Highlights at BESIII

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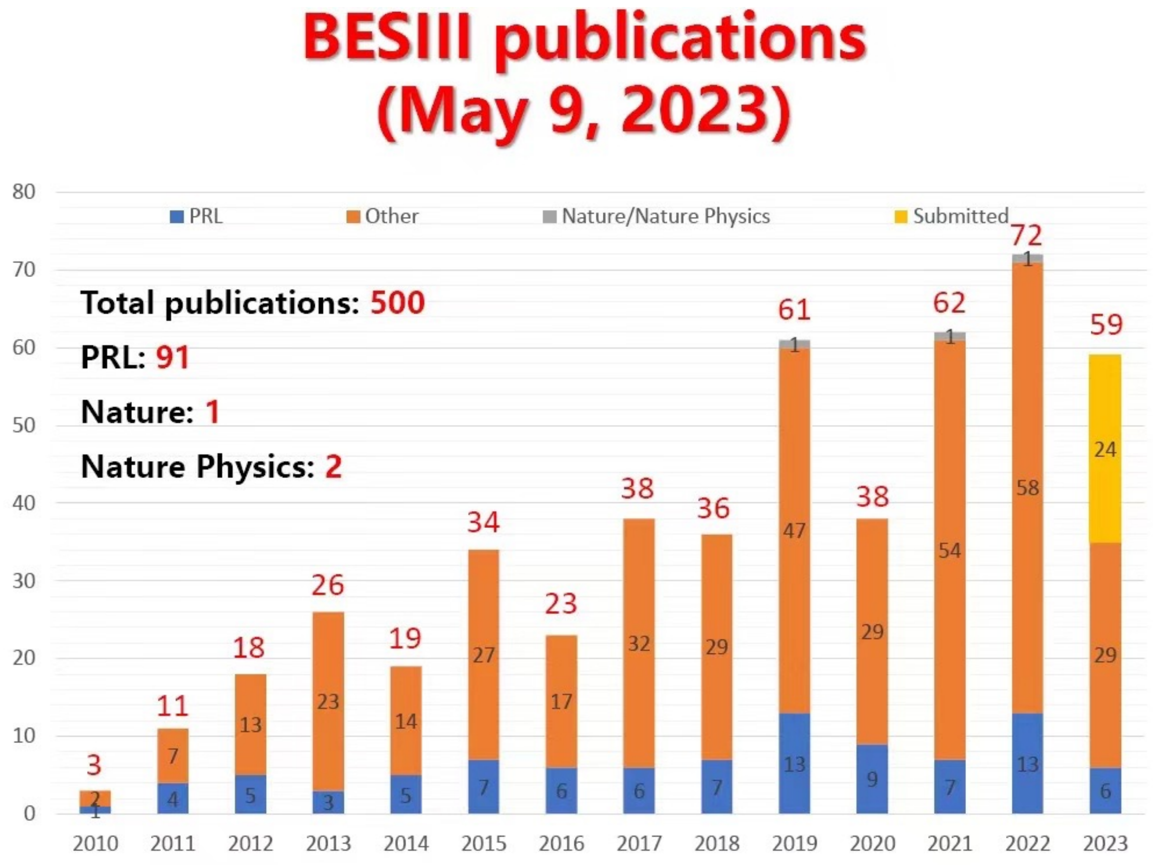
Outline

Selected results on:

- Light hadron spectroscopy
- Charm physics
- XYZ
- Hyperon physics
- R&QCD
- New Physics

- Summary



Light meson spectroscopy contributors

- **COMPASS (stopped running in 2021):**

  a high-energy physics experiment at the Super Proton Synchrotron (SPS) at CERN
  the study of hadron structure and hadron spectroscopy.

- **GlueX@JLAB (Photo-production, phase-1 stopped, phase-2 to 2027):**

- **CLAS12 @ JLAB, MesonEX program**

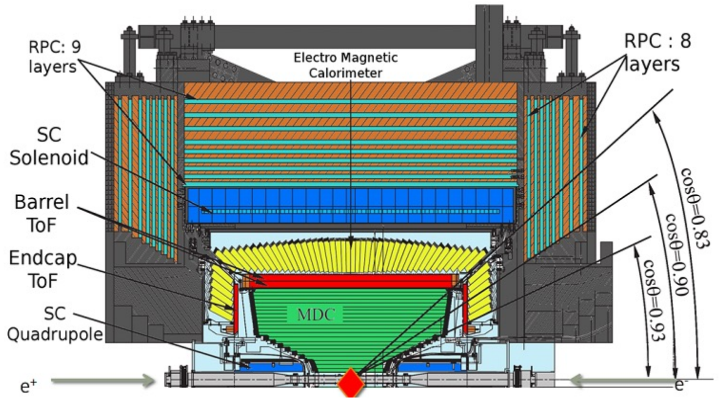
- **BESIII @BEPCII (unique advantages)**

- **$\bar{p}\ p$ @ PANDA (under construction, ~2031)**

- **STCF (proposal, c.m. energy 2-7 GeV)**

- **COMPASS ++/Amber (proposal, cover a broad Q^2 range)**

BESIII @ Beijing Electron Positron Collider (BEPC) – charm facility



MDC: spatial reso. 115μm

dE/dx reso: 5%

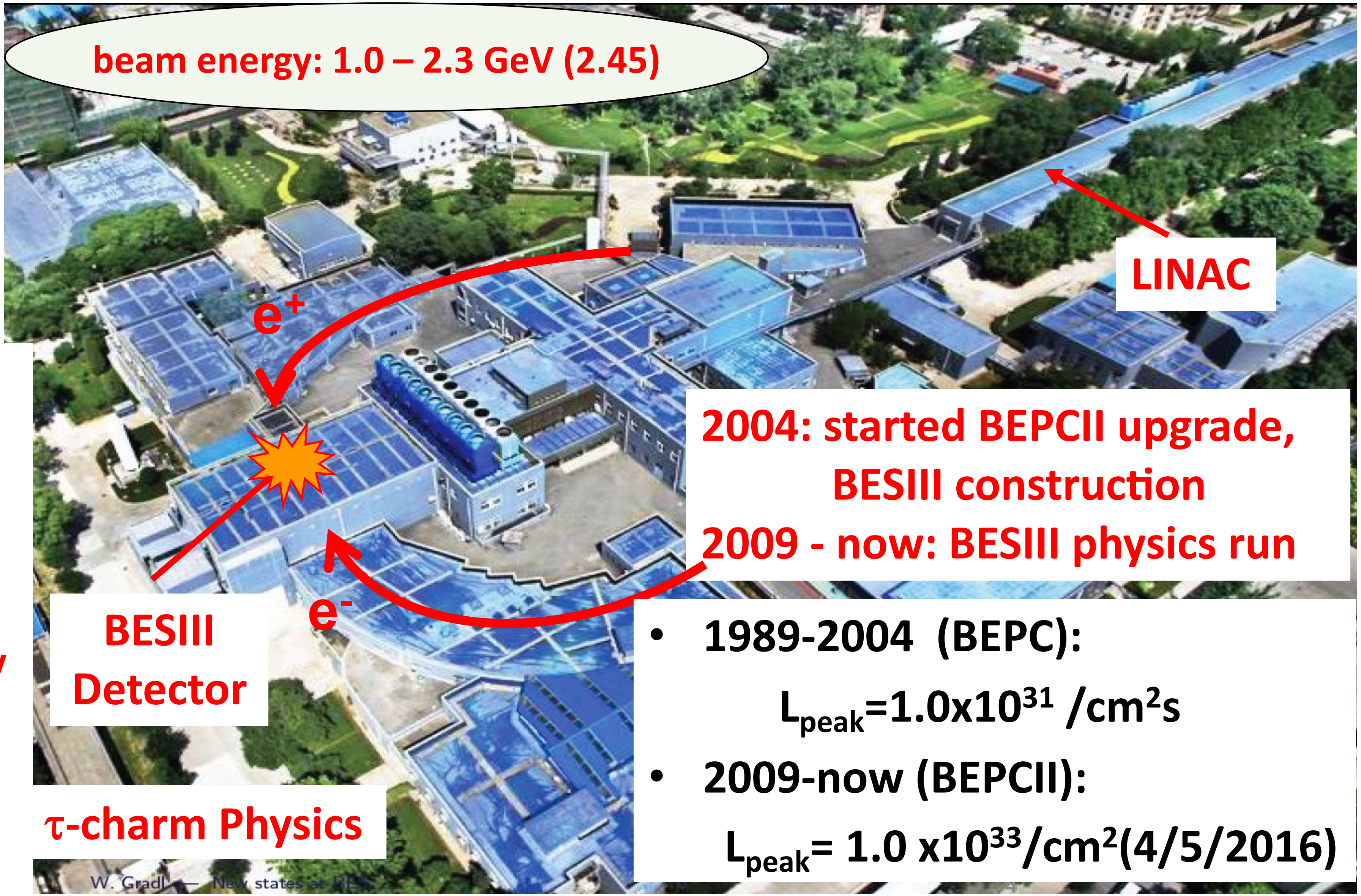
EMC: energy reso.: 2.4%

BTOF: time reso.: 70 ps

ETOF: time reso.: 60 ps

L_{peak}~ 1.1 x10^{33}/cm^2 @3770 MeV

- Production at thresholds
- Fixed initial and final states
- Low background

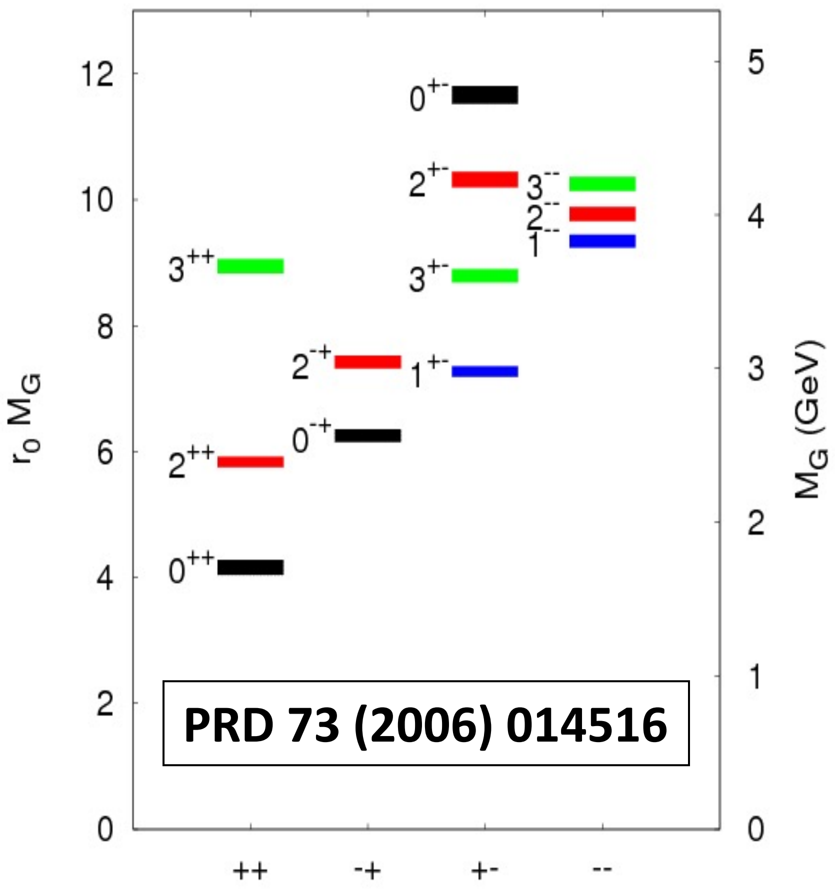


2004: started BEPCII upgrade, BESIII construction

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)

Glueball spectrum – Lattice QCD



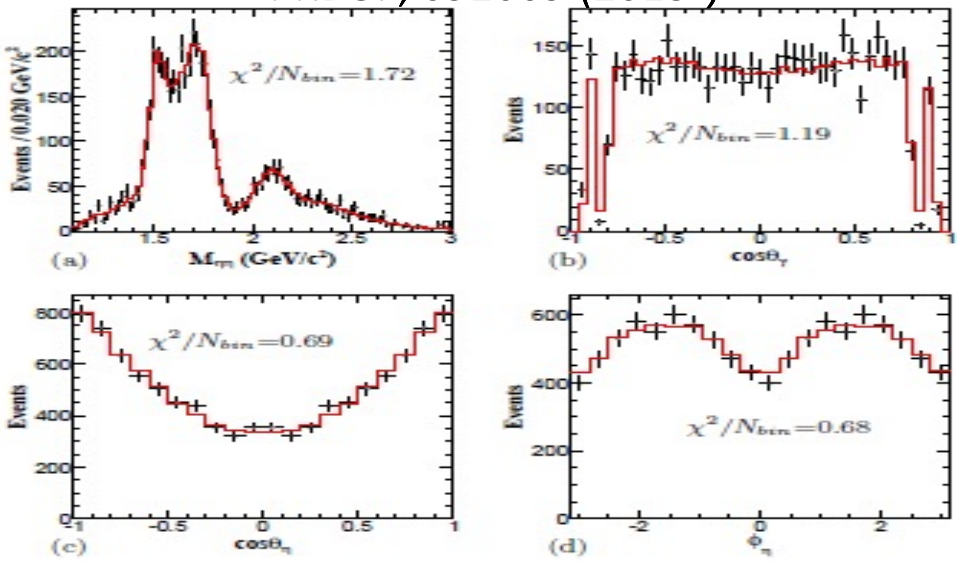
LQCD predicts:

- **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 > 2.4 GeV**
- **The mix of glueballs with ordinary $\bar{q}q$ mesons makes the situation more difficult.**

Unquenched calculations have similar results.

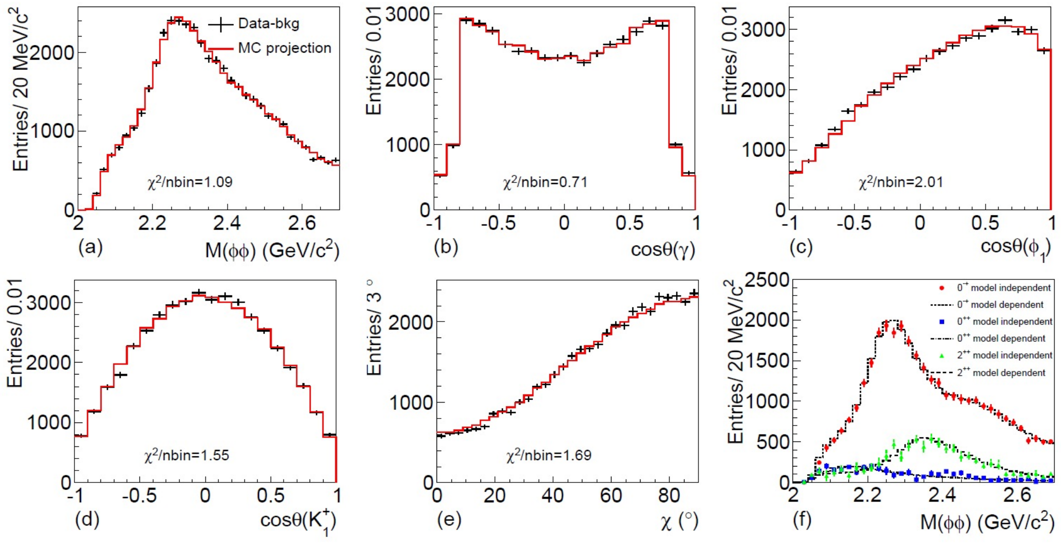
$J/\psi \to \gamma\eta\eta$ (225M J/ψ)

PRD87, 092009 (2013)



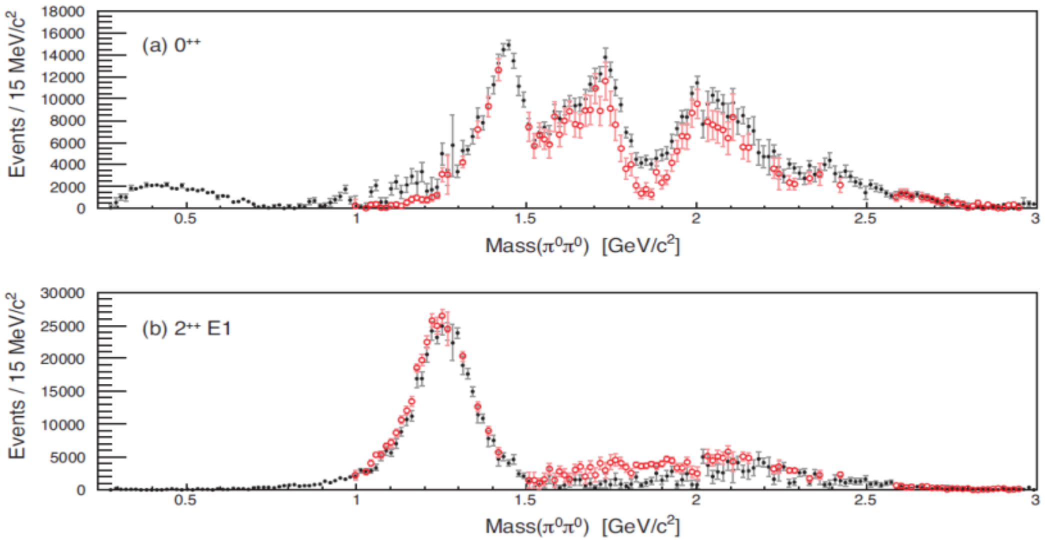
$J/\psi \to \gamma\phi\phi$ (225M J/ψ)

PRD 93, 112011(2016)



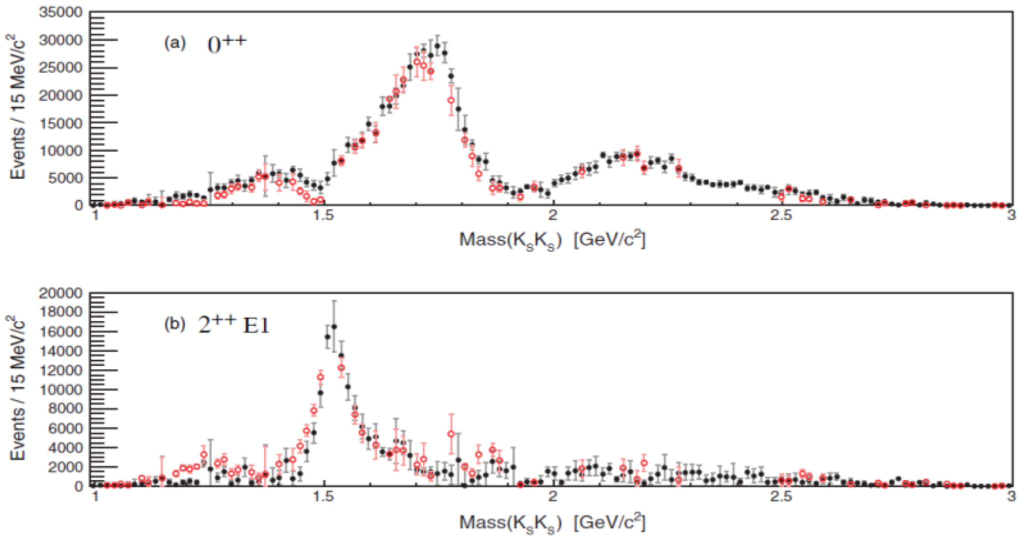
$J/\psi \to \gamma\pi^0\pi^0$ (1.3B J/ψ)

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)

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

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

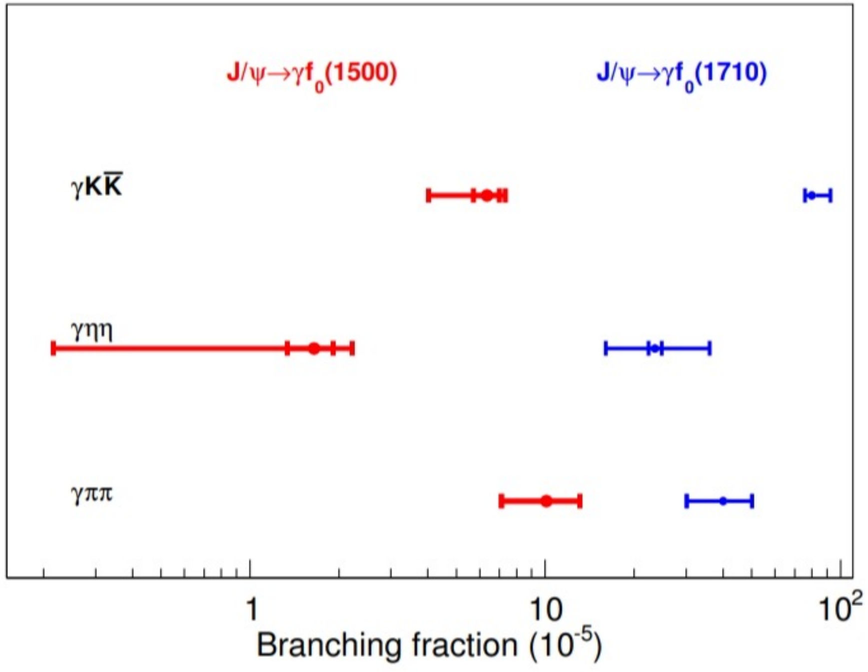
$J/\psi \to \gamma X \to \gamma\eta\eta'$ BESIII, PRL 129 192002(2022) , PRD 106 072012(2022

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

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

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

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



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

$f_0(1710)$: large overlap with scalar glueball

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)
Phys. Rev. Lett. 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

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

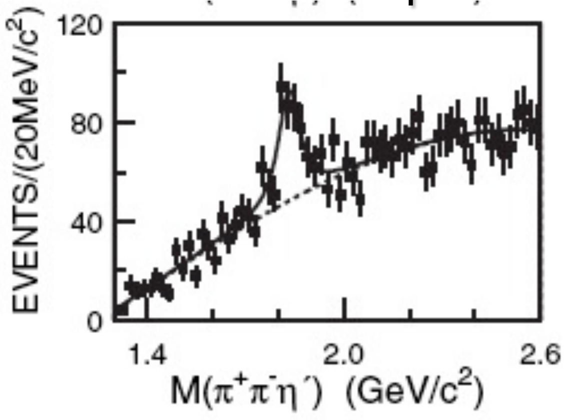
$J/\psi \to \gamma X \to \gamma K_s K_s$ BESIII，PRD 98, 072003 (2018)

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

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

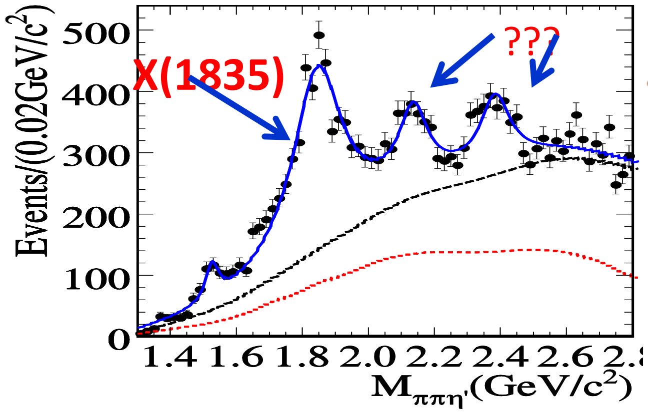
X(1835) and X(2370) in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ ($\eta'\rightarrow\gamma\rho/\eta\pi\pi$) at BESII and BESIII

BESII: 58 M J/ψ events



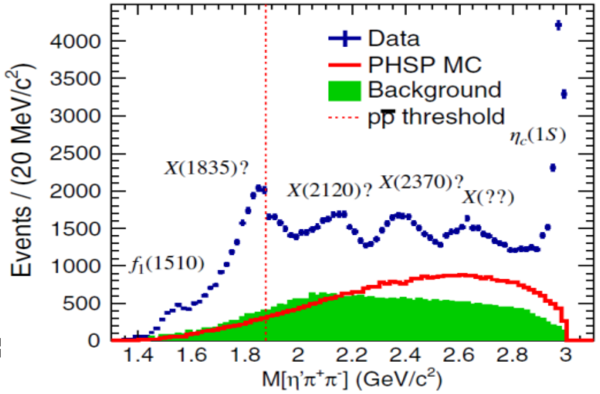
PRL 95,262001(2005)

BESIII: 225 M J/ψ events



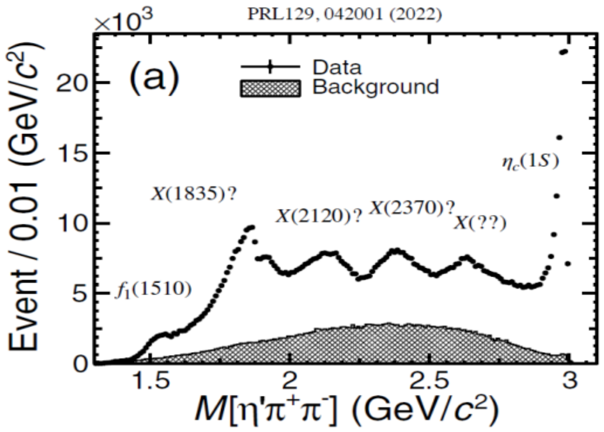
PRL 106, 072002 (2011)

BESIII: 1.1B J/ψ events



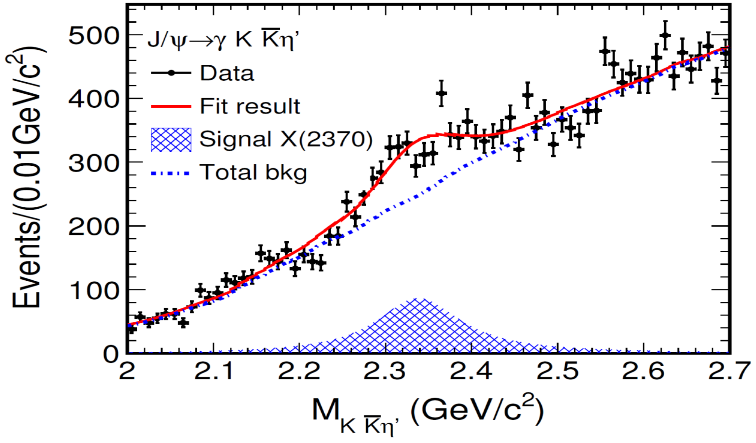
PRL 117, 042002 (2016)

BESIII: 10 B J/ψ events



PRL 129, 042001 (2022)

X(2370) in $J/\psi \rightarrow \gamma K\bar{K}\eta'$



EPJC 80, 746 (2020)

High statistics bring us more opportunities and challenges

- **Detailed structures shown at ~1835 MeV**
- **New resonances X(2120), X(2370) and X(2600)**
- **X(2370) observed in $J/\psi \rightarrow \gamma K\bar{K}\eta'$**
- **The mass of X(2370): consistent with LQCD's prediction to a pseudo-scalar 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^{-+}) candidates:

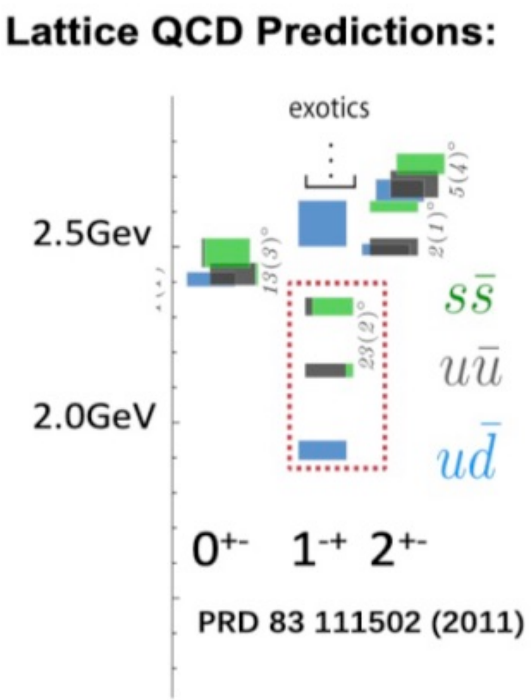
	π_1衰变模式	衰变道	合作组
$\pi_1(1400)$	$\eta\pi$	$\pi^- p \to \pi^- \eta p$[28] $\pi^- p \to \pi^0 \eta n$[27] $\pi^- p \to \pi^- \eta p$[29] $\pi^- p \to \pi^0 \eta n$[30] $\bar{p} n \to \pi^- \pi^0 \eta$[31] $\bar{p} p \to \pi^0 \pi^0 \eta$[32]	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p} p \to 2\pi^+ 2\pi^-$[33]	Obelix
$\pi_1(2015)$	$f_1\pi$	$\pi^- p \to \omega \pi^- \pi^0 p$[38]	E582
	$b_1\pi$	$\pi^- p \to p \eta \pi^+ \pi^- \pi^-$[41]	

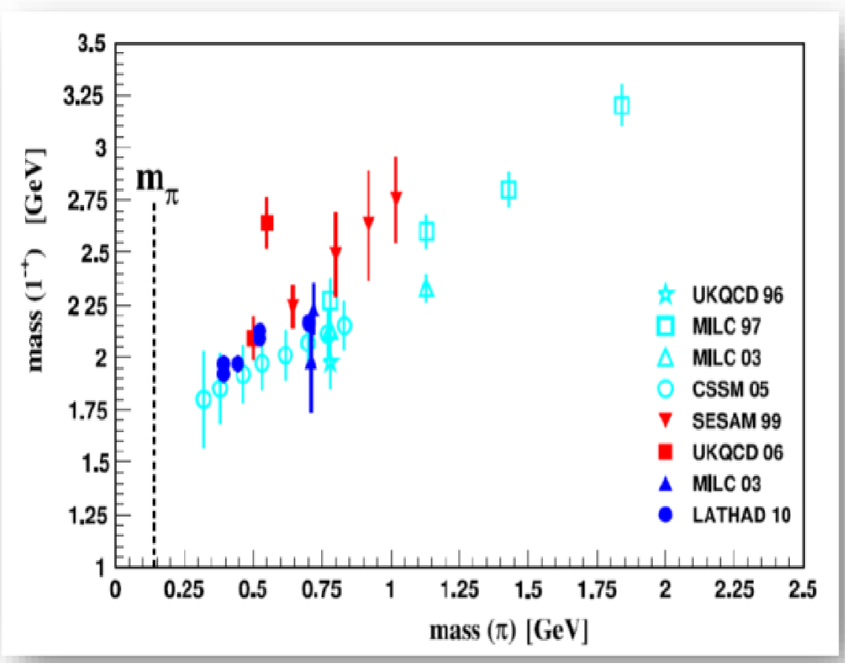
	π_1衰变模式	衰变道	合作组
$\pi_1(1600)$	$\eta'\pi$	$\pi^- Be \to \eta' \pi^- \pi^0 Be$[34] $\pi^- p \to \pi^- \eta' p$[35] $\chi_{c1} \to \eta' \pi^+ \pi^-$[36]	VES E852 CLEO-c
	$b_1\pi$	$\pi^- Be \to \omega \pi^- \pi^0 Be$[34] $\bar{p} p \to \omega \pi^+ \pi^- \pi^0$[37] $\pi^- p \to \omega \pi^- \pi^0 p$[38]	VES CBAR E582
	$\rho\pi$	$\pi^- Pb \to \pi^+ \pi^- \pi^- X$[39] $\pi^- p \to \pi^+ \pi^- \pi^- p$[40]	COMPASS E582
	$f_1\pi$	$\pi^- p \to p \eta \pi^+ \pi^- \pi^-$[41] $\pi^- A \to \eta \pi^+ \pi^- \pi^- A$[42]	E582 VES

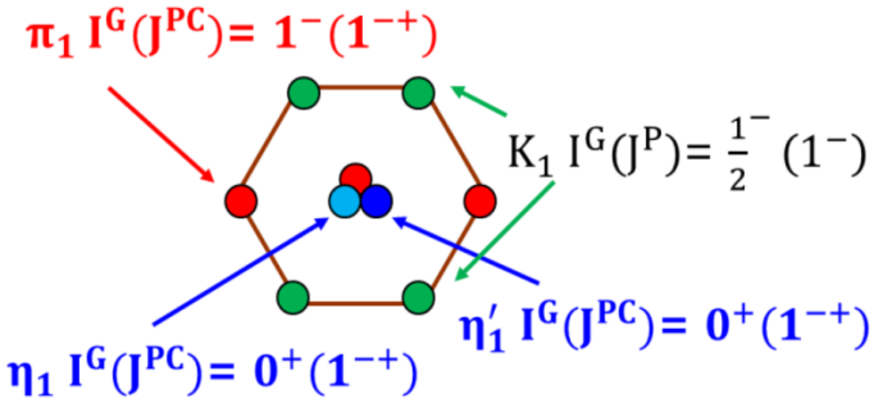
From a recent couple channel analysis, $\pi_1(1400)$ and $\pi_1(1600)$ could be from one pole.

PRL 122, 042002 (2019)

LQCD predictions to hybrid states:





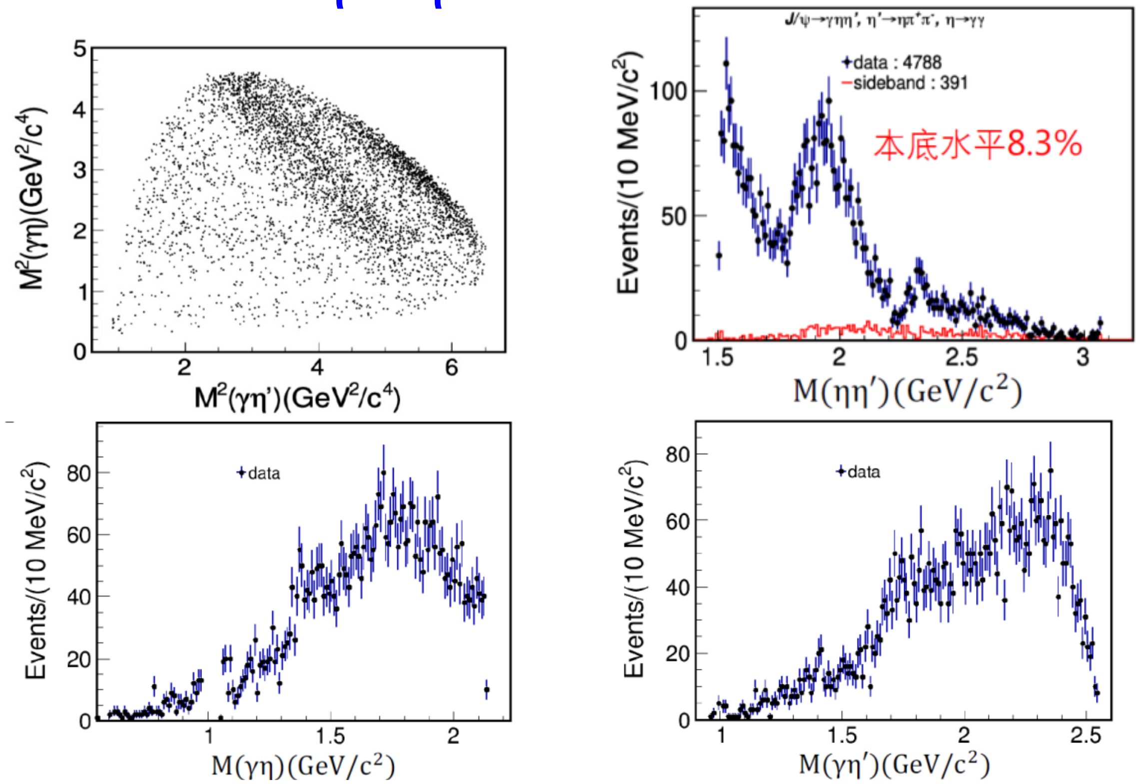


- The lightest exotic state is 1^{-+}
- The dominant decay mode of π_1 is $b_1(1235)\pi$

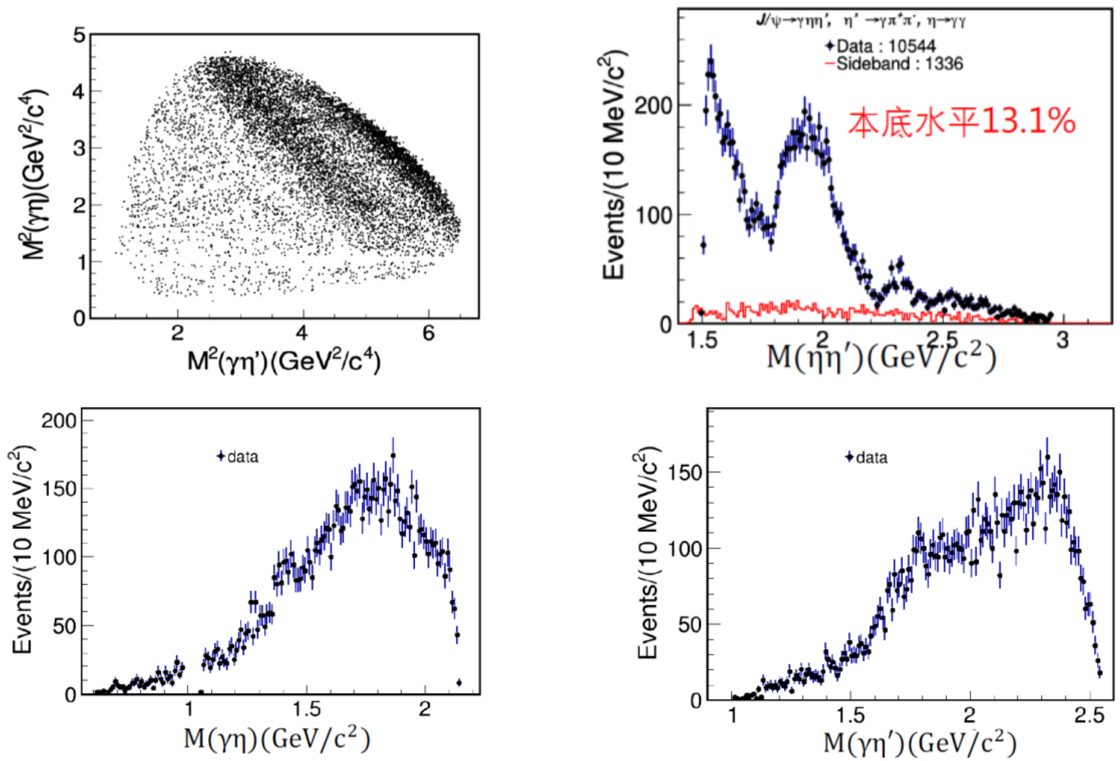
  -- study π_1 in more decay modes
- The observation of I=0 η_1 exotic state crucial

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

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



$\eta'\to\gamma\pi^+\pi^-$ mode



10 B J/ψ

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

PWA results

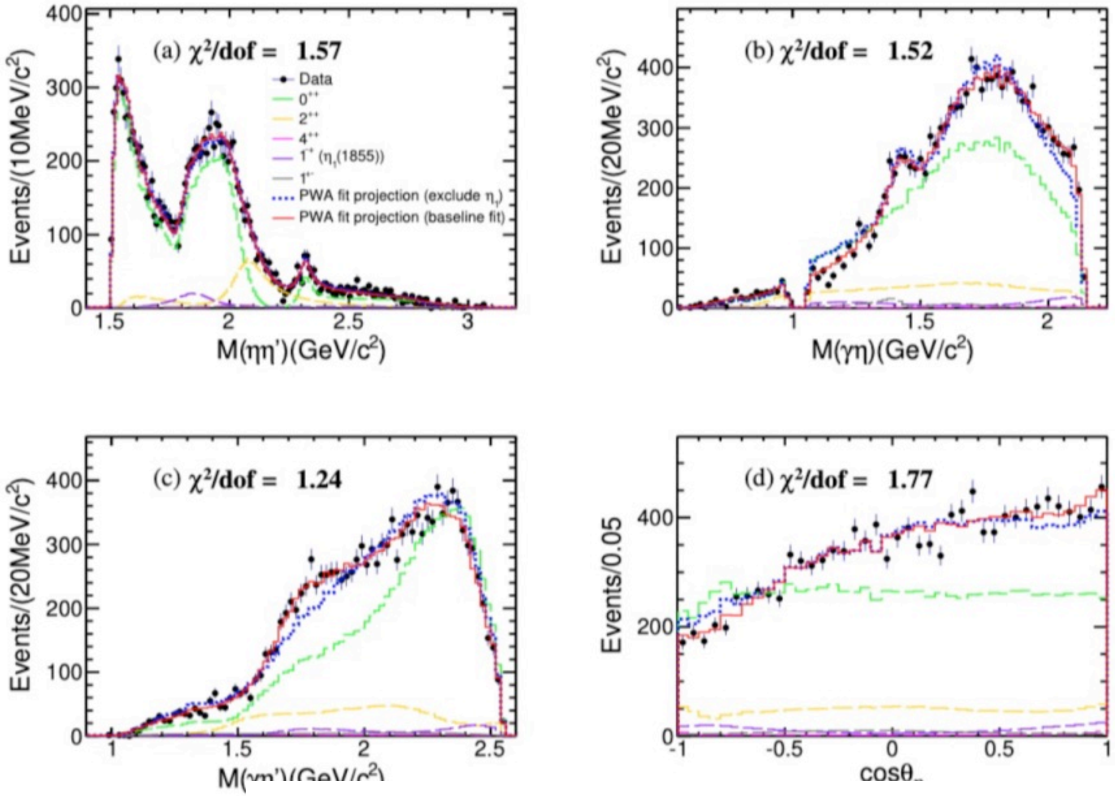
衰变模式	中间共振态	M (MeV/c^2)	Γ (MeV)	B.F. (×10^{-5})	统计显著性
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg30\sigma$
	$f_0(1810)$	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

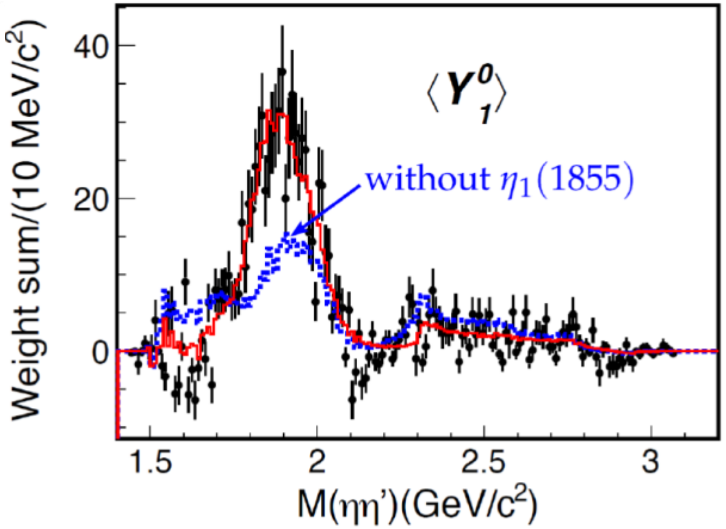
$$M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2,\ \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$$

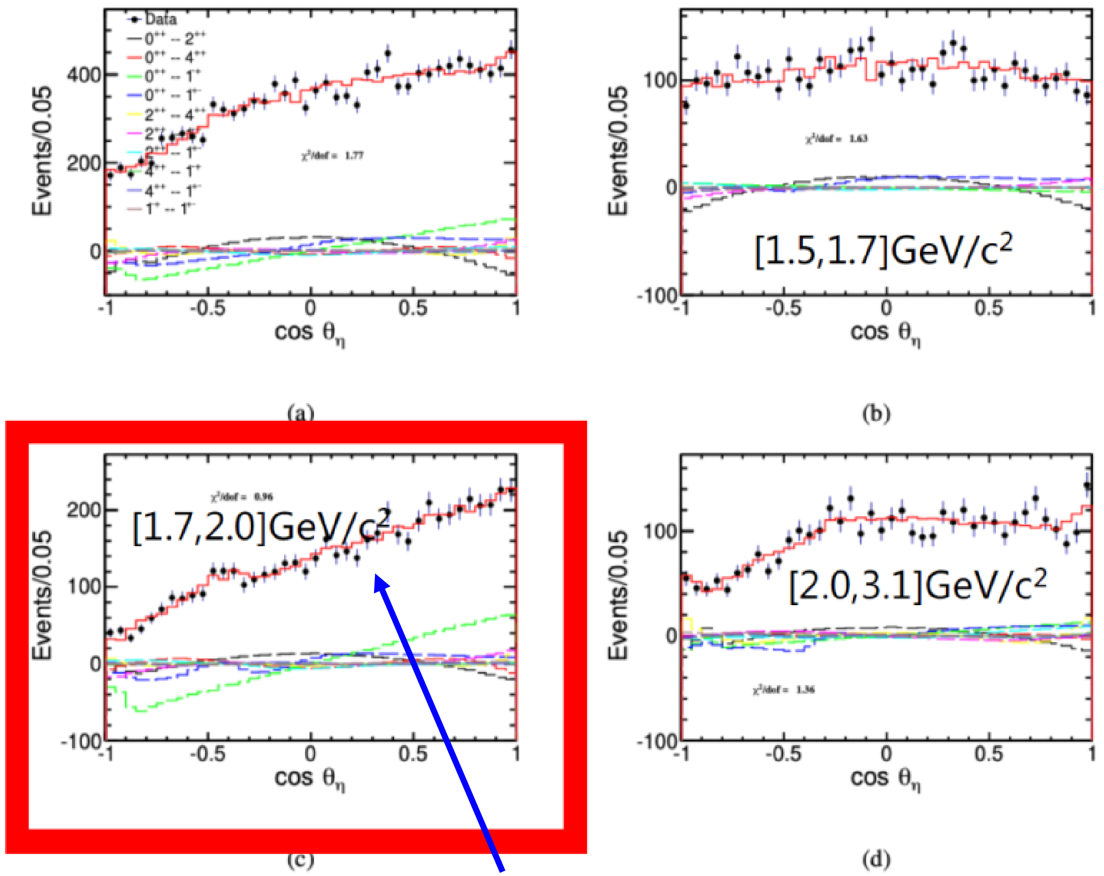
$$B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = \left(2.70 \pm 0.41^{+0.16}_{-0.35}\right) \times 10^{-6}$$

Statistical significance for an additional η_1

~4.6σ at ~ 2.15 GeV, 0.4%







From the interference of S and P waves.

$\eta_1(1855)$ is needed

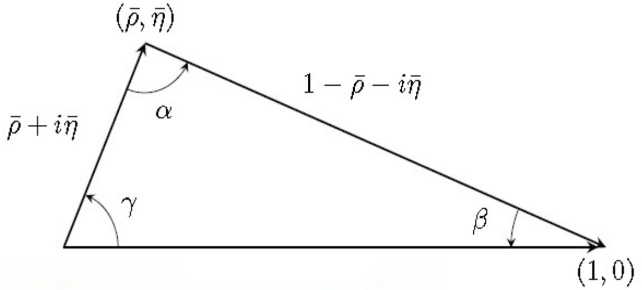
Charm physics

CKM matrix

- 3X3 unitary complex matrix
- 4 parameters
- 3 mixing angles and 1 phase

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3[1-(\rho-i\eta)] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda = \sin\theta_C$

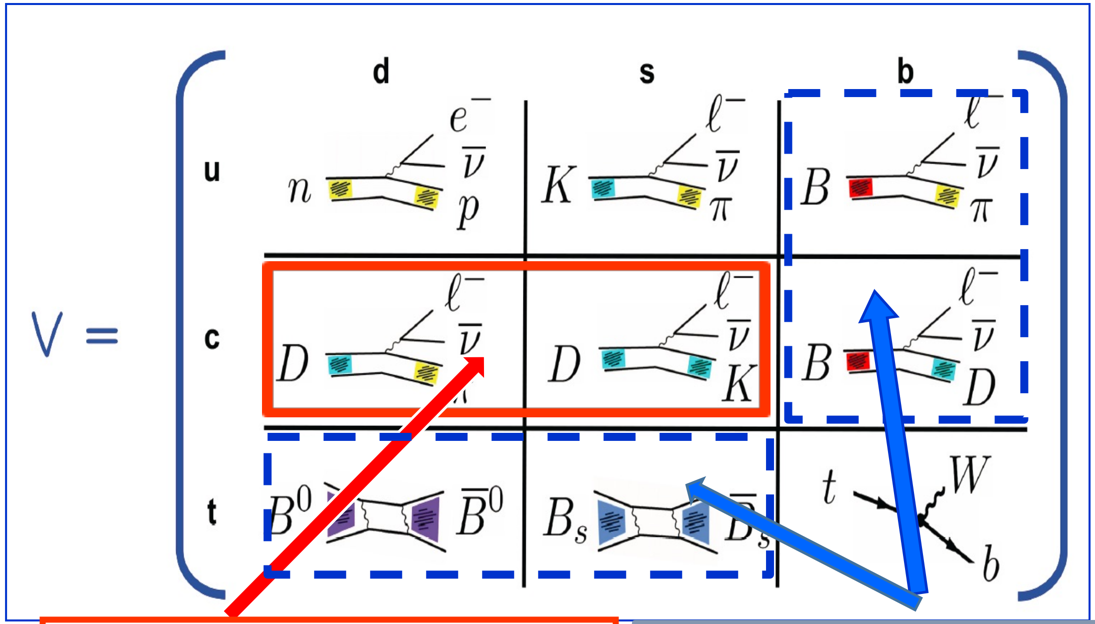


$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \equiv \phi_2, \quad \alpha = (87.6^{+3.5}_{-3.3})^\circ$$

$$\beta = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \equiv \phi_1, \quad \sin 2\beta = 0.691 \pm 0.017$$

$$\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \equiv \phi_3, \quad \gamma = (73.2^{+6.3}_{-7.0})^\circ$$



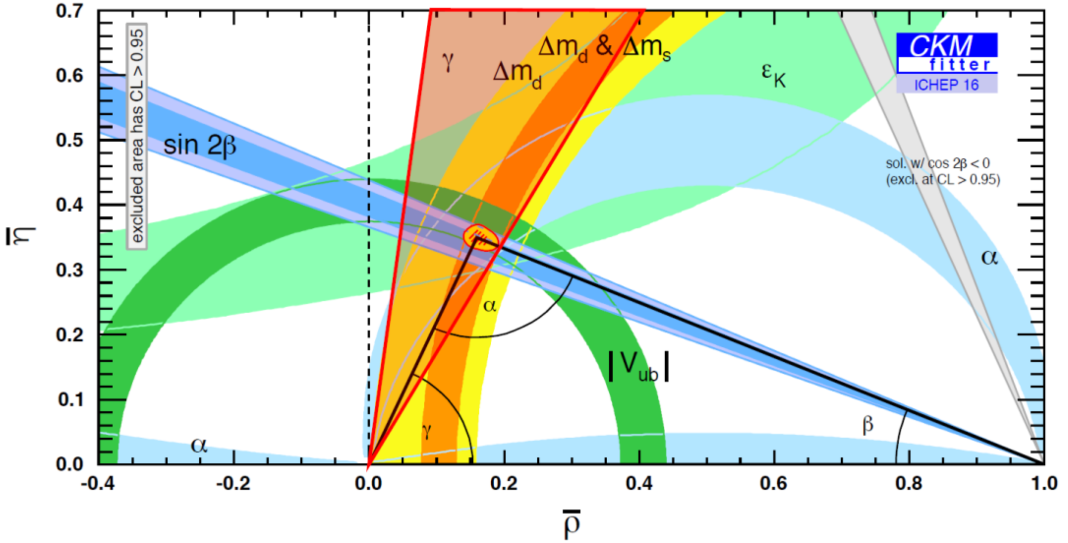
Charm decays + LQCD

Precision ~5-10% before BESIII

Charm decays + B decays + LQCD

Precision: $|V_{ub}|_{exc}$ ~ 4%

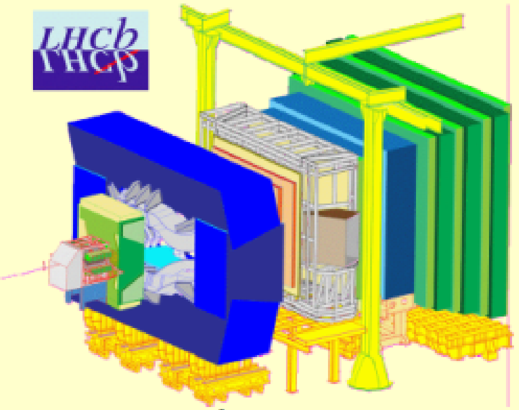
$|V_{cb}|$ ~ 2%



Charm physics contributors

B physics experiments are well suited for charm physics

hadron collider



LHCb at LHC

$\int_{run1} \mathcal{L} \approx 3 fb^{-1}$ $3.6 \cdot 10^{12}\ c\bar{c}$

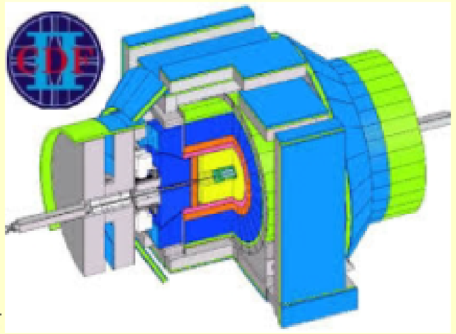
$\int_{run2} \mathcal{L} \approx 5.5 fb^{-1}$ $9.6 \cdot 10^{12}\ c\bar{c}$

world's largest c sample

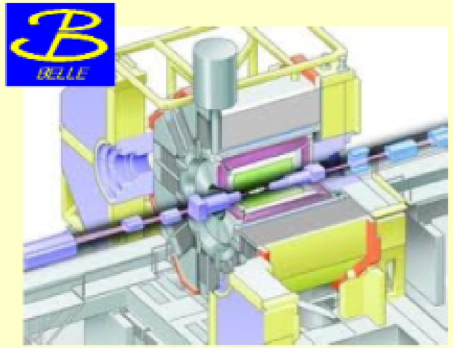
CDF at TEVATRON

$\int \mathcal{L} \approx 9.6 fb^{-1}$

$2.3 \cdot 10^{11}\ c\bar{c}$



e^+e^- collider



Belle at KEKB

$\int \mathcal{L} \approx 1 ab^{-1}$

$1.3 \cdot 10^{9}\ c\bar{c}$

Belle II

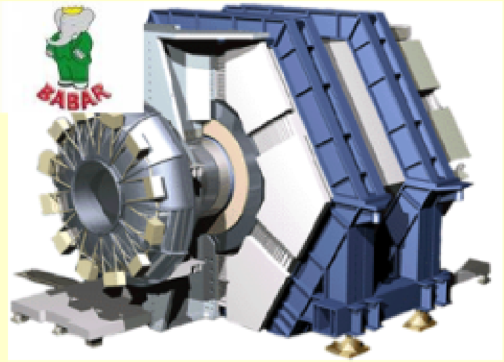
$\int \mathcal{L} \approx 6.5 fb^{-1}$

$8.5 \cdot 10^{6}\ c\bar{c}$

BABAR at PEPII

$\int \mathcal{L} \approx 550 fb^{-1}$

$7 \cdot 10^{8}\ c\bar{c}$

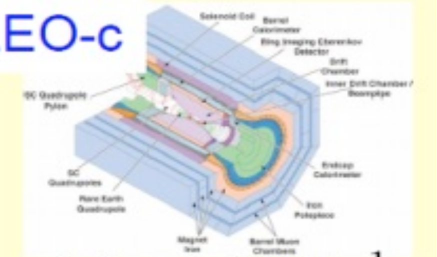


- **LHCb/hadron machine:** huge production X-section, excellent lifetime resolution due to the boost; large combinatorial BG, difficult with neutral and missing particles
- **B factories:** clean environment, good to detect neutral particles; lower boost, poorer lifetime resolution

BESIII Unique data sets at open charm thresholds

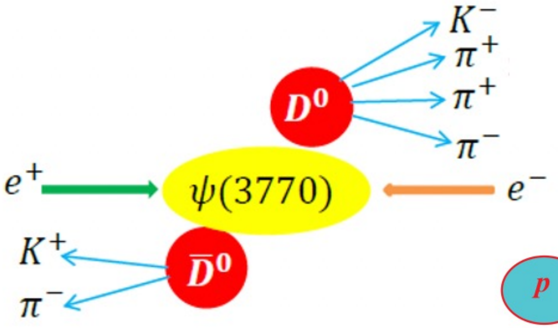
- **$D^{+(0)}$**
  - @ $E_{cm} = 3.773$ GeV
  - Integrated luminosity of 2.93 fb^{-1} → **20 fb^{-1}**
  - $\sigma(e^+e^- \to D^0\overline{D^0}) \sim 3.6$ nb ⇒ 21M D^0 produced
  - $\sigma(e^+e^- \to D^+D^-) \sim 2.9$ nb ⇒ 17M D^+ produced
- **D_s^+**
  - @ $E_{cm} = 4.009$ GeV
    - Integrated luminosity of 0.482 fb^{-1}
    - $\sigma(e^+e^- \to D_s^+D_s^-) \sim 0.3$ nb ⇒ 0.3M D_s produced
  - @ $E_{cm} = 4.178$ GeV
    - Integrated luminosity of 3.19 fb^{-1} → **6 fb^{-1}**
    - $\sigma(e^+e^- \to D_s^{*+}D_s^-) \sim 1$ nb ⇒ 6M D_s produced
- **Λ_c^+**
  - @ $E_{cm} = 4.600$ GeV
  - Integrated luminosity of 0.567 fb^{-1}
  - $\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-) \sim 0.2$ nb ⇒ 0.2M Λ_c produced

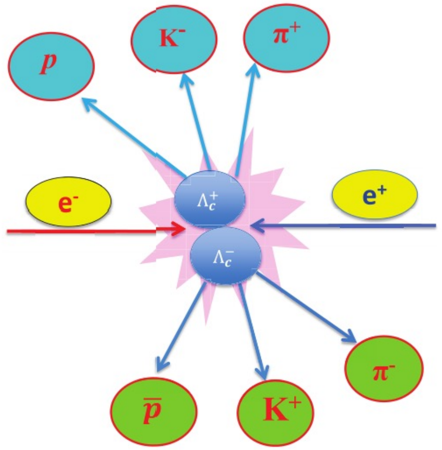
CLEO-c



$\int \mathcal{L} \approx 0.82 fb^{-1}$

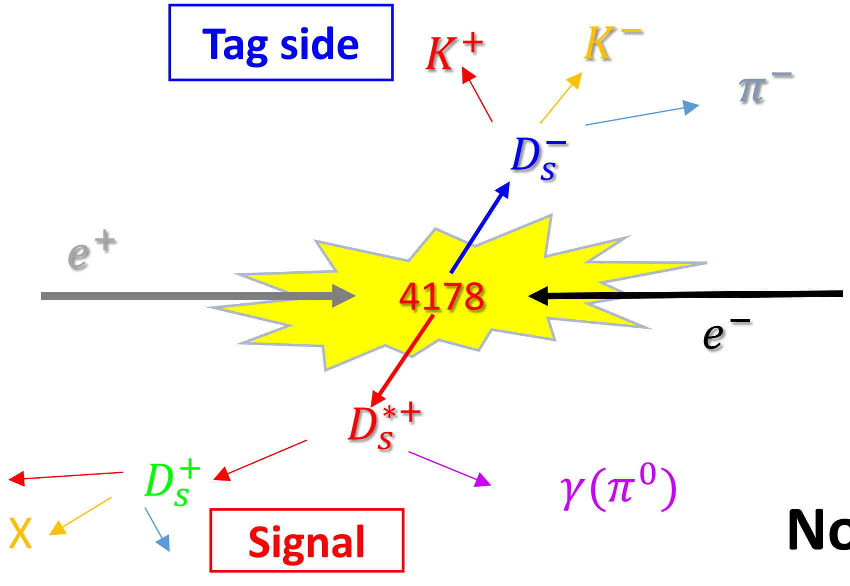
$D^0/\bar{D}^0$	$3.0 \cdot 10^6$
D^+/D^-	$2.4 \cdot 10^6$





- **No boost, no lifetime measurement**
- **Almost free of background**
- **ψ(3770) → DD̄, quantum correlation → strong phase measurement**

Double tag method (DT)



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

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

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

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

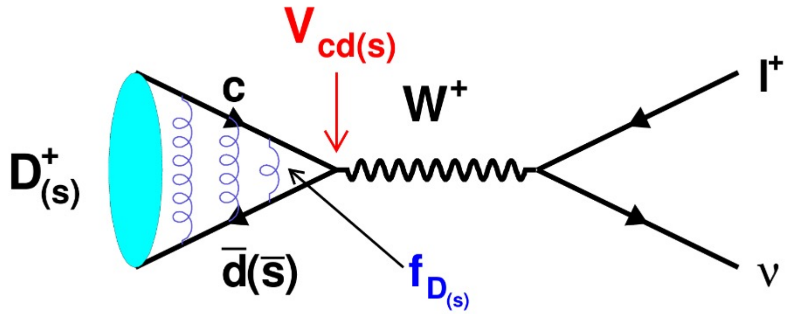
DT yield: $N^i_{\text{DT}} = 2 \times N_{D\bar{D}} \times B^i_{\text{ST}} \times B_{\text{sig}} \times \varepsilon^i_{\text{ST vs.sig}}$

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

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

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)

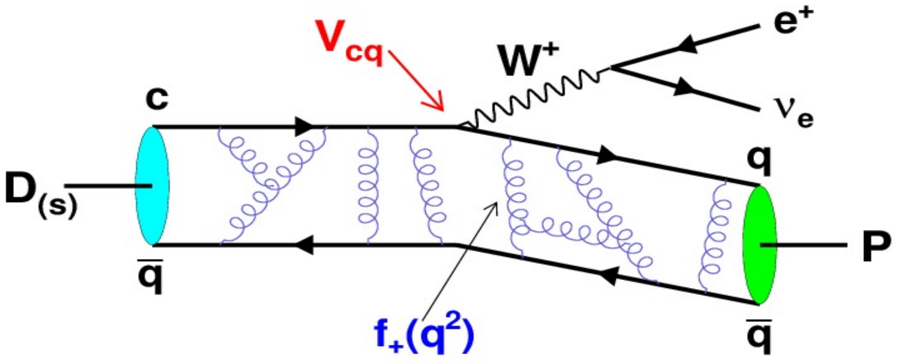
Decay rate (Exp.)

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

CKM matrix element

- Exp. decay rate + $|V_{cs(d)}|^{\text{CKMfitter}}$ → 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:

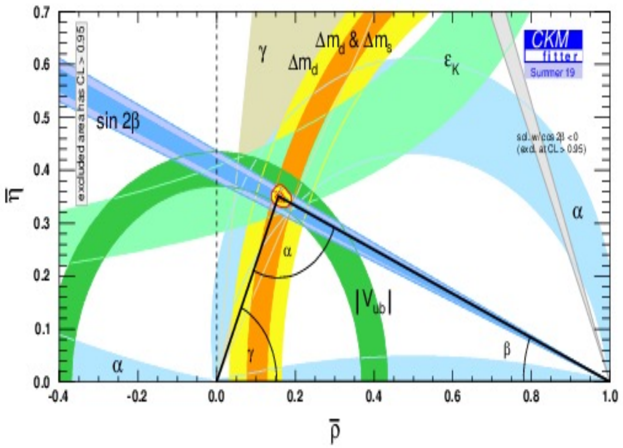
Differential rate (Exp.) — CKM matrix element — Form factor (LQCD)

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

- 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 QCD
- Exp. + LQCD calculation of $f_+^{K}(0)$ and $f_+^{\pi}(0)$ → $V_{cs(d)}$ – constrain CKM

Hadronic decays of charm mesons

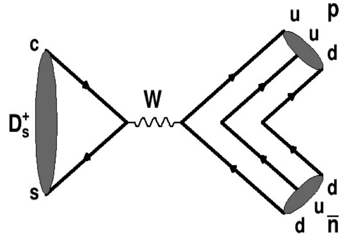
- **Strong phase measurement with quantum correlated $\psi(3770) \to D^0\overline{D}^0$ is crucial in the model-independent determinations of γ and charm mixing/direct CPV.**



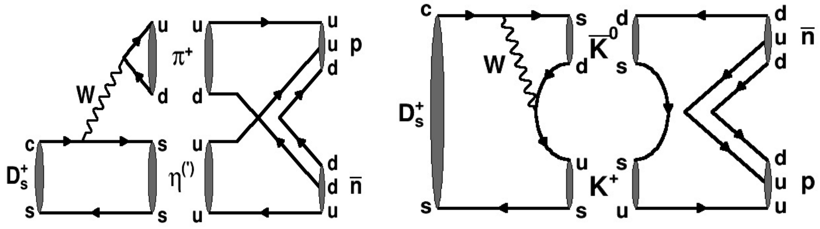
- In SM, CP violation is studied by measuring CKM matrix, represented by the unitarity triangle in complex plane. The angle γ is the only one that can be extracted from tree-level processes, for which the contribution of non-SM effects is small.
- Measurement of γ provides a benchmark for the SM with minimal theoretical uncertainty. Precision measurement of γ provide tests of SM CP violation and probe for new physics.
- γ is the least well known CKM constraint
- γ status:
  Direct measurement $\gamma = (73.5\ ^{+4.2}_{-5.1})^o$,
  indirect measurement $\gamma = (65.8\ ^{+1.0}_{-1.7})^o$

Pre-LHCb: $\gamma = (73^{+22}_{-25})^\circ$

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



Short-distance



Long-distance effect

Test of lepton universality (LU)

- **BaBar, LHCb and Belle found evidence of lepton universality violation in semi-leptonic B decays, either via the Cabibbo-suppressed (CS) transition b → c or flavor-changing-neutral-current (FCNC) transitions in last couple of years.**
- **Study the analogous decays in charm quark sector:**

In Standard Model, (for decays rate: Phys. Rev. D 38, 214 (1988)**)**

$$R \equiv \frac{\Gamma(D^+_{(s)} \to \tau^+\nu)}{\Gamma(D^+_{(s)} \to \mu^+\nu)} = \frac{m^2_{\tau^+}\left(1-\frac{m^2_{\tau^+}}{M^2_{D^+_{(S)}}}\right)^2}{m^2_{\mu^+}\left(1-\frac{m^2_{\mu^+}}{M^2_{D^+_{(S)}}}\right)^2} = 2.67 \pm 0.01\ (9.75 \pm 0.01)$$

$$R^{0(+)} = \frac{B(D^{0(+)} \to \pi^{-(0)}\mu^+ v)}{B(D^{0(+)} \to \pi^{-(0)}e^+ v)} \sim 0.985$$

$$R^{0(+)} = \frac{B(D^{0(+)} \to K^{-(0)}\mu^+ v)}{B(D^{0(+)} \to K^{-(0)}e^+ v)} \sim 0.97$$

EPJC, 78 (2018) 501 , Z. Phys. C46 (1990)93, PRD69 (2004)074025, PLB633(2006)61

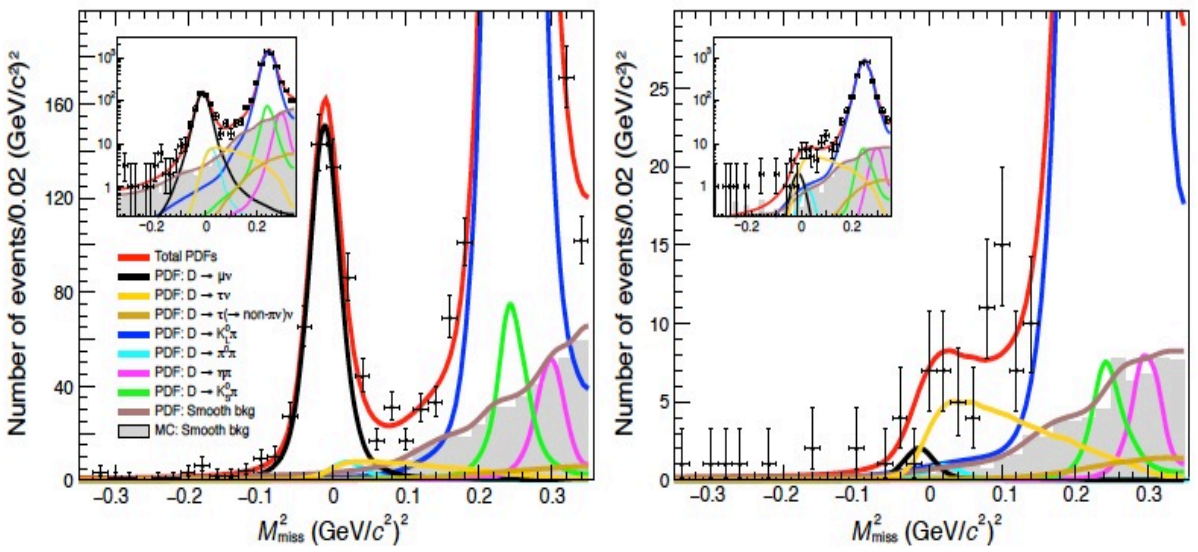
$D^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$: first evidence (4σ)

$2.93\text{f}b^{-1}@E_{cm} = 3.773\text{GeV}$

PRL123(2019)211802

μ-like

π-like



- 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 ⊕ G
- Fix D→μ ν component to the world average

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

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

Split data into two:

- μ-like: E_{EMC} ≤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 $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$).

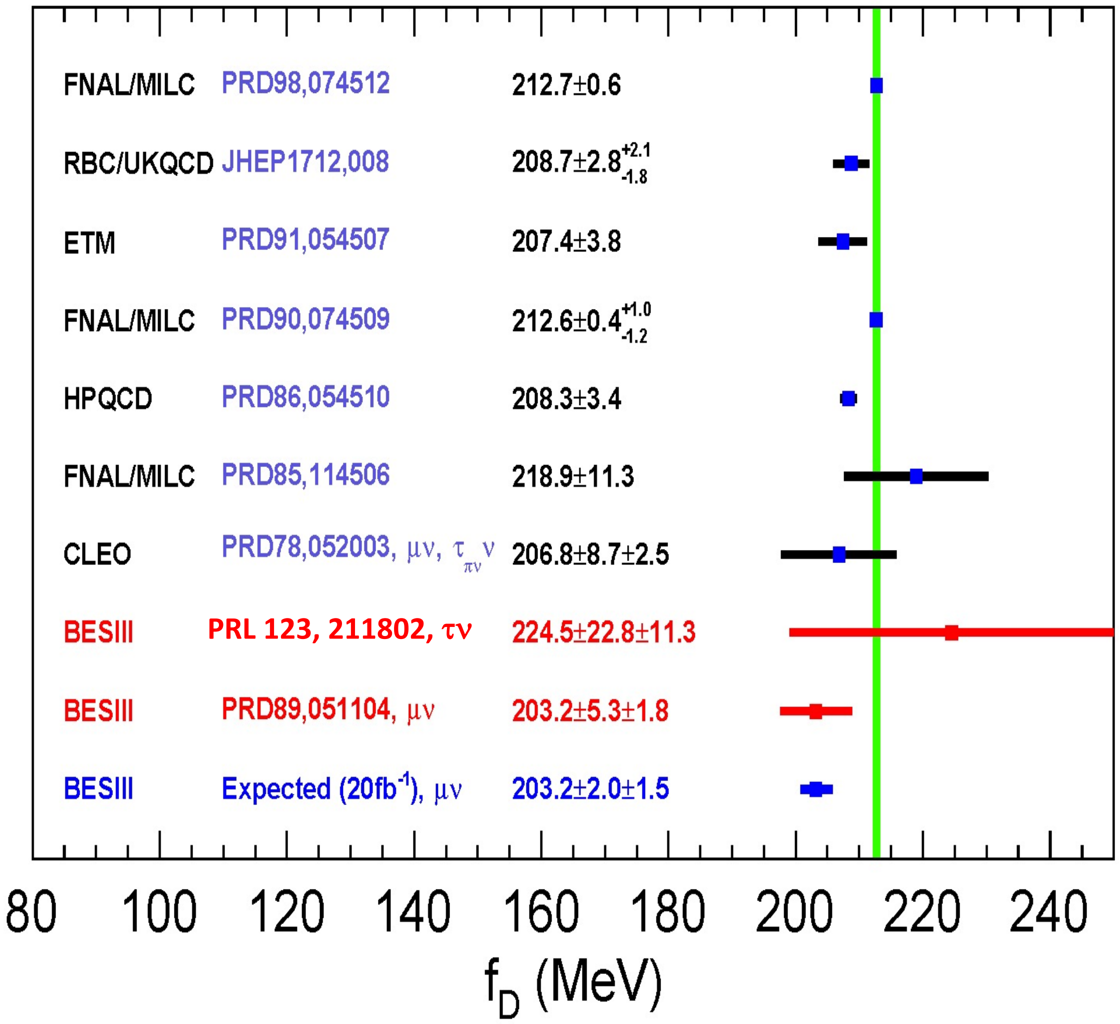
Consistent with SM prediction，R = 2.65±0.01, within ~0.9σ

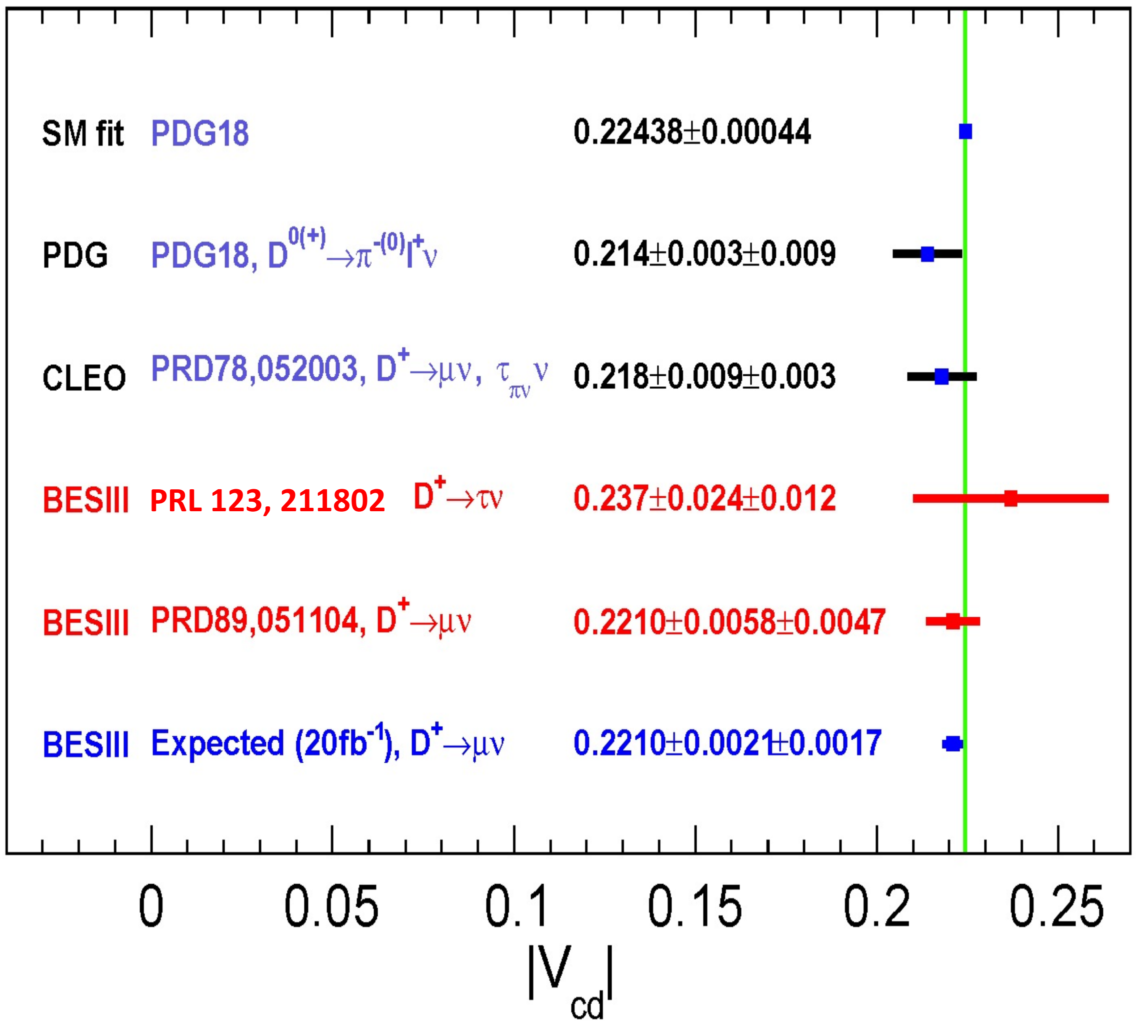
Take $|V_{cd}|^{CKMfitter}$ as input：

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

Take f_D^{LQCD} as input：

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



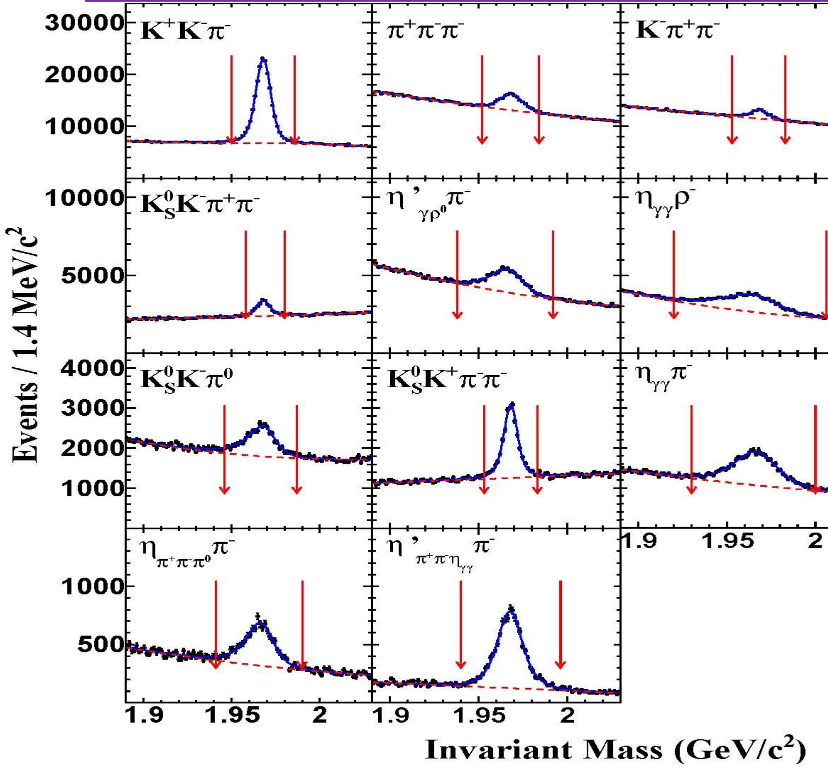


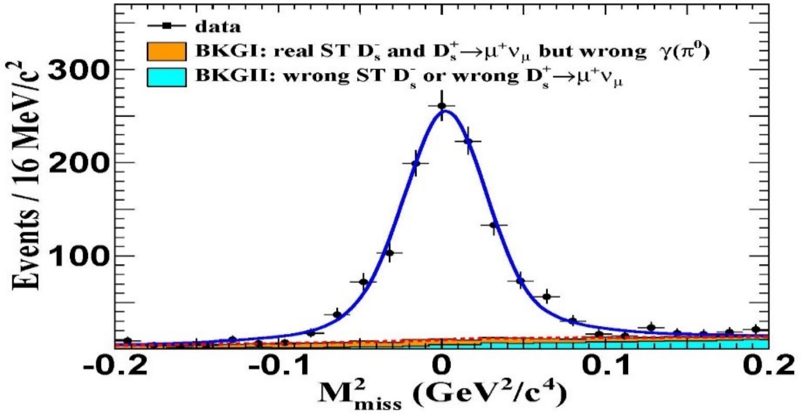
BESIII $D_s^+ \to \mu^+\nu_\mu$

BESIII: PRL 122 (2019) 071802

$3.19fb^{-1}@E_{cm} = 4.178\text{GeV},\ e^+e^- \to D_s^\pm D_s^{*\mp} \to \gamma/\pi^0 D_s^+ D_s^-$

$\sigma(e^+e^- \to D_s^\pm D_s^{*\mp}) \sim 6$ nb, ~ 6 M $D_s^\pm$ produced.





Signal side: fit missing mass square

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

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

$B_{PDG}(D_s^+ \to \tau^+\nu) = (5.48 \pm 0.23)\times 10^{-2}$

$\frac{B(D_s^+ \to \tau^+\nu)}{B(D_s^+ \to \mu^+\nu)} = (9.98 \pm 0.52)\ \ (\text{SM}: 9.75)$

Tag side: 14 Ds^- decay mode

No. of single tags: $(388.7\pm2.6)\text{X}10^3$

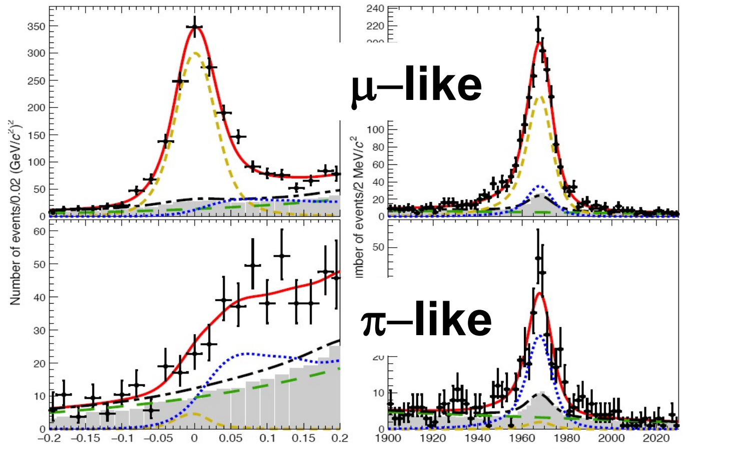
No. of double tags: 1135.9 ± 33.1

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

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

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

BESIII: PRD 104 (2021) 032001



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

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

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

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

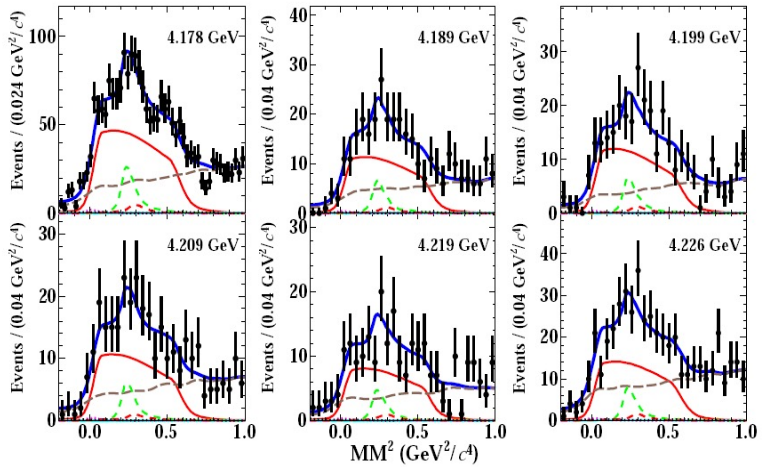
$A_{CP}[\mu v] = (-1.2 \pm 2.7)\%$

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

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

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

BESIII: PRD 104 (2021) 032001



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

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

Take BESIII results and world average：

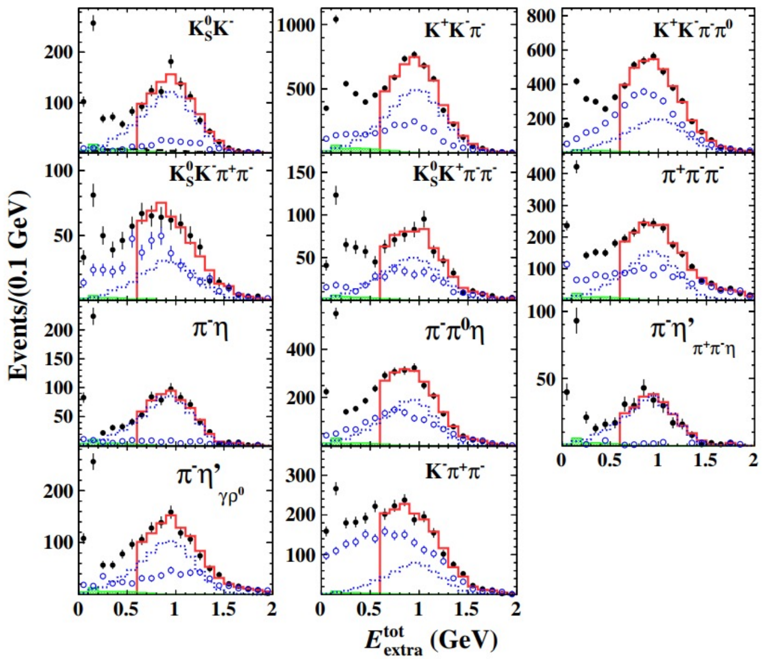
$$\frac{B(D_s^+ \to \tau^+ \nu)}{B(D_s^+ \to \mu^+ \nu)} = (9.67 \pm 0.34)$$

(SM: 9.75)

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

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

BESIII: PRL 127 (2021) 171801

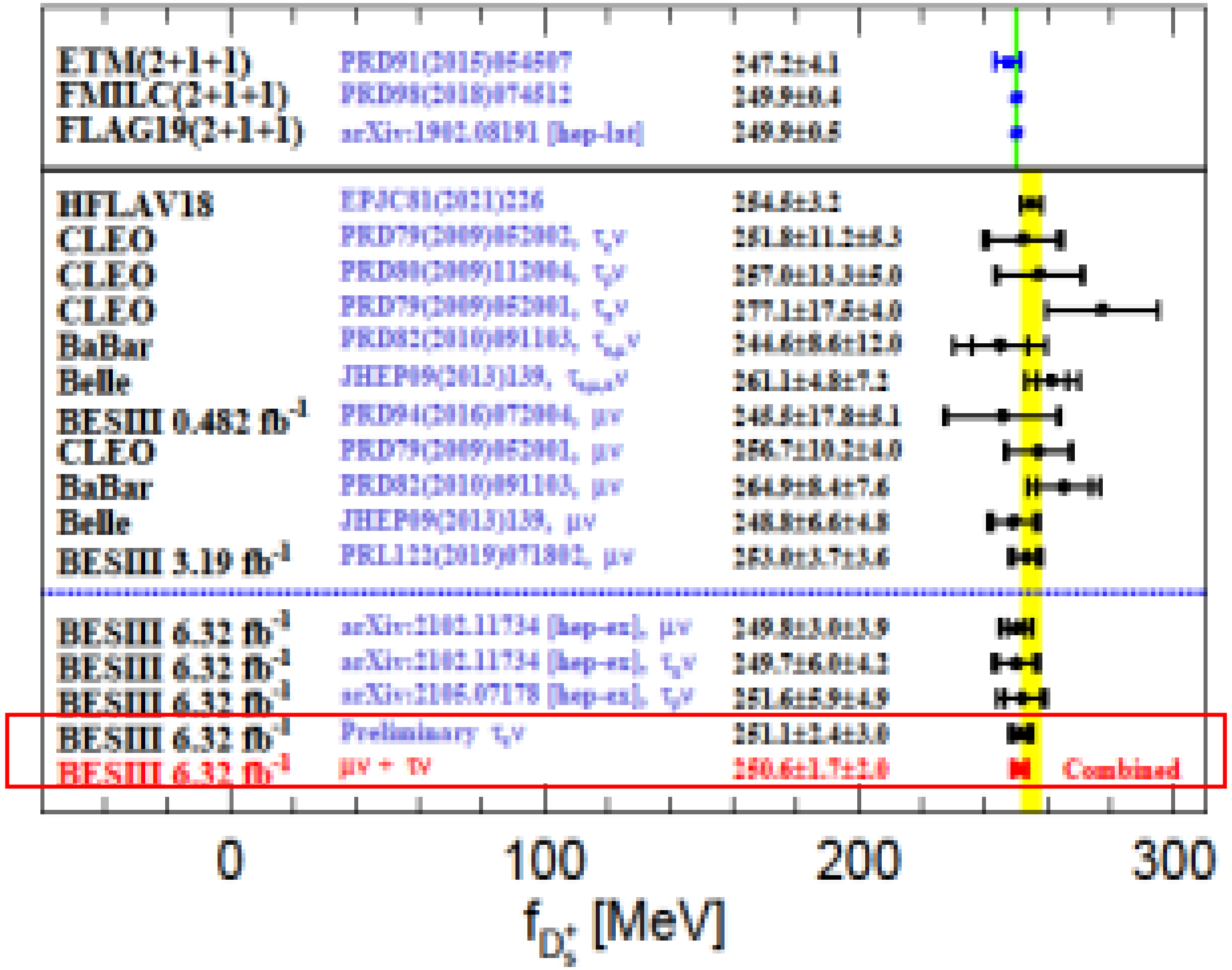


$B[D_s^+ \to \tau^+ v] = (5.27 \pm 0.10 \pm 0.12)\%$

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

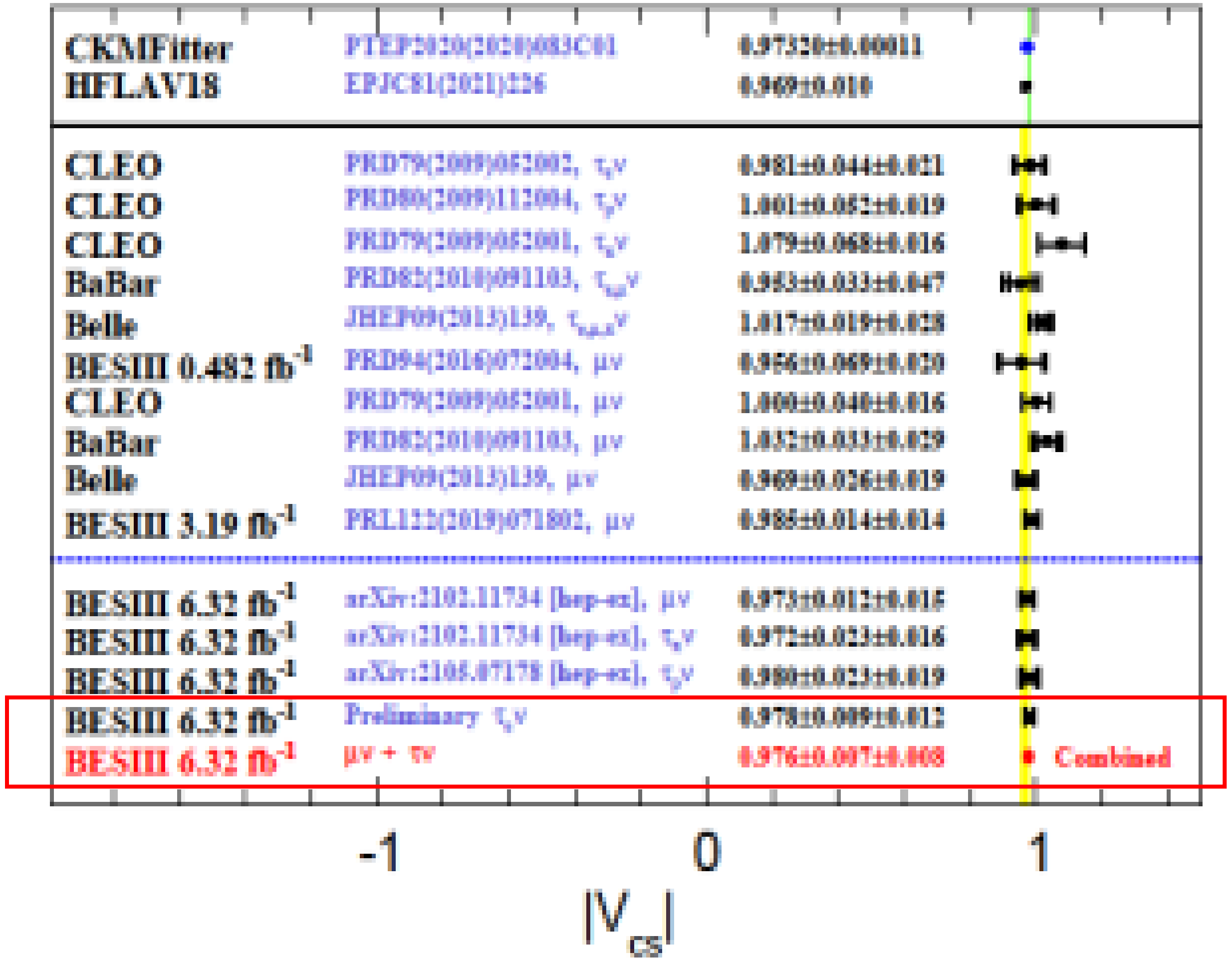
Take $|V_{cs}|^{CKMfitter}$ as input：

$f_{D_s^+}$=(251.1±2.4±3.0) MeV $(\tau^+(e^+\nu\nu)\nu)$



Take $f_{D_s}^{LQCD}$ as input：

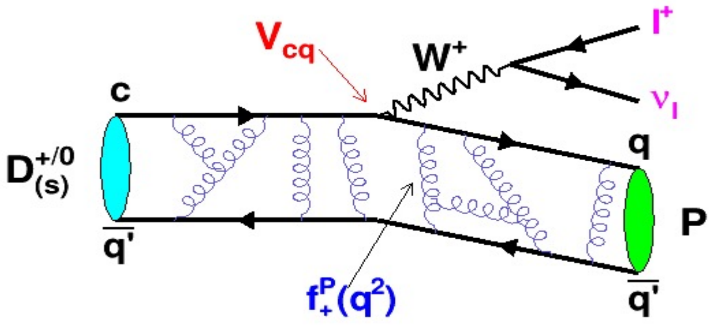
$|V_{cs}|$=(0.978±0.009±0.012) $(\tau^+(e^+\nu\nu)\nu)$



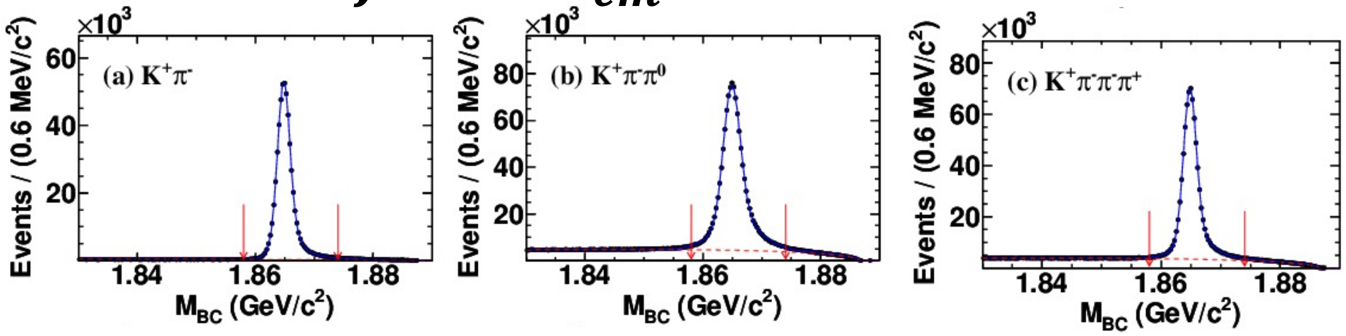
Most precise measurement

BESIII Form factor in $D^0 \to K^- \mu^+ \nu_\mu$

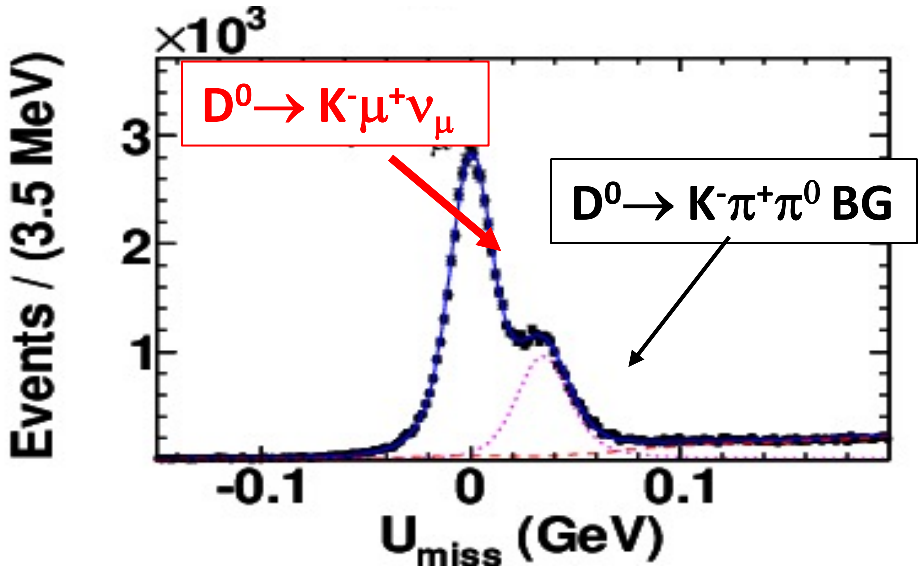
BESIII: PRL 122 (2019) 011804



$2.93\, fb^{-1} @ E_{cm} = 3.770\, GeV$



$D^0 \to K^- \mu^+ \nu_\mu$ is studied in the recoiling system of three tag modes:



- Signal shape: MC simulated shape convoluted with Gaussian.
- BG shape in tag side: ARGUS func.
- BG in signal side:
    - $D^0 \to K^- \pi^+ \pi^0$ MC simulated shape convoluted with Gaussian
    - Continuum background shape : MC simulated shape

No. of single tags: $(2241.4 \pm 2.1) \mathrm{X} 10^3$

No. of double tags: 47100 ± 259

$$\mathcal{B}_{D^0 \to K^- \mu^+ \nu_\mu} = (3.429 \pm 0.019_{\rm stat.} \pm 0.035_{\rm syst.})\%$$

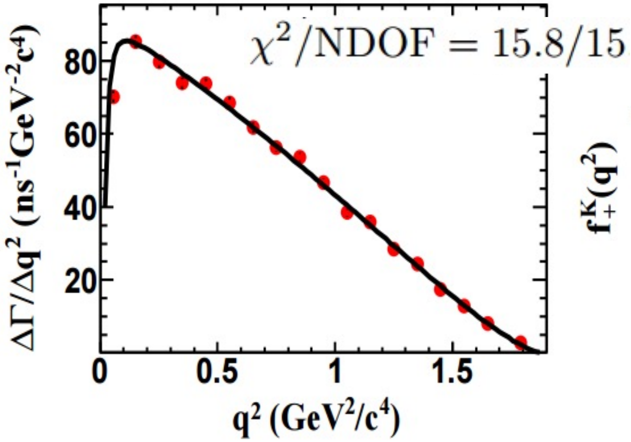
BESIII $D^0 \to K^- \mu^+ \nu_\mu$ Fit to partial decay rates

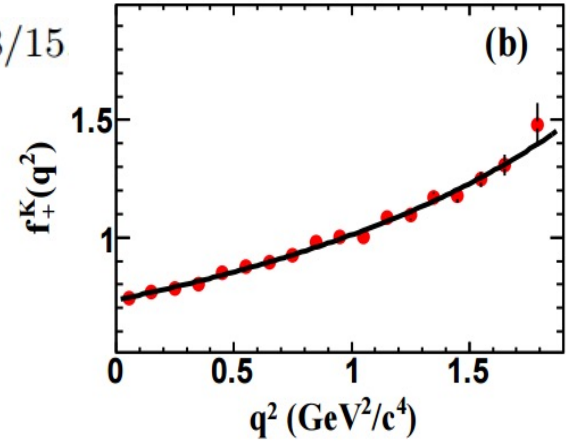
BESIII: PRL 122 (2019) 011804

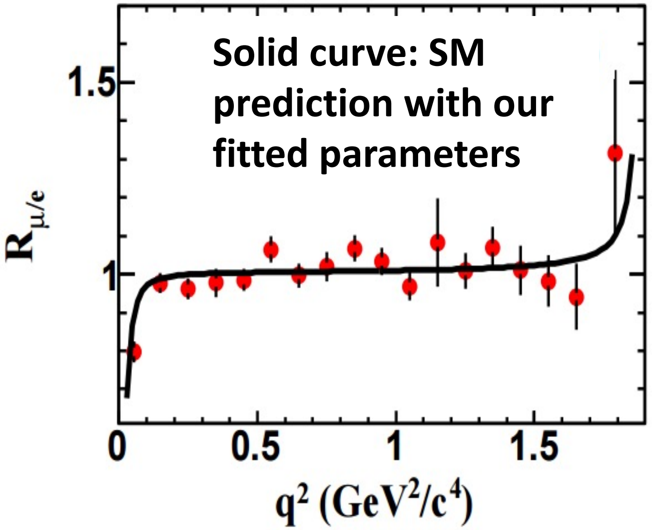
Series expansion parameterization for form factor (2nd order):

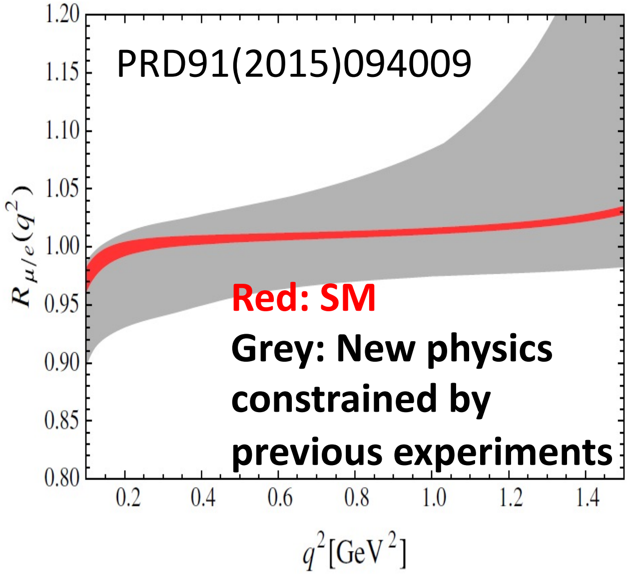
$$f_+^K(t) = \frac{1}{P(t)\Phi(t,t_0)} \frac{f_+^K(0)P(0)\Phi(0,t_0)}{1+r_1(t_0)z(0,t_0)} (1+r_1(t_0)[z(t,t_0)])$$

$$\chi^2 = \sum_{i,j=1}^{N_{\mathrm{intervals}}} (\Delta\Gamma^i_{\mathrm{msr}} - \Delta\Gamma^i_{\mathrm{exp}}) C^{-1}_{ij} (\Delta\Gamma^j_{\mathrm{msr}} - \Delta\Gamma^j_{\mathrm{exp}})$$









$f_+^K(0)|V_{cs}| = 0.7148 \pm 0.0038 \pm 0.0029$

In full q^2 interval: $R_{\mu/e} = 0.974 \pm 0.007 \pm 0.012$

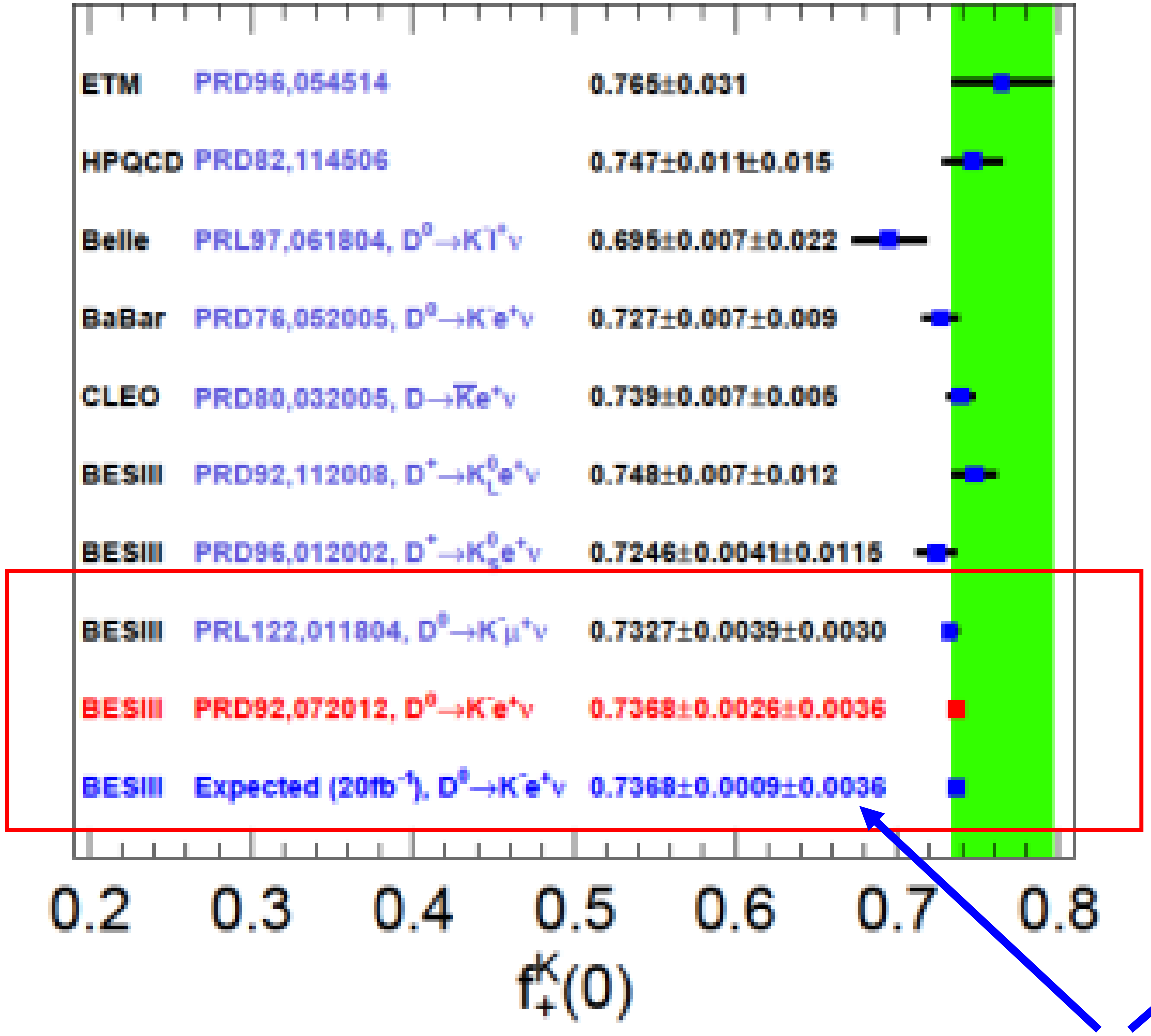
SM prediction: 0.97

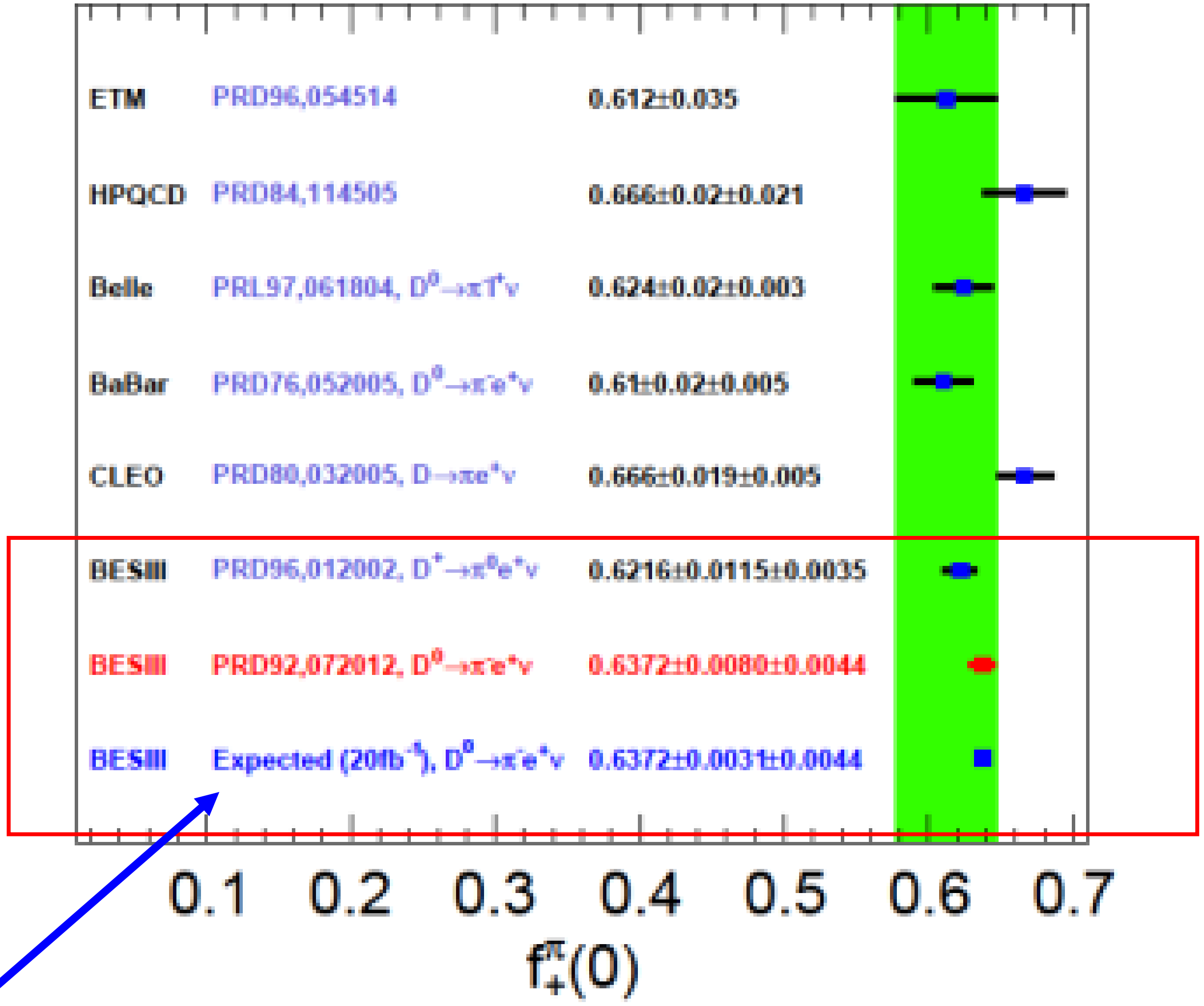
No deviation larger than 2σ is observed in q^2 interval of (0.2, 1.5) GeV^2/c^4.

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

Inputs from 2018 PDG CKMFitter

Inputs:	Inputs:
$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$	$|V_{cd}| = 0.22438 \pm 0.00044$





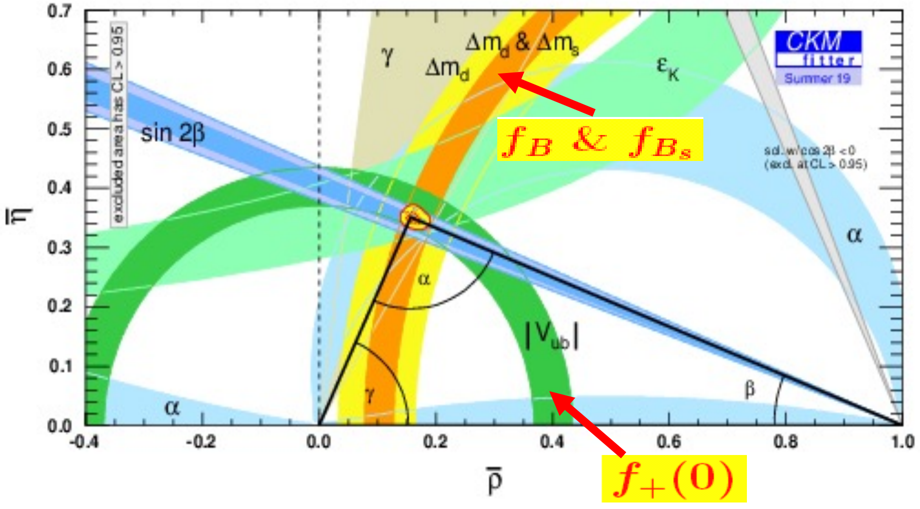
BESIII: 20 fb^{-1} @ 3770 MeV

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

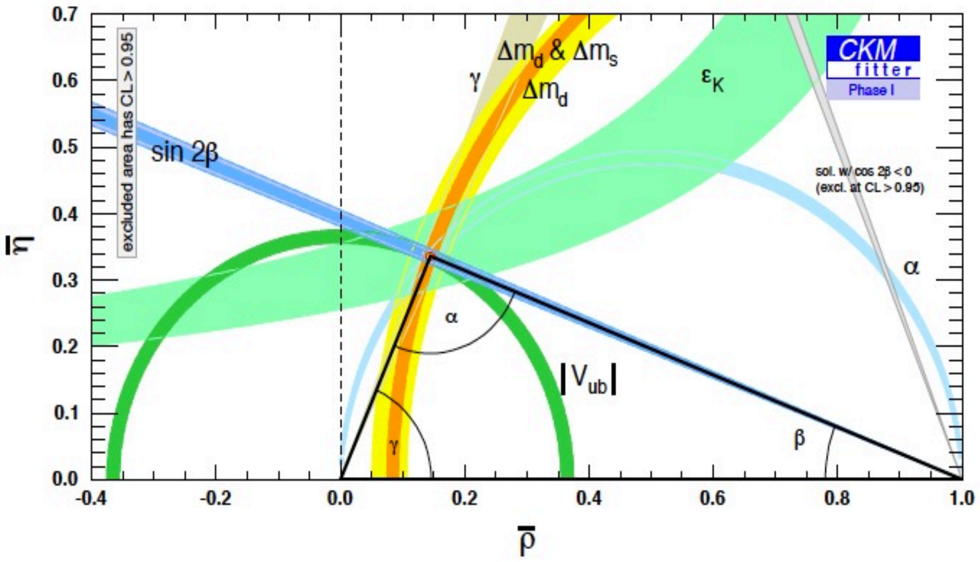
$\psi(3770) \rightarrow D^0\overline{D^0}$ quantum correlation➔strong phase parameters between D^0 and $\overline{D}^0$ decays

➔inputs to LHCb measurement of γ

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

Summary ??

Long history of the collaboration among BES experimentalists and theorists.

- Predictions from LQCD or other models: guidance to the exps.
- Exp. results: test models
- Spectroscopy: PWA

Many joint workshops

Backup sides

Further Checks on the 1^{-+} State $\eta_1(1855)$

- Angular distribution as a function of $M(\eta\eta')$ expressed **model-independently**

$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(\cos\theta_\eta^i)$$

- Related to the spin-0(S), spin-1(P), spin-2(D) amplitudes in $\eta\eta'$ by:

$$\sqrt{4\pi}\langle Y_0^0\rangle = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2,$$

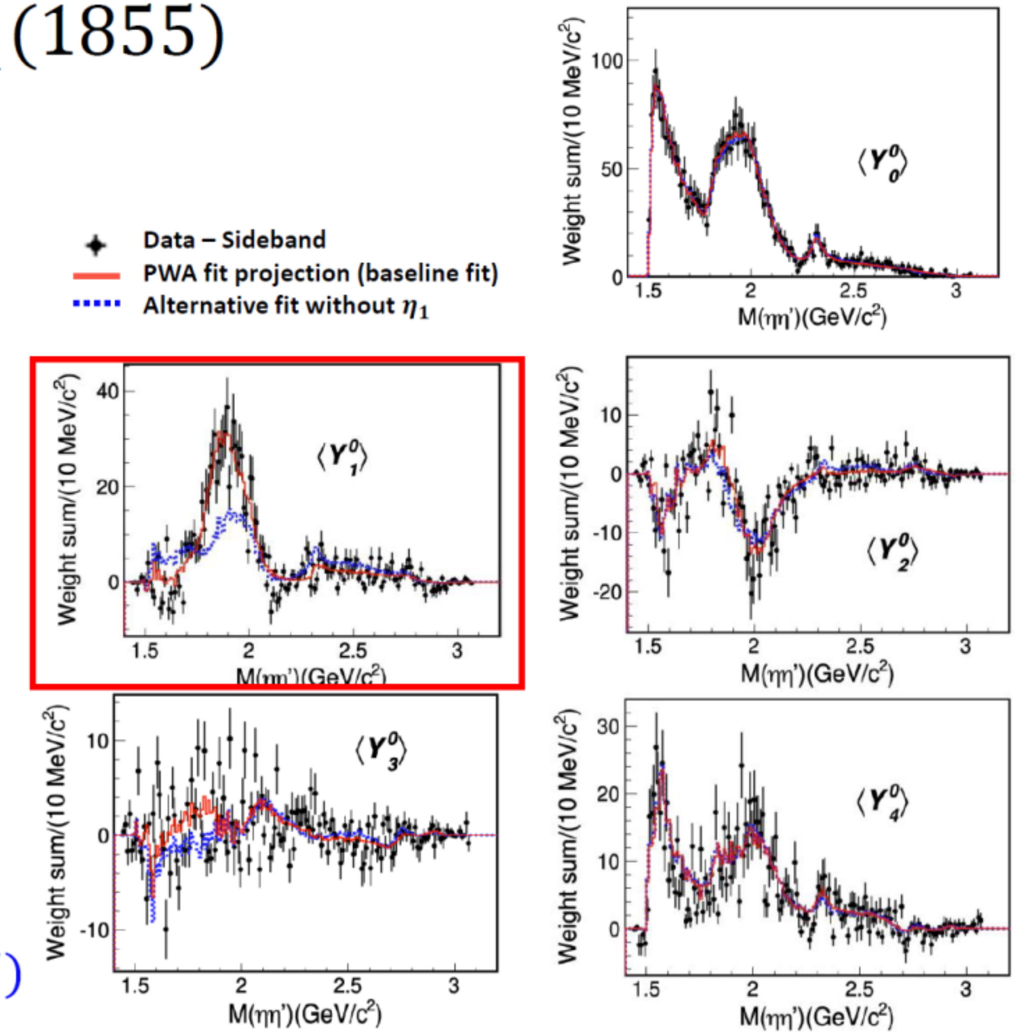
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{1}{7\sqrt{5}}(14P_0^2 - 7P_1^2 + 10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0D_0\cos\phi_{D_0},$$

$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) - P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2).$$

- **Narrow structure** in $\langle Y_1^0 \rangle$
  - **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \to \eta\eta'$ needed**



Charm is charming

- Over-constrain the SM, probe for new physics
  - ✓Precision CKM physics in B sector needs input from charm
- CPV and mixing
  - ✓The only up-type quark to form weakly decaying hadrons, complementary to K and B systems
- Unique to test QCD in low energy

Charm is challenging

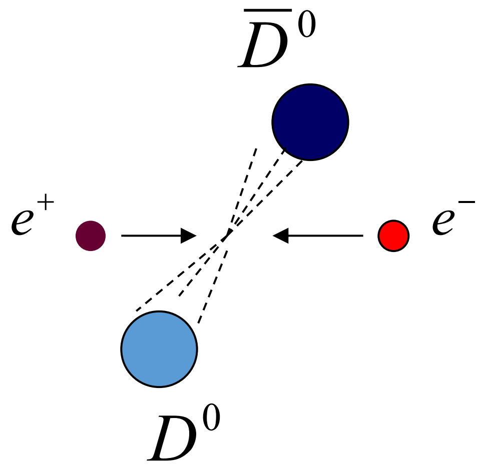
- Intermediate mass, compared to Λ_{QCD} -- not heavy, not light
- Do methods like Heavy Quark Expansion and Factorization work?

] → Theory

- CKM and GIM suppression can be strong – low rates → Large data sample

The correlated state

For a physical process producing $D^0\overline{D}^0$ such as



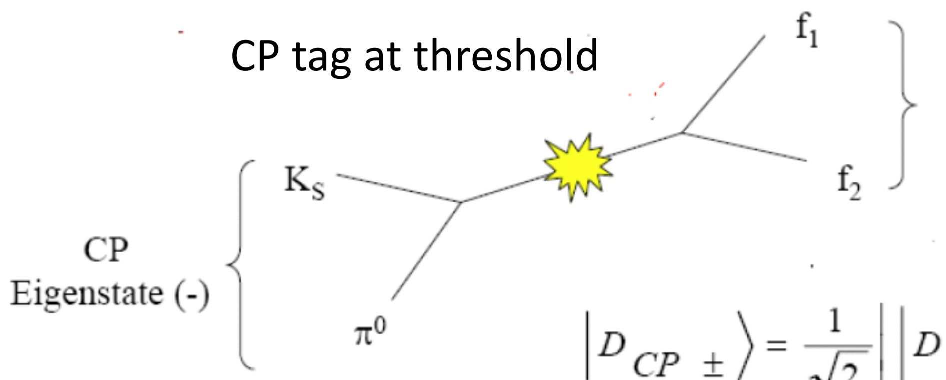
$$e^+e^- \to \psi'' \to D^0\overline{D}^0$$

The $D^0\overline{D}^0$ pair will be a quantum-correlated state

For a correlated state with $C = -$

$$\hat{C}|D^0\rangle = |\overline{D}^0\rangle$$
$$\hat{C}|\overline{D}^0\rangle = |D^0\rangle$$

$$\psi_- = \frac{1}{\sqrt{2}}\left(|D^0\rangle|\overline{D}^0\rangle - |\overline{D}^0\rangle|D^0\rangle\right)$$



$$\frac{\langle K^-\pi^+|\overline{D}^0\rangle^{DCS}}{\langle K^-\pi^+|D^0\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

$$|D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle \pm |\overline{D}^0\rangle\right]$$

$$\sqrt{2}\,A(D_{CP\pm} \to K^-\pi^+) = A(D^0 \to K^-\pi^+) \pm A(\overline{D}^0 \to K^-\pi^+)$$

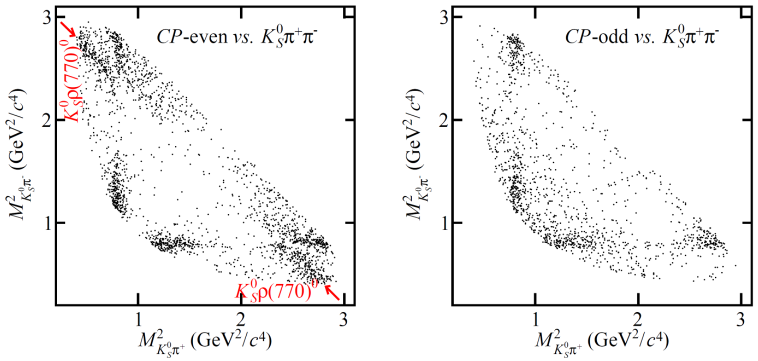
Strong phase measurements at BESIII

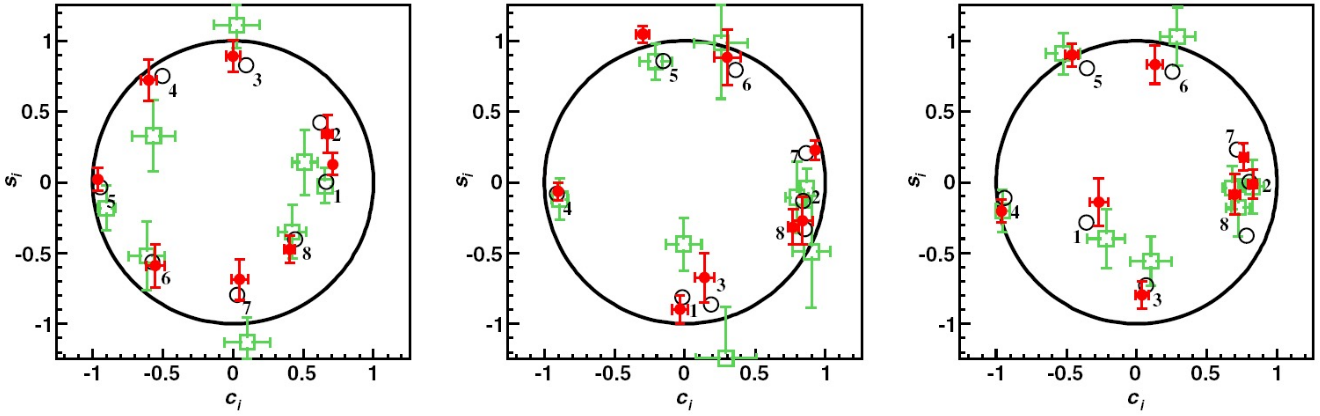
- $\mathbf{D \to K^0_{S/L}\pi^+\pi^-}$

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

PRL 124 (2020)241802

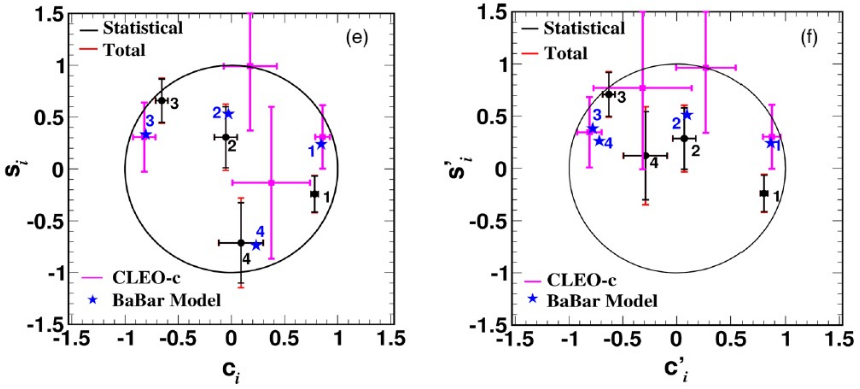
Constraint on γ measurement ~ 0.9^0





- $\mathbf{D \to K^0_{S/L}K^+K^-}$

PRD102(2020)052008



Constraint on γ measurement ~ 1.3^0

- $\mathbf{D \to K^-\pi^+\pi^+\pi^-}$ **and** $\mathbf{K^-\pi^+\pi^0}$

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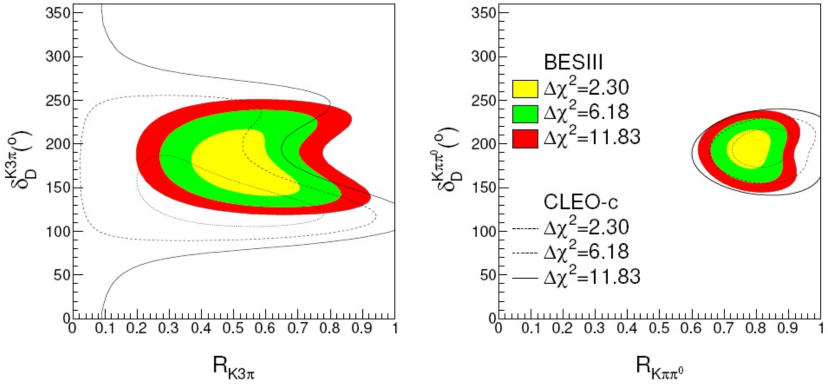
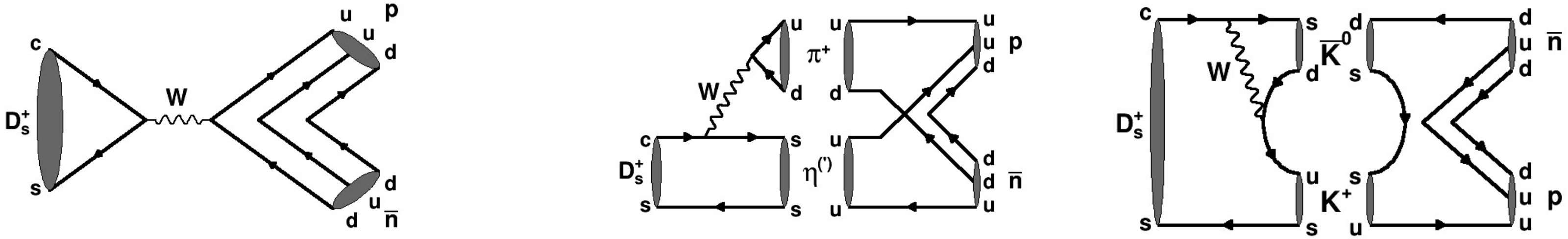


Constraint on γ measurement ~ 6^0

BESIII $D_s^+ \to p\bar{n}$

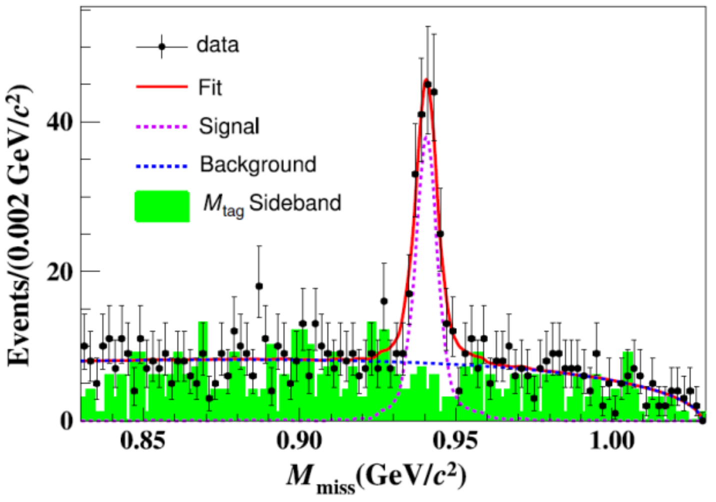
PRD 99 (2019) 031101 (R)

- The only kinematic allowed baryonic charm decay mode
- For the weak annihilation processes, Brs. expected to be ~10^{-6}(chiral suppression by the factor $(m_\pi/m_{Ds})^4$)
- Long distance effect may enhance Br: ~10^{-3} [PLB 663, 326(2008)]
- First evidence by CLEO-c: $(1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$ (PRL 100. 181802(2008))



Weak annihilation (~10^{-6})

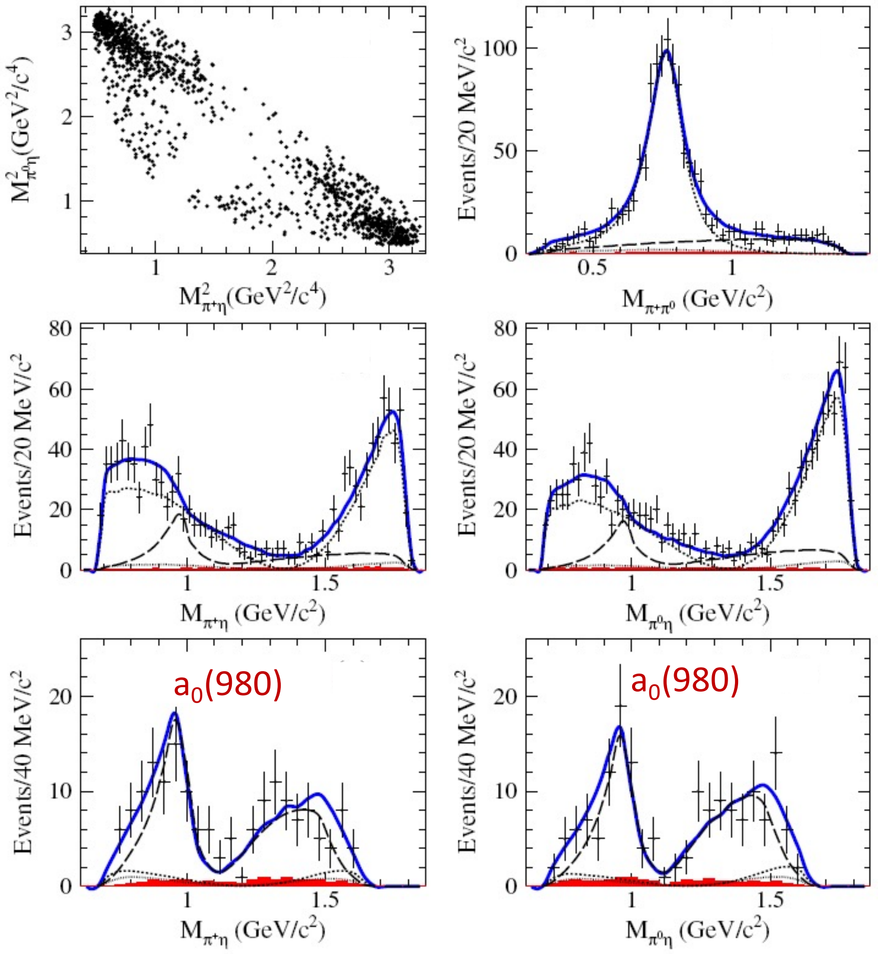
Long-distance effect



$$Br(D_s^+ \to p\bar{n}) = (1.21 \pm 0.10 \pm 0.05) \times 10^{-3}$$

- Weak annihilation process is not the driving mechanism
- The hadronization process driven by non-perturbative dynamics determines underlying physics

BESIII Amplitudes of $D_s^+ \to \eta\pi^+\pi^0$



M(ππ) > 1.0 GeV to exclude ρη.

PRL123(2020)112001

Amplitude	ϕ_n (rad)	FF_n
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.025$
$D_s^+ \to a_0(980)\pi$	$2.794 \pm 0.087 \pm 0.044$	$0.232 \pm 0.023 \pm 0.033$

$$B_{D_s^+ \to \pi^+\pi^0\eta} = (9.50 \pm 0.28 \pm 0.41)\%$$

$$B^{\mathrm{PDG18}}_{D_s^+ \to \pi^+\pi^0\eta} = (9.2 \pm 1.2)\%$$

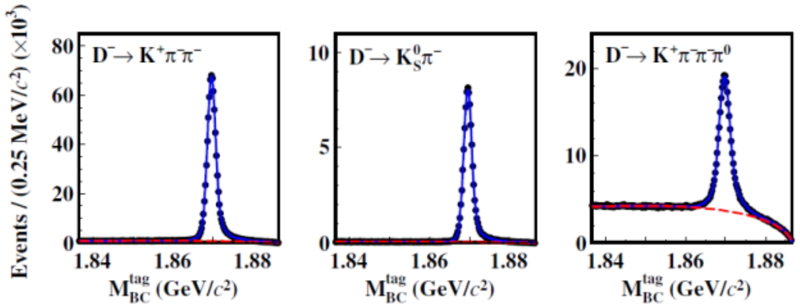
$$B_{D_s^+ \to \rho^+\eta} = (7.44 \pm 0.48 \pm 0.44)\%$$

$$B_{D_s^+ \to a_0(980)\pi} = (2.20 \pm 0.22 \pm 0.34)\%$$

Observation of abnormally large branching fraction for annihilation process.
It is larger than those of known W-annihilation decays by one order of magnitude.

Observation of DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$

PRL 125 (2020) 141802



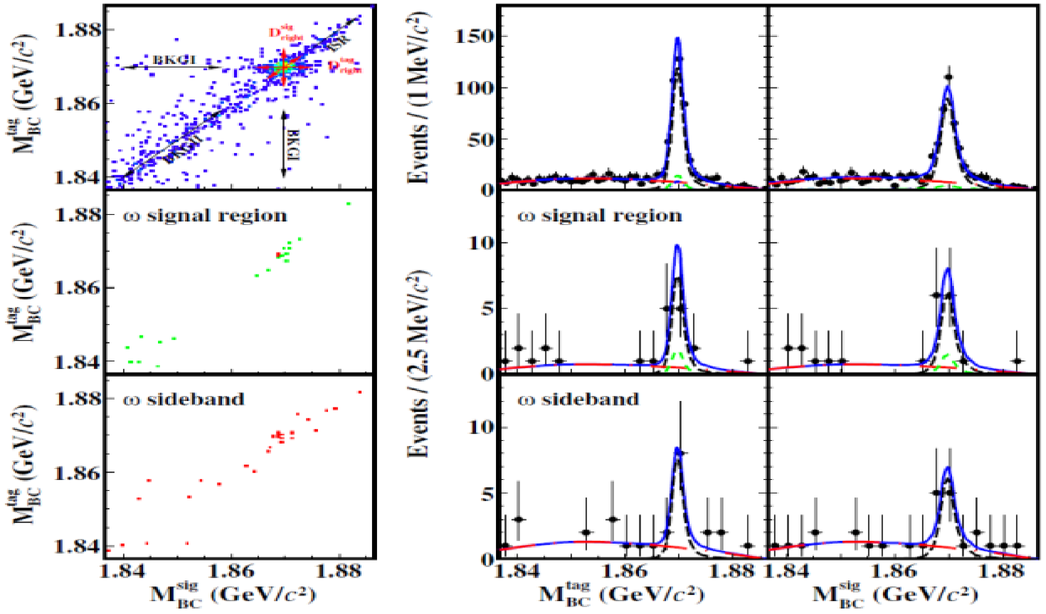
The single tag D^- yield: $(1150.3 \pm 1.5)\times10^3$

$$B_{D^+\to K^+\pi^+\pi^-\pi^0} = (0.113\pm0.008)\%$$

after remove $\eta/\omega/\phi$ K^+ components

$$B_{DCS}/B_{CF} = (1.81\pm0.15)\%$$

$\tan^4\theta_C = 2.88\times10^{-3}$



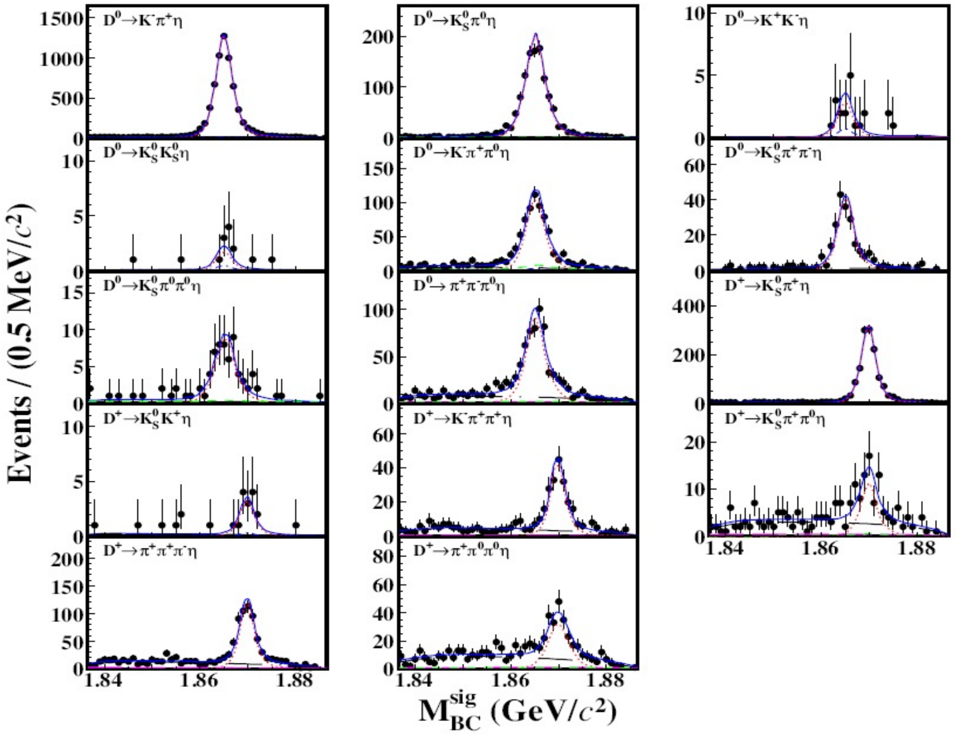
DCS mode	BF($\times10^{-4}$)	CF mode	BF($\times10^{-2}$)	Ratio($\times10^{-3}$)
$D^0\to K^+\pi^-$	1.48±0.07	$D^0\to K^-\pi^+$	3.89±0.04	3.80±0.18
$D^0\to K^+\pi^-\pi^0$	3.01±0.15	$D^0\to K^-\pi^+\pi^0$	14.2±0.5	2.12±0.13
$D^0\to K^+\pi^-\pi^-\pi^+$	2.45±0.07	$D^0\to K^-\pi^+\pi^+\pi^-$	8.11±0.15	3.02±0.10
$D^+\to K^+\pi^+\pi^-$	5.19±0.26	$D^+\to K^-\pi^+\pi^+$	8.98±0.28	5.78±0.34
$D^+\to K^+\pi^+\pi^-\pi^0$	11.3±0.8	$D^+\to K^-\pi^+\pi^+\pi^0$	6.25±0.18	18.10±1.5

- **The BF and B_{DCS}/B_{CF} of $D^+\to K^+\pi^+\pi^-\pi^0$ are significantly larger than those of known DCS charm decays**
- **May indicate massive isospin asymmetry between $D^+\to K^+\pi^+\pi^-\pi^0$ and $D^0\to K^+\pi^-\pi^-\pi^+$ due to final state interaction and different resonances**

BESIII new analysis: arXiv: 2105.1431 confirms above results.

Absolute BFs of $D^{0(+)}\to\eta X$ decays

PRL124(2020)241803



Decay	$\Delta E_{\rm sig}$ (MeV)	$N_{\rm DT}$	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$ ($\times10^{-4}$)
$D^0\to K^-\pi^+\eta$	$(-37,36)$	6116.2 ± 81.8	14.22	185.3(25)(31)
$D^0\to K^0_S\pi^0\eta$	$(-57,45)$	1092.7 ± 35.2	4.66	100.6(34)(30)
$D^0\to K^+K^-\eta$	$(-27,27)$	13.1 ± 4.0	9.53	0.59(18)(05)
$D^0\to K^0_SK^0_S\eta$	$(-29,28)$	7.3 ± 3.2	2.36	1.33(59)(18)
$D^0\to K^-\pi^+\pi^0\eta$	$(-44,36)$	576.5 ± 28.8	5.53	44.9(22)(15)
$D^0\to K^0_S\pi^+\pi^-\eta$	$(-33,32)$	248.2 ± 18.0	3.80	28.0(19)(10)
$D^0\to K^0_S\pi^0\pi^0\eta$	$(-56,41)$	64.7 ± 9.2	1.58	17.6(23)(13)
$D^0\to \pi^+\pi^-\pi^0\eta$	$(-57,45)$	508.6 ± 26.0	6.76	32.3(17)(14)
$D^+\to K^0_S\pi^+\eta$	$(-36,36)$	1328.2 ± 37.8	6.51	130.9(37)(31)
$D^+\to K^0_SK^+\eta$	$(-27,27)$	13.6 ± 3.9	4.72	1.85(52)(08)
$D^+\to K^-\pi^+\pi^+\eta$	$(-33,33)$	188.0 ± 15.3	8.94	13.5(11)(04)
$D^+\to K^0_S\pi^+\pi^0\eta$	$(-49,41)$	48.7 ± 9.7	2.57	12.2(24)(06)
$D^+\to \pi^+\pi^+\pi^-\eta$	$(-40,38)$	514.6 ± 25.7	9.67	34.1(17)(10)
$D^+\to \pi^+\pi^0\pi^0\eta$	$(-70,49)$	192.5 ± 17.1	3.86	32.0(28)(17)

Decay	$\mathcal{B}^+_{\rm sig}$ ($\times10^{-4}$)	$\mathcal{B}^-_{\rm sig}$ ($\times10^{-4}$)	$\mathcal{A}^{\rm sig}_{CP}$ (%)
$D^0\to K^-\pi^+\eta$	182.1 ± 3.5	189.1 ± 3.6	$-1.9\pm1.3\pm1.0$
$D^0\to K^0_S\pi^0\eta$	98.4 ± 4.8	106.3 ± 5.1	$-3.9\pm3.2\pm0.8$
$D^0\to K^-\pi^+\pi^0\eta$	41.7 ± 2.7	48.8 ± 3.2	$-7.9\pm4.8\pm2.5$
$D^0\to \pi^+\pi^-\pi^0\eta$	29.8 ± 2.2	33.3 ± 2.5	$-5.5\pm5.2\pm2.4$
$D^+\to K^0_S\pi^+\eta$	129.9 ± 5.3	132.3 ± 5.4	$-0.9\pm2.9\pm1.0$
$D^+\to \pi^+\pi^+\pi^-\eta$	35.4 ± 2.4	33.7 ± 2.4	$+2.5\pm5.0\pm1.6$

- **Direct measurements of absolute BFs of 14 exclusive hadronic $D^{0(+)}\to\eta X$ decays**
- **Comprehensive information about CP violation in D decays**
- **Combining PWA results gives 2-body decay BFs, benefiting the understanding of quark SU(3)-flavor symmetry and its breaking effect**

COMPASS

- **positive** and **negative muon** beams with a nominal momentum of 160 GeV/c or 200 GeV/c,
- **positive hadron** beams with momentum of 190 GeV/c and a composition of 75% protons, 24% pions and 1% kaons,
- **negative hadron** beams with momentum of 190 GeV/c and a composition of 1% anti-protons, 97% pions and 2% kaons,
- low intensity **electron** beam for calibration purposes (60 and 40 GeV/c).

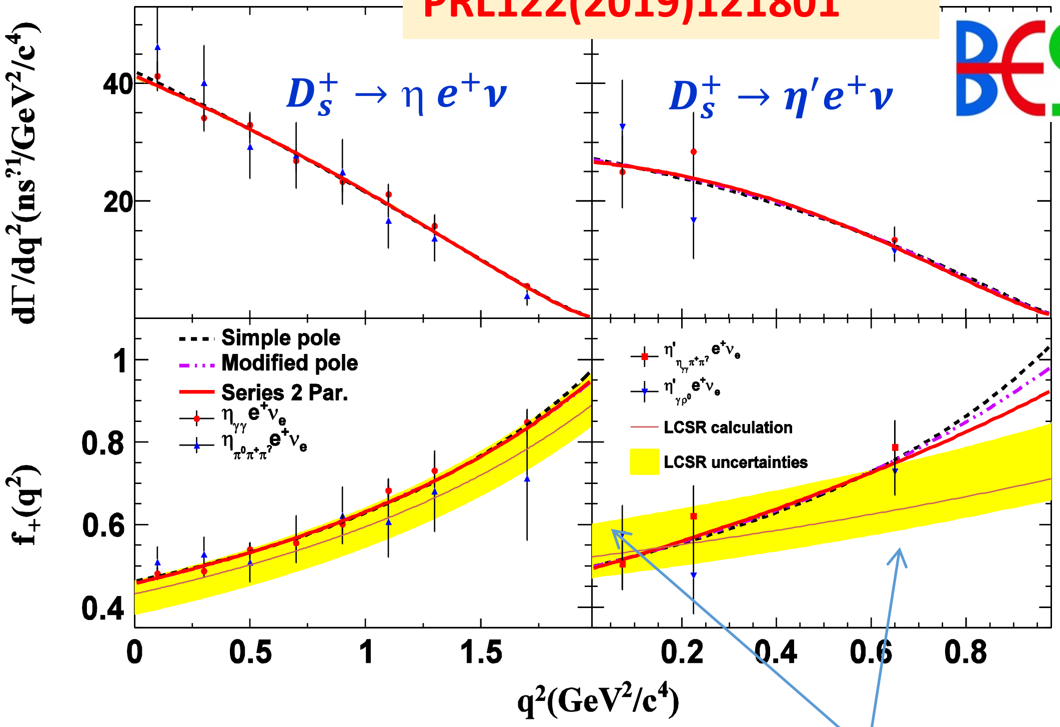
COMPASS ++/Amber: (proposal)

The proposed measurements cover the range from lowest-Q 2 physics as the determination of the proton radius by elastic muon-proton scattering, over average-Q 2 -reactions to study hadron spectroscopy, to high-Q 2 hadron-structure investigations using the Drell-Yan process and Deeply Virtual Compton Scattering.

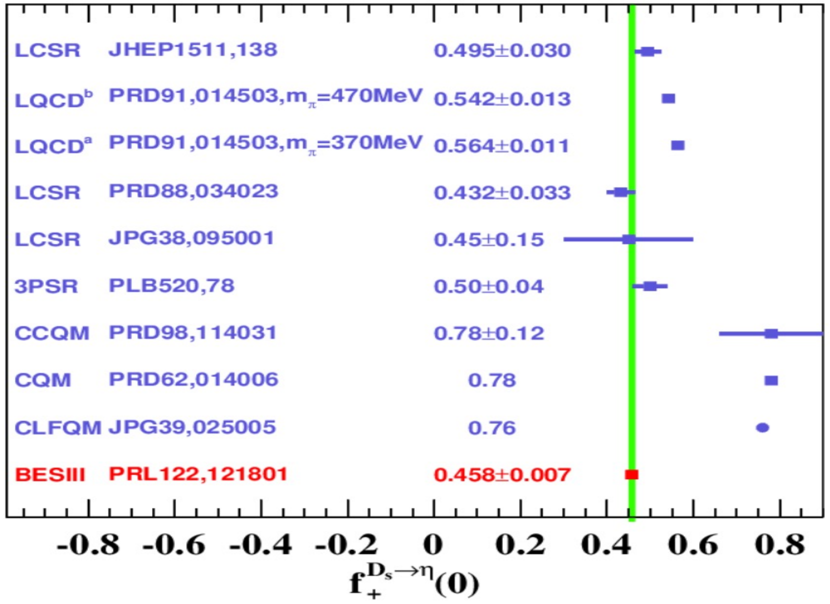
First extractions of FFs of $D_s^+ \to \eta^{(\prime)} e^+ \nu$

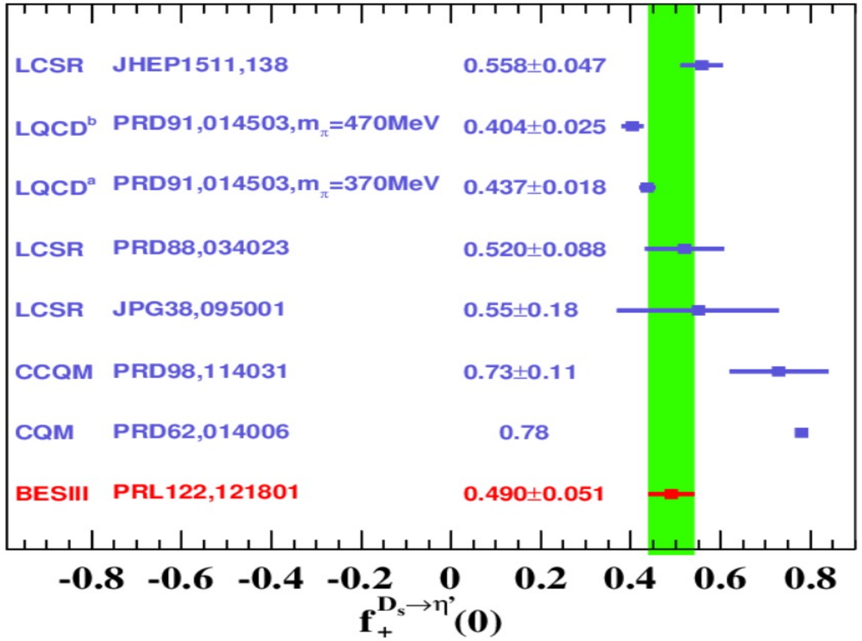
BESIII: 3.19 fb^{-1} @ 4180 MeV

PRL122(2019)121801



PRD88, 034023





$$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.446\pm0.005\pm0.004$$

$$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.477\pm0.049\pm0.011$$

Statistical errors dominate

First observation of $D^+ \to \eta\mu\nu_\mu$

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

$e^+e^- \to \psi(3770) \to D\bar{D}$

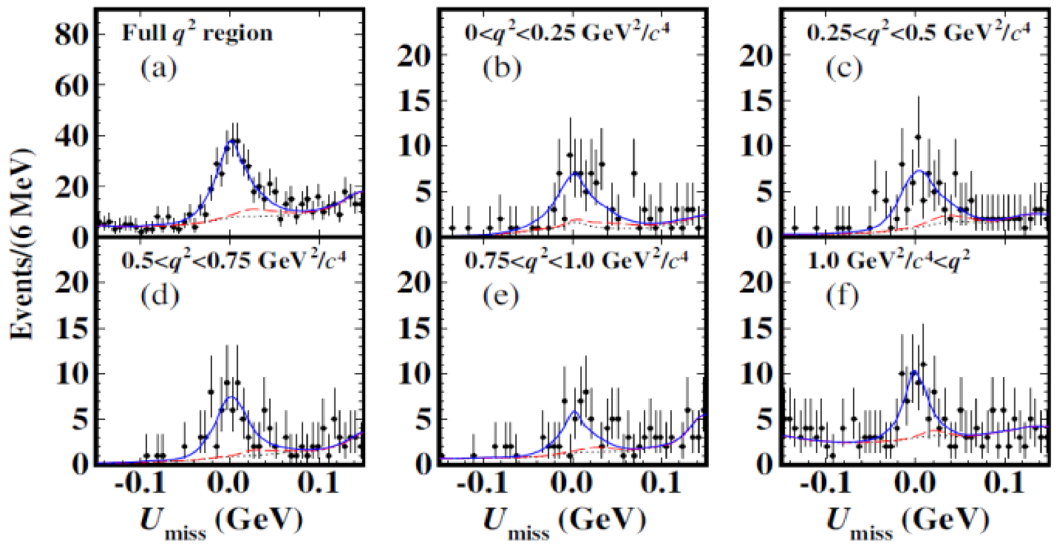
BESIII: PRL 124, 231801 (2020)

$$B[D^+ \to \eta\mu^+ v] = (0.104 \pm 0.010 \pm 0.005)\%$$

$$R_{D\eta} = \frac{\Gamma[D^+ \to \eta\mu^+ v]}{\Gamma[D^+ \to \eta e^+ v]} = 0.91 \pm 0.13$$

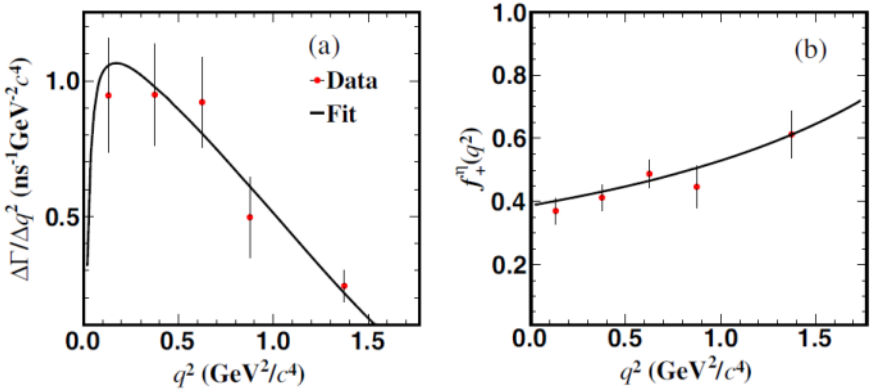
(SM prediction: 0.93-0.96)

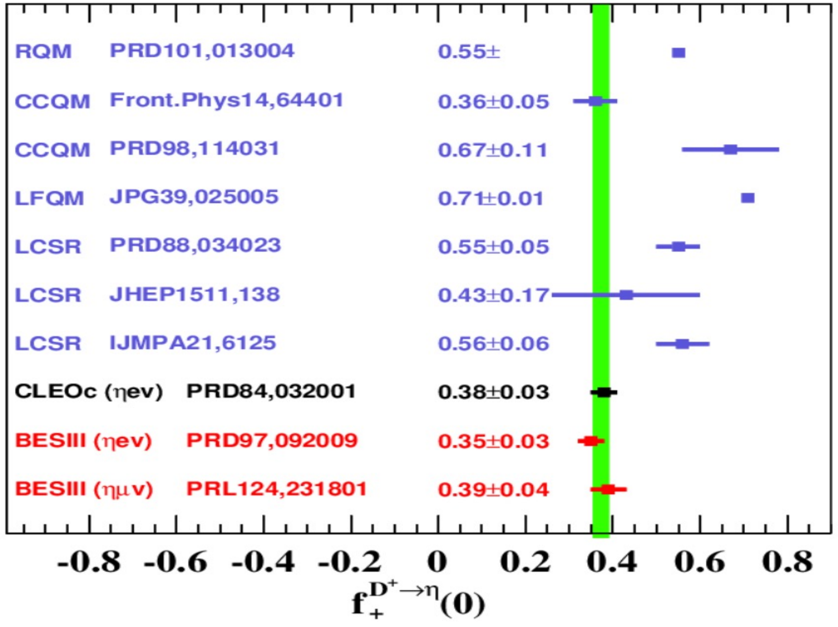
$$f_+^{D\to\eta}(0)|V_{cd}| = 0.087(08)(02)$$



No. of single tags: $(1522.5\pm2.1)\text{X}10^3$

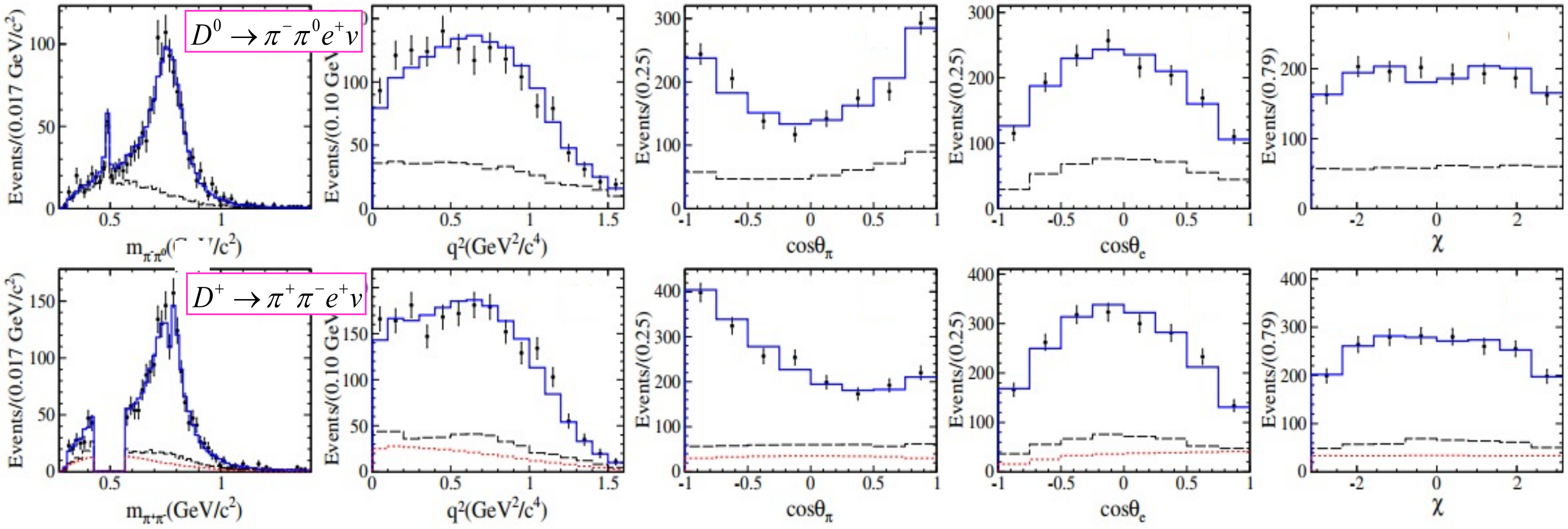
No. of double tags: 234 ± 22





Study of $D^{0+} \to \pi\pi e^+ \nu_e$

PRL122(2019)062001



Signal mode	This analysis ($\times 10^{-3}$)
$D^0 \to \pi^- \pi^0 e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \to \rho^- e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^+ \to \pi^- \pi^+ e^+ \nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \to \rho^0 e^+ \nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \to \omega e^+ \nu_e$	$2.05 \pm 0.66 \pm 0.30$
$D^+ \to f_0(500) e^+ \nu_e$, $f_0(500) \to \pi^+ \pi^-$	$0.630 \pm 0.043 \pm 0.032$
$D^+ \to f_0(980) e^+ \nu_e$, $f_0(980) \to \pi^+ \pi^-$	<0.028

First observation of $D^+ \to f_0(500) e^+ \nu_e$

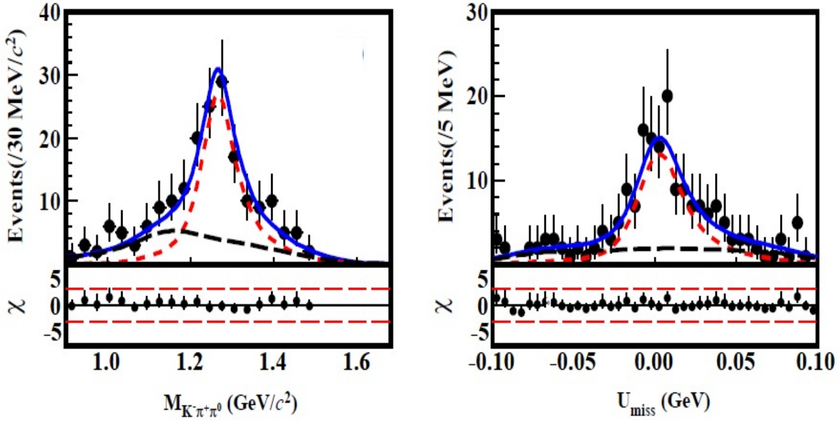
$$R = [B_{D^+ \to f_0(980)^0 e^+ \nu} + B_{D^+ \to f_0(500)^0 e^+ \nu}] / B_{D^+ \to a_0(980)^0 e^+ \nu} \quad >2.7$$

BESIII: PRL 121 (2018) 081802

favors tetraquark assumption for the light scalar mesons

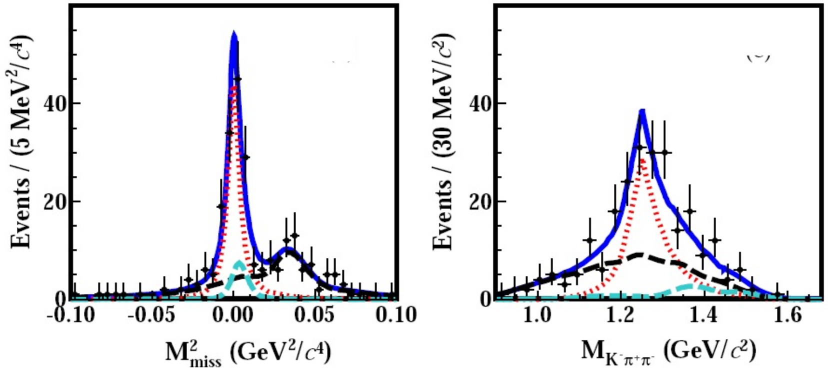
Observation of $D \to K_1(1270)e^+\nu_e$

PRL123(2019)231801



$B_{D^+\to\bar{K}_1^0(1270)e^+\nu} = (2.30 \pm 0.26 \pm 0.18 \pm 0.25)\times 10^{-3}$

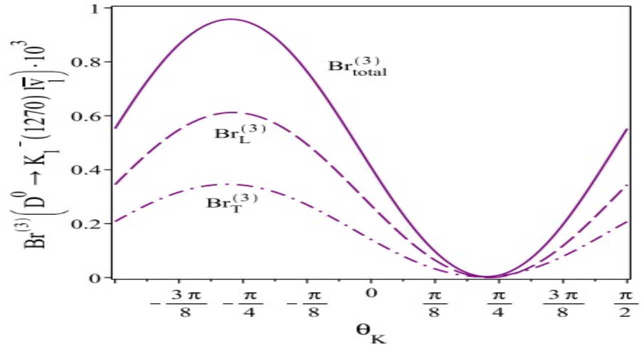
arXiv:2102.10850



$B_{D^0\to K_1(1270)^- e^+\nu} = (1.09 \pm 0.13 \pm 0.13 \pm 0.12)\times 10^{-3}$

$$\frac{\Gamma_{D^0\to K_1(1270)^- e^+\nu}}{\Gamma_{D^+\to\bar{K}_1^0(1270)e^+\nu}} = 1.20 \pm 0.20 \pm 0.15$$

JPG46,105006



PRL125,051802

Combined analysis of $D \to \bar{K}_1\ e^+\nu$ and B→γK$_1$ helps better access photon polarization in b→sγ

- **First observation after it was predicted in 1989**
- **Semileptonic D decays offer ideal environment to study light mesons**
- **Benefit the understanding of K$_1$ mixing angle which is controversial.**