

Towards detection of Breit-Wheeler tunneling positrons in E320 at the FACET-II accelerator

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02.09.2025



Based on [2506.04992](#)

NBW pair production in e -beam collisions

High-energy
electron beam

e_{probe}^- →

**Strong
Fields**

e -beam-based experimental design for NBW pair production

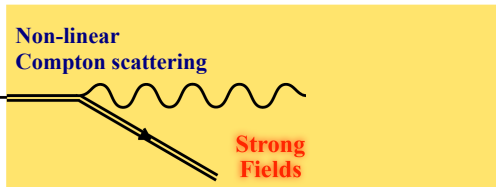
- Accelerated electron beam enters high-intensity EM field

NBW pair production in e -beam collisions

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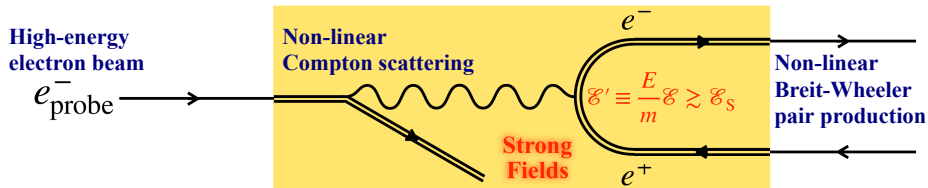
Non-linear
Compton scattering



e -beam-based experimental design for NBW pair production

- Accelerated electron beam enters high-intensity EM field
- Electrons experience Non-linear Compton scattering producing a high-energy photon

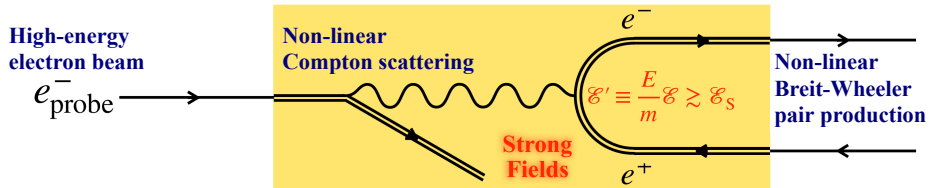
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e -beam-based experimental design for NBW pair production

- Accelerated electron beam enters high-intensity EM field
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- High-energy photon propagates in the SF region converts into e^+e^- pair (relativistic field boost)

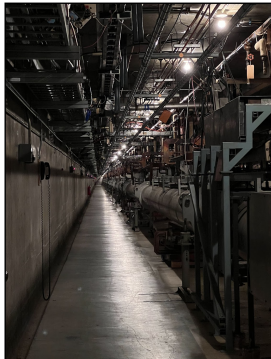
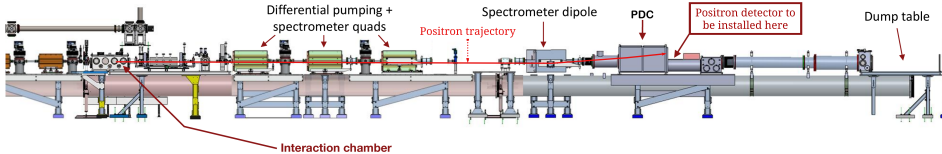
NBW pair production in e -beam collisions



e -beam-based experimental design for NBW pair production

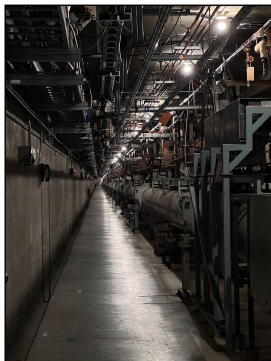
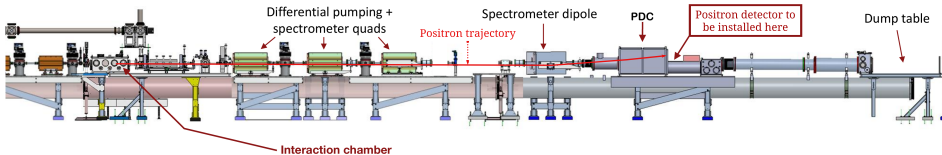
- Accelerated electron beam enters high-intensity EM field
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- High-energy photon propagates in the SF region converts into e^+e^- pair (relativistic field boost)
- This presentation: simulation-based study, detector commissioning and testing

Experiment 320



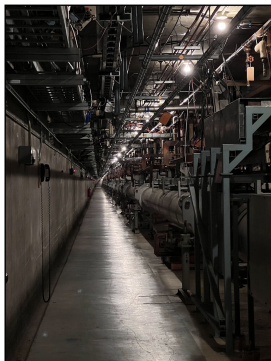
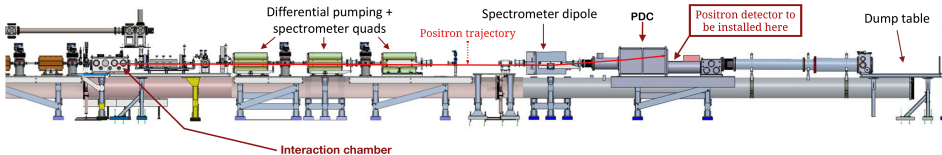
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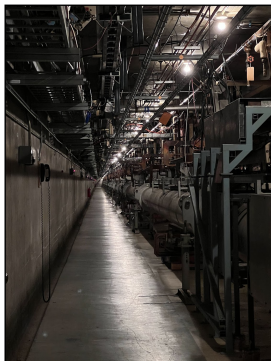
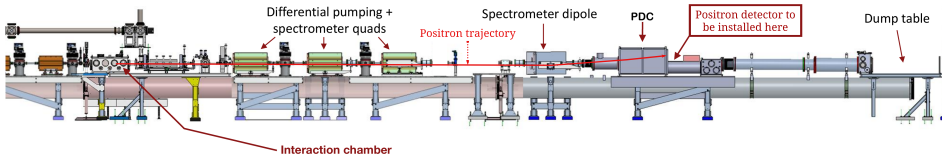
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- 10 GeV e -beam collisions with 10 TW laser (with a prospective 100 TW upgrade)

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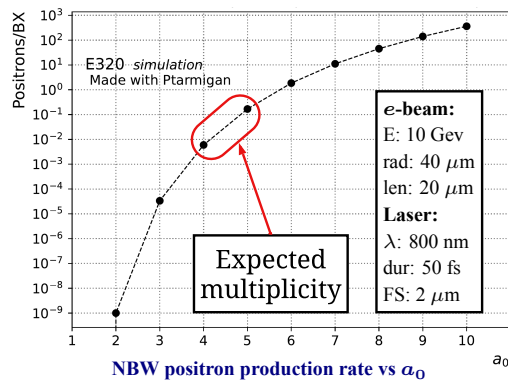
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- Exiting the IP positrons are focused by the three quadrupoles

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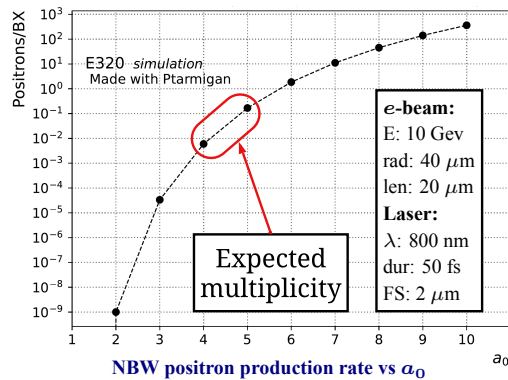
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- The dipole enables spectral characterization of NBW positrons

Experiment 320

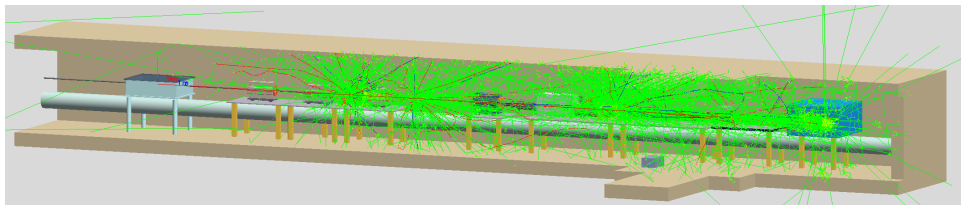


- Current e -beam + laser parameters yield $\mathcal{O}(10^{-2}-10^{-1})$ positrons/BX

Experiment 320

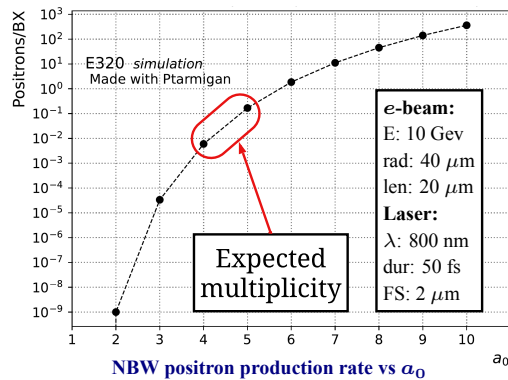


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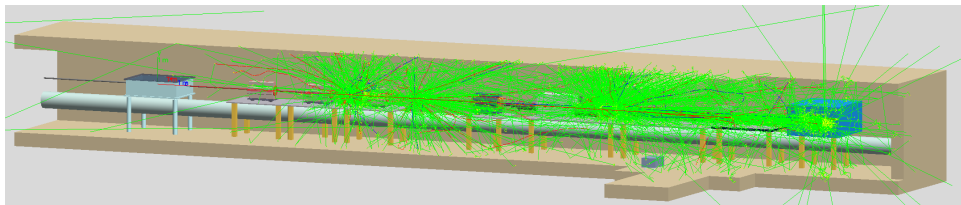


Snapshot of five NCS electrons passing the beamline (simulated in Geant4)

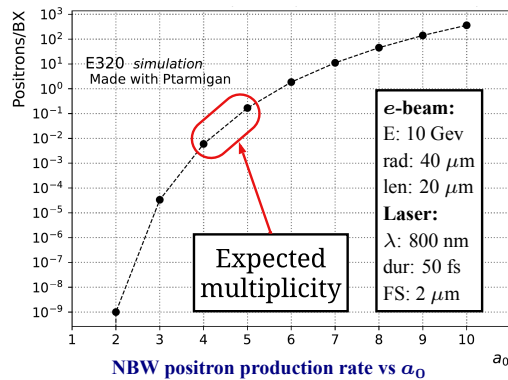
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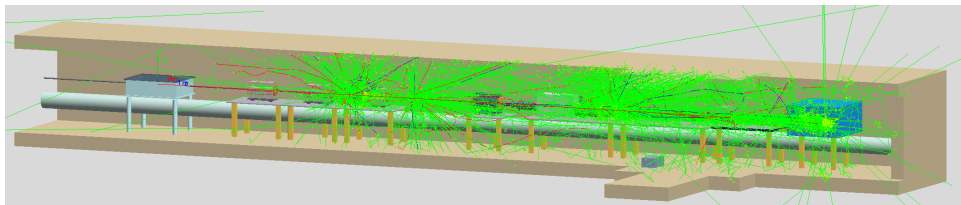
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Experiment 320

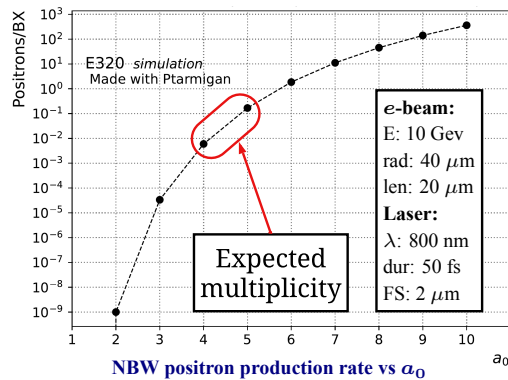


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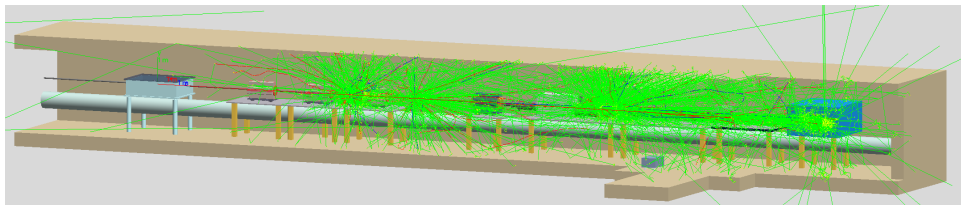


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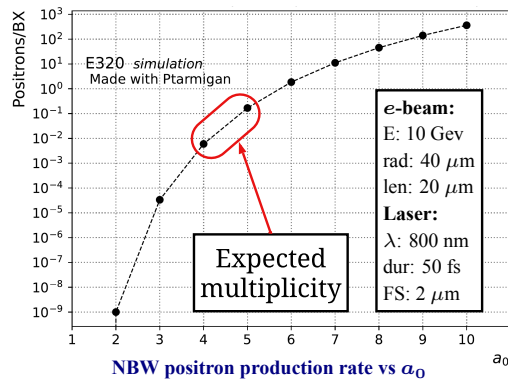


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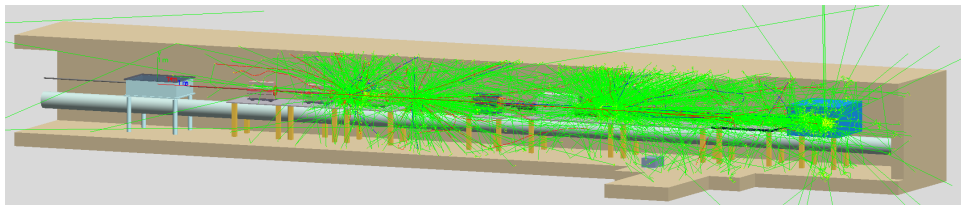


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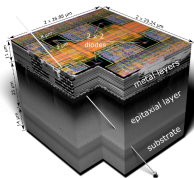
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- Need a detector:
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 - High efficiency
 - Insensitive to neutral particles
 - Radiation hard



Snapshot of five NCS electrons passing the beamline (simulated in Geant4)

E320 tracking detector

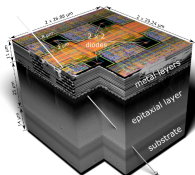
ALPIDE: MAP Sensor



**1024 × 512 matrix
of $27 \times 29 \mu\text{m}^2$ pixels
(5 μm resolution)**

E320 tracking detector

ALPIDE: MAP Sensor



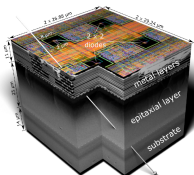
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Stave – ×9 ALPIDEs

E320 tracking detector

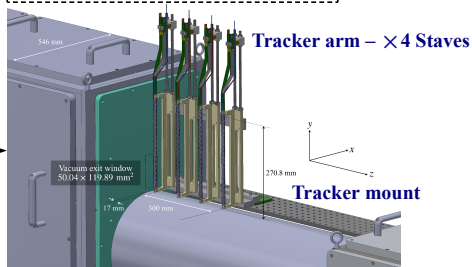
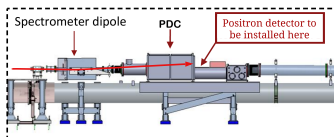
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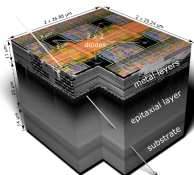


Stave – $\times 9$ ALPIDEs



E320 tracking detector

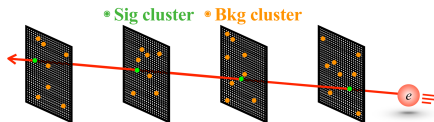
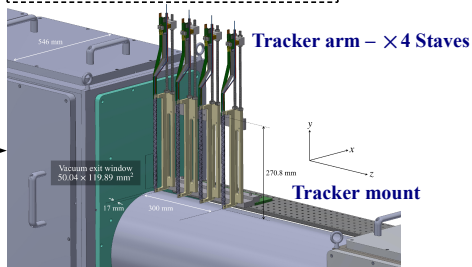
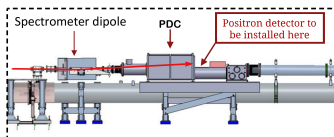
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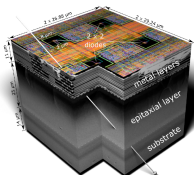
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Track reconstruction

E320 tracking detector

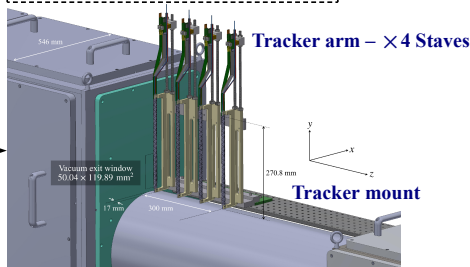
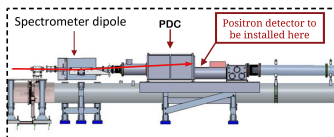
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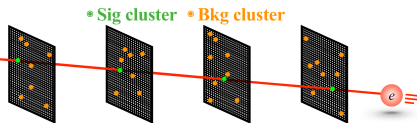
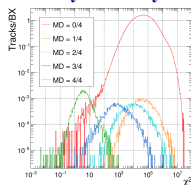
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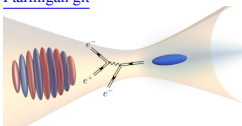
Physics analysis



Track reconstruction

Simulation-based feasibility study pipeline

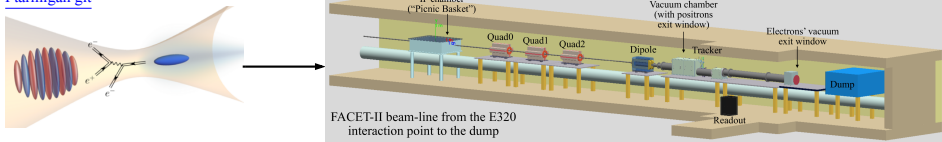
[Ptarmigan git](#)



- Simulated e -beam–laser interaction with Ptarmigan ($a_0 = 5$, $\chi \simeq 0.2$)

Simulation-based feasibility study pipeline

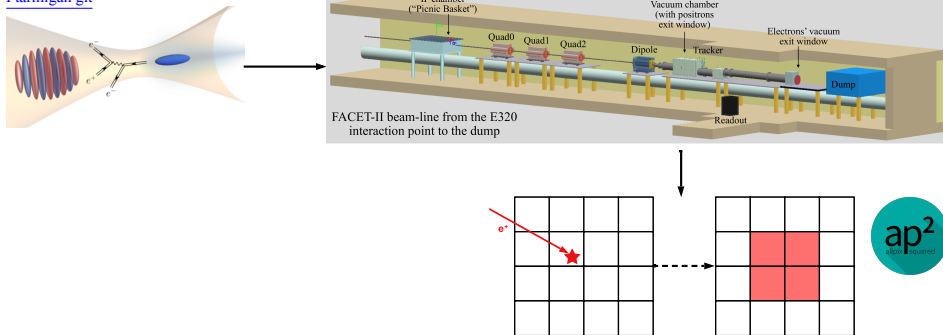
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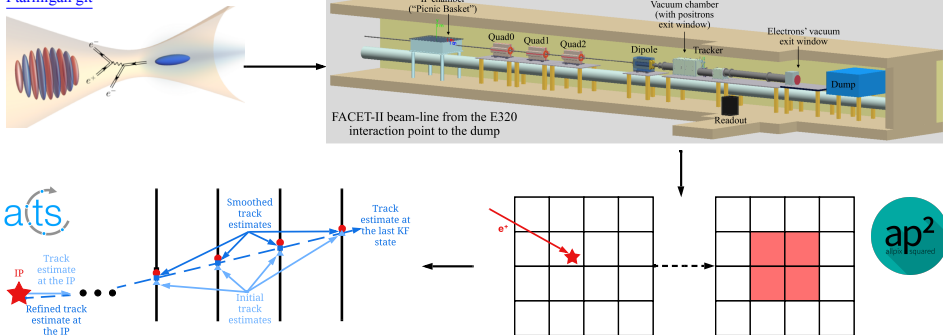
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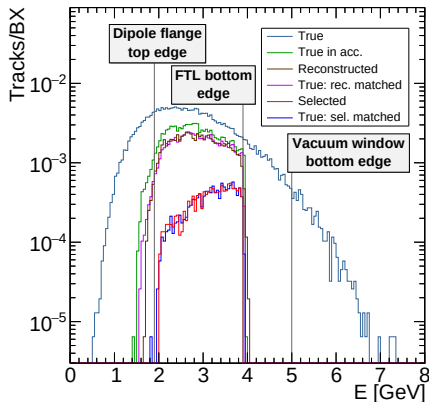
Ptarmigan git



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- Performed track reconstruction with ACTS (combinatorial track finding + Kalman Filter track fitting)

Reconstruction performance

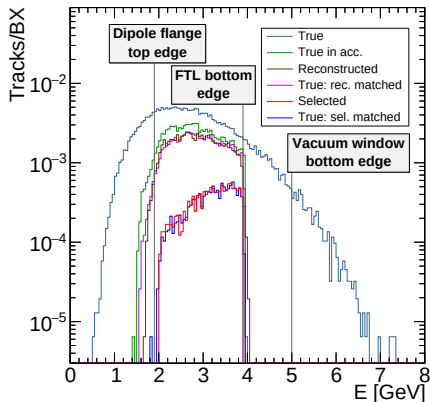
- Signal reconstruction rate: $\rightarrow 0.168 e^+/\text{BX}$ produced in the IP
 - $\rightarrow \sim 71\%$ hit the detector ($0.119 e^+/\text{BX}$)
 - $\rightarrow \sim 63\%$ reconstructed ($0.075 \text{ tracks}/\text{BX}$)
 - $\rightarrow \sim 16\%$ selected ($0.013 \text{ tracks}/\text{BX}$)



Reconstructed energy spectrum

Reconstruction performance

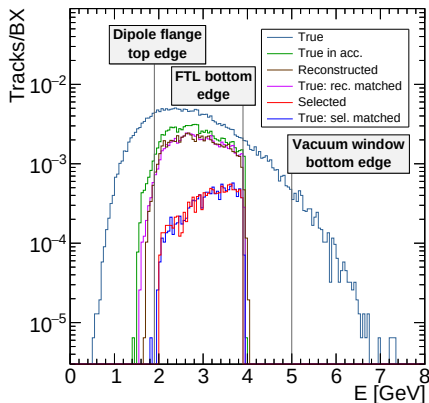
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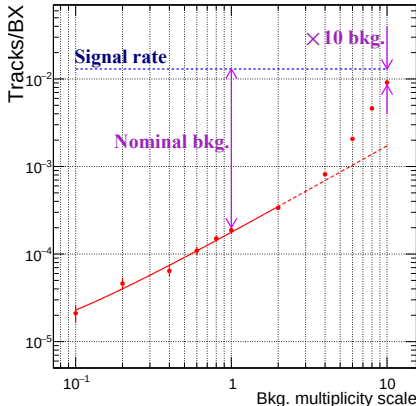
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- Background rate post selection is ~ 70 times smaller (~ 1.5 times at $\times 10$ bkg.)

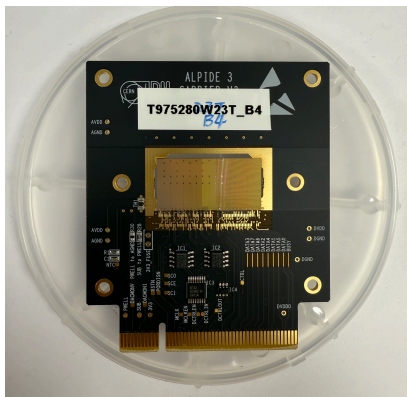


Reconstructed energy spectrum



Bkg. rate vs its multiplicity scale

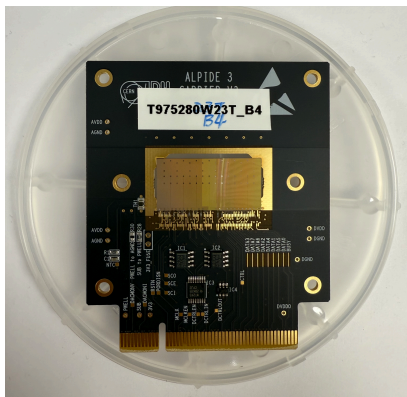
Tracking detector prototype



Single ALPIDE card

- Developed a prototype of the tracker based on single-chip cards

Tracking detector prototype



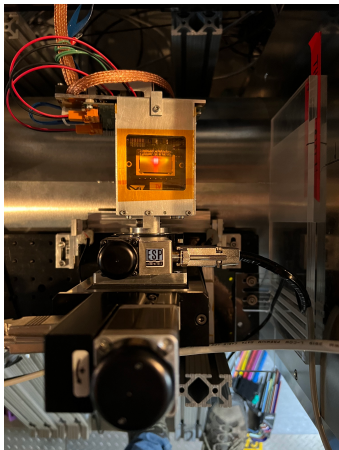
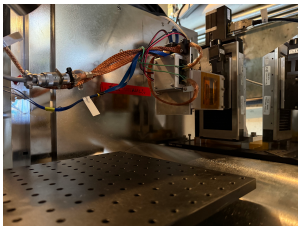
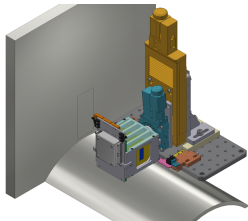
Single ALPIDE card



ALPIDE card adapter

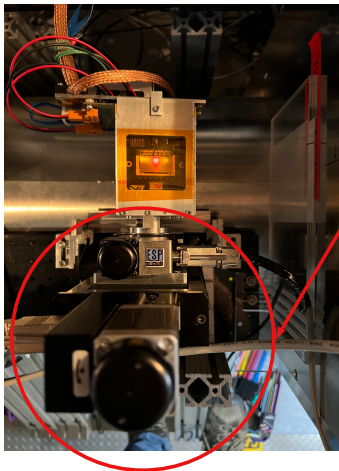
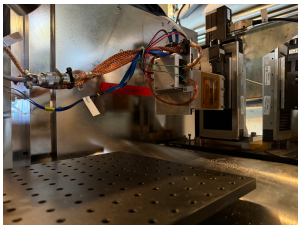
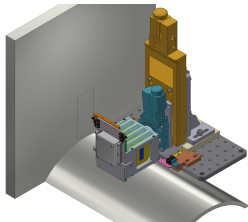
- Developed a prototype of the tracker based on single-chip cards
- ALPIDE card adapter instead of the stave – $\times 9$ smaller acceptance

Tracker commissioning and upgrade at SLAC

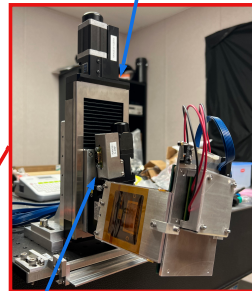


- Installed (Aug. 2024, 4 chips) and upgraded (Feb. 2025, 5 chips) the tracker prototype at FACET-II

Tracker commissioning and upgrade at SLAC



Linear stage



Rotational stage

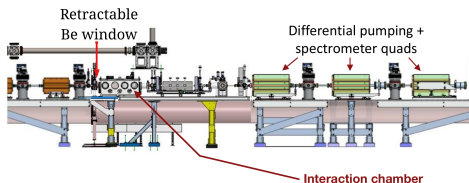
- Installed (Aug. 2024, 4 chips) and upgraded (Feb. 2025, 5 chips) the tracker prototype at FACET-II
- Mechanical stages allow for translation along y and rotation in y - z plane

Data taking campaigns at SLAC

- Conducted multiple data-taking campaigns: Nov. 2024 (initial trial)
Feb. 2025 (toy signal reconstruction)
May 2025 (NBW positrons, being analysed)

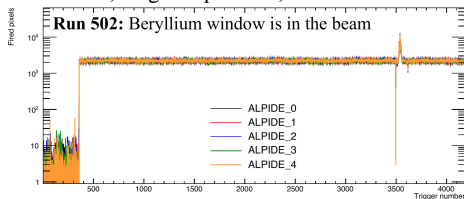
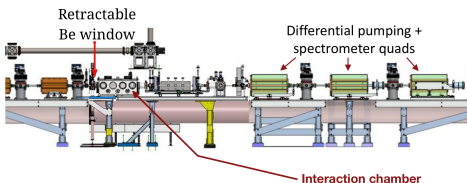
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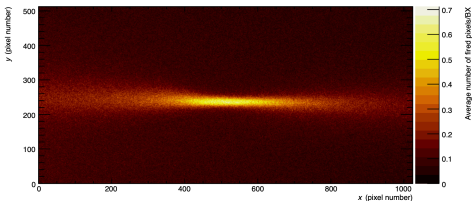


Data taking campaigns at SLAC

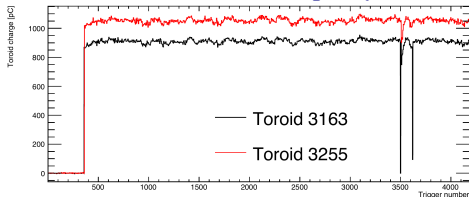
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- Gained experience in alignment, subsystem synchronization, magnet operation, etc.



Detector occupancy



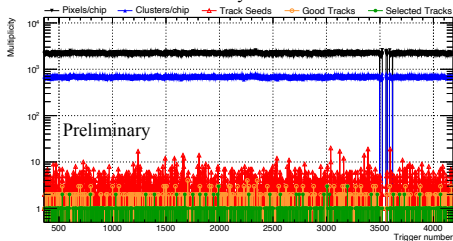
Hit density, strong focusing



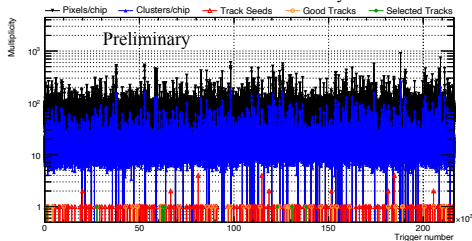
Charge monitor readings

February campaign results

Run 502: Beryllium window

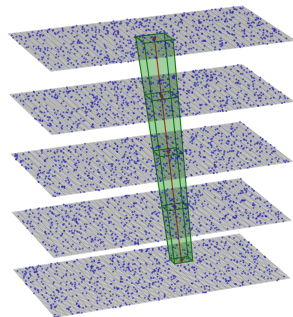


Run 503: Beam-only



Conversion of average detector occupancy to reconstructed tracks

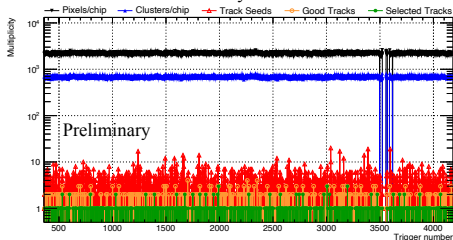
- Studied two runs – one with Be positrons and one with just the beam



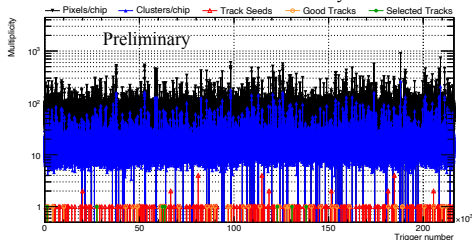
Example reconstructed track

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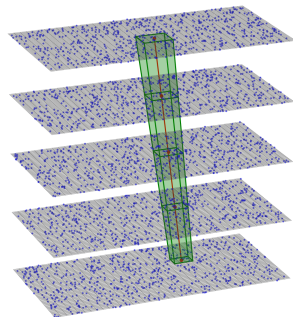


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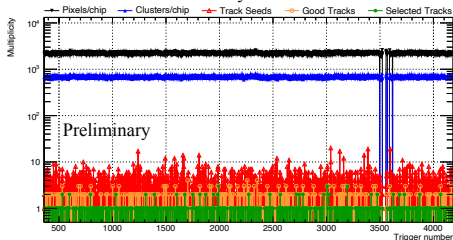
- Studied two runs – one with Be positrons and one with just the beam
- Be window run rate: ~ 0.17 tracks/BX;
Beam-only run rate: 3.4×10^{-5} tracks/BX
(5000 times smaller)



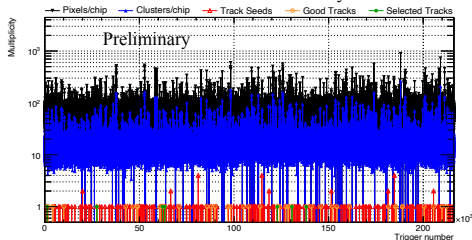
Example reconstructed track

February campaign results

Run 502: Beryllium window

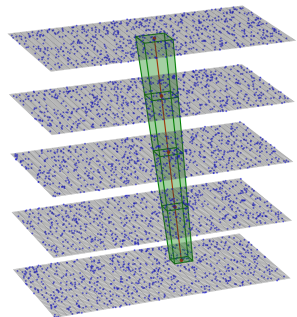


Run 503: Beam-only



Conversion of average detector occupancy to reconstructed tracks

- Studied two runs – one with Be positrons and one with just the beam
- Be window run rate: ~ 0.17 tracks/BX;
Beam-only run rate: 3.4×10^{-5} tracks/BX
(5000 times smaller)
- Able to reconstruct Be positrons and reject dump background



Example reconstructed track

Outline and prospects

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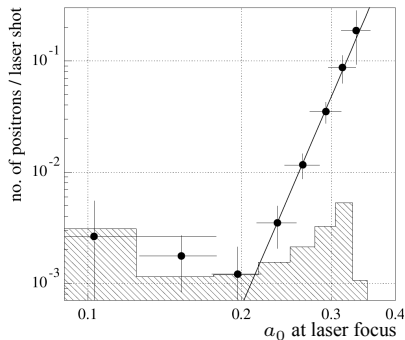
- Performed extensive simulation studies, showed feasibility of NBW positron measurement at E320
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- The Feb. campaign proved tracker's reconstruction/rejection capabilities on real data, May 2025 campaign is being analysed

Outline and prospects

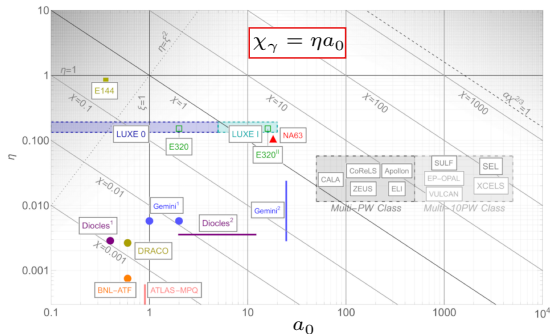
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- Developed, commissioned, and upgraded the tracking detector prototype, conducted data-taking campaigns at FACET-II
- The Feb. campaign proved tracker's reconstruction/rejection capabilities on real data, May 2025 campaign is being analysed
- Similar detector solutions are adapted for LUXE ([2308.00515](#)) and Apollon/ELI-NP user campaigns

Based on [2506.04992](#)

Backup: SFQED experiments



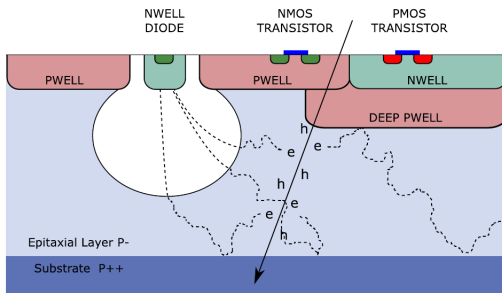
NBW positron production rate vs a_0



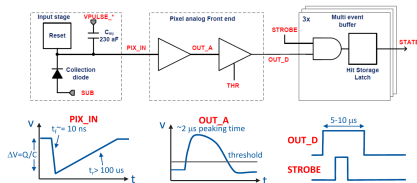
Experiments phase-space in (η, a_0)

- To date, the only experimental measurement of the NBW pair-production – E144
- Was conducted in the $a_0 \lesssim 0.35$ region where the behaviour is perturbative (46.6 GeV electron beam, $5 \times 10^{17} \text{ W cm}^{-2}$ laser pulse)
- Many experiments (E320, LUXE, ELI-NP, APOLLON, CoReLS, etc.) target the non-perturbative NBW pair-production

Backup: ALPIDE chip



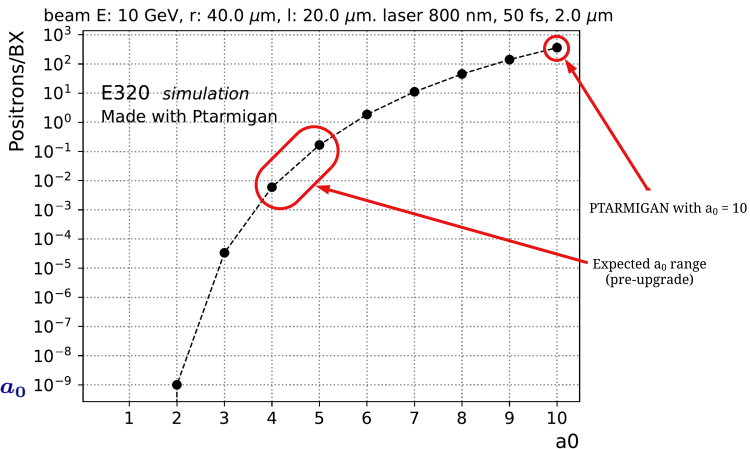
ALPIDE side view



ALPIDE pixel cell

- 50 μm thickness
- 5 μm resolution
- 2 μs rise time, 10 μs pulse duration time
- 99% detection efficiency
- MAPS – diode and the circuitry are integrated
- Collection primarily by diffusion (drift component if bias is applied)
- Bias can be applied to substrate to increase the depletion zone
- Deep p-well protects the n-well for electronics

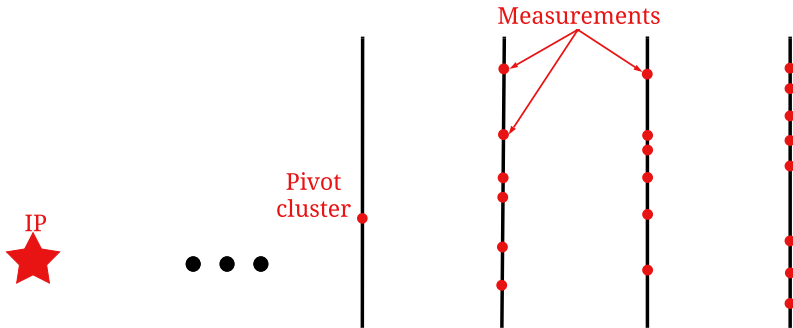
Backup: Event generation strategy



NBW positron
multiplicity vs a_0

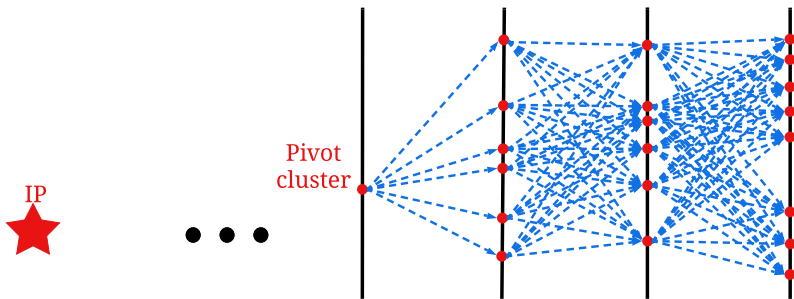
- Generate BXs at $a_0 = 10$ – increased signal statistic, more conservative background estimates
- Split digitization: NBW positrons, NCS background, beam background – for fast simulation
- For tracking – one positron per BX + full background per BX, then scale

Backup: Track reconstruction pipeline



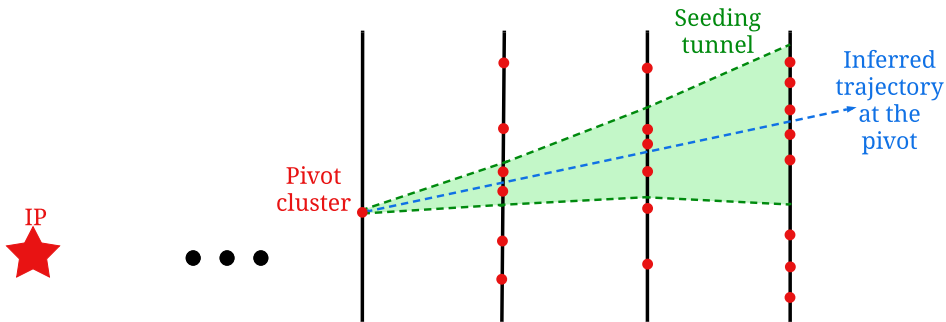
- Detector is not in the magnetic field – straight line fit in the detector

Backup: Track reconstruction pipeline



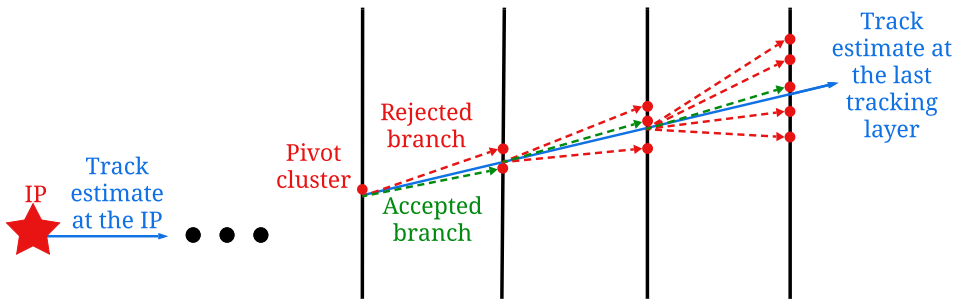
- Detector is not in the magnetic field – straight line fit in the detector
- Need to select the measurements – combinatorics

Backup: Track reconstruction pipeline



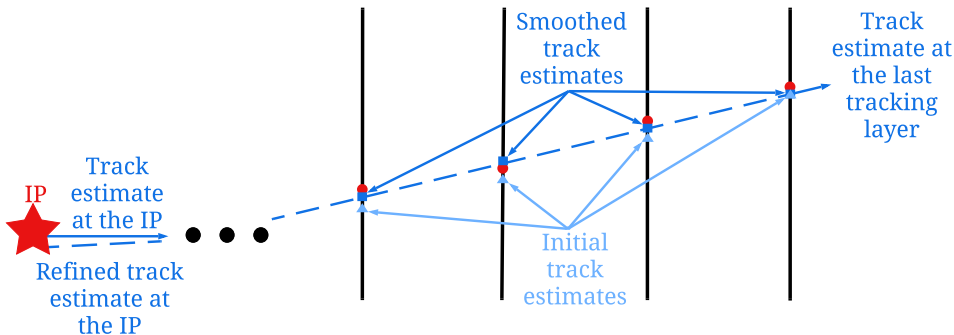
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- Need to select the measurements – combinatorics
- First step – rough measurements filtering and estimation of positrons' IP parameters

Backup: Track reconstruction pipeline



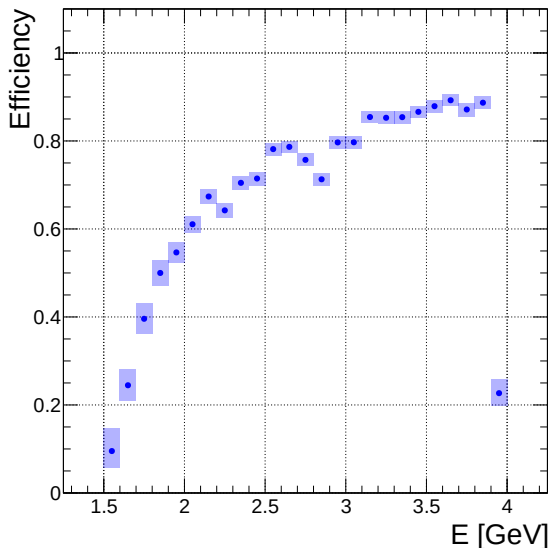
- Detector is not in the magnetic field – straight line fit in the detector
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- First step – rough measurements filtering and estimation of positrons' IP parameters
- Second step – fine-filtering based on the IP estimation

Backup: Track reconstruction pipeline



- Detector is not in the magnetic field – straight line fit in the detector
- Need to select the measurements – combinatorics
- First step – rough measurements filtering and estimation of positrons' IP parameters
- Second step – fine-filtering based on the IP estimation
- Last step – Kalman Filter fit with forward-backward propagation

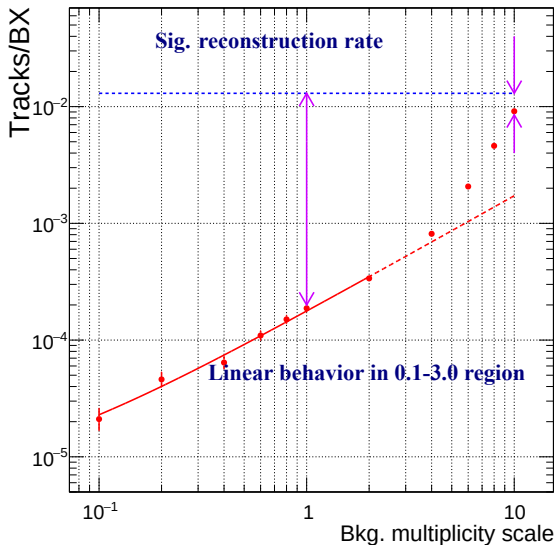
Backup: Reconstruction efficiency



Track reconstruction efficiency

- Signal reconstruction efficiency with respect to the acceptance (signal positron passes through all four layers) is $\sim 70\%$
- The biggest efficiency losses are due to the setup geometry
- E.g, ~ 2.7 GeV drop – gaps between the chips,
 > 3.9 GeV drop – bottom end of the lowest chip

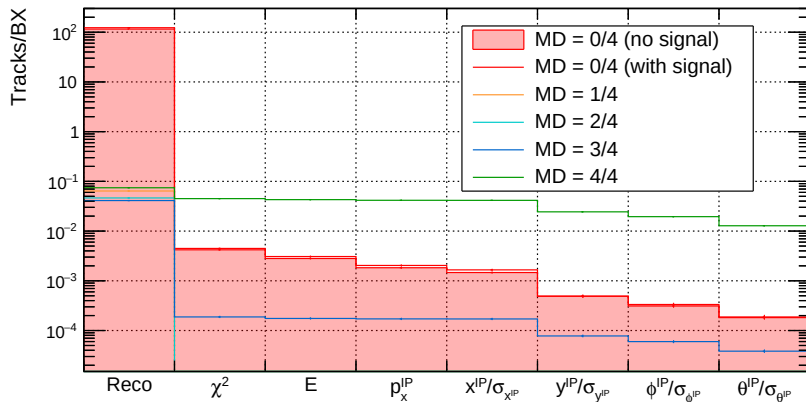
Backup: Background scaling study



- To test rejection capabilities background multiplicity was scaled from 0.1 to 10 nominal
- Signal reconstruction rate is ~ 1.5 times higher than the background rate at $\times 10$ nominal multiplicity

Bkg. reconstruction rate vs its multiplicity scale

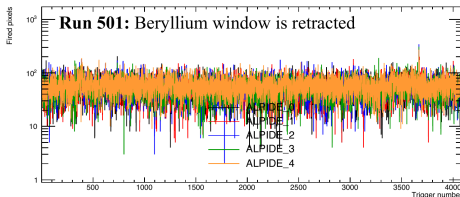
Backup: Selection cutflow



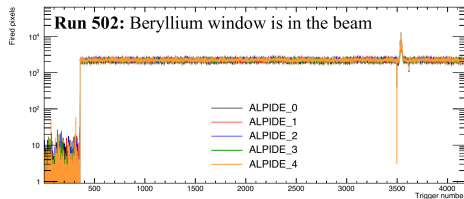
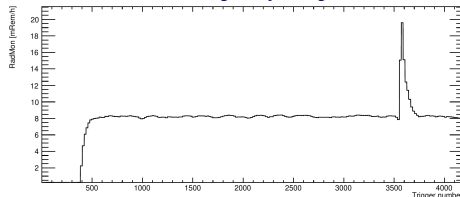
Track reconstruction rate cutflow

- Reconstructed tracks pass a number of cuts (χ^2 , IP kinematics, etc.)
- After the cuts the signal rate (12.8×10^{-3} Tracks/BX) exceeds the background rate (1.82×10^{-4} Tracks/BX) by an order of magnitude

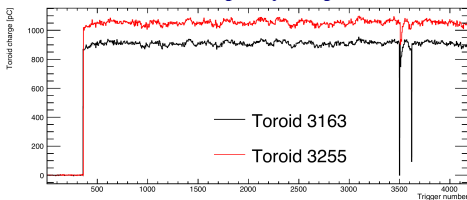
Backup: Accelerator synchronization



Detector occupancy, no positrons



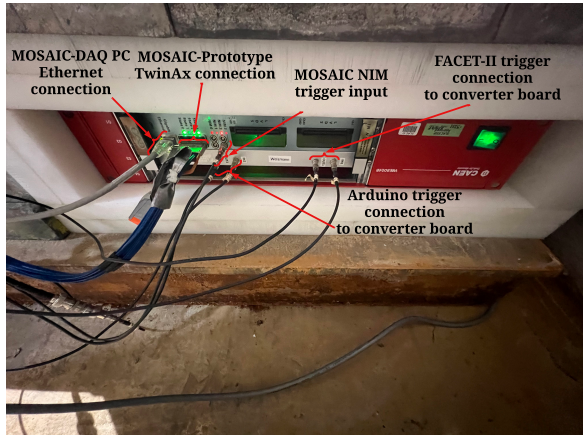
Detector occupancy, Be positrons



FACET-II radiation and charge monitors

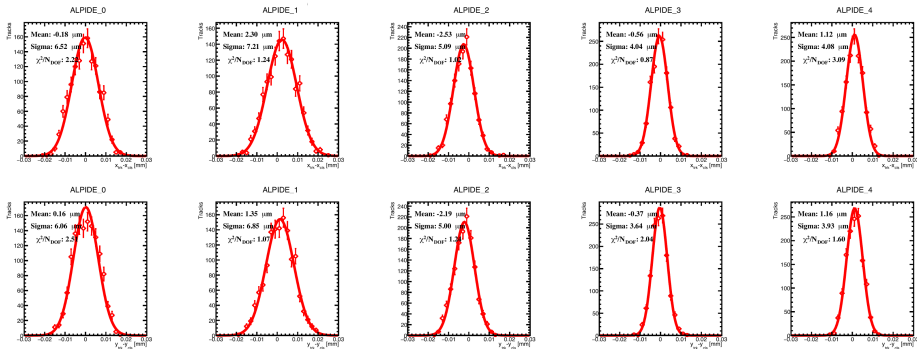
- Dump background occupancy measurements agree with the simulation
- Bremsstrahlung occupancy is to be cross-referenced
- Detector data is synchronized with the accelerator state – useful for noise/physics detection

Backup: Tracker commissioning and upgrade at SLAC



- The prototype is connected to the MOSAIC board (control, data transfer)
- MOSAIC talks to the DAQ PC, where the dedicated DAQ SW is running
- The board supplies trigger, synchronized with the accelerator beam

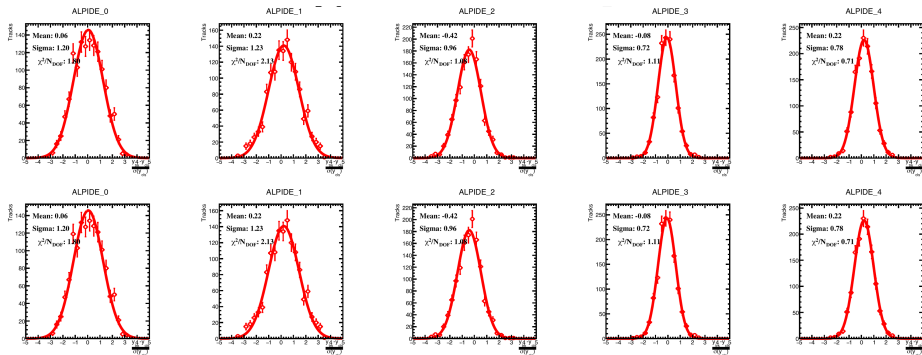
Backup: Prototype alignment (1/2)



Residuals post-alignment

- $|\mu| \lesssim 2.5 \mu\text{m}$, $\sigma \sim 4\text{--}7 \mu\text{m}$
- In agreement with ALPDE specifications

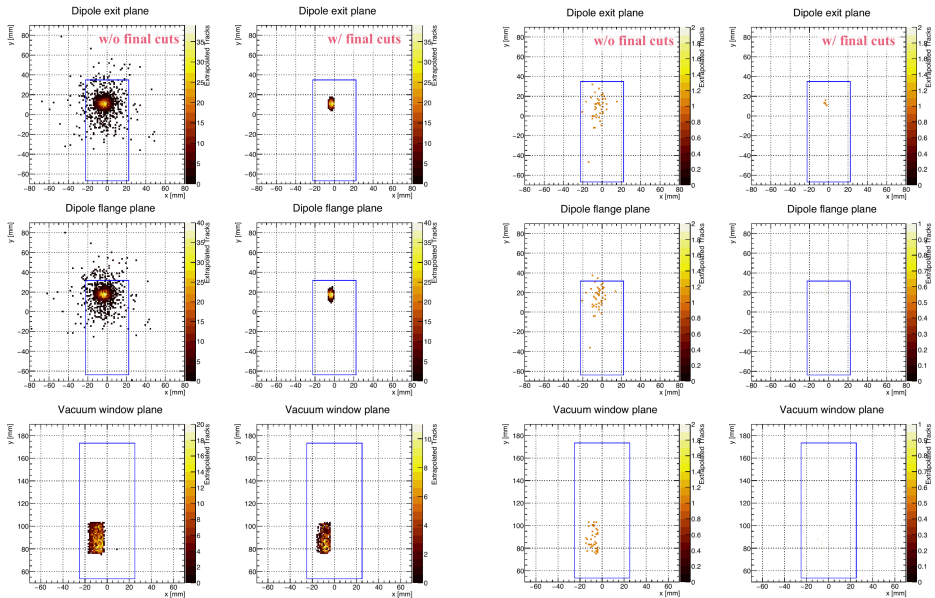
Backup: Prototype alignment (2/2)



Pulls post-alignment

- $|\mu| \lesssim 0.4, \sigma \sim 0.4\text{--}1.2$
- The pulls indicate agreement of the model with the truth

Backup: February runs spatial selection

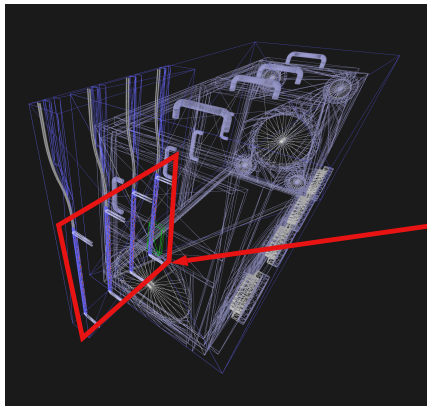


Cut application, Be window

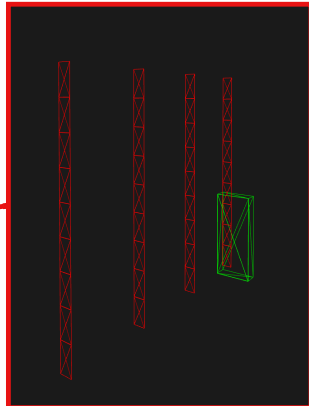
Cut application, beam-only

Backup: ACTS geometry modeling

Geant4 implementation of the tracker



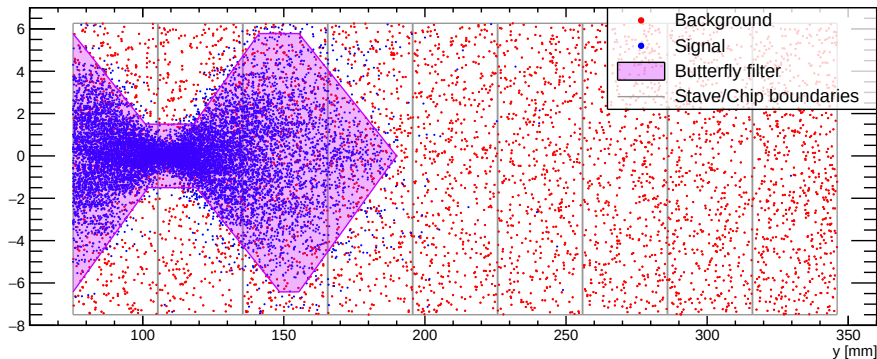
Volumes converted in Acts



- Geant4 volumes are converted to Acts Surfaces
- Only important volumes are converted: sensitive volumes, dense material bulks

- For E320: ALPIDE silicon layers and vacuum exit window
- Effective material description with dedicated algorithm

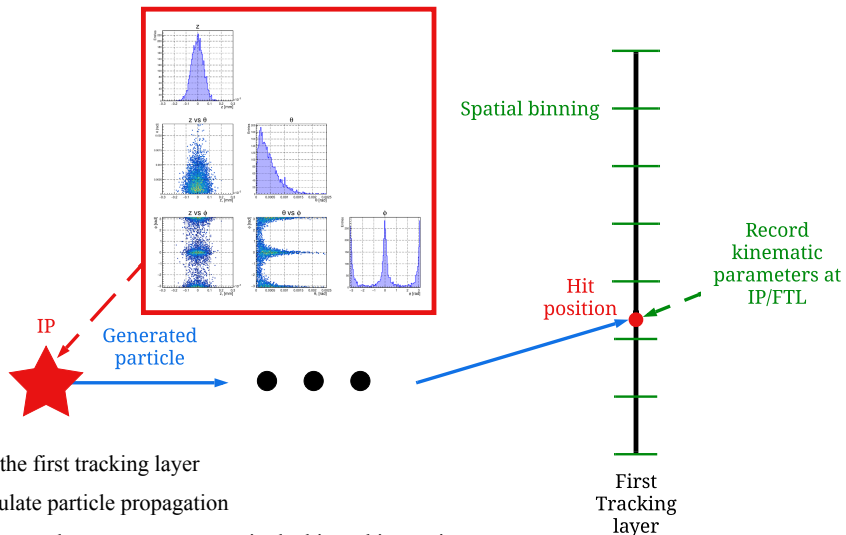
Backup: Measurement treatment



Butterfly filter

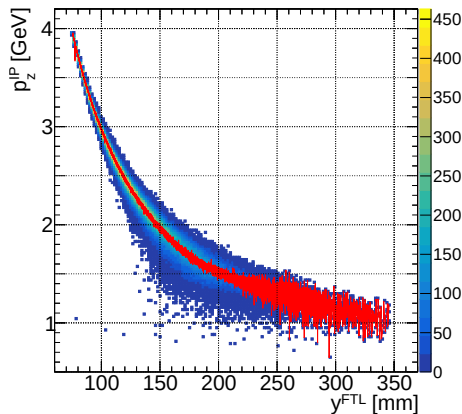
- Due to quads the signal hits have a “butterfly” shape in the x - y plane
- Each pixel – measurement with uniform hypothesis
- $(78.1089 \pm 0.0004)\%$ background rejection,
 $(96.2221 \pm 0.0018)\%$ signal efficiency
- Estimate: $(x_{\text{center}}, y_{\text{center}}) \pm l_{x(y)}/\sqrt{12N}$

Backup: Kinematics guess estimation

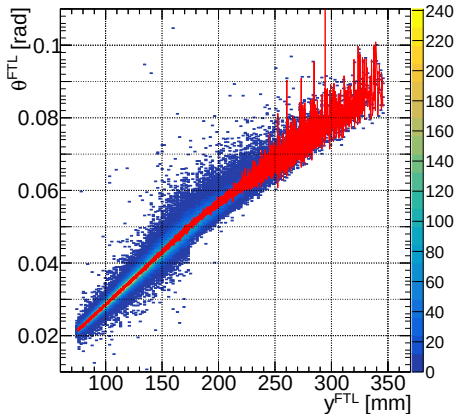


- Bin the first tracking layer
- Simulate particle propagation
- Repeat and average parameters in the bins – kinematics map
- Ptarmigan truth information is used for particles' IP parameters

Backup: Kinematics guess estimation performance



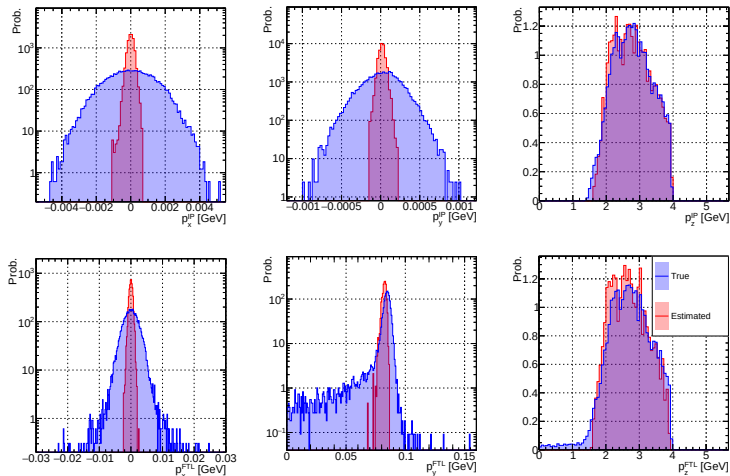
IP z -momentum vs y at FTL



FTL θ -angle vs y at FTL

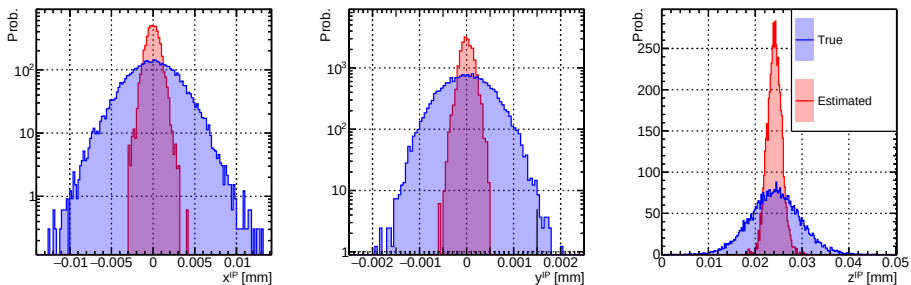
- Quad effects and scattering from the vacuum exit are visible
- Red line – mean used in the algorithms

Backup: Kinematics guess performance



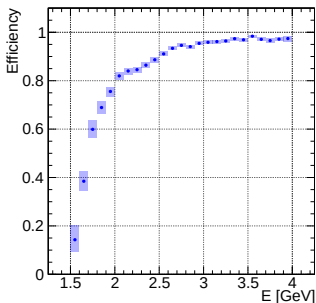
- The IP/FTL z component agreement is good
- Transverse – good agreement with the mean
- Good enough for an initial guess

Backup: Vertex guess performance

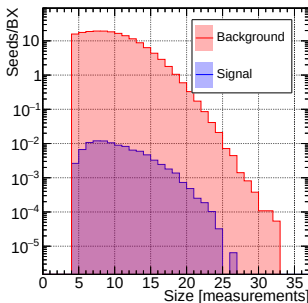


- Good agreement with the mean
- Good enough for an initial guess

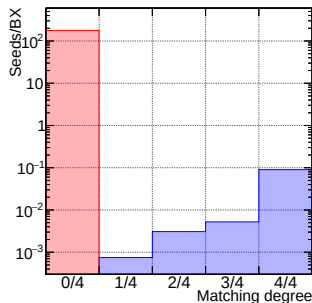
Backup: Seeding performance



Seeding efficiency



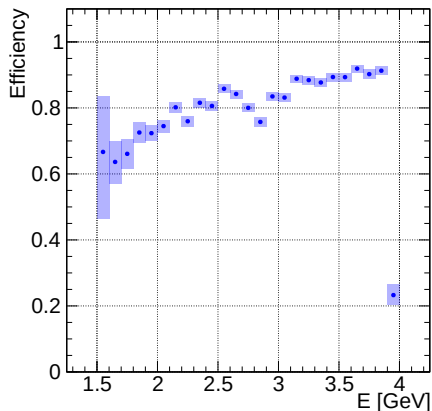
Seed size distribution



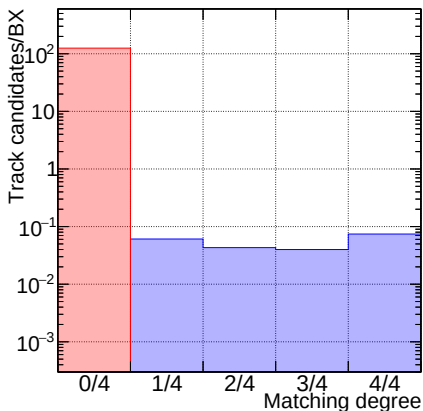
Matching degree distribution

- Efficiency – fraction of fully captured particles
- Size – number of clusters in a seed
- MD – fraction of the captured particle's measurements
- Cuts – $\sim 300\mu\text{m}$ bounds, only seeds with size ≥ 4

Backup: Track finding performance



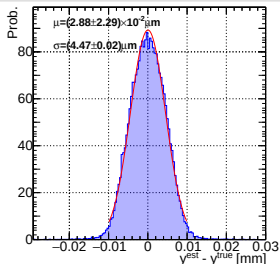
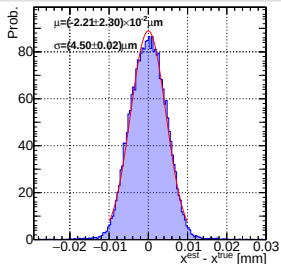
Track finding efficiency



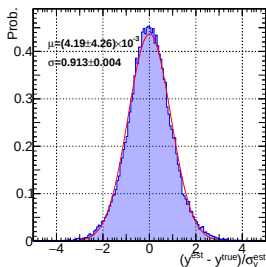
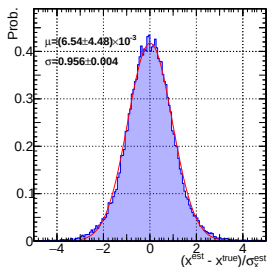
Matching degree distribution

- Efficiency – fraction of fully captured MD 4/4 candidates out of 4/4 MD seeds (cap on the propagation steps of 1000)
- MD – fraction of the signal measurements in a candidate

Backup: Track fitting performance (1/2)

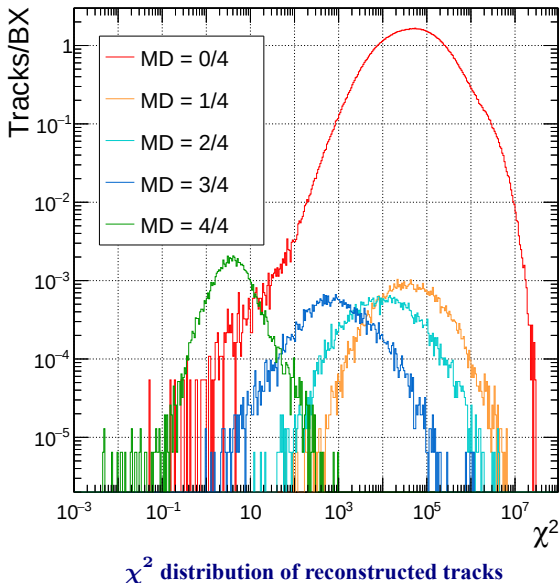


- Residuals are in agreement with the expected ALPIDE resolution of $\sim 5 \mu\text{m}$
- Pulls conform to a Normal distribution
- Slight pulls concentration around zero is attributed to minor mismatches in the material modeling



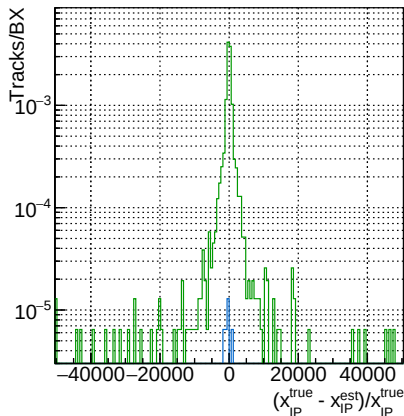
Residuals and pulls of MD 4/4 tracks

Backup: Track fitting performance (2/2)

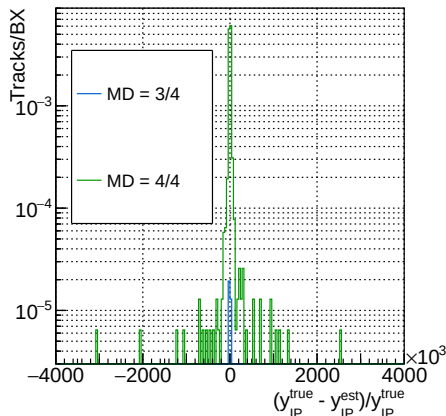


- Matching degree – number of signal clusters is a track
- MD < 4/4 – big χ^2
- Still some tracks are in $\chi^2 < 10$. These are the hardest to reject

Backup: Vertex reconstruction



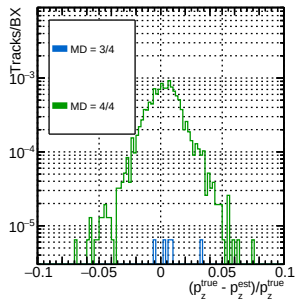
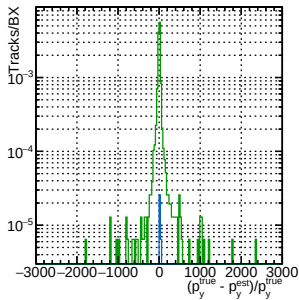
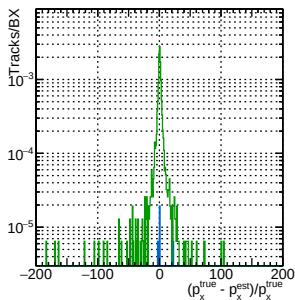
Vertex x response



Vertex y response

- Relative errors are high – 16m of error accumulation, initial guess
- Need a dedicated algorithm

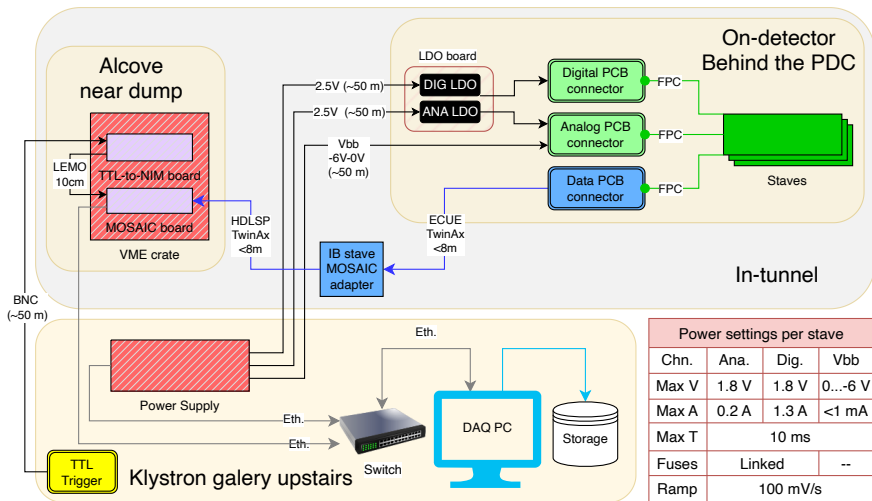
Backup: Momentum reconstruction



Positron IP momentum response

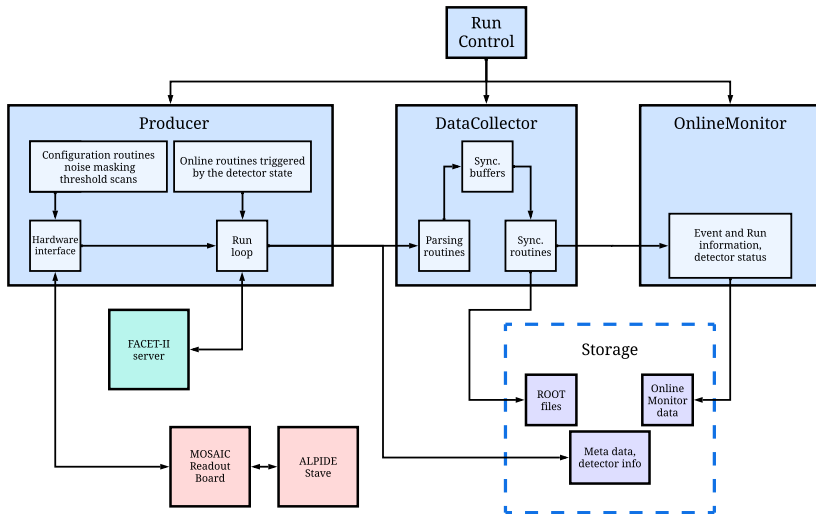
- Relative errors are high for x, y – 16m of error accumulation, initial guess
- Dominant momentum – good agreement

Backup: Prototype setup



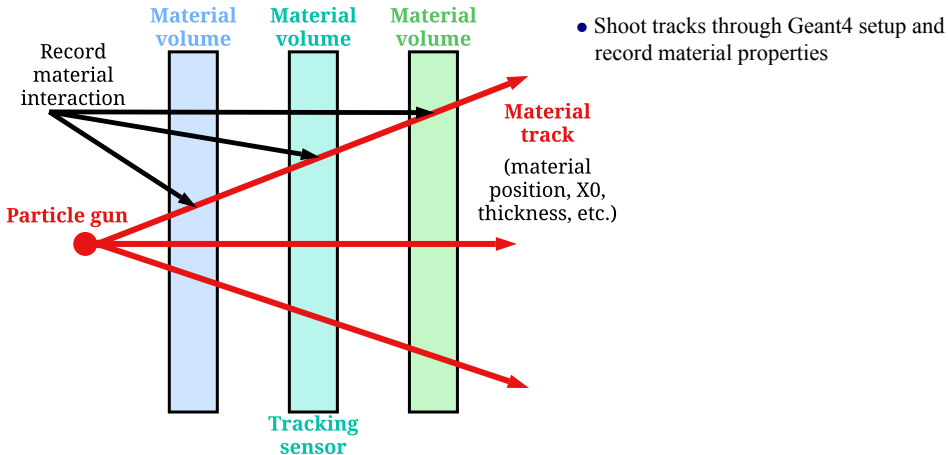
Schematic of the experimental setup in E320

Backup: EUDAQ2 DAQ software

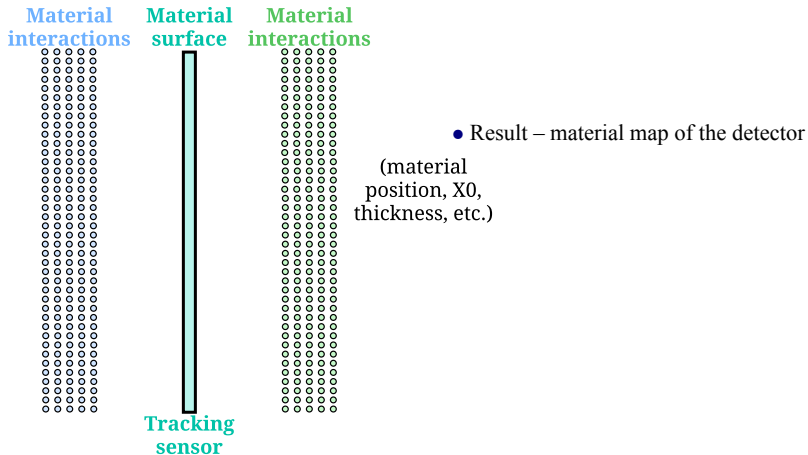


Flow of control and data within EUDAQ2 DAQ

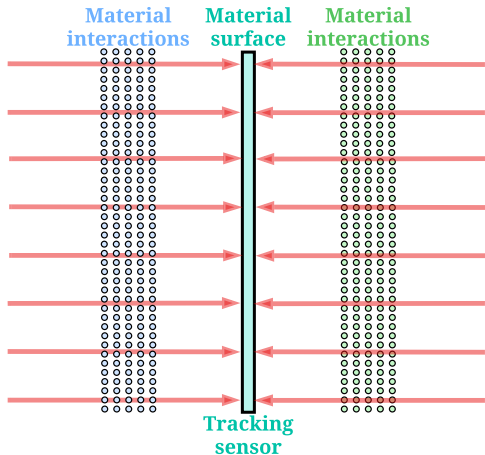
Backup: ACTS material description



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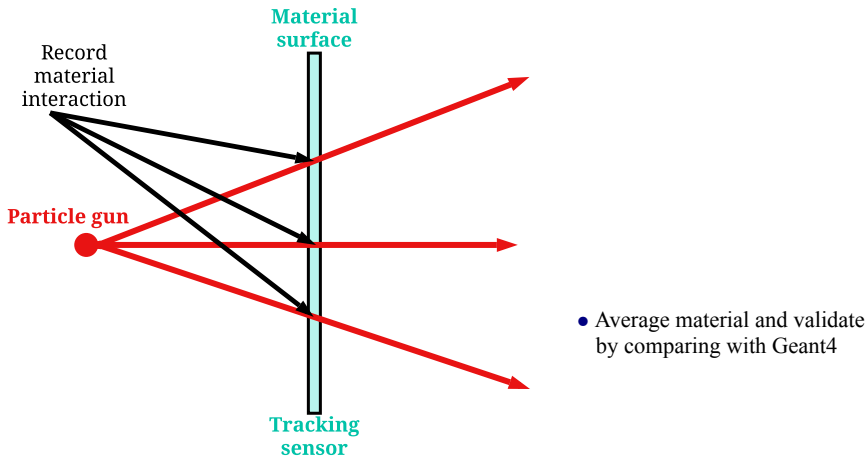


Backup: ACTS material description

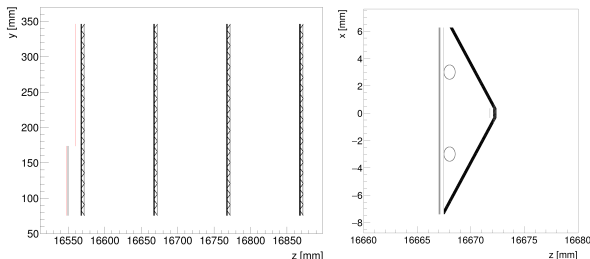


- Project material points onto the sensitive surfaces (may be binned)

Backup: ACTS material description

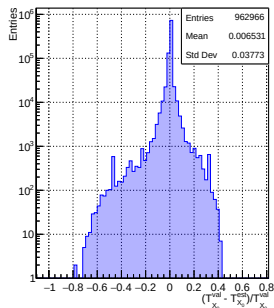
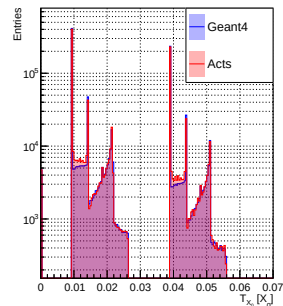


Backup: Material mapping performance



Detector material map

- 1e6 material tracks for sampling and validation
- Separate generator for PDC window area
- Good agreement between the Geant4 and Acts material



Detector material comparison