in hyperon decays (Lee-Yang parameters) (Phys. Rev. 108, 1645(1957)) $Y \to B+\pi$
- $J^P = \frac{1}{2}^+ \to \frac{1}{2}^+ \otimes 0^-$ proceeds to S wave (parity violating) and P wave (parity conserving) final states.

  Lee-Yang parameters α, β and γ (decay parameters, govern the decay angular distribution and the polarization of the final baryon. Only two are independent).

$$\alpha = \frac{2\,\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2\,\mathrm{Im}(S^* P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

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



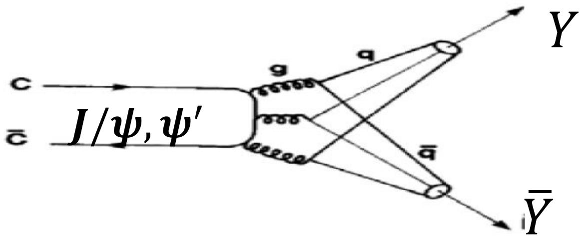
- If Y has a non-zero polarization $\vec{\mathcal{P}}_Y$, the flight direction of B in the Y rest flame relative to the polarization direction θ is:

$$dN/dcos\theta \propto 1 + \alpha_Y |\vec{\mathcal{P}}_Y| cos\theta$$

- The polarization of B, $\vec{\mathcal{P}}_B$, depends on $\mathcal{P}_Y$, θ and α, β, γ parameters
- If CP is conserved, the decay parameters for Y (α and β) and $\overline{Y}$ ($\overline{\alpha}$ and $\overline{\beta}$) are equal in magnitude, but opposite in sign.
- If CP is asymmetry: $A_{CP} = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}$, $B_{CP} = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}}$ (SM: $A_{CP} \sim 10^{-5} - 5 \times 10^{-4}$, $B_{CP} \sim 10^{-3} - 5 \times 10^{-2}$)

Production of entangled hyperon-antihyperon pairs at BESIII

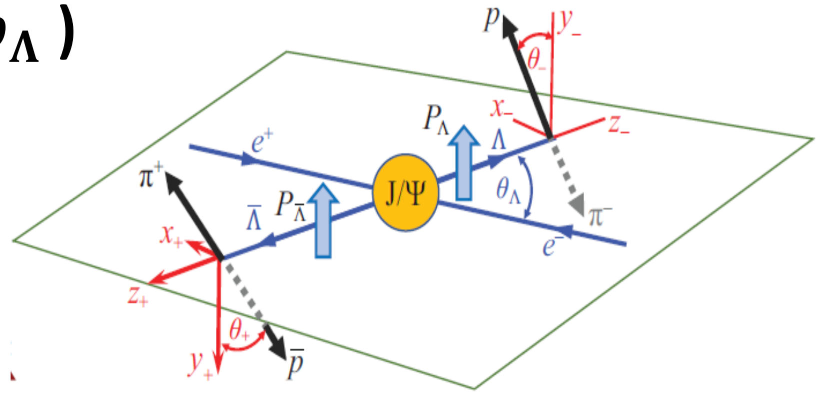
- $e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}, \Lambda_c^+\bar{\Lambda}_c^-, \ldots$ @ $\sqrt{s} = 2.0 \sim 4.95$ GeV
- $J/\psi, \psi' \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$



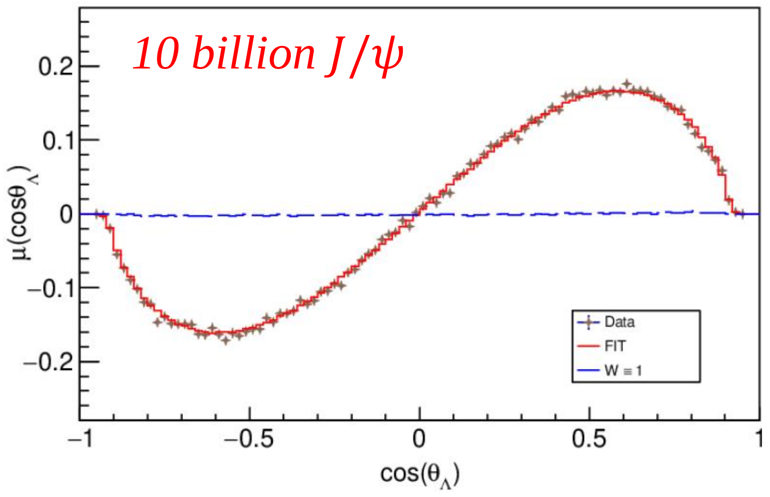
10 billion J/ψ		4 billion ψ'	
1.9×10^7	$\Lambda\bar{\Lambda}$	1.5×10^6	$\Lambda\bar{\Lambda}$
1.2×10^7	$\Sigma^0\bar{\Sigma}^0$	0.9×10^6	$\Sigma^0\bar{\Sigma}^0$
1.5×10^7	$\Sigma^+\bar{\Sigma}^-$	0.9×10^6	$\Sigma^+\bar{\Sigma}^-$
1.1×10^7	$\Xi^0\bar{\Xi}^0$	0.9×10^6	$\Xi^0\bar{\Xi}^0$
1.0×10^7	$\Xi^-\bar{\Xi}^+$	1.1×10^6	$\Xi^-\bar{\Xi}^+$
		0.2×10^6	$\Omega\bar{\Omega}$

- Parity conservation in charmonium decay guarantees that the cosθ dependent for hyperon and anti-hyperon polarizations ($J/\psi, \psi' \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$) are equal and perpendicular to the production plane. (P_Λ along $k_{e^+} \times p_\Lambda$)
(IL NUOVO CIMENTO, 109A, 241 (1996))

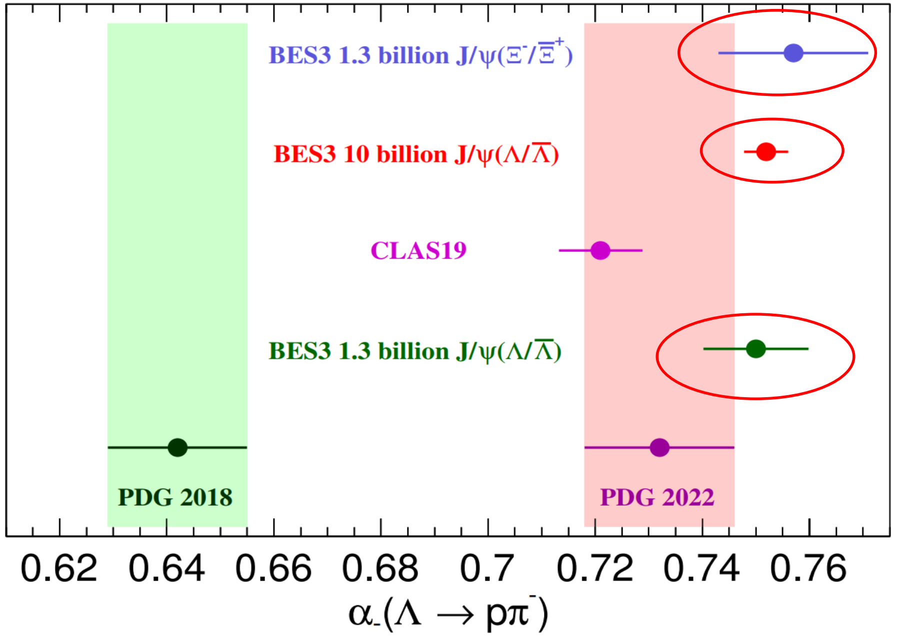
$$\bar{P}_Y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi{}^2}\cos\theta_\Lambda \sin\theta_\Lambda}{1+\alpha_\psi \cos^2\theta_\Lambda}\sin(\Delta\Phi)$$



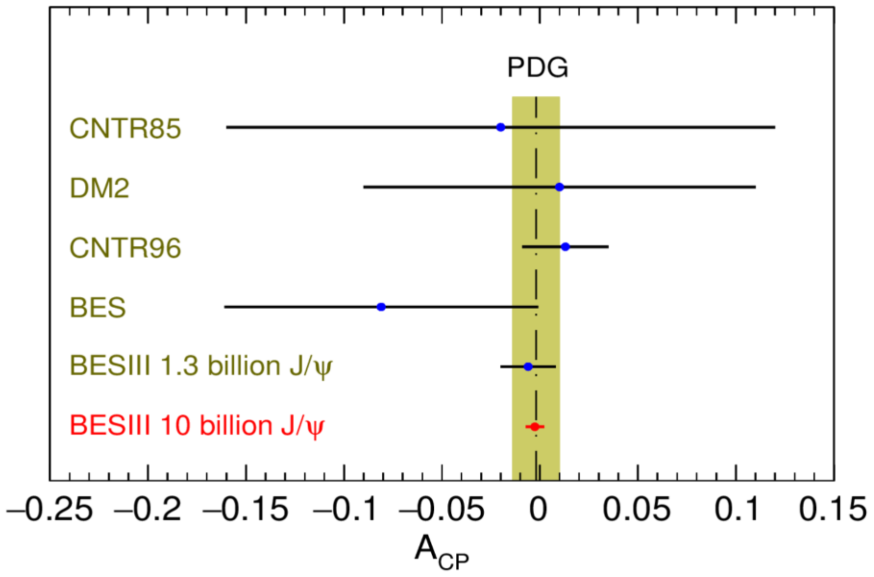
Weak decay parameters and CP test in $J/\psi \to \Lambda\bar{\Lambda}$



- First measurement of hyperon polarization at J/ψ
- Non-zero $\Delta\Phi$ allows for individual determinations of Λ and $\bar{\Lambda}$ decay parameters α_- and α_+, and thus allow for CP test.
- α_-: 7σ shift from PDG2018 average
- Most sensitive test of CP violation for Λ hyperon.
  SM prediction: ~ 10^{-4} (PRD 34, 833 (1986)),
  SM extension may have a large A_{CP} (CPC 42, 013101(2018))



$\alpha_{avg} = 0.7542 \pm 0.0010 \pm 0.0020$

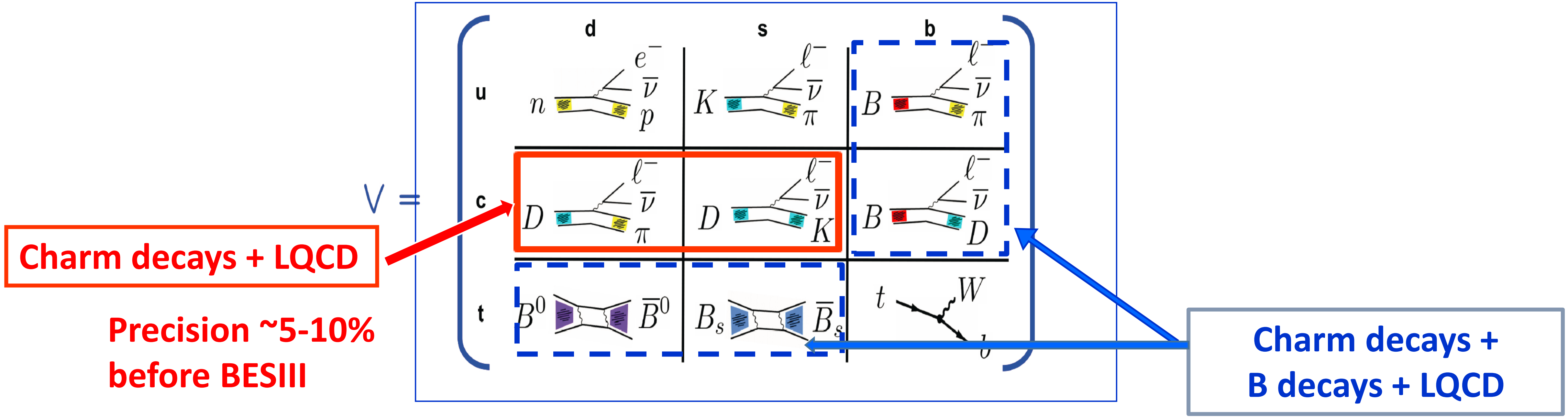


$A_{CP} = -0.0025 \pm 0.0046 \pm 0.0011$

PRL 129, 131801 (2022)

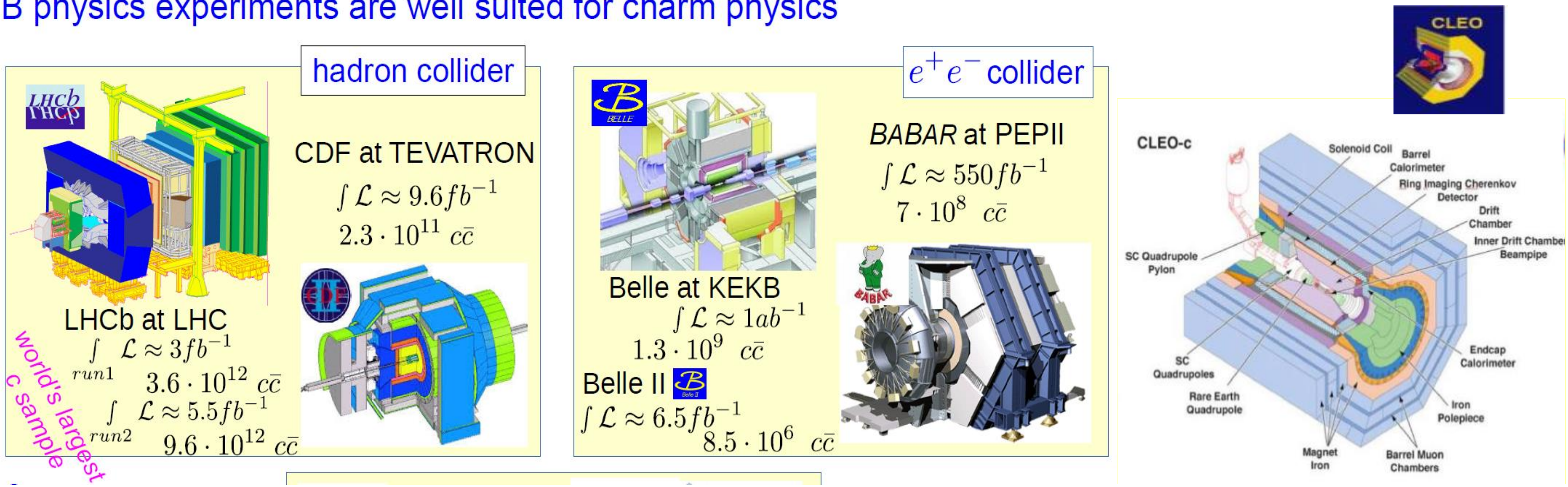
Precision measurement of CKM elements
-- Test EW theory

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



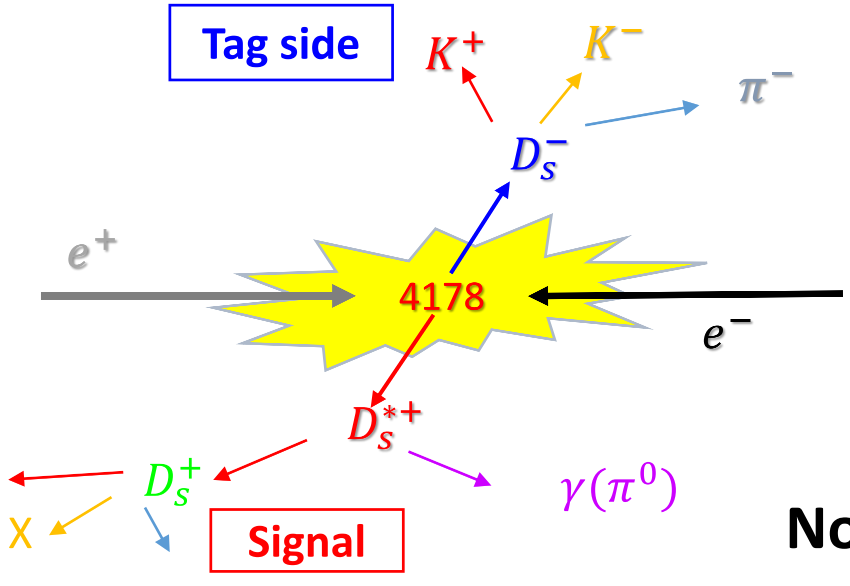
Landscape of Charm Physics

B physics experiments are well suited for charm physics



- **CLEOc exp. contributed much in early days.**
- **B factories: clean environment, good to detect neutral particles; lower boost, poorer lifetime resolution**
- **LHCb/hadron machine: huge production X-section, excellent lifetime resolution due to the boost; large combinatorial BG, difficult with neutral and missing particles**

Unique advantage at BESIII: BG free and Double tag method (DT)



Signal side: μ^+ is reconstructed, ν is reconstructed by MM^2

$$E_{miss} = E_{beam} - E_{\mu^+}, \quad \vec{p}_{miss} = -\vec{p}_{D^-} - \vec{p}_{\mu^+}$$

$$M^2_{miss} = E^2_{miss} - |\vec{p}_{miss}|^2, \quad U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

Tag side: $K^+K^-\pi^-$ +...., very clean decay modes

Non-$D_s^{*+}D_s^-$ events can be suppressed by beam-constrained mass cut $M_{BC} \equiv \sqrt{\left(\frac{E_{CM}}{2}\right)^2 - |\vec{p}_{D_s^-}|^2}$

ST yield: $N^i_{ST} = 2 \times N_{D\bar{D}} \times B^i_{ST} \times \varepsilon^i_{ST}$

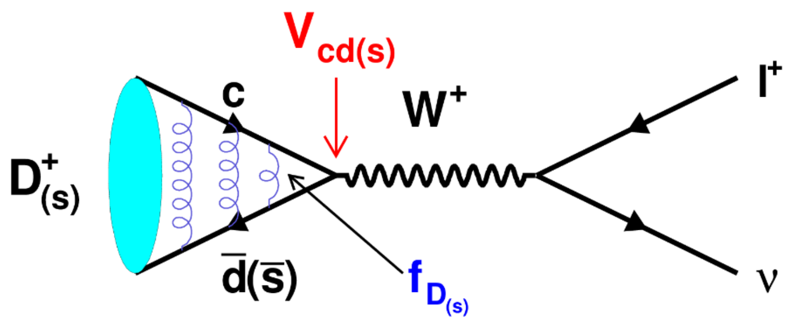
DT yield: $N^i_{DT} = 2 \times N_{D\bar{D}} \times B^i_{ST} \times B_{sig} \times \varepsilon^i_{ST\ vs.sig}$

Average eff.: $\bar{\varepsilon}_{sig} = \sum_{i=1}^{N} (N^i_{ST} \times \varepsilon^i_{ST\ vs.sig} / \varepsilon^i_{ST}) / \sum_{i=1}^{N} N^i_{ST}$

Absolute Br. $B_{sig} = \frac{N^{tot}_{DT}}{N^{tot}_{ST} \times \bar{\varepsilon}_{sig}}$

Advantages: almost background free, absolute Brs.

Charm Leptonic Decays $D_{(s)} \to \ell \nu$



- Charm leptonic decays involve both weak and strong interactions.
- The weak part is easy to be described as the annihilation of the quark-antiquark pair via the standard model W^+ boson.
- The strong interactions arise due to gluon exchanges between the charm quark and the light quark. These are parameterized in terms of the 'decay constant'.

Decay constant (LQCD)

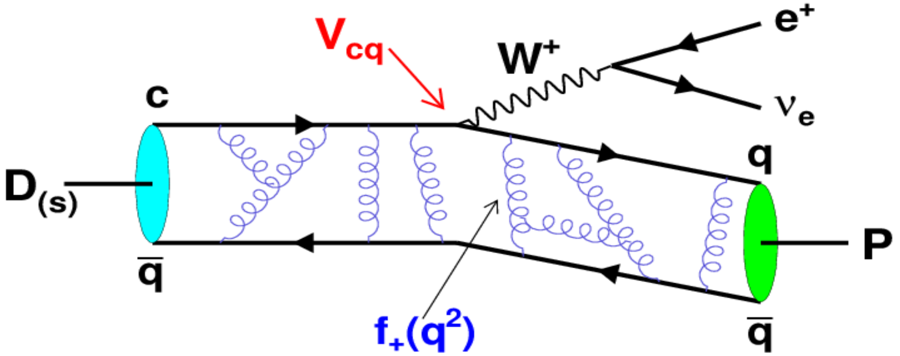
Decay rate (Exp.)

$$\Gamma(D_{(s)} \to \ell\nu) = |V_{cd(s)}|^2 \times f^2_{D_{(s)}} \times \frac{G_F^2}{8\pi} m_\ell^2 m_{D_{(s)}} (1 - m_\ell^2/m^2_{D_{(s)}})^2$$

CKM matrix element

- Exp. decay rate + $|V_{cs(d)}|^{CKMfitter}$ → calibrate LQCD @charm & extrapolate to Beauty
- Exp. decay rate + LQCD → CKM matrix elements

Charm semi-leptonic decays $D_{(s)} \to \pi(K)\ell\nu$



- The effects of the strong and weak interactions can be separated in semi-leptonic decays
- Good place to measure CKM matrix elements and study the weak decay mechanism of charm mesons; calibrate LQCD

At zero positron mass limit:

Differential rate (Exp.) — CKM matrix element — Form factor (LQCD)

$$\frac{d\Gamma(D_{(s)} \to K(\pi)\ l\nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2 P_{K(\pi)}^3}{24\pi^3} |f_+(q^2)|^2$$

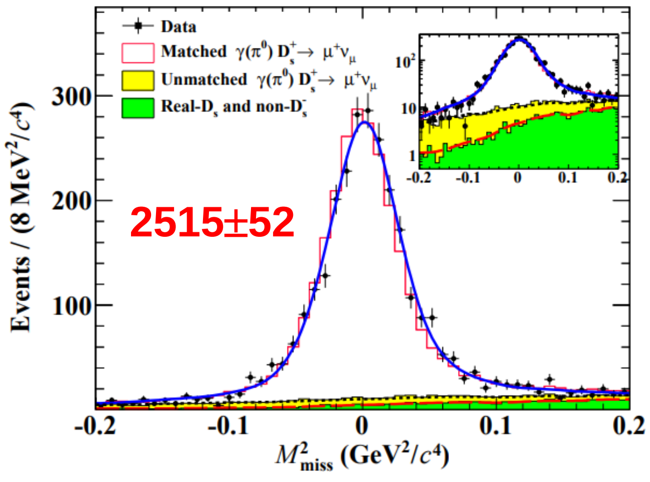
- **Analyze exp. partial decay rates → q^2 dependence of $f_+^{K(\pi)}(q^2)$, extract $f_+^{K(\pi)}(0)$ with $|V_{cs(d)}|^{CKMfitter}$ as input – calibrate LQCD**
- **Exp. + LQCD calculation of $f_+^K(0)$ and $f_+^\pi(0)$ → $V_{cs(d)}$ – constrain CKM**

Precision measurement of $D_{(s)}^{+} \to l^{+}\nu_{l}$

$D_s^+ \to \mu^+\nu_\mu$

PRL122, 071802 (evts. 1136± 33)
PRD104, 052009

PRD108(2023)112001
7.33 fb^{-1}@4.18-4.23GeV



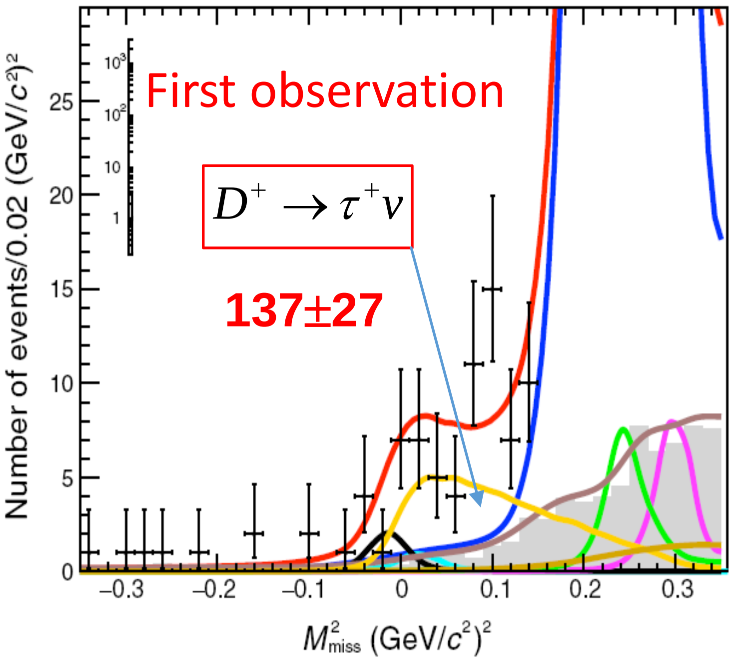
$f_{D_s^+}|V_{cs}| = (241.8 \pm 2.5 \pm 2.2)$ MeV

$\delta f_{D_s^+}|V_{cs}|$ ~1.4%

The most precise to date.

$D^+ \to l^+\nu_l$

PRL123(2019)211802
2.93 fb^{-1}@3.773 GeV

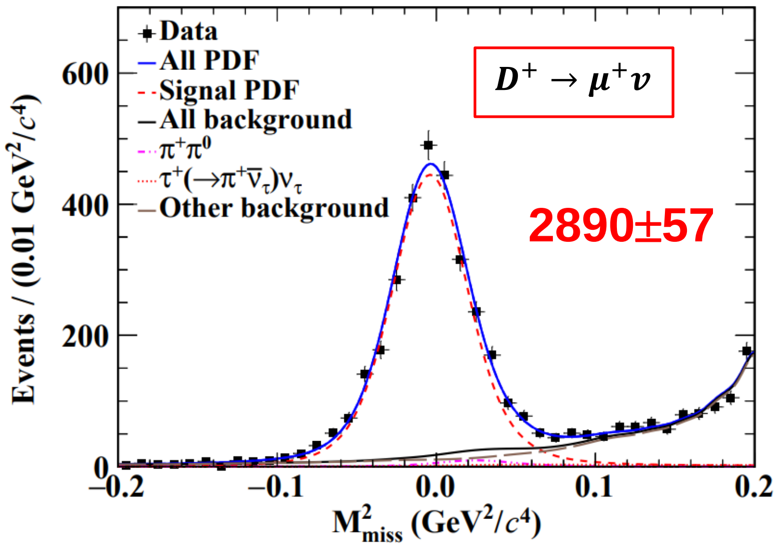


$f_{D^+}|V_{cd}| = 50.4 \pm 5.0 \pm 2.5$ MeV

Precision~11%

PRD89(2014)051104 (evts. 409±21)

arXiv:2410.07626,
20.3 fb^{-1}@3.773 GeV

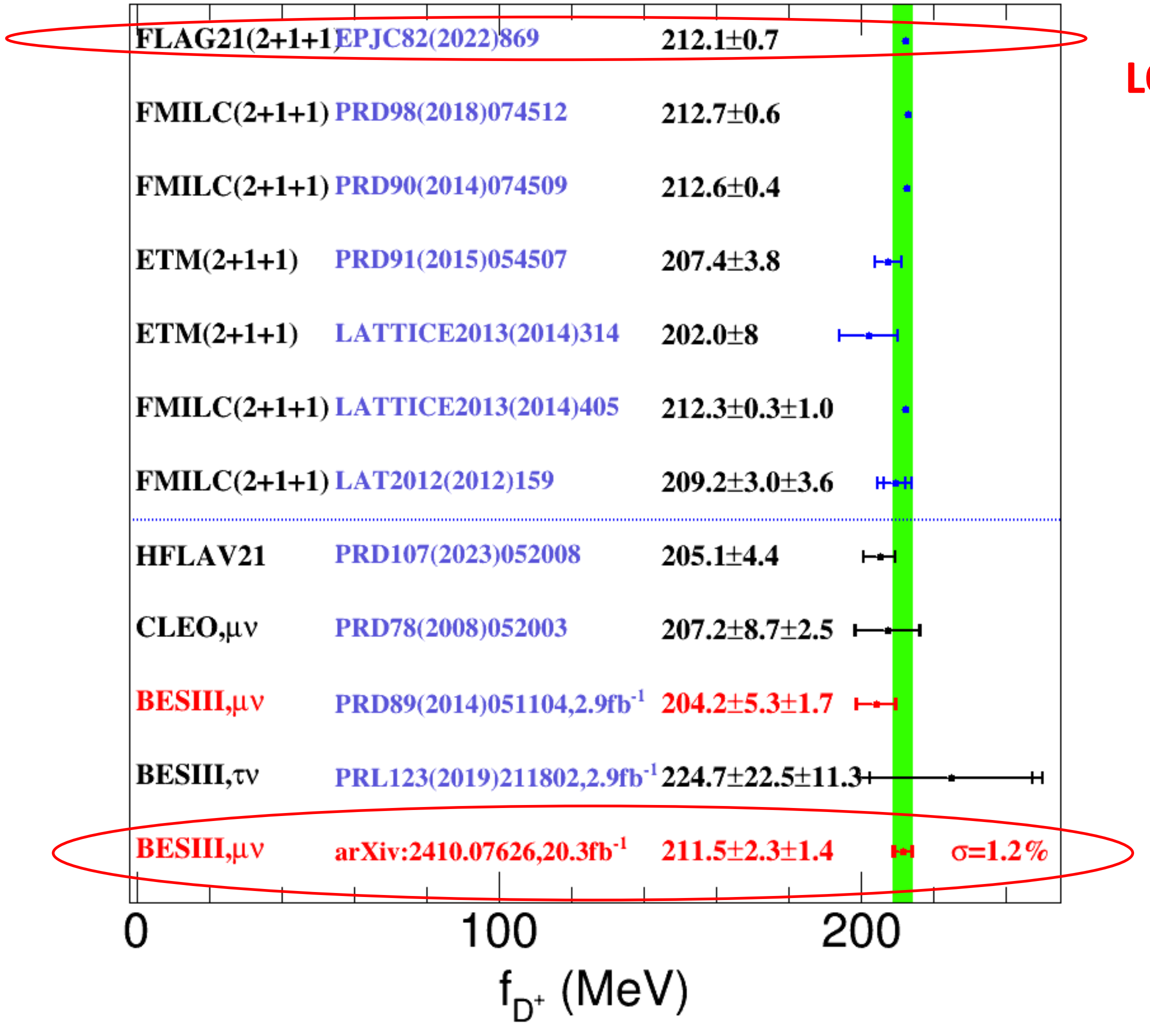


$f_{D^+}|V_{cd}| = 47.53 \pm 0.48 \pm 0.27$ MeV

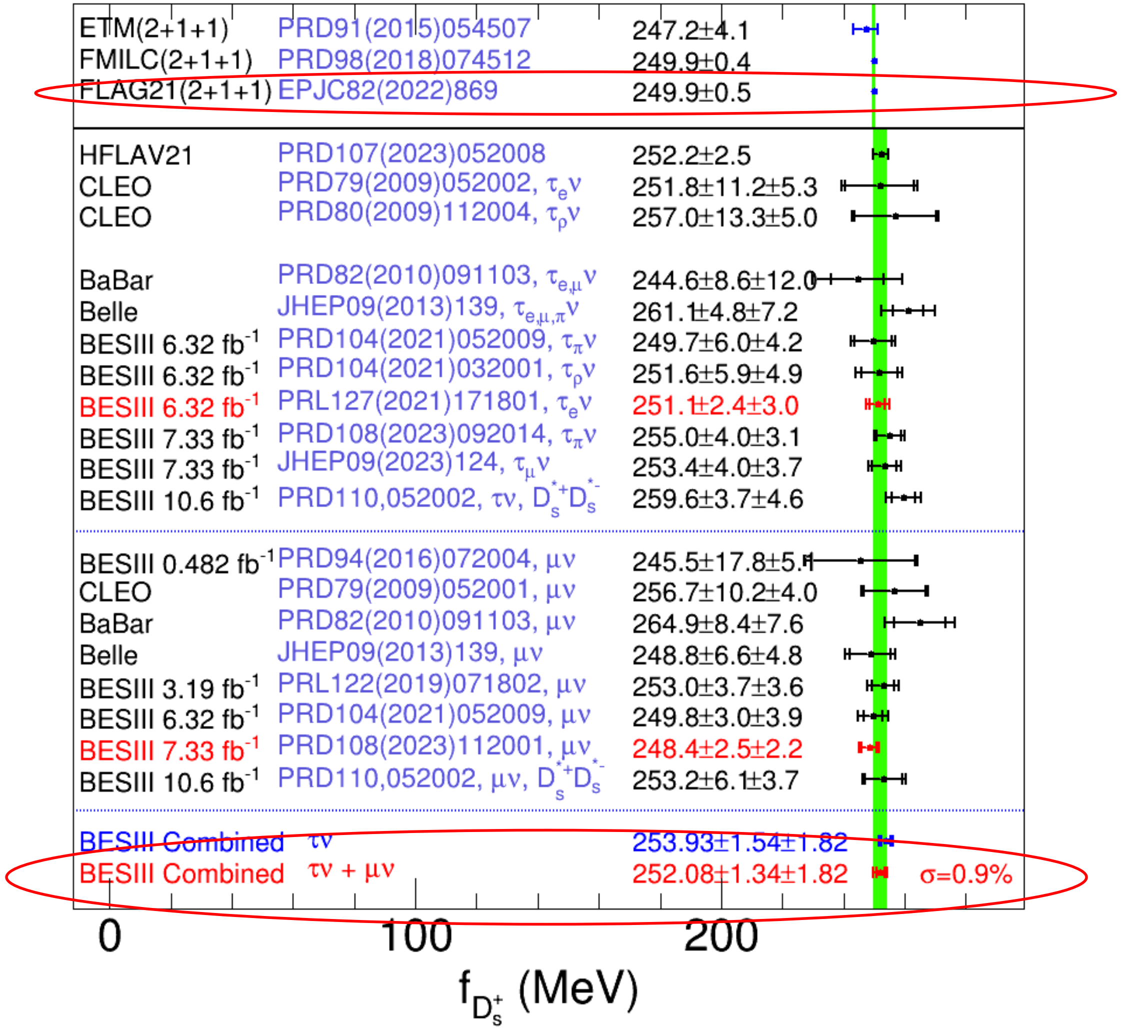
Precision~1.2%

The most precise to date.

Comparisons of f_{D^+} and $f_{D_s^+}$



LQCD

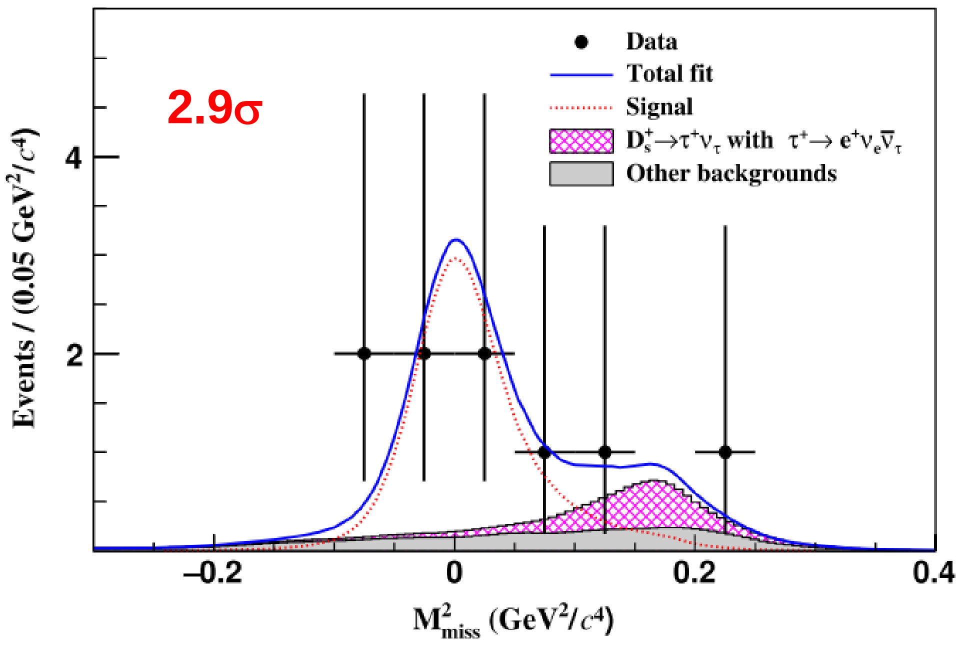


The errors from the exps. are still larger than those from LQCD calculations.

First indication of vector $D_s^{*+} \to e^+\nu_e$

PRL131 (2023) 141802

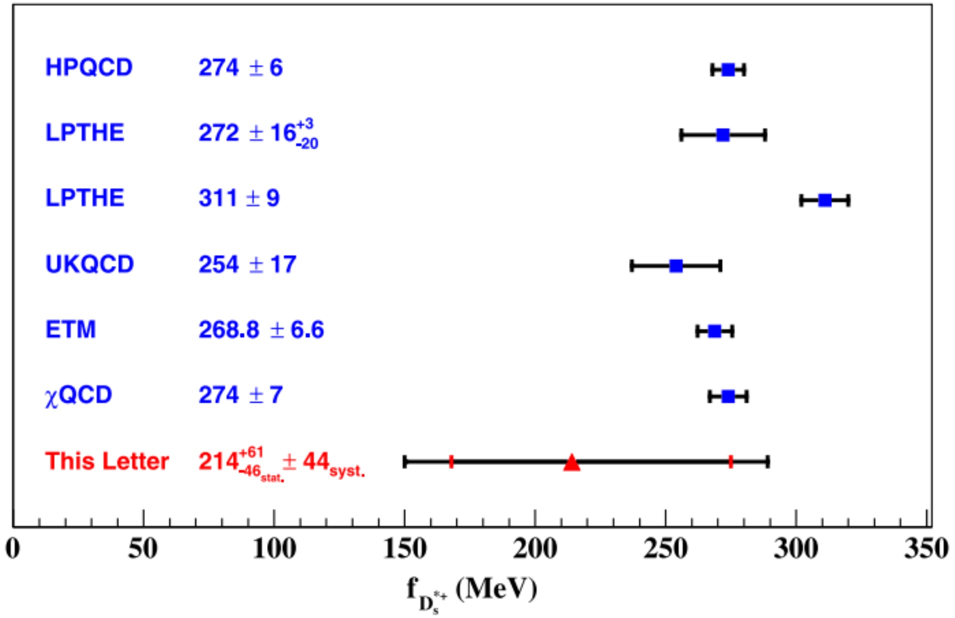
7.33 fb^{-1}@4.13-4.23 GeV



$$\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9\,\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-5}$$

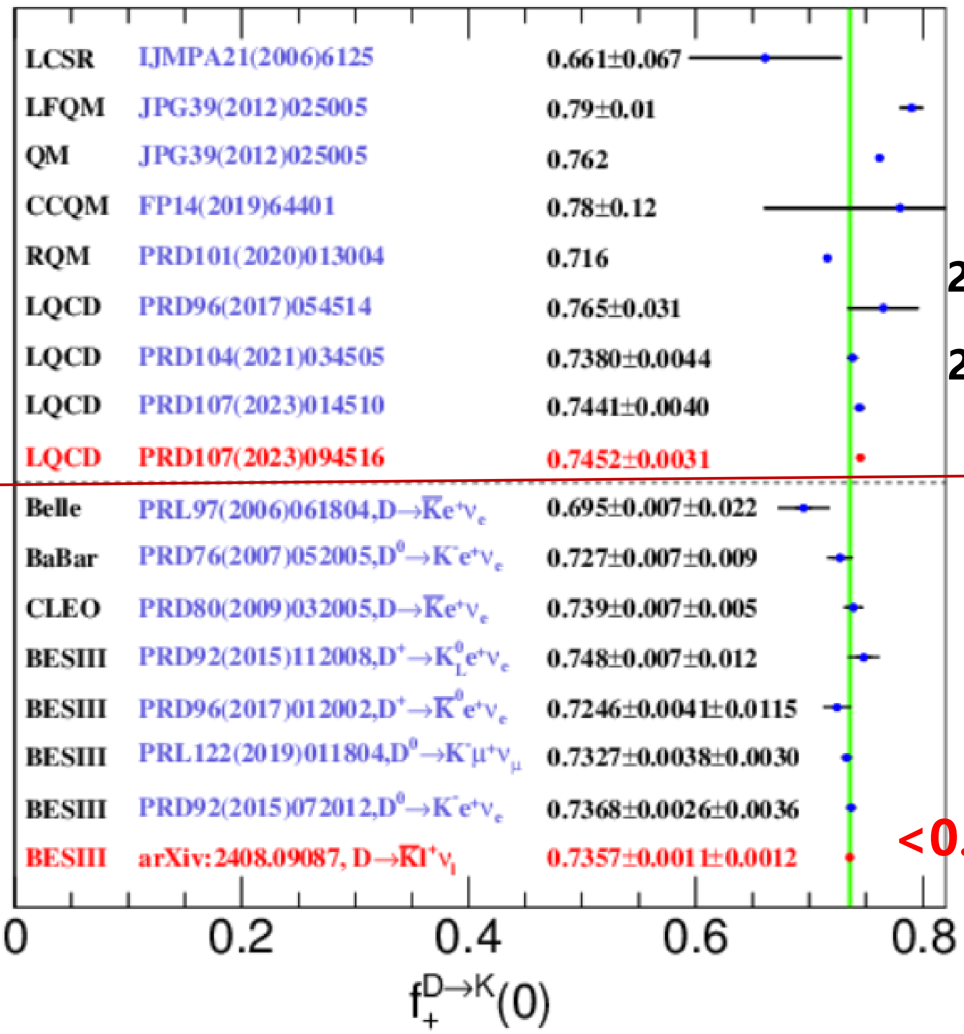
$$\Gamma(D_s^{*+} \to \ell^+\nu_\ell) = \frac{G_F^2}{12\pi}|V_{cs}|^2 f^2_{D_s^{*+}} m^3_{D_s^{*+}} \left(1 - \frac{m^2_{\ell^+}}{m^2_{D_s^{*+}}}\right)^2 \times \left(1 + \frac{m^2_{\ell^+}}{2m^2_{D_s^{*+}}}\right),$$

Taking the total width of the D_s^{*+}[(0.070±0.028) keV] predicted with the radiative D_s^{*+} decay from the LQCD calculation as input, the decay constant of the D_s^{*+} can be extracted.



→ Provide input to constrain LQCD calculation of D_s^{*+} decay constant

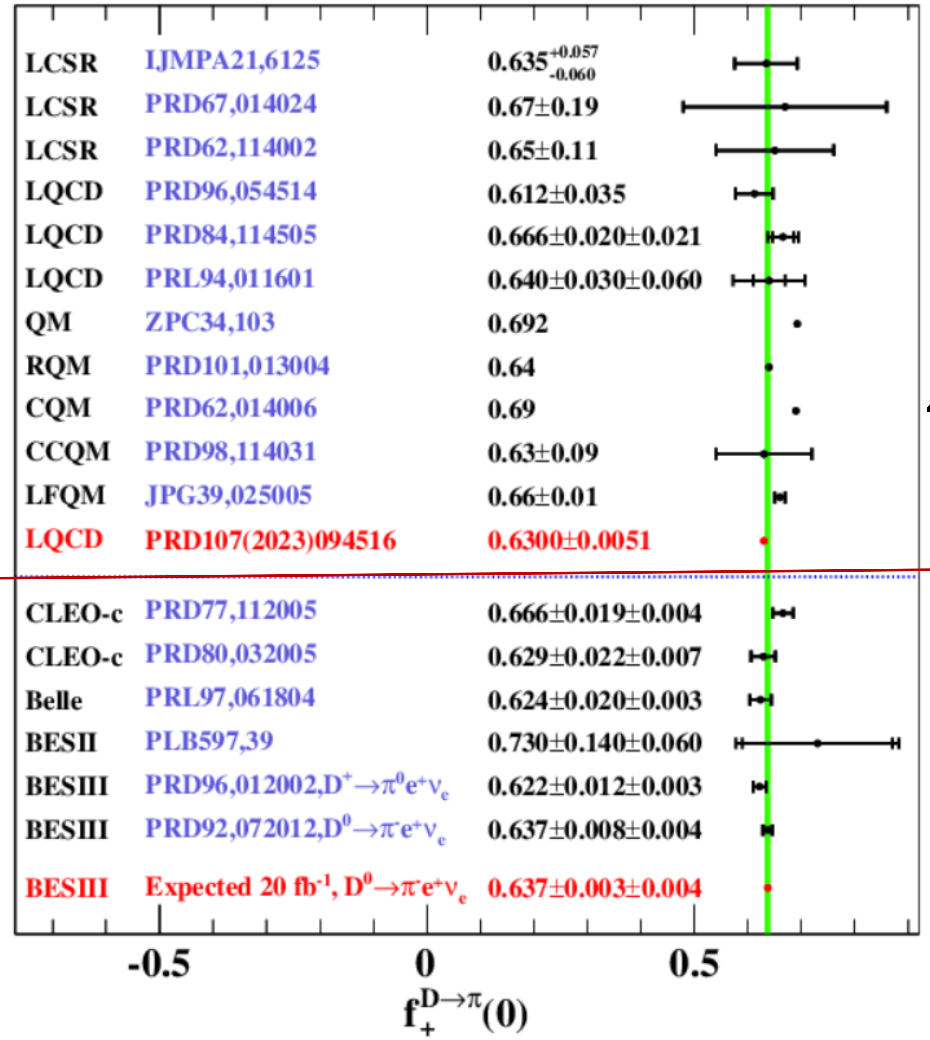
Comparisons of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$



2010→2023

2.4%→0.4%

<0.3%



2011→2023

4.4%→0.8%

1.6%(2.93fb^{-1})

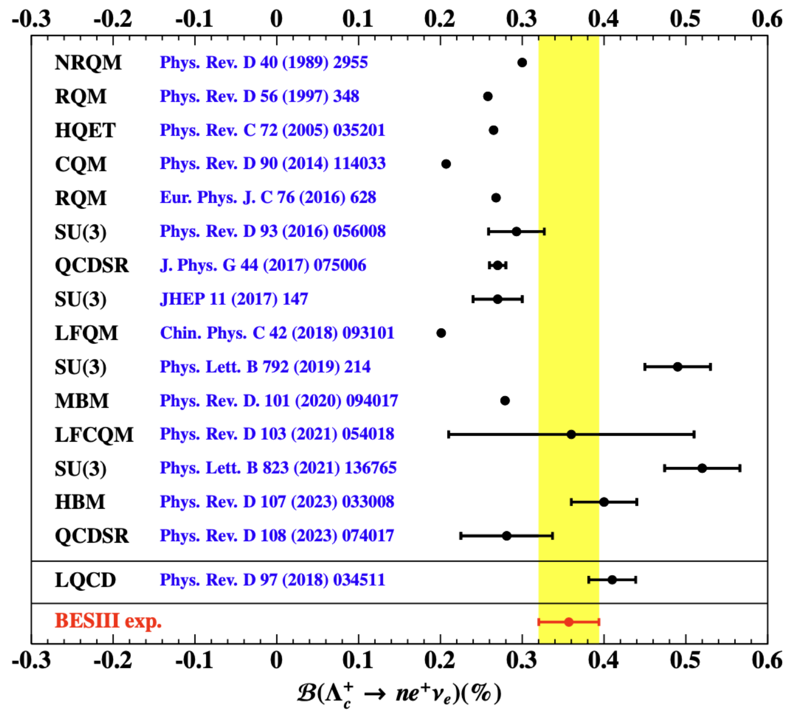
Experimental precision of $f_+^{D\to K}(0)$ is comparable to the latest LQCD precision

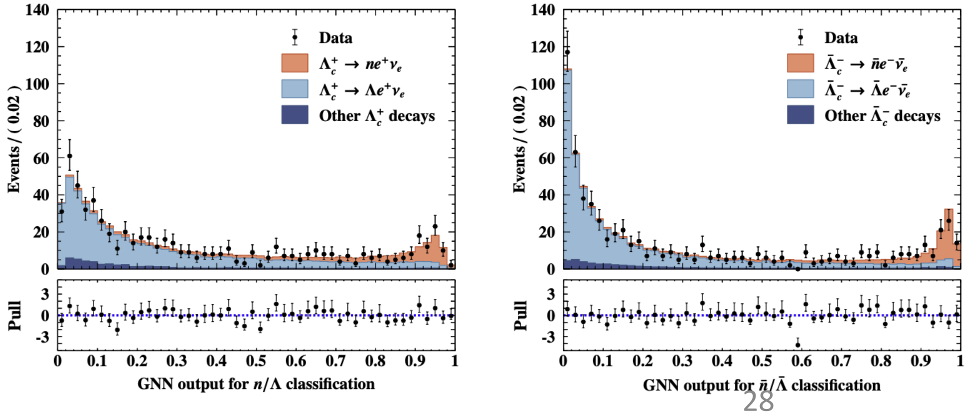
Experimental precision of $f_+^{D\to\pi}(0)$ is still dominated by statistical uncertainties

Observation of $\Lambda_c^+ \to n e^+ \nu_e$ with Deep Learning

arXiv:2410.13515 (submitted to NatComm)

- A novel Deep Learning is utilized to separate signals from dominant background.
- First observation of $\Lambda_c^+ \to n e^+ \nu_e$
  - $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (0.357 \pm 0.034_{\rm stat} \pm 0.014_{\rm syst})\%$ ($> 10\sigma$)
  - $|V_{cd}| = 0.208 \pm 0.011_{\rm exp.} \pm 0.005_{\rm LQCD} \pm 0.001_{\tau_{\Lambda_c^+}}$
- This measurement demonstrates a level of precision comparable to the LQCD prediction.
- The absence of HCAL restricted us to extract the form factors.
- Still, the BF provides significant insights, shedding light on the di-quark structure within the Λ_c^+ core and the $\pi - N$ clouds in the low Q^2.



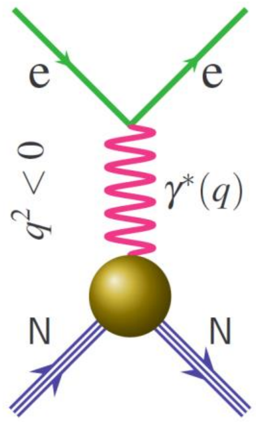


Baryon Form Factors

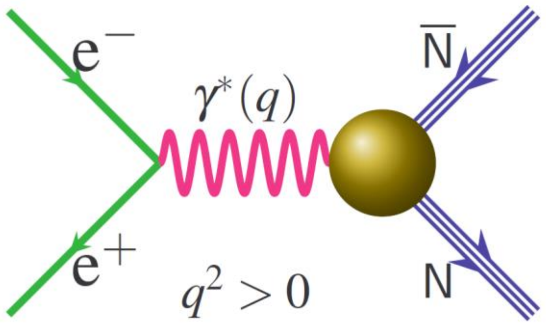
- Fundamental properties
  - Connected to charge, magnetization distribution
  - Crucial testing ground for models of the baryon internal structure
  - Necessary input for experiments probing nuclear structure, or trying to understand modification of nucleon structure in nuclear medium
- Nucleon FF Can be measured from space-like processes (eN) (precision 1%) or time-like process (e^+e^- annihilation) (precision 10%-30%)

eN → eN

Space-like:
FF real



$e^+e^- \leftrightarrow N\bar{N}$, $\Lambda\bar{\Lambda}$

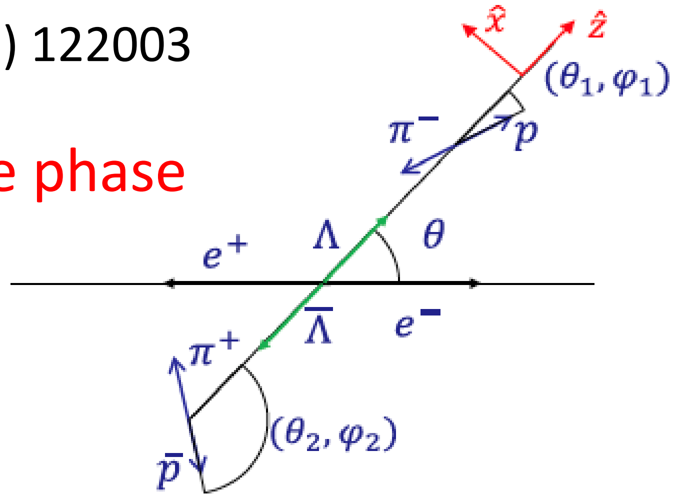


Time-like:
FF complex

First complete measurement of Λ E & M form factors

(E_{cm}=2.396 GeV , L=66.9 pb^{-1})

PRL 123 (2019) 122003



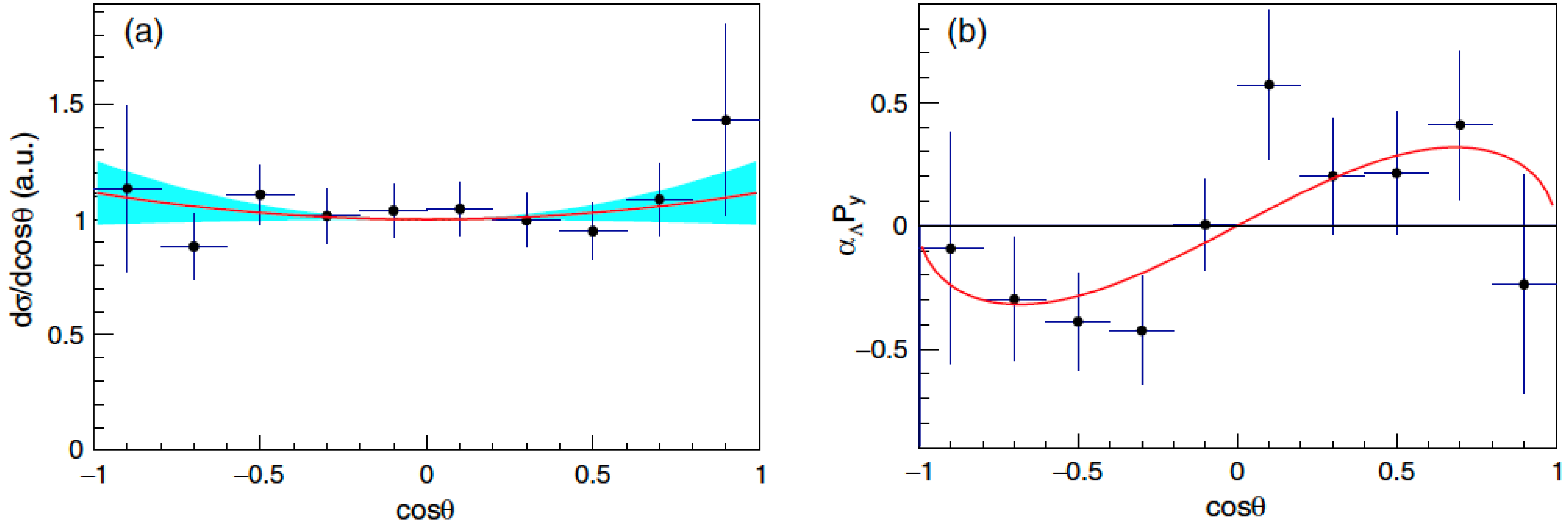
First measurement of the relative phase

$$R = |\frac{G_E}{G_M}| = 0.96 \pm 0.14 \pm 0.02$$

$$\Delta\phi = 37^0 \pm 12^0 \pm 6^0$$

$$\sigma(e^+e^- \to \Lambda\bar{\Lambda}) = 118.7 \pm 5.3 \pm 5.1pb$$

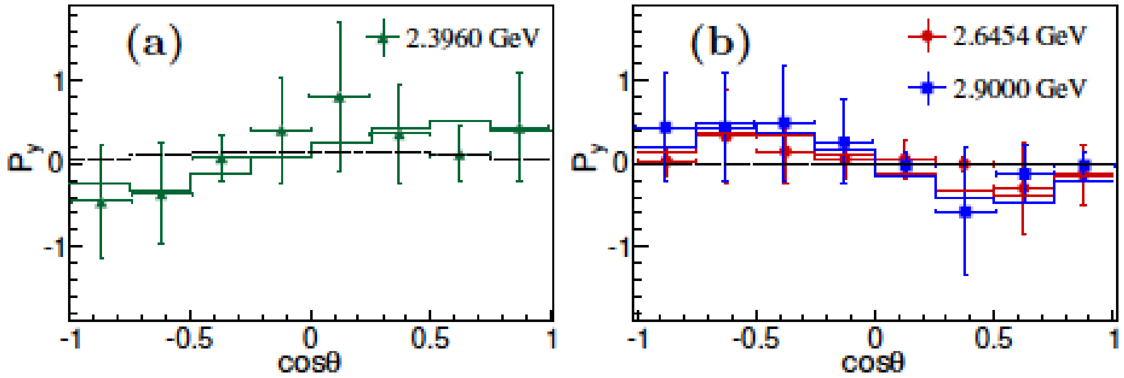
(Relative phase between G_E and G_M FF)



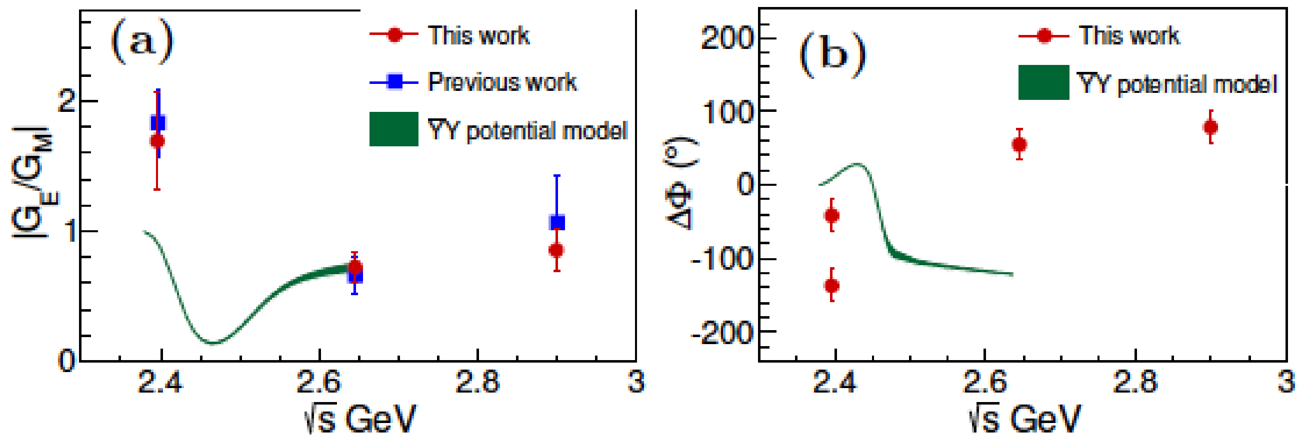
First complete measurement of Σ^+ E & M form-factors

PRL 132 (2024) 081904

Polarization measurements at different center of mass energies



First measurement of the relative phase ΔΦ between G_E and G_M form factors



$\sqrt{s}$ (GeV)	2.3960	2.6454	2.9000
α	-0.47 ± 0.18 ± 0.09	0.41 ± 0.12 ± 0.06	0.35 ± 0.17 ± 0.15
$\Delta\Phi$ (°)	-42 ± 22 ± 14 (-138 ± 22 ± 14)	55 ± 19 ± 14	78 ± 22 ± 9
$\sin\Delta\Phi$	-0.67 ± 0.29 ± 0.18		
$\lvert G_E/G_M\rvert$	1.69 ± 0.38 ± 0.20	0.72 ± 0.11 ± 0.06	0.85 ± 0.16 ± 0.15

Such an evolution will be an important input for understanding its asymptotic behavior and the dynamics of baryons. Moreover, the fact that the relative phase is still increasing at 2.9 GeV indicates that the asymptotic threshold has not yet been reached. A. Mangoni, S. Pacetti, and E. Tomasi-Gustafsson, Phys. Rev. D 104, 116016 (2021).

BESIII achieved much

- Confinement -- far from being understood due to its non-perturbative nature.
  A detailed study of the hadrons and their properties will shed light on this
  part of QCD.
- New sources of CP violation
  BESIII: 4 million hyperon pairs
  Billion of hyperon pairs reconstructed → CPV： $10^{-4} - 10^{-5}$
  challenge SM
- ....

Summary

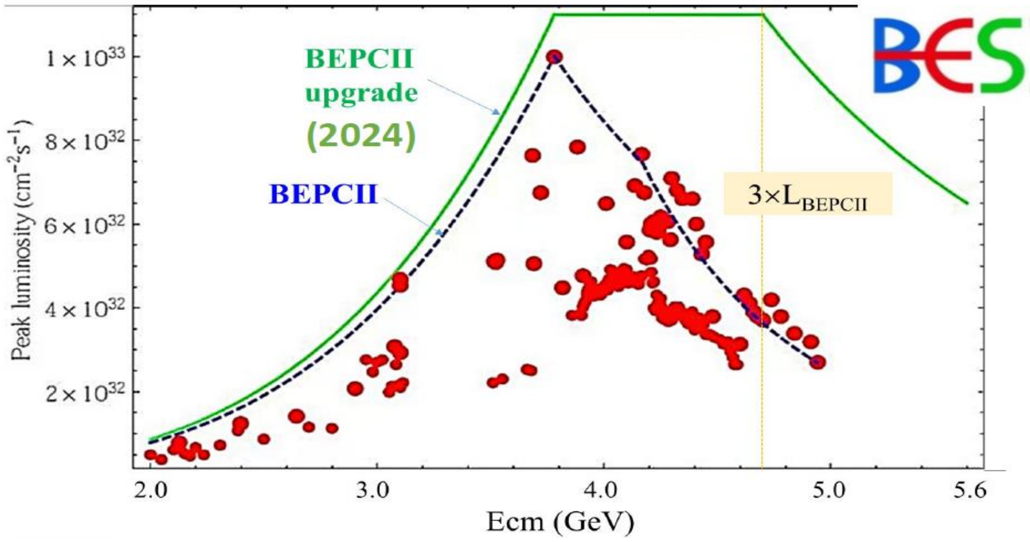
BEPCII upgrade (2024 – 2028)

Highest beam energy: 2.8 GeV

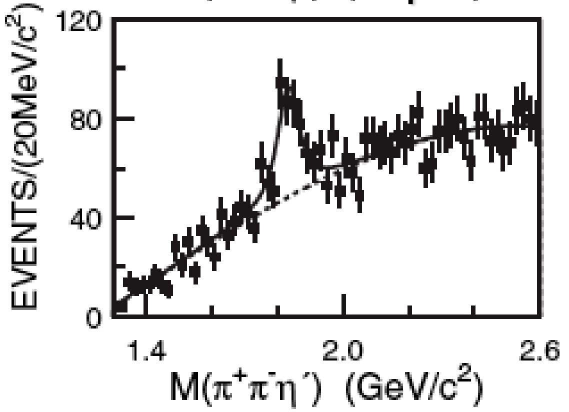
Peak Lum.: 3.77 ~ 4.7 GeV : 1.2 $\times 10^{33}$ cm^{-2}s^{-1}

5.0 ~ 5.6 GeV: (0.5-0.7) $\times 10^{33}$ cm^{-2}s^{-1}

BESIII: CGEM succcessfully installed.

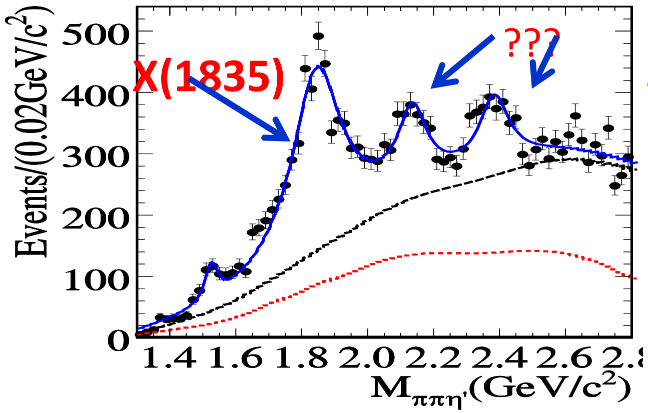


BESII: 58 M J/ψ events



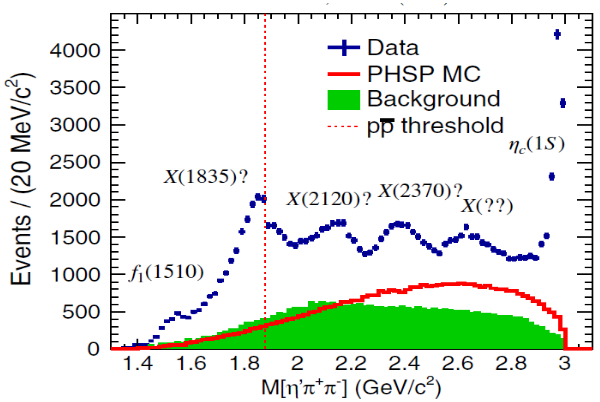
PRL 95,262001(2005)

BESIII: 225 M J/ψ events



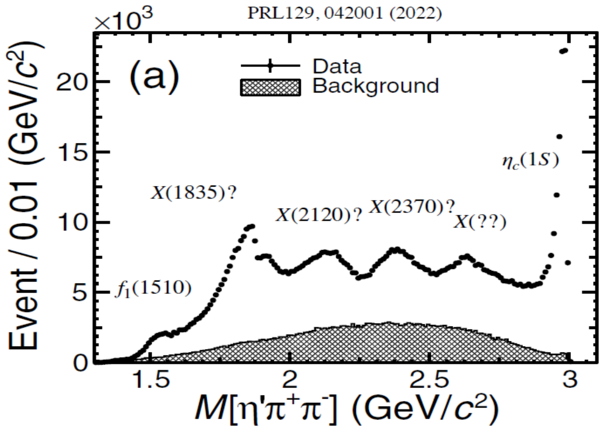
PRL 106, 072002 (2011)

BESIII: 1.1B J/ψ events



PRL 117, 042002 (2016)

BESIII: 10 B J/ψ events



PRL 129, 042001 (2022)

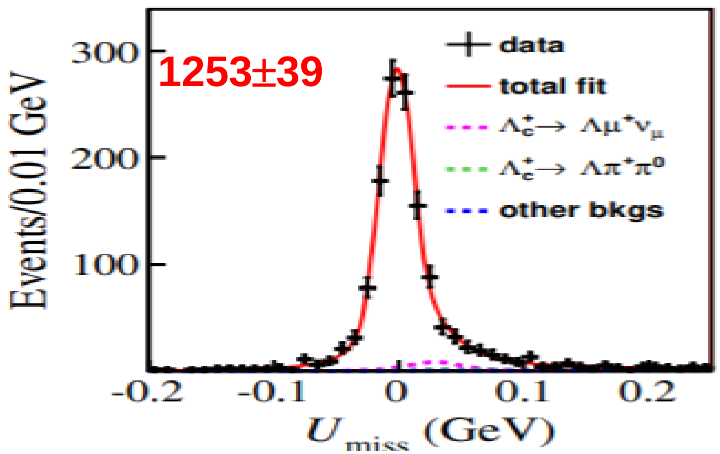
High statistics data bring us more opportunities (surprises) and challenges.

Thanks for your attention

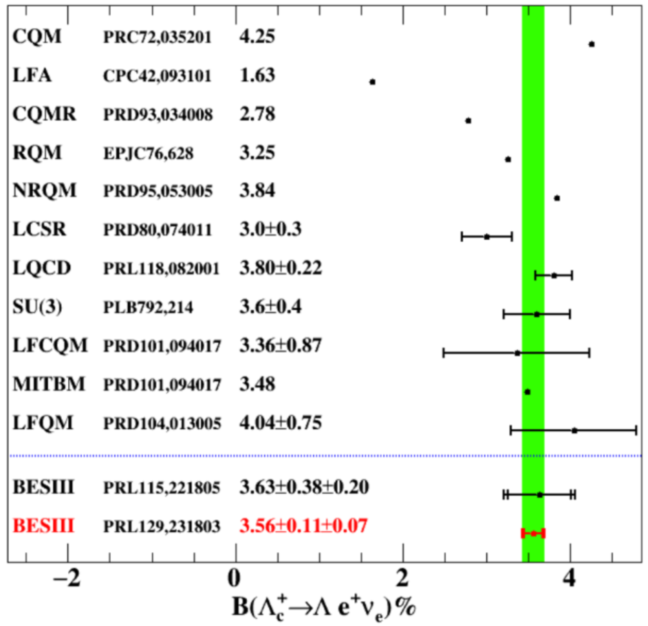
谢谢

First measurement of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ form factors

PRL129(2023)231803



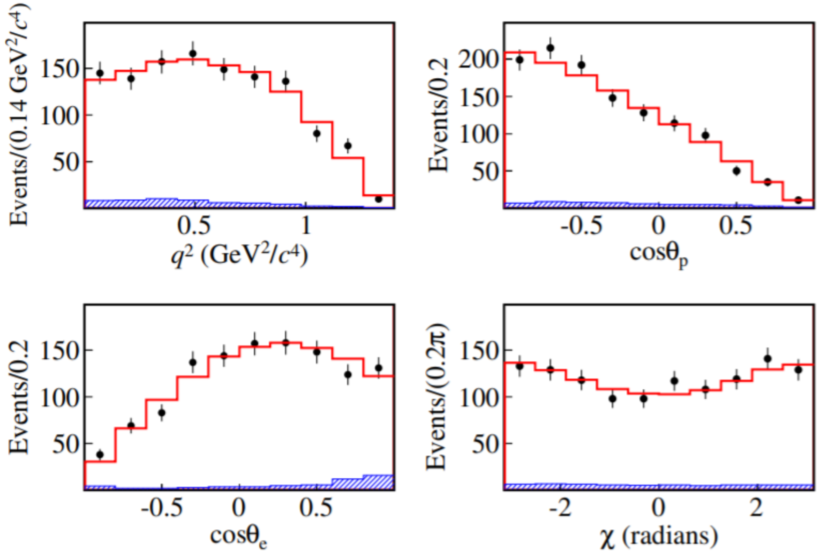
$\mathrm{B}[\Lambda_c^+ \to \Lambda e^+ \nu_e] = (3.56 \pm 0.11 \pm 0.07)\%$



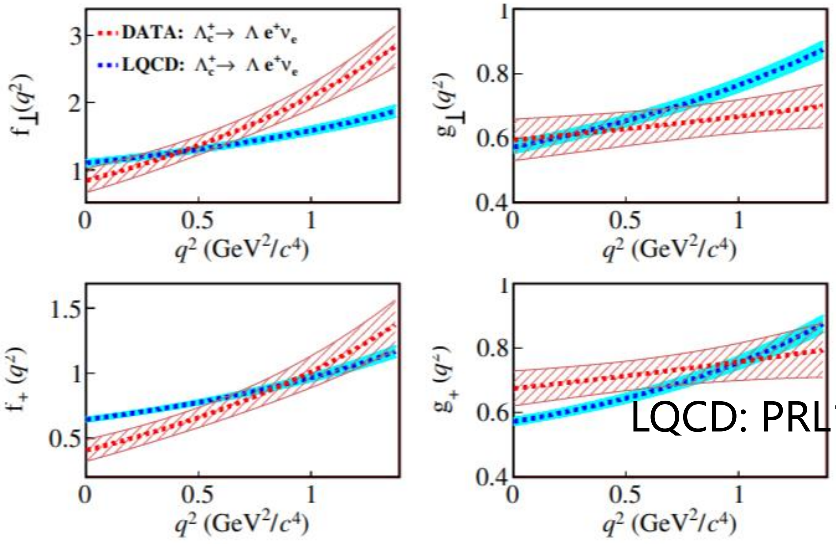
Decay rates

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_e d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4}\cdot\frac{Pq^2}{24M_{\Lambda_c}^2}\times$$
$$\Big\{\frac{3}{8}(1-\cos\theta_e)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{8}(1+\cos\theta_e)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta_e[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]$$
$$+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta_e\sin\theta_p\times$$
$$[(1-\cos\theta_e)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta_e)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]\Big\}, \quad (2)$$

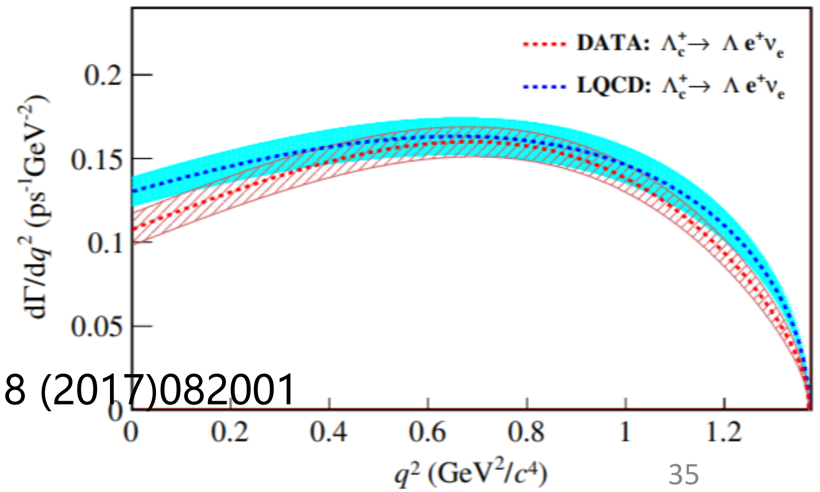
Projections on kinematic variables



Projections on form factors



Compared to LQCD decay rates



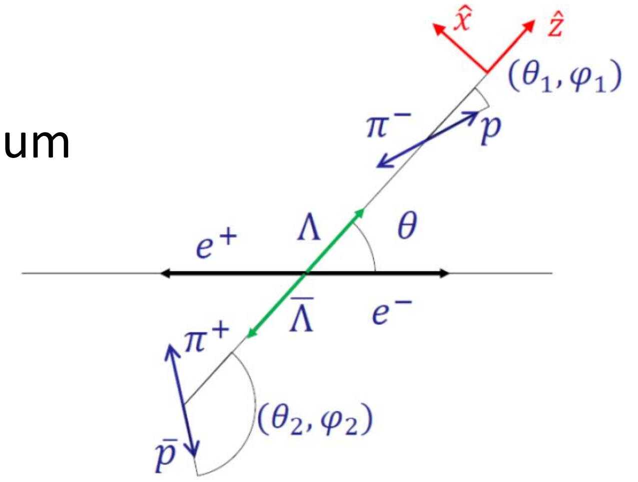
LQCD: PRL118 (2017)082001

Formalism for $e^+e^- \to Y\bar{Y}, Y \to BM$

PLB 772, 16 (2017)

The differential cross-section for events of the reaction $e^+e^- \to \Lambda(\to p\pi)\bar{\Lambda}(\to \bar{p}\pi)$ is:

$d\sigma \propto \mathcal{W}(\xi) \mathrm{d}cos\theta \ \mathrm{d}\Omega_1 \ \mathrm{d}\Omega_2,$



$\xi = (\theta_\Lambda, \hat{n}_1, \hat{n}_2)$ is kinematic variables, $\hat{n}_1(\hat{n}_2)$: unit vector of $p(\bar{p})$ momentum

$\Delta\Phi$: complex phase difference between two different amplitudes

α_1 and α_2: decay parameters of Λ and $\bar{\Lambda}$

$\Omega_1(\theta_1, \varphi_1)$ and $\Omega_2(\theta_2, \varphi_2)$ are decay angles in the rest flame of Λ and $\bar{\Lambda}$

$$\mathcal{W}(\boldsymbol{\xi}) = \mathcal{F}_0(\boldsymbol{\xi}) + \alpha\mathcal{F}_5(\boldsymbol{\xi}) + \alpha_1\alpha_2\left(\mathcal{F}_1(\boldsymbol{\xi}) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\mathcal{F}_2(\boldsymbol{\xi}) + \alpha\mathcal{F}_6(\boldsymbol{\xi})\right) + \sqrt{1-\alpha^2}\sin(\Delta\Phi)\left(\alpha_1\mathcal{F}_3(\boldsymbol{\xi}) + \alpha_2\mathcal{F}_4(\boldsymbol{\xi})\right)$$

Unpolarized part: $\mathcal{F}_0(\boldsymbol{\xi}) + \alpha\mathcal{F}_5(\boldsymbol{\xi})$

Spin correlated part: $\alpha_1\alpha_2\left(\mathcal{F}_1(\boldsymbol{\xi}) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\mathcal{F}_2(\boldsymbol{\xi}) + \alpha\mathcal{F}_6(\boldsymbol{\xi})\right)$

Polarized part: $\sqrt{1-\alpha^2}\sin(\Delta\Phi)\left(\alpha_1\mathcal{F}_3(\boldsymbol{\xi}) + \alpha_2\mathcal{F}_4(\boldsymbol{\xi})\right)$

$$\mathcal{F}_0(\boldsymbol{\xi}) = 1$$
$$\mathcal{F}_1(\boldsymbol{\xi}) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$\mathcal{F}_2(\boldsymbol{\xi}) = \sin\theta \cos\theta \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)$$
$$\mathcal{F}_3(\boldsymbol{\xi}) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$
$$\mathcal{F}_4(\boldsymbol{\xi}) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$
$$\mathcal{F}_5(\boldsymbol{\xi}) = \cos^2\theta$$
$$\mathcal{F}_6(\boldsymbol{\xi}) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2 .$$

BESIII $J/\psi \to \Xi^-\bar{\Xi}^+, \Xi^- \to \Lambda\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

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Parameter	This work	Previous result
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$ *
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010 **
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad **
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$ ***
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$ ***
$\xi_p - \xi_s$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–
$\delta_p - \delta_s$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad ****
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}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$ ***
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad	

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

- First measurement of the polarization
- Direct measurement of all decay parameters (previous exps. determined product $\alpha_\Xi\alpha_\Lambda$)
- Independent measurement of Λ decay parameters, good agreement with previous BESIII results. Similar precision with 6 times smaller data
- Measurement of weak phase difference $(\xi_p - \xi_s) = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad
  One of the most precise tests of CP symmetry for strange baryons.
  Consistent with SM calculation $(\xi_p - \xi_s)_{SM} = (1.8 \pm 1.5) \times 10^{-4}$ rad
- Three independent CP tests in single channel.
- Strong phase result is in tension with HyperCP. Compatible with SM.

* BESIII: PRD 93, 072003 (2018)

** PDG 2020

*** BESIII: Nature Physics 15, 631 (2019)

**** HyperCP, PRL 93, 011802 (2004)

Decays of light mesons

- Many exps. have been involved in the study of light mesons

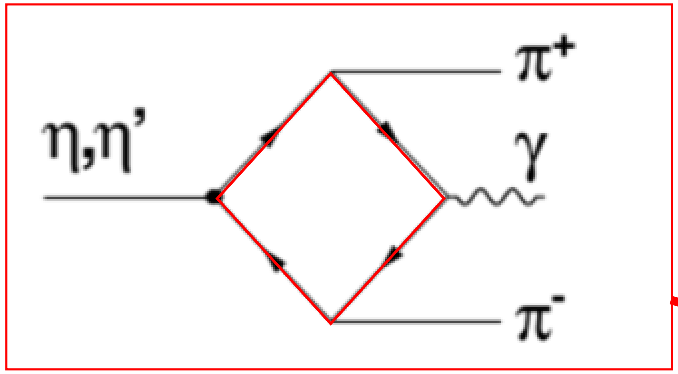
CLAS KLOE-2 A2 WASA-at-COSY

- BESIII is also a light meson factory with low BG
- 10^{10} J/ψ ⟶ 5×10^7 η′ and 1×10^7 η
- The decays of the light mesons:
  - ✓ precision measurement of decay Brs. → test chiral symmetry
  - ✓ measurement of light meson mixing → understand quark internal structure
  - ✓ precision measurement of form factors → muon g-2
  - ✓ rare decays → new physics beyond SM.

First observation of the box-anomaly in $\eta' \rightarrow \gamma\pi^+\pi^-$

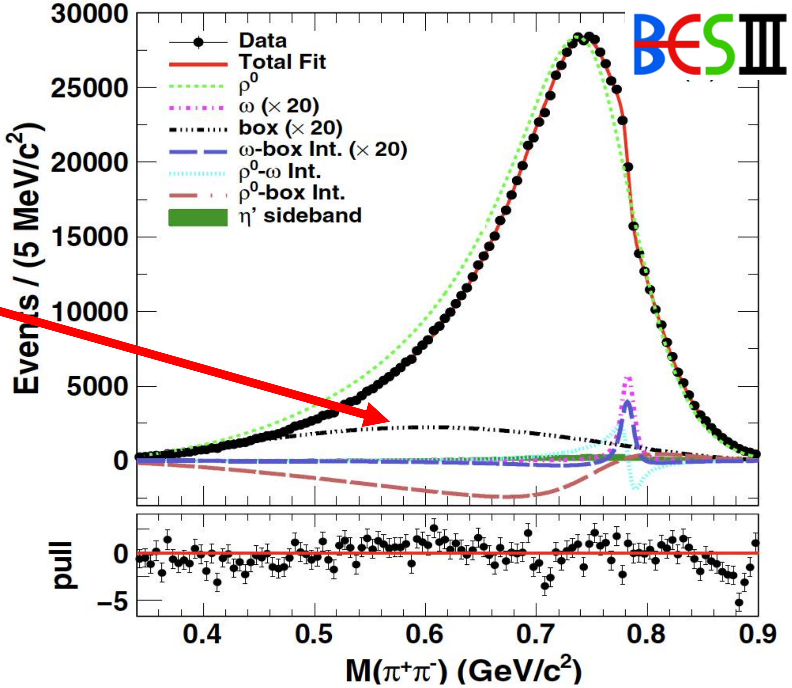
Theory predicted box-anomaly 40 years ago

J. Wess and B. Zumino, Phys. Lett. B **37**, 95 (1971); E.Witten, Nucl. Phys. **B223**, 422(1983)



~1 M $\eta' \rightarrow \gamma\pi^+\pi^-$ evets

box-anomaly observed



Phys. Rev. Lett., 120, 242003 (2018)

Phys. Report. 887,1(2020)

from singly-virtual input only. The dispersive formalism for the singly-virtual η/η' TFF has been established [658]: while the isoscalar part at low energies can be described in a VMD-type approximation due to the narrowness of the $\omega(782)$ and $\phi(1020)$ resonances, the isovector contribution relies, next to the pion vector form factor, heavily on data for the decays $\eta^{(\prime)} \rightarrow \pi^+\pi^-\gamma$ [659–661], which show strong deviations from a simple-minded ρ-dominance