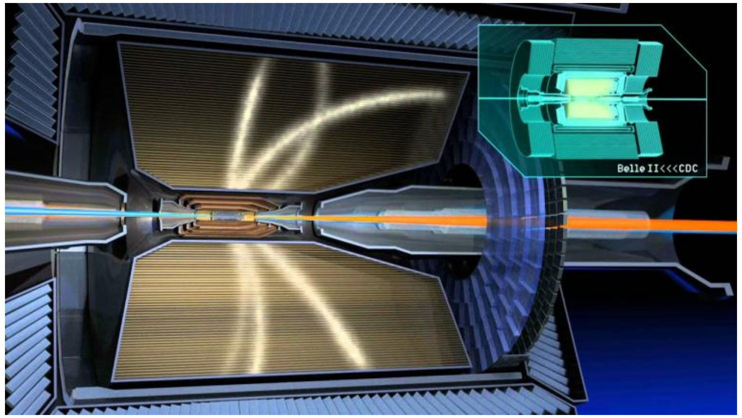
Validation of the GNN tracking at Belle II

Performance studies with $B^0 \to K_S^0 \nu\bar{\nu}$ decays.



Source: KEK, "A Search for New Physics," YouTube (2014)

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Herbstschule HEP in Bad Honnef

September 5th, 2026

Source: CAT-Finder logo, courtesy of Lea Reuter / KIT

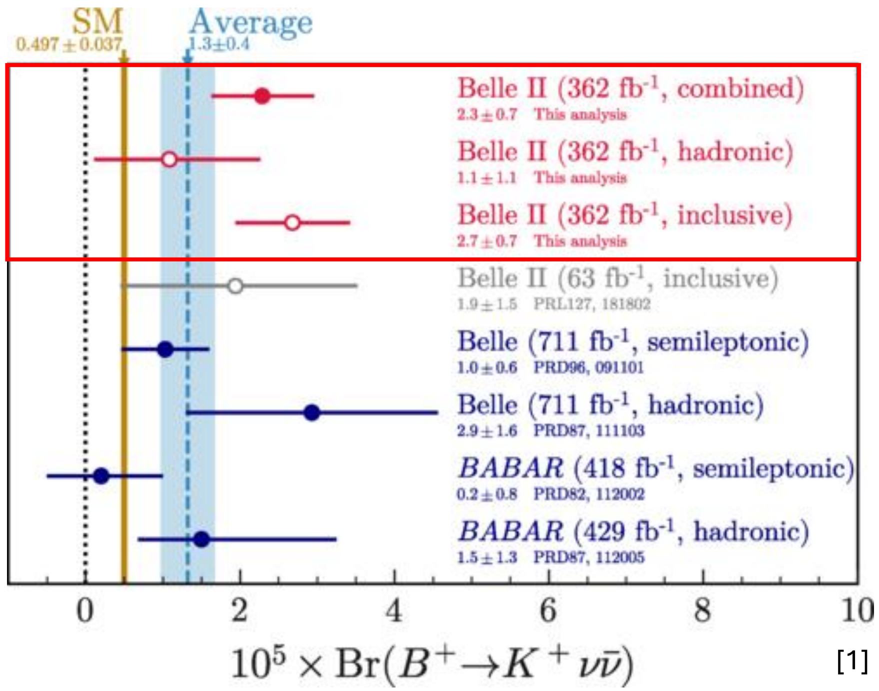
The $B^+ \to K^+ \nu\bar{\nu}$ excess

<u>Summer 2023:</u> First evidence of $B^+ \to K^+\nu\bar{\nu}$ decays published by Belle II Collaboration.

- Branching Fraction measured to be:

$$\boxed{\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}}$$

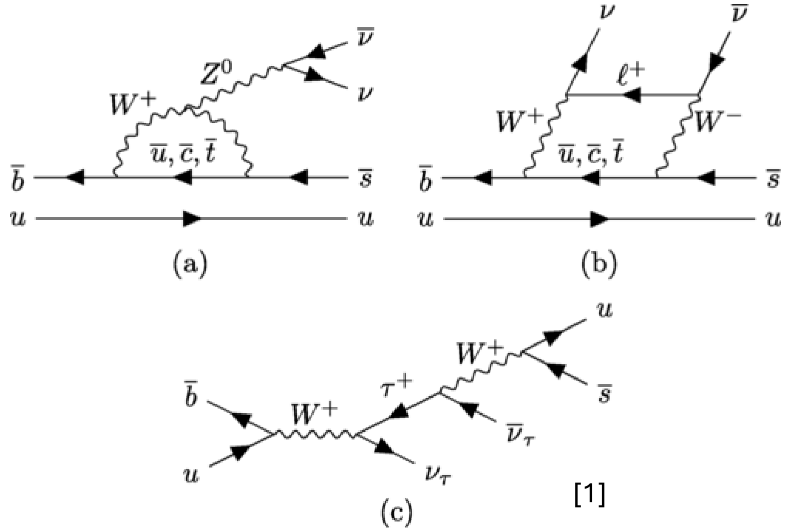
<u>Source:</u>
[1] I. Adachi *et al.*, Phys. Rev. D **109**, 112006 (2024)



[1]

- Result shows **excess of 2.7 σ** to Standard Model expectations.

- Attempted explanations involve wide range of **new physics models.**



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This highlights the importance of further **high precision measurements**, also regarding complementary decay channels, such as $\boldsymbol{B^0 \to K_S^0 \nu\bar{\nu}}$.

The challenges of observing $B^0 \to K_S^0 \nu\bar{\nu}$ decays

Belle II: e^+e^- collision produces $\Upsilon(4S)$ **resonance** that decays to a $B\bar{B}$ pair.

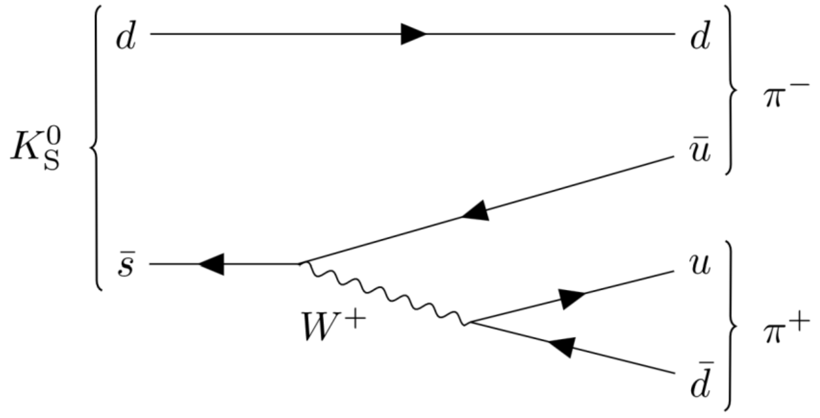
Physics Goal:
Perform **high precision measurement** of $B^0 \to K_S^0 \nu\bar{\nu}$ decays.

Challenges:

- **Neutrinos** can't be experimentally reconstructed.
- Only the **charged pion tracks** can be reconstructed from the ***displaced* decay vertex** of the K_S^0, but:

➢ Momentum of daughter pions is limited to 0.1–2.0 GeV/c.

➢ The tracking volume becomes even more increasingly occupied due to **significant machine backgrounds**.



$\mathcal{B}(K_S^0 \to \pi^+\pi^-) = (69.20 \pm 0.05)\%$

High precision measurements require high precision particle track reconstruction.

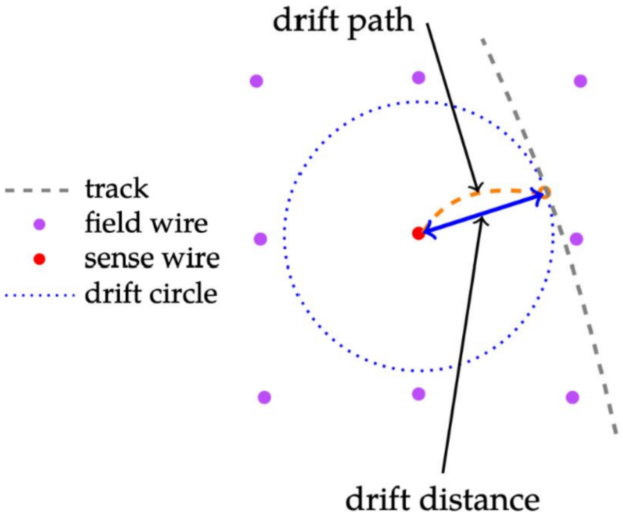
The Central Drift Chamber (CDC)

Sources:
[1] B. Scavino, Belle II Physics Week, Tracking (2025)
[2] E. Kou *et al.*, PTEP 2019, 123C01

The Central Drift Chamber is the main tracking detector of Belle II.

- Large cylindrical **multi-wire drift chamber**, filled with He - C_2H_6 gas mixture.

- It operates inside a 1.5 T solenoidal magnetic field.



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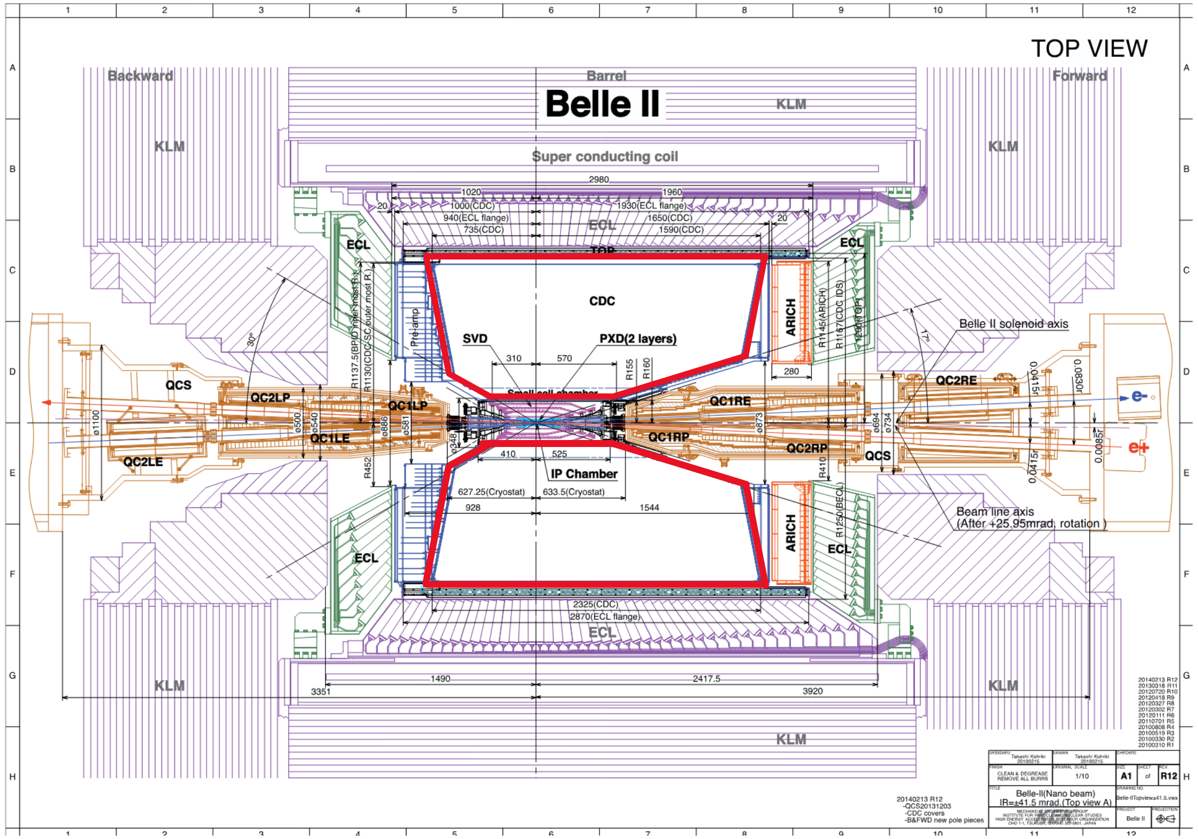
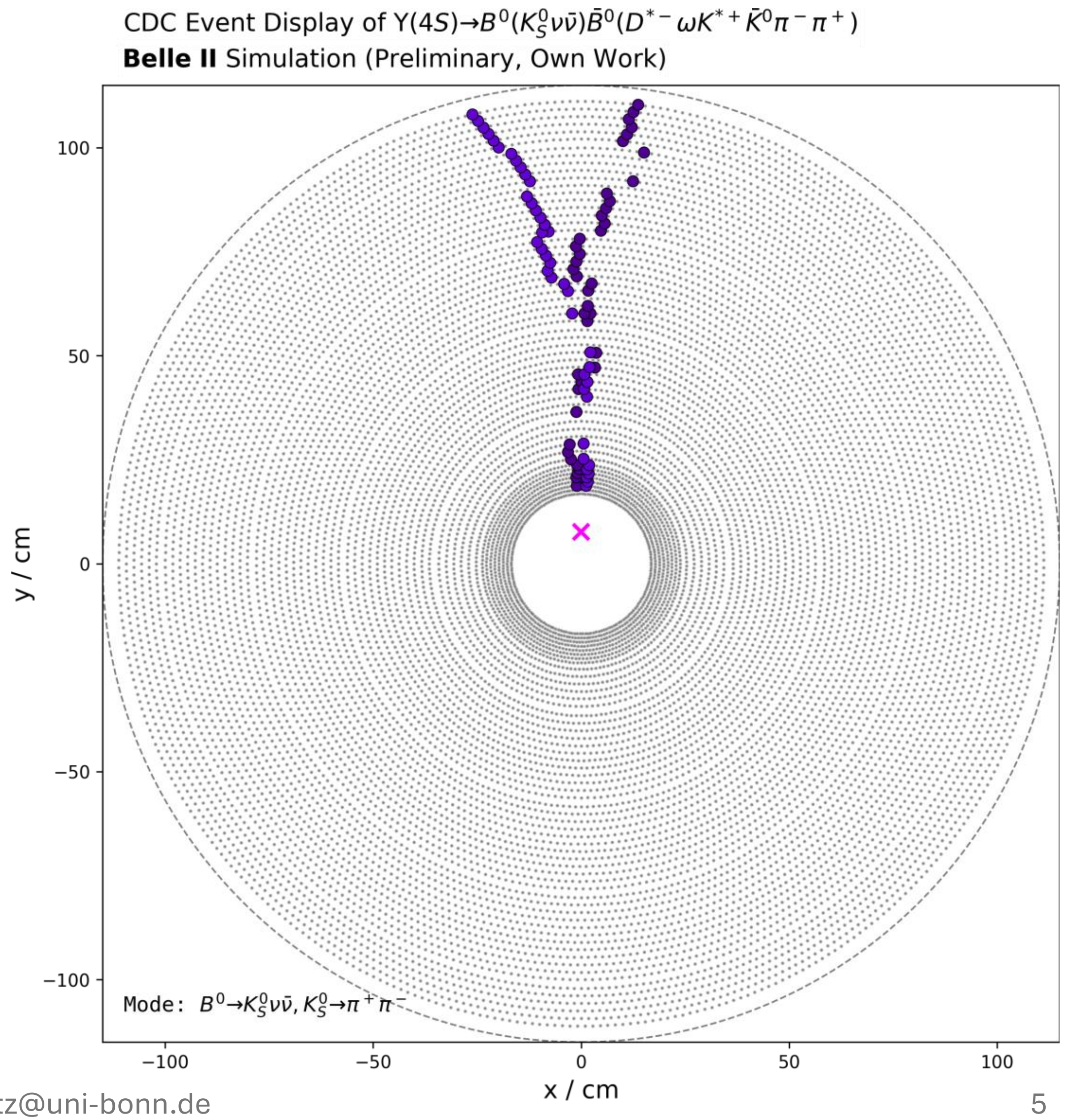


[2]

Provides a measurement with a spatial resolution of 120 μm on average.

Baseline particle track reconstruction in the CDC

- **<u>Principle:</u>** Estimate particle trajectories via detector hits along its flight path.



Baseline particle track reconstruction in the CDC

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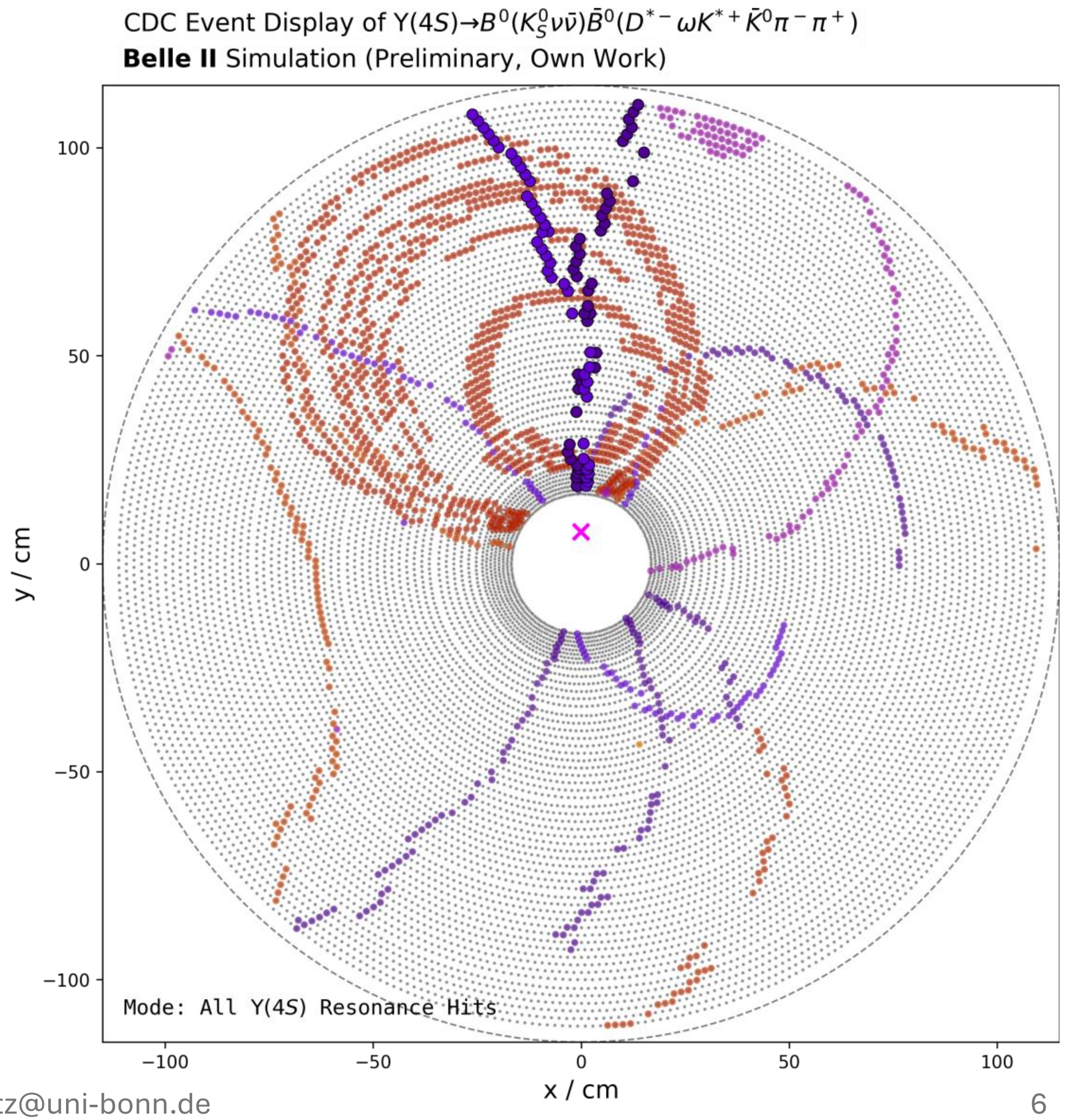
- **<u>Challenges:</u> Multiple scattering** and **significant machine background** occupy tracking environment.



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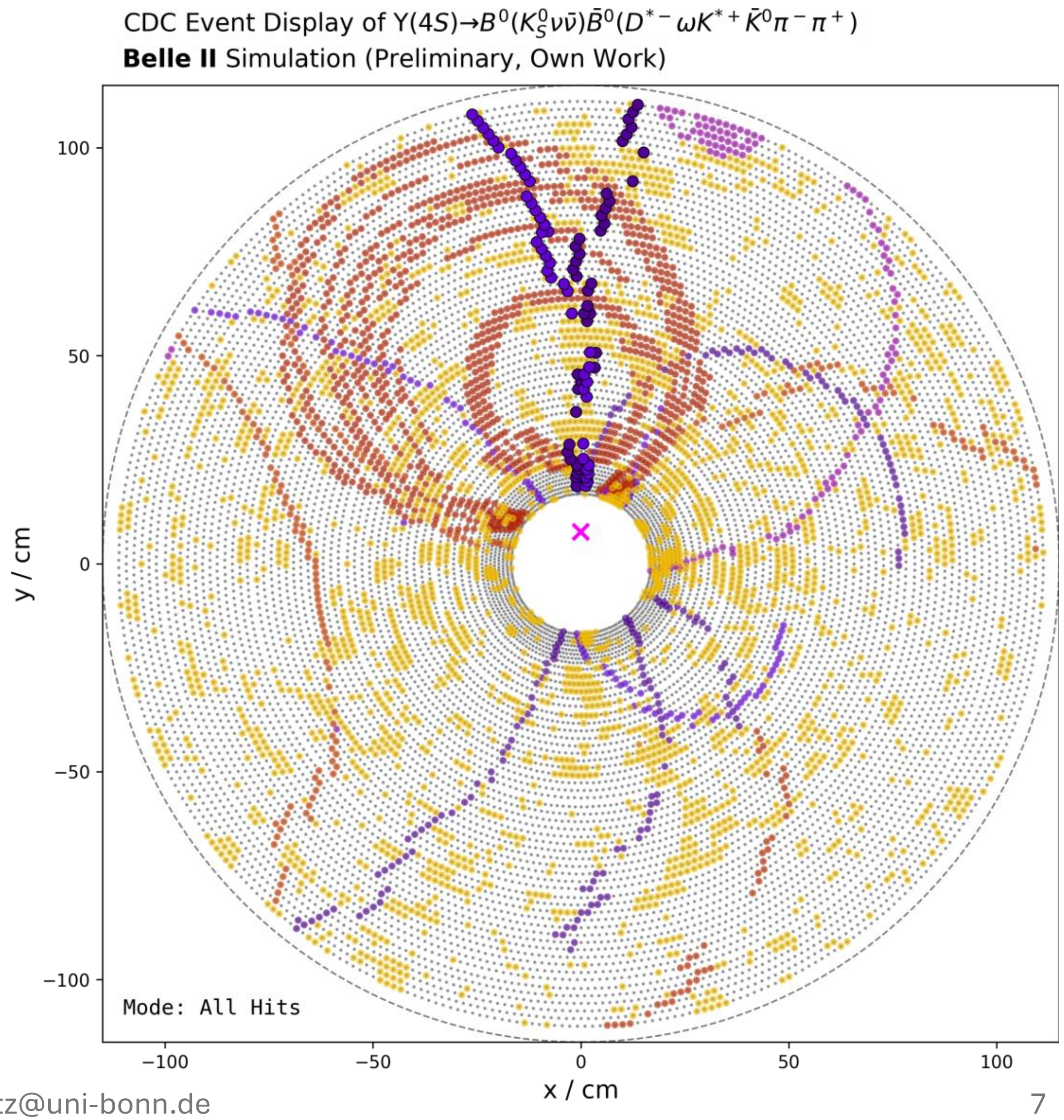

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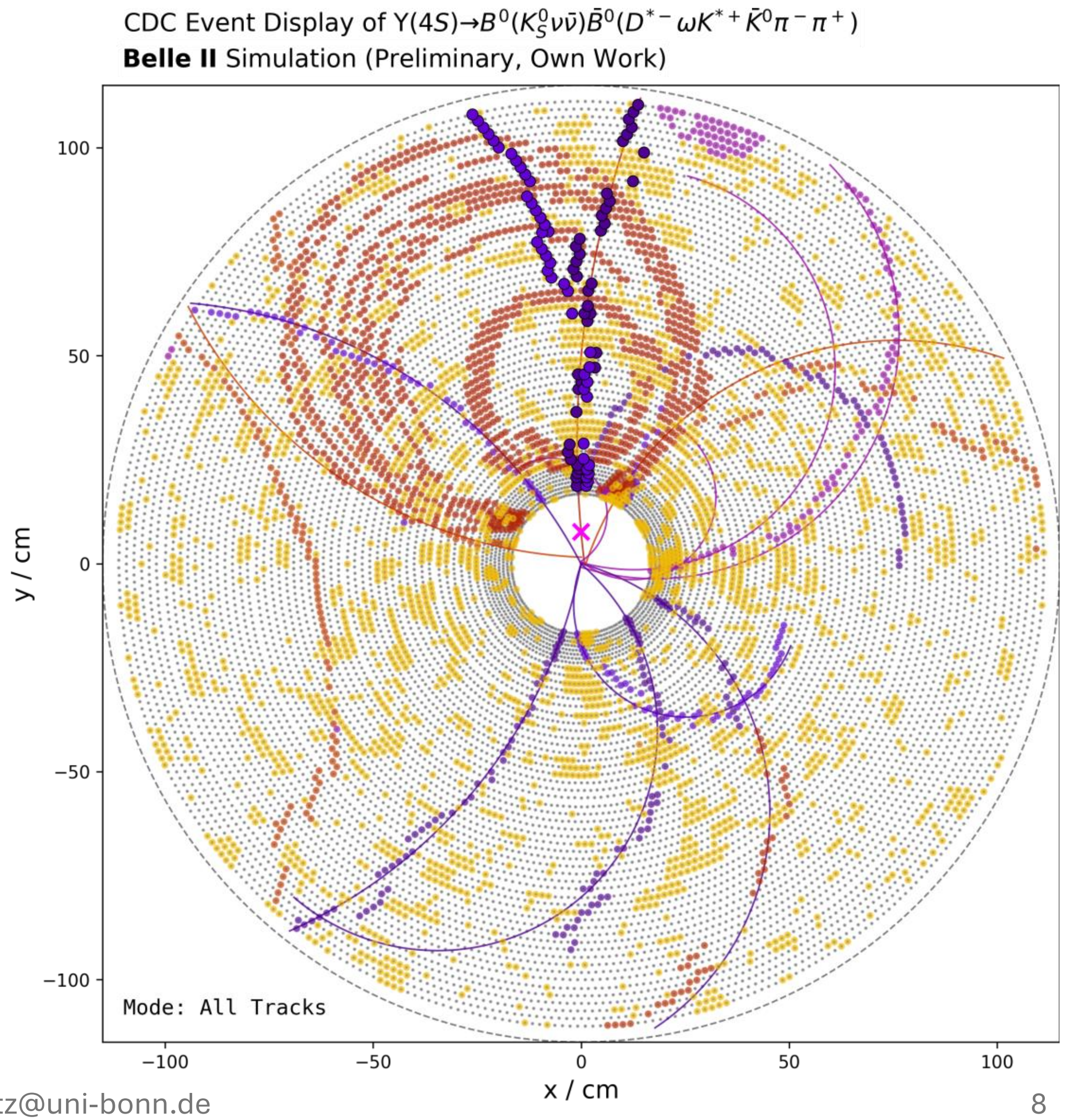

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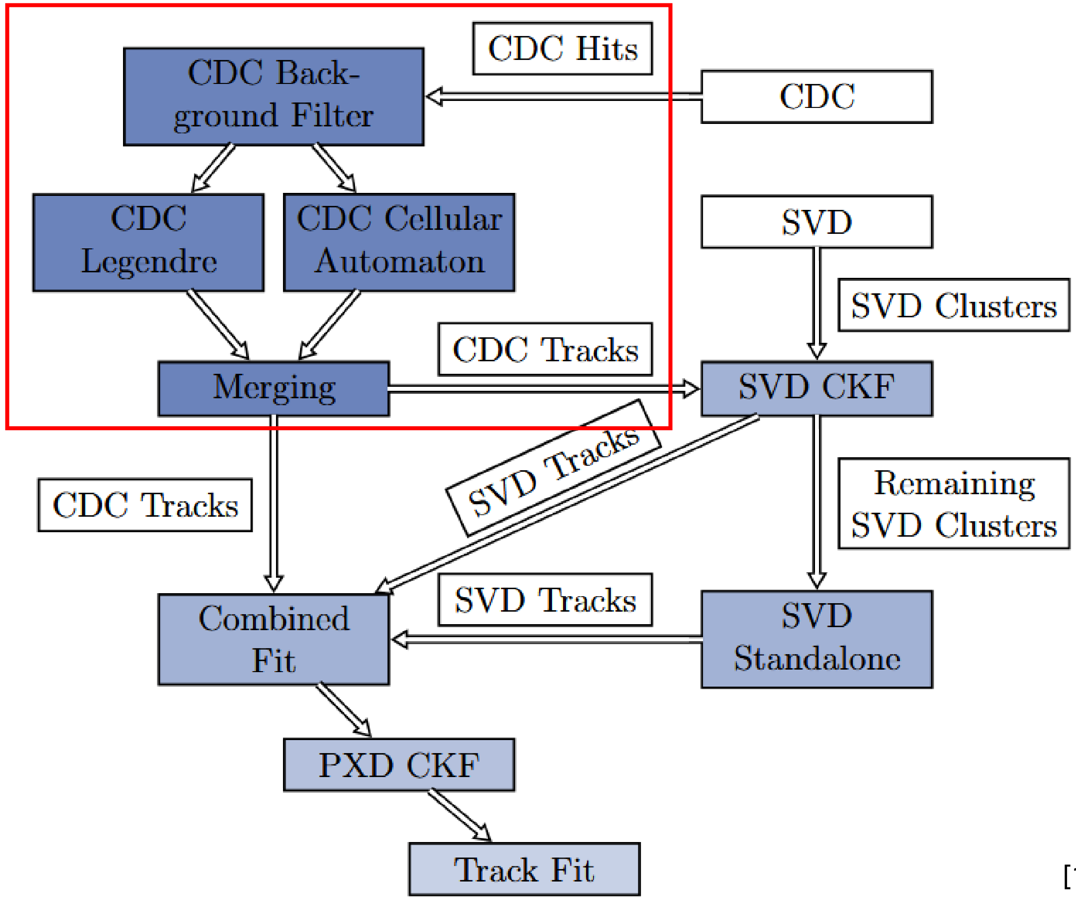


[1]

Source:
[1] V. Bertacchi *et al.*, Comput. Phys. Commun. 259, 107610 (2021)

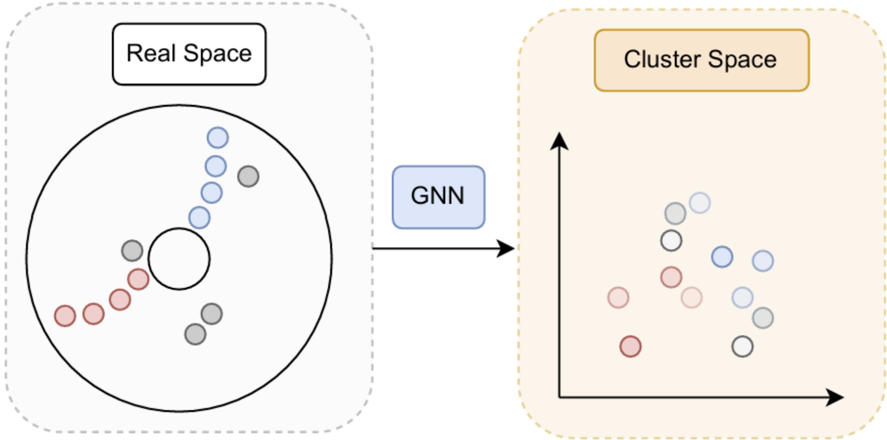
Global and local track results are **merged** and integrated into the full Belle II tracking procedure.

Track finding using object condensation

Sources:
[1] L. Reuter, PhD thesis, KIT (2026)
[2] L. Reuter *et al.*, Comput. Softw. Big Sci. 9, 6 (2025)
[3] J. Kieseler, Eur. Phys. J. C 80, 886 (2020)
[4] J. Kieseler, ML Lecture 2, HEP-Herbstschule 2026

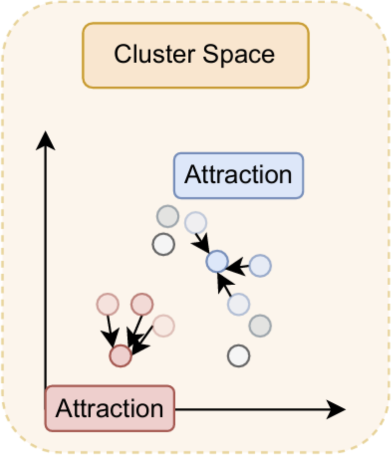
New approach: Graph Neural Network (GNN) based particle track reconstruction in the CDC.

1. Create clustering space with a GNN.



[1]

2. Write loss function that **attracts** points from **same object**.



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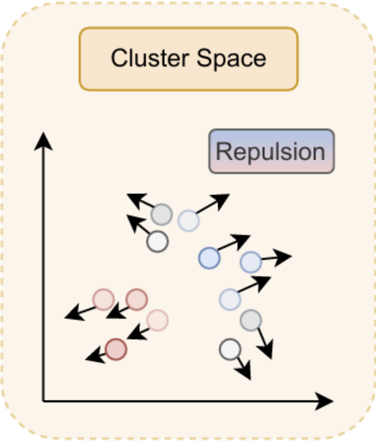
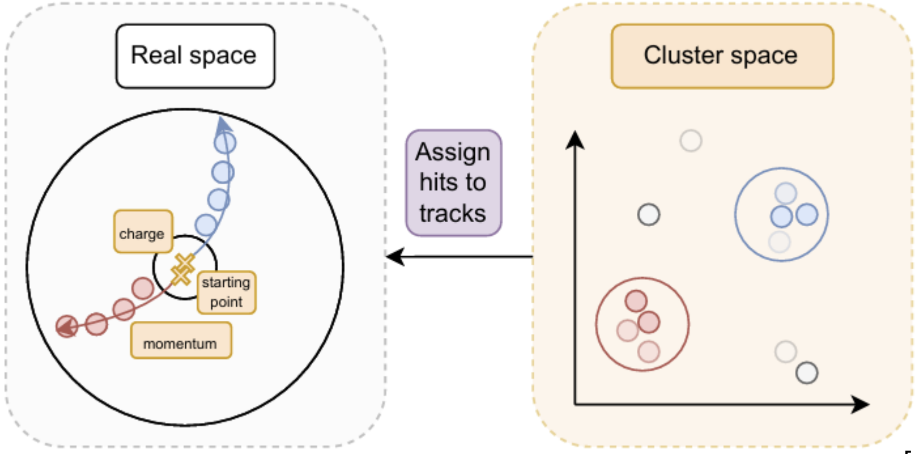
3. Write loss function that **repels** points from **other objects.**



[1]

4. **Clusters** form around **representative points**.



[1]

Validation of the CDC-AI-Track (CAT)-Finder

Source: CAT-Finder logo, courtesy of Lea Reuter / KIT

One simulated campaign

- 10.000 simulated $\Upsilon(4S)$ events with $\mathrm{B}^0 \rightarrow \mathrm{K}_S^0 \nu\bar{\nu}$, per beam-background scenario.
- **5 beam-background scenarios:** none | Run 1 luminosity | design luminosity at x1, x2.5, x5 beam background.
- **4 track finders:** baseline (no bkg filter) | baseline (as deployed)| CAT-Finder | CAT-Finder ($B\bar{B}$ optimized)
- **Same simulated events go through every finder.** → paired comparison

1. Track finding

Does the CAT-Finder find more tracks?

- Clones, merges, hits per track
- Efficiency vs. detector occupancy

2. Physics impact

Does the finding gain reach the physics result?

- Full analysis replayed stage by stage.

3. GNN structure and explainability

Why does it behave this way?

- Condensation space, clone anatomy
- Surrogate model

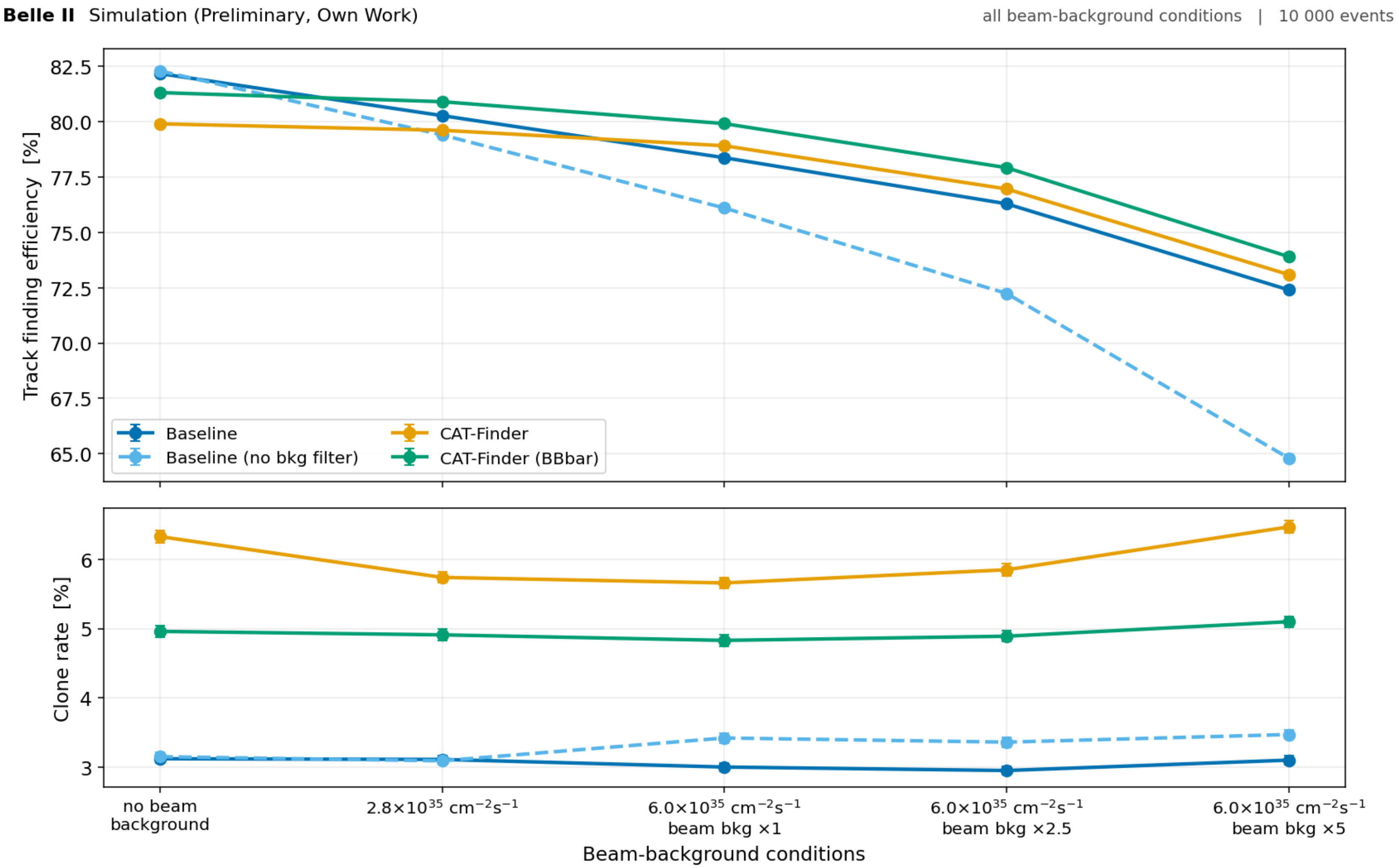
Track finding performance

track finding efficiency

$$\varepsilon_{\text{find}} = \frac{N_{\text{found}} + N_{\text{wrong charge}}}{N_{\text{findable}}}$$

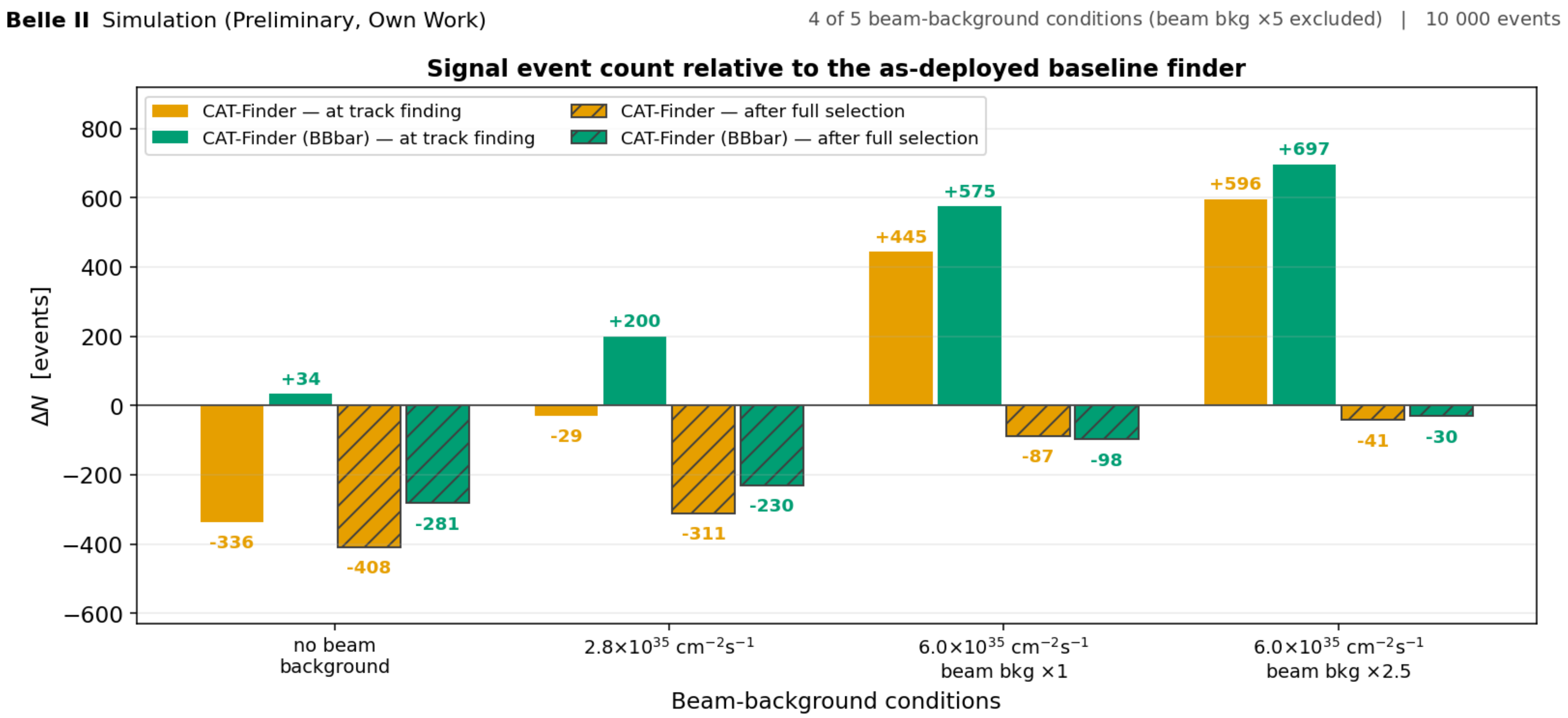
clone rate

$$r_{\text{clone}} = \frac{N_{\text{clone}} + N_{\text{clone, wrong charge}}}{N_{\text{clone}} + N_{\text{matched}} + N_{\text{wrong charge}}}$$



CAT-Finder finds more tracks as beam background rises but produces more clones.

Impact on physics analysis



The finding gain does not reach the physics result.

How many events survive each analysis stage?

+ 697 events at track finding → -30 after full selection.

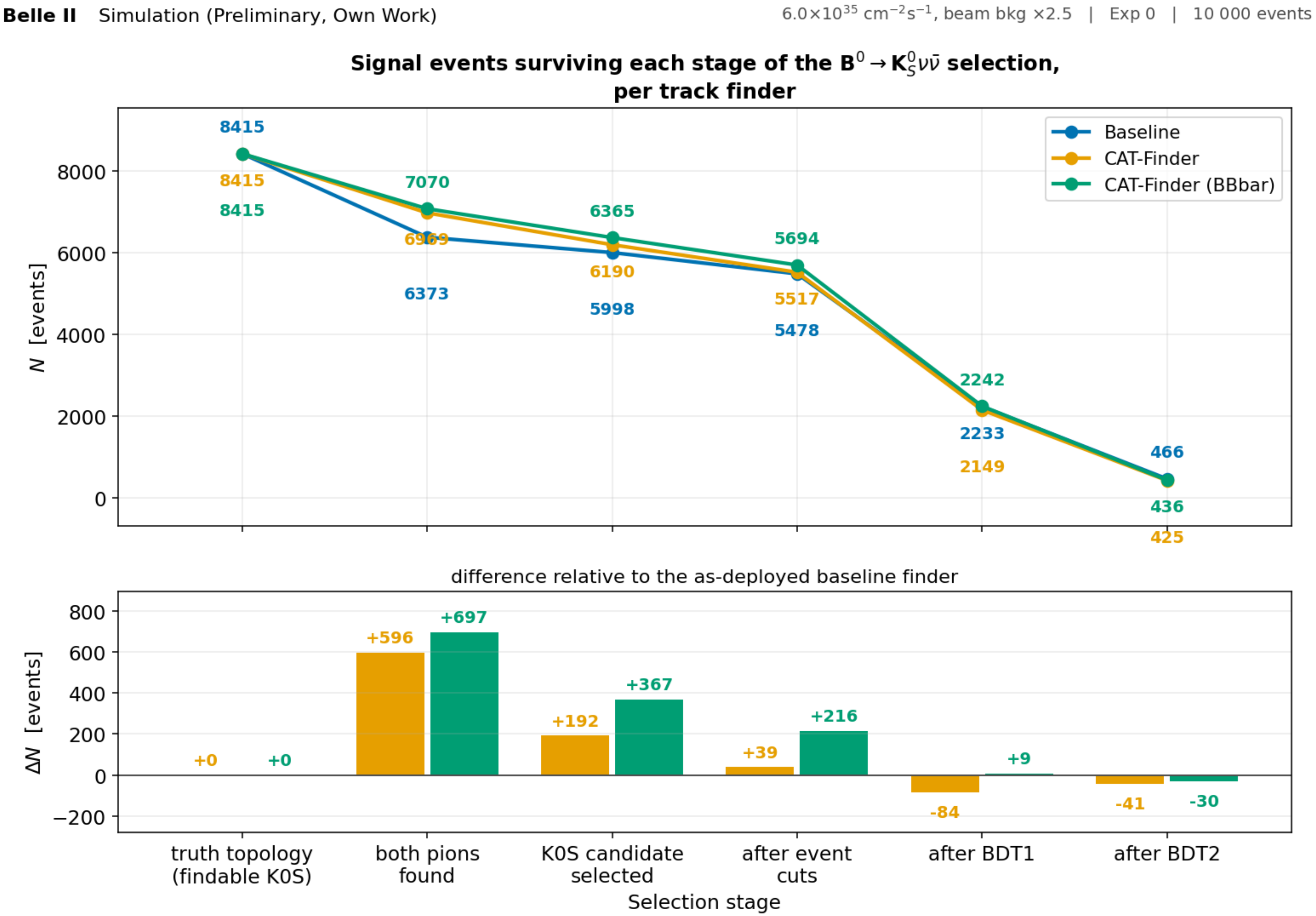
<u>Where the events are lost:</u>

1. CAT-Finder ($B\bar{B}$) loses **roughly double the events** at $\mathrm{K_S^0}$ candidate selection.

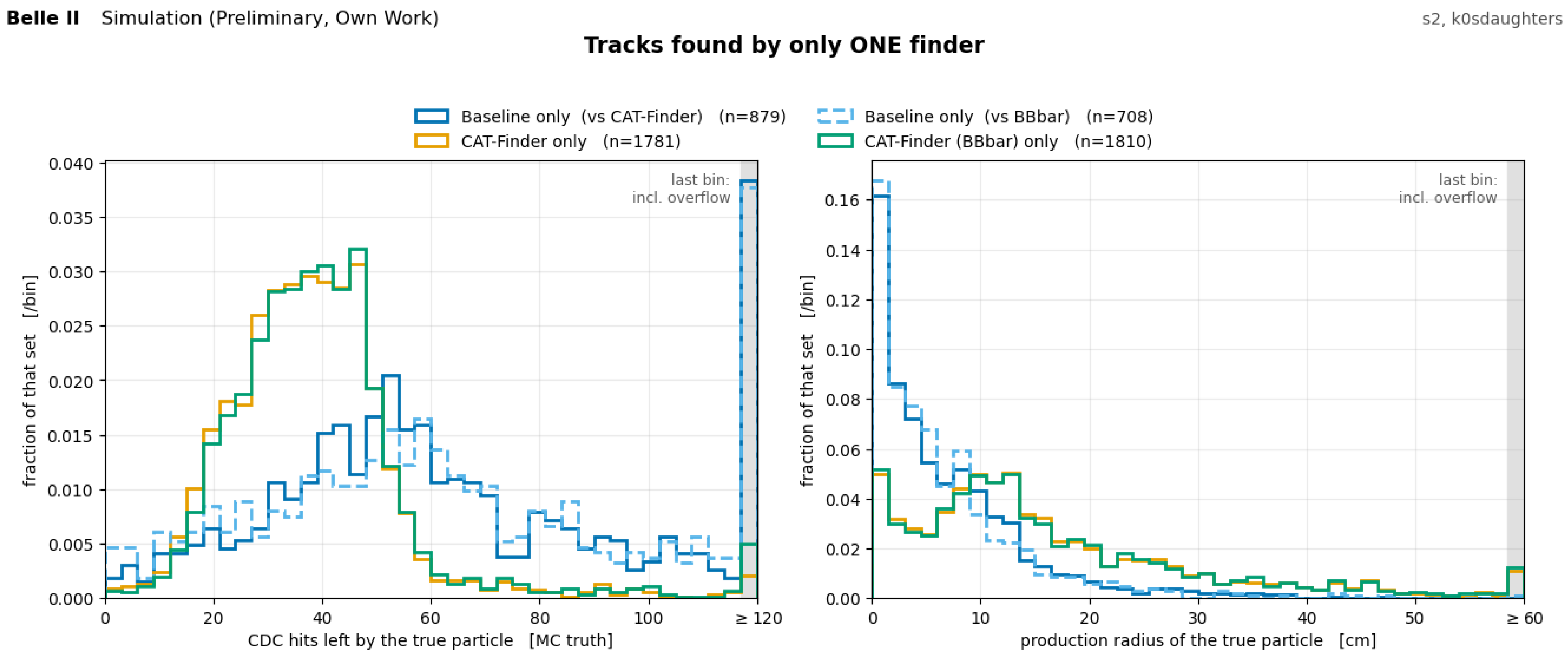
➢ 94.1 % (−375) vs. 90.0 % (−705) retention.

1. BDT1 largest absolute cut in analysis.

➢ 40.8 % (−3245) vs. 39.4 % (−3452) retention.



How do exclusively found tracks differ?



CAT-Finder reaches sparse, displaced tracks.

How do candidates found by both finders compare?

Belle II Simulation (Preliminary, Own Work) 6.0×10^{35} cm^{-2}s^{-1}, beam bkg ×2.5 | Exp 0 | 10 000 events

Medians over the candidates truth-matched in BOTH arms

median, identical particles	Baseline	CAT	CAT (BBbar)
daughter 0 CDC hits	36.5	24	27
daughter 1 CDC hits	38.5	28	31.5
vertex fit chiProb	0.2746	0.0004	0.0052
cos(angle to vertex)	1	0.996	0.9981
daughter 0 pt [GeV]	0.5276	0.539	0.5423
daughter 1 pt [GeV]	0.7127	0.7031	0.7499
K0S mass [GeV]	0.4972	0.4971	0.4977

Same particles but fewer hits → poorer vertex fit.

Implications for the analysis and for CAT-finder

1. Track finding

Does the CAT-Finder find more tracks?

- Track finding efficiency at higher beam backgrounds is improved.
- Clone rate is higher.

2. Physics impact

Does the finding gain reach the physics result?

- K_S^0 selection should be re-examined.
- BDT1 & BDT2 need to be retrained on CAT-Finder tracks.

3. GNN structure and explainability

Why does it behave this way?

- **Open question:** *Why* does the GNN reconstruct these tracks from fewer hits?