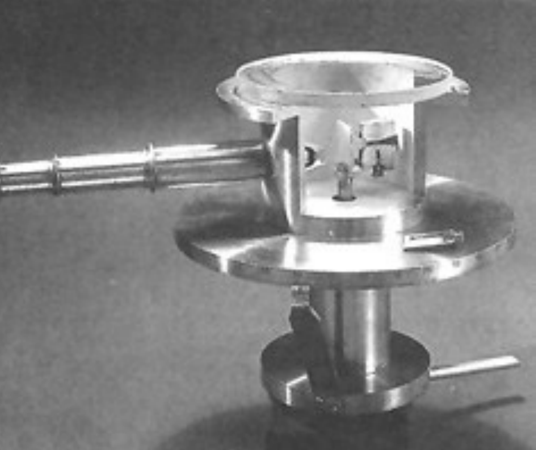
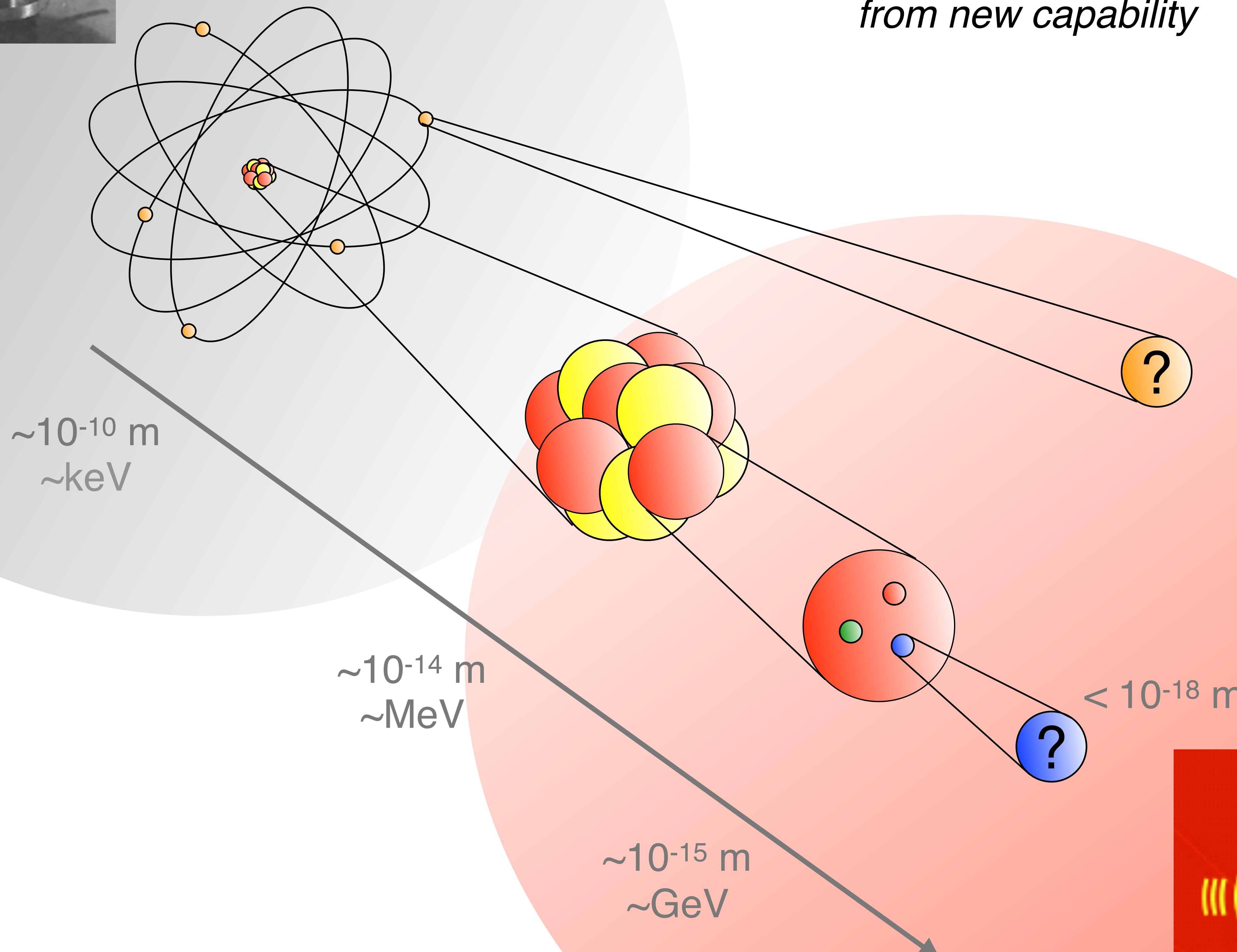
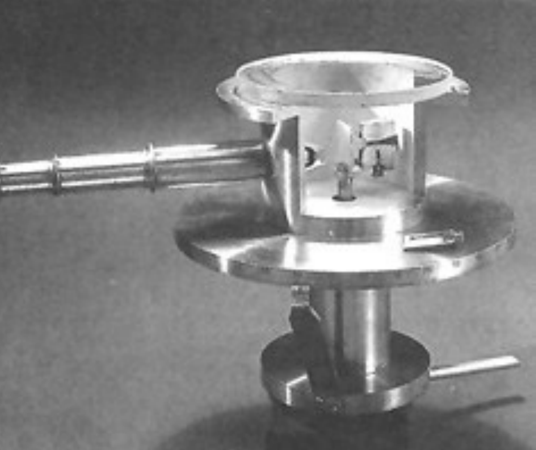
A history of new insight from new capability





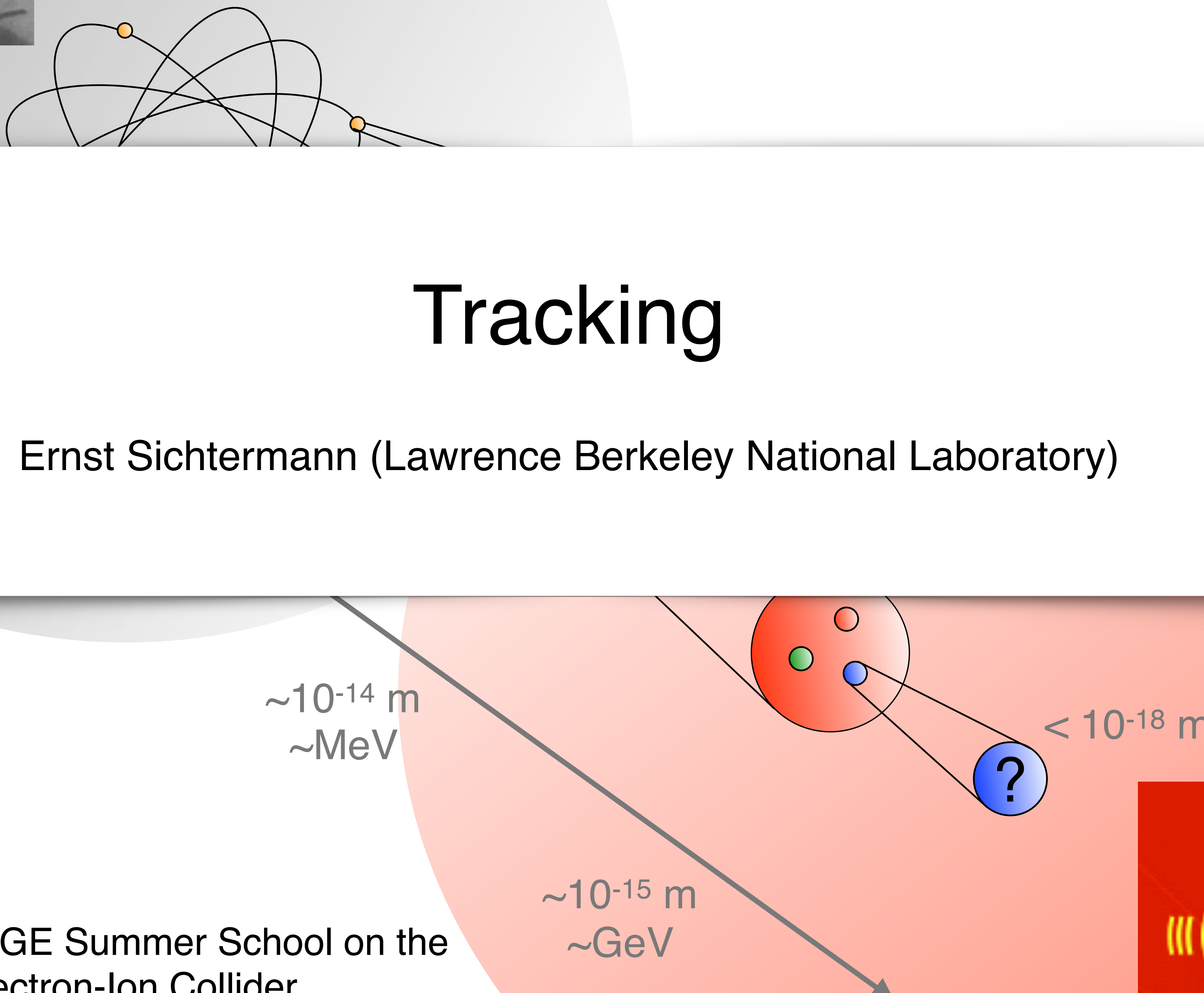
Funding support from:

Office of Science
U.S. Department of Energy



Tracking

Ernst Sichtermann (Lawrence Berkeley National Laboratory)



2025 CFNS-SURGE Summer School on the Physics of the Electron-Ion Collider
Stony Brook University — June 2-13, 2025

Many thanks to the organizers for organizing this school,

you for taking part!

Lectures like this are standing on the shoulders of giants… I owe a debt of gratitude to many giants — errors are of course my own.

References — Tracking

Some useful references:

PDG, “Passage of Particles Through Matter”, c.f.
https://pdg.lbl.gov/2025/reviews/rpp2024-rev-passage-particles-matter.pdf

W. Blum, W. Riegler, L. Rolandi “Particle Detection with Drift Chambers”, chapters 7 and 8 (2nd edition; 6 and 7 in the 1st edition),

The EIC community’s “Yellow Report”, Nucl. Phys. A 1026 (2022) 122447

R.L. Gluckstern, “Uncertainties in track momentum and direction, due to multiple scattering and measurement errors”, NIM 24 (1963) 381,

M. Valentan, M. Regler, R. Fruhwirth, “Generalization of the Gluckstern formulas II: Multiple scattering and non-zero dip angles”, NIM A 606 (2009) 728

P. Avery, Fitting Theory, https://phys.ufl.edu/~avery/fitting.html

Workshop on ACTS Tracking for Nuclear Physics 2025, indico.cern.ch/event/1501989

This list is *far* from complete — it is a start; there are many more.

Particle Detection — Tracking

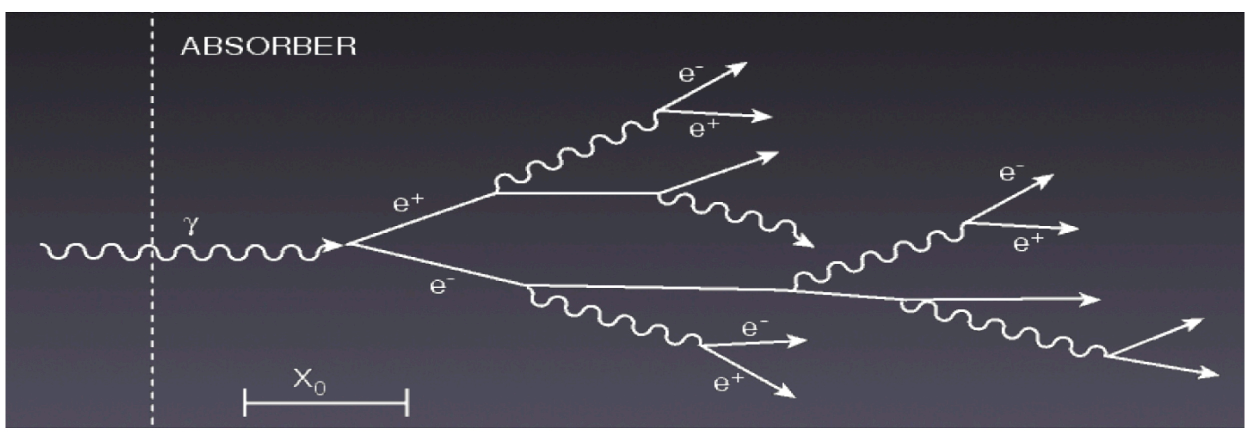
Roughly three classes of particle measurements:

Tracking and vertexing *— minimally invasive, often based on ionization energy transfer*

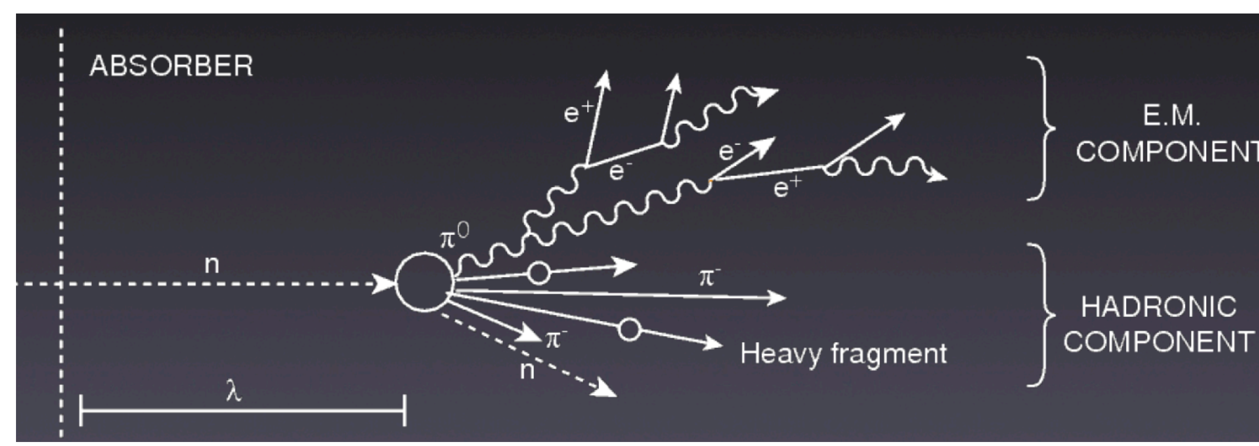
Particle Identification *— minimally invasive, multiple physics mechanisms:*

> *Ionization energy transfer,*
> *Time-of-flight of particles with different mass,*
> *Cherenkov radiation,*
> *Transition radiation,*

Calorimetry *— destructive; aims to capture all energy typically by stopping the particle.*



Electromagnetic



Hadronic

The distinction is, of course, not all that rigid. Time-Projection-Chambers, for example, often provide tracking and particle identification; Time-of-Flight systems often do so as well; Calorimeters are typically segmented and their hits provide some position info.

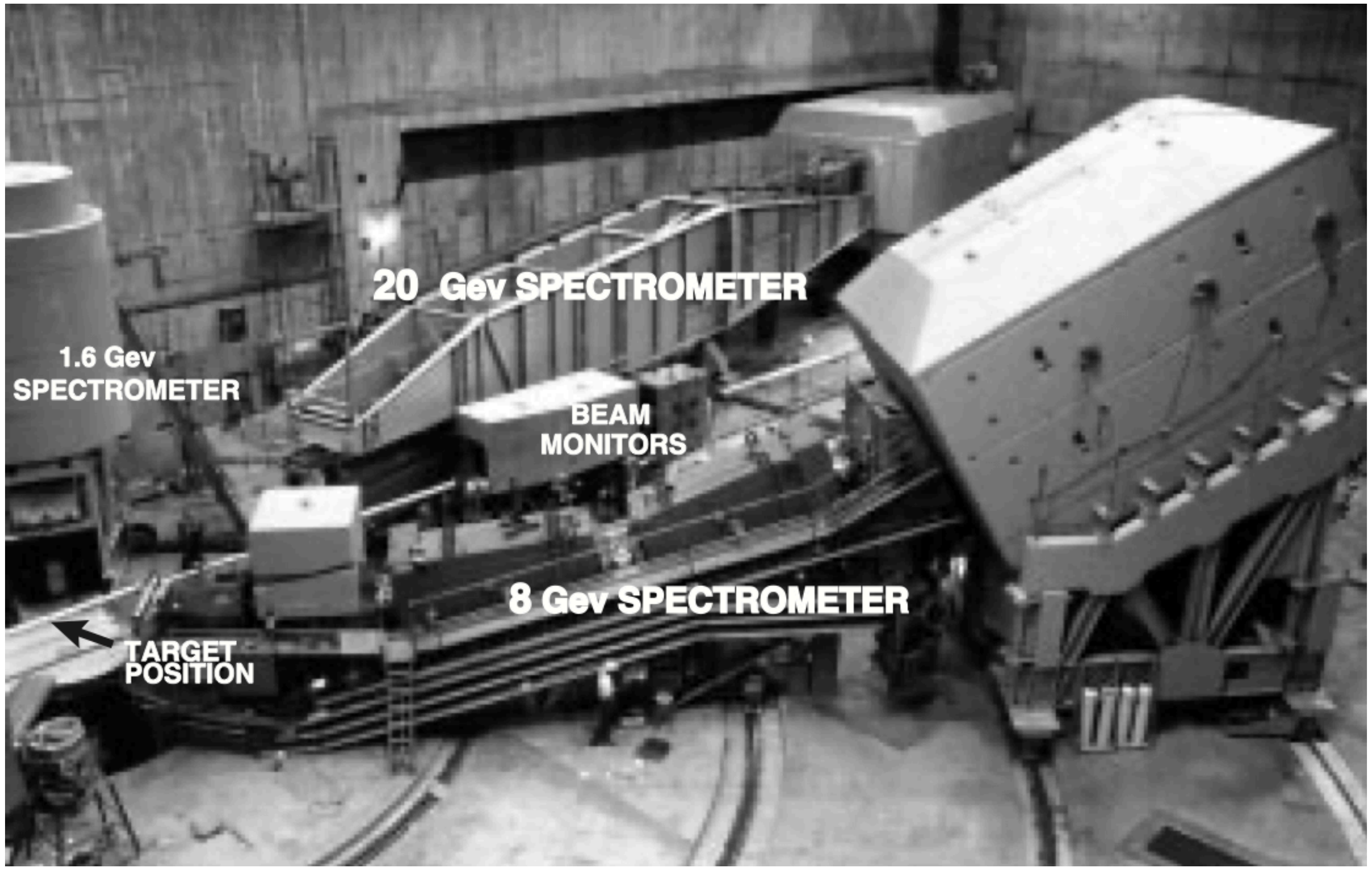
Perhaps for the evening, at what p, E do tracking and calorimeter resolutions cross?

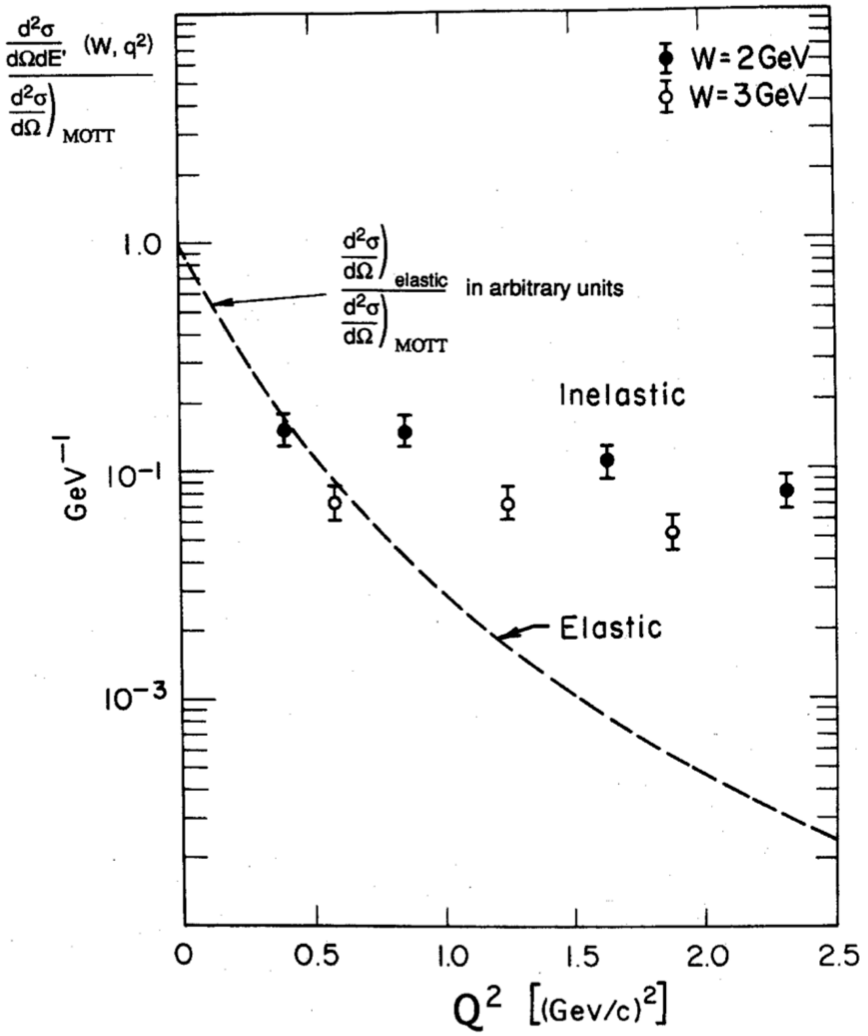
Particles and their Detection

Examples of common particles and their detection methods:

neutrinos	none	Missing energy
electrons	Ionisation, electromagnetic	Track and EM shower
muons	Ionisation	Penetrating track
p, K, π	Ionisation, hadronic	Track and hadron shower
photons	electromagnetic	EM shower
neutrons, K^0_L	hadronic	hadron shower
B, D	Weak decay	Secondary vertex
J/ψ, Υ, W, Z, H, t	prompt decay	Invariant mass

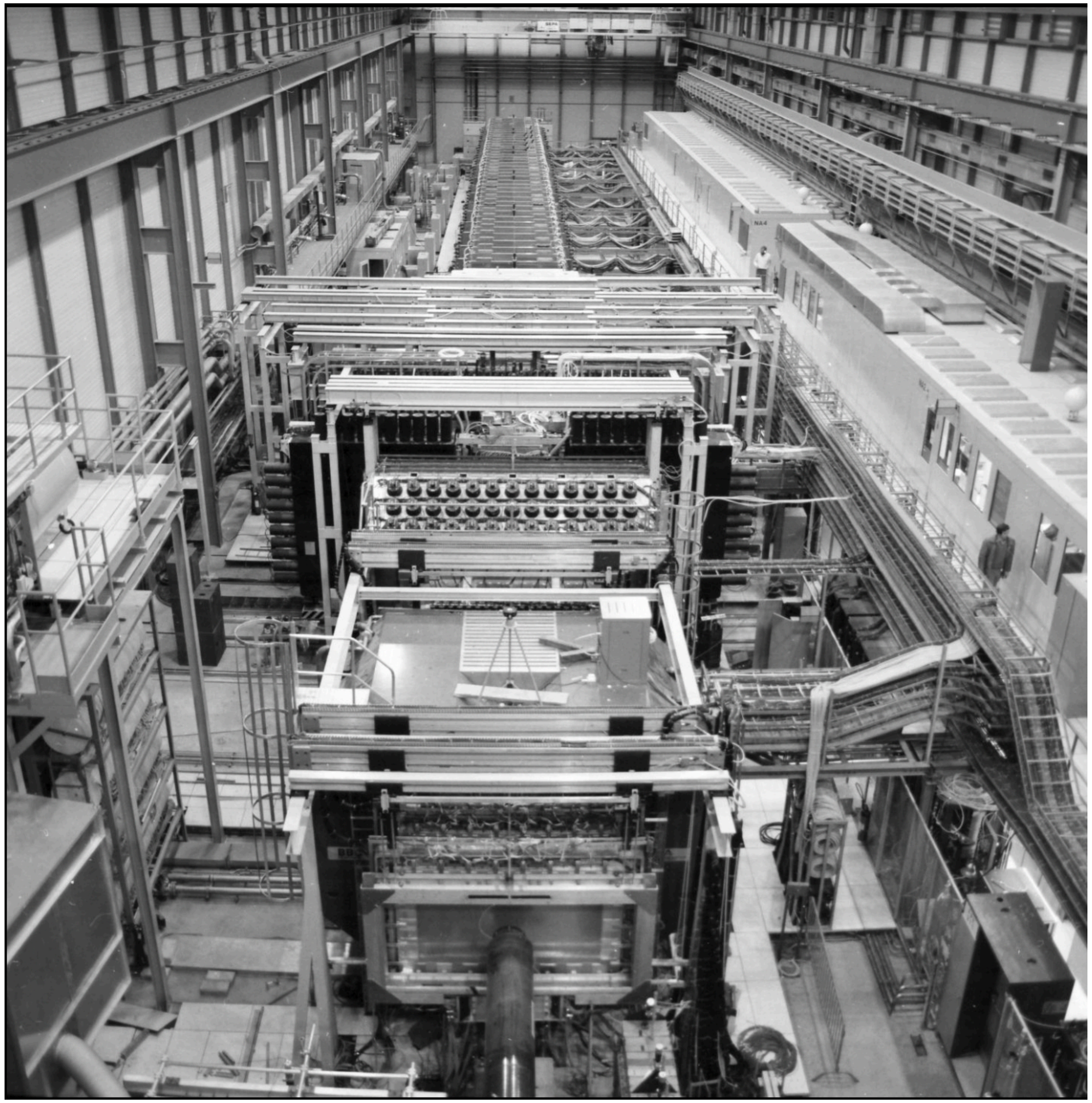
Tracking — SLAC fixed target experiment





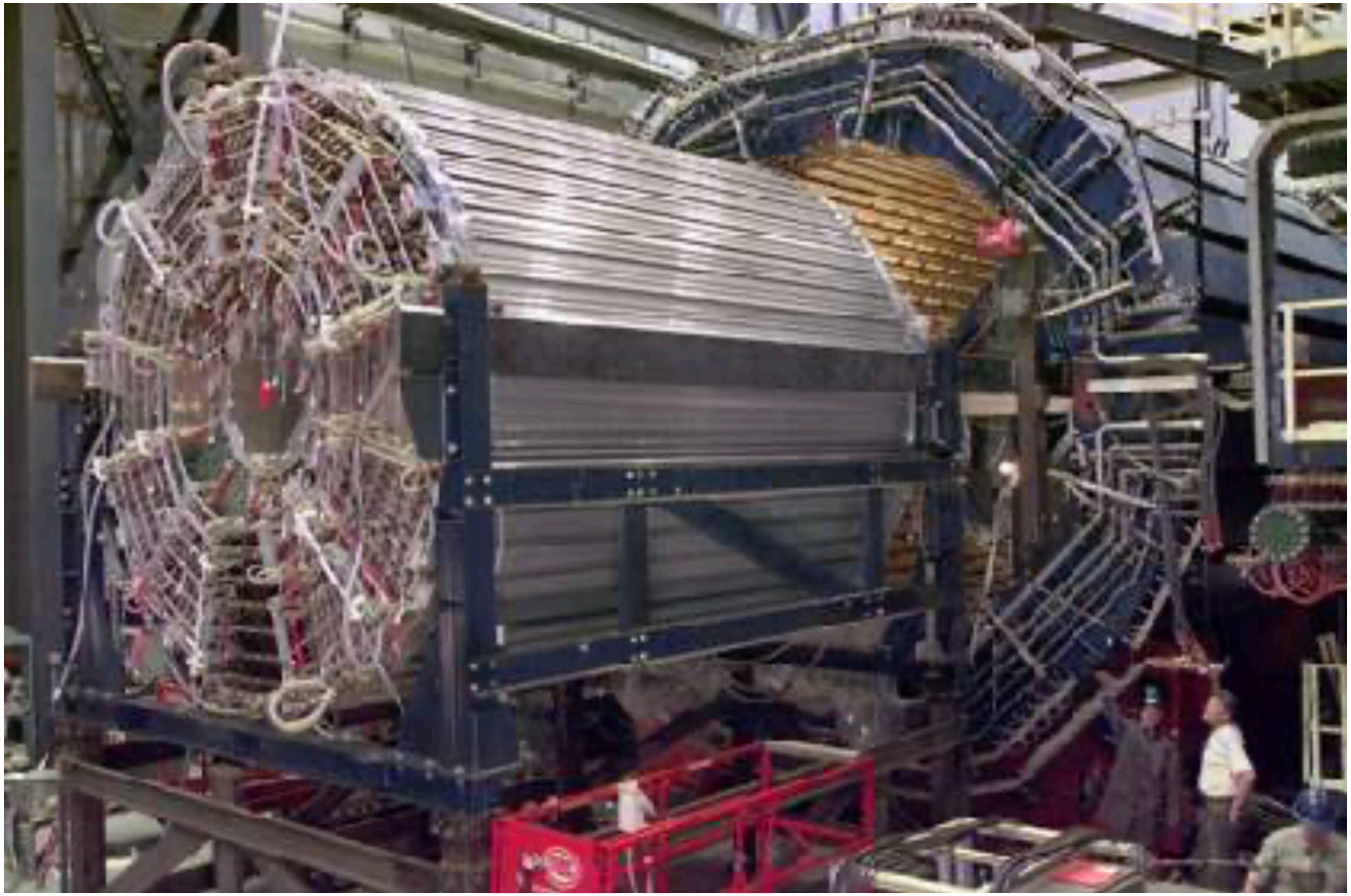
R.E. Taylor, "The discovery of Point-like Structure of Matter", SLAC-PUB-8640 (2000)

Tracking — CERN fixed target experiment



T. Sloan, “History of the European Muon Collaboration (EMC)”, CERN-2019-005
CERN-Photo-8002006

Tracking — RHIC experiment

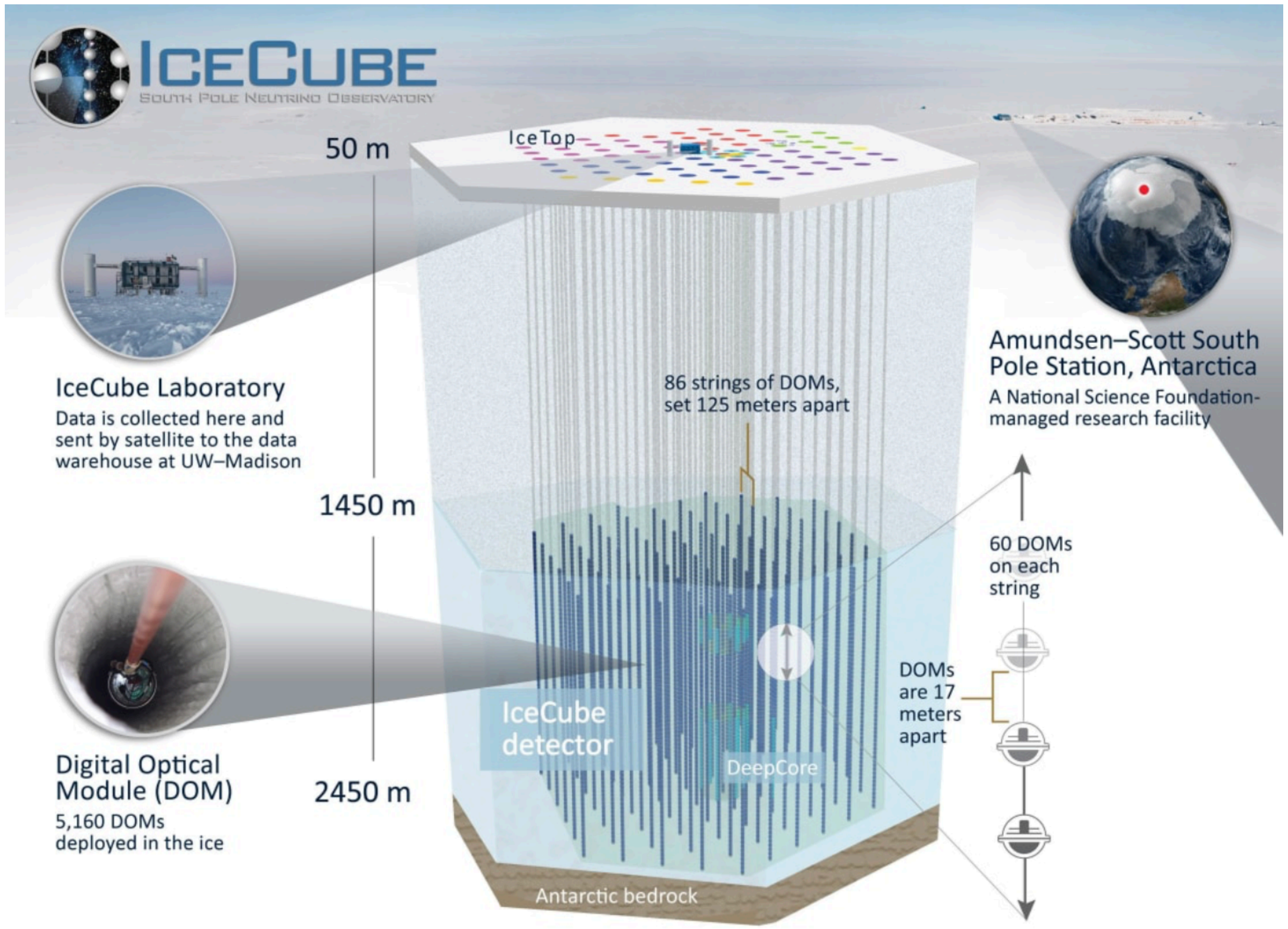


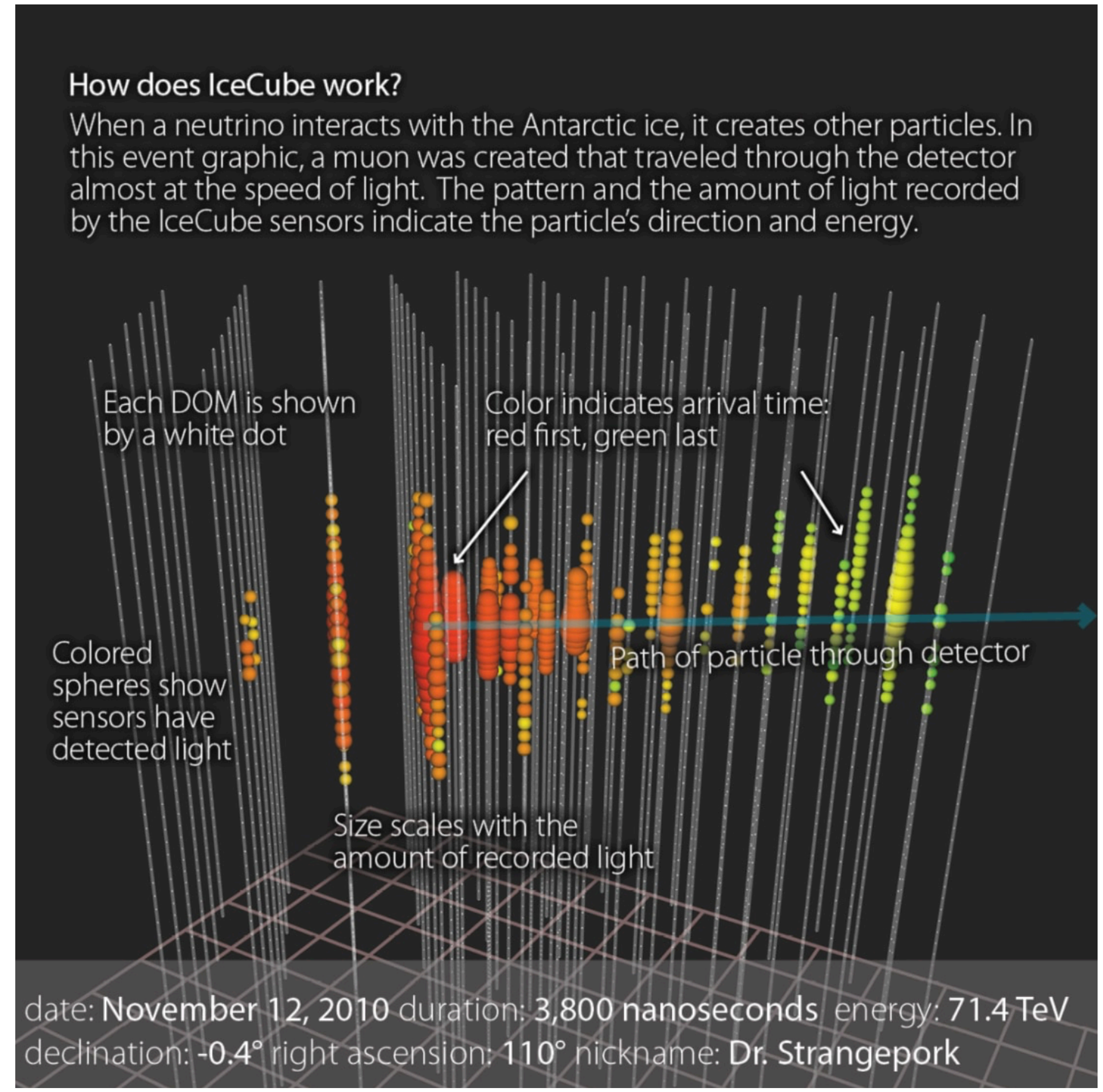
STAR Time Project Chamber, Berkeley Lab Science Beat, February 1999

Tracking — LHC experiment

CMS Silicon Strip Tracking Detector installation, CERN Courier - January 2008

Tracking — neutrino astroparticle physics experiment





IceCube South Pole Neutrino Observatory, c.f. https://icecube.wisc.edu

Lessons from the HERA El(p)C

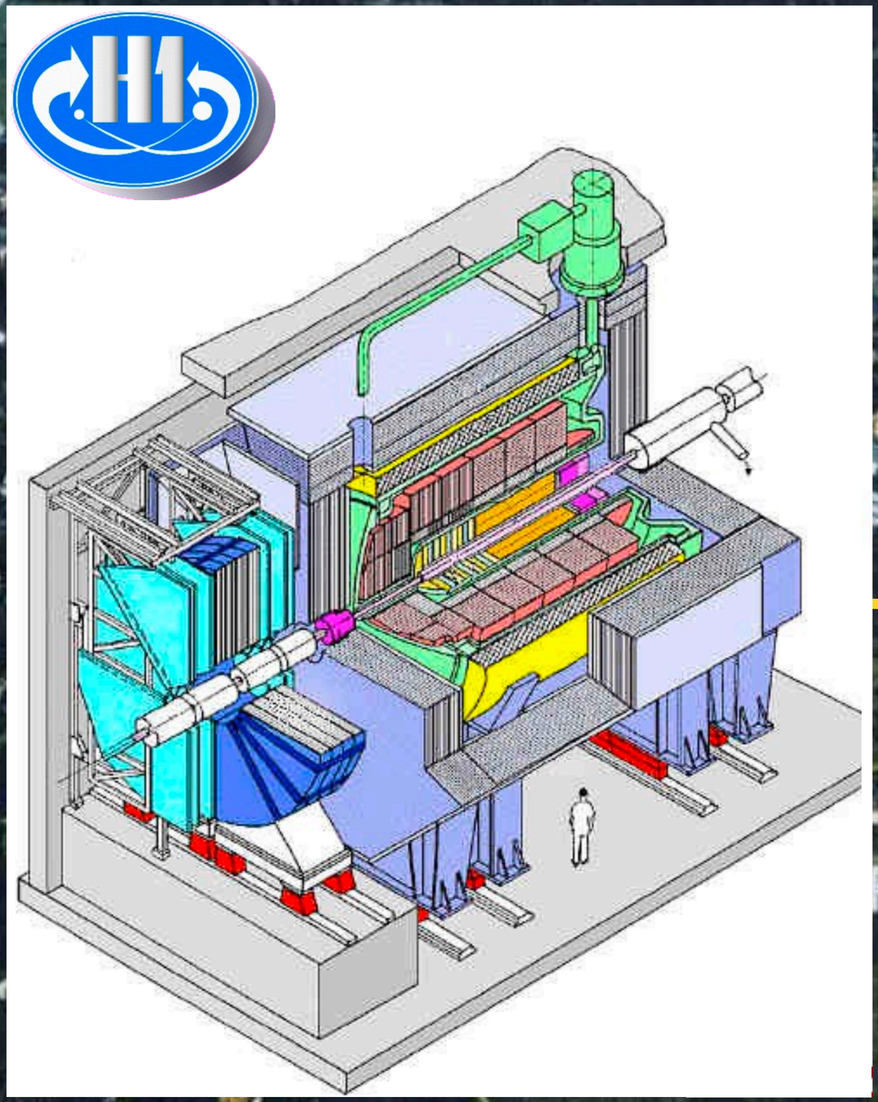
HERA - Detect

H1 was better at electron reconstruction due to its design and EM calorimeter; also unique strengths with forward detectors during HERA-II

~1.2 T solenoidal magnetic field.

H1

20 GeV prot



Zeus had particular strengths in hadron calorimetry thanks to its compensating uranium calorimeter; one of the best calorimeters ever built.

~1.4 T solenoidal magnetic field.

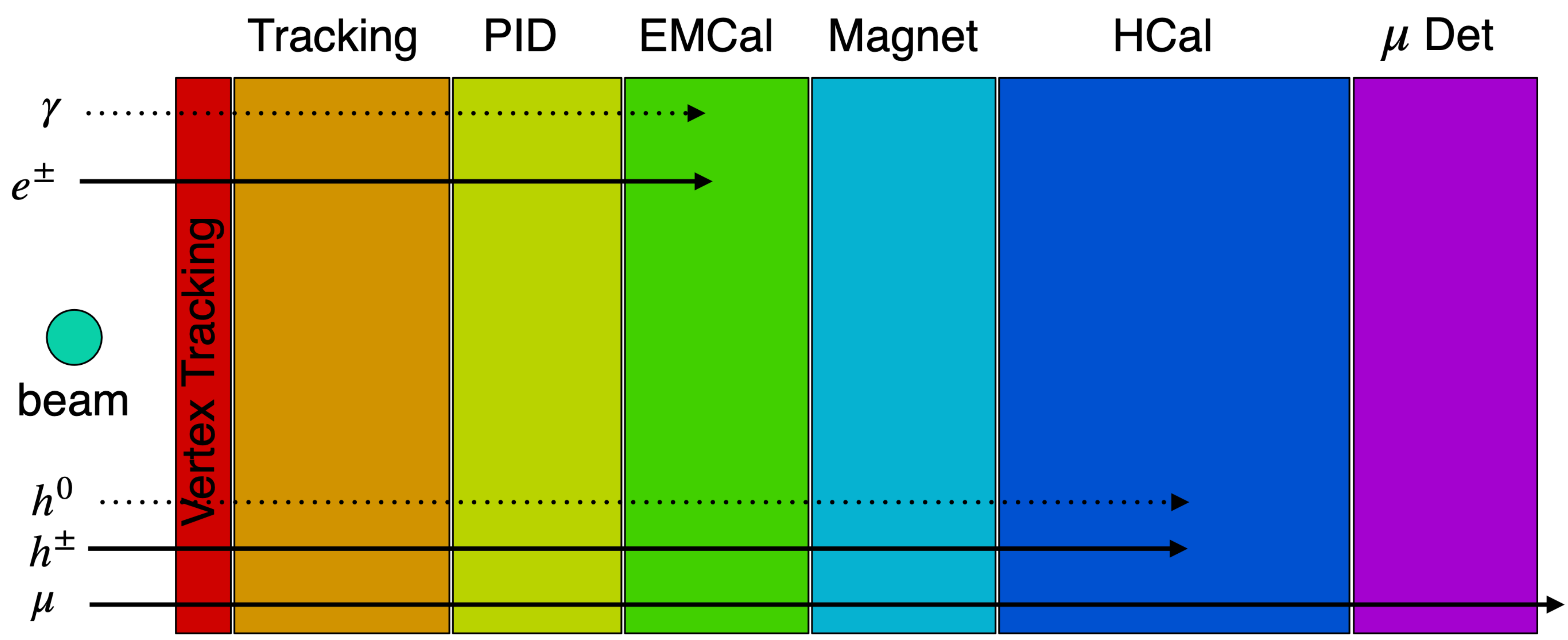
EUS

.5 GeV electrons

RA

HERA-I 1992-2000
HERA-II 2003-2007

Anatomy of a Typical General Purpose Detector



Like mathematics, simple concepts get involved quickly… if only it were so simple.

The typical experimental onion; integration challenges can indeed induce tears…

What should the EIC Detector(s) look like?

The theorist perspective, in a nutshell:

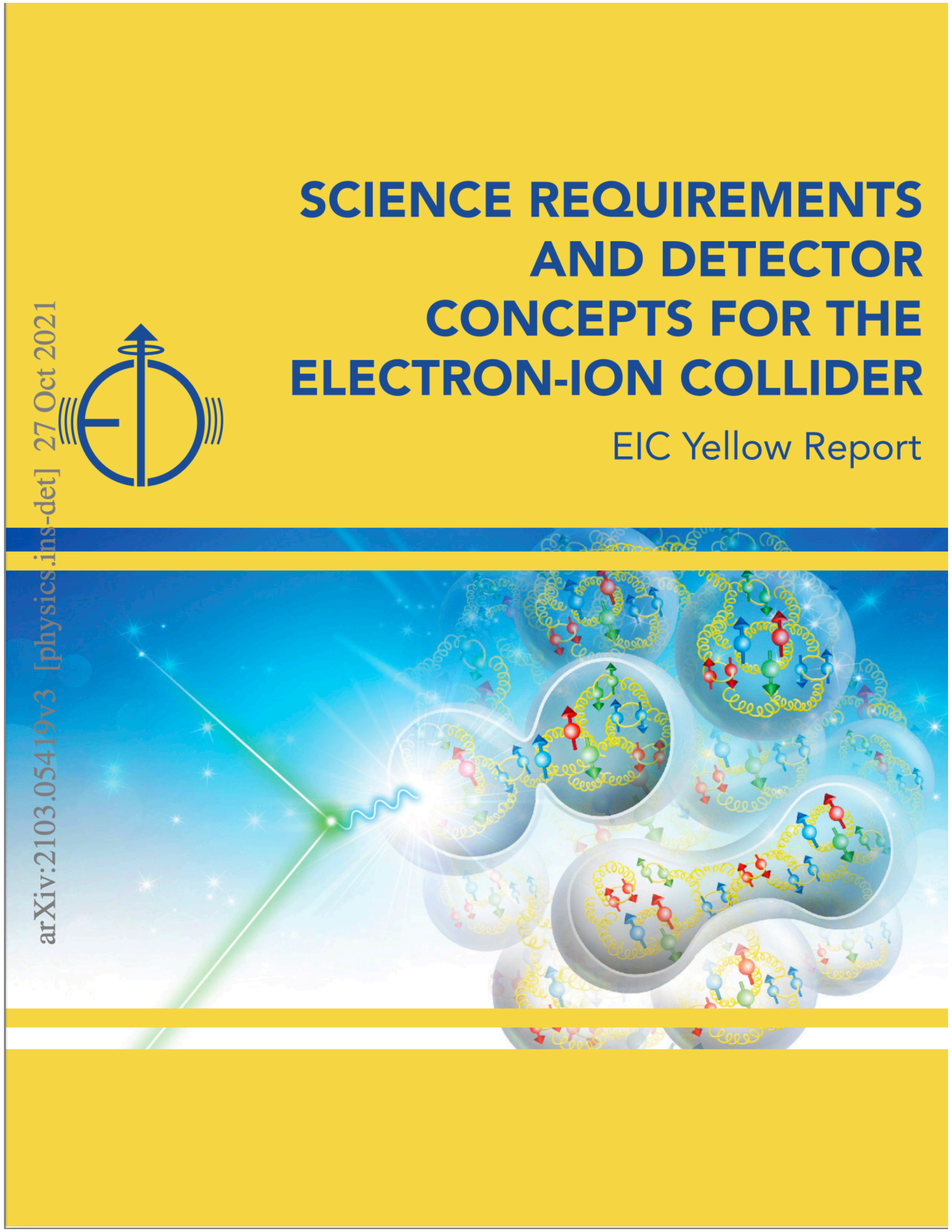
- Detect all final state particles,
- Positively identify them,
- Measure their 4-momenta,
- Uncertainties? What uncertainties?

The experimentalist perspective, in a nutshell:

- Just a few handfuls of particles live longer than 500μm; in practice, many particles are reconstructed via decay products, displaced decay vertices, invariant mass peaks, or missing energy,
- Acceptances are limited by the beam pipe, mounts, gaps, and services,
- Imperfections, coupling to electronics, readout limitations, algorithms and other factors mean that efficiencies are never 100% and usually require extensive study,
- Particle identification is a likelihood,
- Detector resolutions are finite, due to technology limitations and trade-offs,
- Alignment, calibrations, …
- Backgrounds, yes, those too. Purity is usually a trade-off with efficiency.

What roles does/should tracking play in this?

What should the EIC Detector(s) look like?

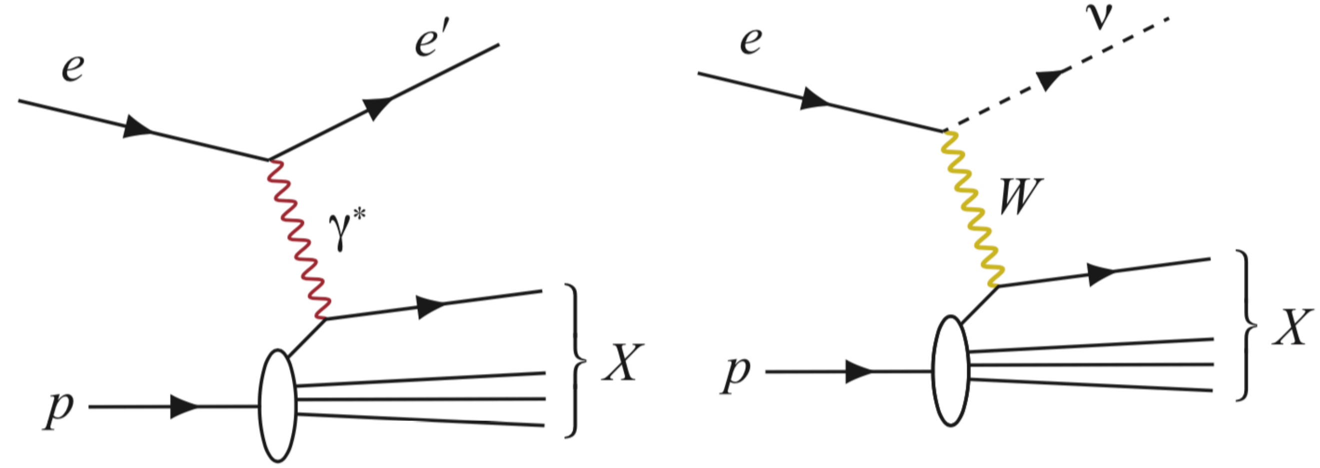


The 884 page version…

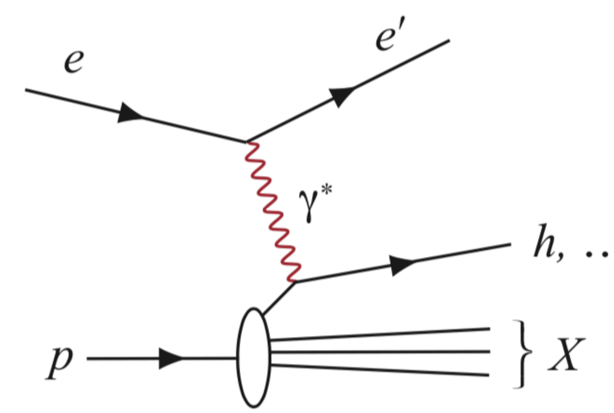
Nucl. Phys. A 1026 (2022) 122447.

Key processes at EIC

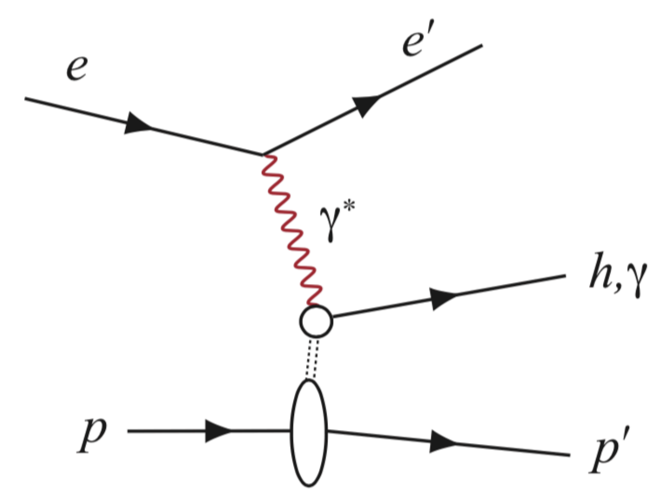
Inclusive deep-inelastic scattering



Semi-inclusive deep-inelastic scattering

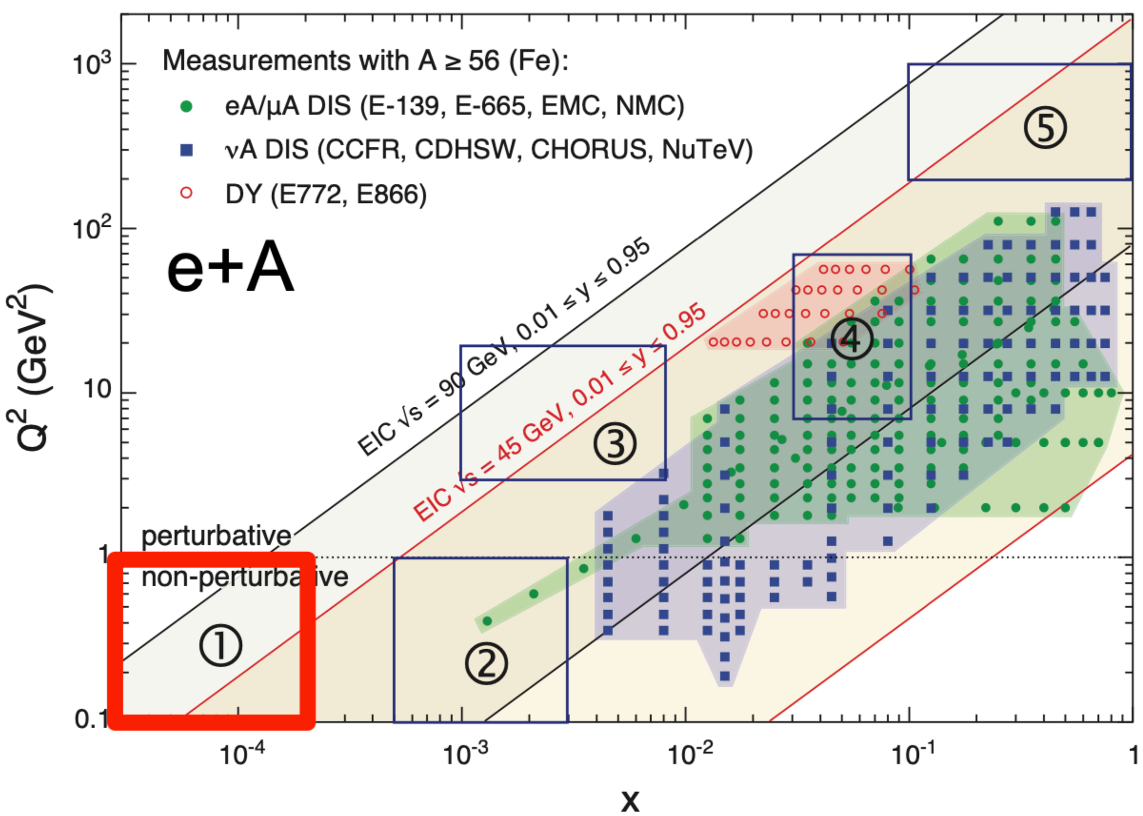


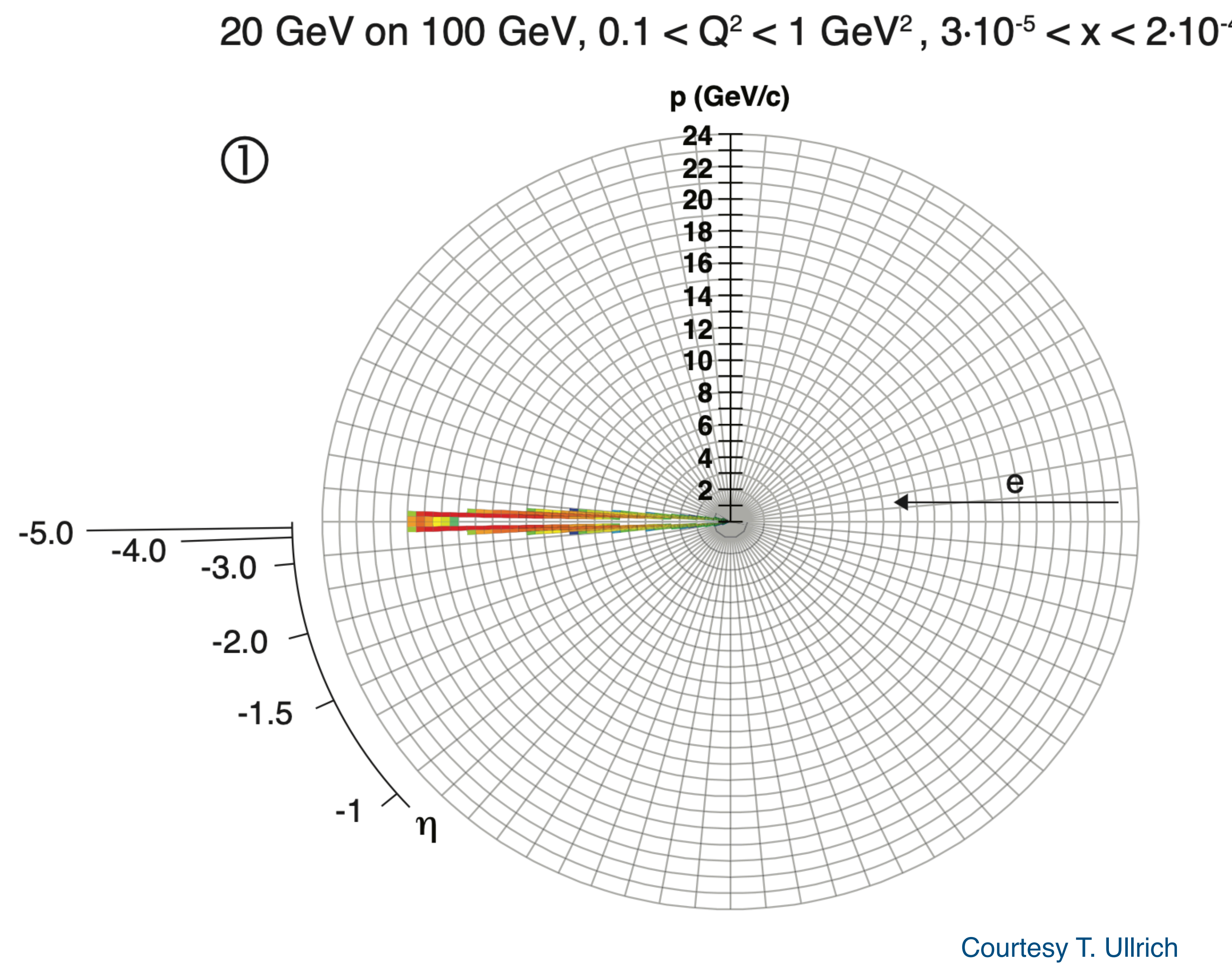
Exclusive deep-inelastic scattering



Scattered electron is obviously essential, but not sufficient (process and measurement)

Scattered Electron at EIC





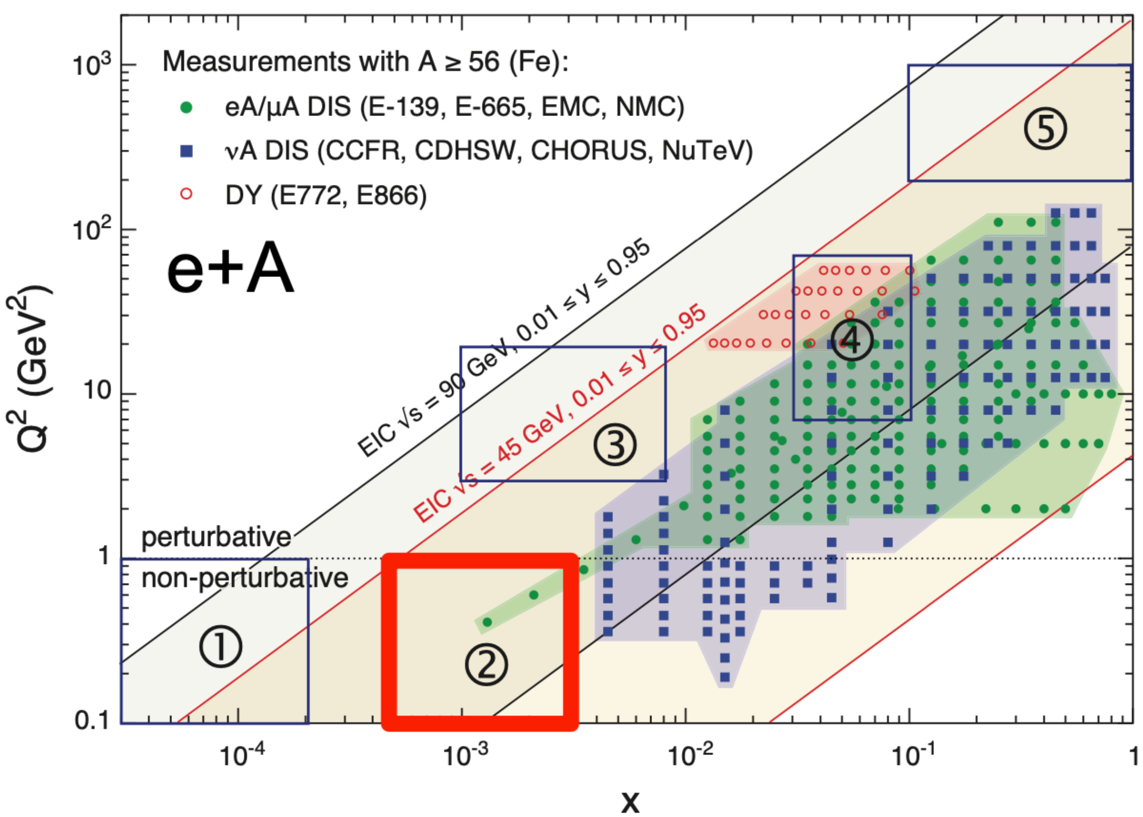
Scattered Electron determines:

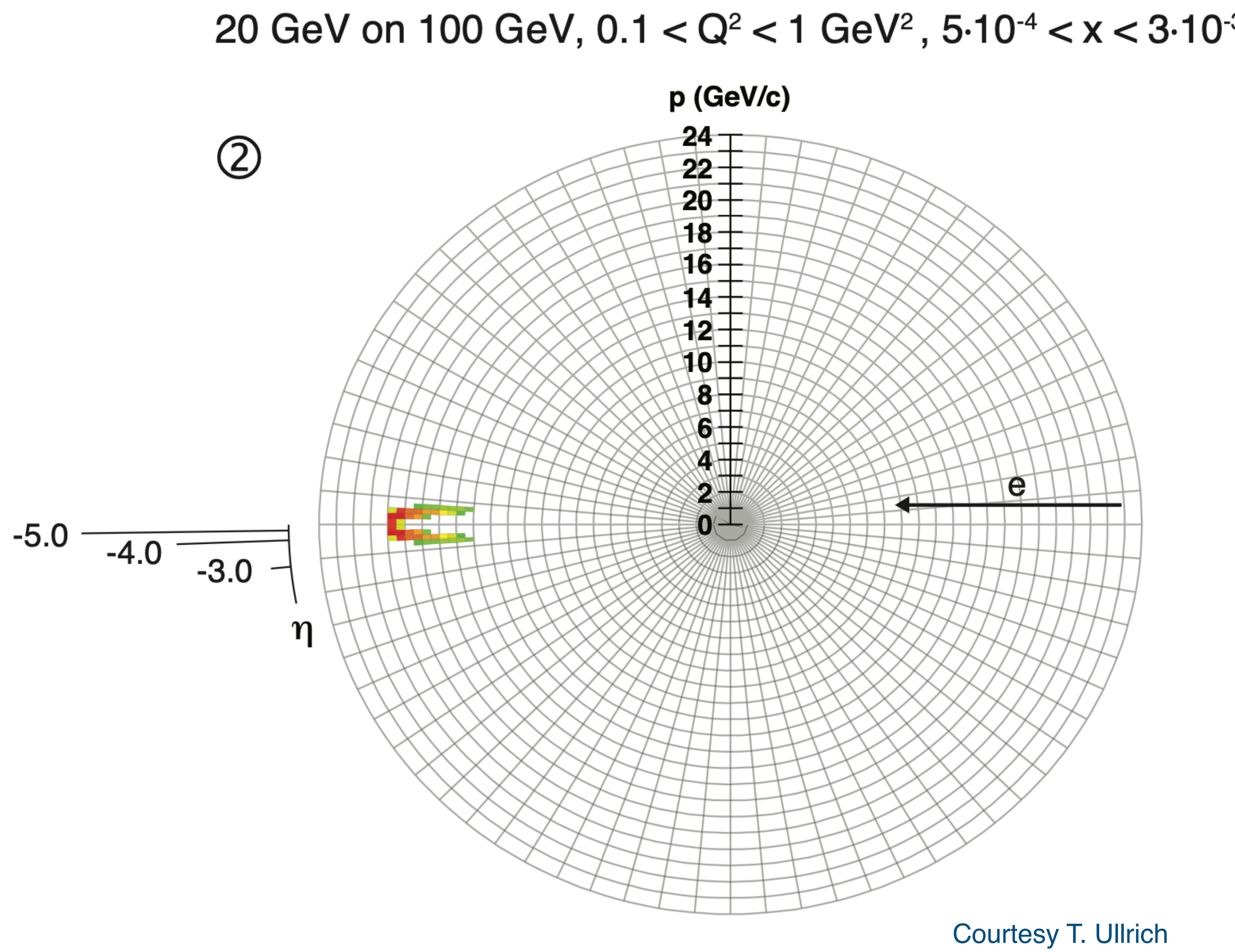
$$y = 1 - (E'_e/2E_e)(1 - \cos\theta'_e)$$

$$Q^2 = 2E'_e E_e(1 + \cos\theta'_e)$$

$$x = E'_e E_e(1 + \cos\theta'_e)/(2yE_p)$$

Scattered Electron at EIC





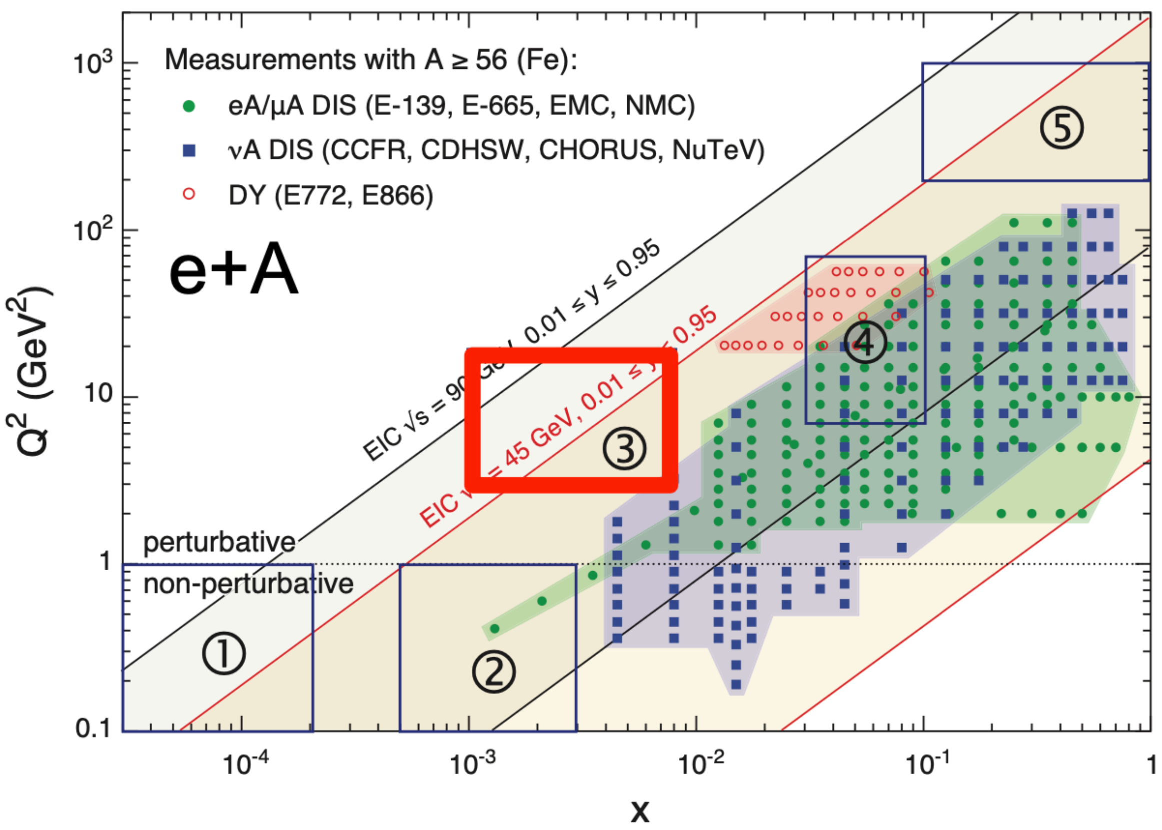
And inversely:

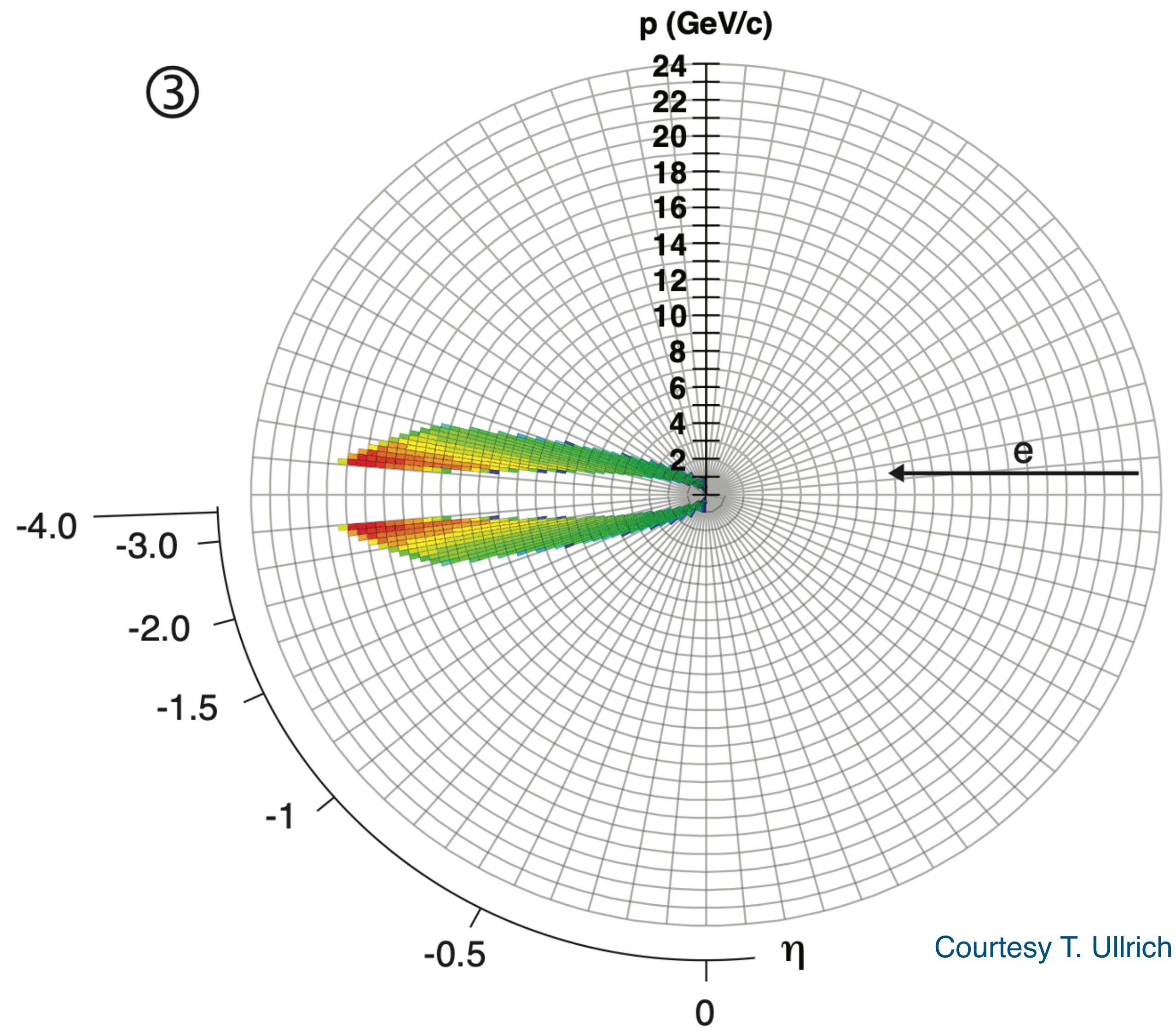
$$E'_e = (1-y)E_e + xyE_p$$

$$\cos\theta'_e = [xyE_p - (1-y)E_e]/[xyE_p + (1-y)E_e]$$

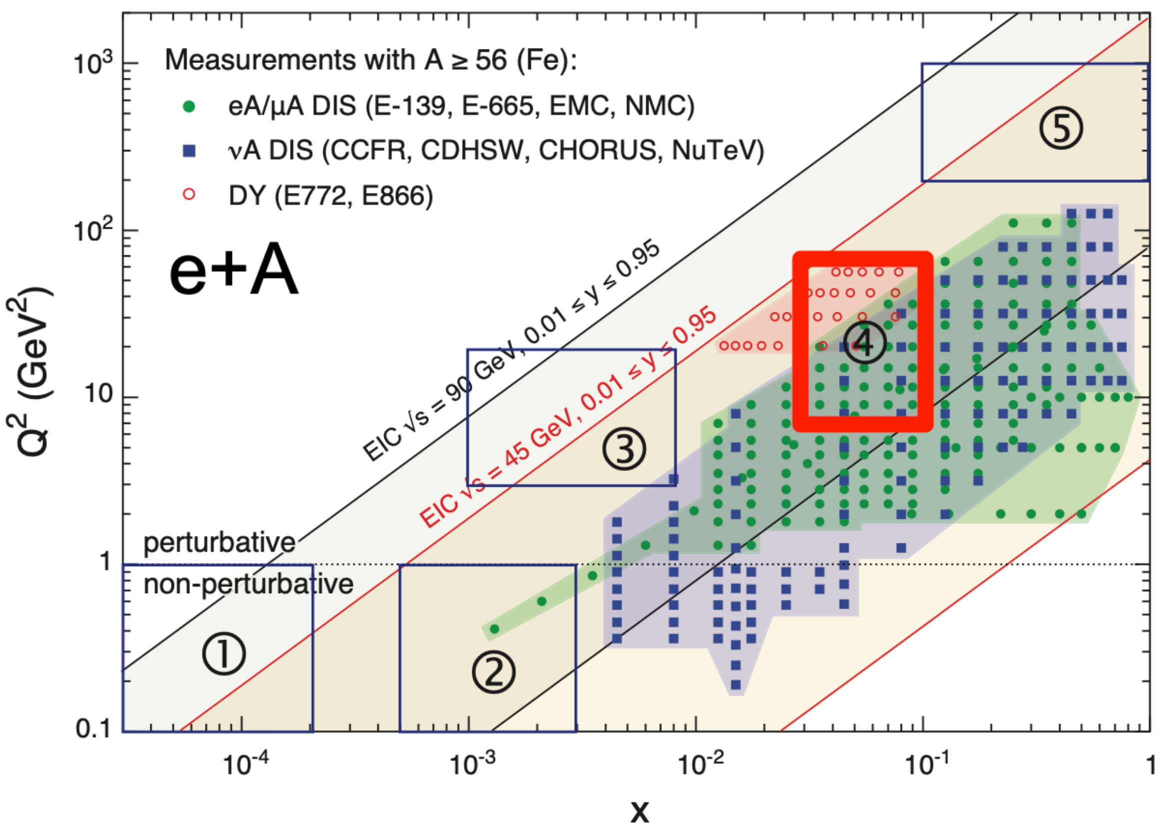
$$E'^2_e \sin^2\theta'_e = 4xy(1-y)E_eE_p$$

Scattered Electron at EIC

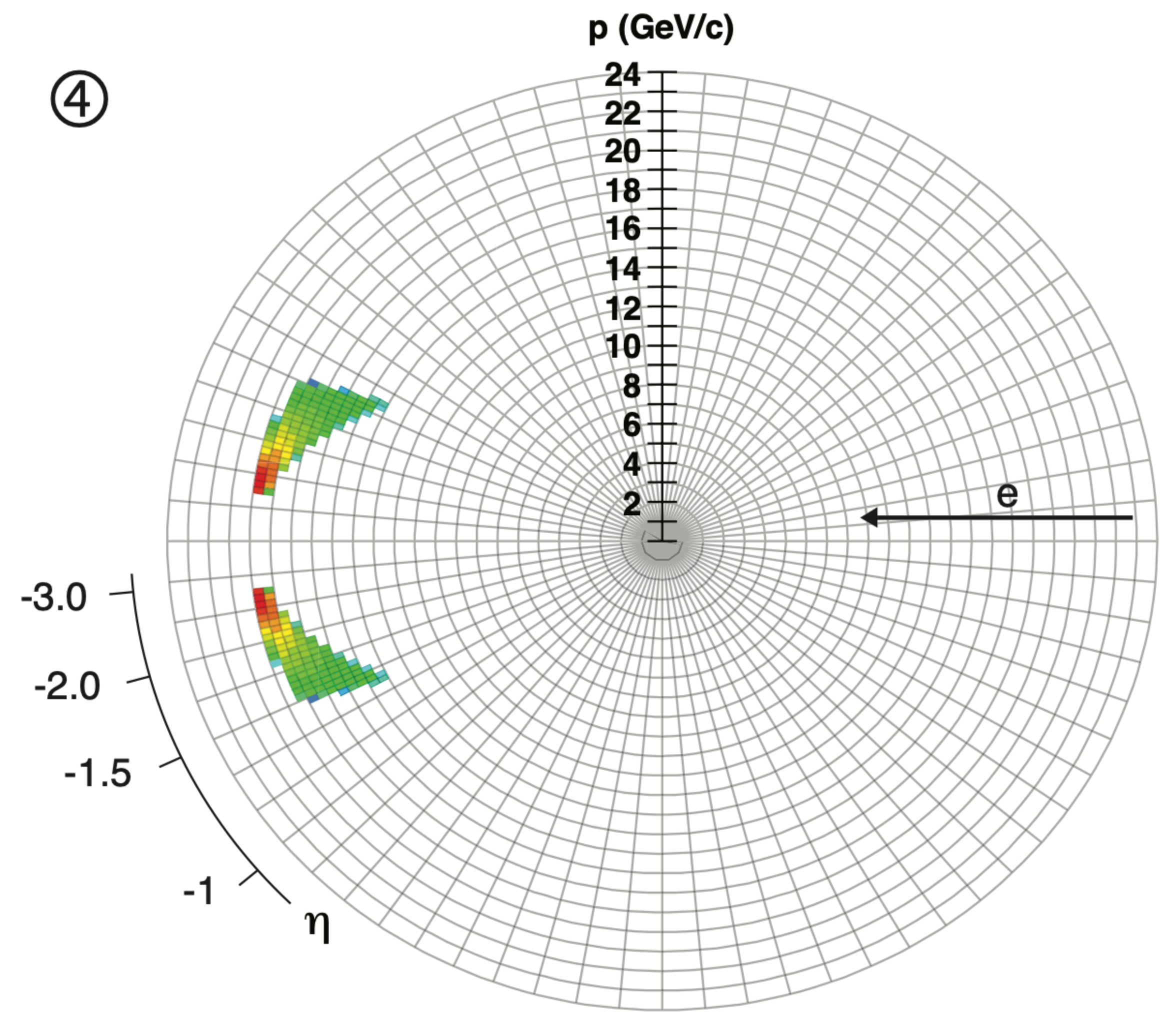




Scattered Electron at EIC

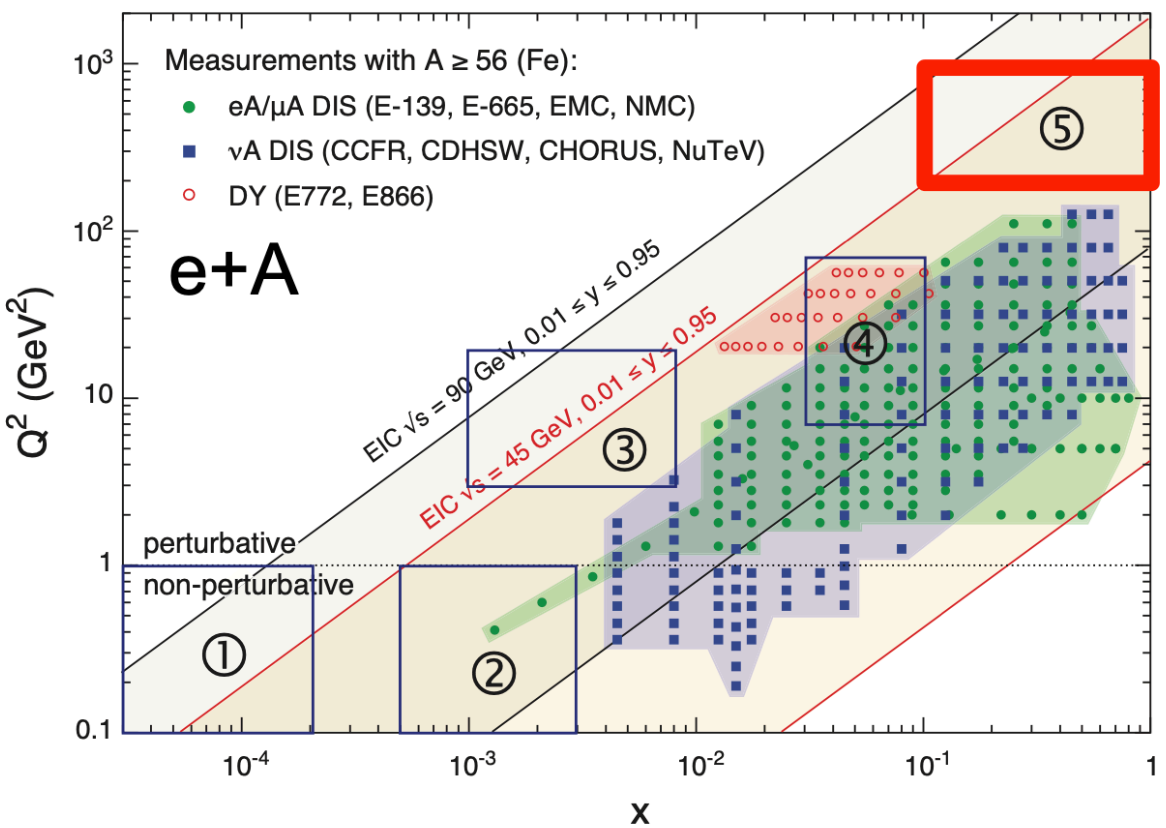


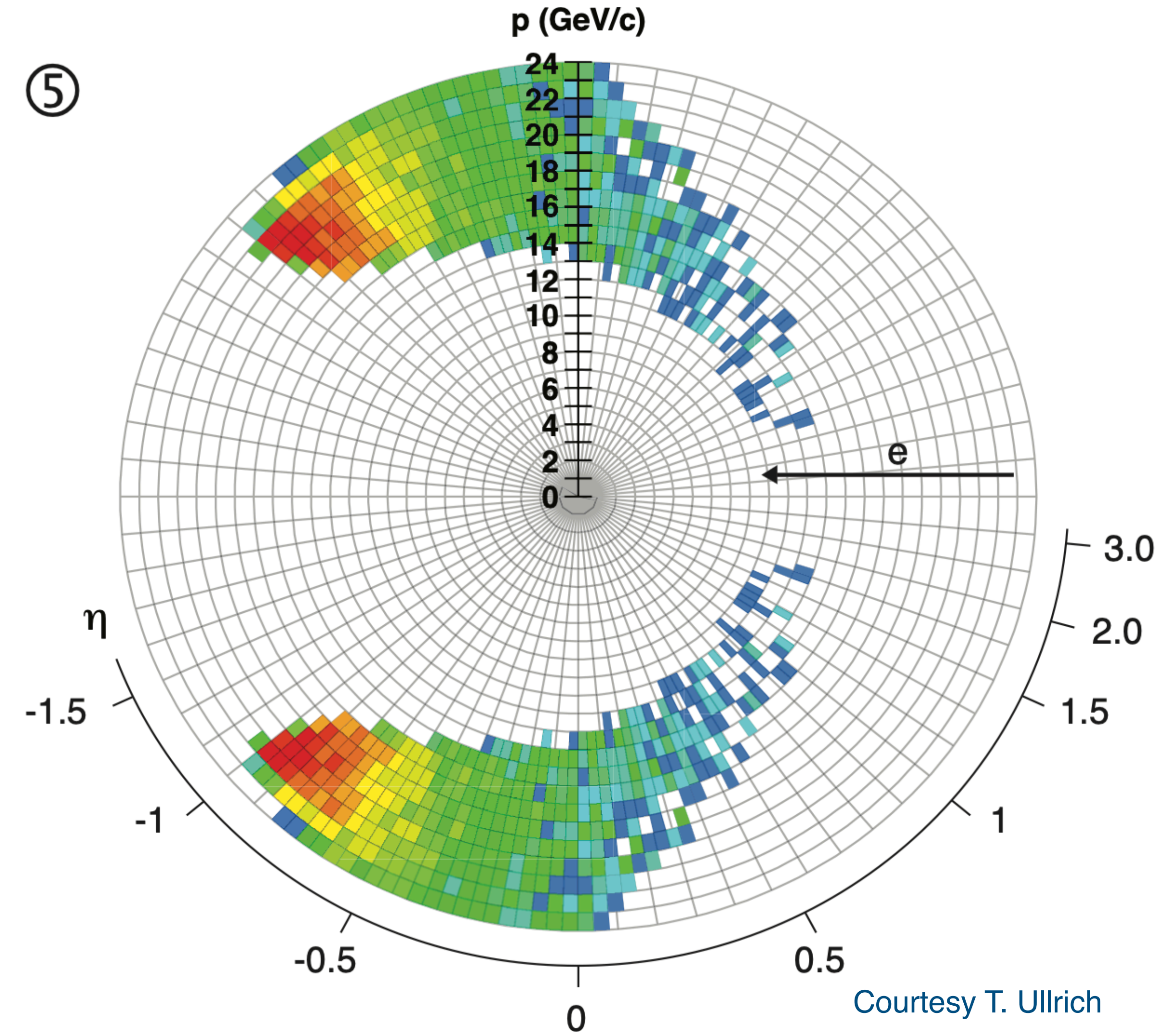
20 GeV on 100 GeV, $7 < Q^2 < 70$ GeV^2, $3 \cdot 10^{-2} < x < 1 \cdot 10^{-1}$



Courtesy T. Ullrich

Scattered Electron at EIC





Scattered Electron determines:

$$y = 1 - (E'_e/2E_e)(1 - \cos\theta'_e)$$

$$Q^2 = 2E'_e E_e(1 + \cos\theta'_e)$$

$$x = E'_e E_e(1 + \cos\theta'_e)/(2yE_p)$$ — note the 1/y; does not work well for small y

Alternative kinematic reconstructions

Fortunately, DIS kinematics can be reconstructed from the electron observables, the hadron observables, and combinations of the two. The standard text on this topic is U. Bassler and G. Bernardi, NIM A361 (1995) 197. It defines:

$$\Sigma = \sum_h (E_h - p_{z,h}) \qquad T = \sqrt{(\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2} \qquad \tan\frac{\gamma}{2} = \frac{\Sigma}{T}$$

	method	y	Q^2	x
Electron method:	e	$1 - \frac{E}{E^e}\sin^2\frac{\theta}{2}$	$4E^e E\cos^2\frac{\theta}{2}$	Q^2/ys
Jacquet-Blondel:	h	$\frac{\Sigma}{2E^e}$	$\frac{T^2}{1-y_h}$	Q^2/ys
Mixed:	m	y_h	Q_e^2	Q^2/ys
Double-angle:	DA	$\frac{\tan\gamma/2}{\tan\gamma/2+\tan\theta/2}$	$4E^{e2}\frac{\cot\theta/2}{\tan\gamma/2+\tan\theta/2}$	Q^2/ys
Sigma:	Σ	$\frac{\Sigma}{\Sigma+E(1-\cos\theta)}$	$\frac{E^2\sin^2\theta}{1-y_\Sigma}$	Q^2/ys

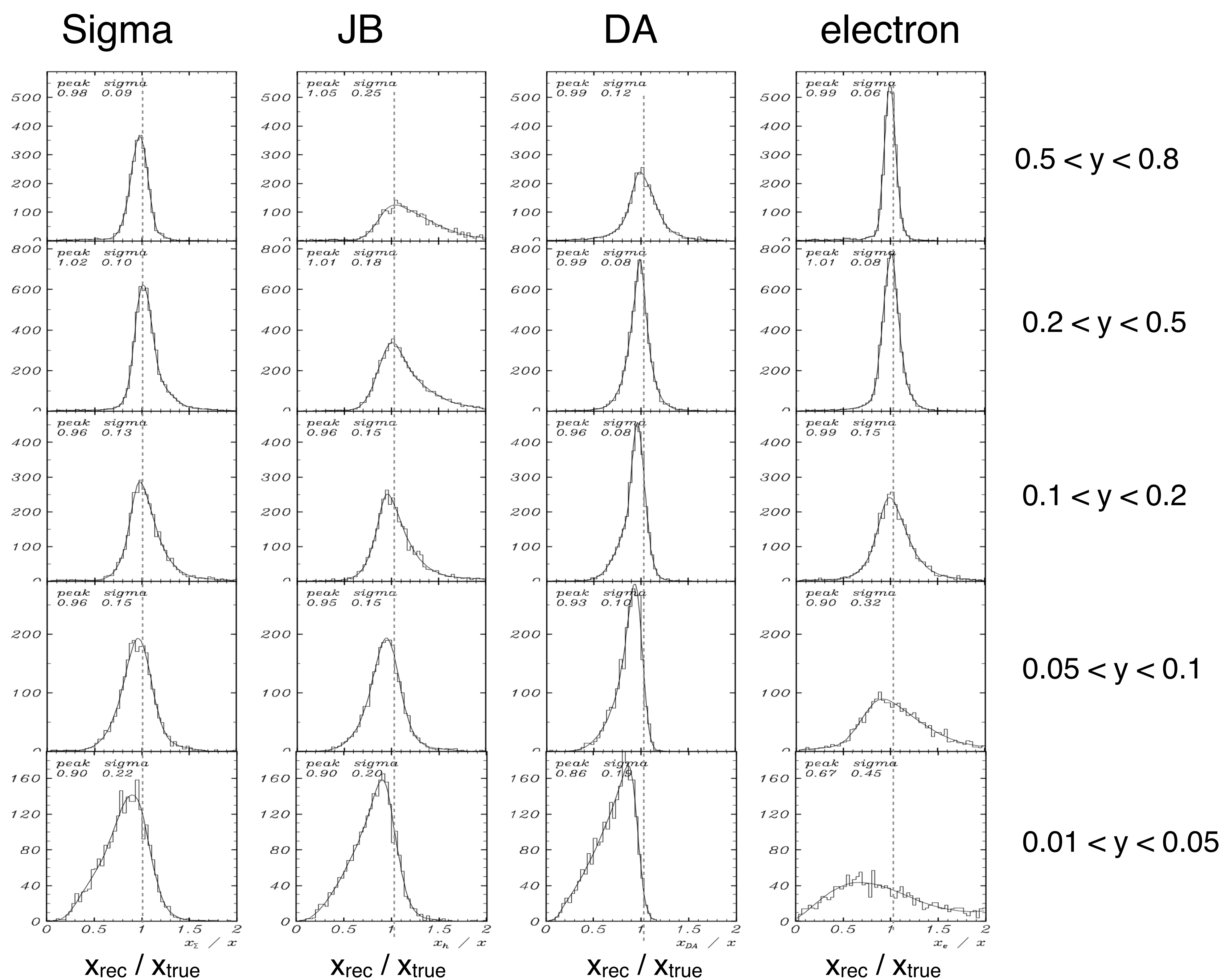
Alternative kinematic reconstructions

U. Bassler and G. Bernardi, NIM A361 (1995) 197:

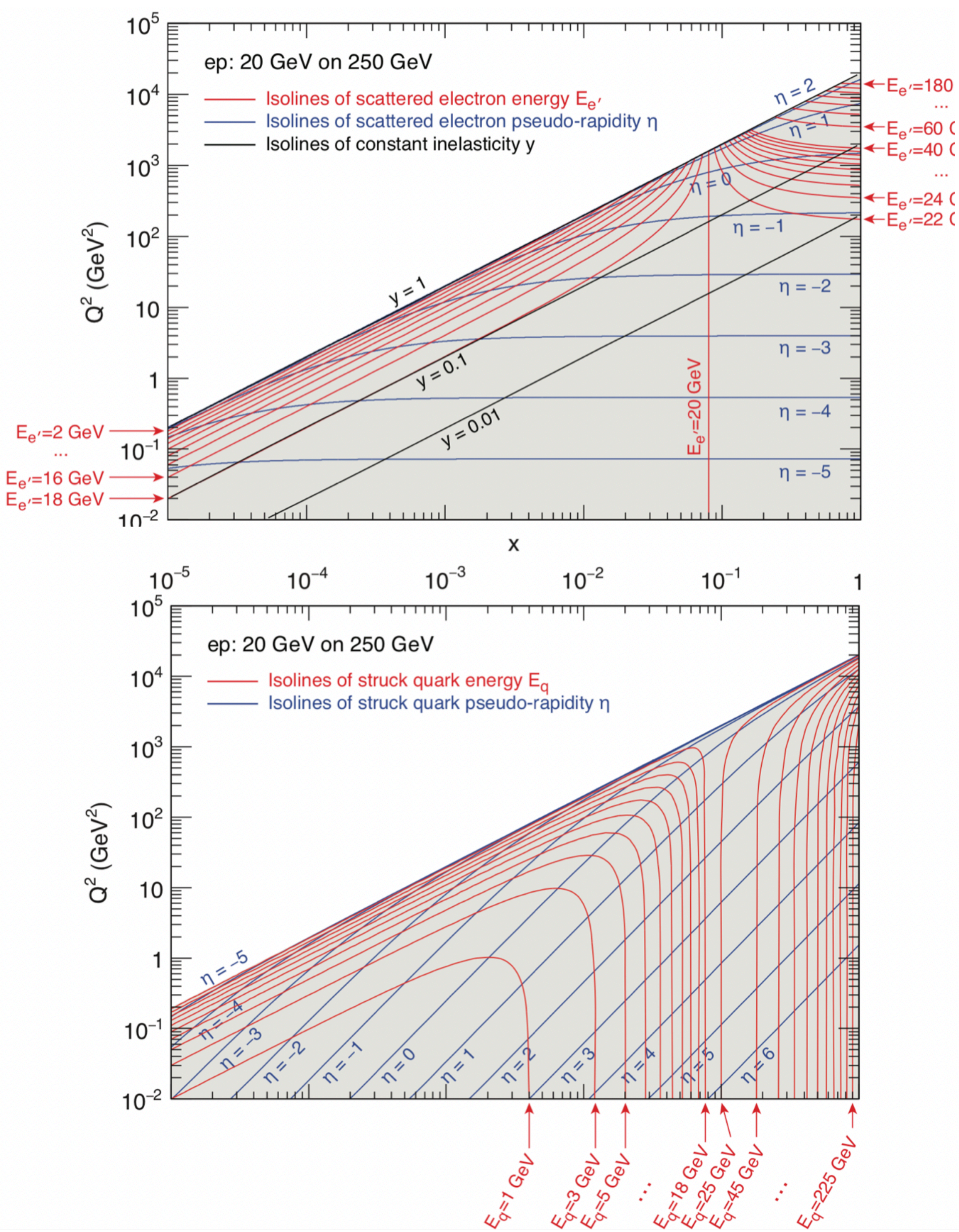
Electron method works very well at high-y; degrades as 1/y

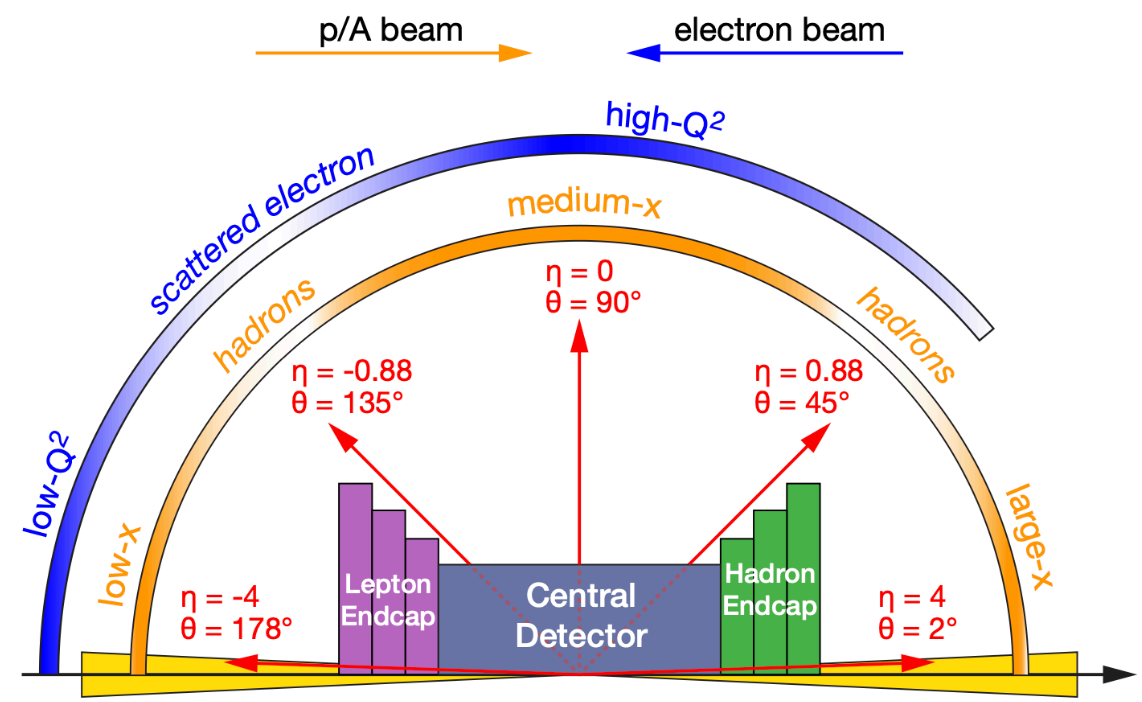
Jacquet-Blondel degrades at high-y, but works well for y < ~0.2,

Double-Angle does not depend on absolute energy calibrations; accurate at high Q^2, degrades at small-x and small Q^2



DIS and SIDIS drive the Central Detector at EIC





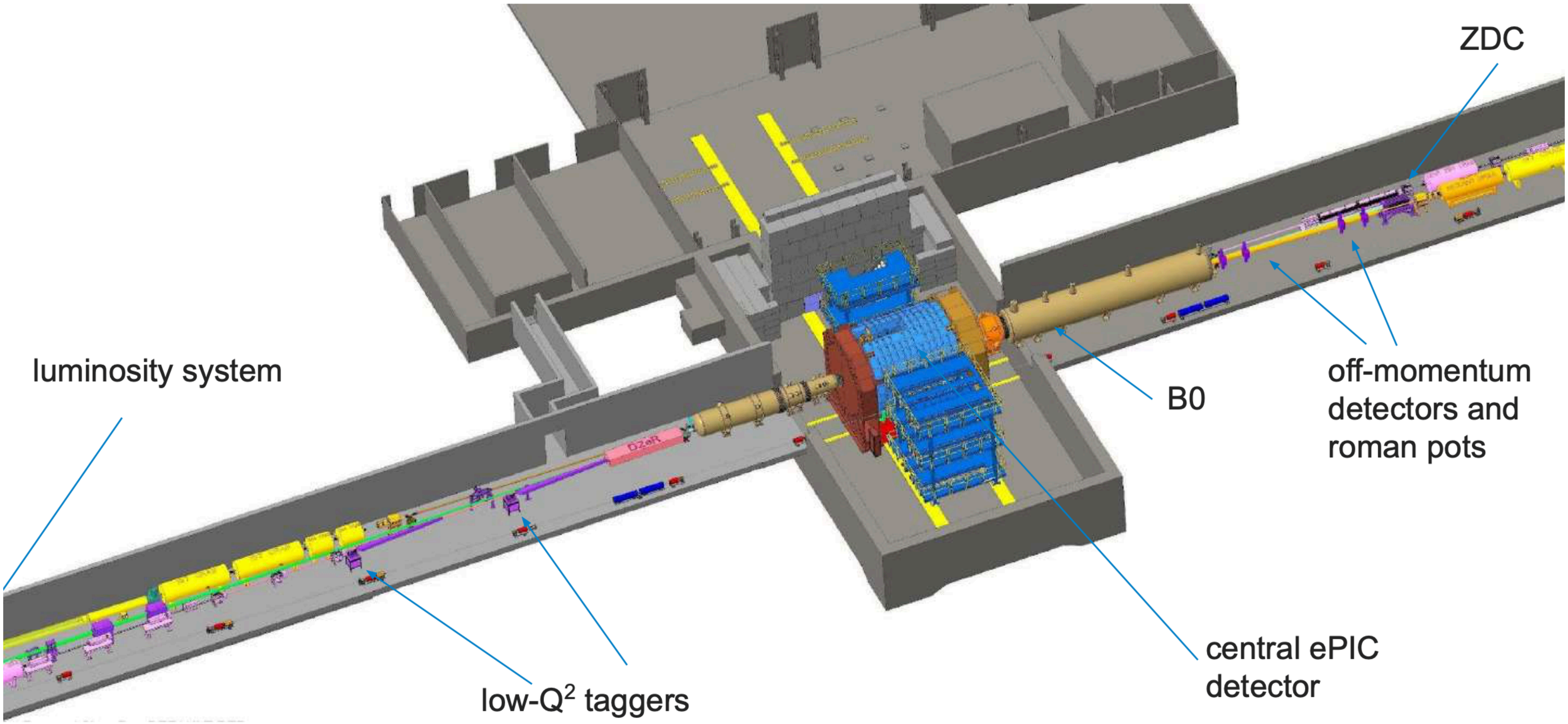
The DIS cross-section typically goes as $1/Q^4$

High momenta, be they electron or hadron, are typically associated with large *x* processes,

Physics in all areas of this (these) kinematic plane(s),

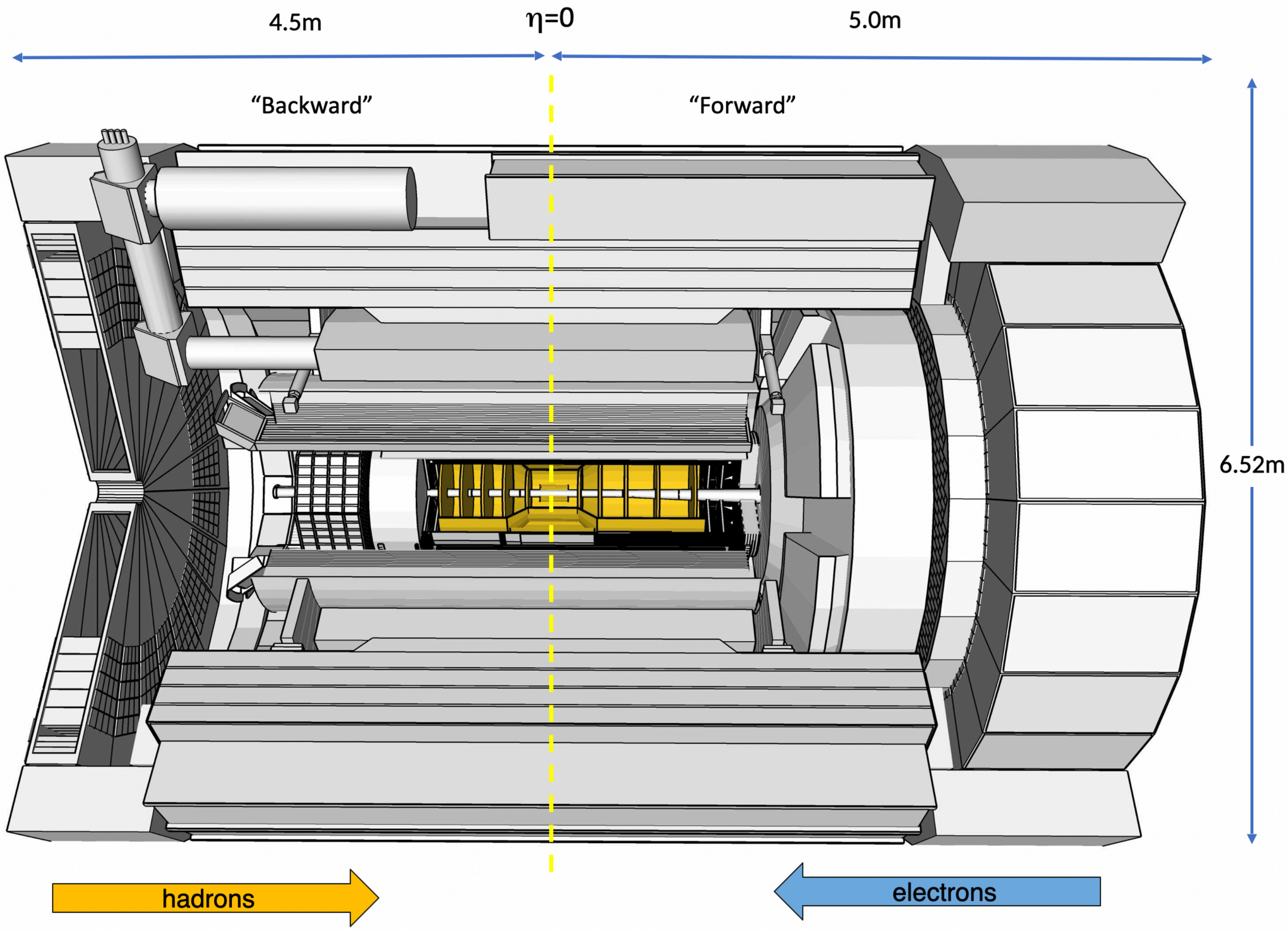
Trade-offs, in parts, “a matter of taste.”

What should the EIC Detector(s) look like?



Tightly integrated with the interaction region design with a compact central detector (component)

What will the EIC Project Detector look like?

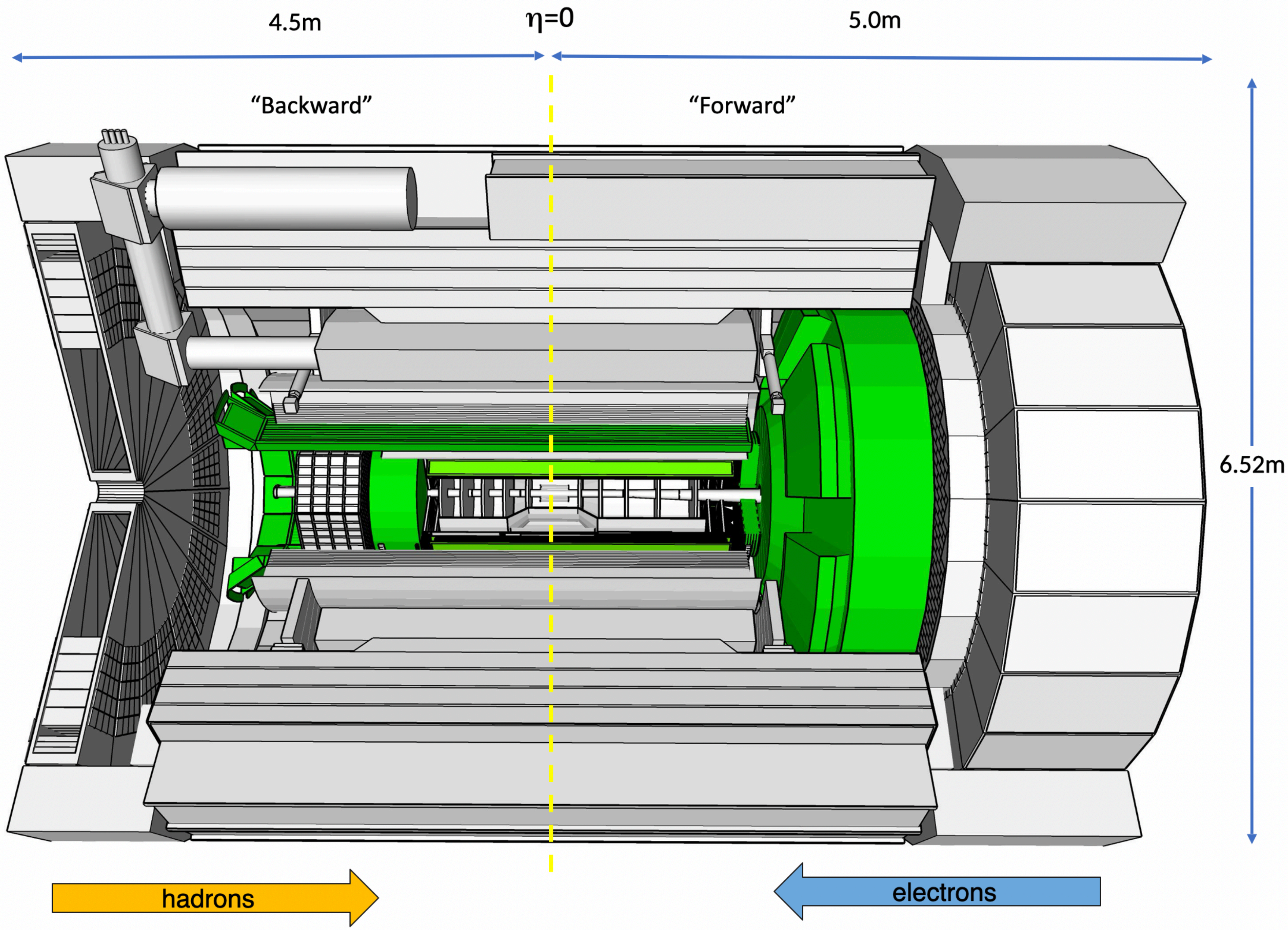


Tracking:

- New 1.7T (2.0T) solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

See Thomas Ullrich's lecture(s) last week

What will the EIC Project Detector look like?



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- New 1.7T (2.0T) solenoid
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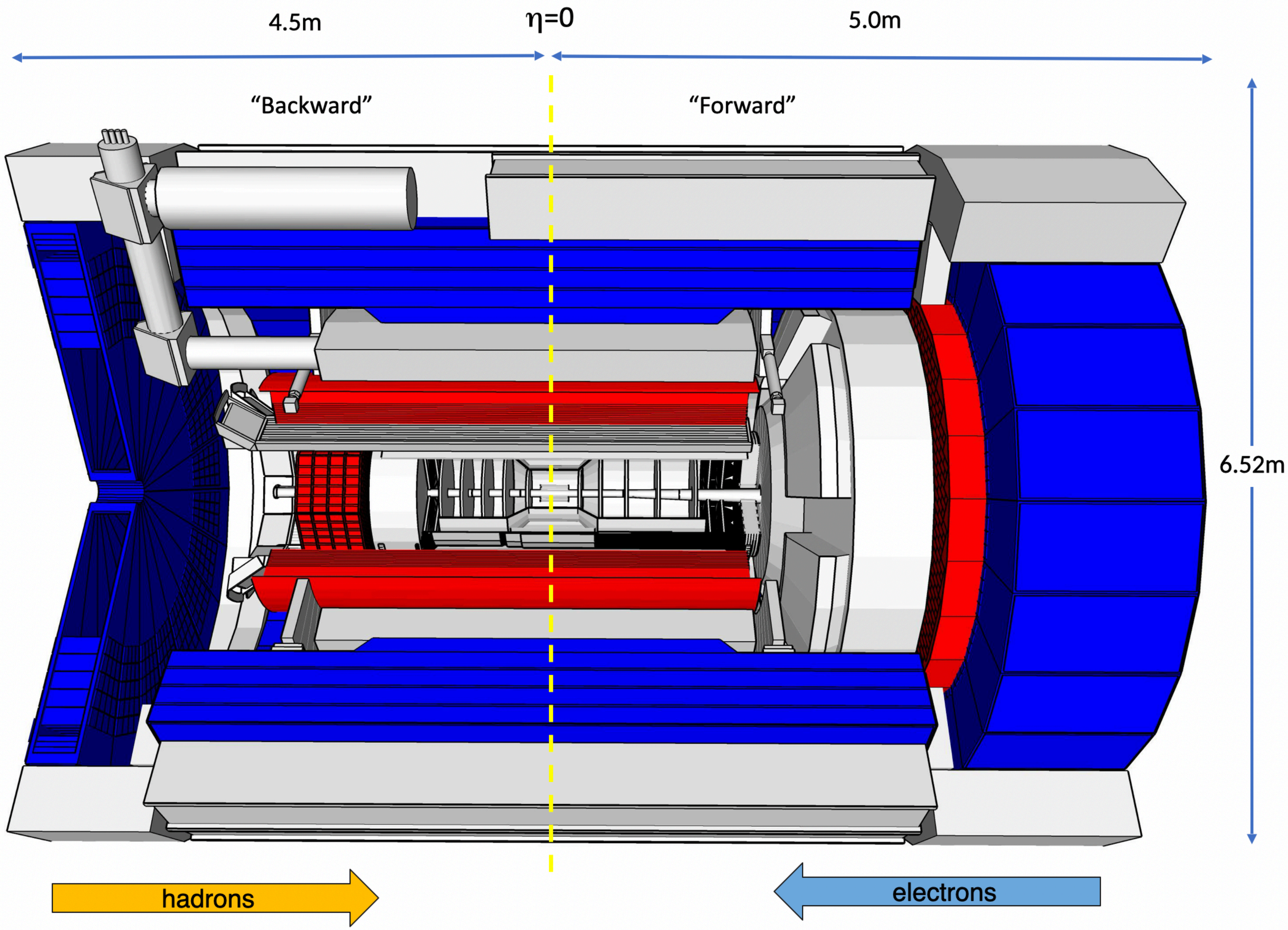
- MPGDs (μRWELL/μMegas)

PID:

- high-performance DIRC
- proximity-focused RICH
- dual-radiator RICH
- AC-LGAD (~30ps TOF)

See Thomas Ullrich's lecture(s) last week

What will the EIC Project Detector look like?



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PID:

- high-performance DIRC
- proximity-focused RICH
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- AC-LGAD (~30ps TOF)

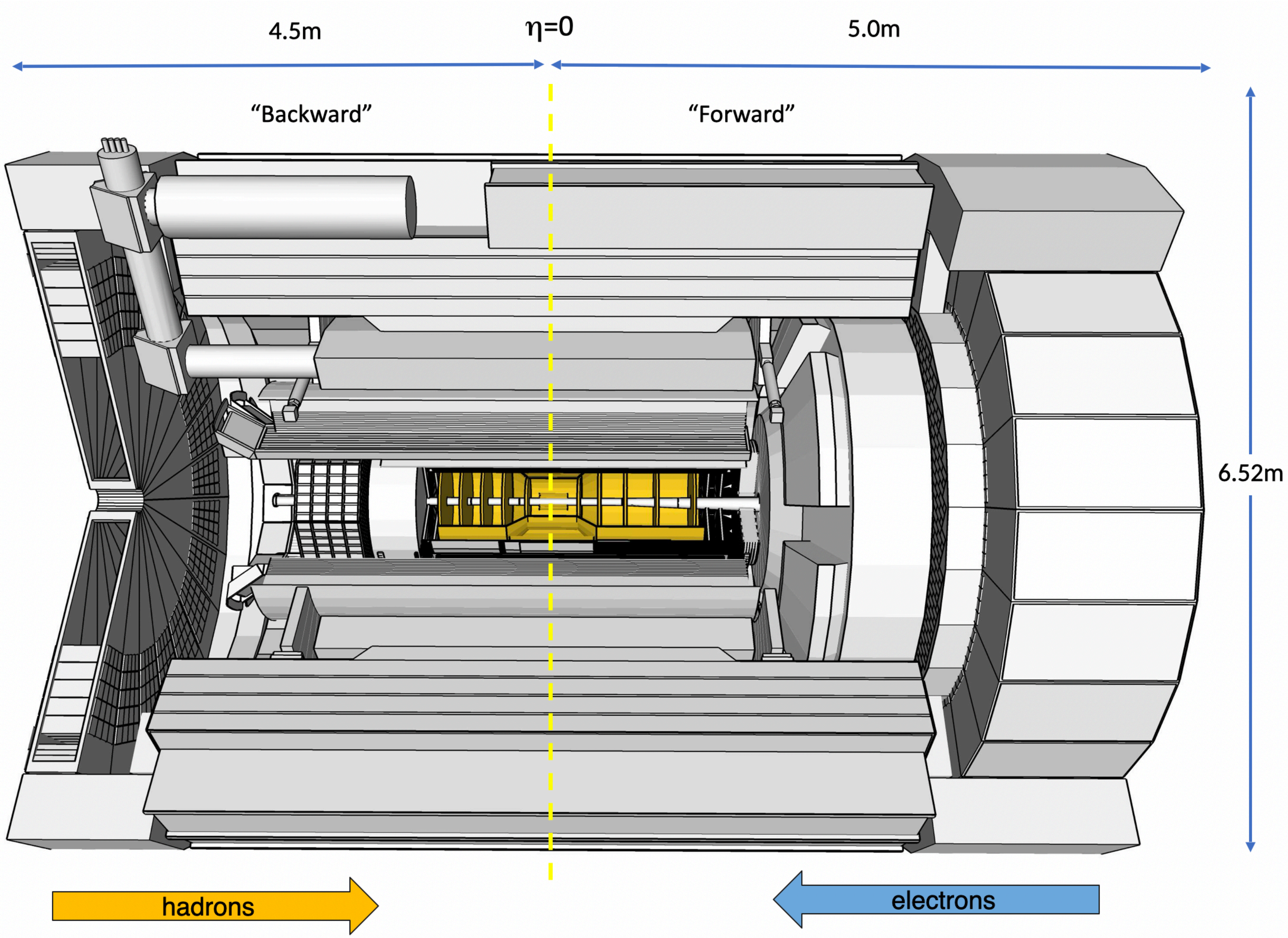
Calorimetry:

- Imaging Barrel EMCal
- PbWO4 EMCal (backwards)
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

See Thomas Ullrich's lecture(s) last week, as well Barak Schmookler's lecture earlier today

Aside, note that the color coding here is different from that used on the Anatomy slide.

What will the EIC Project Detector look like?



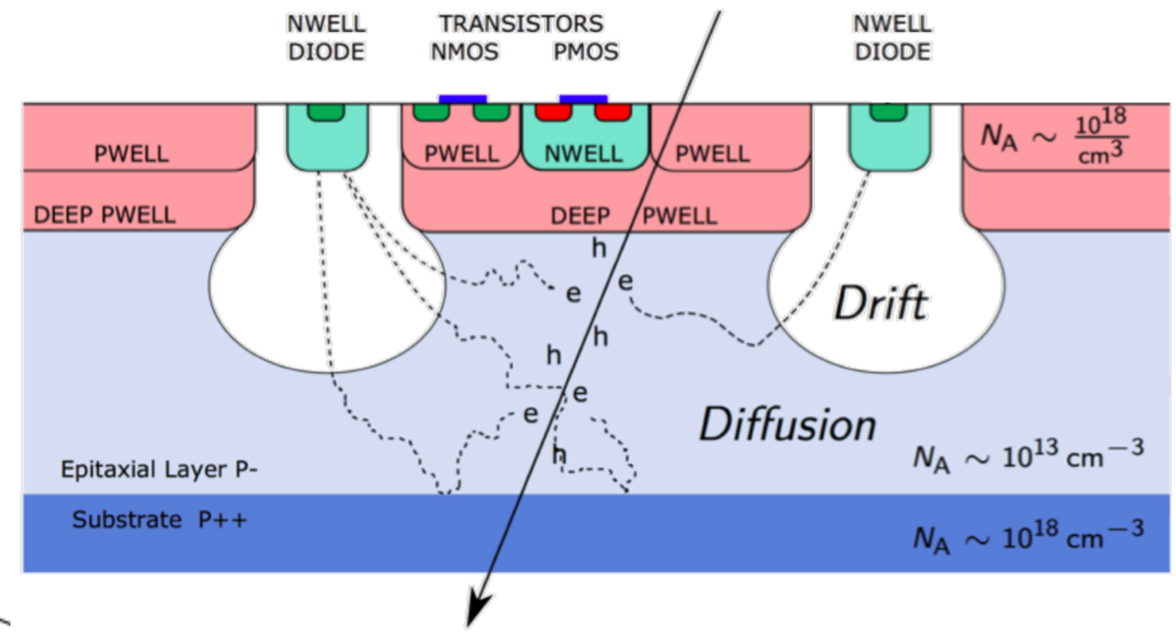
Tracking:
- New 1.7T (2.0T) solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

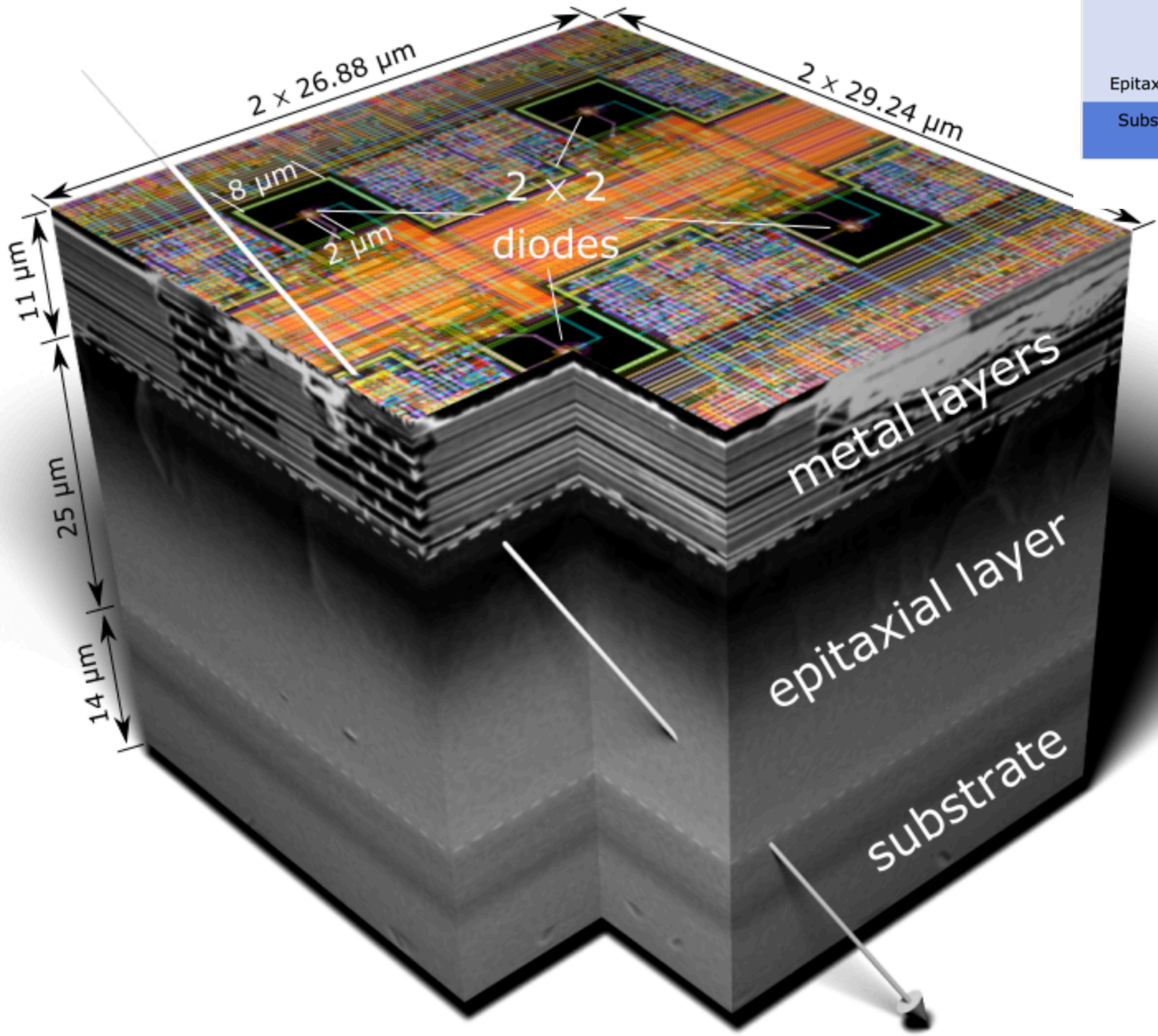
Core detector functions:

precision tracking and vertexing at the IP
track pointing into the PID subsystems, including track length to ToF
pointing into calorimeter subsystems e.g. for E/p

MAPS principle

Monolithic Active Pixel Sensors





Combine charge collection and readout with 50µm traversed "thickness"

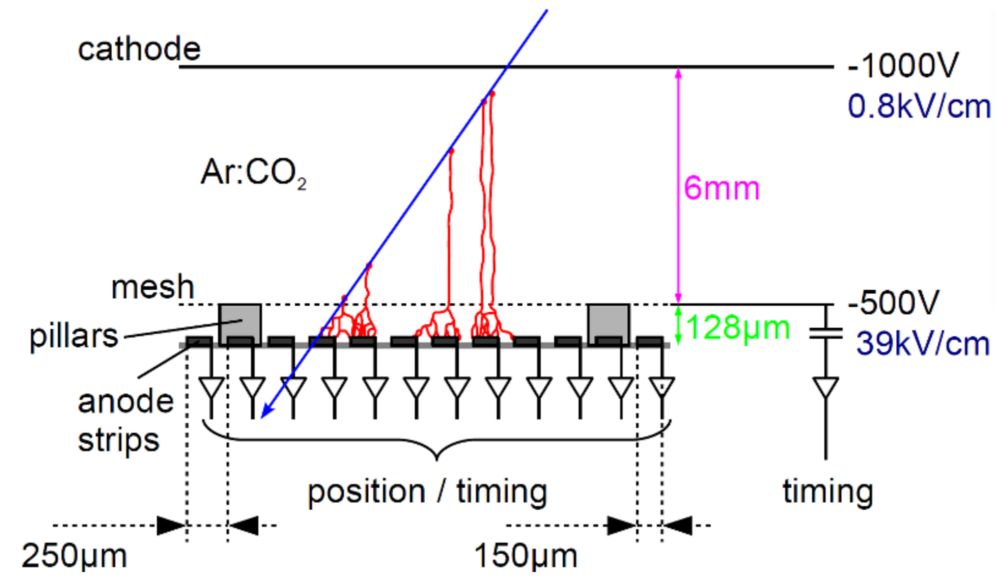
50µm Si has X/X0 ~ 0.05% (!)

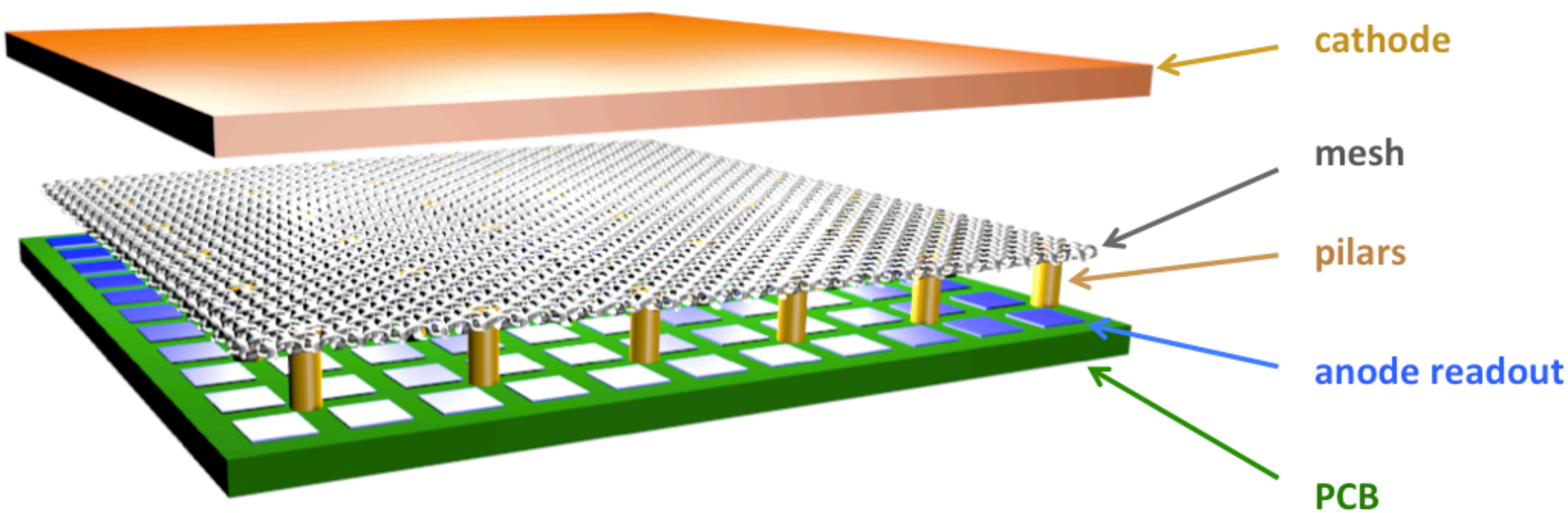
Point resolution ~ 6 µm (!)

MPGD principle(s)

MIcro Pattern Gas Detectors,

μMega or thin-gap μRWell





Fast compared to MAPS, albeit with worse point resolution; important for pattern recognition

Tracking and Vertexing

Coordinate measurement,

Track model,

Track finding and fitting,

Vertex finding and fitting,

Secondary vertices,

Analytical solutions in select cases; approaches and algorithms in many others — see e.g. R. Fruhwirth and A. Strandlie, *“Pattern Recognition, Tracking, and Vertex Reconstruction in Particle Detectors”* (2021) for an overview.

Tracking and Vertexing

Coordinate measurement,

"binary" — $1/\sqrt{12}$ of the typical distance scale (pitch) in any direction,

"clustering" — e.g. averages of (otherwise binary) hits weighted by pulse-height,

"propagation time" — e.g. measurement of the drift-time in a TPC,

"split signal" — e.g. arrival time difference at two wire-ends; ratio of pulse heights,

Tracking and Vertexing

Track model,

straight line, parabola, helical, …

Tracking and Vertexing

Track model,

straight line, parabola, helical, …

A word of caution on projections…

Tracking and Vertexing

Track model,

straight line, parabola, helical, …

Fundamentally determined by equations of motion,

distortions from multiple scattering, energy loss due to ionization, …

Tracking and Vertexing

Track finding and fitting,

Tracking finding,

intuitively clear when hit-densities are low,

often a trade-off between efficiency and purity,

algorithms can be local (e.g. seed finding and ambiguity resolve) or global (e.g. Hough),

Track fitting

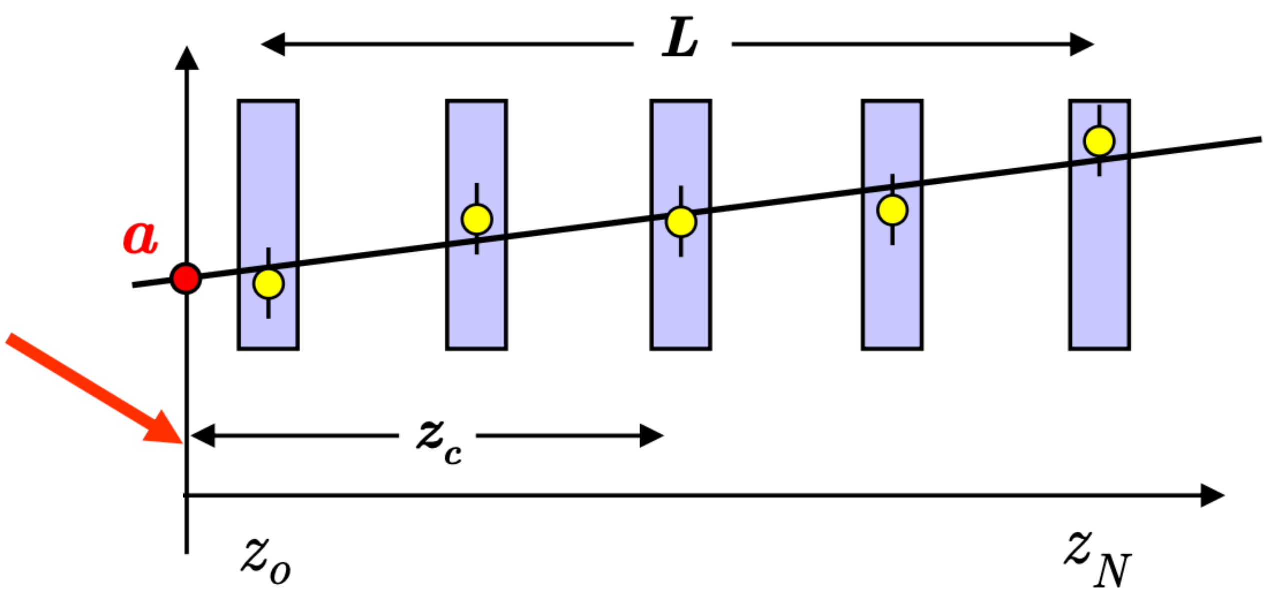
intuitively clear when the problem is Gaussian; it often isn't though — bias, robustness, QA — track hypothesis testing, detection of outliers

Straight Line Fit

Well known problem and applications — found in many textbooks and other lectures,

Let’s see if we can do it on a whiteboard…

Simplified case of equally spaced measurements with equal uncertainties:



$$L = z_N - z_o \qquad z_c = \frac{z_N + z_o}{2}$$

$$\sigma_a^2 = \left[1 + 12\frac{N}{N+2}\frac{z_c^2}{L^2}\right]\frac{\sigma^2}{N+1}$$

$$\sigma_b^2 = \frac{\sigma^2}{(N+1)L^2}\frac{12N}{(N+2)}$$

That is, the uncertainties on the track slope and on the intercept proportionally increase with the measurement uncertainty and proportionally decrease with the lever arm L,

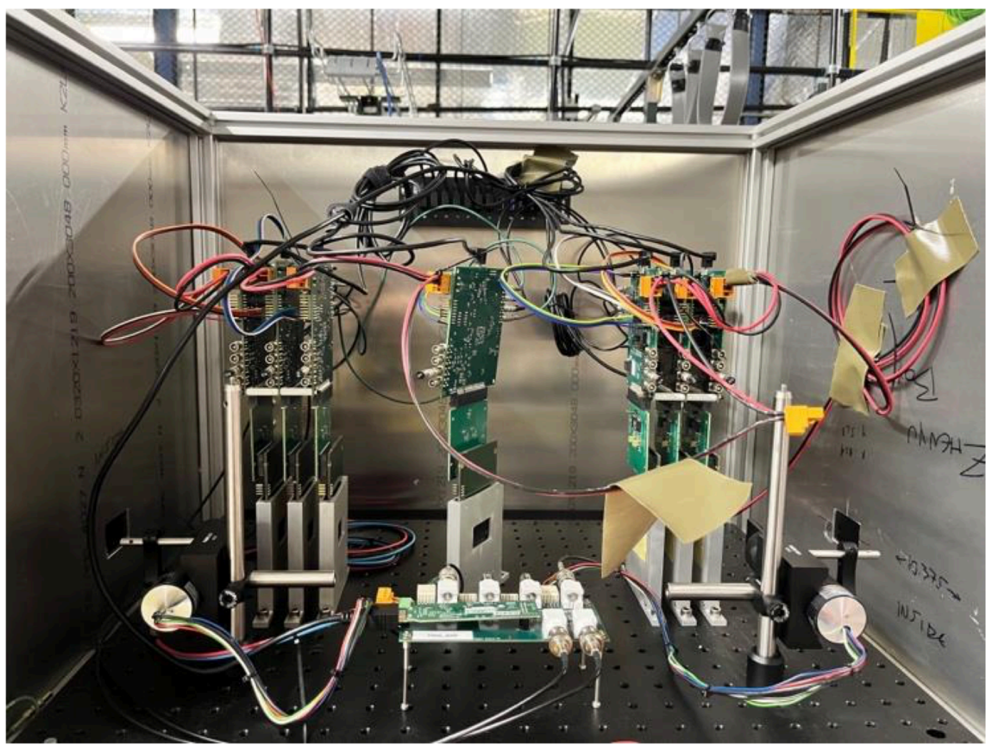
The dependence on the number of measurements is slower and goes as ~ √N for large N

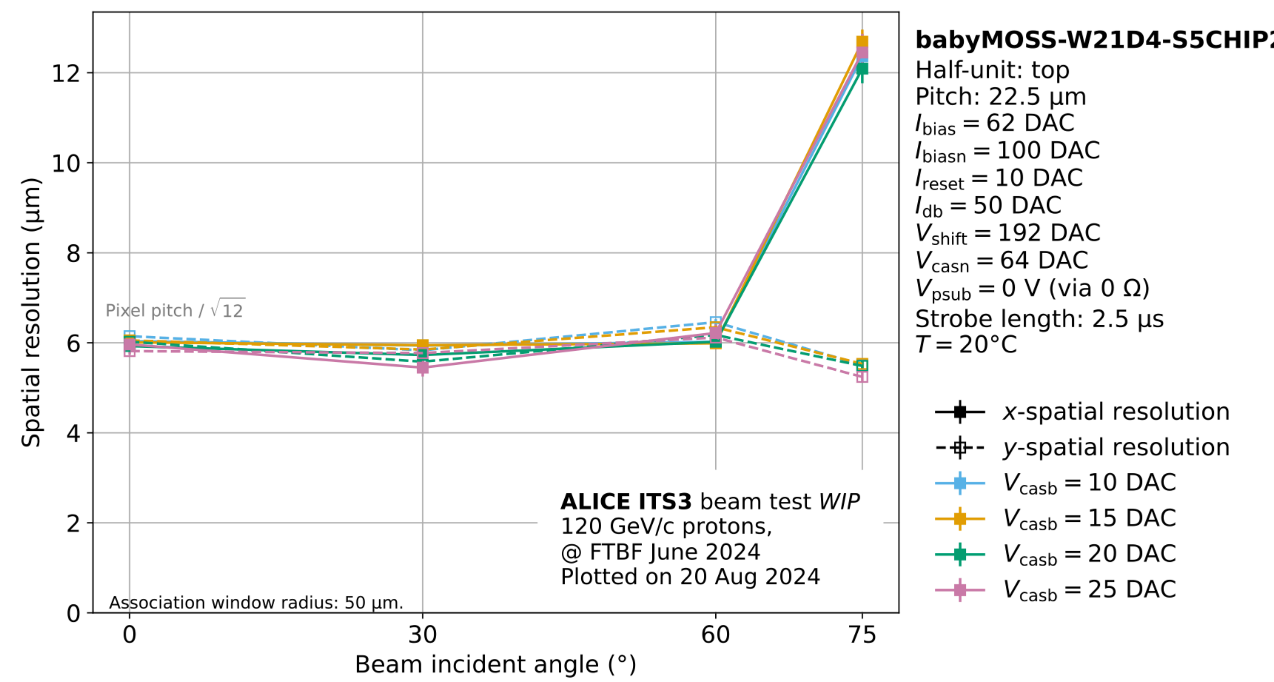
The uncertainty on the intercept increases with z_c — clear implications for vertex tracking (!)

Straight Line Fit

Well known problem and applications — found in many textbooks and other lectures,

Usually directly applicable to test-beam efforts (albeit that material effects can enter),





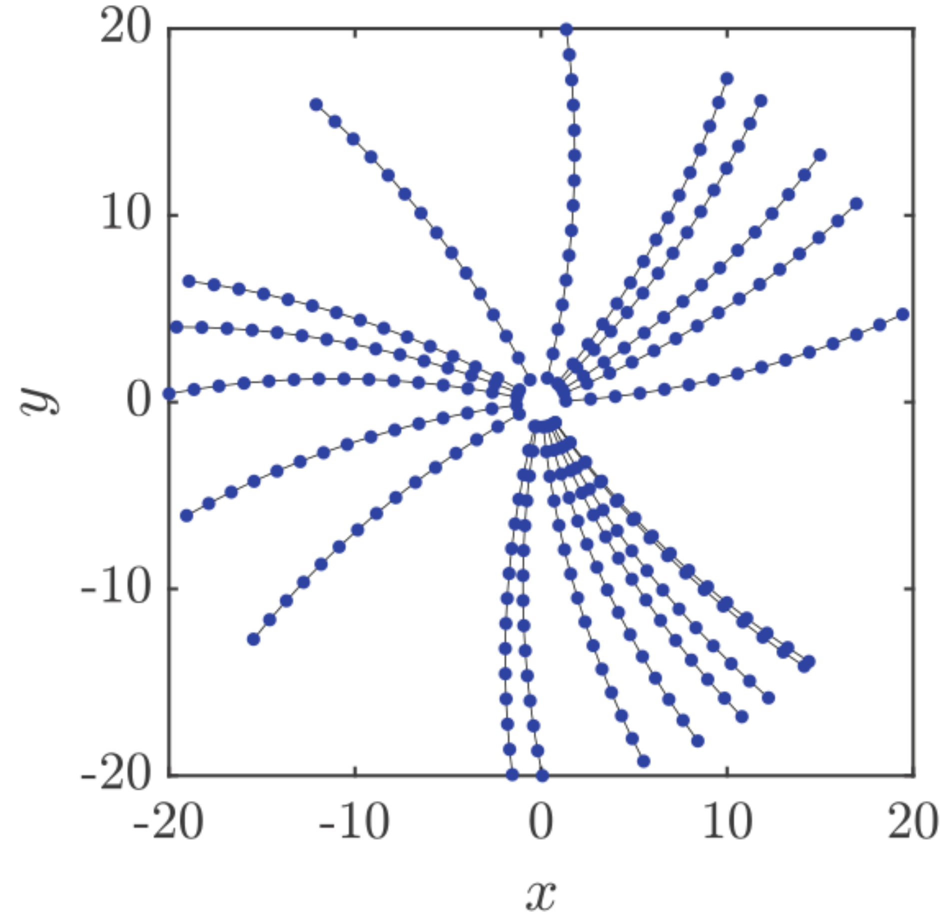
Spatial resolution at largest angle dominated by multiple scattering in the sensor holding frame

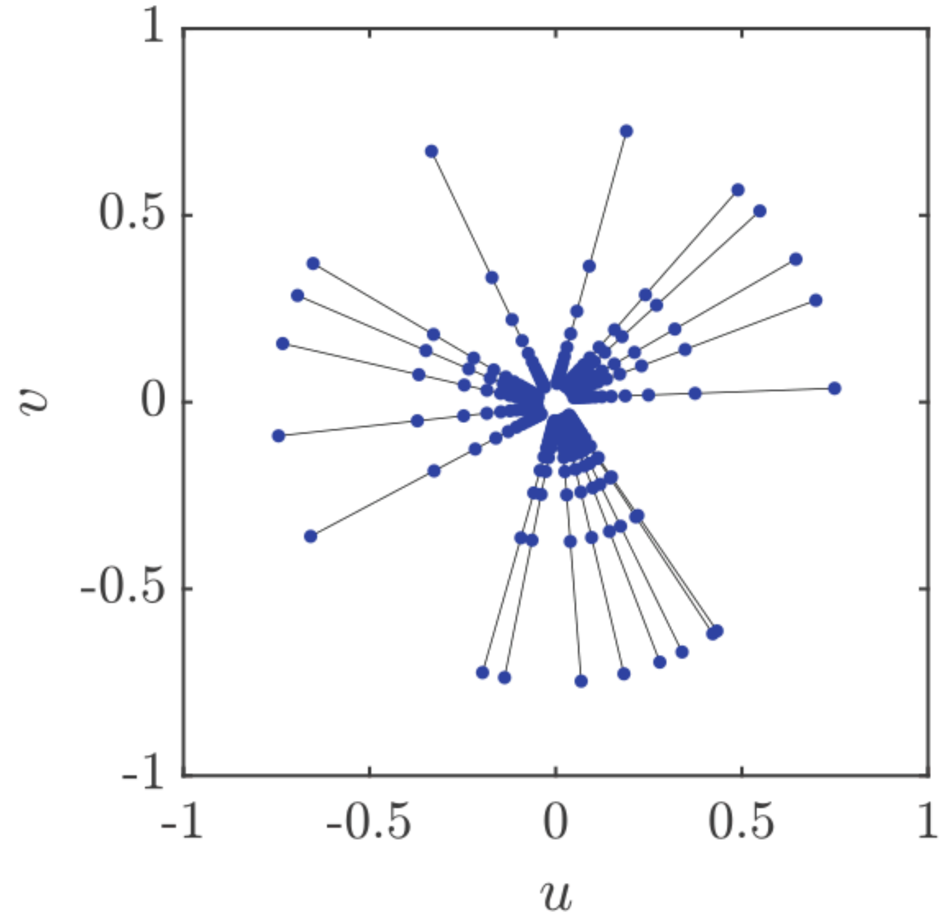
Perhaps for the/an evening discussion, how would you delineate point resolution from the effects of multiple scattering in this case?

Intermezzo — Conformal Mapping and Hough Transform

$$(x-a)^2+(y-b)^2=R^2=a^2+b^2.$$

$$u=\frac{x}{x^2+y^2},\quad v=\frac{y}{x^2+y^2}.$$





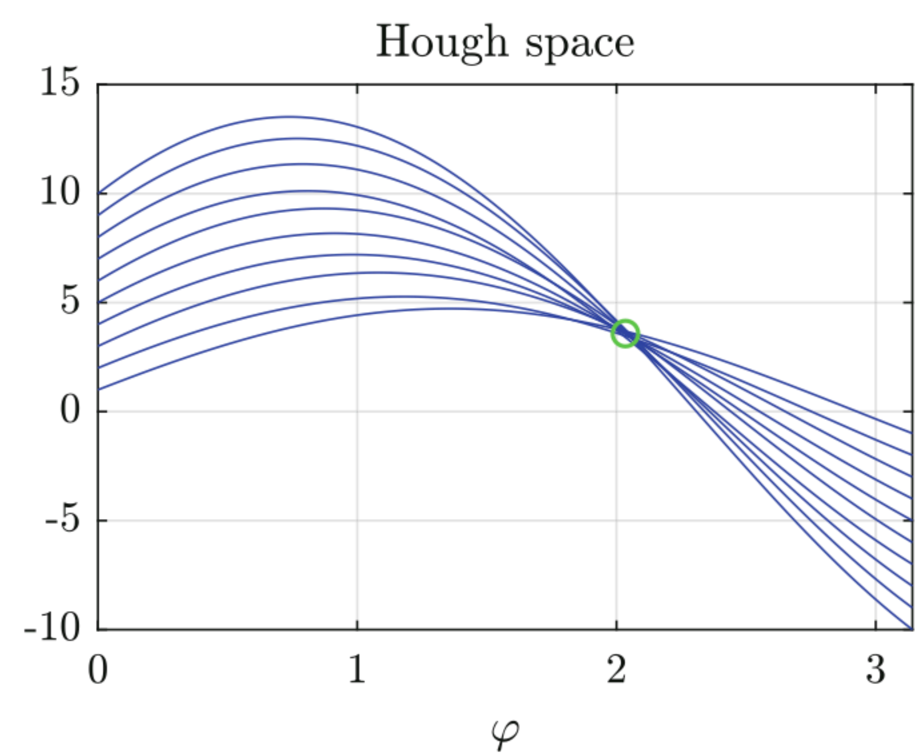
$$2au+2bv=1.$$

$2au+2bv=1.$ is the equation of a line

We do *not* know a, b, or R in advance,

Reparametrize the line to c and an angle,
to handle large (infinite) slopes,

Plot the line-parameters for every point; curves from points along the same circle will intersect.



Motion in an Electro-Magnetic Field

Common magnetic field configurations are dipole, **solenoid**, toroid,

Perhaps for the/an evening discussion, 1) consider electrostatic fields, and 2) discuss the merits of the above magnetic field configurations,

In a magnetic field the motion of a charged particle is determined by the Lorentz force,

$$\frac{d\mathbf{p}}{dt} = e\,\mathbf{v} \times \mathbf{B}$$

or, as a function of track length s,

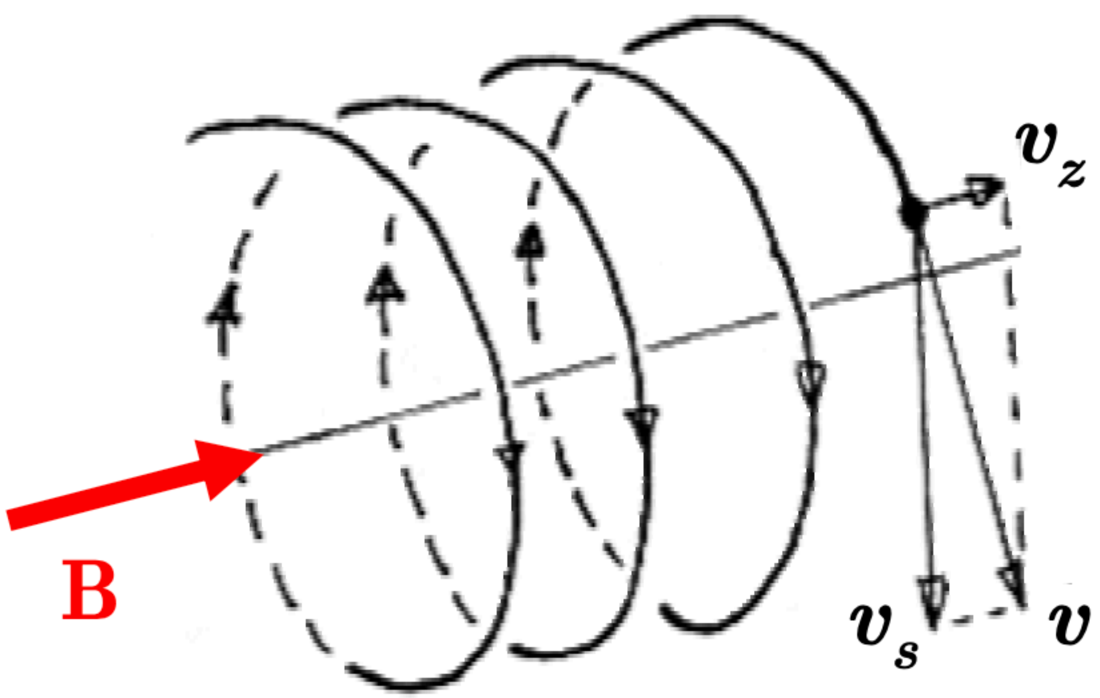
$$\frac{d^2\mathbf{r}}{ds^2} = \frac{e}{p}\frac{d\mathbf{r}}{ds} \times \mathbf{B}$$

If the field is homogeneous, the trajectory is a helix (in the absence of material effects),

Its radius r is then:

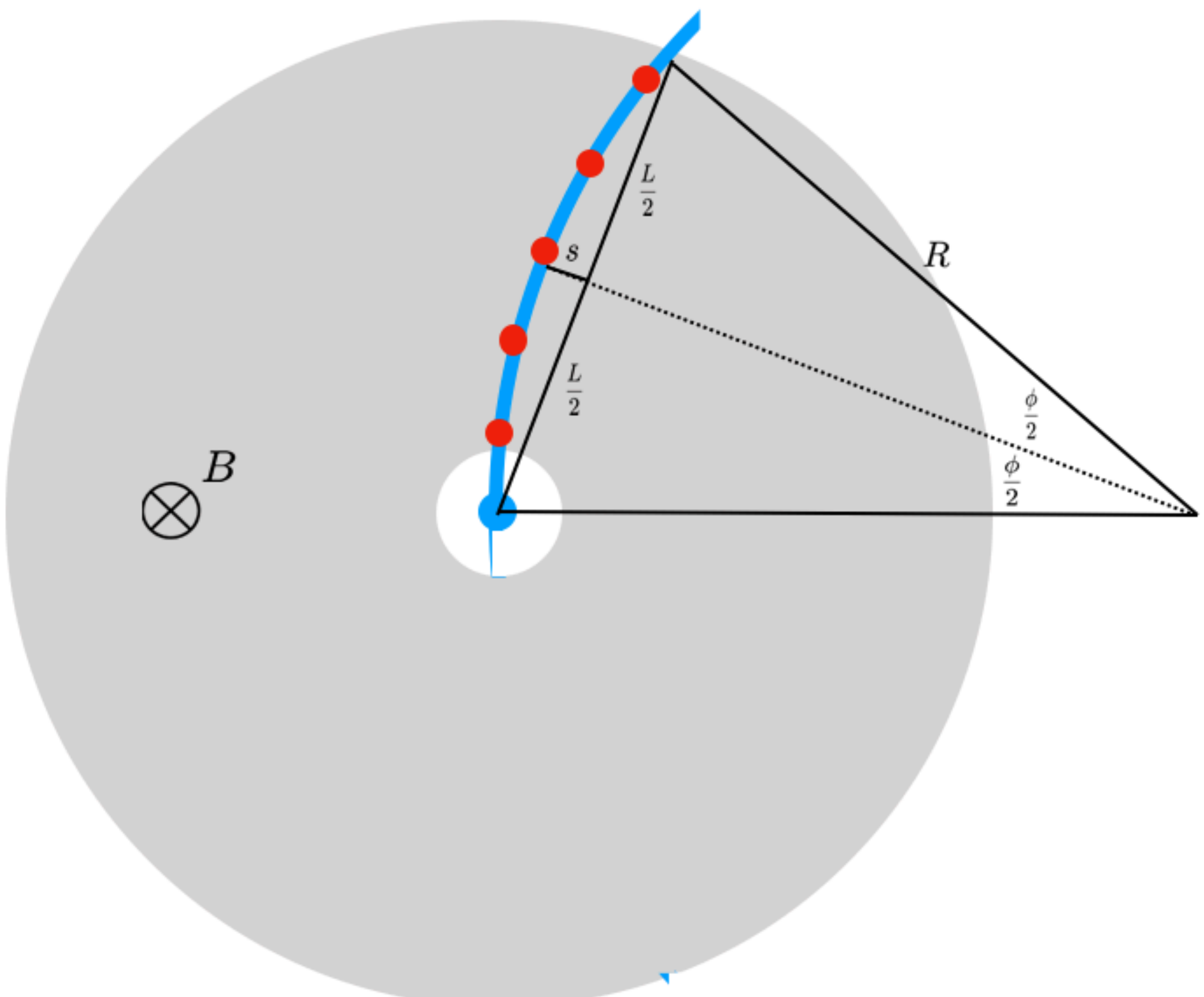
r [m] ~ p_T [GeV] / (0.3 × B [T])

If the field is inhomogeneous, one needs to solve the full differential equation (often numerically)



Forward/Backward Disks in a Solenoidal Field

The basics can be captured by straightforward considerations. Imagine a view along the beam and a helical track model inside a solenoidal field. Then,



$$p_T\,[\mathrm{GeV}] = 0.3B\,[T]\;R\,[m]$$

$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \phi = \frac{L}{R}$$

Hence,

$$\frac{\Delta p_T}{p_T} = \frac{\Delta R}{R} = \frac{\Delta\phi}{\phi} \approx \frac{\Delta s}{L^2}\cdot\frac{8p_T}{B}$$

In other words, a good (transverse) momentum resolution requires:

- a large path length L (scales as L^2)
- a large magnetic field (scales as B)
- good Sagitta measurement.

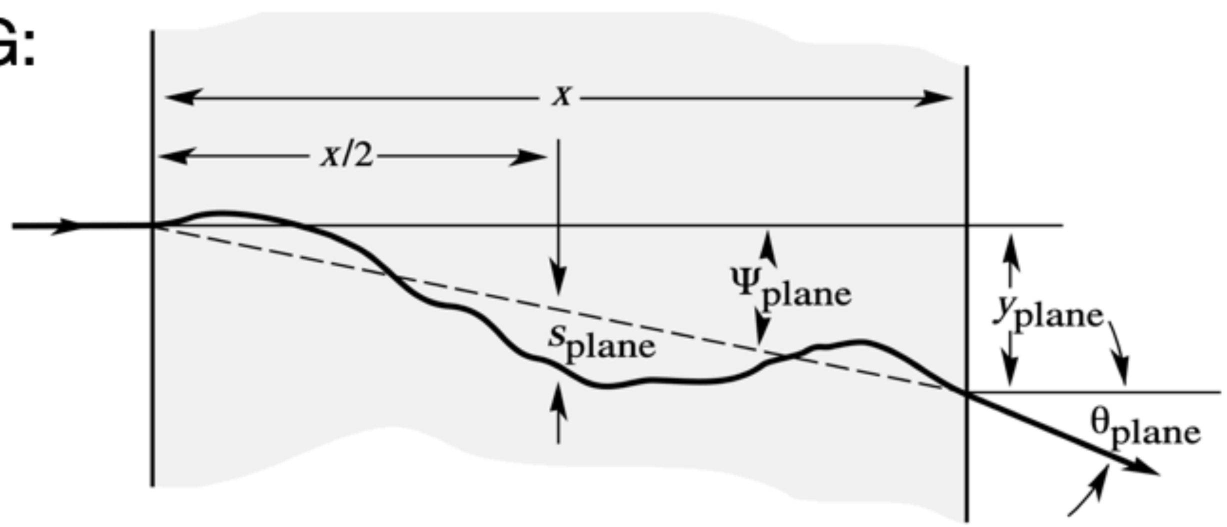
$$\Delta s = \frac{\Delta_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$ (Glückstern, 1963)

Note, however, that multiple scattering through the material of the disks matters.

Forward/Backward Disks in a Solenoidal Field

Regarding the multiple scattering contribution,

PDG:



$$\Delta\phi \approx \frac{14\,\mathrm{MeV}}{p}\sqrt{L/X_0}$$

$$p = \frac{p_\mathrm{T}}{\tan\theta}$$

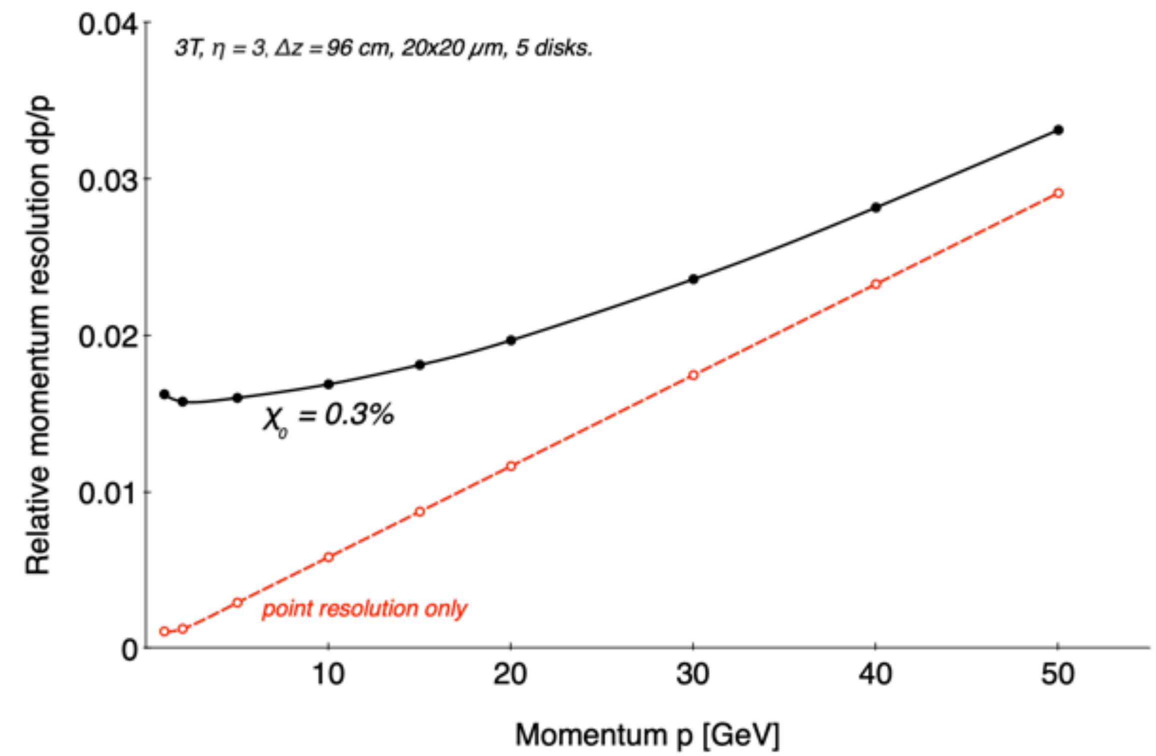
$$\left.\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}}\right|_{\mathrm{m.s.}} \approx \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{L}{X_0}}\cdot\frac{R}{L} = \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{1}{LX_0}}\,\frac{p_T}{eB}$$

Hence, the m.s. contribution depends on the dip-angle θ, though *not* on p or p_T, and

$$\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}} = a\cdot\frac{p_\mathrm{T}}{BL^2} \oplus b(\theta)\cdot\frac{1}{B\sqrt{LX_0}}$$

For forward angles, m.s. is the limiting component in d*p/p for much of the p range.*

There is, indeed, a subtle correlation of m.s. and the dip angle measurement (not explicitly considered in the arguments presented here).

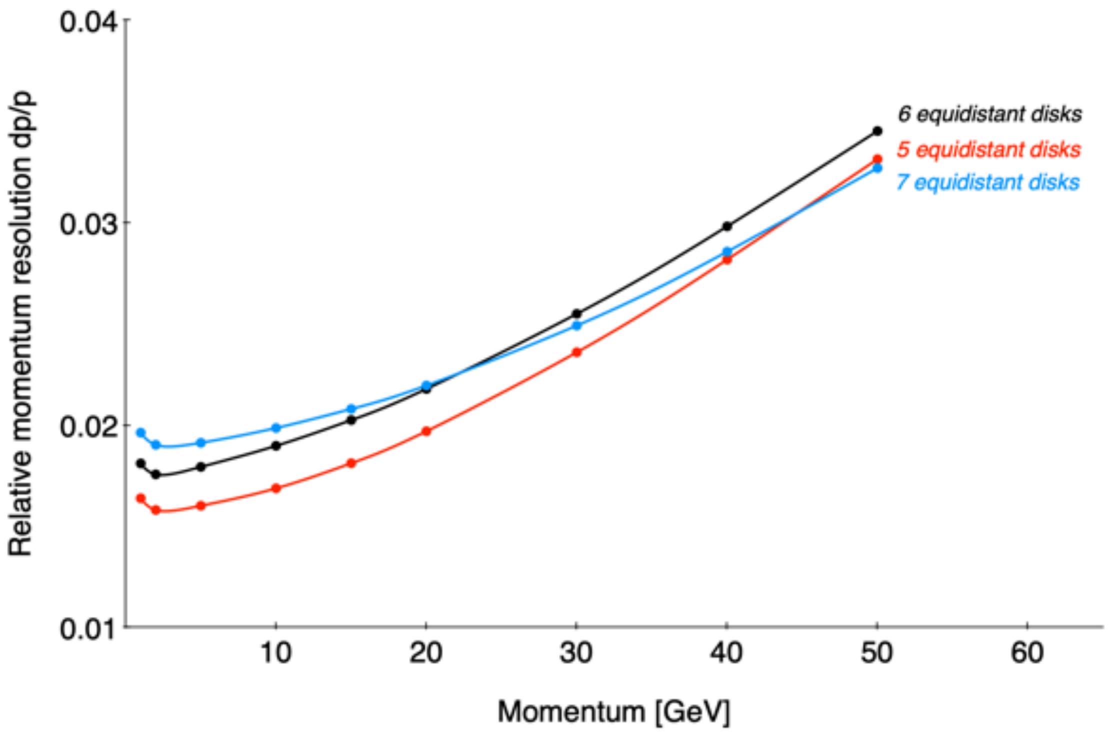


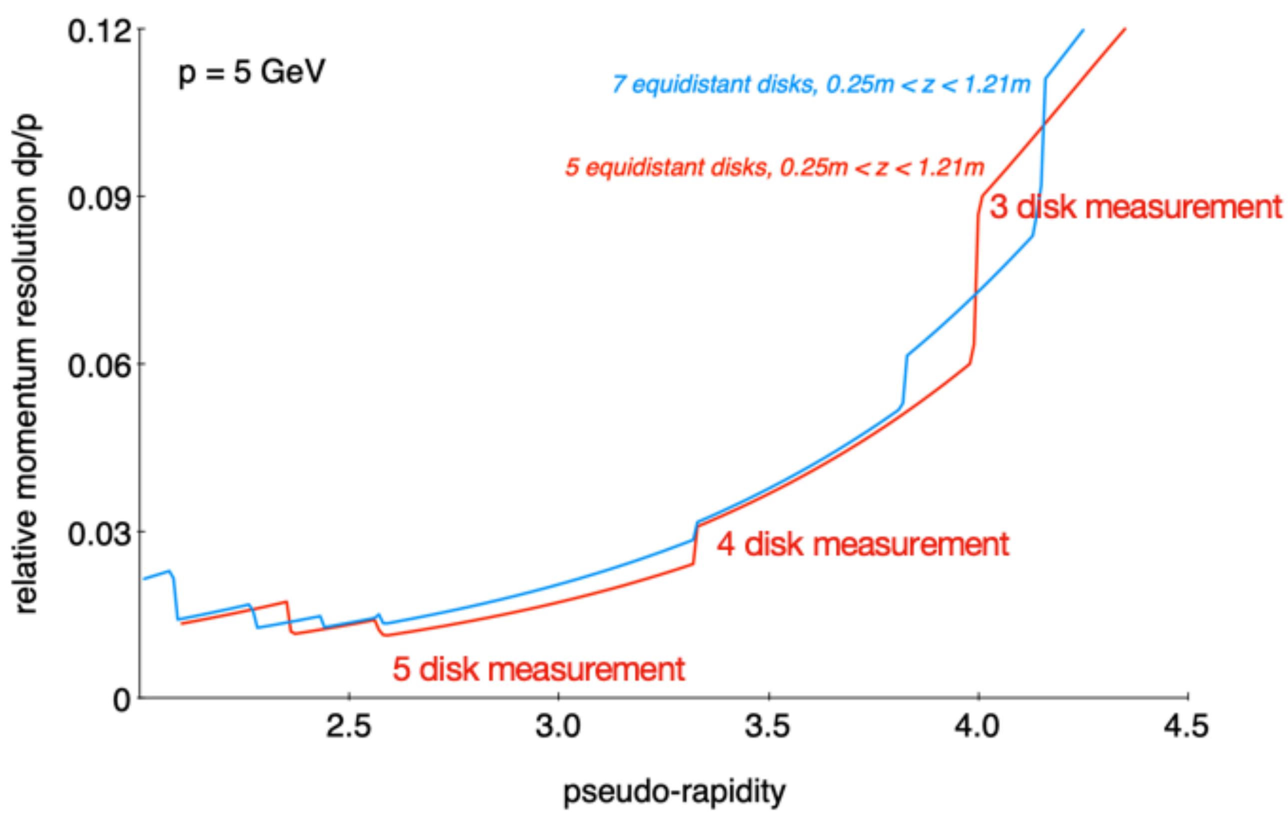
Forward/Backward Disks in a Solenoidal Field

Performance wise, $$\frac{\Delta p_T}{p_T} = a \cdot \frac{p_T}{BL^2} \oplus b(\theta) \cdot \frac{1}{B\sqrt{LX_0}}$$

n_{disk} increases measurement-points ***and*** material

We believe 5—7 disks presents a reasonable trade-off; an odd number tends to capture the Sagitta point and is thus preferred.



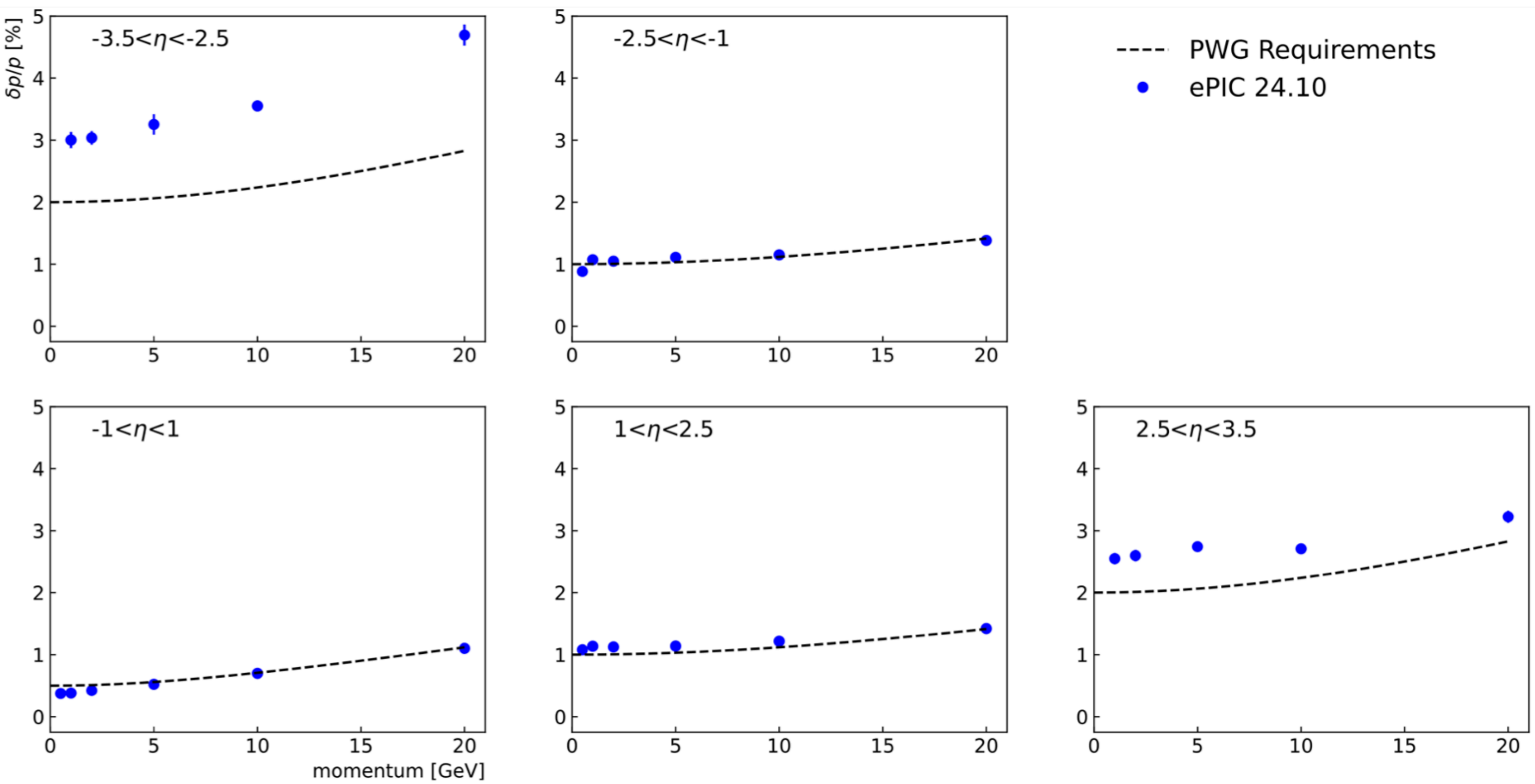


An equidistant configuration is *not* truly optimal in capturing the Sagitta, but avoids *acceptance issues* (illustrated on the left for 5—7 disks; details are geometry-dependent),

Viable ways to improve d*p*/*p* etc. are to increase *L* available for tracking and/or reduce material; increasing points within the same *L* or other technology are ***not***.

ePIC simulated tracking resolutions

relative momentum resolution



Simulated resolutions shown for single pion tracks,

Based on actual track finding and reconstruction,

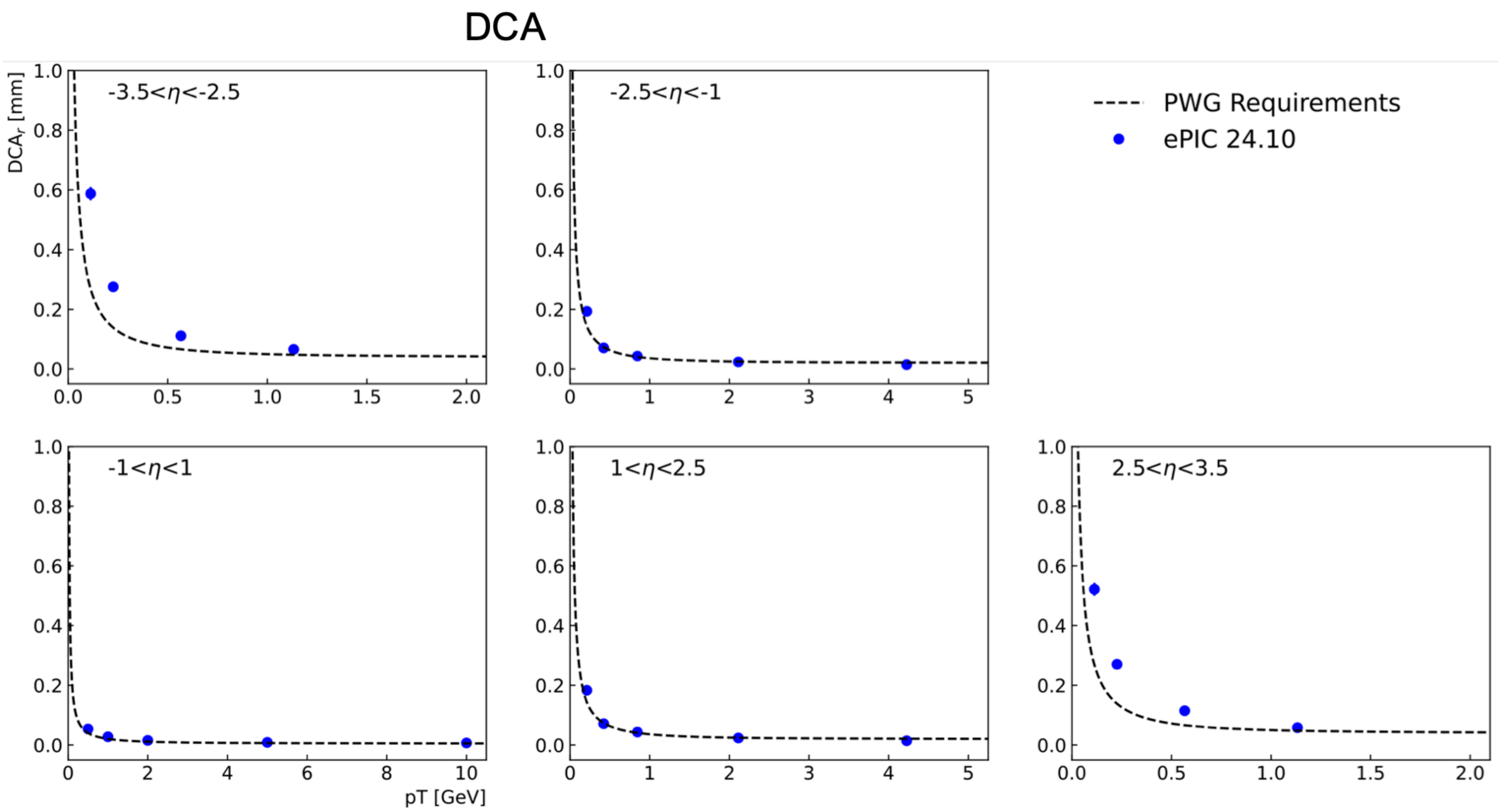
Increasingly realistic descriptions of active elements, supports, and services,

Simulations have been extended to deep-inelastic scattering events; detector noise and backgrounds ongoing.

Difference between most forward/backward resolutions due to asymmetric constraint on spatial extent along the beamline,

Rely on combination with precision EM calorimetry to achieve electron resolutions necessary for EIC science program.

ePIC simulated tracking resolutions



Simulated resolutions shown for single pion tracks,

Based on actual track finding and reconstruction,

Increasingly realistic descriptions of active elements, supports, and services,

Simulations have been extended to deep-inelastic scattering events; detector noise and backgrounds ongoing.

Fast simulations show least resolution sensitivities to material budgets in outermost barrel layer and outermost disks.

Wrapping up

- The Electron-Ion Collider will be a world-wide unique facility with new capabilities to qualitatively and quantitatively advance QCD and answer profound scientific questions about spin, mass, and emergent phenomena in gluon-dense matter.
- The ePIC detector is well into its design; magnet, calorimeters, PID, trackers,
- For tracking, a compact solenoidal magnetic field of 1.7 T has been selected — this will be instrumented with modern MPGDs and MAPS-based (vertex) trackers in a barrel + disk configuration; the Time-of-Flight subsystem is classified as a PID subsystem, but will benefit tracking as well,
- Seemingly simple concepts in tracking — B, lever arm, point resolution, material, number of detection planes — get involved quickly,
- I hope that for many of you this will be a start — this school is a wonderful entry.

Thank you!