Workshop on Status and Perspectives of Physics at High Intensity - Frascati

BESIII Present and Future Contributions to Flavour Physcis

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On behalf of the BESIII Collaboration

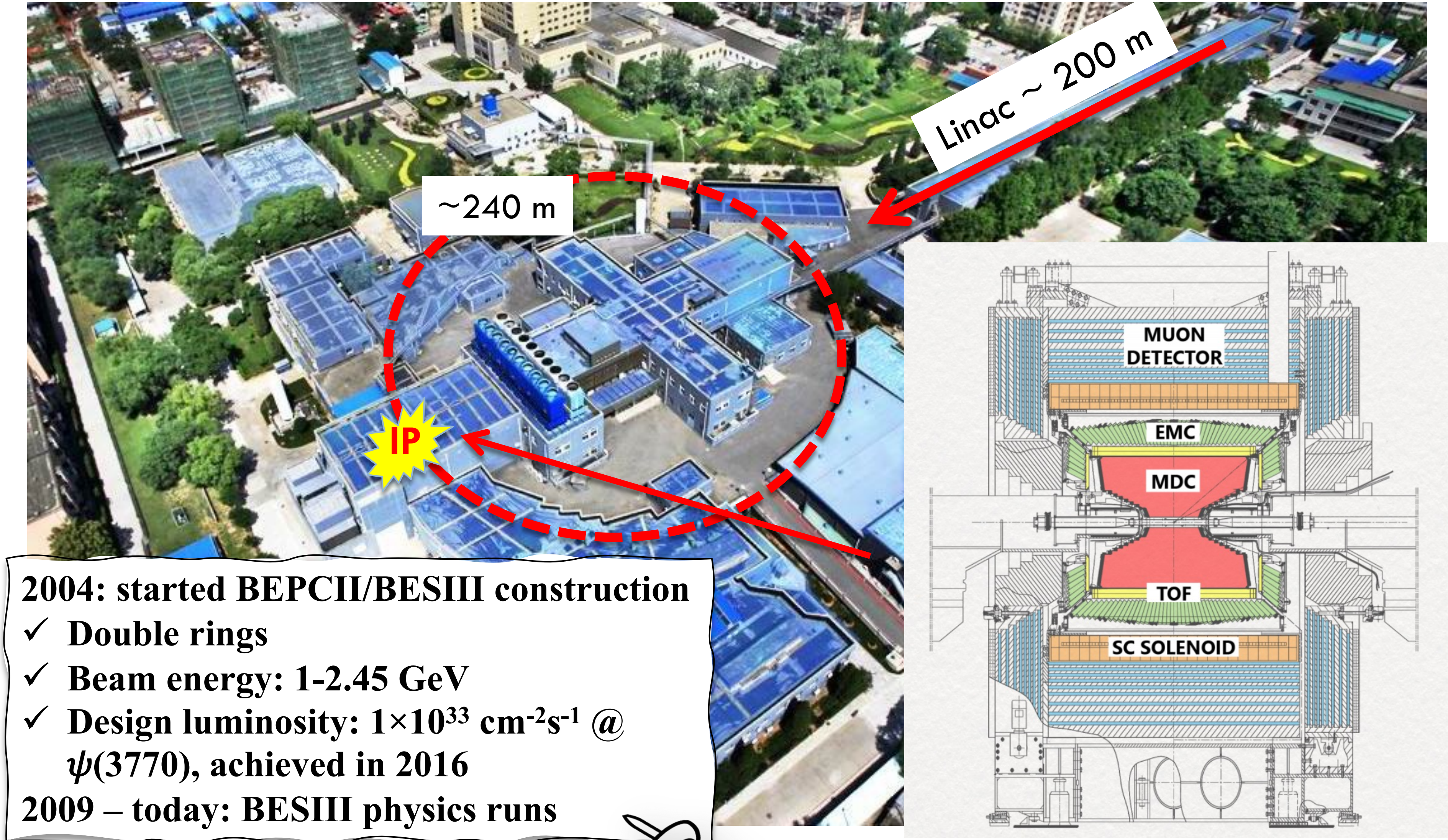
November 10, 2022
Frascati

Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

BESIII - Beijing Spectrometer III

http://english.ihep.cas.cn



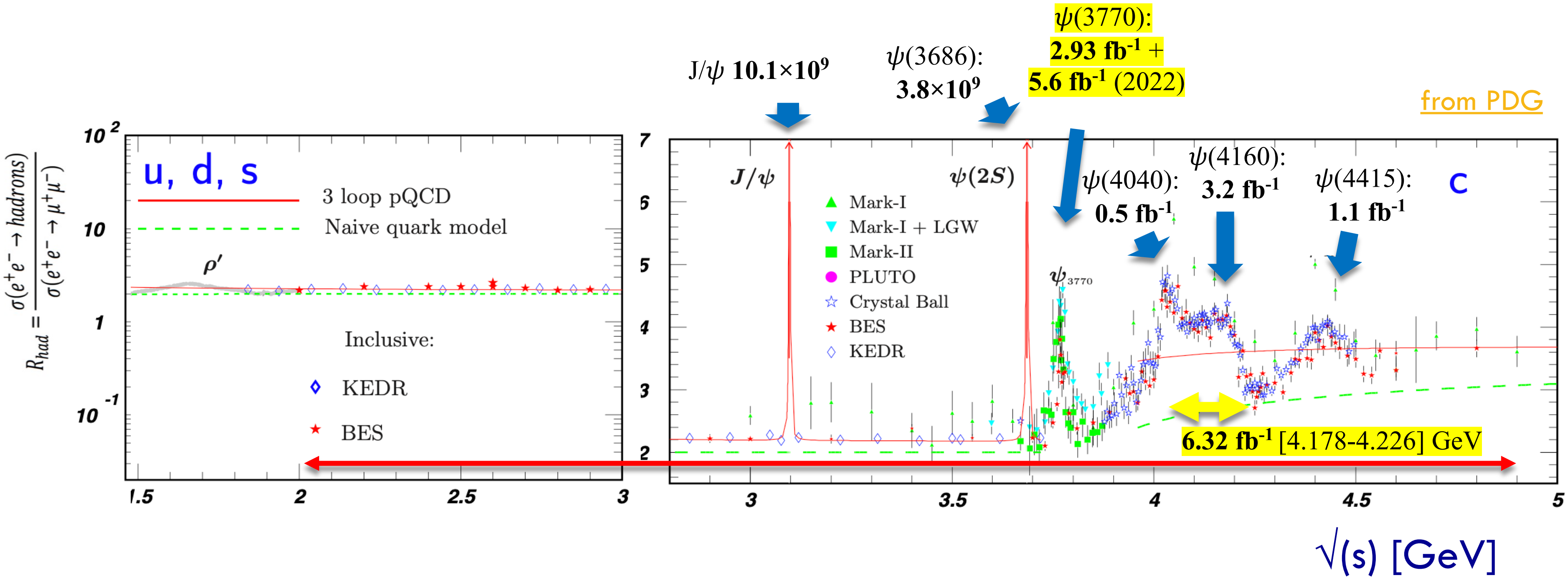
2004: started BEPCII/BESIII construction
- ✓ **Double rings**
- ✓ **Beam energy: 1-2.45 GeV**
- ✓ **Design luminosity: 1×10^{33} cm^{-2}s^{-1} @ $\psi(3770)$, achieved in 2016**

2009 – today: BESIII physics runs

Nucl. Instr. Meth. A614, 345 (2010)

BESIII dataset and physics program

Optimised for flavour physics in the τ-charm region



J/ψ **10.1×10⁹**

ψ(3686): **3.8×10⁹**

ψ(3770): **2.93 fb^{-1}** + **5.6 fb^{-1}** (2022)

ψ(4040): **0.5 fb^{-1}**

ψ(4160): **3.2 fb^{-1}**

ψ(4415): **1.1 fb^{-1}**

6.32 fb^{-1} [4.178-4.226] GeV

from PDG

- 130 points between 2 and 4.6 GeV (~715 pb^{-1} up to 3.08 GeV for ρ*, ω*, ϕ*,… studies)

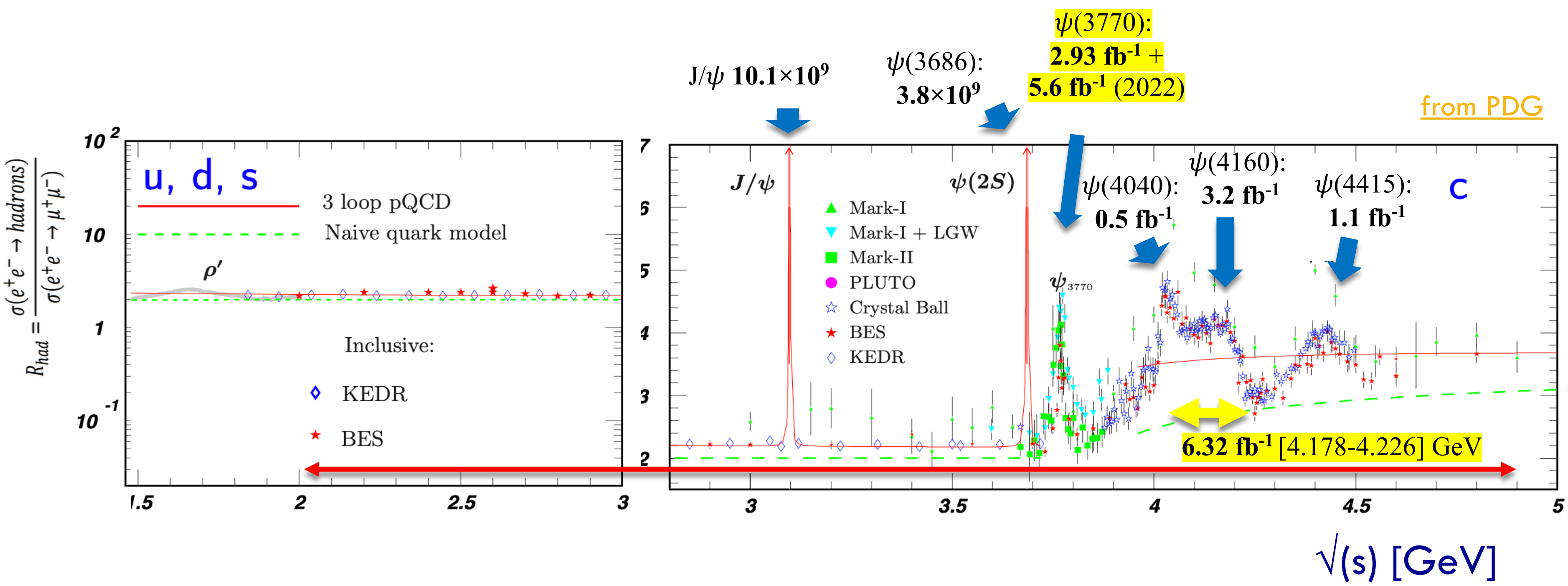
- Light hadron spectroscopy
- η/η’ decays
- Hyperon physics
- Charmonium transitions

- D^0D^0pairs
- $D_{(S)}$ meson decays
- $D^*_{(s)}$
- …

- XYZ decays and spectroscopy
- Open charm production
- Charmed baryons
- ...

BESIII dataset and physics program

Optimised for flavour physics in the τ-charm region



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In this talk:

- (Semi)Leptonic $D_{(s)}$ decays
- Hadronic $D_{(s)}$ decays

- $D^0\bar{D}^0$pairs
- $D_{(S)}$ meson decays
- $D^*_{(s)}$
- …

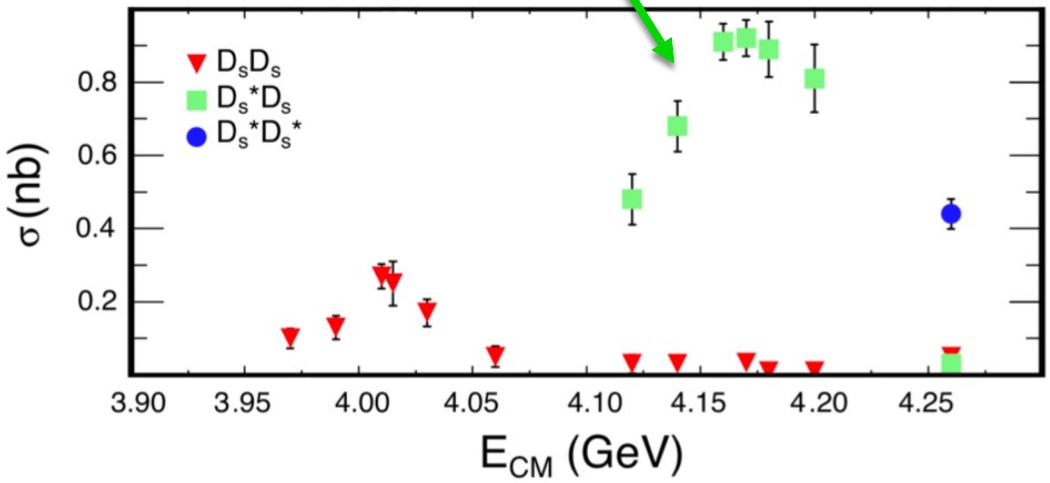
Charm meson production

$\sqrt{s}$(GeV)	Integrated luminosity	Decay chain of interest
3.773	$2.93\ \mathrm{fb}^{-1}$	$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$
		$e^+e^- \to \psi(3770) \to D^+D^-$
$\sqrt{s}$(GeV)	**Integrated luminosity(pb^{-1})**	$e^+e^- \to D_s^* D_s$ Total: $6.32\ \mathrm{fb}^{-1}$
4.178	$3189.0 \pm 0.9 \pm 31.9$	
4.189	$526.7 \pm 0.1 \pm 2.2$	
4.199	$526.0 \pm 0.1 \pm 2.1$	
4.209	$517.1 \pm 0.1 \pm 1.8$	
4.219	$514.6 \pm 0.1 \pm 1.8$	
4.226	$1047.3 \pm 0.1 \pm 10.2$	

$D\bar{D}$ pairs

- ➢ $D_s^+D_s^-$ pairs @ threshold, BUT
- ➢ $D_s^+D_s^{-*}$ ($\to D_s^-\gamma$ or $D_s^-\pi^0$) has a higher cross section @ 4.160 GeV

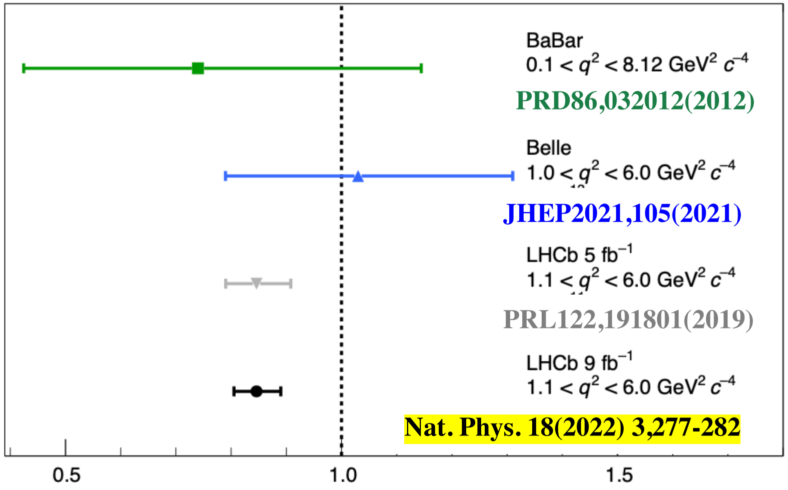
CLEO Phys. Rev. D 80, 072001 (2009)



(Semi) Leptonic Charm Decays

- (Semi)Leptonic $D_{(s)}$ decays: tools for testing SM predictions
  - ✓ LFU anomalies in B meson decays

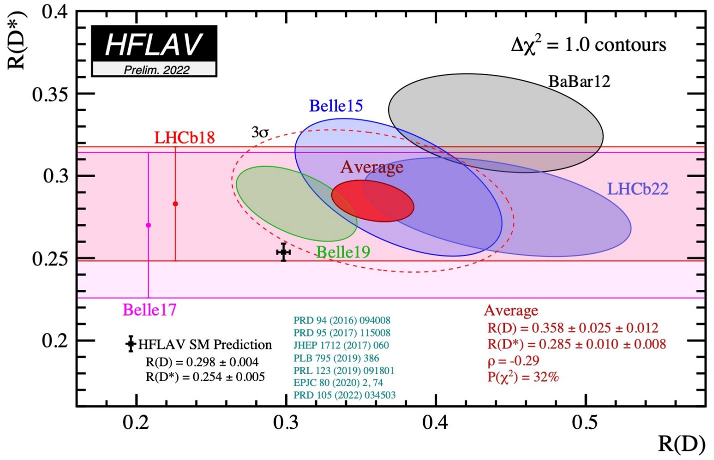
$b \to sll$



$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\to(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to(e^+e^-))}$$

LHCb ~ 3.1σ away from SM prediction

$b \to cl\nu$



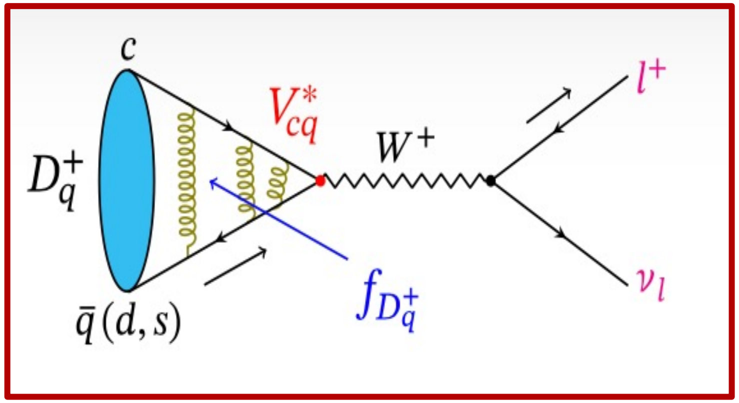
New preliminary average, including first joint measurement of R(D) and R(D∗) at LHCb

3.2σ away from SM prediction

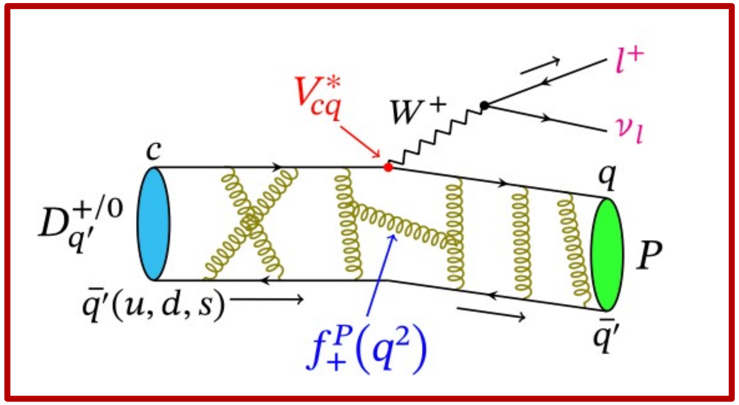
Observation of LFU violation would be a clear signal of new physics

(Semi) Leptonic Charm Decays

Pure leptonic decay



Semi-leptonic decay leptonic decay



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

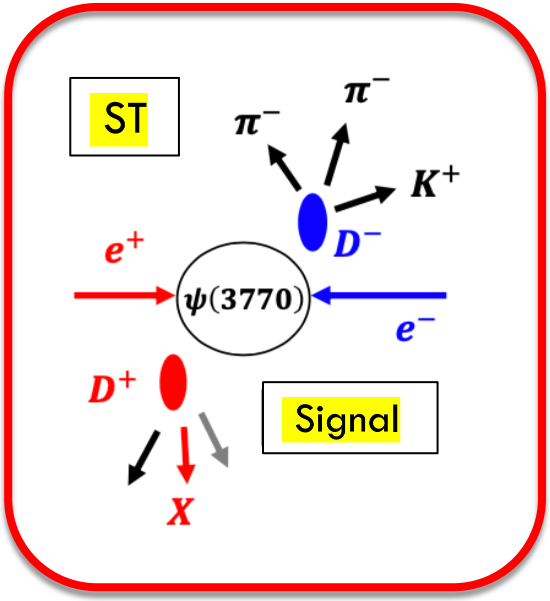
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p_P^3 |f_+^P(q^2)|^2$$

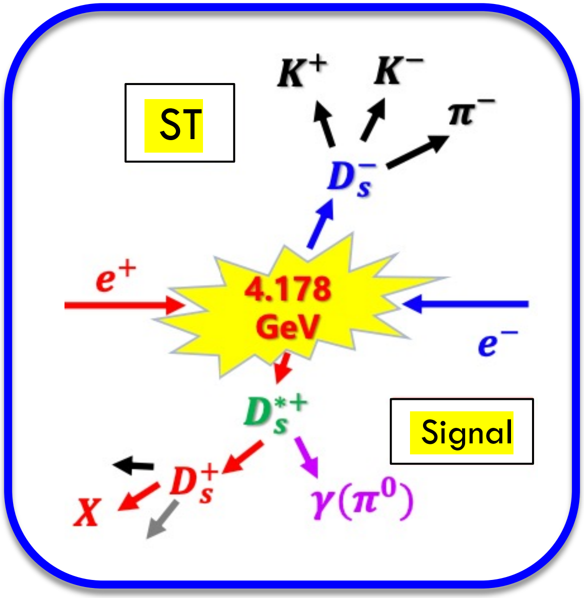
- Test CKM Unitary
- Test of the Lepton Flavour Universality

Pure leptonic decay: $R = \left(1 - \frac{m_\mu^2}{M^2_{D^+_{(s)}}}\right)^2 m_\mu^2 \Big/ \left(1 - \frac{m_e^2}{M^2_{D^+_{(s)}}}\right)^2 m_e^2$; SM Ratio from SL decays require form factor dependent phase- space corrections

- Compare decay constants and form factors to theoretical predictions
  - The study of semi-leptonic decay of charm meson is also helpful to study the meson spectrum

Analysis strategy





- Single Tag (ST): fully reconstruction of hadronic D(s) mesons (typically a clean modes)
- Double tag (DT)
  - Fully reconstruction the tag D(s) taking advantages of kinematic constrains (@ threshold: full kinematic constraint of the decays)
  - Search for the signal mode in the recoiling system
    - Typical kinematic variables: M^2_{miss} or $U_{\text{miss}} = E_{\text{miss}} - p_{\text{miss}}$
  - Advantages: do not need to know the number of D(s) pairs

$$E_{\text{miss}} = E_{\text{cm}} - \sqrt{|\vec{p}_{\text{tag}}c|^2 + m^2_{D_s}c^4} - E_\gamma - E_{\mu/\pi}$$

$$M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}c|^2$$

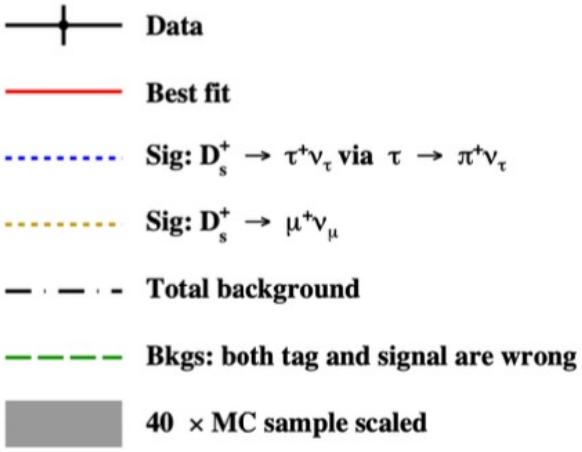
$$\mathcal{B}_{sig} = \frac{N^{DT}_{tag,sig}}{\mathcal{B}_{\gamma(\pi^0)} \sum_\alpha N^{ST,\alpha}_{tag}\, \epsilon^\alpha_{sig}/\epsilon^\alpha_{tag}}$$

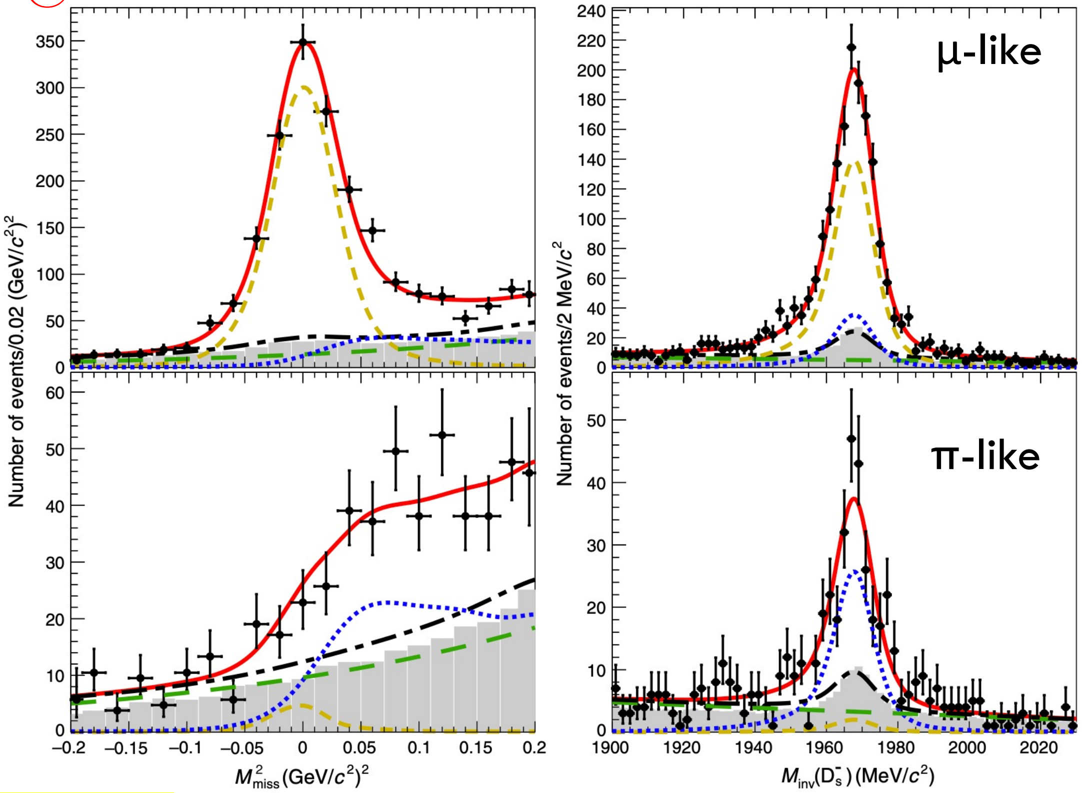
$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $D_s^+ \to \mu^+\bar{\nu}_\mu$

PRD **104,** 052009 (2021)

@4.180 GeV

Signal yield: unbinned simultaneous maximum likelihood fit to the 2D distributions





$$B(D_s^+ \to \mu^+\nu_\mu) = (5.35 \pm 0.13_{\rm stat.} \pm 0.16_{\rm syst.}) \times 10^{-3}$$

$$B(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25_{\rm stat.} \pm 0.17_{\rm syst.}) \times 10^{-2}$$

Most precise to date

$$R = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 9.73^{+0.61}_{-0.58} \pm 0.36$$

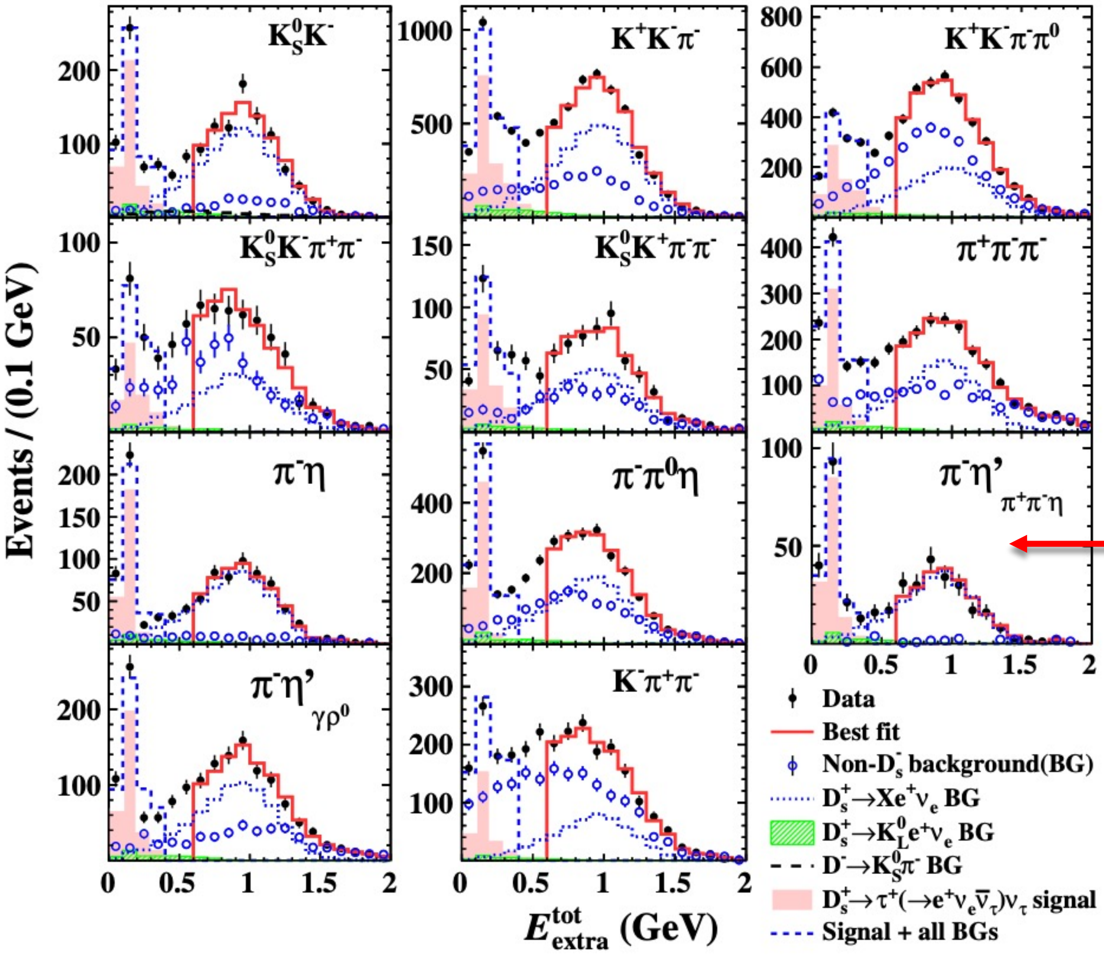
Consistent with SM prediction of 9.75

$$A_{CP} = \frac{\Gamma(D_s^+ \to \ell^+\nu_\ell) - \Gamma(D_s^- \to \ell^-\bar{\nu}_\ell)}{\Gamma(D_s^+ \to \ell^+\nu_\ell) + \Gamma(D_s^- \to \ell^-\bar{\nu}_\ell)}$$

No evidence of CP violation found

$D_s^+\to\tau^+\nu_\tau$ via $\tau^+\to e^+\nu_e\bar{\nu}_\tau$

PRL 127, 171801 (2021)



E^{tot}_{extra} to discriminate between signal and background: tot energy of good EMC showers, excluding those associated with ST candidates and those within 5° of the initial direction of the positron

from Best Fit

DT yield N_{DT} $= N_{DT}^{tot} - N_{DT}^{non-D_s^-} - N_{DT}^{K_L^0e^+\nu_e} - N_{DT}^{Xe^+\nu_e}$

Signal shape from ST sideband

fraction fixed; BR from PRL122, 061801

yield left free

$$\mathcal{B}_{D_s^+\to\tau^+\nu_\tau}/\mathcal{B}^{(PDG)}_{D_s^+\to\mu^+\nu_\mu} = 9.72\pm0.37,$$

SM prediction 9.75 ± 0.01

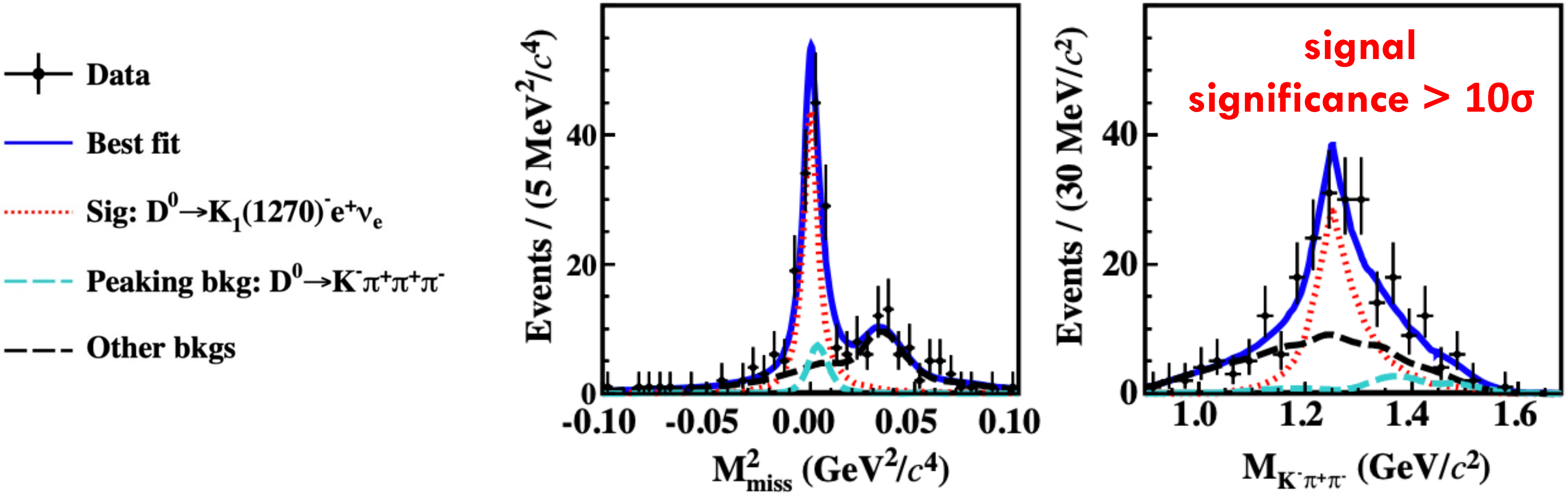
$$\boldsymbol{B_{D_s^+\to\tau^+\nu_\tau} = (5.27\pm0.10_{stat.}\pm0.12_{syst.})\%}$$

Improved precision by a factor 2

Observation of $D^0 \to K_1(1270)^- e^+ \nu_e$

PRL **127,** 131801 (2021)

- Input to determine the photon polarization in b→sγ transition (study of the $K_1(1270)^- \to K^- \pi^+ \pi^-$ hadronic effect)
- The DT yield is obtained from a 2D unbinned extended maximum-likelihood simultaneous fit to the data for the three hadronic tag modes (Kπ, Kππ, Kπππ)



signal significance > 10σ

$$B_{D^0 \to K_1(1270)^- e^+ \nu_e} = \left(1.09 \pm 0.13^{+0.09}_{-0.13} \pm 0.12_{\text{ex.}}\right) \times 10^{-3}$$

$$\frac{\Gamma_{D^0 \to K_1(1270)^- e^+ \nu_e}}{\Gamma_{D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e}} = 1.20 \pm 0.02_{\text{stat.}} \pm 0.14_{\text{syst.}} \pm 0.04_{\text{ex.}}$$

Agrees with unity as predicted by isospin symmetry

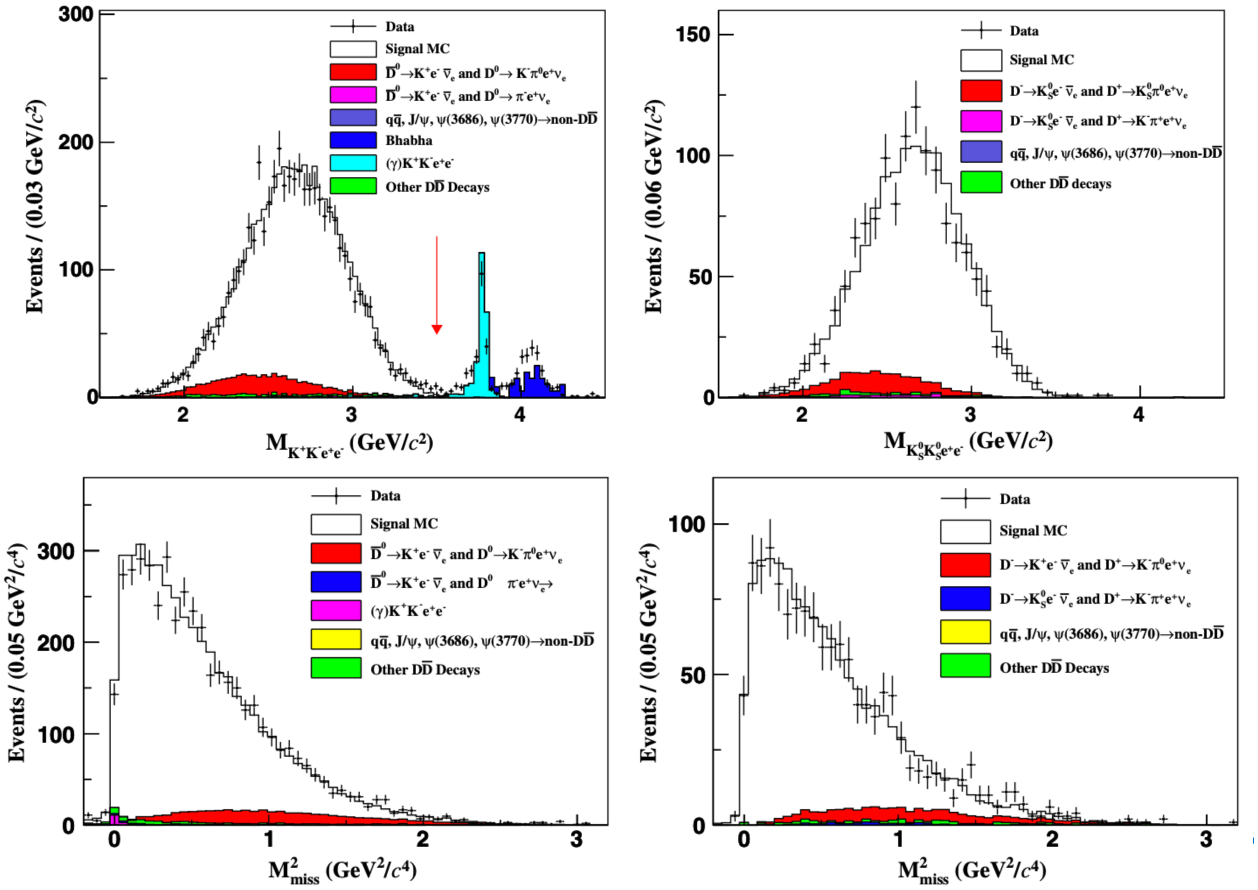
More data are needed to quantify the $K_1(1270) \to K\pi\pi$ hadronic effect

$D^0 \to K^- e^+ \nu_e$ and $D^+ \to K^0 e^+ \nu_e$

PRD **104,** 052008 (2021)

- Largest BFs and clear experimental signature
- Precise measurements help to understand nonperturbative effects in heavy meson decays
- Test of lattice QCD calculation

NEW TECHNIQUE: determine the absolute BFs by reconstructing both $D \to \overline{K} e^+ \nu_e$ and $D \to K e^- \nu_e$ within the same events



$D^0 \to K^- e^+ \nu_e$ and $D^+ \to K^0 e^+ \nu_e$

PRD **104**, 052008 (2021)

$$B_{D^0 \to K^- e^+ \nu_e} = (3.567 \pm 0.031 \pm 0.021) \times 10^{-2}$$

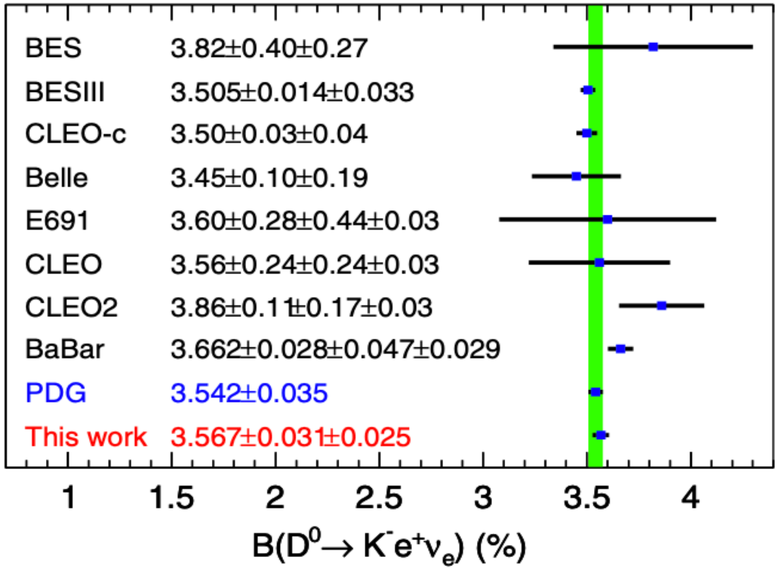
$$B_{D^+ \to \bar{K}^0 e^+ \nu_e} = (8.68 \pm 0.14 \pm 0.16) \times 10^{-2}$$

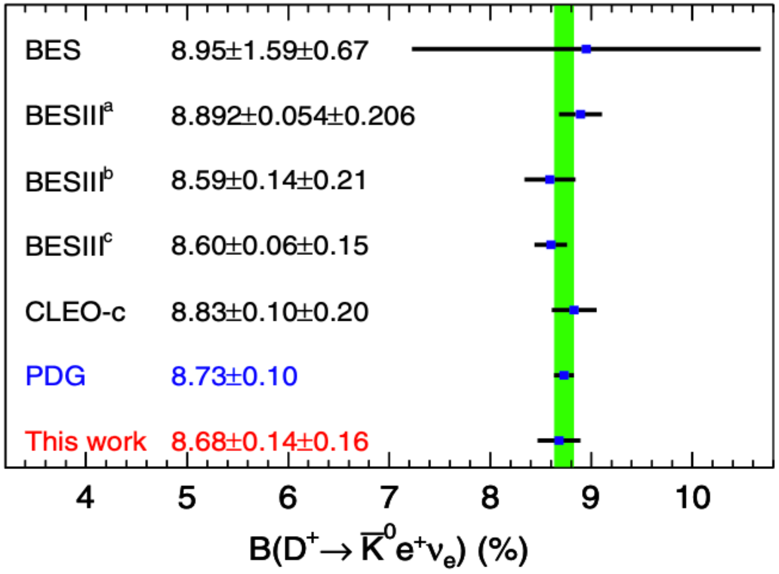
Combining our results with previous BESIII measurements

$$\boxed{\frac{\Gamma_{D^0 \to K^- e^+ \nu_e}^{(*)}}{\Gamma_{D^+ \to \bar{K}^0 e^+ \nu_e}} = 1.039 \pm 0.021}$$

Support isospin symmetry within 1.9σ

(*)reweighted B by D^0 and D^+ lifetime



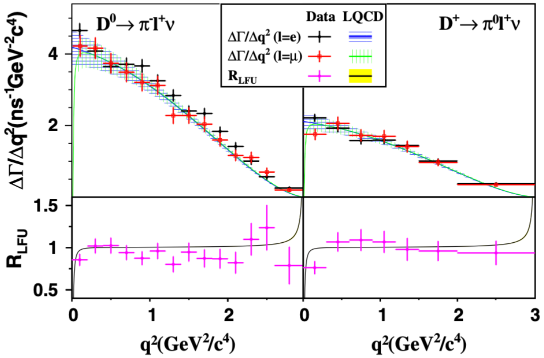


Independent DT signal sample w.r.t. previous BESIII analyses; result consistent with theoretical predictions within 2.5σ

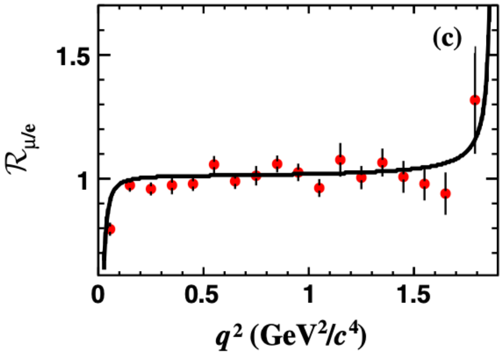
Summary of LFU tests at BESIII

		References	Measured B(l)/B(l')	SM prediction
μ/e	$D^0 \to K^-$	PRL**122**(2019)011804	0.974±0.014	~0.975
	$D^0 \to \pi^-$	PRL**121**(2018)171803	0.922±0.038	~0.985
	$D^0 \to \rho^-$	PRD**104**(2021)L091103	0.90±0.11	0.93-0.96
	$D^+ \to \overline{K}^0$	EPJ C (2016) **76**:369	0.988±0.033	~0.970
	$D^+ \to \pi^0$	PRL**121**(2018)171803	0.964±0.045	~0.985
	$D^+ \to \omega$	PRD**101**(2020)072005	1.05±0.14	0.93–0.99
	$D^+ \to \eta$	PRL**124**(2020)231801	0.91±0.13	0.97-1.00
	$D_s^+ \to \eta$	PRD**97**(2018)012006	1.05±0.24	~1.0
	$D_s^+ \to \eta'$		1.14±0.68	
	$D_s^+ \to \varphi$		0.86±0.29	
	$\Lambda_c^+ \to \Lambda$	PLB**676**(2017)42,47	0.96±0.16	~1.0
τ/μ	$D^+ \to \tau^+ \nu$	PRL**123**(2019)211802	3.21±0.77	2.66
	$D_s^+ \to \tau^+ \nu$	PRL**127**(2021)171801	9.72±0.37	9.75

PRL**121**(2018)171803



PRL**122**(2019)011804



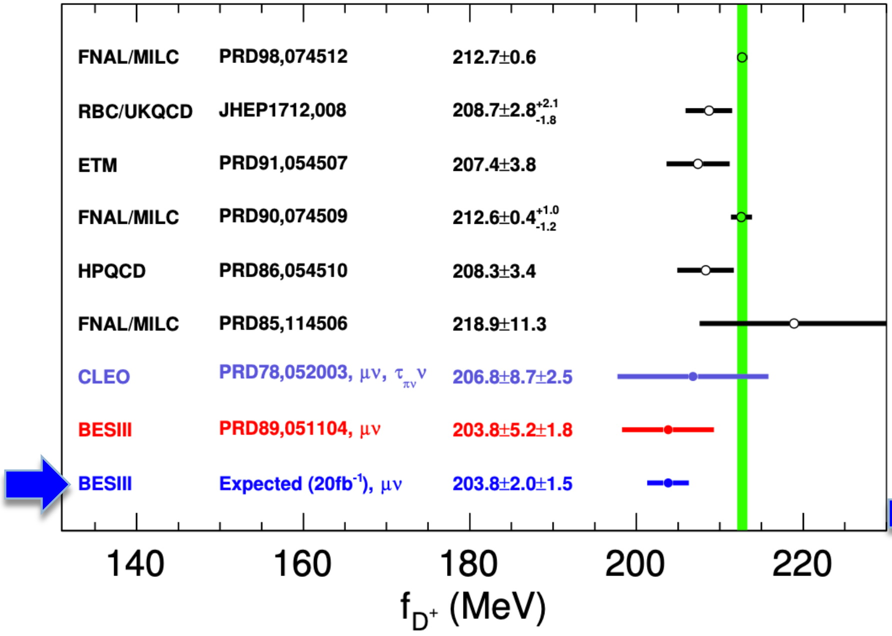
Deviation from one due to the different PS available

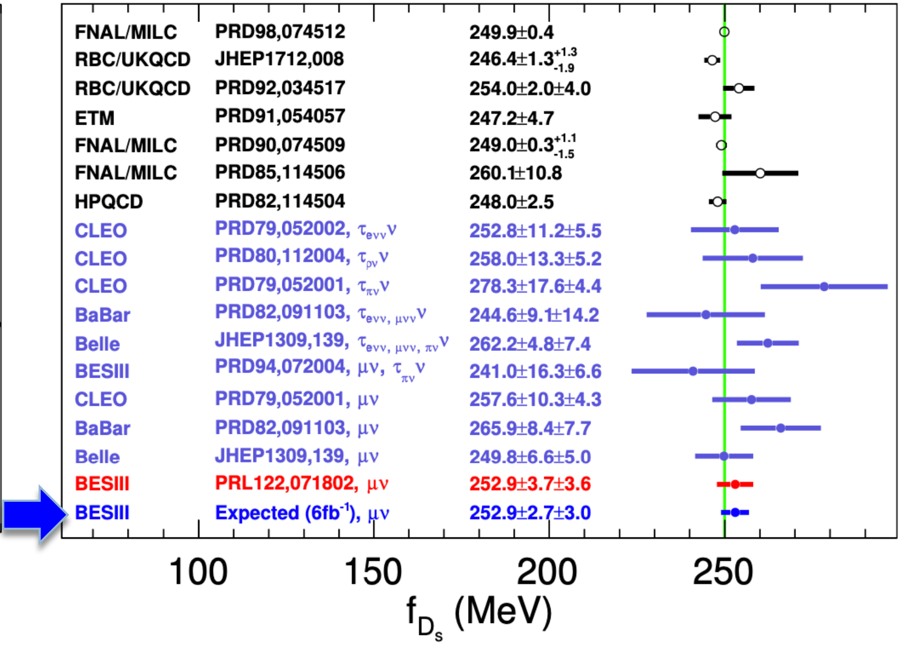
No tensions with the SM expectation within the current precision

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

$|V_{cd(s)}|$ can be taken from the global fits of the other CKM matrix elements assuming unitary in SM, and $f_{D^+(s)}$ can be determined

Chinese Physics C 44, 040001 (2020)





○ LQCD calculations, 🟩 LQCD uncertainty (PRD98, 074512(2018))

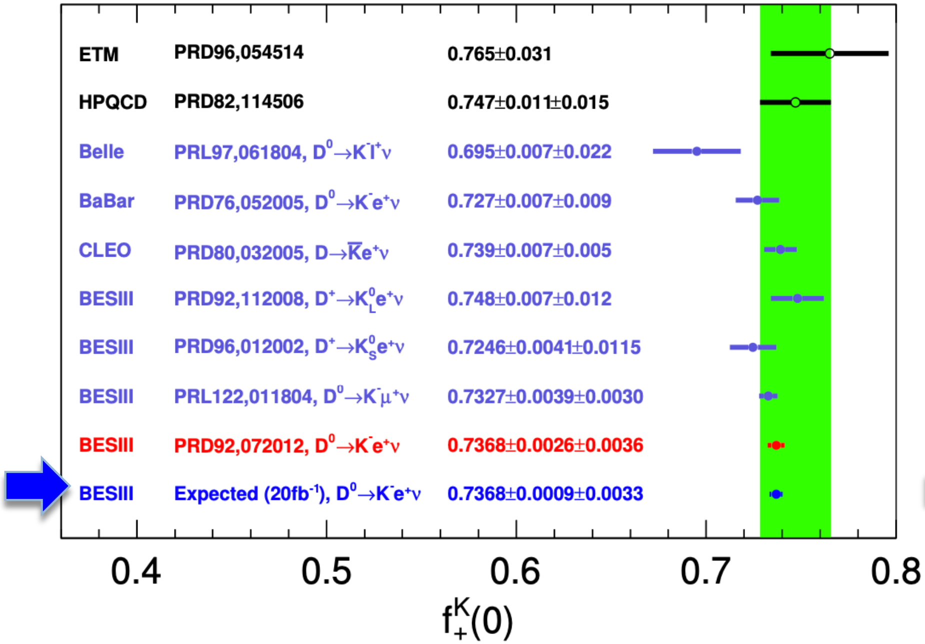
● Best BESIII measurement

● Expected precision with 20 fb^{-1} @ 3.773 GeV or 6fb^{-1} @ 4.178 GeV

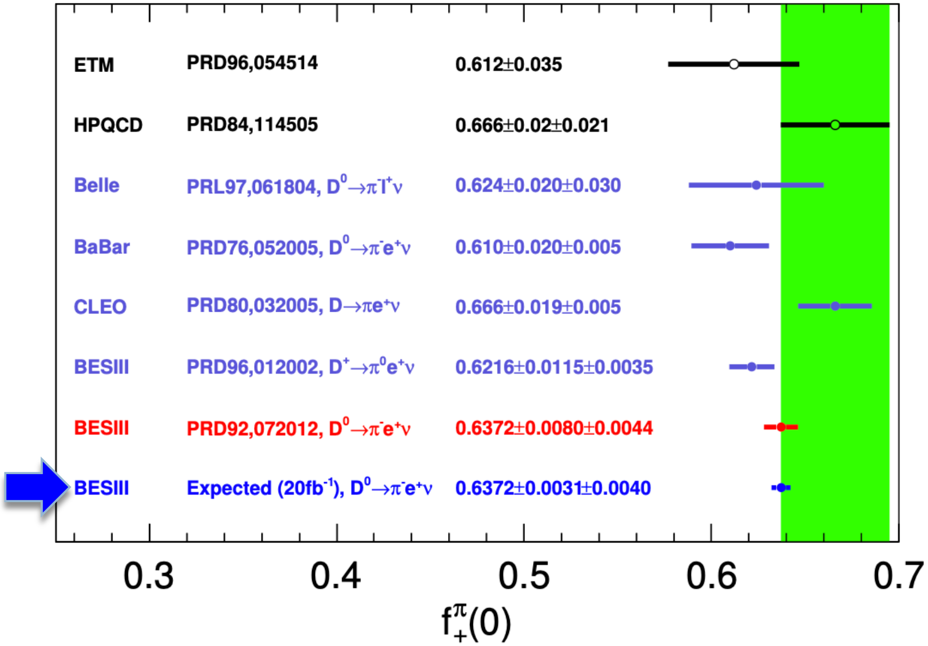
Comparisons of $f_+^{\pi/K}(0)$

$|V_{cd(s)}|$ can be taken from the global fits of the other CKM matrix elements assuming unitary in SM, and $f_{D+(s)}$ can be determined

Chinese Physics C 44, 040001 (2020)



ETM	PRD96,054514	0.765±0.031
HPQCD	PRD82,114506	0.747±0.011±0.015
Belle	PRL97,061804, $D^0\to K^- l^+\nu$	0.695±0.007±0.022
BaBar	PRD76,052005, $D^0\to K^- e^+\nu$	0.727±0.007±0.009
CLEO	PRD80,032005, $D\to \overline{K} e^+\nu$	0.739±0.007±0.005
BESIII	PRD92,112008, $D^+\to K_L^0 e^+\nu$	0.748±0.007±0.012
BESIII	PRD96,012002, $D^+\to K_S^0 e^+\nu$	0.7246±0.0041±0.0115
BESIII	PRL122,011804, $D^0\to K^- \mu^+\nu$	0.7327±0.0039±0.0030
BESIII	PRD92,072012, $D^0\to K^- e^+\nu$	0.7368±0.0026±0.0036
BESIII	Expected (20fb^{-1}), $D^0\to K^- e^+\nu$	0.7368±0.0009±0.0033



ETM	PRD96,054514	0.612±0.035
HPQCD	PRD84,114505	0.666±0.02±0.021
Belle	PRL97,061804, $D^0\to \pi^- l^+\nu$	0.624±0.020±0.030
BaBar	PRD76,052005, $D^0\to \pi^- e^+\nu$	0.610±0.020±0.005
CLEO	PRD80,032005, $D\to \pi e^+\nu$	0.666±0.019±0.005
BESIII	PRD96,012002, $D^+\to \pi^0 e^+\nu$	0.6216±0.0115±0.0035
BESIII	PRD92,072012, $D^0\to \pi^- e^+\nu$	0.6372±0.0080±0.0044
BESIII	Expected (20fb^{-1}), $D^0\to \pi^- e^+\nu$	0.6372±0.0031±0.0040

○ LQCD calculations, 🟩 LQCD uncertainty (PRD82, 114506(2010); PRD 84, 114505(2011))

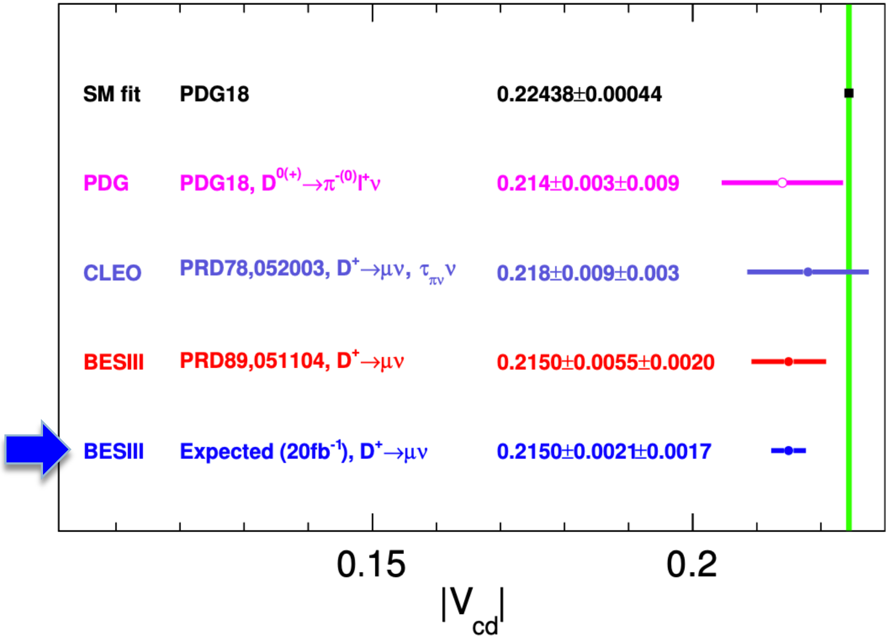
● Best BESIII measurement

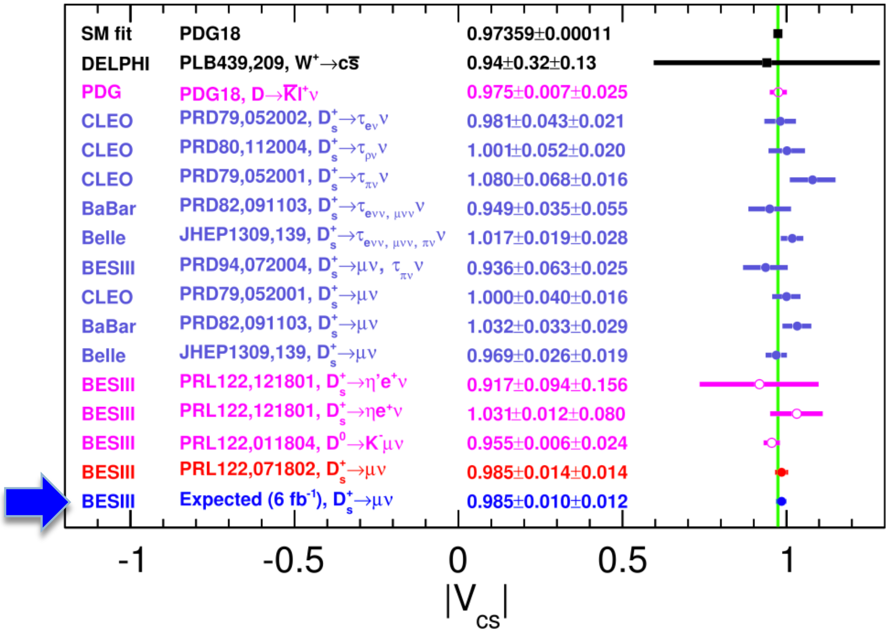
● Expected precision with 20 fb^{-1} @ 3.773 GeV

Comparisons of $|V_{cd}|$ and $|V_{cs}|$

Alternatively, $f_{D^+(s)}$ can be taken as input, and the leptonic BF measurements used to extract $|V_{cd(s)}|$

Chinese Physics C 44, 040001 (2020)





| Uncertainties of the average values from the global fit in SM (PDG(2018))

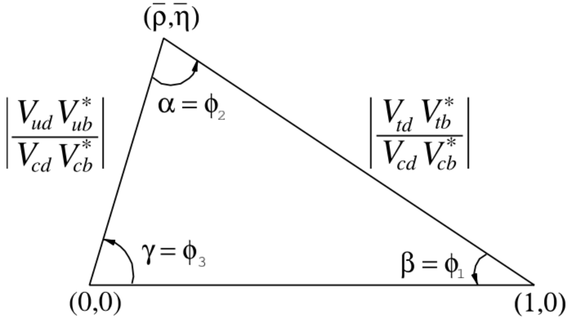
● Best BESIII measurement

● Expected precision with 20 fb^{-1} @ 3.773 GeV or 6fb^{-1} @ 4.178 GeV

Hadronic $D_{(s)}$ Decays

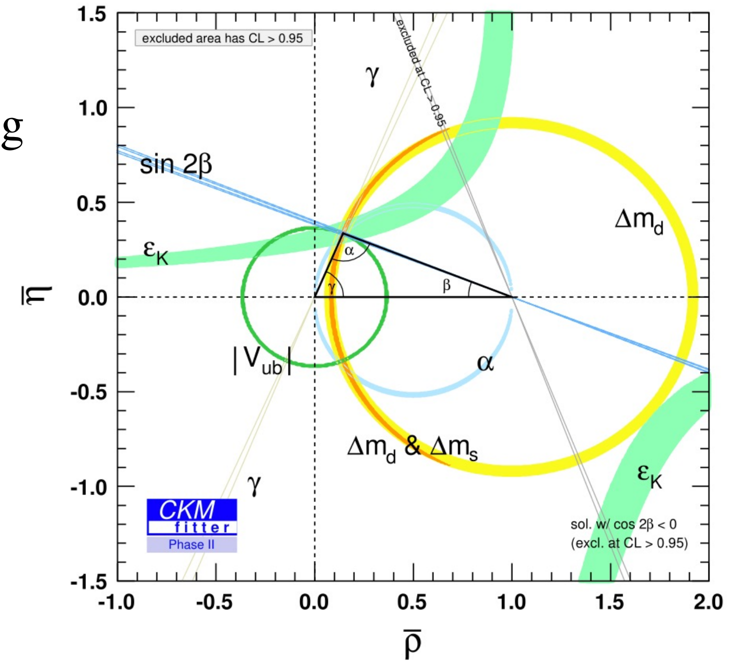
In B physics, precision measurements CKM UT angles are important for testing the CKM unitary and searching for CP violation beyond SM

- Extraction of γ: it is the only CP-violating observable that can be determined using tree-level decays ($B \to D^{(*)}K^{(*)}$)
- Limited knowledge of the strong phases of D decays will restrict the overall sensitivity



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

- from CLEO: contribution of ~4° on the uncertainty to the γ measurement (PRD**82**,112006)
- from BESIII: contribution of ~1° on the uncertainty ($2.93\ fb^{-1}$)
- A $20\ fb^{-1}$ sample of $\psi(3770)$ data would lead to an uncertainty of ~0.4°



Strong-Phase differences $\Delta(\delta_D)$ between D^0 and $\bar{D}^0$

PRD 101, 112002 (2020); PRL 124, 241802(2020)

We analyse the $D \to K^0_S\pi^+\pi^-$ Dalitz plot phase space (PS) of m_-^2 vs m_+^2: the PS is divided into 8 pairs of irregularly shaped bins

- Equal binning
- Optimal binning
- Modified optimal binning

$$\boxed{B^- \to DK^-,\ D \to K^0_S\pi^+\pi^-}$$

Ignoring second-order effects of charm-mixing and CP violation

$$f_{B^-}(\underset{K^0_S\pi^+}{m_+^2}, \underset{K^0_S\pi^-}{m_-^2}) \propto f_D(m_+^2, m_-^2) + r_B e^{i(\delta_B-\gamma)} f_D(m_-^2, m_+^2)$$

Two quantities are introduces to parametrized the interference between the amplitude of the D^0 and $\bar{D}^0$ decays:

$$s_i = \frac{1}{\sqrt{F_i F_{-i}}}\int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \times \sin[\Delta\delta_D(m_+^2, m_-^2)]dm_+^2 dm_-^2,$$

$$c_i = \frac{1}{\sqrt{F_i F_{-i}}}\int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \times \cos[\Delta\delta_D(m_+^2, m_-^2)]dm_+^2 dm_-^2$$

DT analysis:

- 17 decay modes used for ST (CP-even, CP-odd, CP-mixed, flavor-tags) and a second D meson reconstructed as either $K^0_S\pi^+\pi^-$ or $K^0_L\pi^+\pi^-$
- Partial reconstruction technique when one particle is identified by the missing energy and mass in the event
- DT yield extracted for the *i*-th bin of the Dalitz plot + bin migration correction

Strong-Phase differences $\Delta(\delta_D)$ between D^0 and $\overline{D^0}$

PRD 101, 112002 (2020); PRL 124, 241802(2020)

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

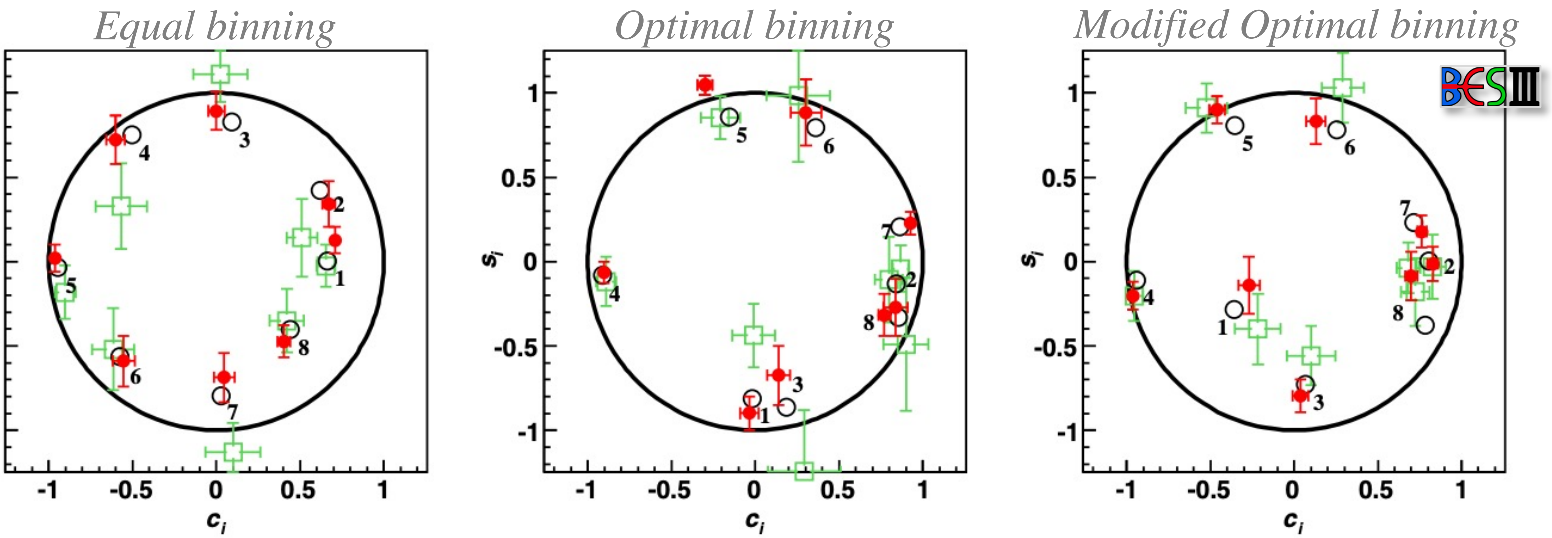
Constraint on γ measurement ~ 1°

● BESIII

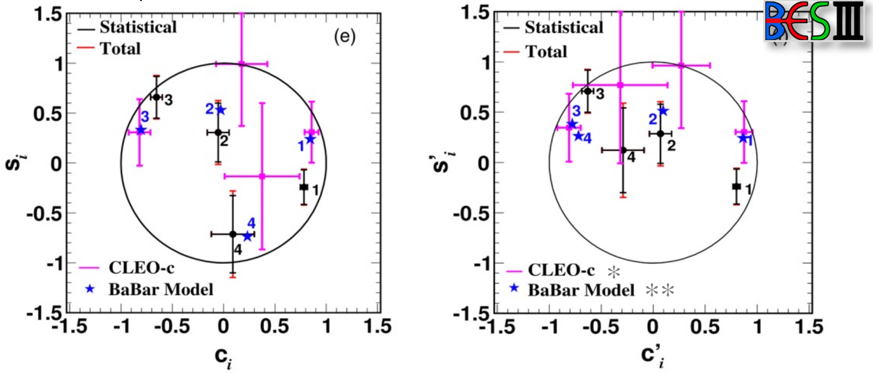
○ expected (PRD98,112012)

□ CLEO meas. (PRD82,112006)

— $c_i^2 + s_i^2 = 1$



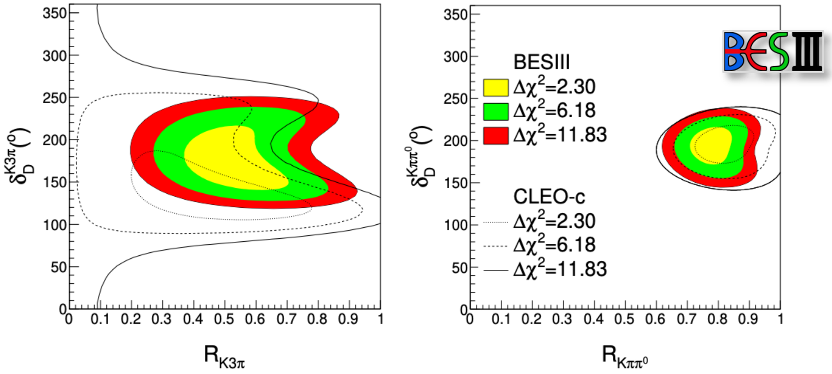
$D \to K^0_{S/L}K^+K^-$ PRD 102, 052008 (2020)



Constraint on γ measurement ~ 1.3°

*:PRD82 ; **: PRD78

$D \to K^-\pi^+\pi^+\pi^-/K^-\pi^+\pi^0$ JHEP05, 164 (2021)



Constraint on γ measurement ~ 6°

CP-even fraction of $D^0 \to \pi^+\pi^-\pi^+\pi^-$

arXiv:2208.10098

Category	Decay modes
CP-even	K^+K^-, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\omega$
CP-odd	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\eta'$, $K^0_S\omega$, $K^0_L\pi^0\pi^0$
Quasi CP-even	$\pi^+\pi^-\pi^0$
Mixed CP	$K^0_S\pi^+\pi^-$, $K^0_L\pi^+\pi^-$

$M(4\pi, f) =$ (Predicted DT yield for a CP-tag mode f) =

$$2N_{D\bar{D}}\mathcal{B}(4\pi)\mathcal{B}(f)\epsilon_{\rm DT}[1-\eta^f_{CP}(2\boxed{F^{4\pi}_+}-1)]$$

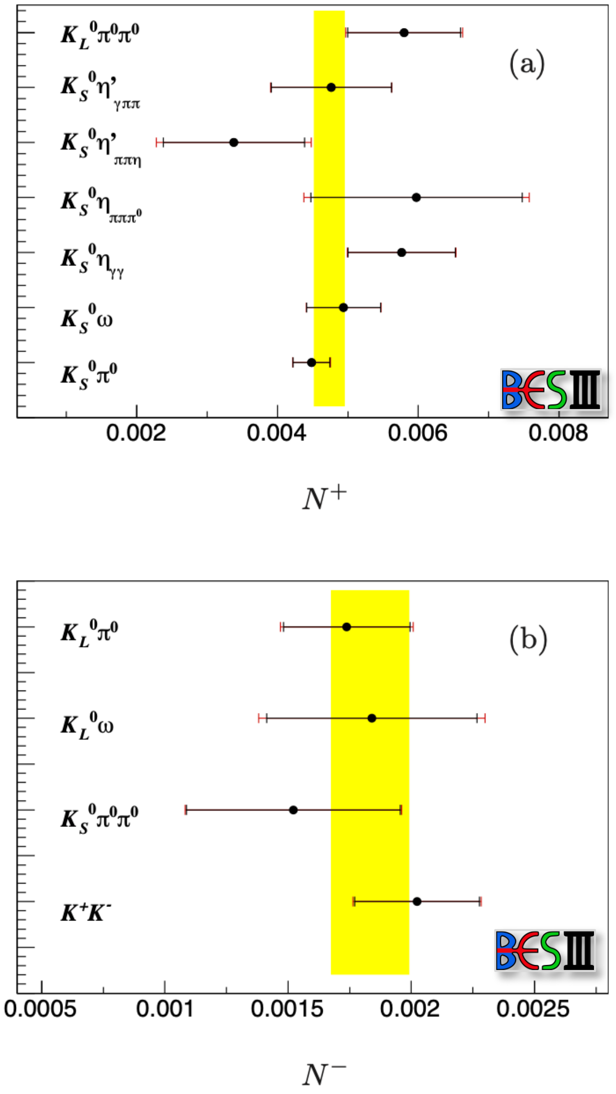
(Predicted ST):

$$S(f) = 2N_{D\bar{D}}\mathcal{B}(f)\epsilon_{\rm ST}[1-\eta^f_{CP}y]$$

$$F^{4\pi}_+ = \frac{N^+}{N^+ + N^-}$$

Tag modes	$F^{4\pi}_+$
CP eigenstates	0.721±0.019±0.007
$D \to \pi^+\pi^-\pi^0$	0.753±0.028±0.010
$D \to K^0_{S,L}\pi^+\pi^-$	0.754±0.031±0.009
Combination	0.735±0.015±0.005

Compatible with previous measurements (PLB**747**,9 and JHEP**01**, 144), but more precise



Amplitude Analysis of $D_s^+ \to K^+\pi^+\pi^-$

DT analysis: 1356 events, about 95% purity

arXiv:2205.08844

$$\mathcal{B}(D_s^+ \to K^+\pi^+\pi^-) = (6.11 \pm 0.18_{\text{stat.}} \pm 0.11_{\text{syst.}}) \times 10^{-3}$$

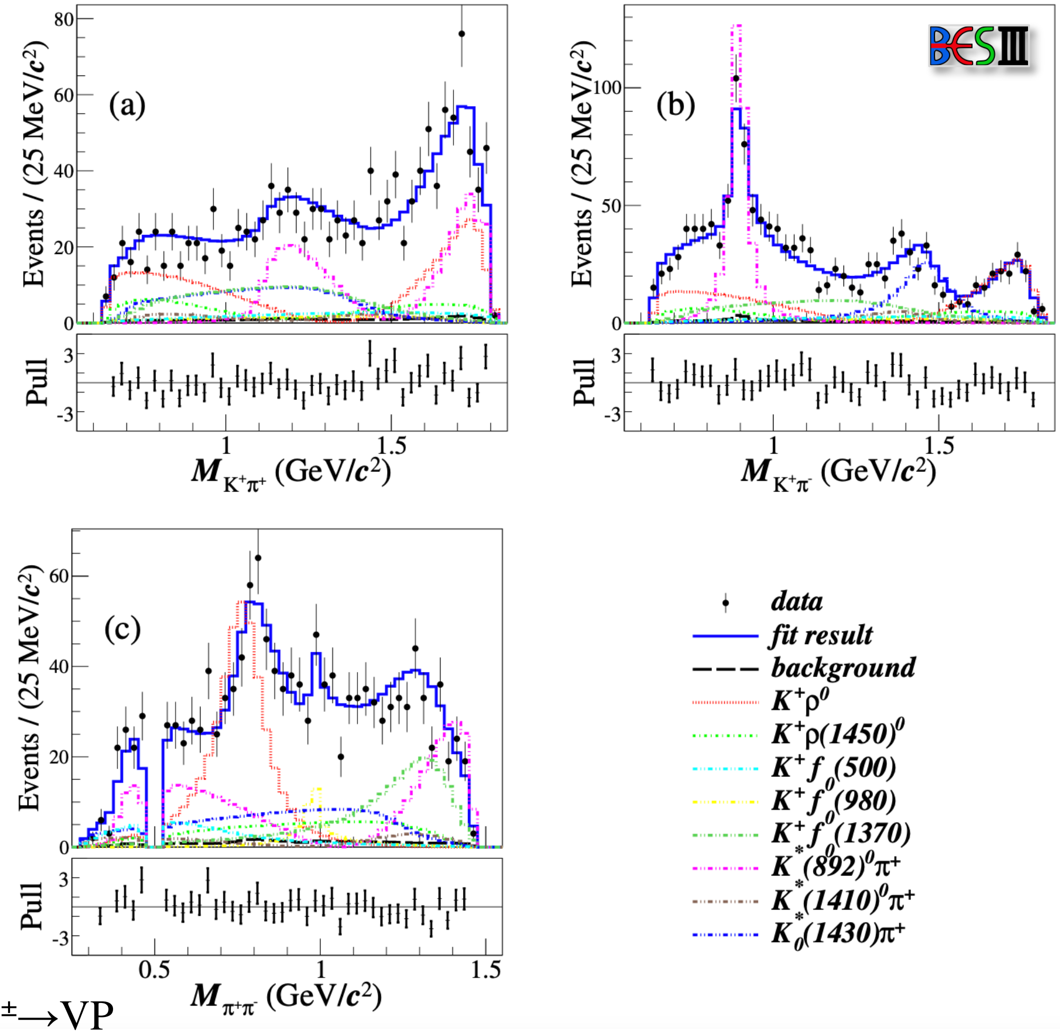
Improvement of a factor 2 w.r.t PDG

Intermediate process	BF(10^{-3})	PDG(10^{-3})
$D_s^+ \to K^+\rho^0$	$1.96 \pm 0.19 \pm 0.23$	2.5 ± 0.4
$D_s^+ \to K^+\rho(1450)^0$	$0.80 \pm 0.19 \pm 0.18$	0.69 ± 0.64
$D_s^+ \to K^*(892)^0\pi^+$	$1.85 \pm 0.12 \pm 0.13$	1.41 ± 0.24
$D_s^+ \to K^*(1410)^0\pi^+$	$0.27 \pm 0.13 \pm 0.15$	1.23 ± 0.28
$D_s^+ \to K_0^*(1430)^0\pi^+$	$1.13 \pm 0.16 \pm 0.16$	0.50 ± 0.35
* $D_s^+ \to K^+f_0(500)$	$0.44 \pm 0.13 \pm 0.27$	-
$D_s^+ \to K^+f_0(980)$	$0.27 \pm 0.08 \pm 0.07$	-
$D_s^+ \to K^+f_0(1370)$	$1.22 \pm 0.18 \pm 0.57$	-
$D_s^+ \to (K^+\pi^+\pi^-)_{NR}$	-	1.03 ± 0.34

*First measurements

$$A_{CP} = \frac{\mathcal{B}(D_s^+)-\mathcal{B}(D_s^-)}{\mathcal{B}(D_s^+)+\mathcal{B}(D_s^-)} = (3.3\pm3.0_{\text{stat.}}\pm1.3_{\text{syst.}})\%$$

No significant CP violation

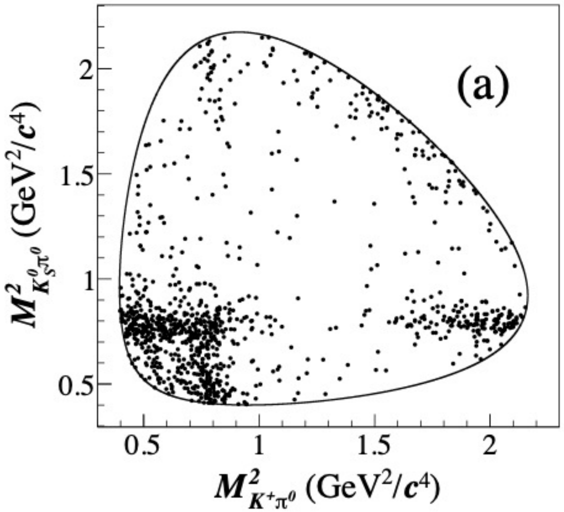


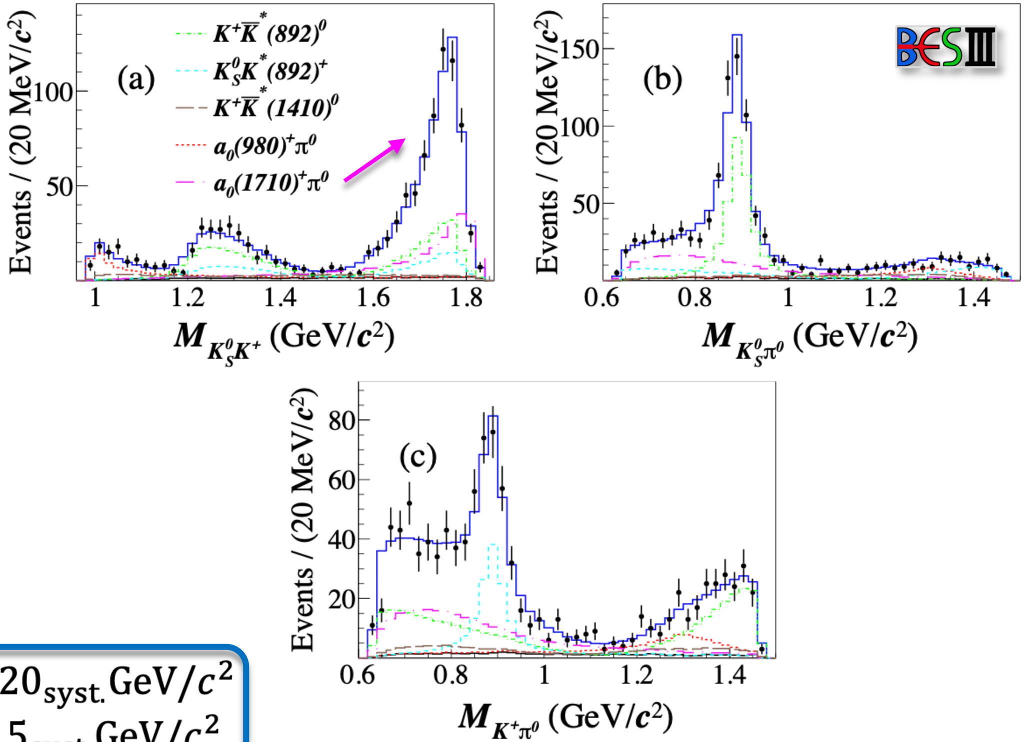
More precise theoretical predictions and measurements are needed to understand the $D_s^\pm \to VP$ processes and $SU(3)_F$ flavor symmetry breaking

Amplitude Analysis of $D_s^+ \to K_S^0 K^+ \pi^0$

arXiv:2204.09614

DT analysis; first Amplitude analysis;
1050 events, about 95% purity





$$M(a_0^+(1710)) = 1.817 \pm 0.008_{\text{stat.}} \pm 0.020_{\text{syst.}}\,\text{GeV}/c^2$$
$$\Gamma(a_0^+(1710)) = 0.097 \pm 0.022_{\text{stat.}} \pm 0.015_{\text{syst.}}\,\text{GeV}/c^2$$

$$\mathcal{B}(D_s^+ \to K_S^0 K^+ \pi^0) = (1.46 \pm 0.06_{\text{stat.}} \pm 0.05_{\text{syst.}})\%$$

Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0(fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K_S^0$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1710)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

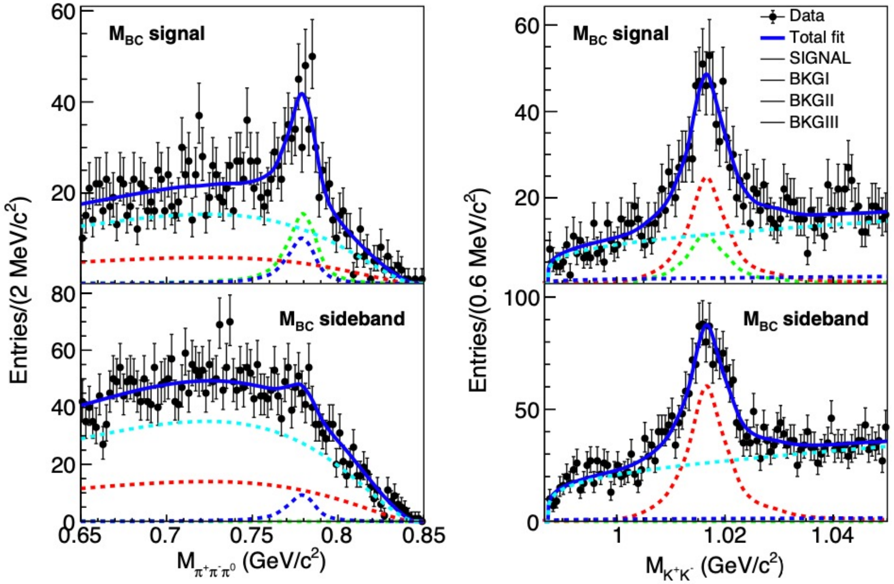
a_0(1710) established as the isovector partner of the f_0(1710) meson;
BF consistent with the prediction by EPJC82,225(2022)

First Measurement of Polarization in $D^0 \to \omega\phi$ decay

PRL**128**, 011803(2022)

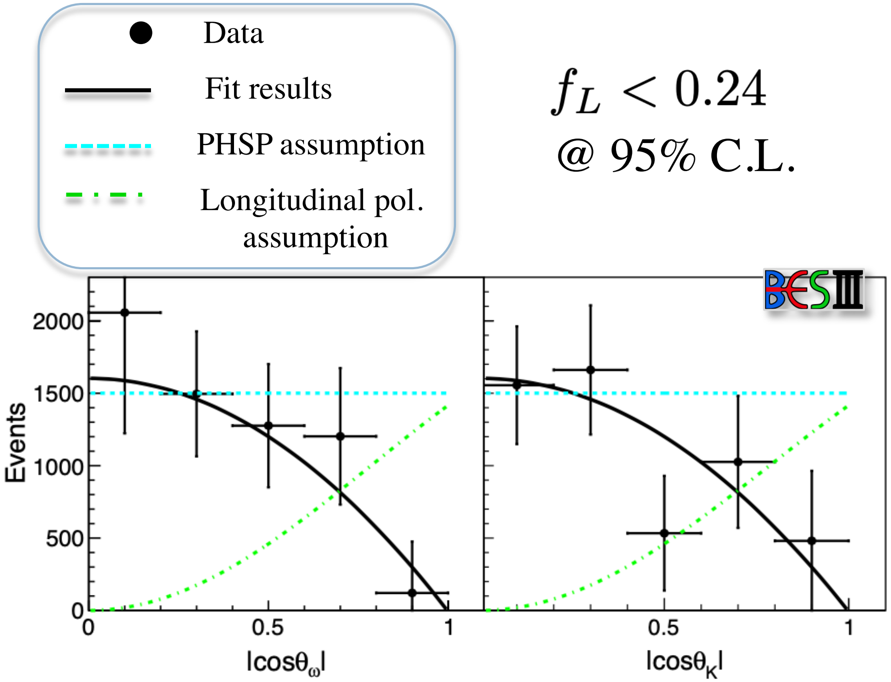
$D^0 \to VV$: understand long-distance contributions to D^0-$\bar{D}^0$ mixing, sensitive to V-A structure of EW interactions in the SM, help to understand the "polarization puzzle" in the decays of heavy mesons to two vectors

- ST analysis: Only one D^0 meson is reconstructed



$D^0 \to \omega\phi$ observed for the first time with a significance of 6.3σ:

$$\mathcal{B}(D^0 \to \omega\phi) = (6.48 \pm 0.96 \pm 0.40) \times 10^{-4}$$



$f_L < 0.24$
@ 95% C.L.

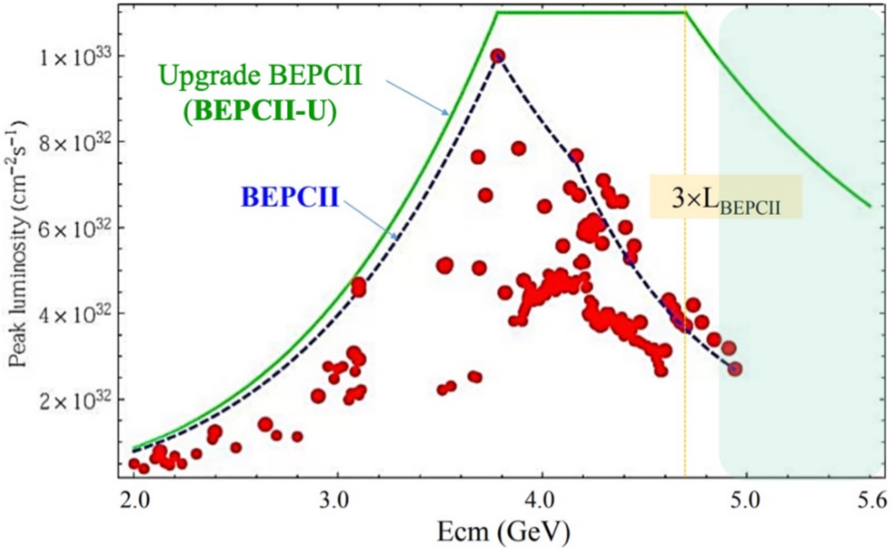
ω and ϕ are transversely polarized:

- Contradicts predictions from PRD**81**,114020 and JHEP**03**, 042 models

Conclusions and Prospects

Complementary information to B-factories and LHCb experiments

- No evidence for LFUV in leptonic/semileptonic charm decays
- Amplitude analyses show great power
  - Establishment of isospin-one particle $a_0(1710)$
  - Validation of various theories
- Large sample for precise measurements
  - Puzzle of $P \to VV$ polarization



- BESIII whitepaper Chinese Physics C 44, 040001 (2020) with outline of physics program for the next years
- List for charm physics:
  - 20 fb^{-1} on $\psi(3770)$
  - 6 fb^{-1} at 4.18 GeV
  - 5 fb^{-1} at 4.46 GeV

- First data at higher c.m. energies in now available ($4.7 < \sqrt{s} < 4.94$ GeV)
- Further upgrade in energy (5.6 GeV) and luminosity (BEPCII-U, 3x) planned for the next year

Back-up slides

SM references

SM predictions for $\mathscr{B}(D^+ \to \eta\ell^+\nu)$

SM Prediction: 0.97 - 1.00 from

- *Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A21,6125 (2006)*
- *H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)*
- *M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T.Tran, Front. Phys.14, 64401 (2019)*

SM predictions for $\mathscr{B}(D^+ \to \omega\ell^+\nu)$

SM Prediction: 0.93 - 0.99 from

- *H.Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)*
- *T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)*
- *N. R. Soni, M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)*
- *M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)*
- *H.B. Fu, W. Cheng, L. Zheng, D.D. Hu, T. Zhong, Phys. Rev. Research 2, 043129 (2020)*
- *R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)*

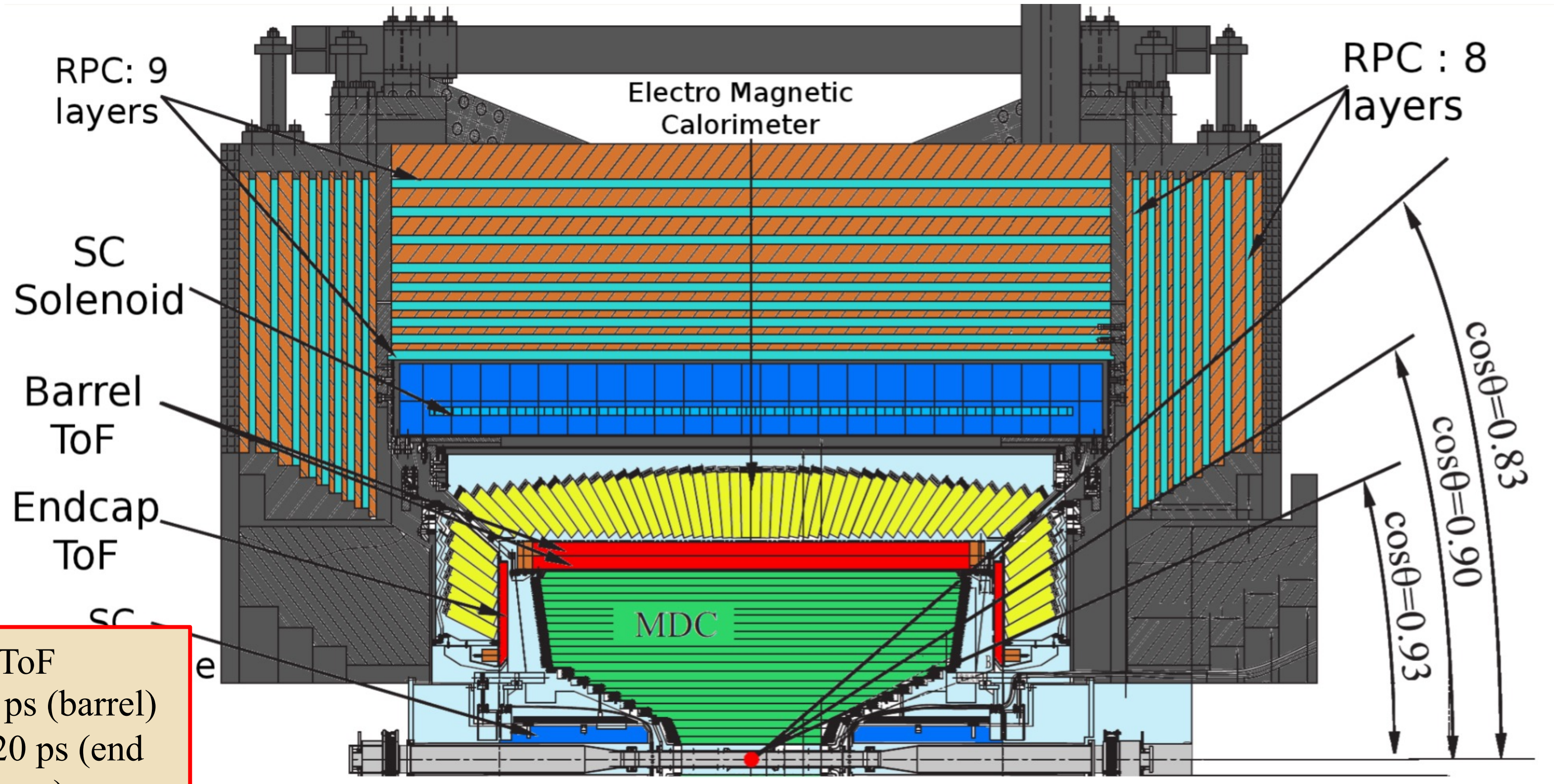
SM predictions for $\mathscr{B}(D^0 \to \rho^-\ell^+\nu)$

SM Prediction: 0.93 - 0.96 from

- *Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A 21, 6125 (2006)*
- *T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)*
- *N. R. Soni, M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)*
- *M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)*
- *H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)*
- *R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)*

The BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)



ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} \sim 130\ \mu m$ (single wire)
$\sigma_{pt}/p_t \sim 0.5\ \%$ @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\ mm)/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

BESIII physics programme

Light hadron physics

- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- two-photon physics
- Form factors

XYZ meson physics

- Y(4260), Y(4360) properties
- $Z_c(3900)^+$, …

Charm physics

- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

QCD and τ

- Precision R measurement
- τ decay

Charmonium physics

- Precision spectroscopy
- Transitions and decays

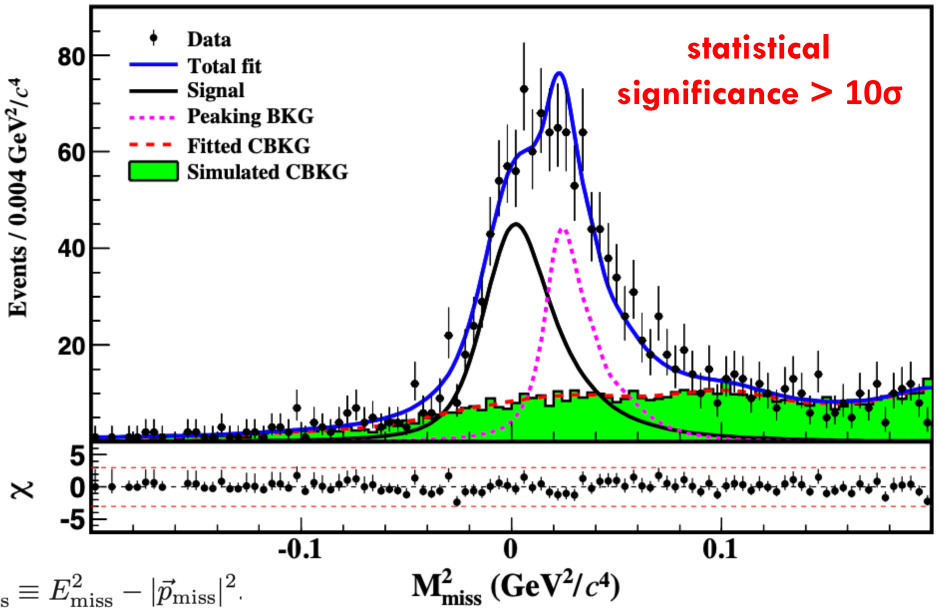
Precision mass measurements

- τ mass
- D, D^* mass

Observation of $D^0 \to \rho^- \mu^+ \nu_\mu$ decay

PRD 104, L091103

- ST: three hadronic tag modes ($K\pi$, $K\pi\pi$, $K\pi\pi\pi$)
- DT: semileptonic decay yield is obtained from an unbinned extended maximum likelihood fit to the missing mass square distribution



statistical significance > 10σ

$M^2_{\rm miss} \equiv E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2.$

- Peaking background from $D^0 \to \pi^+\pi^-\pi^0\pi^0$
- Semileptonic decay observed for the first time

FIRST MEMASUREMENT

$$\mathcal{B}_{D^0\to\rho^-\mu^+\nu_\mu} = (1.35 \pm 0.09 \pm 0.09) \times 10^{-3}$$

$$R_{\mu/e} = \frac{\mathcal{B}_{D^0\to\rho^-\mu^+\nu_\mu}}{\mathcal{B}^{PDG}_{D^0\to\rho^-e^+\nu_\mu}} = 0.90 \pm 0.11$$

$$\frac{\Gamma_{D^0\to\rho^-\mu^+\nu_\mu}}{2\Gamma_{D^+\to\rho^0\mu^+\nu_\mu}} = 0.71 \pm 0.14$$

Results in agreement with LFU expectation within the uncertainties and support isospin symmetry within 2.1σ

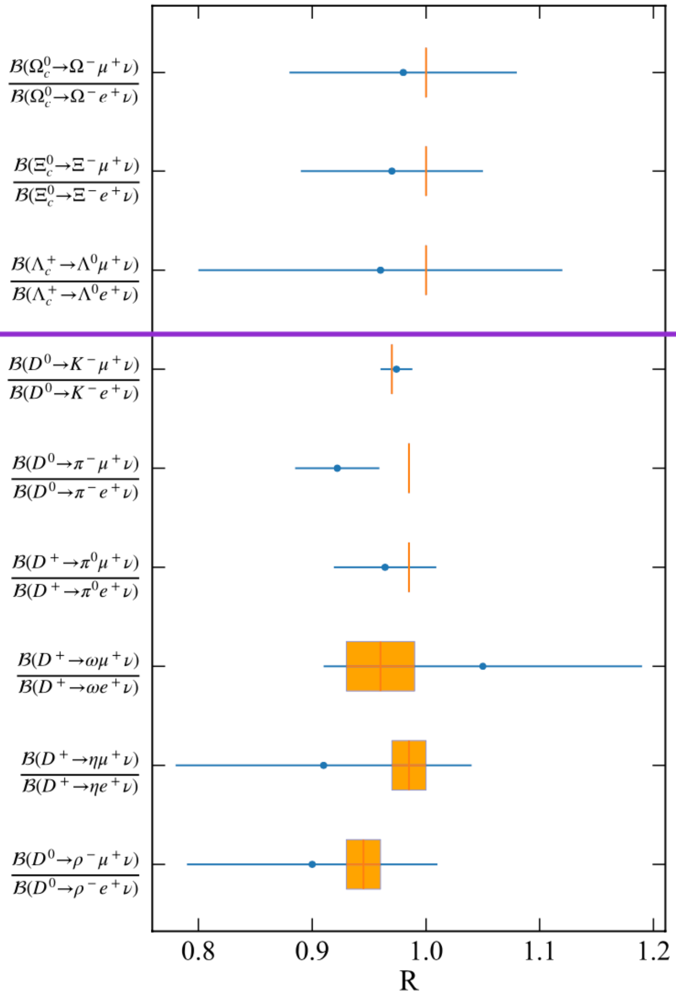
	BESIII	LCSR [24]	LCSR [25]	LFQM [26]	CCQM [27]	CCQM [28]	χUA [29]	RQM [30]
$\mathcal{B}_{D^0\to\rho^-\mu^+\nu_\mu}$ $(\times 10^{-3})$	$1.35 \pm 0.09 \pm 0.09$	$1.73^{+0.17}_{-0.13}$	1.65 ± 0.23	1.7 ± 0.2	2.01	1.55	1.84	1.88
Difference (σ)		2.1	1.1	1.5	5.2	1.6	3.8	4.2

Other analyses …

- $D^+ \to \omega\mu^+\nu_\mu$ PRD **101**, 072005 (2020)
- $D_s^+ \to a_0(980)^0 e^+\nu_e$ PRD **103**, 092004 (2021)
- $D^{0(+)} \to b_1(1235)^{-(0)} e^+\nu_e$ PRD **102**, 112005 (2020)
- $D^+ \to$ Kbar$_1(1270)^0 e^+\nu_e$ PRL **123**, 231801 (2019)
- $D_s^+ \to \pi^0\pi^0 e^+\nu_e$ and $D_s^+ \to K_s^0 K_s^0 e^+\nu_e$ arXiv:2110.13994
- ….

SL charm baryon decays

SL charm meson decays



Belle, Phys. Rev. D 105, L091101 (2022)

Belle, PRL127(2021)121803

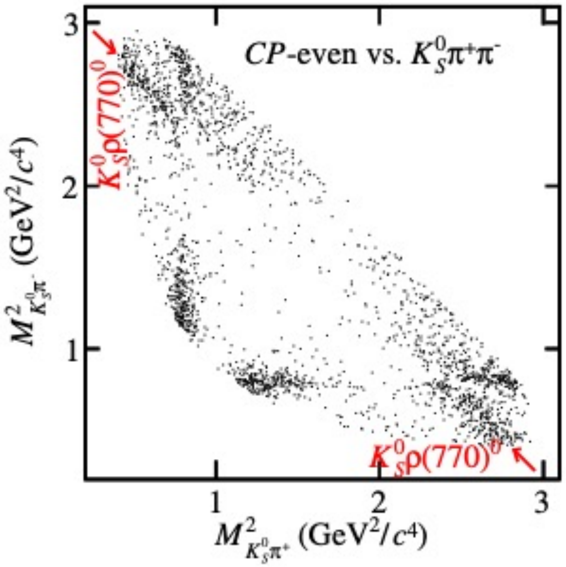
BESIII, Phys. Lett. B, 767 (2017) p 42

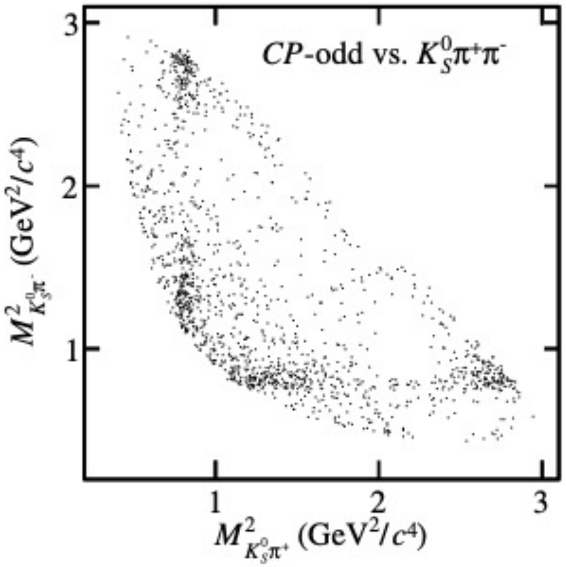
BESIII, Phys. Rev. Lett. 122, 011804 (2019)

BESIII, Phys. Rev. Lett. 121, 171803 (2018)

BESIII, Phys. Rev. Lett. 121, 171803 (2018)

Image credit Adam Davis


CP-even vs. $K_S^0\pi^+\pi^-$
$K_S^0\rho(770)^0$
$K_S^0\rho(770)^0$
$M^2_{K_S^0\pi^-}$ (GeV$^2/c^4$)
$M^2_{K_S^0\pi^+}$ (GeV$^2/c^4$)
1
2
3
1
2
3


CP-odd vs. $K_S^0\pi^+\pi^-$
$M^2_{K_S^0\pi^-}$ (GeV$^2/c^4$)
$M^2_{K_S^0\pi^+}$ (GeV$^2/c^4$)
1
2
3
1
2
3

$$M(4\pi, f) =$$
$$2N_{D\bar{D}}\mathcal{B}(4\pi)\mathcal{B}(\pi\pi\pi^0)\epsilon_{\mathrm{DT}}[1-(2F_+^{\pi\pi\pi^0}-1)(2F_+^{4\pi}-1)]$$

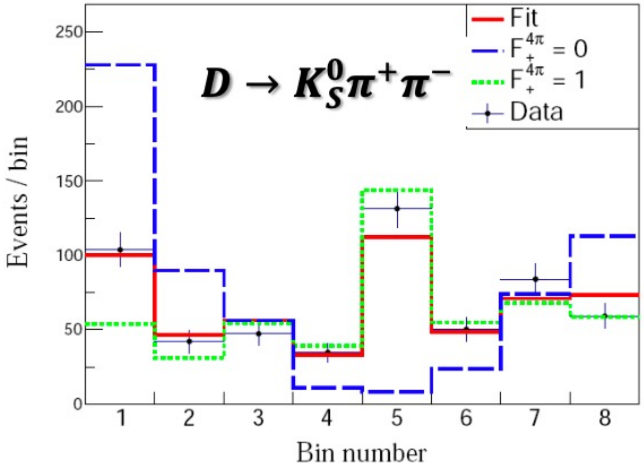
$$S(\pi\pi\pi^0) = 2N_{D\bar{D}}\mathcal{B}(\pi\pi\pi^0)\epsilon_{\mathrm{ST}}[1-(2F_+^{\pi\pi\pi^0}-1)y]$$

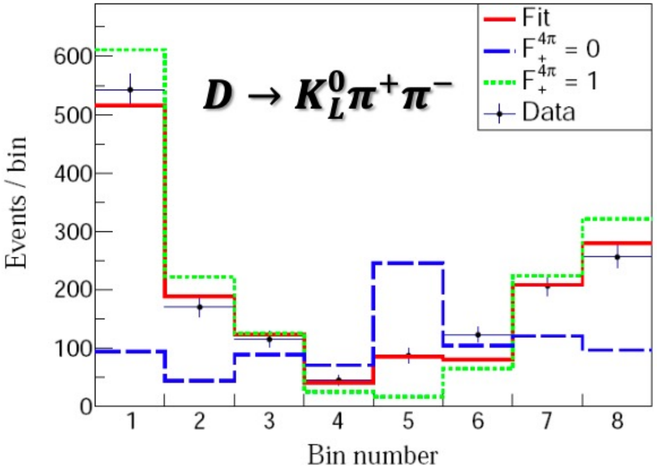
$$F_+^{4\pi} = \frac{N^+F_+^{\pi\pi\pi^0}}{N^{\pi\pi\pi^0}-N^+ + 2N^+F_+^{\pi\pi\pi^0}}$$

$$M_i(4\pi, K_S^0\pi^+\pi^-) =$$
$$H[K_i + K_{-i} - 2\sqrt{K_iK_{-i}}c_i(2F_+^{4\pi}-1)],$$
$$M_i'(4\pi, K_L^0\pi^+\pi^-) =$$
$$H'[K_i' + K_{-i}' + 2\sqrt{K_i'K_{-i}'}c_i'(2F_+^{4\pi}-1)]$$

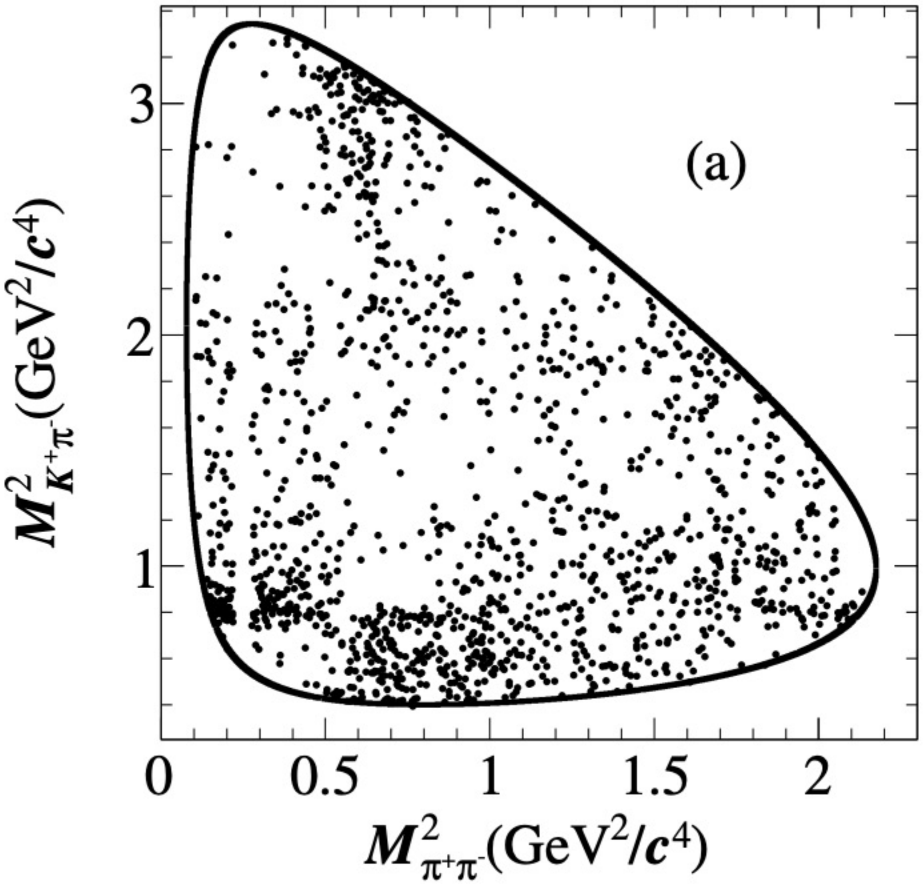
$$F_+^{4\pi} = \frac{N^+}{N^+ + N^-}$$

arXiv:2208.10098



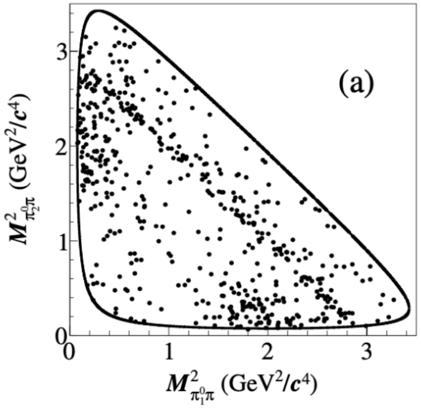


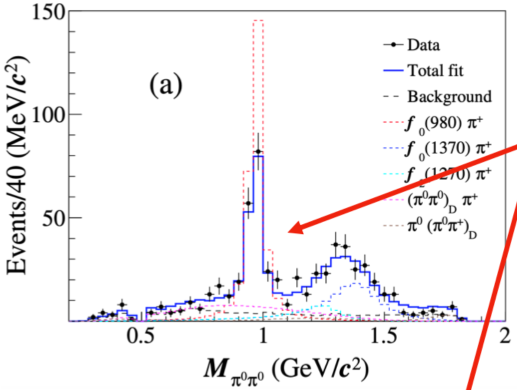
arXiv:2205.08844



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

JHEP01, 052(2022)



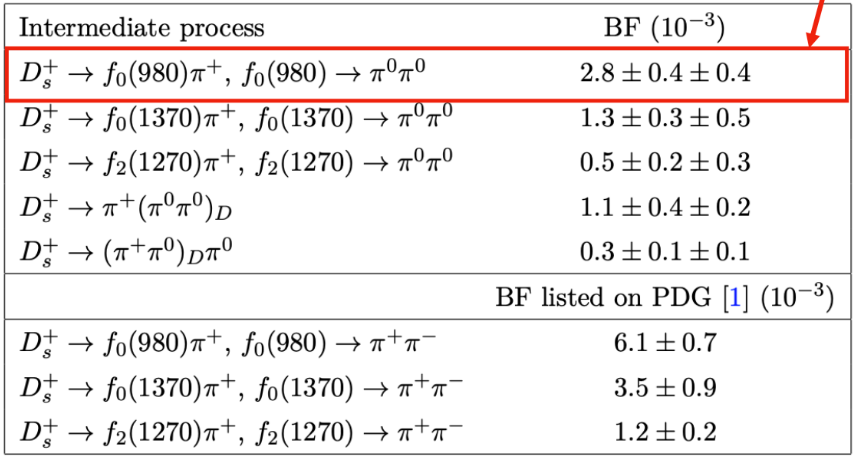


First amplitude analysis, 572 events about 78% purity

$$\mathcal{B}(D_s^+ \to f_0(980)\pi^+, f_0(980) \to \pi^0\pi^0)$$
$$= (2.8 \pm 0.4 \pm 0.4) \times 10^{-3}$$

Measured for the first time

No significant signal of $f_0(500)$



Intermediate process	BF (10^{-3})
$D_s^+ \to f_0(980)\pi^+,\ f_0(980) \to \pi^0\pi^0$	$2.8 \pm 0.4 \pm 0.4$
$D_s^+ \to f_0(1370)\pi^+,\ f_0(1370) \to \pi^0\pi^0$	$1.3 \pm 0.3 \pm 0.5$
$D_s^+ \to f_2(1270)\pi^+,\ f_2(1270) \to \pi^0\pi^0$	$0.5 \pm 0.2 \pm 0.3$
$D_s^+ \to \pi^+(\pi^0\pi^0)_D$	$1.1 \pm 0.4 \pm 0.2$
$D_s^+ \to (\pi^+\pi^0)_D\pi^0$	$0.3 \pm 0.1 \pm 0.1$
	BF listed on PDG [1] (10^{-3})
$D_s^+ \to f_0(980)\pi^+,\ f_0(980) \to \pi^+\pi^-$	6.1 ± 0.7
$D_s^+ \to f_0(1370)\pi^+,\ f_0(1370) \to \pi^+\pi^-$	3.5 ± 0.9
$D_s^+ \to f_2(1270)\pi^+,\ f_2(1270) \to \pi^+\pi^-$	1.2 ± 0.2

$$R(f_0(980)) = 2.2 \pm 0.5$$
$$R(f_0(1370)) = 2.7 \pm 1.4 \qquad R = \frac{f_{0(2)}(\pi^+\pi^-)}{f_{0(2)}(\pi^0\pi^0)}$$
$$R(f_2(1270)) = 2.4 \pm 1.8$$

consistent with $D_s^+ \to \pi^+\pi^+\pi^-$

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$$\mathcal{B}(D_s^+ \to \pi^+\pi^0\pi^0) = (0.50 \pm 0.04_{\text{stat.}} \pm 0.02_{\text{syst.}})\%$$

Improved by a factor of two compared with PDG