Detector design concept of the EIC

Particle Identification

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Inspired by presentations from D. Cockerill, S. Easo , T. Hemmick, A. Kiselev, A Papanestis, D. Petyt, O. Tsai

Outline: PID

- Particle Identification techniques:
  - Ionization energy loss
  - Time of Flight
  - Cherenkov radiation
    - RICH
    - DRICH
    - mRICH
  - Transition radiation (again)
- Summary

Particle Identification

- **PID for hadrons**

  Differentiate between π, K, p, d

  Must-have for “flavor physics”

- PID for e/γ

  Distinguish between e, π, γ

  Kinematics(!), jets, flavor physics

TRD,
Ecal
Hcal
PF

Particle Identification ↔ Particle velocity

Lorentz boosts: $\gamma = \frac{E}{m}$ $\beta = \frac{|\bar{p}|}{E}$ $\beta\gamma = \frac{|\bar{p}|}{m}$

measure velocity → determine mass

Direct measurements:

Record signal time at multiple locations, find v
Must be fast == low transit time spread
(TOF)

Velocity-dependent interaction(s) with detector:

Specific Ionization Energy Loss (dE/dx)
(TPC, Si, …)

Cherenkov Radiation:
$\cos\theta_C = \frac{1}{n\beta}$
(RICH, dRICH, mRICH,…)

Specific Ionization Energy Loss

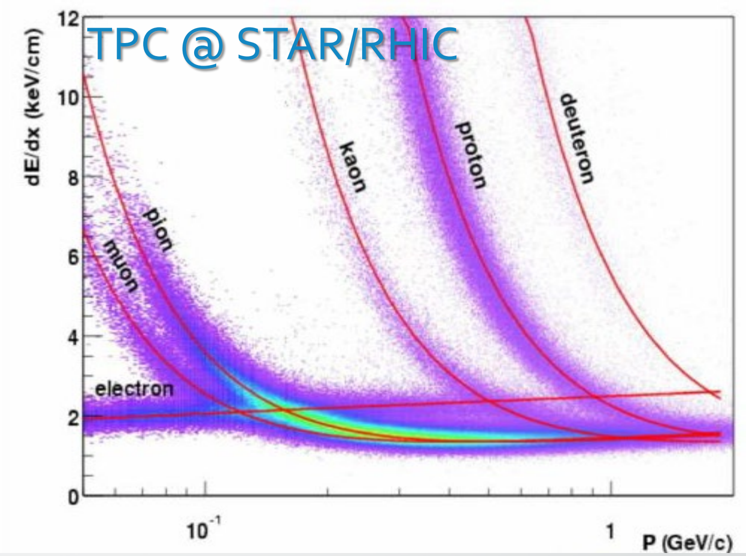
- Back to Bethe-Block formula

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi N e^4}{mc^2\beta^2} z^2 \left(\ln \frac{2mc^2\beta^2\gamma^2}{I} - \beta^2 \right)$$

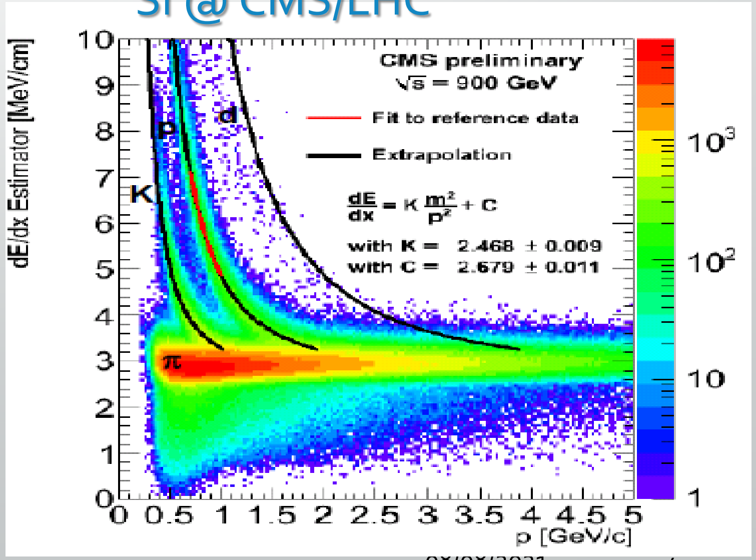
$$p = mv = m_0\beta\gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} ln(\beta^2\gamma^2)$$

- dE/dx measurements are best suited for PID at low momenta: $(0.2 < \beta < 0.9)$


TPC @ STAR/RHIC

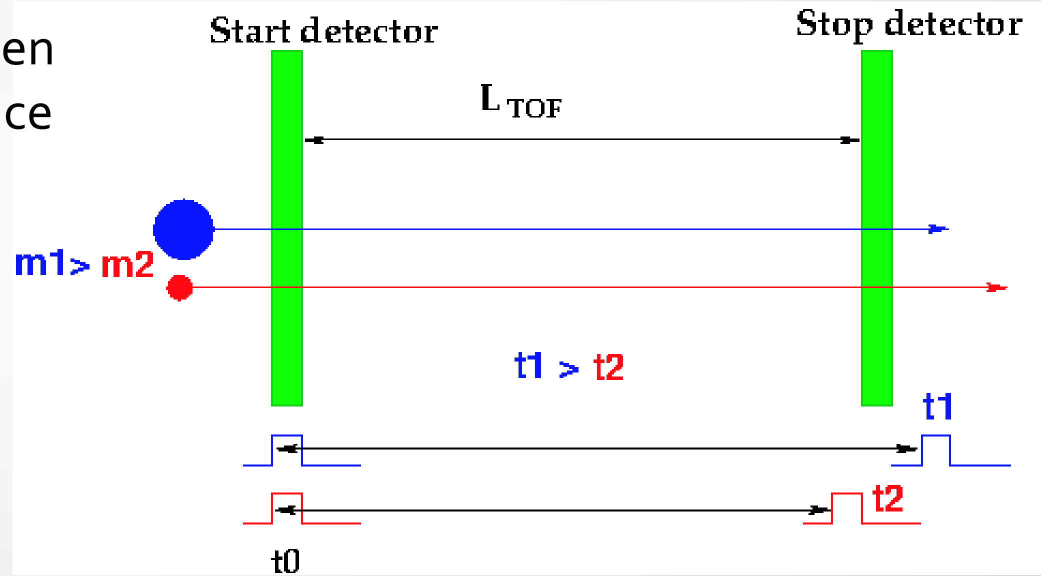
Si @ CMS/LHC



Time of Flight

- At more massive particle has smaller velocity at a given momentum → travels longer *time* over a given distance
- TOF design idea: assuming particle momentum is known (tracking), measure velocity

$$v = \frac{L_{TOF}}{(t_{stop} - t_{start})}$$ to extract mass



- Mass resolution depends on the momentum, path length and timing resolution

- Time difference for two particles with masses m_1 and m_2 for length L and momentum P :

$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left[\sqrt{\left(1 + \frac{m_1^2 c^2}{P^2}\right)} - \sqrt{\left(1 + \frac{m_1^2 c^2}{P^2}\right)}\right]$$

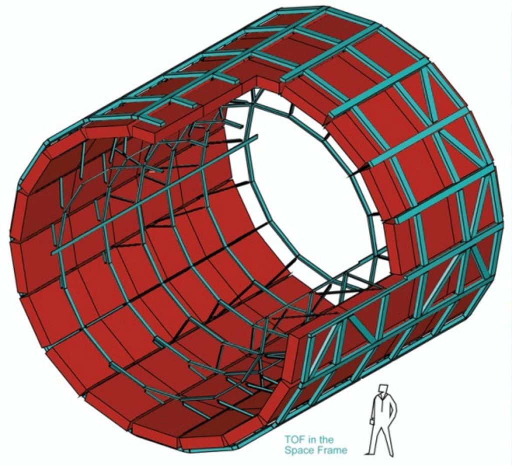
- For $P^2 \gg m^2 c^2$

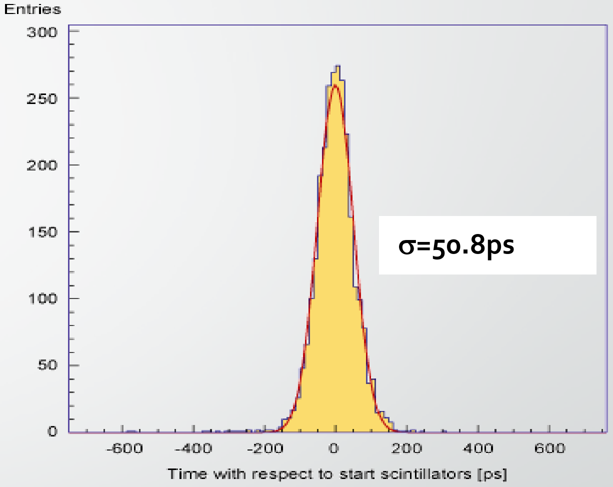
$$\Delta t \sim \frac{Lc(m_1^2 - m_2^2)}{2P^2}$$

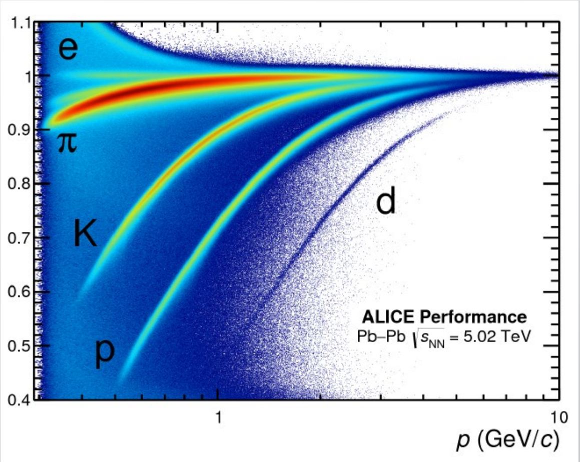
Time of Flight

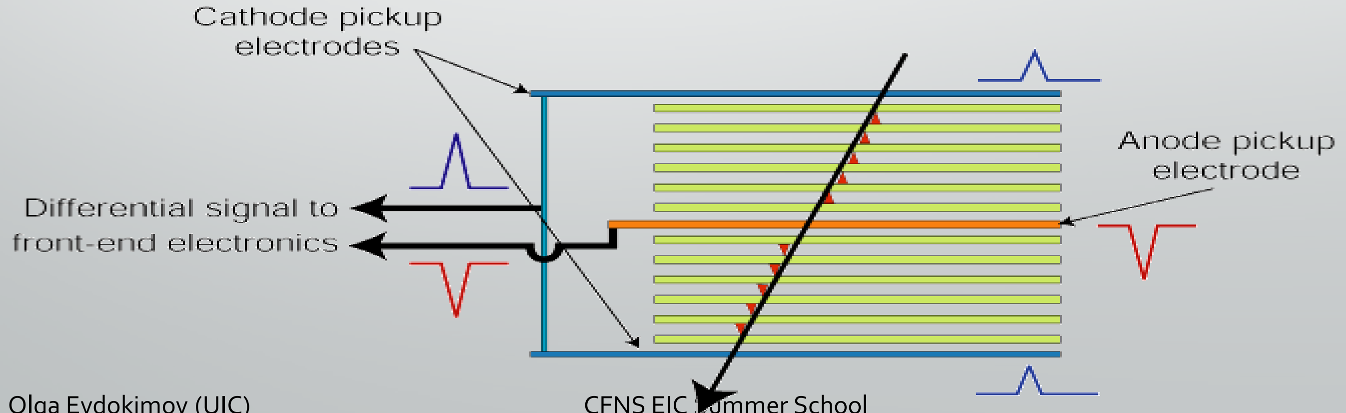
- Example: TOF @ ALICE/LHC:
  - 3σ π/K separation up to 2.2 GeV/c and K/p separation up to 4 GeV/c
  - MRPC with glass resistive plates
  - 2 × 5 gaps : 250 μm
  - Readout by High Performance Time to Digital Converter (HPTDC chip)

http://aliceinfo.cern.ch/Public/en/Chapter2/Chap2_TOF.html

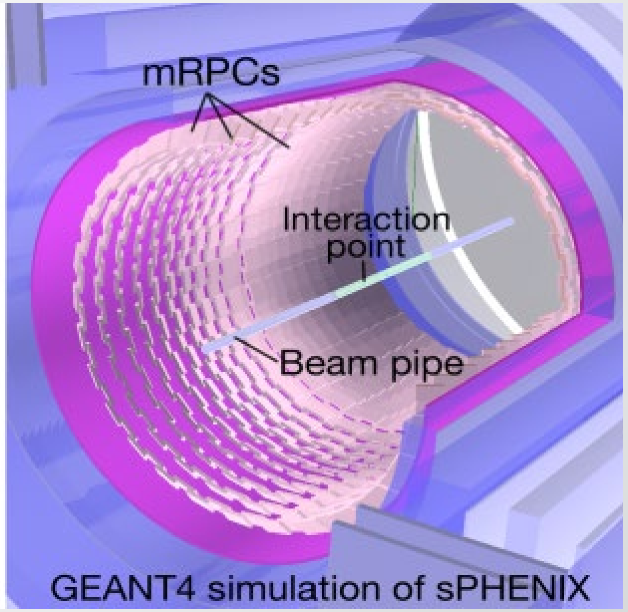








Time of Flight for EIC



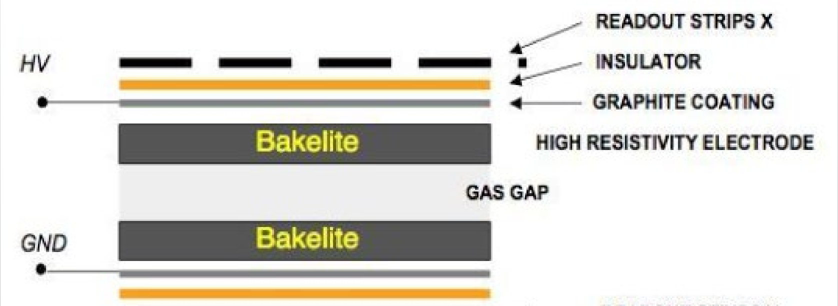
Considerations for EIC applications:

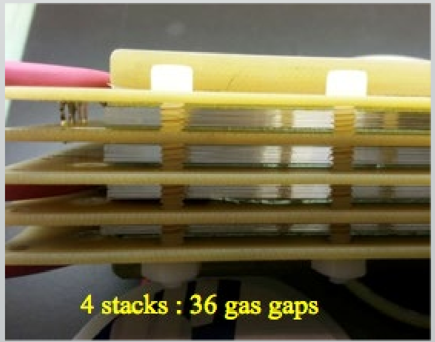
- Full mass resolution is a convolution of momentum, path length and timing resolutions

$$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right).$$

- → best if
  - large detector;
  - low momentum;
  - excellent timing

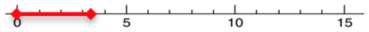
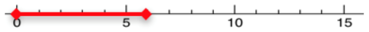
sPHENIX Multigap Resistive Plate Chamber (MRPC) R&D: achieved ~18 ps with 36-105 μm gaps



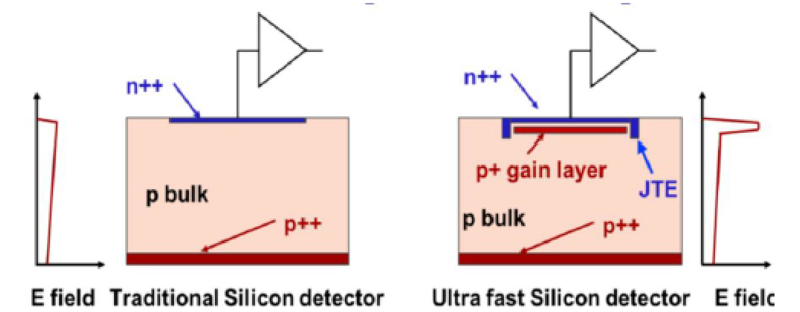


Time of Flight for EIC

- EIC simulation of TOF PID capabilities for 10 ps timing resolution:

		π/K	K/p
σ_{tot}=10 ps	1m (Barrel)		
σ_{tot}=10 ps	4m (Hadron)		

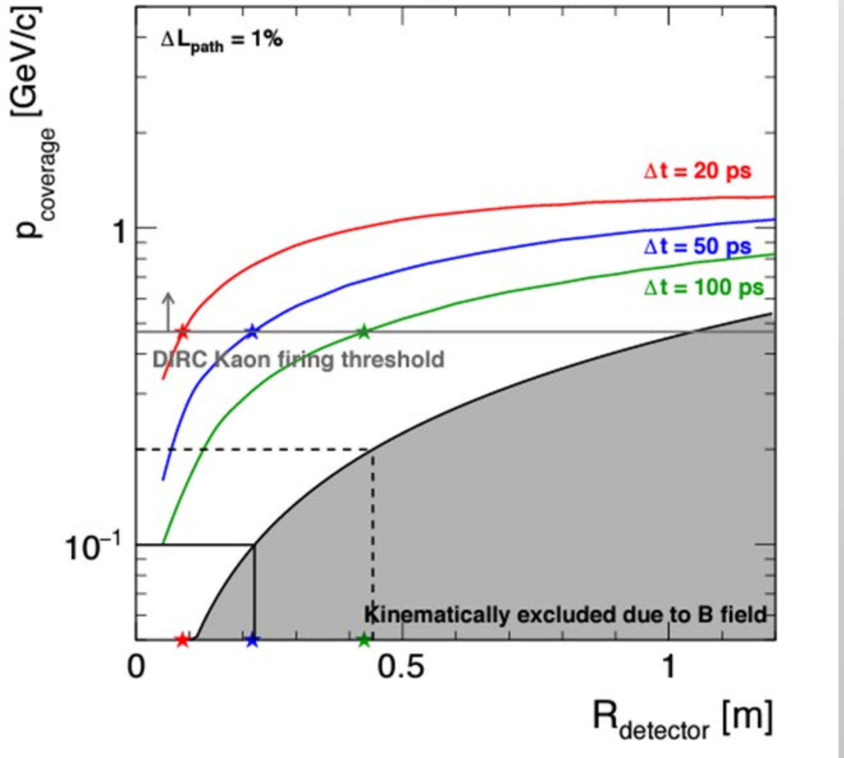
- R&D possibilities: fast silicon R&D
  - **LGAD**
    - DJ-LGAD, TI-LGAD
  - SSEM



S. Grinstein, IAS-HEP 2021

- TOF with better intrinsic resolution can be put closer to the interaction point → smaller area

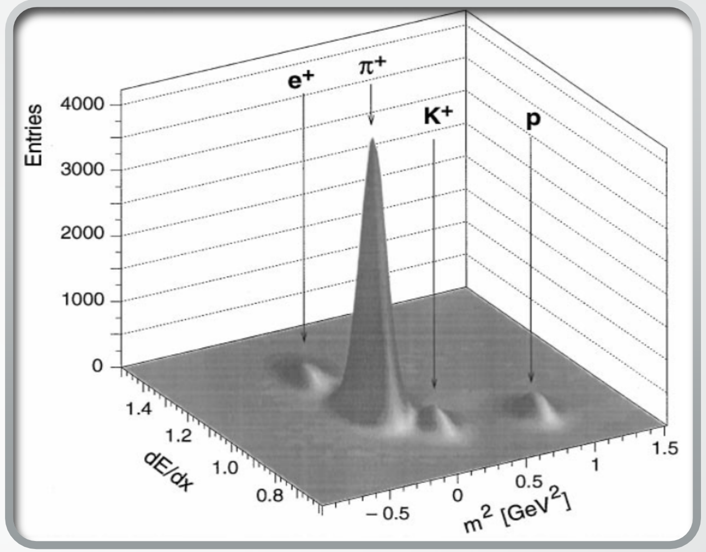
Central Barrel PID (Beast magnet 3T)

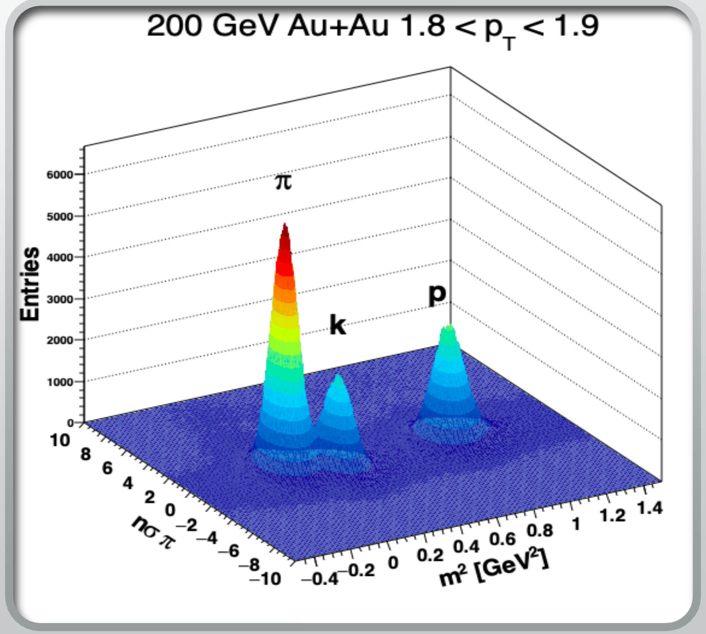


And Two are Better Than One

- Combining dE/dx and Time-of-flight measurements allows to enhance PID performance significantly

- Examples (TOF+TPC):
  - NA49 /SPS
  - STAR/RHIC



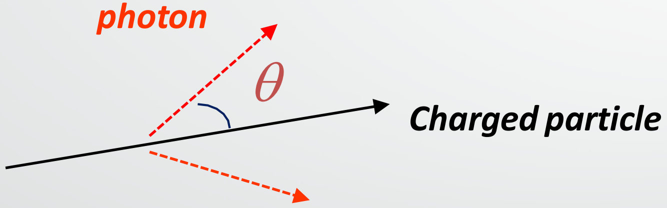


Cherenkov Radiation

- Cherenkov radiation is emitted when a charged particle moves through material faster than the speed of light in that medium: $\beta > \frac{1}{n}$

- It is emitted at an angle, defined by particle β and medium refractive index n:

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



- The energy radiated by the charged particle as Cherenkov Radiation per unit length

$$\frac{dE}{dx} = 4\pi^2 e^2 \int_{\beta n > 1} \frac{1}{\lambda^3}\left(1 - \frac{1}{\beta^2 n^2}\right) d\lambda$$

1958: P. Cherenkov, I. Frank , I. Tamm

"for the discovery and the interpretation of the Cherenkov effect"

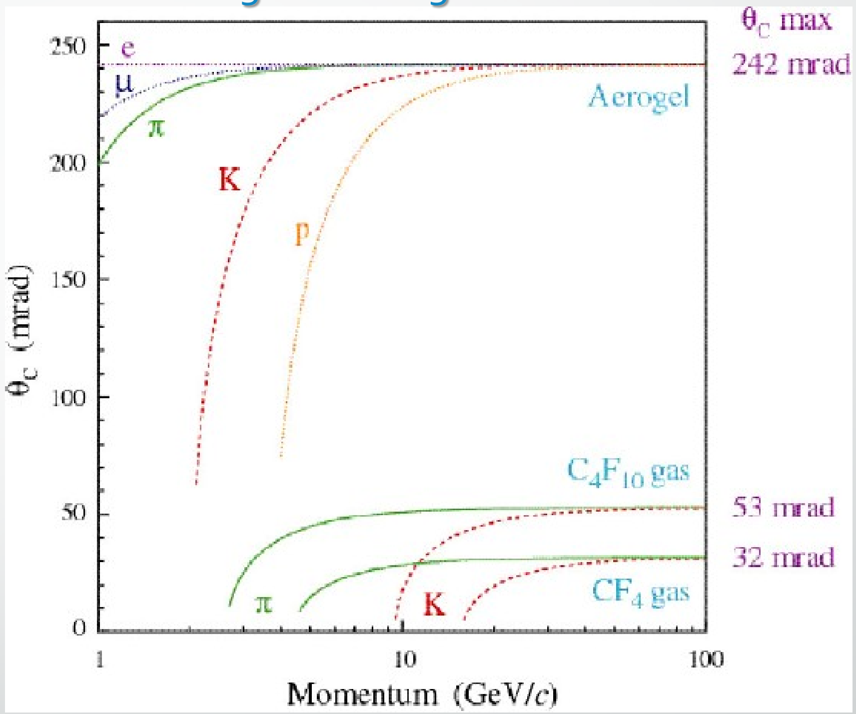
- 1888: Heaviside predicts the $\cos\theta = 1/(\beta n)$ dependance
- ~1900: Marie & Pierre Curie observe 'blue glow' in fluids containing concentrated Radium
- 1934: discovery and validation of Cherenkov effect : 1934-37
- 1937: full explanation using Maxwell's equations: I.M. Frank and I.E. Tamm

Cherenkov Detectors

Cherenkov Detectors:

- Threshold Counters
- Imaging Counters:
  - Differential Cherenkov Detectors
  - Ring Imaging Cherenkov Detectors (RICH)
    - Dual-radiator RICH (dRICH)
    - Modular RICH (mRICH)
  - Detector for Internally Reflected light (DIRC)
  - …

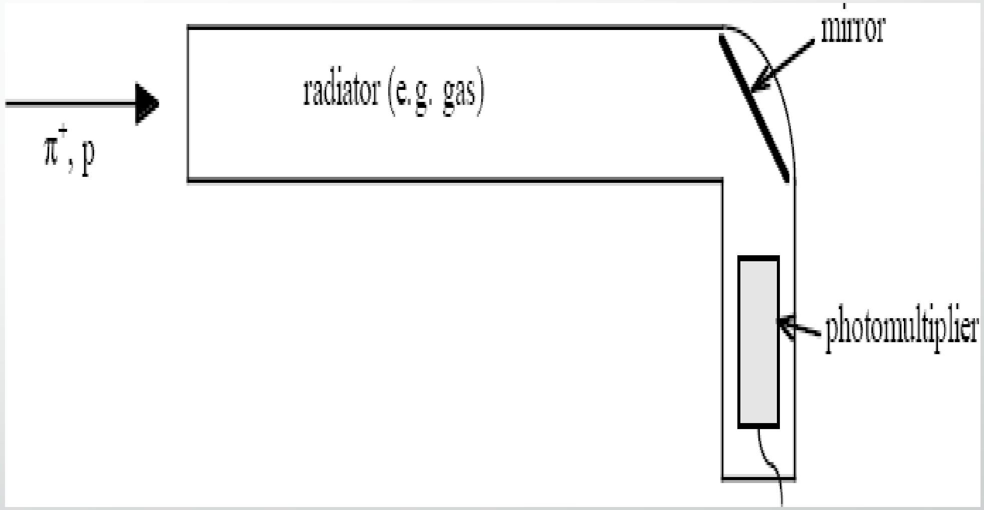
Cherenkov Angle vs Charged Particle Momentum



- Plus: types of Photodetectors:
  - Gaseous
  - Vacuum Based
  - Solid State

Threshold Counters

- Signal is (always) produced only by particles above Cherenkov Threshold, $\beta > \frac{1}{n}$



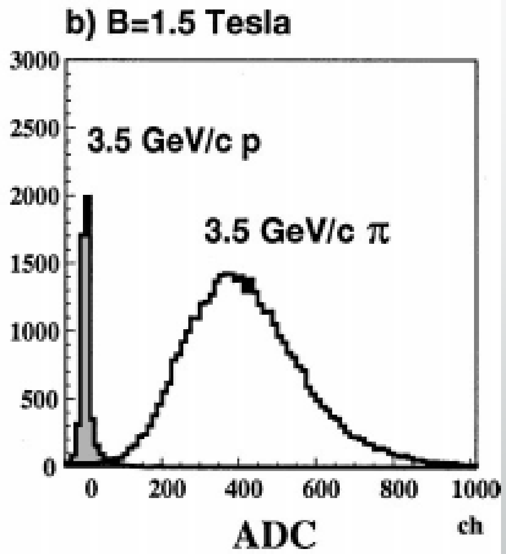
Threshold Counter:

- Basic version:
  - Yes/No decision on presence of particles
  - Counts the number of photoelectrons detected
- Improved version:
  - Use the number of observed photoelectrons or a calibrated pulse height to discriminate between particle types

Threshold Counters: BELLE's Example

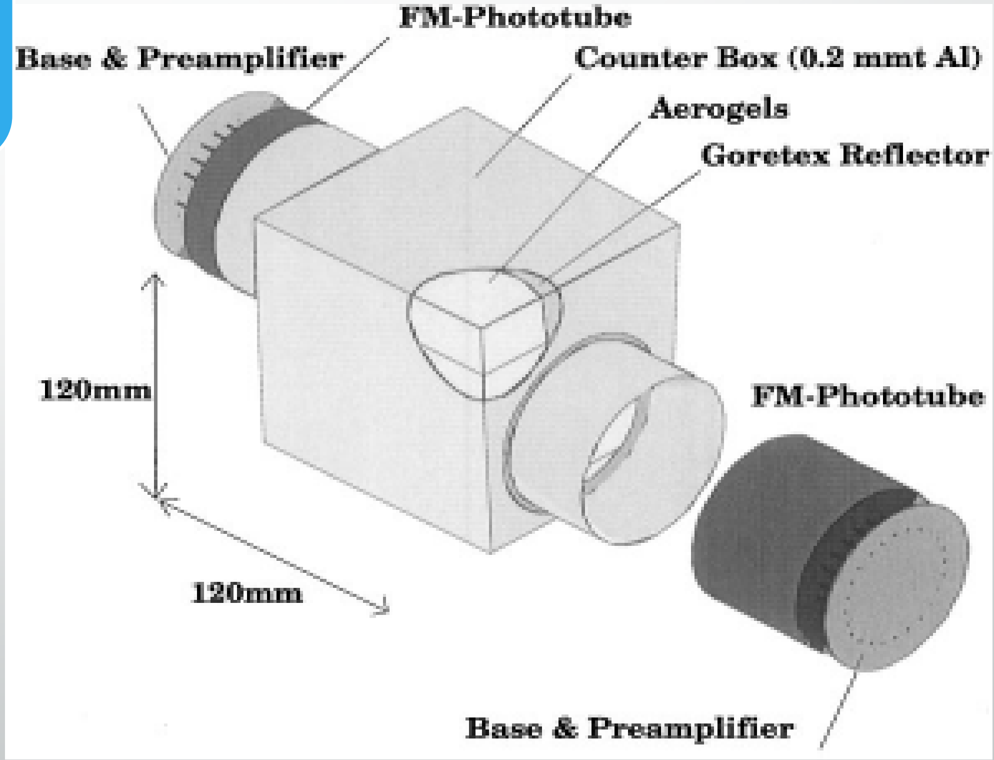
BELLE design: 5 aerogel tiles inside Al box lined with a white reflector

- Detects about 20 photoelectrons per pion @ 3.5 GeV
- More than 3σ π/p separation



Test-beam study

BELLE: Threshold Cherenkov Detector



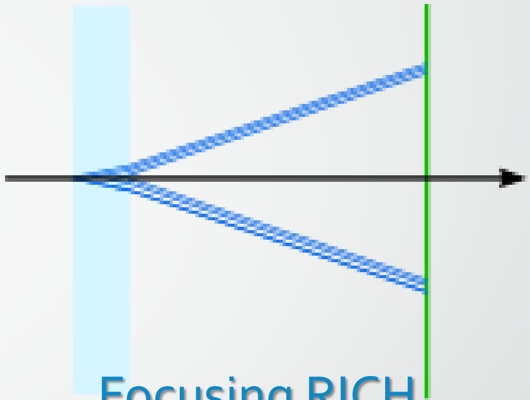
RICH Detectors

RICH - Ring Imaging Cherenkov detectors:

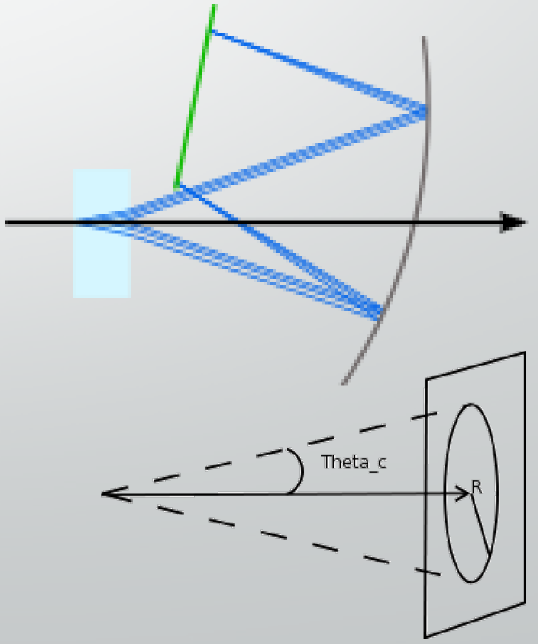
- Measure both the Cherenkov angle and the number of photoelectrons detected
- Can be used for PID over large areas
- Requires excellent photodetection (best with single photon ID capabilities)

Established technology, used in multiple experiments: DELPHI, ALICE, LHCb, …

Proximity RICH



Focusing RICH



Photon Detection

- Rather, detection of photoelectrons:
  - Convert γ to photoelectrons on photocathode
  - Detect those photoelectrons as “charged particles”
  - Measure the position and /or time
- Main options:
  - Gas based detectors: MWPCs, GEMs
  - Vacuum based detectors: PMT HPD
  - Solid state detectors: SiPMs

Making your choices:

Gaseous:

- Pros: can operate in high magnetic field; cheapest option
- Cons: issues related to photon and ion feedback; max resolution in visible wavelength range

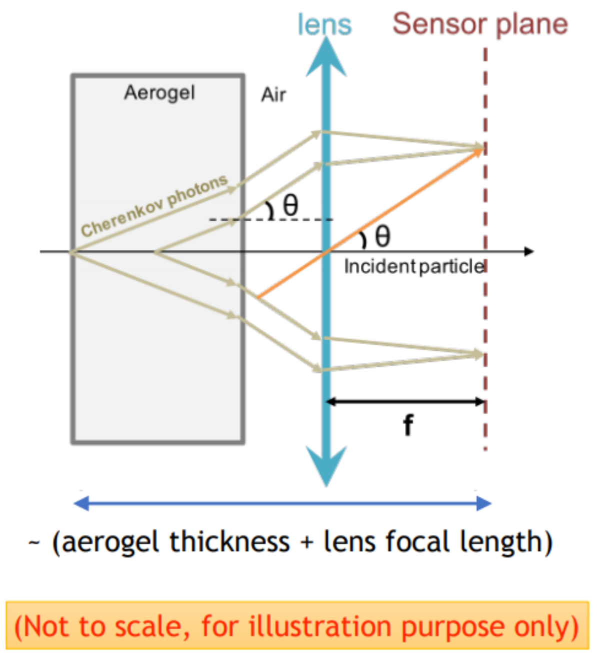
Vacuum-based:

- Pros: can operate at high rates (LHC); uniform gains / small noise
- Cons: sensitivity to magnetic field; active area fraction

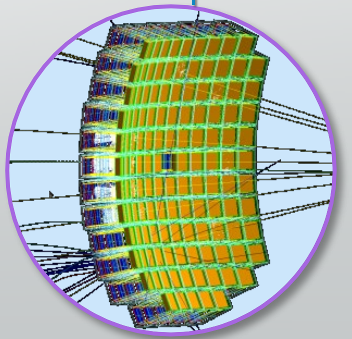
RICH Options for EIC

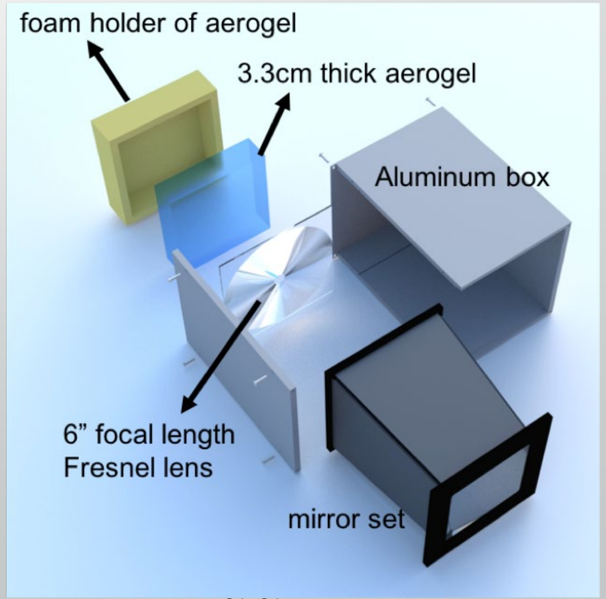
Modular RICH (mRICH)

- At EIC: possible option for backward (electron side) direction
- Particle ID at low/mid- momenta: allows pion/Kaon separation up to ~8 GeV; e/pion to ~4
- Design basics:
    - Radiator: aerogel (low density transparent radiator, $n\sim1.03$)
    - Reflector: Fresnel lens
    - Sensor: 3 mm pixel size, LAPPD



EIC Endcap matrix

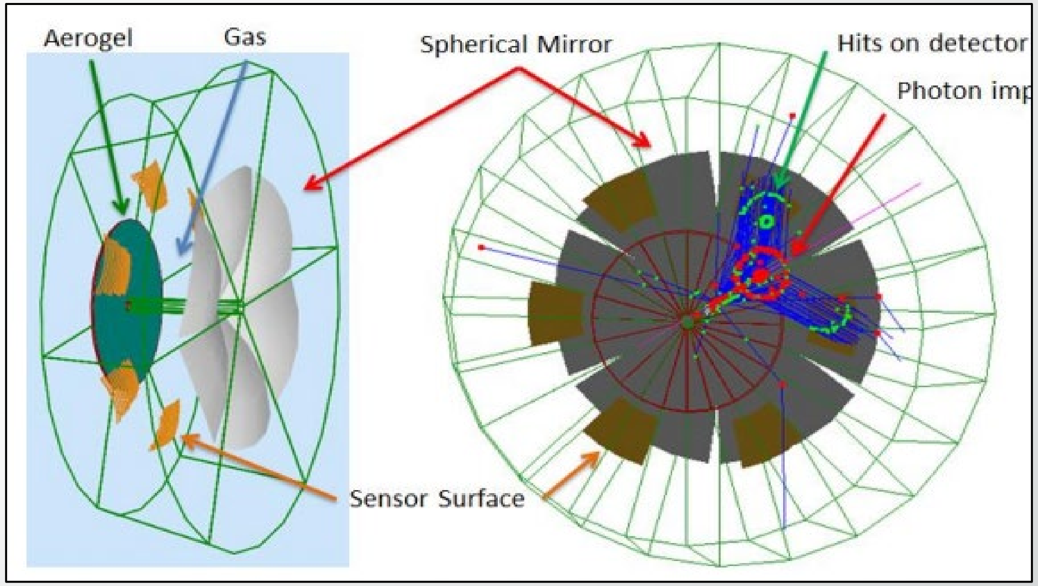


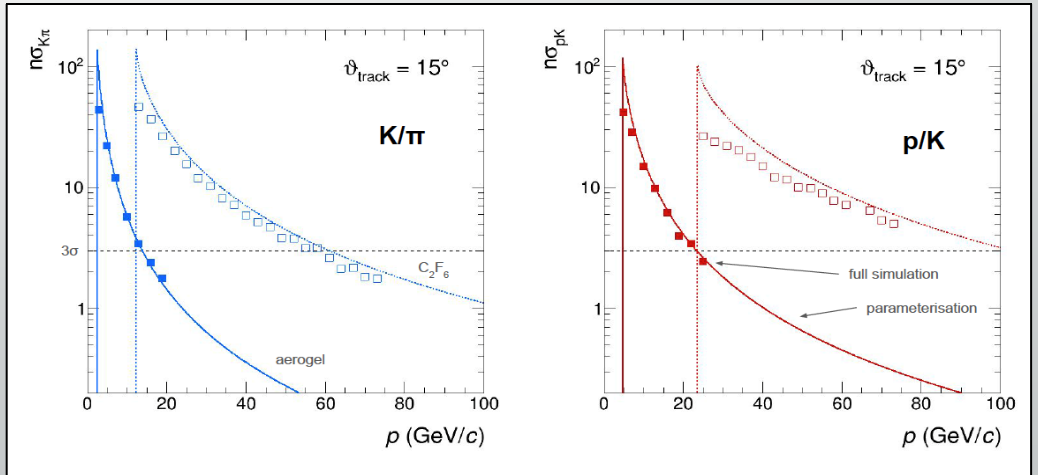


RICH Options for EIC

Dual-radiator RICH (dRICH)

- At EIC: considered implementation for forward (hadron) region
- Design basics:
  - Radiator: n = 1.02 (aerogel) , 1.0008 (C2F6)
  - Reflector: Spherical mirrors
  - Sensor: 3mm pixel size, MAPMT



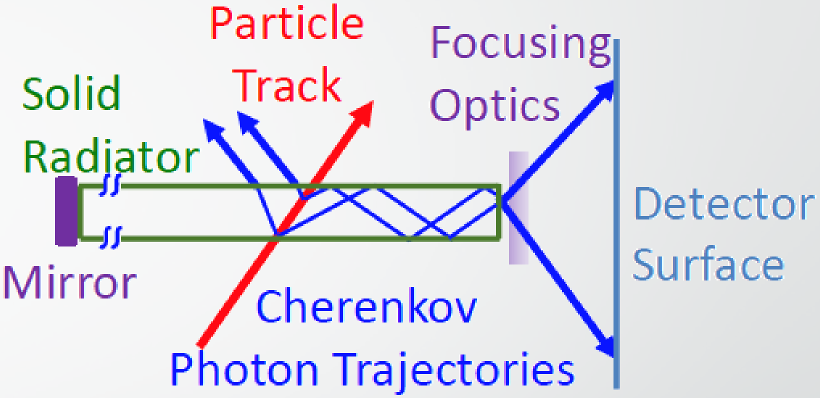


K/π and p/K separation as a function of momentum

RICH Options for EIC

DIRC

- "Detection of Internally Reflected Cherenkov (light)" – internally reflecting imaging Cherenkov detectors
- At EIC: possible option for central region
- Cerenkov light undergoes internal reflection
- With high-resolution timing can achieve π/K separation up to 6 GeV


Particle Track

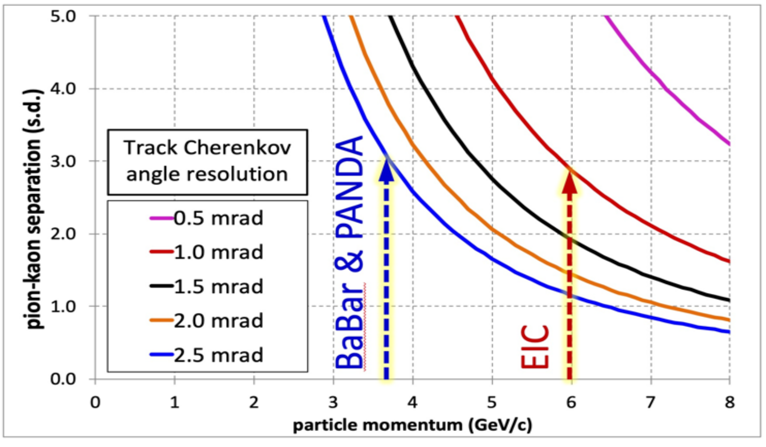
Focusing Optics

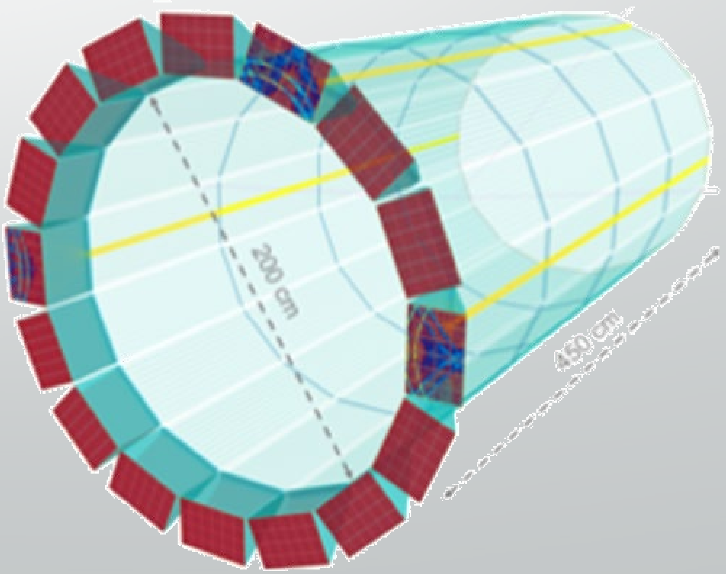
Solid Radiator

Detector Surface

Mirror

Cherenkov Photon Trajectories



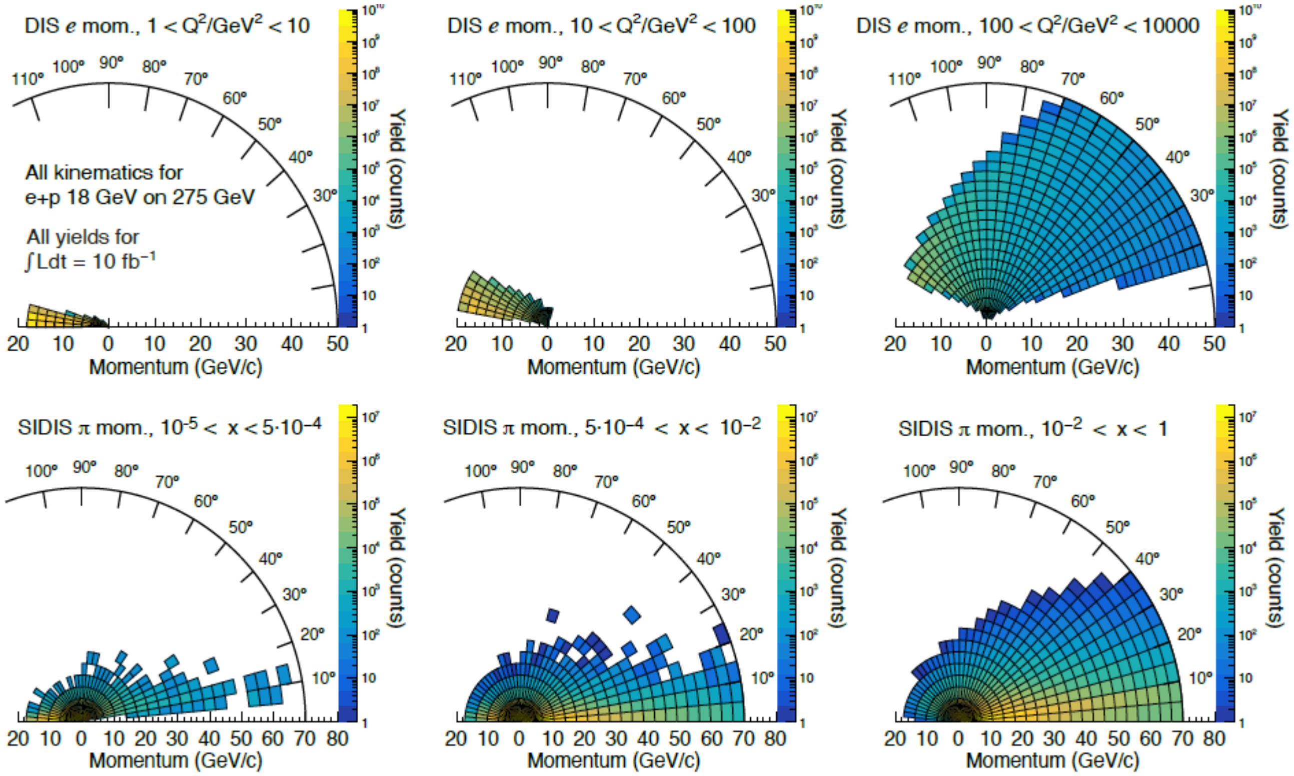


PID: Matching the EIC Kinematics

- Yellow Report:

DIS electron and SIDIS pion for $18\ GeV\ e^- \times 275\ GeV\ p$ beams

$1 < Q^2 < 10$ $10 < Q^2 < 100$ $100 < Q^2 < 1000$

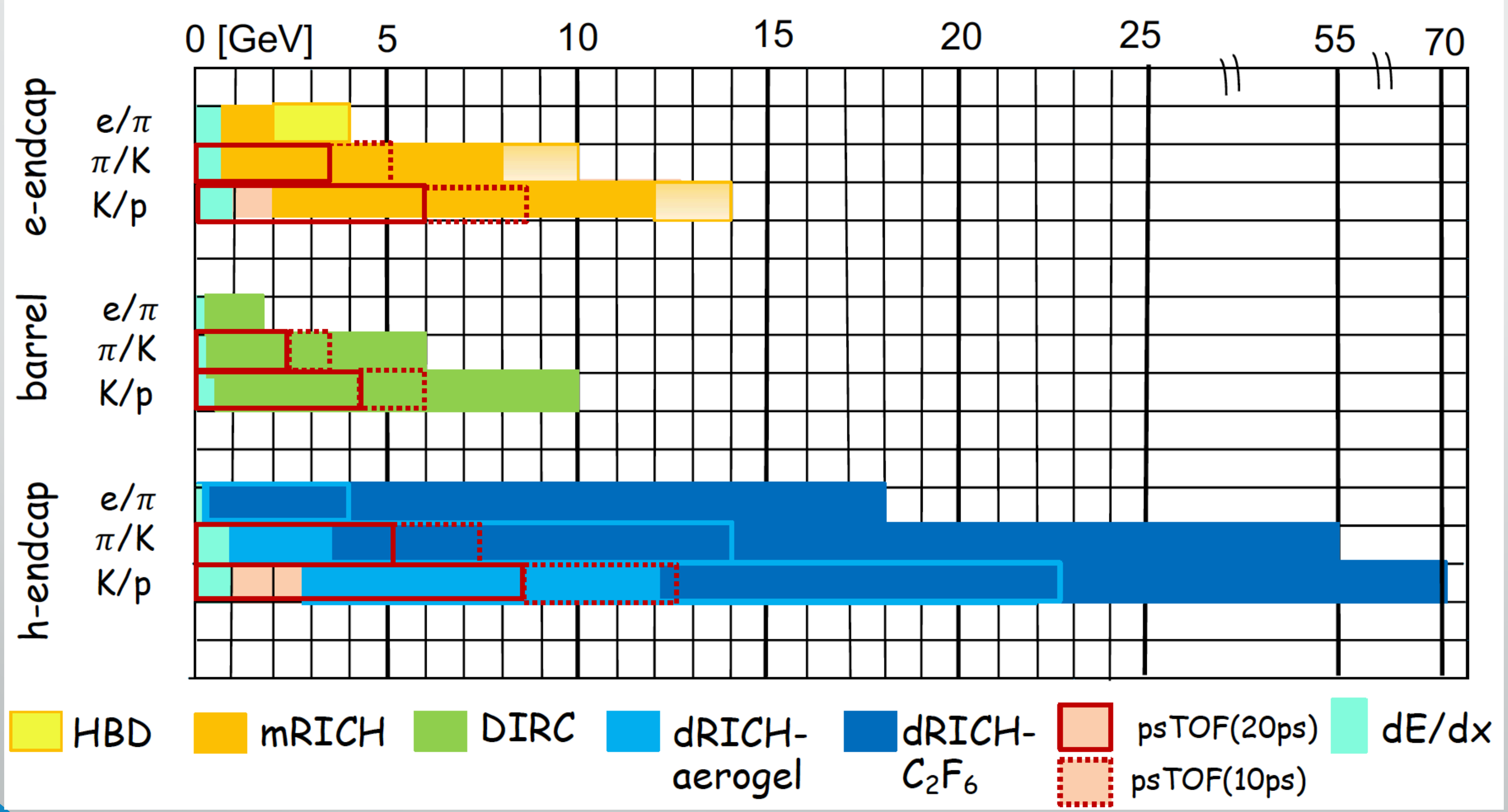


electrons

pions

$10^{-5} < x < 5 \cdot 10^{-4}$ $5 \cdot 10^{-4} < x < 10^{-2}$ $10^{-2} < x < 1$

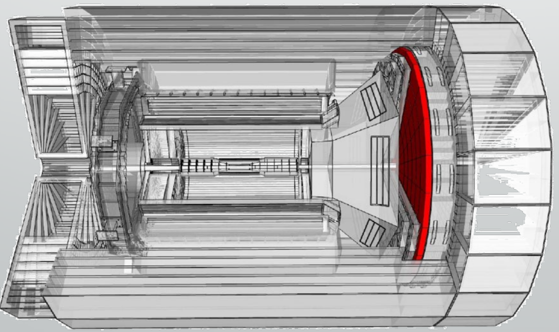
Expected Coverage for PID Options

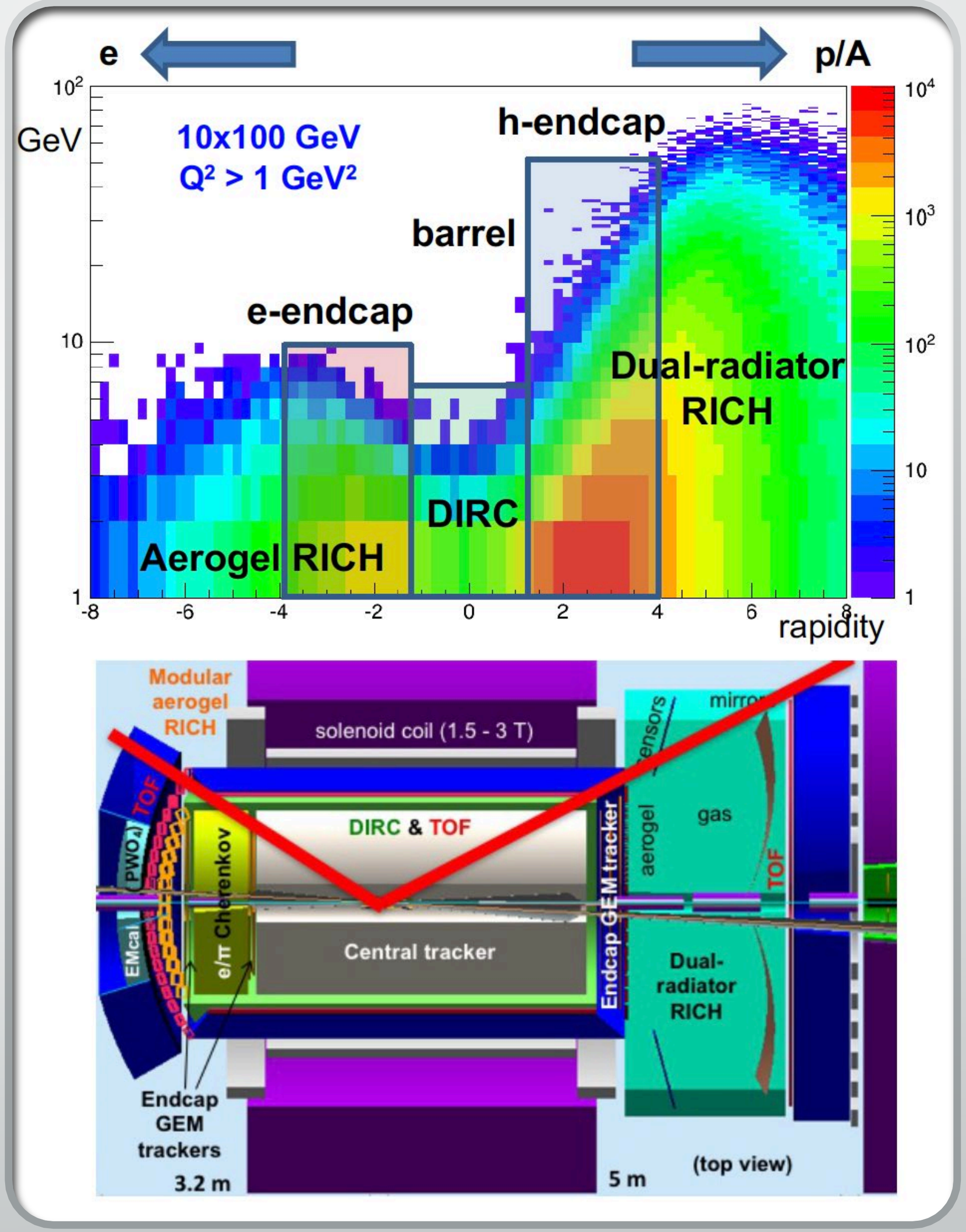


A (Possible) PID solution for EIC

- Backward: mRIHC
    - p/K separation up to ~10 GeV/c
- Barrel: high-performance DIRC, TOF, TPC
    - p/K separation up to ~6-7 GeV/c
- Forward: dRICH
    - p/K separation up to ~50 GeV/c

- Also Forward:
    - TOF ?



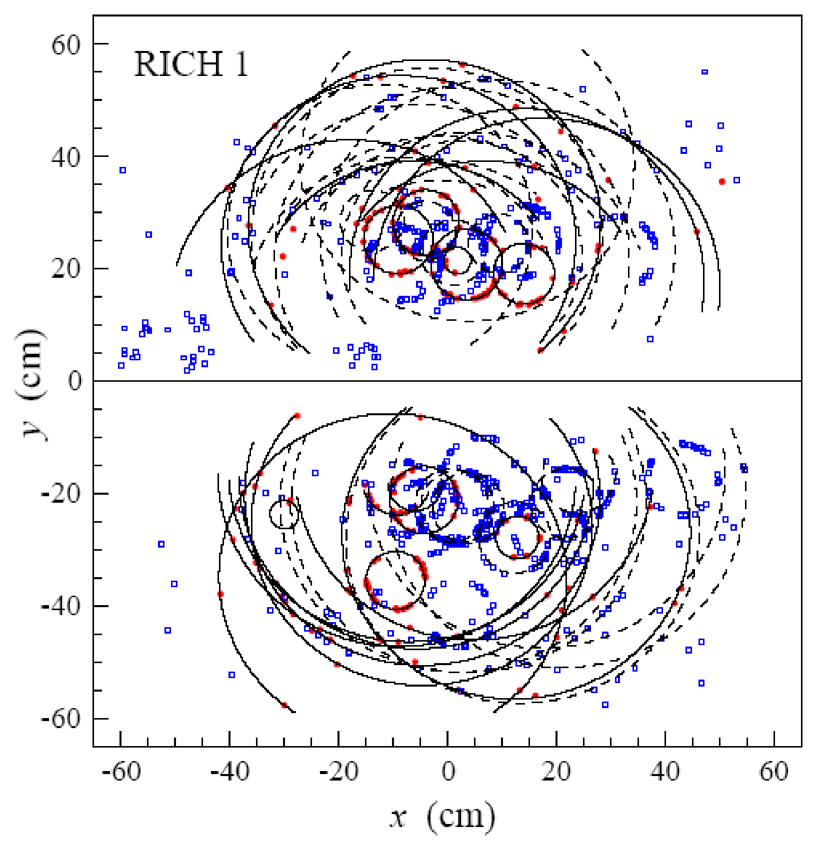


Detectors to Physics

Pattern Recognition in (RICH) Cherenkov Detectors

- Events with large number of charged particles → overlapping rings
- Hough Transform (ALICE):
  - Project the particle direction on to the detector plane
  - Accumulate the distance of each hit from these projection points (think: rings)
  - Use peaks to associate the corresponding hits to the tracks
- Likelihood Method (LHCb):
  - For each track in the event assume a given mass hypothesis, create photons and project them to the detector plane using the knowledge of detector geometry/properties
  - Calculate the probability for signal seen in each pixel of the detector from all tracks
  - Compare this with the observed set of photoelectron signal by creating a likelihood
  - Repeat all the above after changing the set of mass hypothesis of the tracks
  - Find the set of mass hypothesis, which maximize the likelihood

LHCb: RHIC1 MC study



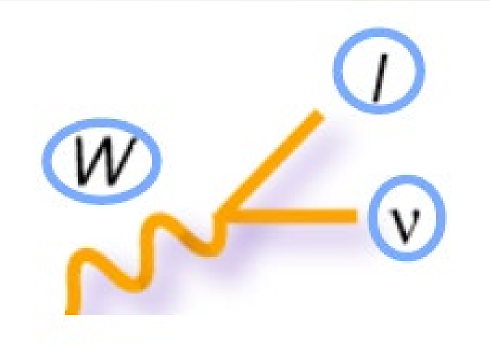
Red: Particles from Primary and Secondary Vertex

Blue: From secondaries and background processes

Detectors to Physics

- Neutrinos via Missing-E_T
- A technique used to reconstruct neutrino without actually seeing a neutrino (Think: charged current events! Also: SM tests, SUSY searches)
- Missing *energy* is not a good quantity in a collider → some energy from the proton remnants is lost near the beampipe
- Missing transverse energy (E_T^{mis}) much more stable quantity!
- Defined as a measure of the lost energy (as in “not found”) due to neutrinos:

$$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ \mathrm{visible}} \vec{\mathrm{E}}_{\mathrm{T}}$$



- Reconstructing E_T^{mis} :
  - Particle flow approach in HEP has been shown to perform the best
  - Need all subsystem input: calorimeter cells, clustered; muons, PID data → matched to tracks to reconstruct event on “particle level”
  - Special care is needed to avoid double-counting

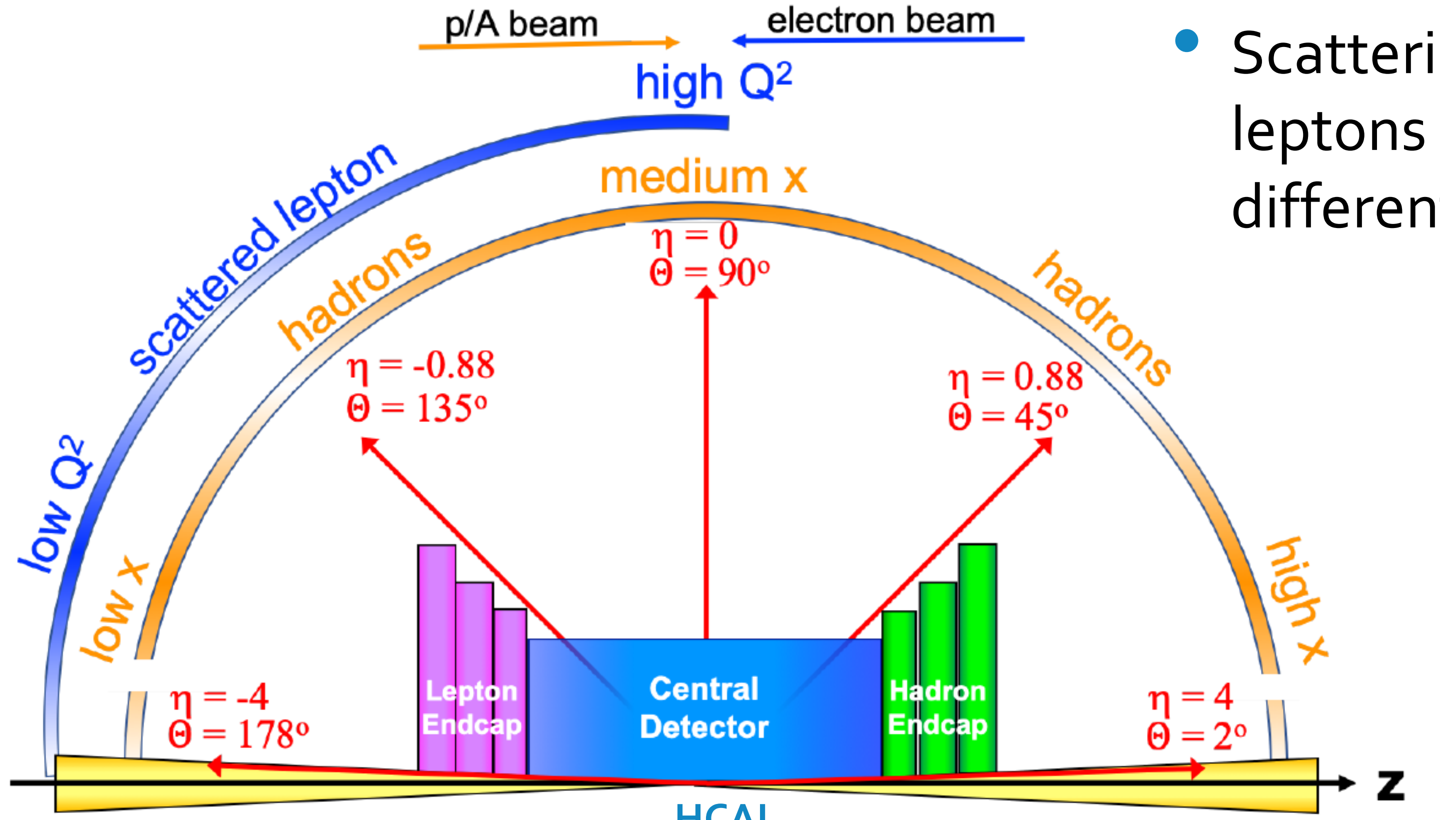
PID: Wrapping Up

- The field of Particle Identification Detectors is an evolving field.
- The particle ID using dE/dx, Time-of-Flight, RHIC and Transition Radiation detectors continue to provide reliable particle identification for Nuclear, Particle and Astro- Physics experiments.
- Particle identification is a crucial part for many high-impact measurements at the upcoming EIC

Back Up Slides

At EIC Calorimeters are Everywhere

- Scattering patterns for leptons and hadrons for different x and Q^2



very low Q²
scattered lepton

Bethe-Heitler
photons
for luminosity

Luminosity Detector

Low Q²-Tagger

HCAL
EMCAL
PID
Tracking

HCAL
Magnet
EMCAL
PID
Tracking
Vertexing

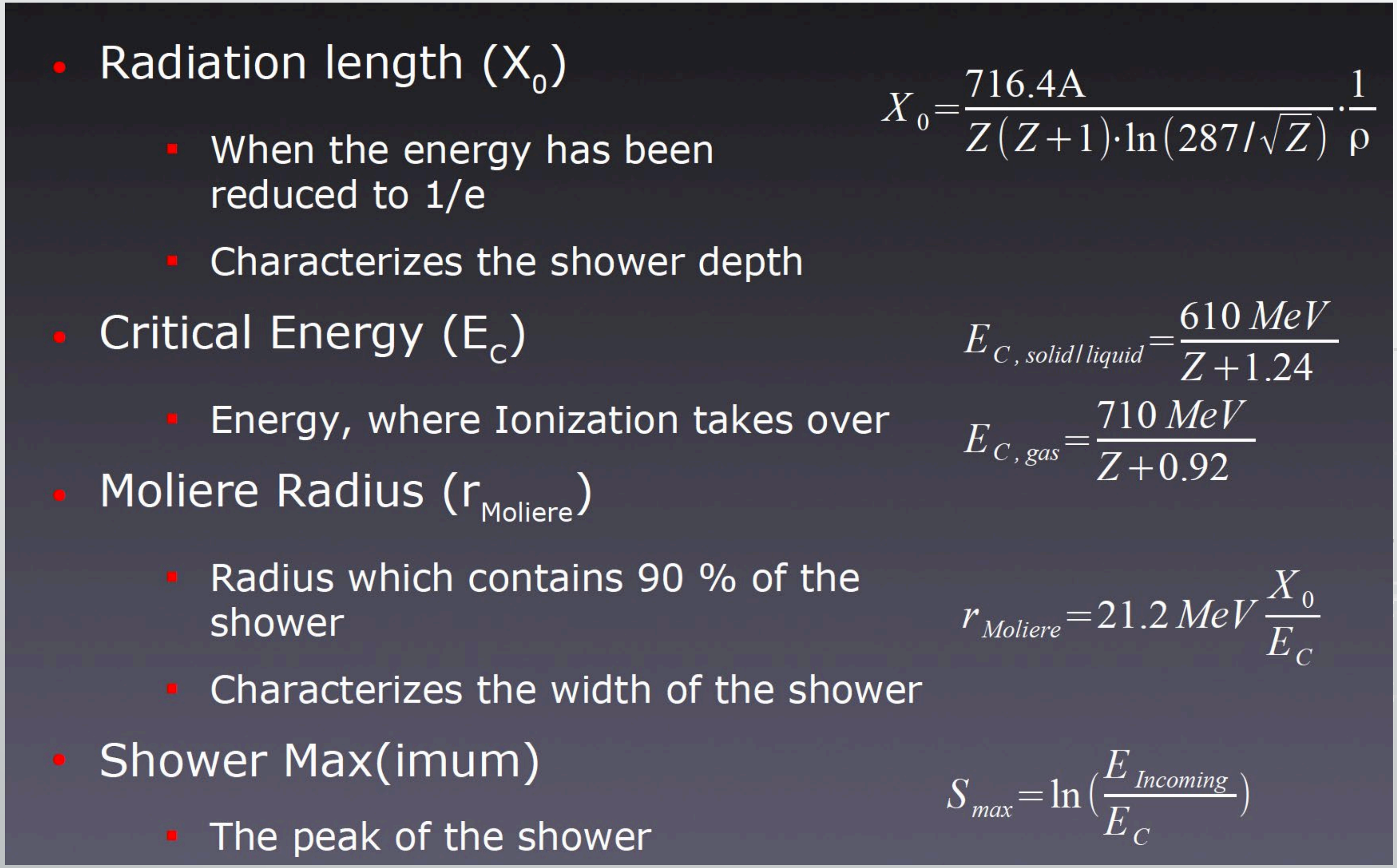
Tracking
PID
EMCAL
HCAL

particles from nuclear
breakup and
from diffractive reactions

ZDC

Forward Tracking

Calorimeters-101



- Radiation length (X_0)
  - When the energy has been reduced to 1/e
  - Characterizes the shower depth
- Critical Energy (E_C)
  - Energy, where Ionization takes over
- Moliere Radius ($r_{Moliere}$)
  - Radius which contains 90 % of the shower
  - Characterizes the width of the shower
- Shower Max(imum)
  - The peak of the shower

$$X_0 = \frac{716.4A}{Z(Z+1)\cdot\ln(287/\sqrt{Z})}\cdot\frac{1}{\rho}$$

$$E_{C,\,solid/liquid} = \frac{610\,MeV}{Z+1.24}$$

$$E_{C,\,gas} = \frac{710\,MeV}{Z+0.92}$$

$$r_{Moliere} = 21.2\,MeV\,\frac{X_0}{E_C}$$

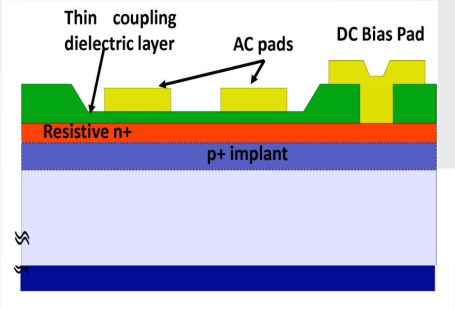
$$S_{max} = \ln\left(\frac{E_{Incoming}}{E_C}\right)$$

Credit: A. Kiselev

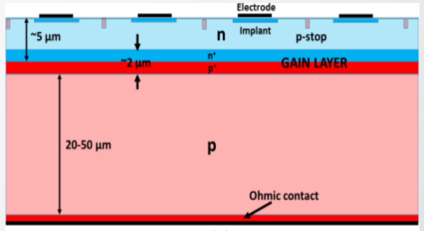
Explosion of Si R&D

- Very active area!
- Example: Low Gain Avalanche Detectors (LGAD)
  - Single layer timing resolution < 20 ps
  - Radiation tolerance: under continuous improvements
- Varieties:
  - AC-LGAD: gain layer charge coupled capacitively to surface through thin (~ 500 nm) oxide layer, segmentation provided simply by surface electrodes
  - Deep Junction (DJ-LGAD)
  - Trench isolated (TI-LGAD)
  - Inverse (iLGAD)…
- Other approaches to fast timing in silicon: 3D, Timepix, Solid-state Electron Multiplier (SSEM),…

AC-LGAD



DJ-LGAD



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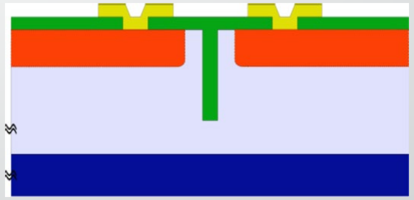

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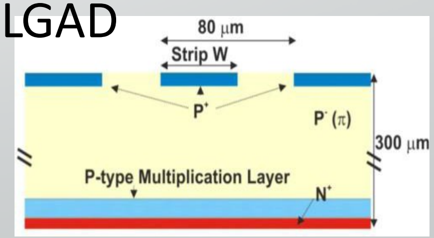
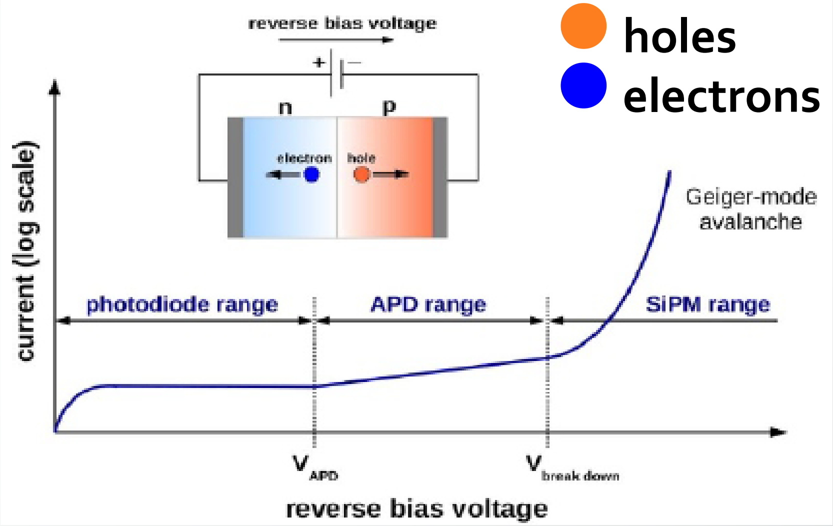


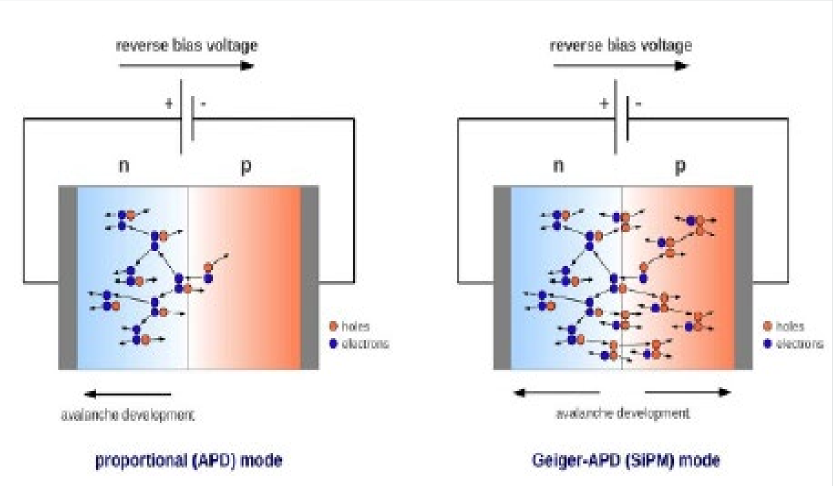
E. Currás, VERTEX 2020
N. Cartiglia, TF3

Detection Options: SiPM

New advances: Silicon Photomultipliers

- a solid-state photodetector made of an array of hundreds or thousands of integrated single-photon avalanche diodes
  - Time resolution= ~ 100 ps.
  - Works in magnetic field
  - High gains $\sim 10^6$
  - Single photon detection potential
- SIPM for Cherenkov Detectors at EIC:
  - Requires additional R&D but initial tests are promising
  - SiPM can suffer radiation damage
  - High impact potential!





Tracking: Ionization

- Mean ionization energy loss is described by Bethe-Bloch formula

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

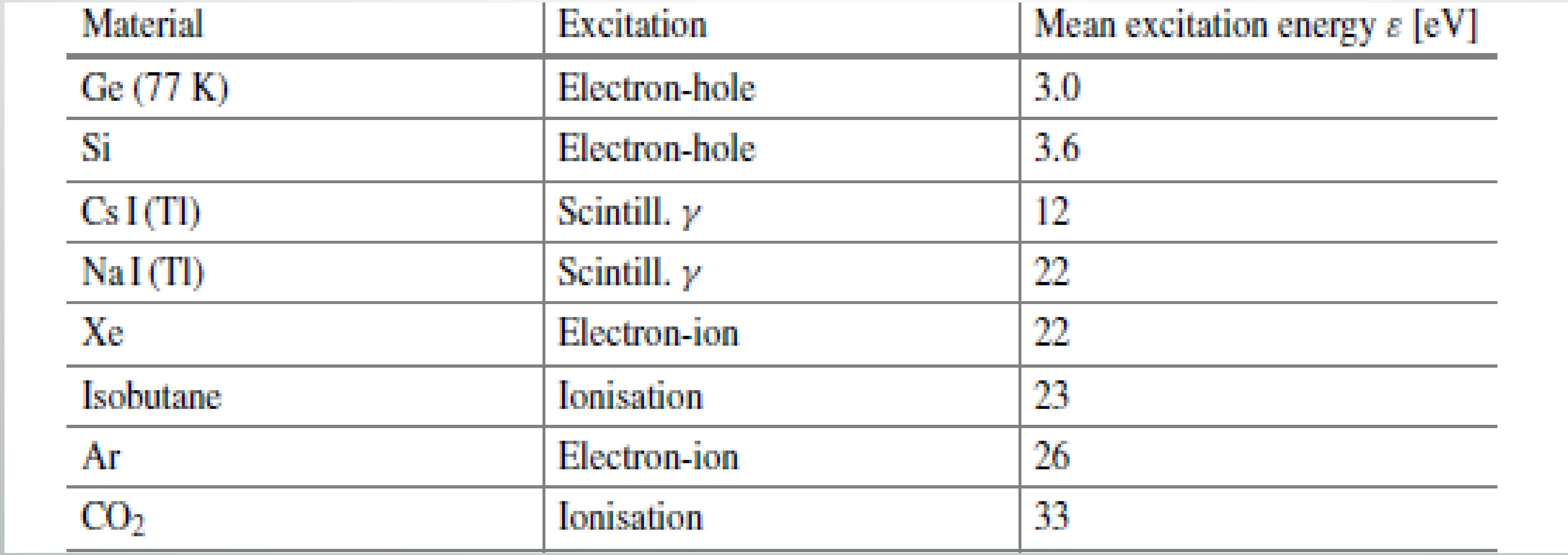
- For electron (switching some of the constants and dropping relativistic rise correction):

$$-\frac{dE}{dx} \approx \left(0.307\frac{MeV\ cm^2}{mol}\right)\rho\left[\frac{Z}{A}\right]\left[\frac{z^2}{\beta^2}\right]\left[ln\frac{2\ 0.511MeV\ \gamma^2\beta^2}{[16\ \cdot Z^{0.9}]^2} - \beta^2\right]$$

- *How many electrons does a charged particle produce an average while crossing 100 μm of Si?*

Tracking: Ionization

Supplementary information: excitation energy data (a minimum amount of ionization required to produce one charge carrier:



Material	Excitation	Mean excitation energy ε [eV]
Ge (77 K)	Electron-hole	3.0
Si	Electron-hole	3.6
Cs I (Tl)	Scintill. γ	12
Na I (Tl)	Scintill. γ	22
Xe	Electron-ion	22
Isobutane	Ionisation	23
Ar	Electron-ion	26
CO_2	Ionisation	33

Tracking: Ionization

- Let’s estimate how many electrons does a charged particle produce an average while crossing 100 μm of Si?
- Let’s assume that the charged particle have $z\ = 1$ and behave like a MIP. For a MIP, the dependance of dE/dx on particle energy is dominated by logarithmic term $\sim\ln\gamma$. Assuming that the particle is produced near global minimum of $\gamma \sim 4$:

$$-\frac{dE}{dx} \approx \left(0.307\frac{MeV\ cm^2}{mol}\right)\rho\left[\frac{Z}{A}\right]\left[\frac{z^2}{\beta^2}\right]\left[ln\frac{2\ 0.511MeV\ \gamma^2\beta^2}{[16 \cdot Z^{0.9}]^2} - \beta^2\right]$$

$$\approx \left(0.307\frac{MeV\ cm^2}{mol}\right)\left[\frac{2.33\ g\ cm^3\ 14}{28.1\ \ g\ mol^{-1}}\right]\left[ln\frac{2\ 0.511MeV\ 4^2}{16\ 14^{0.9}eV} - 1\right] = \frac{3.7MeV}{cm}$$

Then number of electron (and holes) produced while crossing $d\ = 100\mu m$

$$n = \frac{\left\langle\frac{dE}{dx}\right\rangle d}{\varepsilon} = \frac{3.7MeV\ 10^{-2}cm}{cm\ \ 3.6\ eV} \approx 10^4$$

Cherenkov Detectors: FOM

- Frank-Tamm theory : Number of photons produced by a particle with charge Z, along a pathlength L :

$$N_{prod} = \left(\frac{\alpha}{hc}\right) Z^2 L \int sin^2(\theta) dE_{ph},$$

where $$\frac{\alpha}{hc} = 370 eV^{-1} cm^{-1}, \quad E_{ph} = \frac{hc}{\lambda}$$

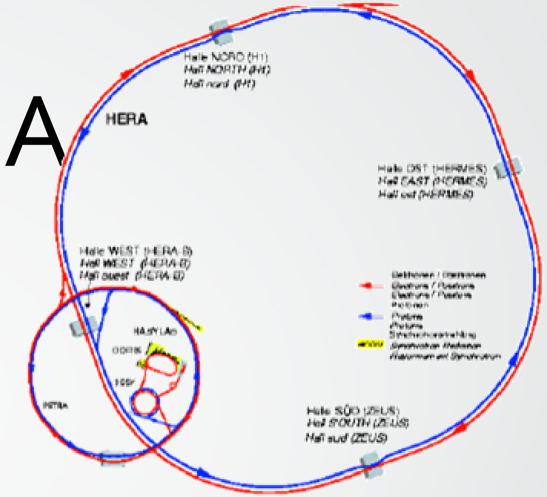
If the photons are reflected by a mirror with Reflectivity $R(Eph)$, are transmitted through a quartz window of Transmission $T(Eph)$ and then are detected by a photon detector with efficiency $Q(E_{ph})$, then number of photons detected :

$$N_{det} = \left(\frac{\alpha}{hc}\right) Z^2\, L\, (RQT) \int sin^2(\theta)\, dE_{ph} = N_0\, L\, sin^2(\theta_c),$$

assuming $\theta = const = \theta_c$ – mean Cherenkov angle

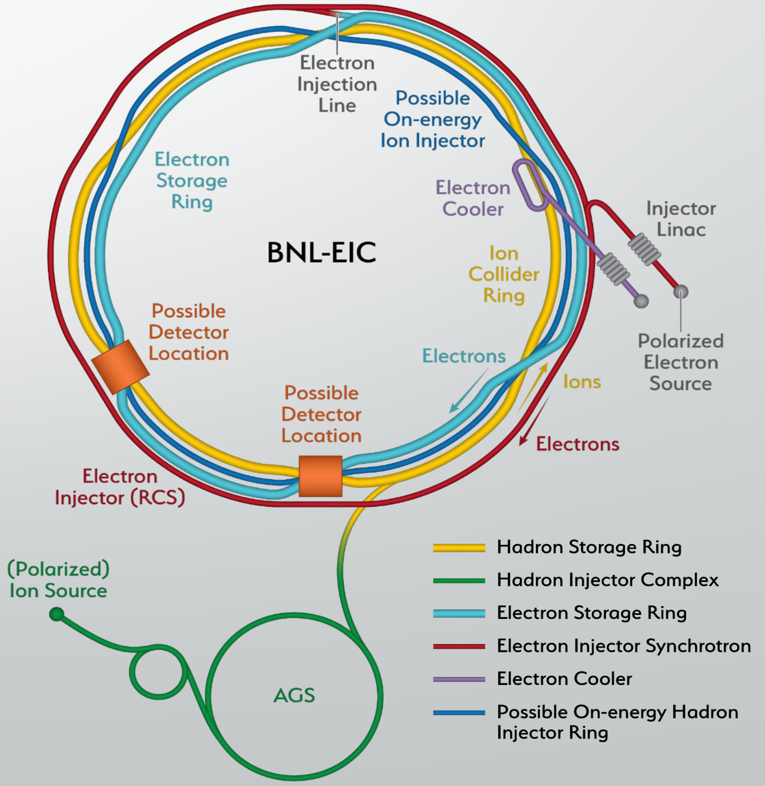
N_0 – is figure of merit for Cherenkov detectors

Kinematics: EIC vs. HERA



- HERA: the first electron-proton collider (1992-2007)
- Beam Energies: e: $27.5\ GeV$ $\quad p$: $820\ (920) GeV$

- EIC: the new frontier for nuclear science
- Beam Energies: $e: 5(20)\ GeV$ $\quad p: 50\ (250) GeV$

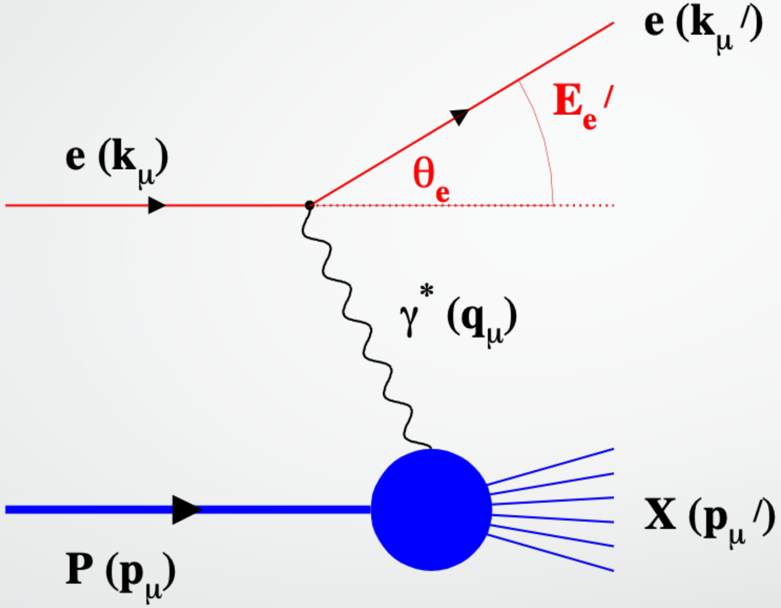


How do the two facilities compare in terms of kinematic reach?

Kinematics: Electron Scattering

$$k = \begin{pmatrix} E_e \\ 0 \\ 0 \\ -E_e \end{pmatrix}$$

$$p = \begin{pmatrix} E_P \\ 0 \\ 0 \\ E_P \end{pmatrix}$$



$$k' = \begin{pmatrix} E'_e \\ E'_e \sin\theta'_e \cos\phi'_e \\ E'_e \sin\theta'_e \sin\phi'_e \\ E'_e \cos\theta'_e \end{pmatrix}$$

$$p' = \begin{pmatrix} \sum_h E_h \\ \sum_h p_{X,h} \\ \sum_h p_{Y,h} \\ \sum_h p_{Z,h} \end{pmatrix}$$

$q^2 = -Q^2 = (k - k')$ – momentum transfer; virtuality

$\nu = E_e - E'_e$ – energy lost by lepton

$s = (p + k)^2$ $\quad y = {}^{\nu}/_{E_e}$ $\quad Q^2 = s \cdot x \cdot y$

Kinematics: EIC vs. HERA

- Center of Mass Energy: $\sqrt{s} \approx \sqrt{4E_e E_p}$
  - HERA: 300 – 320 GeV
  - EIC: 32 – 141 GeV
- Resolution: $Q^2 = sxy \rightarrow Q^2_{max} = s_{max}$
  - HERA: 101,200 GeV^2
  - EIC: 20,000 GeV^2
- x-reach: $Q^2 = sxy \rightarrow x_{min} \approx \frac{(Q^2_{min} \sim 0.1)}{s_{max}(y_{max} \sim 1)}$
  - HERA: $x_{min} \approx 10^{-7}$
  - EIC: $x_{min} \approx 0.5 \cdot 10^{-6}$

Main differences are NOT in kinematic coverage!
EIC will add:
- Better lepton polarization
- Target polarization
- Heavy targets (ions)