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Tracking Performance In The Belle II Experiment

GdR-InF Annual Workshop – 08/10/2020

OUTLINE

1. Belle II experiment and its tracking system
2. Tracking algorithm improvement
3. Fake tracks rate in data using τ events
4. Upgrade of the vertex detector

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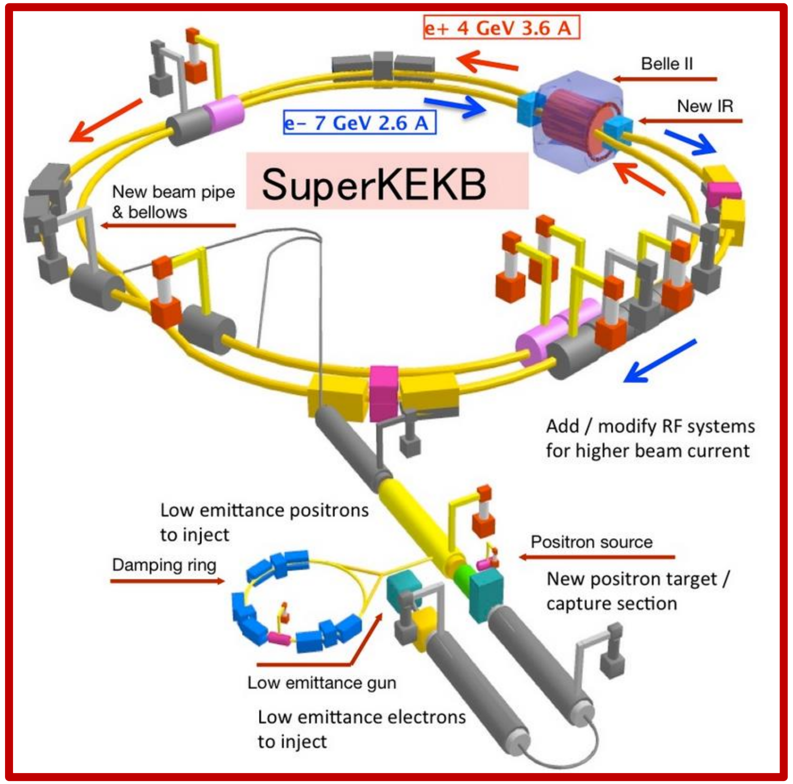
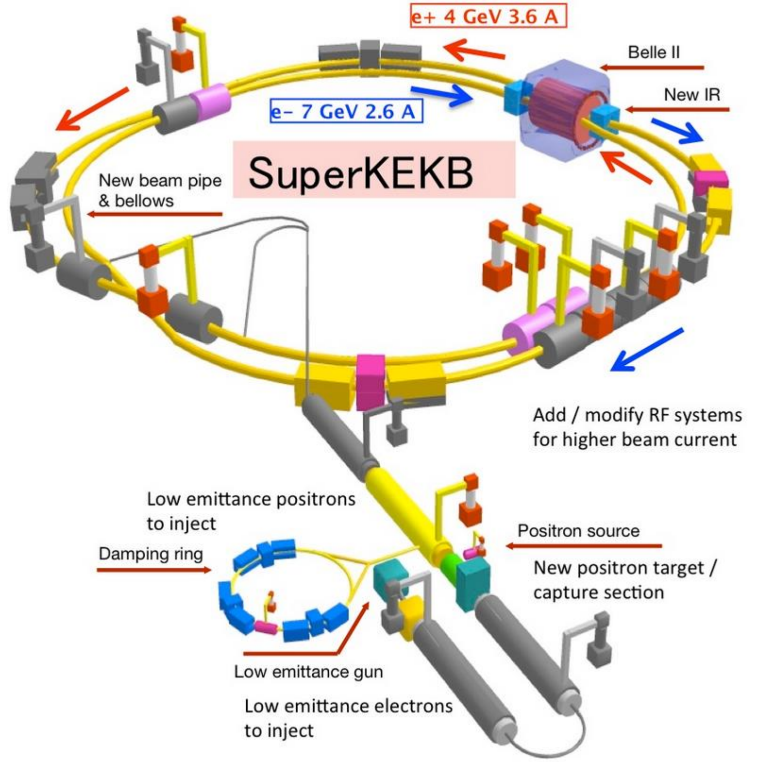
SuperKEKB accelerator



Electron (7 GeV) - **Positron** (4 GeV) collider.
Location: KEK (Tsukuba, Japan).
Successor of KEKB (Belle experiment).

SuperKEKB accelerator



Electron (7 GeV) - **Positron** (4 GeV) collider.

$$e^+e^- \rightarrow \Upsilon(4S)[10.58\ \text{GeV}] \rightarrow \boldsymbol{B\bar{B}}\ (\boldsymbol{\sigma = 1.1\ \text{nb}})$$

$$e^+e^- \rightarrow \boldsymbol{\tau^+\tau^-}\ (\boldsymbol{\sigma = 0.9\ \text{nb}})$$

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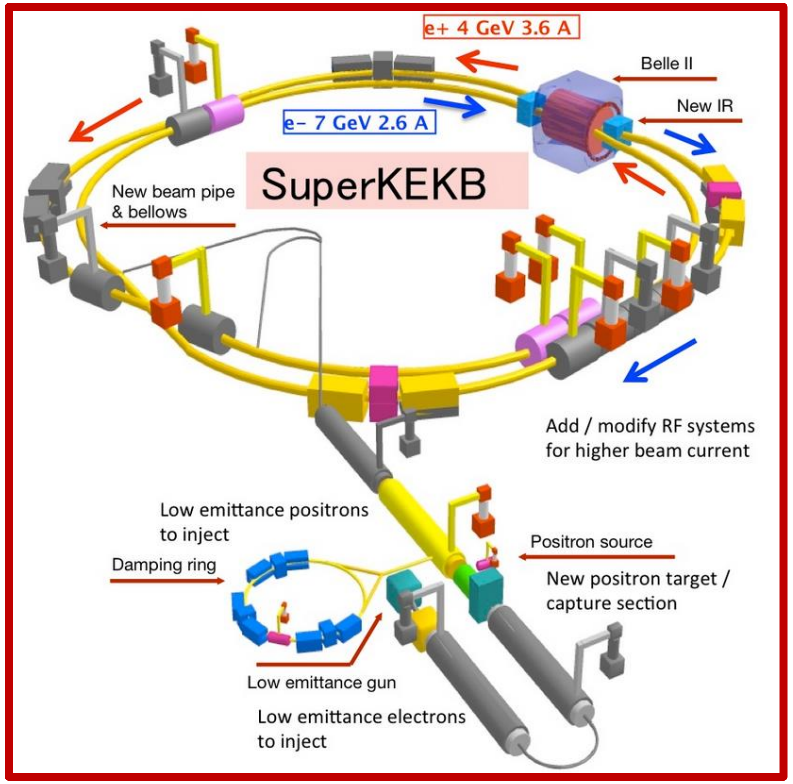

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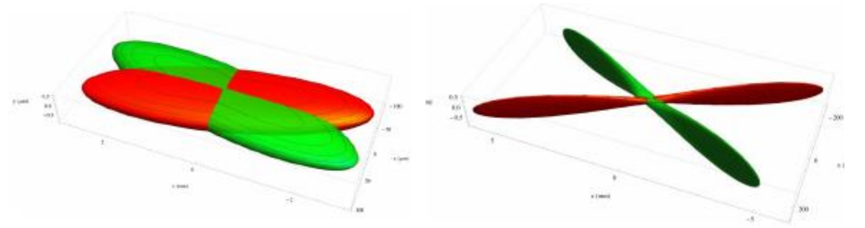
Current ↗
Beam size ↘
} **30x** KEKB peak luminosity

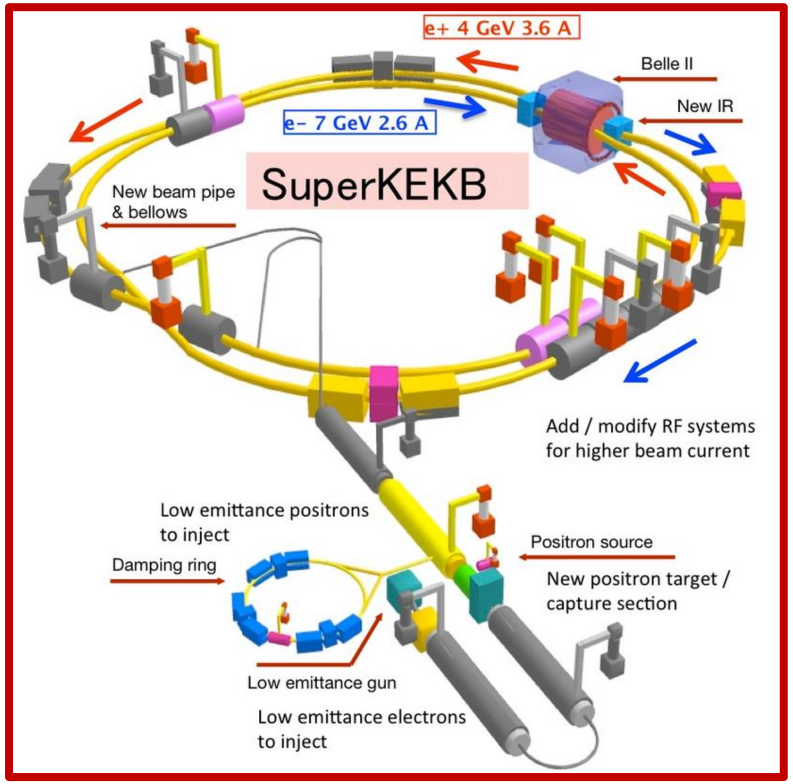


KEKB Interaction region beam overlap

SuperKEKB Interaction region beam overlap

SuperKEKB accelerator

Belle II



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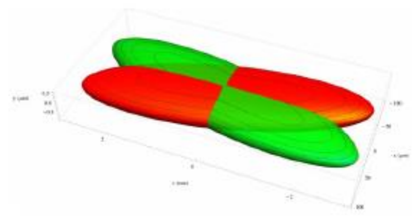
Current ↗ / Beam size ↘ } **30x** KEKB peak luminosity

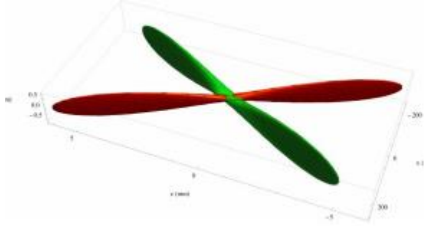
Peak luminosity: **$6{\cdot}10^{35}$ cm^{-2} s^{-1}**

Today: ~ 74 fb^{-1} of data collected | Goal: **50 ab^{-1}**

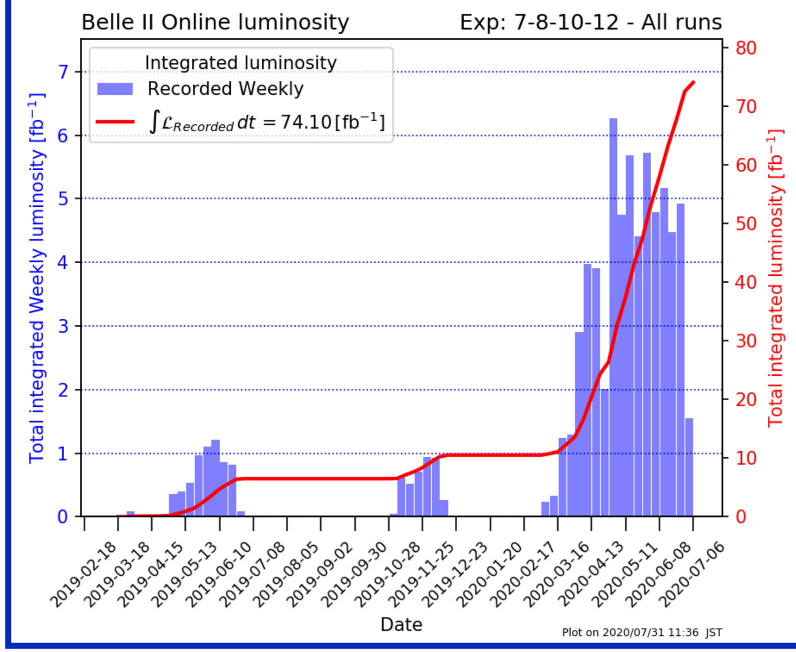
Upgrade of focusing magnets in 2026 (luminosity increase of factor 5).

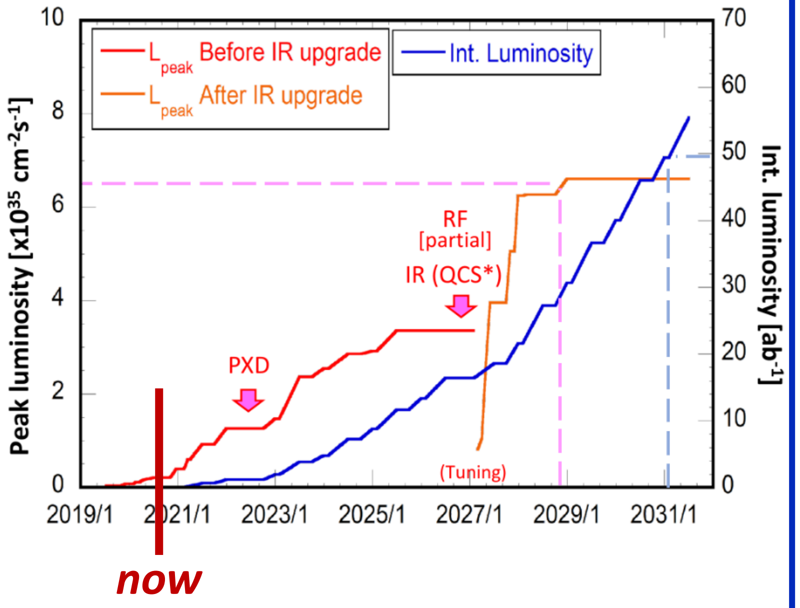


KEKB Interaction region beam overlap



SuperKEKB Interaction region beam overlap



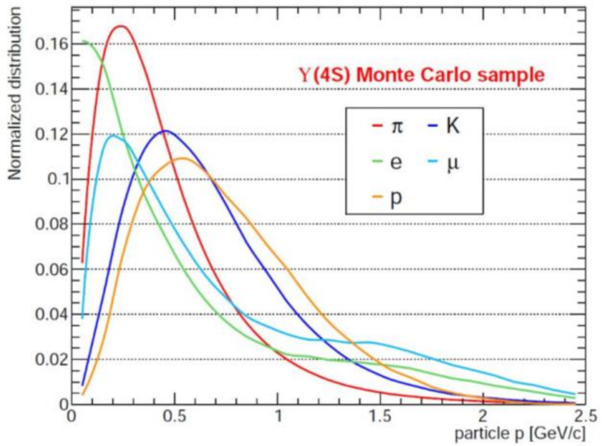


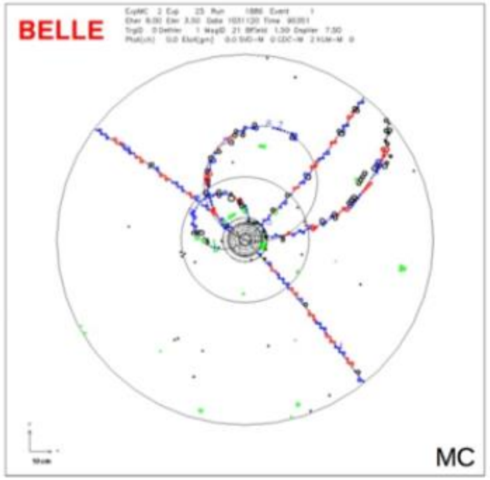
Challenges of tracking at Belle II

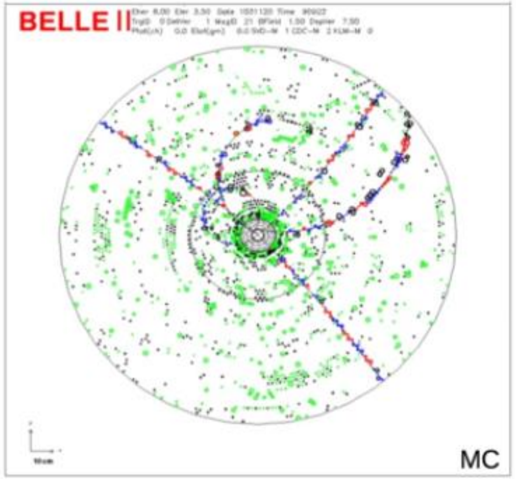
- Average track multiplicity for Υ(4S) is about **11 tracks**.
- Most of the particles that are visible in the detector have **similar momentum ranges and distributions**.
- Many tracks are at **low momentum**.
  → multiple scattering, curling tracks.

Particle types visible in Tracking Detectors of typical Υ(4S) event

Particle type	Average fraction
$\pi^{\pm}$	72.8%
$K^{\pm}$	14.9%
$e^{\pm}$	5.8%
$\mu^{\pm}$	4.7%
$p^{\pm}$	1.8%

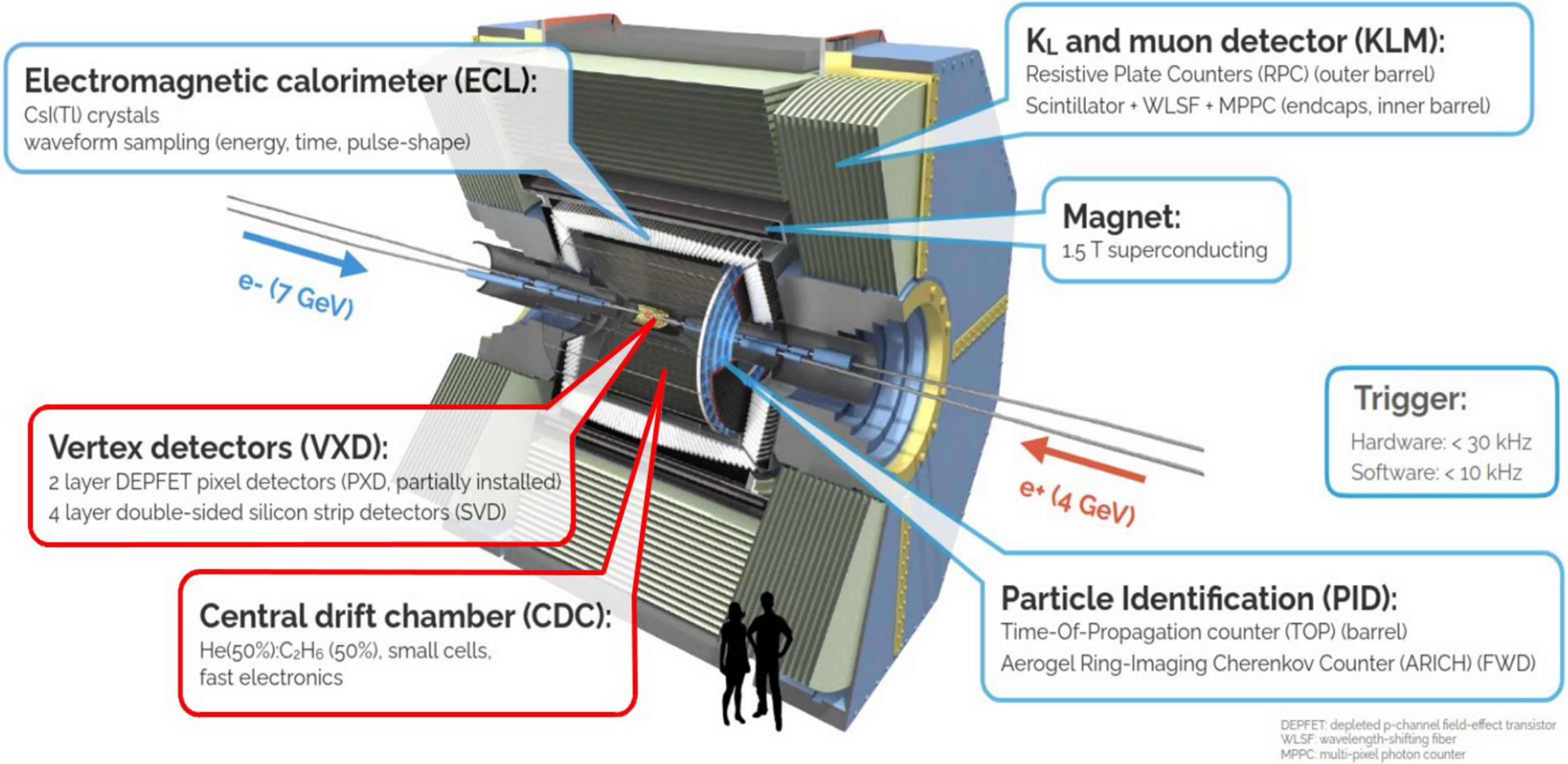






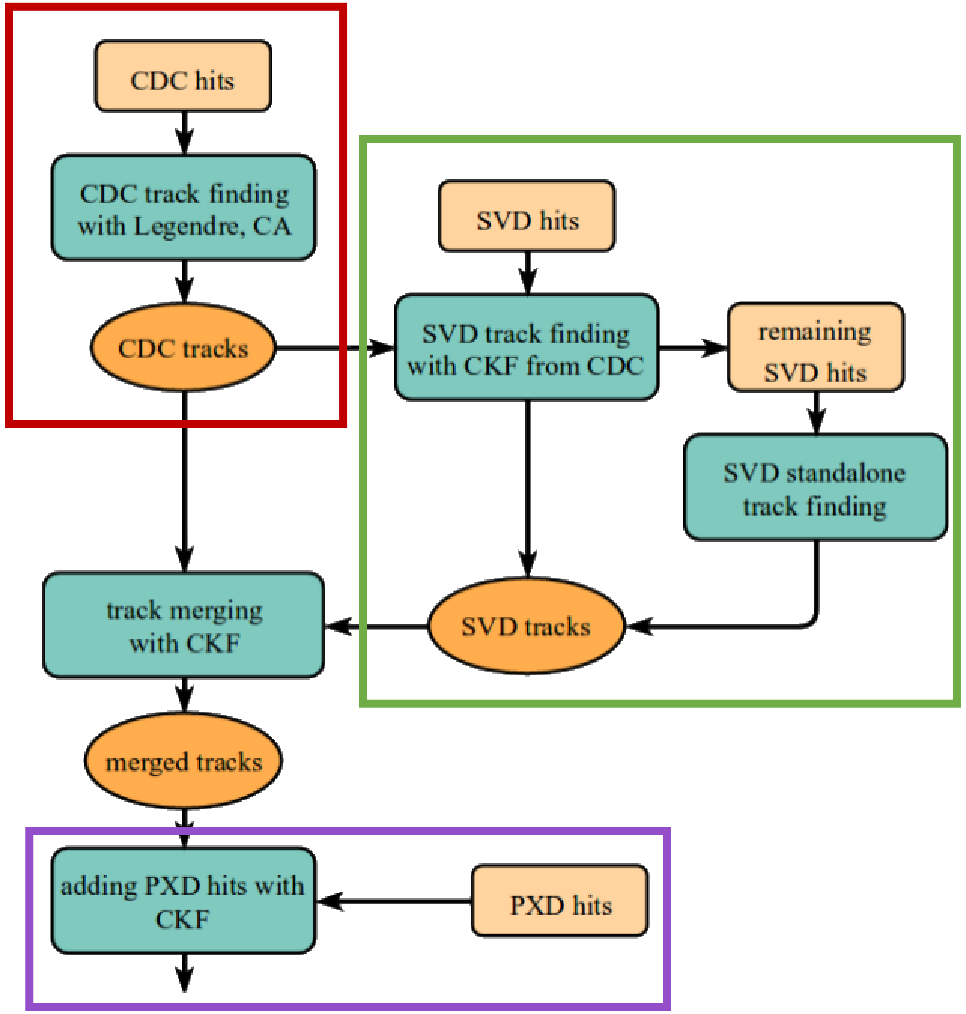
- Sizeable **beam-induced background**.
- **High occupancy** of background: 11 tracks = 10^2 signal hits vs 10^4 beam background hits.
- **Random hit** combinations, **clone** tracks.

Belle II detector

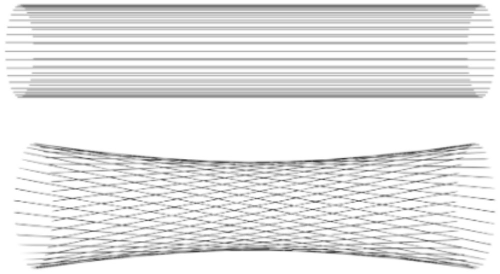


Tracking system of Belle II

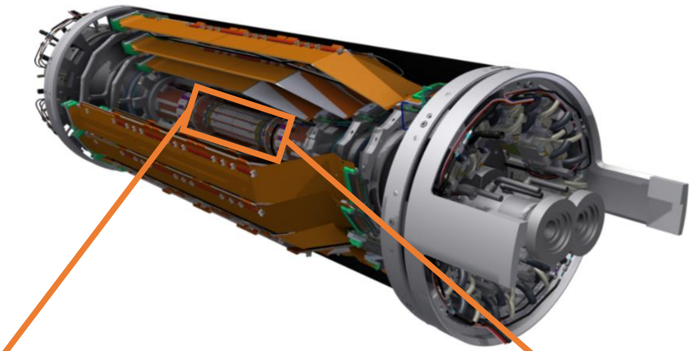
The tracking is performed combining the informations collected by the CDC, VXD (SVD and PXD) with different algorithms.



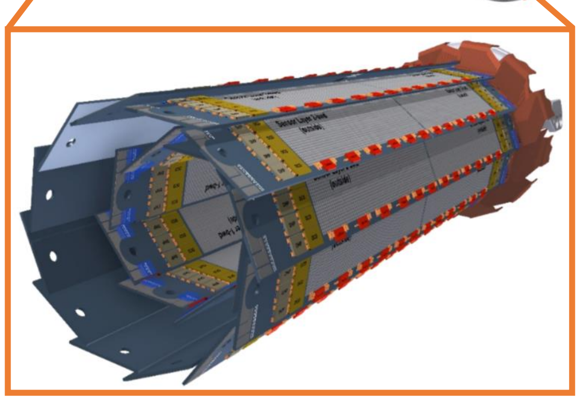
CDC (Central Drift Chamber)
~ 14k sense wires arranged in 56 axial or stereo layers.



SVD (Silicon Vertex Detector)
4 layers of double-sided silicon strip sensors.



PXD (Pixel Detector)
2 layers of DEPFET pixel sensors.



Outline

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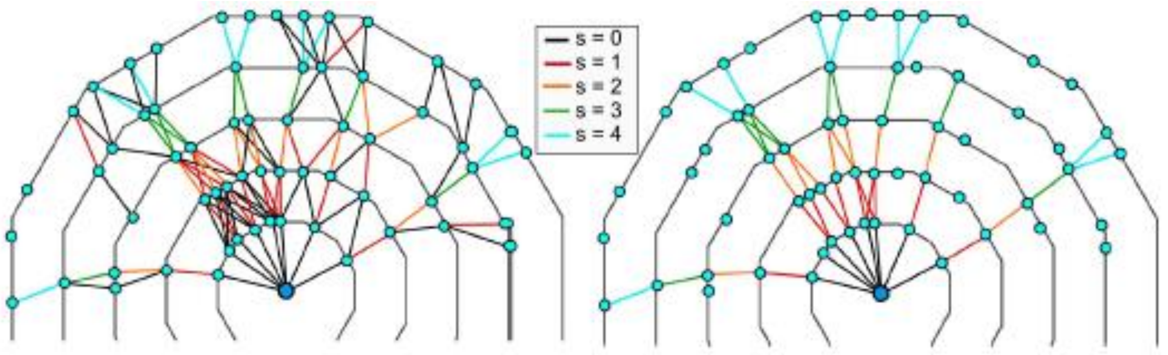
2. Tracking algorithm improvement
3. Fake tracks rate in data using τ events
4. Upgrade of the vertex detector

More info: Track finding paper
https://arxiv.org/abs/2003.12466

Concept of sector map

Belle II

- Cellular automaton: builds segment of at least 2 hits to combine them.
  → Huge combinatorics.



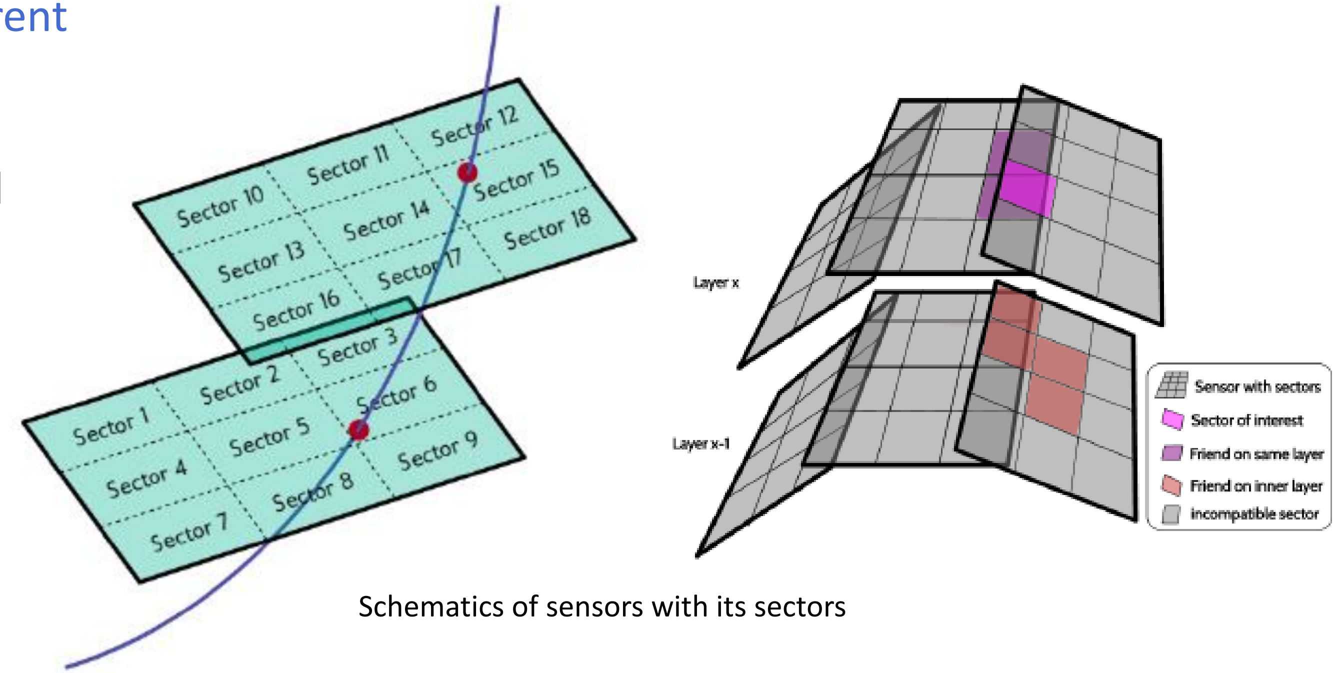
Schematics of the cellular automaton

Sector map

- Object containing information about how space points in different regions of the detector can be related by different tracks.

- Sensors virtually subdivided into smaller sections, called sectors (standard division: 3x3)
  → Reduce combinatorics.

- **Sector maps holds**:
  - “friendship relations” between sectors that usually are crossed by the same tracks,
  - ”filters” combining different space points information, mostly geometrical quantities.



Schematics of sensors with its sectors

More info: Track finding paper
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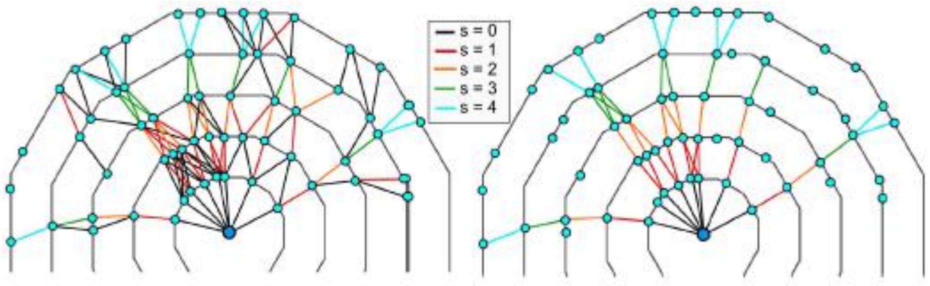
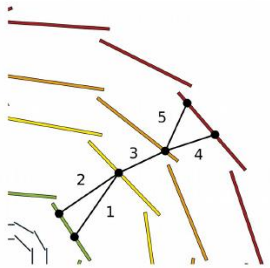
Training of the sector map

Belle II

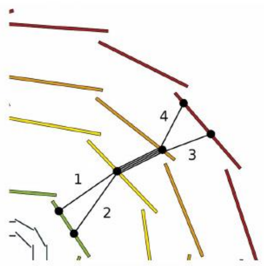
- **Steps to train a sector map**:
  - Take all the space points and find all friendship relations.
    - Needs a large training sample.
    - 10 Mio [Y(4S) + 2 muons uniformly distributed].
  - Use those relations to make 2-(3-)hits combinations.
    - Can count how many times a relation has been used.
  - Use cellular automaton + filters + quality estimations to make the final track.



Schematics of the cellular automaton



2-hits combinations



3-hits combinations

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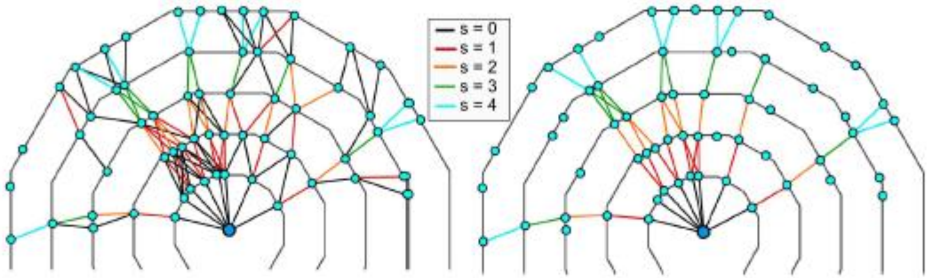

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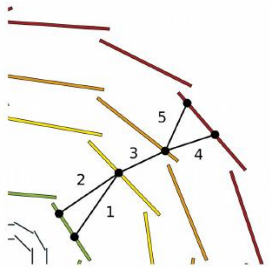
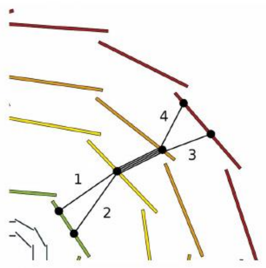
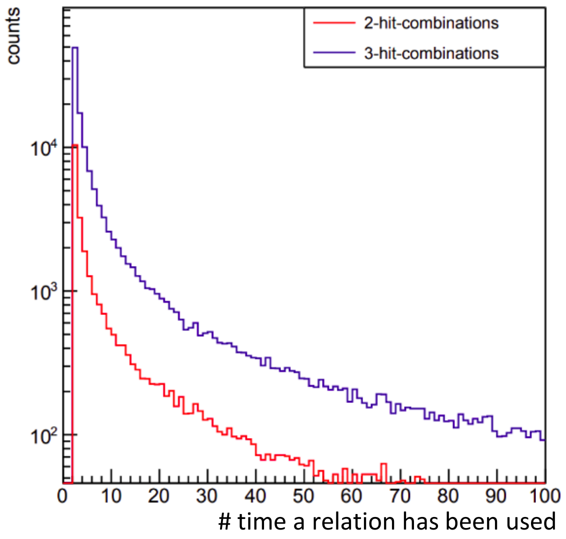
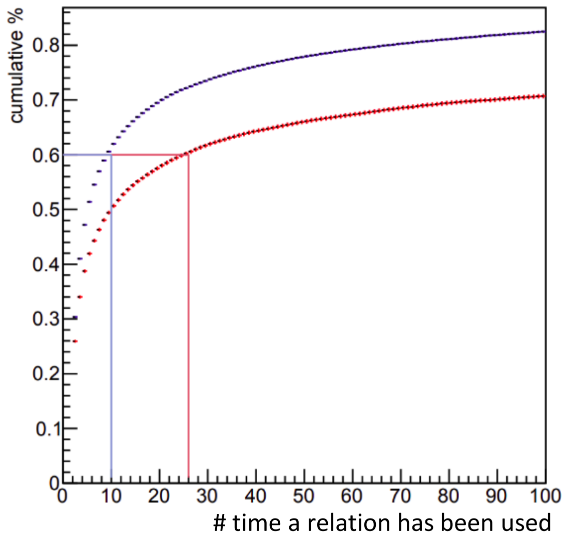


2-hits combinations



3-hits combinations





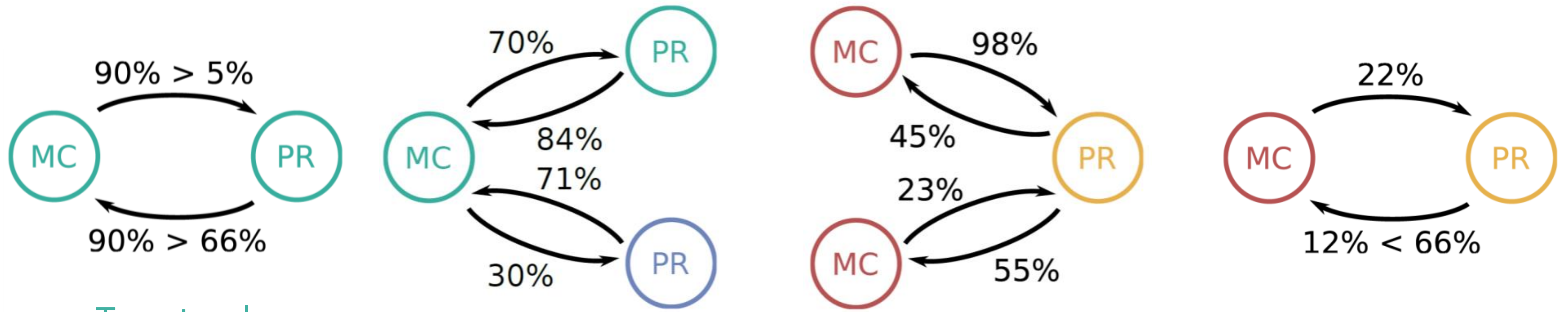
→ ~60% of the relation used less than 10 times

- **My work**: change the segmentation of the sector maps and prune (remove) the least used relations.

Segmentation tested: 3x3, 4x4, 5x5, 6x6, 6x4
Pruning tested: 0%, 40%, 50%, 60%, 70%, 80%, 90%

Validation figures

- The reconstructed tracks from pattern recognition (PR) are tagged following the number of hits they share with Monte Carlo tracks (MC)



True track

True track
Clone track

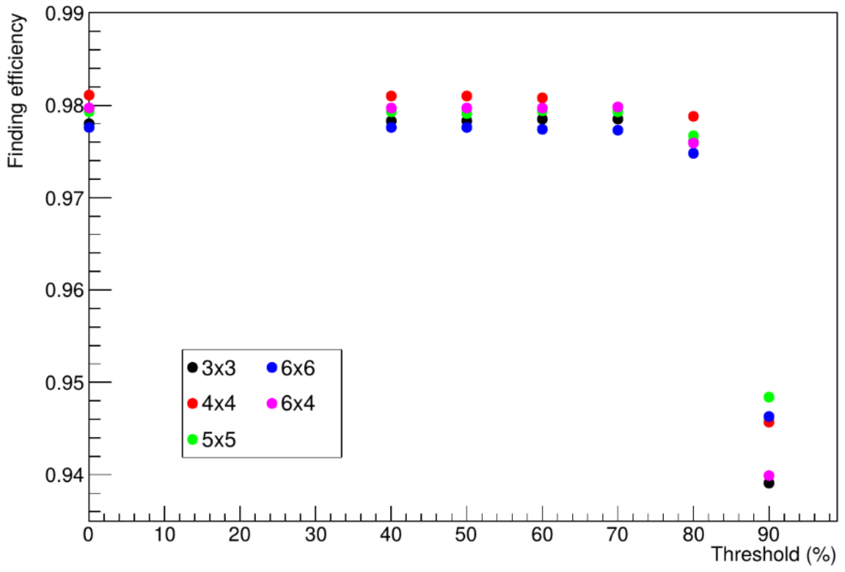
Fake track

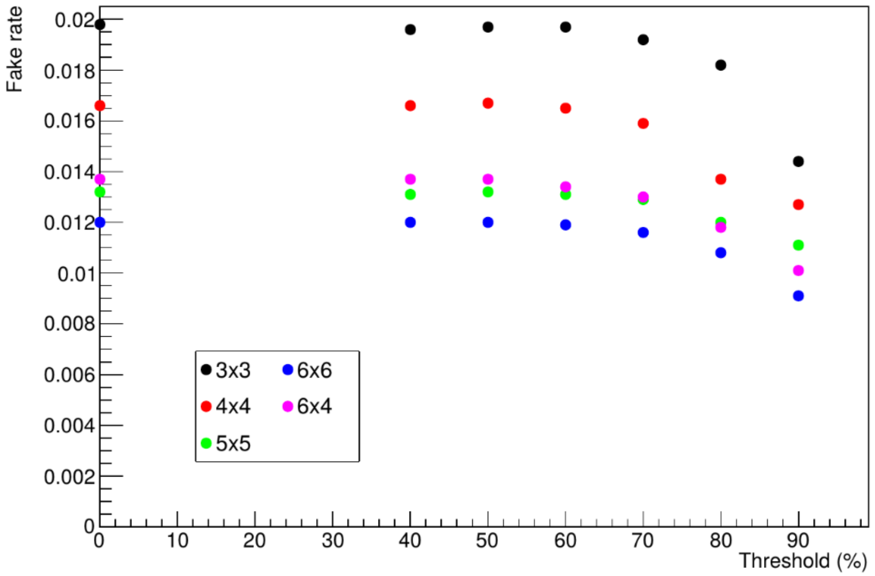
Fake track

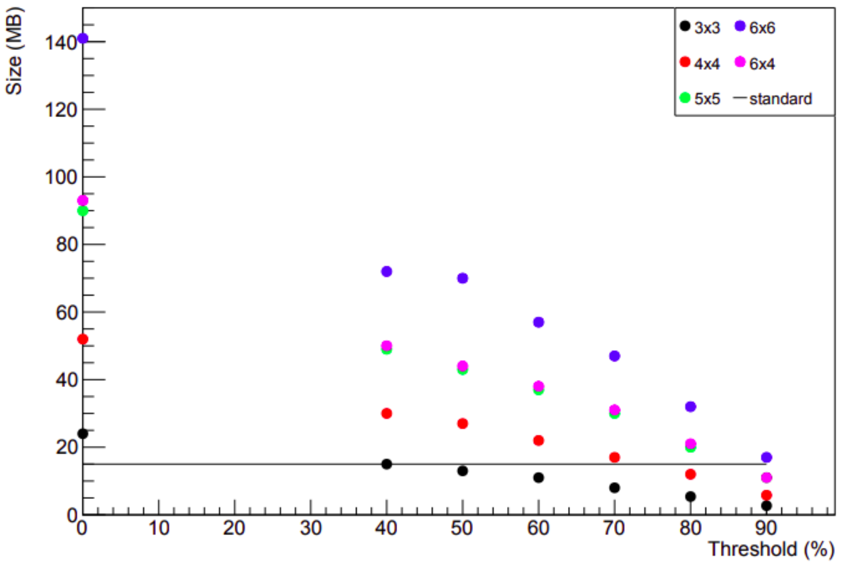
Definitions:

- Finding efficiency: $\frac{\text{number of true tracks}}{\text{number of generated particles}}$
- Clone rate: $\frac{\text{number of clone tracks}}{\text{number of true tracks}}$
- Fake rate: $\frac{\text{number of fake tracks}}{\text{number of reconstructed tracks}}$

Validation plots







- No change in finding efficiencies with the pruning and thinner segmentation.
- ~50% decrease of the fake and clone rates with thinner division.
- Constant before 70% threshold.
- Size decreases linearly: size/3 without loss in efficiencies.

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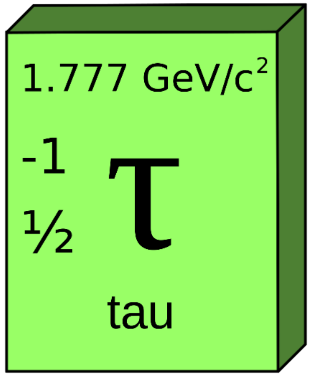
Motivation



- <u>In the previous part</u>: fake rate at *tracking* level. <u>Now</u>: *analysis* level.
- Belle II is powerful for performing analyses on final states with missing particles, like in τ events.
- τ events provide a clean environment (less tracks than $B\bar{B}$), enough to perform some tracking studies.
- The fake rate is an important quantity for evaluating systematic uncertainties in physics analyses.

<u>**Here, fake tracks include**</u>:

1. tracks originating from **wrong combinations of hits**,
2. **clones**: tracks generated by a low-momentum particle curling inside the detector, without being merged.

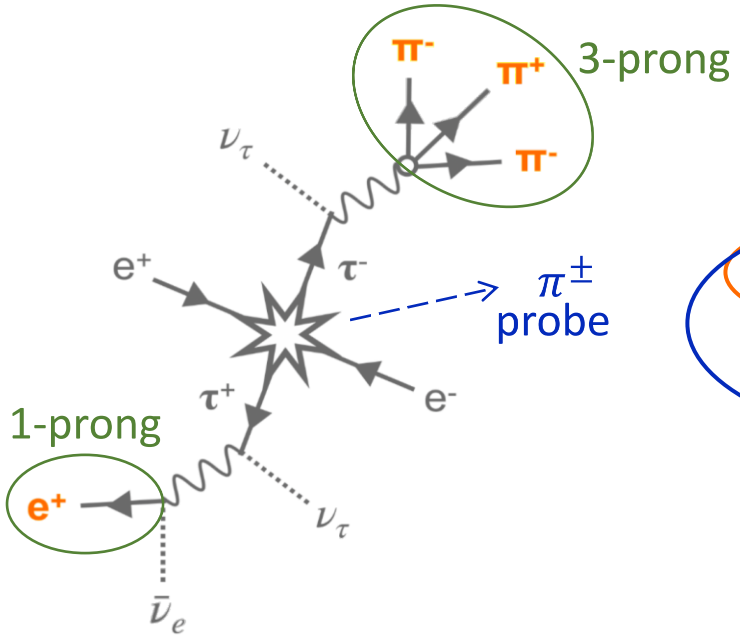
Method

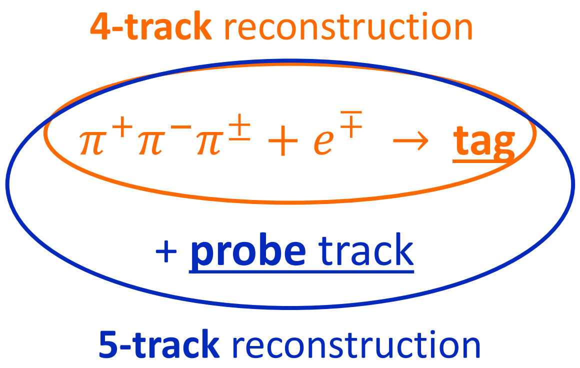
Belle II

- We work on: $e^+e^- \rightarrow [\tau^\pm \rightarrow \pi^+\pi^-\pi^\pm\nu] + [\tau^\mp \rightarrow e^\mp\nu\bar{\nu}]$

- Taus travel back-to-back in CM frame, along a **thrust axis:** pions are define as "*3-prong*" tracks and the lepton as "*1-prong*" track.

- **Tag-and-probe method** to measure the fake rate: reconstruct full event (at least 4 tracks) and search if there is an unexpected 5th track.





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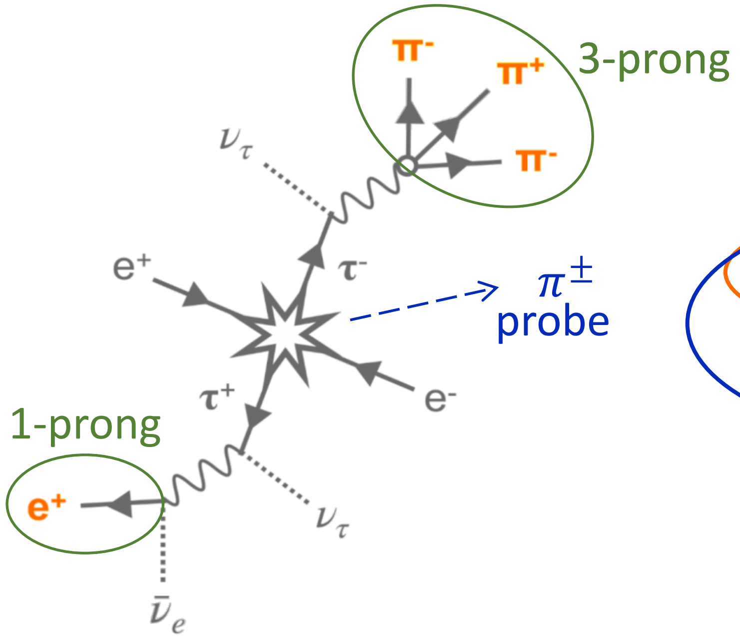
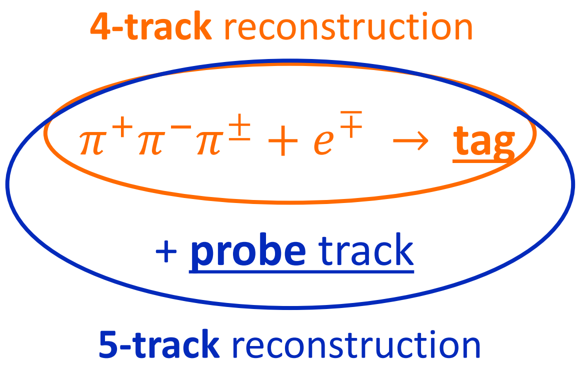




$$\textbf{Fake tracks rate} = \frac{N_5}{N_4+N_5}$$

$N_{4/5}$: nb. of events where 4/5 tracks are found.

Data samples

- Data collected in **2019**.
- Total integrated luminosity: $\mathbf{8.8\ fb^{-1}}$.

Monte-Carlo samples

- **Generic**: τ-pair, $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}$.
- **Low multiplicity** events.

includes expected background at nominal instantaneous luminosity + takes into account beam conditions

Reconstruction of the event

Belle II

- We gather all the tracks identified in the detector in **orthogonal track lists** (they don't share any track), one for each relevant final state particle.

- **For each MC or data sample**, we use these tracks to reconstruct the event:

  → once with **4 tracks**: $[\tau^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}] + [\tau^{\mp} \to e^{\mp}]$

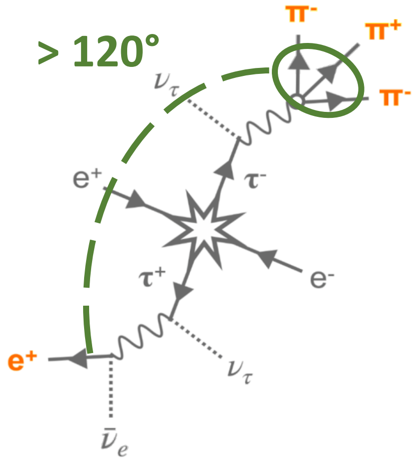
  → then with **5 tracks**: $[\tau^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}] + [\tau^{\mp} \to e^{\mp}] + \pi_{probe}$

- In addition to all the information stored in ROOT files, we add the **truth-matching** information (MC only) that allows us to define signal and background events.

Signal definition:

- Event must have a **3×1 topology:** one τ decays into 3 charged final state particles, the other into 1.
- All tag tracks must **originate from** a track truth-matched to a **τ**.

Background suppression

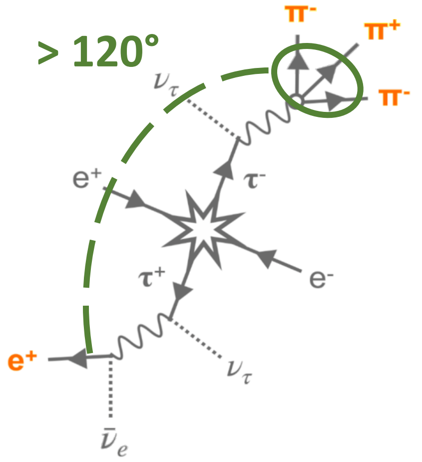


1. *Angular separation*: 3-prong and 1-prong tracks in opposite hemispheres w.r.t. the thrust axis, and minimum opening angle of 120° between each 3-prong track and the 1-prong.

2. *Reduction of low-momentum (radiative QED) and $q\bar{q}$ continuum*: narrowing the ranges of the 1-prong momentum in CM frame and of the three 2-pion masses $m_{\pi\pi}$.

3. *Suppression of remaining $q\bar{q}$ background*: a set of additional cuts (mass, transverse momentum, γ and π^0 multiplicity, electron and kaon ID), optimised w.r.t. a $\boldsymbol{S/\sqrt{B}}$ figure of merit.

Background suppression



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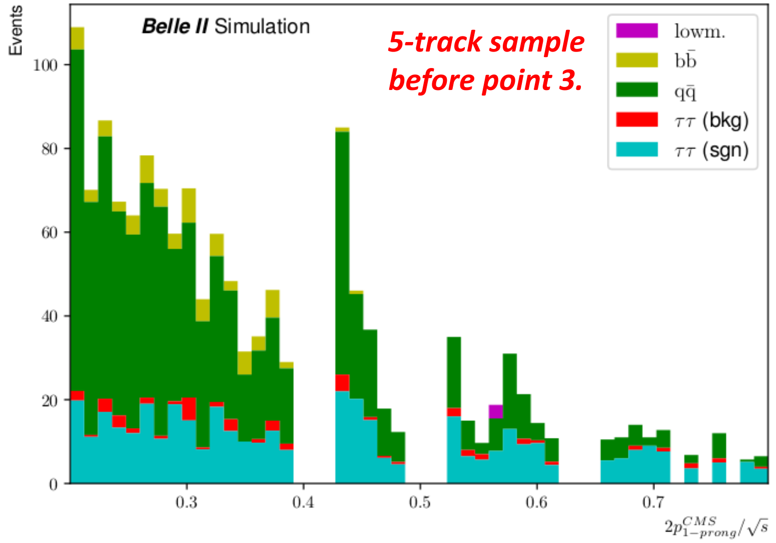
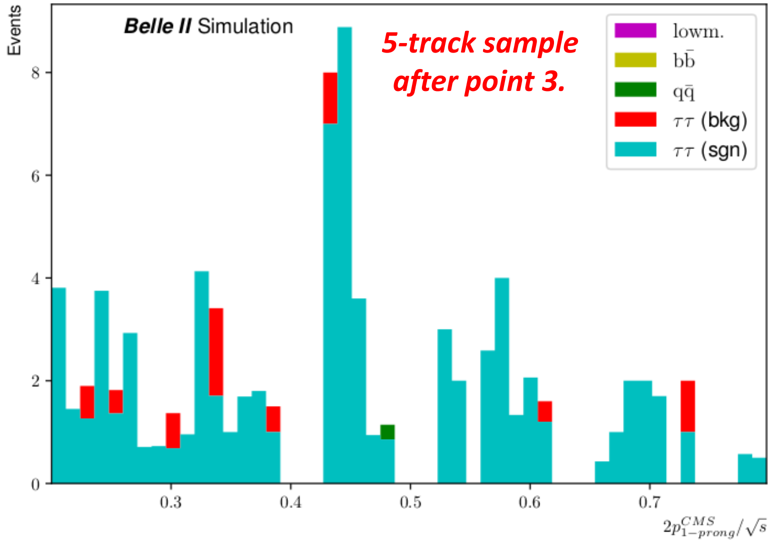
$2p_{1-prong}^{CMS}/\sqrt{s}$

($\sqrt{s}/2$: beam energy)

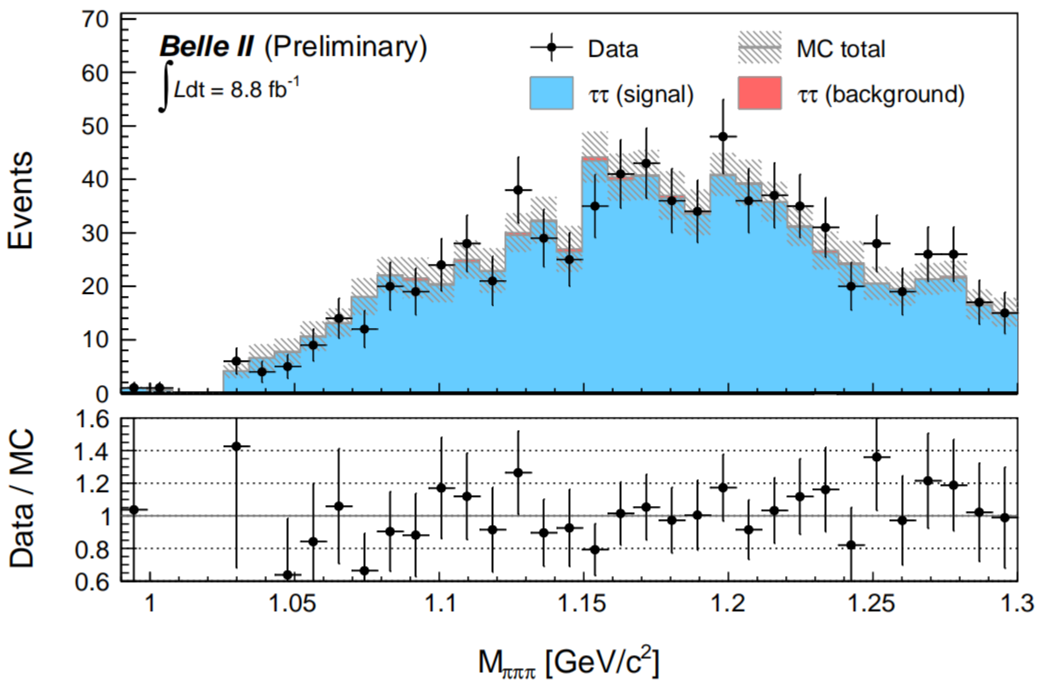




Data/MC comparison and Results

- **No remaining background** apart from $\tau^+\tau^-$.
- In combined 4- and 5-track samples, **Data and MC** distributions are **compatible** with each other within 1σ range of statistical uncertainty.

4- and 5-track samples

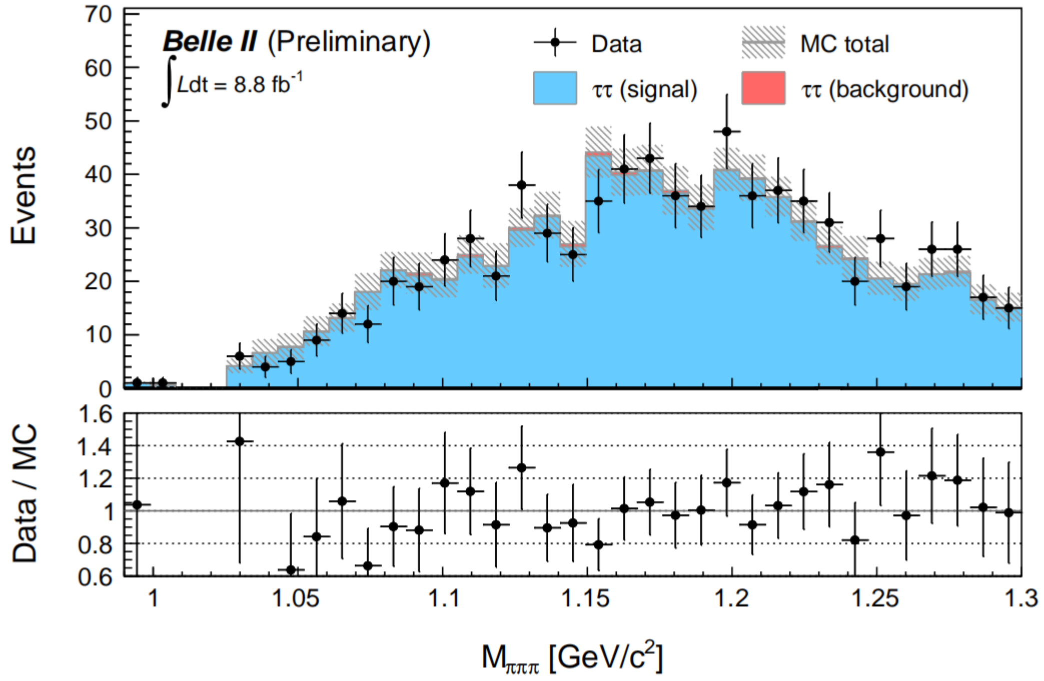


Data/MC comparison and Results

- **No remaining background** apart from $\tau^+\tau^-$.
- In combined 4- and 5-track samples, **Data and MC** distributions are **compatible** with each other within 1σ range of statistical uncertainty.

*We estimate the **signal yields** in data using the signal fraction **S/(S+B)** from MC.*

4- and 5-track samples



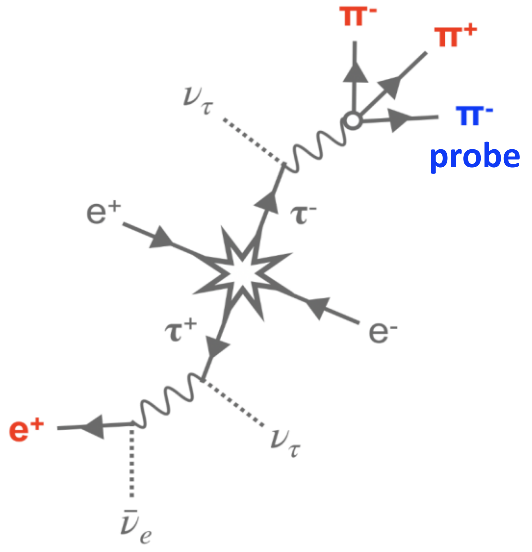
	Fake tracks rate
Monte-Carlo	0.96 ± 0.33 (stat) %
Data	0.96 ± 0.35 (stat) %

→ **Belle II's fake tracks rate is less than 1%, results are compatible with each other.**

Tracking efficiency in τ events

- Study performed by other members of Belle II's Tracking and τ Working Groups.

- Same kind of event: $[\tau^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}\nu] + [\tau^{\mp} \rightarrow e^{\mp}/\mu^{\mp}\nu\bar{\nu}]$, similar tag-and-probe method: probe = 4th track.



3-track reconstruction

$\pi^{+}\pi^{-} + e^{\mp} \rightarrow$ **tag**

$+ \pi^{\pm}$ **probe**

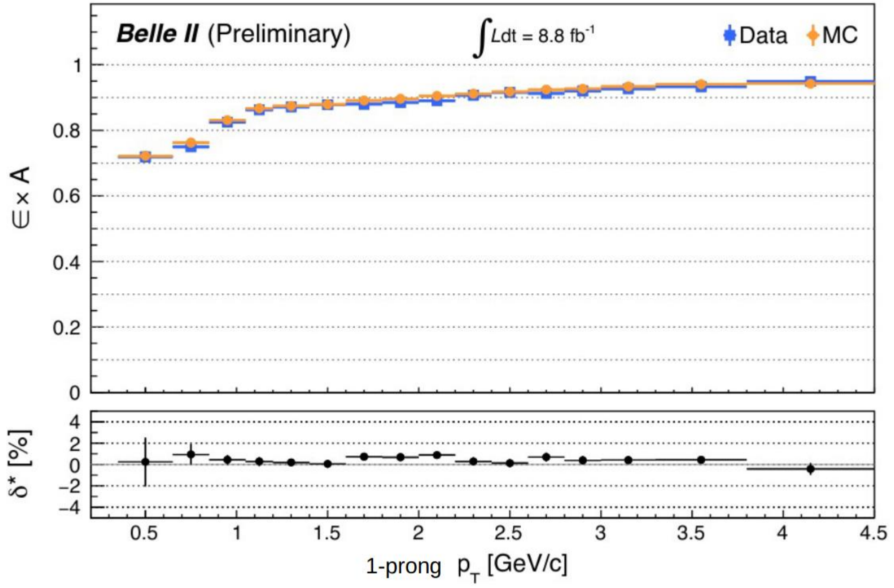
4-track reconstruction

- Tracking efficiency: $A \cdot \varepsilon = \frac{N_4}{N_3 + N_4}$

  ↳ A: detector acceptance.
  ↳ ε: track reconstruction efficiency.
  ↳ N_3: nb. of events with only 3 reconstructed tracks.

- Data/MC discrepancy: $\delta^{*} = \frac{1}{k}\left(1 - \frac{\varepsilon_{Data}^{meas}}{\varepsilon_{MC}^{meas}}\right)$

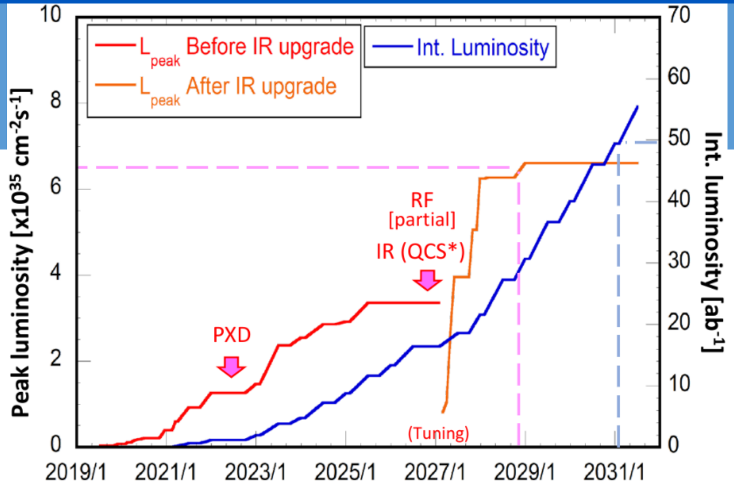
  ↳ k: calibration factor.



$\delta^{*}_{\text{overall}} = 0.28 \pm 0.15\ (\text{stat}) \pm 0.73\ (\text{sys})\ \%$

Outline

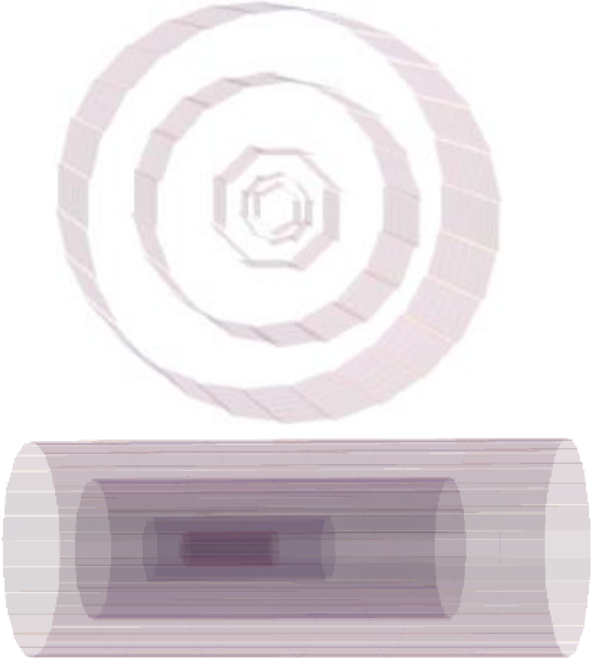
New geometries



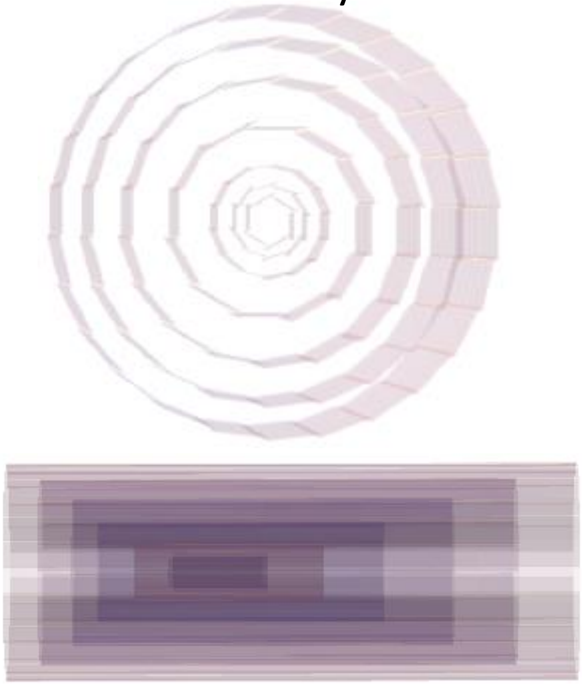
- **2026:** Opportunity to replace the current VXD for:
  - Better performances,
  - Better background handling,
  - Fully pixelated detector (CMOS technology),
  - All layers contributing to tracking.

- 3 new “**VTX**” (*Vertex*) geometries proposed, implemented and connected to existing tracking:

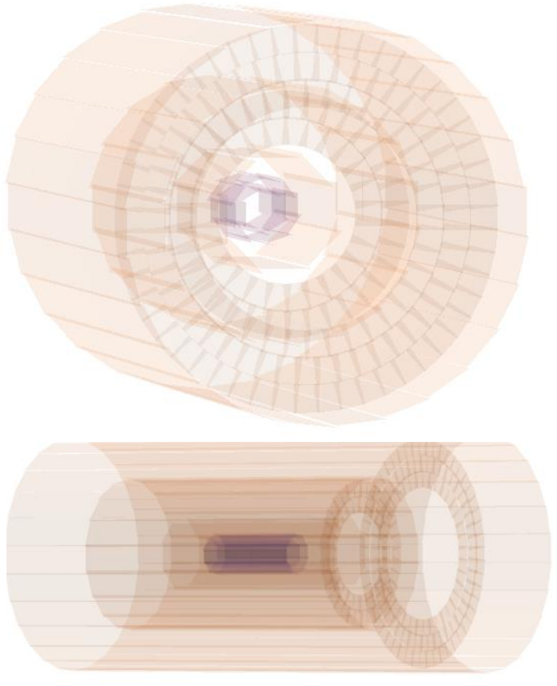
CMOS 5 layers



CMOS 7 layers



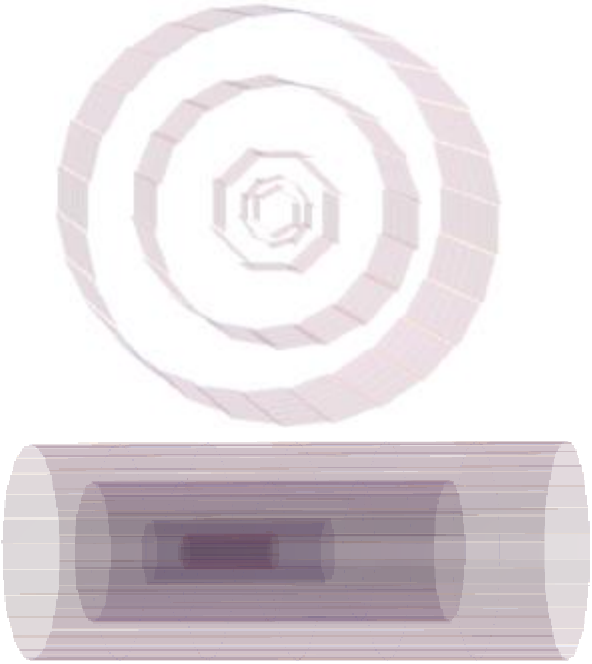
CMOS 5 layers + forward discs



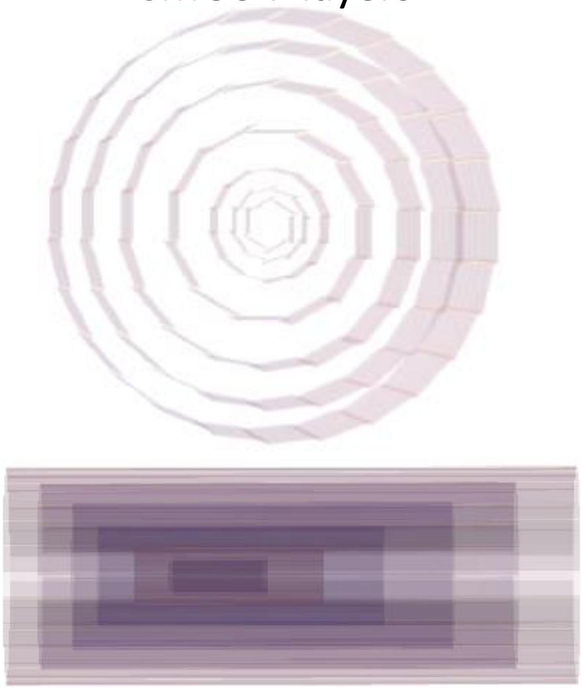
New geometries

- Requirements for the sensors:
  - **Reconstruct the primary vertex:**
    - Radius: first layer at 1.4 cm
    - Material budget: 0.1% / 0.3%
    - Pitches: 33x33 µm
    - Power dissipation < 200 mW/cm²
- **Acceptance**
  - Radius: last layer at 14 cm
  - Length: from 12 cm to 72 cm
- **Cope with the high beam-induced background**
  - Integration times < 100 ns
- 3 new "**VTX**" (*Vertex*) geometries proposed, implemented and connected to existing tracking:

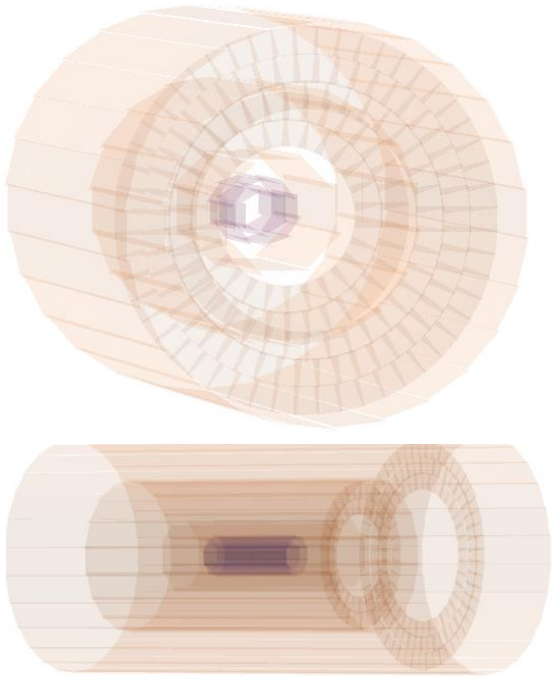
CMOS 5 layers



CMOS 7 layers

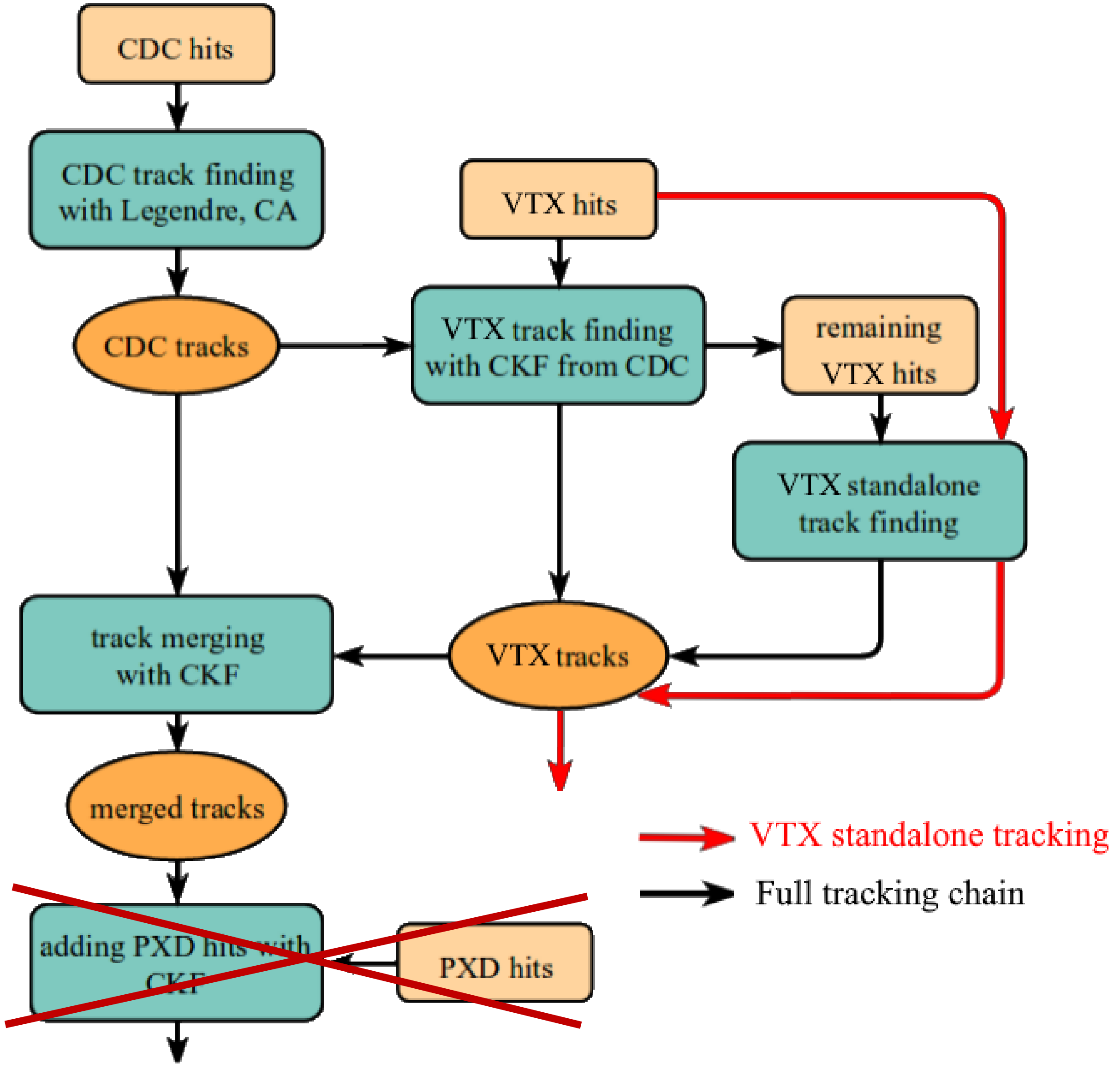


CMOS 5 layers + forward discs



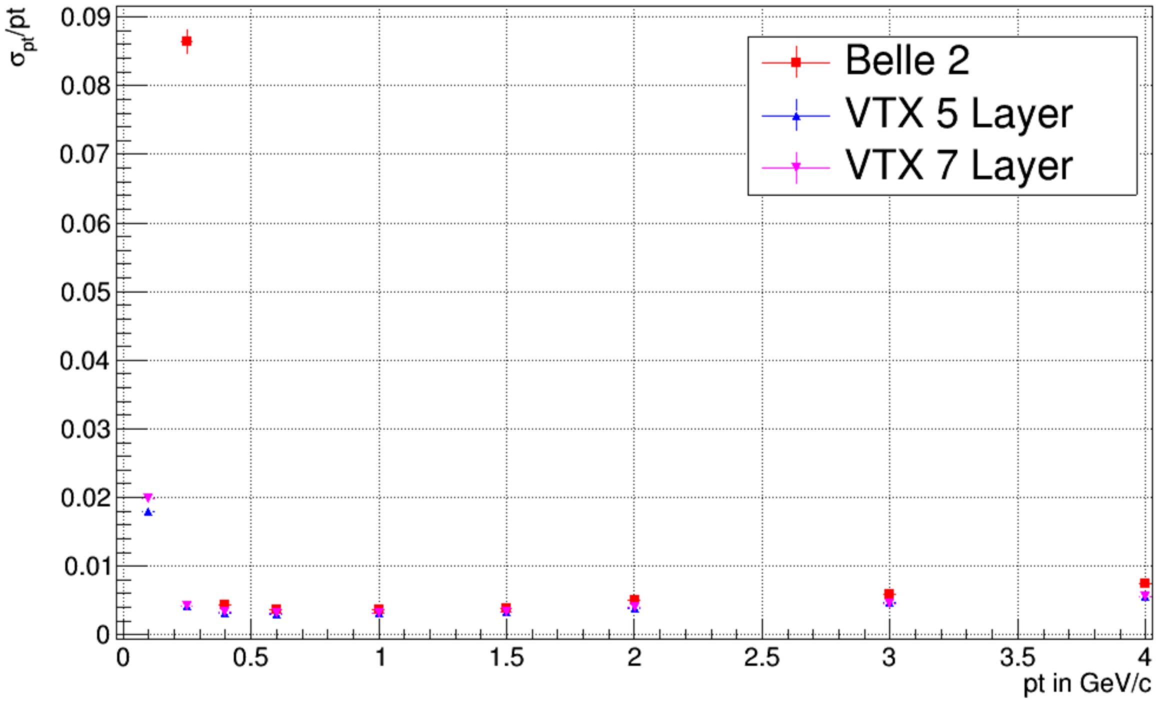
Tracking scheme

- 2 types of studies

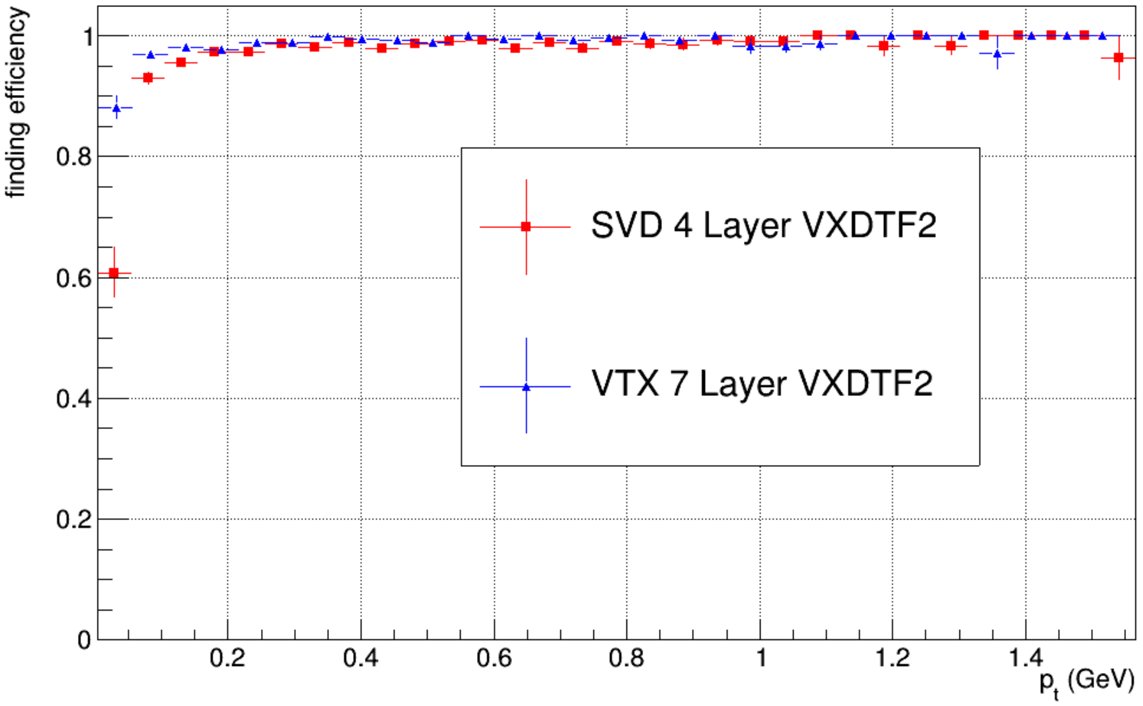


Standalone performance

- **Transverse momentum resolution vs p_t**



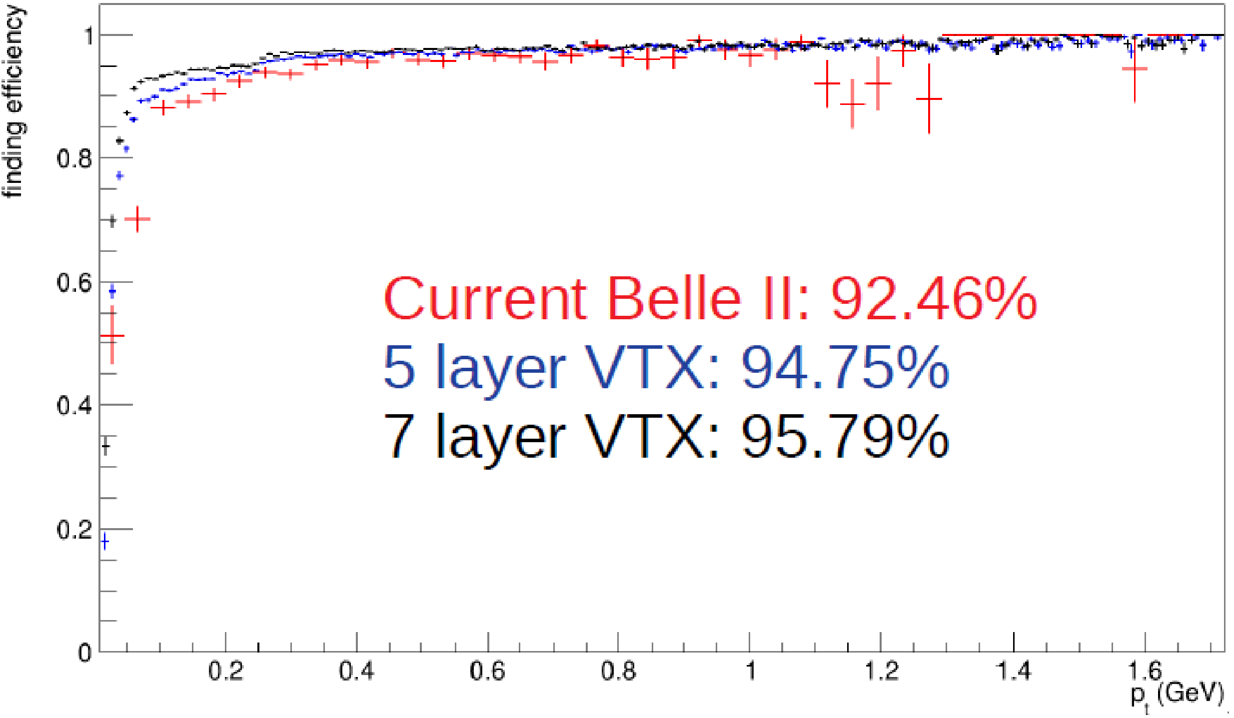
- **Finding efficiency vs p_t**



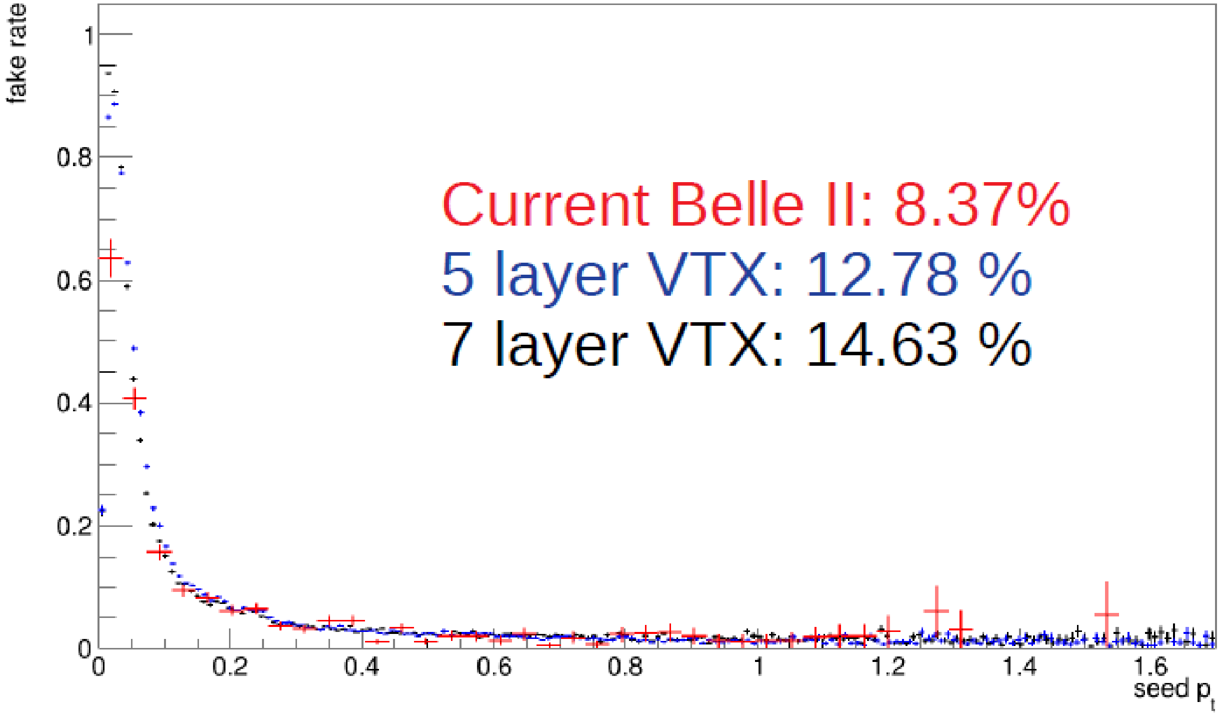
- Better standalone tracking performances than current VXD.
- VTX best resolution at low p_t.
- Similar high finding efficiencies.

Full tracking performance

- **Finding efficiency as a function of p_t**



- **Fake rate as a function of p_t**



- Better full tracking performances than current VXD.
- Slightly higher fake rate.
- Everything still work in progress, but the results are promising and the tools are here to study the impact of the different characteristics of the sensors and the geometries.

Summary and Conclusions

Belle II detector's tracking system is well-functioning and realistically simulated:

Tracking algorithm improvement:

- Belle II's software has already been updated with a new 4×4 sector map with 70% pruning.
- It reduces the clone and fake rates for the same efficiencies as the previous 3×3 sector map.

Fake tracks rate in data using τ events:

- The fake tracks rate and tracking efficiency studies show that the tracking system is well understood.
- The results could work as figures of merit or help assigning systematic uncertainties to other analyses.

However, the future increase in luminosity will result in more beam-induced background, thus some improvements are considered for the tracking system:

Upgrade of the vertex detector:

- According to MC, the future upgrade of the vertex detector will give better tracking performances and better background handling compared to the current PXD and SVD.
- Opportunity for a VXD upgrade in 2026.

TRISTAN FILLINGER
IPHC, Strasbourg

GÜNEY POLAT
CPPM, Marseille

THANK YOU FOR YOUR ATTENTION

GdR-InF Annual Workshop – 08/10/2020

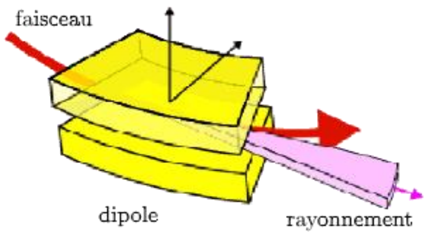
Backup

Beam-induced background

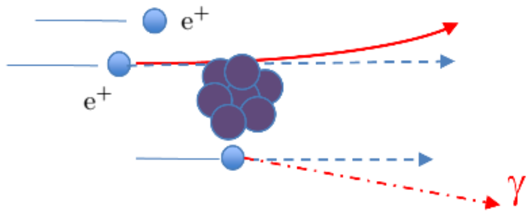
One beam background:

- Dominant at low luminosity.
- Difficult to simulate.
- Predictions inferiors by a factor 2 to 5 compared to the measurements.

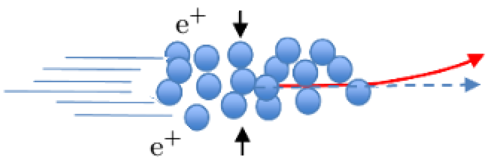
Synchrotron radiation



Beam gas



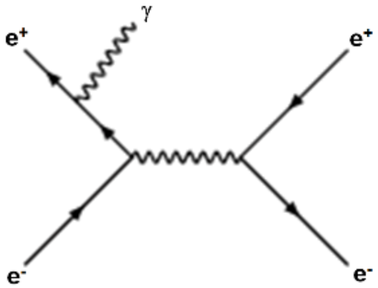
Touschek effect



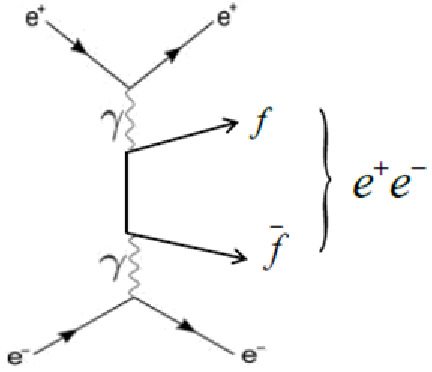
Beam-beam interaction:

- Dominant at high luminosity (> 30 ab^{-1}).
- Prediction with QED and simulations.
- No measurement yet.

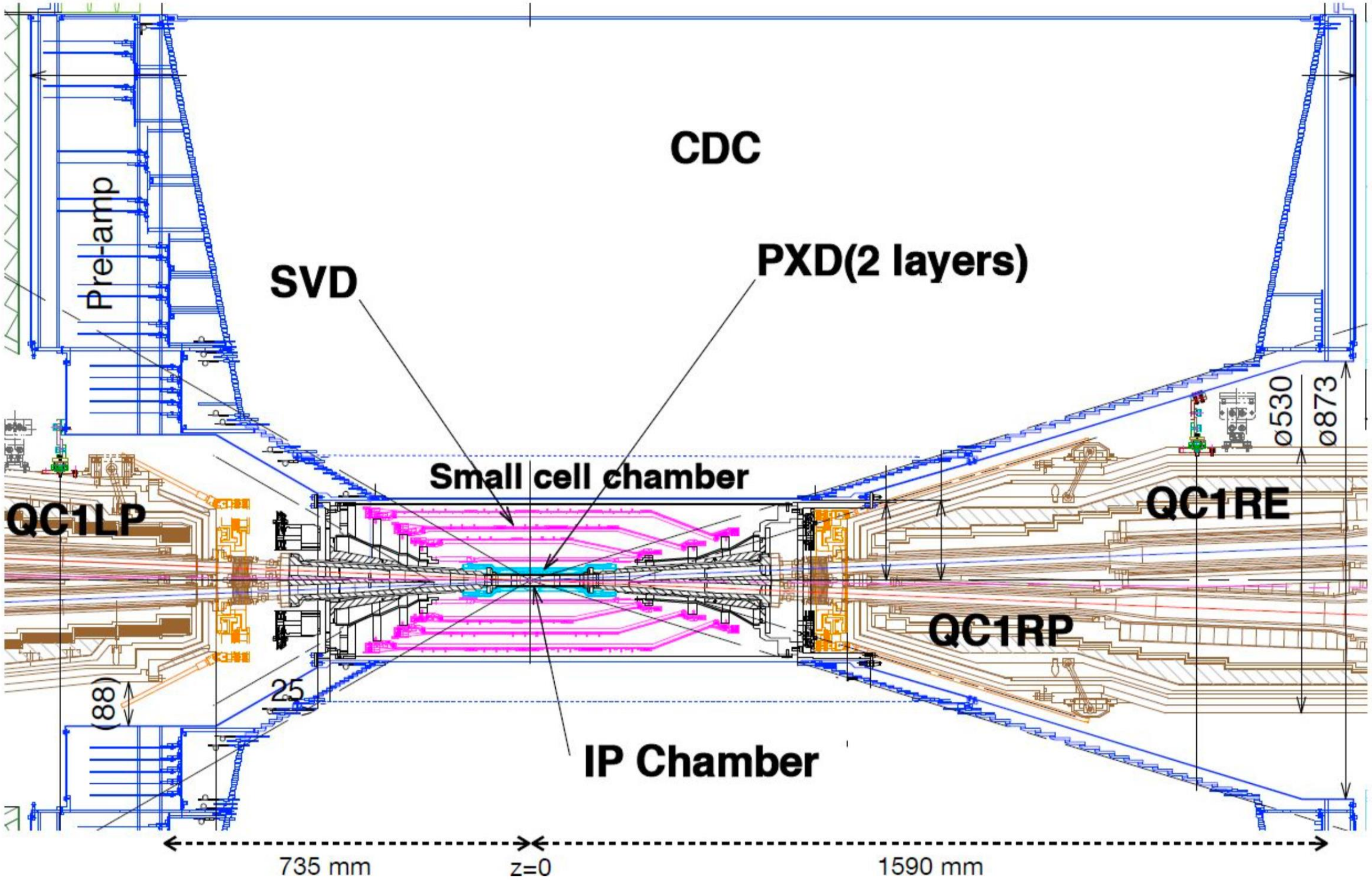
Radiative Bhabha



Pair creation



Technical schematic of the CDC + VXD



Specifications of the VXD

Layer	Radius (mm)	Ladders	Sensors /ladder	Sensors /layer	Pixel u × v	Pitch u × v (μm × μm)
1	14	8	2	16	250×(256+512)	50 × 55 / 60
2	22	12	2	24	250×(256+512)	50 × 70 / 85
Sum		20		40	7680000	

Table 1: Specifications of the Belle II PXD.

Readout time: 20 µs
Thickness: 75 µm
CO2 cooling

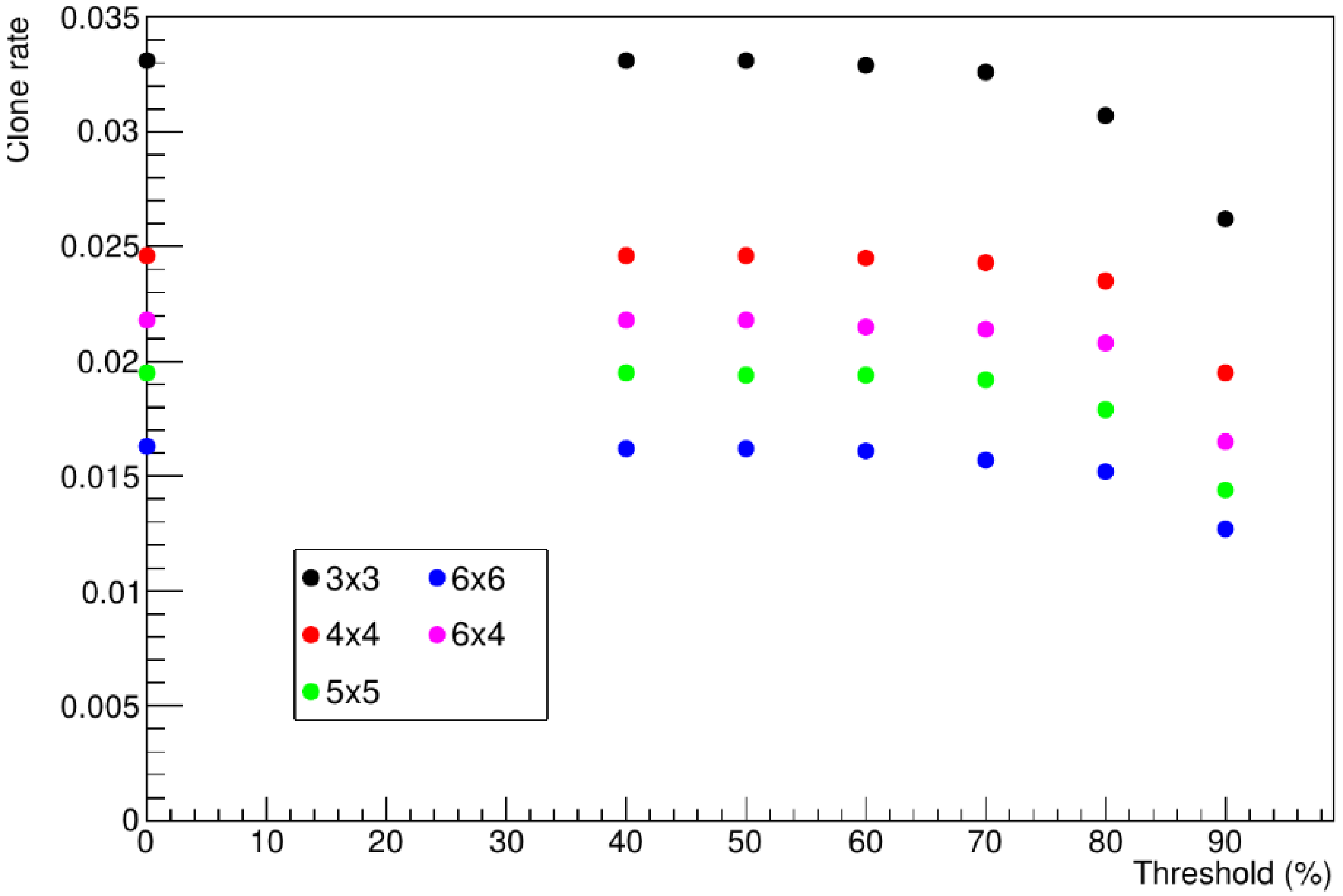
Layer	Radius (mm)	Ladders	Sensors /ladder	Sensors /layer	P-Side (slanted) Strips / Pitch (μm)	N-Side Strips / Pitch (μm)
3	39	7	2	14	768 / 50	768 / 160
4	80	10	3	30	768 / 75 (down to 50)	512 / 240
5	104	12	4	48	768 / 75 (down to 50)	512 / 240
6	135	16	5	80	768 / 75 (down to 50)	512 / 240
Sum		35		172	132096	91648

Table 2: Specifications of the Belle II SVD.

Readout time: 50 ns
Thickness: 320 µm
300 µm forward
CO2 cooling

Layer	BP 1.0-1.2 cm	1.4 cm	2.2 cm	3.9 cm	8.0 cm	10.4 cm	13.5 cm
% radiation length	0.8%	0.2%	0.2%	0.55%	0.55%	0.55%	0.55%

Clone rate vs threshold



Background suppression cuts

Belle II

- $\text{cosToThrustOfEvent}(\pi_1^{tag}/\pi_2^{tag}/\pi_3^{tag}/probe) \times \text{cosToThrustOfEvent}(e^{tag}) < 0$
- $\cos\theta^{CMS}_{e^{tag}-\pi_1^{tag}/\pi_2^{tag}/\pi_3^{tag}/\pi^{probe}} < -0.5$
- $0.2 < 2p^{CMS}_{1-prong}/\sqrt{s} < 0.8$
- Opposite charge pions: $\left|m_{\pi_1^{tag}\pi_2^{tag}} - m_\rho\right|, \left|m_{\pi_2^{tag}\pi_3^{tag}} - m_\rho\right| < 100\ \text{MeV}$
- Same charge pions: $300\ \text{MeV} < m_{\pi_1^{tag}\pi_3^{tag}} < m_\tau$

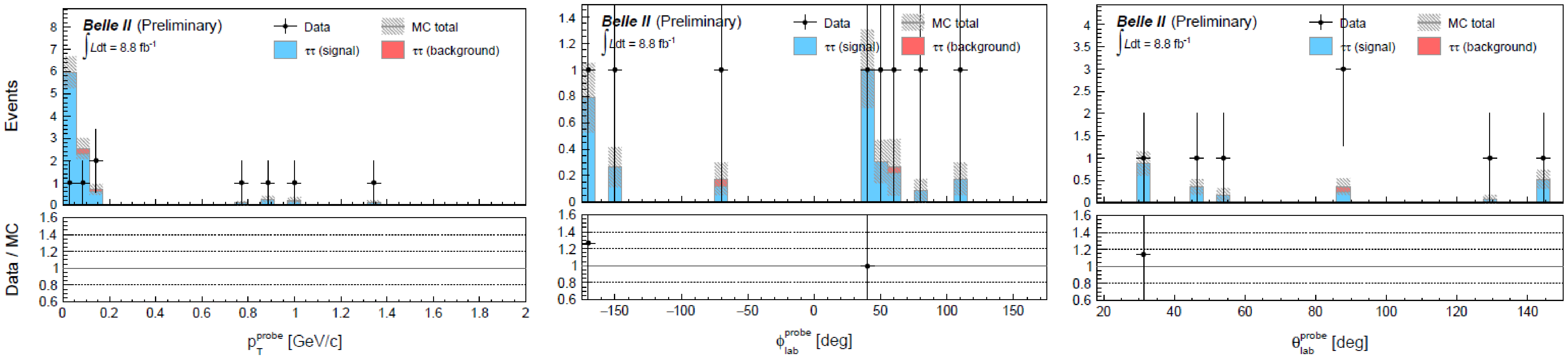
inspired by the study on tracking efficiency

- good γ multiplicity $= 0$ and good π^0 multiplicity $= 0$
- $M_{\pi\pi\pi} < 1.3\ \text{GeV}$
- $3\ \text{GeV/c} < p_T^{3-prong}$ and $1\ \text{GeV/c} < p_T^{1-prong}$
- electronID of $e^{tag} > 0.9$ and kaonID of $\pi_2^{tag} < 0.6$

optimized according to a S/√B figure of merit in the run-independent 5-track MC sample

Data/MC comparison: 5-track samples

- Looking at the comparison between data and MC in 5-track samples alone, the ratio Data/MC is far from 1 and the MC yields are not consistent between the three variables.
- This is due to the small statistics and the non-flat trigger efficiency ($= 0$ or 1) from data, that is computed bin-by-bin and applied as it is to MC.



Results

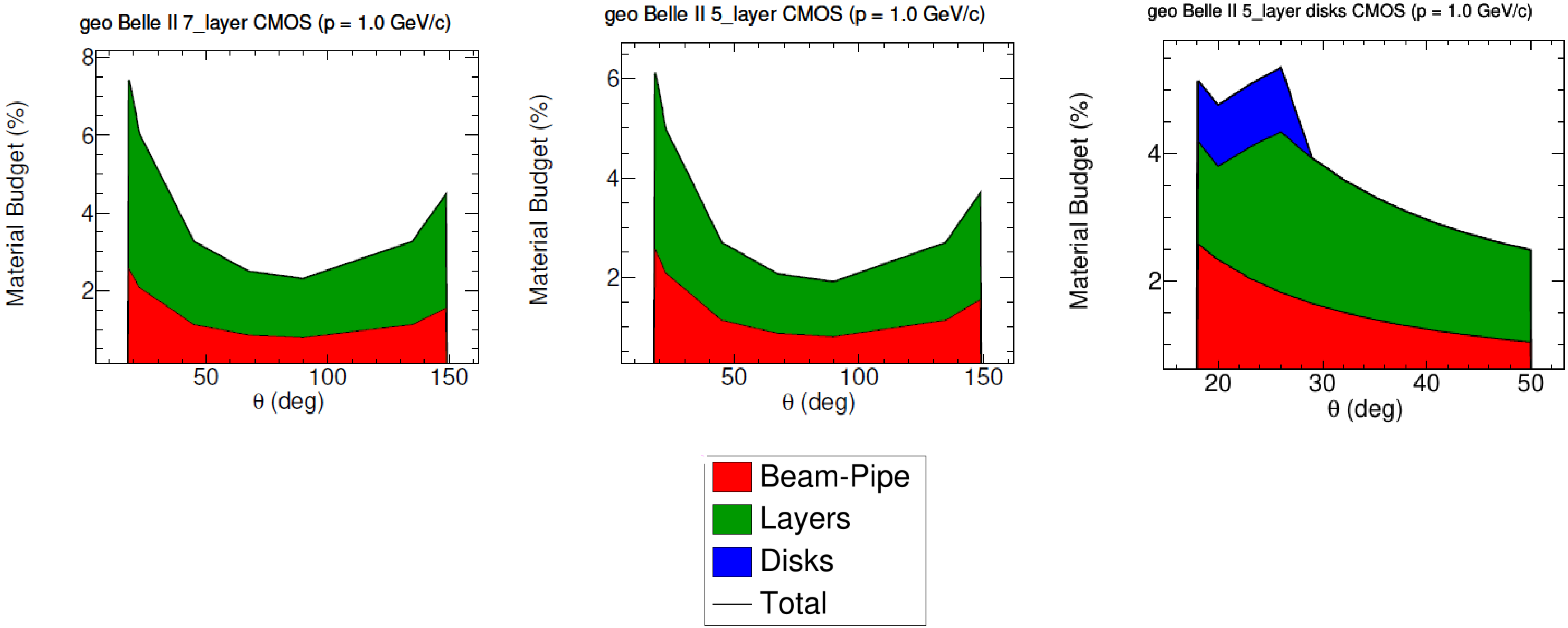
	Fake tracks rate
Monte-Carlo run-independent	**1.14 $\pm$ 0.25 (stat) %**
Monte-Carlo run-dependent	**0.96 $\pm$ 0.33 (stat) %**

Run-(in)dependent: (not) taking into account beam conditions.

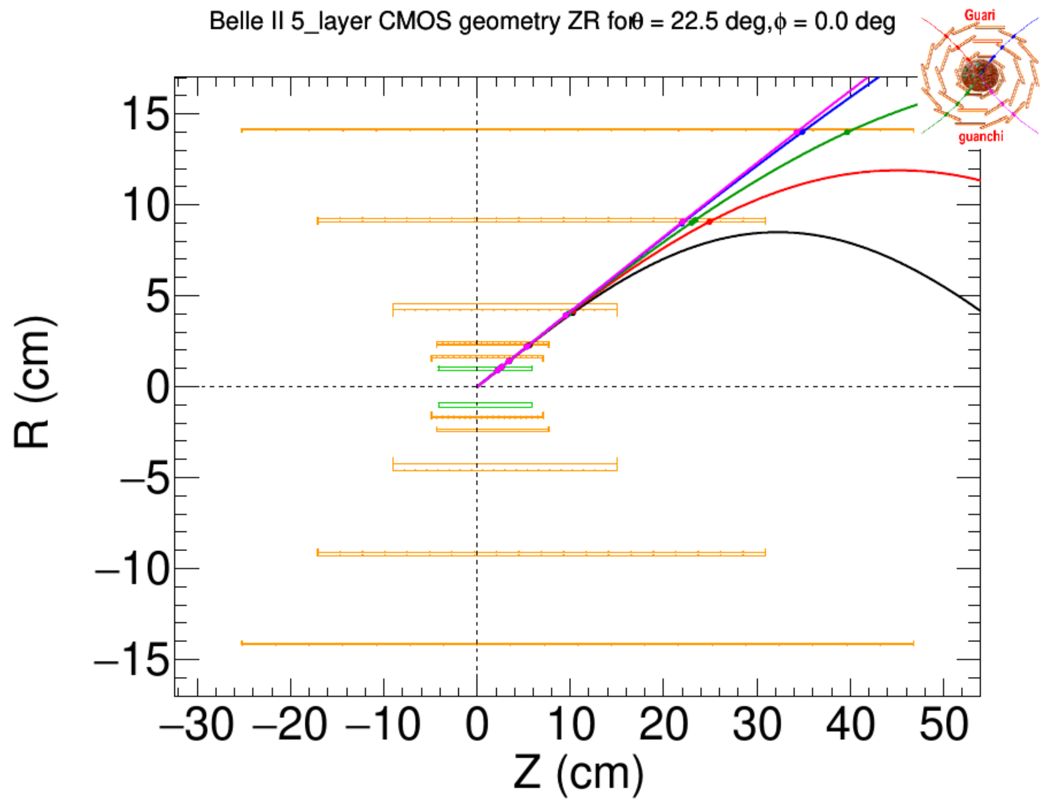
*We estimate the **signal yields** in data using the signal fractions **S/(S+B)** either from run-independent or run-dependent MC.*

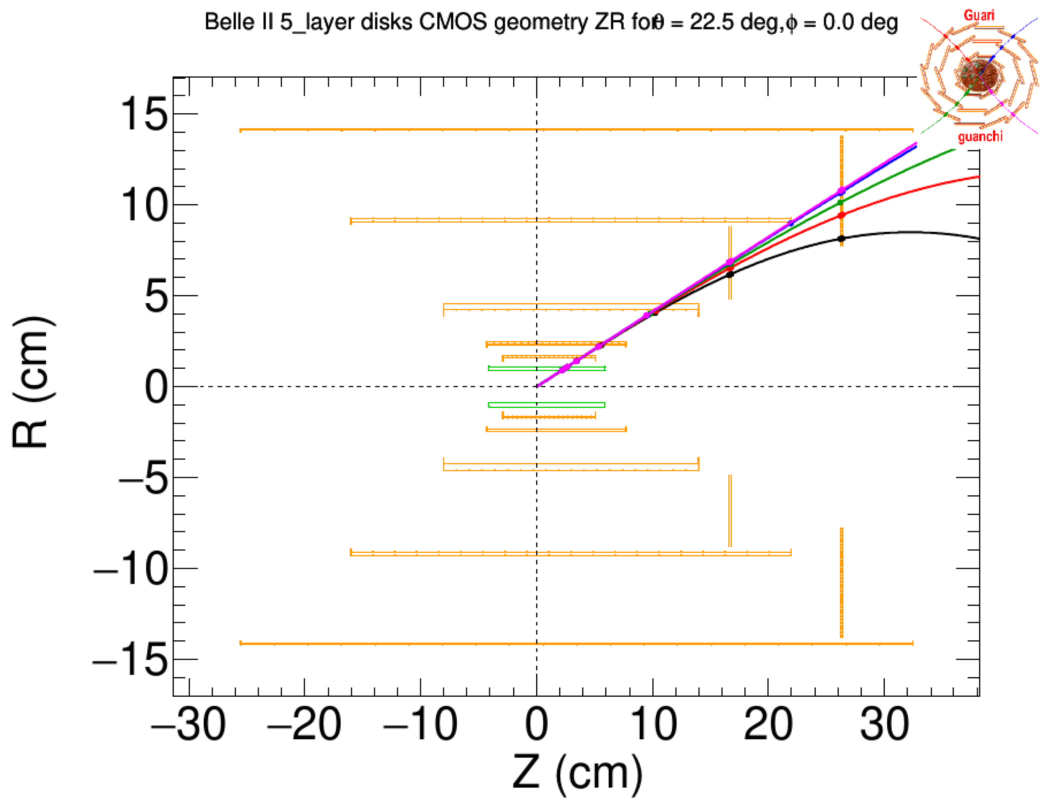
	Fake tracks rate (run-independent)	**Fake tracks rate** (run-dependent)
Data	**0.97 $\pm$ 0.34 (stat) %**	**0.96 $\pm$ 0.35 (stat) %**

Material budget of the VTX



Material budget of the VTX





- Geometry with disk increases acceptance for low momentum tracks at small angles but according to simulations, performances doesn’t improve compared to CMOS 5 layers.