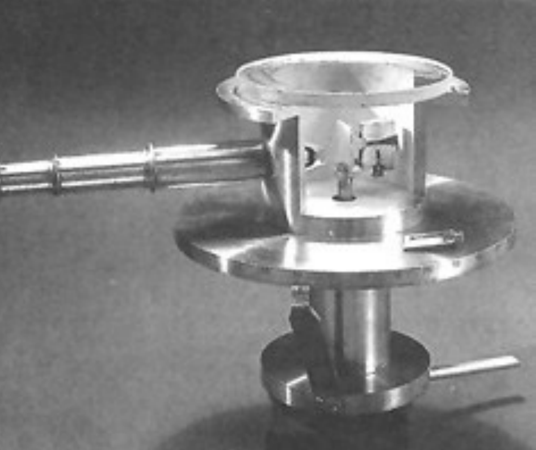
Funding support from:



EIC Physics

An Experimentalist's Perspective

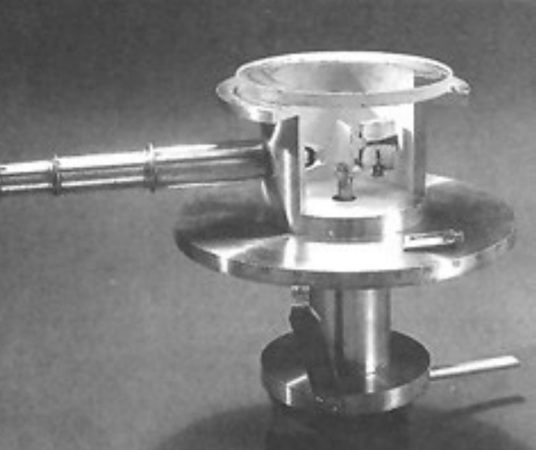
Ernst Sichtermann (Lawrence Berkeley National Laboratory)

~10^{-14} m
~MeV

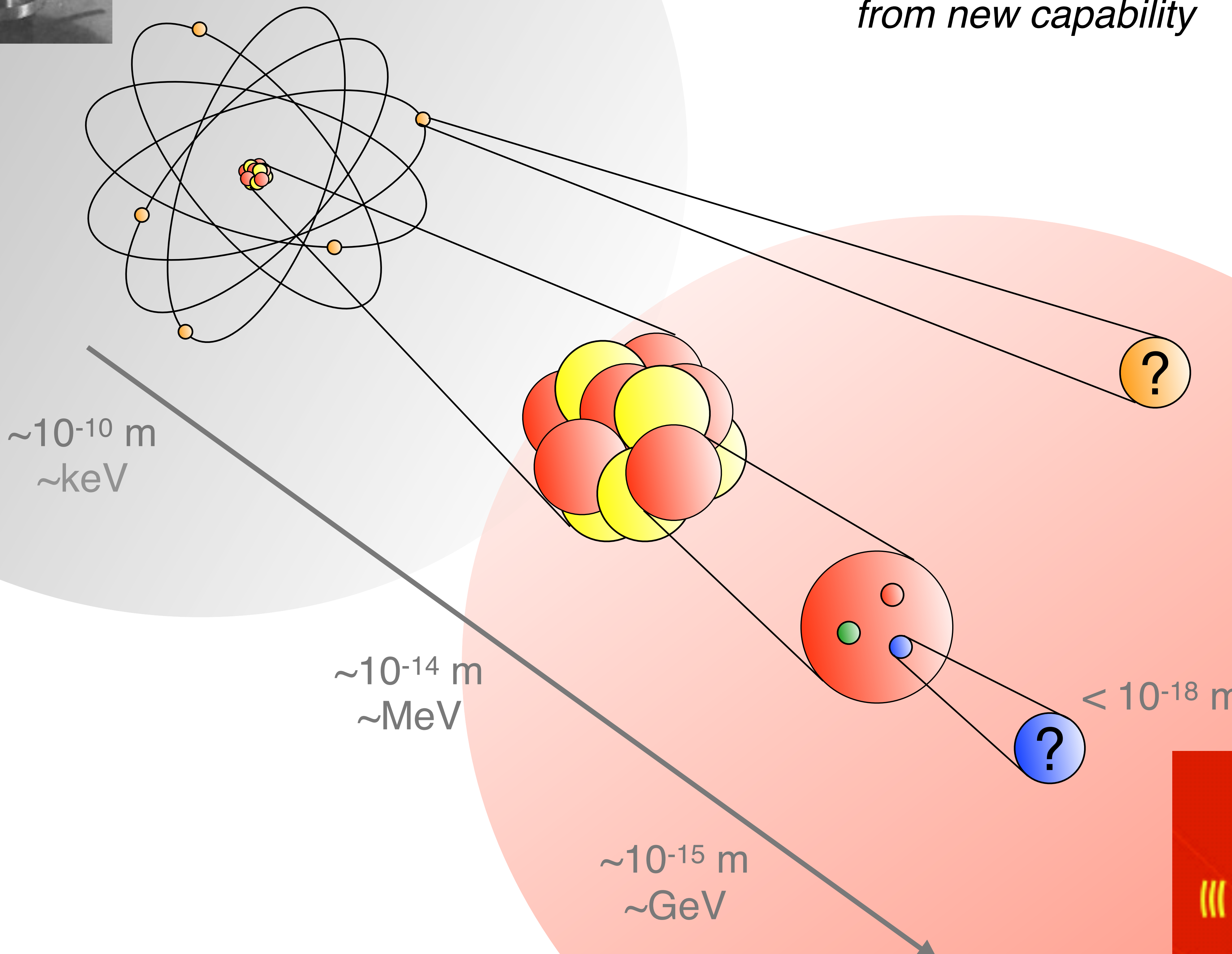
< 10^{-18} m

~10^{-15} m
~GeV

2023 CFNS-CTEQ Summer School on the
Physics of the Electron-Ion Collider
Stony Brook University — June 5-16, 2023



A history of new insight from new capability



EIC Physics: An Experimentalist's Perspective

Many thanks to the organizers for organizing this school,

you for taking part!

Lectures like these take a village… I owe a debt of gratitude to many friends and colleagues over many years — errors are of course my own.

Several useful references:

G. Wolf "HERA Physics" DESY-94-22 (1994),

PDG, "Passage of Particles Through Matter", c.f.
https://pdg.lbl.gov/2022/reviews/rpp2022-rev-passage-particles-matter.pdf

T. Ullrich, "Technology Overview" at a recent EIC Detector-II workshop, c.f.
https://indico.bnl.gov/event/18414/contributions/76157/

The EIC community's "Yellow Report", Nucl. Phys. A 1026 (2022) 122447.

EIC Physics Experimental Perspective

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
ion	p	p, Pb, ...	p - U	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	3×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031

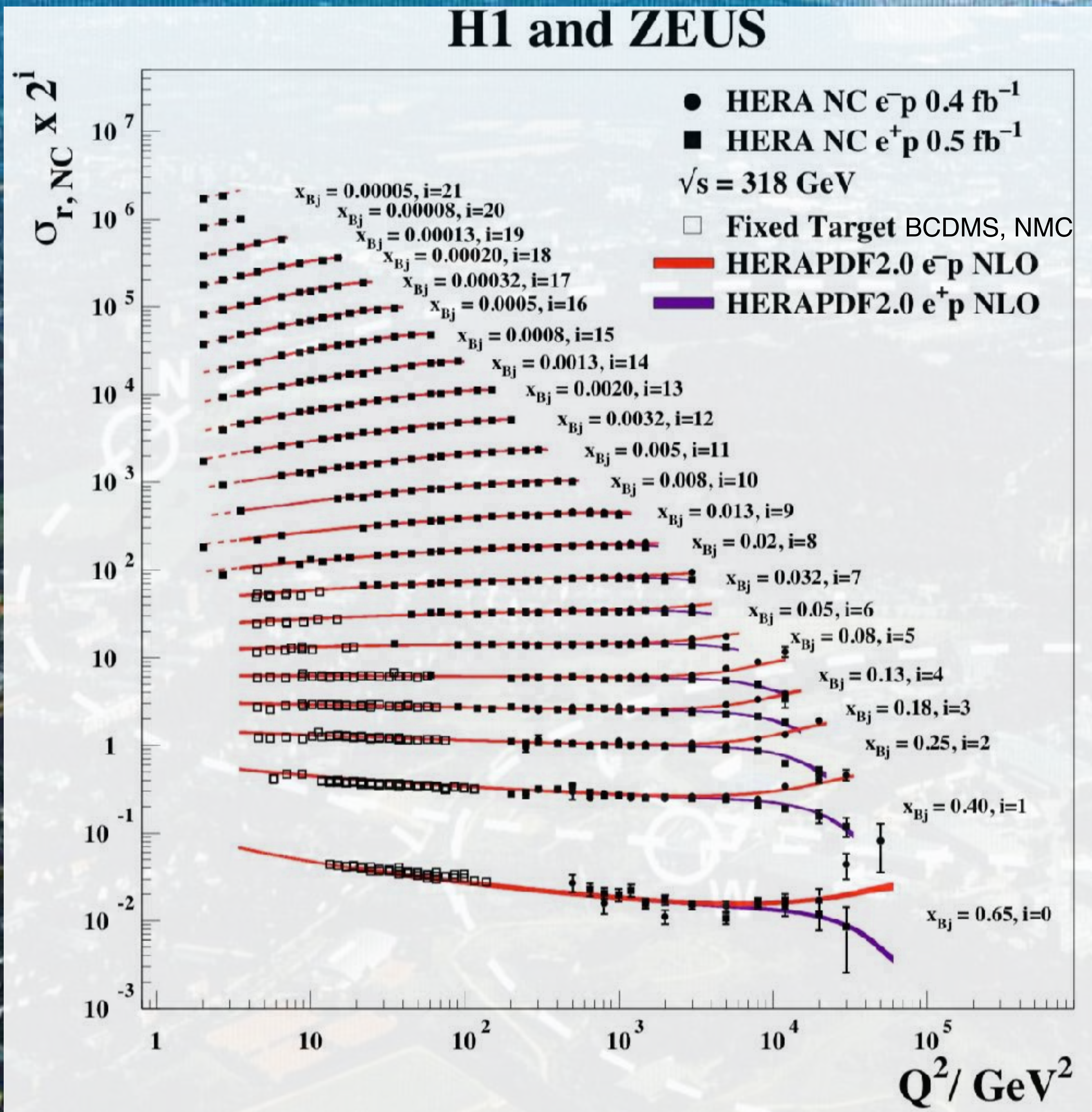
High-Energy Physics

Nuclear Physics

Goal: EIC context and capabilities (yesterday)

Brief Recap — HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580

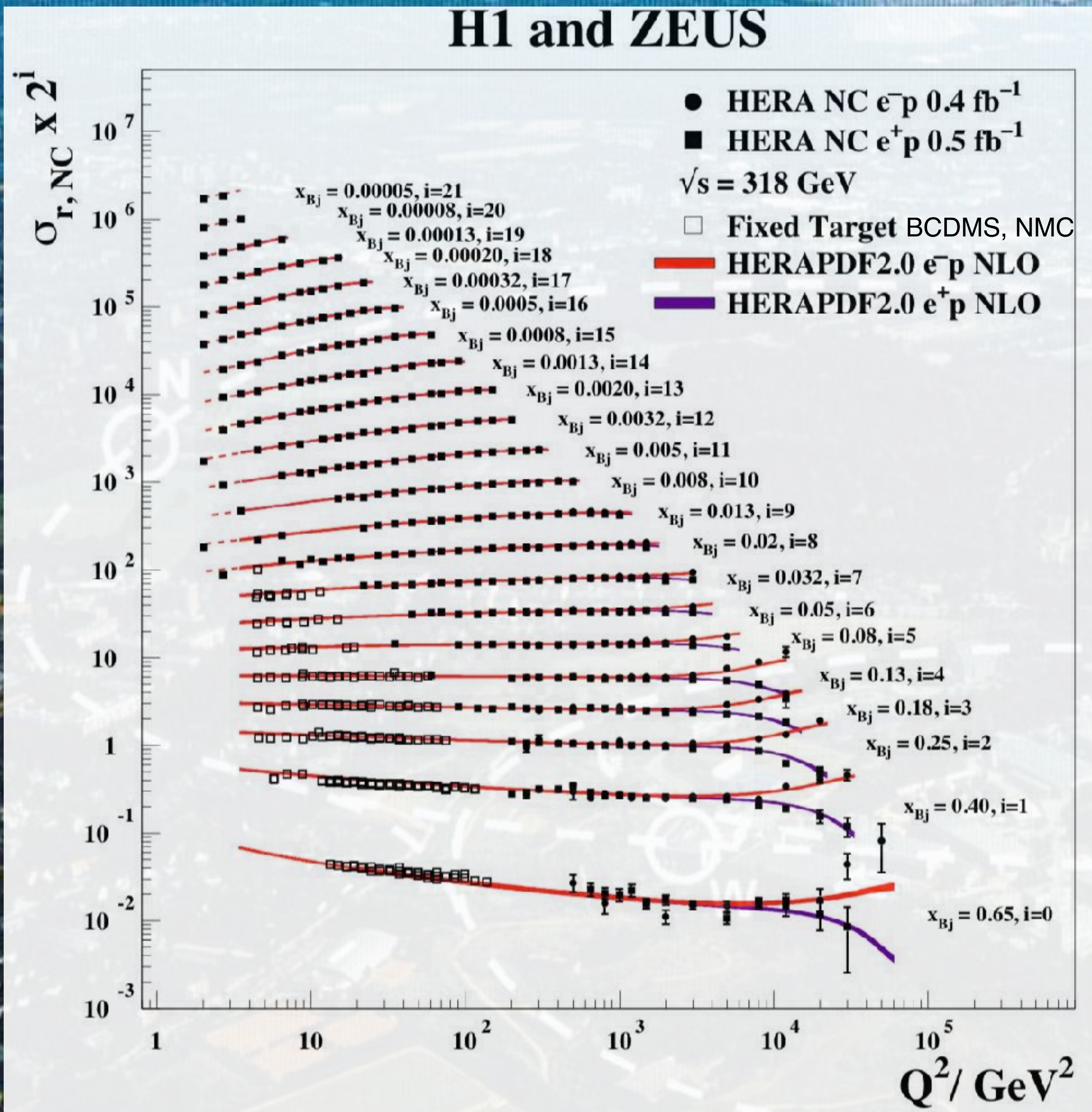


A lot in this plot:

- covers about five orders of magnitude in *x* and Q^2,
- consistency of fixed-target data and HERA data,
- scaling at *x* ~ 0.1 and violations elsewhere,
- strong rise of gluon density,
- E.W. interference at high Q^2,
- crucial input to “PDF fits”

Brief Recap — HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580



A lot in this plot:

- covers about five orders of magnitude in x and Q^2,
- consistency of fixed-target data and HERA data,
- scaling at $x \sim 0.1$ and violations elsewhere,
- strong rise of gluon density,
- E.W. interference at high Q^2,
- crucial input to “PDF fits”

Brief recap — EIC

Approach: combine strengths
use existing investments (risk, cost),
pursue luminosity;100x - 1000x HERA
nuclei and *polarization*,
optimized instrumentation.

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
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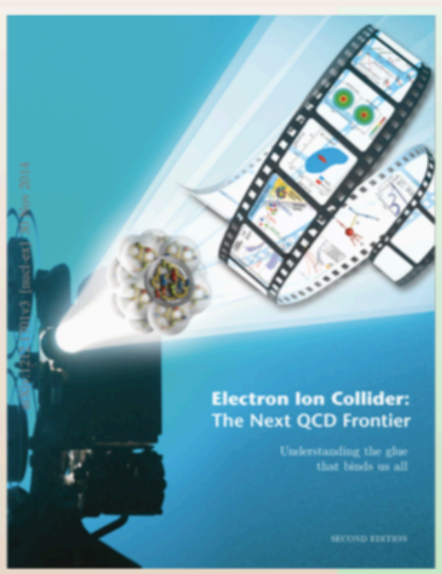
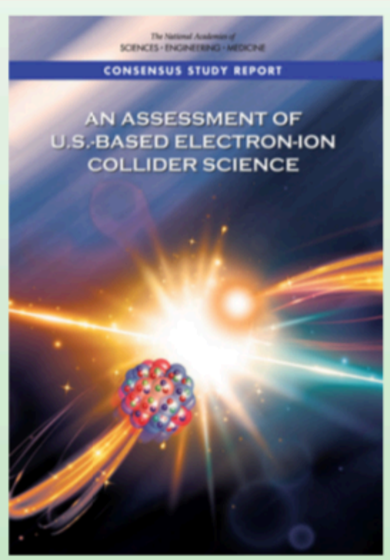
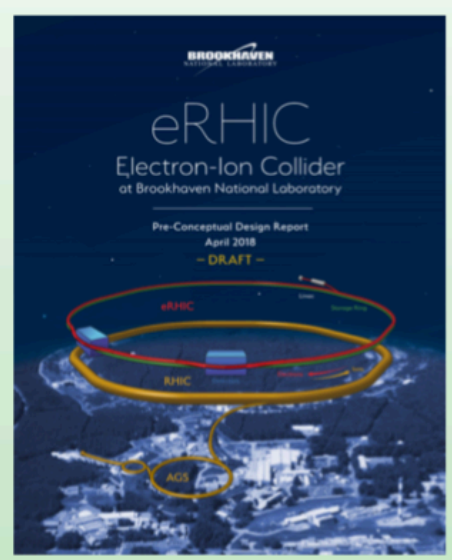
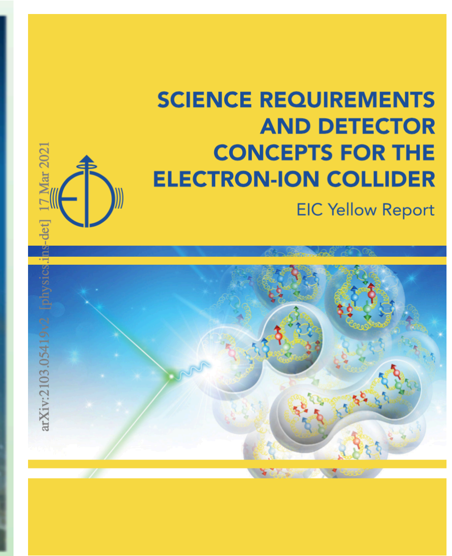


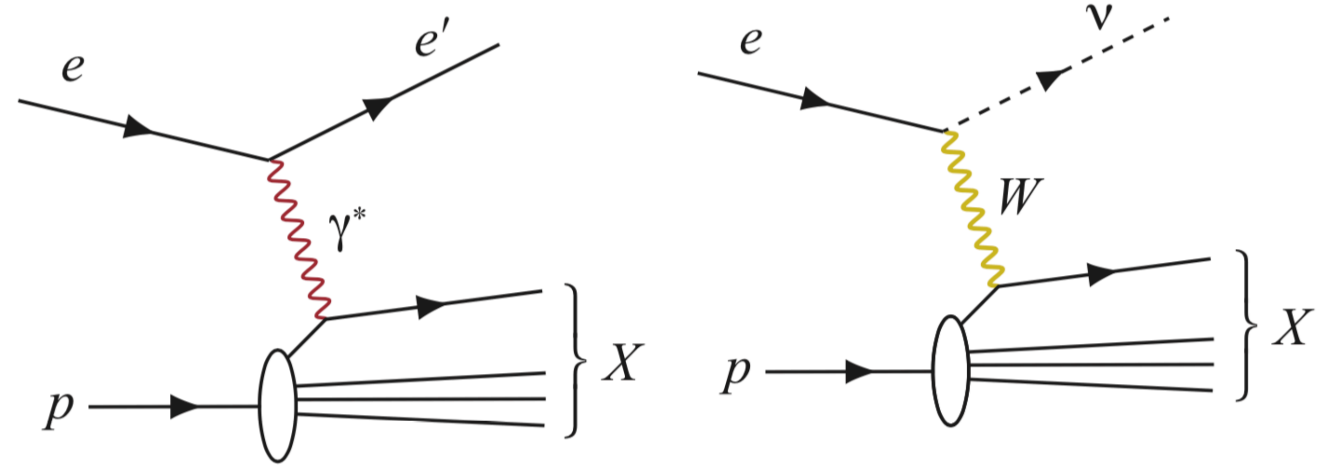




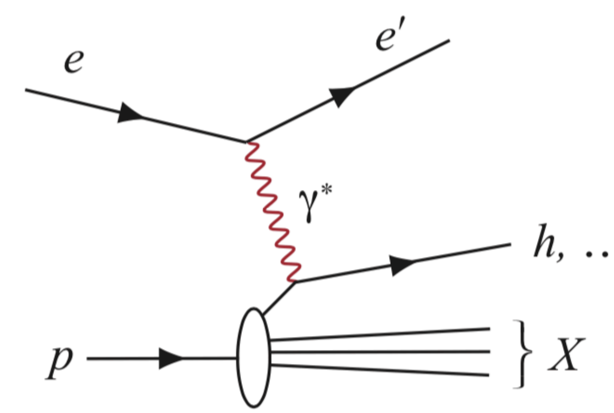


Brief recap — key processes at EIC

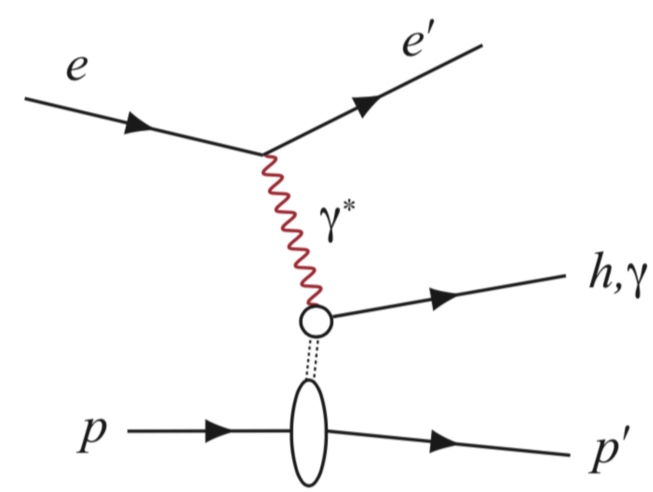
Inclusive deep-inelastic scattering



Semi-inclusive deep-inelastic scattering

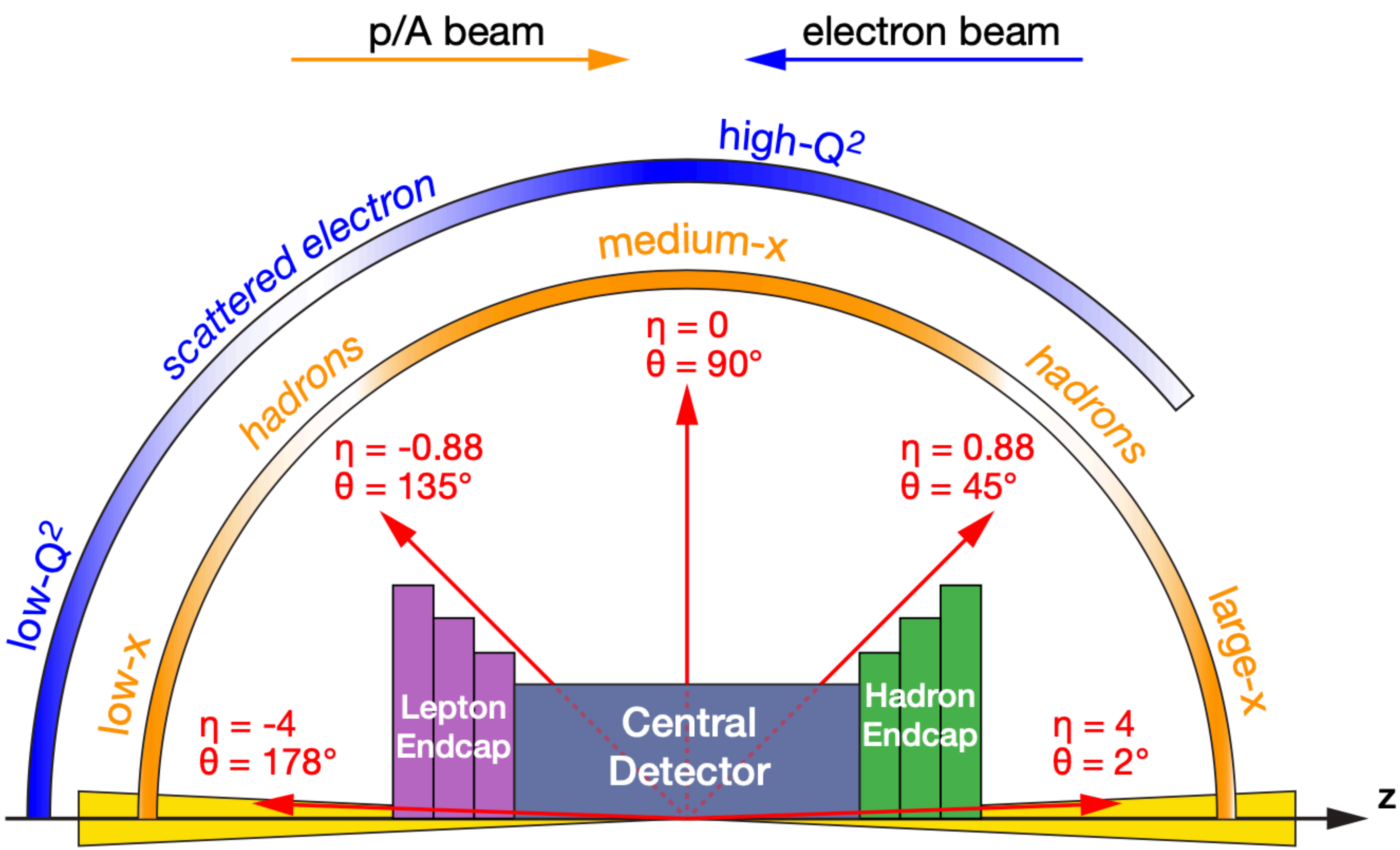


Exclusive deep-inelastic scattering



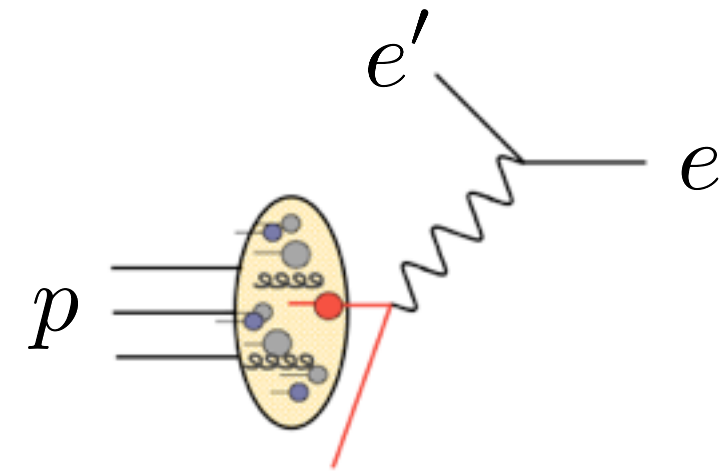
Scattered electron is obviously key.

EIC Physics Experimental Perspective



Goal: EIC experiment concepts (today)

Observed (or known):



$$e = (0, 0, -E_e, E_e)$$

$$e' = (E'_e \sin\theta'_e, 0, E'_e \cos\theta'_e, E_e)$$

$$p = (0, 0, E_p, E_p)$$

i.e. angles are defined *w.r.t. the hadron beam direction* (HERA-convention).

Relevant invariants:

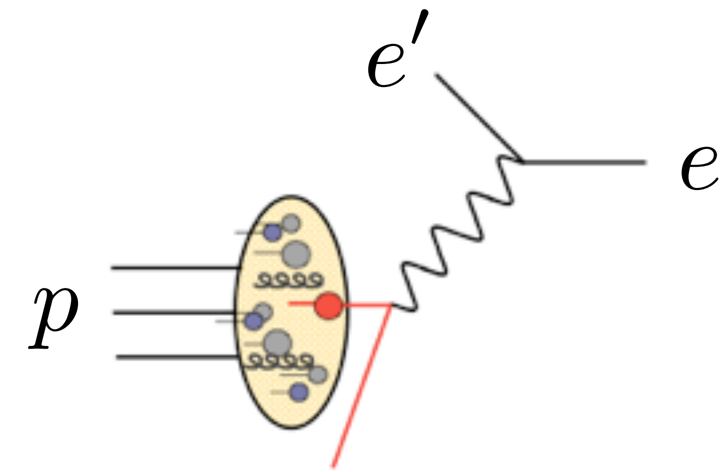
$s = (e + p)^2$	Square of total c.m. energy
$q = e - e' \qquad Q^2 = -(e - e')^2$	Square of (4-)momentum transfer
$x = \dfrac{Q^2}{ys}$	Bjorken-x, ~parton mom. fraction
$y = (q.p)/(e.p)$	Fractional energy transfer

x, Q ^{2} can be reconstructed from the scattered electron, the “current jet”, or hybrids.

Relevant invariants:

$$s = (e + p)^2$$

$$x = \frac{Q^2}{ys}$$



What was the maximum center-of-mass energy achieved at HERA?

What is the minimum value of Bjorken-x that could be reached for $Q^2 > 1$ GeV^2

What is the maximum value of Q^2 that could be reached for x = 0.1 ?

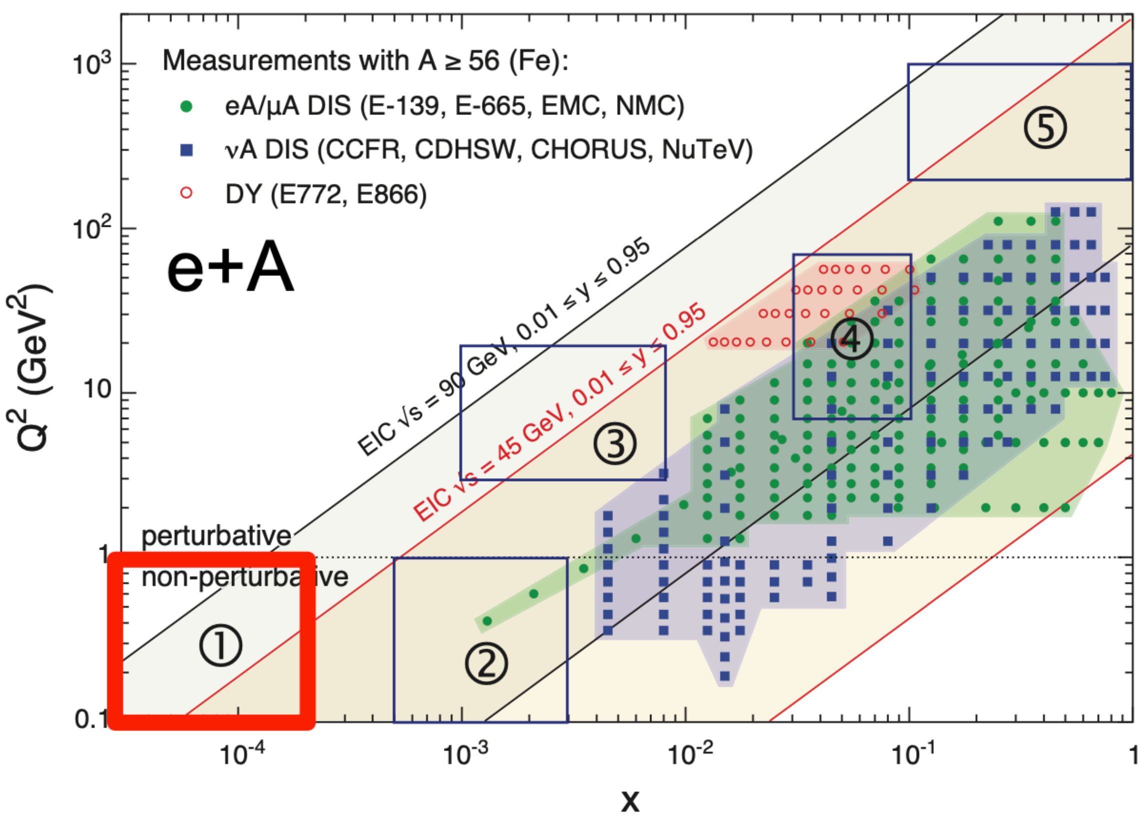
What would the electron beam energy need to be to achieve the same center-of-mass energy in a fixed-target experiment?

For discussion in the evening,

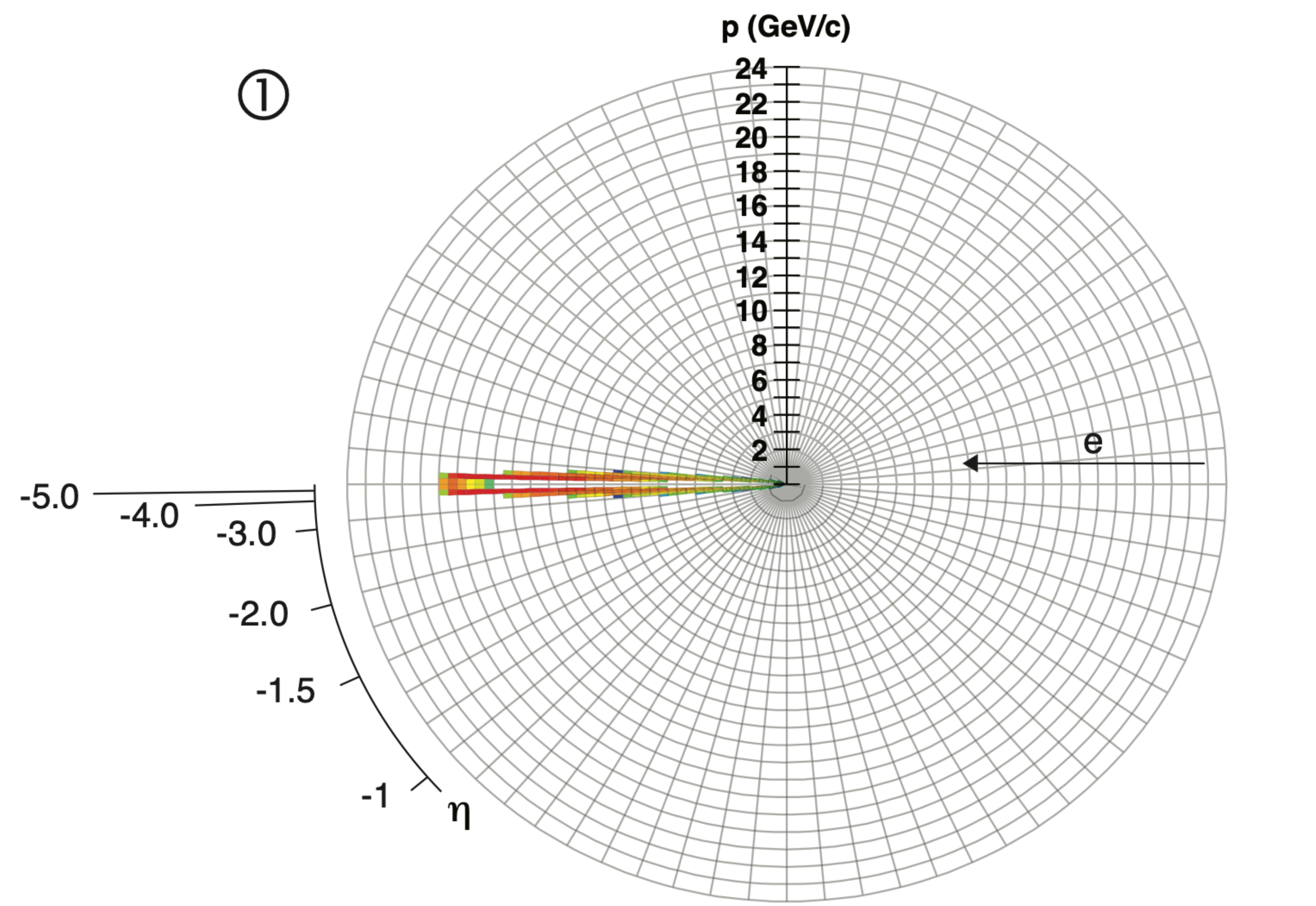
What are the energy and angle of the scattered electron for $x = 10^{-3}$ and $Q^2 = 10$ GeV^2?

What is the angle of the struck quark (“current jet”)? What would it be in a fixed-target experiment with the same center-of-mass energy?

Scattered Electron at EIC



20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV^2, $3{\cdot}10^{-5} < x < 2{\cdot}10^{-4}$



Courtesy T. Ullrich

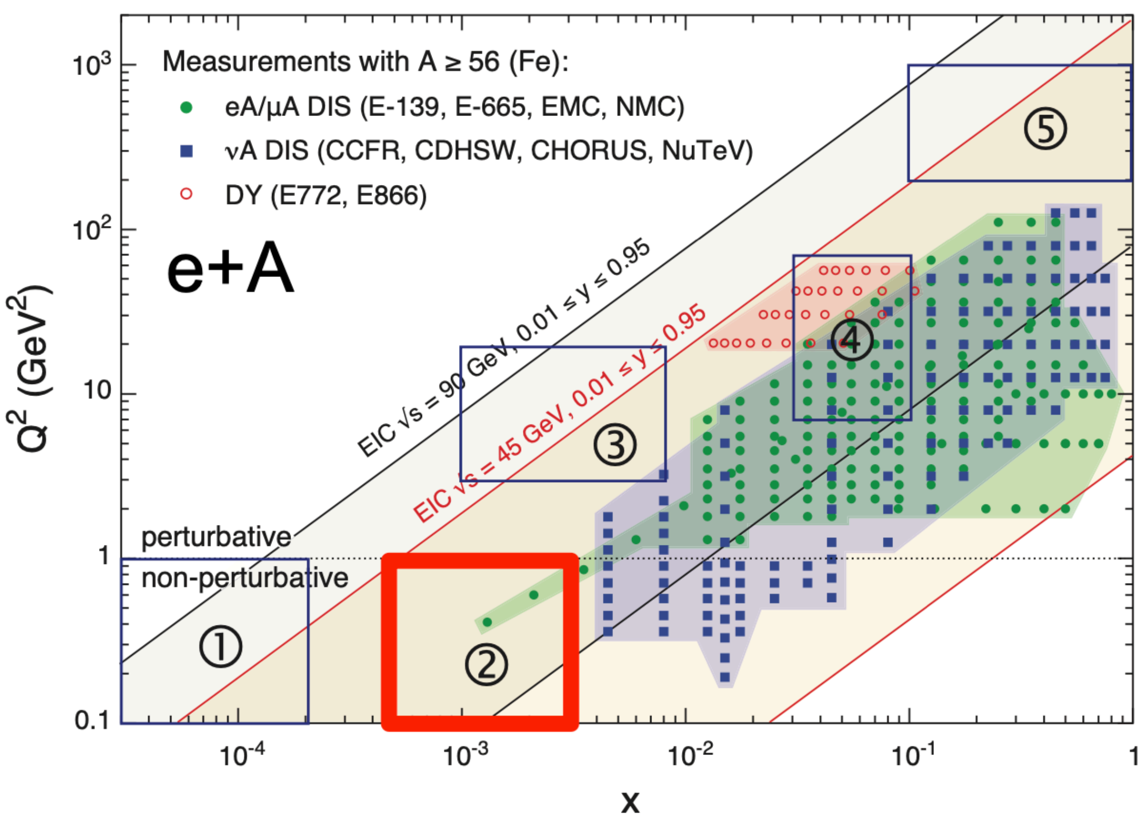
Scattered Electron determines:

$$y = 1 - (E_e'/2E_e)(1 - \cos\theta_e')$$

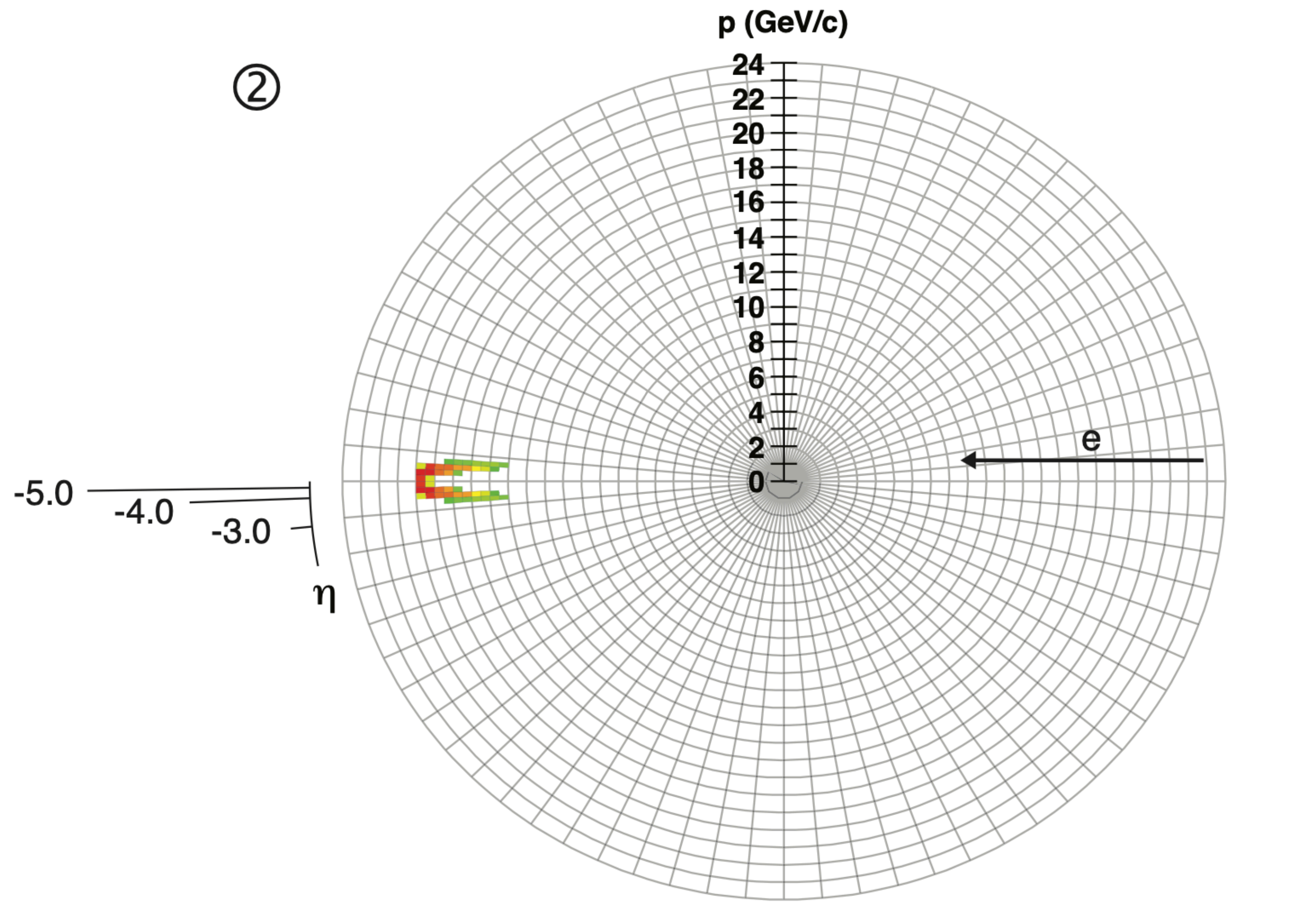
$$Q^2 = 2E_e'E_e(1 + \cos\theta_e')$$

$$x = E_e'E_e(1 + \cos\theta_e')/(2yE_p)$$

Scattered Electron at EIC



20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV^2, $5 \cdot 10^{-4} < x < 3 \cdot 10^{-3}$



Courtesy T. Ullrich

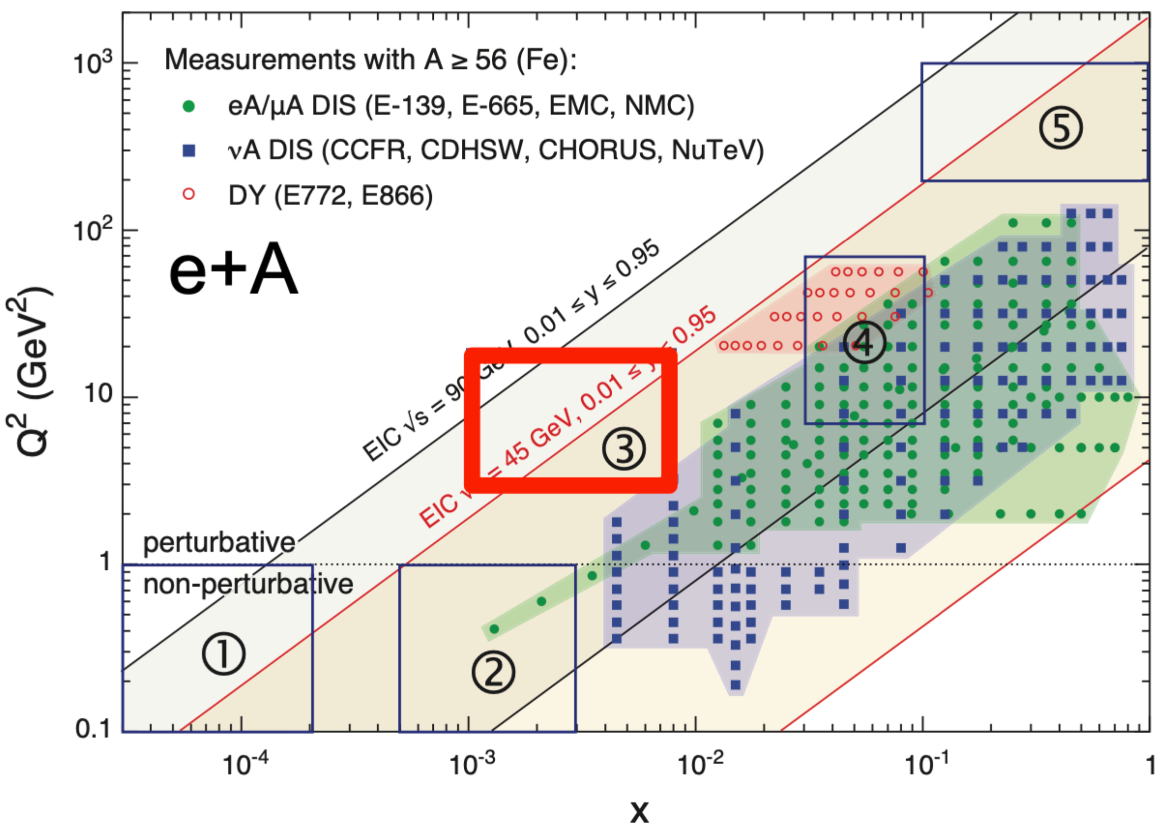
And inversely:

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

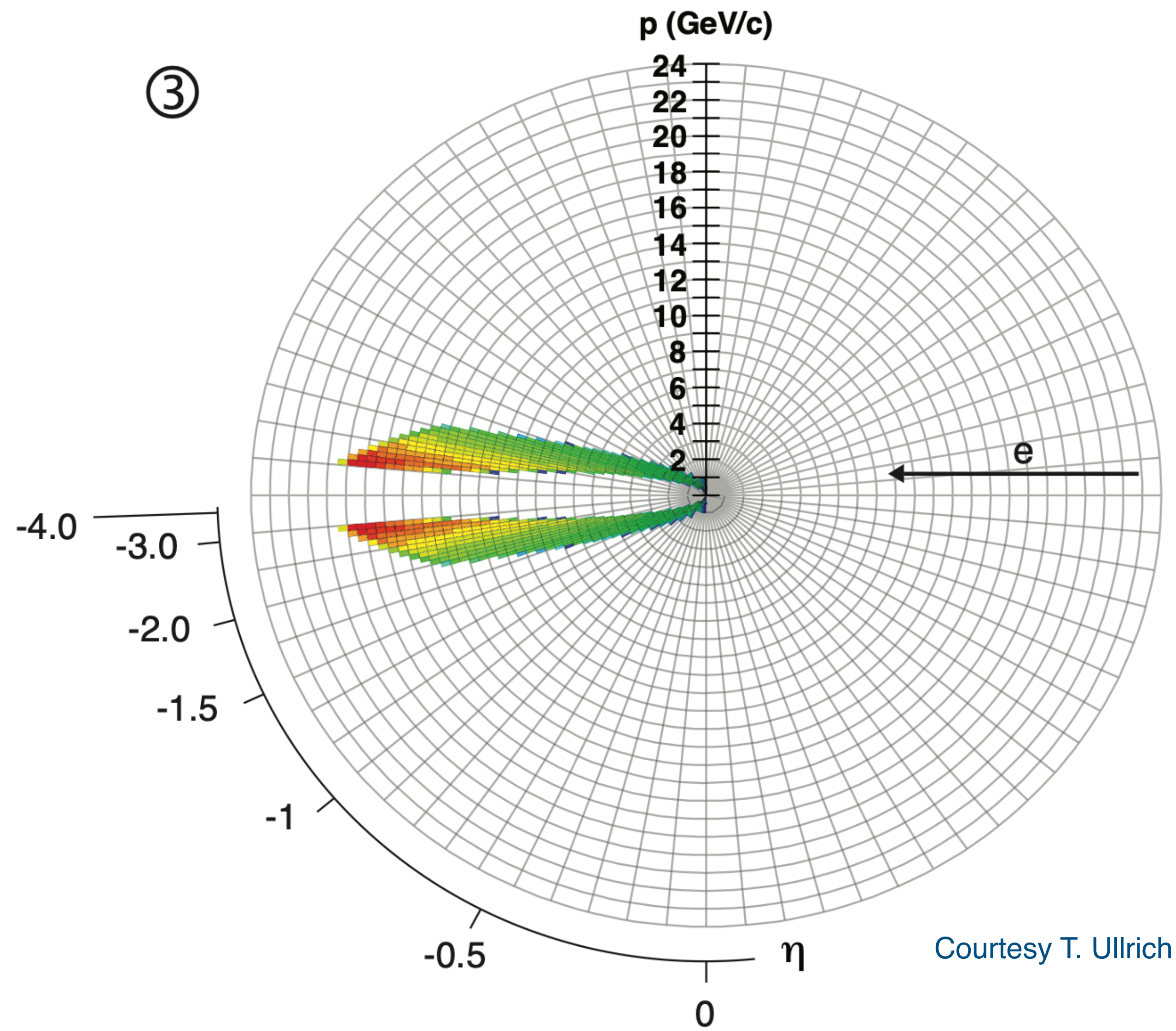
$$\cos\theta'_e = [xyE_p - (1-y)E_e]/[xyE_p + (1-y)E_e]$$

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

Scattered Electron at EIC

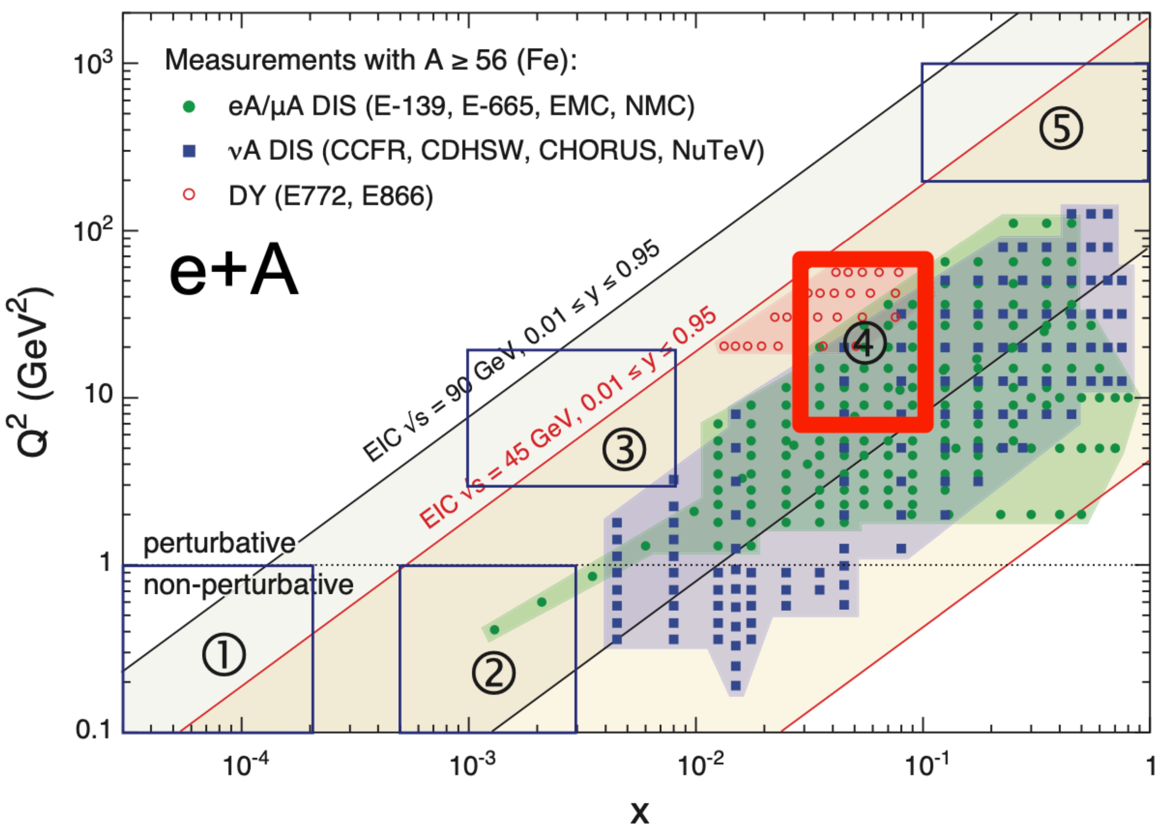


20 GeV on 100 GeV, $3 < Q^2 < 20\ \text{GeV}^2$, $1\cdot10^{-3} < x < 8\cdot10^{-3}$

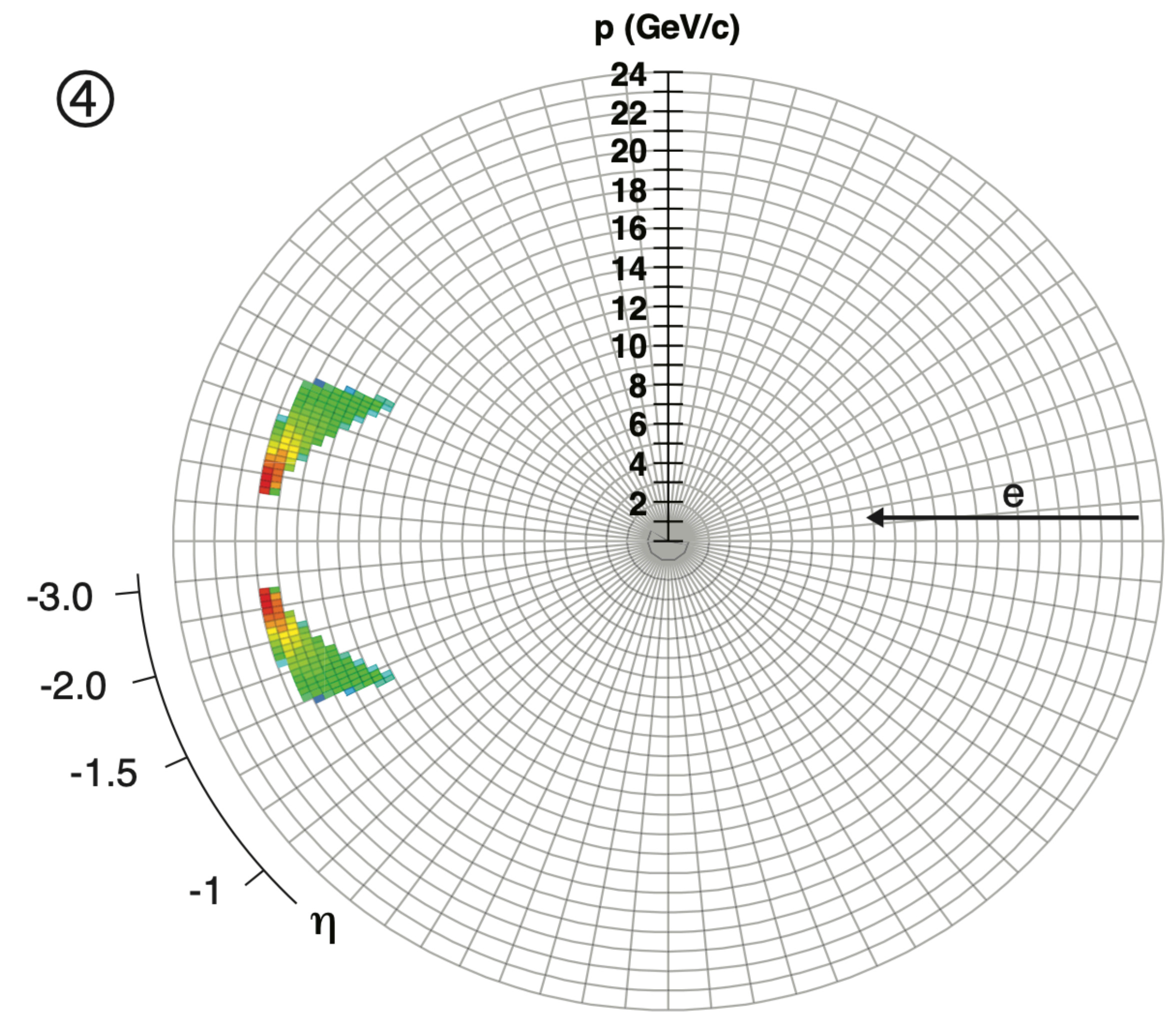


Courtesy T. Ullrich

Scattered Electron at EIC

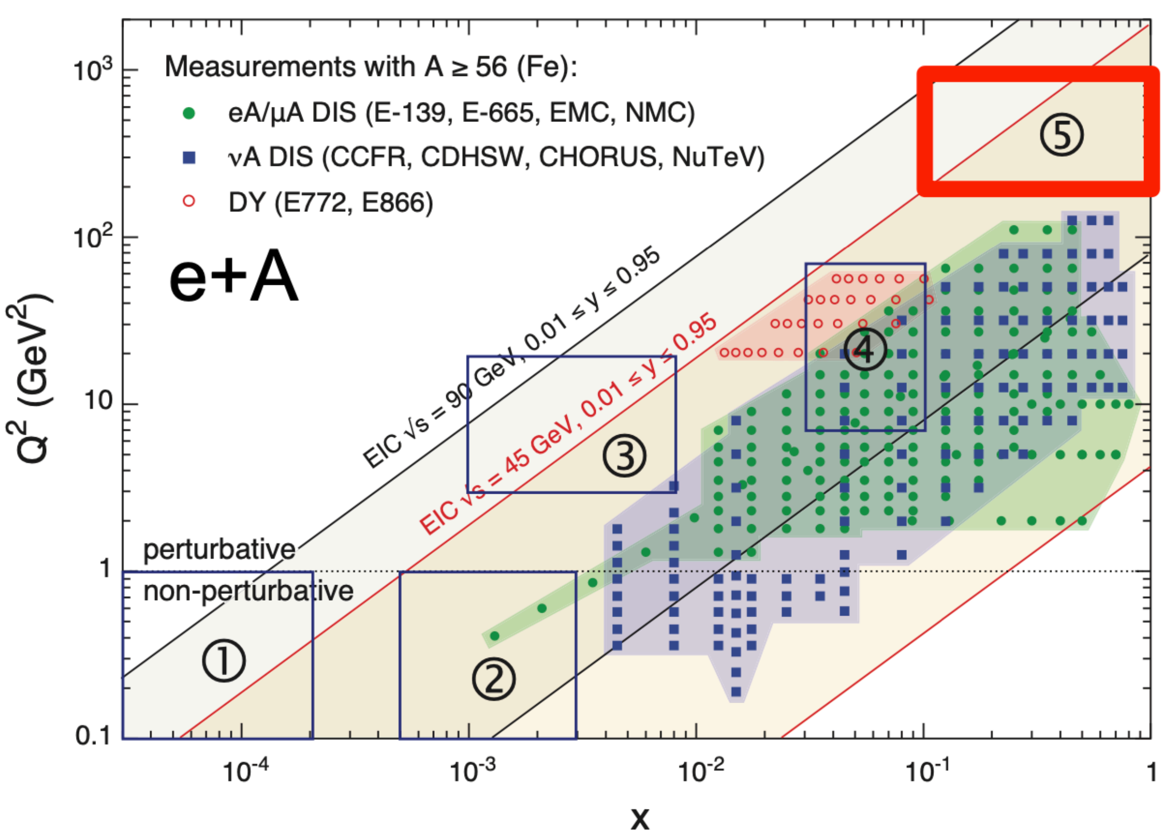


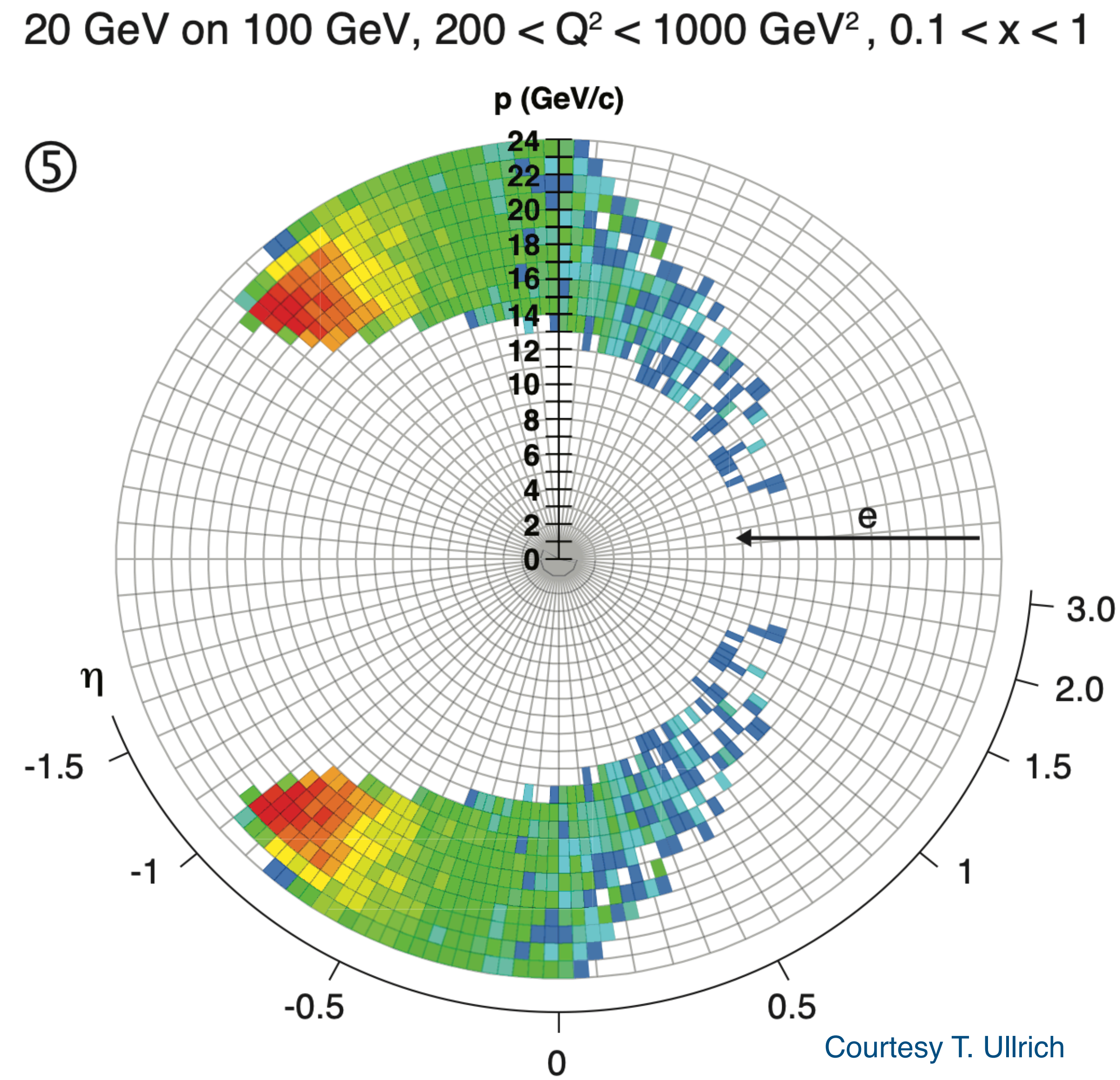
20 GeV on 100 GeV, $7 < Q^2 < 70$ GeV^2, $3\cdot10^{-2} < x < 1\cdot10^{-1}$



Courtesy T. Ullrich

Scattered Electron at EIC





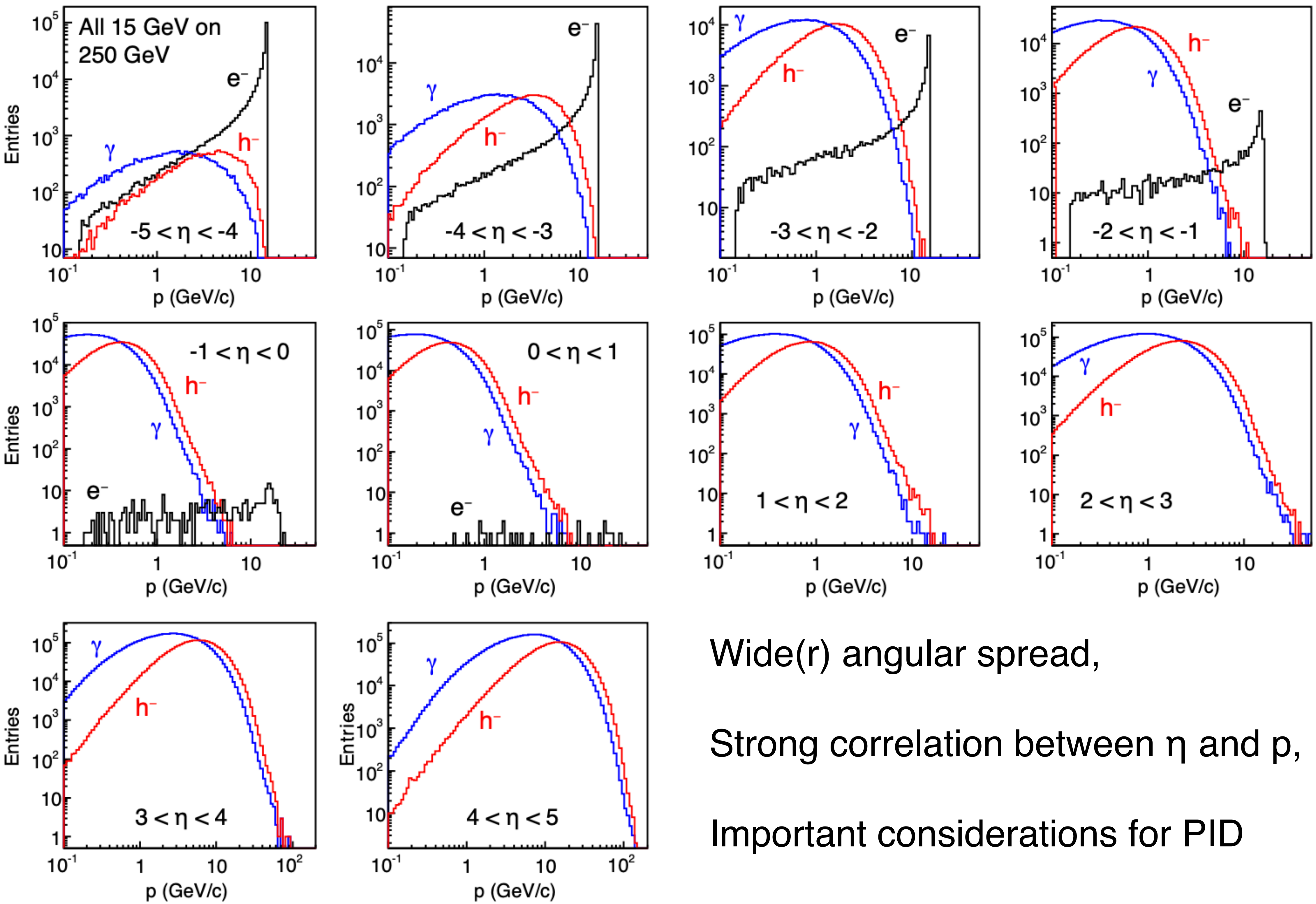
Scattered Electron determines:

$$y = 1 - (E_e'/2E_e)(1 - \cos\theta_e')$$

$$Q^2 = 2E_e'E_e(1 + \cos\theta_e')$$

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

Scattered electron and SIDIS hadrons



Wide(r) angular spread,

Strong correlation between η and p,

Important considerations for PID

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

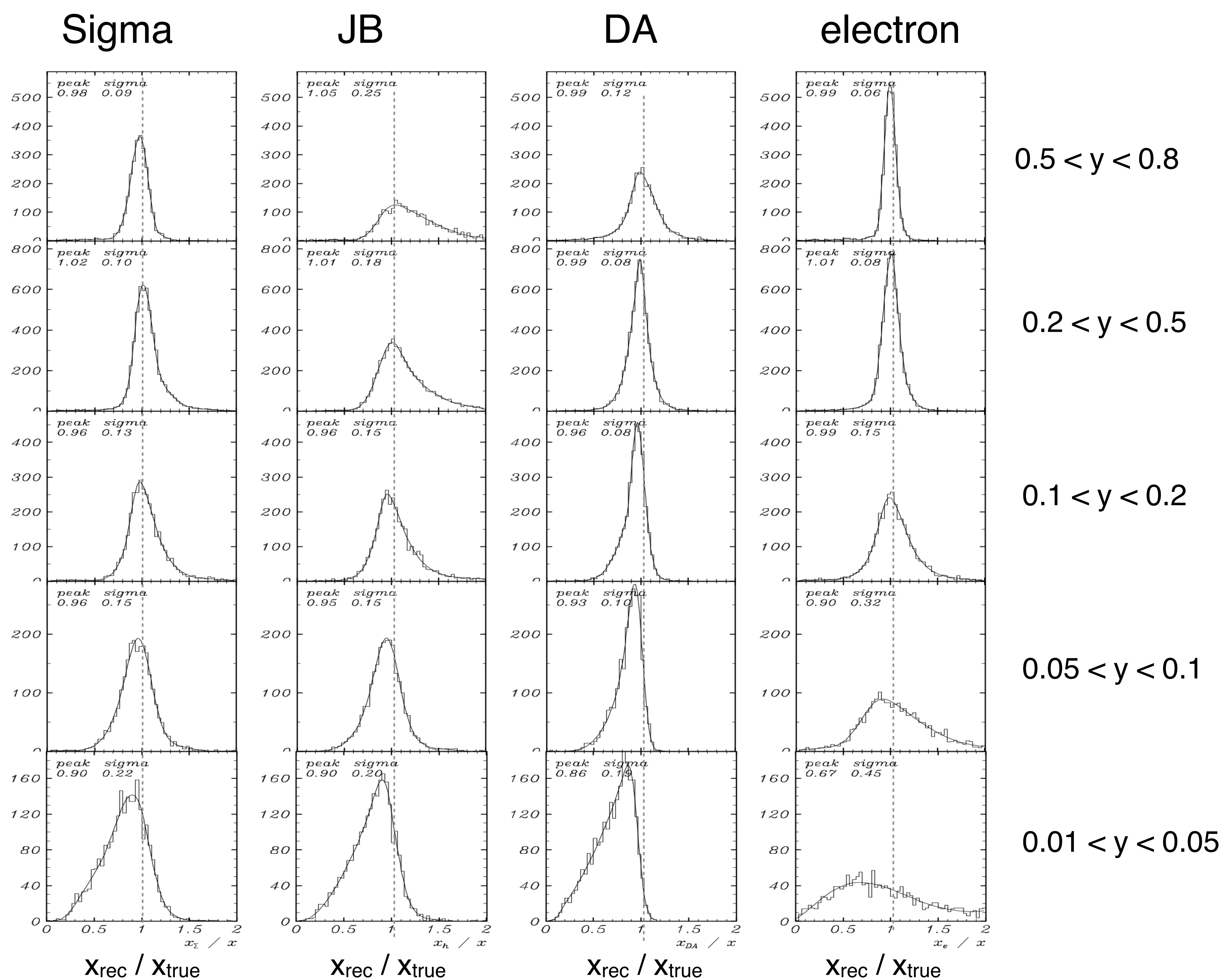
Alternative kinematic reconstructions

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



Alternative kinematic reconstructions

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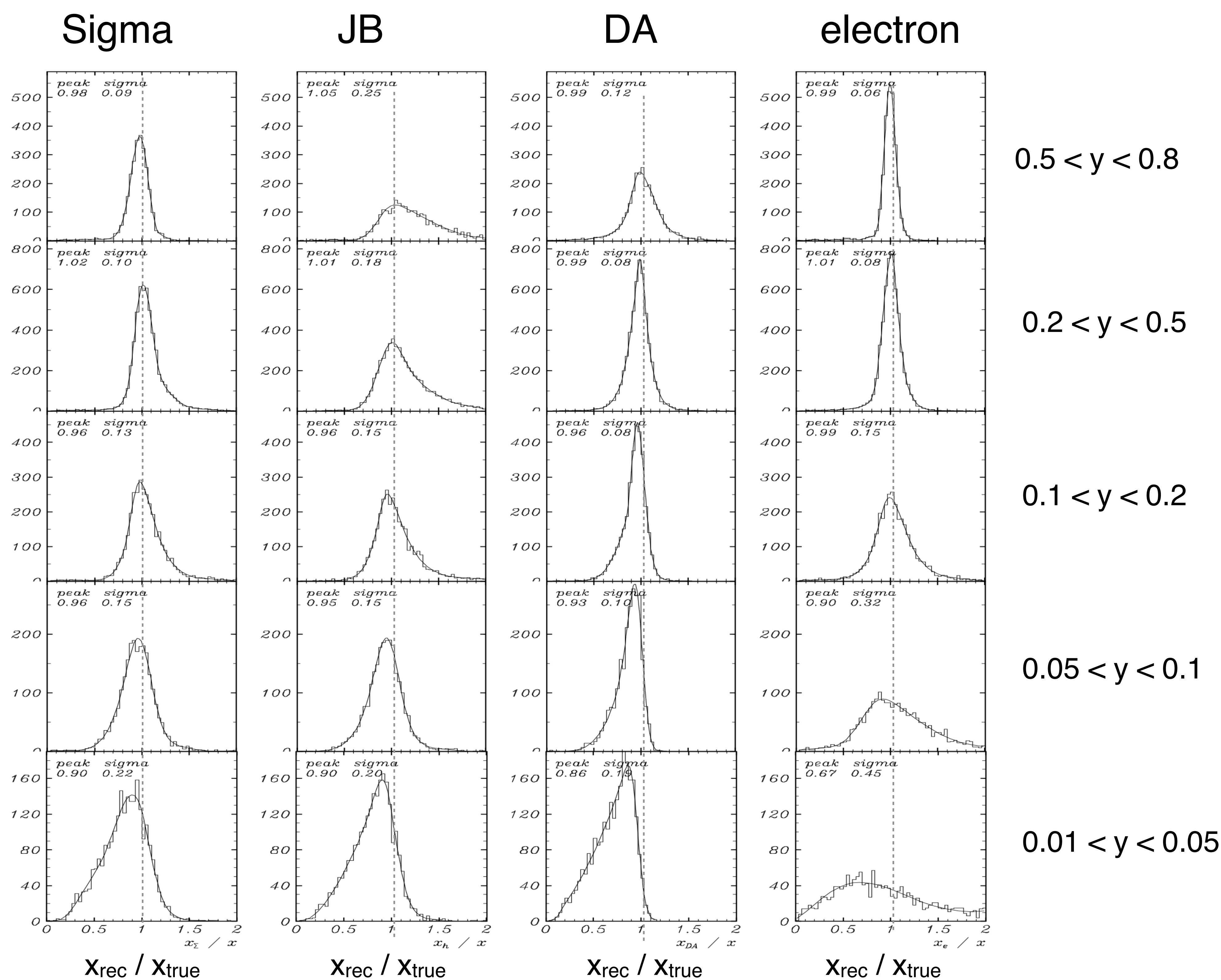

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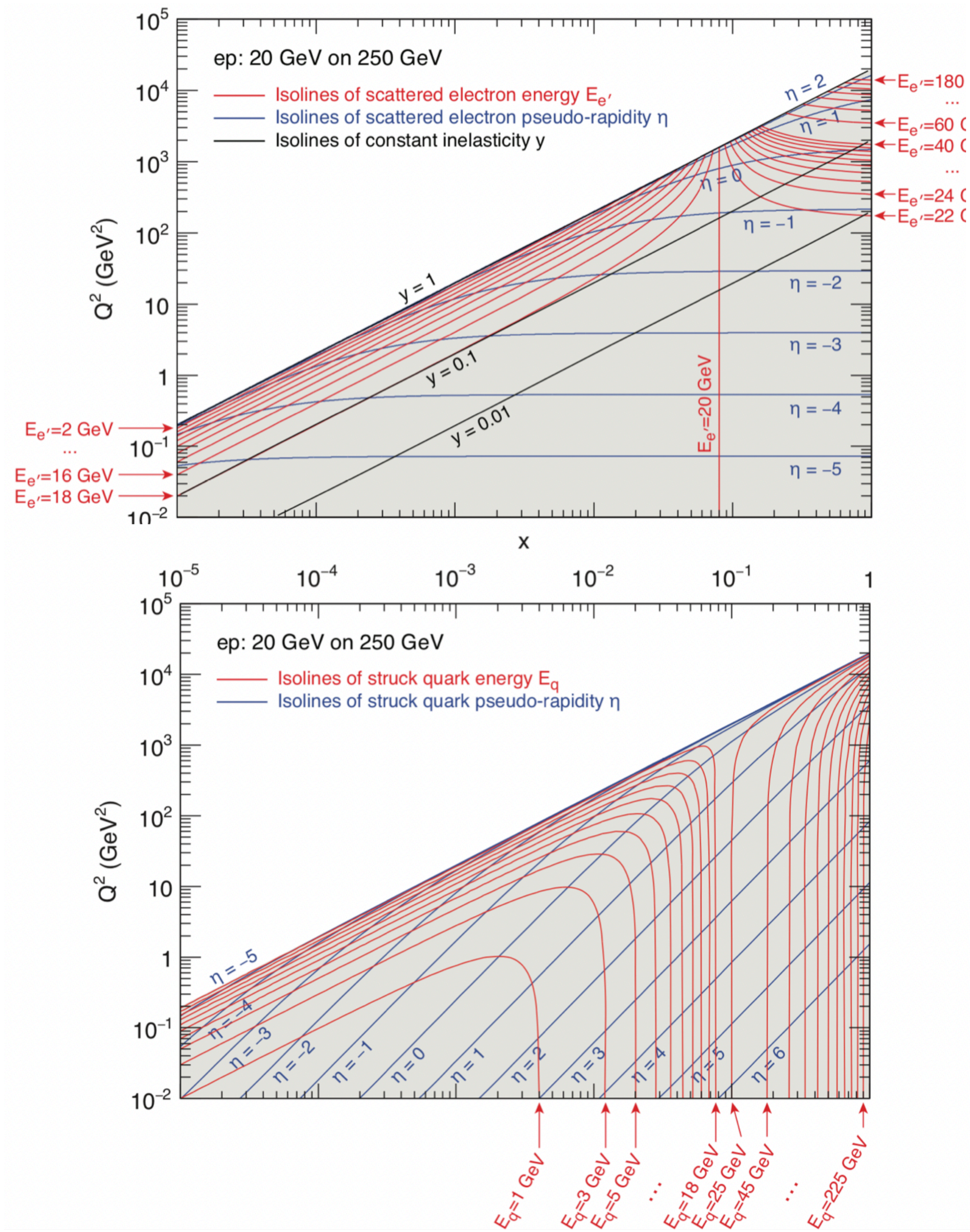
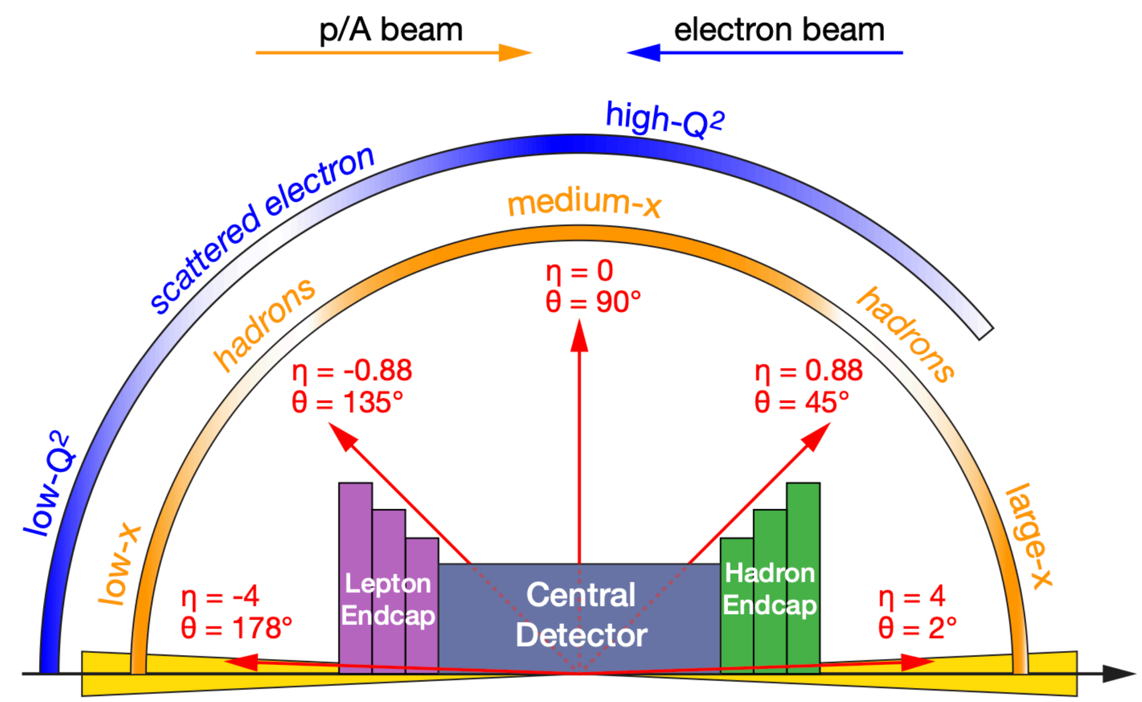
DIS at EIC





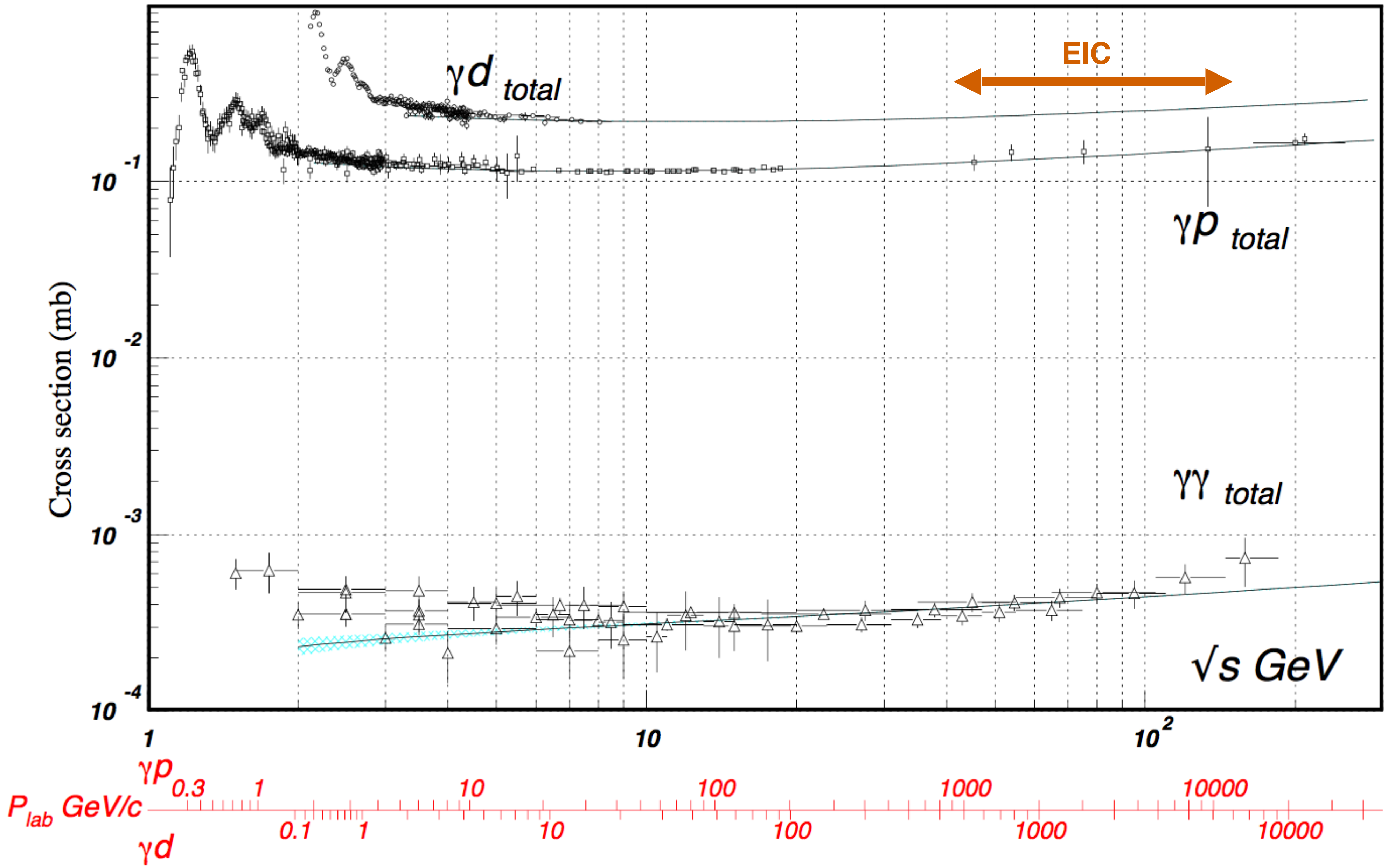
The DIS cross-section typically goes as $1/Q^4$

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.”

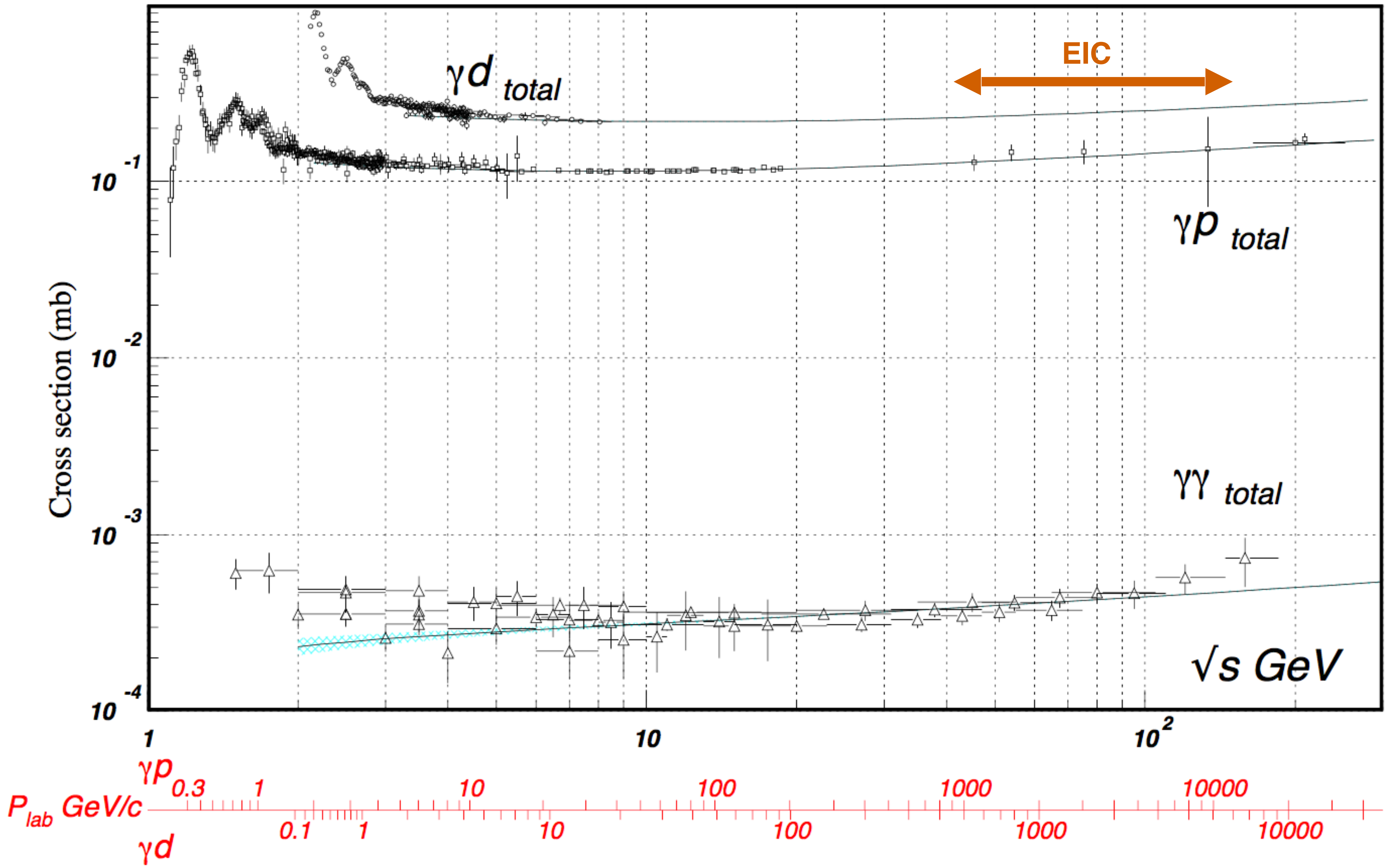
EIC Physics Rate Environment



Photoproduction is the dominant cross-section; well known,

2 orders below RHIC, LHC

EIC Physics Rate Environment



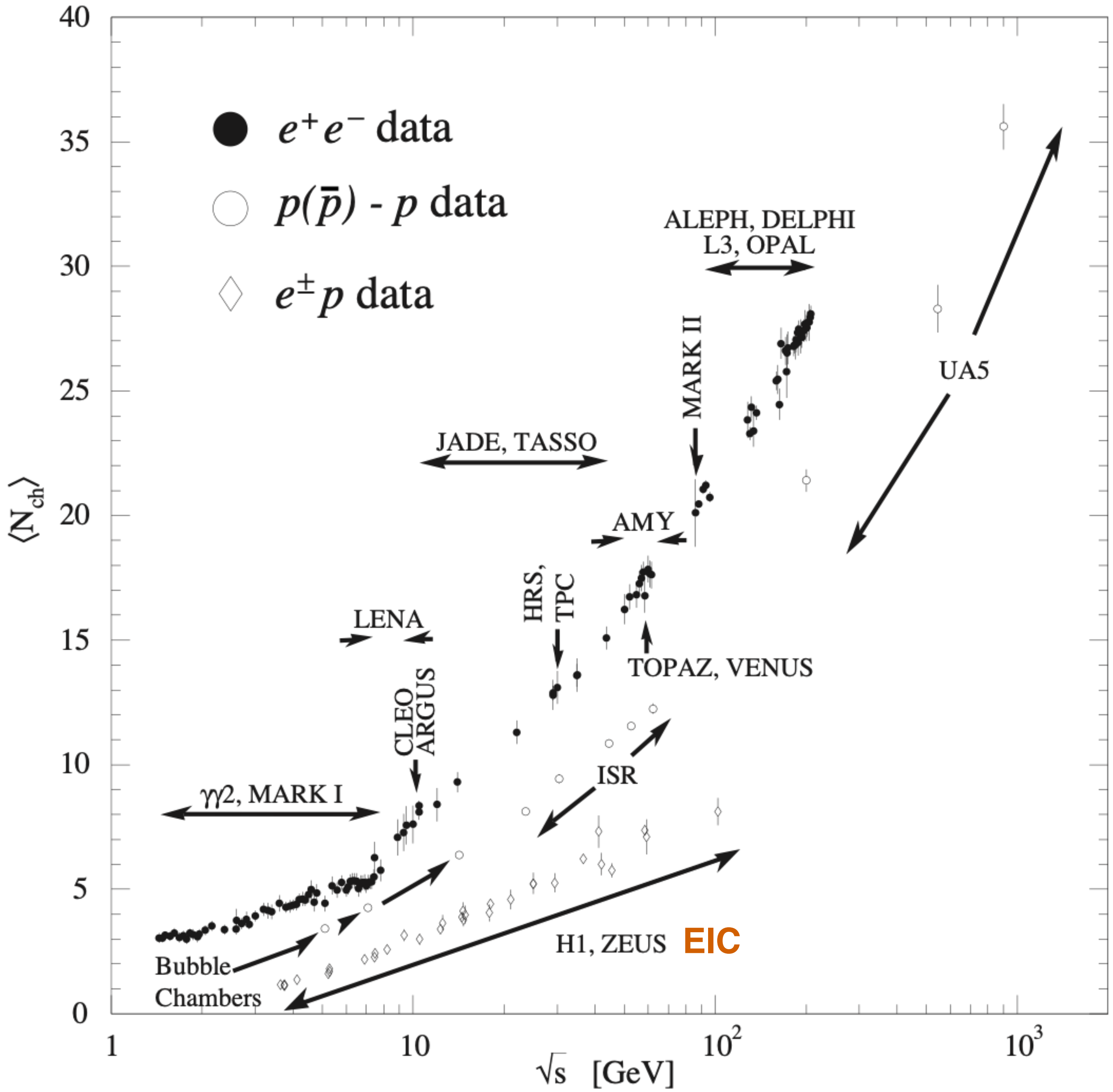
L ~ $10^{33(34)}$cm^{-2}s^{-1} implies a ~50 (500) kHz collision-event rate,

<< EIC bunch cross crossing rate

~ similar to μs integration times

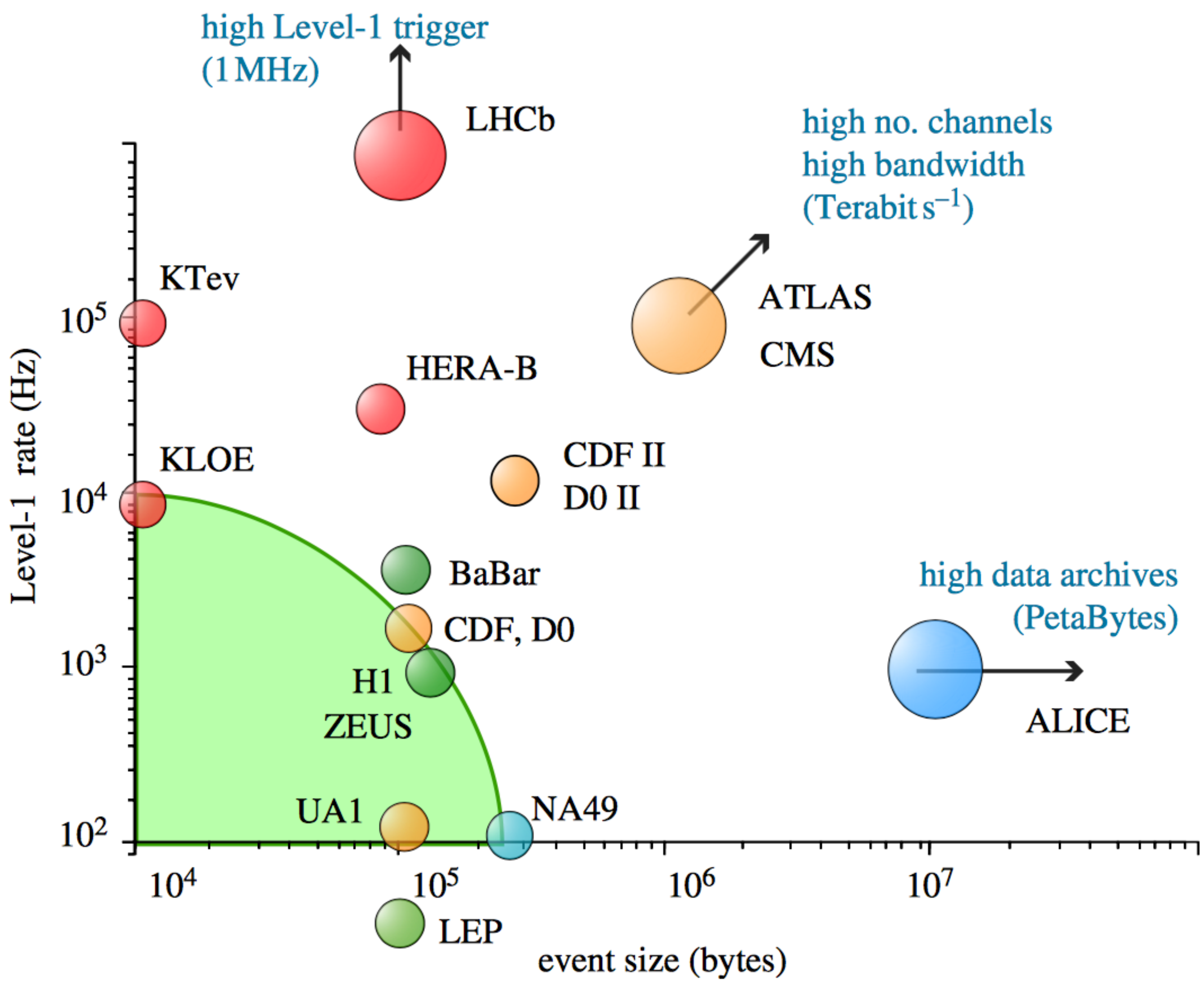
Note: backgrounds can overwhelm this rate and need to be minimized.

EIC Physics Rate Environment



Likewise, particle multiplicities are known and well below those at the hadron colliders,

EIC Physics Compute Environment



LHC: a sounding success of bold extrapolations and numerous technological breakthroughs,

40 MHz beam bunch crossing rates with multiple collisions per crossing,

*"Big Data" by size and rate, **and** analysis speed,*

S. Cittolin, Phil. Trans. R. Soc. A (2012) 370, 954

High-Intensity LHC is on its way: LHCb, for example, will move to a triggerless-readout system for LHC run 3 (2021-2023, prior to EIC), and process 5TB/s in real time on the CPU farm (M. Williams at the Future Trends in NP Computing),

EIC is likely operate well-within the rate-size frontier — new analysis paradigms (?)

EIC Detector Requirements

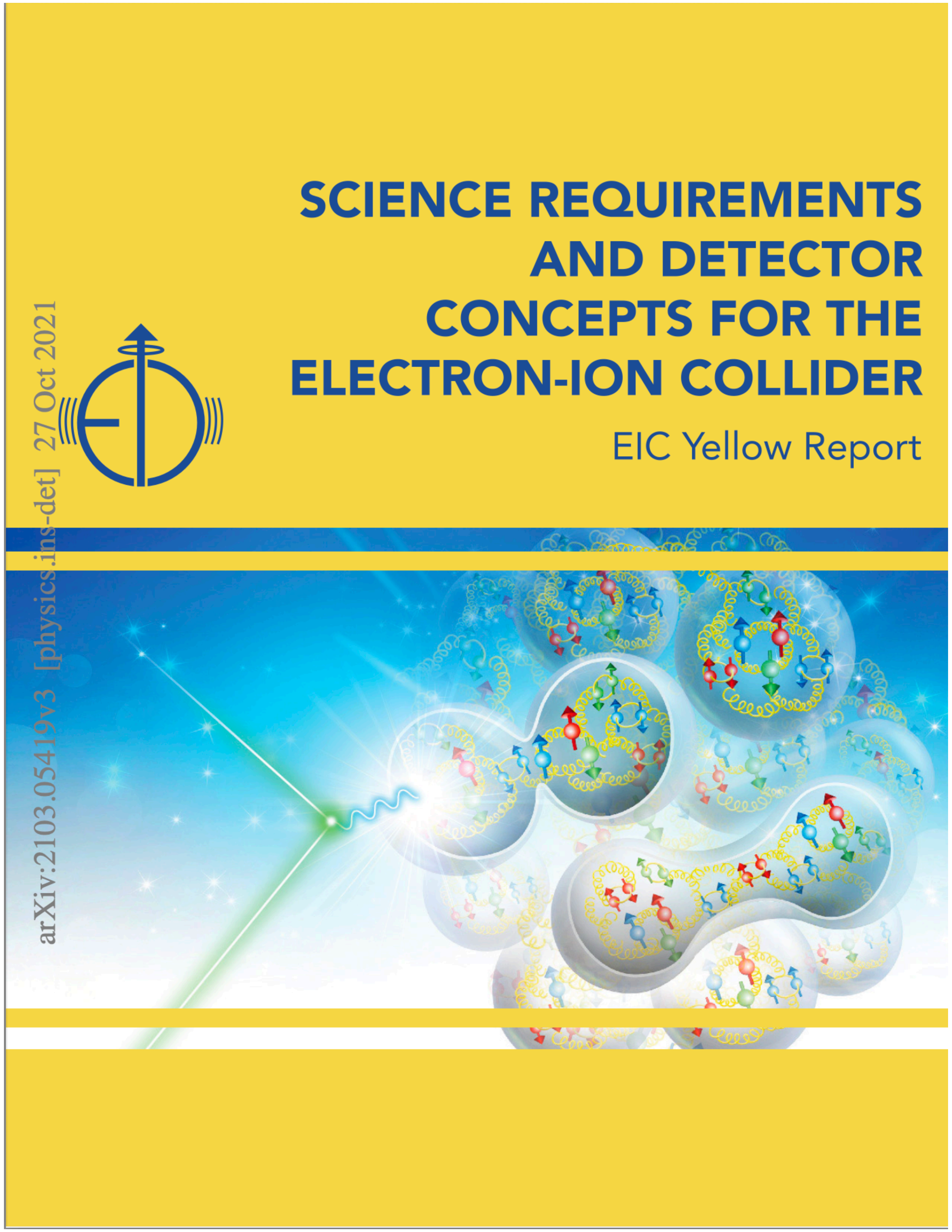
The theorist perspective:

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

The experimentalist perspective:

- 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.

EIC Detector Requirements



The 884 page version…

Nucl. Phys. A 1026 (2022) 122447.

EIC Detector Requirements in a Nutshell

Electron and identified hadron and jet measurements for approximately -4 < η < 4,

Hermetic detector with low inner material budget,

Good vertexing capabilities, including displaced vertex $\mathcal{O}(10\,\mu\mathrm{m})$

Good charged-particle tracking resolutions, $dp/p = 0.05\% p \oplus 0.5\%$

Good to excellent EM calorimeter resolutions, in particular in the electron-going (backward) direction, $2\%/\sqrt{(E)} \oplus 2\%$

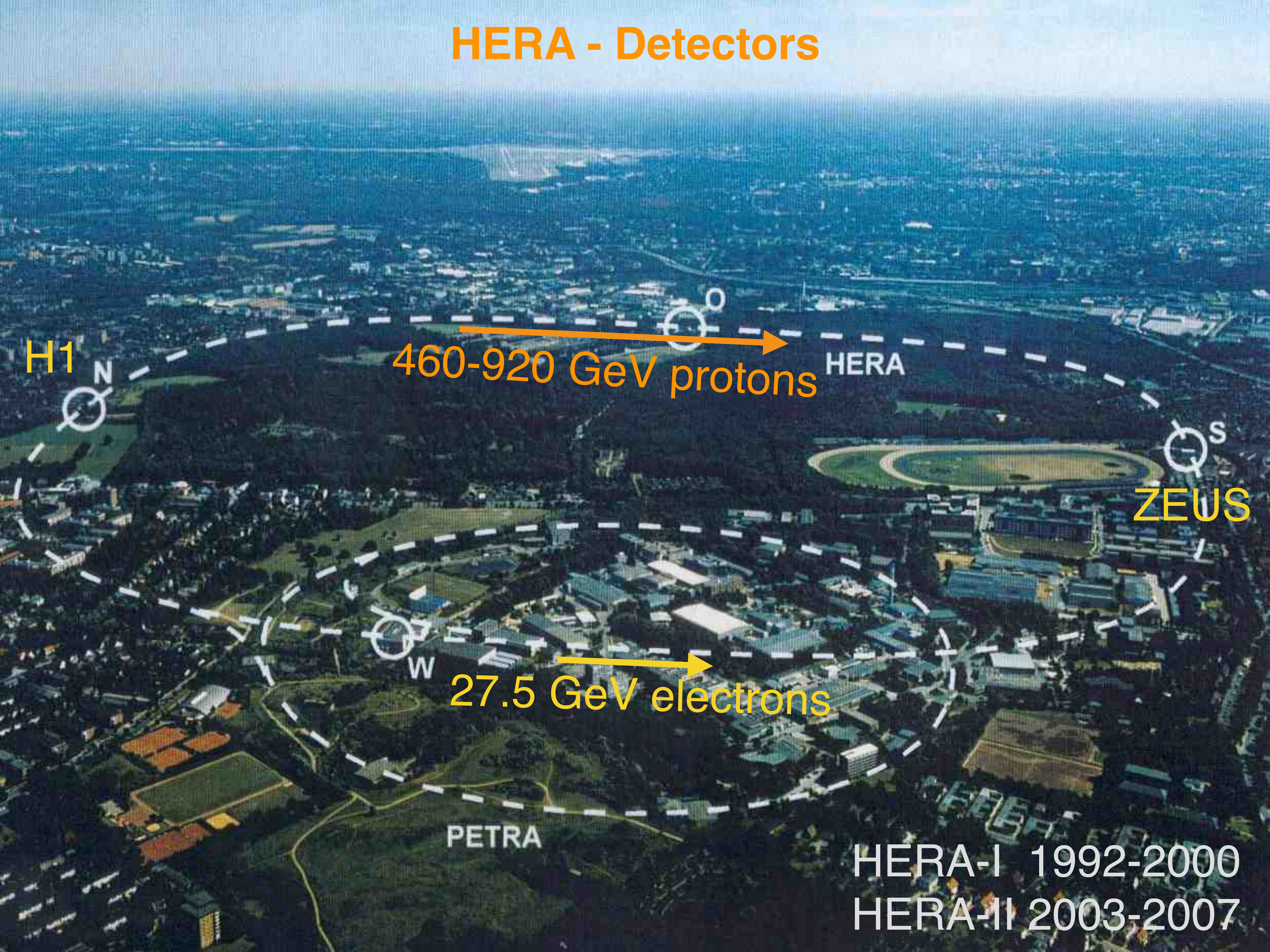
Decent hadronic calorimeter resolution

Excellent PID for charged pions, Kaons, and protons over a wide kinematic range,
forward up to p ~50 GeV (!)
backward and central up to p ~7 GeV,

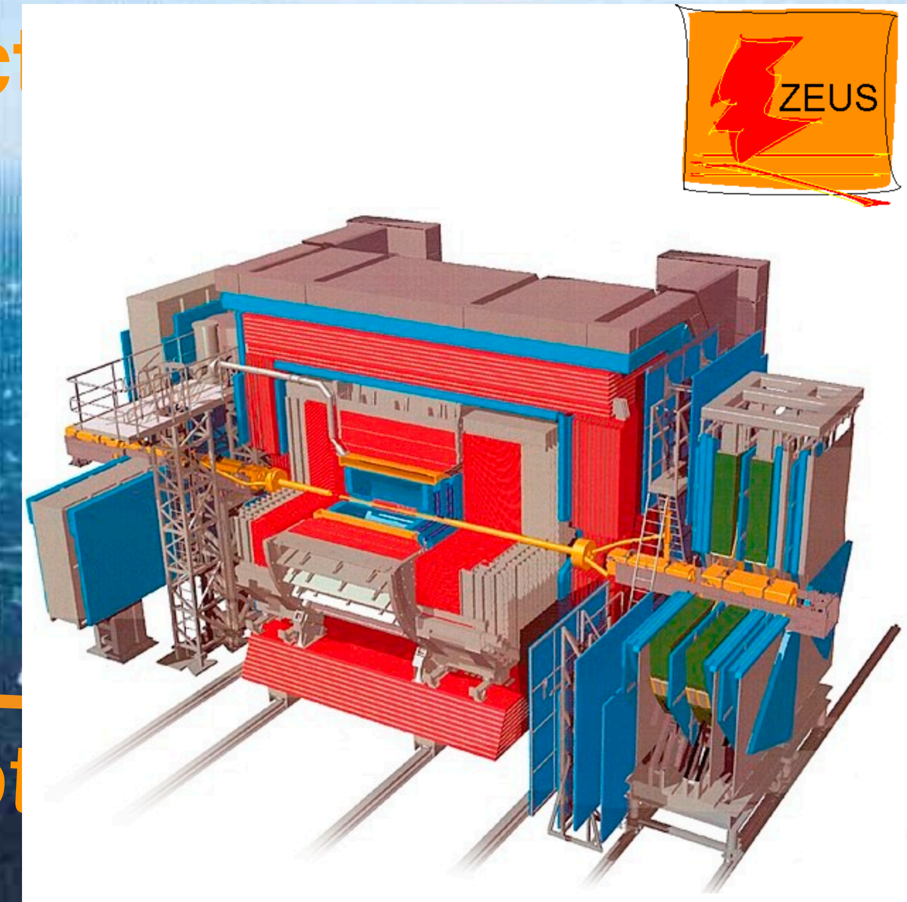
No bending of the electron beam from the magnetic field.

For the discussion this evening: discuss the merits of electrostatic bending versus magnetic bending of particles.

HERA - Detectors



HERA - Detect

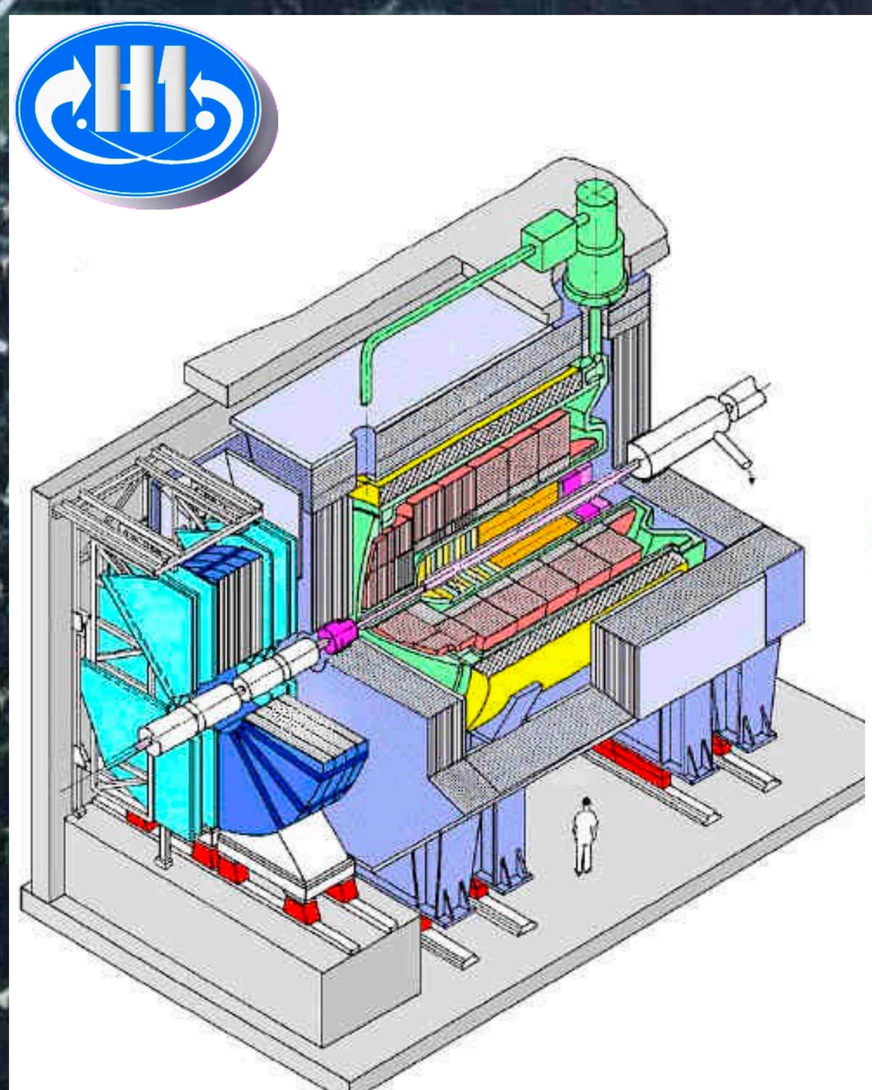


H1 was better at electron reconstruction due to its design and EM calorimeter; also unique strengths with forward detectors during HERA-II

~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.

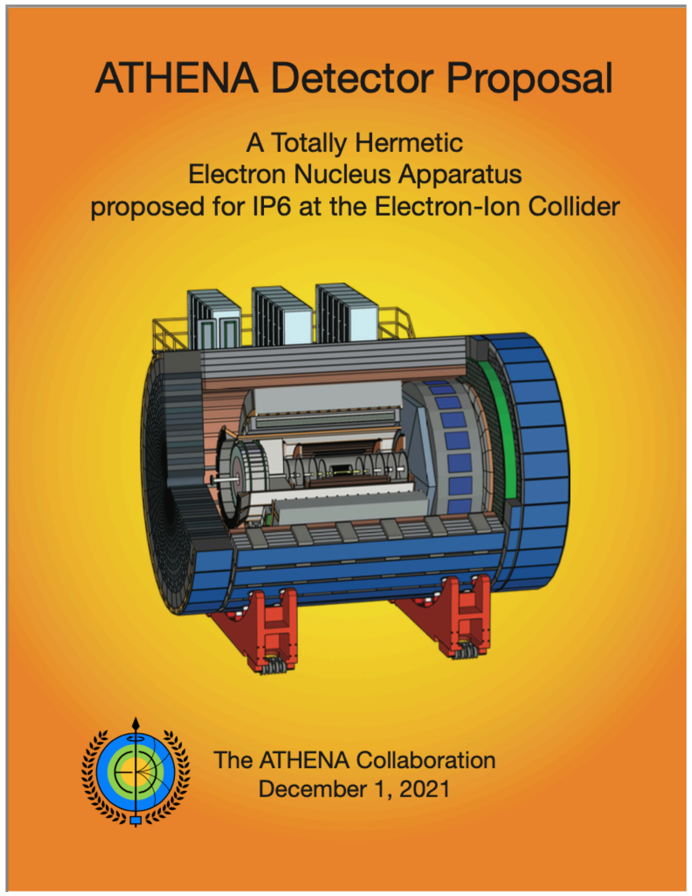
EUS

.5 GeV electrons

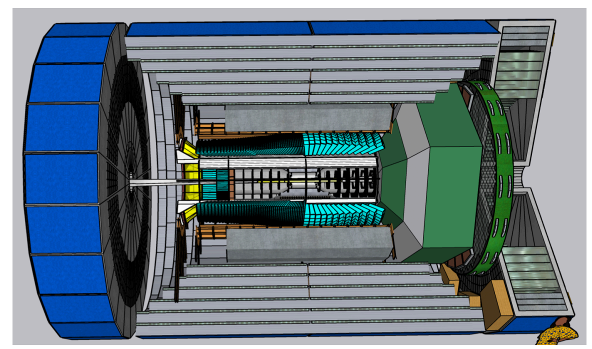
RA

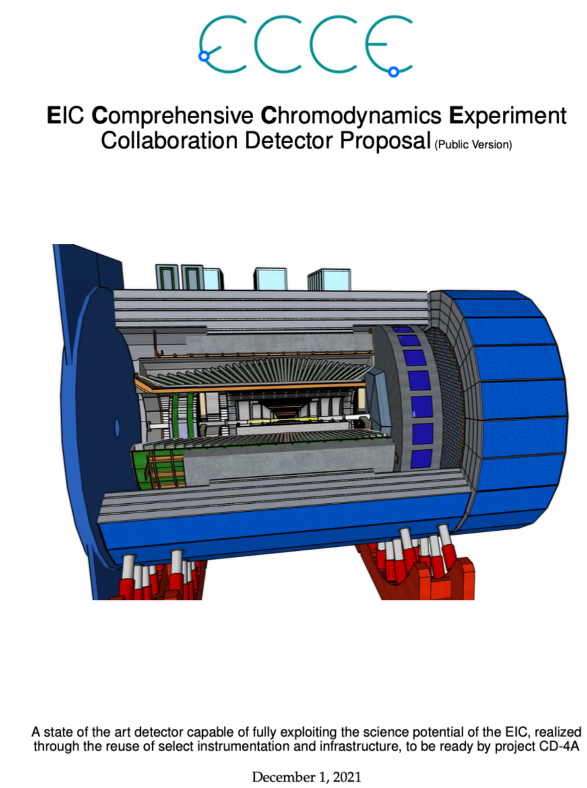
HERA-I 1992-2000
HERA-II 2003-2007

EIC Project Detector



CORE





Detector Proposal Advisory Panel (DPAP) reviewed three proposals; ATHENA, CORE, and ECCE,

Finds that ATHENA and ECCE fulfill all requirements for a Detector 1, i.e. NAS science case,
none of the collaborations is strong or large enough to develop Detector 1 for Day 1

Recommended ECCE as Detector 1 in Spring 2022 – adopted by the EIC Project as Reference,

The collaboration and detector is now called ePIC. It is based 1.7 T solenoidal field that is aligned with the electron beam. Much more in John Lajoie's lectures later this week.

Particle Detection 101

Short-lived particles are usually reconstructed via detection of their long-lived decay products followed by reconstruction of invariant mass and/or displaced vertex,

Long-lived particles are usually detected through their interactions with matter inside a detector, possibly in an external field,

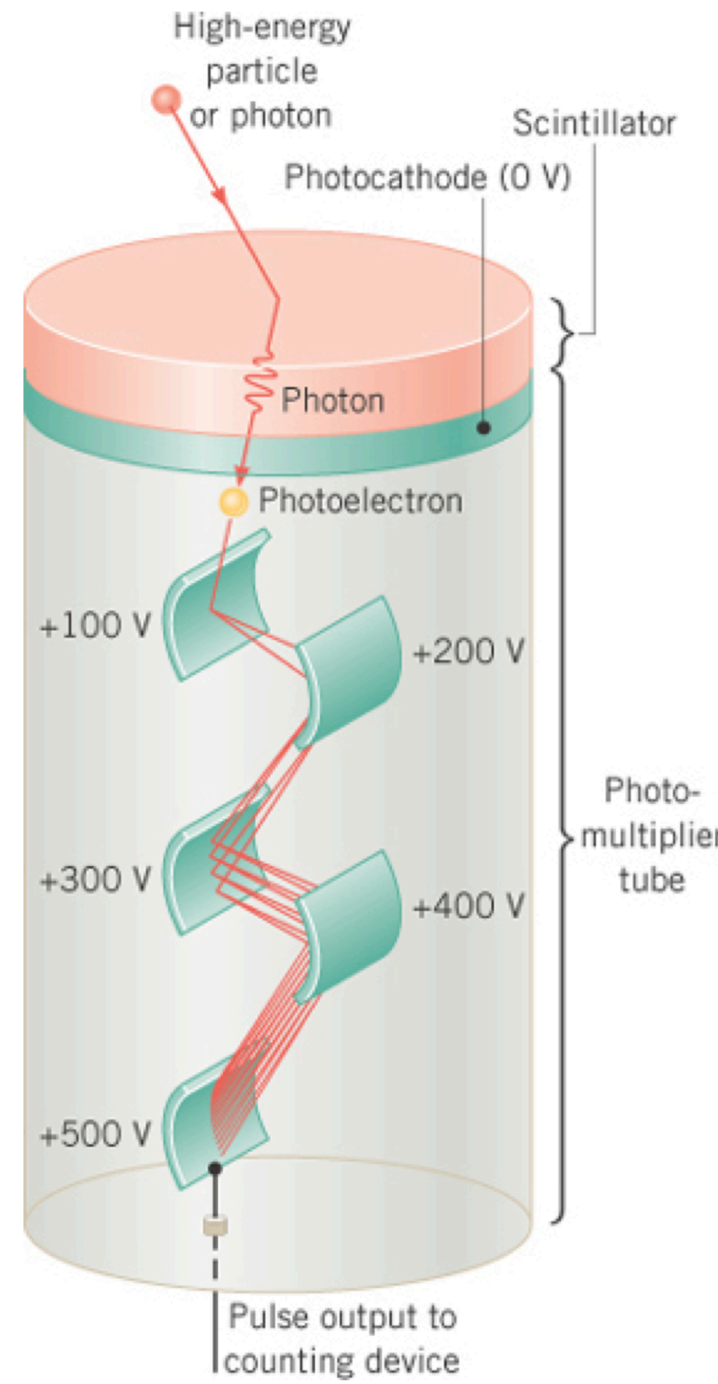
These interactions typically produce light or another form of EM signal, that then needs to be coupled into one form or another of readout,

Photomultiplier is a text-book example of a device to detect (scintillation) photons and turn this into an electric pulse,

There are many others,

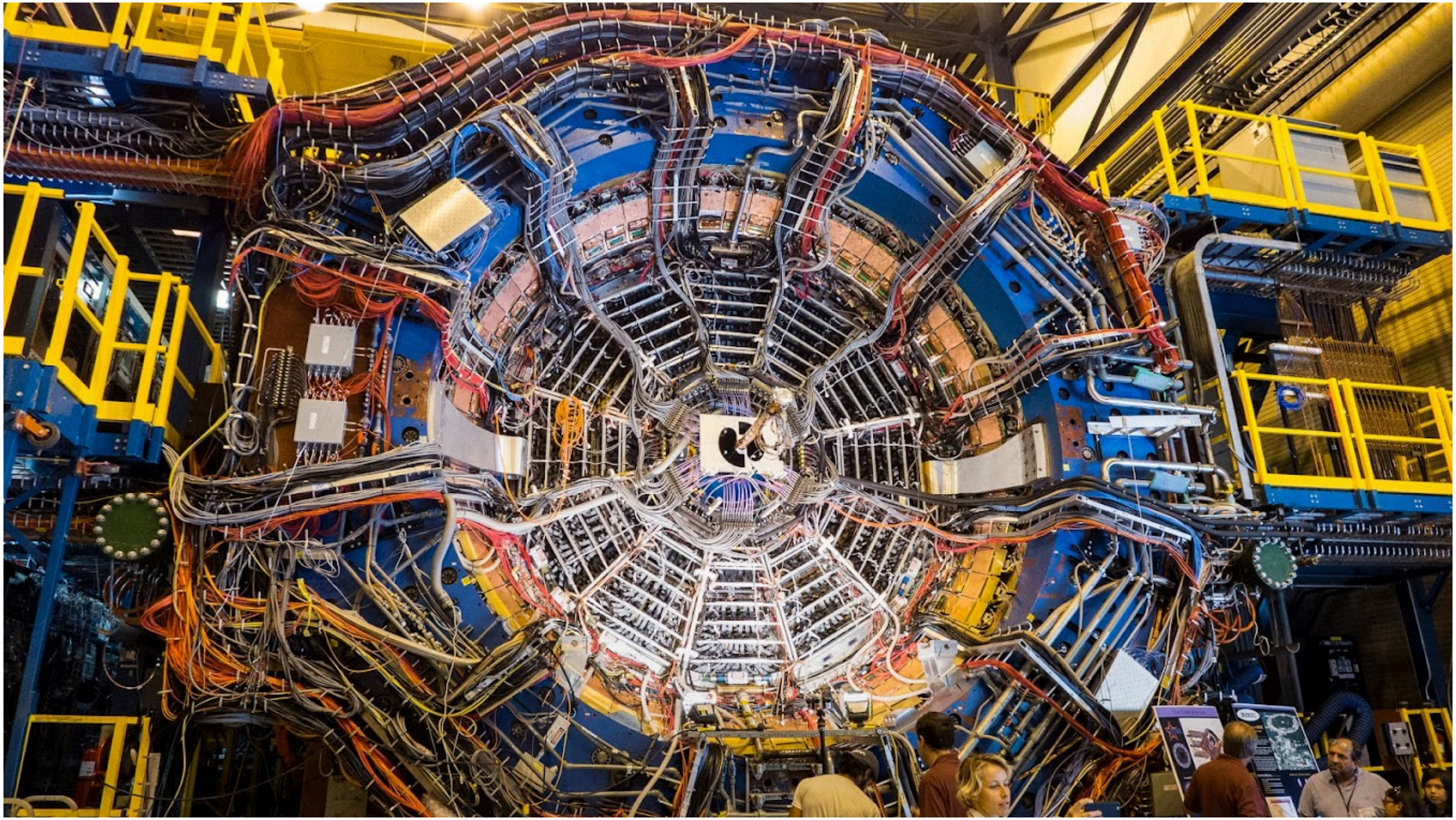
The physics is often well-known/understood; their application are quite innovative — often stunningly so,

Not for the impatient — development cycles are years if not decades; new capability is worth it!



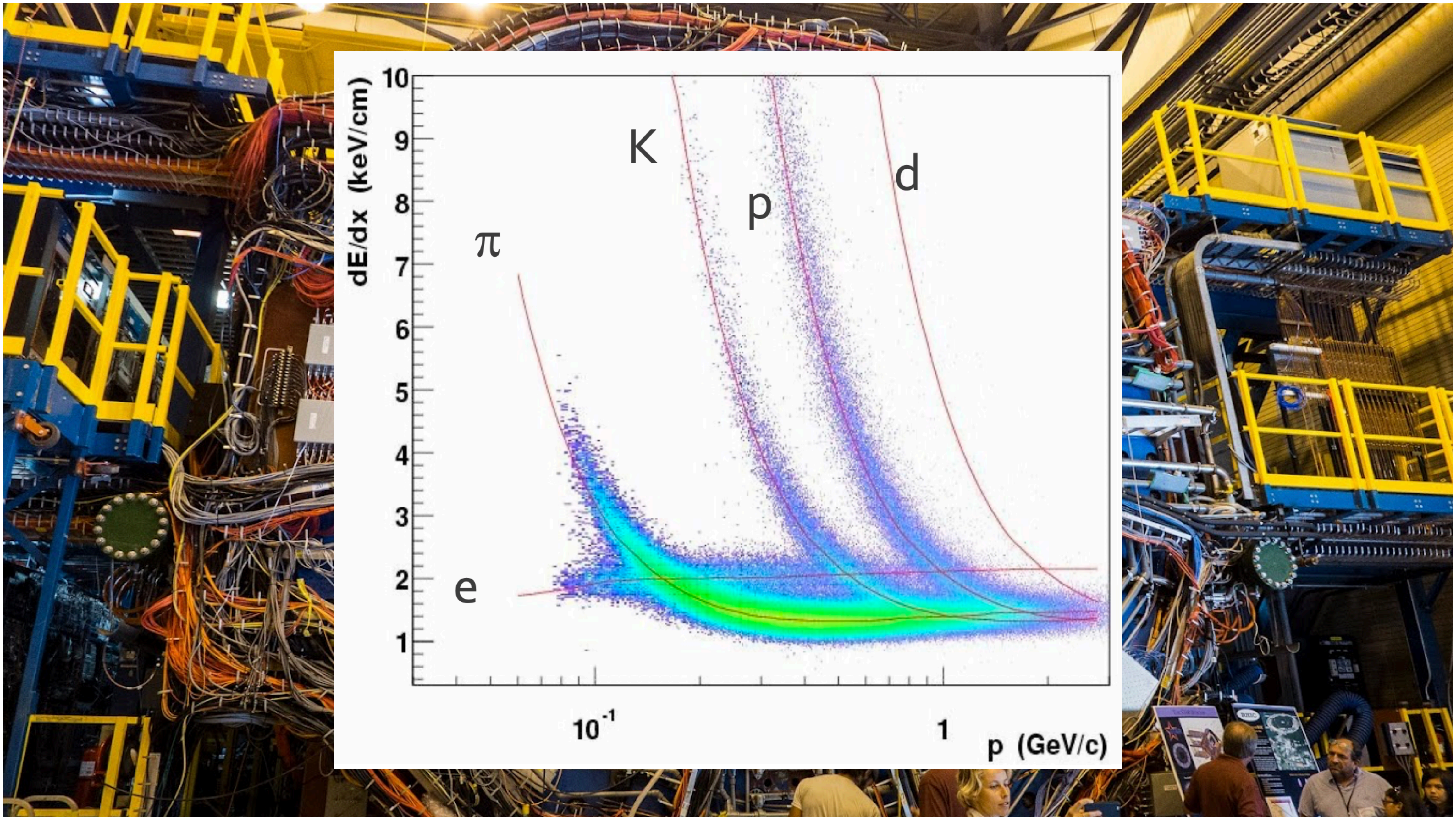
Particle Detection 101

Time projection chamber is another…



Particle Detection 101

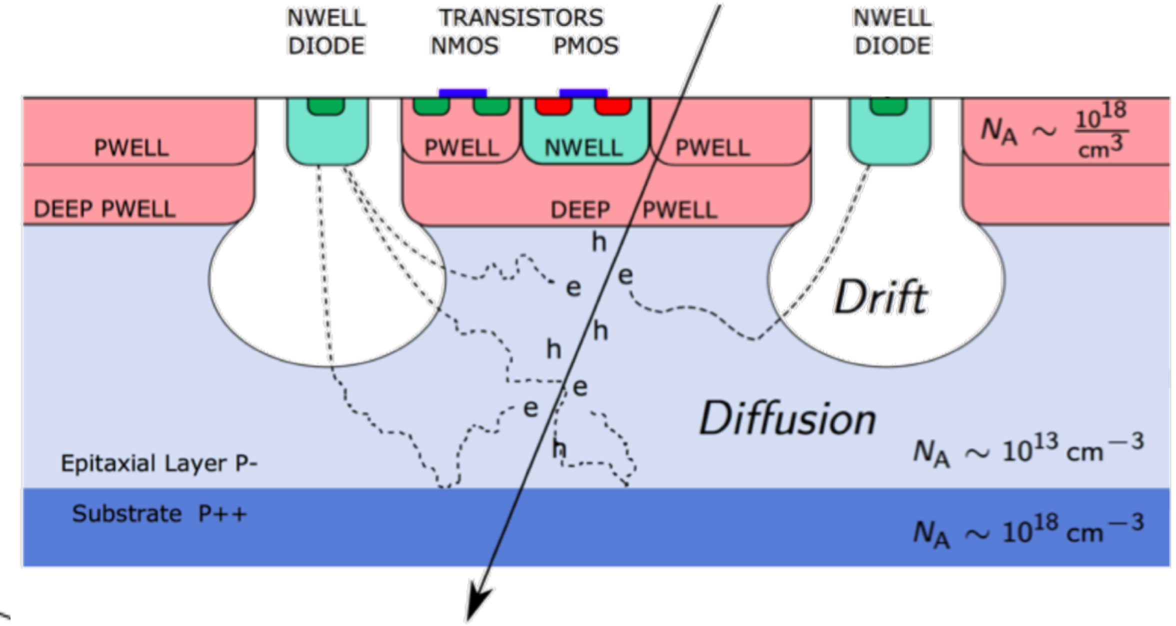
Time projection chamber is another…

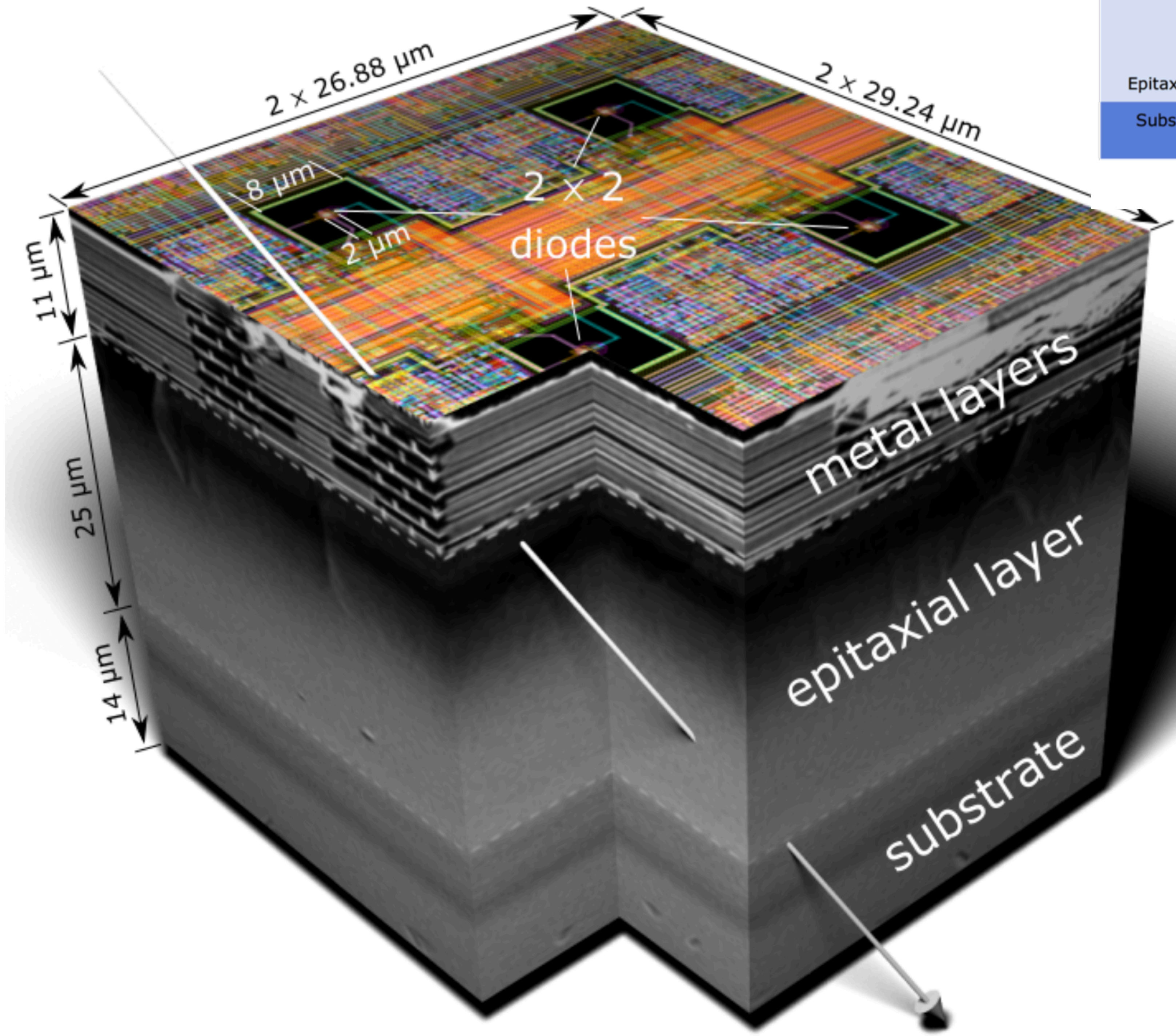


Often serving both tracking and particle-identification!

Particle Detection 101

Monolithic Active Pixel Sensors are another…





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

50μm Si has X/X0 ~ 0.05% (!)

Particle Detection 101

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

Particle Detection 101

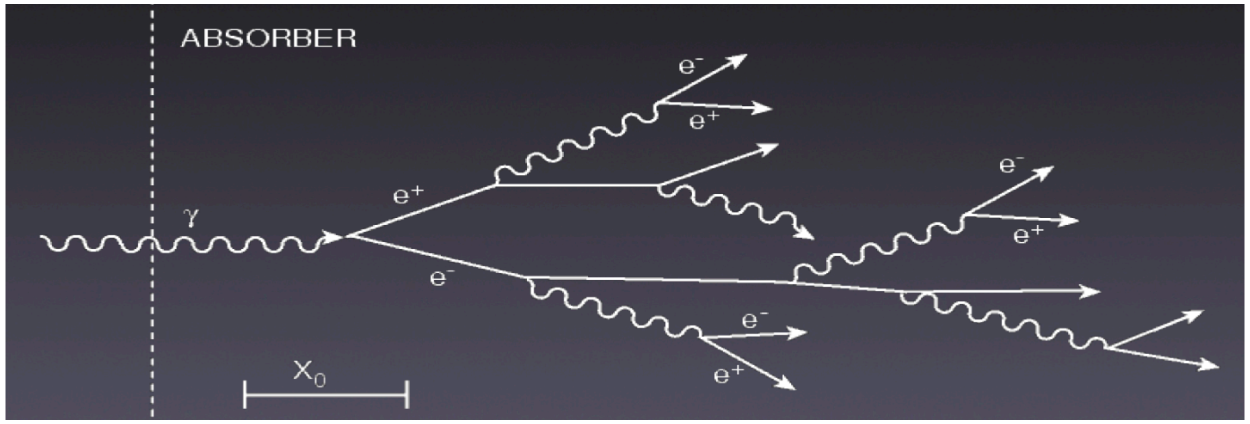
Roughly three classes of particle measurements:*

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

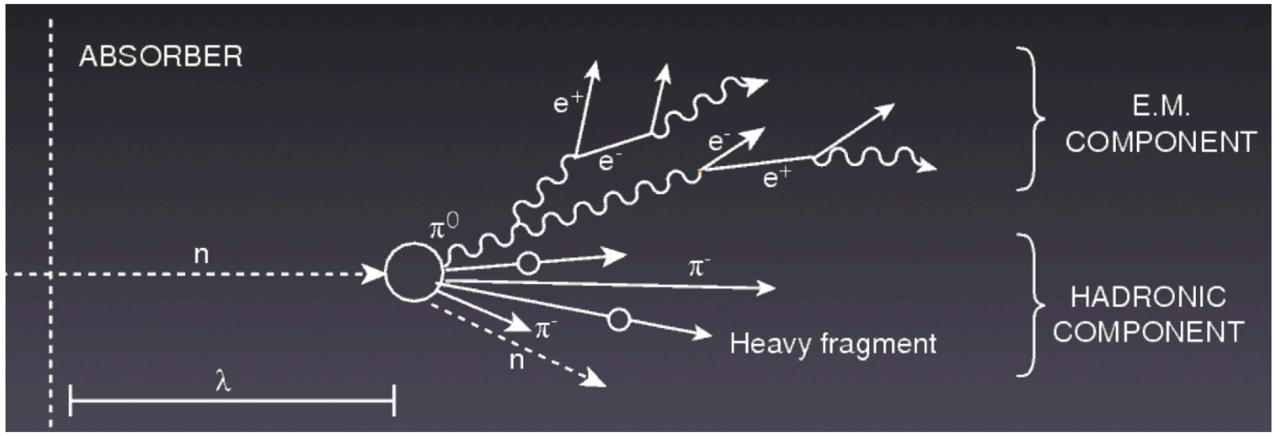
***Particle Identification** — minimally invasive, multiple physics mechanisms:*

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

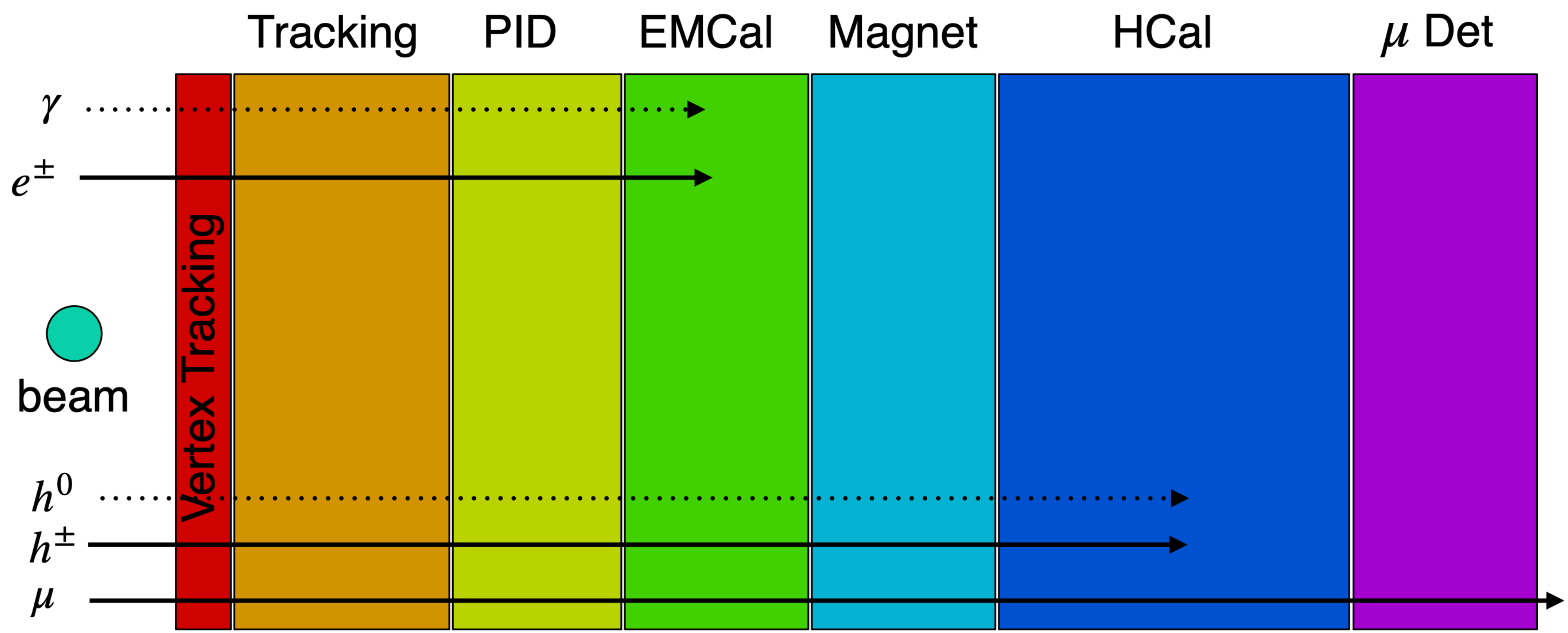


Hadronic

Which is typically larger? The radiation length X_0 or the interaction length λ?
What implications does this have for an actual detector?

** Distinction is not all that strict as we saw with the TPC; note also that calorimeters are usually segmented so that they provide position information.*

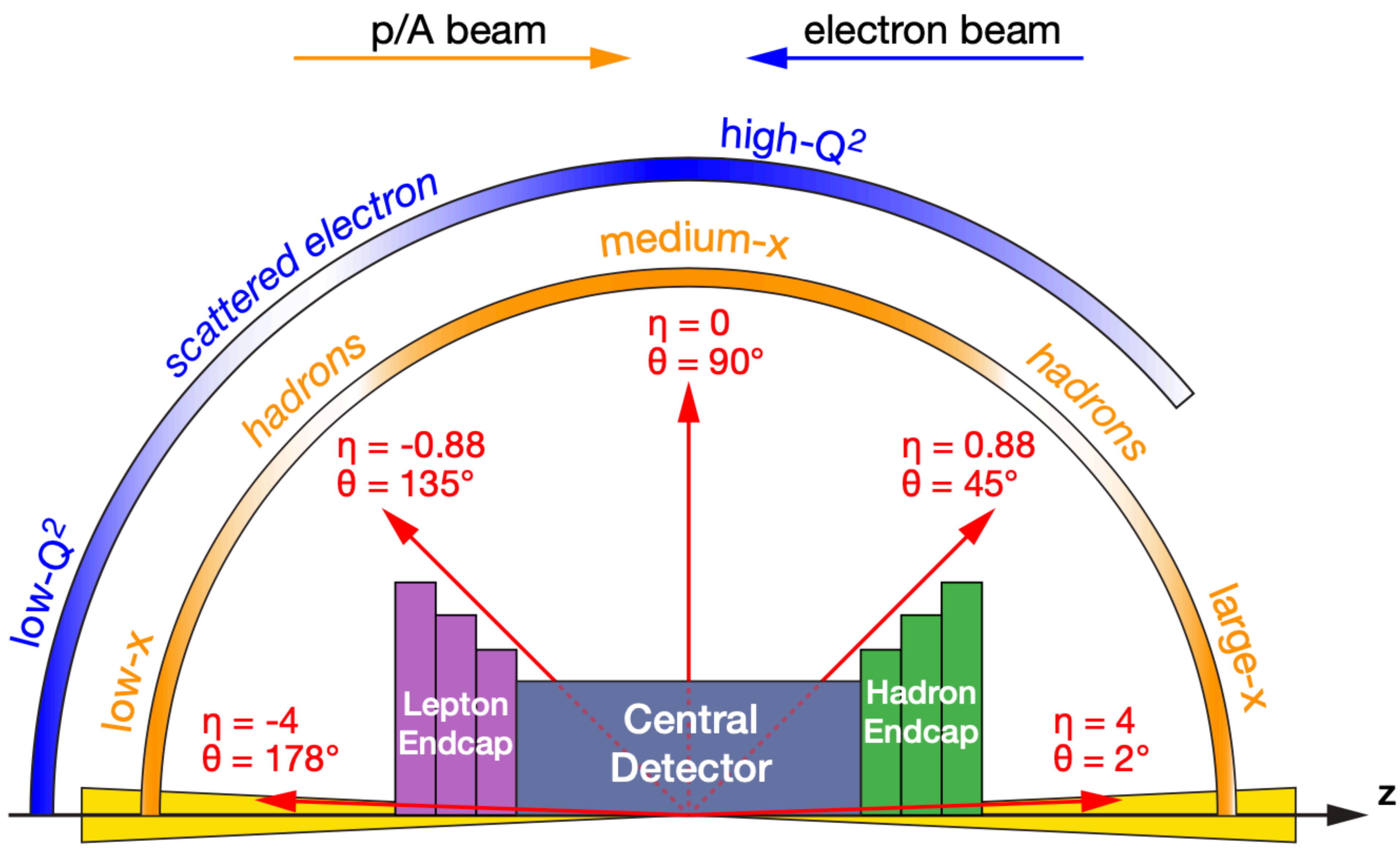
Bringing it All Together



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

The typical experimental onion; integration challenges indeed often induce tears.

EIC Physics Experimental Perspective



High luminosity drives the need for a compact device, ~ 9m along the beam axes,
Large acceptance required by the science drives the need for (very) careful integration,
Combination with calorimetry and PID drives the need for a compact tracking subsystem.
Not discussed here, far-forward and auxiliary instruments.

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 machine design well established: meets all the requirements on high luminosity, high polarization for electron and light hadron beams, a wide range of center of mass energies, variety of ion beams with up to high A

- Physics requirements and detector concepts developed for Yellow Report and the subsequent proposals — lots to be had from simple kinematics considerations,

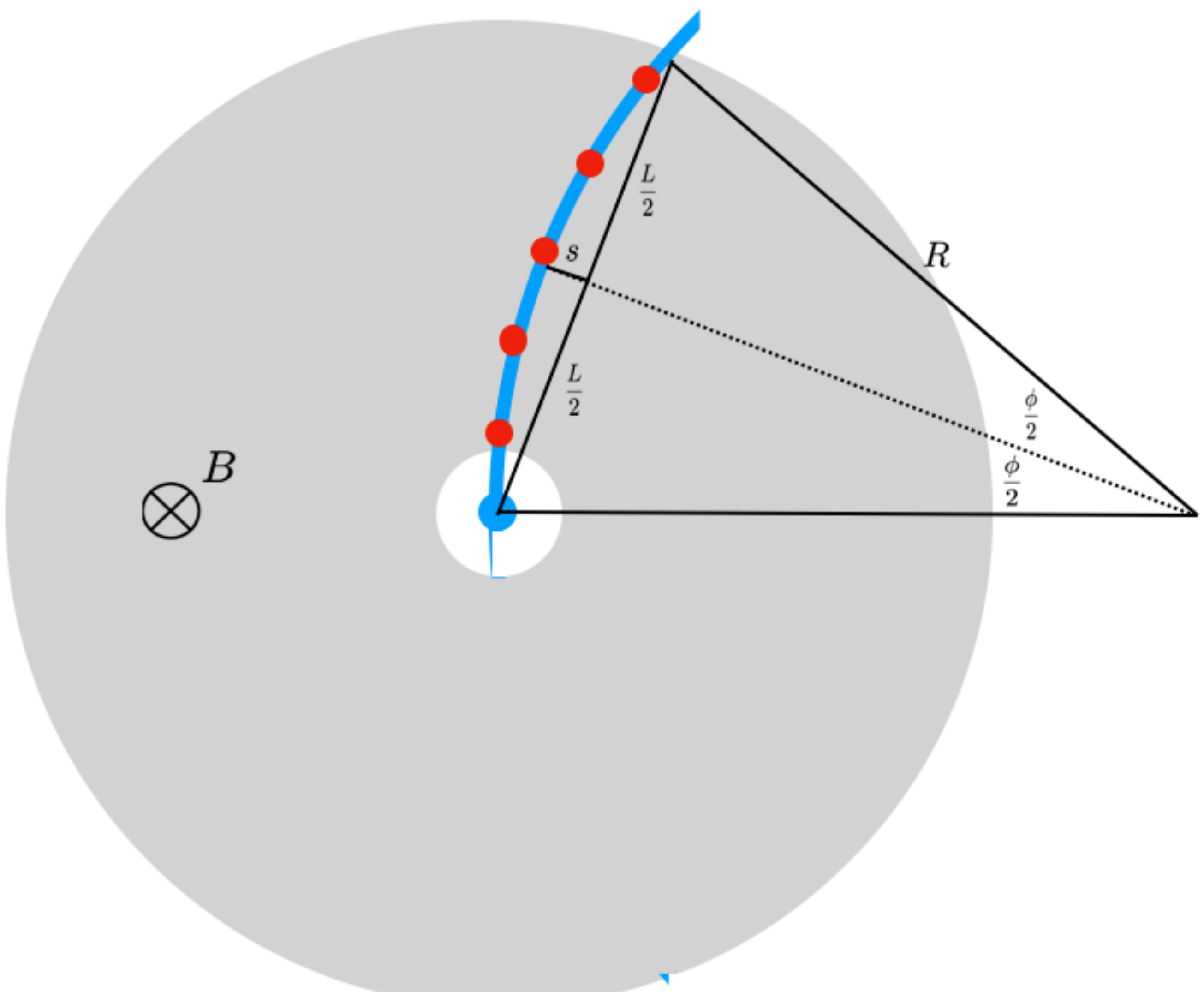
- Detector R&D is a vital part of the EIC efforts and many other fields,

- Not too soon to engage — this school is a *great* step.

Thank you!

Tracking 101 – apologies to experts

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



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

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

Hence,

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

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.

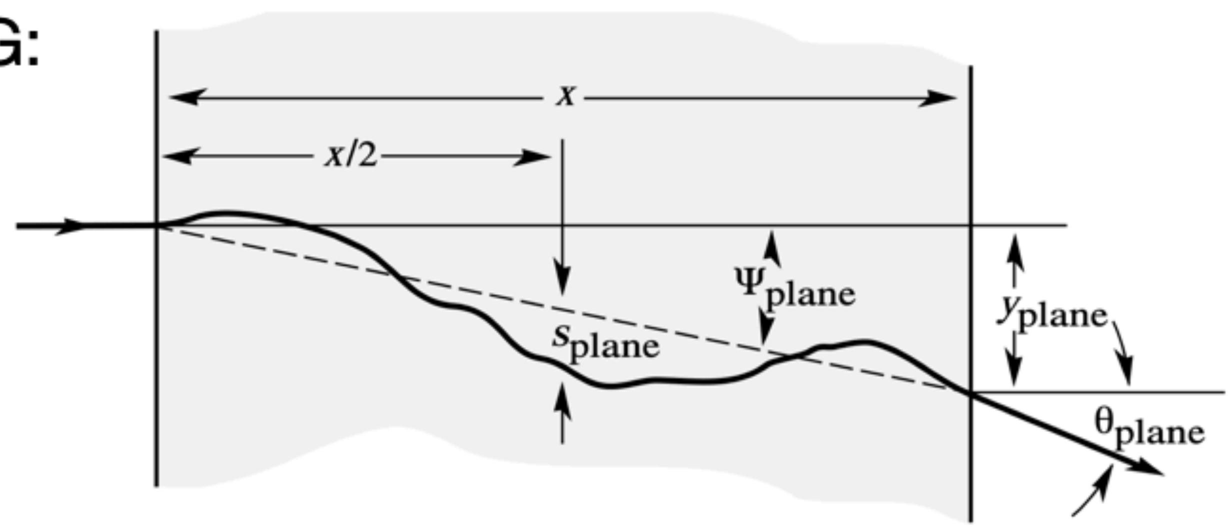
$$\Delta s = \frac{\Delta_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$ (Glückstern, 1963)

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

Tracking 101 – apologies to experts

Regarding the multiple scattering contribution,

PDG:



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

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

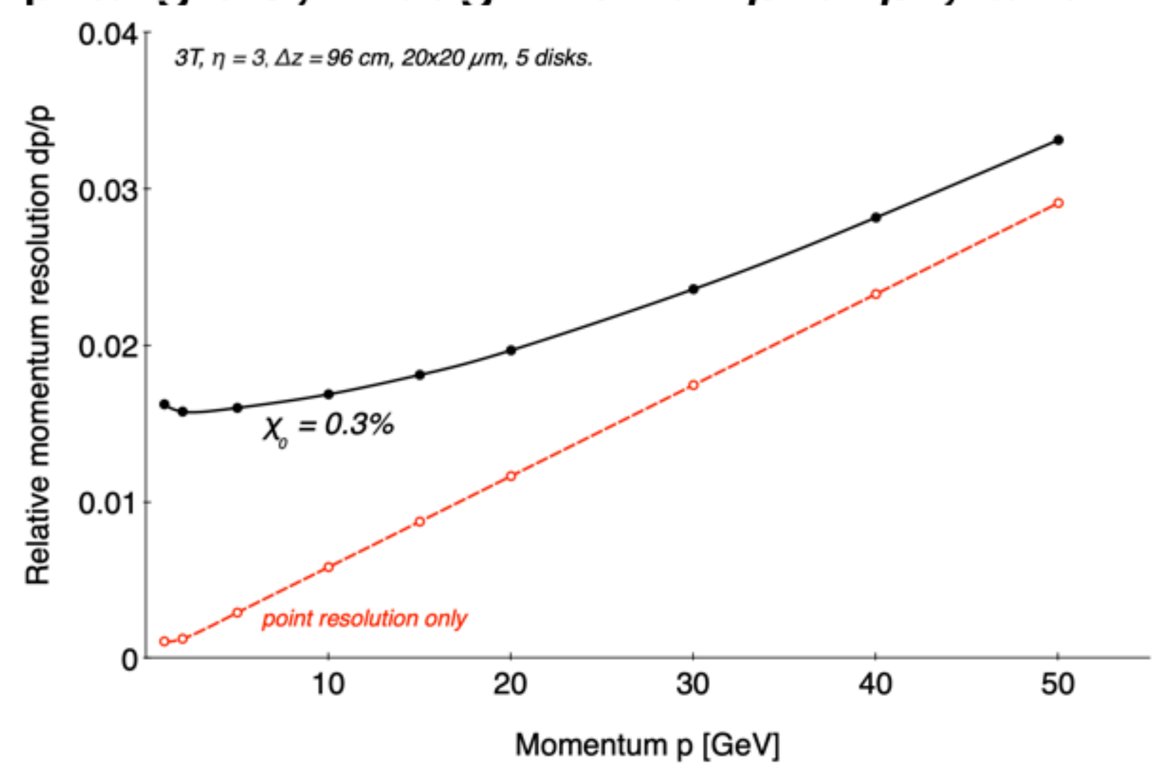
$$\left.\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}}\right|_{\mathrm{m.s.}} \approx \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{L}{X_0}}\cdot\frac{R}{L} = \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{1}{LX_0}}\frac{p_T}{eB}$$

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).

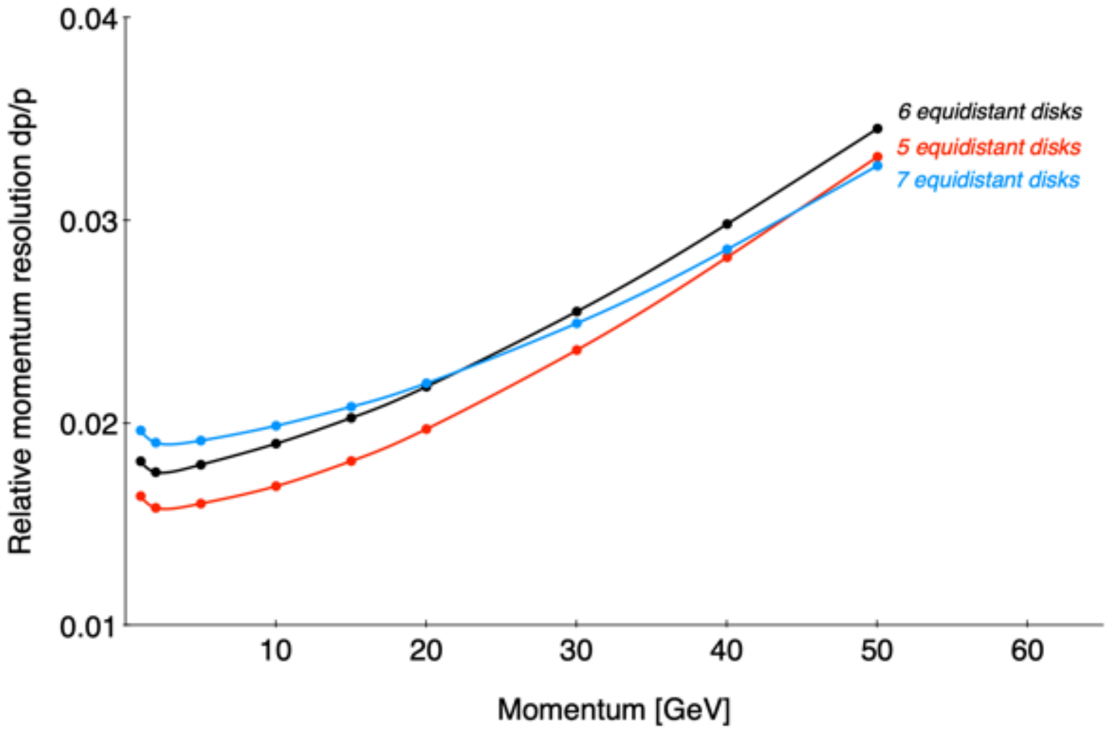


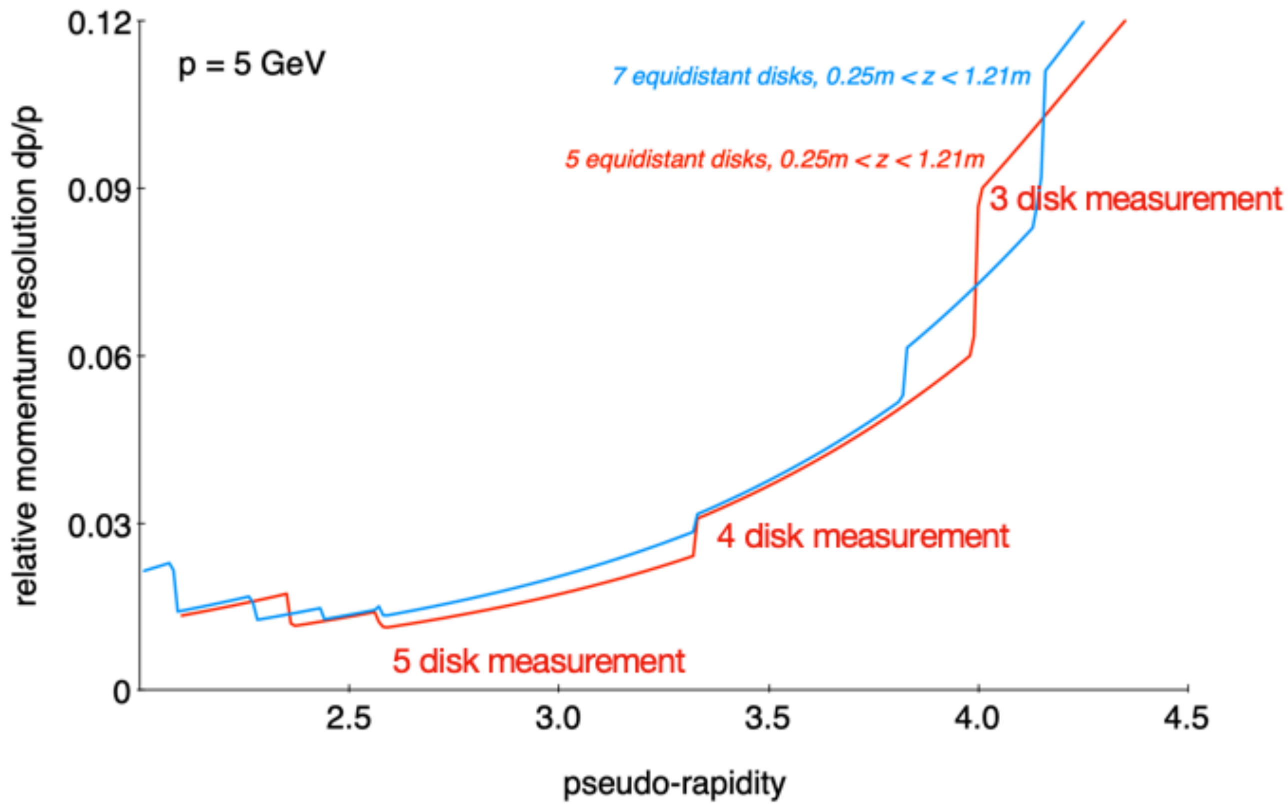
Tracking 101 – trade-offs for disks

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

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*.