Upgrade L1 Neural Track Trigger for Run 2

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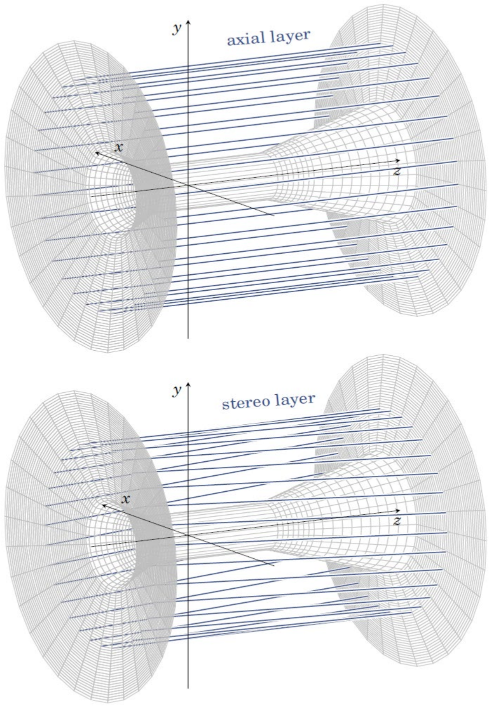
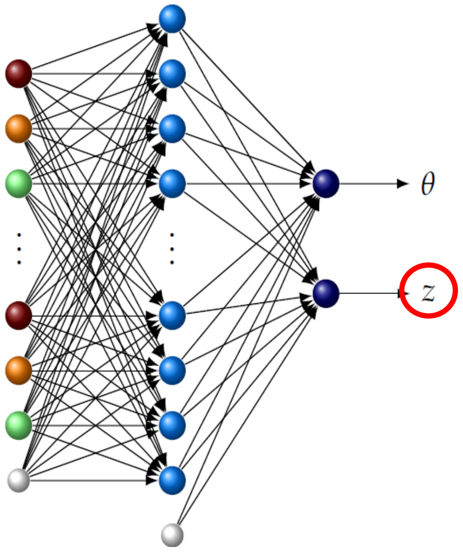
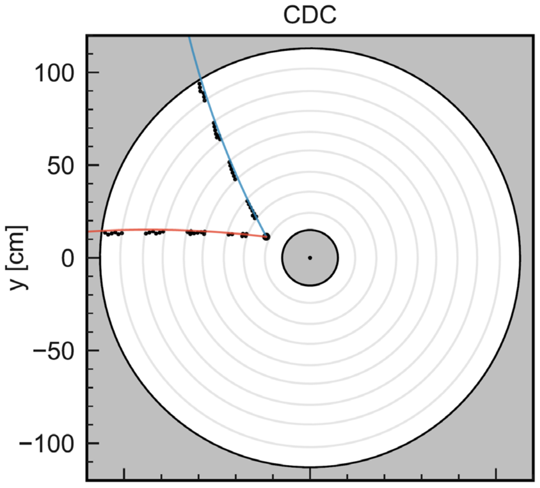
for the AI Trigger Group of Belle II







Overview:

- Upgrade of z-Trigger
- New project: Displaced Vertex Trigger
- Schedule & Milestones

AI Trigger Group at Belle II

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- Marc Neu
- Kai Unger
- **Jürgen Becker**

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KIT ETP
- Lea Reuter
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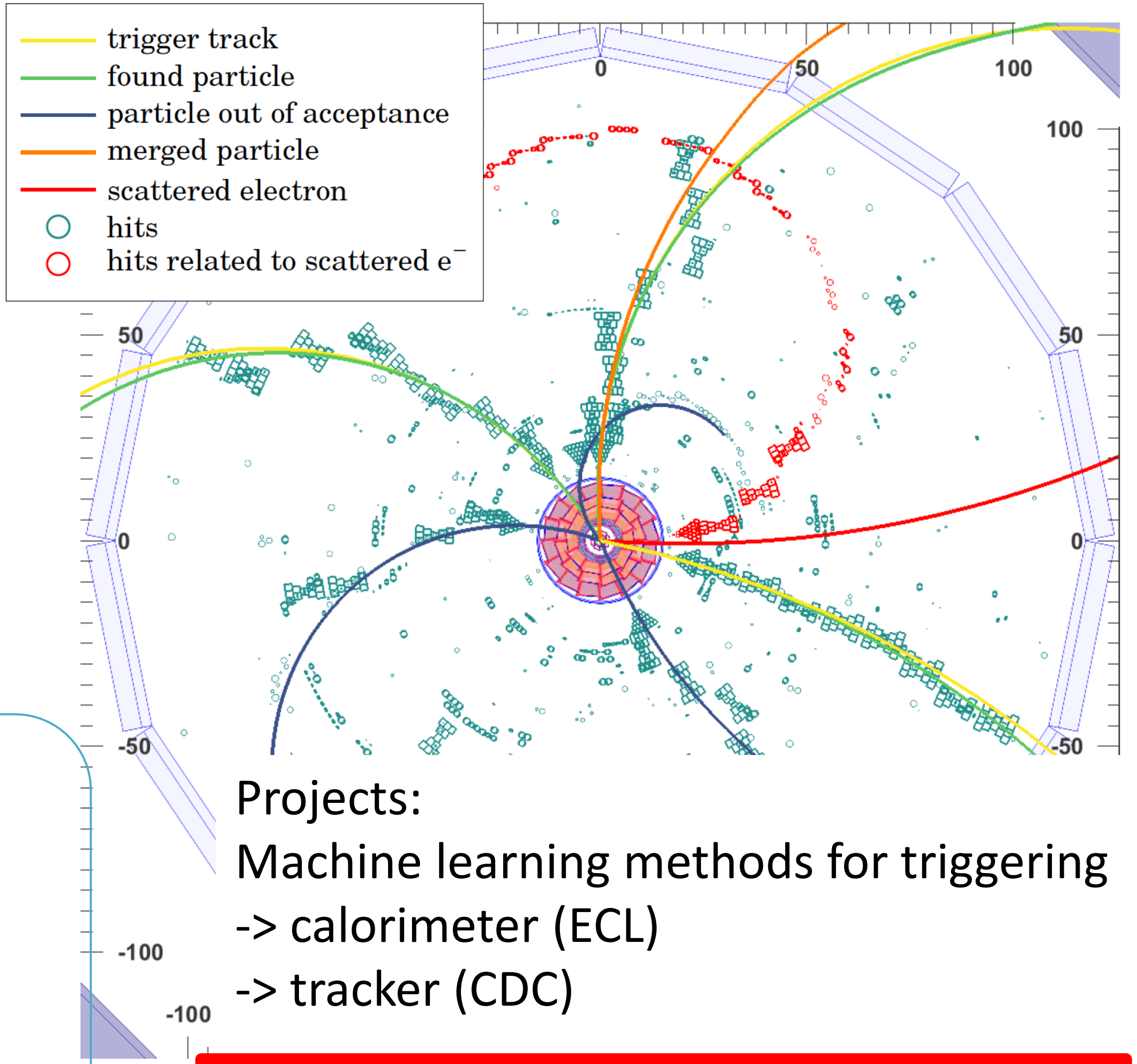
MPI / TUM /LMU
- Felix Meggendorfer
- Simon Hiesl
- Timo Forsthofer
- **Christian Kiesling**
- **Alois Knoll**
- **Thomas Kuhr**



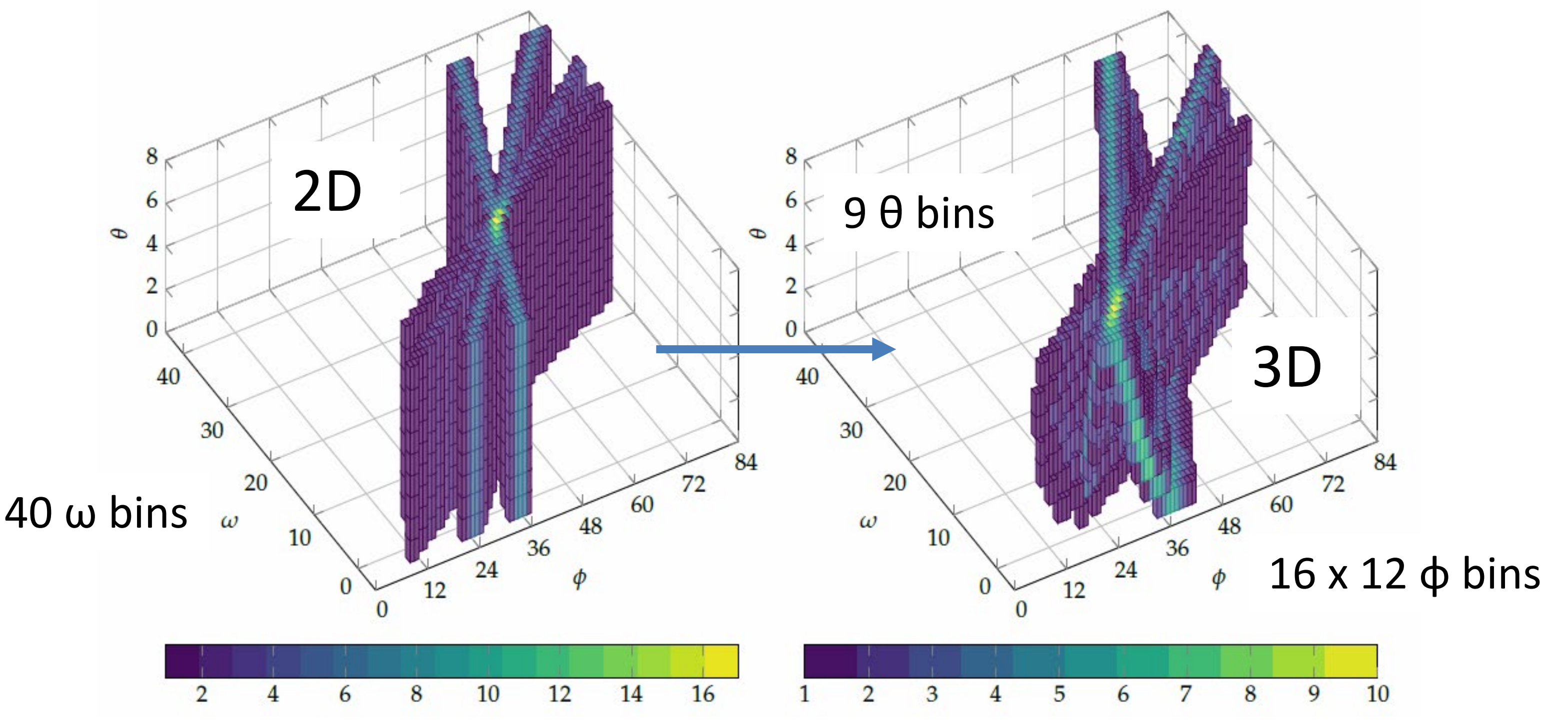
Projects:
Machine learning methods for triggering
-> calorimeter (ECL)
-> tracker (CDC)

here: Neural Network Track Trigger @L1

New 3D Hough Track Model („3DH“)

- Extend traditional 2D ($\omega=1/p_T$, ϕ=azimuth angle) Hough space by a third dimension, the (binned) polar angle θ
- Track finding with axial and stereo track segments (->3D)
- Peak finding in 3D Hough space

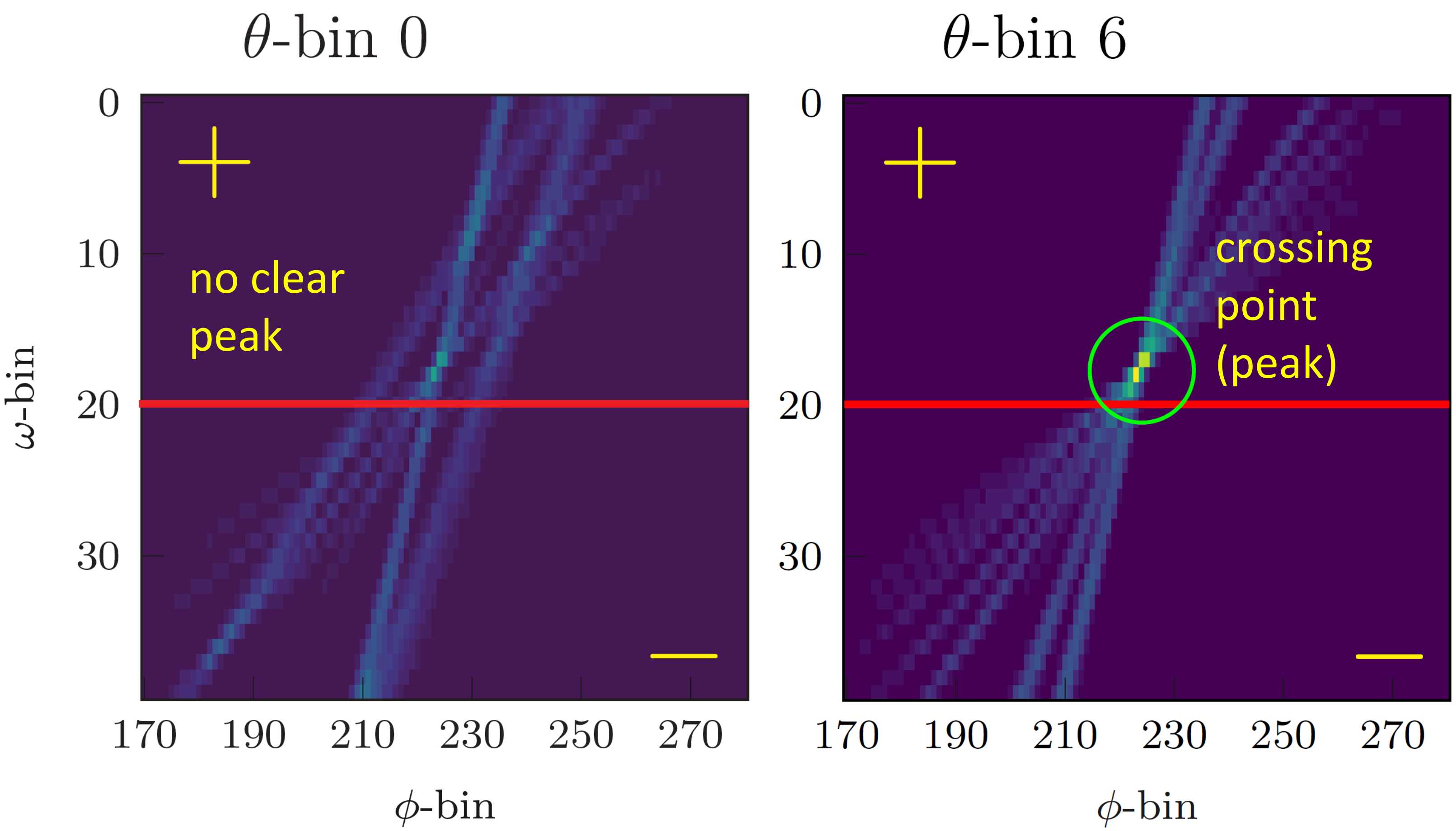
S. Skambraks (MPI & LMU)

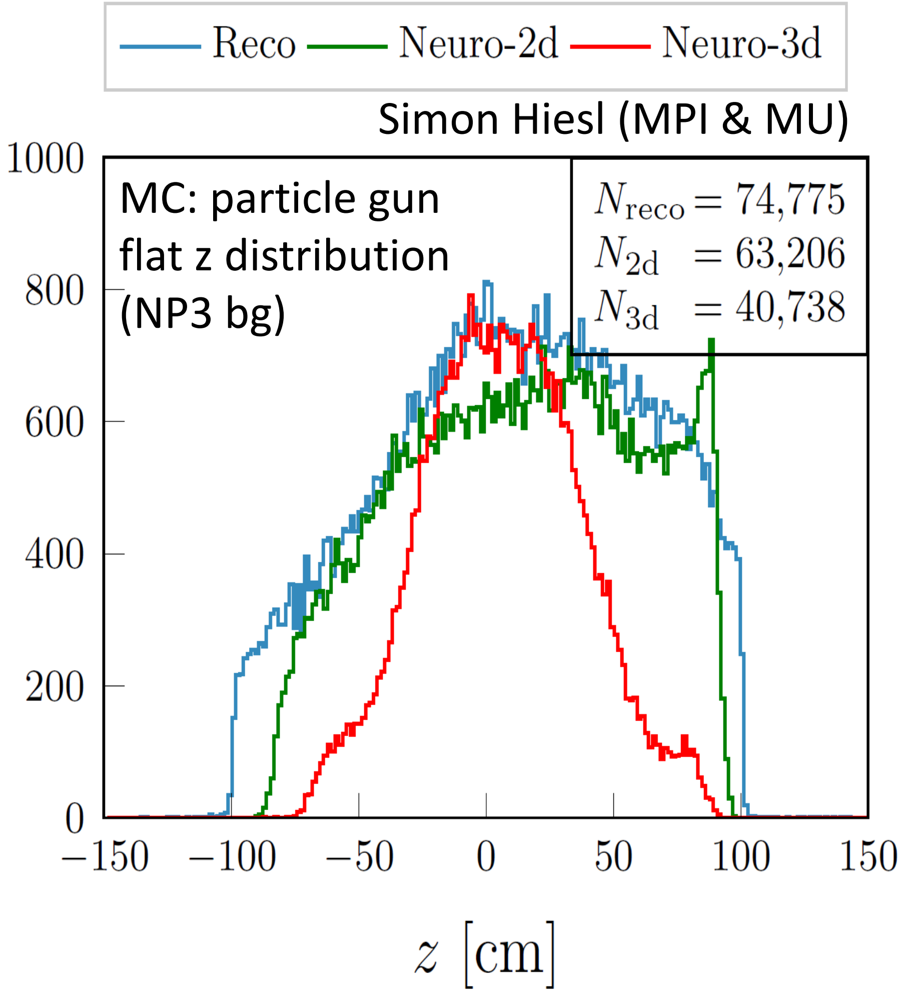


Main advantages:

- more TS (9 vs 5)
  -> suppress fakes
- no need to choose STS by min drift time
  -> find „correct“ STS by default
- force track model to originate from IP (x, y, z) = (0, 0, 0)
  -> “natural” suppress of candiates far from IP
- 3D track candidates come with θ estimate:
  -> improve z resolution

New 3D Hough Track Model („3DH“)





Simon Hiesl (MPI & MU)

Positive (negative) tracks in upper (lower) ω-halfplane

Peak finding in 3D hough space -> < ϕ>, <ω>, < θ>

Implicit 3DHough constraint:
track origin = IP (0,0,0) ->
„natural“ suppression of tracks
from „outside“ of IP

Expected Performance of z-Trigger Upgrade („3DHDNN")

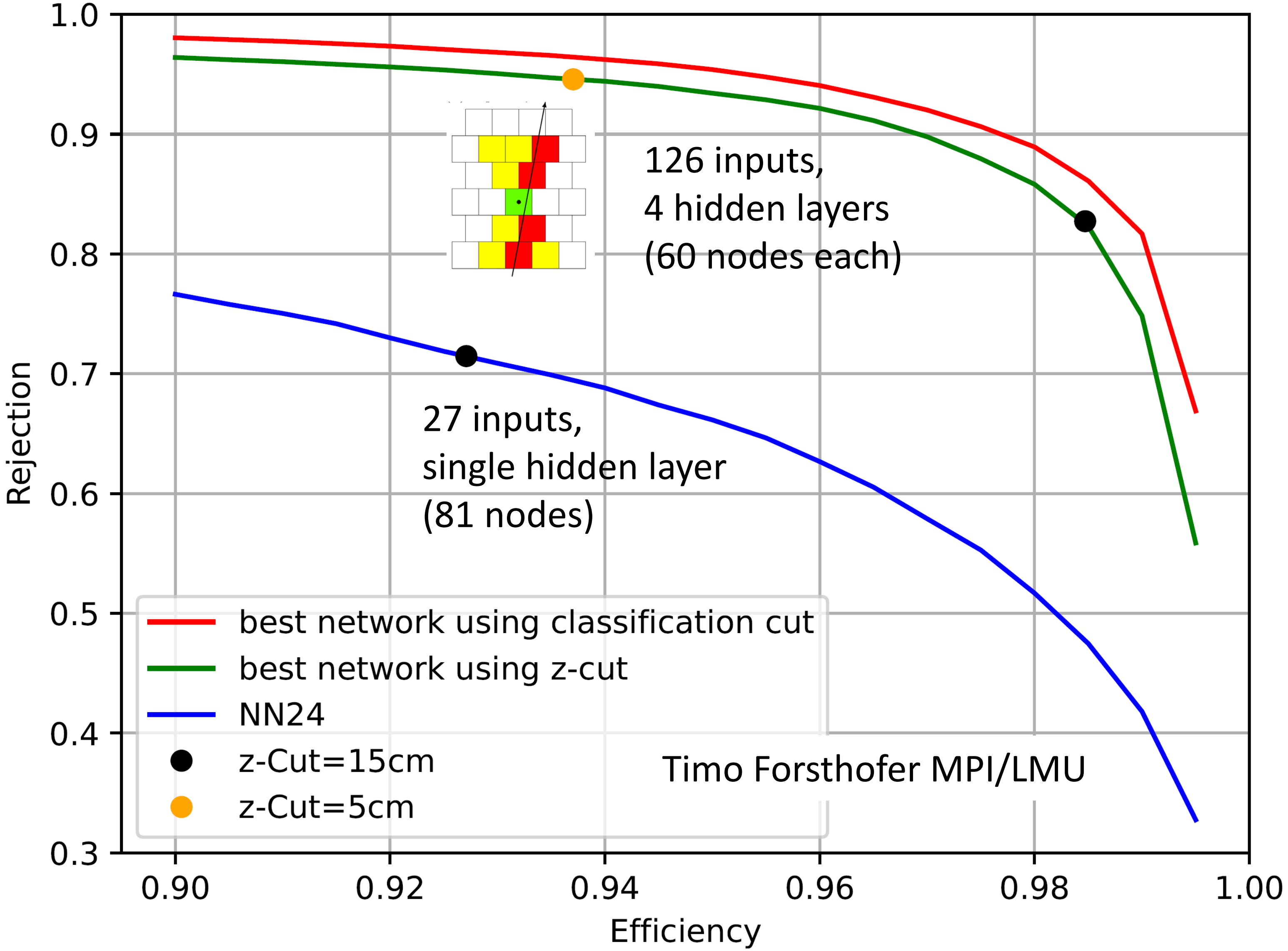
Extended inputs to network

- „standard" priority wire (Δϕ, α, DT)
- plus entire wire pattern in TS
  (10 additional binary inputs per TS)
- with condition: ADC count > min
  (remove bg from electronic
  cross-talk & synchr. photons)

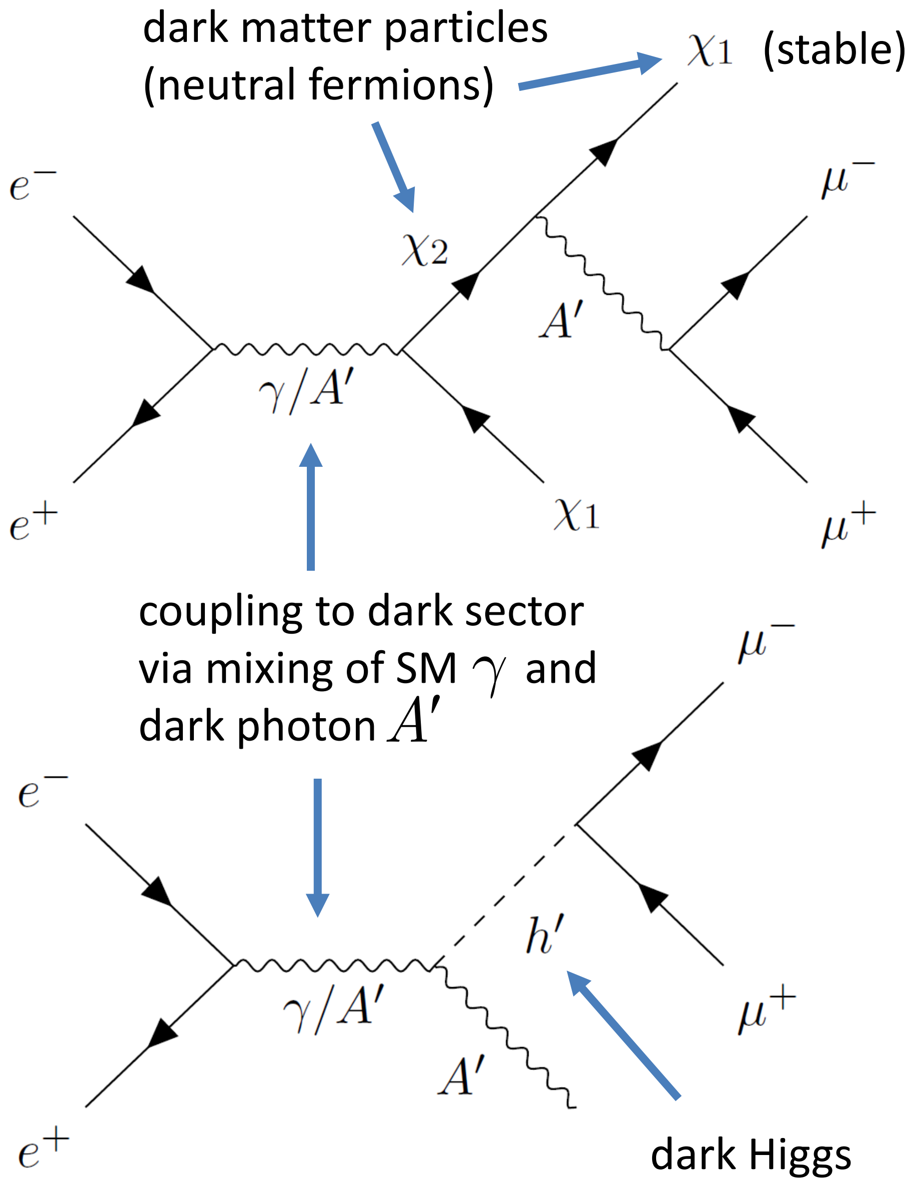
Multi-hidden-layer network
(„deep learning")

- Several architectures investigated
- „optimal" configuration with 4 hidden layers and fewer (!) nodes when using 3D track model (easier to implement in HW)
- added 3rd output: classification CL (CL = 1, for |z| < 1 cm, else CL = 0

Nework trained with data from 2022, tested with recent extremely high background runs (fall 2024)



Dark Matter Detection: Belle II‘s Potential

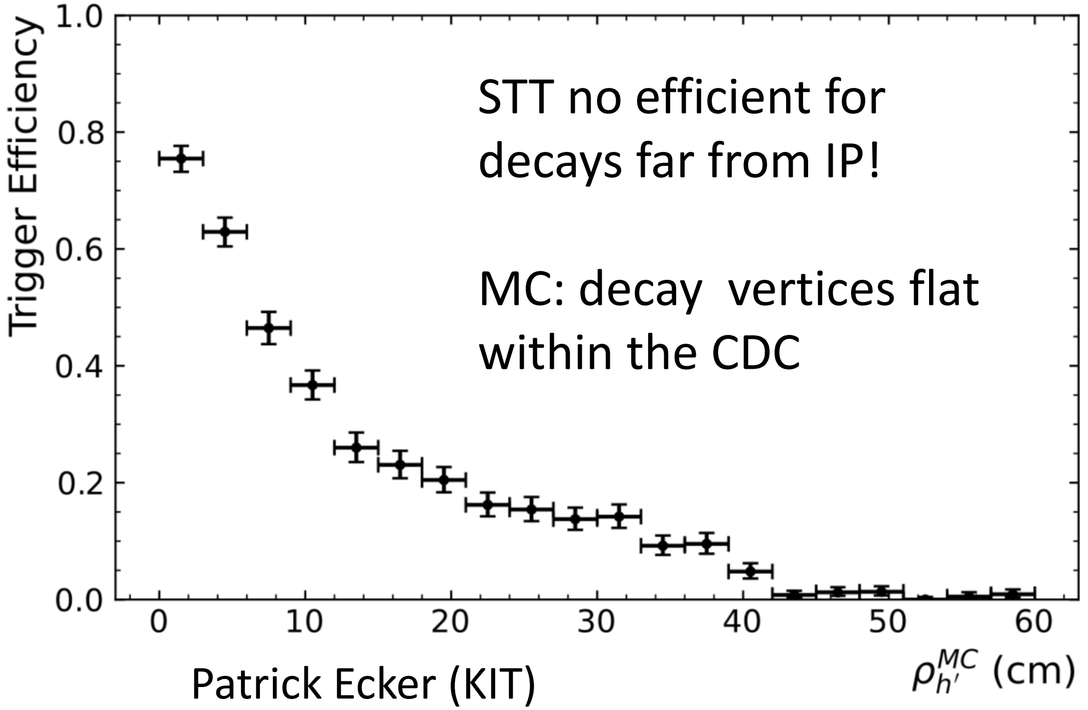


Popular models: Inelastic Dark Matter production

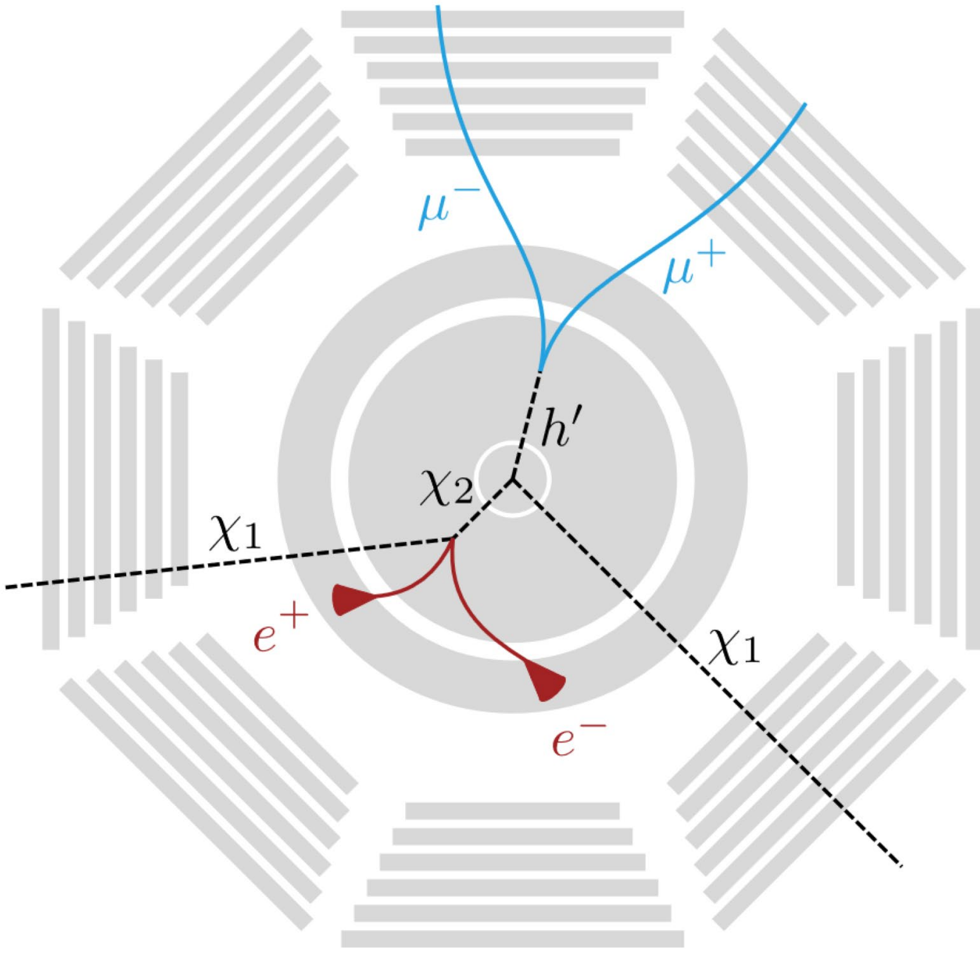
see, e.g. D. Smith and N. Weiner. Inelastic dark matter. *Physical Review D*, 64(4), jul 2001.
E. Izaguirre, G. Krnjaic, and B. Shuve. Discovering inelastic thermal relic dark matter at colliders. *Physical Review D*, 93(6), mar 2016.

-> common feature of dark mediators: very long lifetimes compared to SM weak decays (K_s, Λ)

-> “feably interacting particles” -> vertices displaced from IP



How to Trigger on Feebly Interacting Neutral Particles

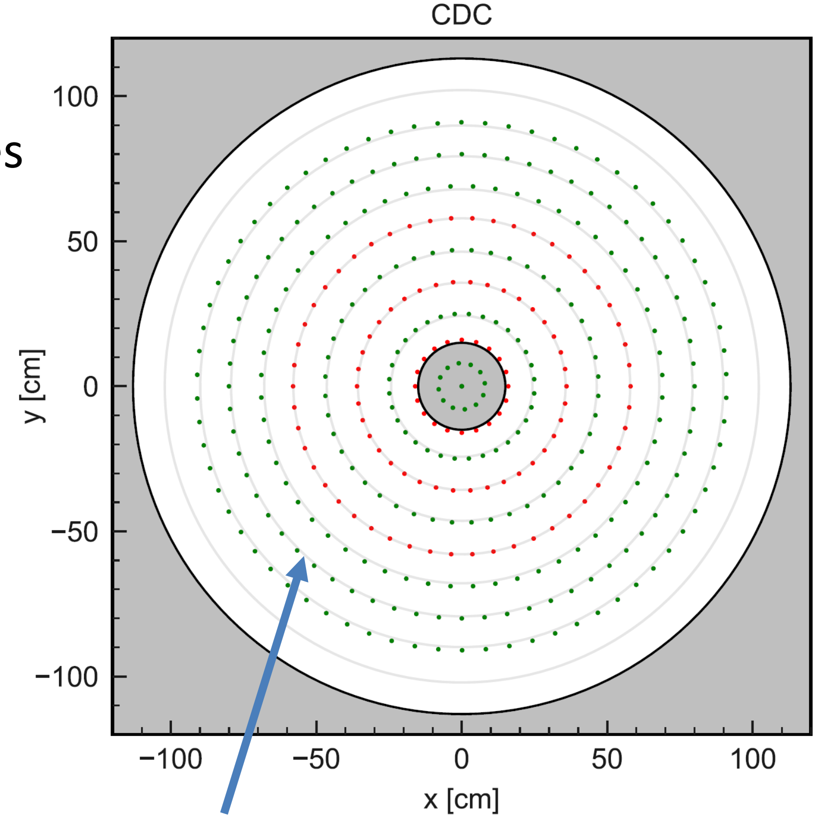


M. Dürr et al., https://arxiv.org/abs/2012.08595)

Basic problem:
Track finding with Hough method needs a vertex hypothesis!
e.g. 3DHough: (x,y,z,) = (0,0,0).
Here: vertex unknown, possibly not even pointing to IP

Solution (2D tracks):
Divide the CDC axial wire planes into a set of „Macro Cells“, serving as origins for the Hough transforms

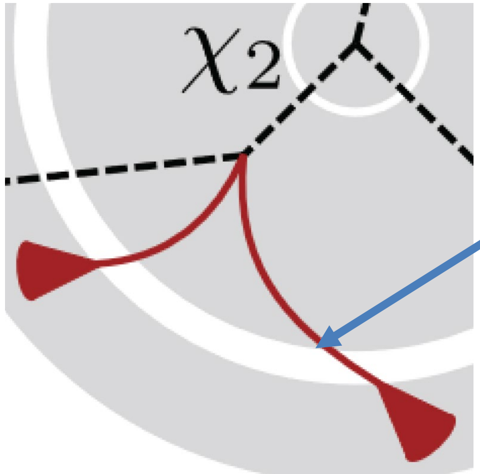
FPGA:
execute all Hough transforms with origins in each of the Macro cells in parallel
(typically -> O(100))



macro cell size typically 10 x 10 cm^2

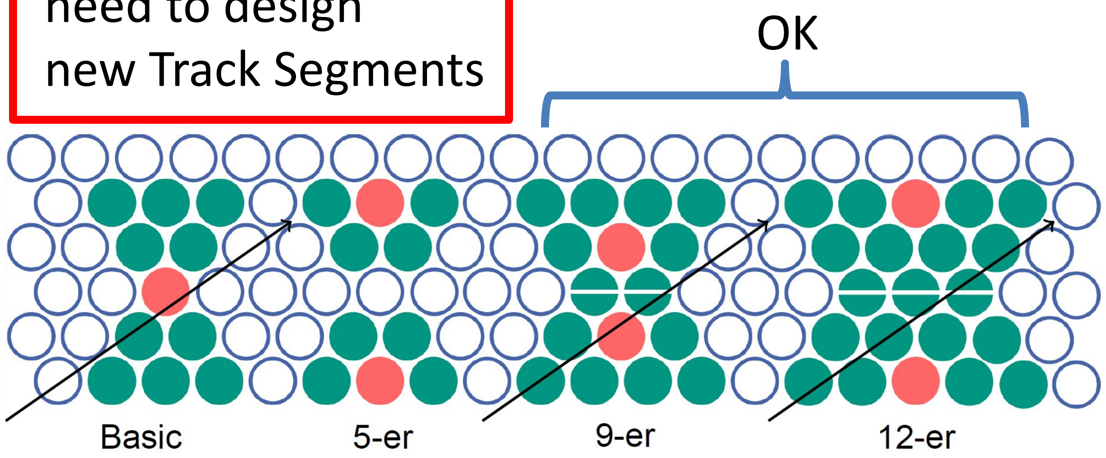
How to Trigger on Feebly Interacting Neutral Particles

Tracks may have arbitrary directions in the CDC

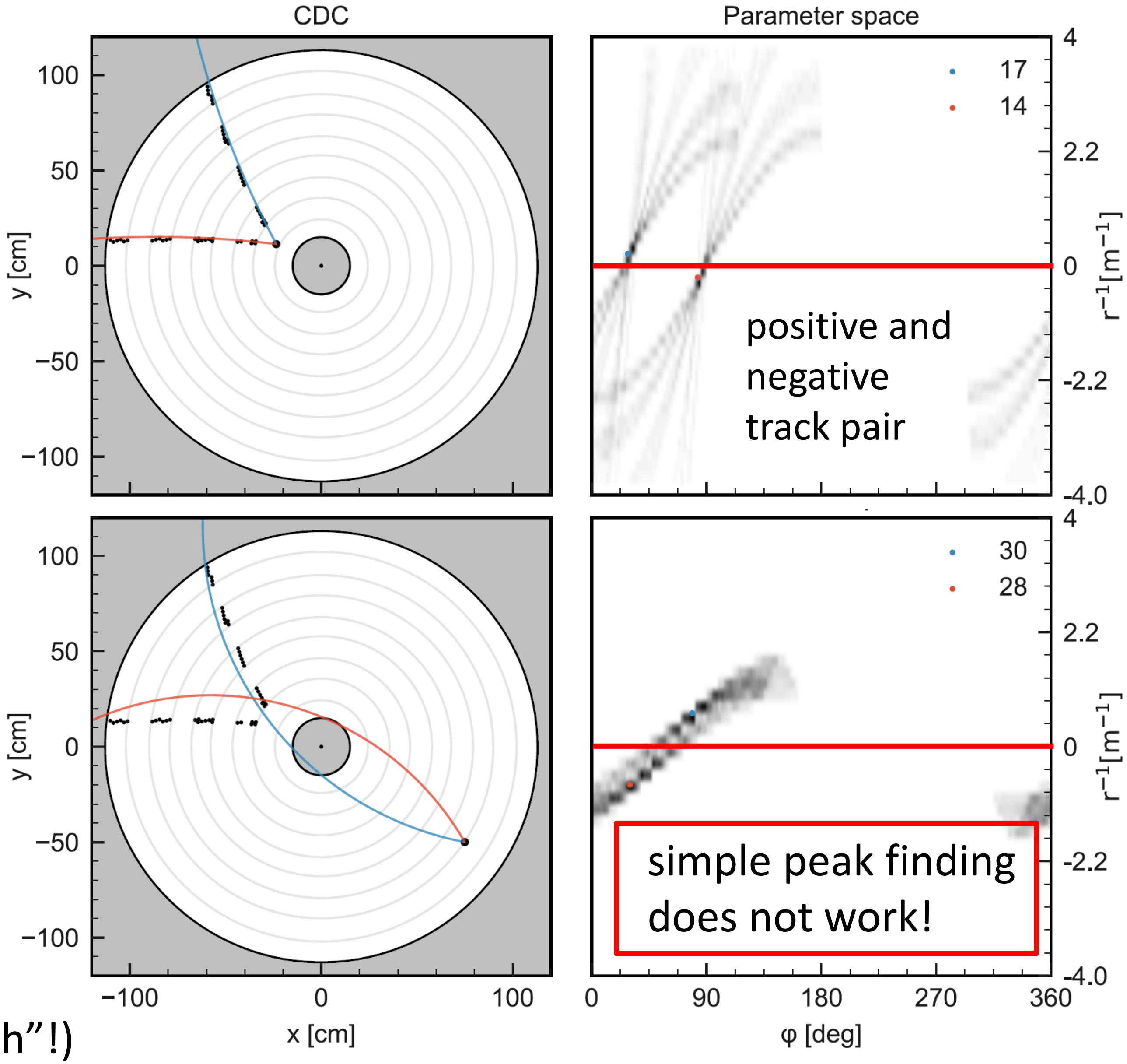


tracks with large crossing angles through the wire planes
-> will not fire present Track Segments (TS)

need to design new Track Segments

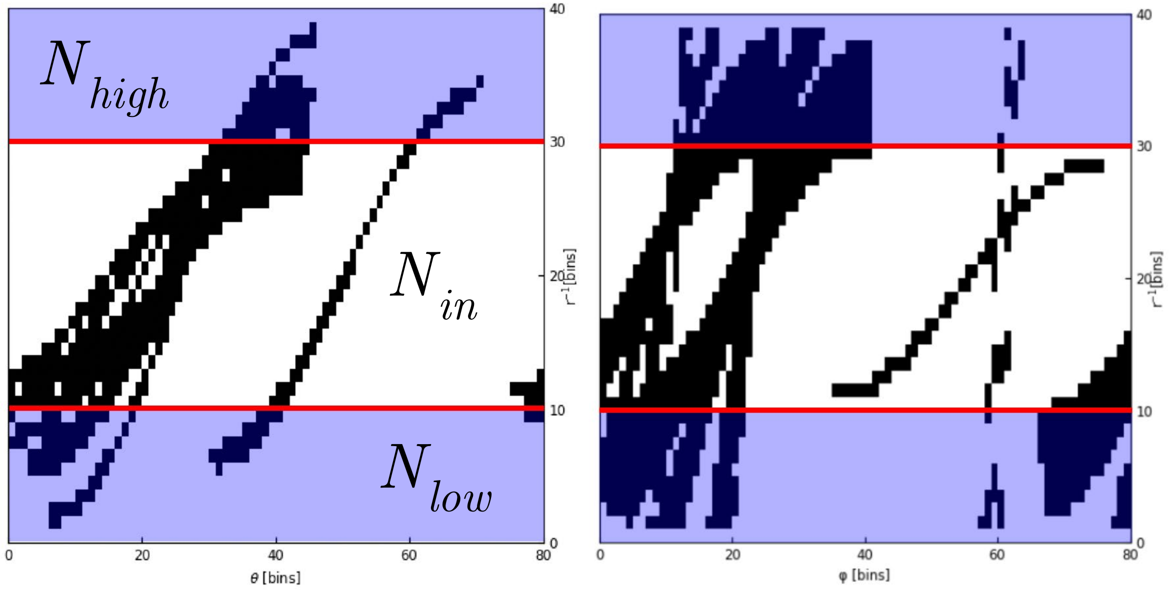


FPGA: calculate O(100) Hough planes from new TS
(parallel in 4 qudrants -> still marginal ("sportlich"!)



E. Schmidt (MPP & LMU)

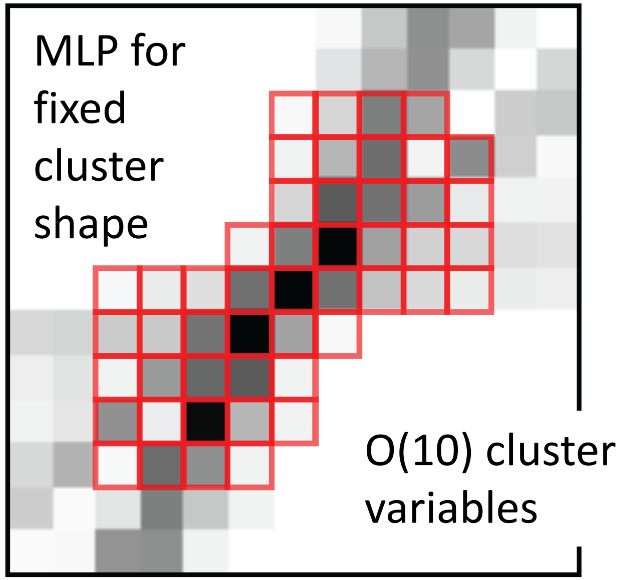
Selection of „Hot“ Candidates: B/W Hough Map

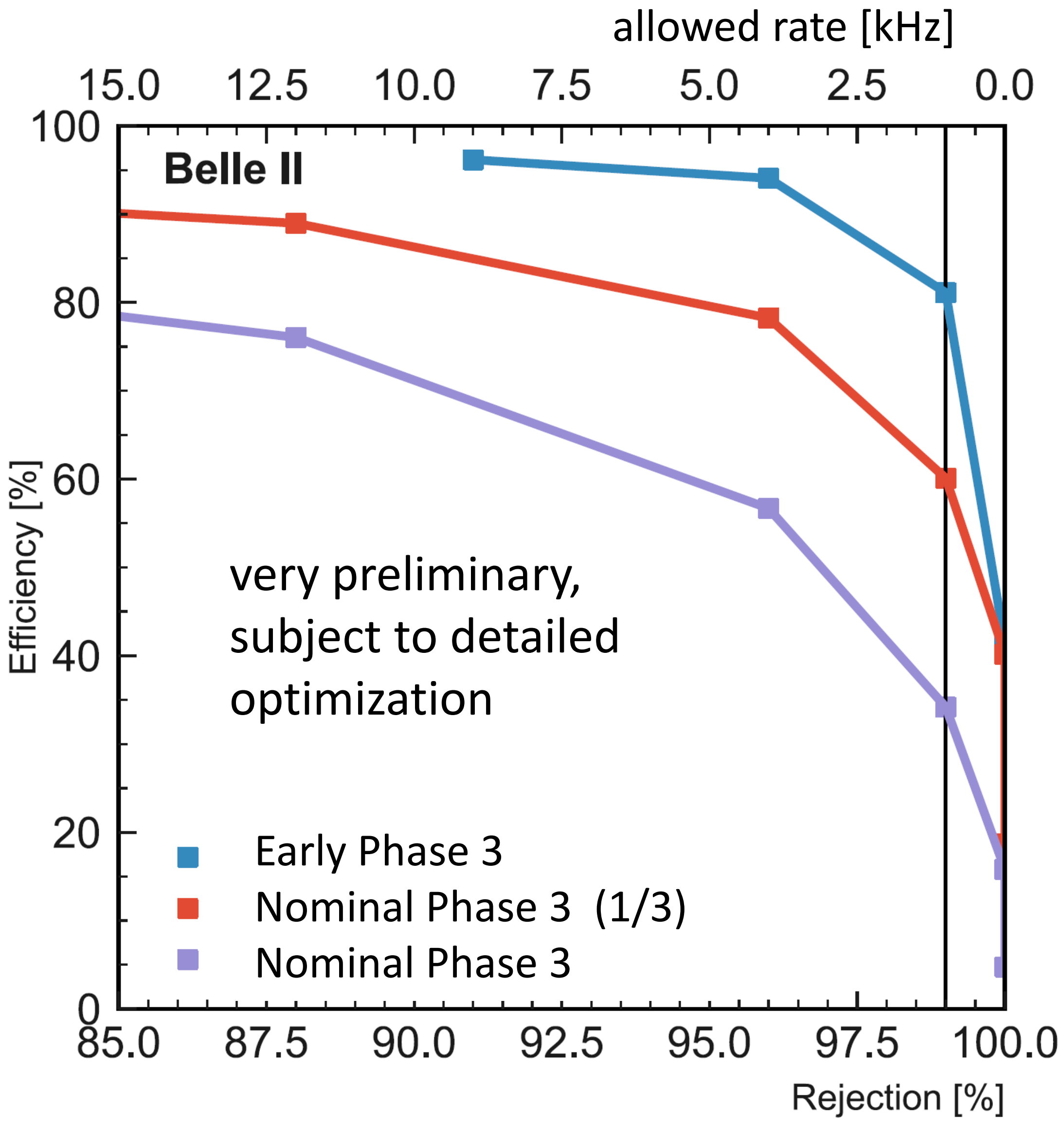


FPGA implementation:
- Black&White Hough maps
- Calculate for each map

$$r = (N_{high} + N_{low}) \,/\, N_{in}$$

- retain the 5 largest
- build the 5 “colored” maps
- select most probable map
  via single hidden layer net

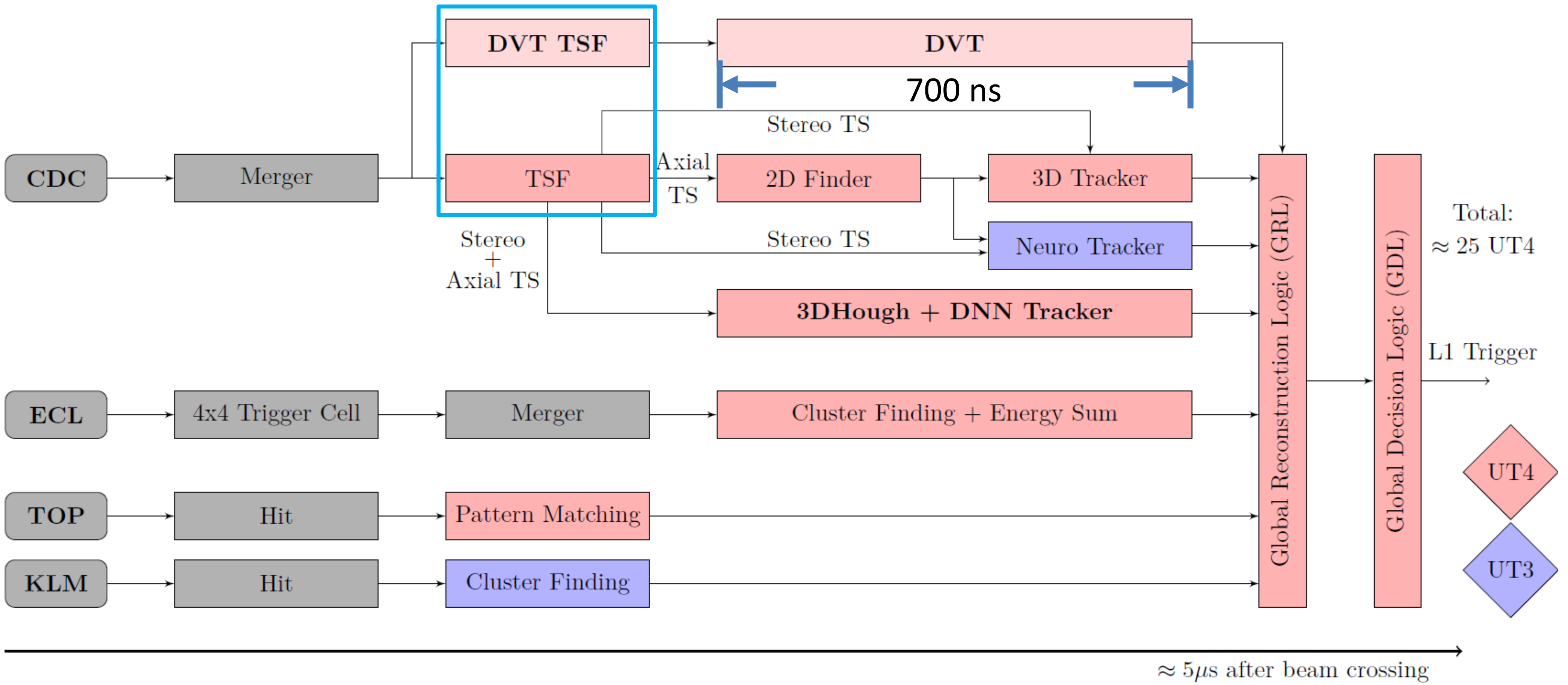




E. Schmidt -> S. Hiesl (MPP & LMU)

L1 Trigger Pipeline (upgraded version)

- UT4 Hardware for 3DHDNN already existing (4 units)
- Hardware implementation of DVT: add new TS to present Track Segment Finder Unit (UT4)
  + new DVT Units (UT4), 4 quadrants

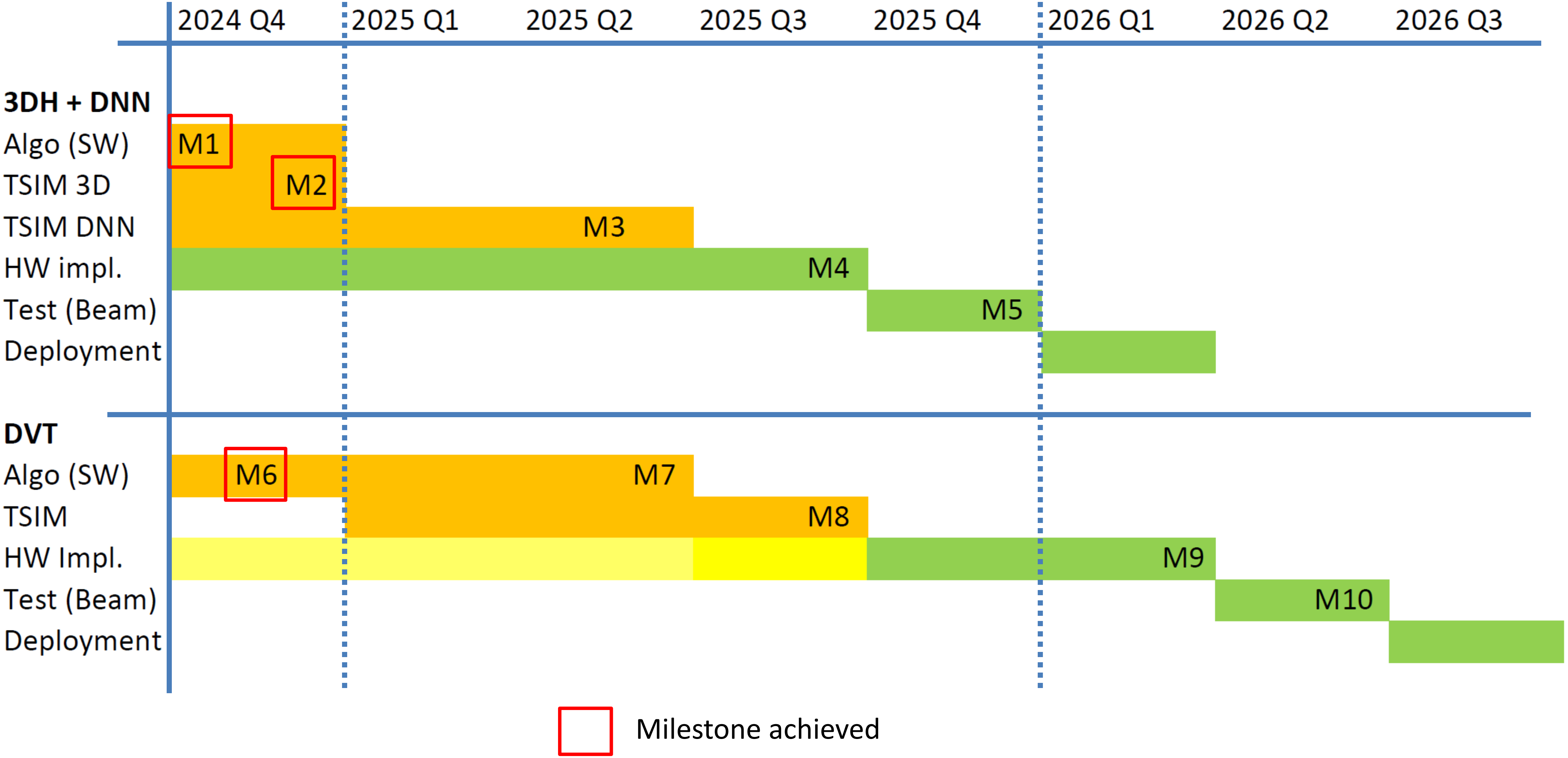


New UT4s required for DVT

Once verified, 3DHDNN will replace standard z-Trigger

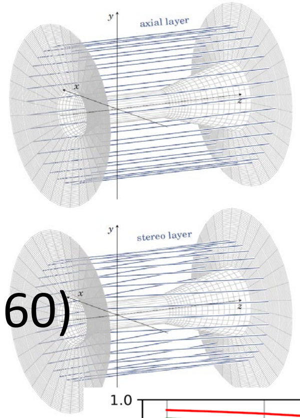
= UT4 VME modules, equipped with Xilinx Ultracale 7 XCVU080/160/190 FPGAs

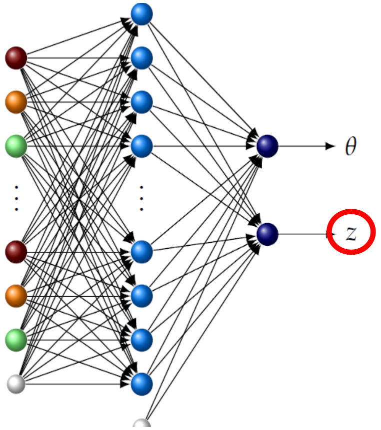
Schedule & Milestones



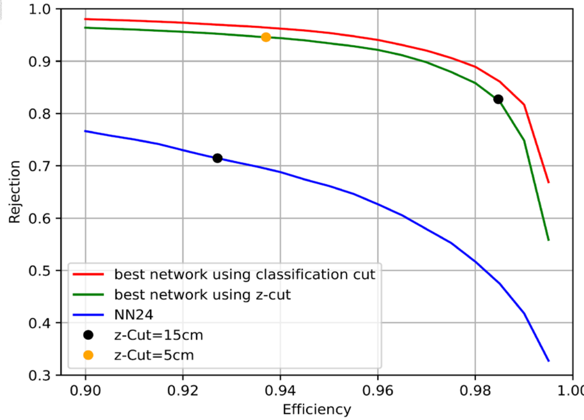
Summary: L1 Neural Track Triggers for Run 2

- **Minimum Bias Single Track Trigger (STT)** as global trigger
  - excellent performance even under present severe background conditions
  - But: “Feed-down” and “Fakes” need attention with rising luminosity (& bg)

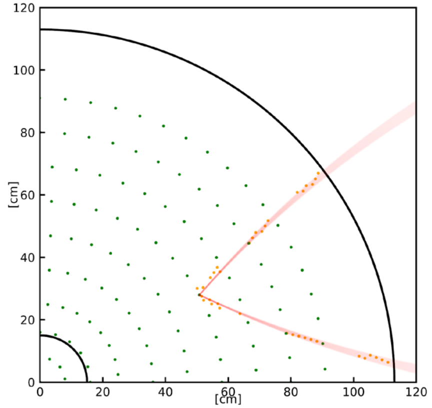




- **Upgrade:** More powerful FPGA boards now available (Virtex UltraScale 7 XCVU160)
  - track finding via optimized 3D Hough cluster algorithm (novel method!)
  - additional inputs from all wires within the TSs (126 inputs total)
    (ADC cut for CDC wire signals to suppress background)
  - deep-learning neural network architectures (4 x 60 hidden nodes)
  - commissioning by fall 2025, launch planned for the winter 2025 data taking



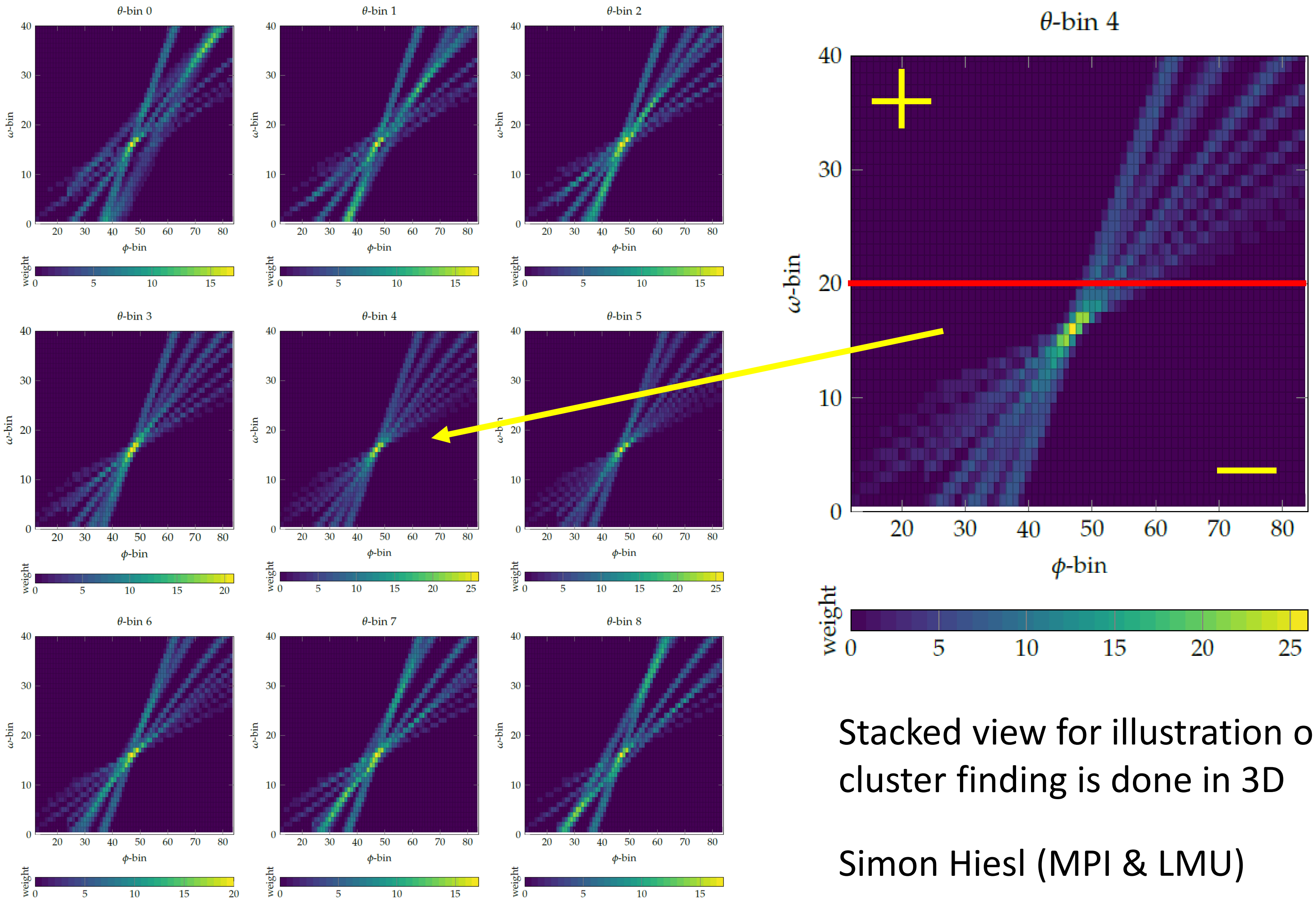
- Neural **Displaced Vertex Trigger (DVT)**, aiming at long-lived new particles (“FIPs”), basic algorithm exists, HW implementatioin planned for early 2026



- **Beyond Run2**: KIT group -> track finding via GNNs at hit level (offline very successful!)
  -> data from CDC & new silicon VTX -> need new trigger hardware -> UT5 (FPGA++)

Backup

Example of the full 3D Hough Map (Particle Gun)



Stacked view for illustration only, cluster finding is done in 3D

Simon Hiesl (MPI & LMU)

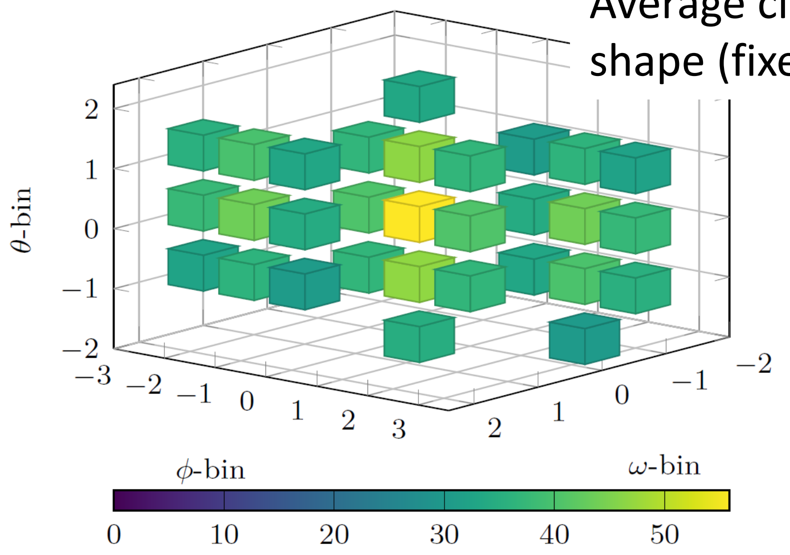
Track Finding in 3 Hough Dimensions

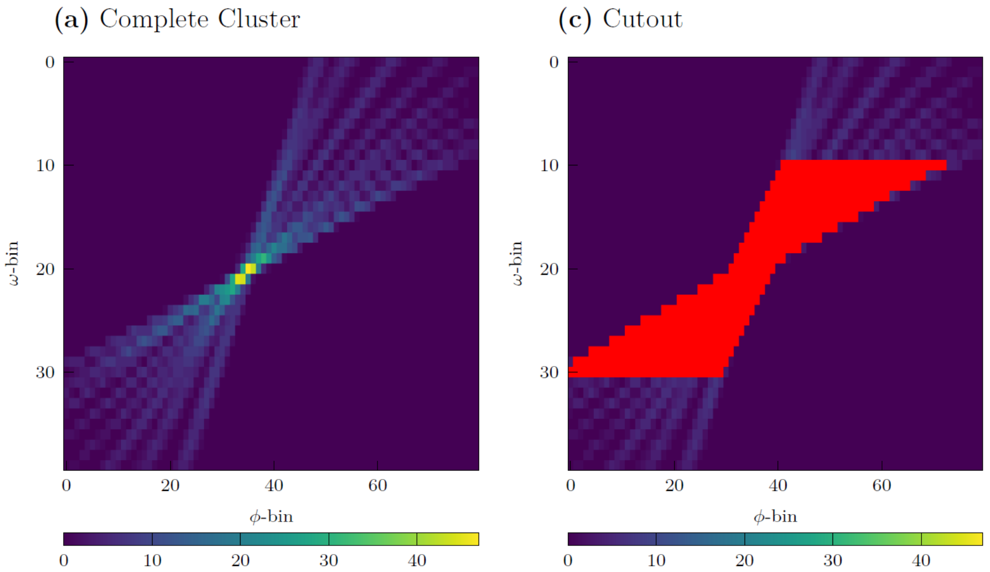
- „Classical“ cluster algorithm (DBSCAN) not suited for hardware implementation

- **New cluster (track) finding algorithm** (S. Hiesl)
  - fill cells in Hough space from all TS (use trained cell weights)
  - find maximum cell in Hough space ($w(cell) > w_{min}$)
  - require associated TS from ≥n axial and ≥m stereo different superlayers ($n = 4$, $m = 3$)
  - store associated track segments within fixed cluster shape
  - select unique TS in each superlayer (maximum cell weight / shortest DT)
  - determine < ϕ>, <pt>, < θ>
  - clear all Hough cells around maximum cell (-> butterfly cut)
  - iterate k times (k typically 2 in each quadrant)

-> find typically up to 8 tracks per clock cycle
(maximal drift time ~ 16 clock cycles)

-> next step: neural architectures for precise estimates of z and θ





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Cleanup of CDC Hits

Real data: Dominating background in the CDC from synchrotron radiation & electronic cross talk -> typically small charge depositions on the wires

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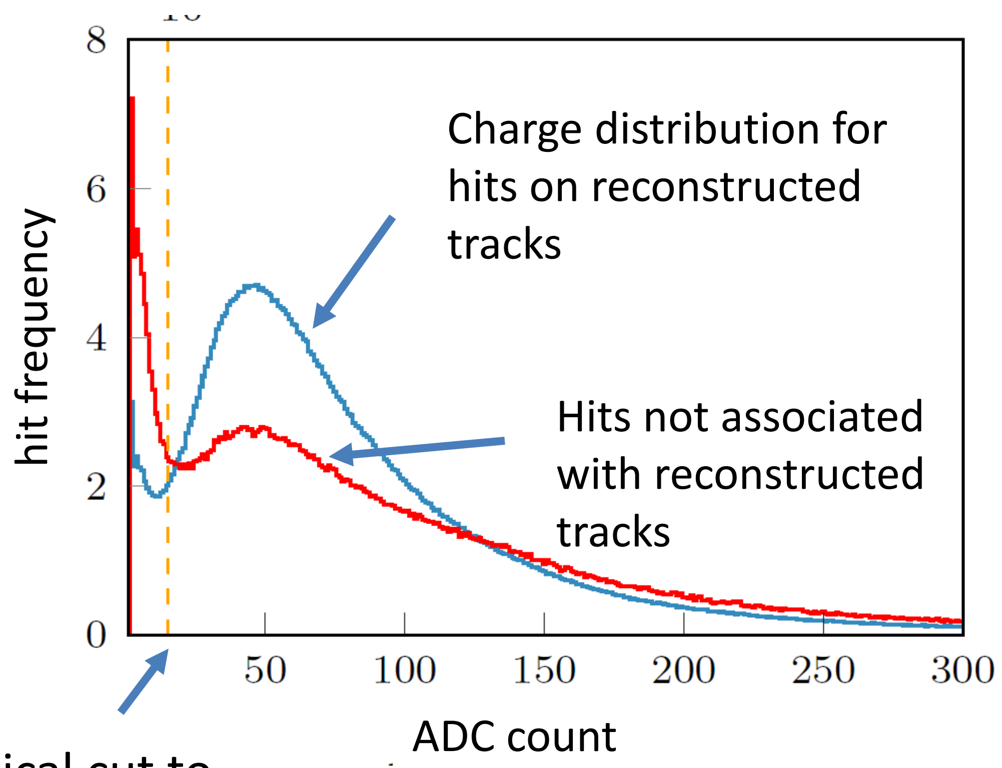
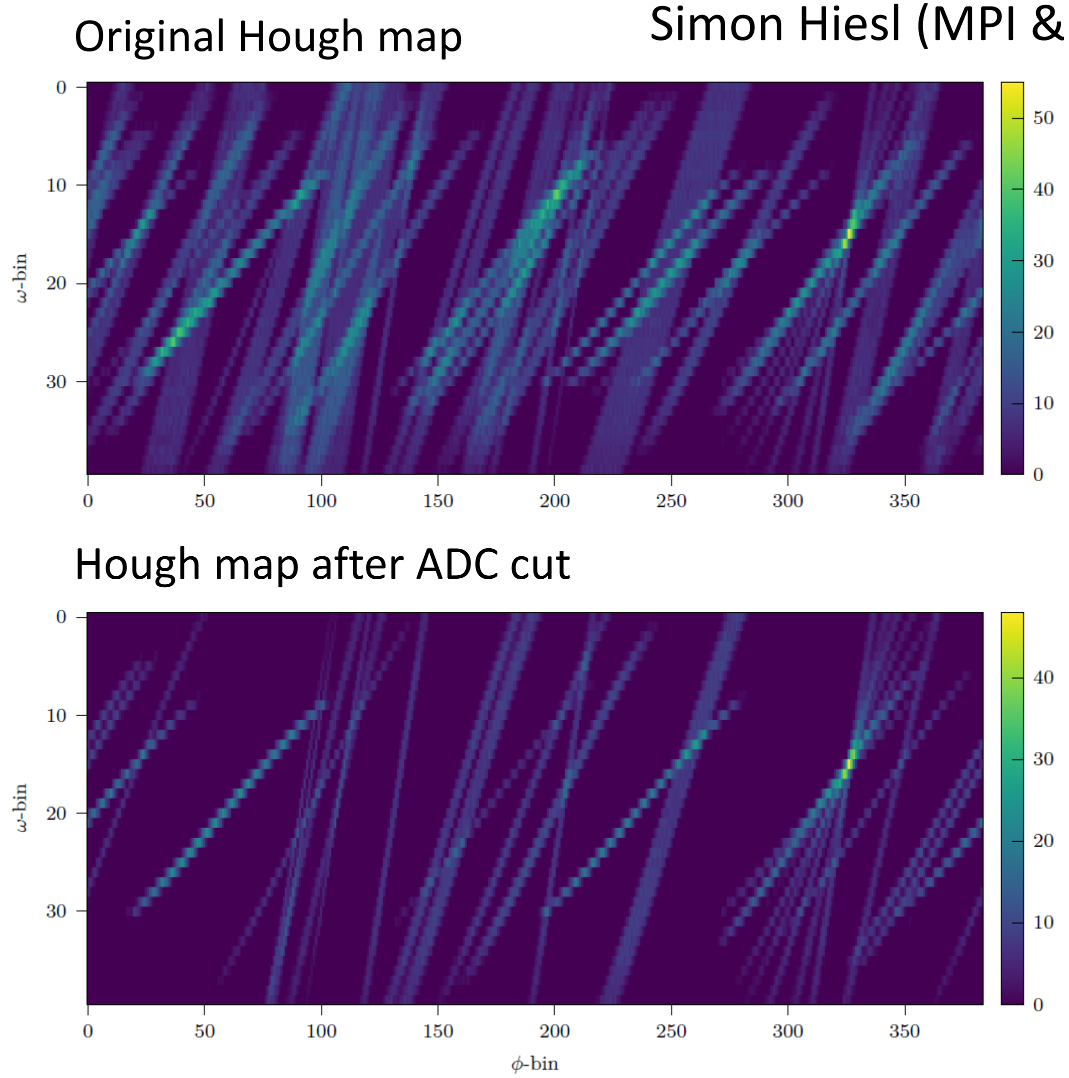


typical cut to remove “noise”: ADC < 10 counts

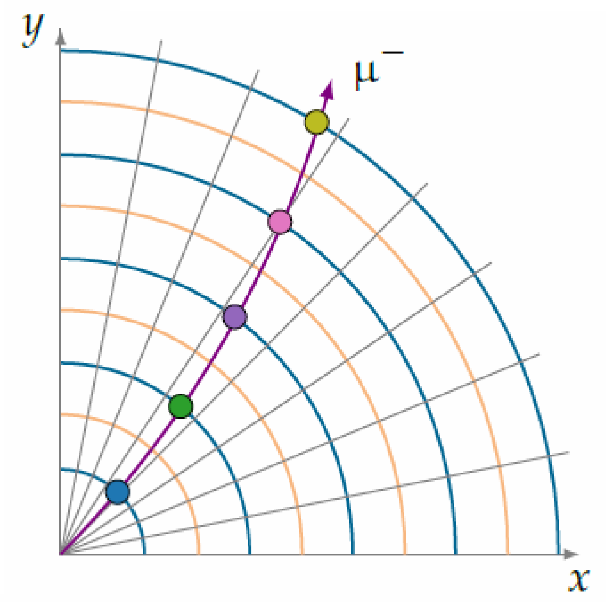


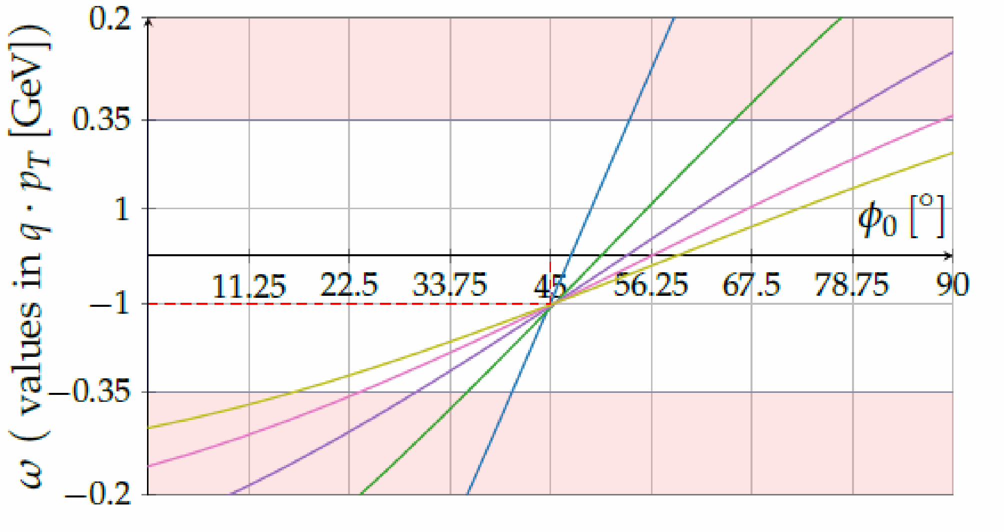
Effect of ADC cut on the Hough map

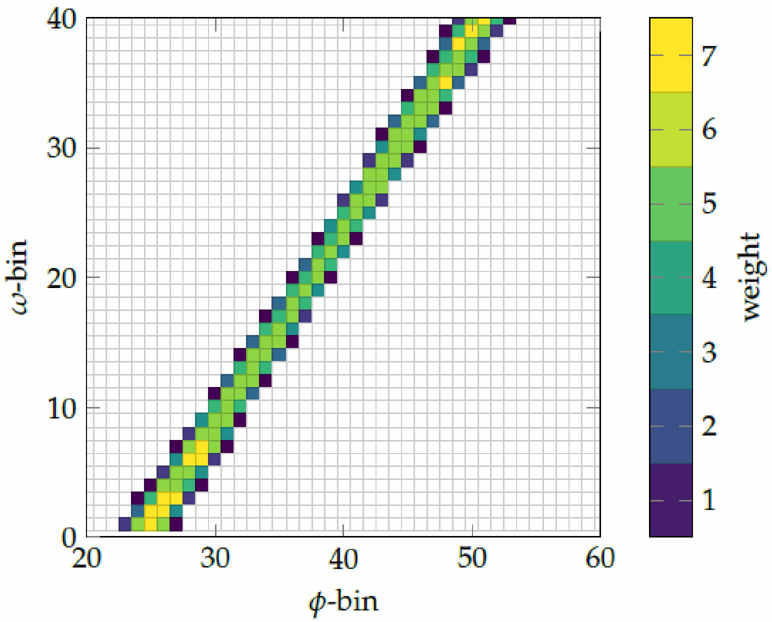
Weighted Hough Cells

Improved algorithm for hit curves:

- Standard method in binned Hough space: equal weight for each hit cell.
- Distributions of distance of track to cell center („drifttime“) are trained and stored in LUTs
- weight encoded in 3-bits: $w_{\omega\phi\theta}$ (bins close to real track receive higher weights)
- provides better accuracy for the crossing location in the binned Hough space







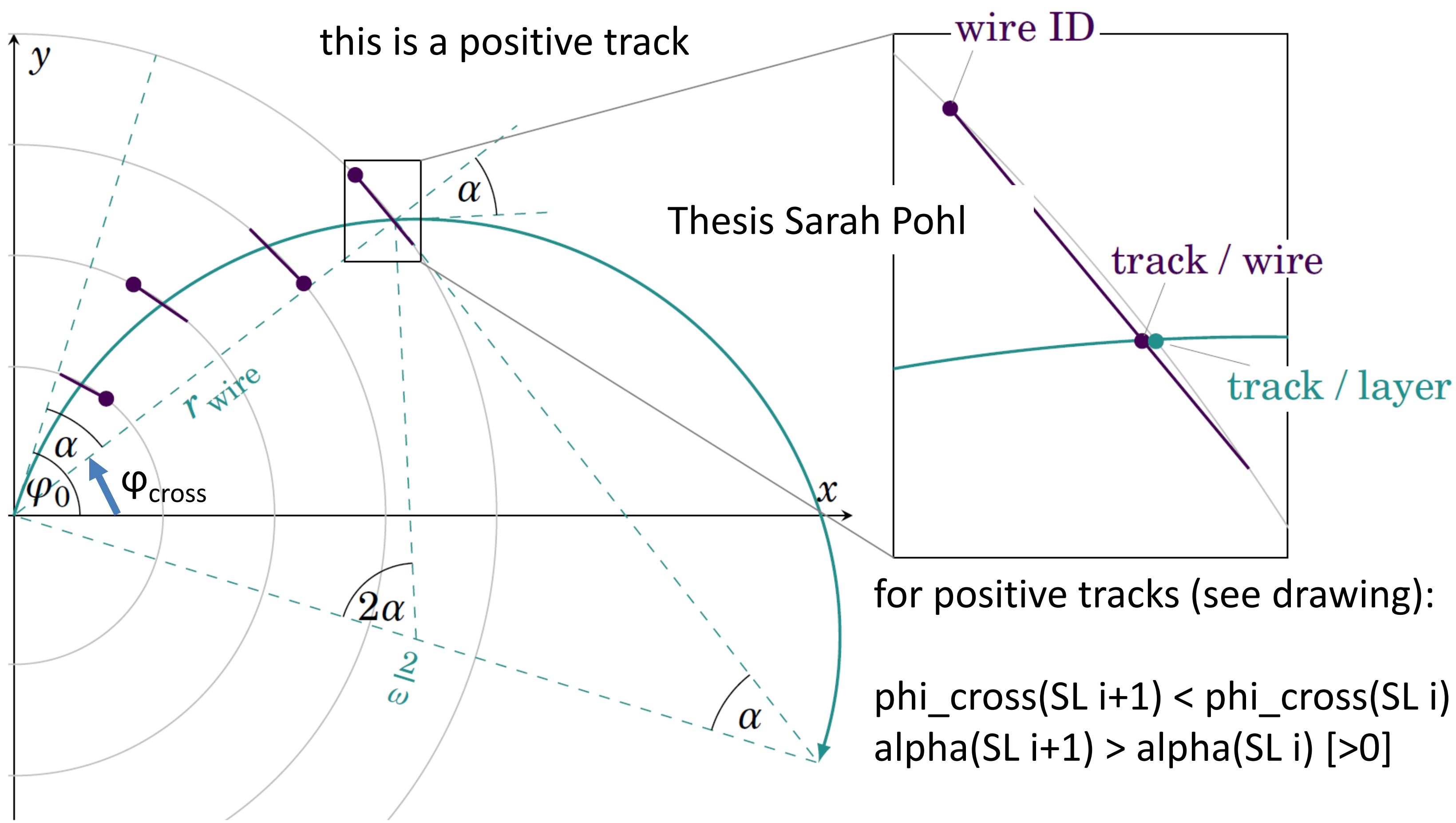
weight distributions of cells depend on the granularity of the Hough grid

(highest granularity in azimuth ϕ)

ω: 40, ϕ: 384(160), θ: 9

Reminder: Calculation of Network Inputs

this is a positive track



Thesis Sarah Pohl

for positive tracks (see drawing):

phi_cross(SL i+1) < phi_cross(SL i)
alpha(SL i+1) > alpha(SL i) [>0]

negative tracks: “<“ ↔ “>“

$$\varphi'_{\text{cross}} = \varphi_0 - \boxed{\arcsin\left(\frac{1}{2} \cdot r_{\text{wire}} \cdot \omega\right)} \equiv \varphi_0 - \alpha\,. \qquad (6.4)$$

the 3D Hough method supplies:

- phi (φ_0) in quadrant
- ±ω (charge curvature = $1/R_{track}$)
- θ (polar scattering angle)

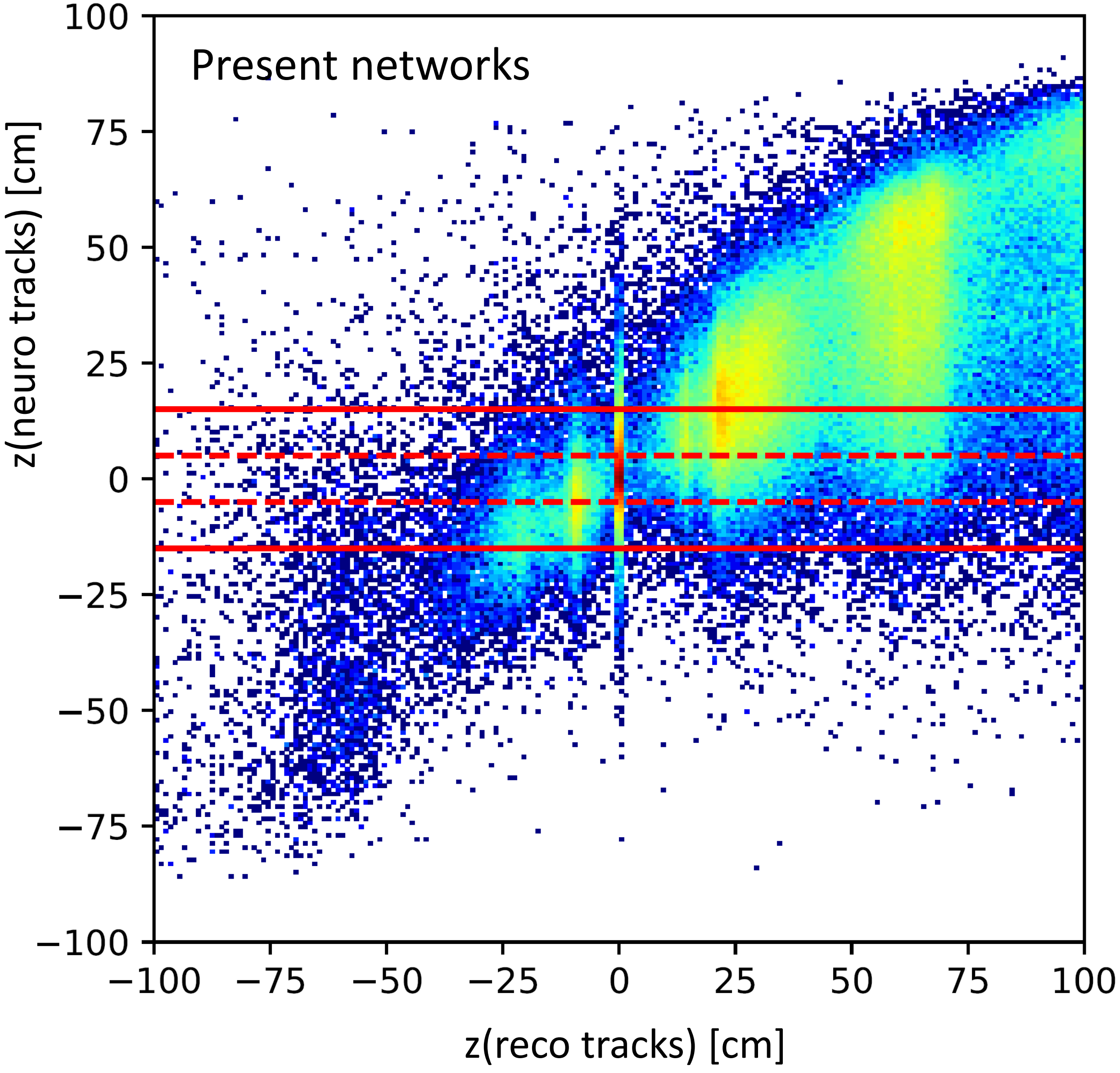
- from TSF: wire# and DT and R/L index [1,2,3] for prio wire, DT for other wires [ADC > cut]

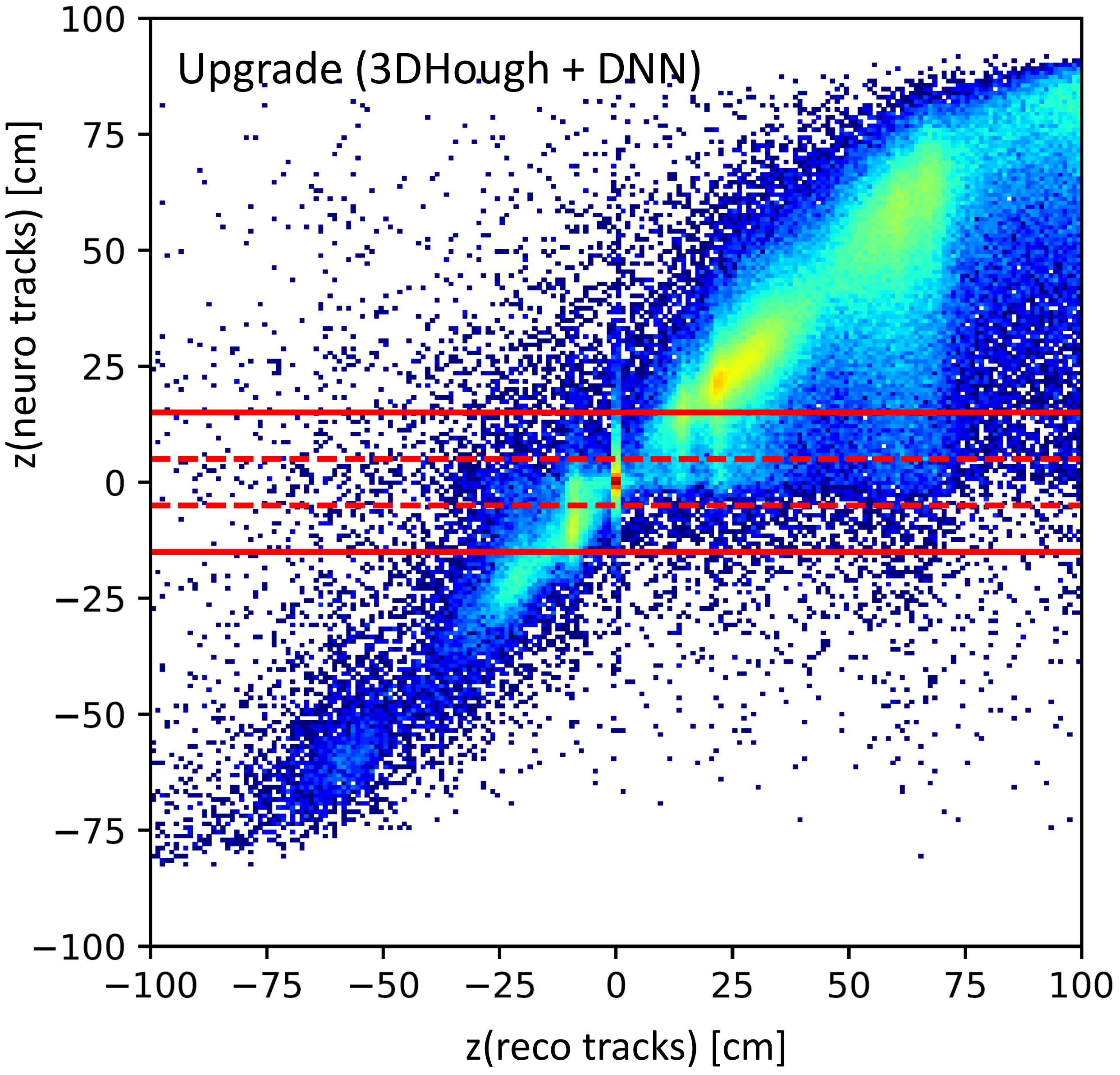
For the standard network input we need to calculate

- α (see formula)
- $\pm\Delta DT_i = (DT_i - DT(\min))$ (self timing from all DTs in track) sign from R/L
- phi_rel in the full 2π plane

phi_rel = phi(wire) – phi_cross

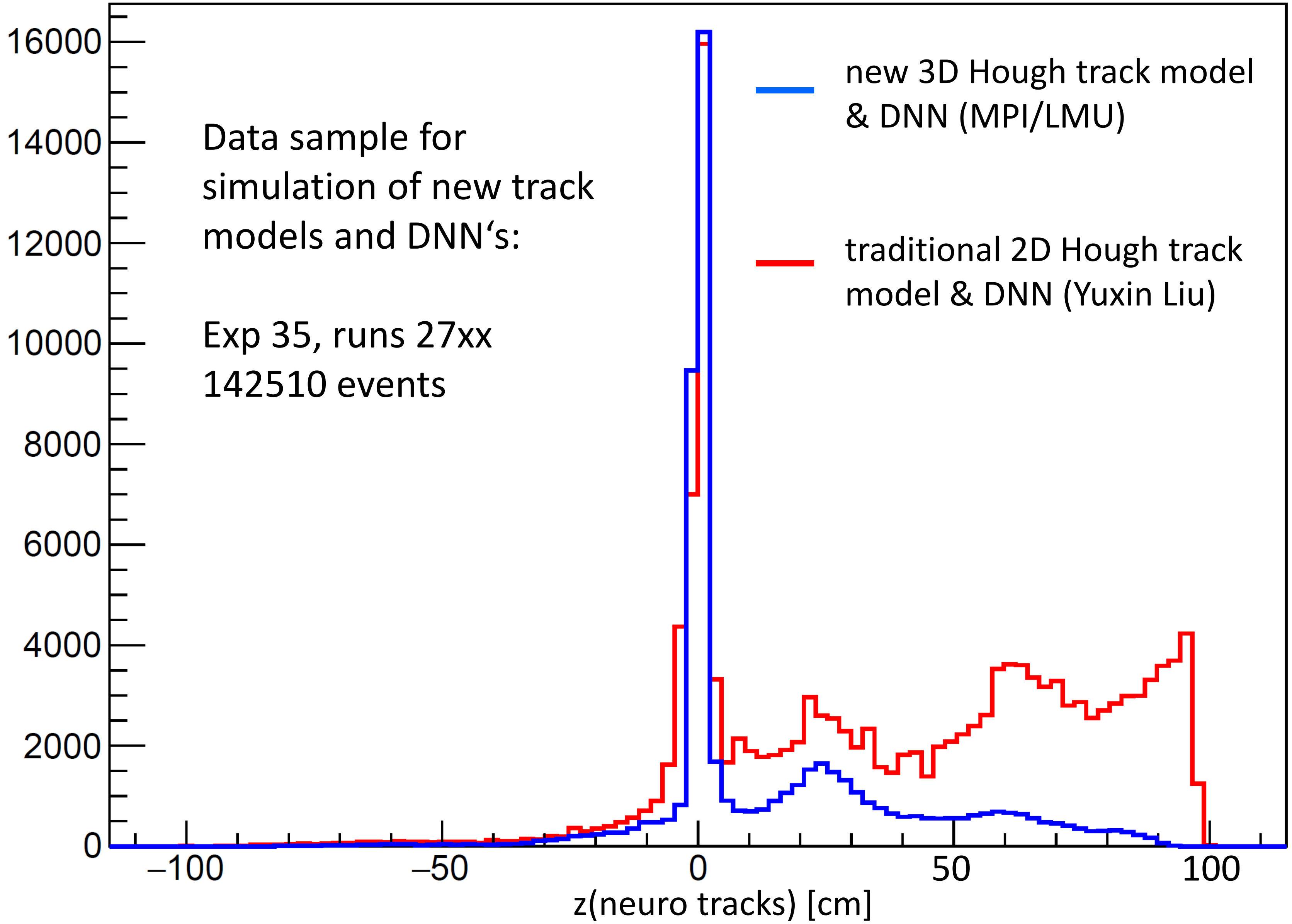
Expected Performance of Upgrade





Timo Forsthofer MPI/LMU

Expected Performance of Upgrade



Simulation of new track model (3D Hough) followed by a DNN for precision (4 hidden layers, 60 nodes each)

For comparison:
traditional 2D track model + DNN (by Yuxin Liu)

3DHough + DNN:

- superior resolution at IP
- natural suppression of track candidates for large |z|

-> robust against large background

Simon Hiesl MPI/LMU
Timo Forsthofer MPI/LMU