Charm Physics at BESIII/BEPCII Experiment

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(on behalf of BESIII Collaboration)

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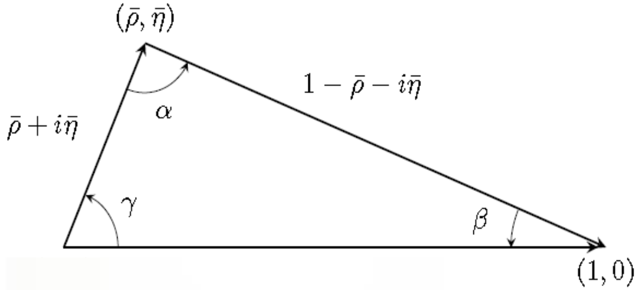
Outline

- Introduction on charm physics
  - Charm is charming and charm is challenging
  - Charm samples
- Introduction on BESIII/BEPCII
- Selected charm physics results at BESIII/BEPCII
  - Pure and semi-leptonic decays
  - Hadronic decays
- Summary

CKM matrix

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

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



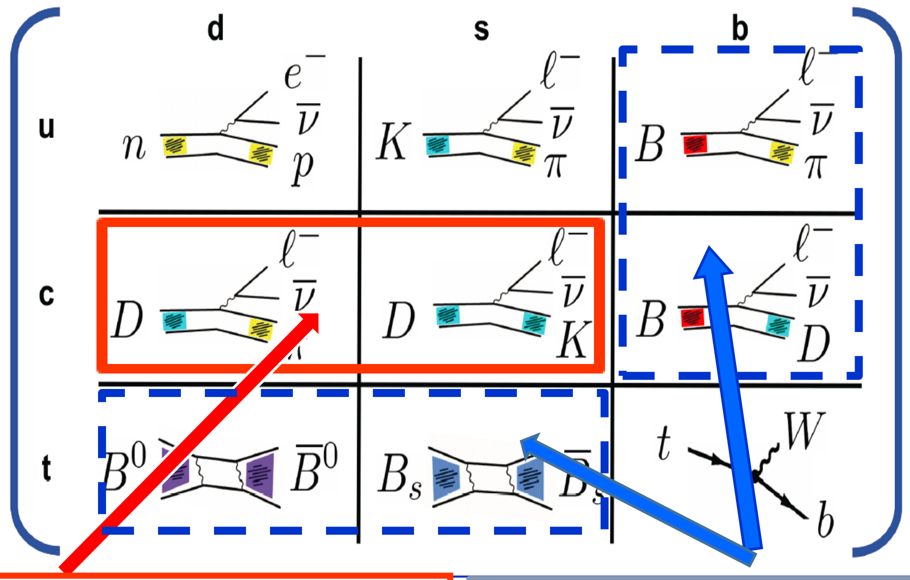
$V_{ud}V_{ub}^*+V_{cd}V_{cb}^*+V_{td}V_{tb}^* = 0$

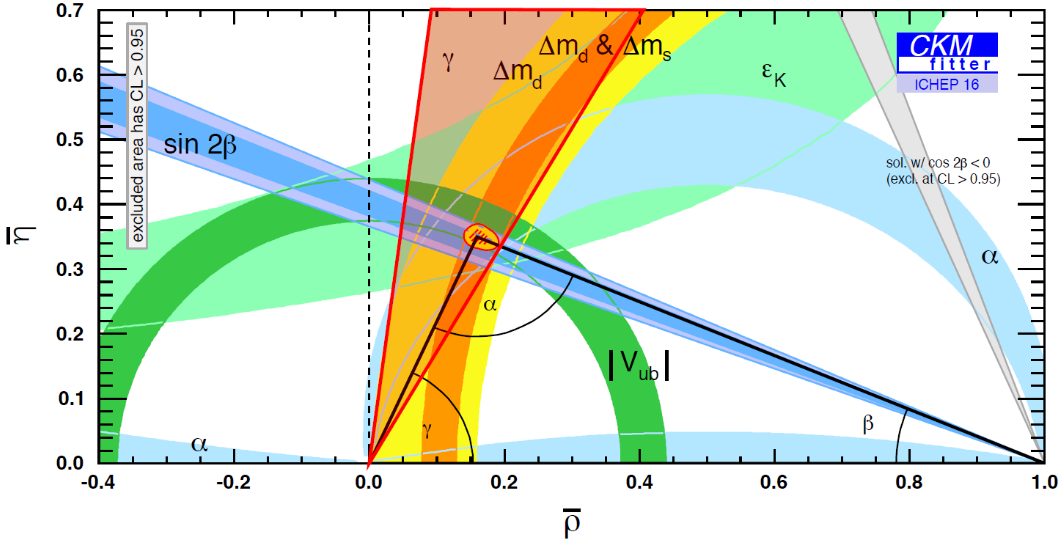
$$\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \equiv \phi_2, \quad \alpha = (87.6^{+3.5}_{-3.3})^\circ$$

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

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

V =





Charm decays + LQCD

Precision ~5-10% before BESIII

Charm decays + B decays + LQCD

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

$|V_{cb}|$ ~ 2%

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?

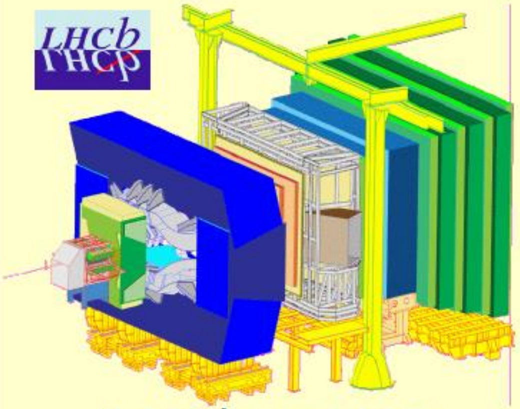
] → Theory

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

Charm physics contributors

B physics experiments are well suited for charm physics

hadron collider



LHCb at LHC

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

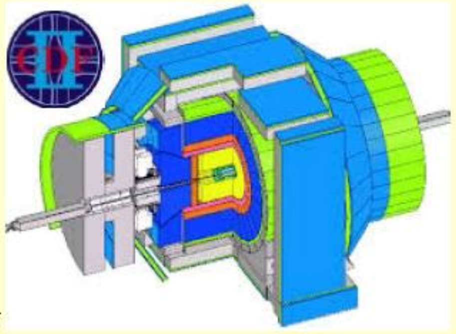
$\int_{run2} \mathcal{L} \approx 5.5fb^{-1}$ $9.6 \cdot 10^{12}\ c\bar{c}$

world's largest c sample

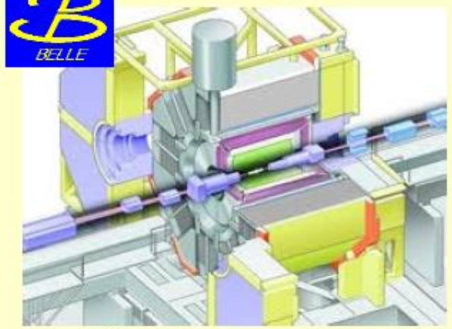
CDF at TEVATRON

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

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



e^+e^- collider



Belle at KEKB

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

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

Belle II

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

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

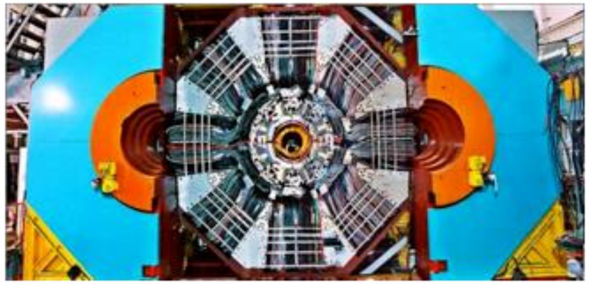
BABAR at PEPII

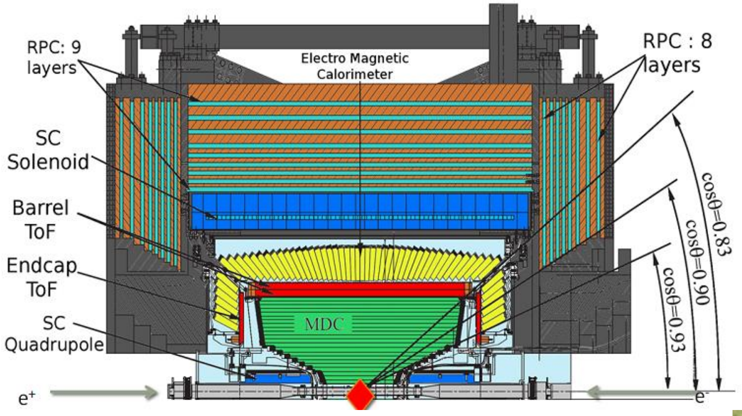
$\int \mathcal{L} \approx 550fb^{-1}$

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

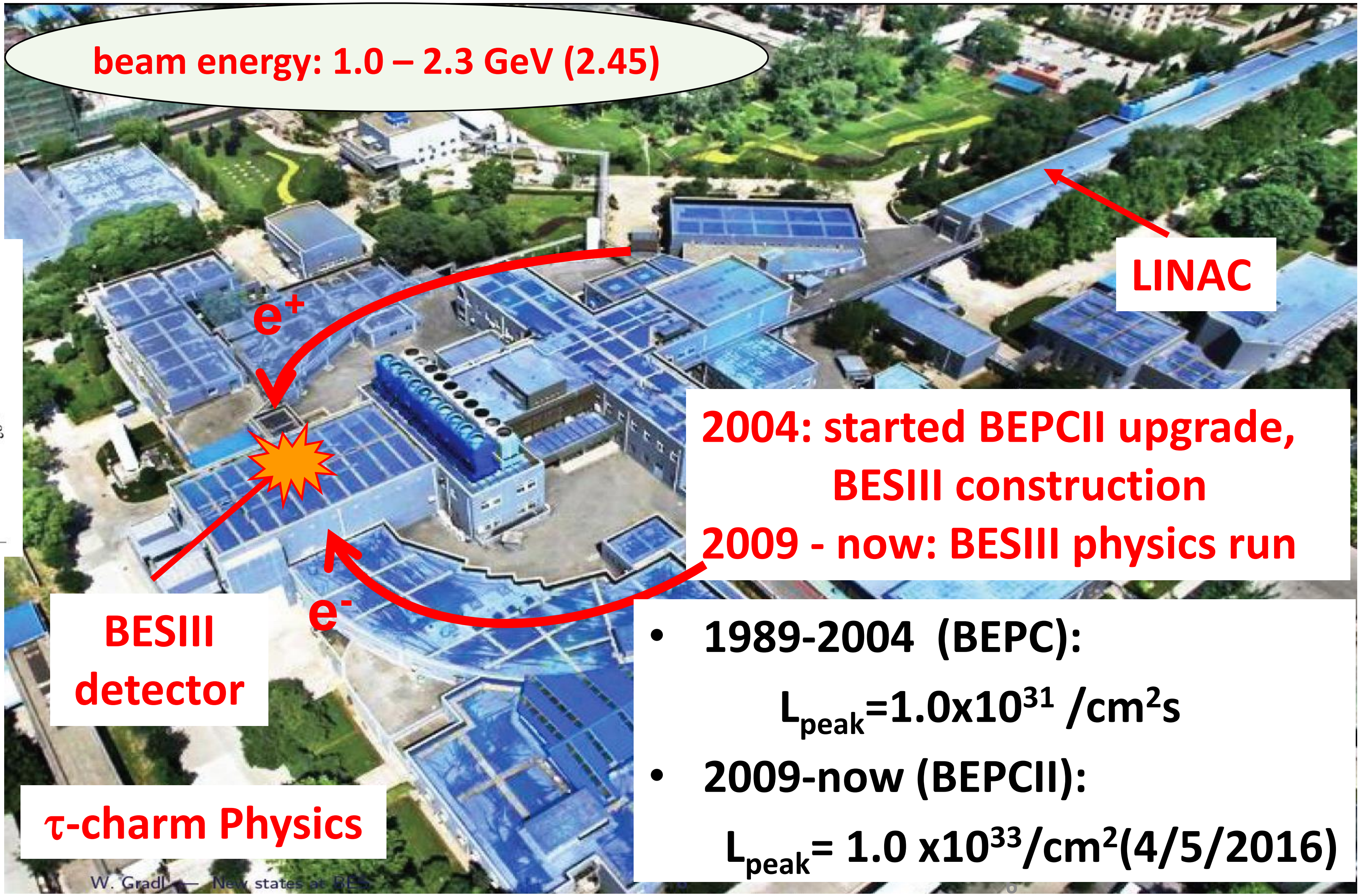
- **LHCb/hadron machine:** huge production X-section, excellent lifetime resolution due to the boost; large combinatorial BG, difficult with neutral and missing particles
- **B factories:** clean environment, good to detect neutral particles; lower boost, poorer lifetime resolution

BESIII @ 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



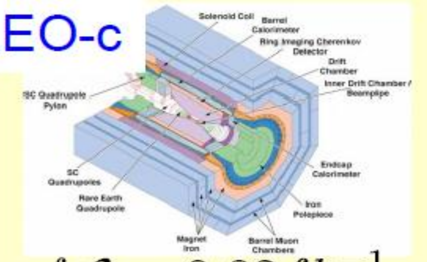
2004: started BEPCII upgrade, BESIII construction
2009 - now: BESIII physics run

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

Unique data sets at open charm thresholds

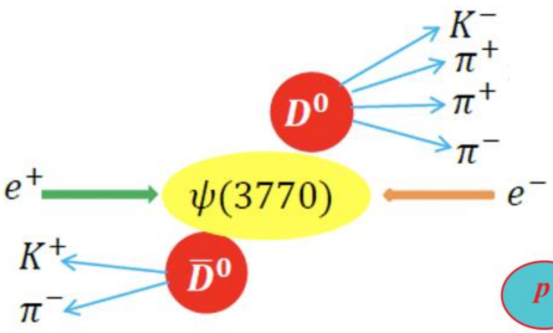
- $D^{+(0)}$
  - @ $E_{cm} = 3.773$ GeV
  - Integrated luminosity of 2.93 fb^{-1} → 20 fb^{-1}
  - $\sigma(e^+e^- \to D^0\overline{D^0}) \sim 3.6$ nb $\Rightarrow$ 21M D^0 produced
  - $\sigma(e^+e^- \to D^+D^-) \sim 2.9$ nb $\Rightarrow$ 17M D^+ produced
- D_s^+
  - @ $E_{cm} = 4.009$ GeV
    - Integrated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

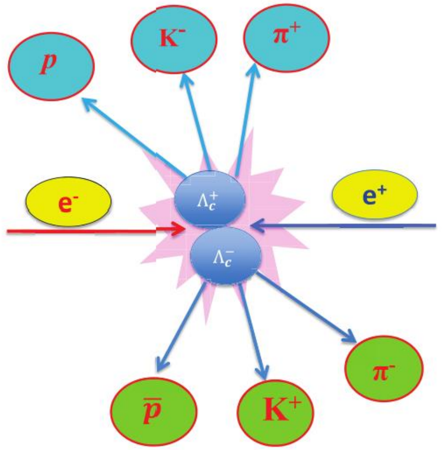
CLEO-c



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

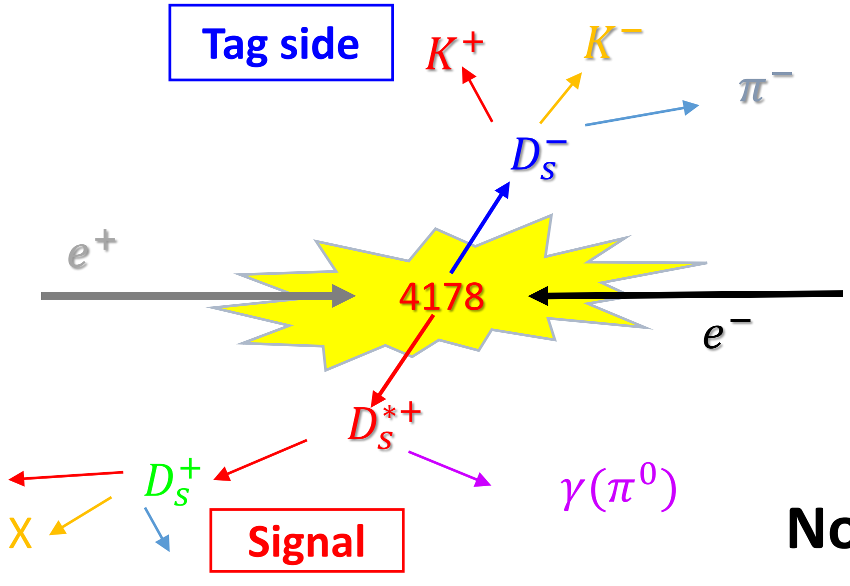
$D^0/\bar{D}^0$	$3.0 \cdot 10^6$
D^+/D^-	$2.4 \cdot 10^6$





- 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 MM²

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

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

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

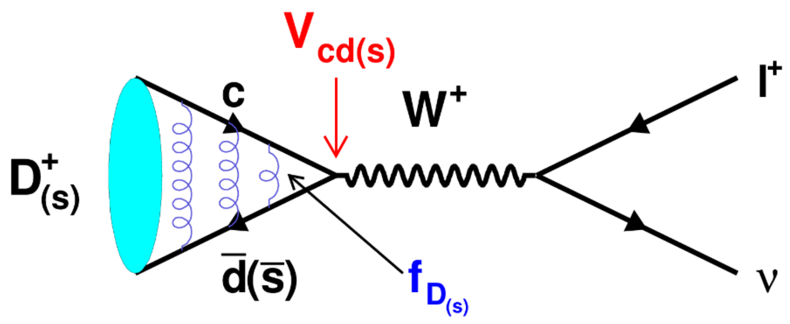
DT yield: $N^i_{\text{DT}} = 2 \times N_{\text{D}\bar{\text{D}}} \times B^i_{\text{ST}} \times B_{\text{sig}} \times \varepsilon^i_{\text{ST vs.sig}}$

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

Advantages: almost background free, absolute Brs.

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



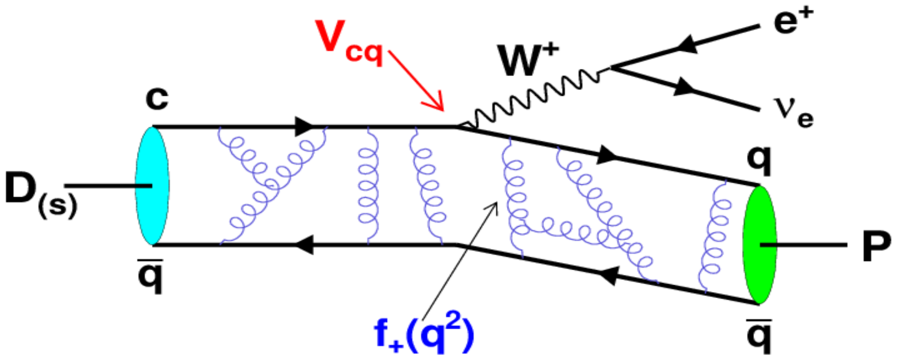
- Charm leptonic decays involve both weak and strong interactions.
- The weak part is easy to be described as the annihilation of the quark-antiquark pair via the standard model W^+ boson.
- The strong interactions arise due to gluon exchanges between the charm quark and the light quark. These are parameterized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

Decay rate (Exp.) — CKM matrix element — Decay constant (LQCD)

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

- 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:

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

Differential rate (Exp.)

CKM matrix element

Form factor (LQCD)

- 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

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.**
- **Study the analogous decays in charm quark sector:**

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

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

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

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

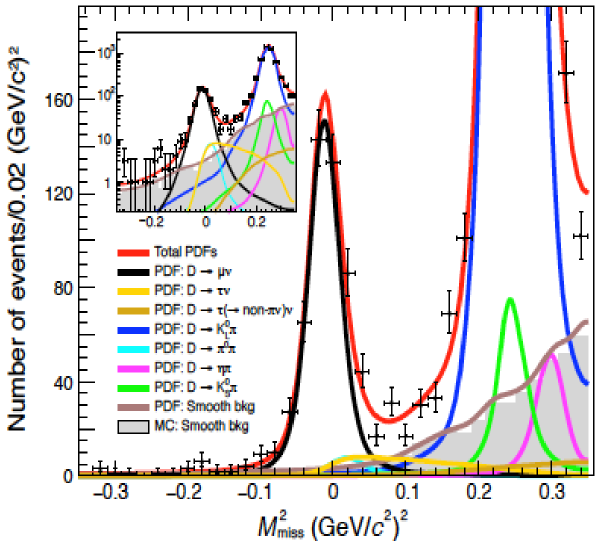
EPJC, 78 (2018) 501 , Z. Phys. C46 (1990)93, PRD69 (2004)074025, PLB633(2006)61

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

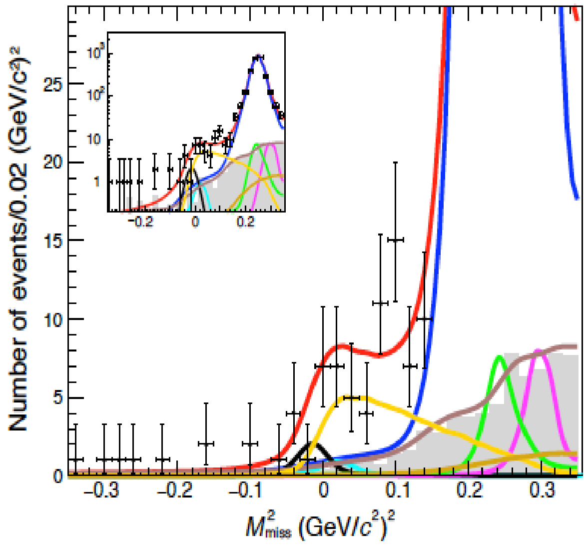
$2.93\mathrm{f}b^{-1}@E_{cm} = 3.773\mathrm{GeV}$

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

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 $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$).

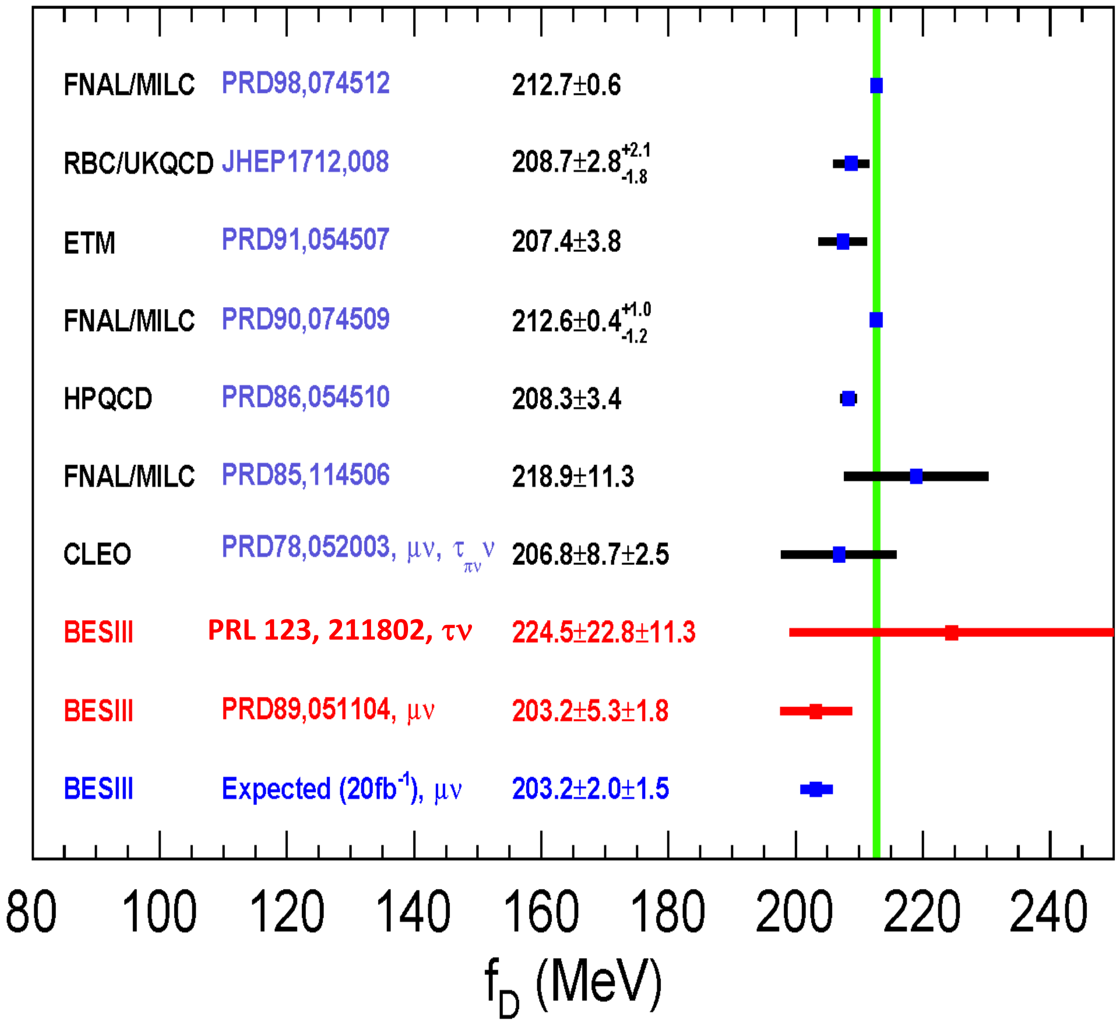
$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

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

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

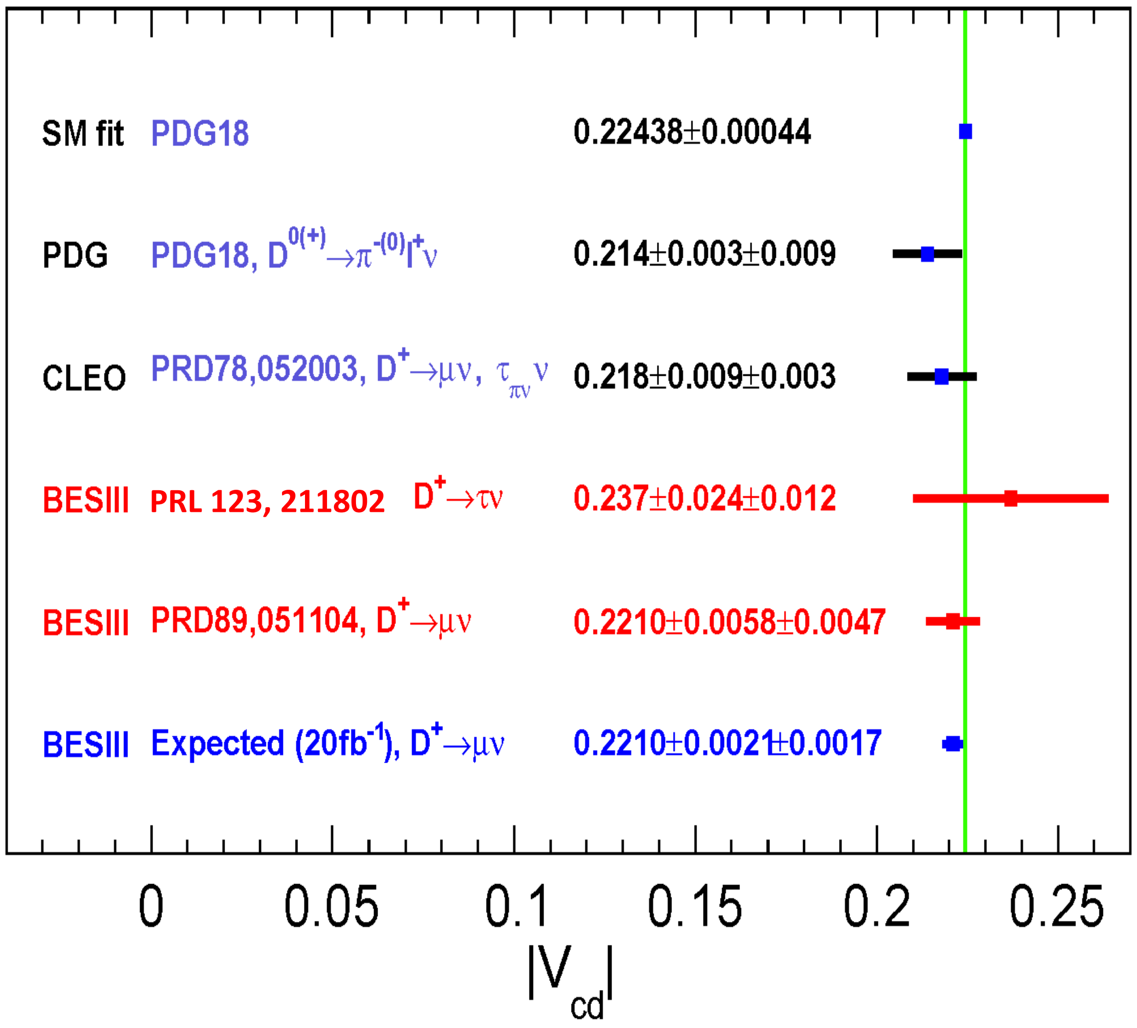
Take $|V_{cd}|^{CKMfitter}$ as input：

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)

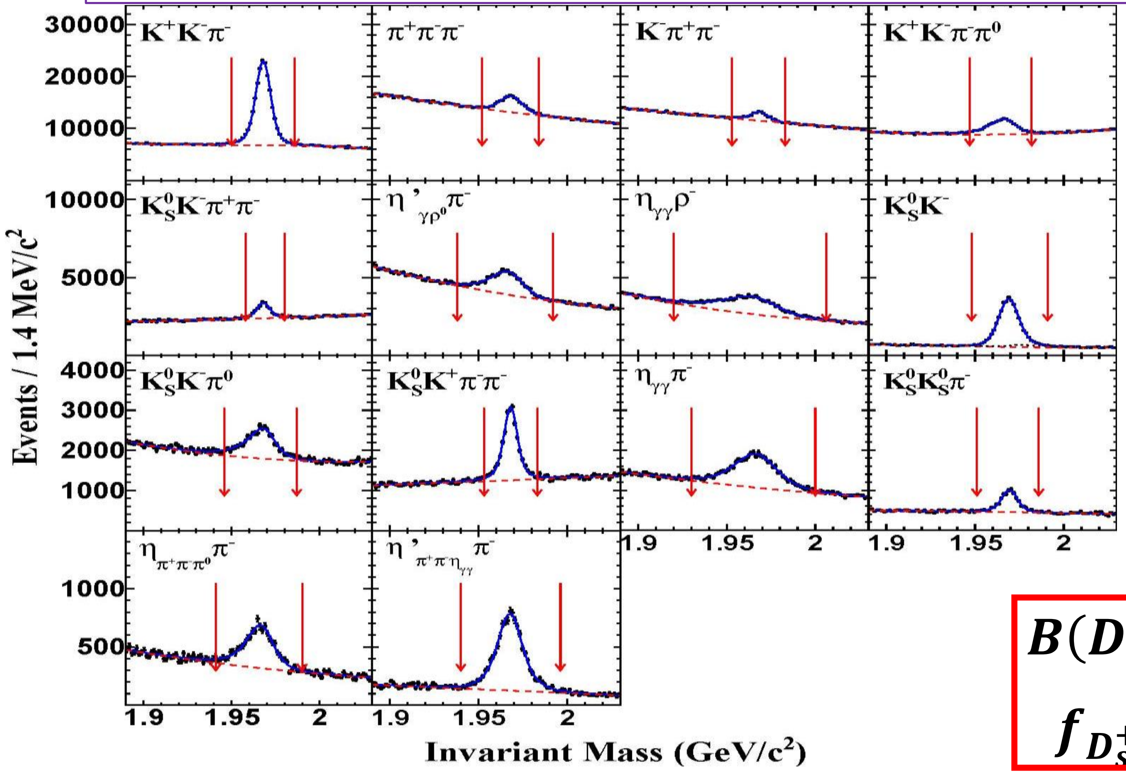


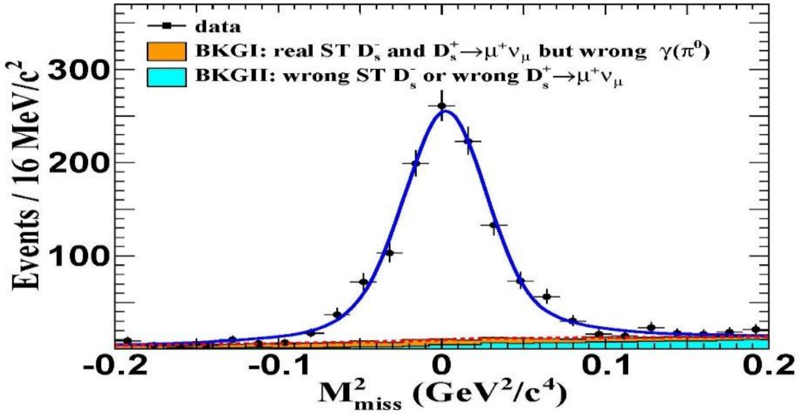
BESIII $D_s^+ \to \mu^+\nu_\mu$

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

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

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

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

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

Tag side: 14 Ds^- decay mode

No. of single tags: $(388.7 \pm 2.6)\text{X}10^3$

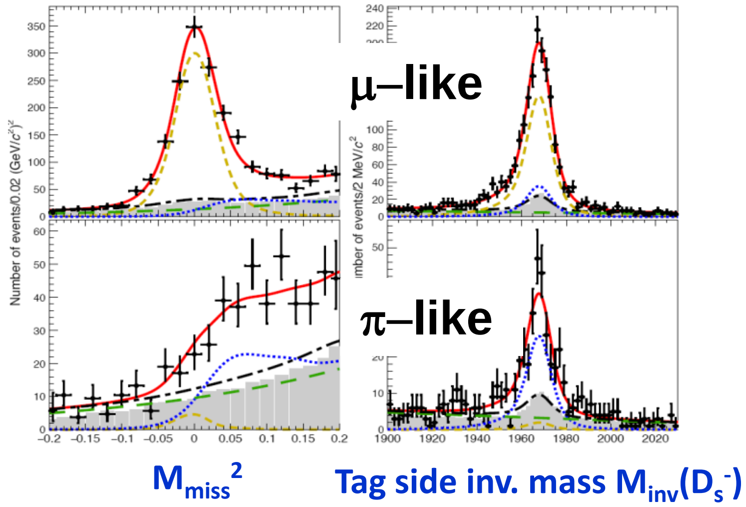
No. of double tags: 1135.9 ± 33.1

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

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

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

arXiv:2105.07178



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

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

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

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

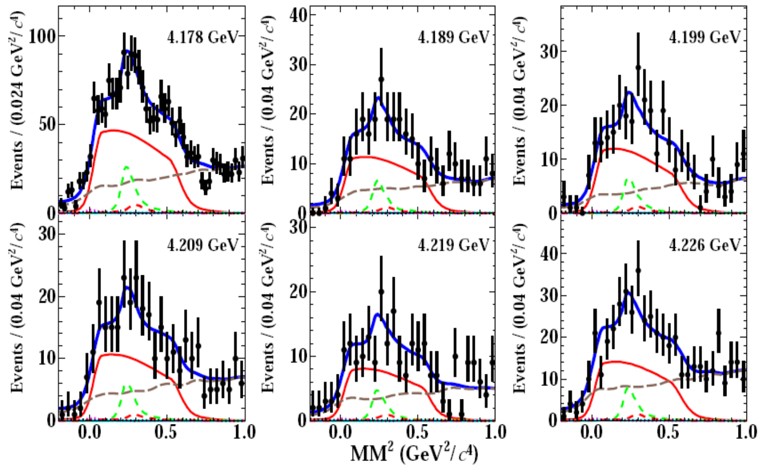
$A_{CP}[\mu\nu] = (-1.2 \pm 2.7)\%$

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

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

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

arXiv:2105.07178



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

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

Take BESIII results and world average：

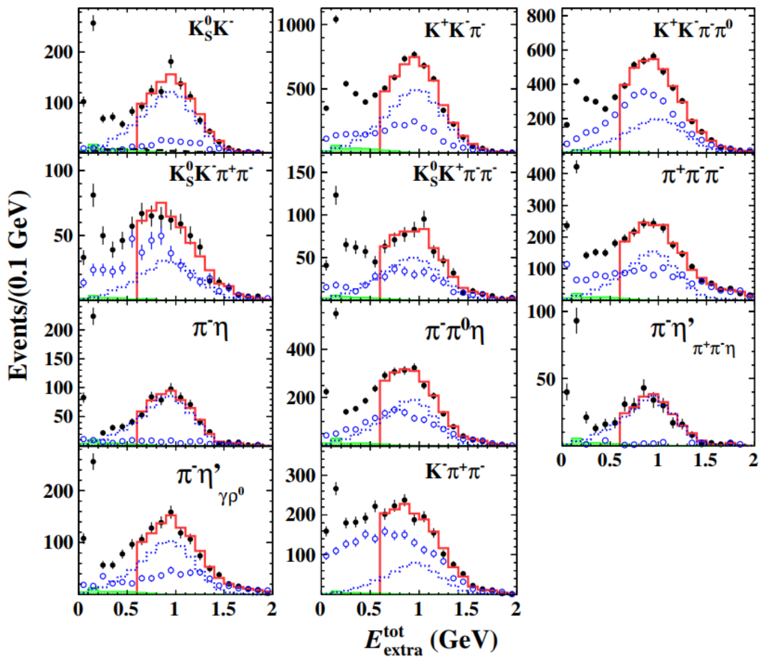
$$\frac{B(D_s^+ \to \tau^+ \nu)}{B(D_s^+ \to \mu^+ \nu)} = (9.67 \pm 0.34)$$

(SM: 9.75)

$D_s^+ \to \tau^+(e^+ \nu\nu)\nu$

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

BESIII Preliminary

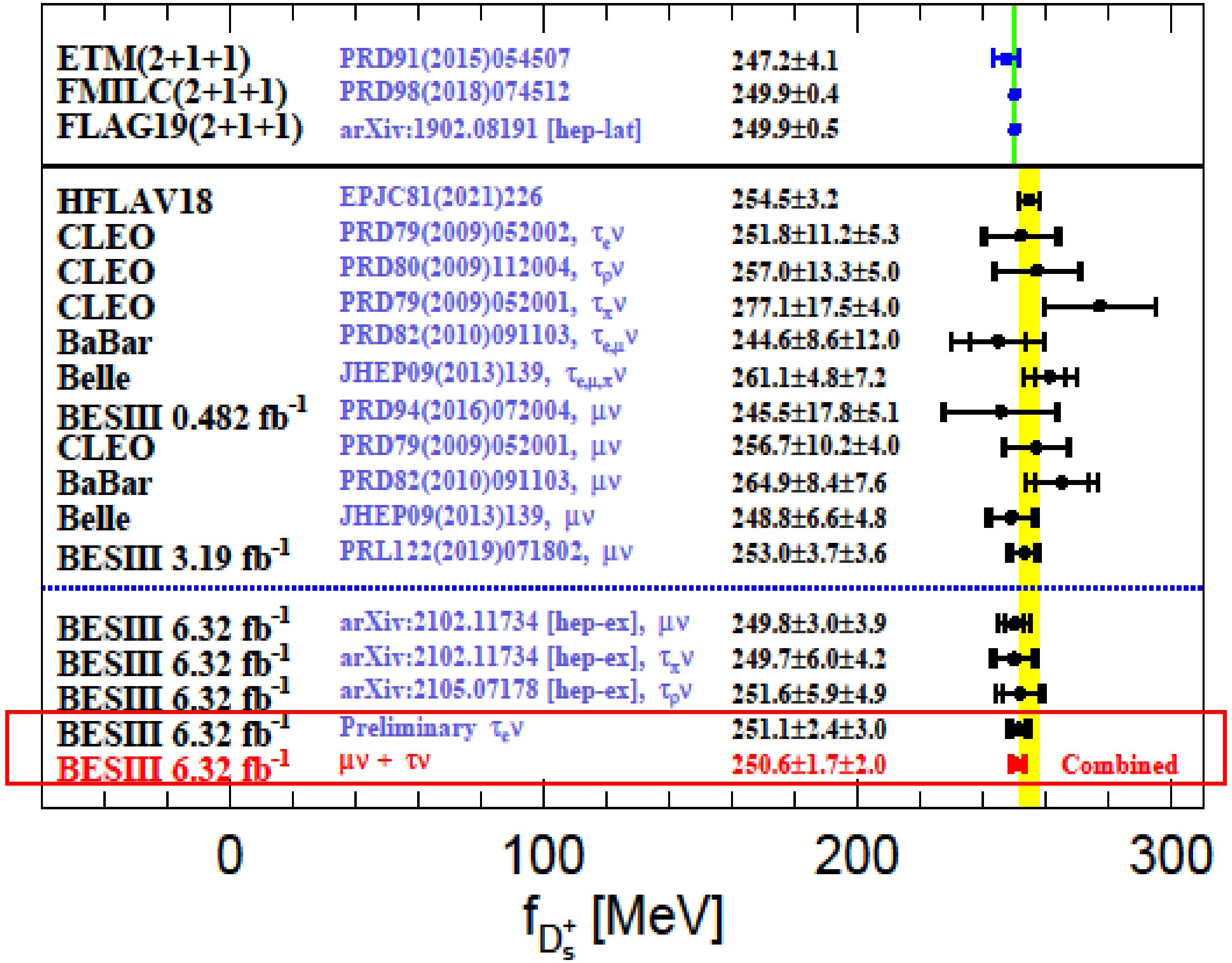


$B[D_s^+ \to \tau^+ \nu] = (5.27 \pm 0.10 \pm 0.12)\%$

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

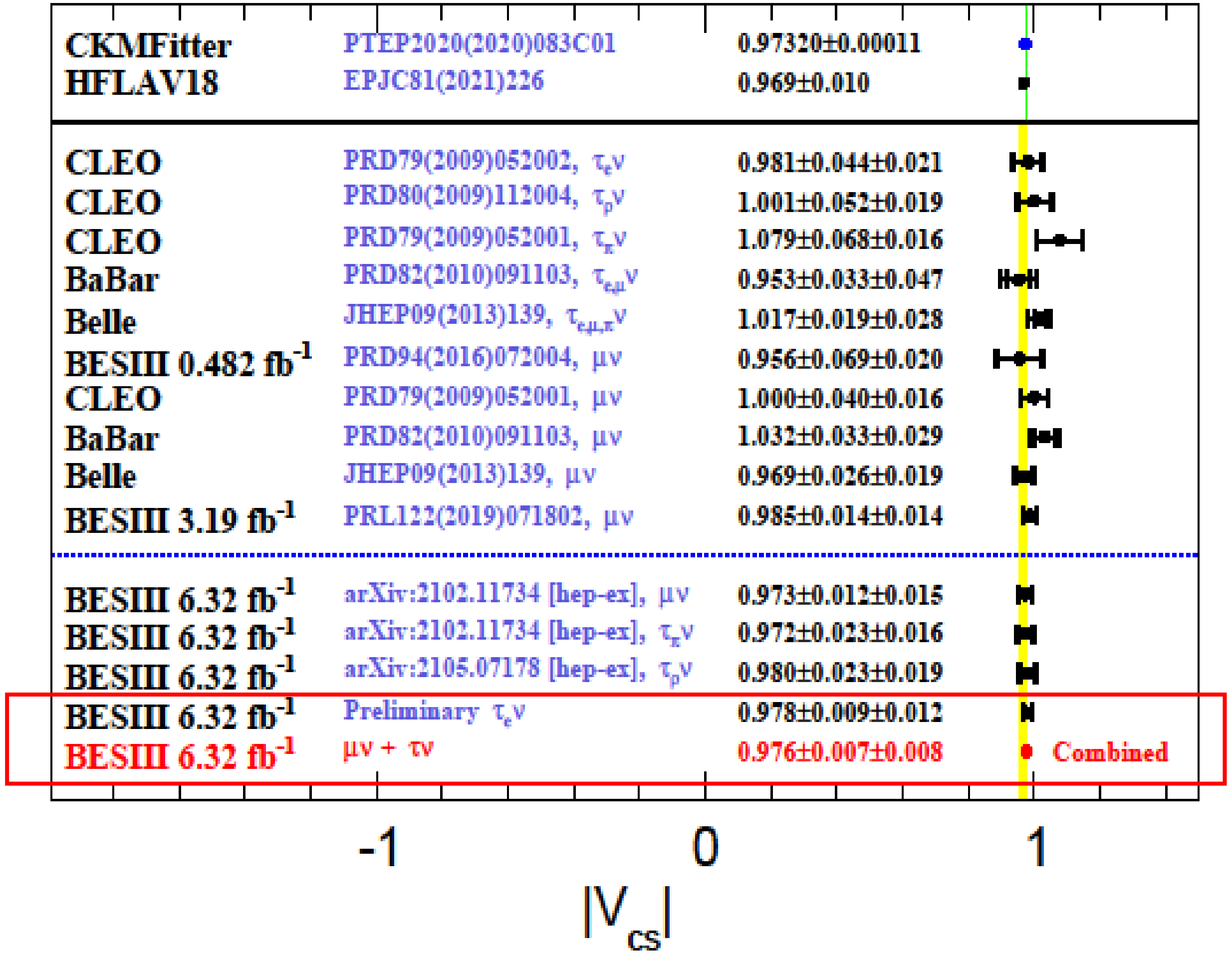
Take $|V_{cs}|^{CKMfitter}$ as input：

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



Take f_{Ds}^{LQCD} as input：

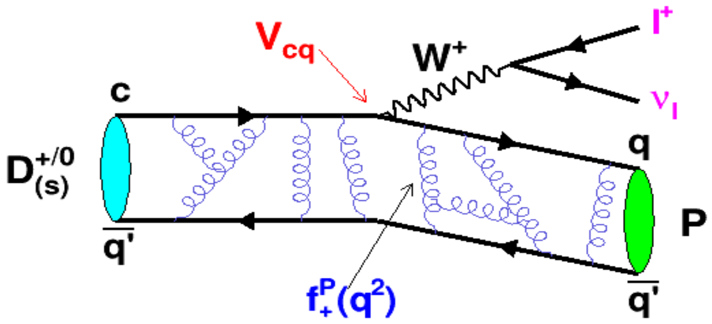
$|V_{cs}|$=(0.978±0.009±0.012) ($\tau^+(e^+\nu\nu)\nu$)



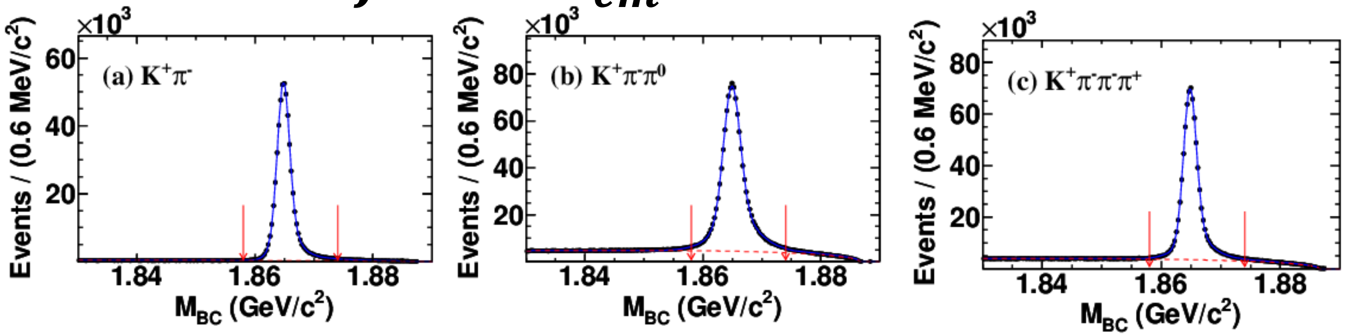
Most precise measurement

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

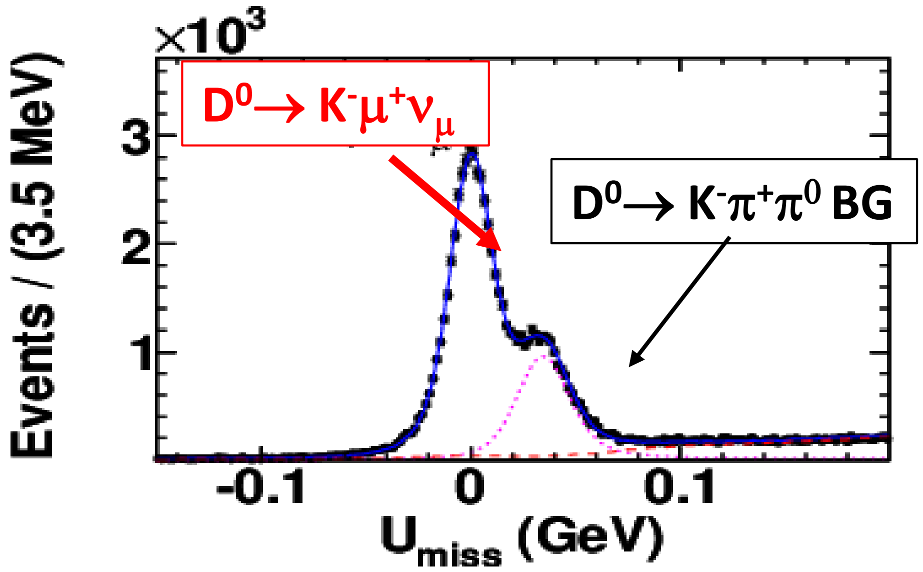
BESIII: PRL 122 (2019) 011804



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



$D^0 \to K^-\mu^+\nu_\mu$ 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: $(2241.4 \pm 2.1)\text{X}10^3$

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

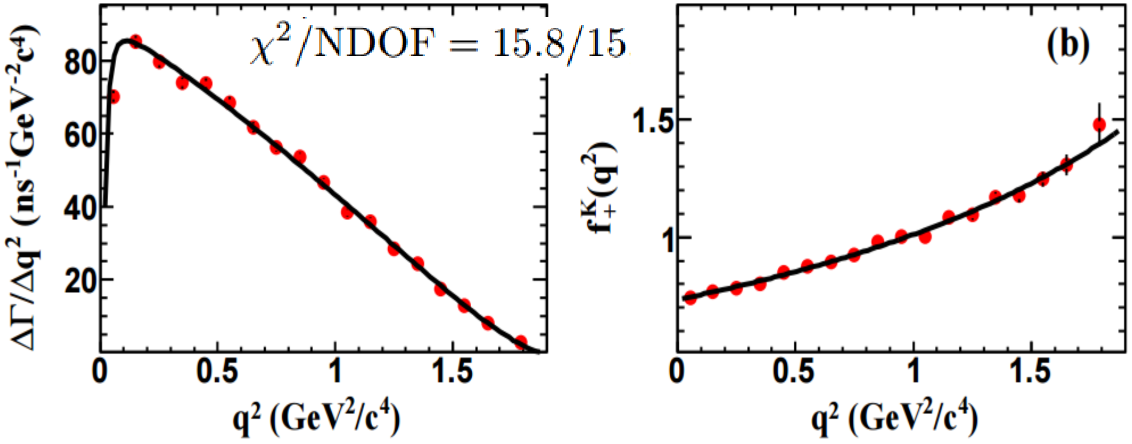
$D^0 \to K^- \mu^+ \nu_\mu$ Fit to partial decay rates

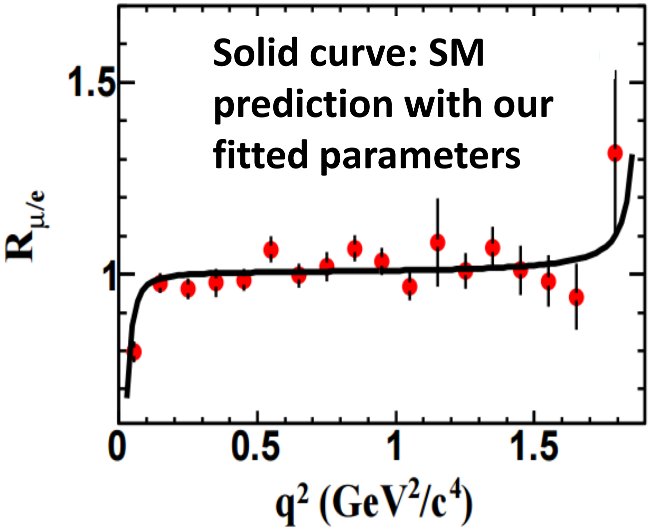
BESIII: PRL 122 (2019) 011804

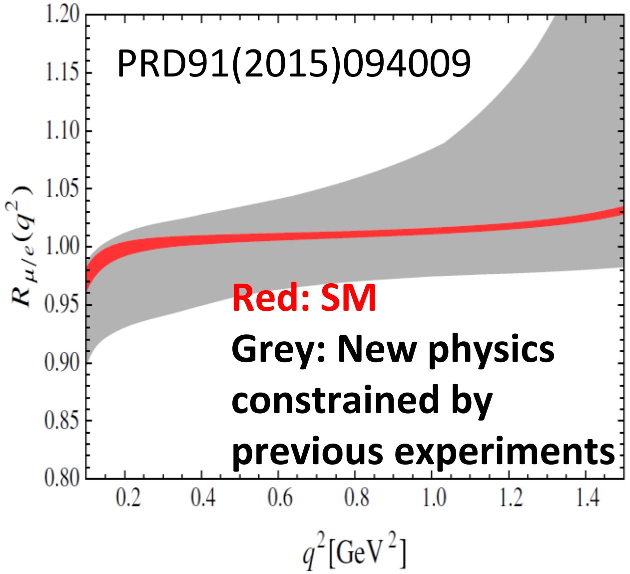
Series expansion parameterization for form factor (2nd order):

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

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







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

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

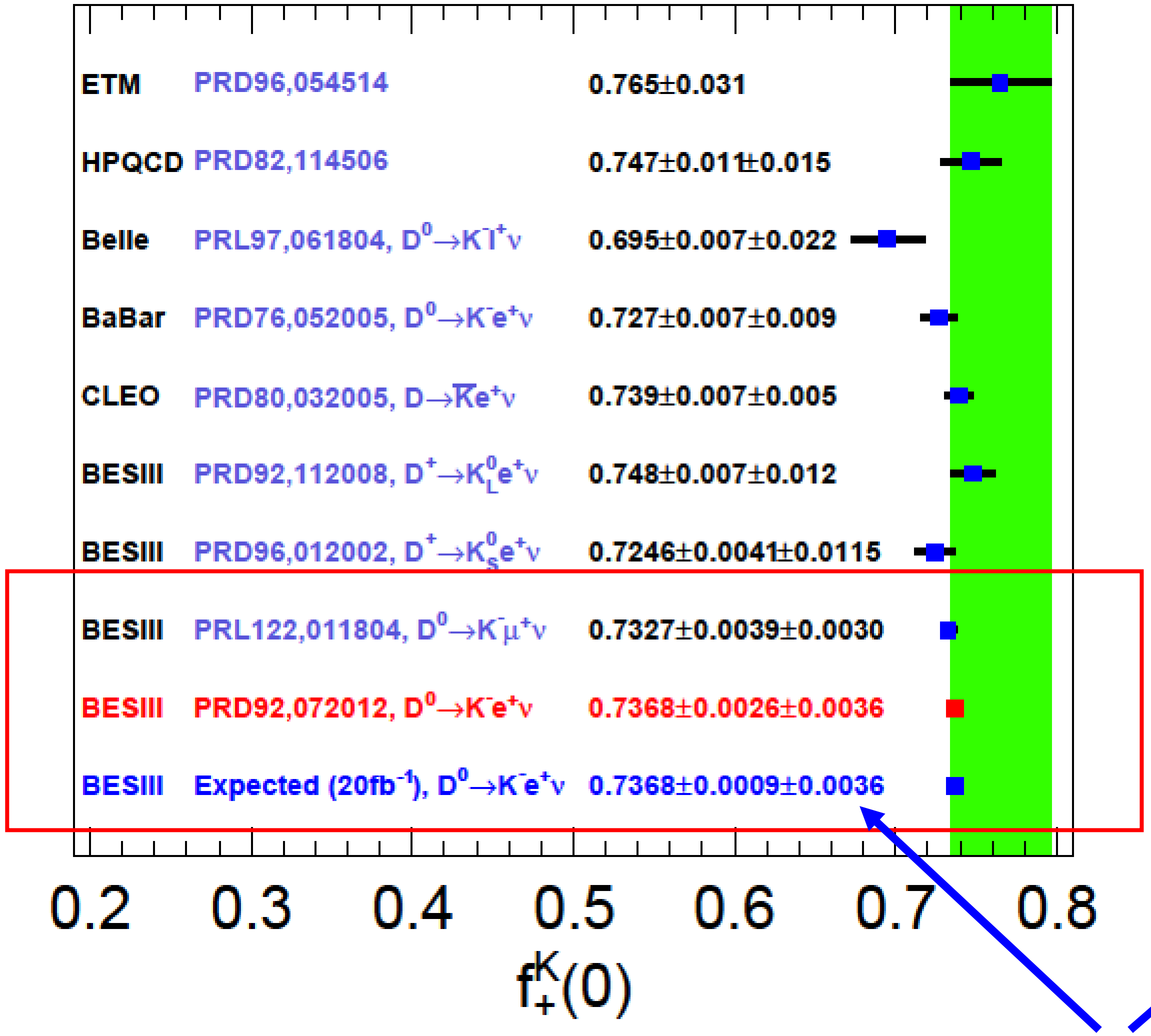
SM prediction: 0.97

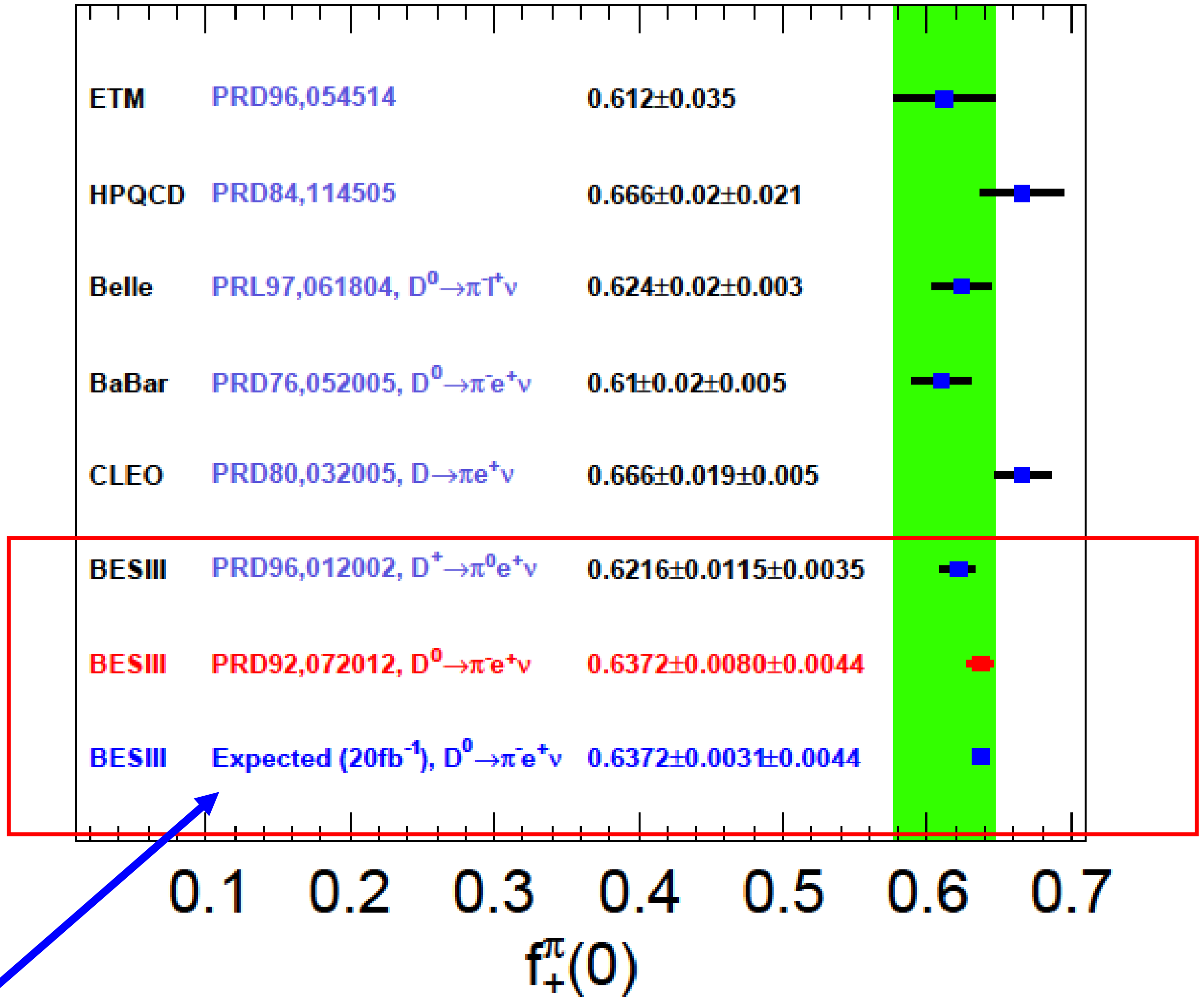
No deviation larger than 2σ is observed in q^2 interval of (0.2, 1.5) GeV^2/c^4.

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

Inputs from 2018 PDG CKMFitter

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



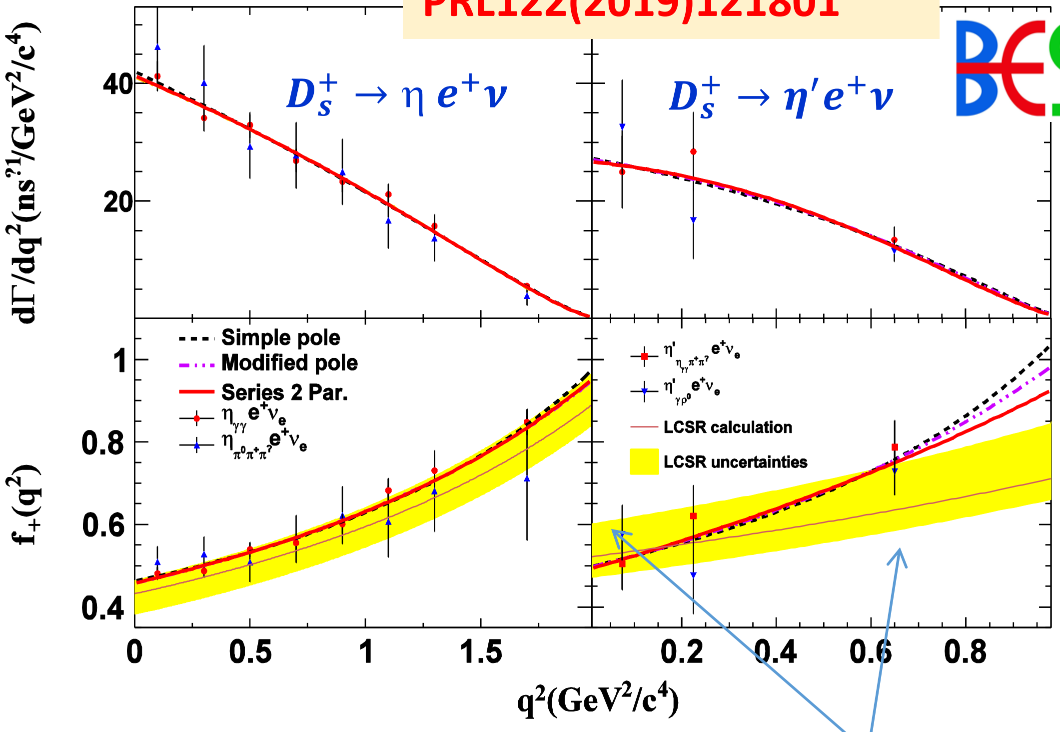


BESIII: 20 fb^{-1} @ 3770 MeV

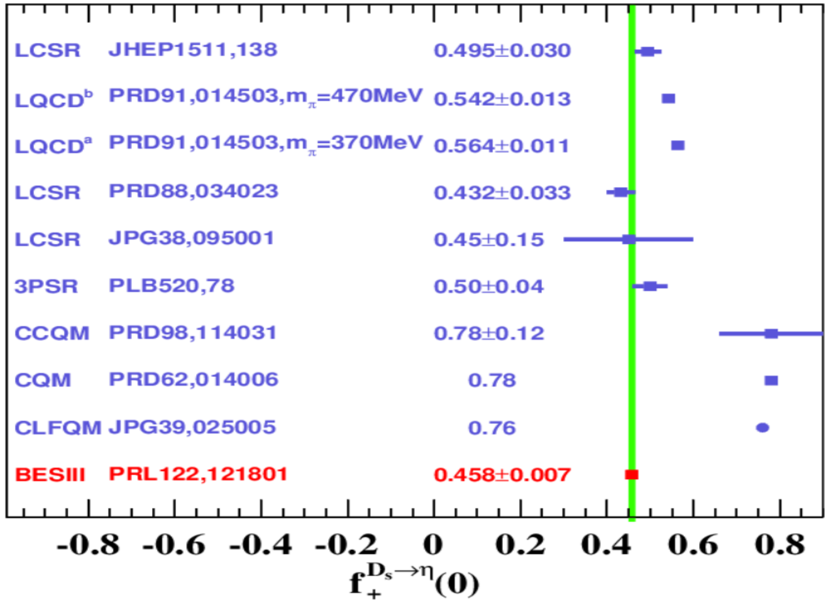
First extractions of FFs of $D_s^+ \to \eta^{(\prime)} e^+ \nu$

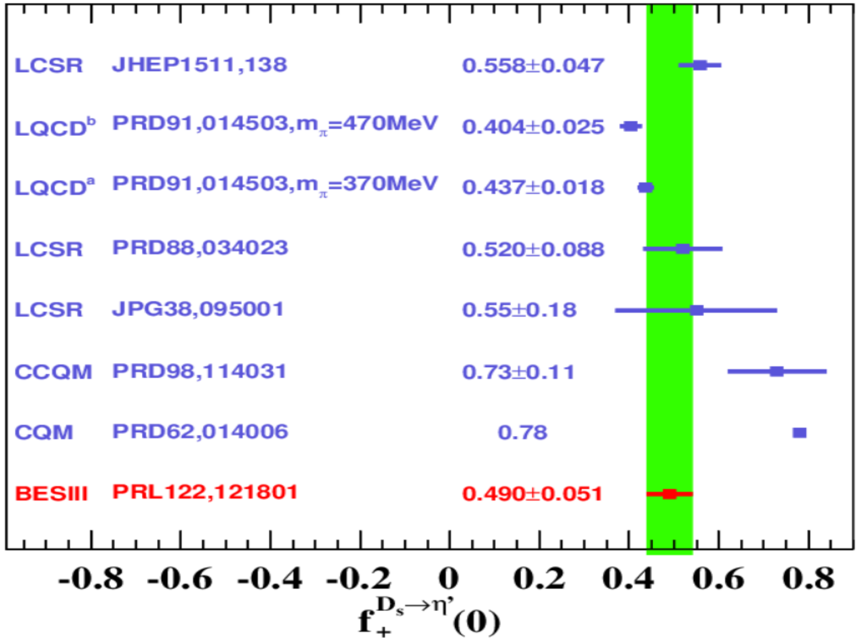
BESIII: 3.19 fb^{-1} @ 4180 MeV

PRL122(2019)121801



PRD88, 034023





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

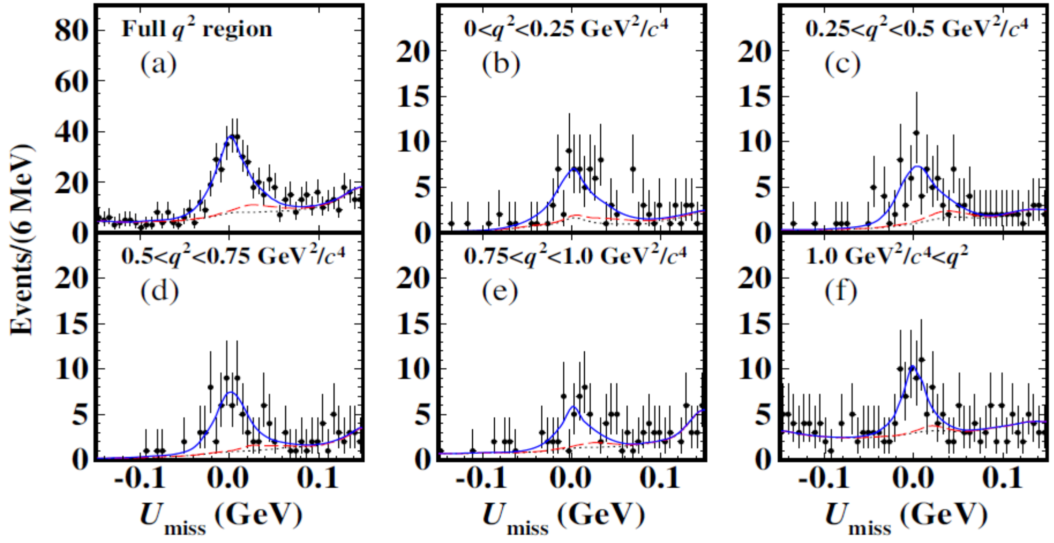
$$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.477\pm0.049\pm0.011$$

Statistical errors dominate

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

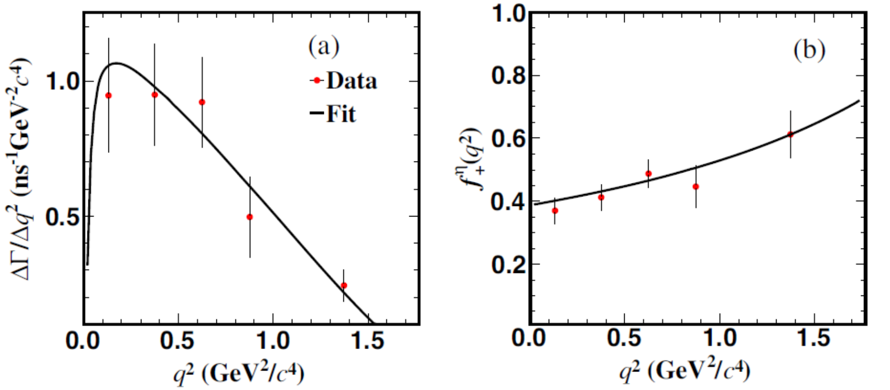
$2.93 fb^{-1} @ E_{cm} = 3.773 \text{GeV}$

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



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

No. of double tags: 234 ± 22



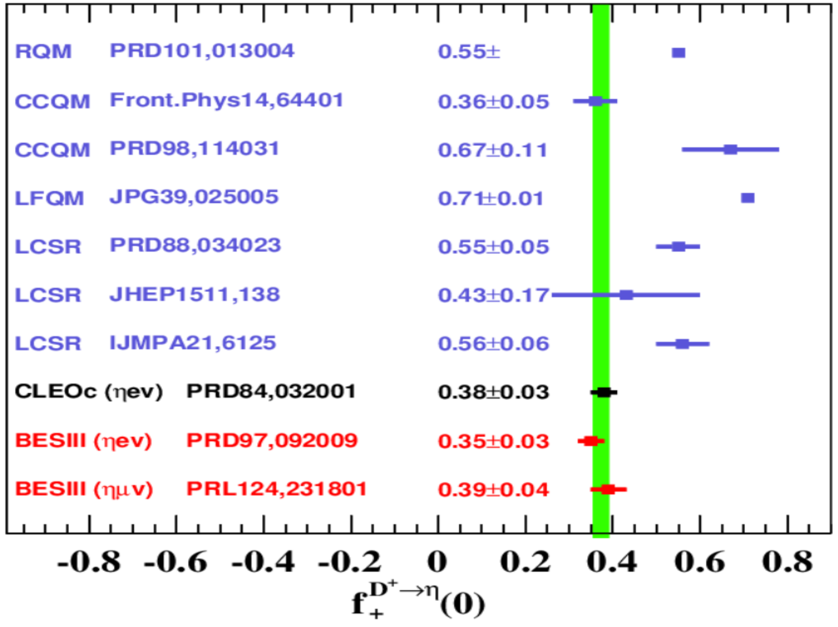
BESIII: PRL 124, 231801 (2020)

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

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

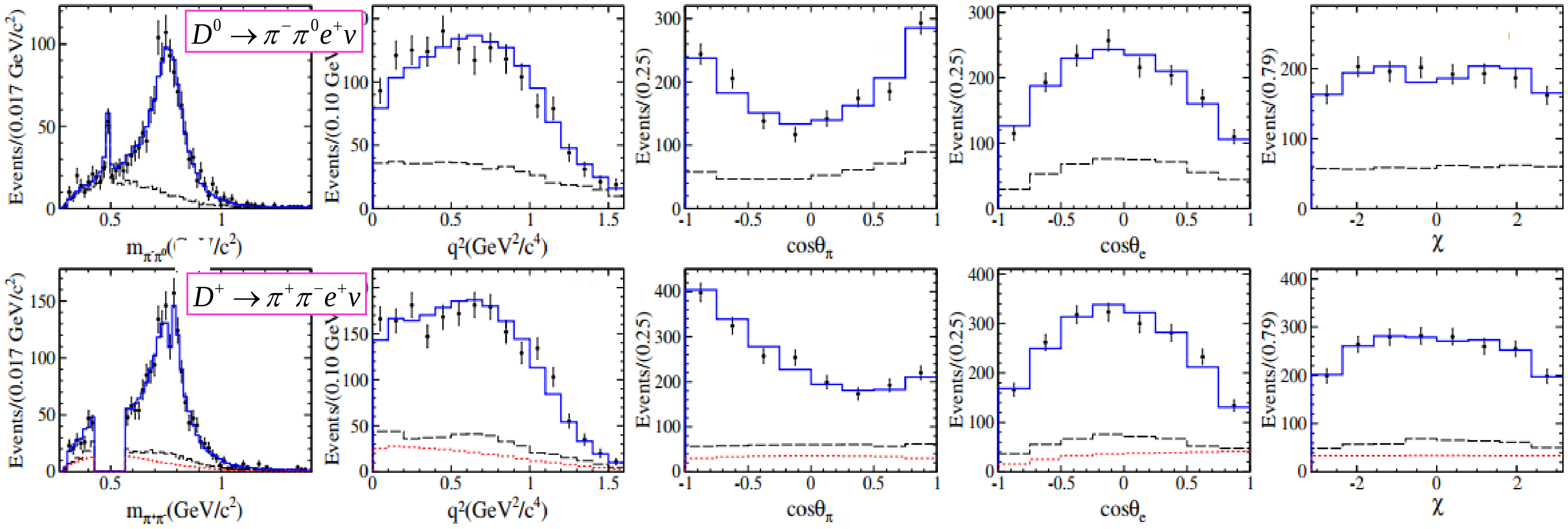
(SM prediction: 0.93-0.96)

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



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

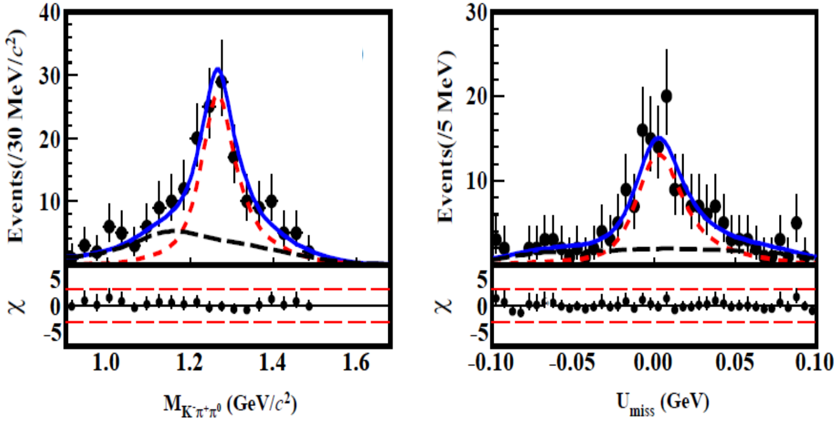
$$R = [B_{D^+ \to f_0(980)^0 e^+ \nu} + B_{D^+ \to f_0(500)^0 e^+ \nu}] / B_{D^+ \to a_0(980)^0 e^+ \nu} \quad > 2.7$$

BESIII: PRL 121 (2018) 081802

favors tetraquark assumption for the light scalar mesons

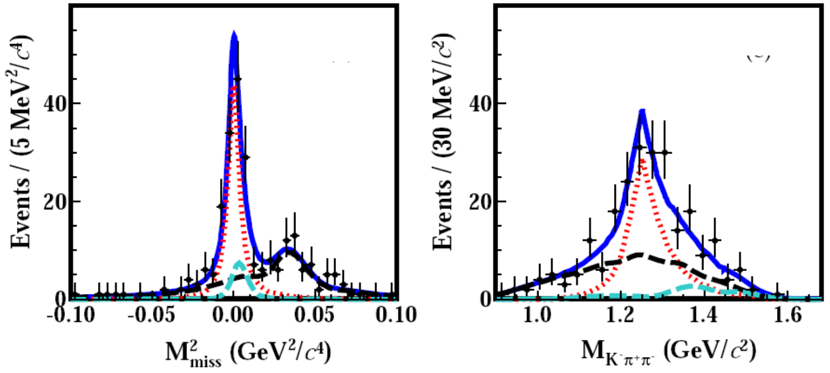
Observation of $D \to K_1(1270)e^+\nu_e$

PRL123(2019)231801



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

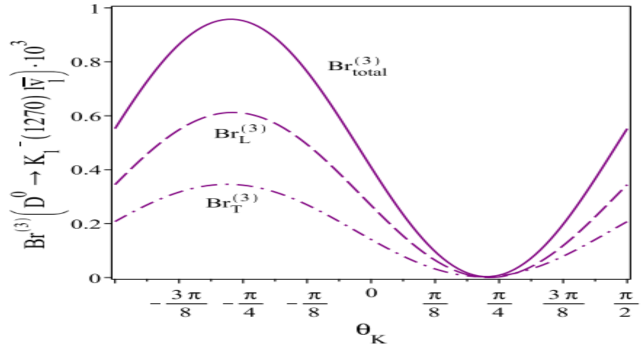
arXiv:2102.10850



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

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

JPG46,105006



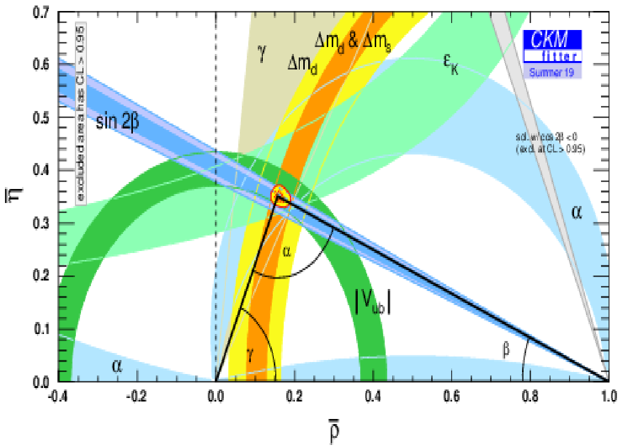
PRL125,051802

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.**

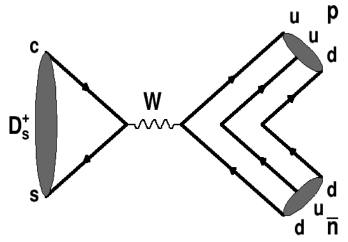
Hadronic decays of charm mesons

- **Strong phase measurement with quantum correlated $\psi(3770) \to D^0\bar{D}^0$ is crucial in the model-independent determinations of γ and charm mixing/direct CPV.**
  - 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 $\gamma = (65.8^{+1.0}_{-1.7})^{o}$

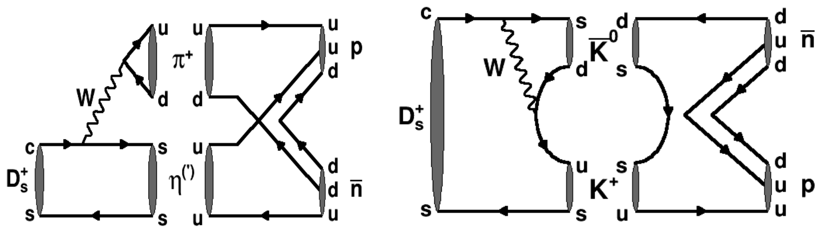


Pre-LHCb: $\gamma = (73^{+22}_{-25})^{\circ}$

- **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

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

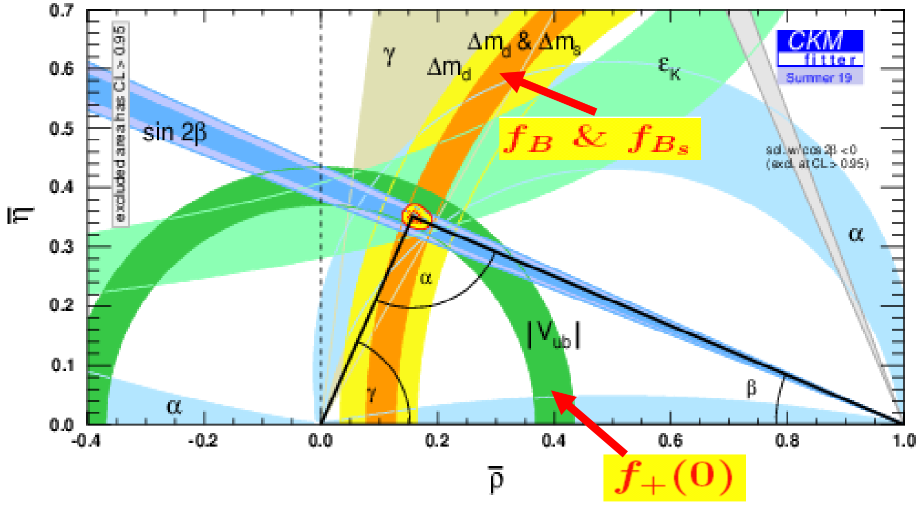
$\psi(3770) \rightarrow D^0\overline{D^0}$ quantum correlation➔strong phase parameters between D^0 and $\overline{D}^0$ decays

➔inputs to LHCb measurement of γ

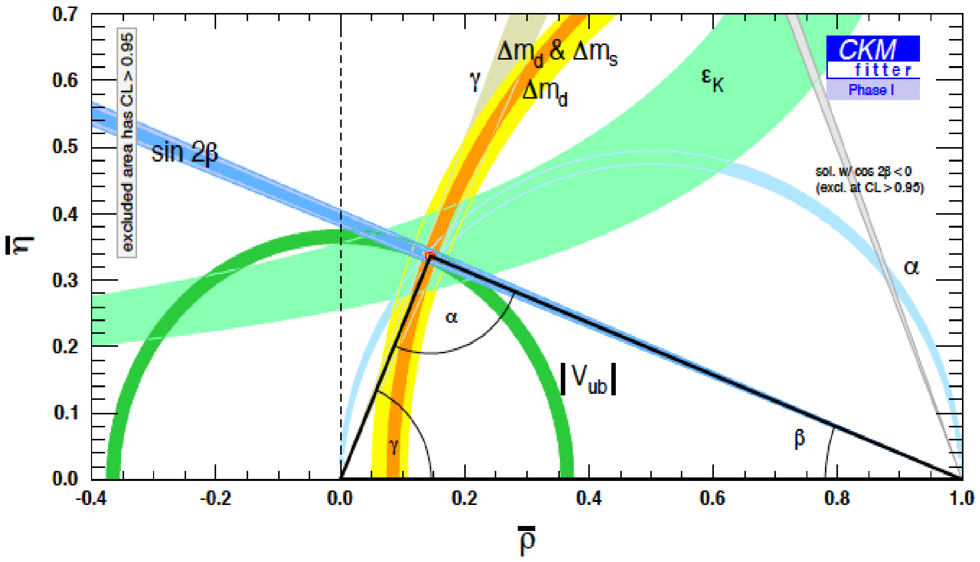
Belle II (arXiv:1808.10567): 1.5^0 with 50 ab^{-1}

LHCb (arXiv:1808.08865v2): < 1°, 50 fb^{-1}, phase-1 upgrade (2030),

< 0.4°, 300 fb^{-1}, phase-2 upgrade (> 2035)



2019

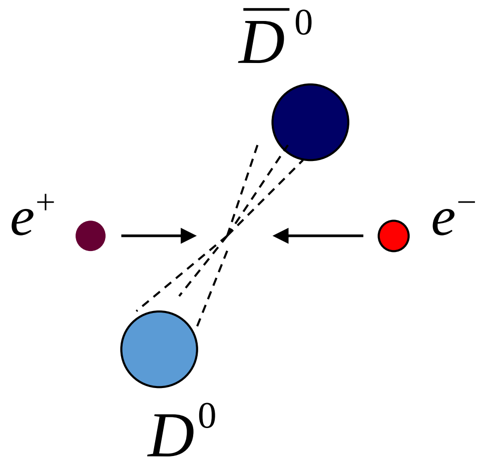


>year of 2030 (BESIII 20 fb^{-1} data as inputs)

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

The correlated state

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



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

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

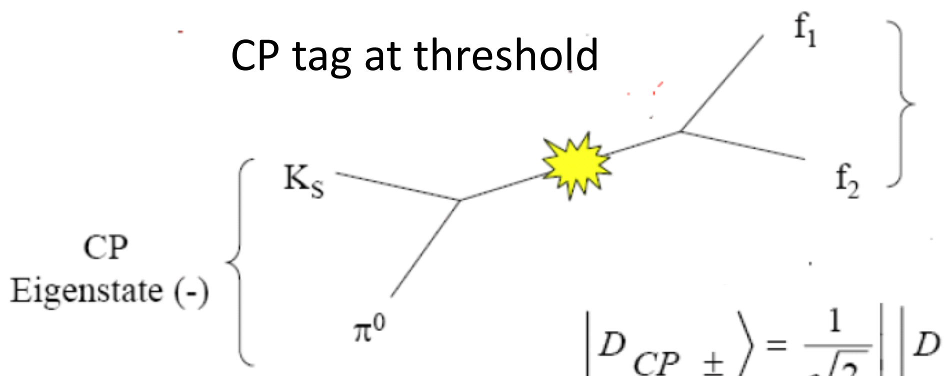
For a correlated state with $C = -$

$$\hat{C}\left|D^0\right\rangle = \left|\bar{D}^0\right\rangle$$

$$\hat{C}\left|\bar{D}^0\right\rangle = \left|D^0\right\rangle$$

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

CP tag at threshold



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

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

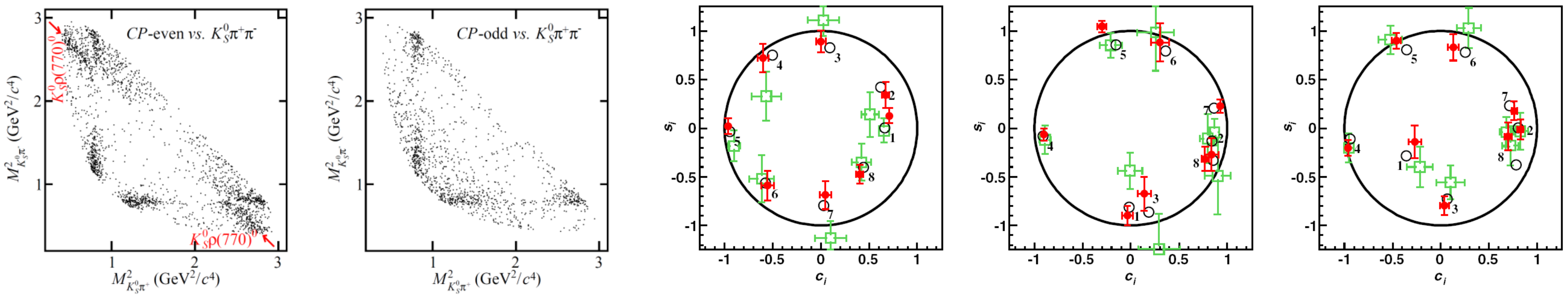
$$\sqrt{2}\,A\left(D_{CP\pm} \to K^-\pi^+\right) = A\left(D^0 \to K^-\pi^+\right) \pm A\left(\bar{D}^0 \to K^-\pi^+\right)$$

Strong phase measurements at BESIII

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

■ $D \rightarrow K^0_{S/L}\pi^+\pi^-$

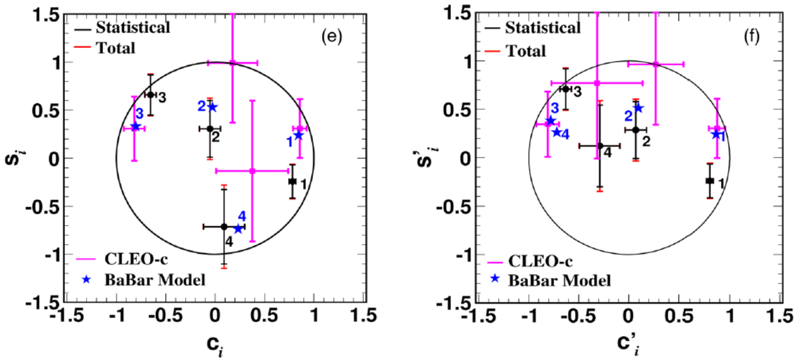
PRL 124 (2020)241802



Constraint on γ measurement ~ 0.9^0

■ $D \rightarrow K^0_{S/L}K^+K^-$

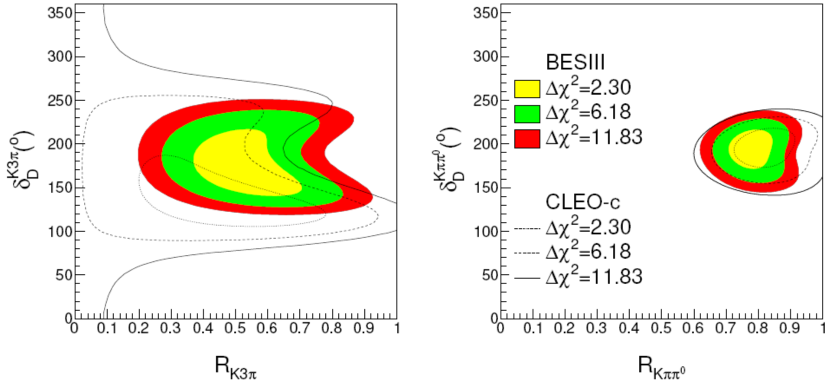
PRD102(2020)052008



Constraint on γ measurement ~ 1.3^0

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

JHEP 2021 (5) (2021) 164

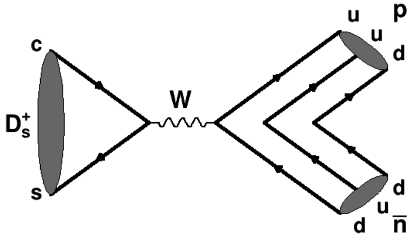


Constraint on γ measurement ~ 6^0

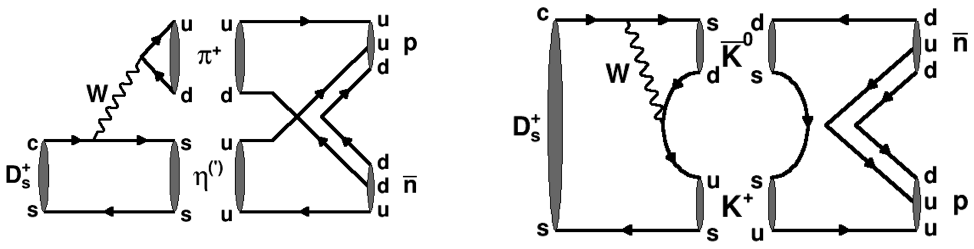
BESIII $D_s^+ \to p\bar{n}$

PRD 99 (2019) 031101 (R)

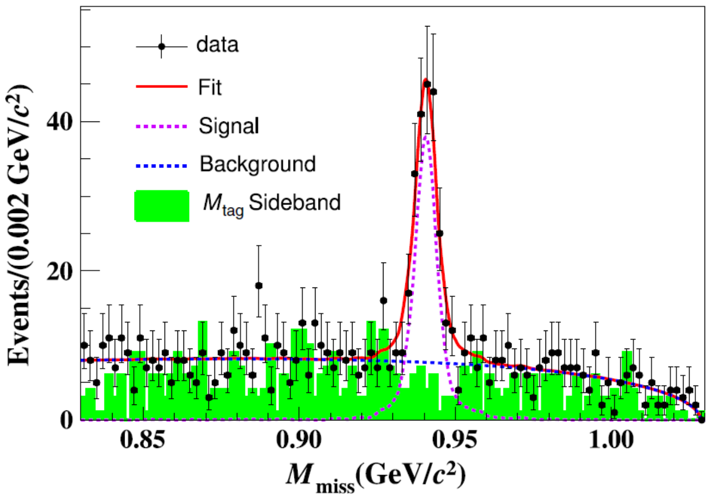
- The only kinematic allowed baryonic charm decay mode
- For the weak annihilation processes, Brs. expected to be ~10^{-6}(chiral suppression by the factor $(m_\pi/m_{Ds})^4$)
- Long distance effect may enhance Br: ~10^{-3} [PLB 663, 326(2008)]
- First evidence by CLEO-c: $(1.30 \pm 0.36^{+0.12}_{-0.16})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



Weak annihilation (~10^{-6})



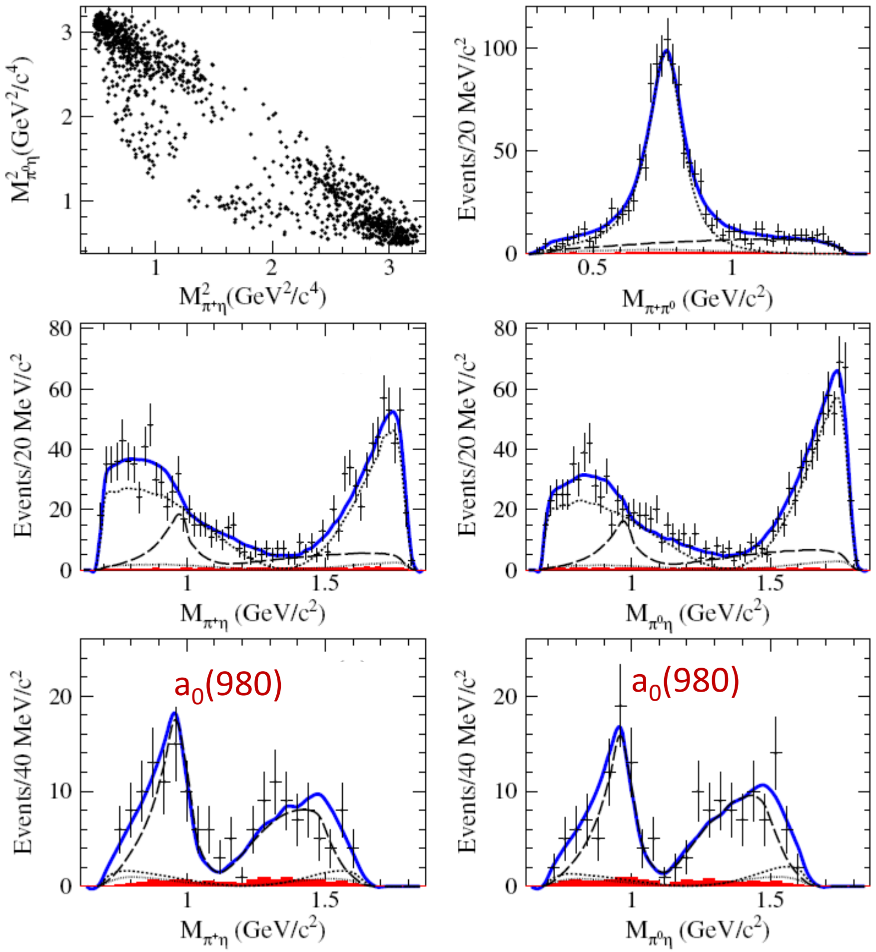
Long-distance effect



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

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

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

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

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

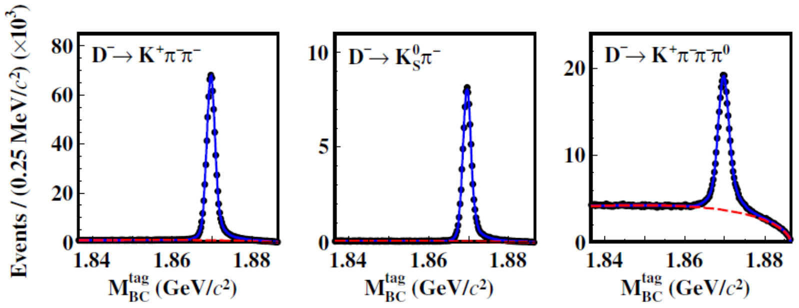
$$B_{D_s^+ \to \rho^+\eta} = (7.44 \pm 0.48 \pm 0.44)\%$$

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

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



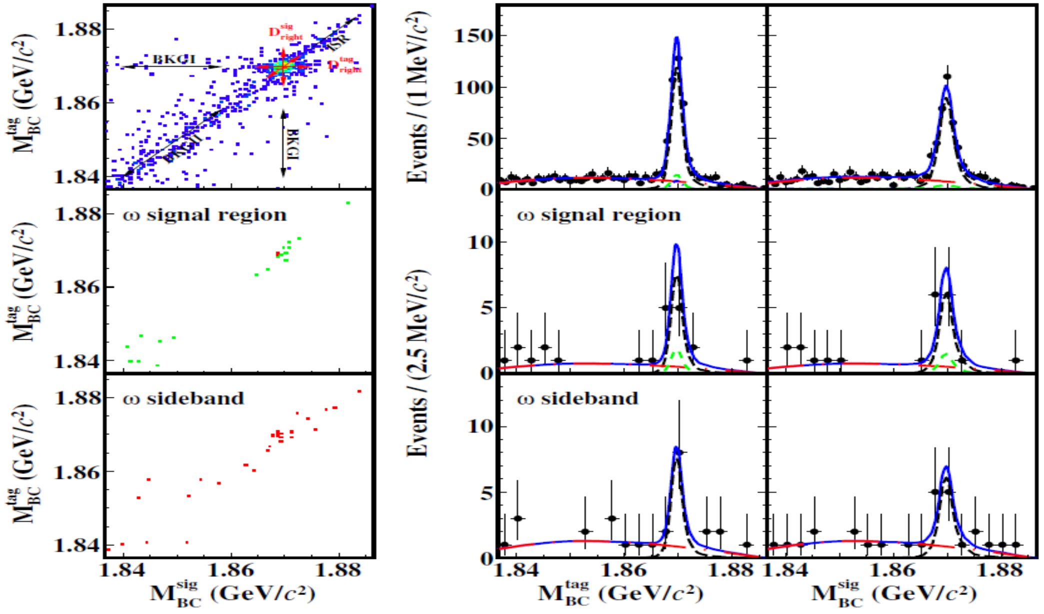
The single tag D^- yield: $(1150.3 \pm 1.5)\times10^3$

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

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

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

$$\tan^4\theta_C = 2.88 \times 10^{-3}$$



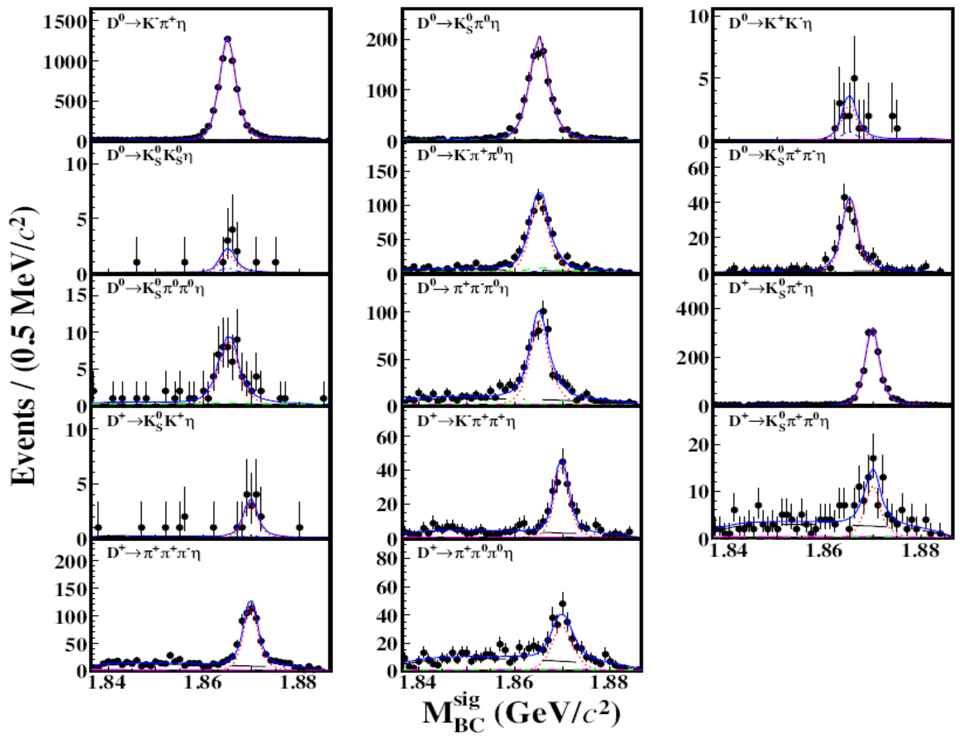
DCS mode	BF($\times10^{-4}$)	CF mode	BF($\times10^{-2}$)	Ratio($\times10^{-3}$)
$D^0 \to K^+\pi^-$	1.48±0.07	$D^0 \to K^-\pi^+$	3.89±0.04	3.80±0.18
$D^0 \to K^+\pi^-\pi^0$	3.01±0.15	$D^0 \to K^-\pi^+\pi^0$	14.2±0.5	2.12±0.13
$D^0 \to K^+\pi^-\pi^-\pi^+$	2.45±0.07	$D^0 \to K^-\pi^+\pi^+\pi^-$	8.11±0.15	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 $D^{0(+)} \rightarrow \eta X$ decays

PRL124(2020)241803



Decay	$\Delta E_{\rm sig}$ (MeV)	$N_{\rm DT}$	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$ ($\times 10^{-4}$)
$D^0 \to K^-\pi^+\eta$	$(-37, 36)$	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	$\mathcal{B}^+_{\rm sig}$ ($\times 10^{-4}$)	$\mathcal{B}^-_{\rm sig}$ ($\times 10^{-4}$)	$\mathcal{A}^{\rm sig}_{CP}$ (%)
$D^0 \to K^-\pi^+\eta$	182.1 ± 3.5	189.1 ± 3.6	$-1.9 \pm 1.3 \pm 1.0$
$D^0 \to K^0_S\pi^0\eta$	98.4 ± 4.8	106.3 ± 5.1	$-3.9 \pm 3.2 \pm 0.8$
$D^0 \to K^-\pi^+\pi^0\eta$	41.7 ± 2.7	48.8 ± 3.2	$-7.9 \pm 4.8 \pm 2.5$
$D^0 \to \pi^+\pi^-\pi^0\eta$	29.8 ± 2.2	33.3 ± 2.5	$-5.5 \pm 5.2 \pm 2.4$
$D^+ \to K^0_S\pi^+\eta$	129.9 ± 5.3	132.3 ± 5.4	$-0.9 \pm 2.9 \pm 1.0$
$D^+ \to \pi^+\pi^+\pi^-\eta$	35.4 ± 2.4	33.7 ± 2.4	$+2.5 \pm 5.0 \pm 1.6$

- **Direct measurements of absolute BFs of 14 exclusive hadronic $D^{0(+)} \rightarrow \eta X$ 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**

Summary

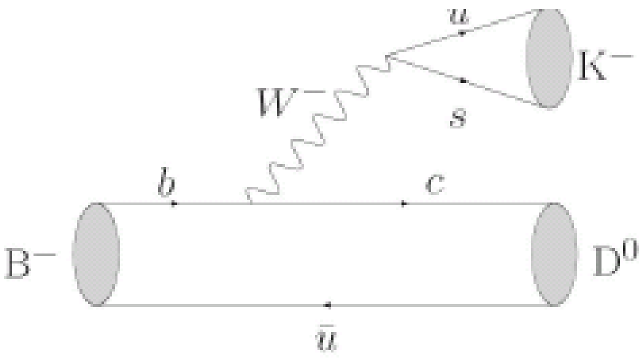
- **Charm (semi-)leptonic decays provide precision calibration of LQCD; precision measurements of CKM matrix elements**
- **Charm hadronic decays are key labs to understand non-perturbative QCD; provide important inputs to model-independent determination of γ and charm mixing/CPV**
- **BESIII will collect 20 fb^{-1} data (17+3) at $\psi(3773)$ in next two years time.**

  →a new era of precision charm physics

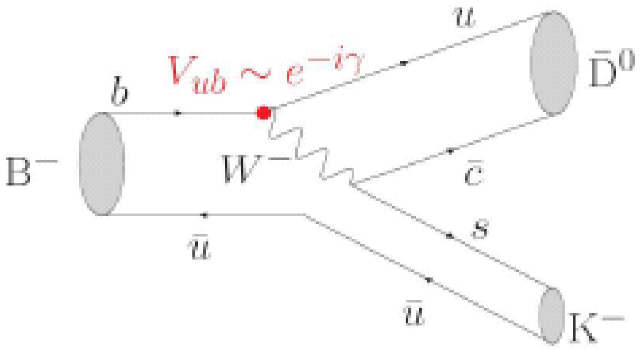
Thank you!

γ/ϕ_3 extraction

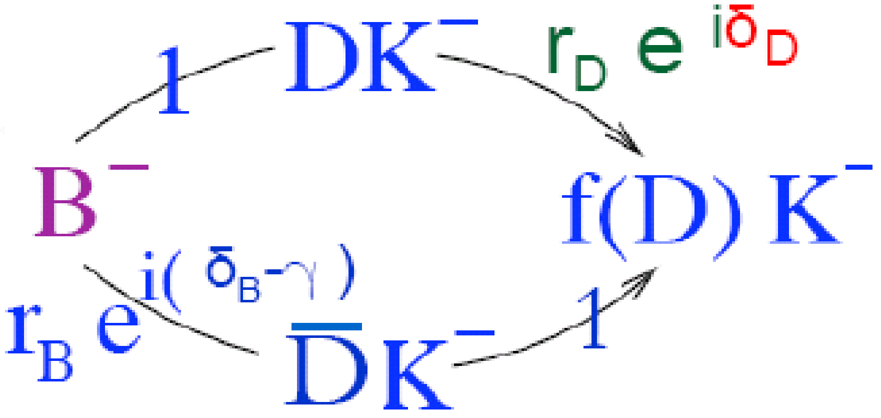
$B^- \longrightarrow D^0K^-$



$B^- \longrightarrow \overline{D}^0K^-$



$$\frac{< B^- \longrightarrow \overline{D}^0K^- >}{< B^- \longrightarrow D^0K^- >} = r_Be^{i(\delta_B-\gamma)}$$



- Sensitivity through interference between b→u and b→c transitions
- Require D^0 and $\overline{D^0}$ decay to a common final state, f(D): Interference occurs when D^0 and $\overline{D}^0$ decay to the same final state f

  K^0_Shh ; $K\pi$; $K\pi\pi\pi$; $K\pi\pi^0$

r_D & δ_D analogous to B-decay quantities. For multibody decays, these vary over Dalitz space

- Comparison of B^- and B^+ rates allow γ to be extracted
- But other parameters to be considered
  - in particular δ_D – accessed in quantum-correlated D-decays

BESIII $D_s^+ \to \omega\pi^+$ and ωK^+

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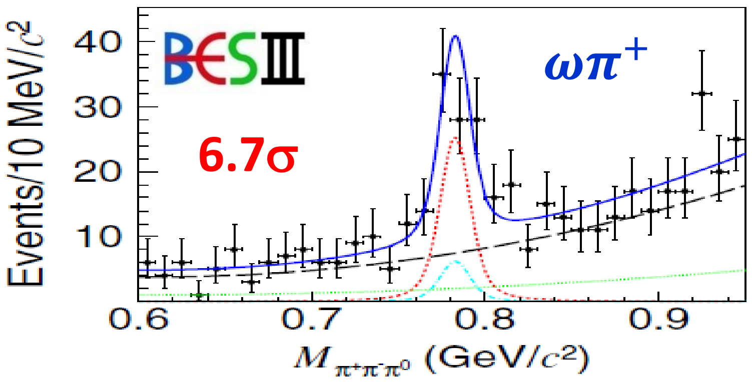
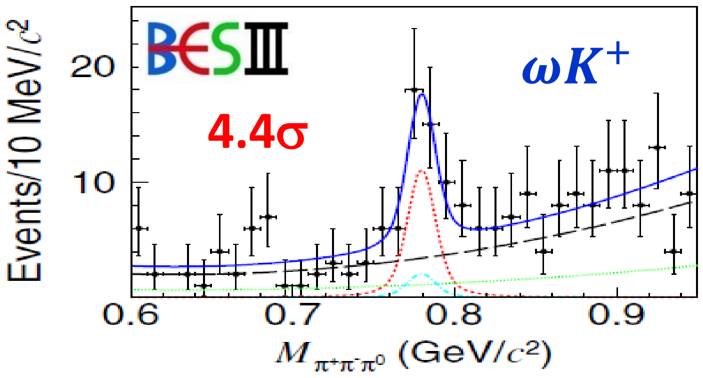
- $D_s^+ \to \omega\pi^+$: pure W-annihilation process, first evidence by CLEO: $(2.1 \pm 0.9 \pm 0.1) \times 10^{-3}$ with 6.0 ± 2.4 events
- Q. Qin et al. [PRD 89, 054006] predicts, with Br($D_s^+ \to \omega\pi^+$) as one input:

$$\mathcal{B}(D_s^+ \to \omega K^+) = 0.6 \times 10^{-3}, A_{CP}(D_s^+ \to \omega K^+) = -0.6 \times 10^{-3}$$ (without $\rho - \omega$ mixing)

$$\mathcal{B}(D_s^+ \to \omega K^+) = 0.07 \times 10^{-3}, A_{CP}(D_s^+ \to \omega K^+) = -2.3 \times 10^{-3}$$ (with $\rho - \omega$ mixing)

- $D_s^+ \to \omega K^+$(SCS): CLEO set UL: $< 2.4 \times 10^{-3}$@90% C.L.





$Br(D_s^+ \to \omega\pi^+) = (1.77 \pm 0.32 \pm 0.13) \times 10^{-3}$

$Br(D_s^+ \to \omega K^+) = (0.87 \pm 0.24 \pm 0.08) \times 10^{-3}$