Charm Decays
and
Quantum Coherence

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Rare/Forbidden Decays
Not supposed to see them according to the SM.
Then look for them, just in case!

(semi-) Leptonic Decays
Extractions of $|V_{cx}|$, and decay constants.

Hadronic Decays
i.e. BFs of $D_{(s)}$ decays (often, important inputs in B decays).
Charm productions in continuum (i.e., $\psi(3770) \rightarrow D\bar{D}$ line shape).

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Use the quantum-correlated Charm mesons
- usually produced at mass threshold → relevant experiments: CLEO-c/BESIII.
- can extract $D\bar{D}$ mixing parameters.
- can also help the γ/ϕ_3 measurement (i.e., via the GGSZ method).

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Charm Decays

I will briefly go through some of the recent experimental results in these three topics today

Quantum Coherence

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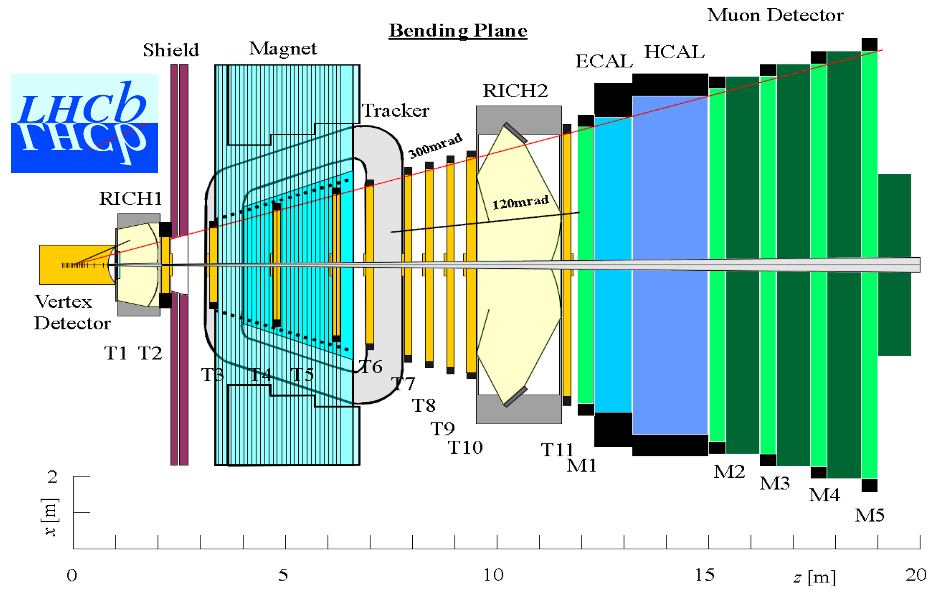
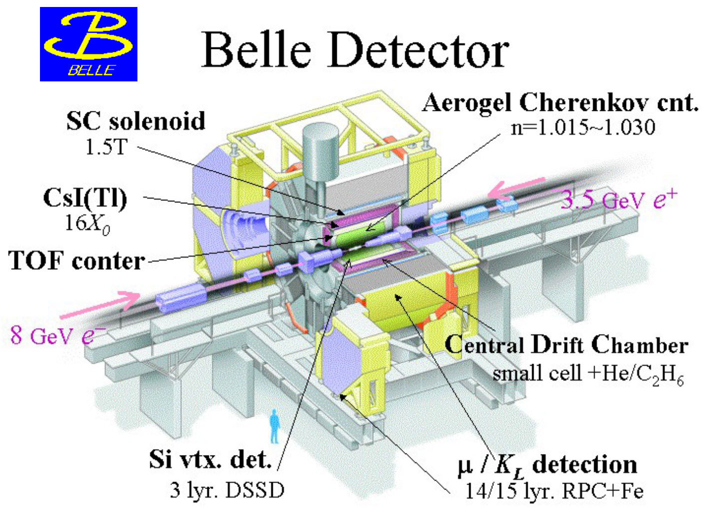
- usually produced at mass threshold → relevant experiments: CLEO-c/BESIII.
- can extract $D\bar{D}$ mixing parameters.
- can also help the γ/ϕ_3 measurement (i.e., via the GGSZ method).

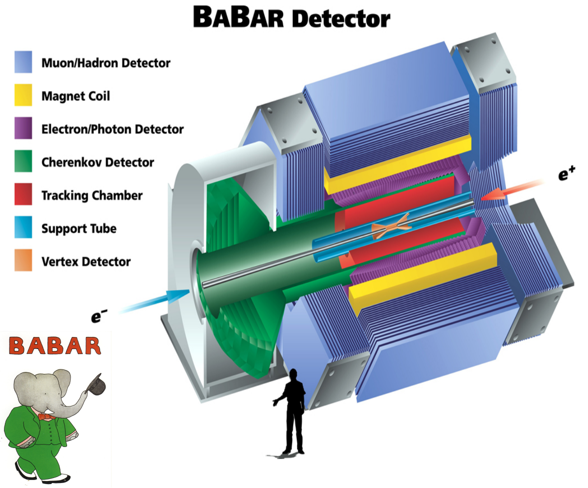
Outline

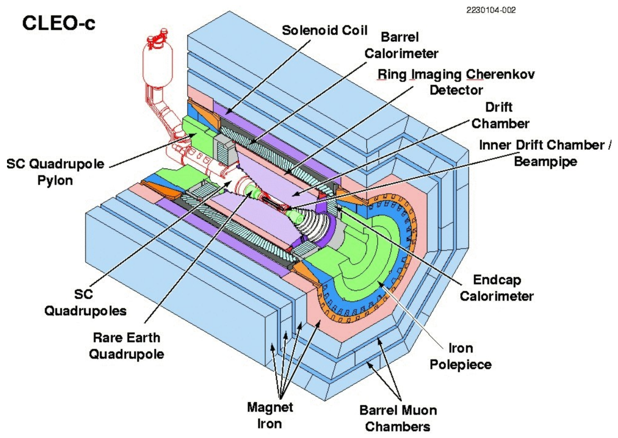
1. **Rare/Forbidden searches**
   - Experimental limits are starting to reach BF~10^{-9} and starting to overlap some non-SM predictions.
   - Will go through two recent results on FCNC transitions.
2. **Leptonic and semi-leptonic decays.**
   - Access to CKM matrix elements, $V_{cd(s)}$.
   - Will go through recent results on D^0 and D^+ decays.
3. **Quantum-Correlated Charm analyses**
   - Provide access to the mixing parameters.
   - can also contribute the γ/ϕ_3 measurement.
   - Will go through the recent measurements of $\delta_{K\pi}$, y_{cp}, as well as the c_i and s_i.

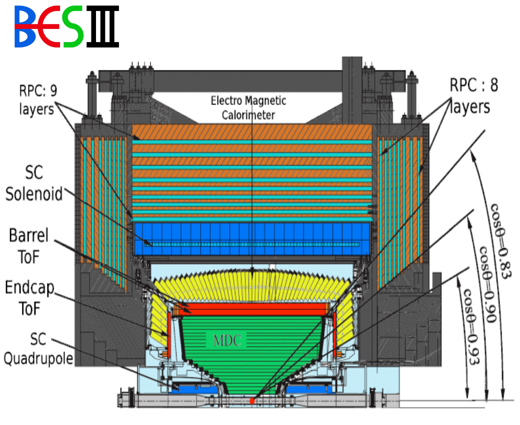
All results are from
Modern Heavy Flavor Factories











Wire tracker (no Si); TOF + dE/dx for PID; CsI Ecal; RPC muon

Why Rare Charm Decay?

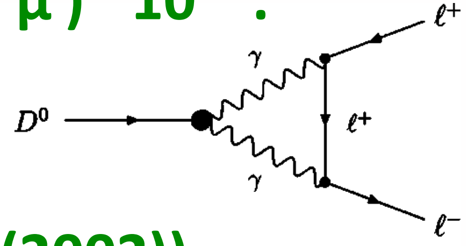
- Charm is unique.
  FCNC transitions are highly suppressed in the SM.
  - mediated by the lighter down-quark sector.
  - more effective GIM suppression here than in B decays.

- That is, the "SM noise" is much lower in Charm!
  (non-existent at current experimental limits)
  Of course, this does not mean the signature of
  new Physics (NP) is larger in Charm, however.

- Observing or even NOT observing rare decays help to constrain effects from NP.

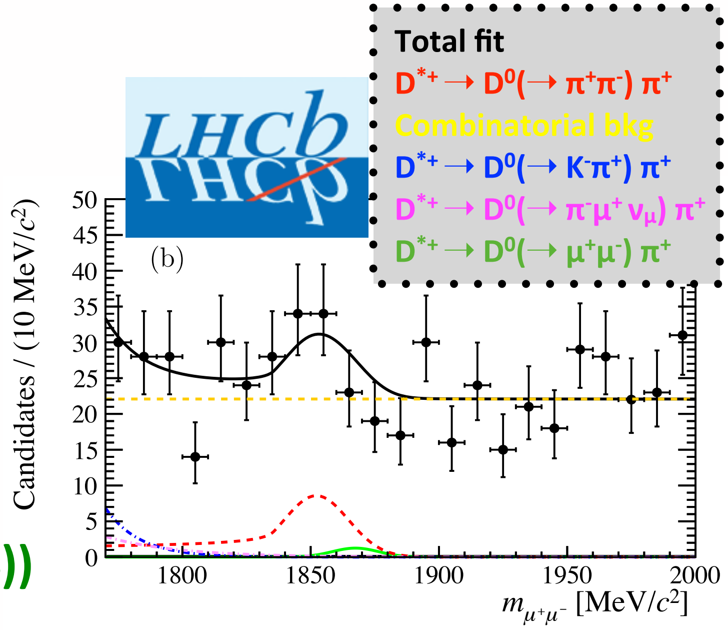
$D^0 \rightarrow \mu^+\mu^-$

- Expect small short distance contribution: $B(D^0 \rightarrow \mu^+\mu^-) \sim 10^{-18}$.



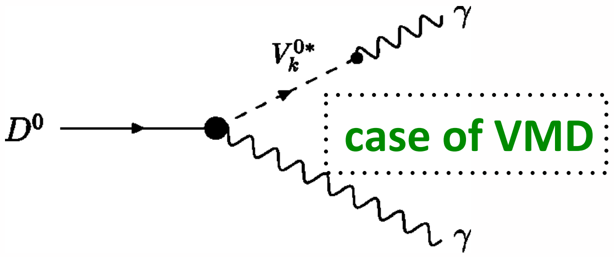
- The long distance might be dominated by the two photon intermediate state; $B(D^0 \rightarrow \mu^+\mu^-) \sim 2.7\times10^{-5}\times B(D^0\rightarrow\gamma\gamma)$ (PRD66, 014009 (2002)). If we take $B(D^0\rightarrow\gamma\gamma) < 2.2\times10^{-6}$ @90% C.L. (PRD85, 091107 (2012)), then $B(D^0 \rightarrow \mu^+\mu^-) <\sim 6\times10^{-11}$.

- LHCb (PLB725, 15 (2013))
  - $B(D^0 \rightarrow \mu^+\mu^-) < 6.2\times10^{-9}$ @ 90% C.L.
  - Still some room to reach the prediction
  - Some BSM predict BF ~ 10^{-10} (R-parity violation, PRD66, 014009 (2002); Warped extra dimensions, PRD90, 014035 (2014))

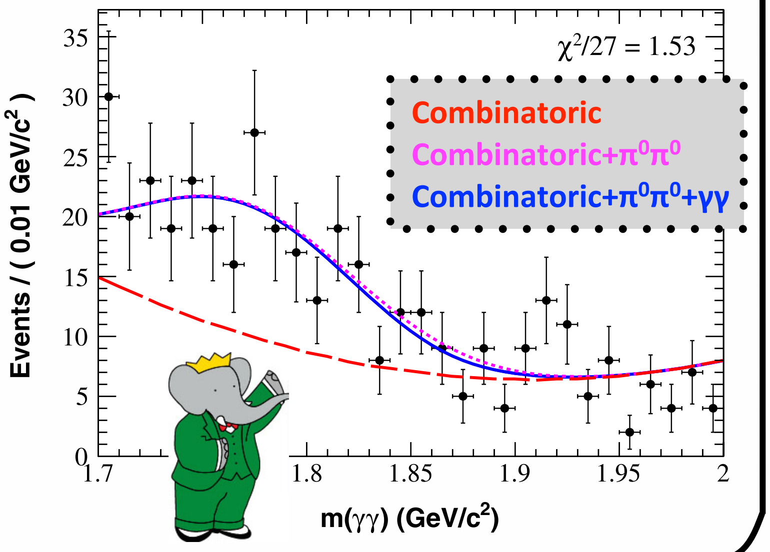


- More data at LHCb would be very interesting!

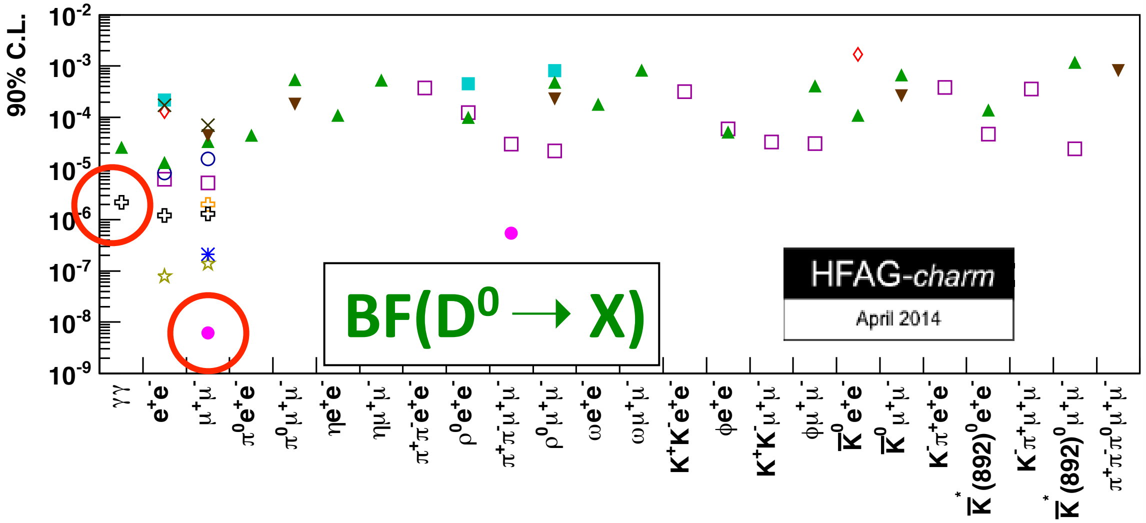
$D^0 \rightarrow \gamma\gamma$



- Forbidden by the tree level.
- Short distance : BF ~ 10^{-11} (PRD66, 014009)
- Long distance : (VMD, HQχPT) : BF ~ 10^{-8}
  [(PRD66, 014009 (2002)), (PRD64, 074008 (2001))]
- MSSM could enhance the rate up to ~10^{-6} ($c \rightarrow u\,\gamma$ via gluino exchange) (PLB500, 304 (2001)).
- BaBar (PRD85, 091107(R) (2012)):
  - Reconstruct through $D^{*+} \rightarrow D^0(\rightarrow \gamma\gamma)\,\pi^+$, normalized by $D^{*+} \rightarrow D^0(\rightarrow K_S\pi^0)\,\pi^+$.
  - Peaking background from $D^0 \rightarrow \pi^0\pi^0$.
  - $B(D^0 \rightarrow \gamma\gamma) < 2.2\times10^{-6}$ @ 90% C.L.

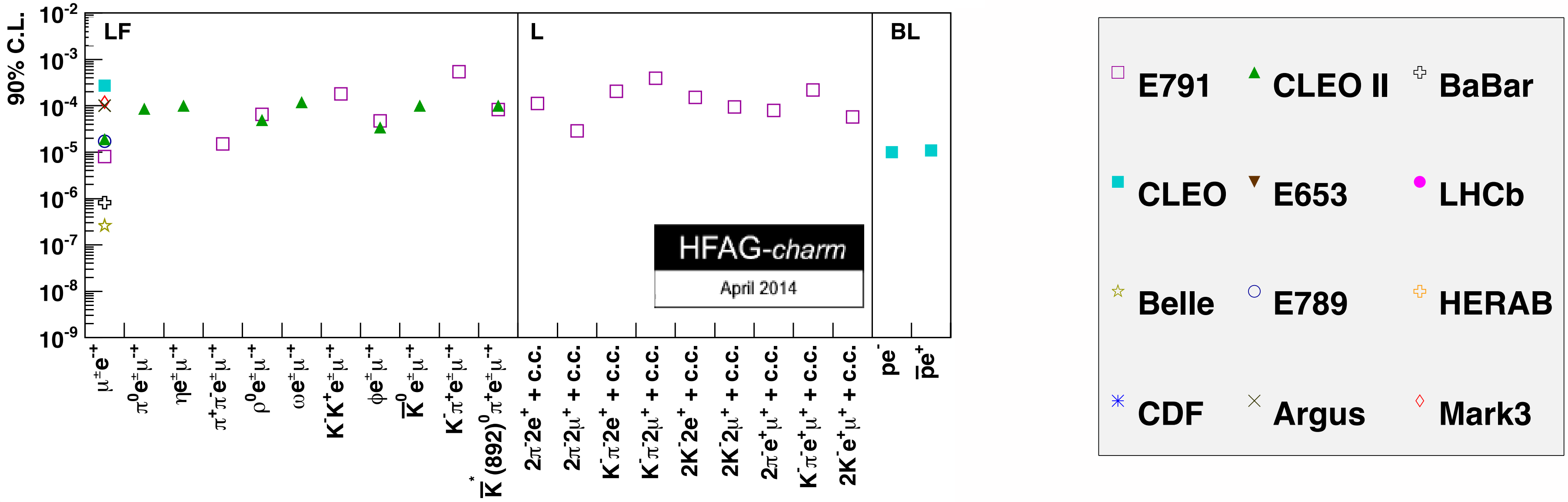


Experimental status in Charm decays - I (from HFAG 2014)

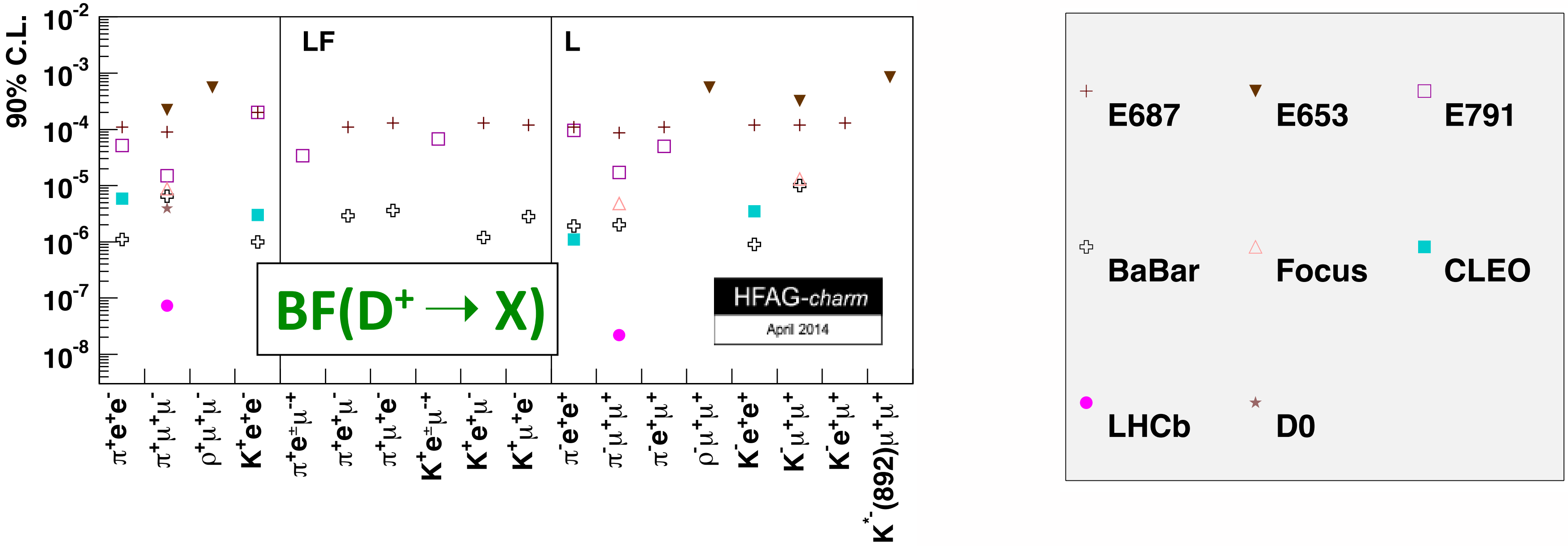


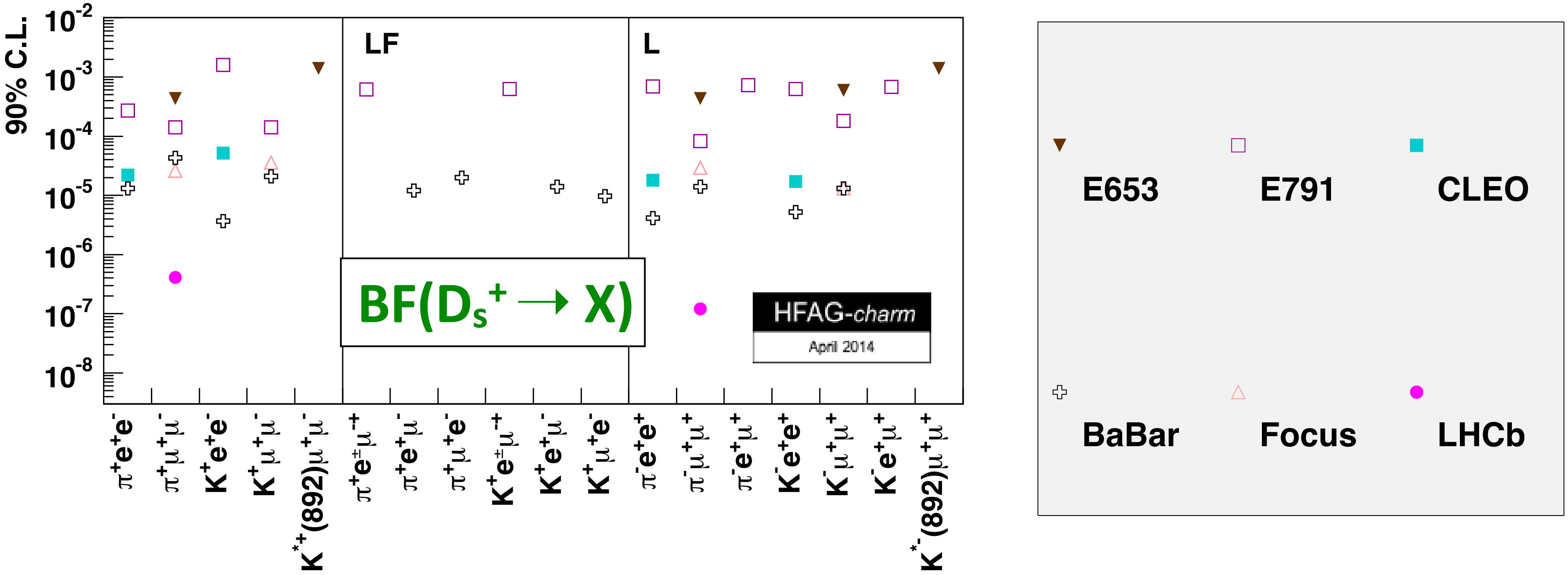
- LHCb ULs are now reaching ~10^{-7}-10^{-8} level.
- B factories are doing well, reaching 10^{-6}-10^{-7} level.

Looking forward to the Belle II!

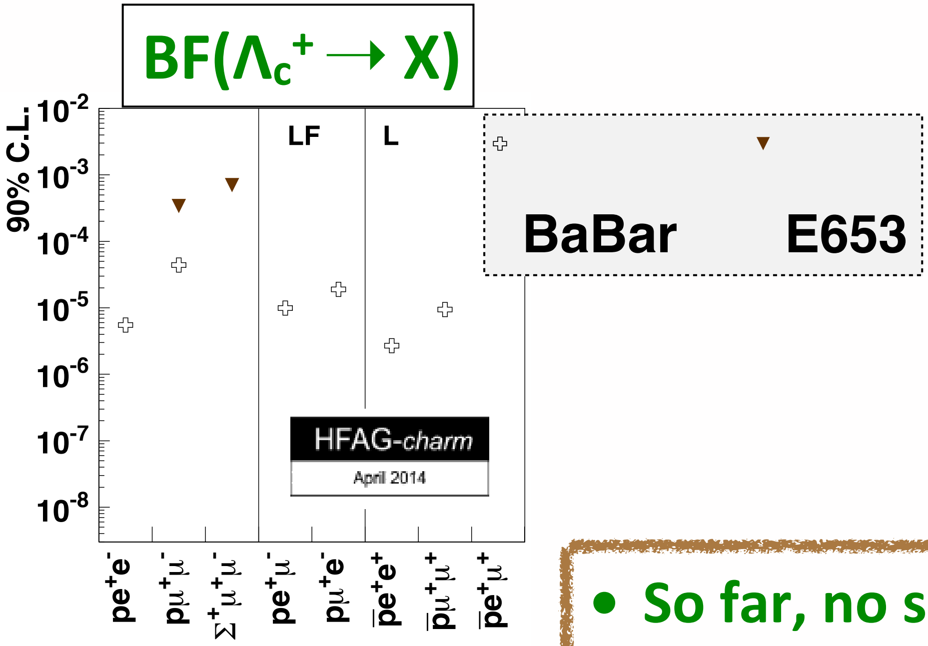


Experimental status - II





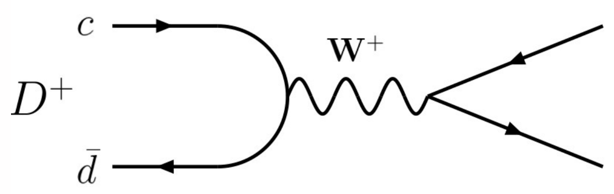
Experimental status - III



- So far, no surprises.
- LHCb upgrade and Belle II are on the horizon.
- Should be able to see some of the listed rare decays soon
  ... or we may see a surprise!?

Recent results in leptonic and semi-leptonic decays of Charm mesons

Leptonic decays $D_{(s)}^+ \rightarrow l + \nu_l$

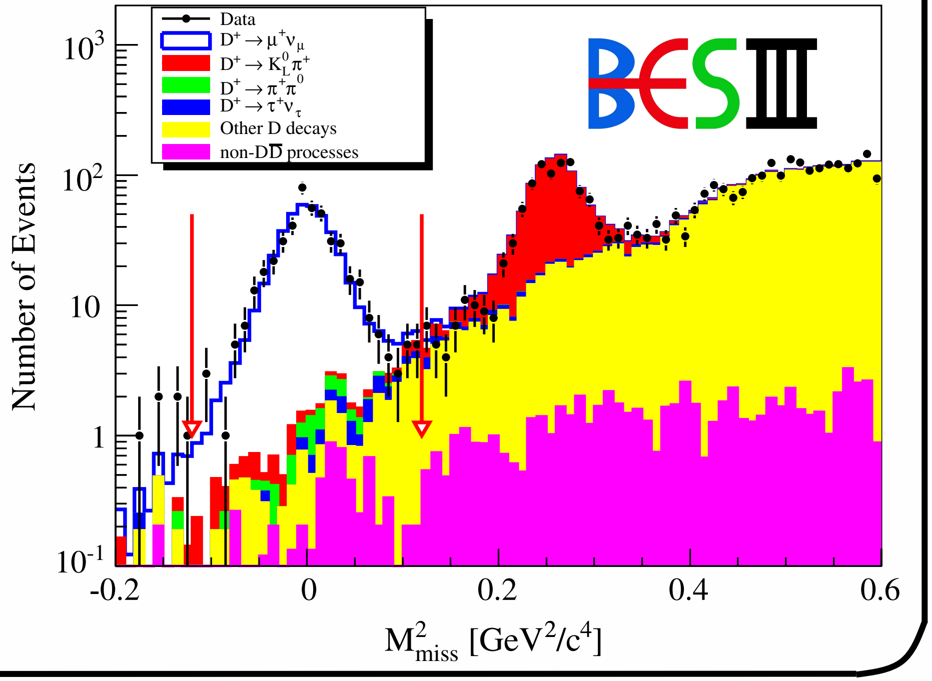


$$\Gamma\left(D^+ \rightarrow \ell^+ \nu_\ell\right) = \boxed{f_D^2 \left|V_{cd}\right|^2} \frac{G_F^2}{8\pi} m_D m_\ell^2 \left(1 - \frac{m_\ell^2}{m_D^2}\right)^2$$

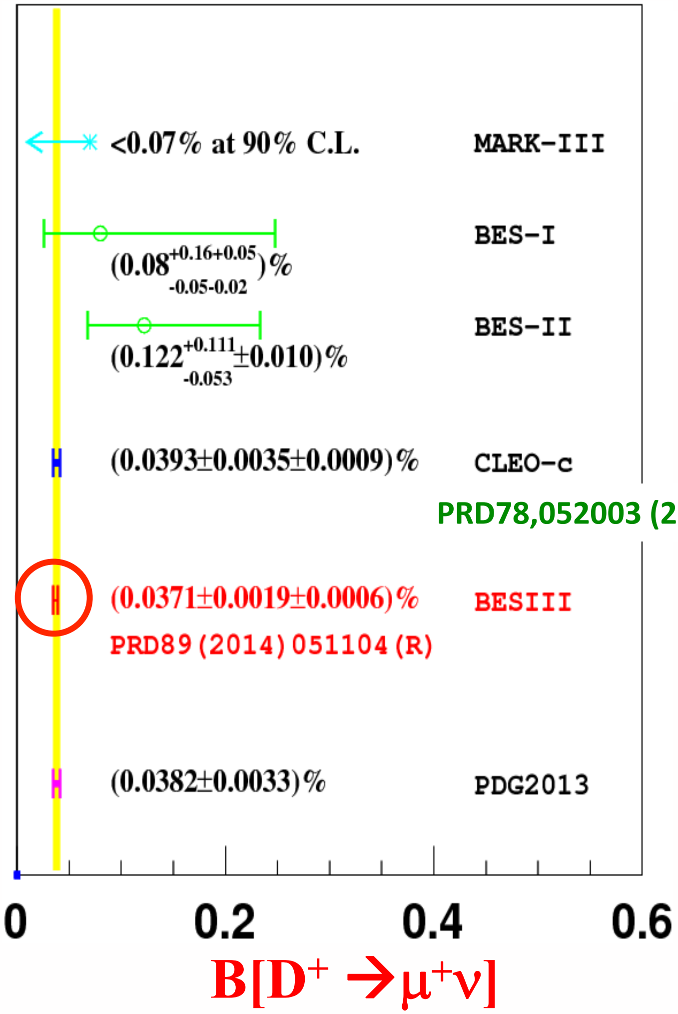
- **With the knowledge of $|V_{cd(s)}|$, extract the decay constant, $f_{D(s)}$ ➜ compare to the Lattice QCD ➜ validate the Lattice QCD calculations in $f_{B(s)}$.**
- **Or vice versa: Taking the calculated $f_{D(s)}$, extract $|V_{cd(s)}|$ to help to over-constrain the CKM unitarity.**
- **Also interesting is:**
  $\Gamma(D^+ \rightarrow \tau^+ \nu_\tau) : \Gamma(D^+ \rightarrow \mu^+ \nu_\mu) : \Gamma(D^+ \rightarrow e^+ \nu_e) = 2.67 : 1 : 2.35\times10^{-5}$
  comes with the minimal uncertainties.
  (masses of the meson and the lepton)
  But $D^+ \rightarrow \tau^+ \nu_\tau$ has not been seen, yet.
  $BF<1.2\times10^{-3}$ @90% CL: CLEO PRD78,052003 (2008)
  Notice: this UL is ~$3.14\times BF(D^+ \rightarrow \mu^+ \nu_\mu)$. Could BESIII see this?

$D^+ \to \mu^+ \nu_\mu$

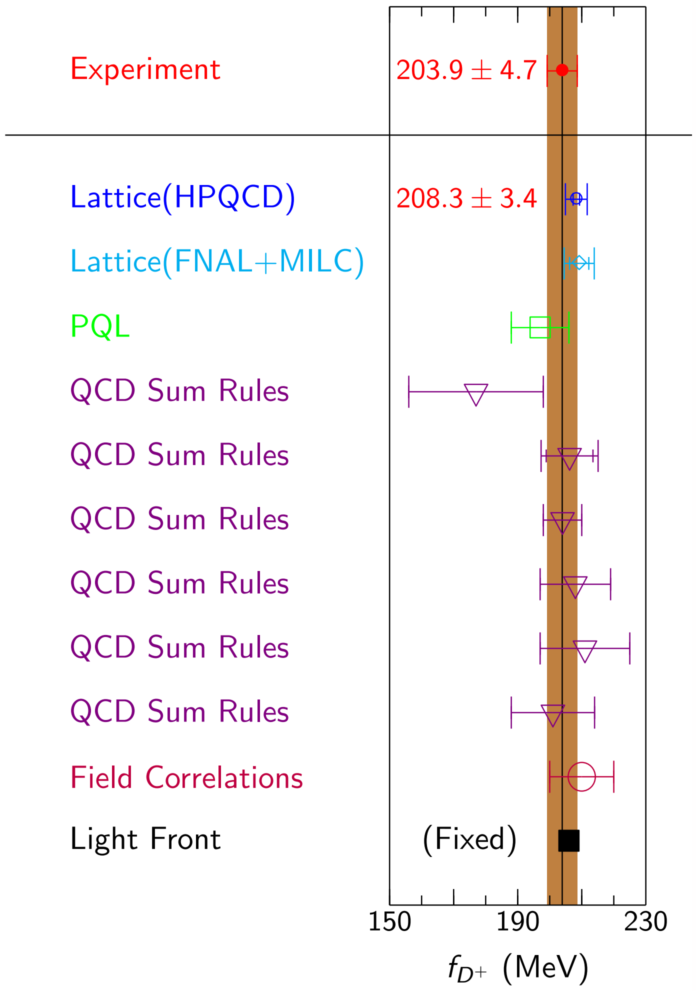
- BESIII (PRD89, 051104(R) (2014)) : 2.9 fb^{-1} at E_{cm} = 3.773 GeV.
- Measured $B(D^+ \to \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$
  The most precise measurement to date.
  - With $|V_{cd}|$ of CKM-fitter input, $f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV
  - With f_{D+} of LQCD input (PRL100, 062002 (2008))
    $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$.
- Statistically limited.
  More data would be welcome.
- BESIII plans to take
  ~10 fb^{-1} in the future!



Comparison of $B(D^+ \rightarrow \mu^+ \nu_\mu)$ and f_{D+}

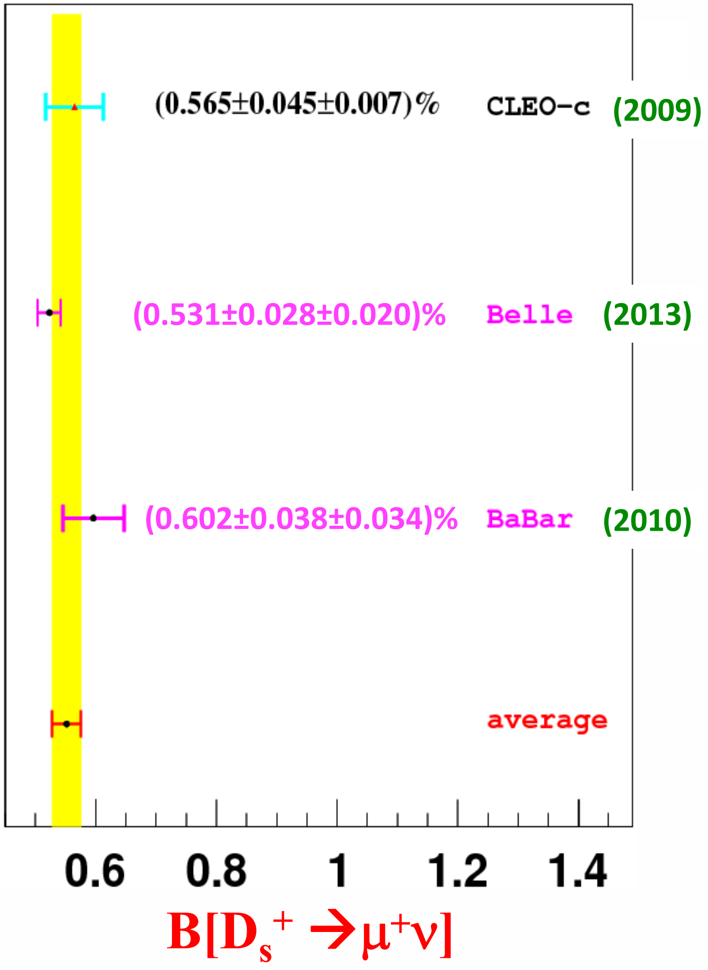


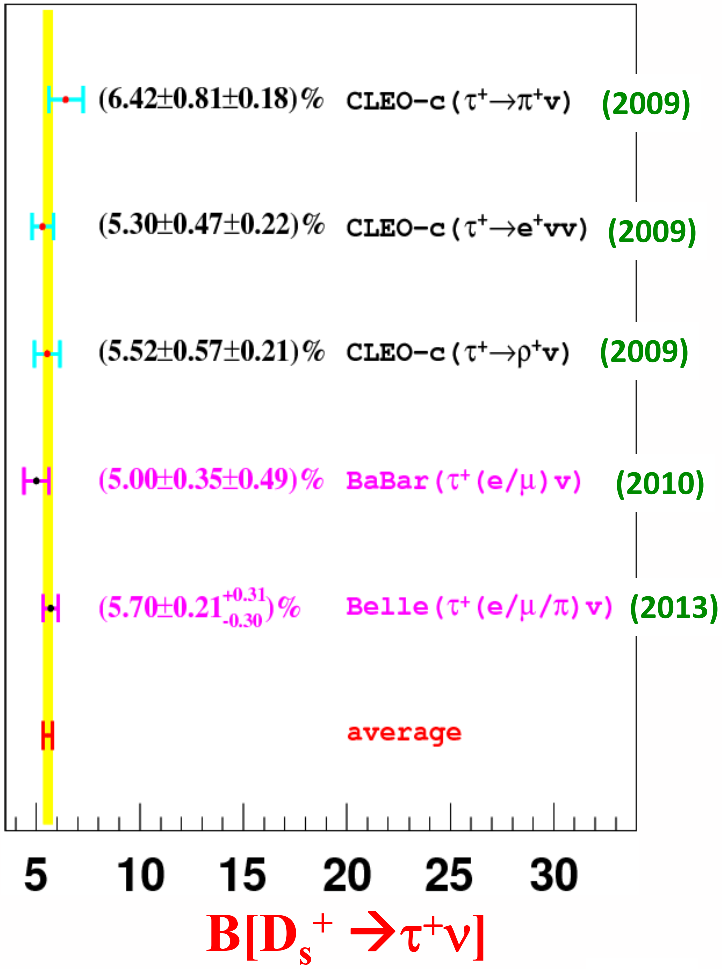
PRD78,052003 (2008)



Good consistencies are seen among the previous experimental results.

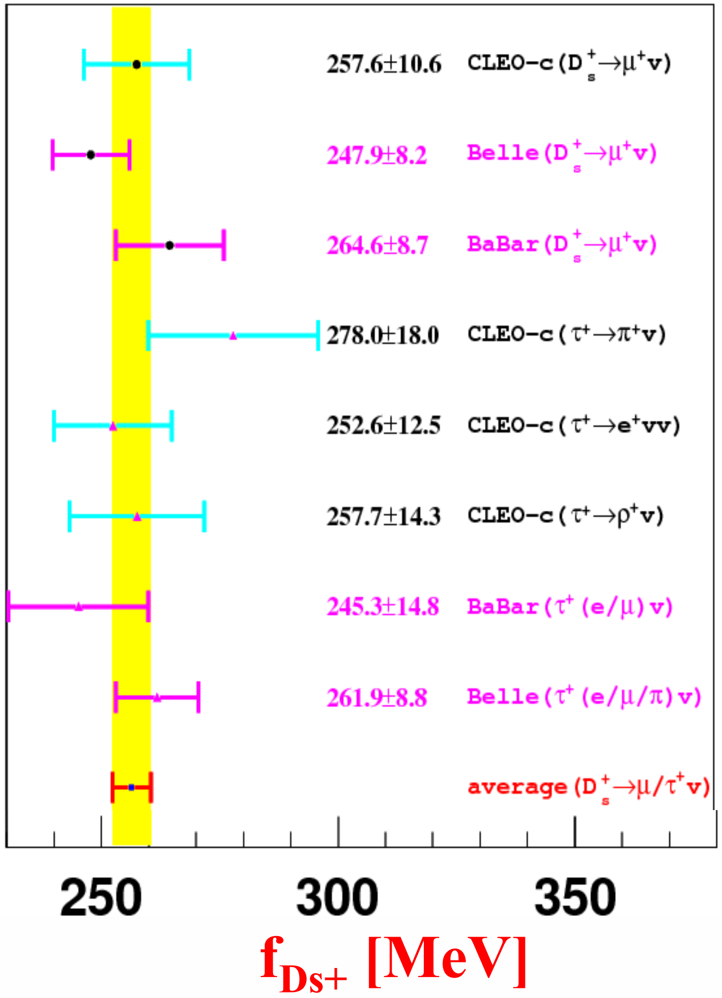
Comparison of B($D_s^+ \to (\mu^+/\tau^+)\,\nu_\mu$)

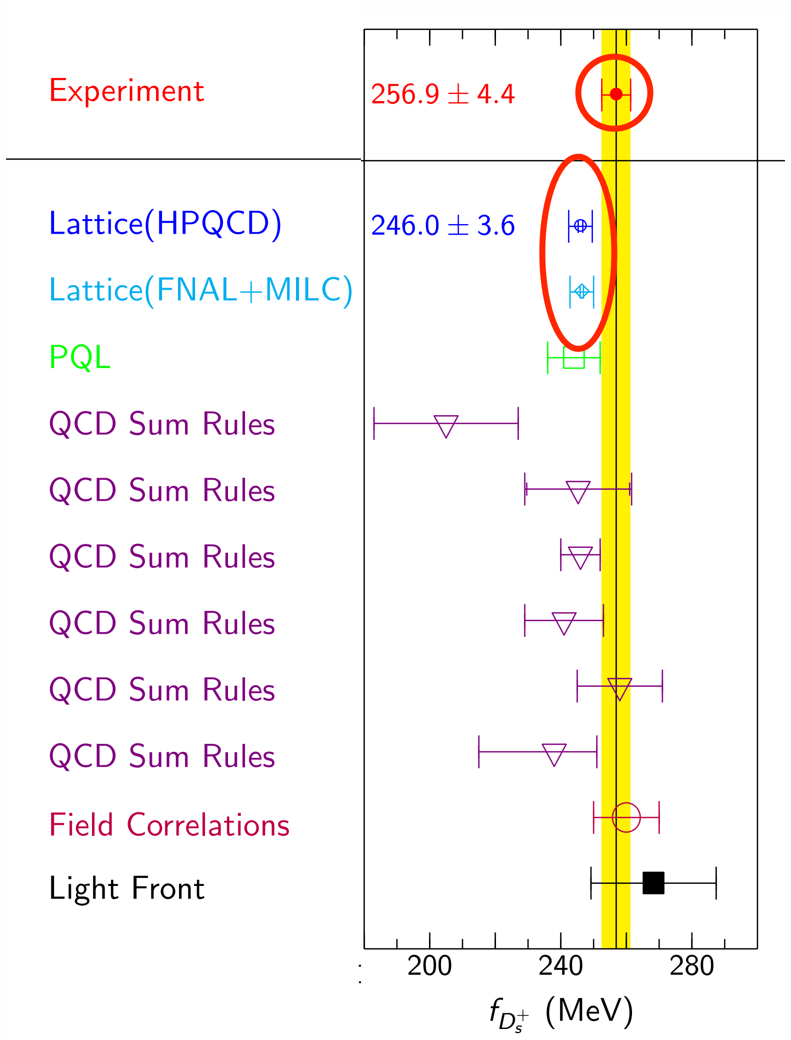




- **Similar results in the Charmed strange meson.**
- **Good overall consistency in BFs.**

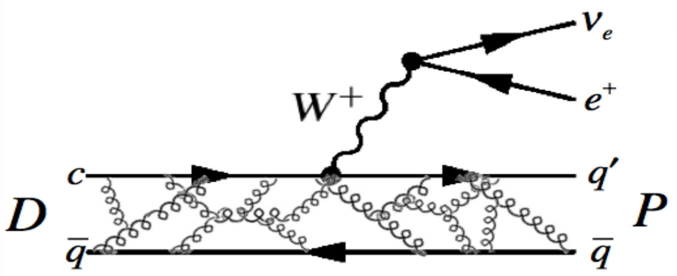
Comparison of f_{Ds}





- **Reasonable consistencies.**
- **BESIII plans to have a dedicated D_S data taking in the near future.**

Semi-Leptonic decays $D_{(s)}^+ \to P + l + \nu_l$

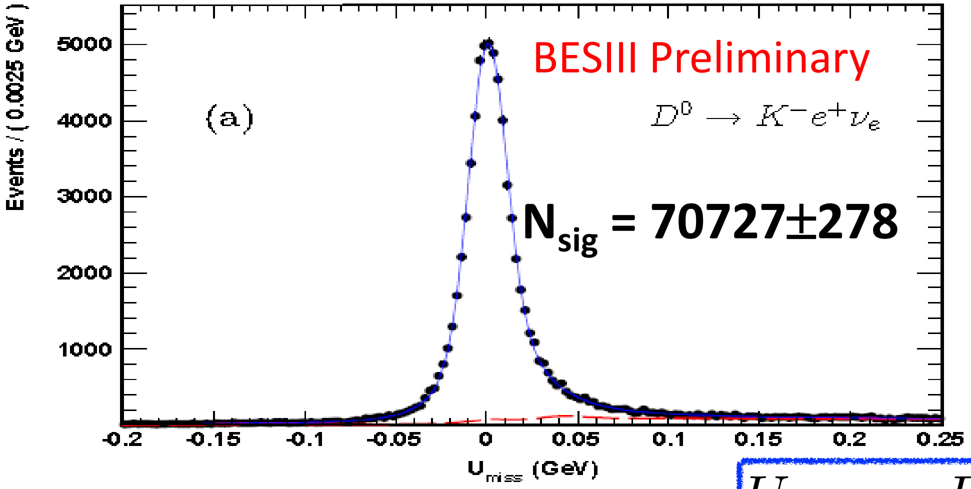


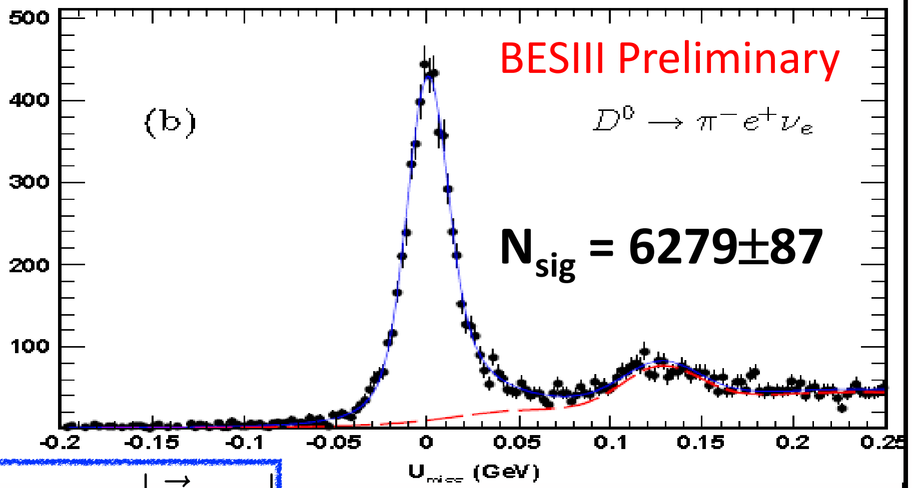
$$\frac{d\Gamma\left(D \to K(\pi) e\nu\right)}{dq^2} = \frac{G_F^2 \left|V_{cs(d)}\right|^2 P_{K(\pi)}^3}{24\pi^3} \boxed{\left|f_+\left(q^2\right)\right|^2}$$

$q^2=(p_l+p_\nu)^2 \Rightarrow M^2_{inv}$
of lepton pair

- **Essentially measure $|V_{cd(s)}| \times |f(q^2)|$.**
- **Input $|V_{cs(d)}|$ → extract $|f(q^2)|$ → compared to the LQCD. Validating the FF calculations of LQCD here is important i.e., the measurement of $|V_{ub}|$ via $B \to \pi l \nu$ has a large dependence on the "theoretical input (its FF)" from LQCD.**
- **Or vice versa:**
  Input $|f(q^2)|$ from LQCD → extract $|V_{cs(d)}|$
  → constrain the CKM unitarity.

$D^0 \to K/\pi\, e^+ \nu_e$

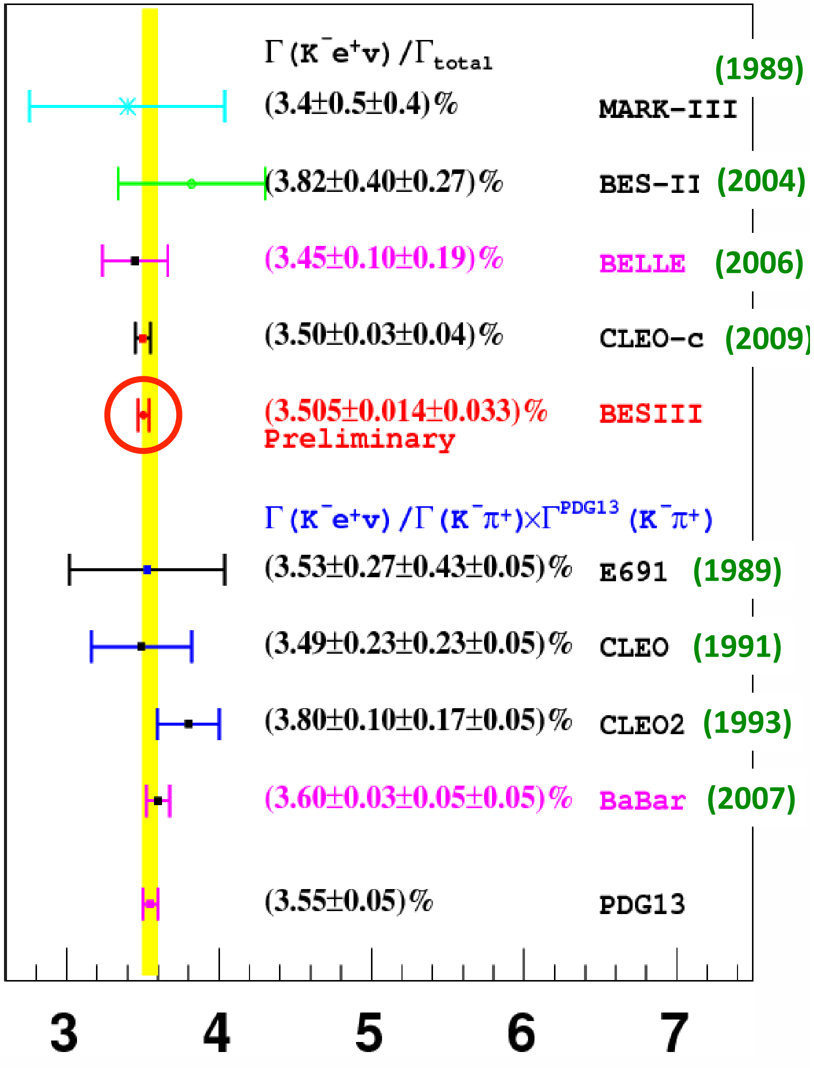




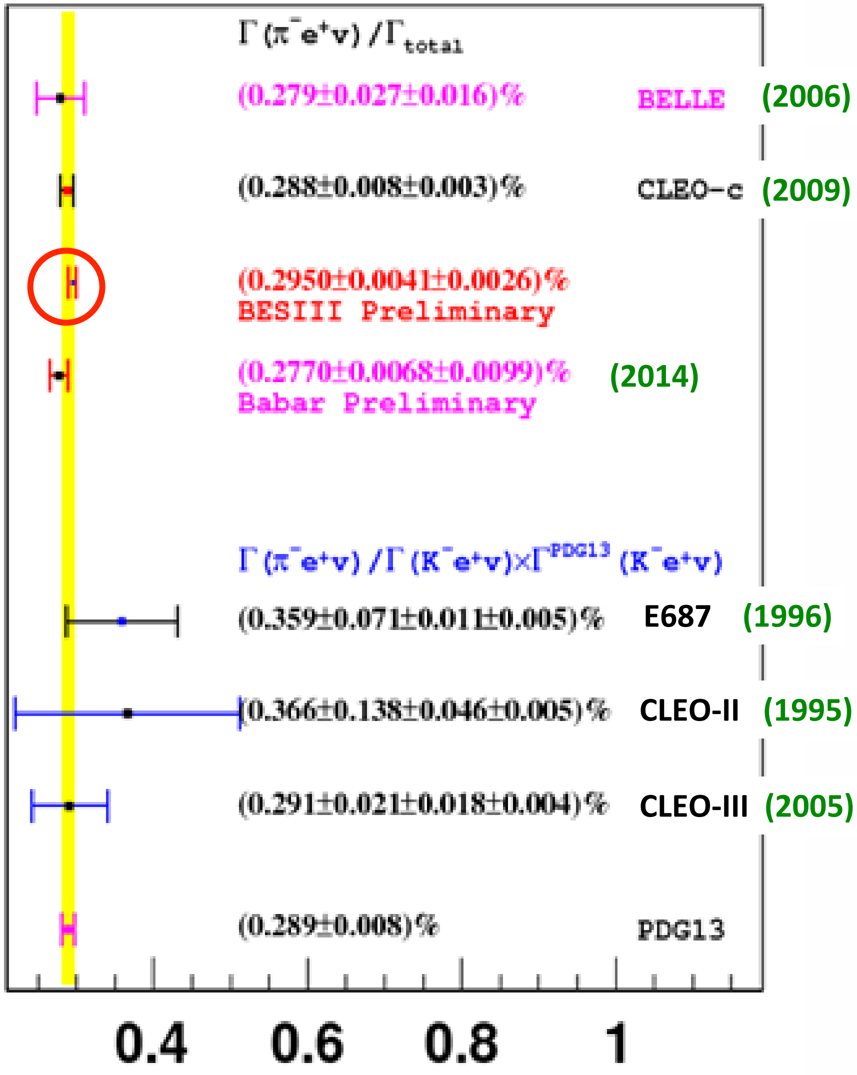
$$\boxed{U_{\mathrm{miss}} \equiv E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|}$$

- **BESIII : 2.9 fb^{-1} at E_{cm} = 3.773 GeV.**
- **U_{miss} ~ 0 if the missing particle is a neutrino.**
- **The resultant BFs are consistent with the previous measurements (see the next slide).**
  Most precise to date.

Comparison of B($D^0 \rightarrow (K/\pi)^- e^+ \nu_e$)



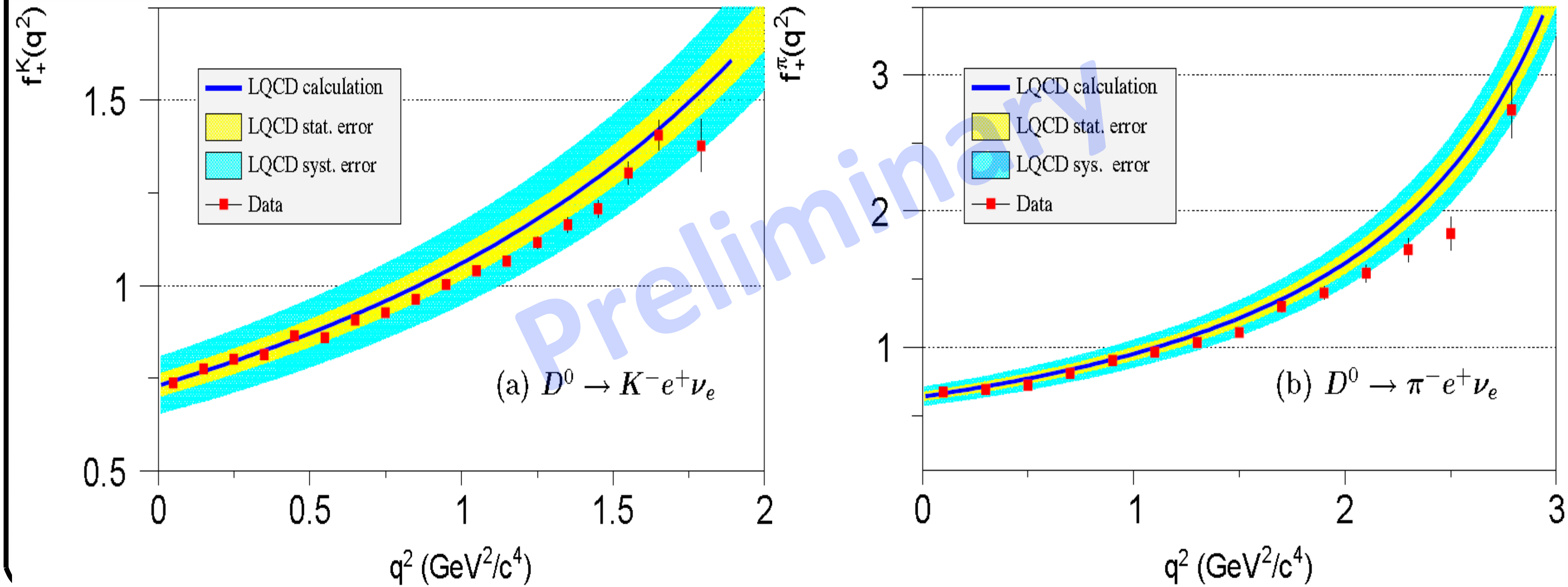
B[$D^0 \rightarrow K^- e^+ \nu$]



B[$D^0 \rightarrow \pi^- e^+ \nu$]

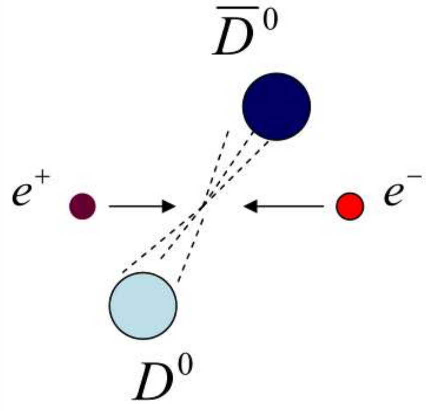
Comparison of form factors

- **Points: BESIII**
- **Curves: Fermilab Lattice, MILC, and HPQCD (PRL94, 011601 (2005))**
  Fermilab Lattice and MILC (PRD80, 034026 (2009))
  Based on the BK model (PLB478, 417 (2000))
- **Consistent with each other.**
- **Would be nice to have an even larger sample to probe the higher q^2 bins.**



Quantum Coherence in e^+e^- annihilation near Charm mass threshold

The decay rate of a correlated state



At E_{cm}~ M(ψ(3770)), a pair of $D^0\bar{D}^0$ is produced via

$e^+e^- \rightarrow \gamma^* (\rightarrow \psi(3770)) \rightarrow D^0\bar{D}^0$.

This obeys the following selection rules on the produced pair of D mesons.

- **The two produced neutral mesons must have opposite CP (i.e., see Goldhaber and Rosner, PRD15, 1254 (1977). For instance,**
  - **$D^0 \rightarrow$ CP+ final states (such as K^+K^-) AND $\bar{D}^0 \rightarrow$ CP+ final states (such as $\pi^+\pi^-$) does NOT happen. And (CP-, CP-) combo does not happen either.**
    → can be used to suppress backgrounds.
  - **$D^0 \rightarrow$ CP+ final states (such as K^+K^-) AND $\bar{D}^0 \rightarrow$ CP- final states (such as $K_S\pi^0$) are maximally enhanced (doubled). That is, the measured $BF_{eff}(D^0 \rightarrow K_S\pi^0)$ is twice as $BF(D^0 \rightarrow K_S\pi^0)$ with no such coherence effect on the parent D.**

The decay rates in mixed CP final states

- $D^0 \rightarrow$ CP+ final states (such as K^+K^-) **AND**
  $\bar{D}^0 \rightarrow$ generically (not look at its decay experimentally).
  This decay rate (e.g., $D^0 \rightarrow K^+K^-$) is not affected.

- $D^0 \rightarrow$ Flavored final states (CF+DCSD, such as $K^-\pi^+$) **AND**
  $\bar{D}^0 \rightarrow$ CP± final states.

  The rates are still affected due to the interference between CF and DCS.
  ➔ extract $\delta_{K\pi}$, where $\langle K^-\pi^+ | \bar{D}^0 \rangle / \langle K^-\pi^+ | D^0 \rangle = -r \cdot e^{-i\delta}$.

  For multi-body (such $K_S\pi^+\pi^-$), one can obtain the δ, averaged over each bin of a Dalitz distribution.

The decay rates in semi-leptonic decays

- On the other hand, for the case of semi-leptonic decay, such as
  $D^0 \to K^- e^+ \nu$ (only the CF mode!) AND
  $\bar{D}^0 \to$ CP± final states, there is no interference.

Its decay rate does not depend on the CP content of its parent D.

Yet, the total width of its parent D depends on CP.

For instance,

$$N(D^0 \to K^- e^+ \nu; \bar{D}^0 \to CP\pm)/N(\bar{D}^0 \to CP\pm) = B_{eff}(D^0 \to K^- e^+ \nu)$$
$$= B(D^0 \to K^- e^+ \nu) \times \Gamma/\Gamma_{CP\pm}$$
$$\simeq B(D^0 \to K^- e^+ \nu) \times (1 \pm y)$$
(neglecting terms with y^2 or higher).

→ can extract the y via semi-leptonic tags.

The latest measurement of $\delta_{K\pi}$ from BESIII

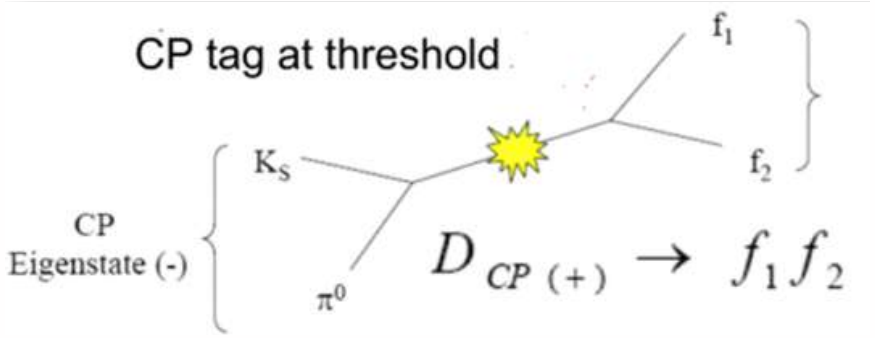
- In $D^0 \rightarrow K\pi$ decays, its CF and DCSD interfere.
  The ratio of the two amplitudes is $\langle K^-\pi^+|\bar{D}^0\rangle / \langle K^-\pi^+|D^0\rangle = -r \cdot e^{-i\delta}$.
- Neglecting higher orders in the mixing parameters (e.g., y^2), one can arrive at the following relation:

$$A_{CP\rightarrow K\pi} = r \cdot \cos\delta_{K\pi} + \text{[D-mixing correction (y and } R_{WS})]$$

where $A_{CP\rightarrow K\pi}$ = CP-tagged rate asymmetry

$$= [B(D_2\rightarrow K^-\pi^+) - B(D_1\rightarrow K^-\pi^+)]/B(D_2\rightarrow K^-\pi^+) + B(D_1\rightarrow K^-\pi^+)].$$

- $B(D_{1,2}\rightarrow K\pi)$ can be measured by tagging one D (tag side) with exclusive CP-eigenstates which then defines the eigenvalue of the other D.



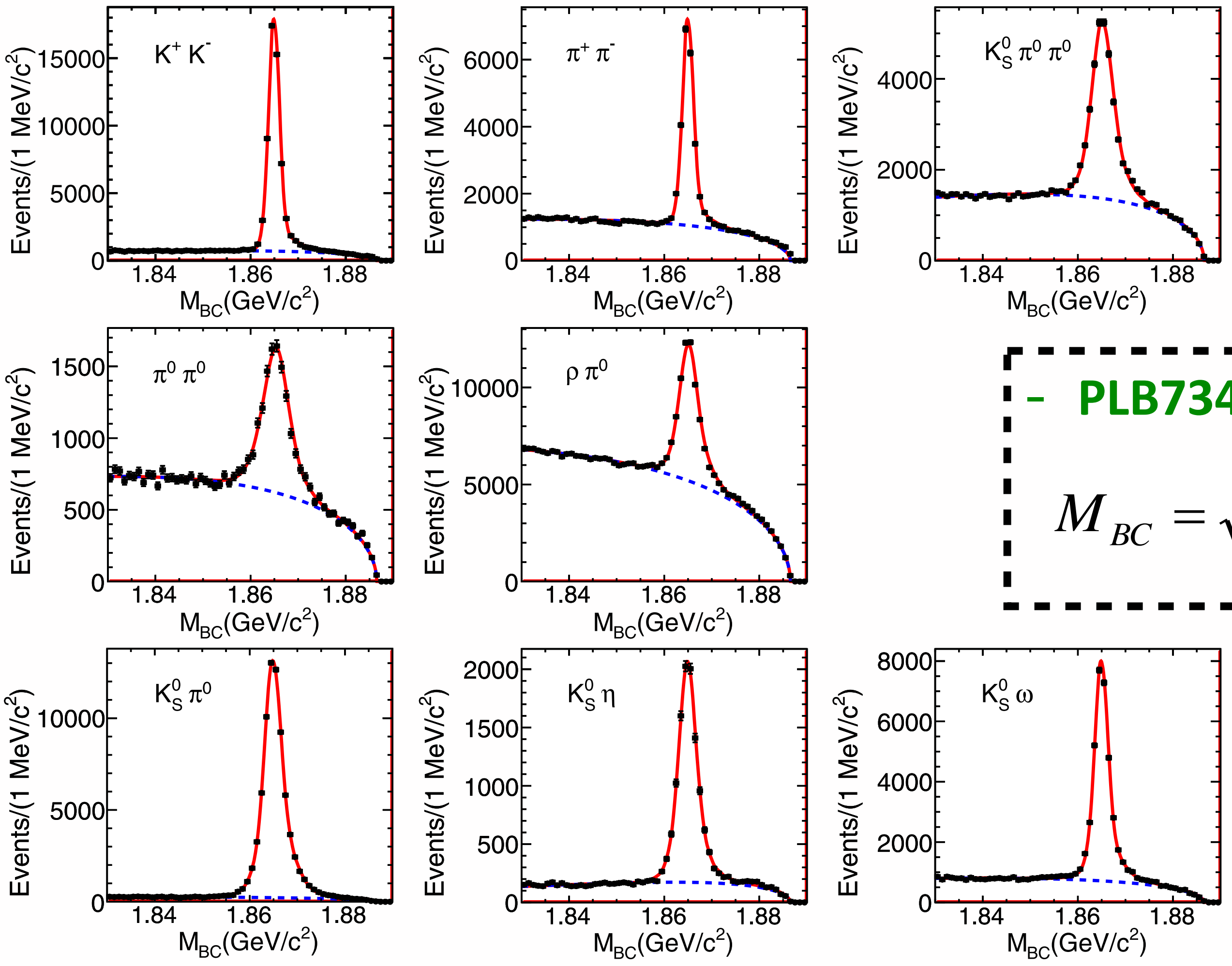
D → CP states

(no requirement on how the other D decays)

CP+

CP+

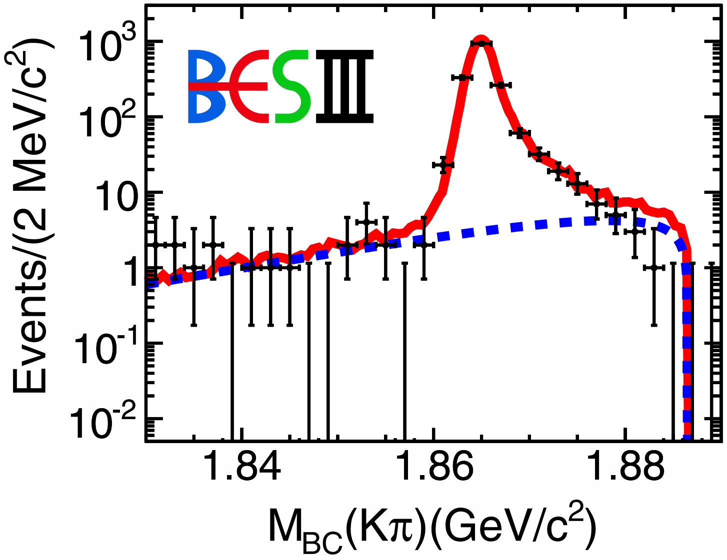
CP-



- **PLB734, 227 (2014)**

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

$D_{1,2} \to K\pi$, $D_{2,1} \to$ CP states



- Example fit for the case of ($K\pi$, $K_S\pi^0$)
- PLB734, 227 (2014)

- Measured $A_{CP\to K\pi}$ = $(12.77\pm1.31(\text{stat.})^{+0.33}_{-0.31}(\text{syst.}))\%$.
- With external inputs from HFAG2013 and PDG (for y and R_{WS})

  $\cos\delta_{K\pi} = 1.03\pm0.12(\text{stat.})\pm0.04(\text{syst.})\pm0.01(\text{external})$.
- This result is consistent with and more precise than the recent CLEO-c result (PRD86, 112001 (2012)):

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

Could also determine the mixing parameter, y_{CP}

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

- y_{CP} is defined as;

$$2\cdot y_{CP} = (|q/p|+|p/q|)\cdot y\cdot\cos\phi - (|q/p|-|p/q|)\cdot x\cdot\sin\phi,$$

where p and q are mixing parameters, and $\phi = \arg(q/p)$ is the weak phase difference of the mixing amplitudes.

Notice: for no CPV case, $p = q = 1/\sqrt{2}$ and $y_{CP} \equiv y$.

- From the fact that

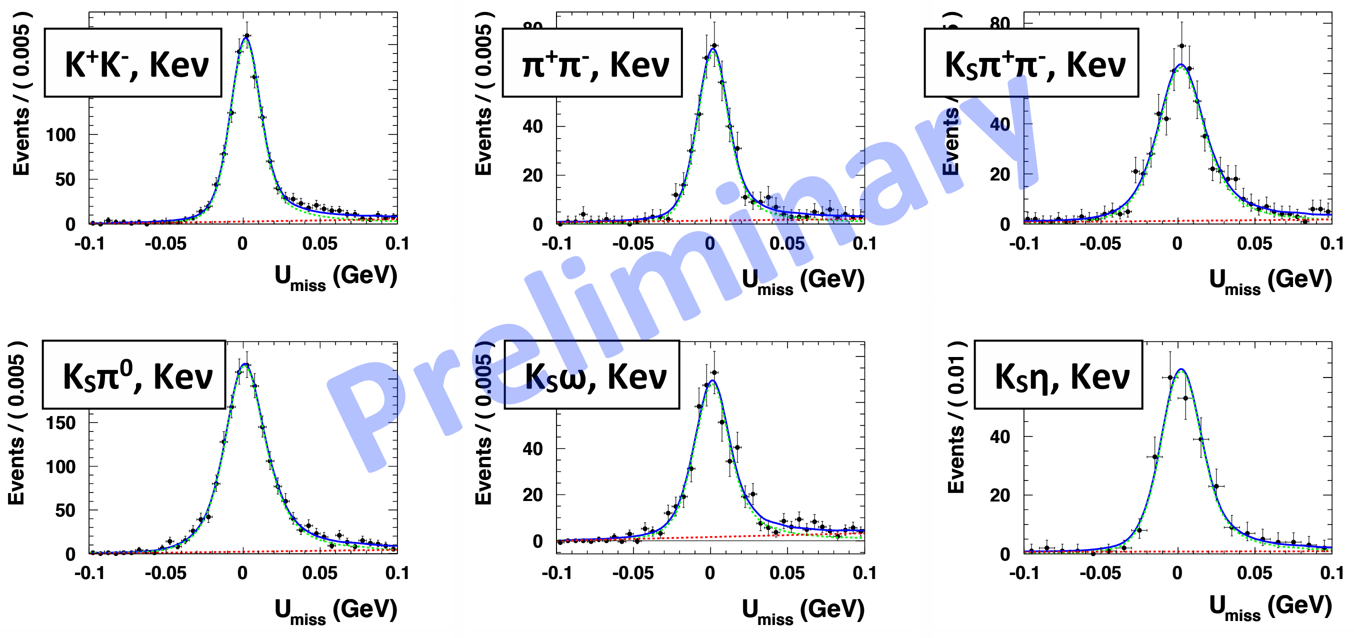
semileptonic BF of $D_{1,2}$, $B(D_{CP\pm}\rightarrow l)$,

gets modified by a factor of $1\pm y_{CP}$,

and neglecting terms with y^2 (or higher), one can arrive at

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

Extracting y_{CP} in BESIII data



- Fit to U for Kev
- Similar for Kμν

$$U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|$$

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

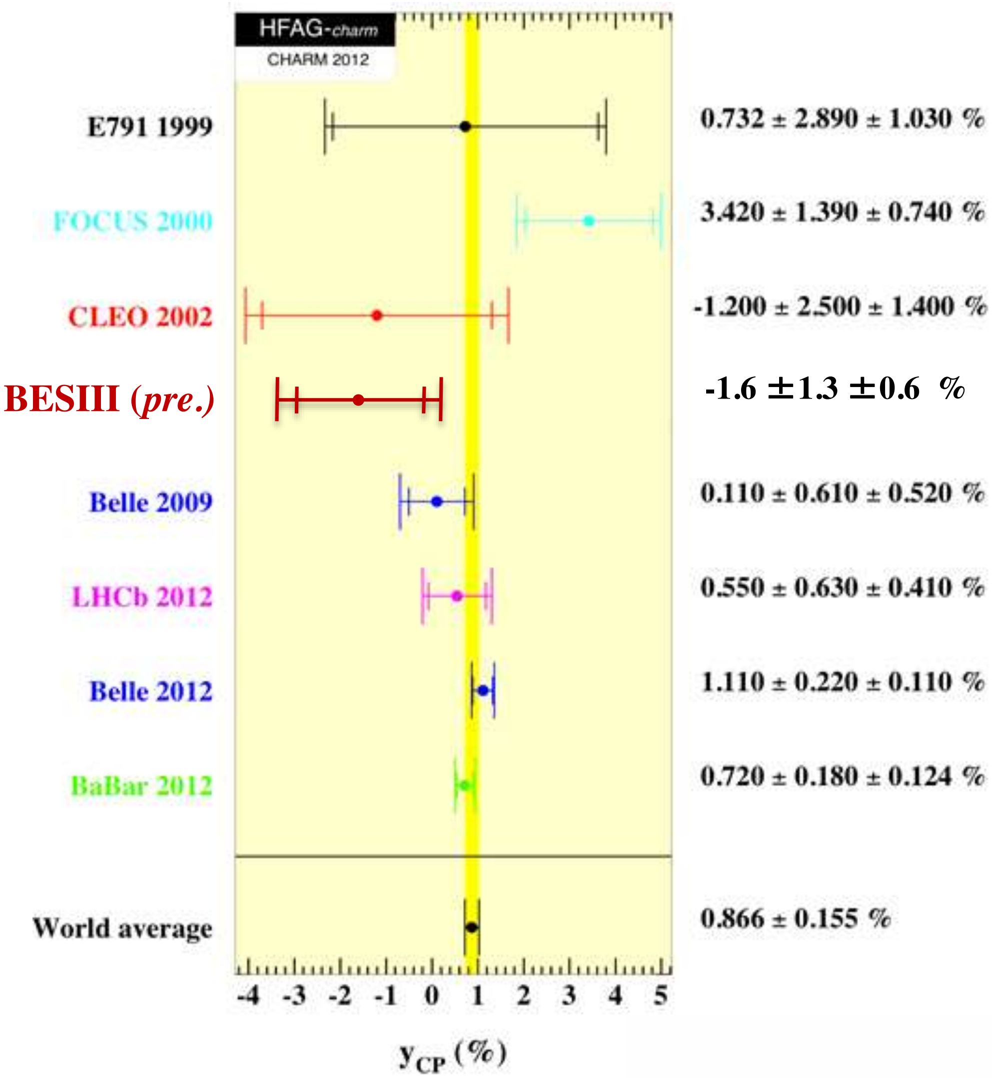
BESIII preliminary result;

y_{CP} = [-1.6±1.3(stat.)±0.6(syst.)]%.

Most precise result based on QC Charm mesons.

Having a larger sample would be a help.

Comparison with other measurements



- Our result is consistent with the world average (HFAG2013; this preliminary result is not included in the average).
- Also consistent with the latest result from CLEO-c (PRD86, 112001 (2012));

  y_{CP} = (4.2±2.0±1.0)%.

  (not listed in the figure).

Can also contribute to the measurement of γ/ϕ_3

- B factories can measure γ/ϕ_3 through B → D K.
- The latest comes from the LHCb (arXiv:1408.2748) via the GGSZ method in $D^0 \rightarrow K_S \pi\, \pi^-$ and $K_S K^+ K^-$.
- Measured $\gamma = (62^{+15}_{-14})°$ (along with $r_B = 0.080^{+0.019}_{-0.021}$ and $\delta_B = (134^{+14}_{-15})°$).
  A single most precise measurement of γ to date.
- They needed inputs, c_i and s_i:
  cosine and sine of the strong-phase difference between the D^0 and $\bar{D}^0$ decay, averaged in each Dalitz bin, *i*.
- Took the CLEO-c (statistically limited) results (PRD82, 112006, (2010)).
- BESIII has recently repeated this CLEO-c analysis based on their data which is ~3.5× larger than that of CLEO.

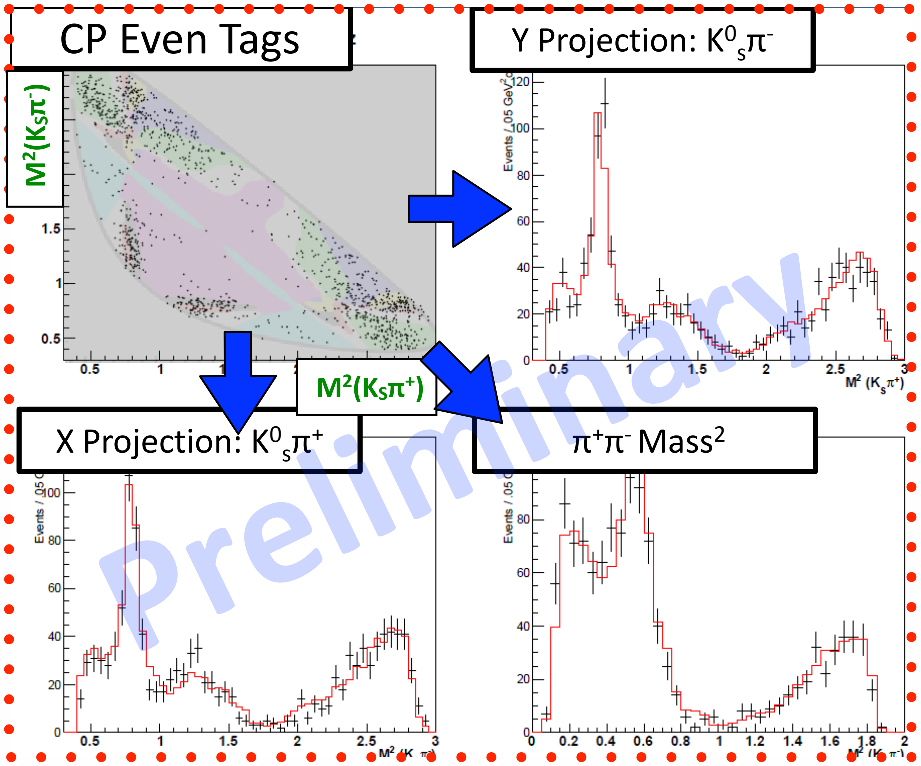
Relations between c_i, s_i, and yields in Dalitz bins

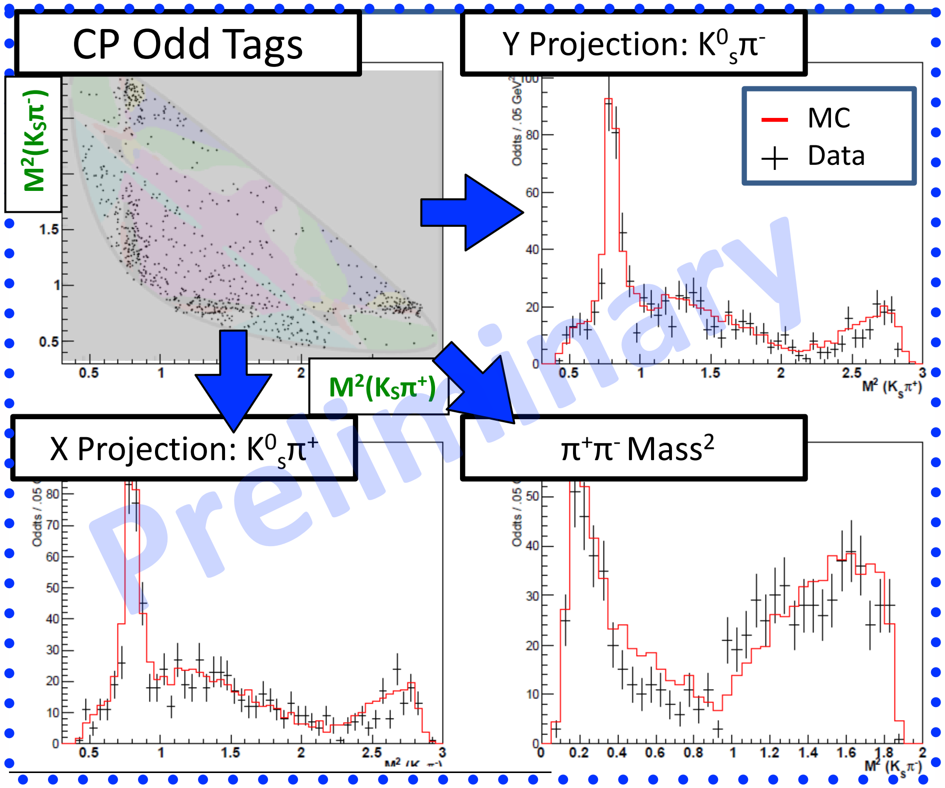
- One could derive the following relations between efficiency-corrected yields in the ith Dalitz bins and c_i (s_i) (see backups more details and PRD82, 112006 (2010)).
  - For the case of $D \rightarrow$ CP states AND $D \rightarrow K_S\pi^+\pi^-$:
    Yields in ith bin $\propto \pm c_i$
  - For the case of $D \rightarrow K_S\pi^+\pi^-$ AND $D \rightarrow K_S\pi^+\pi^-$:
    Yields in ith and jth bins of the two Dalitz plots $\propto c_i c_j + s_i s_j$
- Simultaneously fit to these "Yields in each bin" to extract c_i and s_i.
- One could also gain statistical power by employing $K_L\pi^+\pi^-$.

For the case of “CP tag vs $K_S\pi^+\pi^-$”

CP Tag modes

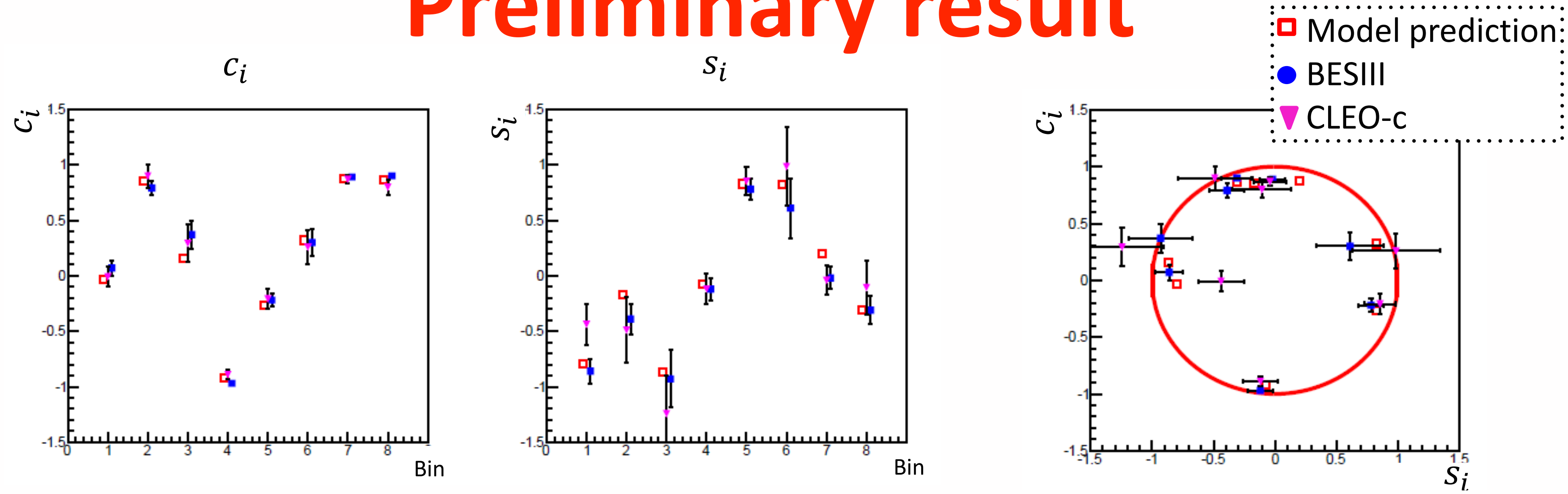
Type	
CP+	$K^+K^-,\ \pi^+\pi^-,\ K_S\pi^0\pi^0,\ K_L\pi^0$
CP-	$K_S\pi^0,\ K_S\eta(\to\gamma\gamma),\ K_S\eta(\to\pi^+\pi^-\pi^0),\ K_S\omega,\ K_S\eta'$





- Data is using the full 2.9 fb^{-1} $\psi(3770)$ dataset
- Results presented here will be using Optimal Binning scheme.

Preliminary result



- Only statistical uncertainties are shown in the optimal binning scheme (which dominate in most of the bins).
- Consistent results with the previous CLEO-c measurement, but statistically superior.
- What this result could do to the γ/ϕ_3 is, if we take the Belle's Dalitz result (PRD85, 112014 (2012)),

  γ (in degrees) = $77.3^{+15.1}_{-14.9}$ (stat.) ± 4.2 (syst.) ± 4.3 (c_i/s_i) → ± 2.5 (c_i/s_i)

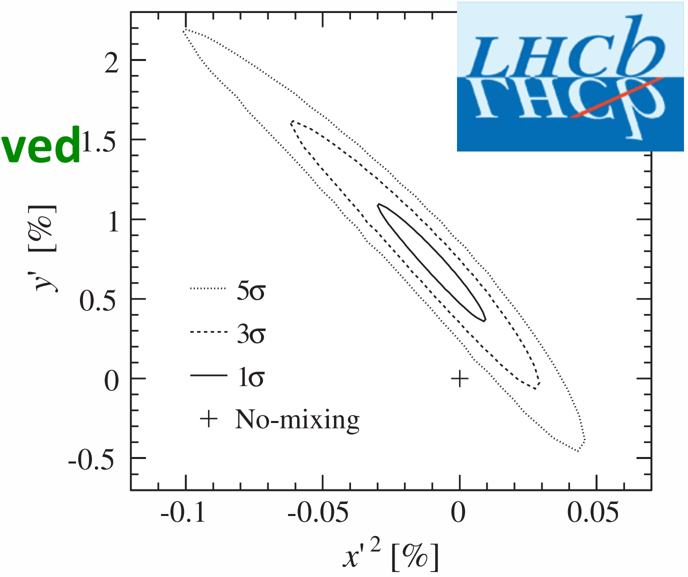
  We expect the uncertainly would be reduced by ~40%
- Very important inputs for the future analyses by LHCb and Belle II, where the statistical sensitivity starts to reach ~1~2 degrees.

Summary

- Searches for rare/forbidden Charm decays are finally becoming interesting (exciting) with LHCb upgrade and Belle II on the horizon.
- Leptonic and semi-leptonic decays in Charm provide access to $|V_{cx}|$ and complementary to the B Physics. Having even larger Charm samples at BESIII improves the current results further.
- Quantum-correlated $D^0\overline{D}^0$ in e^+e^- annihilations near threshold:
  - provides an unique way to measure the Charm mixing parameters.
  - also can provide precise measurements on c_i and s_i.

Backups

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



- Observation of $D\bar{D}$ mixing, first seen by the B factories (HFAG: arXiv 1207.1158) and now observed by LHCb: PRL110, 101802 (2013).
- $D\bar{D}$ mixing is conventionally described by two parameters:

  $x = 2(M_1-M_2)/(\Gamma_1+\Gamma_2)$, $y = (\Gamma_1-\Gamma_2)/(\Gamma_1+\Gamma_2)$,

  where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the neutral D meson mass eigenstates.

  (Flavor eigenstates, $D^0/\bar{D}^0$, are not the same as mass eigenstates, D_1/D_2)

  Or $x' = x\cdot\cos\delta_{K\pi} + y\cdot\sin\delta_{K\pi}$, $y' = y\cdot\cos\delta_{K\pi} - x\cdot\sin\delta_{K\pi}$.
- $\delta_{K\pi}$ is the strong phase difference between the doubly Cabibbo suppressed (DCS) decay, $\bar{D}^0 \rightarrow K^-\pi^+$ and the Cabibbo favored (CF) decay, $D^0 \rightarrow K^-\pi^+$ or $\langle K^-\pi^+|\bar{D}^0\rangle/\langle K^-\pi^+|D^0\rangle = -r\cdot e^{-i\delta}$.

  So one can connect (x,y) with (x',y') via $\delta_{K\pi}$.
- For this part of my talk, I present preliminary results on $\delta_{K\pi}$ and y using the quantum correlation between the produced D^0 and $\bar{D}^0$ pair in data taken at BESIII. This will then improve the determination of the mixing params, (x,y).

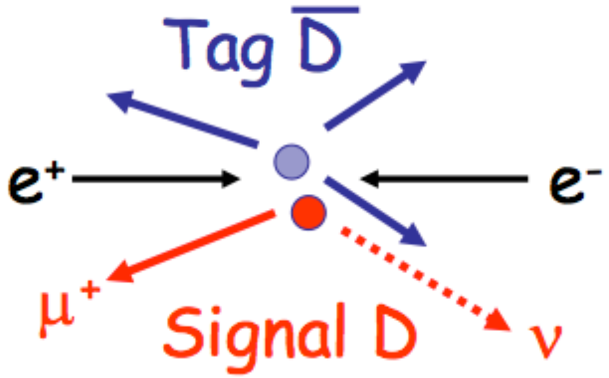
Reconstructing events with a neutrino

- **Reconstruct the all decay particles, except the neutrino.**
- **At CLEO-c and BESIII, where they take the data close to the mass threshold (i.e., $e^+e^- \to (\psi(3770)) \to D\bar{D}$),
  one can reconstruct one of the D mesons fully (tag side),
  while the other D is reconstructed, except the neutrino (signal side).
  The existence of neutrino can be inferred by
  a missing variable such as;**

$$M^2_{\rm miss} = (E_{\rm beam} - E_{\mu^+})^2 - (-\vec{p}_{D^-_{\rm tag}} - \vec{p}_\mu)^2$$

for the case of $D^+ \to \mu^+ \nu_\mu$.

$M^2_{\rm missing} \sim 0$ for the signal events.



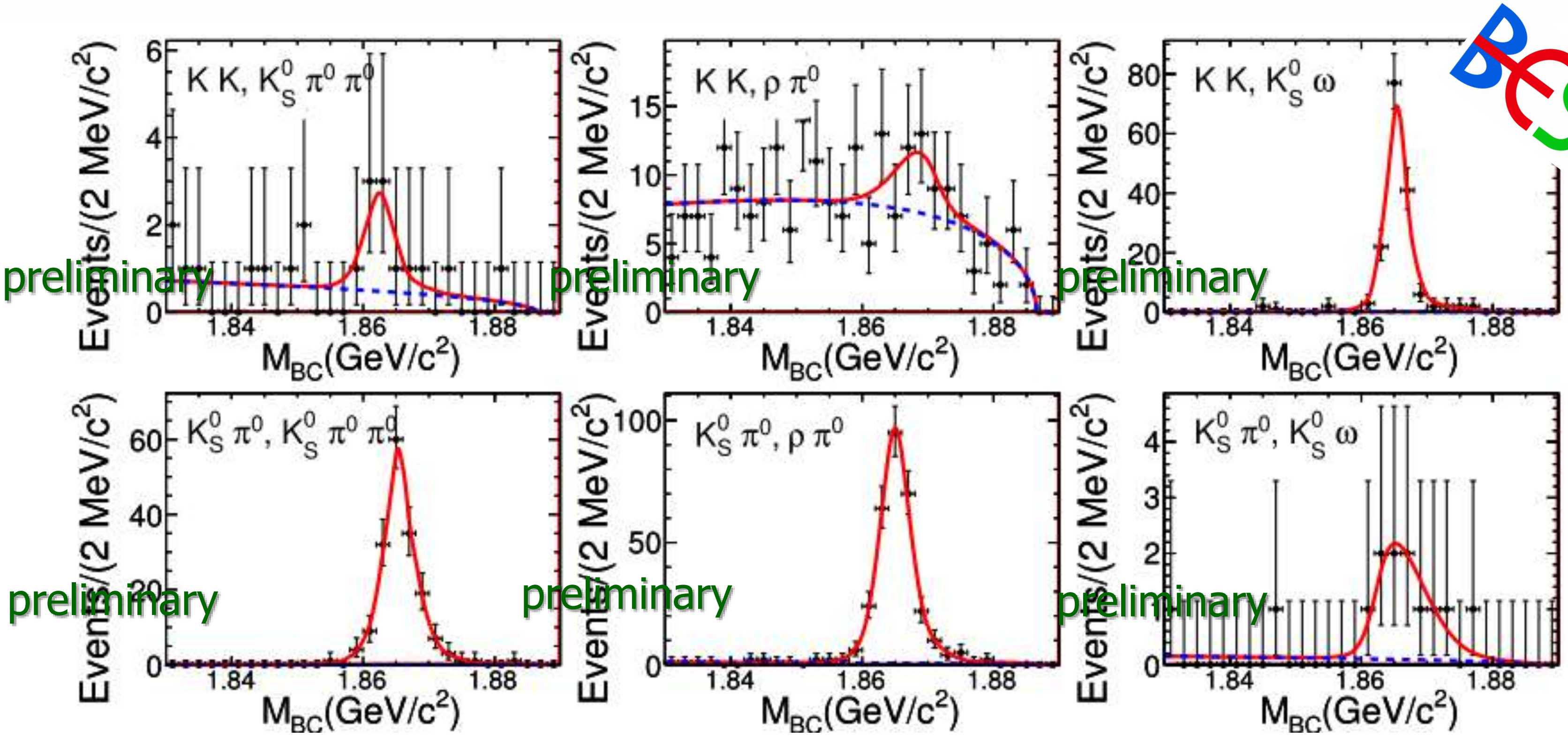
Measuring $B(D_{CP\pm}\to K^-\pi^+)$

- Double-Tag technique:
  $B(D_{CP\pm}\to K\pi) = [B(D_{CP\mp}\to CP^{\mp}\text{ states})\times B(D_{CP\pm}\to K\pi)]/B(D_{CP\mp}\to CP^{\mp}\text{ states})$.
  So they need to measure;
  - Yields (BF) when one D decays a CP final state while the other D decays generically
  - Yields (BF) when one D decays a CP final state while the other D decays into Kπ.
- CP states they employ (8 modes):

$CP+$	$K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$
$CP-$	$K_S^0\pi^0, K_S^0\eta, K_S^0\omega$

  where we reconstruct $K_S\to\pi^+\pi^-$, $\pi^0/\eta\to\gamma\gamma$, $\omega\to\pi^+\pi^-\pi^0$, $\rho\to\pi^+\pi^-$.
- Notice that most of systematics on the tag side get canceled in $B(D_{CP\pm}\to K\pi)$.
  The remaining systematics (reconstruction/simulation) of Kπ are also canceled in the determination of $A_{CP\to K\pi}$.

The selection rule can be seen in data

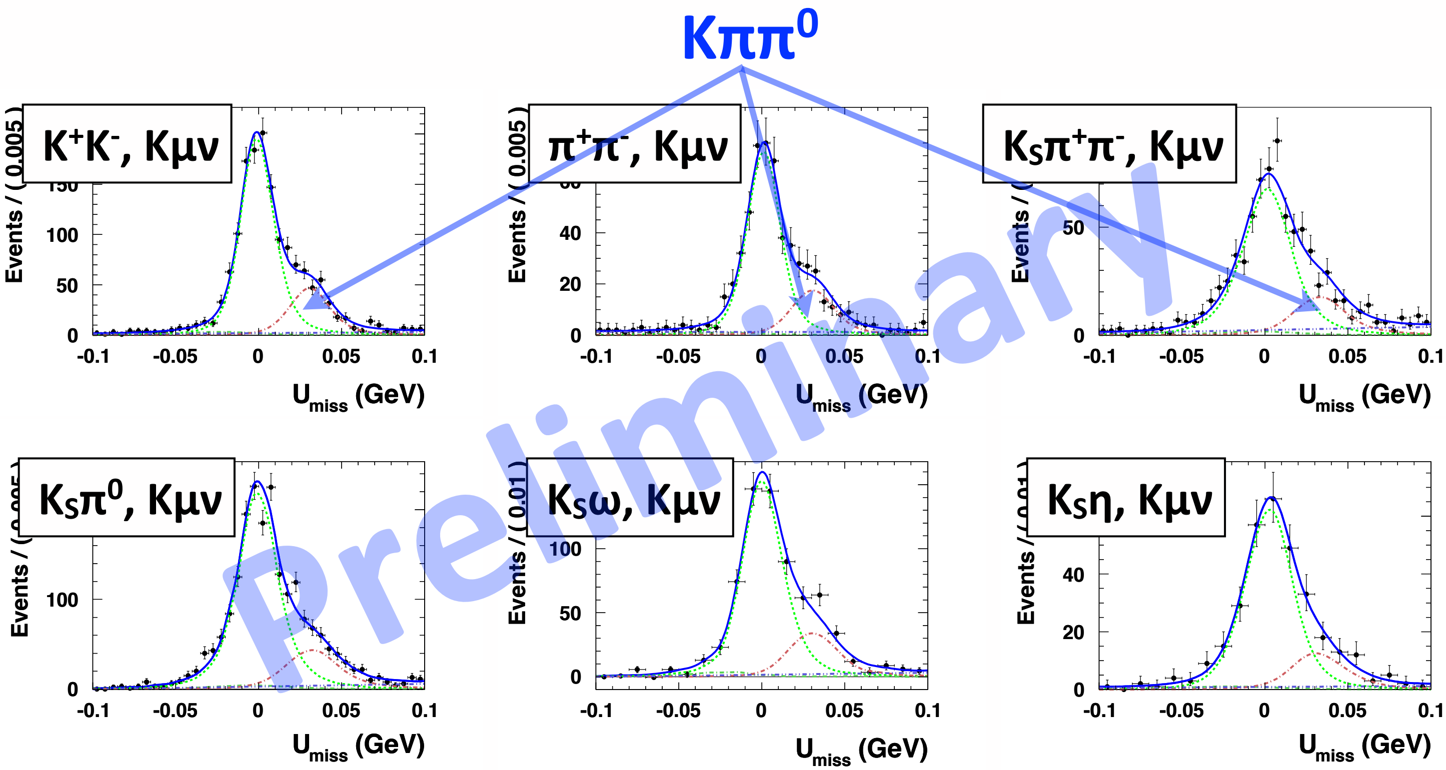


		CP+		CP-	
	Mode	Yield(tag KK)	efficiency(%)	Yield(tag $K^0_S\pi^0$)	efficiency(%)
CP+	$K^0_S\pi^0\pi^0$	$8 \pm 3(*)$	11.80 ± 0.11	171 ± 14	7.20 ± 0.09
CP+	$\rho\pi^0$	$13 \pm 8(*)$	24.44 ± 0.16	299 ± 19	15.87 ± 0.16
CP-	$K^0_S\omega$	158 ± 13	11.02 ± 0.11	$7 \pm 3(*)$	6.77 ± 0.08

- ✳ **Consistent with zero.**
- ✳ **Consider as one of the systematics.**

Yields of Kμν in double tags ($n_{K\mu\nu,CP\mp}$)

(reconstruct CP-final states from one D decay, with "Kμν" from the other D)



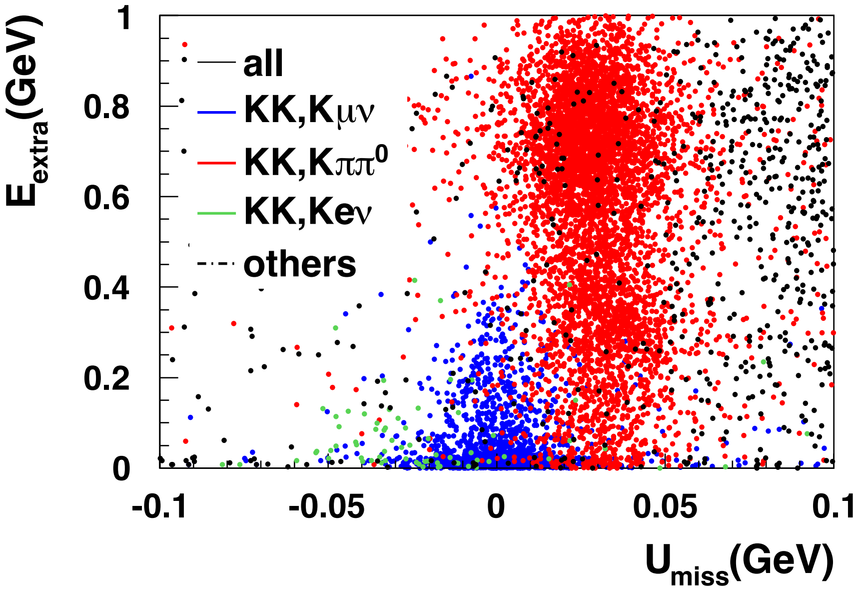
- Kππ^0 shapes and sizes are fixed based on control samples of actual data.
- The control samples are obtained by the same CP states and Kππ^0, while ignoring the two photons from π^0 decays to calculate U$_{miss}$.

See the next slide for detail.

- Signal shape: MC shape, convoluted with an asymmetric Gaussian.
- Background: A 1st order polynomial. Kππ^0 (dominant).

Fixing the $K\pi\pi^0$ shape

- Obtain E_{extra} ≡ Sum of the all un-used energies deposited in EM calorimeter.
- E_{extra} tends to be larger if it is $K\pi\pi^0$ due to the ignored extra photons from π^0 decay and is small if it is $K\mu\nu$.
- We actually do require $E_{extra}<0.2$ GeV to select $K\mu\nu$ signal candidates.



Fix shape

- Fit to U_{miss} in $E_{extra}>0.5$ GeV where $K\mu\nu$ peak is suppressed.
- The fitted shape ≡ MC shape, convoluted with a Gaussian.

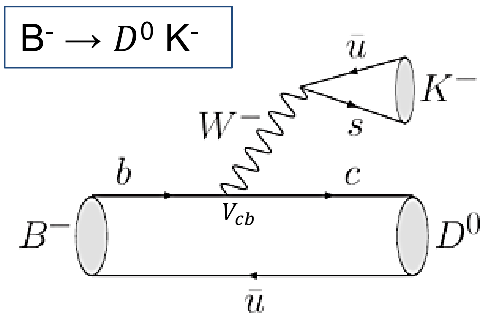
Fix size

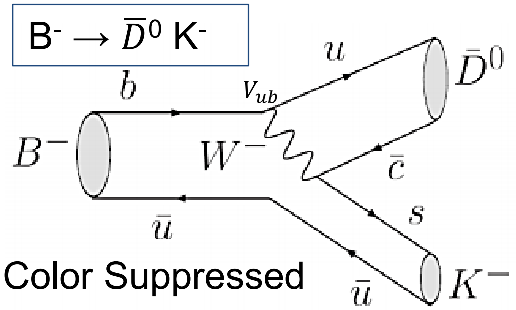
($K\pi\pi^0$ yields in data in $E_{extra}<0.2$ GeV) = R×($K\pi\pi^0$ yields in data in $E_{extra}>0.5$ GeV), where R = ($K\pi\pi^0$ yields in MC in $E_{extra}<0.2$ GeV)/($K\pi\pi^0$ yields in MC in $E_{extra}>0.5$ GeV).

Can also contribute to the measurement of γ/ϕ_3

- **Extract the γ through the measurement of the interference between b → c and b → u when both D^0 and $\bar{D}^0$ decay to the same final state, f(D).**

$A_{B\pm} \propto A_D + r_B\, e^{i(\delta_B \pm \gamma)} A_{\bar{D}}$ **(where r_B is $|\langle B^- \to \bar{D}^0 K^- \rangle| / |\langle B^- \to D^0 K^- \rangle|$. δ_B is the strong phase difference).**





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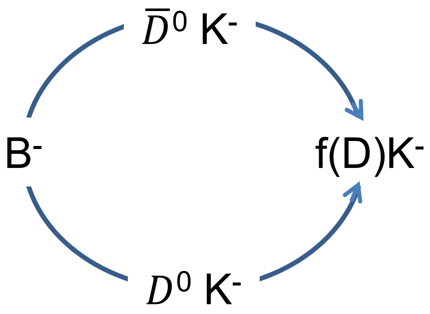


$\bar{D}^0$ K-

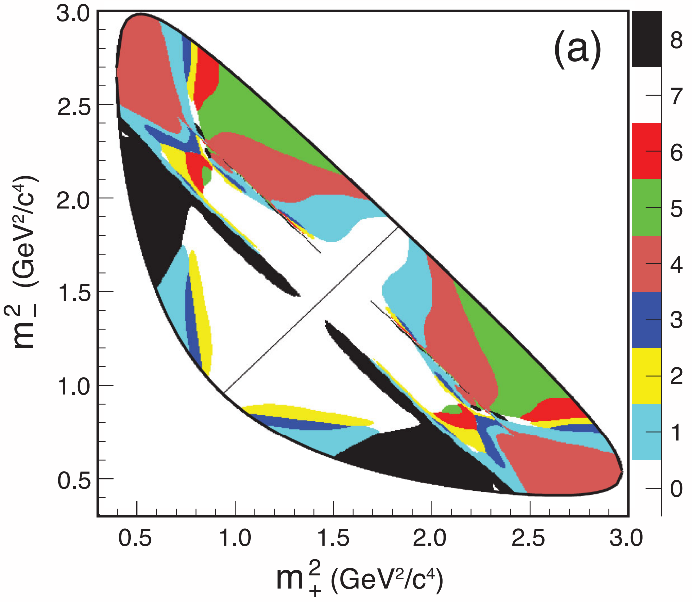
B-

f(D)K-

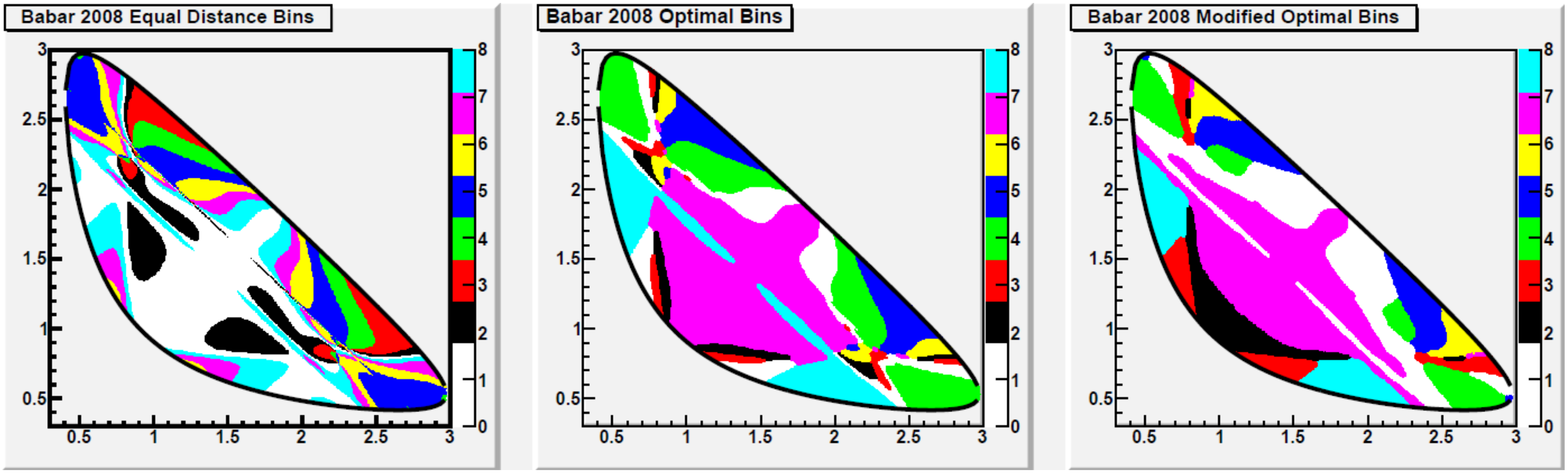
D^0 K-

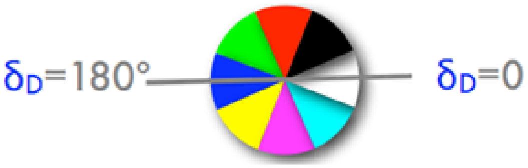
Can also contribute to the measurement of γ/ϕ_3

- This is one of the popular binning scheme, "Optimal binning", where bins are adjusted to maximize the sensitivity to γ/ϕ_3 (CLEO: PRD82, 112006 (2010)).
- BESIII has recently repeated this analysis based on their data which is ~3.5× larger than that of CLEO.



c_i and s_i in $D^0 \rightarrow K_{S,L}\pi^+\pi^-$ Dalitz analysis





Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

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

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

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Equation on calculating c_i

For the CP tag modes, one can show that the total bin yields are related to c_i by

$$M_i^{\pm} = \frac{S_{\pm}}{2S_f}\left(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i}\right)$$

$M_i^+(M_i^-)$ yields in each bin of Dalitz plot for CP even(odd) modes.
$S_+(S_-)$ number of single tags for CP even(odd) modes.
S_f number of single tags for flavor modes.
$K_i(K_{-i})$, yields in each bin of Dalitz plot in flavor modes.

Single Tag modes

Type	Tag List
Pseudo-Flavored	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
S^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$, $K_L\pi^0$
S^-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$

Calculating both c_i and s_i

Using $D^0 \rightarrow K_s\pi^+\pi^-$ vs $\overline{D}^0 \rightarrow K_s\pi^+\pi^-$ we can calculate both c_i and s_i:

$$\boxed{M_{i,j} = \frac{N_{D,\overline{D}}}{2S_f^2}\left(K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}\left(c_ic_j + s_is_j\right)\right)}$$

$M_{i,j}$ yields in bin i of first Dalitz plot
and bin j of second Dalitz plot.
S_f number of single tags for flavor modes.
$N_{D,\overline{D}}$ total number of $D^0\overline{D}^0$ events.
$K_i(K_{-i})$, yields in each bin of Dalitz plot
in flavor modes.