Strong phase at BESIII and possible new charm physics at LHCb

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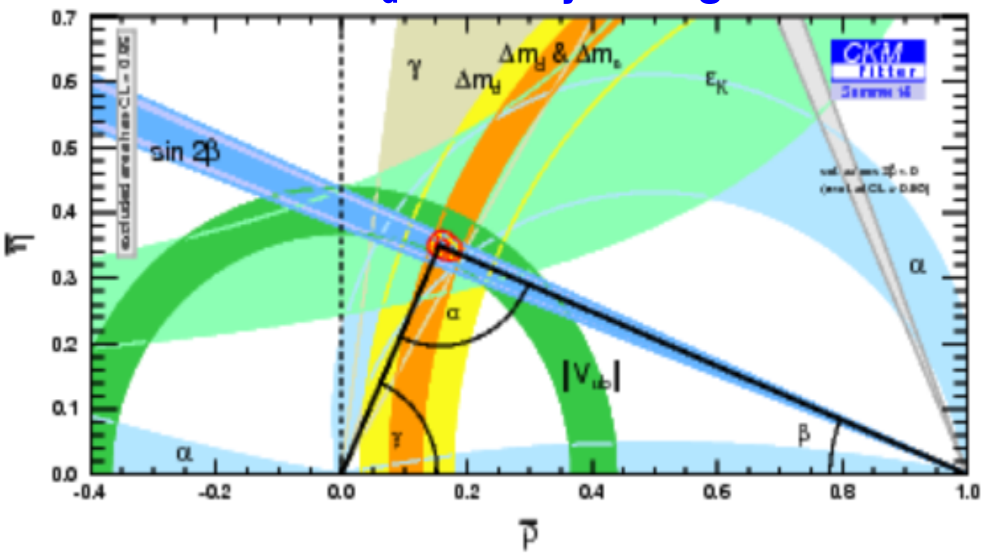
Outline

- Introduction
- Strong phase measurement at BESIII
- Future prospects on Strong phase measurement
- Some new charm physics at LHCb
- Summary and Outlook

Introduction

- γ/ϕ_3 is the only CKM angle that can be measured in tree-level processes, in which the contribution of non-SM effects is expected to be small [JHEP 01(2014)051].
- Measurement of γ provides a benchmark of the SM with negligible theoretical uncertainty.



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Phases of CKM elements:

$$\beta = \varphi_1 = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \quad \beta = (22.0 \pm 0.7)^o$$

$$\alpha = \varphi_2 = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \quad \alpha = (84.9^{+5.1}_{-4.5})^o$$

$$\gamma = \varphi_3 = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \quad \gamma = (73.5^{+4.2}_{-5.1})^o$$

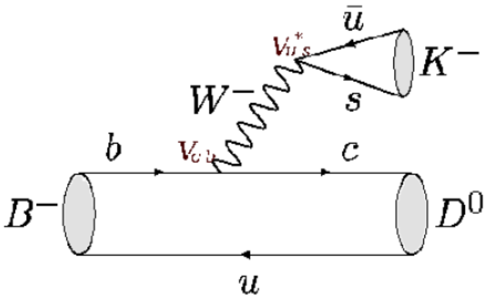
~ an order of magnitude worse than that on β.

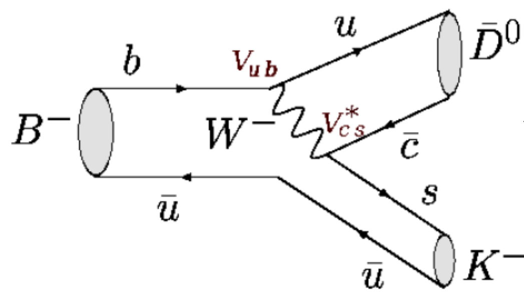
γ from CKM fitter: $\gamma = (65.8^{+1.0}_{-1.7})^o$

- The current world-average of γ deviates the indirect determination from CKM fitter by ~1.5σ.
- Clearly, an improved knowledge of the measurement of γ is important to further test the SM and probe for new physics.

Strong phase as inputs

- γ/ϕ_3 can be measured by studying the interference between $B^- \rightarrow D^0K^-$ and $B^- \rightarrow \bar{D}^0K^-$





$$A(B^- \rightarrow D^0K^-) = A_B A_D$$

$$A(B^- \rightarrow \bar{D}^0K^-) = A_B r_B e^{i(\delta_B - \gamma)} A_{\bar{D}}$$

where r_B is ratio of suppressed to favored amplitudes, δ_B is the strong-phase difference between the favoured and suppressed amplitudes.

- Generally, three methods were proposed to measure γ/ϕ_3:
  - ✓ GLW [1]: via $D^0 \rightarrow$ CP eigenstate, K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0$ etc.
  - ✓ ADS [2]: via $D^0 \rightarrow$ CF and DCS, such as $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$ etc.
  - ✓ GGSZ [3]: via with $D^0 \rightarrow$ Multi-body self-conjugate decays, $K_S^0\pi^+\pi^-$ etc.

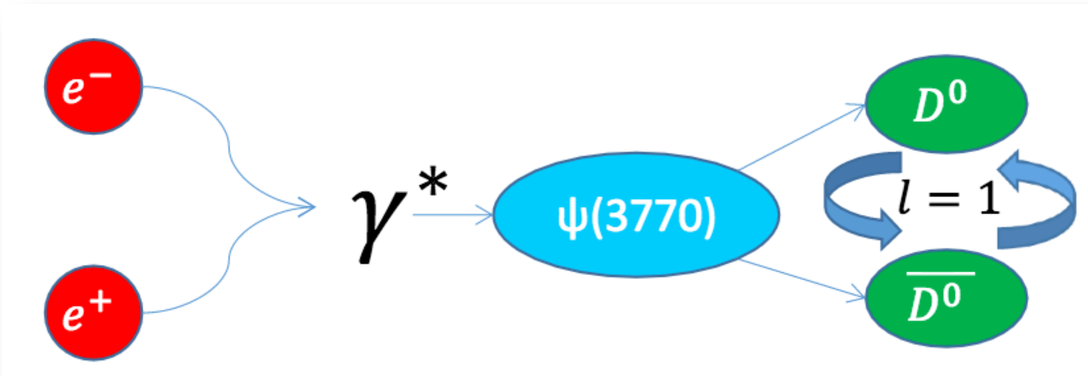
Measurements from strong phases are key inputs.

For GGSZ:

$$d\Gamma(B^\pm \rightarrow DK^\pm) = |\mathcal{A}_D|^2 + r_B^2|\mathcal{A}_{\bar{D}}|^2 + 2r_B|\mathcal{A}_D||\mathcal{A}_{\bar{D}}| \times [\cos\Delta\delta_D \cos(\delta_B \pm \phi_3) + [\sin\Delta\delta_D \sin(\delta_B \pm \phi_3)]$$

[1] M. Gronau, D. London, Phys. Lett. B 253, 483 (1991); M. Gronau, D. Wyler, Phys. Lett. B 265, 172 (1991).
[2] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. 78, 3257 (1997).
[3] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68, 054018 (2003).

Quantum correlated (QC) neutral D state near threshold

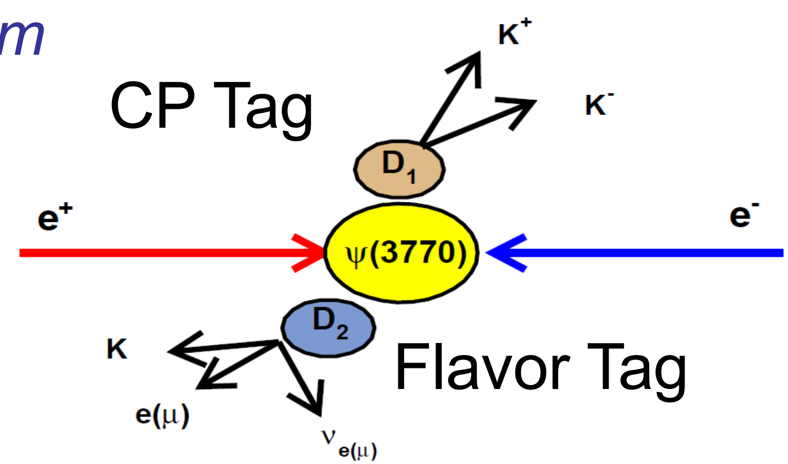


If D^0 in CP eigenstate, $\overline{D^0}$ must be in opposite CP eigenstate

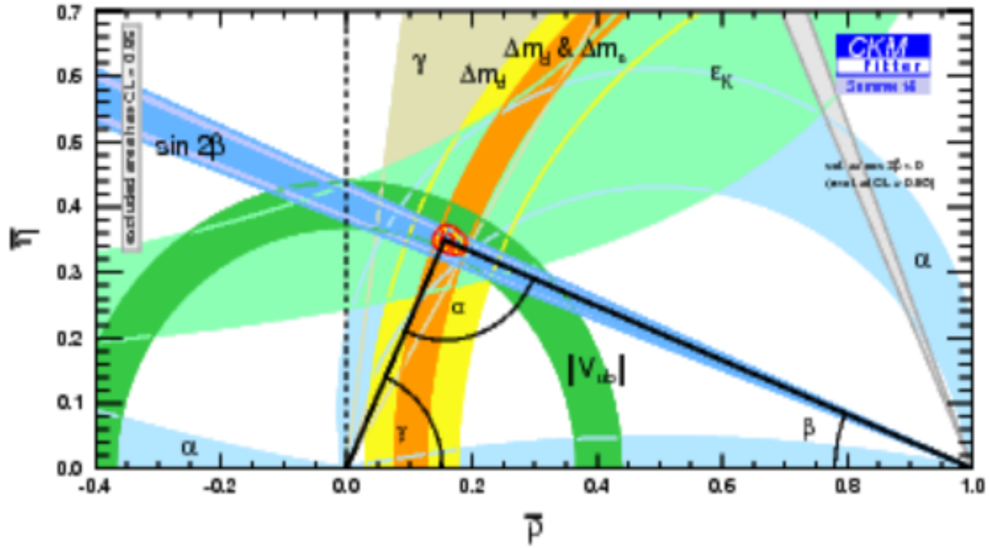
Quantum Correlations (QC) and CP-tagging are unique

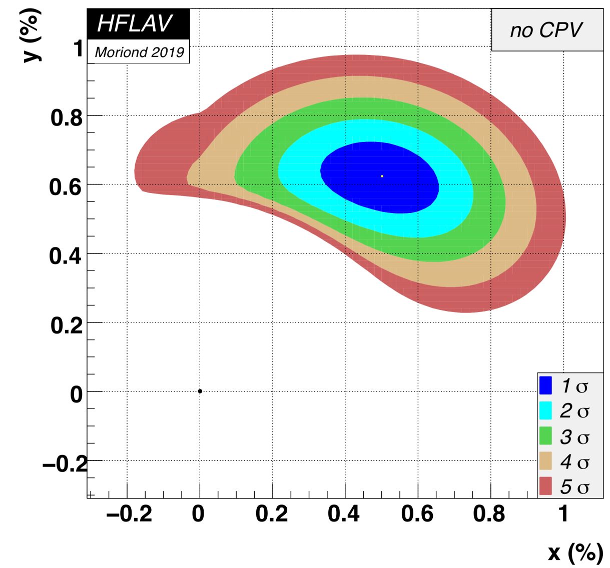
Taking advantage the quantum coherence of $D\underline{D}$ pairs, BESIII can study the charm physics in an unique way

- *strong phase in D decays*
- *D mixing parameters*
- *direct CP violation*
- *…*



QC inputs for Charm Physics



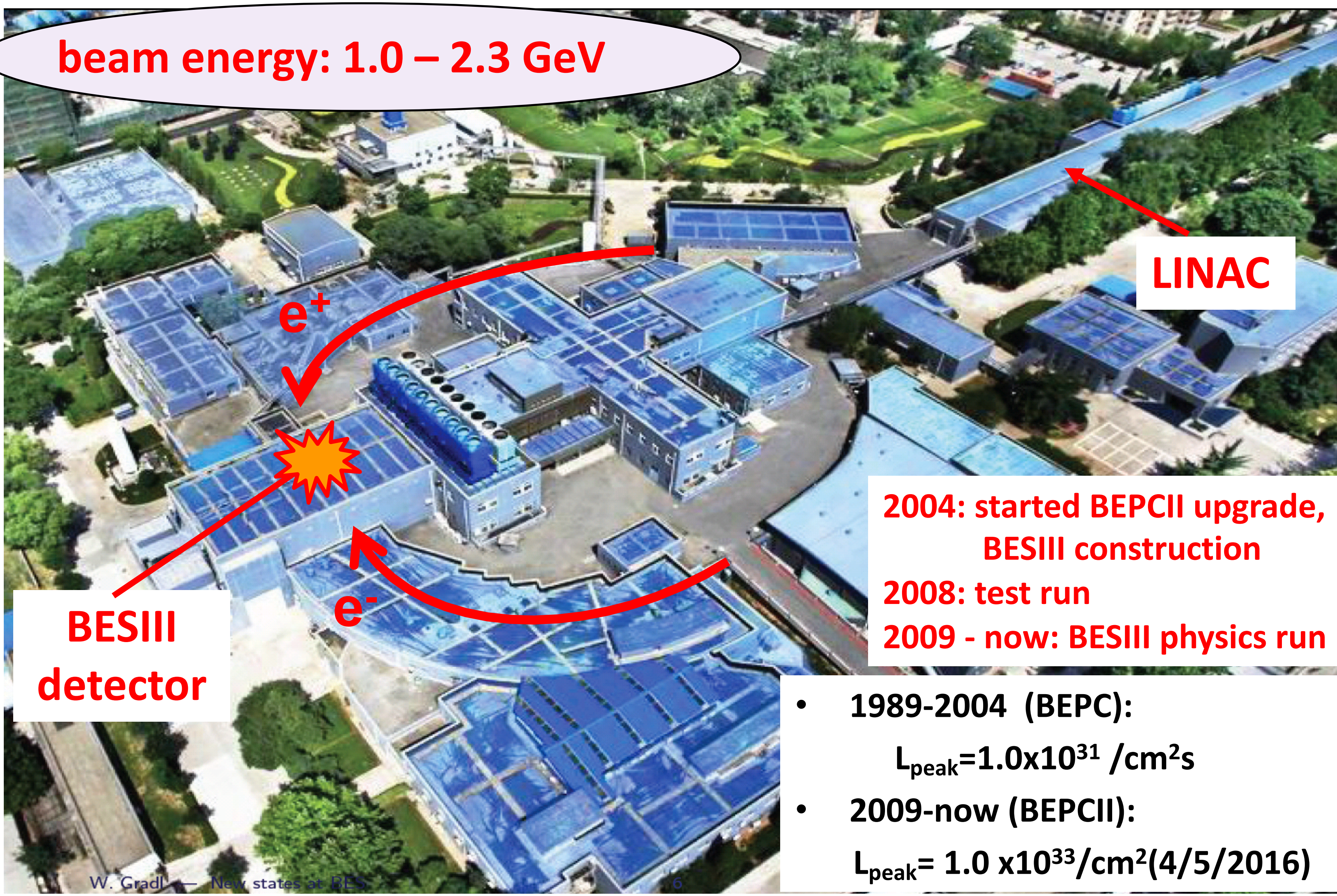


Precision CKM test

Charm Mixing & CP violation

- **inputs from Quantum Correlated (QC) $\psi(3770)\to D\bar{D}$ decays**
  - **(Averaged)Strong phase difference: δ_D**
  - **Coherent factors: R_D**
  - **(Averaged)Strong phase in Dalitz bins: c_i, s_i**
- ***B* factories, LHCb, Super *B* factories are the customers**

Beijing Electron Positron Collider (BEPC)



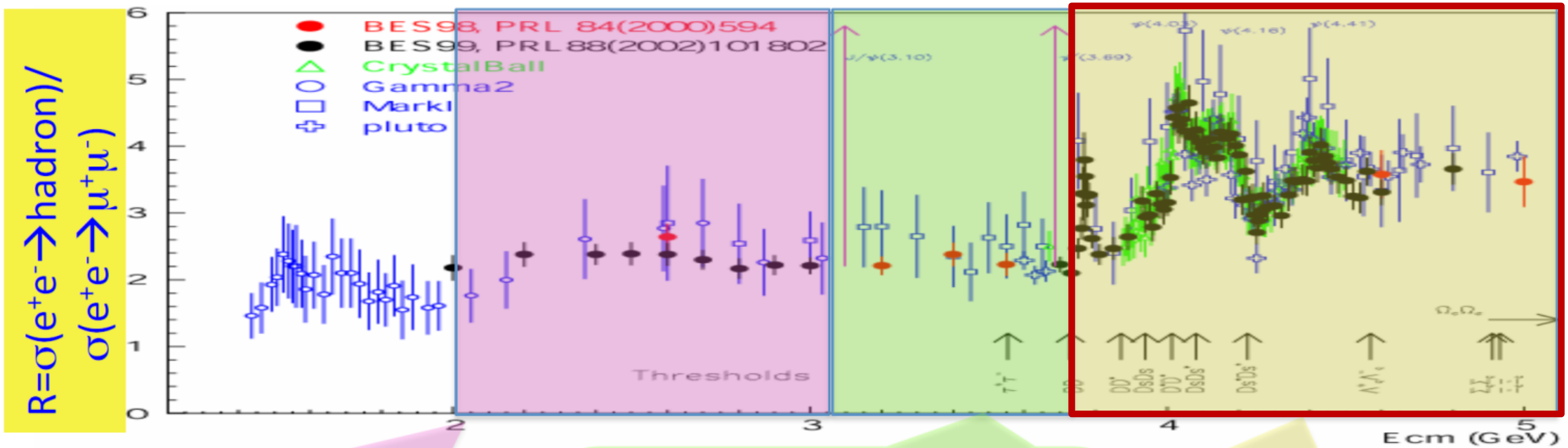
2004: started BEPCII upgrade, BESIII construction

2008: test run

2009 - now: BESIII physics run

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

Physics at tau-charm Energy Region



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

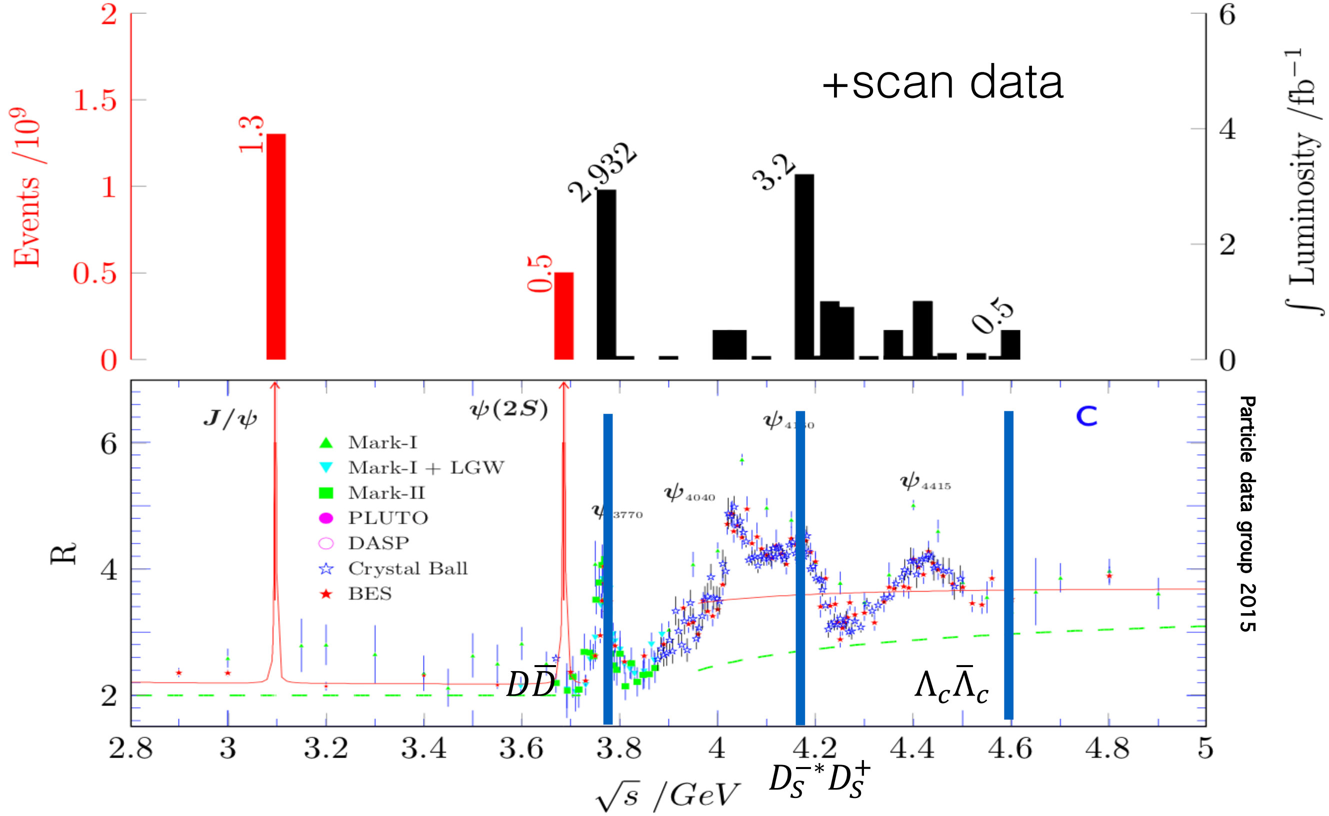
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

Data for studying charmed hadron decays

$D_{(s)}$ & Λ_c decays:

- (semi-)leptonic decays
- hadronic decays



The Quantum Correlated $D\bar{D}$ meson pairs

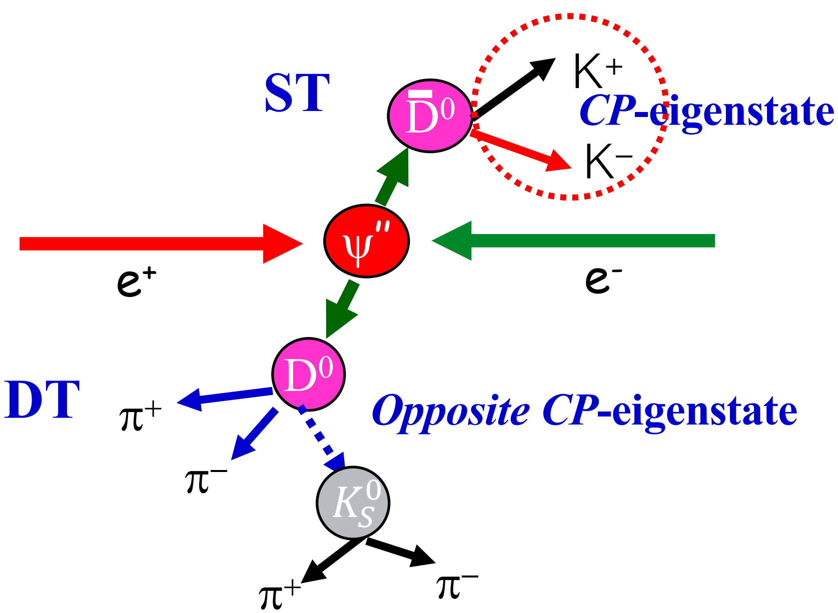
- ψ(3770) is a spin -1 state and therefore the amplitude of ψ(3770)→$D^0\bar{D}^0$:

$$(|D^0\rangle|\overline{D^0}\rangle - |\overline{D^0}\rangle|D^0\rangle)/\sqrt{2}$$ [anti-symmetric wave function]

The amplitude for two D mesons to decay to states ***F*** and ***G*** is [D. Atwood and A. Soni, PRD68, 033003 (2003)]:

$$\Gamma(F|G) = \Gamma_0\,[A_F^2\bar{A}_G^2 + \bar{A}_F^2 A_G^2 - 2R_F R_G A_F \bar{A}_F A_G \bar{A}_G \cos[\delta_D^F - \delta_D^G]]$$

The coherence factors R_F, the strong-phase difference (or the related parameters) δ_D^F, can be extracted based on the study of the quantum correlated $D\bar{D}$ meson pairs.



The DT mode K^+K^- *vs.* $K_S^0\pi^+\pi^-$ is selected as an example.

- ✓ **Single tag (ST) samples:** decay products of only one D meson are reconstructed
- ✓ **Double tag (DT) samples:** decay products of both D mesons are reconstructed
- ✓ **Some typical reconstructed D decay modes**

Tag group	
Flavor	$K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^+e^-\bar{\nu}_e$
CP-even	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$, $\pi^+\pi^-\pi^0$
CP-odd	$K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$, $K_S^0\eta'$, $K_L^0\pi^0\pi^0$
Mixed-CP	$K_S^0\pi^+\pi^-$

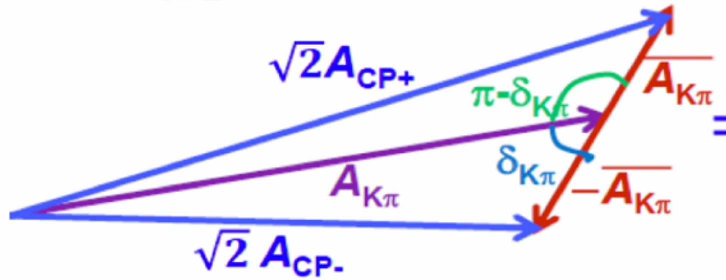
- ✓ ***Using this method, CLEO had performed lots of important and excellent measurements related to strong phases.***

ADS input: strong phase $\delta_{K\pi}$

2.93 fb^{-1} @3.773GeV

Quantum correlation → Interference → access strong phase!

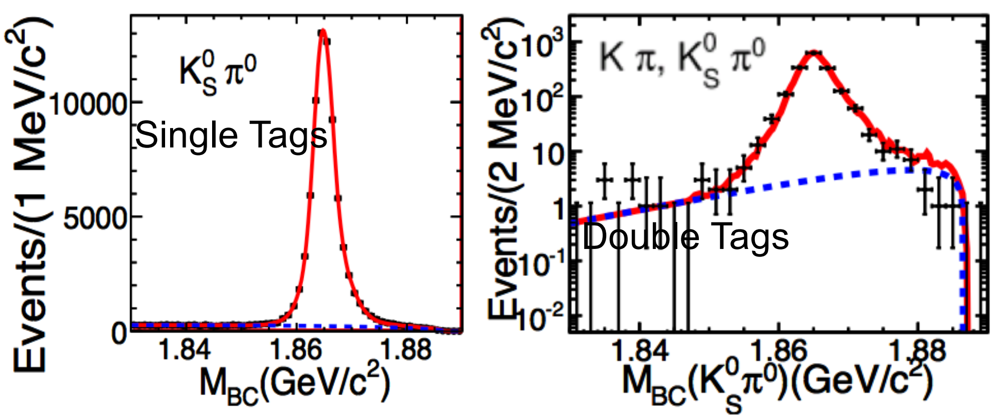
$$\langle K\pi|D_{CP\pm}\rangle = (\langle K\pi|D^0\rangle \pm \langle K\pi|\overline{D^0}\rangle)/\sqrt{2} \Rightarrow \sqrt{2}A_{CP\pm} = A_{K\pi} \pm \overline{A_{K\pi}}$$



$$\Rightarrow 2r_{K\pi}\cdot\cos\delta_{K\pi} \approx A_{CP\to K\pi} \equiv \frac{|A_{CP-}|^2 - |A_{CP+}|^2}{|A_{CP-}|^2 + |A_{CP+}|^2} = \frac{Br(D_{CP-}\to K\pi) - Br(D_{CP+}\to K\pi)}{Br(D_{CP-}\to K\pi) + Br(D_{CP+}\to K\pi)}$$

Strong phase: $\frac{\langle K^-\pi^+|\overline{D^0}\rangle^{DCS}}{\langle K^-\pi^+|D^0\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$

- Flavor tags: $K^-\pi^+$, $K^+\pi^-$
- CP+ tags (5 modes): K^-K^+, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
- CP- tags (3 modes): $K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$



PLB 734, 227 (2014)

BESIII results:

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

- The third error is due to the input parameters
- World best precision
- In 10 /fb BESIII data, precision of $\cos\delta_{K\pi}$ will reach ~0.07

GGSZ input: (c_i, s_i) in $D^0 \to K_{S,L}\pi^+\pi^-$ Dalitz analysis

$B^{\pm} \to DK^{\pm}$ yields

from flav.-tagged $D \to K_S\pi\pi$

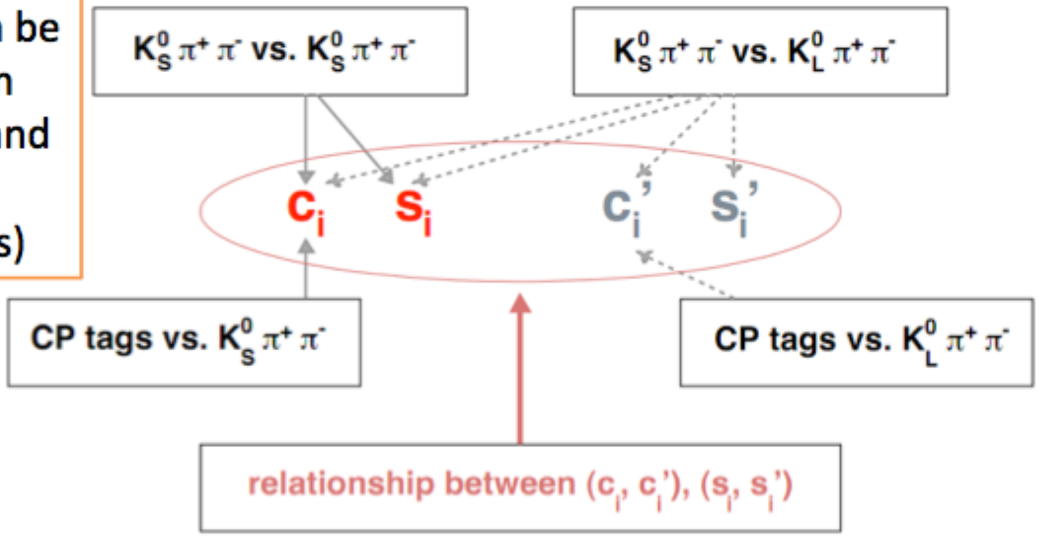
extracted from fit to the $B^{\pm}$ yields

measured by CLEO [PRD82, 112006 (2010)]

$$N_i^{\pm} = h_B\left[K_{\pm i} + r_b^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i \pm y_{\pm} s_i)\right]$$

We can calculate c_i and s_i from double tags of $D^0 \to K_S\pi^+\pi^-$ vs $D^0 \to (K_{S,L}\pi^+\pi^-$ or CP eigenstates)

A relationship can be shown between Dalitz bin yields and c_i and s_i (in backup slides)

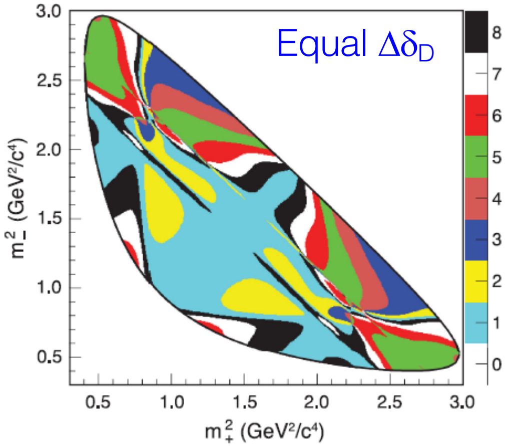


Only c_i, s_i from $K_s\pi^+\pi^-$ is used to calculate γ.
However adding in $D^0 \to K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

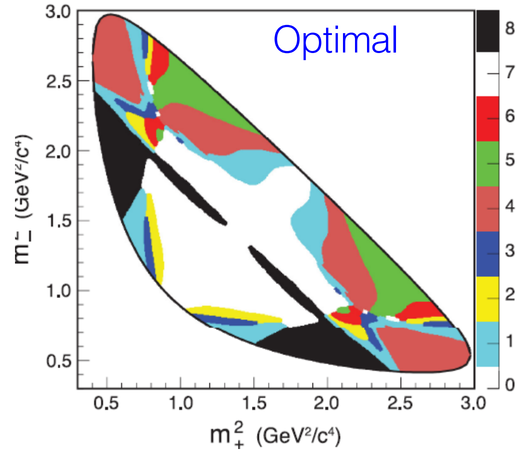
Strong-phase parameters in $D \to K_S^0 \pi^+ \pi^-$

❑ Three typical binning schemes

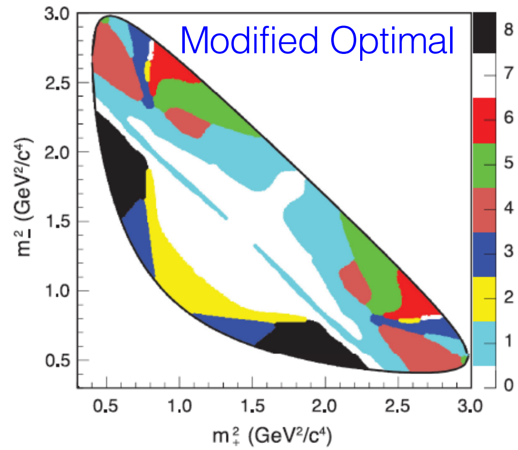
[J. Libby et al. (CLEO Collaboration), Phys. Rev. D 82,112006 (2010)]



DD-mixing[1], β measurements[2]
[minimum variation in $\Delta\delta_D$]



γ measurements[3,4]
[Optimized sensitivity]



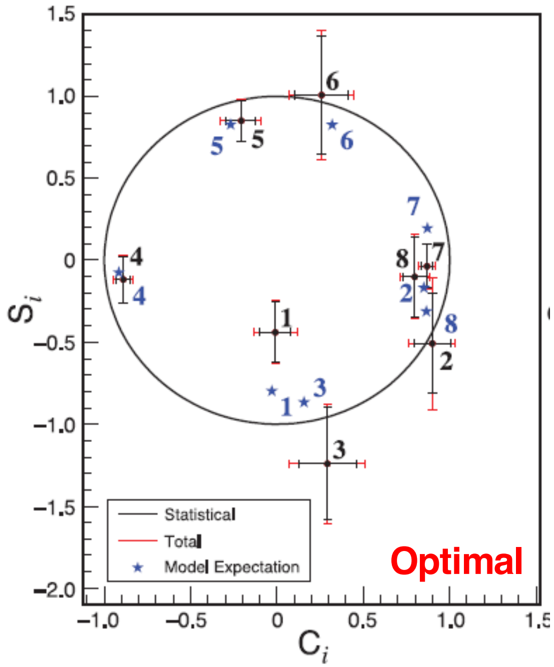
γ in Low yields
[Optimization including backgrounds]

- ✓ "BaBar K-matrix" $D^0 \to K_s^0 \pi^+ \pi^-$ model as in Ref. [Phys. Rev. D 78, 034023 (2008)].
- ✓ It should be noted that although the choice of binning is model-dependent, however, a poor choice of model results only in a loss of precision, instead of bias in measuring γ/ϕ_3.

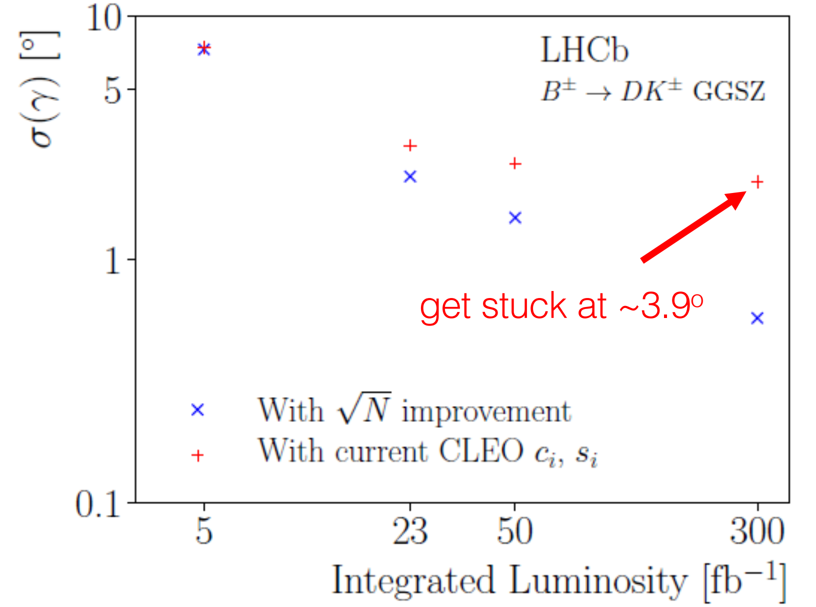
[1] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 122, 231802 (2019); JHEP 04(2016) 033.
[2] V. Vorobyev et al. (Belle Collaboration), Phys. Rev. D 94, 052004 (2016).
[3] R. Aaij et al. (LHCb Collaboration), Phys. Lett. B 718, 43 (2012); JHEP 10 (2014) 097; JHEP 06 (2016) 131; JHEP 08 (2018) 176.
[4] H. Aihara et al. (Belle Collaboration), Phys. Rev. D 85, 112014 (2012).

Strong-phase parameters in $D \to K_{S/L}^0 \pi^+ \pi^-$

✓ Results of c_i and s_i in optimal binning from CLEO experiments.



[LHCb Collaboration, arXiv: 1808.08865]

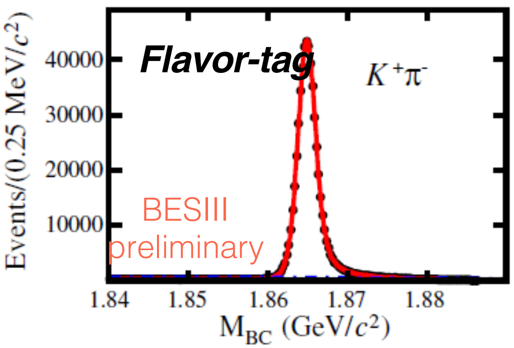


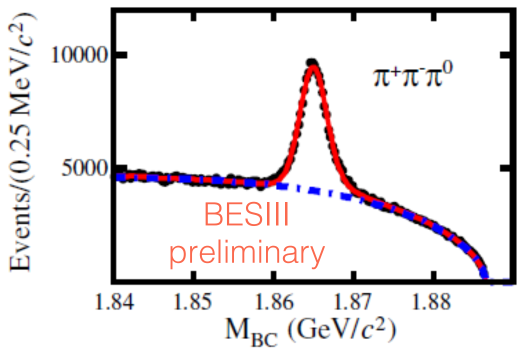
✓ The systematic uncertainty in measurement of γ due to input strong-phase parameters is 3.9° for optimal binning. The overall sensitivity is limited to ~3.9° for model-independent GGSZ approach.

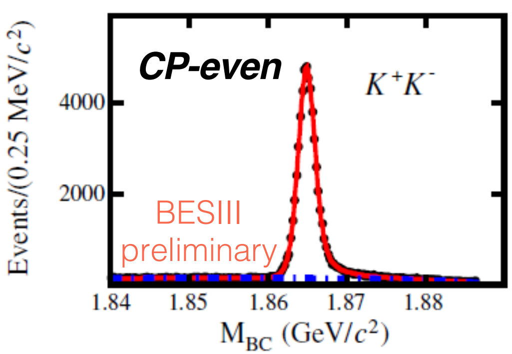
✓ *Therefore, improved measurements in c_i & s_i from BESIII are essential for degree-level precision of measuring γ via model-independent GGSZ approach.*

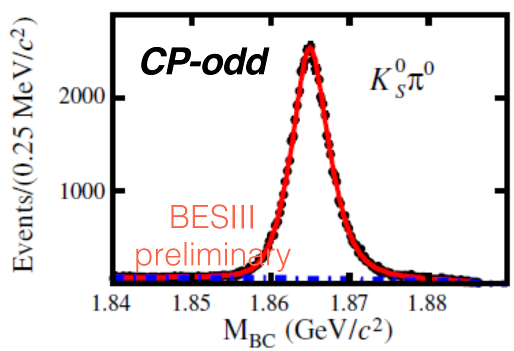
Beam-constrained mass distributions

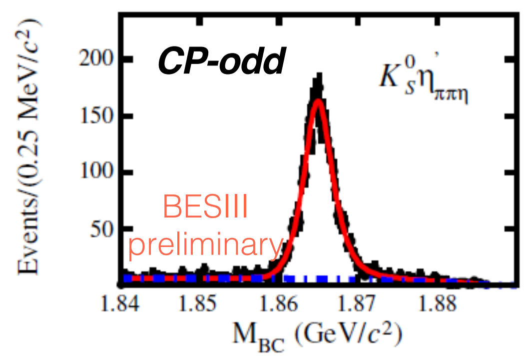
The M_{BC} distributions for ST D mesons











- ✓ A list of tag decay modes used in this analysis

Tag group	
Flavor	$K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^+e^-\bar{\nu}_e$
CP-even	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $\pi^+\pi^-\pi^0$
CP-odd	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\eta'$, $K^0_L\pi^0\pi^0$
Mixed-CP	$K^0_S\pi^+\pi^-$

- ✓ Beam-constrained mass (M_{BC})

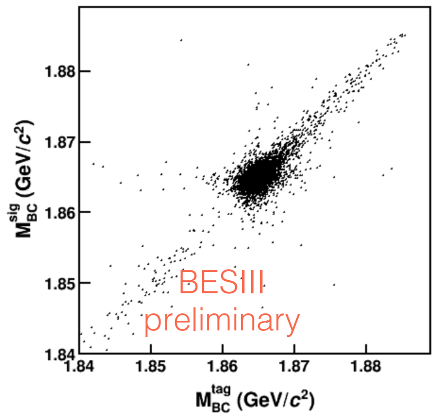
$$M_{BC} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_{D_{tag}}|^2}$$

- ✓ D→$\pi^+\pi^-\pi^0$ is not fully CP-even and the corrections for the decay is always applied.
- ✓ The fractional *CP*-even content of D→$\pi^+\pi^-\pi^0$: $F_+^{\pi+\pi-\pi0}$=0.973±0.017 [PLB747, 9 (2015)].

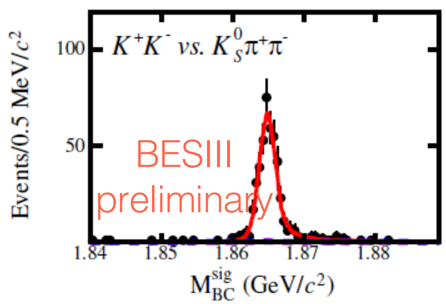
DT samples of $D \rightarrow K_S\pi^+\pi^-$ and $D \rightarrow K_L\pi^+\pi^-$

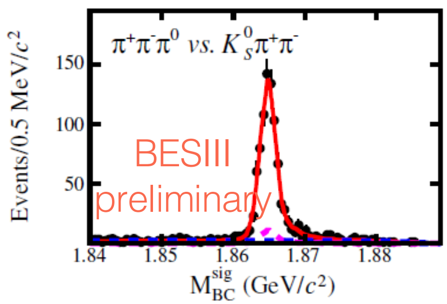
✓ The fully reconstructed DT $K_S\pi^+\pi^-$ events are obtained by searching for the $K_S\pi^+\pi^-$ signals in the recoiling system of fully-reconstructed ST events.

Scatter plot of M_{BC}^{sig} *vs.* M_{BC}^{tag}



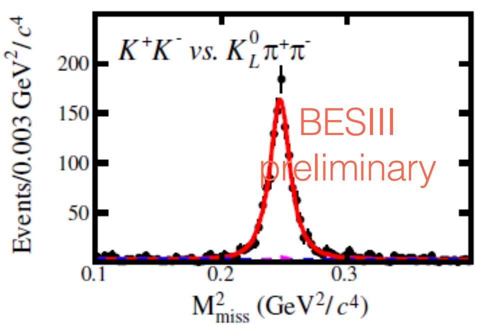
projections of the two-dimensional fits on M_{BC}^{sig}

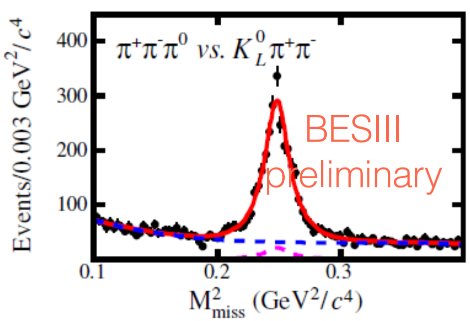


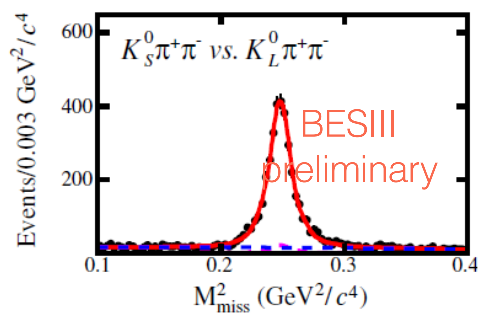


The pink curves show peaking backgrounds dominated by $D \rightarrow \pi^+\pi^-\pi^+\pi^-$.

✓ DT events containing K_L^0 particles are identified via kinematic variable missing-mass-square (M^2_{miss}).



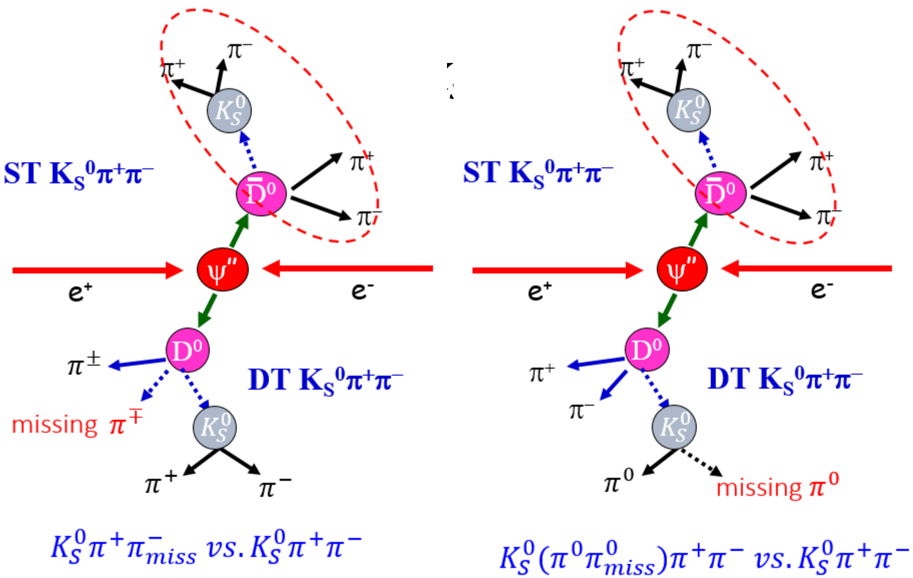




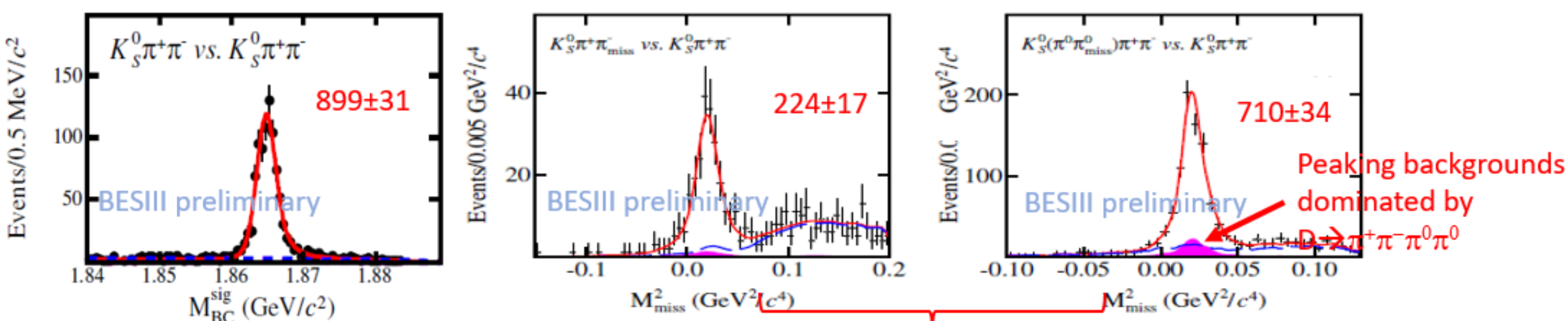
The pink curves show peaking backgrounds dominated by $D \rightarrow K_S\pi^+\pi^-$ with $K_S^0 \rightarrow \pi^0\pi^0$.

DT sample of $K_S\pi^+\pi^-$ vs. $K_S\pi^+\pi^-$ events

✓ To increase the sensitivity of measuring s_i, the partially-reconstructed events are introduced into analysis to increase the yield of events .



The yield of DT $K_S^0\pi^+\pi^-$ vs. $K_S^0\pi^+\pi^-$ is doubled by adding the partially-reconstructed samples.



Comparisons of DT events between BESIII and CLEO

Mode	BESIII [signal yields] $N^{DT}_{K^0_S\pi^+\pi^-}$	BESIII [signal yields] $N^{DT}_{K^0_L\pi^+\pi^-}$	CLEO [raw yields] $N^{DT}_{K^0_S\pi^+\pi^-}$	CLEO [raw yields] $N^{DT}_{K^0_L\pi^+\pi^-}$
Flavor tags				
$K^+\pi^-$	4740 ± 71	9511 ± 115	1444	2857
$K^+\pi^-\pi^0$	8899 ± 95	19225 ± 176	2759	5133
$K^+\pi^-\pi^-\pi^+$	5695 ± 78	11906 ± 132	2240	4100
$K^+e^-\bar{\nu}_e$	4123 ± 75		1191	
CP-even tags				
K^+K^-	443 ± 22	1289 ± 41	124	357
$\pi^+\pi^-$	184 ± 14	531 ± 28	61	184
$K^0_S\pi^0\pi^0$	198 ± 16	612 ± 35	56	
$\pi^+\pi^-\pi^0$	790 ± 31	2571 ± 74	– –	– –
$K^0_L\pi^0$	913 ± 41		237	
CP-odd tags				
$K^0_S\pi^0$	643 ± 26	861 ± 46	189	288
$K^0_S\eta_{\gamma\gamma}$	89 ± 10	105 ± 15	39	43
$K^0_S\eta_{\pi^+\pi^-\pi^0}$	23 ± 5	40 ± 9	– –	– –
$K^0_S\omega$	245 ± 17	321 ± 25	83	– –
$K^0_S\eta'_{\pi^+\pi^-\eta}$	24 ± 6	38 ± 8	– –	– –
$K^0_S\eta'_{\gamma\pi^+\pi^-}$	81 ± 10	120 ± 14	– –	– –
$K^0_L\pi^0\pi^0$	620 ± 32		– –	
Mixed CP tags				
$K^0_S\pi^+\pi^-$	899 ± 31	3438 ± 72	473	1201
$K^0_S\pi^+\pi^-_{\rm miss}$	224 ± 17			
$K^0_S(\pi^0\pi^0_{\rm miss})\pi^+\pi^-$	710 ± 34		– –	

new modes

BESIII preliminary

✓ "– –" stands for unused mode in CLEO analysis.

- More tag decay modes are used in BESIII analysis.
- DT events detected at BESIII and comparisons with CLEO [J. Libby et al. (CLEO Collaboration), Phys. Rev. D 82,112006 (2010)]:

$CP-eigenstate\ vs.\ K^0_S\pi^+\pi^-$: 5.3×CLEO

$CP-eigenstate\ vs.\ K^0_L\pi^+\pi^-$: 9.2×CLEO

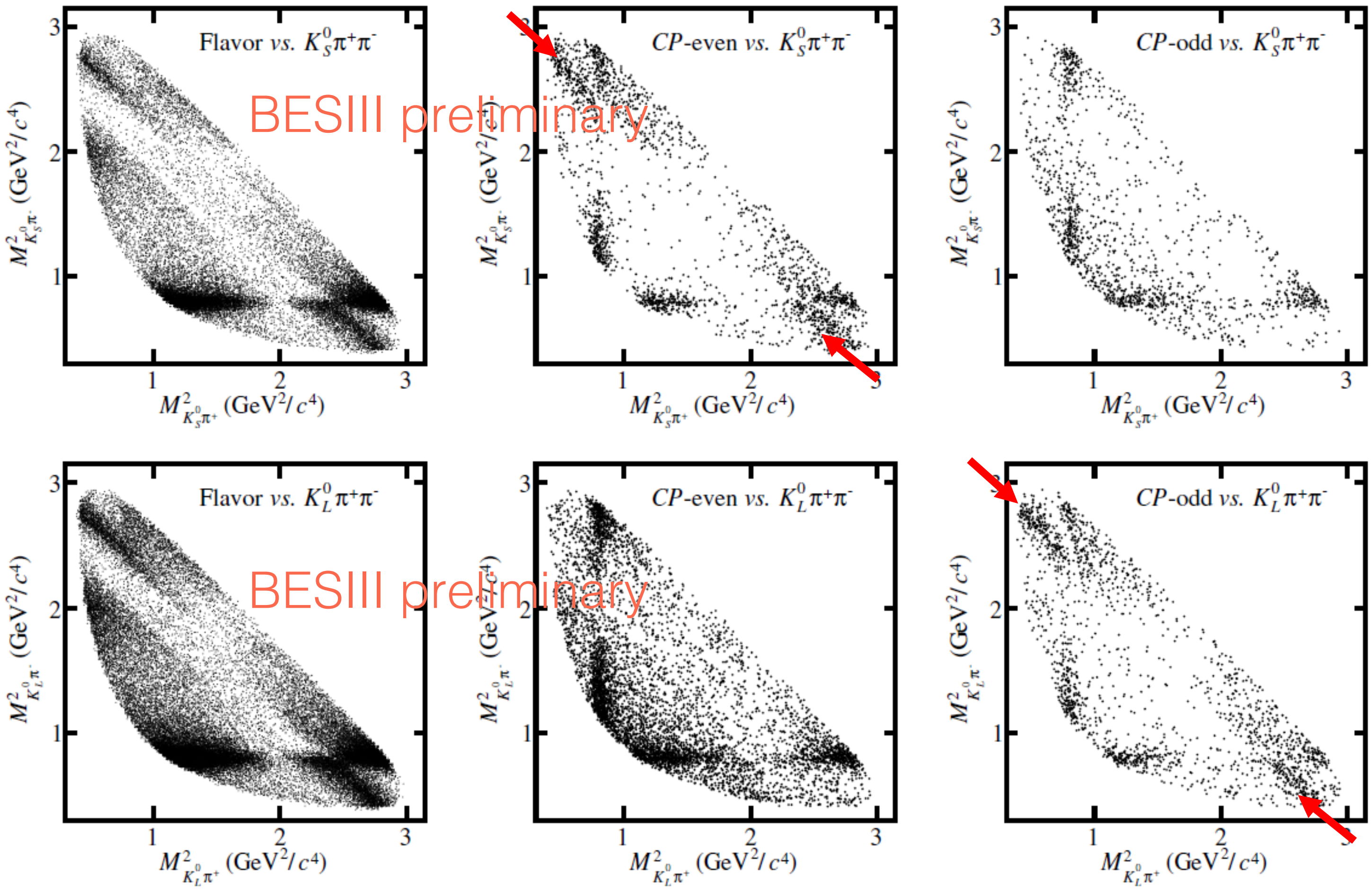
$K^0_S\pi^+\pi^-\ vs.\ K^0_S\pi^+\pi^-$: 3.9×CLEO

$K^0_L\pi^+\pi^-\ vs.\ K^0_S\pi^+\pi^-$: 2.9×CLEO

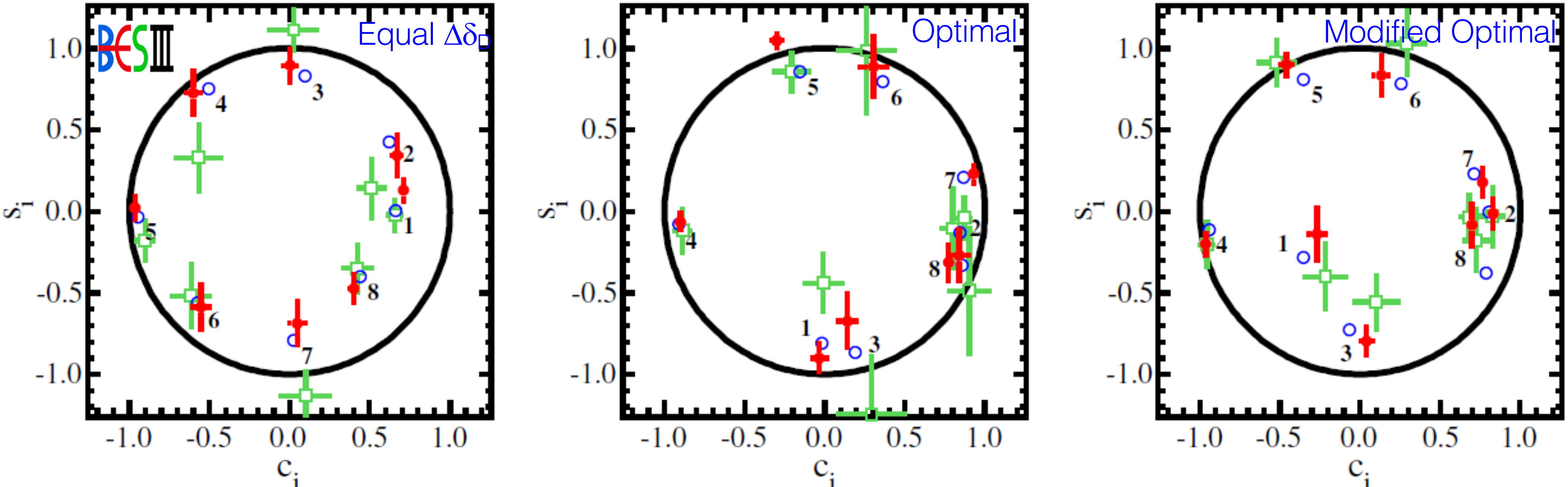
Dalitz plots observed in data

The effect of quantum correlation is immediately seen in Dalitz plots.

✓ The CP-odd component $K_S^0\rho(770)^0$ is visible in CP-even tagged $K_S^0\pi^+\pi^-$ decays, but is absent in CP-odd tagged $K_S^0\pi^+\pi^-$ decays.



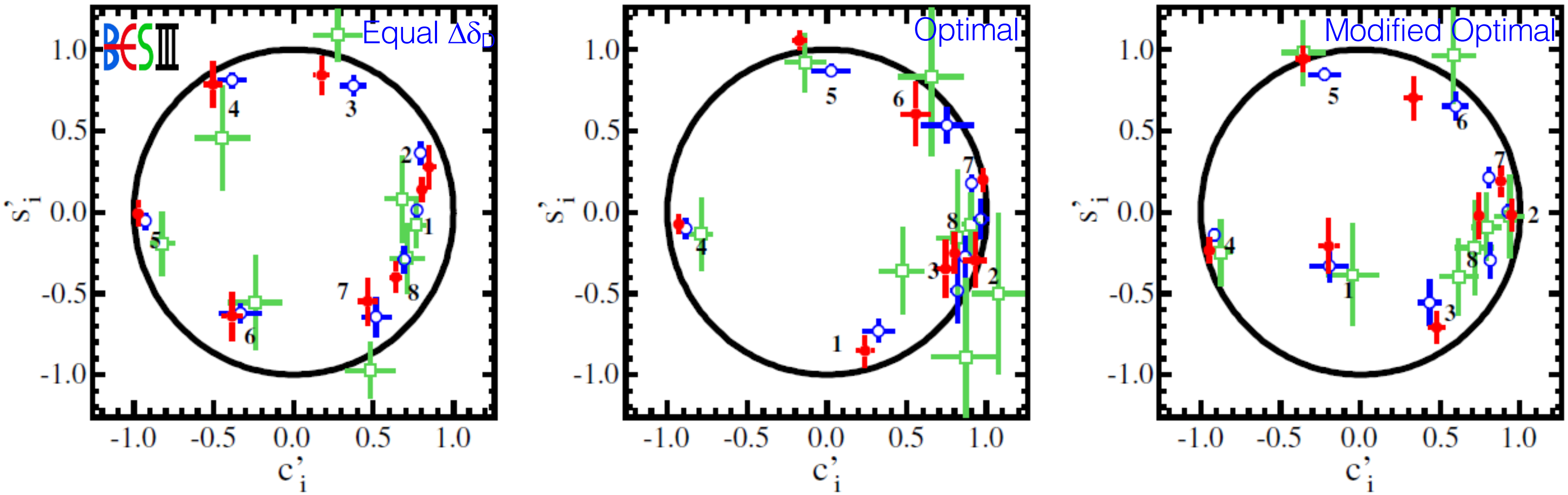
The preliminary strong-phase parameters (c_i, s_i)



The c_i and s_i measured in this work (red dots with error bars), the expected results from Ref. [BaBar&Belle, PRD98, 110212 (2018)] (blue open circles) and the CLEO results (green open squares with error bars) [CLEO, PRD 82,112006 (2010)].

- ✓ The strong-phase parameters are **limited by statistical errors.**
- ✓ *There is no single dominant systematic uncertainty in measurement of c_i & s_i.*
- ✓ On average a factor of ~2.5 (2.0) more precise for c_i (s_i) than CLEO measurements.
- ✓ Using BESIII results, the associated uncertainty on γ/ϕ_3 is expected to be approximately a factor of three smaller than that from CLEO analysis, if using an analysis of $B^- \rightarrow DK^-$, $D \rightarrow K_S^0\pi^+\pi^-$.

The preliminary strong-phase parameters (c'_i, s'_i)

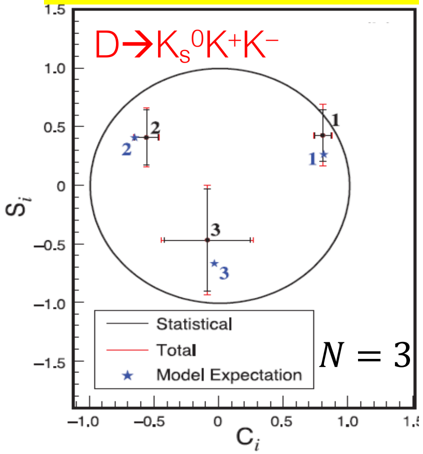


The c'_i and s'_i measured in this work (red dots with error bars), the expected results from Ref. [BaBar&Belle, PRD98, 110212 (2018)] (blue open circles) and the CLEO results (green open squares with error bars) [CLEO, PRD 82,112006 (2010)].

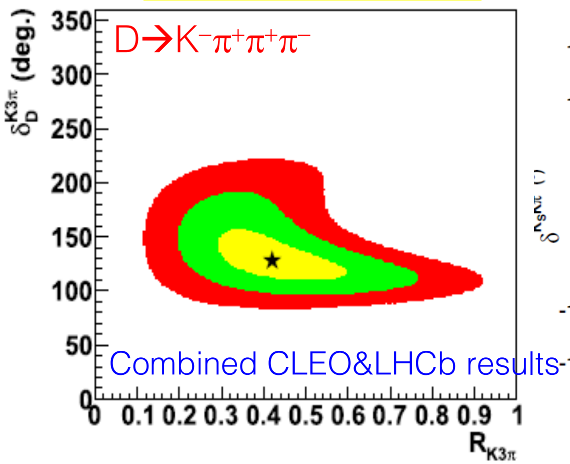
- ✓ The strong-phase parameters are **limited by statistical errors.**
- ✓ *There is no single dominant systematic uncertainty in measurement of c_i' & s_i'.*
- ✓ on average a factor of ~2.8 (2.2) more precise for c'_i (s'_i) than CLEO measurements.
- ✓ The improved precision on c'_i and s'_i are important for Belle-II experiment in γ measurement, if using an analysis of $B^- \to DK^-$, $D \to K_L^0\pi^+\pi^-$.

Other related strong-phase measurements at CLEO

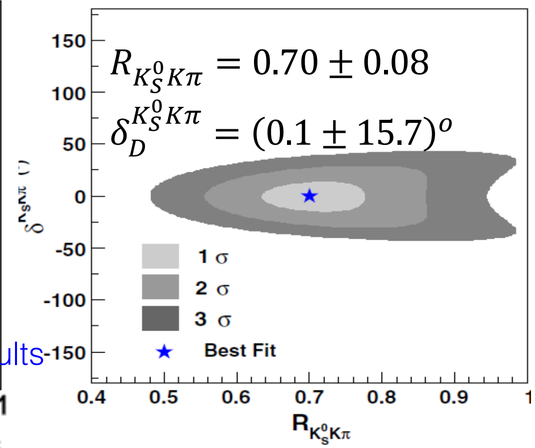
[PRD82, 112006(2010)]



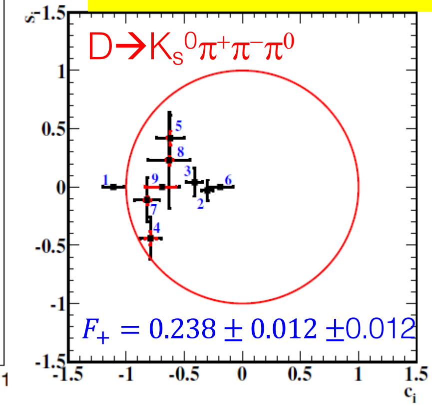
[PLB757, 520(2016)]

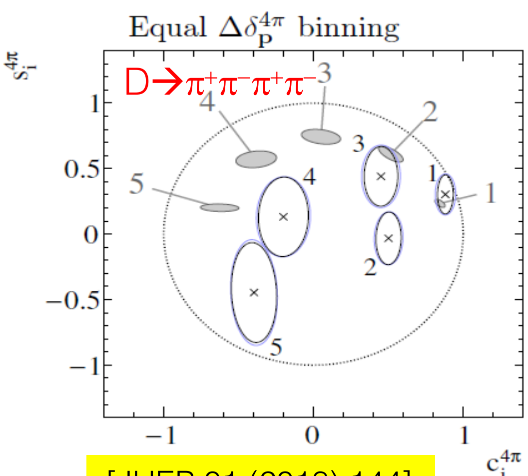


[PRD85, 092016(2012)]



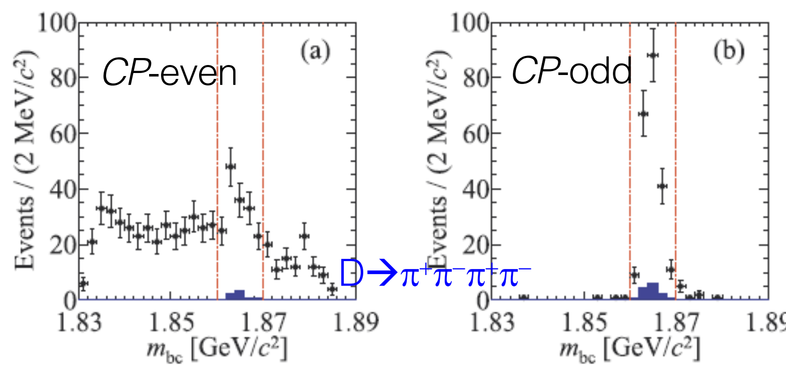
[JHEP 01 (2018) 082]





[JHEP 01 (2018) 144]

✓ *CP*-even fractions $F_+ = \frac{N_{CP+}}{N_{CP+} + N_{CP-}}$



- D→$\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$
- D→$\pi^+\pi^-\pi^+\pi^-$

[PLB740, 1(2015); PLB 747, 9 (2015)]

- $\delta_D^{K\pi}$ was also measured by using quantum-correlated data at CLEO, but mixing inputs dominate.
[PRD78,012001 & PRL100,221801]

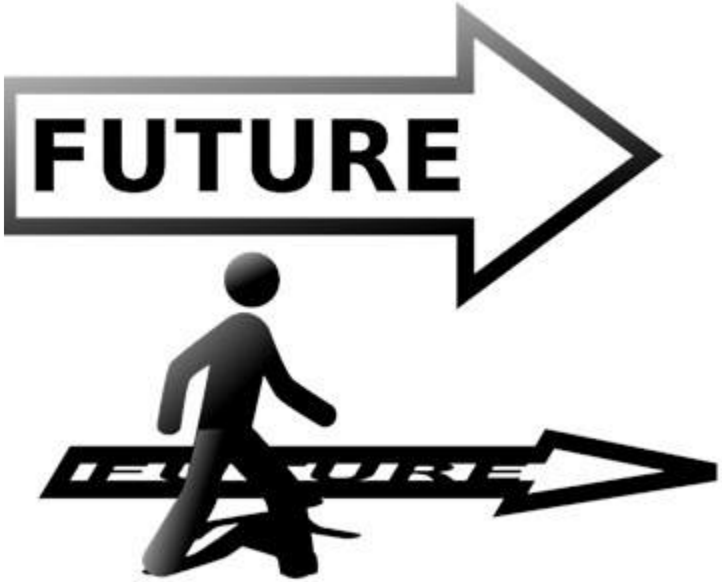
These analyses are ongoing at BESIII

Strong phases in D hadronic decays

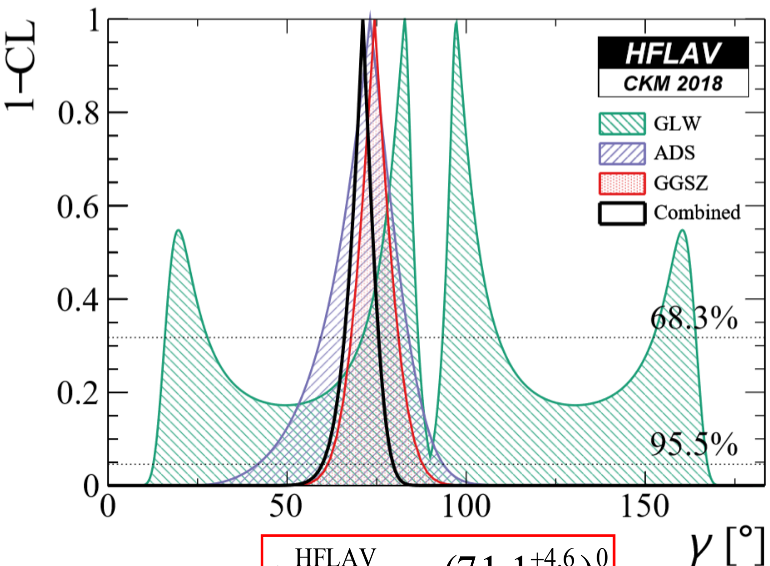
Status	Decay mode	Quantity of interest	Comments
➢	$D\to K_S^0\pi^+\pi^-$ *prel. release*	c_i and s_i	Binning schemes as those used in the CLEO-c analysis. With future, very large $\psi(3770)$data sets, it might be worthwhile to explore alternative binning.
➢	$D\to K_S^0K^+K^-$	c_i and s_i	Binning schemes as those used in the CLEO-c analysis. With future, very large $\psi(3770)$data sets, it might be worthwhile to explore alternative binning.
➢	$D\to K^\pm\pi^\mp\pi^+\pi^-$	R, δ	In bins guided by amplitude models, currently under development by LHCb.
➪	$D\to K^+K^-\pi^+\pi^-$	c_i and s_i	Binning scheme can be guided by the CLEO model [18] or potentially an improved model from LHCb in the future.
➪	$D\to\pi^+\pi^-\pi^+\pi^-$	F_+ or c_i and s_i	Unbinned measurement of F_+. Measurements of F_+ in bins or c_i and s_i in bins could be explored.
➢	$D\to K^\pm\pi^\mp\pi^0$	R, δ	Simple 2-3 bin scheme could be considered.
➪	$D\to K_S^0K^\pm\pi^\mp$	R, δ	Simple 2 bin scheme where one bin encloses the K^* resonance.
➢	$D\to\pi^+\pi^-\pi^0$	F_+	No binning required as $F_+\sim 1$.
➪	$D\to K_S^0\pi^+\pi^-\pi^0$	F_+ and c_i and s_i	Unbinned measurement of F_+ required. Additional measurements of F_+ or c_i and s_i in bins could be explored.
➢	$D\to K^+K^-\pi^0$	F_+	Unbinned measurement required. Extensions to binned measurements of either F_+ or c_i and s_i possible.
➡	$D\to K^\pm\pi^\mp$	δ	Of low priority due to good precision available through charm-mixing analyses.

LHCb-PUB-2016-025

Status at BESIII
➡ published
➢ under study
➪ in plan

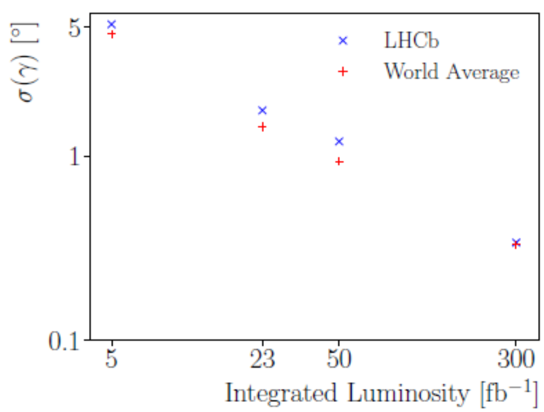

FUTURE

Status and prospects of γ measurements

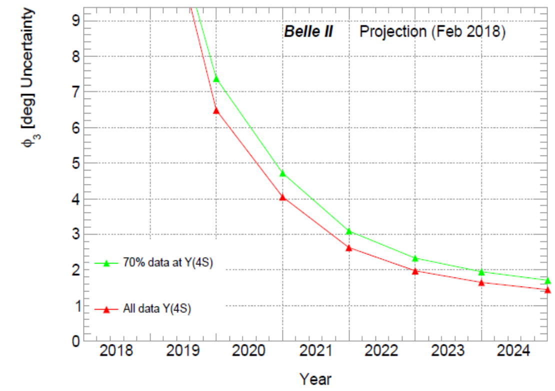


$\gamma_{\mathrm{CKM2018}}^{\mathrm{HFLAV}} = (71.1^{+4.6}_{-5.3})^{0}$

[arXiv: 1808.08865]



[arXiv: 1808.10567]



✓ dominated by LHCb measurements
The latest LHCb γ combination gives

$$\gamma = (74.0^{+5.0}_{-5.8})^{o}$$

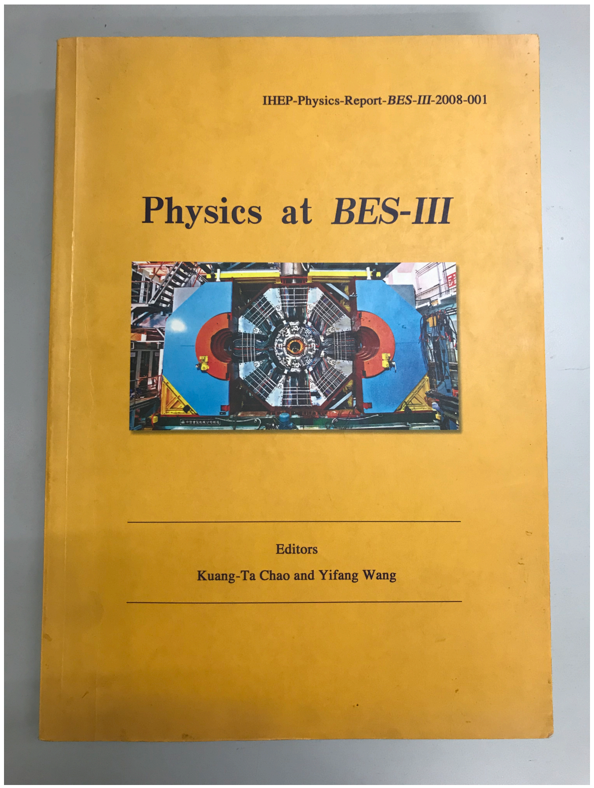
✓ The degree-level precision on γ can be expected in near future.

	Collected/ Expected luminosity	Year attained	γ sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	5.5°
LHCb Run-2 [13 TeV]	5 fb^{-1}	2018	2.8°
LHCb phase-1 upgrade [14 TeV]	50 fb^{-1}	2030	0.71°
LHCb phase-2 upgrade [14 TeV]	300 fb^{-1}	2035(?)	0.28°
Belle-II Run	50 ab^{-1}	2025	1.5°

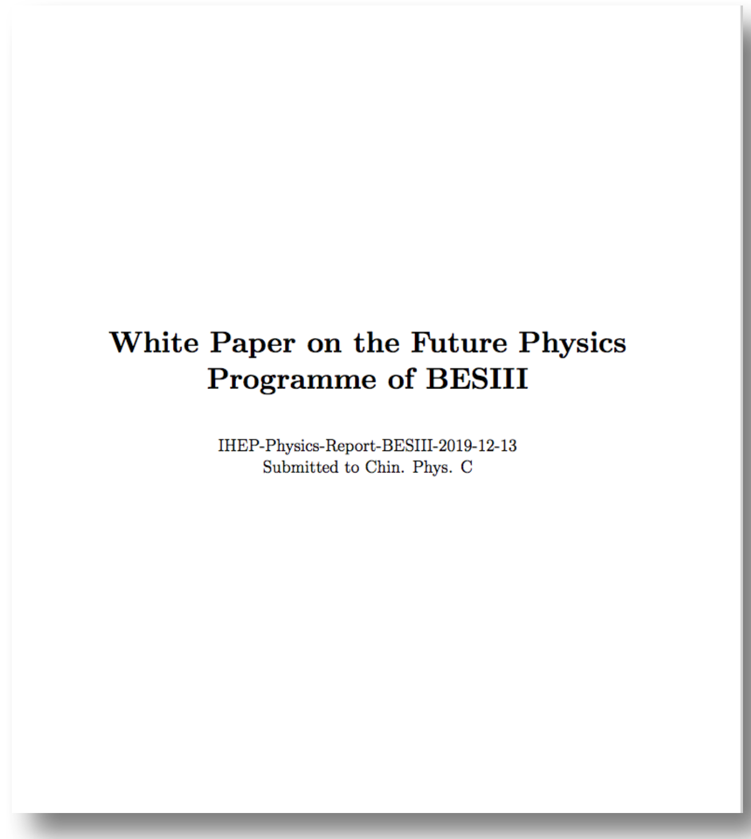
- In above table, sensitivity from LHCb is obtained by scaling Run-I statistical error.

From BESIII physics (yellow) book to BESIII white paper

2008



arXiv:1912.05983


White Paper on the Future Physics Programme of BESIII

IHEP-Physics-Report-BESIII-2019-12-13
Submitted to Chin. Phys. C

Future BESIII precision

Energy	Physics motivations	Current data	Expected final data
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}

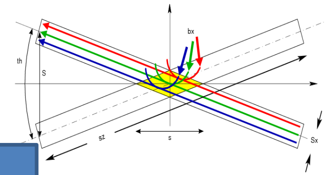
- 2.9/fb $\psi(3770)$ data: strong phase uncertainty to γ is ~1°
- 20/fb $\psi(3770)$ data: strong phase uncertainty to γ is ~0.4°
  ➔ sufficient for LHCb upgrade I
- While not enough for LHCb upgrade II

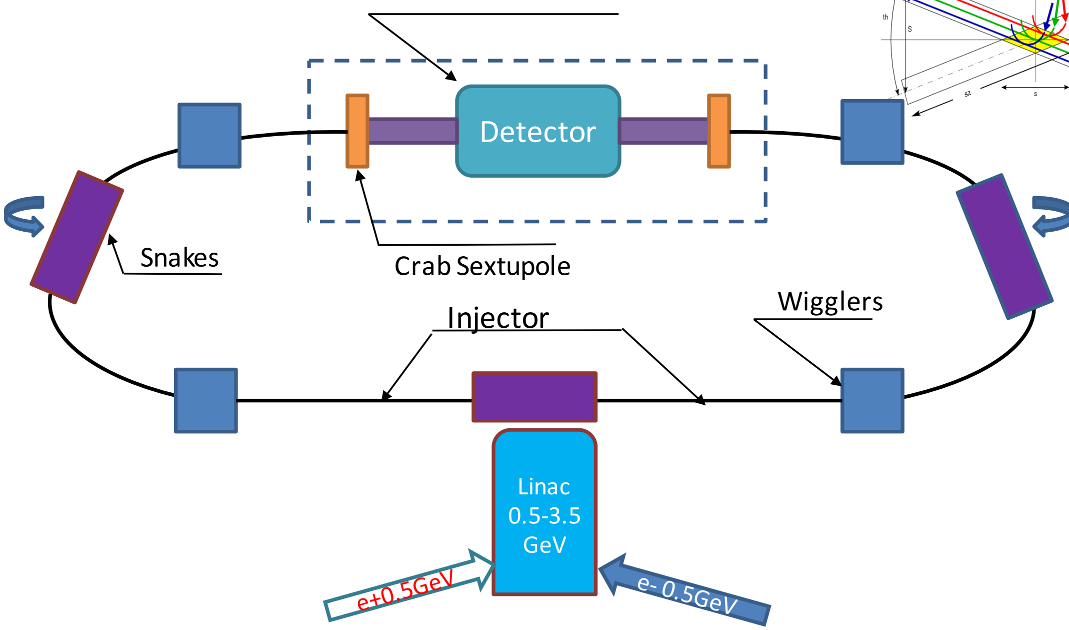
Runs	Collected / Expected integrated luminosity	Year attained	γ/ϕ_3 sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	8°
LHCb Run-2 [13 TeV]	5 fb^{-1}	2018	4°
Belle II Run	50 ab^{-1}	2025	1.5°
LHCb upgrade I [14 TeV]	50 fb^{-1}	2030	$< 1°$
LHCb upgrade II [14 TeV]	300 fb^{-1}	(>)2035	$< 0.4°$

BESIII 20/fb:
$\sigma(\gamma)$ ~0.4°

→ STCF is needed!

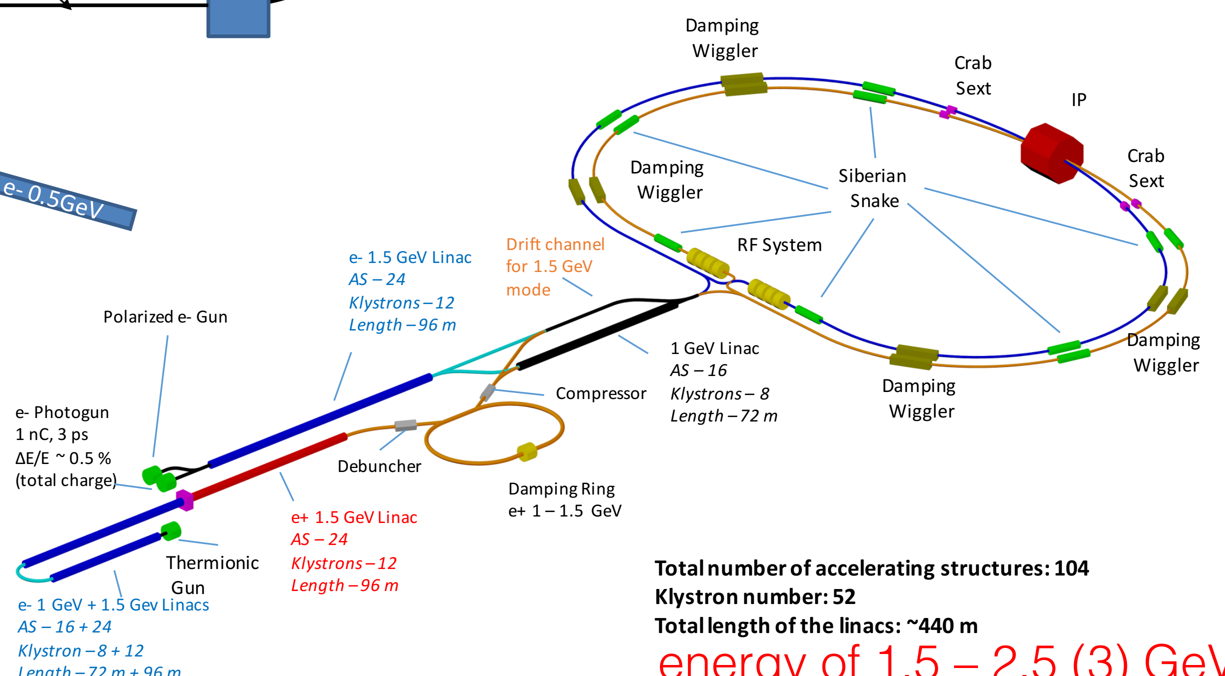
Proposals of the Super Tau-Charm Factory (STCF)





HIEPA in China

Super-CT Project in Russia



Total number of accelerating structures: 104
Klystron number: 52
Total length of the linacs: ~440 m

energy of 1.5 – 2.5 (3) GeV

Prospects at the STCF

Data samples with 1 ab^{-1} integral luminosity

	STCF					Belle II		
Data Set	process	σ/nb	N	ST eff./%	ST N	σ/nb	N	Tag N
J/ψ	–	–	1.0×10^{12}	–	–	–	–	–
$\psi(2S)$	–	–	3.0×10^{11}	–	–	–	–	–
D^0	$D^0\bar{D}^0(3.77)$	~ 3.6	3.6×10^{9}	10.8	0.78×10^{9}	–	1.4×10^{9}	–
D^+	$D^+D^-(3.77)$	~ 2.8	2.8×10^{9}	9.4	0.53×10^{9}	–	7.7×10^{8}	–
D_s	$D_sD_s^*(4.18)$	~ 0.9	0.9×10^{9}	6.0	0.11×10^{9}	–	2.5×10^{8}	–
τ^+	$\tau^+\tau^-(3.68)$	~ 2.4	2.4×10^{9}	–	–	0.9	0.9×10^{9}	–
	$\tau^+\tau^-(4.25)$	~ 3.6	3.5×10^{9}	–	–	–	–	–
Λ_c	$\Lambda_c\Lambda_c(4.64)$	~ 0.6	5.5×10^{8}	5.0	0.55×10^{8}	–	1.6×10^{8}	$3.6\times10^{4*}$

The luminosity is 1.0 ab^{-1}. * process $e^+e^- \to D^{(*)-}\bar{p}\pi^+\Lambda_c^+$.

- Belle-II (50/ab) has 50~100 times more statistics
- STCF is expected to have higher detection efficiency
- STCF has low backgrounds for productions at threshold

CKM unitarity triangle

Runs	Collected / Expected integrated luminosity	Year attained	γ/ϕ_3 sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	8°
LHCb Run-2 [13 TeV]	5 fb^{-1}	2018	4°
Belle II Run	50 ab^{-1}	2025	1.5°
LHCb upgrade I [14 TeV]	50 fb^{-1}	2030	< 1°
LHCb upgrade II [14 TeV]	300 fb^{-1}	(>)2035	< 0.4°

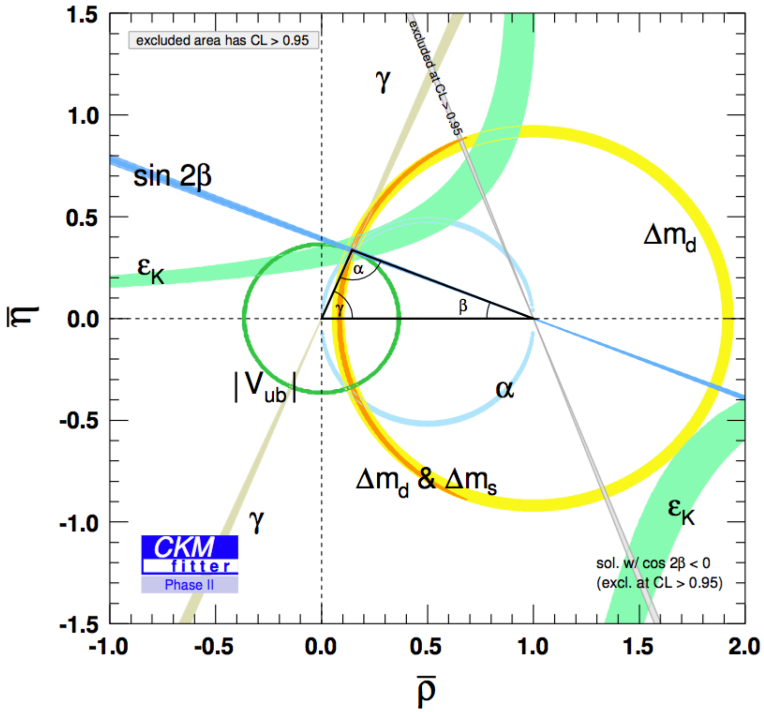
BESIII 20/fb: $\sigma(\gamma) \sim 0.4^o$

STCF is needed!

- ADS method: use *D* doubly Cabibbo-suppressed decays, e.g. $D^0 \rightarrow K^+\pi^-$
  - With 1 ab^{-1} @ STCF : $\sigma(\cos\delta_{K\pi}) \sim 0.007$; $\sigma(\delta_{K\pi}) \sim 2^o$ ➔ $\sigma(\gamma) < 0.5^o$
- GGSZ method: use Dalitz plot analysis of 3-body D^0 decays, e.g. $K_s \pi^+ \pi^-$ high statistics; need precise Dalitz model
  - STCF reduces the contribution of *D* Dalitz model to a level of $\sim 0.1^o$, since expected precision from future HL-LHCb projects would be $<0.4^o$.
- Cross checks among different methods and modes are crucial to test their consistency and searching for new physics

Scenario beyond 2035

STCF will provide complementary information on the strong phase and allow detailed comparisons in different models



- 300 /fb for LHCb
- 3000 /ab for CMS/ATLAS
- 50 /ab for Belle II
- 20 /fb @ 3773MeV for BESIII

Decay mode	Quantity of interest
$D \to K^0_S \pi^+\pi^-$	c_i and s_i
$D \to K^0_S K^+K^-$	c_i and s_i
$D \to K^\pm\pi^\mp\pi^+\pi^-$	R, δ
$D \to K^+K^-\pi^+\pi^-$	c_i and s_i
$D \to \pi^+\pi^-\pi^+\pi^-$	F_+ or c_i and s_i
$D \to K^\pm\pi^\mp\pi^0$	R, δ
$D \to K^0_S K^\pm\pi^\mp$	R, δ
$D \to \pi^+\pi^-\pi^0$	F_+
$D \to K^0_S \pi^+\pi^-\pi^0$	F_+, c_i and s_i
$D \to K^+K^-\pi^0$	F_+
$D \to K^\pm\pi^\mp$	δ

Possible **New** Charm physics at LHCb

Opportunities

Semi-leptonic (SL) decays of charmed hadron: with neutrino

- semileptonic charm hadron decays differential rate

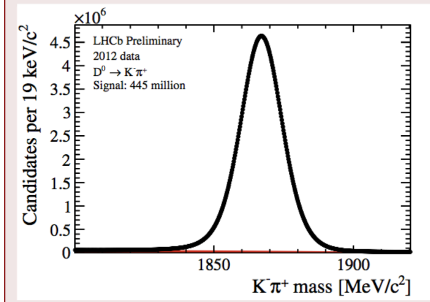
$$\frac{d\Gamma(X_c \to h\ell\nu)}{dq^2} = (\text{Constants}) \cdot |V_{cy}|^2 \cdot F[\text{form factors}(q^2, m_\ell)], \quad y = d, s$$

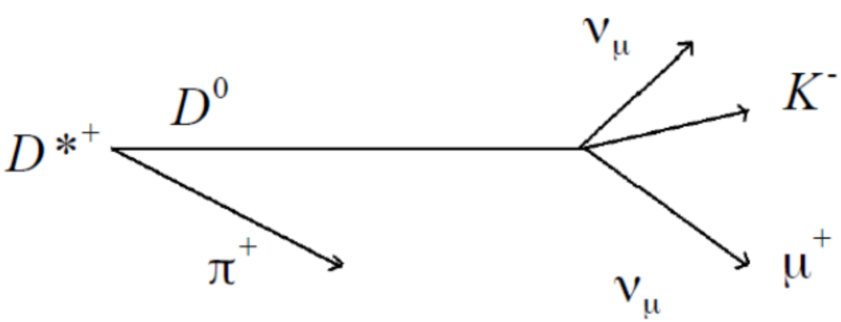
$$\frac{d\Gamma(D \to P\ell\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} \cdot |V_{cy}|^2 \cdot \left|f_{DP}^{+}(q^2)\right|^2 \cdot p^{*3}, \quad y = d, s$$

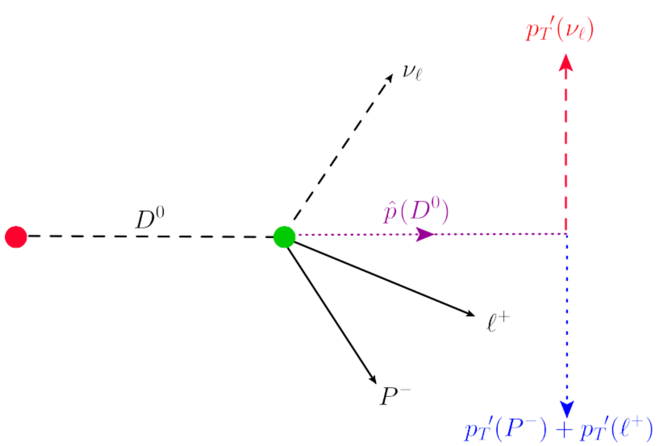
- experimental measurements can:
  - measure $|V_{cs}|$, $|V_{cd}|$ and/or form factors
  - measure D^0 mixing and CPV
  - test Lepton Flavour Universality on charm decays

LHCb is a charm factory

- 1.4 billion charm hadrons reconstructed in 2010-2015 (LHCb-CONF-2016-005)
- higher efficiency since 2015





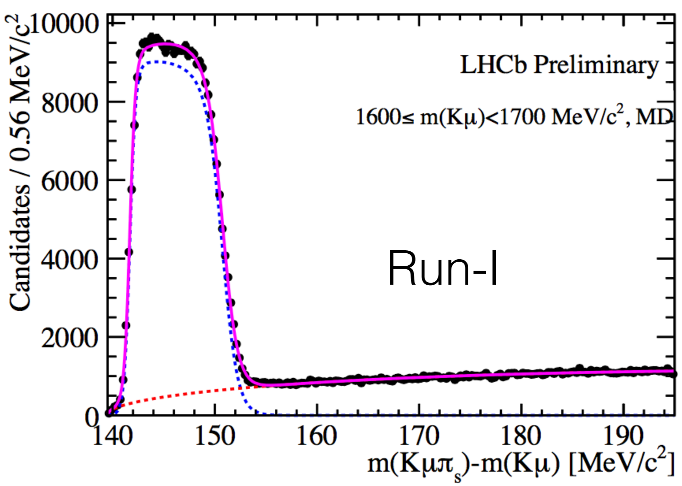


Neutrino reconstruction using *D* meson flight direction

Ongoing charm SL analyses at LHCb

Many ongoing LHCb charmed-meson SL analyses are using promote production $D^{*+} \to D^0\pi^+$

- Pros: high production rate,…
- Cons:
  - ✓ hard to well control signal shape and non-trivial background treatment in the fit
  - ✓ optimal only for the neutral D meson



$|V_{cd}|/|V_{cs}|$ with world-leading precision

- measure $\frac{|V_{cd}|^2}{|V_{cs}|^2}$ using $\frac{\mathcal{B}(D^0 \to \pi^-\mu^+\nu)}{\mathcal{B}(D^0 \to K^-\mu^+\nu)}$

Mixing/*CPV* measurements on semileptonic *D* decays

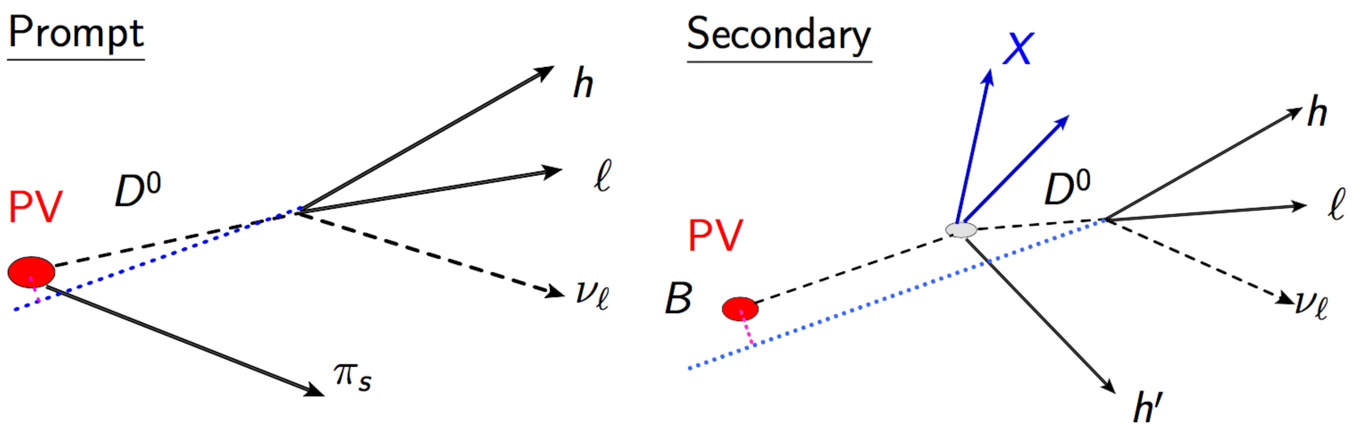
- measure $\frac{N(D^0 \to K^+\mu^-\nu_\mu)}{N(D^0 \to K^-\mu^+\bar{\nu}_\mu)}$

Test lepton universality in *D* meson decays

- measure $\frac{\mathcal{B}(D \to h\mu\nu)}{\mathcal{B}(D \to he\nu)}$

- SL decays of many other charmed baryons can be studied in a similar fashion: $\Sigma_c^0 \to \Lambda_c^+\pi^-$, $\Xi_c(2645) \to \Xi_c\pi$, Ω_c, Ξ_{cc} etc.

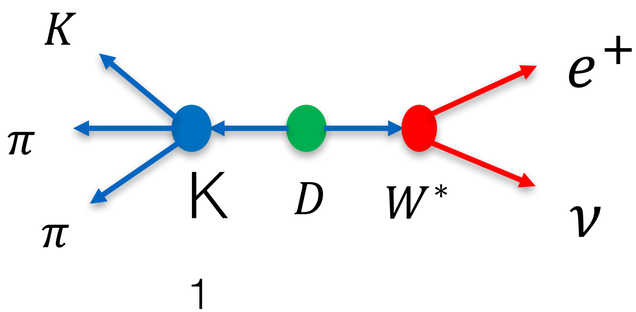
Through b-hadron decays

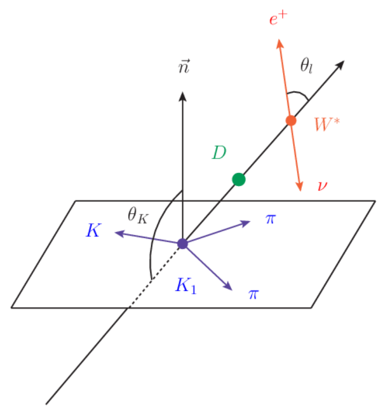


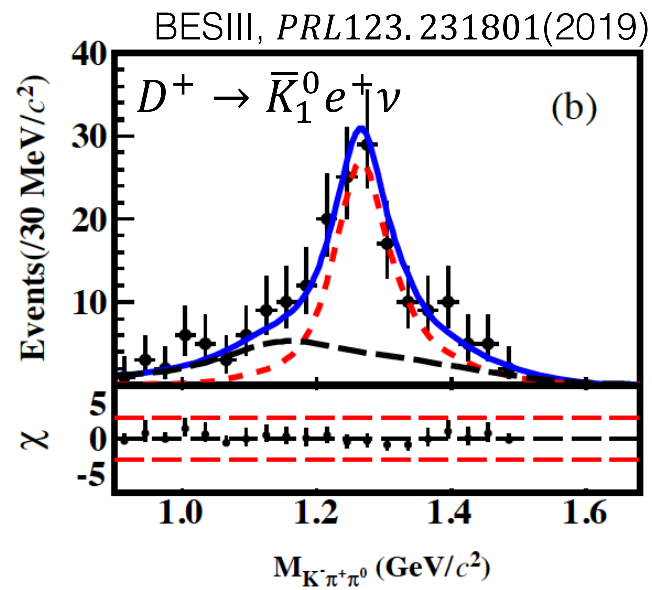
- RUN I+II: keep increasing statistics
- We can study charm SL decays using b-hadron decays, where we expect much lower background level
- More importantly, we will be able to extend to all the charmed hadrons, including **the charged D⁺/Ds⁺ meson** and many other charged baryons: Λ_c, Ξ_c, Ω_c

D^0		D^+		D_s	
$D^0 \to \pi\mu\nu$	$(\mathcal{B} = 0.238 \pm 0.024\%)$	$D^+ \to K\pi\mu\nu$	$(\mathcal{B} = 3.9 \pm 0.4\%)$	$D_s^+ \to \phi\mu\nu$	$(\mathcal{B} =\sim 2\%)$
$D^0 \to K\mu\nu$	$(\mathcal{B} = 3.3 \pm 0.13\%)$	$D^+ \to K^0\mu\nu$	$(\mathcal{B} = 9.3 \pm 0.7\%)$	$D_s^+ \to K^0\mu\nu$	$(\mathcal{B} =\sim 0.3\%)$
$D^0 \to K^*(892)^-\mu\nu$	$(\mathcal{B} = 1.92 \pm 0.25\%)$	$D^+ \to K^{*0}\mu\nu$	$(\mathcal{B} = 5.3 \pm 0.15\%)$	$D_s^+ \to \eta^{(\prime)}\mu\nu$	$(\mathcal{B} =\sim 3\%)$
		$D^+ \to \eta\mu\nu$	$(\mathcal{B} =\sim 1\%)$		

Semileptonic decay of $D \to K\pi\pi\, l^+\nu$







ratio of up-down asymmetries

33

$$\mathcal{A}'_{\rm UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_K}}{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_l}}$$

$D \to K_1(\to K\pi\pi)e^+\nu$

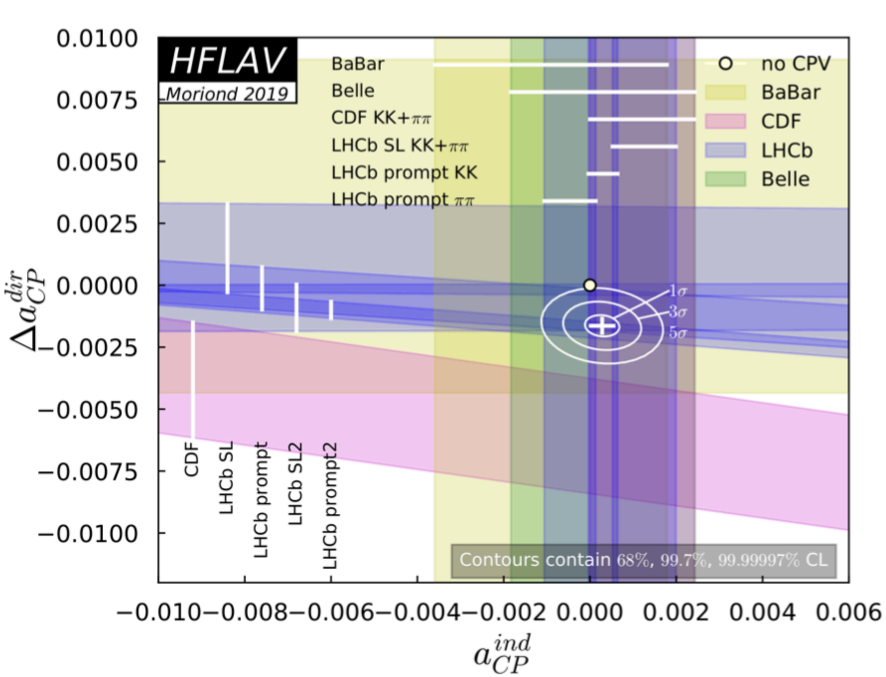
$$\mathcal{A}'_{\rm UD} = \frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}.$$

$$\mathcal{A}_{UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}} = \lambda_\gamma \frac{3}{4}\frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

$B \to K_1(\to K\pi\pi)\gamma$

- LHCb can measure mounic mode: $D^0 \to K_1^- \mu^+\nu$, $K_1^- \to K^-\pi^+\pi^-$
- Provides model-independent input to extract photon polarization in B → $K_1\gamma \to$ (Kππ)γ
  [Wei Wang et al, arXiv:1909.13083]

Charm CPV

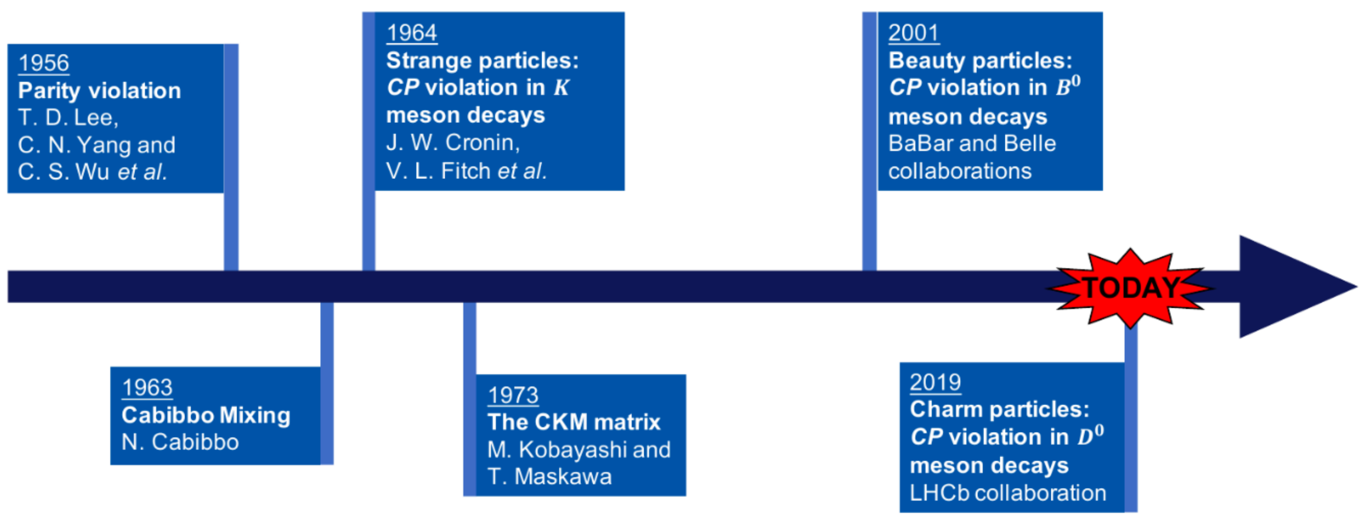


- Updated HFLAV fit

$$\Delta a_{CP}^{dir} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$\Delta a_{CP}^{ind} = (2.8 \pm 2.6) \times 10^{-4}$$

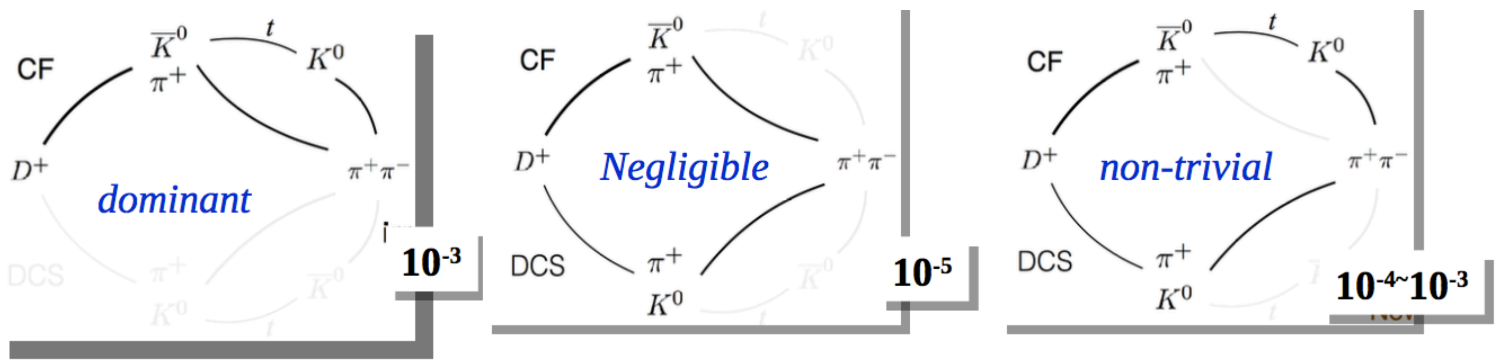
- Compatible with SM
  - Most predictions on 10^{-4} - 10^{-3} level
- Observation in other channels could provide a confirmation of this effect



Another Charm CPV source

- New CP-violation effect, in order up to 10^{-3}, in charm decays into neutral kaons was proposed [Phys. Rev. Lett. 119, 181802 (2017)].
- This effect emerges from interference between CF and DCS amplitudes with the mixing of final-state kaons by Fu-Sheng et al
- Signal channels: $D^+ \to K^0_S \pi^+$, $D_s^+ \to K^0_S K^+$
- Control channels: $D^+ \to K^- \pi^+ \pi^+$, $D_s^+ \to K^+ K^- \pi^+$

$$\Delta A_{CP} = A_{CP}(D_s^+ \to K_S K^+) - A_{CP}(D^+ \to K_S \pi^+)) = [(A_{raw}(D_s^+ \to K_S K^+) - A_{raw}(D_s^+ \to K^+ K^- \pi^-))- (A_{raw}(D^+ \to K_S \pi^+) - A_{raw}(D^+ \to K^- \pi^+ \pi^+))]$$



- Sensitivity expectation with Run II data (prospect with the full Run II data):

$$D^+ \to K^0_S \pi^+ : \ \delta A^{raw}_{CP} = 0.03\ \%$$

$$D_s^+ \to K^0_S K^+ : \ \delta A^{raw}_{CP} = 0.07\ \%$$

Summary and Outlook

- Quantum correlation of $D^0\underline{D}^0$ pairs produced at threshold is a unique technique to access information of strong-phase parameters in D hadronic decays, which provide the key inputs in ranges of γ measurements, $D^0\underline{D}^0$ mixing and CPV studies.
- A range of quantum-correlated studies are undergoing at BESIII:
  - ✓ Studies in $D \to K_{S/L}\pi^+\pi^-$ show excellent preliminary results. These results will have important impacts over a wide range studies in flavour physics.
  - ✓ Current BESIII $\psi(3770)$ data will constrain the strong phase uncertainty of γ to be ~1°
- The future 20 fb^{-1} $\psi(3770)$ data and STCF will be crucial to improve the precision of γ measurement to the level of 0.1°
- Some ideas, like studying semi-leptonic decays and charm CPV searches, at LHCb are discussed

Thank you!

谢谢！

Strong-phase parameters in $D \rightarrow K_{S/L}^0\pi^+\pi^-$ at $\psi(3770)$

- ❑ $\psi(3770)$ is a spin -1 state and therefore the amplitude of $\psi(3770) \rightarrow D^0D^0$:

$$(|D^0\rangle|\overline{D^0}\rangle - |\overline{D^0}\rangle|D^0\rangle)/\sqrt{2}$$

[anti-symmetric wave function]

✓ For CP-tagged $K_S^0\pi^+\pi^-$, its amplitude is expressed by:

$$f_{CP\pm} = \frac{1}{\sqrt{2}}[f_D(m_+^2, m_-^2) \pm f_D(m_-^2, m_+^2)]$$

The expected yields in Dalitz Plot (DP) bins:

$$M_i^\pm = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_iK_{-i}} + K_{-i})$$

✓ Similarly, for $K_S^0\pi^+\pi^-$ *vs.* $K_S^0\pi^+\pi^-$, the expected yields in DP bins is:

$$M_{ij} = h_{\mathrm{corr}}[K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}(c_ic_j + s_is_j)]$$

c_i&s_i are obtained by studying DT events: $K_S^0\pi^+\pi^-$ *vs. CP*-tag & $K_S^0\pi^+\pi^-$ *vs.* $K_S^0\pi^+\pi^-$ *tags*

Here $h_{cp\pm}$ and h_{corr} are the normalization factors related to yields of single tags and the number of neutral D meson pairs.

From above equations, the precision on $\boldsymbol{s_i}$ *is constrained by the mode* $K_S^0\pi^+\pi^-$ *.vs.* $K_S^0\pi^+\pi^-$.

Measurements of strong-phase parameters (c_i, s_i) at BESIII

- To improve the precision of measuring $\boldsymbol{s_i}$, the $K_S^0\pi^+\pi^-$ *vs.* $K_L^0\pi^+\pi^-$ events are added, which is dependent on (c_i, s_i, c_i' and s_i'). Due to similarities between the decays, weak model assumptions[1,2,3] can provide a constraint on the differences between c_i and c_i', s_i and s_i'.

$K_S^0\pi^+\pi^-\ vs.\ K_L^0\pi^+\pi^-$ $$M'_{ij} = h'_{\mathrm{corr}}\left[K_i K'_{-j} + K_{-i}K'_j + 2\sqrt{K_i K'_{-j} K_{-i} K'_j}(c_i c'_j + s_i s'_j)\right]$$

$CP\ tag\ \ vs.\ K_L^0\pi^+\pi^-$ $$M'^{\pm}_i = h'_{CP\pm}(K'_i \mp 2c'_i\sqrt{K'_i K'_{-i}} + K'_{-i})$$

- The c_i' and s_i' parameters are useful for Belle-II experiment if they use the decay mode B→DK, with D→$K_L^0\pi^+\pi^-$ to measure γ.

- The strong-phase parameters are obtained by minimizing the log-likelihood function constructed by using the observed and expected yields.

[1] R. A. Briere et al. (CLEO Collaboration), Phys. Rev. D 80, 032002 (2009).
[2] J. Libby et al. (CLEO Collaboration), Phys. Rev. D 82, 112006 (2010).
[3] I.I.Bigi and H. Yamamoto, Phys. Lett. B 349, 363 (1995).