New Physics Prospects in Mixing and CP Violation at Belle II

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University of Hawaii
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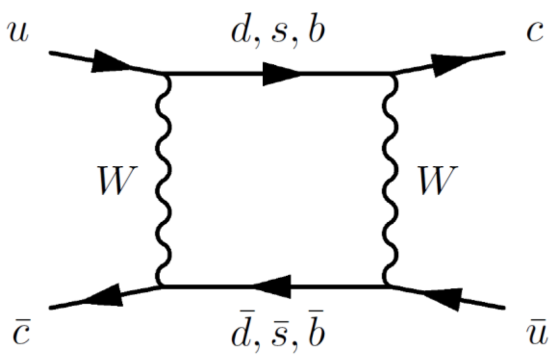
Mixing in the D System

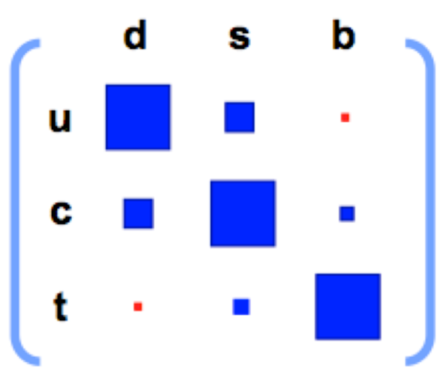
- Mass & flavor eigenstates differ:
  - $|D_{1,2}>= p|D^0> \pm q|\overline{D^0}>$
  - Note: if $p \neq q$, CP is violated.
- Mixing parameterized by mass/width splittings:

$$x \equiv \frac{(m_1 - m_2)}{\Gamma} \qquad y \equiv \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma}$$

  - In SM, *D* mixing is heavily suppressed:
    - CKM suppressed:
      - V_{cb} *and* V_{ub} negligble.
    - GIM suppressed:
      - Exactly zero in the limit of flavor SU(3).

$$x \propto \frac{m_s^2 - m_d^2}{m_W^2}$$





➔ Standard model expectation: |x|,|y| ~ O(10^{-3} – 10^{-2}).

CP Violation

- Three sources: $A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = a_f^d + a_f^m + a_f^i$
  - Mixing (a_f^m):

    $|q/p| \neq 1$
  - Decay (a_f^d):

    $|\mathcal{A}(D \to f)/\mathcal{A}(\bar{D} \to \bar{f})| \neq 1$
  - Interference between mixing and direct:

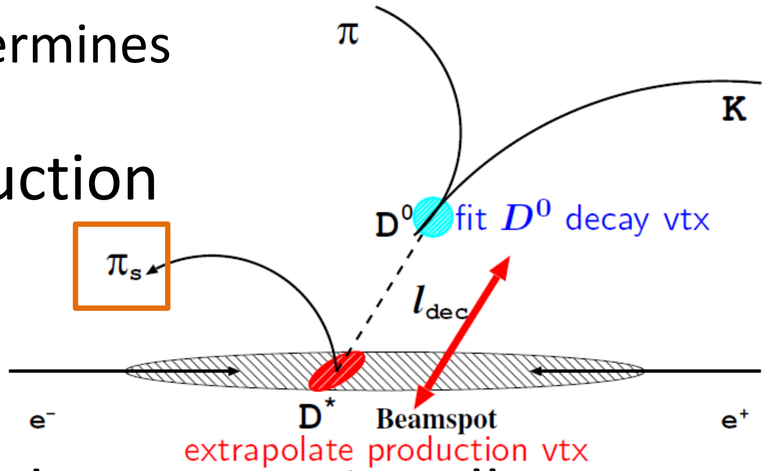
    $$\phi = \arg\left(\frac{\mathrm{q}\mathrm{A}(\bar{\mathrm{D}} \to \bar{\mathrm{f}})}{\mathrm{p}\mathrm{A}(\mathrm{D} \to \mathrm{f})}\right)$$
- CP violation requires complex phase of CKM:
  - In SM, complex phase appears as $V_{cs} \sim \eta A^2 \lambda^4 \sim O(10^{-3})$

  ➔ Observation of "large" CPV could indicate contributions from new physics.

Measuring D Mixing in $e^+e^- \to c\bar{c}$

- Continuum production of neutral D mesons.
- Typically use $D^{*\pm} \to \pi_s^{\pm} D^0$
  - Charge of slow pion, π_s, determines the D flavor.
- Measure length from production vertex to D^0 decay vertex:

$$\beta\gamma = \frac{p_D}{M_D} \qquad t = \frac{l_{\rm dec}}{c\beta\gamma}$$



- Decay time distributions and asymmetries allow access to x, y (different combinations for different final states).
- Measurements also possible at hadron machines…
  - …but e^+e^- provides an excellent environment for reconstruction of final states with neutrals, missing energy.
  - At B factories, background D^* from B decays are kinematically well-separated from signal D^*.

Current Measurements of *D* Mixing

Decay time distribution sensitive to mixing parameters x and y and CPV in mixing and depends on the final state:

$$\frac{dN(D^0 \to f)}{dt} \propto \left| \langle f | D^0 \rangle + \frac{q}{p} \left(\frac{ix+y}{2} \langle f | \overline{D}^0 \rangle \right) \right|^2$$

Final state	Belle	BaBar	LHCb	CDF	Cleo	E791	Focus	BES III
$K^+\pi^-$	√	★		★	√	√	√	Coming soon.
KK, $\pi\pi$	★	★	√		√	√	√	
$K_S^0\pi\pi$	√	√			√			
$K_S^0 KK$	√	√						
$K^+\pi^-\pi^0$		★						
$K^+\pi^-\pi^-\pi^+$		√						
$K^+\ell^-\nu_\ell$	√	√			√	√		
quantum corr. in $\psi(3770) \to D^0\overline{D}^0$					√			

√ – measurement performed; ★ – evidence for mixing

Full list of all $D^0 - \overline{D}^0$ mixing measurements is available at:
http://www.slac.stanford.edu/xorg/hfag/charm/index.html

***For new mixing results from Belle, see this morning's slides from M. Staric.**

Current Measurements of *D* Mixing

Final state	Belle	BaBar	LHCb	CDF	Cleo	E791	Focus	BES III
$K^+\pi^-$	✓	★		★	✓	✓	✓	Coming soon.
KK, $\pi\pi$	★	★	✓		✓	✓	✓	
$K_S^0\pi\pi$	✓	✓			✓			
K_S^0KK	✓	✓						
$K^+\pi^-\pi^0$		★						
$K^+\pi^-\pi^-\pi^+$		✓						
$K^+\ell^-\nu_\ell$	✓	✓			✓	✓		
quantum corr. in $\psi(3770) \to D^0\overline{D}^0$					✓			

- Each final state has unique sensitivity to mixing,CPV parameters, e.g.:
  - Observables for K^+K^- and $\pi^+\pi^-$: y_{CP}, A_Γ

$$y_{CP} = y\cos\phi - \frac{1}{2}A_M x\sin\phi$$

$$A_\Gamma = \frac{1}{2}A_M y\cos\phi - x\sin\phi$$

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

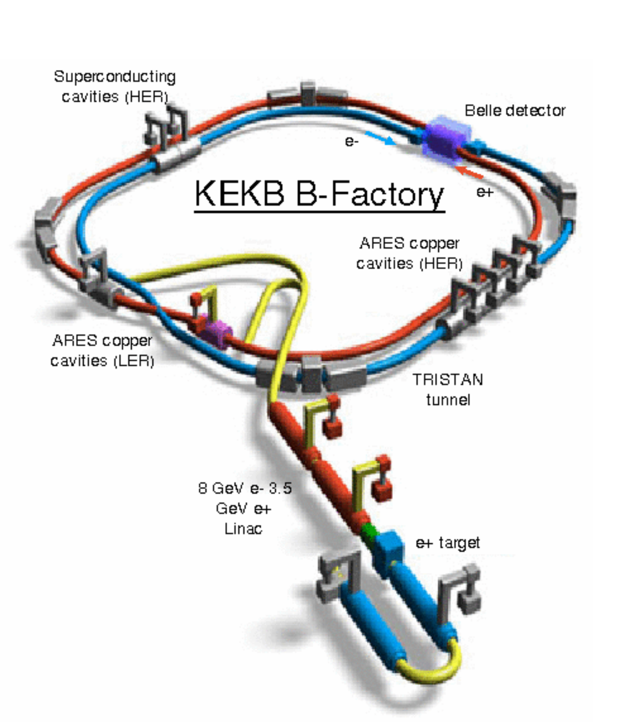
  - Observables for $K_S\pi^+\pi^-$: x, y, $|q/p|$, ϕ

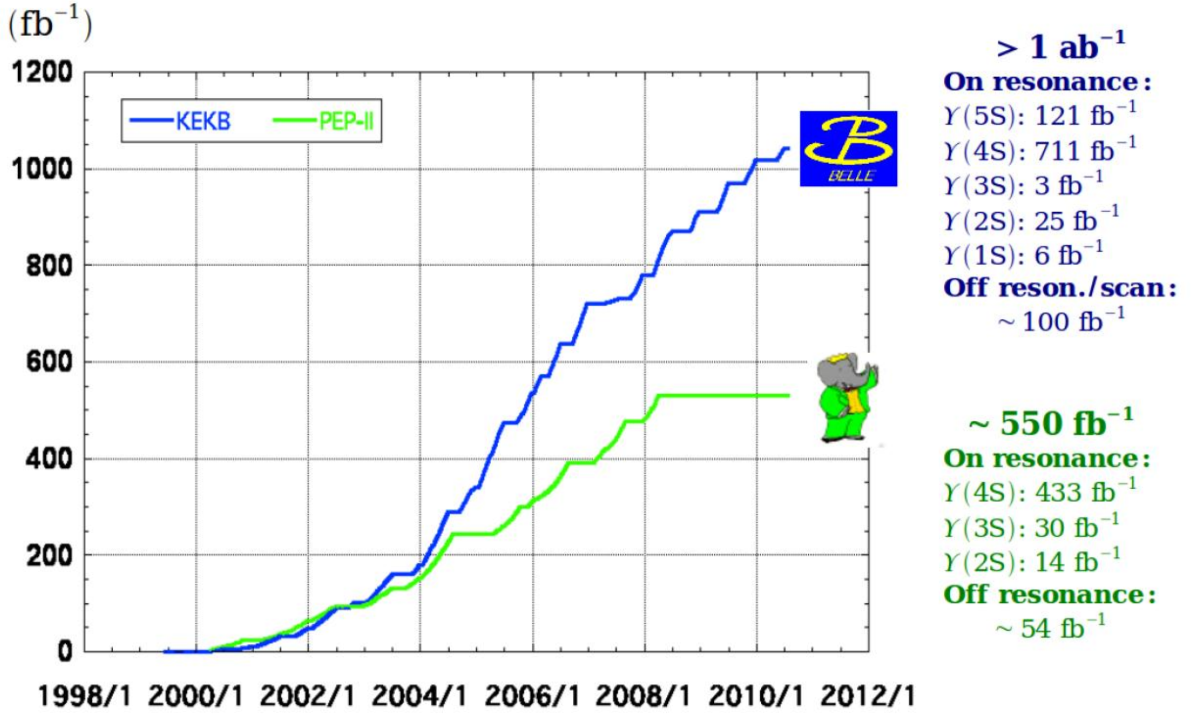
➔ Full measurement program requires measurements in many decay modes.

B factories have shown excellent sensitivity to a variety of final states.

Charm Production at KEKB, Belle

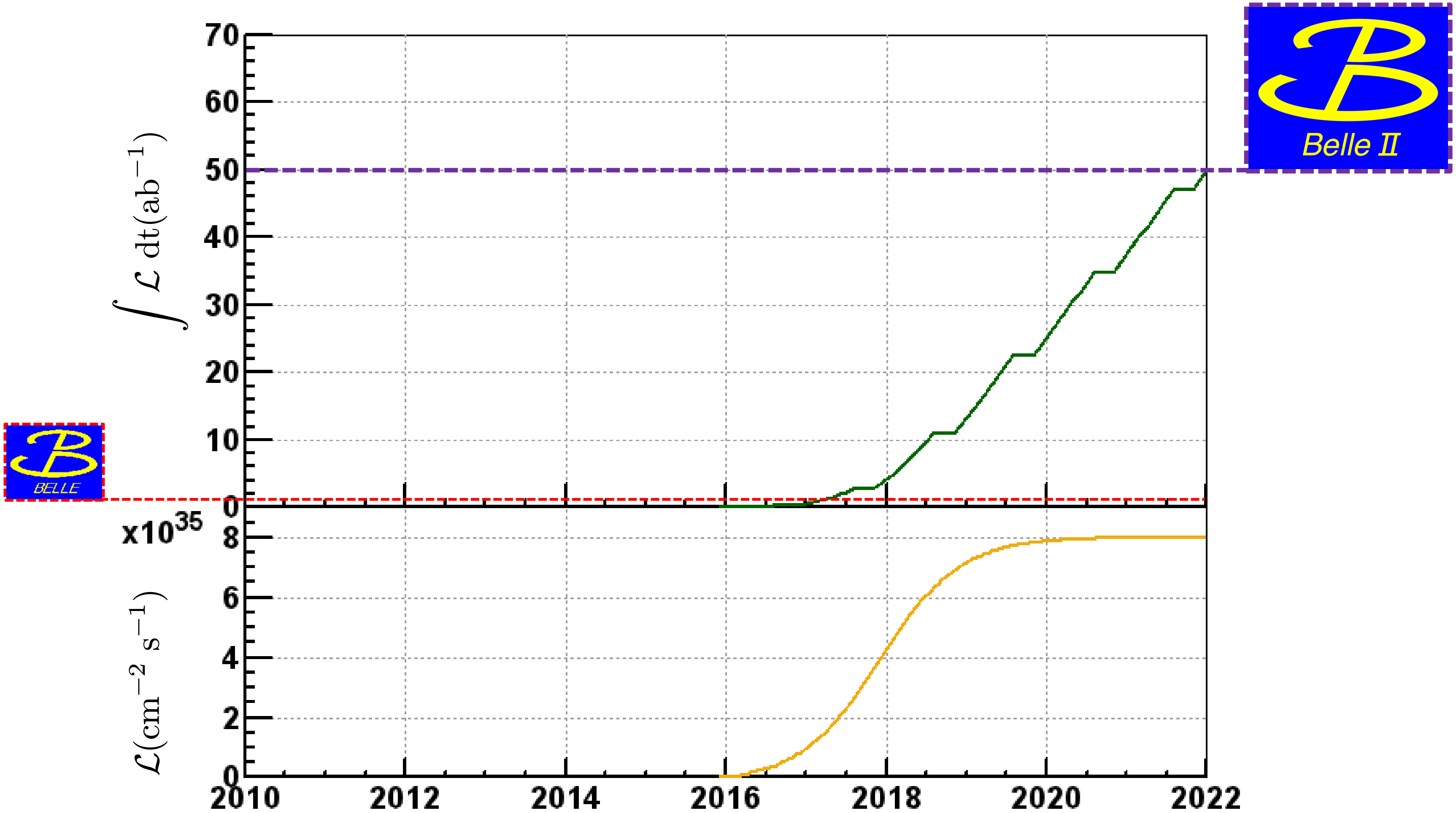
- Belle collected ~1 ab^{-1} mostly at $\Upsilon(4S)$:
  - Large sample of charm events in addition to $B\bar{B}$:
    - $\sigma_{B\bar{B}} \approx 1.1$ nb; $\sigma_{c\bar{c}} \approx 1.3$ nb ($\approx 10^9$ charm events)



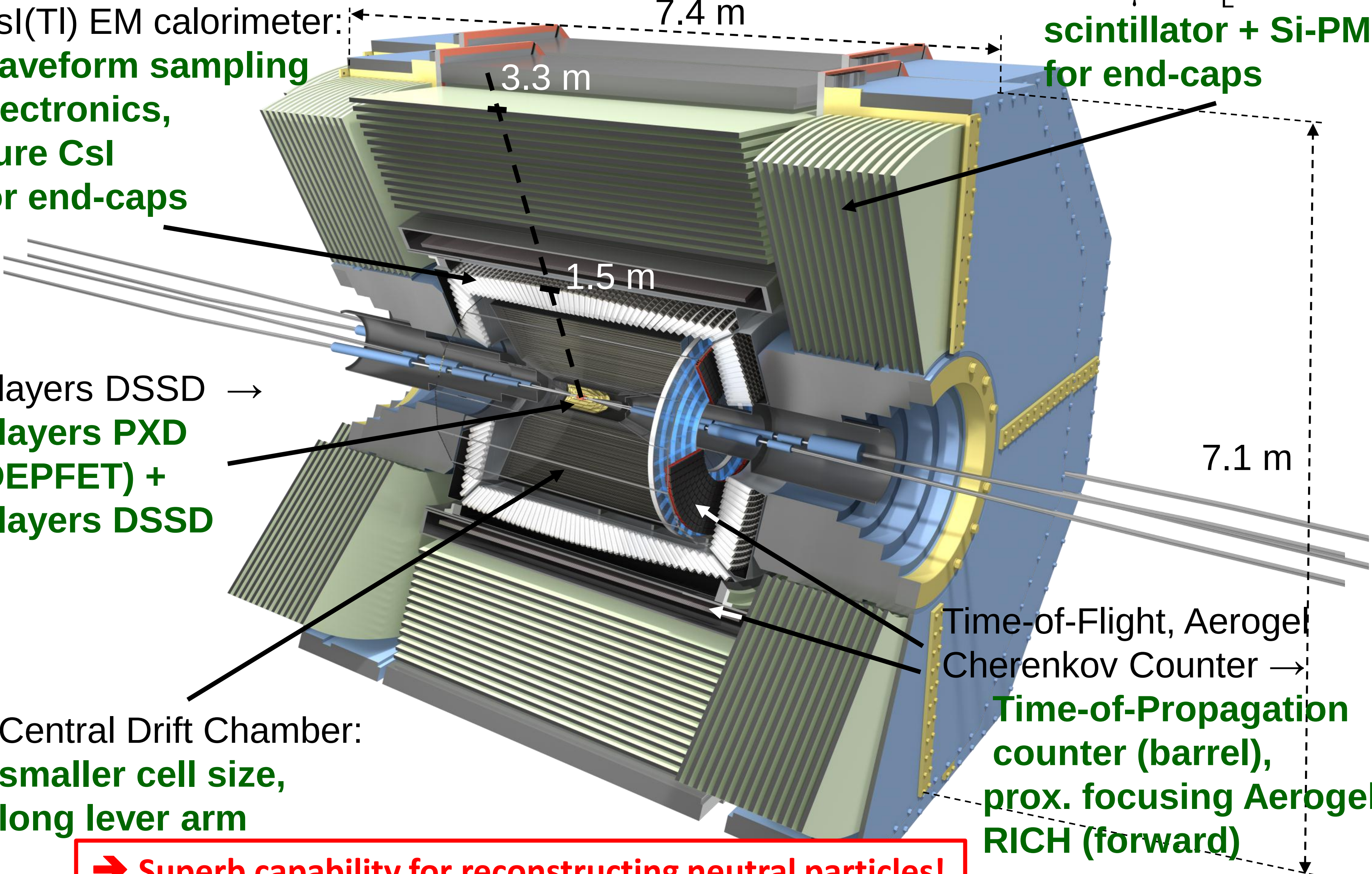


Charm Production at SuperKEKB, Belle II

- Belle II, 50 ab^{-1} in 2022: > 6×10^{10} charm events!



The Belle II Detector

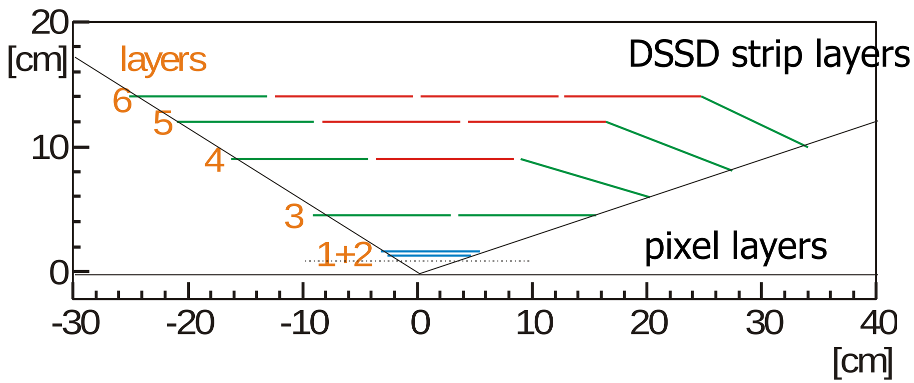


➔ Superb capability for reconstructing neutral particles!

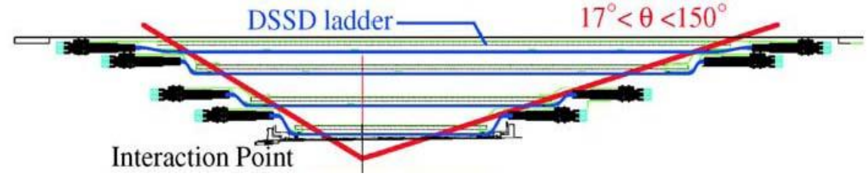
***For more details on Belle II, see talk tomorrow by A. Schwartz.**

Improved *D* Measurements at Belle II

Belle II: Pixels (2 layers) + SVD (4 layers)



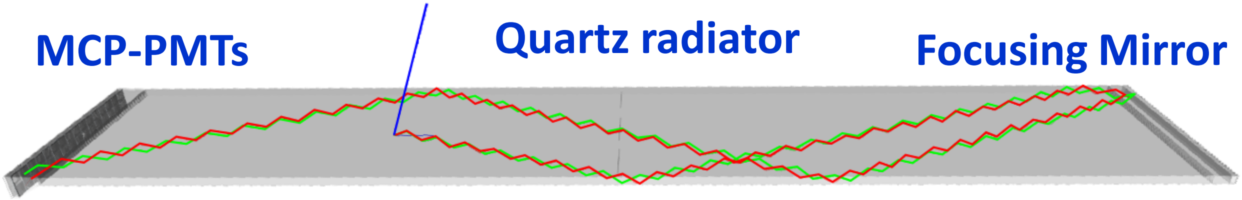
Belle: SVD (4 layers)

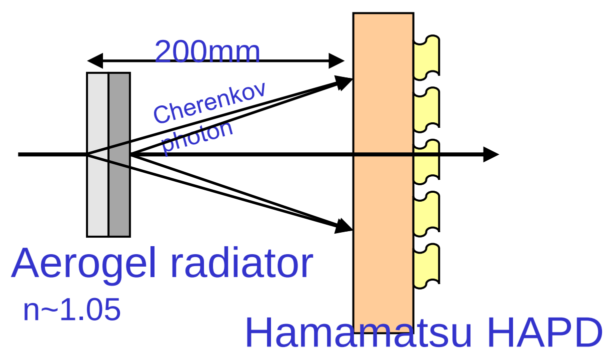


Vertexing improvements:

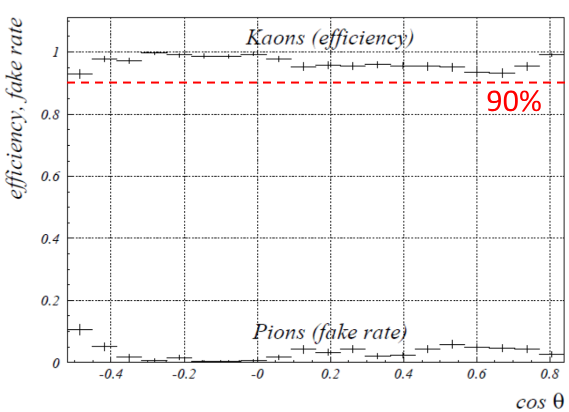
- ~25% Improvement in vertex resolution.
- ~30% higher $K_S \to \pi^+\pi^-$ efficiency.

Belle II K/π PID: Time-of-propagation + Focusing Aerogel RICH



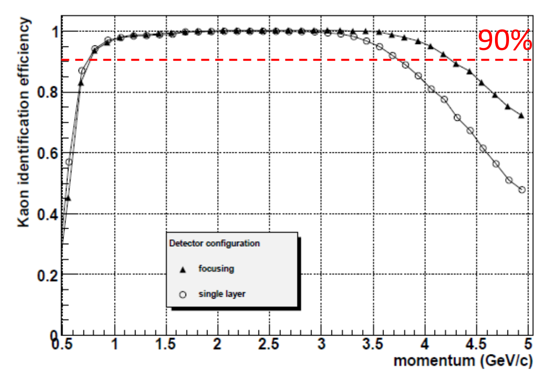


TOP performance at 3 GeV/c

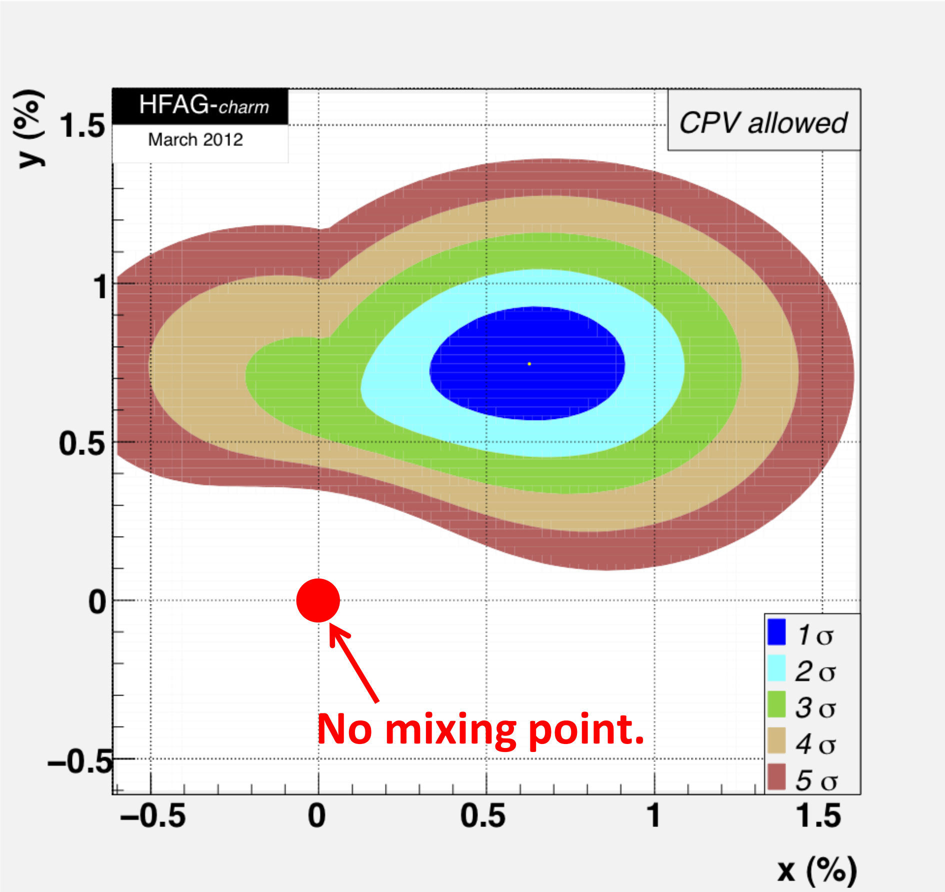


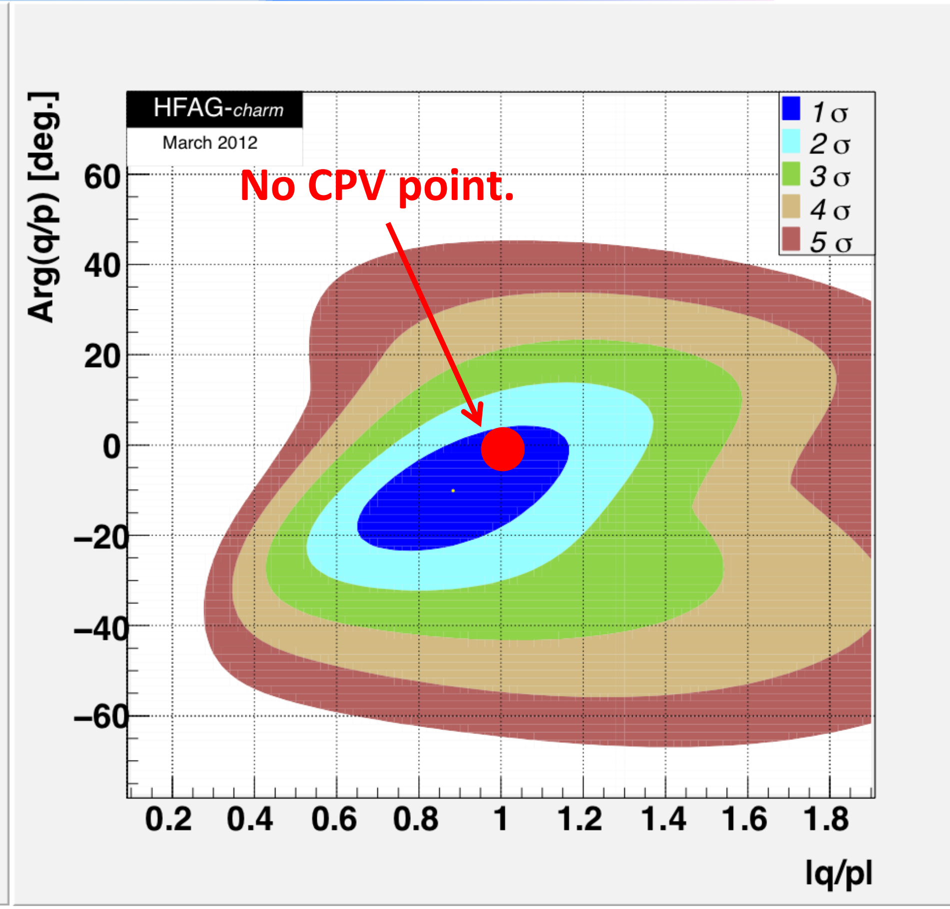
Particle ID improvements:

- Improved high momentum K/π separation relative to Belle time-of-flight and threshold aerogel.



D Mixing Parameters – World Average





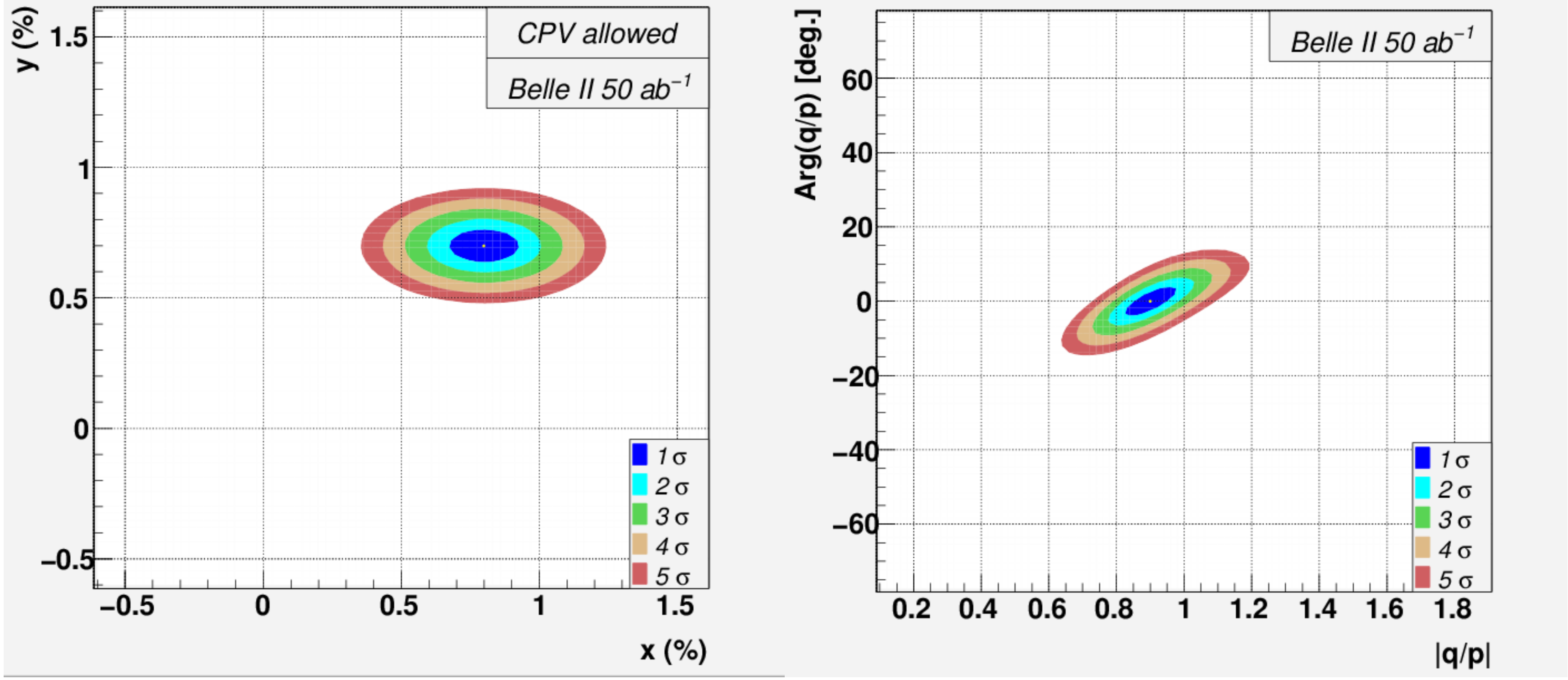
World average (mixing):
$x = (0.63 \pm 0.19)\%$
$y = (0.75 \pm 0.12)\%$

World average (CPV):
$|q/p| = (0.88 \pm 0.17)$
$\phi = (-10.3 \pm 9.2)^\circ$

➔ No-mixing excluded at > 10 σ; no CPV consistent within 1 σ.

Expected Belle II Precision

- Expected precision using 50 ab^{-1}:
  - HFAG-like fit using Belle II est. precision for K^+K^-, $\pi^+\pi^-$, $K^+\pi^-$, $K_S\pi^+\pi^-$:



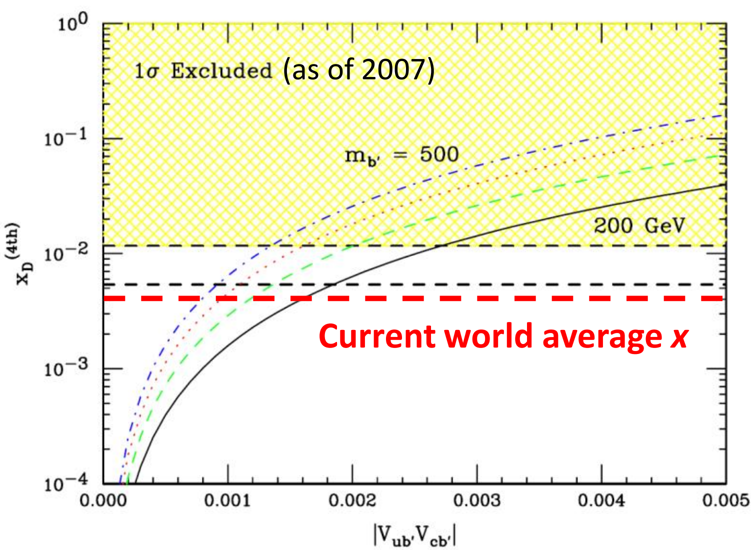
Current WA	**Belle II (50 ab^{-1})**	**Current WA**	**Belle II (50 ab^{-1})**
$\delta x = 0.19\%$	$\delta x = 0.09\%$	$\delta\|q/p\| = 0.17$	$\delta\|q/p\| = 0.05$
$\delta y = 0.12\%$	$\delta y = 0.04\%$	$\delta\phi = 9^\circ$	$\delta\phi = 3^\circ$

***Many systematics are expected to improve with higher statistics control samples.**

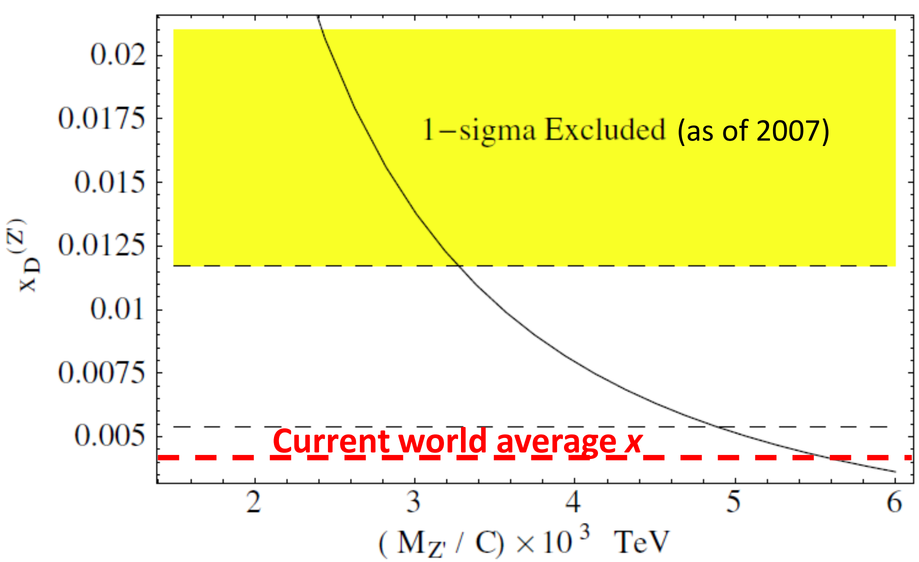
New Physics Implications

- *D* mixing provides constraints on many models:
  - e.g., fourth generation, extra gauge bosons, left right symmetric models, and others…
    - Golowich, Hewett, Pakvasa, Petrov [PRD 76, 095009 (2007)]

Fourth family model:



Extra gauge boson model:



Time Integrated CP Violation

- Look for asymmetry between $\Gamma(D \to f)$ and $\Gamma(\bar{D} \to \bar{f})$
  - Absolute A_{CP} measurements require removal of other asymmetries:
    - Reconstruction asymmetry:
      - Detector effects can cause asymmetry in efficiency of reconstruction for $K^{\pm}$, $\pi^{\pm}$.
    - Production asymmetry:
      - Belle/BaBar: γ/Z interference causes forward-backward asymmetry.
      - CDF: No production asymmetry.
      - LHC: pp initial state is **<u>not</u>** CP symmetric.
    - Reconstruction and production asymmetries can be removed by use of control samples.
      - Study slow $\pi^{\pm}$ reconstruction asymmetries with tagged and untagged samples of $D^0 \to K^- \pi^+$.
      - Use Cabbibo favored decays (e.g., $D_s^+ \to \phi\pi^+$) with negligible assumed intrinsic A_{CP} to subtract out other contributions.
      - At Belle, systematic uncertainties on these corrections are limited by statistics on control samples ➔ <u>projected to improve with luminosity</u>.

Time Integrated CP Violation

- Look for asymmetry between $\Gamma(D \to f)$ and $\Gamma(\bar{D} \to \bar{f})$
  - Absolute A_{CP} measurements require removal of other asymmetries:
    - Reconstruction asymmetry:
      - Detector effects can cause asymmetry in efficiency of reconstruction for $K^{\pm}$, $\pi^{\pm}$.
    - Production asymmetry:
      - Belle/BaBar: γ/Z interference causes forward-backward asymmetry.
      - CDF: No production asymmetry.
      - LHC: pp initial state is **<u>not</u>** CP symmetric.
    - Another approach: make ΔA_{CP} measurements where many asymmetries cancel out. Recently done for **K^+K^-** and $\pi^+\pi^-$:
      - LHCb [PRL 108,111602 (2012)]:

        $\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$ **(3.5 σ)**
      - CDF [Public Note 10784 (2012)]:

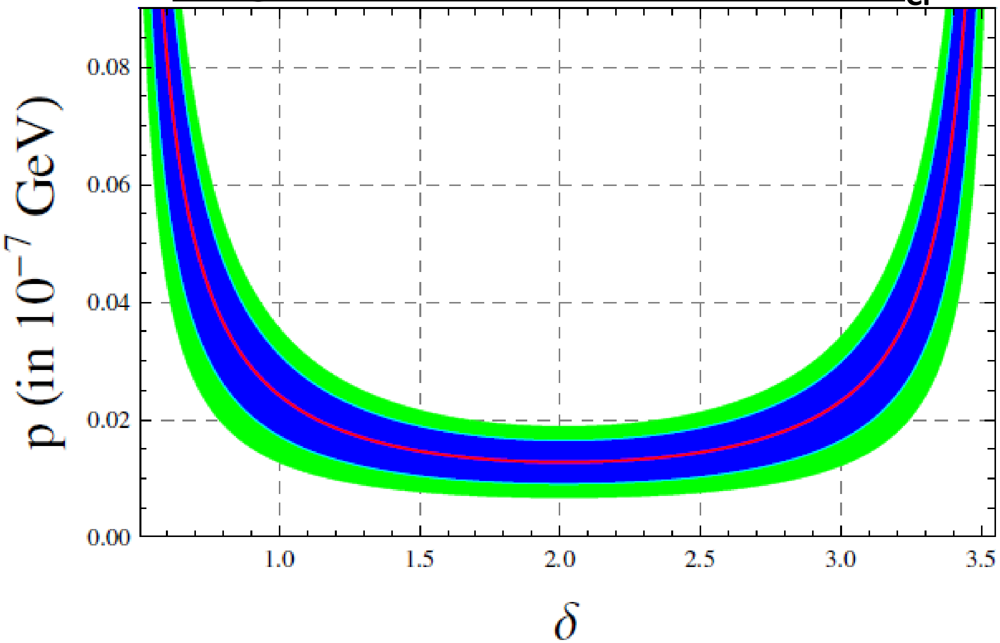
        $\Delta A_{\text{CP}} = \left[-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst})\right]\%$ **(2.7 σ)**
      - Combined result ➔ ~3.8 σ evidence for CP violation.

      …Is this a sign of new physics…?

CP Violation Interpretation… New Physics?

- Not necessarily…
  - Singly Cabbibo suppressed modes can have contributions from SM penguin amplitudes.
    - Bhattacharya, Gronau, Rosner [arXiv:1201.2351]

Penguin constraints from current ΔA_{CP}



- A relatively small SM penguin amplitude, p, could explain observed ΔA_{CP} for a wide range of strong phases, δ.
- LHCb and CDF measurements define a contour in p,δ space.

Mode-specific A_{CP} measurements provide important constraints…

Time Integrated CPV at Belle

- Reconstruction systematics well understood at Belle; have allowed a rich program of mode-specific A_{CP} measurements:

Mode	$\mathcal{L}$ [fb^{-1}]	A_{CP} [%]	Reference
$D^0 \to K_S^0 \pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	PRL 106, 211801 (2011)
$D^0 \to K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	PRL 106, 211801 (2011)
$D^0 \to K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	PRL 106, 211801 (2011)
$D^0 \to \pi^+ \pi^-$	540	$+0.43 \pm 0.52 \pm 0.12$	PLB 670, 190 (2008)
$D^0 \to K^+ K^-$	540	$-0.43 \pm 0.30 \pm 0.11$	PLB 670, 190 (2008)
$D^0 \to \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	PLB 662, 102 (2008)
$D^0 \to K^+ \pi^- \pi^0$	281	-0.6 ± 5.3	PRL 95, 231801 (2005)
$D^0 \to K^+ \pi^- \pi^+ \pi^-$	281	-1.8 ± 4.4	PRL 95, 231801 (2005)
$D^+ \to \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	PRL 108, 071801 (2012)
$D^+ \to \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	PRL 107, 221801 (2011)
$D^+ \to \eta' \pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	PRL 107, 221801 (2011)
$D^+ \to K_S^0 \pi^+$	673	$-0.71 \pm 0.19 \pm 0.20$	PRL 104, 181602 (2010)
$D^+ \to K_S^0 K^+$	673	$-0.16 \pm 0.58 \pm 0.25$	PRL 104, 181602 (2010)
$D_s^+ \to K_S^0 \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	PRL 104, 181602 (2010)
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	PRL 104, 181602 (2010)

***For latest updates on CPV searches at Belle, see E. White's slides from yesterday.**

Time Integrated CPV at Belle II

- Belle II can reach < 0.1% uncertainty on A_{CP} for a variety of modes…

Mode	$\mathcal{L}$ [fb^{-1}]	A_{CP} [%]	Belle II with 50 ab^{-1} [%]
$D^0 \to K_S^0 \pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.05
$D^0 \to K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.10
$D^0 \to K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.10
$D^0 \to \pi^+ \pi^-$	540	$+0.43 \pm 0.52 \pm 0.12$	± 0.07
$D^0 \to K^+ K^-$	540	$-0.43 \pm 0.30 \pm 0.11$	± 0.05
$D^0 \to \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	
$D^0 \to K^+ \pi^- \pi^0$	281	-0.6 ± 5.3	
$D^0 \to K^+ \pi^- \pi^+ \pi^-$	281	-1.8 ± 4.4	
$D^+ \to \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.05
$D^+ \to \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.20
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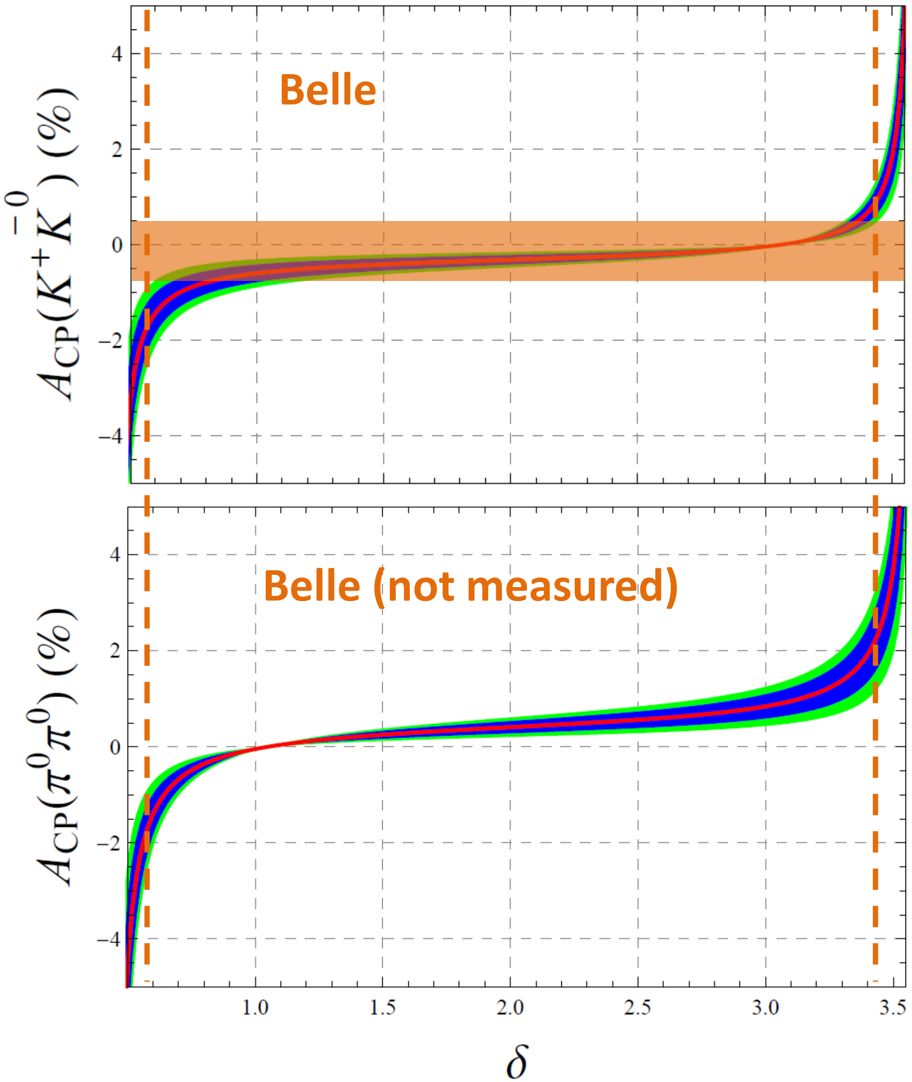
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.10

Modes well suited to measurement at Super B factories.

*Systematics related to control sample statistics are assumed to scale with luminosity.

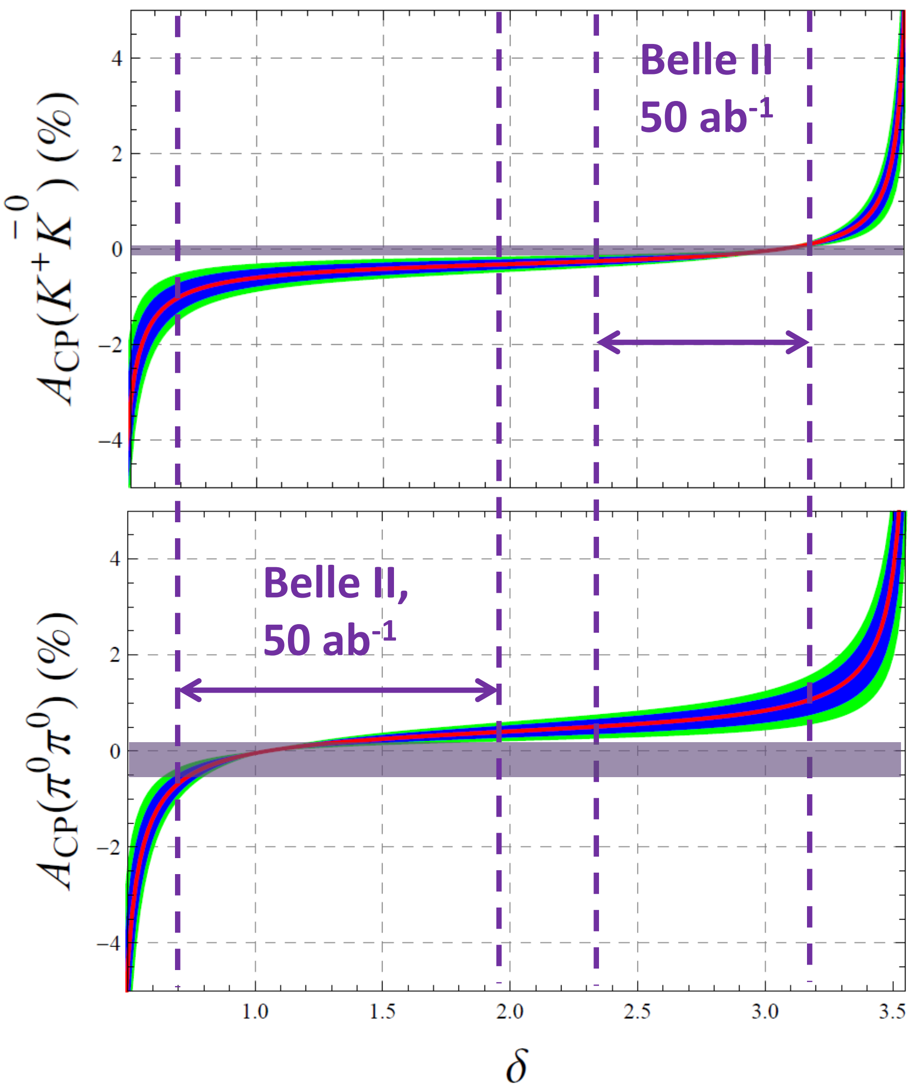
Direct CPV at Belle/Belle II



- SM penguin mechanism:
  - Predicts relations between A_{CP} for different modes, related by strong phase δ.
    - Some of the strongest constraints are from modes with K^0, π^0.
  - Existing mode-specific A_{CP} measurements only constrain δ loosely…

***[Bhattacharya, Gronau, Rosner arXiv:1201.2351]**

Direct CPV at Belle/Belle II



- SM penguin mechanism:
  - Predicts relations between A_{CP} for different modes, related by strong phase δ.
    - Some of the strongest constraints are from modes with K^0, π^0.
    - Bhattacharya, Gronau, Rosner] [arXiv:1201.2351]
- Other new physics searches:
  - A_{CP} ($D^+ \to \pi^+\pi^0$) $\neq 0$ would need $\Delta I = 3/2$ new physics.
    - Grossman, Kagan, Zupan [arXiV:1204.3557]

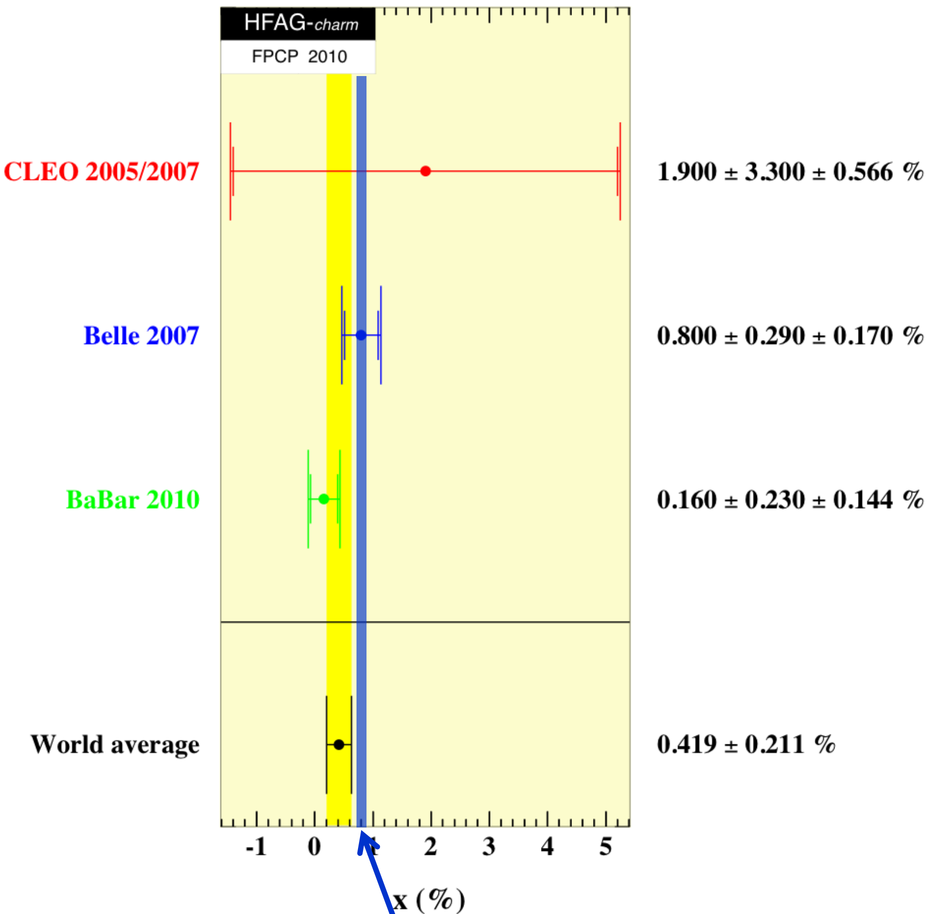
➔ **Belle II well suited for new physics searches in *D* CPV.**

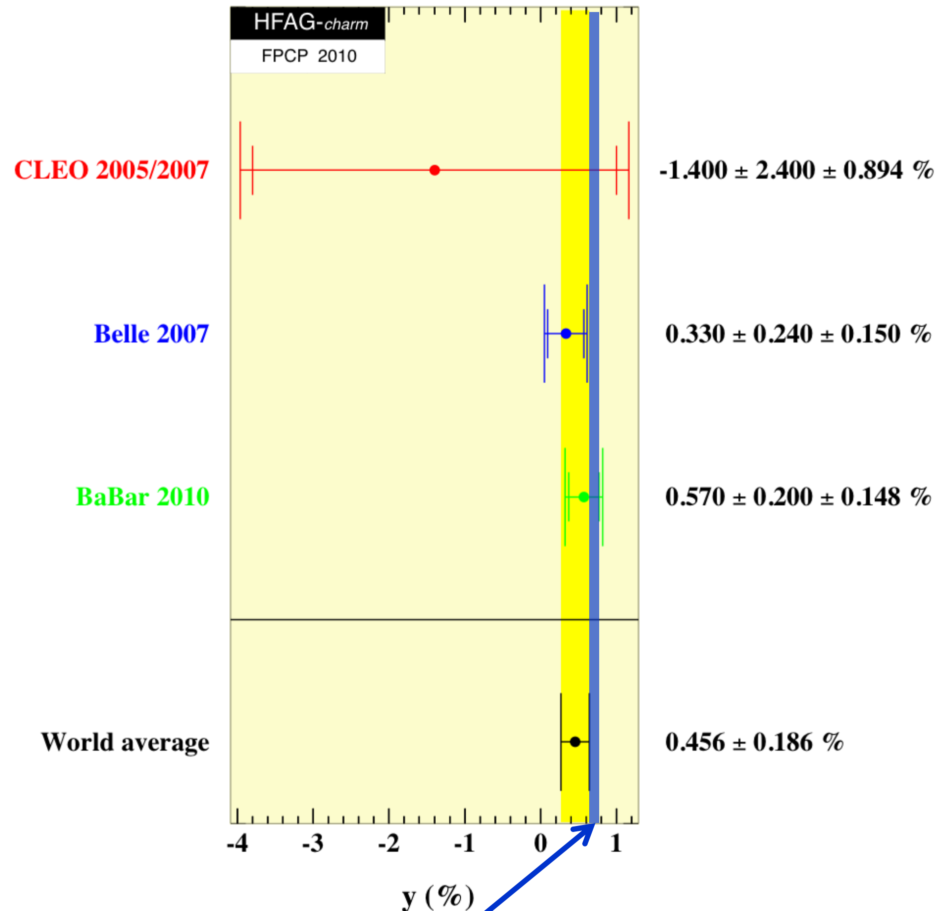
Conclusions

- Charm mixing and CP violation provides a unique window to search for new physics.
  - Interpretation of the situation in mixing and CPV requires a program of measurements in many decay modes.
  - Belle has already made many of these measurements.
  - Belle II will further extend physics reach:
    - Some hints already exist that suggest new physics…
    - …Belle II precision measurements will complement those of LHCb to provide a better understanding of if and how new physics is manifested in the charm sector.

BACKUP

Expected Belle II Precision (No CPV)





Expected Belle II precision @ 50 ab^{-1}

- **Using: K^+K^-, $\pi^+\pi^-$, $K^+\pi^-$, $K_S\pi^+\pi^-$**

***Systematics are expected to improve with higher statistics control samples.**

Detector asymmetries at Belle

Developed methods for measuring recon. asym. of $\pi^{\pm}_{\rm slow}$, $\pi^{\pm}$ and $K^{\pm}$

- $\pi^{+}_{\rm slow}$ from $D^{*+} \to D^0 \pi^{+}_{\rm slow}$ decays
  $\hookrightarrow$ Using tagged and untagged samples of $D^0 \to K^- \pi^+$ decays
  $A_{\varepsilon}^{\pi_{\rm slow}}(p_T^{\pi_{\rm slow}}, cos\theta^{\pi_{\rm slow}}) \approx (+0.14 \pm 0.07)\%$ [791 $\rm fb^{-1}$]
- $\pi^{\pm}$
  $\hookrightarrow$ Using $D^0 \to K^- \pi^+ \pi^0$ and $D^+ \to K^- \pi^+ \pi^+$ decays
  $A_{\varepsilon}^{\pi}(p_T^{\pi}, cos\theta^{\pi}) \approx (+0.078 \pm 0.040)\%$ [977 $\rm fb^{-1}$]
- $K^{\pm}$
  $\hookrightarrow$ Using $D_s^+ \to \phi \pi^+$ and $D^0 \to K^- \pi^+$ decays
  $A_{\varepsilon}^{K}(p^{K}, cos\theta_{K}) \approx (-0.4 \pm 0.2)\%$ [673 $\rm fb^{-1}$]

Need to make assumptions:

1. No CP violation in Cabbibo favored decays
2. Forward-backward asymmetry the same for all charm meson species

Uncertainties on corrections are dominated by the statistics!

$\overline{D}^0$-D^0 mixing and CPV:

	CDF		BELLE	CLEO	LHCb	Belle II	
√		√	√	√	√	√	• Wrong-sign semileptonic $D^0(t) \to K^+ l^- \nu$ measures x^2+y^2, no DCS contamination
√	√	√	√		√	√	• Wrong-sign hadronic $D^0(t) \to K^+\pi^-$ measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$
√		√	√	√	√	√	• Decays to CP eigenstates: $D^0(t) \to K^+K^-, \pi^+\pi^-$ measures y_{CP}, A_K, A_π
		√	√			√	• Dalitz plot analysis of $D^0(t) \to K^0\pi^+\pi^-$ measures x, y
		√				√	• Dalitz plot analysis of $D^0 \to K^+\pi^-\pi^0$ measures x'', y''
		√	√			√	• Dalitz plot analysis of $D^0 \to K^0K^+K^-$ measures y_{CP} (CLEO, Belle)
				√			• Quantum correl. in $e^+e^- \to \psi(3770) \to D^0\overline{D}^0(n\pi^0)$ measures x^2+y^2, y, R_D, $\sqrt{R_D}\cos\delta$

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Belle II approval + funding status:

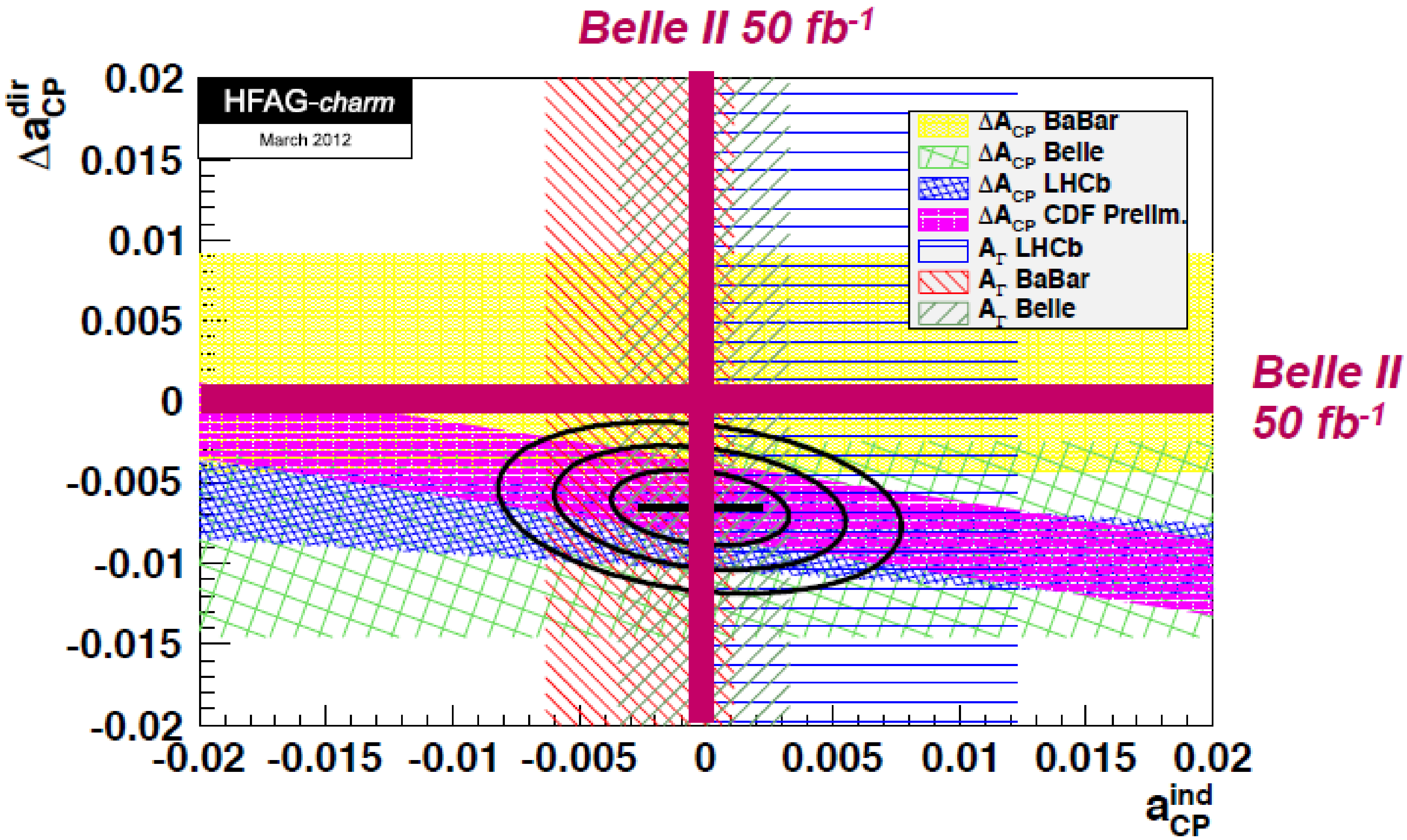
◆ The KEKB upgrade was fully approved by the Japanese government in December 2010. The project is in the JFY2011 budget as approved by the Japanese Diet at the end of March 2011

◆ $32M were allocated for detector R&D in FY2009; $6M were allocated for the damping ring in FY2010; and $110M have been allocated for the machine in FY2011 (Very Advanced Research Support Program)

◆ Super-KEKB and Belle-II are priorities of KEK

◆ Several non-Japanese funding agencies have already budgeted sizable funds for the upgrade (Germany, Russia, Korea). The US DOE has declared Belle II to be their priority project for e^+e^- physics.

Direct CPV:



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