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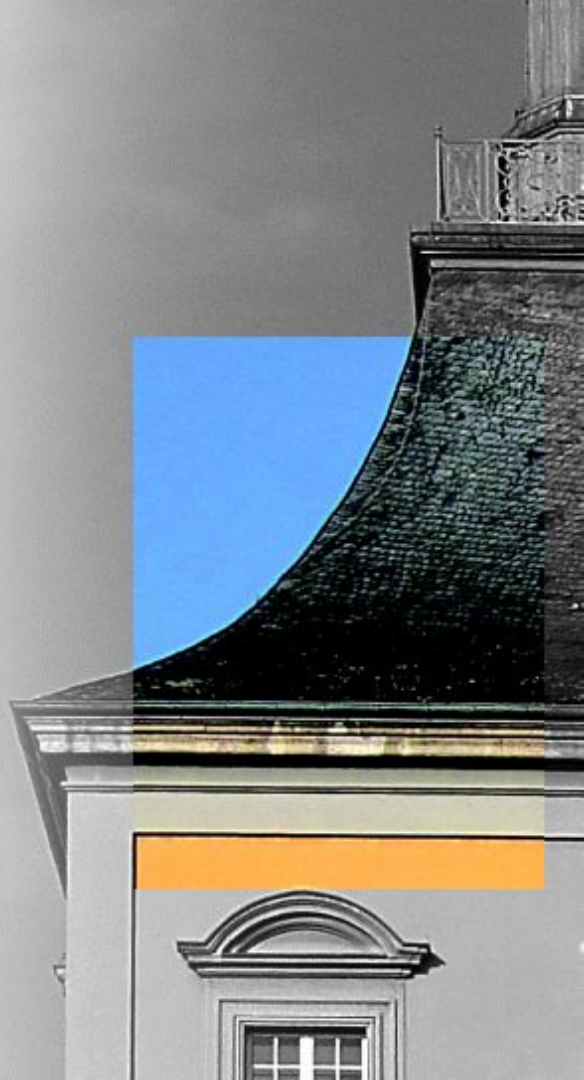
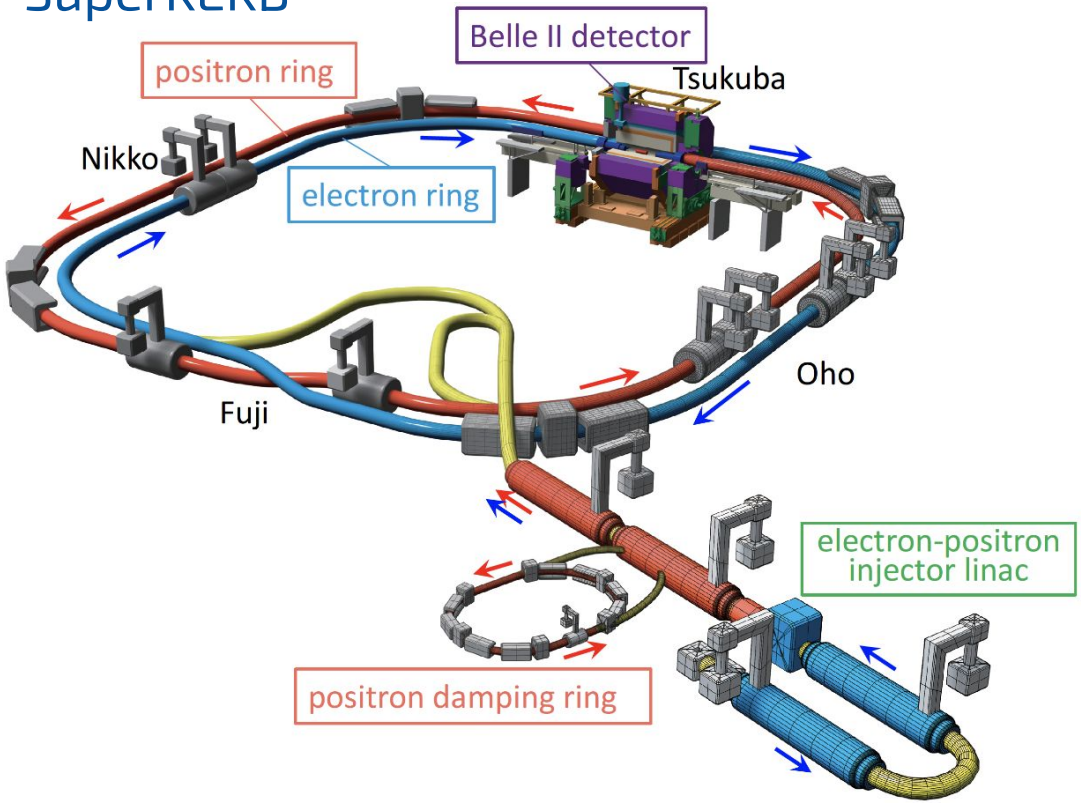
Jochen Dingfelder, Peter Lewis, Christian Wessel

# First Conceptual Design and Studies for a Tracking TPC for the Belle II Experiment

LCTPC Workpackage Meeting, October 13th 2022



## SuperKEKB

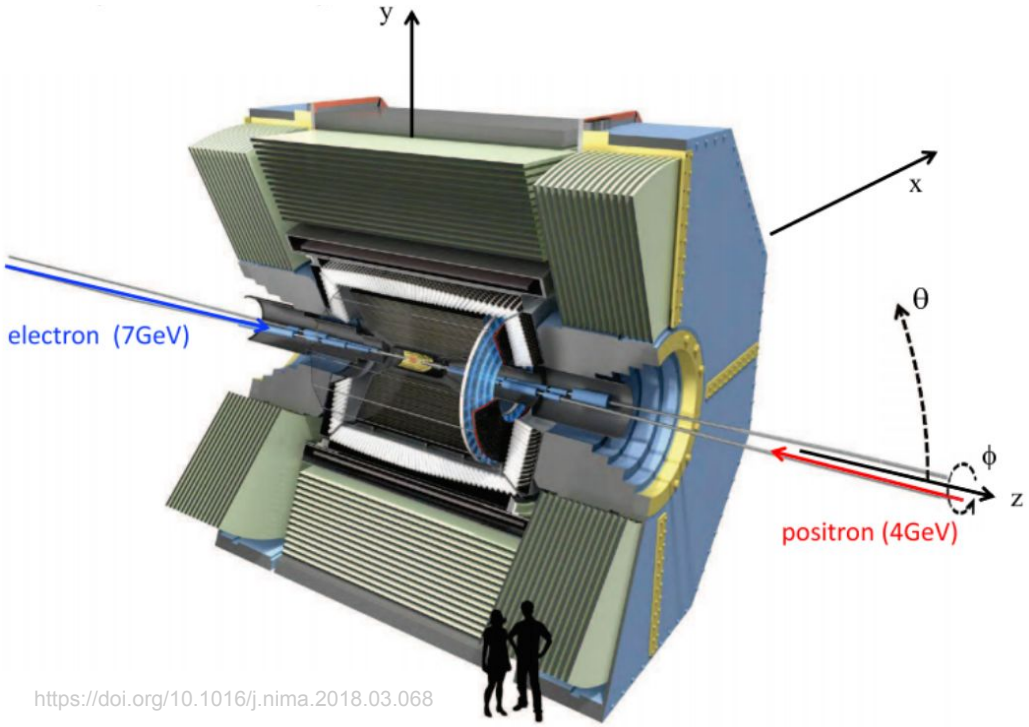



- Asymmetric $e^+e^-$ collider
  - electrons: 7 GeV
  - positrons: 4 GeV
- B-Factory by creating $\Upsilon(4S)$
- Design luminosity (at time of thesis)

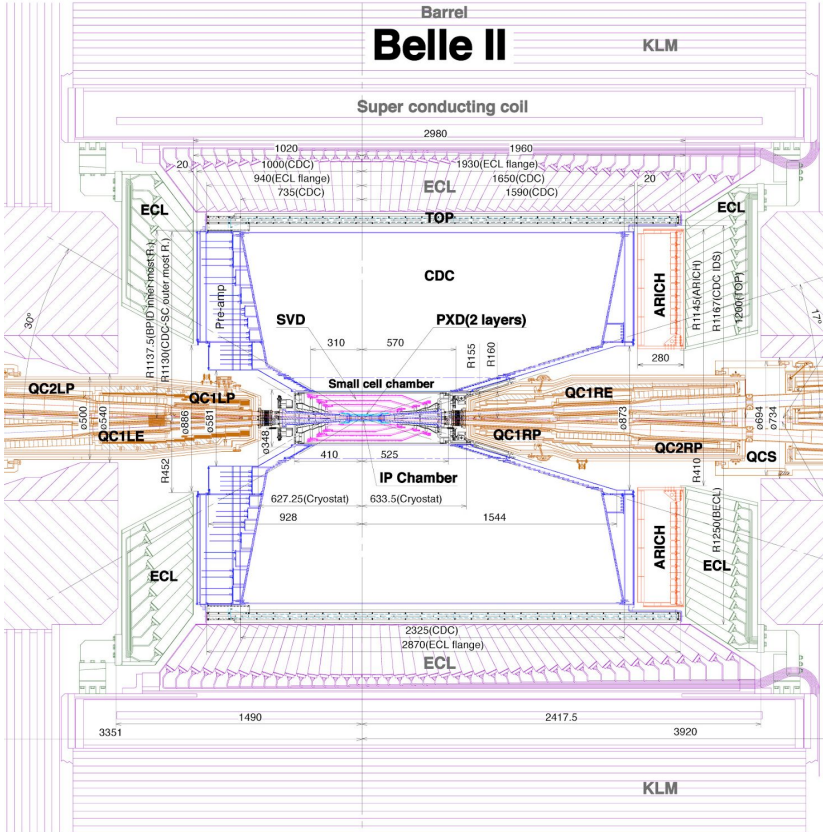
$$\mathscr{L} = 6.5 \times 10^{35}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

- Top-up injection scheme

# Belle II Detector

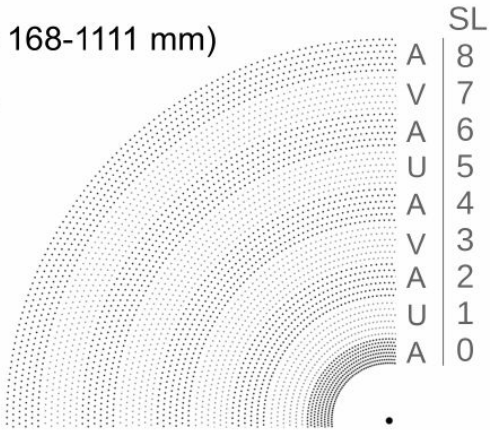


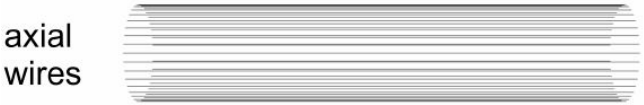

https://doi.org/10.1016/j.nima.2018.03.068

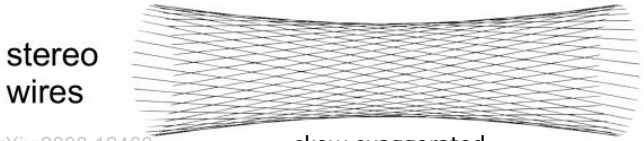


# Central Drift Chamber (CDC)

- 56 layers (r = 168-1111 mm)
- arranged into superlayers of axial (A) & stereo (U,V) wires

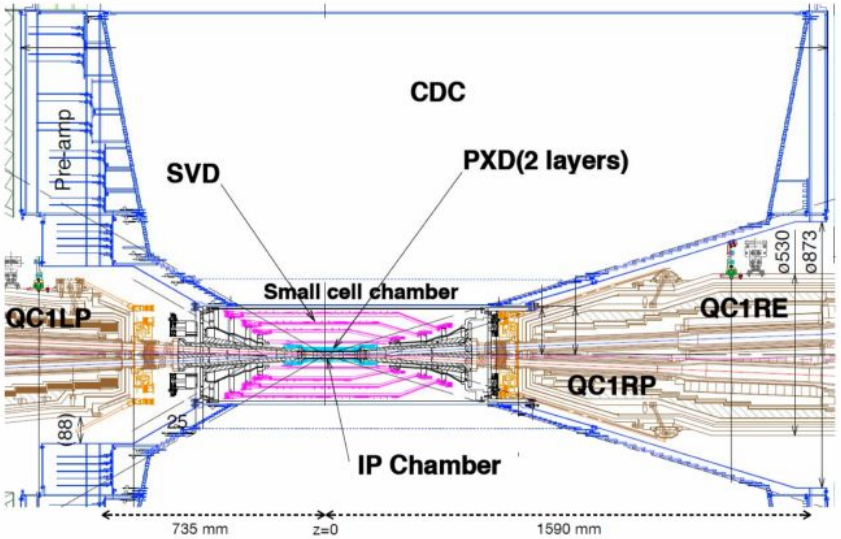



skew exaggerated

arXiv:2003.12466



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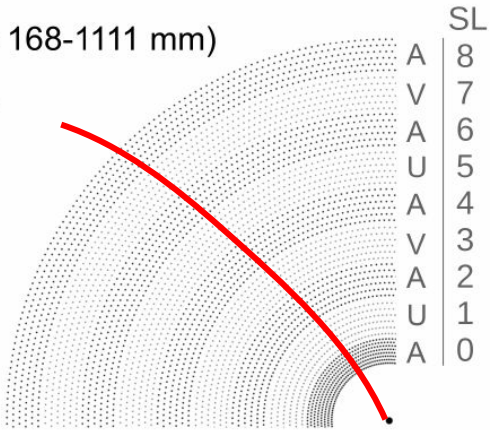


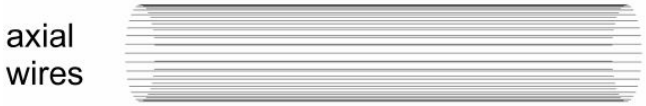


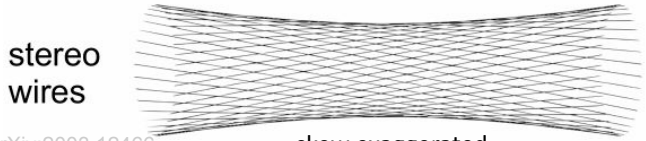


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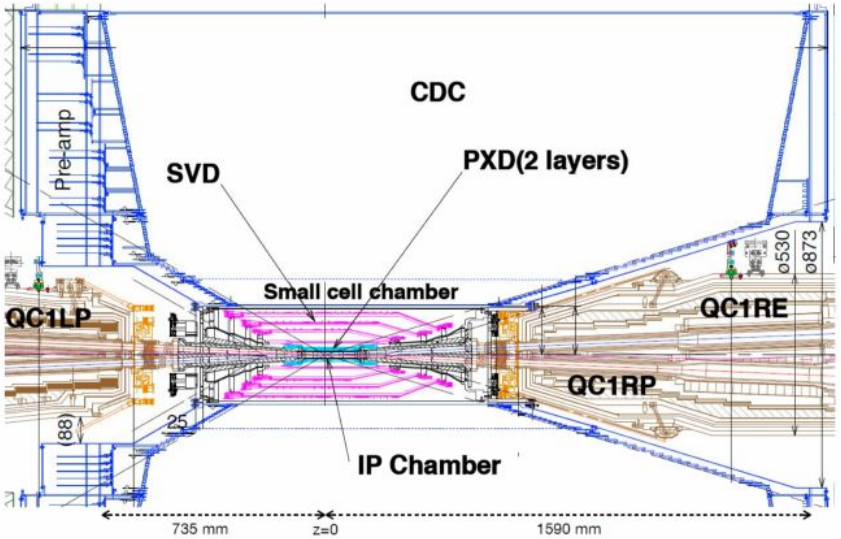
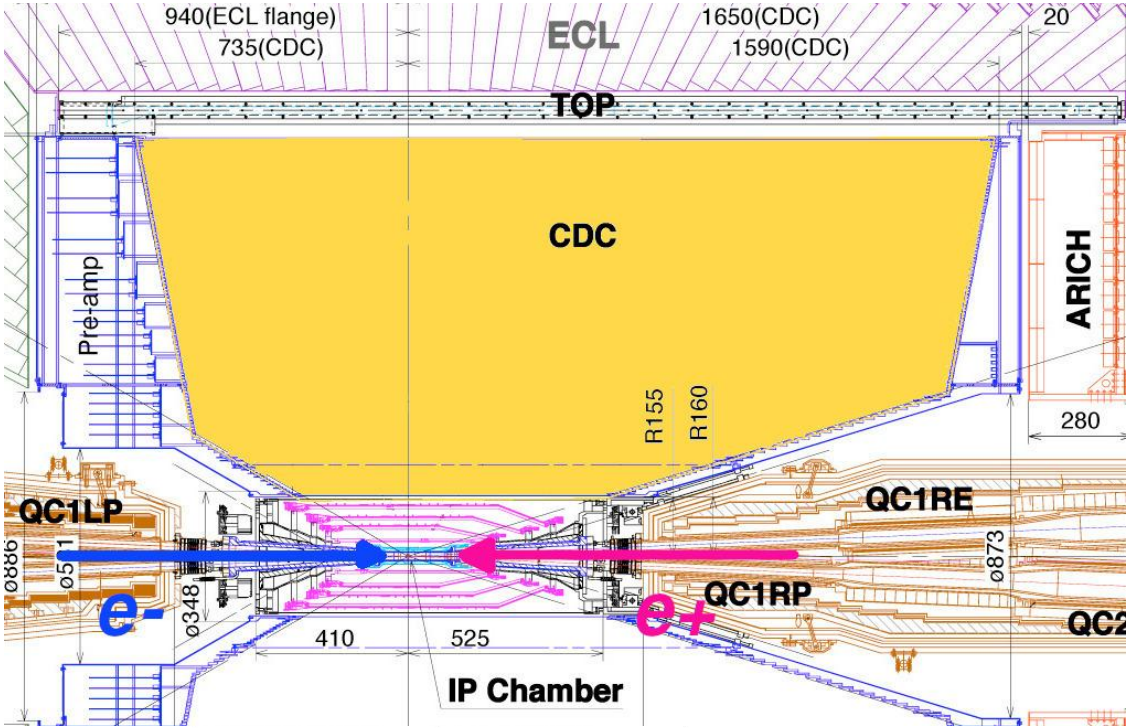



- tracker: measures (transverse) momentum
- PID (dE/dx measurement)
- source of trigger

# Basic Concept

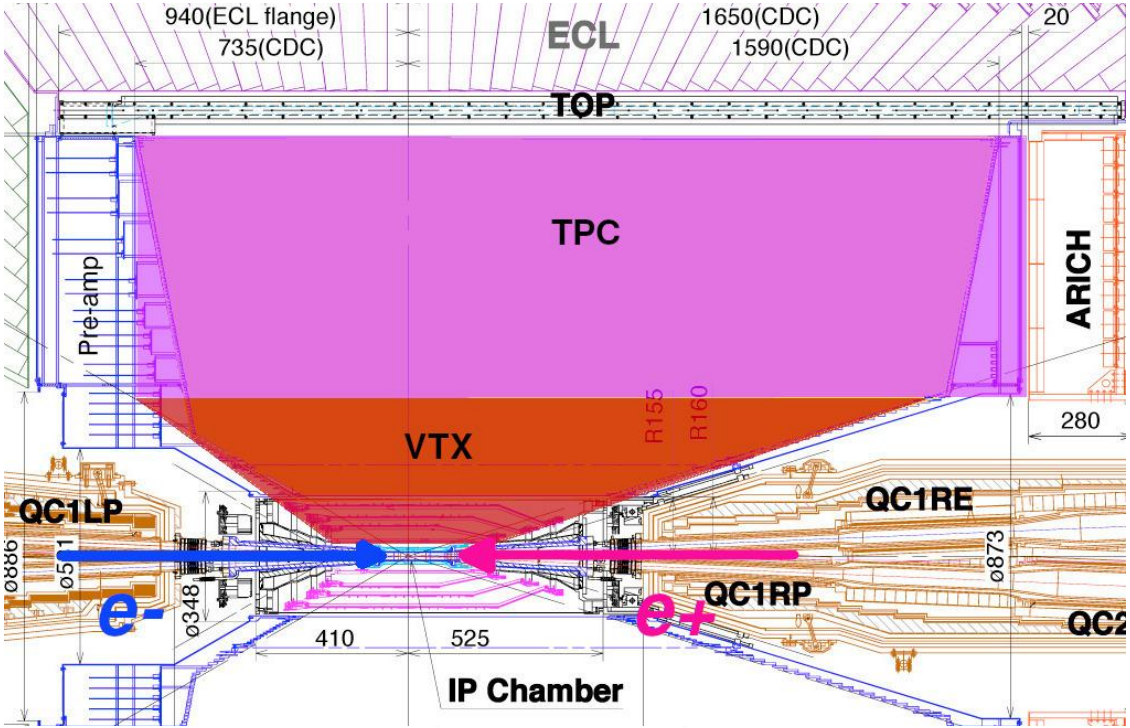
- CDC @ full design lumi:
  - Large cross-talk effects
  - High occupancy due to unexpectedly large bkg



## Basic Concept

- CDC @ full design lumi:
  - Large cross-talk effects
  - High occupancy due to unexpectedly large bkg
- Proposal to replace the drift chamber with a **tracking TPC**
- Project to upgrade silicon detectors (“**VTX**”) already underway

*This project*: produce a **proof-of-concept conceptual design** of a tracking TPC using simulation in the Belle II software and analysis framework

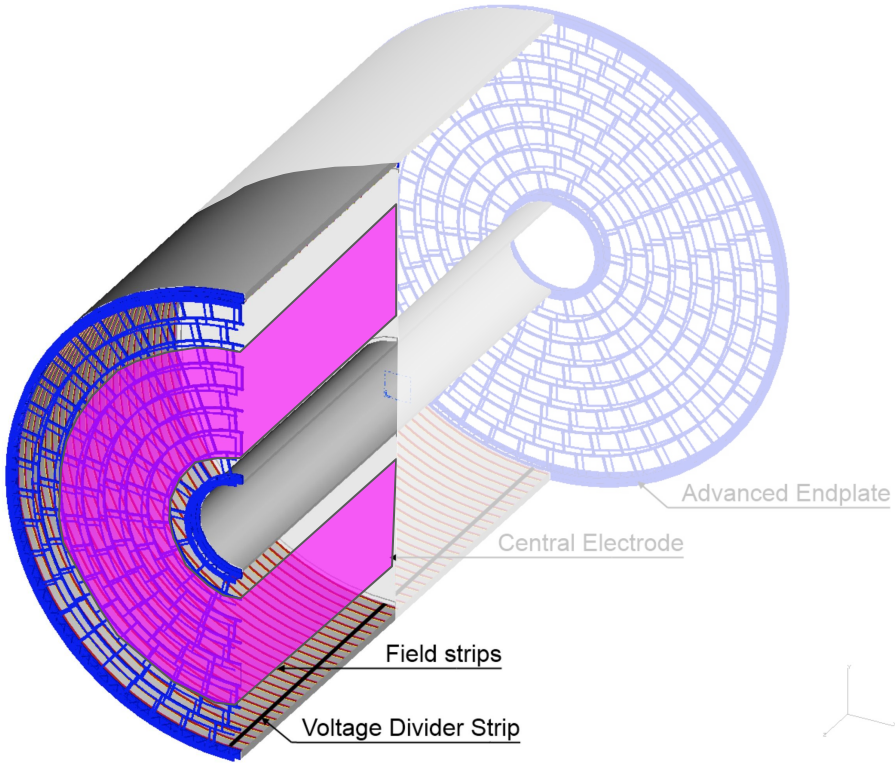


# Geometry

- TPC dimensions (compared to single LCTPC drift volume):
  - Length: 2.3 (2.35) m
  - Inner radius: 0.45 (0.33) m
  - Outer radius: 1.14 (1.8) m
- Single drift volume due to PID in forward direction

Use LCTPC as a starting point for Belle II TPC choices:

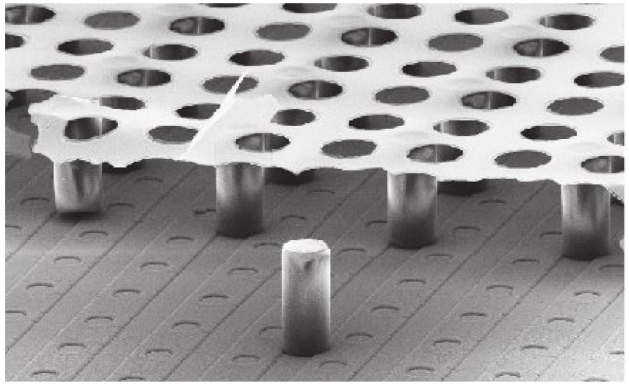
- T2K gas mixture (95% Ar, 3% CF4, 2% Isobutane)
- Drift field of 289 V/cm



# Implementation into basf2 (Geant4)

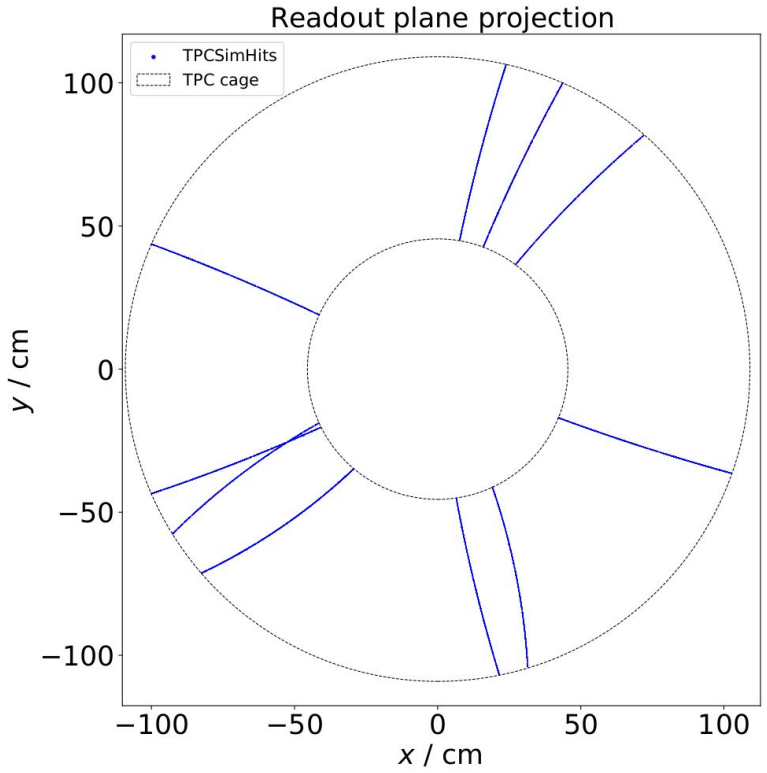
- Simplified geometry:
  - Cylindrical volume filled with T2K gas mixture
  - No additional materials (support structure, cables, …)
- **Modelled** drift and diffusion (instead of simulated)
  - Drift properties well known
  - Apply Gaussian smearing to coordinates of ionization
- Digitization:
  - Completely pixelated plane over entire area of endplate
  - Binary readout
    - assumes mapping of 1 $e^-$ to 1 pixel
    - no charge sharing between pixels

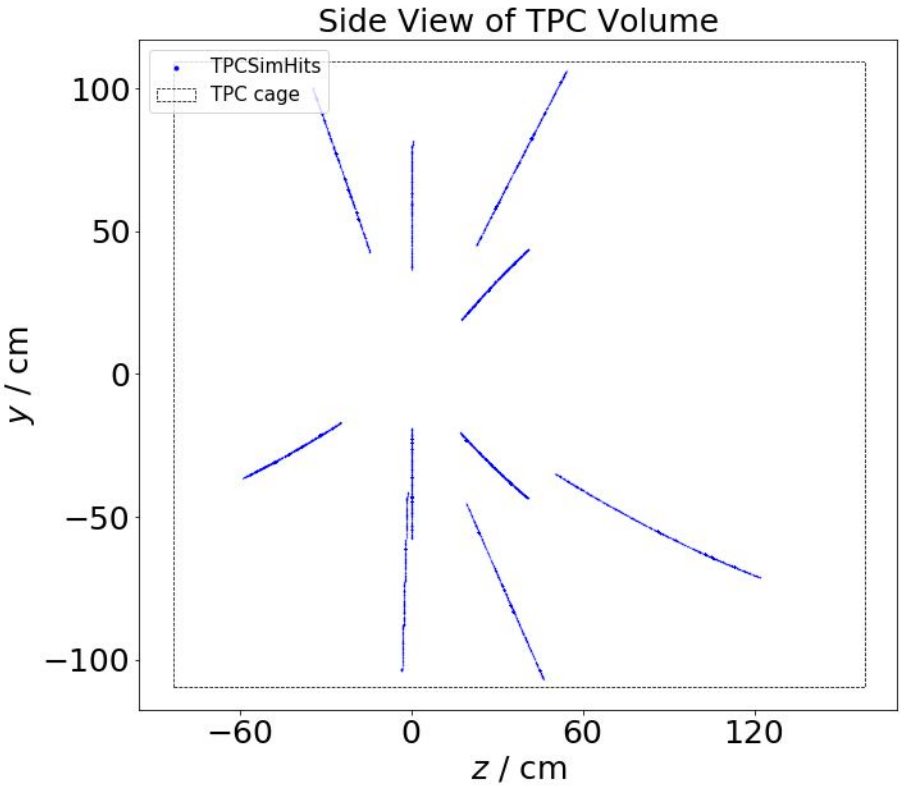
GridPix:
- 55µm pitch
- amplification structure aligned with pixels



arXiv:1311.3125

# Simulating First Tracks: 10 Muons ($p$ = 1-4 GeV)



## Displaying of Overlapping Events

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  Event overlap due to large drift times (30 µs) expected
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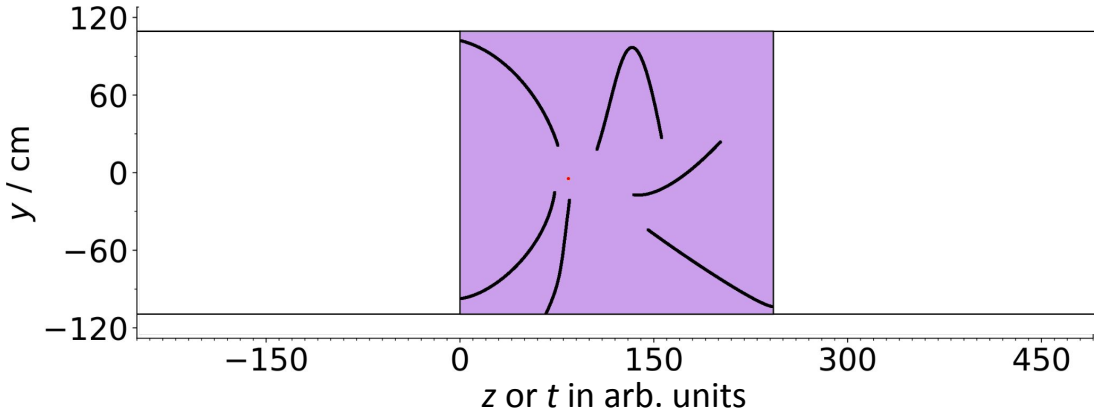

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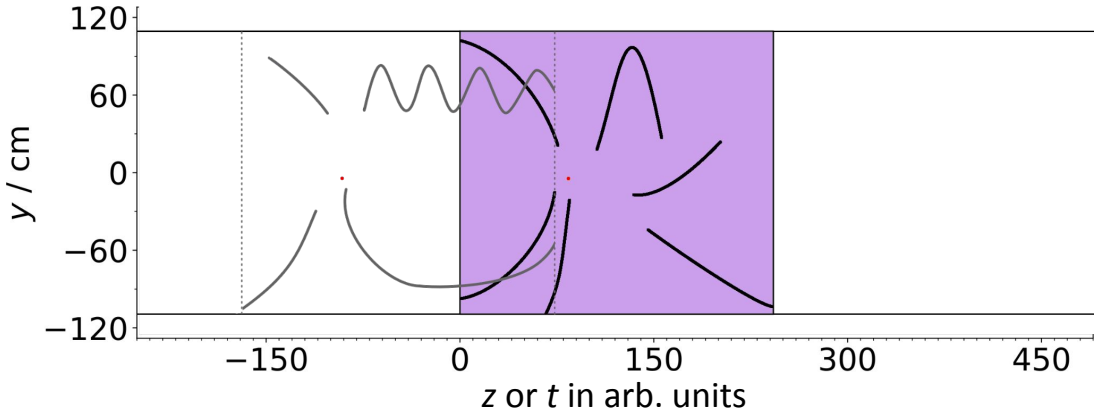

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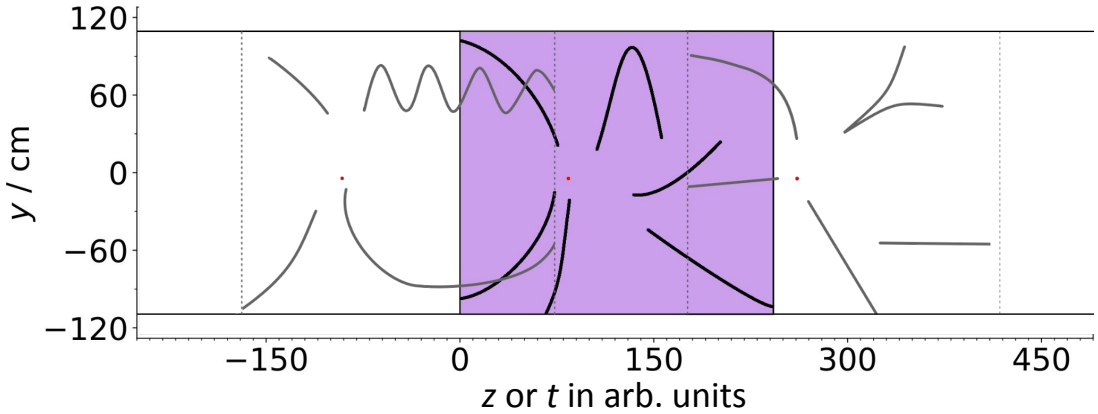

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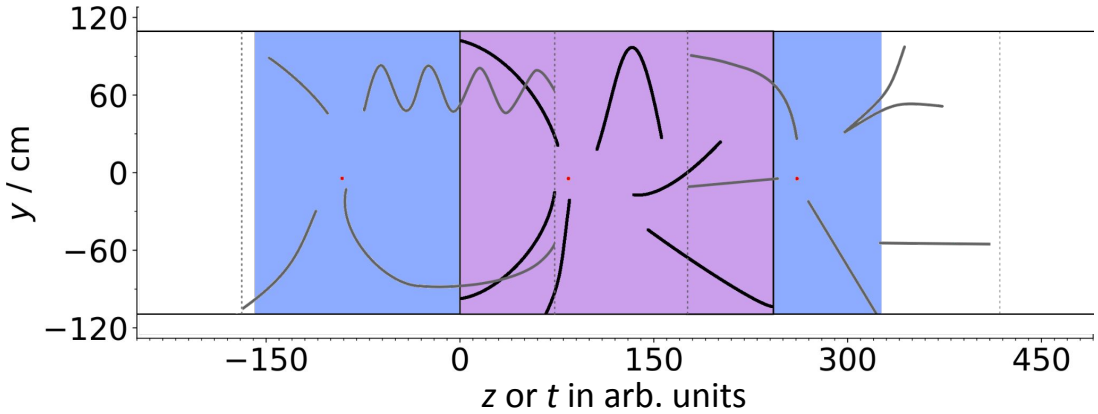
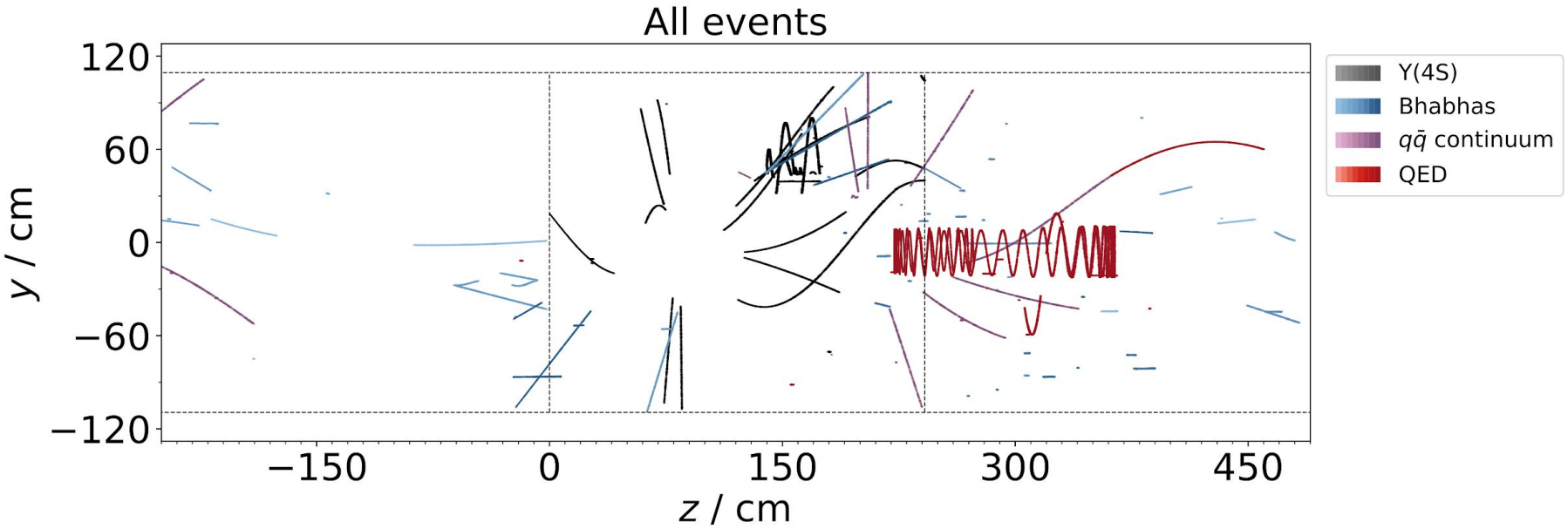


# Overlaid Events (No Beam Background)



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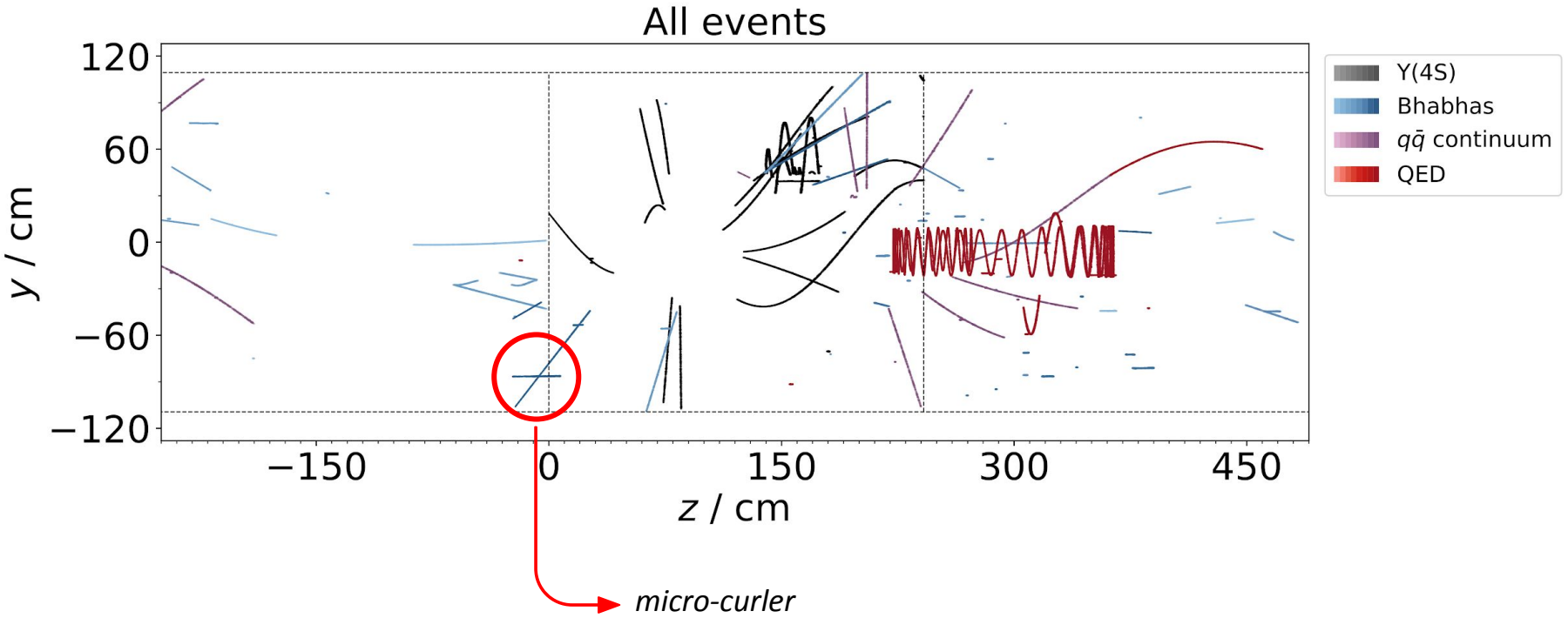


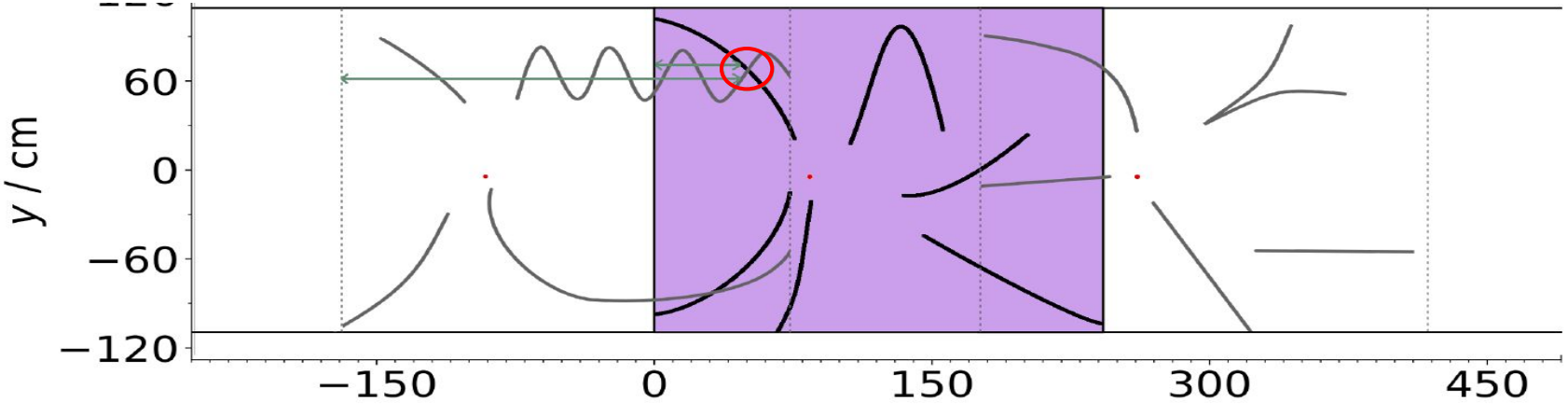
## Belle II Event Rates (Luminosity: 6.5e35 $cm^{-2}s^{-1}$)

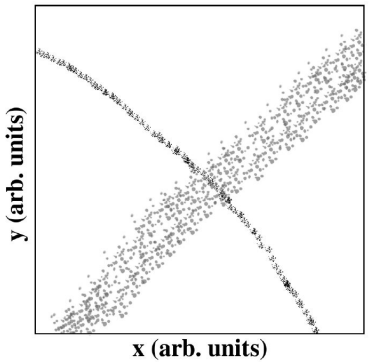
| Process | σ / nb | Rate / $(60\mu s)^{-1}$ | No. of tracks (estimate) |
|---|---|---|---|
| ϒ(4S) | 1.11 | 0.04 | 11 |
| uubar | 1.61 | 0.06 | 8 |
| ddbar | 0.4 | 0.03 | 8 |
| ssbar | 0.38 | 0.02 | 8 |
| ccbar | 1.3 | 0.05 | 10 |
| Bhabha | 300 | 11.7 | 2 |
| γγ | 4.99 | 0.20 | 4 |
| ττ | 0.919 | 0.04 | 2 |
| eeee | 39.7 | 1.55 | 4 |
| eeμμ | 18.9 | 0.74 | 4 |
| μμ | 1.148 | 0.04 | 2 |

→ Avg. No. of track per 60 μs: **35.82**

(not including acceptance of TPC)

## Event Separation




- Belle II TPC has single drift volume
- Tracks from different events can have same reconstructed *z* coordinate
- Tracks from event at $t_{-1}$ has unaccounted drift length/time
- Because diffusion width will depend directly on drift length:

➢ **Can use width of tracks to separate events**

# Beam Backgrounds (BG19 campaign)

- Touschek Scattering:
  Scattering of two beam particles within one bunch
- Coulomb/Beam-gas Scattering
  Elastic Coulomb scattering of beam particles with residual beam gas
- Bremsstrahlung
  Inelastic scattering of beam particles with gas nuclei

| Process | Rate / MHz | Rate / $(60\mu s)^{-1}$ |
|---|---|---|
| Brems HER | 2.46479 | 147.89 |
| Brems LER | 8.2928 | 497.57 |
| Coulomb HER | 16.335 | 980.10 |
| Coulomb LER | 191.641 | 11498.46 |
| Touschek HER | 0.242353 | 14.54 |
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- Injection Backgrounds not included!
  Betatron-oscillating injection particles lost in interaction region due to strong magnetic fields of focussing magnets

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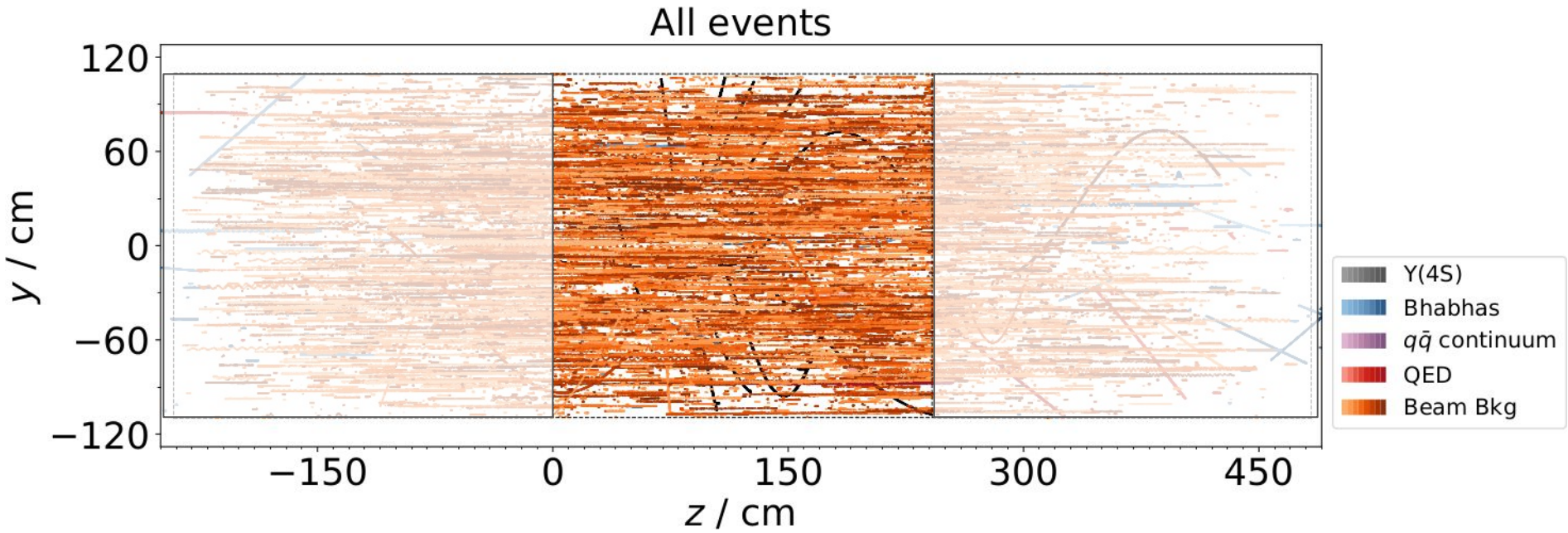
## Including Beam Background



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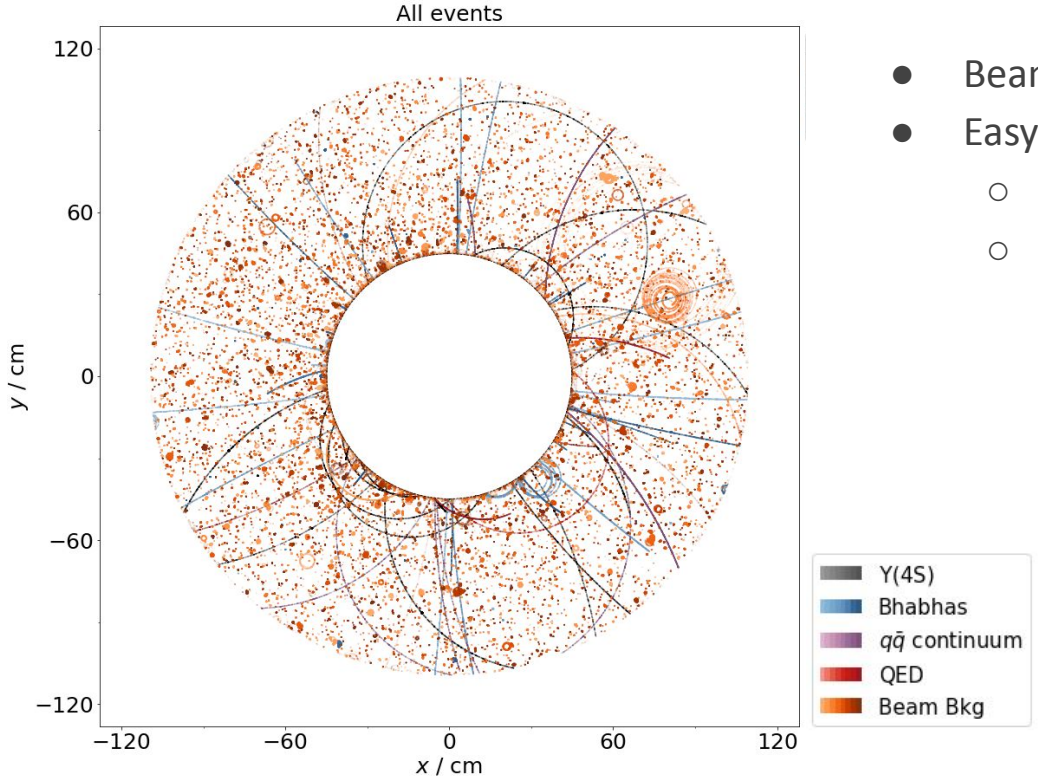


- Beam background mainly produces micro-curlers
- Easy to identify:
  - Horizontal in *z*
  - Isolated clump in *x*-*y*

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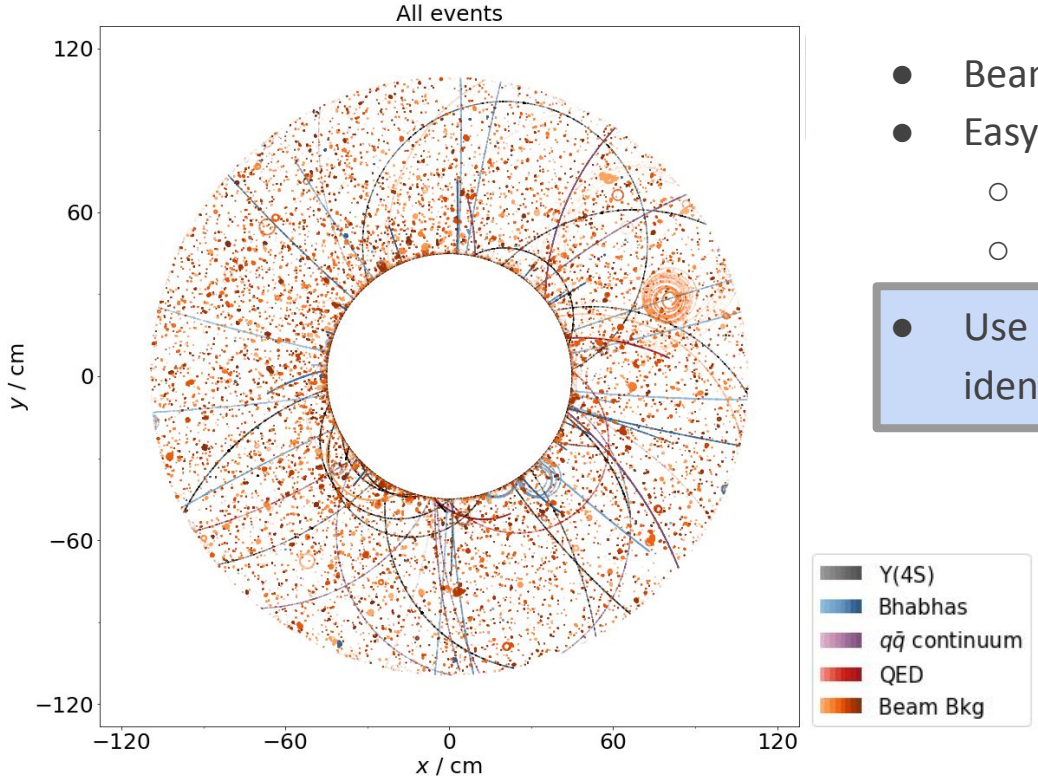


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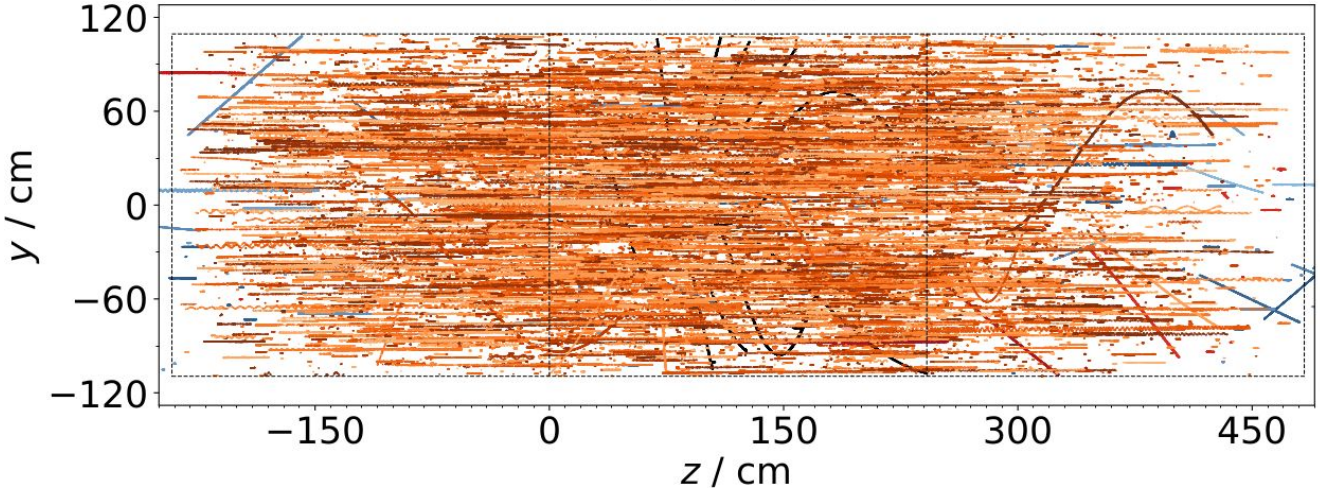
- Use pattern recognition algorithm for identification and rejection

## Background Rejection by Christian Wessel




- Volume is separated into 2x2x2 cm³ cells
  - inspired by size of readout chip: rejection at hardware level
- Reject cells with hits which are either
  - completely isolated
  - connected in *z*-direction in one spot in *x-y*

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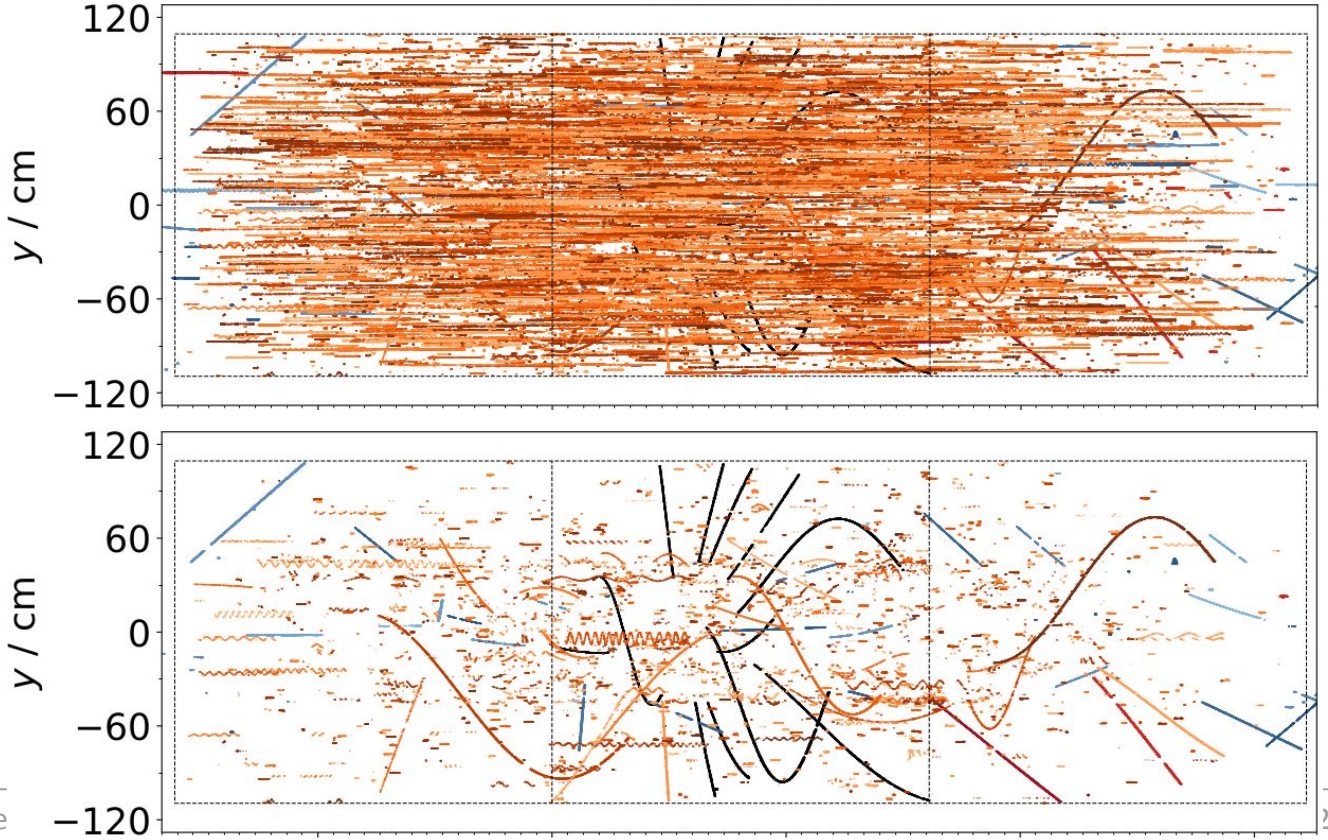

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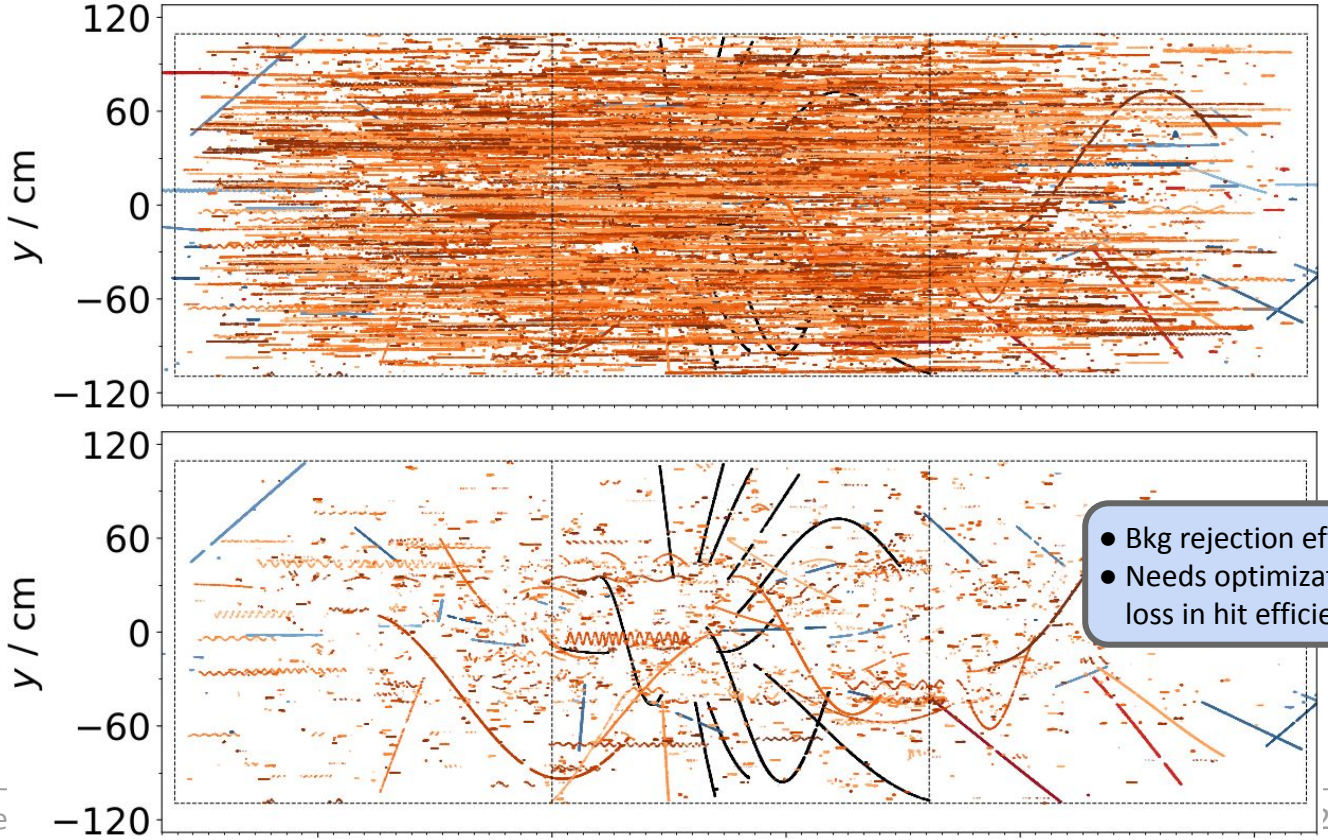
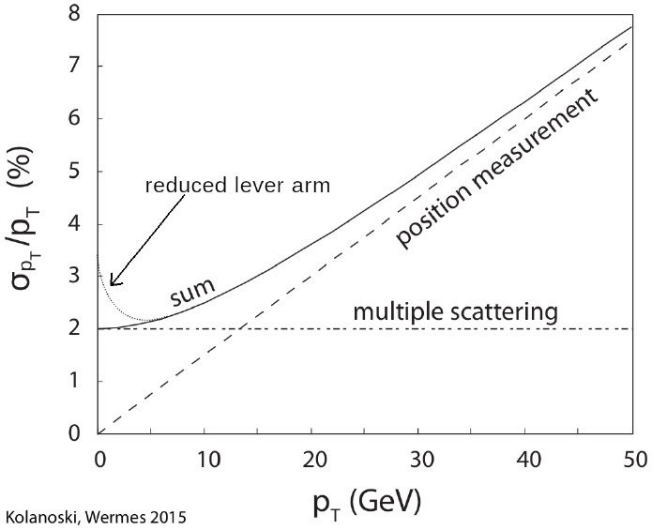



- Bkg rejection efficiency > 90%
- Needs optimization to prevent loss in hit efficiency

## pT Resolution Studies

- Measure $\sigma_{pT}/pT$ as function of
  - electron efficiency
  - spatial point resolution σ (disguised as pixel pitch *d*)

$$\sigma = \frac{d}{\sqrt{12}}$$

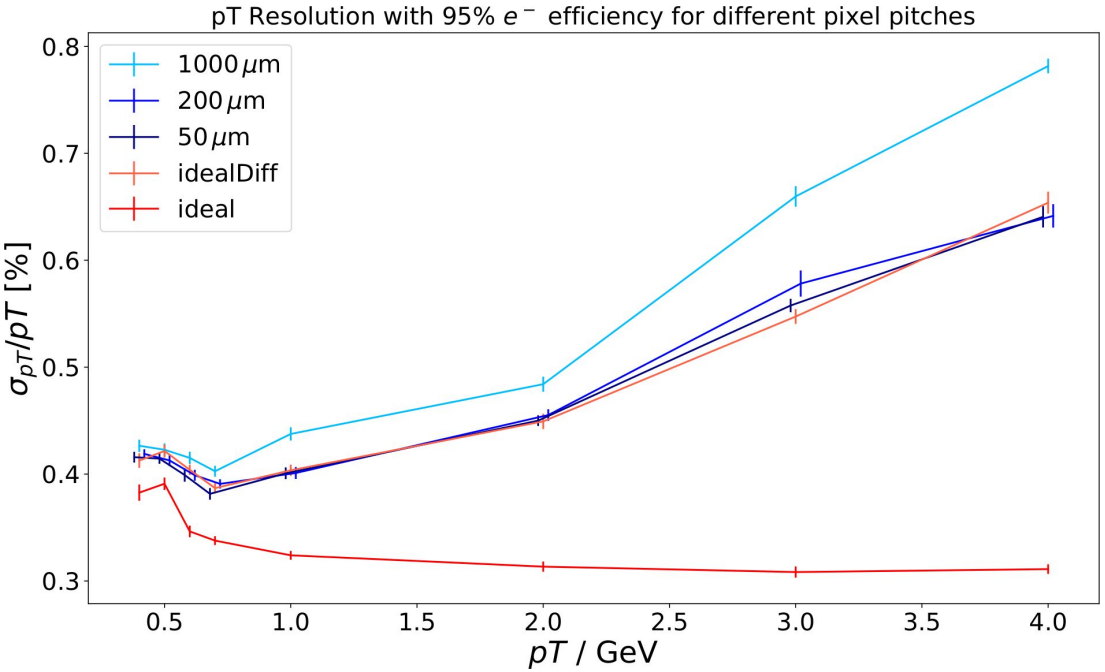


Kolanoski, Wermes 2015

- Additionally compared to ideal scenario:
  - no diffusion
  - no digitization (discretization of coordinates from pixels)
    - realized by very small pixel pitch
  - 100 % electron efficiency

# *pT* Resolution

- ideal:
  - 100 % eff
  - No digitization
  - No diffusion
- idealDiff:
  - 100 % eff
  - No digitization
  - *With* diffusion
- Material: only TPC
- 1000 muons per pT
  - 40° < θ < 140°



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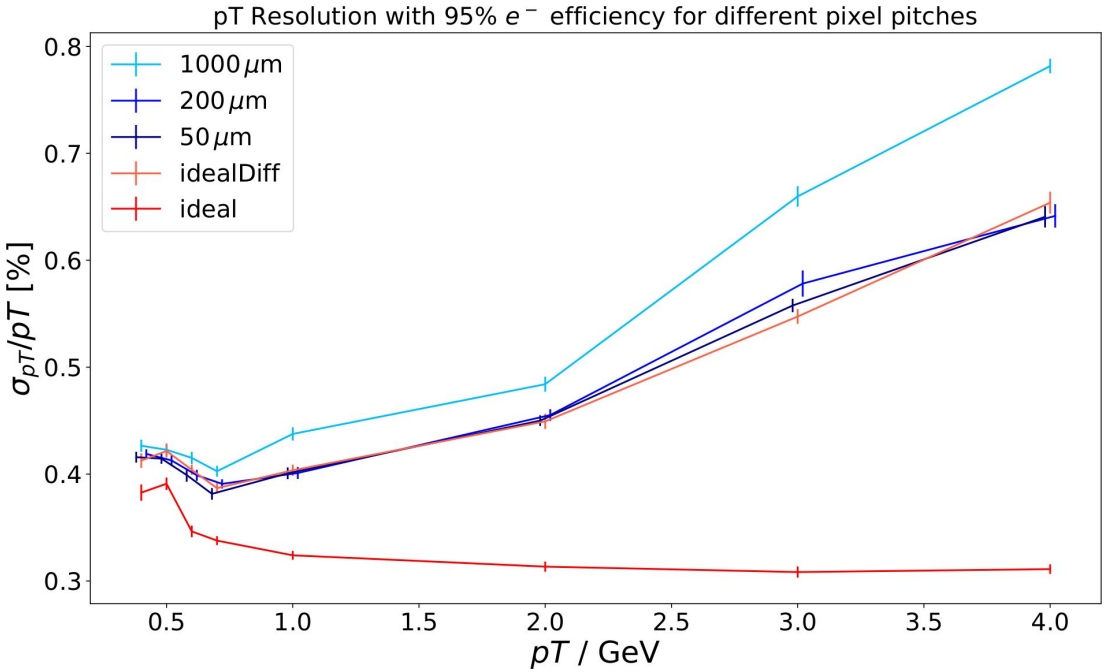


staying below effects of diffusion in pixel size seems to be sufficient

➢ 200 µm adequate

➢ cuts down on # of channels

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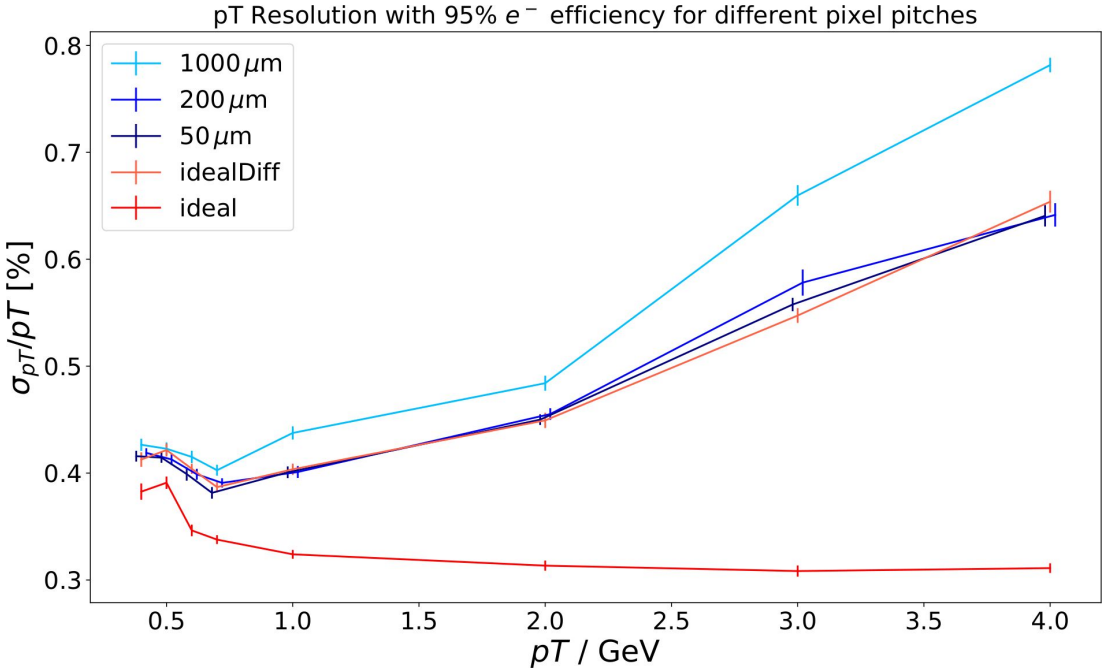


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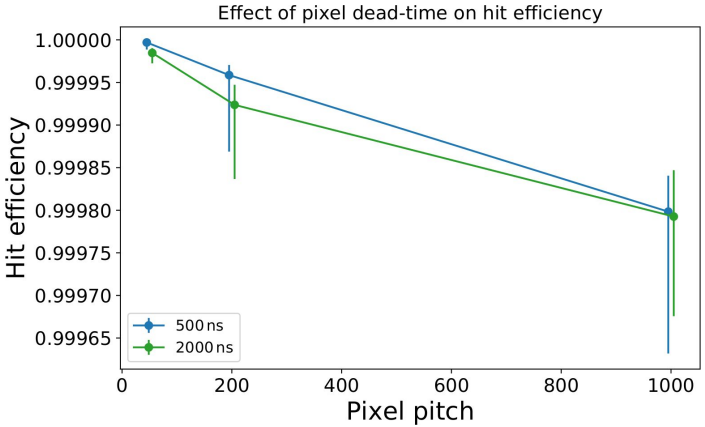
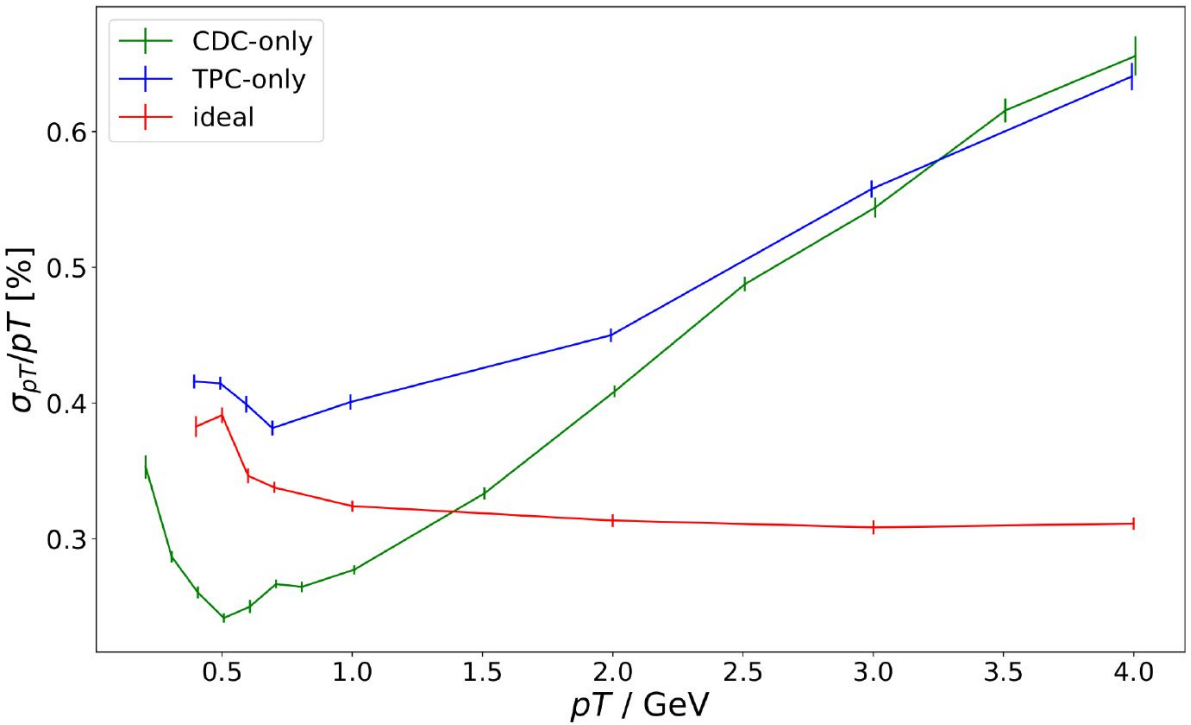


## Comparing with CDC




- Material: only TPC/CDC
- 1000 muons per pT
  - 40° < θ < 140°

- Constant MS term lower for CDC
  - 2 mm aluminium for TPC
  - 0.1 mm aluminium + 0.46 mm carbon-fibre-reinforced polymers for CDC
- TPC performs better in linear rise (position measurement) despite diffusion and shorter lever arm

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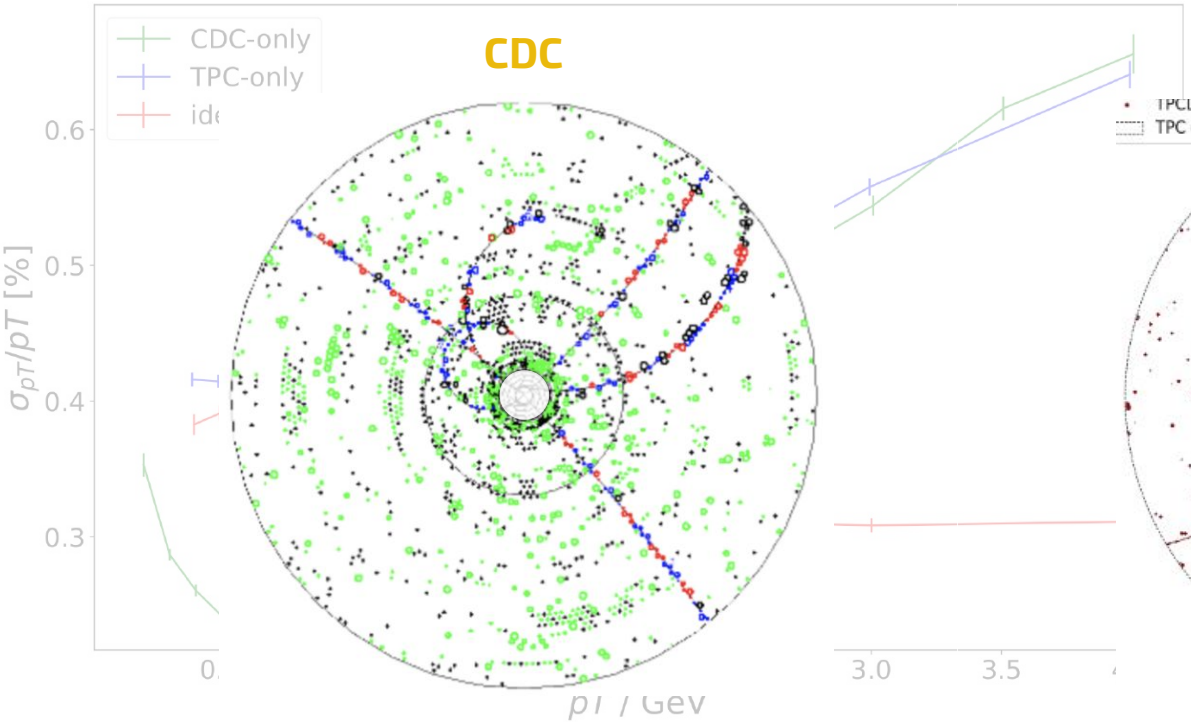
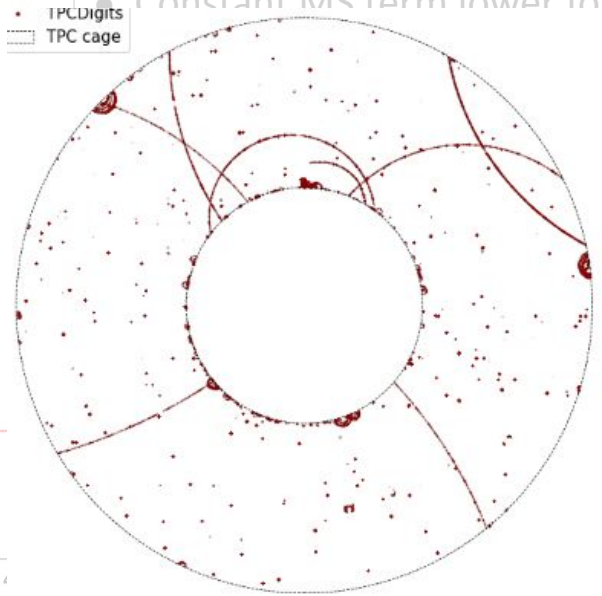



**CDC**



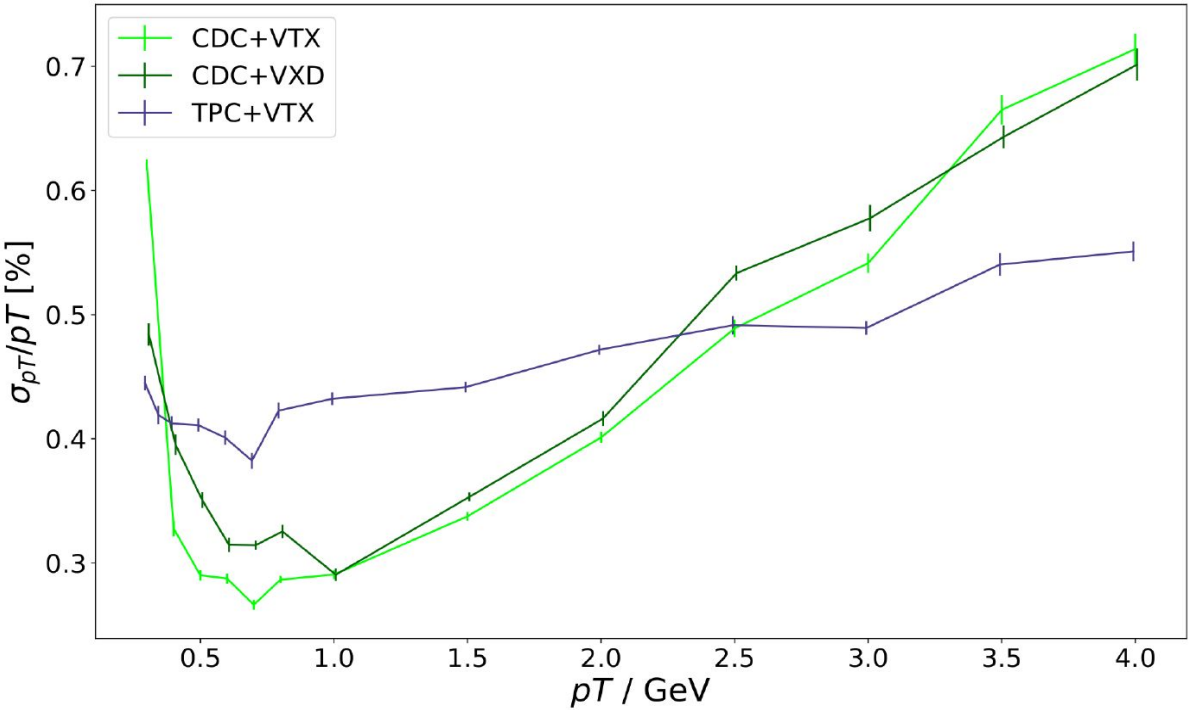

**TPC**

- Constant MS term lower for CDC

6 mm

ar rise
spite
arm

## Including the VTX




- Material: only TPC/CDC
- 1000 muons per pT
  - 40° < θ < 140°

- VTX greatly improves position measurement term in resolution (linear rise) for TPC
- Mainly contribution to lever arm
  - No notable difference between CDC+VXD and CDC+VTX

# Conclusion & Outlook

- Tracking with a TPC seems viable
  - Event overlap is manageable
  - Beam background micro-curlers can effectively be removed
    - Could use some improvement
  - Track finding is next step
- First requirements on readout:
  - **200 µm pitch is sufficient**
  - Question of gating still open

- Trigger replacement (STOPGAP)
- **Consider contributions from Injection Background**

# Conclusion & Outlook

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**Plenty of reason to be optimistic about a Tracking TPC for Belle II**

- Trigger replacement (STOPGAP)
- **Consider contributions from Injection Background**

# Conclusion & Outlook

- Tracking with a TPC seems viable
  - Event overlap is manageable
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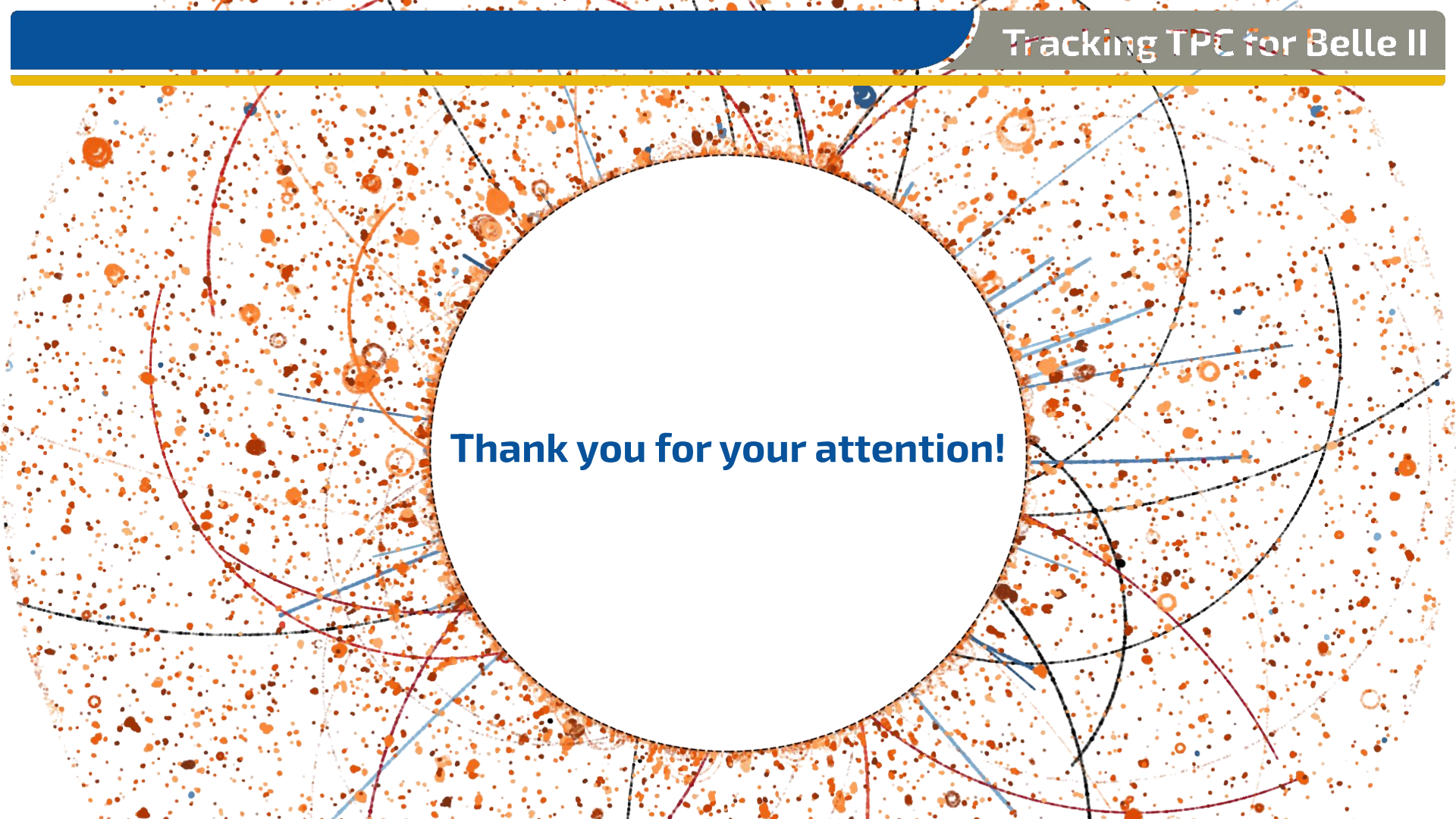
    - Could use some improvement
  - Track finding is next step
- First requirements on readout:
  - **200 µm pitch is sufficient**
  - Question of gating still open

**1 year later …**
**… still interest from various groups, but no further progress.**
**If you're interested please contact Peter Lewis (lewis@physik.uni-bonn.de)**

- Trigger replacement (STOPGAP)
- **Consider contributions from Injection Background**

## Resources

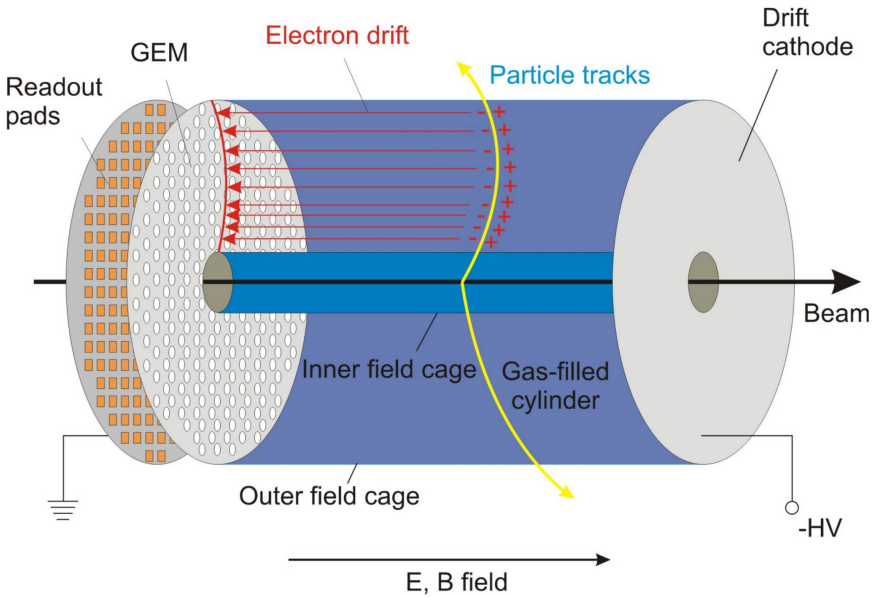
- Masters Thesis: **First Conceptual Design and Studies for a Tracking Time Projection Chamber for the Belle II Experiment**
- Snowmass 2021 white-paper: **A TPC-based tracking system for a future Belle II upgrade**
- Snowmass IF5 Meeting Presentation: **A tracking TPC for a future Belle II upgrade**



**Thank you for your attention!**

# Backup Slides

# Time Projection Chamber (TPC)

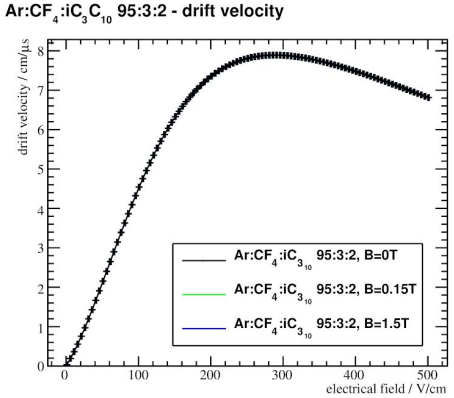


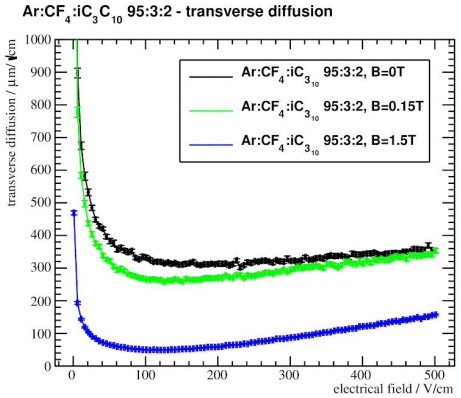

arXiv:1207.0013

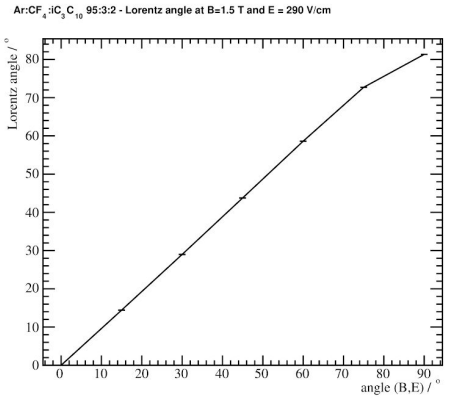
- Full 3D tracker
- generally good dE/dx resolution due to large number of sampling points
- Low material budget
- Better background tolerance
- A lot of R&D already present
  - Use LCTPC for ILD as starting point

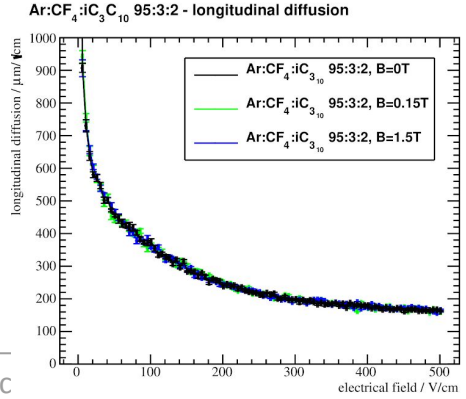
- Cannot provide trigger due to long drift times
- Large amount of event overlap in drift volume

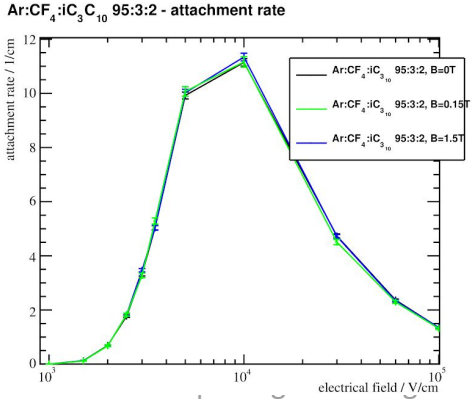
# Magboltz Simulation

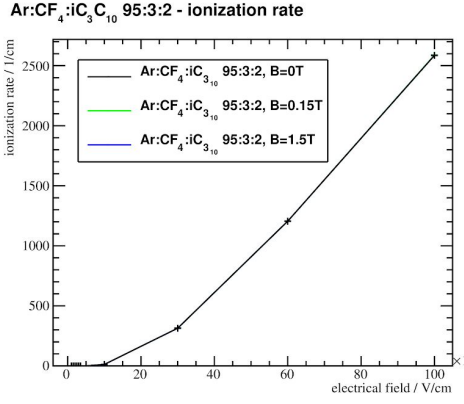


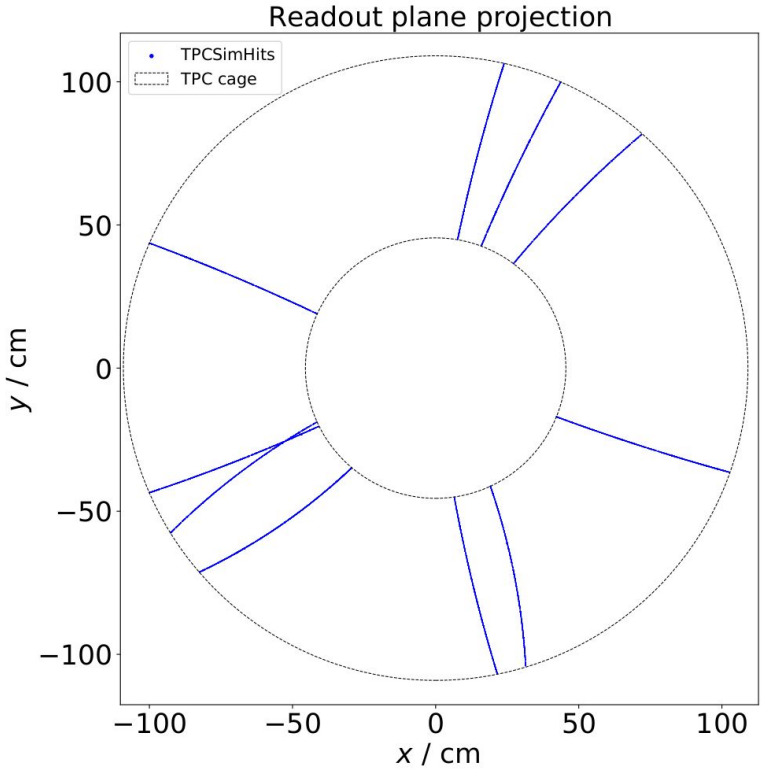



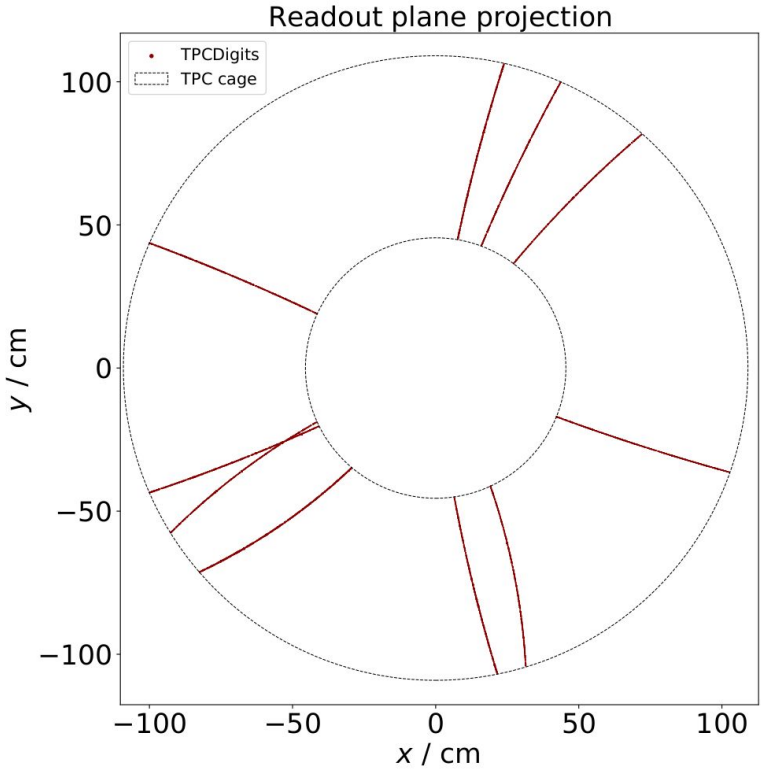



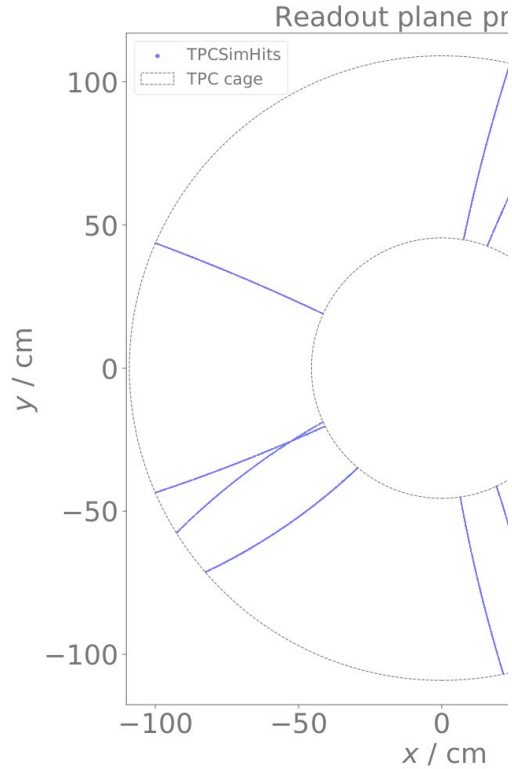



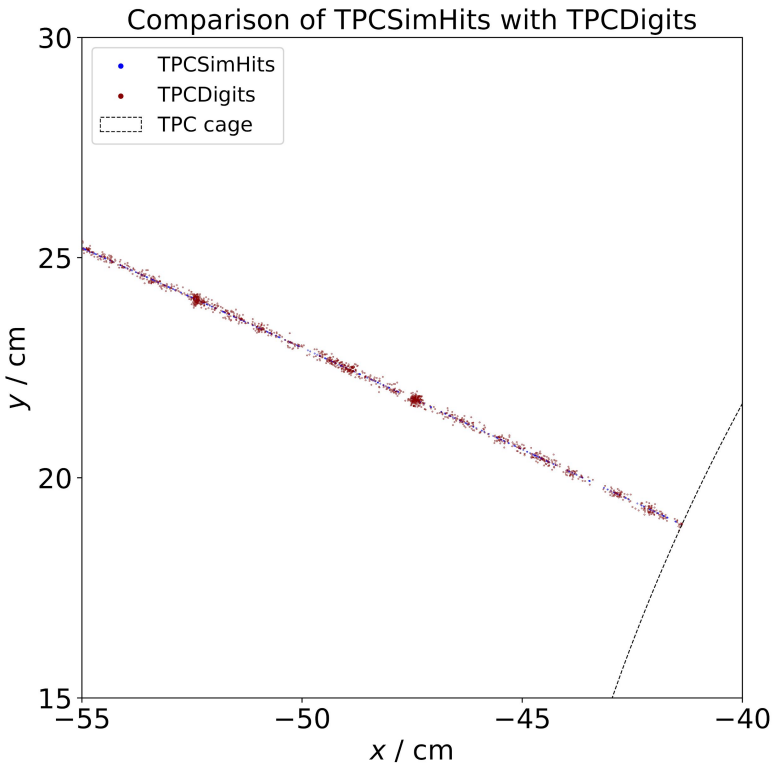



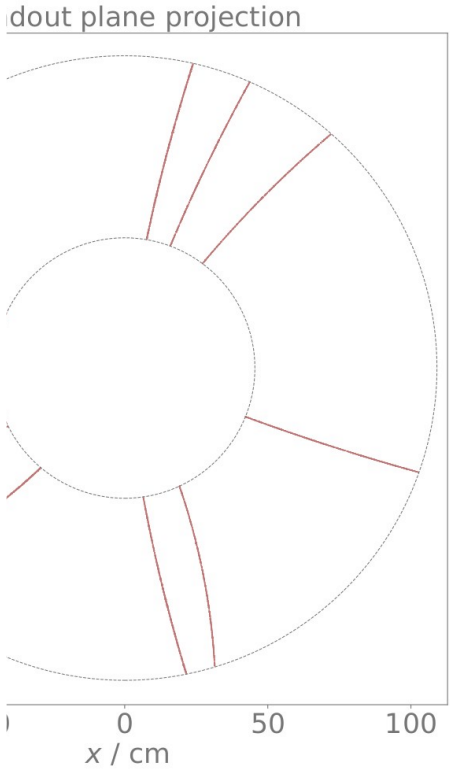
# SimHits and Digits



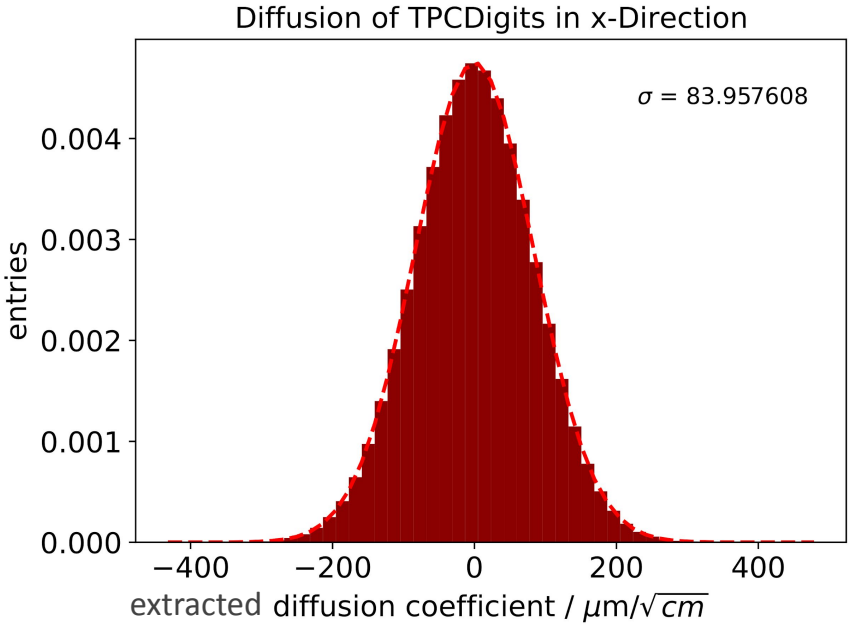



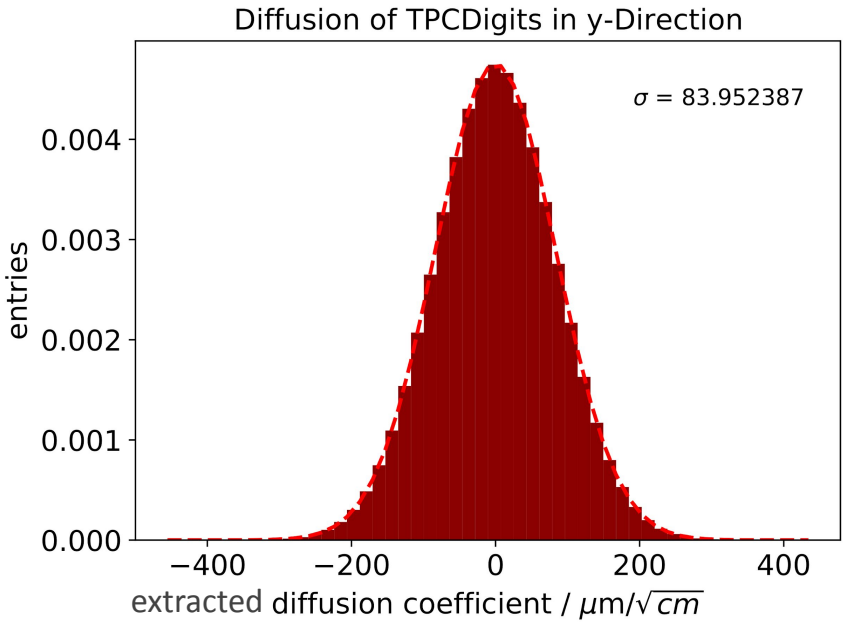

Readout plane pr
TPCSimHits
TPC cage
100
50
0
−50
−100
y / cm
−100
−50
0
x / cm


Comparison of TPCSimHits with TPCDigits
TPCSimHits
TPCDigits
TPC cage
30
25
20
15
y / cm
−55
−50
−45
−40
x / cm


dout plane projection
0
50
100
x / cm

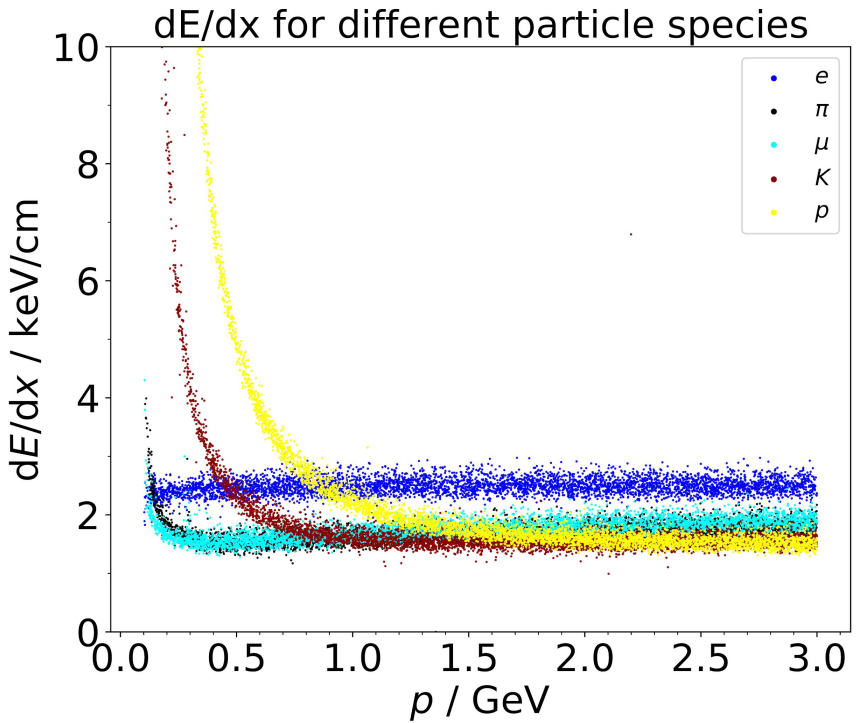
# Transverse Diffusion: 1000 Muons ($p$ = 1-4 GeV)

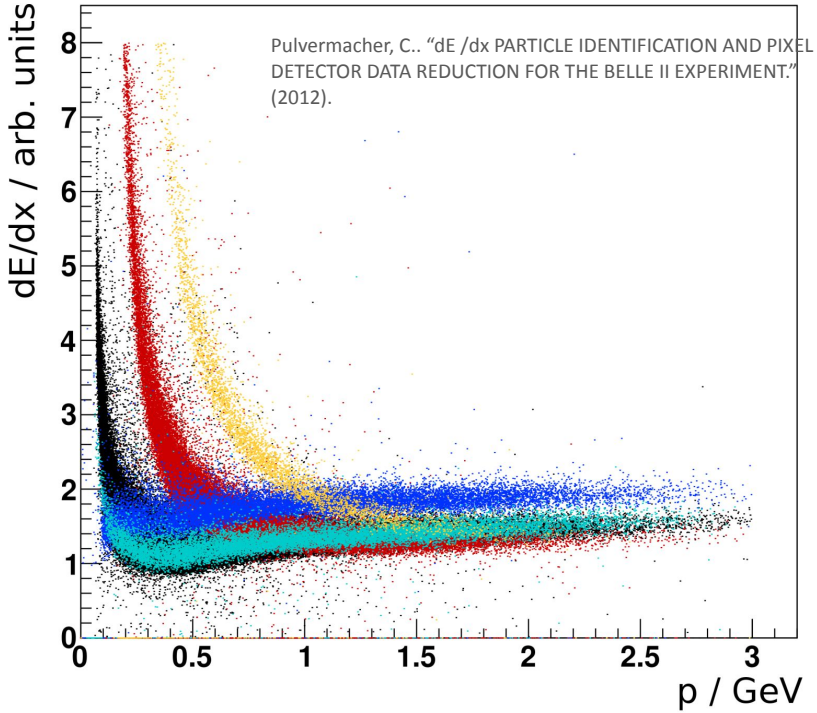



transverse diffusion coefficient for T2K gas mixture: 84 µm/sqrt(cm) at 296 V/cm
(simulated with Magboltz by Jochen Kaminski)

# dE/dx Distribution



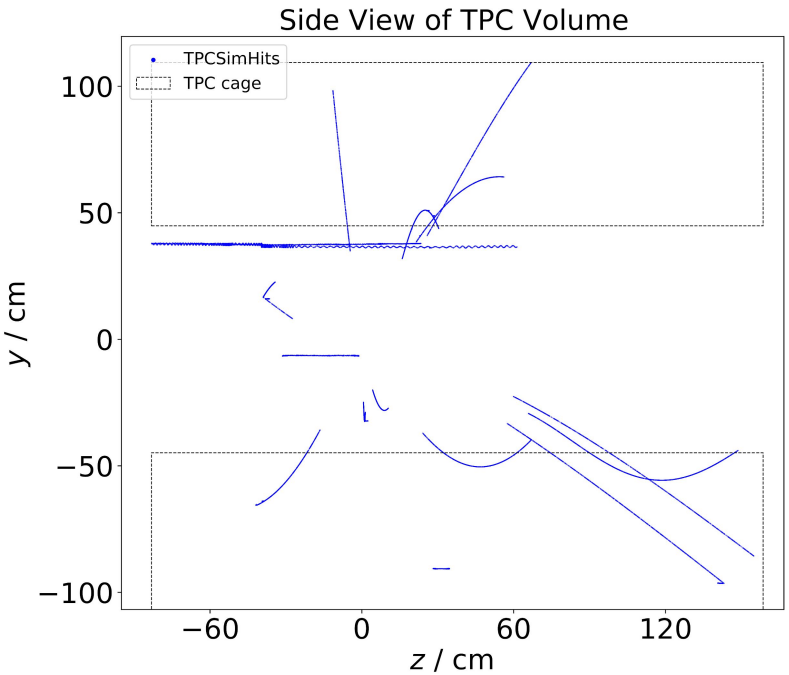



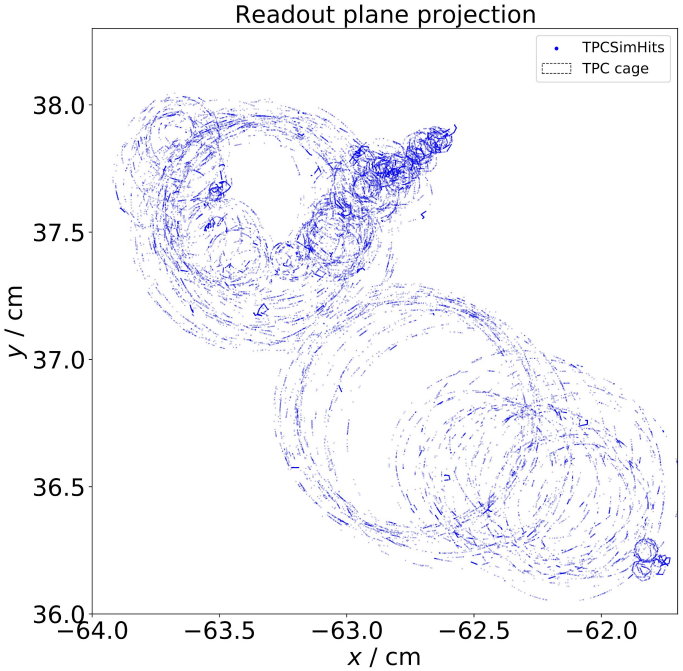
# Beam Background Conditions (BG19 campaign)

1. Beam current: LER 3.6A, HER 2.6A.
2. Number of bunches: 2500
3. Luminosity 8e35 /cm2/s.
4. Beam pipe gas pressure: <P> = 1nTorr using values from June 27, 2020.
5. The realist collimator profile and tip-scattering physics for particles scattered off by collimators.
6. For HER, the collimator mask was re-optimized to suppress the background.

| Process | Rate / MHz | Rate / $(60\mu s)^{-1}$ |
|---|---|---|
| Brems HER | 2.46479 | 147.89 |
| Brems LER | 8.2928 | 497.57 |
| Coulomb HER | 16.335 | 980.10 |
| Coulomb LER | 191.641 | 11498.46 |
| Touschek HER | 0.242353 | 14.54 |
| Touschek LER | 119.409 | 7164.54 |

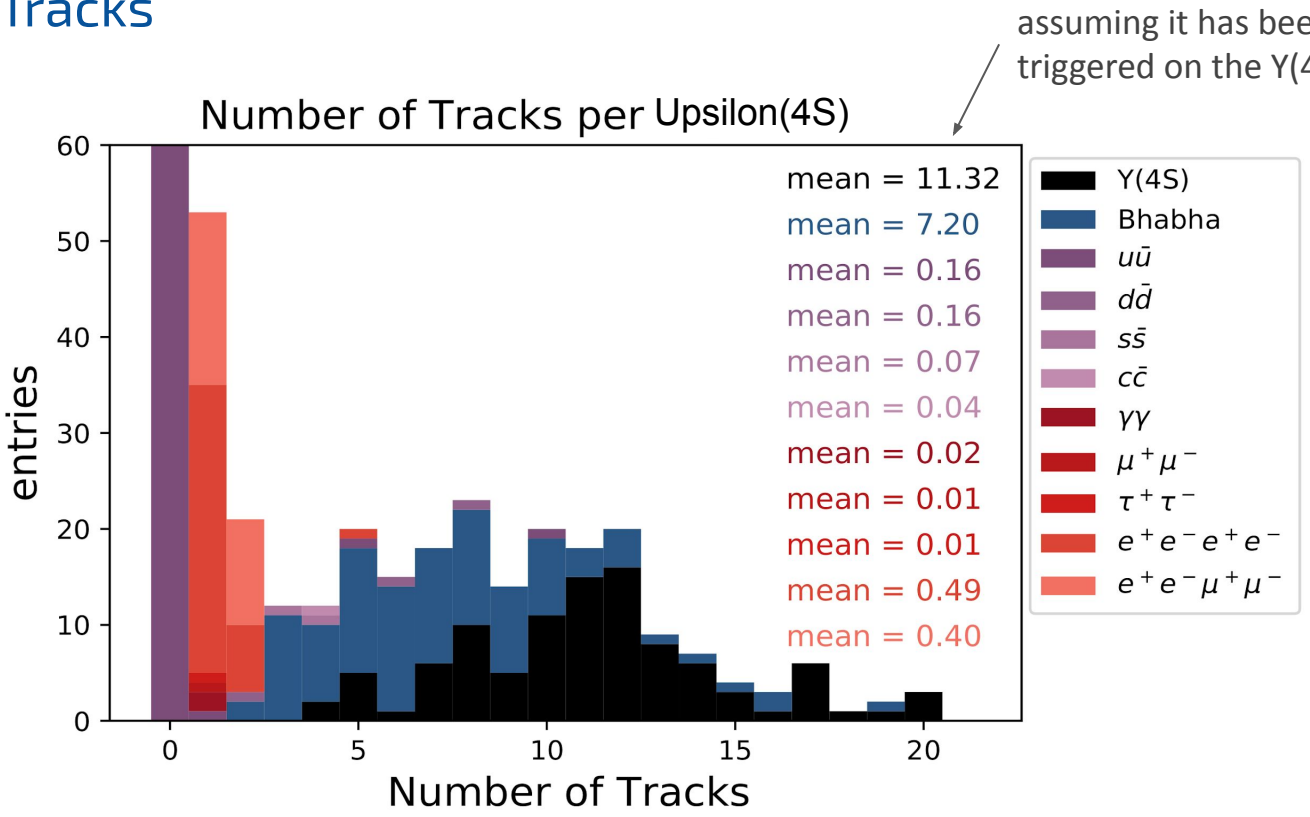
# Micro-Curler



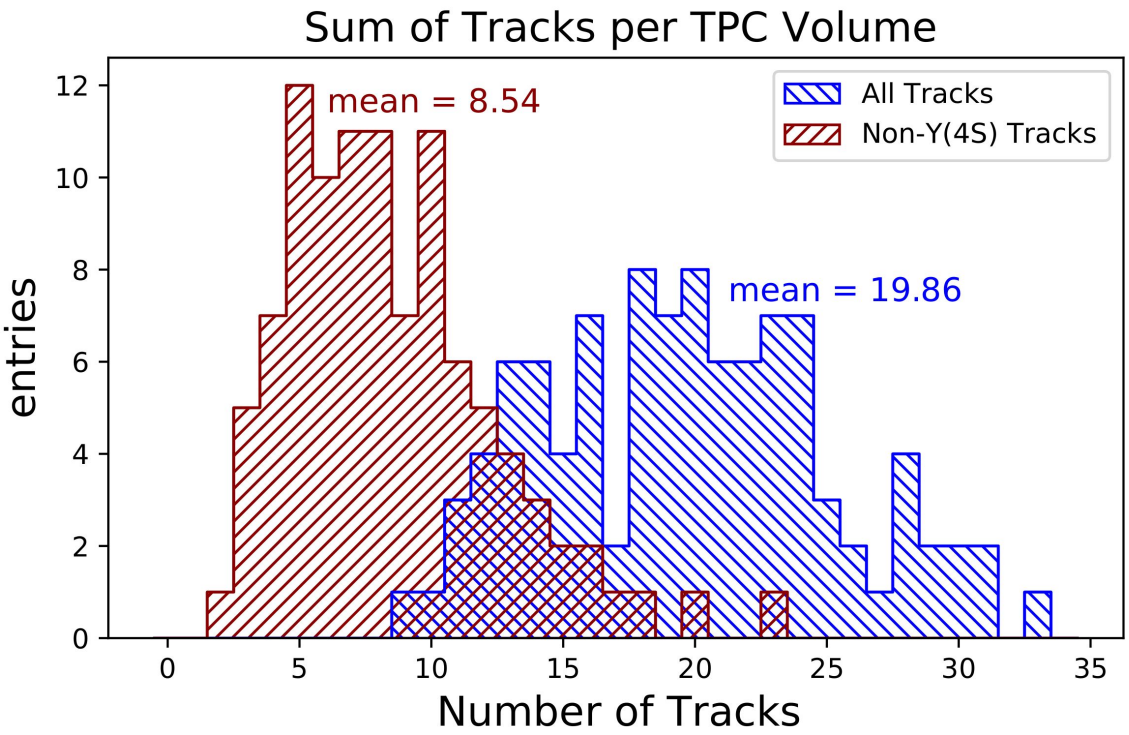




**δ- or Compton-electrons**

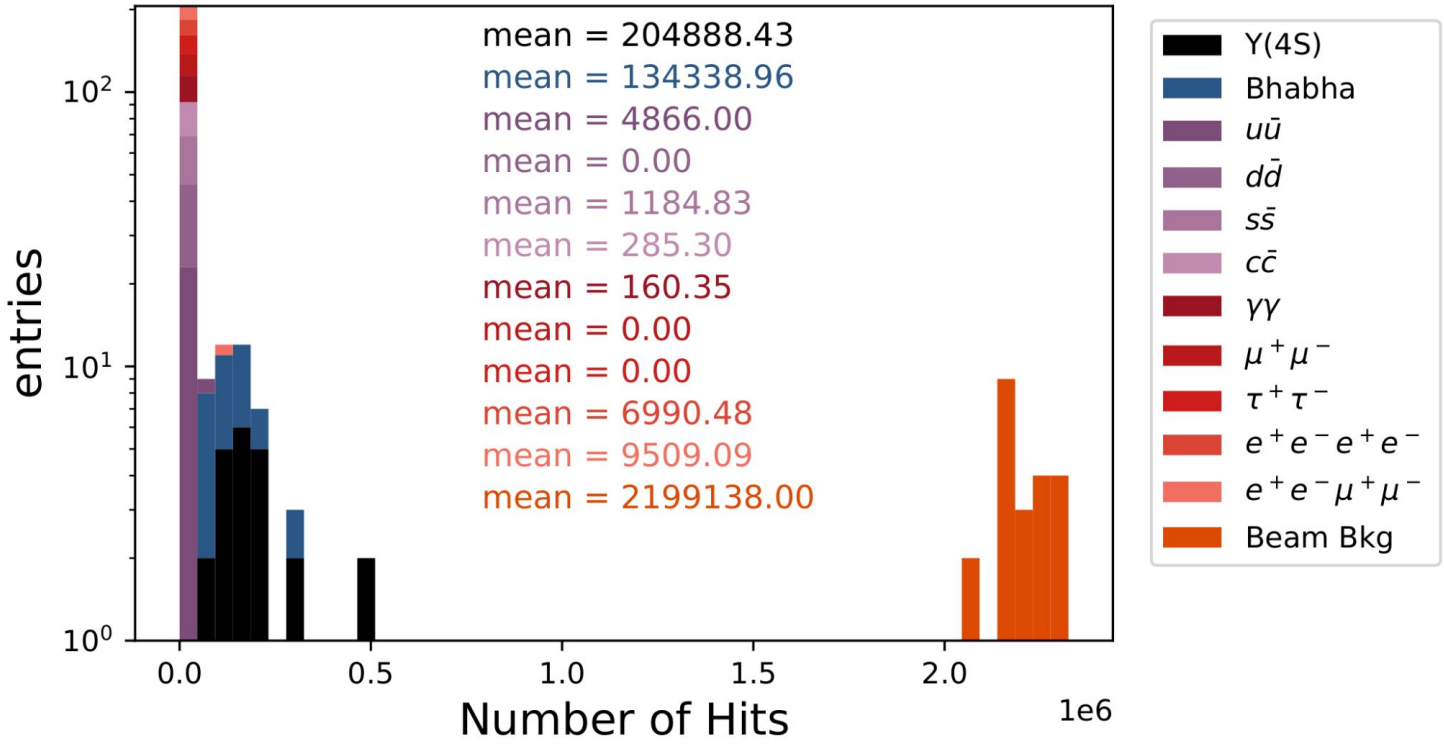
# Number of Tracks



# Sum of Tracks



# Overlaying Background (x1 Background)



# Ion Density (x5 Background)

- Using simple assumption for amplification region (gain, backflow) and ion mobility: calculate charge density in TPC volume

  => 4633.63 ions / $cm^3$

  or around **0.74 fC / $cm^3$**

- Comparable to other TPC examples
- Solid micro-curler rejection needed
  - First tracking studies done by Christian Wessel

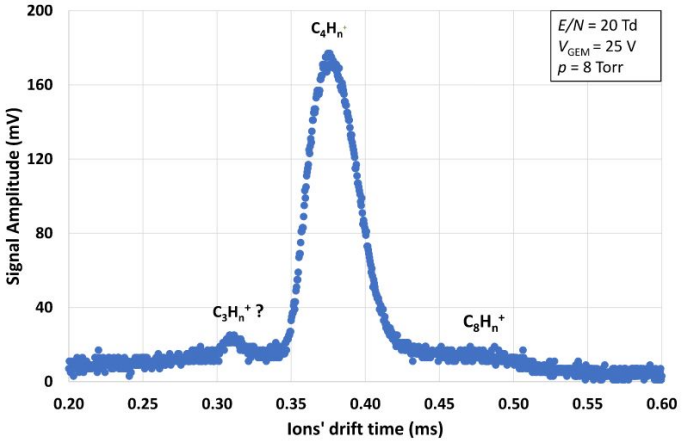
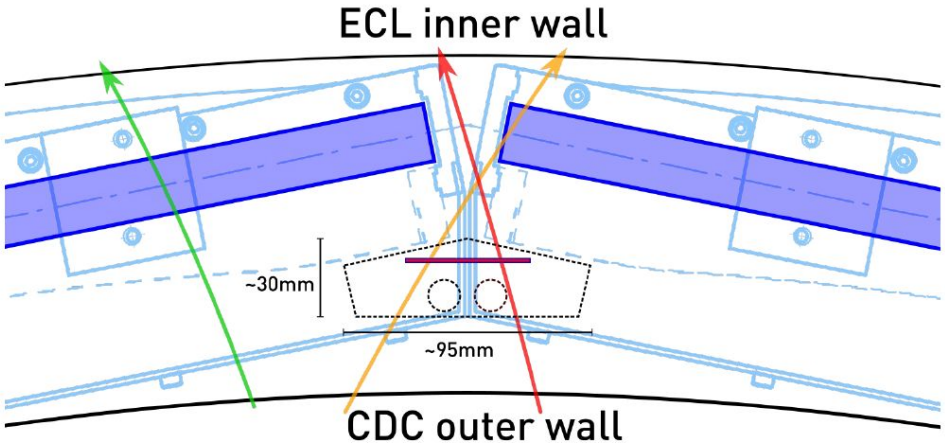



**Fig. 1.** A typical drift spectrum for Ar-$CF_4$-i$C_4H_{10}$ (95-3-2) obtained at a pressure of 8 Torr, $E/N$ of 20 Td, and a $V_{GEM}$ of 25 V and at room temperature.

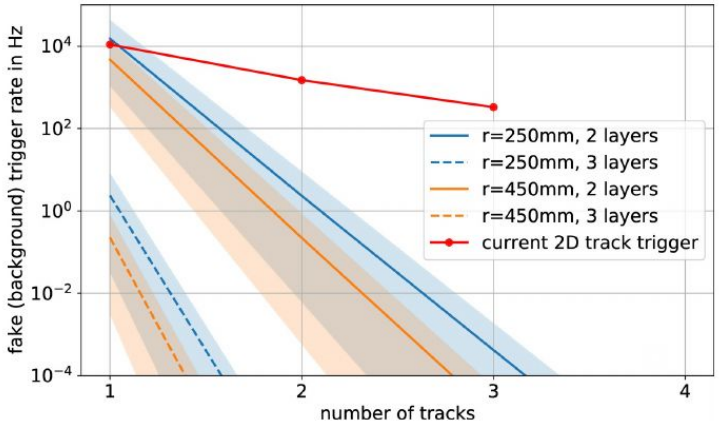
https://doi.org/10.1016/j.nima.2018.11.049

# Time-of-Flight Extension for the TOP PID System

- TOP not hermetic
- Supplemental TOP Gap Instrumentation with time-of-flight sensors




- 50-70 ps time resolution for MIPs
- Novel fast MAPS suitable
- Can provide missing dE/dx
  - excellent π/K separation
- Double timing layer can provide trigger



# *pT* Resolution

- ideal:
  - 100 % eff
  - No digitization
  - No diffusion
- idealDiff:
  - 100 % eff
  - No digitization
  - *With* diffusion
- Material: only TPC
- 1000 muons per pT
  - 40° < θ < 140°