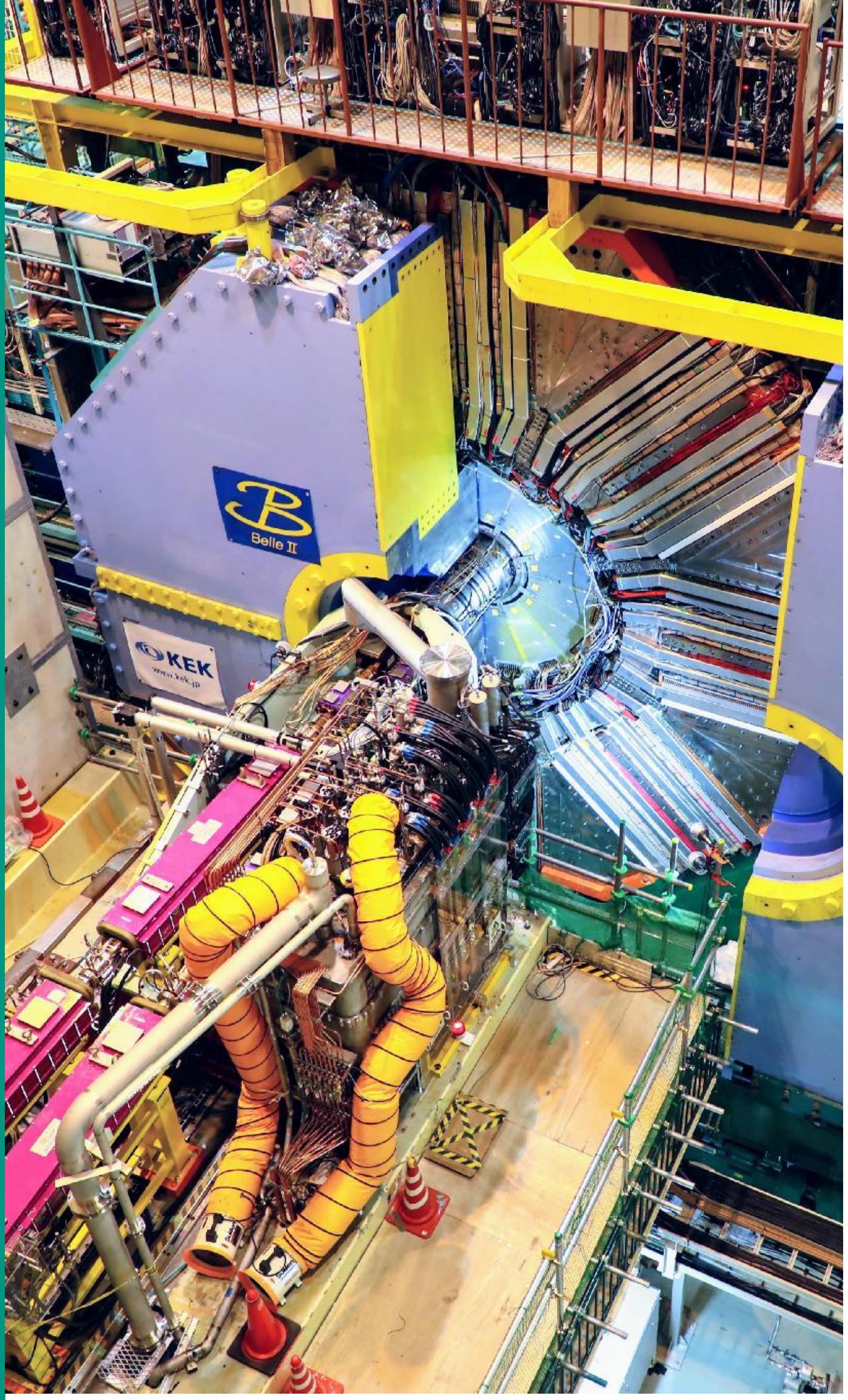
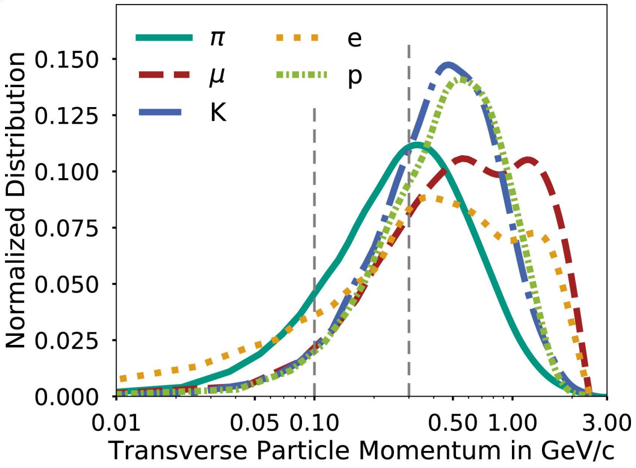
Towards an Implementation of ACTS for Track Fitting in the Belle II Experiment

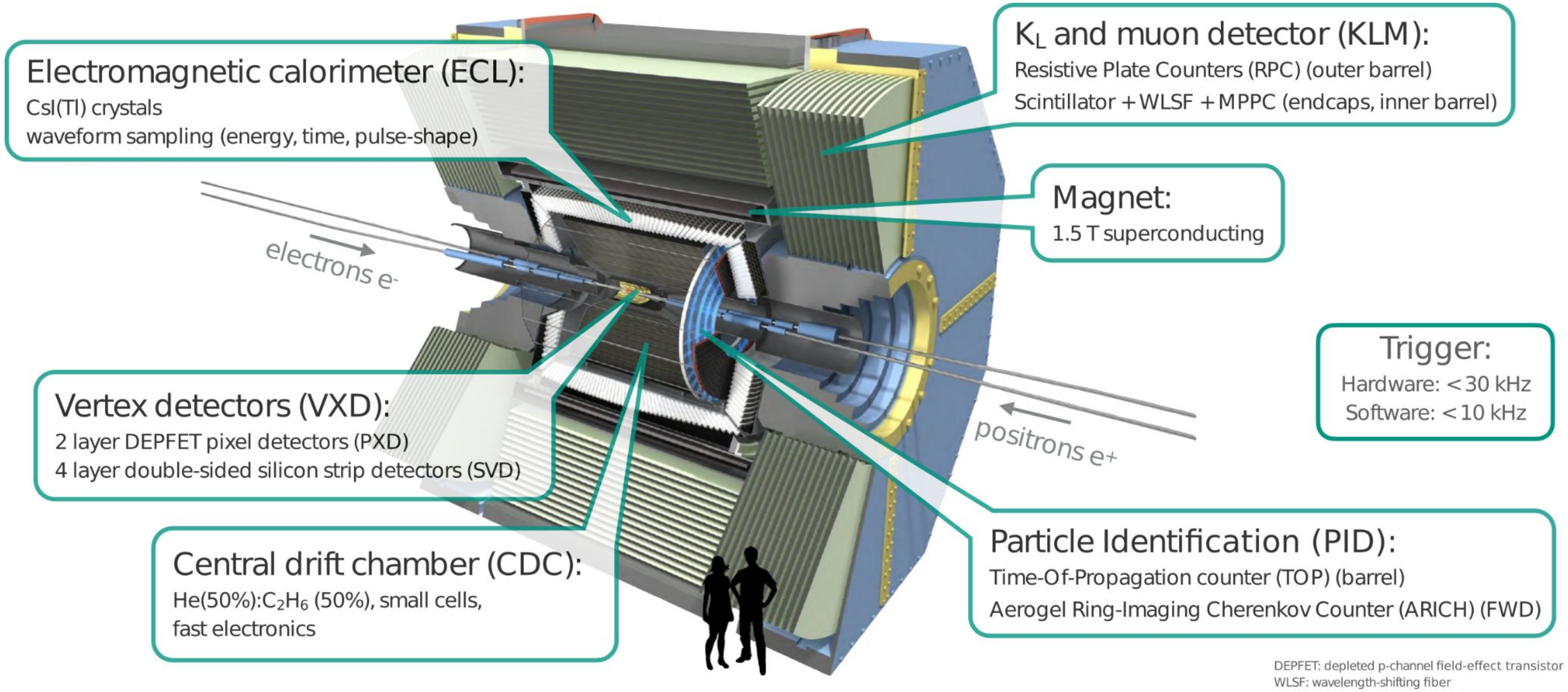


Marc-Philipp Thomas (ucjcv@student.kit.edu),
Giacomo De Pietro, Torben Ferber
24.08.2026

Institut für Experimentelle Teilchenphysik

The Belle II Experiment

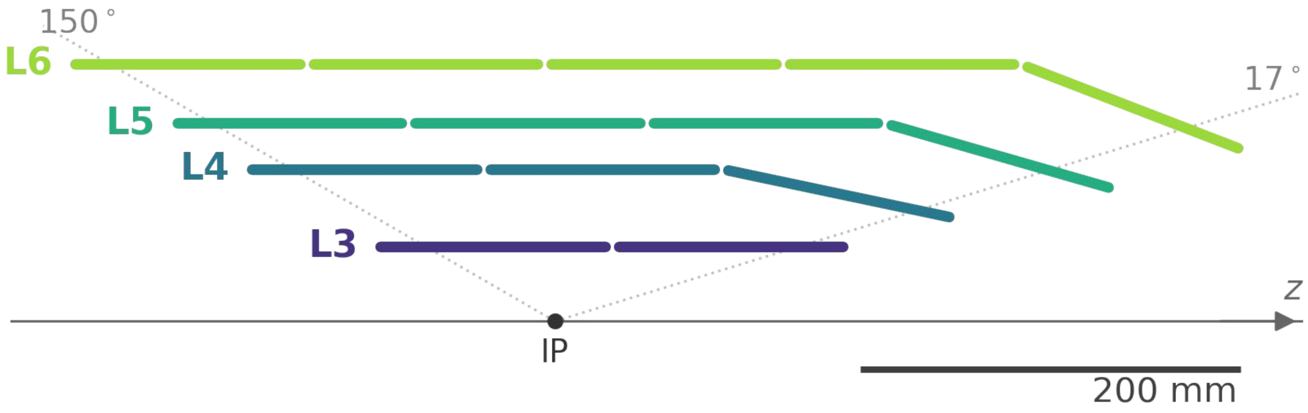


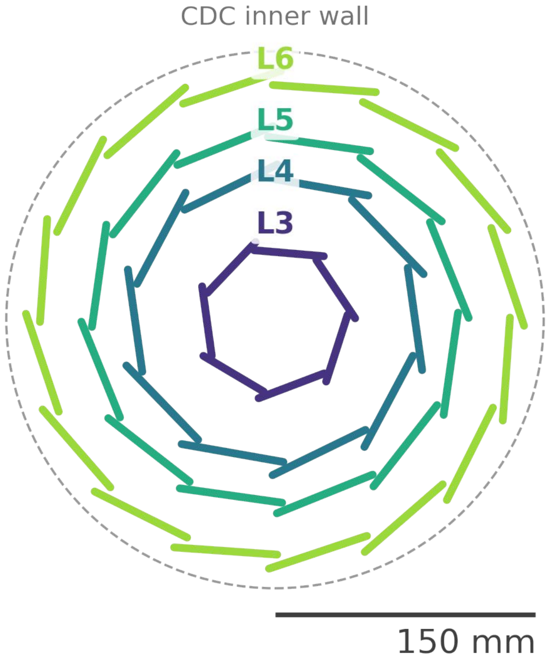


DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

The Belle II Experiment
Silicon Vertex Detector

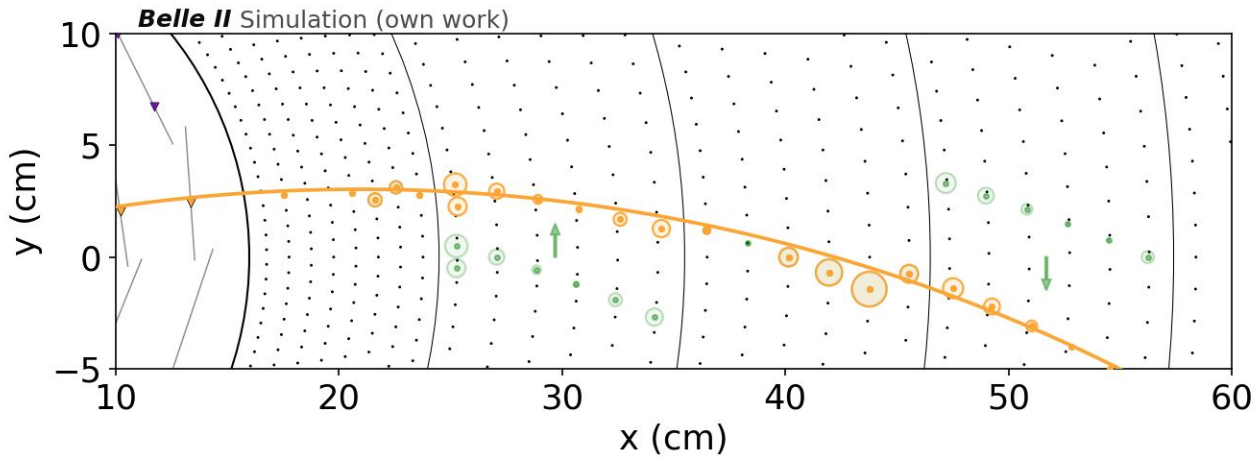
- Vertexing and tracking detector
- 4 layers of double-sided silicon strip sensors
- Enough to perform standalone track reconstruction
- Slanted part required by the asymmetric beam energies of SuperKEKB

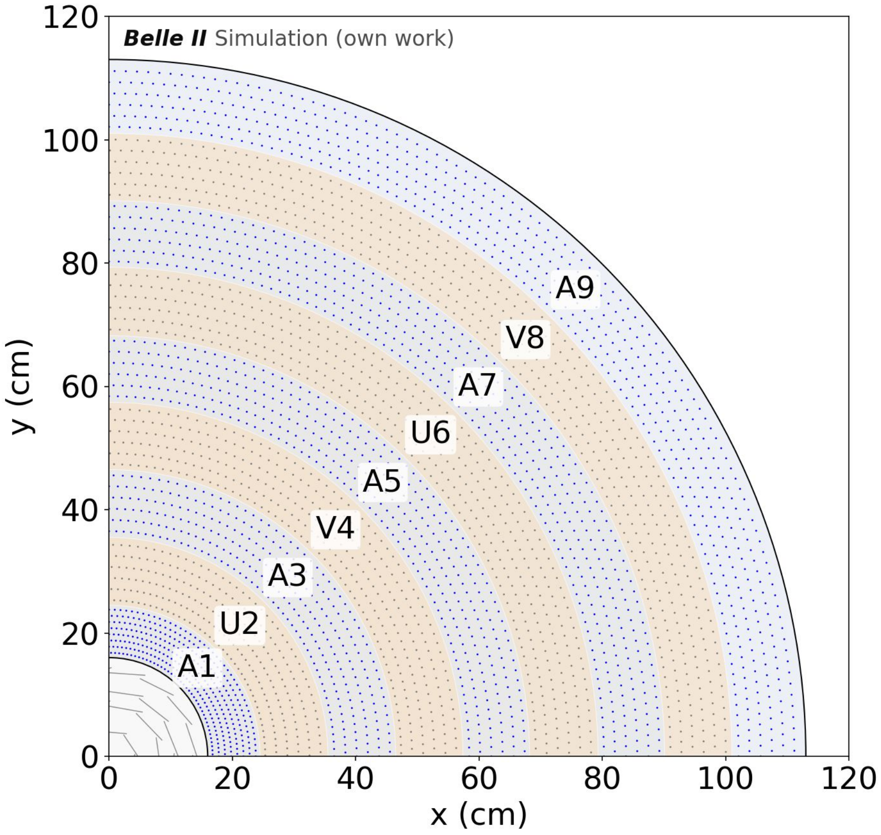




The Belle II Experiment
Central Drift Chamber

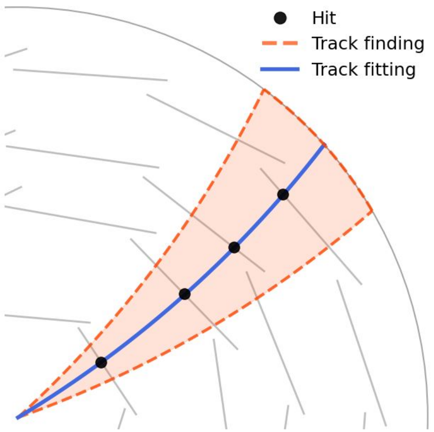
- Main tracking detector in Belle II
- ~14000 Wires organized in 9 Superlayers
- Axial Layers provide r - ϕ information
- Stereo Layers provide z information
- Quantity measured: **Drift-time *t***
  - Drift-radius obtained through calibrated ***x-t*-relation**
  - Drift-radius: Point of closest approach of the particle and the wire



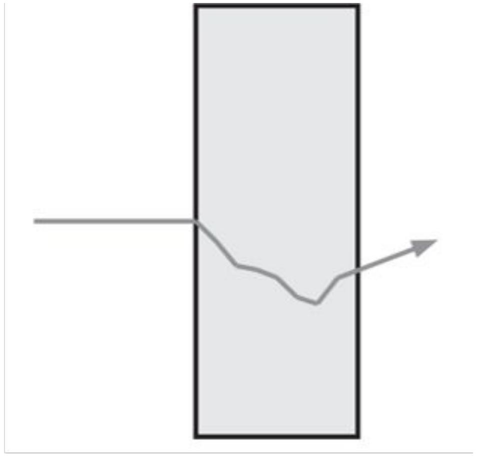


Challenges of Track Fitting

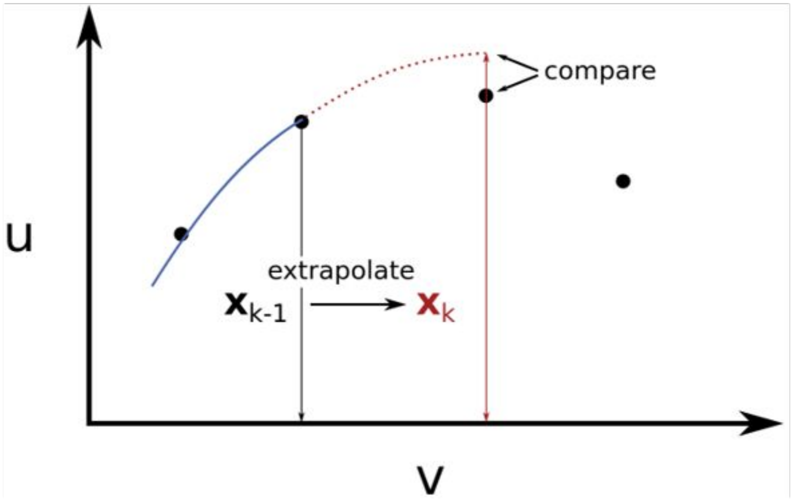
- Multiple scattering: Particles change direction due to interactions with matter
- Magnetic field: The magnetic field is location dependent and not homogenous
- Computing resources: Track fitting involves resource-consuming mathematical operations



Track reconstruction



Multiple scattering

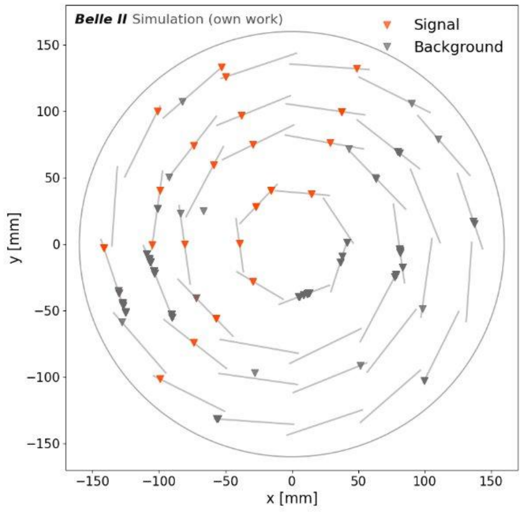


Kalman filter

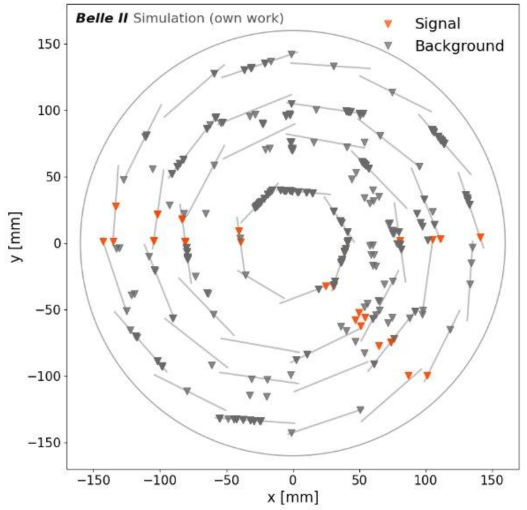
Motivation

- GenFit2* (currently used for fitting in Belle II)
  - No longer actively developed
  - Not designed for modern multi-threading or vectorization
  - Difficult integration of heterogeneous hardware
- Increasing SuperKEKB luminosity and increasing beam background will lead to critical computing time bottlenecks and new requirements:
  - A natively **thread-safe** design
  - **Modular** architecture to easily integrate hardware accelerators and machine learning algorithms

current background



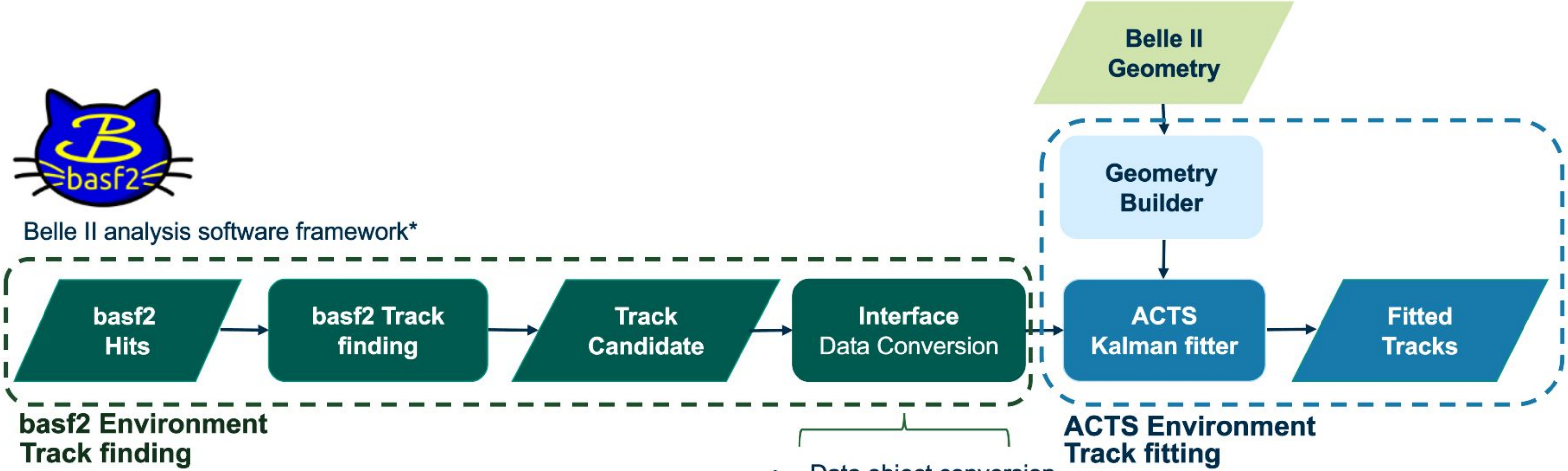
future background



ACTS
A Common Tracking Software

- **Experiment-independent** toolkit for tracking
- **Active R&D**: Hardware acceleration, Machine learning
- **Event Data Model**: Track parameters (l_0, l_1, ϕ, θ, q/p, t)
- **Geometry**: A model of the geometry of the experiment is necessary and needs to be built
- **Material interaction**: Material budget is mapped onto material surfaces
- **Track fitting & finding**: Tools for seeding, finding and fitting

Workflow



- Data object conversion
- Geometry ID mapping
- Track Parameter Transformation

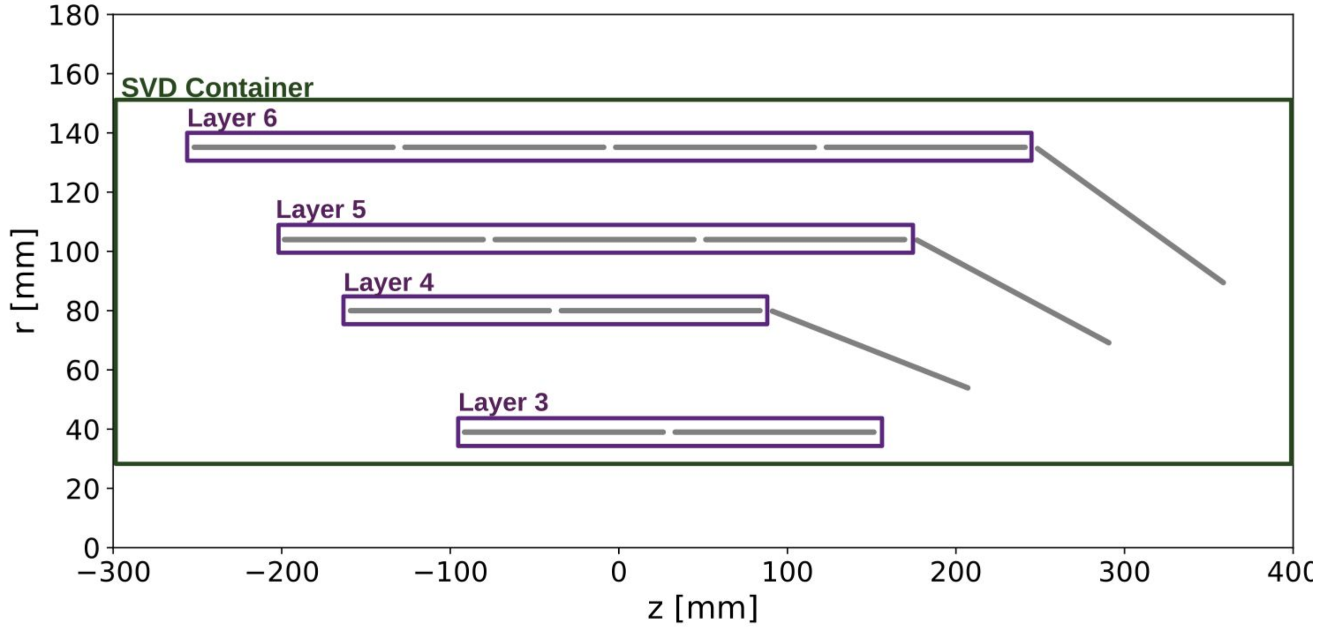
*github.com/belle2/basf2

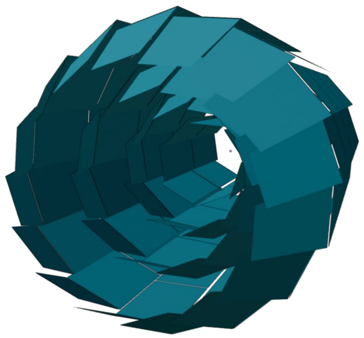
What you need to build a detector in ACTS

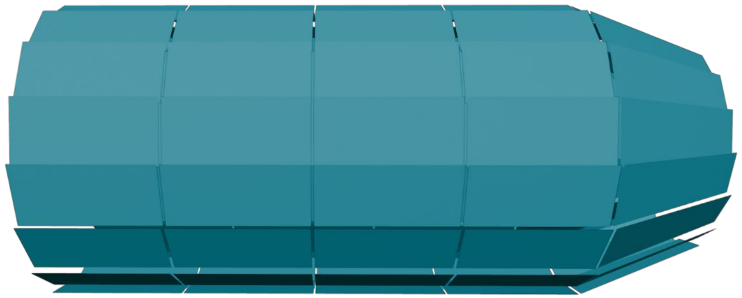
- Simplified ACTS representation of the detectors geometry
- Mapping of the material onto surfaces, to account for material interactions
- Use of the complex magnetic field

Geometry Implementation SVD

- Complex Geometry: Successfully modeled forward slanted sensors
- Sensor Organization:
  - Flat sensors grouped by layers
  - Slanted sensors placed within the mother volume

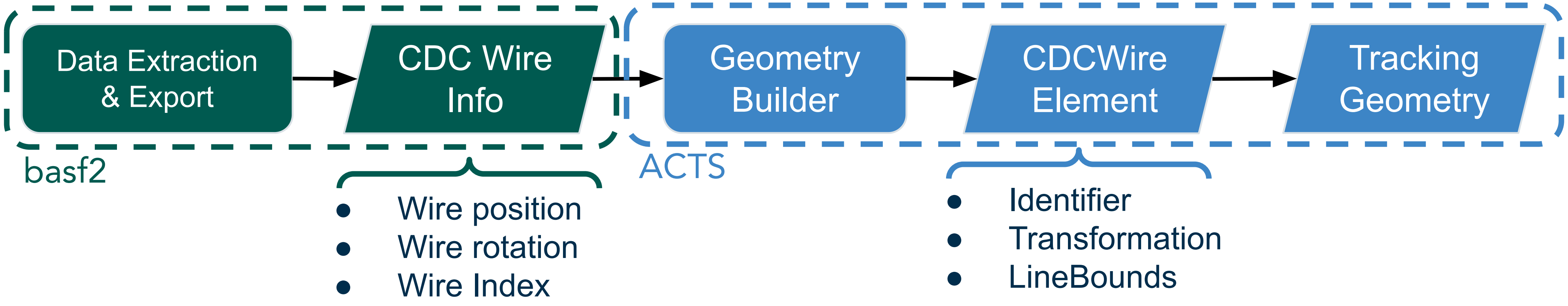






Geometry Implementation: CDC

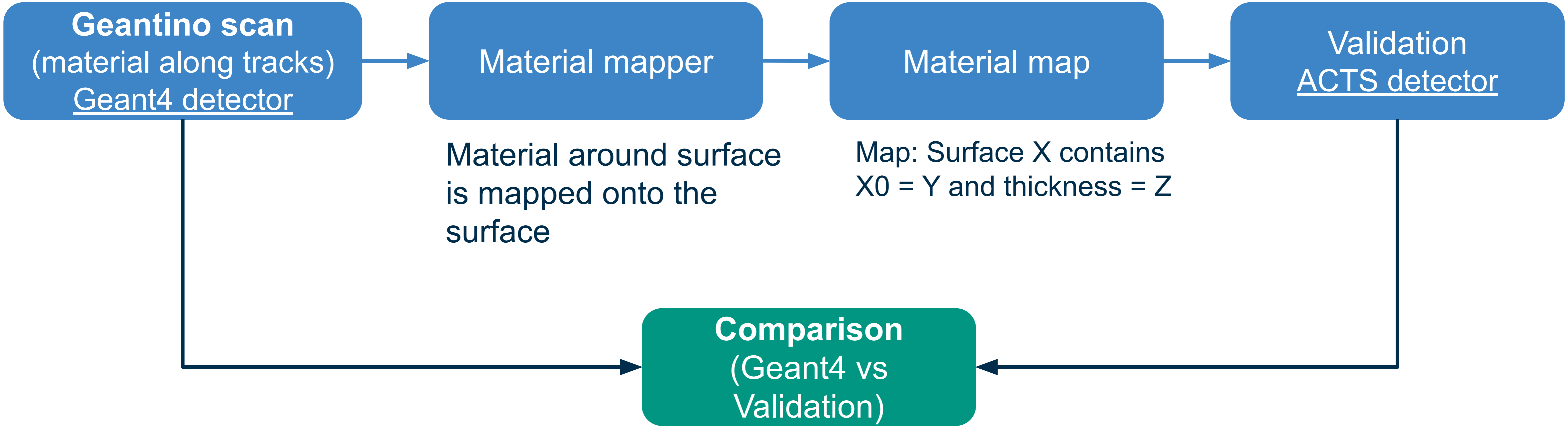
- ACTS was originally not designed for drift chambers, but implementation is possible
- CDC implementation is inspired by Xiaocong Ai*
- Implementation of geometry is straightforward
- Implementation of measurement principles is the hard part



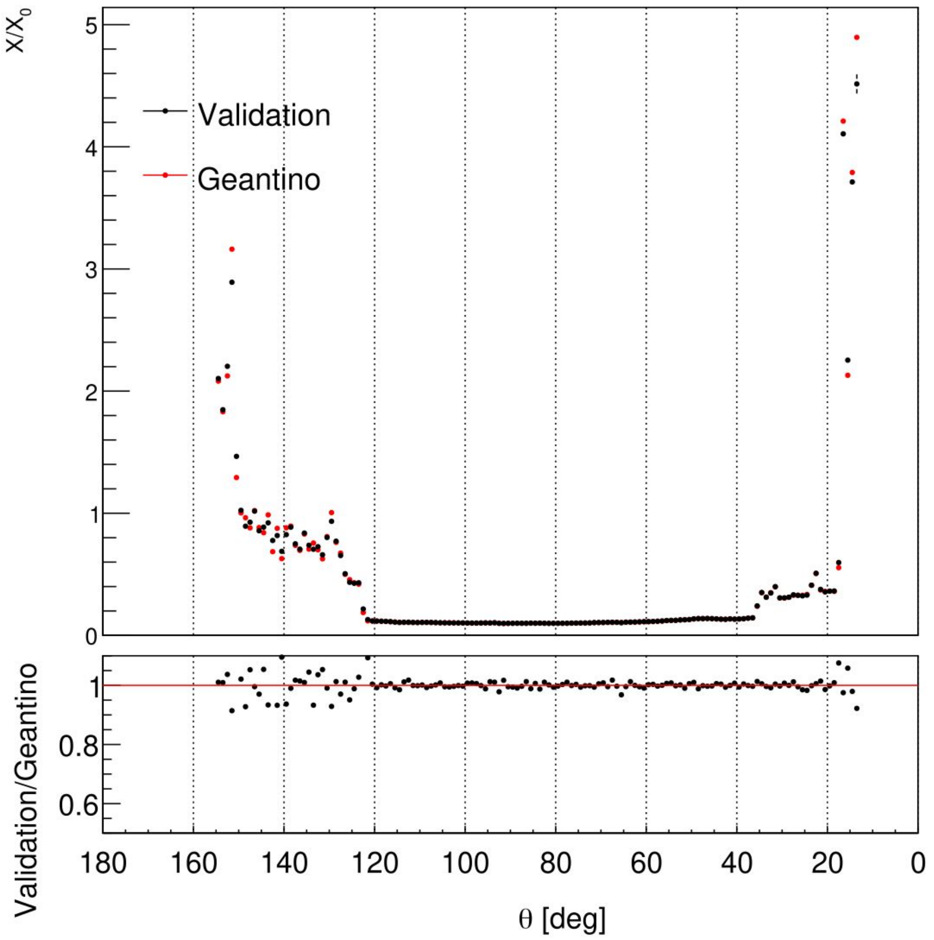
* https://github.com/XiaocongAi

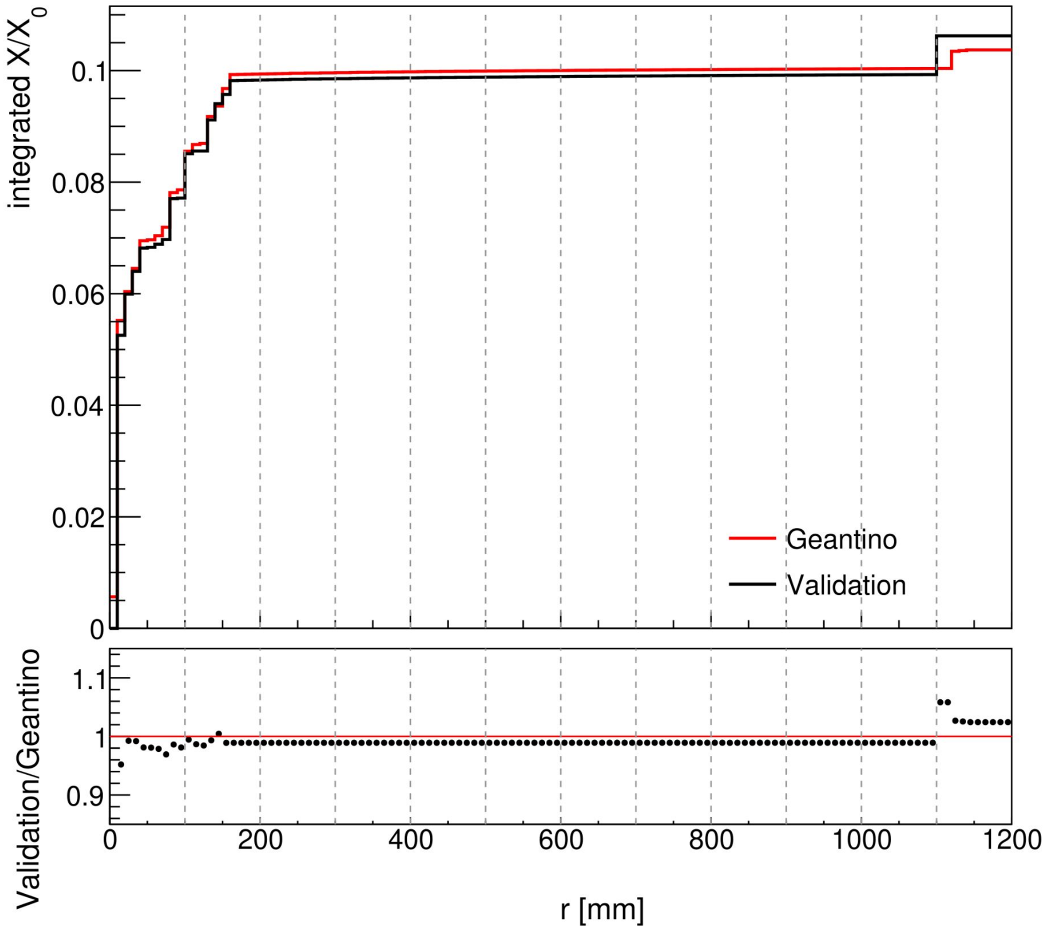
Material Mapping: Workflow

- Objective: Represent the material of the detailed detector (Geant4) geometry onto dedicated surfaces in ACTS



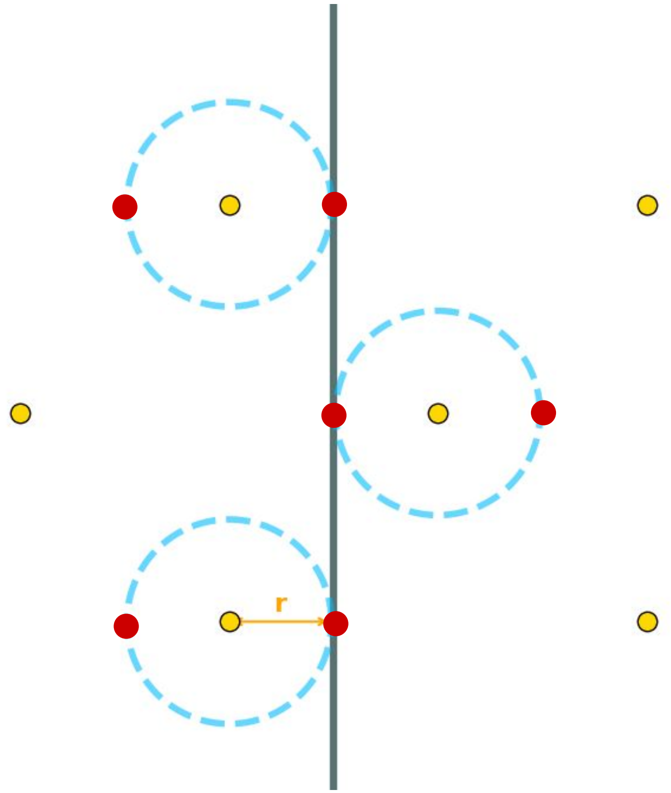
Material Mapping
Beampipe, PXD, SVD, CDC

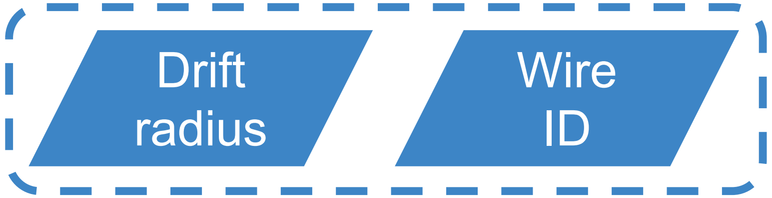




Drift Chambers in ACTS

- **Measurement**: Drift-radius (the x-t-relation is evaluated in basf2)
  - No direct information about direction
- **Problem**: Right-Left-Ambiguity
  - Two possible tangential points for track
- **Solution**:
  - Prediction: Extrapolated track is on the left or right side
  - Decision: Choose Measurement depending on the prediction
  - Robustness is very dependent on the starting parameters of the fit

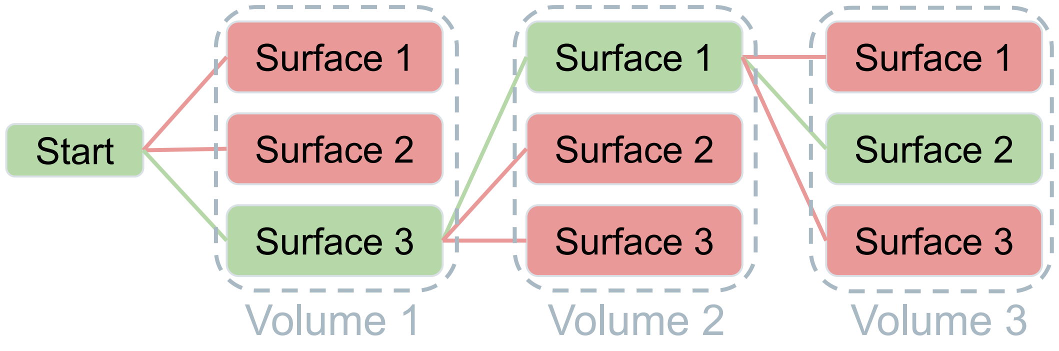




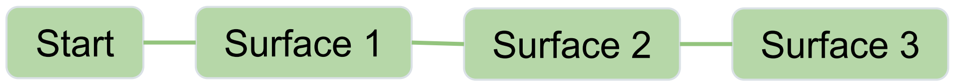
Measurement

Direct Navigation

- Track propagation in ACTS:
  - **Stepper**: solves the equation of motion
  - **Navigator**: Keeps track of the location and volume
- Navigators:
  - Standard Navigation: Hierarchical volume navigation, has to determine which surfaces are relevant for the track
  - Direct Navigation: Receives a list of surfaces (measurement/material) and visits only them
  - Direct Navigation can be used if pattern recognition is already done



Standard Navigation



Direct Navigation

SVD Performance

Simulation:

- 10 000 particle gun pi+ events
- Momentum [0-4] GeV
- 5 Particles/Event

Track finding:

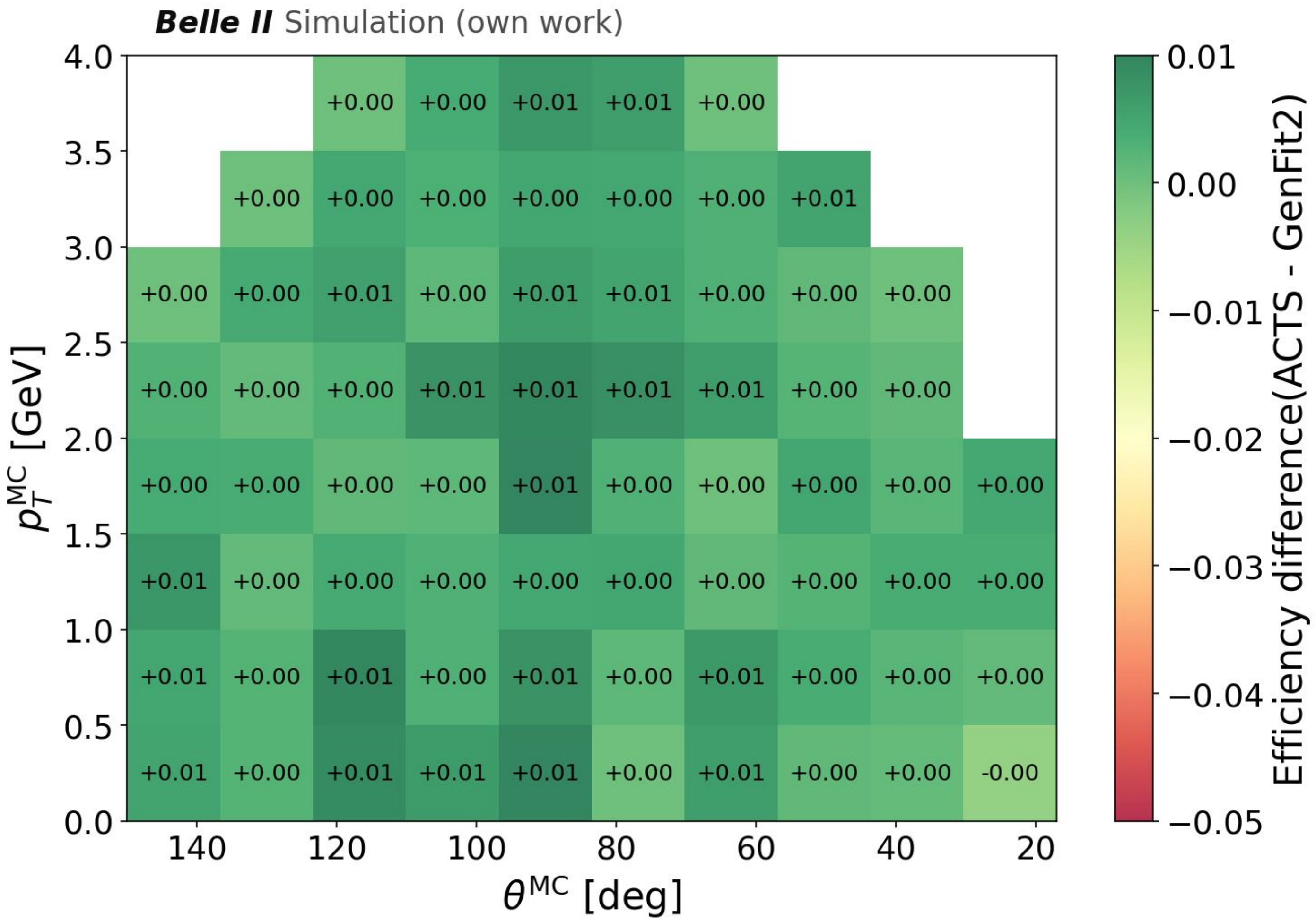
- Performed with basf2

Track fitting:

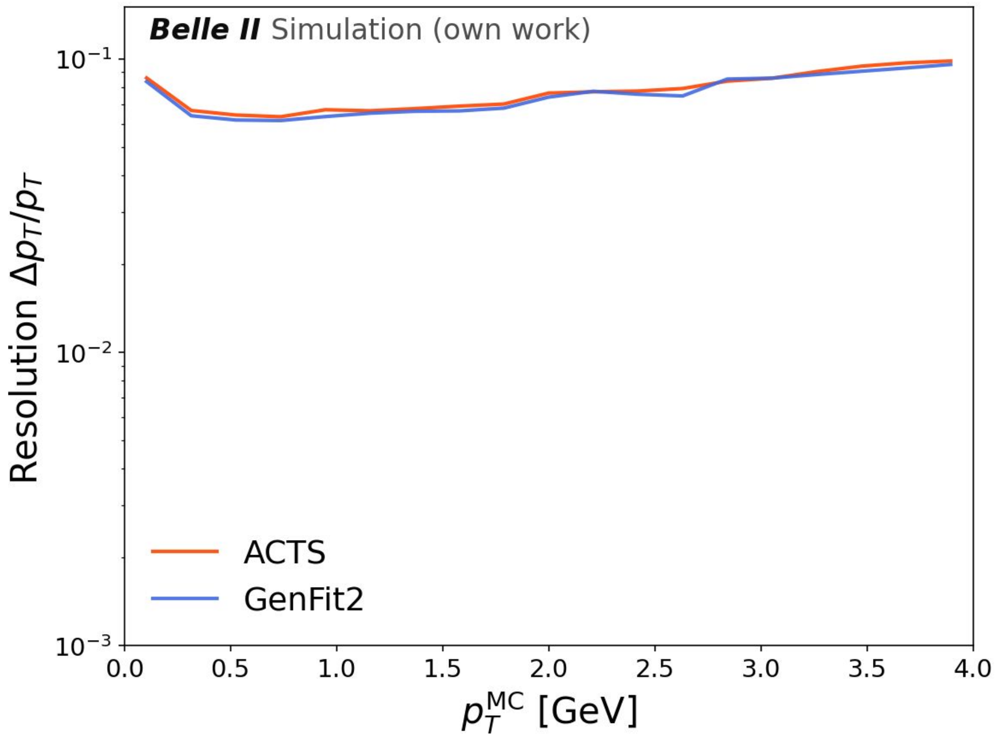
- Performed with ACTS and GenFit2 on the same tracks

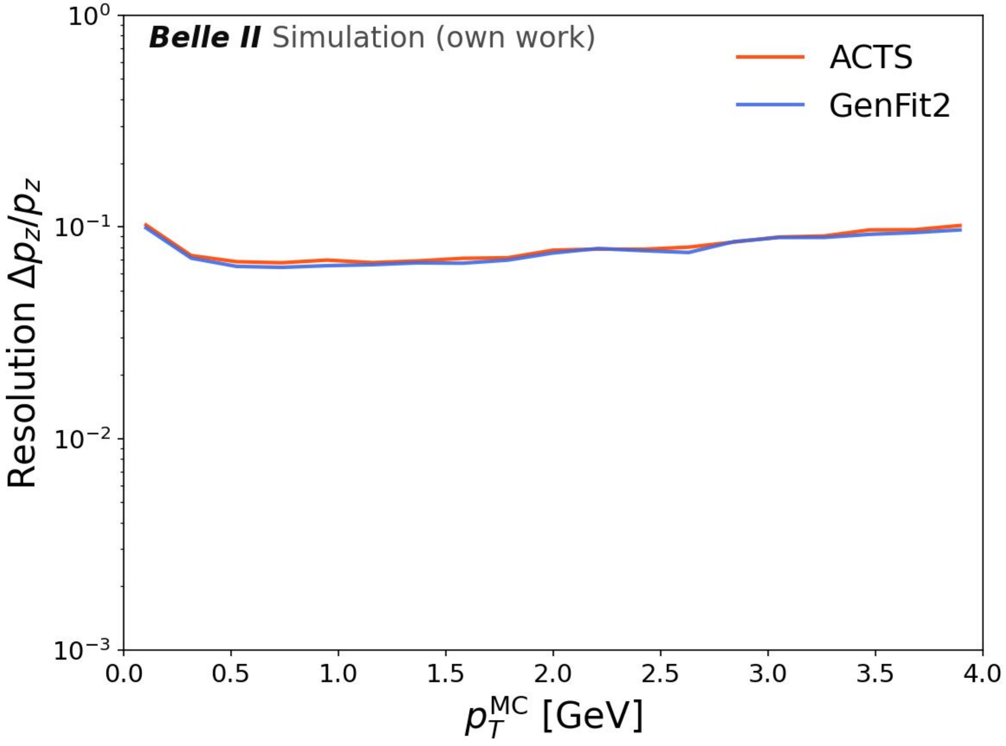
Performance metrics:

- Track fitting efficiency: $\varepsilon_{\text{fit}} = \frac{N_{\text{fitted}}}{N_{\text{found}}}$
- Resolution: $r(p_{\text{T}}) = P_{68\%}\left(\left|\frac{\Delta p_{\text{T}}}{p_{\text{T}}} - P_{50\%}\left(\frac{\Delta p_{\text{T}}}{p_{\text{T}}}\right)\right|\right)$



SVD Performance





Evaluation on B-Events

Simulation:

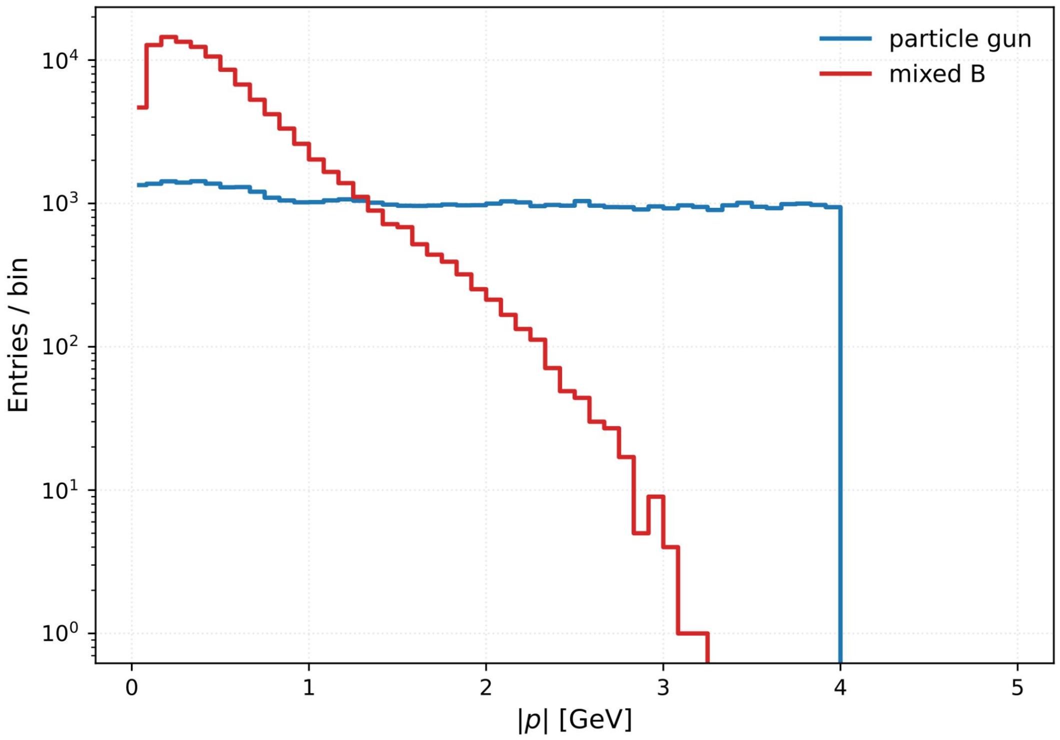
- 10 000 mixed neutral B-events with background

Track finding:

- Performed with basf2

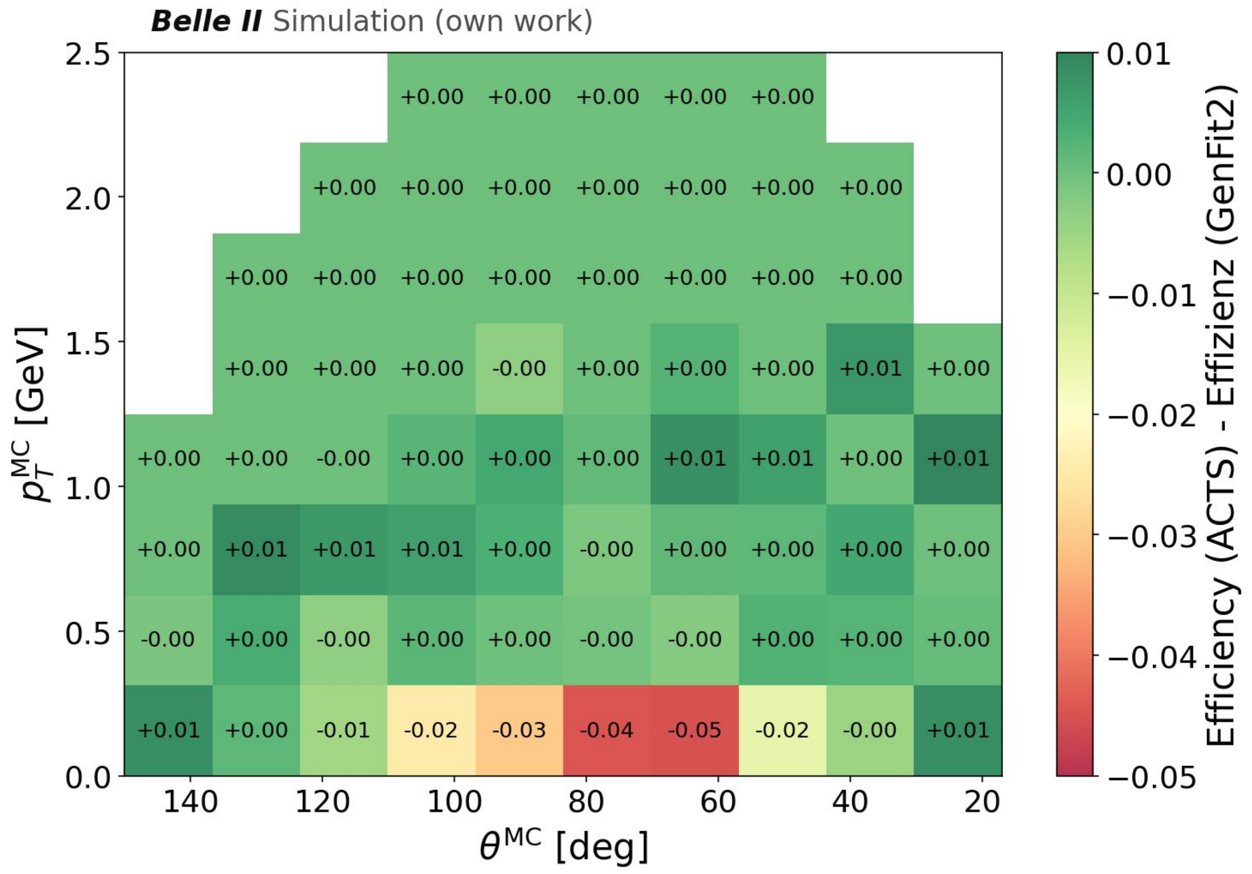
Track fitting:

- Performed with ACTS and GenFit2 on the same tracks



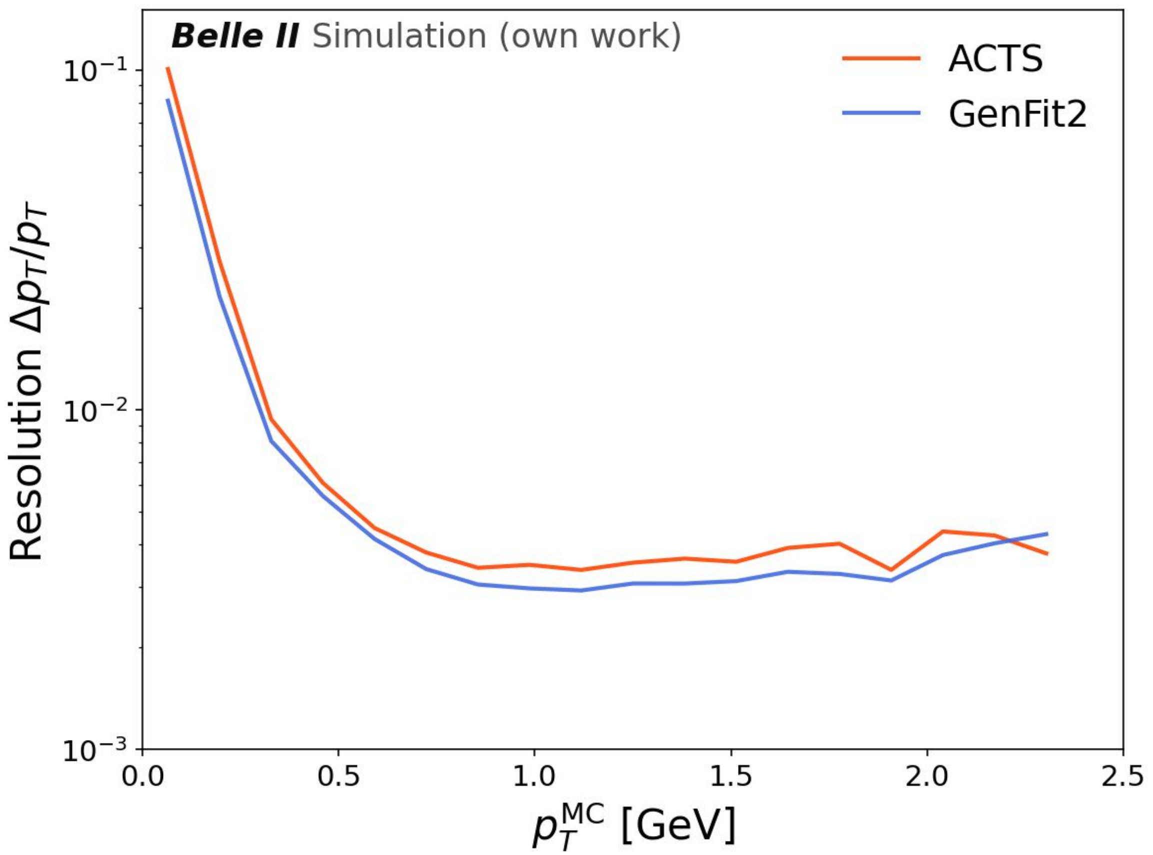
SVD + CDC Performance

- Mixed B-events
- Differences in the low momentum region
  - Fitting works, but extrapolation to the perigee surface doesn’t
  - Direct Navigator is not fully optimized
- ACTS and GenFit2 use different approaches for the extrapolation to the perigee surface
- ACTS has problems especially with low momentum secondary tracks



SVD + CDC Performance

- Overall ACTS resolution is 10-15% worse than GenFit2
- Resolution is worse due to some approximations and differences between the frameworks:
  - x-t-relation is not evaluated during the fit
  - L/R-ambiguity solving is worse than GenFit2's DAF



Runtimes

- Same tracks fitted in both frameworks (particle gun dataset)
- ACTS currently using the standard Kalman Filter with one iteration
- GenFit2 uses the deterministic annealing filter with multiple iterations

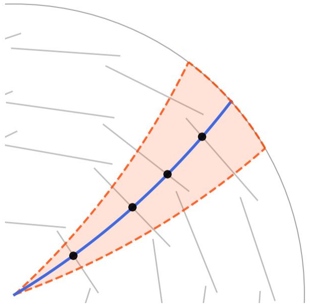
Detectors	Fitter	t (ms/event)
SVD	ACTS (KF), 1 Iteration	1.05 ± 0.02
	GenFit2 (DAF)	3.66 ± 0.02
SVD+CDC	ACTS (KF), 1 Iteration	2.18 ± 0.17
	GenFit2 (DAF)	22.50 ± 0.33

Outlook: GPU Track Fitting with traccc

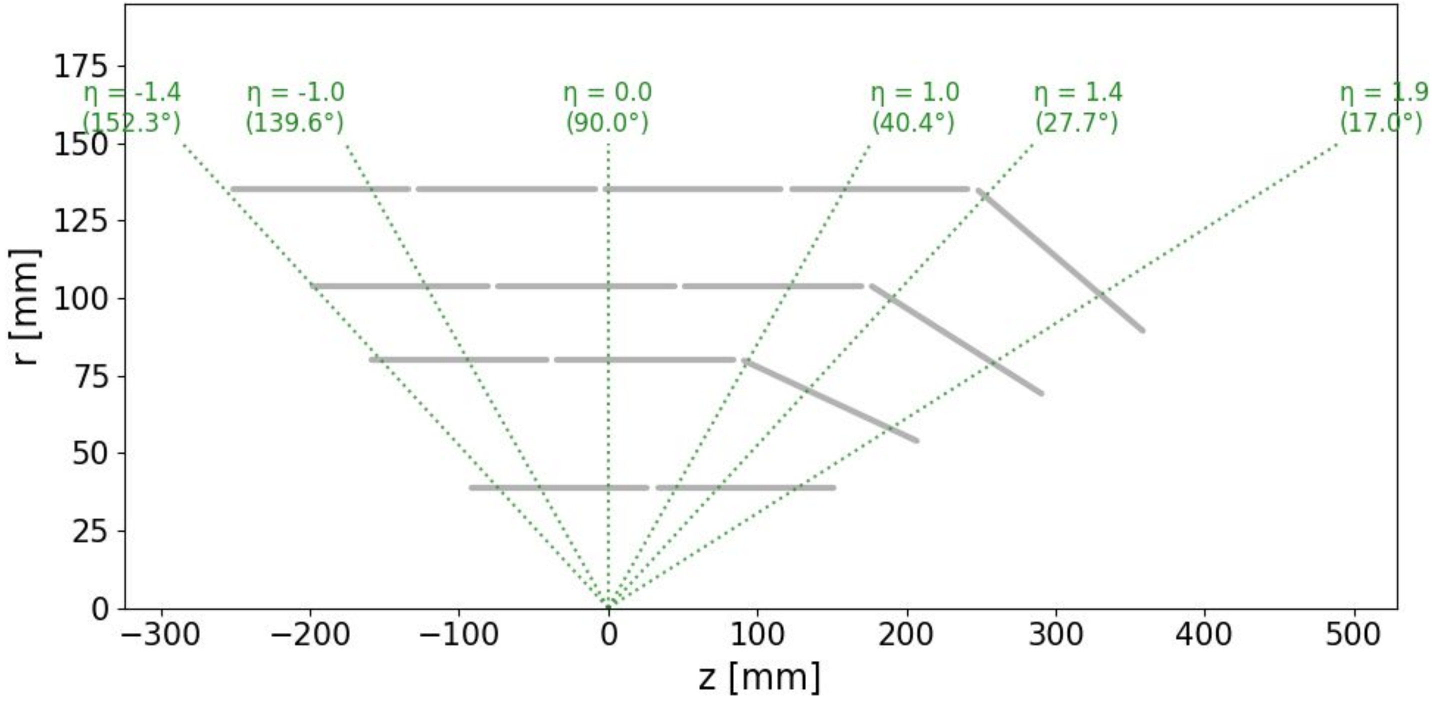
- traccc: Hardware acceleration tracking project and part of the ACTS project
- GPU-friendly memory- and detector-structure
- Proof-of-concept for the SVD: Barrel-SVD fits run on GPUs

Conclusion

- Belle II geometry, magnetic field and material mapping is implemented fully in ACTS
- SVD performs on the same level in ACTS as GenFit2 with less execution time
- CDC performance is slightly worse for ACTS than GenFit2
  - Reasons: Direct Navigator, x-t relation evaluation, no iterations
- GPU acceleration of the SVD track fitting works for the barrel region

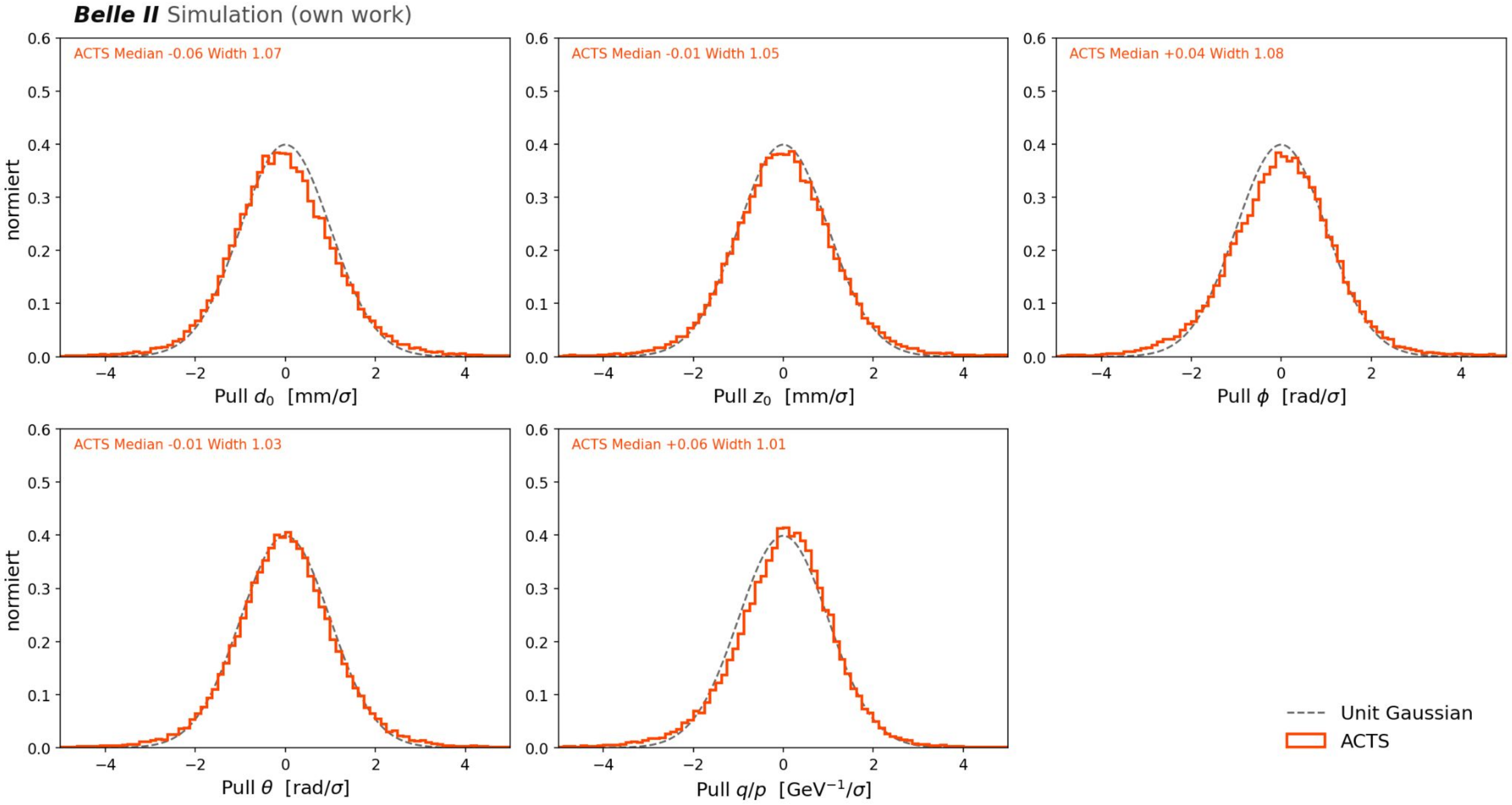


Backup



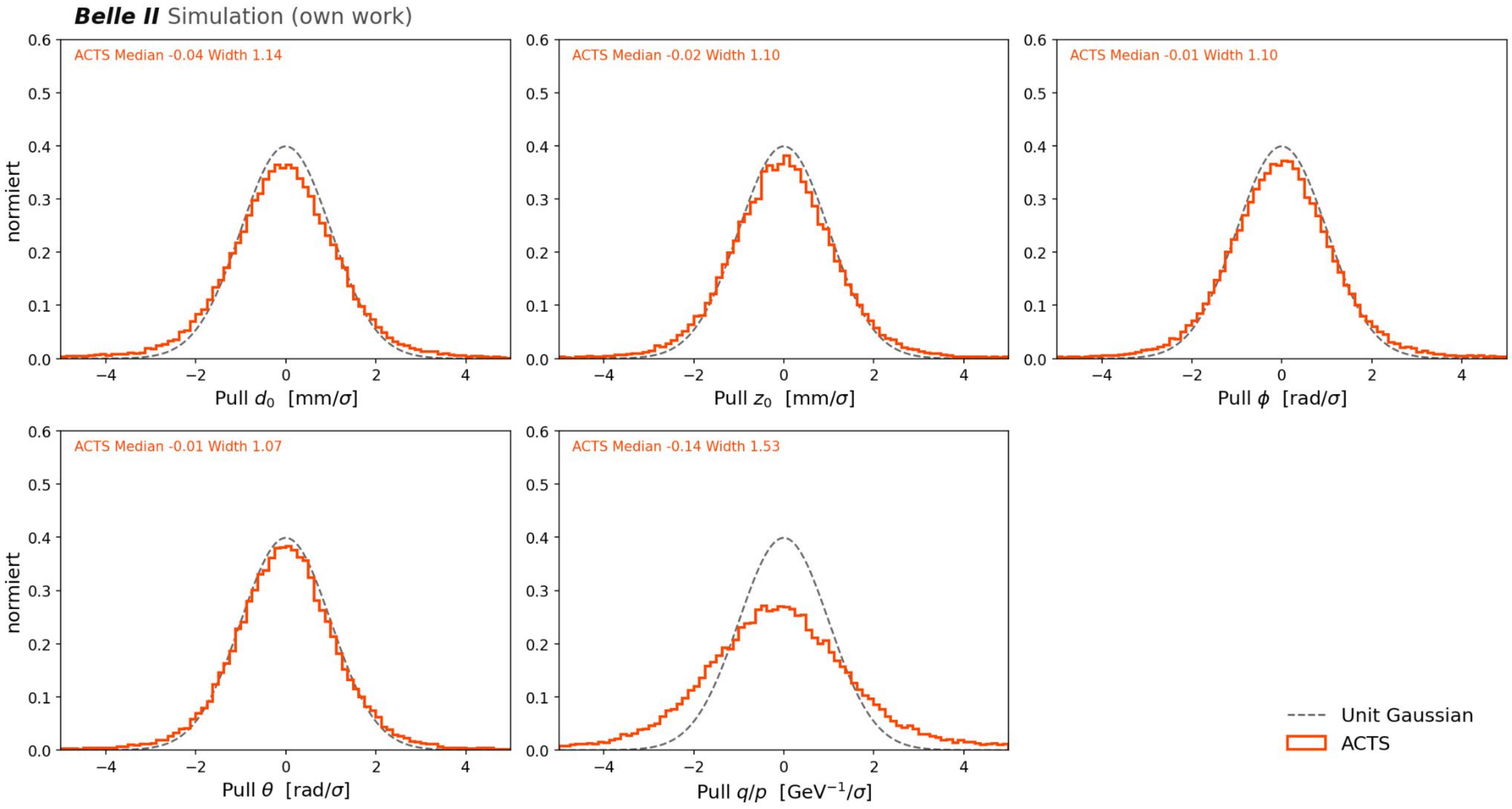
Karlsruhe Institute of Technology

Backup
SVD Pulls



Backup

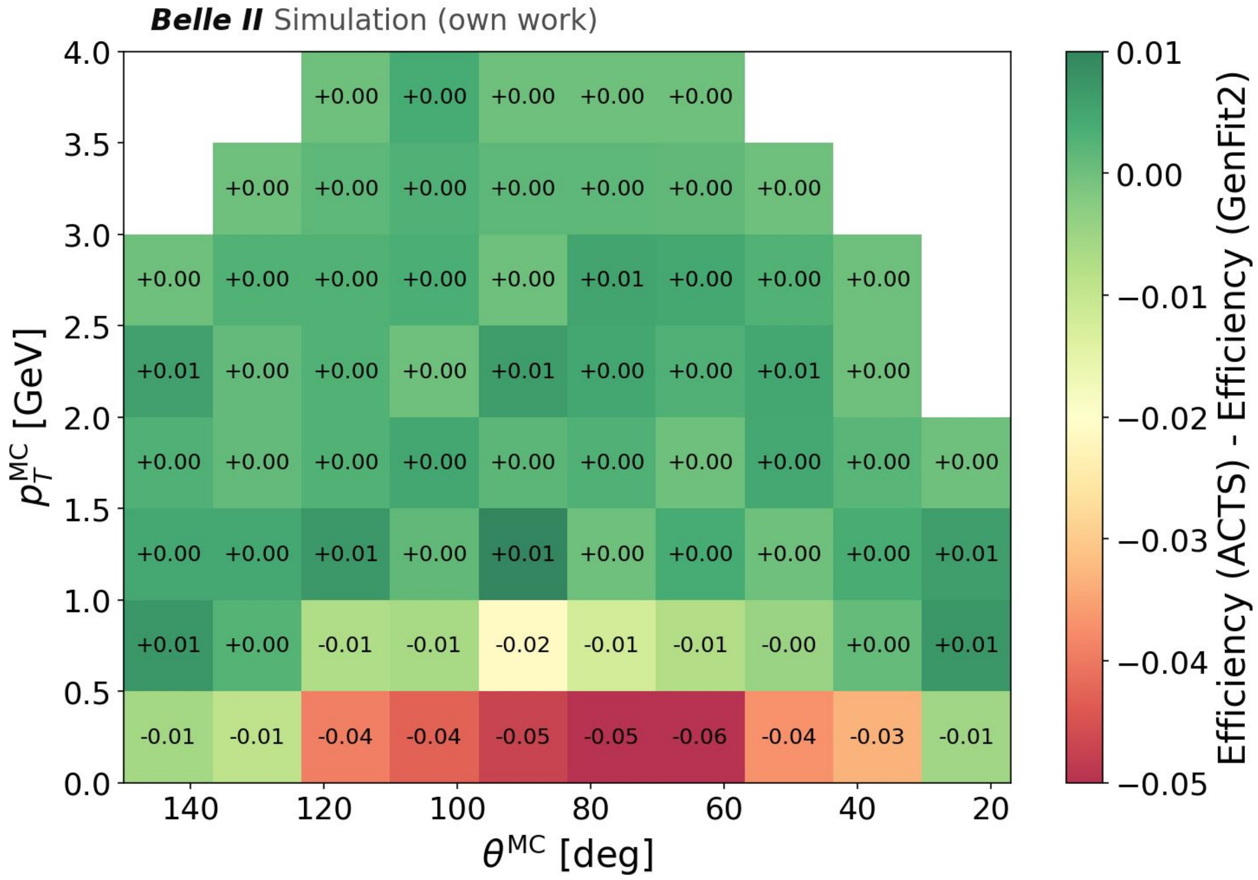
Backup
SVD-CDC Pulls



Karlsruhe Institute of Technology

SVD + CDC Performance

- Particle gun events
- Differences in the low momentum region
  - Fitting works, but extrapolation to the perigee surface doesn’t
  - Direct Navigator needs tuning in terms of surface selection
- ACTS and GenFit2 use different approaches for the extrapolation to the perigee surface
- ACTS has problems especially with low momentum secondary tracks



SVD + CDC Performance

- Overall ACTS resolution is 10-20% worse than GenFit2
- Resolution is worse due to some approximations and differences between the frameworks:
    - x-t-relation is not evaluated during the fit
    - L/R-ambiguity solving is worse than GenFit2
    - Direct Navigation is not fully optimized