Performance of Belle II Tracking on Collision Data

Connecting The Dots

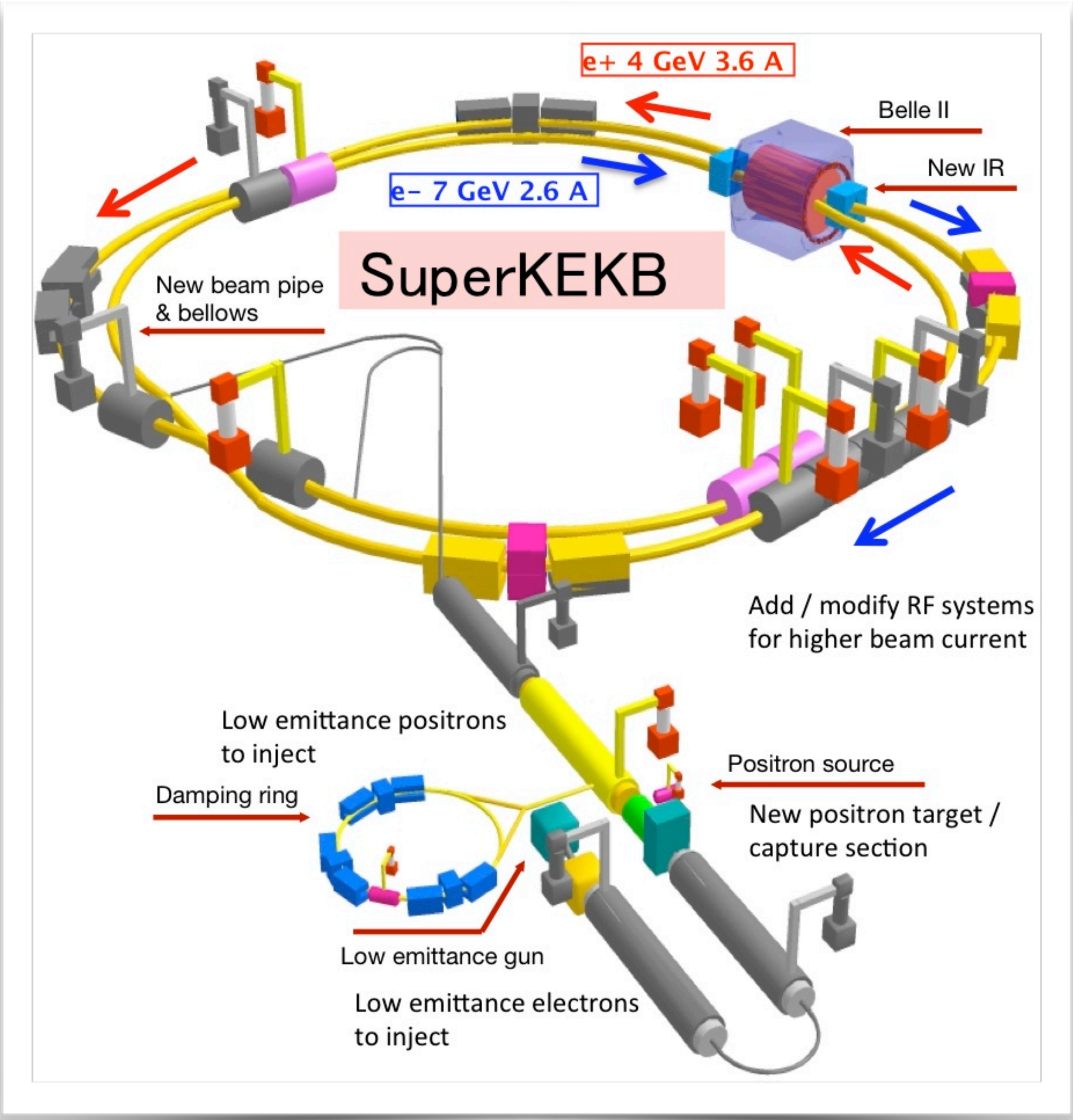
Simon Kurz on behalf of the ***Belle II*** **Tracking Group**

April 22-24, 2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

SuperKEKB

B-Factory for the Belle II Experiment

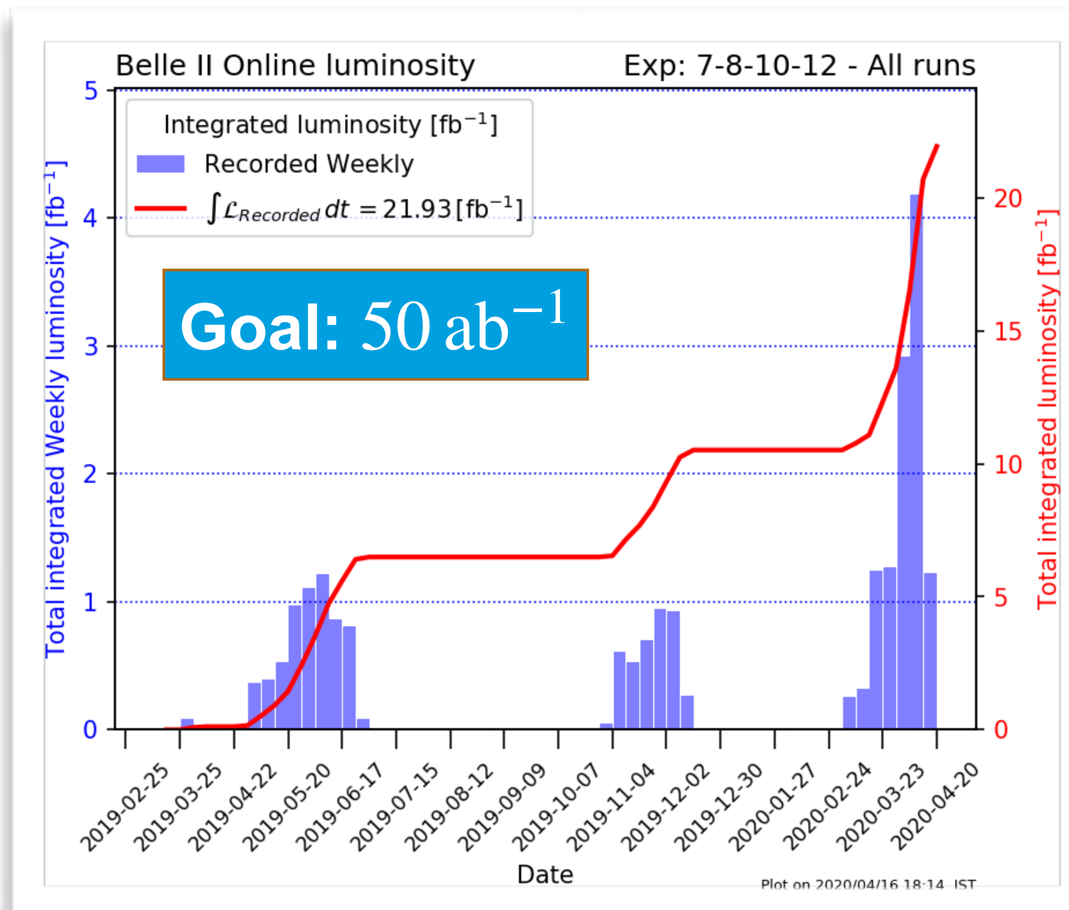


Asymmetric e⁺e⁻ *B*-factory to study CP-violation and rare decays

- Boost of $\beta\gamma = 0.28$
- $E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV

Peak luminosity 40x higher than KEKB, up to $L = 8 \times 10^{35}$ cm^{-2}s^{-1}

- Reduction of beam size ('nano beam')
- Higher beam current (x2)

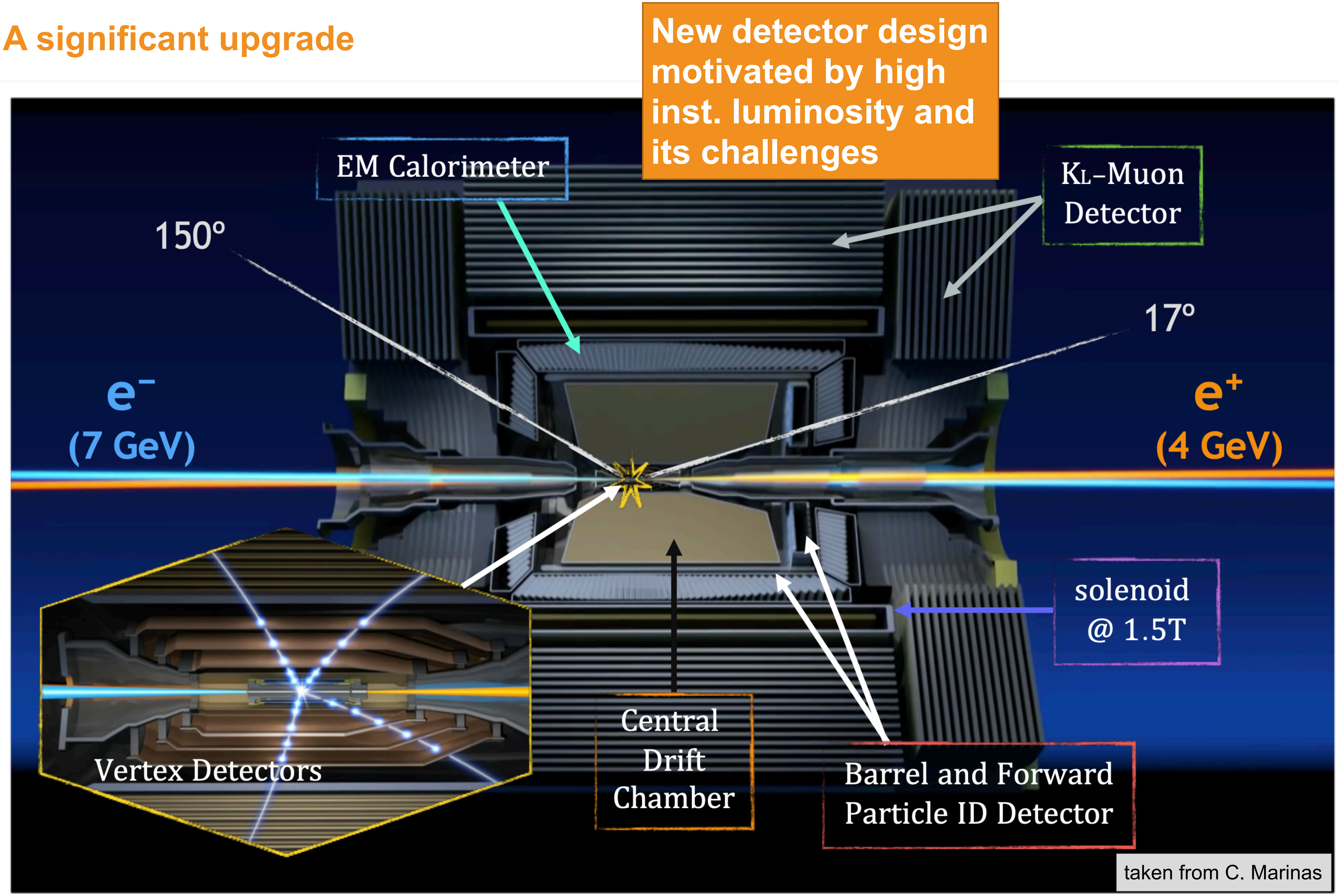


Current challenges:

- Increase inst. luminosity
- Reduce beam backgrounds

The Belle II Detector

A significant upgrade

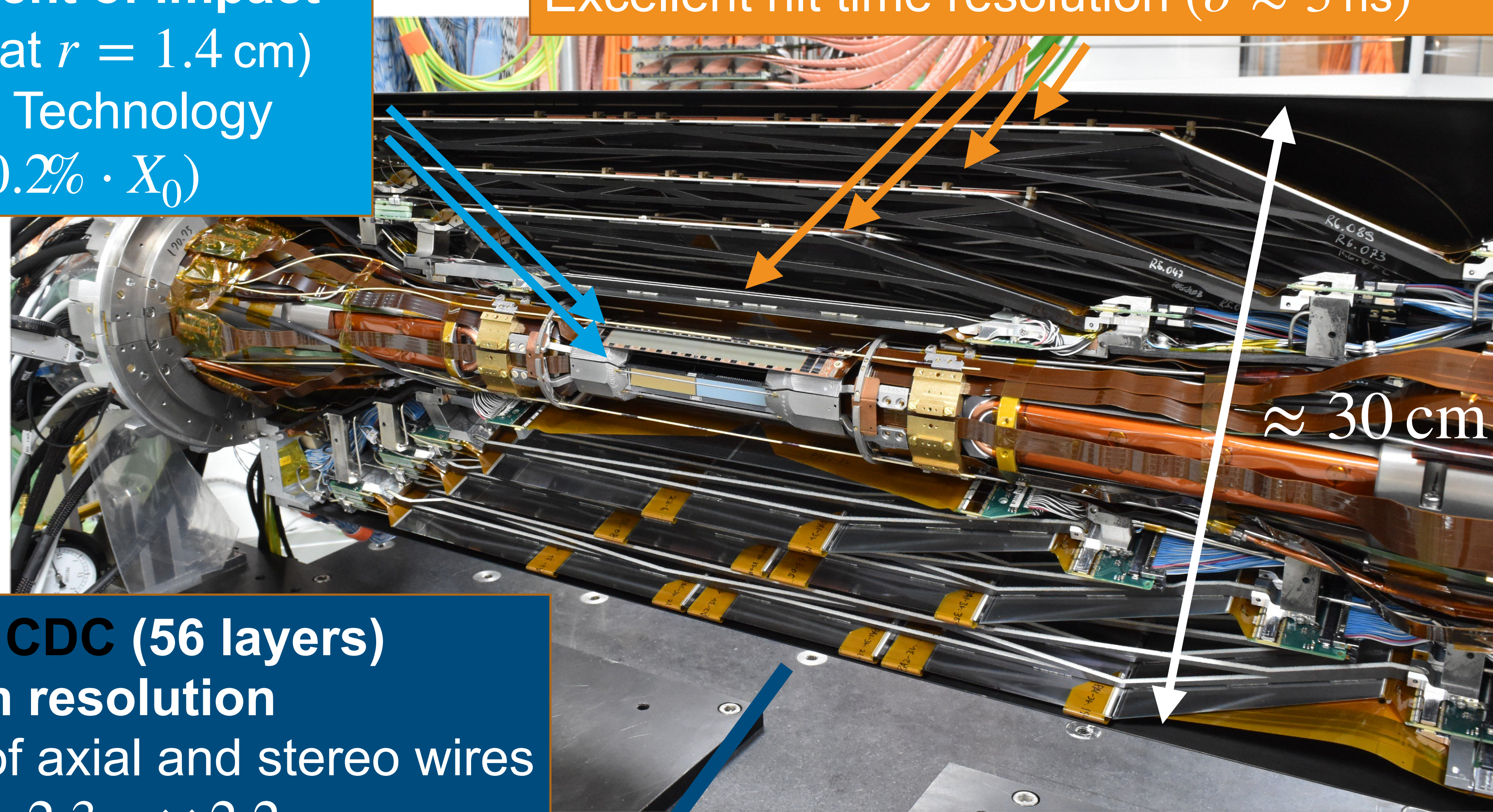


Belle II Tracking Detectors

Vertex Detectors (VXD) and Drift Chamber (CDC)

Silicon Vertex Detector: SVD (4 layers)
➡ Robust tracking despite backgrounds (also for standalone tracking)
Double Sided Silicon Strip Detector
Low material budget ($\approx 0.7\% \cdot X_0$)
Excellent hit time resolution ($\sigma \approx 3$ ns)

Pixel Detector: PXD (2 layers, currently only 2 ladders of 2nd layer)
➡ Precision measurement of impact parameter (First layer at $r = 1.4$ cm)
Based on DEPFET Pixel Technology
Low material budget ($\approx 0.2\% \cdot X_0$)



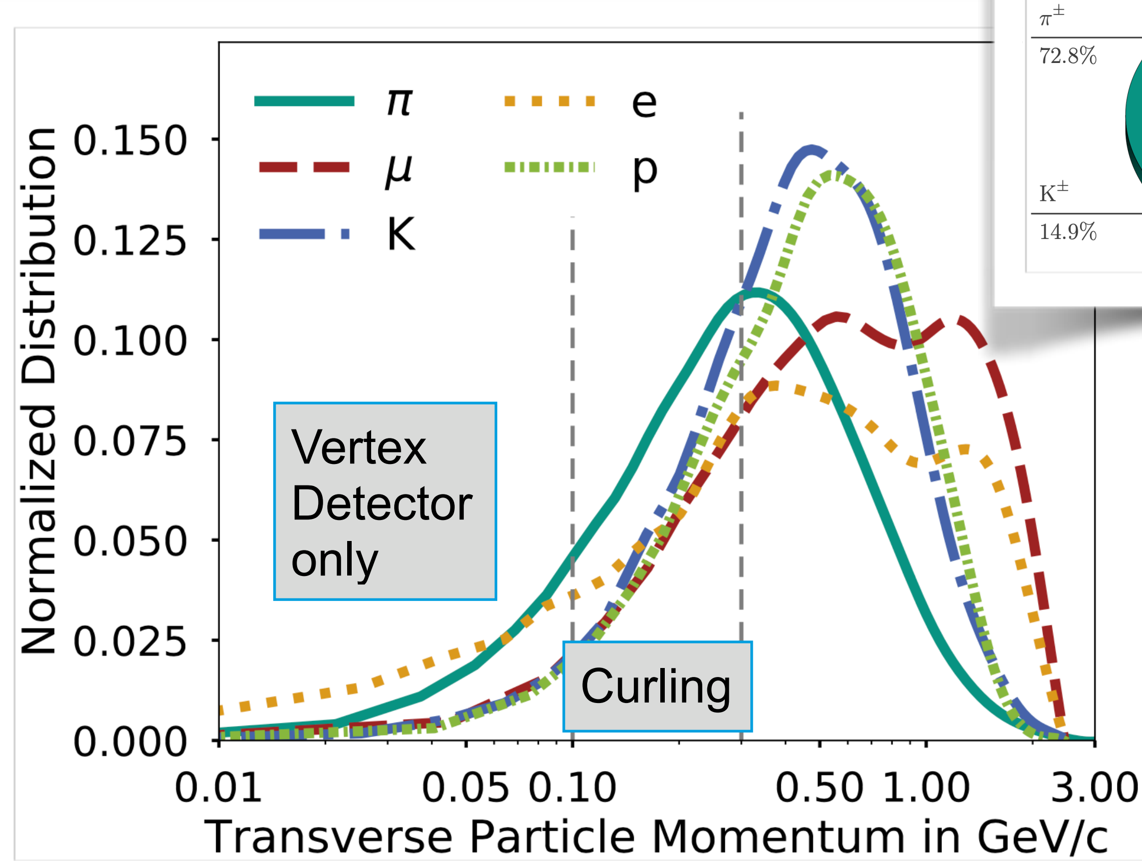
Central Drift Chamber: CDC (56 layers)
➡ Excellent momentum resolution
Alternating superlayers of axial and stereo wires
Covers volume of $l \times r = 2.3\,\text{m} \times 2.2\,\text{m}$

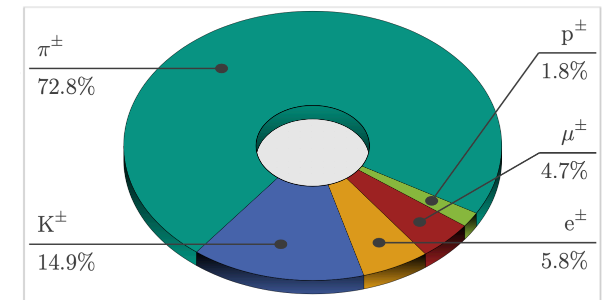
Event Properties and Tracking Challenges

…at a *B*-Factory

Typical $\Upsilon(4S)$ event:

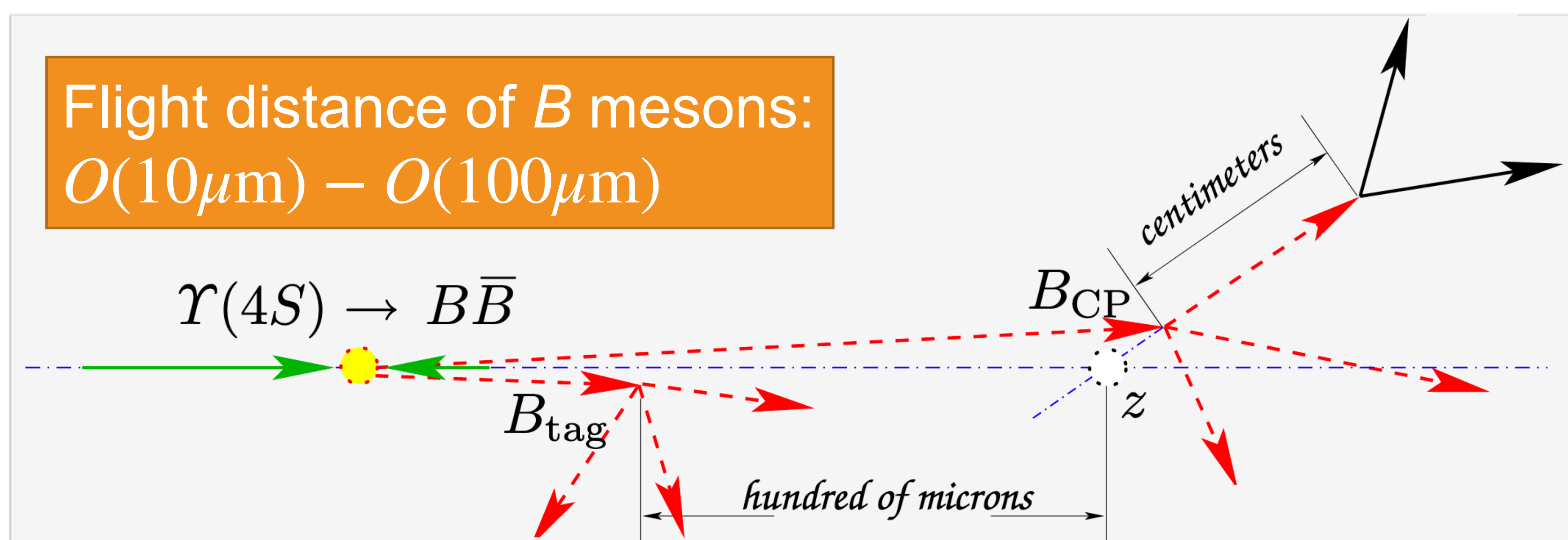
- 11 charged tracks with soft momentum spectrum
- High machine background: Number of background hits about <u>2 orders of magnitude</u> larger than signal hits





Analysis requirements:

- Precise measurement of primary and secondary vertices
- Often using full event reconstruction:
  - <u>Find all tracks</u> ($p_T \gtrsim 50$ MeV)
  - <u>No fakes or duplicates</u>

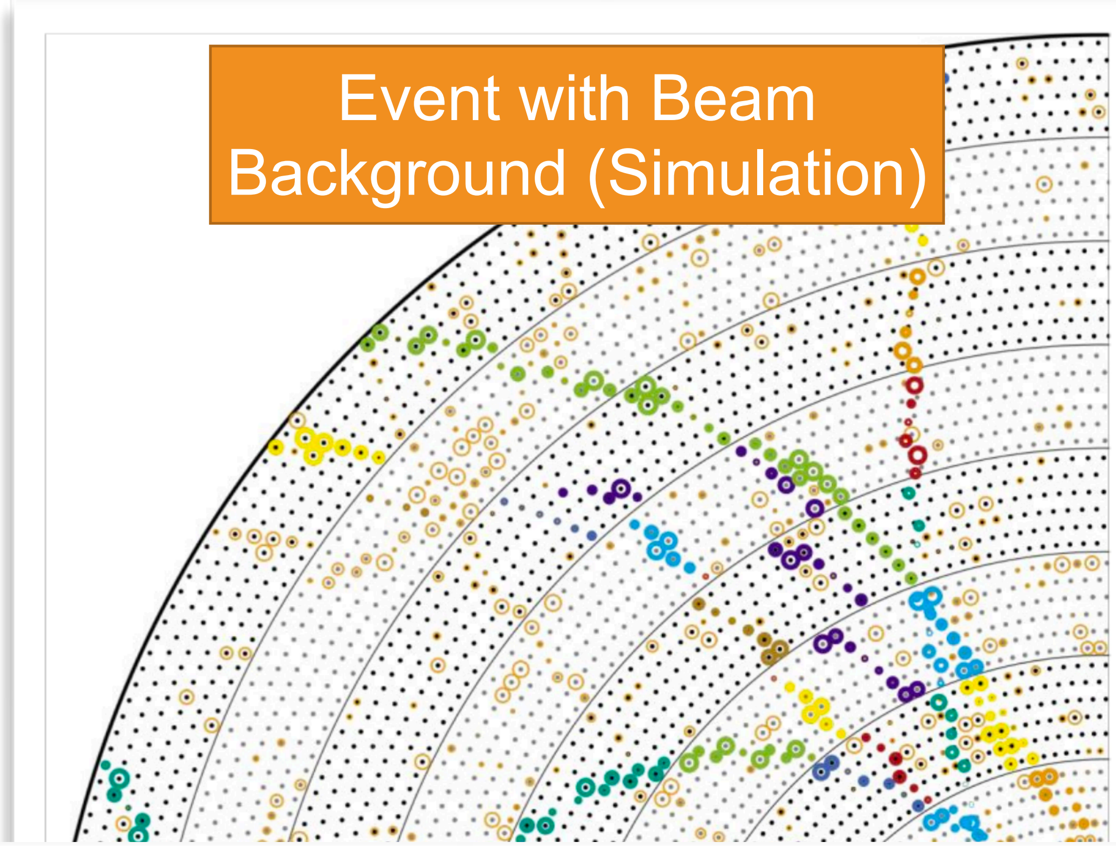


Background Suppression

Example: CDC - Machine Background and Cross Talk

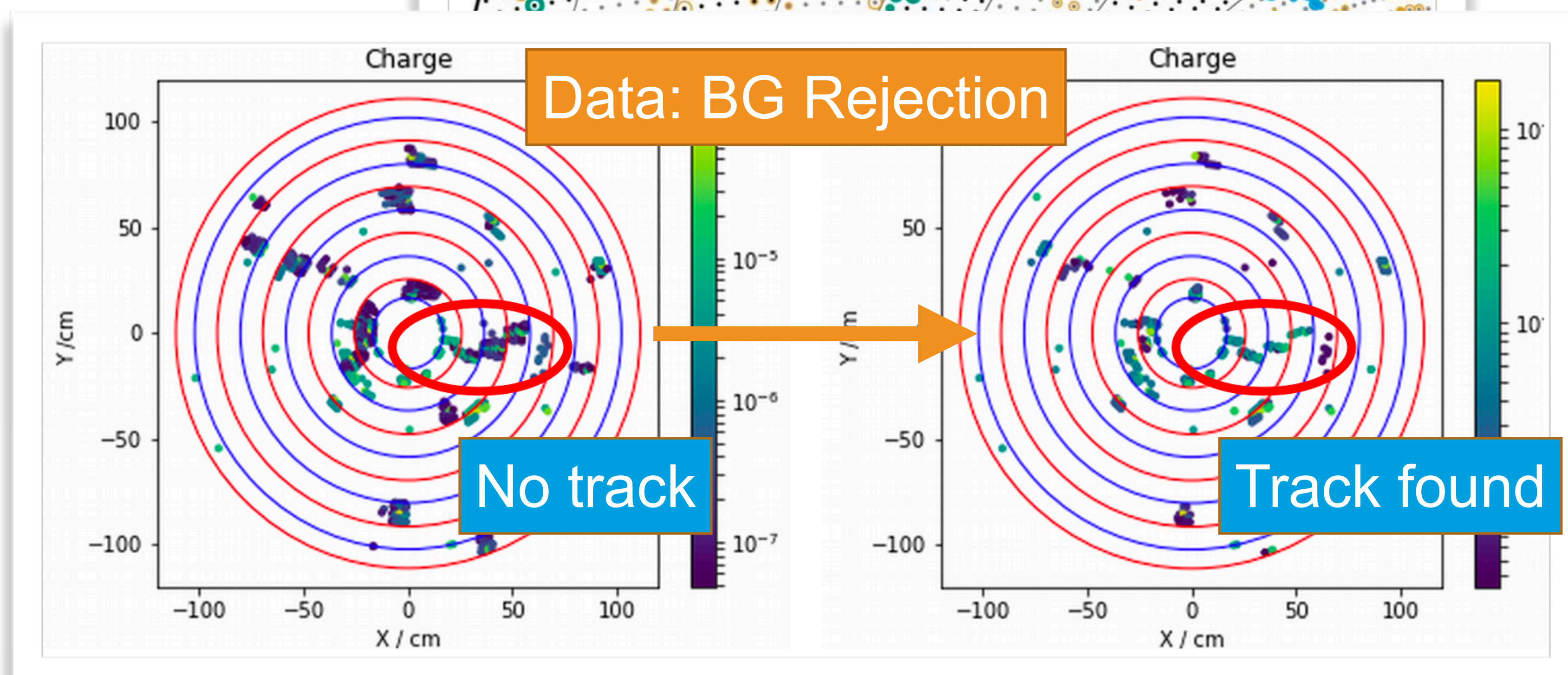
Necessary to reject background hits as much as possible while preserving signal hits

- Classical approach: require minimum of deposited charge, time over threshold



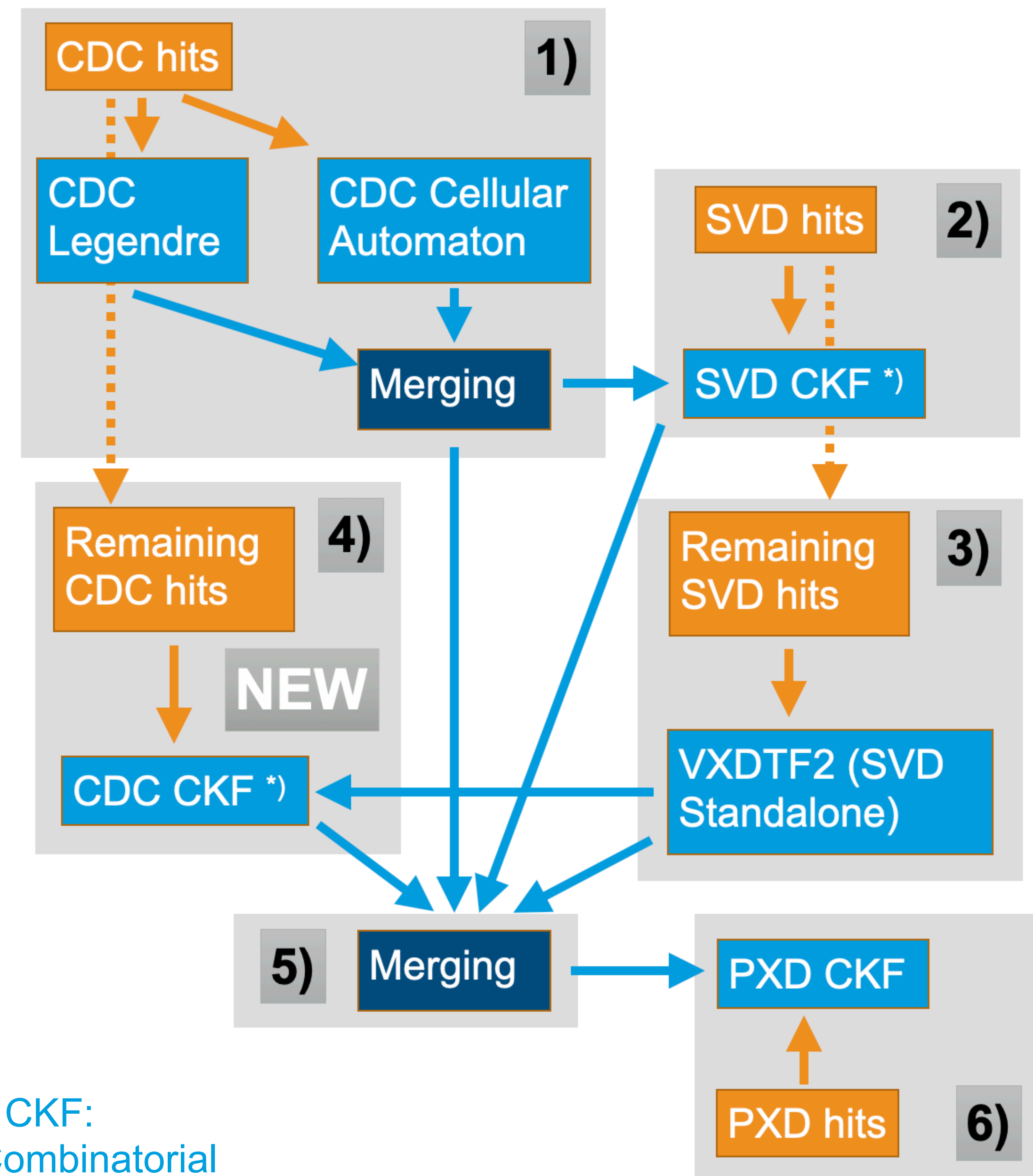
Observed significant amount of 'cross talk'

- Neighbouring channels in ASIC light up
- Small charge, peculiar time structure
- Implement a designated filter targeting expected topology



The Tracking Algorithms

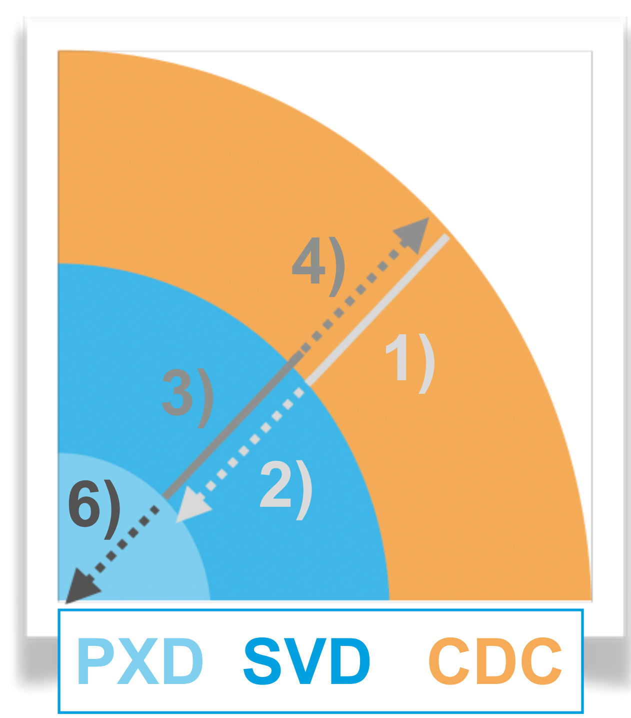
A Modular Approach



*) CKF: Combinatorial Kalman Filter

The modular system allows for different track finding sequences in case it's needed

- Can be adapted to background conditions, degradation of detector performance, etc.
- CDC track finding used as baseline
- PXD currently not used for standalone track finding
- Extension with SVD to CDC CKF **(4)** new (more later)
- Novel approaches can be added (see ECL seeded tracking, later)



The Tracking Algorithms

A Modular Approach

Track Finding at Belle II

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Find a detailed description of our tracking algorithms in the *Belle II Tracking Paper* that has just been submitted

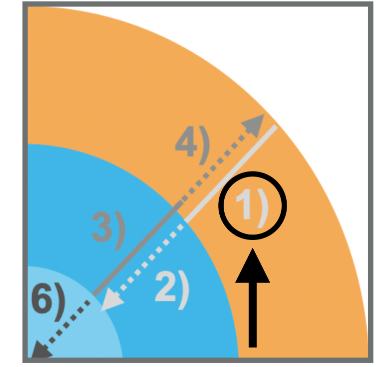
- Only brief overview on the following slides

Belle II Tracking Paper submitted!
arXiv:2003.12466

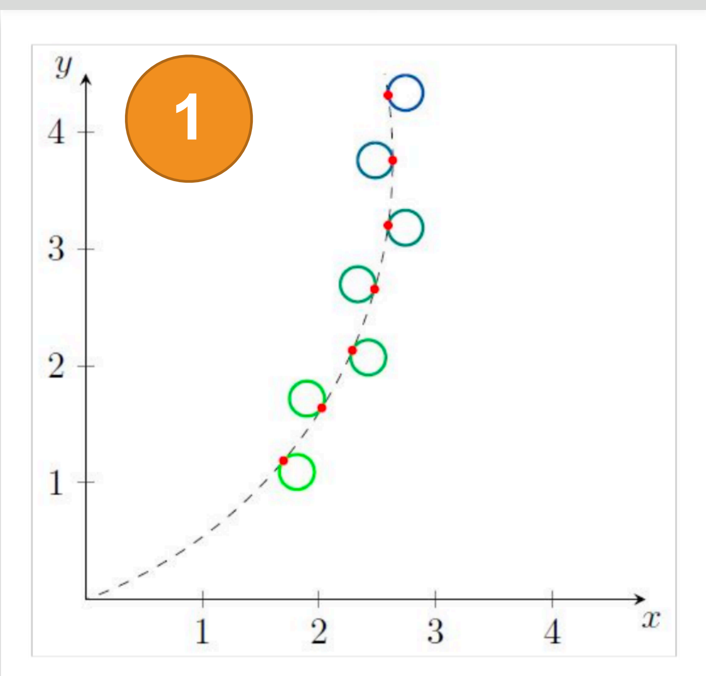
CDC Track Finding

Legendre Track Finder (Global TF)

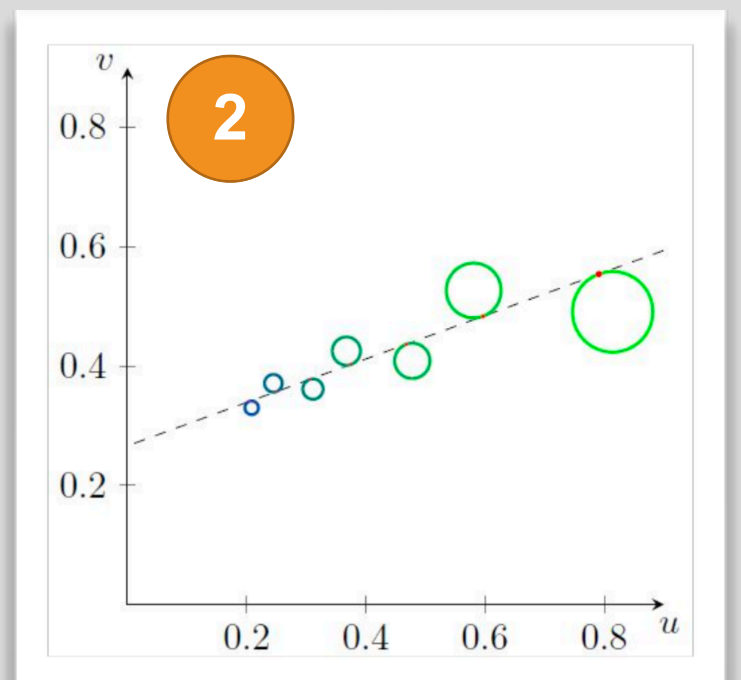
*) (x_0, y_0), R_{dr}
Center of drift circle and radius



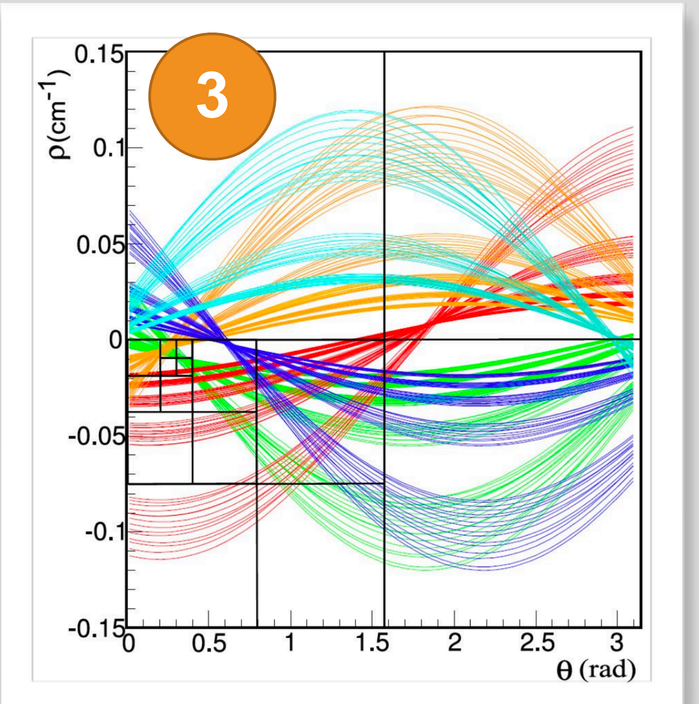
- Start with axial wires ($r-\phi$ plane)
- Add z information in the end using hits in the stereo layers
- Hit positions are approximated by drift circles



- Conformal transformation:
  - circular trajectory → straight line
  - drift circle → circle
- Simplified problem: find common tangent for set of circles

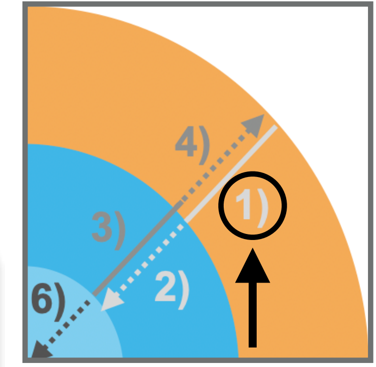


- Use Legendre Parameters to describe drift circles:
  $\rho = x_o \cos\theta + y_o \sin\theta + R_{dr}$ *)
- Determine point of maximum density (→ 2D binary search)
- <u>Efficient implementation:</u> dedicated quadtree structure, 'sliding bins'



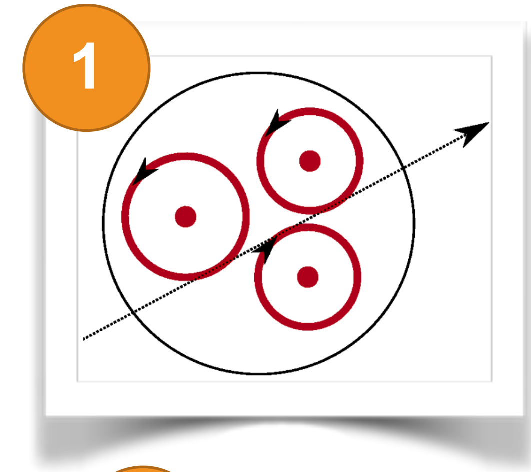
CDC Track Finding

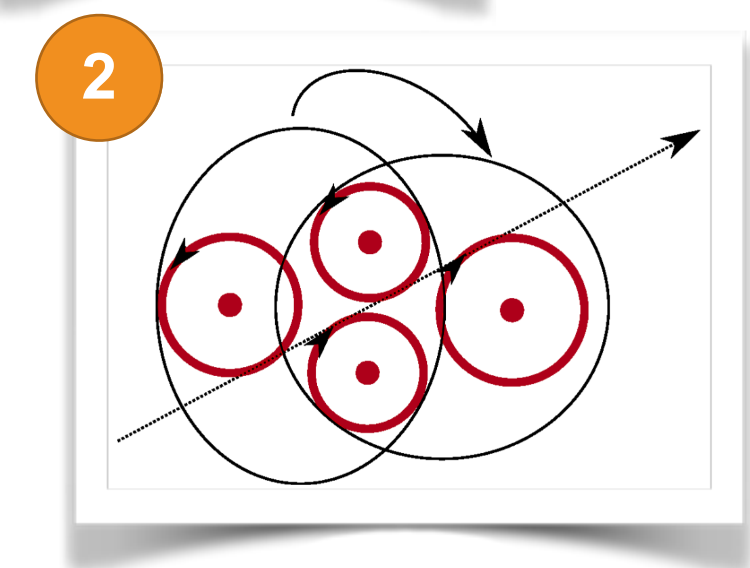
Cellular Automaton Track Finder (Local TF)



Use local TF for short and displaced tracks based on a Cellular Automaton

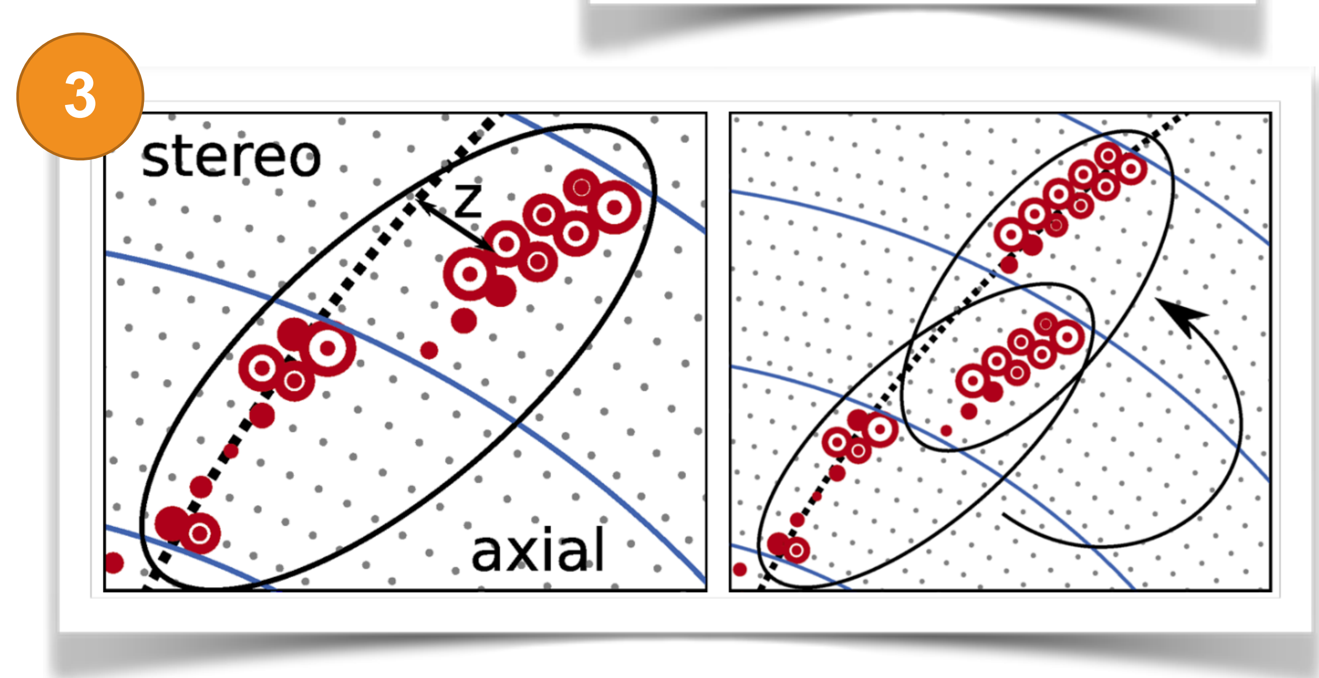
1. Find triplets of hits in neighbouring layers assuming a certain right-left-passage
2. Connect triplets that share two hits and assign weights based on common fit to ‘segments’
3. Combine overlapping segments and calculate weight based on common fit





Currently not used as a standalone algorithm due to non-negligible fake rate

- Found segments added to tracks reconstructed by global TF using multivariate methods
- In the end, several further MVA-based filters to improve fake/clone rate, as well as purity and track parameter resolution

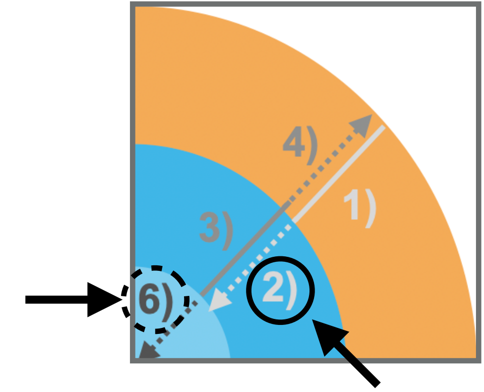


Additional quality indicator*) is being studied to reduce fake rate of local TF

*) Belle software usually based on FastBDT: arXiv:1609.06119

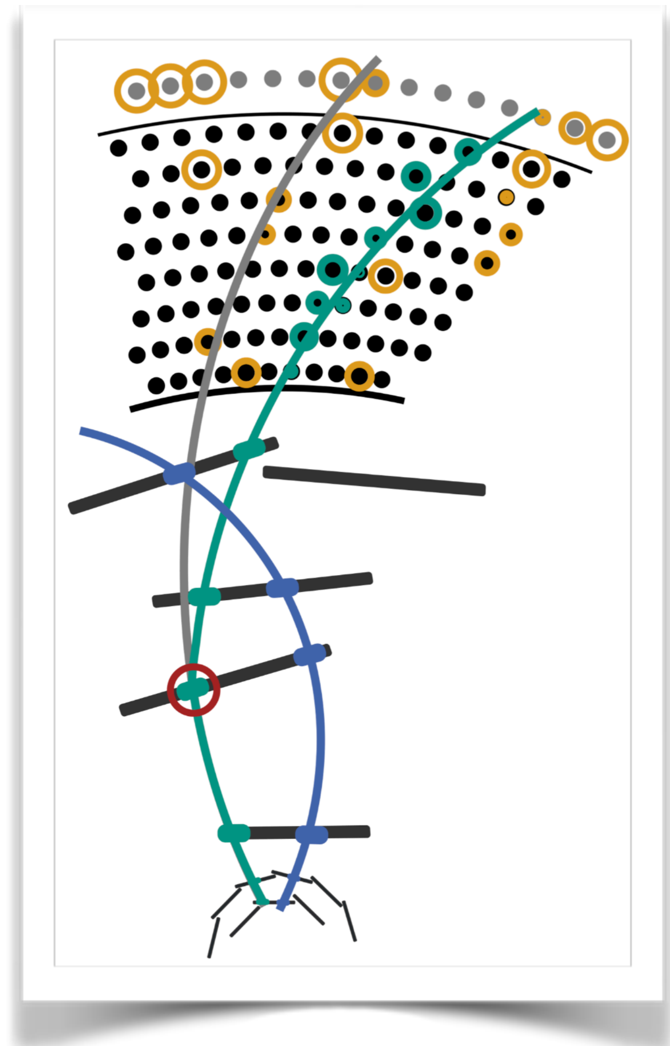
Combinatorial Kalman Filter (I)

CDC to SVD CKF



Extrapolate CDC track inwards and try to attach SVD hits

- Algorithm may skip detector layers to account for inefficiencies
- Consider hits within a certain $\phi \times \theta$ window and pick best candidates using MVA based filters
- Define new paths based on all selected candidates and repeat procedure for each of them
- In the end, select best candidate for each CDC track seed



Highly configurable implementation (template-based)

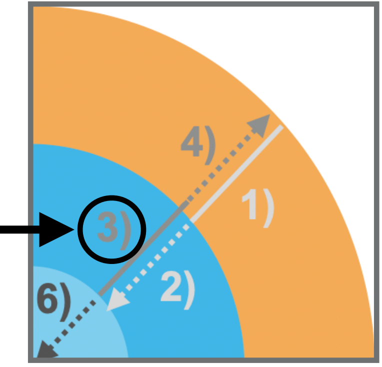
- Filters used for selection of best hit and path candidates can be modified/tuned easily
- Same code used in the last step for the extrapolation of tracks to the PXD

Material interactions currently disabled during CKF as many extrapolations are done
→ Ongoing studies to replace GENFIT2 tracking toolkit with ACTS (faster)

GENFIT2: arXiv:1902.04405 ACTS: arXiv:1910.03128

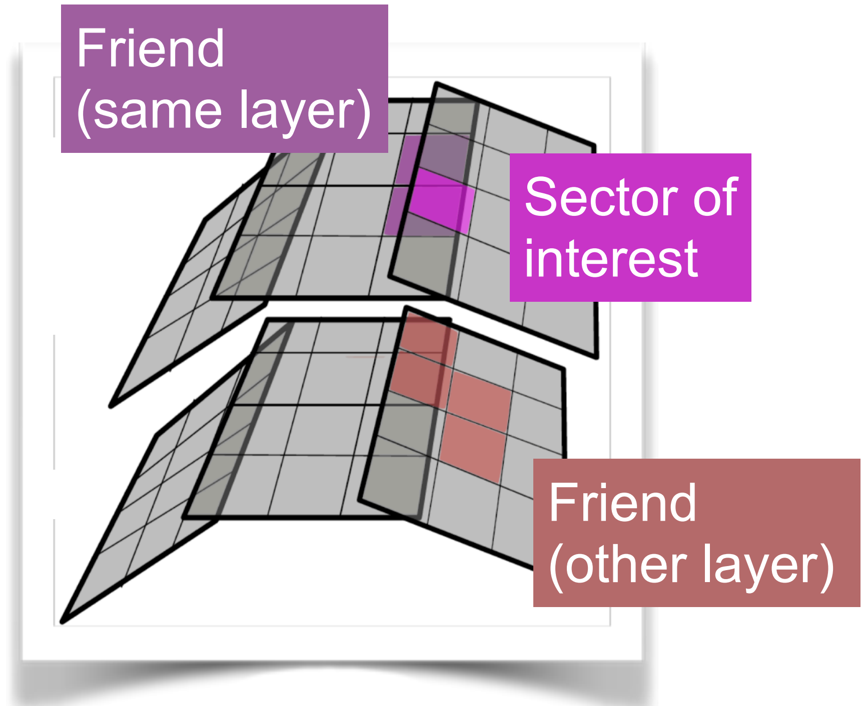
SVD Standalone Track Finding

VXDTF2



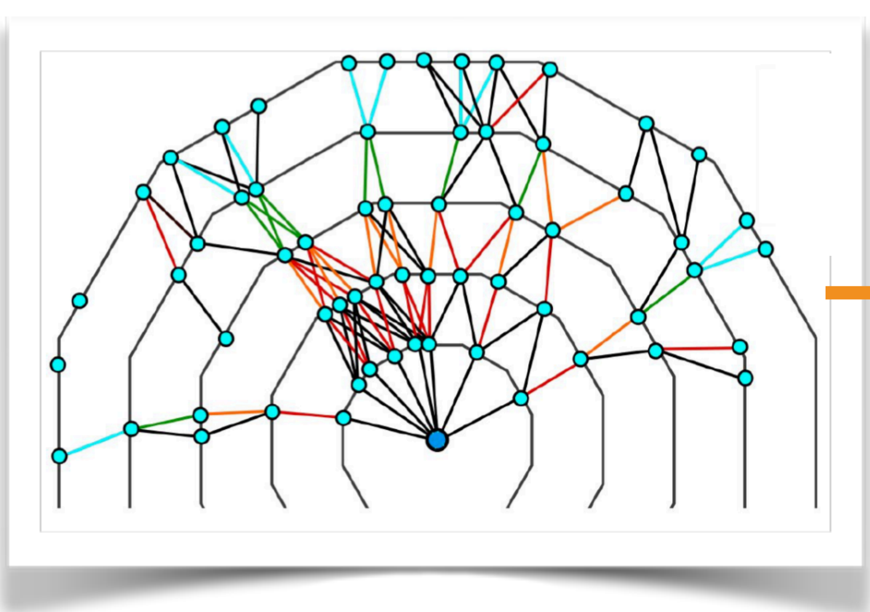
Train a ‘sector map’ that stores friendship relations between sensors (sensors split in 3x3 sectors)

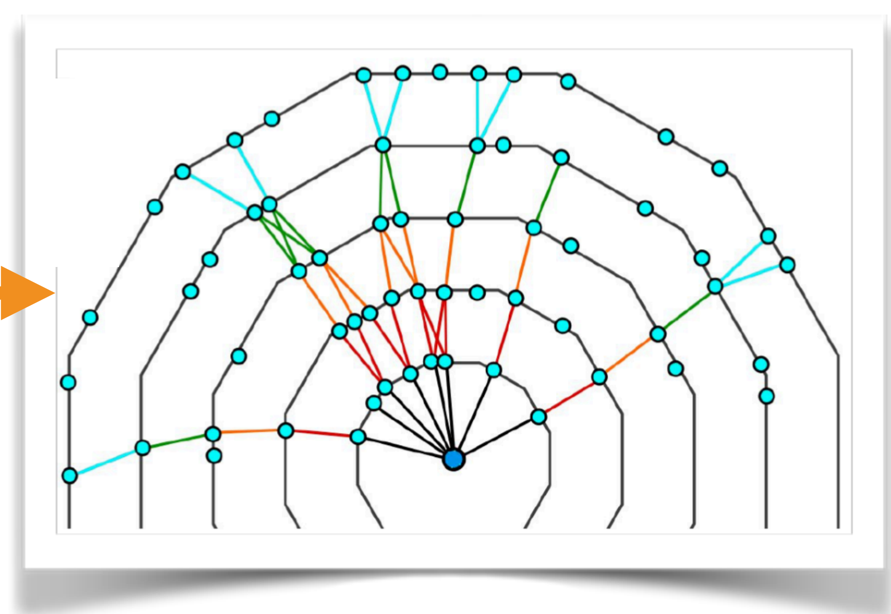
- Friendship defined by consecutive hits of simulated tracks (+ filters)
- Greatly reduces complexity of track finding problem by lowering potential combinations of hit points
- Granularity of sectors can be tuned for high efficiency and low fake rate



Use a cellular automaton based on pairs of space points with friend relation

- Use filters to reject bad combinations (angle, **timing** etc.)
- Train MVA to reject fake and clone tracks

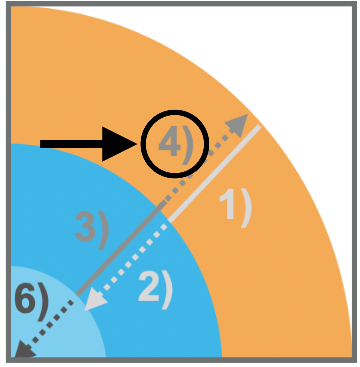




➡ Very good perform once at current background conditions!

Combinatorial Kalman Filter (II)

SVD to CDC CKF

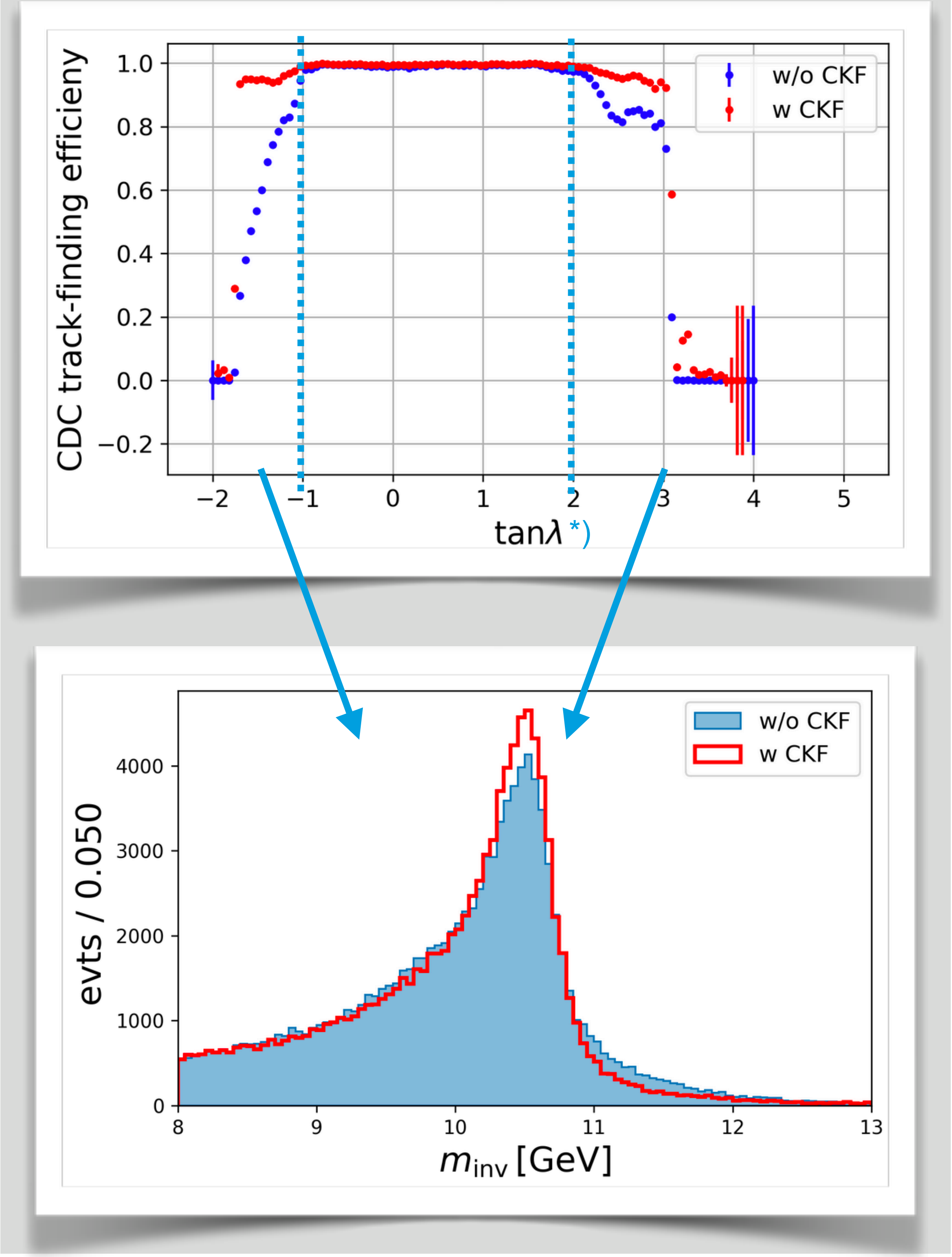


- Forward tracks are sometimes not reconstructed in the CDC
  - Low number of hits
  - Higher than expected background levels
- VXDTF2 finds a significant fraction of these tracks
  - SVD has larger acceptance
  - More robust against background
  - Momentum resolution can be improved by adding CDC hits to the tracks

➡ **Additional CKF from SVD to CDC increases tracking performance**

- Basic code is the same as for the other CKFs but necessary to take effects like drift time, left/right passage etc. into account

2 track events (data)



*) describes slope:
$\tan\lambda = 0 \rightarrow$ track $\perp$ beam

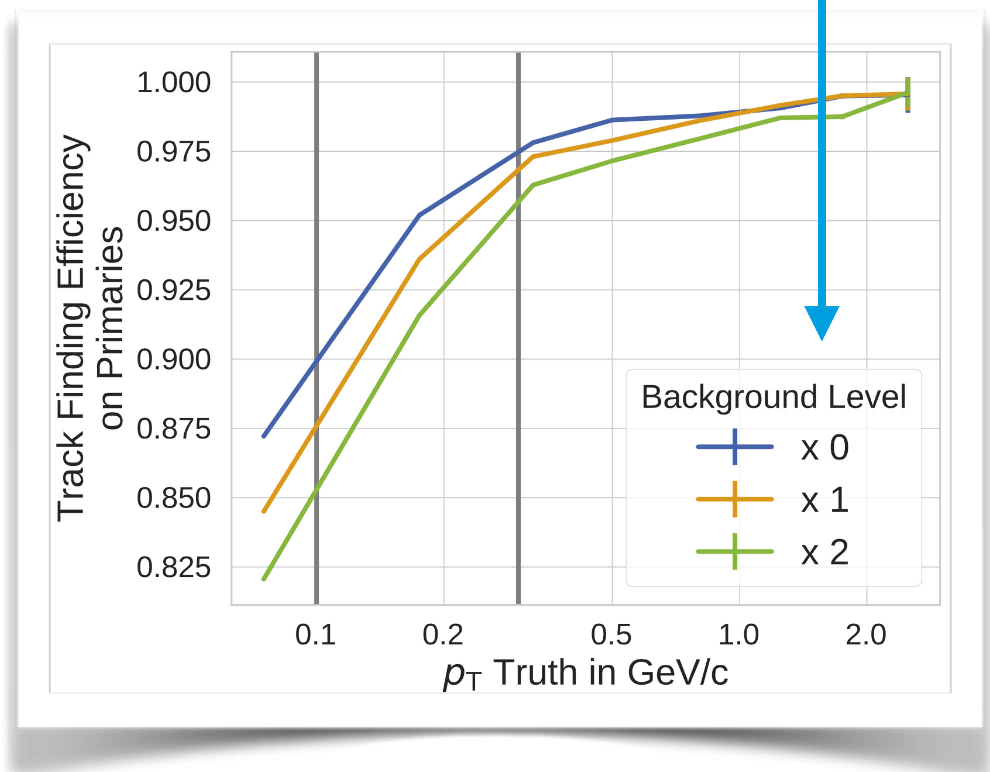
Performance on Simulated Events

Benchmark

Track finding efficiency quite robust against beam background

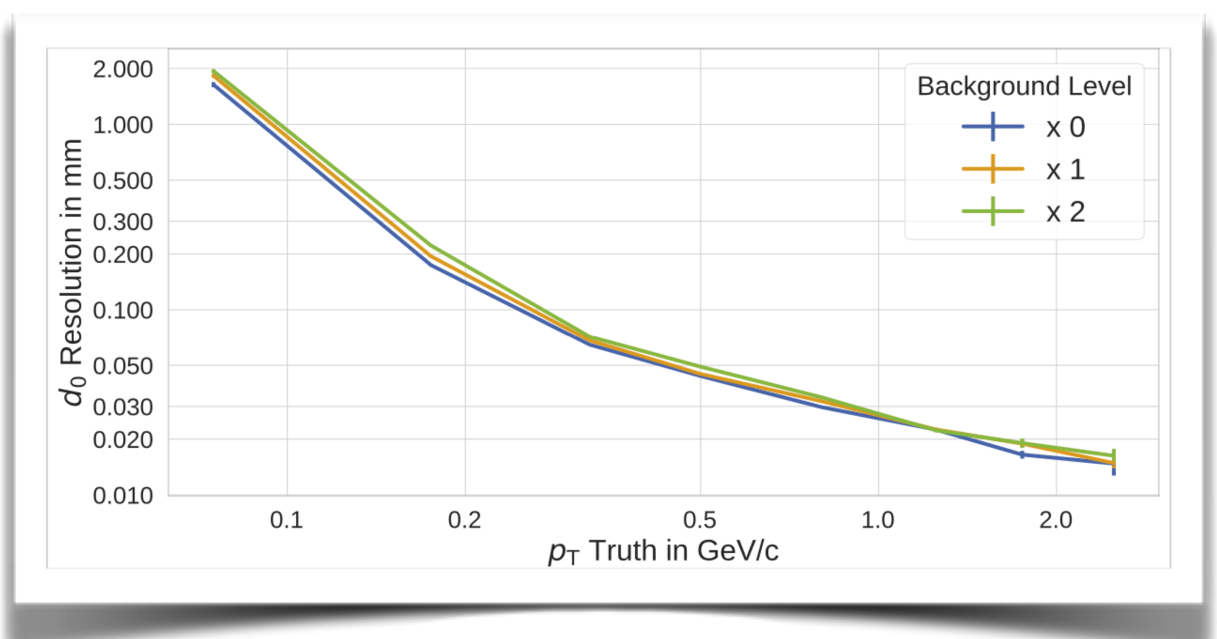
- Performance acceptable with twice the expected background level
- Still room for improvements as no optimisation done for higher than expected background levels

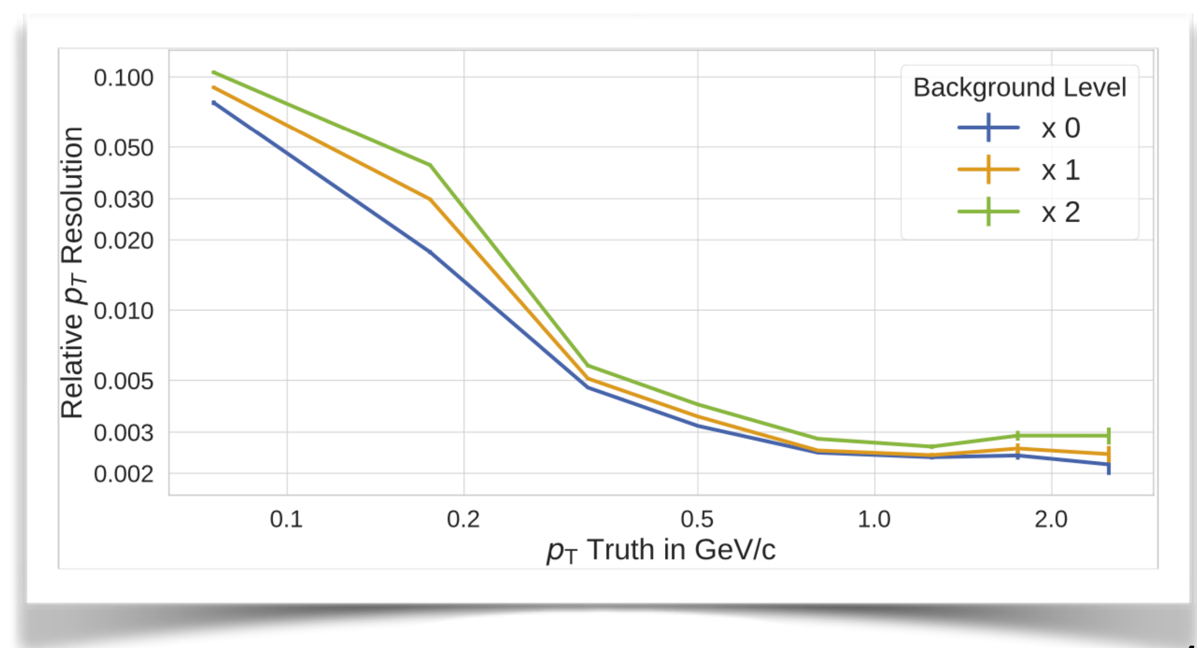
Background level at nominal luminosity



Excellent track parameter resolution

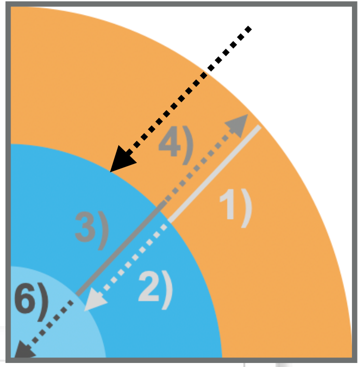
- d_0 resolution dominated by PXD hits and basically independent of background levels
- p_T resolution degrades slightly for low momentum particles at higher background levels



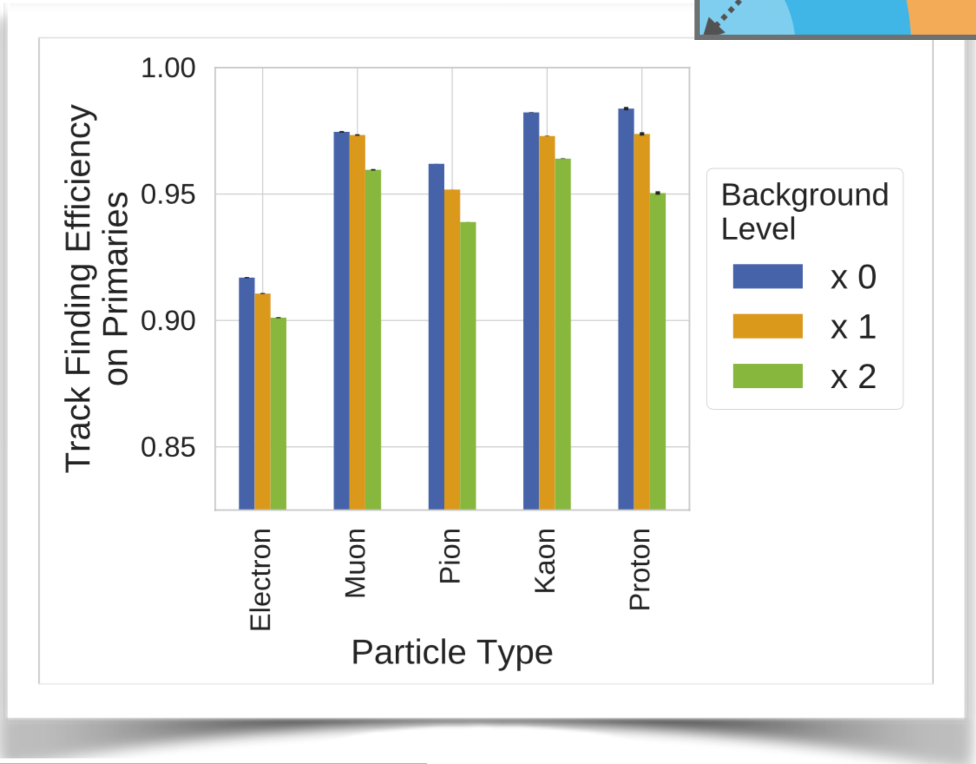


Further Developments

Example: ECL seeded CKF

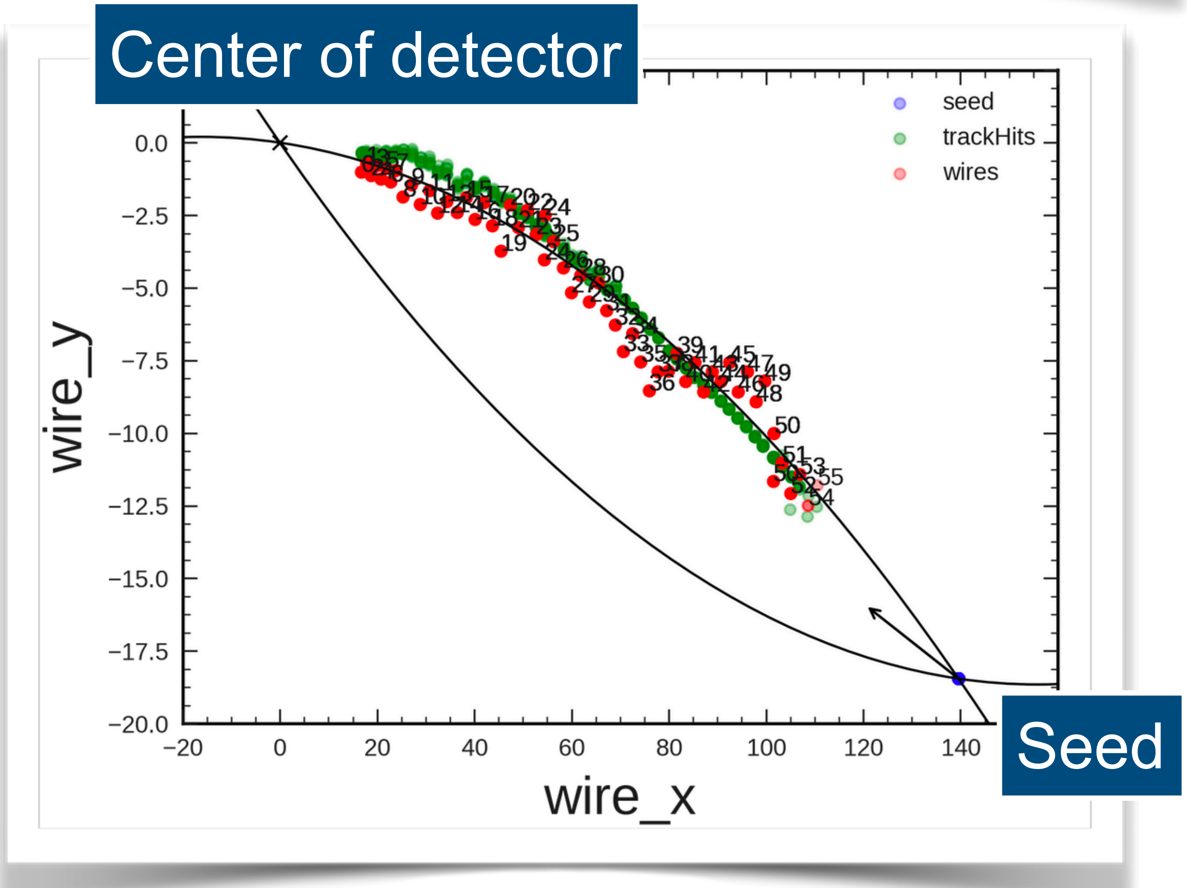


- Electron track finding efficiency about 5% lower due to material effects (Bremsstrahlung)



Idea to use ECL showers as seed for CKF

- Expected to increase tracking efficiency especially in forward regions
- Easy code development (template-based implementation of CKF)
- Do helix extrapolation for both charge assumptions from shower to center of detector and try to find track
- Implementation done, currently optimising parameters of CKF and validation on data
- Room for improvements:
  add Bremsstrahlung photons to track, find vertex from pair production,…



Performance on High Level Trigger (HLT)

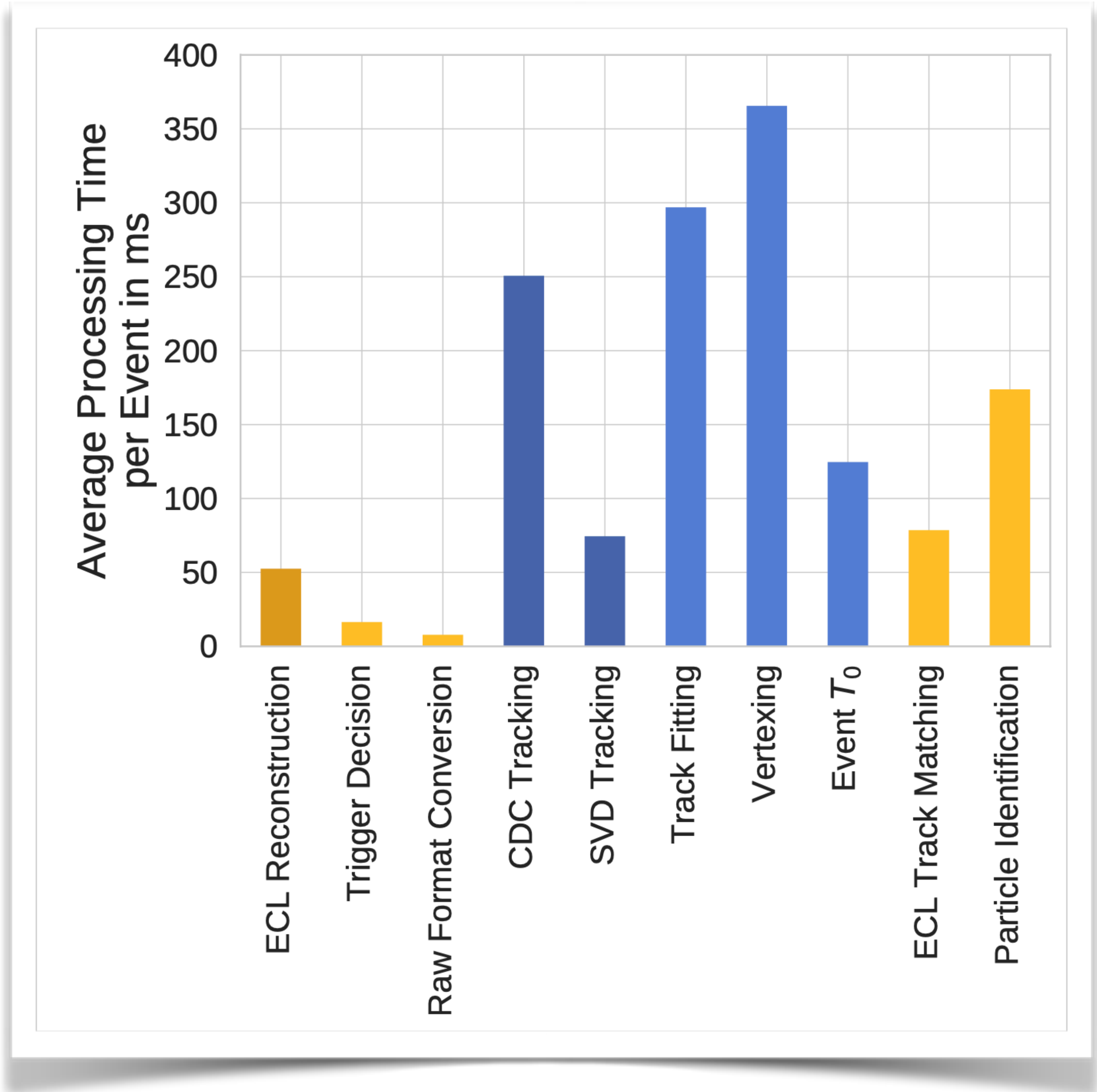
Running Stable

As expected, tracking most time-consuming process

- About 1s/per event needed for tracking
- CDC track finding, track fitting and vertexing take most of the time
- Not critical at current conditions but for higher background levels computing time will rise

Room for improvement:

- Replace GENFIT2 with ACTS for faster fitting
- Restructure track finding chain (modularity)

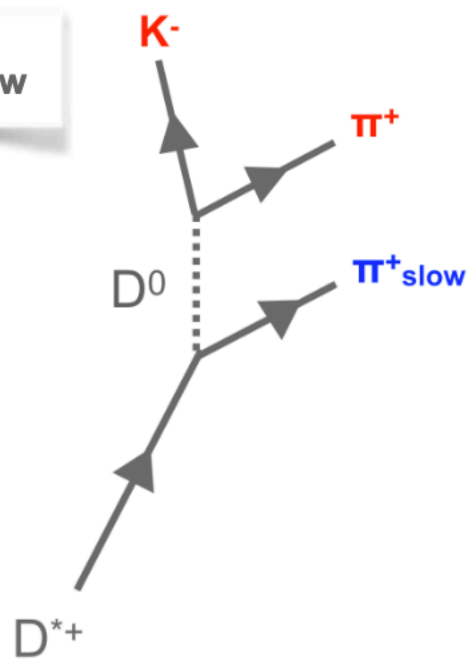


Tracking Efficiency Studies

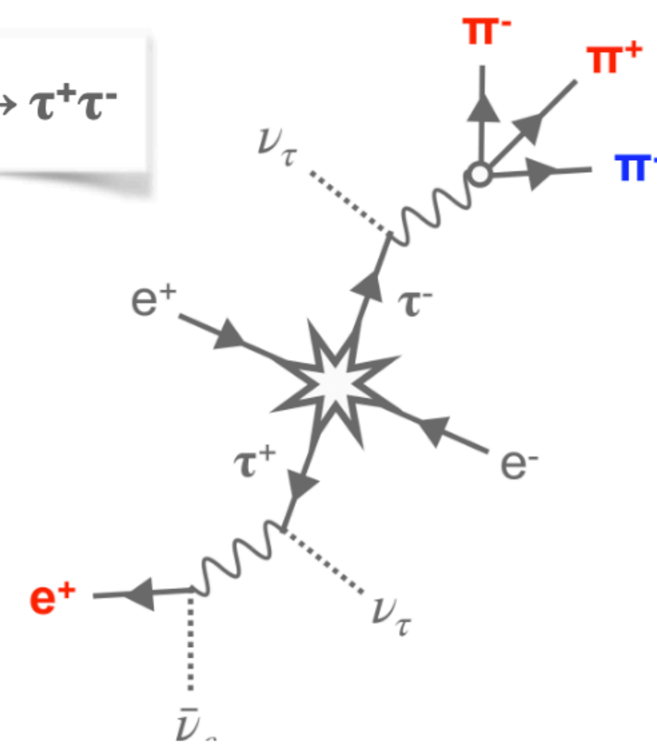
Comparison of Data and Simulation

Track finding efficiency is a key performance driver for Belle II physics:
Several tag-and-probe studies used to validate efficiency for different momentum ranges

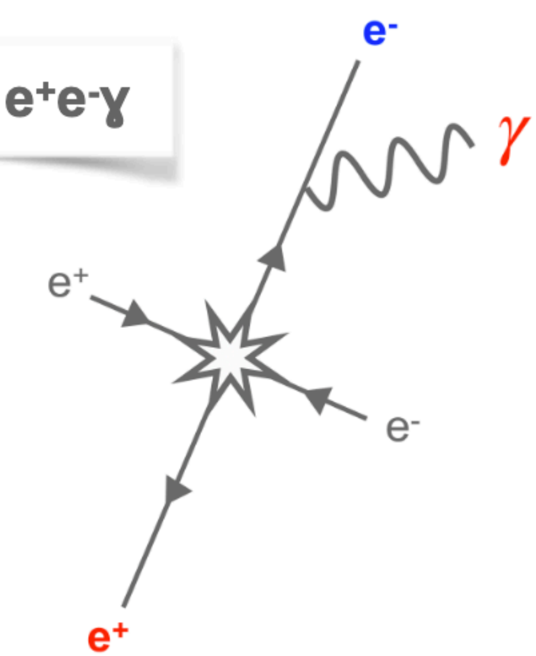
$D^{*+} \rightarrow D^0 \pi^+_{slow}$

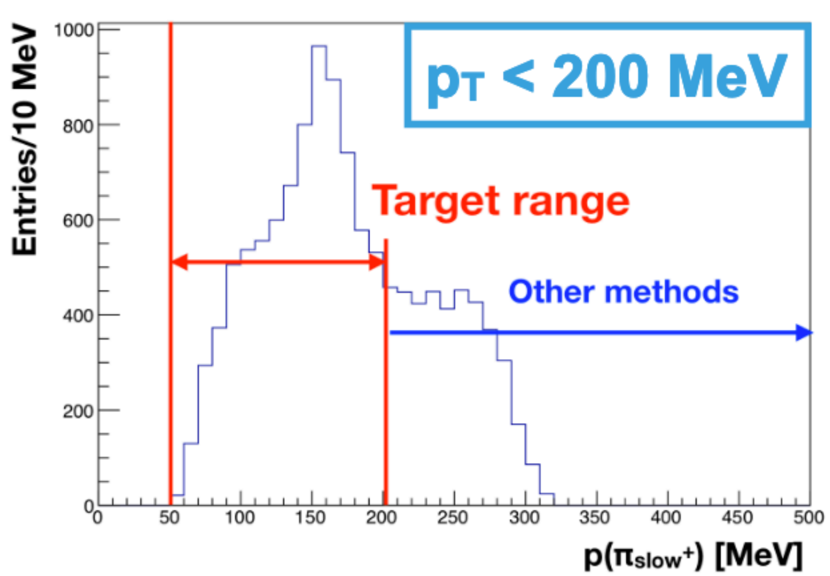


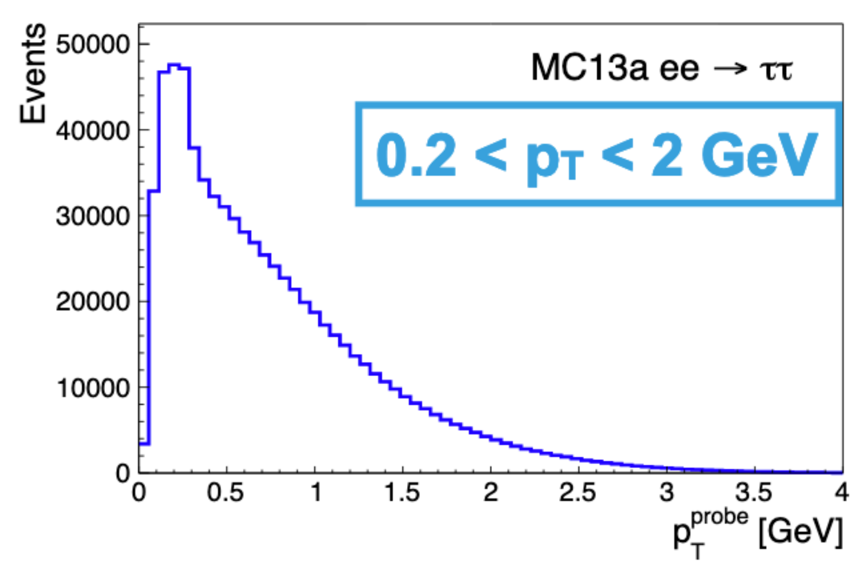
$e^+e^- \rightarrow \tau^+\tau^-$

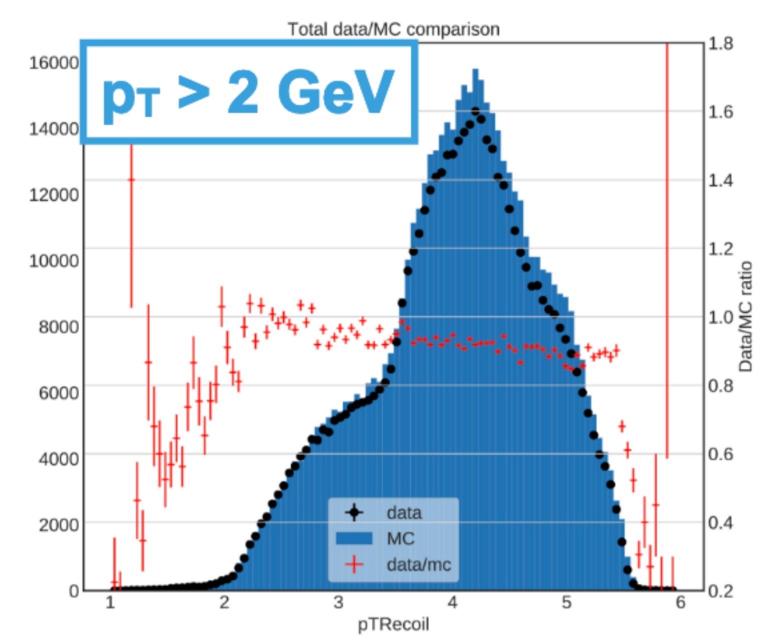


$e^+e^- \rightarrow e^+e^-\gamma$









Tracking Efficiency Studies

Example: Tau-Pair Study

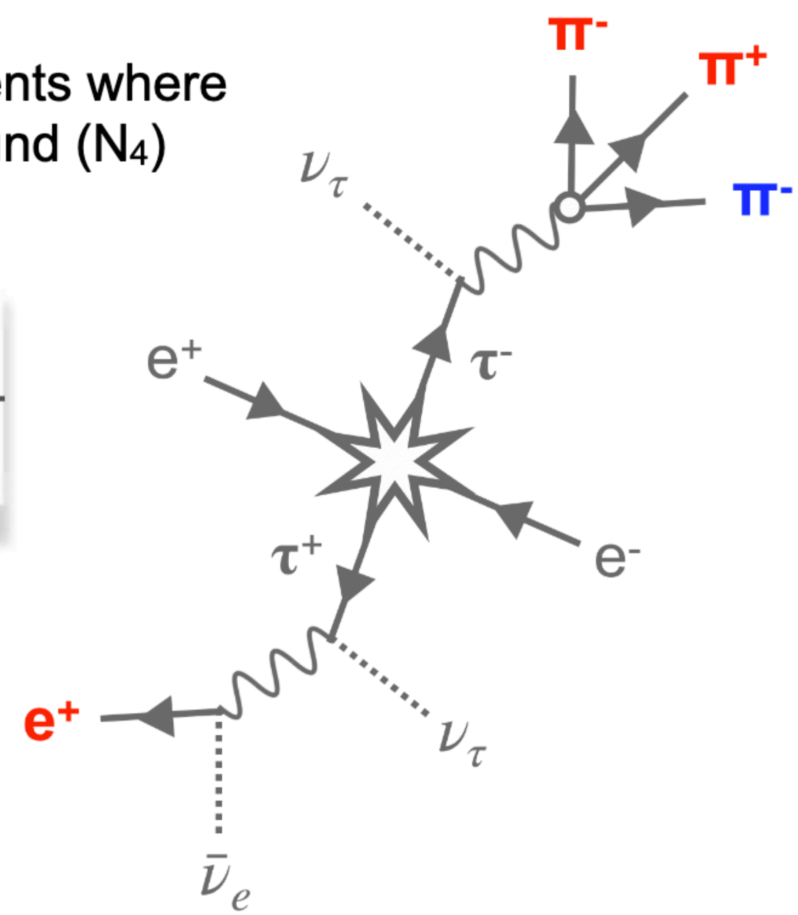
Method

- **tag** = 3 good quality tracks with $\sum q = \pm 1$
- **probe** = look for 4th track that passes loose selections, and conserves charge ($\sum q = 0$)
- Count number of events where the probe track is found (N_4) and not found (N_3):

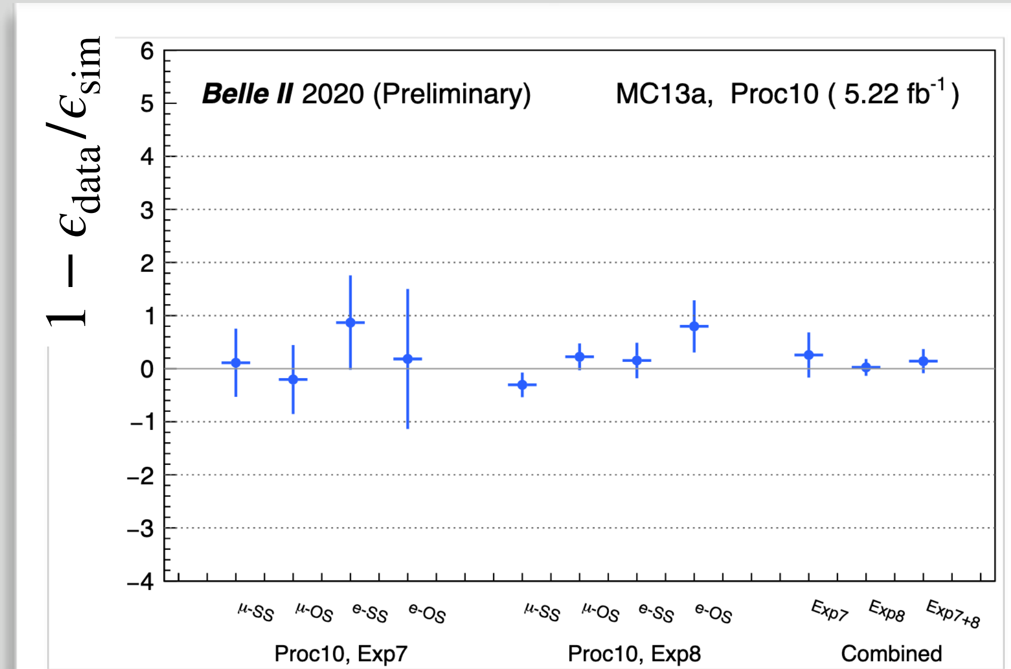
$$\epsilon \cdot A = \frac{N_4}{N_3 + N_4}$$

where:

- $\in$ is tracking efficiency
- A is geometric acceptance



Study shows high level of agreement between data and simulation

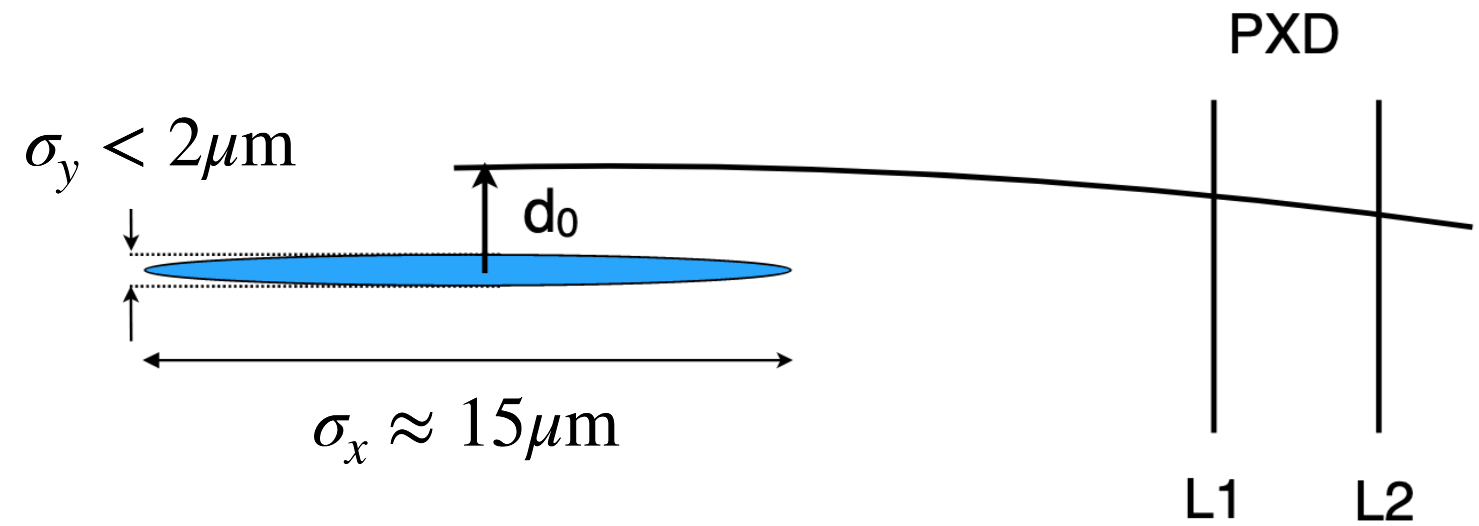


Beam Spot Width and Alignment

Monitoring and Performance

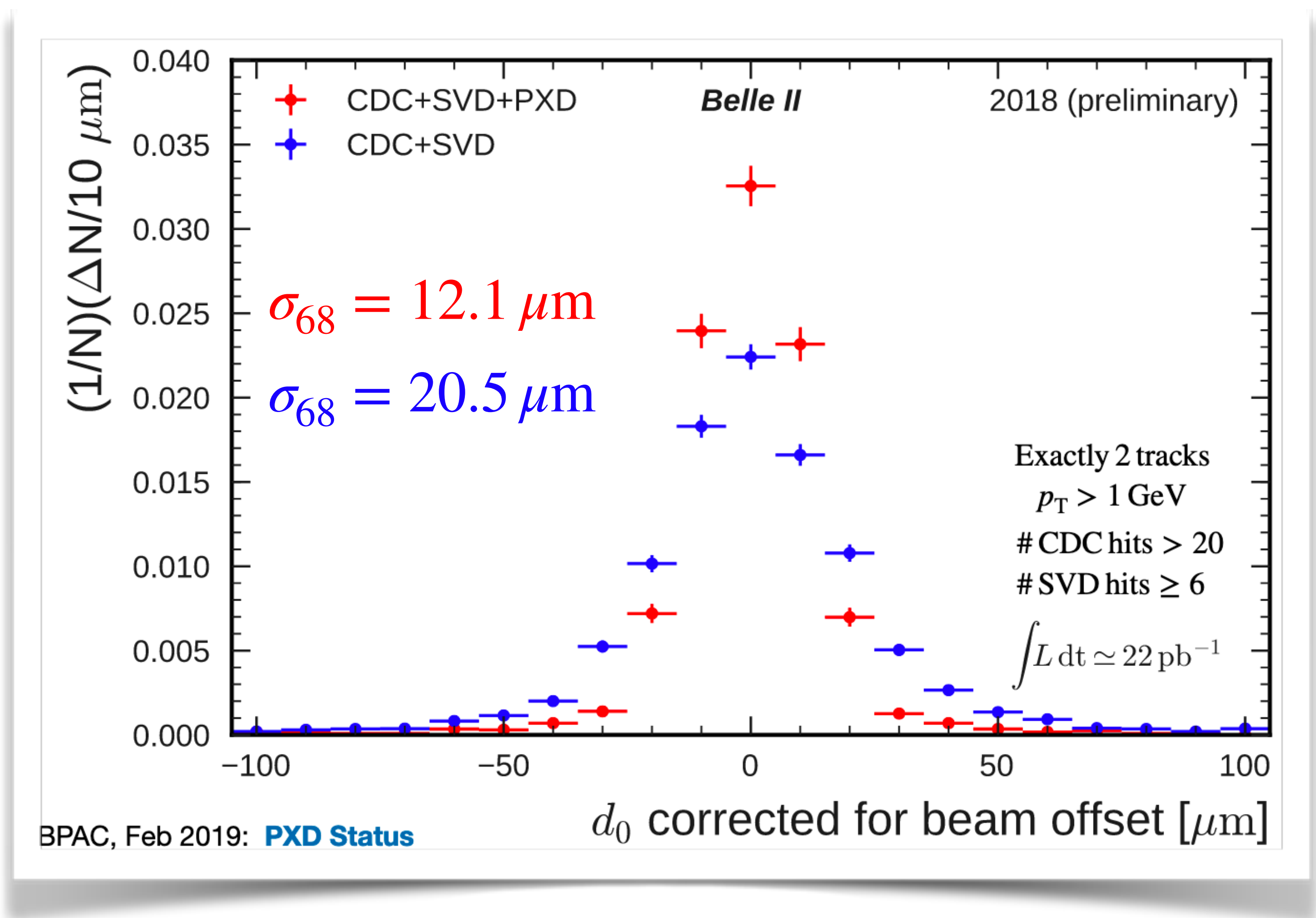
Beam profile strongly squeezed in vertical direction

- Vertical beam spot size much smaller than d0 resolution
- Length of the beam $\sigma_z \approx 350\,\mu\mathrm{m}$



As expected, PXD significantly increases impact parameter resolution

- $\sigma(d_0) \approx 12\,\mu\mathrm{m}$ [10μm expected]



Good alignment is key ingredient to a high tracking performance

- Tracker alignment done with the ***Millipede-II*** framework

MPII

Beam Spot Width and Alignment

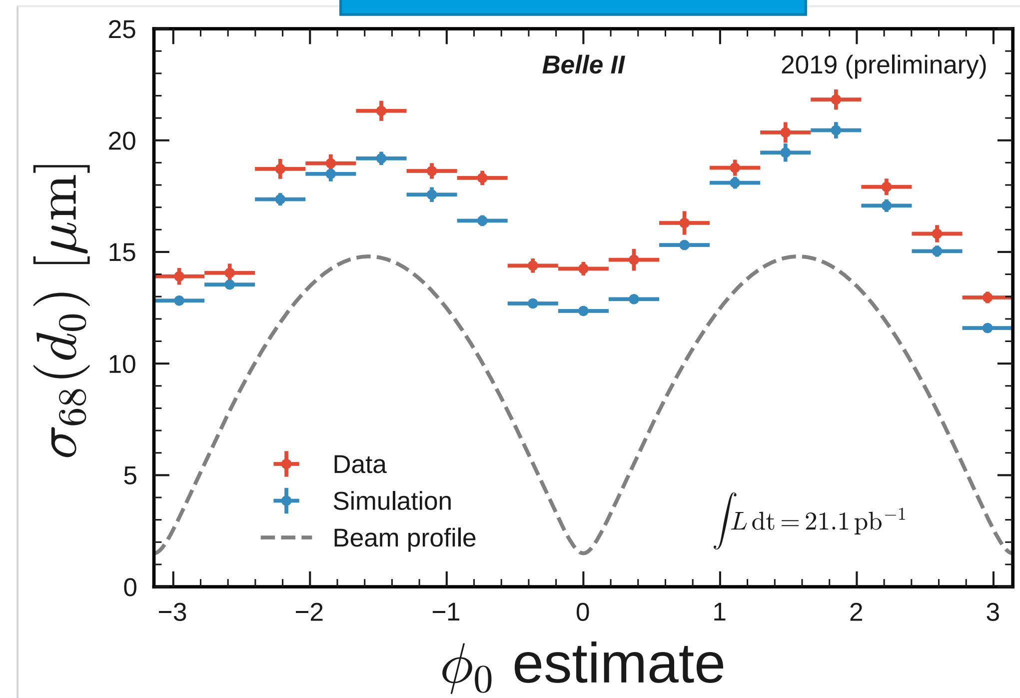
Monitoring and Performance

Measurement of d_0 distribution provides direct feedback to simulation

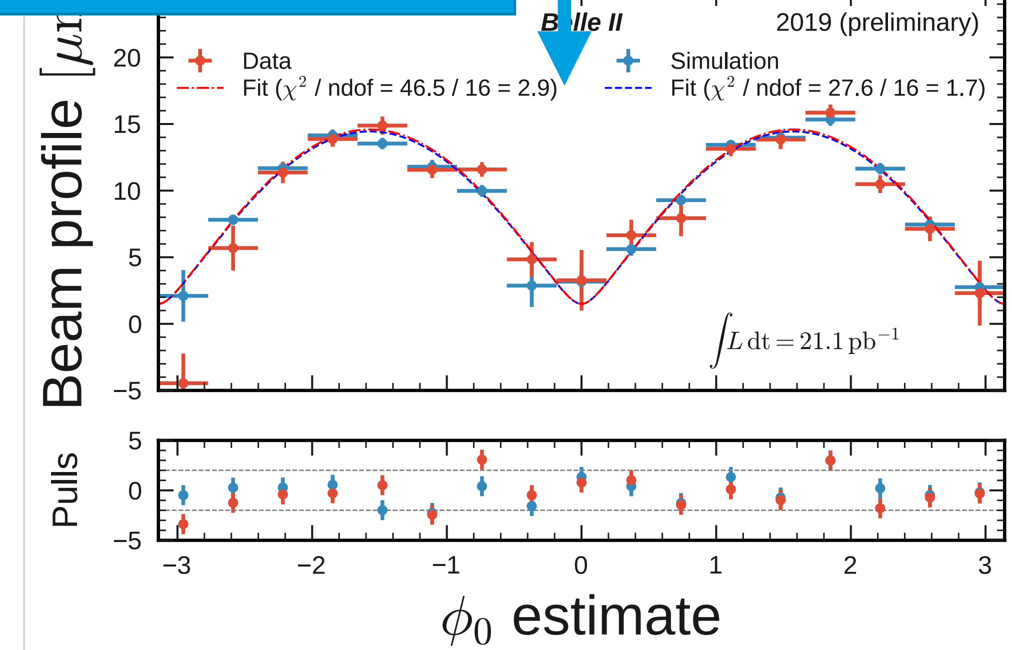
- Beam profile depends on ϕ_0 ($\sigma_y < \sigma_x$)
- Simulation slightly underestimates d_0 distribution
- Unfolding shows good simulation of beam profile

➡Excellent performance of tracking and alignment

d_0 distribution



Unfold using measured d_0 resolution (prev. slide)



Beam profile

Measurement of D^0 Lifetime

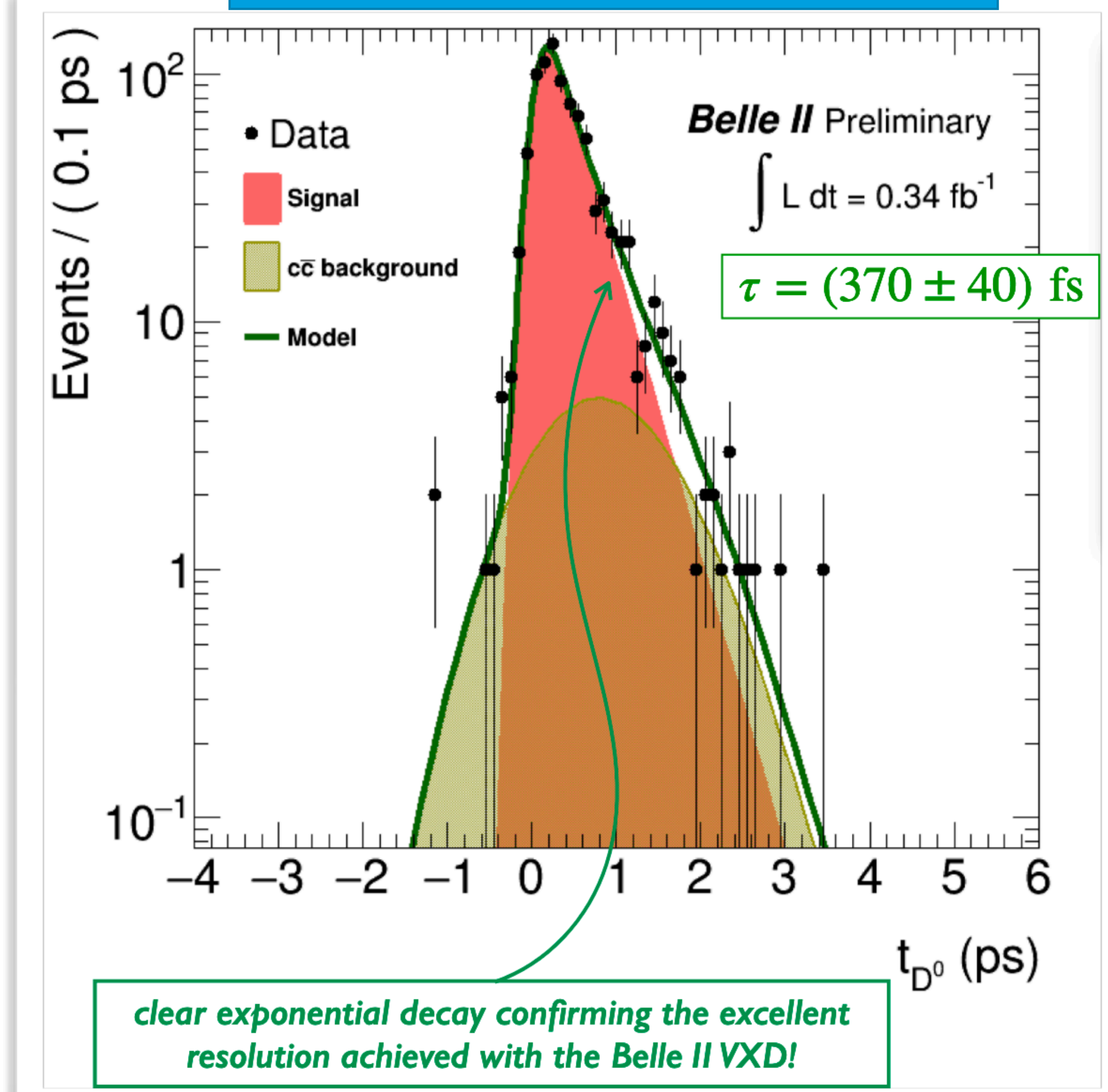
A Track-based Analysis

Excellent exercise to test vertexing and alignment (apart from physics aspect)

- Select a very pure sample of $D^{*+} \to D^0\pi^+$candidates, with the D^0 reconstructed in three different final states
- Largest systematic uncertainties expected from residual misalignment and beam spot measurements
  $\to$ **under control**

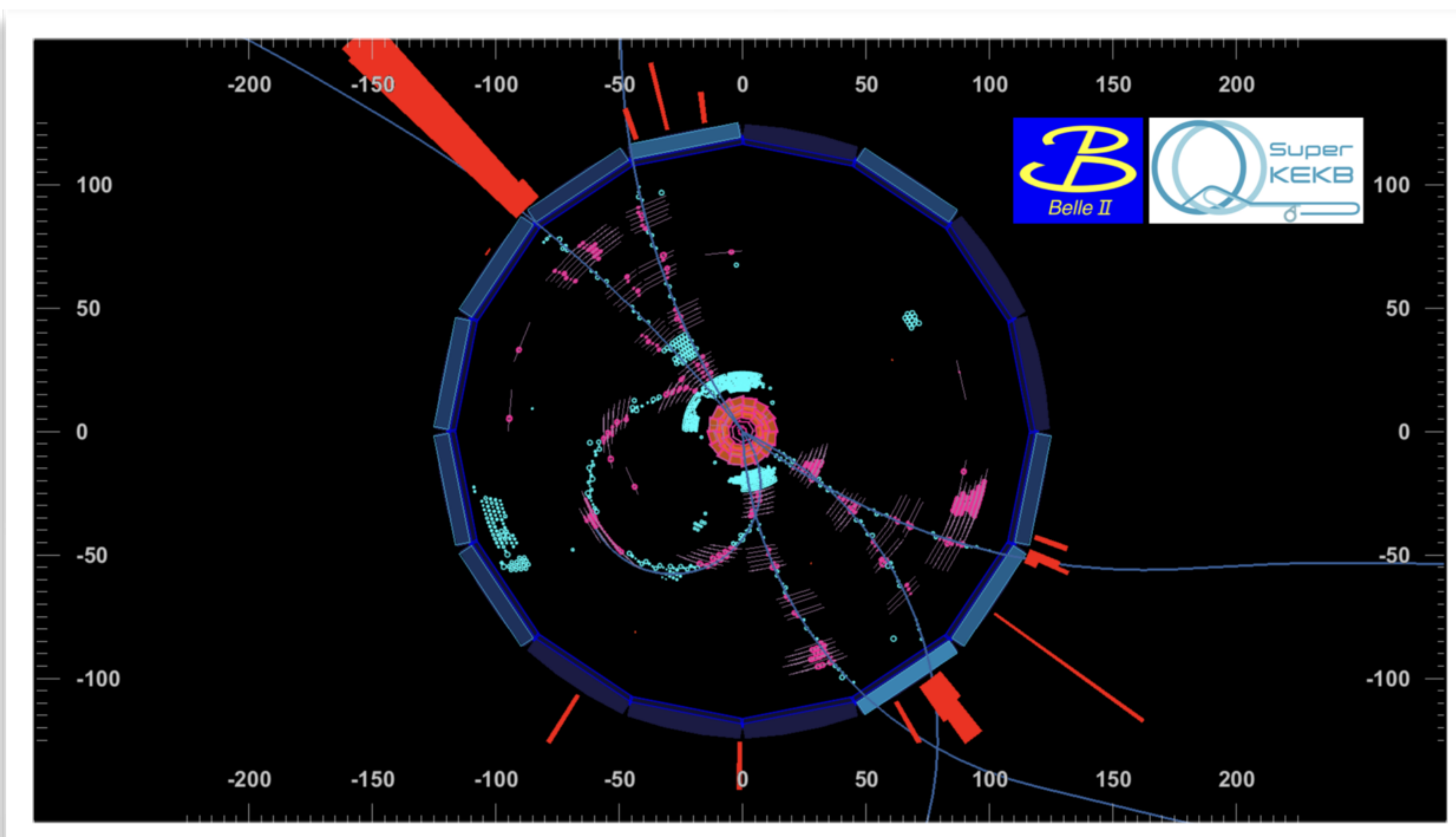
First (preliminary) results compatible with expectations, illustrating good performance of tracking detectors and algorithms

D_0 lifetime (from $D^0 \to K^-\pi^+$)



Summary

- **Excellent performance** of Belle II tracking detectors and algorithms
- **High flexibility of modular approach** proves to be advantageous to adjust tracking to background conditions and performance requirements, as well as future extensions of algorithms
- **Many studies** going on trying to exploit **MVA-based approaches** for all kinds of use cases (background rejection, track quality, etc.)
- **Promising results** of first tracking-focused studies and analyses



Backup

Further Developments

Track Quality Indicators and CDC Local Track Finder

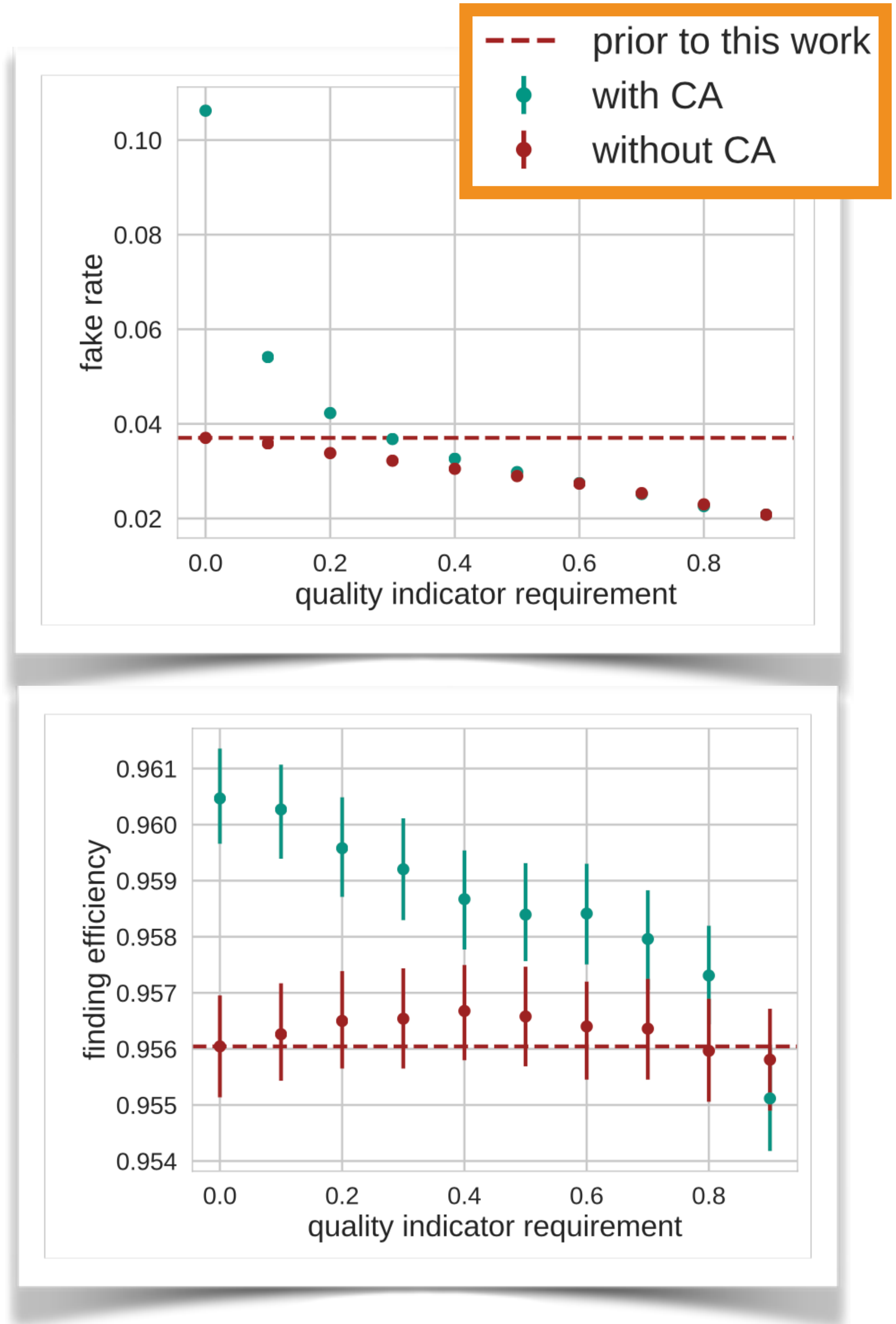
Use MVA-based methods to reduce fake and duplicated tracks

- 3 track quality indicators are being developed, which are applied at different stages of the track finding

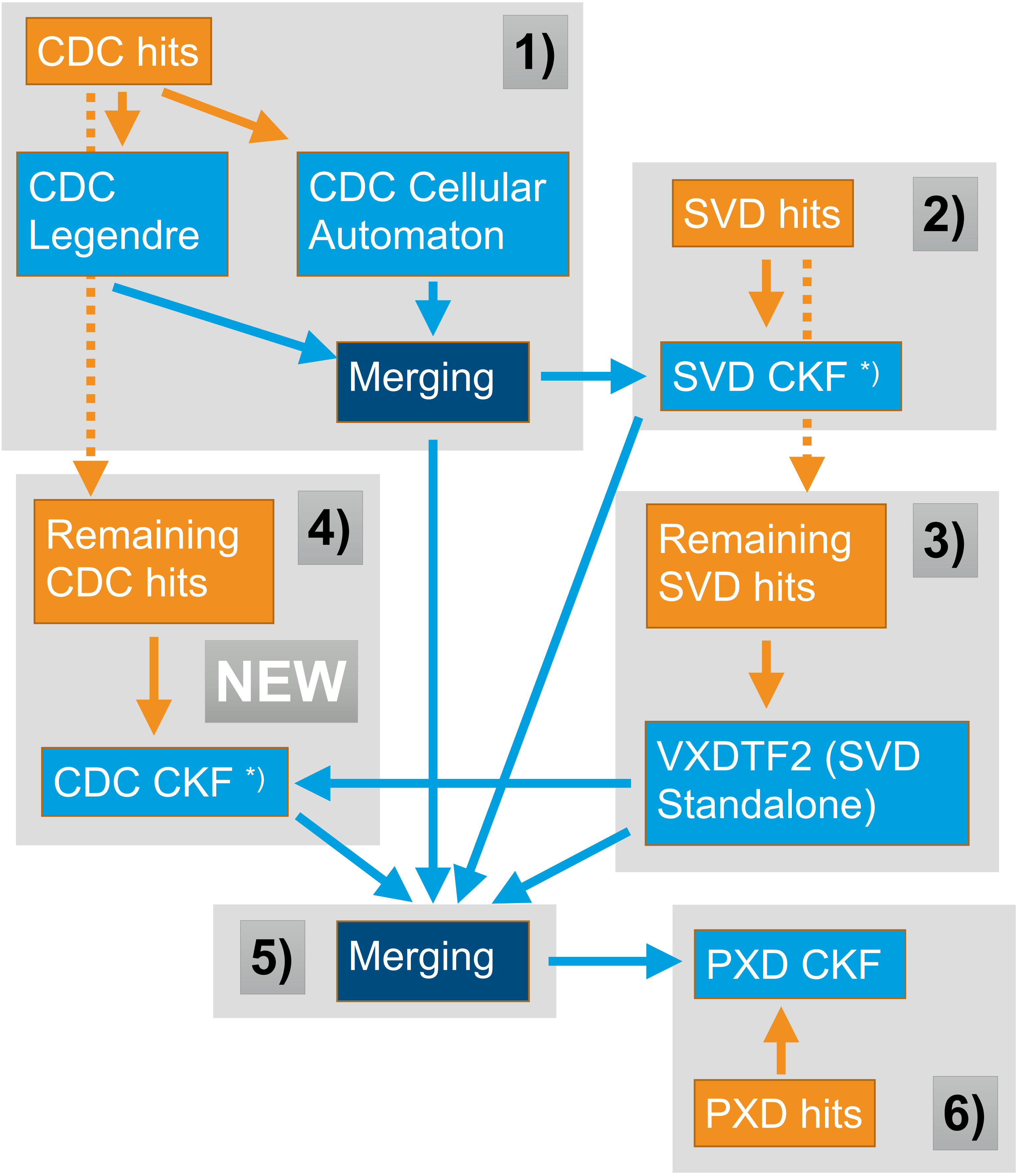
As previously mentioned, local CDC TF not used as standalone algorithm due to high fake rate

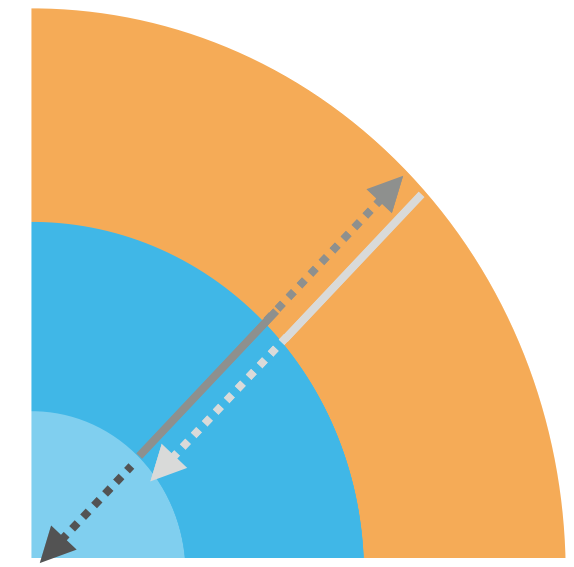
- Interested in adding this algorithm as currently no tracks with vertices within the CDC can be found
- MVA based track quality indicators can be trained to reduce fake rate

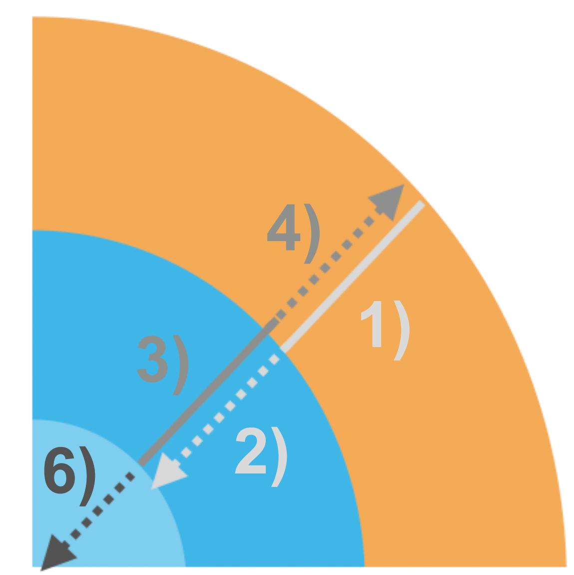
➡ Still in development, more work has to be done



Stuff


CDC hits
1)
CDC Legendre
CDC Cellular Automaton
Merging
SVD hits
2)
SVD CKF *)
Remaining CDC hits
4)
NEW
CDC CKF *)
Remaining SVD hits
3)
VXDTF2 (SVD Standalone)
5)
Merging
PXD CKF
PXD hits
6)




4)
1)
3)
2)
6)