Belle II Tracking Performance

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on behalf of the Belle II Tracking Group

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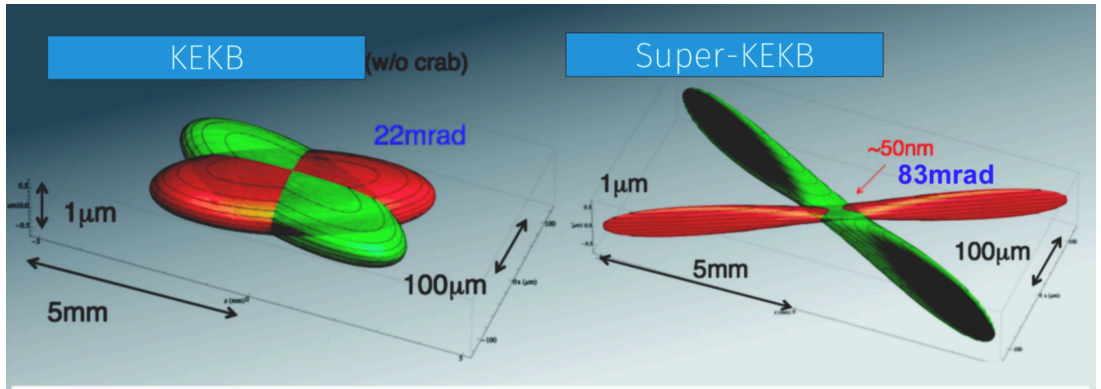
SuperKEKB Accelerator

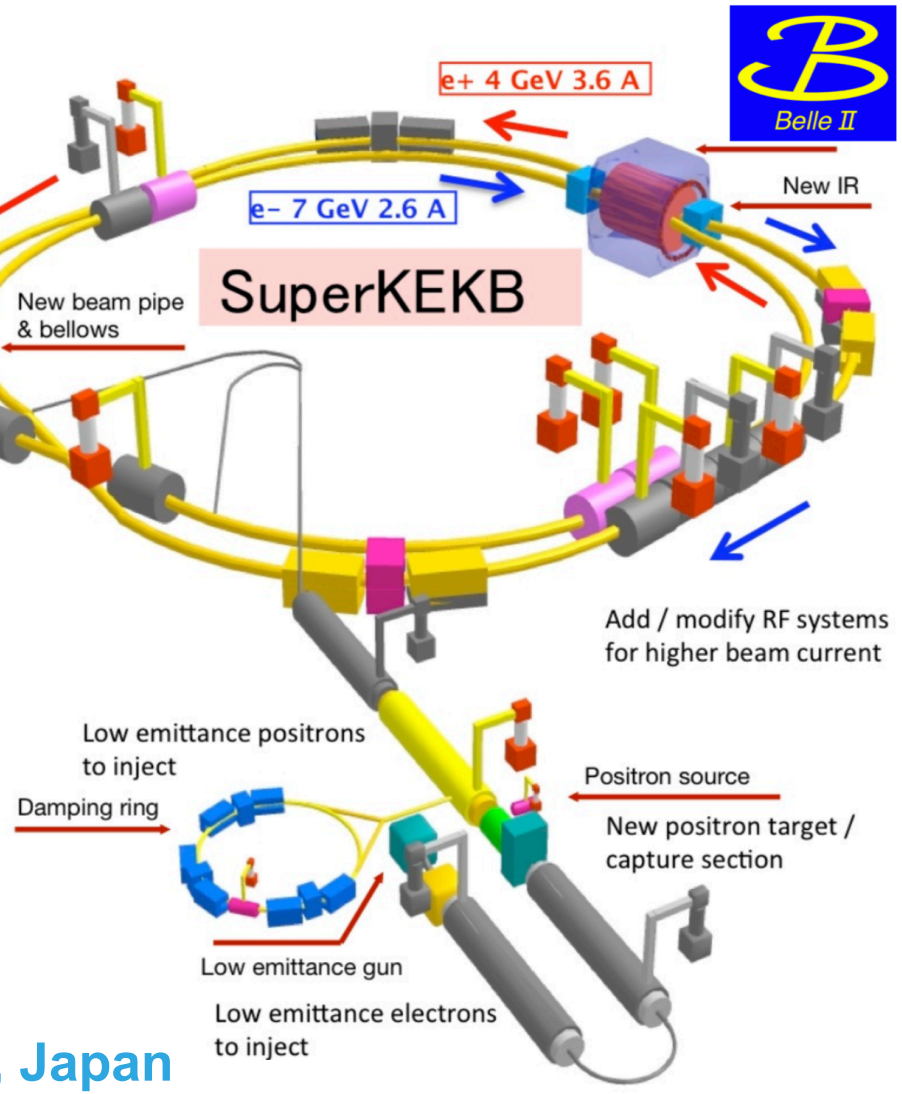
- New facility to search for new physics by studying *B*, *D* and τ decays
- Electron-positron collisions at √s ≈ 10.6 GeV



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20 factor 2-3

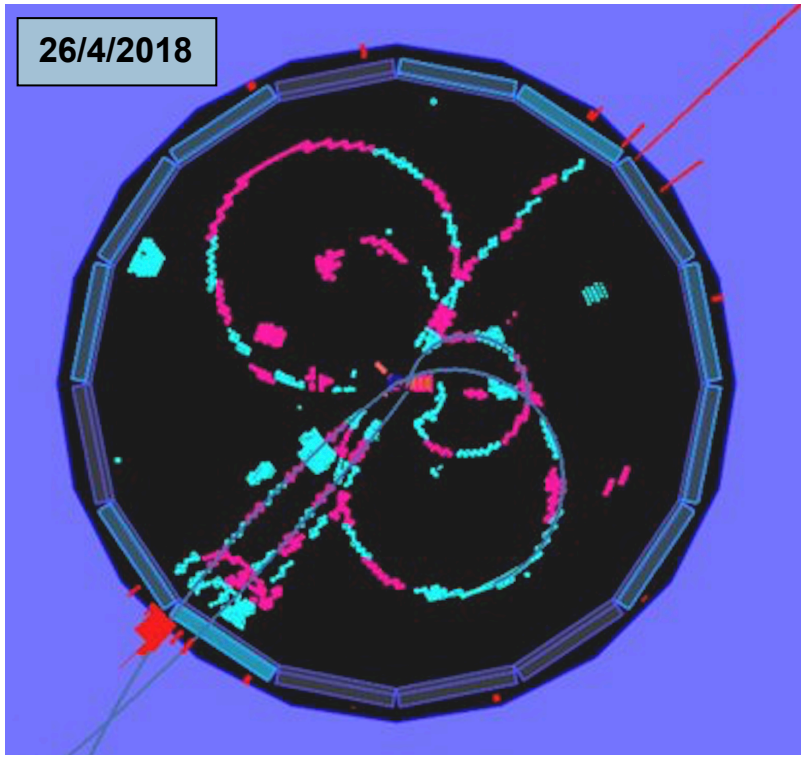
- Unprecedented design luminosity of 8×10^{35} $cm^{-2}s^{-1}$
- First beams and commissioning in 2016, Belle II detector rolled in 2017

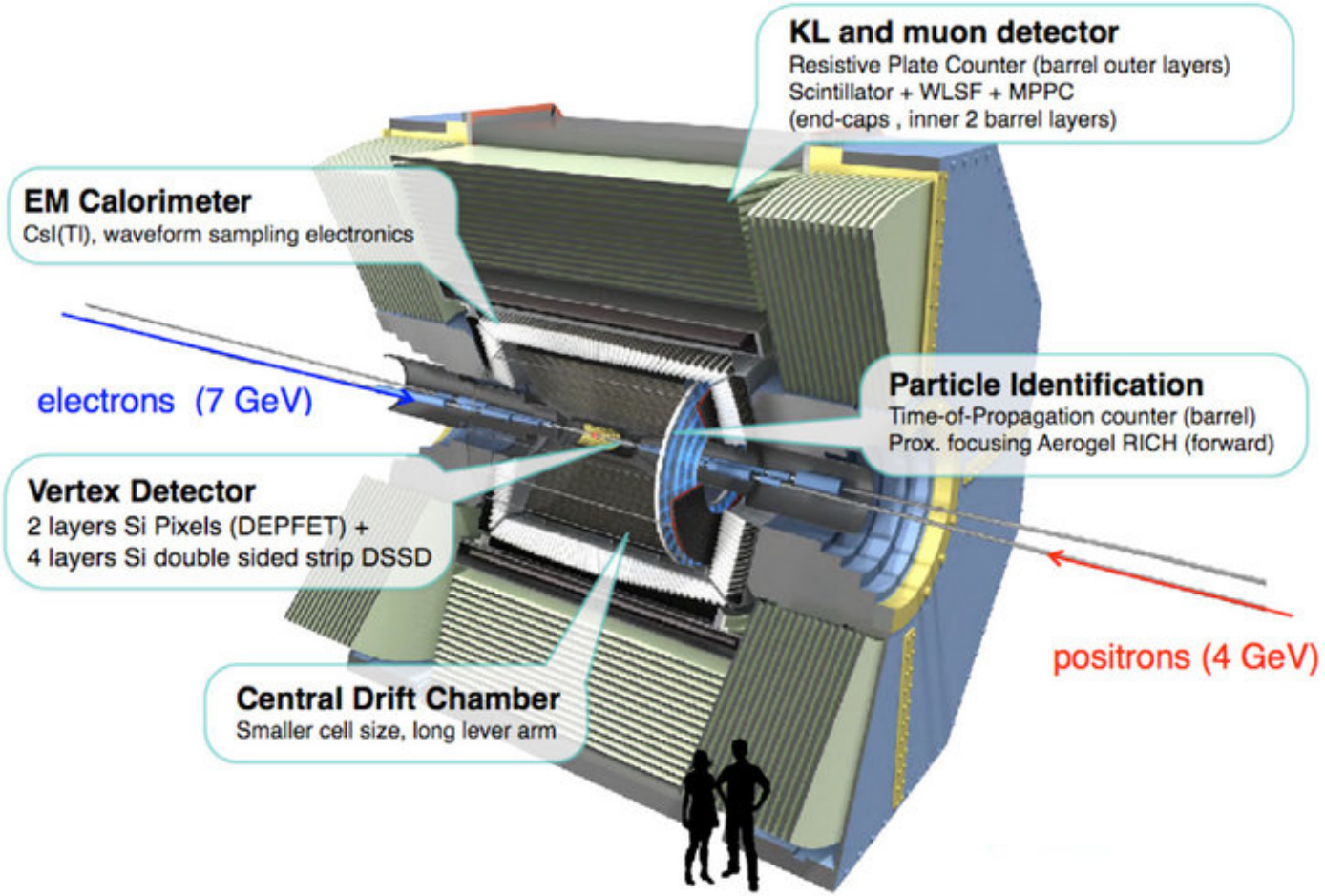


@KEK Tsukuba, Japan

Belle II Detector

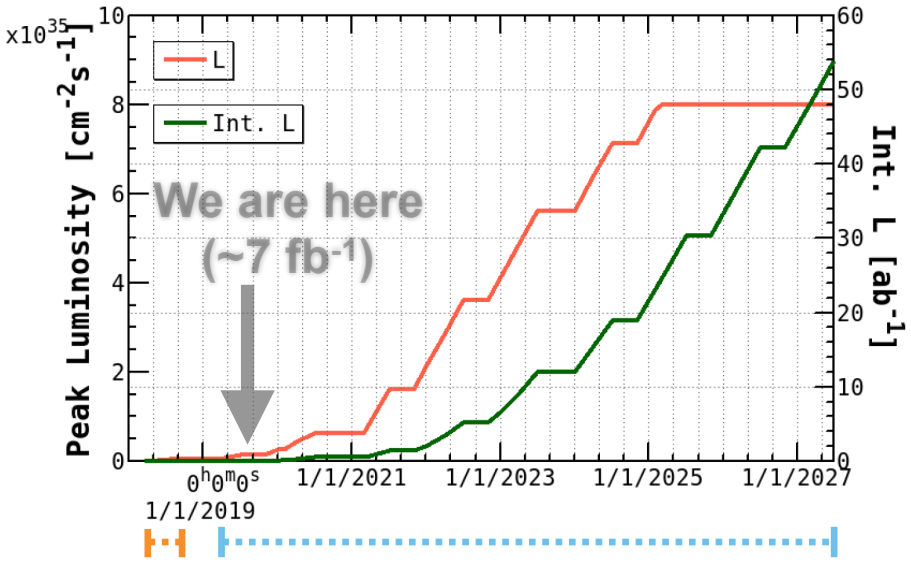
- First e^+e^- collisions recorded by Belle II in April 2018

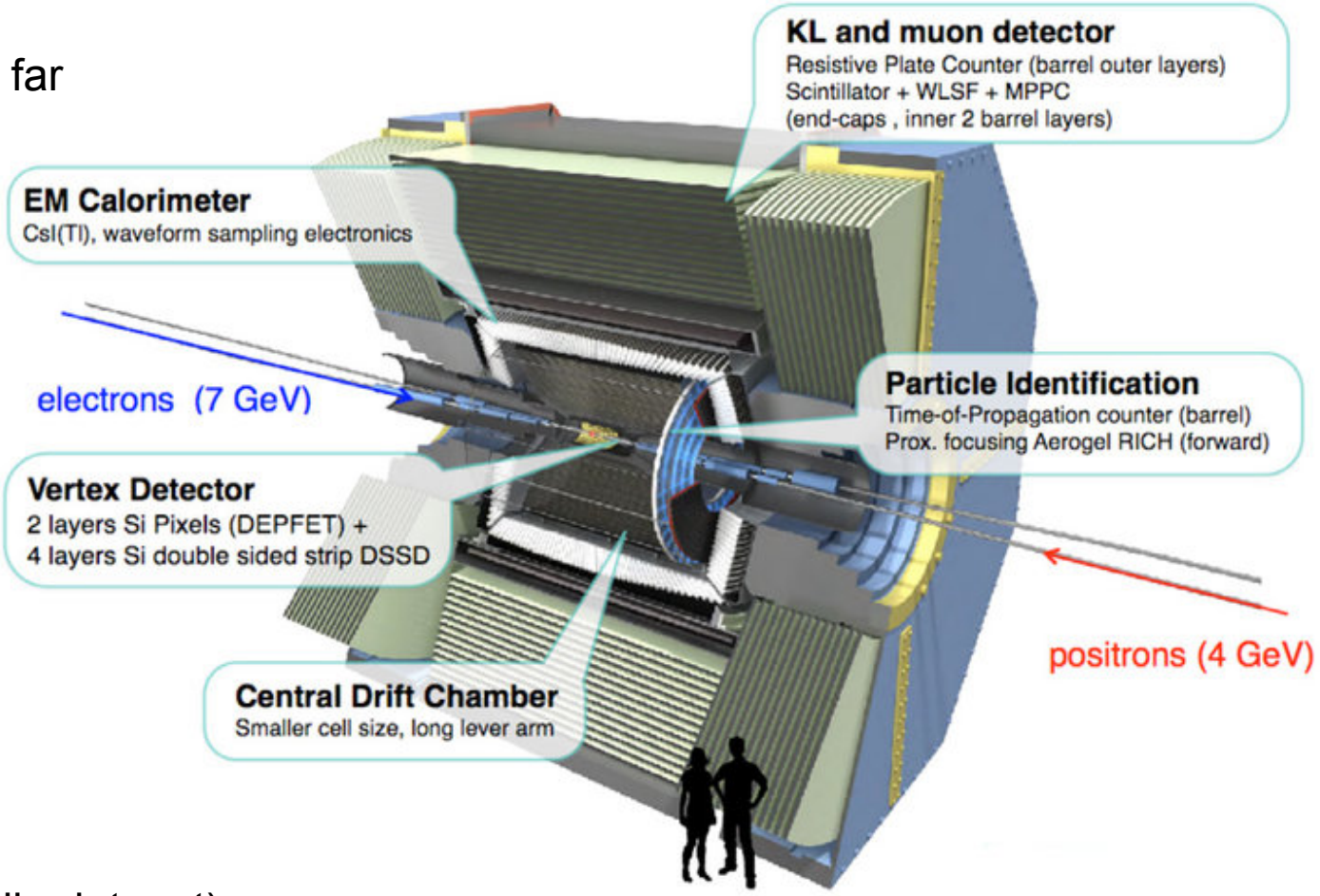




Belle II Detector

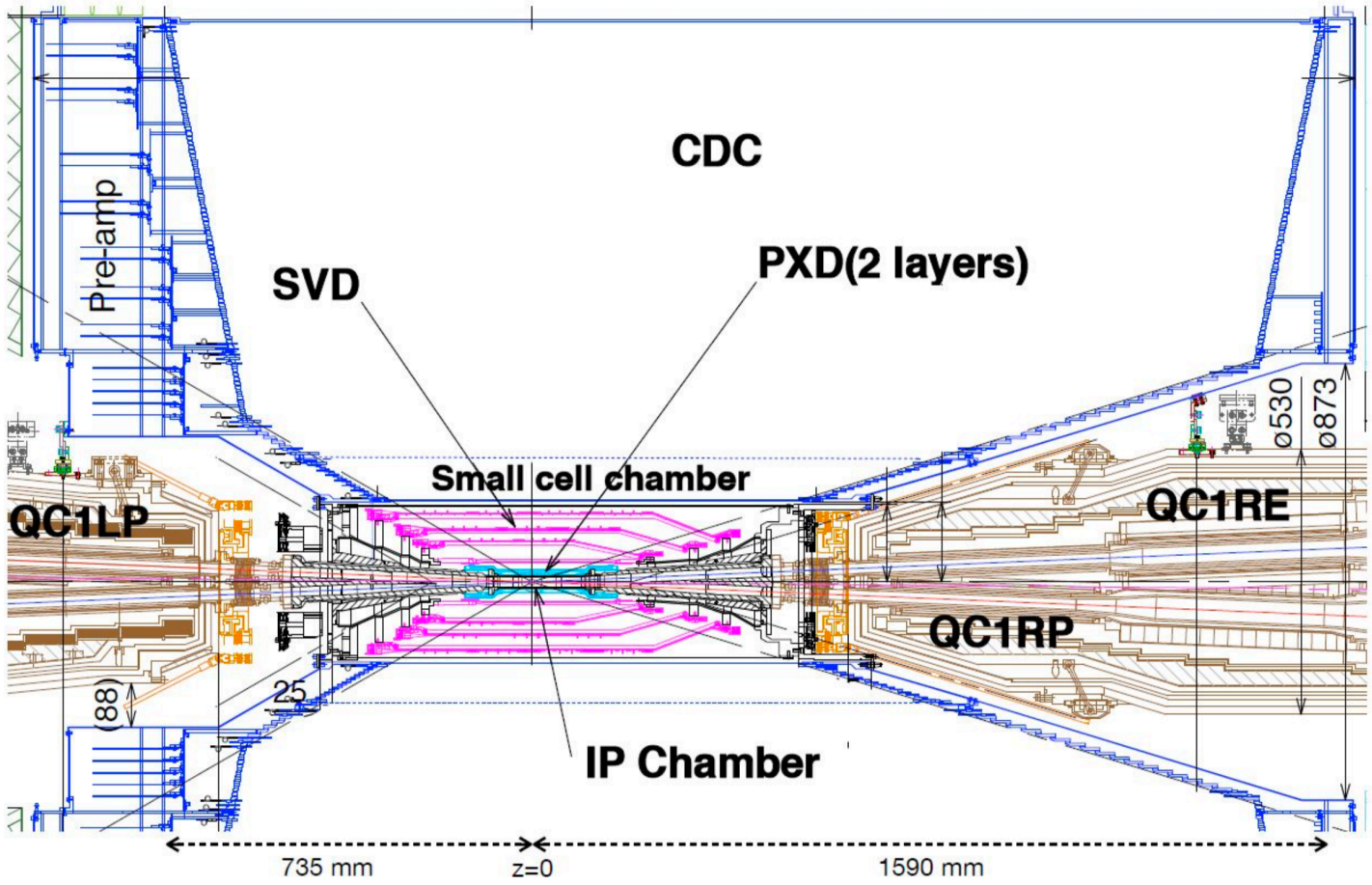
- **Phase 2** completed in April-July last year ⇒ ~0.5 fb^{-1} recorded
- **Phase 3** began in March 2019 ⇒ ~6.5 fb^{-1} so far





- Aim for **50 ab^{-1}** by around 2027 (50 times Belle dataset)

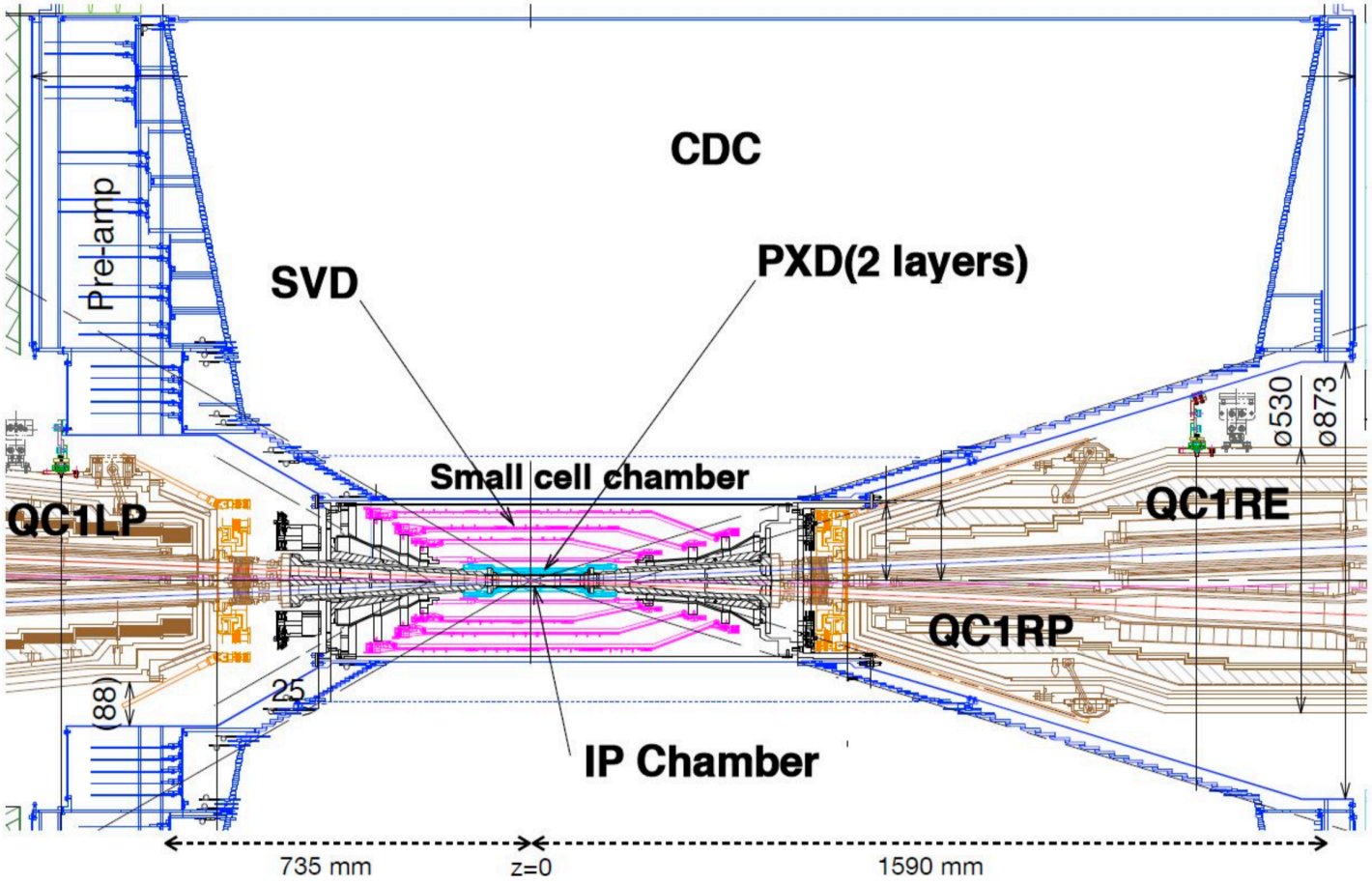
Tracking System of Belle II



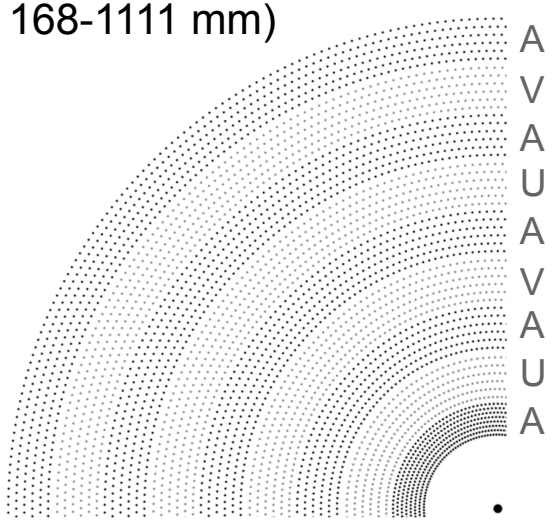
- Three tracking sub-systems:
  - central drift chamber (**CDC**)
  - silicon vertex detector (**SVD**)
  - pixel detector (**PXD**)

- 1.5T solenoid and final focusing magnets inside detector volume
  (moderate non-uniformity of *B*-field)

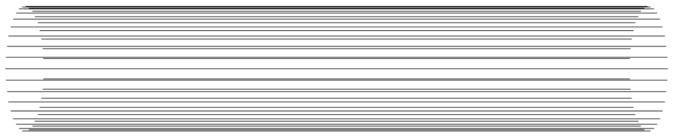
Tracking System of Belle II



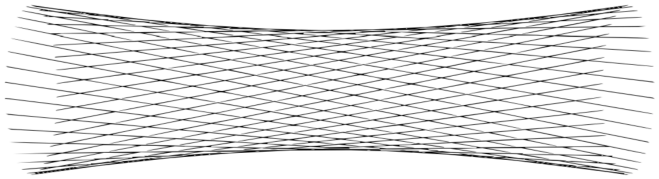
- **CDC**
  - 56 layers (r = 168-1111 mm)
  - arranged into superlayers of axial (A) & stereo (U,V) wires



axial wires



stereo wires



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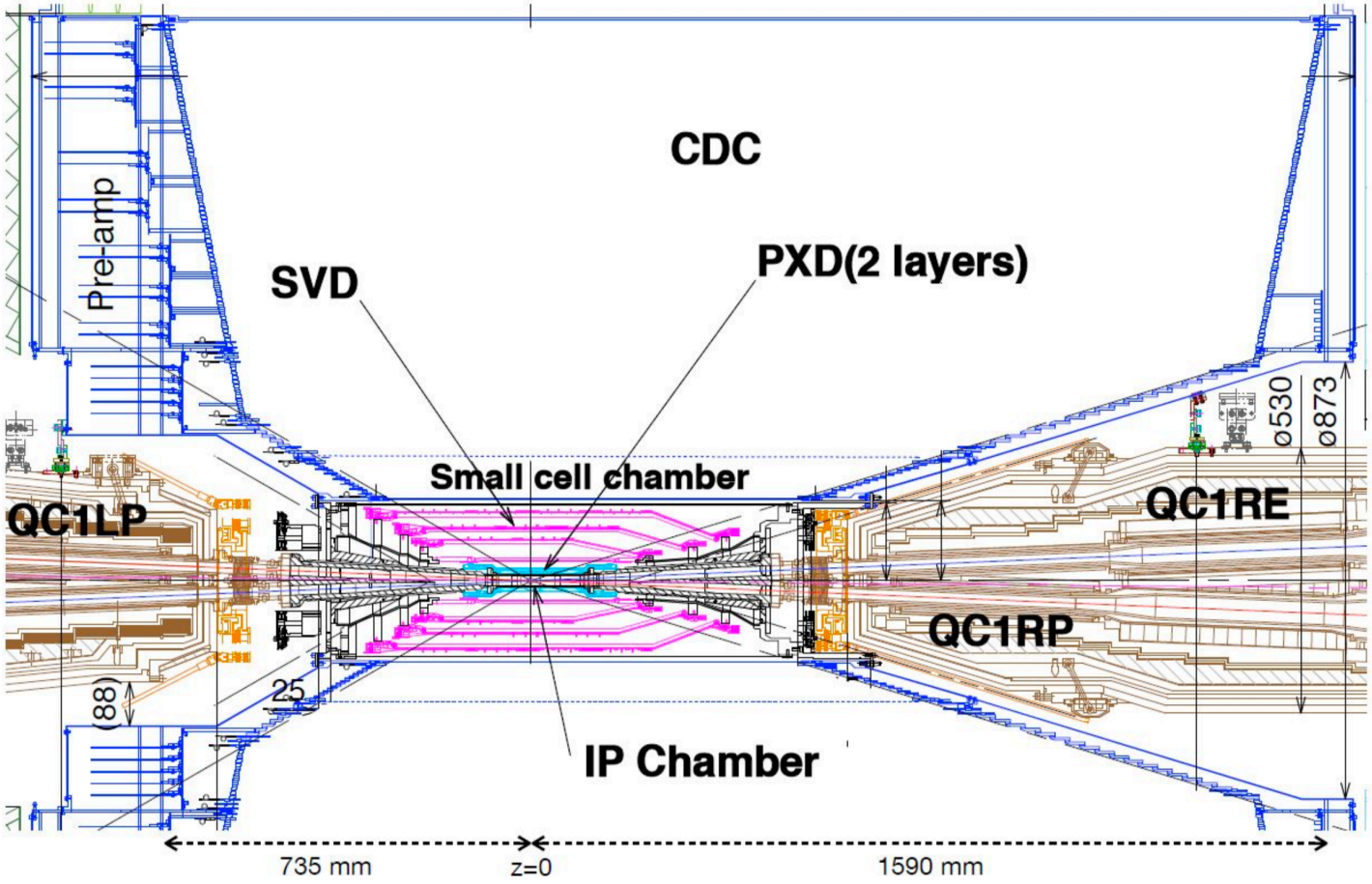
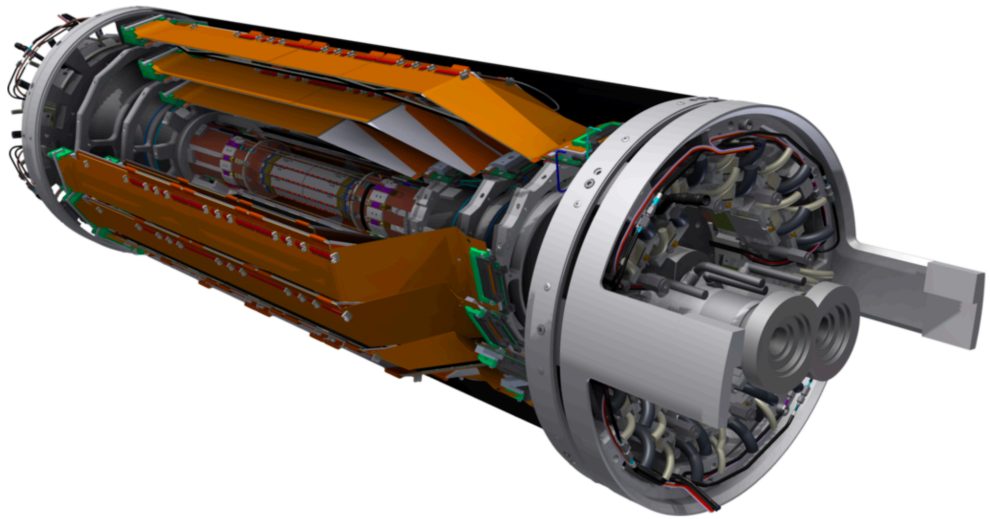


- **SVD**
  - 4 layers of double-sided silicon strip sensors (r = 39, 80, 104, 135 mm)
  - 172 sensors, 220k read-out strips



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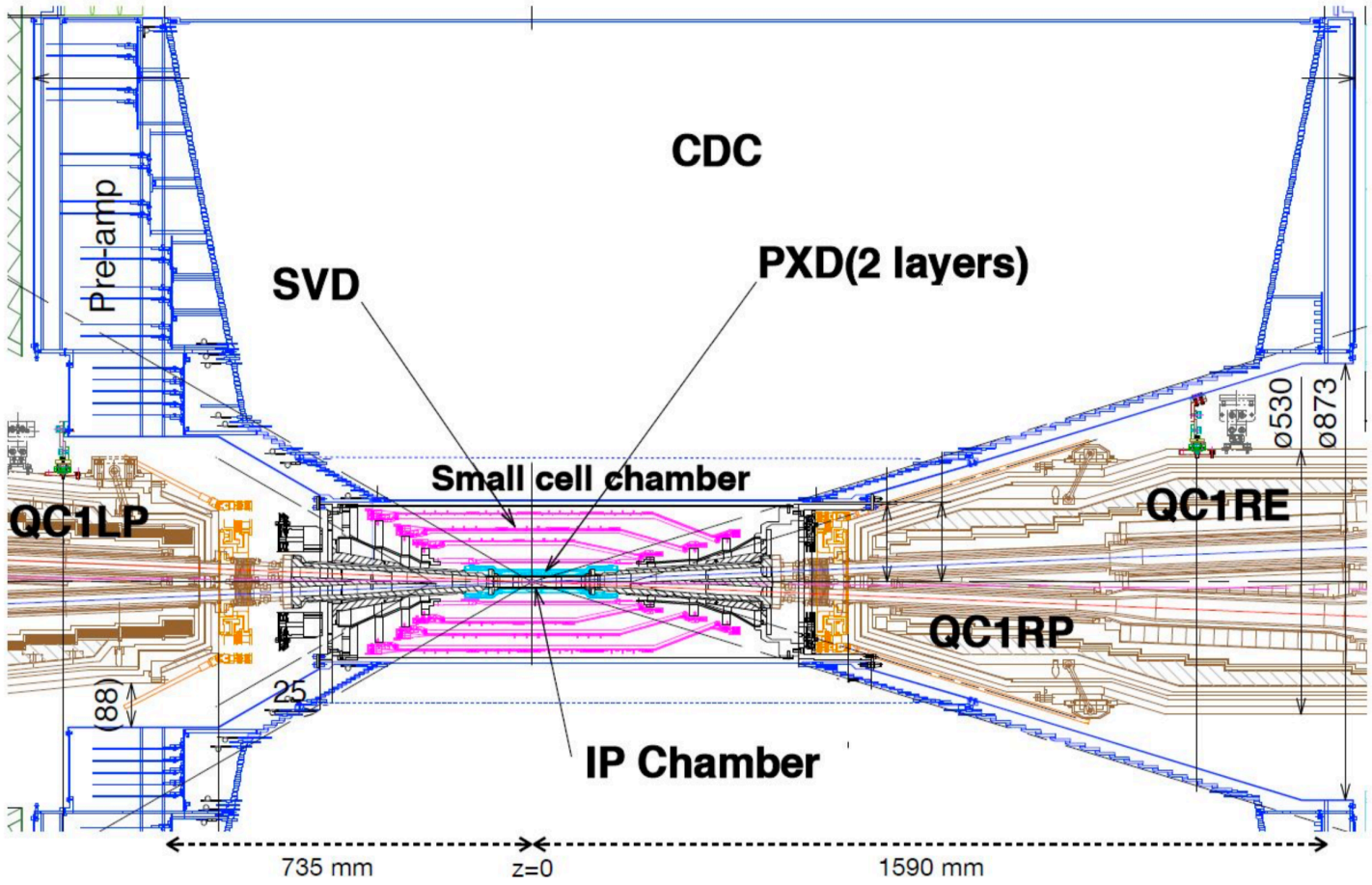
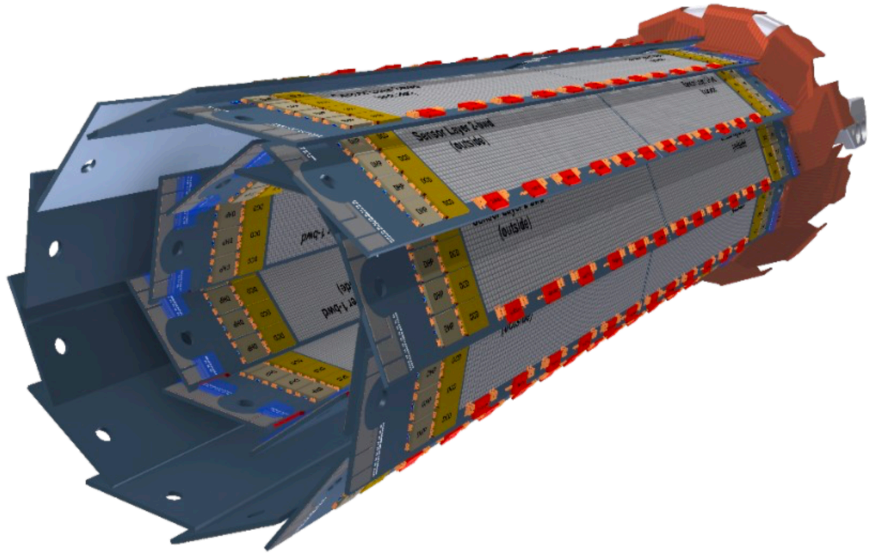
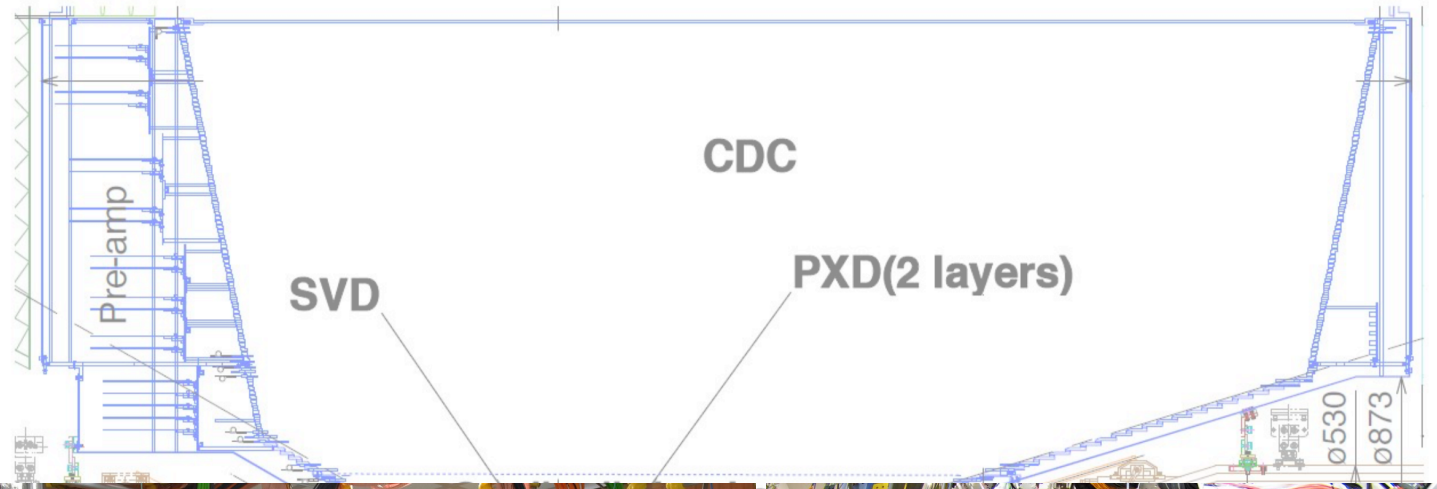
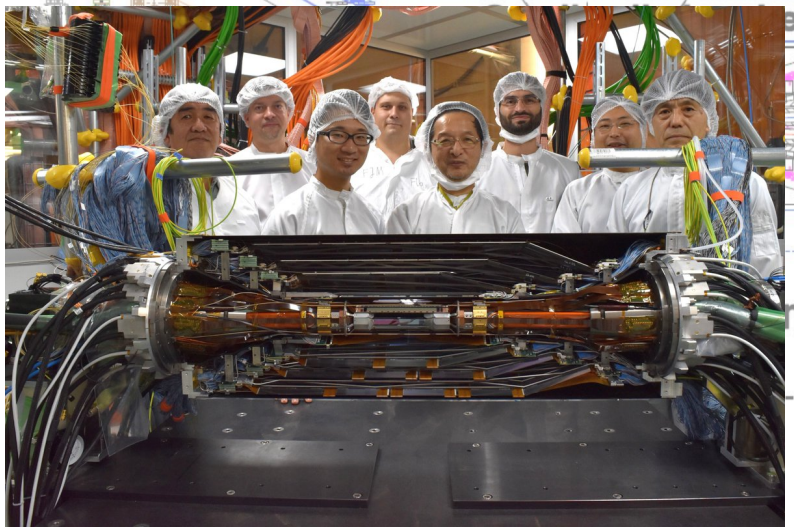


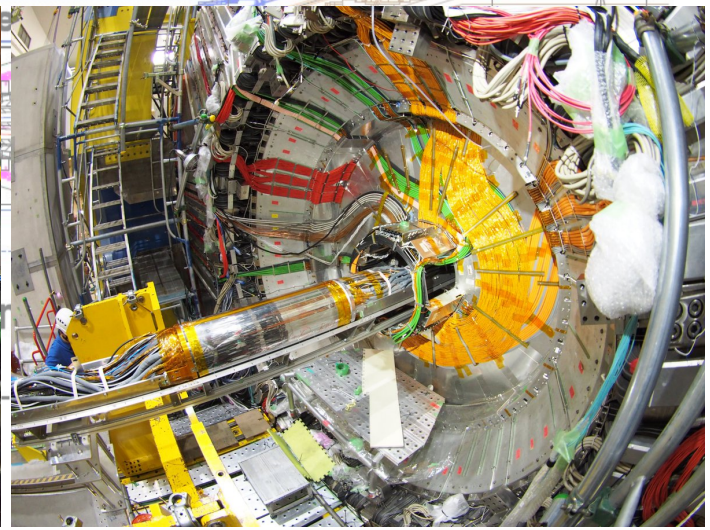
- **PXD**
  - 2 layers of DEPFET pixel sensors (r = 14, 22 mm)
  - 40 sensors, 7.7 million total pixels



Tracking System of Belle II







- **PXD**
  - 2 layers of DEPFET pixel sensors (r = 13, 22 mm)
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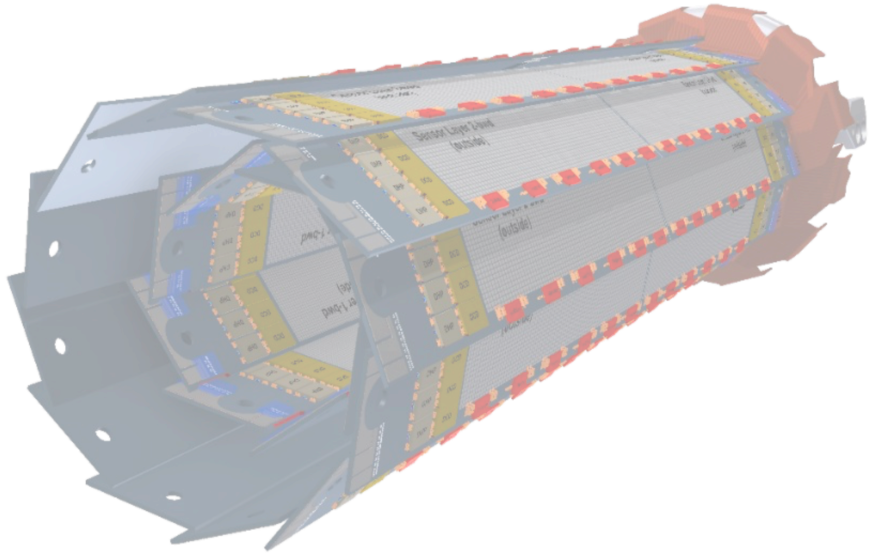


- **Phase 2**: one sector of VXD installed
- **Phase 3**: full coverage, 2nd PXD layer with only 4 sensors installed

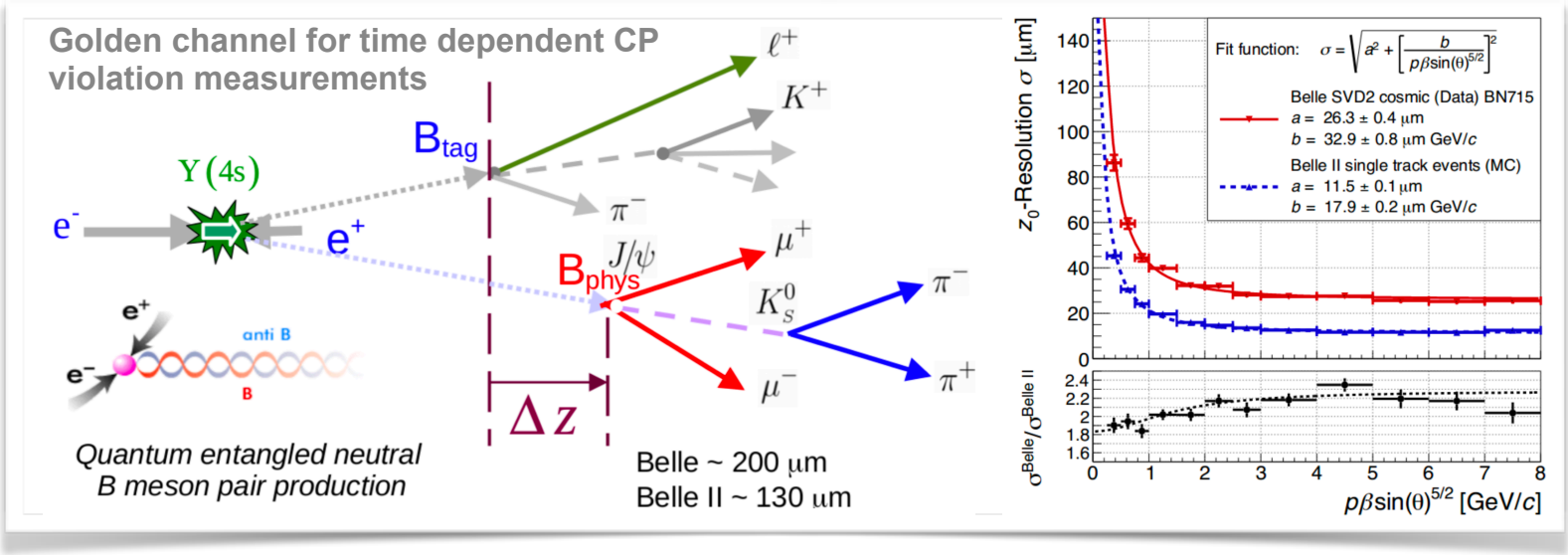
Challenges of Tracking @ Belle II

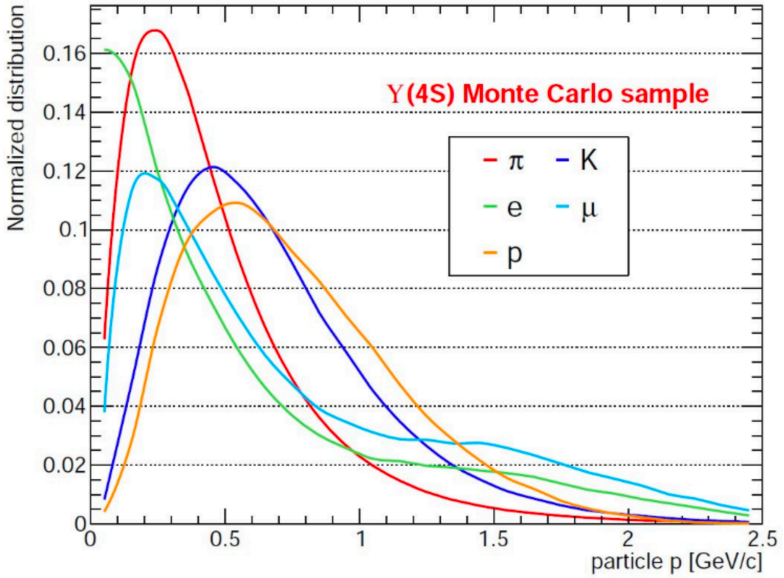
- Tracking performance is critical for achieving Belle II physics goals

  ⇒ PXD provides ~2x better single vertex resolution wrt Belle

- **Typical Υ(4S) event has 11 tracks**

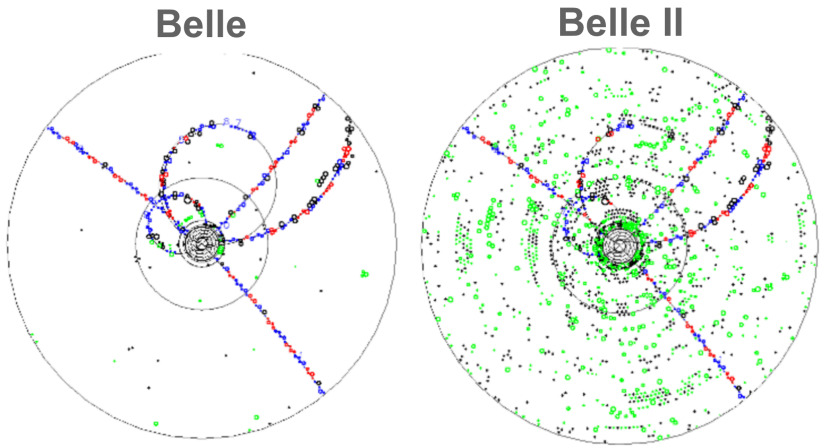
  B/D meson tagging requires both high efficiency and purity of the tracks.





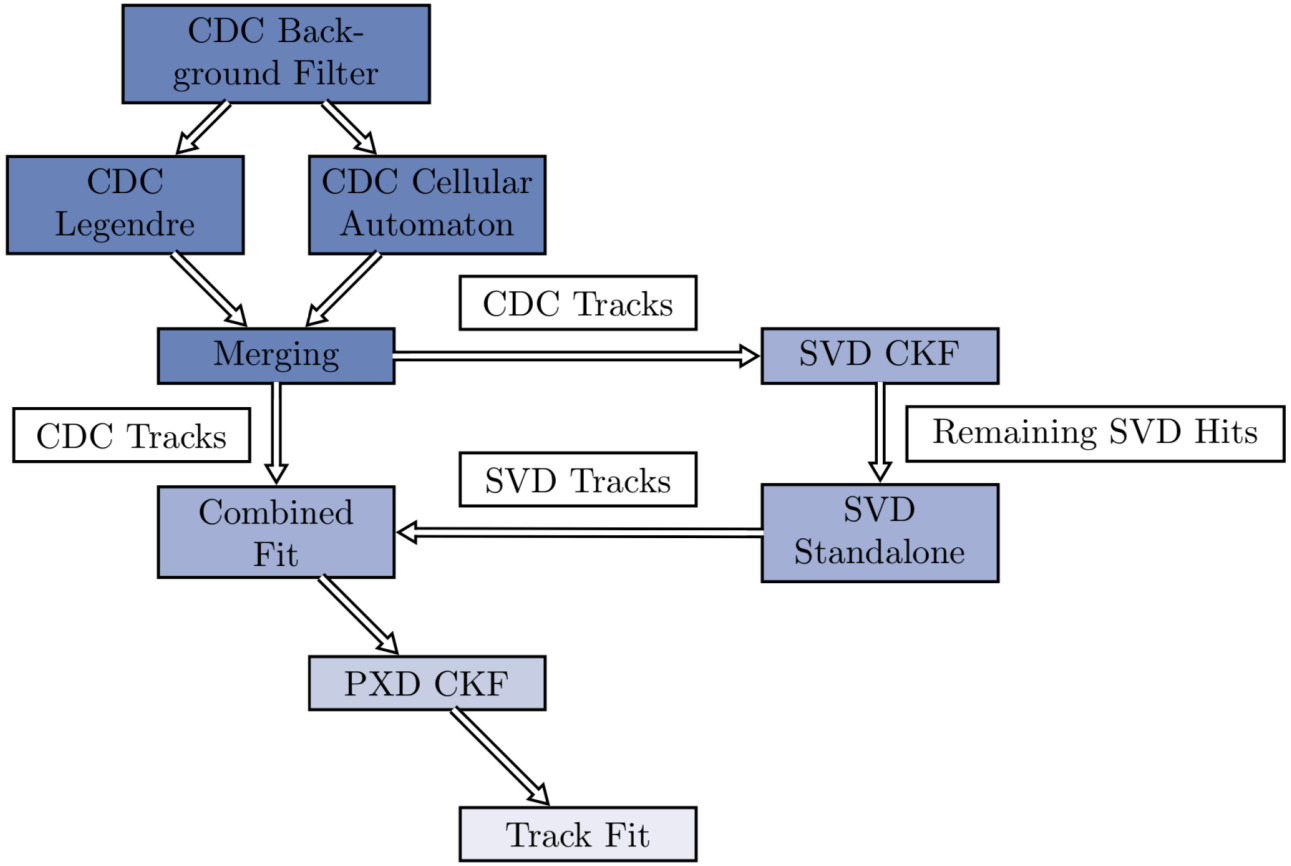
- **Many tracks are at low momentum** ⇒ multiple scattering, curling tracks
- **Sizeable machine background**
  - Synchotron radiation, Touscheck, beam-gas and Radiative Bhabha scattering, e^+e^- production
  - high-occupancy

    11 tracks ⇒ 10^2 signal hits vs 10^4 bkg hits



Track Finding @ Belle II

- Belle II has state-of-the-art tracking detectors *and software*
- Modular code structure, with flexibility for reconstruction sequence



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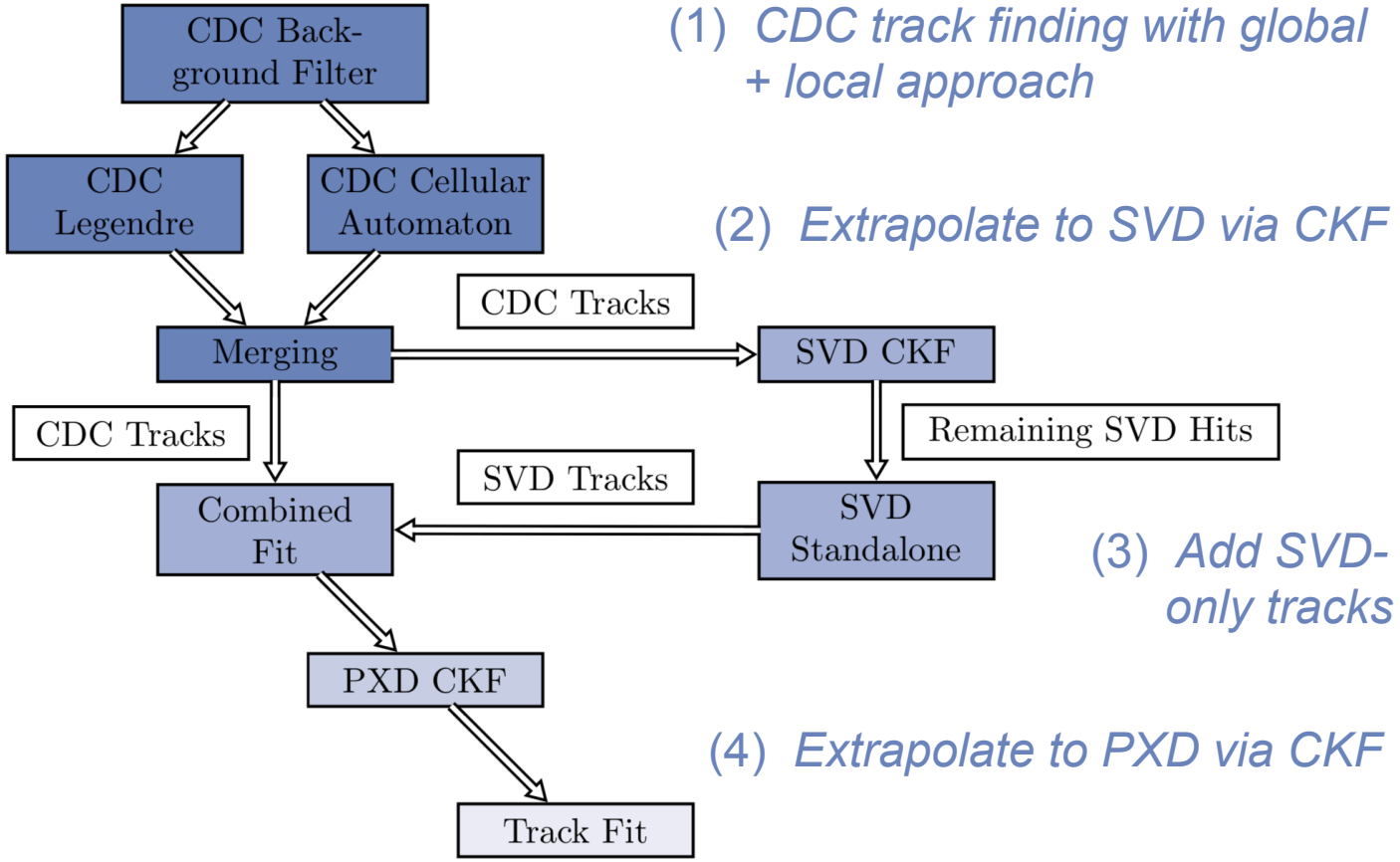

(1) *CDC track finding with global + local approach*

(2) *Extrapolate to SVD via CKF*

(3) *Add SVD-only tracks*

(4) *Extrapolate to PXD via CKF*

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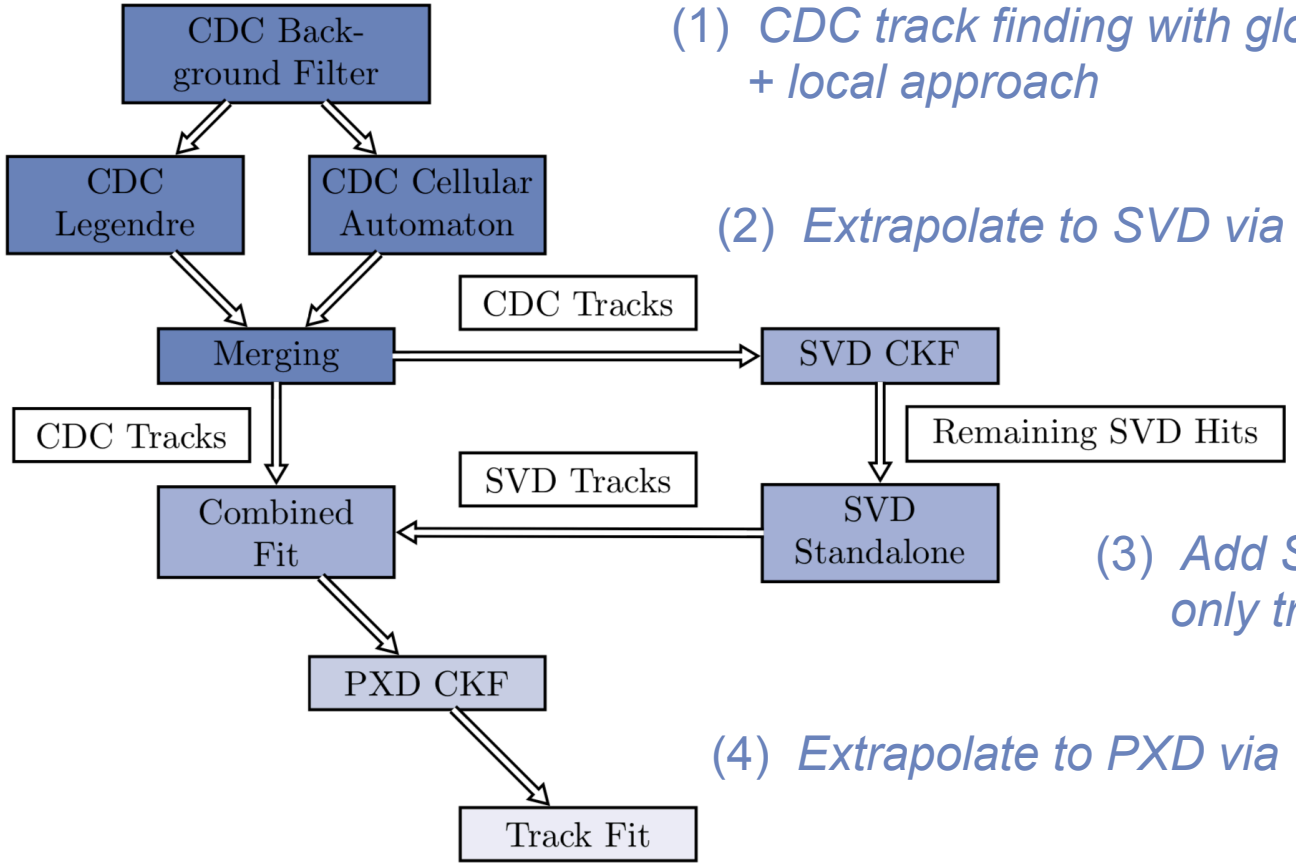


(1) *CDC track finding with global + local approach*

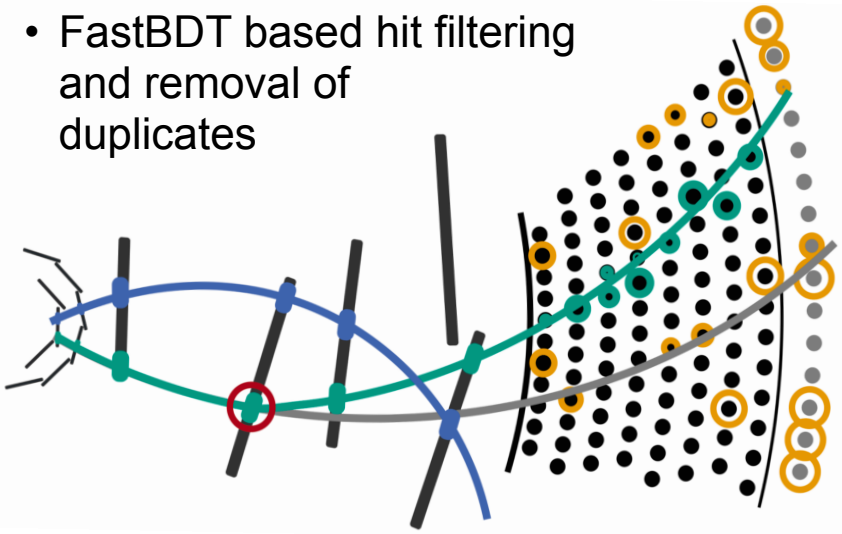
(2) *Extrapolate to SVD via **CKF***

(3) *Add SVD-only tracks*

(4) *Extrapolate to PXD via **CKF***

Combinatorial Kalman Filter (**CKF**)

- Extrapolates track inward, looking for SVD or PXD hits to attach
- Updating track parameters
- FastBDT based hit filtering and removal of duplicates

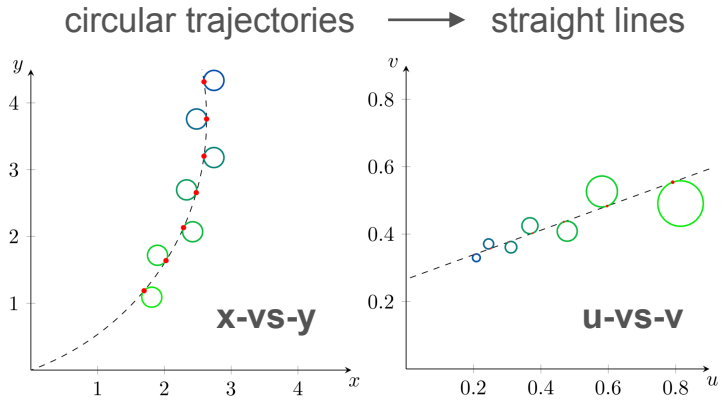


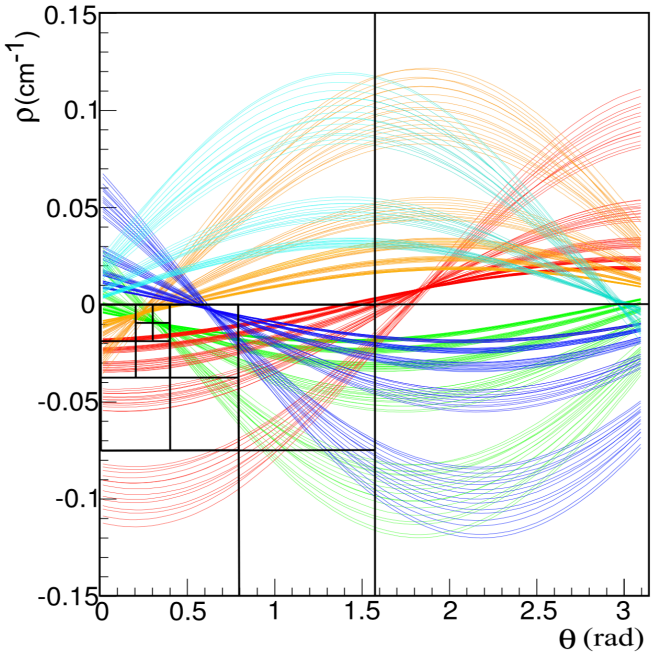
CDC Track Finding

Global Algorithm

- **Legendre transformation**

⇒ conformal map, track finding reduced to finding a common tangent to set of circles





- **Search in ρ-θ plane**

⇒ in conformal space, the equation of tangent to a drift circle is

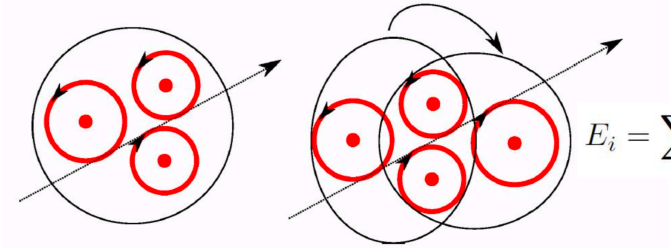
$$\rho = x_0 \cos\theta + y_0 \sin\theta \pm R_{\mathrm{dr}}$$

⇒ Find points of maximum density in parameter space

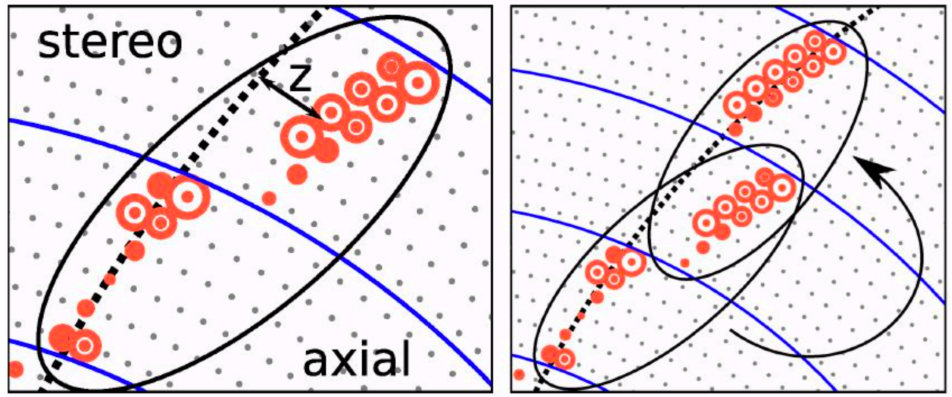
2D binary search + sliding window algorithm

Local Algorithm

- **Segment building:** cellular automaton with vertices from hit triplets + linear trajectory. Edges from neighbouring triplets sharing two hits. Weights based on common fit quality.



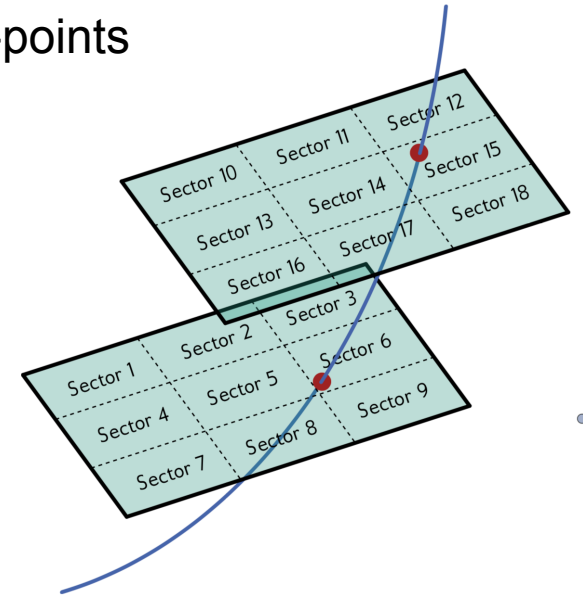
- **Track building:** CA with vertices from pair of segments in axial + stereo layers. Edges from common segments. Weights from Riemann fit in x-y and linear fit in s-z space.

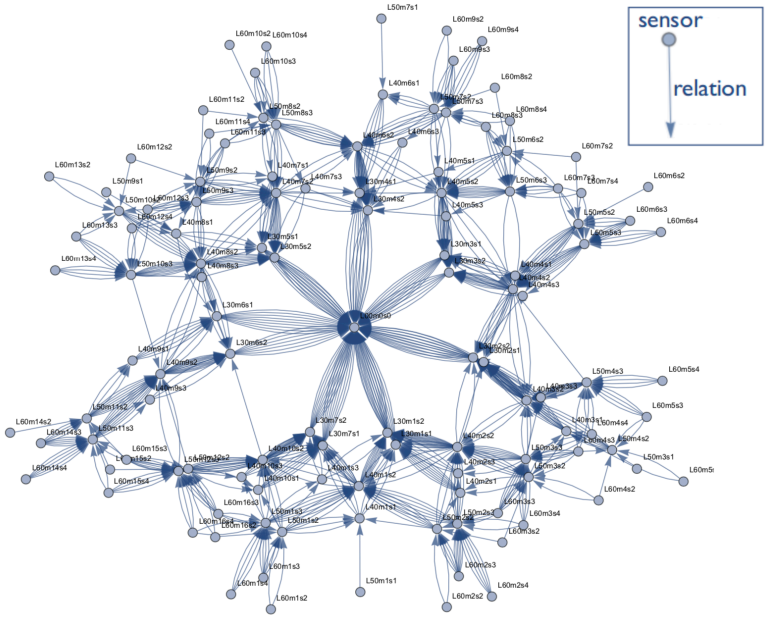


SVD Standalone Tracking

- Reduce combinatorics by combining 3D space-points from compatible (friend) sectors and applying filters to reject background hits

  Training of friendship relations + filters on MC
  ⇒ **SectorMap**

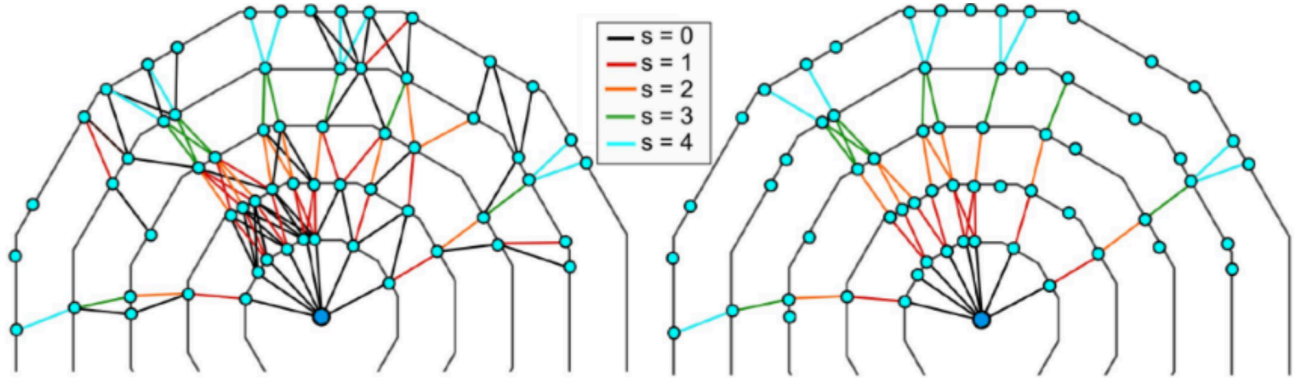




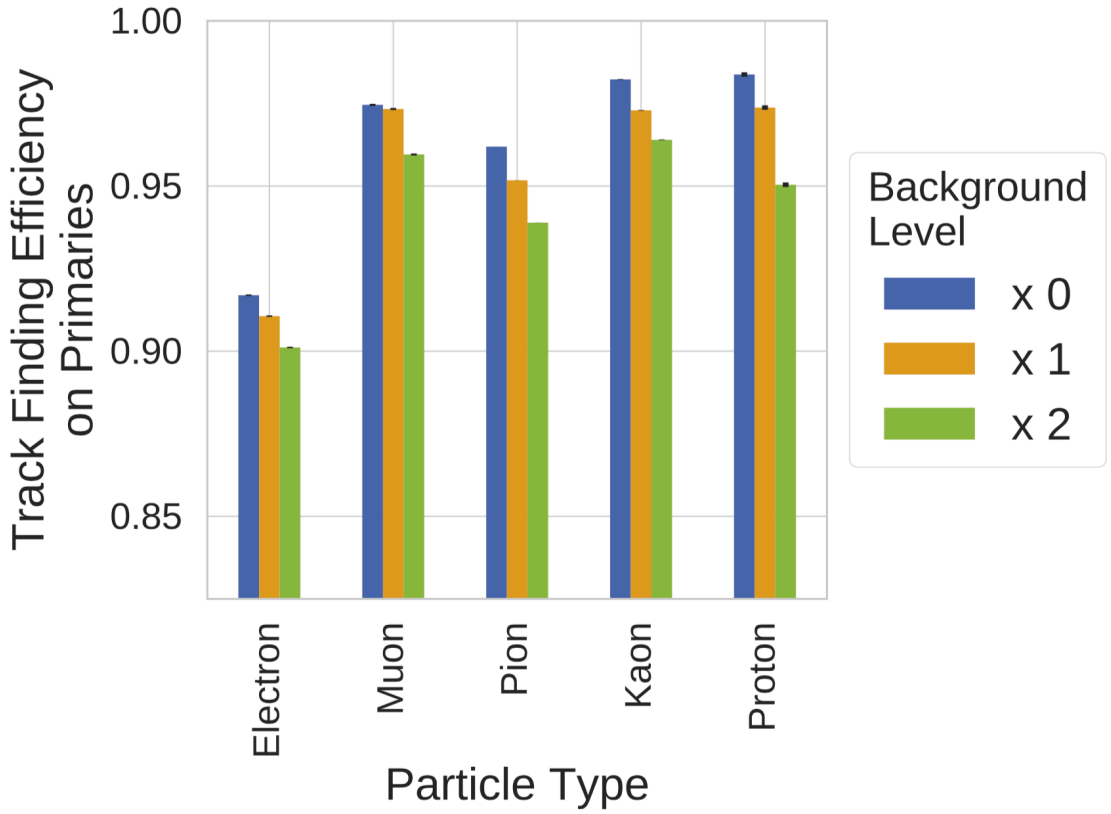
- **Cellular automaton** collects longest paths beginning with outermost space-points

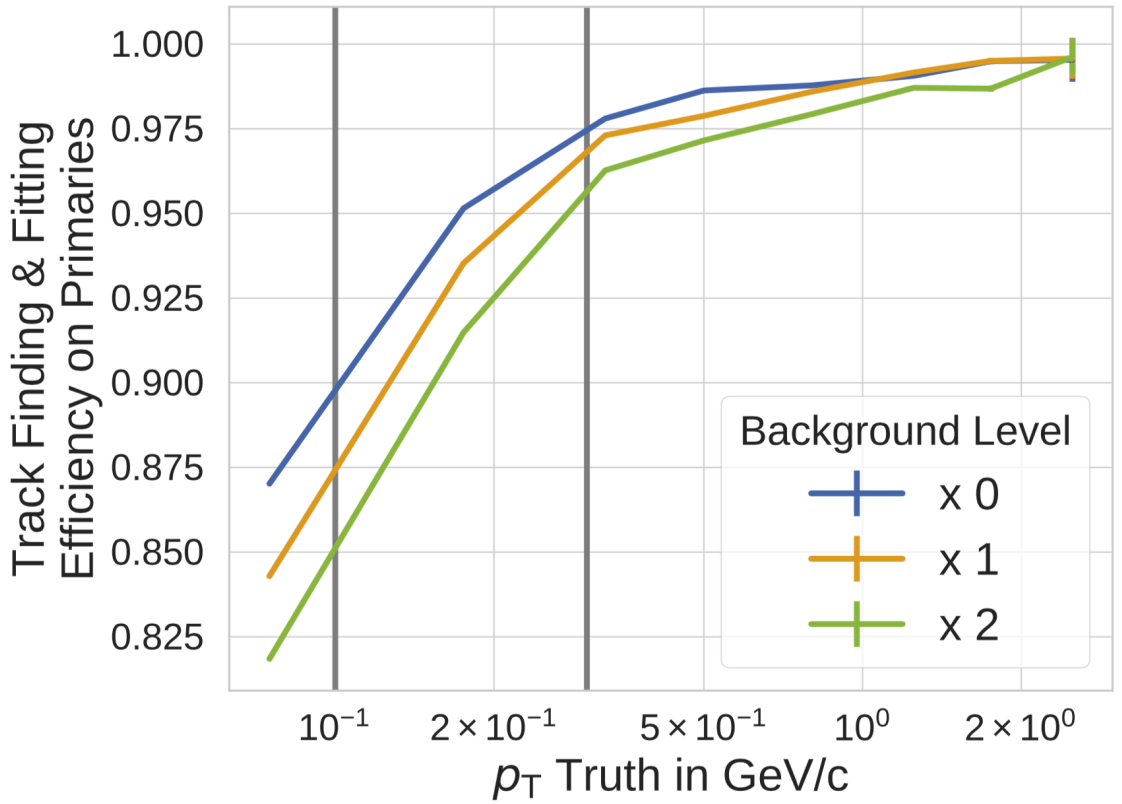
- Final set of tracks is chosen from all paths such that no tracks share an SVD hit

  For competing paths a **quality estimation** is employed (triplet fit, Chi2 of triplets, p-value of competing tracks)



Performance in MC

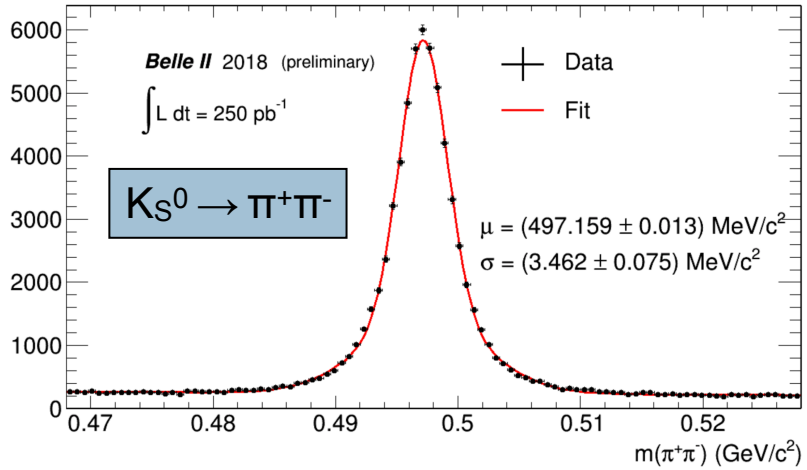


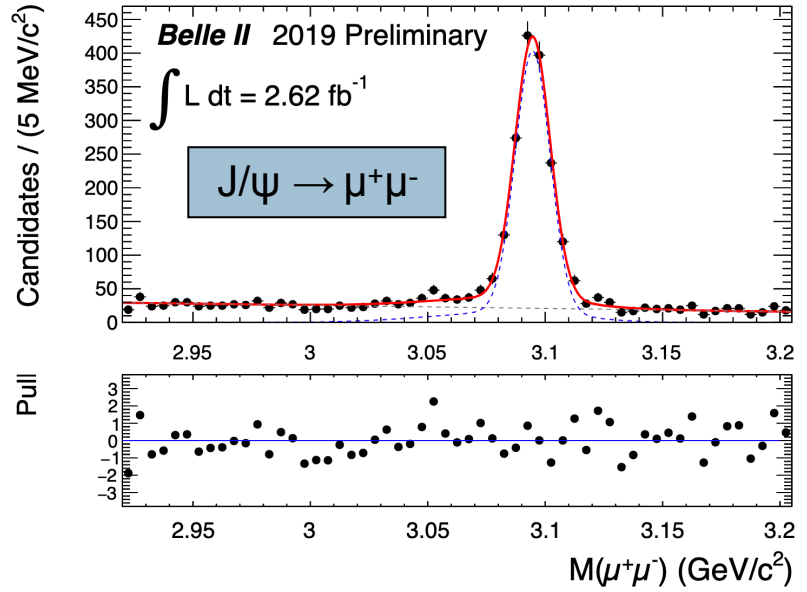


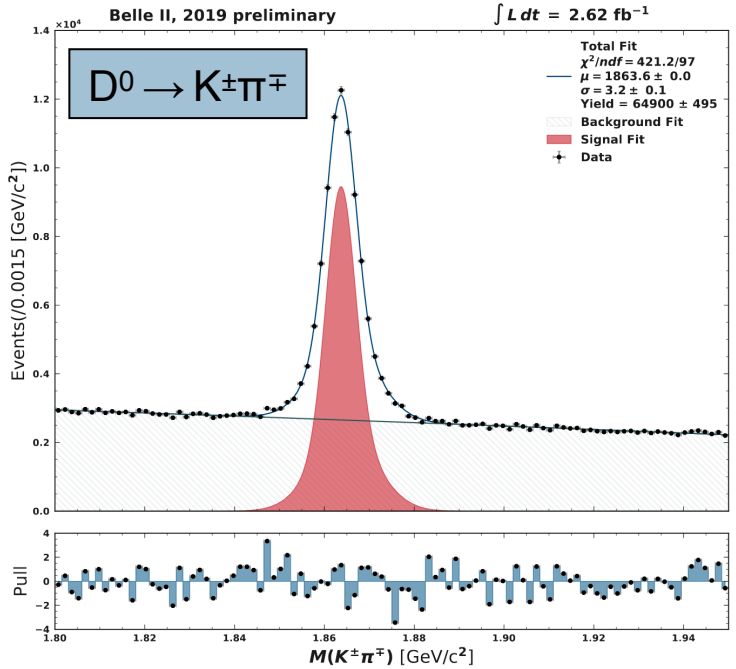
Performance in Data: Rediscoveries

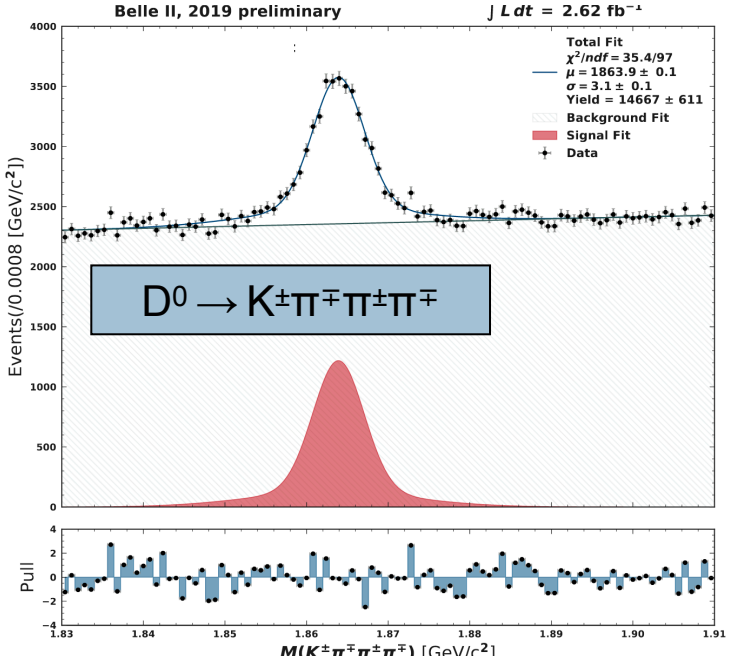
- Many known processes have been “rediscovered” in early Belle II data
- Clear mass peaks from tracks

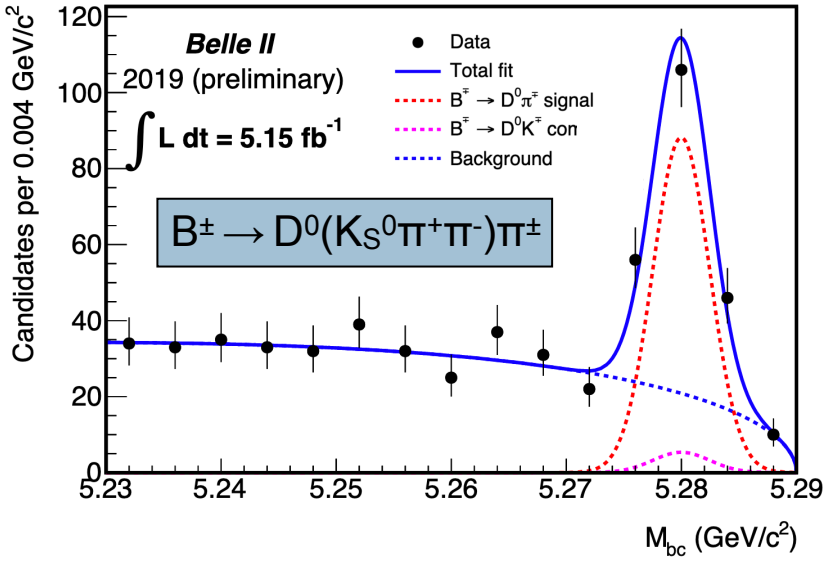
⇒ **VXD+CDC detectors and track finding algorithms performing as expected**





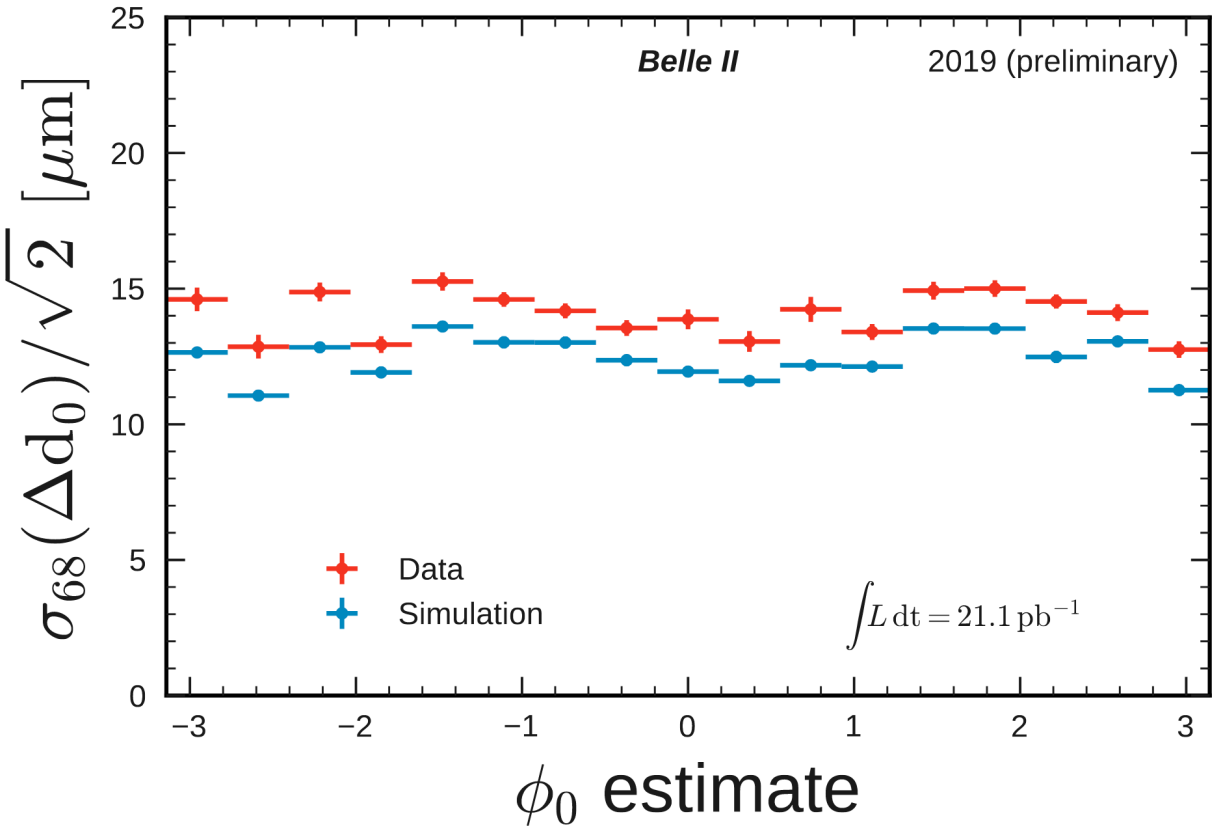


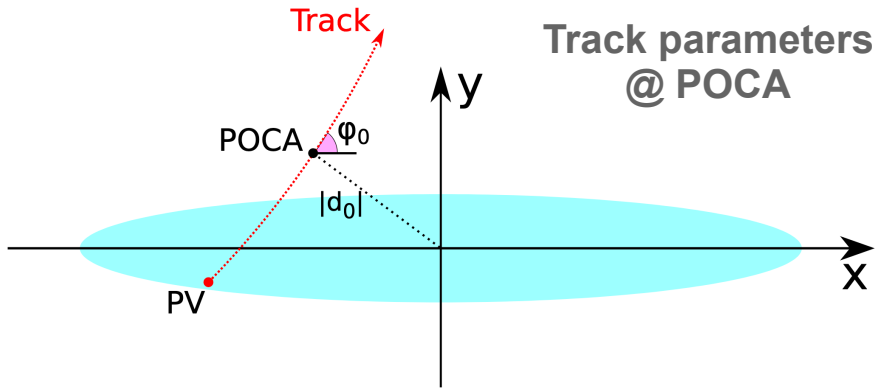




Performance in Data: IP Resolution

- Study of impact parameter resolutions in early Phase 3 data
- Using back-to-back two track events with both tracks detected by the CDC, SVD and PXD





- Assuming two tracks come from same vertex, we can estimate d_0 resolution as:

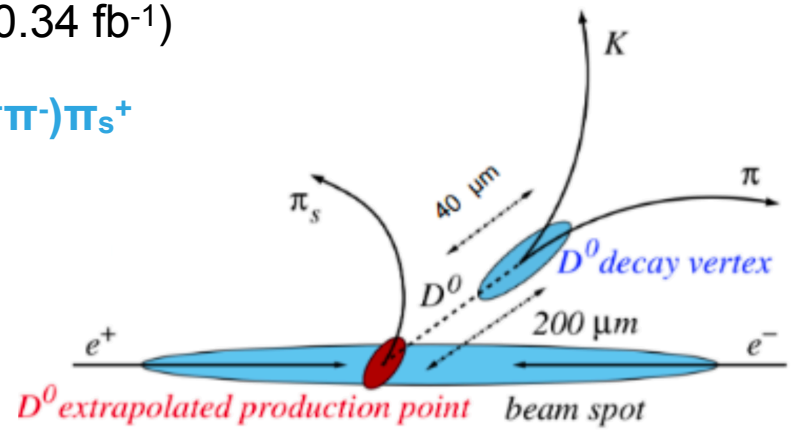
$$\Delta d_0 = d_0(t_-) + d_0(t_+) \qquad \hat{\sigma}(d_0) = \sigma_{68}(\Delta d_0)/\sqrt{2}$$

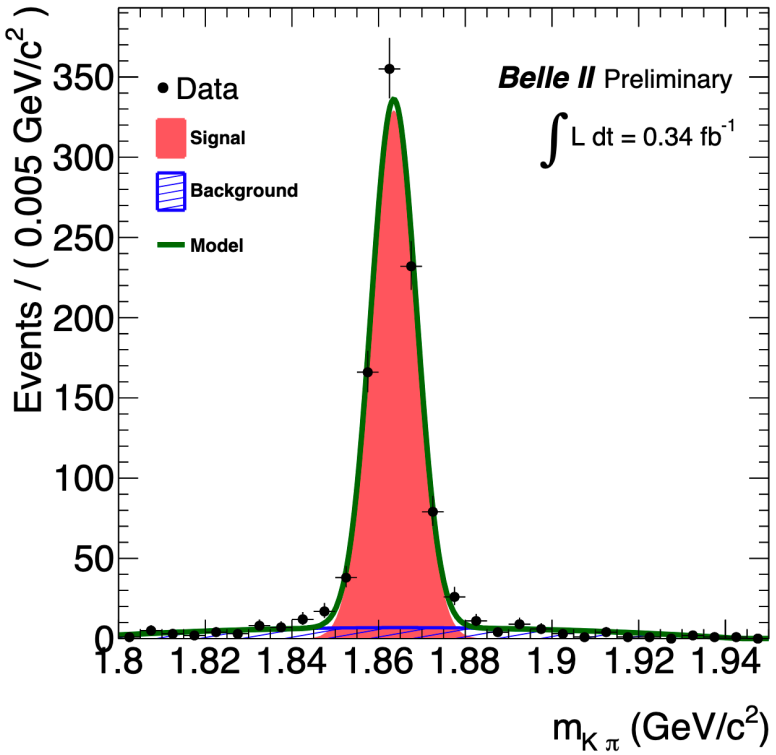
Data: 14.2 ± 0.1 µm **MC: 12.5 ± 0.1µm**

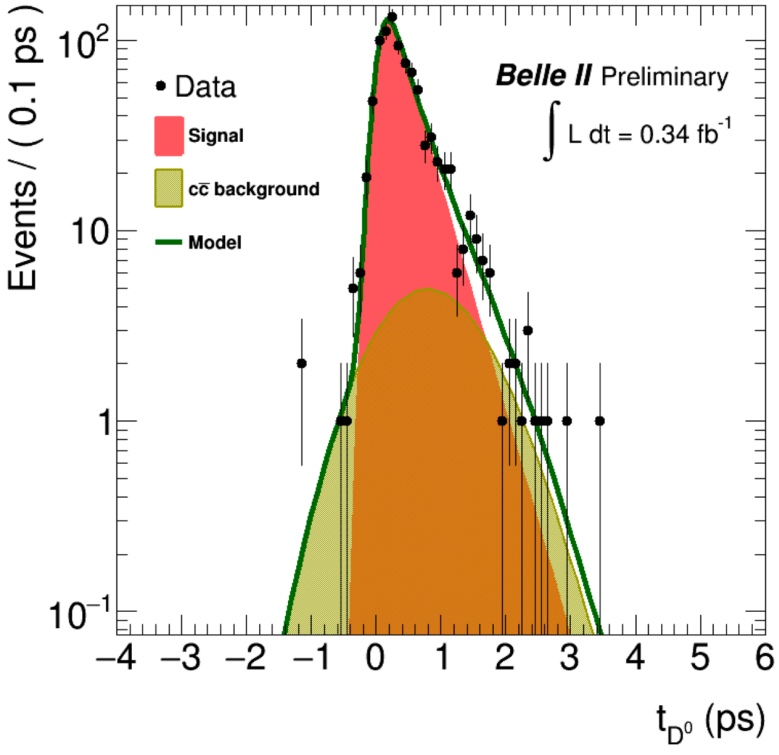
- 13% larger in data than simulation
  - hit cluster resolution too optimistic in MC
  - sensor parameters not optimal

Performance in Data: D^0 Lifetime

- Measurement of D^0 lifetime using only a small fraction of the Phase 3 data (0.34 fb^{-1})
- Fit to proper time distribution of D*-tagged D^0 candidates from $D^{*+} \to D^0(\to K^+\pi^-)\pi_s^+$
- **TreeFitter** for full decay chain fit
  - ⇒ direct extraction of long-live particle lifetimes, short-lived D* constrained to measured beamspot







Measured: **370 ± 40 (stat) fs**

(PDG = 410.1 ± 1.5 fs)

- **Important test of Belle II tracking performance!**

  (VXD reconstruction, track finding, and vertex fitting)

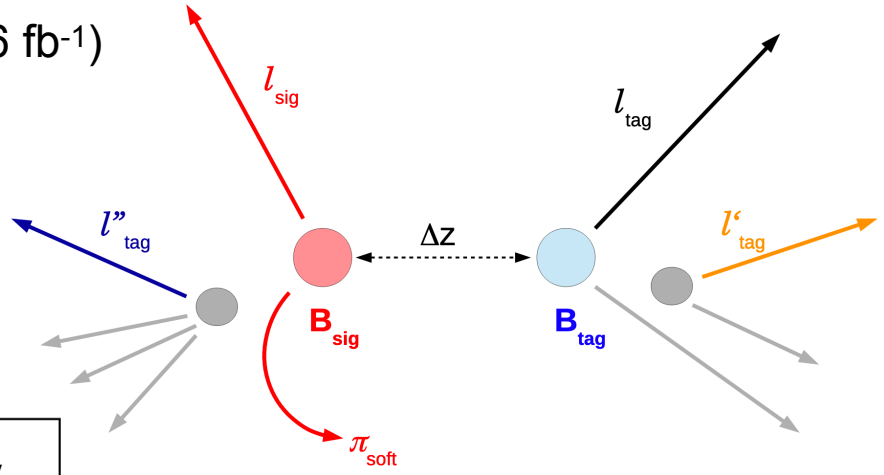
Summary and Outlook

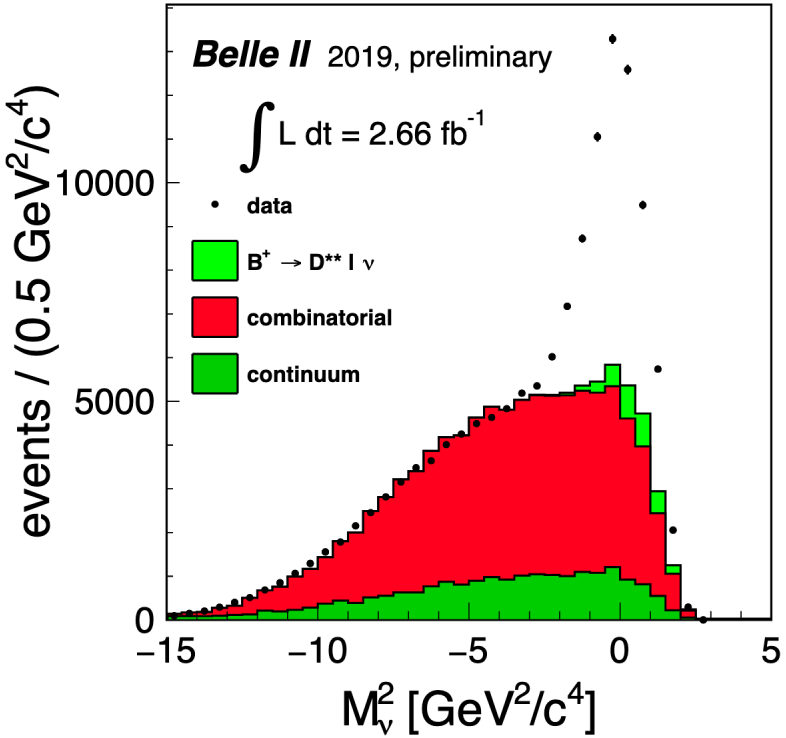
- In order to achieve its physics goals, Belle II requires excellent tracking performance
- Modular track finding approach has been developed, combining several algorithms tailored for track finding in VXD and CDC detectors
- Performing well in early data from Phase 2 and Phase 3 operations of SuperKEKB
- Further improvements and adjustments are possible, depending on machine background and performance requirements
- More data will come quickly…**exciting times ahead!**

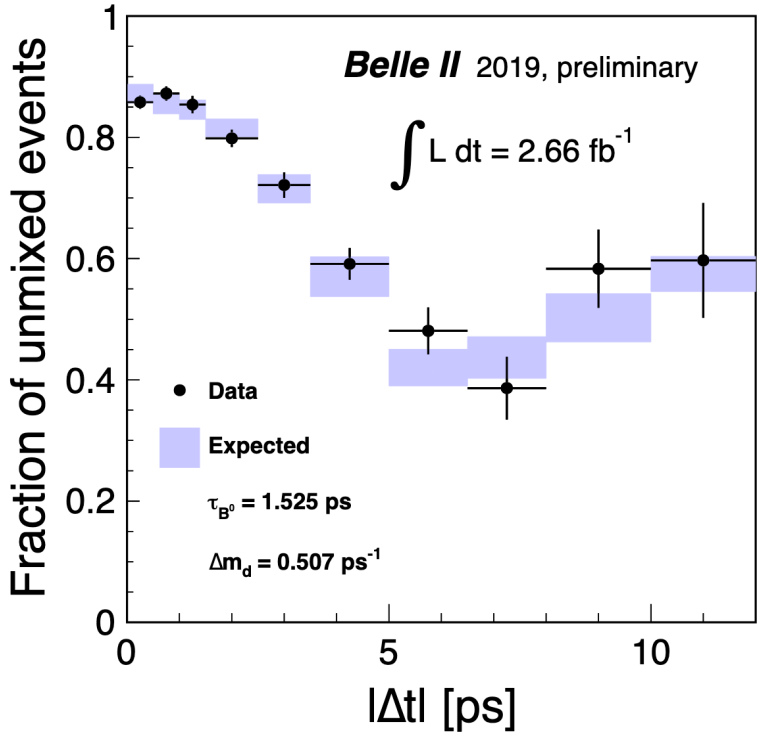
BACKUP

Performance in Data: $B^0\bar{B}^0$ Mixing

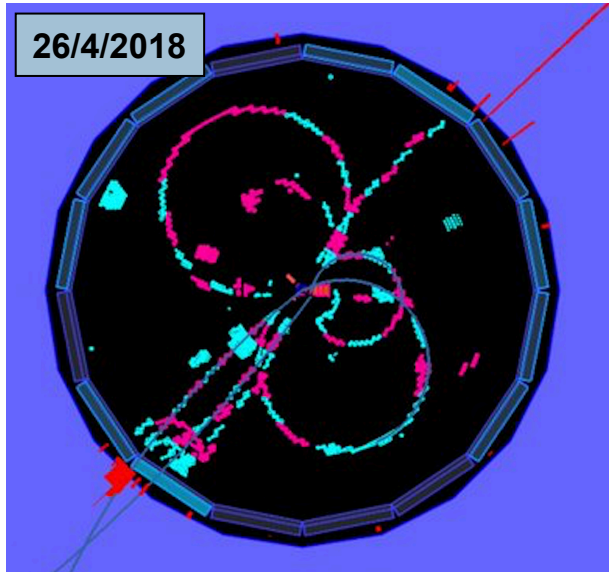
- First glimpse of B^0 lifetime + $B^0\bar{B}^0$ mixing frequency in Phase 3 data (2.66 fb^{-1})
- **TO DO…**



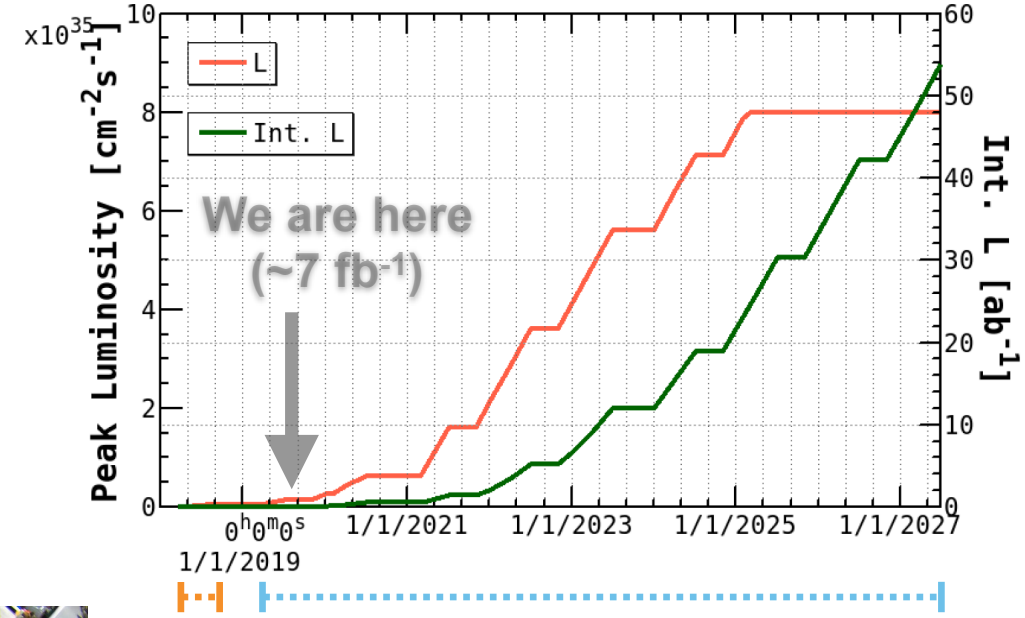


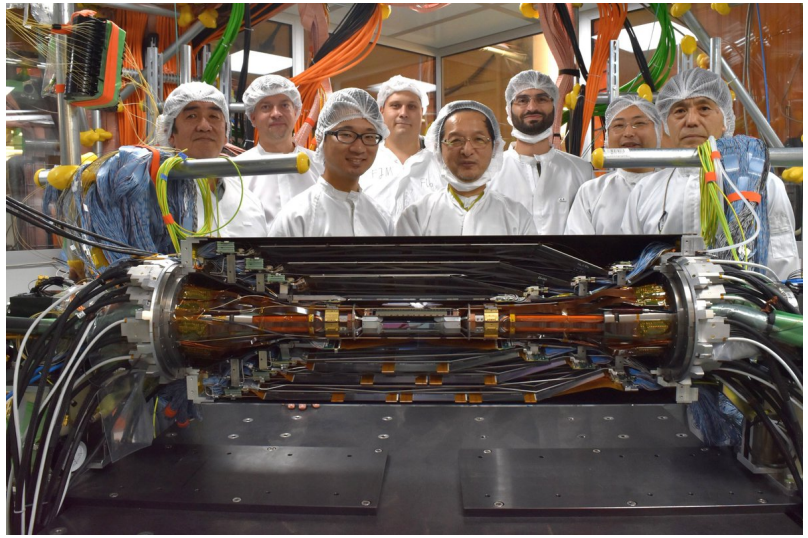


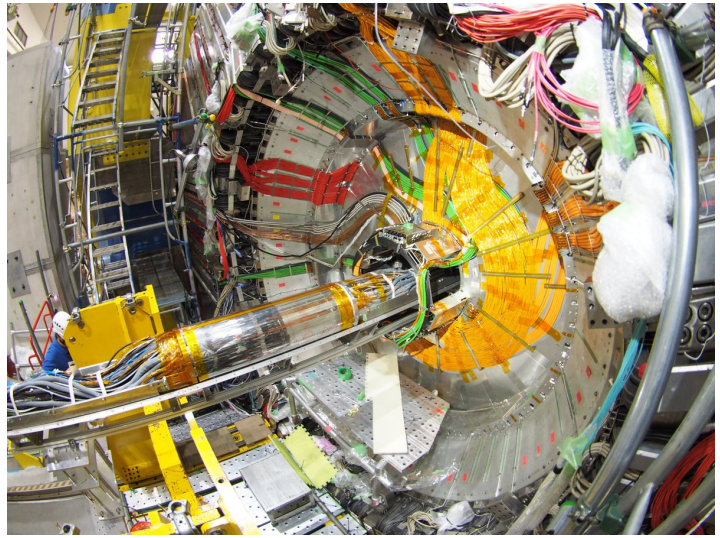
Belle II Timeline



- First collisions recorded by Belle II on 26th April 2018
- **Phase 2** of data taking completed last year
  - April-July 2018
  - around 0.5 fb^{-1} of data recorded
  - one sector of VXD installed







- **Phase 3** started in March this year
  - around 6.5 fb^{-1} recorded so far
  - full VXD coverage, 2nd PXD layer has only 4 sensors installed
- Aim for **50 ab^{-1}** by 2027 (x50 Belle)

Outline

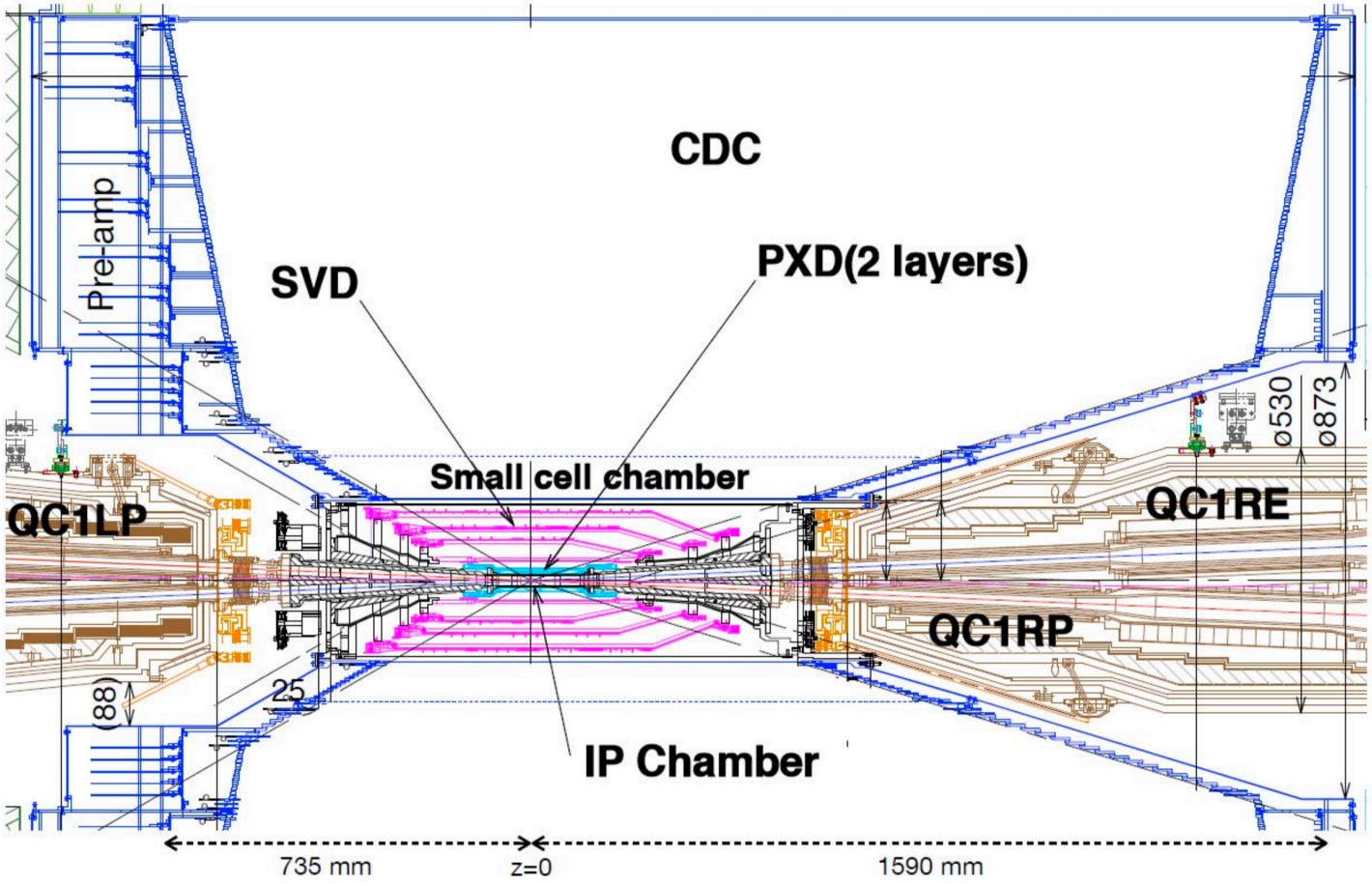
1) Overview of SuperKEKB, Belle II and its tracking system

2) Track finding at Belle II and performance in MC

3) Performance in collision data

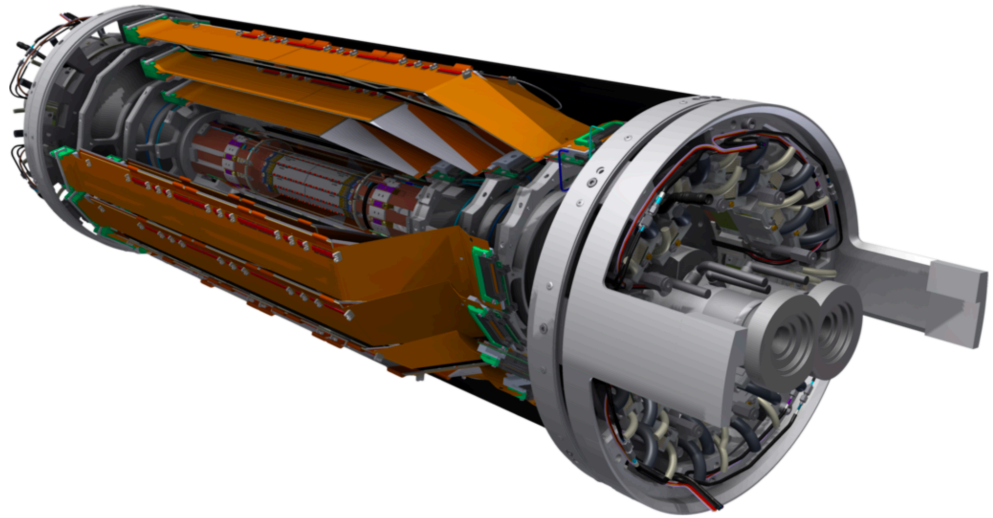
4) Summary and outlook

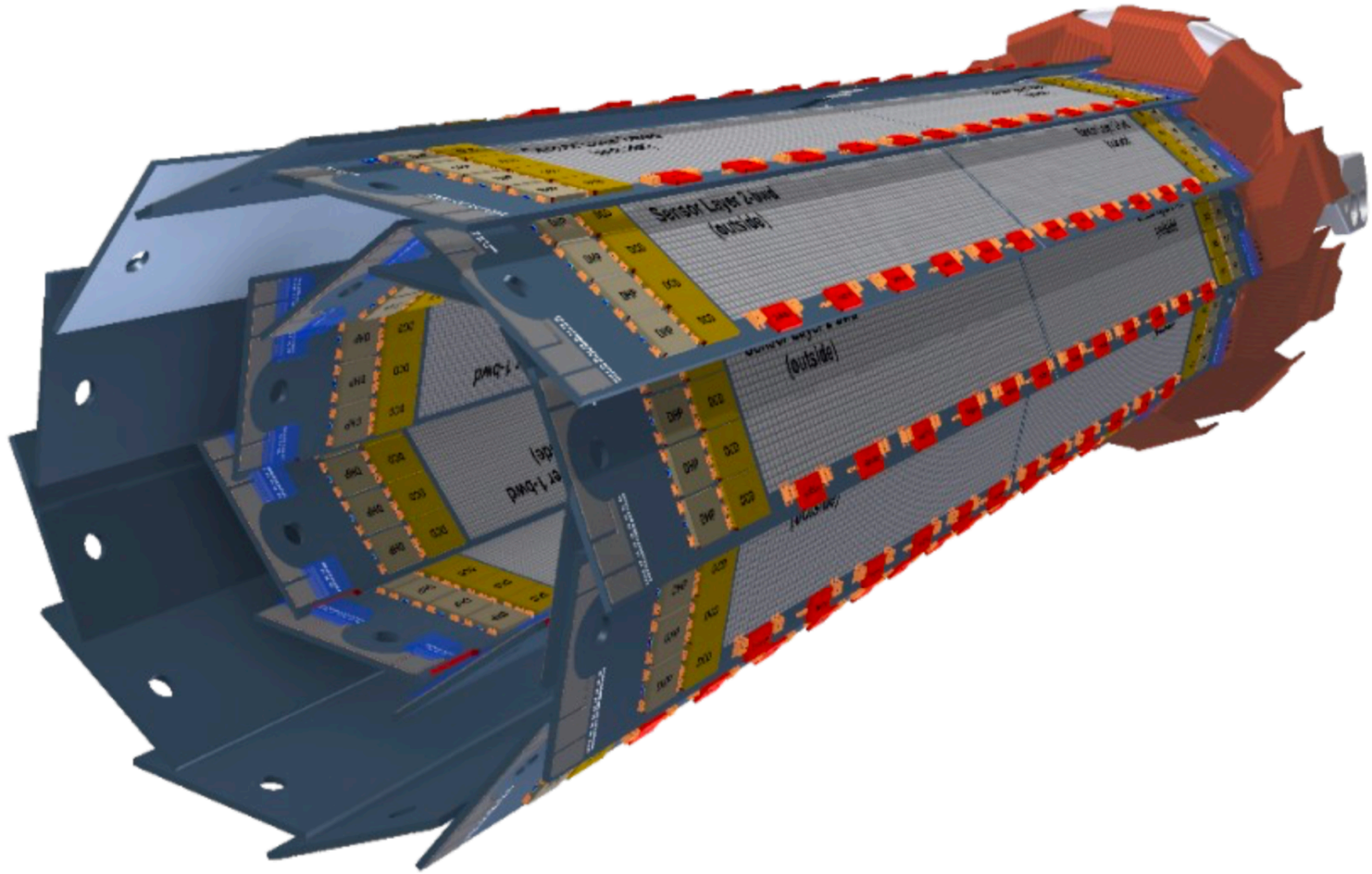
Tracking System of Belle II



- **PXD**
  - 2 layers of DEPFET pixel sensors (r = 13, 22 mm)
  - 40 sensors, 7.7 million total pixels

- **SVD**
  - 4 layers of double-sided silicon strip sensors (r = 39, 80, 104, 135 mm)
  - 172 sensors, 220k read-out strips




Sensor Layer 2 unit
(outside)
(outside)