Prospects of Direct CPV Measurements in Charm Decays at Belle II

Giulia Casarosa

on behalf of the Belle II Collaboration

Belle II

10^{th} International Workshop on the CKM Unitary Triangle

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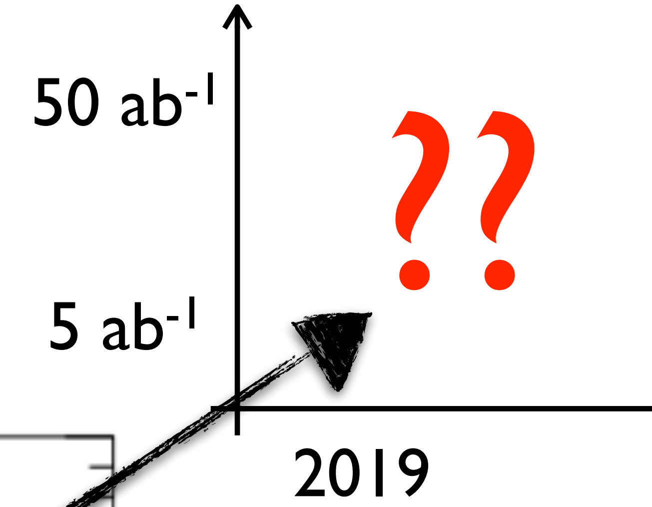
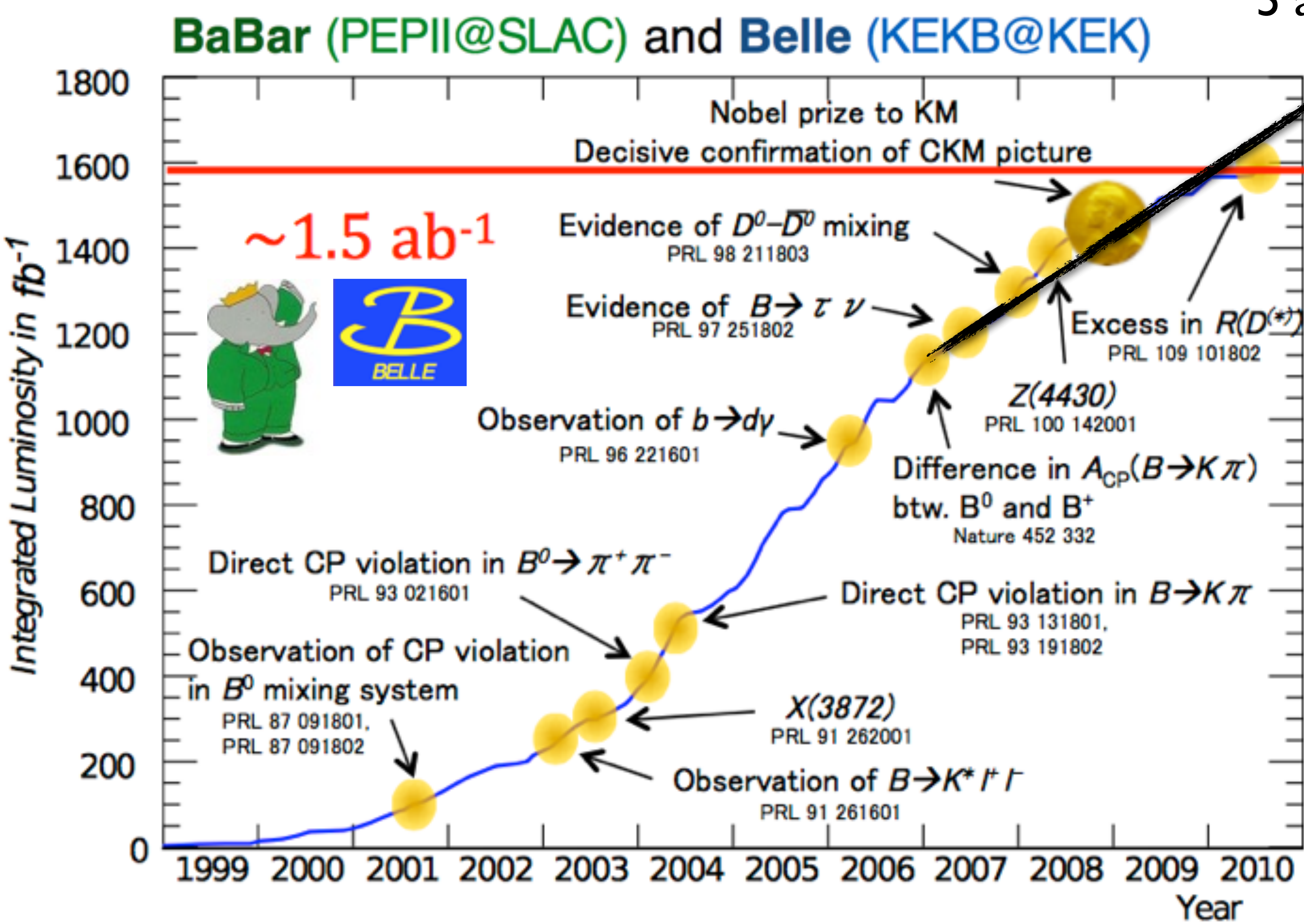
Outline

- ☑ *SuperKEKB and Belle II Design and Current Status*
- ☑ *Belle II Prospects on Direct CPV in Charm*

Flavour Physics @ B Factory

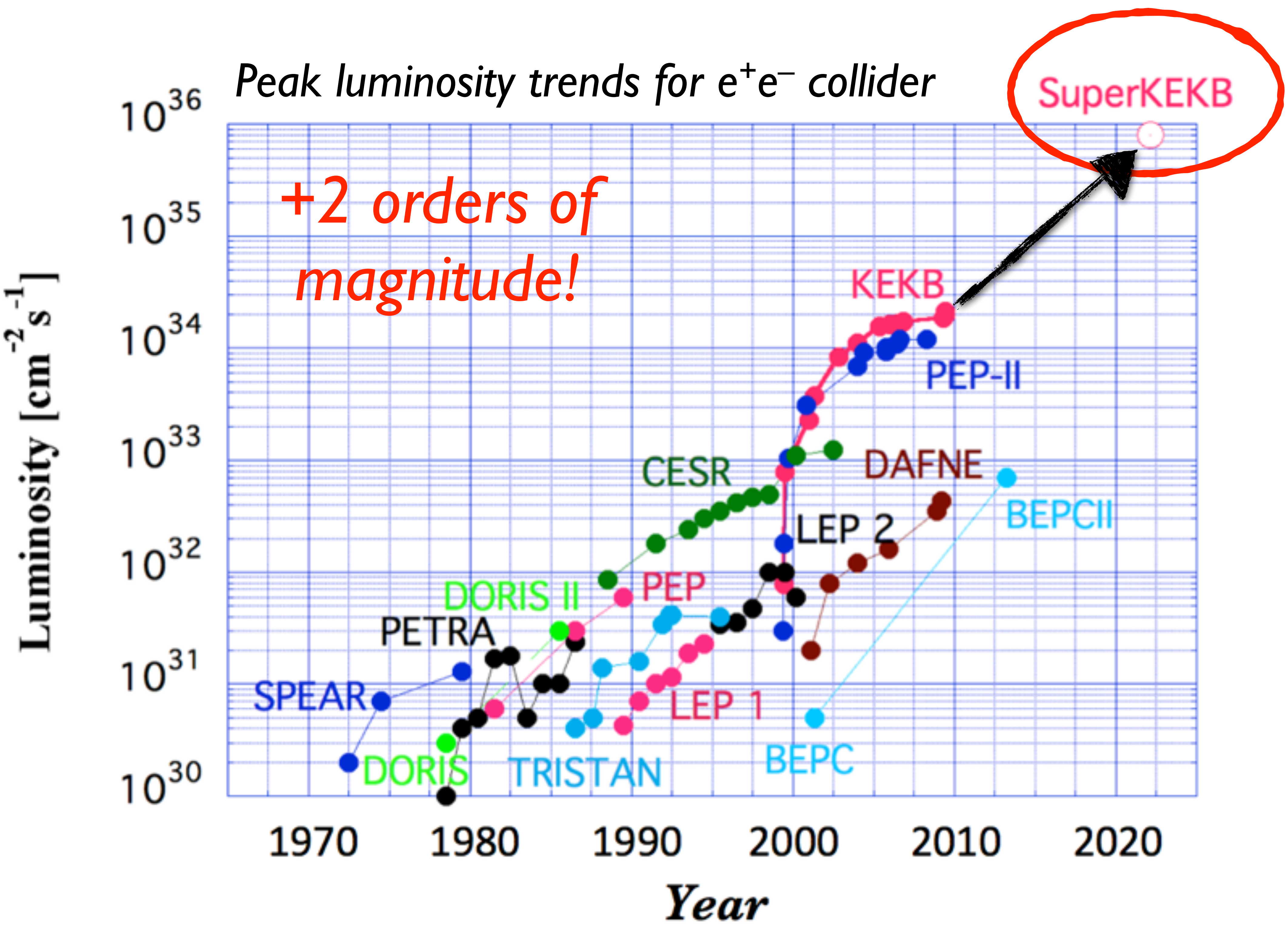




- Belle and BaBar have a produced a large number of important results, since the beginning of their data taking
- Competition between the two experiments has helped in pulling out the best from the two datasets
- First Results of *combined* analysis are coming out

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

On the leading edge of Luminosity



High-Luminosity Asymmetric B Factory

- ➡ Target luminosity is $\mathscr{L}$ = 8x10^{35} cm^{-2}s^{-1} (x40 w.r.t. KEKB)
- ➡ Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

beam current

beam-beam parameter

geometrical reduction factors

beam aspect ratio at the IP

vertical beta-function at the IP

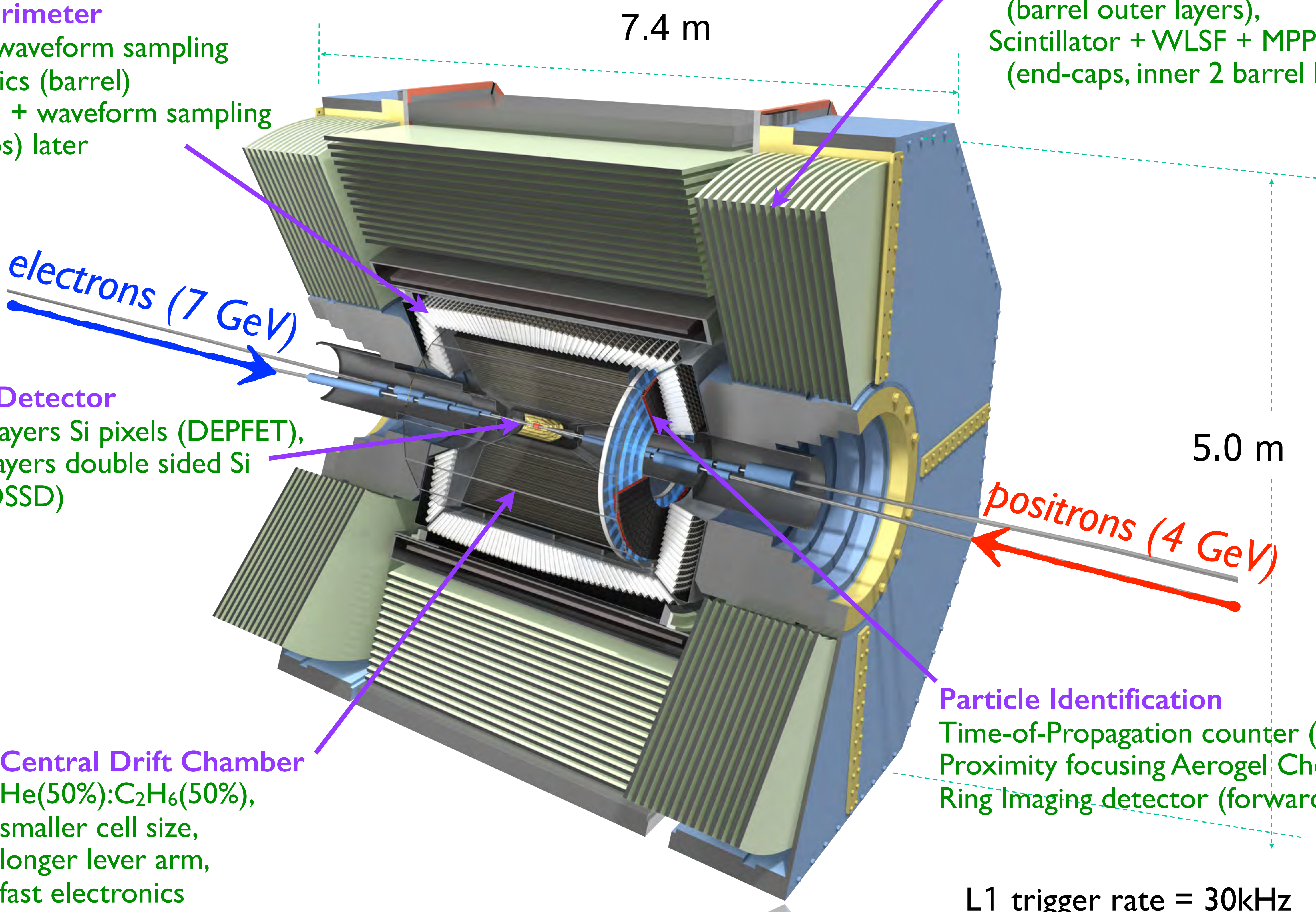
parameters		KEKB LER	KEKB HER	SuperKEKB LER	SuperKEKB HER	units
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		*μm*
Luminosity	$\mathscr{L}$	2.1x10^{34}		**8x10^{35}**		cm^{-2}s^{-1}

- ➡ squeezed beams @ IP → greatly improved constraint for decay chain vertex fitting
- ➡ reduced CM boost → increased detector hermiticity
- ➡ but also higher bkg & event rates, reduced vertex separation → require an improved detector

The *Belle II* Detector

EM calorimeter
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later

K_L & μ Detector
Resistive Plate Counter (barrel outer layers),
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)



Vertex Detector
PXD: 2 layers Si pixels (DEPFET),
SVD: 4 layers double sided Si strips (DSSD)

Central Drift Chamber
He(50%):C_2H_6(50%),
smaller cell size,
longer lever arm,
fast electronics

Particle Identification
Time-of-Propagation counter (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

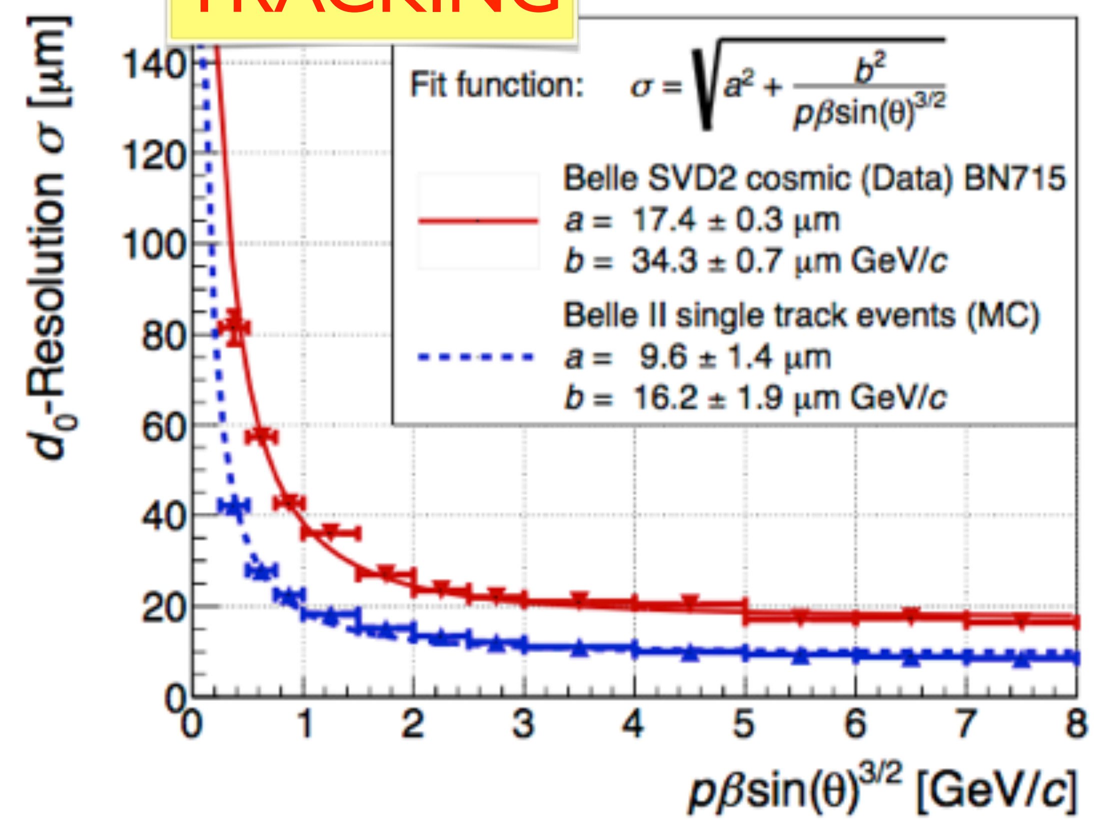
L1 trigger rate = 30kHz
HLT trigger rate = 10kHz

Belle II Performance Improvements

➡ B-Factory advantages over hadron collider detectors:

- clean event environment
- high trigger efficiency
- high-efficiency detection of neutrals (γ, π^0, η, η', …)
- many control samples to study systematics
- good kinematic resolution (Dalitz plots analysis)
- missing energy and missing mass analysis are straightforward (for B physics)

TRACKING

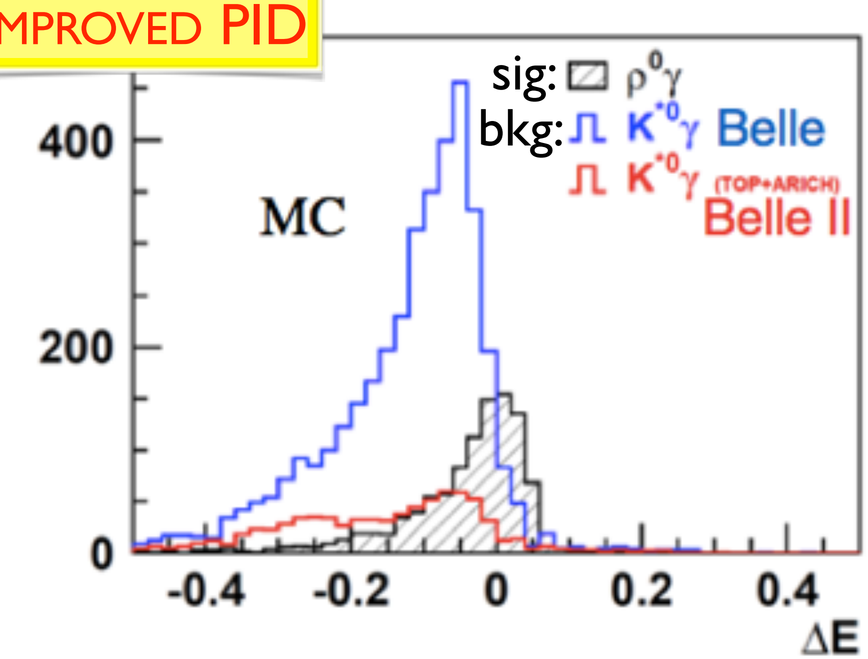


IMPROVEMENTS wrt Belle

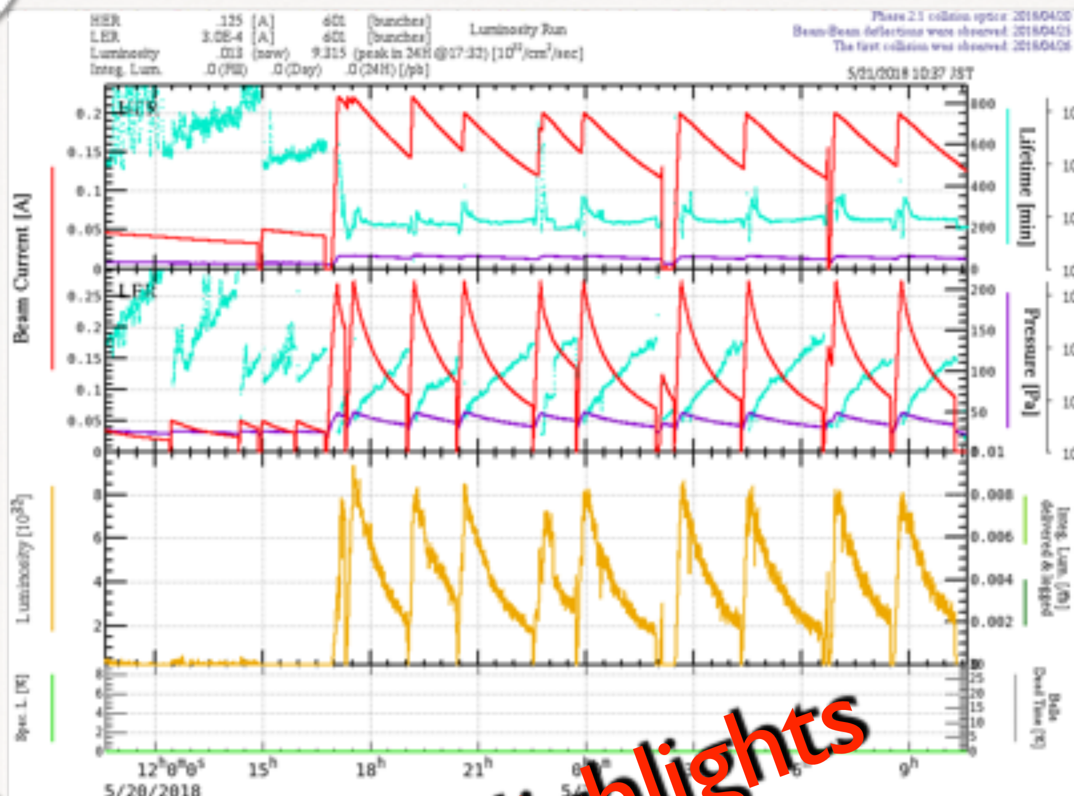
- primary and secondary vertex resolution
- K_S and π^0 reconstruction
- K/π separation
- PID and μ ID in the end caps

particularly relevant for direct CPV measurements!

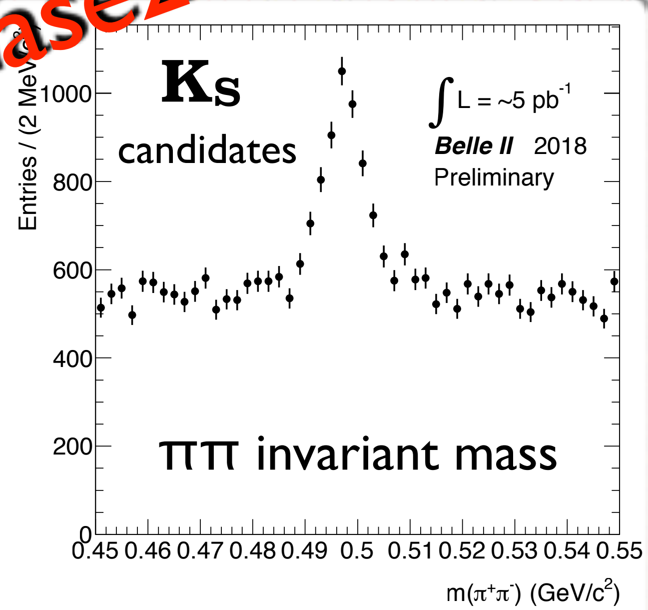
IMPROVED PID



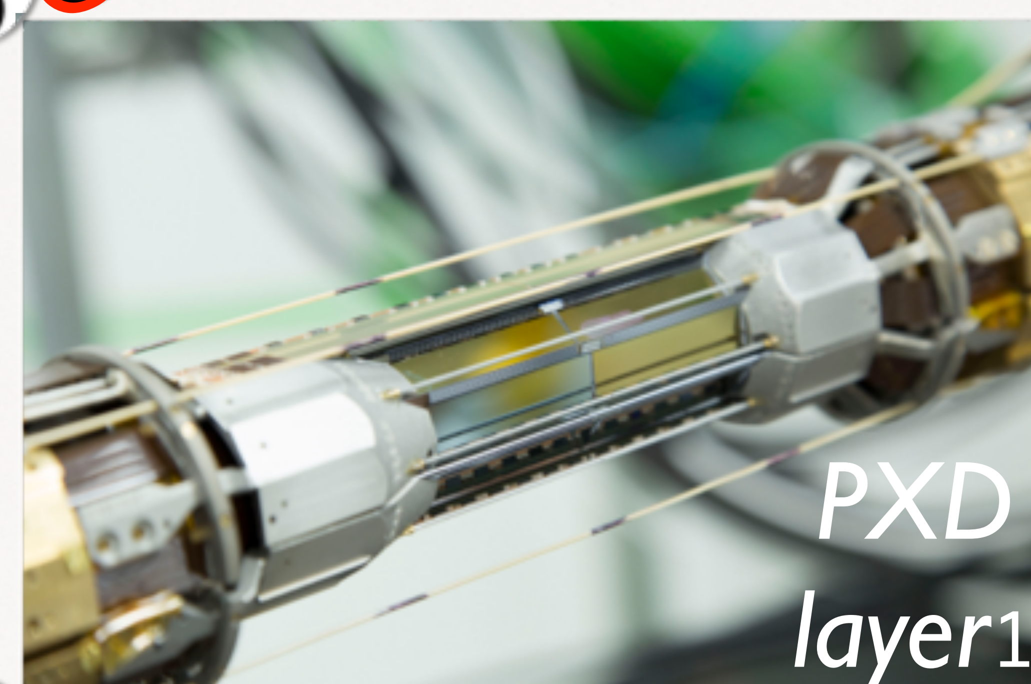
Current Status



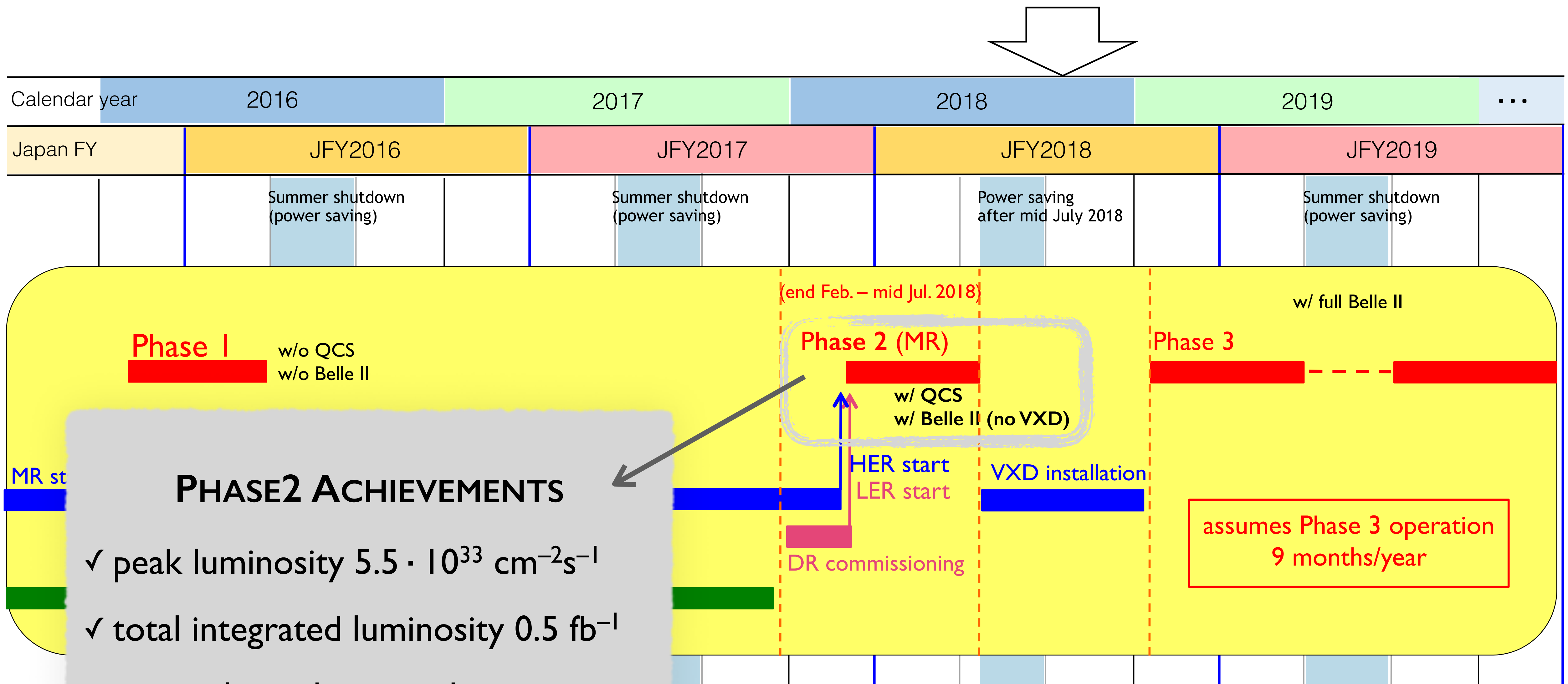
Phase2 Highlights



VXD Commissioning



SuperKEKB and *Belle II* Schedule

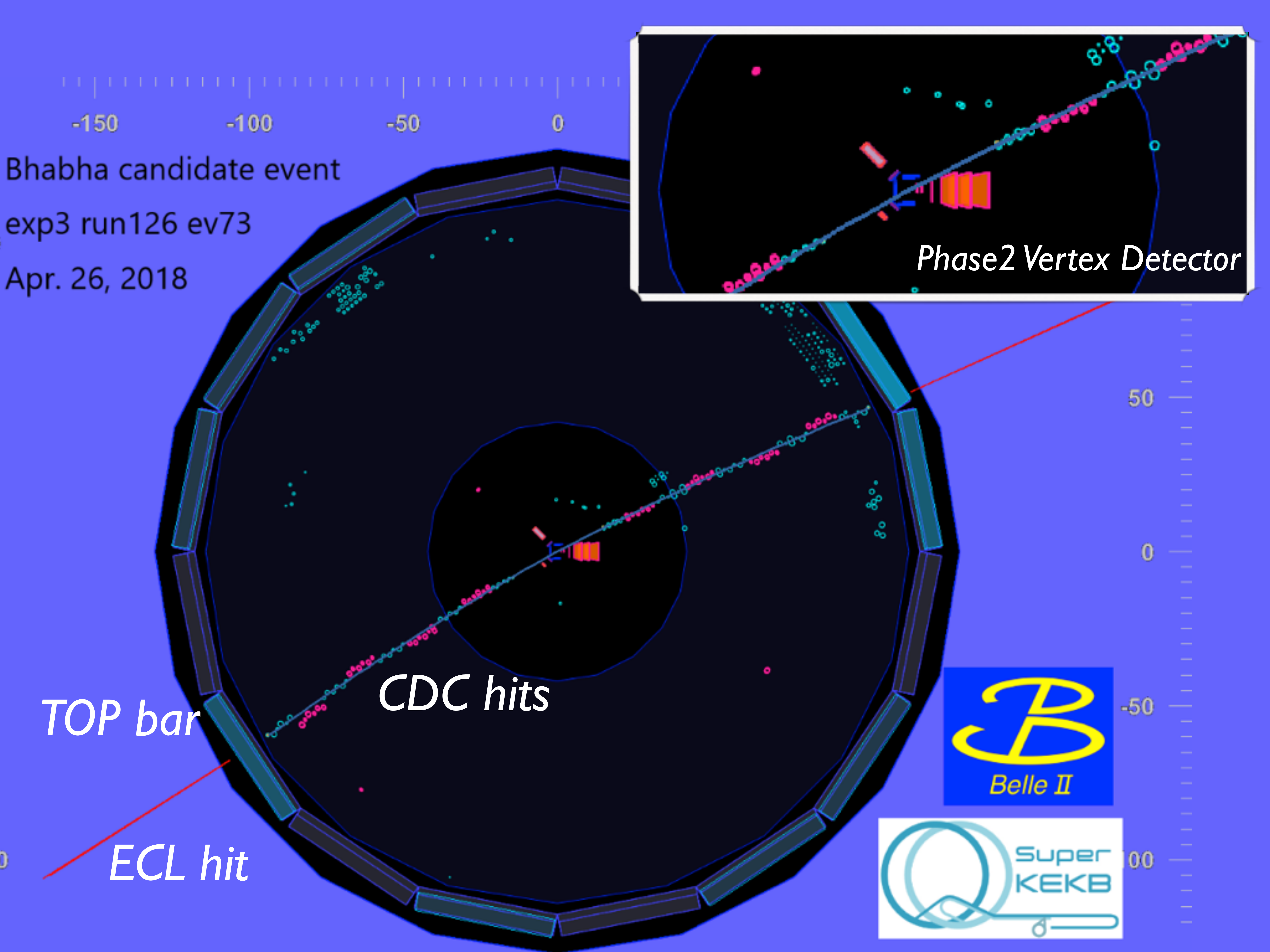


Phase2 Achievements

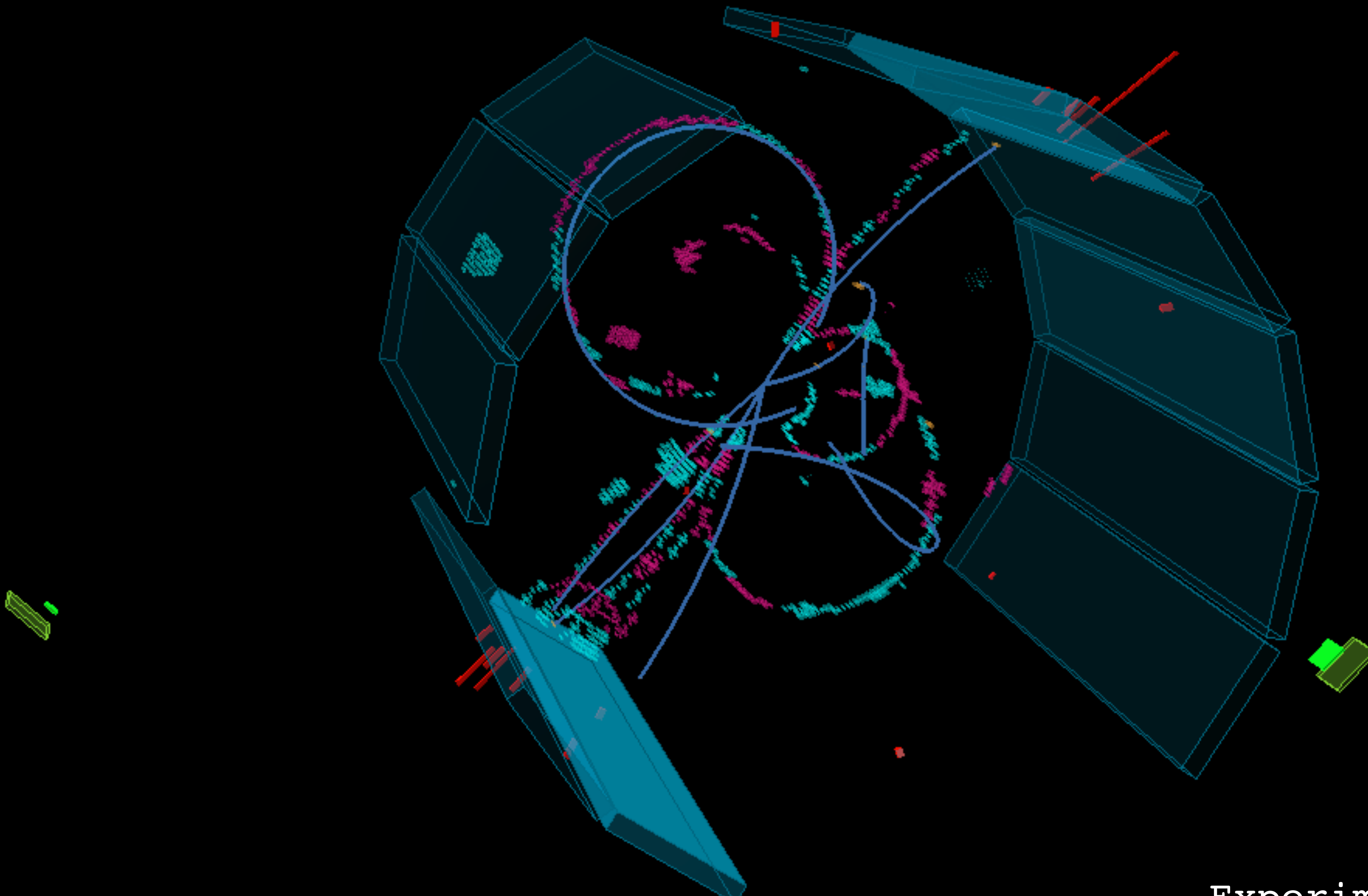
- ✓ peak luminosity $5.5 \cdot 10^{33}$ cm^{-2}s^{-1}
- ✓ total integrated luminosity 0.5 fb^{-1}
- ✓ currently studying machine background and understanding detector performances
- ✓ exercise reconstruction and calibration algorithms in order to be ready for the beginning of the Physics run (work in progress)

➡ **First collisions recorded on April 26th 2018!!**

➡ **Phase2 detector**: *Belle II* with no VXD but the Beast2 detector = one VXD ladder per layer installed on the horizontal plane + dedicated beam-background detectors


Bhabha candidate event
exp3 run126 ev73
Apr. 26, 2018
Phase2 Vertex Detector
CDC hits
TOP bar
ECL hit
-150
-100
-50
0
50
0
-50
Belle II
Super
KEKB

Luminosity Run, 26th April 2018 First Hadronic Event



Experiment 3
Run 125
Event 223

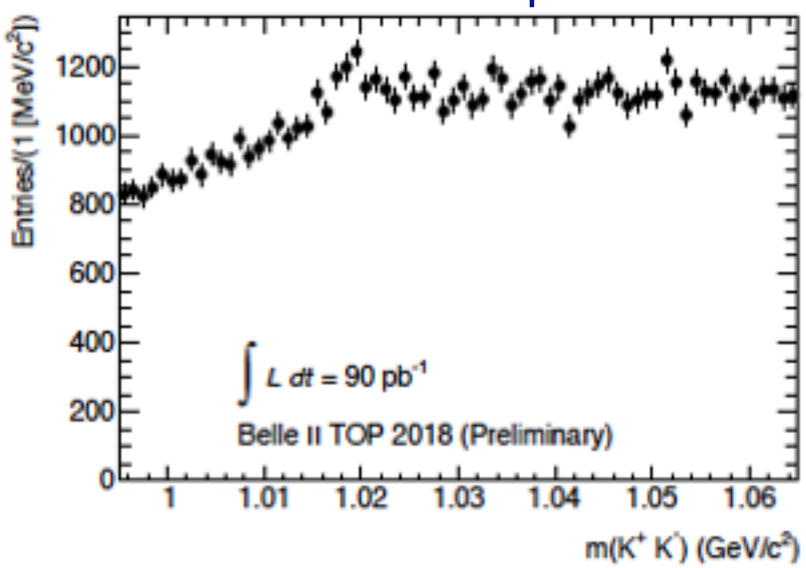
note: vertex detector not shown

Reconstruction Highlights

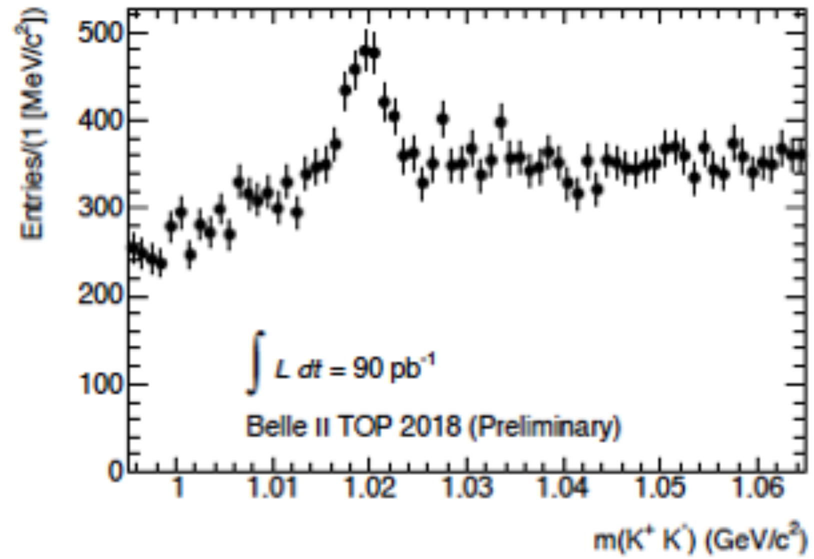
➡ Phase2 data taking is crucial to exercise calibration and reconstruction in order to be ready for the beginning of the Physics run

- **$\Phi \rightarrow K^+K^-$** reconstruction, impact of the PID using TOP detector:

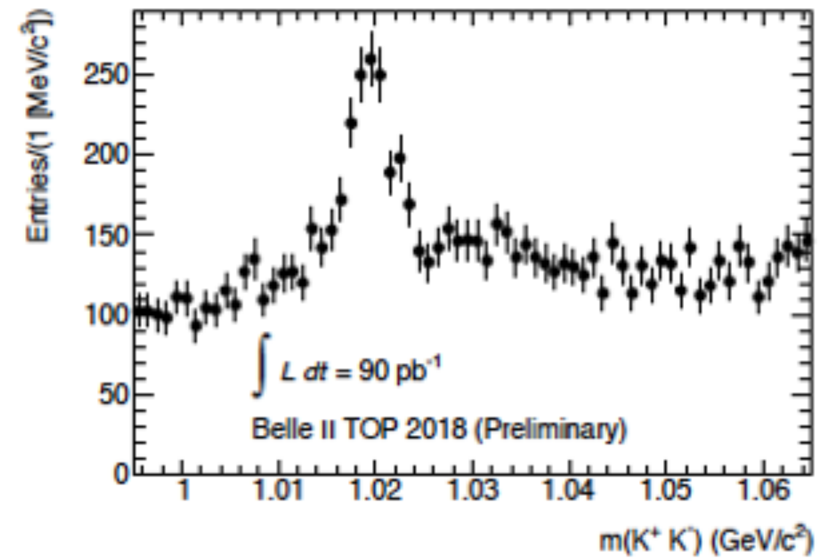
No kaon ID required



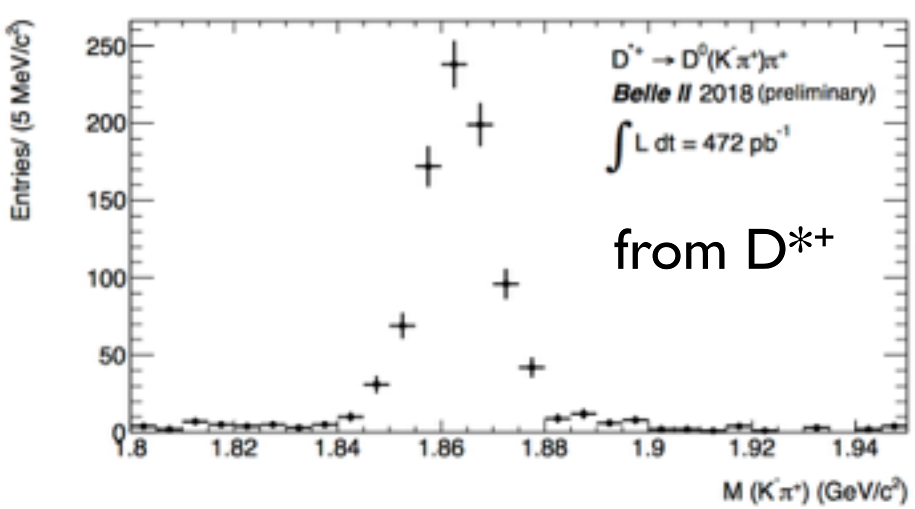
One kaon identified in TOP



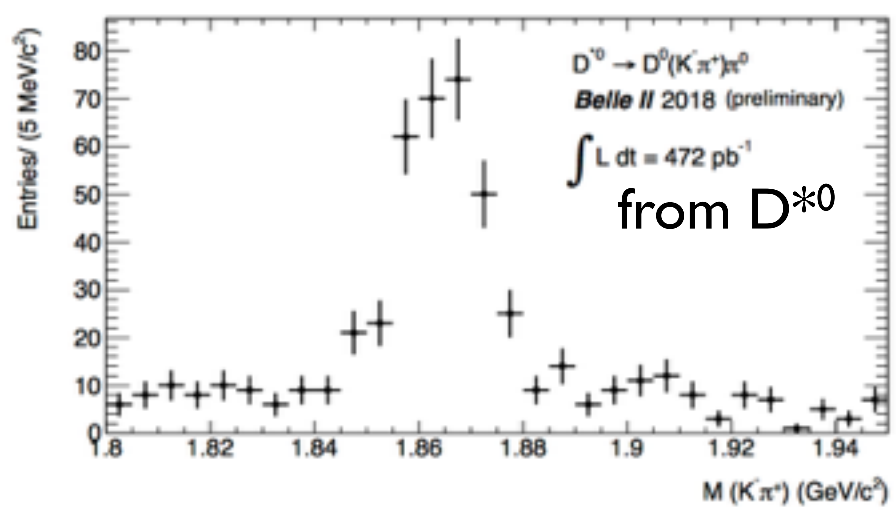
Both kaons identified in TOP



- Neutral pion reconstruction: **$D^0 \rightarrow K^-\pi^+$** from $D^{*+} \rightarrow D^0\,\pi^+$ and $D^{*0} \rightarrow D^0\,\pi^0$



$0.14 < \Delta M\ (GeV/c^2) < 0.16$



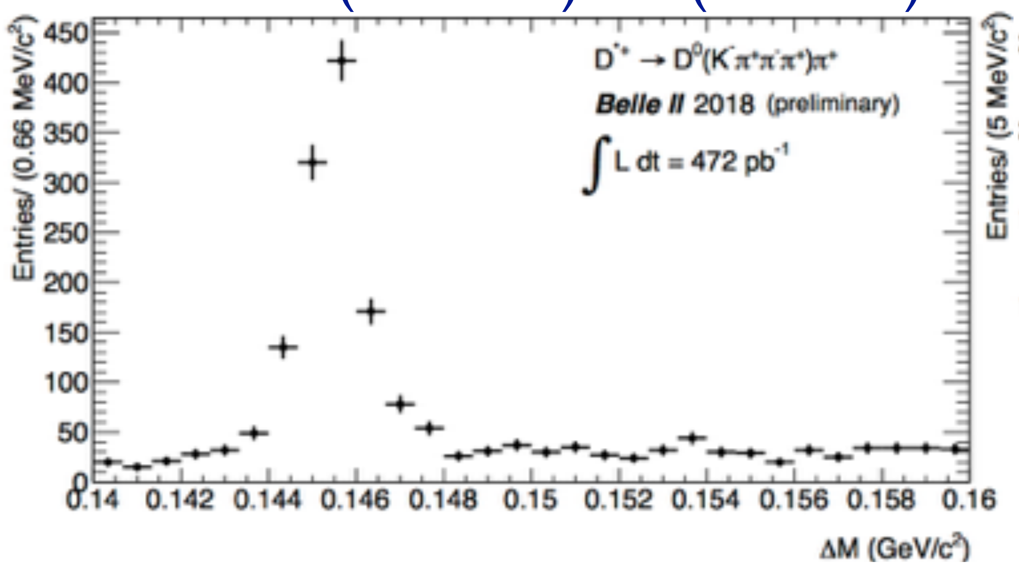
$0.1405 < \Delta M\ (GeV/c^2) < 0.1425$

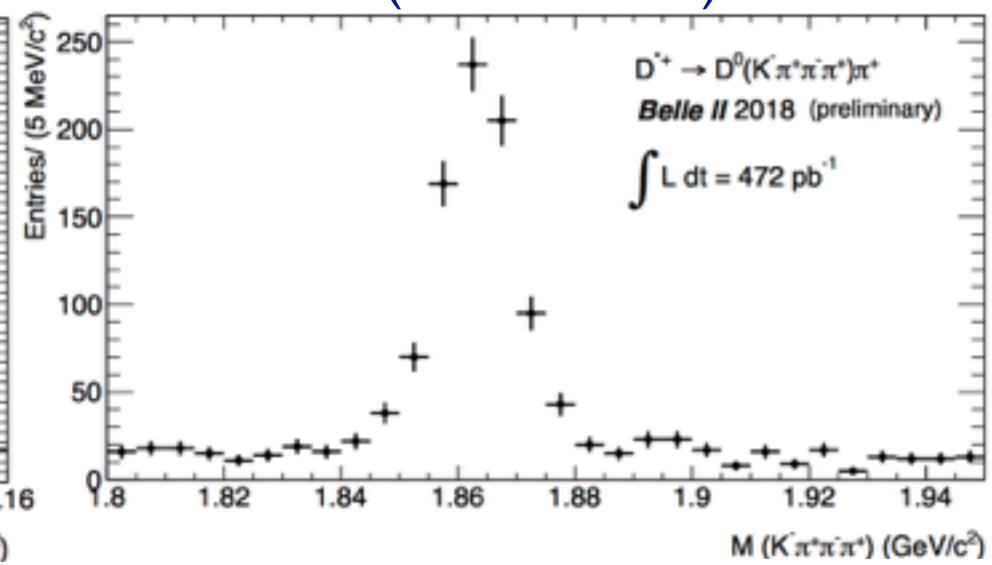
Calibration of the reconstruction is continuously improving, promising an efficient start of the physics run next year, and first results coming soon after

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

Belle II is ready for charm physics!

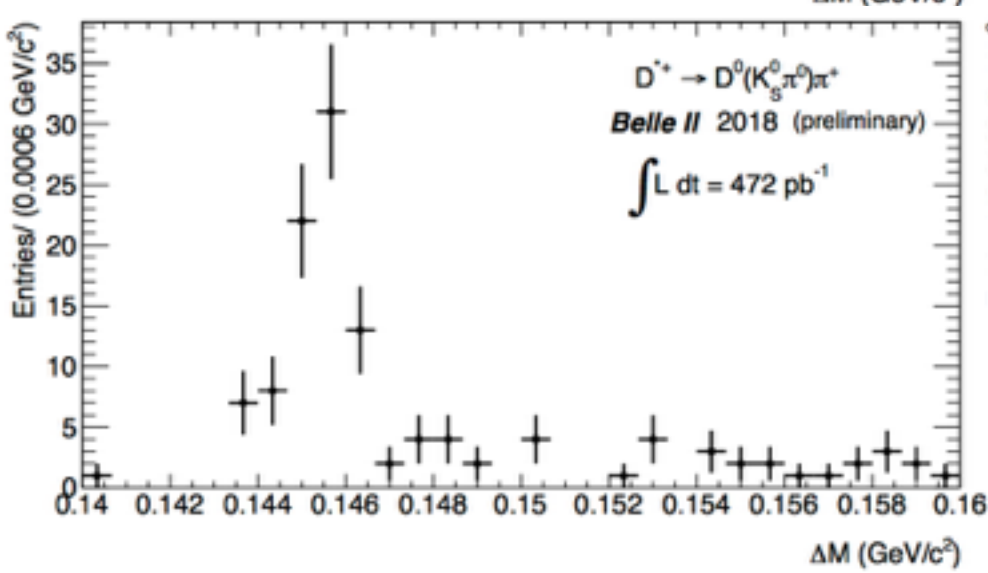
ΔM = M(D^* cand.) – M(D^0 cand.) | M(D^0 candidate)

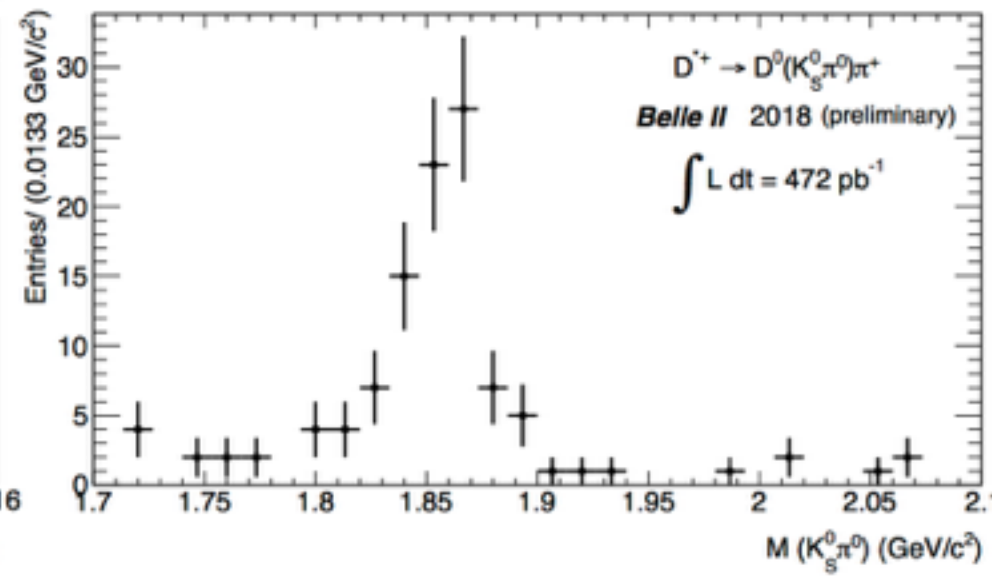




$D^{*+} \to D^0\pi^+$

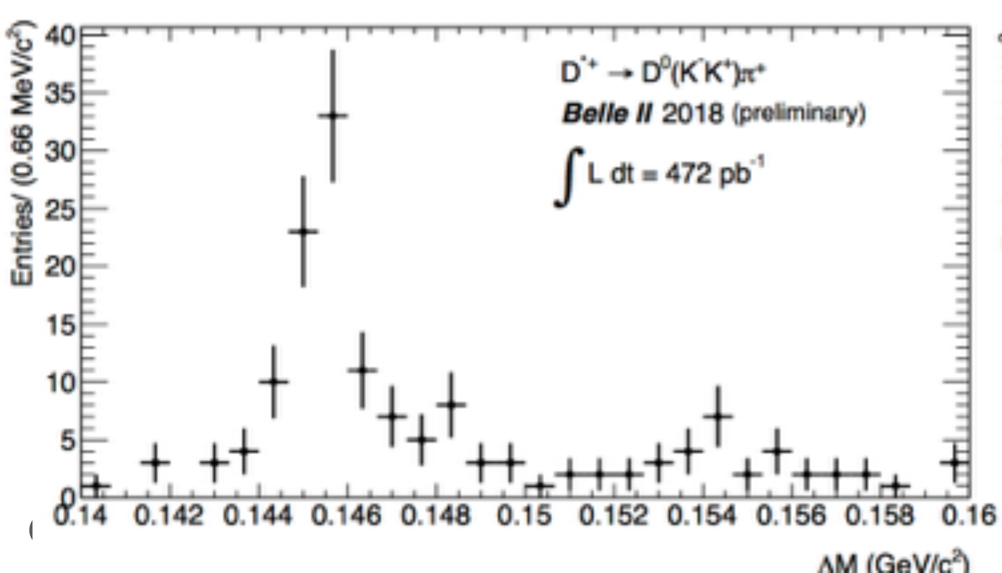
$D^0 \to K^-\pi^+\pi^-\pi^+$

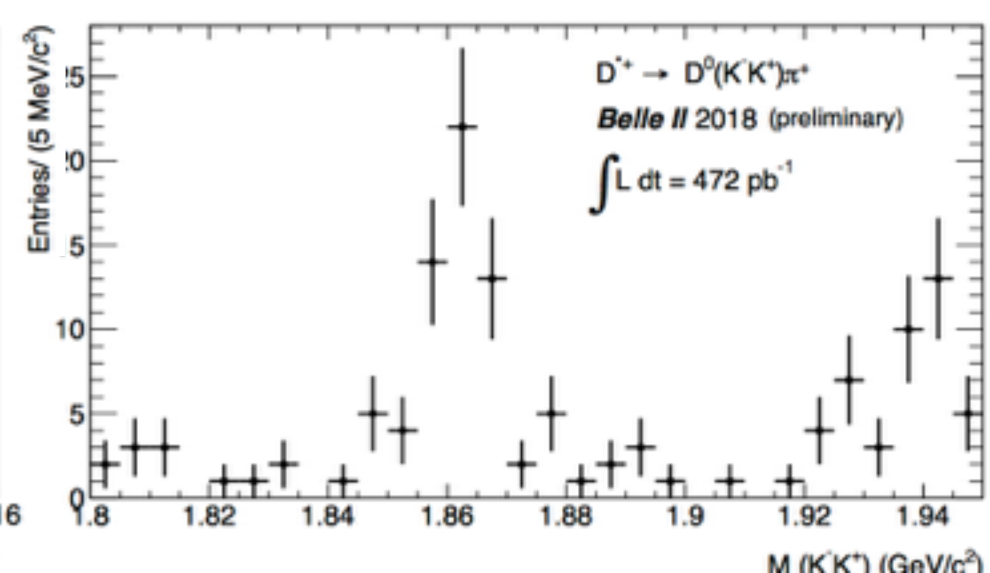




$D^{*+} \to D^0\pi^+$

$D^0 \to K_S\pi^0$





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

$D^0 \to K^-K^+$

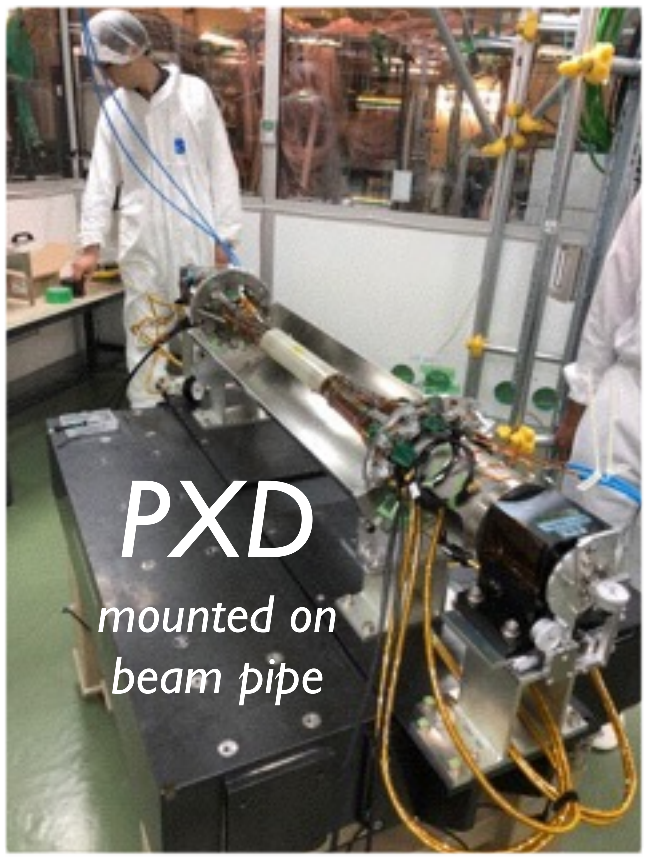
SCS decay

VXD Commissioning

Silicon Vertex Detector (SVD):

- both half-shells of the final SVD detector have been taking cosmic data *smoothly* and *stably* since more than one month, first efficiency measurements expected soon

+



PiXel Detector (PXD):

- the first layer of the PXD has been installed on the beam pipe
- issues occurred during the assembly of the second layer, its installation has been postponed until problems are understood and solved

VerteX Detector Assembly = PXD + SVD

- SVD half shells will be closed around the beam-pipe+PXD soon, the procedure will begin in a few weeks
- VXD installed in *Belle II* by the end of the year

Belle II Prospects on Direct CPV in Charm

- The following projections are extrapolated from Belle measurements

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

- we assumed that most of the systematics scale with statistics
- There 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

Direct CP Violation

- CP Violation in the charm sector is predicted to be *small*, but not zero.
- The observable that is sensitive to direct CPV is the time-integrated CP asymmetry (A_{CP}):

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

- No experimental evidence of CPV in charm so far, so the first goal is to measure CPV in charm (then we can look for NP)
  - **$D^0 \to K_S K_S$**: A_{CP} up to 1% within SM, could give *first evidence* of CPV in charm
    [Nierste Schacht 1508.00074]
- SM predictions on A_{CP} are hard$^{(*)}$. Theory needs experimental inputs not only to check the final predictions but also to test the model hypotheses
  - employ a parameterisation that is appropriate for the level of precision expected in the *BelleII*/LHCb-upgrade era (true mostly for indirect CPV)
  - infer the presence of NP in direct CPV measurements using SM SU(3) relations (+ evaluate SU(3) breaking) → A_{CP} sum rules involving >2 channels [Grossman Kagan Nir 2006]
- $^{(*)}$… but there are exceptions:
  - **$D^+ \to \pi^+\pi^0$**: A_{CP} = 0 in the SM, search for NP with *straightforward interpretation* of the results
    [Buccella et al PLB302, 319 (1993)]
    [Grossman et al PRD85, 114036 (2012)]

Prospects for CP Asymmetries

➡ *Belle II* will be able to measure A_{CP} on many channels, reaching precisions of the order of 10^{-4}:

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
$D^0 \to K_S^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K_S^0K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K_S^0\eta$	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
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	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	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K_S^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_S^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

important for A_{CP} sum rules → ($D^0 \to \pi^0\pi^0$ … $D^0 \to K^+\pi^-\pi^0$)

SM $A_{CP} \simeq 1\%$ → ($D^0 \to K_S^0K_S^0$)

important for A_{CP} sum rules → ($D^+ \to \pi^+\pi^0$ … $D^+ \to \eta'\pi^+$)

SM $A_{CP} = 0$ → ($D^+ \to \pi^+\pi^0$)

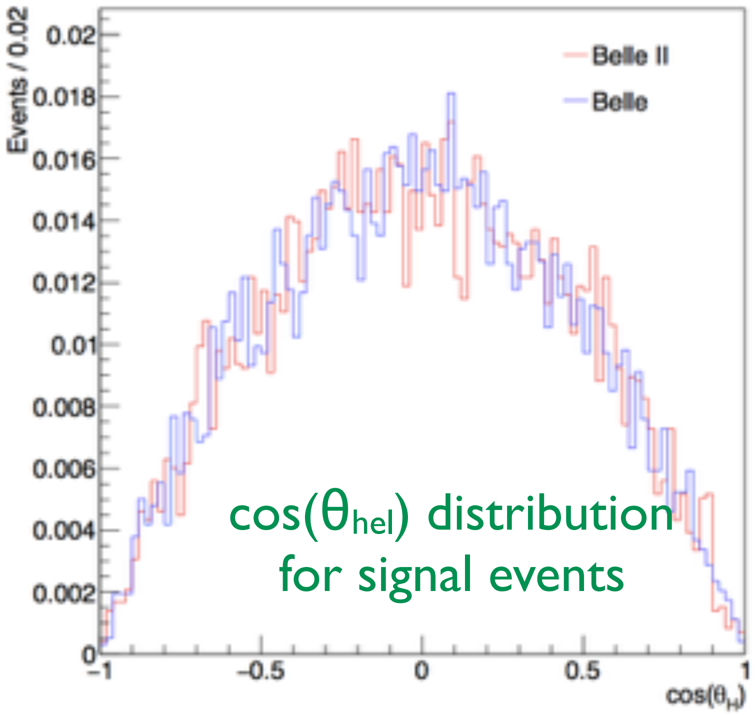
➡ *Belle II* is favoured with respect to other experiments in channels with neutrals in the final state, but its measurements of A_{CP} on channels with charged tracks in the final state will be important too

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

1. CP Violation: SM expectations on the order of 10^{-3}, NP contributions can enhance it up to an order of magnitude
2. tests of QCD: 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

Inclusive Λ_c^+ Sample

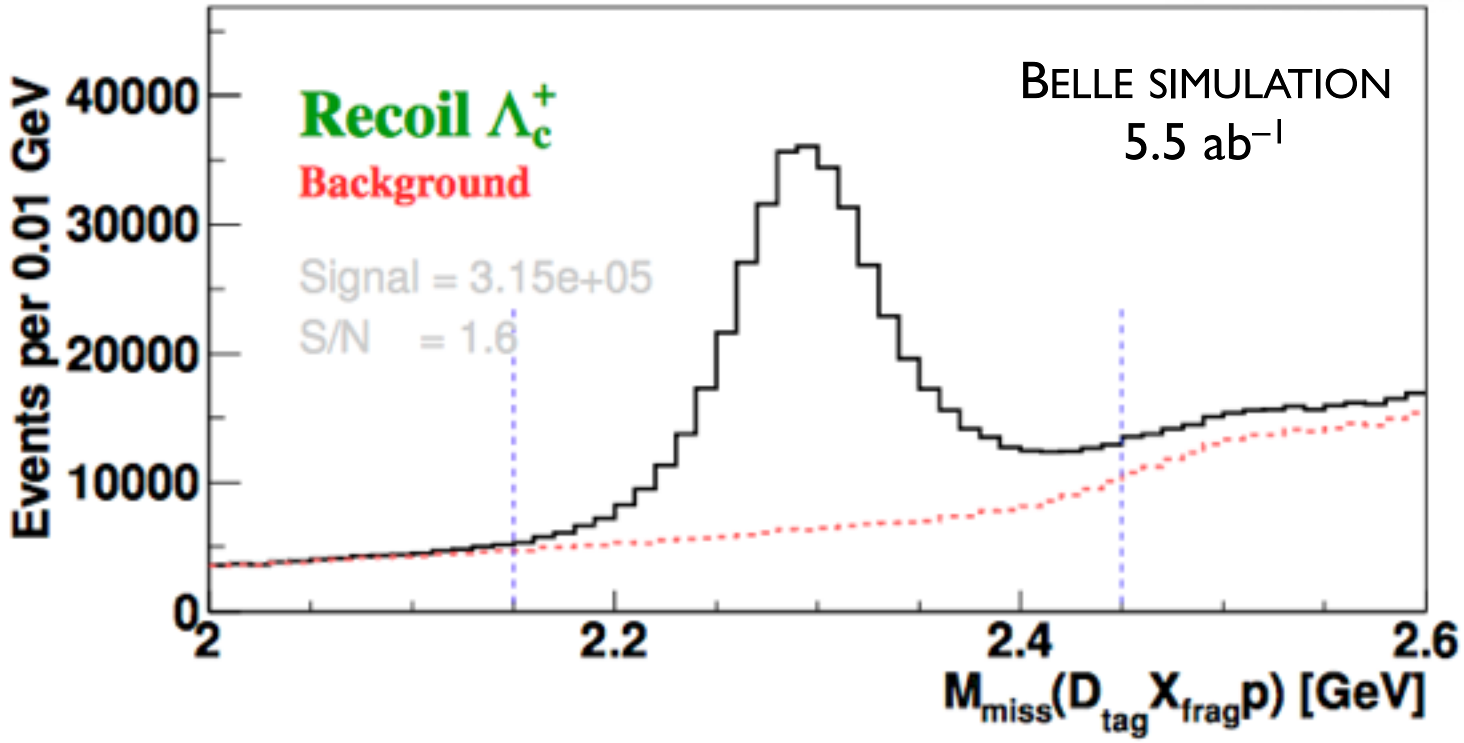
Extend the **recoil method** successfully exploited for D_s decays to reconstruct Λ_c^+:

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

recoil method

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

- X_{frag}: light mesons (K, π, …)
- D_{tag}: reconstructed in several channels (D^0, D^*, D_s, …)
- D_{sig}: signal channel



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

- compute the invariant mass of the rest of the event w.r.t. Λ_c^+
- M_{miss} = Λ_c^+ mass

➡ BELLE simulation scaled to 50 ab^{-1} yields **2.8x10^6 inclusive Λ_c^+**

➡ **Unique** sample that allows to:

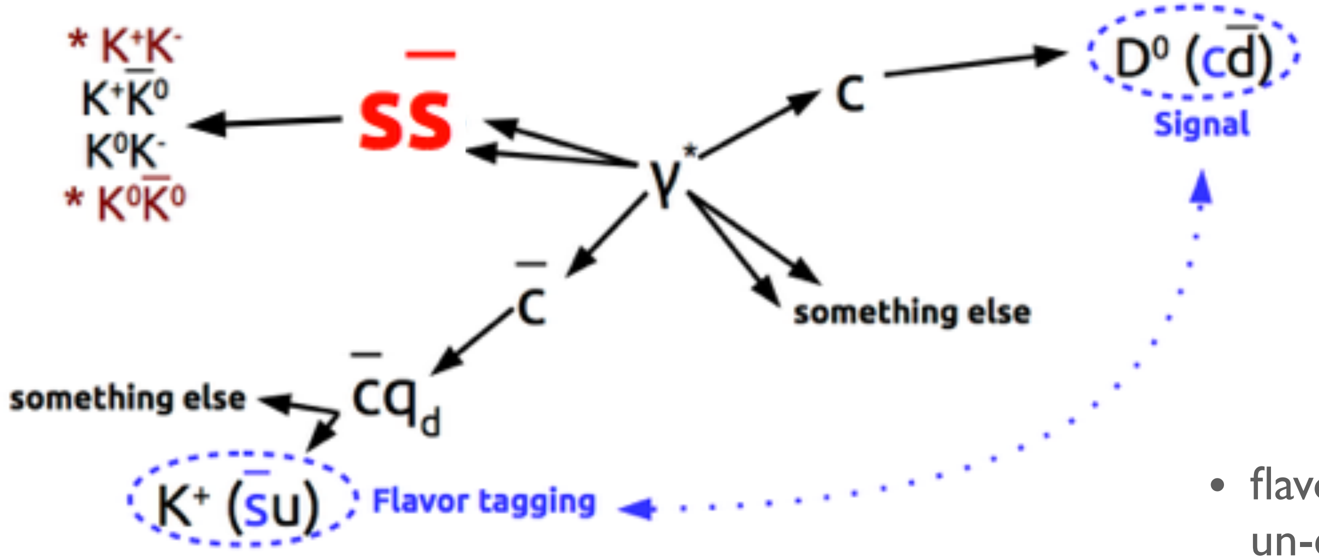
- measure absolute branching fractions and **CP asymmetries**
- measure semileptonic decays, search for rare decays with missing energy

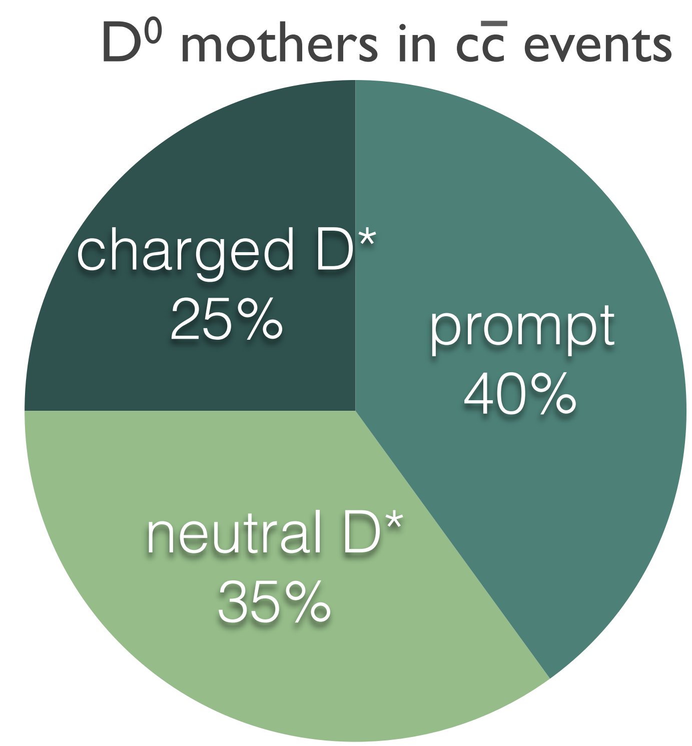
Prompt D^0 Flavour Tagging

BONUS

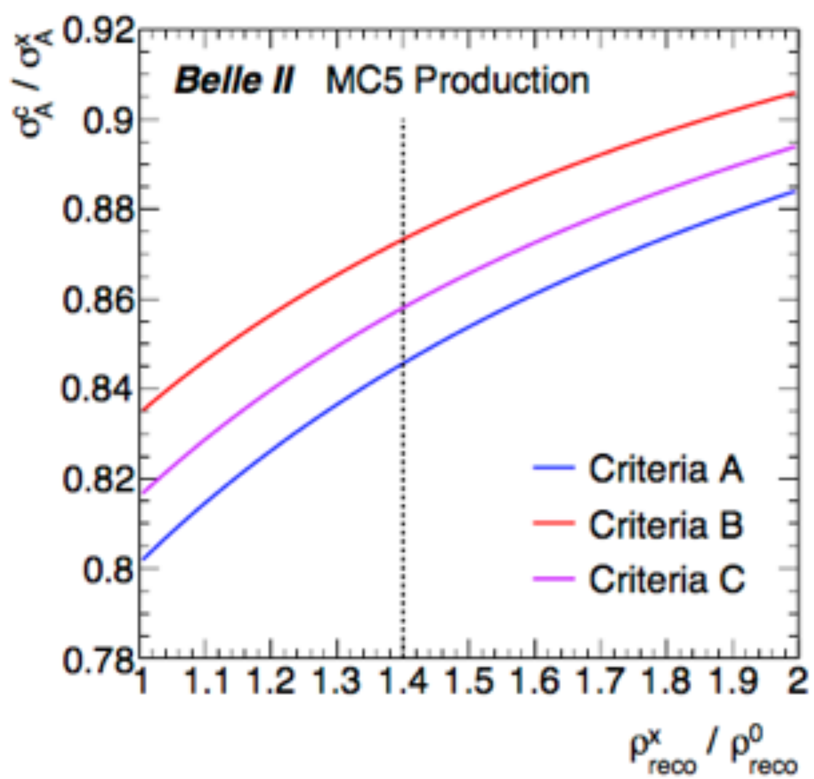
➡ New reconstruction technique that allows to tag the flavour the rest 75% of produced D^0 looking at the rest of the event (ROE)

- select events with one single D^0 and one single charged K in the rest of the event





- flavour mis-tagging due to $c\bar{c}s\bar{s}$ events that introduce un-correlated charged kaons into the rest of the event
- irreducible bkg due to DCS decays



preliminary studies indicate that combining A_{CP} measurements from D-tagged and ROE-tagged samples is equivalent to an effective increase of luminosity of ~ 40%*

Conclusions

- ☑ *A lot of lessons learnt during Phase2 data taking on accelerator and detector operation*
- ☑ *Phase2 data very useful to exercise reconstruction and calibration on real data*
- ☑ *Physics Run will start soon, at the beginning of 2019*
- ☑ *Search of direct CPV will benefit from increased data sample, improved detector performances and new reconstruction algorithms*
- ☑ *A rich charm physics program ahead, ready to improve precision on:*
  - *direct CP asymmetries, mixing and CPV parameters*
  - *V_{cd} and V_{cs} from semileptonic decays, decay constants f_D, f_{Ds}*
  - *measurements of charm baryons*
  - *limits on rare and forbidden decays*

The BelleII Physics Book is now available online:
https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

Full Charm Event Reconstruction

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

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

- D_{tag}: reconstructed in several channels (D^0, D^*, D_s, …)
- X_{frag}: light mesons (K, π, …)
- D_{sig}: signal channel

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

- *example*:

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

- "miss" quantities computed for the system:

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

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