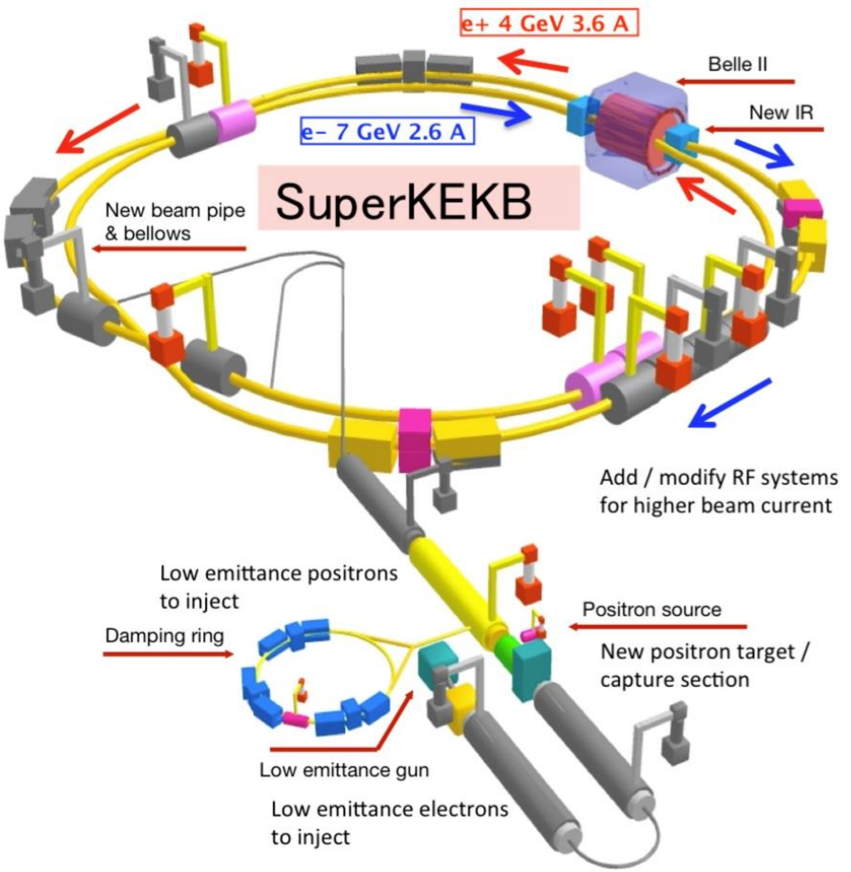
Prospect of charm physics at Belle II

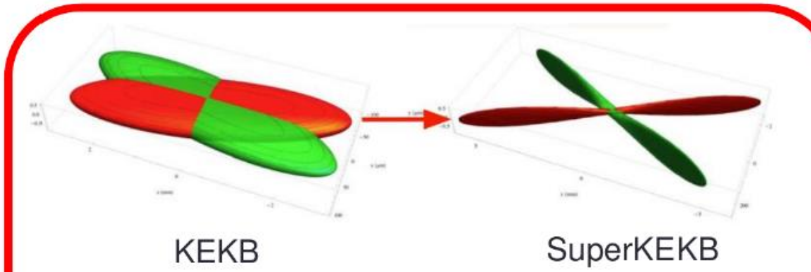
鄢文标 (中国科学技术大学)

- Introduction: SuperKEKB and Belle II
- Introduction: D^0-$\bar{D}^0$ mixing and CP violation
- $D^0/\bar{D}^0$ tag and performance with D^0 at Belle II
- D^0-$\bar{D}^0$ mixing and CP violation at Belle II
- Time-integrated CP asymmetry A_{CP} at Belle II

"Joint Workshop on Charmed Hadron Decays @ BESIII, Belle, LHCb"，2019.11.02，临汾

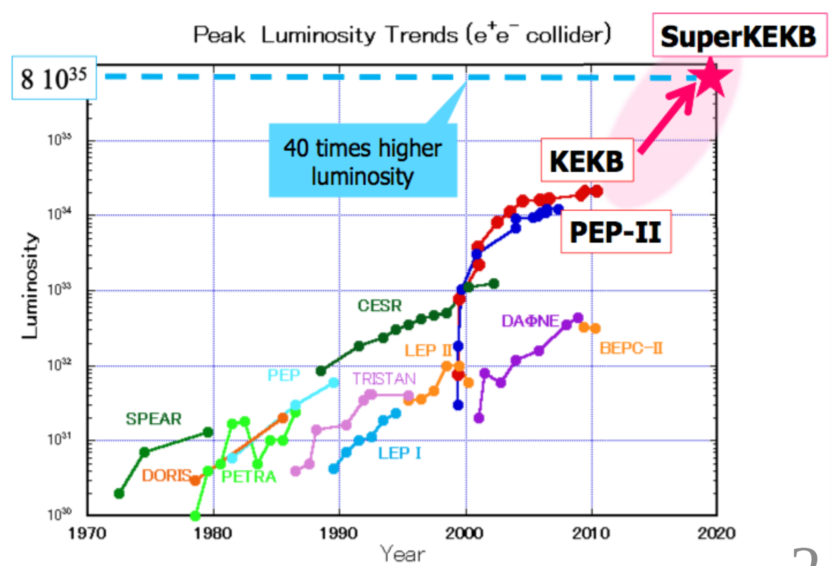
The SuperKEKB accelerator



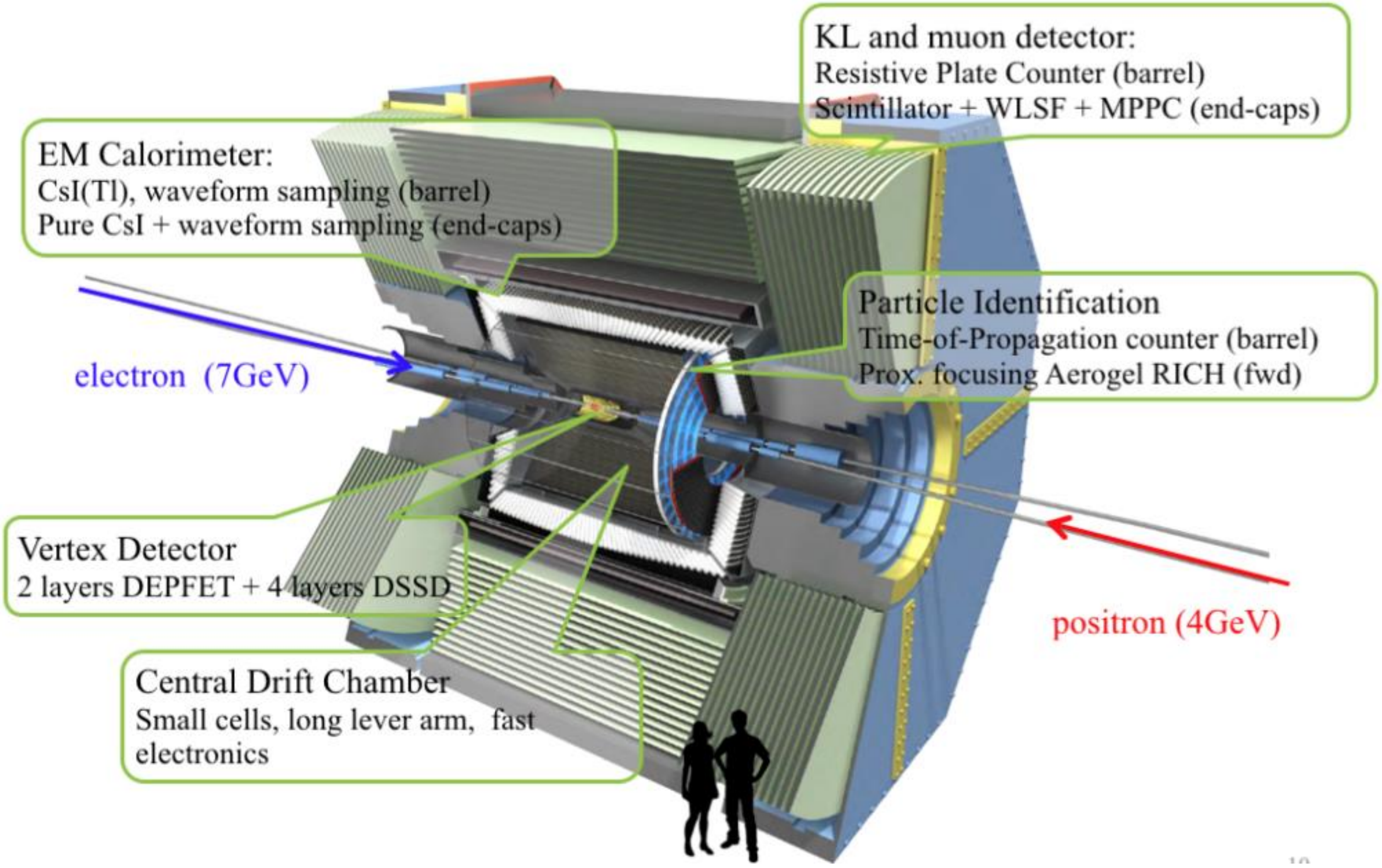


“nano-beam” scheme

Beam squeezing: x20 smaller at IR



Belle II detector



- **Phase III @ Belle II: Physics run already started in 2019**

Belle II data

Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment

F. Abudinén,[39] I. Adachi,[18,16] P. Ahlburg,[99] H. Aihara,[116] N. Akopov,[122] A. Aloisio,[88,32] L. Andricek,[56] N. Anh Ky,[29] D. M. Asner,[2] H. Atmacan,[101] T. Aushev,[58] V. Aushev,[79] K. Azmi,[107] V. Babu,[8] S. Baehr,[43] S. Bahinipati,[21] A. M. Bakich,[115] P. Bambade,[49] Sw. Banerjee,[106] S. Bansal,[71] V. Bansal,[70] M. Barrett,[18] J. Baudot,[97] A. Beaulieu,[118] J. Becker,[43] P. K. Behera,[23] J. V. Bennett,[110] E. Bernieri,[37] F. U. Bernlochner,[43] M. Bertemes,[26] M. Bessner,[103] S. Bettarini,[92,35] V. Bhardwaj,[20] F. Bianchi,[94,38] T. Bilka,[5] S. Bilokin,[97] D. Biswas,[106] G. Bonvicini,[120] A. Bozek,[64] M. Bračko,[108,78] P. Branchini,[37] N. Braun,[43] T. E. Browder,[103] A. Budano,[37] S. Bussino,[93,37] M. Campajola,[88,32] L. Cao,[43] G. Casarosa,[92,35] C. Cecchi,[91,34] D. Červenkov,[5] M.-C. Chang,[12] P. Chang,[63] R. Cheaib,[100] V. Chekelian,[55] Y. Q. Chen,[112] Y.-T. Chen,[63] B. G. Cheon,[17] K. Chilikin,[50] H.-E. Cho,[17] K. Cho,[45] S. Choudhury,[22] D. Cinabro,[120] L. Corona,[92,35] L. M. Cremaldi,[110] S. Cunliffe,[8] T. Czank,[117] F. Dattola,[8] E. De La Cruz-Burelo,[4] G. De Nardo,[88,32] M. De Nuccio,[8] G. De Pietro,[93,37] R. de Sangro,[31] M. Destefanis,[94,38] S. Dey,[82] A. De Yta-Hernandez,[4] F. Di Capua,[88,32] S. Di Carlo,[49] J. Dingfelder,[99] Z. Doležal,[5] I. Domínguez Jiménez,[87] T. V. Dong,[13] K. Dort,[42] S. Dubey,[103] S. Duell,[99] S. Eidelman,[3,66,50] M. Eliachevitch,[43] T. Ferber,[8] D. Ferlewicz,[109] G. Finocchiaro,[31] S. Fiore,[36] A. Fodor,[57] F. Forti,[92,35] A. Frey,[14] B. G. Fulsom,[70] M. Gabriel,[55] E. Ganiev,[95,39] M. Garcia-Hernandez,[4] A. Garmash,[3,66] V. Gaur,[119] A. Gaz,[61] U. Gebauer,[14] A. Gellrich,[8] J. Gemmler,[43] T. Geßler,[42] R. Giordano,[88,32] A. Giri,[22] B. Gobbo,[39] R. Godang,[113] P. Goldenzweig,[43] B. Golob,[105,78] P. Gomis,[30] P. Grace,[98] W. Gradl,[41] E. Graziani,[37] D. Greenwald,[81] C. Hadjivasiliou,[70] S. Halder,[80] K. Hara,[18,16] T. Hara,[18,16] K. Hayasaka,[65] H. Hayashii,[62] C. Hearty,[100,28] I. Heredia de la Cruz,[4,7] M. Hernández Villanueva,[110] A. Hershenhorn,[100] T. Higuchi,[117] H. Hirata,[60] M. Hoek,[41] S. Hollitt,[98] T. Hotta,[69] C.-L. Hsu,[115] Y. Hu,[27] K. Huang,[63] T. Iijima,[60,61] K. Inami,[60] G. Inguglia,[26] J. Irakkathil Jabbar,[43] A. Ishikawa,[18,16] R. Itoh,[18,16] M. Iwasaki,[68] Y. Iwasaki,[18] S. Iwata,[86] P. Jackson,[98] W. W. Jacobs,[24] D. E. Jaffe,[2] S. Jia,[1] Y. Jin,[39] C. Joo,[117] J. Kahn,[43] H. Kakuno,[86] G. Karyan,[122] Y. Kato,[61] T. Kawasaki,[44] H. Kichimi,[18] C. Kiesling,[55] B. H. Kim,[75] C.-H. Kim,[17] D. Y. Kim,[77] Y. K. Kim,[123] T. D. Kimmel,[119] K. Kinoshita,[101] C. Kleinwort,[8] B. Knysh,[49] P. Kodyš,[5] T. Koga,[18] I. Komarov,[8] T. Konno,[44] S. Korpar,[108,78] N. Kovalchuk,[8] T. M. G. Kraetzschmar,[55] P. Križan,[105,78] R. Kroeger,[110] J. F. Krohn,[109] P. Krokovny,[3,66] W. Kuehn,[42] T. Kuhr,[52] M. Kumar,[54] R. 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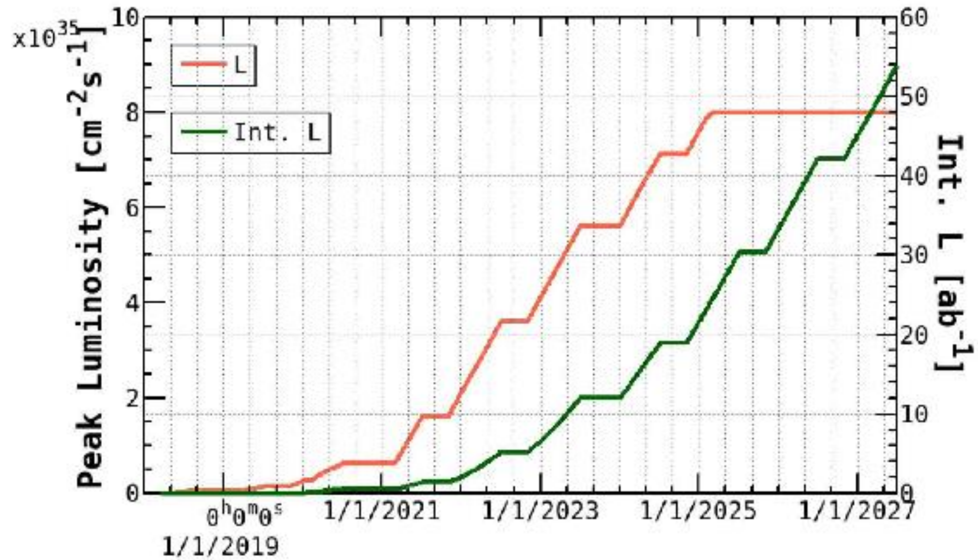
(Belle II Collaboration)



- **Belle II submitted first paper with phase II data**
- **Belle II plan to have 50 ab^{-1} data**

Charm meson data

Experiment	Machine	C.M $\sqrt{s}$	Luminosity	charm sample	efficiency
CLEOc	CESR (e^+e^-)	3.77 GeV	0.8 fb^{-1}	$2.9 \times 10^6 (D^0)$ $2.3 \times 10^6 (D^+)$	~10-30%
		4.17 GeV	0.6 fb^{-1}	$0.6 \times 10^6 (D_s^+)$	
BESIII	BEPC-II (e^+e^-)	3.77 GeV	2.9 fb^{-1}	$10.5 \times 10^6 (D^0)$ $8.4 \times 10^6 (D^+)$	
		4.18 GeV	3.0 fb^{-1}	$3 \times 10^6 (D_s^+)$	
		4.6 GeV	0.6 fb^{-1}	$1 \times 10^5 (\Lambda_c^+)$	
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	$1.3 \times 10^9 (D^0)$ $7.7 \times 10^8 (D^+)$ $2.5 \times 10^8 (D_s^+)$ $1.5 \times 10^8 (\Lambda_c^+)$	~5-10%
	PEP-II (e^+e^-)	10.58 GeV	0.5 ab^{-1}	$6.5 \times 10^8 (D^0)$ $3.8 \times 10^8 (D^+)$ $1.2 \times 10^8 (D_s^+)$ $0.7 \times 10^8 (\Lambda_c^+)$	
	Tevatron $(p\bar{p})$	1.96 TeV	9.6 fb^{-1}	1.3×10^{11}	<0.5%
LHCb	LHC (pp)	7 TeV 8 TeV	1.0 fb^{-1} 2.0 fb^{-1}	5.0×10^{12}	

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

D^0 and $\bar{D}^0$ are flavor eigenstates, propagate and decays according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

D^0 and $\bar{D}^0$ are combinations of mass eigenstates

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

The mass eigenstates develop in time as

$$\begin{aligned} |D_{1,2}(t)\rangle &= e_{1,2}(t)|D_{1,2}(0)\rangle \\ e_{1,2}(t) &\equiv e^{\left[-i\left(M_{1,2}-\frac{i}{2}\Gamma_{1,2}\right)t\right]} \end{aligned}$$

Two parameters describe D^0 and $\bar{D}^0$ mixing

$$x \equiv \frac{\Delta M}{\Gamma} \qquad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma} \qquad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

If either x or y are not zero, mixing occurs

$$|\langle\bar{D}^0|D^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[cosh(y\Gamma t) - cos(x\Gamma t)\right]$$

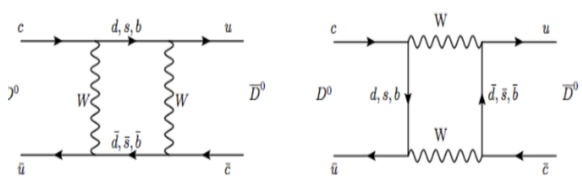
$$|\langle D^0|\bar{D}^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[cosh(y\Gamma t) - cos(x\Gamma t)\right]$$

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

- D^0-$\bar{D}^0$ mixing: only up-type quark meson system

  $K^0 \Leftrightarrow \bar{K}^0$, $B_d^0 \Leftrightarrow \bar{B}_d^0$ and $B_s^0 \Leftrightarrow \bar{B}_s^0$

- In Standard model (SM) , D^0-$\bar{D}^0$ mixing is
  - ✓ GIM & CKM
- The SM predicts: |x|, |y| ~*O*(1%)



short distance (<0.1%)

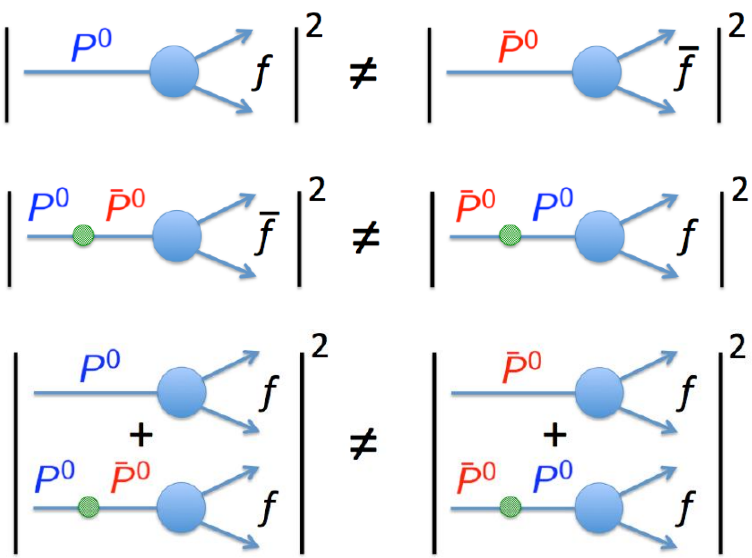
long distance (~1%)

- Precisely measured x and y
  - ✓ Test SM prediction
  - ✓ Sensitive to new physics

CP violation

- CP V @SM: phase in CKM
  - ✓ @ charm sector: ~O(10^{-3})
  - ✓ ~1% exp. sensitivity to observe NP
- Time integrated CP asymmetry A_{CP}
  - ✓ Decay @ D^+ & D_s^+: direct CPV
  - ✓ Decay @ D^0: direct and indirect CPV combined

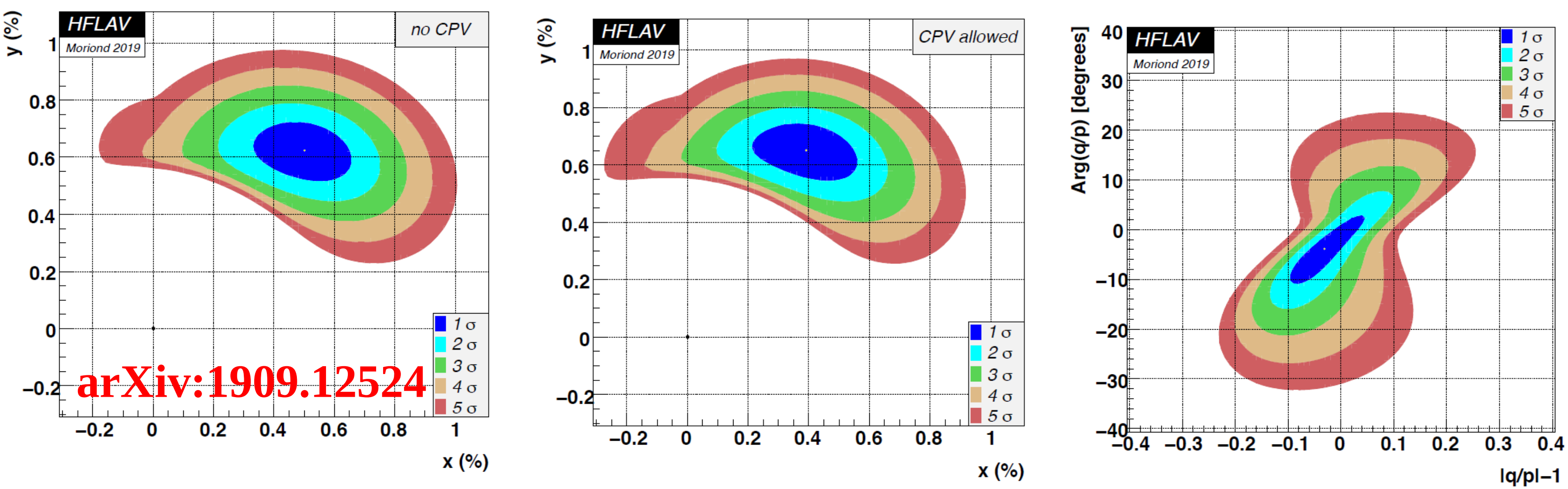
$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$



- **Direct** CPV, $|\bar{A}_{\bar{f}}/A_f| \neq 1$
- CPV in mixing, $|q/p| \neq 1$
- CPV in interference, $\mathrm{Arg}(q/p)=\phi\neq 0$

Status of D^0-$\bar{D}^0$ mixing and CPV

- D^0-$\bar{D}^0$ mixing is well established, x and y are small than < 10^{-2}
  - ✓ If p = q, no CP violation
  - ✓ If $|q/p| \neq 1$, CP violation (CPV) occurs, $|q/p|$ and $Arg(q/p) = \phi$

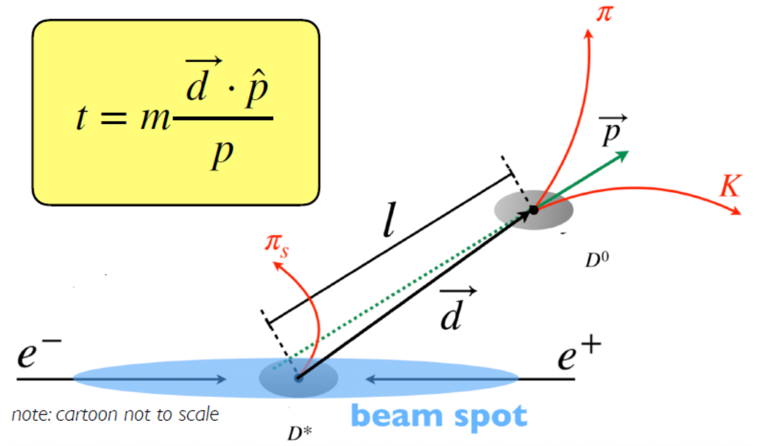


- No evidence for CPV from D^0-$\bar{D}^0$ mixing $|q/p| \neq 1$ and $\phi \neq 0$.

Tag D^0 and $\bar{D}^0$

- Decay $e^+e^- \longrightarrow c\bar{c} \longrightarrow D^* + X$
  - ✓ $D^0/\bar{D}^0$ tagged by π_s of D^*

$$D^{*+}(c\bar{d}) \rightarrow D^0(c\bar{u})\pi_s^+$$
$$D^{*-}(\bar{c}d) \rightarrow \bar{D}^0(\bar{c}u)\pi_s^-$$

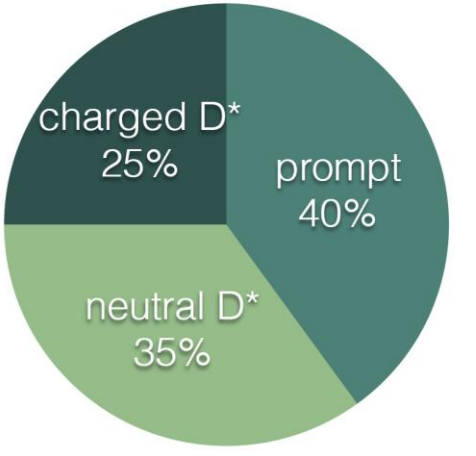


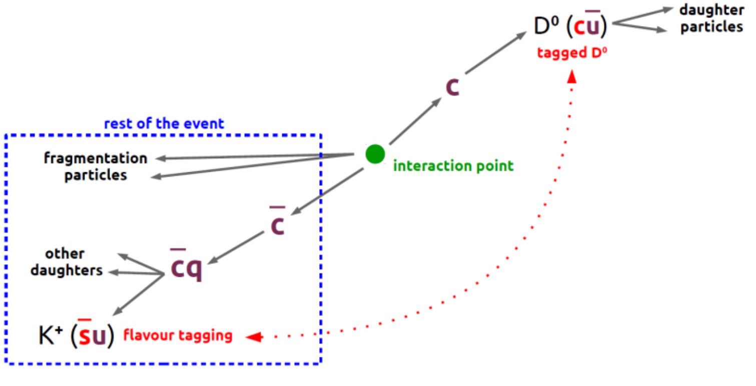
  - ✓ select $D^0/\bar{D}^0$ from $c\bar{c}$ events by momentum of D^0 at CMS > (about) 2.5GeV/c
  - ✓ Determine $D^0/\bar{D}^0$ lifetime t and its
  - ✓ error σ_t with vertices and momentum
- Partial reconstruction: B^0-> D^{*+} l ν_l and D^{*+} -> $D^0\pi_s$s
  - ✓ High efficiency (~65%) and low mis-tagging rate
  - ✓ Absolute branching fraction
  - ✓ Low $D^0/\bar{D}^0$ yield ⇒ Belle II

Prompt $D^0/\bar{D}^0$ flavor tag

- **(New) ROE method: tag $D^0/\bar{D}^0$ from non-charged D* decay**
  - ✓ Events with one $K^{\pm}$
  - ✓ Flavor tagged by charge of kaon
  - ✓ Flavor mis-tagging due to $c\bar{c}s\bar{s}$ events
  - ✓ Irreducible background due to DCS decay
- **ROE method with higher mis-tagging rate and lower purity**
- **D* & ROE methods, almost double $D^0/\bar{D}^0$ sample**
- **A reduction of ~15% of σ_{stst} on A_{CP}**

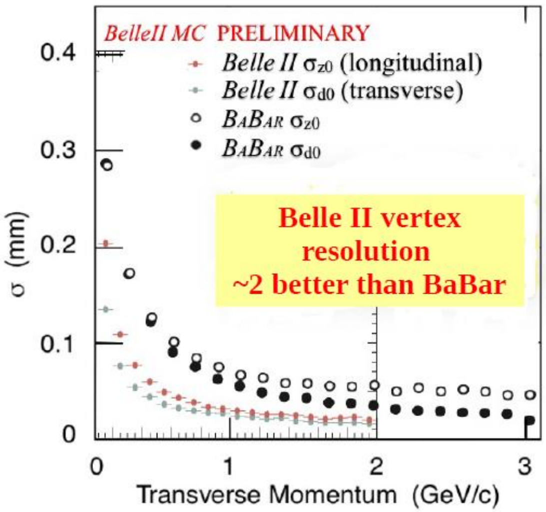
$D^0/\bar{D}^0$ mother in $c\bar{c}$ events

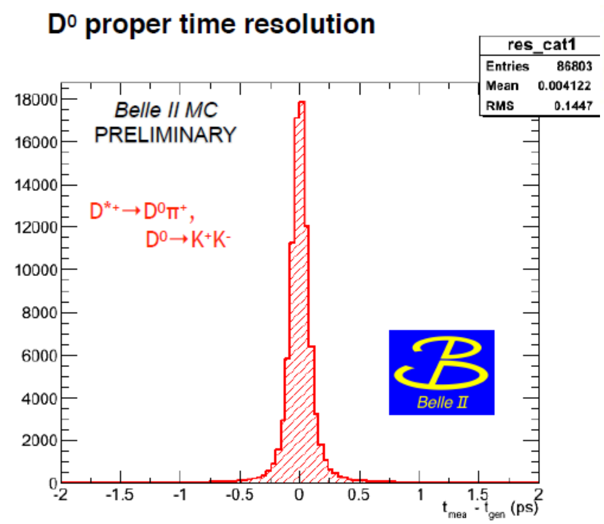


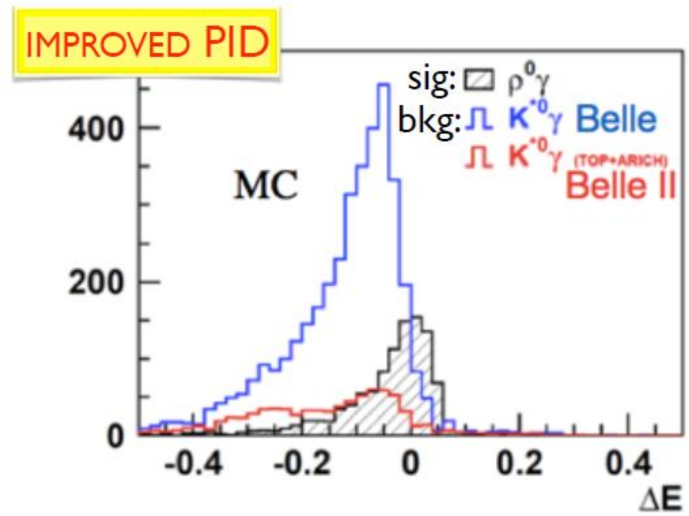


Flavor-tagging Method	Produced D^0 N_{D^0}	Mistagging ω	ϵ	Efficiency $Q = \epsilon\,(1-2\omega)^2$
D*	1	0.2%	80%	79.7%
ROE - criteria A	3	13.3%	26.7%	20.1%
ROE - criteria B	3	9.8%	16.8%	13.7%
ROE - criteria C	3	4.9%	15.9%	15.7%
partial B reconstruction	0.13	$< 1\%$	65%	$\sim 62\%$

Performance with D^0

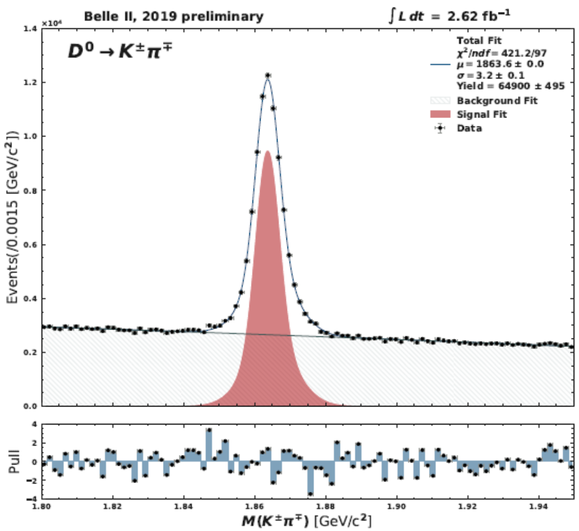


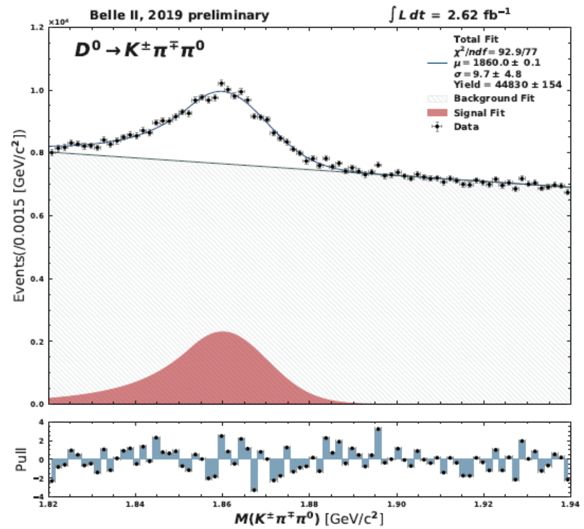


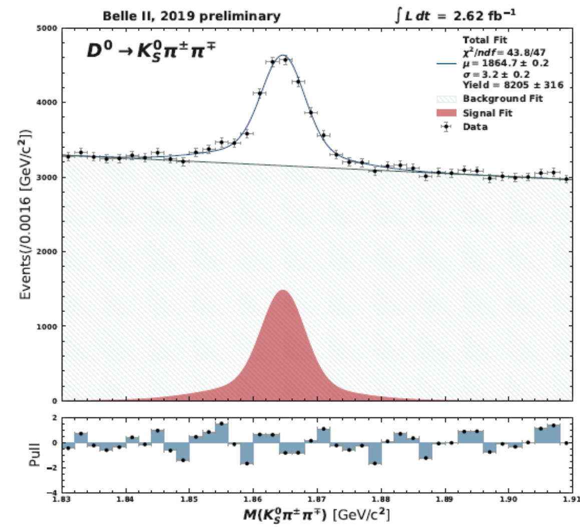


- **Belle II vertex resolution, ~2 better than BaBar**
- **Decay time resolution 0.14ps, ~2 better than Belle,**
- **Increased tracking volume in SVD & CDC ⇒ ~30% higher K_S efficiency**
- **Improved PID with better K/π separation relative to Belle**

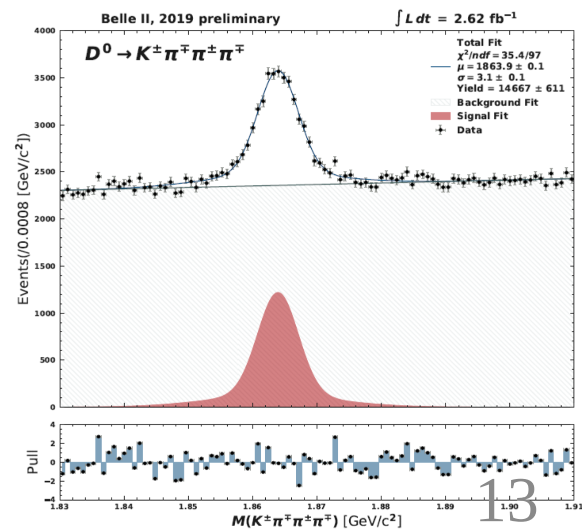
Charm from $e^+e^- \to c\bar{c}$







- Reconstructed D^0 with 2.62 fb^{-1} data
- Belle II is ready for charm physics



Prospects for charm at Belle II

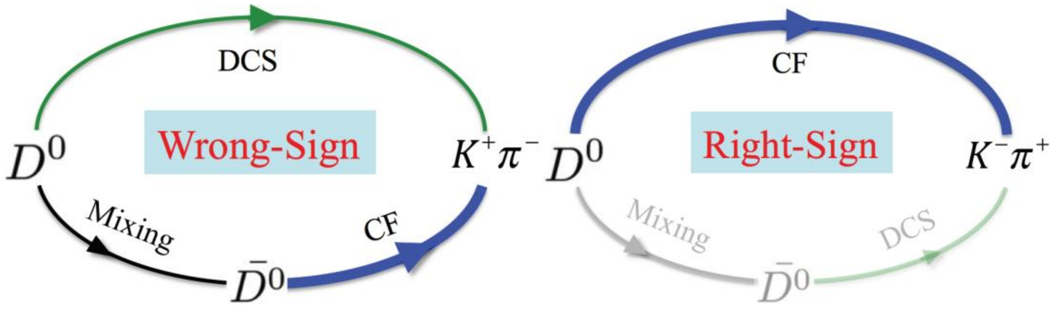
- **The following projections are extrapolated from Belle results**

$$\sigma_{\mathrm{Belle\ II}} = \sqrt{(\sigma^2_{\mathrm{stat}} + \sigma^2_{\mathrm{syst}}) \cdot (\mathcal{L}_{\mathrm{Belle}}/50\ \mathrm{ab}^{-1}) + \sigma^2_{\mathrm{irred}}}$$

- **Assumption: most of systematics scale with statistics**
- **Maybe (other) sources of systematics errors that do no scale with statistics, that show up in very high statistics samples.**
    - ✓ **Belle II will have high statistics control samples to keep them under control**
- **The detector improvements w.r.t. Belle will be helpful, but their effect is not included in these extrapolations unless Otherwise stated.**

Wrong-sign $D^0 \to K^+ \pi^-$

- **Time-depend ratios of WS to RS decay rates with CP conservation**

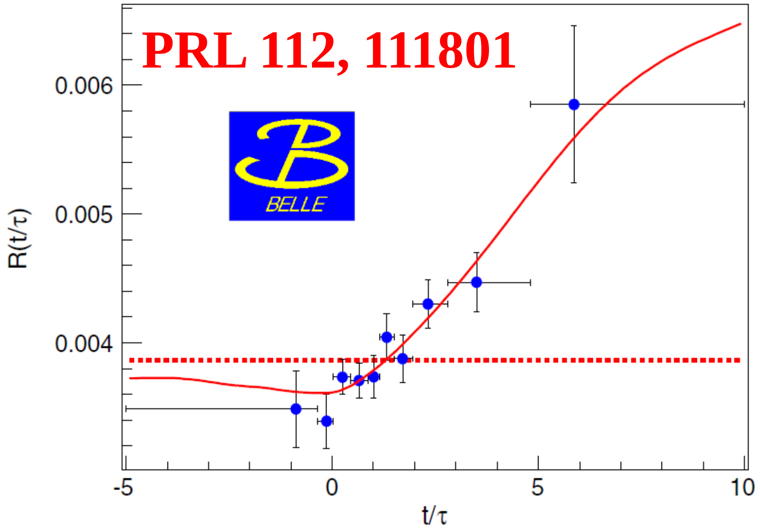


$$R(\tilde{t}/\tau) = \frac{\Gamma_{WS}(\tilde{t}/\tau)}{\Gamma_{RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\, y' \frac{\tilde{t}}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{\tilde{t}}{\tau}\right)^2$$

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

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

$\delta_{K\pi}$: relative strong phase



Test hypothesis (χ^2/DOF)	Parameters	Fit results (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (4.2/7)	R_D	3.53 ± 0.13	1	−0.865	+0.737
	y'	4.6 ± 3.4		1	−0.948
	x'^2	0.09 ± 0.22			1
No mixing (33.5/9)	R_D	3.864 ± 0.059			

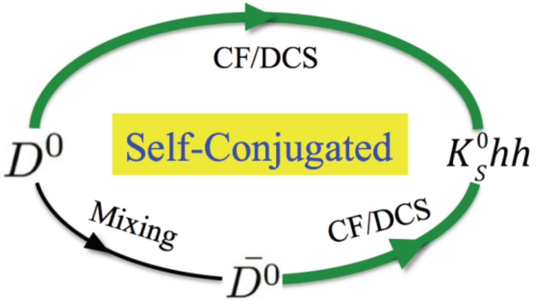
Wrong-sign $D^0 \to K^+ \pi^-$

		$0.976ab^{-1}$	$5\ ab^{-1}$	$20\ ab^{-1}$	$50\ ab^{-1}$
NO CPV	$\delta x'^2 (10^{-5})$	22	7.5	3.7	2.3
	$\delta y'(\%)$	0.34	0.11	0.056	0.035
CPV allowed	$\delta x'(\%)$		0.37	0.23	0.15
	$\delta y'(\%)$		0.26	0.17	0.10
	$\delta\|q/p\|$		0.197	0.089	0.051
	$\delta\phi(^o)$		15.5	9.2	5.7

- **About factor 8-10 better**

Self-conjugated D^0 -> $K_s\ \pi^+\ \pi^-$

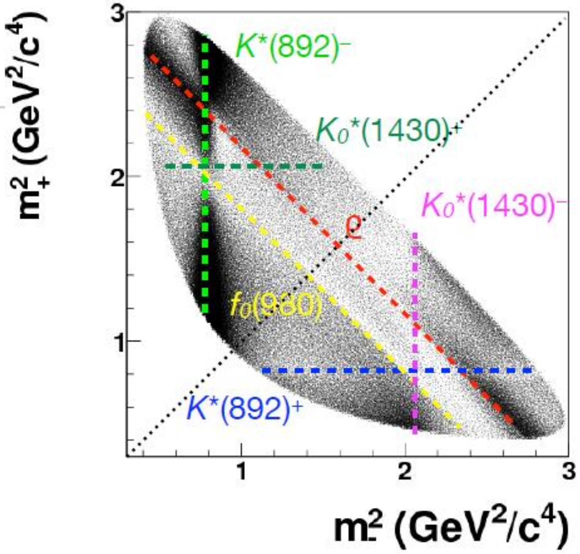
- **Time-depend Dalitz analysis allows a direct measurement of (x, y), |q/p| and Arg(q/p)= ϕ**

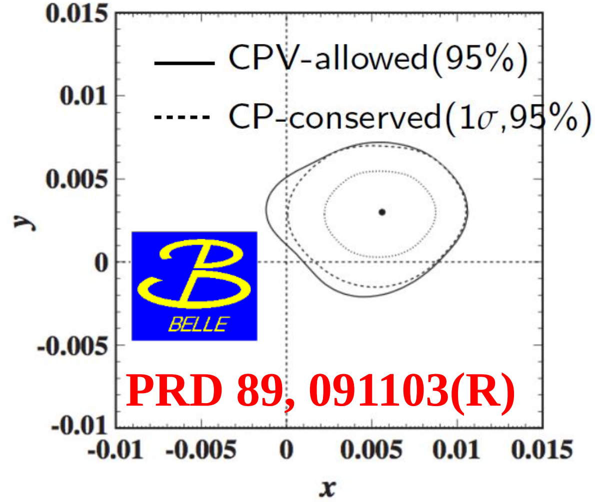


$$|\mathcal{M}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}[(|\mathcal{A}_f|^2 + |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cosh(y\Gamma t) + (|\mathcal{A}_f|^2 - |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cos(x\Gamma t)$$
$$+2\,\mathrm{Re}[\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f^*]\sinh(y\Gamma t) + 2\,\mathrm{Im}[\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f^*]\sin(x\Gamma t)]$$

- **Belle used 1.23×10^6 sample, rich physics process**

  - ✓ **RS: $K^{*-}\ \pi^+$**
  - ✓ **WS: $K^{*+}\ \pi$-**
  - ✓ **CP+: K_Sf_0**
  - ✓ **CP-: $K_S\rho$**

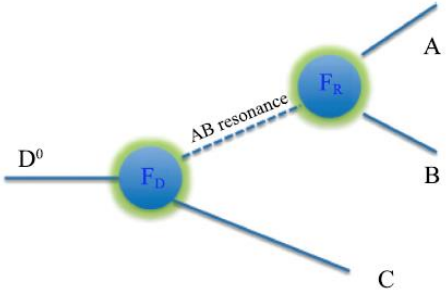




PRD 89, 091103(R)

Self-conjugated $D^0 \to K_s \pi^+ \pi^-$

- **Expected Belle II sensitivity**
  - ✓ A significantly improved σ_{stat}
  - ✓ Irreducable uncertainty is Dalitz model
  - ✓ (dominant) Dalitz model uncertainty
  - ✓ (promising) model independent approach

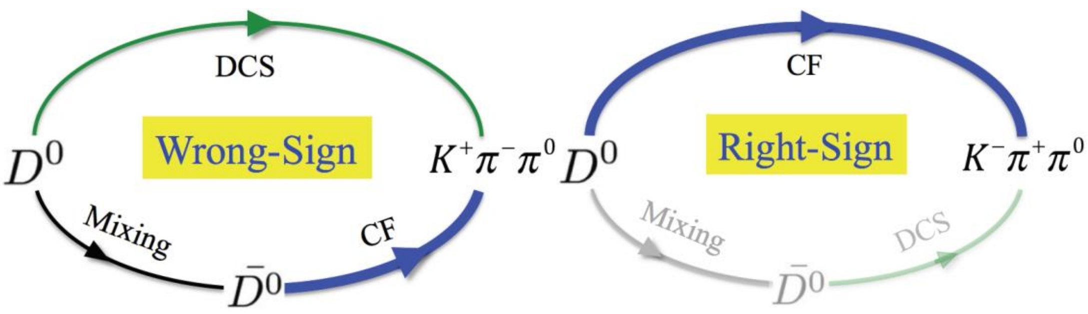


Data	stat.	syst. red.	syst. irred.	Total	stat.	syst. red.	syst. irred.	Total
	σ_x (10^{-2})				σ_y (10^{-2})			
976 fb^{-1}	0.19	0.06	0.11	0.20	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	0.02	0.01	0.04	0.05
	$\lvert q/p \rvert$ (10^{-2})				ϕ $(^\circ)$			
976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8	10.7	4.4-4.5	3.8-3.7	12.2
5 ab^{-1}	6.9	2.3-2.5	7.0-6.7	9.9-10.1	4.7	1.9-2.0	3.8-3.7	6.3-6.4
50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	1.5	0.6	3.8-3.7	4.0-4.2

Wrong-sign $D^0 \to K^+ \pi^- \pi^0$

- **Time-depend Dalitz analysis**

$$\frac{dN_{\bar f}(s_{12}, s_{13}, t)}{ds_{12}ds_{13}dt} \propto e^{-\Gamma t} r_0^2 \Big\{ |A_{\bar f}^{DCS}|^2 + |A_{\bar f}^{DCS}||A_{\bar f}^{CF}|[\tilde y \cos\delta_{\bar f} - \tilde x \sin\delta_{\bar f}](\Gamma t) + \frac{\tilde x^2 + \tilde y^2}{4} |A_{\bar f}^{CF}|^2 (\Gamma t)^2 \Big\},$$



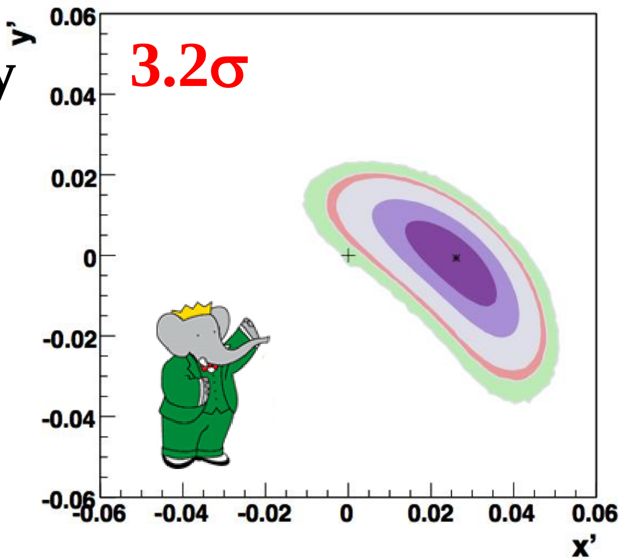
$$x'_{K\pi\pi^0} \equiv x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0},$$
$$y'_{K\pi\pi^0} \equiv y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}.$$

- **veto no D^0-$\bar{D}^0$ mixing @ three-body decay**

Resonance	a_j^{DCS}	δ_j^{DCS} (°)	f_j (%)
$\rho(770)$	1 (fixed)	0 (fixed)	39.8 ± 6.5
$K_2^{*0}(1430)$	0.088 ± 0.017	−17.2 ± 12.9	2.0 ± 0.7
$K_0^{*+}(1430)$	6.78 ± 1.00	69.1 ± 10.9	13.1 ± 3.3
$K^{*+}(892)$	0.899 ± 0.005	−171.0 ± 5.9	35.6 ± 5.5
$K_0^{*0}(1430)$	1.65 ± 0.59	−44.4 ± 18.5	2.8 ± 1.5
$K^{*0}(892)$	0.398 ± 0.038	24.1 ± 9.8	6.5 ± 1.4
$\rho(1700)$	5.4 ± 1.6	157.4 ± 20.3	2.0 ± 1.1

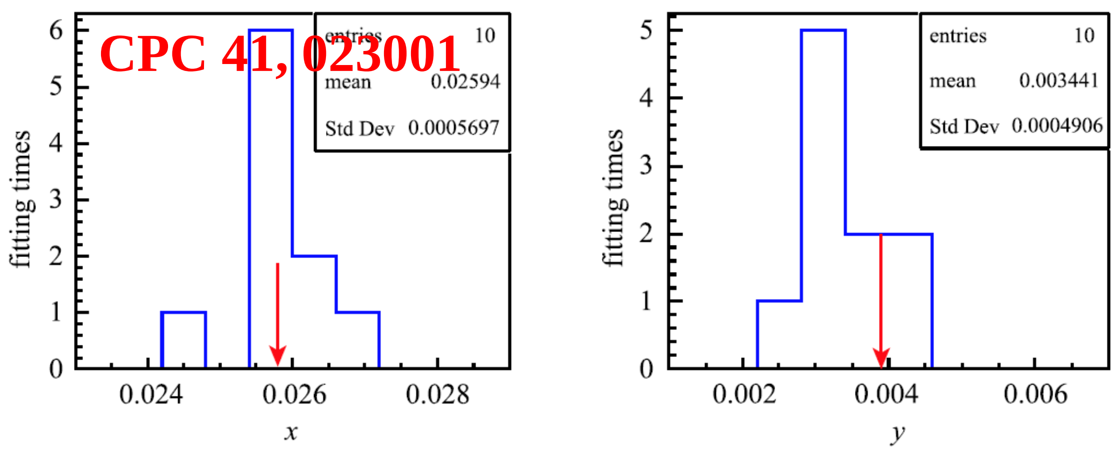
$x'_{K\pi\pi^0}/r_0 = 0.353 \pm 0.091 \pm 0.066$
$y'_{K\pi\pi^0}/r_0 = -0.002 \pm 0.090 \pm 0.059$

PRL 103, 211801



Wrong-sign $D^0 \to K^+ \pi^- \pi^0$

- **For 50 ab^{-1} data, there are (about) 225K $D^0 \to K^+ \pi^- \pi^0$ events**
- **MC study, smear exponential time with Gauss (σ=140 ps)**
- **Without considering background effect**
- **BaBar results @ MC production, fixed δ and r_0 fixed**
  - ✓ **An order of magnitude better than BaBar, if no background**
  - ✓ **Statistical uncertainty only**
  - ✓ **More improvement from ROE method**



$\sigma_{x'} = 0.057\%$

$\sigma_{y'} = 0.049\%$

Time-integrated CP asymmetry A_{CP}

- **For Belle II 50 ab^{-1} data, A_{CP} with precision of order 0.1%**

Table 121: Time-integrated CP asymmetries measured by Belle, and the precision expected for Belle II in 50 ab^{-1} of data.

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

SCS decay $D^0 \to K^0_S K^0_S$

$$A_{CP} = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\bar{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\bar{D}^0 \to K^0_S K^0_S)} \quad A_{CP} = A^d_{CP} + A^m_{CP} + A^i_{CP}$$

- **Direct CPV @ SCS decay: order 10^{-4}, interference of tree and penguin amplitudes.**
- **SCS decay: sensitive to contribution by strong penguin operator**
- **Promising channel, CPV can be as large as 1% in SM**

$$A_{\rm raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{CP} + A_{\rm FB} + A^{\pm}_{\epsilon} + A^{K}_{\epsilon}$$

- ✓ **A_{CP}: true CP asymmetry**
- ✓ **A^K_ϵ: different strong interaction of $K^0/\bar{K}^0$ with detector material**
- ✓ **A_{FB}: forward-backward production asymmetry of D^0**
- ✓ **$A^{\pm}_\epsilon$: from different detection efficiencies for $\pi^\pm$**

Normalization mode $D^0 \to K^0_S \pi^0$

SCS decay $D^0 \to K_S^0 K_S^0$

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

- **Due to $K_S^0 K_S^0$, asymmetry from A_ϵ^K is null**
- **Dominant uncertainty by $A_{CP}(D^0 \to K_S^0 \pi^0)$.**
- **With Belle II 50 ab^{-1} data, $\sigma_{stat} = 0.23\%$**

PRL 119, 171801

Source	$\mathcal{A}_{CP}$ (%)	$\mathcal{B}$ (%)
$D^0 \to K_S^0 K_S^0$ PDF parametrization	± 0.01	± 0.28
$D^0 \to K_S^0 \pi^0$ PDF parametrization	± 0.00	± 0.23
$D^0 \to K_S^0 K_S^0$ peaking background	± 0.01	± 0.59
$D^0 \to K_S^0 \pi^0$ peaking background	± 0.00	± 0.03
$K^0/\bar{K}^0$ material effects	± 0.01	$\cdots$
K_S^0 reconstruction efficiency	$\cdots$	± 1.57
π^0 reconstruction efficiency	$(\cdots)$	± 2.16
Quadratic sum of above	± 0.02	± 2.76
External input ($D^0 \to K_S^0 \pi^0$ mode)	± 0.17	± 3.33

Exp.	Results	$\mathcal{L}$ (fb^{-1})
CLEO A_{CP}	(-23±19)%	13.7
LHCb A_{CP}	(2.0±2.9±1.0)% (Beauty 2018)	5
Belle A_{CP}	(-0.02±1.53±0.02±0.17)%	921
BESIII Br	$(1.67\pm0.11\pm0.11)\times10^{-4}$	2.93
Belle Br	$(1.32\pm0.02\pm0.04\pm0.04)\times10^{-4}$	921

SCS decay $D^+ \longrightarrow \pi^+\pi^0$

- **Because CPV in $\pi^+\pi^0$ is tiny in SM, any CP asymmetry found would point to NP**

$$A_{\rm raw}^{\pi\pi} = \frac{N(D^+ \to \pi^+\pi^0) - N(D^- \to \pi^-\pi^0)}{N(D^+ \to \pi^+\pi^0) + N(D^- \to \pi^-\pi^0)} \quad A_{\rm raw}^{\pi\pi} = A_{CP}^{\pi\pi} + A_{FB} + A_{\varepsilon}^{\pi^\pm}$$

- ✓ **A_{CP}: true CP asymmetry**
- ✓ **A_{FB}: forward-backward production asymmetry of D^0**
- ✓ **$A_\epsilon^\pm$: from different detection efficiencies for $\pi^\pm$**

Normalization mode $D^+ \longrightarrow \pi^+K_S^0$

TABLE II. Summary of systematic uncertainties (%) on A_{CP}.

PRD 97, 011101(R)

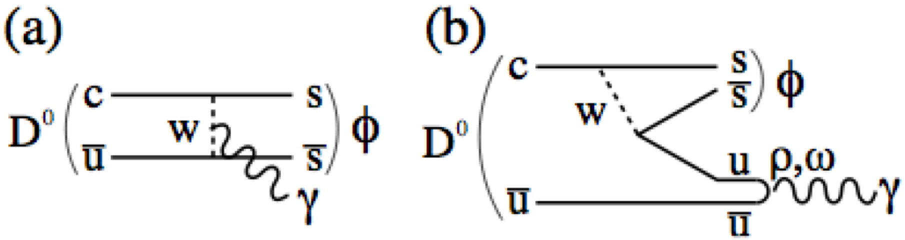
Source	$D \to \pi\pi$ tagged	$D \to \pi\pi$ untagged
Signal shape	±0.02	±0.23
Peaking background shape	±0.19	±0.22
$\Delta A_{\rm raw}$ measurement	±0.19	±0.32
$A_{CP}(D \to K_S^0\pi)$ measurement	±0.12	
Total (combined A_{CP} measurement)	±0.23	

- **Belle: 0.921 ab^{-1} data**

$$A_{CP}(D^+ \to \pi^+\pi^0) = (+2.31 \pm 1.24 \pm 0.23)\%$$

- **Belle II: 50 ab^{-1} data**
  - ✓ **$\sigma_{\rm stat}$ = 0.2-0.4%**

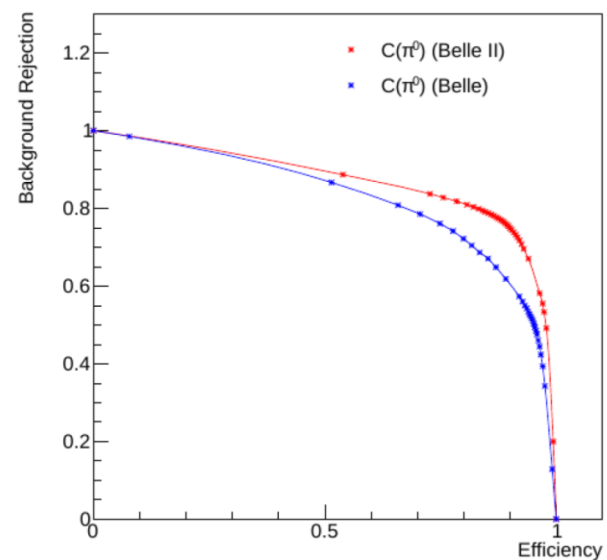
D^0 -> γϕ and γρ



$$\mathcal{A}_{CP}(D^0 \to \rho^0\gamma) = +0.056 \pm 0.152 \pm 0.006,$$
$$\mathcal{A}_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001,$$
$$\mathcal{A}_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000,$$

PRL 118, 051801

- **Direct CPV in radiative decays can be enhanced by chromomagnetic dipole operators PRL 109, 171801**
  - ✓ **A_{CP} up to several %**
- **MC study: (similar) veto D^0 -> $V\pi^0$ by π^0 neutral network and D^0 mass resolution**

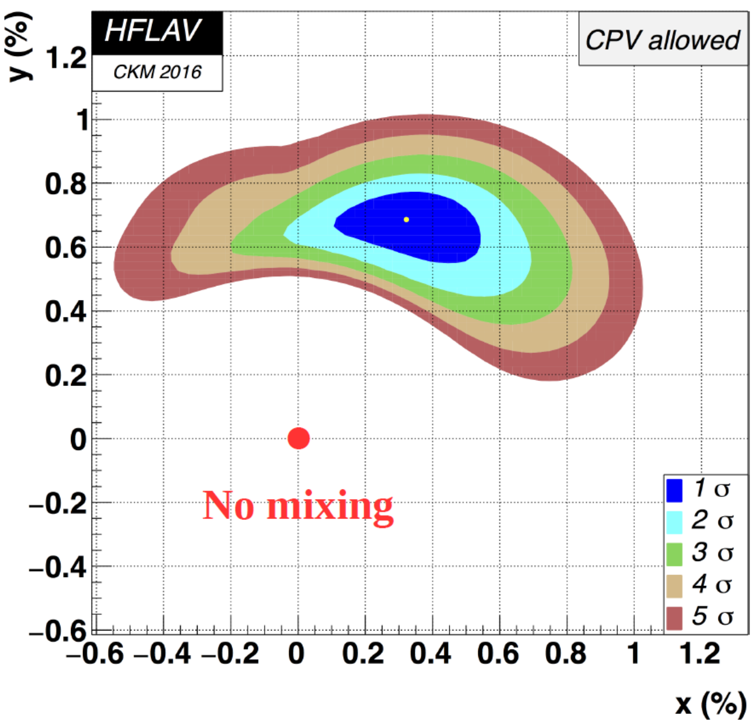


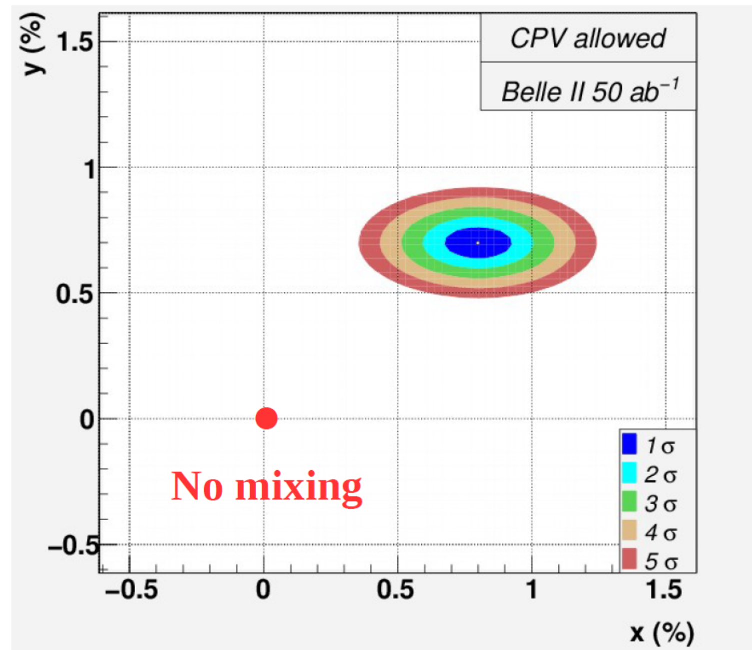
	Belle σ_{sta}	Belle II: σ_{stat}		
	0.976	5	15	50
D^0 -> γρ	±0.152	±0.07	±0.04	±0.02
D^0 -> γϕ	±0.066	±0.03	±0.02	±0.01

Summary and outlook

- SuperKEKB & Belle II are excellent platform for charm physics
  - ✓ Phase III already started in 2019
  - ✓ Belle II will collect 50 ab^{-1} data
  - ✓ Belle II has better D^0 decay time resolution, K_S & neutrals reconstruction, PID and D^0 tag than Belle
- Better precision on x and y variables is expected
- A_{CP} with precision of order 0.1% is expected
- More details at Belle Physics Book arXiv:1808.10567

Expected Belle II precision





World average (mixing):

x = (0.32 ± 0.14)%, y = $(0.69^{+0.06}_{-0.07})$%

Belle II (50 ab^{-1})

x = 0.8 ± 0.09%, y = 0.7 ± 0.04%

(result is conservative, does not include modes: $K^+\pi^-\pi^0$, $K_SK^+K^-$ etc.)