The Charm

Vishal Bhardwaj, IISER Mohali

19 October-23 October 2024

Belle Analysis Workshop 2024
(BAW 2024) @ IIT Hyderabad

The Charm^{errr}

Vishal Bhardwaj, IISER Mohali

19 October-23 October 2024

Belle Analysis Workshop 2024 (BAW 2024) @ IIT Hyderabad

A series of fortunate events

Strange 1964

CPV in Kaon system
$K_L \to \pi^+\pi^-$, 45 events
23 x 10³ in $K_L \to \pi^+\pi^-\pi^0$

J. Cronin, V. Fitch 1980

Beauty 2001

CPV in Beauty system
Large CPV in B^0 system
$B^0 \to J/\psi K_s$ ~ 700 events

M. Kobayashi, T. Maskawa 2008

Beauty become strange

Charm 2019

CPV in Charm system
$D^0 \to \pi\pi$ ~ 14 x 10⁶ events

Charm is the new strange.

We have saved the worst for the last

Charm is really strange !

As one can see, *CPV in charm requires large data sample* along with good control of systematic uncertainty.

CP violation in the Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5[1-2(\rho+i\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)(1-\lambda^2/2)] & -A\lambda^2 + A\lambda^4[1-2(\rho+i\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

Here $\lambda=\sin(\theta_c)$, and A, ρ, η are all real

This representation is easy for relating CP violation to specific decay rates.

η is the only CPV source in the Standard Model.

Unitarity condition $V^\dagger V=1$ gives six relations between the CKM matrix elements.

$V_{ud}^*V_{us} + V_{cd}^*V_{cs} + V_{td}^*V_{ts}=0$ $V_{ud}^*V_{cd} + V_{us}^*V_{cs} + V_{ub}^*V_{cb}=0$ $[\mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0]$

$V_{us}^*V_{ub} + V_{cs}^*V_{cb} + V_{ts}^*V_{tb}=0$ $V_{cd}^*V_{td} + V_{cs}^*V_{ts} + V_{cb}^*V_{tb}=0$ $[\mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0]$

$V_{td}^*V_{ud} + V_{ts}^*V_{us} + V_{tb}^*V_{ub}=0$ $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td}=0$ $[\mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0]$

Each of these relations can be visualized as triangle in the complex plane.

relating elements which appear in **strange and charmed particles**, are flat (despite having same area), so that one of the angles representing the relative phases of the CKM matrix elements is tiny . *Related to K & D meson* system

One side is still small, angles not that large. Related to physics in B_S system.

All sides almost equal. Angles (relative phases) are large. Related to physics in B_d system.

Why the Charm ?

- SM larger CP violation effects are expected with heavy quarks, in which complex phase of CKM matrix can appear directly rather through virtual transitions.

- D^0dominated by first two quarks families, and therefore large CP-violating effects are not expected.
- Top quark loops which provide largest effects in K and B decays are absent for D.

- Many channels are possible for D mesons, which are not suppressed by small mixing angles.
- Leading to large decay widths making observation of small effects a bit difficult.

- SM actually predicts very small mixing and CP violation.
  - 0.1 % CP violation in decays can be searched in single cabibbo suppressed as SM predicts small asymmetries.

❖ Not only this but one can also improve and test the understanding of the QCD

❖ Decays of charmed mesons are currently the only way to probe flavor violation in the up-quark sector.
  - ➢ Non SM effects might show different patterns for the *u* and *d.*

Where to study charm ?

Clean environment

e^+e^- colliders

CLEO (3.77, 4.17 GeV)
$3.5 \times 10^6\ (D)$, $2.3 \times 10^6 (D^+)$

BESIII (3.77, 4.18-4.23, 4.6-4.7 GeV)
1.0 x 10^7 ($D^{0,+}$), 5x10^6(Ds+),
0.8x10^6(Λ_c^+)

$\varepsilon \sim 10-30\%$

Pure sample with no background.
Quantum Coherence.
No T-dependent analyses.

BaBar 0.5 ab^{-1}
6.5 x 10^8 (D),

Belle (1 ab^{-1}),
1.3 x 10^9 (D),
10^9 (Ds+),
1.5 x 10^8 (Λ_c^+)

Belle II (0.43 ab^{-1} 50ab^{-1}),
~5.5 x 10^8 (D), 10^8 (Ds+)
6.4 x 10^7 (Λ_c^+),
~10^{10} (D), 10^{10} (Ds+), 10^9 (Λ_c^+)

$\varepsilon \sim 1-10\%$

High efficiency detection of neutral.
Time-dependent analysis.
High statistics control sample.
Higher trigger event.

Large production

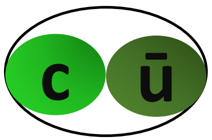
$p\bar{p}$ colliders

Tevatron (1.96 TeV)
1.3 x 10^{11}

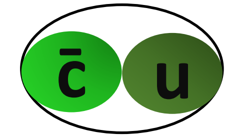
LHCb (7 TeV,8 TeV)
5 x 10^{12}

$\varepsilon < 0.5\%$

Large production cross-section
Large boost
Excellent time resolution.
Dedicated trigger required



$D^0 - \bar{D}^0$ mixing



Mass : (1864.83±0.05) MeV τ_{D0} = (410.1±1.5) x10^{-15} s

Phenomenon of mixing can be described as a decaying two-component quantum state.

Mass eigenstates (D_1, D_2) $\neq$ Flavor eigenstates (D^0, $\bar{D}^0$).

Time evolution : $|D_{1,2}(t)\rangle = e^{-im_{1,2}t}e^{-\frac{\Gamma_{1,2}t}{2}}|D_{1,2}(t=0)\rangle$

$m_1(m_2)$ and Γ_1 (Γ_2) are the mass and decay width of $D_1(D_2)$

Flavor states

$$|D^0(t)\rangle = \frac{1}{2p}[|D_1(t)\rangle + |D_2(t)\rangle] \text{ and } |\bar{D}^0(t)\rangle = \frac{1}{2q}[|D_1(t)\rangle - |D_2(t)\rangle]$$

At t=0, states are produced as pure D^0 or $\bar{D}^0$

$$|D^0(t)\rangle = \left[|D^0\rangle \cosh\left(\frac{ix+y}{2}\bar{\Gamma}t\right) - \frac{q}{p}|\bar{D}^0\rangle \sinh\left(\frac{ix+y}{2}\bar{\Gamma}t\right)\right]e^{-i\bar{m}t-\frac{\bar{\Gamma}}{2}t}$$

$$|\bar{D}^0(t)\rangle = \left[|\bar{D}^0\rangle \cosh\left(\frac{ix+y}{2}\bar{\Gamma}t\right) - \frac{q}{p}|D^0\rangle \sinh\left(\frac{ix+y}{2}\bar{\Gamma}t\right)\right]e^{-i\bar{m}t-\frac{\bar{\Gamma}}{2}t}$$

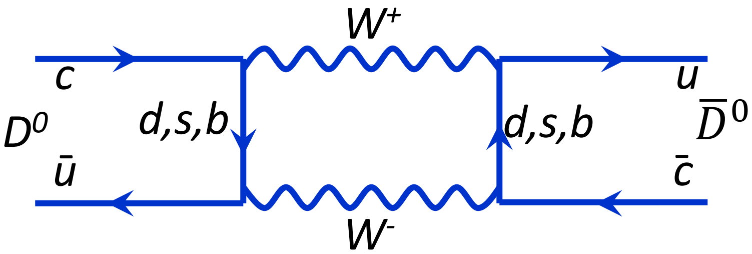
At later time can be D^0 or $\bar{D}^0$, depending on the value of mixing parameter *x, y*:

$$x \equiv \frac{m_1 - m_2}{\bar{\Gamma}};\ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\bar{\Gamma}};\ \bar{\Gamma} \equiv \frac{\Gamma_1 + \Gamma_2}{2};\bar{m} \equiv \frac{m_1 + m_2}{2}$$

* under CPT conservation assumption: $|p|^2+|q|^2 = 1$

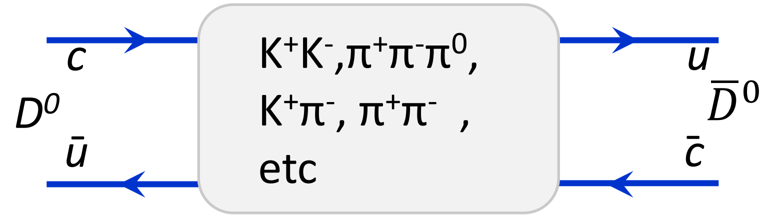
D^0 - $\overline{D}^0$ mixing

In SM, D^0 meson can change to $\overline{D}^0$ via



Doubly Cabibbo Suppression vanishes in exact $SU(3)_{FLAVOR}$

Double weak boson exchange
(Short distance effects)



Difficult to calculate

Intermediate state common to both
(Long distance effects)

SM predictions for x and y suffers from larger uncertainties.
Generally, Mixing in charm system strongly suppressed : $|x|, |y| \sim 1\%$

Sensitive to New Physics effects : $|x| \gg |y|$

Observables at *B* factories :

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|A_f + \frac{q}{p}\frac{ix+y}{2}\overline{A}_f\,\overline{\Gamma}t\right|^2 \qquad \frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|\overline{A}_f + \frac{p}{q}\frac{ix+y}{2}A_f\,\overline{\Gamma}t\right|^2$$

$$A_f = \langle f | D^0 \rangle,\ \overline{A}_f = \langle f | \overline{D}^0 \rangle$$

Decay time distribution of accessible states D^0, $\overline{D}^0$ are sensitive to mixing parameters (x and y), depending on the final state.

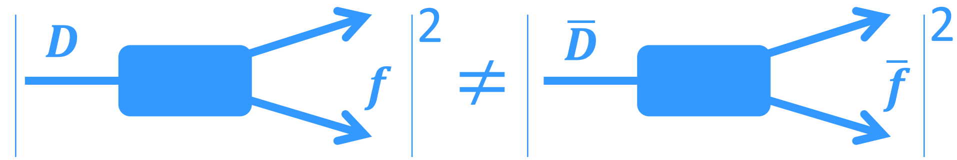
$dN(D^0 \to f)/dt$ is different function of x, y (and q,p) for different A_f, A_f

CP violation in charmed mesons

Direct CPV (neutral and charged, mode dependent)

CP violation in decay appears on the amplitude level. Occurs if two different amplitude contribute to a single decay

$$\left|\frac{A(D \to f)}{A(\overline{D} \to \overline{f})}\right| \neq 1$$



Indirect CPV (neutral, common for all decay modes)

In Mixing :

CP violation in mixing occurs if a particle D^0 can't decay into a final state f̄ buts CP-conjugate $\overline{D}^0$ can. $\boldsymbol{D^0 \longrightarrow \overline{D}^0 \longrightarrow Y^+X^- \nleftarrow D^0}$ $\boldsymbol{\overline{D}^0 \longrightarrow D^0 \longrightarrow Y^-X^+ \nleftarrow \overline{D}^0}$

$$\boldsymbol{r_m = |q/p| \neq 1}$$

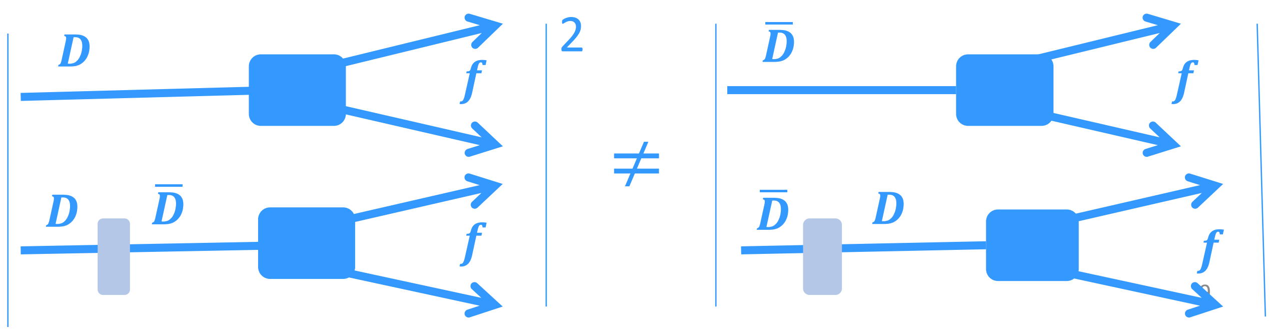
In interference of decays with and without mixing:

If mixing followed by decay and direct decay interfere. Final state must be common to D^0 and $\overline{D}^0$.

Two conditions :

$$\boldsymbol{x = \frac{\Delta M}{\Gamma} \neq 0}$$

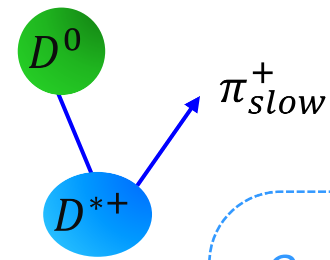
$$\boldsymbol{arg\left(\frac{q\overline{A}_f}{pA_f}\right) \neq 0}$$



How they study the charm

Belle (II), LHCb

$$D^{*+} \rightarrow D^0 \pi^+_{slow}$$



Charged of the slowπ tell the flavor of D

For signal extraction and background reduction

$$\Delta M = M(D^0\pi^+_{slow}) - \mathrm{M}(D^0)$$

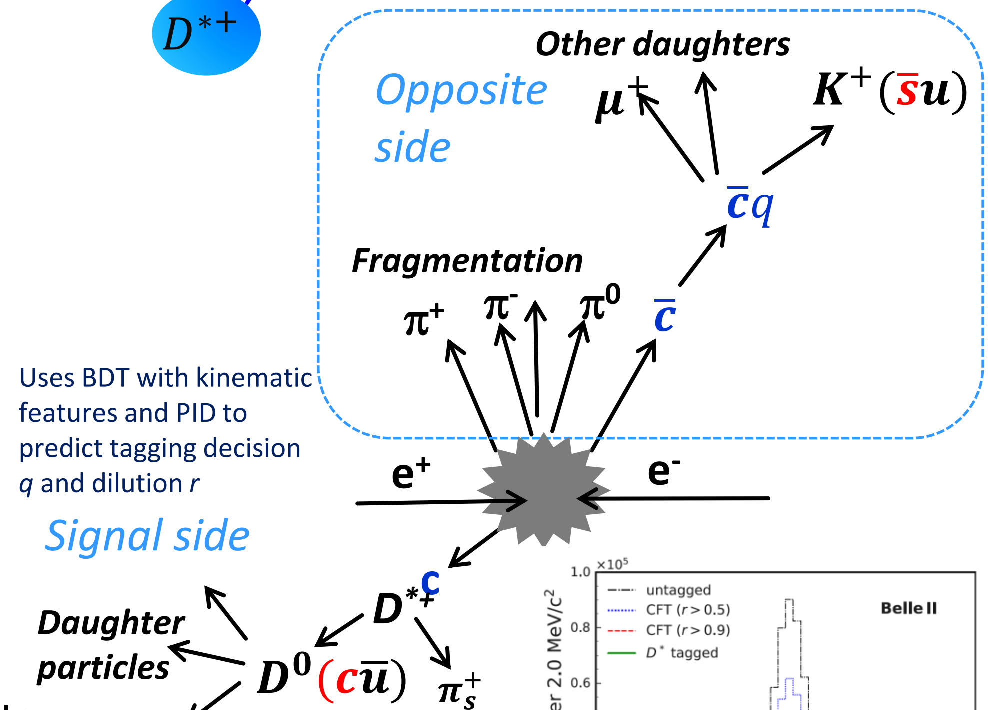
or $q = \Delta M - m(\pi^+_{slow})$

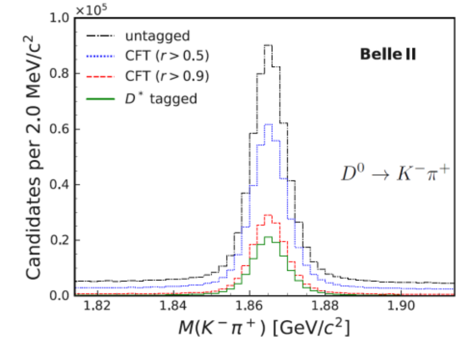
$$\varepsilon(D^*) \sim 80\%, \omega(D^*) \sim 0.2\%$$

Belle II CFT
(Charm Flavor tagging)

$$\varepsilon^{eff}_{tag} \sim 48\%$$

Double the sample size w.r.t. D^{*+} tagged events

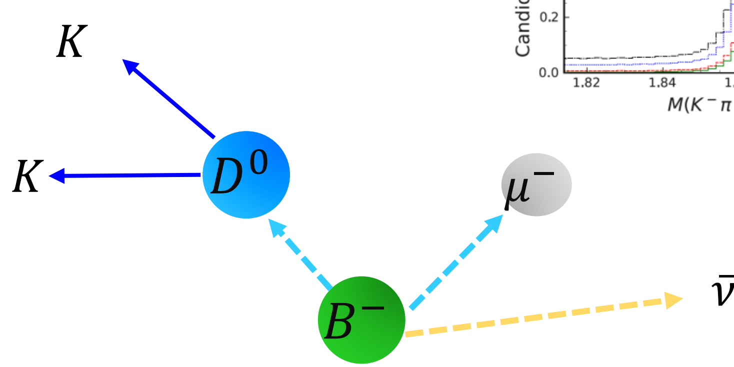




LHCb (Semileptonic B decays)

$$b \rightarrow c\mu^-\bar{\nu}_\mu$$

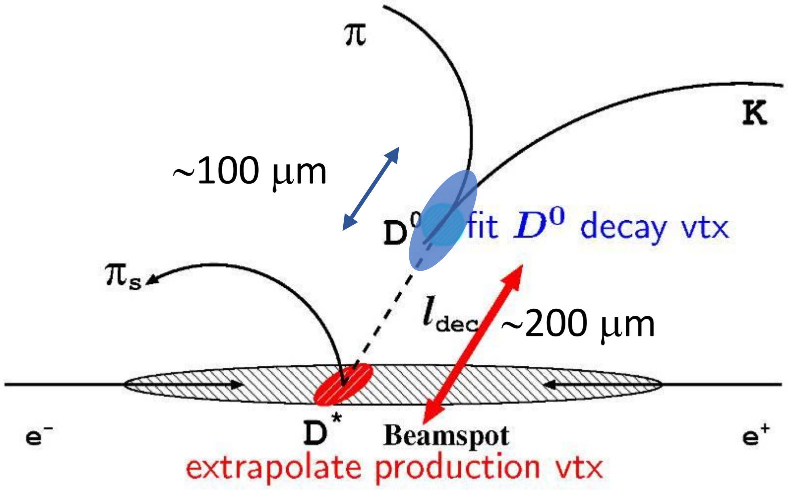
20% of the prompt tagging



ε: *Efficiency* ω: *Mistagging*

Let's start with the (not so) simple and easy measurement :

Lifetime measurement



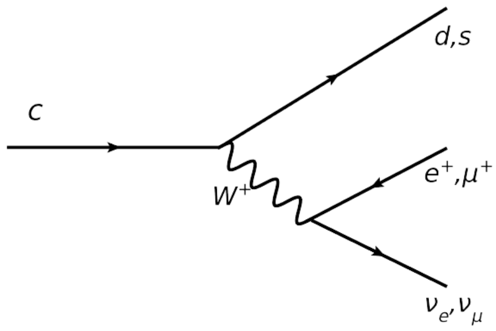
Momentum vector provides flight direction and helps determination of the decay distance

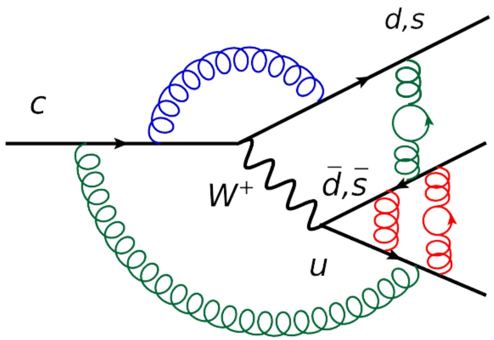
$$t = \frac{l_{dec}}{c\beta\gamma} \qquad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

σ_t calculated from vtx error matrices

for charm hadrons, ℓ is between 100 and 500 μm

A charm quark can decay weakly into a strange- or a down-quark and a W^+ -boson, which then further decays either into leptons (semi-leptonic decay) or into quarks (non-leptonic decay).





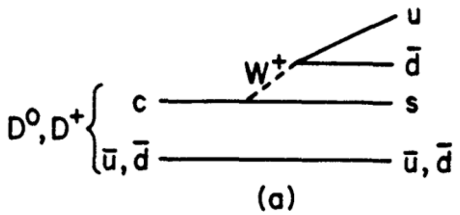
- Predictions of the lifetimes of free quarks have a huge parametric dependence on the definition of the quark mass.
- Also, in the charmed mesons a very sizeable contribution comes from non-spectator effects

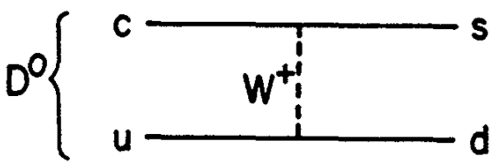
❖ Precise lifetime measurements provide excellent tests of strong-interaction theory e.g. HQE.

Comparing lifetime calculations with measurements tests/improves our understanding of QCD

D^+/D^0 lifetime

- Relatively long lifetime of the D^+ meson, 2.5 times that of D^0, implies there is reduction in hadronic partial widths.
- This reduction is attributed to destructive interference between spectator amplitude and colour suppressed amplitude.

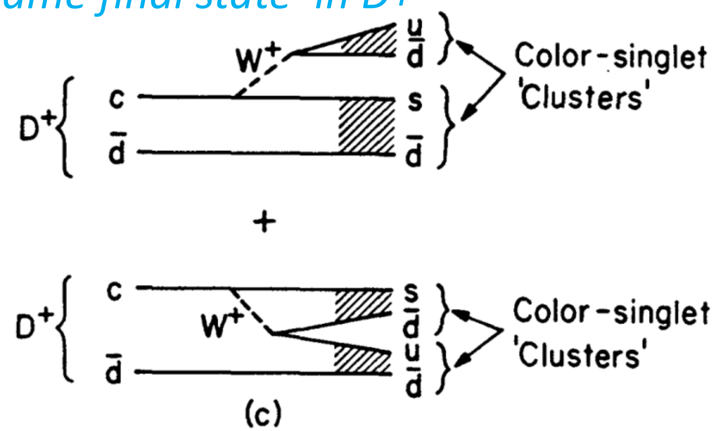




(b) *W*-exchange for *D⁰*

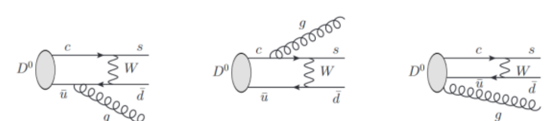
J. Hauser, Ph.D. Thesis Caltech

Possible interference between spectator diagram leading to the same final state in D+



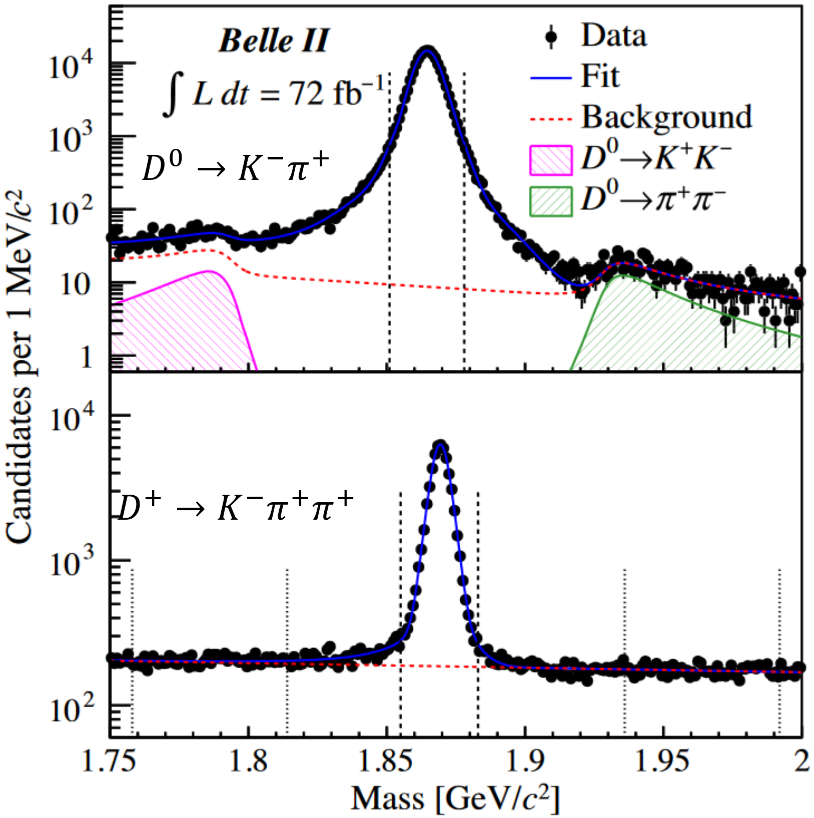
- Hadron lifetimes are difficult to calculate theoretically, as they depend on nonperturbative effects arising from QCD.
- Lifetime calculations are performed using phenomenological methods such as the heavy quark expansion .
- Comparing calculated values with measured values improves our understanding of QCD, which leads to improved QCD calculations of other quantities such as hadron masses, structure functions

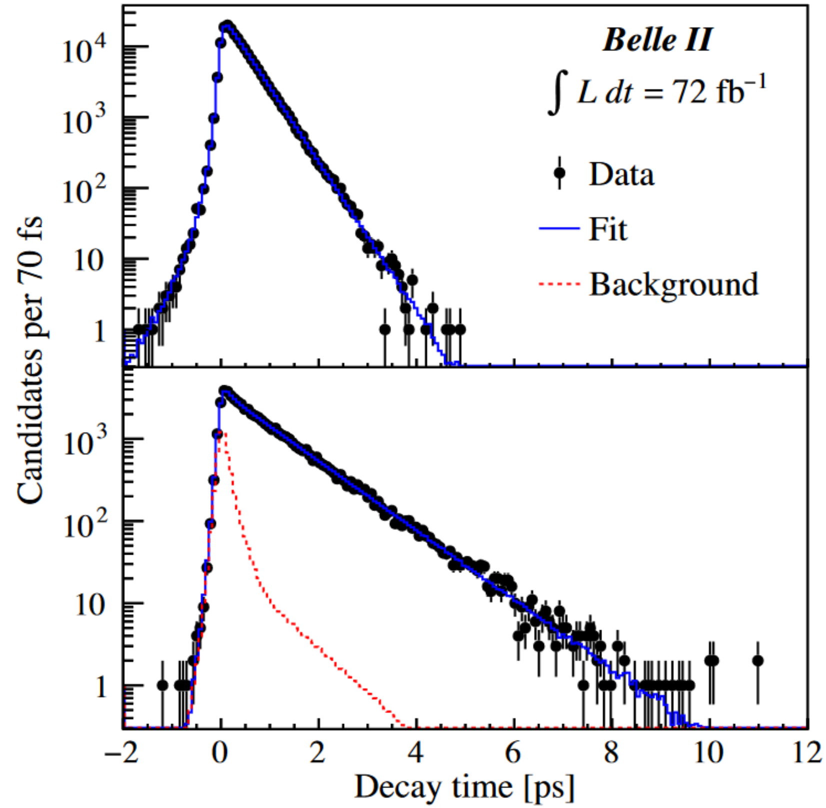
Bander, Silverman, Soni, PRL 44,7 (1979)



Belle II has better (x2) time resolution than Belle/BaBar.

PRL 127, 211801 (2021)





Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

$$\tau(D^0) = 410.5 \pm 1.1\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst})\ \mathrm{fs} \quad \text{and}$$

$$\tau(D^+) = 1030.4 \pm 4.7\ (\mathrm{stat}) \pm 3.1\ (\mathrm{syst})\ \mathrm{fs},$$

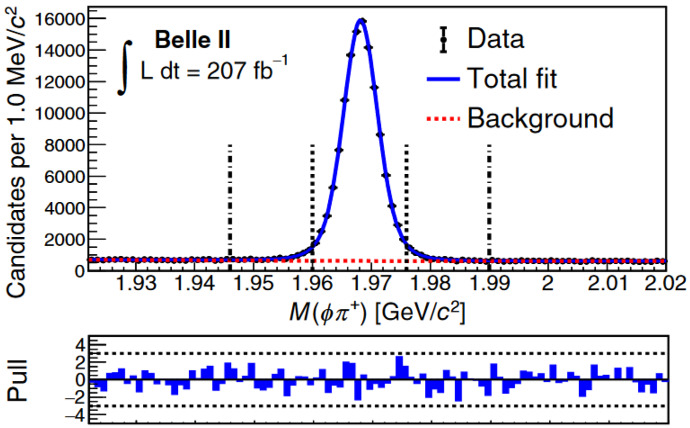
$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.013(\mathrm{stat}) \pm 0.007(\mathrm{syst})$$

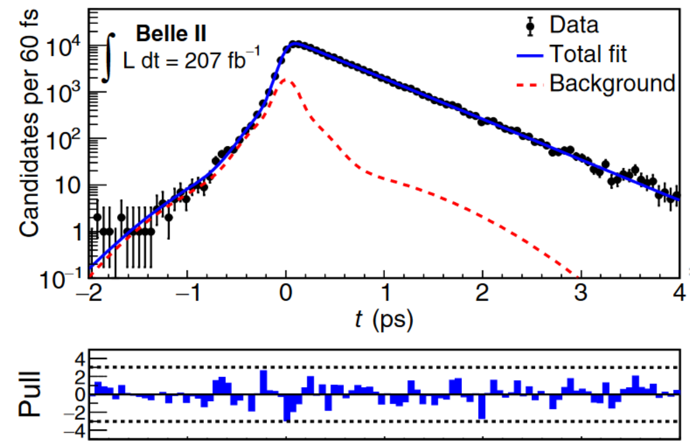
D_s^+ lifetime

PRL 131, 171803 (2023)

The difference between D^0 and D_s^+ is attributed to :

- *dominance of the spectator amplitude for hadronic decays*
- *different color factors enter subdominant "exchange" D^0 and "annihilation" D_s^+ amplitude*





Source	Uncertainty (fs)
Resolution function	± 0.43
Background (t, σ_t) distribution	± 0.40
Binning of σ_t histogram PDF	± 0.10
Imperfect detector alignment	± 0.56
Sample purity	± 0.09
Momentum scale factor	± 0.28
D_s^+ mass	± 0.02
Total	± 0.87

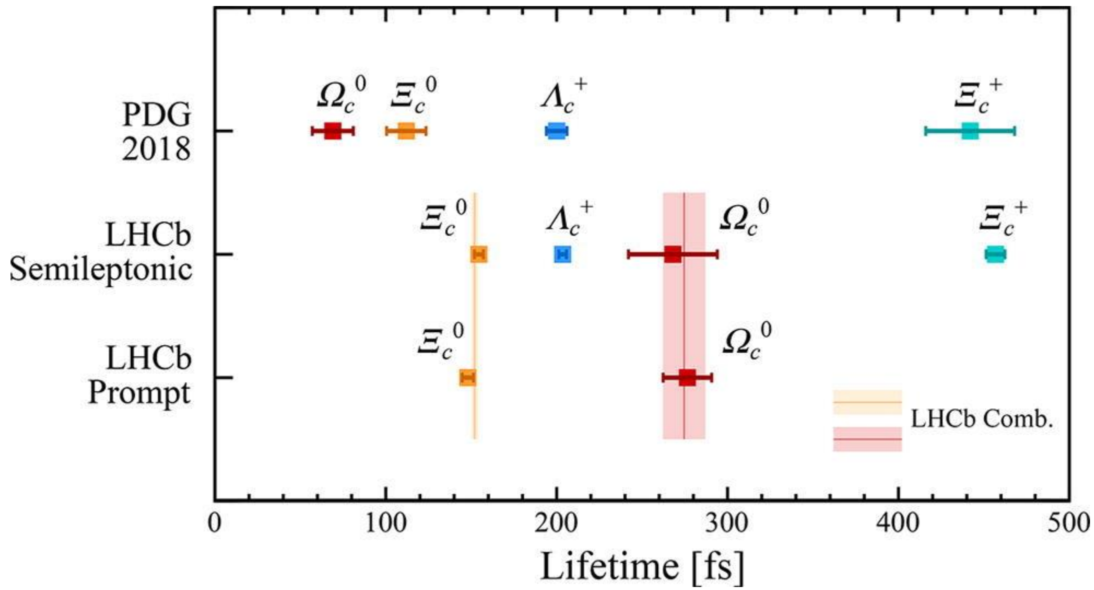
$$\tau_{D_s^+} = (499.5 \pm 1.7 \pm 0.9)\ \text{fs},$$

$$\tau(D^0) = 410.5 \pm 1.1\ (\text{stat}) \pm 0.8\ (\text{syst})\ \text{fs} \quad \text{and}$$

Charmed Baryon lifetime

Theory expectation: $\tau(\Omega_c) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$

LHCb 2018, 2022 : $\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c) < \tau(\Xi_c^+)$



Recently Belle II confirmed the result of the Ω_c of LHCb and also precisely measured the Λ_c^+

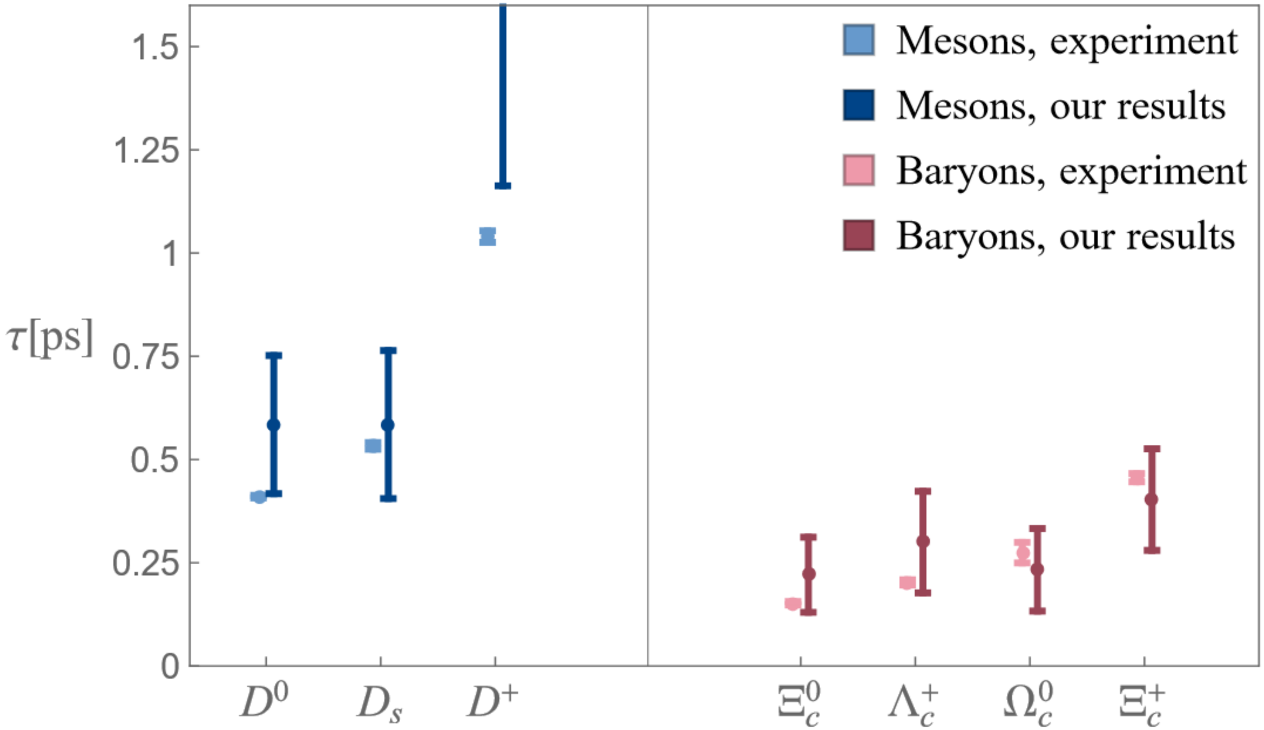
$$\tau(\Omega_c^0) = 243 \pm 48(\text{stat}) \pm 11(\text{syst})\ \text{fs},$$ PRD 107, L031103 (2023)

$$\boldsymbol{\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77\ \text{fs}}$$ PRL 130, 071802 (2023)

Heavy quark expansion fails to predict the newly observed hierarchy.

Recent calculation by Gratrex, Melic, Nišandžić, JHEP 07(2022) 058 shows agreement in baryon sector

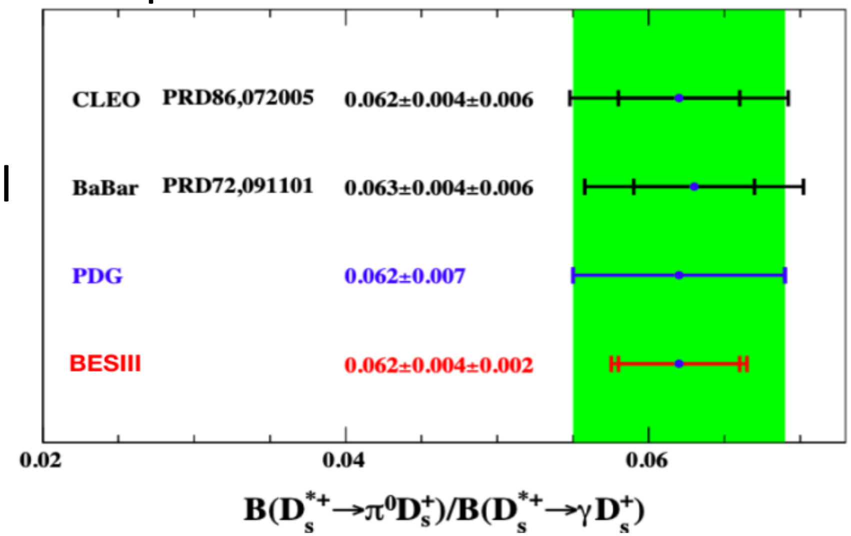
- Include the Darwin Contributions and dimension-seven four-quark operator contributions.
- In addition, they also include existing next-to-leading order (NLO) contributions to the Wilson coefficients of two-quark operators at dimension-three and four-quark operators at dimension-six.



$D_s^* \to D_s\pi^0$ / $D_s^* \to D_s\gamma$

- Mass difference between D_s^* and D_s is slightly larger than the neutral pion mass by about 2 MeV.
- This makes $D_s^* \to D_s\pi^0$ and $D_s^* \to D_s\gamma$ the dominant decay modes of the D_s^*
- Strong decay $D_s^* \to D_s\pi^0$ violated the isospin symmetry.
- The isospin violating effect is attributed to the $\pi^0 - \eta$ mixing effect, which is driven by the mass difference of the up and down quarks.

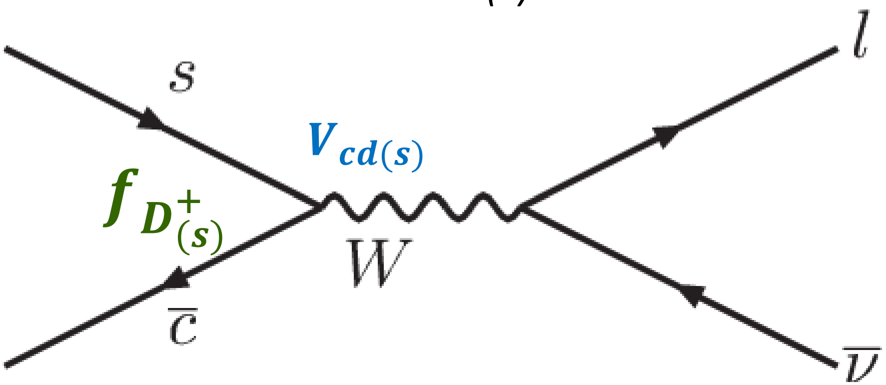
Decay widths of D_s^* have been theoretically predicted based on effective phenomenological models : chiral perturbation theory, light-front quark model, QCD sum rules , LQCD, NRQM, ..



- ❖ Precision measurements of these BFs help to constrain the parameters of the low-energy effective models.
- ❖ In addition, the BFs are important inputs in the precise determination of the Ds decay constant $f_{D_s^+}$ and |Vcs|

Belle II can reduce statistical uncertainty by 70% and also improve systematics

Pure leptonic $D_{(S)}$ decay



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

One can extract CKM matrix element $\left|V_{cd(s)}\right|$:

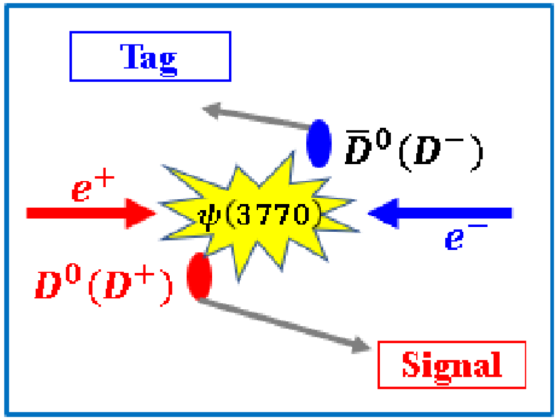
Extract $|V_{cd}|$ in D+

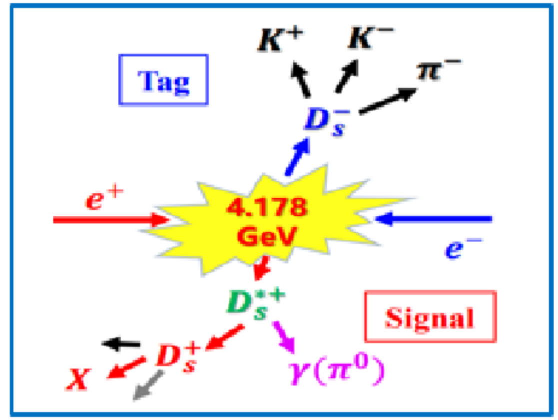
$|V_{cs}|$ in Ds+

Decay constant $f_{D^+_{(s)}}$ calibrate Lattice QCD

Test Lepton flavor universality

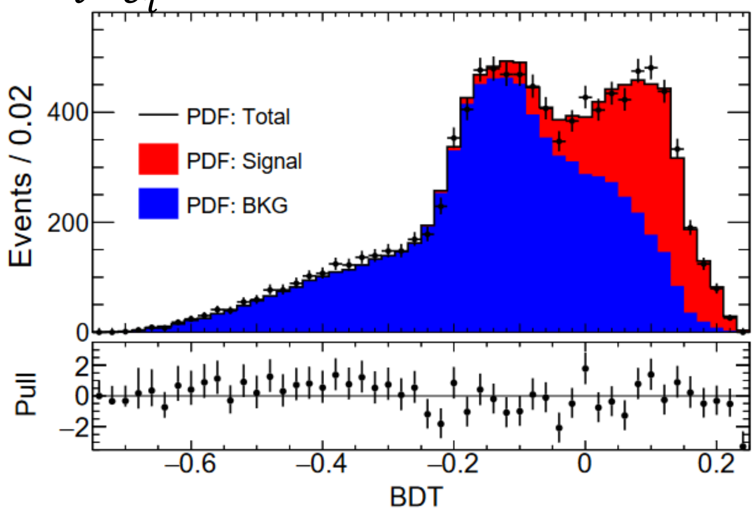
BESIII unique opportunity to study $e^+e^- \to D_s^{*\pm}D_s^{\mp}$





T. Wang CKM 2023

$D_s^+ \to \tau^+ \upsilon_\tau$ *BESIII, PRD 108, 112001 (2023)*

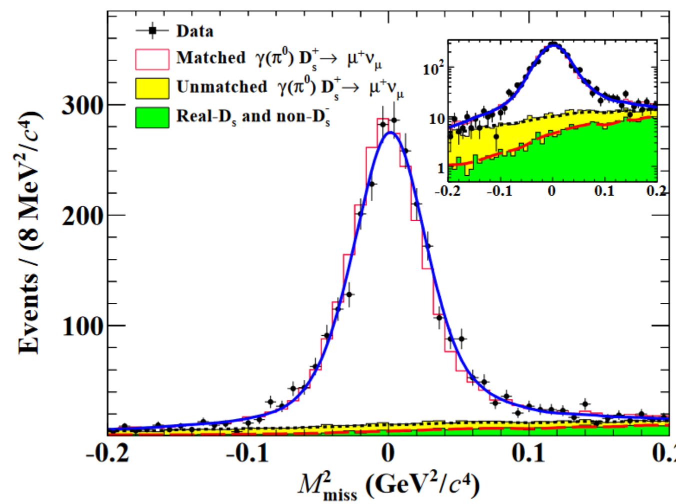


$$\mathcal{B} = (5.41 \pm 0.17 \pm 0.13)\%$$

$$f_{D_s^+}|V_{cs}| = (247.6 \pm 3.9 \pm 3.2) \text{ MeV}$$

Statistical precision improved by factor of 1.5

BESIII, PRD 108, 092014 (2023) $D_s^+ \to \mu^+ \upsilon_\mu$



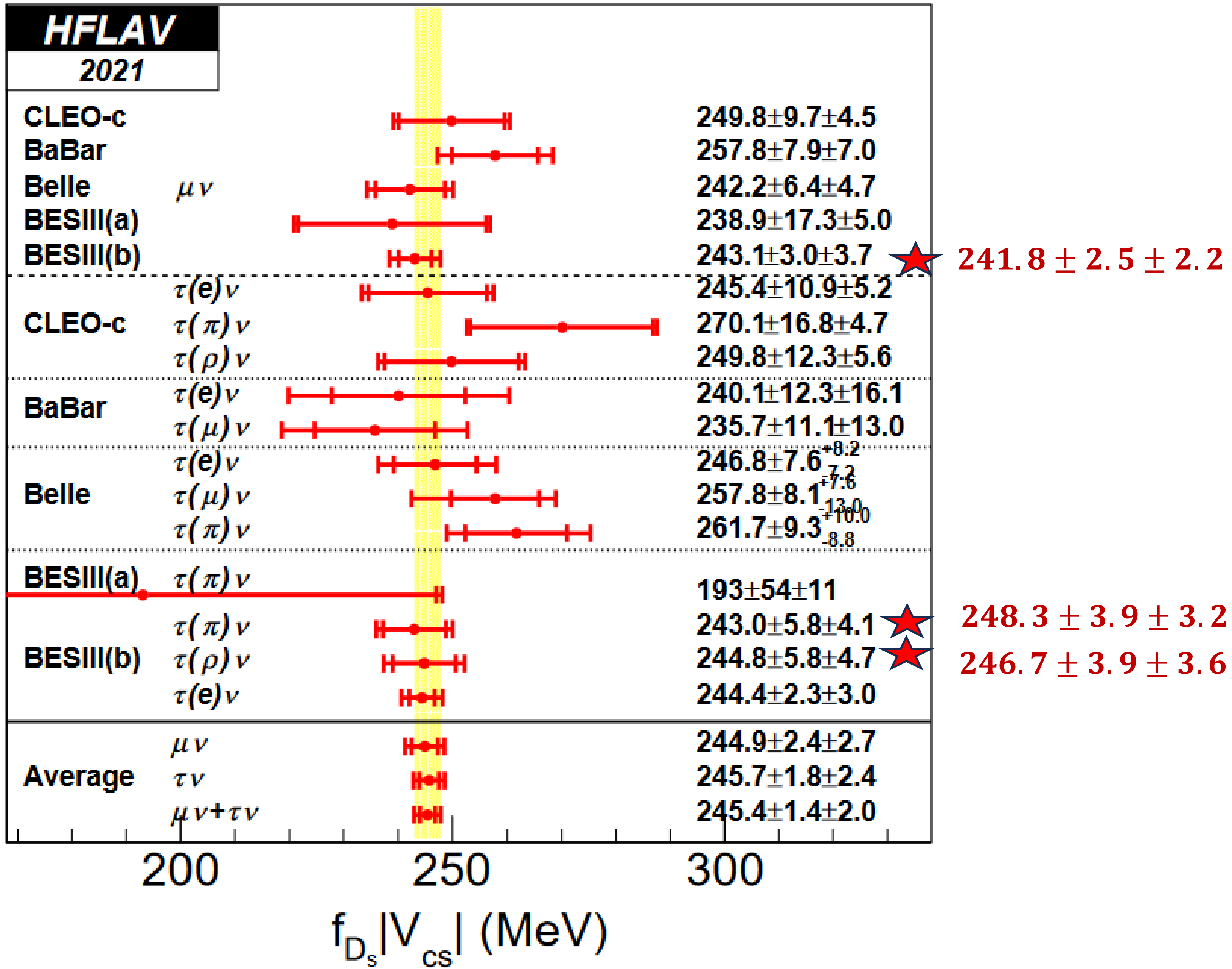
$$\mathcal{B} = (5.294 \pm 0.108 \pm 0.085) \times 10^{-3}$$

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

Most precise single measurement

Test on Lepton flavor universality

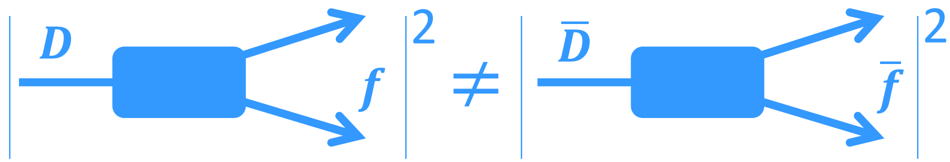
$R_{D_s^+} = 10.05 \pm 0.35$ consistent with the SM value of 9.75 ± 0.01


HFLAV
2021
CLEO-c 249.8±9.7±4.5
BaBar 257.8±7.9±7.0
Belle μν 242.2±6.4±4.7
BESIII(a) 238.9±17.3±5.0
BESIII(b) 243.1±3.0±3.7
241.8 ± 2.5 ± 2.2
CLEO-c τ(e)ν 245.4±10.9±5.2
τ(π)ν 270.1±16.8±4.7
τ(ρ)ν 249.8±12.3±5.6
BaBar τ(e)ν 240.1±12.3±16.1
τ(μ)ν 235.7±11.1±13.0
Belle τ(e)ν 246.8±7.6 +8.2 -7.2
τ(μ)ν 257.8±8.1 +7.6 -13.0
τ(π)ν 261.7±9.3 +10.0 -8.8
BESIII(a) τ(π)ν 193±54±11
BESIII(b) τ(π)ν 243.0±5.8±4.1
248.3 ± 3.9 ± 3.2
τ(ρ)ν 244.8±5.8±4.7
246.7 ± 3.9 ± 3.6
τ(e)ν 244.4±2.3±3.0
Average μν 244.9±2.4±2.7
τν 245.7±1.8±2.4
μν+τν 245.4±1.4±2.0
200
250
300
f_{D_s}|V_cs| (MeV)

Direct CP violation in charmed mesons

Direct CPV (neutral and charged, mode dependent)

CP violation in decay appears on the amplitude level. Occurs if two different amplitude contribute to a single decay

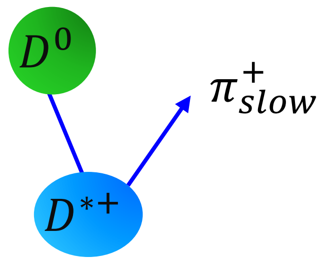


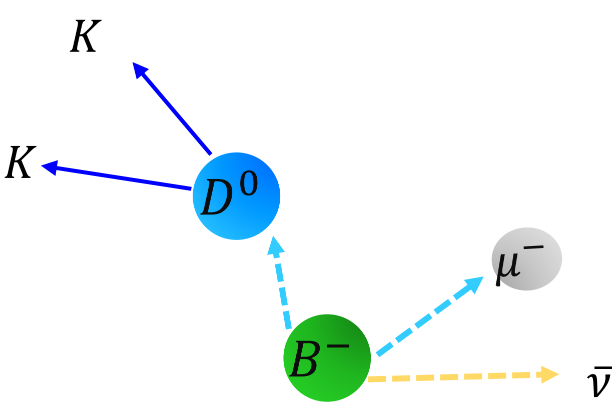
$$a_f^d = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \neq 0$$

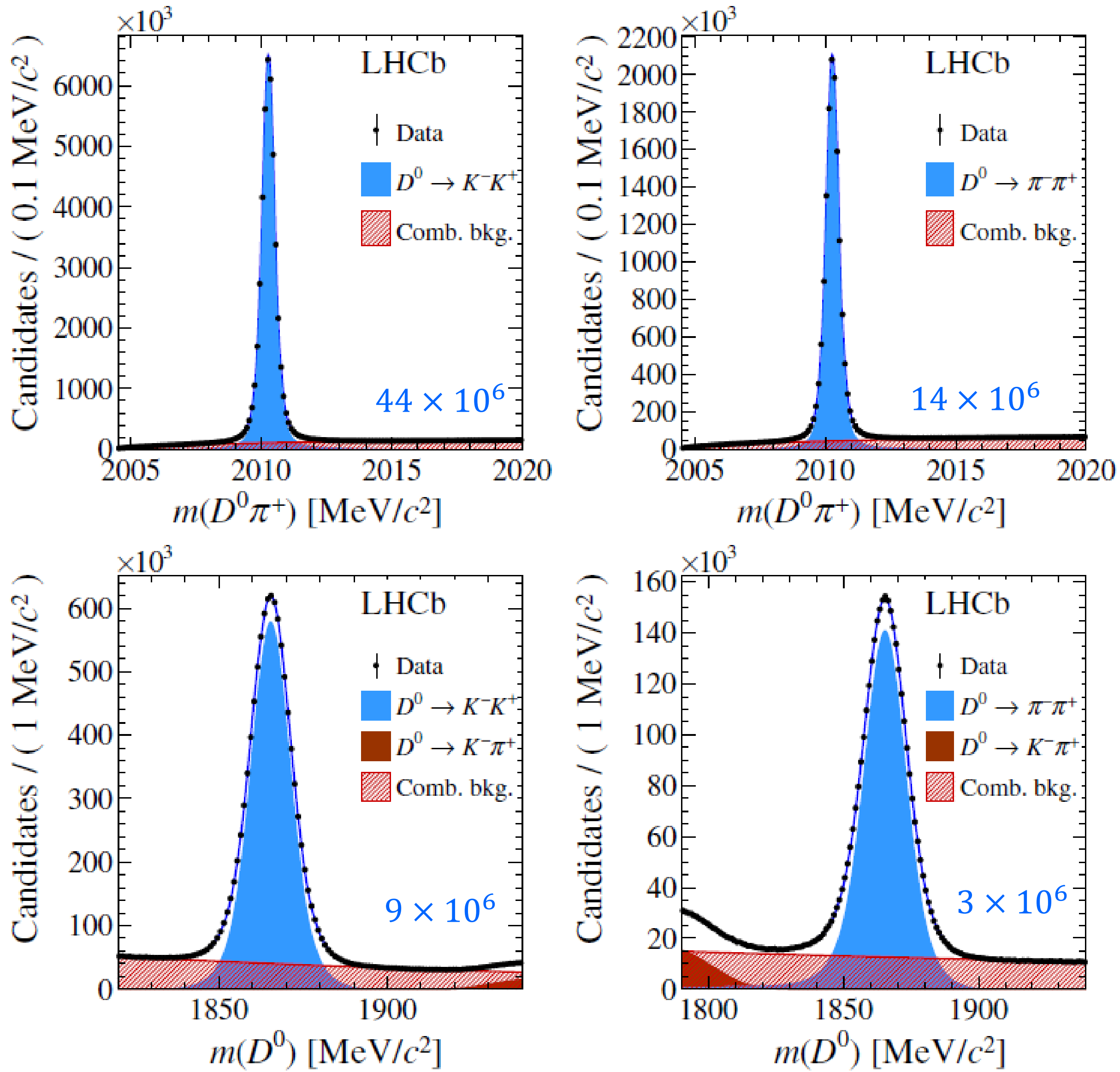
Most promising channels are Cabibbo-suppressed decays because CPV may arise from the interference between the tree and the penguin amplitude

First observation of CP violation in charm

Measurement of time-integrated CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays







$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

$$A_{raw} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

SM estimate

$\Delta A_{CP}^{SM} \sim \frac{\alpha_s}{\pi} \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} \sim 10^{-4}$

But can also be as large as

$\Delta A_{CP}^{SM} \sim \text{few} - \text{several} \times 10^{-3}$

If the kinematics are similar then one can expect same to cancel.

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

Not simple, one need to perform reweighting procedure to match kinematics of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

Run2 result:

$\Delta A_{CP} = \left(-18.2 \pm 3.2(\text{stat.}) \pm 0.9(\text{syst.})\right) \times 10^{-4}$

$\Delta A_{CP} = \left(-9.0 \pm 8.0(\text{stat.}) \pm 5.0(\text{syst.})\right) \times 10^{-4}$ PRL 122, 211803 (2019)

Run1 result:

$\Delta A_{CP} = \left(-10 \pm 8(\text{stat.}) \pm 3(\text{syst.})\right) \times 10^{-4}$ JHEP 07,041 (2014)

$\Delta A_{CP} = \left(-14 \pm 16(\text{stat.}) \pm 8(\text{syst.})\right) \times 10^{-4}$ PRL 116, 191601 (2016)

Combining the two modes + Run1 measurement:

$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

First observation of charm CPV at 5.3σ

Time-integrated CP asymmetry between decay rates doesn't only correspond to a_f^d but is affected by $D^0 - \overline{D^0}$ mixing

$$A_{CP}(f) = \frac{\int \varepsilon(t)\left[\Gamma(D^0 \to f)(t) - \Gamma\left(\overline{D^0} \to \bar{f}\right)(t)\right]dt}{\int \varepsilon(t)\left[\Gamma(D^0 \to f)(t) + \Gamma\left(\overline{D^0} \to \bar{f}\right)(t)\right]dt} = a_f^d + \frac{< t >_f}{\tau_{D^0}} \Delta Y_f$$

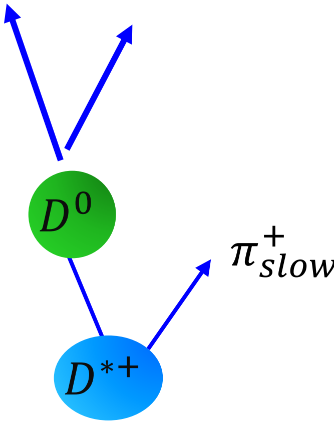
$\varepsilon(t)$ is the time-dependent reconstruction efficiency

ΔY_f is related to parameters describing mixing and interference between mixing and decay

$< t >_f$ is the average acceptance-dependent decay time of D^0 mesons in the experimental sample

Raw asymmetry (A) in $D^0 \to K^- K^+$ decays

Prompt D^0



$$A_{raw} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

Nuisance asymmetry

Production asymmetry of D^{*+}

$$A_{prod} = \frac{\sigma(D) - \sigma(\bar{D})}{\sigma(D) + \sigma(\bar{D})}$$

Detection asymmetry of π^+_{soft}

$$A_{det} = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})}$$

Correct raw asymmetry *A* using samples of Cabibbo-favored D^0/D_s decays (where CPV can be neglected)

$$A_{raw} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

Two methods to cancel Nuisance asymmetries:

D^+ decays, as used in Run-1 analysis (C_{D^+})

D_s^+ decays, $C_{D_s^+}$

$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

PRL 131, 091802 (2023)

C_{D^+}

$$A_{CP}(D^0 \to K^+K^-) = A(D^{*+} \to [D^0 \to K^+K^-]\pi^+_{soft}) - A(D^{*+} \to [D^0 \to \pi^+K^-]\pi^+_{soft})$$
$$+A(D^+ \to K^-\pi^+\pi^+) - [A(D^+ \to \bar{K}^0\pi^+) - A(\bar{K}^0)]$$

$C_{D_s^+}$

$$A_{CP}(D^0 \to K^+K^-) = A(D^{*+} \to [D^0 \to K^+K^-]\pi^+_{soft}) - A(D^{*+} \to [D^0 \to \pi^+K^-]\pi^+_{soft})$$
$$+A(D_s^+ \to \phi\pi^+) - [A(D_s^+ \to \bar{K}^0K^-) - A(\bar{K}^0)]$$

Where $A(\bar{K}^0)$ involves detection asymmetry of neutral kaons, mixing and CP-violating effects.

For each kinematically weighted sample, raw asymmetry *A* is determined with simultaneous fit to positive and negative final state invariant-mass distributions.

One has to be careful in re-weighting and is done based on the particle p_T, η, ϕ and same cuts are used.

To avoid statistical overlap, sample of $D^0 \to \pi^+K^-$ is randomly split into two

$A_{CP}(K^+K^-)$

$\boldsymbol{C_{D^+}}$ $A_{CP}(K^+K^-) = [13.6 \pm 8.8(stat) \pm 1.6\ \ (syst)] \times 10^{-4}$

$\boldsymbol{C_{D_s^+}}$ $A_{CP}(K^+K^-) = [2.8 \pm 6.7(stat) \pm 2.0\ \ (syst)] \times 10^{-4}$

With an overall correlation coefficient 0.06 and are found to be compatible within 1 standard deviation

$$A_{CP}(K^+K^-) = [6.8 \pm 5.4(stat) \pm 1.6\ (syst)] \times 10^{-4}$$

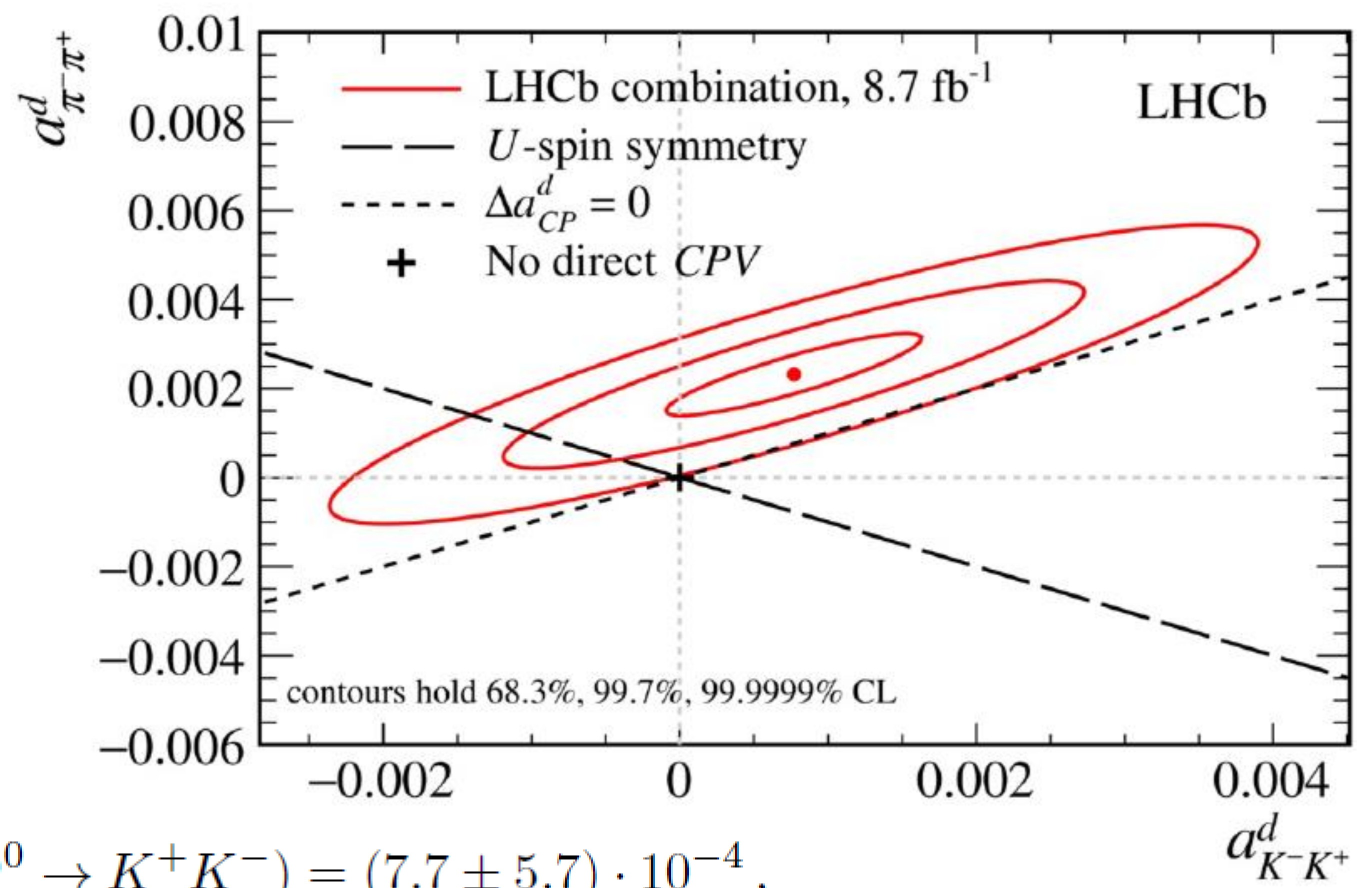
Direct CP violation parameters a_{KK}^d and $a_{\pi\pi}^d$ are calculated from combination of $A_{CP}(KK)$ and ΔA_{CP}

$$A_{CP}(f) = \frac{\int \varepsilon(t)\left[\Gamma(D^0 \to f)(t) - \Gamma\left(\overline{D^0} \to \bar{f}\right)(t)\right]dt}{\int \varepsilon(t)\left[\Gamma(D^0 \to f)(t) + \Gamma\left(\overline{D^0} \to \bar{f}\right)(t)\right]dt} = a_f^d + \frac{< t >_f}{\tau_{D^0}}\Delta Y_f$$

$$A_{CP}(K^+K^-) = a_{KK}^d + \frac{< t >_{KK}}{\tau_{D^0}}\Delta Y_f$$

$$\Delta A_{CP} = a_{KK}^d - a_{\pi\pi}^d + \frac{< t >_{KK} - < t >_{\pi\pi}}{\tau_{D^0}}\Delta Y_f$$

One can then fit and try to get global χ^2 , taking correlations



$$a_{CP}^{dir}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4} \,,$$

$$a_{CP}^{dir}(D^0 \to \pi^+\pi^-) = (23.2 \pm 6.1) \cdot 10^{-4}$$

First evidence of direct CPV in $D \to \pi\pi$ at level of 3.8σ

$$\Sigma a_{CP}^{dir} \equiv a_{CP}^{dir}(D^0 \to K^+K^-) + a_{CP}^{dir}(D^0 \to \pi^+\pi^-) \overset{U\text{-spin limit}}{=} 0$$

U-spin breaking $a_{KK}^{dir} + a_{\pi\pi}^{dir} \neq 0$ at the level of2.7σ

U-spin is approximate but the result implies large *U-spin* breaking, which exceed SM expectation of ~30% by almost a factor six, at 2.0σ **S. Schacht JHEP03 (2023) 205**

Might be sign of new physics : additional scalar particle or a flavorful *Z'*

My naïve understanding?

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

$$a_{\rm CP}^{\rm dir}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4}\,,$$
$$a_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-) = (23.2 \pm 6.1) \cdot 10^{-4}$$

U-spin breaking $a_{KK}^{dir} + a_{\pi\pi}^{dir} \neq 0$ at the level of 2.7σ

Difficult to estimate in SM.

Physics beyond SM seems a tempting approach

It is crucial to measure all CP asymmetries of singly-Cabibbo suppressed charm decays in order to test different theoretical scenarios

But there are other ways, one can enhance in SM
Possible enhancement if rescattering through scalar resonance close to D^0 mass, might enhance CP asymmetry in the SM

S. Schacht , A. Soni, PLB 825, 136855 (2022)

I. Bediaga, T. Frederico, P.C. Magalhaes PRL 131, 051802 (2023)

Enhancement is a consequence of $\pi^+\pi^-$ and K^+K^- coupling via the FSI, whose strong phase contribute to both amplitudes with opposite sign, due to CPT invariance. If $a_{CP}^{dir}(KK)$ is confirmed by more precision to be positive, this may be disfavoured.

QCD dynamics enhancing *P* and *PA* ?

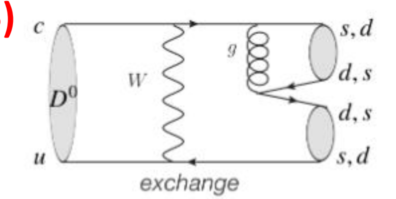
In order to pin-point the reason for this, one need to measure precise CP asymmetries in other charm decays.

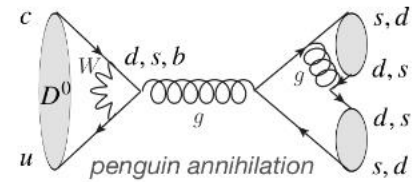
$|a_{CP}^{\rm dir}(D^0 \to \bar{K}^{*0}K_S)| \leq 0.003,\ \ |a_{CP}^{\rm dir}(D^0 \to K_SK_S)| \leq 1.1\%$ @95% C.L.

QCD dynamics enhancing P and PA by factor of 7 can't enhance $|A_{CP}^{dir}(D^0 \to K_sK_s)|$ or $|A_{CP}^{dir}(D^0 \to \bar{K}^{*0}K_s)|$ by same factor of 7.

Search for CP violation in $D^0 \to K_S K_S$

- SM limit 1 % for direct CPV in $D^0 \to K_S^0 K_S^0$ **PRD92,054036 (2015)**
- SCS decays (such as $D^0 \to K_S^0 K_S^0$) are special interest: possible interference with NP amplitude could lead to larger nonzero CPV.





- CP asymmetry in this decay is sensitive to a different mix of amplitudes compared to $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
- Provides independent information which can help to learn about CPV mechanism in charm

PRL119,171801(2017)

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.17)\% \quad \text{Belle}$$

$$A_{CP}(D^0 \to K_s K_s) = A_{raw}(D^0 \to K_S K_S) - A_{raw}(D^0 \to K_s \pi^0) + A_{CP}(D^0 \to K_S \pi^0) + A_{K^0/\bar{K}^0}$$

Ko *et al* PRD 84, 111501 (2011)

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\% \quad \text{LHCb}$$

$$A_{CP}(D^0 \to K_s K_s) = A_{raw}(D^0 \to K_S K_S) - A_{raw}(D^0 \to K^- K^+) + A_{CP}(D^0 \to K^- K^+)$$

Recent measurement : $(-1.4 \pm 1.3 \pm 0.1)\%$ (Belle + Belle II) K. Lalwani PPC2024

$$A_{CP}(D^0 \to K^+K^-) = A_{CP}^{dir}(D^0 \to K^+K^-) + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$$

direct CP Asymmetry
Phys. Rev. Lett. 131 (2023) 091802

asymmetry from CP violation in mixing and in the interference between mixing and decay
Phys. Rev. D104 (2021) 072010

In Belle II, we expect to reach sensitivity of ± 0.23 % with 50 ab^{-1}.

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

Some other measurements from *D*

LHCb JHEP 06 (2021) 019

SCS	$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%,$	
DCS	$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%,$	
SCS	$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%,$	
DCS	$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%,$	
SCS	$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%,$	$(6.4 \pm 4.4 \pm 1.1)\%$
CF	$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%,$	$(0.2 \pm 0.3 \pm 0.3)\%$
SCS	$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%,$	$(2.1 \pm 2.1 \pm 0.4)\%$

Belle, PRD 103, 112005 (2021)

A_{CP} sensitivity

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

Belle II compliment LHCb in neutrals

Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_S^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K_S^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_S^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K_S^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K_S^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

$0.005 \pm 0.042 \pm 0.029$

$-0.009 \pm 0.065 \pm 0.048$

$0.13 \pm 0.19 \pm 0.05$

LHCb, PRL 122,191803 (2019).

A tale of two asymmetries

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

- Obtain asymmetry from difference in partial widths.
- What we measured is A_{raw} which include other nuisance parameters also.
- Need control mode to correct or cancel the nuisance parameter

$$A_{CP} \propto \sin\phi \sin\delta$$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \bar{A}_T = \frac{\Gamma(-\overline{C_T} > 0) - \Gamma(-\overline{C_T} < 0)}{\Gamma(-\overline{C_T} > 0) + \Gamma(-\overline{C_T} < 0)}$$

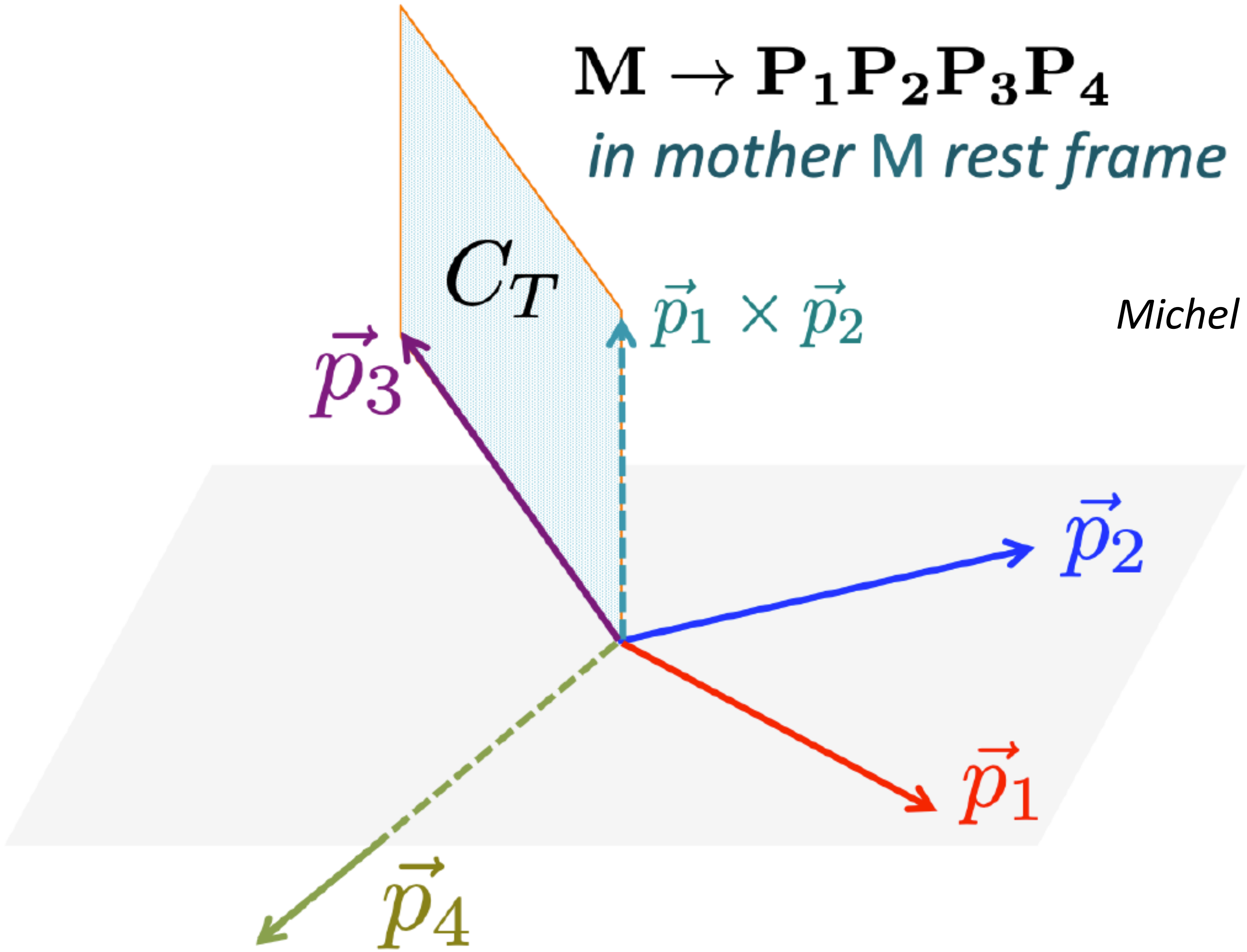
- Measure asymmetry in triple products
- $C_T = \overrightarrow{v_1} \cdot (\overrightarrow{v_2} \times \overrightarrow{v_3})$
- $A_T \neq 0$ can also arise from final-state interaction. Strong phases can produce nonzero value even if the weak phases are zero, that is *CP* and *T* violation are not necessarily present.
- Strictly speaking, the asymmetry is not in fact a *T*-violating effect.
- One can isolate T-violating signal with a_{CP}^{T-odd}

$$a_{CP}^{T-odd} = \frac{1}{2}(A_T - \bar{A}_T)$$

- a_{CP}^{T-odd} doesn't include any other nuisance parameter

$$A_T \propto \sin\phi \cos\delta$$

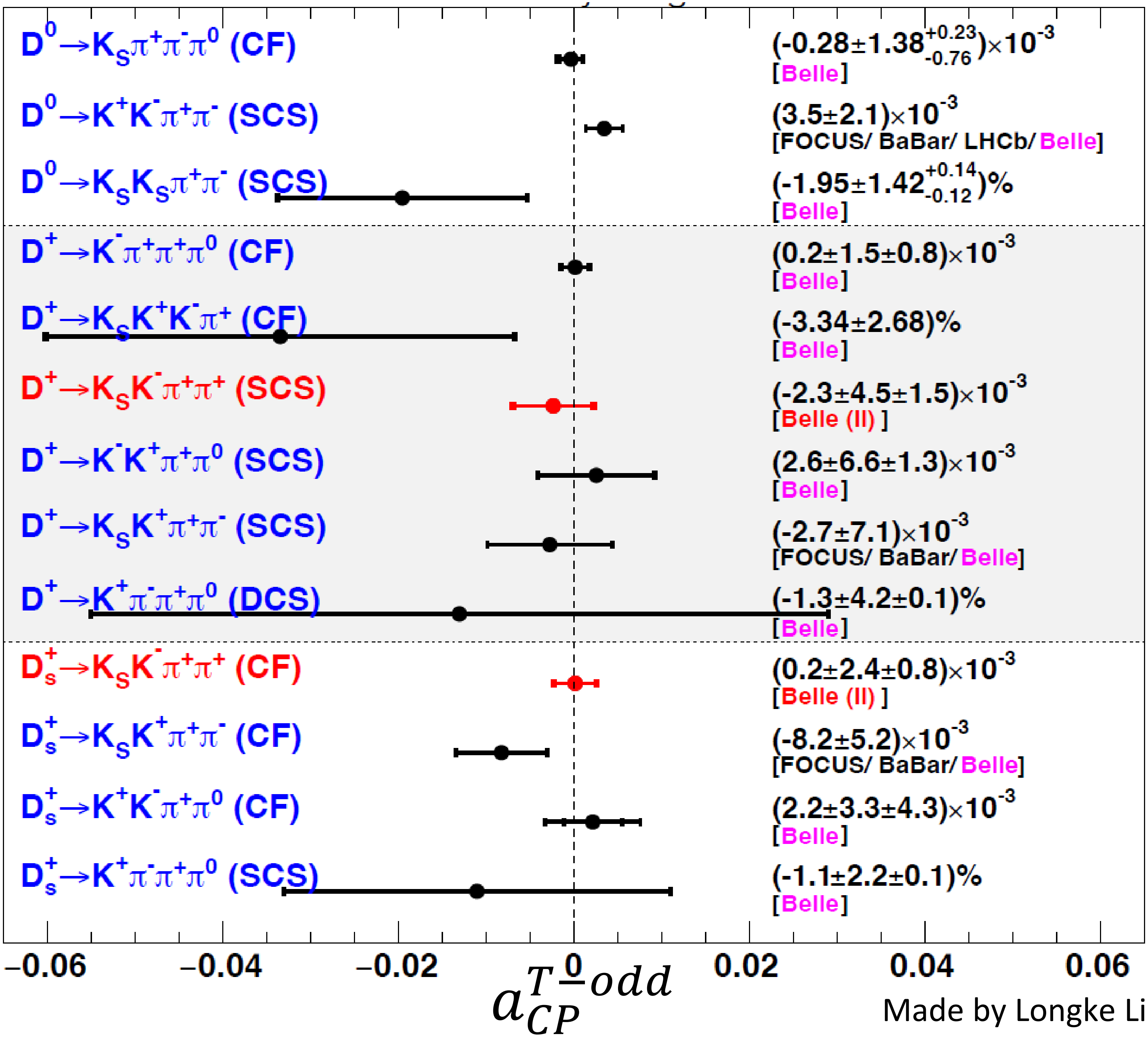
Weak and strong phase differences



Michel Bertemes

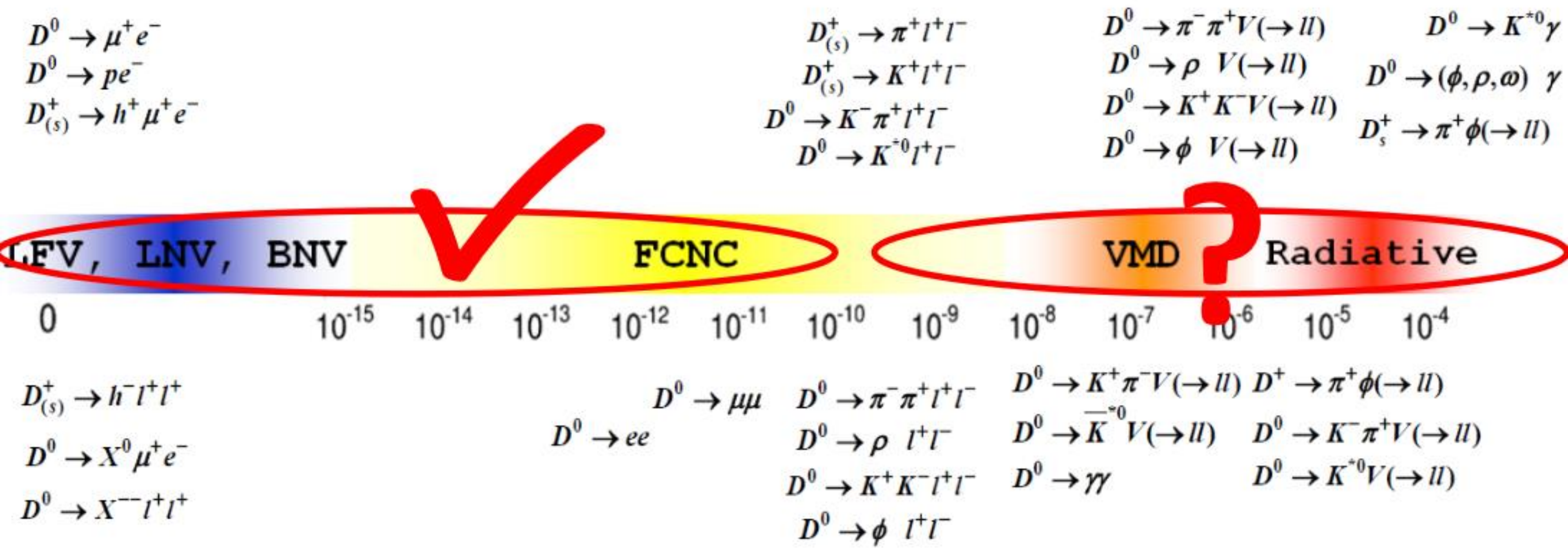
T-odd correlation in $D^+ \to K^+ K_S^0 \pi^+ h^-$

$$C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{h^-})$$



Made by Longke Li

M.G Jao, HQL 2021



FCNC: Flavor Changing Neutral Current

LFV : Lepton Flavor Violation

LNV : Lepton Number Violation

BNV : Baryon Number Violation

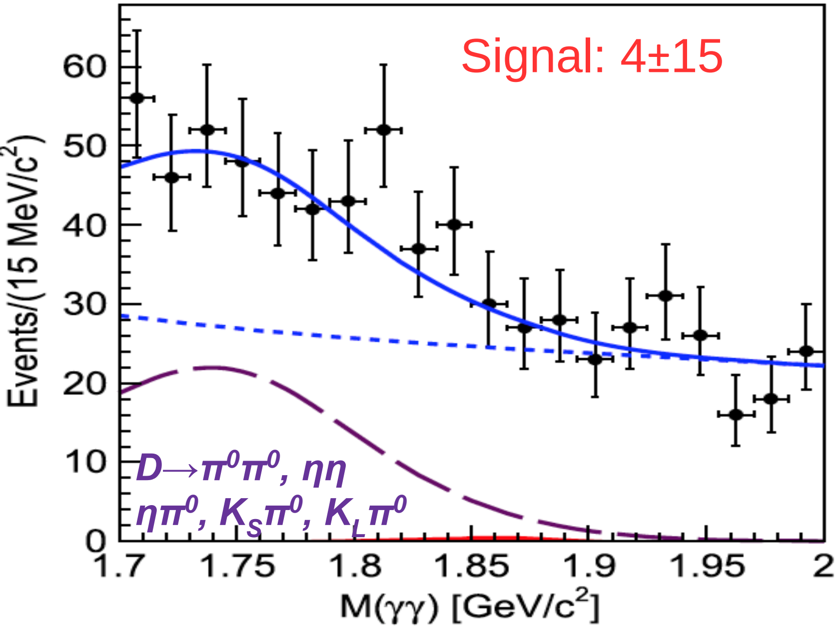
Search for rare decay $D^0 \to \gamma\gamma$

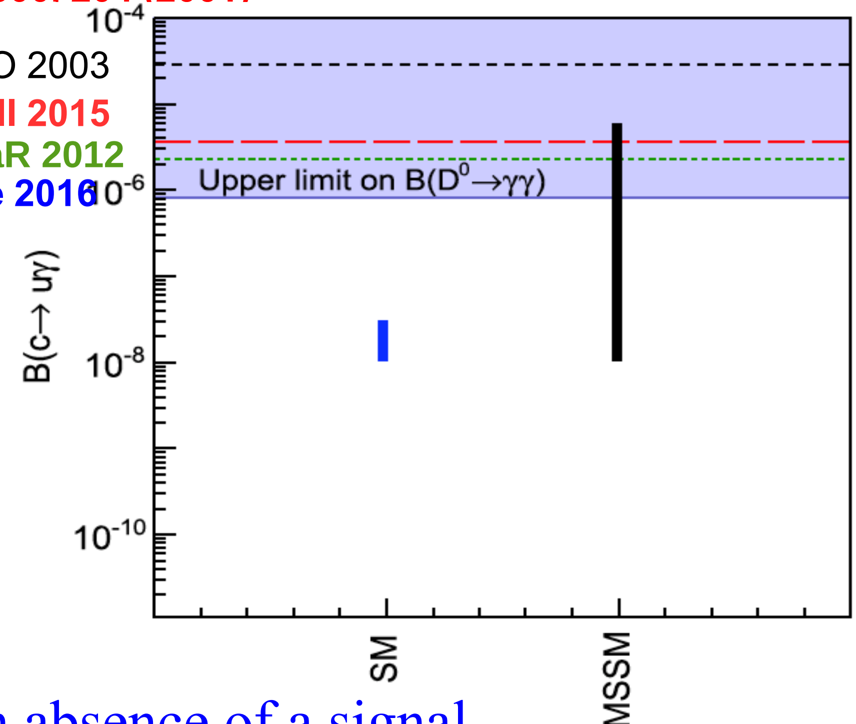
PRD 93, 051102 (2016)(R)

Decay is sensitive to search for new Physics :
mediated by FCNC ($c \to u$), forbidden in the tree level and highly suppressed due to GIM in SM

SM Prediction : B ~ 10^{-8} **PRD 66,014009 (2002)**

In MSSM B ~ 10^{-6} with gluinos exchange **PLB 500. 204 (2001)**





Set world's best limit at 8.5×10^{-7} in absence of a signal

In Belle II, with 50 ab^{-1}, one might expect to reach : 10^{-7}-10^{-8}.

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

Search for *CP* violation in FCNC $D^0 \to V\gamma$, $V=\varphi, \bar{K}^{*0}, \rho^0$

943fb^{-1}

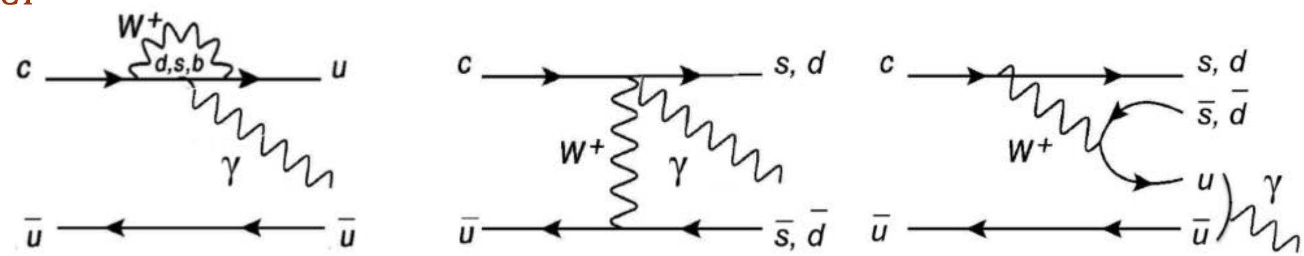
Radiative charm decays are dominated by long-range non-perturbative processes

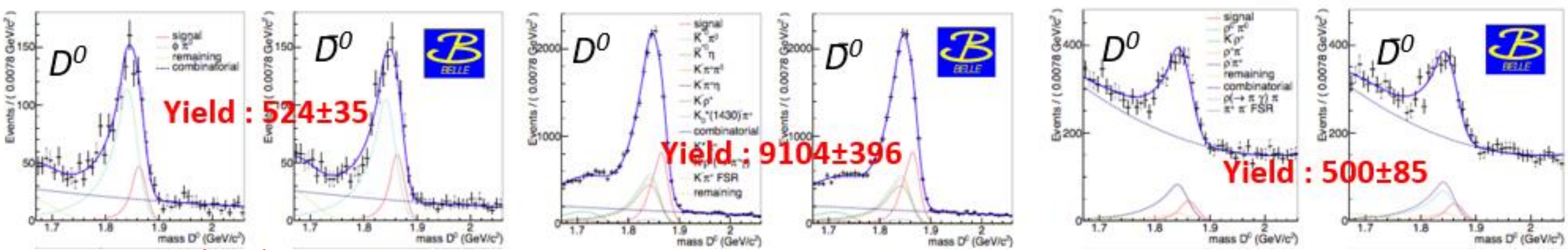
- enhance B.F. up to 10^{-4}, PRD 52, 6383 (1995)
- whereas short-range interactions are predicted to yield rates at the level 10^{-8}.

arXiv:1509.01997

❖ In some SM extensions sizeable CP asymmetry expected in radiative charm decays:

- $A_{CP}^{V\gamma} > 3\%$ signal of New Physics PRL 109, 171801 (2012)





PRL118,051801(2017)

$\mathcal{A}_{CP}^{\phi\gamma} = -0.094 \pm 0.066 \pm 0.001$ $\mathcal{A}_{CP}^{\bar{K}^{*0}\gamma} = -0.003 \pm 0.020 \pm 0.000$ $\mathcal{A}_{CP}^{\rho^0\gamma} = +0.056 \pm 0.151 \pm 0.006$

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

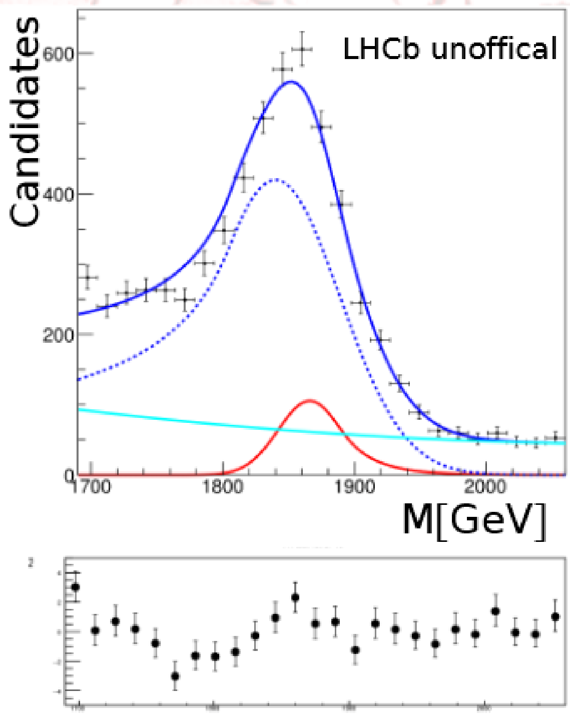
radiative decays	Belle A_{CP} results [1] 976 fb^{-1}	Belle II uncertainty 5 ab^{-1}	15 ab^{-1}	50 ab^{-1}
$D^0 \to \rho^0\gamma$	$+0.056 \pm 0.152 \pm 0.006$	± 0.07	± 0.04	± 0.02
$D^0 \to \phi\gamma$	$-0.094 \pm 0.066 \pm 0.001$	± 0.03	± 0.02	± 0.01
$D^0 \to \bar{K}^{*0}\gamma$	$-0.003 \pm 0.020 \pm 0.000$	± 0.01	± 0.005	± 0.003

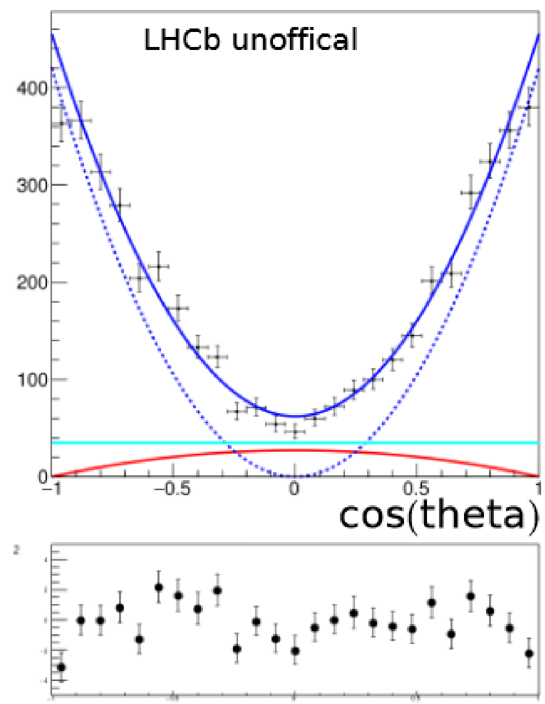
LHCb unofficial !

Chapter III: LHCb

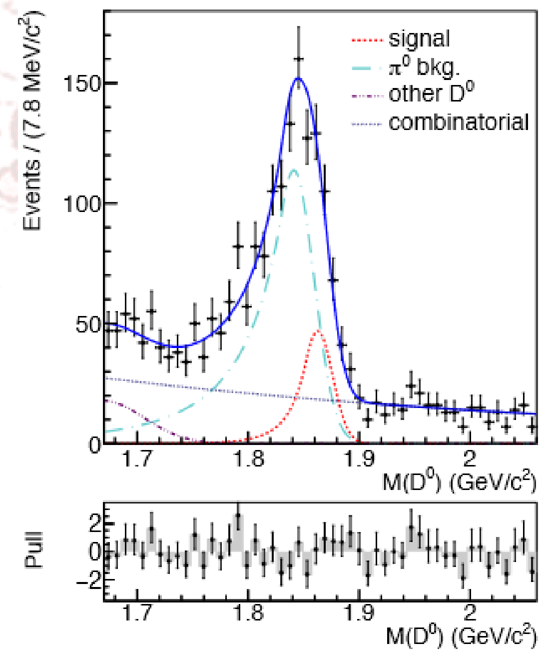
2017 study - UNOFFICIAL

$N(\phi\gamma) = 392 \pm 0.5$
$N(\phi\pi^0) = 4961 \pm 74$





Belle, only D^0



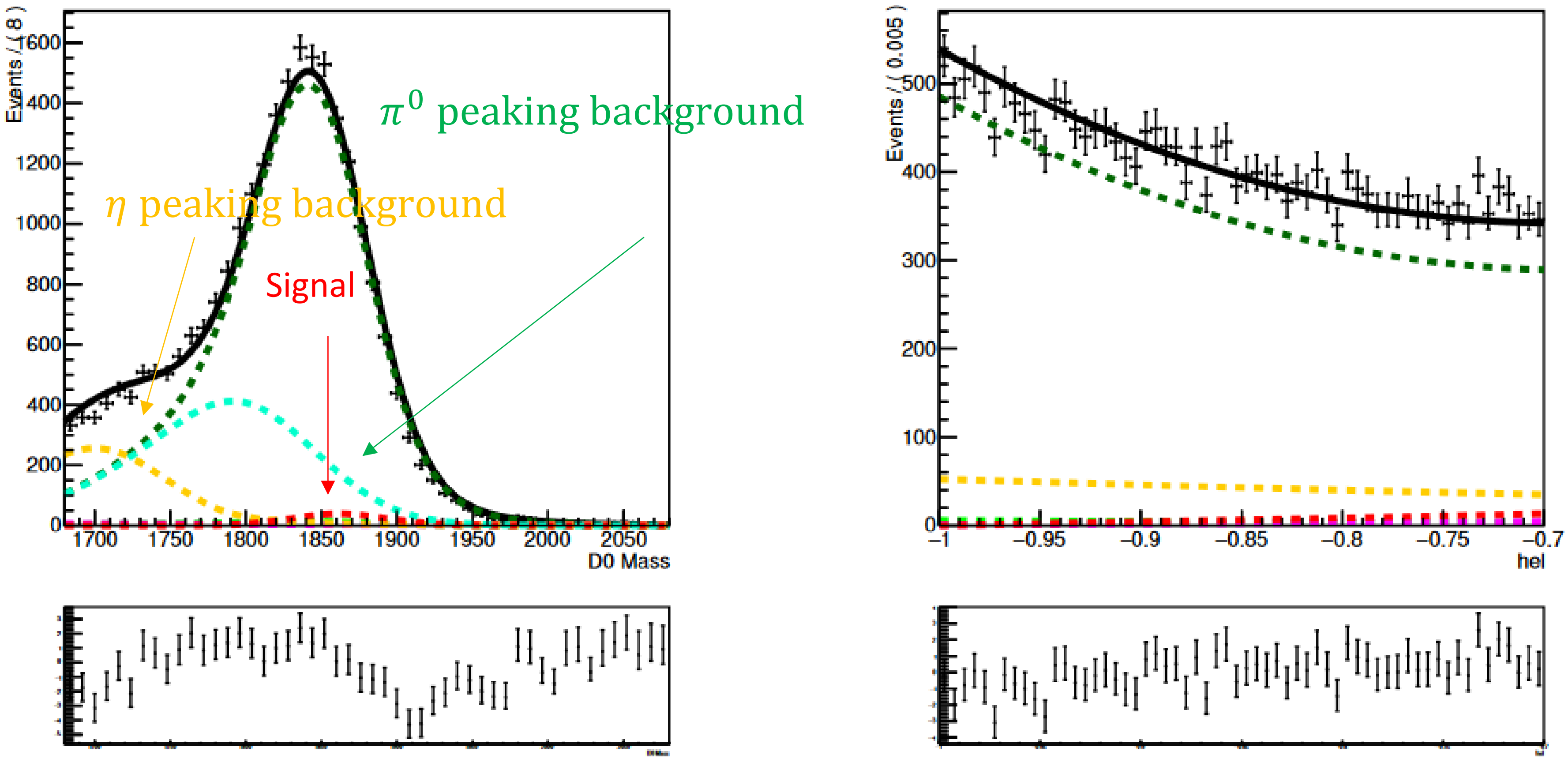
Better yield and sig. significance as in previous study!
Signal and π^0 background CAN be separated!

Radiative charm in LHCb could be competitive!

https://cds.cern.ch/record/2314208/files/Warwick_tara%20nanut%2016.04.pdf

$D \to K^* \gamma$

LHCb unofficial !



https://inspirehep.net/files/55197dccfeeb4e06ac6c75d3f9f620b1

LHCb run 1 data unofficial

Radiative D_s decays

- As mentioned earlier $c \rightarrow u\gamma$ decays might have some contributions coming from the non-minimal supersymmetry which is NP scenario.
- Therefore, one can search for NP using $c \rightarrow u\gamma$ transitions. It was suggested that NP will result in deviation from

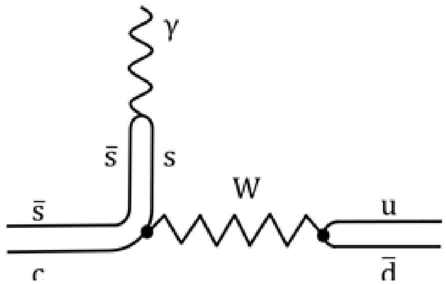
$$R_{\rho/\omega} = \frac{\Gamma(D^0 \rightarrow \rho^0/\omega\,\gamma)}{\Gamma(D^0 \rightarrow K^{*0}\gamma)} = \frac{\tan^2\theta_c}{2}$$

B. Bajc *et al* PRD 54 5883 (1996) studied cabibbo suprpressed D^0, D^+ D_s^+ radiative weak decays in order to find the best mode to test $c \rightarrow u\gamma$ decay

They calculated the ratios between various Cabibbo suppressed and Cabibbo allowed charm meson radiative weak decays, as predicted by SM.
They found D_s^+ radiative decays offers much better test for $c \rightarrow u\gamma$

$$R_K = \frac{\Gamma(D_s^+ \rightarrow K^{*+}\gamma)}{\Gamma(D_s^+ \rightarrow \rho^+\gamma)} = \tan^2\theta_c$$

S. Fajfer et al. PRD.56.4302



Decay Mode	Branching Fraction
$D_s^+ \rightarrow \rho^+\gamma$	$(3\text{-}5) * 10^{-4}$
$D_s^+ \rightarrow K^{*+}\gamma$	$(2.1\text{-}3.2) * 10^{-5}$

$B(D_s^+ \rightarrow \rho^+\gamma) < 6.1 \times 10^{-4}$ (@ 90% CL) BESIII arXiv: 2408.03980

Belle (II) seems perfect place to search for these decays

Search for massless dark photon

PRD (2022) 106, 072008

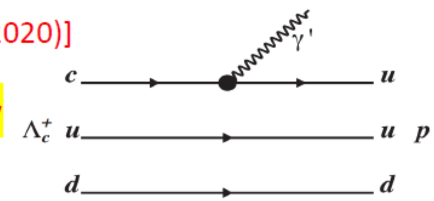
BESIII

Search for massless dark photon via $\Lambda_c \to p\gamma'$

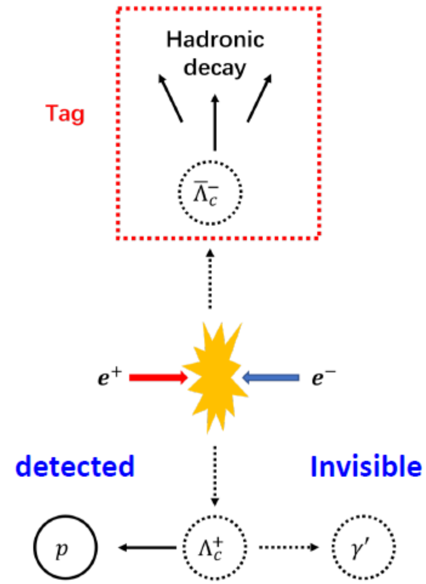
- New physics: An extra Abelian gauge group, $U(1)_D$, Causing the associated gauge boson, the dark photon
- If symmetry remains unbroken, it will cause a massless dark photon γ'
- γ' can be produced via FCNC process $c \to u\gamma'$ (BF $\mathbf{10^{-5}}$ in new physics)

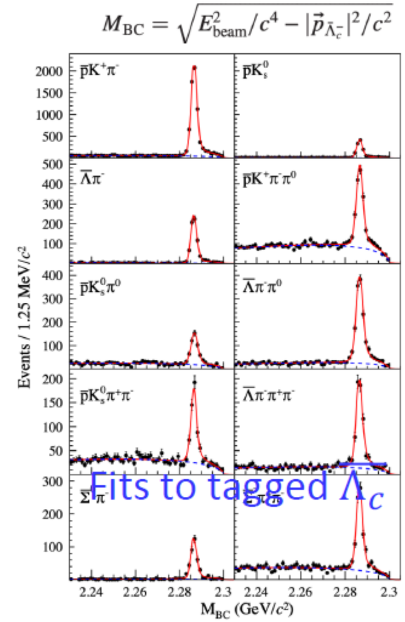
[PRD 102, 115029 (2020)]

Within sensitivity Like BESIII



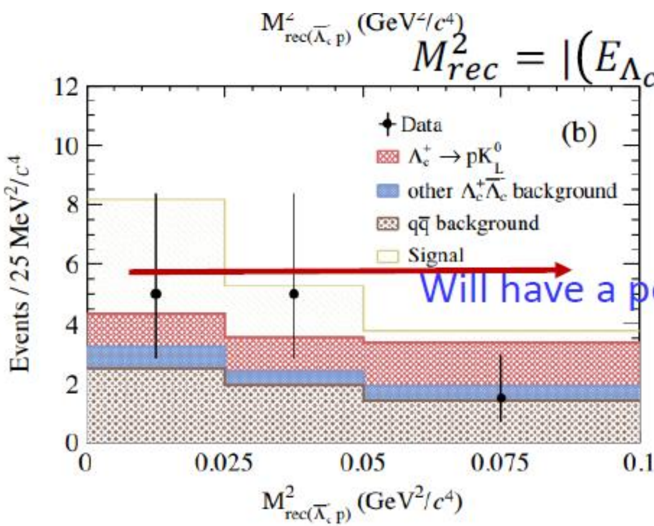
- Analyzing $\mathbf{4.5\ fb^{-1}}$ data at
- $\sqrt{s} = 4.6\sim4.699$ GeV
- Double-tag Method





9

$$M^2_{rec} = |(E_{\Lambda_c} - E_p)^2 - (\vec{P}_{\Lambda_c} - \vec{P}_p)^2|$$



T. Wang HQL 2023

- The first search for massless dark photon
- $\mathcal{B}(\Lambda_c \to p\gamma') < 8.0\times10^{-5}$ @ 90% C. L.
- New physics prediction: $\sim10^{-5}$

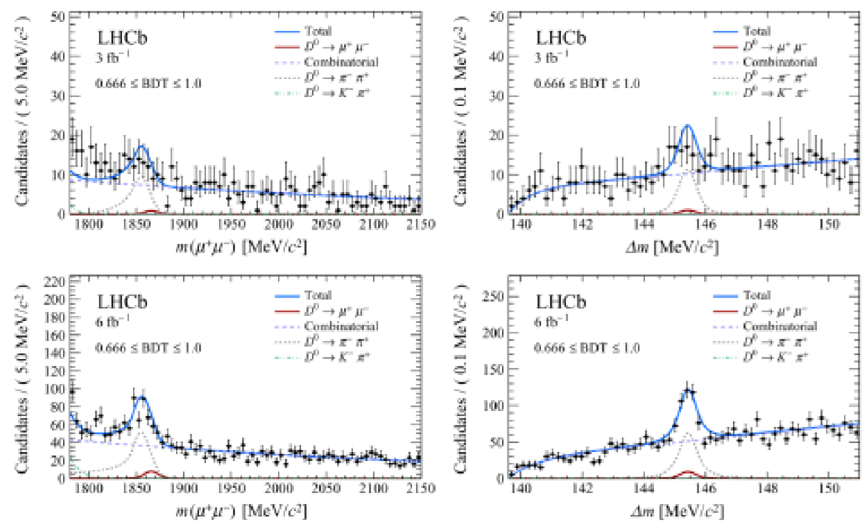
PRL (2023) 131, 041804

Search for $D^0 \to \mu^+\mu^-$

- Run1+2 dataset ($9\ \mathrm{fb}^{-1}$)
- Tagged $D^{*+} \to D^0\pi^+$ decays
- Main backgrounds:
  - Mis-identified $h^+h^- \to \mu^+\mu^-$: PID variables
  - Combinatorial: multivariate analysis (BDT)
- SM SD contributions additionally helicity suppressed with minimal hadronic uncertainties: BF ~ 10^{-18} expected
- Long distance contribution via intermediate two-photon state: BF$\sim 10^{-13}$
- BF measured relatively to the normalisation channels $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$

$$B(\mathrm{D}^0 \to \mu^+\mu^-) = \frac{N(\mathrm{D}^0 \to \mu^+\mu^-)}{N(\mathrm{D}^0 \to h^+h^-)} \frac{\epsilon(\mathrm{D}^0 \to h^+h^-)}{\epsilon(\mathrm{D}^0 \to \mu^+\mu^-)} B(\mathrm{D}^0 \to h^+h^-)$$

Signal yield extracted from a simultaneous fit on $m(D^0)$ and $\Delta(m) = m(D^{*+} - m(D^0))$ in three different BDT intervals



- ✓ $N = 79 \pm 45$
- ✓ $\mathcal{B} < 3.1(3.5)\times 10^{-9}$ @90(95)%C.L.
- ✓ Most stringent limit of FCNC on charm sector

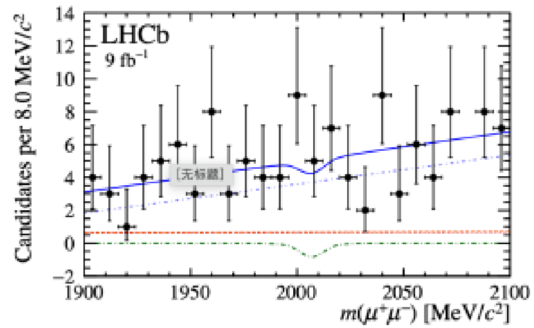
$B^- \to \mu\mu\pi^-$

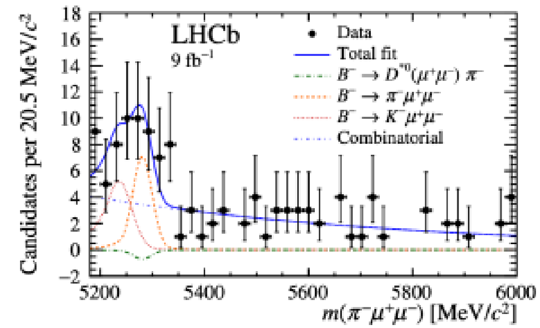
T. Wang HQL 2023

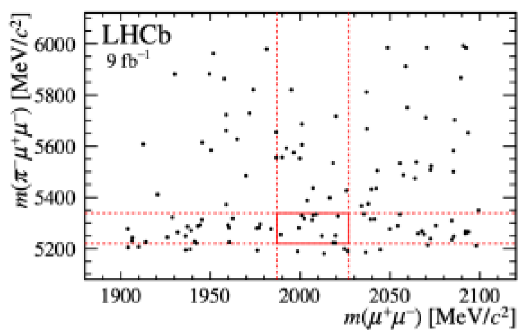
arXiv:2304.01981

Search for $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \mu\mu$

- Electromagnetic and strong interactions have widths many orders of magnitude larger than those for the weak decays.
- SM Predictions BF: $\sim 10^{-19}$
- Run1+2 dataset ($\mathbf{9}$ fb$^{-\mathbf{1}}$)
- Looking for $B^- \to D^{*0}\pi^-$ decays
- First rare charm study exploiting B production
- Normalisation channels $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$







- ✓ $N = -2 \pm 3$
- ✓ $\mathcal{B} < 2.6\times10^{-8}$ @90%C.L.
- ✓ First time search and most stringent limit on D^{*0} decays to leptonic final states

$$B(D^{*0} \to \mu^+\mu^-) = \frac{N(D^{*0} \to \mu^+\mu^-)}{N(J/\psi \to \mu^+\mu^-)} \frac{\epsilon(J/\psi \to \mu^+\mu^-)}{\epsilon(D^{*0} \to \mu^+\mu^-)} \frac{B(B^- \to J/\psi K^-)}{B(B^- \to D^{*0}\pi^-)} B(J/\psi \to \mu^+\mu^-)$$

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.565-0.950]\ \mathrm{GeV}} = (40.6 \pm 5.7) \times 10^{-8},$$

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.950-1.100]\ \mathrm{GeV}} = (45.4 \pm 5.9) \times 10^{-8},$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-)|_{[>0.565]\ \mathrm{GeV}} = (12.0 \pm 2.7) \times 10^{-8},$$

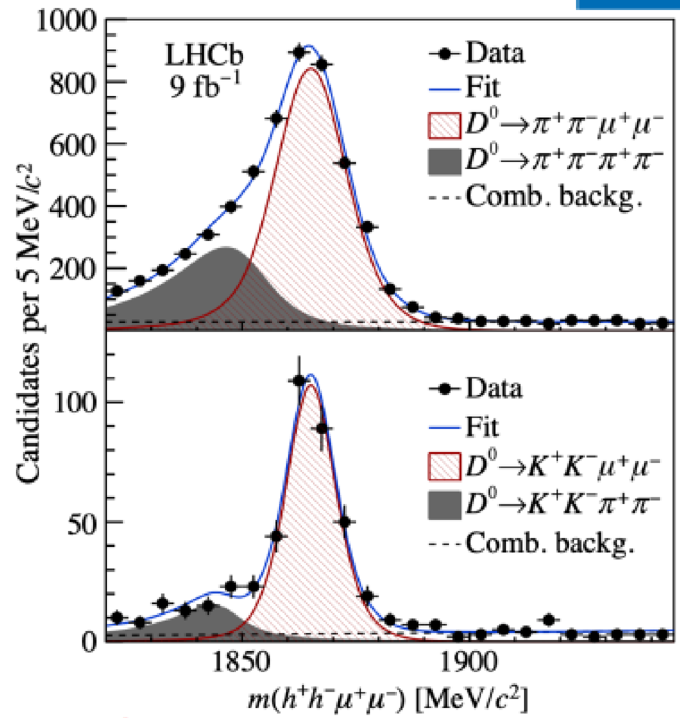
PRL (2022) 128, 221801

T. Wang HQL 2023

Angular analysis of $D^0 \to h^+h^-\mu^+\mu^-$

- BF($D^0 \to X\mu^+\mu^-$) of LD: $\sim 10^{-6}$ expected in the SM
- First observed by LHCb with Run1

  [PRL 119)2017 181805]
- Full angular analysis with Run1+2 dataset (9 fb^{-1})
- Angular studies and CP asymmetries in the vicinity of intermediate resonances offer a access to observables with negligible theoretical uncertainties
- Perform SM null tests in the resonant regions, testing the possible interference between long-distance and BSM contributions



Decay mode	low mass	η	ρ/ω		ϕ		high mass
	$m(\mu^+\mu^-)$ [MeV/c^2]						
$D^0 \to K^+K^-\mu^+\mu^-$	< 525	NS	> 565		NA		NA
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	< 525	NS	565-780	780-950	950-1020	1020-1100	NS

NA = not available, NS = no signal

✓ $N(D^0 \to \pi^+\pi^-\mu^+u^-) = 3579 \pm 71$

✓ $N(D^0 \to K^+K\mu^+\mu^-) = 318 \pm 19$

PRL (2022) 128, 221801

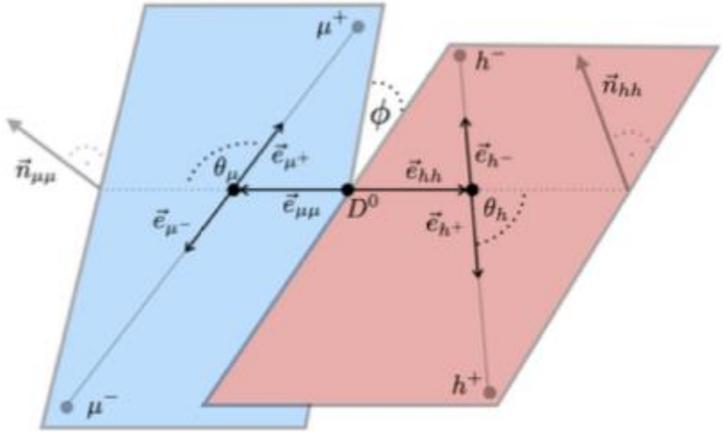
Angular analysis of $D^0 \to h^+h^-\mu^+\mu^-$

T. Wang HQL 2023

CP averaged and asymmetries

Differential decay rate expressed as a sum of nine angular coefficients I_{1-9} function of:

- $q^2 = m^2(\mu^+\mu^-)$ and $p^2 = m^2(h^+h^-)$
- Three angles: θ_μ, θ_h and ϕ



Define $\langle I_i \rangle$ integrated over p^2, θ_h, for D^0 and $\overline{D}^0$

For example, the forward-backward asymmetry:

- $\langle I_6 \rangle = \mathrm{A_{FB}} = \frac{\Gamma(\cos\theta_\mu>0)-\Gamma(\cos\theta_\mu<0)}{\Gamma(\cos\theta_\mu>0)+\Gamma(\cos\theta_\mu<0)}$

CP asymmetry:

$$\mathrm{A_{CP}} = \frac{\Gamma(D^0\to h^+h^-\mu^+\mu^-)-\Gamma(\overline{D}^0\to h^+h^-\mu^+\mu^-)}{\Gamma(D^0\to h^+h^-\mu^+\mu^-)+\Gamma(\overline{D}^0\to h^+h^-\mu^+\mu^-)}$$

The CP averaged $\langle S_i \rangle$ and asymmetries $\langle A_i \rangle$:

- $\langle S_i \rangle = \frac{1}{2}[\langle I_i \rangle + (-)\langle \bar{I}_i \rangle] \rightarrow \langle S^{SM}_{5,6,7} \rangle = 0$ CP even
- $\langle A_i \rangle = \frac{1}{2}[\langle I_i \rangle - (+)\langle \bar{I}_i \rangle] \rightarrow \langle A^{SM}_{i} \rangle = 0$ CP odd

$$I_2 = \int_{-\pi}^{\pi} d\phi \left[\int_{-1}^{-0.5} d\cos\theta_\mu + \int_{0.5}^{1} d\cos\theta_\mu - \int_{-0.5}^{0.5} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

$$I_3 = \frac{3\pi}{8}\left[\int_{-\pi}^{-\frac{3\pi}{4}} d\phi + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} d\phi + \int_{\frac{3\pi}{4}}^{\pi} d\phi - \int_{-\frac{3\pi}{4}}^{-\frac{\pi}{4}} d\phi - \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

$$I_4 = \frac{3\pi}{8}\left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi - \int_{-\pi}^{-\frac{\pi}{2}} d\phi - \int_{\frac{\pi}{2}}^{\pi} d\phi\right]\left[\int_{0}^{1} d\cos\theta_\mu - \int_{-1}^{0} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

$$I_5 = \left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi - \int_{-\pi}^{-\frac{\pi}{2}} d\phi - \int_{\frac{\pi}{2}}^{\pi} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

$$I_6 = \int_{-\pi}^{\pi} d\phi \left[\int_{0}^{1} d\cos\theta_\mu - \int_{-1}^{0} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

$$I_7 = \left[\int_{0}^{\pi} d\phi - \int_{-\pi}^{0} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

$$I_8 = \frac{3\pi}{8}\left[\int_{0}^{\pi} d\phi - \int_{-\pi}^{0} d\phi\right]\left[\int_{0}^{1} d\cos\theta_\mu - \int_{-1}^{0} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,,$$

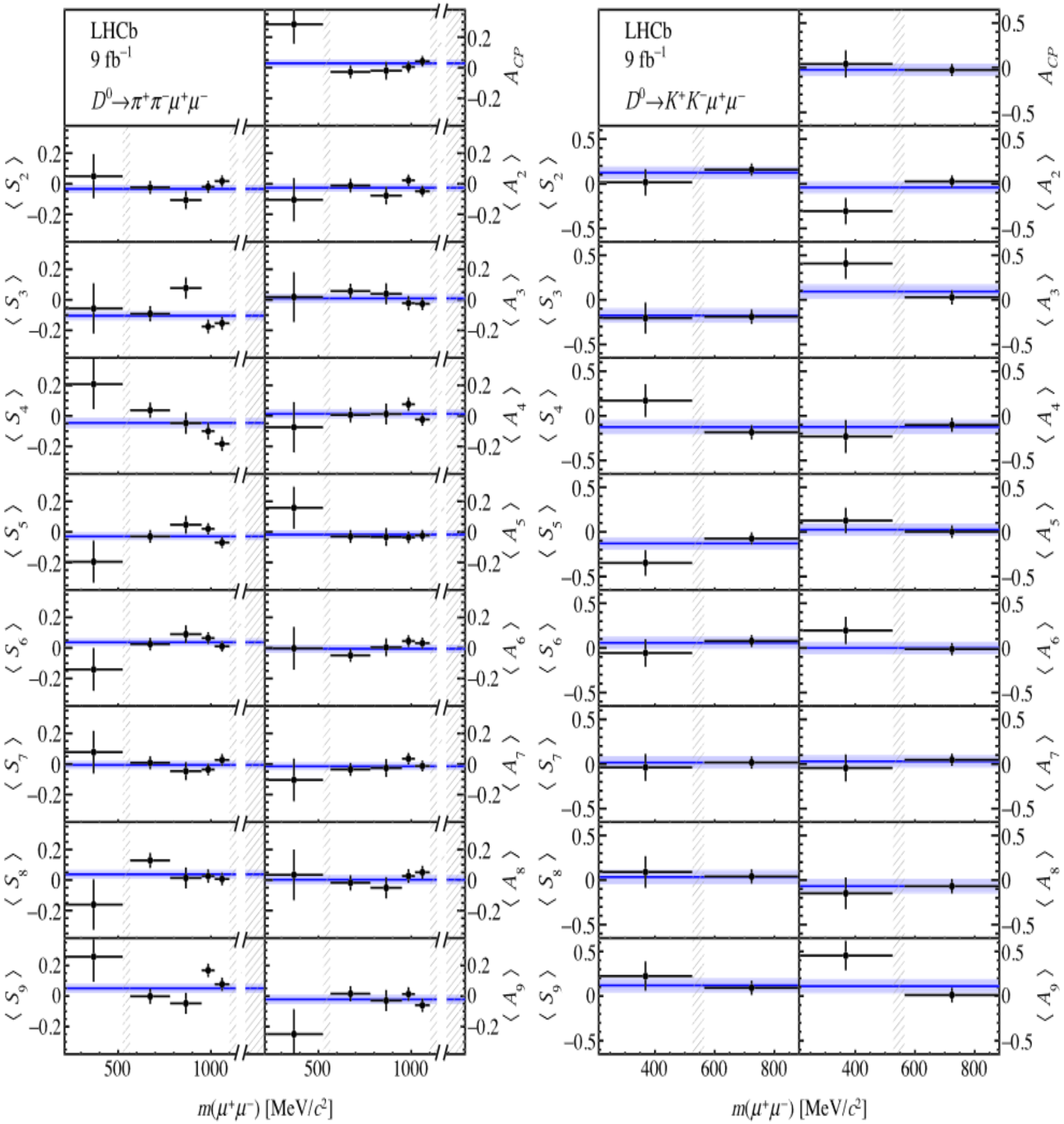
$$I_9 = \frac{3\pi}{8}\left[\int_{-\pi}^{-\frac{\pi}{2}} d\phi + \int_{0}^{\frac{\pi}{2}} d\phi - \int_{-\frac{\pi}{2}}^{0} d\phi - \int_{\frac{\pi}{2}}^{\pi} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}\,.$$

The observables $\langle I_{\rm i}\rangle$, measured separately for D^0 and $\overline{D}^0$ mesons, are labelled as $\langle I_{\rm i}\rangle$ and $\langle \overline{I}_{\rm i}\rangle$, respectively. The observables reported in the Letter are the *CP* averages, $\langle S_{\rm i}\rangle$, and asymmetries, $\langle A_{\rm i}\rangle$, defined as

$$\begin{aligned}\langle S_{\rm i}\rangle &= \frac{1}{2}\left[\langle I_{\rm i}\rangle + (-)\langle \overline{I}_{\rm i}\rangle\right]\,,\\ \langle A_{\rm i}\rangle &= \frac{1}{2}\left[\langle I_{\rm i}\rangle - (+)\langle \overline{I}_{\rm i}\rangle\right]\,,\end{aligned} \tag{S9}$$

for the *CP*-even (*CP*-odd) coefficients $\langle I_{2,3,4,7}\rangle$ ($\langle I_{5,6,8,9}\rangle$).

T. Wang HQL 2023



- This is the first full angular analysis of a rare charm decay ever performed.

Null-test observables A_{CP}, $\langle S_{5-7} \rangle$, and $\langle A_{2-9} \rangle$ are agreement in with the SM predications with over p values of 79% and 0.8% for $D^0 \to \pi^+\pi^-\mu^+u^-$ and $D^0 \to K^+K^-\mu^+u^-$, corresponding to

- ✓ $D^0 \to \pi^+\pi^-\mu^+u^- = 0.3\sigma$
- ✓ $D^0 \to K^+K^-\mu^+u^- = 2.7\sigma$
- ✓ σ : Gaussian deviation

YoungJun Kim,
ICHEP 2024

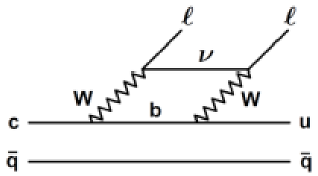
Search for $D^0 \to hh'e^+e^-, (h = K, \pi)$

- FCNC processes with $c \to ull$ are suppressed in SM, good probe for NP
- SM long-distance contributions dominate, especially near resonances.

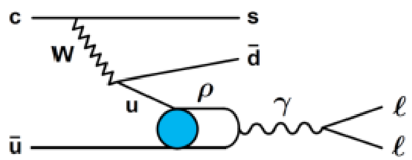
➡ BSM contributions may be visible far from resonances.

BABAR: PRL **122**, 081802 (2019)
BESIII: PRD **97**, 072015 (2019)
LHCb: PRL **119**, 181805 (2017)
PLB **517**, 558(2016)

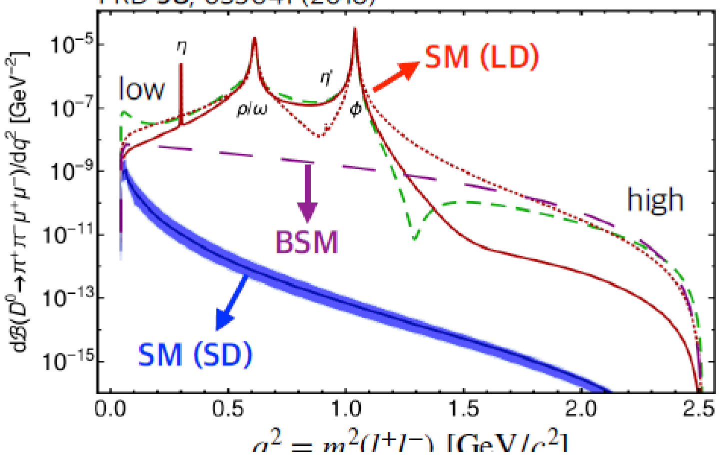
Short distance



Long distance



PRD **98**, 035041 (2018)



Measured BFs or ULs at 90% CL [$\times 10^{-7}$]

	$KKee$	$\pi\pi ee$	$K\pi ee$
BABAR	–	–	$40.0 \pm 5.0 \pm 2.3$ (ρ/ω) < 31 (non-resonant)
BESIII	< 110	< 70	< 410
	$KK\mu\mu$	$\pi\pi\mu\mu$	$K\pi\mu\mu$
LHCb	$1.54 \pm 0.27 \pm 0.19$	$9.64 \pm 0.48 \pm 1.10$	$4.17 \pm 0.12 \pm 0.40$ (ρ/ω)

- Search for signal candidates in $q^2 = m^2(e^+e^-)$ regions

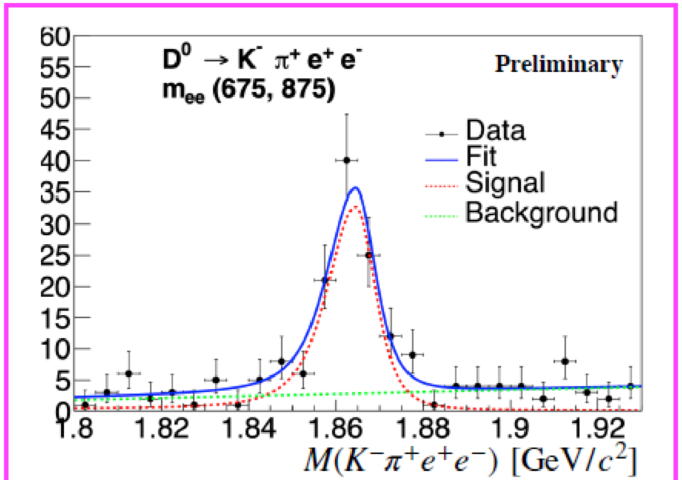
➡ Near resonances → BR measurement

➡ Far from resonances (non-resonant) → Sensitive to NP

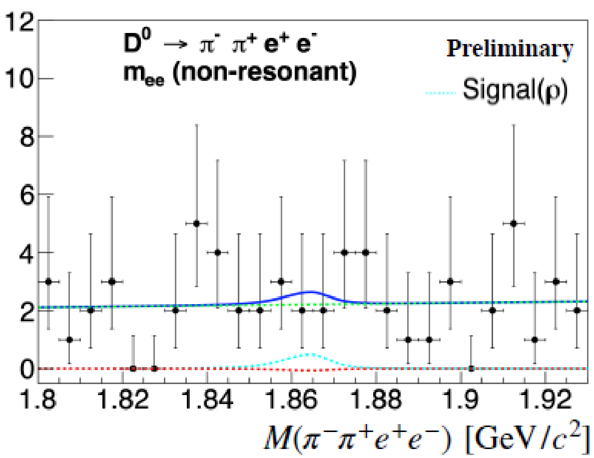
YoungJun Kim,
ICHEP 2024

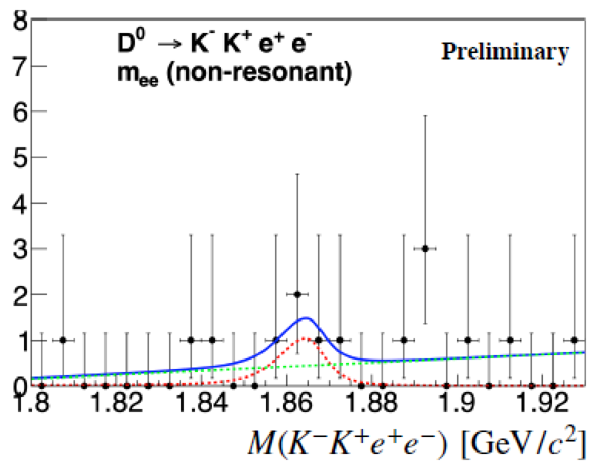
$D^0 \to hh'e^+e^-, (h = K, \pi)$ Results

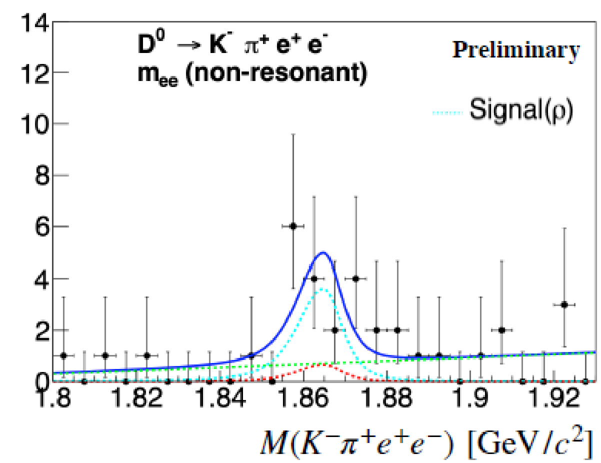
Preliminary Belle 942/fb



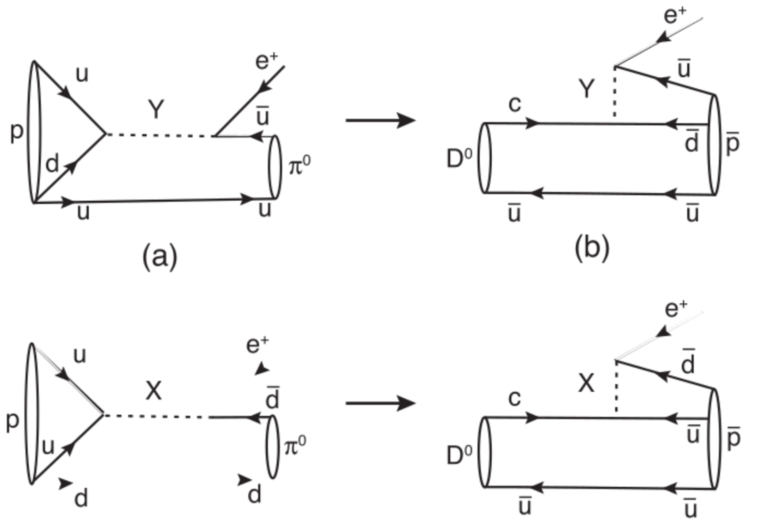
- New Belle Results
  - Signal in ρ/ω region: $\mathscr{B}(K\pi e^+e^-) = (39.6 \pm 4.5 \pm 2.9) \times 10^{-7}$ (11.8σ), matches BABAR with higher precision and SM expectations
  - 90% CL upper limits set at $(2-8) \times 10^{-7}$ for other regions (best to date)
    - Significant improvements than BESIII and BABAR but different m_{ee} regions



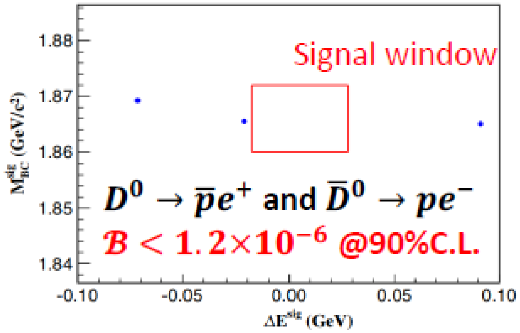


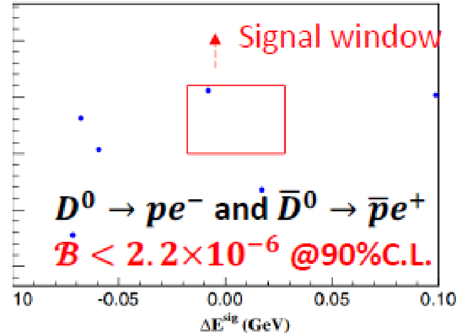


- Various GUT and many SM extensions and SUSY predict BNV, and as a consequence nucleons can have finite, if long, lifetimes.
- In all these theories baryon (B) and lepton (L) number violations are allowed but the difference Δ(B − L) is conserved.
- D ➔ pl(e/μ) simultaneously violate B and L but conserve Δ(B−L).
- Several models of proton decay, e.g. in GUT, superstrings and SUSY can be augmented to provide predictions on possible decay mechanisms.
- No tree level diagrams allow D → pl in SU(5).
- The X and Y bosons have charge *4/3e* and *1/3e* and couple a quark to a lepton, hence they are sometimes called "***lepto-quarks***."



The branching fractions for D ➔ pe^{+} are predicted to be of the order of 10^{-39}





BESIII, PRD (2022) 105, 032006

Decay mode	ϵ (%)	N_S	$\mathcal{S}$ (σ)	N_{pl}^{UL}	$\mathcal{B} \times 10^{-7}$
$D^0 \to pe^-$	10.2	-6.4 ± 8.5	—	17.5	< 5.5
$\overline{D}^0 \to pe^-$	10.2	-18.4 ± 23.0	—	22.0	< 6.9
$D^0 \to \overline{p}e^+$	9.7	-4.7 ± 23.0	—	22.0	< 7.2
$\overline{D}^0 \to \overline{p}e^+$	9.6	7.1 ± 9.0	0.6	23.0	< 7.6
$D^0 \to p\mu^-$	10.7	11.0 ± 23.0	0.9	17.1	< 5.1
$\overline{D}^0 \to p\mu^-$	10.7	-10.8 ± 27.0	—	21.8	< 6.5
$D^0 \to \overline{p}\mu^+$	10.5	-4.5 ± 14.0	—	21.1	< 6.3
$\overline{D}^0 \to \overline{p}\mu^+$	10.4	16.7 ± 8.8	1.6	21.4	< 6.5

Belle, PRD 109, L031101 (2024)

Mode (+c.c.)	$\mathcal{B}^{UL}$ @90%C.L.
$D^+ \to \bar{n}e^+$	$< 1.4\times10^{-5}$
$D^+ \to ne^+$	$< 2.9\times10^{-5}$

BESIII, PRD (2022) 106, 112009

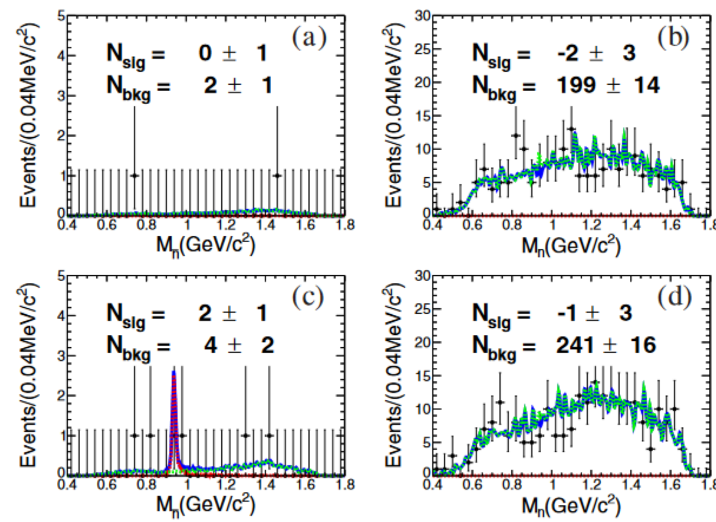
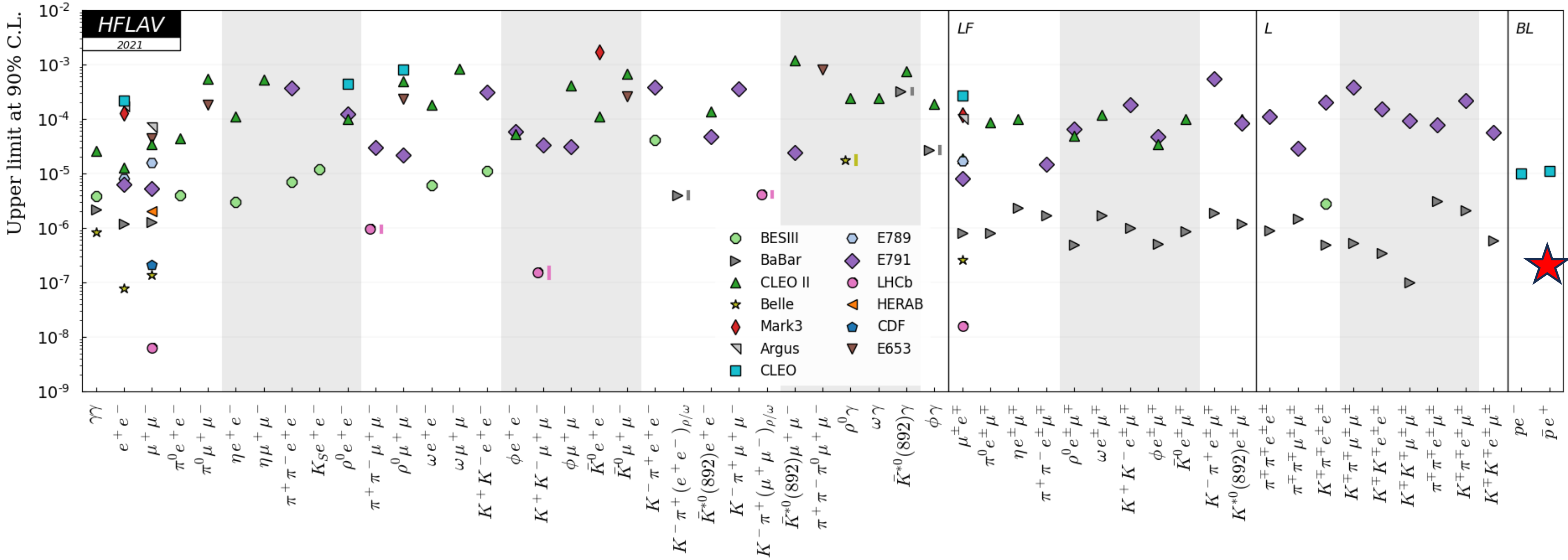
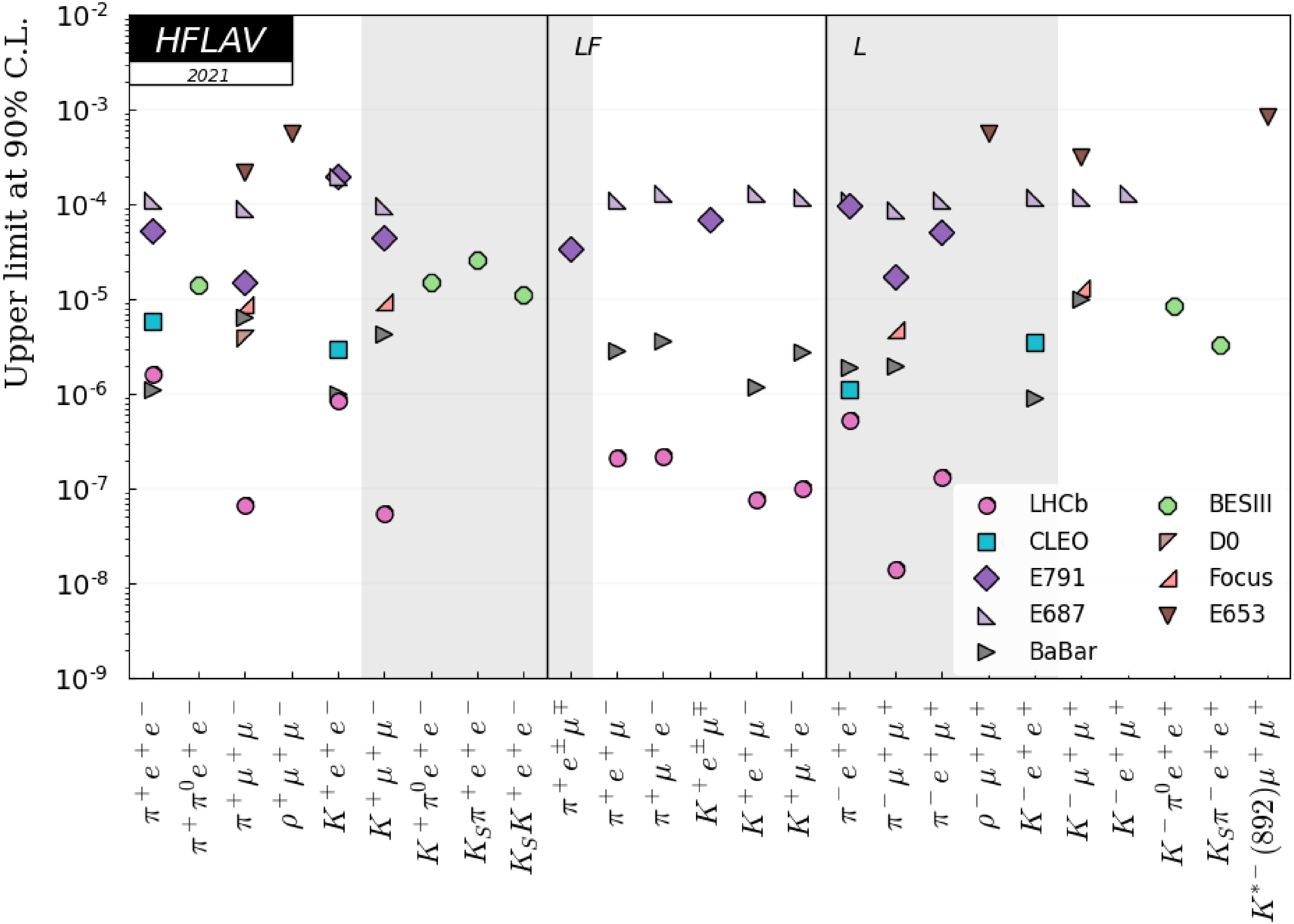


FIG. 4. Fit for $M_{n/\bar{n}}$ distributions for processes (a) $D^+ \to \bar{n}e^+$, (b) $D^- \to ne^-$, (c) $D^- \to \bar{n}e^-$, and (d) $D^+ \to ne^+$. The black dots with error bar are data. The red dotted, green dotted and blue solid lines are signal, background, and the sum of signal and background, respectively.

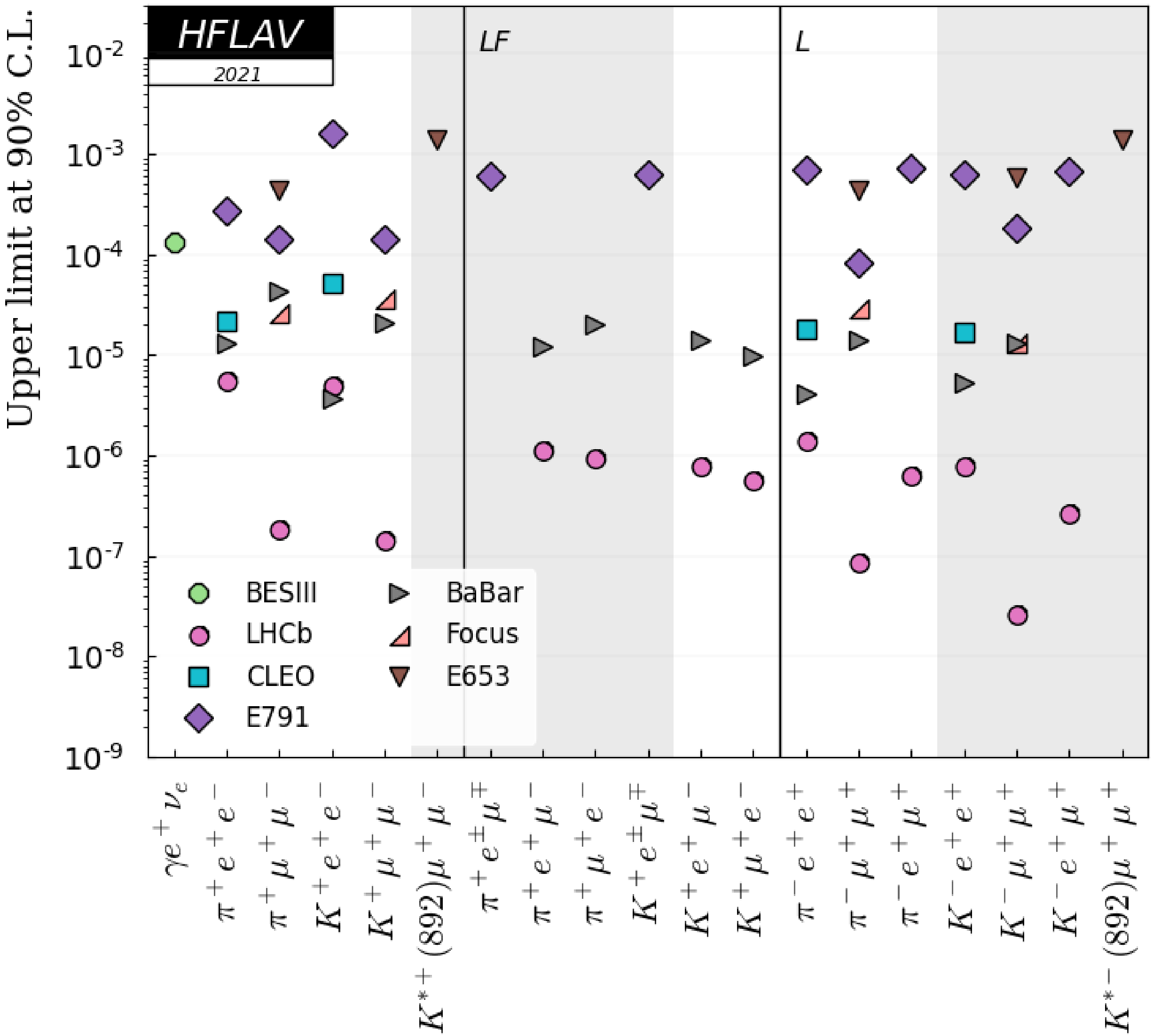
D^0 rare decay summary



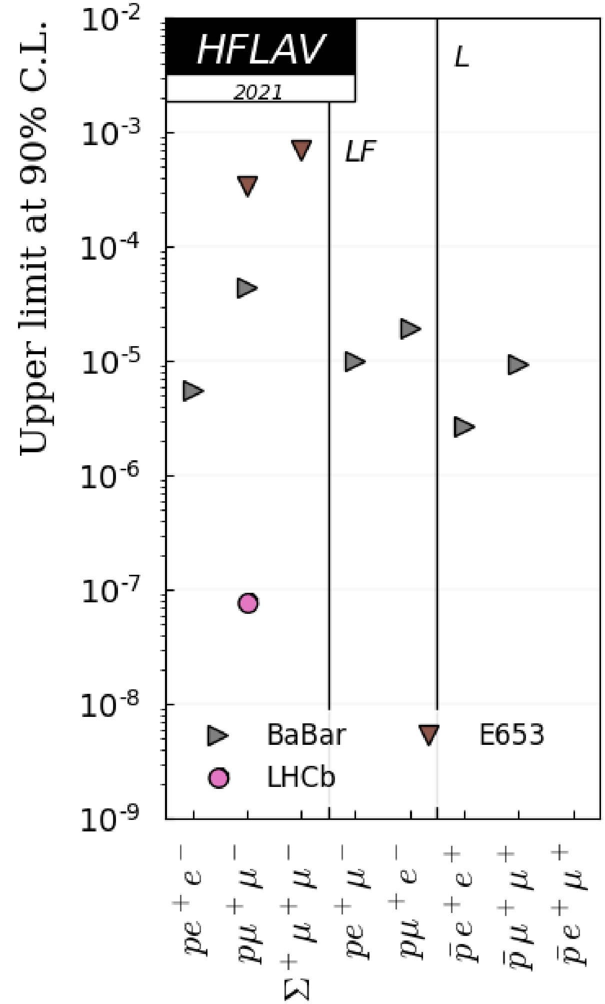
D⁺ rare decay summary



D_s^+ rare decay summary



Λ_c^+ rare decay summary



Search for $D \rightarrow$ *invisible decay*

In the Standard Model (SM), D meson decay to $\nu\bar{\nu}$ helicity suppressed by a factor of

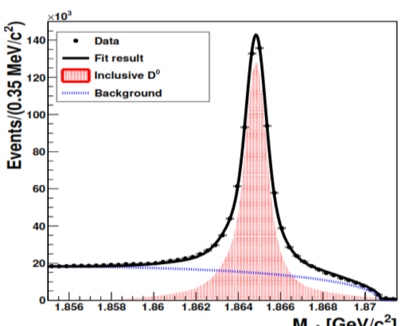
$$\left(\frac{m_\nu}{m_{D^0}}\right)^2 : \mathcal{B}(D^0 \to \nu\bar{\nu})_{SM} = 1.1 \times 10^{-30}$$ **PRD 82, 034005 (2010)**

NP contributions such as scalar Dark matter, right-handed neutrino or Majorana fermion could substantially enhance the value up to 10^{-15} **PLB 651, 374 (2007)** **PR 117, 75 (1985)**

DM search associated with *D* meson : alternative way for search for DM.

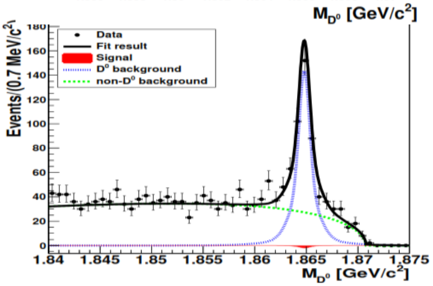
Reconstruct $D_{tag}^{(*)}, X_{frag}$ *and* π^-. Get M_{miss} to get inclusive D^0 sample.

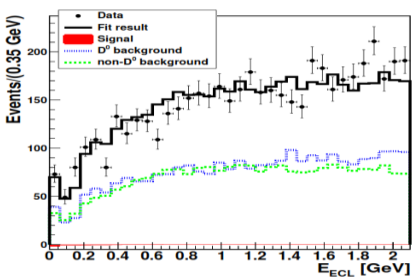
PRD95, 011102 (2017)(R)



$$e^+e^- \to c\bar{c} \to D_{\rm tag}^{(*)} X_{\rm frag} \bar{D}_{\rm sig}^{*-} \text{ with } \bar{D}_{\rm sig}^{*-} \to \bar{D}_{\rm sig}^0 \pi_s^-$$

$$B(D^0 \to f) = \frac{N_{sig}(D^0 \to f)}{\varepsilon \times N_{D^0}^{inclusive}}$$





90% CL upper limit at 9.4×10^{-5}

	Luminosity, ab^{-1}	Inclusive D yield, in 10^6
Belle	0.9	0.6
Belle II	50	38

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

CPV in charmed Baryons

https://indico.cern.ch/event/1184945/contributions/5437898/attachments/2716989/4719351/CKM2023.pdf

Recent publications on hadronic, (semi)leptonic, and rare decays of charmed hadrons

- Recently experiments reported > 70 branching fractions ($\mathcal{B}$) of charmed hadron decays.

First observation	Publication
$D^0 \to K_L^0 P$ ($P = \omega, \phi, \eta^{(\prime)}$)	BESIII, PRD 105, 092010 (2022)
$D_s^+ \to \omega\pi^+\eta$	BESIII, PRD 107, 052010 (2023)
$D_s^+ \to K_S^0 K^+ K^- \pi^+$	Belle, arXiv:2305.11405
$\Lambda_c^+ \to n\pi^+$	BESIII, PRL 128, 142001 (2022)
$\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^+h^-$	BESIII, CPC 47, 023001 (2023)
$\Lambda_c^+ \to p\eta'$	Belle, JHEP 03, 090 (2022)
$\Lambda_c^+ \to pK_S^0K_S^0$	Belle, PRD 107, 032004 (2023)
$\Omega_c^0 \to \Xi^-\pi^+, \Omega^-K^+$	LHCb, arXiv:2308.08512

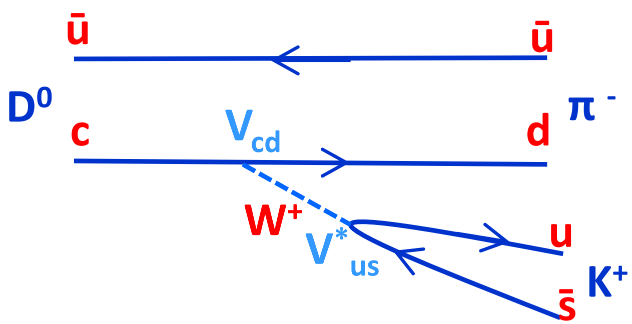
Improved $\mathcal{B}$	Publication
$\Lambda_c^+ \to p\eta$	BESIII, arXiv:2307.09266
$\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$	BESIII, arXiv:2304.09405
$\Lambda_c^+ \to (\Lambda, \Sigma^0)K^+$	Belle, Sci. Bull. 68, 583 (2023)
$\Lambda_c^+ \to \Sigma^+(\eta, \eta')$	Belle, PRD 107, 032003 (2023)
$\Lambda_c^+ \to pK_S^0\eta$	Belle, PRD 107, 032004 (2023)
$D^+ \to K_S^0\pi^+\eta$	BESIII, arXiv:2309.05760
$D_s^+ \to K_S^0K_S^0\pi^+$	BESIII, PRD 105, L051103 (2022)
$D_s^+ \to K_S^0K^+\pi^0$	BESIII, PRL 129, 182001 (2022)
$D_{(s)}^+ \to K^+h^-\pi^+\pi^0$	Belle, PRD 107, 033003 (2023)
$\Xi_c^0 \to \Lambda_c^+\pi^-$	Belle, PRD 107, 032005 (2023)
$D_s^{*+} \to D_s^+\pi^0$	BESIII, PRD 107, 032011 (2023)
$D^{0,+} \to \pi^+\pi^+\pi^-X$	BESIII, PRD 107, 032002 (2023)
$D^{0,+} \to K_S^0X$	BESIII, PRD 107, 112005 (2023)
$D_s^+ \to \pi^+\pi^+\pi^-X$	BESIII, PRD 108, 032001 (2023)
$\bar{\Lambda}_c^- \to \bar{n}X$	BESIII, PRD 108, L031101 (2023)
......	......

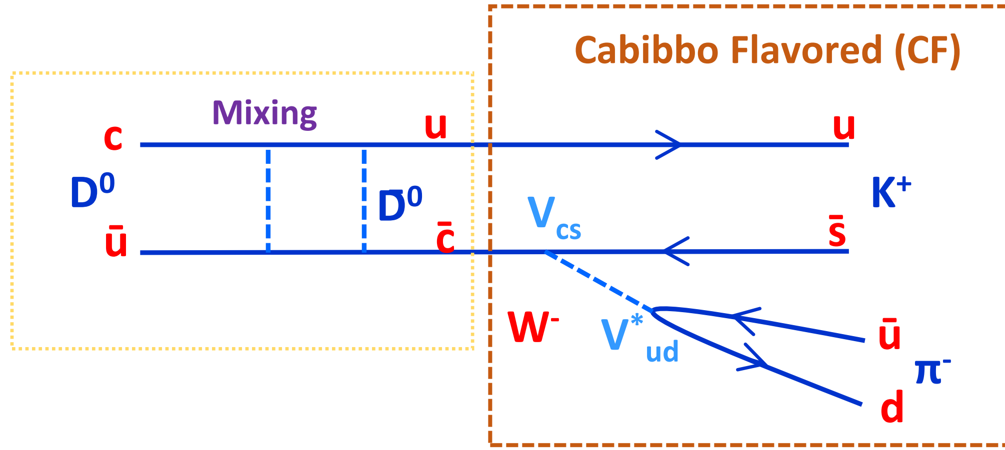
(Semi-)leptonic decay	Publication
$D_s^+ \to \mu^+\nu_\mu$	BESIII, arXiv:2307.14585
$D_s^+ \to \tau^+\nu_\tau, \tau \to \pi^+\bar{\nu}_\tau$	BESIII, arXiv:2303.12600
$D_s^+ \to \tau^+\nu_\tau, \tau \to \mu^+\nu_\mu\bar{\nu}_\tau$	BESIII, arXiv:2303.12468
$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$	BESIII, arXiv:2307.12852
$D_s^+ \to \eta^{(\prime)}e^+\nu_e$	BESIII, arXiv:2306.05194
$D_s^+ \to \pi^+\pi^-e^+\nu_e$	BESIII, arXiv:2303.12927
$D_s^+ \to K^+K^-\mu^+\nu_\mu$	BESIII, arXiv:2307.03024
$D_s^+ \to \pi^0e^+\nu_e$	BESIII, PRD 106, 112004 (2022)
$D_s^+ \to (K_1(1270)^0, b_1(1235)^0)e^+\nu_e$	BESIII, arXiv:2309.04090
$D_s^{*+} \to e^+\nu_e$	BESIII, arXiv:2304.12159
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	BESIII, PRD 108, L031105 (2023)
$\Lambda_c^+ \to \Lambda e^+\nu_e$	BESIII, PRL 129, 231803 (2022)
$\Lambda_c^+ \to pK^-e^+\nu_e$	BESIII, PRD 106, 112010 (2022)
$\Lambda_c^+ \to (\Lambda\pi^+\pi^-, pK_S^0\pi^-)e^+\nu_e$	BESIII, PLB 843, 137993 (2023)
$\Lambda_c^+ \to Xe^+\nu_e$	BESIII, PRD 107, 052005 (2023)

Rare dcays	Publication
$D^0 \to \mu^+\mu^-$	LHCb, PRL 131, 041804 (2023)
$D^0, \bar{D}^0 \to p\ell$	Belle, Preliminary
$D^0 \to \bar{p}e^+, D^0 \to pe^-$	BESIII, PRD 105, 032006 (2022)
$D^\pm \to (n, \bar{n})e^\pm$	BESIII, PRD 106, 112009 (2022)
$D^0 \to \pi^0\nu\bar{\nu}$	BESIII, PRD 105, L071102 (2022)
$D^*(2007)^0 \to \mu^+\mu^-$	LHCb, EJPC 83, 666 (2023)
$\Lambda_c^+ \to \Sigma^+\gamma, \Xi_c^0 \to \Xi^0\gamma$	Belle, PRD 107, 032001 (2022)
$\Lambda_c^+ \to \Sigma^+\gamma$	BESIII, arXiv:2212.07214
$\Lambda_c^+ \to p\gamma'$	BESIII, PRD 106, 072008 (2022)

$D^0 \rightarrow K^+\pi^-$ wrong sign analysis

Doubly Cabibbo Suppressed (DCS)





Same initial-and final state

Interference between the two amplitude will occur

In the limit of CP conservation

Normalize wrong sign rate to the right sign to obtain

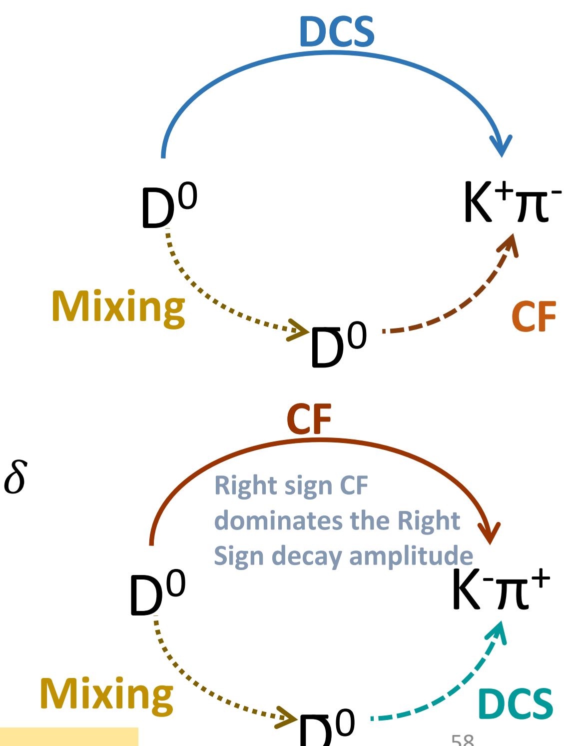
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = RD + \sqrt{R_D}\, y' \Gamma_{D^0}\, t + \frac{x'^2 + y'^2}{4} (\Gamma_{D^0}\, t)2$$

DCS *interference* *mixing*

$$R_D = \left| \frac{A_{DCS}}{A_{CF}} \right|^2 \qquad x' = x\cos\delta + y\sin\delta\, ,\, y' = -x\sin\delta + y\cos\delta$$

$$\delta = arg\left(\frac{A_{DCS}}{A_{CF}}\right) \qquad x = \frac{\Delta m_{D^0}}{\Gamma_{D^0}} \qquad y = \frac{\Delta\Gamma_{D^0}}{2\Gamma_{D^0}}$$

δ → strong phase not directly measurable at B-factories



y' and x'^2 accessible

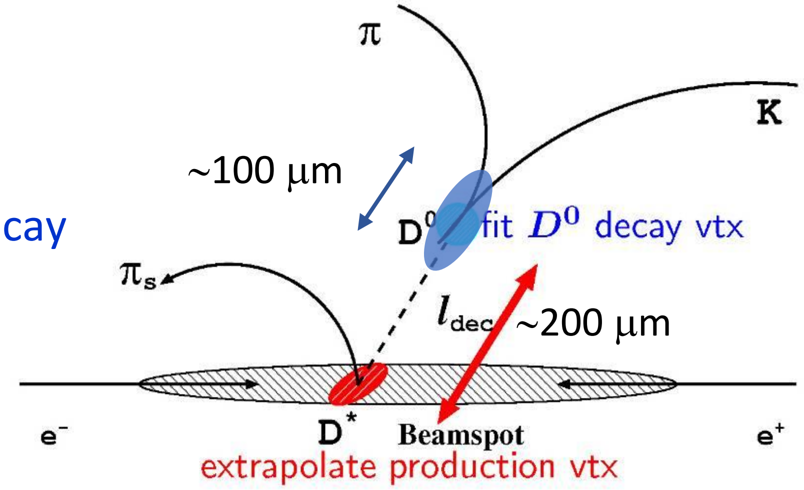
$D^0 - \overline{D}^0$ mixing at B factories $\quad D^0 \to K^+\pi^-$

Experimental method

Tag and suppress background

- $D^{*+} \to D^0\pi^+_{slow}$
- Flavor of D^0 → using charge of π_{slow}
- $p^{CMS}_{D^*}$ > 2.5 GeV/c to eliminate D^0 from B decay

Measure D^0 proper time t, its error σ_t by reconstructing D^0 momentum and flight length l



$$t = \frac{l_{dec}}{c\beta\gamma} \qquad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

σ_t calculated from vtx error matrices

Mixing parameters (x'^2,y') extracted by the fit to the time-dependent ratio of wrong sign to right sign decays

$$R\left(t/\tau_{D^0}\right) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS}\left(t'/\tau_{D^0}\right)\mathcal{R}\left(t/\tau_{D^0} - t'/\tau_{D^0}\right)d(t'/\tau_{D^0})}{\int_{-\infty}^{+\infty} \Gamma_{RS}\left(t'/\tau_{D^0}\right)\mathcal{R}\left(t/\tau_{D^0} - t'/\tau_{D^0}\right)d(t'/\tau_{D^0})}$$

$\mathcal{R}\left(t/\tau_{D^0} - t'/\tau_{D^0}\right)$ is resolution function of the real decay time t'.

WS decay $D^0 \to K^+\pi^-$

Belle, PRL 112, 111801(2014)

976fb^{-1}

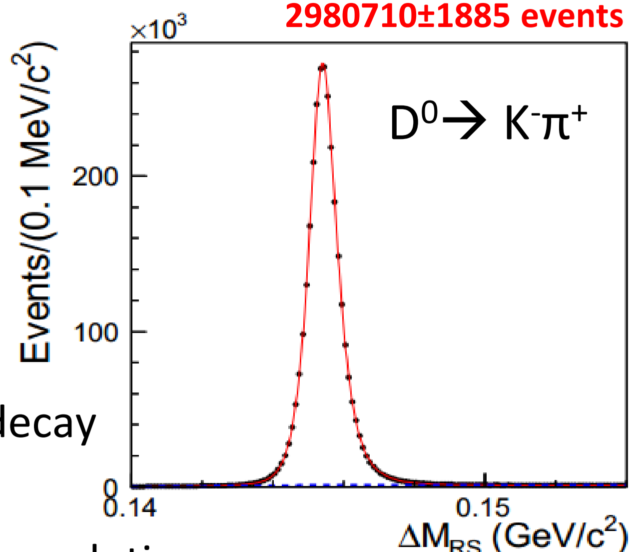
$\Delta M = M(D^{*+} \to D^0(\to K\pi)\pi_s^+) - M(D^0 \to K\pi)$

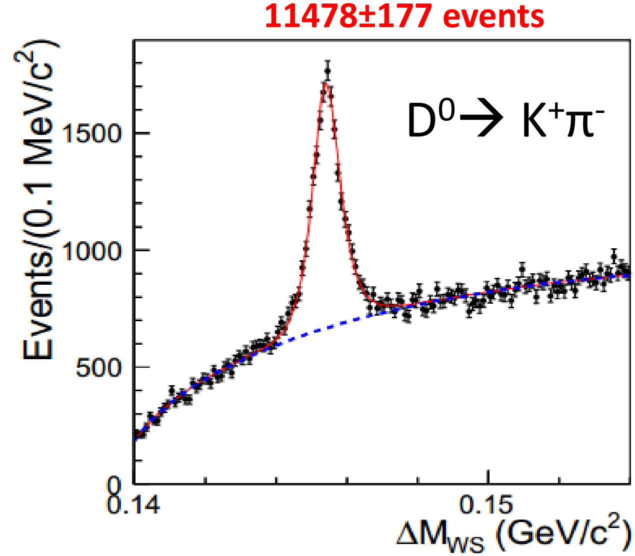
Gaussian + Johnson S_U

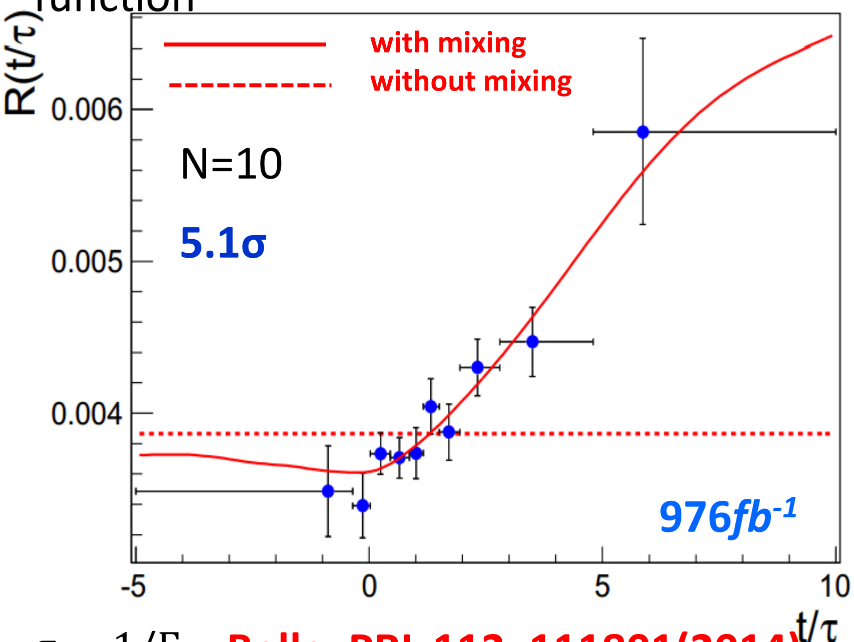
R_{WS}: (0.385±0.006) %

Divide sample into **N** bins of decay time and fit ΔM

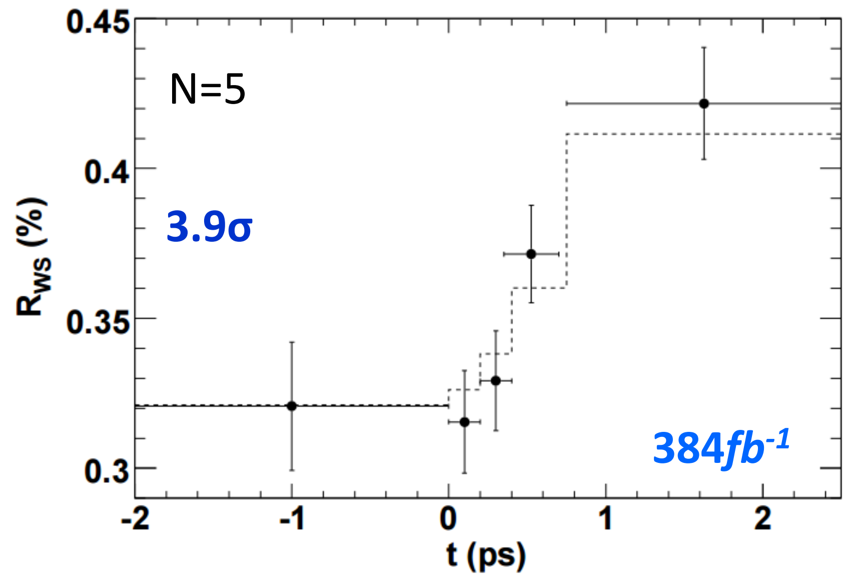
Fitting ratios less sensitive to resolution function







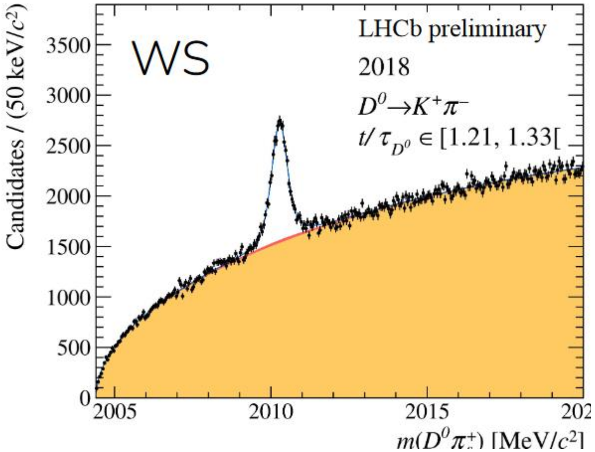
$\tau = 1/\Gamma_{D^0}$ **Belle, PRL 112, 111801(2014)**

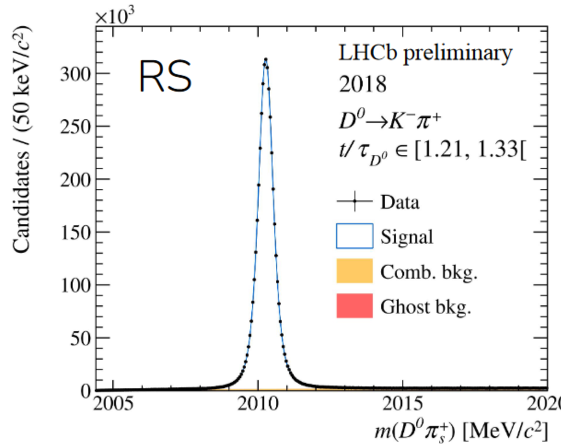


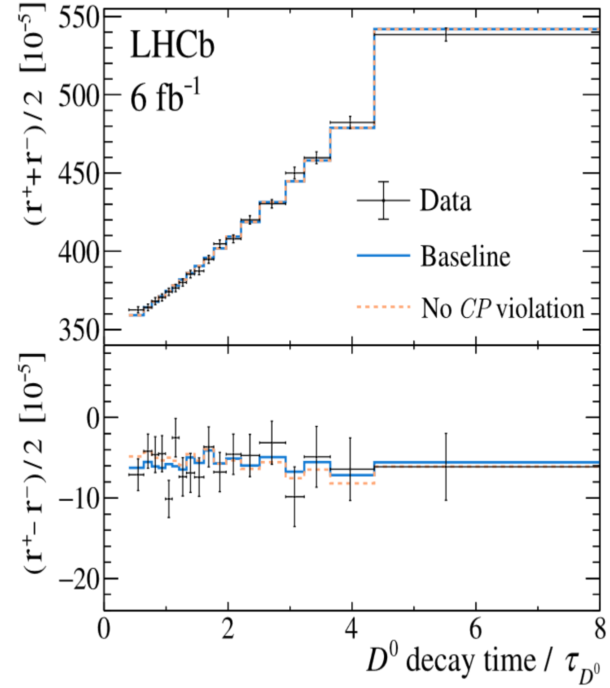
BaBar, PRD 98, 211802(2007)

Most precise measurement by LHCb

LHCB, arXiv:2407.18001







	This result Run 1 + 2	PRD97,031101 Run 1 + 2015/16
$R_{K\pi}$	$(342.7 \pm 1.9)\times10^{-5}$	$(345.2 \pm 3.1)\times10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3)\times10^{-4}$	$(53.3 \pm 5.1)\times10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5)\times10^{-6}$	$(15.8 \pm 5.2)\times10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7)\times10^{-3}$	$(-0.9 \pm 8.9)\times10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4)\times10^{-4}$	$(-2.0 \pm 5.1)\times10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6)\times10^{-6}$	$(4.4 \pm 5.2)\times10^{-6}$

Experiment	R_D $(\times10^{-3})$	y' $(\times10^{-3})$	x'^2 $(\times10^{-3})$
Belle [18]	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$
BaBar [7]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF [5]	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18
LHCb [17]	3.568 ± 0.066	4.8 ± 1.0	0.055 ± 0.049
Belle (this work)	3.53 ± 0.13	4.6 ± 3.4	0.09 ± 0.22

Parameter		Belle	Belle II		
		976 /fb	5 /ab	20 /ab	50 /ab
no CPV	$\sigma(x'^2)(10^{-5})$	22	7.5	3.7	2.3
	$\sigma(y')(\%)$	0.34	0.11	0.056	0.035
CPV-allowed	$\sigma(x')(\%)$		0.37	0.23	0.15
	$\sigma(y')(\%)$		0.26	0.17	0.10
	$\sigma(\|q/p\|)$		0.197	0.089	0.051
	$\sigma(\phi)(^\circ)$		15.5	9.2	5.7

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

y_{CP} in $D^0 \to K_s\omega$

Belle PRD 102, 071102(R) (2020)

CP-odd decays: $\mathcal{B}(D^0 \to K_s\omega) = 5$ times $\mathcal{B}(D^0 \to K_s\phi)$ in PDG

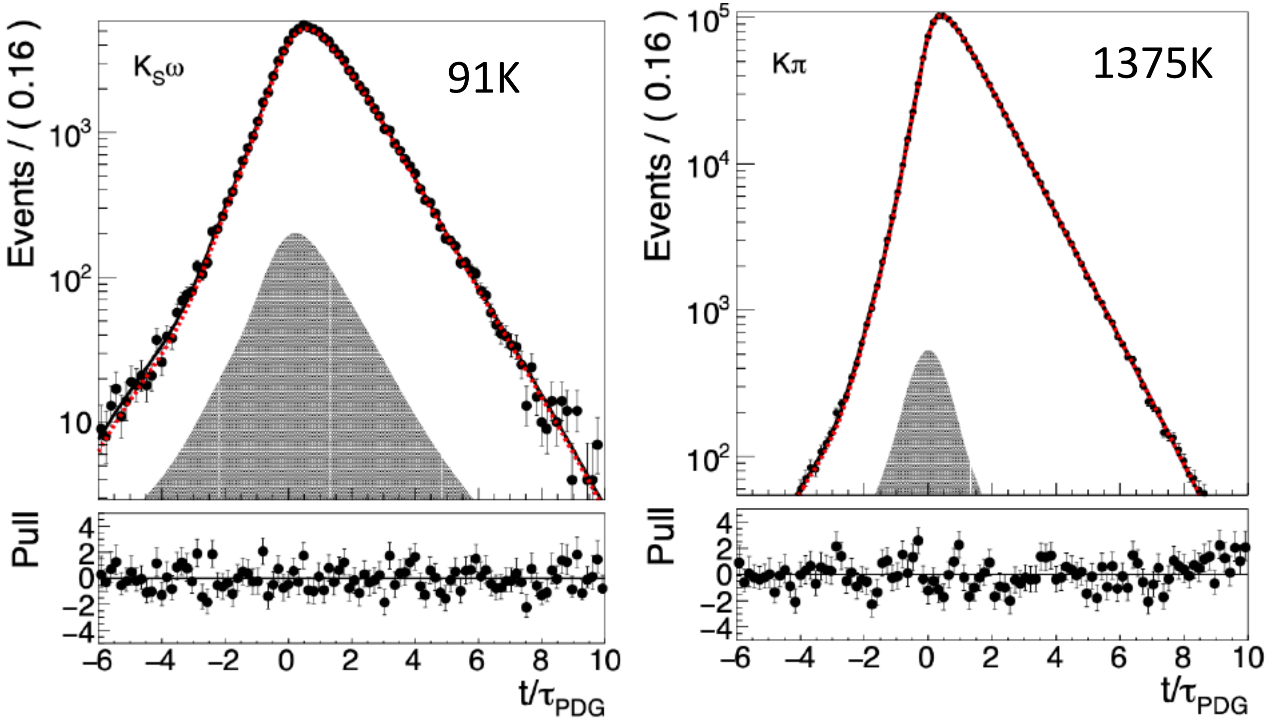
Measure y_{CP} in $D^0 \to K_s\omega$ for the first time.

Utilizes the full Belle data set.

Parameter y_{CP} is determined by

$$y_{CP} = 1 - \tau(D^0 \to K^-\pi^+)/\tau(D^0 \to K_s\omega)$$

Lifetime fitting is performed with resolution (triple Gaussians) and background (with nonzero- and zero-lifetime components),



We get

$$y_{CP} = (0.96 \pm 0.91 \pm 0.62^{+0.17}_{-0.00})\%$$

Statistical, systematic, and from possible CP-even decays in the final state.

The Charm

Not so calm

Thank you