Charm Physics

— Recent Experimental Progress—

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Charm Physics

SM predictions :

- a rather dull EW phenomenology of CKM parameters
- a low frequency for the $D\bar{D}$ oscillations
- tiny CP asymmetries
- extremely rare FCNC decay

Challenging experimental measurement

Motivations for dedicated and comprehensive studies :

- Provide an unique and powerful laboratory for studying the impact of non-pQCD dynamics and for testing the validity of theoretical methods
- Provides a calibration of the theoretical tools for the B decays
- Provide a novel widow on NP search

Charming Promising

Topics to be covered

- D^0-$\bar{D}^0$ Oscillation and CP Violation
- Quantum-Correlated Charm @ threshold
- (Semi-) Leptonic Decay
- Hadronic Decay
- Rare Decay

For each I will highlight recent prgress and speculate on future developments

Apology I can not cover all of results

Charm facilities

Hadron Colliders (Huge cross-section, energy boost)

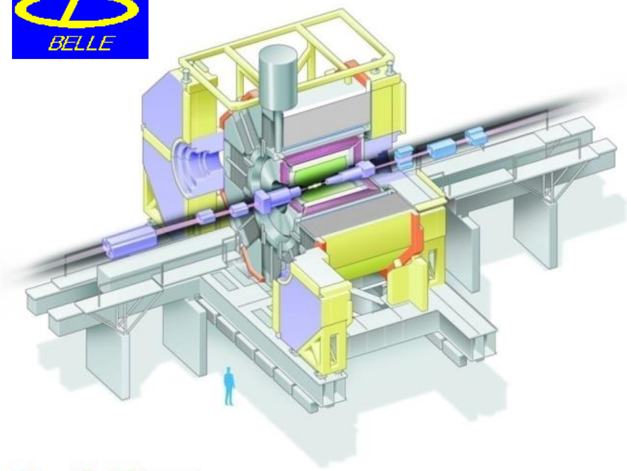
- Tevetron (CDF, D0)
- LHC (LHCb, CMS, ATLAS)

$e^+ e^-$ Collider (more kine. constrains, clean envir., ~100% trigger eff.)

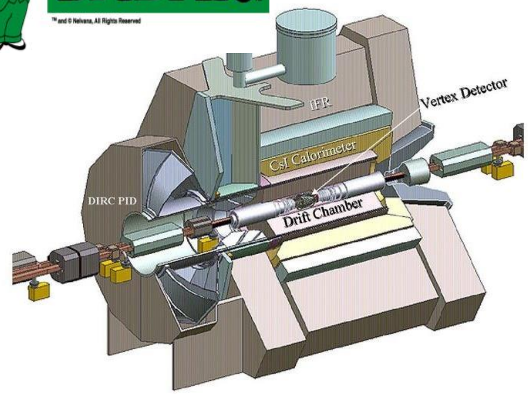
- B-Factories (Belle, BaBar)
  - Prompt D* decay : slow pion tag D flavor, $D^{*+} \to D^0 \pi^+$ or $D^{*-} \to D^0 \pi^-$
  - Semileptonic B decay : muon tag D flavor, $B \to D^0 \mu^+ \nu_\mu X$ or $B \to D^0 \mu^- \nu_\mu X$
- Threshold Production (CLEOc, BESIII)
  - Can not compete in statistics with Hadron colliders & B-Factories
  - Only D meson pairs, no extra CM energy for pions
  - Quantum correlations (QC) and CP-tagging are unique
  - Systematic uncertainties cancellations while applying double tag technique

Results from These Experiments

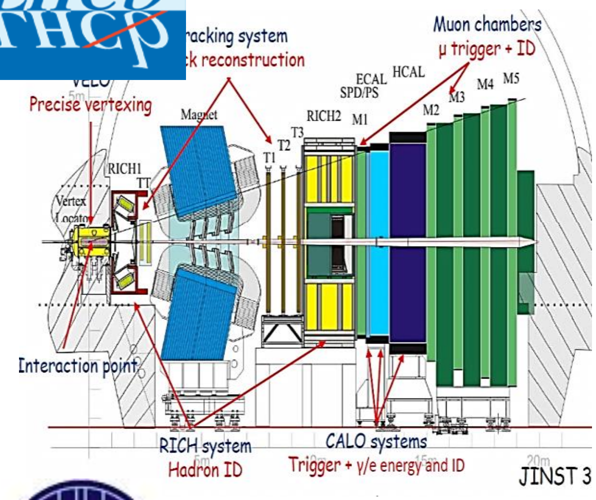
BELLE



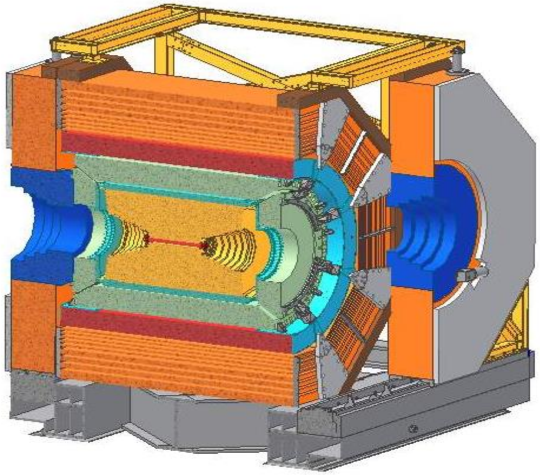
BABAR

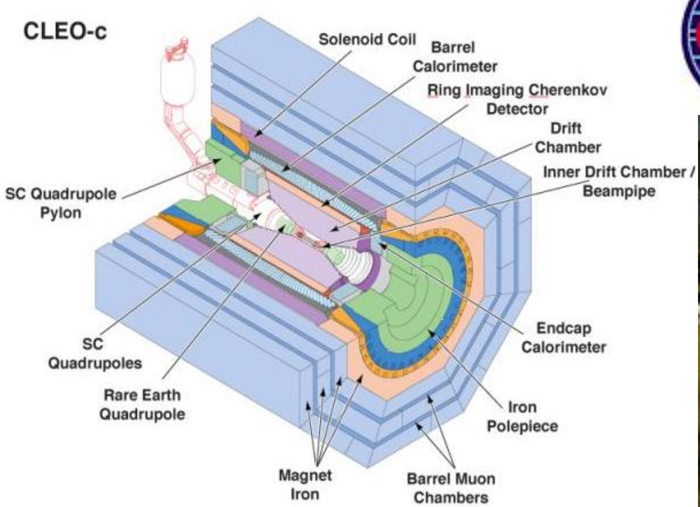


LHCb



BESIII





CDF II b

D^0-$\bar{D}^0$ Oscillation and CPV

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

- D^0 is the only mixing meson with up-type quarks
- Neutral D mass eigenstates are linear combination of flavor states

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \qquad |p|^2 + |q|^2 = 1$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle \qquad \phi = arg(q/p)$$

- Mixing parameters :

$$x = \frac{m_2 - m_1}{\Gamma}$$ ~ Mixing frequency

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$ ~ Lifetime difference

$$P(D^0 \to \bar{D}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\{-\cos(x\Gamma t) + \cosh(y\Gamma t)\}$$

- Short distance is highly suppressed by the GIM mechanism and the matrix elements within the SM. $x \sim \mathcal{O}(10^{-5}), \quad y \sim \mathcal{O}(10^{-7})$

  (NP, e.g. FCNC processes with up-type quark, might manifest in the loop)

- Long distance is dominant, but theoretical uncertainty is large $x, \ y \sim \mathcal{O}(10^{-3})$
- Improving the constraints on the charm mixing parameters is important to testing the SM, such as long-distance effect.

CP Violation

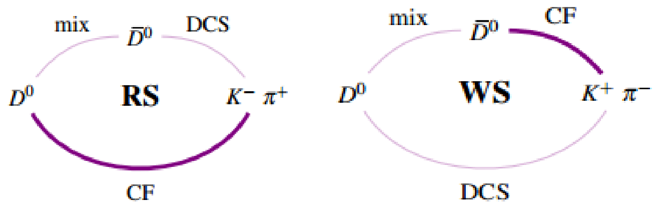
- CP Violation occurs if $|q/p|\neq1$ or CPV phase $\phi\neq0$
- In SM, CPV is expected to be small for charm, theory calculation is challenging.
- Enhancement hits at NP, and CPV search in charm provide probe for NP
- CPV in decay : $A_d \equiv (|A_f|^2 - |\bar{A}_{\bar{f}}|)/(|A_f|^2 - |\bar{A}_{\bar{f}}|)$
- CPV in mixing : $A_m \equiv (|q/p|^2 - |p/q|^2)/(|q/p|^2 + |p/q|^2)$
- CPV in interference through : $\phi = arg\left(\frac{q\bar{A}_{\bar{f}}}{pA_f}\right)$
- No strong evidence for CPV in charm

D^0-$\bar{D}^0$ Mixing in $D^0 \to K\pi$

PRL 110 (2013) 101802

- Measurement of time-dependent ratio of $D^0 \to K^-\pi^+$ (RS) and $D^0 \to K^+\pi^-$ (WS) decays

RS



WS

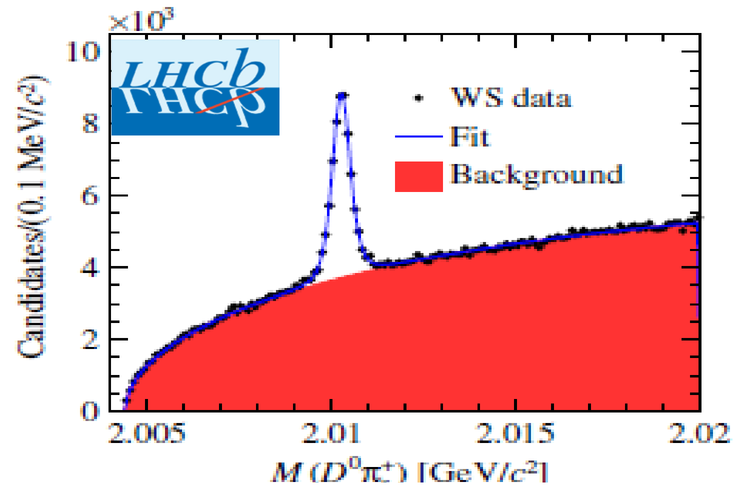
- In limit of small mixing and negligible CPV

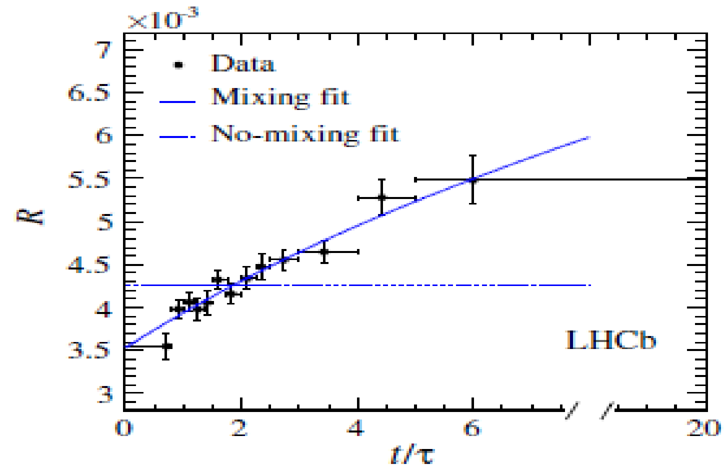
$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(D^0 \to K^-\pi^+) = \sqrt{R_D}\, e^{-i\delta}$$

$$x' \equiv x \cos\delta_{K\pi} + y \sin\delta_{K\pi}, \quad y' \equiv y \cos\delta_{K\pi} - x \sin\delta_{K\pi}$$

- LHCb 1 fb^{-1} data @ 7 TeV :
  - D^0 flavor tagged by slow π^+ charge from $D^{*+} \to D^0\pi^+$
  - Extract the x', y' and R_D by bin χ^2 fit to R(t)
  - No mixing hypothesis excluded at 9.1σ

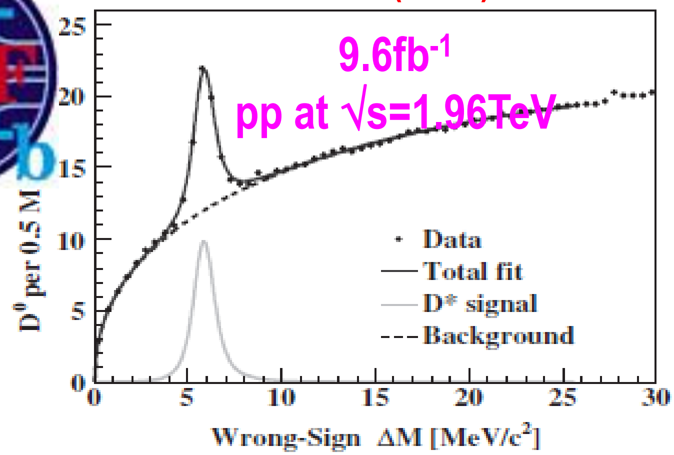




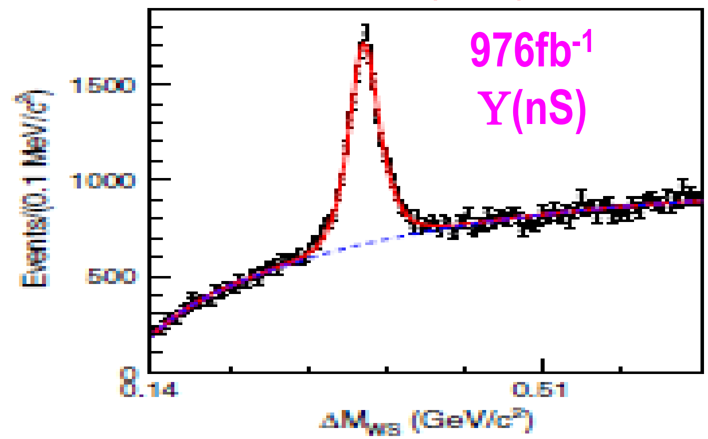
First observation of D^0-$\bar{D}^0$ mixing in a single measurement

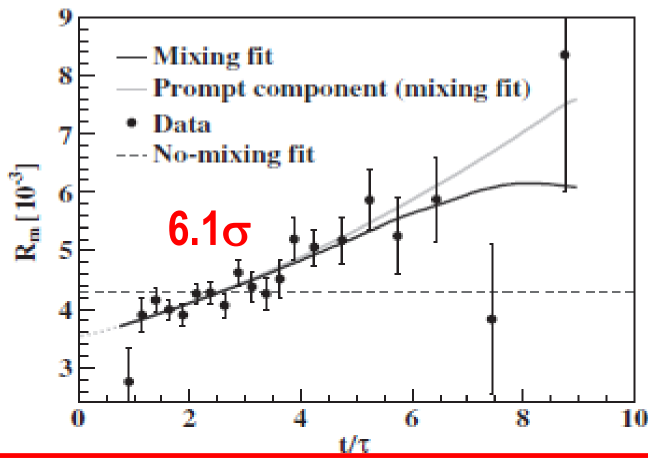
D^0-$\bar{D}^0$ Mixing in $D^0 \to K\pi$

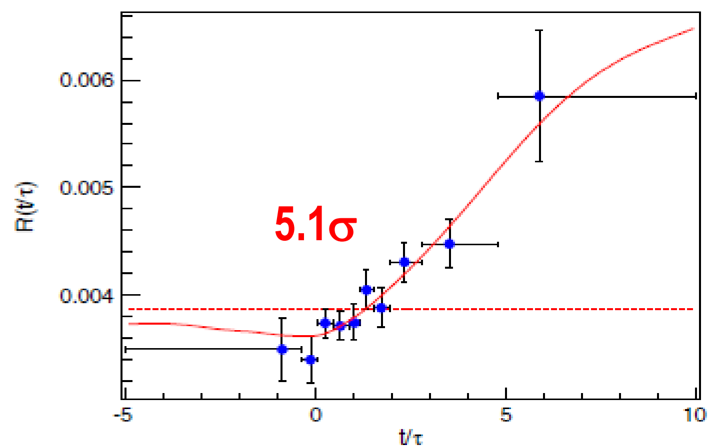
PRL 111 (2013) 231802



PRL 112 (2014) 111801



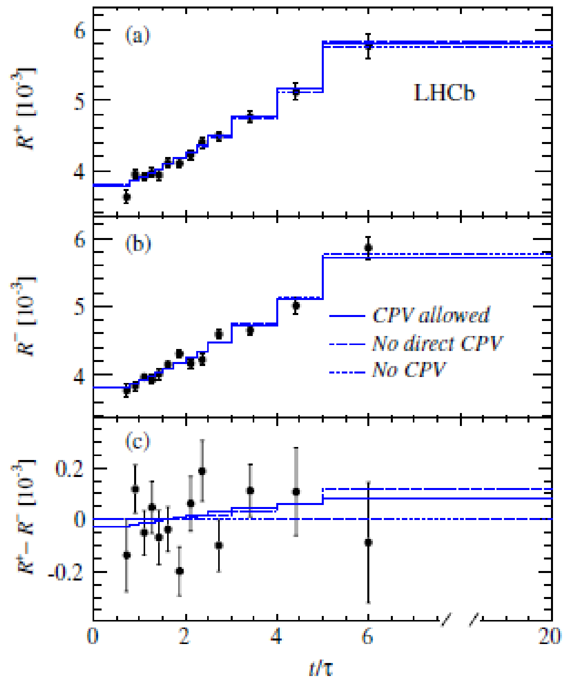




D^0-$\bar{D}^0$ mixing is confirmed by hadron collider CDF and e^+e^- collider Belle

D^0-$\bar{D}^0$ Mixing & CPV in $D^0 \to K\pi$

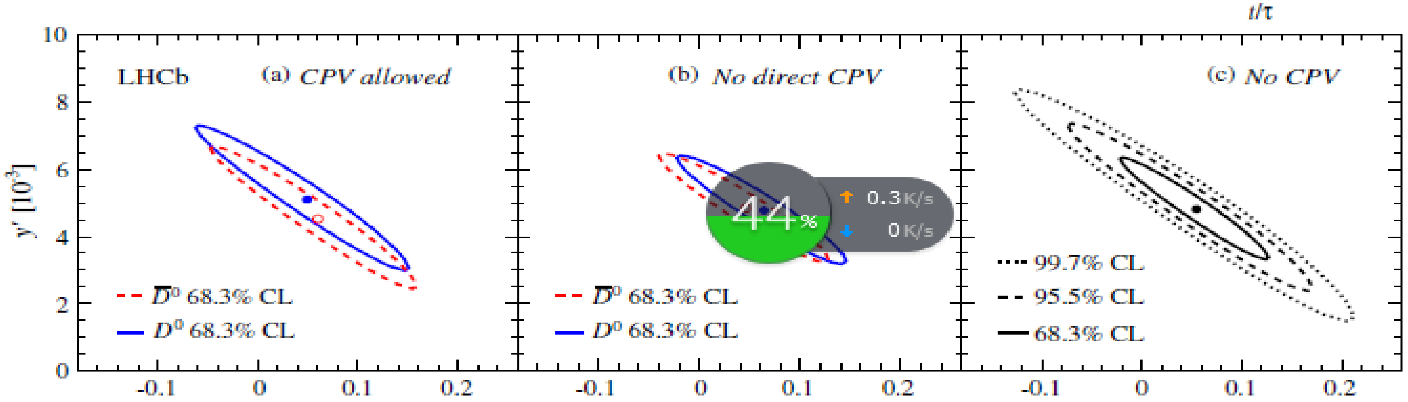
PRL 111 (2013) 251801



- LHCb updated results with 3fb^{-1} pp collision data
- CPV search : splitting D^0 and $\bar{D}^0$ samples, fit to $R^{\pm}(t)$
  - Same parameters : no CPV
  - Different in $R_D^{\pm}$: direct CPV
  - Different in (x'^{2+}, y'^{+}) and (x'^{2-}, y'^{-}) : indirect CPV
- Results compatible with CP conservation :

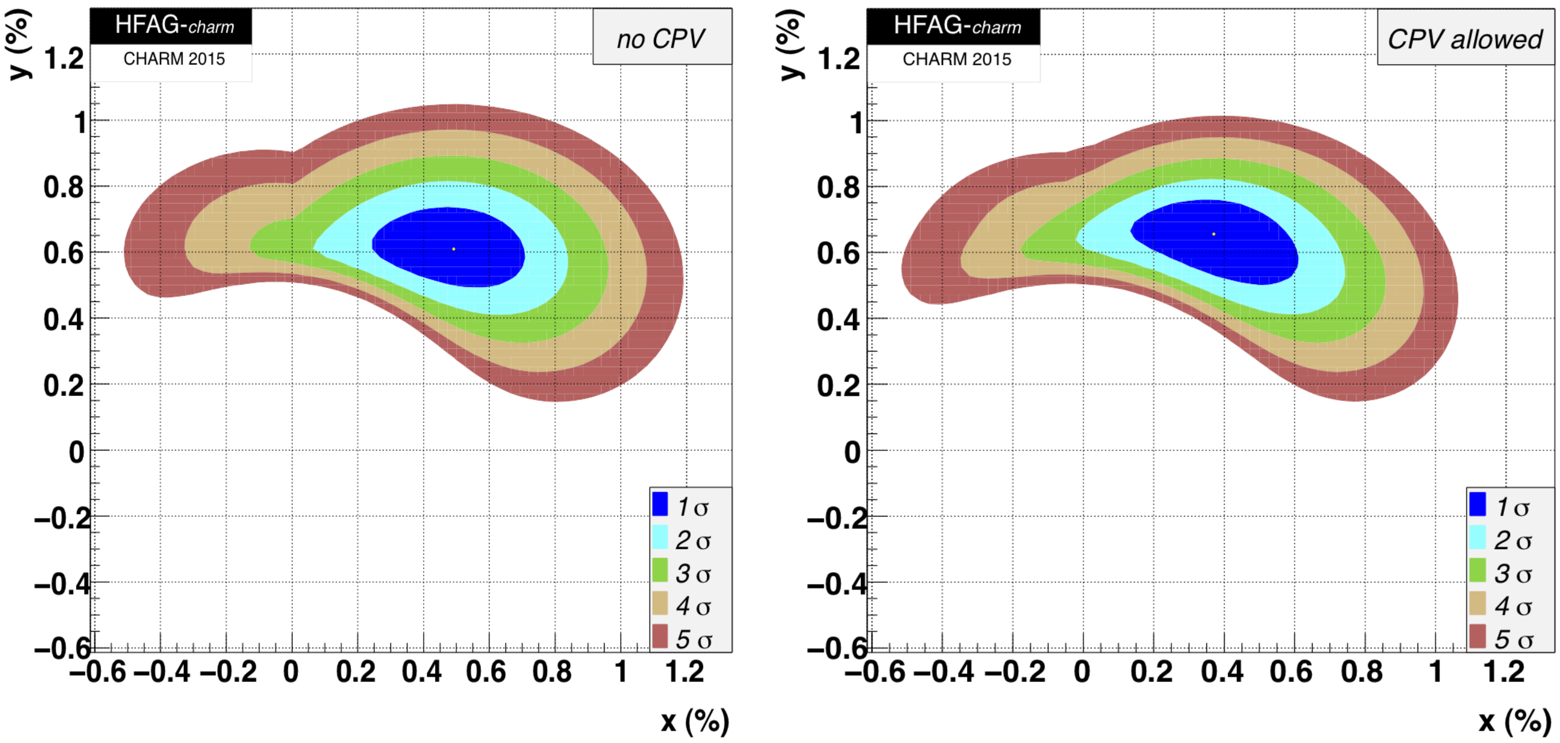
$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

- The mixing Parameters are consistent with, 2.5 times more precise then previous results



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

http://www.slac.stanford.edu/xorg/hfag/charm/CHARM15/results_mix_cpv.html



D^0-$\bar{D}^0$ mixing is well established in different experiments

Indirect CPV in $D^0 \to h^+h^-$

JHEP 04 (2015) 043

- Time-dependent CP asymmetry for a neutral D meson decay to a CP eigenstate :

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f;t) - \Gamma(\bar{D}^0 \to f;t)}{\Gamma(D^0 \to f;t) + \Gamma(\bar{D}^0 \to f;t)}$$

- Approximated as linear-time dependence :

$$A_{CP}(t) \approx A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}$$

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \approx (A_{CP}^{mix}/2 - A_{CP}^{dir})\, y \cos\phi - x \sin\phi$$

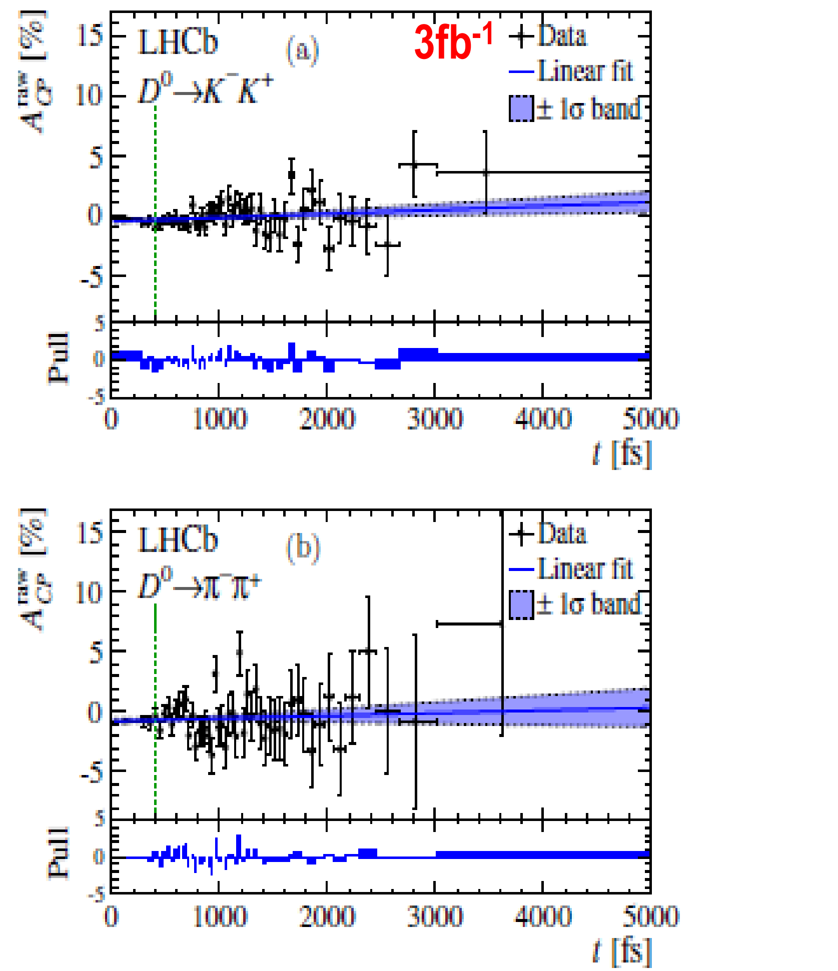
- D^0 flavor tagged by the muon from SL b-hadron decay.
- Consistent with no indirect CPV hypothesis

$$A_\Gamma(K^+K^-) = (-0.134 \pm 0.077^{+0.025}_{-0.034})\%$$

$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.034})\%$$

Assume indirect CPV is universal:

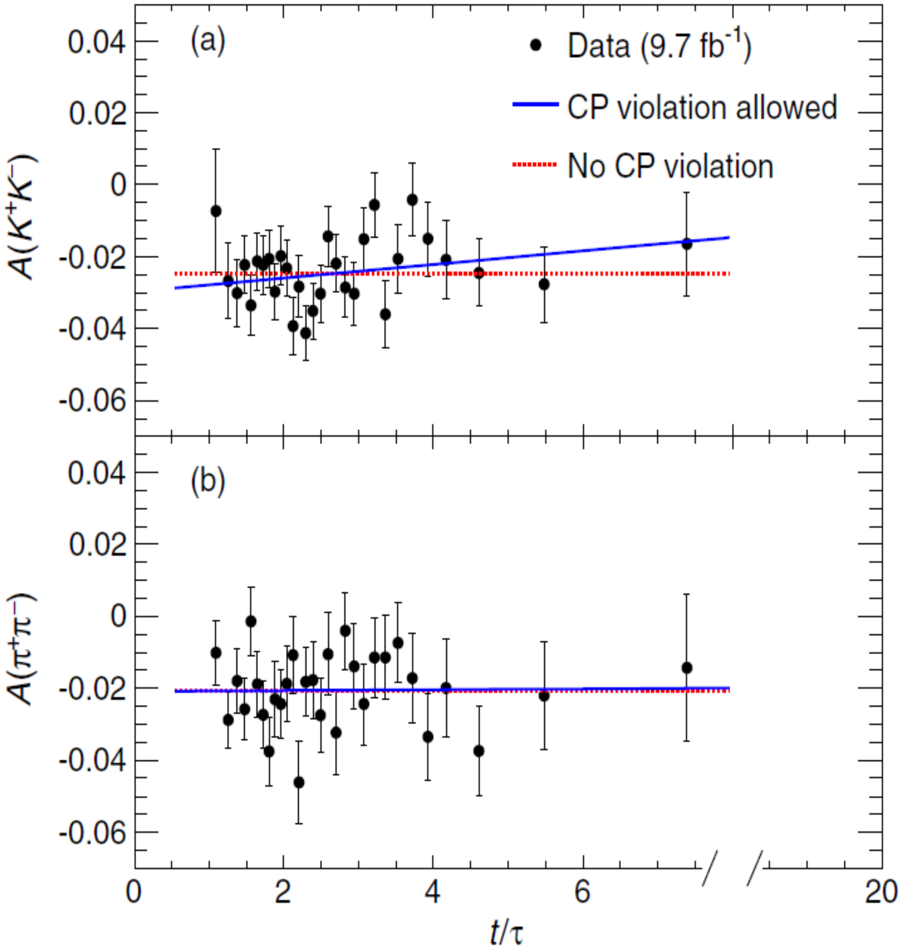
$$A_\Gamma = (-0.125 \pm 0.072)\%$$



Indirect CPV in $D^0 \to h^+h^-$

9.7fb^{-1} 1.96TeV ppbar collision

PRD 90 (2014) 111103 (R)



- D^0 is tagged with slow π in $D^{*+} \to D^0\pi^+$
- CDF Results :

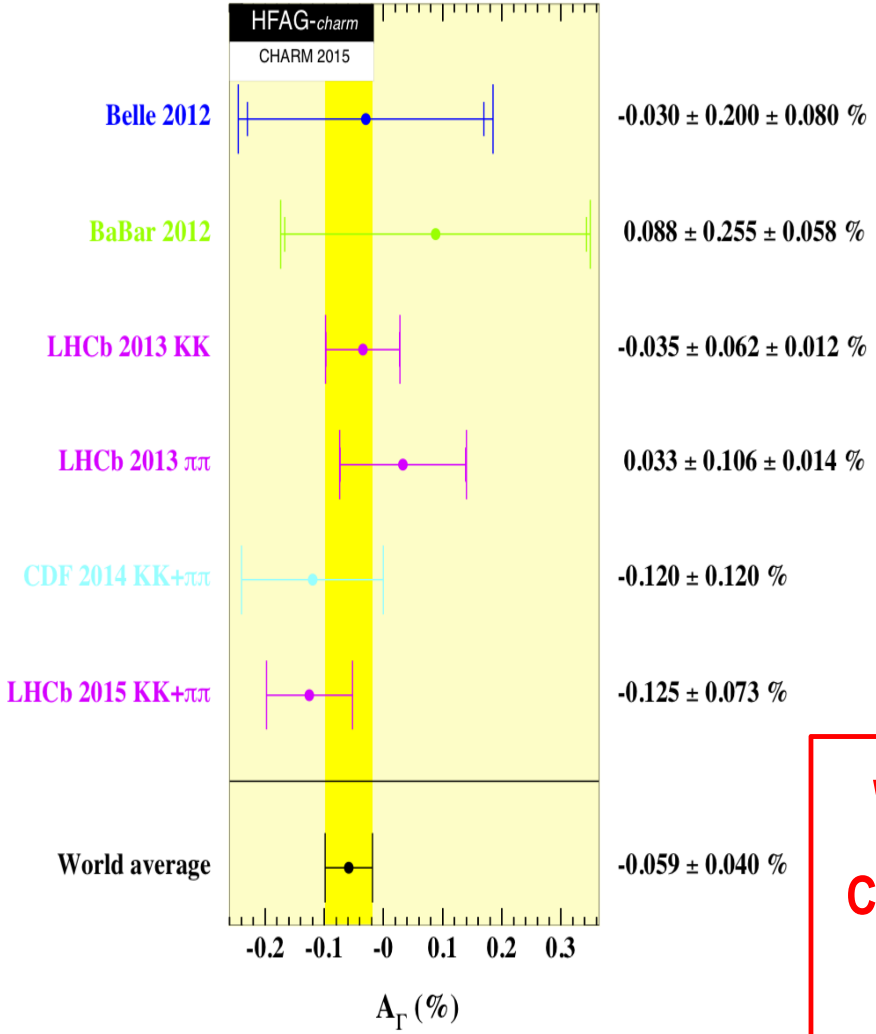
$$A_\Gamma(K^+K^-) = (-0.19 \pm 0.15(\text{stat}) \pm 0.04(\text{syst}))\%$$

$$A_\Gamma(\pi^+\pi^-) = (-0.01 \pm 0.18(\text{stat}) \pm 0.03(\text{syst}))\%$$

- Compatible with the absence of CPV
- Consistent with determination from other experiments
- Among the world's best results

Indirect CPV in $D^0 \to h^+h^-$

http://www.slac.stanford.edu/xorg/hfag/charm/CHARM15/results_mixing.html



arXiv:1212.3478

PRD 87 (2012), 012004

PRL 112 (2014) 041801

PRL 112 (2014) 041801

PRD 90 (2014) 111103 (R)

JHEP 04 (2015) 043

World Average : -0.059±0.040%

Consistent with the hypothesis of no indirect CPV in $D^0 \to h^+h^-$

Direct CPV in $D^0 \to h^+h^-$

- Time integrated CP asymmetry receives contributions from both direct and indirect CPV

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

- Assuming ind. CPV is decay mode independent, Only the effect of direct CPV remain in ΔA_{CP}

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$= [a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)] + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{ind}$$

Vanish in the limit

JHEP 07 (2014) 041

- LHCb 3fb^{-1} data, muon flavor tagged D^0 in B hadron SL decay
- The raw asymmetry for a D meson decay :

$$A_{raw} = \frac{N(D \to f) - N(\bar{D} \to f)}{N(D \to f) + N(\bar{D} \to f)} = A_{CP} + A_D(\mu^-) + A_P(\bar{B})$$

- And ΔA_{CP}

$$\Delta A_{CP} = A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- No significant CPV in SCS decay at the level 10^{-3}

$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$$
$$A_{CP}(K^+K^-) = (-0.06 \pm 0.15 \pm 0.10)\%$$
$$A_{CP}\pi^+\pi^- = (-0.20 \pm 0.19 \pm 0.10)\%$$

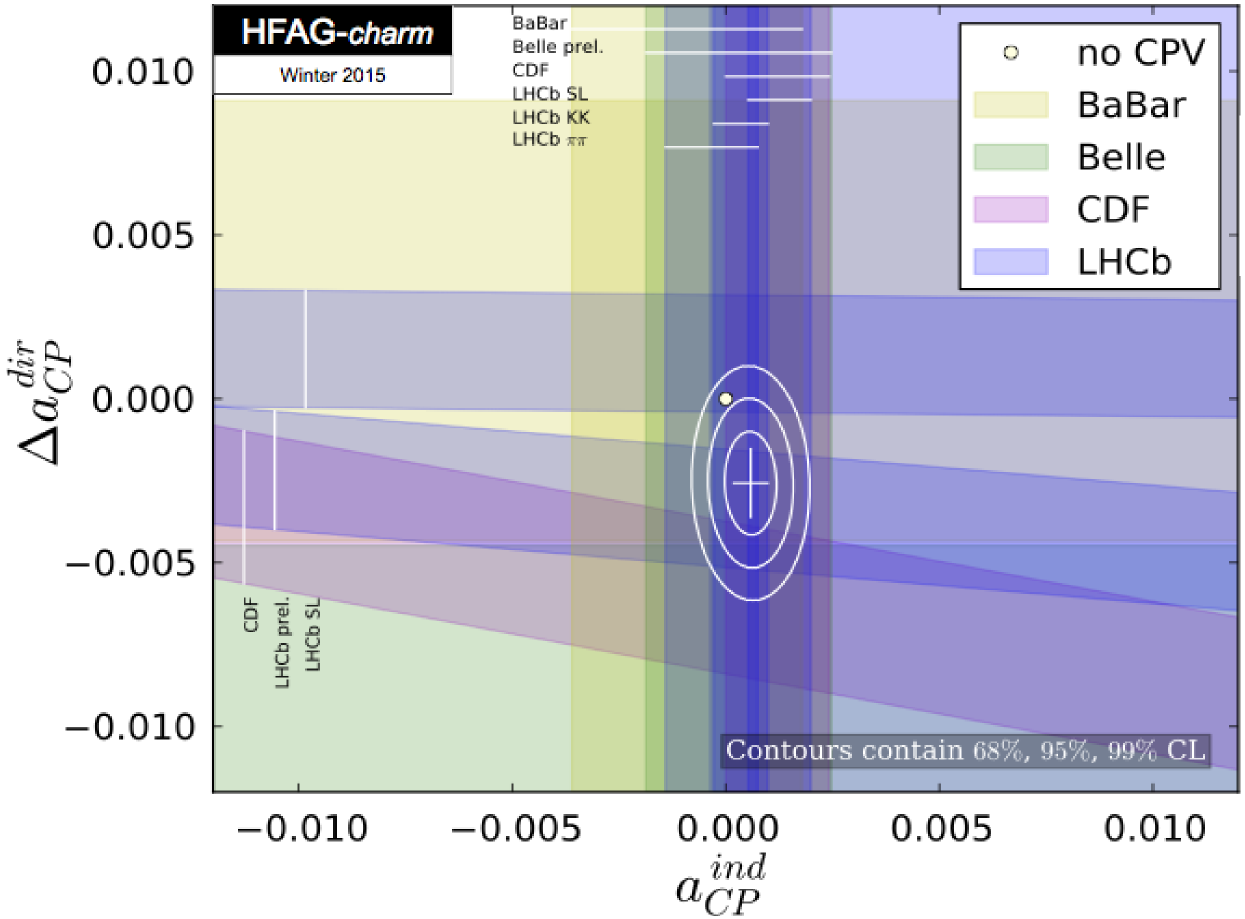
Most precise measurement of time-integrated CPV $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$

Belle update the results of similar analysis with full data set, please see Tara's talk at Charm 2015
http://belle.kek.jp/belle/talks/CHARM15/nanut.pdf

CPV in $D^0 \to h^+h^-$

http://www.slac.stanford.edu/xorg/hfag/charm/April15/DCPV/direct_indirect_cpv.html

Combine time-dependent and time-integrated CPV results



$$a_{CP}^{ind} = (0.058 \pm 0.040)\%$$

$$\Delta a_{CP}^{dir} = (-0.257 \pm 0.104)\%$$

P = 0.018 of no CPV

CP Asymmetry in $D^0 \to K_s K_s$

- D^0 decay into a neutral mesons pair is particular interest for the search of NP and the understanding of penguin contributions.
- CPV is expected larger if CPV exists in D^0 decay to charge meson pair
- SM predicts a 95% CL UL of 1.1% for direct CPV in decay $D^0 \to K_s K_s$

- LHCb performed the search of time integrated CP asymmetry with 3 fb^{-1} data

$$A_{CP} = \frac{N^+ - N^-}{N^+ + N^-}$$

- The D^0 flavor is tagged by the slow π^+ from $D^{*+} \to D^0 \pi^+$
- The CP asymmetry is obtained in four KsKs reconstruction categories

$$A_{CP} = -0.029 \pm 0.052 \pm 0.022$$

arXiv:1508.06087
LHCb-PAPER-2015-030

- Consistent with no CP Violation and with SM expectation
- Three times smaller for uncertainty than previous measurement (PRD 63, 2001, 071101)

CP Asymmetry in $D^0 \to \pi^0\pi^0$

- Search for the time integrated CPV using data sample 966 fb^{-1}
- The flavor of D^0 is tagged with the slow π^+ in decay $D^{*+} \to D^0\pi^+$
- The reconstructed asymmetry :

$$A_{rec} = \frac{N_{rec}^{D^{*+}\to D^0\pi_s^+} - N_{rec}^{D^{*-}\to \bar{D}^0\pi_s^-}}{N_{rec}^{D^{*+}\to D^0\pi_s^+} + N_{rec}^{D^{*-}\to \bar{D}^0\pi_s^-}}$$

$$= A_{CP} + A_{FB} + A_{\epsilon}^{\pi_s}$$

The underlying CP asymmetry

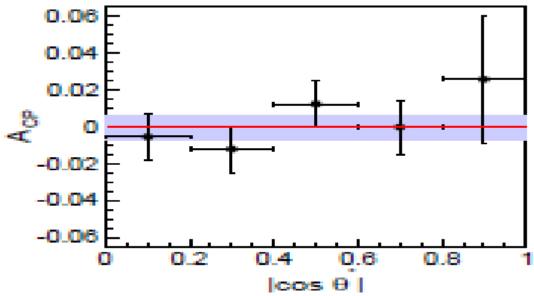
The Forward-backward asymmetry due to γ-Z^0 interference and High order QED effects
Is an odd function of the cosine of D^{*+} polar angle

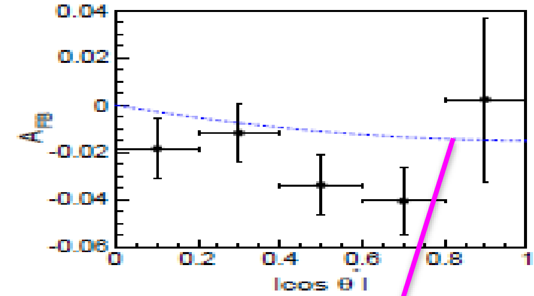
Estimated with CF decay $D^{*+} \to D^0\pi_s \to K^-\pi^+\pi_s$

- Corrected A_{rec}^{cor} :

$$A_{rec}^{cor} = A_{CP} + A_{FB}(\cos\theta^*)$$
$$A_{CP} = |A_{rec}^{cor}(\cos\theta^*) + A_{rec}^{cor}(-\cos\theta^*)|/2$$
$$A_{FB} = |A_{rec}^{cor}(\cos\theta^*) - A_{rec}^{cor}(-\cos\theta^*)|/2$$

PRL 112 (2014) 211601





Lower than leading order QED prediction,
High-order correction may bring better agreement

$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$$

No evidence for CP Violation

An order of magnitude improvement in precision

Others CPV Measurement

Two-body Final States :

- Search for direct CPV in SCS $D_{(S)}^{\pm} \to K_S h^{\pm}$

  (LHCb, $3fb^{-1}$, JHEP 1410 (2014) 025, BaBar, $469fb^{-1}$, PRD 87 (2013), 052012)

Multi-body Final States :

- Model-independent searches for CPV in $D^+ \to \pi^+\pi^-\pi^+$ (LHCb, $1fb^{-1}$, PLB 728 (2014) 585)
- Search for direct CPV in SCS decay $D^{\pm} \to K^+K^-\pi^{\pm}$ with Model-(in)dependent Dalitz analysis

  (BaBar, $476fb^{-1}$, PRD 87 (2013), 052010)
- Search for indirect CPV using $D^+ \to \pi^+\pi^-\pi^+$ with a time-dependent amplitude analysis

  (Belle, $921fb^{-1}$, PRD 89 (2014), 091103)
- Time-integrated CPV in SCS process $D^0 \to \pi^+\pi^-\pi^0$ (LHCb, $2fb^{-1}$, PLB 740 (2015) 158)
- Time-dependent Dalitz analysis in $D^0 \to K_s\pi^-\pi^+$

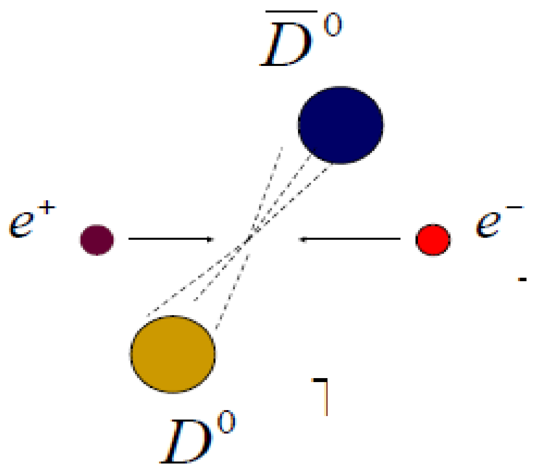
  (LHCb, $1fb^{-1}$, LHCb-Paper-2015-042, see Canto's talks at LHCP 2015 meeting)
- CPV via T-odd moments in $D^0 \to K^+K^-\pi^+\pi^-$ (LHCb, 3fb-1, JHEP 10 (2015) 005)
- ....

No CPV observation, more results are expected soon

Quantum-Correlated Charm

@ Threshold

Quantum Correlated $D^0\bar{D}^0$ States



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 should be a quantum-correlated state

The J^{PC} of ψ'' is 1^{--}, a definite C = – 1 state for D^0D^0 pair

D^0 mesons will have opposite CP

The quantum coherence of $D^0\bar{D}^0$ pairs play an unique way to study :

- Strong phase, $\cos\delta$: Double tag events, e.g. $K^-\pi^+$ VS. CP±
- Strong phase c_i, s_i (Dalitz) : $K_s\pi^+\pi^-$ VS. CP± , $K_s\pi^+\pi^-$ VS. Flavor Tag, $K_s\pi^+\pi^-$ VS. $K_s\pi^+\pi^-$
- Charm mixing, y_{CP} : Flavor tag VS. CP±
- Mixing parameters, (x^2+y^2) : $(K^-\ell^+\nu)2$, $(K^-\pi^+)2$
- DCS : Wrong sign decay $K^-\pi^+$ VS. $K^-\ell^+\nu$
- ....

Typical kinematic variables :

$$\Delta E = E_D - E_{Beam}$$

$$M_{BC} = \sqrt{E_{Beam}^2 - \vec{p}_D^{\,2}}$$

Strong Phase $\delta_{K\pi}$ in $D^0 \to K\pi$

Time-dependent decay rate of WS process $D^0 \to K^+\pi^-$, most precise measurement for the mixing parameter, sensitive to :

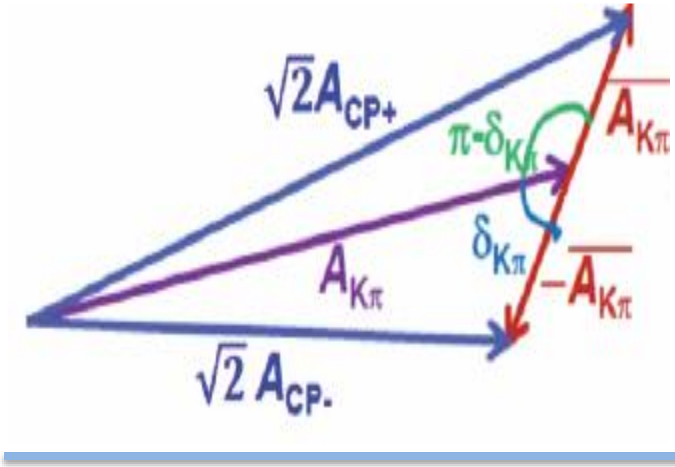
$$x' \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

$$y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

Strong phase $\delta_{K\pi}$: Difference between the DCS and CF amplitude

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

Important for extracting x and y from x' and y'



$$\langle K\pi|D^0_{CP\pm}\rangle = (\langle K\pi|D^0\rangle \pm \langle K\pi|\bar{D}^0\rangle)/\sqrt{2} \Rightarrow \sqrt{2}A_{CP\pm} = A_{K\pi} \pm \bar{A}_{K\pi}$$

$$2r_{K\pi}\cdot\cos\delta_{K\pi} \approx \mathcal{A}_{CP\to K\pi} \equiv \frac{|A_{CP-}|^2 + |A_{CP+}|^2}{|A_{CP-}|^2 + |A_{CP+}|^2}$$

$$= \frac{Br(D_{CP-}\to K\pi) - Br(D_{CP+}\to K\pi)}{Br(D_{CP-}\to K\pi) + Br(D_{CP+}\to K\pi)}$$

Ignore the mixing effect

Strong Phase $\delta_{K\pi}$ in $D^0 \to K\pi$

Signal reconstruction :

- Single Tag (ST) : CP Tags (5 modes CP+, 3 modes CP–)
- Double Tag (DT) : $K\pi$ + CP Tag

Type	Mode
Flavored	$K^-\pi^+$, $K^+\pi^-$
$S+$	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
$S-$	$K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$

BESIII 2.9 fb^{-1} ψ'' data PLB 734 (2014) 227

Branching Ratio Measurement :

$$Br(D_{CP\pm} \to K\pi) = \frac{N_{K\pi,CP\pm}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}$$

Asymmetry of CP tagged D decay rate : $A_{CP\to K\pi} = (12.7 \pm 1.3 \pm 0.7) \times 10^{-2}$

Consider the mixing effect

$$2r_{K\pi} \cdot \cos\delta_{K\pi} + y = (1 + R_{WS}) \cdot A_{CP\to K\pi}$$

External input from HFAG2013 and PDG

- $r^2_{K\pi} = (0.347 \pm 0.006)\%$
- $y = (0.66 \pm 0.09)\%$
- $R_{WS} = (0.380 \pm 0.005)\%$

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

- World best precision
- The statistical errors dominant the precision
- BESIII 20 fb^{-1} data, precision will reach 0.05

CLEO-c results *[Phys. Rev. D 86 (2012) 112001]*

$$\cos\delta_{K\pi} = 0.81^{+0.22+0.07}_{-0.18-0.05}$$

$$\cos\delta_{K\pi} = 1.15^{+0.19+0.00}_{-0.17-0.08} \quad \text{(globalfit)}$$

y_{CP} Measurement

The mixing parameters extracted from time-dependent decay $D^0 \to K\pi$ is highly corrected, it is important to access the mixing parameters directly.

$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

In absence of CPV, $|P/q|=1$ and $\phi=0$, leading to $y_{CP} = y$

- The D^0 semileptonic decay is sensitive to flavor content and does not depend on the CP eigenvalue
- The total decay width of the $D_{CP\pm}$ depend on its CP eigenvalue : $\Gamma_{CP\pm}=\Gamma(1\pm y_{CP})$

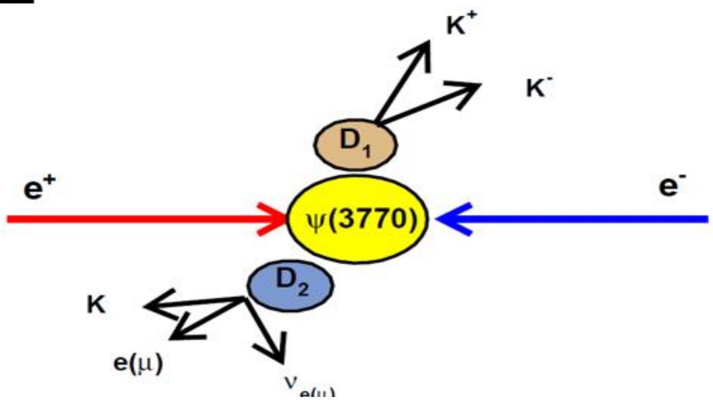
The semileptonic decay of the CP eigenstates $D_{CP\pm}$

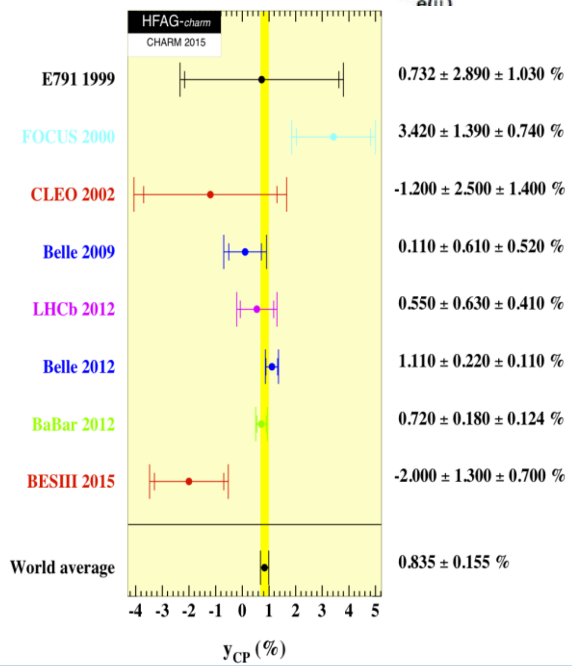
$$B_{D_{CP\pm}\to l} \approx B_{D\to l}(1 \mp y_{CP})$$

$$y_{CP} \approx \frac{1}{4}\left(\frac{B_{D_{CP-}\to l}}{B_{D_{CP+}\to l}} - \frac{B_{D_{CP+}\to l}}{B_{D_{CP-}\to l}}\right)$$

y_{CP} Measurement

BESIII 2.9 fb^{-1} ψ″ data PLB 744 (2015) 339





PRL 83 (1999) 32

PLB 485 (2000) 62

PRD 65 (2002) 092001

PRD 80 (2009) 052006

JHEP 04 (2012) 129

Charm 2012

PRD 87 (2013) 012004

Measure y_{CP} using CP-tagged semi-leptonic D decay

- Single Tag : 3 modes from CP+ and CP-
- Double Tag : CP Tag + Semi-leptonic D

Type	Mode
CP+	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$
CP−	$K_S^0\pi^0$, $K_S^0\omega$, $K_S^0\eta$
Semileptonic	$K^\mp e^\pm \nu$, $K^\mp \mu^\pm \nu$

- Branching fraction measurement

$$B_{D_{CP\mp}\to l} = \frac{N_{CP\pm;l}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{CP\pm;l}}$$

BESIII Results

$$y_{CP} = (-2.0 \pm 1.3 \pm 0.7)\%$$

- Compatible with previous measurement
- Statistically limited, less precise than average
- More data may help

γ/ϕ_3 measurement from $B^- \to D^0 K^-$

CKM direct Measurement

$$\alpha/\phi_2 = (87.6^{+3.5}_{-3.3})^o$$

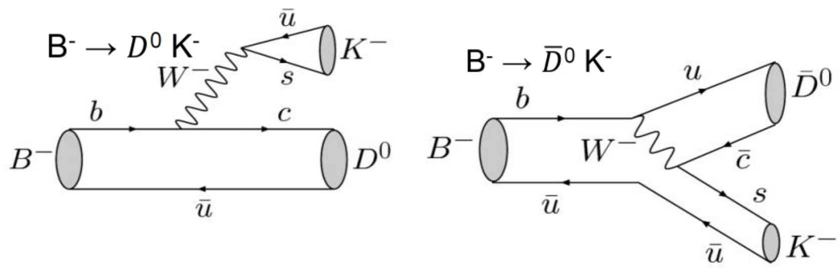
$$\beta/\phi_1 = (21.85^{+0.68}_{-0.67})^o$$

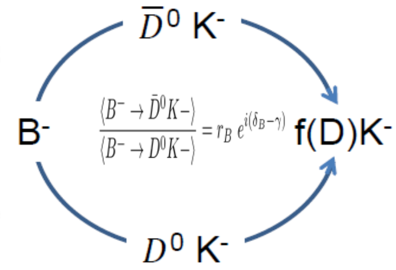
$$\gamma/\phi_3 = (73.2^{+6.3}_{-7.0})^o$$

Least precisely measure angle

The most sensitive method to constrain γ/ϕ_3 nowadays

Determine γ/ϕ_3 through the measurement of the inference between $b \to c$ and $b \to u$ transitions when D^0 and $\bar{D}^0$ both decay to the same final state f(D)





Binned Decay rate :

$$\Gamma(B^\pm \to D(K_s\pi^+\pi^-)K^\pm)_i = T_i + r_B{}^2 T_{\bar{i}} + 2r_B\sqrt{T_i T_{\bar{i}}}\cos(\delta_B \pm \gamma - \Delta\delta_D)$$

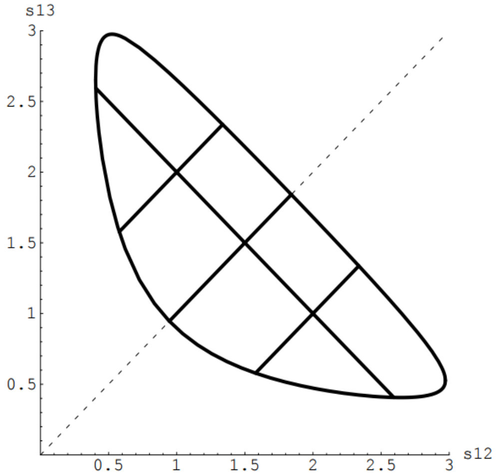
$$= T_i + r_B{}^2 T_{\bar{i}} + 2r_B\sqrt{T_i T_{\bar{i}}}\{c_i\cos(\delta_B \pm \gamma) + s_i\sin(\delta_B \pm \gamma)\}$$

- T_i : Bin yield measured in flavor decays
- r_B : color suppression factor~0.1
- δ_B : strong phase of B decay
- c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively

  where $\Delta\delta_D$ is the difference between phase of D^0 and D^0

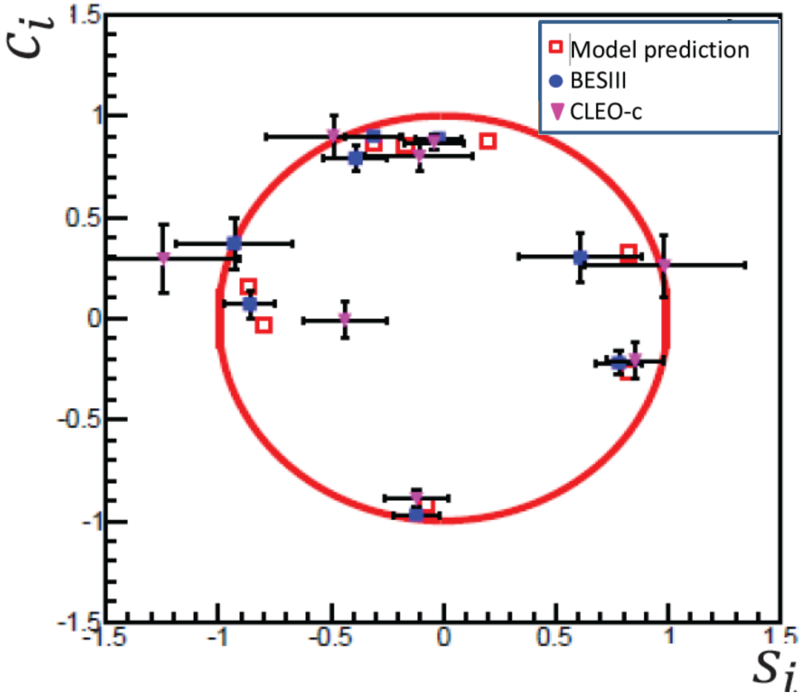
Measured at B-Factories

Through $D^0 \to K_S\pi^+\pi^-$ analysis



Mirrored binning over x=y makes it so $c_i = c_{-i}$ and $s_i = -s_{-i}$

BESIII Preliminary Results



BESIII 2.9 fb^{-1} ψ'' data

$D^0 \to K_S \pi^+ \pi^-$

- Still statistical limited, only Statistical errors are shown
- Consistent with CLEO-c measurements, but superior in statistical errors

- The reduction in c_i, s_i contribution to the uncertainty in γ/ϕ_3 of ~40% (~80% for 20fb^{-1} data)

BELLE, Model-Independent Dalitz, PRD 85, 112014 (2012)

$$\gamma/\phi_3 = (77.3^{+15.1}_{-14.9}(stat.) \pm 4.1(syst.) \pm 4.3(c_i/s_i))^o$$

$$\downarrow$$

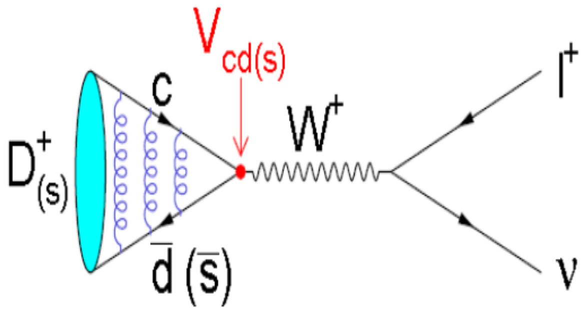
$$\pm 2.5(0.9)(c_i/s_i)$$

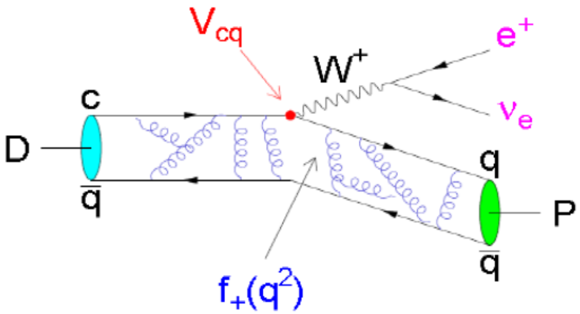
- Crucial inputs for the future analysis carried out in the LHCb and BELLE II experiment (stat. sensitivity reaches 1~2%)

(Semi-) Leptonic Decay

(Semi-) Lepton Decay

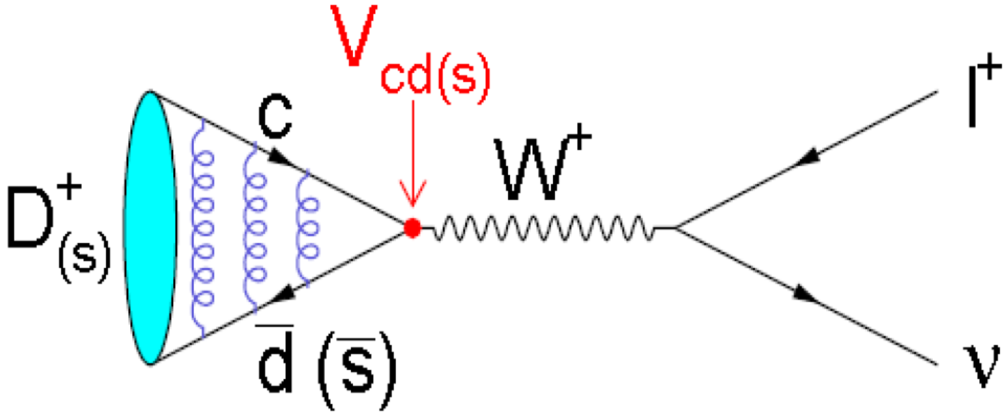
D leptonic and semi-lepton decay are ideal window to probe for weak and strong effects





- In CKM, the uncertainty is dominated by the uncertainty of of $f_{B(S)}$ and $f_+^{b\to\pi}(q^2)$ of B meson calculated in LQCD
- Precision measurement of (semi-) leptonic decay rata can be used to validate $f_{D(S)+}$ and $f_+^{D\to K(\pi)}(q^2)$ calculated in LQCD, and then improve LQCD calculation of $f_{B(S)}$ and $f_+^{b\to\pi}(q^2)$ for B meson.
- Recent improved LQCD calculation on $f_{D(S)+}$ (0.5%) and $f_+^{D\to K(\pi)}(q^2)$ (1.7%, 4.4%) provide good chance to constrain the CKM matrix element $|V_{cs(d)}|$, test the unitarity of CKM and search for NP

$D^+_{(s)}$ Leptonic Decay



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

Bridge to precisely measure :

- Decay constants $f_{D(s)+}$ with input $|V_{cd(s)}|$ of CKMfit
- CKM matrix element $|V_{cd(s)}|$ with input $f_{D(s)+}$ from LQCD

Search for new physics

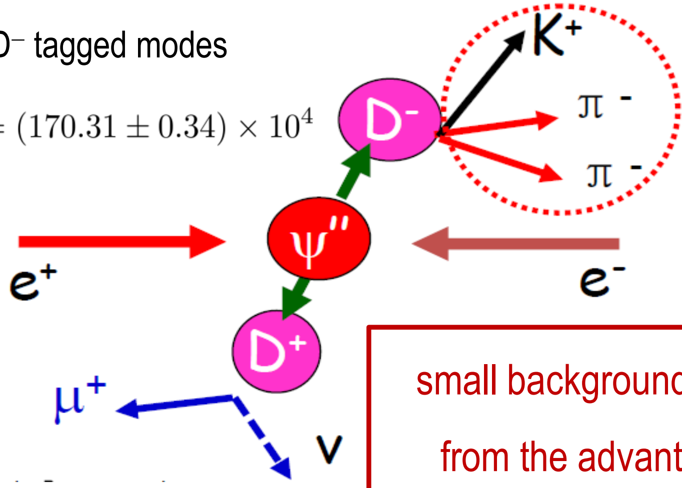
D^+ Leptonic Decay

$$e^+e^- \to \psi'' \to D^+D^-$$

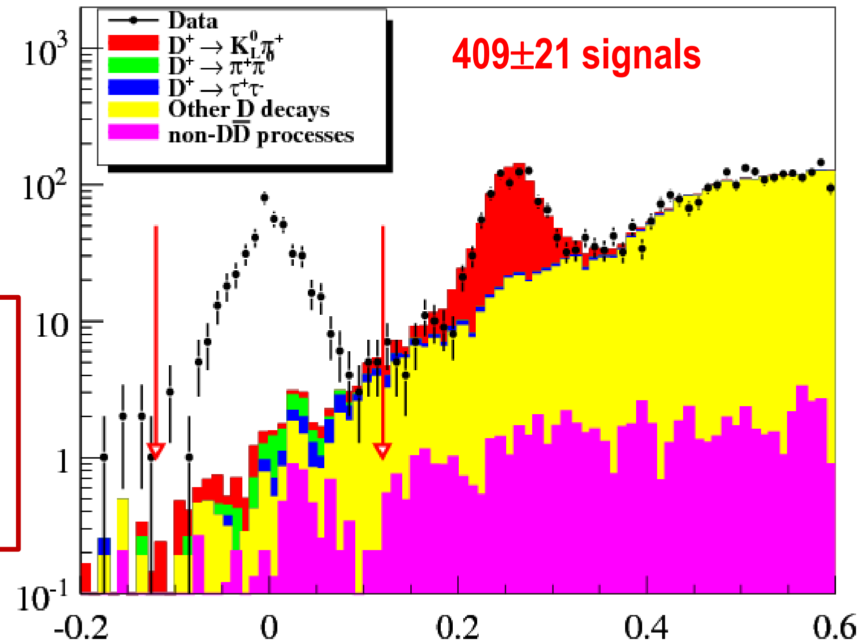
BESIII 2.9 fb^{-1} ψ'' data PRD 89 (2014) 051104

9 D^- tagged modes

$$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$$



small background benefit from the advantage of threshold production



$B(D^+ \to \mu\nu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

$|V_{cd}|$ of CKM-Fitter | Others from PDG | f_{D+} of LQCD

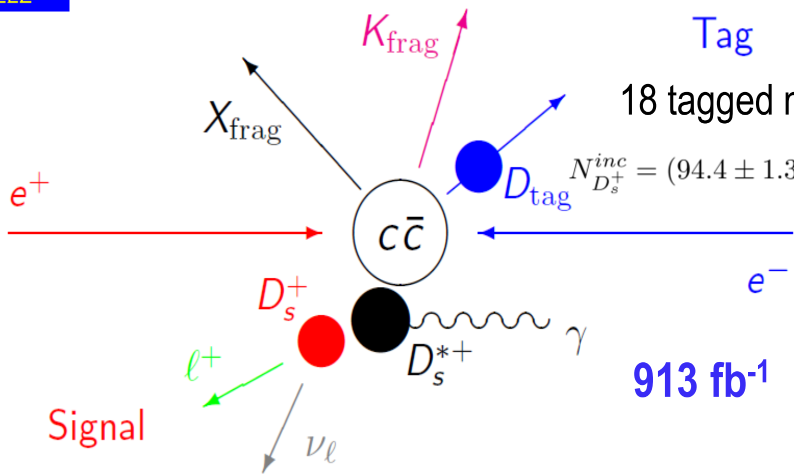
$f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV

$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

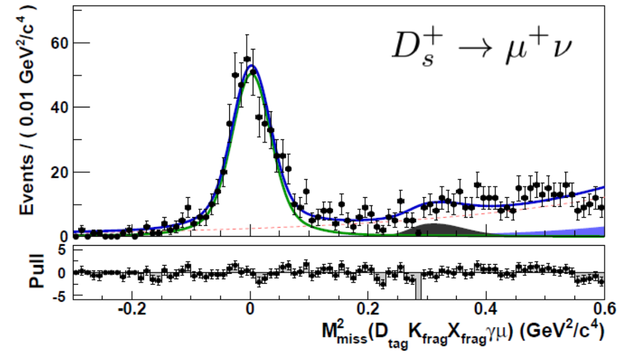
Most precise measurement, but statistical uncertainty dominant

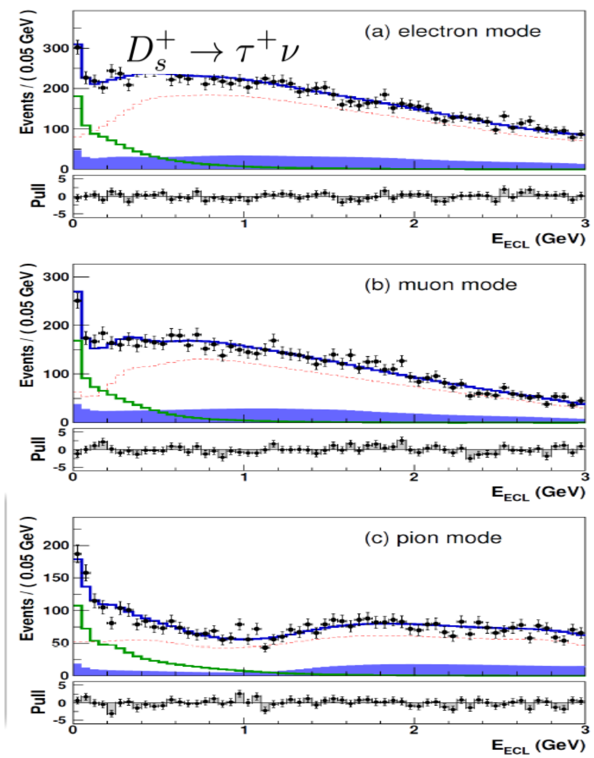
D^+_s Leptonic Decay

$$e^+e^- \to c\bar{c} \to D_{tag}K_{frag}X_{frag}D_s^{*+}, D_s^{*+} \to D_s^+\gamma$$



$$N^{inc}_{D_s^+} = (94.4 \pm 1.3_{stat} \pm 1.5_{sys}) \times 10^3$$





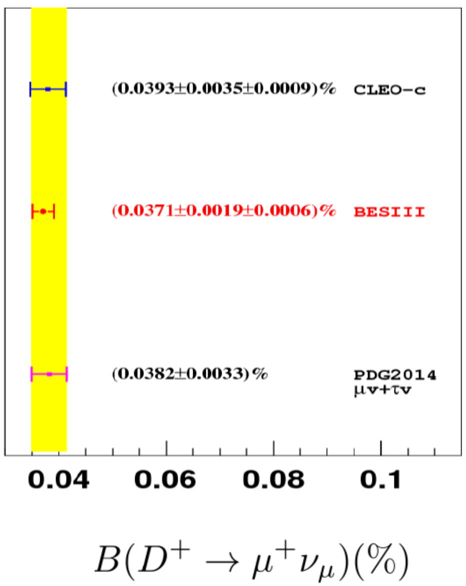
JHEP 1309 (2013) 139

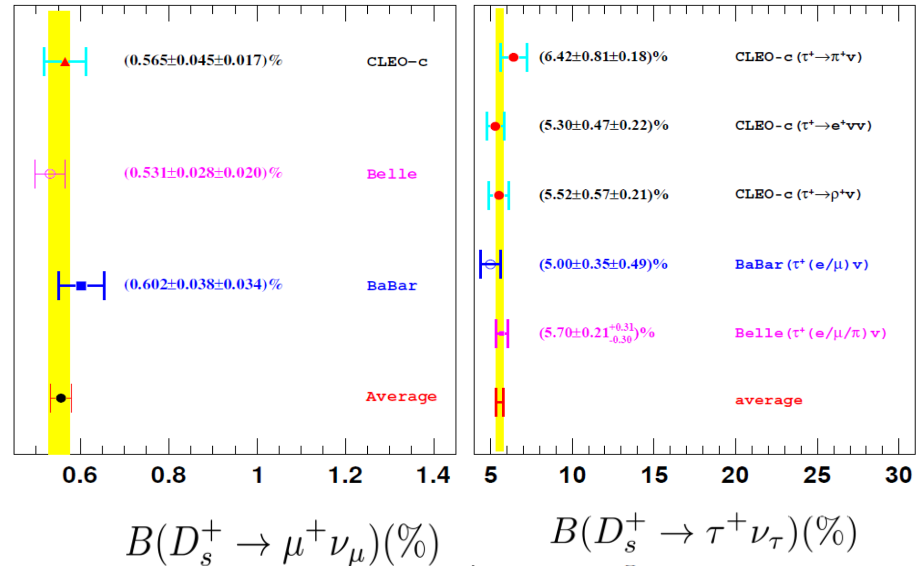
$$B(D_s^+ \to \mu^+\nu_\mu) = (0.531 \pm 0.028 \pm 0.020)\%$$

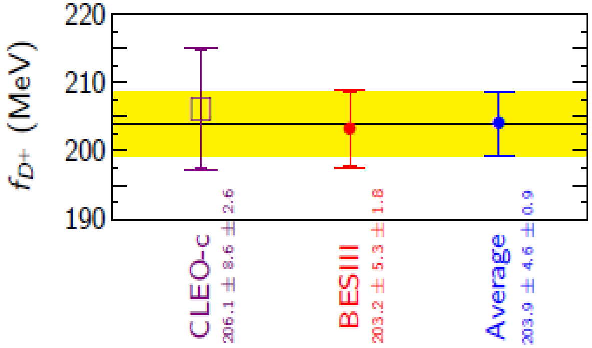
$$B(D_s^+ \to \tau^+\nu_\tau) = (5.70 \pm 0.21 {}^{+0.31}_{-0.30})\%$$

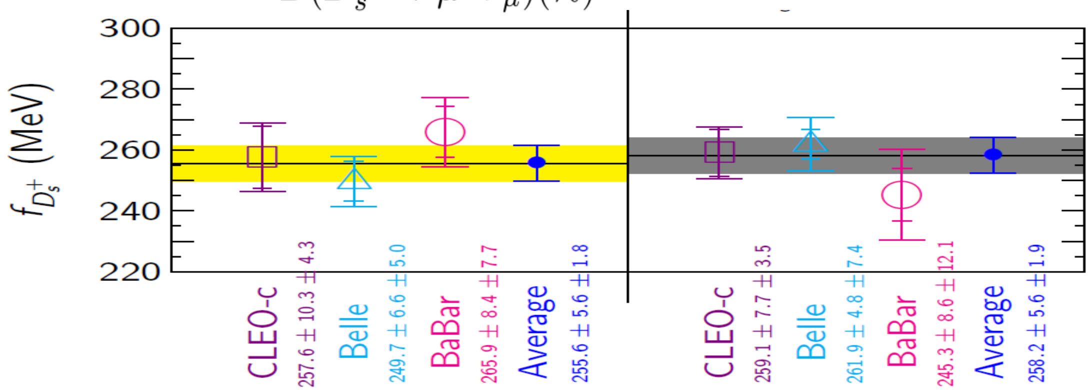
$D_s^+ \to \ell^+\nu_\ell$	$f_{D_s^+}$ (MeV)
$\mu^+\nu_\mu$	$249.8 \pm 6.6(\text{stat.}) \pm 4.7(\text{syst.}) \pm 1.7(\tau_{D_s})$
$\tau^+\nu_\tau$	$261.9 \pm 4.9(\text{stat.}) \pm 7.0(\text{syst.}) \pm 1.8(\tau_{D_s})$
Combination	$255.5 \pm 4.2(\text{stat.}) \pm 4.8(\text{syst.}) \pm 1.8(\tau_{D_s})$

Comparison BR and $f_{D(s)+}$









BESIII : 2.7% with 2.92fb^{-1}

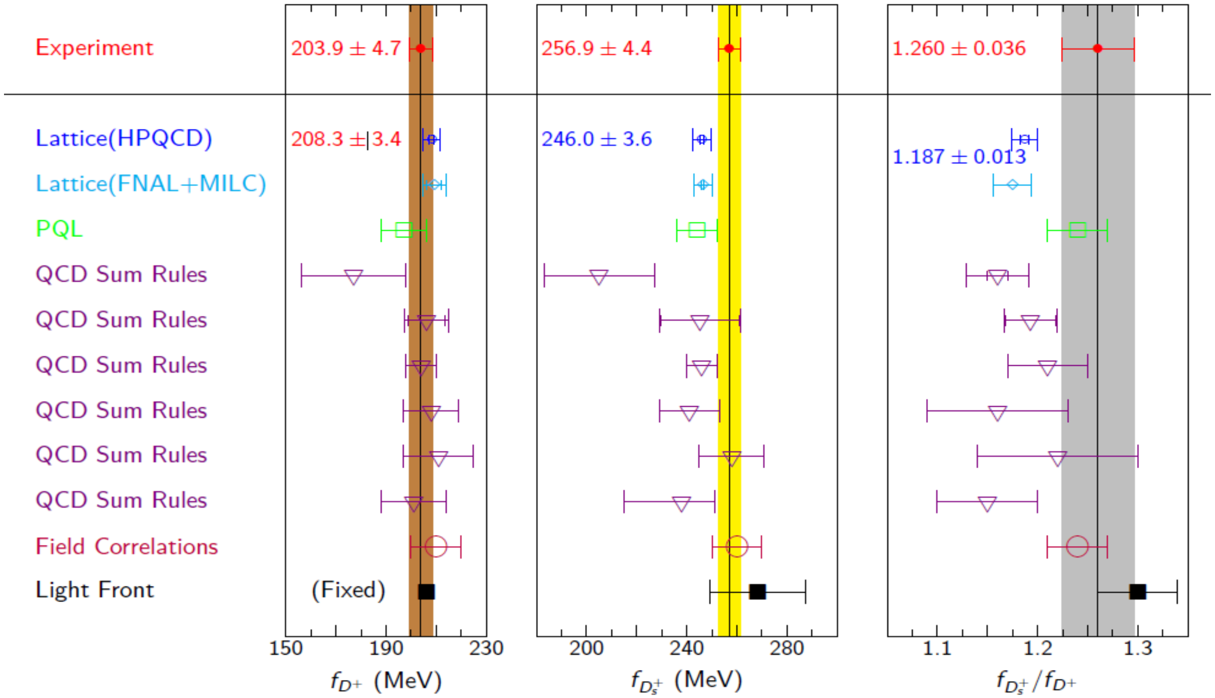
Expected: 1.5% with 10 fb^{-1}

CLEO-c : 2.5% with 0.68fb^{-1}

BESIII expected: 1.25% with 5 fb^{-1}

Comparisons of $f_{D(s)+}$

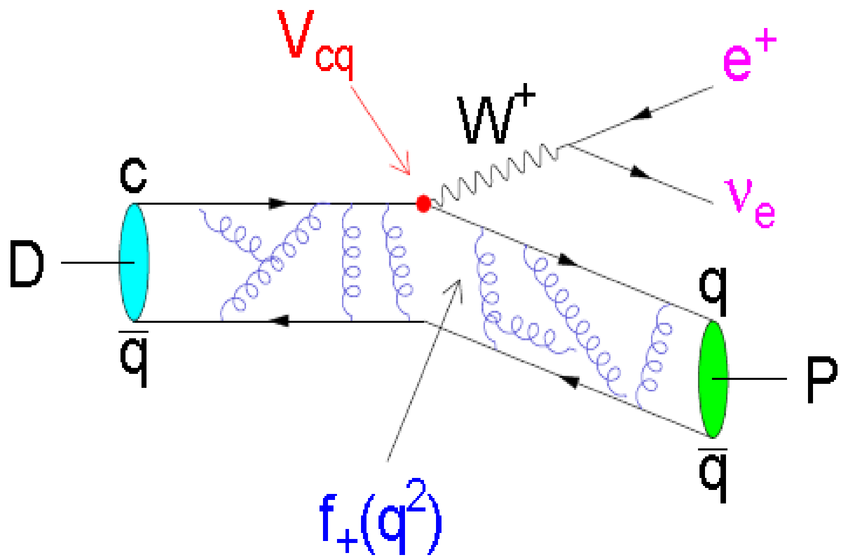
The plots taken from Gang's talk at CMK2014



	Experiments	Femilab Lattice+MILC (2014)		HPQCD (2012)	
	Averaged	Expected	Δ	Expected	Δ
f_{D+}(MeV)	203.9±4.7	$212.6\pm0.4^{+1.0}_{-1.2}$	1.8σ	208.3±3.4	0.8σ
f_{Ds+}(MeV)	256.9±4.4	$249.0\pm0.3^{+1.1}_{-1.5}$	1.7σ	246.0±3.6	1.4σ
f_{D+}:f_{Ds+}	1.260±0.036	$1.1712\pm0.0010^{+0.0029}_{-0.0032}$	2.5σ	1.187±0.013	1.9σ

- The experiment have worse precision
- Precision of the LQCD calculation of f_{D+}, f_{DS+}, f_{D+}:f_{DS+} reach ~0.5%, are really challenging the experiments
- The experimental measured and the LQCD calculation different by ~2σ for f_{D+}:f_{DS+}
- Improving measurement with larger data samples is expected

D Semi-leptonic Decay



In SM, the differential rates :

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

Bridge to precisely measure :

- Form factors $f^{D\to K(\pi)}_+(q^2)$ with input $|V_{cd(s)}|$ of CKMfit
  - Validate $f^{K(\pi)}_+$ (q2) calculated in LQCD
  - Improve $f^{B\to\pi}_+(0)$ calculated in LQCD, then improve $|V_{ub}|$
  - Improve the precision of the unitarity triangle
- CKM matrix element $|V_{cd(s)}|$ with input $f^{D\to K(\pi)}_+(0)$ from LQCD

Different FF parameterization

Simple Pole Model	$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M^2_{pole})}$
Modified Pole Model	$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M^2_{pole})/(1-\alpha q^2/M^2_{pole})}$
ISGW2 Model	$f_+(q^2) = f_+(q^2_{max})(1+\frac{r^2}{12}(q^2_{max}-q^2))^{-2}$
Series Expansion	$f_+(q^2) = \frac{1}{P(q^2)\Phi(q^2,t_0)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$

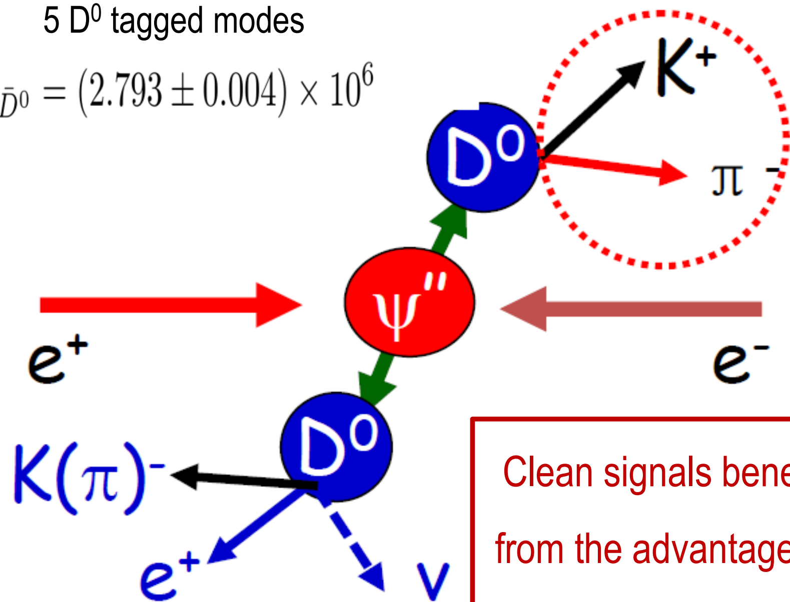
$D^0 \to K(\pi)^- e^+ \nu_e$ Decay @ BESIII

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

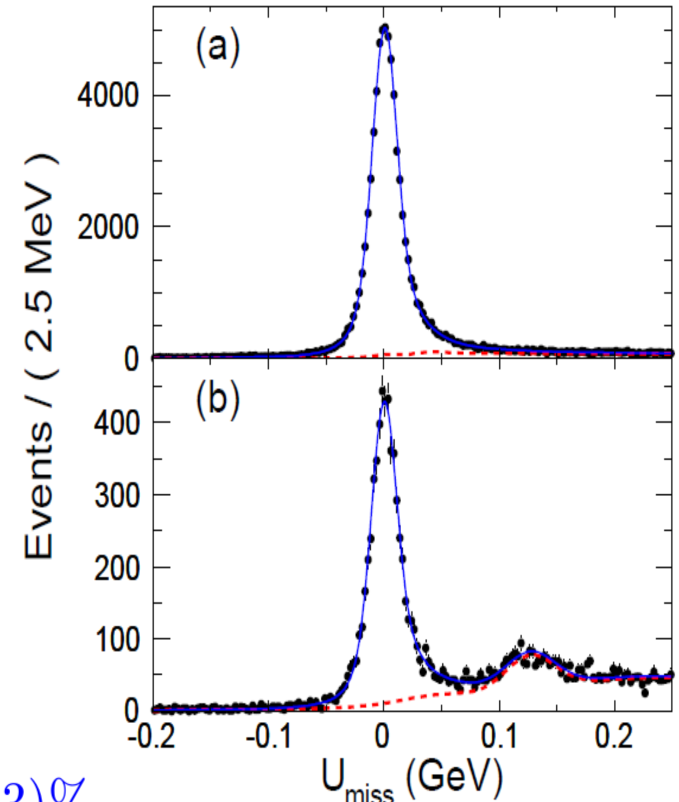
BESIII 2.9 fb^{-1} ψ'' data arXiv:1508.07560

5 D^0 tagged modes

$$N_{\bar{D}^0} = (2.793 \pm 0.004) \times 10^6$$



Clean signals benefit from the advantage of threshold production



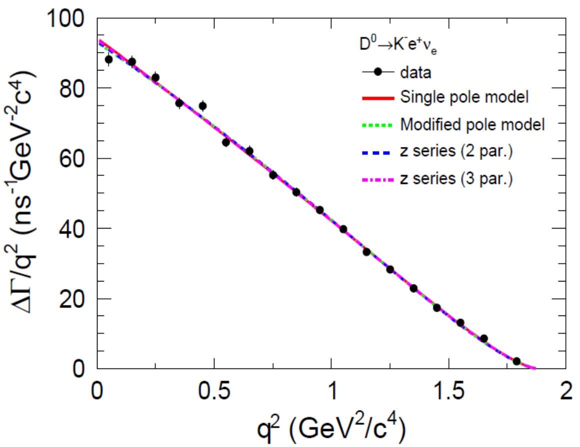
$$B(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$$

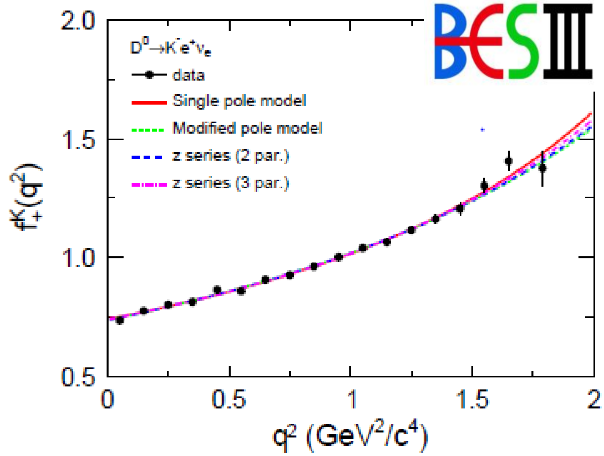
$$B(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%$$

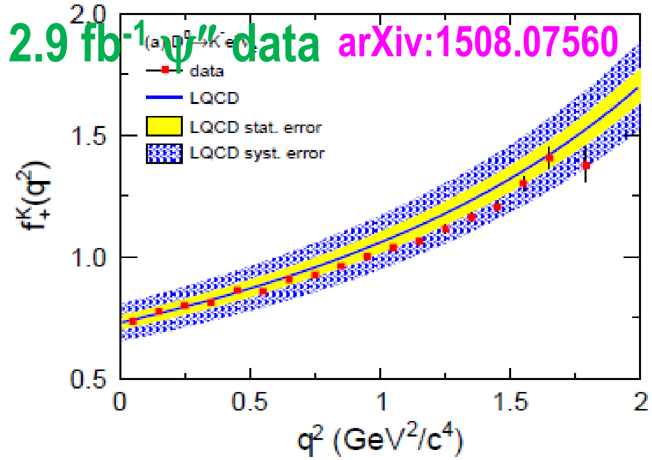
Most precise measurements

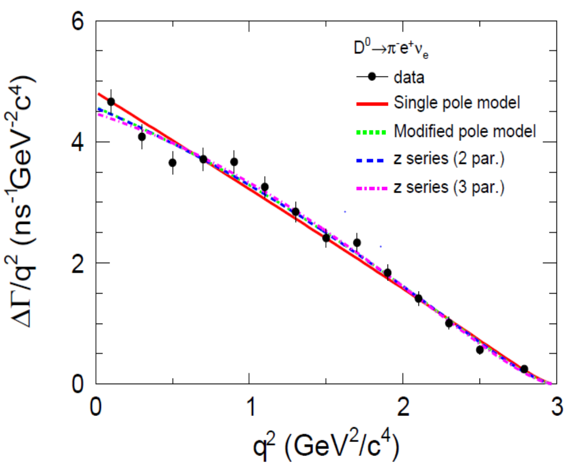
Measurement of $f_+^{K(\pi)}(q^2)$

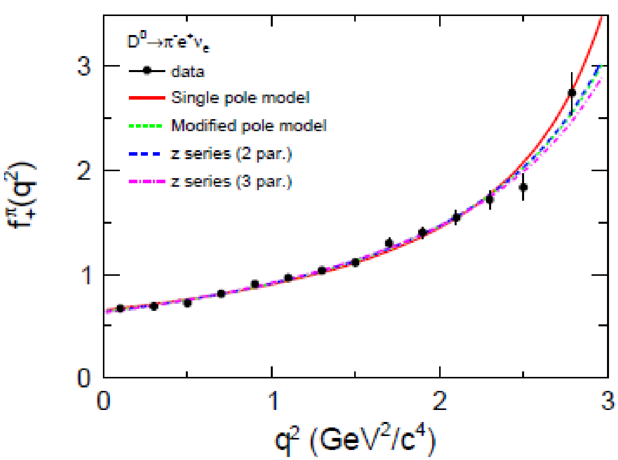
2.9 fb^{-1} ψ'' data arXiv:1508.07560

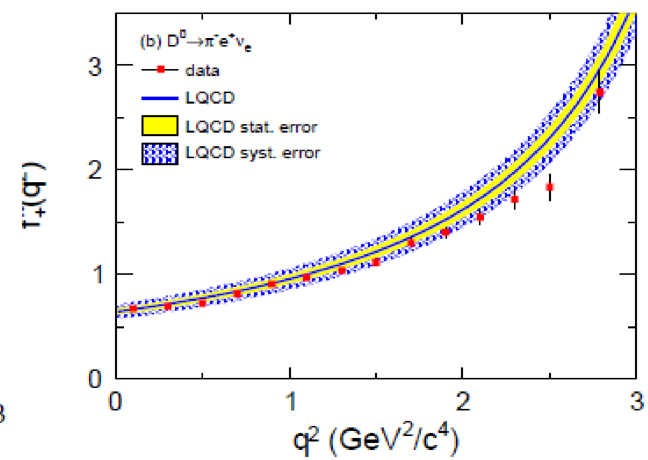












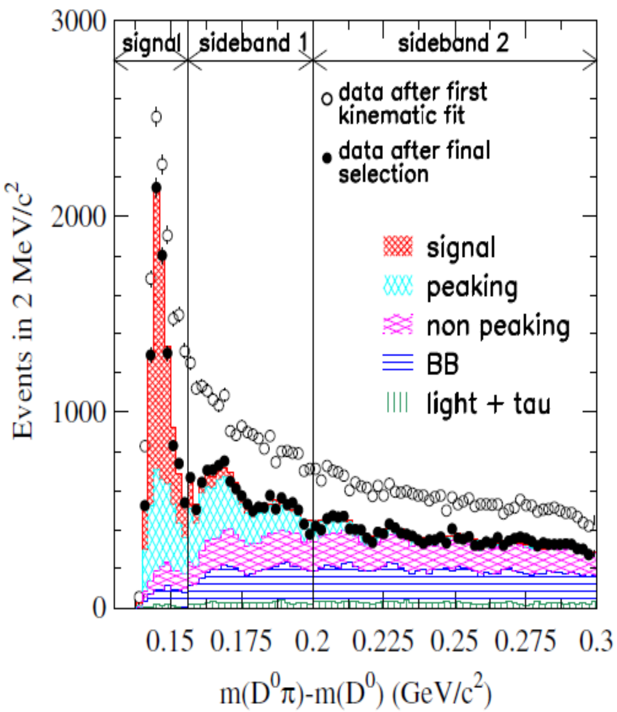
Fit with different FF parameterization

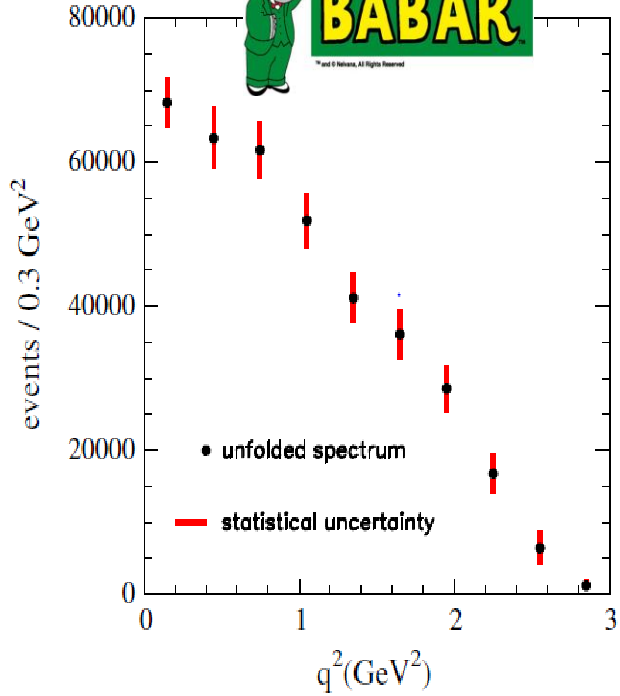
Projection on FF with $|V_{cd(s)}|$ from CKMfiter

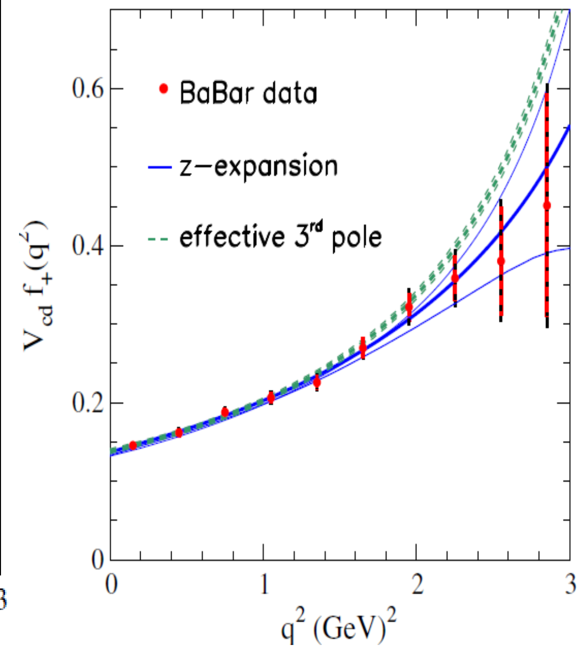
Comparisons of measured FF with LQCD predictions

$D^0 \to \pi^- e^+ \nu_e$ Decay @ BABAR

347.2 fb^{-1} $\Upsilon(4S)$ PRD 91 (2015), 052022







$$B(D^0 \to \pi^- e^+ \nu_e) = (0.2770 \pm 0.0068_{stat} \pm 0.0092_{syst} \pm 0.0037_{ext})\%$$

LQCD calculation

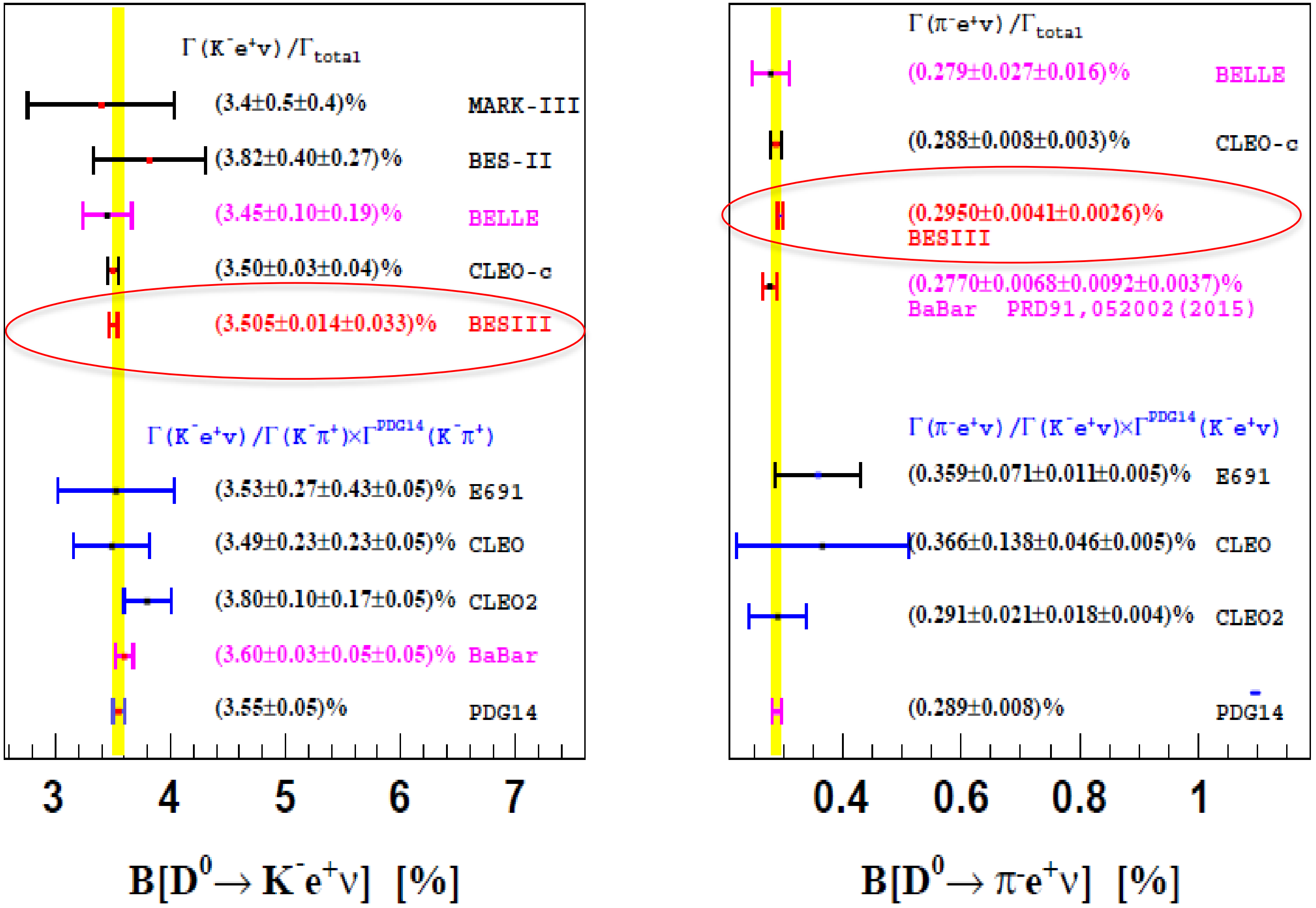
$$f_+^\pi(0) = 0.610 \pm 0.029_{exp}$$

$$|V_{cd}| = 0.206 \pm 0.007_{exp} \pm 0.009_{LQCD}$$

$$|V_{cd}| = |V_{us}| = 0.2252 \pm 0.0009$$

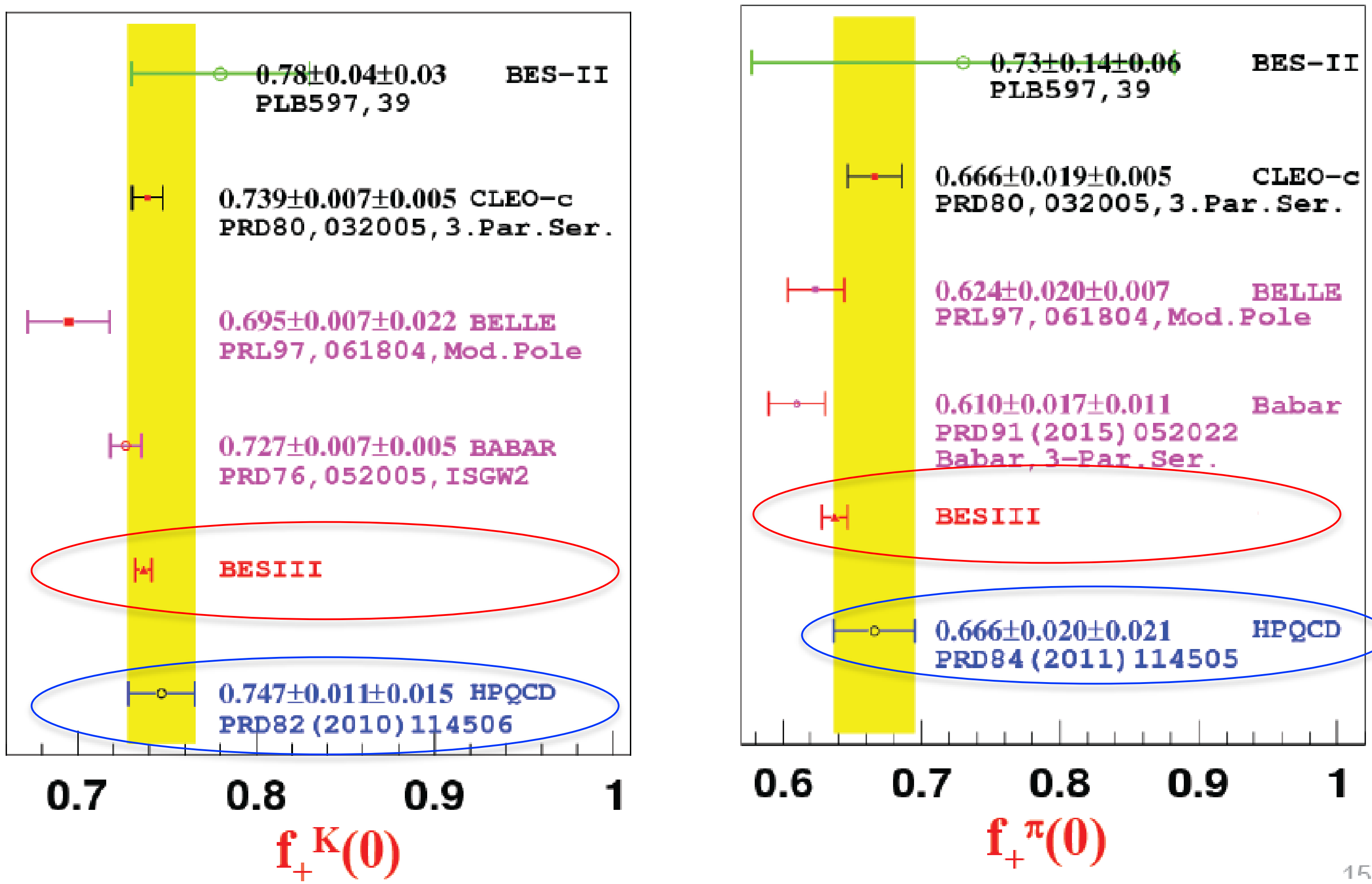
$$f_+^\pi(0) = 0.610 \pm 0.020_{exp} \pm 0.005_{ext}$$

Comparisons of BR



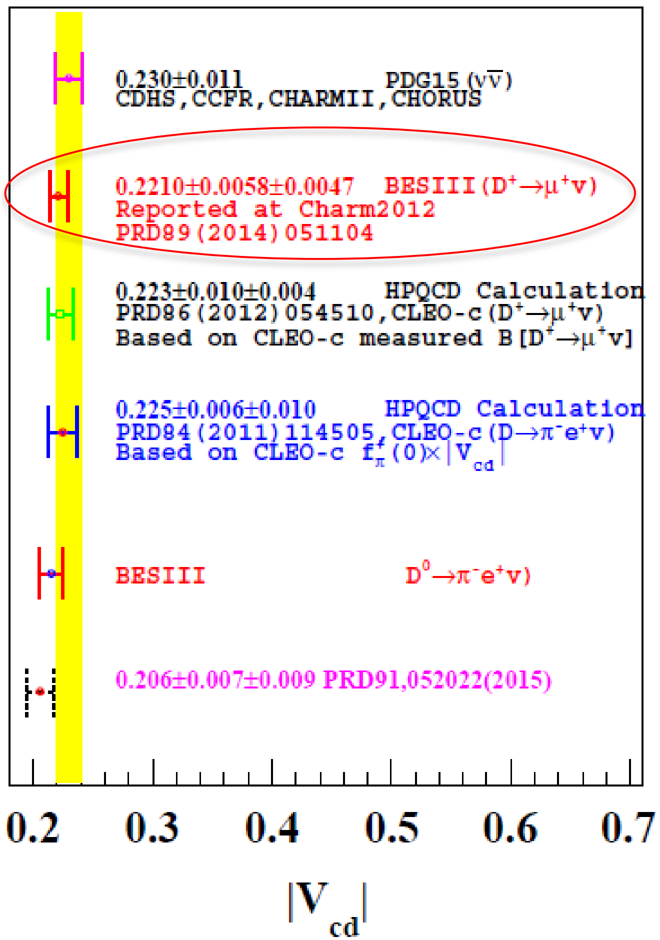
BESIII experiment achieved most precise measurement.

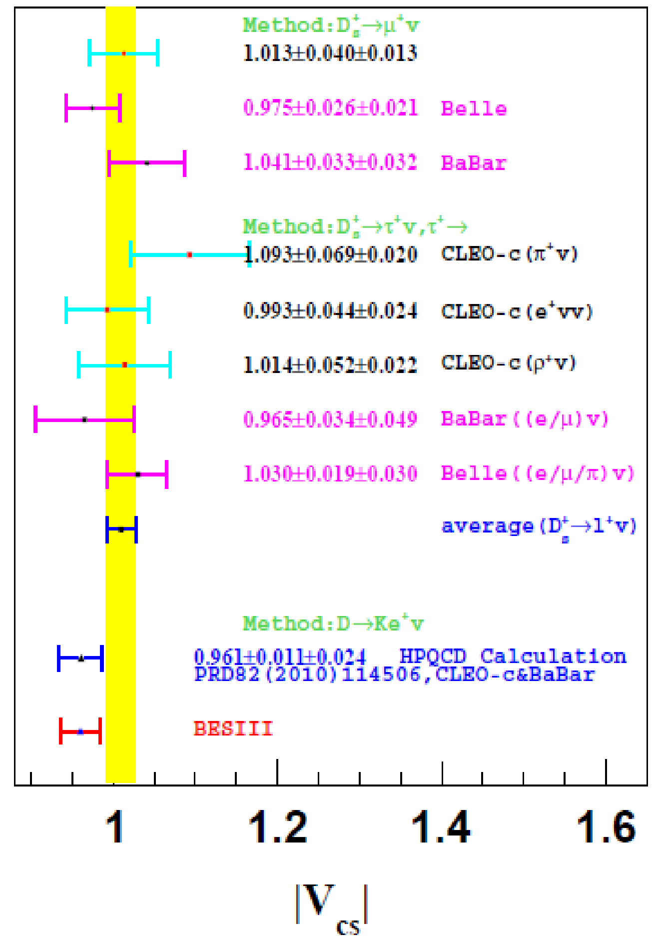
Comparisons of FF



- BESIII experiment achieved most precise measurement.
- The experimental accuracy is better than that of theoretical predictions

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

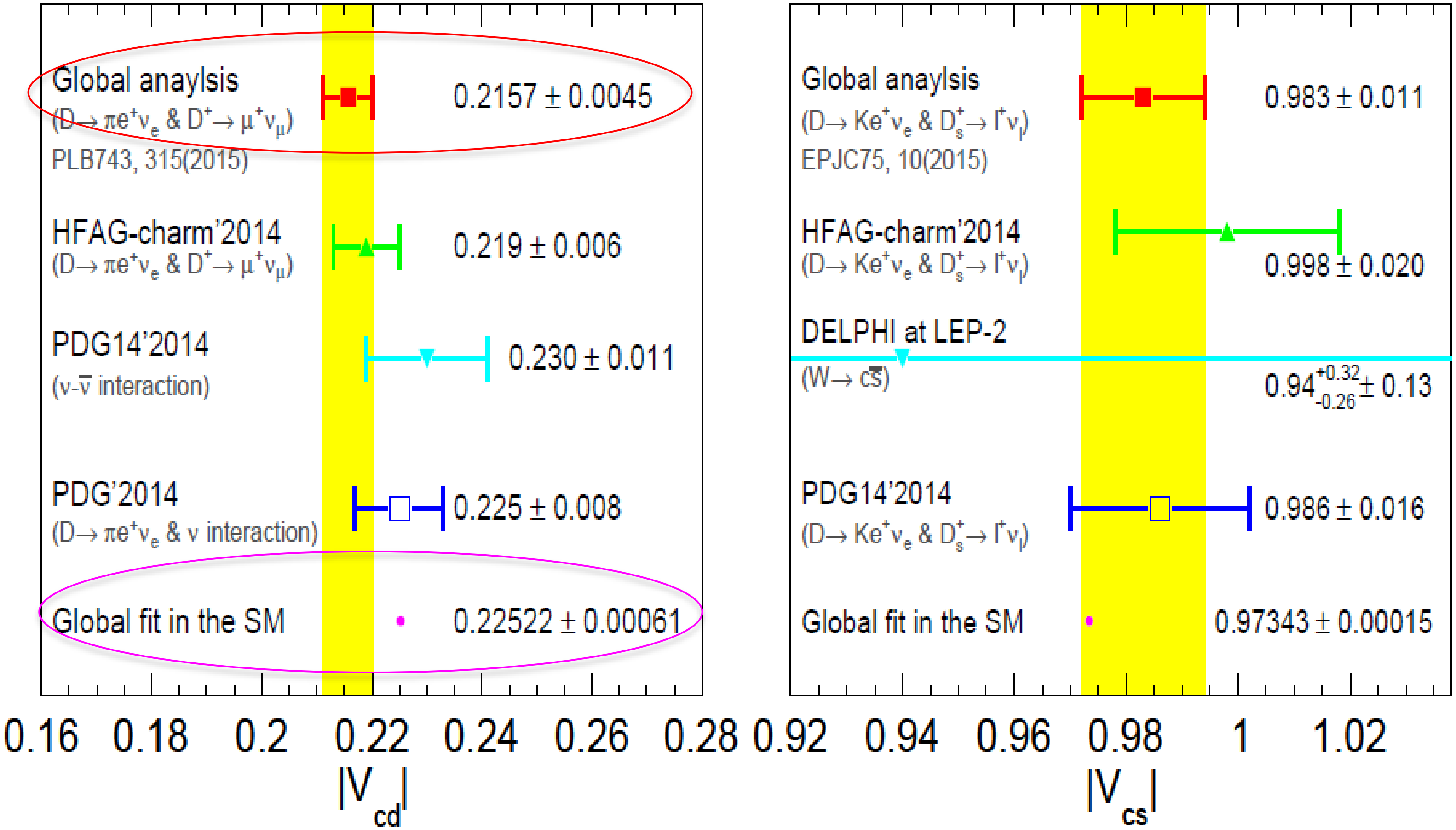




BES used the leptonic $D^+ \to \mu^+ \nu_\mu$ to extract the $|V_{cd}|$ for the first time

The accuracy is better than that of PDG2015 average from $\nu\nu$ interactions

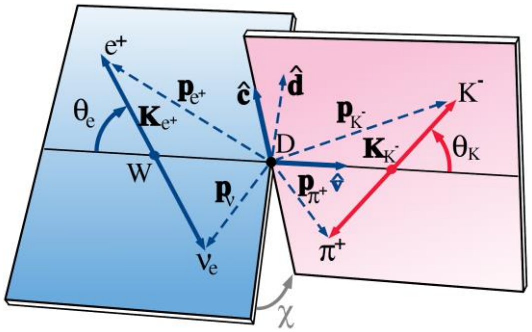
Comparisons of $|V_{cd}|$ and $|V_{cs}|$



Comparison between the PDG 2014, HFAG-Charm 2014, Global analysis and Global fit in SM

The values from the global analysis deviates from that obtained from the SM global fit by 2.1σ

Semileptonic $D \to V \ell^+ \nu_\ell$ Decay



$D^+ \to K^{*0} e^+ \nu_e$, $K^{*0} \to K^- \pi^+$

- $m^2 = (p_{\pi^+} + p_{K^-})^2$
- $\cos(\theta_K) = \frac{\hat{\nu} \cdot \mathbf{K}_{K^-}}{|\mathbf{K}_{K^-}|}$
- $\cos(\chi) = \hat{\mathbf{c}} \cdot \hat{\mathbf{d}}$

- $q^2 = (p_{e^+} + p_{\nu_e})^2$
- $\cos(\theta_e) = -\frac{\hat{\nu} \cdot \mathbf{K}_{e^+}}{|\mathbf{K}_{e^+}|}$
- $\sin(\chi) = (\hat{\mathbf{c}} \times \hat{\nu}) \cdot \hat{\mathbf{d}}$

Decay rates depend on 5 variables and 3 form factors

$$d^5\Gamma = \frac{G_F^2 |V_{cs}|^2}{(4\pi)^6 m_D^2} X \beta \mathcal{I}(m^2, q^2, \theta_K, \theta_e, \chi) dm^2 dq^2 d\cos(\theta_K) d\cos(\theta_e) d\chi$$

- $X = p_{K\pi} m_D$, $p_{K\pi}$ is the momentum of the $K\pi$ system in the D rest frame
- $\beta = 2p^*/m$, p^* is the breakup momentum of the $K\pi$ system in its rest frame
- $\mathcal{I}$ can be expressed in terms of helicity amplitudes $H_{0,\pm}$:

$$H_0(q^2) = \frac{1}{2m_q}\left[(m_D^2 - m^2 - q^2)(m_D + m)A_1(q^2) - 4\frac{m_D^2 p_{K\pi}^2}{m_D+m} A_2(q^2)\right]$$

$$H_\pm(q^2) = (m_D + m)A_1(q^2) \mp \frac{2m_D p_{K\pi}}{m_D+m} V(q^2)$$

- Vector form factor: $V(q^2) = \frac{V(0)}{1-q^2/m_V^2}$; or: FF ratio $r_V = V(0)/A_1(0)$
- Axial-vector form factor: $A_1(q^2) = \frac{A_1(0)}{1-q^2/m_A^2}$, $A_2(q^2) = \frac{A_2(0)}{1-q^2/m_A^2}$; or: FF ratio $r_2 = A_2(0)/A_1(0)$

- BESIII : 2.92fb^{-1}, PWA of $D^+ \to K^- \pi^+ e^+ \nu_e$,
  Preliminary results, see Fenfen's talk at CHARM 2015
- BESIII :2.92fb^{-1}, Study of $D^+ \to \omega/\phi e^+ \nu_e$,
  ArXiv:1508.00151
- CLEO-C : 818 pb^{-1}, $D^0 \to \rho^- l^+ \nu_l$, $D^+ \to \rho^0/\omega l^+ \nu_l$
  PRL 110 (2013) 131802

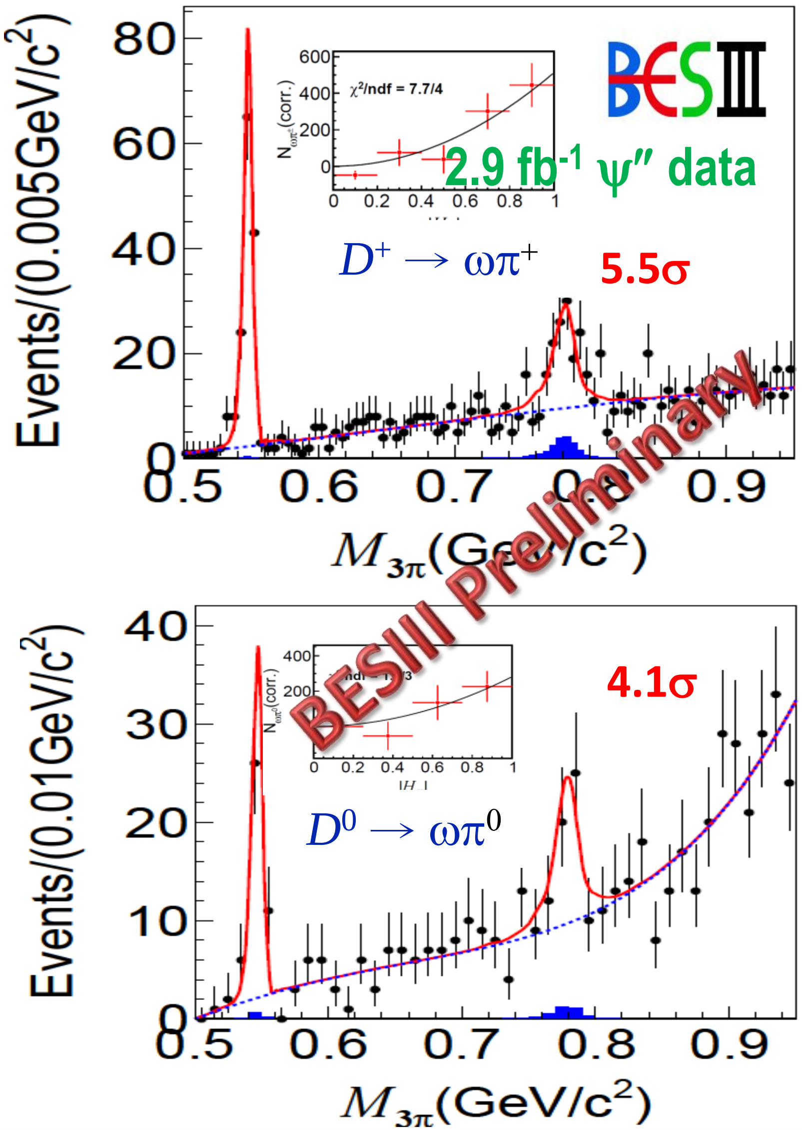
Hadronic Decay

Observation of SCS decay $D^{\pm 0} \to \omega\pi^{\pm 0}$

- **CLEO-c (281pb^{-1}) ψ'' data did not obeserve CSC decay $D^{\pm 0} \to \omega\pi^{\pm 0}$ [PRL 96, 081802 (2006)]**
- **Theory predicts $D^{\pm 0} \to \omega\pi^{\pm 0}$ ~1.0×10^{-4} due to the destructive interference between color-suppressed diagrams [PRD 81, 074021 (2010)]**
- **BESIII first observation :**
  - **Consistent with theory prediction in BR**
  - **ω helicity angle ~$\cos^2\theta$ distribution**
  - **BR($D\to\eta\pi$) consistent previous measurement**

Decay mode	This work	Previous meausurements
$D^+ \to \omega\pi^+$	$(2.74 \pm 0.58 \pm 0.17) \times 10^{-4}$	$< 3.4 \times 10^{-4}$ at 90% C.L.
$D^0 \to \omega\pi^0$	$(1.05 \pm 0.41 \pm 0.09) \times 10^{-4}$	$< 2.6 \times 10^{-4}$ at 90% C.L.
$D^+ \to \eta\pi^+$	$(3.13 \pm 0.22 \pm 0.19) \times 10^{-3}$	$(3.53 \pm 0.21) \times 10^{-3}$
$D^0 \to \eta\pi^0$	$(0.67 \pm 0.10 \pm 0.05) \times 10^{-3}$	$(0.68 \pm 0.07) \times 10^{-3}$

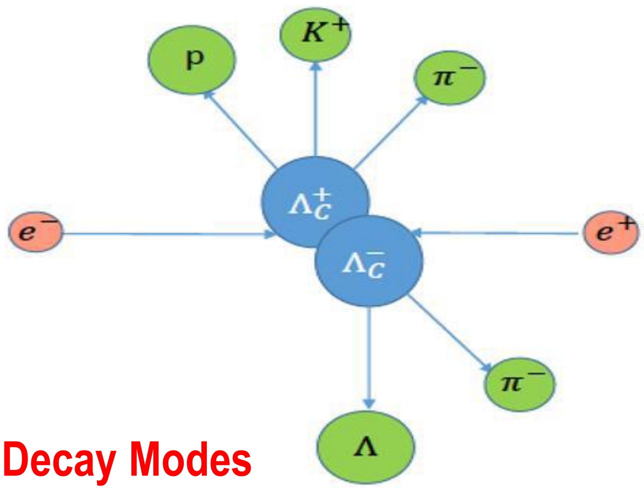
See Peter's talk at CHARM2015 for details



Absolute BR of Λ_c^+ hadron decays

- **Absolute branching fraction of Λ_c^+ are not well determined since its discovery**
  - BFs of ~85% decay modes are measured relative to $\Lambda_c^+ \to pK^-\pi^+$
  - However, no completely model-independent measurements of the absolute BF of $\Lambda_c^+ \to pK^-\pi^+$ (from Argus and CLEO very old results)
  - The uncertainties of BFs of Λ_c^+ decays are 25%~40% in PDG2014
- **Until Belle's first "model-independent" measurement:**
  - $B(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24 - 0.27 + 0.21)\%$ precision reaches to 4.7% [PRL 113 (2014) 042002]
- **Measurement using the threshold pair-productions via e+e- annihilations ($e^+e^- \to \Lambda_c^+\Lambda_c^-$) is unique: the most simple and straightforward**
  - BESIII preliminary analysis based on $567 pb^{-1}$ data @ 4.6GeV
  - Kinematics does not allow additional particles, clean
  - Fully reconstruct the pairs and double tagged method

Absolute BR of Λ_c^+ hadron decays



BESIII 567 pb^{-1} @ 4.6 GeV

See Xiaorui's talk at CHARM2015 for detail

A least square global fitter [CPC 37, 106201 (2013)]

BESIII Preliminary

Decay modes	global fit $\mathcal{B}$	PDG $\mathcal{B}$	Belle $\mathcal{B}$
pK_S	1.48 ± 0.08	1.15 ± 0.30	
$pK^-\pi^+$	5.77 ± 0.27	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S\pi^0$	1.77 ± 0.12	1.65 ± 0.50	
$pK_S\pi^+\pi^-$	1.43 ± 0.10	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	4.25 ± 0.22	3.4 ± 1.0	
$\Lambda\pi^+$	1.20 ± 0.07	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	6.70 ± 0.35	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	3.67 ± 0.23	2.6 ± 0.7	
$\Sigma^0\pi^+$	1.28 ± 0.08	1.05 ± 0.28	Global fit : Stat. Err. only
$\Sigma^+\pi^0$	1.18 ± 0.11	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	3.58 ± 0.22	3.6 ± 1.0	
$\Sigma^+\omega$	1.47 ± 0.18	2.7 ± 1.0	

12 Decay Modes

Mode
pK_S^0
$pK^-\pi^+$
$pK_S^0\pi^0$
$pK_S^0\pi^+\pi^-$
$pK^-\pi^+\pi^0$
$\Lambda\pi^+$
$\Lambda\pi^+\pi^0$
$\Lambda\pi^+\pi^-\pi^+$
$\Sigma^0\pi^+$
$\Sigma^+\pi^0$
$\Sigma^+\pi^+\pi^-$
$\Sigma^+\omega$

- B($\Lambda_c^+ \to pK^-\pi^+$) :
  - BESIII have comparable precision of Belle's results, but smaller rate
- Improved precision of the other 11 modes significantly (mostly ≤8%)

Others Hadronic Decay

A lot of others progress on multi-body hadronic decay (Amplitude/Daltiz) analysis (e.g. $D^0 \to K_S K^+ K^-$,/$K_S K^+ \pi^-$), please see the talks :

- Peter Weidenkaff's talk at Charm2015
- Angelo Di Canto's talk at LHCP2015
- ……

Rare Decay

How rare of rare Charm Decay

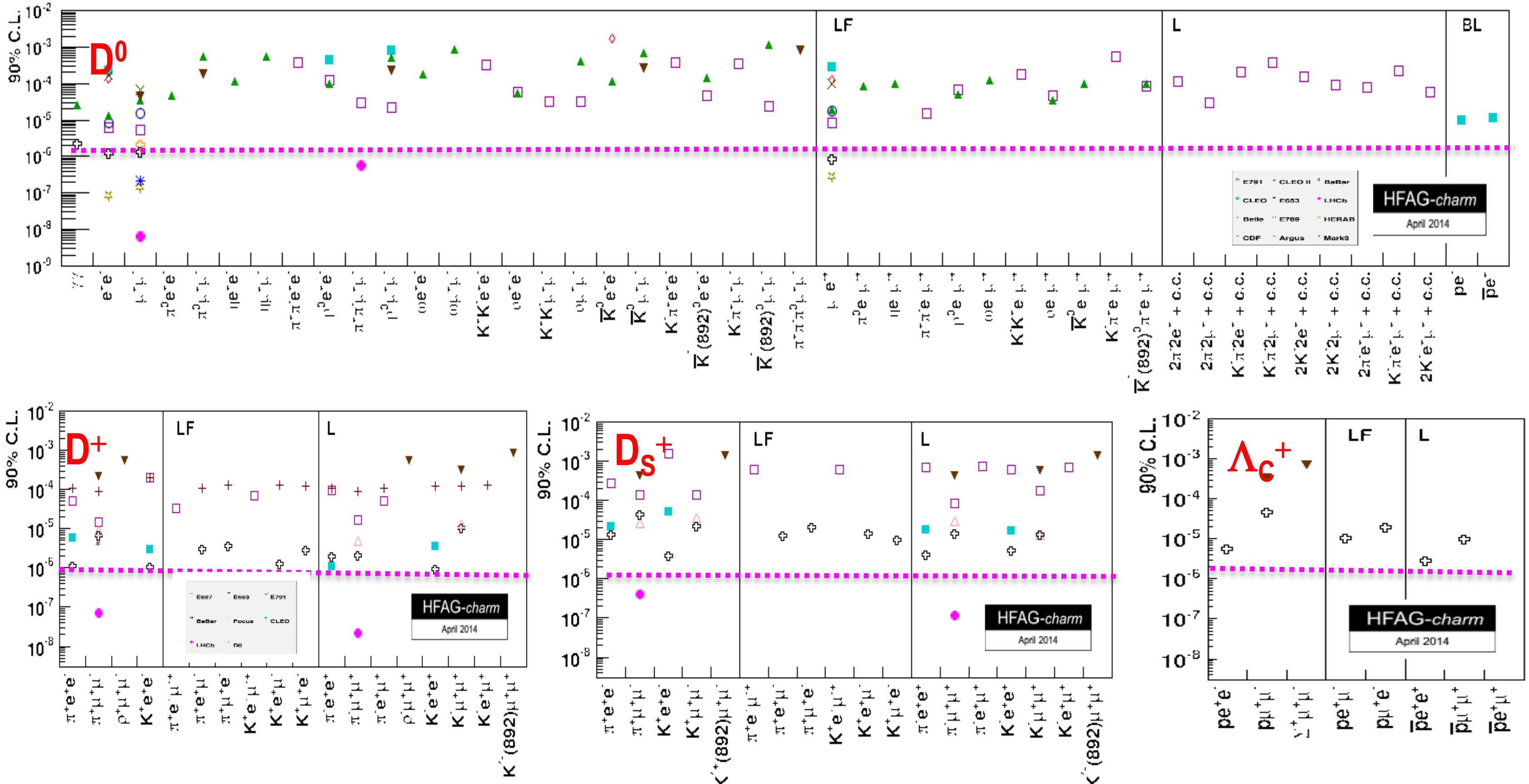
Charm provide a unique environment for testing the SM rare/forbidden decays and searching for NP

SM predictions and experimental reaches

10^{-0}			
10^{-1}			
10^{-2}	Cabibbo favor		
10^{-3}	Single Cabibbo suppressed		
10^{-4}	Doubly Cabibbo suppressed		CLEO-c
10^{-5}	Radiative decays	$D^0 \to K^{*0}\gamma/\phi\gamma/\omega\gamma/\rho\gamma$	BESIII
10^{-6}		$D^+_{(S)} \to K^{*+}\gamma/\rho^+\gamma$	BESIII final/B factory
10^{-7}	Long distance: Vector meson Dominance	$D^{0+} \to \gamma\gamma/VV'(l^+l^-)/ hV(l^+l^-)/ hh'V(l^+l^-)$	LHCb
10^{-8}			Super-B
10^{-9}			Super-τ-charm
10^{-10}	Short distance FCNC	$D^{0/+} \to \gamma\gamma/Vl^+l^-/hl^+l^-/hh'l^+l^-$	
10^{-11}		$D^0 \to \mu^+\mu^- /e^+ e^-$	
10^{-12}			
10^{-13}		$D \to (hh)\mu^+\mu^+/(hh)e^+e^+$	
10^{-14}		$D \to (h)\mu^+e^-$	
10^{-15}	Forbidden decays: LNV, LFV, BNV	$D \to (h)pe^-$	

Charm Rare Decay

HFAG : http://www.slac.stanford.edu/xorg/hfag/charm/April14/Rare/rare_charm.html



- Very few limit below 10^{-6}, are still well above SM prediction
- Many channels studies more than a decade ago
- LHCb shows great potential in several process, (e.g. $D^0 \to \mu^+\mu^-$, but still 100×SM and 10× NP)

Summary & Prospects

- Charm physics provide a unique environment for the testing SM and searching from new physics, very broad topics
  - D^0-$\bar{D}^0$Mixing : is well established in a single experiment
  - CPV : no CPV observed at 10^{-3} level, need more data and new method
  - Quantum-Correlated @ threshold : unique input for testing CKM, mixing and searching for CPV
  - Semilepton decay : Validate LQCD calculation and improve the CKM matrix elements measurement. LQCD prediction is precise, and challenge experimental measurement.
  - Hadronic decay : more precise measurement are necessary
  - Rare decay : lots of measurements, but limits are still well above SM prediction

Summary & Prospects

- **Results still coming in from Belle with full data set (~950fb^{-1})**
- **BESIII team has built and developed technology with charm at threshold, and more and wide results are coming**
- **LHCb is producing a wide new results, including Dalitz plot/amplitude analyses**
- **Perspectives :**
  - BESIII will continue to run 6-8 years, will continue play role with the data produced at threshold.
  - LHCb runII (2015-2018), 10 times charm data ($2\times\sigma(cc)_{7TeV}$, $2\times$better trigger, 50fb^{-1}) will play the key role for charm in next few years.
  - BELLE-II will collect 50 ab^{-1} from $e^{+}e^{-}$ collision
  - Super τ-Charm Factory (Russia, China)?

Thanks

Backup Slides

CPV in $D_{(s)}^{+} \to K_S h^{+}$ @ LHCb

Paras Naik's talk at Charm 2015

JHEP 1410 (2014) 25
$3fb^{-1}$

- Search for direct CP asymmetry in the **SCS** decays
- Measured asymmetries are affected by other asymmetries

$$\mathcal{A}_{\rm meas}^{D_{(s)}^{\pm}\to K_S^0 h^{\pm}} \approx \mathcal{A}_{CP}^{D_{(s)}^{\pm}\to K_S^0 h^{\pm}} + \mathcal{A}_{\rm prod}^{D_{(s)}^{\pm}} + \mathcal{A}_{\rm det}^{h^{\pm}} + \mathcal{A}_{K^0/\overline{K}^0}$$

- **measure**
- **want**
- Production asymmetry
- f's detection asymmetry
- Correction due to CPV in kaon system

- Combine with **CF** decays where CPV is not expected. Take asymmetries to isolate CP asymmetries e.g.

$$\mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0 \pi^{\pm}} = \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0 \pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi \pi^{\pm}} - \mathcal{A}_{K^0}$$

$\mathcal{A}_{K^0} = (+0.07 \pm 0.02)\%$
calculation described in JHEP 07 (2014) 041

- Results:

$$\mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} = (+0.03 \pm 0.17 \pm 0.14)\%$$

$$\mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0 \pi^{\pm}} = (+0.38 \pm 0.46 \pm 0.17)\%$$

- Can also get a sum of both **SCS** asymmetries using **CF** $D_{(s)}^{+} \to K_S h^{+}$

$$\mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} + \mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0 \pi^{\pm}} = (+0.41 \pm 0.49 \pm 0.26)\%$$

CPV via T-odd moments in $D^0 \to KK\pi\pi$

Paras Naik's talk at Charm 2015

- Search for CPV in the **SCS** decay $D \to KK\pi\pi$ using triple products

$$D^0 \to K^- K^+ \pi^- \pi^+ \qquad \overline{D}^0 \to K^+ K^- \pi^+ \pi^-$$

$$C_T = \mathbf{p}_{\mathbf{K}^+} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-}) \qquad \overline{C}_T = \mathbf{p}_{\mathbf{K}^-} \cdot (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^+})$$

- These are non-vanishing since there are four distinct final state particles
- These triple products are odd under T (hence the name "T-odd")
  - We cannot reverse the decay, their P-odd nature is more important

- In the absence of final state interactions (FSI) due to long-distance strong interaction effects, if the number of decays with $C_T < 0$ is different from the number of decays with $C_T > 0$ this implies parity violation.
- We form triple-product asymmetries for both D flavors:

$$A_{C_T} = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \overline{A}_{\overline{C}_T} = \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)}$$

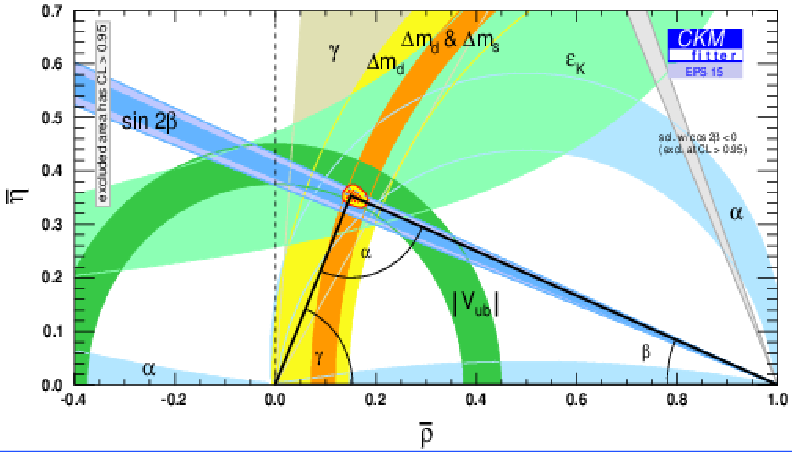
Status of the CKM UT

CKM Fitter 2015 Summer

Direct Measurement

$$\alpha/\phi_2 = (87.6^{+3.5}_{-3.3})^o$$
$$\beta/\phi_1 = (21.85^{+0.68}_{-0.67})^o$$
$$\gamma/\phi_3 = (73.2^{+6.3}_{-7.0})^o$$

- γ/ϕ_3 is the least precisely measured angle
- Precision is statistically limited
- Precise measurement of γ/ϕ_3 is needed to test the UT of CKM
- Any difference between tree measurement to loop measurement might be a sign of NP in flavor sector



$$\gamma = arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$$

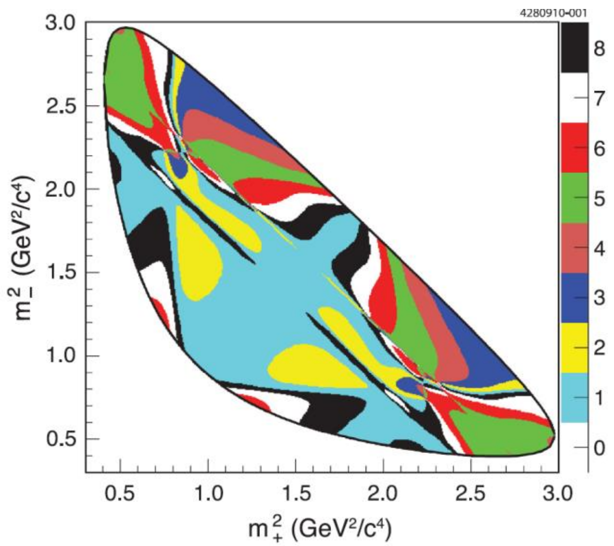
- GGSZ (Dalitz) method in $B^- \to D^0K$ is Most sensitive method to constrain γ/ϕ_3 nowadays
- With the amount of data LHCb collecting, $\gamma/\phi3$ measurement soon will be systematically limit
- BESIII can help reducing the systematics with providing more information on $D^0 \to K^0\pi^+\pi^-$

Binning in Dalitz plots

BESIII performing analysis with 2.9fb^{-1} ψ'' data

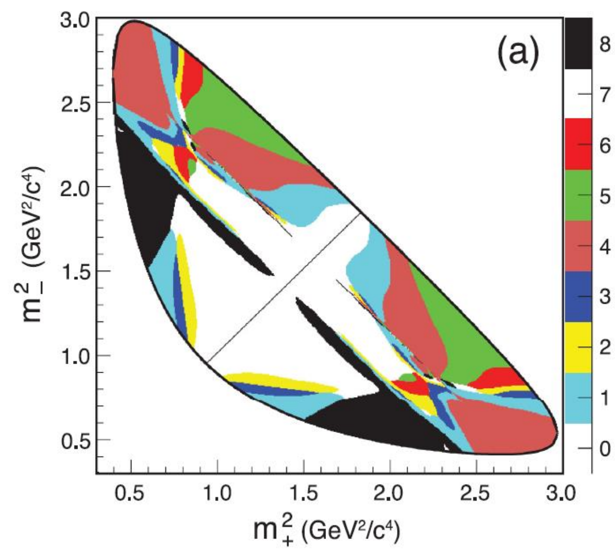
Same method as CLEO-c (PRD 82 (2010) 112006)

BaBar 2008 Equal Distance Bins



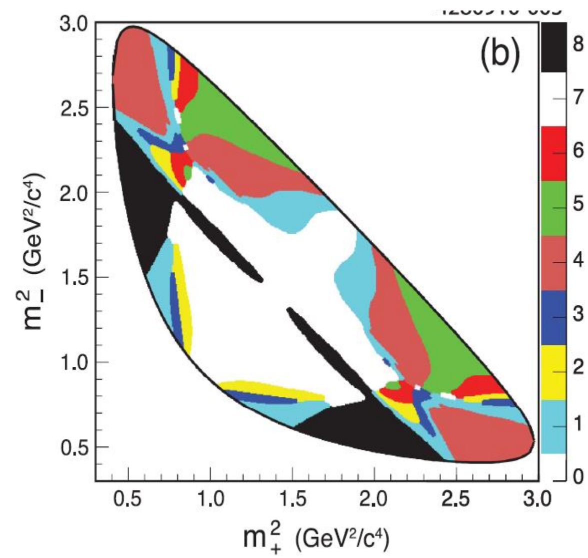
Result of splitting the Dalitz PHSP into 8 equally spaced phase bins base on BaBar 2008 Model

BaBar 2008 Optimal Bins



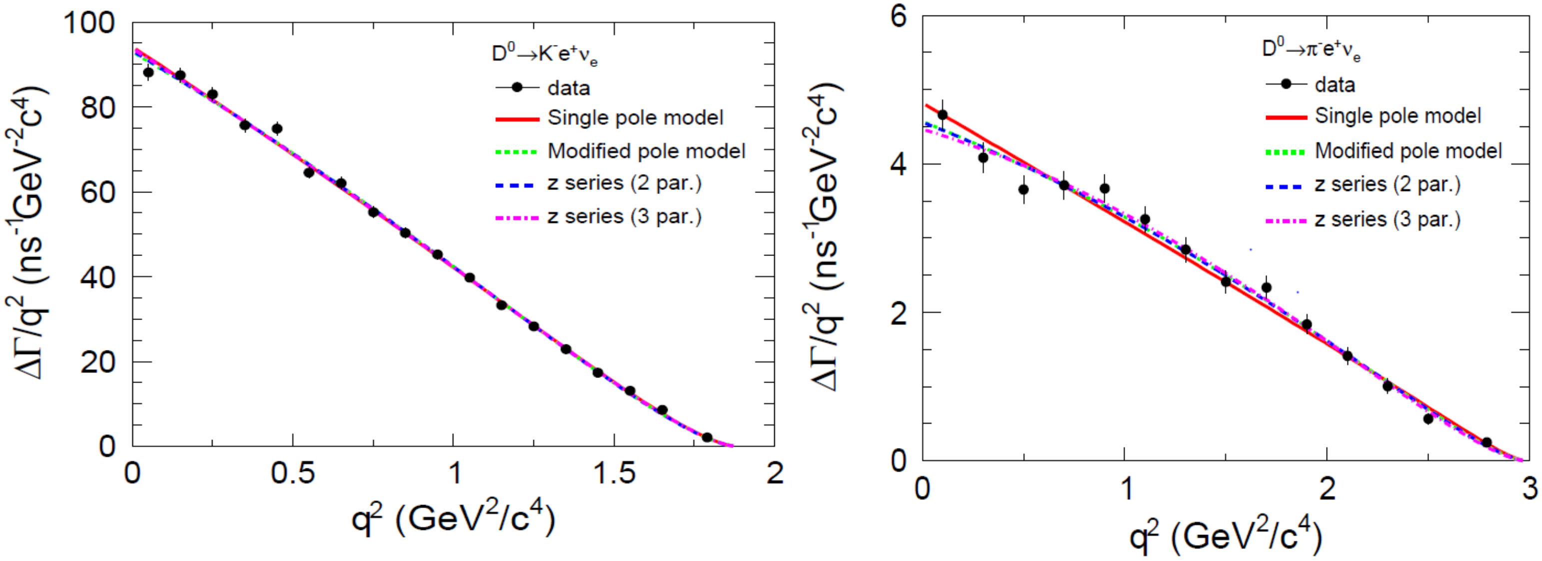
Starting with the equally spaced bins, bins are adjusted to optimize the sensitively to γ. A secondary adjustment smooths binned areas smaller than detector resolution

BaBar 2008 Modified Optimal Bins



Similar to the "optimal binning" except the expected background is taken into account before optimizing to γ sensitivity

Measurement of $f_+^{K(\pi)}(q^2)$



		Single pole model	
Decay mode	$f_+^{K(\pi)}(0)\lvert V_{cs(d)}\rvert$	$M_{\rm pole}$ (GeV/c^2)	
$D^0 \to K^- e^+ \nu_e$	$0.7209 \pm 0.0022 \pm 0.0035$	$1.921 \pm 0.010 \pm 0.007$	
$D^0 \to \pi^- e^+ \nu_e$	$0.1475 \pm 0.0014 \pm 0.0005$	$1.911 \pm 0.012 \pm 0.004$	
		Modified pole model	
Decay mode	$f_+^{K(\pi)}(0)\lvert V_{cs(d)}\rvert$	α	
$D^0 \to K^- e^+ \nu_e$	$0.7163 \pm 0.0024 \pm 0.0034$	$0.309 \pm 0.020 \pm 0.013$	
$D^0 \to \pi^- e^+ \nu_e$	$0.1437 \pm 0.0017 \pm 0.0008$	$0.279 \pm 0.035 \pm 0.011$	
		Two-parameter series expansion	
Decay mode	$f_+^{K(\pi)}(0)\lvert V_{cs(d)}\rvert$	r_1	
$D^0 \to K^- e^+ \nu_e$	$0.7172 \pm 0.0025 \pm 0.0035$	$-2.2286 \pm 0.0864 \pm 0.0573$	
$D^0 \to \pi^- e^+ \nu_e$	$0.1435 \pm 0.0018 \pm 0.0009$	$-2.0365 \pm 0.0807 \pm 0.0257$	
		Three-parameter series expansion	
Decay mode	$f_+^{K(\pi)}(0)\lvert V_{cs(d)}\rvert$	r_1	r_2
$D^0 \to K^- e^+ \nu_e$	$0.7195 \pm 0.0035 \pm 0.0041$	$-2.3338 \pm 0.1587 \pm 0.0804$	$3.4188 \pm 3.9090 \pm 2.4098$
$D^0 \to \pi^- e^+ \nu_e$	$0.1420 \pm 0.0024 \pm 0.0010$	$-1.8432 \pm 0.2212 \pm 0.0690$	$-1.3874 \pm 1.4615 \pm 0.4680$

Study of $D^+ \to K_L e^+ \nu_e$

– Never been studied BESIII Preliminary, 2.9 fb^{-1} ψ'' data, see Fenfen's talk at Charm2015

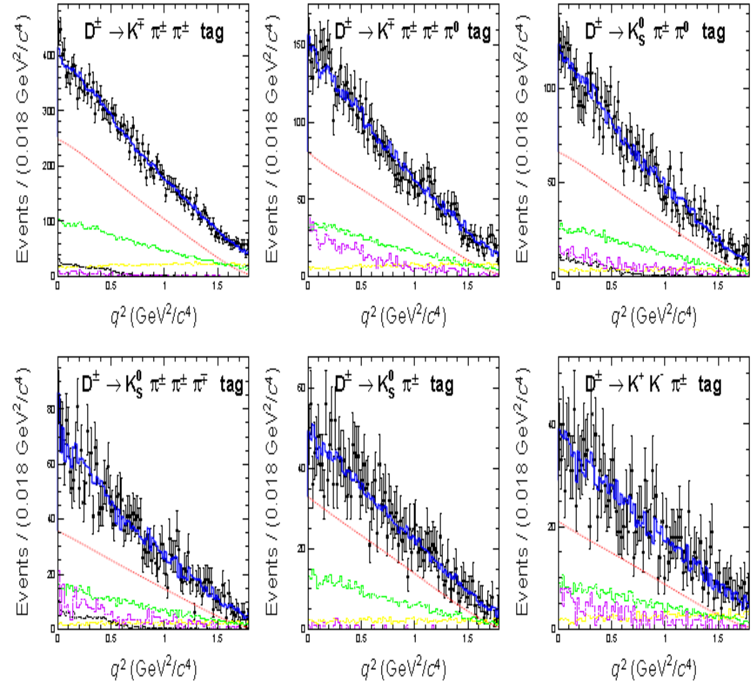
– A CP asymmetry with magnitude of about ~-3.3×10^{-3} due to K^0–K^0 mixing

[PLB 353(1995) 31, 363 (1995) 266]

– K_L reconstruction :

- Get position of the K_L in EMC by fining a neutral cluster
- Use the constraint of Umiss=0 to get the momentum of K_L

Simultaneous fit to event density with 2-parameters series FF



BESIII Preliminary Results

$$A_{CP}(D^+ \to K_L e^+ \nu_e) = (-0.59 \pm 0.60_{stat} \pm 1.48_{syst})\%$$

$$B(D^+ \to K_L e^+ \nu_e) = (4.482 \pm 0.027_{stat} \pm 0.103_{syst})\%$$

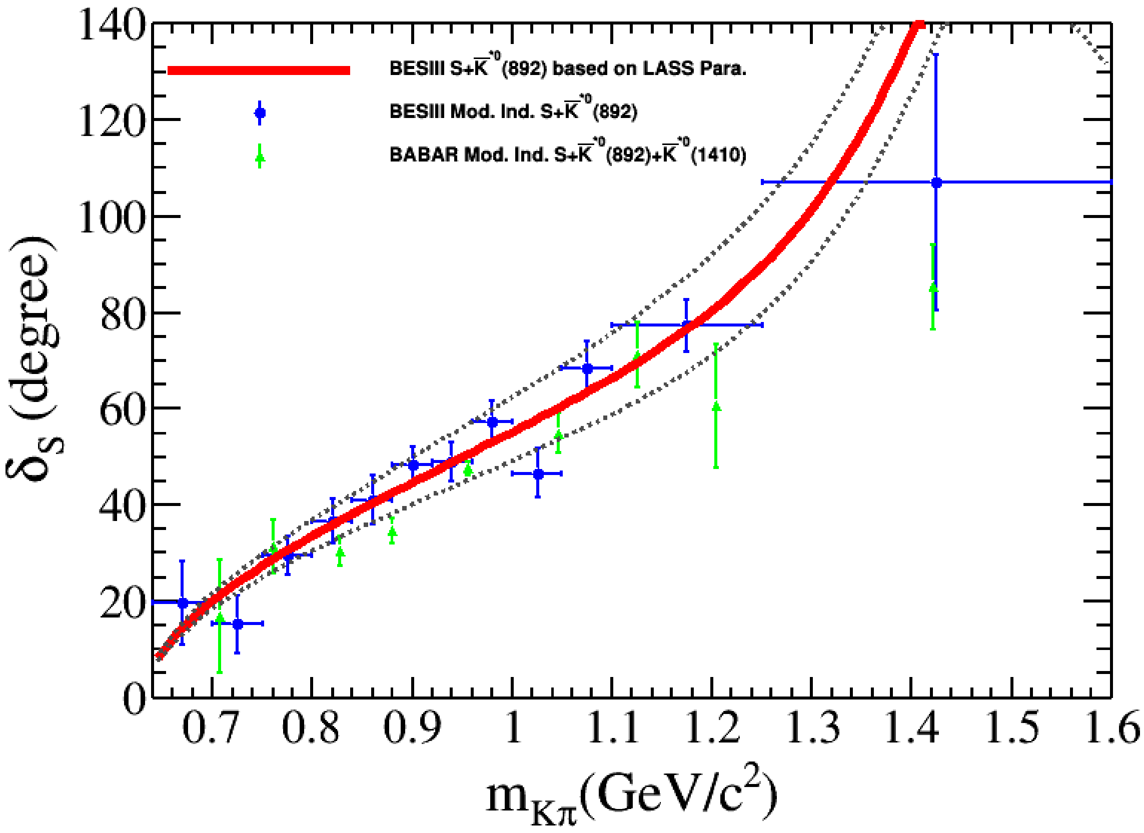
$$f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$$

$$|V_{cs}| = 0.975 \pm 0.008 \pm 0.015 \pm 0.025$$

With $f_+^K(0) = 0.747 \pm 0.019 \quad (PRD82, 114506)$

PWA of $D^+ \to K^-\pi^+e^+\nu_e$

BESIII 2.9 fb^{-1} ψ'' data, see Fenfen's talk at Charm2015



Model-independent measurement of BESIII are consistent with its result from amplitude analysis within 1σ.

CPV via T-odd moments in $D^0 \to KK\pi\pi$

Paras Naik's talk at Charm 2015

JHEP 10 (2015) 005, $3.0 fb^{-1}$

- To eliminate the effects of FSI, which conserve P, we form an asymmetry of asymmetries which cancels out the FSI; any remaining asymmetry implies that either C or P is violated, i.e. we have CPV

$$a_{CP}^{T-\text{odd}}(D^0) = \frac{1}{2}\left(A_{C_T} - \overline{A}_{\overline{C}_T}\right)$$

- LHCb measured these asymmetries using SL flavor-tagged D decays.

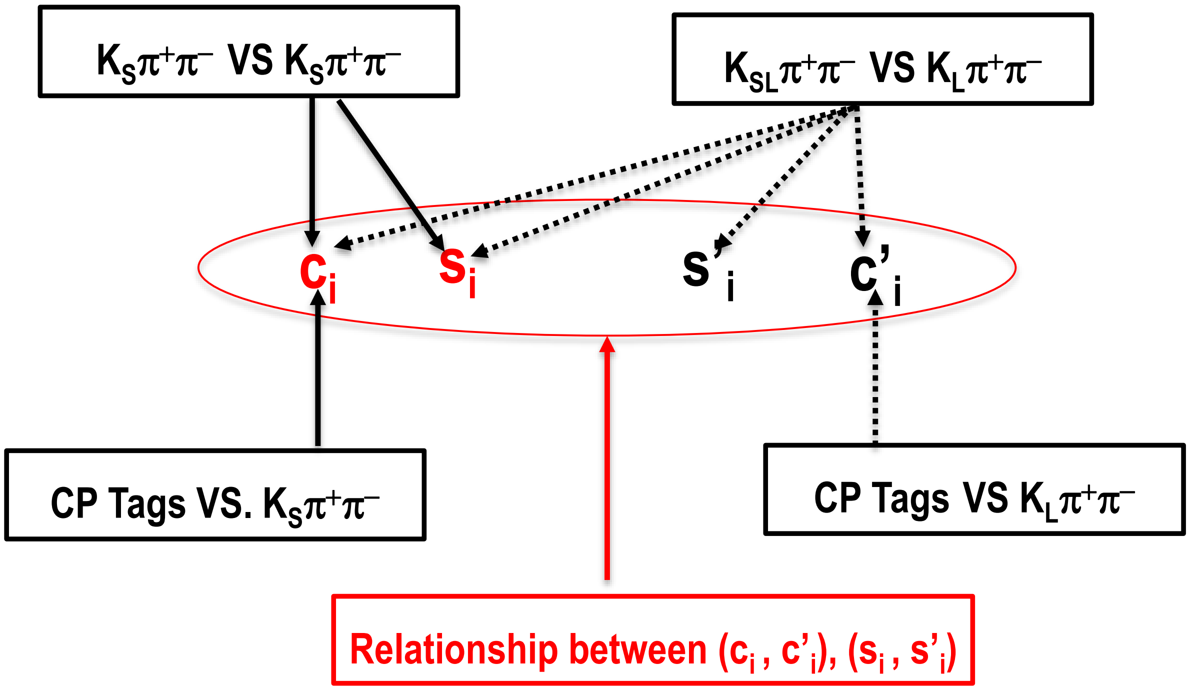
$$A_{C_T} = (-71.8 \pm 4.1(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-3}$$
$$\overline{A}_{\overline{C}_T} = (-75.5 \pm 4.1(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-3}$$

$$a_{CP}^{T-\text{odd}}(D^0) = (1.8 \pm 2.9(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3}$$

- We also searched for local CPV in bins of phase space, and evidence of CPV in bins of proper time. No CPV was found.

c_i/s_i in $D^0\to K_{S/L}\pi^+\pi^-$ Analysis

c_i and s_i can be calculated from double tags of $D^0\to K_S\pi^+\pi^-$ VS. $D^0\to$ ($K_{S/L}\pi^+\pi^-$ or CP eigenstates)

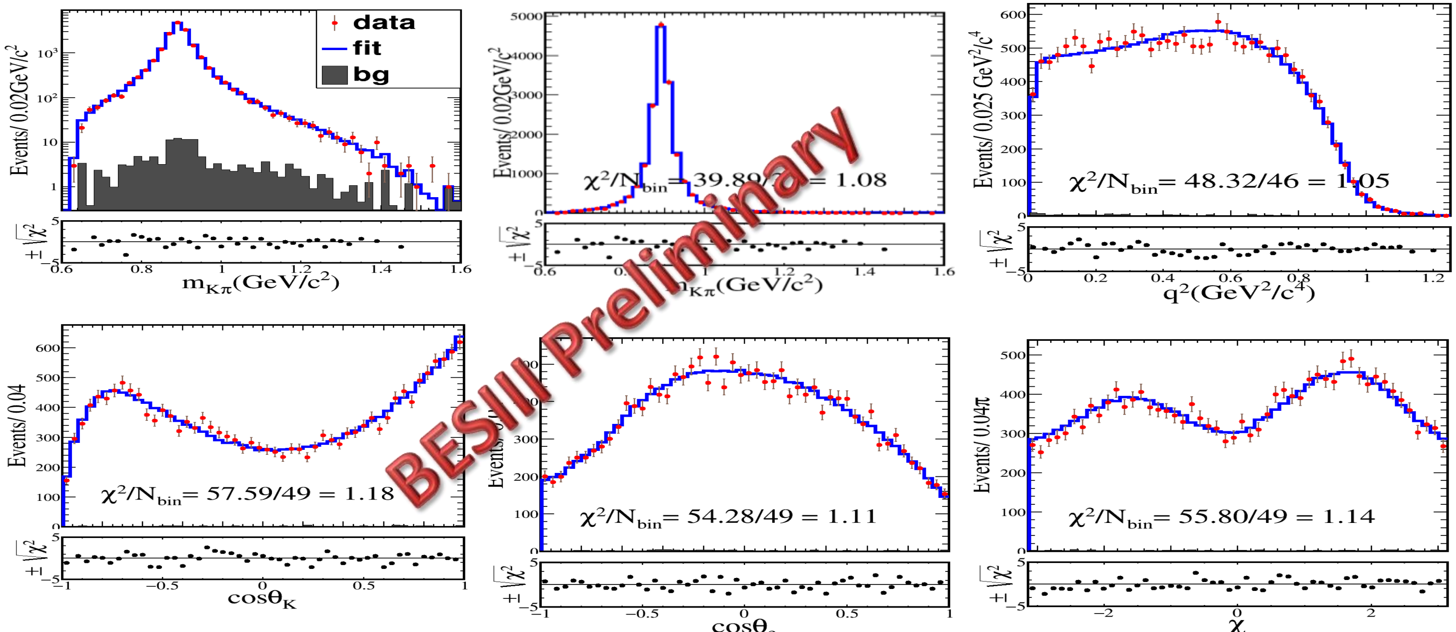


Only c_i, s_i from $D^0\to K_S\pi^+\pi^-$ is used to calculated γ.

However adding in $D^0\to K_L\pi^+\pi^-$ to calculate c'_i, s'_i and use the relationship to c_i, s_i to further constrain the results in a global fit

PWA of $D^+ \to K^- \pi^+ e^+ \nu_e$

BESIII 2.9 fb^{-1} ψ'' data, see Fenfen's talk at Charm2015



- **$K^{*0}(892)$ mass and width**

$$M_{K^{*0}(892)} = (894.60 \pm 0.25 \pm 0.08) MeV/c^2$$
$$\Gamma_{K^{*0}(892)} = (46.42 \pm 0.56 \pm 0.15) MeV/c^2$$

- **The fractions of components**

$$f(D^+ \to (K^-\pi^+)_{K^{*0}(892)} e^+ \nu_e) = (93.93 \pm 0.22 \pm 0.18)\%$$
$$f(D^+ \to (K^-\pi^+)_{S-wave} e^+ \nu_e) = (\ 6.05 \pm 0.22 \pm 0.18)\%$$

- **Pole mass**

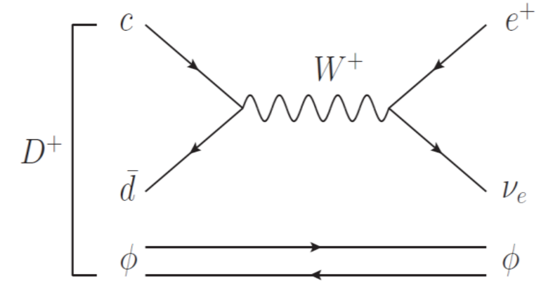
$$m_V = (1.81^{+0.25}_{-0.17} \pm 0.02) GeV/c^2$$
$$m_A = (2.61^{+0.22}_{-0.17} \pm 0.03) GeV/c^2$$

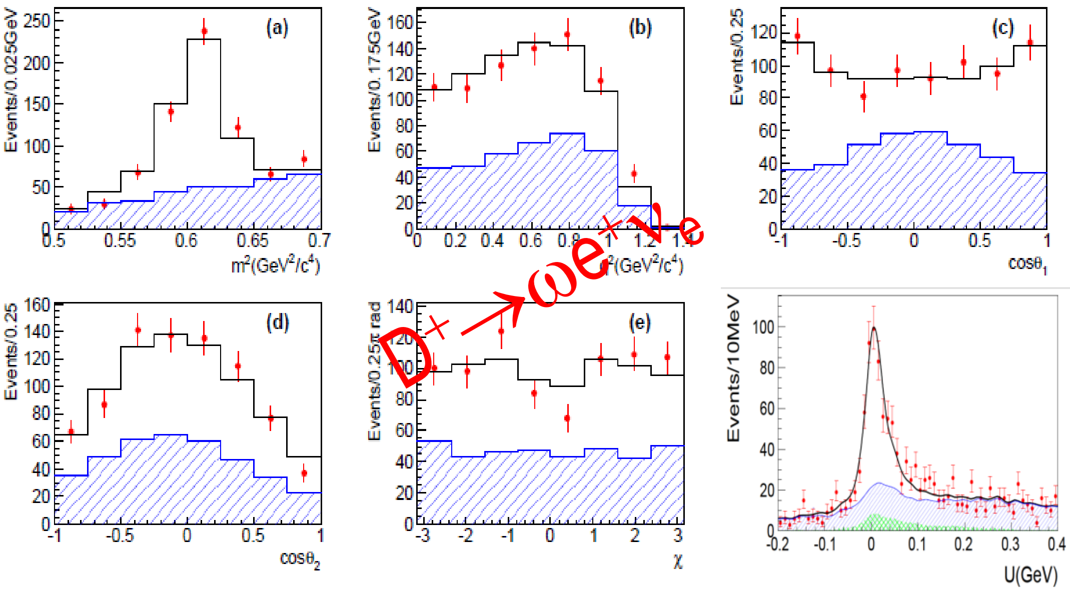
- **Form factor and ratios :**

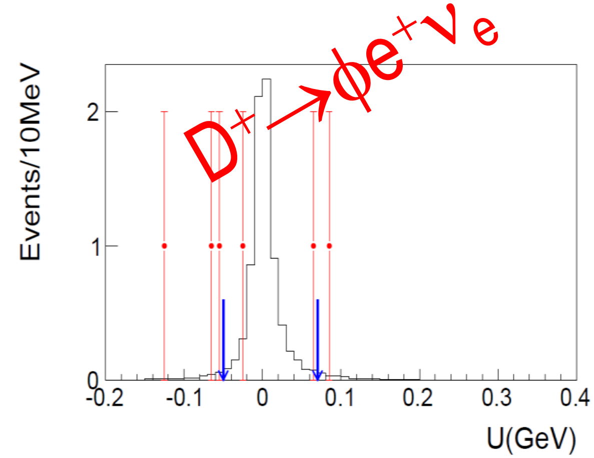
$$A_1(0) = 0.573 \pm 0.011 \pm 0.020$$
$$r_V = V(0)/A_1(0) = 1.411 \pm 0.058 \pm 0.007$$
$$r_A = A_2(0)/A_1(0) = 0.788 \pm 0.042 \pm 0.008$$

Study of $D^+ \to \omega/\phi e^+ \nu_e$

- Form factor of decay $D^+ \to \omega e^+ \nu_e$ have never been measured BESIII 2.9 fb^{-1} ψ'' data arXiv:1508.00151
- $D^+ \to \phi e^+ \nu_e$ proceeds only by ω–ϕ mixing or non-perturbative "Weak Annihilation" (WA) process, measure of its BR can help to judge the dominant process





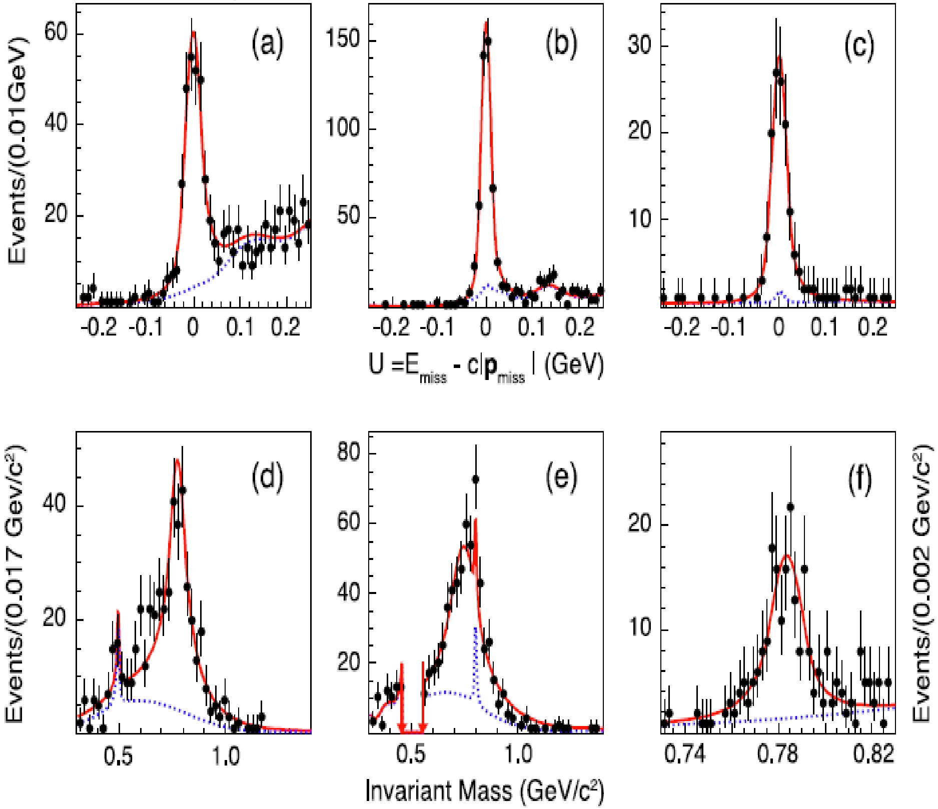


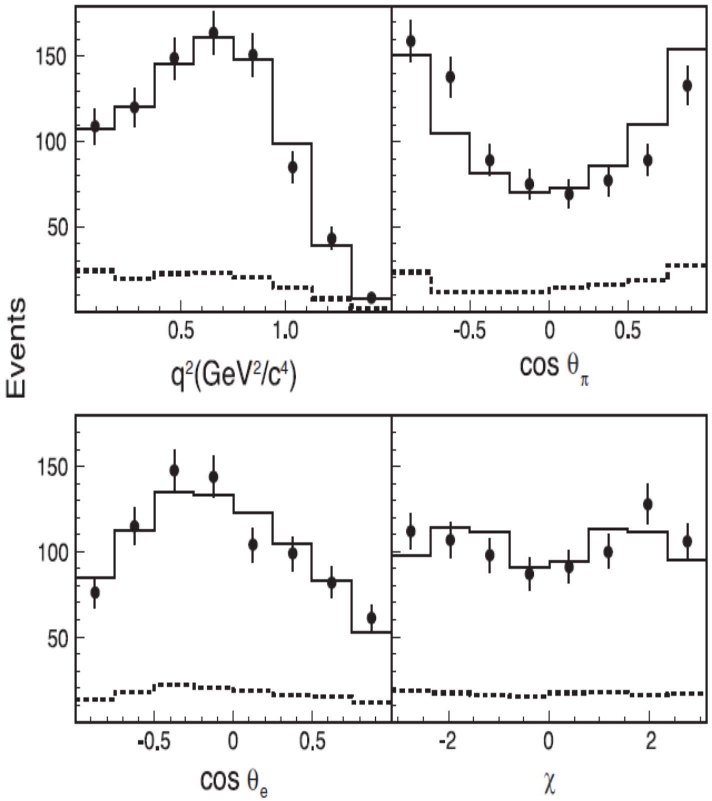
$$r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$$
$$r_A = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$$

Mode	This work	Previous
$\omega e^+ \nu_e$	$(1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$	$(1.82 \pm 0.18 \pm 0.07) \times 10^{-3}$
$\phi e^+ \nu_e$	$< 1.3 \times 10^{-5}$ (@90%C.L.)	$< 9.0 \times 10^{-5}$ (@90%C.L.)

CLEO-C : $D^0 \to \rho^- \ell^+ \nu_\ell, D^+ \to \rho^0/\omega \ell^+ \nu_\ell$

818 pb^{-1} @ ψ'', PRL 110 (2013) 131802





$$B(D^0 \to \rho^- \ell \nu_\ell) = (1.77 \pm 0.12 \pm 0.10)\%$$

$$B(D^+ \to \rho^0 \ell \nu_\ell) = (2.17 \pm 0.12^{+0.12}_{-0.22})\%$$

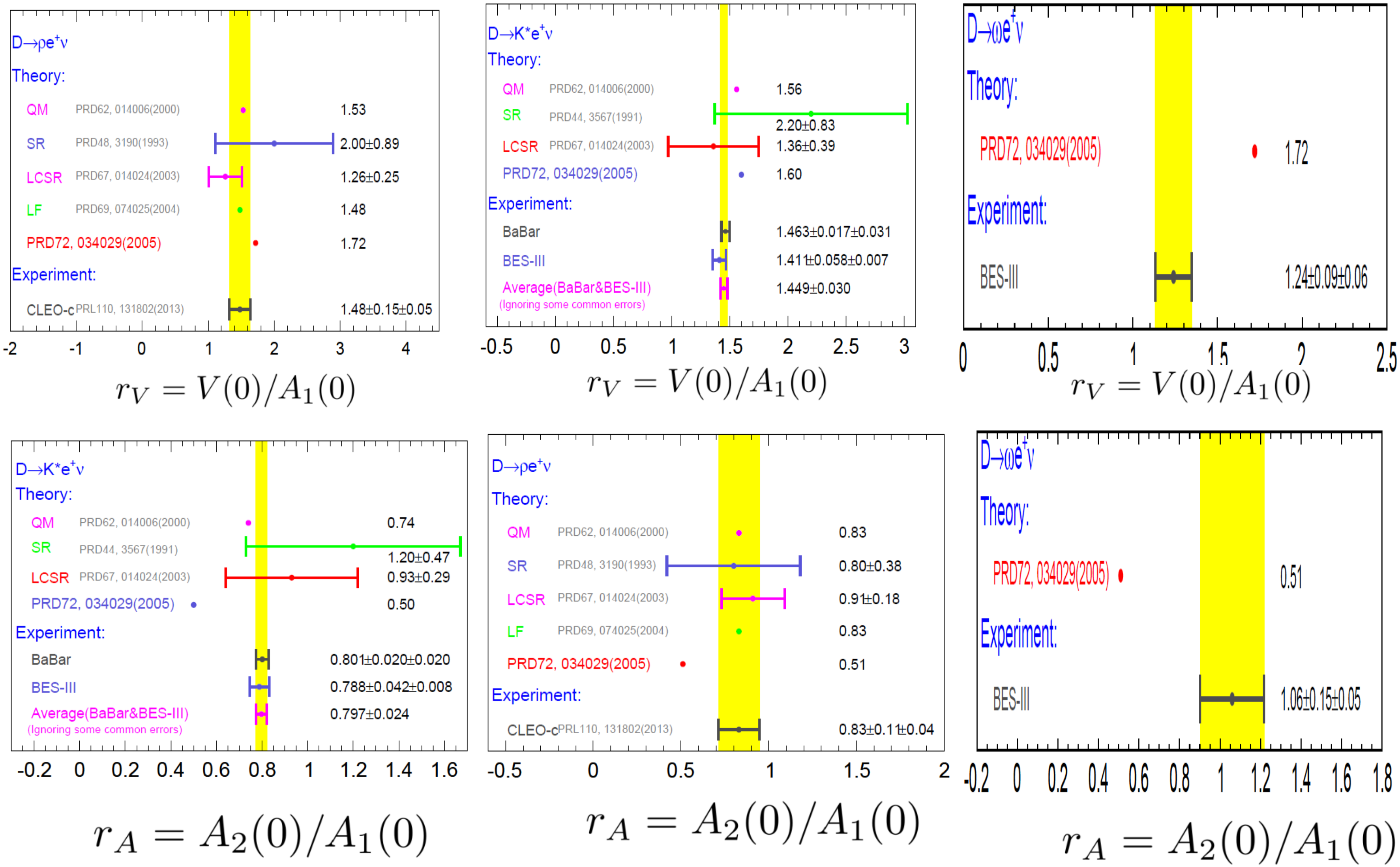
$$B(D^+ \to \omega \ell \nu_\ell) = (1.82 \pm 0.18 \pm 0.07)\%$$

$$\frac{\Gamma(D^0 \to \rho^- \ell \nu_\ell)}{2\Gamma(D^0 \to \rho^- \ell \nu_\ell)} = 1.03 \pm 0.09^{+0.08}_{-0.02}$$

$$r_V = V(0)/A_1(0) = 1.48 \pm 0.15 \pm 0.05$$

$$r_A = A_2(0)/A_1(0) = 0.83 \pm 0.11 \pm 0.04$$

Comparison of $r_{V/A}$ in $D \to V \ell^+ \nu_\ell$

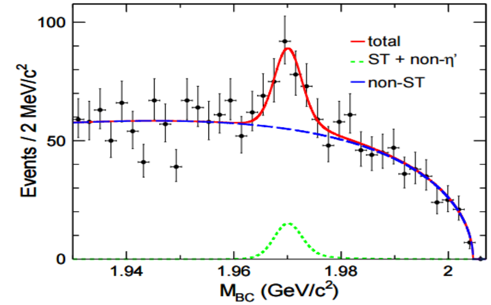


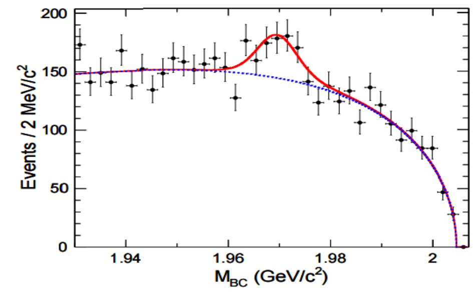
Measurement of $D_s^+ \to \eta' X / \eta' \rho^+$

BESIII 482 pb^{-1} @ 4.009GeV arXiv:1506.08952

- Inclusive measurement on BR :
  - BR($D_s^+ \to \eta' X$)=(11.7±1.8)% [CLEO-c, PRD79, 112008 (2009)]
  - BR($D_s^+ \to \eta' X$)=(18.6±2.3)% [sum over all exclusive measurement in PDG]
- Exclusive measurement on BR :
  - BR($D_s^+ \to \eta' \rho^+$)=(12.5±2.2)% [CLEO2, PRD58, 052002 (1998)]
  - BR($D_s^+ \to \eta' \pi^+ \pi^0 (\rho^+)$)=(5.6±0.5±0.6)% [CLEO-c, PRD88, 032009 (2013)]
- A factorization method predicts :
  - BR($D_s^+ \to \eta' \pi^+ \pi^0 (\rho^+)$)=(3.0±0.5)% [F. S. Yu et al, PRD84, 074019 (2011)]
- BESIII Measurement based on 482pb^{-1} data at 4.009 GeV
  - BR($D_s^+ \to \eta' X$)=(8.8±1.8±0.5)%
  - BR($D_s^+ \to \eta' \rho^+$)=(5.8±1.4±0.4)%
  - BR($D_s^+ \to \eta' \pi^+ \pi^0 (\rho^+)$)≤5.1%@90% C.L.

A interesting situation on BR measurement

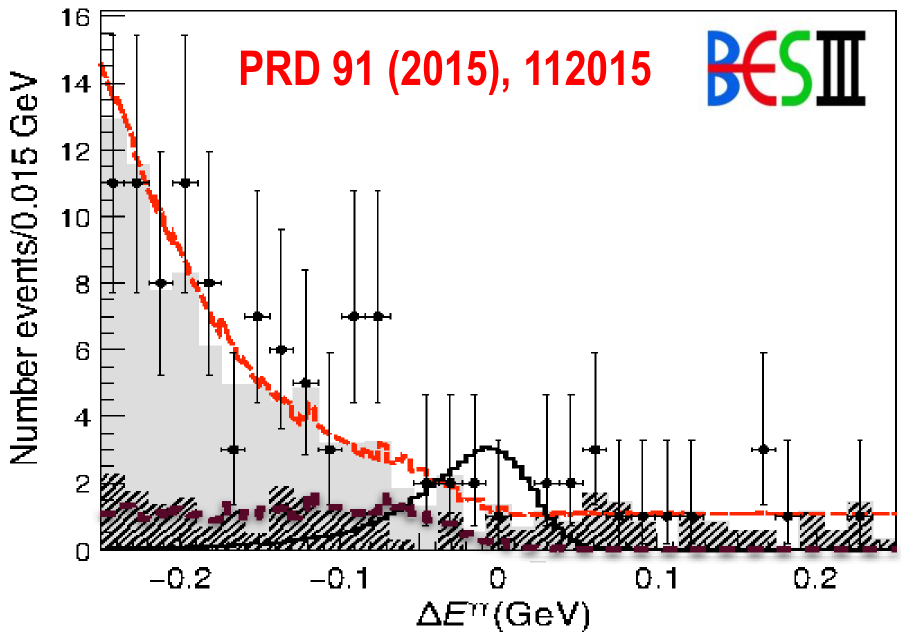


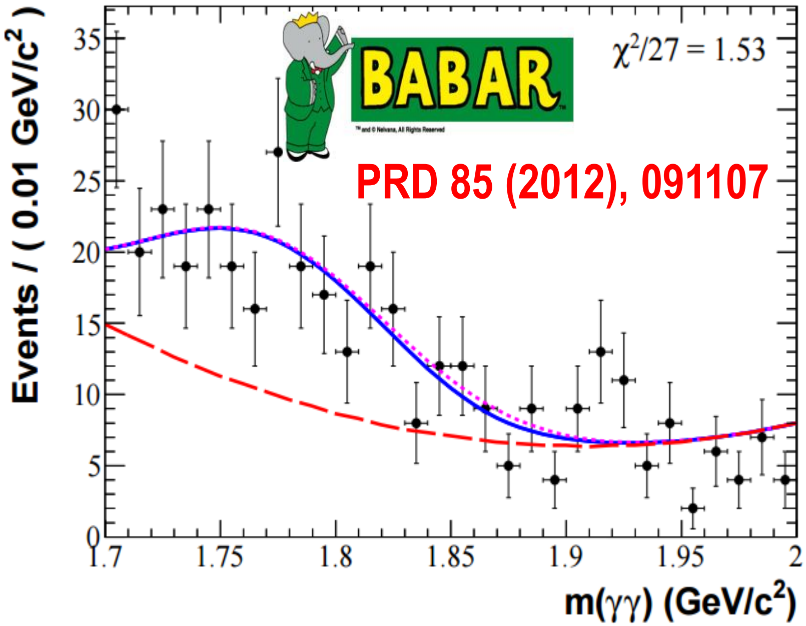


Consistent with CLEO-c recent measurement,

Reconcile the tension between experimental data and theoretical prediction

$D^0 \to \gamma\gamma$ Measurement





BESIII Double tagged method (5 tag modes)

- 2.9 fb^{-1} results: $B(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$ @ 90% C.L.
- 10.0 fb^{-1} expected: $B(D^0 \to \gamma\gamma) < 1.0 \times 10^{-6}$ @ 90% C.L.

BESIII has much smaller bkg than that at B factory, peaking bkg from $D^0 \to \pi^0\pi^0$ is under control

Belle II (470.5fb-1) :

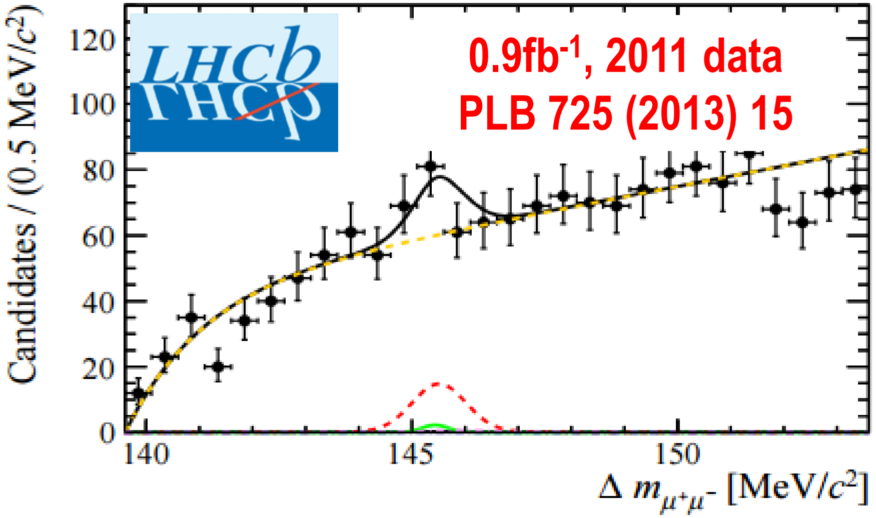
$$B(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6} \text{ @ } 90\% \text{ C.L.}$$

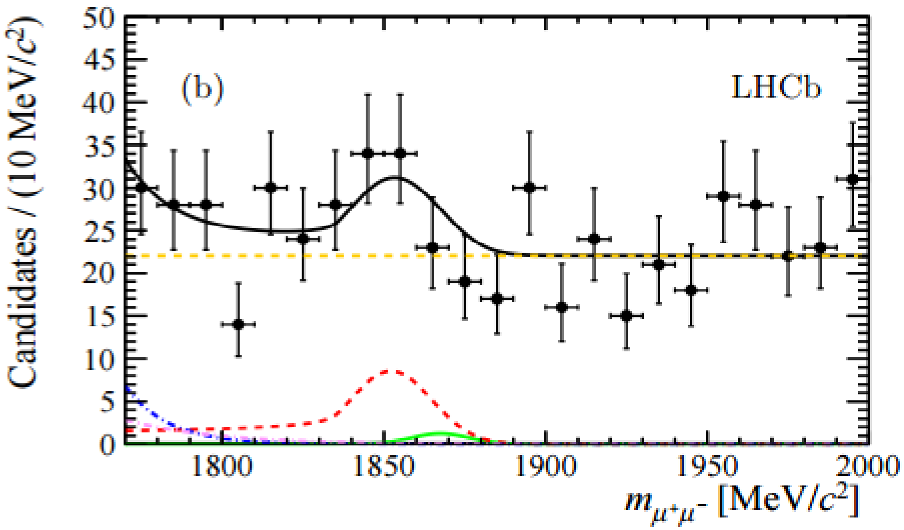
Theory prediction :

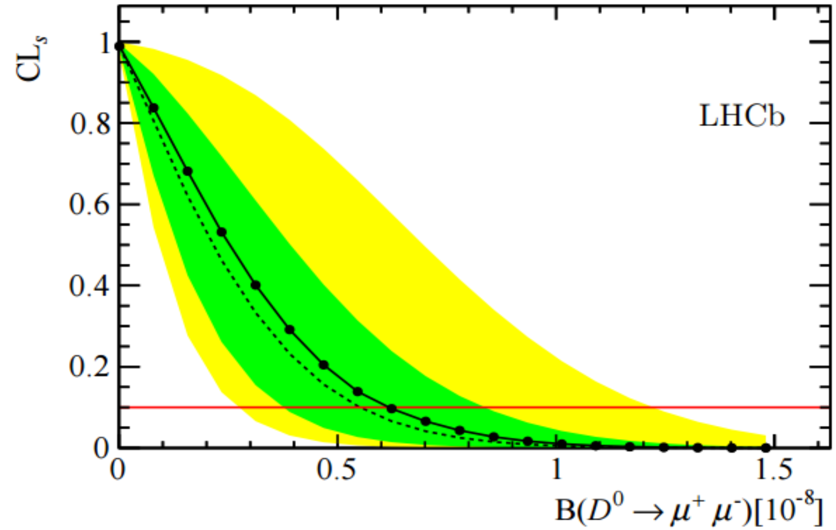
$$B(D^0 \to \gamma\gamma)^{VMD} \simeq (3.5^{+4.0}_{-2.6}) \times 10^{-8}$$

$$B(D^0 \to \gamma\gamma)^{SD} \simeq 3 \times 10^{-11}$$

$D^0 \to \mu^+\mu^-$ Measurement







- Using D* chain : $D^{*+} \to D^0(\mu^+\mu^-)\pi_s^+$:

  $B(D^0 \to \mu^+\mu^-) \leq 6.2(7.6) \times 10^{-9}$ @ 90 (95)% C. L.

- Current best limit
- But still 100×SM or 10×NP prediction
- Also best limit for FCNC in charm

Prospects on Rear Decays

LHCb :

- For run II (2015–2018) expect mild improvements wrt run I
- LHCb upgrade:
  $\sigma(c\bar{c})_{14\,\mathrm{TeV}} \sim 2\sigma(c\bar{c})_{7\,\mathrm{TeV}}$, trigger $\sim 2\times$ better, $\sim 50\ \mathrm{fb}^{-1}$
- $10\times$ charm per year

Modes	Run I	Run II	Upgrade
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}
$D^+_s \to K^+\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$D^0 \to h^+h'^{(-)}\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}

- Rare charm program in LHCb includes/foresee:
  $D^0 \to \ell^+\ell'^-$, $\Lambda_c \to p\ell^+\ell^-$, $D \to h(h')\ell\ell'$, $D^0 \to \phi\gamma$
  with $\ell = \mu, e$ (FCNC, LFV and LNV modes)

BELLE-II

- Should collect 50 ab^{-1} from e^+e^-
  low background, excellent γ and π^0 reconstruction
- Simple projections from BaBar $X_c \to h\ell\ell$ analysis [PRD 84 (2011) 072006]
  $\sim 100\times$ statistics
  $\Rightarrow$ should achieve U.L. of $\sim 10^{-7}$ for D^+ and 10^{-6} for D_s^+, Λ_c^+ on semileptonic FCNC, LNV and LFV
- also extrapolating from BaBar, could reach $\mathcal{B}(D^0 \to \gamma\gamma) \lesssim 10^{-7}$
- Can do a great job in $h\ell\ell$ with $h = \pi^0, \eta, \omega$

Super τ-charm Factory

- Assuming to collect $\sim 10^{10}$ D pairs $\Rightarrow$ $10^4\times$ Cleo-c
- can achieve U.L of few 10^{-8} for 3-body D^+ and 10^{-7} for 4-body D^0
- could reach $\mathcal{B}(D^0 \to \gamma\gamma) \lesssim 10^{-7}$

Carla's Talk at CHARM2015