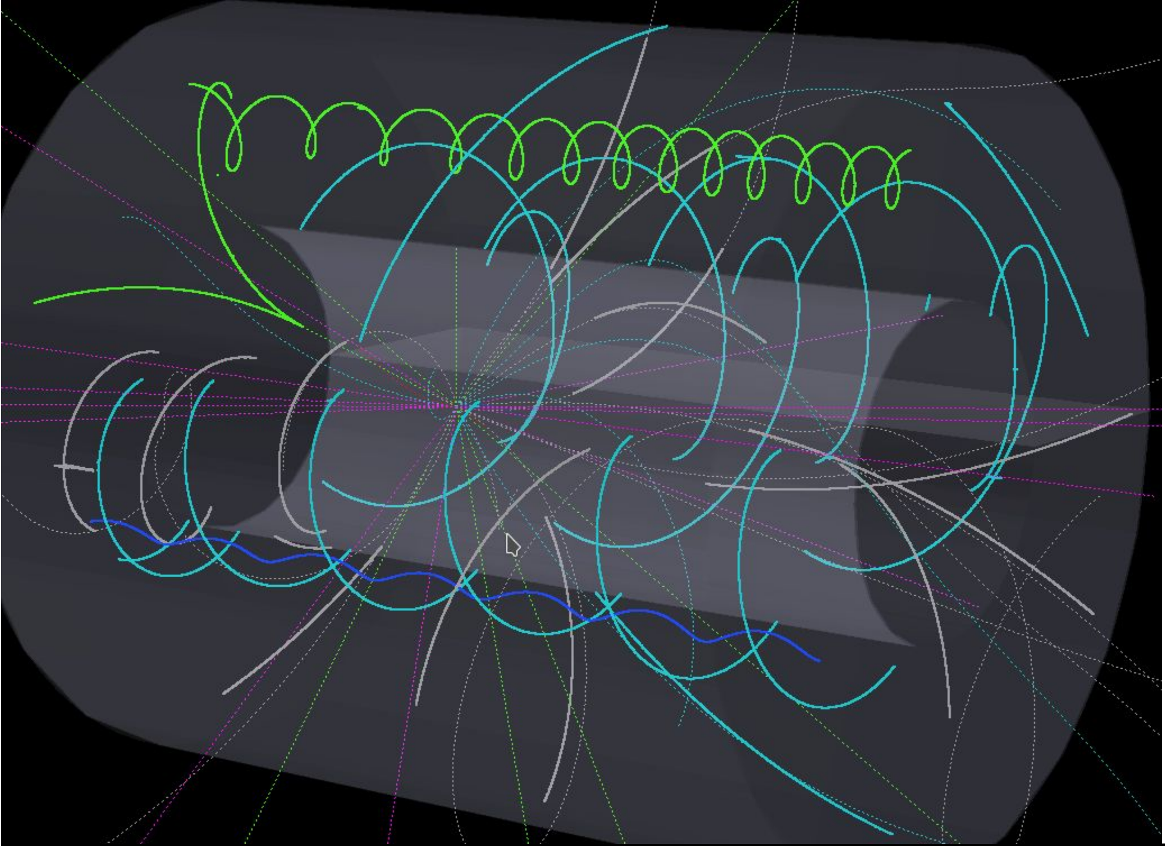
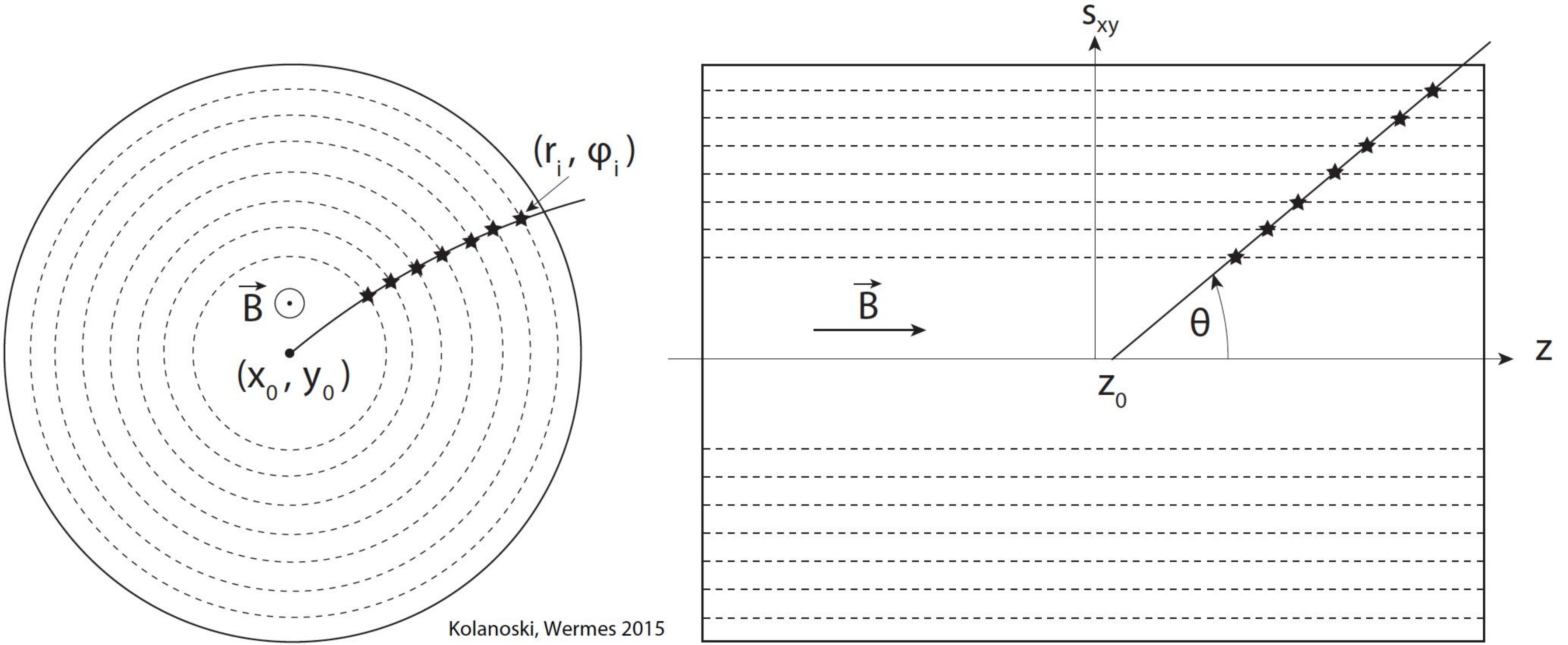


The near-future of advanced particle tracking technology

Peter Mandeville Lewis | Universität Bonn

UH Mānoa Physics Seminar | April 28 2023

Multiple measurement points ⋆ to determine p_T and (θ,ϕ)



Kolanoski, Wermes 2015

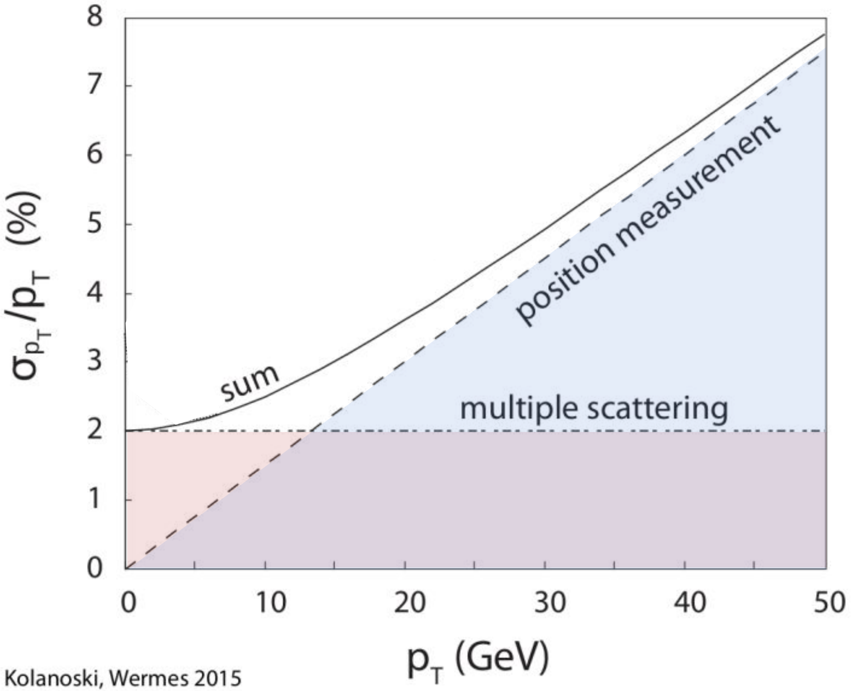
Considerations

Material budget:

- Absolute floor to p_T resolution
- Critical for low-E colliders like SuperKEKB ($\sqrt{s}$=10.58 GeV)
- **Gas trackers** preferred

Position measurement

- Mostly relevant for high-p_T tracks
- More measurement points
- Better resolution per point



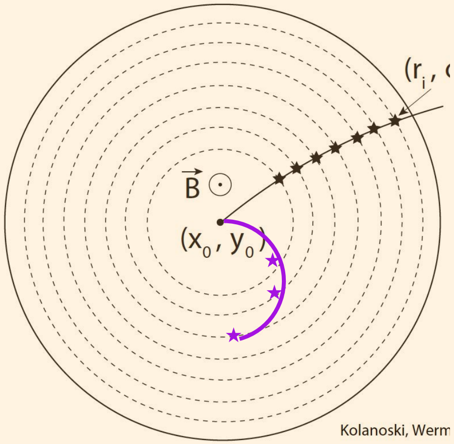
Kolanoski, Wermes 2015

But that's not all that matters…

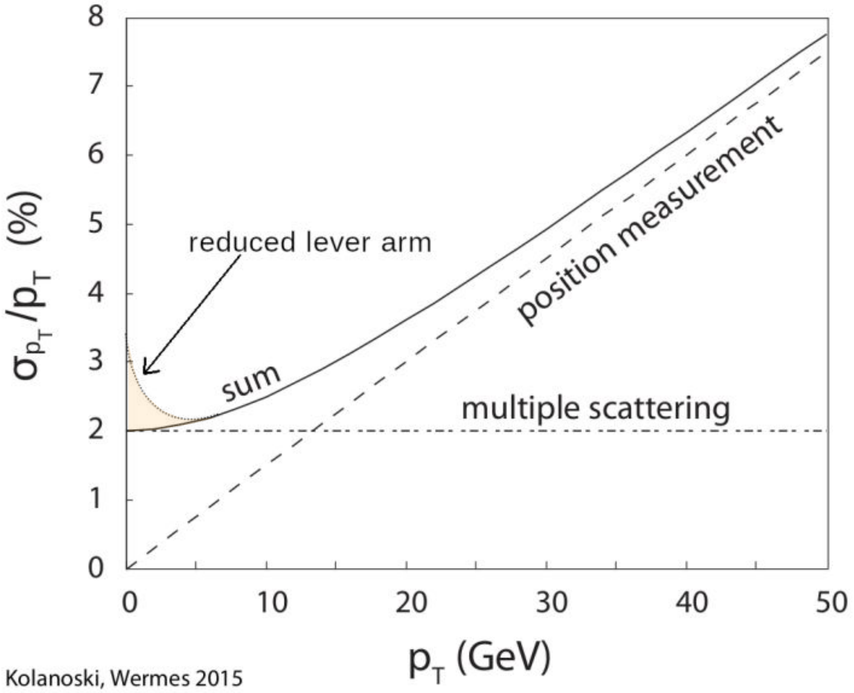
Further considerations

Reduced lever arm

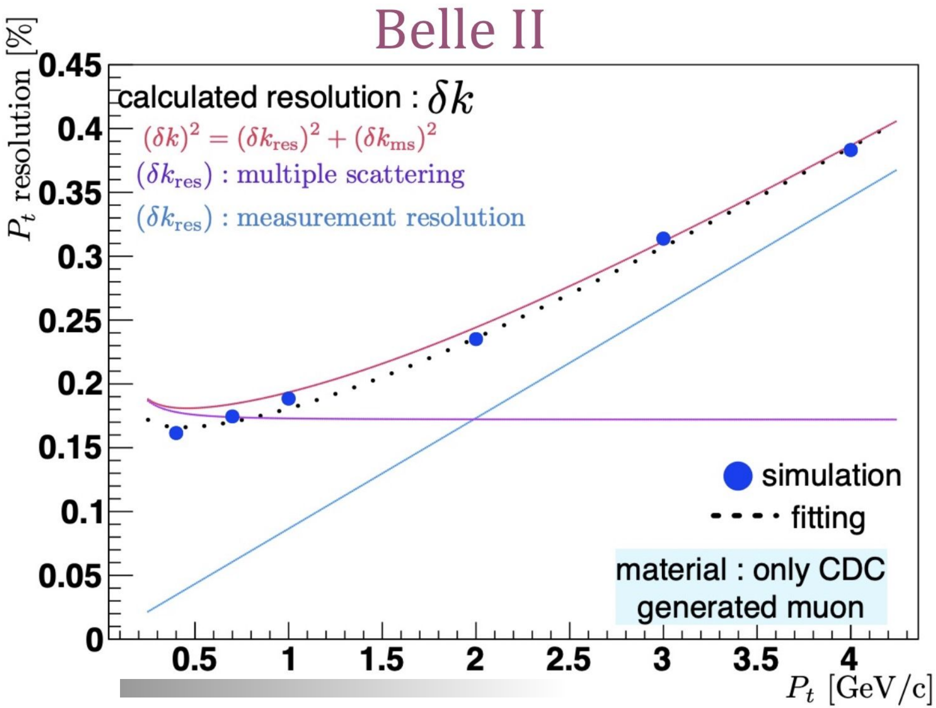
- **Low-p_T tracks** leave fewer hits



- Partially recovered by **reducing inner radius** of tracker



For Belle II, **multiple scattering** dominates…



Most of the interesting physics is here

→ *material budget* is the name of the game. Let's look closer at the Belle II tracking system…

Belle II tracker

Central beam pipe: diameter 3cm → 2cm (Beryllium)

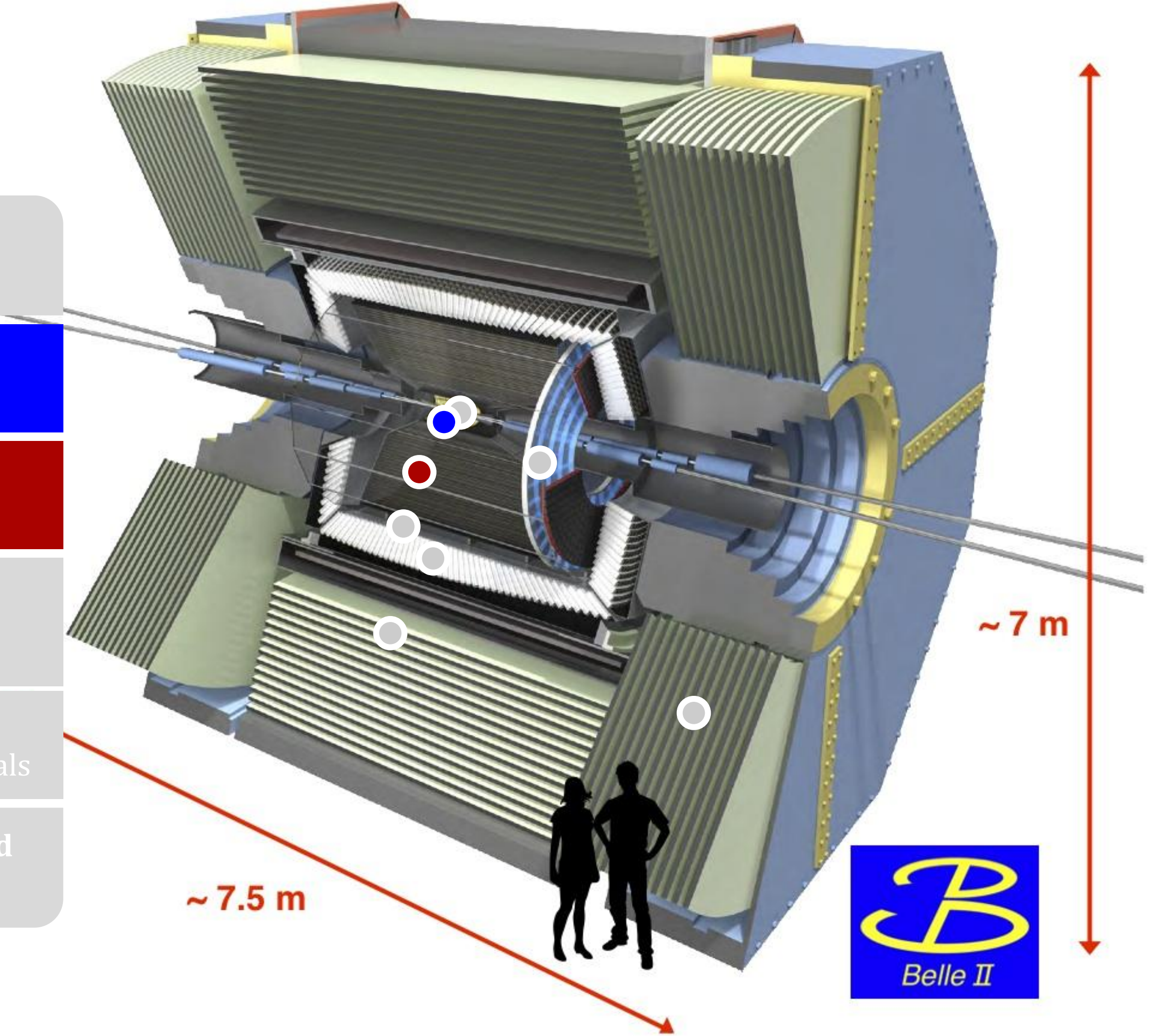
Vertexing: 2 layers of pixels + 4 double-sided strips

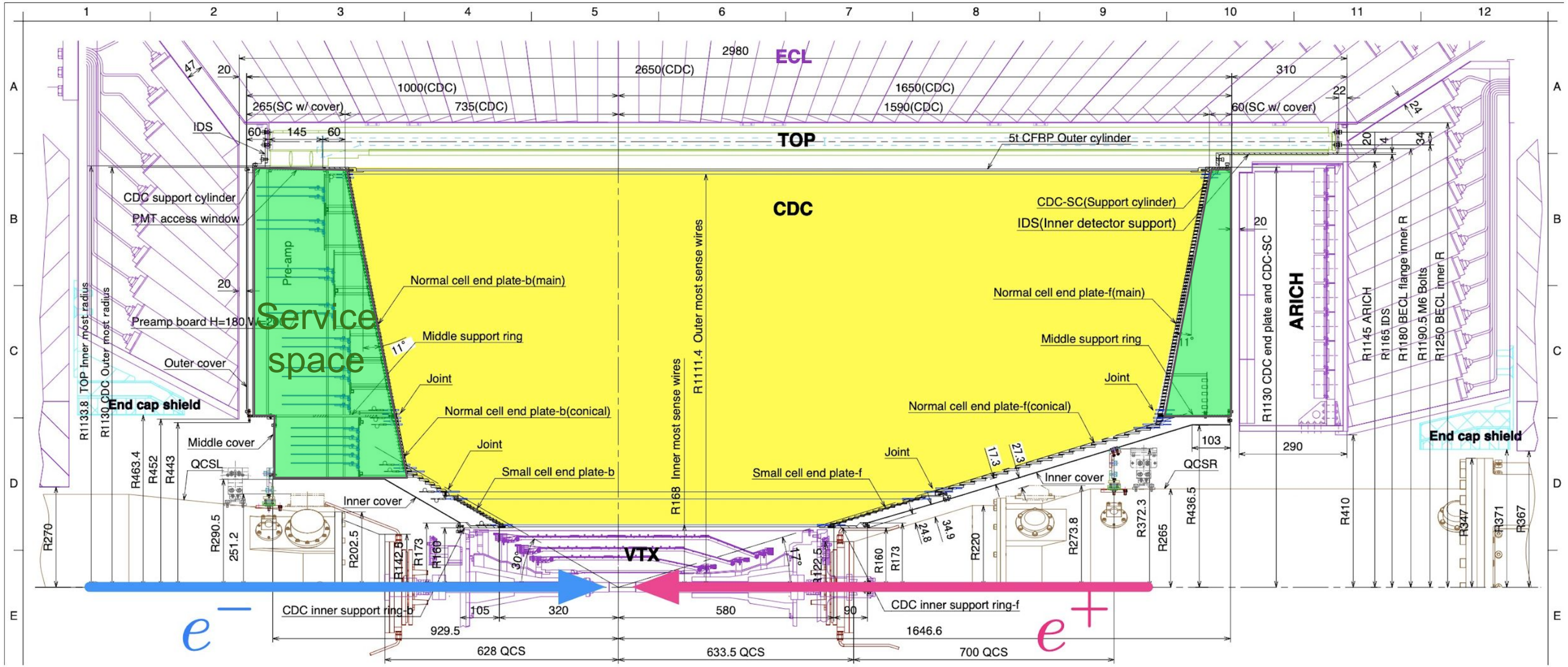
Tracking: 14K-wire drift chamber

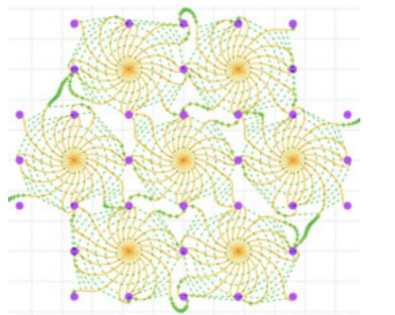
PID: time-of-flight (barrel), threshold Cherenkov aerogel → time-of-propagation (barrel), proximity focusing aerogel (endcap)

EM calorimetry: CsI → same crystals upgrade of electronics and processing with legacy CsI(Tl) crystals

KL and μ: scintillators replace RPCs (endcap and inner two layers of barrel)




ECL
TOP
CDC
VTX
ARICH
Service space
Pre-amp
CDC support cylinder
PMT access window
Preamp board H=180
Outer cover
End cap shield
Middle cover
QCSL
Inner cover
IDS
5t CFRP Outer cylinder
CDC-SC(Support cylinder)
IDS(Inner detector support)
Normal cell end plate-b(main)
Middle support ring
Joint
Normal cell end plate-b(conical)
Small cell end plate-b
Normal cell end plate-f(main)
Normal cell end plate-f(conical)
Small cell end plate-f
QCSR
CDC inner support ring-b
CDC inner support ring-f
R1111.4 Outer most sense wires
R168 Inner most sense wires
R1133.8 TOP Inner most radius
R1130 CDC Outer most radius
R1130 CDC end plate and CDC-SC
R1145 ARICH
R1165 IDS
R1180 BECL flange inner R
R1190.5 M6 Bolts
R1250 BECL inner R
2980
2650(CDC)
1000(CDC)
1650(CDC)
265(SC w/ cover)
735(CDC)
1590(CDC)
60(SC w/ cover)
929.5
1646.6
628 QCS
633.5 QCS
700 QCS
e^-
e^+



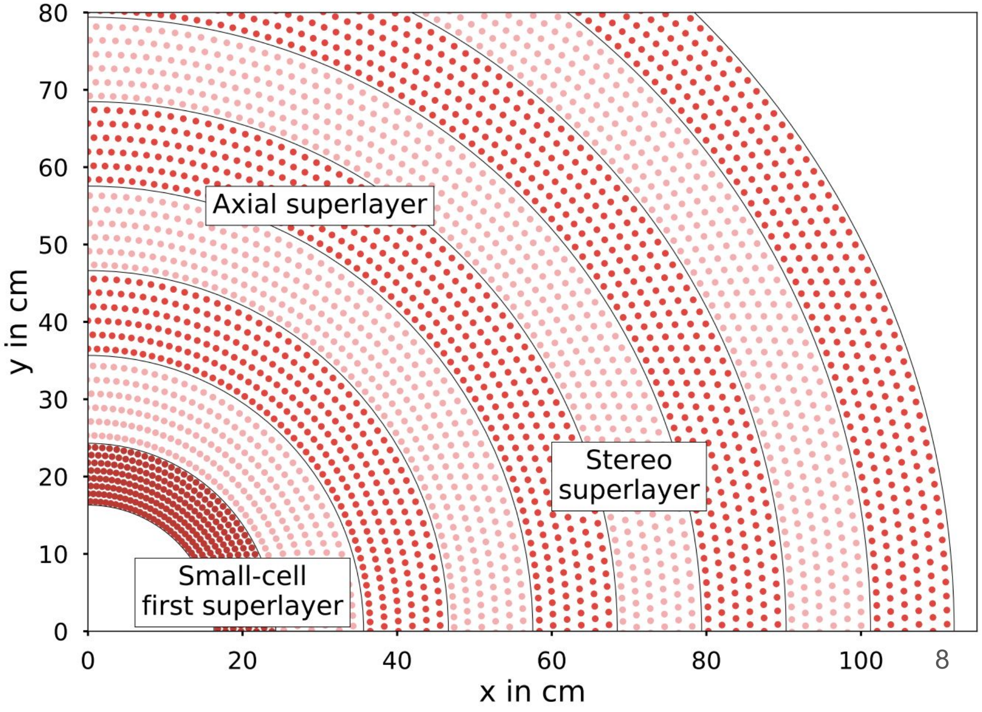
Overview of Belle II CDC

Concept:

- Position via **drift time** of charge in drift cells
- Low-*Z* gas: 50% He, 50% C_2H_6

Wires:

- 14335 wires in 56 layers and 9 “superlayers”
- 30µm Tungsten (**sense**) and 120µm Aluminum (**field**)
- High density in inner layers (**small-cell**)
- Stereo superlayers provide *z* information

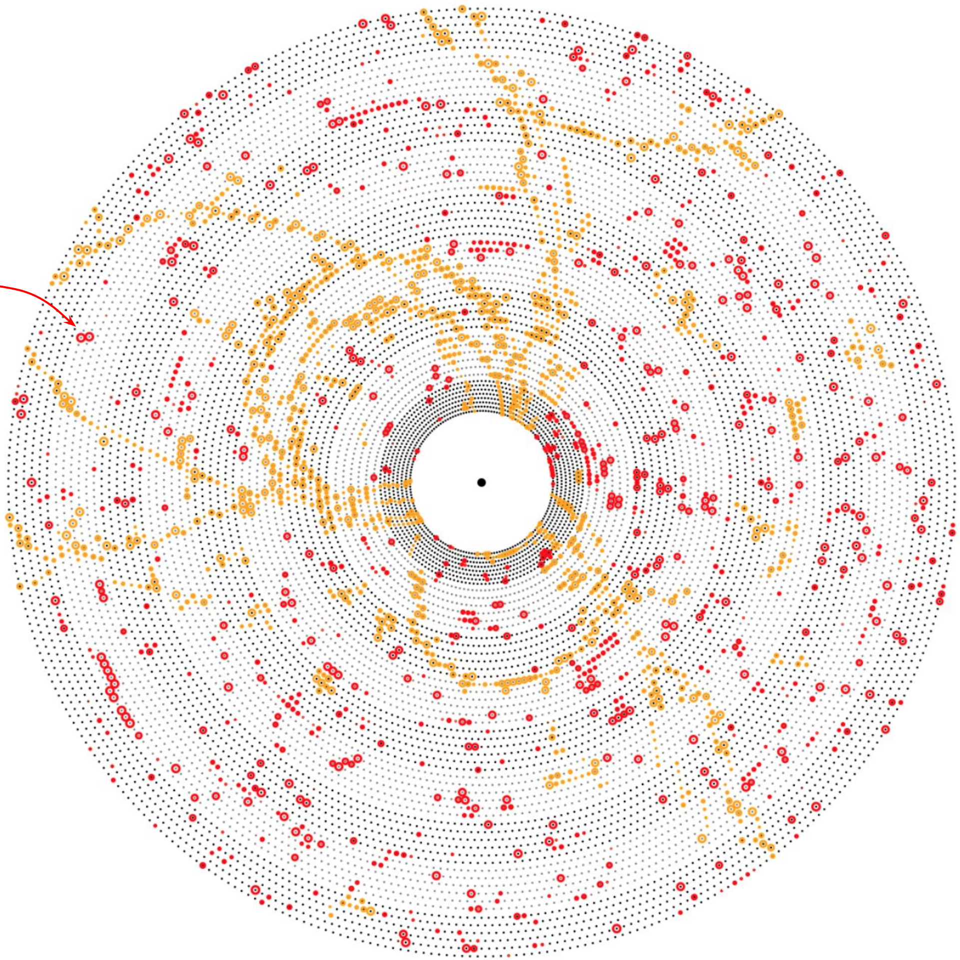


Let’s look at a *simulated* event…

In terms of **occupancy**, this is effectively a **2D** detector

Beam backgrounds!

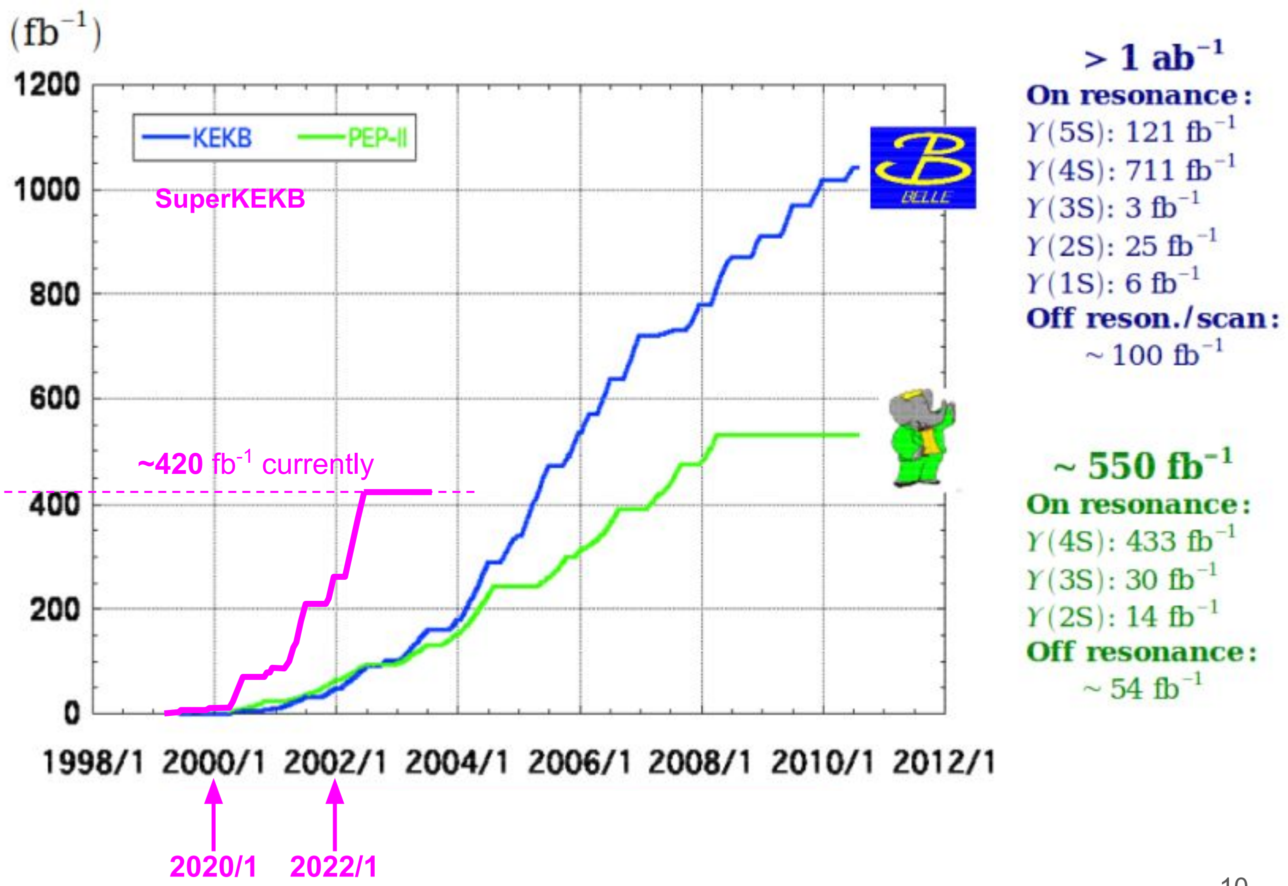
Typical beam background levels in inner region **far** higher. **Signal hits** are **~1%** of total.



Operational experience

2+ years of running now

- World-record luminosities (but still far from design)
- Challenging beam-background environment
- A dataset already comparable to BaBar's

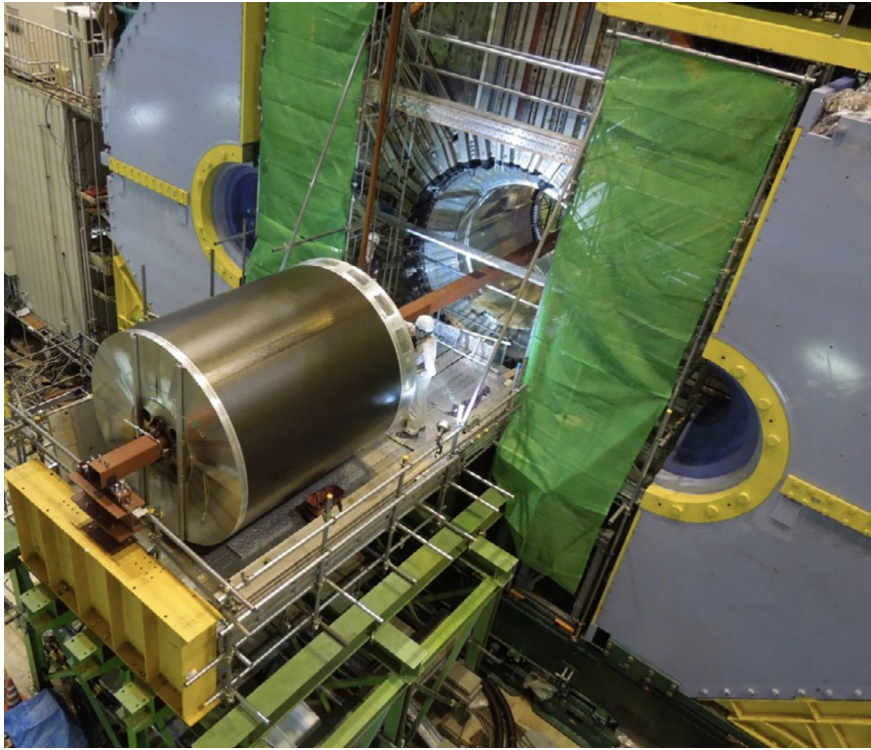


How did the CDC do?

How did the CDC do?

Well…. not great

- Very high occupancy in inner layers (beam backgrounds)
    - Many injections of water vapor as quencher
- Significant short-and long-term gain drops
    - Some aging?
    - Too much water (+ broken sensor)
    - Oxygen contamination (+ broken sensor)
    - Inadequate fresh gas distribution (+ broken hose)
- ***Chronic personnel shortage***



What can we do from here?

Belle II CDC upgrade scenarios

What can we do from here?

I have been asked to step in here

Short term (*now*)

- Immediate intervention with competent technical leadership
- Test vessel studies (aging, gain, gas, etc.)

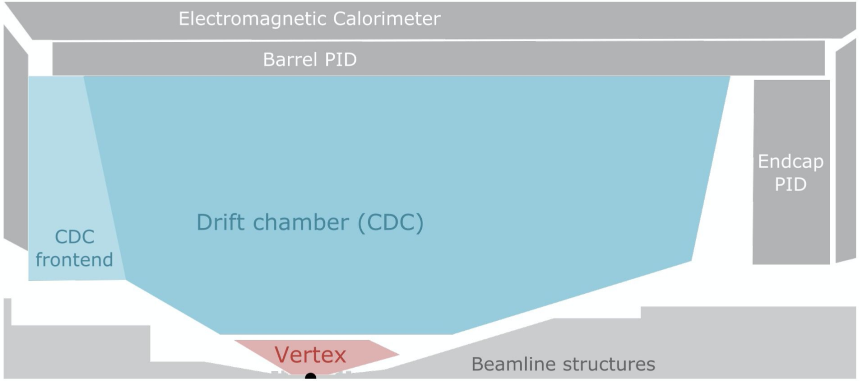
Medium-term (by *2026*)

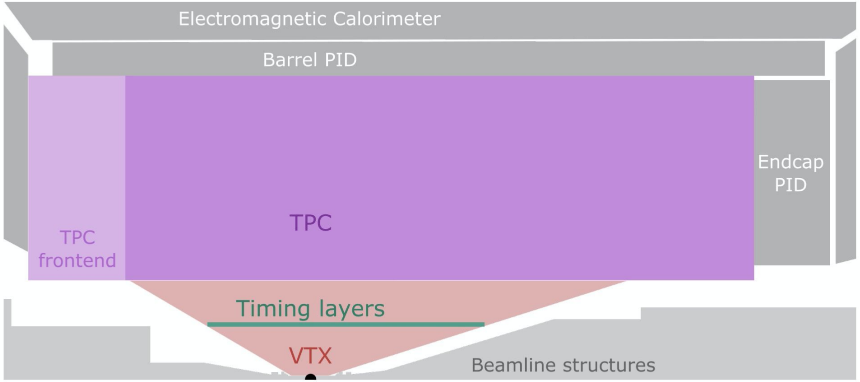
- Expansion of upgraded silicon detector?
- Other ideas?

I'm somewhat involved here

Longer-term (by *2032*)

- Full silicon tracker
- Tracking TPC ← Project lead here





Let's look at these options in more detail…

2026: Expansion of upgraded silicon pixels?

Current upgrade concept

- Replace both inner detectors (silicon pixels + strips)
- Depleted Monolithic Active pixels (CMOS)
- Smaller pitch (~30μm^2), reduced integration time (25-100 ns), thinner sensors (~0.5%X_0/layer)

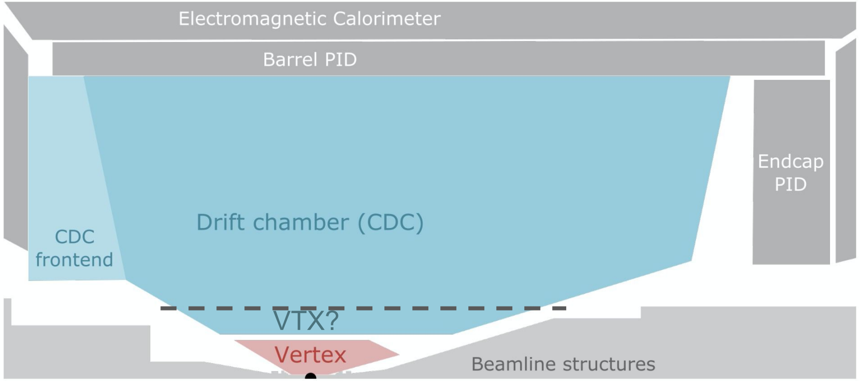
Extension possibility

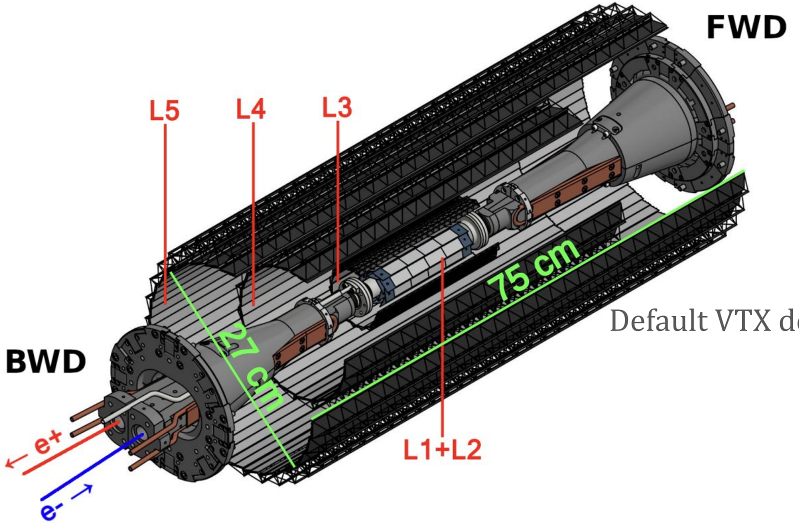
- Replace CDC small-cell superlayer (modular)
- Far lower background occupancy

Drawbacks

- (Marginally?) more material
- Huge technical (and economic!) challenge on short timeline

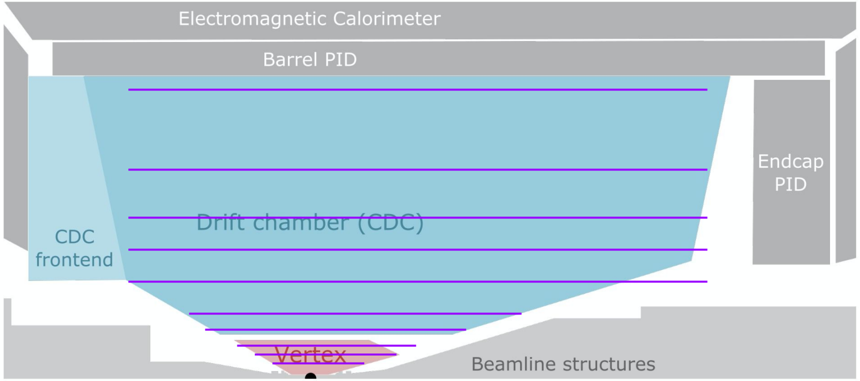
Nobody is seriously working on this "expanded VTX" scenario, but I think it's the most plausible solution





Default VTX design

2032+: Full silicon tracker?



Concept

- Completely replace CDC volume with VTX or future silicon detectors
- (similar to other next-generation trackers)

Benefits

- Reduced occupancy
- Better position resolution
- Single technology/detector everywhere

Drawbacks

- (even) more material → worse p_T resolution (?)
- $$$

Some support within Belle II, but my view is this is not feasible for Belle III…

2032+: Tracking TPC?

Concept

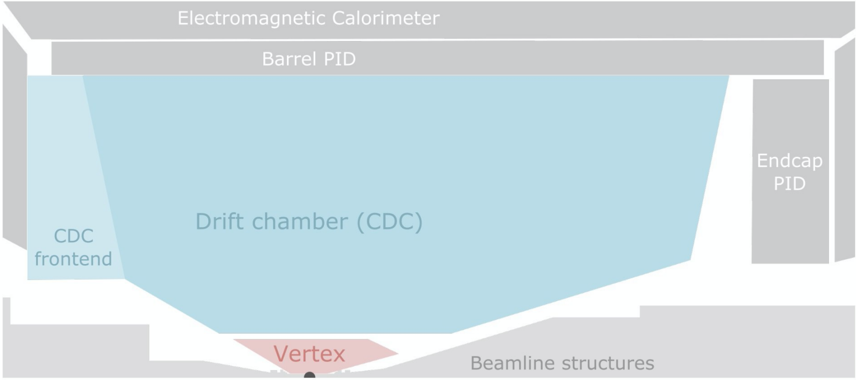
- Expand VTX as in first scenario
- Replace rest of CDC with single-volume **tracking TPC**

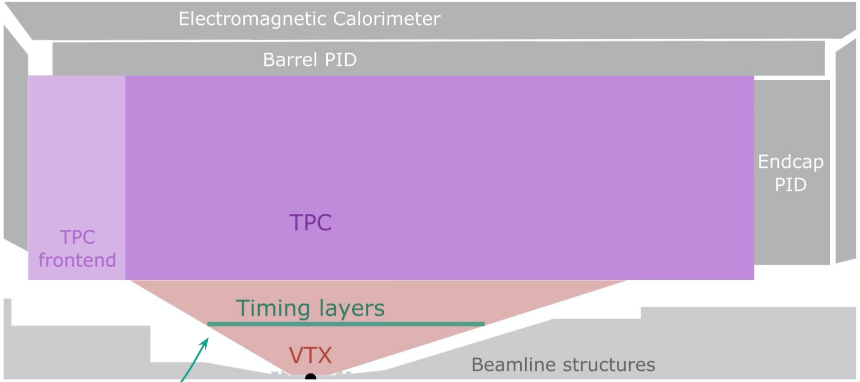
Benefits

- 2D ⟶ finely segmented 3D (**lower occupancy**)
    - 14*K* wires ⟶ **1*T* voxels** (200 µm)^3
- Minimum material (improved p_T resolution)

Drawbacks

- Diffusion ⟶ *degraded* resolution
- No trigger output ⟶ add timing layer*
- **Event and background pileup**
    - Entangled events
    - Huge number of background hits





Let's look at this closer…

This is an IDL concept!

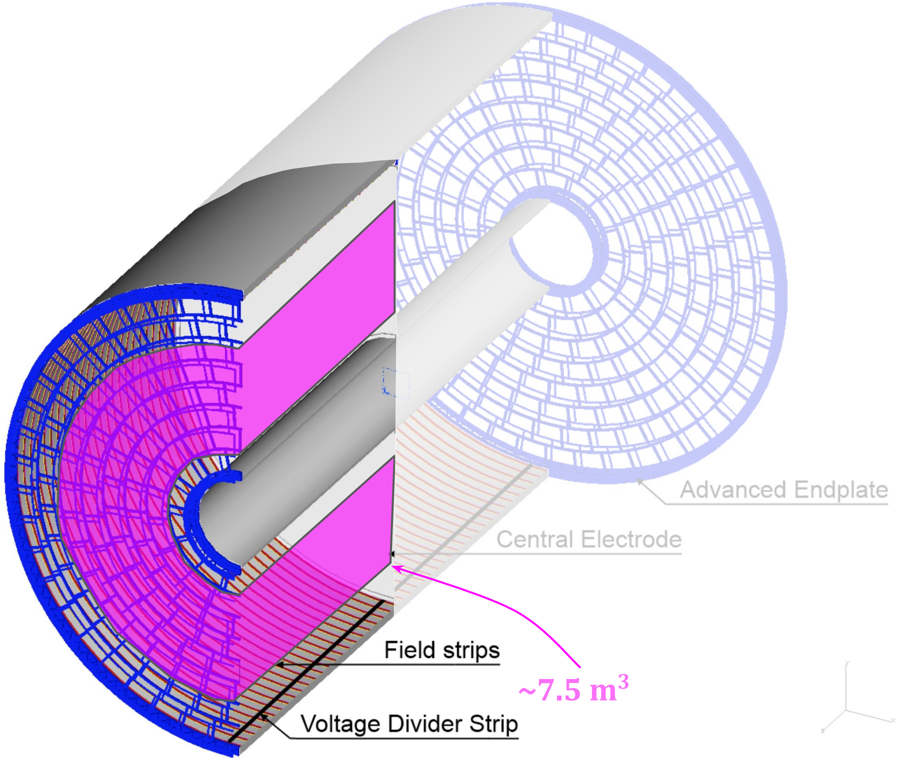
Leveraging ILD TPC design

Surprisingly similar technical requirements

- Higher energy, but higher *B*-field → comparable typical track curvature
- Comparable resolution targets
- Same **drift lengths**

Still, some *major* differences

- SuperKEKB: continuous injection
- ILC: pulsed bunch trains, with 200ms gap between
  - ILD TPC can be gated, Belle TPC **cannot** be
- “HyperKEKB” will undoubtedly have huge beam backgrounds

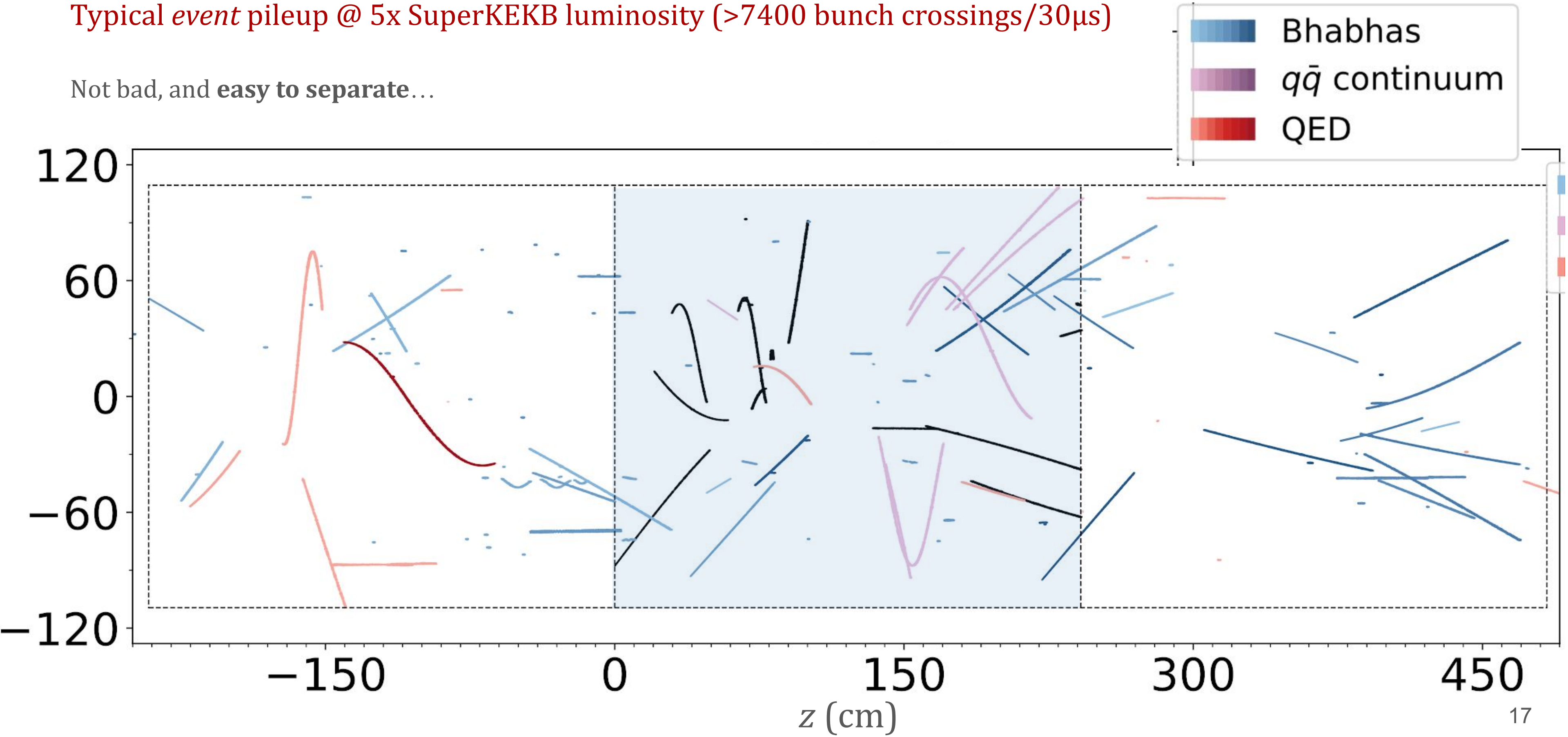


Belle III TPC must be capable of continuous readout while integrating enormous background rates

Belle III TPC concept

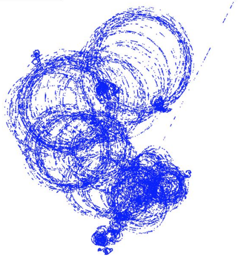
Typical *event* pileup @ 5x SuperKEKB luminosity (>7400 bunch crossings/30μs)

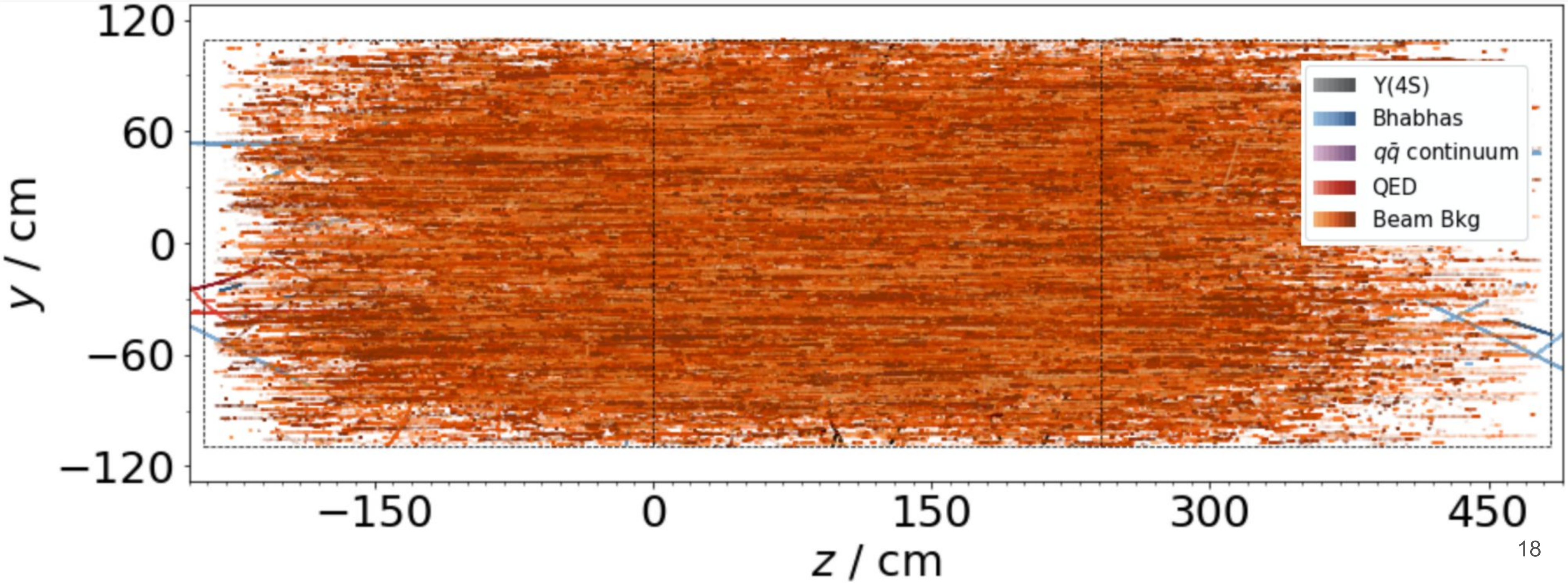
Not bad, and **easy to separate**…



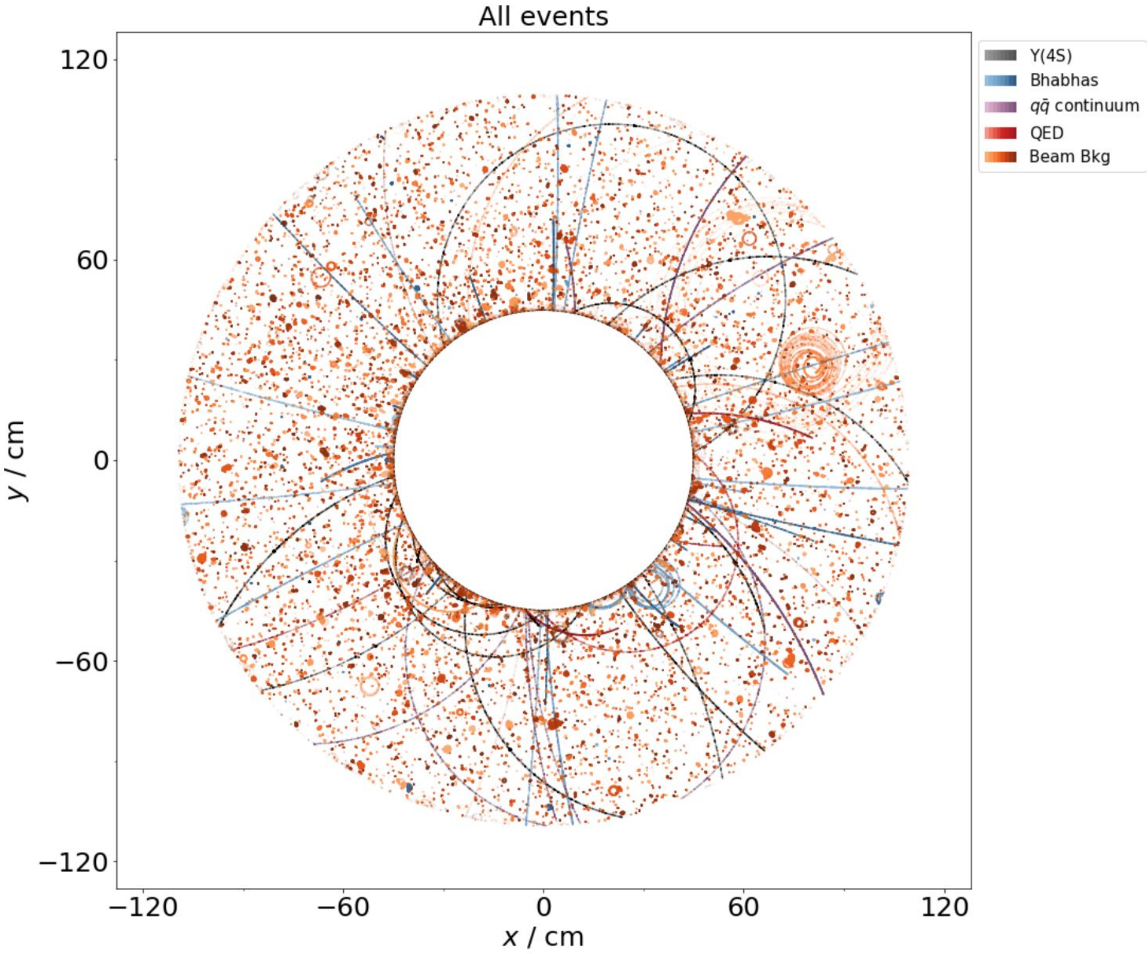
Typical *background* pileup

These are almost entirely *microcurlers*





Belle III TPC concept



Remember:

- CDC is 2D, TPC is 3D
- CDC is triggered, TPC integrates charge

Which one "wins"?

The TPC does… because **1T is *a lot* more than 10K**

Belle II CDC

Background pileup (@ 5x SuperKEKB lumi.)

Total hit rate **completely dominated** by beam backgrounds (→ microcurlers)

However:

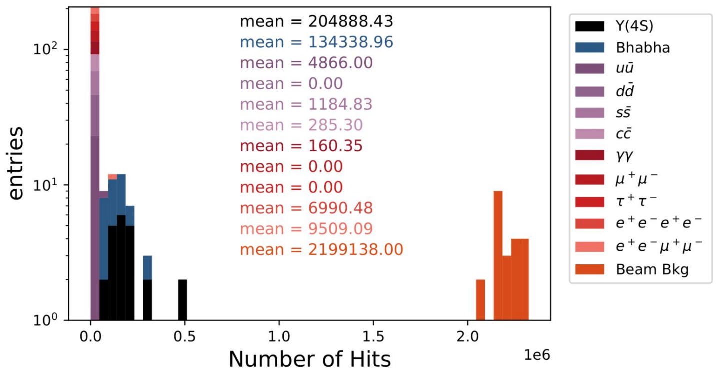
- **Occupancy <10^{-4}** with very conservative assumptions
- Microcurlers are easy to ID and ignore early in readout chain
- Injection background is *not simulated* and could be large; but we have a very large safety factor

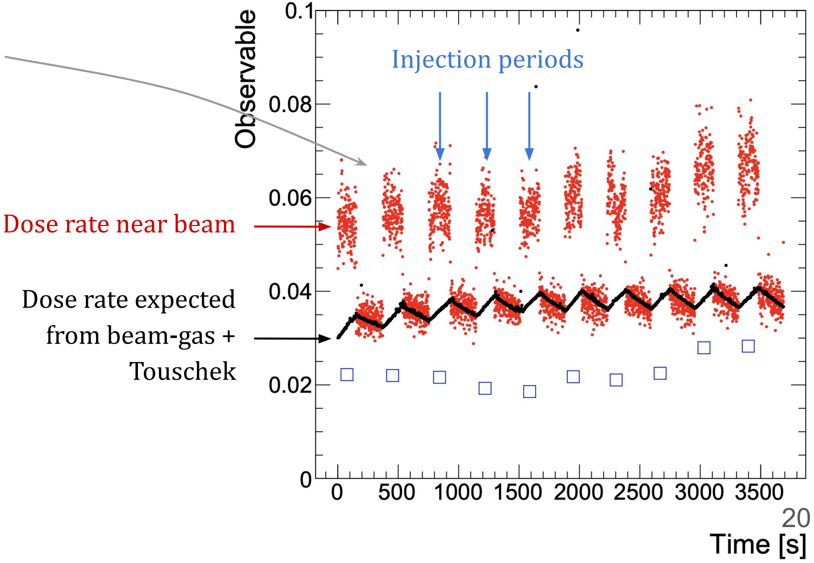
Some demanding sensor requirements:

- Fully continuous readout @ >**10Ghit/s**
- Excellent resolution in presence of huge numbers of background hits
- Ion backflow does not significantly degrade p_T resolution

Enter *InGrid* detectors…

Hits per 30us Y(4S) event





InGrid

Integrated Grid (InGrid) detectors

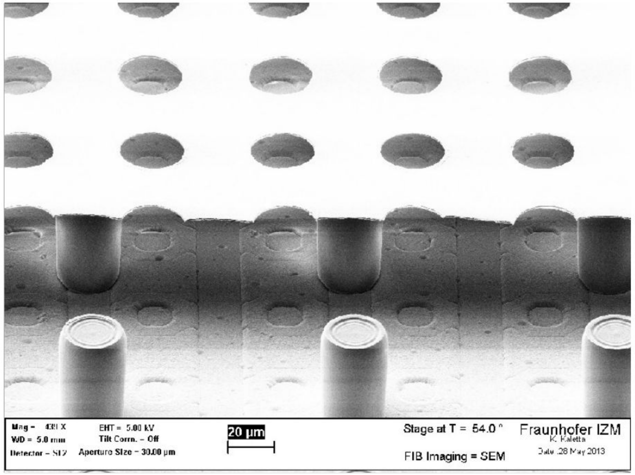
Model: GridPix

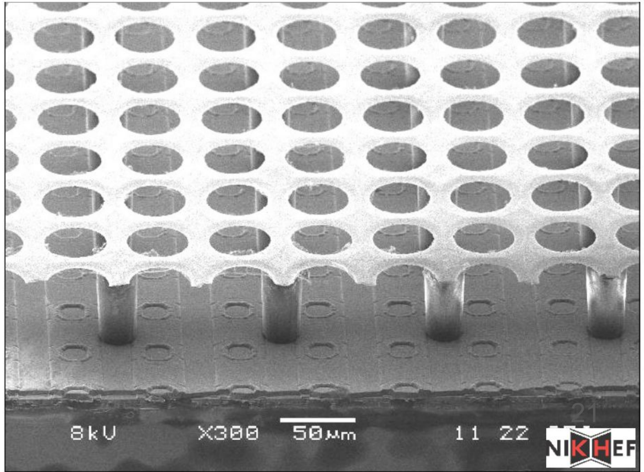
- TimePix3 ASIC (55x55 μm^2 pixels)
- Resistive layer on surface
- Integrated MICROMEGAS amplification grid

Key advantages:

- *Ideal* resolution (55 μm/√12 = 16 μm)
- **Single-electron counting** → *binary* readout possible → minimal throughput
- Low(-ish) ion backflow (~1% at gain of 2000); **20** backflowing ions per primary electron

Proof of principle from ILD TPC group @Bonn…

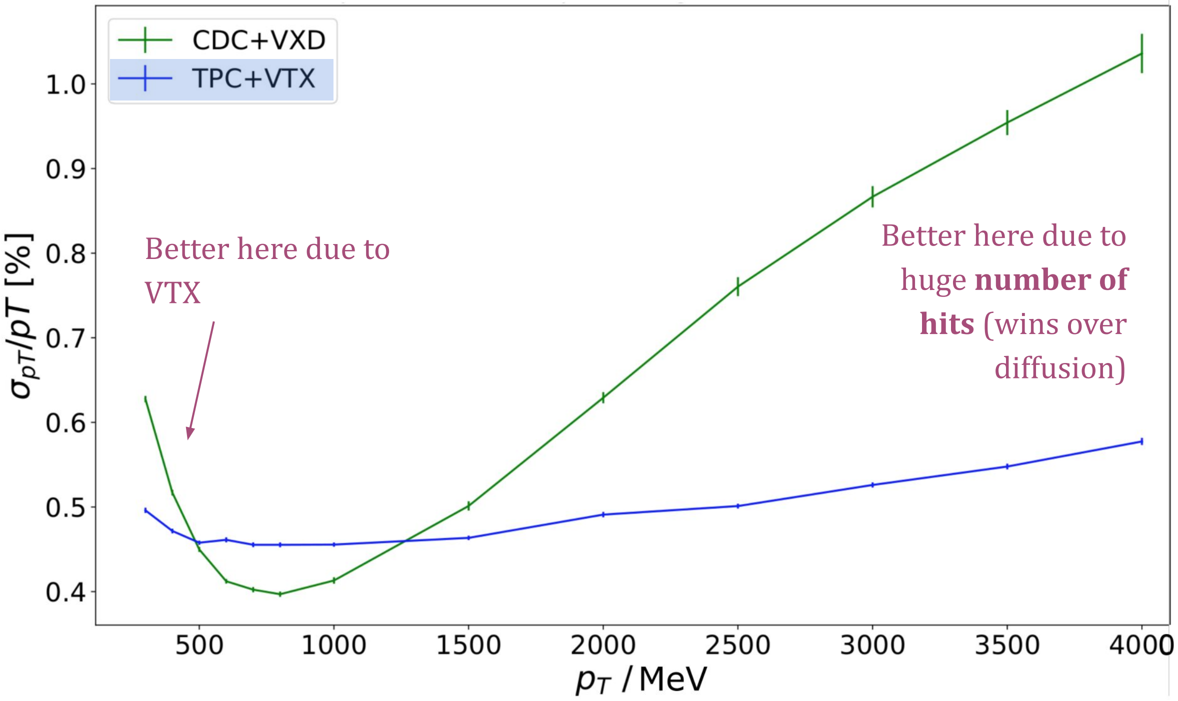




GridPix


TOSView
Run files: /home/testbeam/TOS_SRS_quad_EventDisplay/RunData/ForBarbara
Show every 1th frame
0
2000
4000
6000
8000
10000
Hits
/home/testbeam/TOS_SRS_quad_EventDisplay/RunData/ForBarbara/run_000143_data_001418_150404_04-26-27.txt

How would it perform?



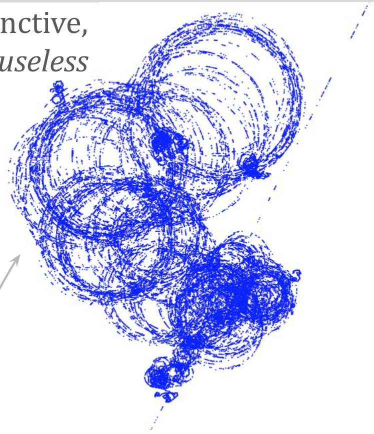
Better here due to VTX

Better here due to huge **number of hits** (wins over diffusion)

Vertical offset (MS) largely arbitrary

What would the Belle III TPC sensor look like?

Microcurlers are distinctive, abundant, and *useless*

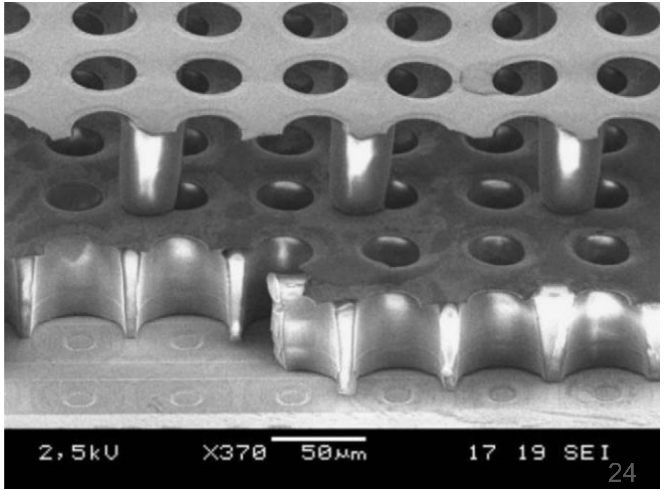


Pixel ASIC:

- "Large" pixels (200x200 μm^2 sufficient)
- 25ns time resolution sufficient
- TOT unnecessary; binary readout only (hit: time and pixel ID only)
- Hit buffering: continuous hit collection, but accept external trigger for readout
- Hit logic for microcurler suppression highly desirable

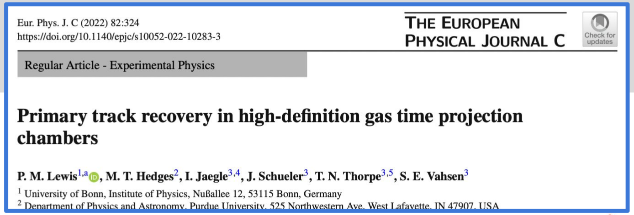
Amplification:

- Strong case for ***TwinGrid***…
  - Still capable of single-electron counting…
  - …but can drastically **reduce ion backflow** (to **~0.6** per electron)



NIM-A 610 (2009) 644–648

InGrid sensors have many uses…


Eur. Phys. J. C (2022) 82:324
https://doi.org/10.1140/epjc/s10052-022-10283-3
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Primary track recovery in high-definition gas time projection chambers

P. M. Lewis[1,a], M. T. Hedges[2], I. Jaegle[3,4], J. Schueler[3], T. N. Thorpe[3,5], S. E. Vahsen[3]
[1] University of Bonn, Institute of Physics, Nußallee 12, 53115 Bonn, Germany
[2] Department of Physics and Astronomy, Purdue University, 525 Northwestern Ave, West Lafayette, IN 47907, USA

InGrid sensors are also ideal for low-*E* **nuclear recoil tracking**

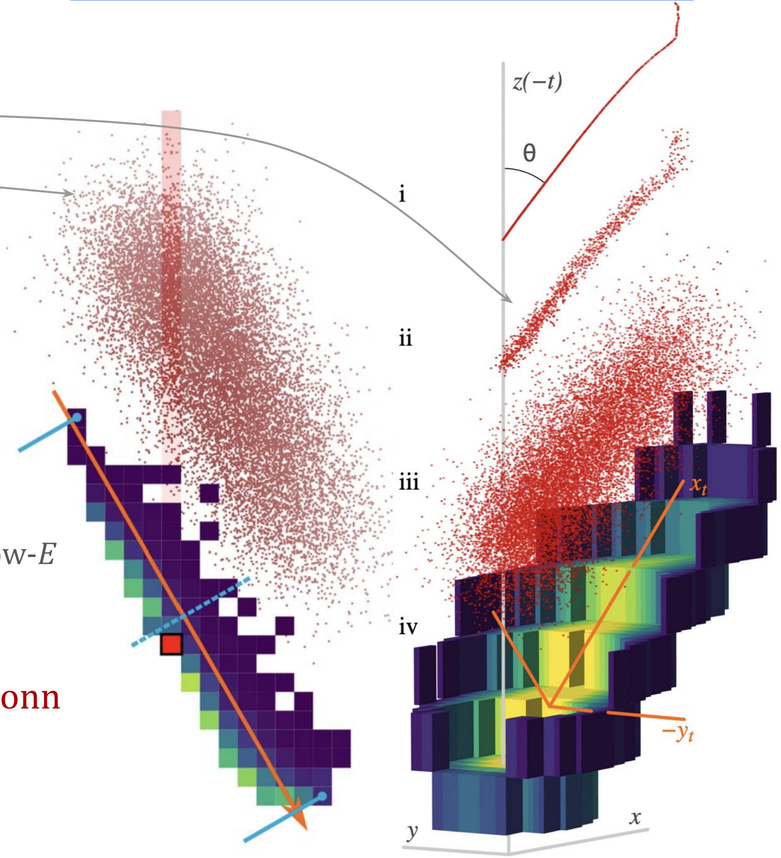
Compared to GEMs + pixels:

- Far better resolution [basically directly detect **step ii**]
- Bypasses all **charge integration** effects
- Avoids unparameterizable **Shockley-Ramo** dynamics
- **Fully 3D electron counting** (best with negative ion drift)

In the context of Cygnus

- Potentially significantly **better low-*E* reach** for WIMP searches
- Expensive at scale; probably best used in R&D stages to understand low-*E* recoils

Ongoing collaboration with Vahsen lab @UH and Desch group @Bonn (NIGHT detector*)… super exciting work to be done!



Summary

Technical opportunities from tracking challenges in near-term

1. Ultra low-X_0, high-resolution tracking detectors (like for "Belle III") → **TPCs with MPGD readout**
2. *Ideal* sensor: **(Tw)InGrid** pixels
3. The technology now exists but is **under-utilized**
4. Huge potential for **synergies/other applications**:
   a. Directional Dark Matter searches (Cygnus)
   b. ILD TPC
   c. Future colliders

Thank you! Questions?

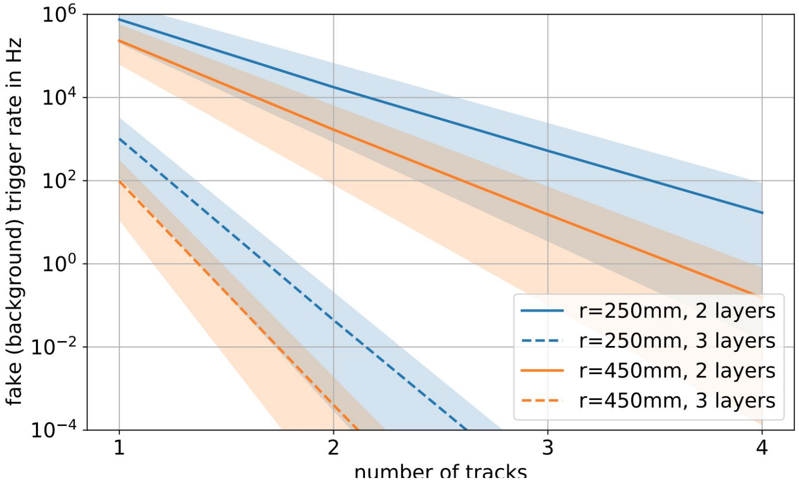
BACKUP

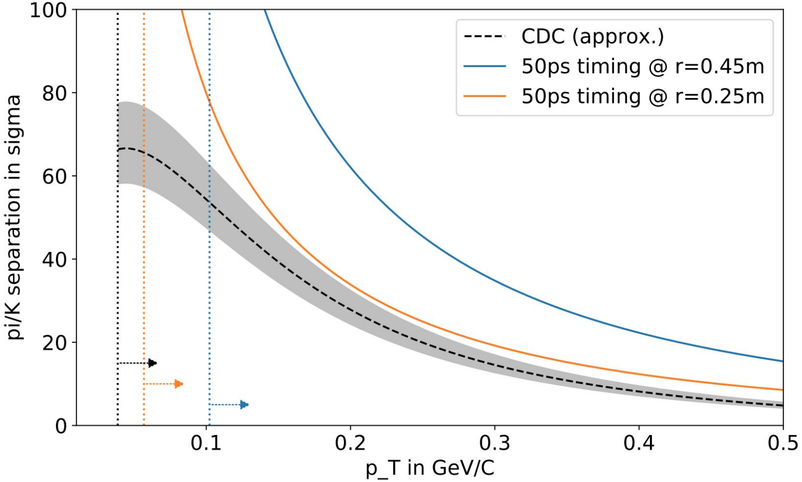
Trigger

Timing layer findings

- Can replace trigger role of drift chamber with **tolerable fake trigger rate** (*top*)
- Major added bonus: PID via **time-of-flight**
  - *More than* replaces missing dE/dx info
  - Pion/kaon separation excellent for low-p tracks…
  - …could significantly improve efficiency of slow pion reconstruction in D* decays

Conclusion: existing technology can solve triggering issue of TPC, *and* missing dE/dx issue, with significant physics performance benefits





Resources

Bonn Master's thesis from Andreas Loeschcke Centeno
[https://docs.belle2.org/record/2631/files/BELLE2-MTHESIS-2021-073.pdf]

This whitepaper
[arXiv:2203.07287]

Belle II upgrade whitepaper
[https://arxiv.org/abs/2203.11349]

Timing layer
[https://arxiv.org/abs/2203.04847]

A TPC-based tracking system for a future Belle II upgrade

Andreas Löschcke Centeno[1], Christian Wessel[1], Peter M. Lewis *[1], Oskar Hartbrich[2], Jochen Kaminski[1], Carlos Mariñas[3], and Sven Vahsen[2]

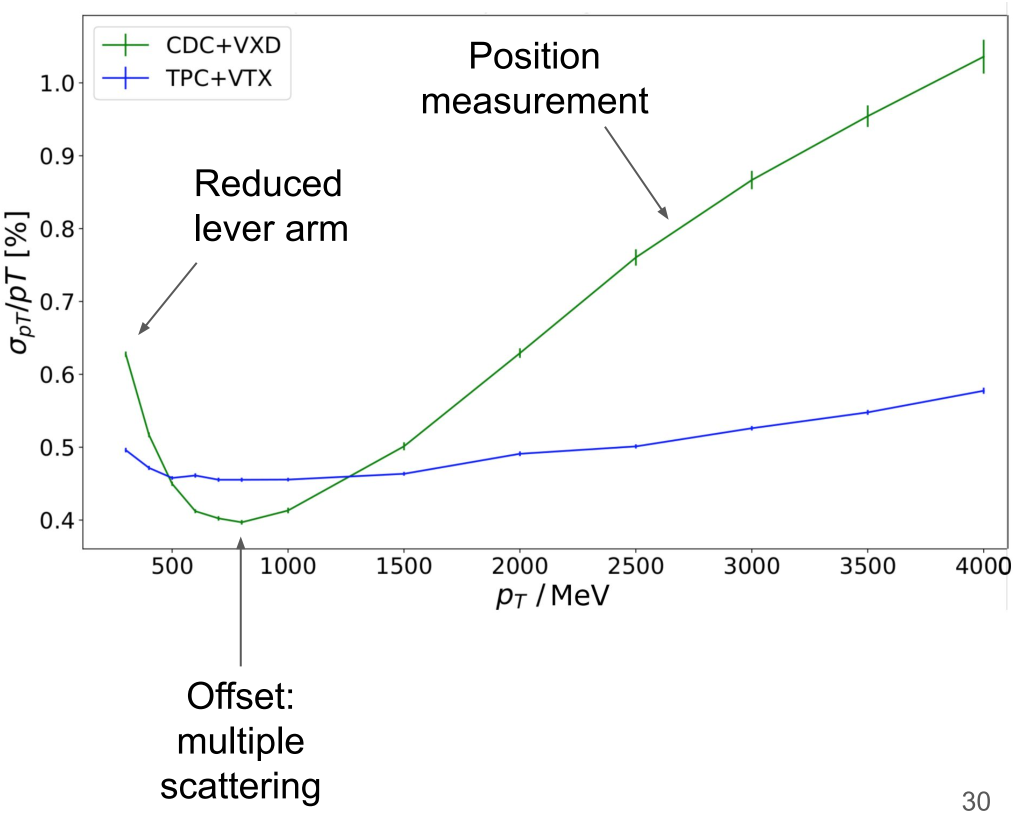
[1] *University of Bonn, Institute of Physics, Nußallee 12, 53115 Bonn, Germany*
[2] *University of Hawaii, Department of Physics and Astronomy, 2505 Correa Rd., Honolulu, HI 96822, USA*
[3] *University of Valencia - CSIC, Instituto de Fisica Corpuscular (IFIC), Spain*

March 15, 2022

Concern 4: diffusion

Suitable tracking performance?

- Used modified basf2 track-finding and track-fitting algorithms fitting 3D space-points
- The key metric is p_T resolution (*right*)
- The high resolution of the TPC design gives better resolution everywhere…
- …but we still lack a realistic *mechanical* design, which will affect multiple scattering



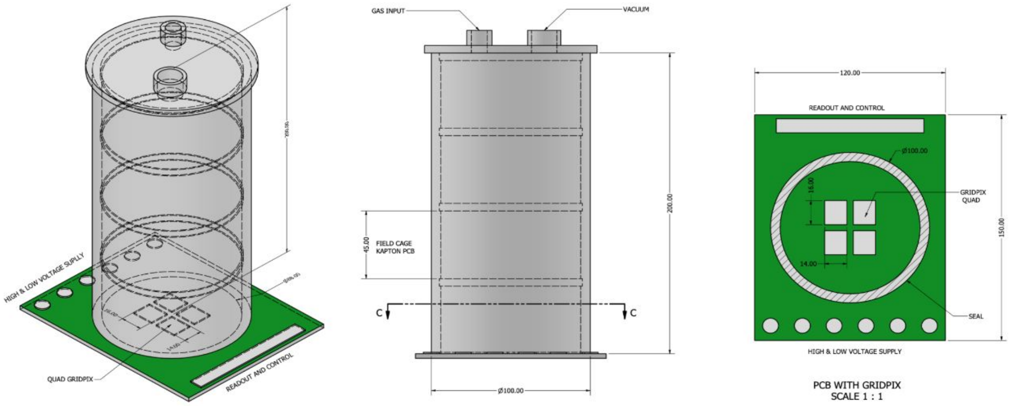
NIGHT DETECTOR

Negative **I**on **G**ridpix-based **H**igh-resolution **T**PC

Dr. Saime Gürbüz 03.04.2023 CYGNUS gas meeting

NIGHT (rough) design

- Height adjustable



NIGHT DETECTOR

PCB WITH GRIDPIX
SCALE 1 : 1

Micro pattern gas detectors

MICROMEGAS

- Notice some interesting features of the field lines
- The mesh is **~100% transparent** to **electrons** even though the holes are far less that 100% of the surface of the mesh (provided that the amplification field is high enough)
- The mesh is **far less transparent** to **ions**, significantly reducing ion backflow (count the fraction of field lines at the bottom that end on the grid instead of in the drift gap)