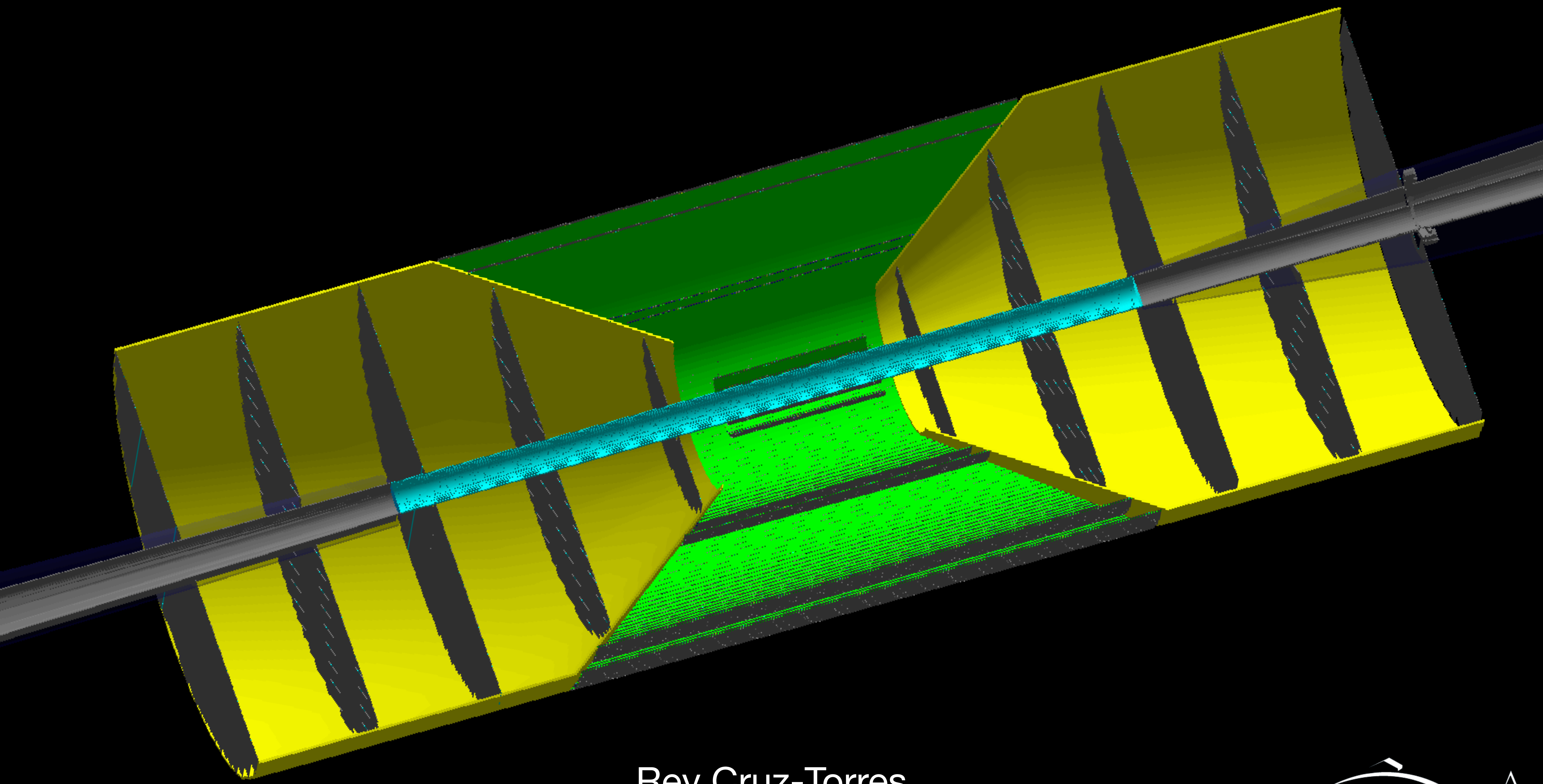
Using simulations as a tool for detector design



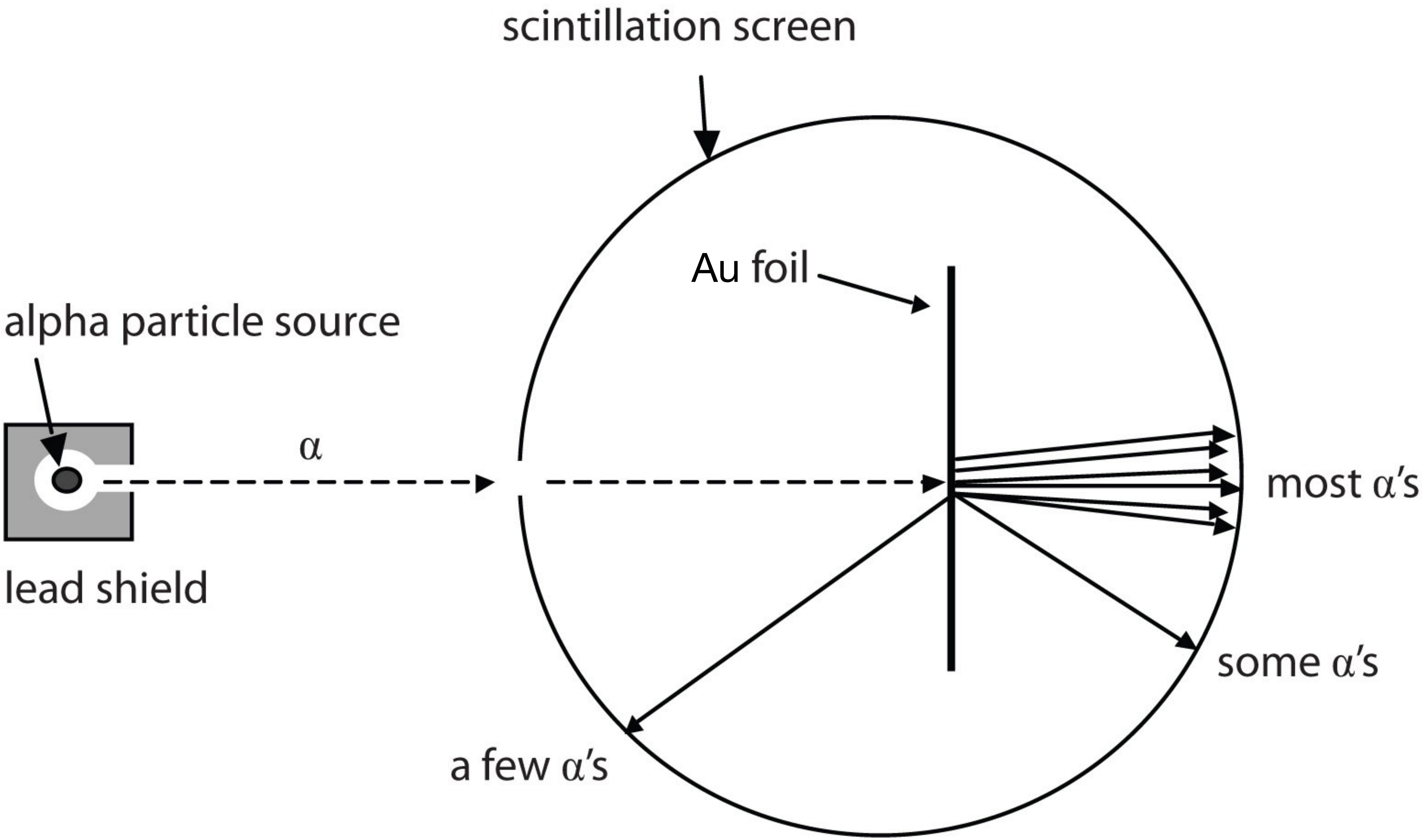
Rey Cruz-Torres

Physics 290e Seminar

02/10/2021

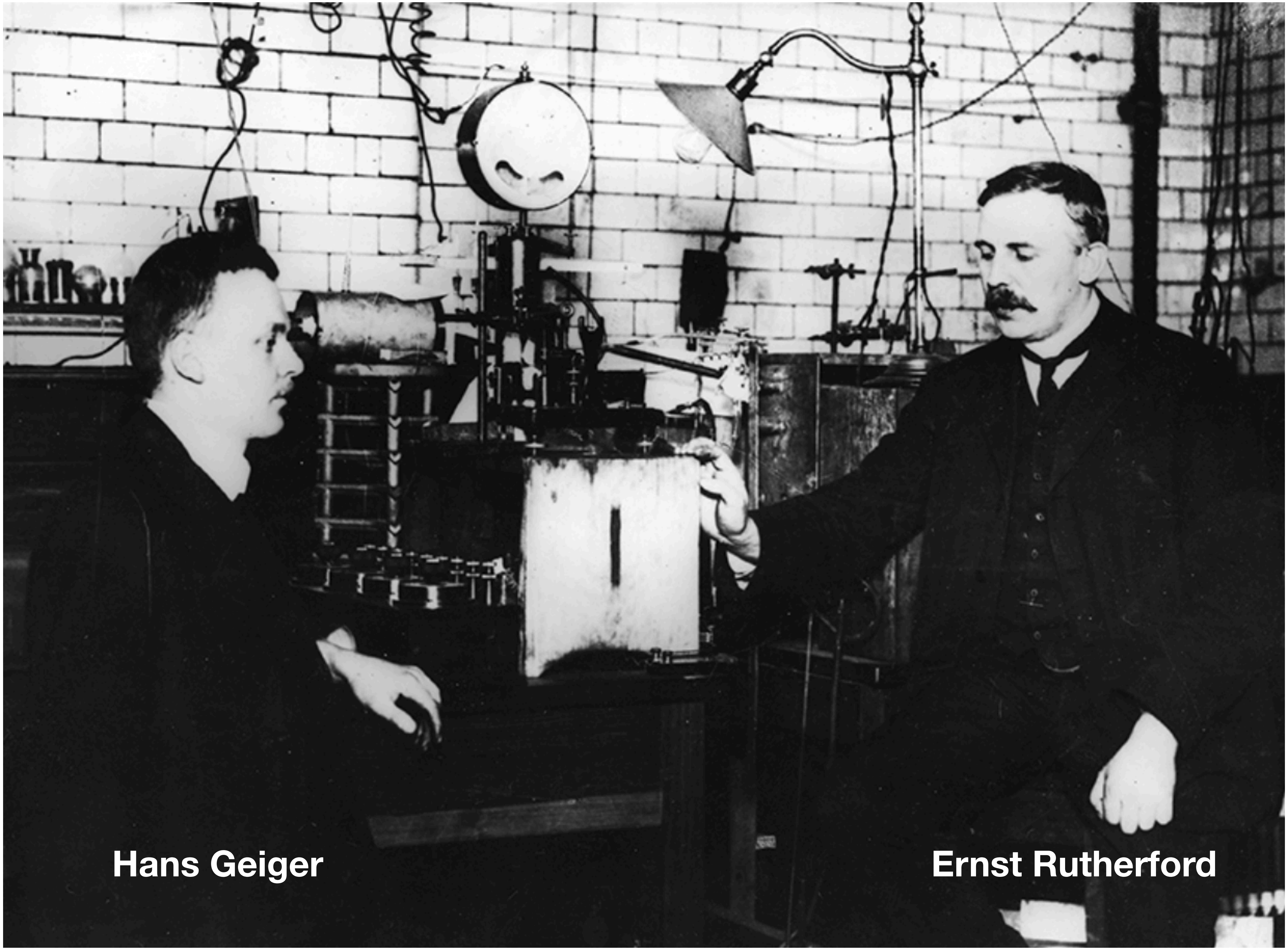
BERKELEY LAB

The Rutherford-Geiger-Marsden Experiment



1911 - Discovery of the atomic nucleus

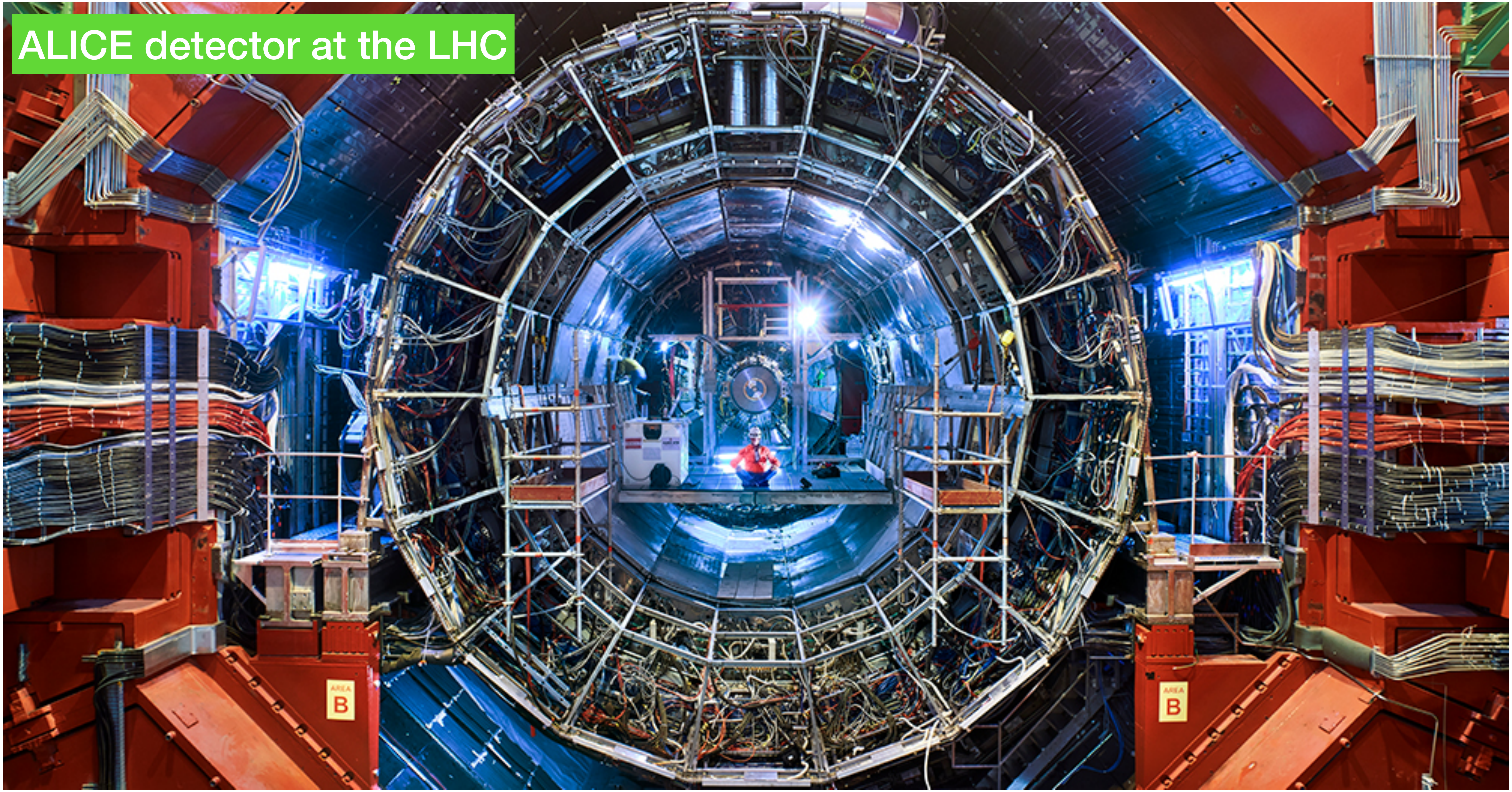
The Rutherford-Geiger-Marsden Experiment



Their experimental setup can be recreated in a school lab

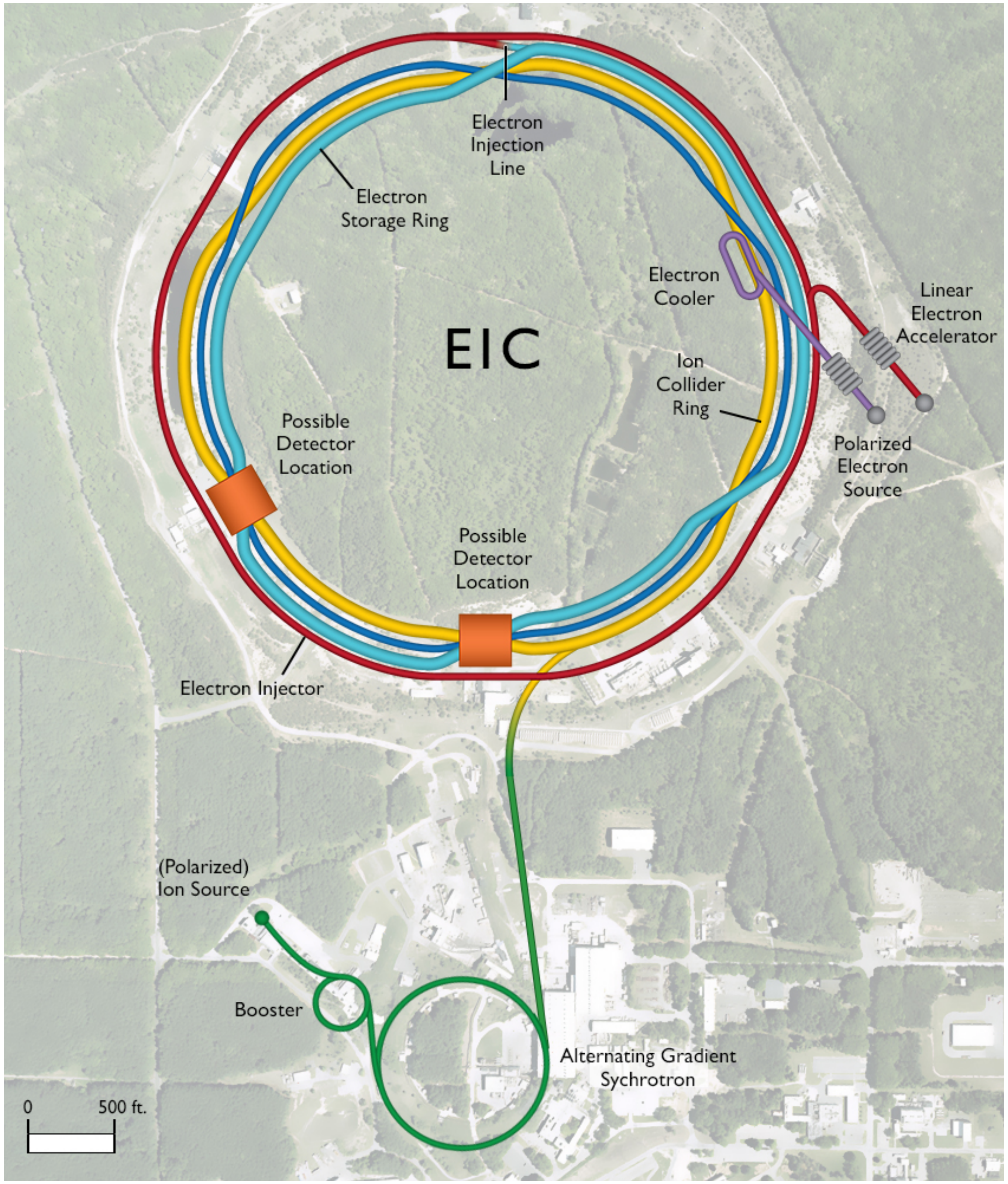
Modern Detectors

Detectors used in modern nuclear / particle physics have become very complex (and expensive)



You may want to get it right before starting construction

Electron Ion Collider (EIC)



Study of QCD through precision measurements of collisions of electrons with (un)polarized protons, light ions, and heavy ions.

Wide range of physics topics, including:

* spin structure of protons and light nuclei
* partonic structure of light and heavy ions
* parton energy loss in nuclear matter

To fulfill the challenging EIC program, cutting-edge detectors will be needed.

Outline

Requirements for an EIC tracker

Using simulations to design a tracker

Testing tracker performance (resolutions)

Improving performance when needed

Physics studies with the tracker

Summary and Conclusions

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Tracking Requirements for the EIC

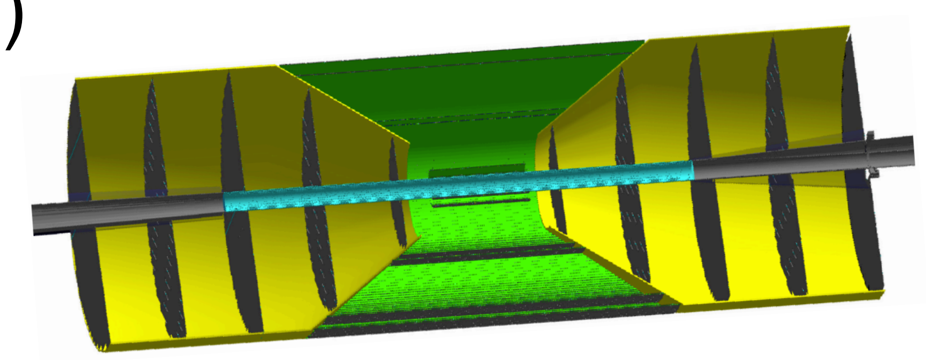
(Preliminary) requirements outlined in the EIC detector handbook:

- Hermetic -> allows full kinematical coverage
- Compact -> allows for smaller magnets and additional detectors
- Low-material-budget -> minimizes multiple scattering (significant for soft particles)
- Excellent primary vertex resolution -> precision measurement of displaced vertex in HF
- Excellent momentum resolution -> allows for studies with unprecedented precision
- Excellent angular resolution -> allows tracker to assist PID detectors

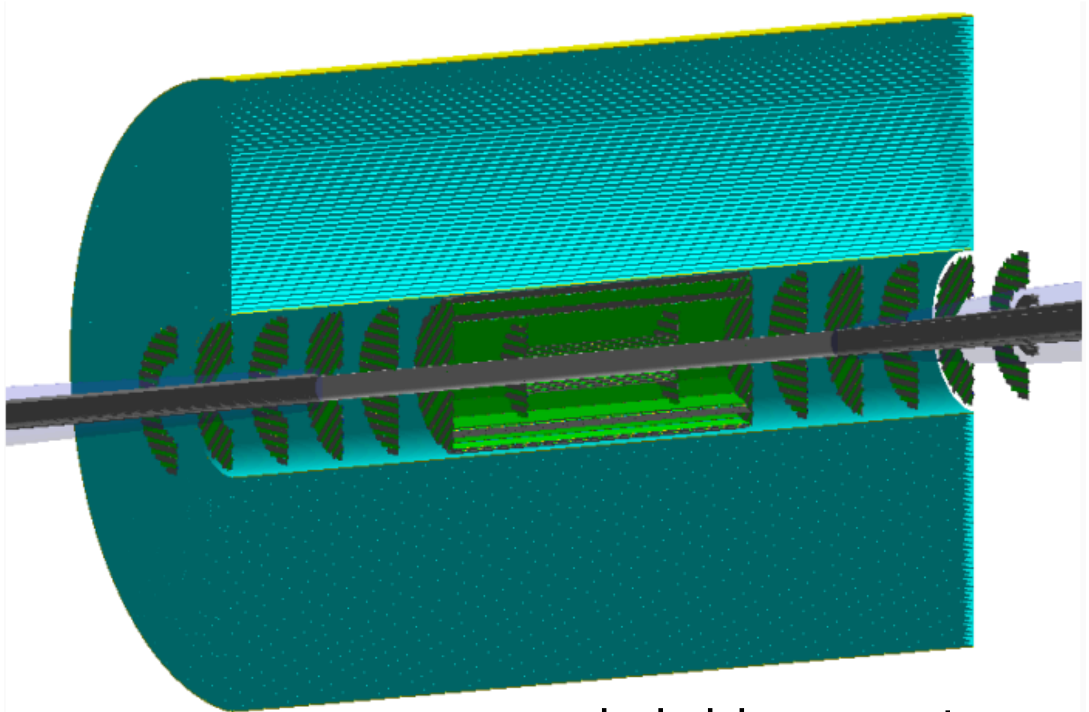
Tracking Requirements for the EIC

(Preliminary) requirements outlined in the EIC detector handbook:

- Hermetic ($2 < \theta < 178^{\circ}, 0 \leq \phi < 2\pi$ coverage)
- Compact (r ~ 88 cm, l ~ 300 cm)
- Low-material-budget ($X/X_0 < 5\%$)
- Excellent primary vertex resolution (< 20 μm)
- Excellent momentum resolution
- Excellent angular resolution (~1 mrad)



All-silicon concept



hybrid concept

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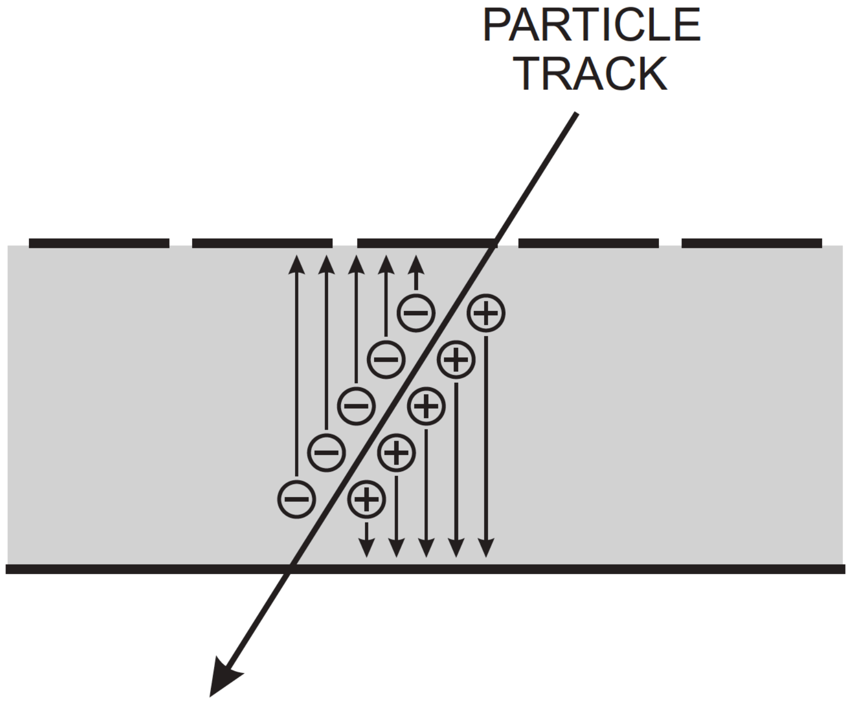
Semiconductor Detectors

- medium in nuclear / high-energy physics trackers usually Silicon
- passage of ionizing radiation → electron-hole pairs (analogous to ionization)
- pairs then collected by an electric field
- average energy required to create an electron-hole pair 10x smaller than that required for gas ionization



Disadvantages:

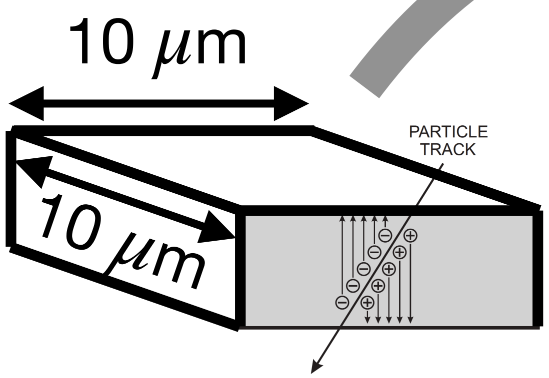
- Expensive
- Need cooling
- Sensitive to radiation damage

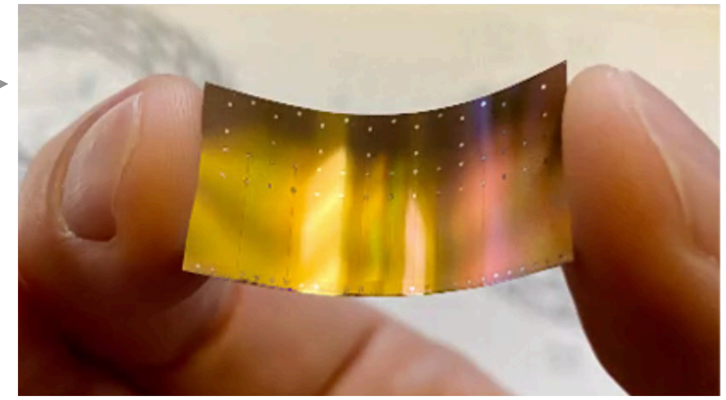
Advantages:

- High granularity, low intrinsic noise → High resolution
- High density → measurable signal in small space → compact detector
- Mechanically rigid → self supporting
- Successfully used in the LHC and many other experiments

From sensor to full detector

pixel

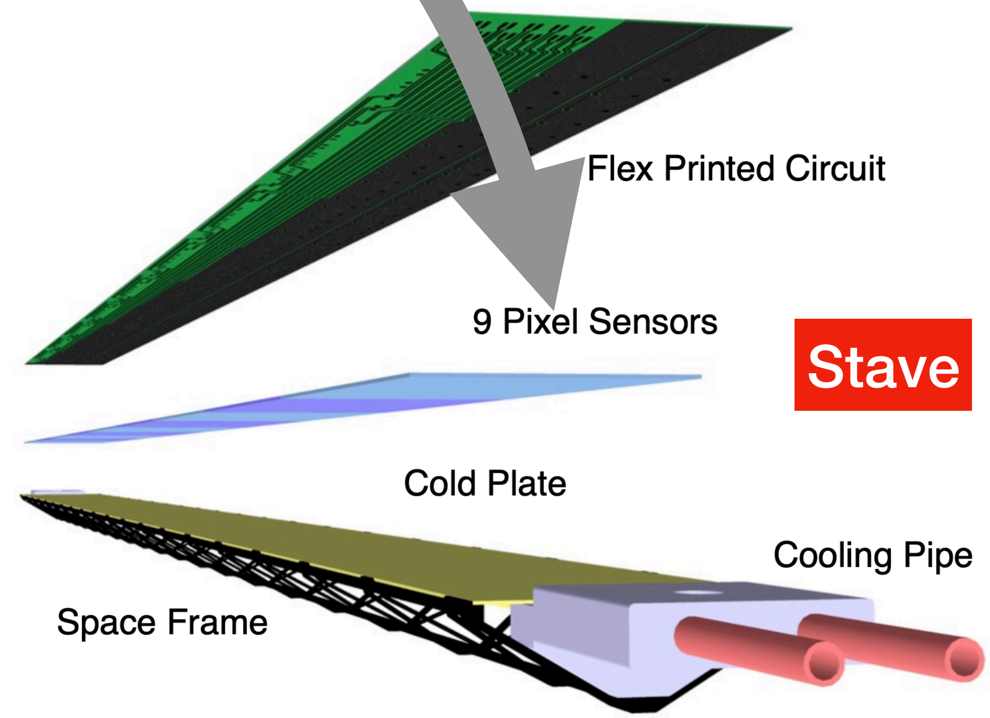


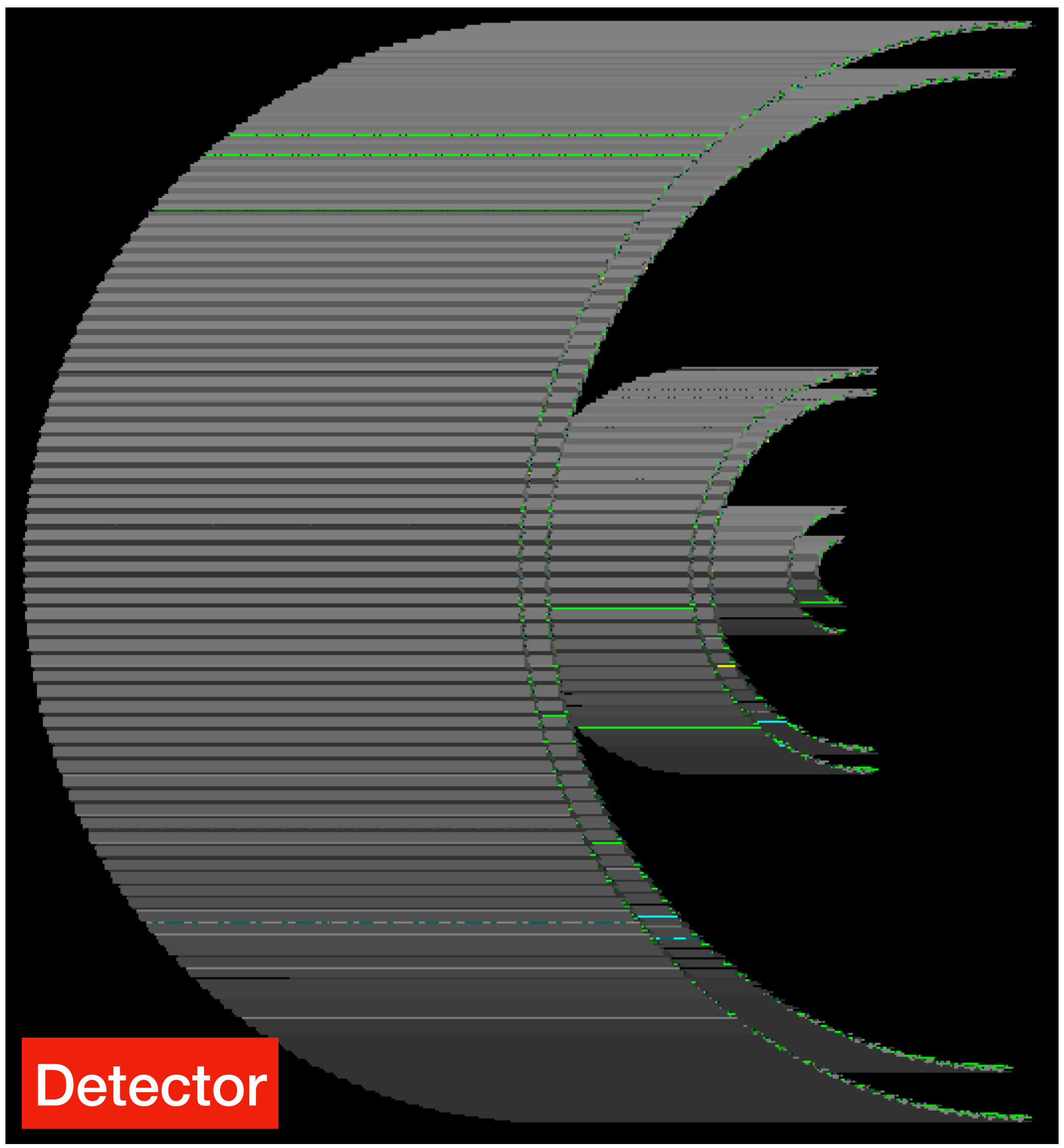


30 mm x 15 mm

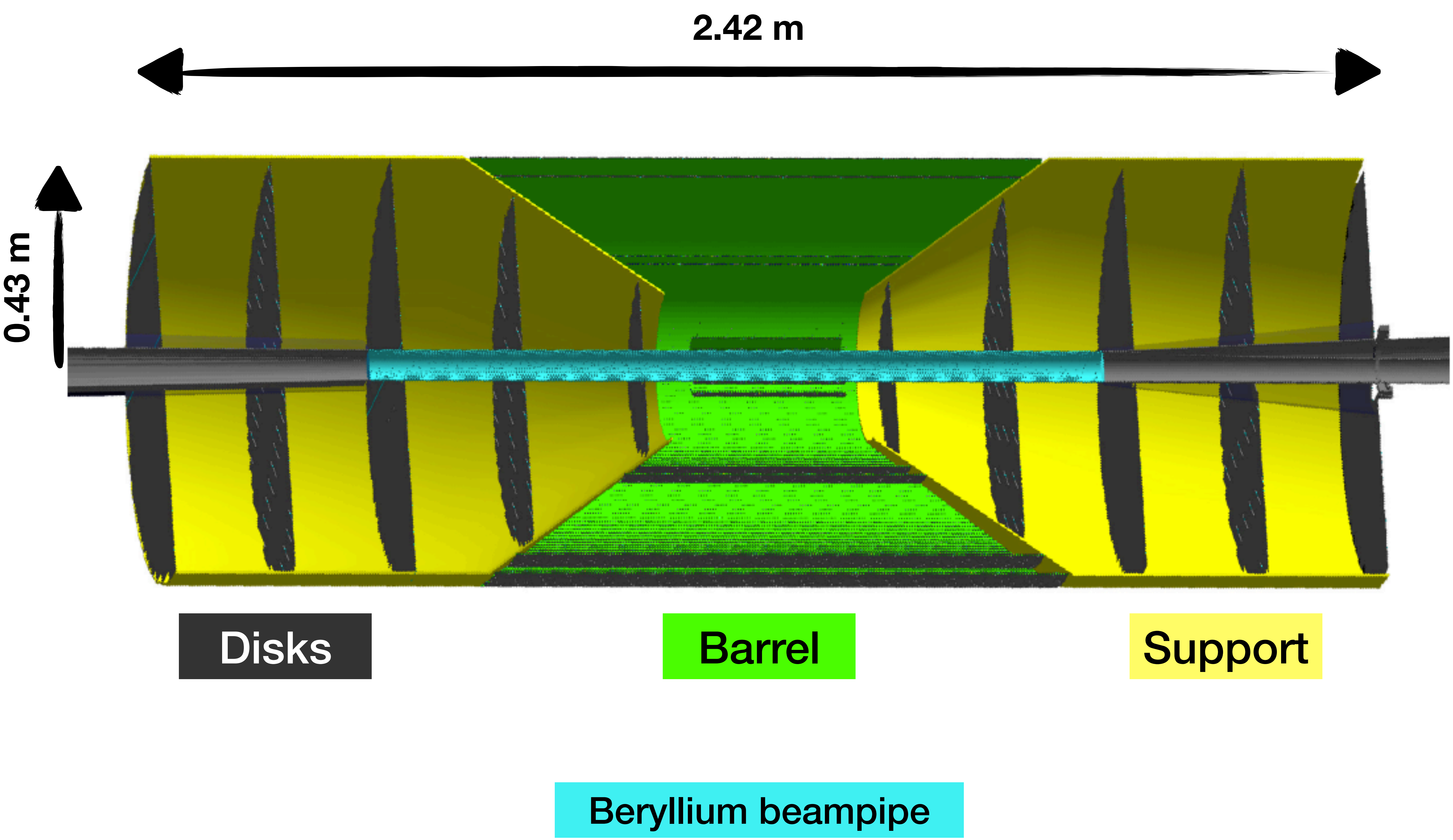
50-μm-thick chip

Stave





EIC All-Silicon Tracker Prototype



Designing barrel layers

Momentum measurement -> measurement of track bending in a B field

Designing barrel layers

3-layer barrel configuration

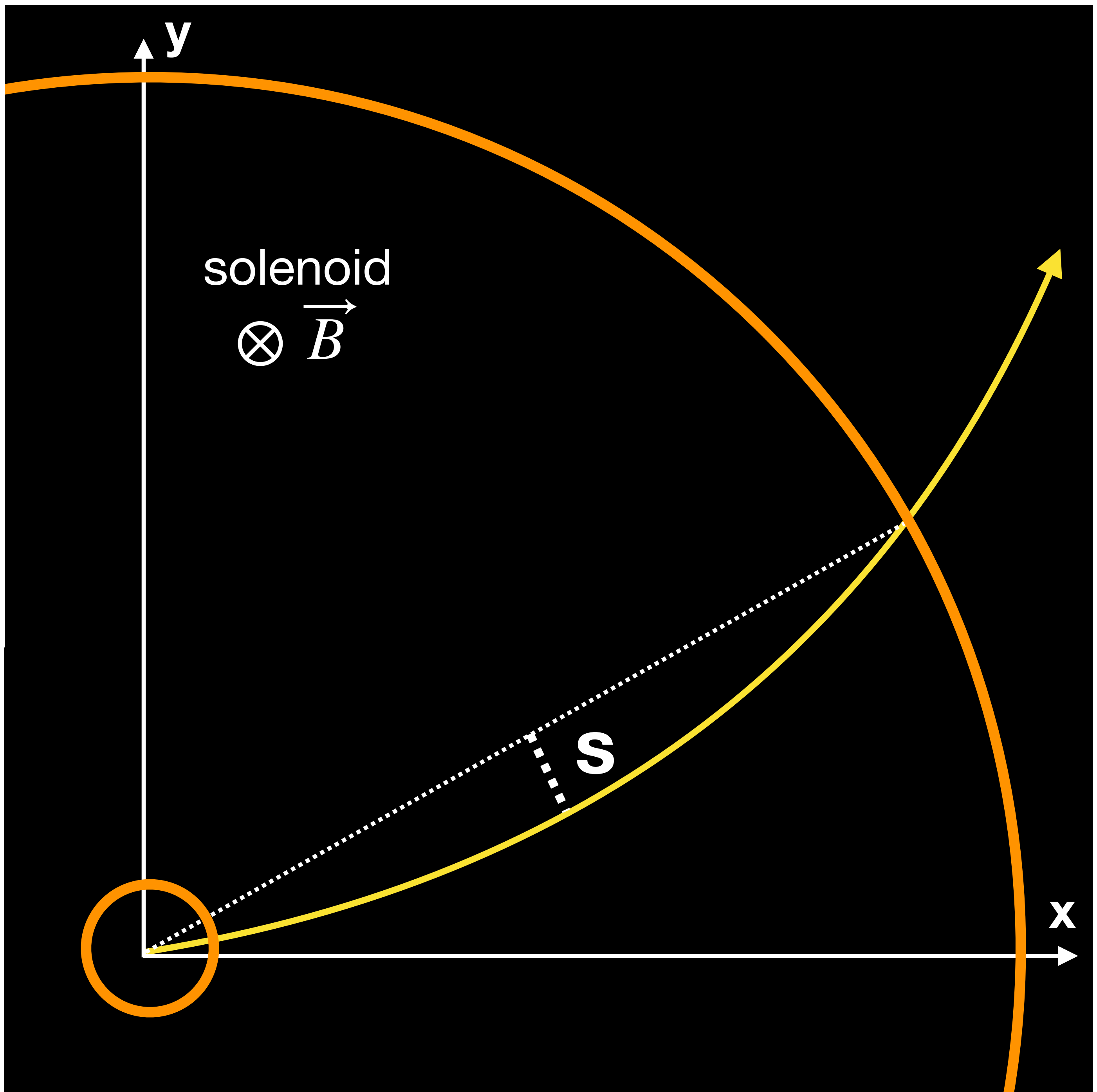
Three-layer barrel configuration for optimal momentum resolution:

- Place inner layer at smaller radius possible, r_{min}*

* limited by beampipe

Designing barrel layers

3-layer barrel configuration



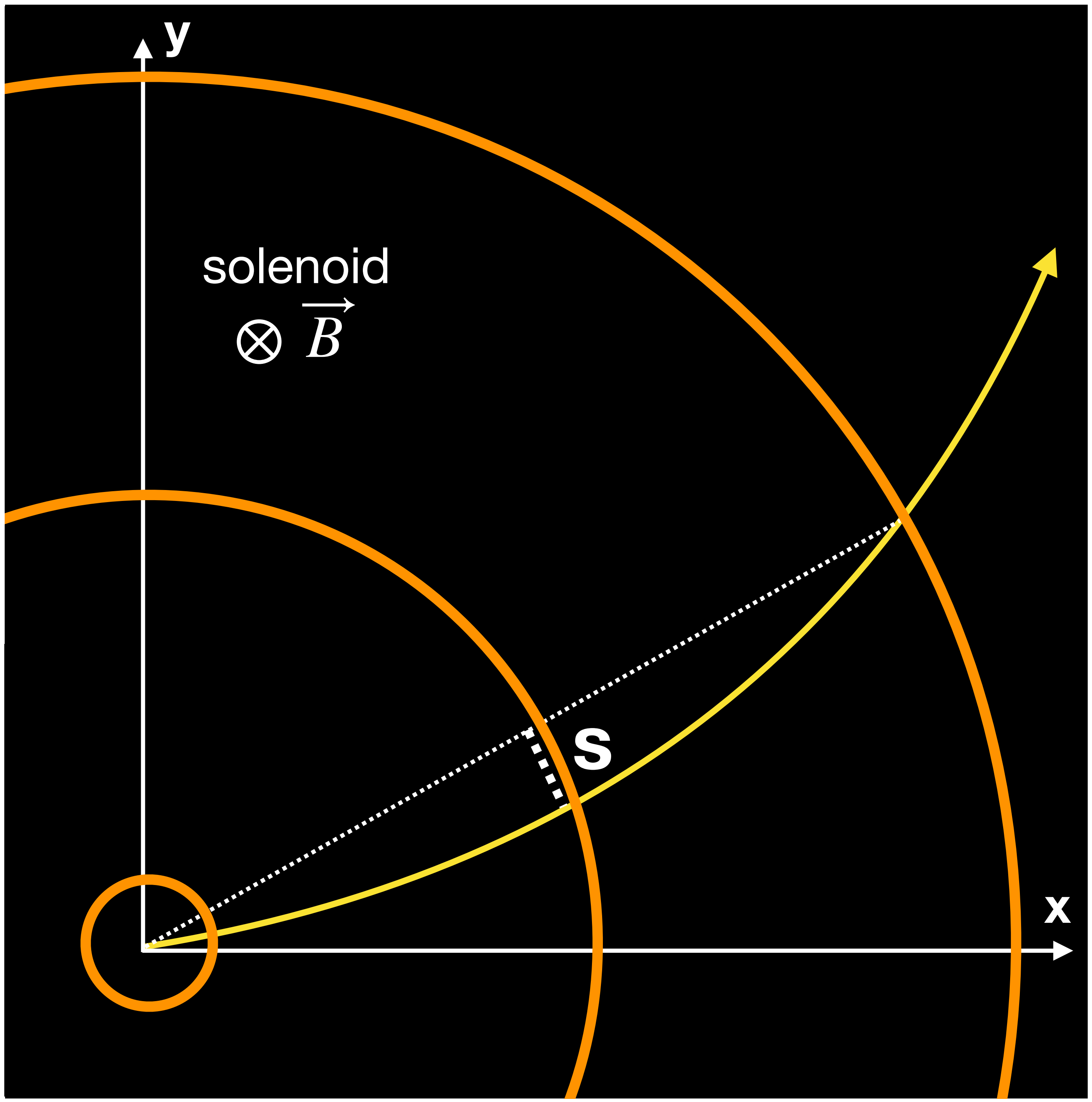
Three-layer barrel configuration for optimal momentum resolution:

- Place inner layer at smaller radius possible, r_{min}*
- Place outer layer at largest radius possible r_{max}**

* limited by beampipe
** limited by available space and low-momentum acceptance

Designing barrel layers

3-layer barrel configuration



Three-layer barrel configuration for optimal momentum resolution:

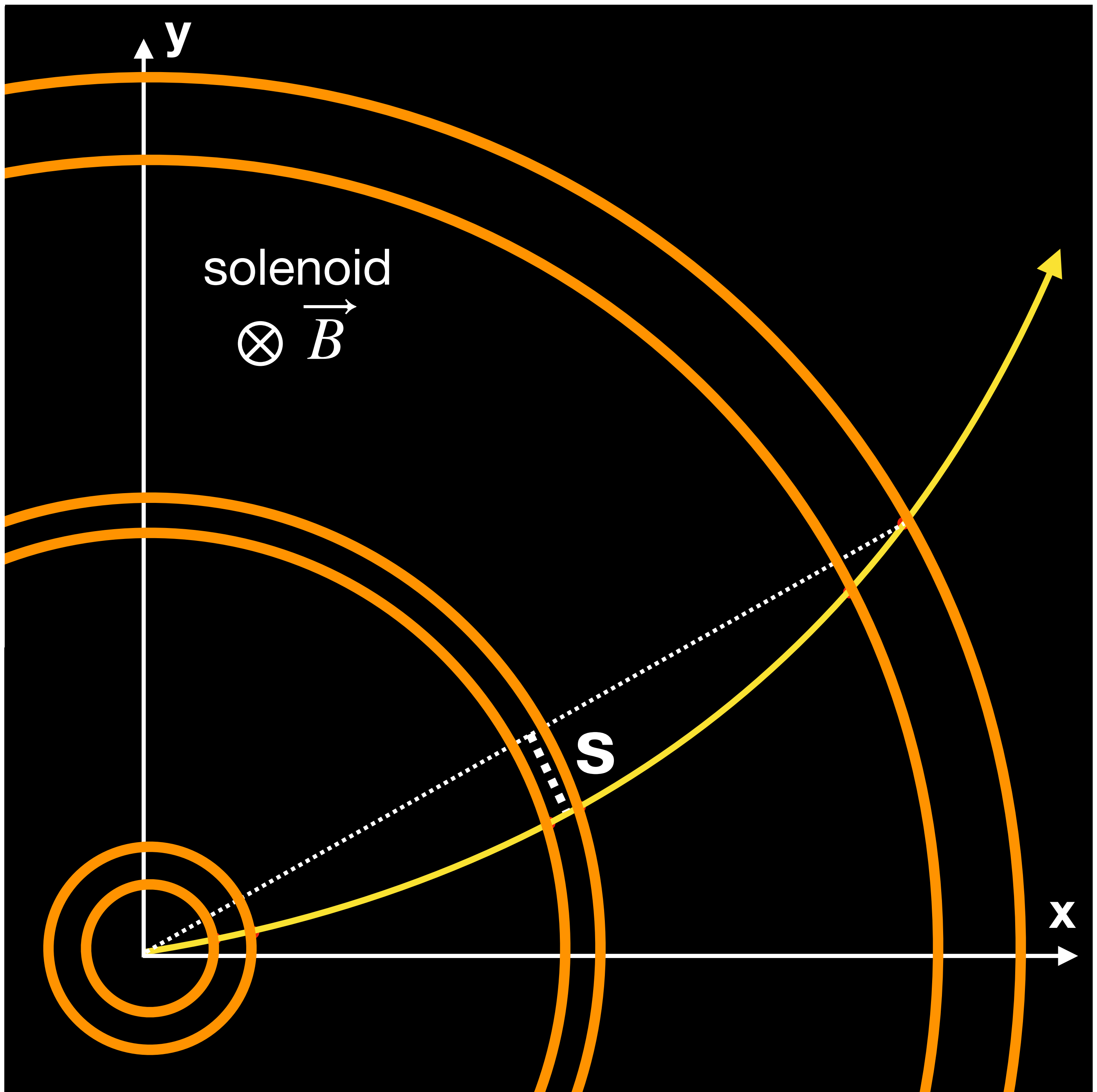
- Place inner layer at smaller radius possible, r_{min}*
- Place outer layer at largest radius possible r_{max}**
- Place middle layer at $(r_{min}+r_{max})/2$

* limited by beampipe

** limited by available space and low-momentum acceptance

Designing barrel layers

3-double-layer barrel configuration



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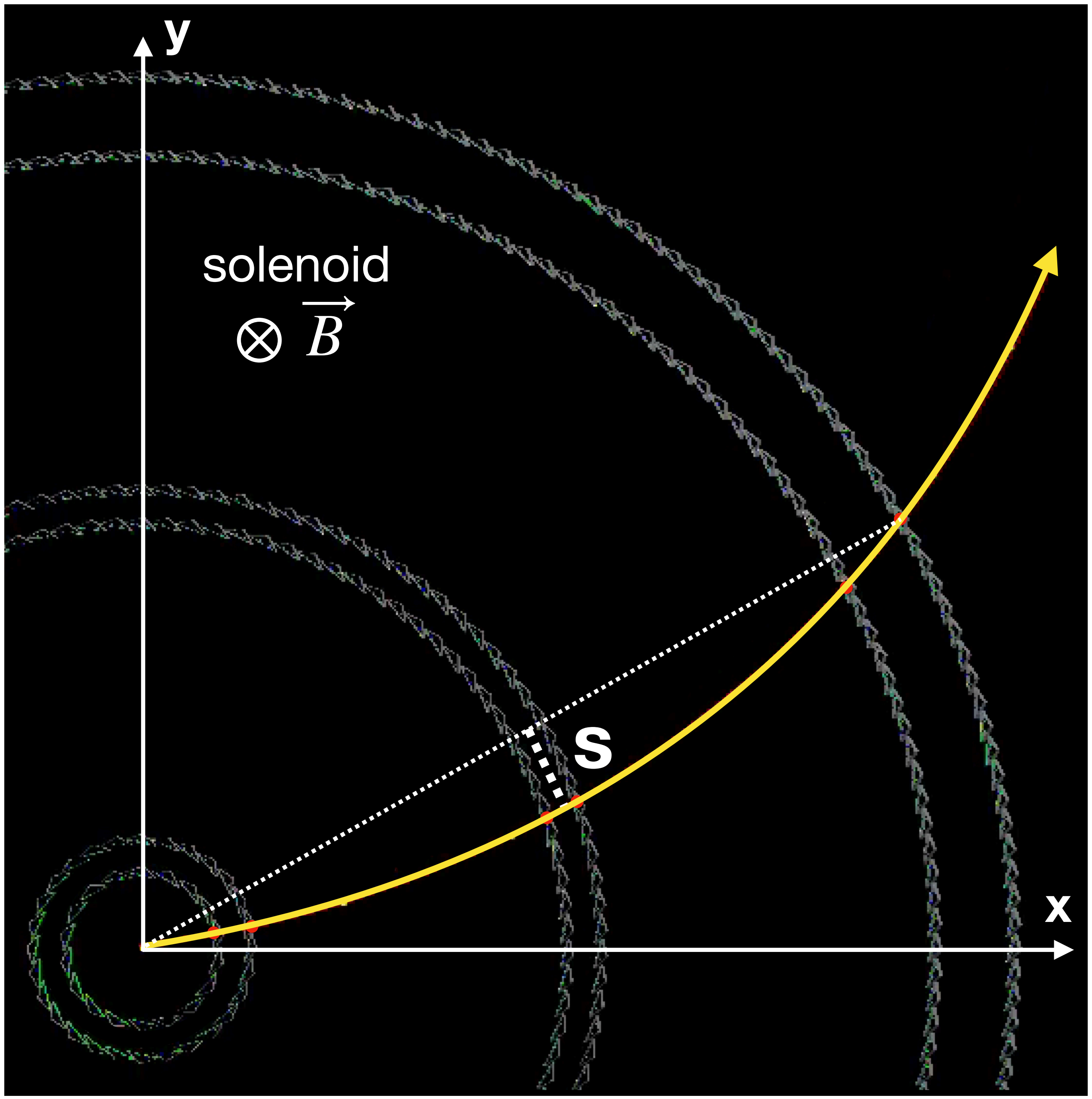
Designing barrel layers

3-double-layer barrel configuration



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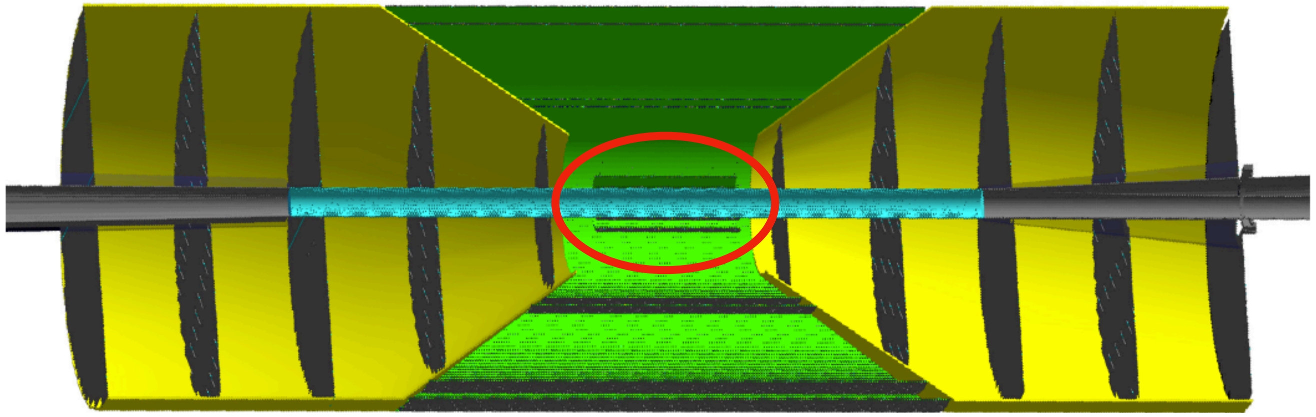
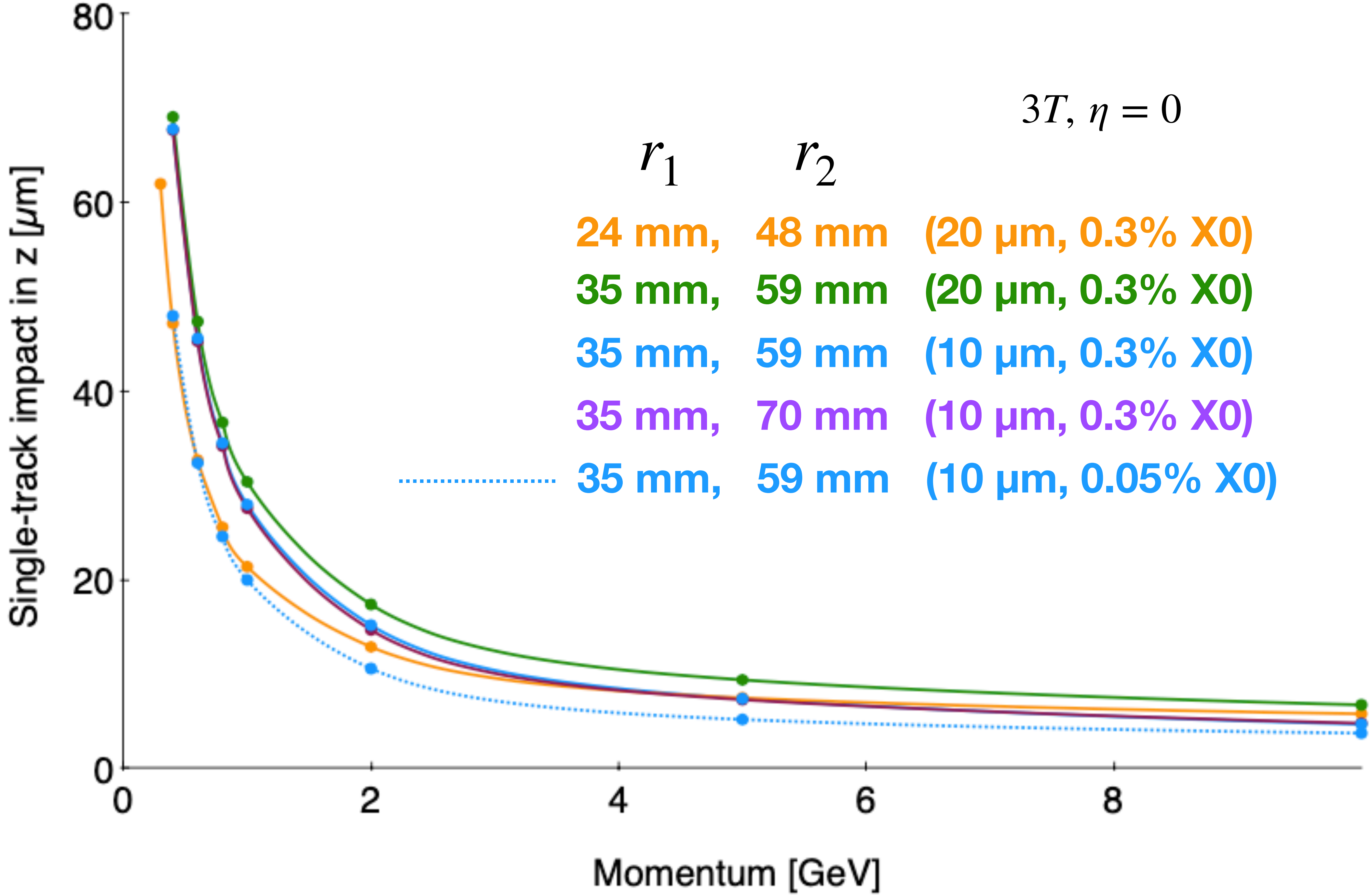
Designing vertexing layers



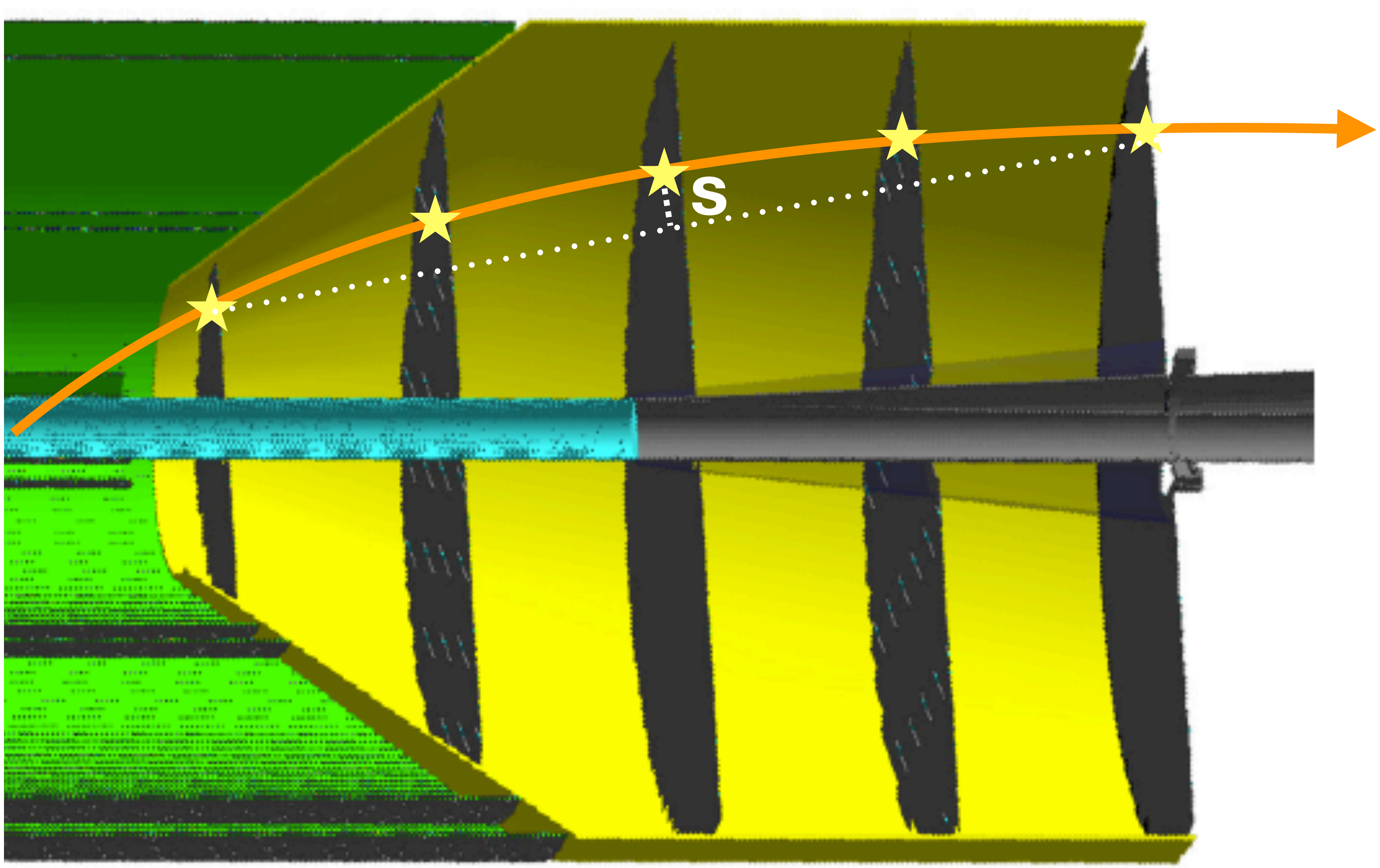
Detector vertexing performance driven by barrel layers closest to the beampipe

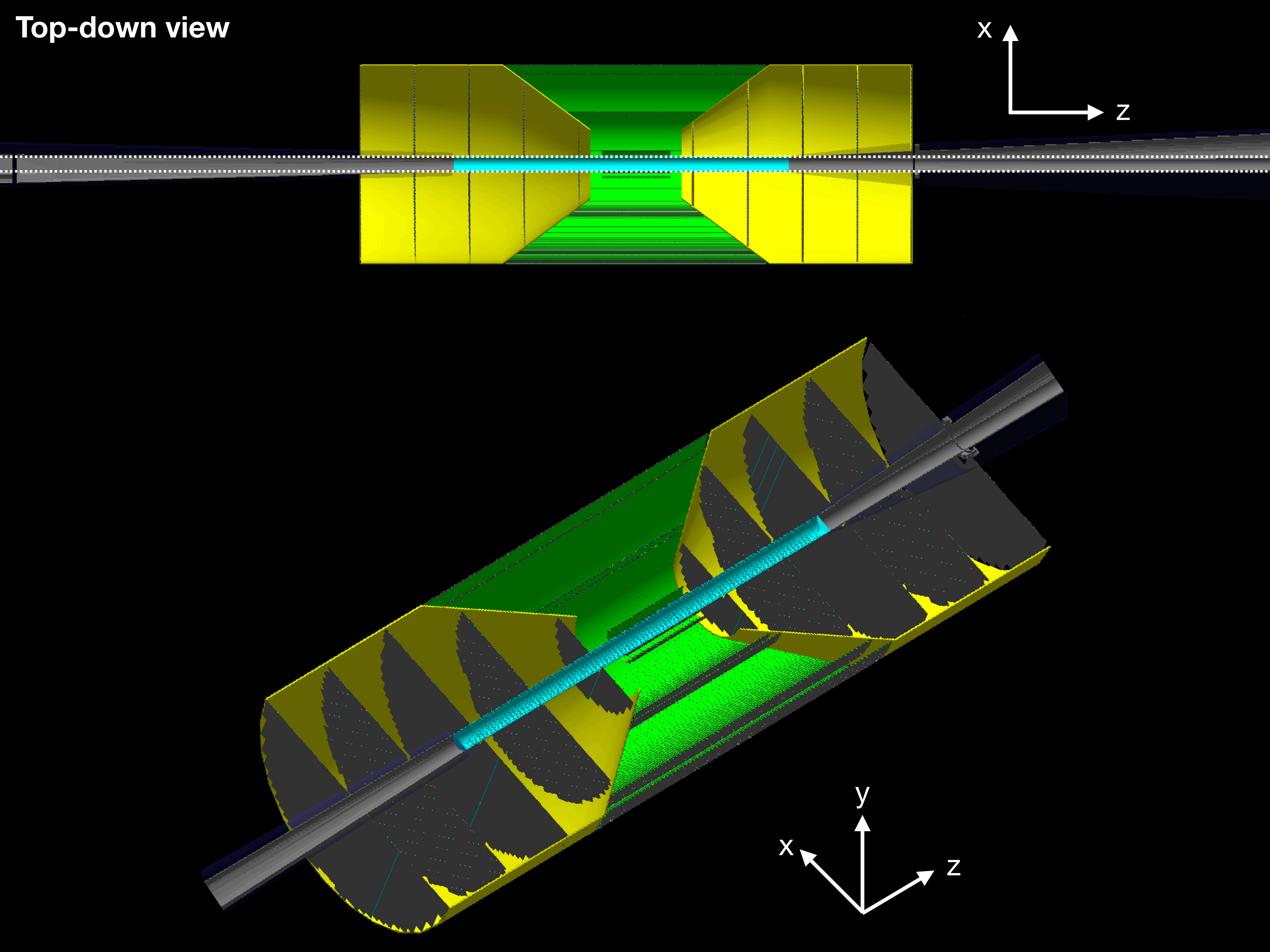


Designing disk layers

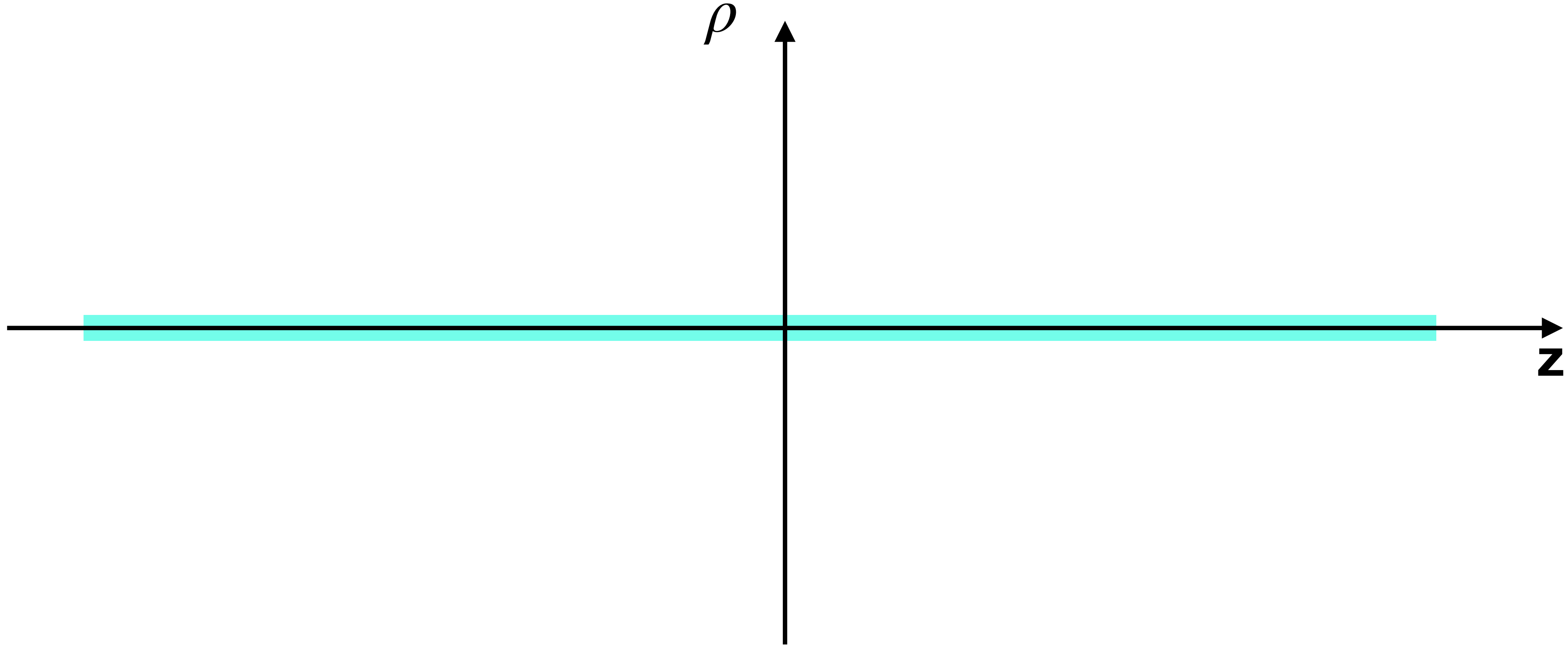
Considerations similar to barrel:

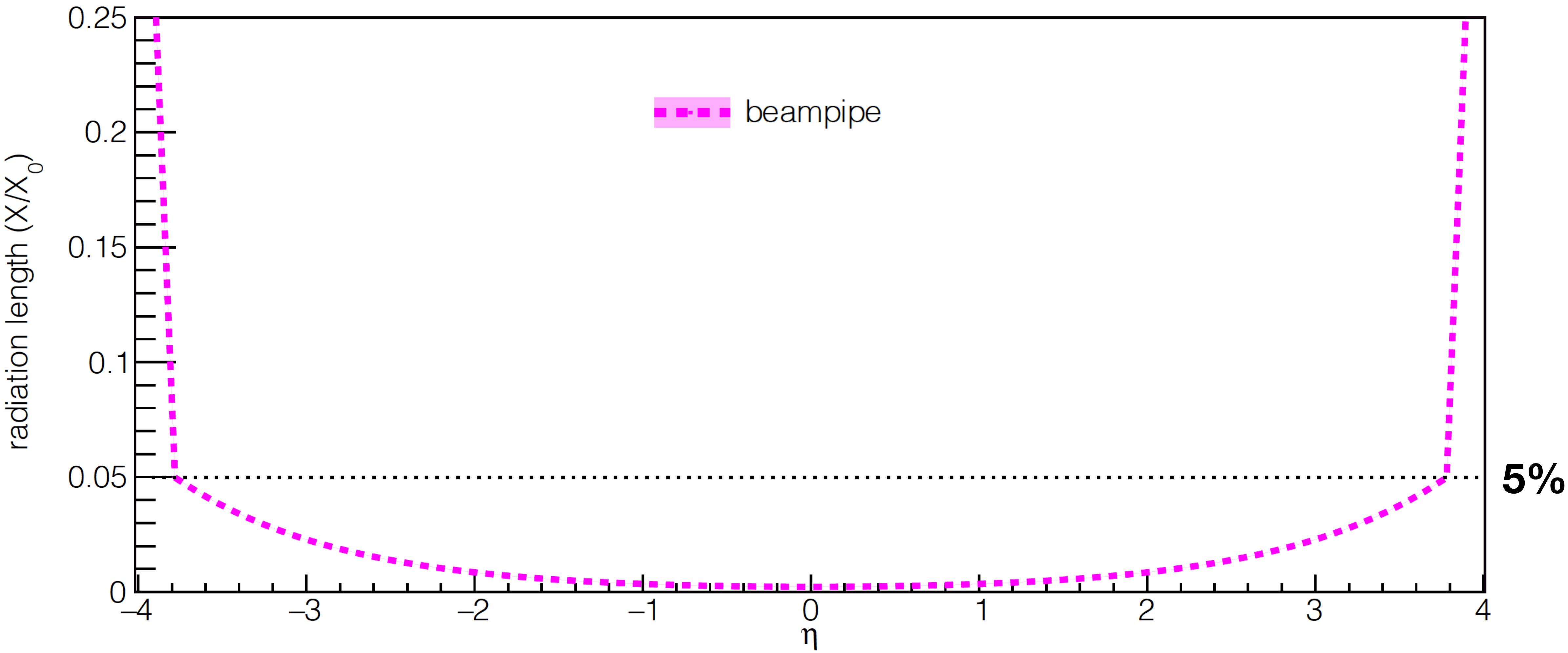
* disk as close to the IP as possible
* disk as far away as possible
* disk in mid point (odd number of disks preferred)
* additional disks as needed



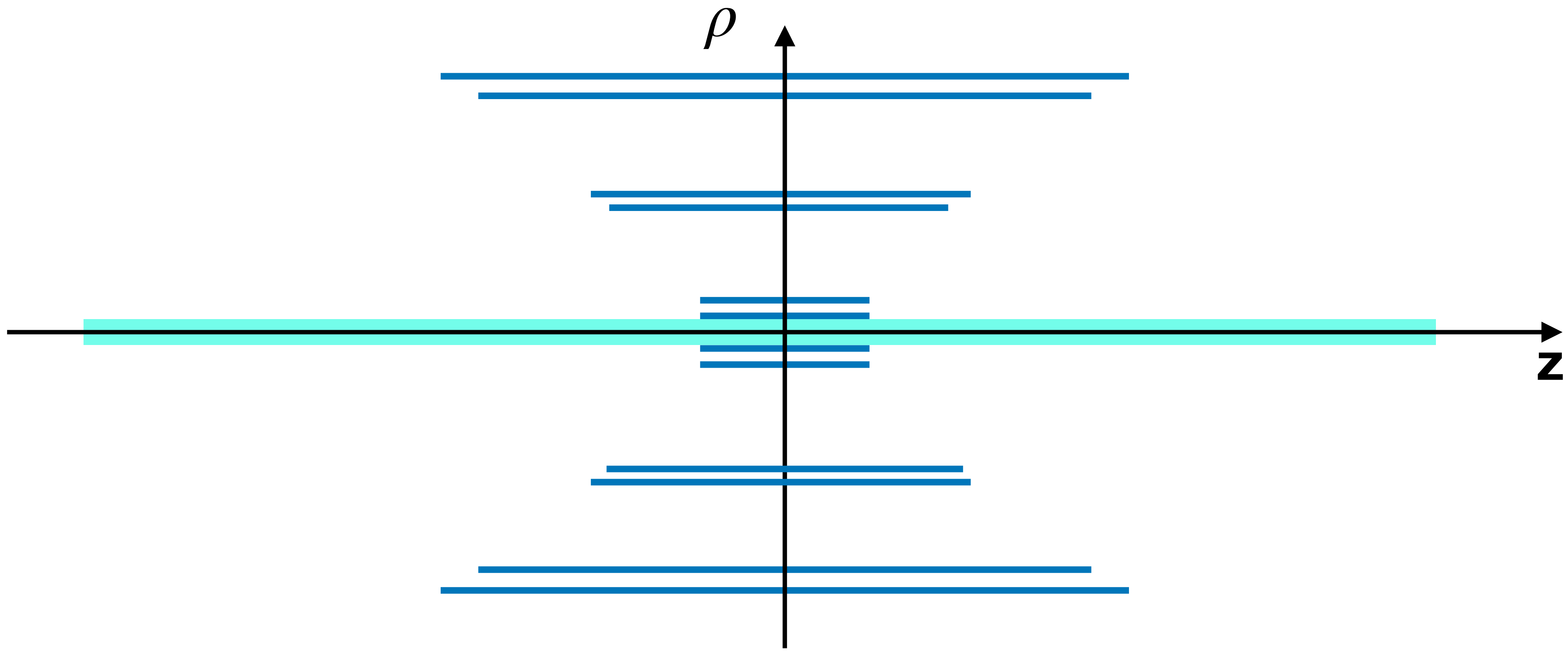

Top-down view
x
z
y
x
z

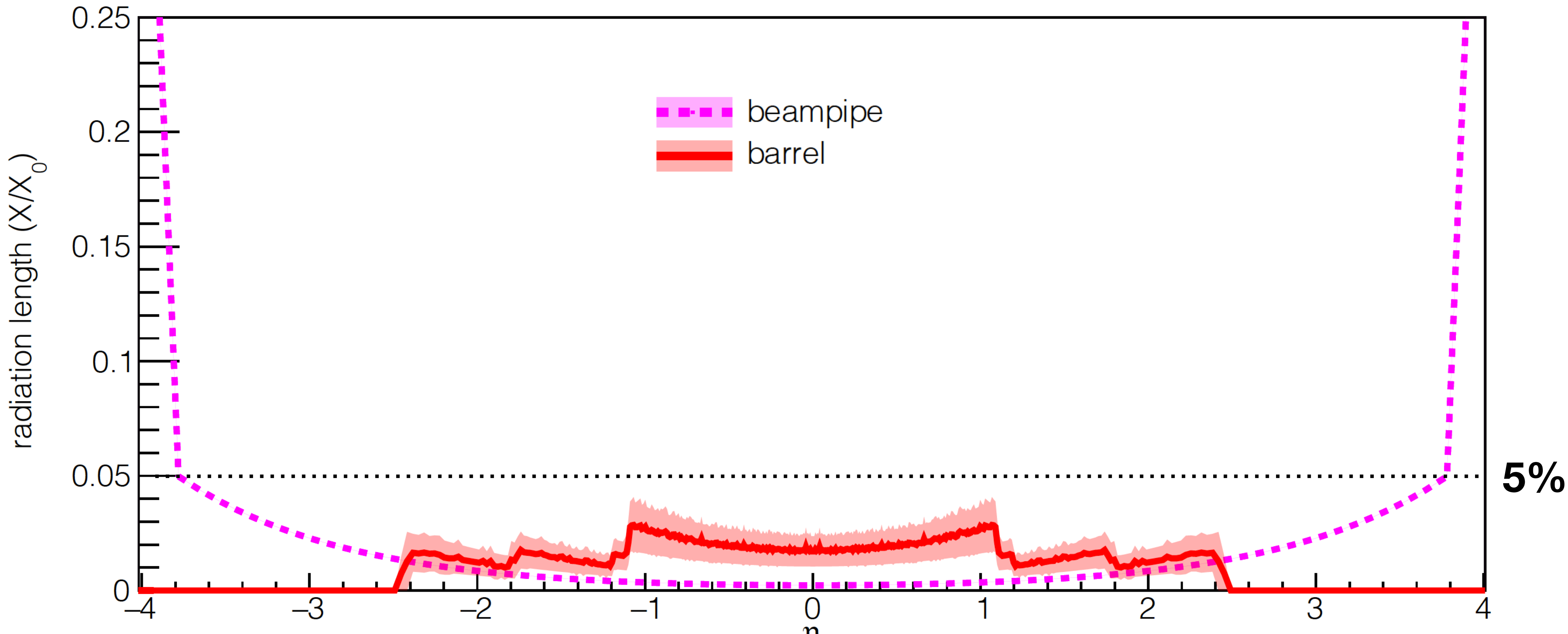
Material Budget



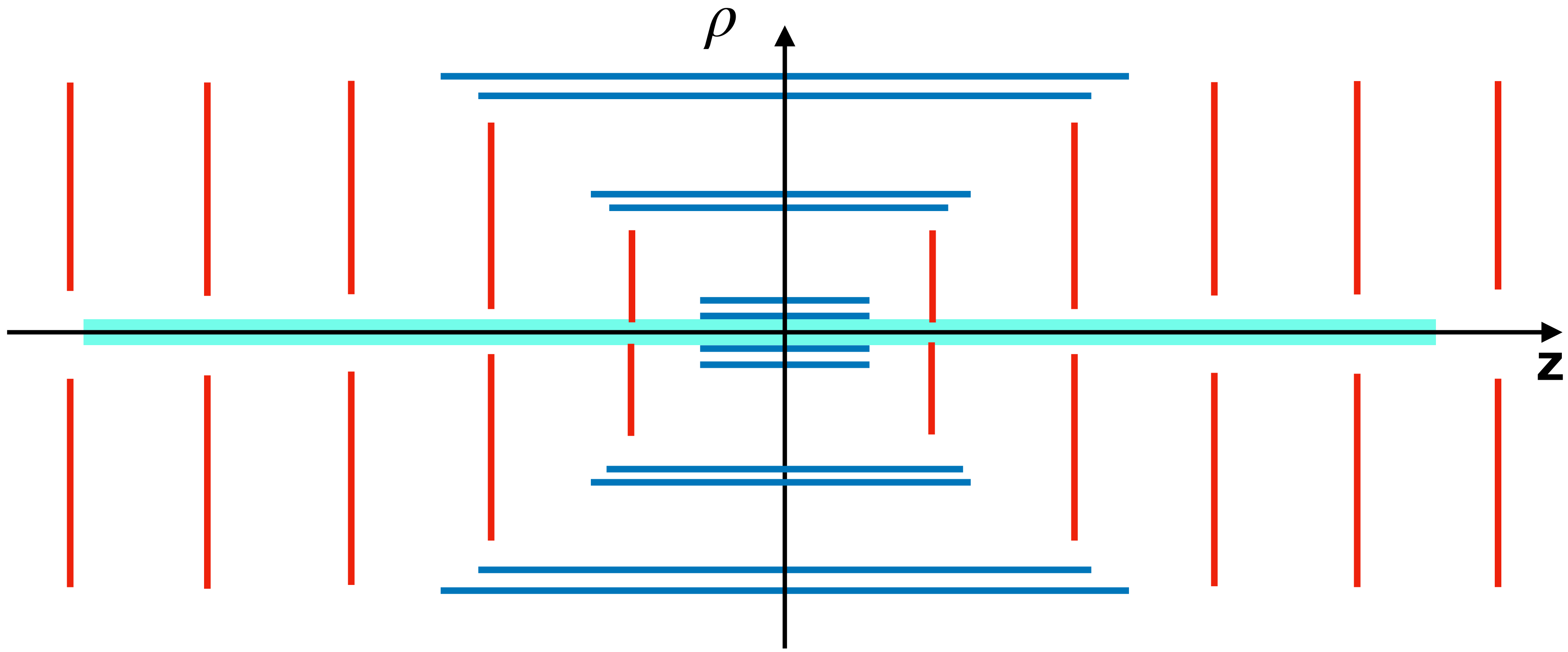


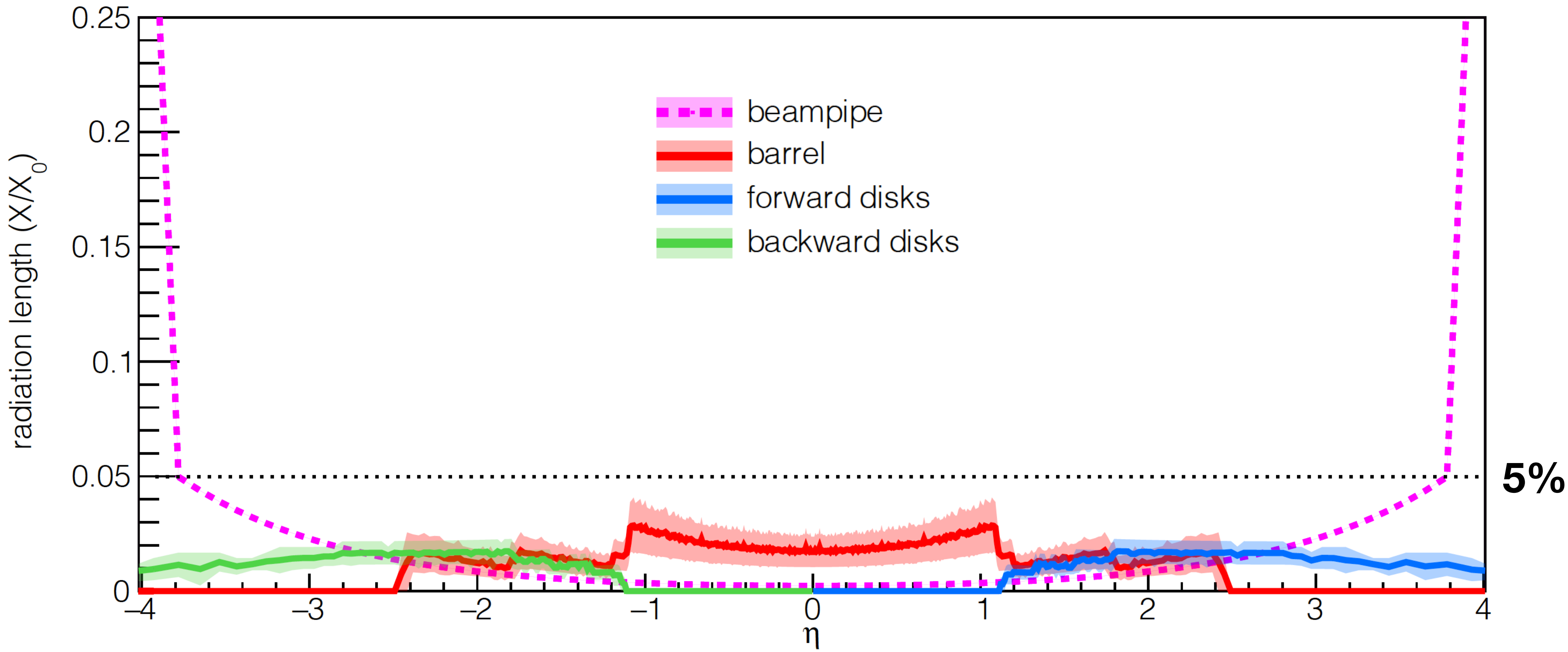
Material Budget





Material Budget





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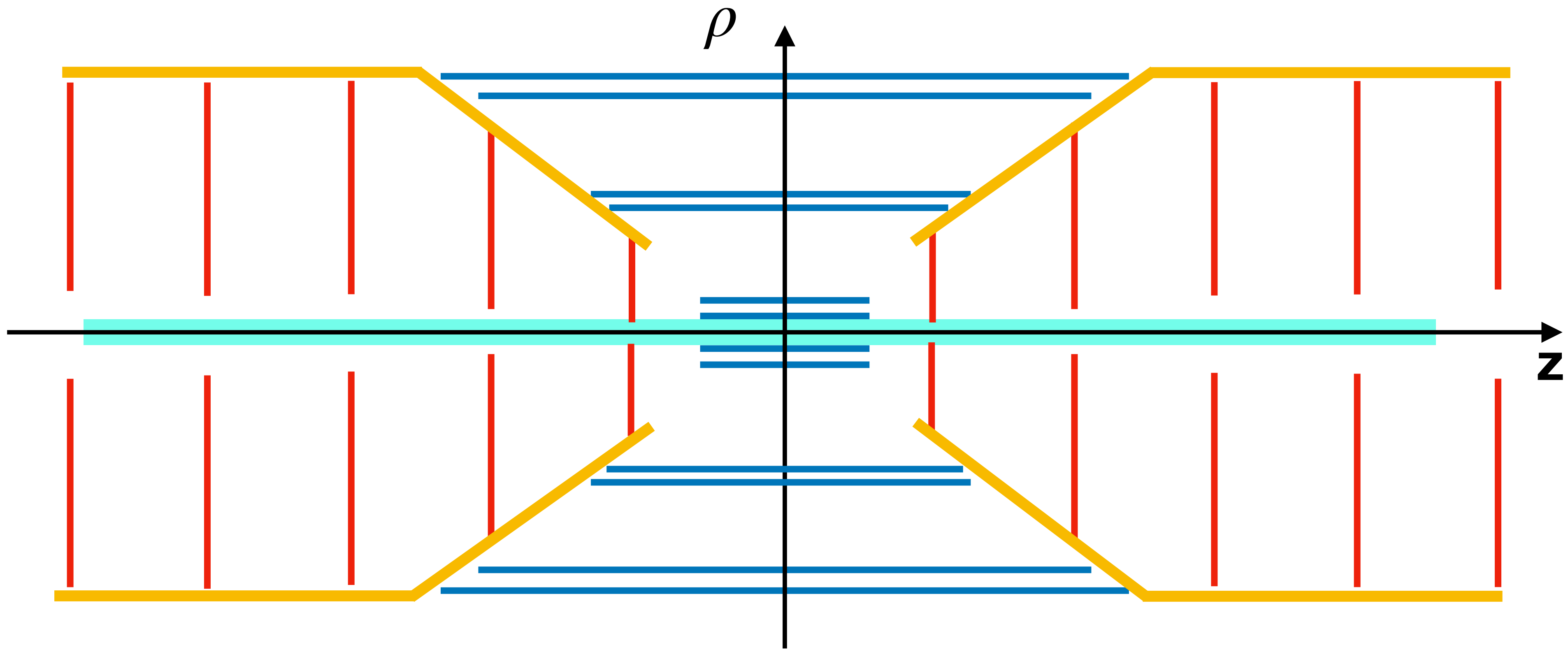

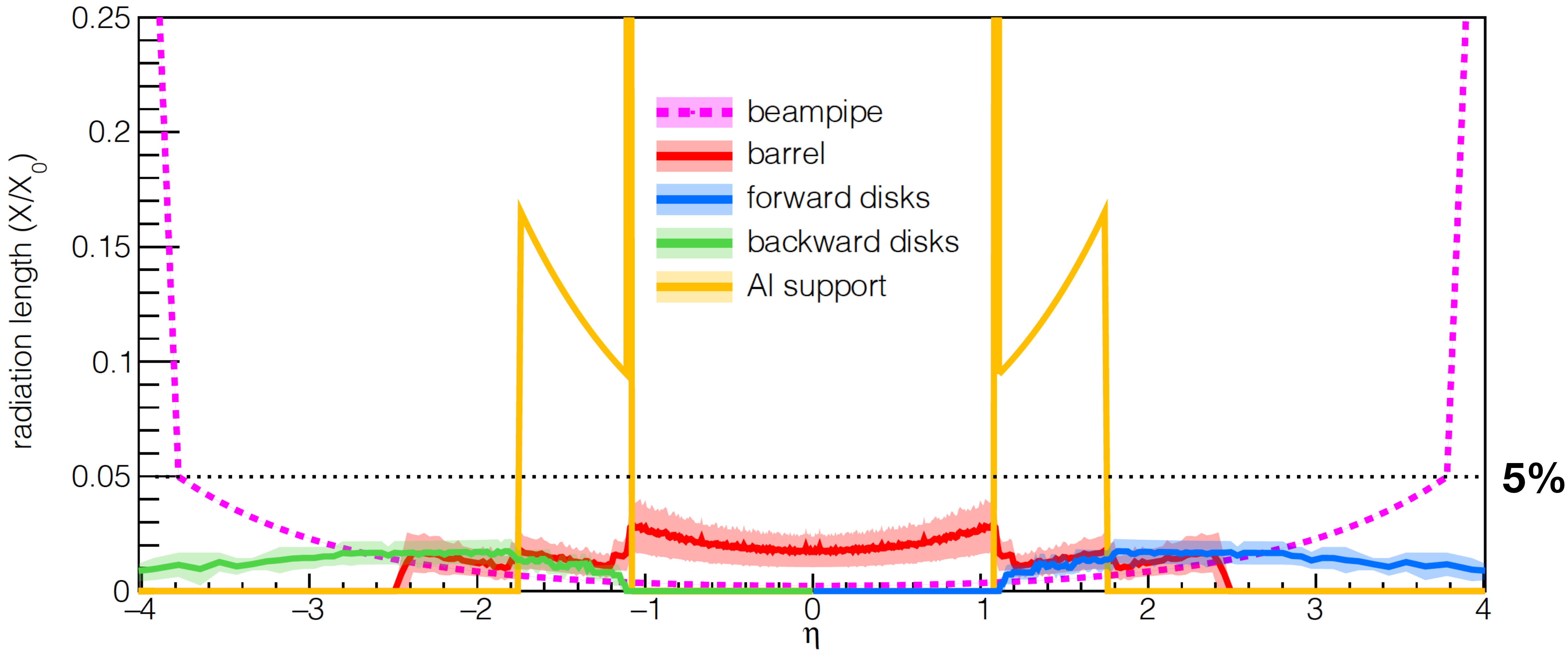

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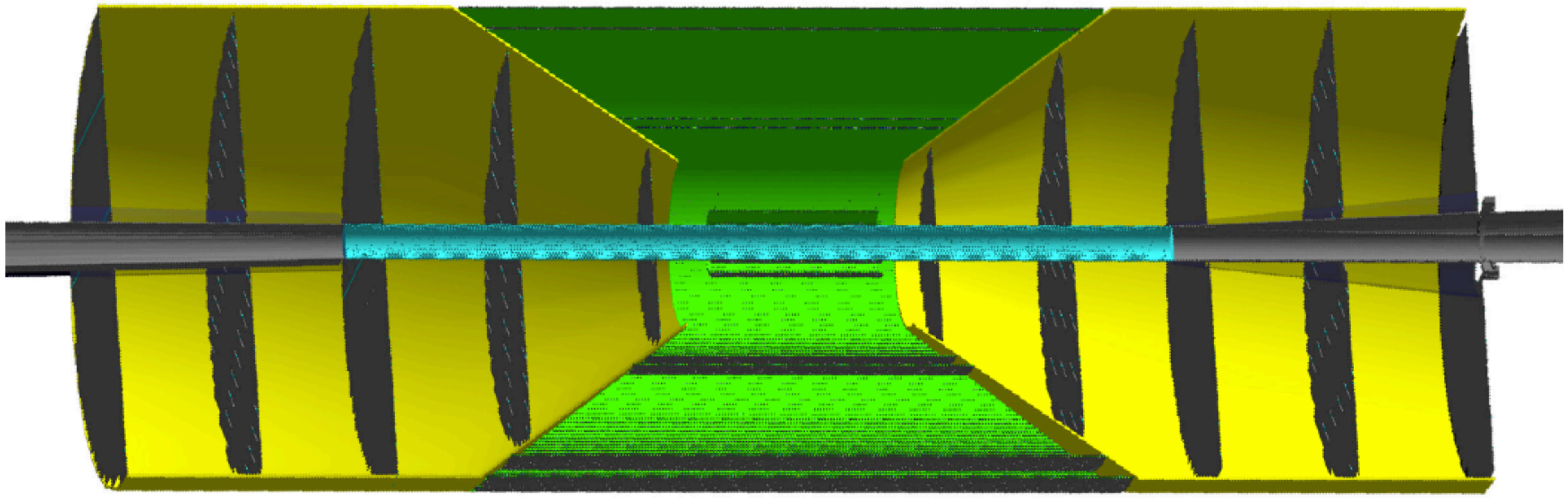

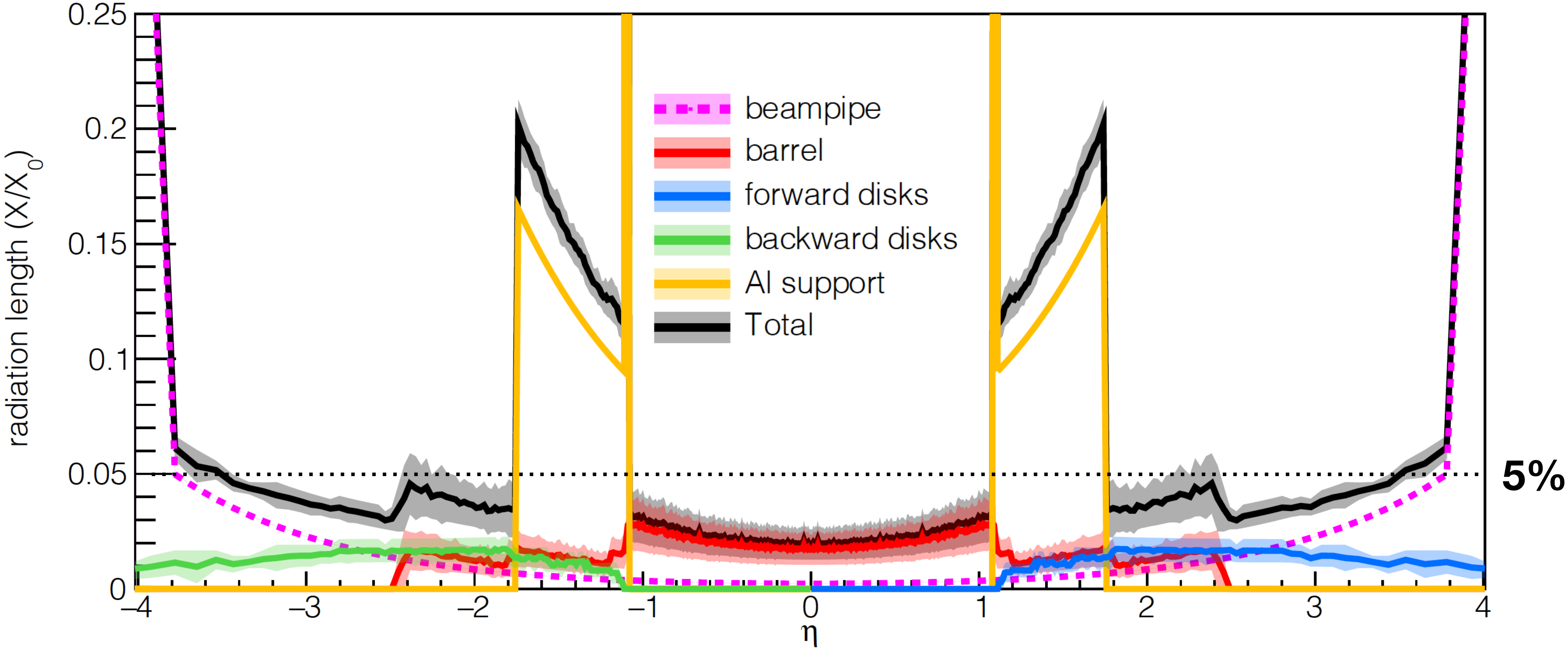

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Requirements for an EIC tracker

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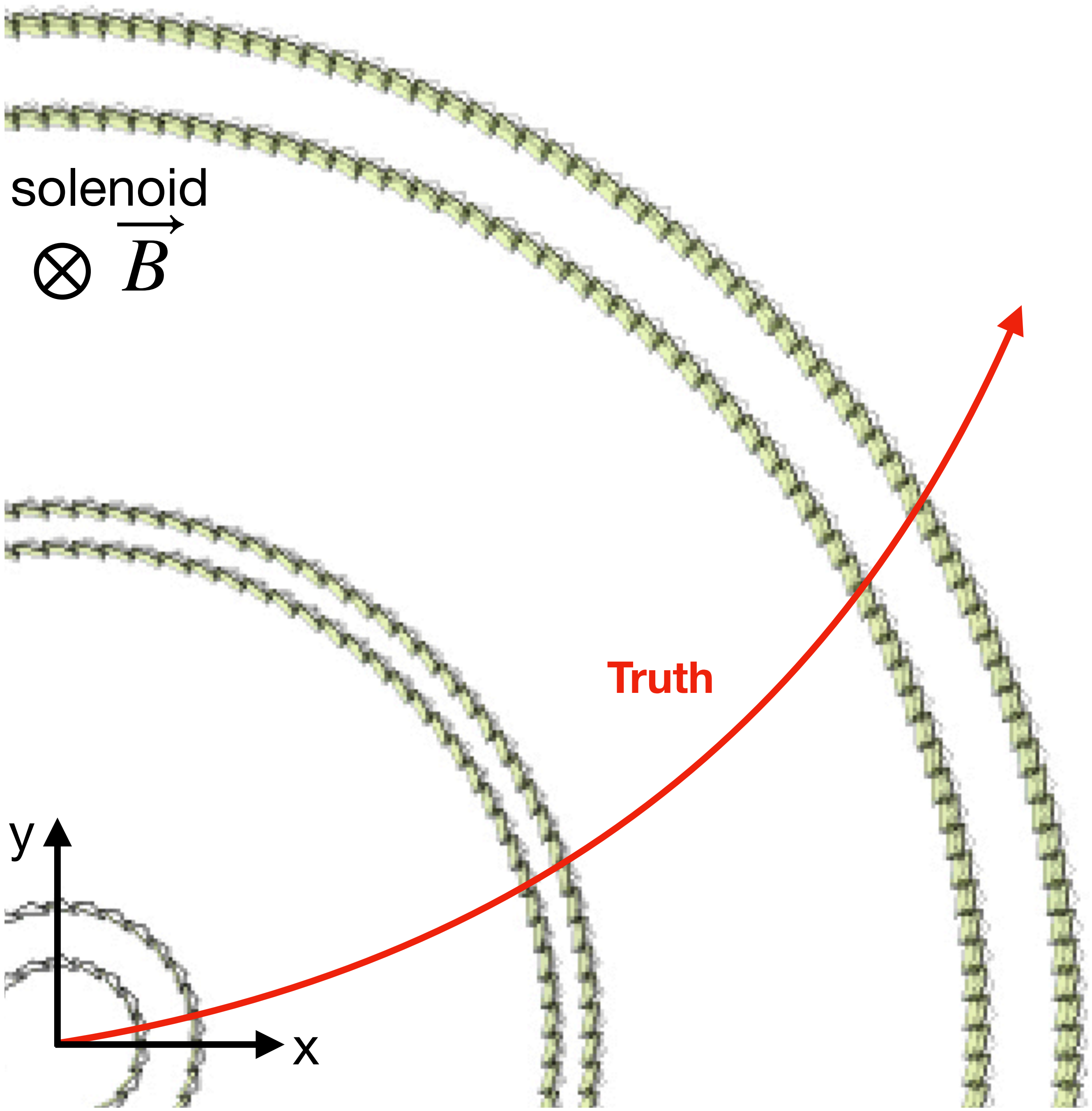
Summary and Conclusions

Extracting resolutions

1) Generate particles from the IP in all directions and within a broad momentum range



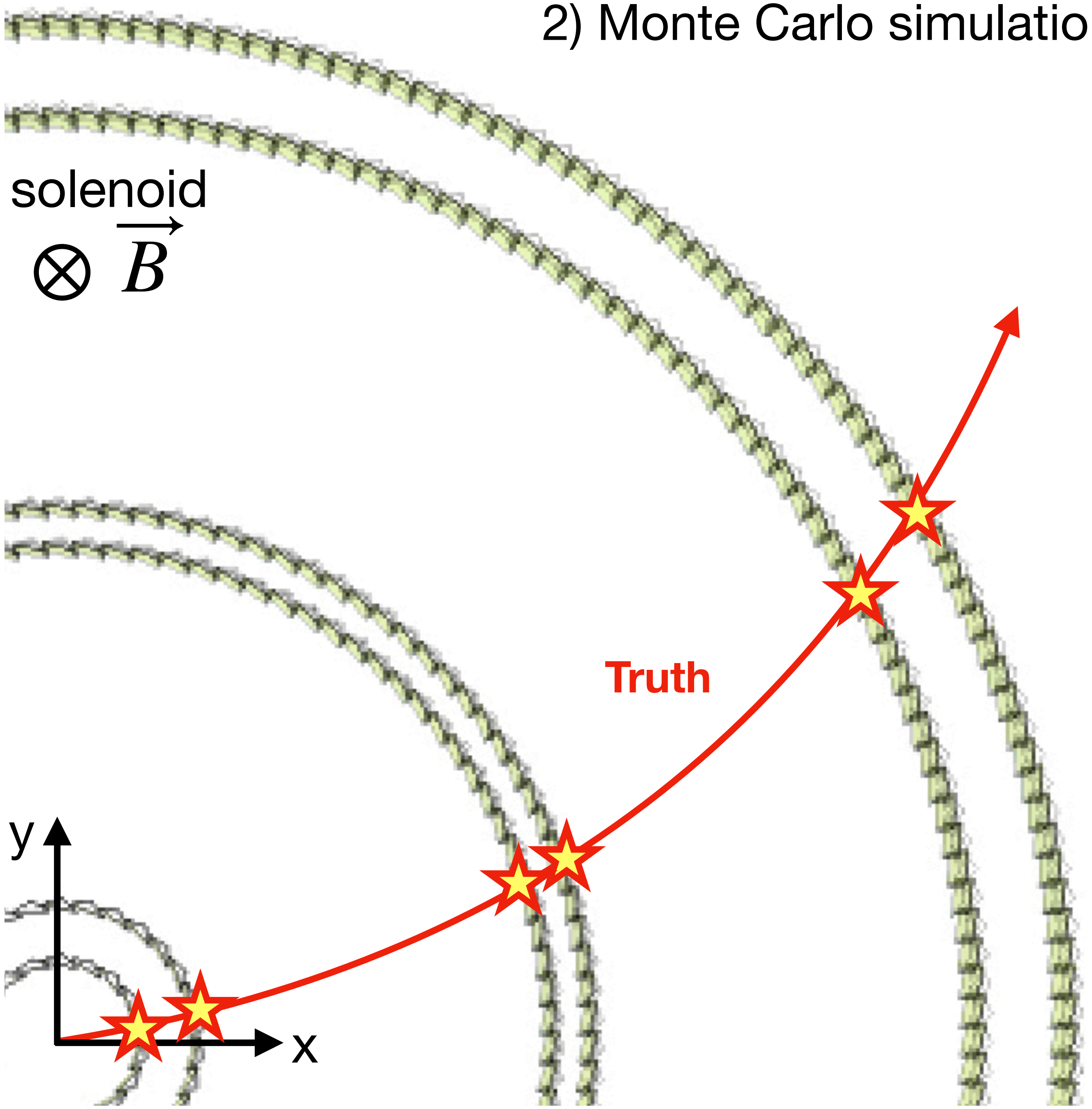
Event generator

- Particle gun
- Pythia
- Herwig
- …

Extracting resolutions

1) Generate particles from the IP in all directions and within a broad momentum range

2) Monte Carlo simulation of detector response



Detector response

- Toy Monte Carlo
- Fast Simulation
- Full Simulation

GEANT4 A SIMULATION TOOLKIT

* Detailed implementation of detector geometries (volumes, materials, magnetic fields)

* Comprehensive library of physics models describing interaction of particles with matter and fields.

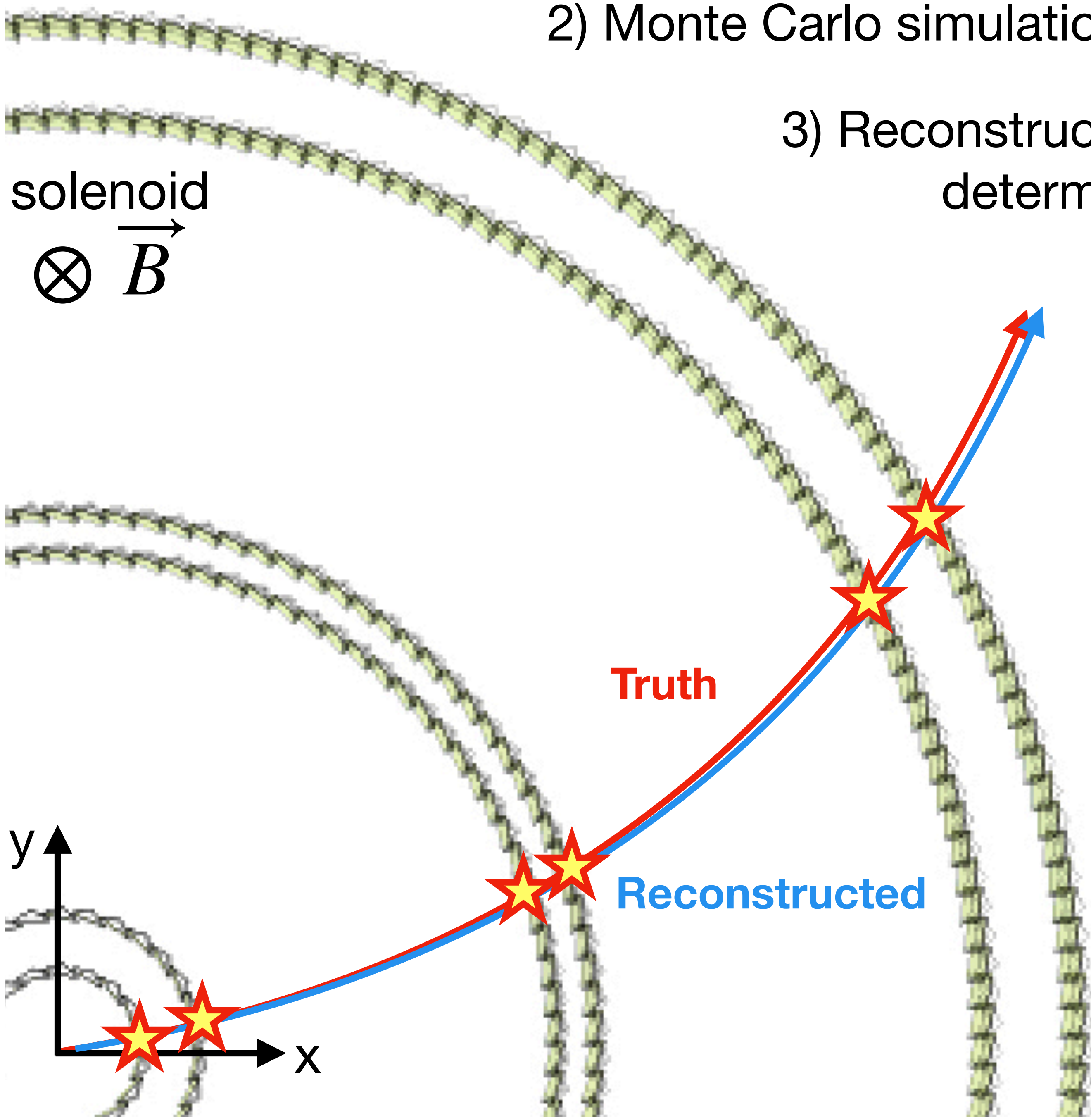
* Used in particle/nuclear, accelerator, medical, and astrophysics

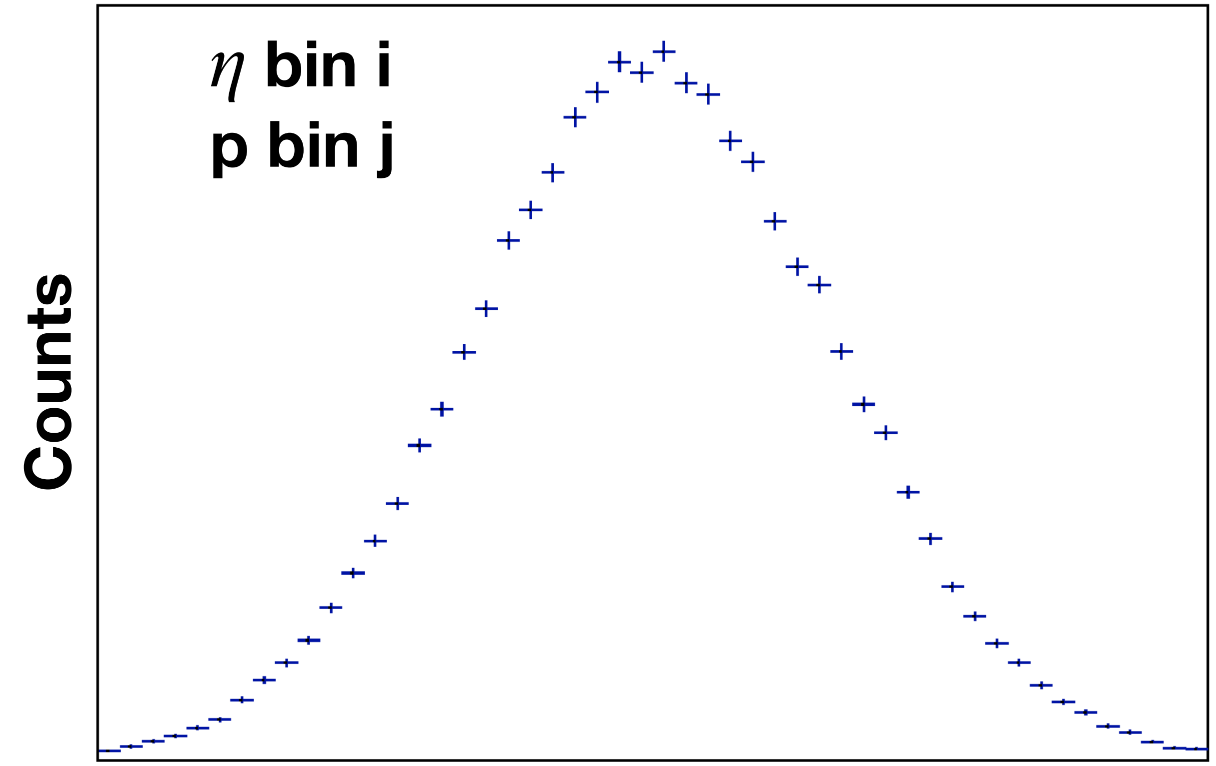
Extracting resolutions

1) Generate particles from the IP in all directions and within a broad momentum range

2) Monte Carlo simulation of detector response

3) Reconstruct the momenta of each generated particle and determine relative difference between generated and reconstructed momenta





$$\frac{dp}{p} \equiv \frac{p_{reco} - p_{truth}}{p_{truth}}$$

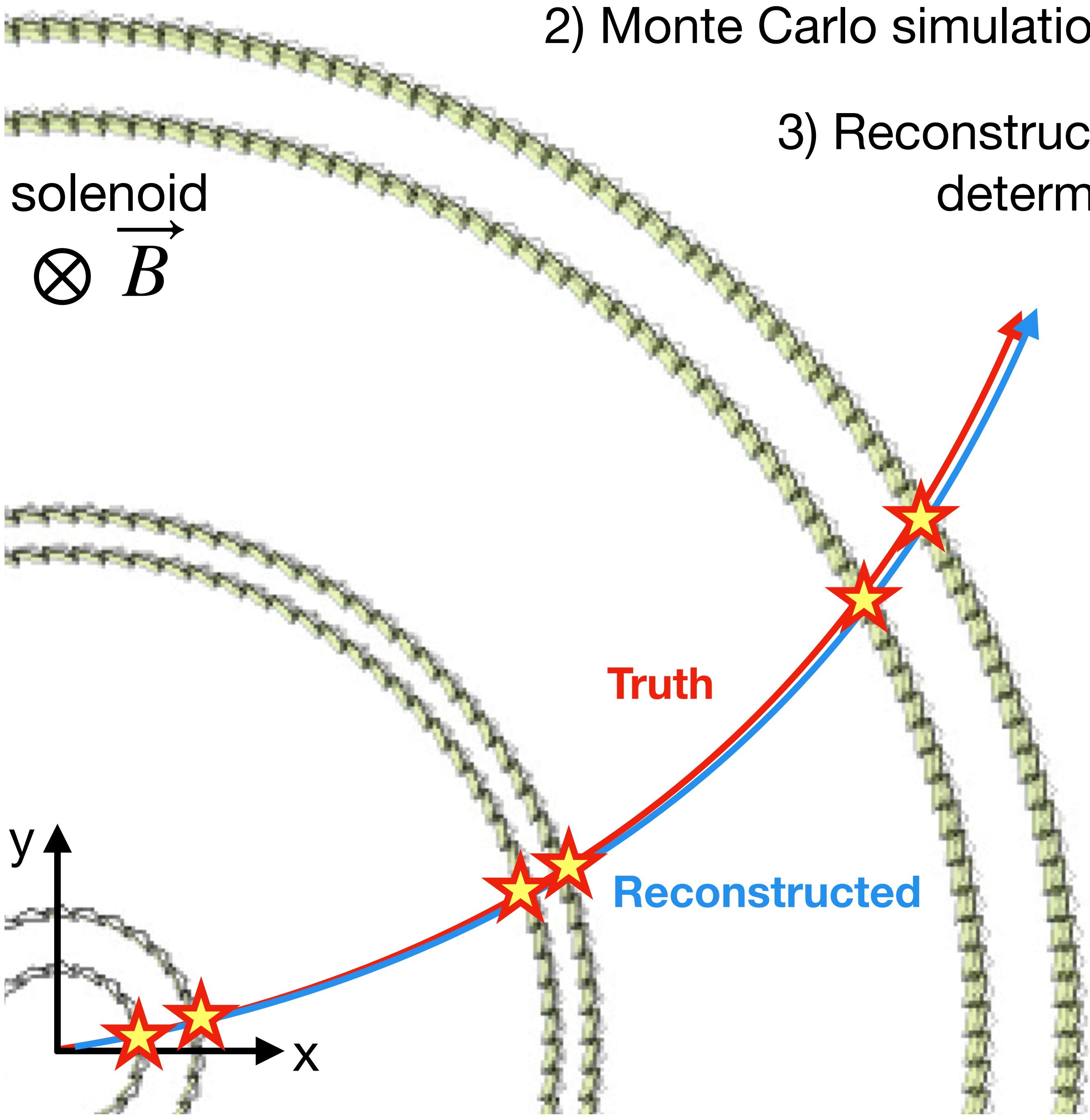
Extracting resolutions

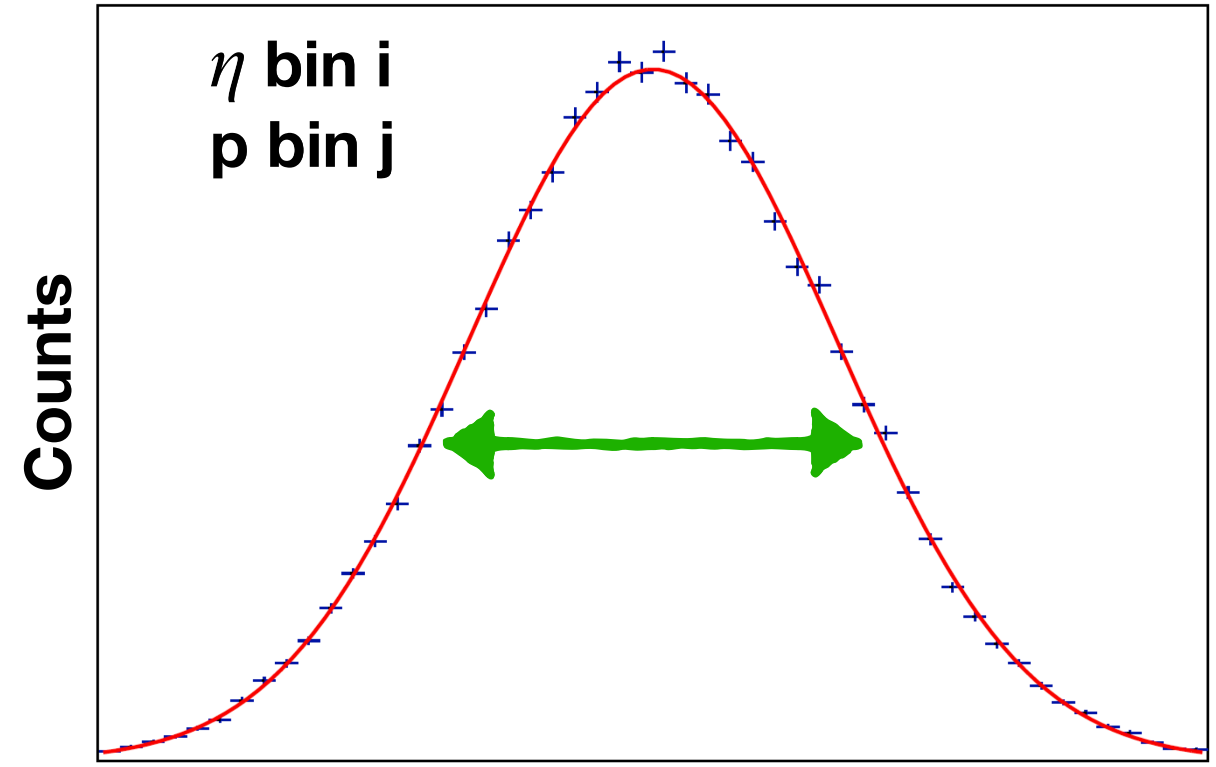
1) Generate particles from the IP in all directions and within a broad momentum range

2) Monte Carlo simulation of detector response

3) Reconstruct the momenta of each generated particle and determine relative difference between generated and reconstructed momenta

4) Fit a normal curve to the resulting distribution





$$\frac{dp}{p} \equiv \frac{p_{reco} - p_{truth}}{p_{truth}}$$

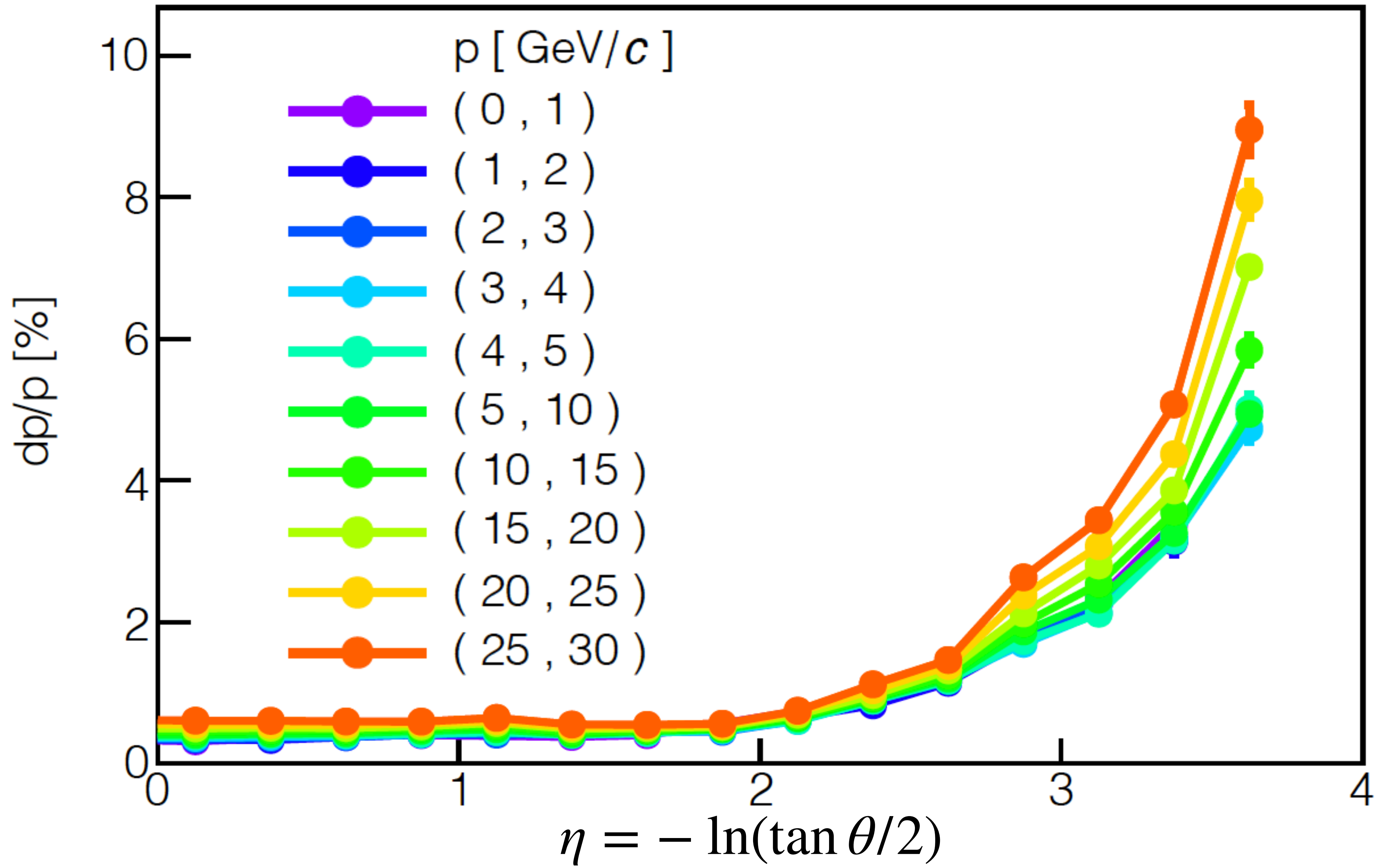
Momentum resolution in a given momentum and pseudorapidity bin defined as the standard deviation of the resulting fit

Resulting Momentum Resolutions

Magnetic field: Beast map (~3.0T solenoid)

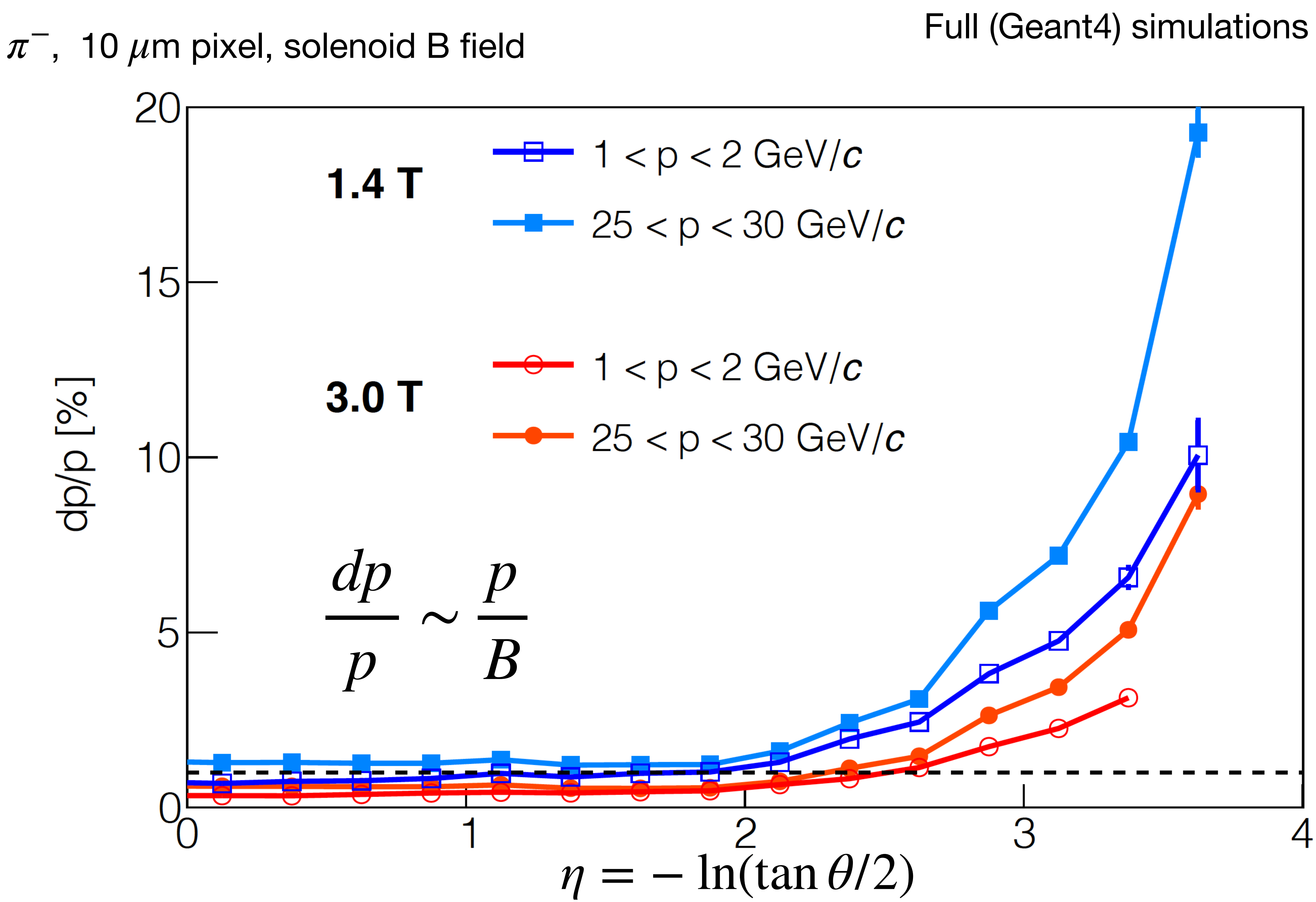
π^-, 10 μm pixel

Full (Geant4) simulations



η	0	0.5	1	1.5	2	3	4	5
θ [deg]	90	62	40	25	15	5.7	2.1	0.8

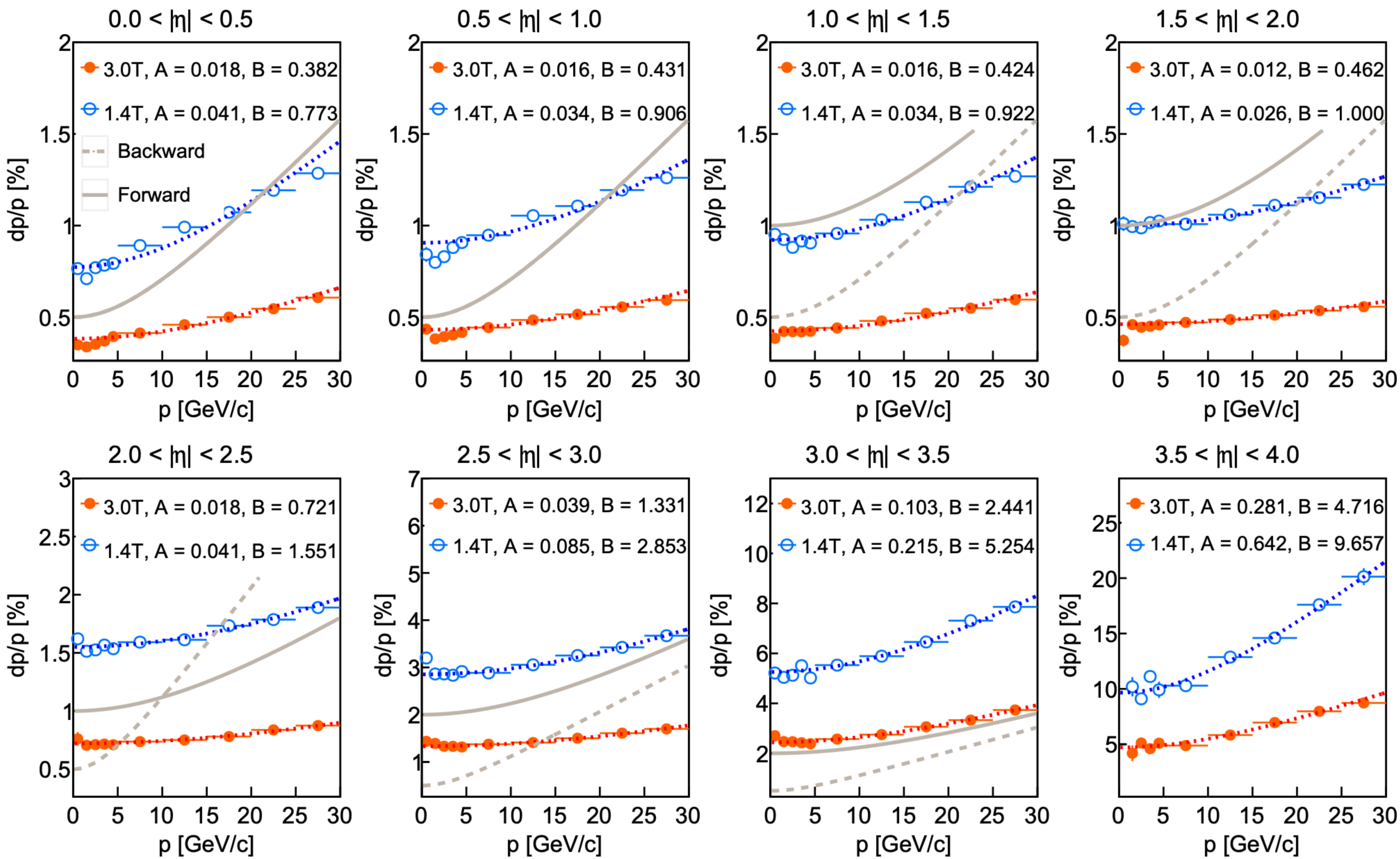
B-field comparison



η	0	0.5	1	1.5	2	3	4	5
θ [deg]	90	62	40	25	15	5.7	2.1	0.8

Resulting Momentum Resolutions

$\eta = -\ln(\tan\theta/2)$ π^-, 10 μm pixel $dp/p = Ap \oplus B$



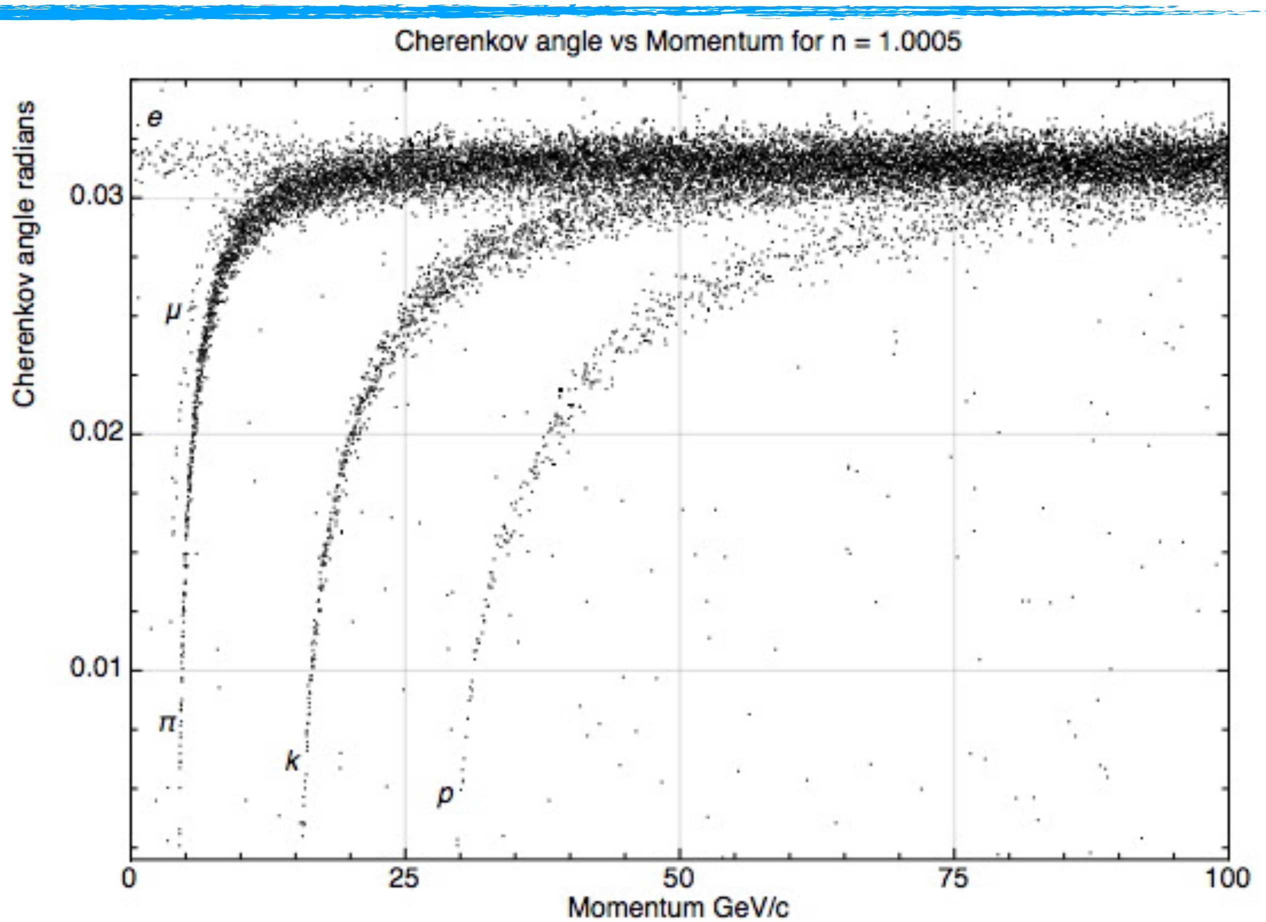
η	0	0.5	1	1.5	2	3	4	5
θ [deg]	90	62	40	25	15	5.7	2.1	0.8

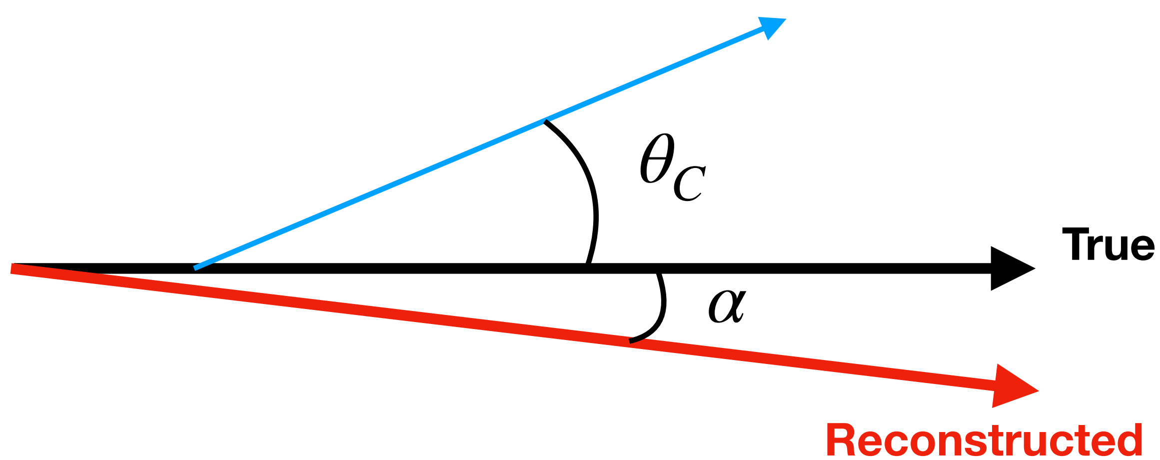
Angular resolutions at PID detectors

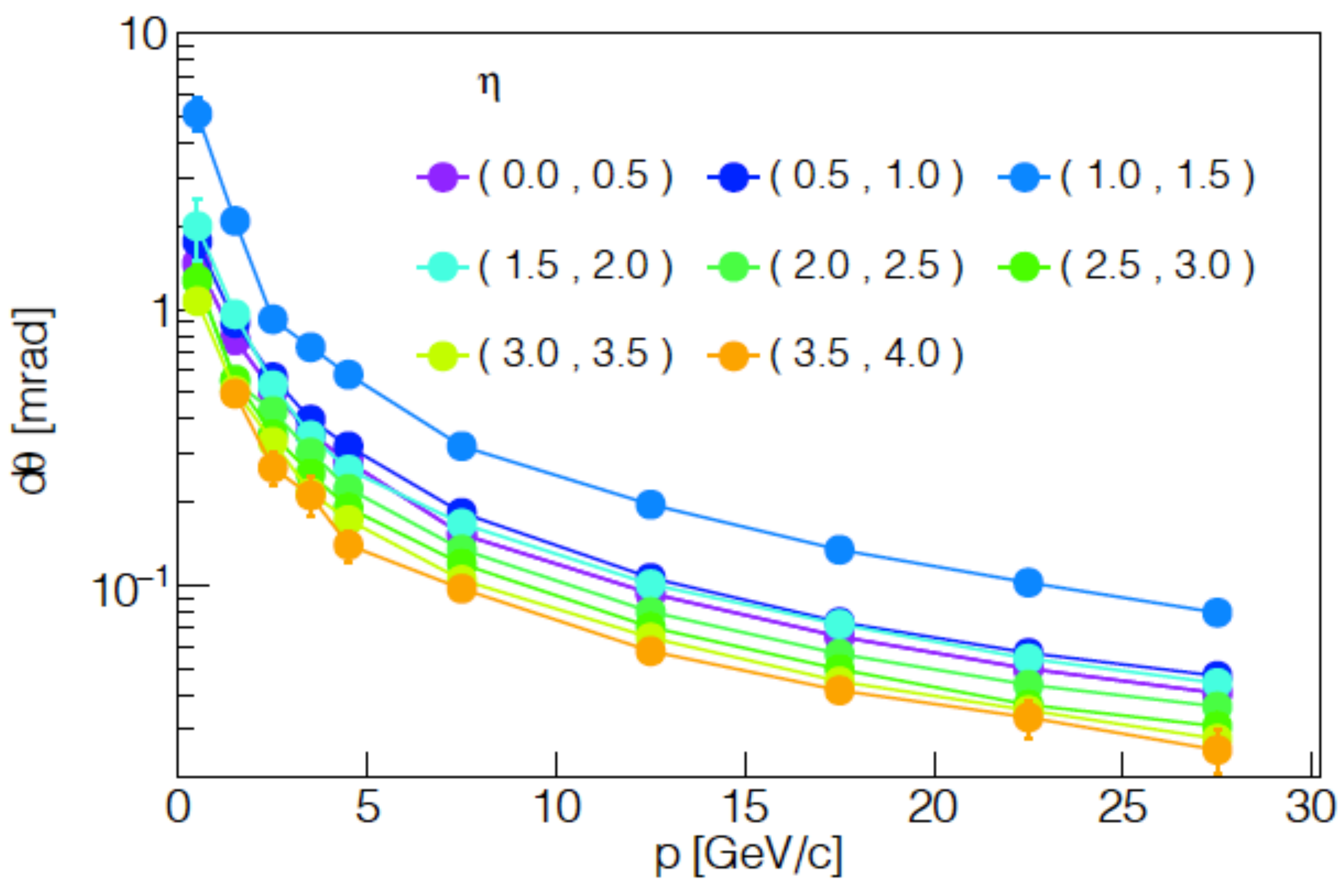
Cherenkov radiation:

- electromagnetic radiation emitted when a charged particle traverses a medium of refraction index *n* at speed greater than the speed of light in that medium.
- radiation is emitted within a cone of angle:

$$\cos(\theta_C) = 1/n\beta$$







Good angular resolution is needed at the entrance of Cherenkov detectors

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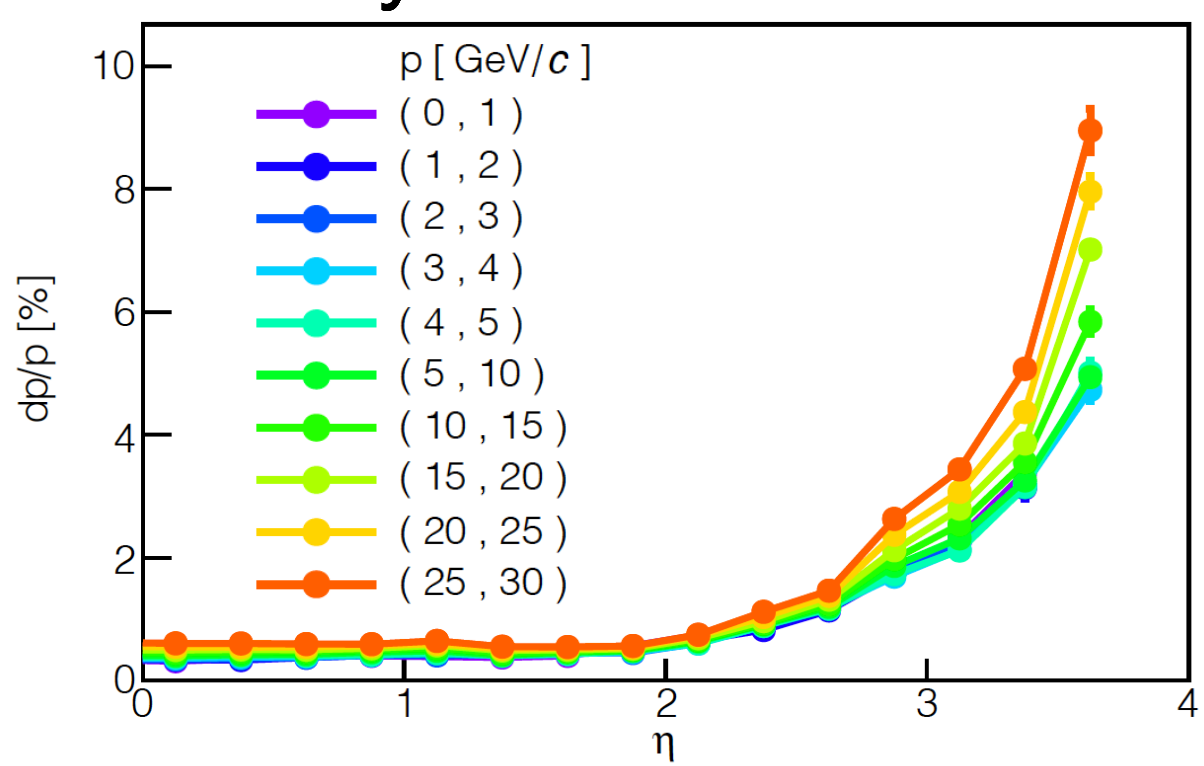
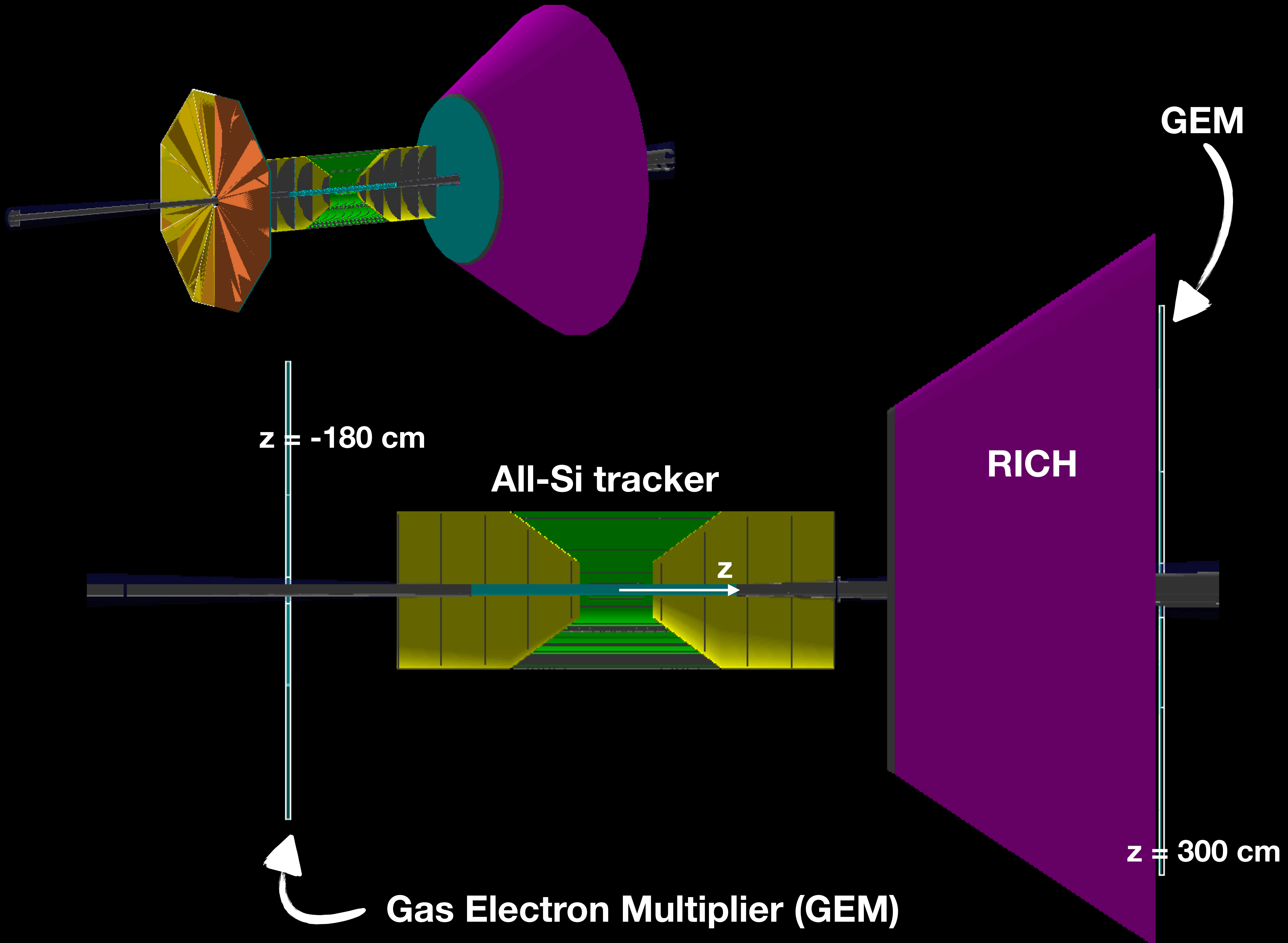
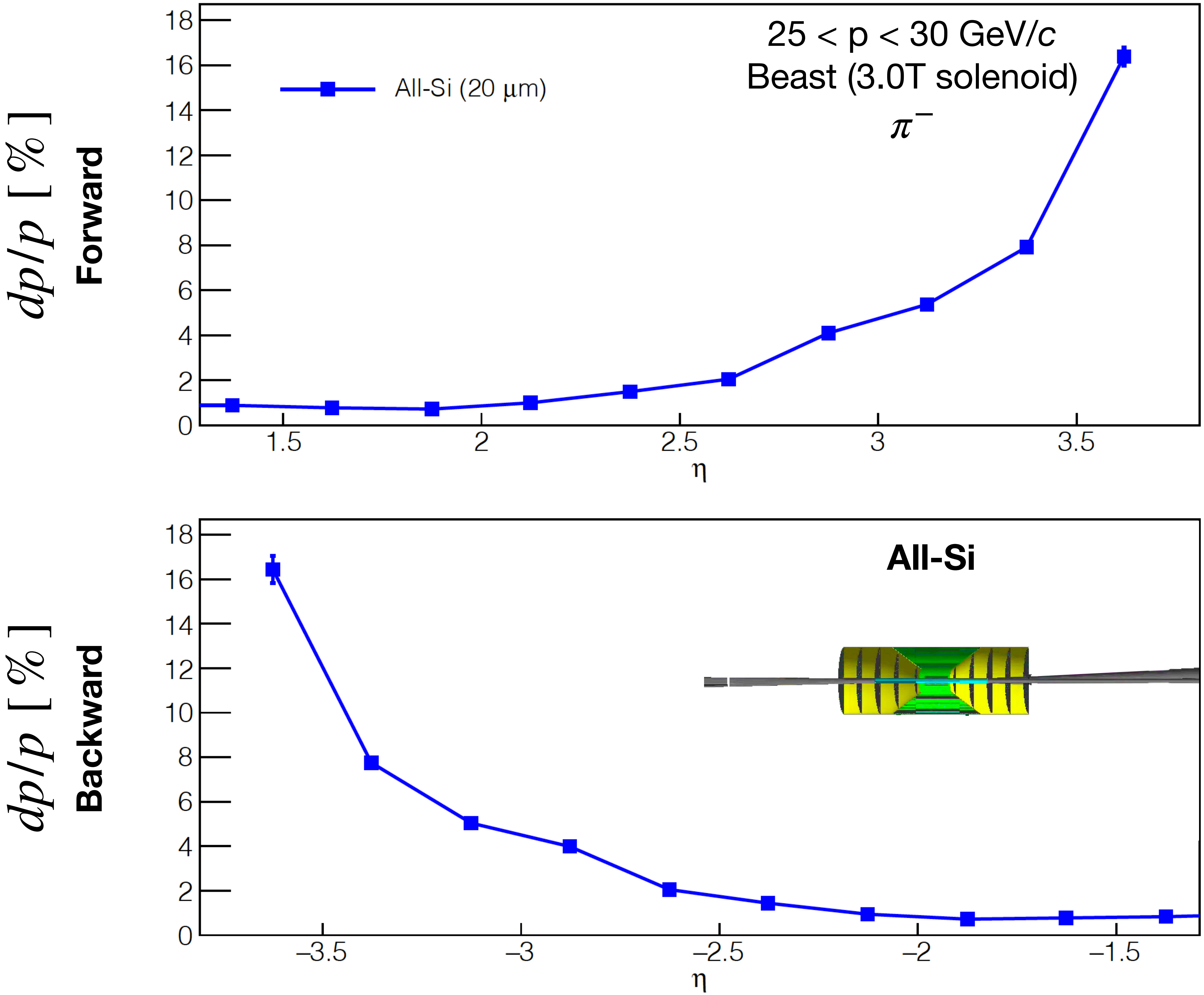
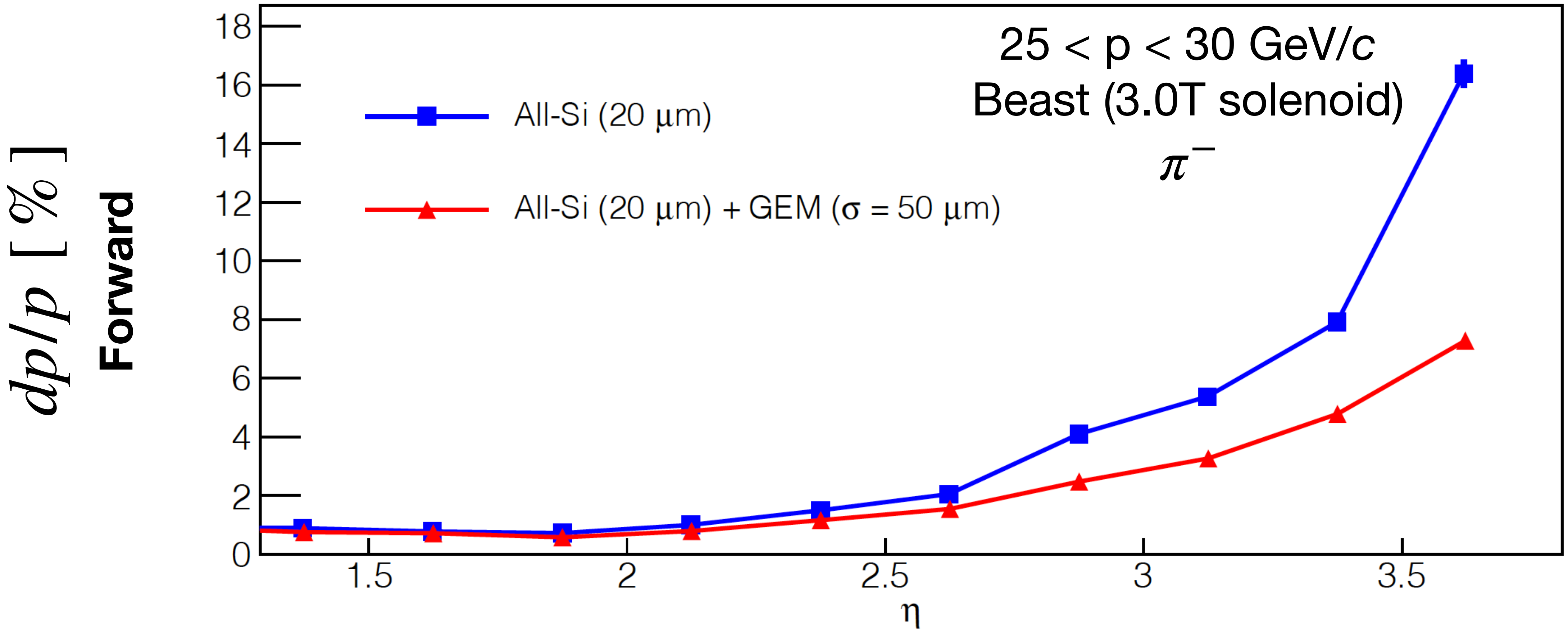


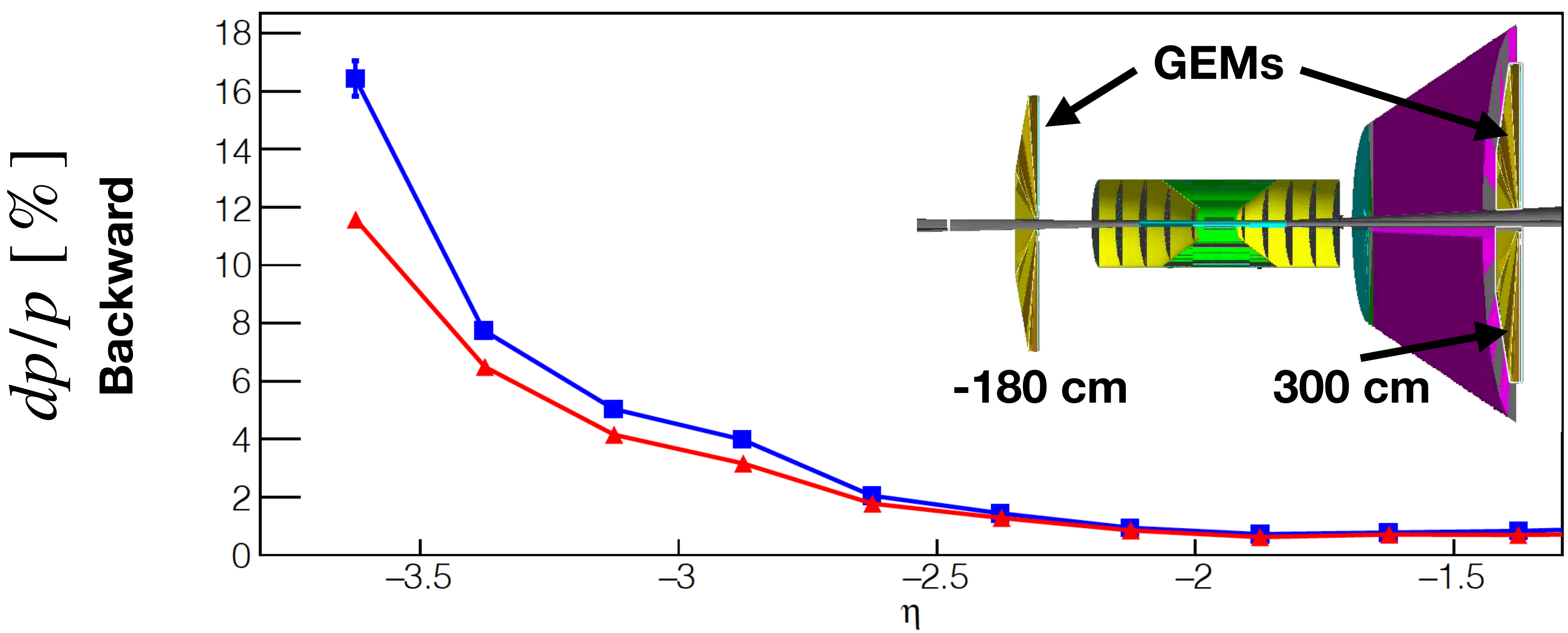

GEM
z = -180 cm
All-Si tracker
z
RICH
z = 300 cm
Gas Electron Multiplier (GEM)

Complementing All-Si tracker with other detectors

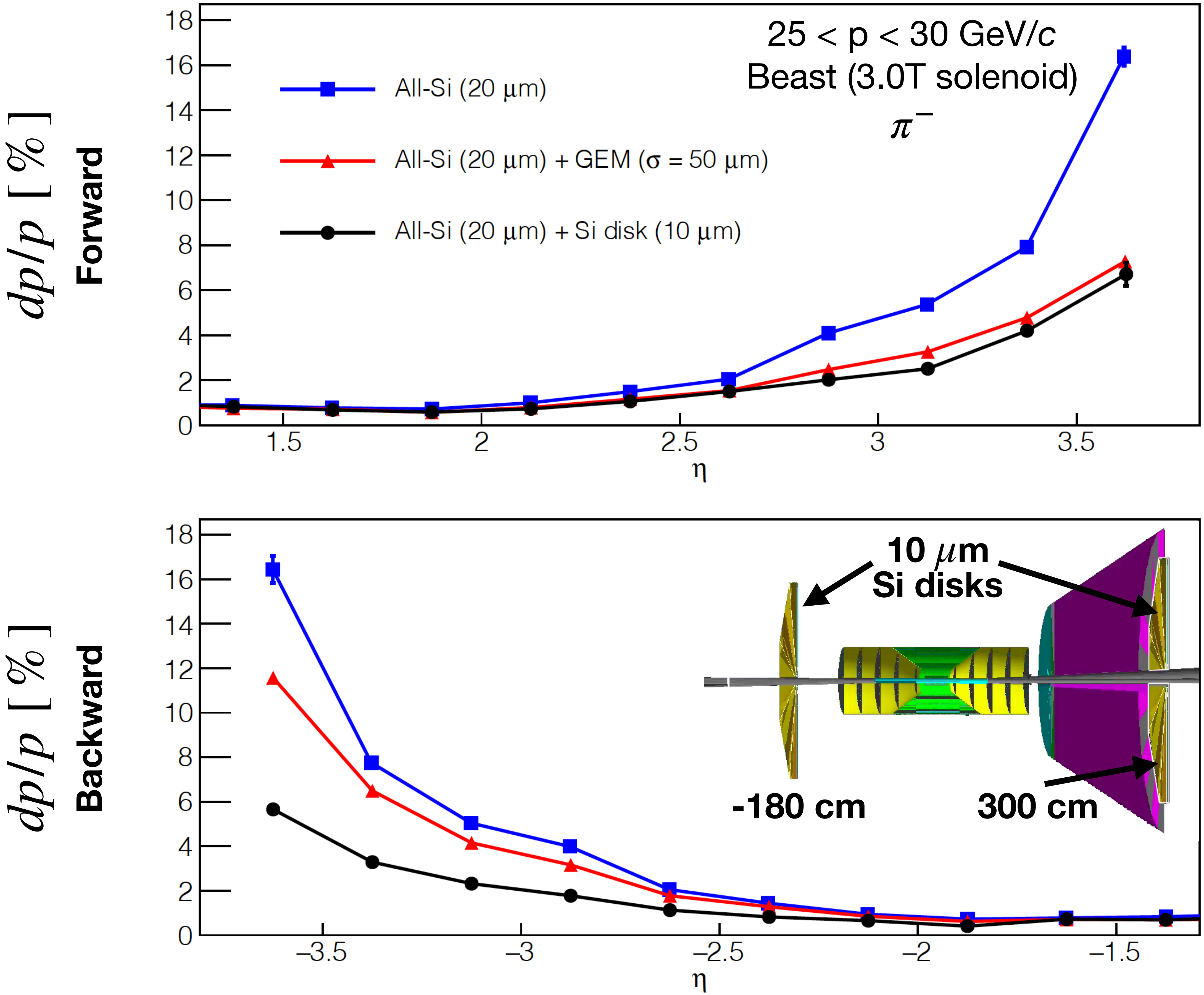


Complementing All-Si tracker with other detectors





Complementing All-Si tracker with other detectors



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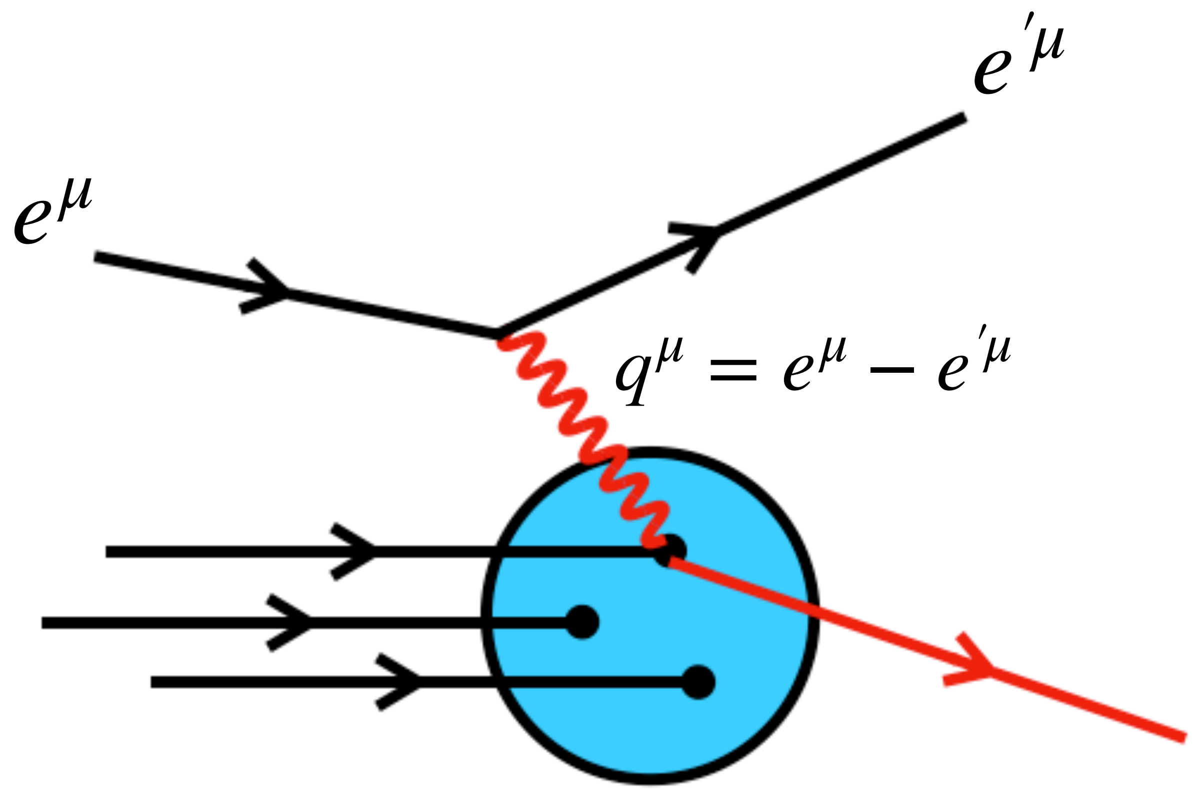
Electron scattering 101

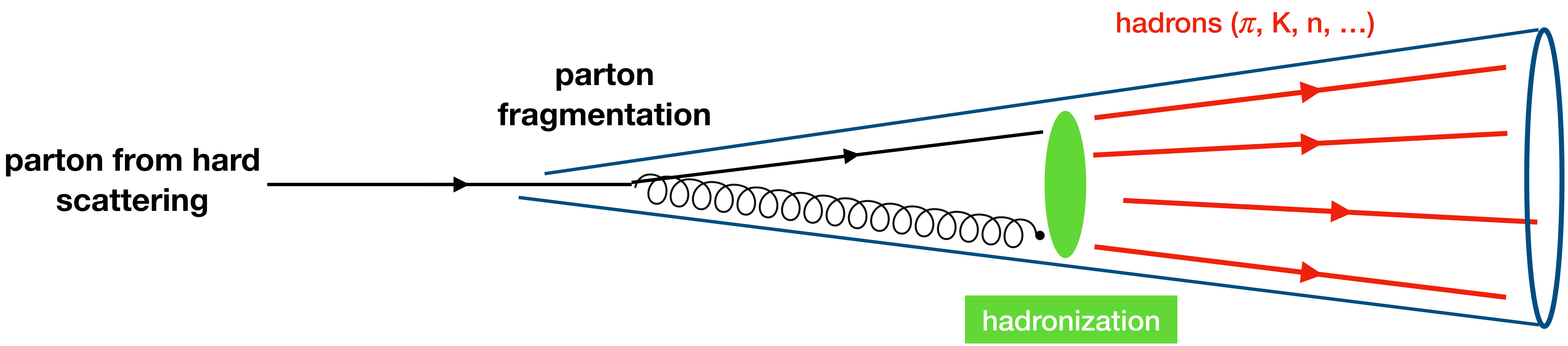


transfer energy	$\nu = E - E'$
transfer momentum squared	$Q^2 = -q^{\mu} \cdot q_{\mu}$
Bjorken scaling variable	$x_B = \dfrac{Q^2}{2m\nu}$
inelasticity	$y = \nu / E$

* structureless probe
* electromagnetic interaction well understood
* relative weakness of the electromagnetic interaction -> 1-photo exchange and probe of the entire nucleus
* tunable virtual photon wavelength

Jets

Collimated sprays of hadrons resulting from the fragmentation and subsequent hadronization of partons from hard scattering

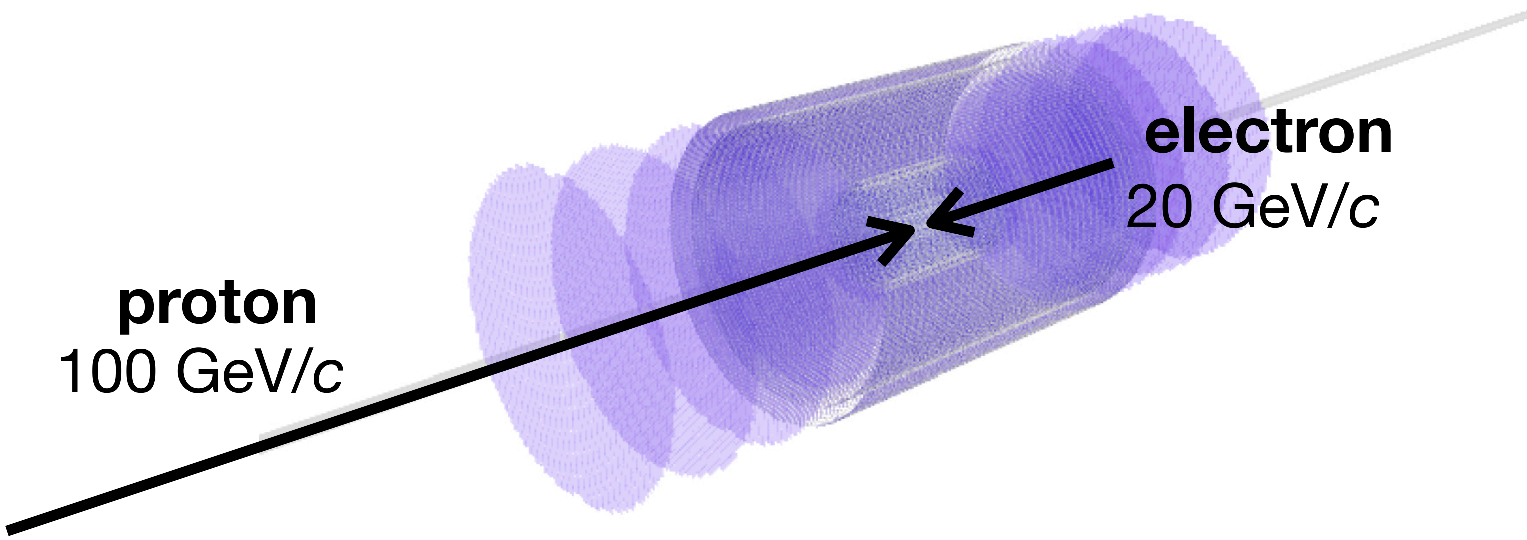


jets are sensitive to parton kinematics

Sensitive probes for EIC studies of:

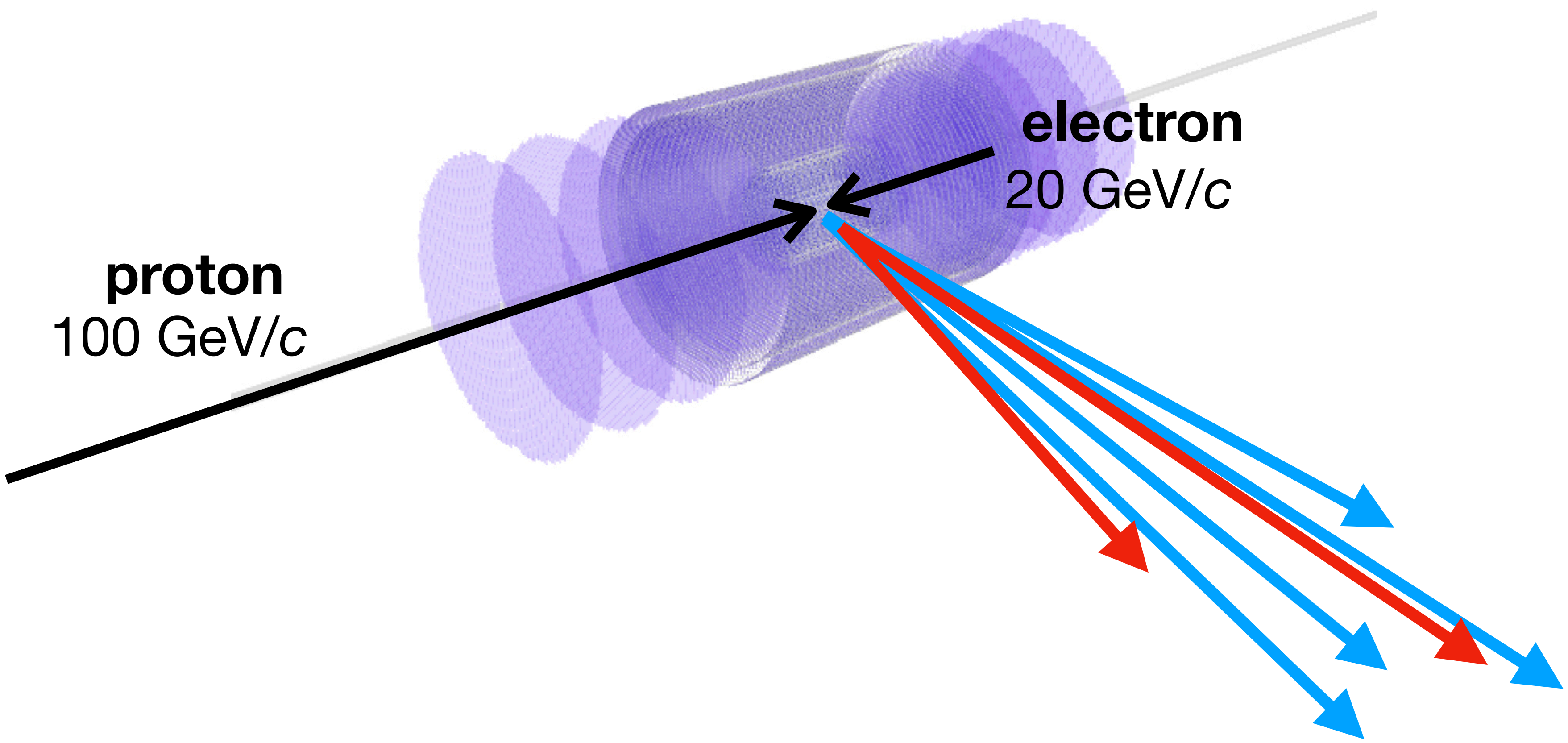
- energy loss and interactions in cold nuclear matter
- parton distribution functions (PDF) of protons, nuclei, photons
- transverse spin effects in the nucleon
- strangeness content of the proton

Pythia 8 generator and jet clustering



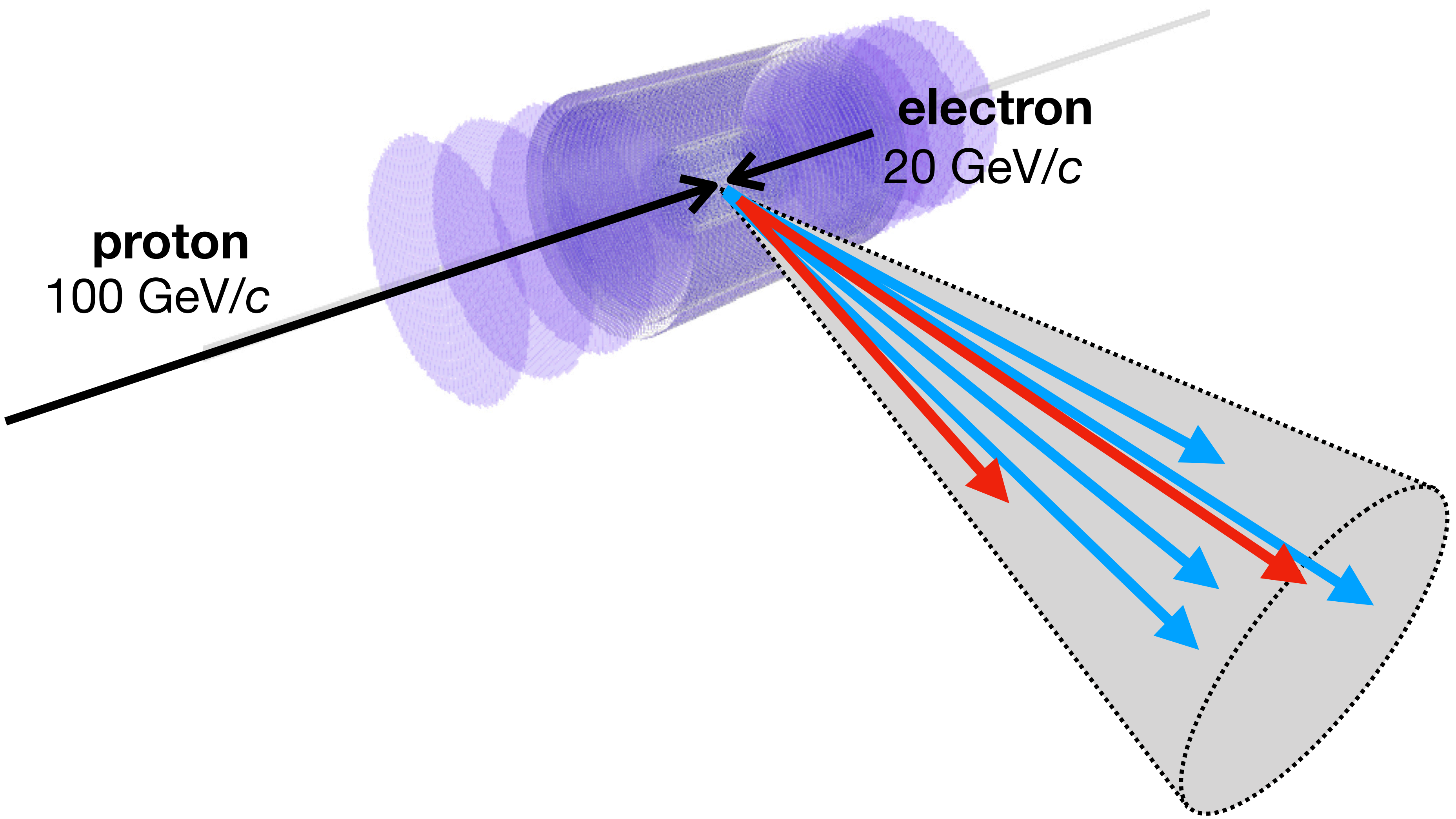
Pythia: Generator of physics processes that can occur in collisions between high-energy particles, e.g. at the LHC, EIC, …

Pythia 8 generator and jet clustering



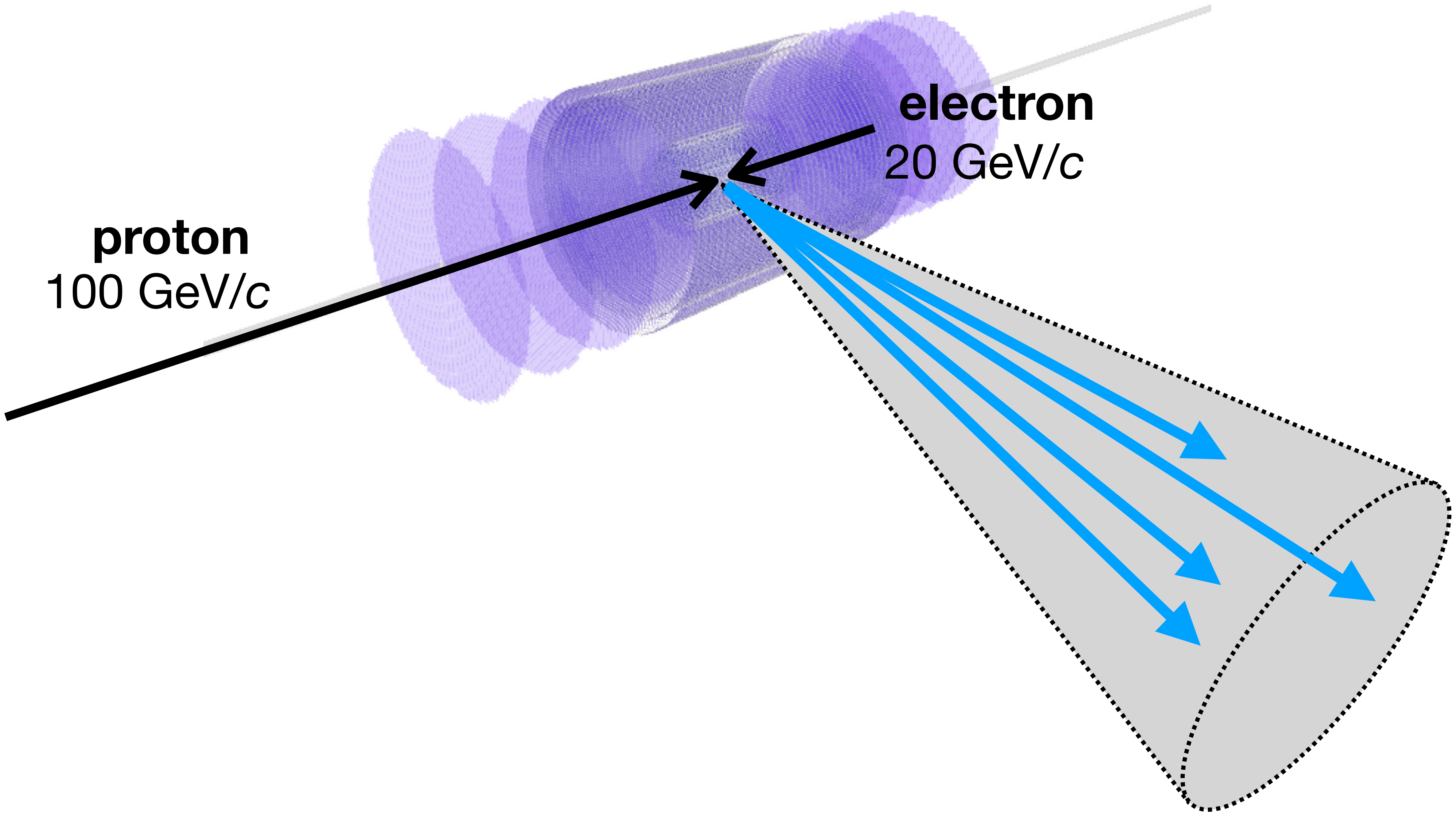
Pythia: Generator of physics processes that can occur in collisions between high-energy particles, e.g. at the LHC, EIC, …

Pythia 8 generator and jet clustering



Jets:
Anti-k_T
E-scheme
R = 1.0

Pythia 8 generator and jet clustering



Jets:
Anti-k_T
E-scheme
R = 1.0

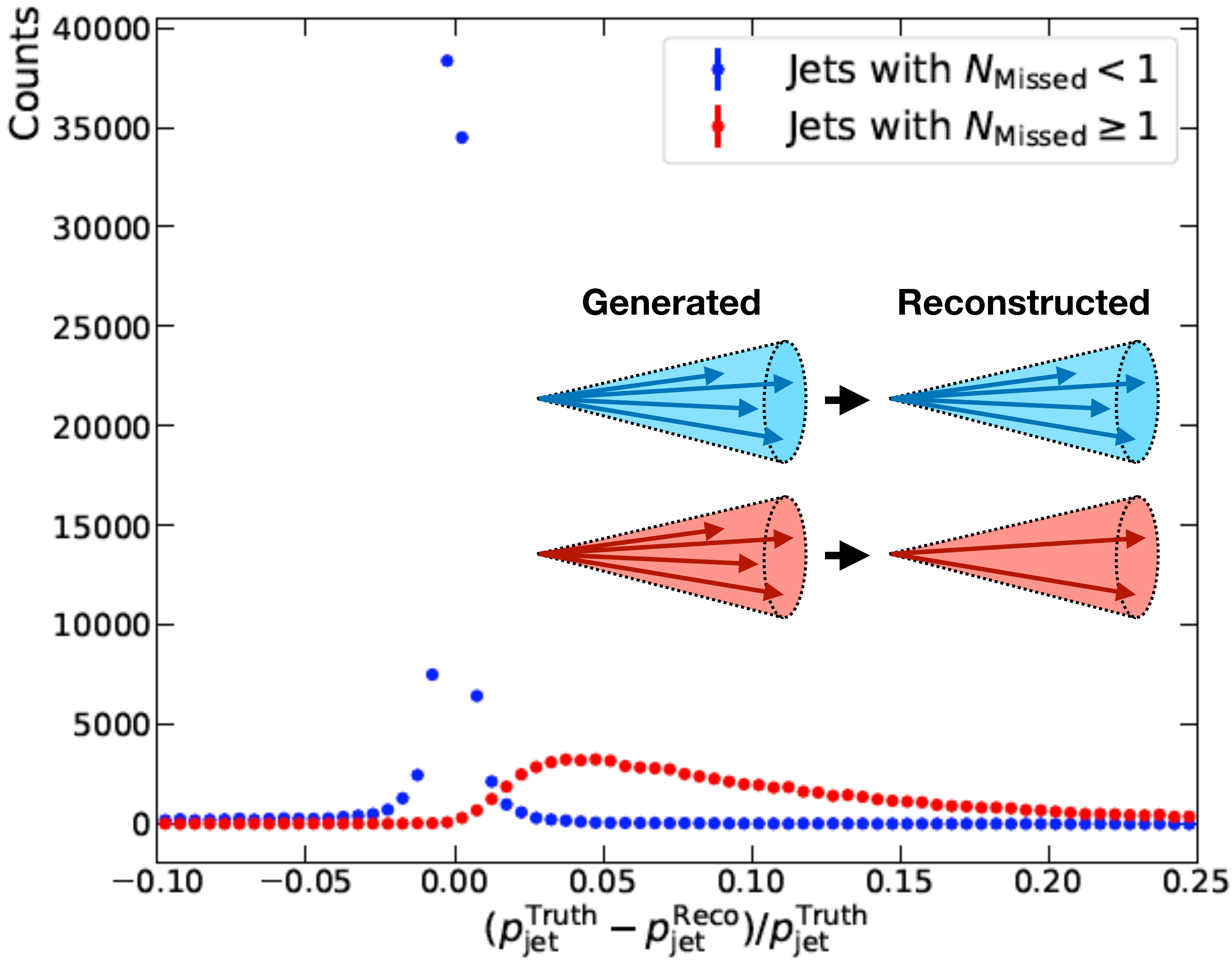
$$p^{jet,\,\mu}_{\mathrm{truth}} = p^{jet,\,\mu}_{\mathrm{charged}} + p^{jet,\,\mu}_{\mathrm{neutral}}$$

Sum of charged constituent 4-momenta

Sum of neutral constituent 4-momenta

We are using at the moment only tracker (i.e. the detector cannot "see" neutrals)

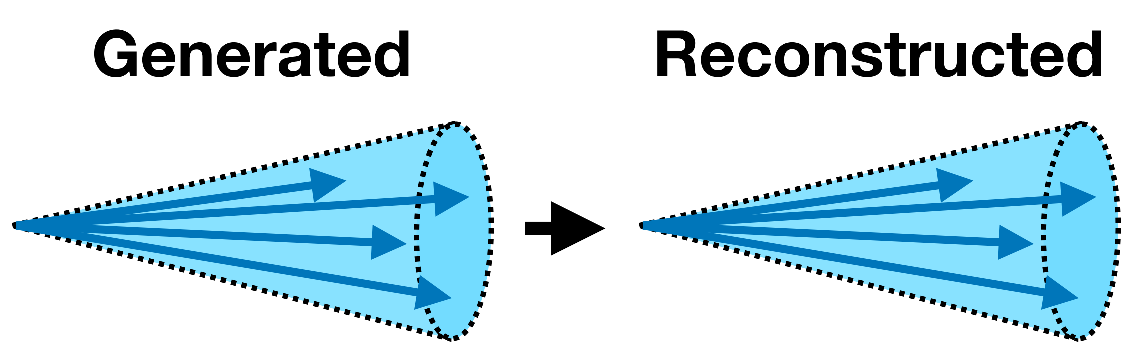
Jet reconstruction with the all-silicon tracker

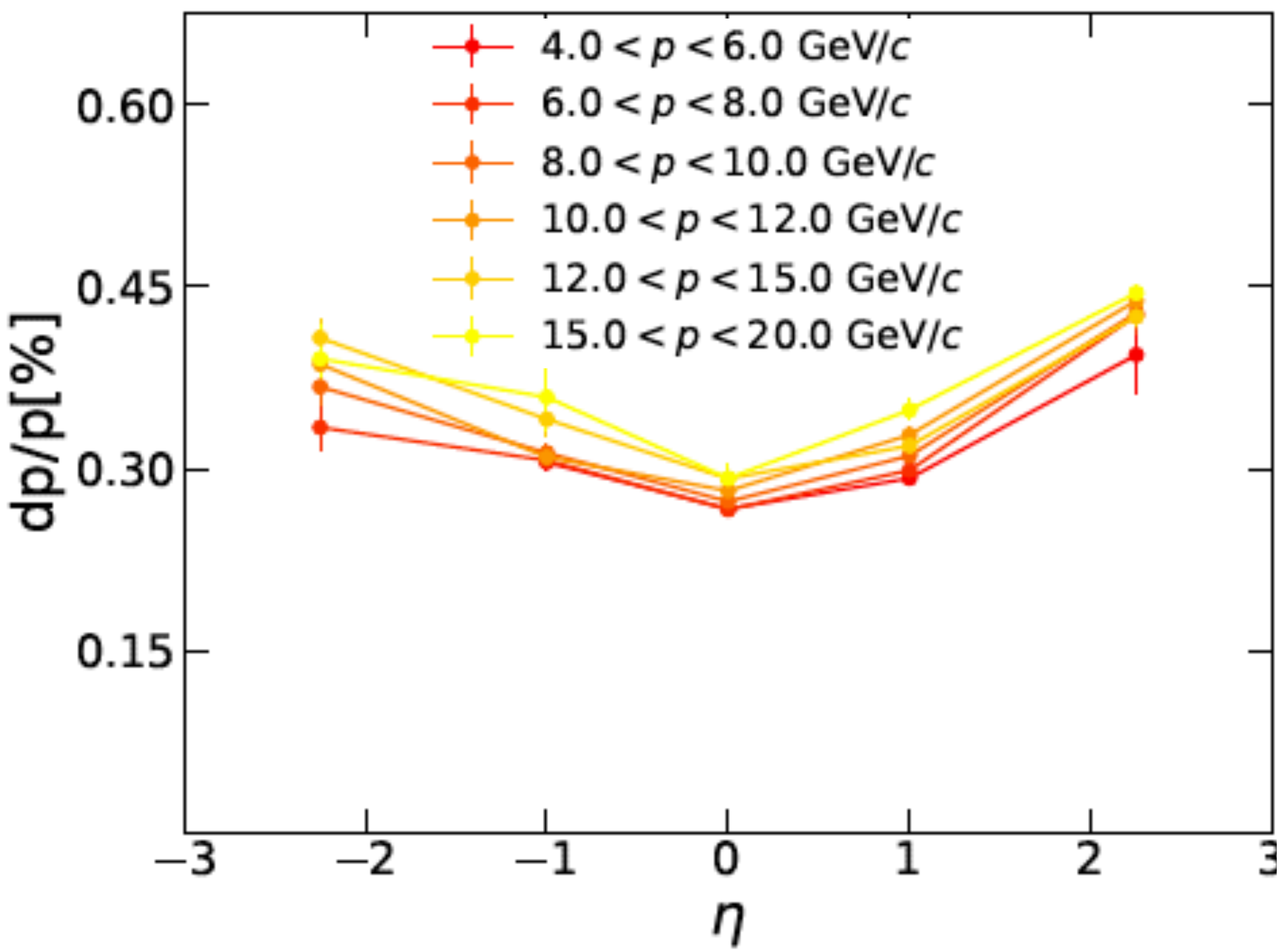


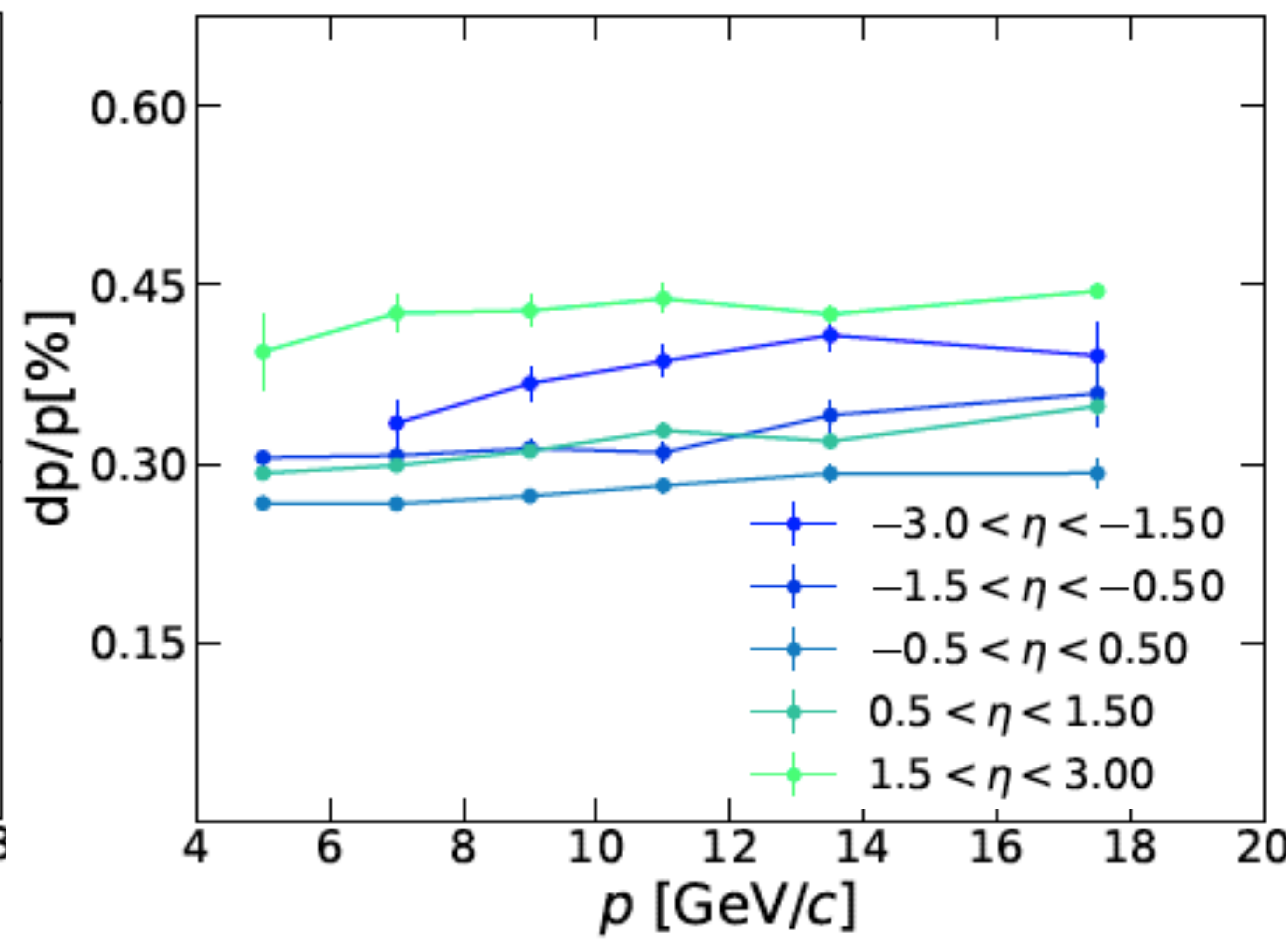
study by F. Torales Acosta

Jet momentum resolution

Jets with no missing constituents in the reconstruction





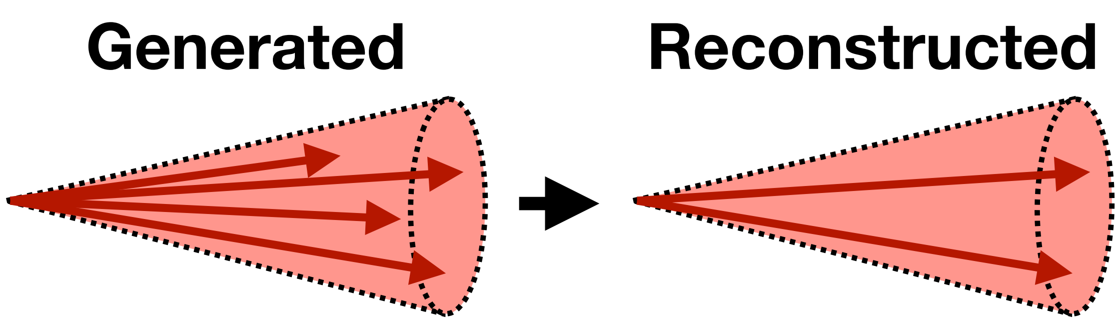


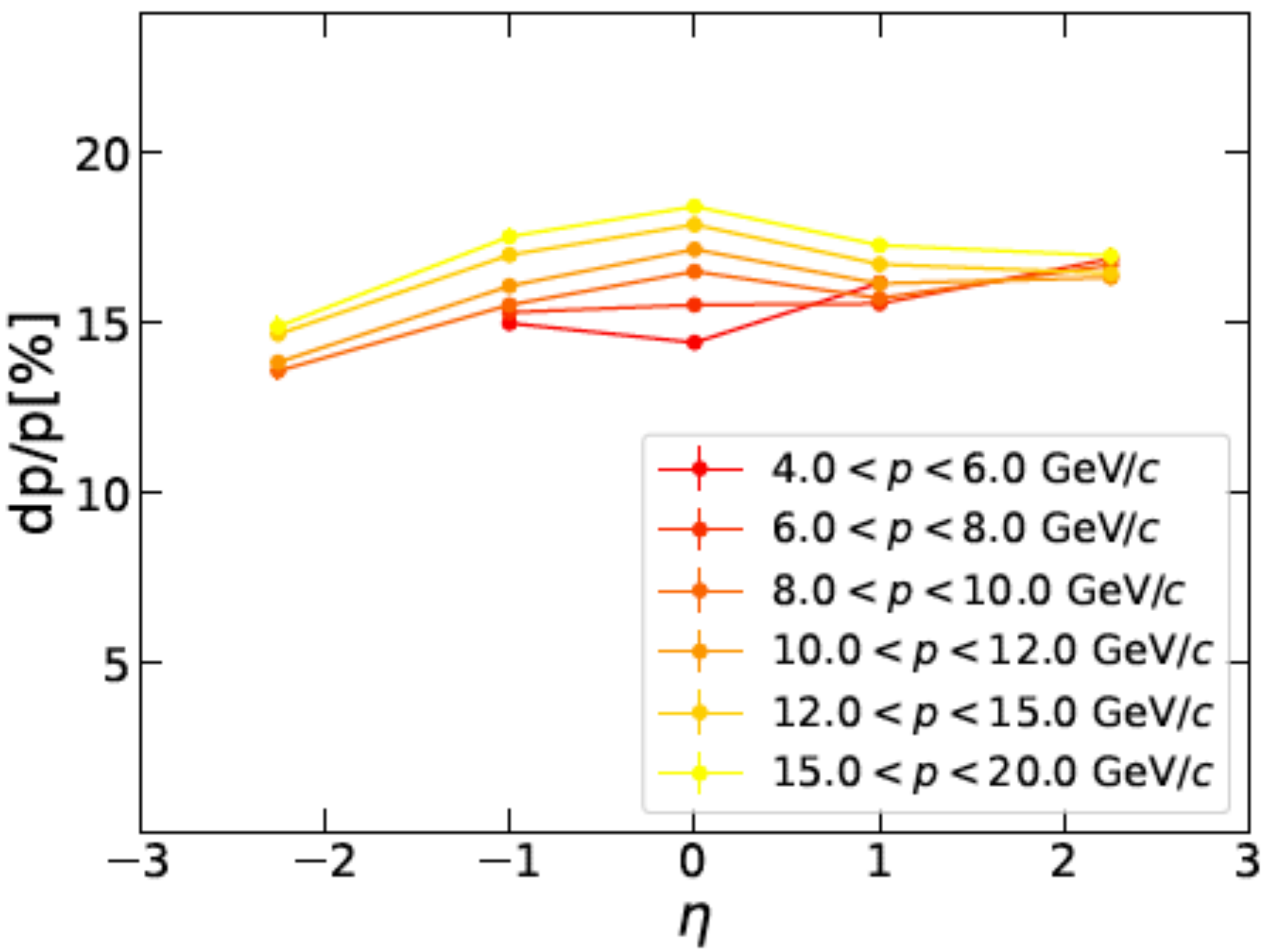
resolutions defined as the width of Gaussian fits

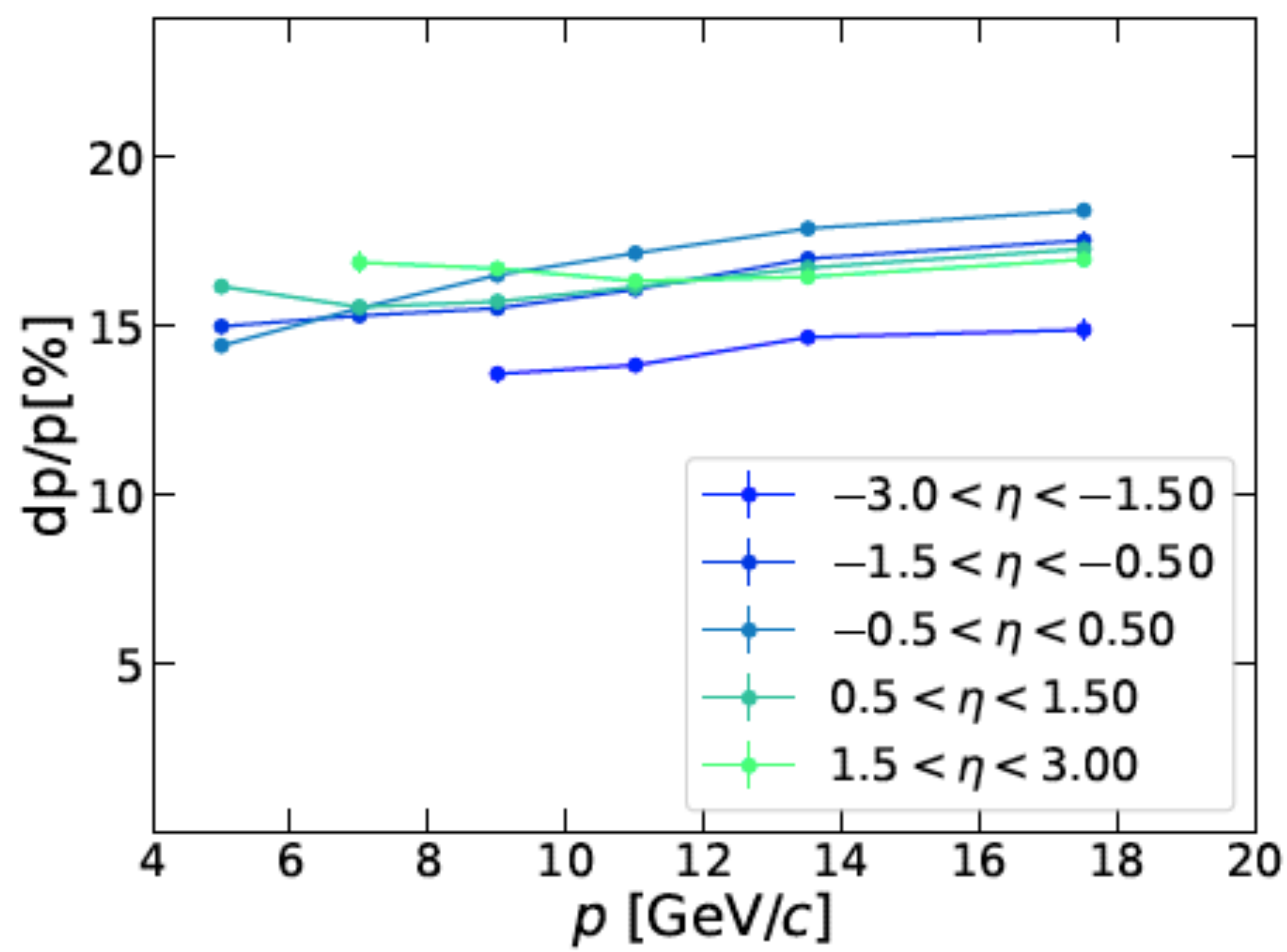
study by F. Torales Acosta

Jet momentum resolution

Jets with one or more missing constituents in the reconstruction







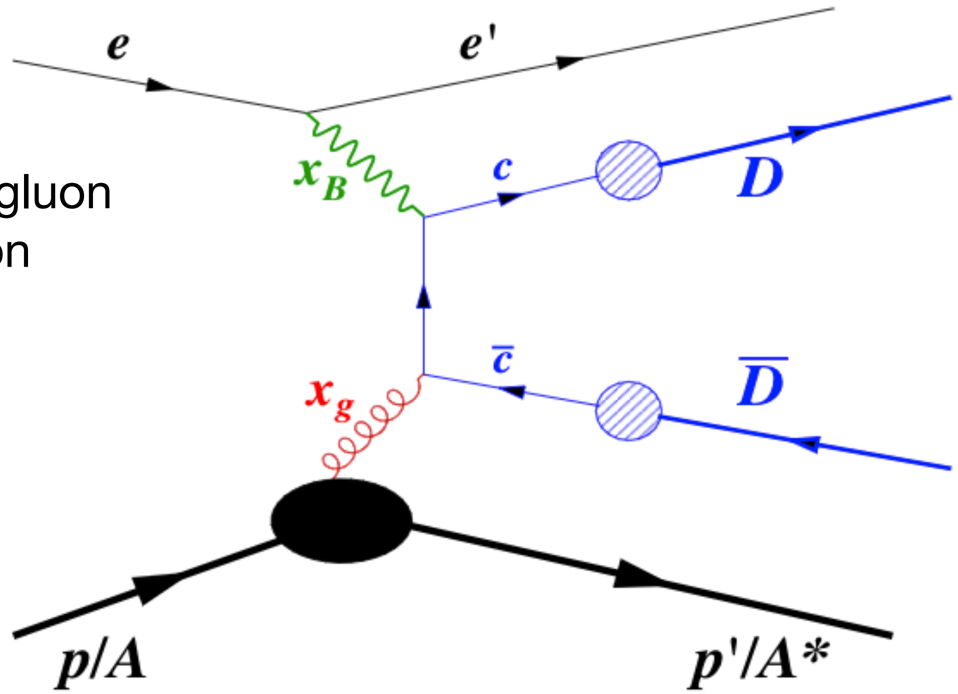
resolutions defined as the standard deviation of the dp/p distribution

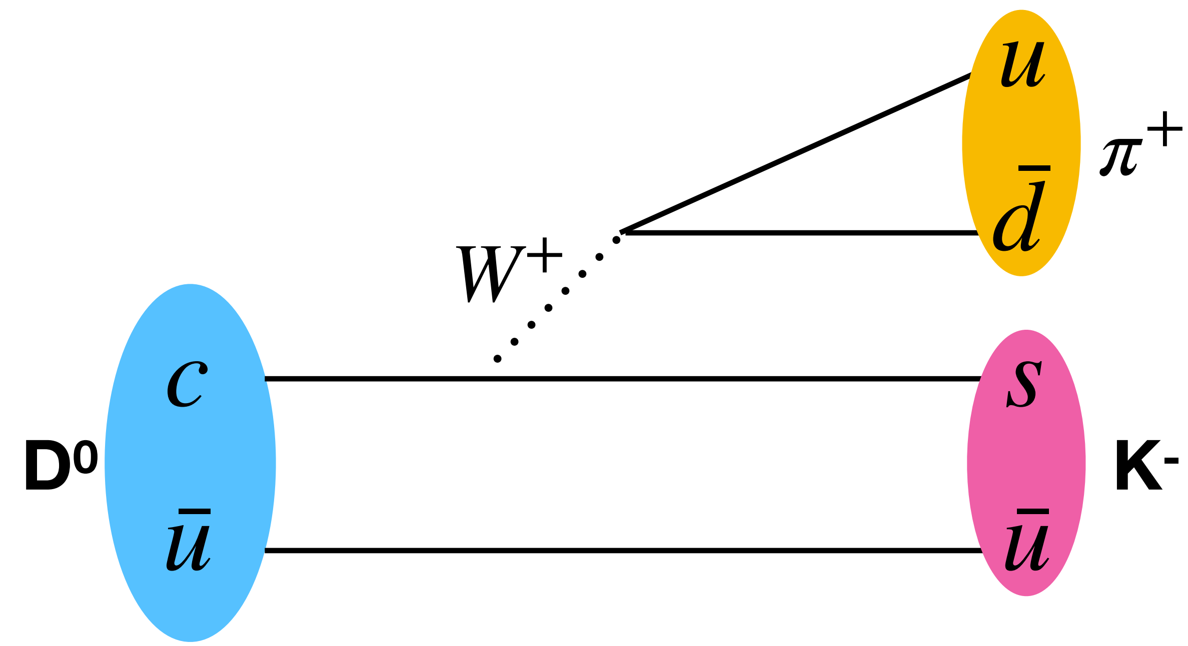
study by F. Torales Acosta

Heavy quark studies

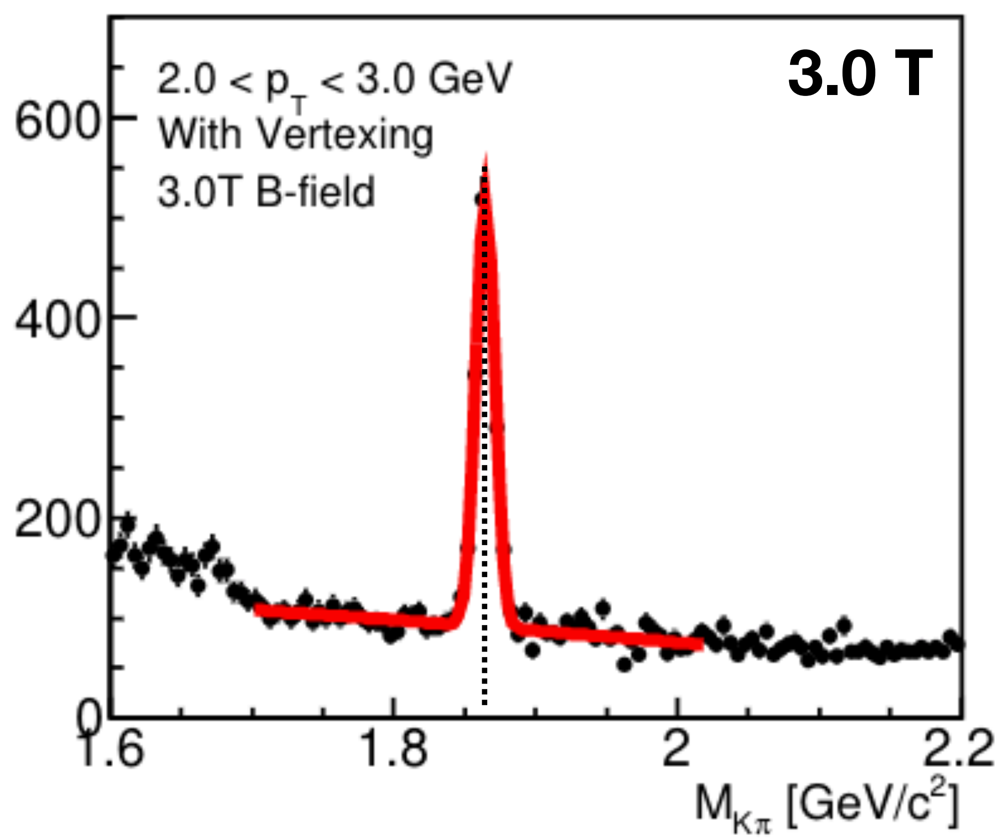
* Sensitive effects including gluon distributions, partonic structure of hadrons, fragmentation and hadronization effects, ...

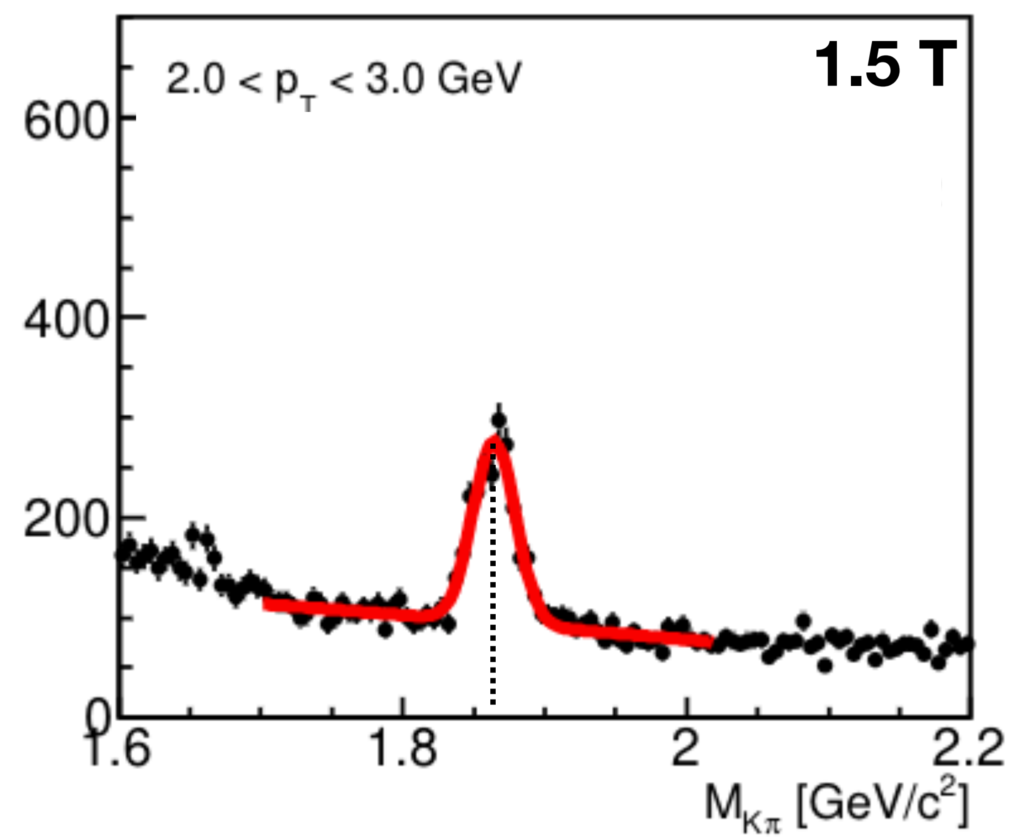
Photon-gluon fusion





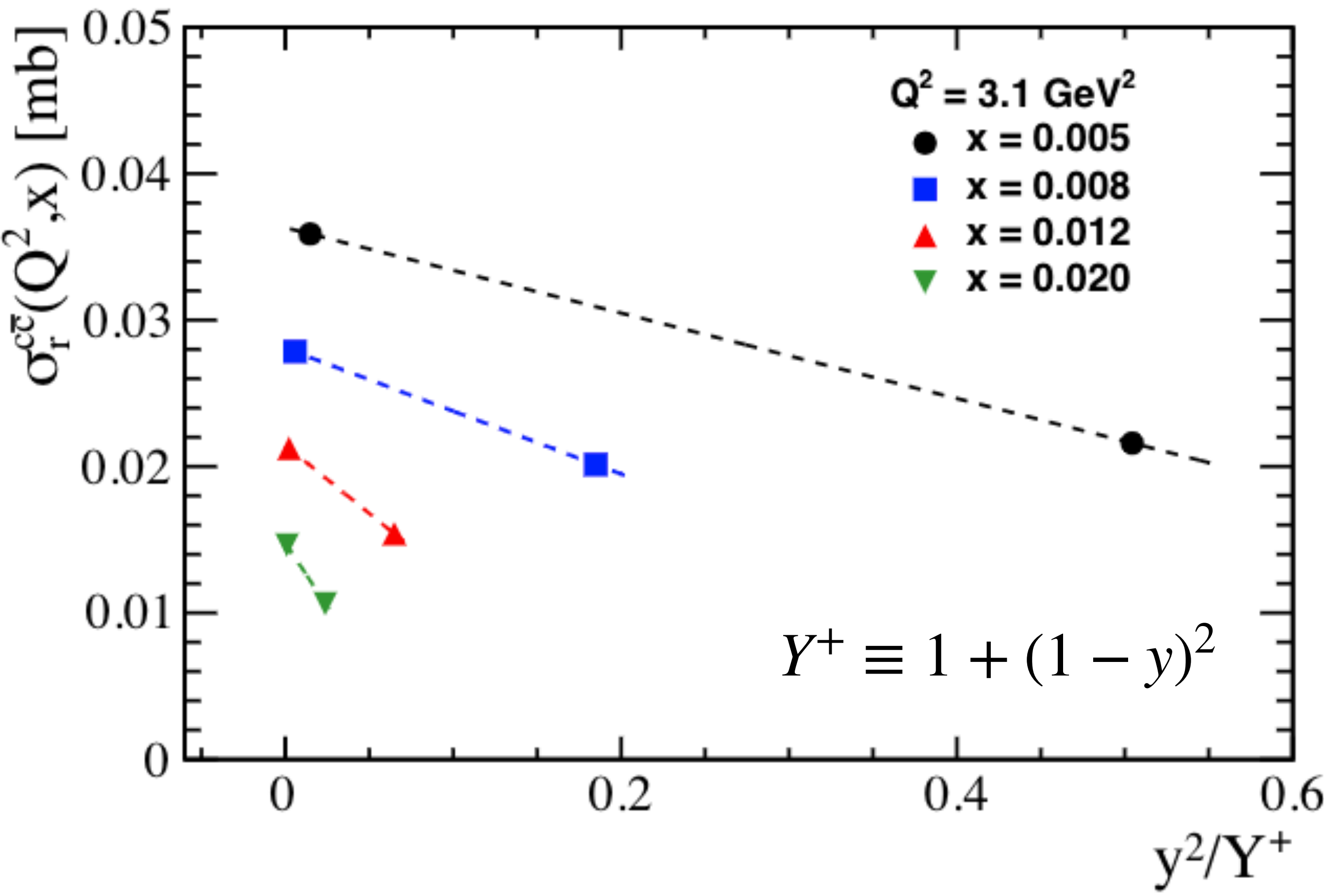
$m(D^0) = 1.86\ GeV/c^2$

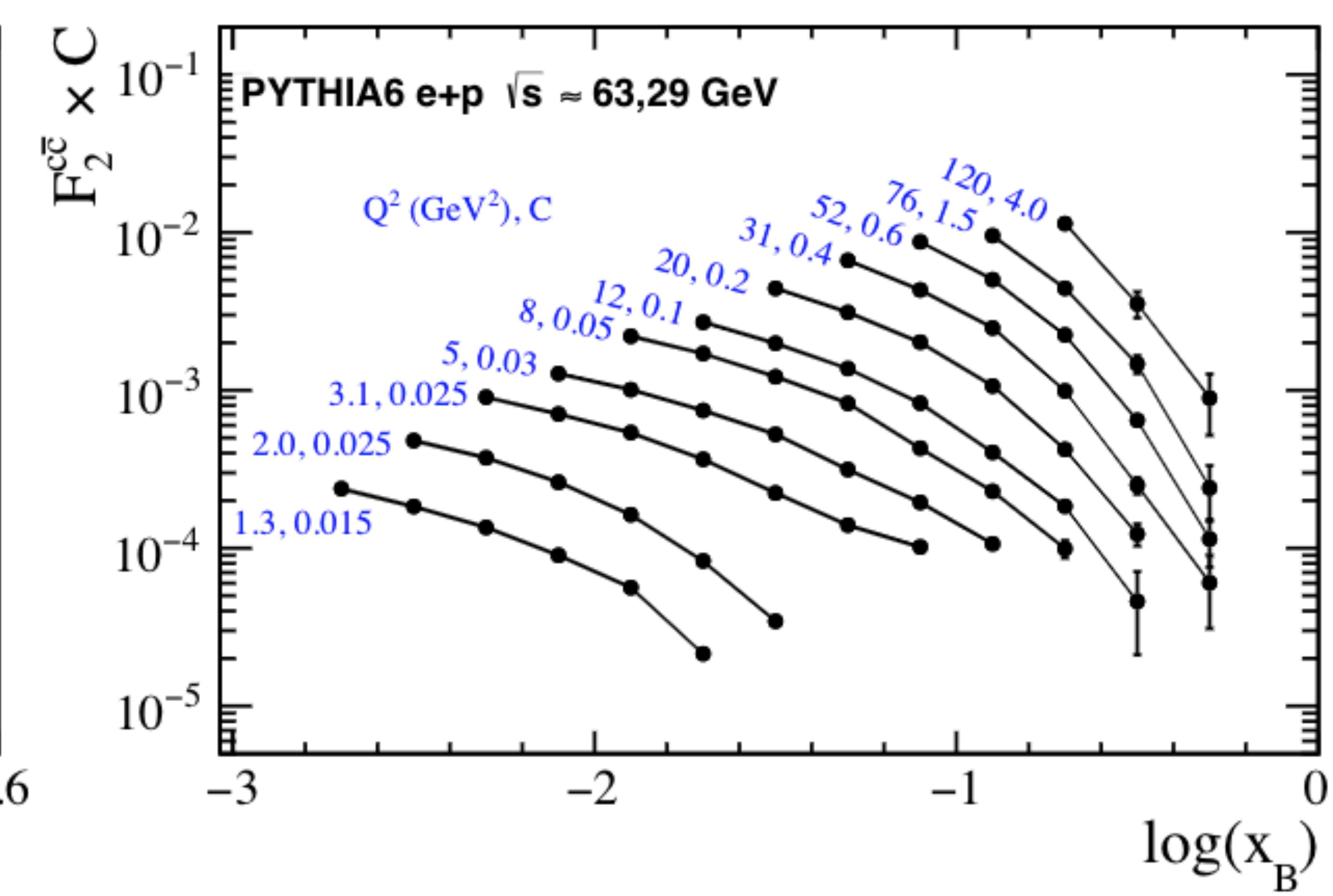




Extracting the $F_2^{c\bar{c}}$ structure function

$$\sigma_r^{c\bar{c}}(Q^2, x_B) = F_2(Q^2, x_B) - \frac{y^2}{Y^+} F_L(Q^2, x_B)$$





Structure functions:

* measure of the partonic structure of hadrons
* important for processes involving colliding hadrons
* key ingredient for deriving partons distributions in nucleons

These simulations confirm the feasibility of the all-silicon tracker for HF studies

Outline

Requirements for an EIC tracker

Using simulations to design a tracker

Testing tracker performance (resolutions)

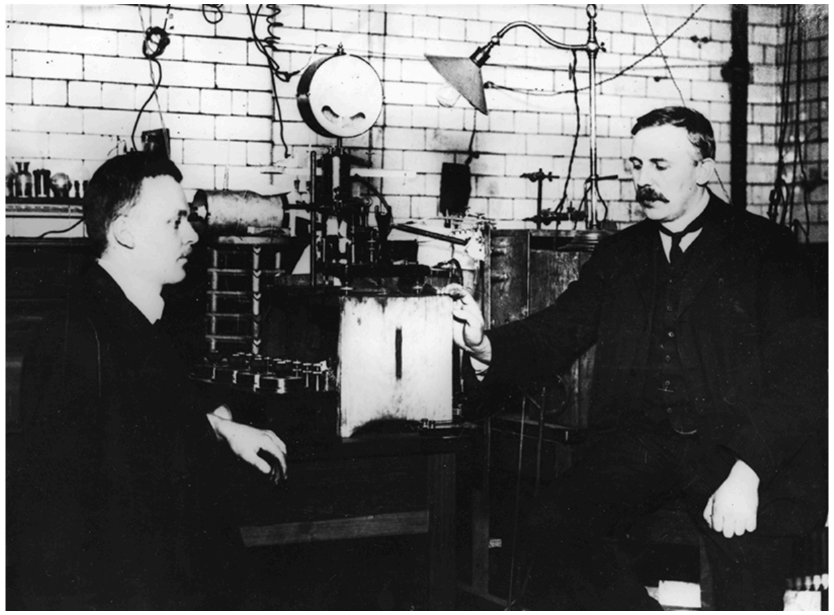
Improving performance when needed

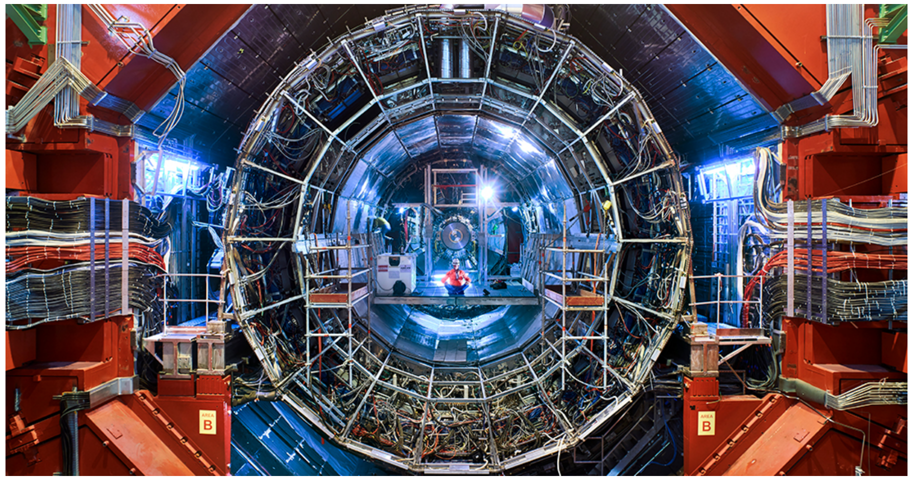
Jet studies with the tracker

Summary and Conclusions

Summary and Conclusions

- Simulations are needed to design the complex detectors used in modern nuclear and particle physics.





Summary and Conclusions

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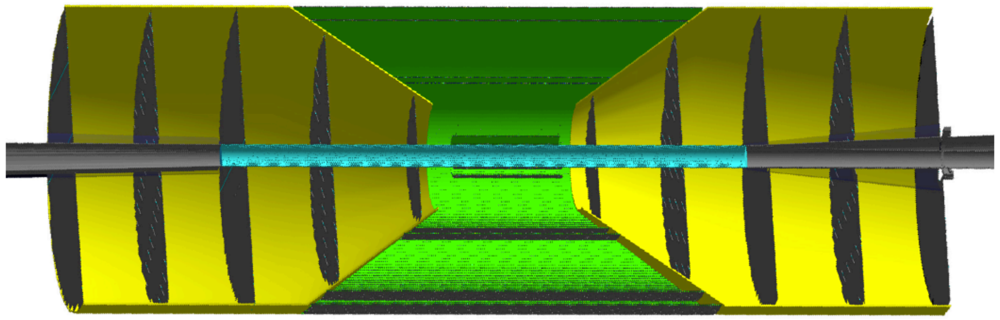
- We are designing an all-silicon tracker for the EIC using full simulations.



Summary and Conclusions

- Simulations are needed to design the complex detectors used in modern nuclear and particle physics.
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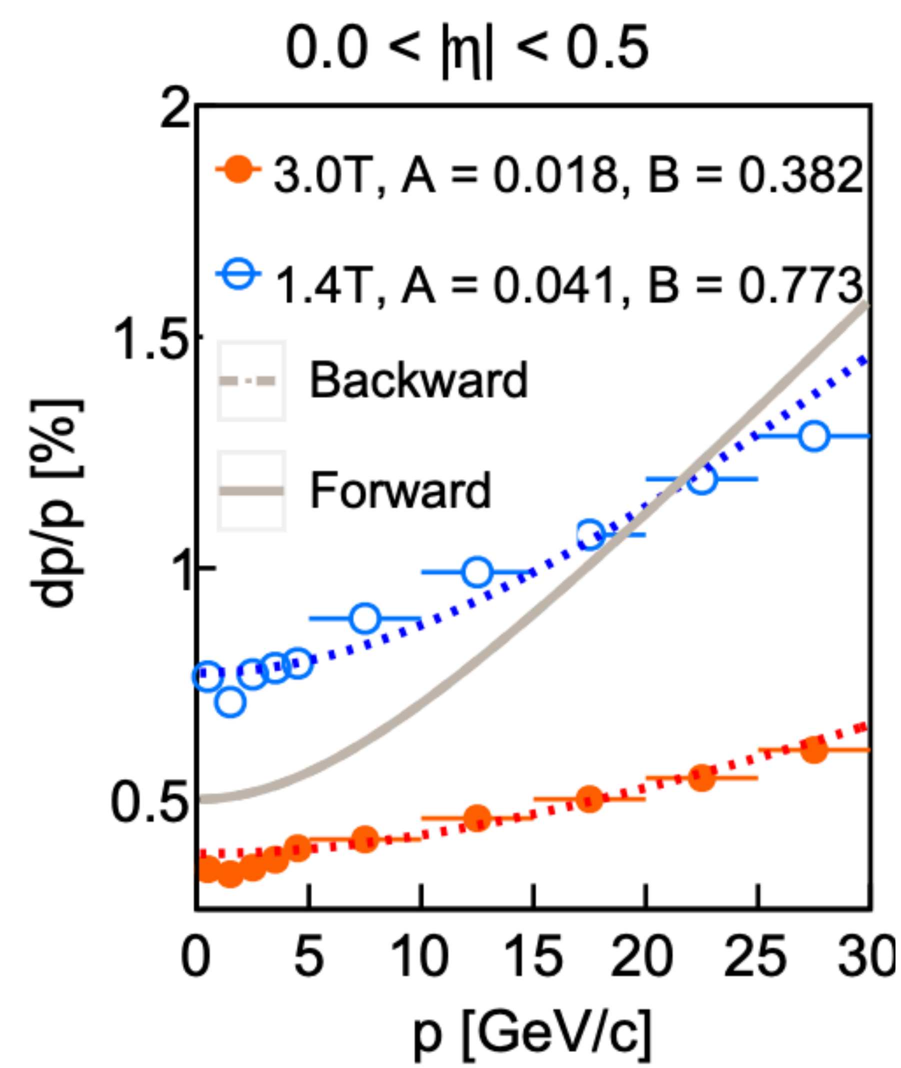
- This tracker satisfies the tracking requirements outlined by physics working groups (for $B = 3\,\mathrm{T}, |\eta| < 2.5$).



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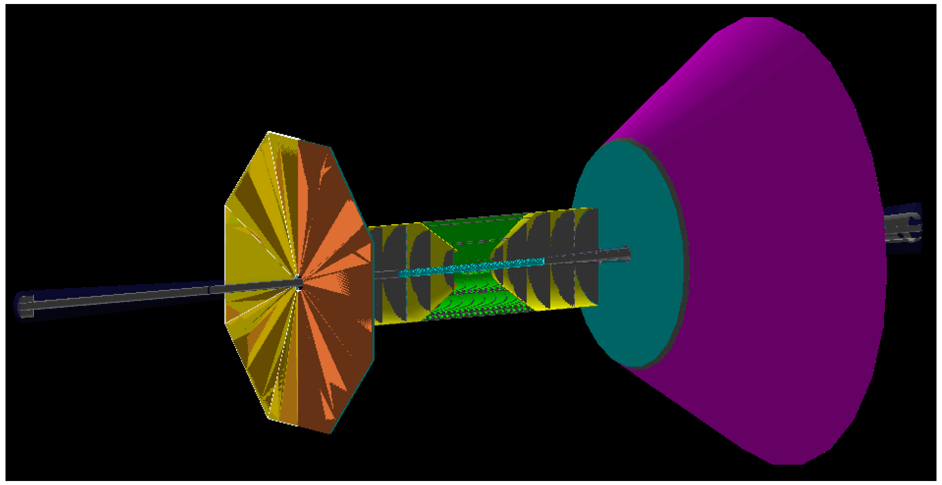

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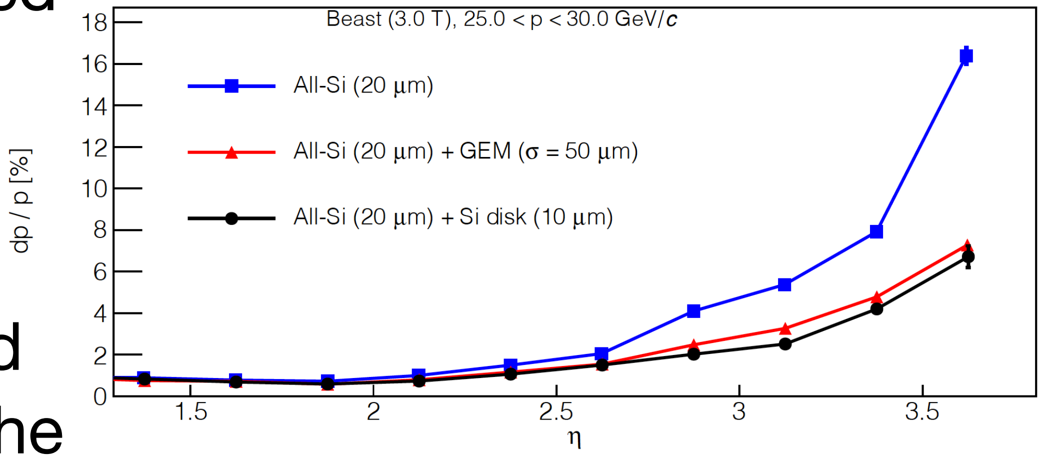

- The high-$|\eta|$ momentum resolution can be enhanced with the use of auxiliary tracking stations away from the IP.

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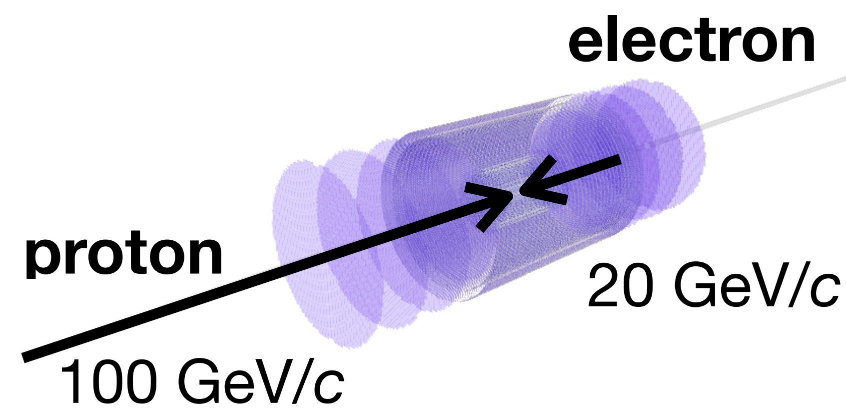

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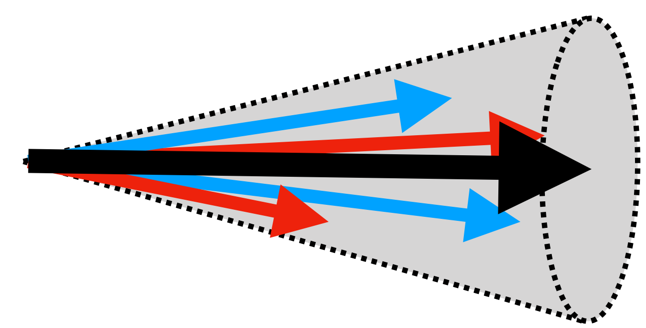
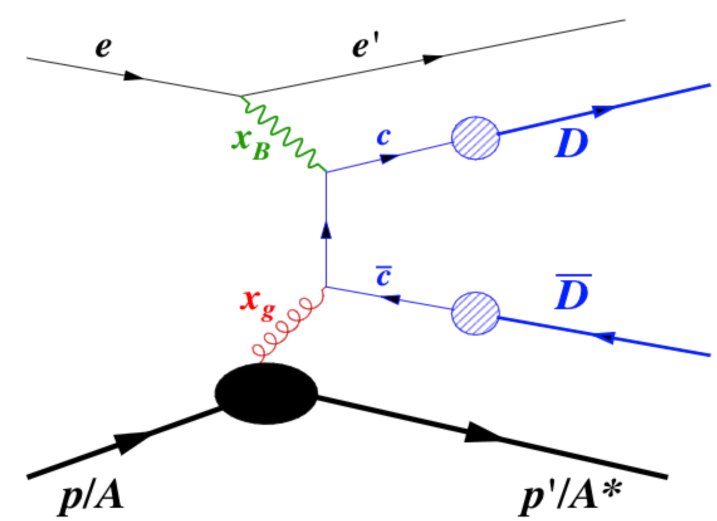


- The high-$|\eta|$ momentum resolution can be enhanced with the use of auxiliary tracking stations away from the IP.

- Once the detector is fully designed and characterized, the feasibility of different physics can be explored



Thanks for your attention