Charm Physics Prospects at the *Belle II* Experiment

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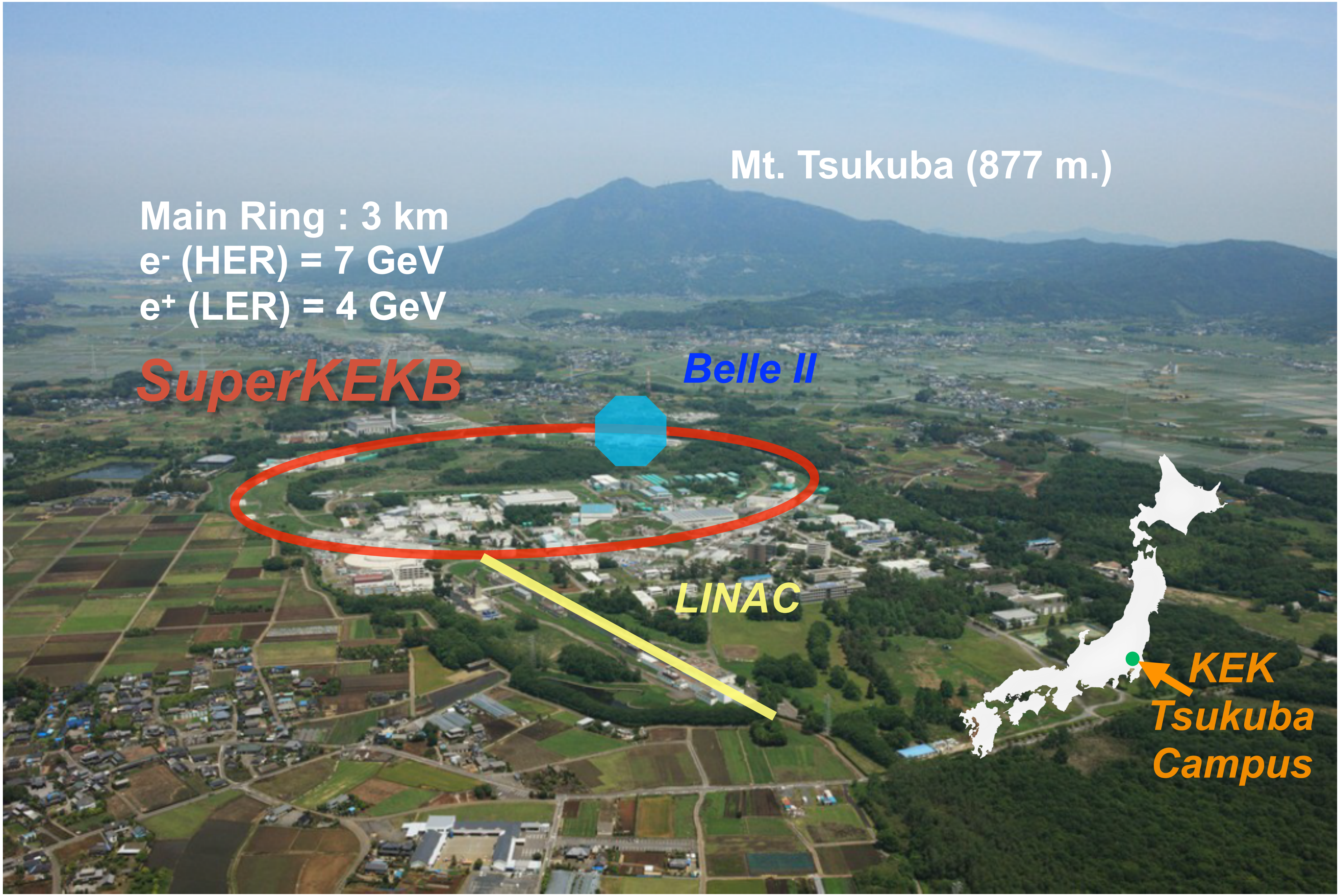
University of Cincinnati

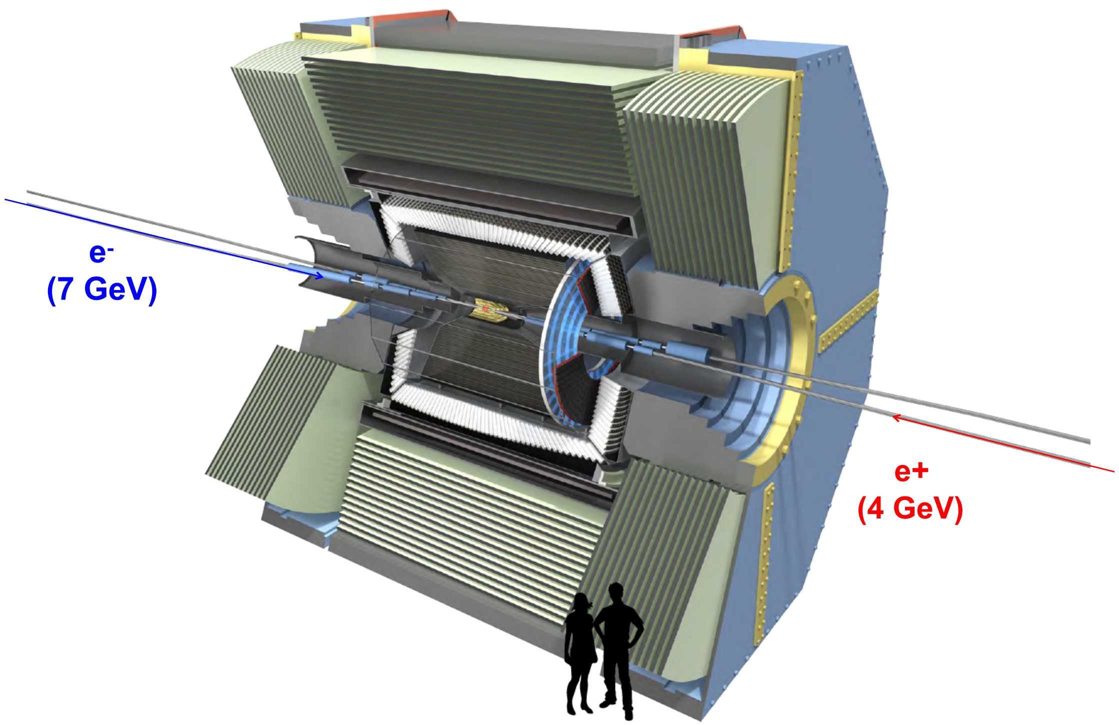
On Behalf of the Belle II Collaboration

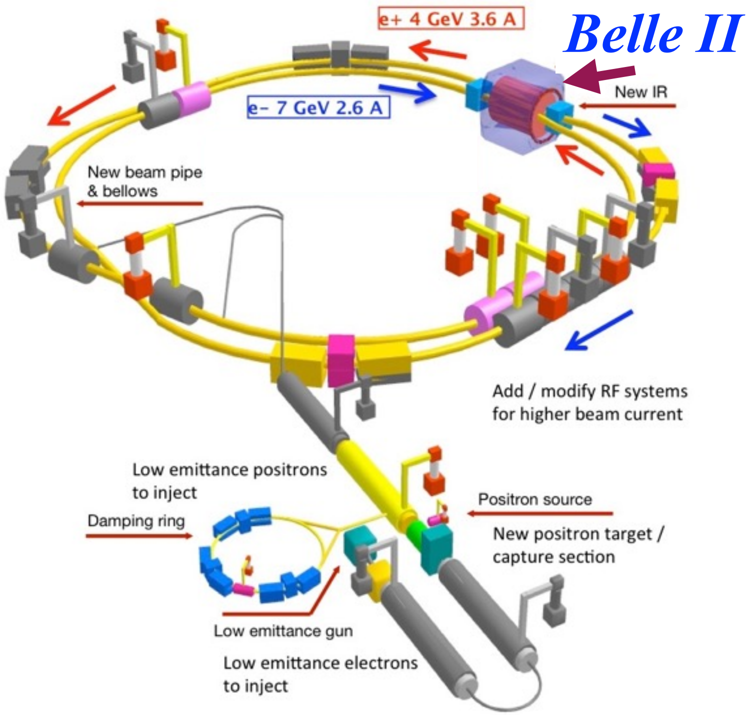
July 6, 2018

Belle II and SuperKEKB



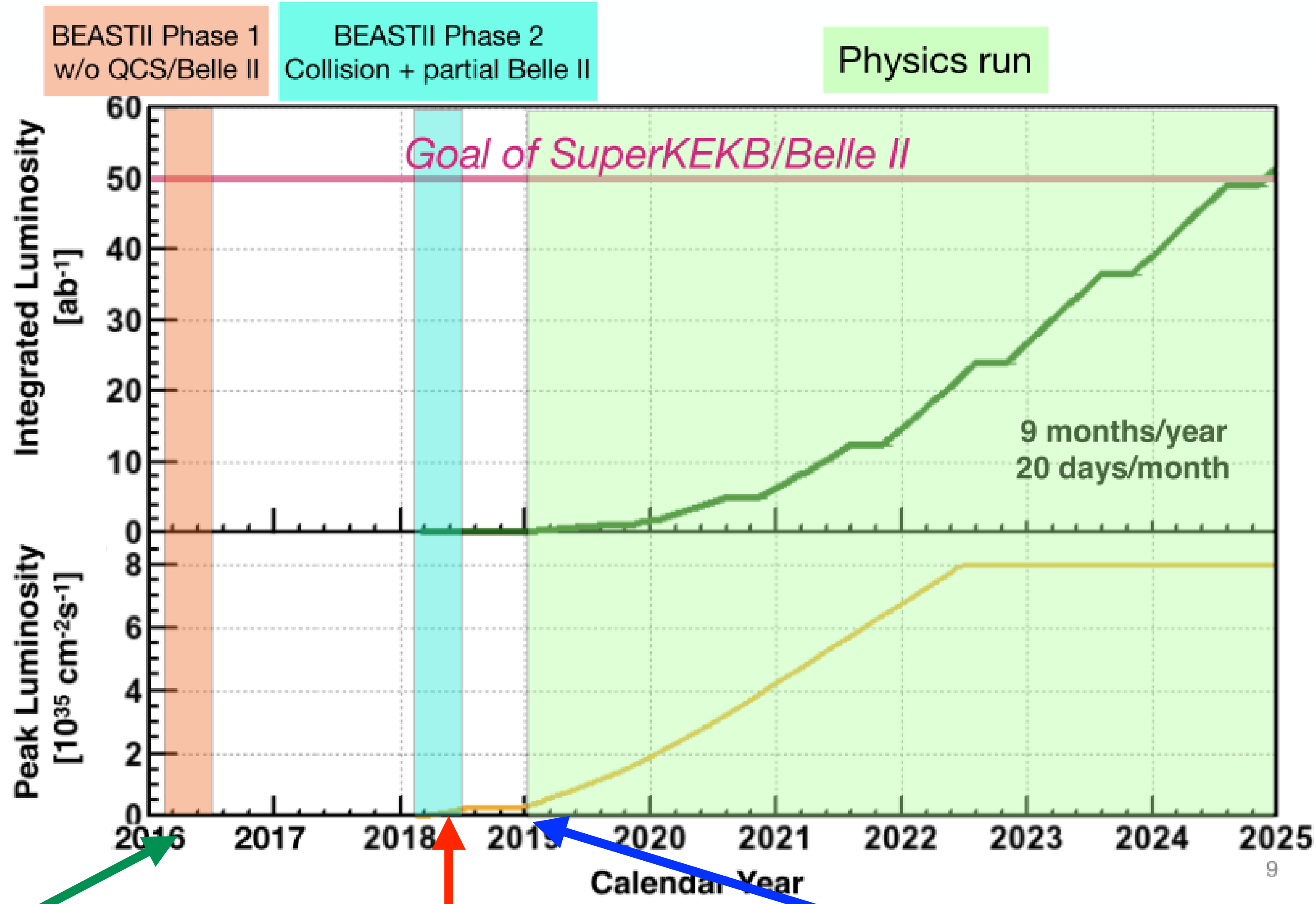
Belle II Experiment @ SuperKEKB





More Details on July 7 2018, 9:12 am
- Detector Session -
by SHUJI TANAKA

Schedule



Phase I
w/o *Belle II*
(2016… done)

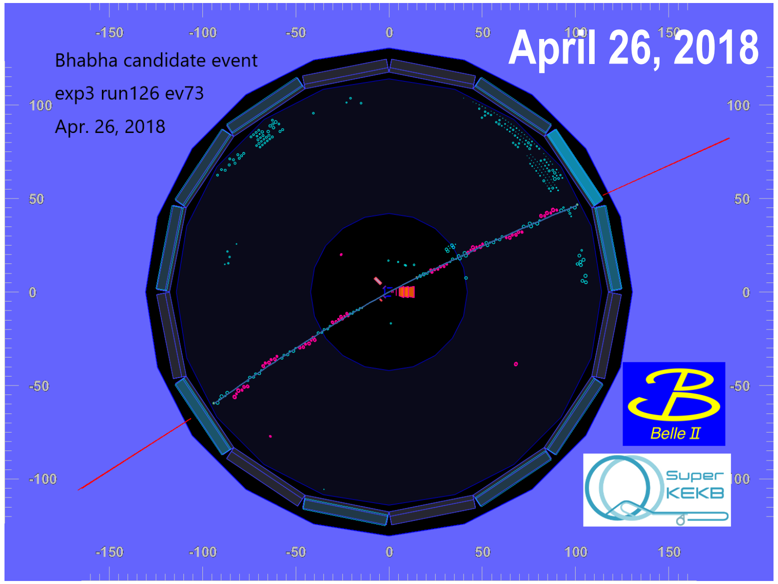
We are here

Phase II
partial *Belle II*
(early 2018 - until July 17, 2018)

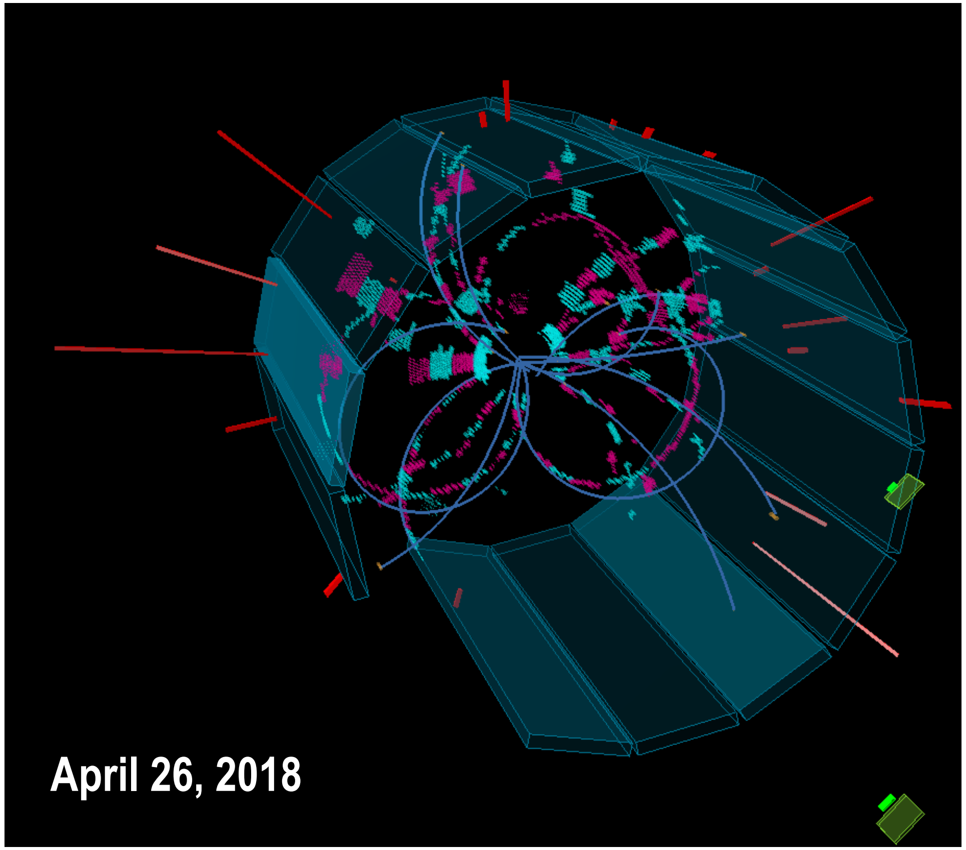
Phase III
with *Belle II*
(plan for early 2019)

First Collision at April 26!

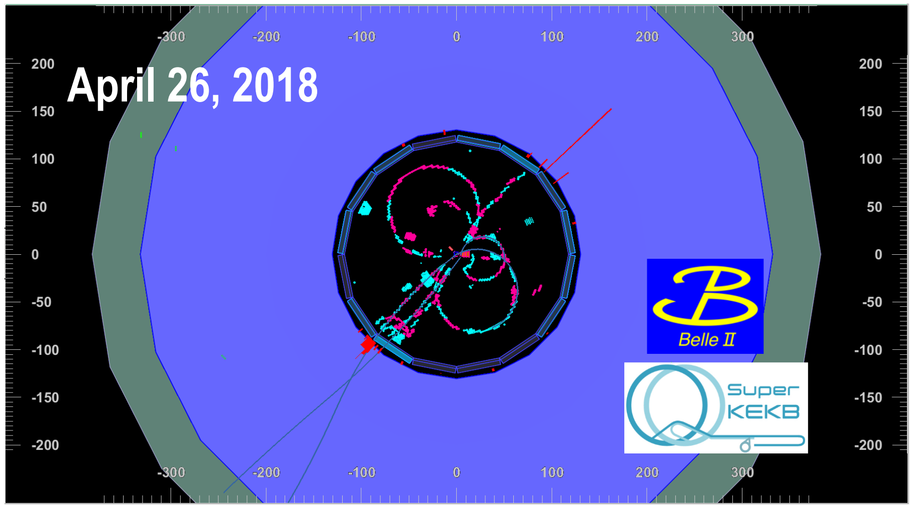
Some "First" Events



Bhabha event



$B\bar{B}$ like event



Hadronic event

Phase II Collision Data Sample

- Data sample taken between April 26 - June 10, 2018.

$$\int \mathcal{L}\, dt = 250 \text{ pb}^{-1}$$

N.B.

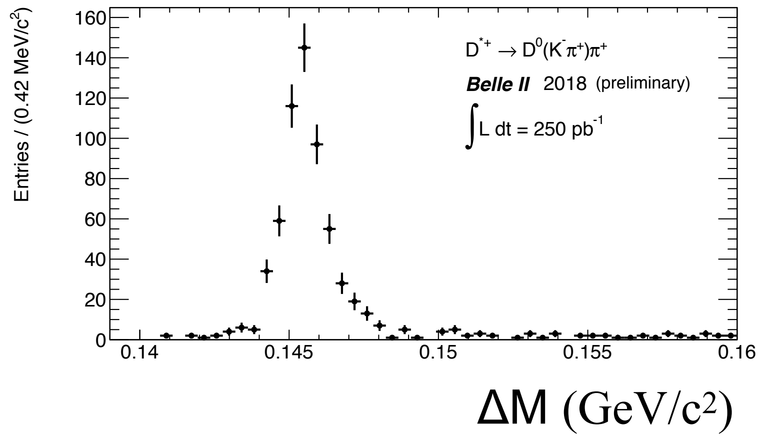
- *Plots which will be shown on next pages are prepared by using events*
  - *with at least three tracks from the IP region while veto Bhabha events.*

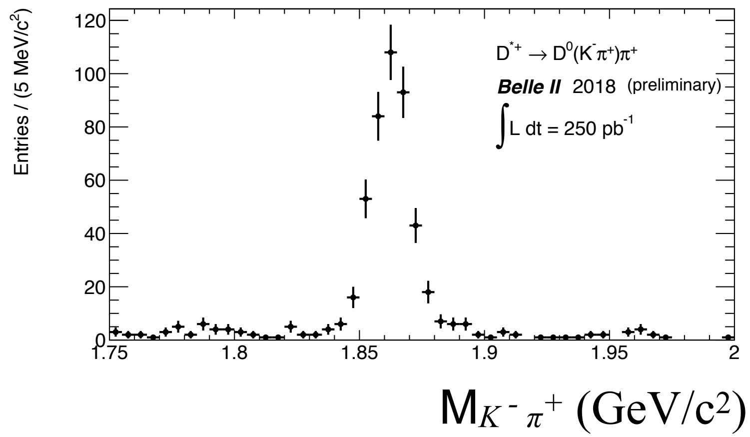
REDISCOVERIES with Phase II Collision Data Sample

- Cabibbo Favored (CF) D decays $K\,\pi$, $K\,\pi\,\pi^0$ and $K\,\pi\,\pi\,\pi$ are observed.

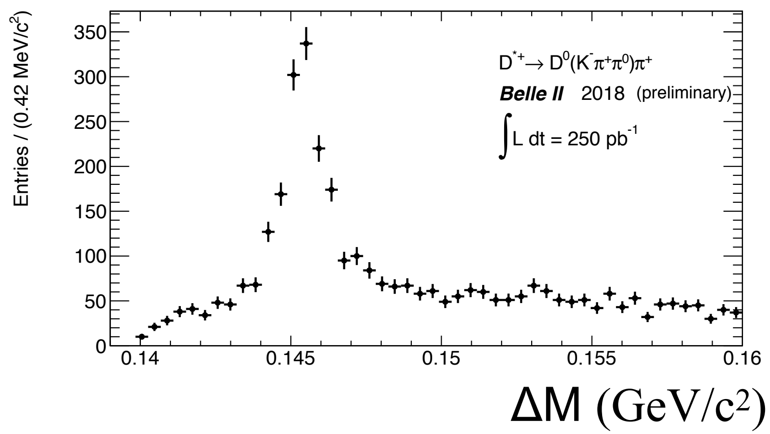
$\Delta M = M(D^*) - M(D)$

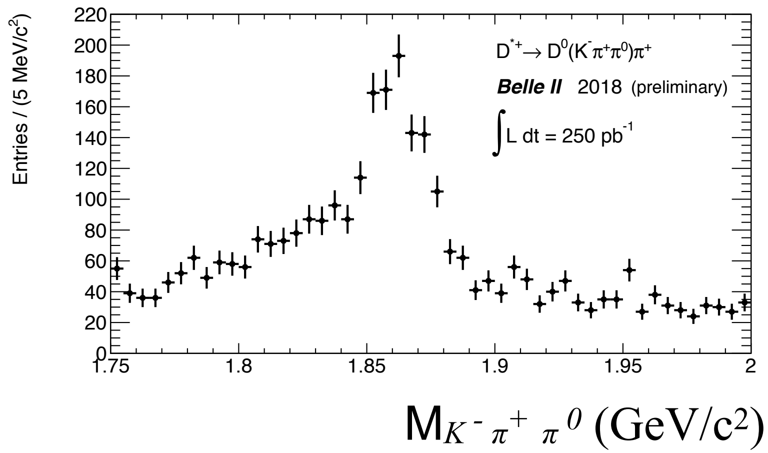
$D^{*\pm} \to D\,(K^- \pi^+)\,\pi^\pm$



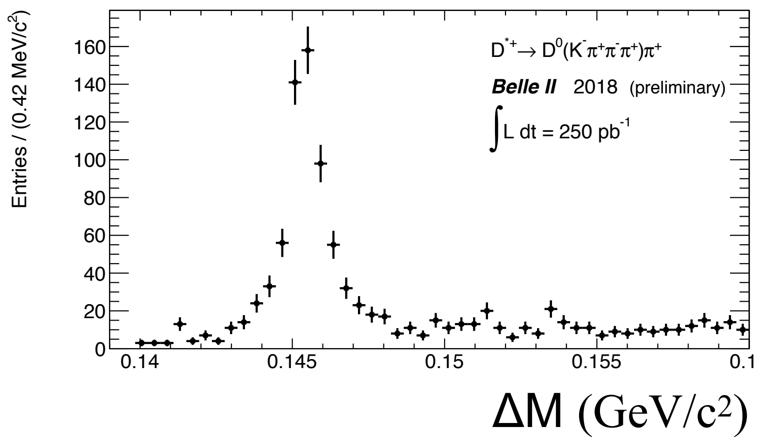


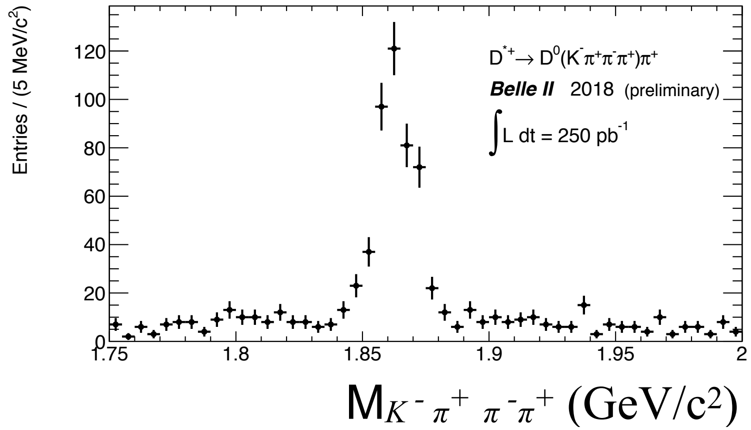
$D^{*\pm} \to D\,(K^- \pi^+ \pi^0)\,\pi^\pm$





$D^{*\pm} \to D\,(K^- \pi^+ \pi^- \pi^+)\,\pi^\pm$

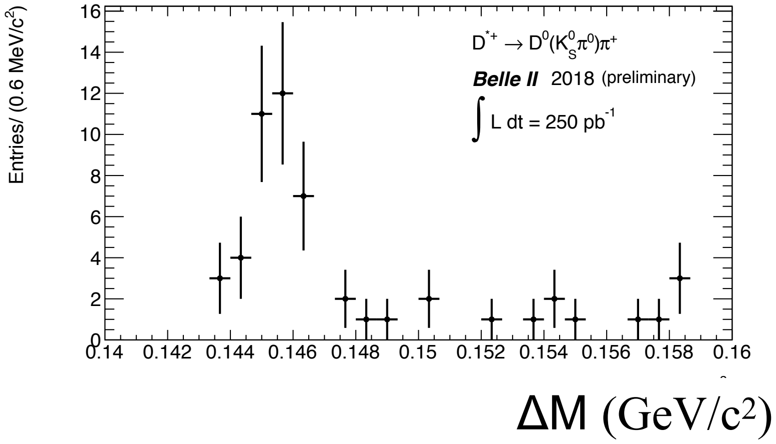


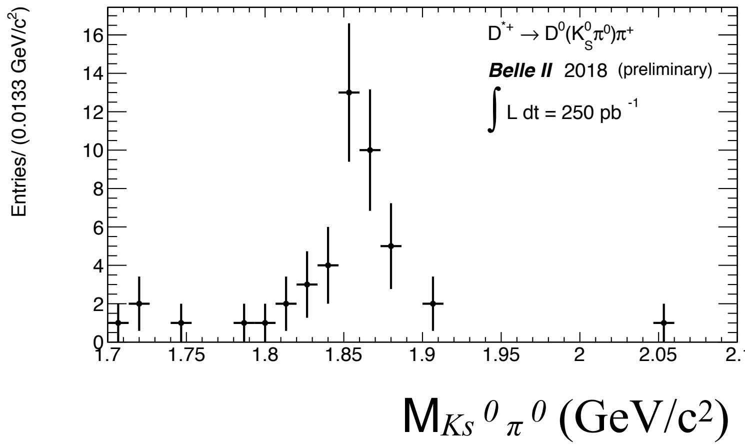


REDISCOVERIES with Phase II Collision Data Sample

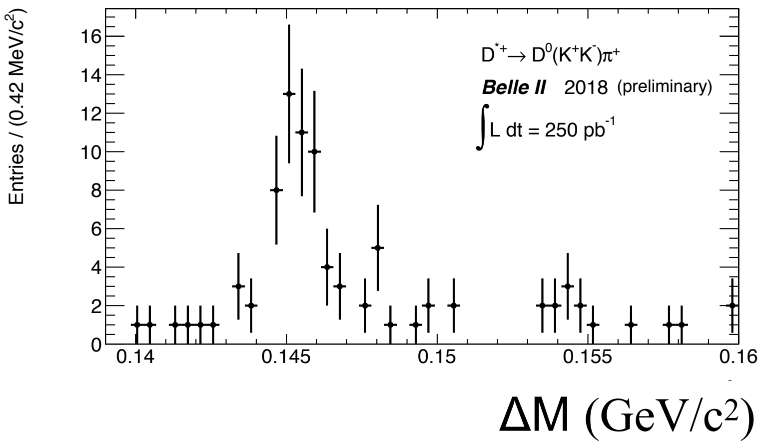
- *CP* eigenstates $K_s^0\,\pi^0$ and K^+K^- (Singly Cabibbo Suppressed) of D decay **are observed.**

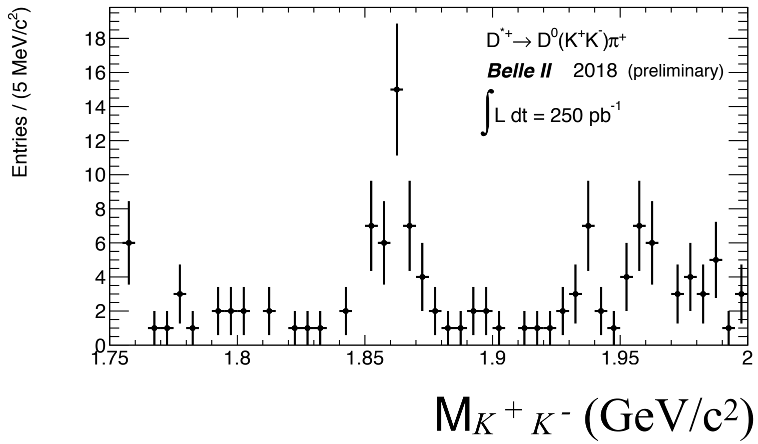
$D^{*\pm} \rightarrow D\,(K_s^0\,\pi^0)\,\pi^\pm$





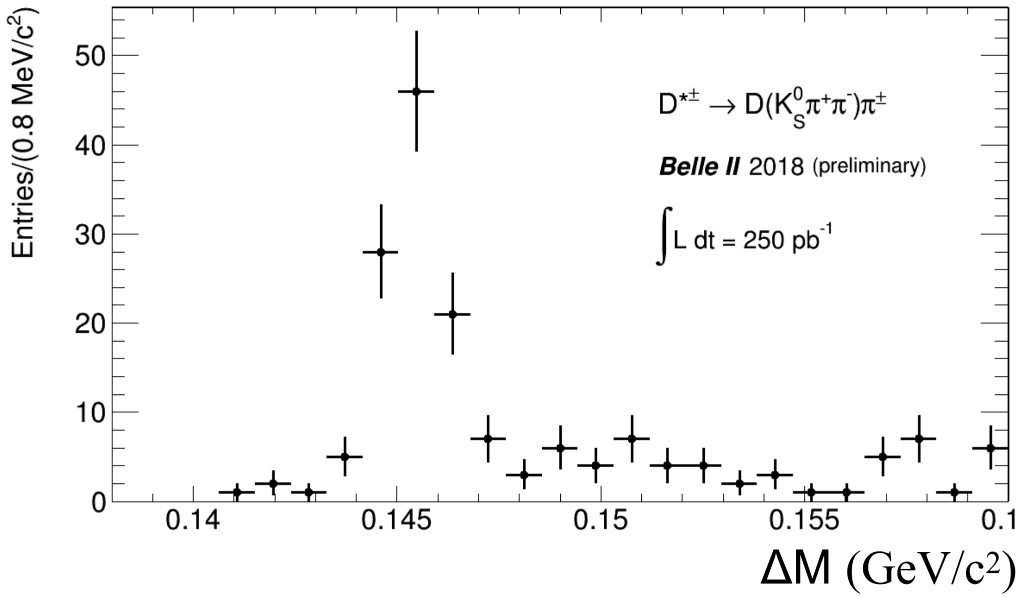
$D^{*\pm} \rightarrow D\,(K^-\,K^+)\,\pi^\pm$

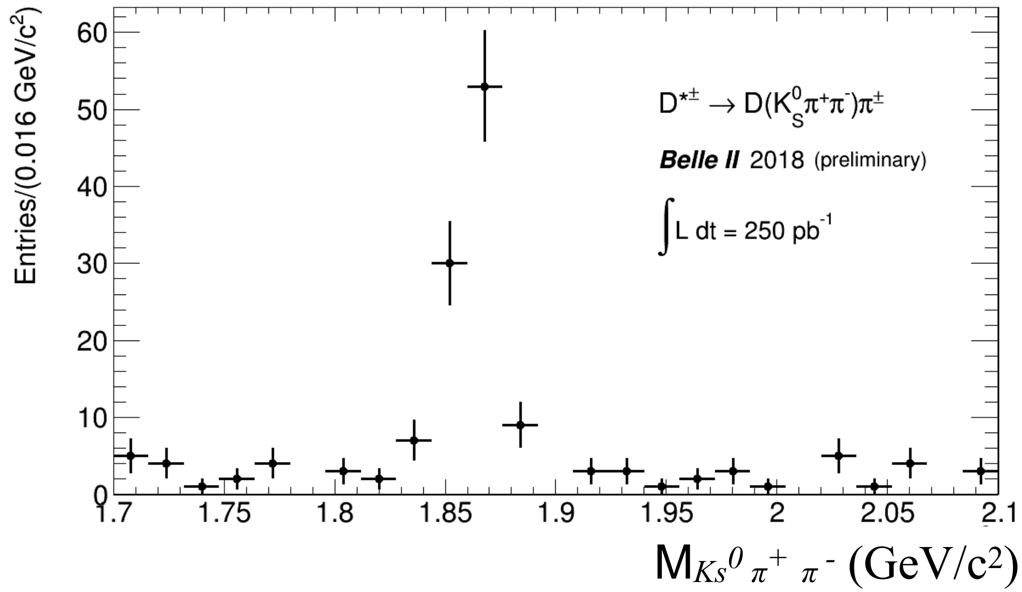




REDISCOVERIES with Phase II Collision Data Sample

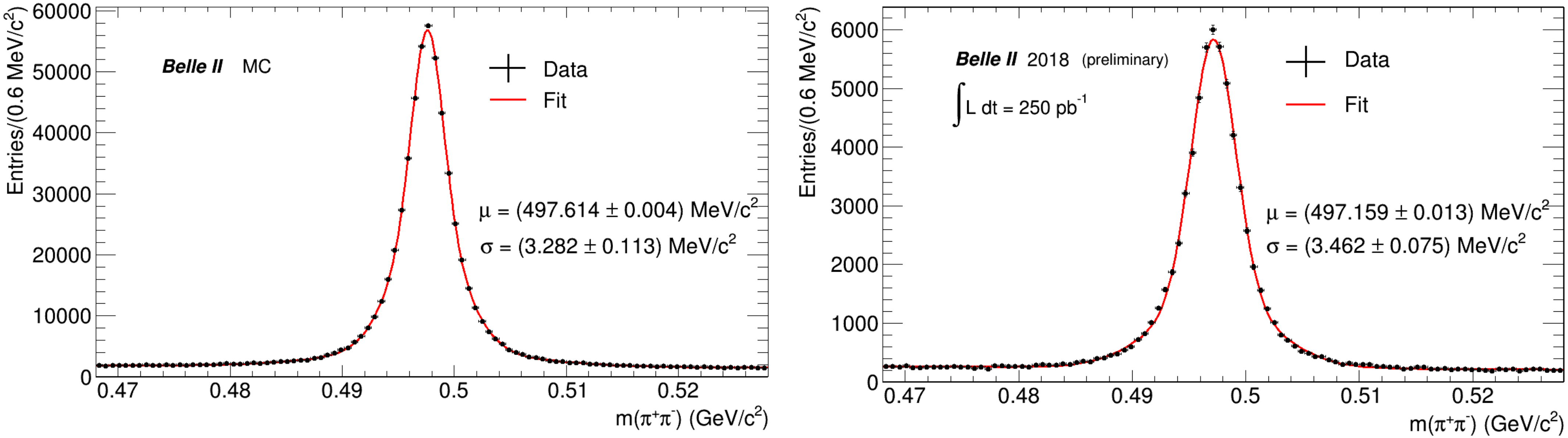
- $D^{*\pm} \to D\,(\boldsymbol{K_s\,\pi^+\,\pi^-})\,\pi^{\pm}$ is observed.
- Important D final state for γ/ϕ_3 measurement from $B \to DK$.





K_s^0 Invariant Mass

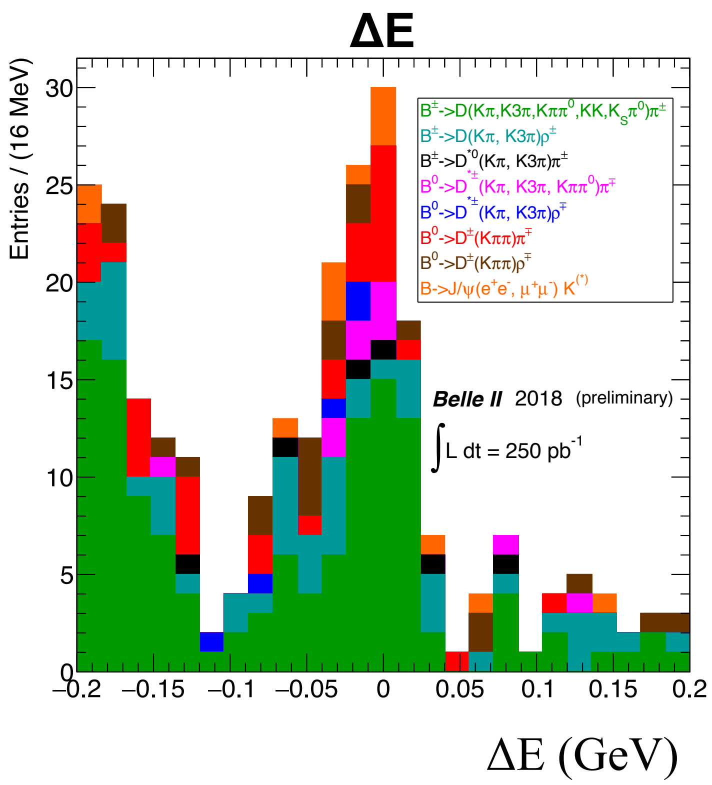
Belle II MC | Collision Data

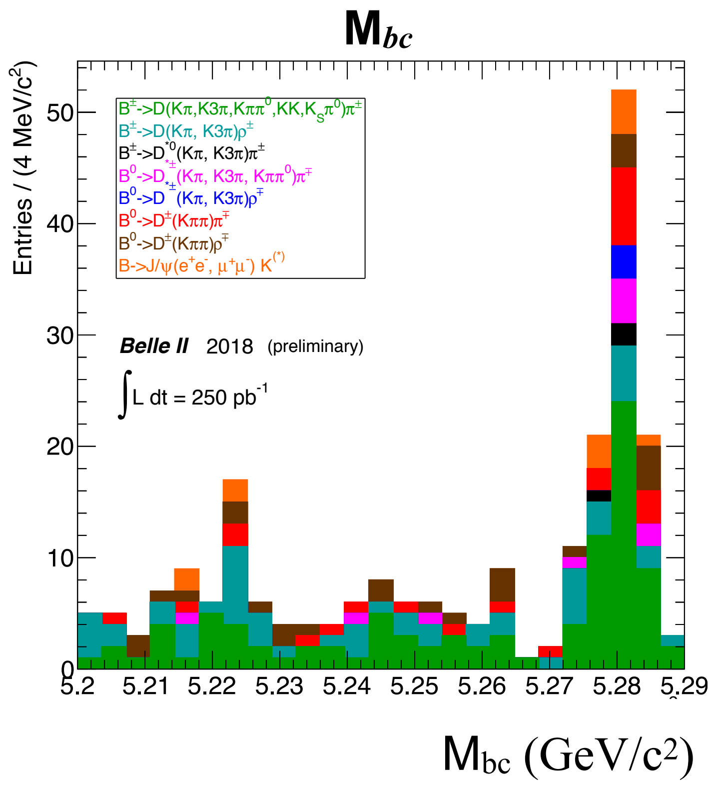


- MC sample is produced in a way to mimic the real data [$e^+e^- \to qq$ (where q = b, c, s, d, u) $e^+e^- \to \mu^+ \mu^-$ and $e^+e^- \to \tau^+ \tau^-$].
- Mass resolution difference already is order of 5 %.
- Tracking efficiency measurements are ongoing.

REDISCOVERIES with Phase II Collision Data Sample

- ***B → D hadron*** **rediscoveries:**



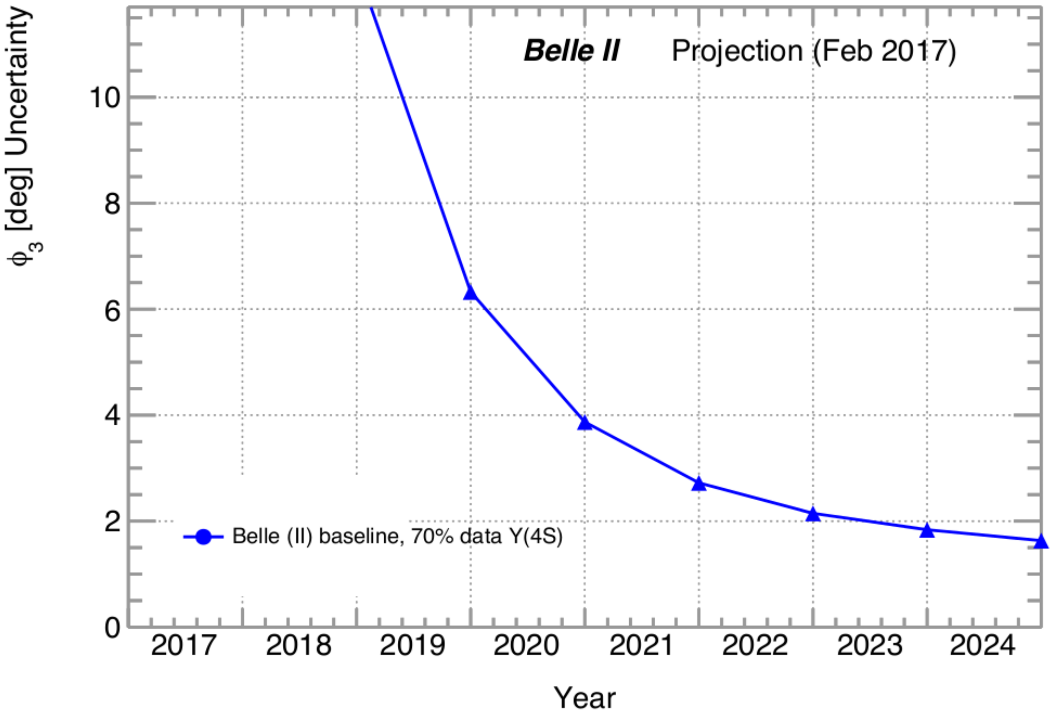


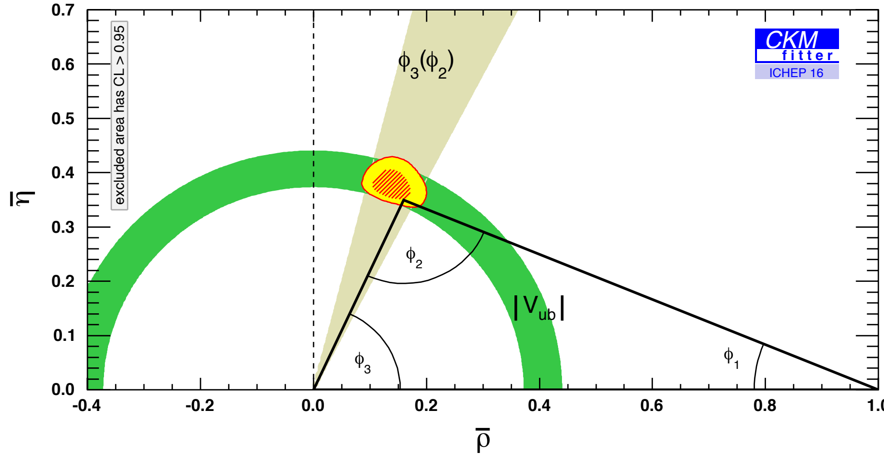
Mode	yield
$B^{\pm} \to D\pi^{\pm}$	51
$B^{\pm} \to D\rho^{\pm}$	16
$B^{\pm} \to D^{*}\pi^{\pm}$	3
$B^{0} \to D^{*\pm}\pi^{\mp}$	7
$B^{0} \to D^{*\pm}\rho^{\mp}$	3
$B^{0} \to D^{\pm}\pi^{\mp}$	13
$B^{0} \to D^{\pm}\rho^{\mp}$	8
$B \to J/\psi K^{(*)}$	8

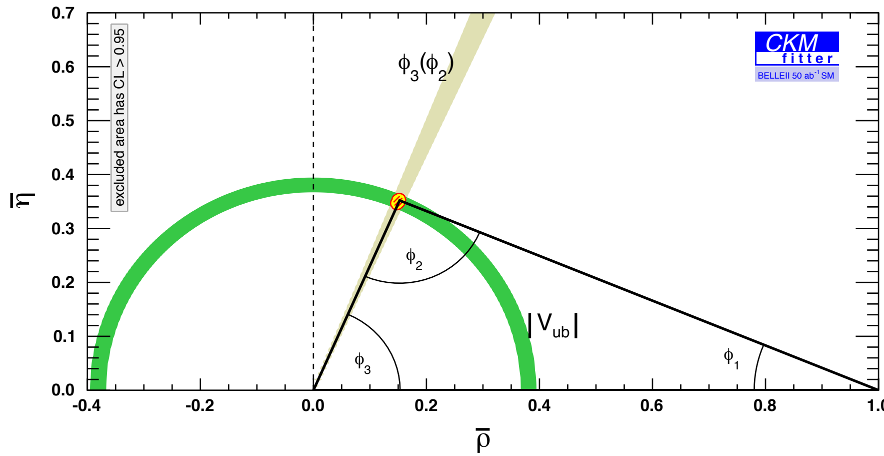
Measurement of γ/ϕ_3 @ *Belle II*

- γ/ϕ_3 precision is now better than 5°.
- $B^\pm \to D\,(\to K_s^0\,\pi^+\,\pi^-)\,K^\pm$ → the most sensitive single analysis in *Belle II*.
- Conservatively, combined sensitivity:

$$\delta(\gamma/\phi_3)^{50\,ab^{-1}} = \mathbf{1.6°}$$







CKM constraints from tree-dominated decays. Now and at 50 ab^{-1}

Prospects for Charm at *Belle II*

- The following projections are extrapolated from Belle measurements:

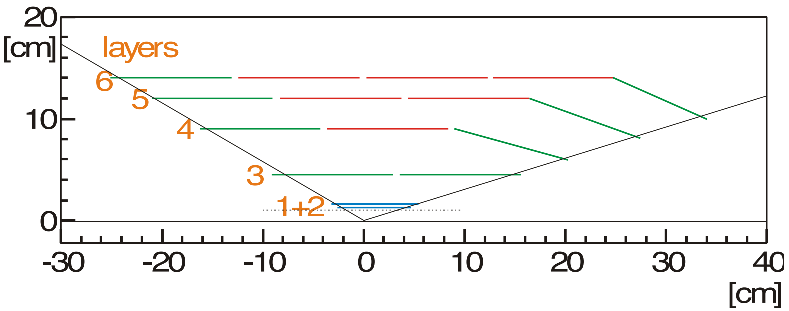
$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys}) \cdot \frac{\mathcal{L}_{Belle}}{50ab^{-1}} + \sigma^2_{irreducible}}$$

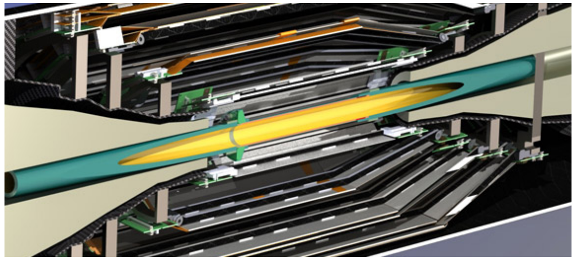
- Assumption : most of the systematics scale with statistics.

  - Maybe (other) sources of systematic errors that do not scale with statistics, that show up only in very high statistics samples.
    - *Belle II* will have high statistics control samples to keep them under control

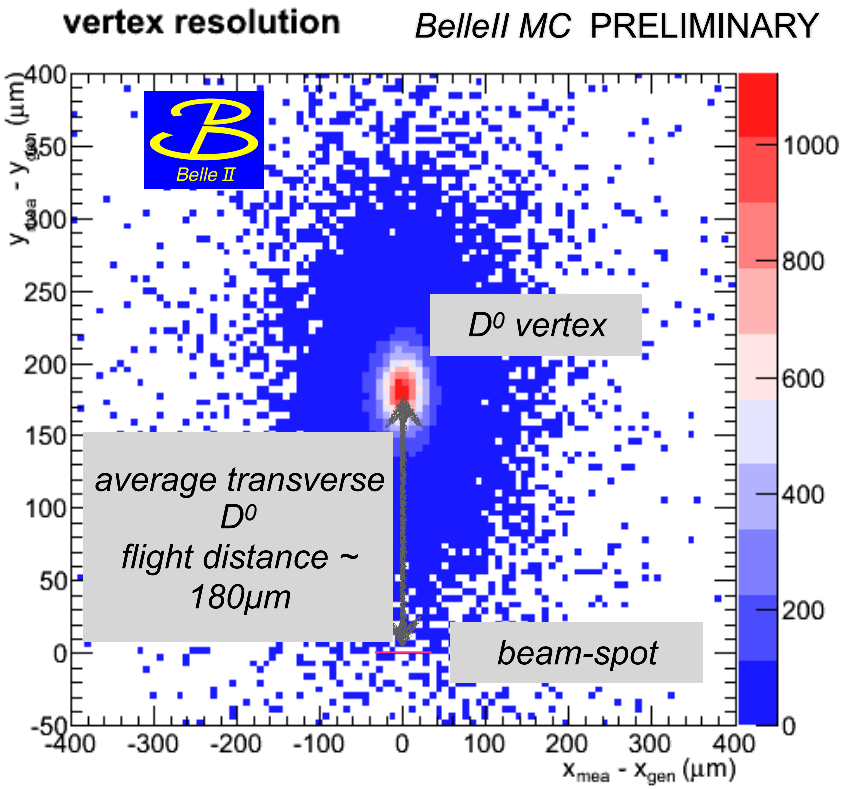
- The detector improvements w.r.t. *Belle* will be helpful, but their effect is *not included* in these extrapolations unless otherwise stated.

D^0 Decay Vertex Resolution

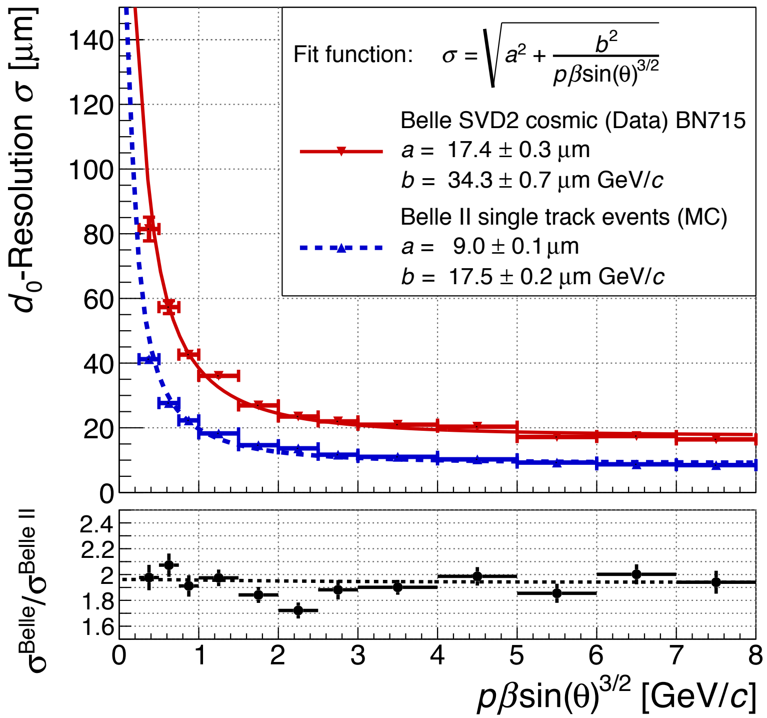


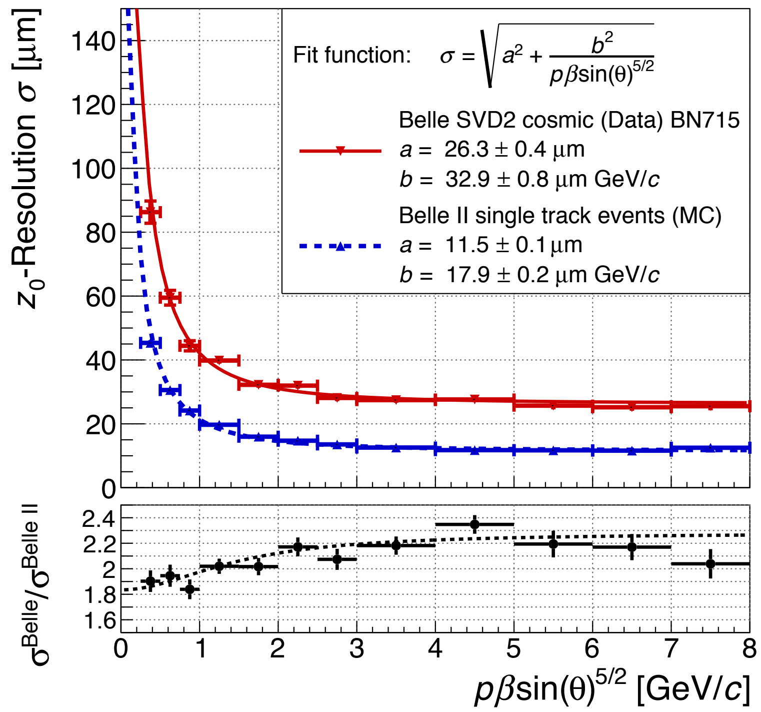


Vertex detector:
double layer of DEPFET pixels + 4 layers DS Si strips



Belle II:
σ≈40 μm

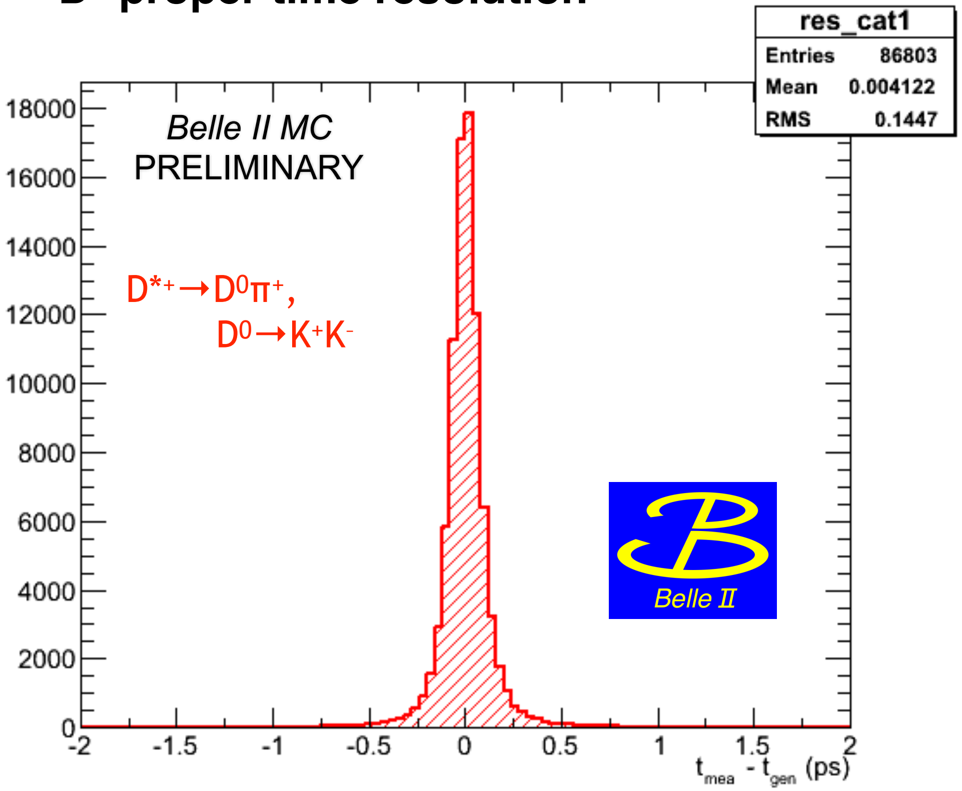


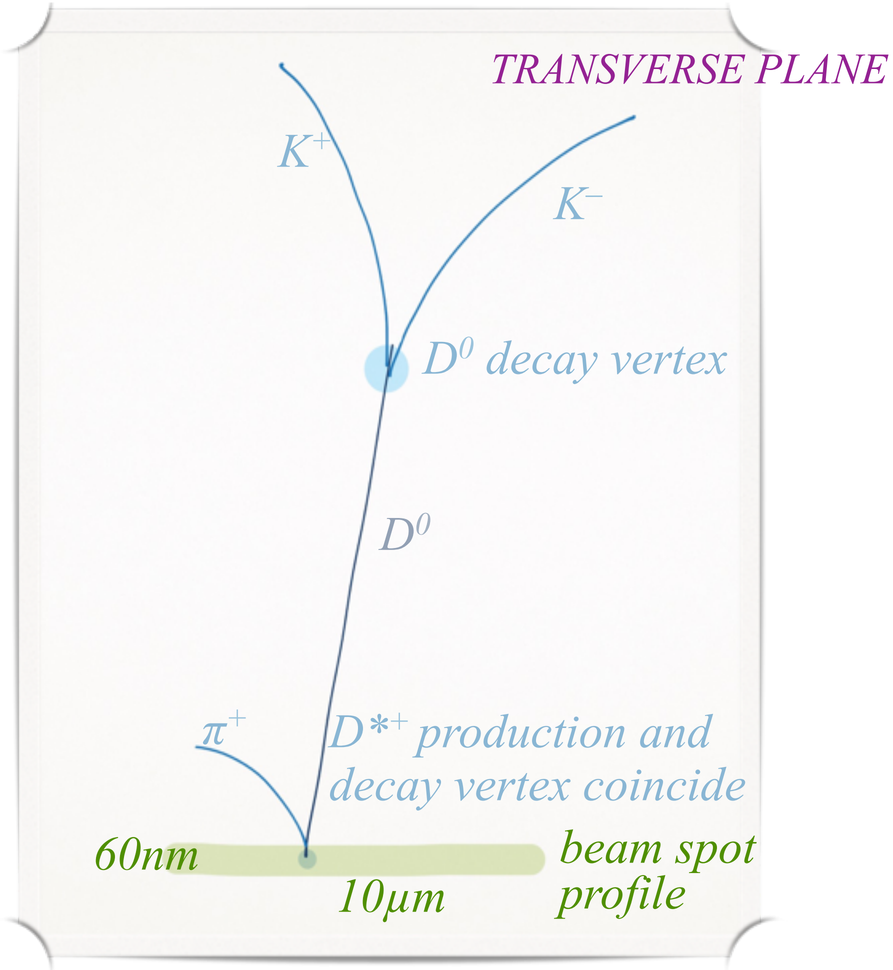


D^0 Proper Time Resolution

$$t = \frac{\ell}{\beta\gamma c} = \frac{\ell}{c}\frac{m_D}{|\vec{p}|}$$

D^0 proper time resolution





resolution = 0.14 ps

(2 times better than Belle/BABAR (0.27 ps))

$K\pi$, $\pi\pi$ results are similar

Mixing and Indirect *CPV*

Belle II

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys}) \cdot \frac{\mathcal{L}_{Belle}}{50ab^{-1}} + \sigma^2_{irreducible}}$$

Comment	Mode	observable	Belle ~ 1 ab⁻¹	Belle II 50 ab⁻¹	
systematics free measurement	$D^0 \to K^+\pi^-$	x'^2 (%)	± 0.022	± 0.003	~ factor 8-10 better
		y' (%)	± 0.34	± 0.04	
		$\|q/p\|$	± 0.6	± 0.06	
		ϕ	± 25°	± 2.3°	
comparable contributions from statistical and systematic errors	$D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$	y_{CP} (%)	± 0.22	± 0.04	~ factor 6 better
		A_Γ (%)	± 0.20	± 0.03	
limited by systematics related to DP model. will be improved by model-independent approach	$D^0 \to K_S\pi^+\pi^-$	x (%)	± 0.19	± 0.08	~ factor 3 better
		y (%)	± 0.15	± 0.05	
		$\|q/p\|$	± 0.16	± 0.06	
		ϕ	± 11°	± 4°	

Time-integrated CP Asymmetry

$$A_{CP}^{f} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} = a_d^f + a_{ind}^f$$

$$\sigma_{BelleII} = \sqrt{(\sigma_{stat}^2 + \sigma_{sys}^2) \cdot \frac{\mathcal{L}_{Belle}}{50ab^{-1}} + \sigma_{irreducible}^2}$$

Channel	Current measurement $\mathcal{L}$(/fb)	value(%)	References	Belle II 50 ab^{-1}(%)
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	PRL **112**, 211601 (2014)	± 0.09
$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.17$	PRL **119**, 171801 (2017)	± 0.20
$D^0 \to K_S^0 \pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	PRL **112**, 211601 (2014)	± 0.03
$D^0 \to K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	PRL **106**, 211801 (2011)	± 0.07
$D^0 \to K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	PRL **106**, 211801 (2011)	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 0.41 \pm 1.23$	PLB **662**, 102 (2008)	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	PRL **95**, 231801 (2005)	± 0.40
$D^+ \to \pi^0\pi^+$	921	$+2.31 \pm 1.24 \pm 0.23$	Belle Preliminary	± 0.40
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	PRL **107**, 221801 (2011)	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	PRL **107**, 221801 (2011)	± 0.14
$D^+ \to K_S^0\pi^+$	977	$-0.363 \pm 0.094 \pm 0.067 (3.2\sigma)$	PRL **109**, 021601 (2012)	± 0.03
$D^+ \to K_S^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	JHEP **02** (2013) 098	± 0.05
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	PRL **104**, 181602 (2010)	± 0.29
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	PRL **104**, 181602 (2010)	± 0.05

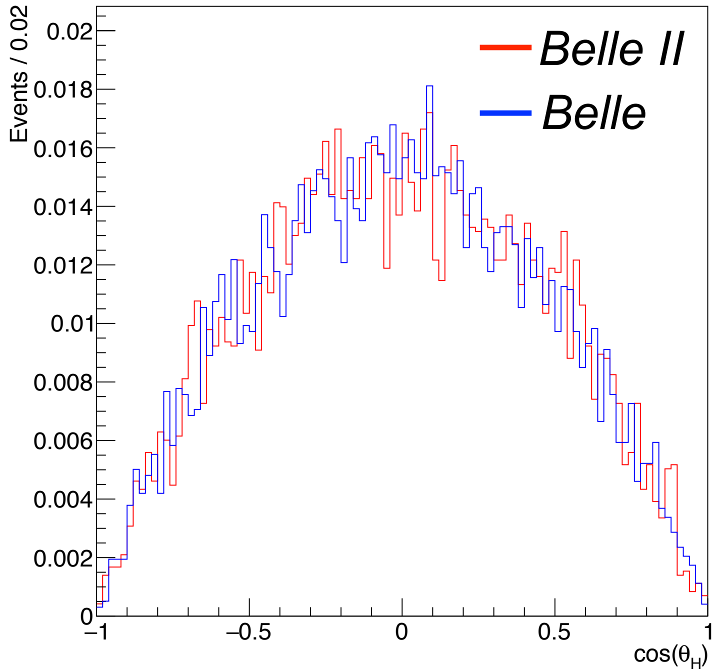
- *Belle II* has advantages of excellent γ and π^0 reconstruction.
- A_{CP} precision will reach $\mathcal{O}$ (0.01%).

Direct *CPV* in $D^0 \to \phi\gamma$ and $D^0 \to \rho\gamma$

- Sensitive to New Physics (NP) in terms of A_{CP}.
  - Standard Model (SM) prediction: $\mathcal{O}(10^{-3})$
  - NP contributions: up to several % . *[Phys. Rev. Lett. 109, 171801 (2012)]*

- A_{CP} and branching fraction ($\mathcal{B}$) → completed at *Belle.*
- *Belle II* sensitivity estimation for A_{CP} based on MC study

- Statistical error is dominant for A_{CP}.



Radiative Decays	*Belle* A_{CP} Results	*Belle II* Uncertainty		
	976 fb^{-1}	5 ab^{-1}	15 ab^{-1}	50 ab^{-1}
$D^0 \to \rho^0\gamma$	+0.056 ± 0.152 ± 0.006	± 0.07	± 0.04	± 0.02
$D^0 \to \phi\gamma$	-0.094 ± 0.066 ± 0.001	± 0.03	± 0.02	± 0.01

[Phys.Rev.Lett.118,051801 (2017)]

Full Charm Event Reconstruction

- Use energy and momentum conservation to search for rare $D^+ \to l^+ \nu$ and $D^0 \to \nu\, \nu$ etc.

  [JHEP 09, 139 (2013)]

light mesons (K, π, ...)

$$e^+e^- \to c\bar{c} \to D_{tag}X_{frag}D_{sig}$$

($D^{(*)0}$, $D^{(*)+}$, $D_s^{(*)+}$, Λ_c^+) signal

- **Example:** Leptonic decay $D^+ \to \mu^+ \nu$

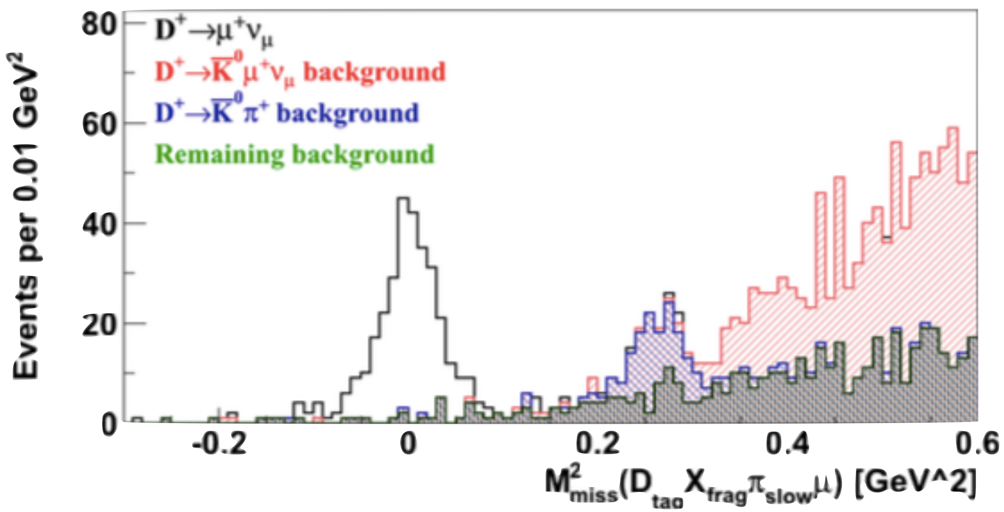
$$e^+e^- \to c\bar{c} \to D_{tag}X_{frag}D^{*+}$$
$$\hookrightarrow D^+\pi^0$$

- missing quantities are computed for the system

$$D_{tag} + X_{frag} + \pi_{slow} + \mu^+$$

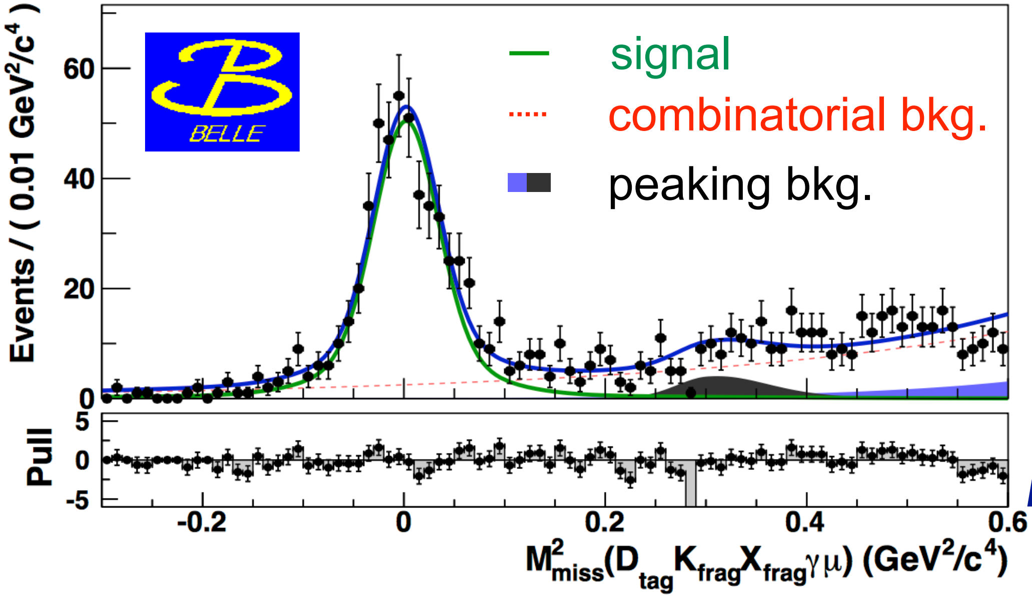
$$M^2_{miss}(\nu) = (E_{miss} - |\vec{p}|_{miss})(E_{miss} + |\vec{p}|_{miss})$$

***Belle* MC Simulation [5.5 ab^{-1}]**



Leptonic Decays $D_s^+ \rightarrow \mu^+ \nu$

$$e^+e^- \rightarrow D_{tag} X_{frag} K D_s^{*+}$$
$$\hookrightarrow D_s^+ \gamma$$



[JHEP 09, 139 (2013)]

- Require one charged track passing μ ID and pointing to IP
- Fit to missing mass distribution
- Same analysis procedure for $D^+ \rightarrow \mu^+ \nu$

- Belle simulation with 5.5 ab^{-1}, scaled to 50 ab^{-1}, yields:

	$D_s^+ \rightarrow \mu^+ \nu$ (yields)		$D^+ \rightarrow \mu^+ \nu$ (yields)	
	inclusive	exclusive	inclusive	exclusive
Belle, 913 fb^{-1}	94400	490	–	–
BelleII, 50 ab^{-1}	5.2 x 10^6	27 x 10^3	3.5x10^6	1250

$\delta(|V_{cs}|) = 0.004$(stat)

$\delta(|f_{Ds}|) = 0.9$(stat)

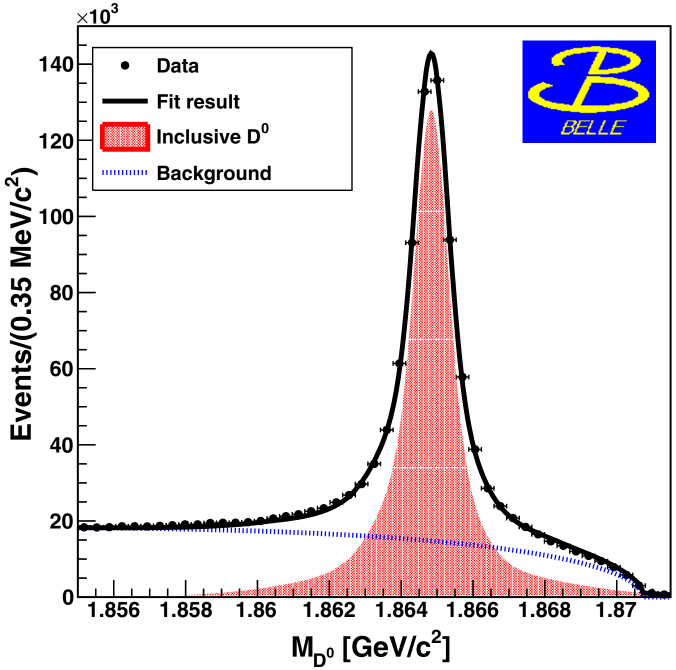
~1/3 of the theory error

$\delta(f_D|V_{cd}|) = 1.3$

competitive with CLEOc (1.2) and BESIII (1.9)

D^0 Decays to Invisible : $D^0 \to \nu\nu$

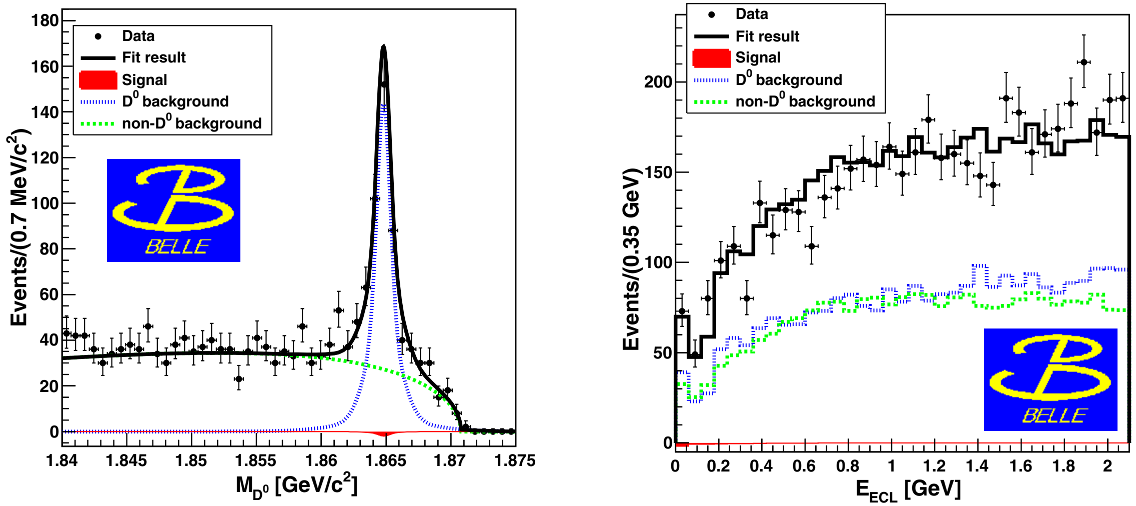
$$e^+e^- \to D_{tag} X_{frag} D^{*+}$$
$$\hookrightarrow D^0 \pi_s^+$$



$$M_{D^0} \equiv M_{miss}(D_{tag}^{(*)} X_{frag} \pi_s^-)$$

1D fit on recoil D^0 mass

- 924 fb^{-1} *Belle* data
- no remaining final state particles associated with $D^0{}_{sig}$.
- 2D fit: M_D (recoil D^0 mass) and E_{ECL} (residual energy on calorimeter)



N$_{sig}$ = $-6.3^{+22.5}_{-21.0}$ consistent with zero.

	inclusive D^0 yield
Belle, 924 fb^{-1}	695000
***BelleII*, 50 ab^{-1}**	**38 x 10^6**

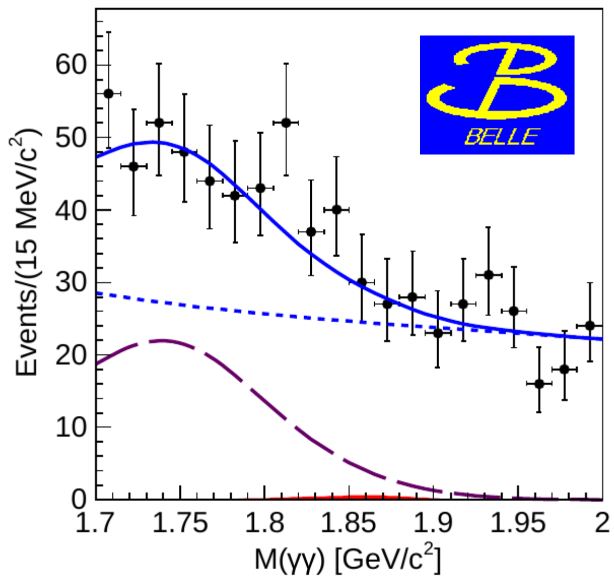
Rare Radiative Decay of $D^0 \to \gamma\gamma$

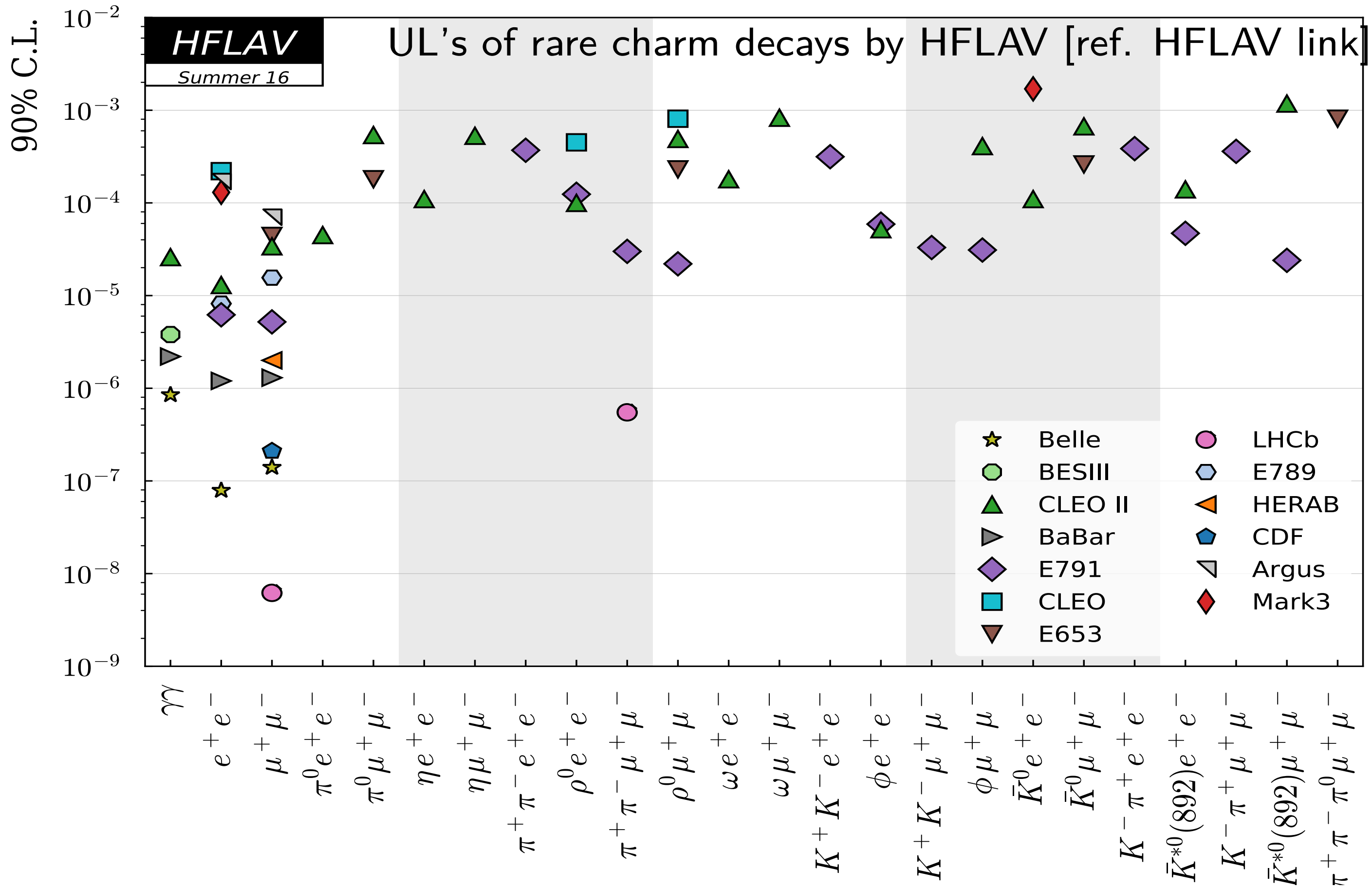
- $D^0 \to \gamma\gamma$ a sensitive probe to NP.
- *Belle* 832 fb^{-1} data:

  $\mathcal{B}$ < 8.5 x 10^{-7} at 90% CL approaching SM prediction (10^{-8})

- *Belle II* at 50 ab^{-1} : 10^{-7} to 10^{-8}

[PRD 93, 051102 (2016)]





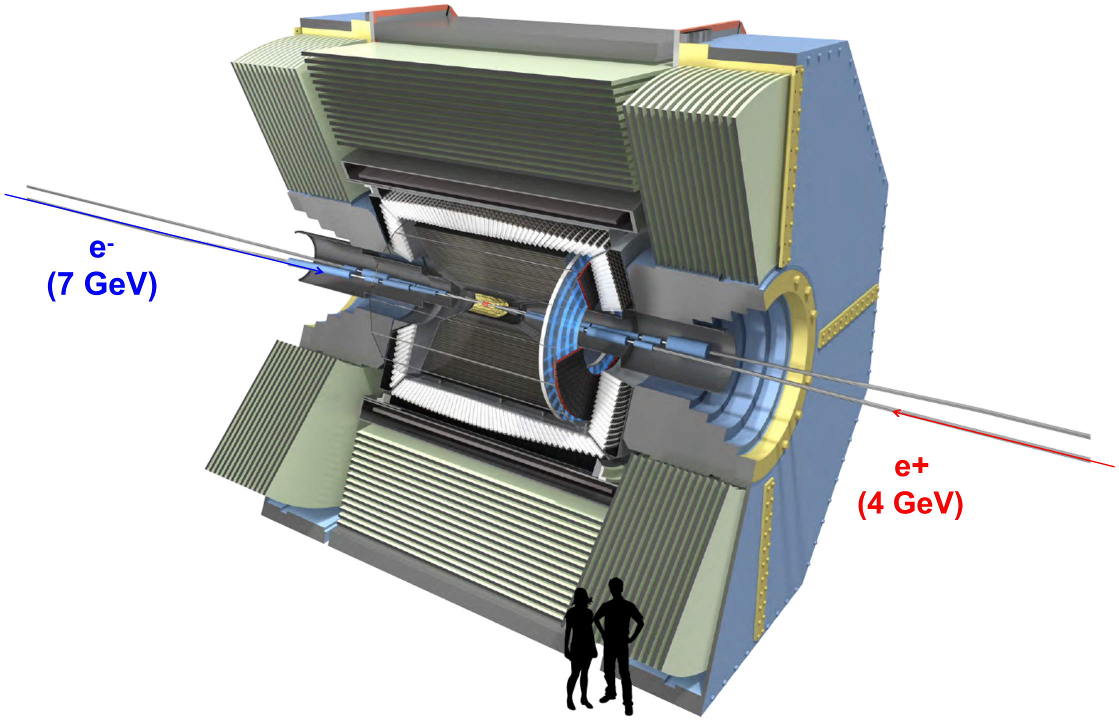
- Decays involving π^0, η and ω were mostly done by CLEO.
- *Belle II* can improve these UL by several orders of magnitude.

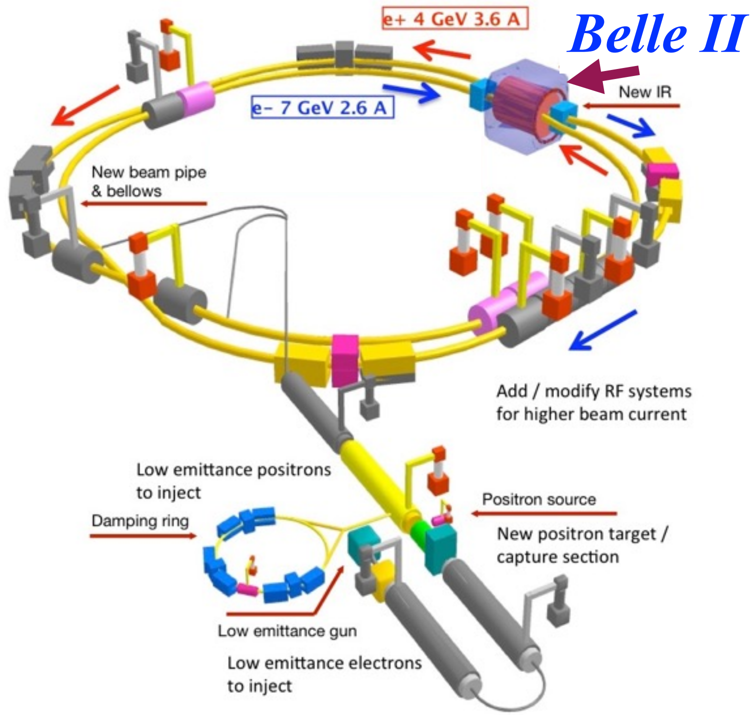
Summary

- First collision → April 26, 2018
- Phase II (partial *Belle II*) data taking is ongoing
  - will end on July 17, 2018.
- Physics Run (Phase III) will start in less than a year.
- γ/ϕ_3 precision at 50 ab^{-1} : **~1.6°** from $B \to D K$ decays.
- A rich *Belle II* charm physics program will
  - improve precision of
    - mixing and *CPV* parameters, direct *CP* asymmetries,
    - V_{cd} and V_{cs} from (semi)leptonic decays, decay constants f_D , f_{Ds}.
  - lower limits more on rare and forbidden decays.

EXTRA

Belle II Experiment @ SuperKEKB





- full solid angle detector; clean event environment; well defined initial state.
- Increase K_s^0 efficiency.
- improved K/π separation.
- improved reconstruction, selection and tagging algorithms.
- ....

- $\mathcal{L}_{peak}$ = 8 x 10^{35} cm^{-2} s^{-1} (40 x *KEKB*)
- $\mathcal{L}_{int}$ > 50 ab^{-1} by 2025 (50 x *Belle*)
- Each 1 ab^{-1} experimental data
  - ~1.1 x 10^9 $B\bar{B}$ ⇒ a super B-factory;
  - ~1.3 x 10^9 $c\bar{c}$ ⇒ a super charm-factory;
  - ~0.9 x 10^9 $\tau^+\tau^-$ ⇒ a super τ-factory;