A 3D Track Finder for the Belle II CDC L1 Trigger

Sebastian Skambraks

Max Planck Institute for Physics

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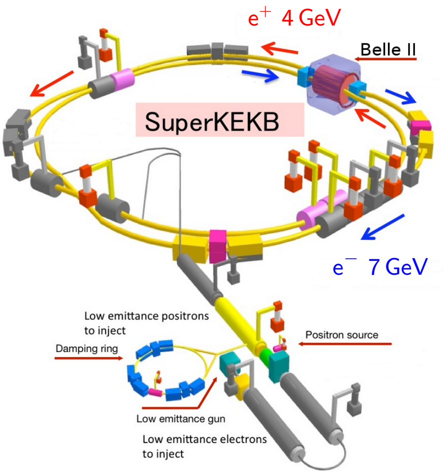
Outline

Introduction - Belle II at SuperKEKB

located in Tsukuba, Japan at **KEK**

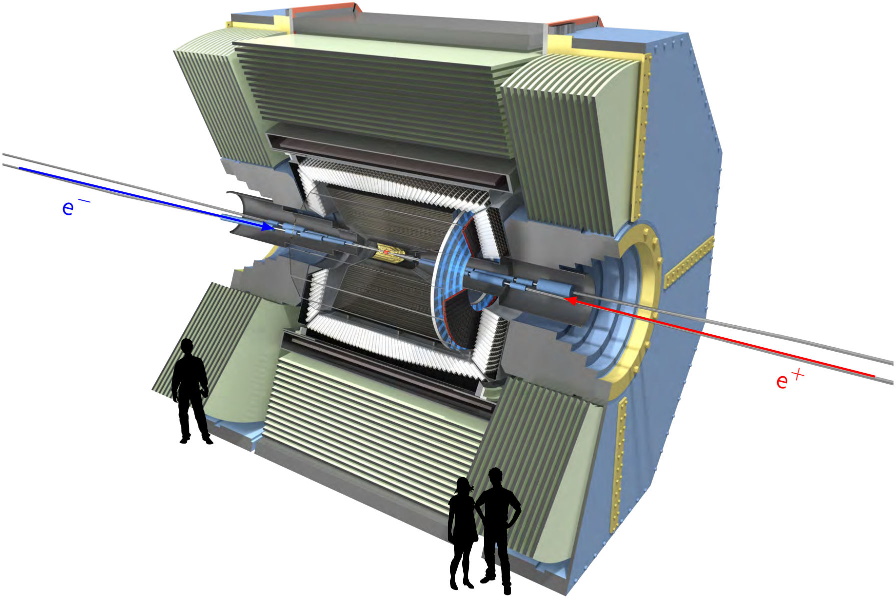
高エネルギー加速器研究機構
Kō **E**nerugī **K**asokuki kenkyū kikou

High Energy Accelerator Research Organization



- asymmetric $e^+ e^-$ collider
- $\Upsilon(4S)$ resonance
  ↳ $B^0 \overline{B}^0 / B^+ B^-$
- $\mathcal{L} = 8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (40× KEKB)
- average p_T: 500 MeV
- average track multiplicity: 11

Introduction - The Belle II Detector



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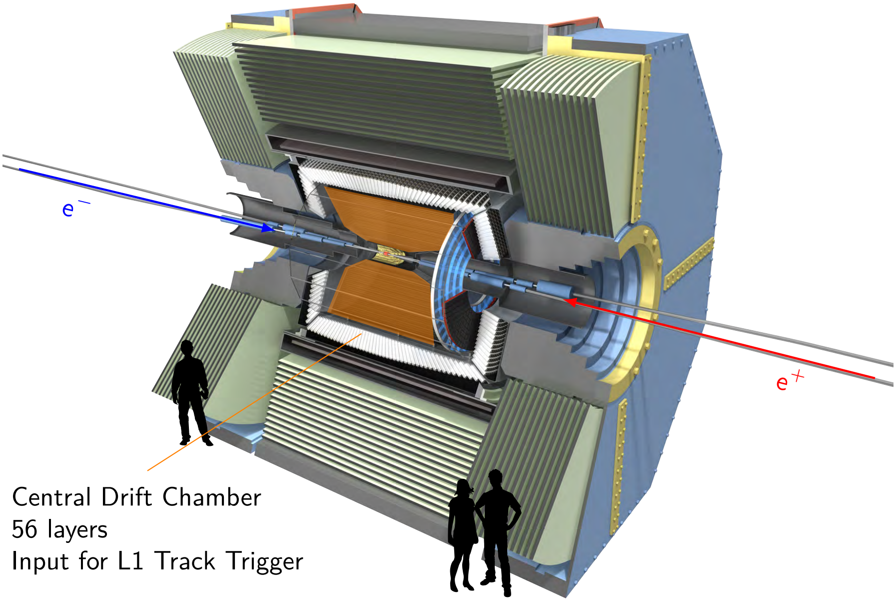
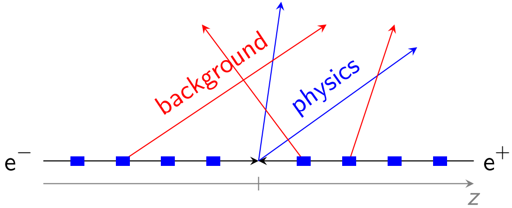


Central Drift Chamber
56 layers
Input for L1 Track Trigger

Introduction - Belle II Background

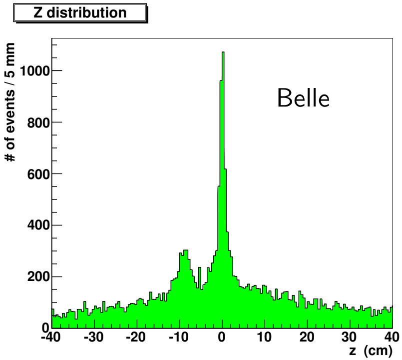
Beam Background Tracks



- tracks generated at the beam-line & -wall with vertices $z \neq 0\,\text{cm}$
- increase with luminosity
- main processes:
  - Touschek effect
  - radiative Bhabha back scatters
  - beam gas

NeuroTrigger Goals

- reject tracks from $z \neq 0\,\text{cm}$
- single track z-vertex resolution $< 2\,\text{cm}$
- latency $< 1\,\mu\text{s}$



$\Rightarrow$ need z vertex reconstruction at 1st trigger level

Introduction - Belle II Background

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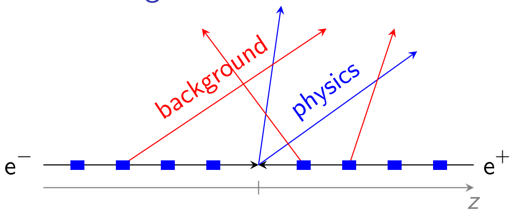

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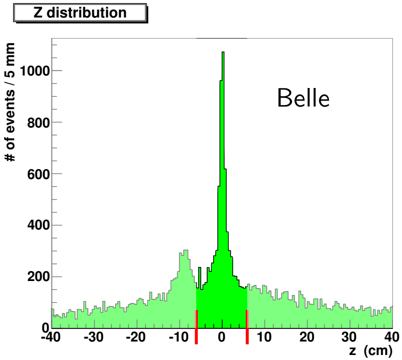
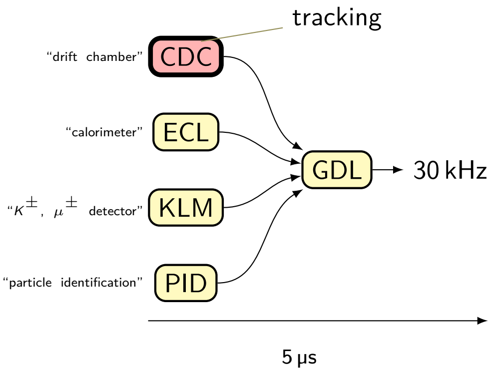


$\Rightarrow$ need z vertex reconstruction at 1$^{\mathrm{st}}$ trigger level

Introduction - Belle II First Level Trigger

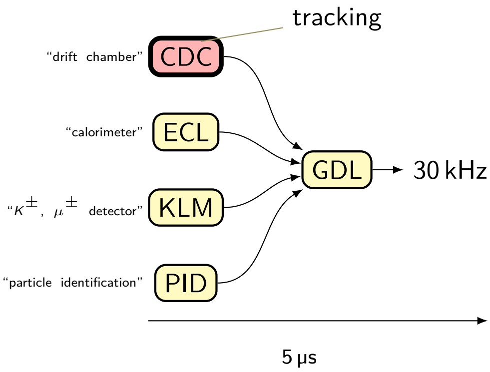


Requirements

- 30 kHz trigger rate
- 5 µs latency

⇒ deadtime-free pipelined operation

Introduction - Belle II First Level Trigger



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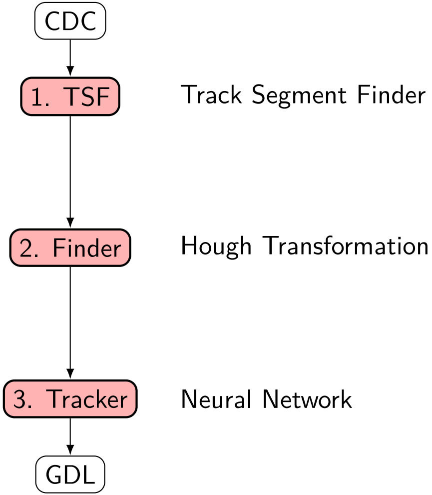
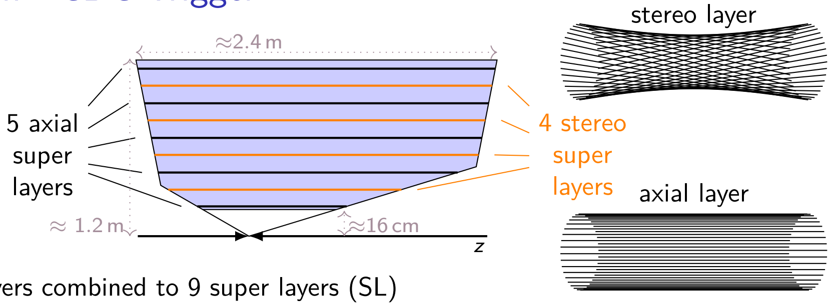
CDC Trigger Pipeline



Introduction - CDC Trigger

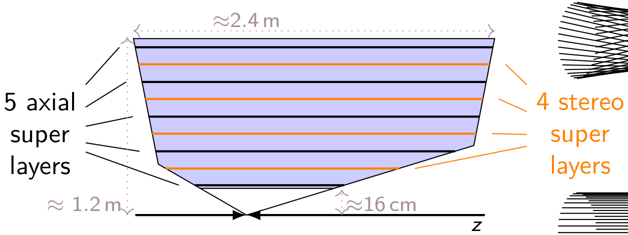


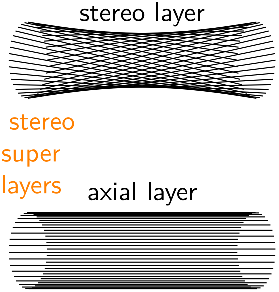
- 56 layers combined to 9 super layers (SL)
- 2336 track segments (TS) in 9 SL

SL	angle (mrad)
2	45.4 – 45.8
4	-55.3 – -64.3
6	63.1 – 70.0
8	-68.5 – -74.0

Stereo SL configuration

Introduction - CDC Trigger





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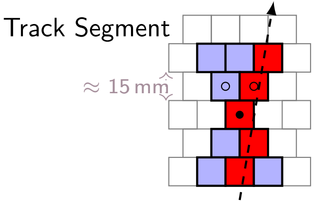
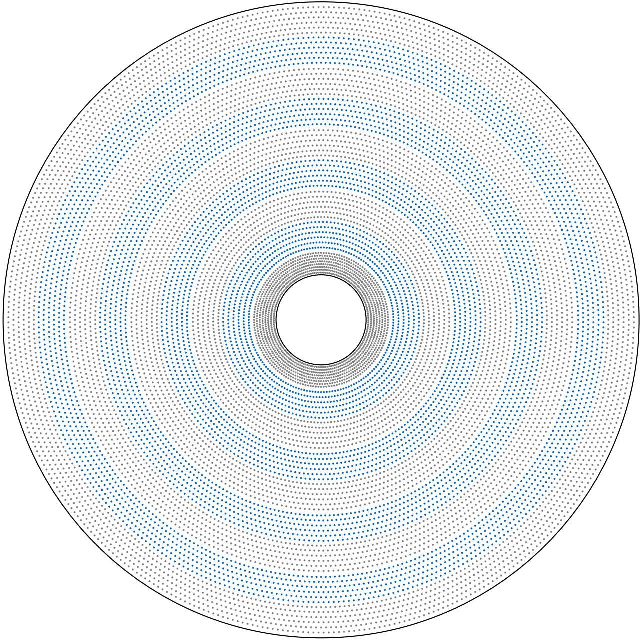


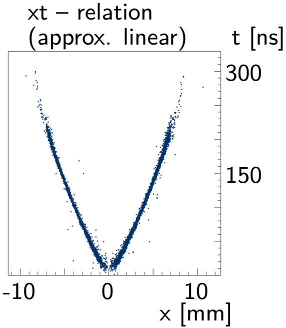
NeuroTrigger Input

- position, drift time and left/right information of TS priority wires
- 2D track estimates (p_T, φ)

Introduction - CDC Trigger



- axial layers
- stereo layers



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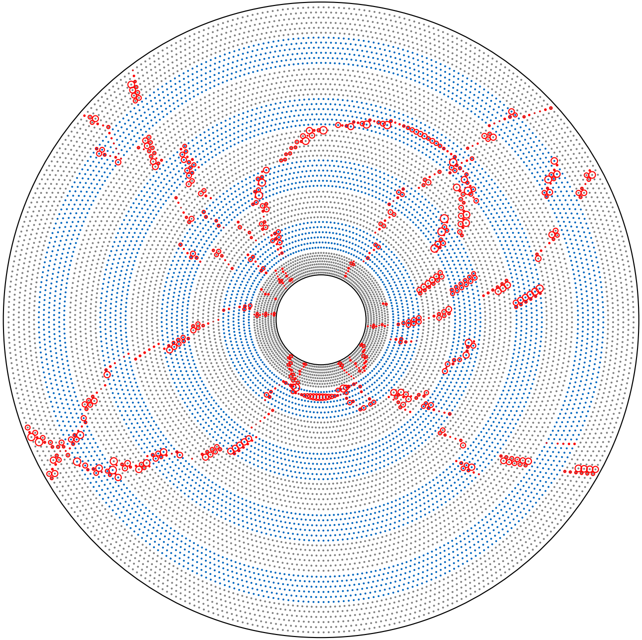
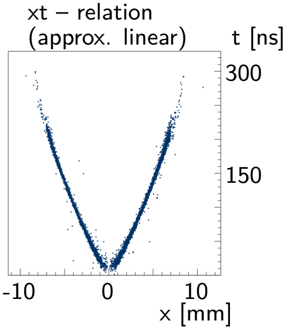


- axial layers
- stereo layers
- $\Upsilon(4S)$ Event



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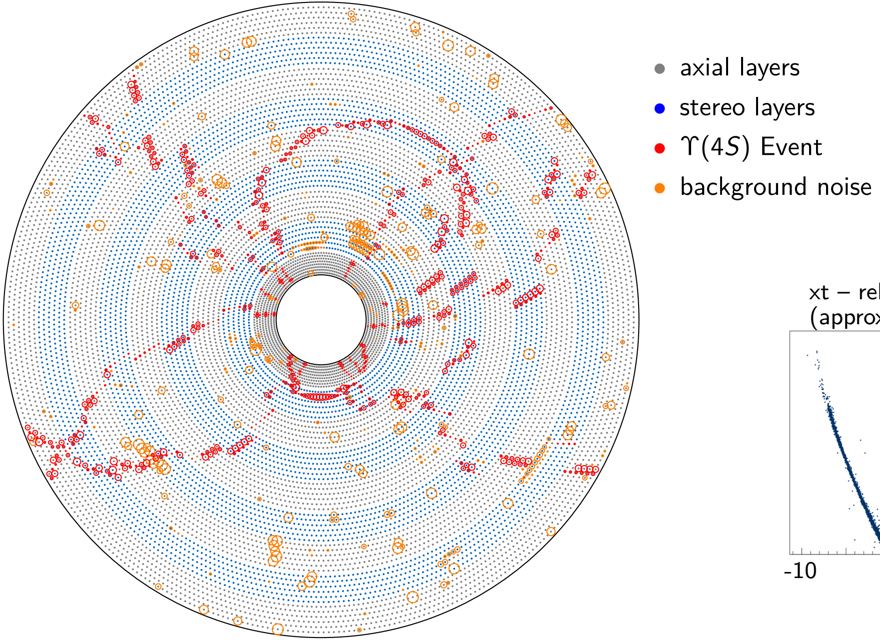

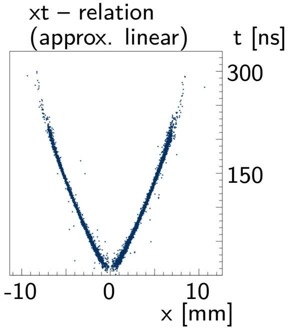

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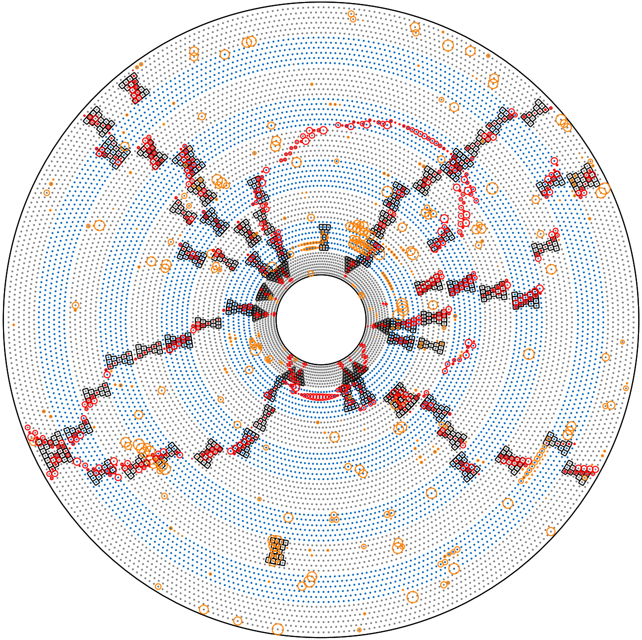
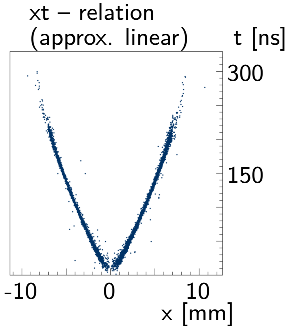


- axial layers
- stereo layers
- $\Upsilon(4S)$ Event
- background noise
- track segments (TS)



NeuroTrigger - Multi Layer Perceptron

Properties

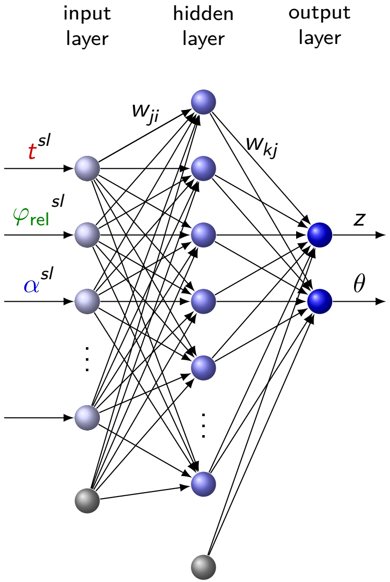
- robust function approximator
- massively parallel processing
- short deterministic runtime
- neuron: $y = \tanh(w_i x_i + w_0)$
- network: $z_k = f(w_{kj} f(w_{ji} x_i))$

Training

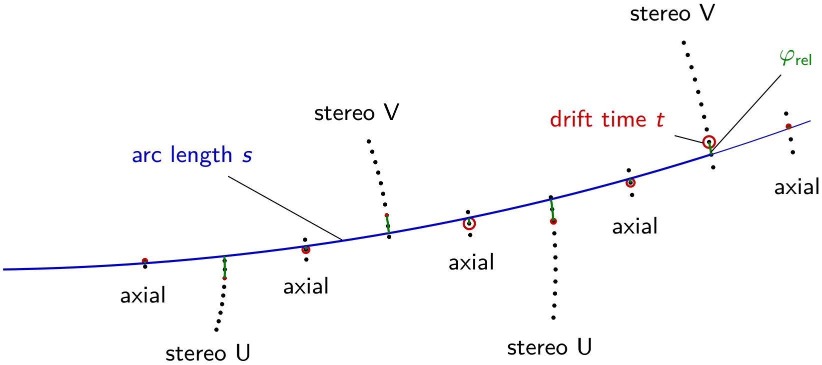
- minimize $\sum_i \left(z_i^{\text{True}} - z_i^{\text{Net}}\right)^2$
- RPROP (backpropagation)

input: one TS Hit per SL per track (position φ_{rel}, α and time t)

output: z, θ estimate



NeuroTrigger - Input Representation



3 input values per SL

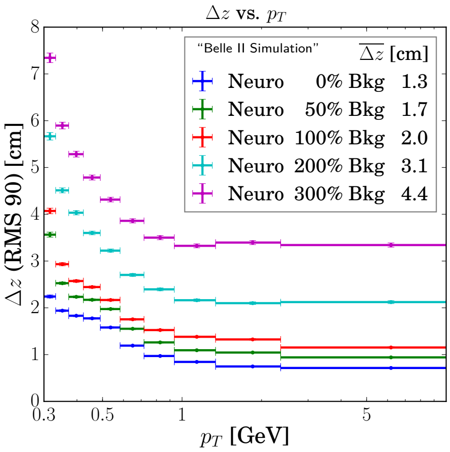
- φ_{rel} : TS position relative to 2D track
- α : $\frac{\text{2D arc length to Layer}}{r_{2D}}$
- t : drift time

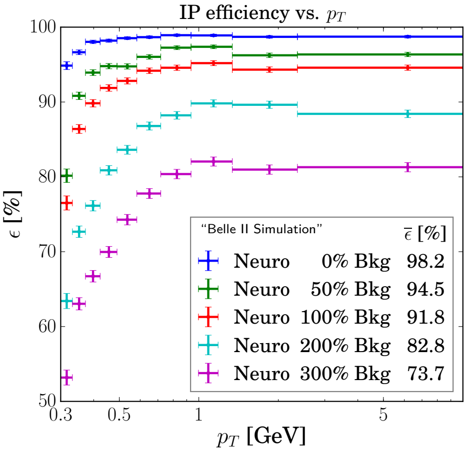
Preprocessing

- use (p_T, φ) estimates from the track finder
- select hits
- calculate input values
- select dedicated network for missing hits

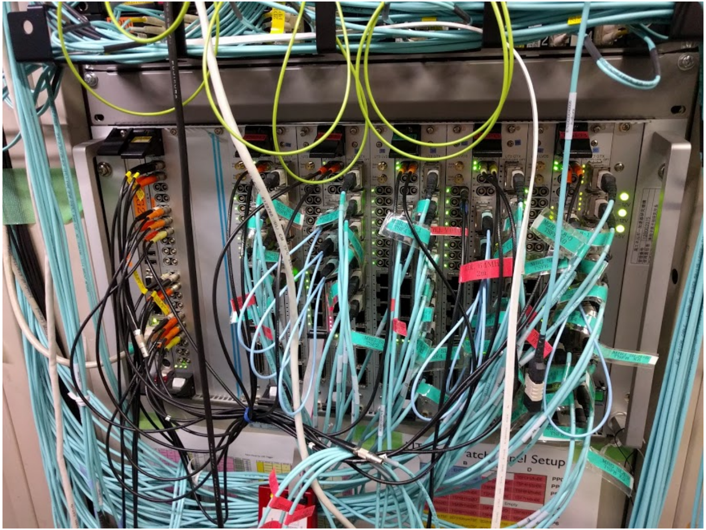
NeuroTrigger - Accuracy

- 5 networks total (for missing stereo hits)
- different bkg noise levels
- IP efficiency: flag IP events with $z \in [-6, 6]$ cm





NeuroTrigger - Hardware



Installation

- implemented on FPGA hardware (universal trigger board 3)
- installed in Belle II electronics hut
- ready for the start-up of Belle II phase 3 (this spring)

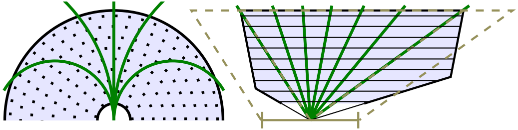
Neural Network

- real time application with low latency requirement
- shallow 3-layer network is used (instead deep architecture with high latency)

3D Hough Finder $(p_T, \varphi, \vartheta)$

Motivation

- include CDC stereo hits
- improve track finding efficiency
- get NN hit selection in one step (axial & stereo)
- estimate ϑ (allow NN sectorization)



Sectors in p_T (left) and in ϑ (right).

Track Finder Concept

Bayes'ian estimation

$$P(tracks|hits) = \frac{P(hits|tracks) \cdot P(tracks)}{P(hits)}$$

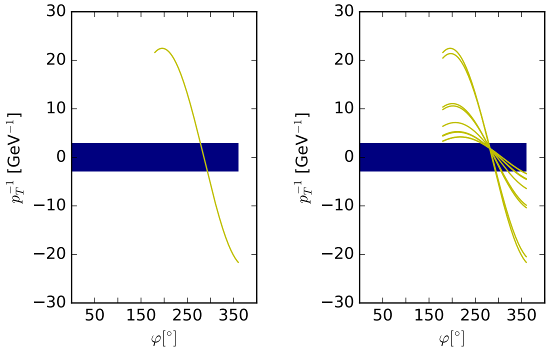
with a set *tracks* and a set *hits*.

- general approach
- allows easy change of the track and hit parametrization
- results equivalent to a Hough transformation

2D Hough Transformation

Hits in Parameter Space

1. conformal mapping: $x' = \frac{2x}{x^2 + y^2}; y' = \frac{2y}{x^2 + y^2}$
2. Hough transform: $p_T^{-1}(\varphi) = C \cdot (x' cos(\varphi) + y' sin(\varphi))$



- hits are sine curves in the p_T^{-1}, φ space
- tracks are intersections
- blue region: $p_T > 350\,\text{MeV}$

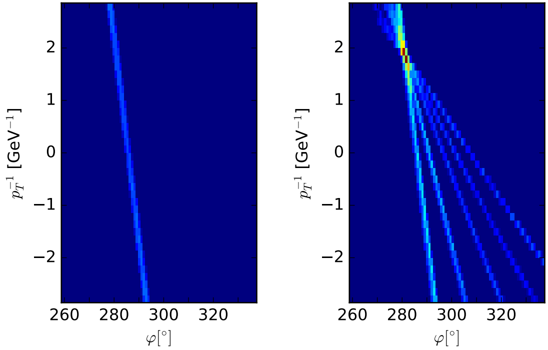
Discrete 2D Hough Space

binning of track parameters (φ, p_T)

Construct Houghplane

$$H(t|hits) = \sum_{h \in hits} P(t|h)$$

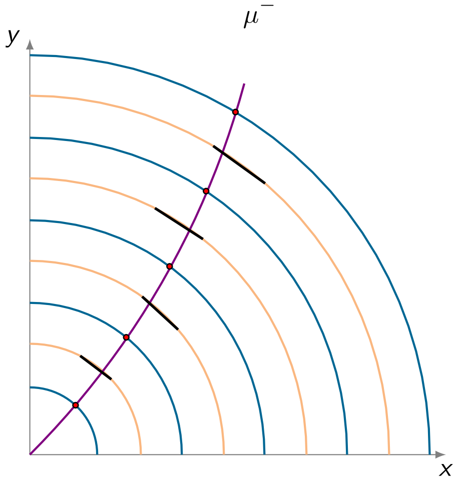
$P(t|h)$ single hit contributions. $H(t|hits)$: Houghplane for all hits.



Cluster Peaks

- identify tracks
- are local maxima
- have a minimum weight

Transverse Hit Positions



- axial hits appear as points
- stereo hits as line segments
- ϑ binning allows to represent stereo hits as points

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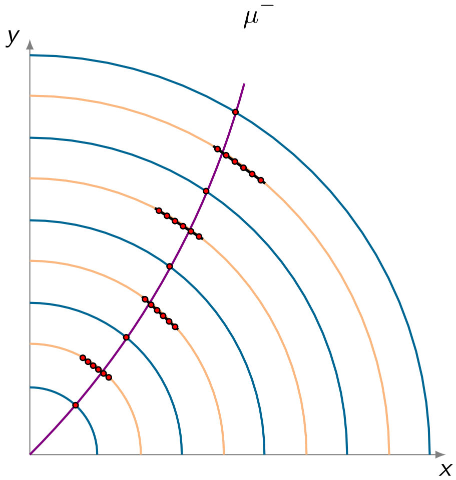

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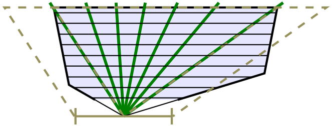
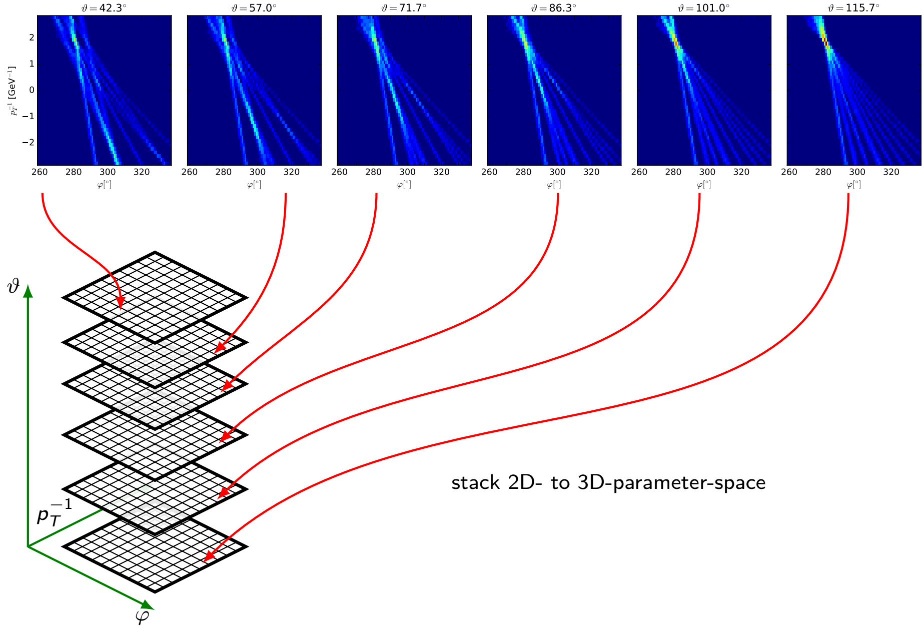


3D Hough Finding



stack 2D- to 3D-parameter-space

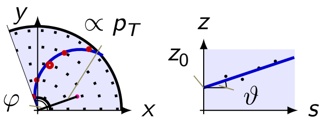
3D Finder Setup

$$H(t|hits) = \sum_{h \in hits} P(t|h)$$

weights for all possible tracks t given a set $hits$.

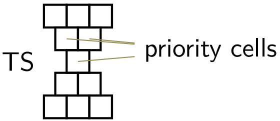
Track Phase Space

- $p_T^{-1}, \varphi, \vartheta$



Hit Phase Space

- TS-id, priority



$P(t|h)$

- approximated by a 5D array A (stored as lookup table)
- A can be trained using Monte Carlo

	p_T	φ	ϑ	id	prio
bins	40	384	6	2336	3

Table: size of the array A

3D Finder Training

Filling

for each track

1. find related hits: h
2. bin track parameters: t
3. increment $A[t, h]$ for all pairs $[t, h]$

Normalization

normalize A for all tracks t ($\equiv$ all tracks are equally probable)

$$A[t, h] = \frac{A[t, h]}{\sum_{\text{all} h} A[t, h]}$$

Set Bit Width

- adjust maximum bit width of each cell in A
- currently 3 bits are used

Track Finding

Construct “Houghplane“

$$H[tracks] = \sum_{h \in hits} A[tracks, h]$$

for an event with a set *hits*, *tracks* are peaks in H

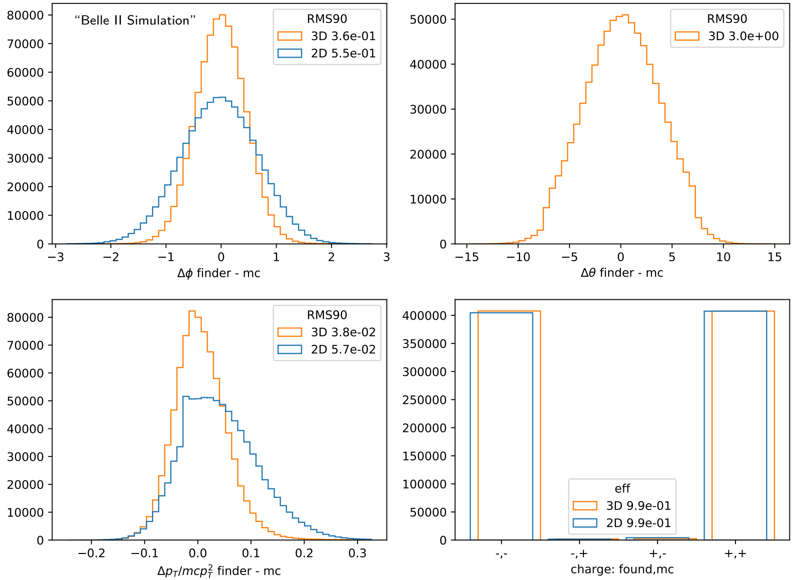
Clustering

1. find clusters
   density based clustering algorithm (DBSCAN)
   requirement for cluster cells: weight $> 90\%$ *peakweight*
2. select contributing hits
   hits with high weight contribution to the cluster
   require a minimum number of hits related to a cluster

Track Parameters

1. calculate track parameters
   weighted mean of selected cluster cells

Accuracy

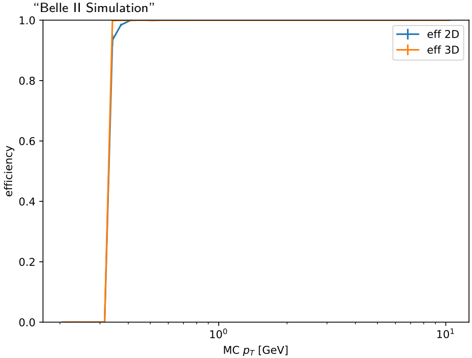


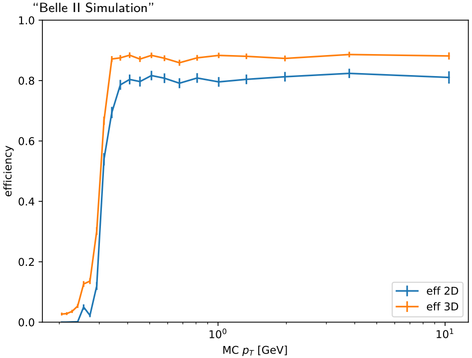
- single $\mu^{\pm}$ IP tracks
-

var	range
p_T	$[0.35, 7]$ GeV
ϕ	$[0, 360]^{\circ}$
z	$[-1, 1]$ cm
ϑ	$[35, 123]^{\circ}$

- 3D resolution $\Delta\vartheta \approx 3^{\circ}$

Track Finding Efficiency





- tracks in the acceptance region
- $\mu^{\pm}$ track parameters

p_T [GeV]	ϕ [°]	z [cm]	ϑ [°]
[0.35, 7]	360	[−1, 1]	[35, 123]

- tracks with low p_T and ϑ
- $\mu^{\pm}$ track parameters

p_T [GeV]	ϕ [°]	z [cm]	ϑ [°]
[0.2, 7]	360	[−1, 1]	[19, 140]

Conclusion

Neural Network Trigger

- noise robust z vertex estimation
- requires preprocessing
  (track finding, hit selection, input calculation)
- sectorization improves MLP accuracy
- already implemented in HW

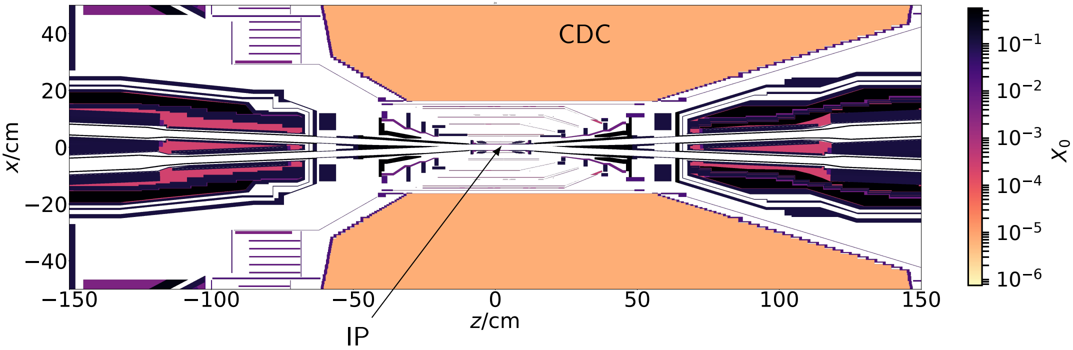
3D Track Finder

- high track finding efficiency
- improves 2D track parameters
- provides ϑ estimate
- directly relates stereo hits to tracks
- Hough map construction implemented in HW
- HW clustering under investigation

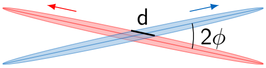
Backup

Introduction - Interaction Region

- scattering at material → background tracks
- two separate rings with different energies



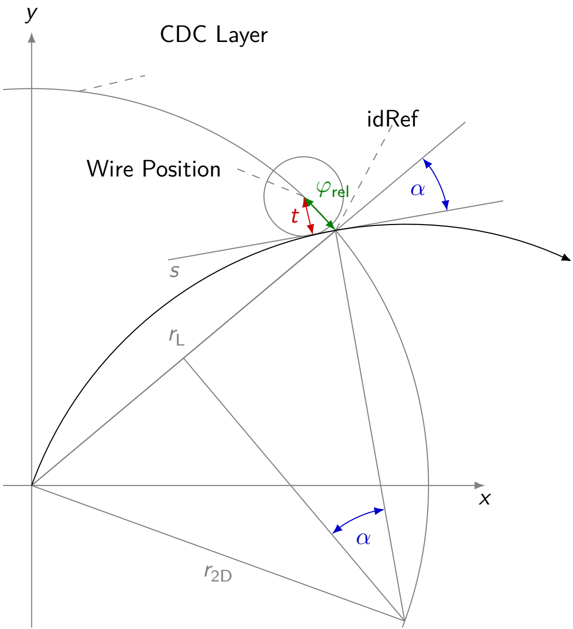
Bunch crossing:



Nano-Beam scheme

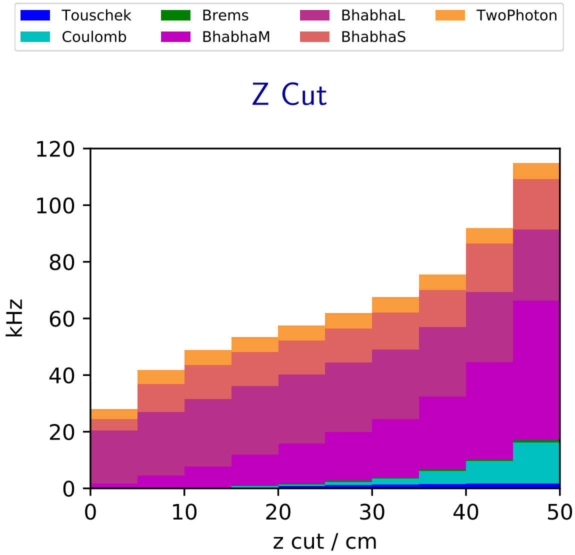
$\sigma_{x,y,z}$	beam size	$\sigma_y \approx 60\,\mathrm{nm}$
ϕ	crossing angle	$\phi \approx 40\,\mathrm{mrad}$
$d = \frac{\sigma_x}{\phi}$	eff. bunch length	$d \approx 0.2\,\mathrm{mm}$

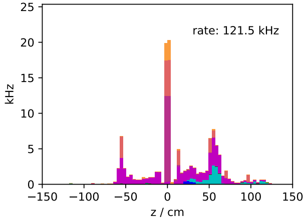
NeuroTrigger - Input Representation



- idRef: crossing point of the track with the layer
- α: crossing angle of the track with the layer
- φ_{rel}: distance of the wire position to idRef
- t: drift time

Background - Suppression





- cumulative bkg rate after a cut on the neural network z
- z_{cut} is varied in 5 cm steps

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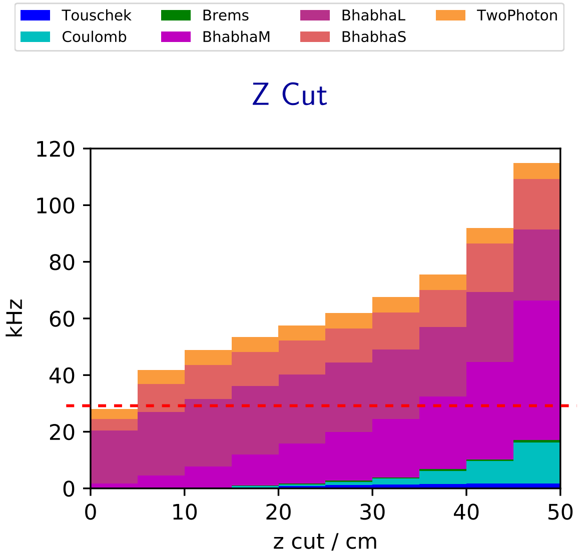

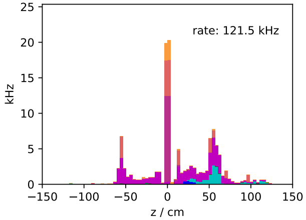

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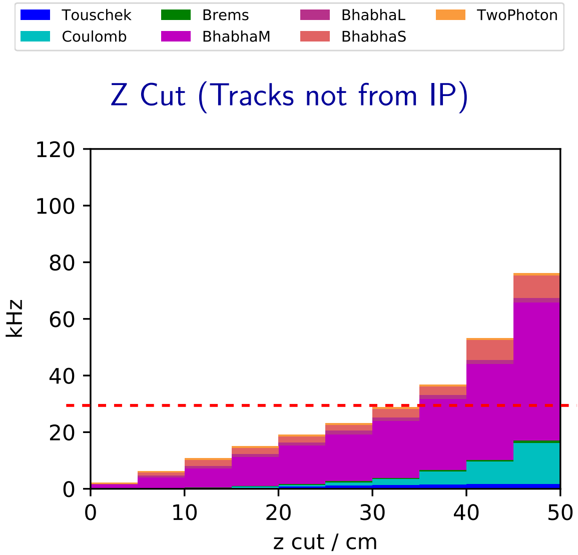

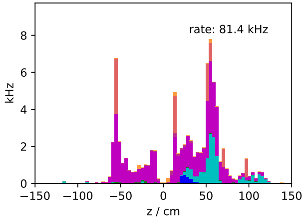

- only tracks with $|z_{MC}| \geq 1\,\text{cm}$
- cumulative bkg rate after a cut on the neural network z
- z_{cut} is varied in 5 cm steps