Particle Detection, Detector Technologies, and **Research & Development**

… and All That in One Lecture

based on drawing by Enki Bilal

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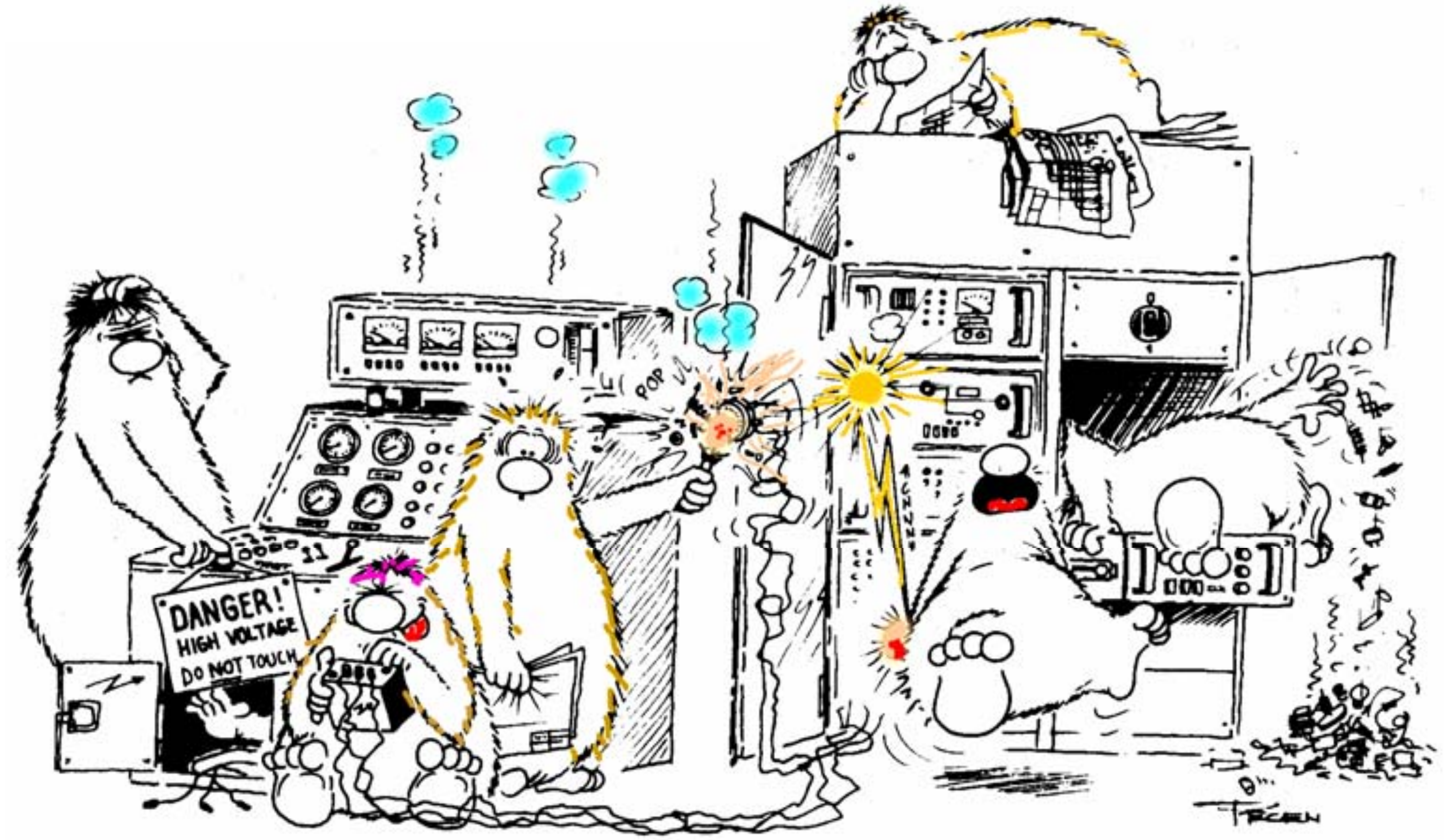
CFNS Summer School 2022
July 13, 2022

Yale BROOKHAVEN NATIONAL LABORATORY

Outline

What I will try to cover:

- Particle interaction with matter and magnetic fields
- Detector Types
  - Tracking detectors
  - Calorimeters
  - Particle Identification
- How to design and EIC detector
- the EIC R&D Program



We will just concentrate on the detectors

Material taken shamelessly from:
M. Lefebvre (Victoria), O. Ullaland (CERN), L. Serin (Orsay), W. Kühn (Giessen), E. Sichtermann (LBL), Particle Data Group, Participants of EIC Generic R&D Program.

A perfect detector would be able to …

- Detect charged particles
  - charged leptons, charged hadrons, …
- Detect neutral particles
  - photons, neutral hadrons, neutrinos
- Perform particle identification
- Precisely measure the energy and/or the momentum of each particle
  - allow to construct 4-vectors for all particles produced in an interaction
- Do so even at very high interaction rates …
- … and withstands high radiation doses without any damage to itself

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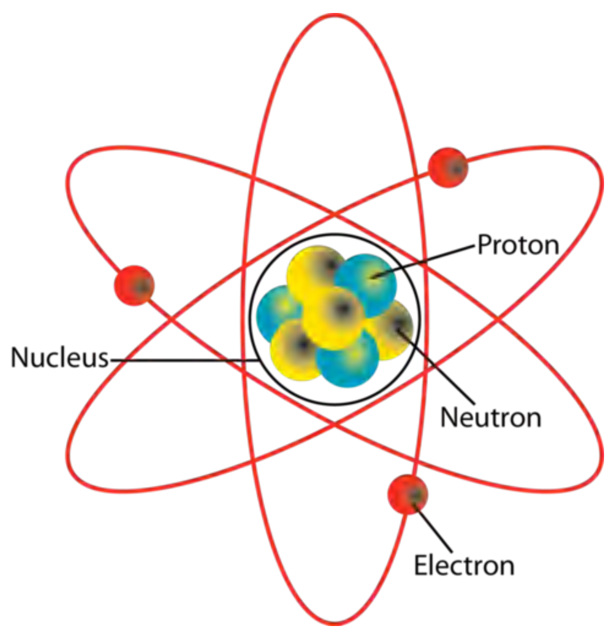
Sadly there is no such thing as a perfect detector
Building a detector means compromising (and doing more R&D)

Detectors are made out of matter …

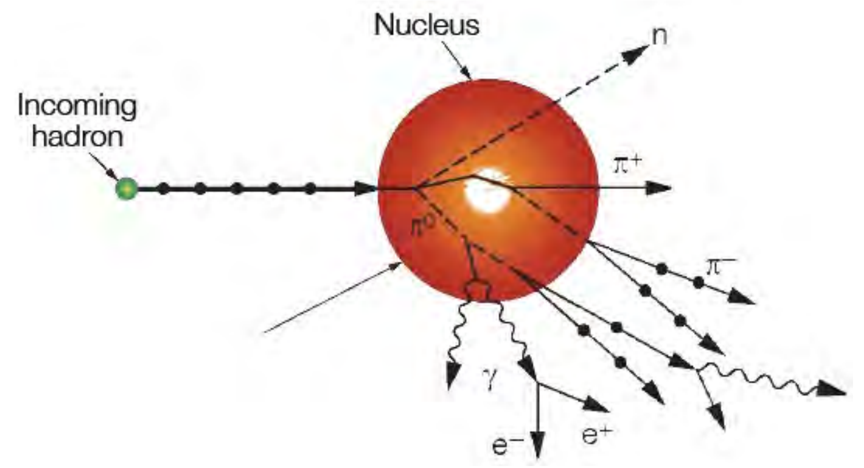
Any device that is to detect a particle must interact with it in some way

Interaction of particles with matter

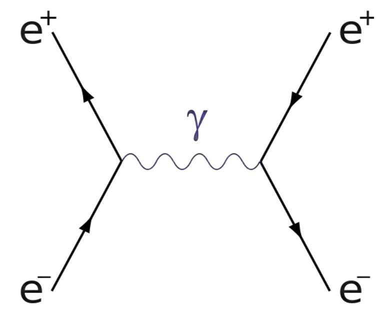
- Matter : Atoms = Electrons + Nuclei
- Interactions depend on particle type
- Energy loss strongly dependent on energy



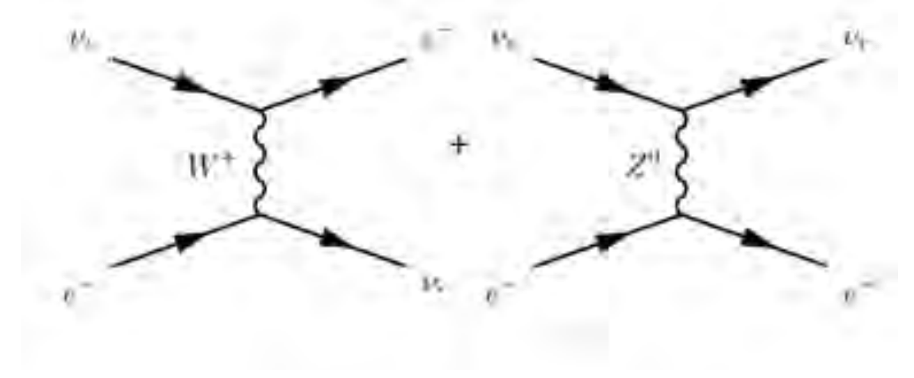
Strong interaction of hadrons with nuclei



Electromagnetic interaction of charged particles and photons with electrons and nuclei

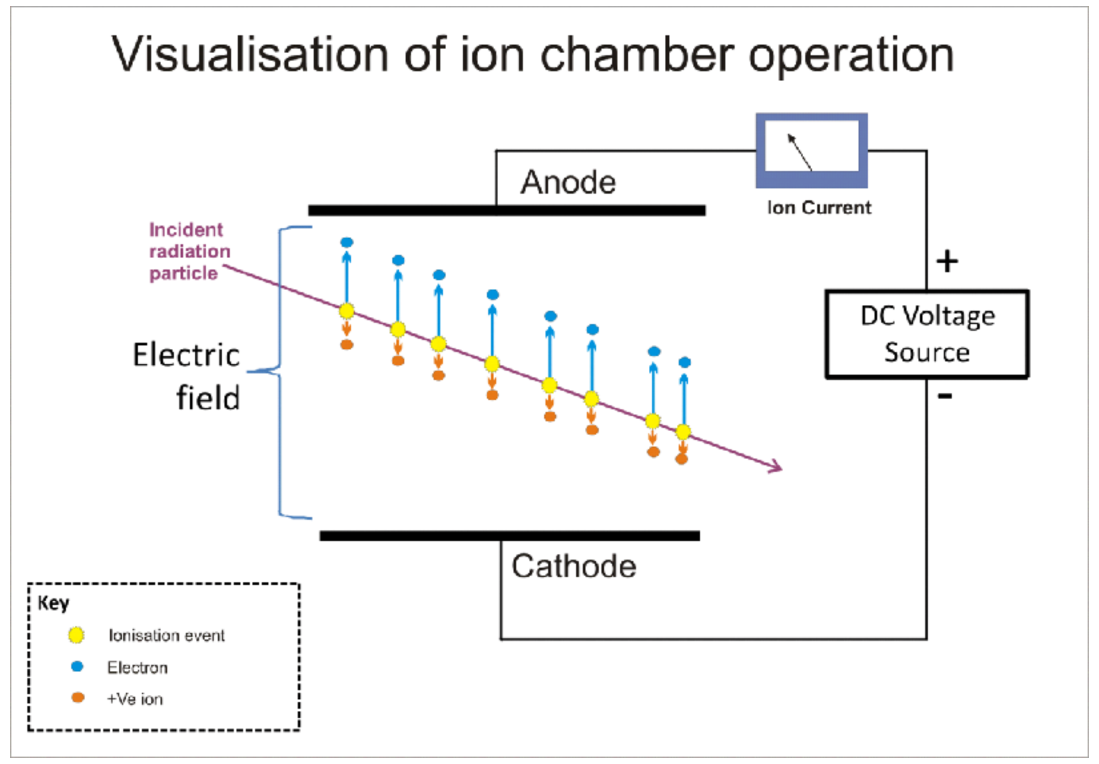


Weak interaction of neutrinos with electrons and nuclei

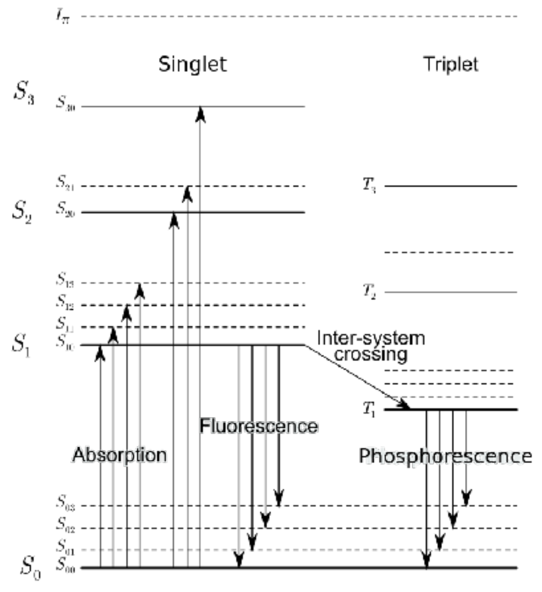


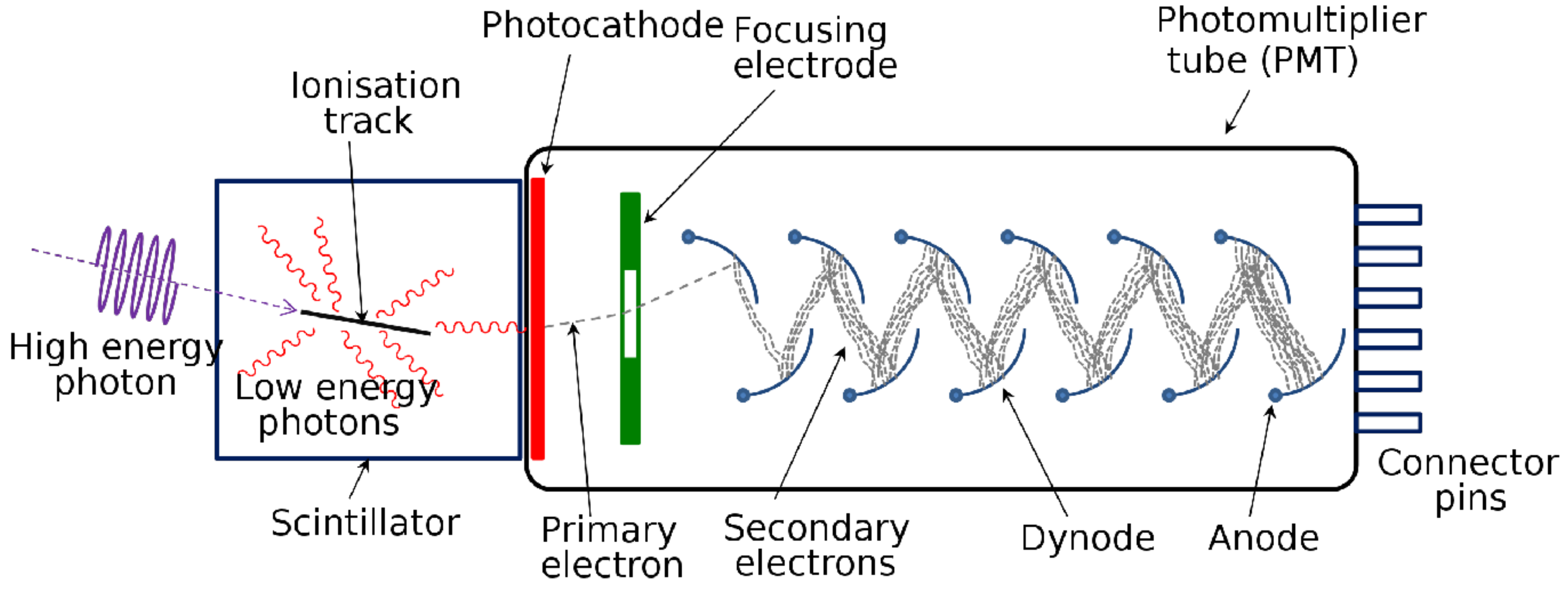
From Basic Ideas to Complex Detectors

Large majority of the physics detection processes are well known and studied since long time and based mainly on electromagnetic interaction: ionization, excitation, photo-electric effect, pair creation / bremsstrahlung, Cherenkov radiation, transition radiation….

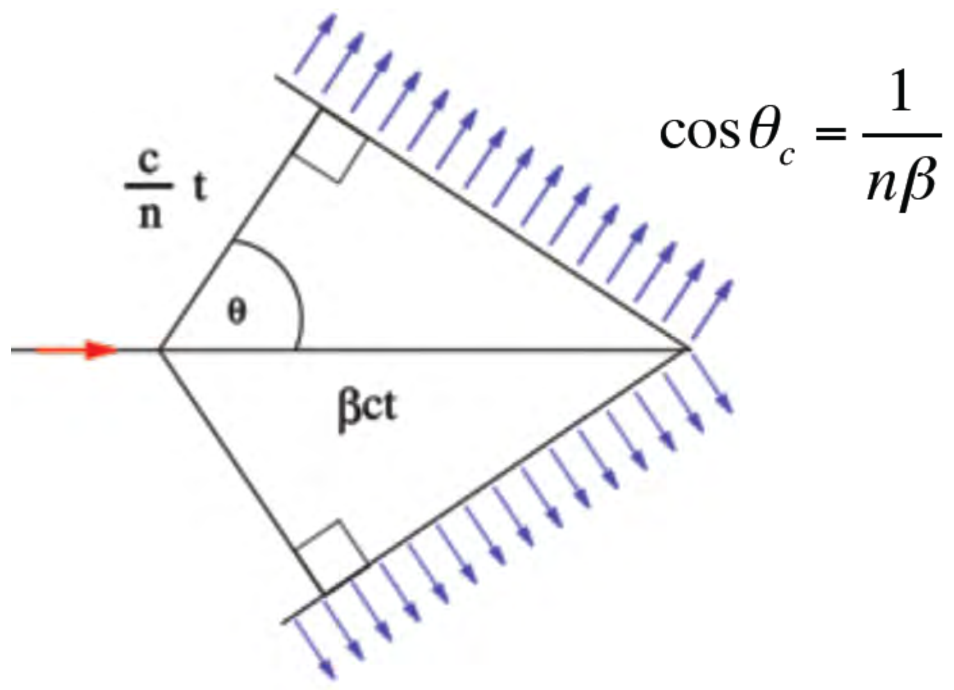


Ionization





Scintillation



Cherenkov

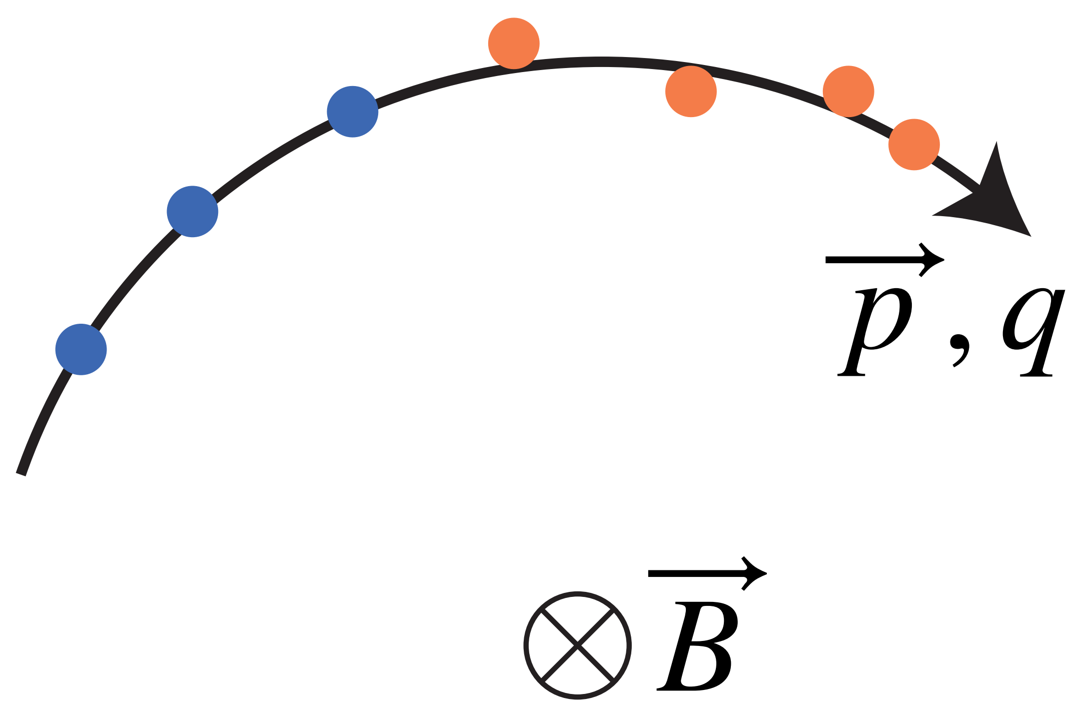
All the cleverness lies in the best way to use these processes to build a detector and to measure a signal :

- Electric signal: charge collection
- Optical signal: light collection

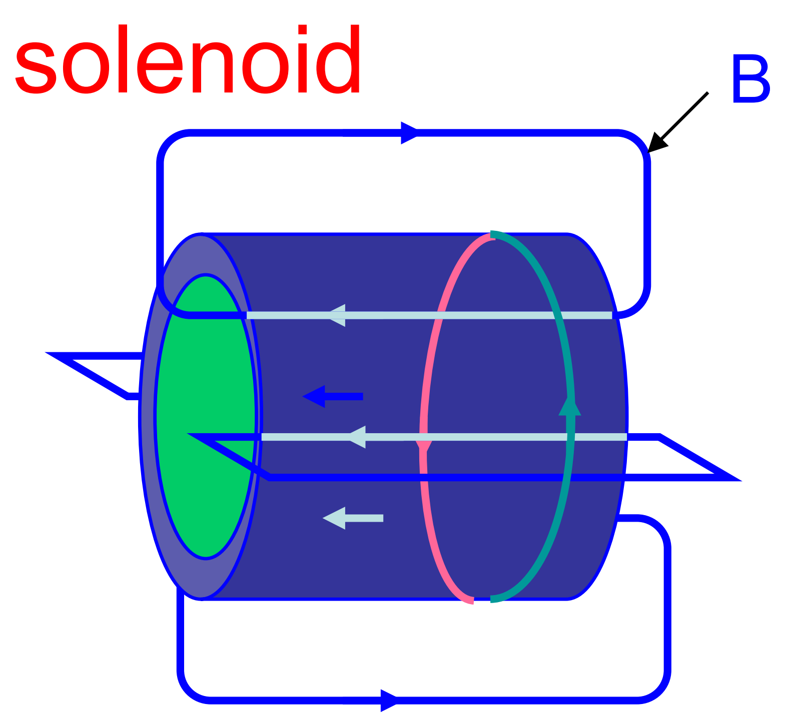
Much of the progress in detection has been allowed by the impressive progress in electronics/computing (speed, low noise, complex logic)

Tracking ($\vec{p}$)

- Recipe (for charged particles):
  - Need accurate x, y, z position of many hits to assemble a trajectory (track)
  - Need magnetic field of some sort that bends the trajectory. From the bending and the knowledge of B we can derive the momentum.

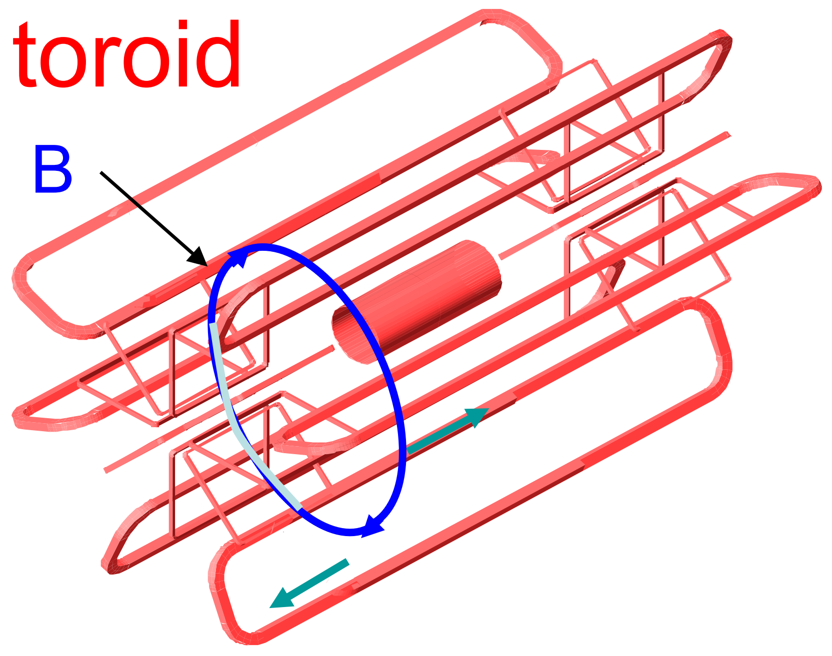


What field?



Solenoid:
Large homogeneous field inside the coil
Weak opposite field in the return yoke
Cost limits the size
Relatively high material budget
Track of a charged particle represents a helix

Examples:
Delphi, L3, CMS, STAR, sPHENIX, EIC



Toroid:
Relatively large fields over large volume
Relatively low material budget
Non-uniform field
Complex structure

Examples:
ATLAS

Remember:
$$p_T[GeV] = 0.3 \cdot B[T]\ R[m]$$

Closer Look at Tracking

Gluckstern (1963)

Tracking Resolution:

Precision term: $$\left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{meas}} = \frac{p_T\ \sigma_{r_{\phi r}}}{0.3\ L^2\ B}\sqrt{\frac{720}{N+5}}$$

MS term: $$\left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{MS}} = \frac{0.05}{L\ B\ \beta}\sqrt{1.43\frac{L}{X_0}}\left[1+0.038\ \log\frac{L}{X_0}\right]$$

where

$\sigma_{r_{\phi r}}$ is point resolution in meter

L is lever arm in meter

B is magnetic field in Tesla

N are number of measurements (hits)

β velocity of particle

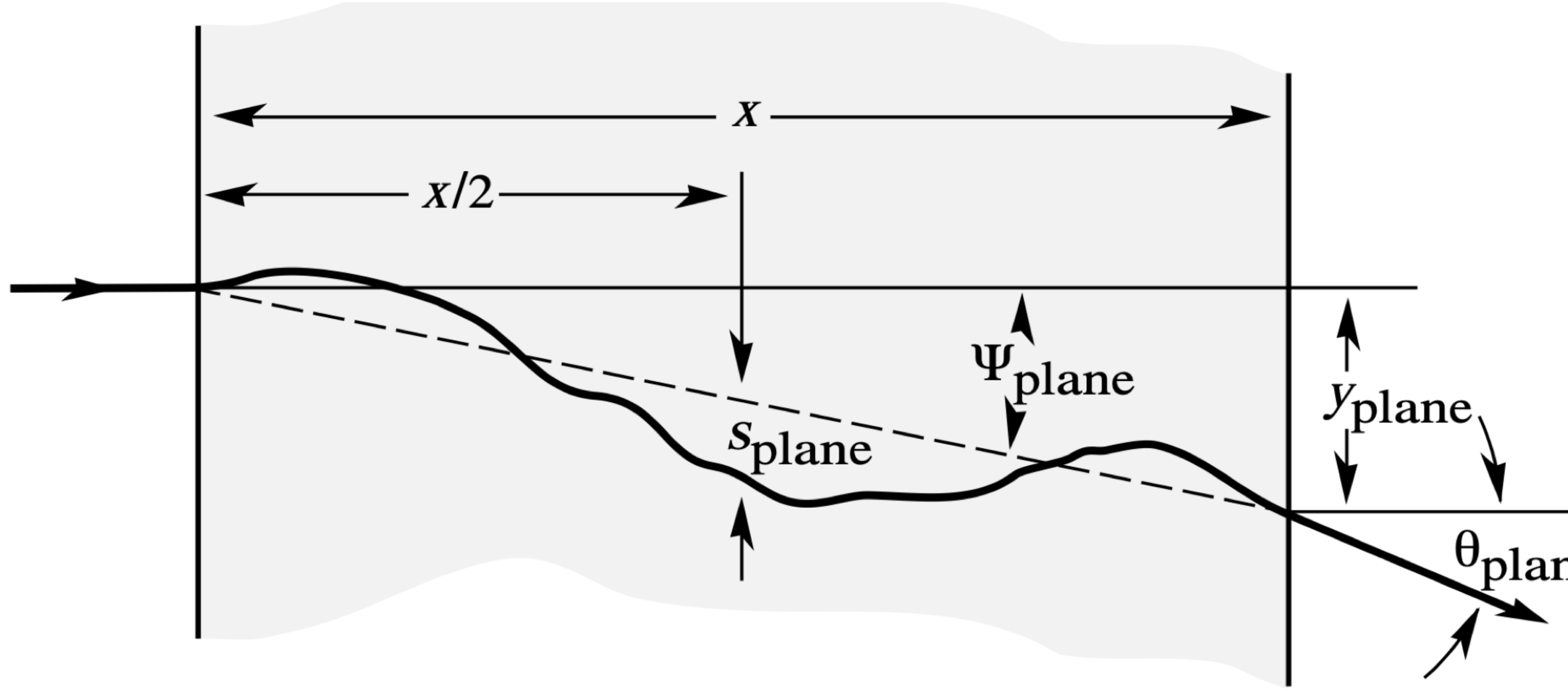
X_0 is gas/material density in meter

Track momentum resolution: $$\frac{\sigma_{p_T}}{p_T} = \left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{meas}} \oplus \left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{MS}}$$

Momentum resolution is limited:

- At high momentum by position resolution of the detector and strength of magnetic field
- At low momentum by multiple scattering due to material in the path

PDG:



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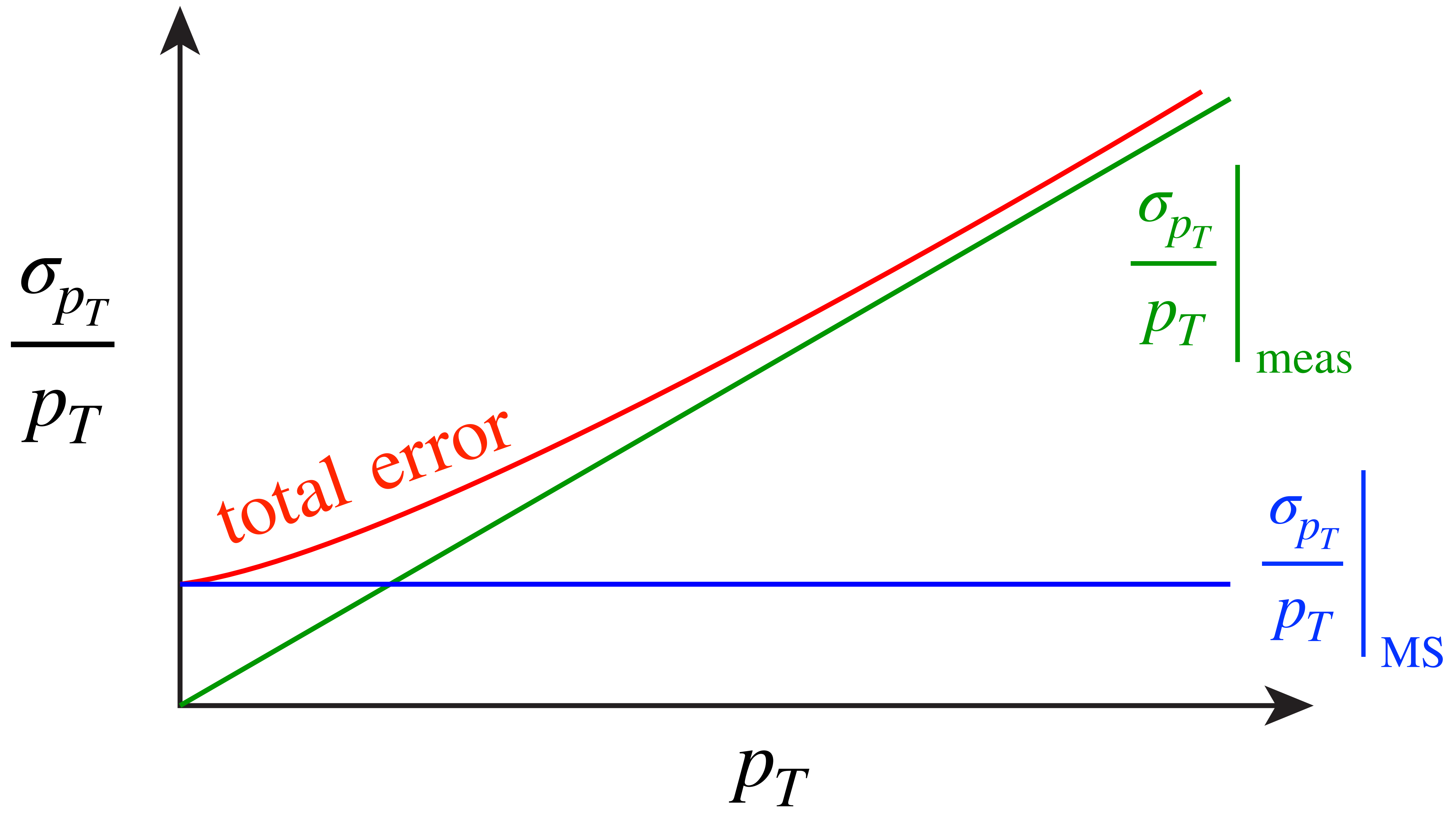

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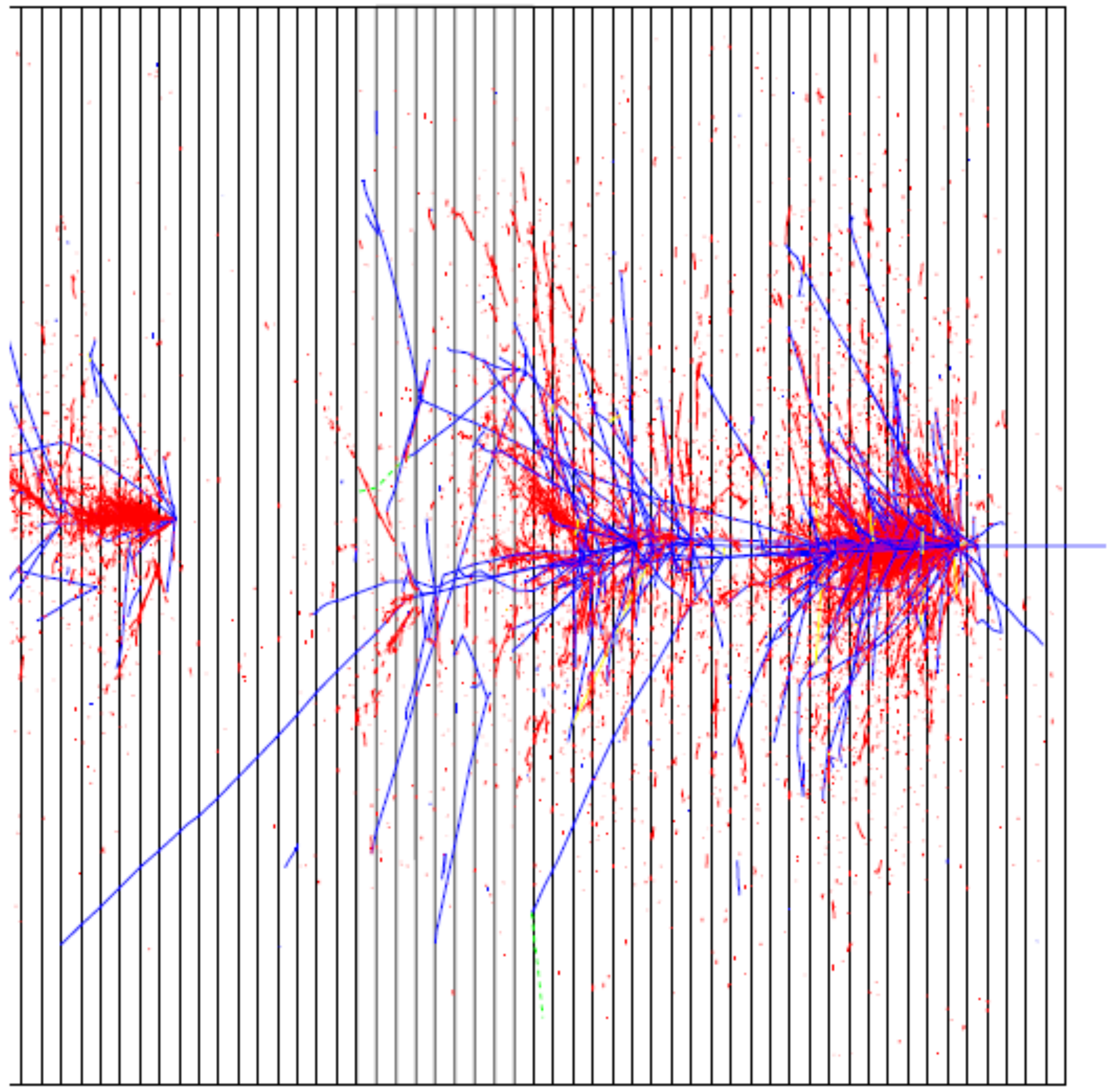
Maximize Resolution:

- N ↑: good but adds material and services
- σ_r ↑: good, but increases channel count & heat, limited by technology
- X_0↓: important but also affects N
- L↑: Good, needs room/space
- B↑: Good, affects photosensors, low-p_T PID

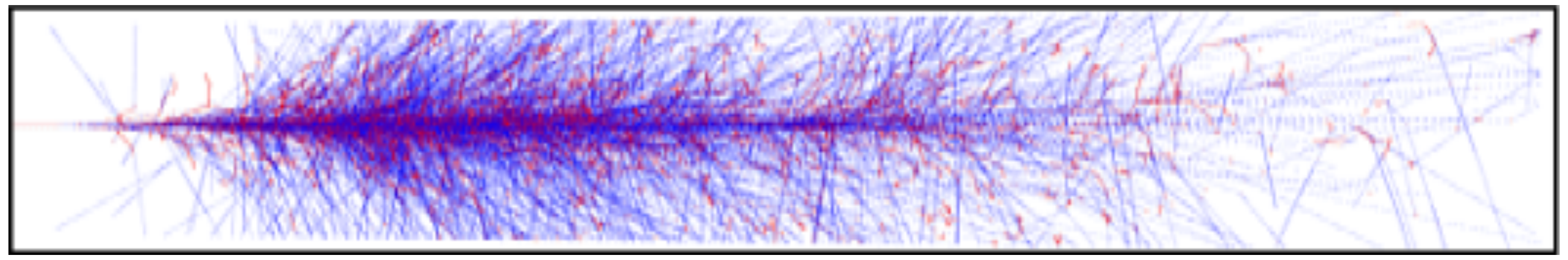
Calorimetry (E)

- Energy measurement by total absorption
  - works for charged and neutral particles
  - spatial reconstruction
  - particle identification capability
- Measured particle is lost (destructive method)
- Basic mechanisms
  - electromagnetic or hadronic showers
- Detector response is proportional to E
  - not always true for hadronic showers
- Energy converted into ionization and/or excitation of matter



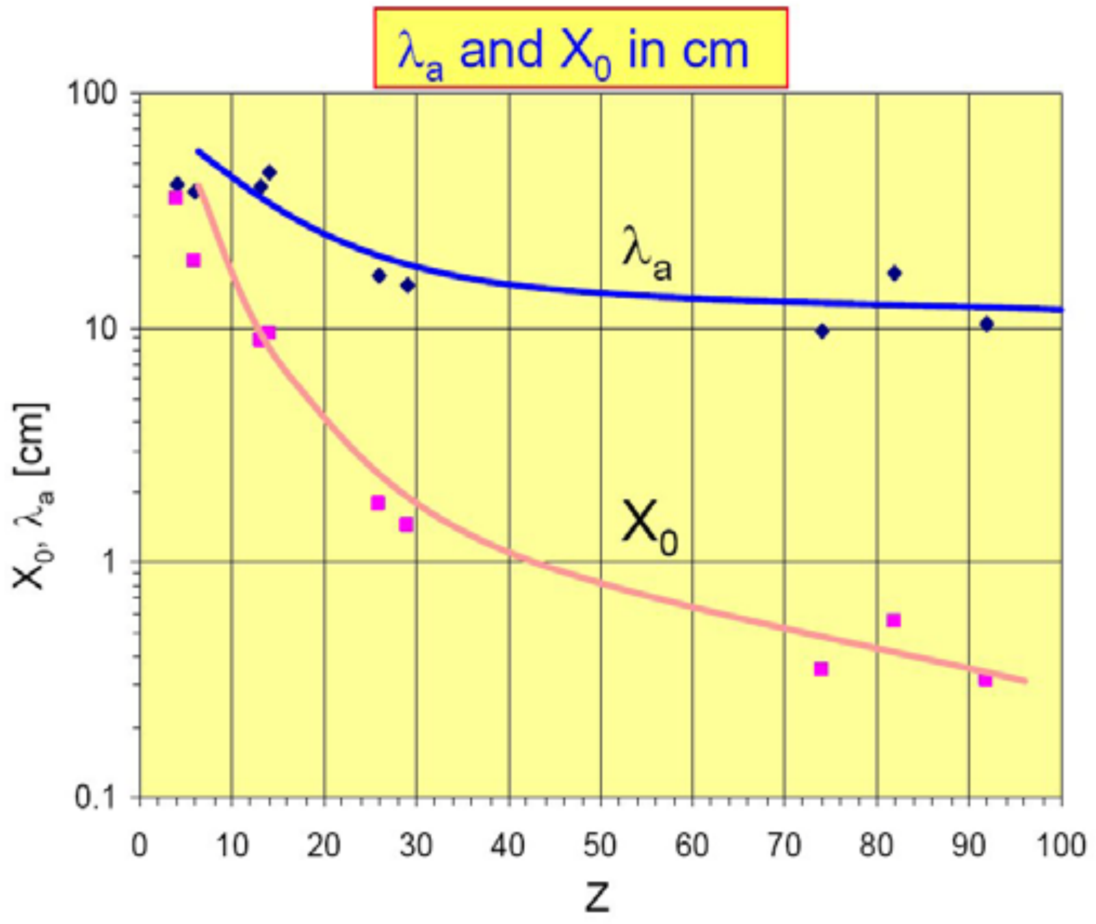
Categories of Calorimeters

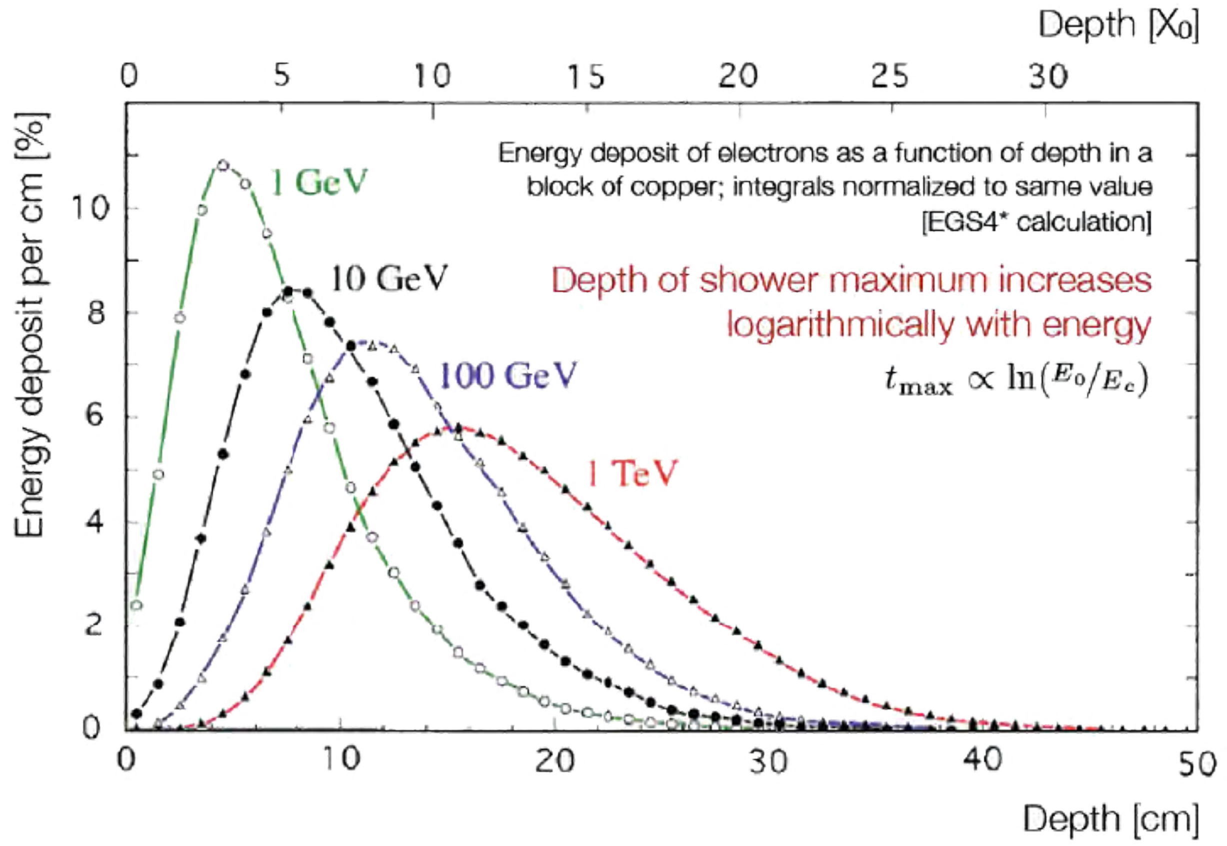
EM Calorimetry for γ and $e^{\pm}$



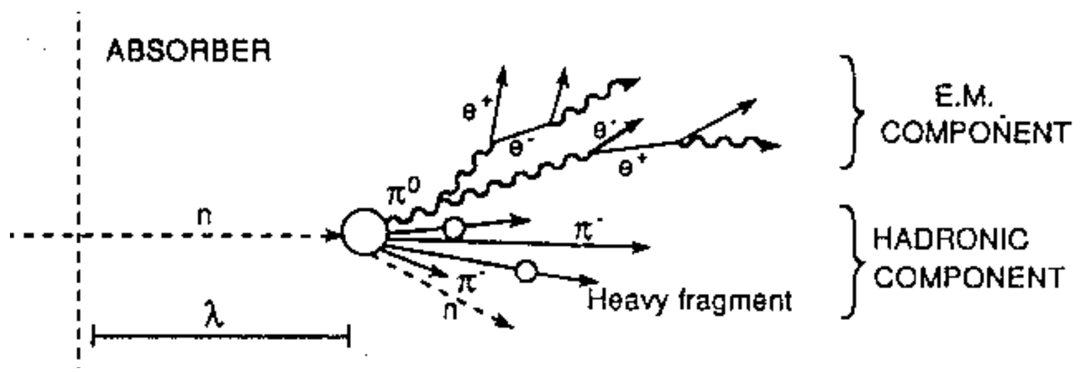
- Main processes
  - photoelectric effect (γ)
  - Compton effect (γ)
  - $e^{+}e^{-}$ pair creation (γ)
  - Ionization ($e^{\pm}$)
  - Bremsstrahlung ($e^{\pm}$)
- The radiation length X_0 is defined as the distance over which the mean energy of an incident electron is reduced by a factor e, $E = E_0 \exp(-x/X_0)$

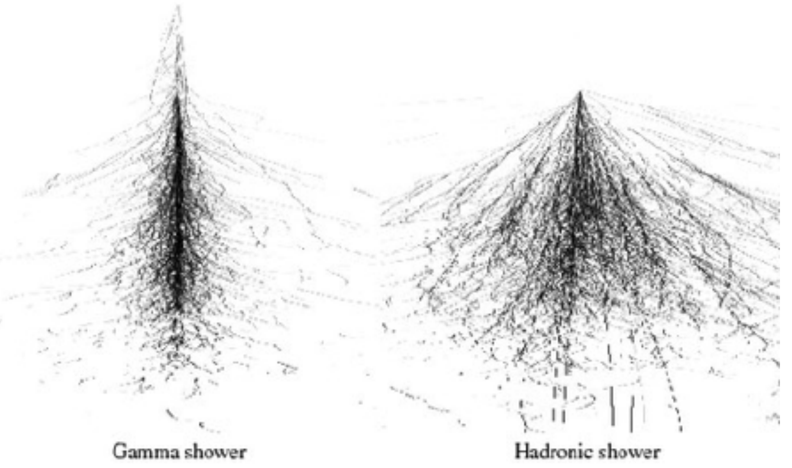
key parameter





Hadron Calorimetry for $h^{\pm,0}$

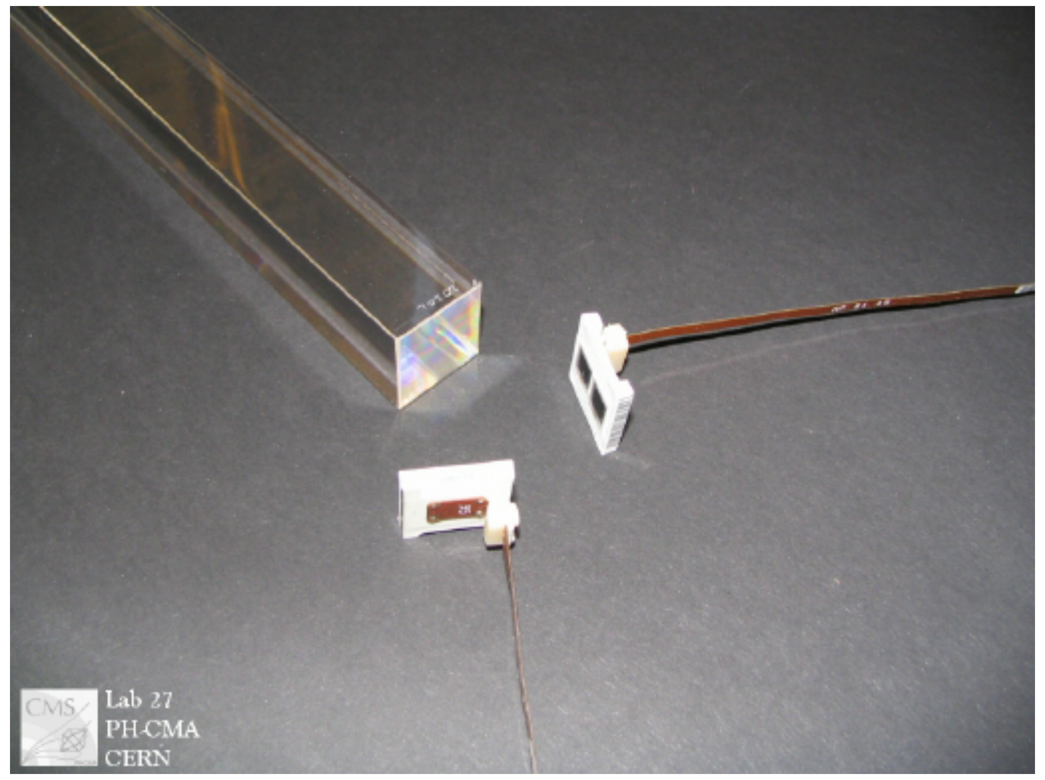


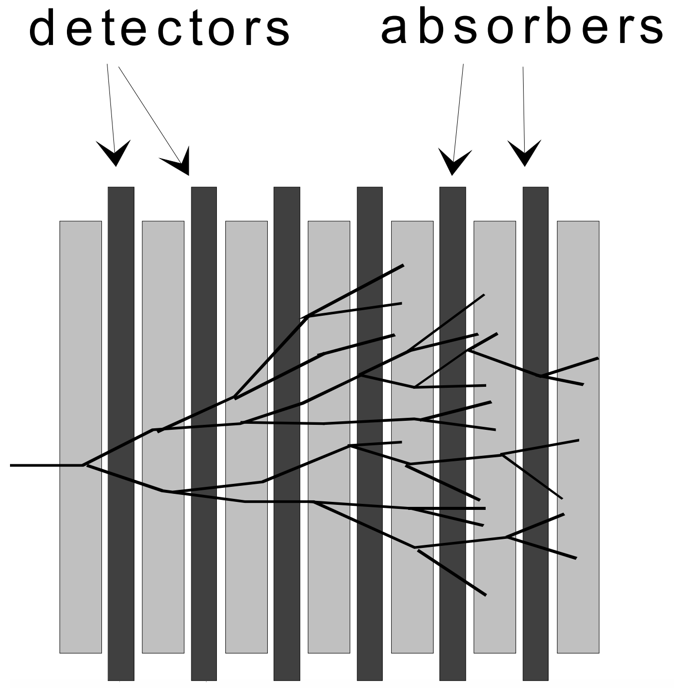


- Interaction of charged/neutral hadrons involves mainly nuclear interaction:
  - excitation and nucleus break-up
  - production of secondary particles + fragment
- Hadronic shower : typically 10 times wider and deeper/longer than EM showers (see left plot)
- Large fluctuation of the shower development
- In general worse resolution than EM calorimeters
- Λ_{int}: mean free path between nuclear collisions

Types of Calorimeter

- Homogeneous calorimeters (EM only)
  - detector is absorber: Scintillation crystals, glass blocks, Cherenkov radiation
  - good energy resolution, limited spatial resolution
  - Examples: $PbWO_4$ (CMS), L3 (BGO)
- Sampling calorimeters
  - detector and absorber separated
  - limited energy resolution, good spatial resolution





General resolution parametrization:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

stochastic or sampling term

constant term

comes from inhomogeneity, bad calibration, non-linearity

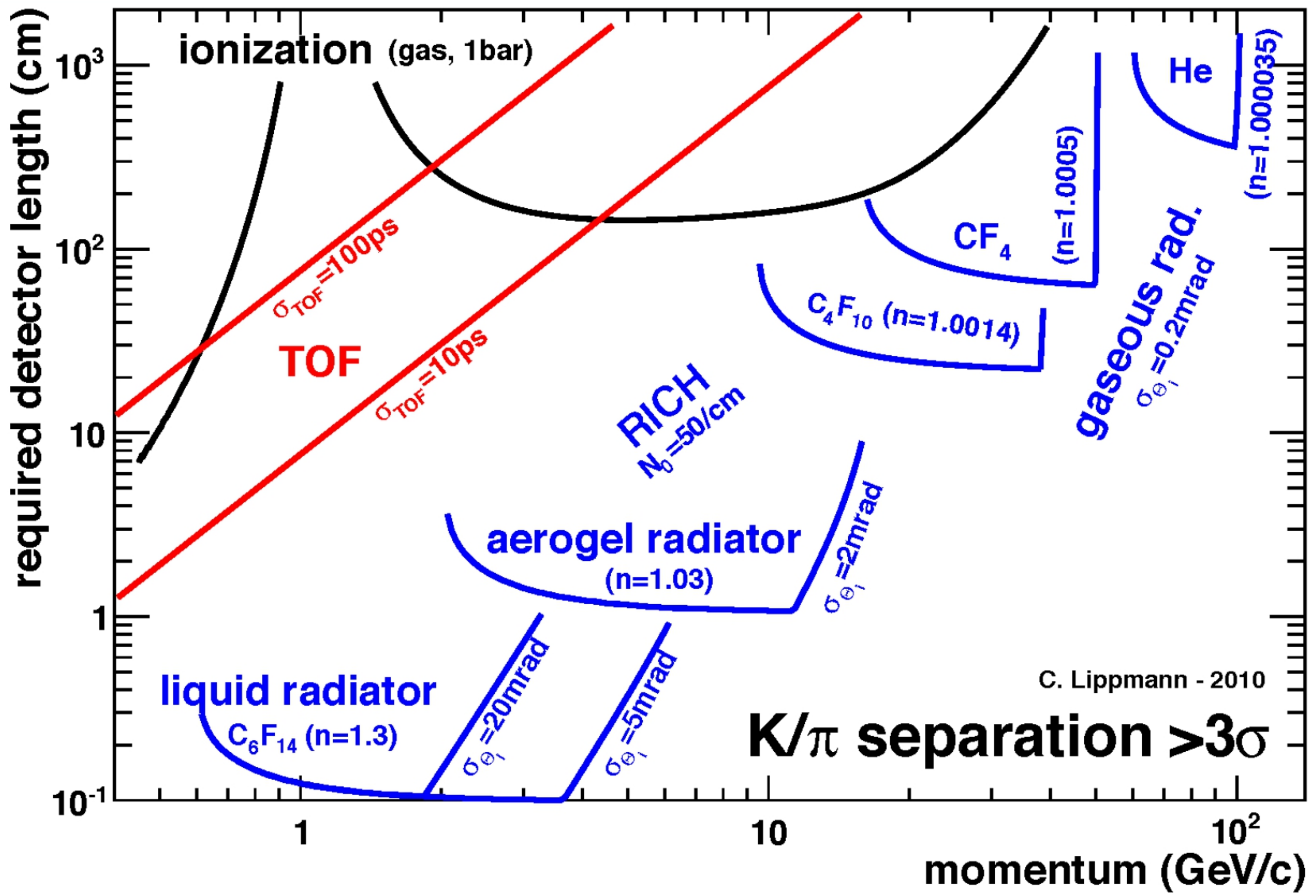
noise term

including electronic and pileup noise

EM: a ~ 2-15%
H: a ~ 40-100%

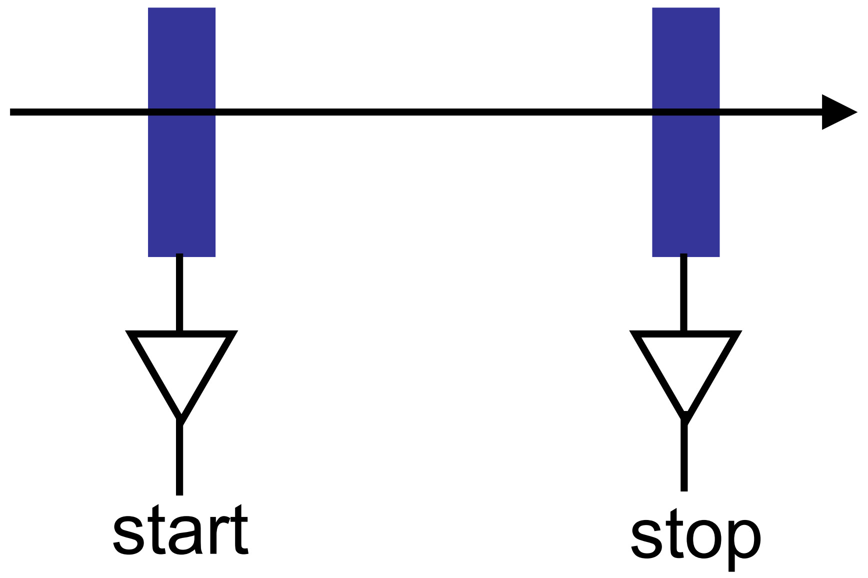
Particle Identification (m)

- Particle Identification
  - dE/dx (energy loss) measurement
  - Time of flight
  - Cherenkov detectors
  - Transition radiation detectors
- Different p ranges require different technologies
- Almost all methods assume that the momentum $\vec{p}$ is known



Types of PID Detectors

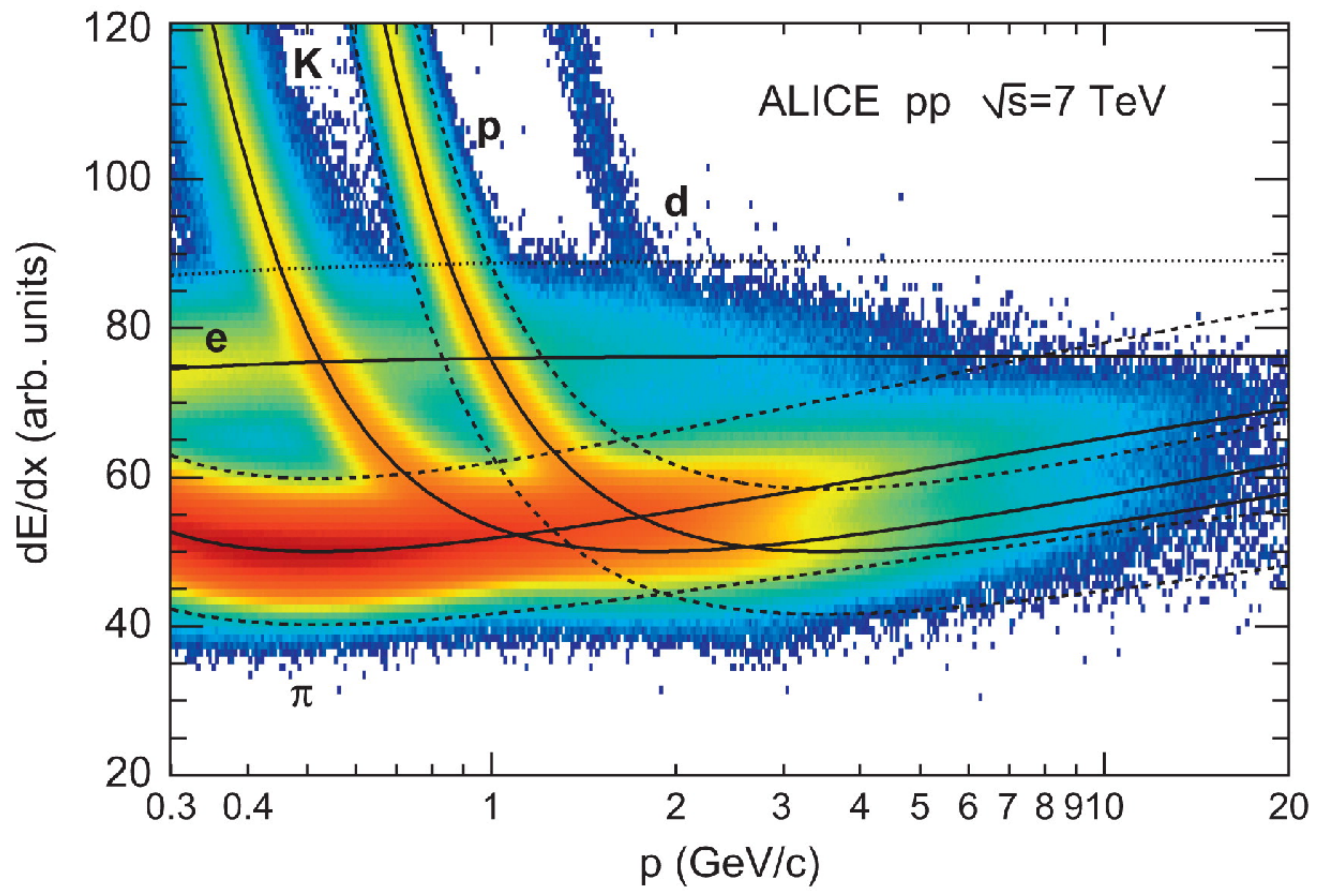
- PID with dE/dx
  - measure dE/dx many times along tracks
  - governed by Bethe-Bloch equation
  - electrons reach Fermi plateau at 1.4 MIP
  - most used in TPC like detectors (ALICE, STAR)
  - less prominent in Si-Detectors (1 vs 8 bit)
- PID with Time-of-Flight
  - requires fast detectors (small jitter)
  - fast electronics
  - good knowledge of start time t_0

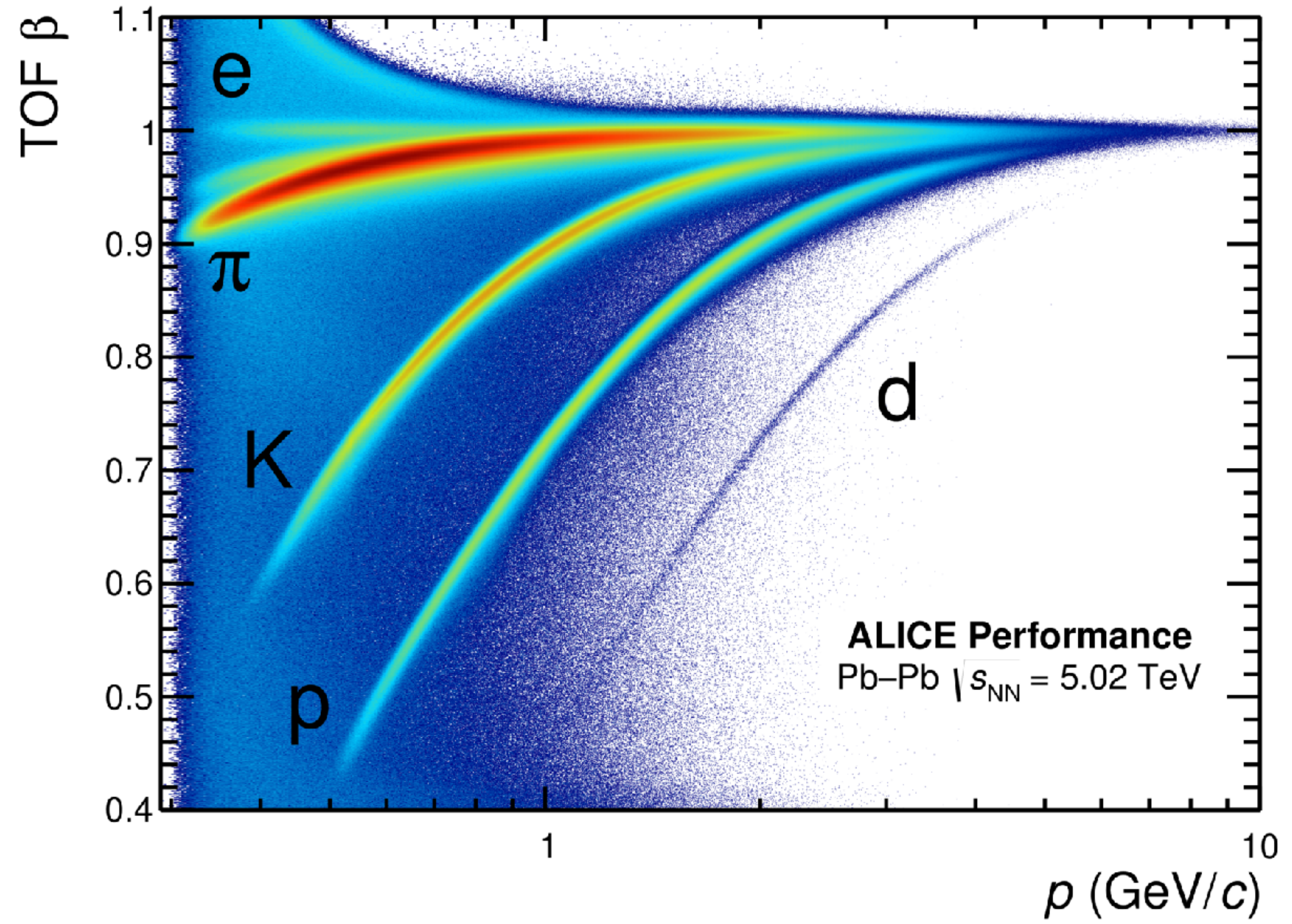


$$t = \frac{L}{\beta c} \qquad p = \gamma m \beta$$

$$m = \frac{p}{\gamma\beta} = p\sqrt{\beta^{-2} - 1} = p\sqrt{\left(\frac{ct}{L}\right)^2 - 1}$$

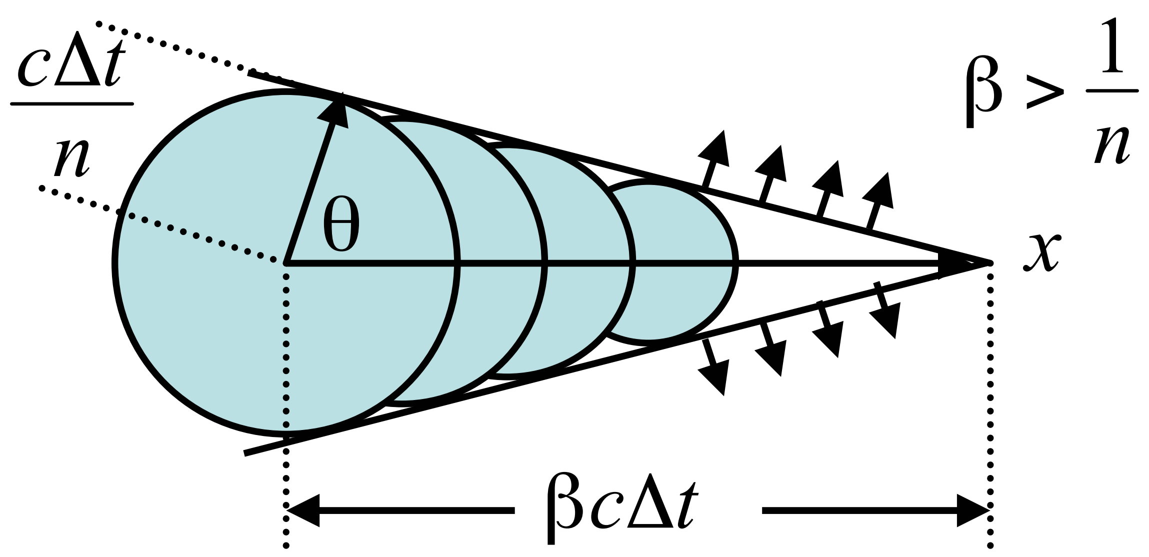
$$\left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_p}{p}\right)^2 + \gamma^4\left[\left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2\right]$$

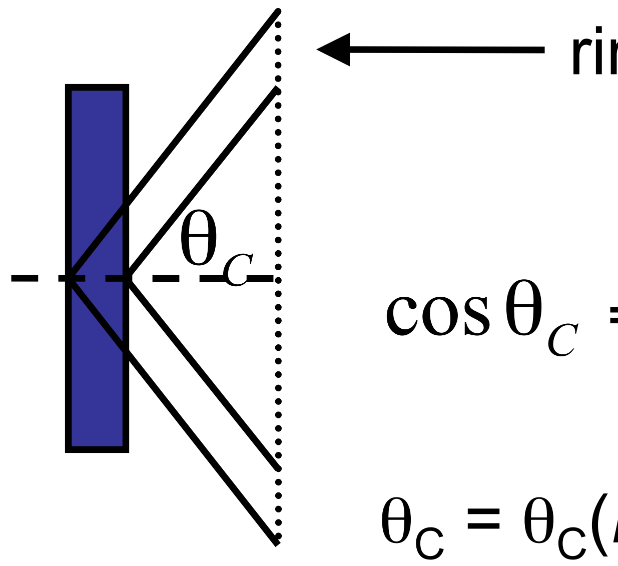




Types of PID Detectors

- PID with Cherenkov radiation
  - charged particle travels faster than light in medium
  - high-p_T → gas, medium-p_T → aerogel, low-p_T → quartz
  - Critical parameter: $N_{photons}$
  - Implementations:
    - RICH (Ring Imaging Cherenkov Counter)
    - DIRC (Detection of Internally Reflected Cherenkov Light)
    - Threshold Counter
- Transition radiation detector
  - energy radiated when a z charged particle crosses the boundary between vacuum and a dielectric layer
  - number of photons emitted per boundary is small
  - photons are emitted close to the track $\theta \approx 1/\gamma$
  - typical energy is in the keV range
  - low Z material preferred to keep re-absorption small ($\propto Z^5$) • stacks of CH_2 foils
  - hydrocarbon foam and fibre materials

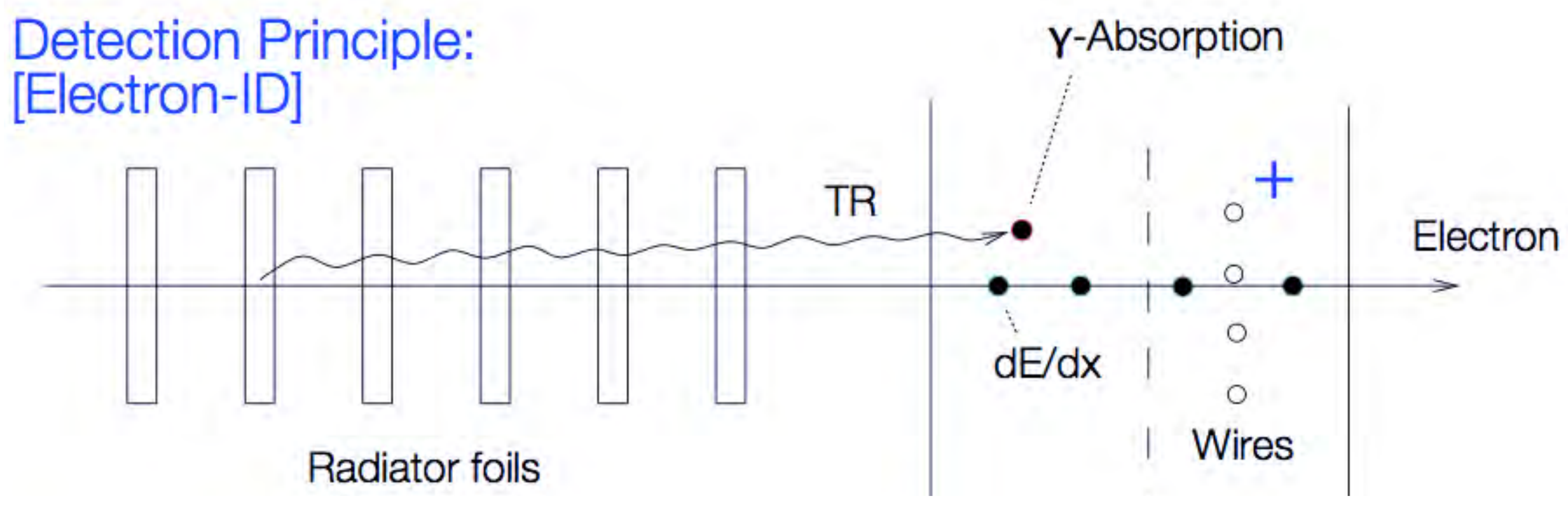




$\cos\theta_C = \frac{1}{n\beta}$

$\theta_C = \theta_C(E_\gamma)$ since in general $n = n(E_\gamma)$

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4



So what about the EIC Detector (Part I)?

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Big questions

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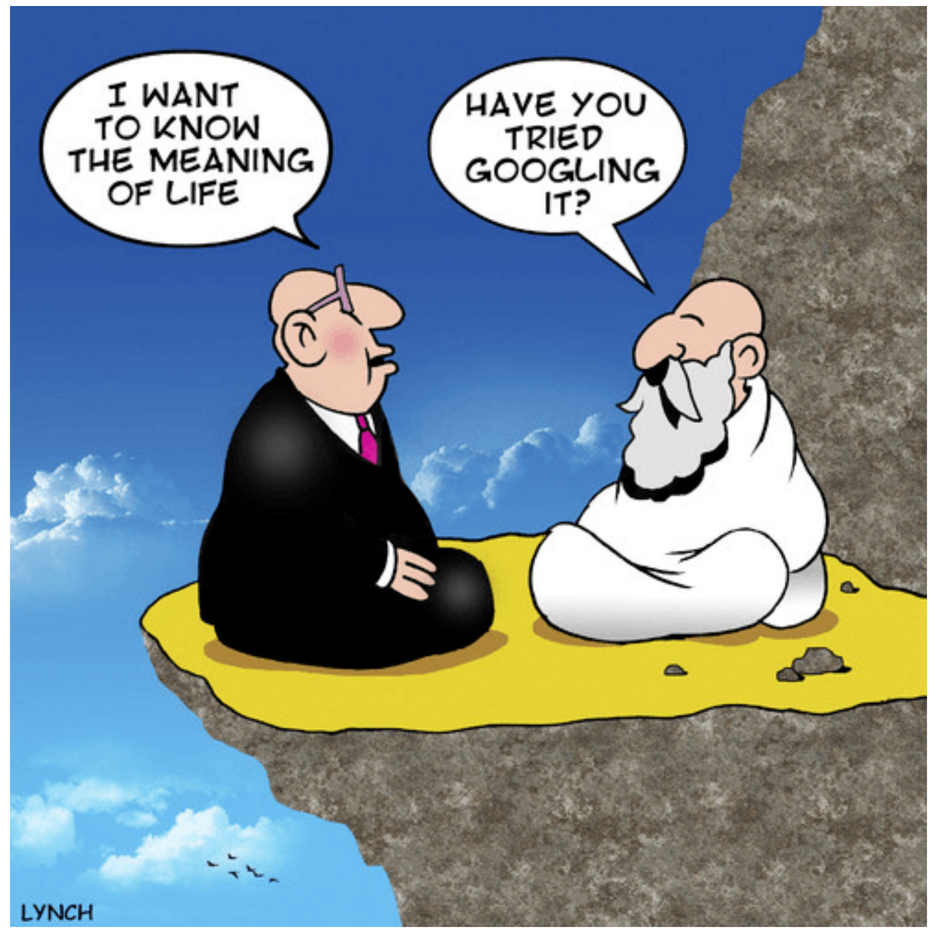
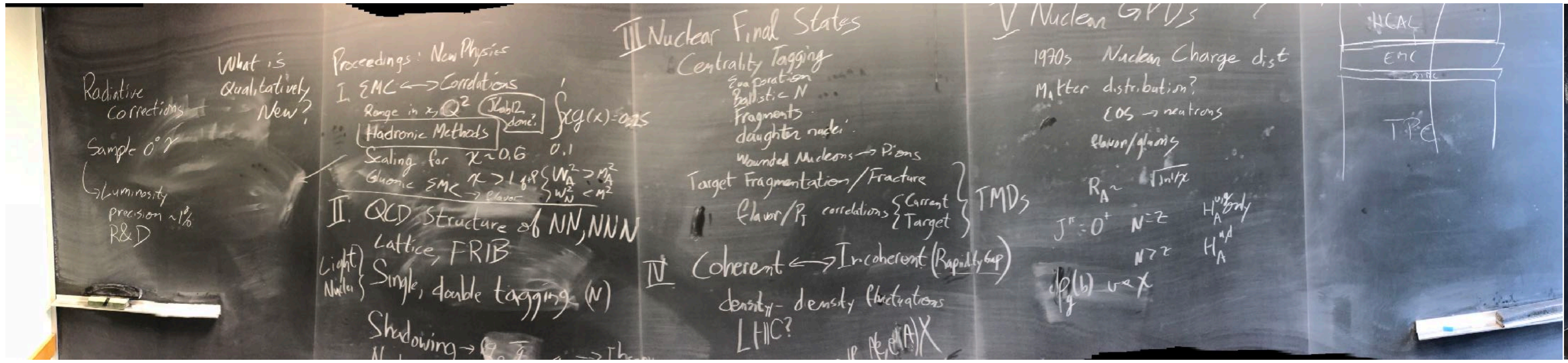


INT, Seattle



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Big questions ⟶ Physics case

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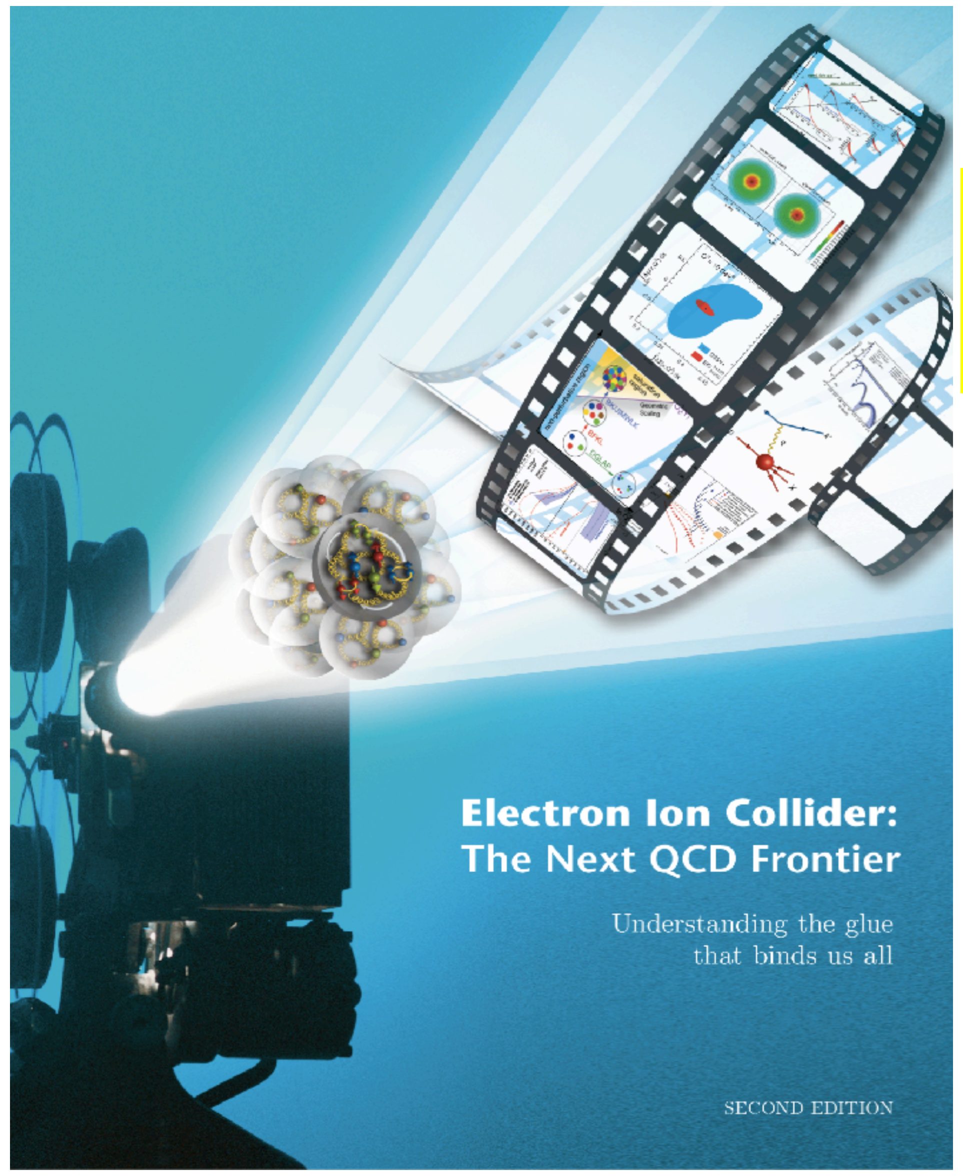
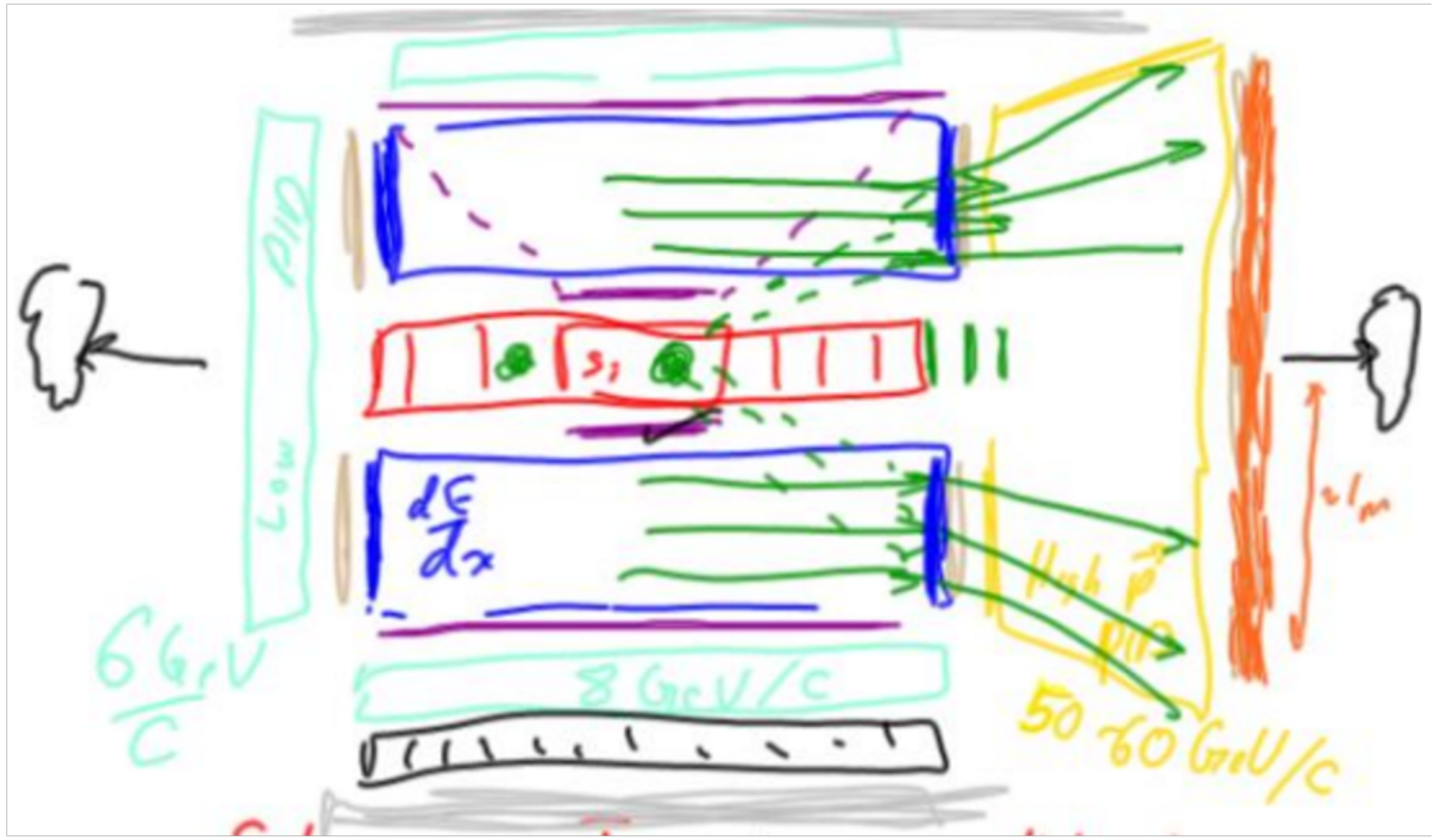


EIC White Paper

1212.1701.v3
A.Accardi et al
Eur. Phy. J. A, 52 9(2016)

So what about the EIC Detector (Part I)?

Big questions ⟶ Physics case ⟶ Early detector drafts



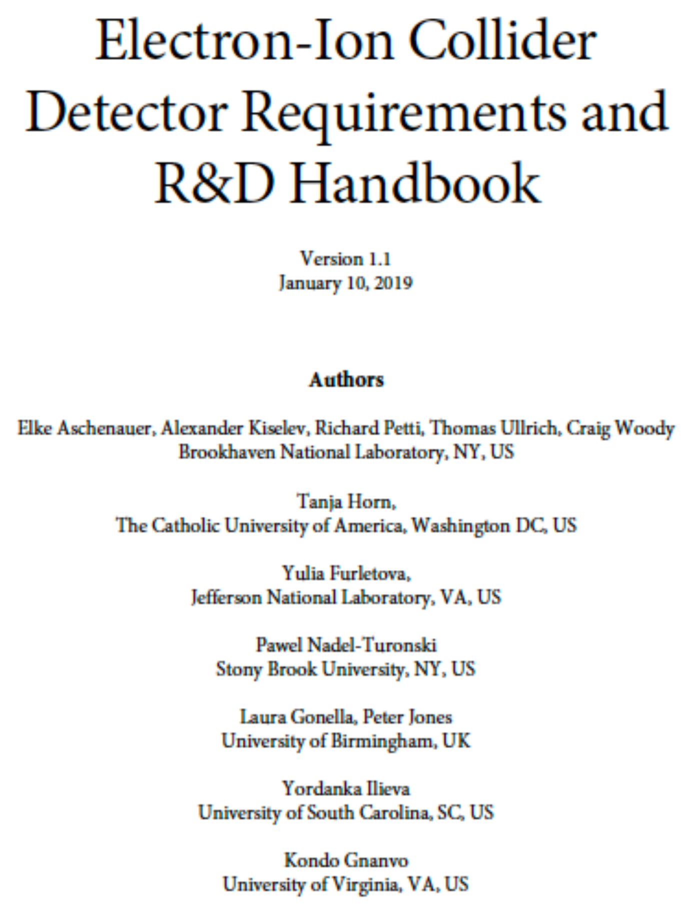
eRD6/Tracking Group Meeting

So what about the EIC Detector (Part I)?

Big questions → Physics case → Early detector drafts

Physics case → Early detector requirements → Early detector drafts

Early detector requirements


Electron-Ion Collider
Detector Requirements and
R&D Handbook

Version 1.1
January 10, 2019

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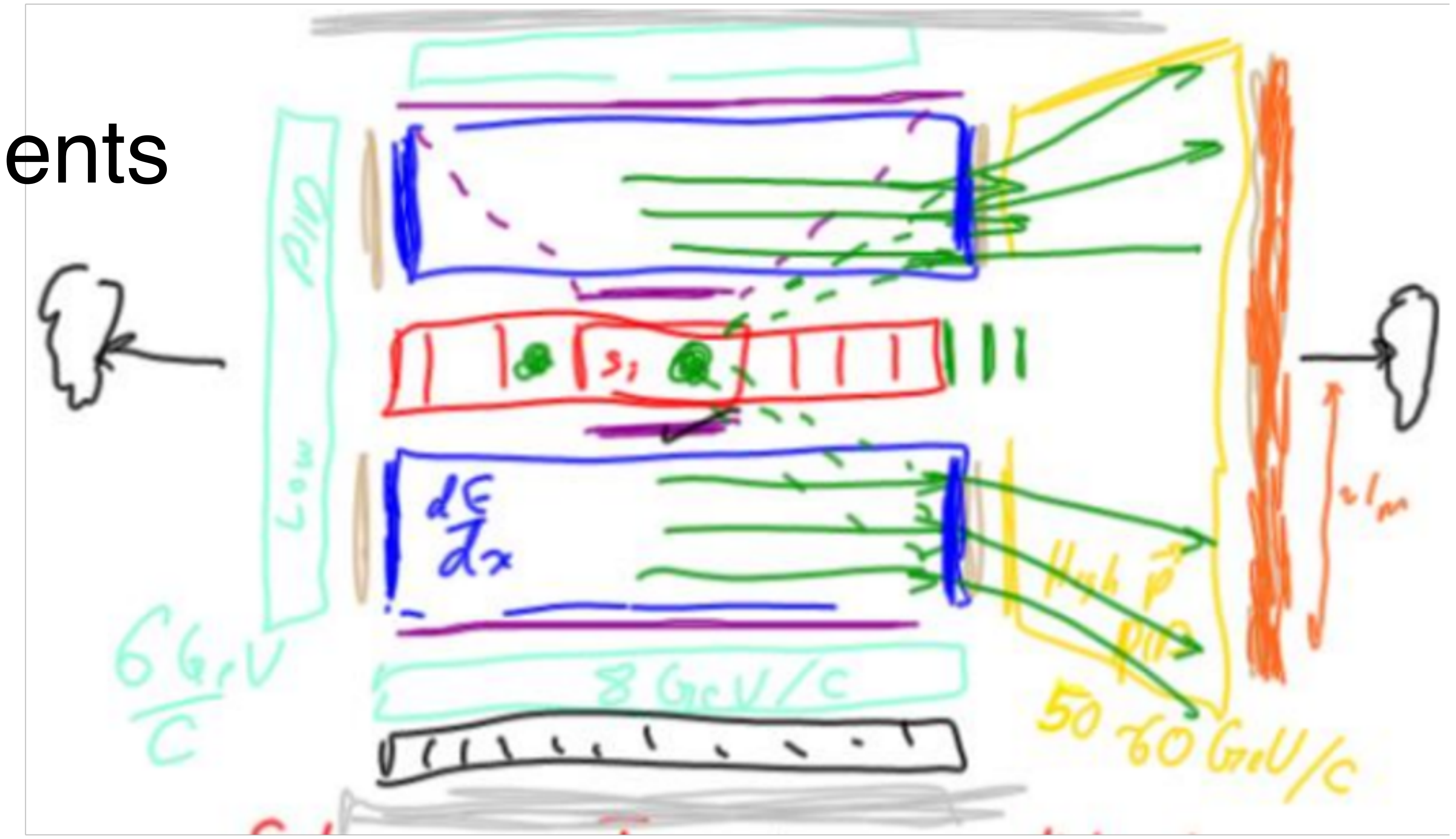

eRD6/Tracking Group Meeting

So what about the EIC Detector (Part I)?

Big questions → Physics case → Early detector drafts

Physics case → Early detector requirements → Early detector drafts

Early detector drafts → Research & Development (R&D)

So what about the EIC Detector (Part II)?

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Detailed detector requirements

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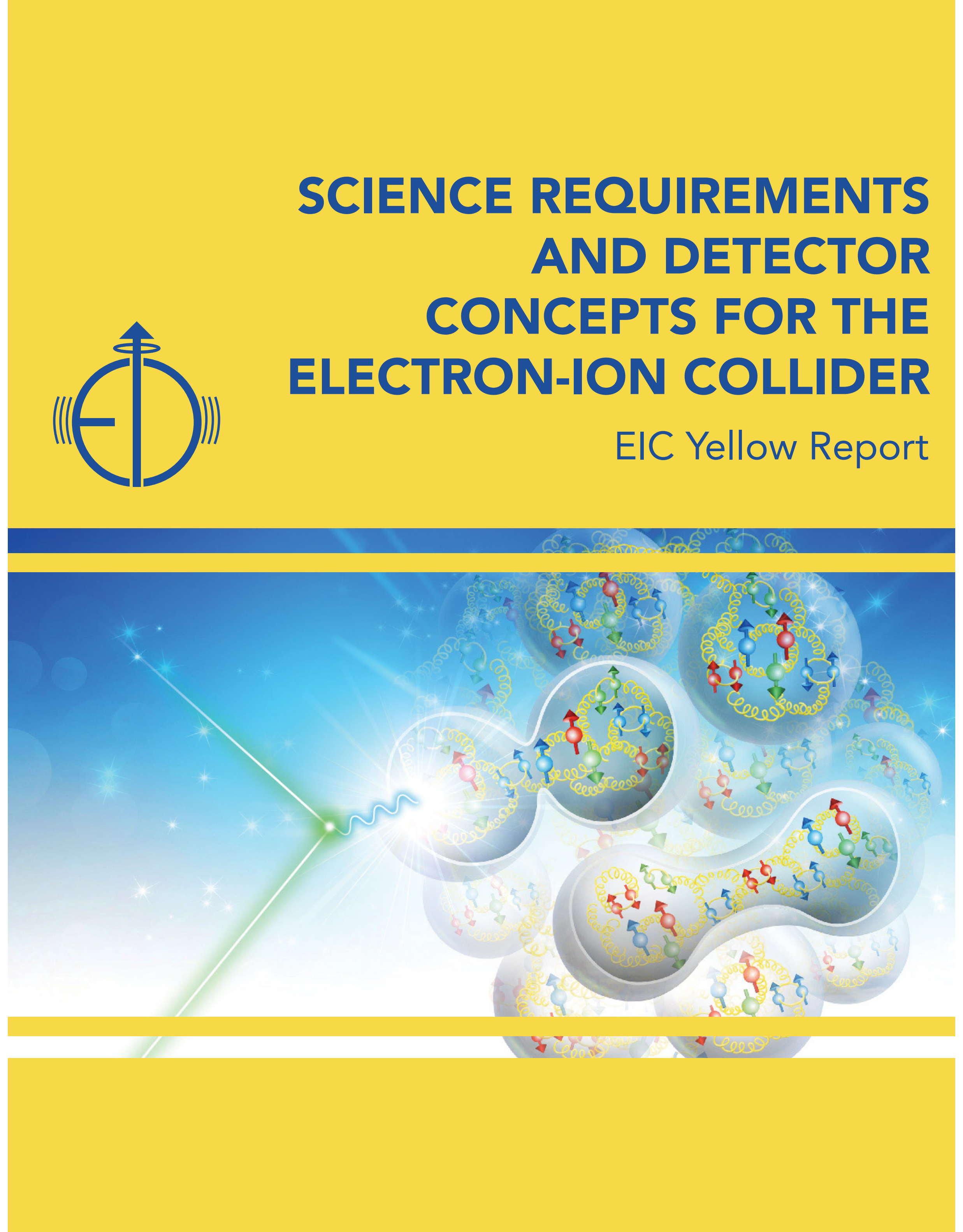
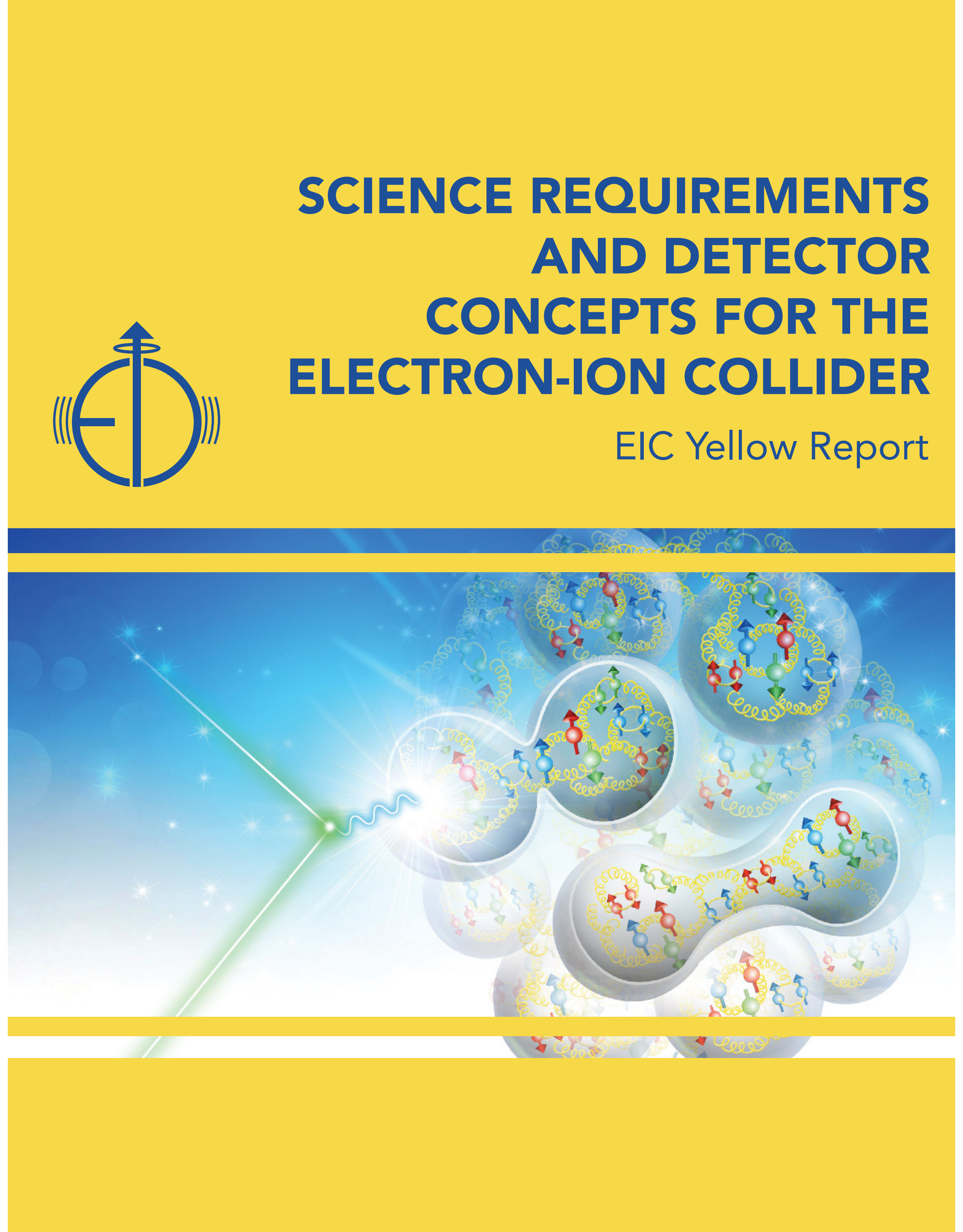
Detailed detector requirements



- **EIC User Group "Yellow Report" Effort**
  - Initiative to advance the state and detail of requirements and detector concepts in preparation for the realization of the EIC.
  - 1 year effort concluded in March 2021 with a comprehensive "Yellow" Report
  - 902 Pages, 414 authors from 121 institutions, 675 figures
  - arXiv:2103.05419

So what about the EIC Detector (Part II)?

Detailed detector requirements



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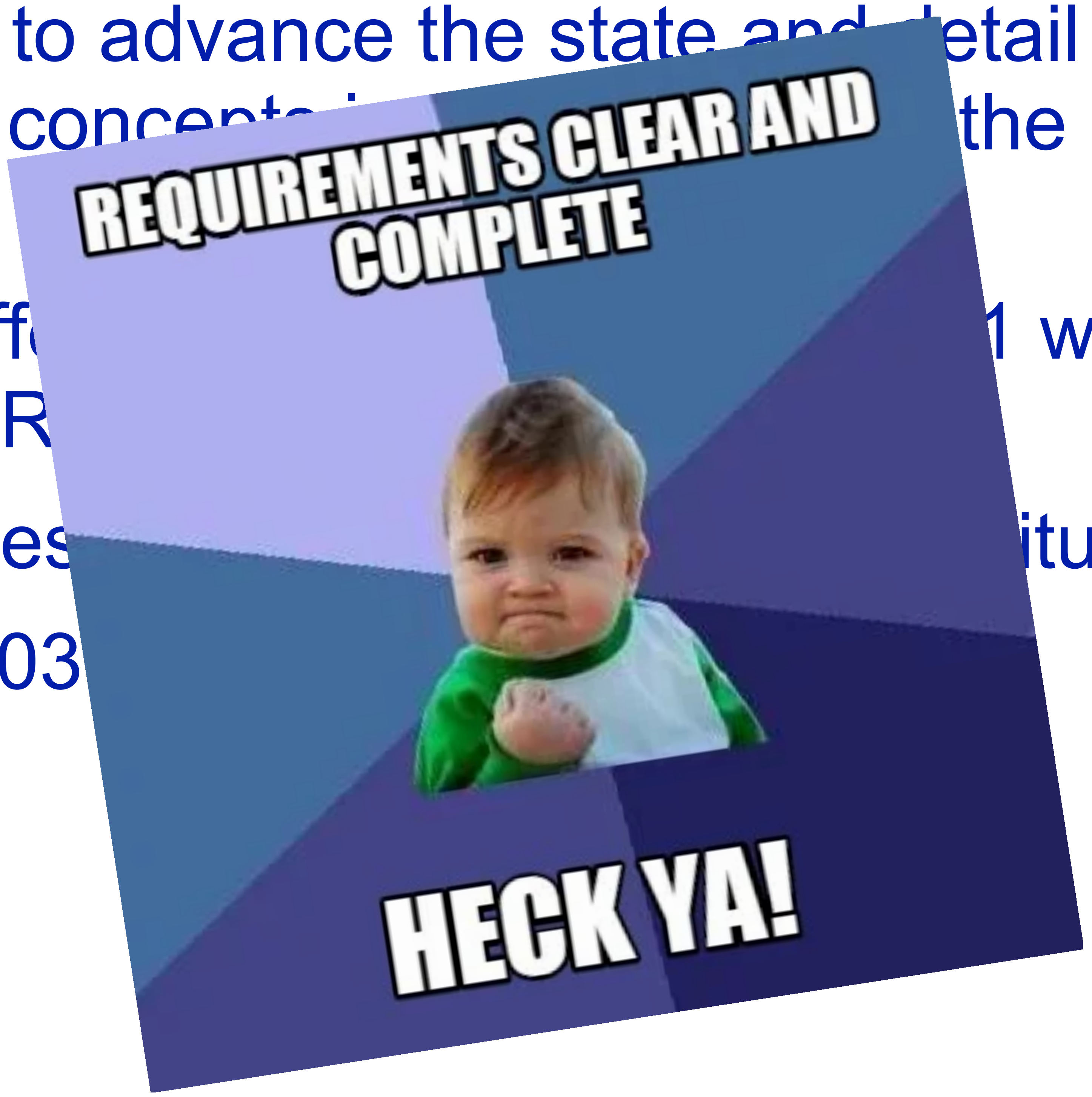

So what about the EIC Detector (Part II)?

Detailed detector requirements → Suite of viable detector technologies

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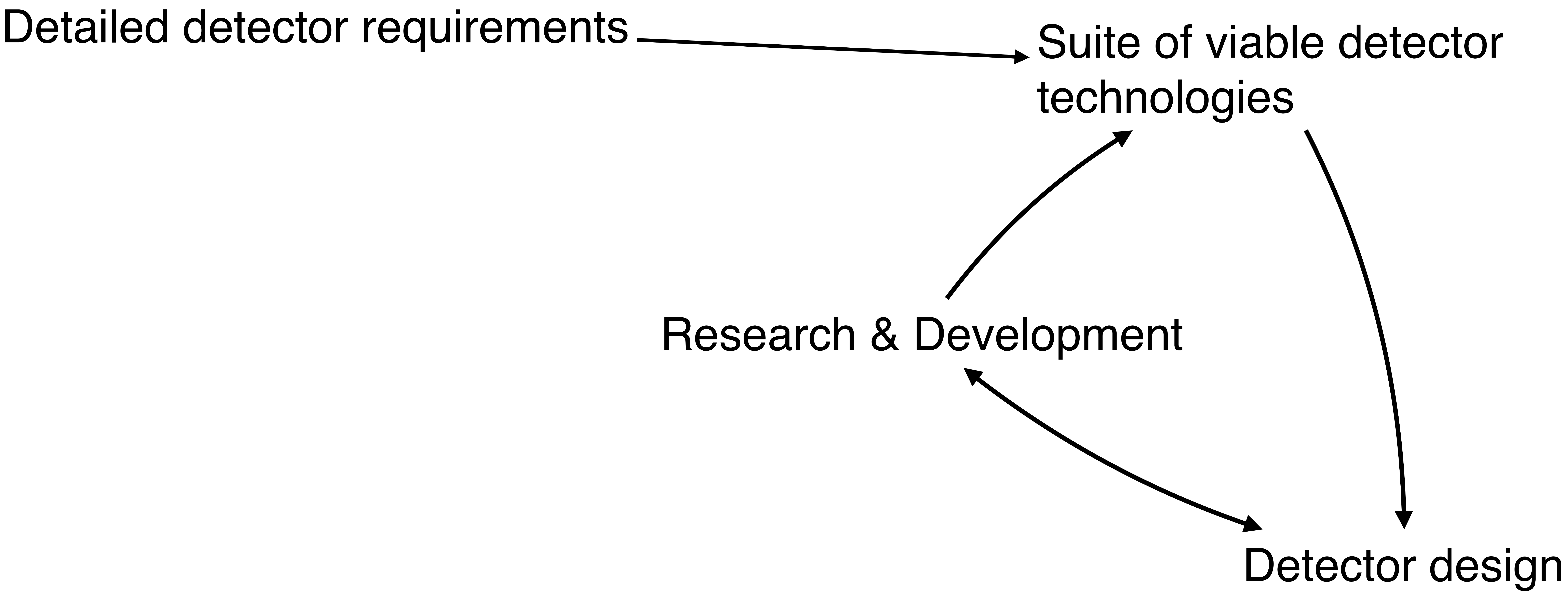

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Detailed detector requirements → Suite of viable detector technologies

Research & Development

Detector design

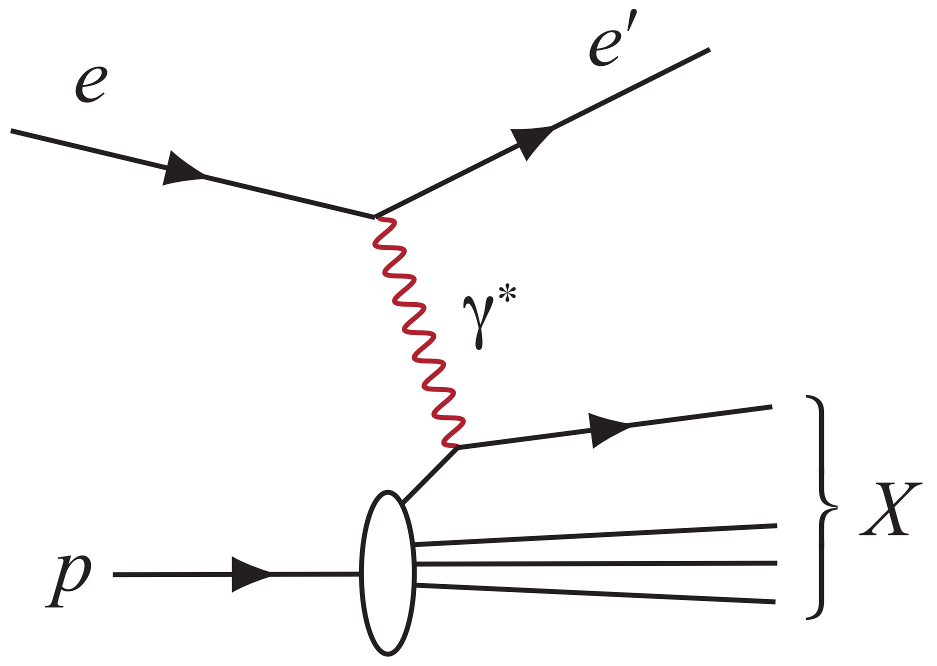
Loop/iterate until you run out of patience, money or both

🎉 Final Design

Category of Processes to Study

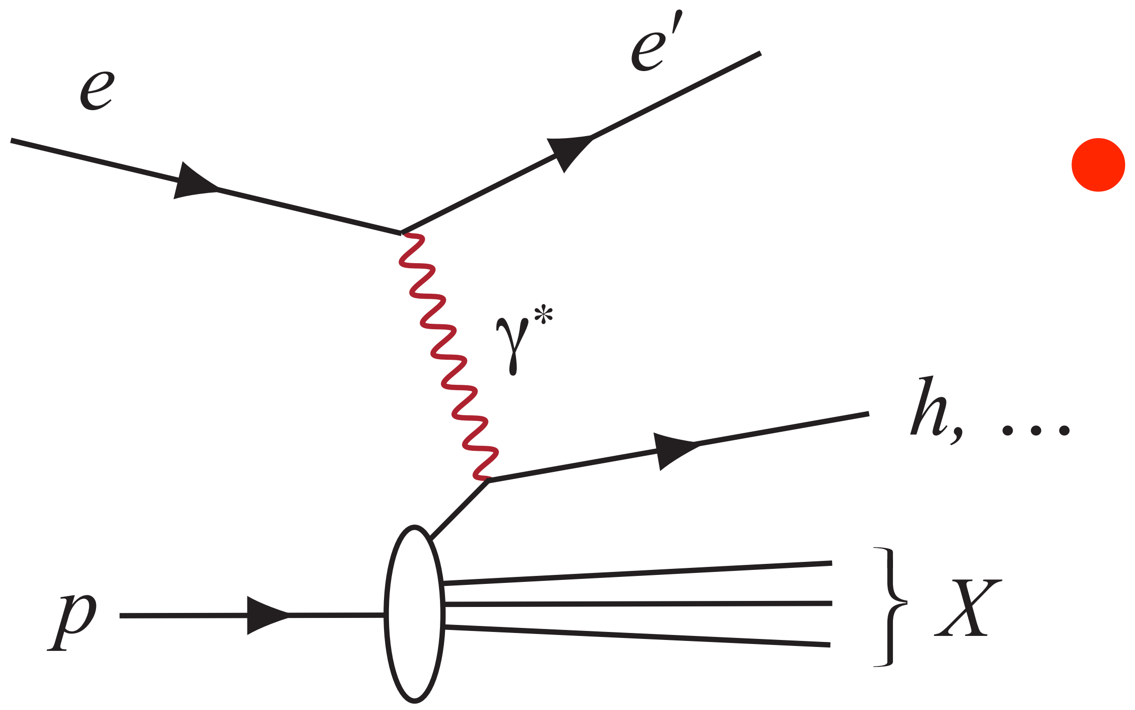
Measurement categories to address EIC physics:

$\int \mathscr{L} dt$



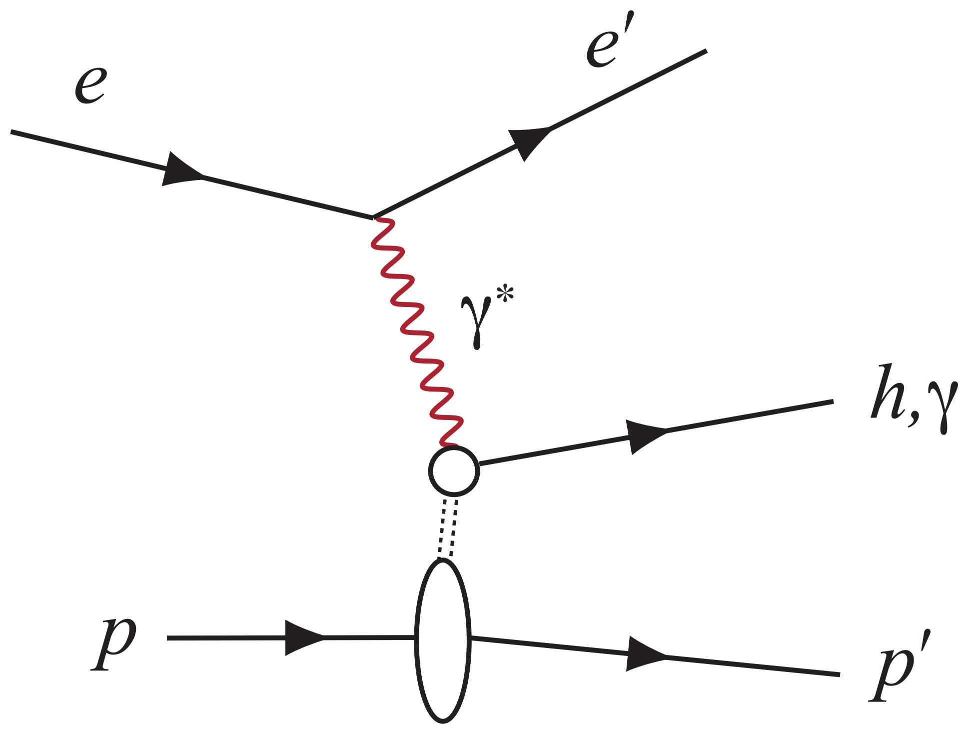
- Inclusive DIS (e')
  - fine multi-dimensional binning in x, Q^2

1 fb^{-1}



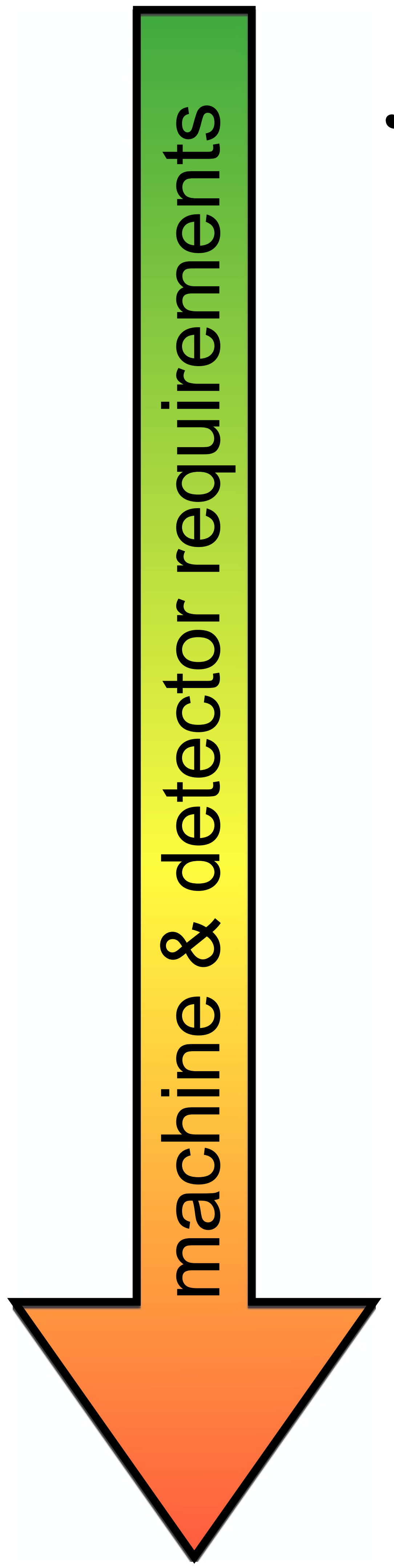
- Semi-inclusive DIS / SIDIS (e' & fwd hadrons)
  - 5-dimensional binning in x, Q^2, z, p_T, θ

10 fb^{-1}



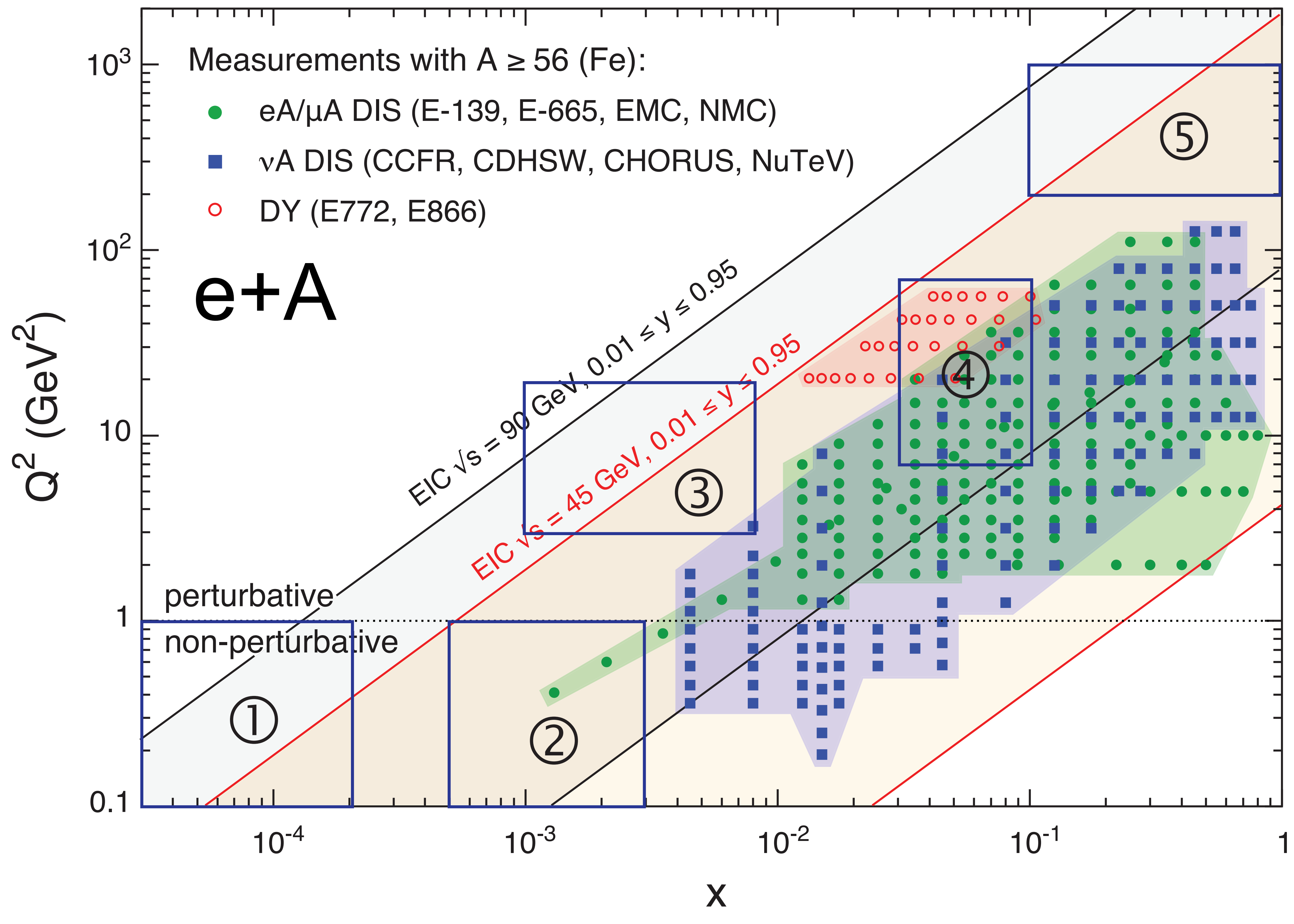
- Exclusive processes (e' & hermeticity)
  - 4-dimensional binning in x, Q^2, t, θ to

10-100 fb^{-1}



DIS: Scattered Electron is Key

The energy and angle of scatter electron gives key variables x, y, Q^2



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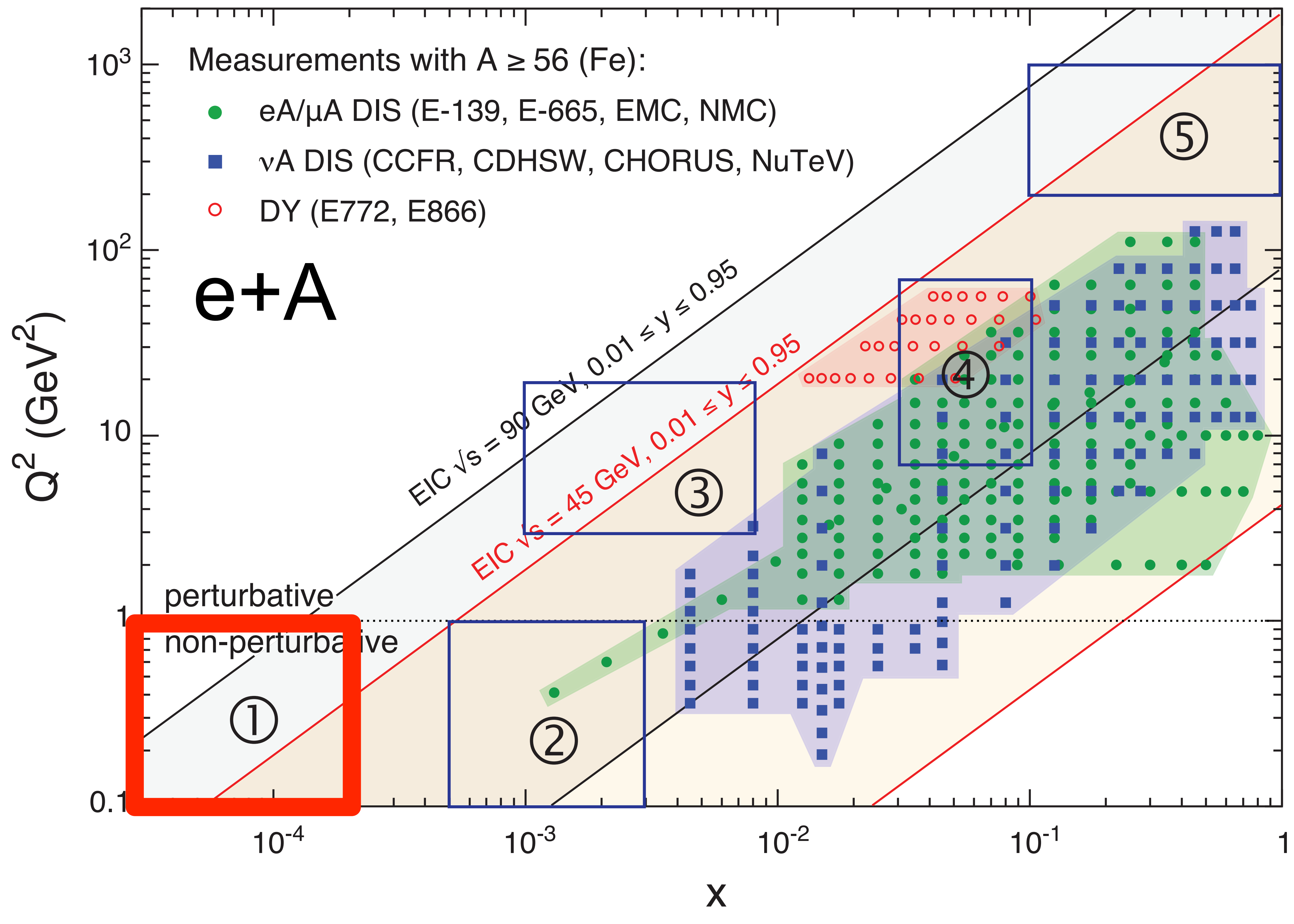
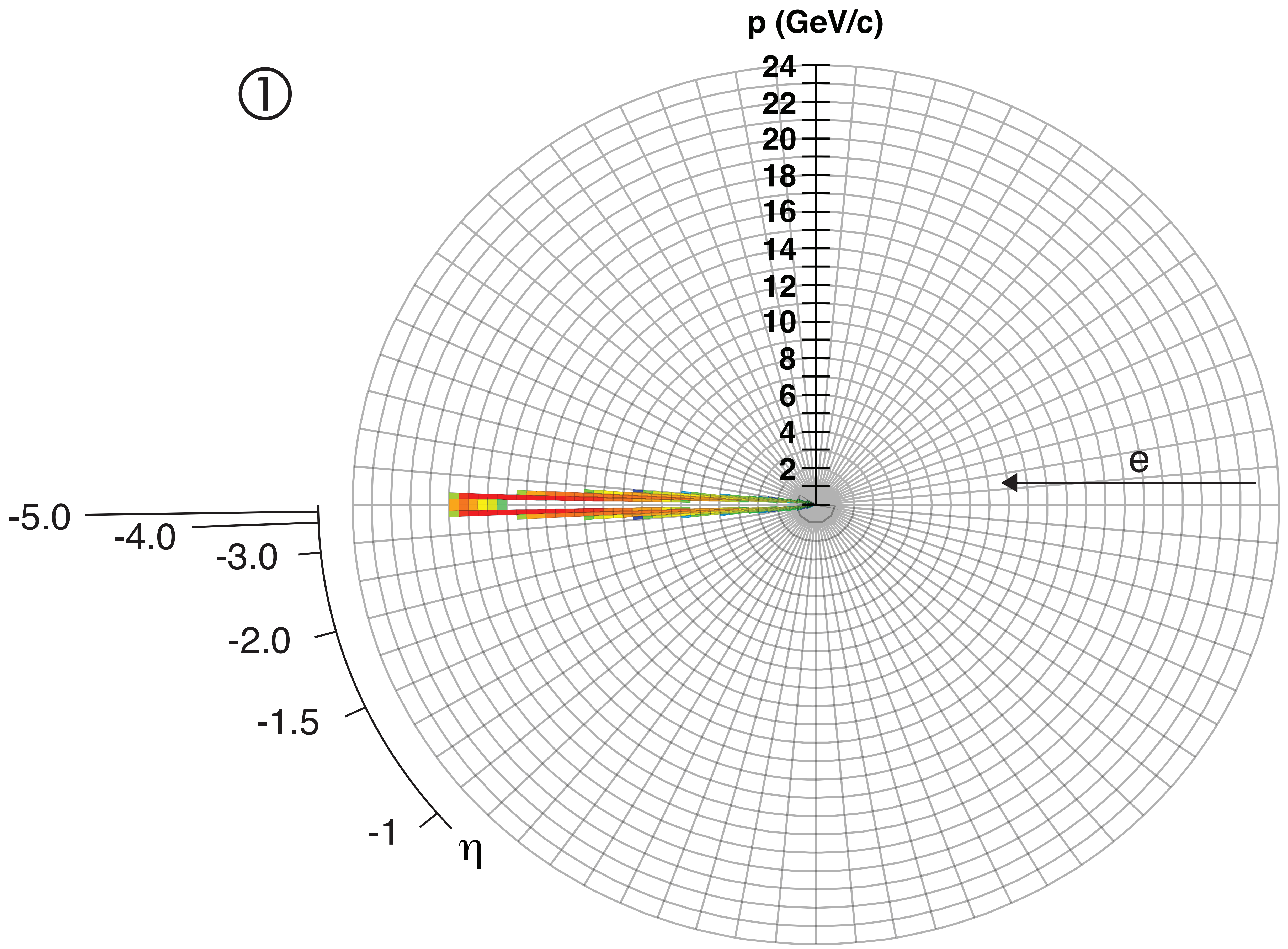


20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV^2, $3 \cdot 10^{-5} < x < 2 \cdot 10^{-4}$



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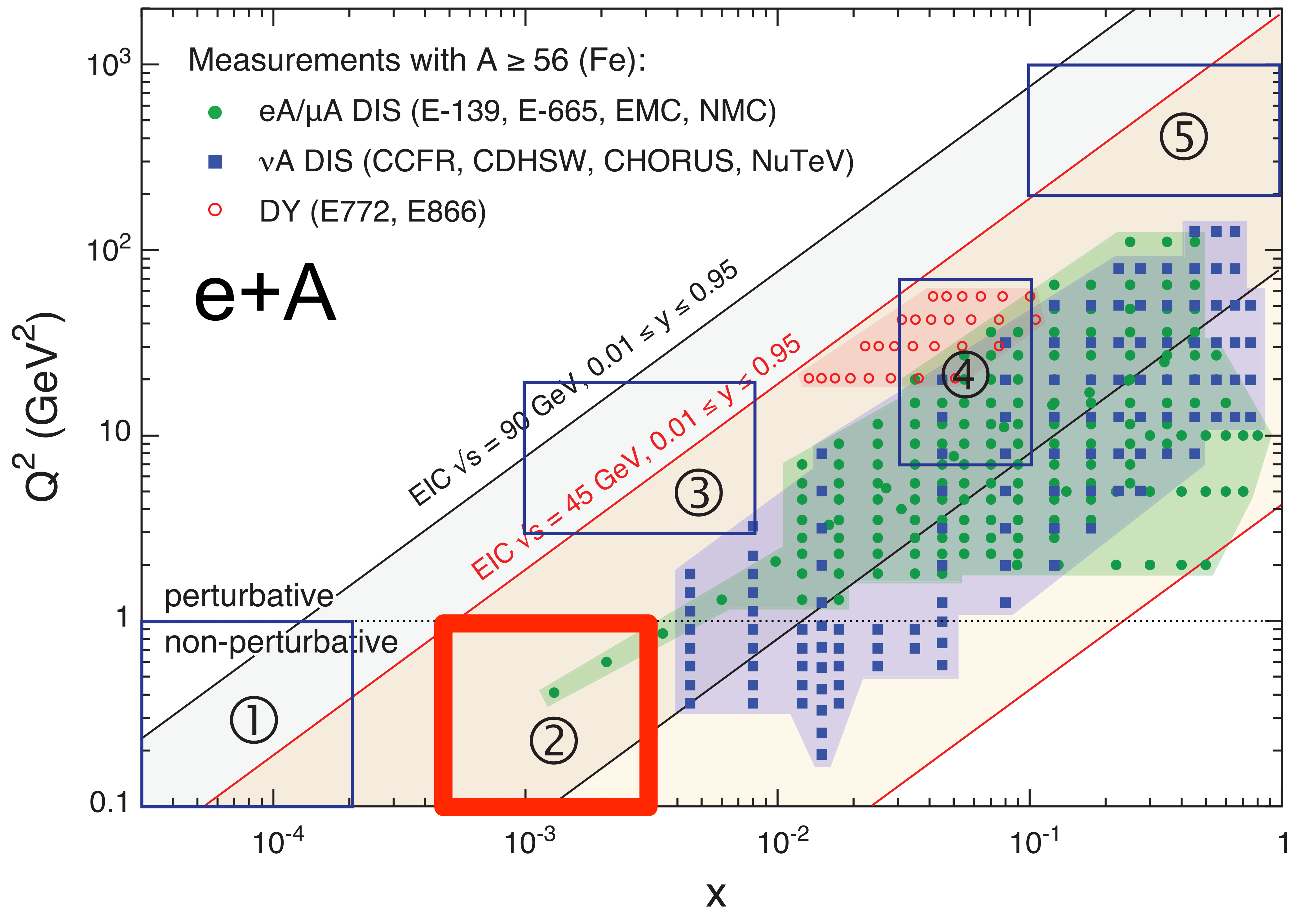
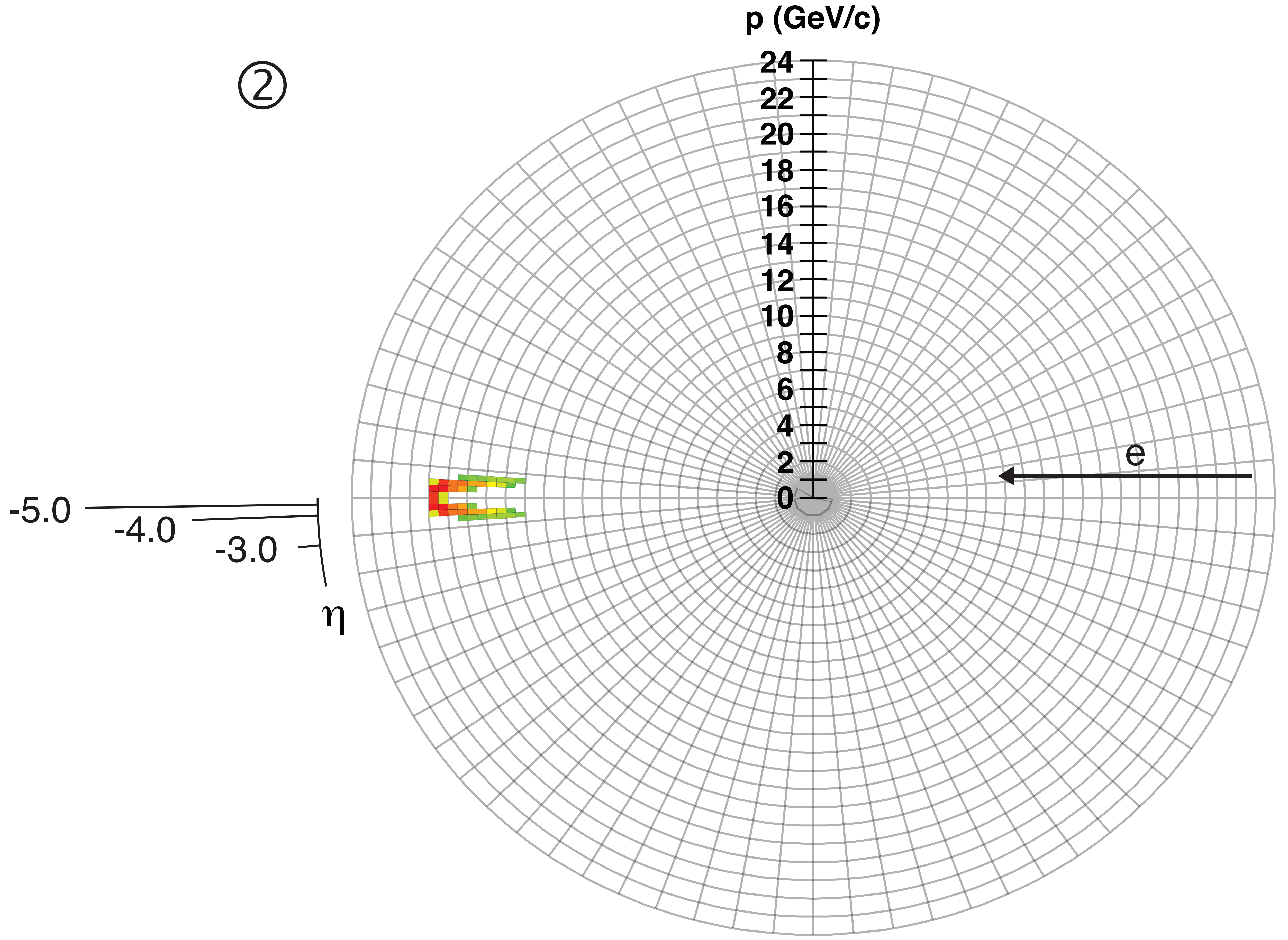


20 GeV on 100 GeV, 0.1 < Q^2 < 1 GeV^2, $5{\cdot}10^{-4} < x < 3{\cdot}10^{-3}$



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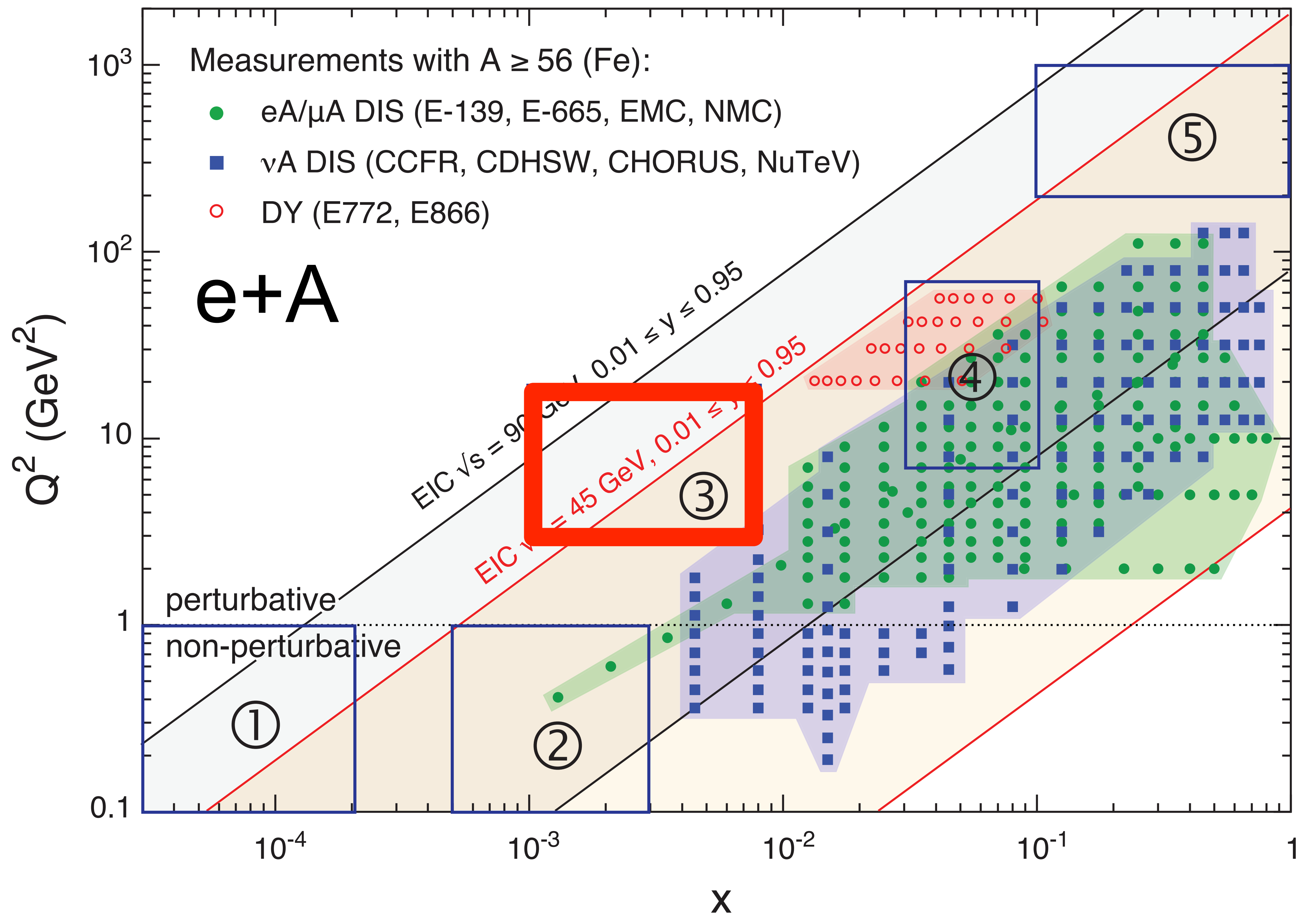
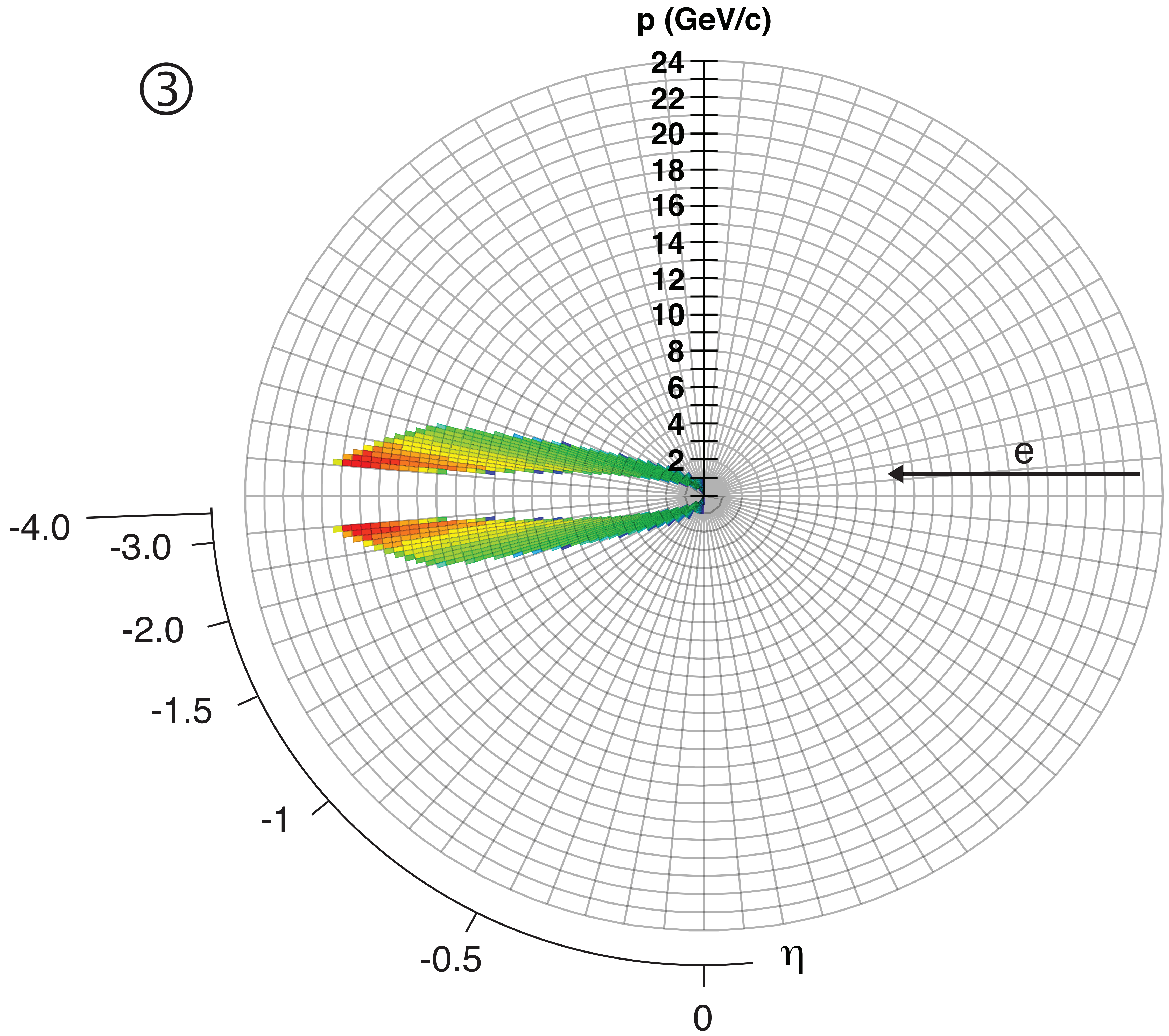


20 GeV on 100 GeV, $3 < Q^2 < 20$ GeV^2, $1 \cdot 10^{-3} < x < 8 \cdot 10^{-3}$



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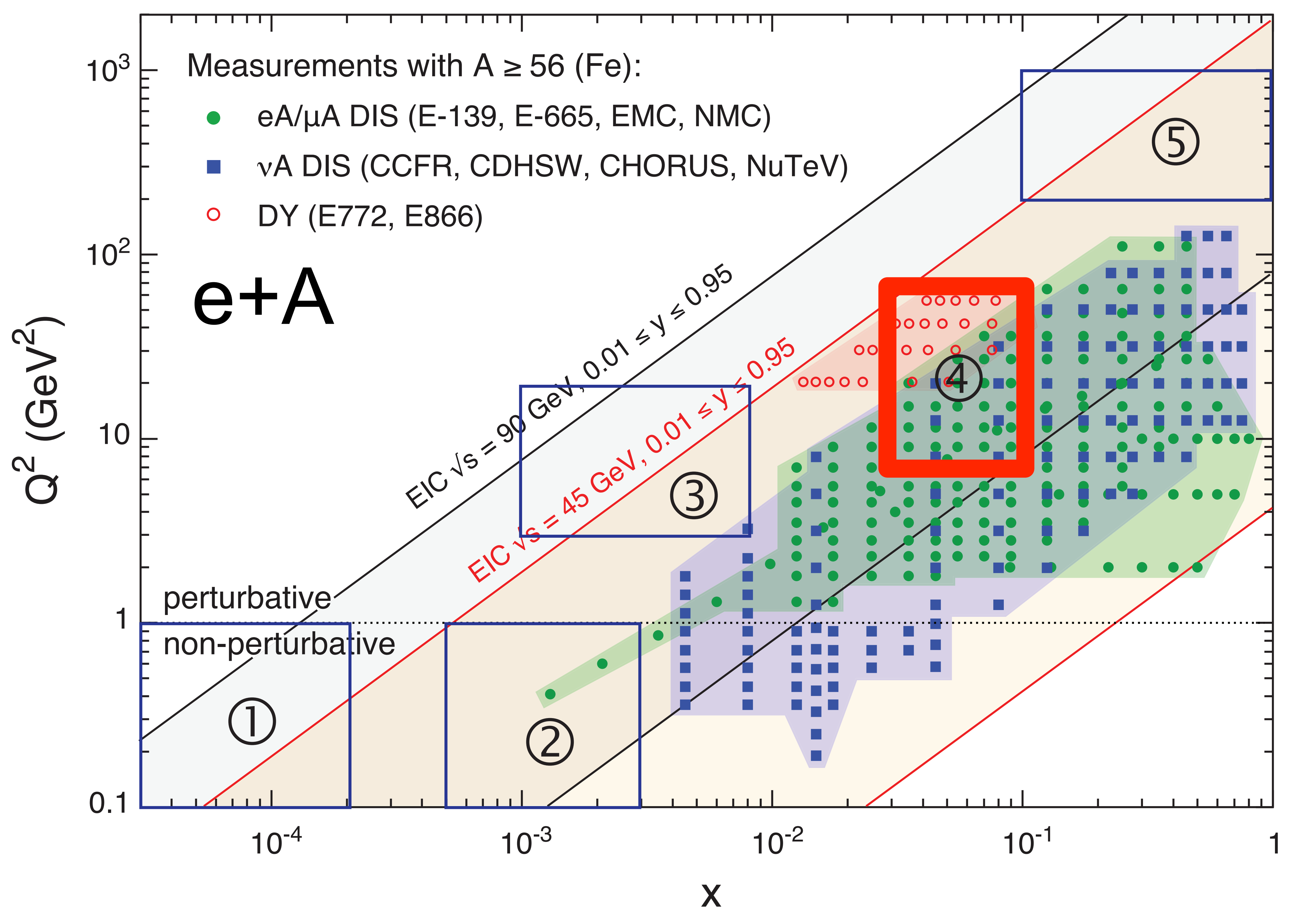
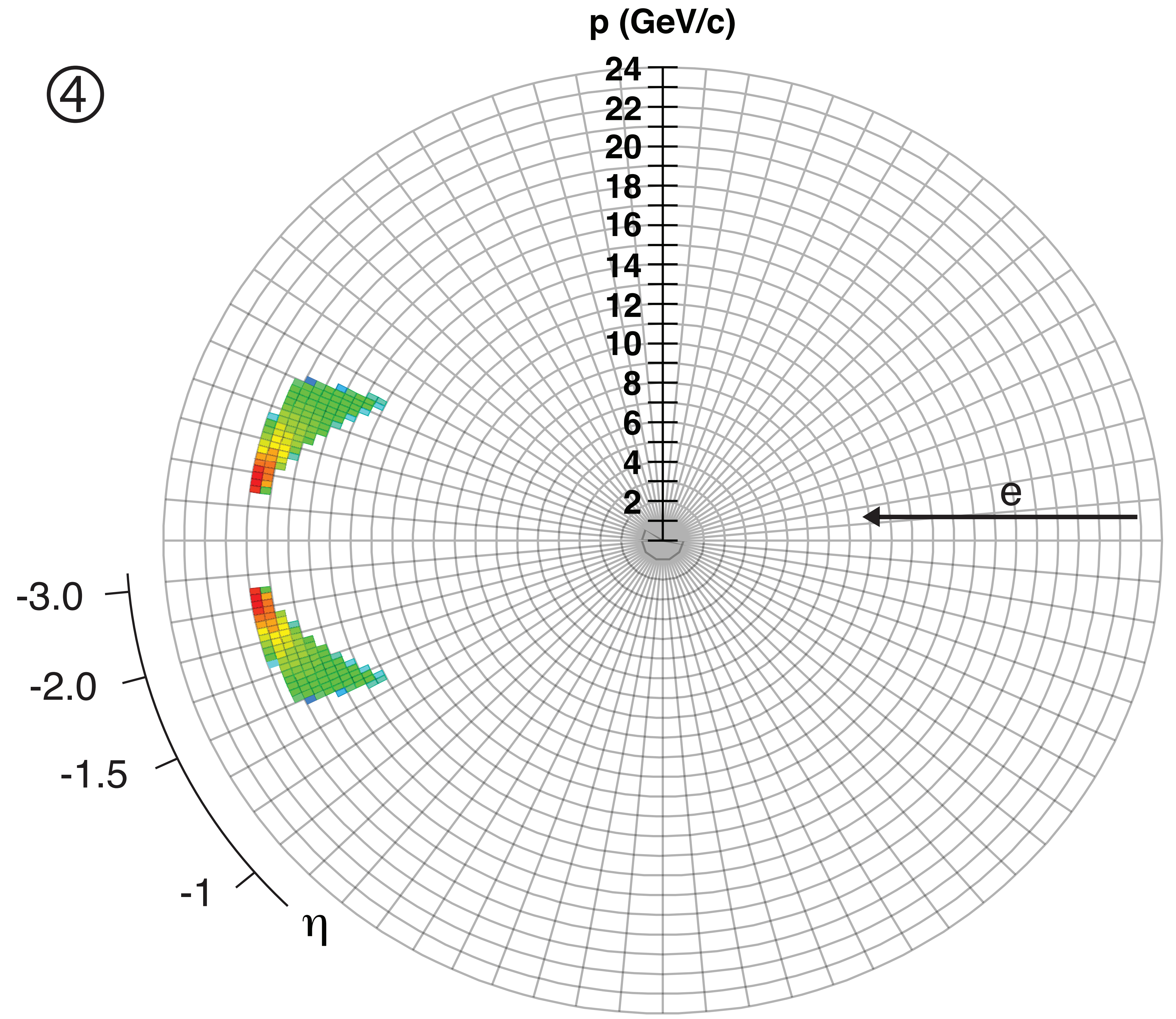


20 GeV on 100 GeV, 7 < Q^2 < 70 GeV^2 , $3 \cdot 10^{-2} < x < 1 \cdot 10^{-1}$



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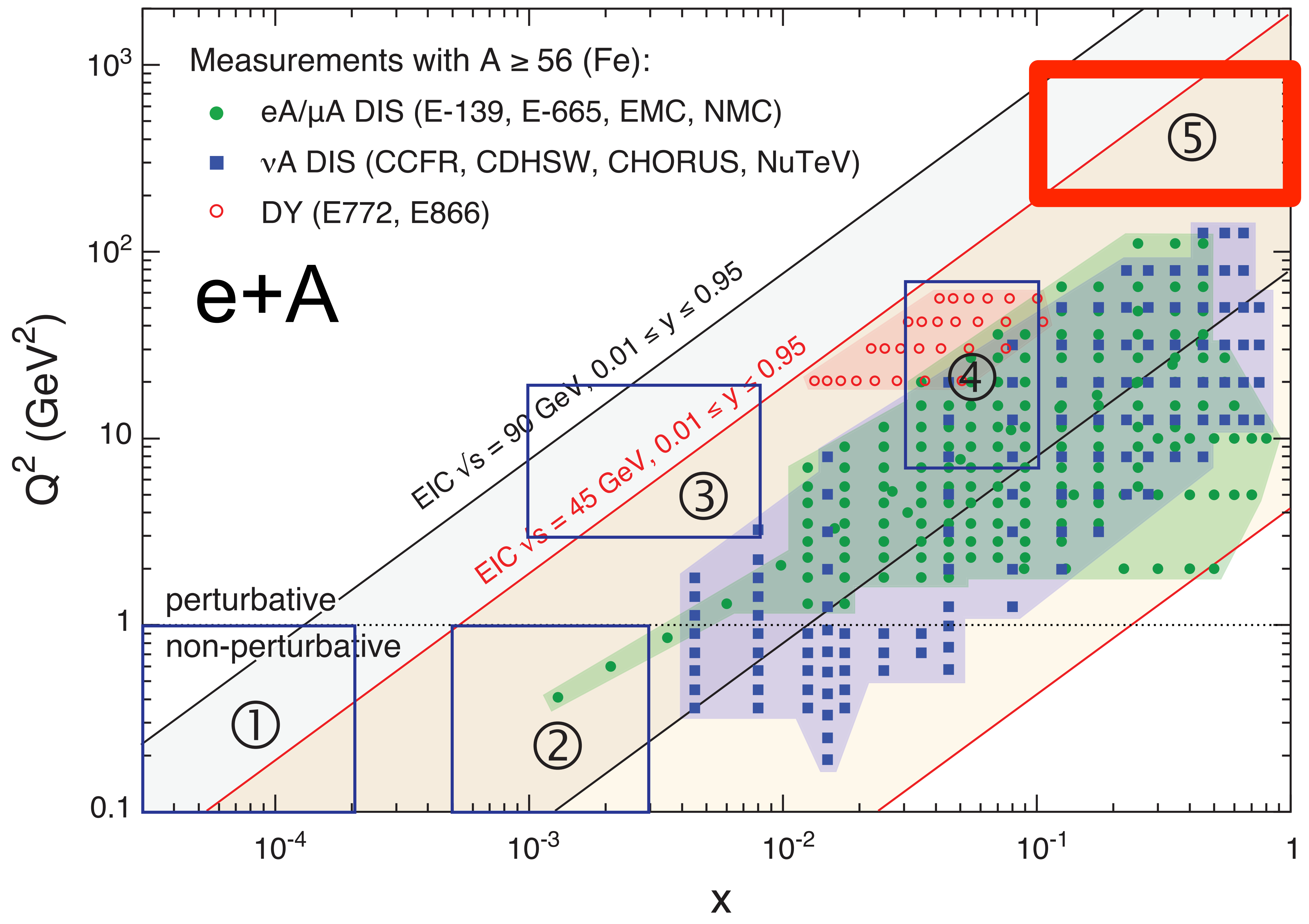
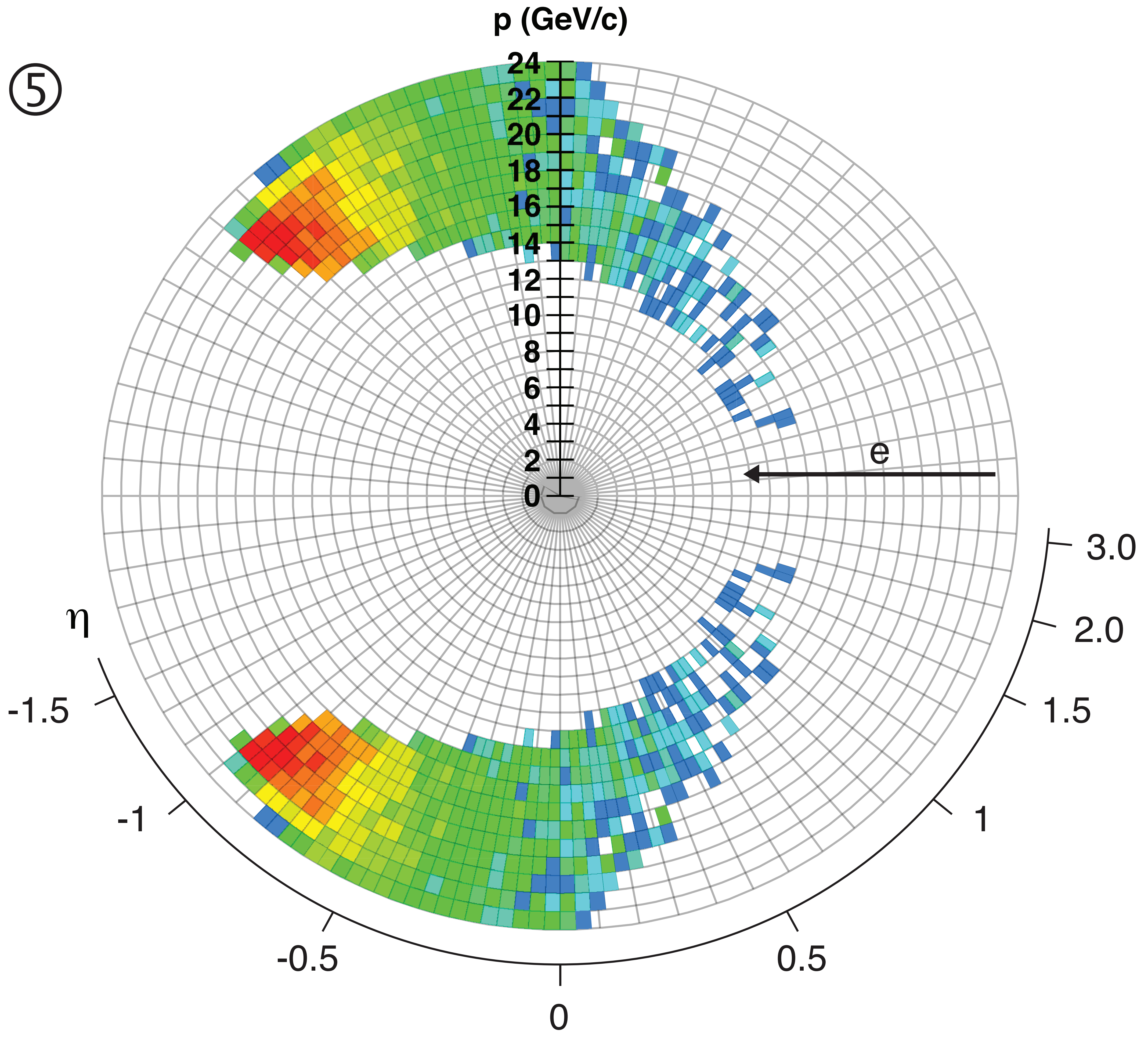


20 GeV on 100 GeV, 200 < Q^2 < 1000 GeV^2, 0.1 < x < 1

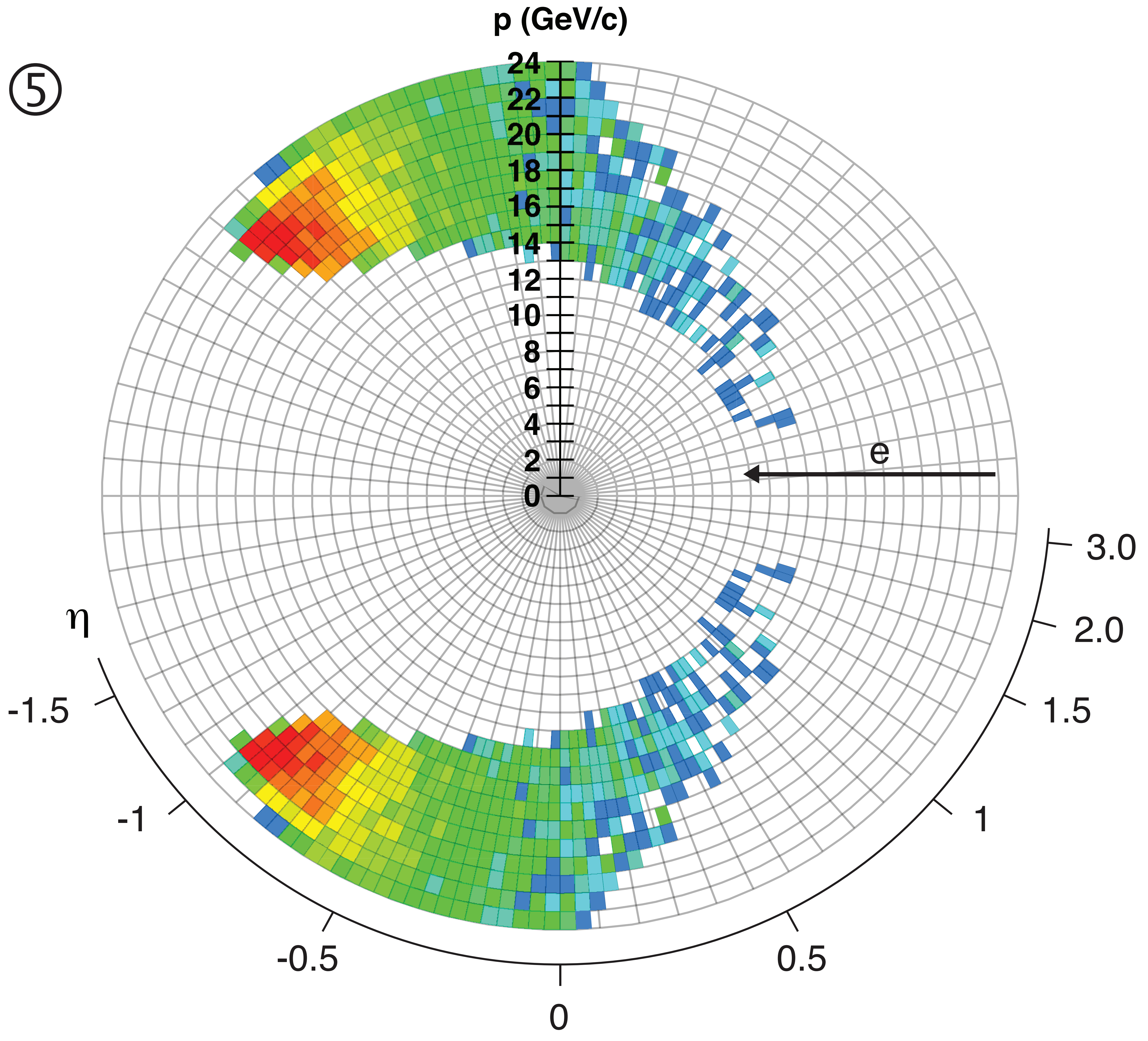


DIS: Scattered Electron is Key

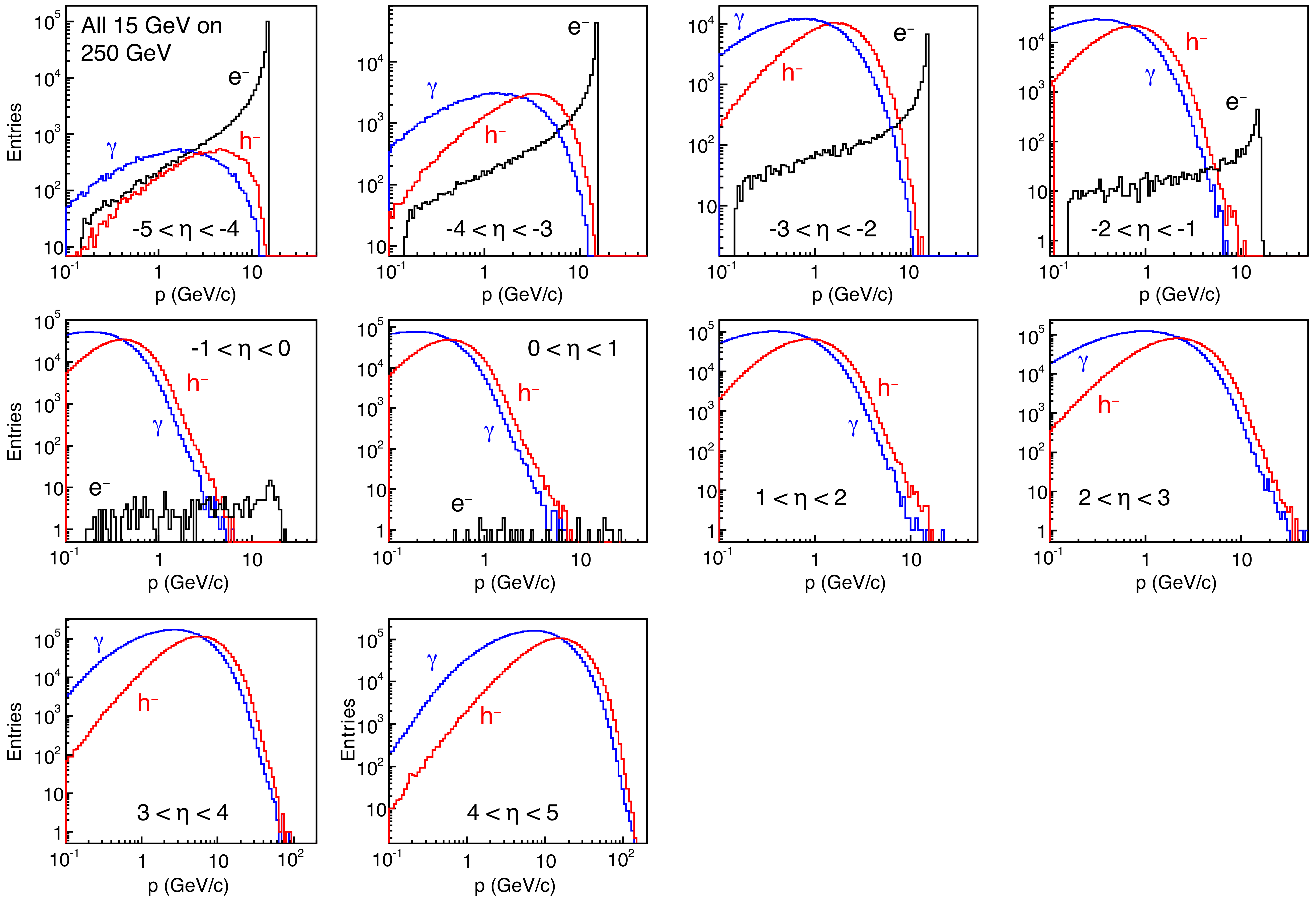
The energy and angle of scatter electron gives key variables x, y, Q^2

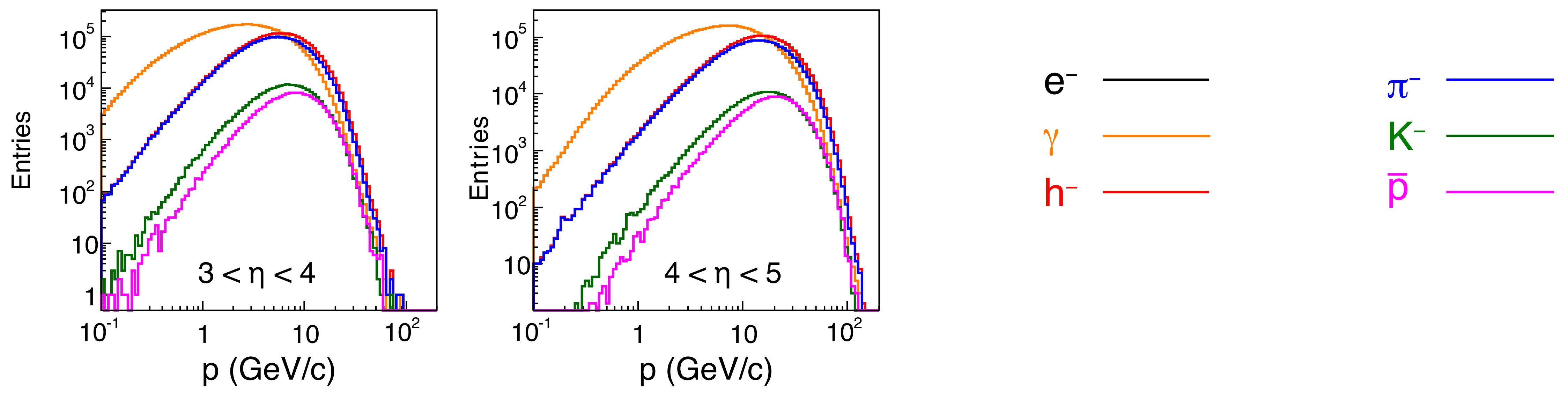
- e' Measurement Requires:
  - excellent electron identification (e/h)
  - equal rapidity coverage for tracking and calorimeter
  - low material budget to reduce bremsstrahlung
  - momentum/energy and angular resolution are critical

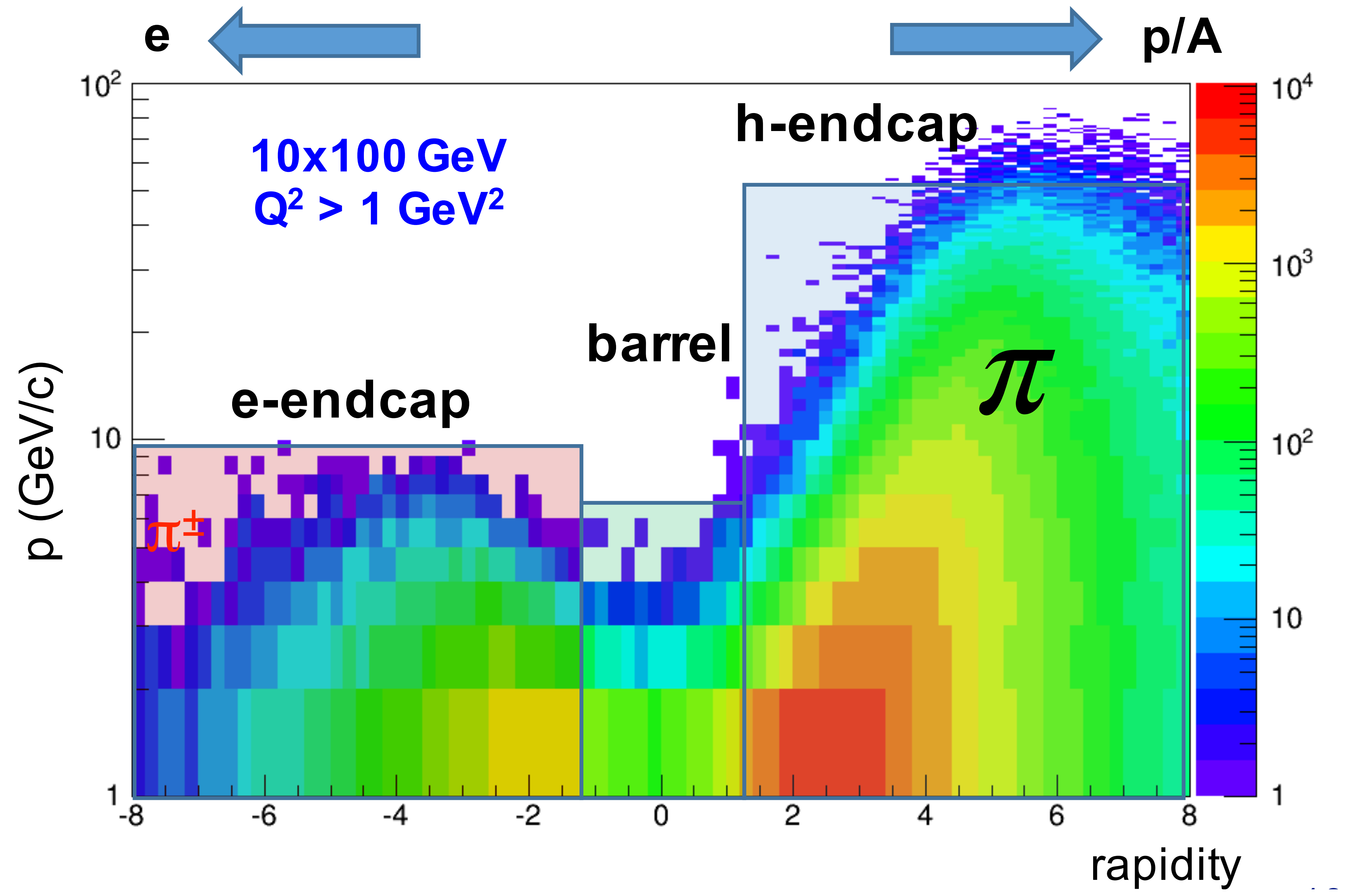
20 GeV on 100 GeV, 200 < Q^2 < 1000 GeV^2, 0.1 < x < 1



SIDIS: Hadron Identification Requirements







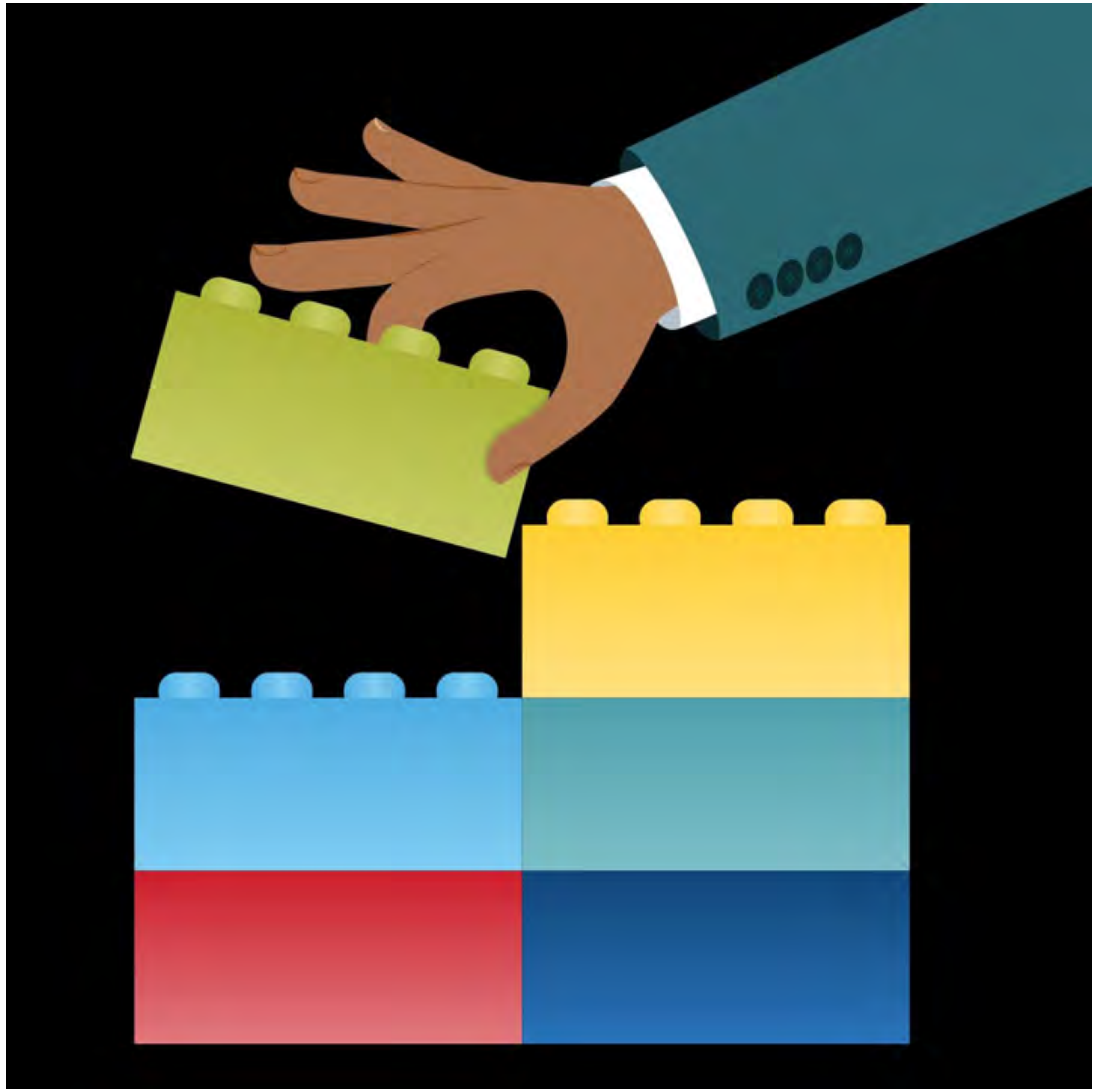
- Physics Requirements
  - $\pi^{\pm}, K^{\pm}, p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
- Strong Momentum–η correlation
  - -5 < η < 2: 0.2 < p < 10 GeV/c
  - 2 < η < 5: 0.2 < p < 50 GeV/c

Brief Review of Requirements (see Yellow Report)

- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements
- Electron measurement & jets in approx. -4 < η < +4
- Good momentum resolution
  - central: $\sigma(p)/p = 0.05\,\%\,p \oplus 0.5\,\%$
  - fwd/bkd: $\sigma(p)/p = 0.1\% \oplus 0.5\,\%$
- Good impact parameter resolution: $\sigma = 5 \oplus 15/p \sin^{3/2}\theta$ (μm)
- Excellent EM resolution
  - central: $\sigma(E)/E = 10\,\%/\sqrt{E}$
  - backward: $\sigma(E)/E < 2\,\%/\sqrt{E}$
- Good hadronic energy resolution
  - forward: $\sigma(E)/E \approx 50\,\%/\sqrt{E}$
- Excellent PID π/K/p
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c
- Low pile-up, low multiplicity, data rate ~500kHz (full lumi)

Hermeticity, low mass, and PID requirements makes EIC detector design challenging

Putting it All Together



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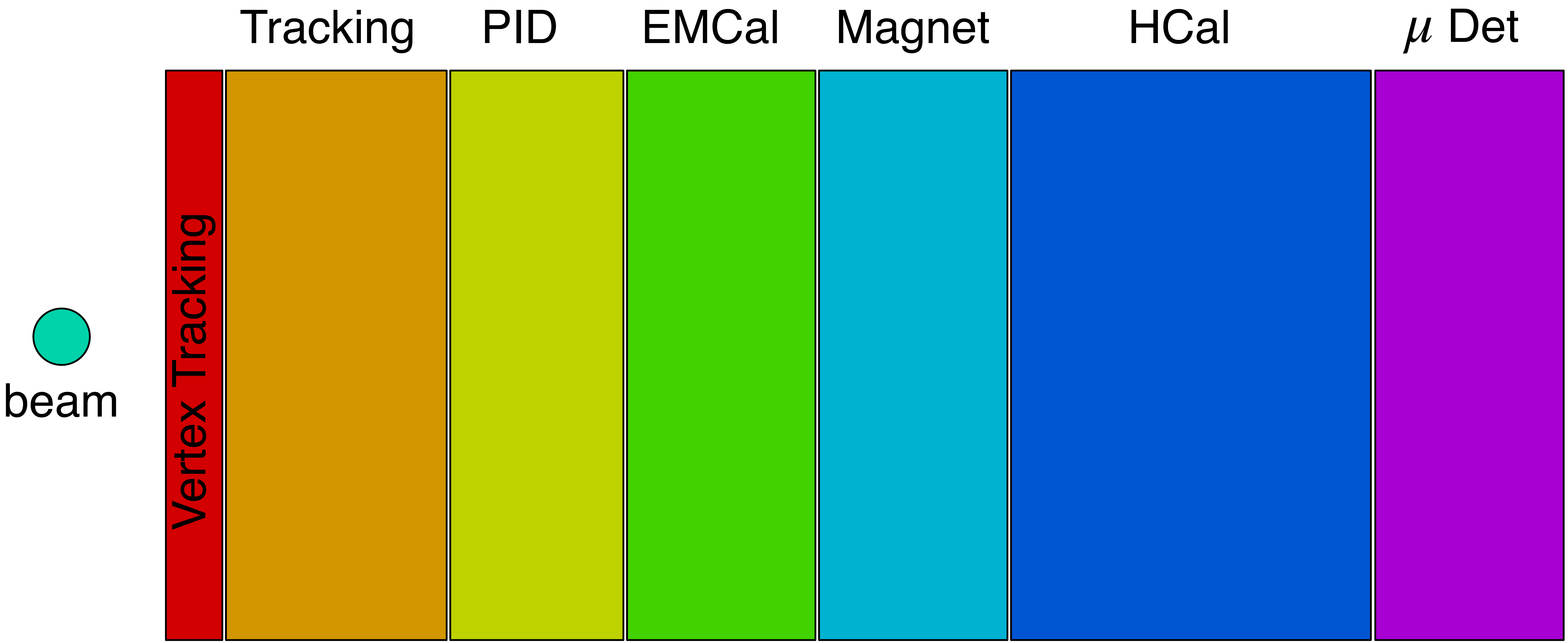

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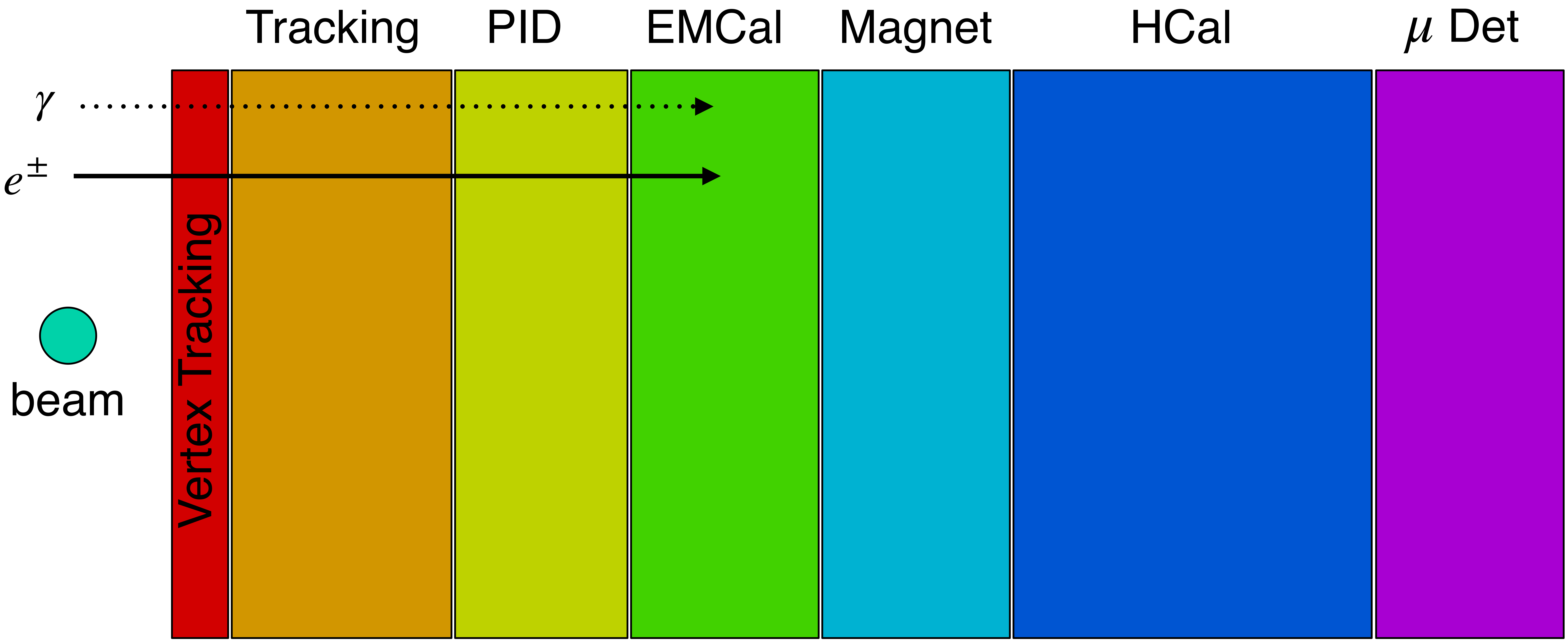

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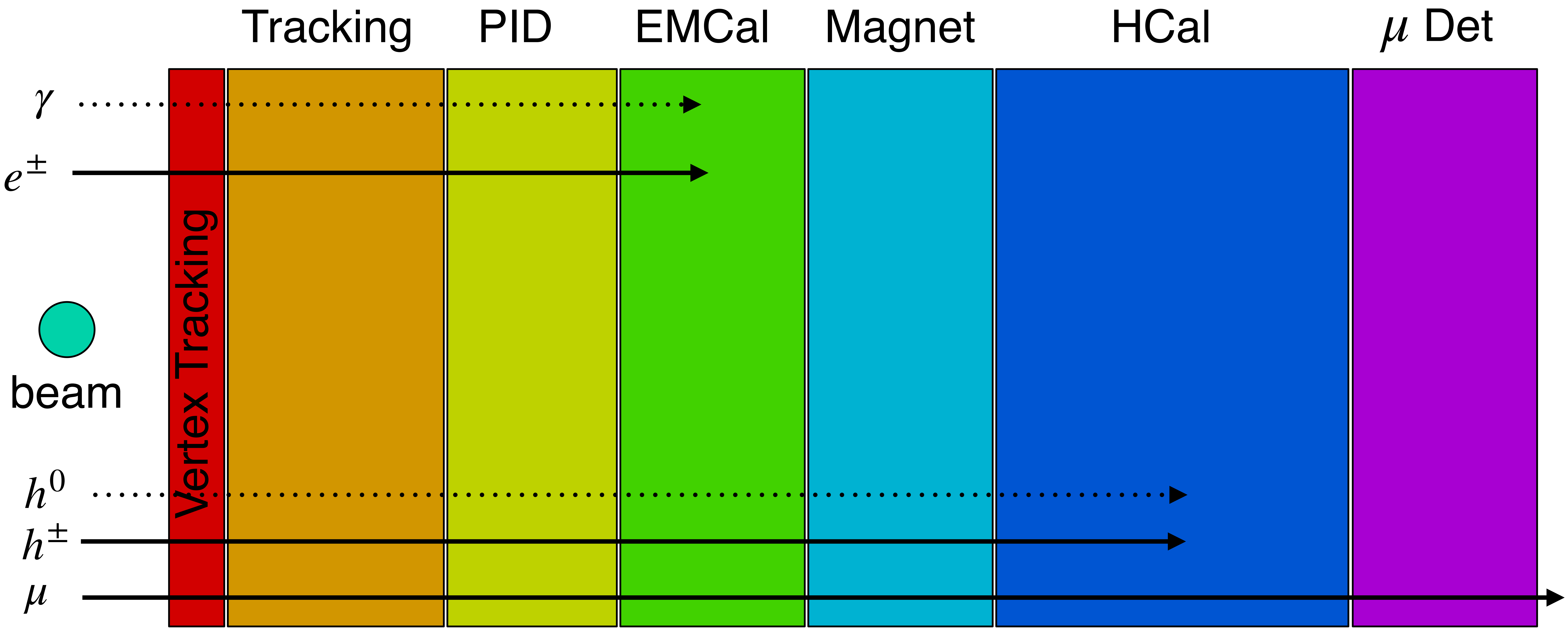

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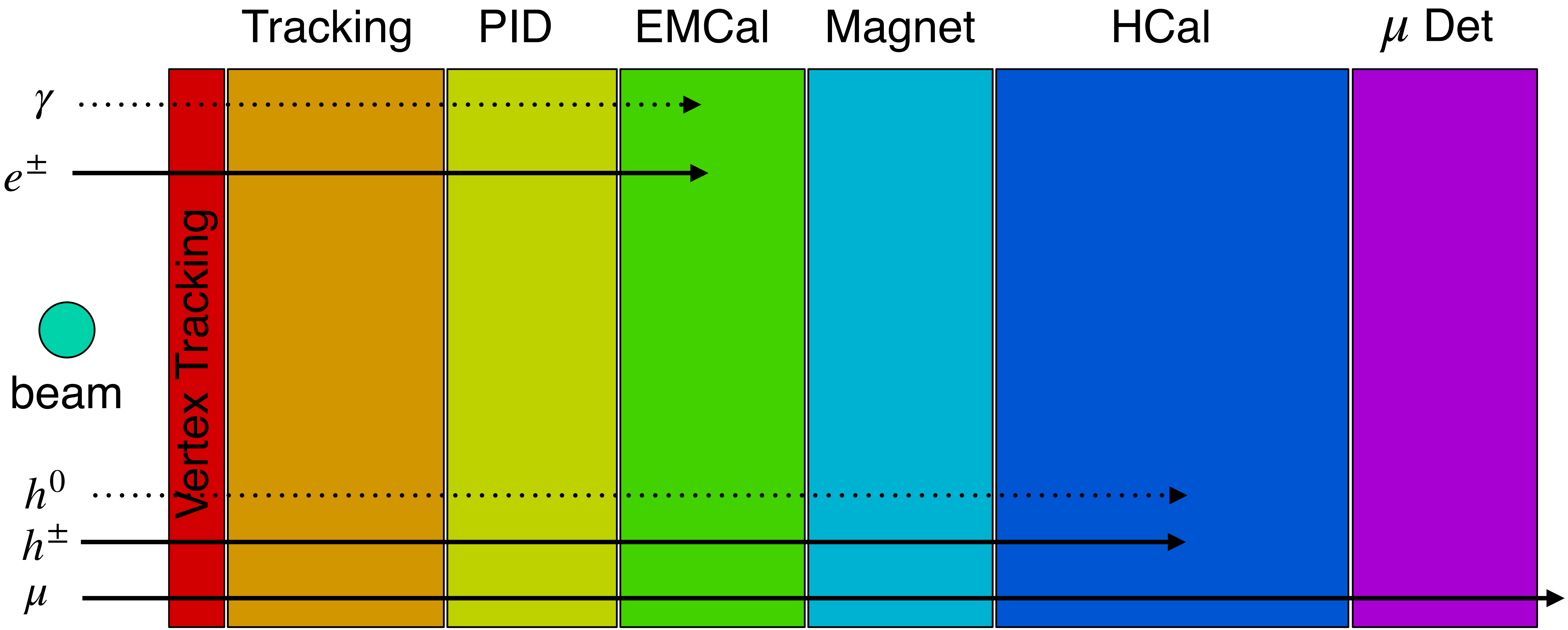
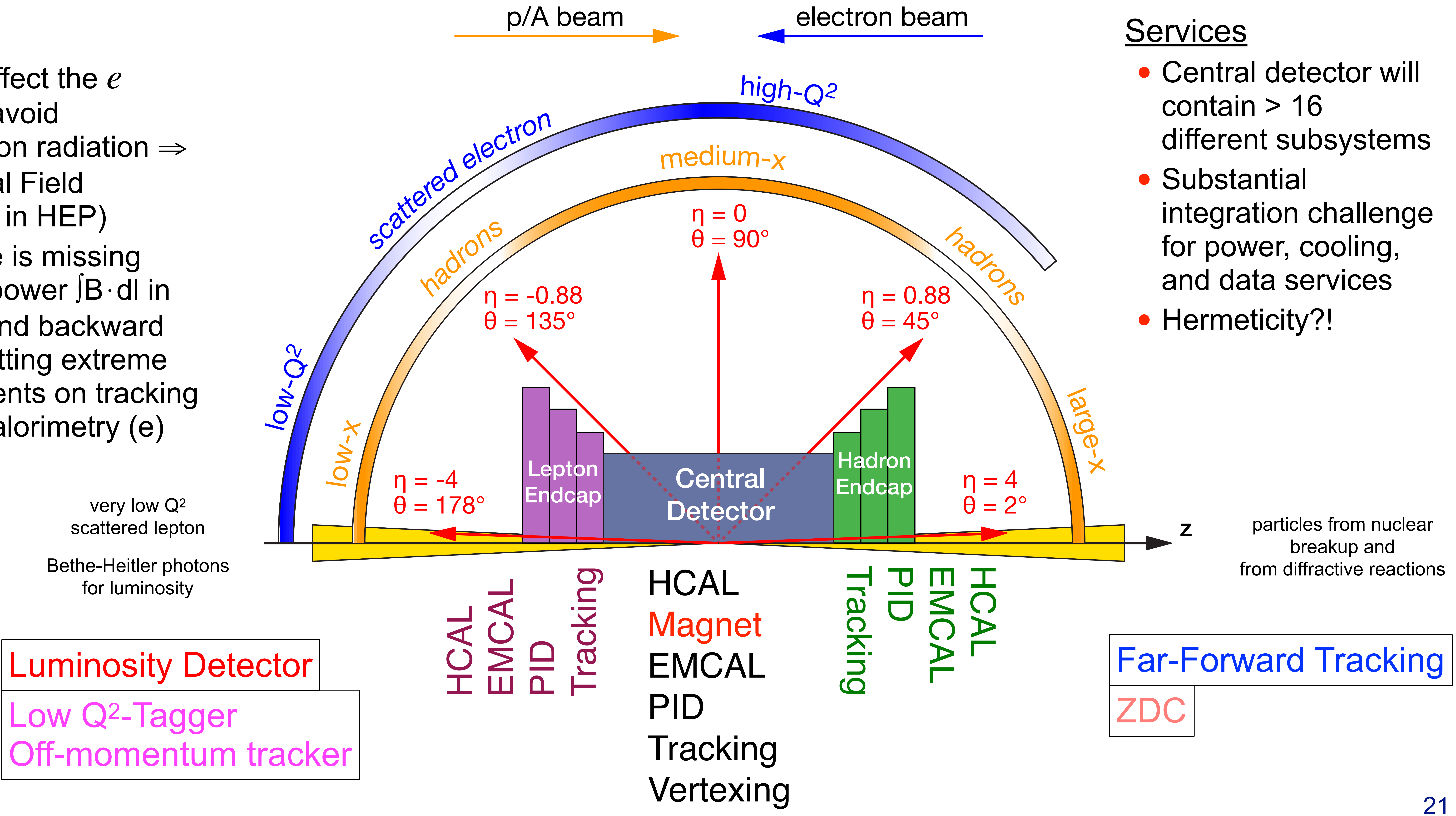


If things would be that easy …

EIC General Purpose Detector Concept

Magnet

- Cannot affect the *e* beam to avoid synchrotron radiation ⇒ Solenoidal Field (common in HEP)
- Downside is missing bending power ∫B·dl in forward and backward region putting extreme requirements on tracking (h) and calorimetry (e)

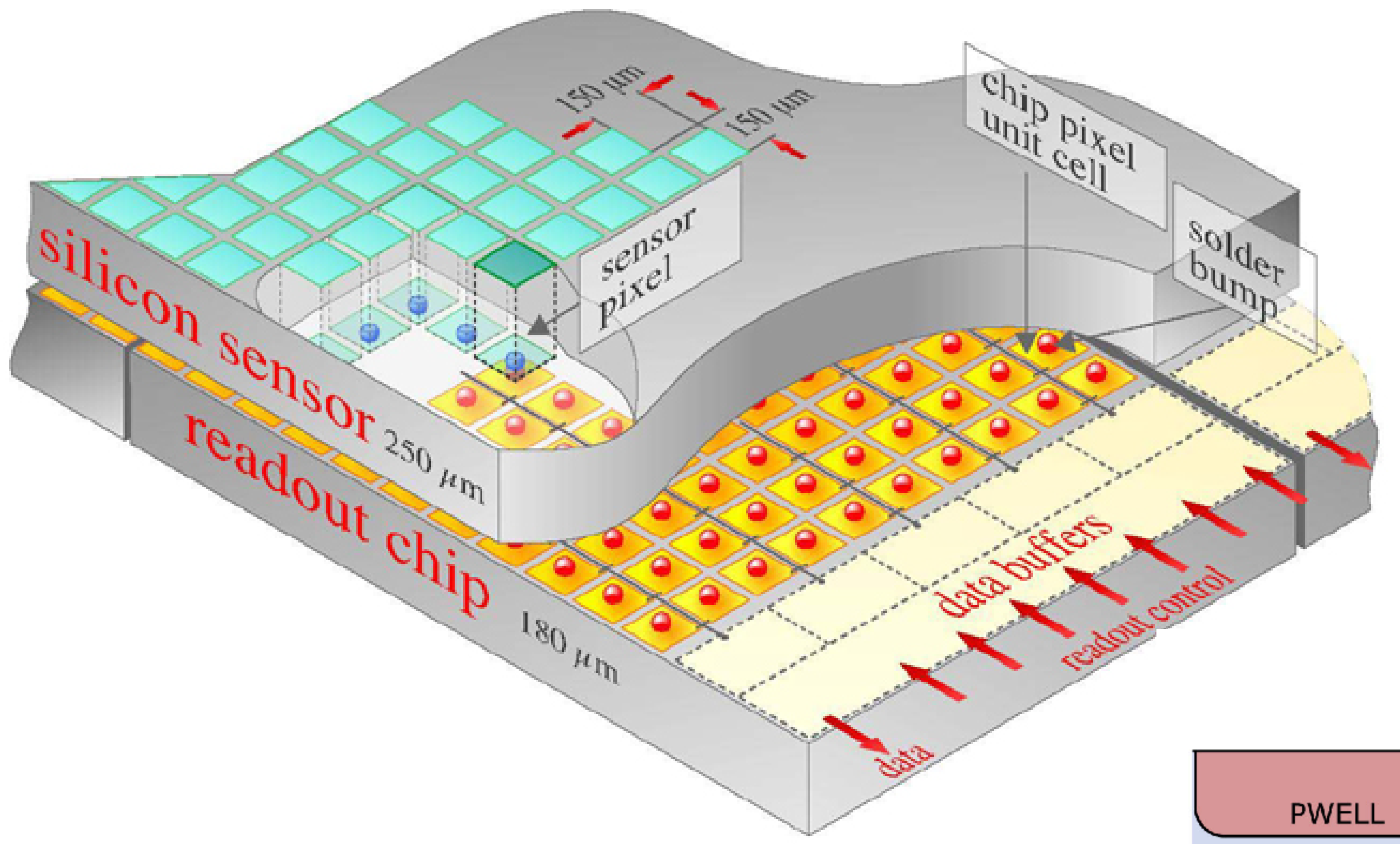


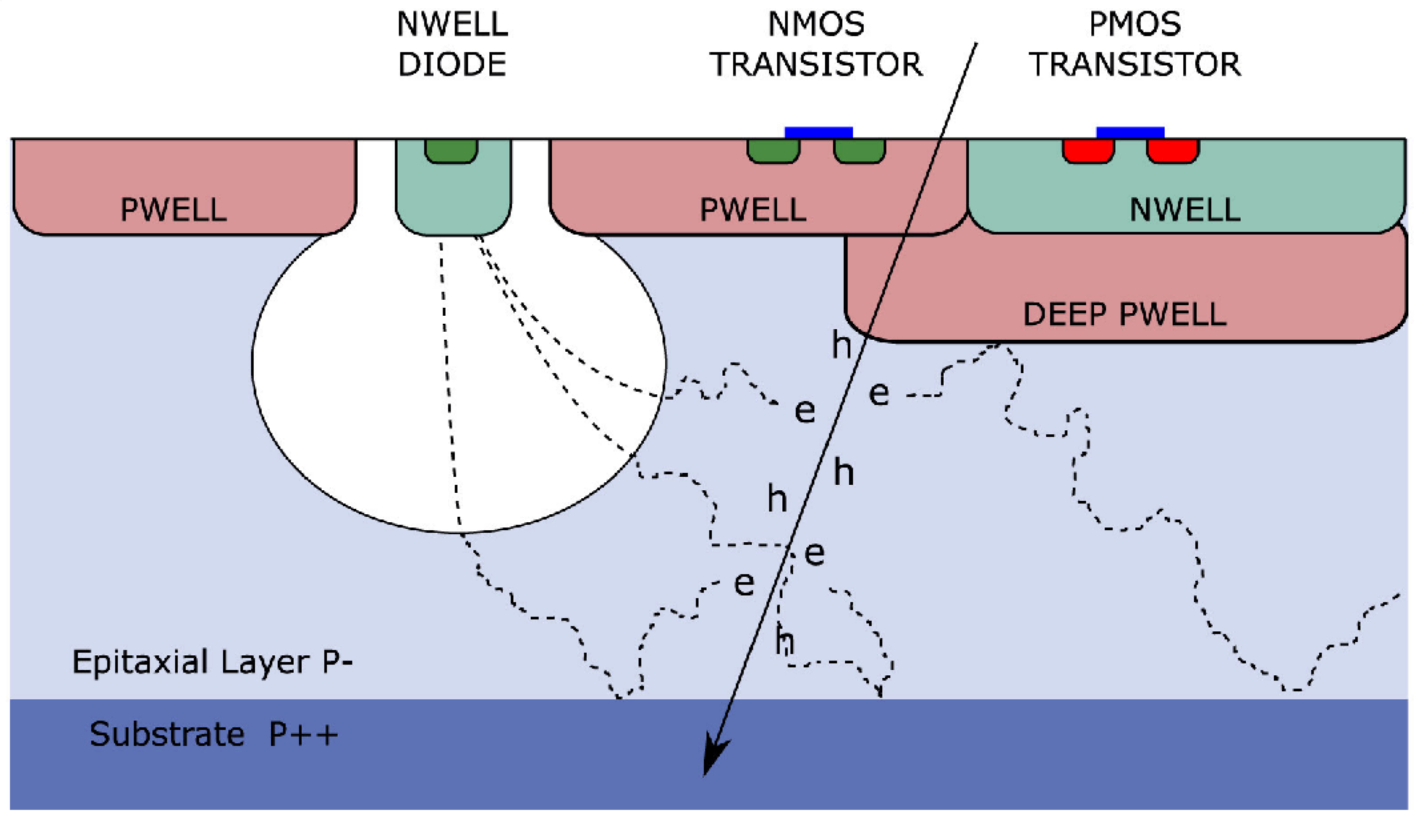
Services

- Central detector will contain > 16 different subsystems
- Substantial integration challenge for power, cooling, and data services
- Hermeticity?!

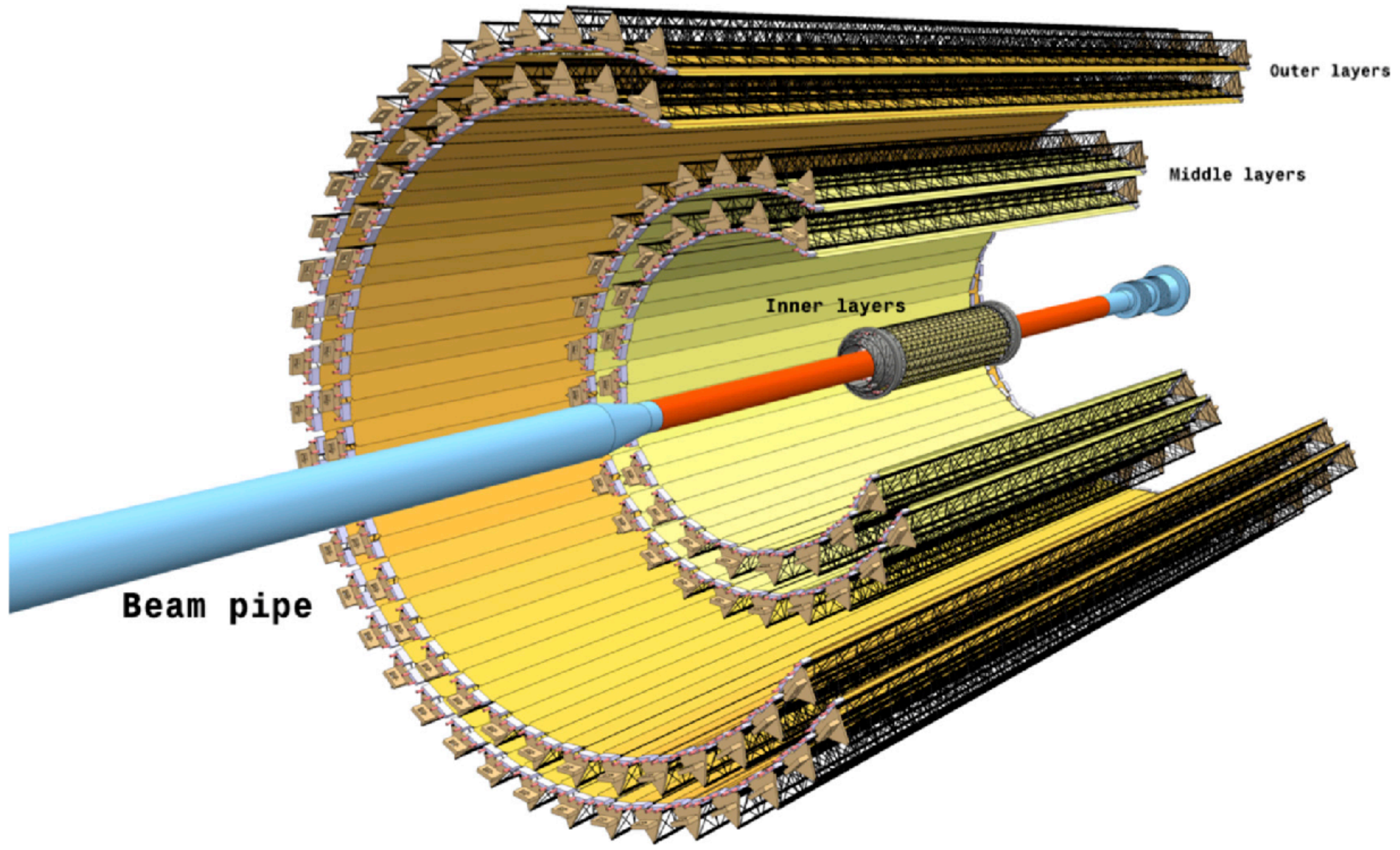
Tracking Detector Technologies Considered (Now)

- Silicon Sensors
  - CMOS Monolithic Active Pixel Sensors (MAPS)
  - Low Gain Avalanche Detector (AC-LGAD) - see PID later





- Solid state ionization detector
  - traversing charged particle creates e^--hole pairs
- low dE/dx required to produce pairs
  - Si: 3.6 eV Ge: 2.9 eV (gases: 20 eV to 40 eV)
- electric field across the junction causes e^--hole to drift apart, producing a detectable current
- good resolution 5-40 μm
- thin $\mathcal{O}(100\ \mu m)$, low X/X_0
- old: pixel detector bump bonded to read out chip
- new MAPS: readout chip part of sensor (waver)



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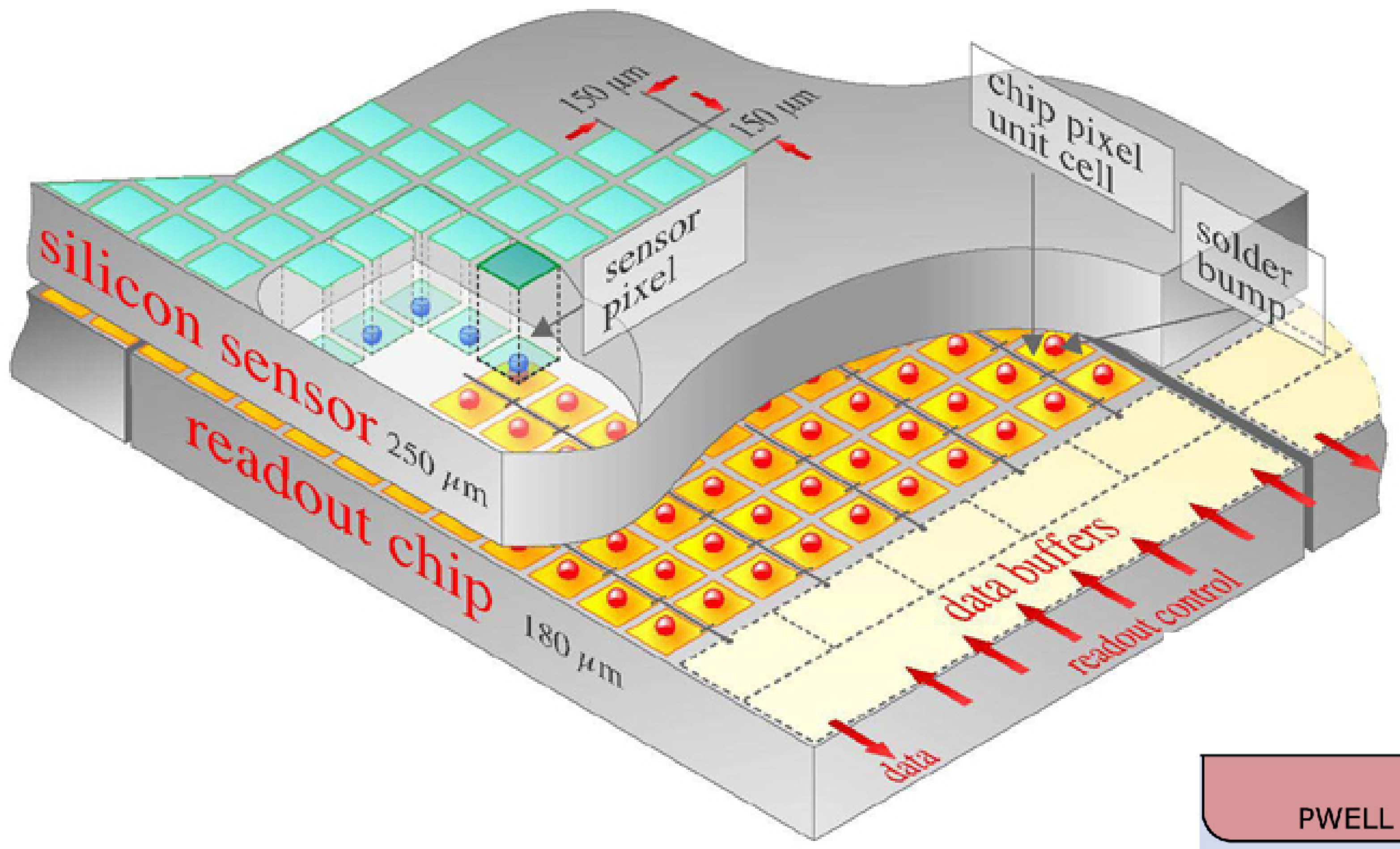
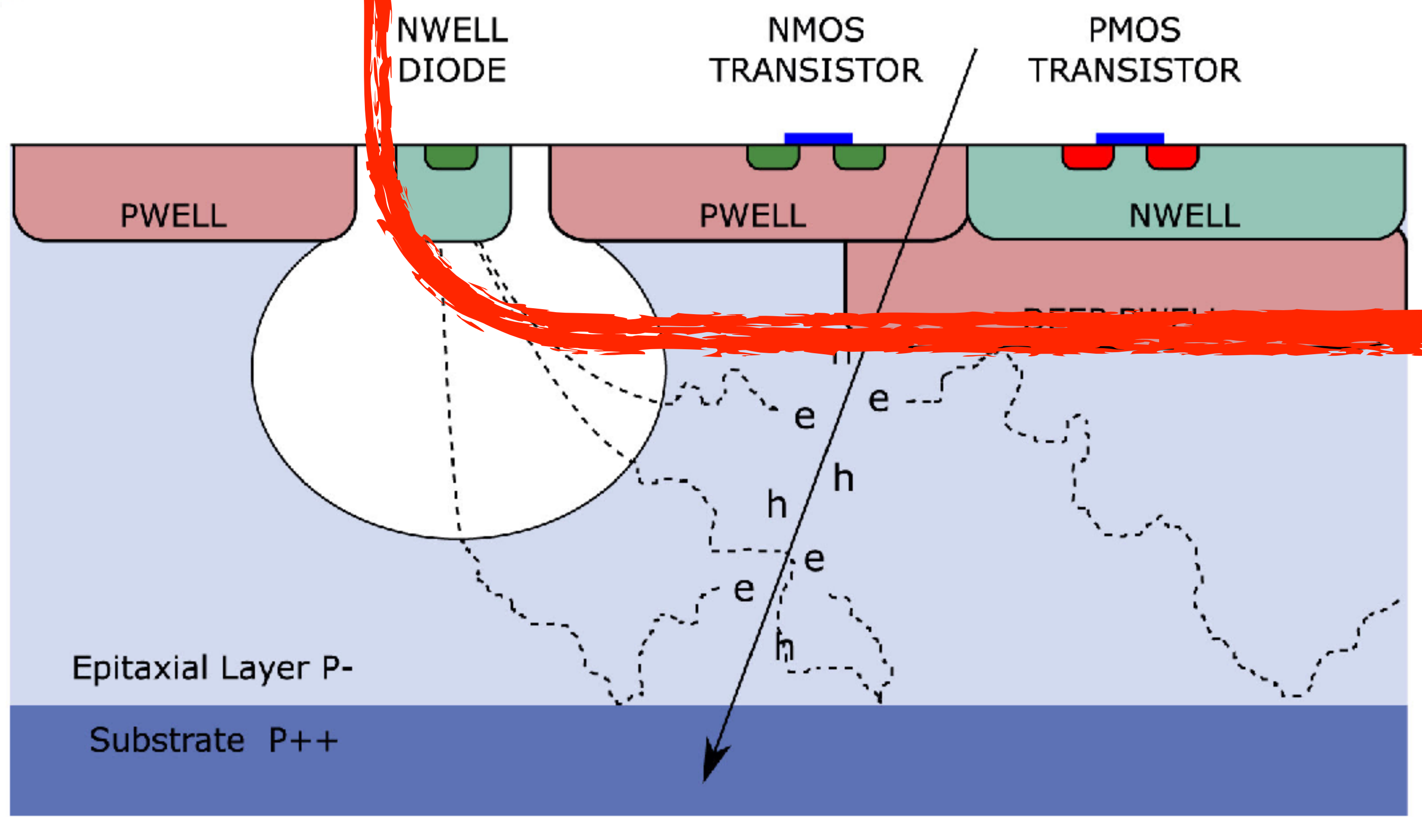
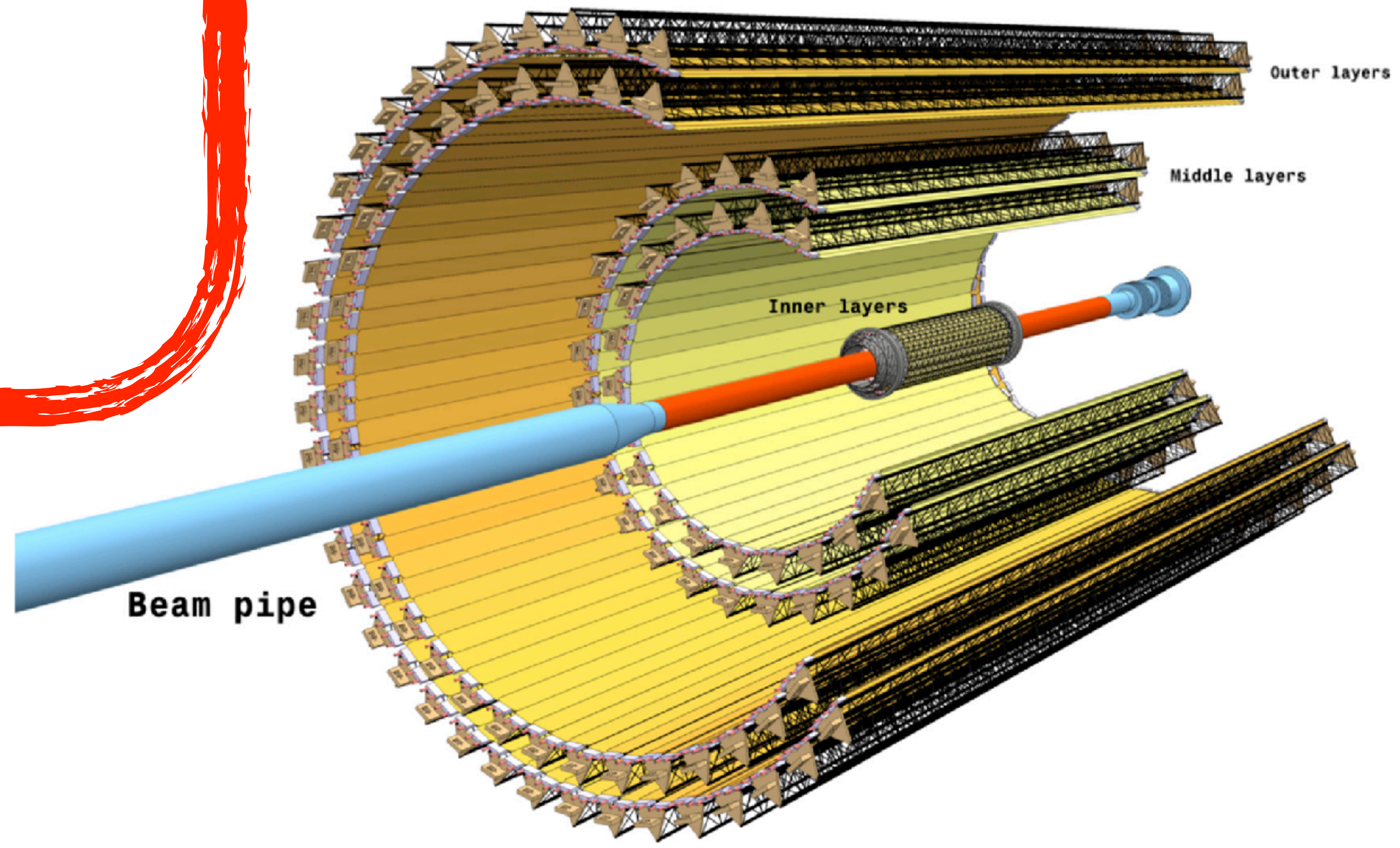
R&D







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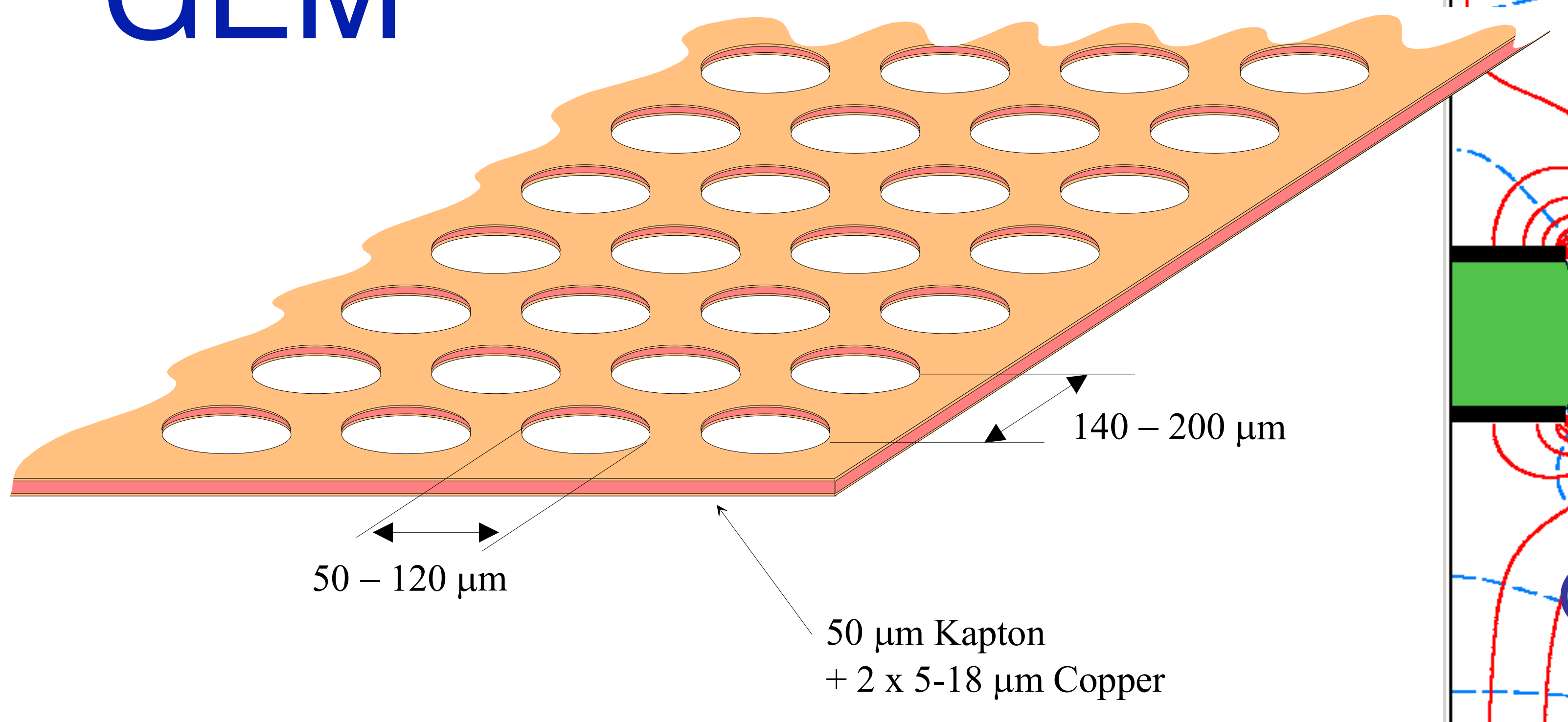
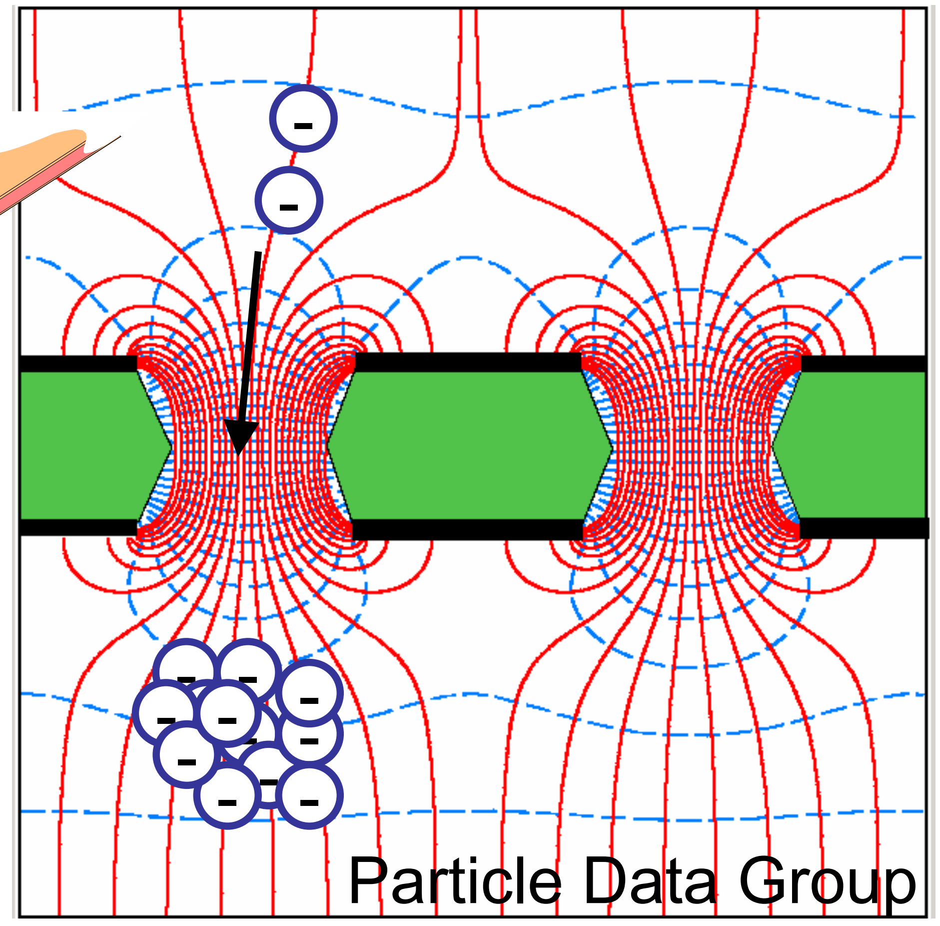
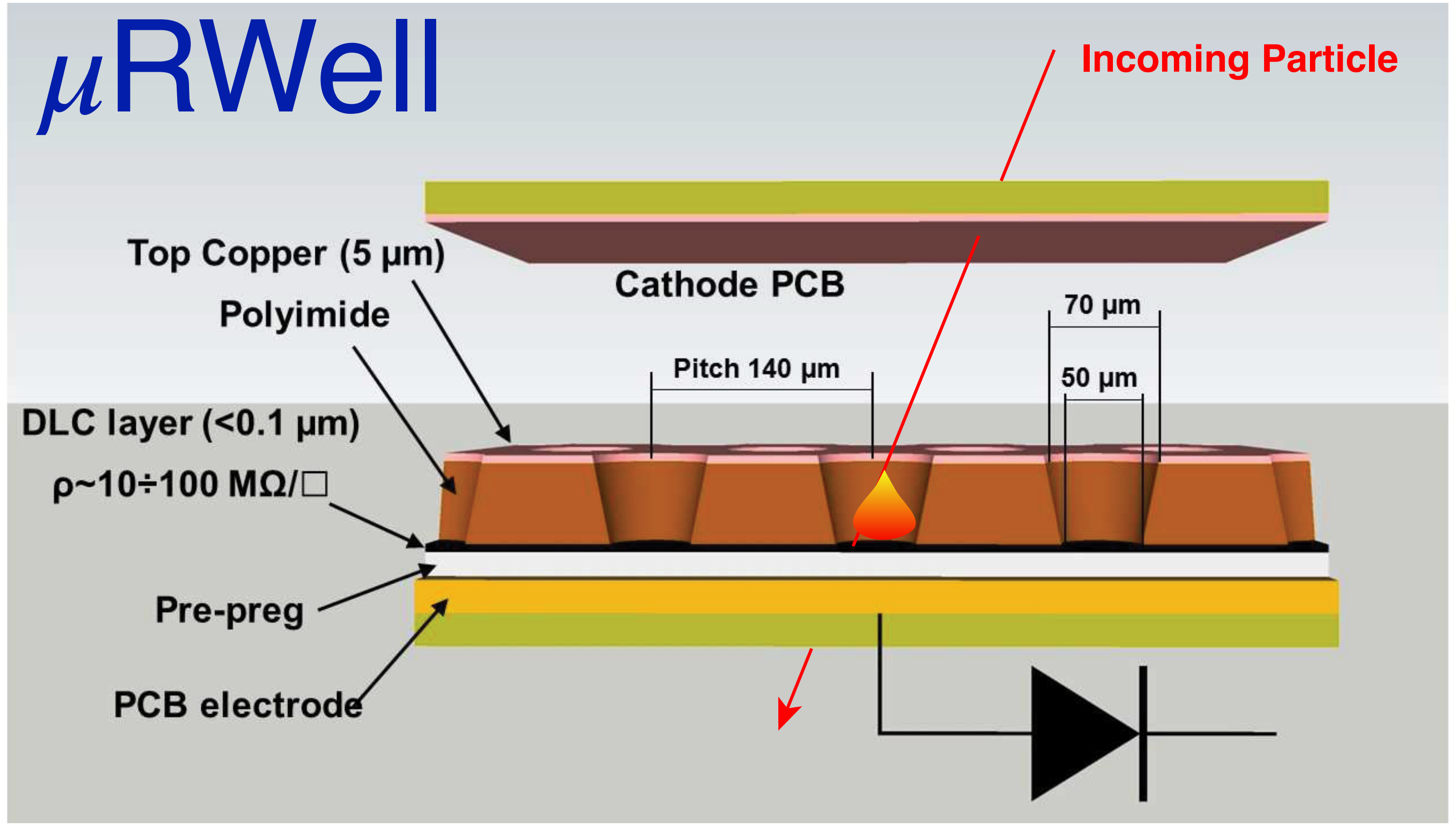
- Micropattern Gas Detectors
  - Gas Electron Multiplier (GEM)
  - Micromesh Gaseous Structure (Micromegas)
  - Micro-resistive well detector (μRWell)

GEM





- MPGDs
  - fast and good precision $\mathcal{O}(100\ \mu m)$
- Example: Gas electron multiplier (GEM)
  - thin metal-clad polymer foil, chemically pierced by a high density of holes
  - electrons drift into holes, multiply, and get out
- Example: μRWell technology is recent development
  - easier detector construction, no stretching as for GEMS, lower material budget



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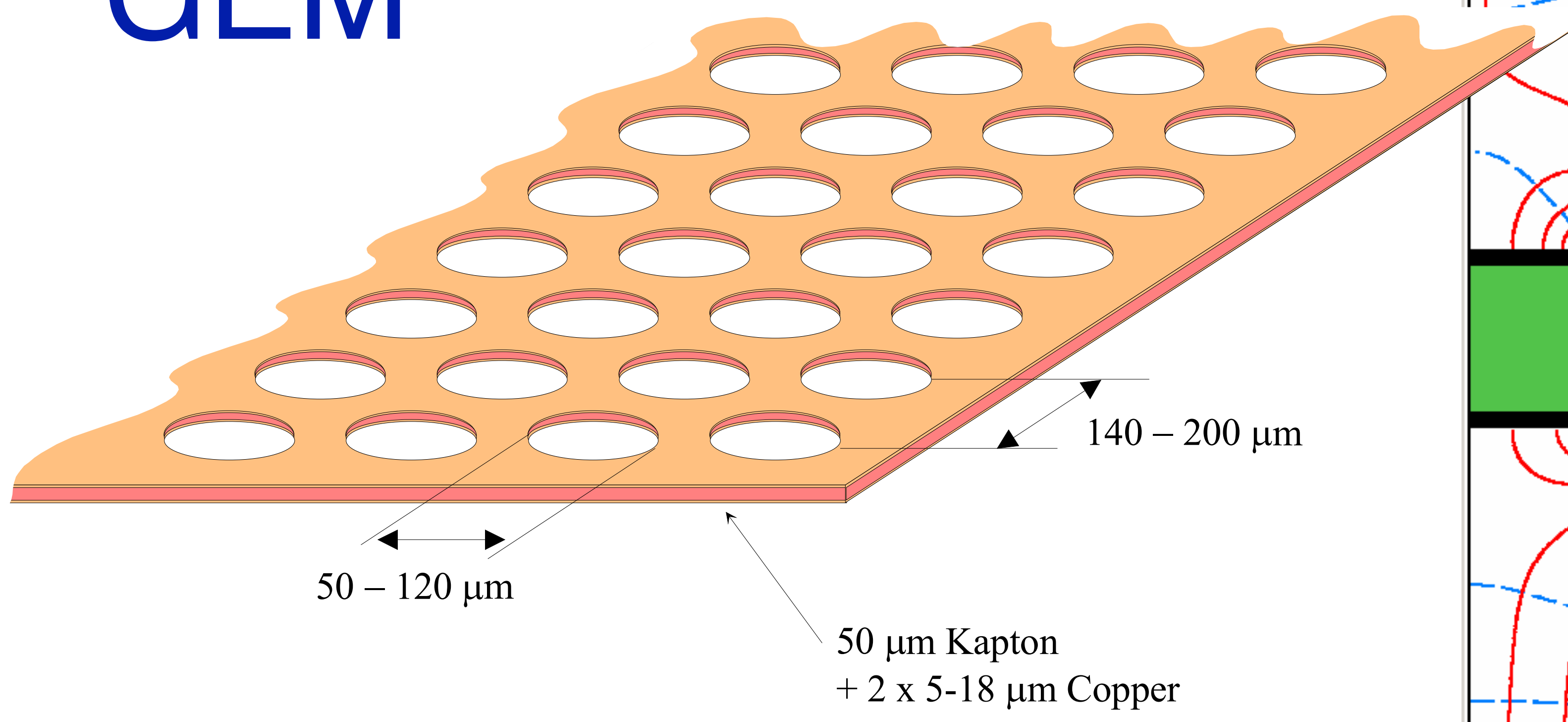
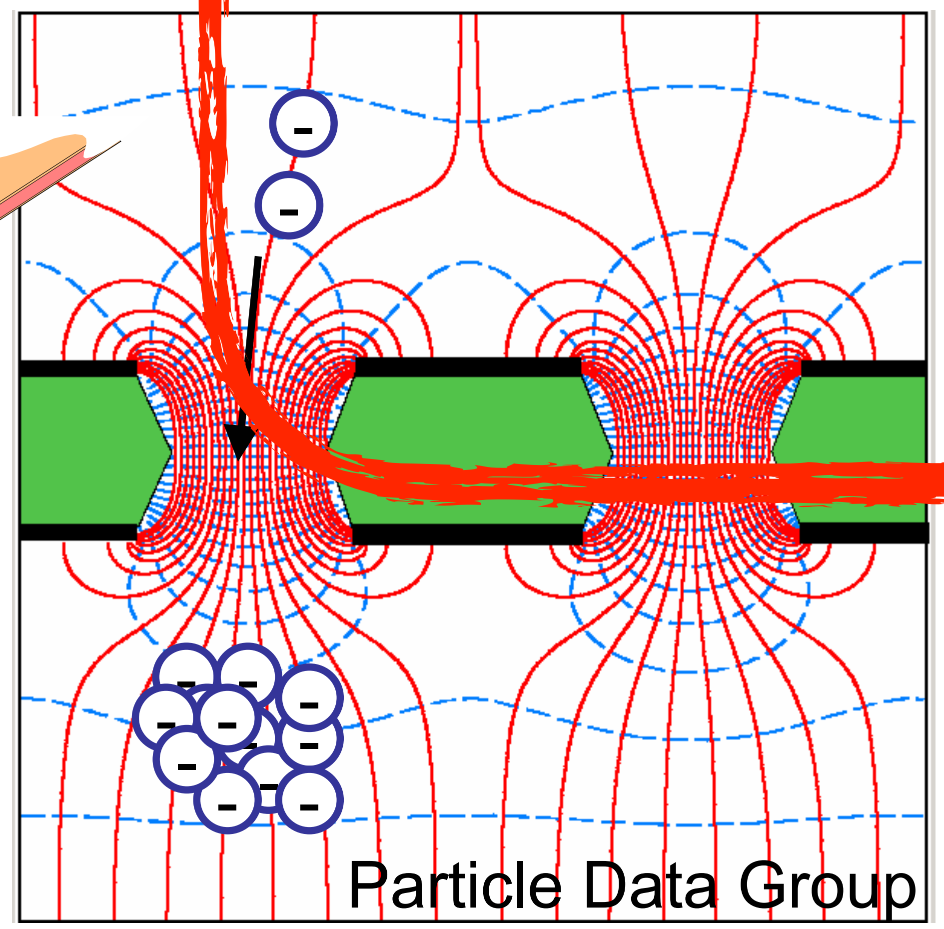
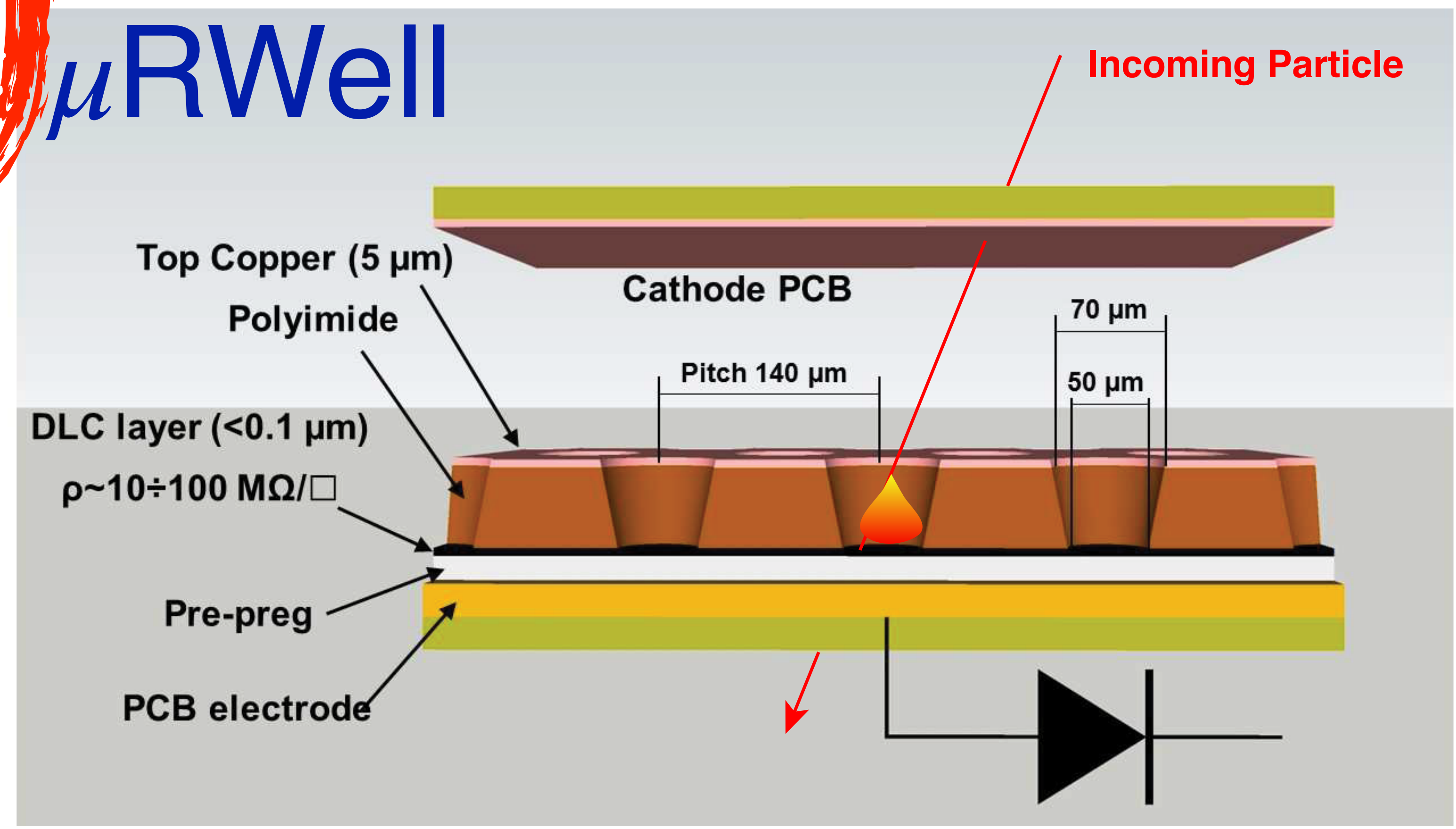
R&D

GEM







PID Detector Technologies Considered (Now)

- Cherenkov Detectors
  - Detection of Internally Reflected Cherenkov light (DIRC)
  - Dual Ring Imaging CHerenkov detector (dRICH)
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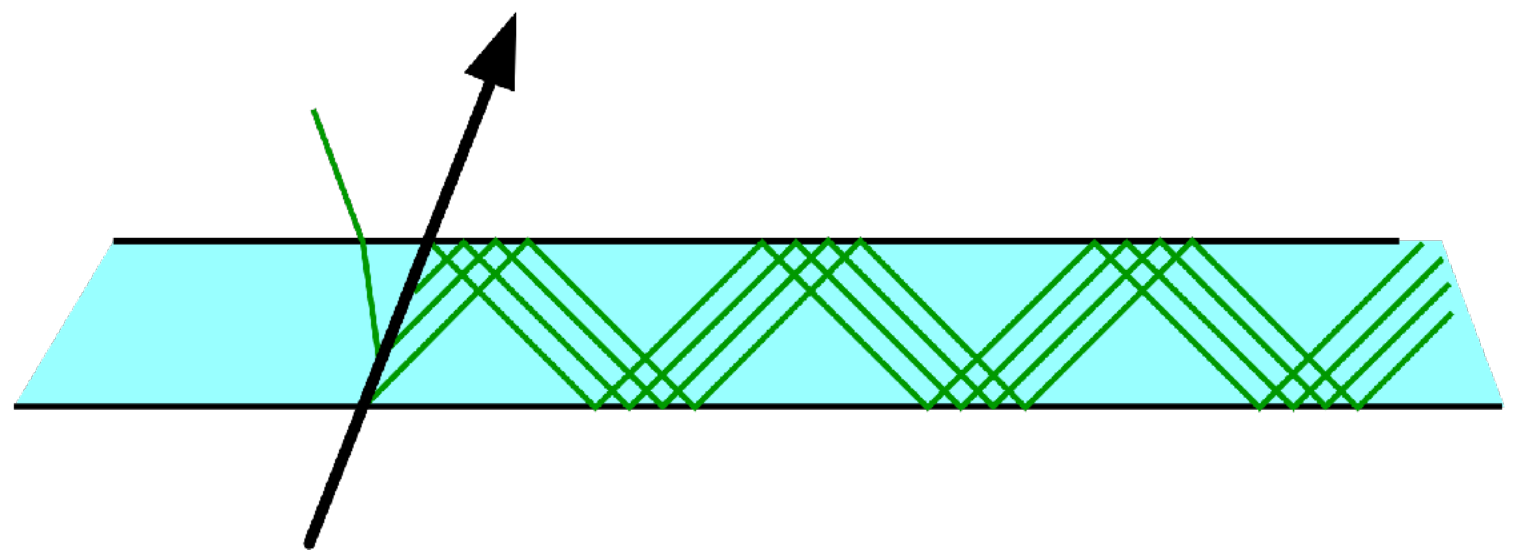
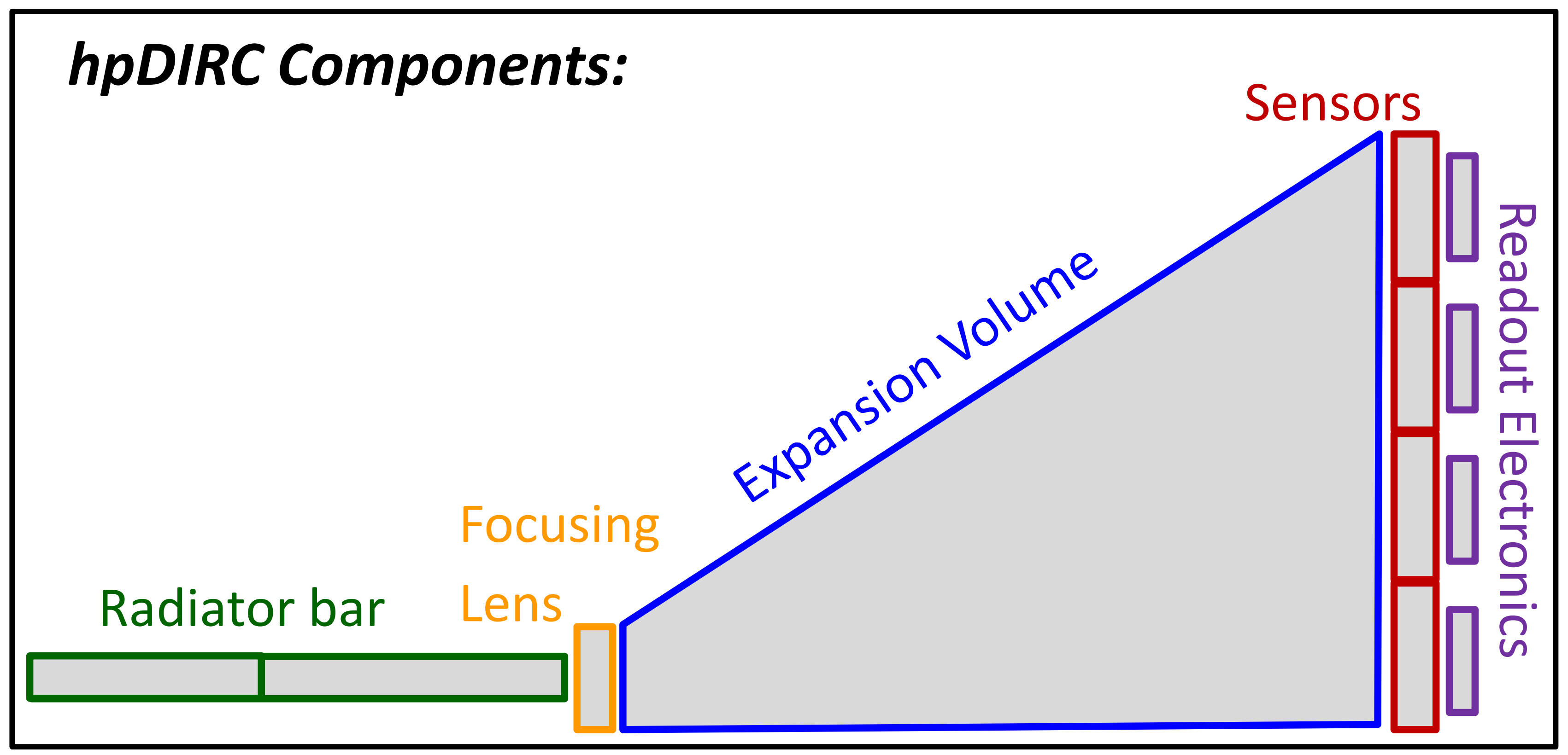
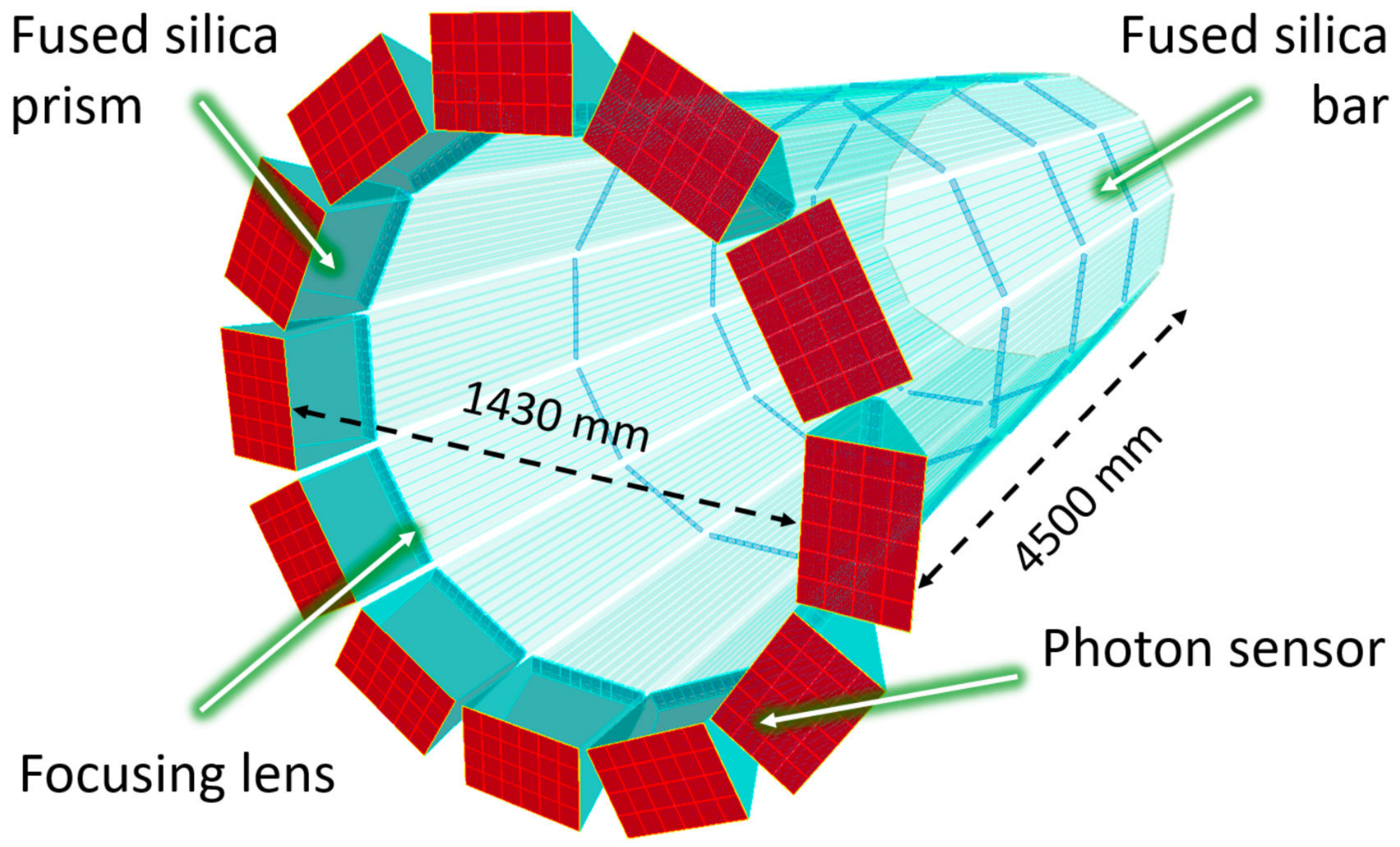
- DIRC
  - Radiator bars ~ 420cm bar length
  - 12 bar boxes, 10 long bars side-by-side in a bar box
  - Expansion volume: Solid fused silica prism
  - Readout baseline: MCP-PMT Sensors
  - $3\sigma\ K/\pi$ for p < 6.5 GeV/c







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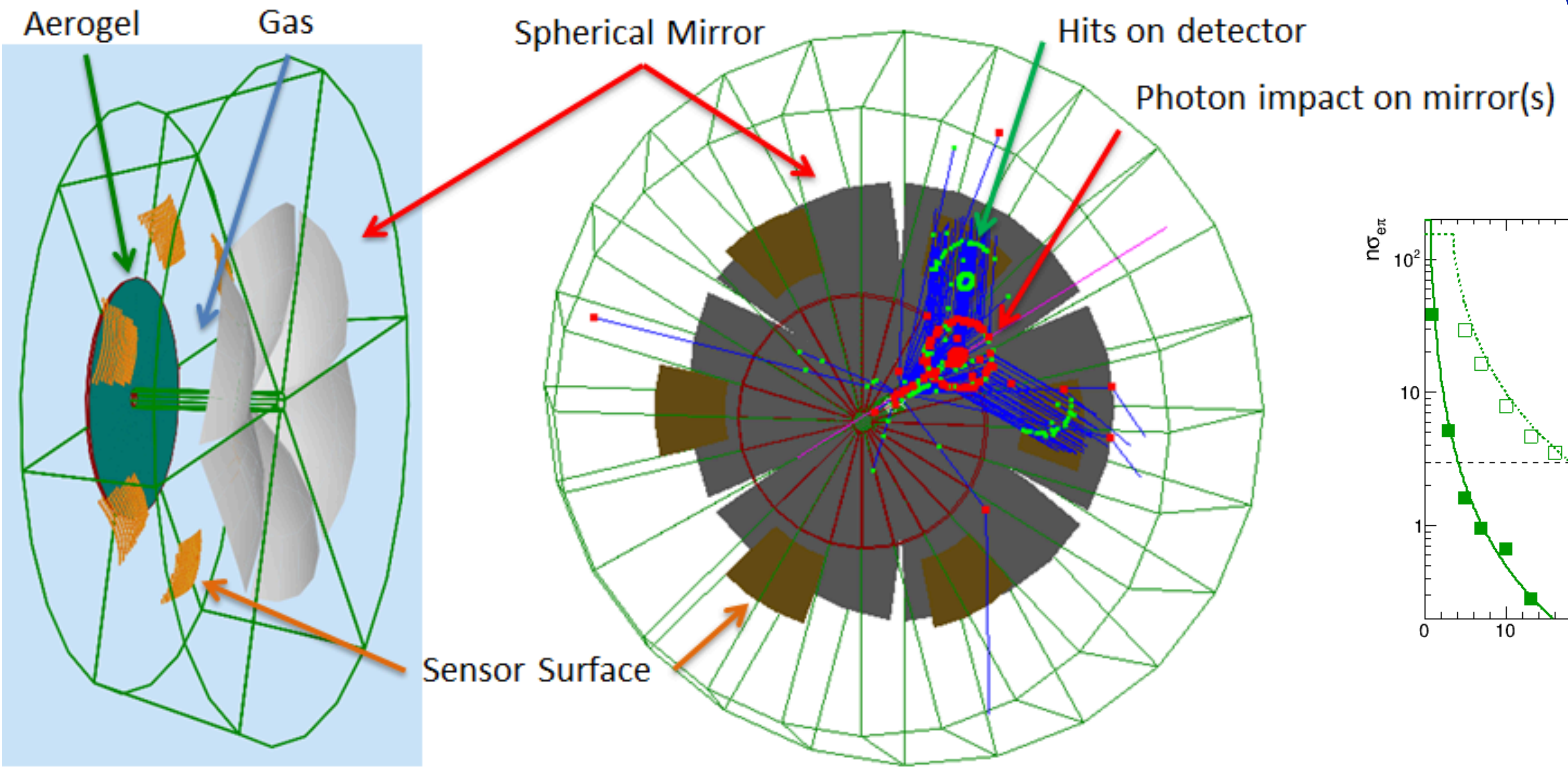
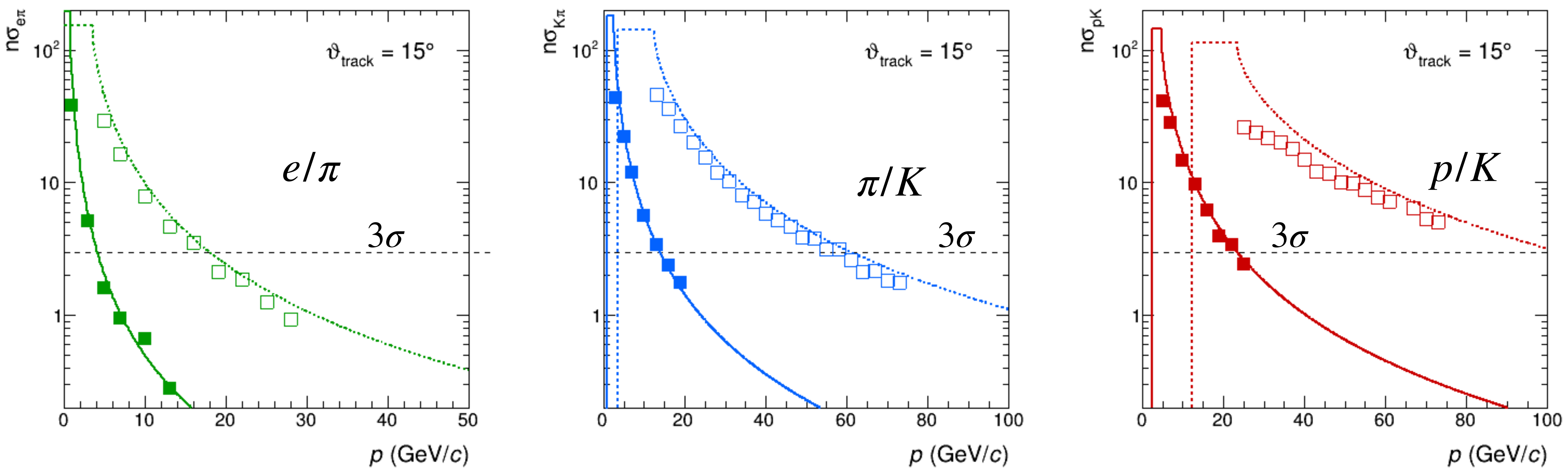
  - Combination of C_2F_6 gas and n=1.02 aerogel
  - Outward-reflecting mirrors reduce backgrounds and (UV) scattering in aerogel
  - Requires sophisticated 3D focusing to reduce photosensor area
  - Continuous momentum coverage (3-60 GeV/c)





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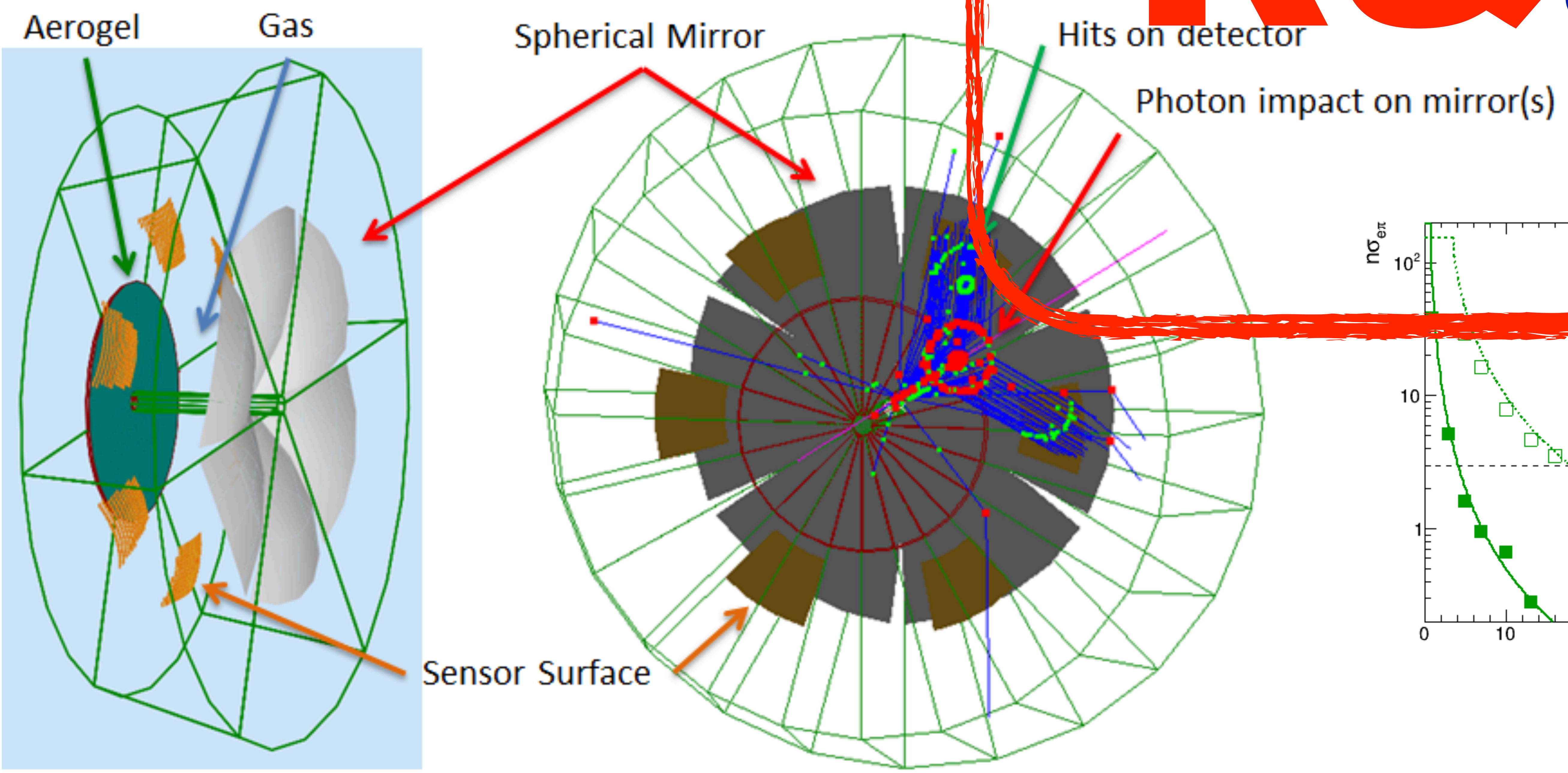
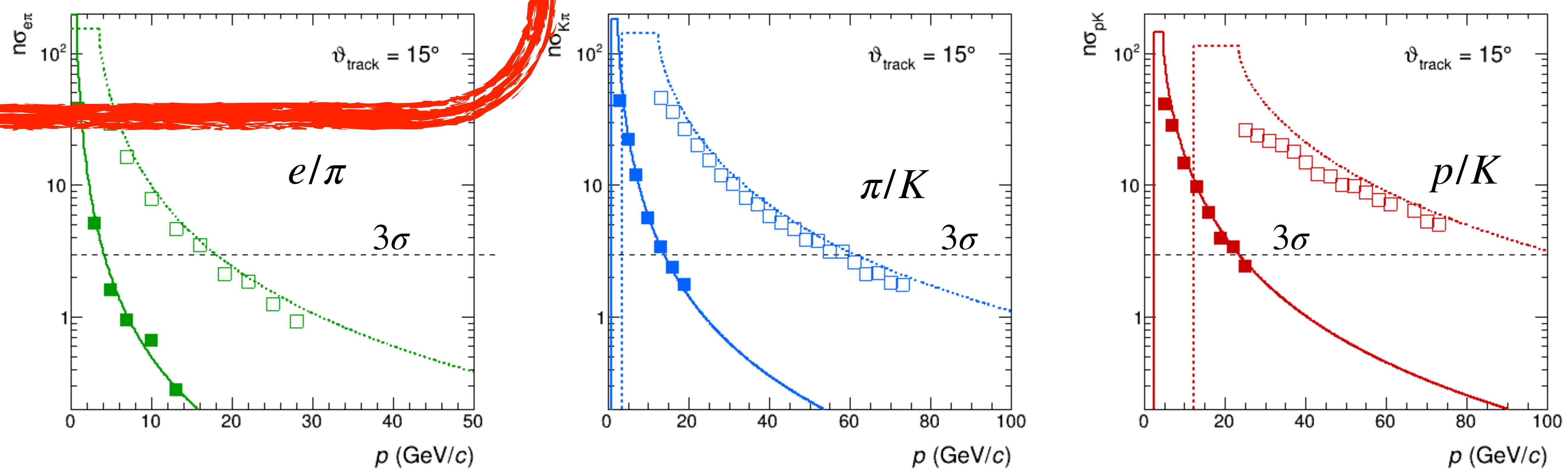
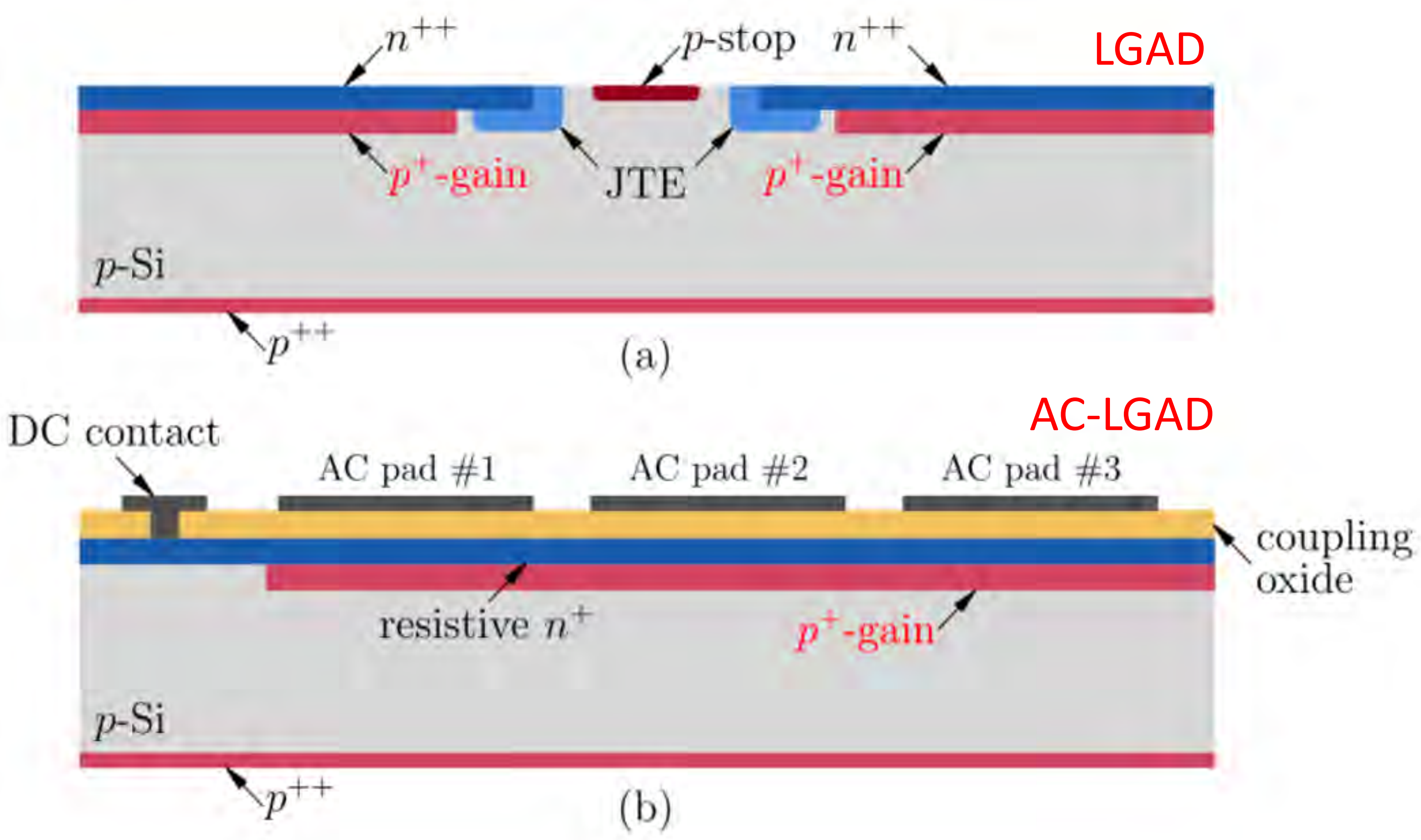
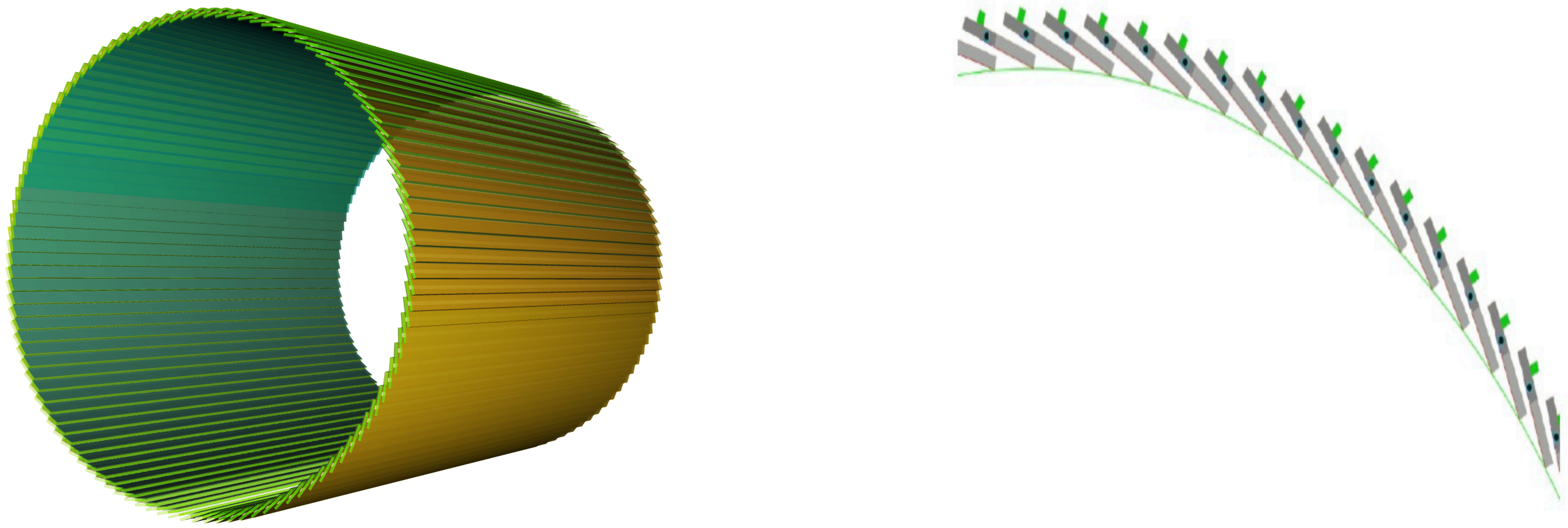




PID Detector Technologies Considered (Now)

- Time-Of-Flight
  - Low Gain Avalanche Detector (AC-LGAD)





- LGADs
  - recently-developed class of silicon sensors
  - HV drift cathode, a drift gap, and a micro-well layer (similar to a single GEM foil) which is mounted on a resistive readout board
  - feature fast signals and exhibit excellent timing performance of ~30 ps
  - LGADL: to achieve a spatially uniform multiplication a large pixel pitch is needed, preventing a fine spatial resolution.
  - New AC-coupled LGAD approach was introduced to achieve better resolution $\mathcal{O}(50\ \mu m)$.
  - AC-LGAD improves on LGAD in terms of timing and position resolution.

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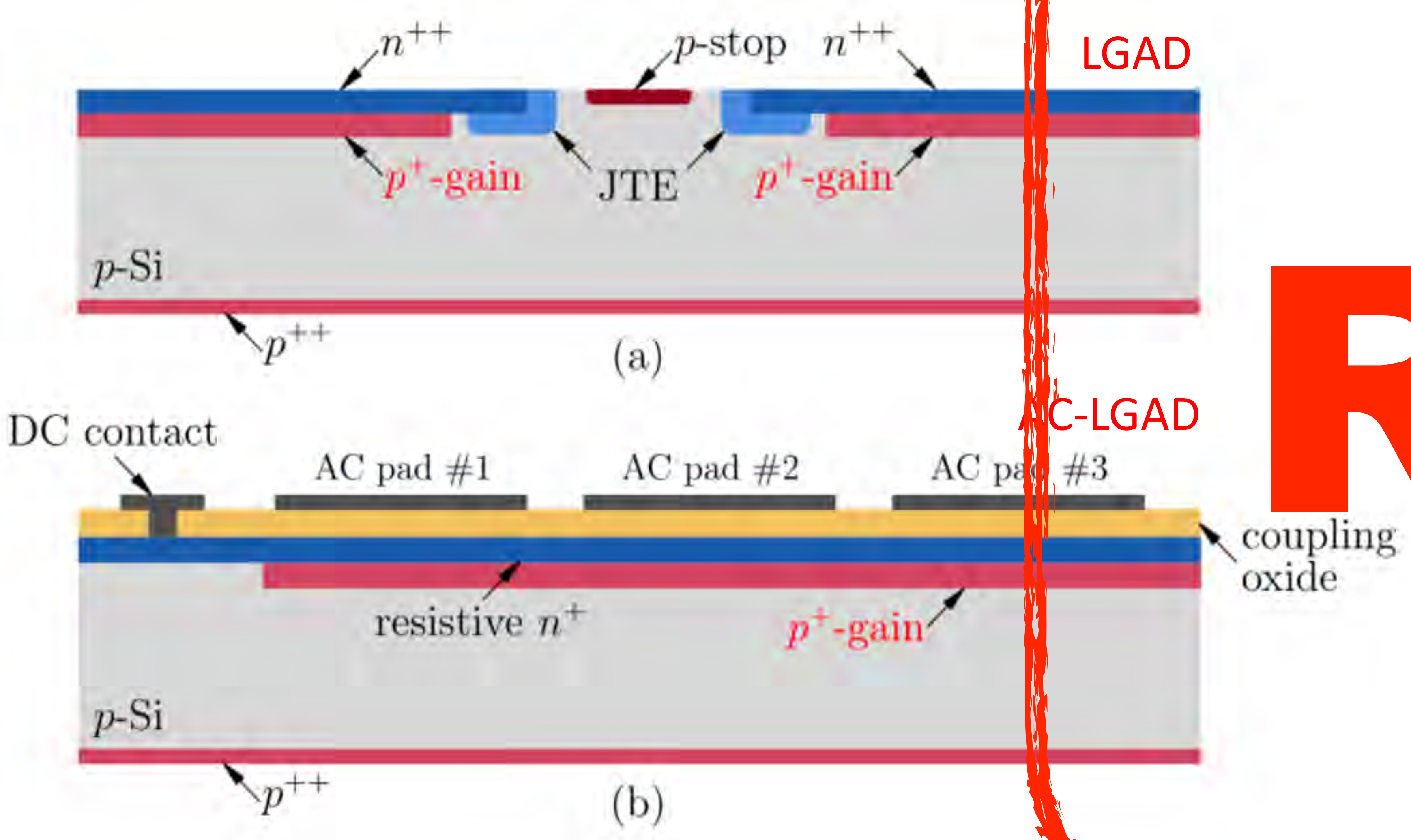

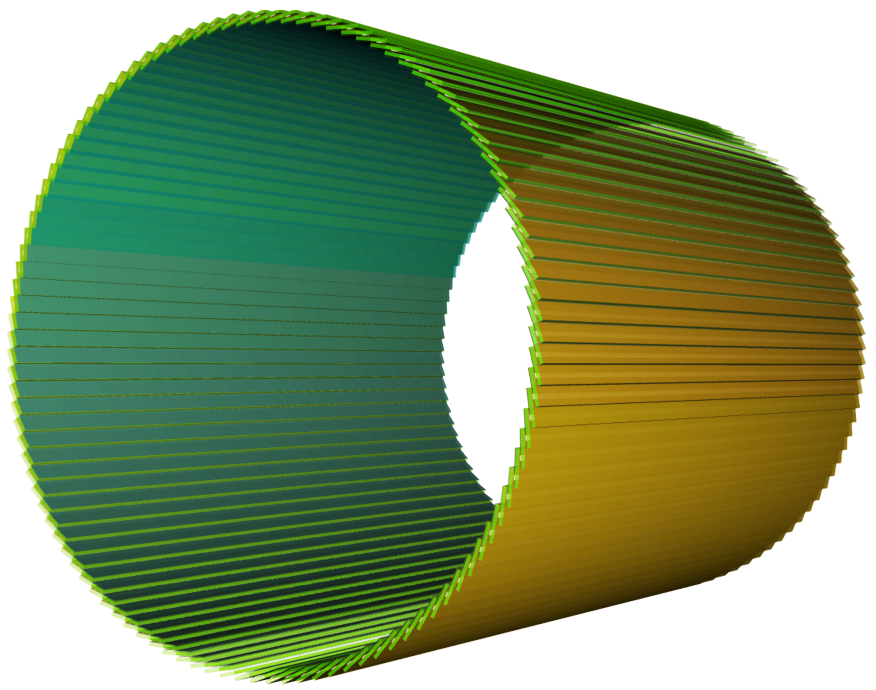

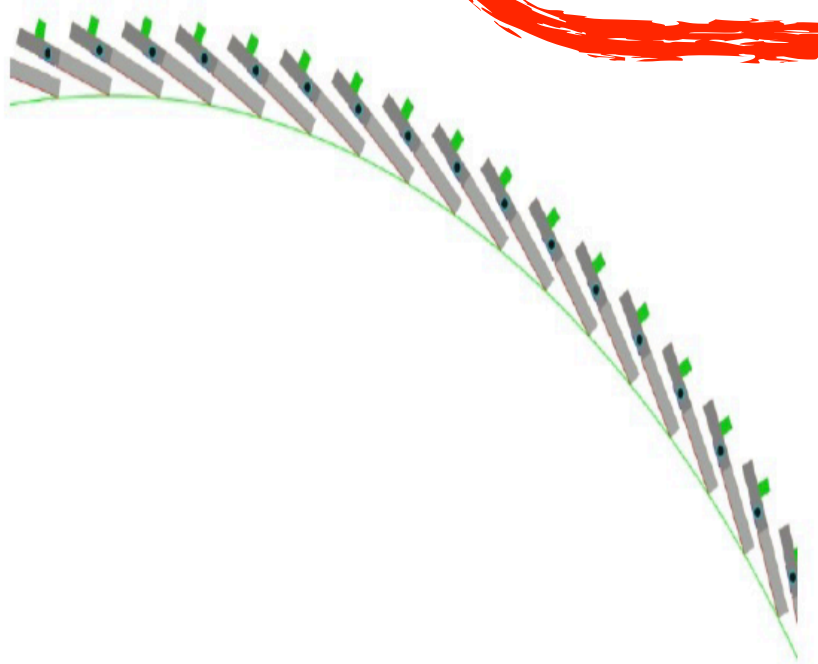

R&D

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Calorimeter Technologies Considered (Now)

- EMCalorimeter
  - Scintillating Glass (SciGlass)
  - Crystal ($PbWO_4$)
  - Imaging (Astropix) Sampling Pb/Sci Calorimeter
  - Tungstate-Scintillating Fiber Calorimeter (WSciFi)
- Hadron Calorimeter
  - Fe/Sci Sampling

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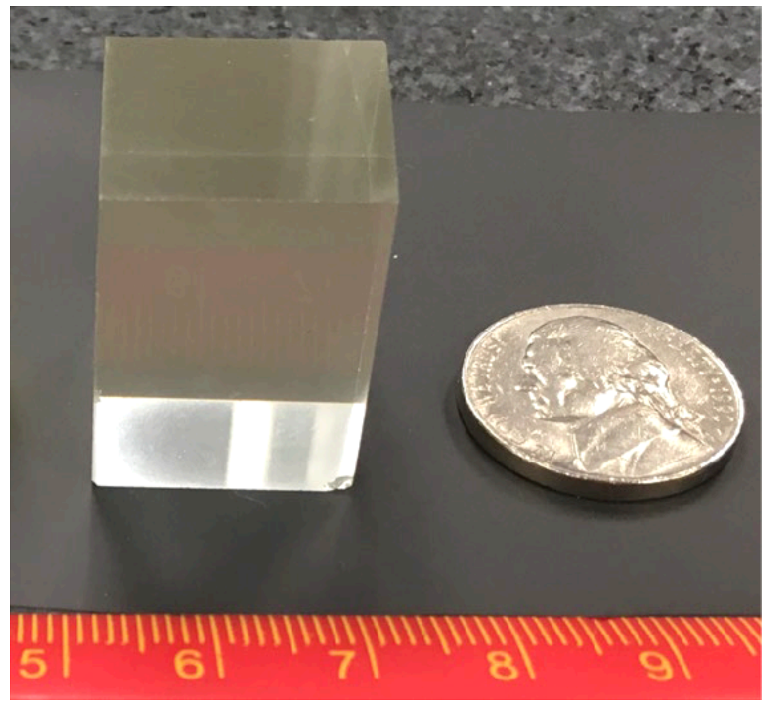
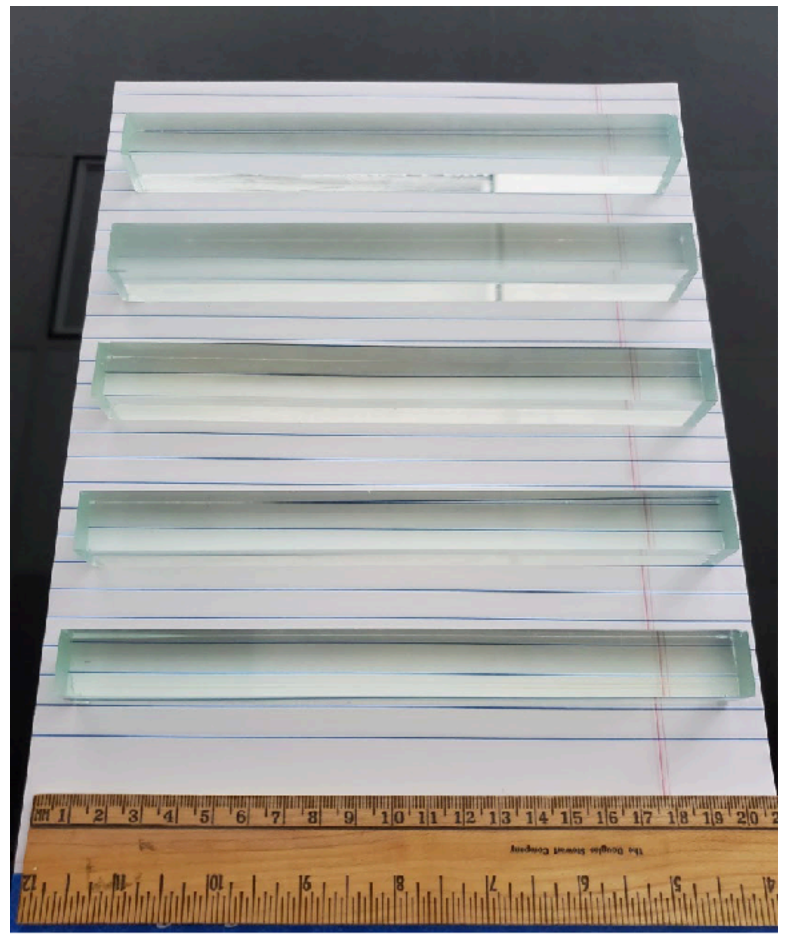
- SciGlass
  - EIC: e-going direction needs high precision calorimetry Typically requires Lead Tungstate (PbWO4) crystals
  - SciGlass similar to lead glass ($PbWO_4$) in many properties but exhibit >30× the light yield per GeV
  - Nano-sized particles of $BaSi_2O_5$
  - Allows doping: Gd, Yb, Ce, … to make denser and more radiation hard
  - Path to inexpensive high resolution EM calorimeters
  - Crystal need to be longer than $PbWO_4$ (~45 cm versus ~24 cm)

Steady progress due to R&D program

2018: 1cm x 1cm x 1cm



2019: 2cm x 2cm x 4cm



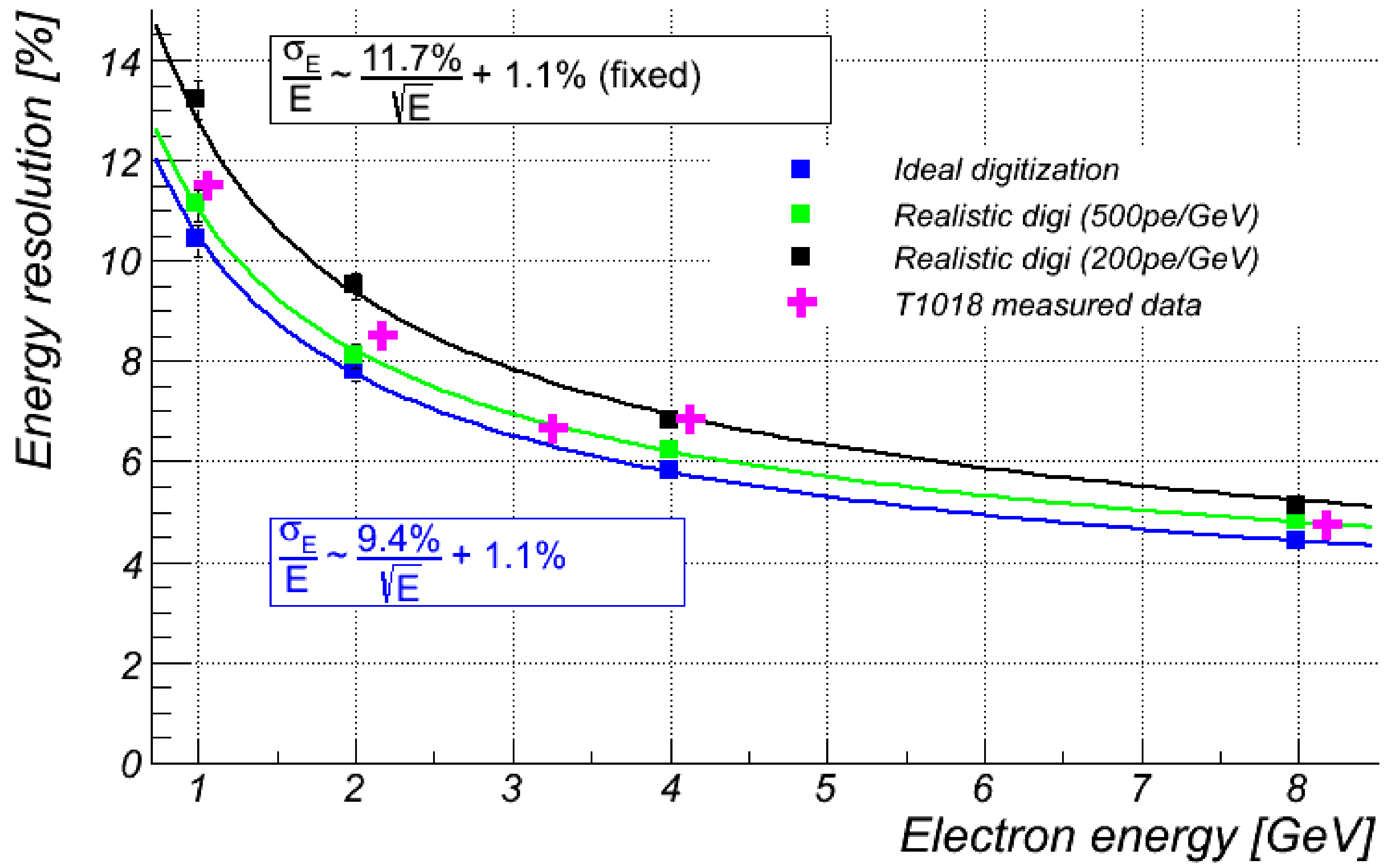
2020: 2cm x 2cm x 20cm (7 X_0)

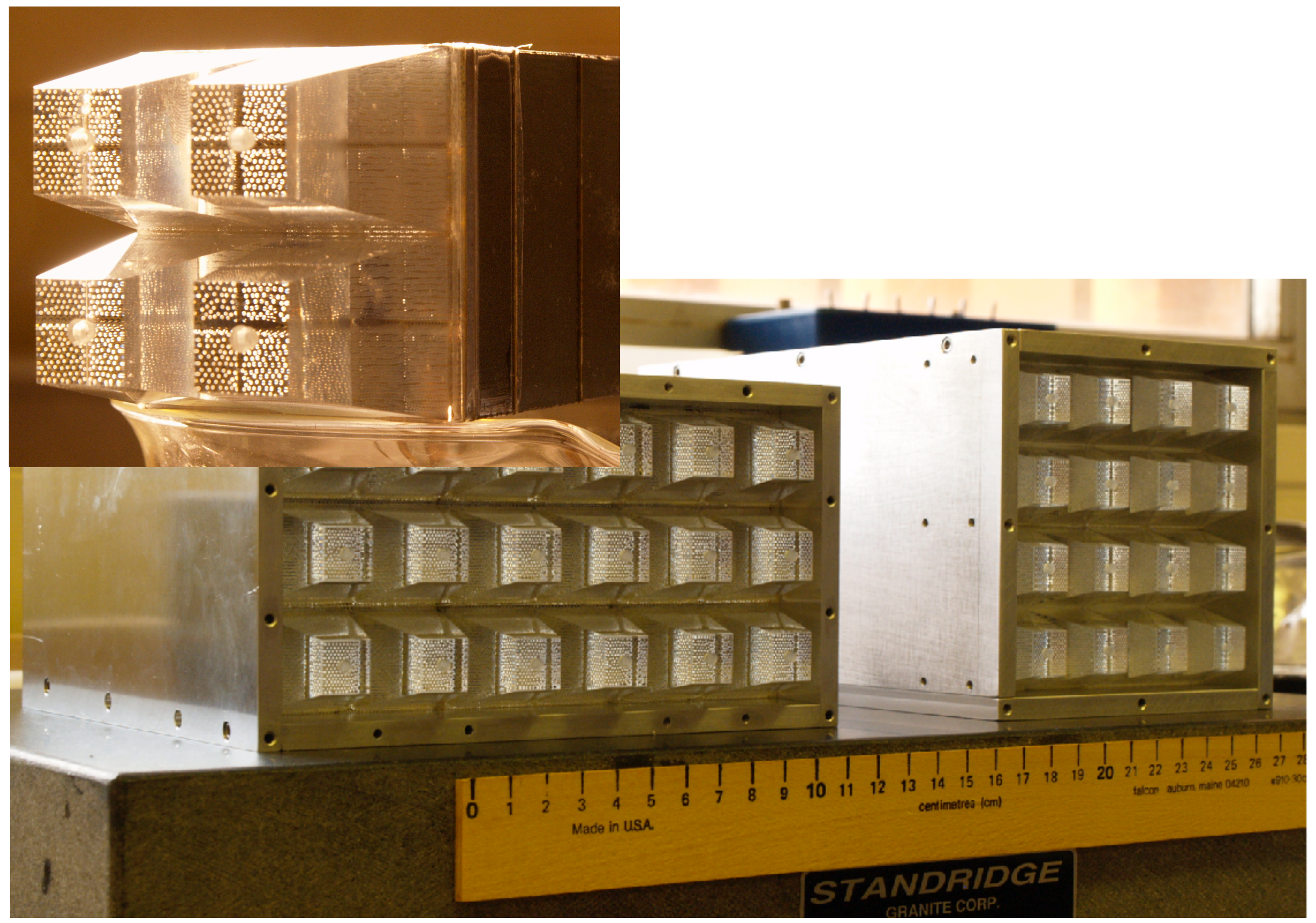
2021: 2cm x 2cm x 40cm (10-20 X_0)

Calorimeter Technologies Considered (Now)

- EMCalorimeter
  - Scintillating Glass (SciGlass)
  - Crystal ($PbWO_4$)
  - Imaging (Astropix) Sampling Pb/Sci Calorimeter
  - Tungstate-Scintillating Fiber Calorimeter (WSciFi)
- Hadron Calorimeter
  - Fe/Sci Sampling

- W-SciFi Calorimetry
  - Sampling calorimeter
  - Scintillating fibers embedded in W-powder composite absorber
  - good energy & position resolution
  - good radiation hardness
  - Technology is used for EMCal in sPHENIX





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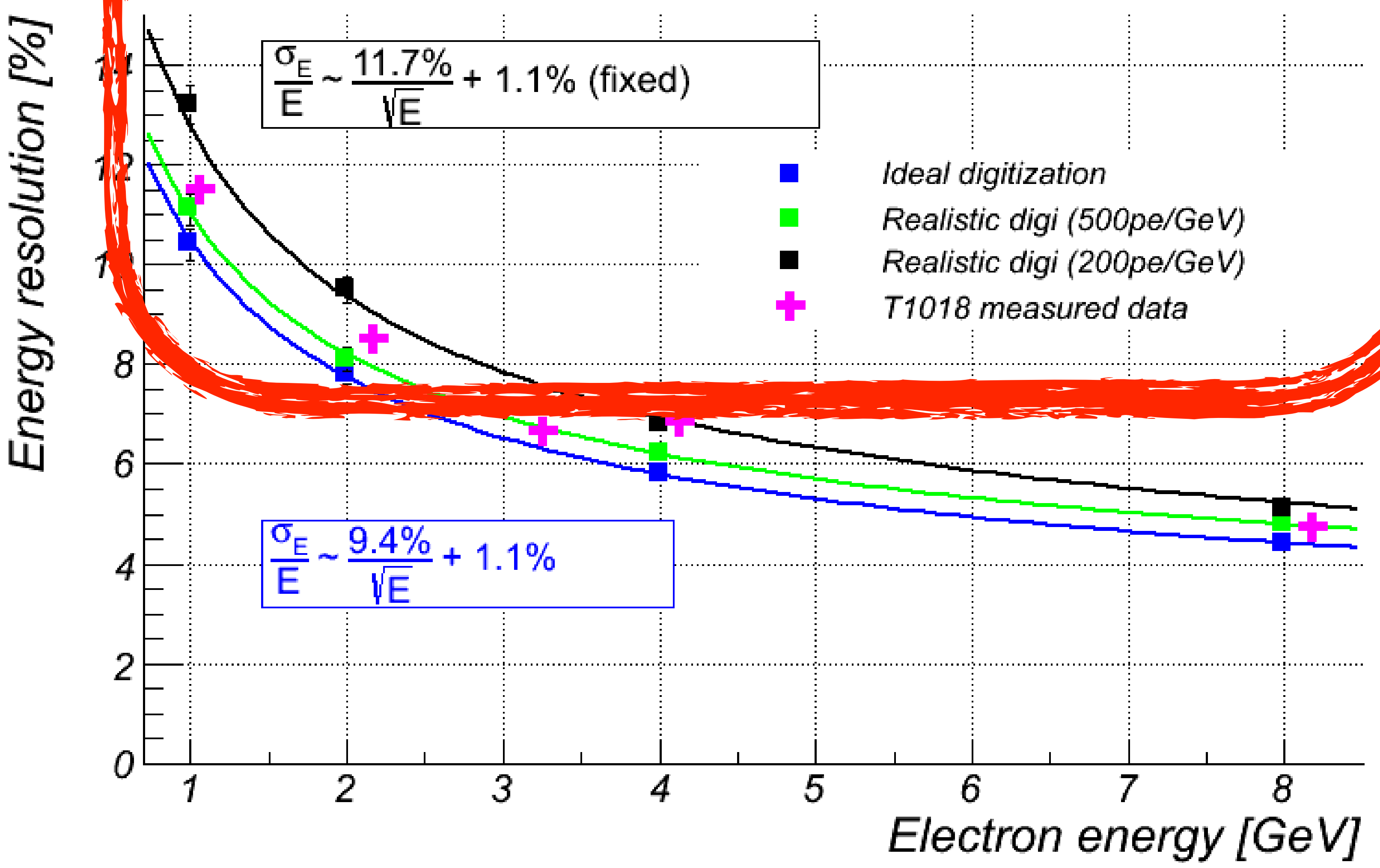
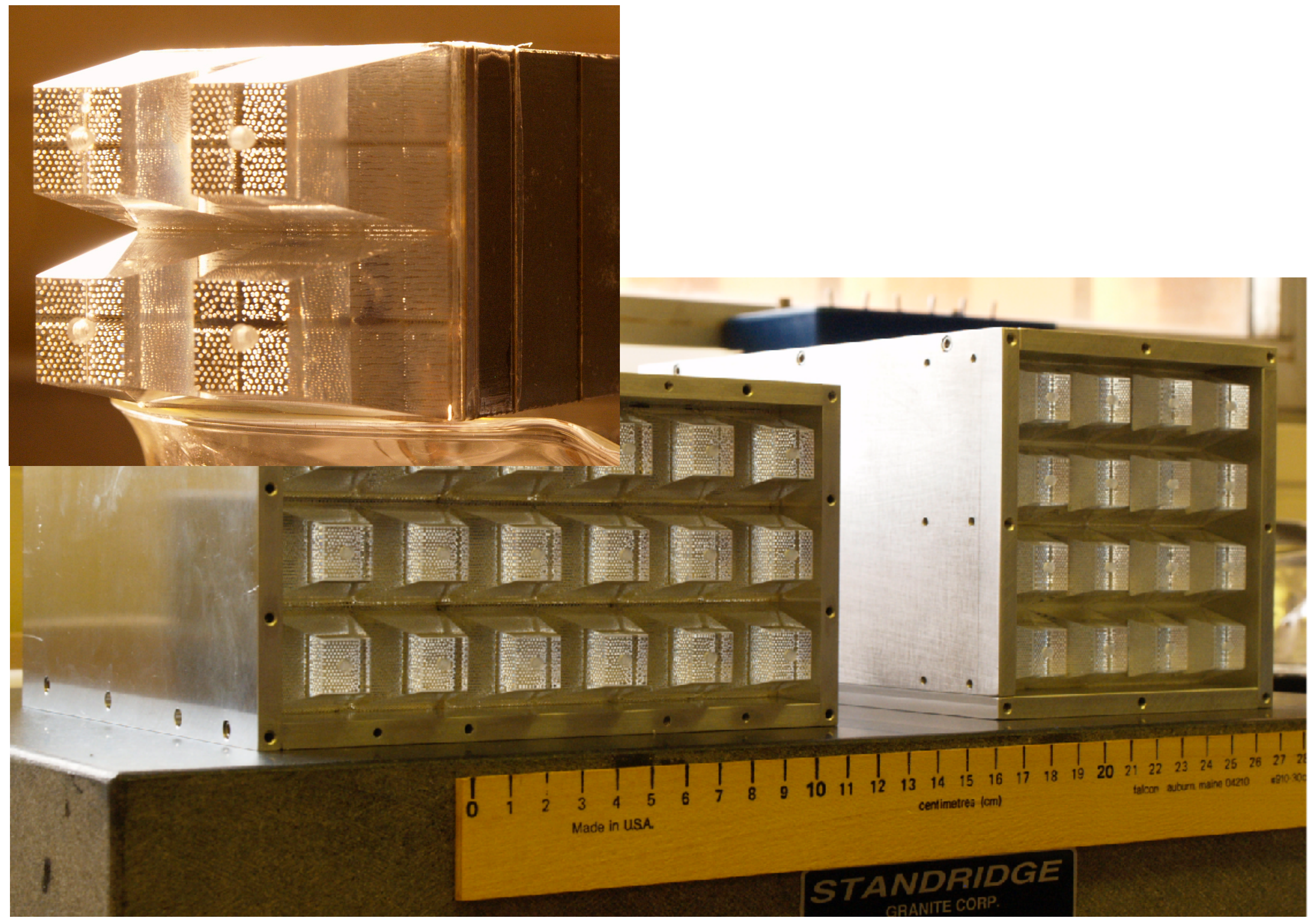
R&D

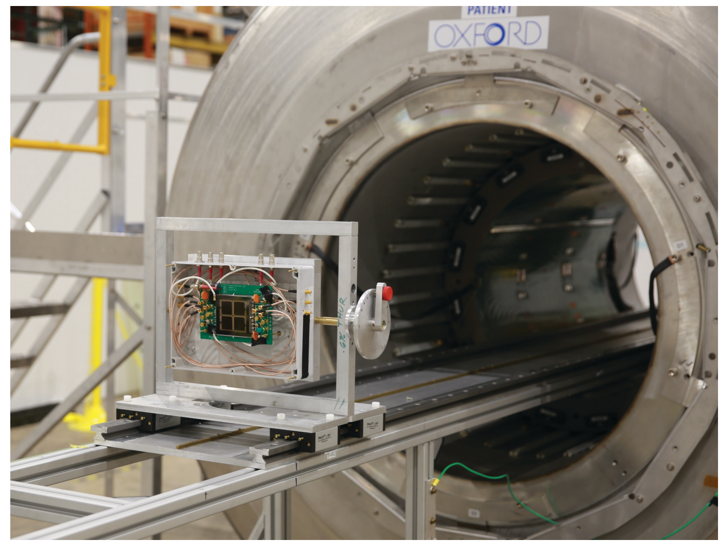


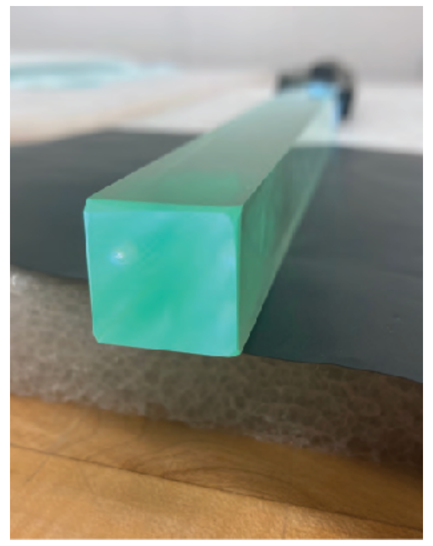
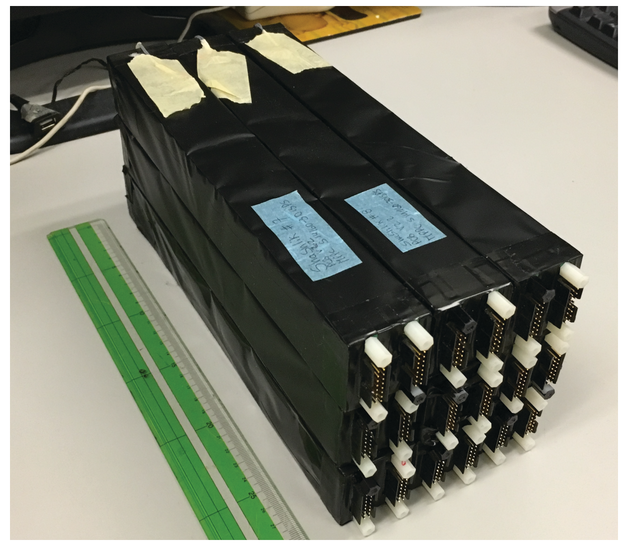
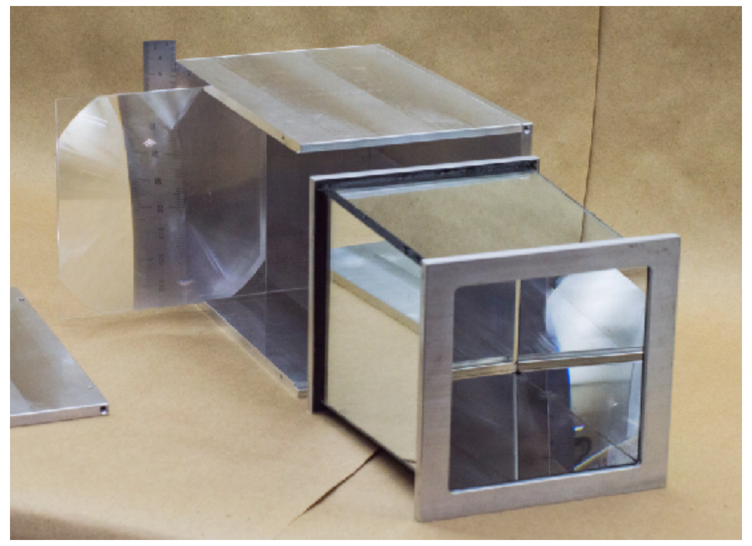
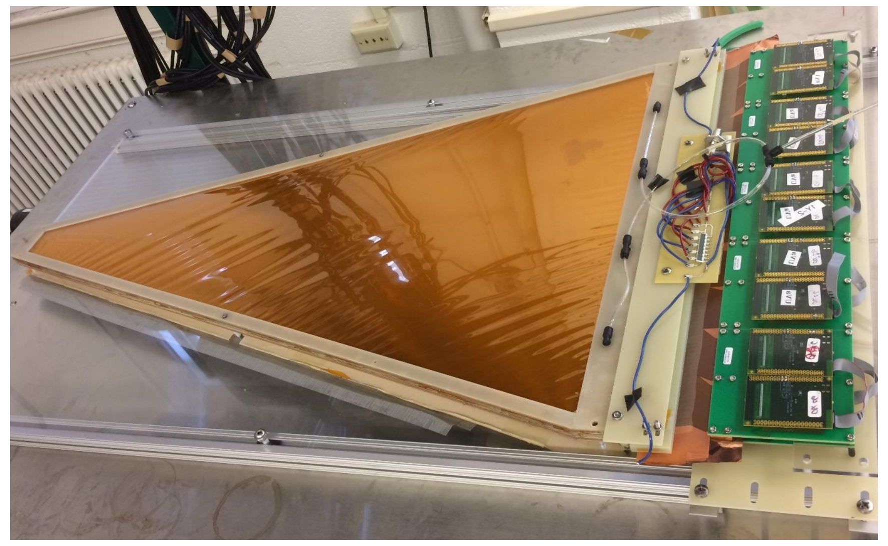


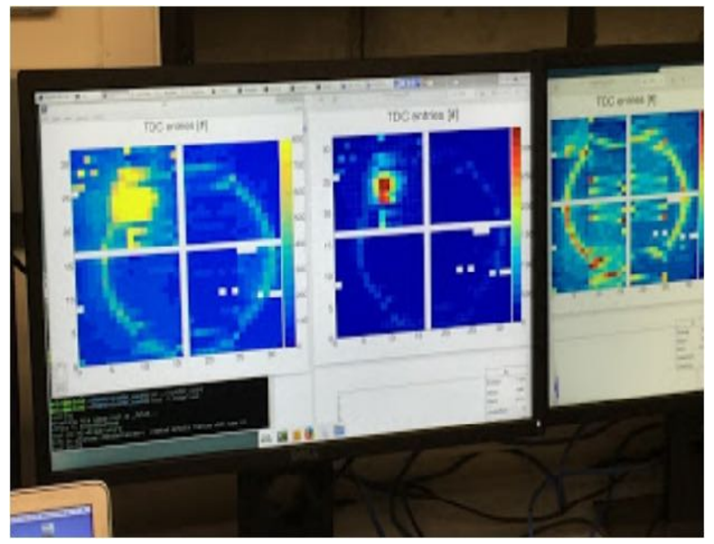
The EIC R&D Programs (I)

Generic program (2011-2021)

- Started 2011 at BNL, in association with JLab and the DOE Office of NP
- Funded by DOE through RHIC operations funds
- Program explicitly open to international participation
- Goals of Effort
  - Quantify the key physics requirements that drive instrumentation
  - Develop instrumentation solutions that meet realistic cost expectations
  - Stimulate the formation of user collaborations to design and build experiments
- Advisory Committee consisting of internationally recognized experts
- Over 281 participants from 75 institutions (37 non-US)
- Many of the considered subsystems were developed and matured in the Generic EIC Detector R&D Program
- Many PIs and participants of this program now active in detector working groups for Detector-1





On the web: `https://wiki.bnl.gov/conferences/index.php/EIC_R%25D`

Generic R&D Projects 2014-2021

Project	Topic
eRD1	EIC Calorimeter Development
eRD2	A Compact Magnetic Field Cloaking Device
eRD3	Design and assembly of fast and lightweight forward tracking prototype systems
eRD6	Tracking and PID detector R&D towards an EIC detector
eRD10	(Sub) 10 Picosecond Timing Detectors at the EIC
eRD11	RICH detector for the EIC's forward region particle identification - Simulations
eRD12	Polarimeter, Luminosity Monitor and Low Q2-Tagger for Electron Beam
eRD14	An integrated program for particle identification (PID)
eRD15	R&D for a Compton Electron Detector
eRD16	Forward/Backward Tracking at EIC using MAPS Detectors
eRD17	BeAGLE: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing/Saturation Regime
eRD18	Precision Central Silicon Tracking & Vertexing
eRD19	Detailed Simulations of Machine Background Sources and the Impact to Detector Operations
eRD20	Developing Simulation and Analysis Tools for the EIC
eRD21	EIC Background Studies and the Impact on the IR and Detector design
eRD22	GEM based Transition Radiation Tracker R&D
eRD23	Streaming Readout for EIC Detectors
eRD24	Silicon Detectors with high Position and Timing Resolution as Roman Pots at EIC
eRD25	Si-Tracking
eRD26	Pulsed Laser System for Compton Polarimetry
eRD27	High Resolution ZDC
eRD28	Superconducting Nanowire Detectors
eRD29	Precision Timing Silicon Detectors for combined PID and Tracking System

Tracking | PID | Calorimetry | Software/Simulations | Other

The EIC R&D Programs (II)

Project R&D (2022-202?)

- aims at achieving the maturity required to carry out final design and construction for Detector-1
- will support only projects that are actual technologies used
- often called “targeted” R&D (although the project doesn’t like the term)
- `https://wiki.bnl.gov/conferences/index.php?title=General_Info`

Project R&D Projects 2022

Project	Topic
eRD101	mRICH / aerogel RICH
eRD102	dRICH
eRD103	hpDIRC
eRD104	Service reduction
eRD105	SciGlass
eRD106	Forward EMCAL
eRD107	Forward HCAL
eRD108	Cylindrical & Planar MPGD
eRD109	ASICs/Electronics
eRD110	Photosensors
eRD111	Si-Tracker (no sensors)
eRD102	ToF with AC-LGAD

- Guided by Detector Advisory Committee (DAC)
- Currently R&D funding not available due to Continuing Resolution in the US
- R&D plan will have to be adjusted depending on the outcome of proposal selection program

Tracking | PID | Calorimetry | Sensors | Electronics

The EIC R&D Programs (II)

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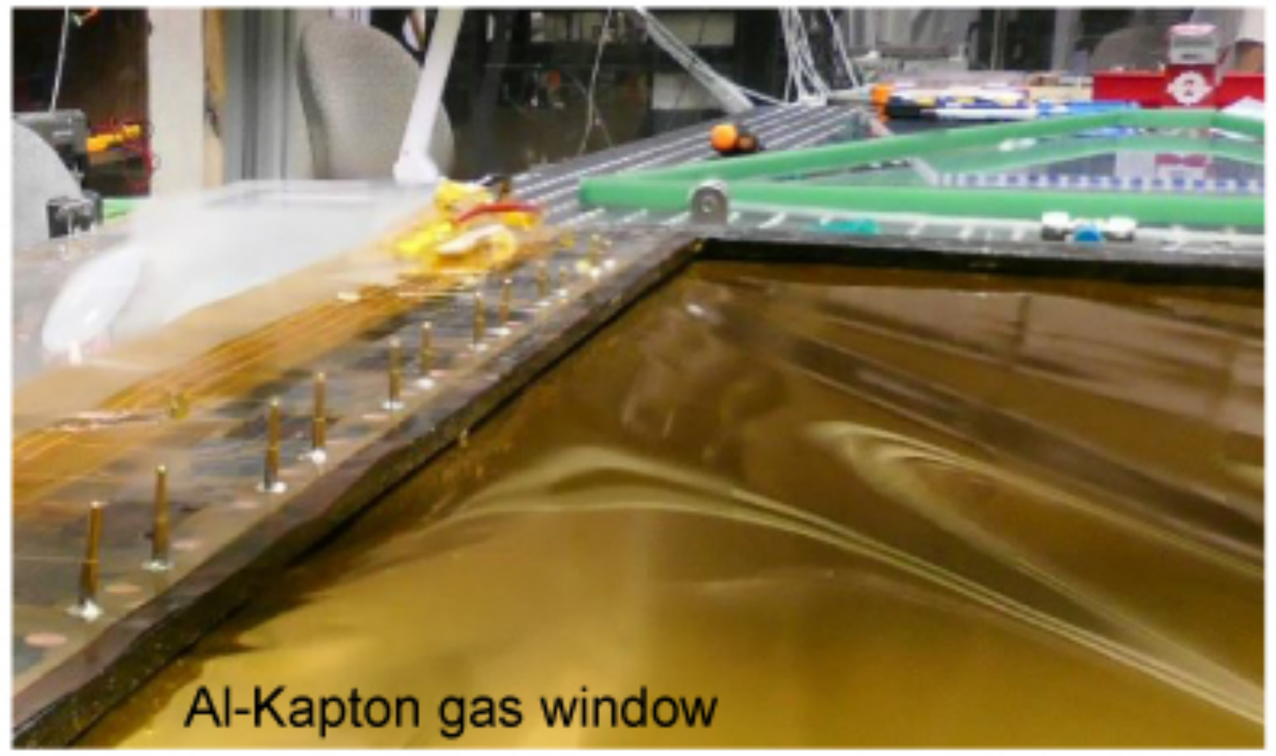
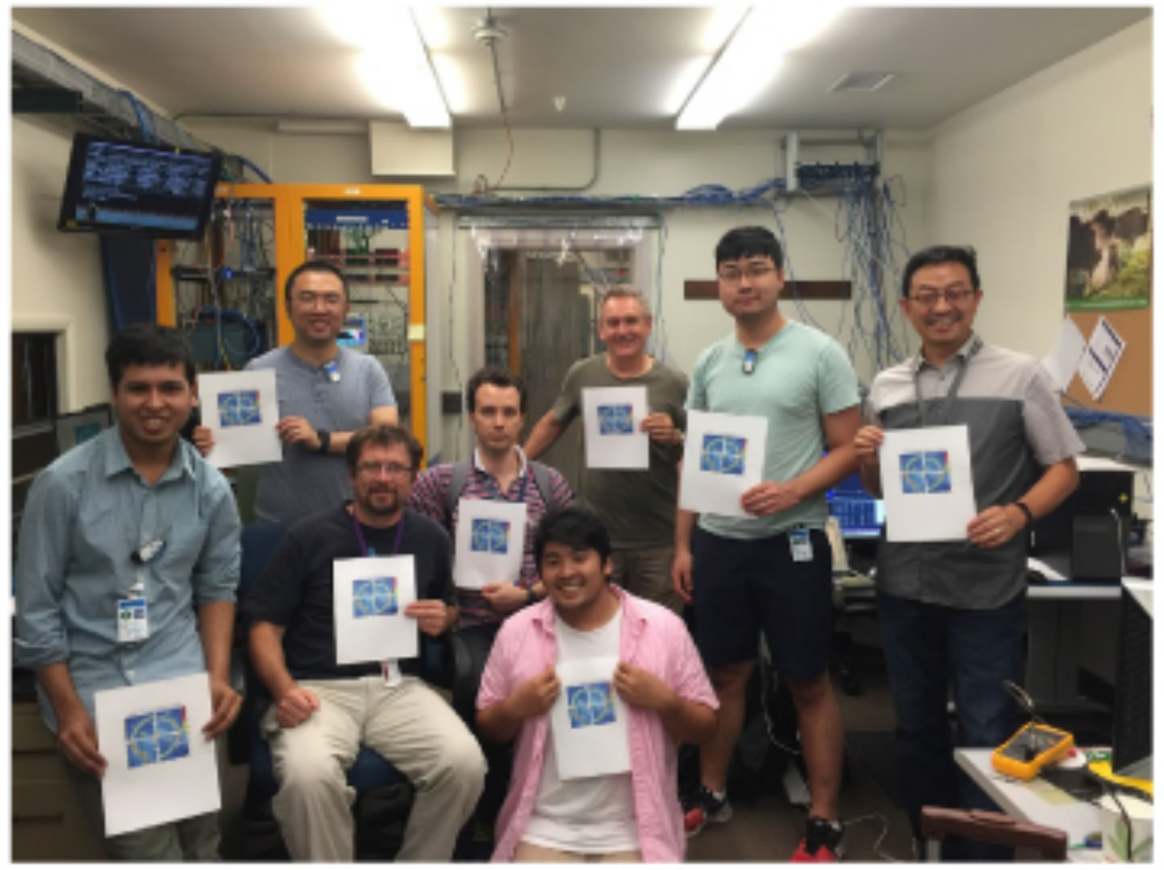
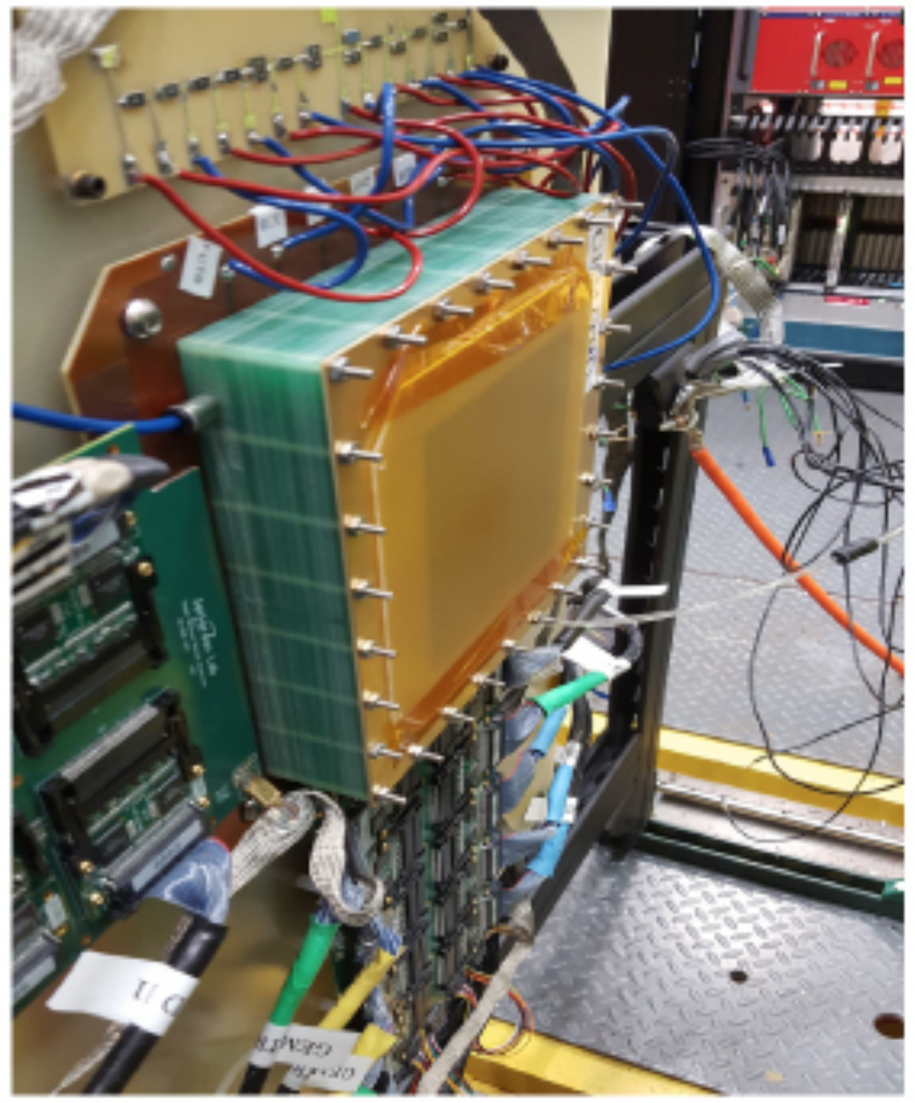
Generic R&D (2022 - …)

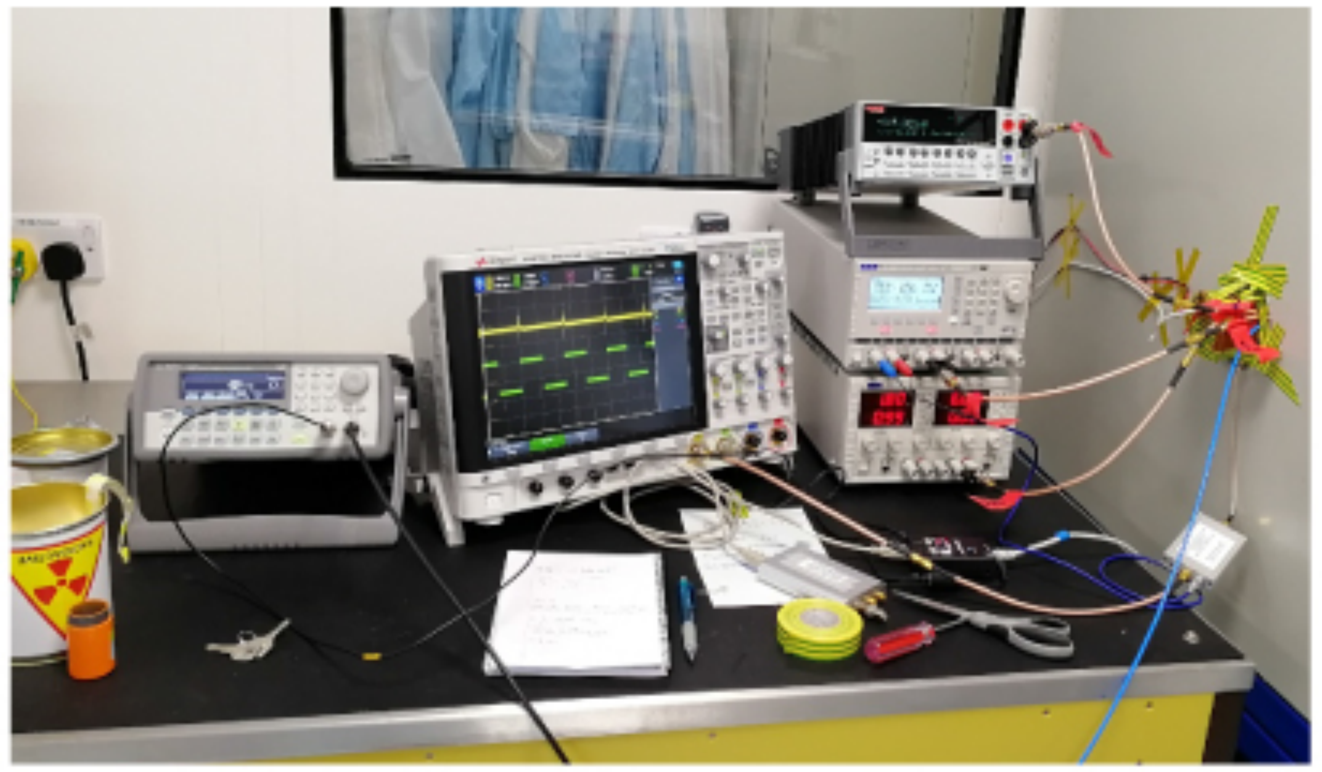
- after lots of effort (proposes, letters, pleas, begging) DOE reinstated the generic program (with even better funding)
- coordinated by JLab
- deadline for 1st round of proposals is 5pm EST on July 25, 2022.
- `https://www.jlab.org/research/eic_rd_prgm`

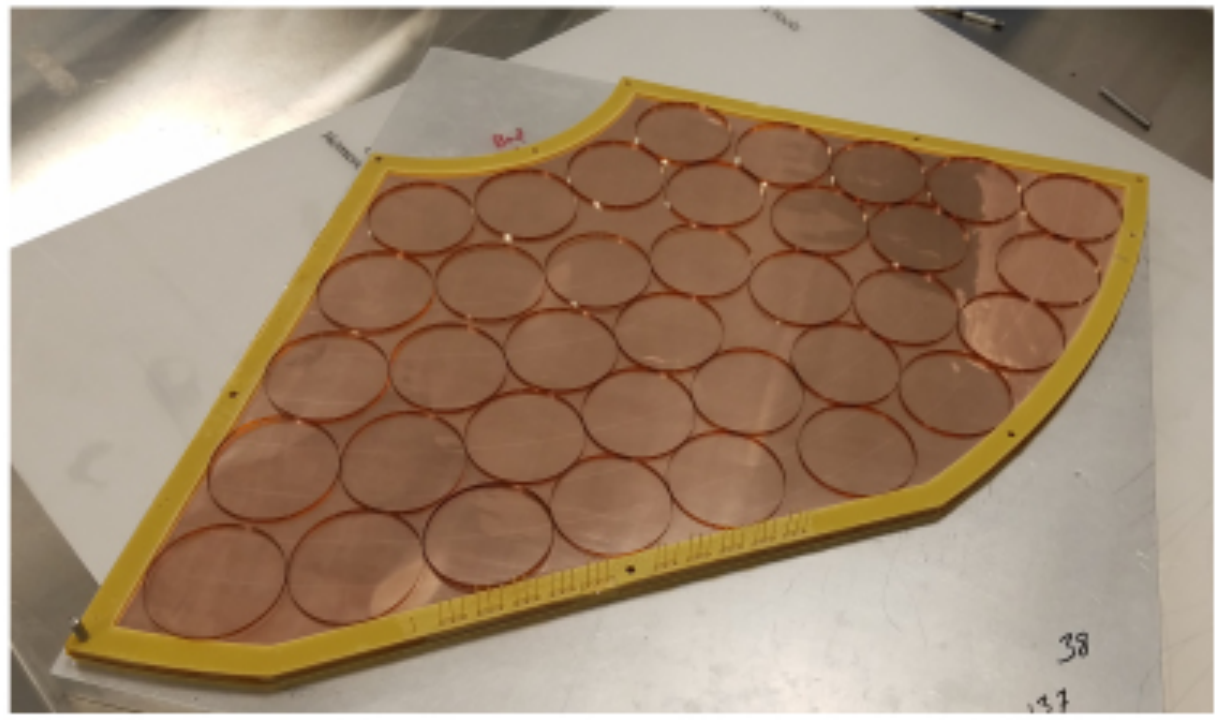
R&D - Inventing, Creating, Building, Teamwork











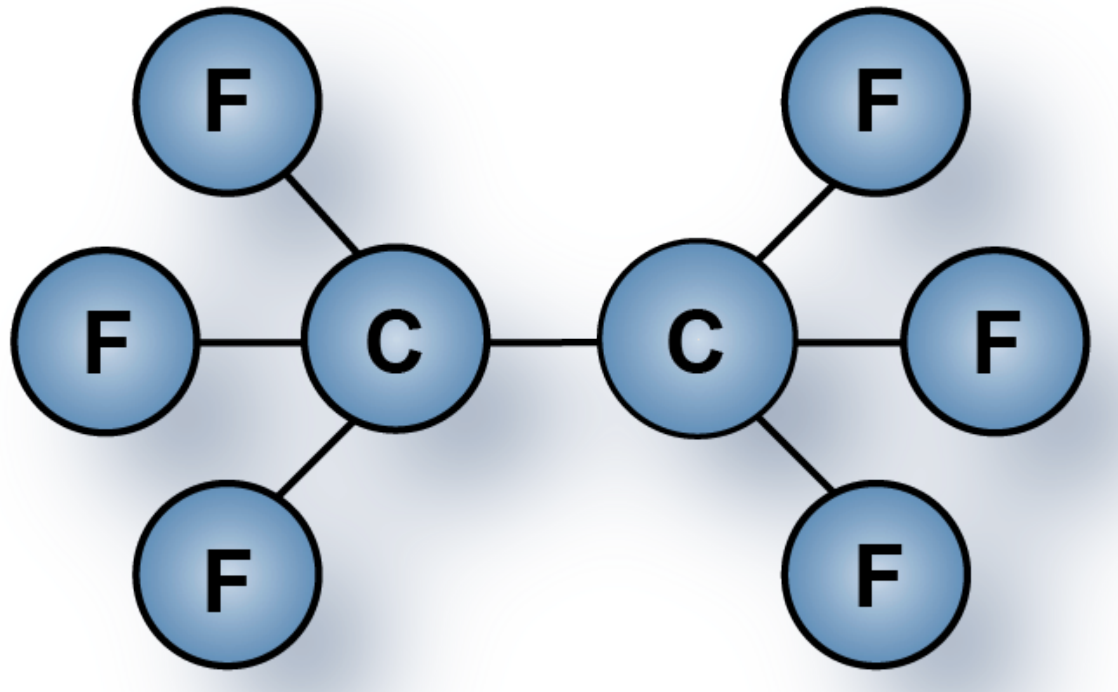
That is all Folks …. there will be no test

Thank you for listening and for your questions

Backup Slides

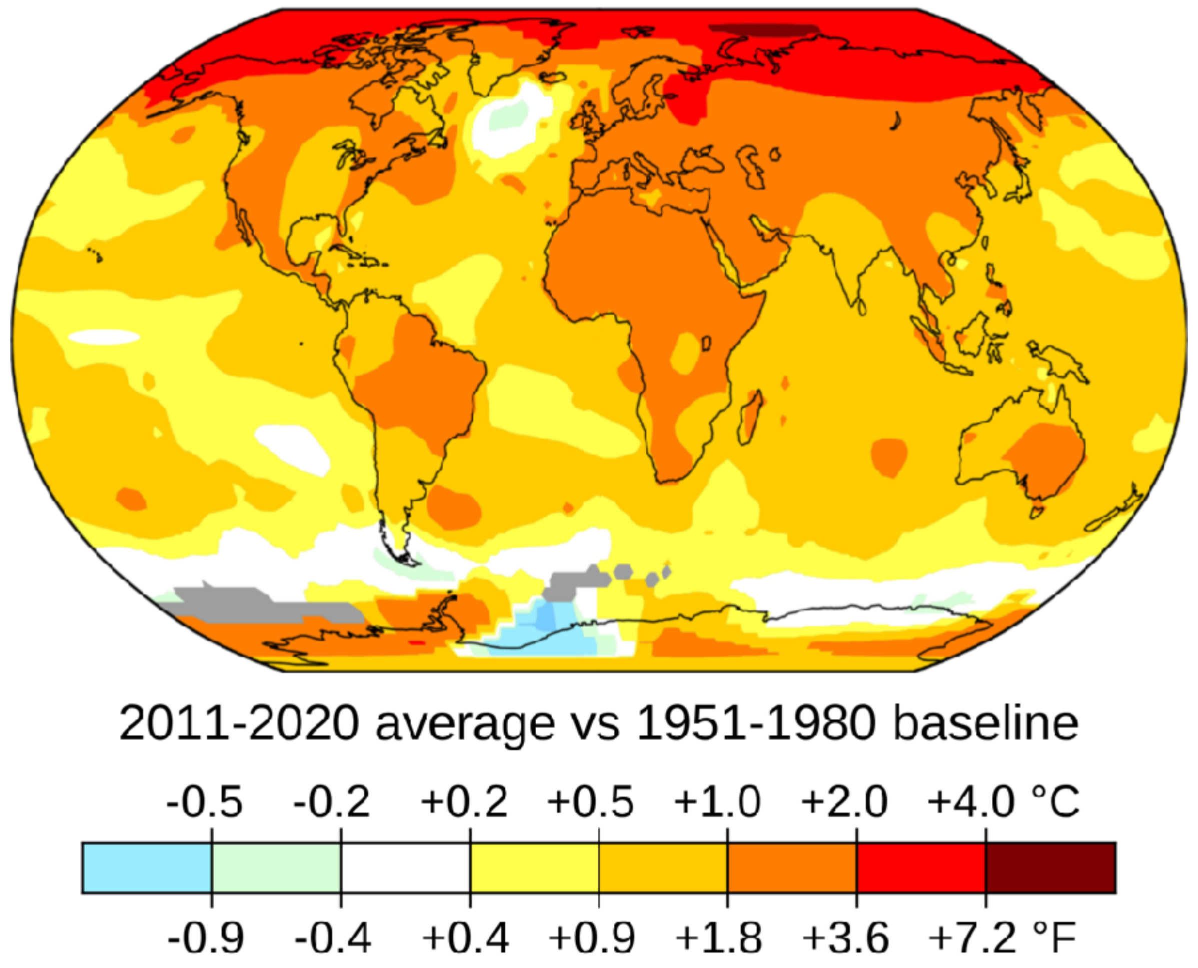
Example: Radiator Gases

- Radiator gases for EIC RICH detectors are fluorocarbons that exhibit extremely high Global Warming Power: GWP(C_2F_6) ~$\mathcal{O}$(10k), GWP(CO_2) = 1
- Increasingly prohibited across the world
- Where used
  - complex and expensive close circulation systems needed
  - increasing procurement issues expected
- RICH performance is preserved when fluorocarbons at atmospheric pressure are replaced with argon pressurized at a few bar
- The challenge is to design vessel that allows
  - safe high-pressure operation
  - minimizing its impact on the overall detector material budget.
  - engineering in progress - awaiting results



Formula	Name	Lifetime years	Global Warming Potential (GWP) 100-yr horizon	100-yr horizon	500-year horizon
			(SAR[a])	(AR4[b])	(AR4)
CF_4	PFC-14	50 000	6500	7390	11 200
C_2F_6	PFC-116	10 000	9200	12 200	18 200
C_3F_8	PFC-218	2600	7000	8830	12 500

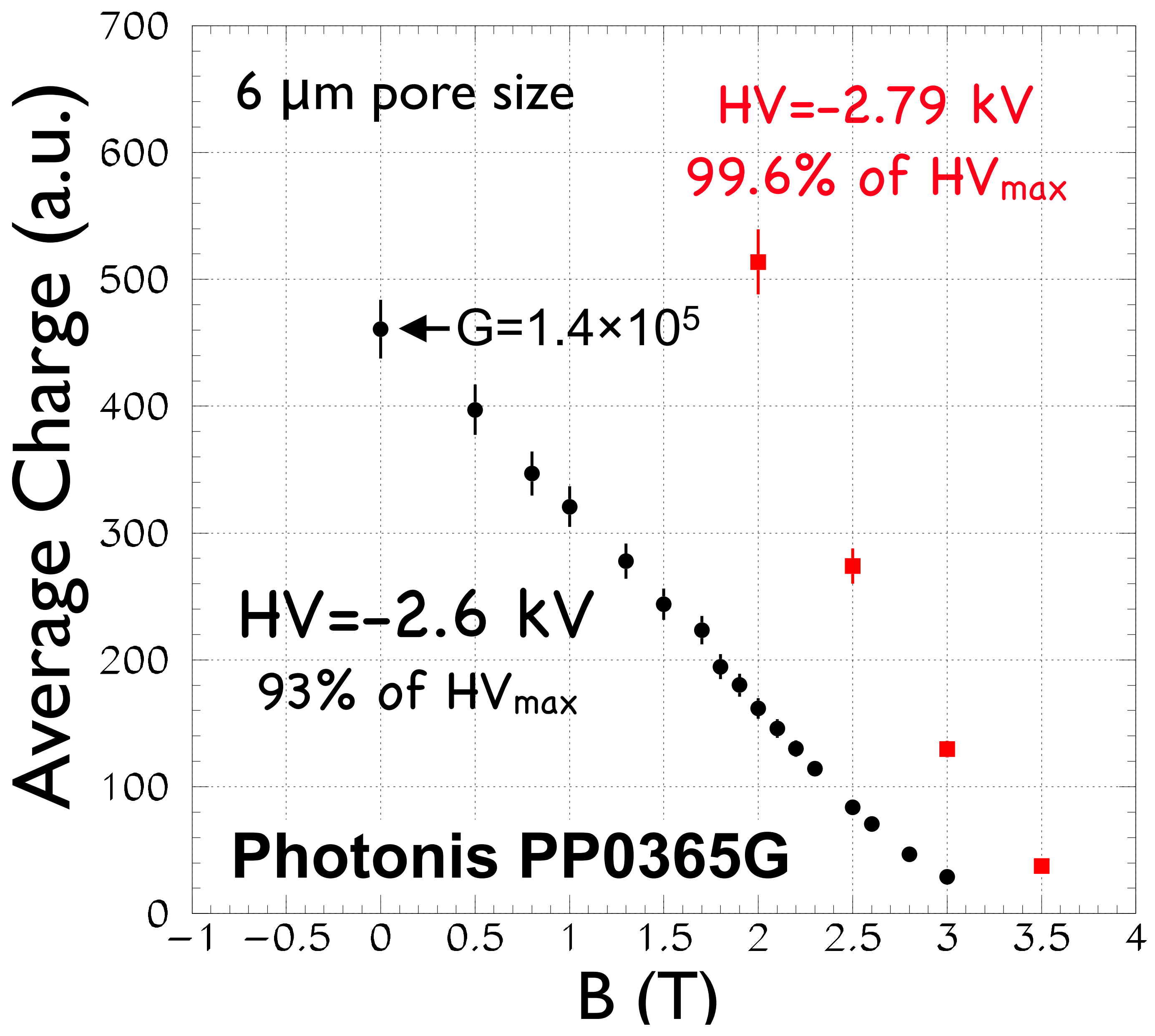
Temperature change in the last 50 years

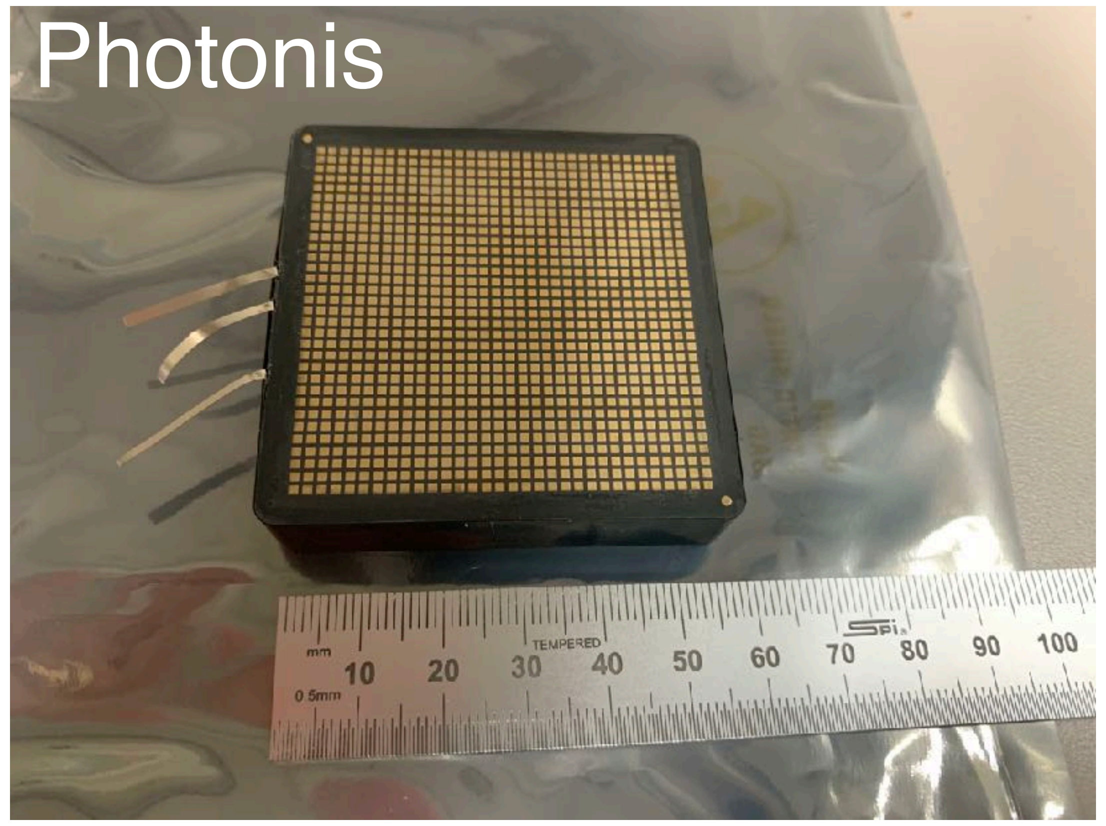


2011-2020 average vs 1951-1980 baseline

Example: Photosensors (eRD14 & eRD110)

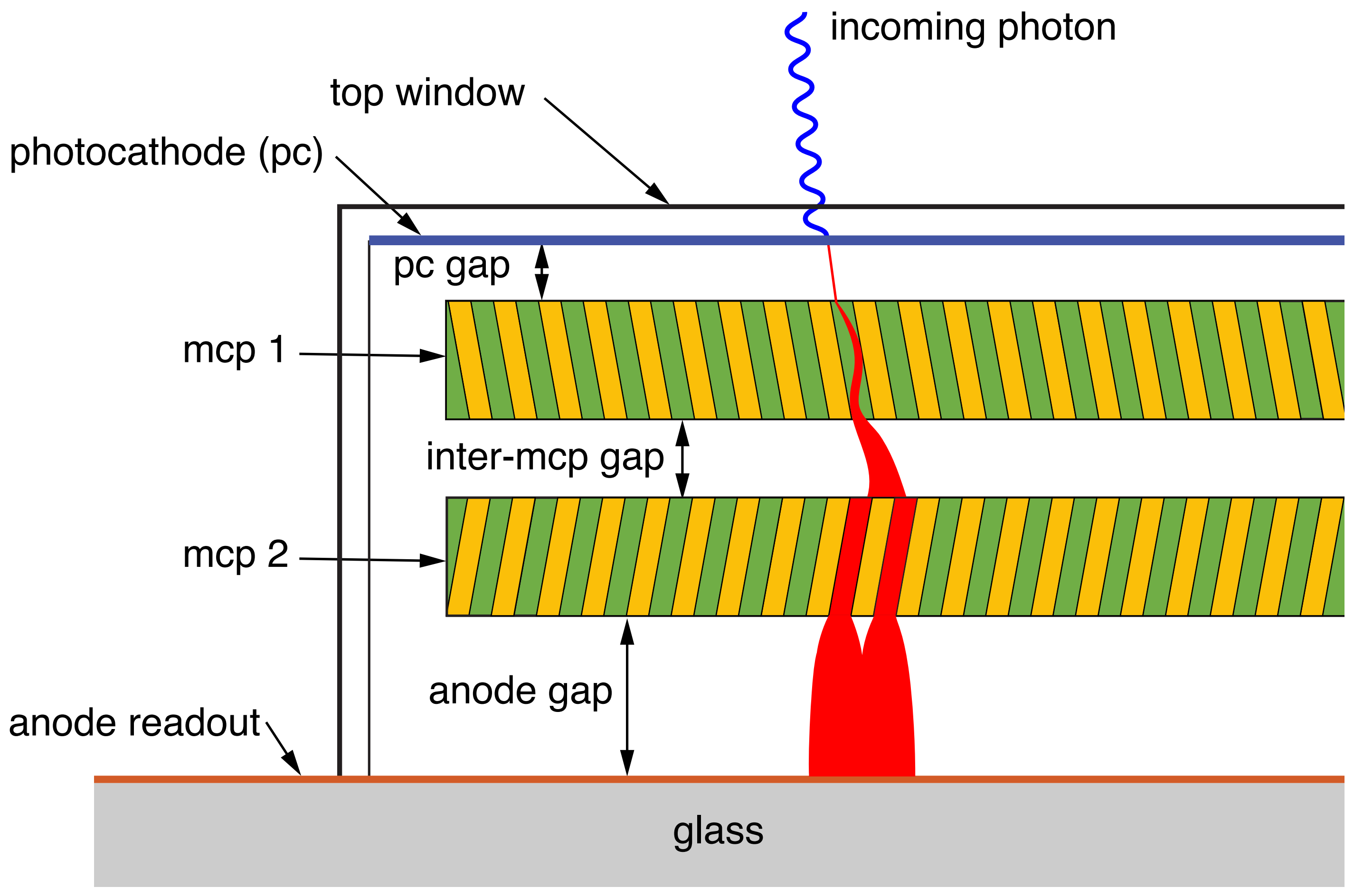
- EIC requires highly-pixilated photodetectors working at 1.5-3 T. This problem is most critical for RICH detectors and is not fully solved yet.
- Currently
  - Calorimetry ➟ SiPM (~OK)
  - RICH detectors ➟ SiPM (noise, mitigation strategies)
  - hpDIRC ➟ MCP PMT (~OK but expensive, field resistance on edge)
- MCP-PMTs
  - On market: Photonis/Photek
  - Characterization of performance in eRD14
  - Not tolerant to magnetic fields (angle!)
  - OK for hpDIRC (readout in low B region)
  - No collaboration with vendor



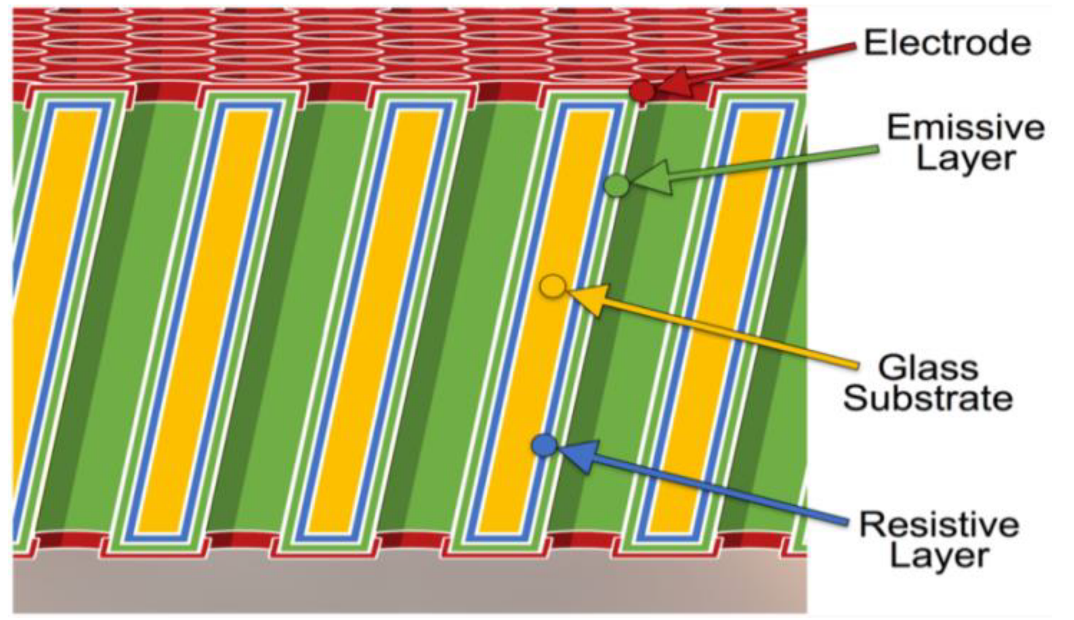


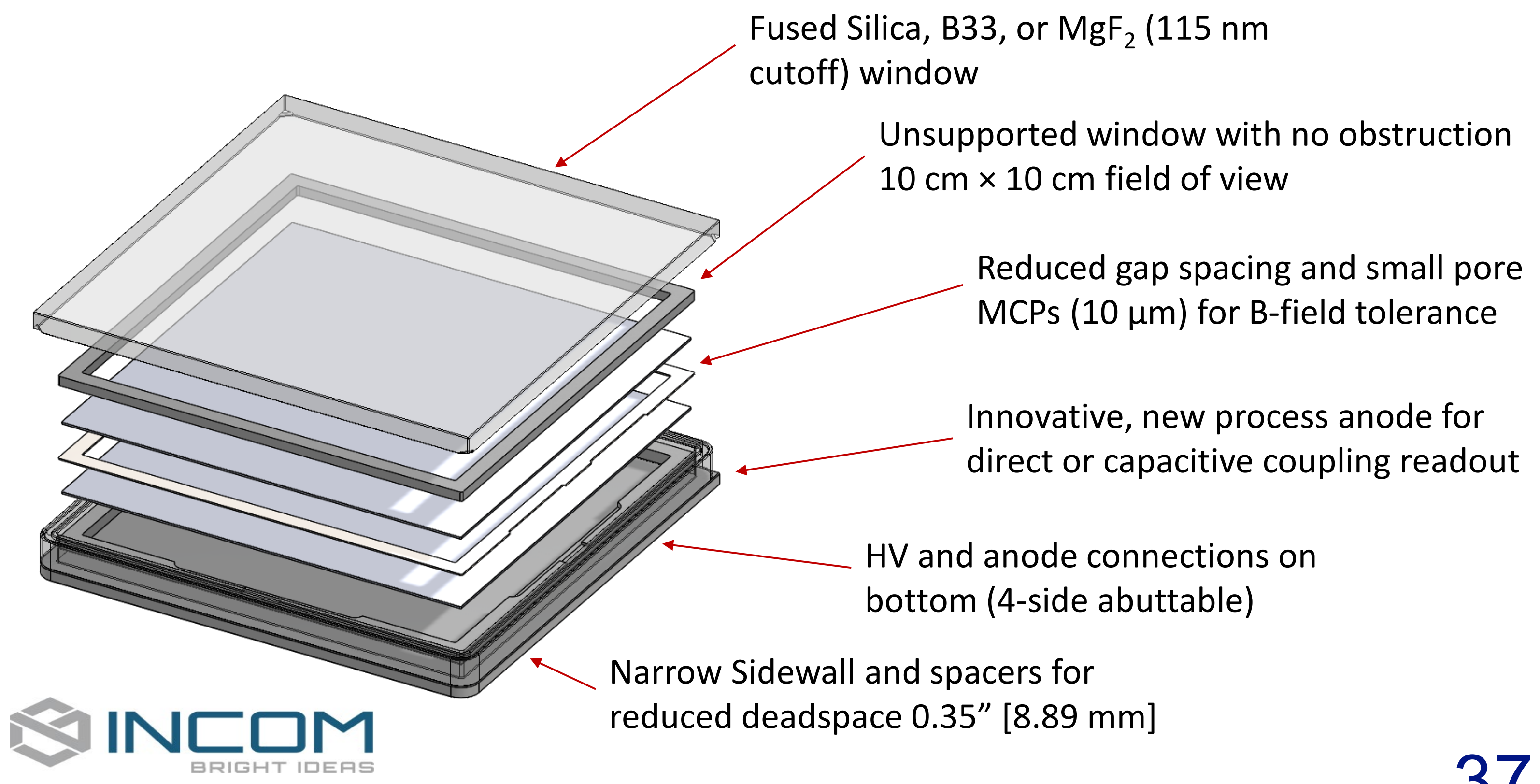
Example: Photosensors (cont.)

- LAPPD/HRPPD potential solution for EIC
  - Photon detector **+** ~10 ps ToF detector at the same time
- Large-Area Picosecond PhotoDetector (LAPPD)
  - Microchannel plate (MCP) based large area picosecond photodetector
  - Original LAPPD-Collaboration (HEP), now INCOM (Gen-II)
  - Promising but still not fully applicable for EIC needs
    - good but not sufficient field resilience
    - no pixelization
  - Efforts at ANL to develop pixelized more field resistant version in collaboration with INCOM
- High-Resolution Picosecond PhotoDetector (HRPPD)
  - In development by manufacturer (INCOM)
  - Novel multi-anode direct readout
  - Reduced gap spacing for improved timing resolution and B-Field tolerance
  - DOE SBIR support



ALD+ glass substrate MCP: cross section





Energy Loss by Ionization and Excitation

Bethe-Bloch formula

- mean rate of energy loss, or stopping power
  - ionization only + density and shell corrections
  - for moderately relativistic charged particles ($m > m_e$)

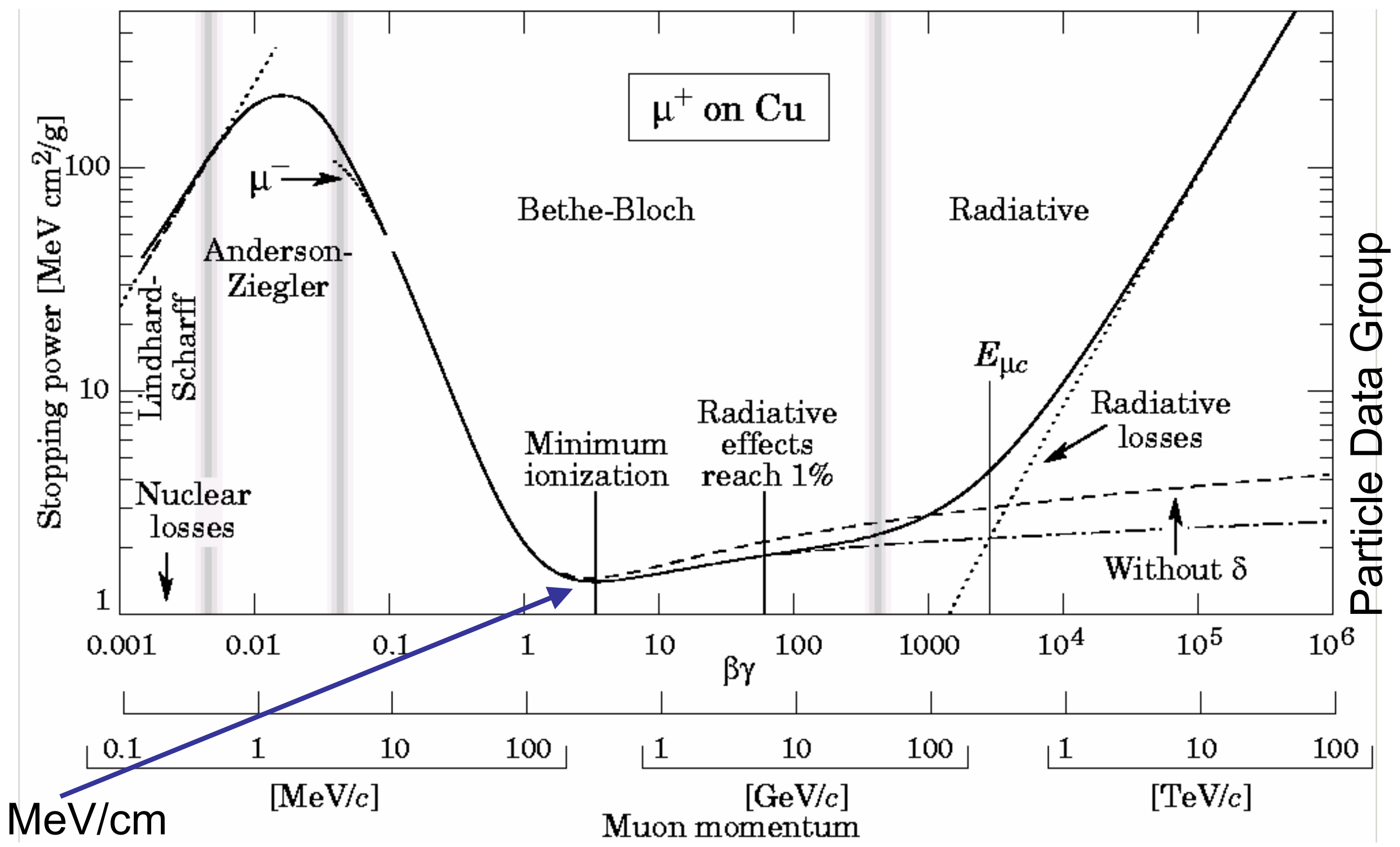
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T^{\max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

- MeV g^{-1} cm^2 ➔ beware x is (length)×(density)
- incident particle: z, β, γ, m, $T^{\max}$
- absorber: Z, A, I, δ, C (atomic shell corrections)

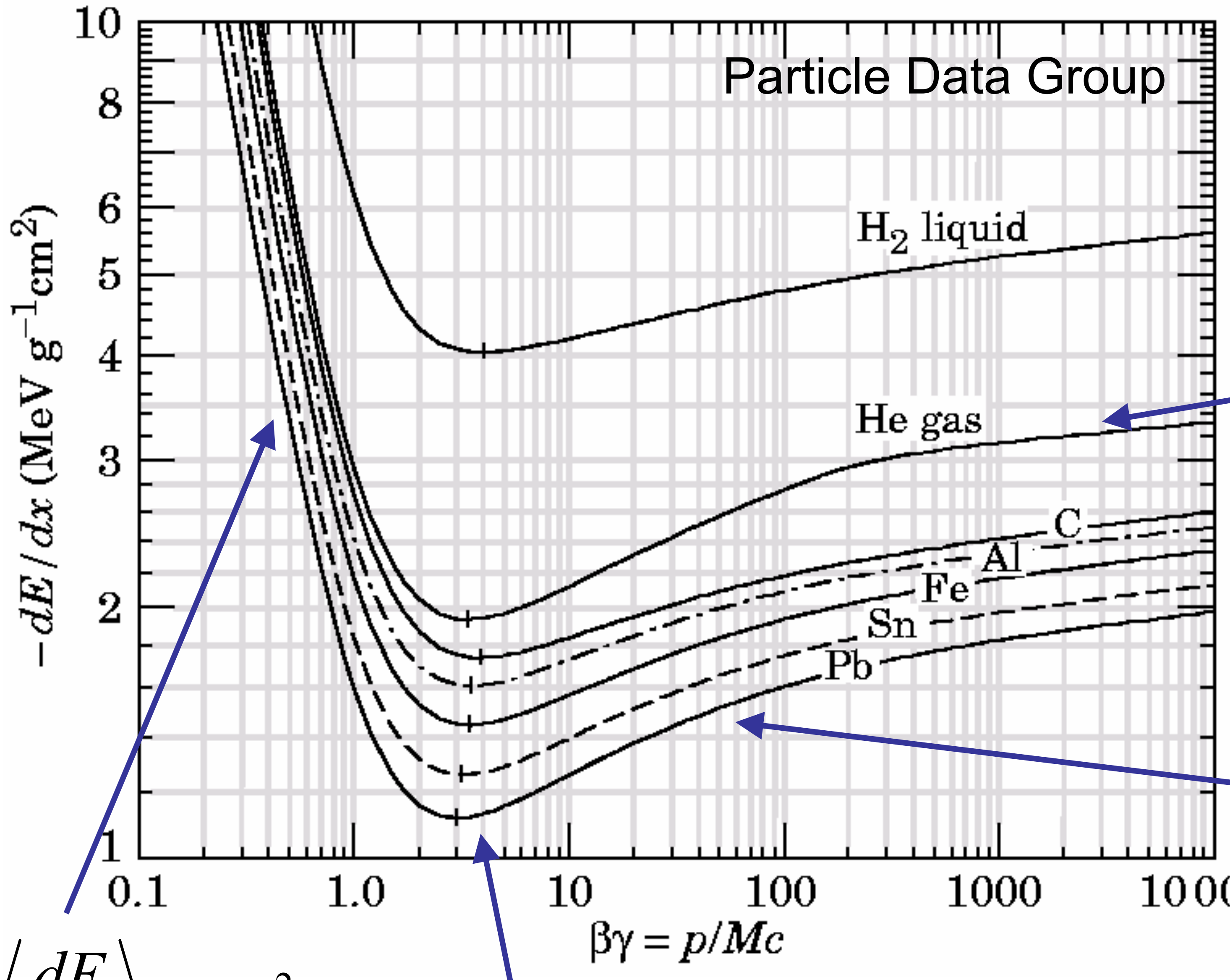
$I \approx 16 Z^{0.9}$ eV for $Z > 1$ — ionization constant

$\delta \approx 2\ln\gamma + \text{constant(material)}$ — density effect ➔ Fermi plateau

- constant: $4\pi N_A r_e^2 m_e c^2 = 0.3071$ MeV $cm^2 mol^{-1}$



12.90 MeV/cm



$\frac{Z}{A} = 1$

"density effect", "Fermi plateau"

$\frac{Z}{A} \approx 0.5$ ~ electron density

$\left\langle \frac{dE}{dx} \right\rangle \propto \ln\beta^2\gamma^2$ "relativistic rise"

$\left\langle \frac{dE}{dx} \right\rangle \propto \beta^{-2}$ "kinematical term"

$\beta\gamma \approx 3$ to 4 MIP (minimum ionizing particle)