Prospects of Charm Physics at Belle II

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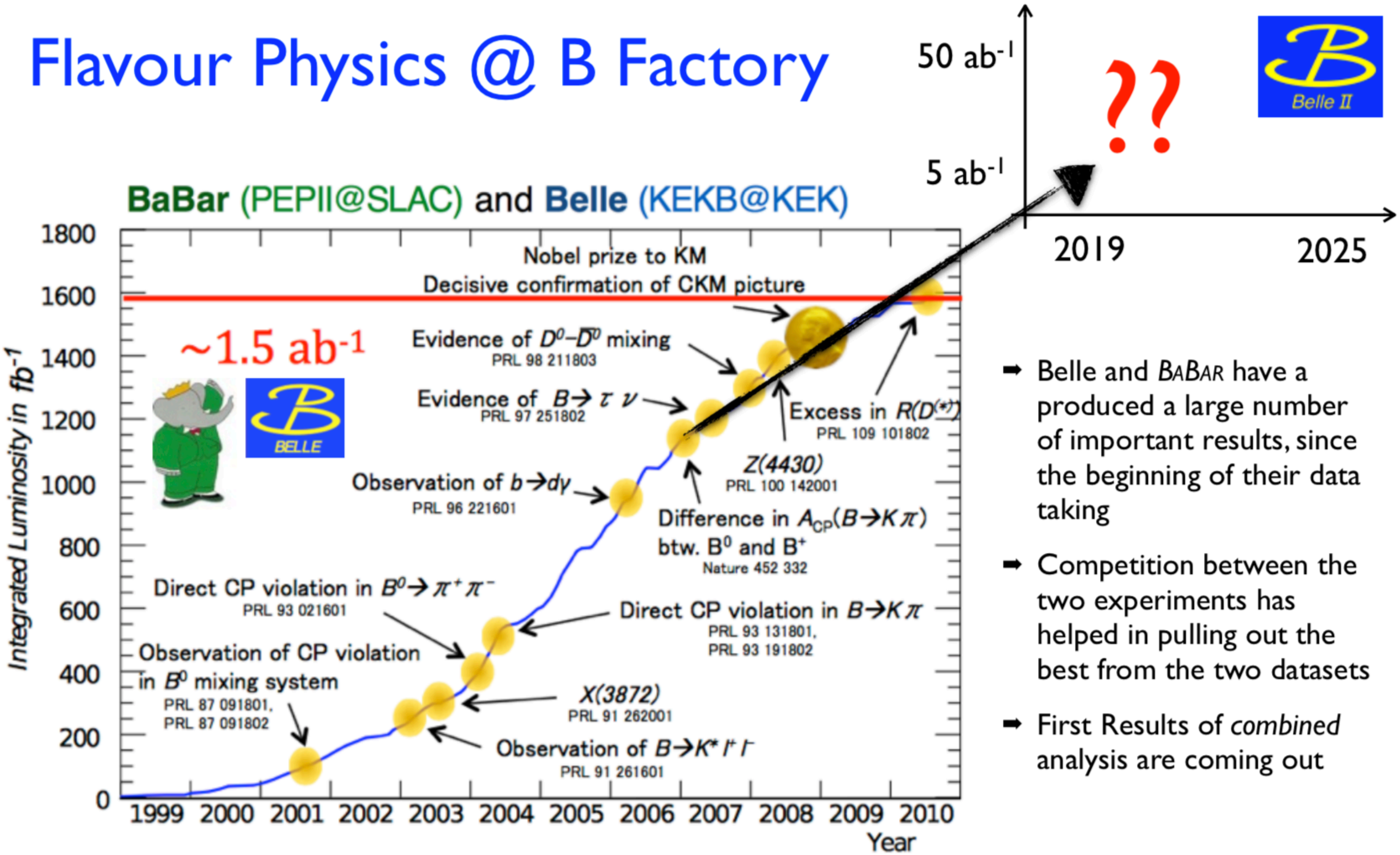
Wuhan, Nov.09-12, 2018

Outline

- SuperKEKB and Belle II
- Prospects of charm physics at Belle II
  - Mixing and indirect CP Violation
  - Direct CPV
  - Rare and radiative decays
  - Leptonic decay
- Status of Belle II
- Summary

Achievements of B Factory

Flavour Physics @ B Factory

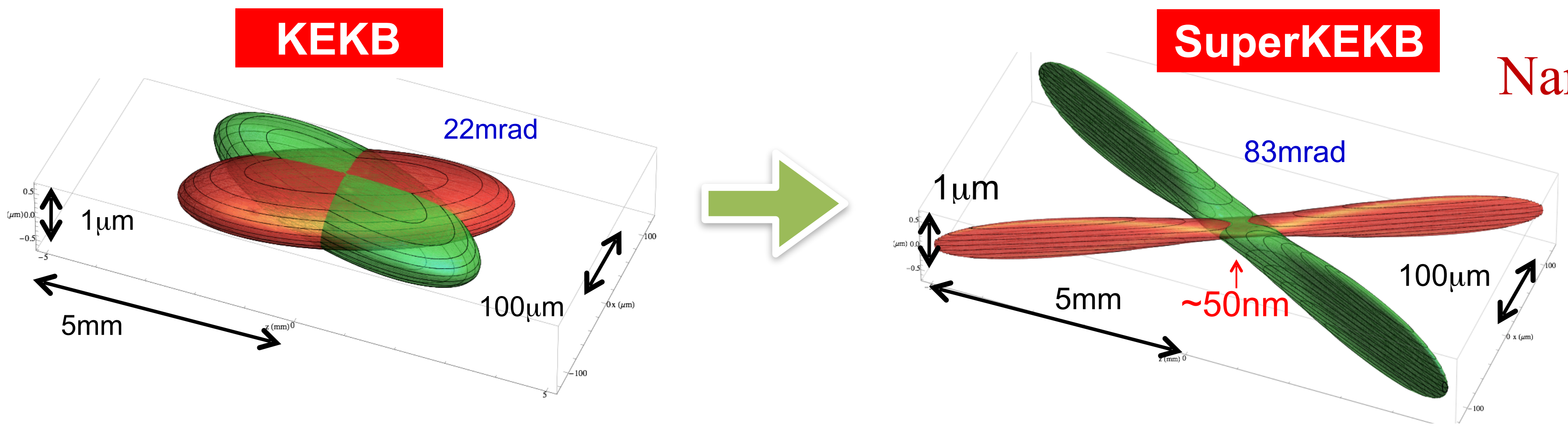


- Belle and BABAR have a produced a large number of important results, since the beginning of their data taking
- Competition between the two experiments has helped in pulling out the best from the two datasets
- First Results of *combined* analysis are coming out

Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

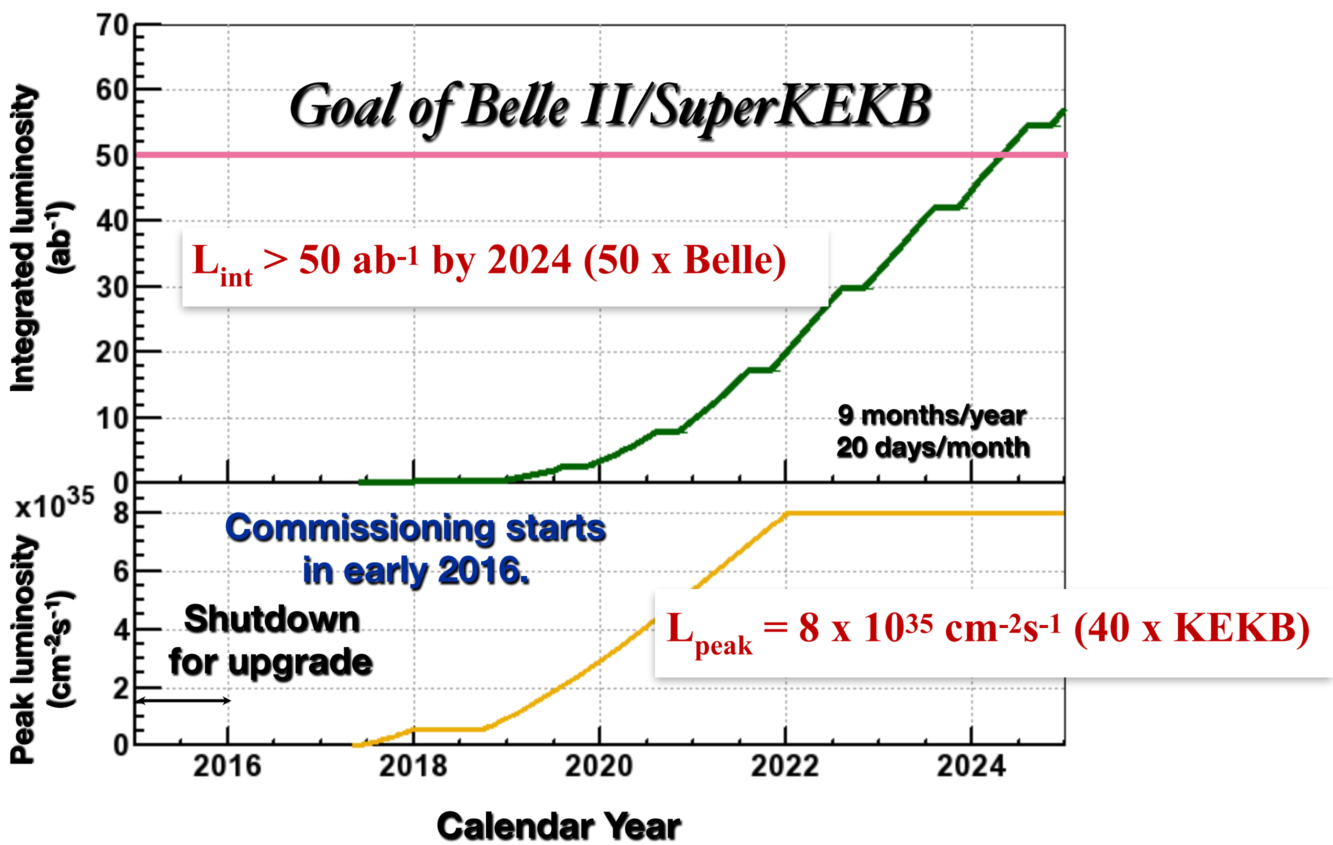

SuperKEKB
An asymmetric electron-positron collider
e+~ 4GeV e-~ 7GeV
~3km circumference
Belle II detector
@KEK, Tsukuba
One hour away from Tokyo

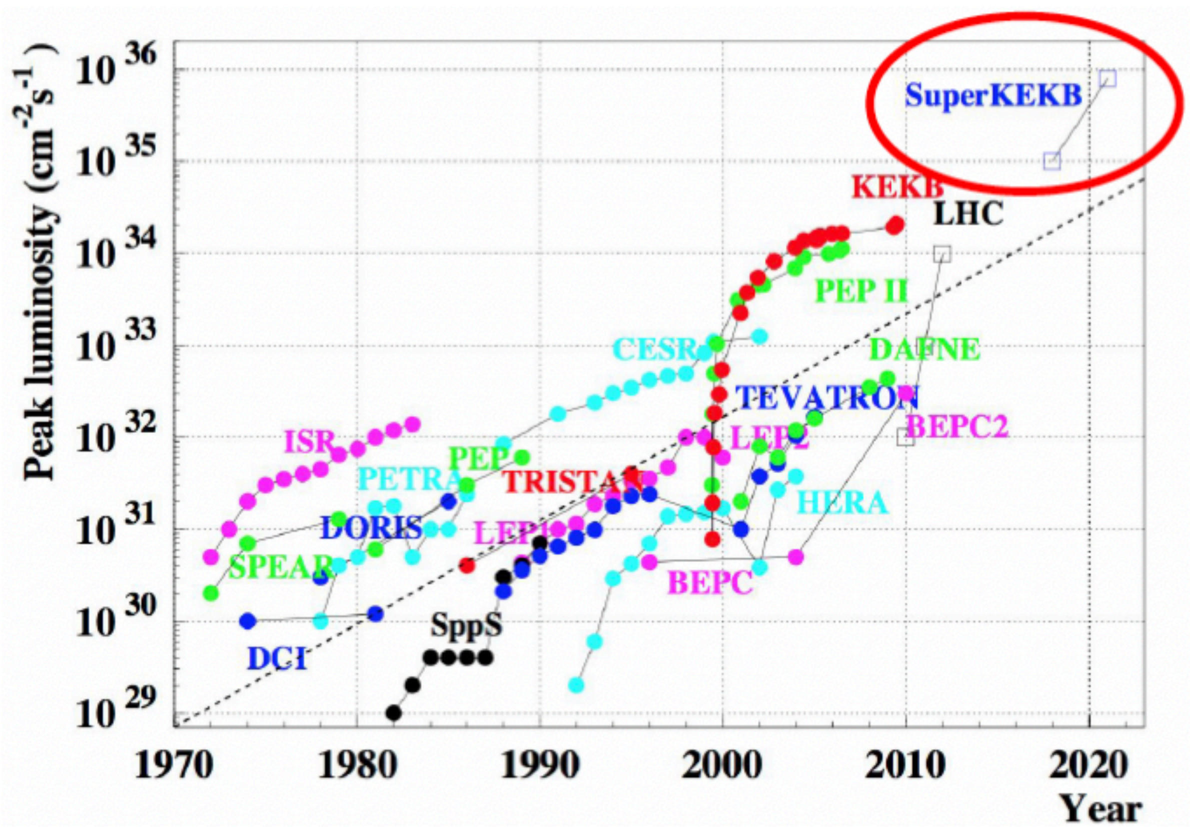
SuperKEKB



Nano-Beam Scheme

SuperKEKB Luminosity Project

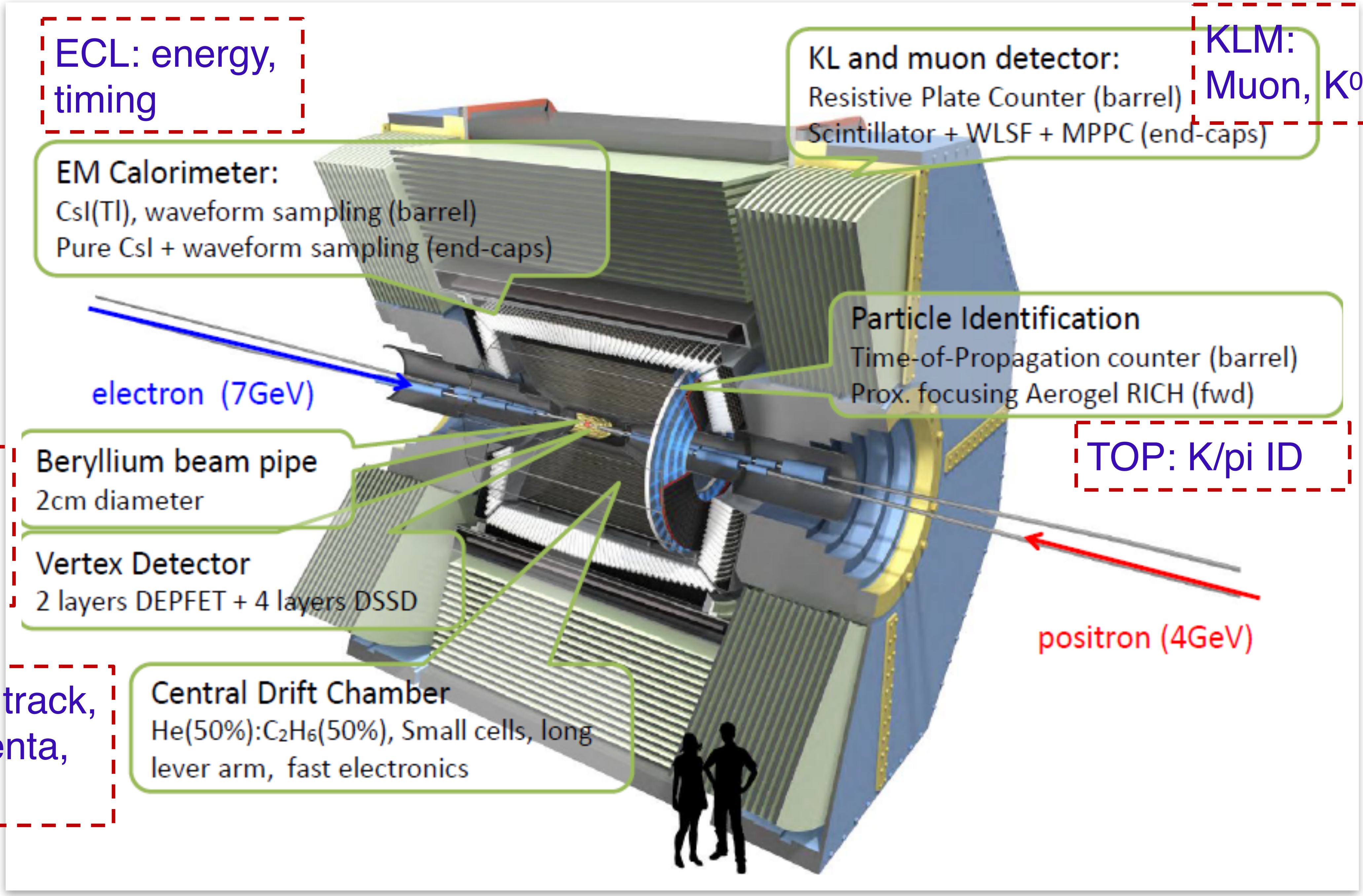




Belle II Detector

ECL: energy, timing

KLM: Muon, K^0_L



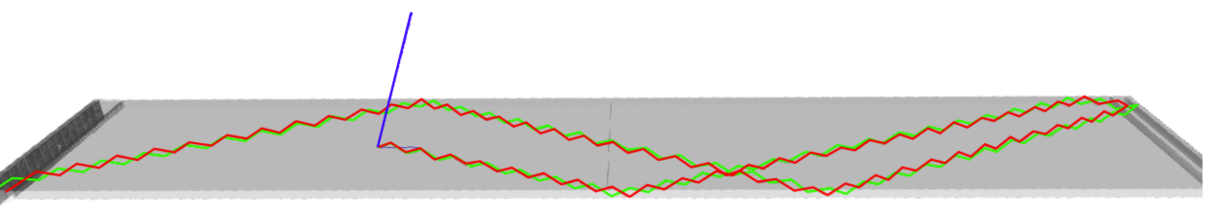
TOP: K/pi ID

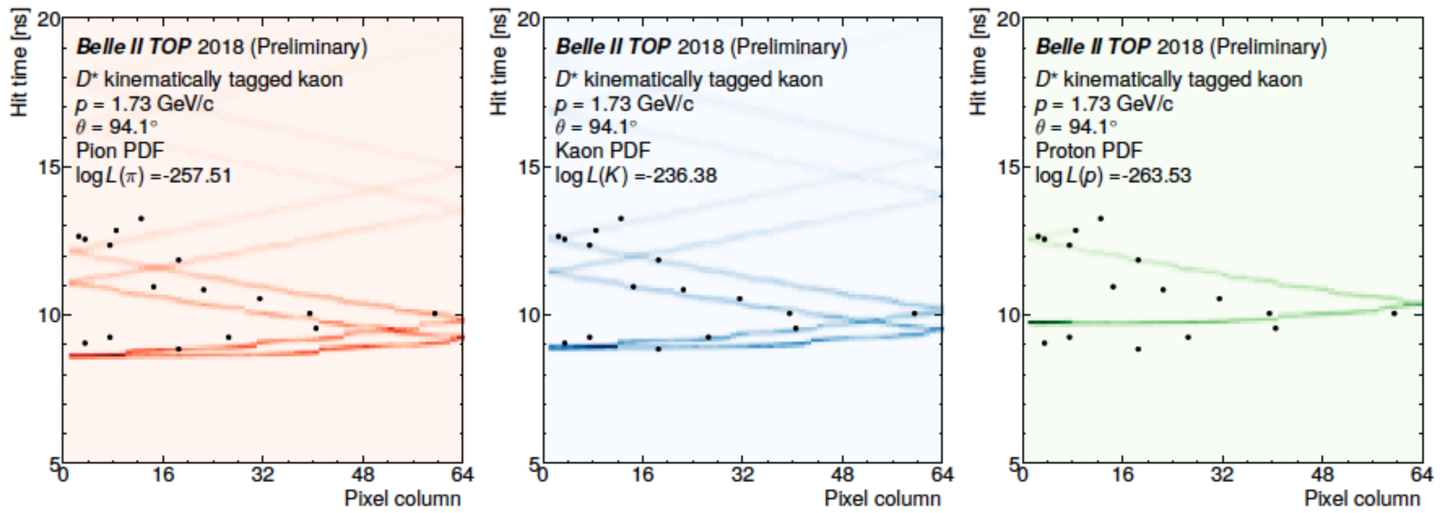
PXD,SVD: Decay vertex position

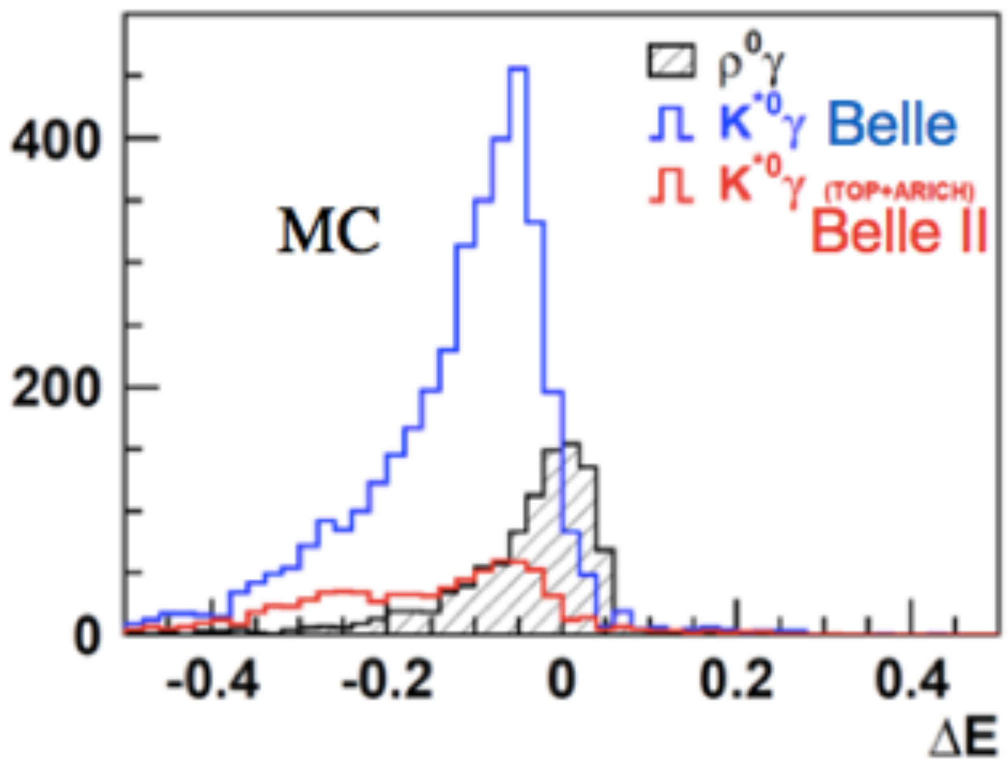
CDC: track, momenta, dE/dx

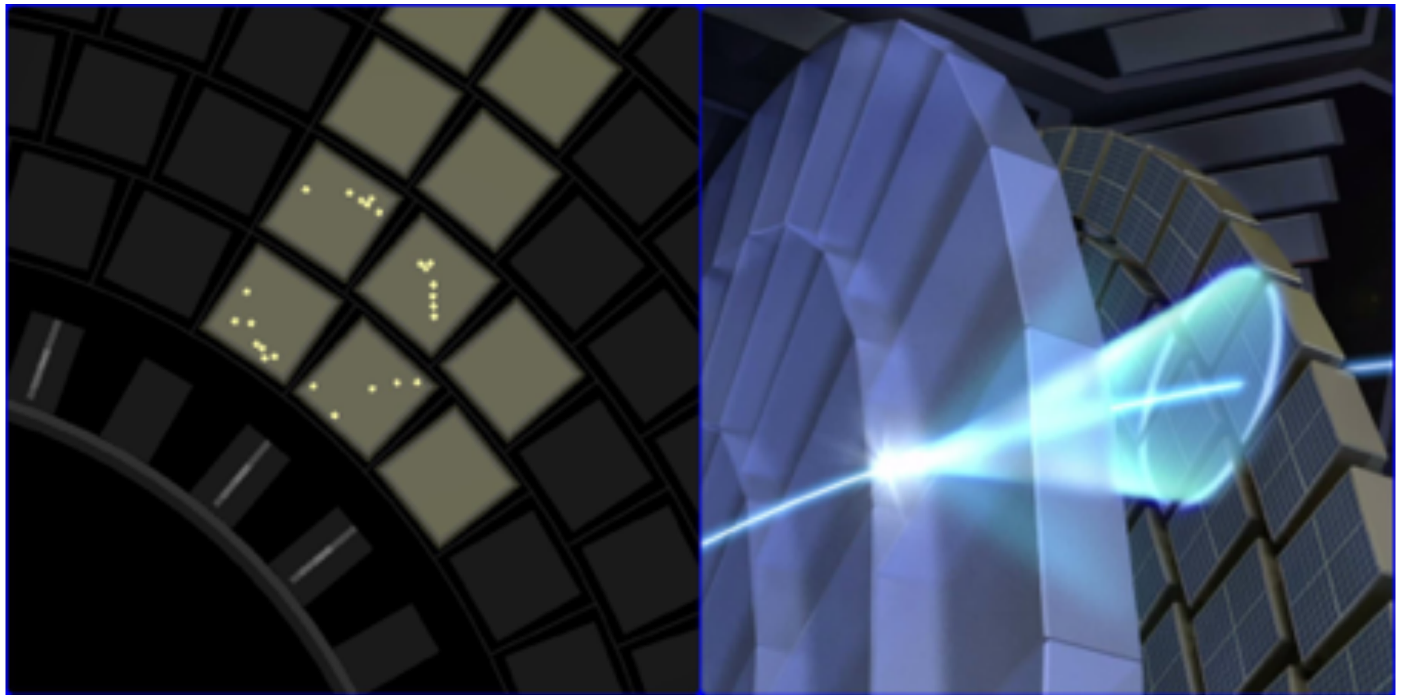
From Belle to Belle II

New PID System: Barrel TOP + Endcap ARICH







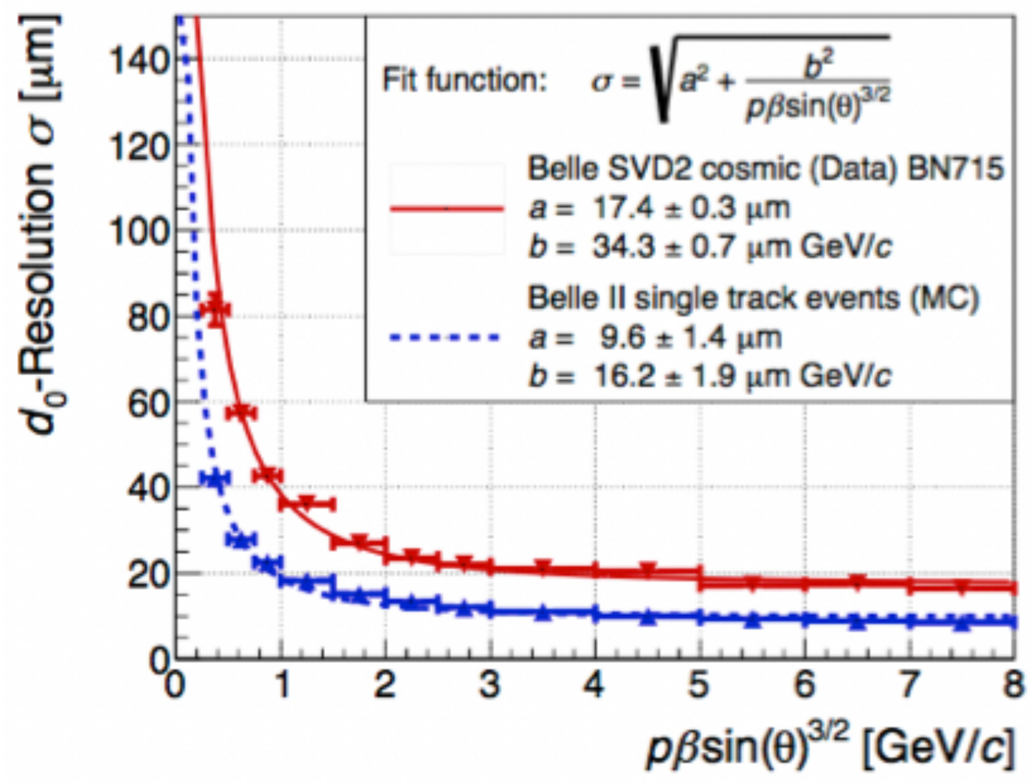


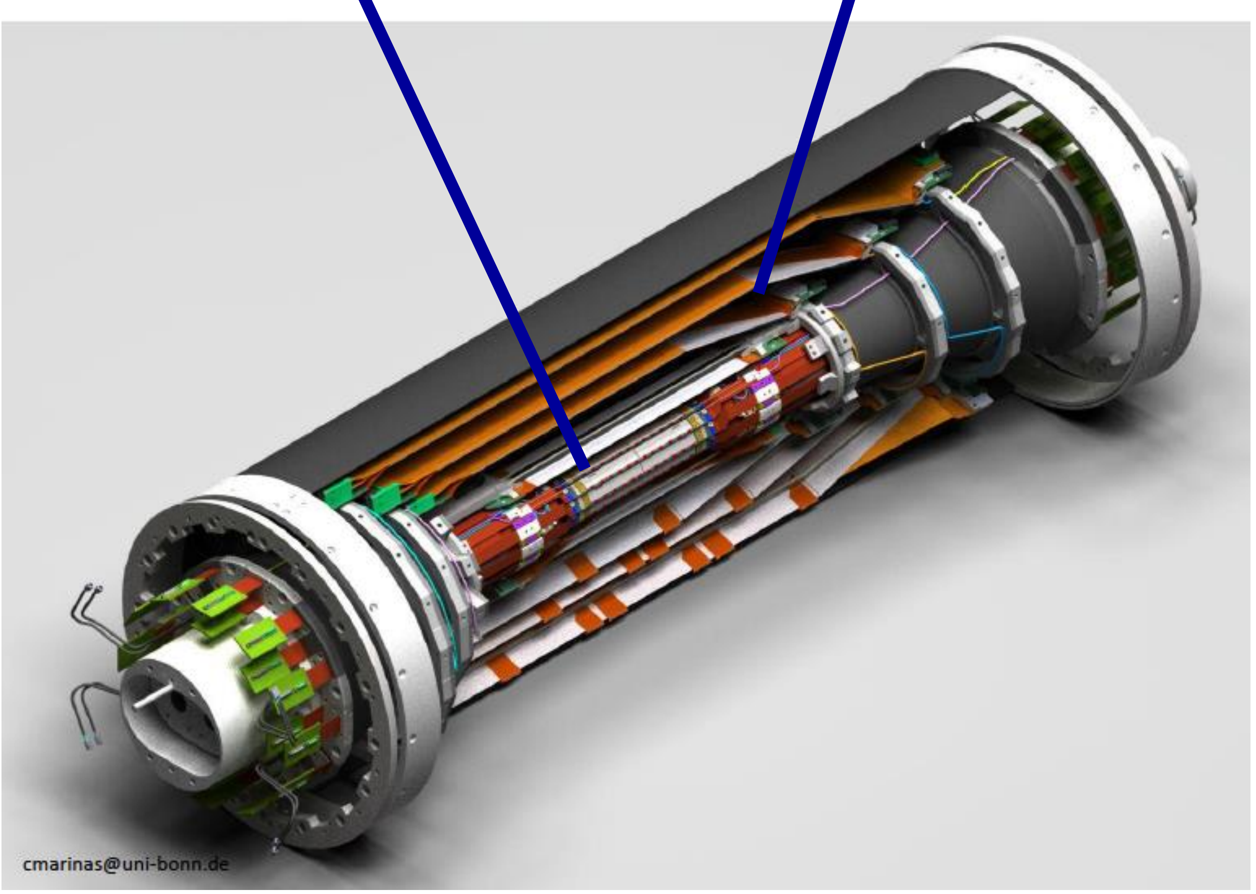
From Belle to Belle II

New Vertex Detectors

PXD: 1-2 layers
- 2 layers of pixel detectors
- Inner most layer very close to IP (r = 1.4cm)

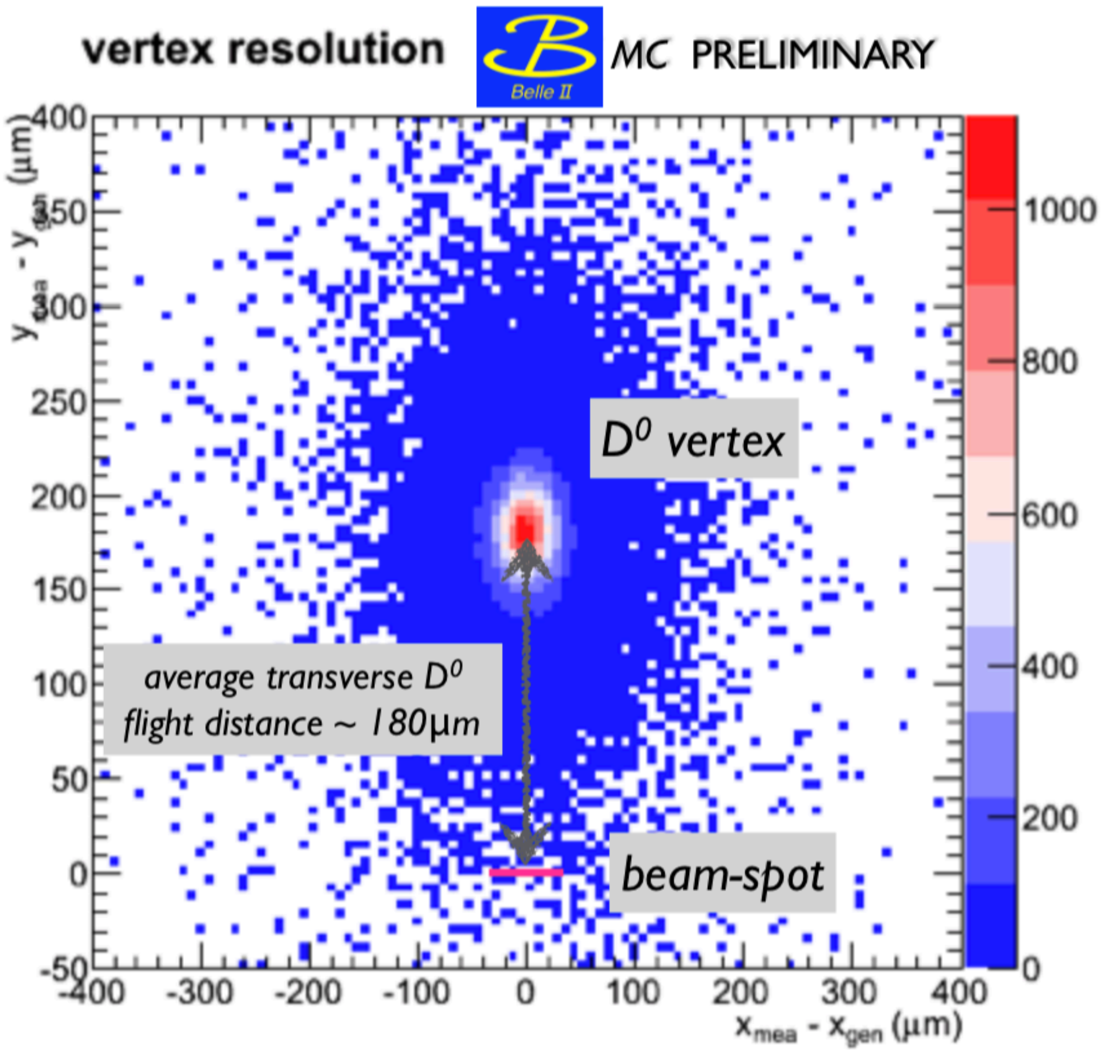
SVD: 3-6 layers
- 4 layers of strip detectors
- covers the full Belle II angular acceptance of $17^{o} < \theta < 150^{o}$

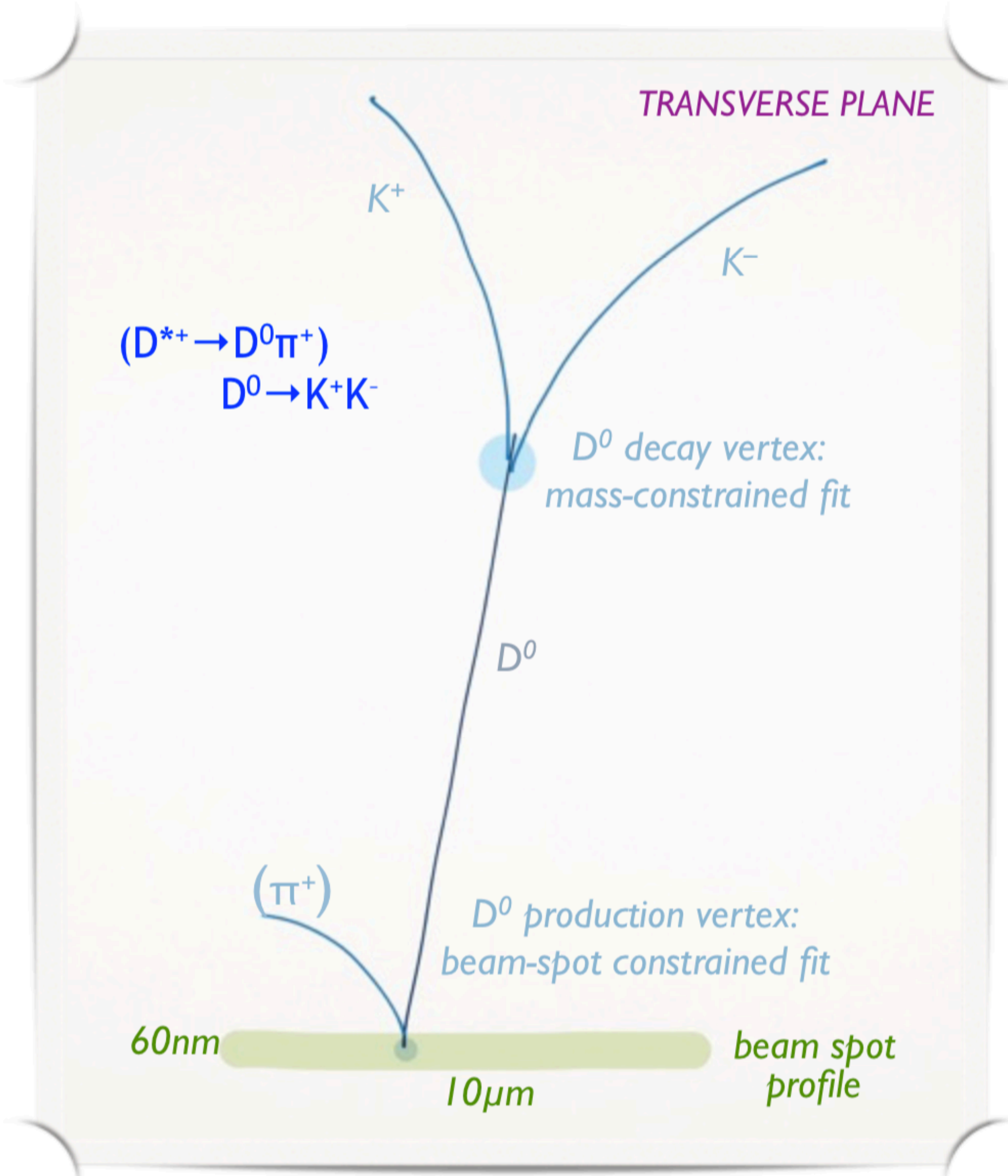




SVD

D^0 Decay Vertex Resolution



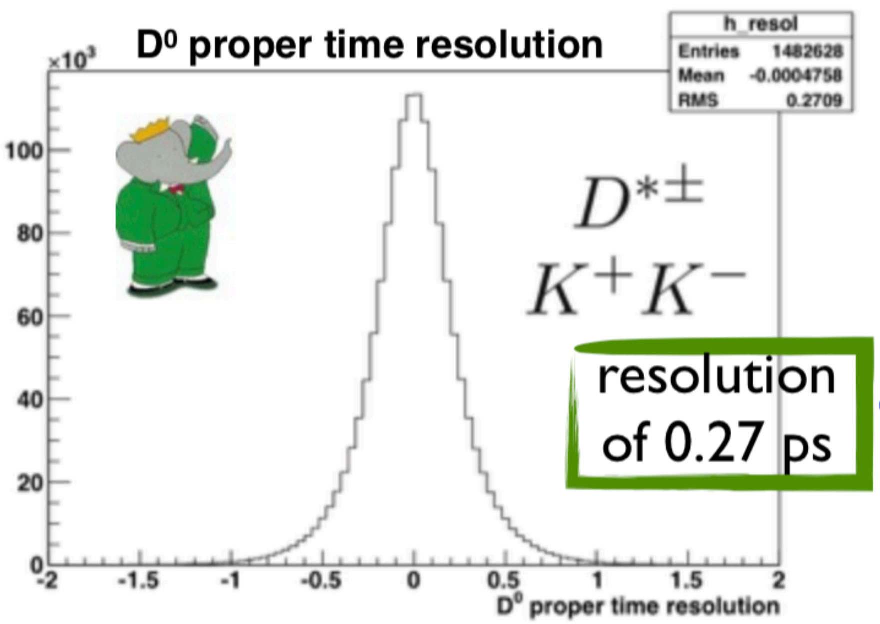


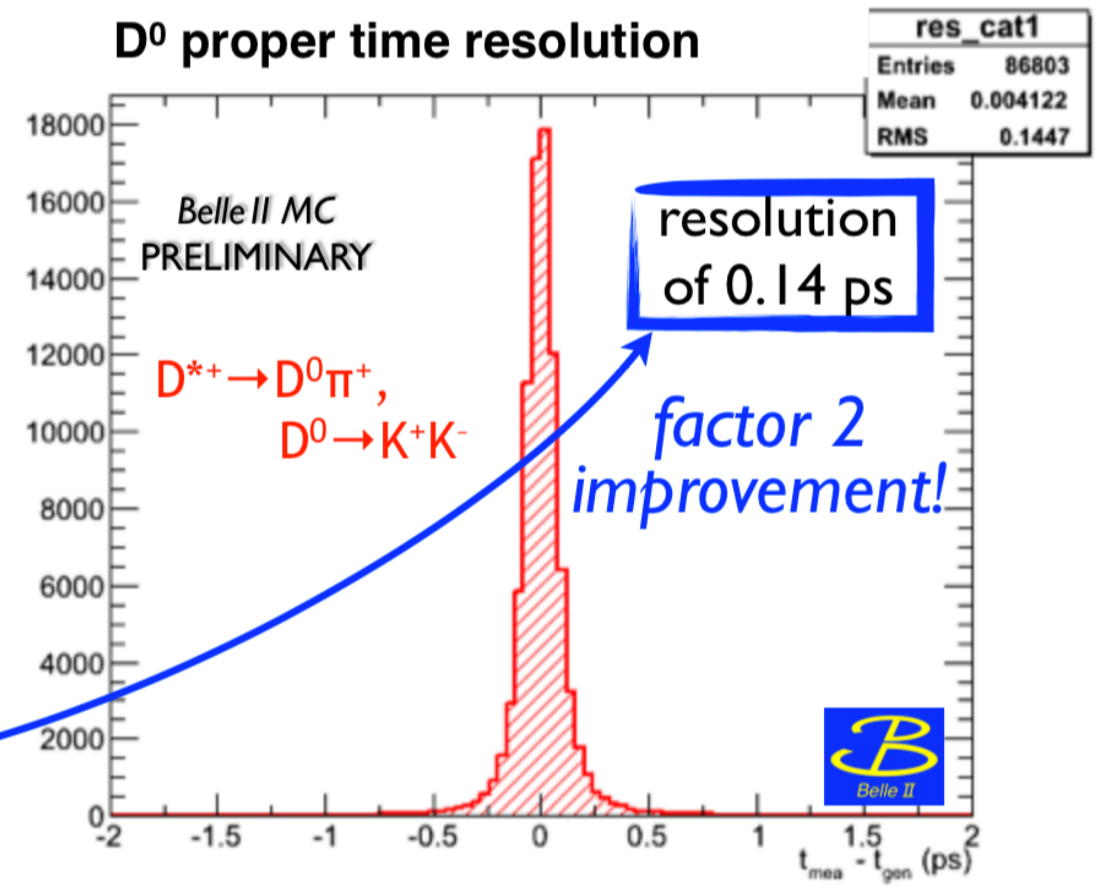
NOTE: the cartoon is not to scale

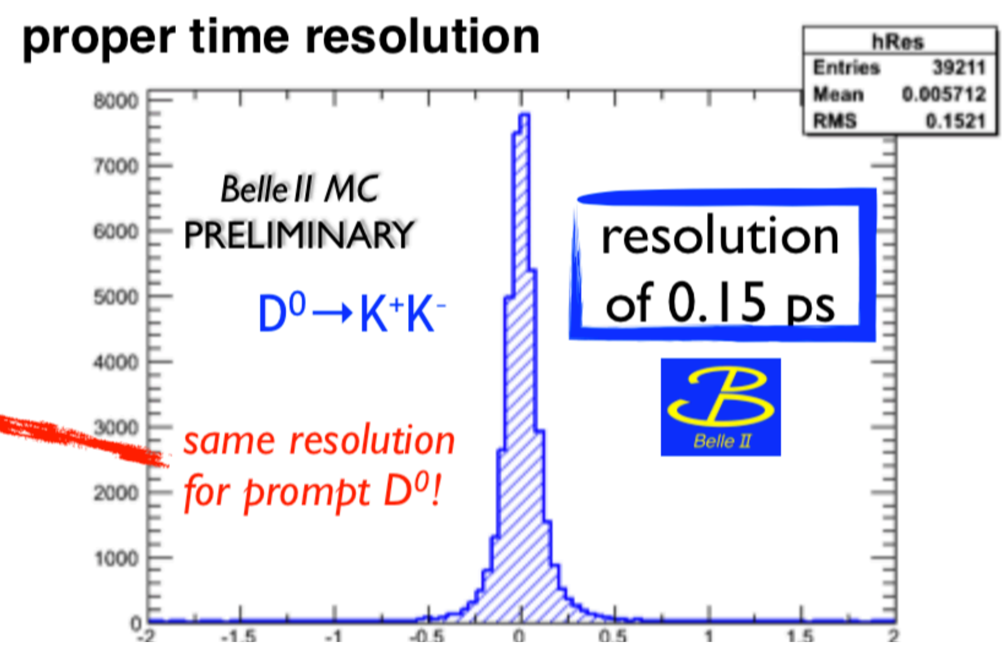
- ➡ D^0 *mass–constrained* vertex fit yields a resolution of the vertex position of ~40μm in transverse plane and also in the longitudinal direction
- ➡ $D^{*+} \to D^0\pi^+$ beam-spot constrained fit yields an unprecedented precision of the determination of the D^0 decay vertex

D^0 Proper Time Resolution

➡ The factor 2 improvement on the track impact parameters directly reflects on charm reconstruction







Is there a way to determine the flavour of the prompt D^0 , i.e. not coming from a charged D^* decay?

… work in progress …

Prospects at Belle II

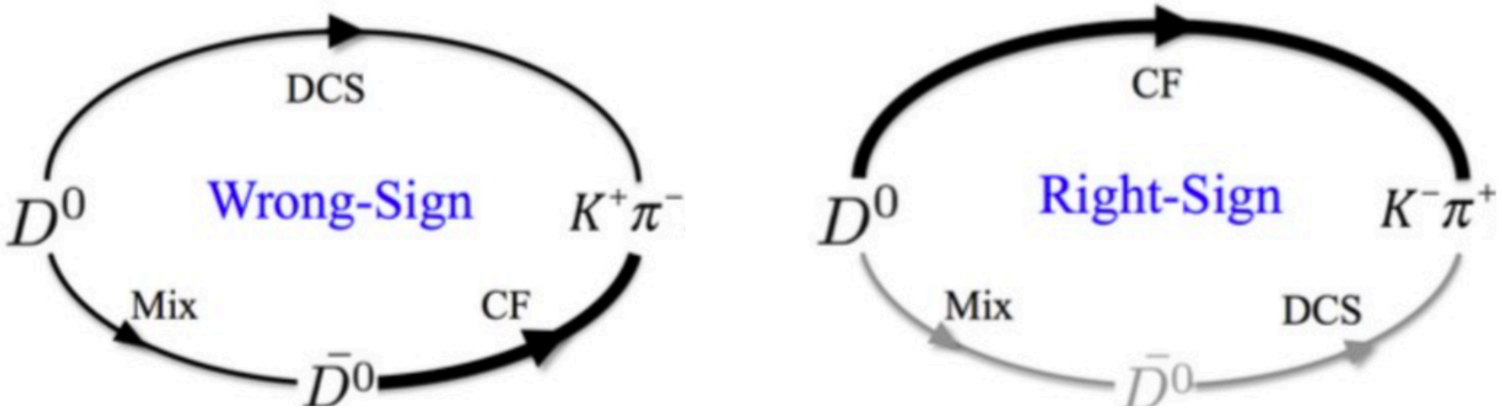
Some slides are from Giulia Casarosa @CHARM2018
& Hulya Atmacan @ICHEP2018

Mixing and Indirect CPV $D^0 \to K^+\pi^-$

PRL 112, 111801 (2014)

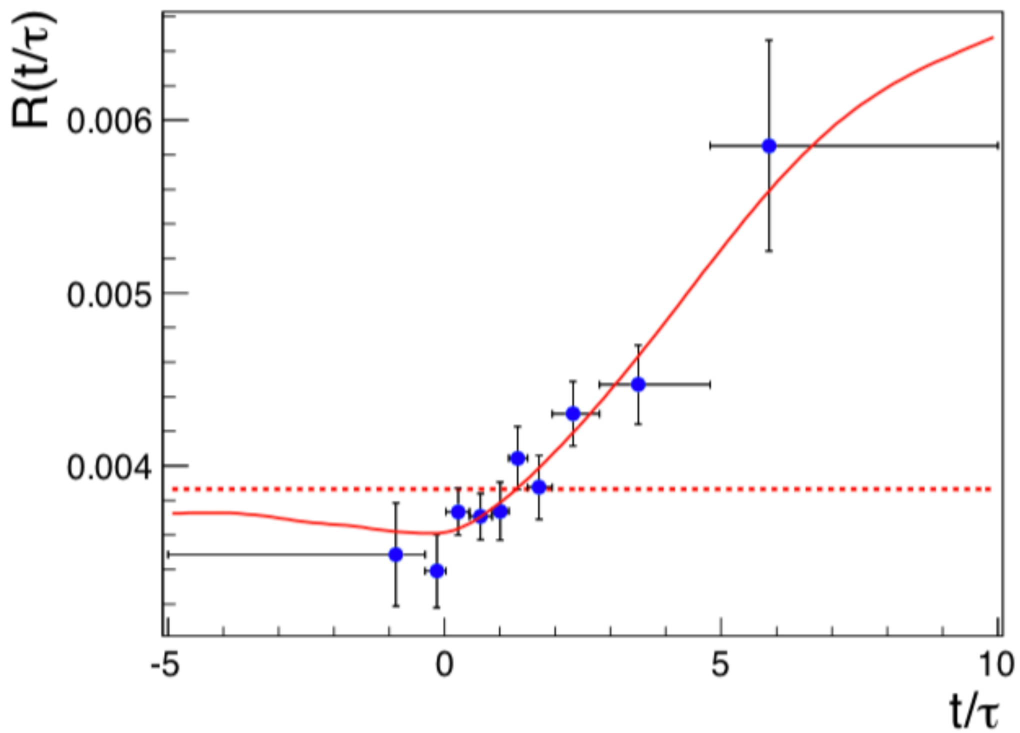
- The flavor of D^0 is tagged with D* decay

$$D^{*+} \to D^0(\to K^{\mp}\pi^{\pm})\pi_s^+$$



- Fit to the time-dependent ratios of WS to RS decay rates

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



$$x'^2 = (0.09 \pm 0.22) \times 10^{-3} \text{ and } y' = (4.6 \pm 3.4) \times 10^{-3}$$

Mixing and Indirect CPV

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

Detector performance improvements are not included in the extrapolation

M. Staric @ KEK FF 2014

channel	observable	*Belle* ~ 1 ab^{-1}	*Belle II* 50 ab^{-1}
$D^0 \to K^+\pi^-$	x'^2 (%)	± 0.022	± 0.003
	y' (%)	± 0.34	± 0.04
	$\|q/p\|$	± 0.6	± 0.06
	ϕ	± 25°	± 2.3°
$D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$	y_{CP} (%)	± 0.22	± 0.04
	A_Γ (%)	± 0.20	± 0.03
$D^0 \to K_S\pi^+\pi^-$	x (%)	± 0.19	± 0.08
	y (%)	± 0.15	± 0.05
	$\|q/p\|$	± 0.16	± 0.06
	ϕ	± 11°	± 4°

~ *factor 8-10 better*

systematics free measurement

~ *factor 6 better*

comparable contributions from statistical and systematic errors

~ *factor 3 better*

limited by systematics related to DP Model

can be improved using a model-independent approach to reduce the systematics!

Time-integrated CP Asymmetry

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

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 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
$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.21
$D^0 \to K_s^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_s^0\eta'$	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
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K_s^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_s^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

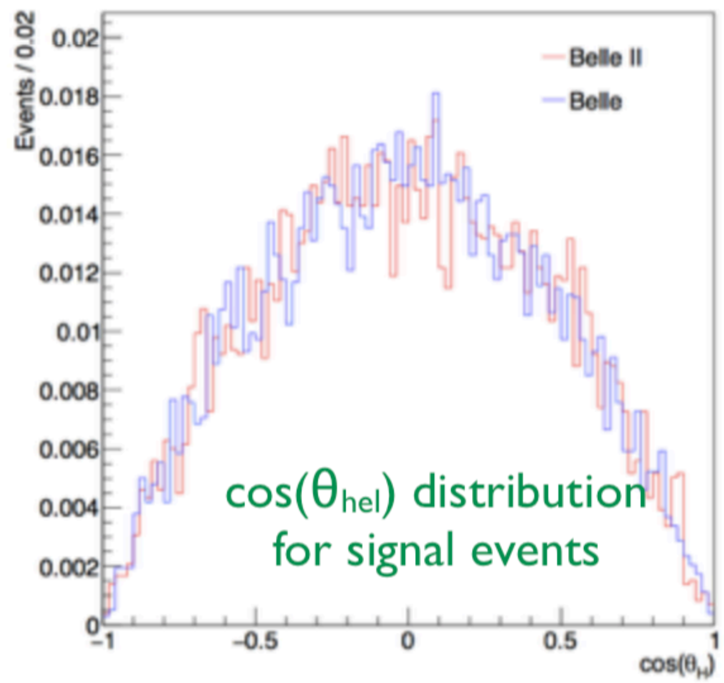
- *Belle II* has advantages of excellent γ and π^0 reconstruction.
- A_{CP} precision will reach $\mathcal{O}$ (0.01%).

Radiative Decays $D^0 \to V\gamma$

1. <u>CP Violation</u>: SM expectations on the order of 10^{-3}, NP contributions can enhance it up to an order of magnitude
2. <u>tests of QCD</u>: transitions dominated by long-range diagrams

- ➡ A_{CP} and BR measurements of decays $D^0 \to V\gamma$ completed at Belle
- ➡ dominant error for A_{CP} is statistical, *BelleII* can significantly improve the precision

  - *Studies on BelleII official MC have shown that $m(D^0)$ and $\cos(\theta_{hel})$ distributions have resolutions similar Belle, allowing an extrapolation based on luminosity*



A_{CP} estimated error on	Belle	Belle II statistical error		
	1/ab	5/ab	15/ab	50/ab
$D^0 \to \rho^0 \gamma$	± 0.152 ± 0.006	± 0.07	± 0.04	± 0.02
$D^0 \to \phi \gamma$	± 0.066 ± 0.001	± 0.03	± 0.02	± 0.01
$D^0 \to \overline{K}^{*0} \gamma$	± 0.020 ± 0.000	± 0.01	± 0.005	± 0.003

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

Full Charm Event Reconstruction

➡ use the **recoil method** successfully exploited for D_s decays:

light mesons (K, π, …)

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

reconstructed in several channels (D^0, D^*, D_s, …)

signal channel

➡ use energy and momentum conservation to search for the desired final state:

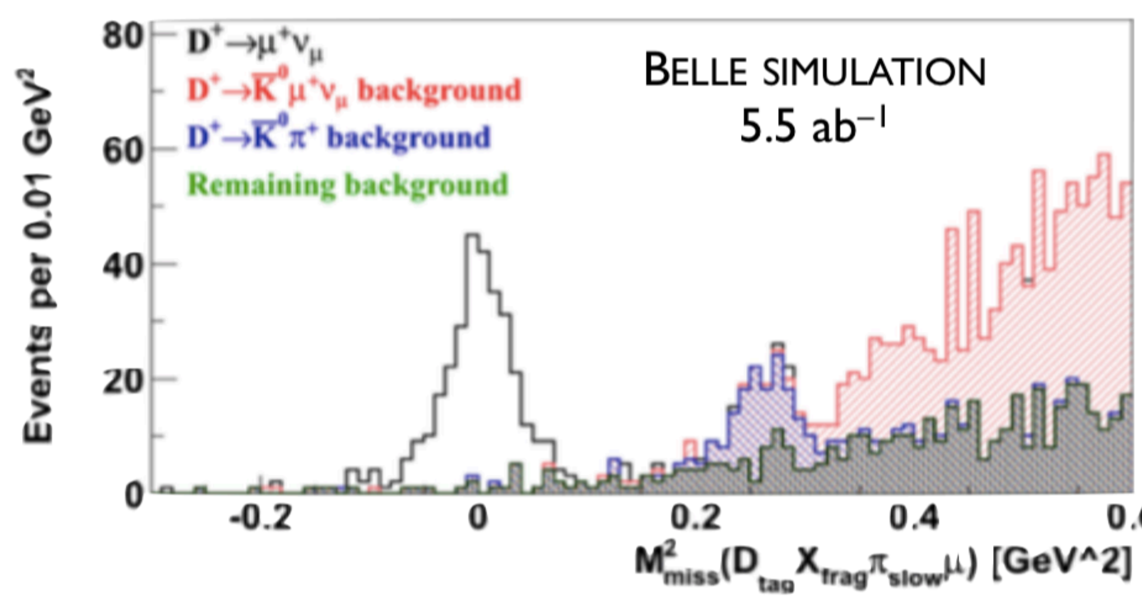
- *example*:

$$D_{\rm sig} = D^{*+} \to D^+\pi_{\rm slow};\ D^+ \to \mu^+\nu$$

- "miss" quantities computed for the system:

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

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



Rare Decay of $D^0 \to \nu\nu$

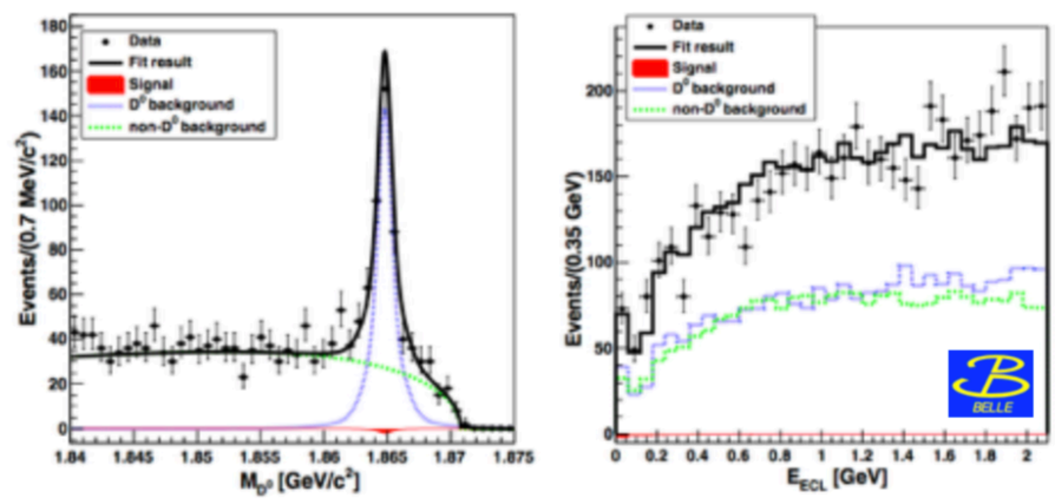
SM prediction $B(D^0 \to \nu\nu) \sim 10^{-30}$
May enhanced by NP e.g. D→Dark Matter

$D^0 \to \nu\nu$ Belle Analysis:

$$e^+e^- \to D_{\text{tag}} X_{\text{frag}} D^{*+}$$

$$D^{*+} \to D^0 \pi_s^+$$

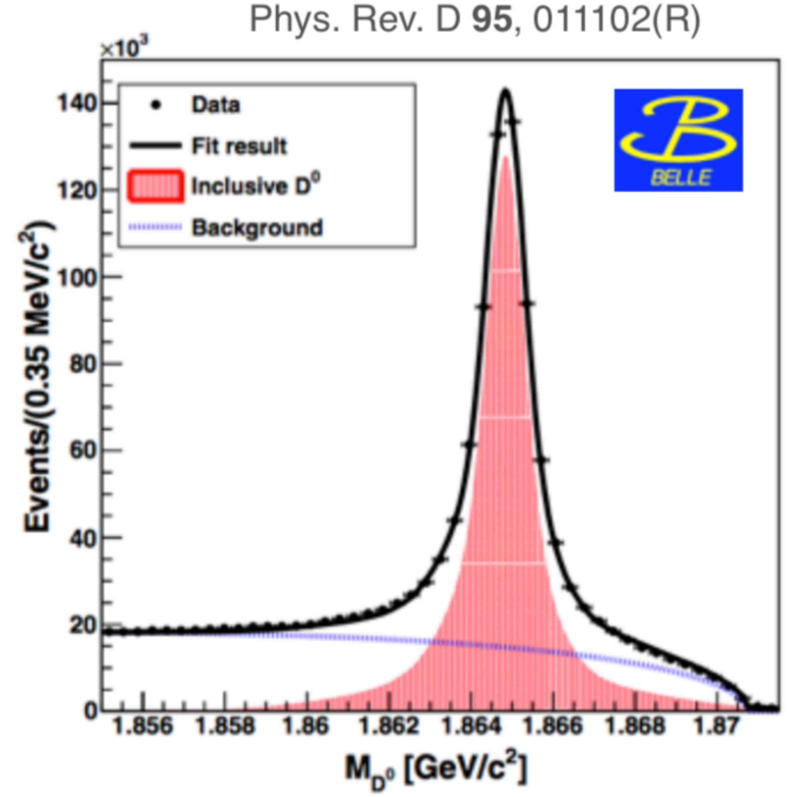
- require no extra-charged tracks of photons, π^0, …
- fit the missing mass and ECL energy distributions.



yields	inclusive D^0
Belle, 924 fb^{-1}	695000
BelleII, 50 ab^{-1}	38×10^6

nearly 40M inclusive D^0 decays to search for forbidden/rare decays

Phys. Rev. D **95**, 011102(R)



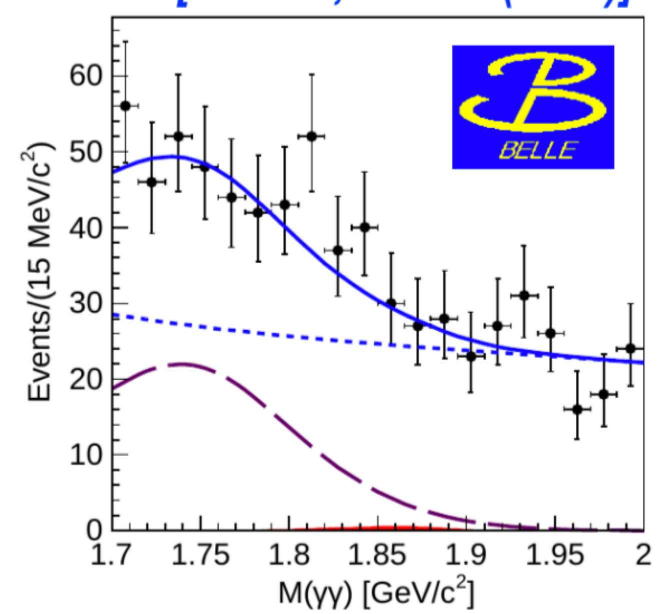
Rare Decay of $D^0 \to \gamma\gamma$

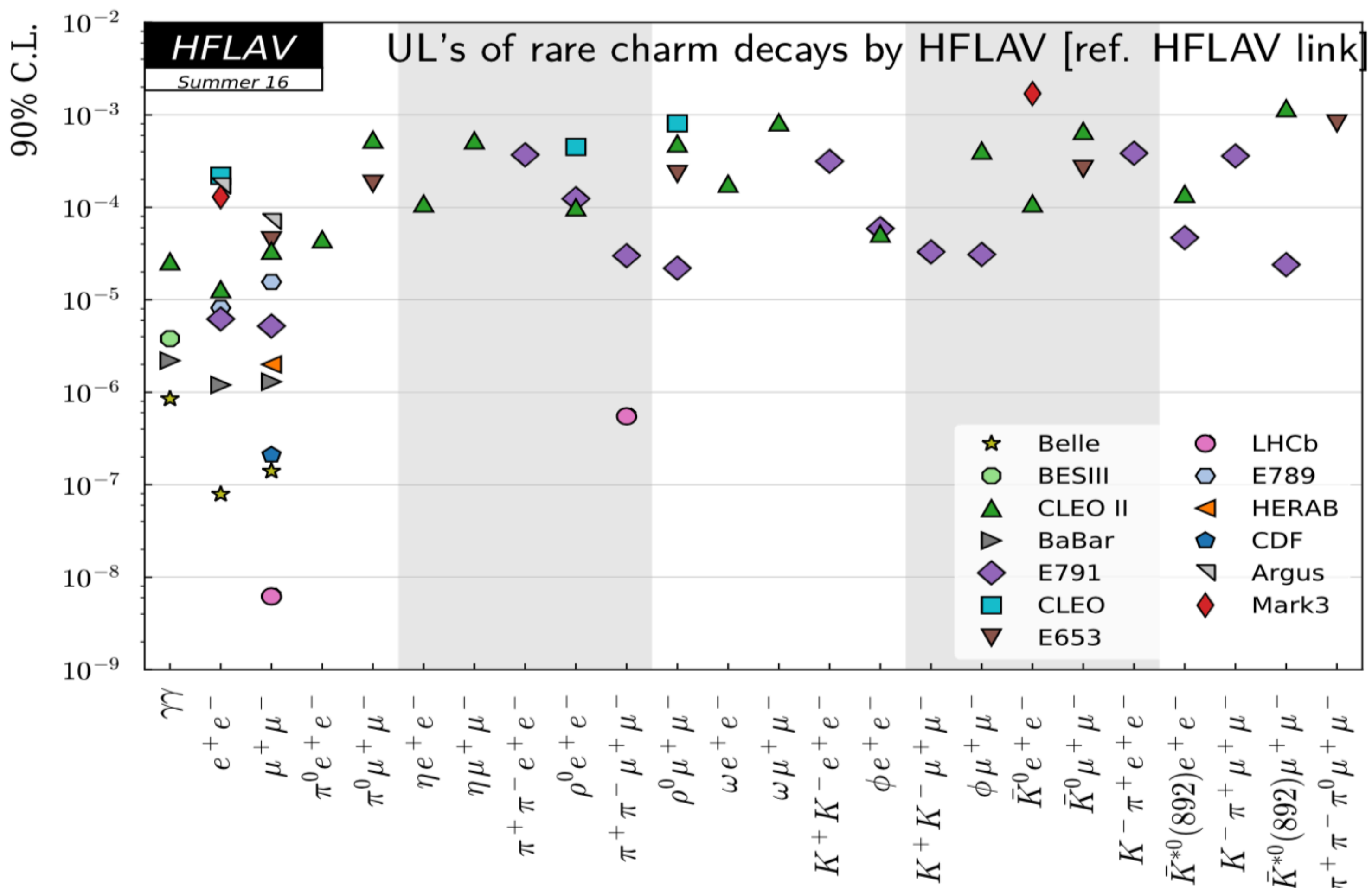
- $D^0 \to \gamma\,\gamma$ a sensitive probe to NP.
- *Belle* 832 fb^{-1} data:

  $\mathcal{B}$ < 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)]

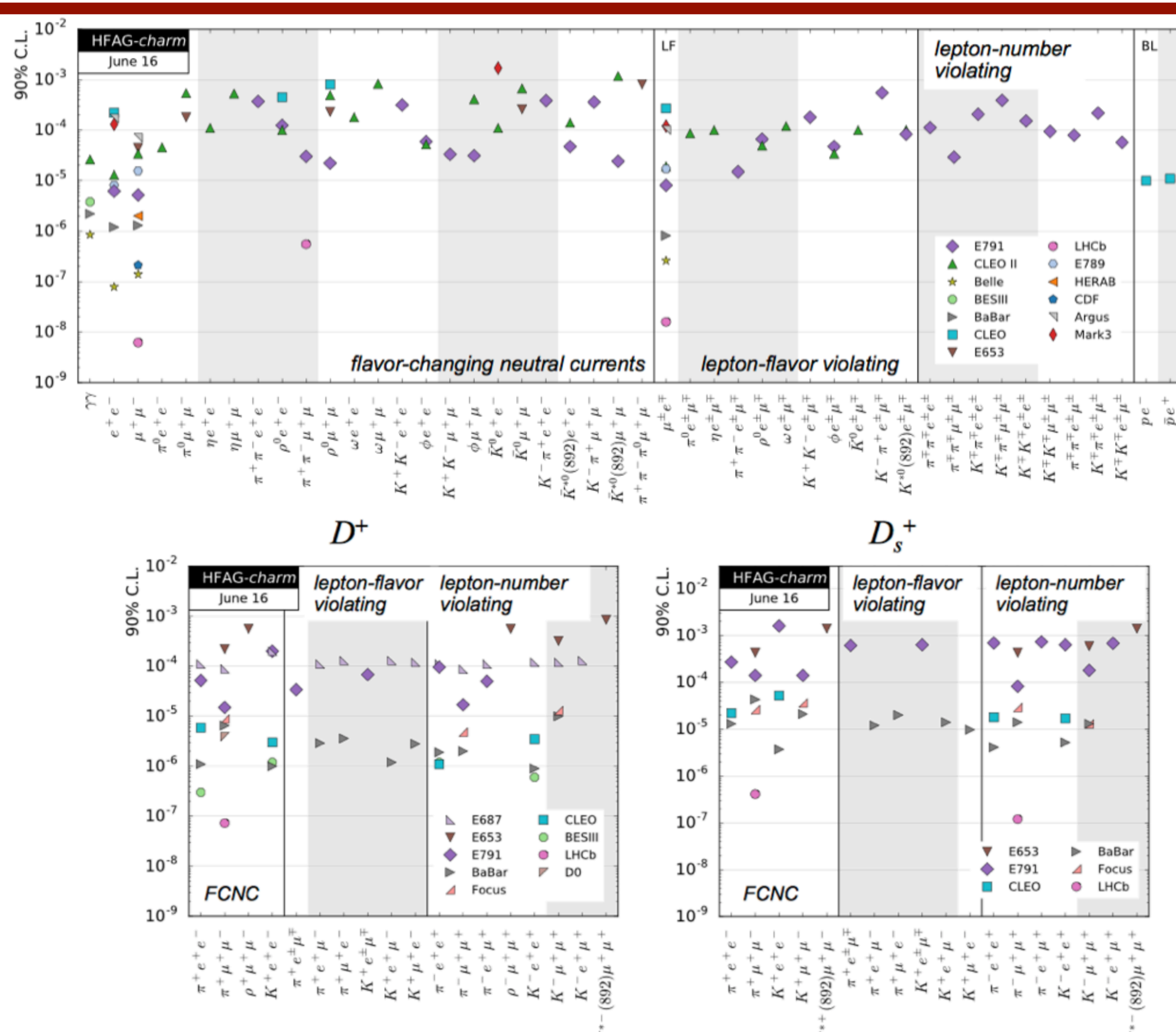




- Decays involving π^0, η and ω were mostly done by CLEO.
- *Belle II* can improve these UL by several orders of magnitude.

Rare/Forbidden $D^0/D^+_{(s)}$ Decays

- *BelleII* can improve on many of these channels up to one order of magnitude at 50 ab^{-1}
- having largest impact on the modes with π^0s (and electrons) in the final state.

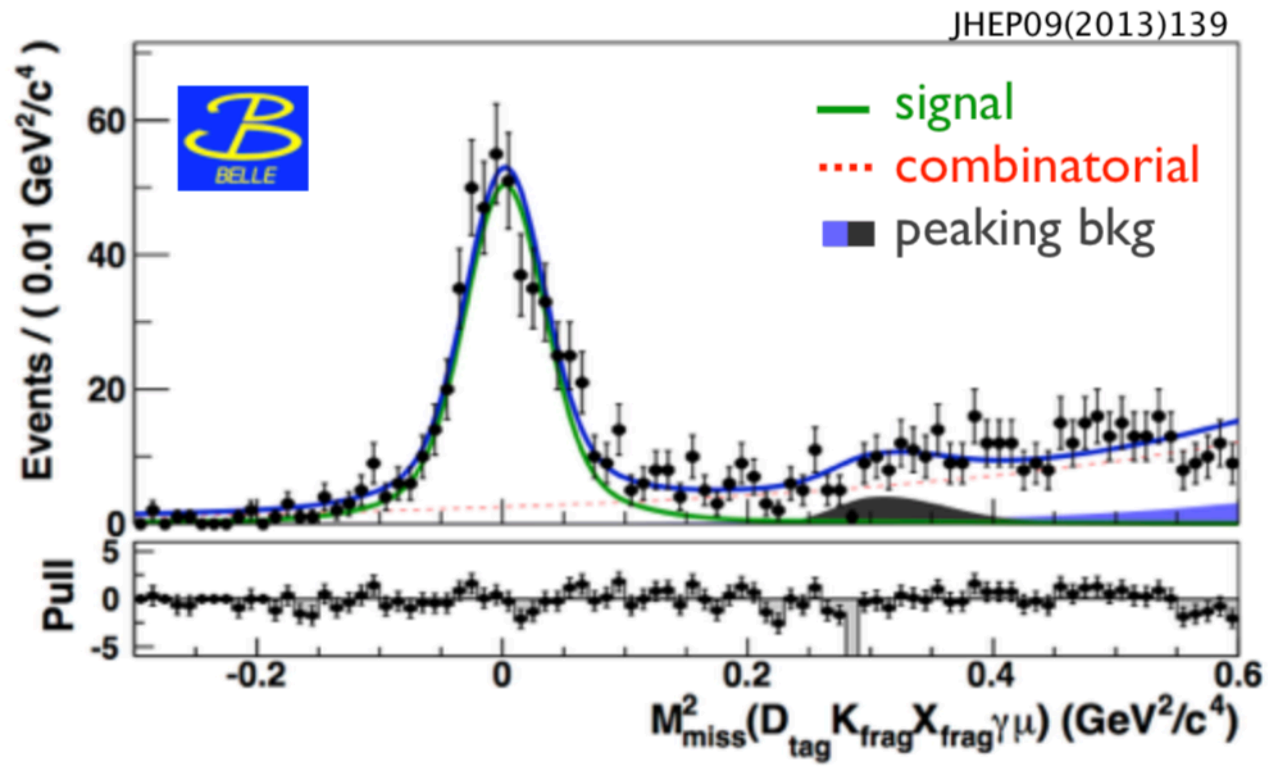


Leptonic Decay of $D_s \to \mu^+ \nu$

- ➡ $D_s^+ \to \mu^+ \nu$ Belle Analysis:

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

  - require one charged track passing muon-ID pointing the IP
  - fit the missing mass distribution.



- ➡ Same analysis method for the D^+ channel
  - Belle simulation with 5.5 ab^{-1}, scaled to 50 ab^{-1}, yields:

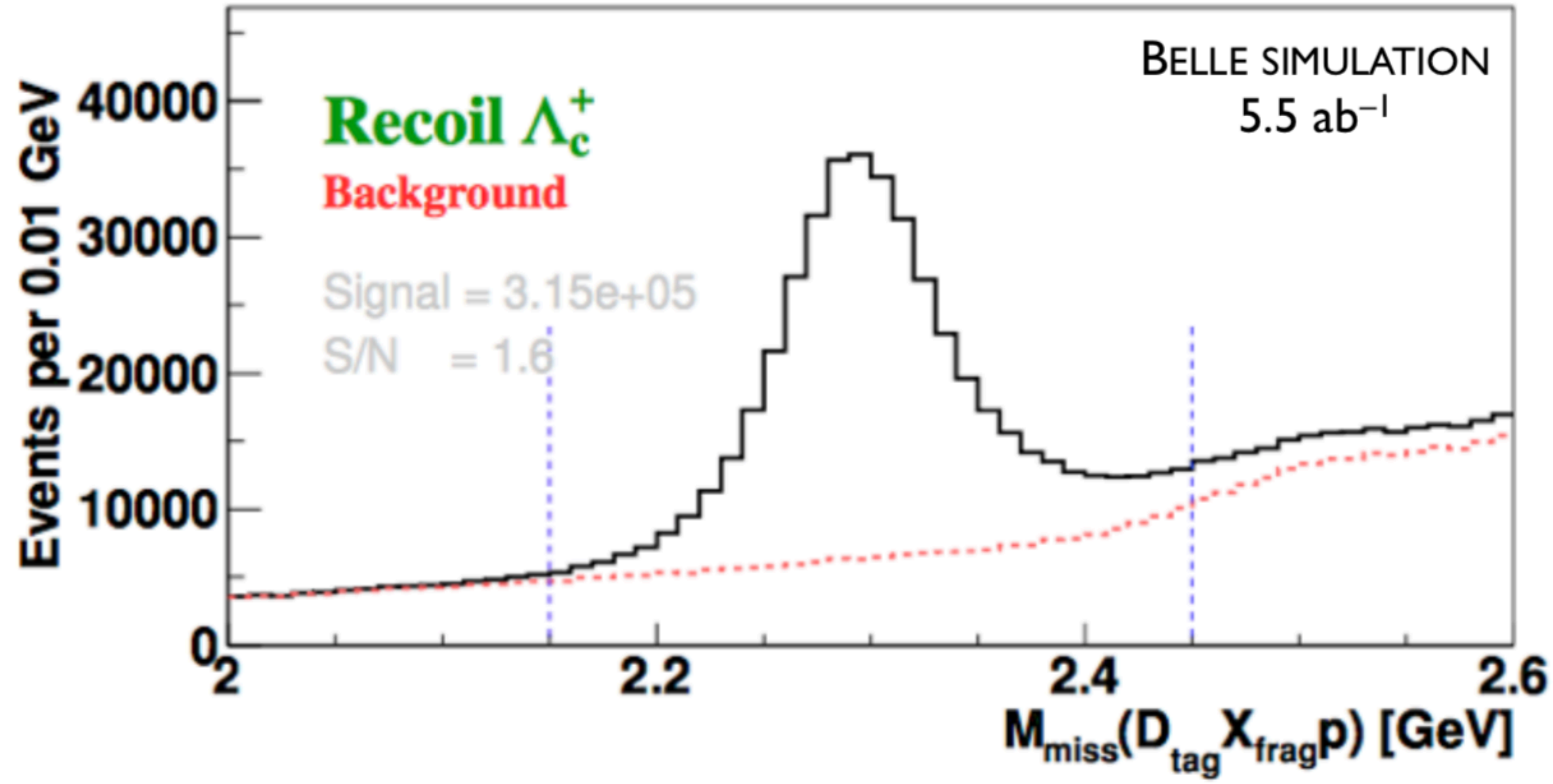
yields	$D_s^+ \to \mu^+\nu$		$D^+ \to \mu^+\nu$	
	inclusive	exclusive	inclusive	exclusive
Belle, 913 fb^{-1}	94400	490	–	–
BelleII, 50 ab^{-1}	5.2×10^6	27×10^3	3.5×10^6	1250
	$\delta(\lvert V_{cs}\rvert) = 0.004$, $\delta(\lvert f_{Ds}\rvert) = 0.9$ statistical error ~1/3 of the theory error		$\delta(f_d \lvert V_{cd}\rvert) = 1.3$ competitive with CLEOc and BESIII	

Inclusive Λc Sample

Extension of the Full Charm Event Reconstruction with:

$$e^+e^- \rightarrow D_{tag} X_{frag}\, p\, \Lambda_c^+$$

- in this case M_{miss} = Λ_c^+ mass



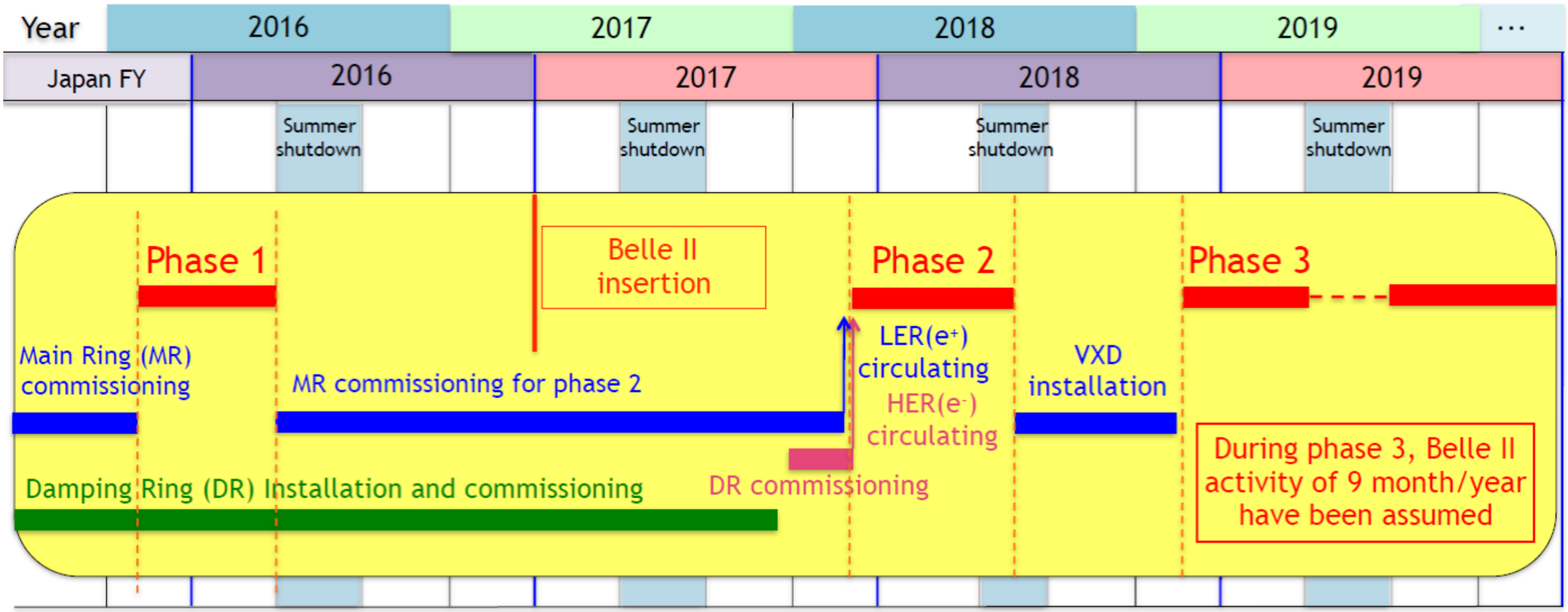
➡ *BelleII* simulation scaled to 50 ab^{-1} yields **2.8×10^6 inclusive Λ_c^+**

➡ **Unique** sample that allows to:

- measure absolute branching fractions
- measure semileptonic decays
- search for rare decays with missing energy

Status of Belle II

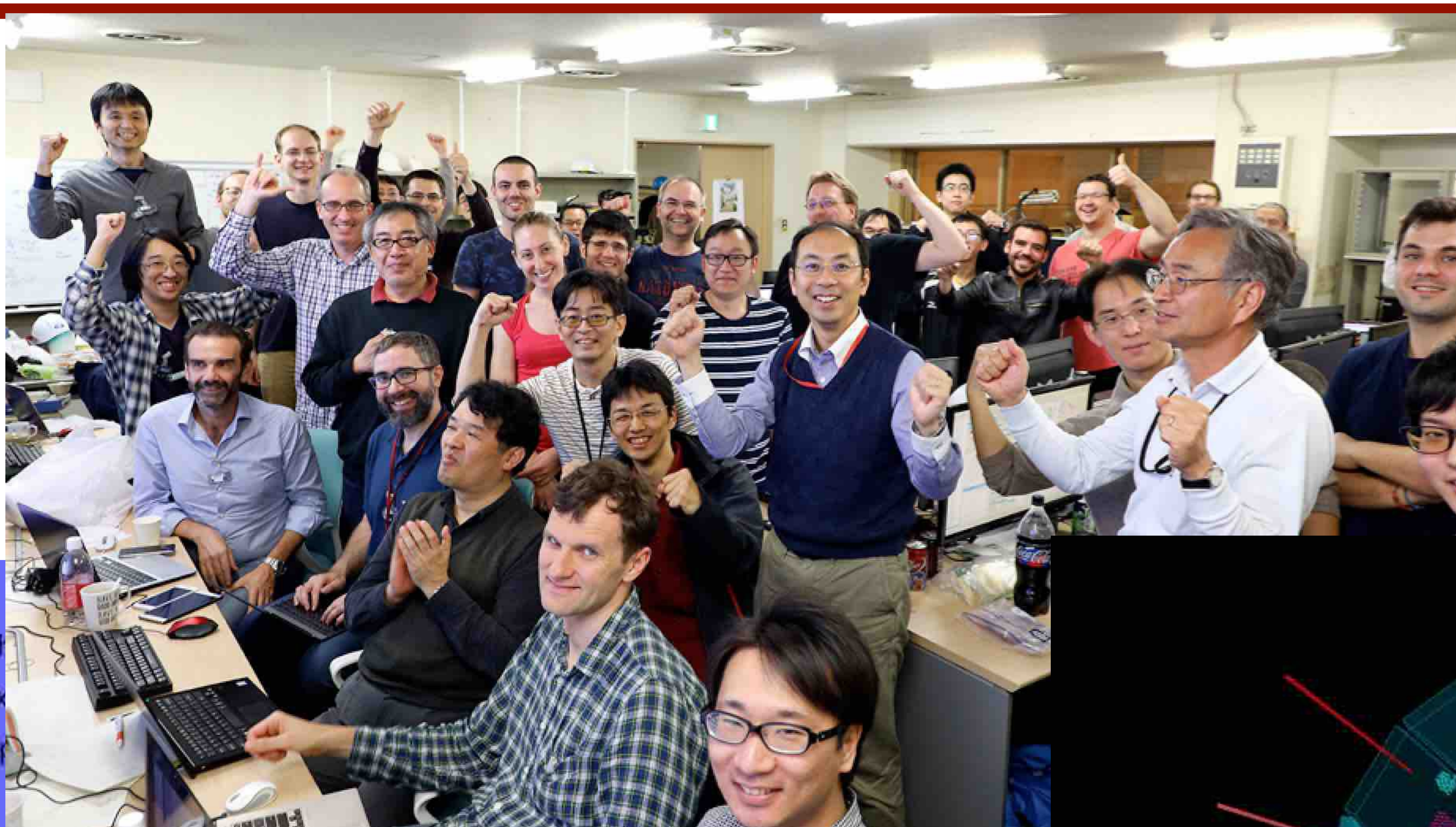
SuperKEKB and Belle II Schedule

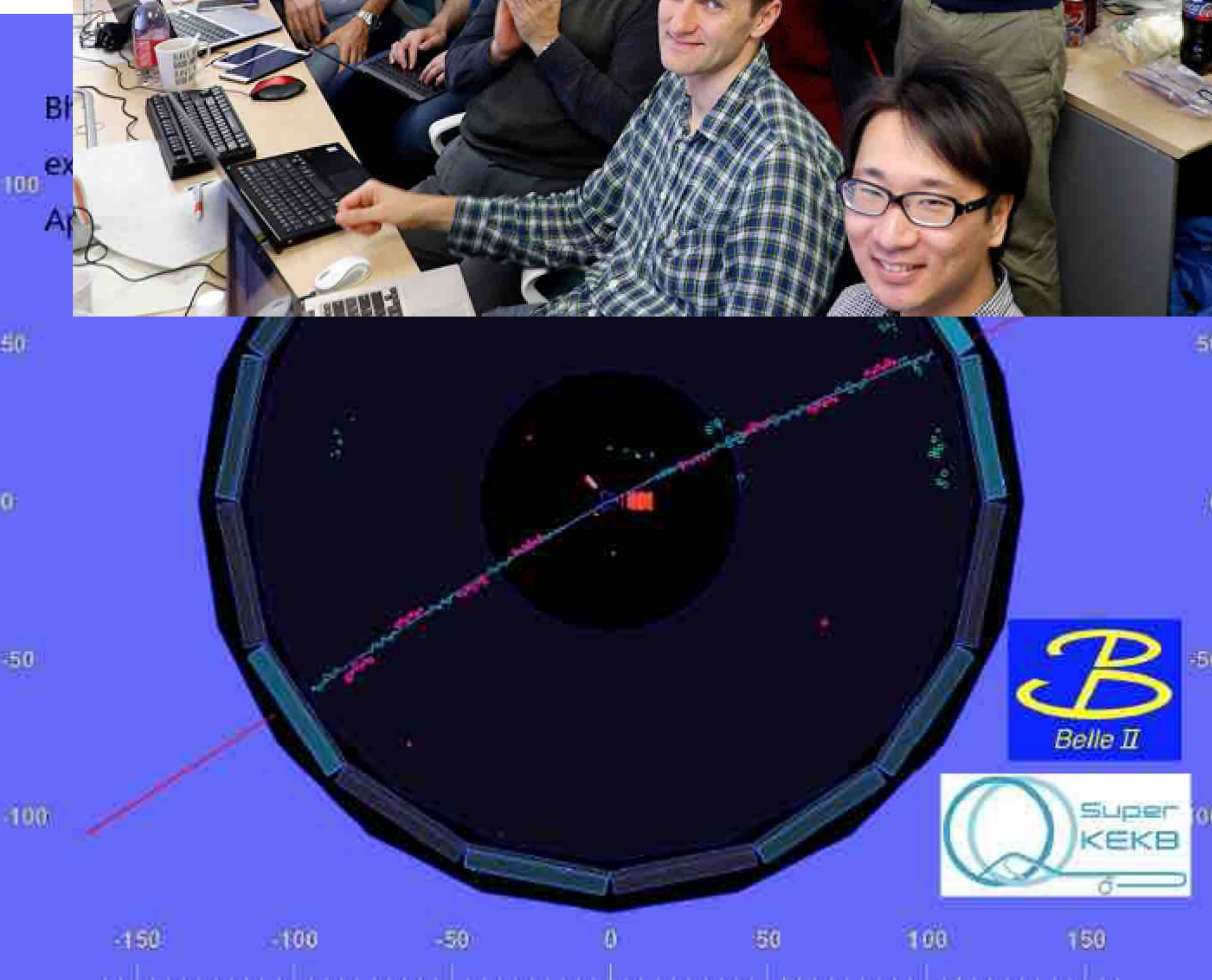


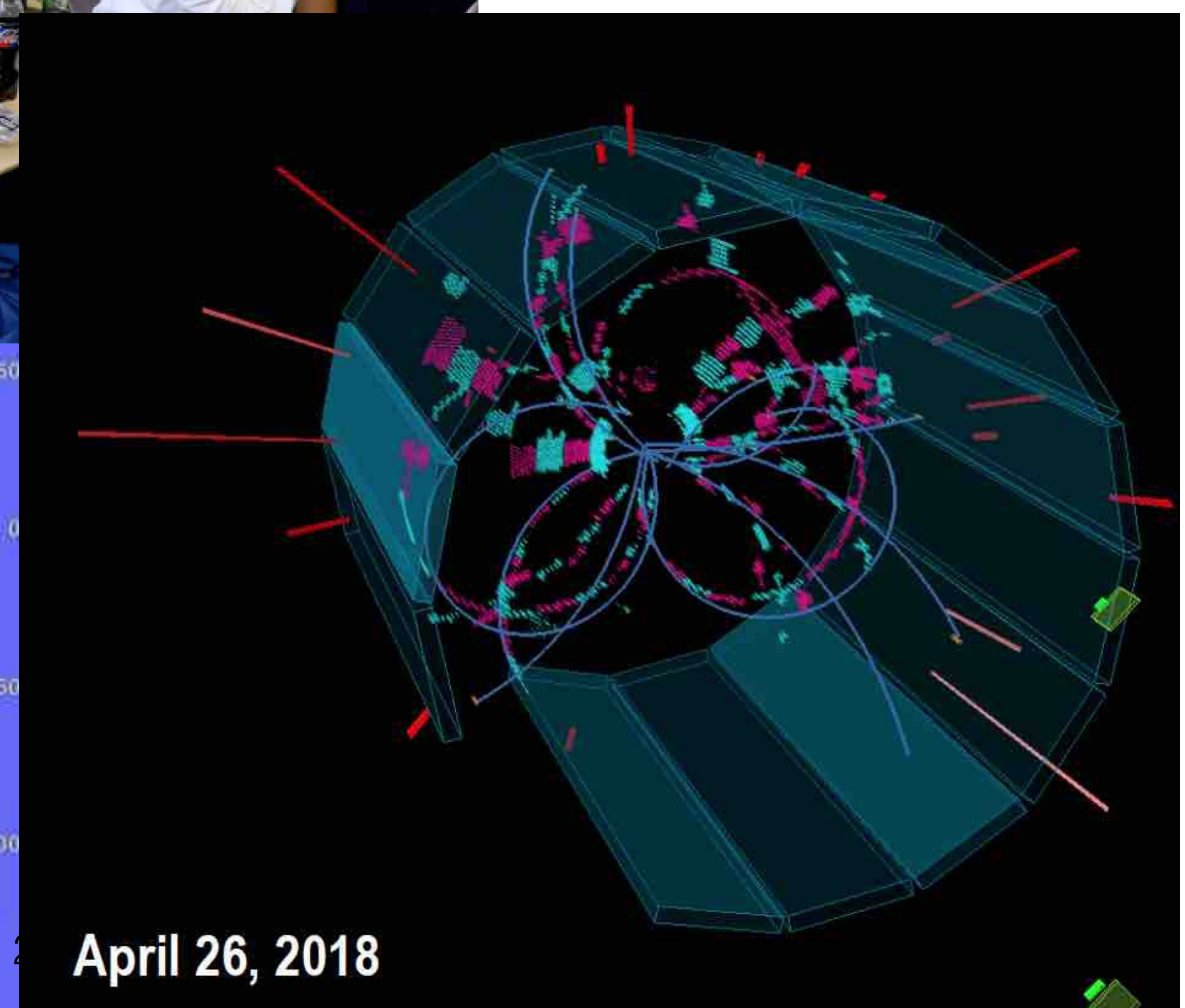
✅ • **Phase1, Feb.-June, 2016**
  - **Accelerator commissioning, no collision**

✅ • **Phase2, Feb.-July 17, 2018**
  - **Collision w/o vertex detectors**
  - **Understand background and detector performance**
  - **Instantaneous luminosity reach $\sim 0.5 \times 10^{34}$ cm^{-2}s^{-1}**
  - **$\sim$0.5 fb^{-1} data at the Y(4S) resonance was collected**

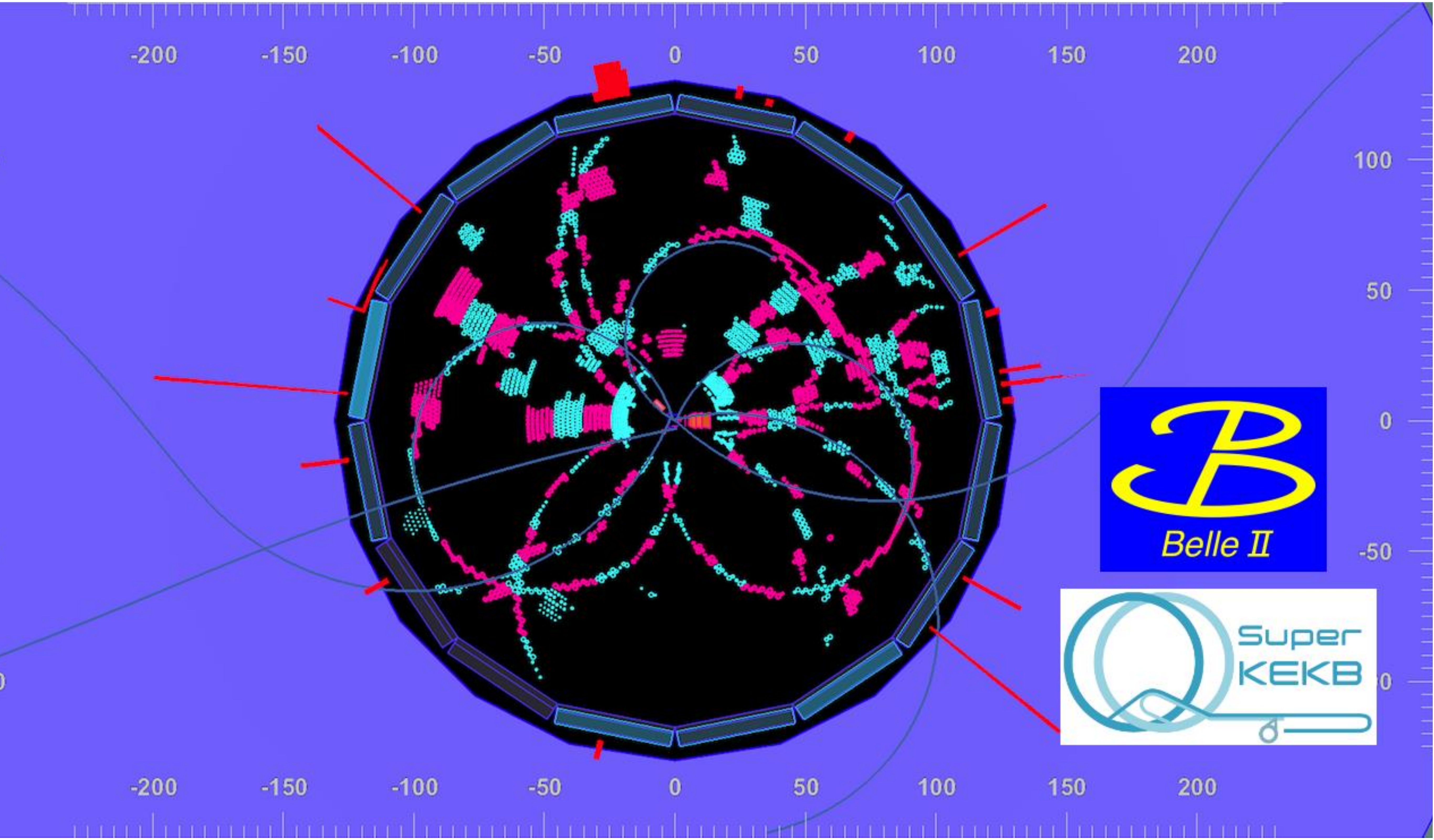
First Collision on Apr.26, 2018





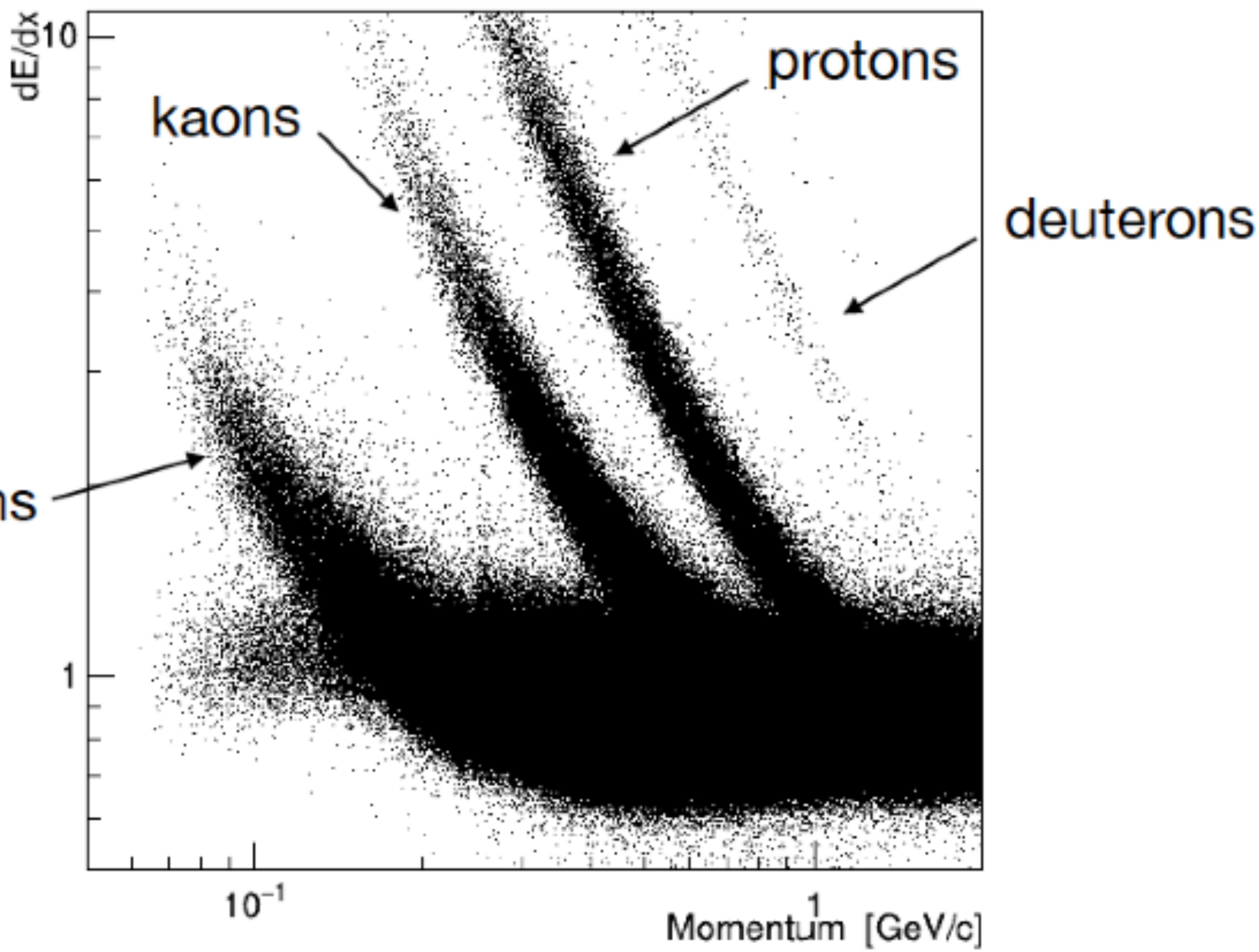


e+e-→BBbar Candidate on Apr. 26 evening



Belle II Performance

CDC dE/dx particle identification with early calibration in the hadronic event sample

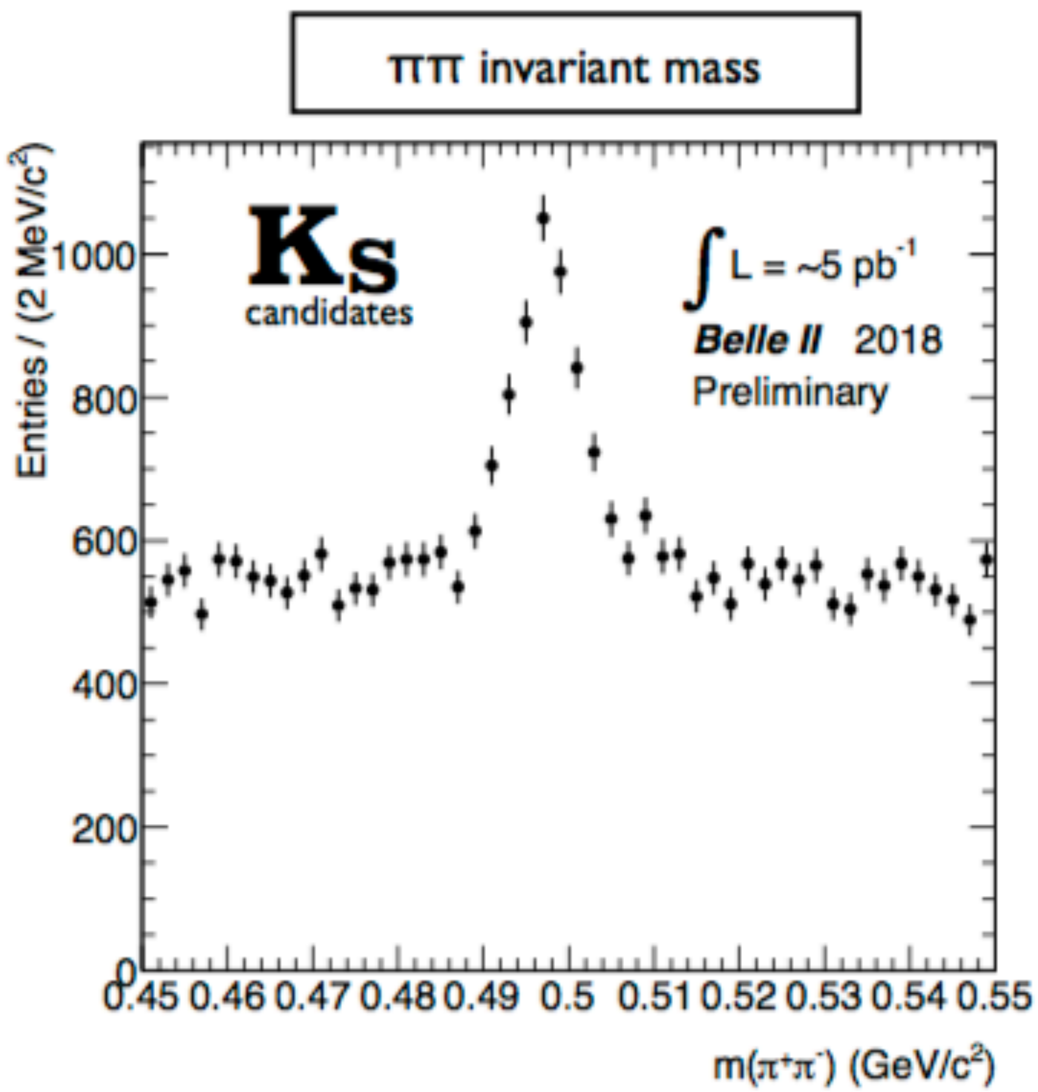


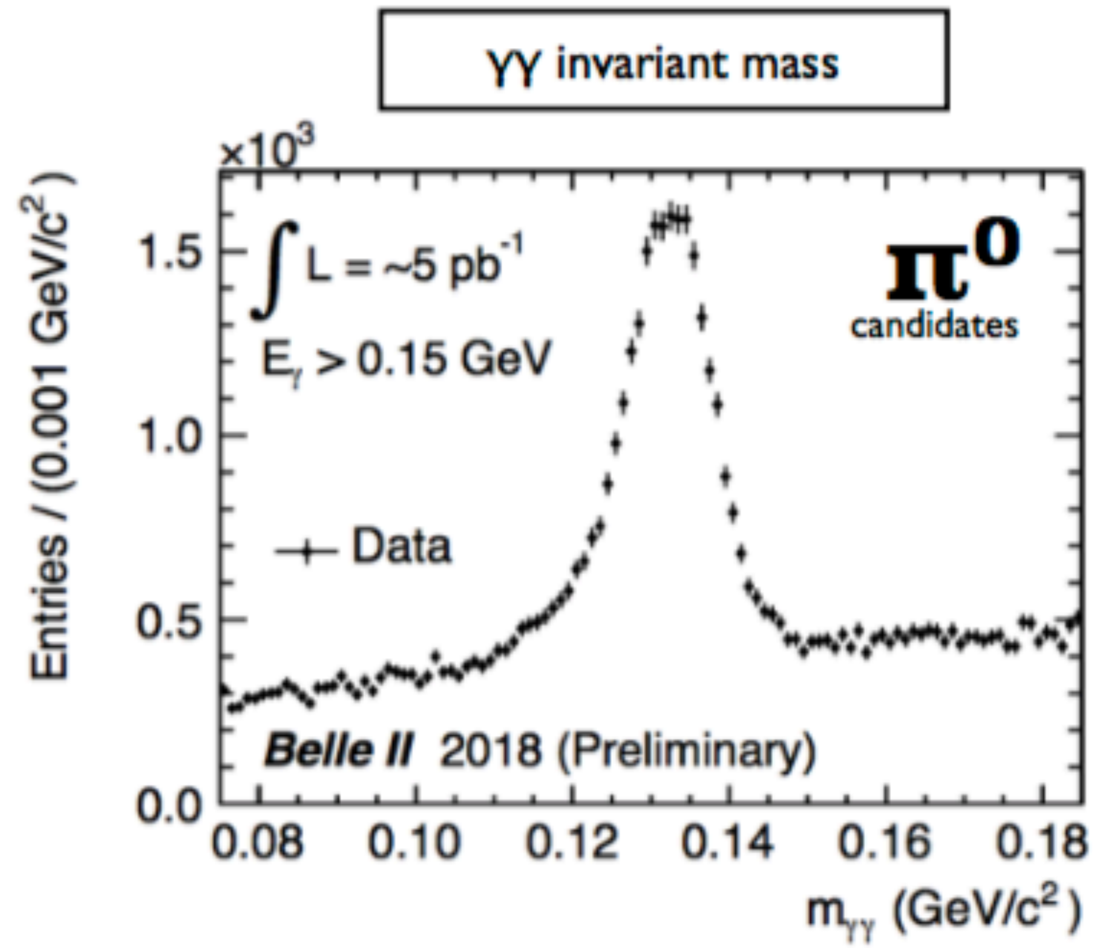
Extra cuts:

- |d0| < 1
- |dz| < 3
- # layers hit > 20

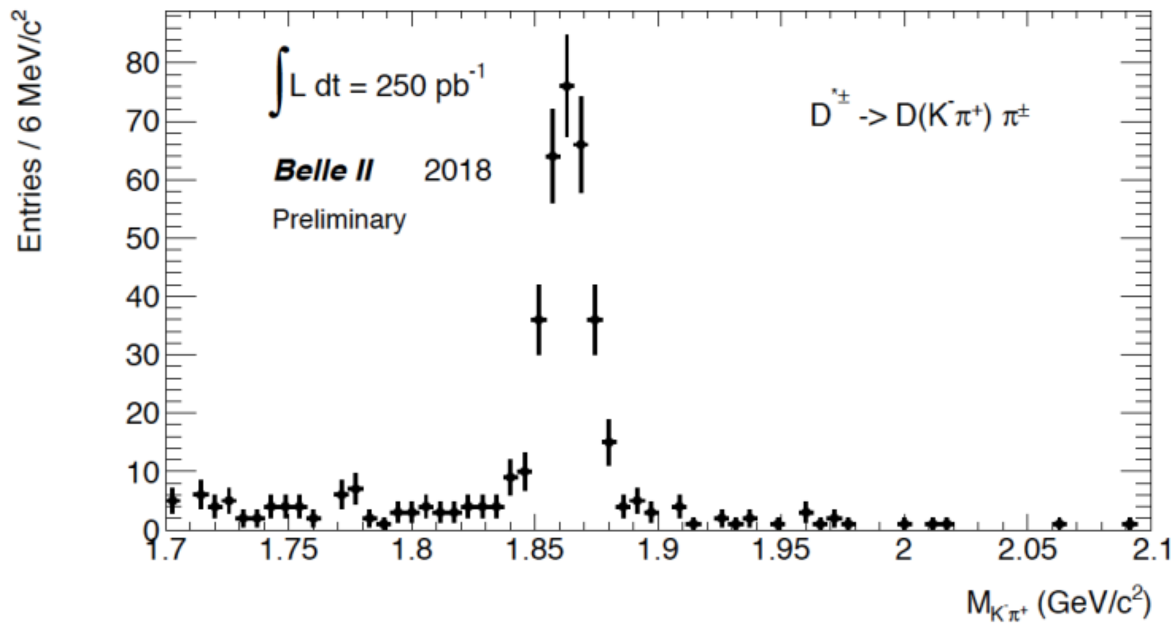
Belle II Performance

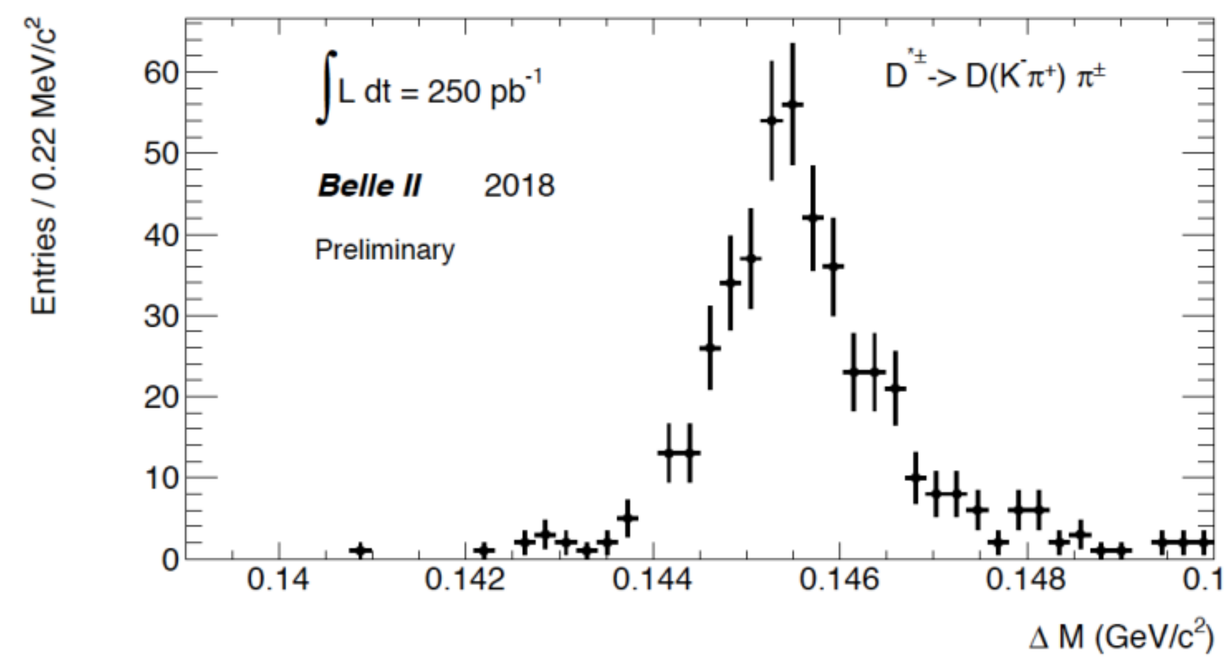
First glance at data
Clear Ks and pi0 signals

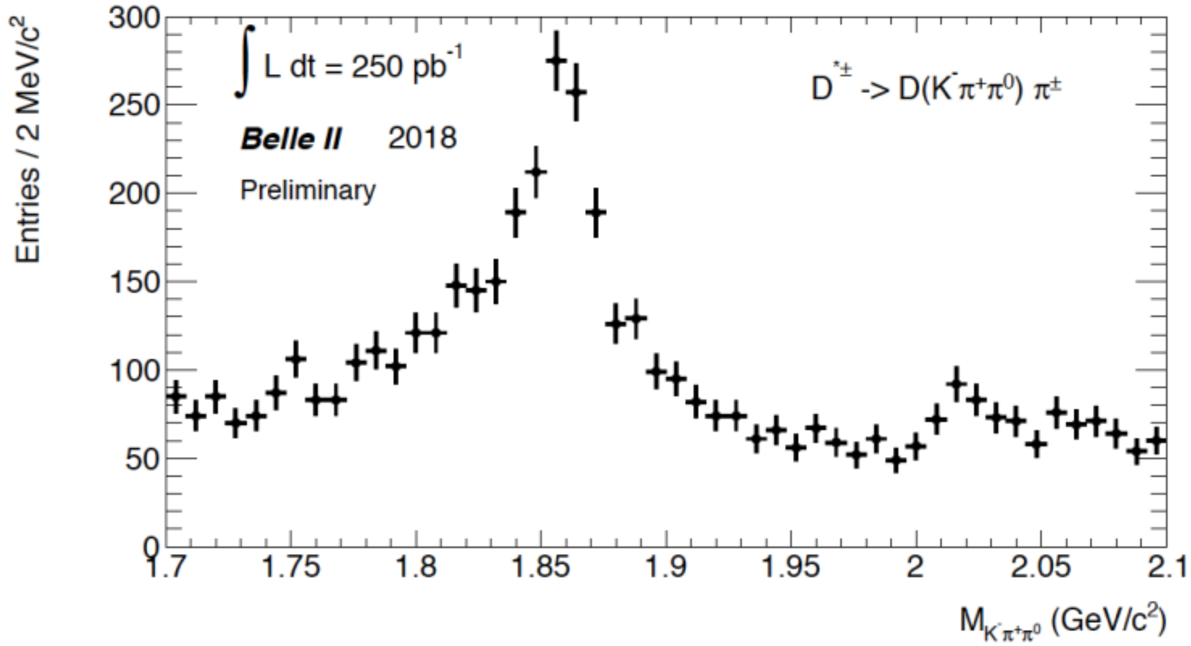


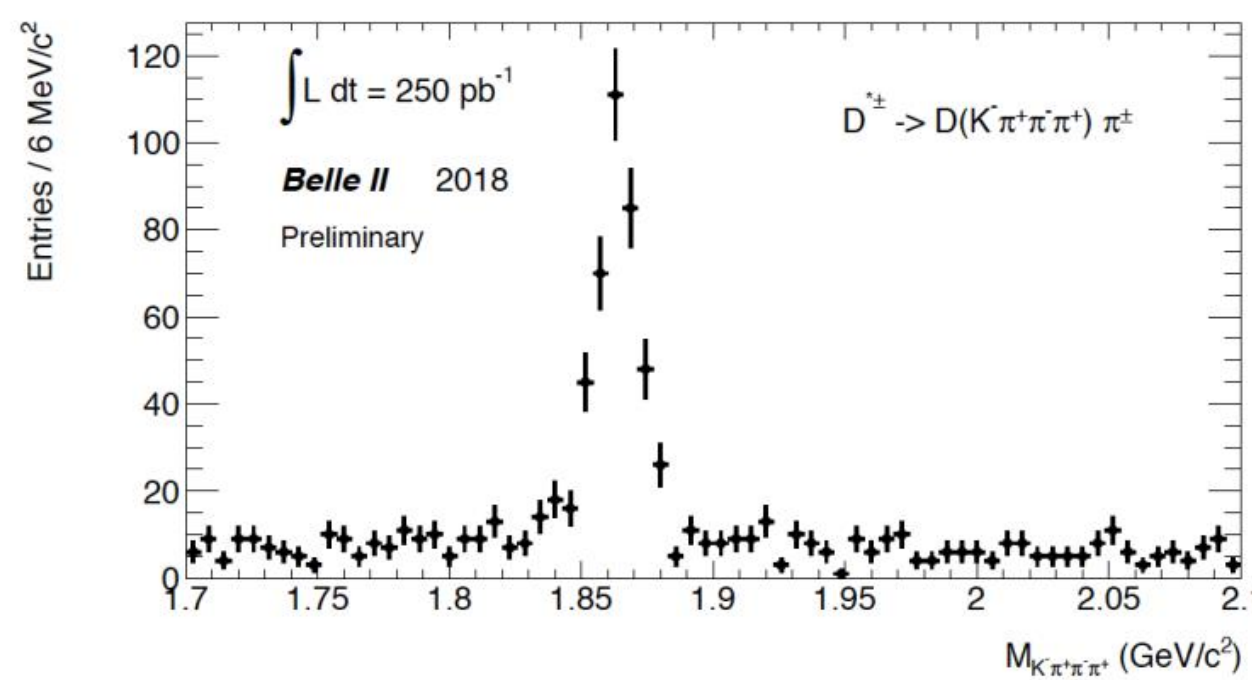


Belle II Performance





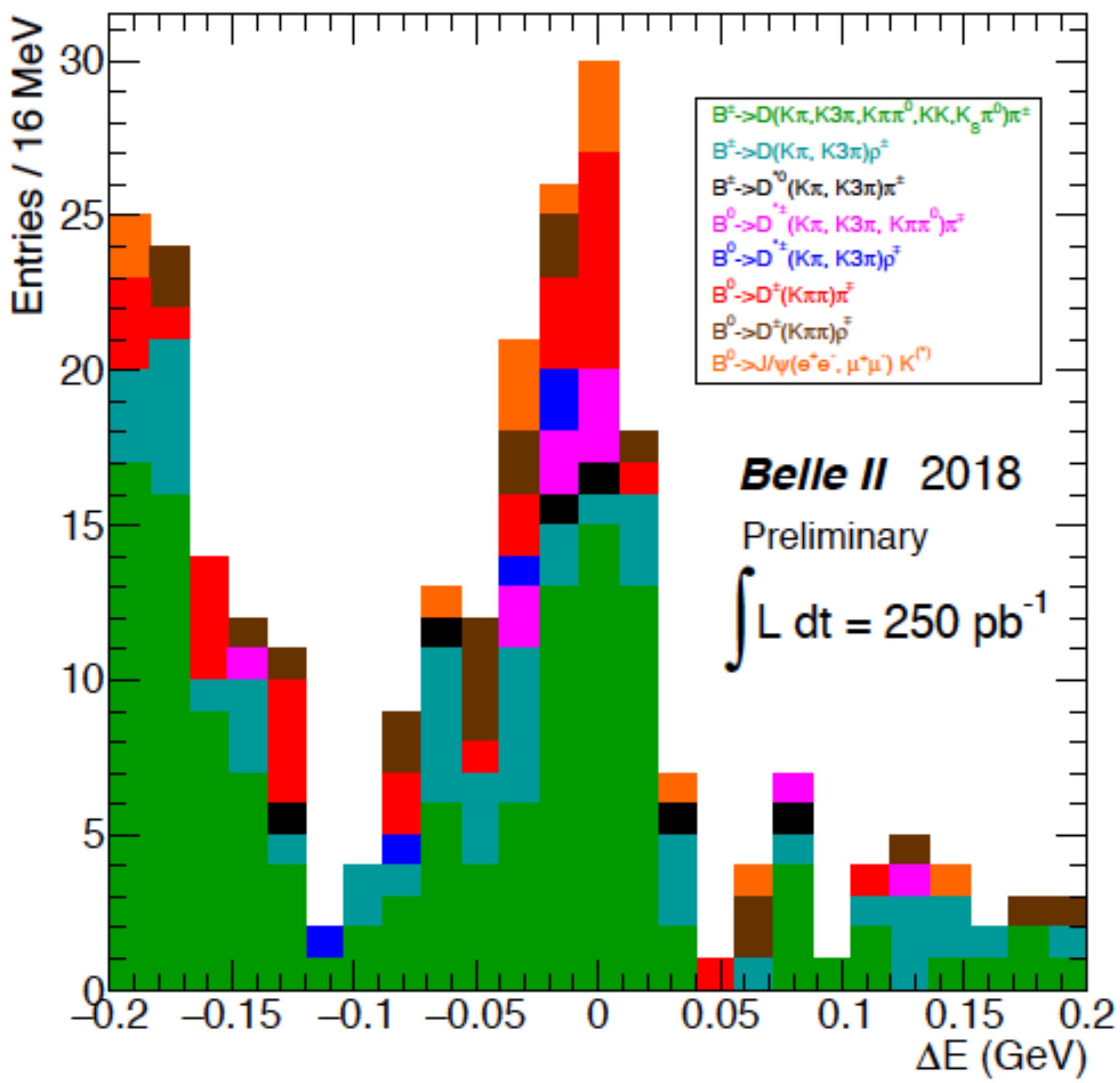


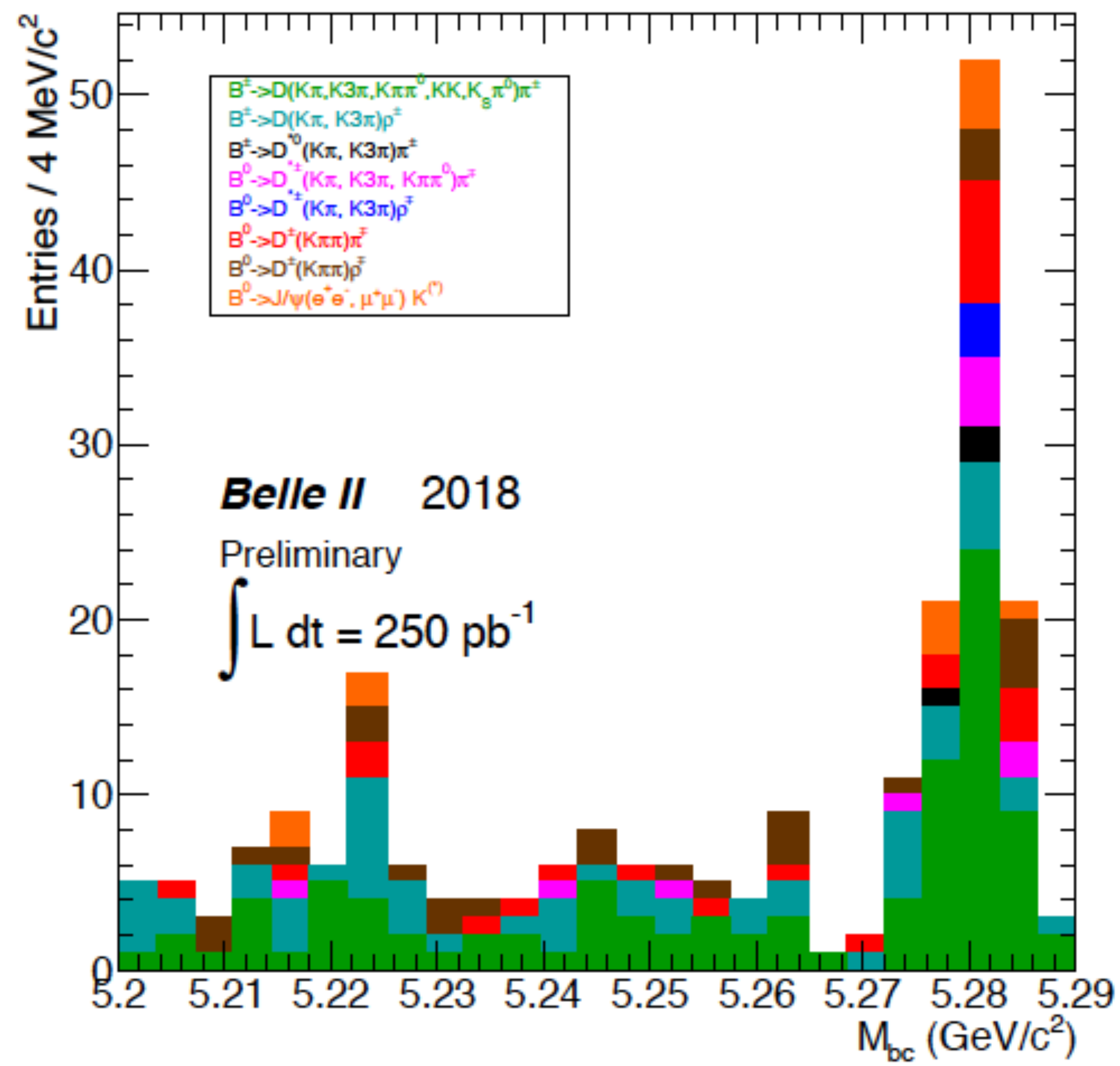


Clear charm signals e+e- → ccbar
Belle II detector is working well!

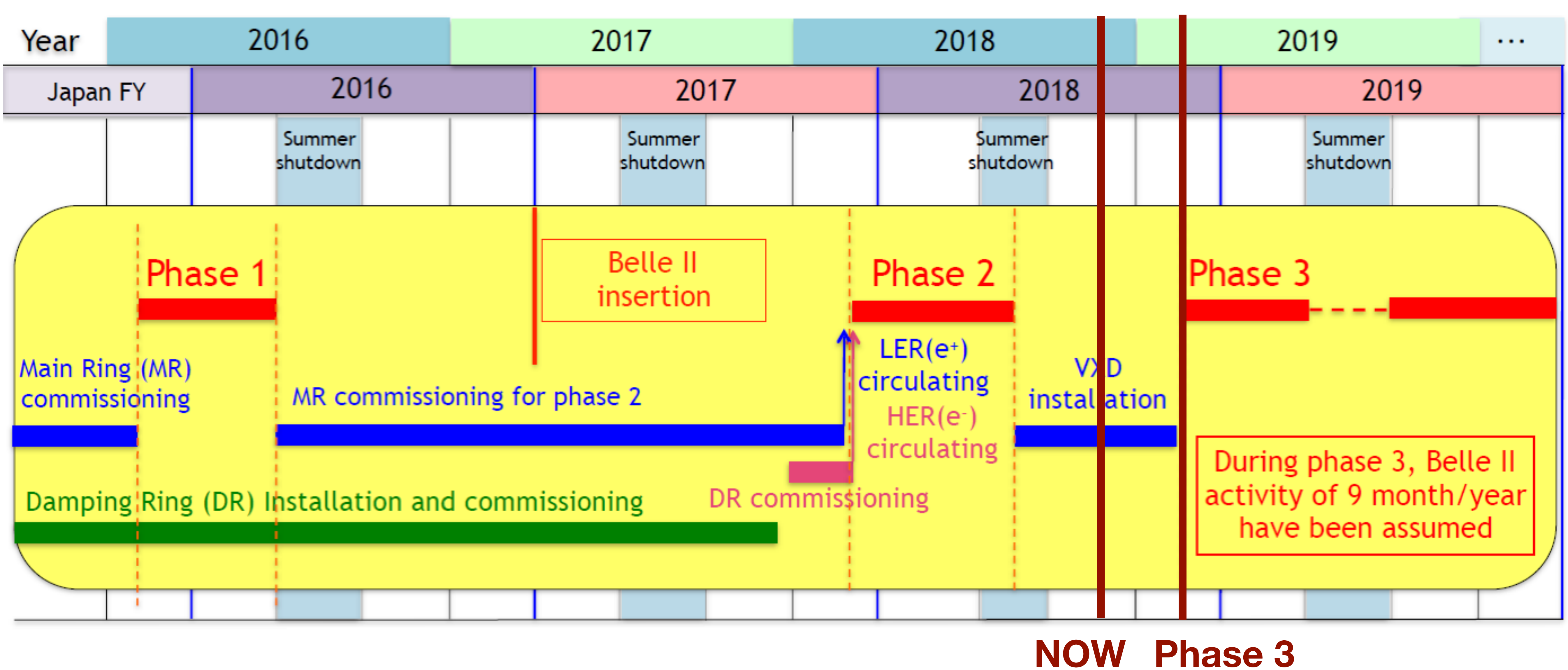
Belle II Performance

We are seeing B signals!





Belle II in future



Phase 3

- **Installation of VXD**
- **Start physics run with full detectors in Spring 2019**
- **Operate 9 months per year**

Summary

- As a “Luminosity Frontier” experiment, Belle II play an important role in charm physics.
  - Search for CPV in charm
  - Search for rare and forbidden charm decays
  - Precise measurements of CKM parameters
- First collision of SuperKEKB achieved on Apr.26, 2018.
- Data collected at Phase 2 illustrates that Belle II detectors are working well.
- We will start physic operation with full detectors in Spring 2019, and aim to operate 9 months per year

Backup

Belle II Collaboration

Belle II中国成员
北京大学
中国科学技术大学
高能所
北京航空航天大学
复旦大学
辽宁师范大学
苏州大学

~800 Colleagues
~110 Institutions
25 Countries/regions

Energy frontier of Belle II

Current samples in fb^{-1} (millions of events), and the proposal for BelleII

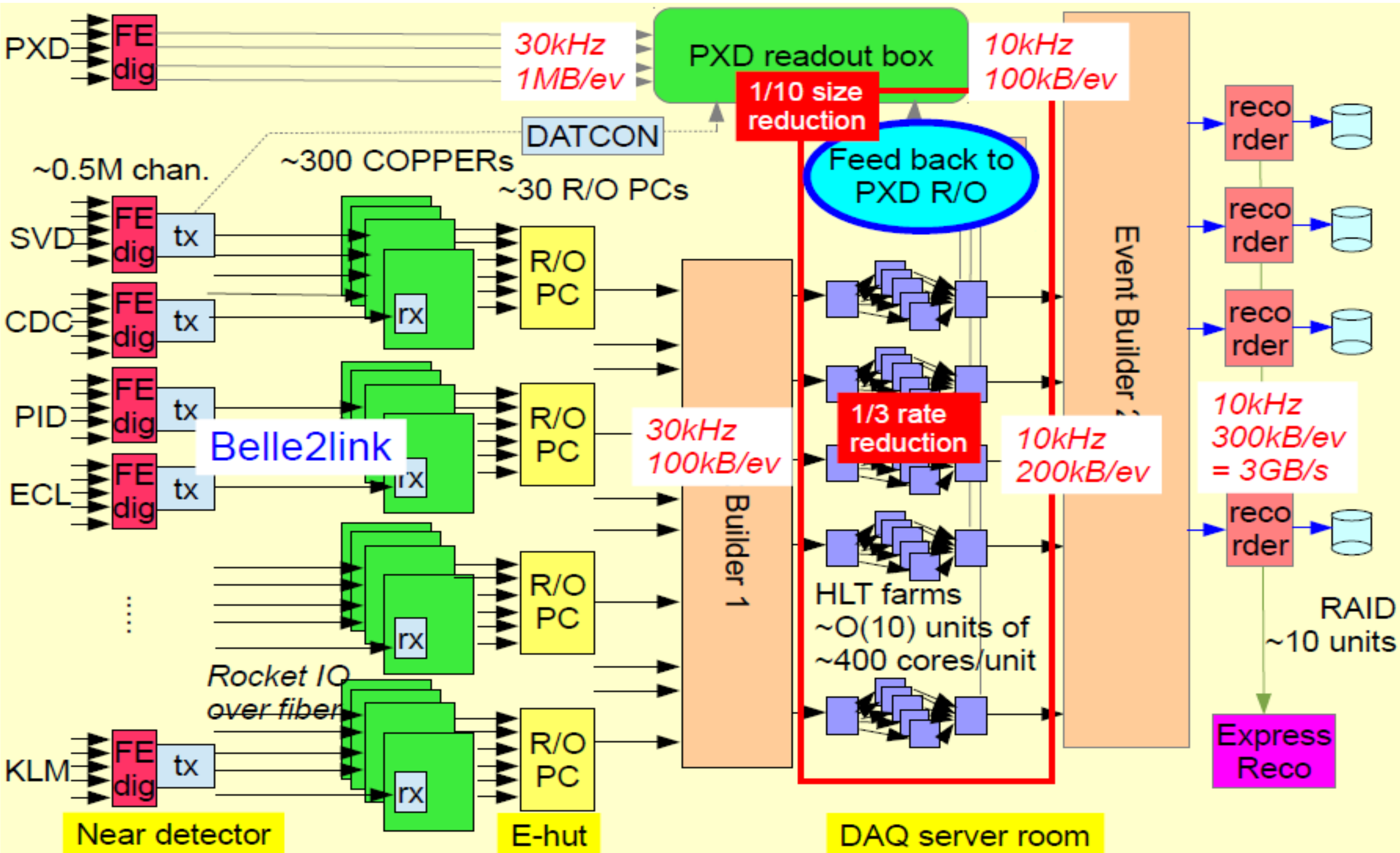
Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

- **Interesting physics beyond Y(6S)**
  - **$\Lambda_b\Lambda_b$ threshold ~ 11.24 GeV, up to 11.35GeV could cover $\Lambda_b\Lambda_b$ threshold region**

- **Machine limits**
  - **The range of beam energies covers the Y(1S) and Y(6S) resonance for physics operation, but no enough spare cavities to run safely at Y(6S)**
  - **Maximum center of mass energy is 11.24GeV in SuperKEKB due to the maximum beam energy of the injector linac**
  - **Linac upgrade is required for running beyond 11.24GeV.**

From Belle to Belle II

DAQ



L1 trigger = 30 kHz
Software Trigger = 10kHz