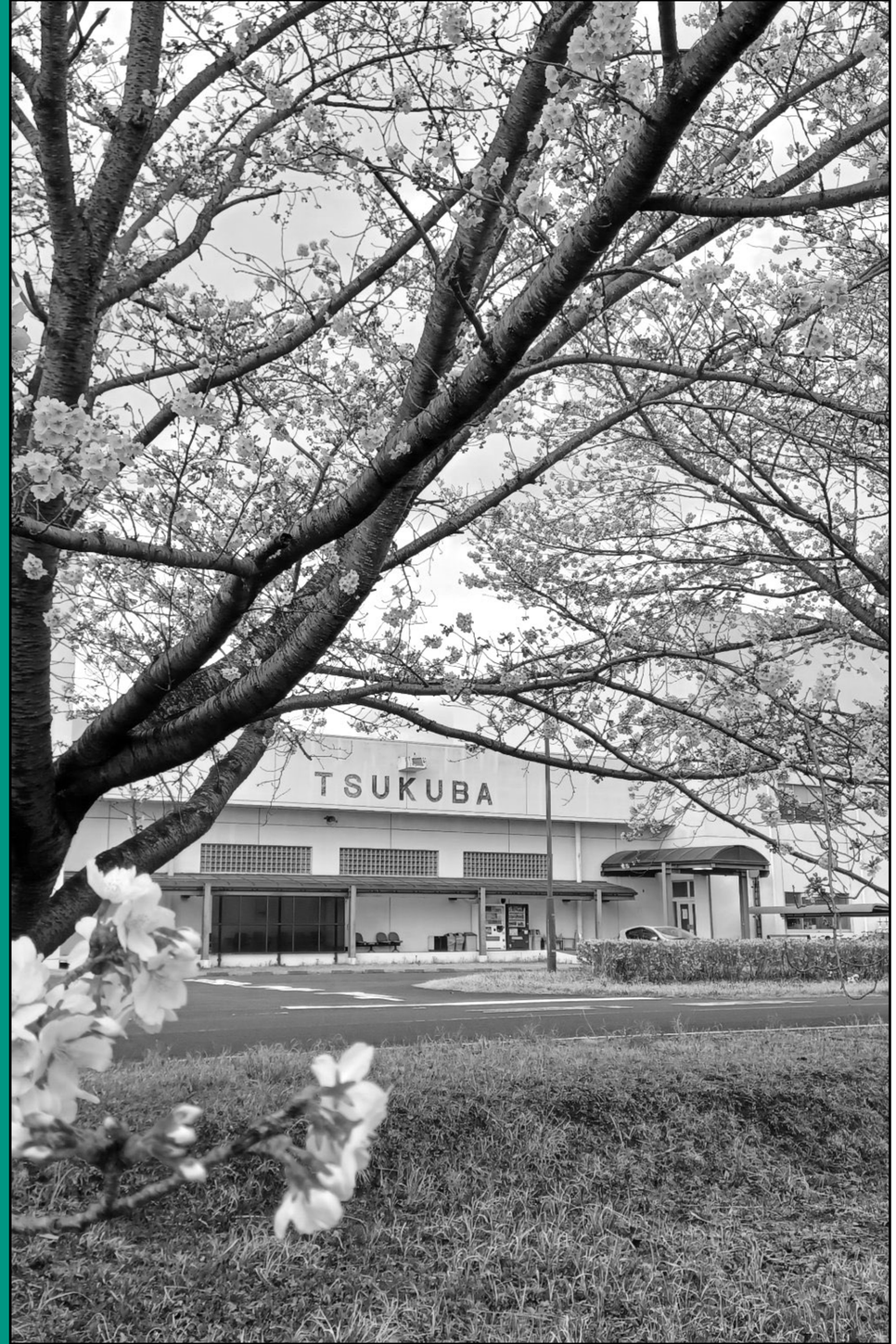
CDC Trigger upgrade: After LS2



23.10.2025 Belle II TRG/DAQ Workshop 2025

Torben FERBER (torben.ferber@kit.edu)
Institute of Experimental Particle Physics

State of the art at Belle II

- *Today:*

  2D Hough Finder and single layer NN (“Neuro-Z”)

- *Future, but before LS2:*

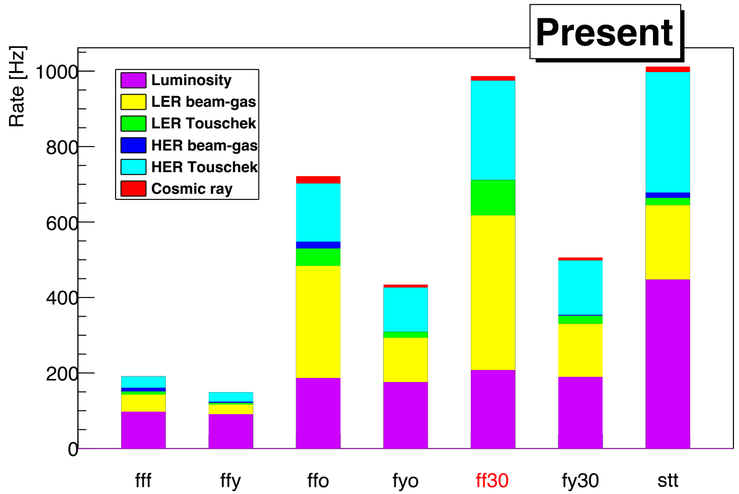
  3D Hough Finder and multi-layer NN

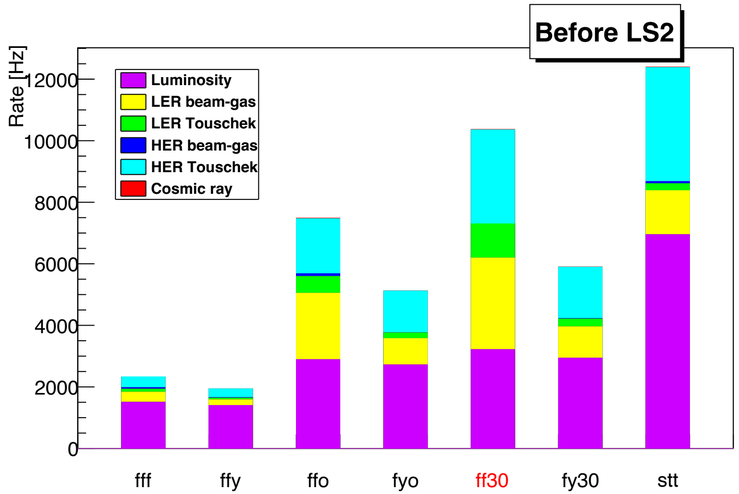
  Displaced vertex finder*

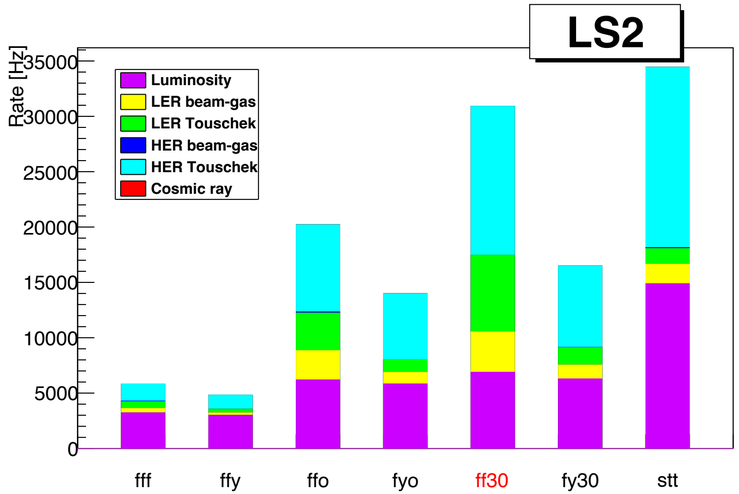
*Trigger for dedicated signature are important if we have to remove more inclusive trigger like the single-track-trigger (stt)

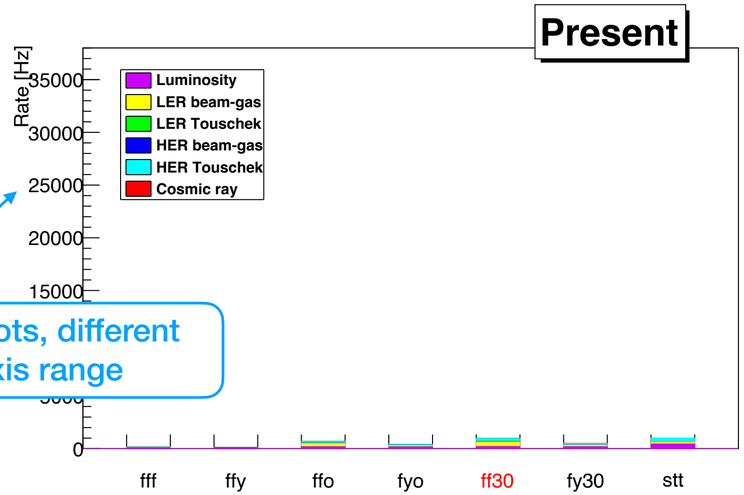
Trigger rate extrapolations*

I have reproduced the numbers. I find systematic uncertainties of 10-20% for the fitted coefficients, adding very large uncertainties to the extrapolated rates.

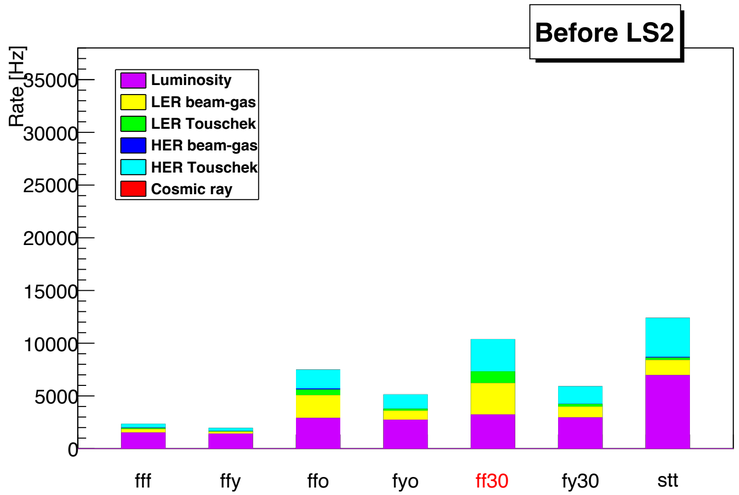


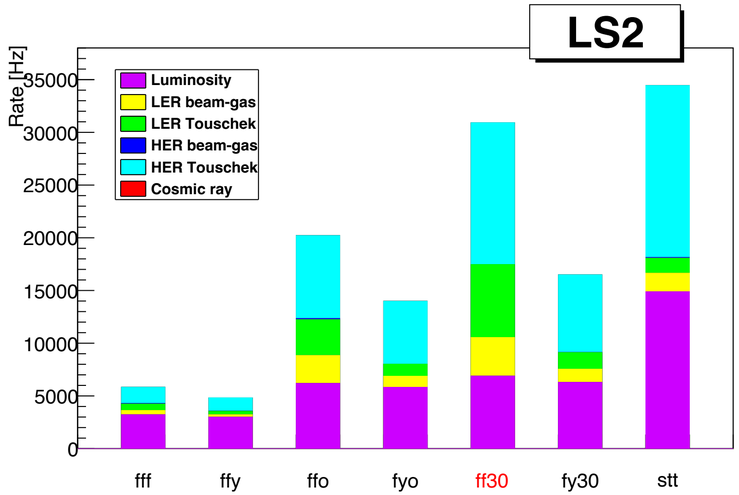






same plots, different y-axis range

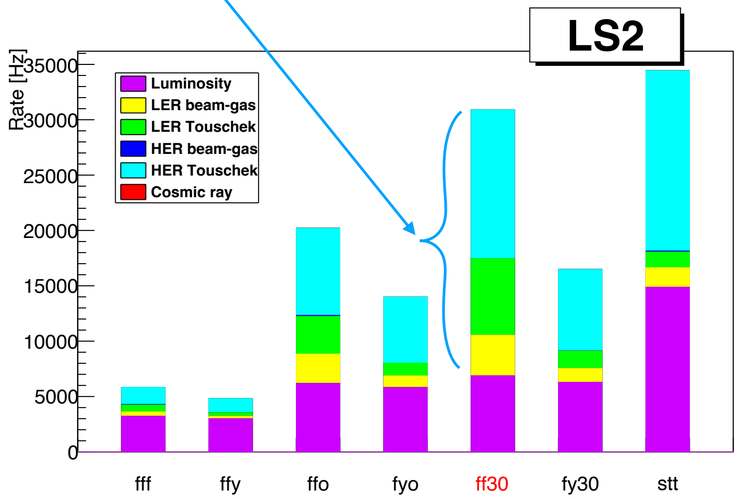




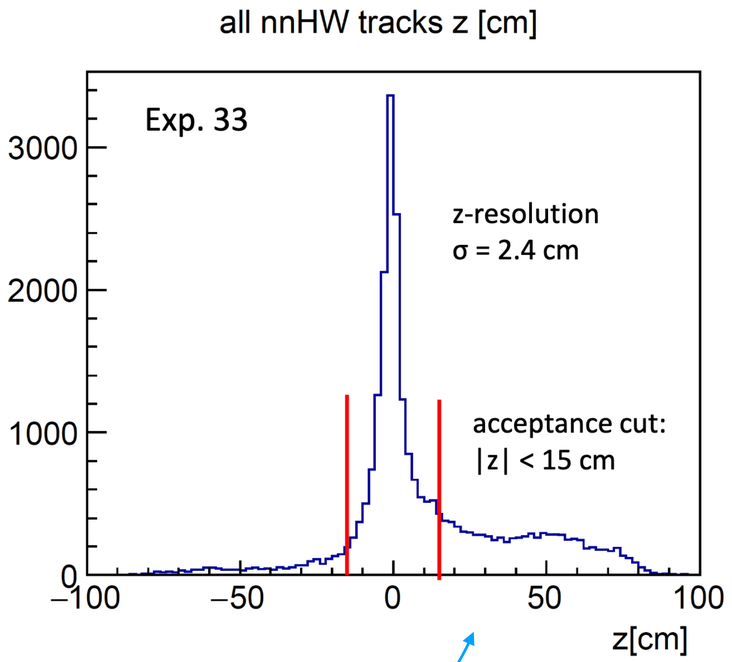
*from BELLE2-NOTE-TE-2024-022

Current CDC trigger challenges

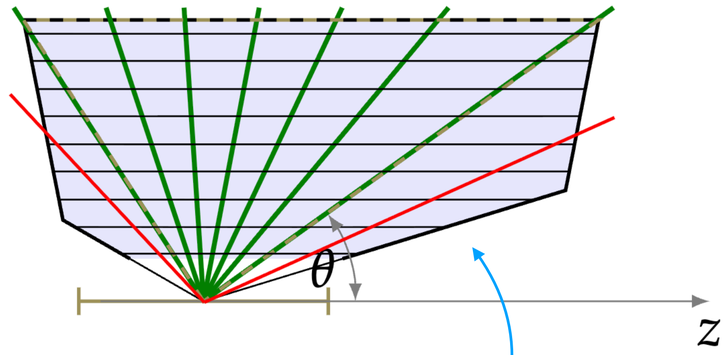
50-70% contribution from single beams



from BELLE2-NOTE-TE-2024-022



large contribution from off-IP tracks

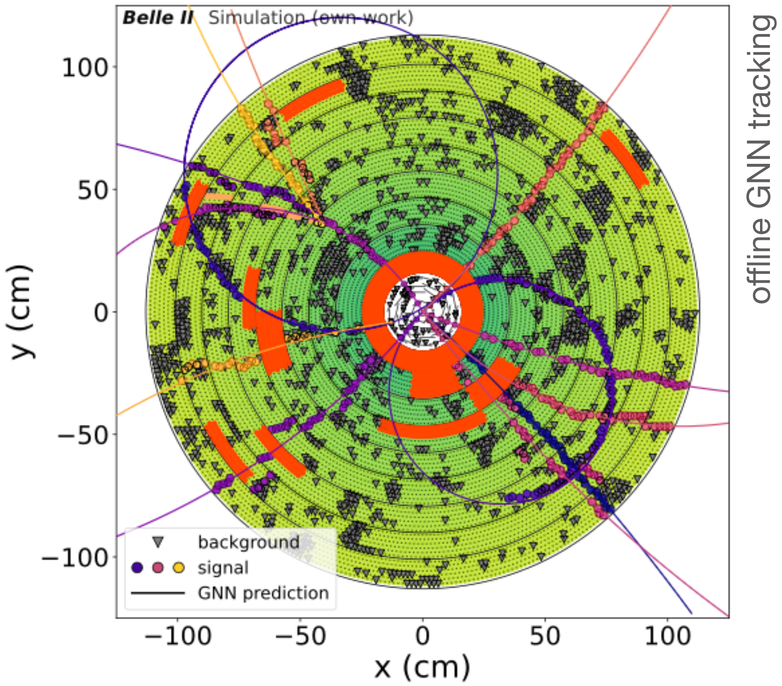


Efficiency reduction in endcaps (also for offline CDC tracking)

from https://indico.cern.ch/event/1488410/contributions/6561551/

Current (or expected) CDCTRG problems

Masked boards and gain reduction:
First tests with reduced HV show rather small impact on trigger efficiency.
Largest concern is possible loss of full super layers due to damage. This is in particular relevant for forward/backward tracks (so called “short tracks” or s)



from L. Reuter PhD thesis (to be published soon)

	exp1003 [kHz]		Scenario 1 [kHz]		Scenario 2 [kHz]		Scenario 3 [kHz]	
$ee \to ee$ (BHWIDE 0.5deg)	stt:	2.1	stt:	76.8	stt:	93.1	stt:	131.3
	fy30:	0.9	fy30:	34.1	fy30:	54.3	syo:	85.4
	fyo:	0.8	fyo:	29.6	fyo:	46.4	fy30:	85.0
	fyb:	0.3	syo:	16.3	syo:	32.1	fyo:	68.1
	syo:	0.2	fyb:	14.8	fyb:	19.8	syb:	36.0
$ee \to ee$ (BHWIDE 1deg)	stt:	0.7	stt:	23.5	stt:	28.8	stt:	35.9
	fy30:	0.3	fy30:	9.7	fy30:	11.9	fy30:	20.1
	fyo:	0.3	fyo:	8.6	syo:	10.8	syo:	20.1
	fyb:	0.1	fyb:	4.1	fyo:	9.3	fyo:	16.6
	syo:	0.1	syo:	4.1	syb:	5.0	syb:	10.1
$ee \to ee$ (BABAYAGA.NLO 1deg)	stt:	33.0	stt:	392.4	stt:	295.5	stt:	236.2
	fy30:	1.1	fy30:	25.0	fy30:	30.2	fy30:	44.6
	fyo:	1.0	fyo:	21.5	fyo:	24.8	syo:	44.0
	fyb:	0.7	syo:	14.9	syo:	18.4	fyo:	34.3
	syo:	0.5	fyb:	14.3	fyb:	15.9	syb:	22.1
$ee \to ee$ (BHWIDE 2.5deg)	stt:	0.5	stt:	7.0	stt:	8.2	stt:	7.1
	fy30:	0.2	fy30:	2.8	fy30:	3.8	fy30:	4.1
	fyo:	0.2	fyo:	2.7	fyo:	3.3	syo:	3.8
	fyb:	0.1	syo:	1.7	syo:	2.0	fyo:	3.4
	syo:	0.0	fyb:	1.5	fyb:	1.8	syb:	2.0
$ee \to ee$ (BABAYAGA.NLO 2.5deg)	stt:	2.2	stt:	26.2	stt:	19.5	stt:	17.8
	fy30:	0.2	fy30:	3.4	fy30:	4.2	syo:	5.8
	fyo:	0.2	fyo:	2.7	fyo:	3.4	fy30:	4.8
	fyb:	0.1	syo:	1.7	syo:	2.7	fyo:	3.8
	syo:	0.1	fyb:	1.6	fyb:	1.8	syb:	2.8
$ee \to ee$ (BHWIDE 5deg)	stt:	0.4	stt:	4.9	stt:	4.1	stt:	3.6
	fy30:	0.1	fy30:	1.1	fy30:	1.2	syo:	1.4
	fyo:	0.1	fyo:	1.0	fyo:	1.1	fy30:	1.4
	fyb:	0.1	fyb:	0.7	syo:	0.7	fyo:	1.1
	syo:	0.0	syo:	0.6	fyb:	0.7	syb:	0.7
$ee \to ee$ (BABAYAGA.NLO 5deg)	stt:	0.6	stt:	6.5	stt:	5.6	stt:	4.5
	fy30:	0.1	fy30:	1.2	fy30:	1.3	fy30:	1.5
	fyo:	0.1	fyo:	1.1	fyo:	1.2	syo:	1.4
	fyb:	0.1	fyb:	0.7	syo:	0.9	fyo:	1.2
	syo:	0.0	syo:	0.7	fyb:	0.7	syb:	0.9

Simulations can not reproduce the extrapolated trigger rates.
Significant differences between different Bhabha event generators and rate fully dominated by luminosity background.

CDCTRG: State of the art at Belle II

- *Today:*

  2D Hough Finder and single layer NN (“Neuro-Z”)

- *Future, but before LS2:*

  3D Hough Finder and multi-layer NN

  Displaced vertex finder*

- ***Far future, after LS2:***

  CDCFE cleanup

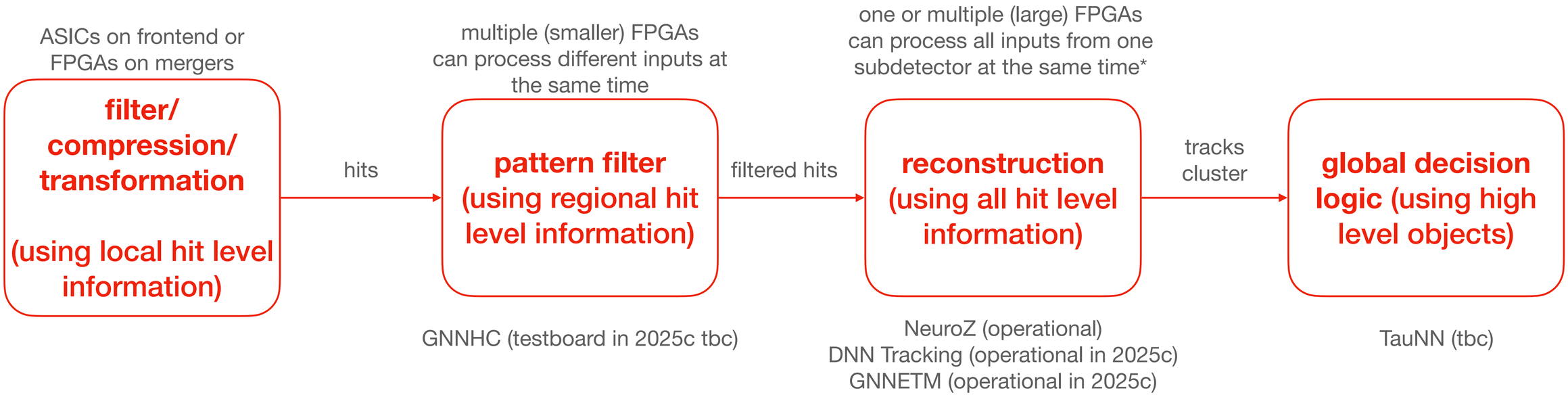
  GNN-based hit cleanup } Reduce beam backgrounds (and simplify subsequent track finding)

  GNN-based track finding and parameter estimation Improved resolution and robustness

  Combined VTX+CDC2.0 track finding and parameter est. Combine CDC momentum resolution and SVD endcap efficiency.

*Trigger for dedicated signature are important if we have to remove more inclusive trigger like the single-track-trigger (stt)

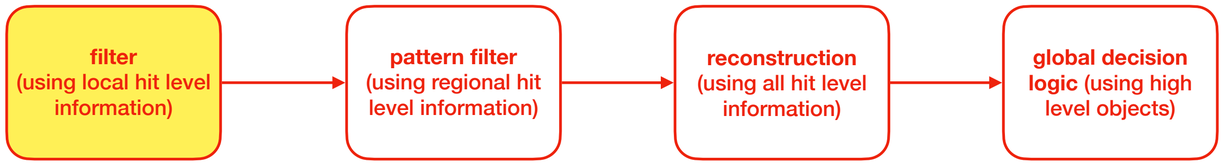
CDCTRG upgrade opportunities



GNNHC: ACAT2025 (https://indico.cern.ch/event/1488410/contributions/6562818/)
NeuroZ/DNN Tracking: ACAT2025 https://indico.cern.ch/event/1488410/contributions/6561551/
(**GNNETM**: FastML2025 (paper in preparation): https://indico.cern.ch/event/1496673/contributions/6637978/
TauNN: FastML2025 https://indico.cern.ch/event/1496673/contributions/6637927/)

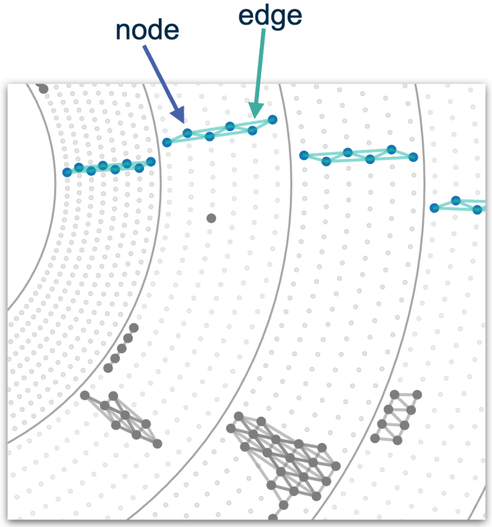
Opportunities: CDCTRG hit filter

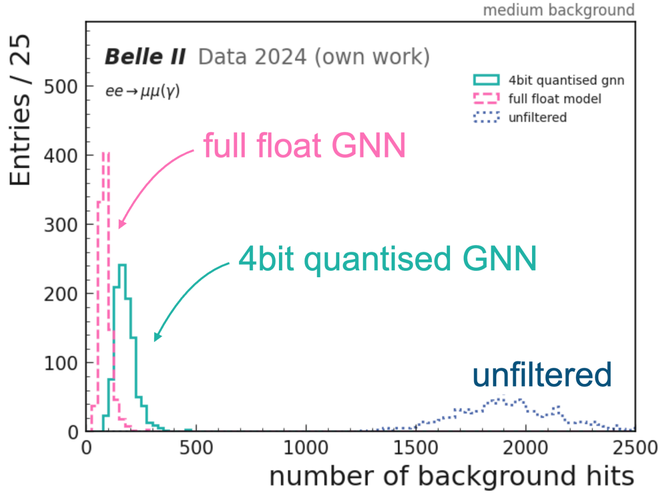
- Improved feature extraction from waveforms (better energy and time resolution), either conventional fits or ML
- Noise filtering using single node information (similar to offline BDT: https://indico.belle2.org/event/11972/contributions/76390/attachments/27967/41345/CDC-background-filter.pdf) possible on limited ressources.
- Other possible directions:
  - Latent space learning learning or preprocessing for subsequent track finding
  - Compression of groups of hits, either conventional or using autoencoders (e.g. CMS HGCAL)

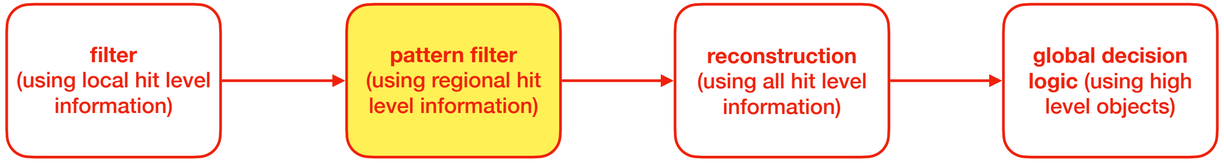


Opportunities: CDCTRG pattern filter

- If information from multiple spatially close wires can be combined, hit filtering can effectively perform track segment finding
- GNN-based hit filtering is very powerful in removing various backgrounds from crosstalk or beam backgrounds.
  - Currently rather limited by very reduced information available per wire
- Large number of inputs requires ~20 FPGAs in parallel, each processing several hundreds nodes and a few thousand edges (overlapping sectors, no superlayer boundary crossing):
  - We reach 32MHz inputs with <500ns latency (https://indico.cern.ch/event/1502285/contributions/6554672/). Next step by end of 2025: Real-time prototype running on evaluation hardware as important step toward in-detector deployment.



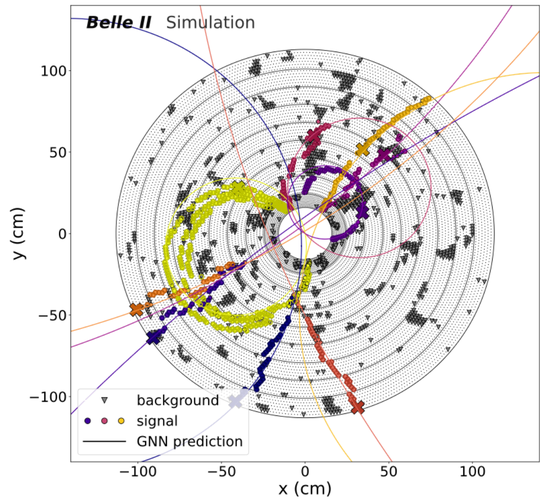


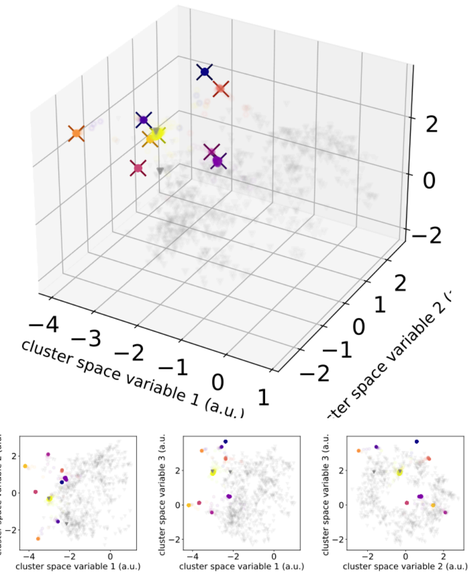


from G. Heine

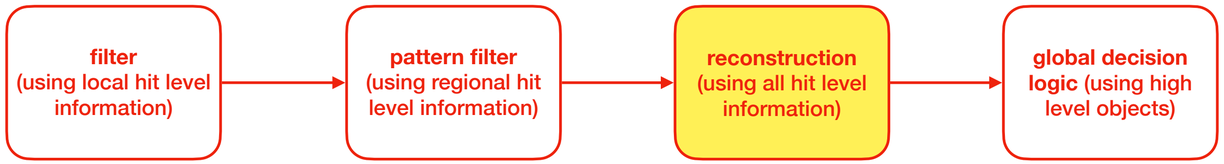
Opportunities: CDCTRG reconstruction

- Offline state-of-the-art: End-to-end (“hits in, tracks out”) single step inference, fully differentiable object detection and parameter regression GNN
  - Offline implementation for Belle II: Comput Softw Big Sci 9, 6 (2025) https://arxiv.org/abs/2411.13596
  - Biggest challenge is simultaneous optimization of hit assignment and fitting → not needed on TRG
- Bringing this to hardware requires rather significant steps:
  - Need better inputs (ADC, TDC) than currently available (CDC frontend!)
  - Significant reduction of model size (currently ~1M weights, unquantized), possibly requires multiple FPGAs/Versal for a single GNN (joint projects CERN+KIT+ETH Zurich started)
  - Requires significant reduction of number of inputs via Φ-segmentation followed duplicate removal, even after hit filtering



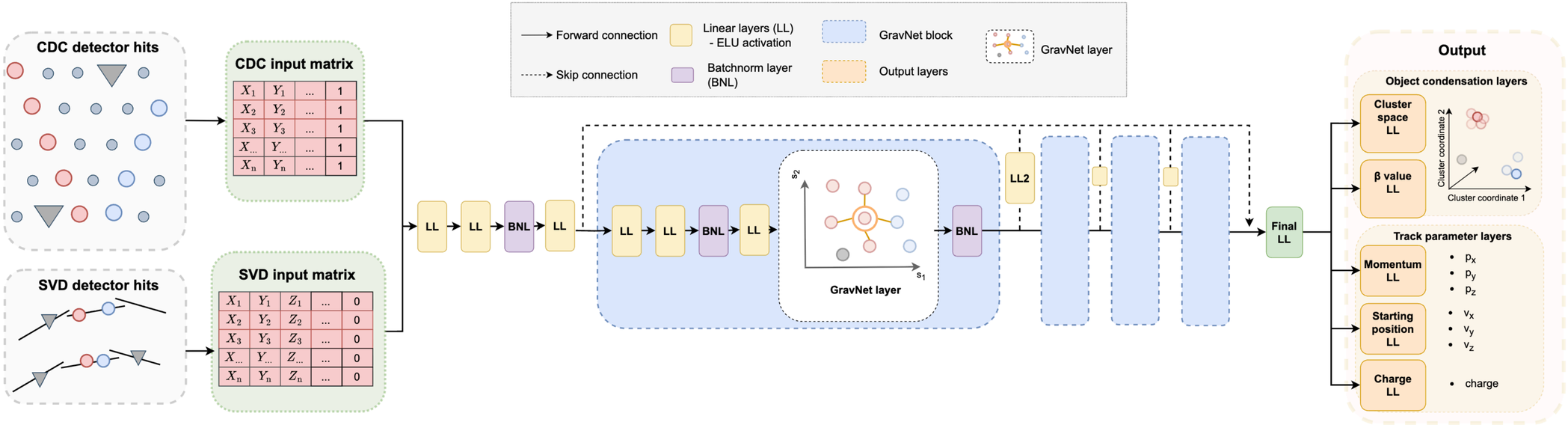


from L. Reuter



Opportunities: Combined VTXCDCTRG reconstruction

- Offline, first results for so-called multi-modal GNNs look very promising (https://indico.cern.ch/event/1488410/contributions/6561505/)
  - SVD recovers CDC inefficiency in endcaps and low transverse momentum, CDC provides momentum resolution



filter (using local hit level information) → **pattern filter** (using regional hit level information) → **reconstruction** (using all hit level information) → **global decision logic** (using high level objects)

from L. Reuter and T. Brandes

Summary

- LS2 trigger rate extrapolation shows large contributions form single beam backgrounds in the CDC, however, there are three (large) caveats:
  - Re-design of the IP region probably completely changes the background situation
  - Current CDC performance will probably degrade significantly already well before LS2
  - We can not reproduce this well in simulation
- Pattern hit filtering on FPGAs is mature and at the level of implementation details
- Complete redesign of track finding is more challenging. Offline GNNs have best performance, also in combining multiple different detector types.
- Conceptual work is needed for optimization of multi-step ML solutions, but also for very large GNN implementation, potentially on multiple FPGAs