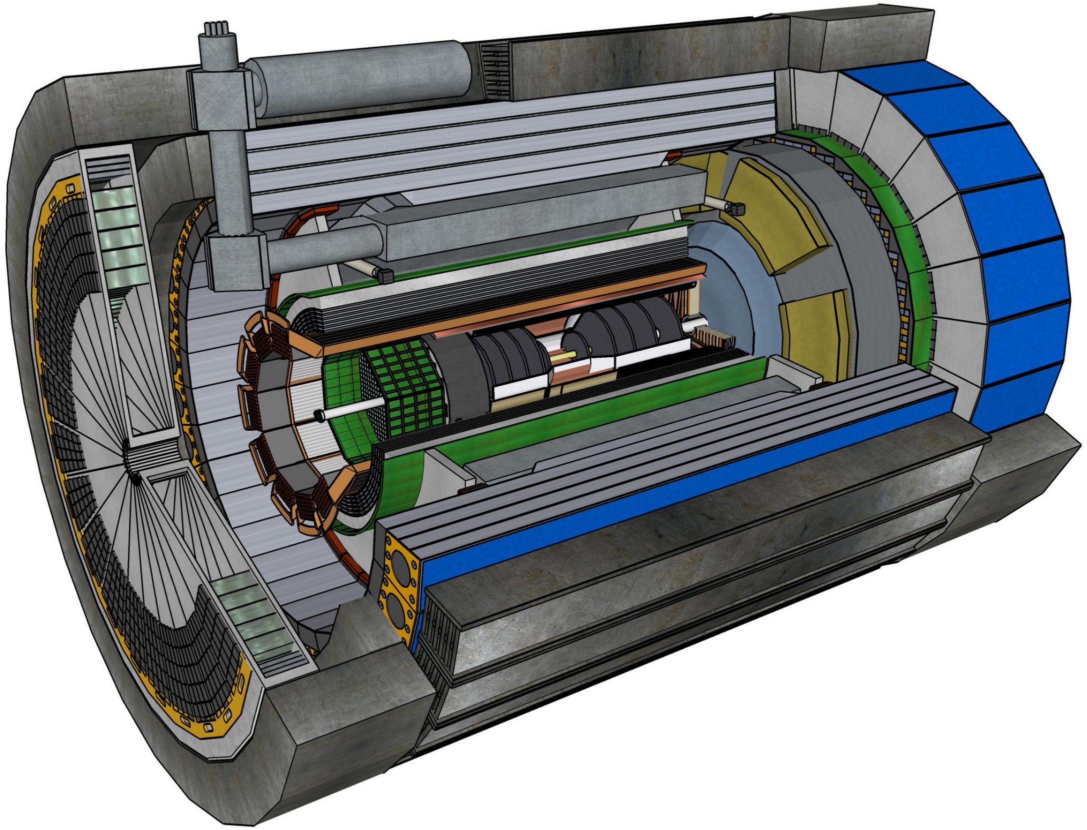
Physics of the Electron Ion Collider: *Experimental Introduction Part 1*



Rosi Reed

Lehigh University

EICUG/ePIC Collaboration Meeting

- Details and Registration at: Indico
- Early Career Day - Mon July 22nd
- EICUG - Tues July 23rd - Wed July 24th
- ePIC Collaboration Meeting - Wed July 24th - Sat July 27th
- Social Dinner at Zest - Wednesday July 24th
- Networking Reception - Friday July 26
- Reduced registration and some travel for Early Career members

Multiple Airports

We will arrange some shuttles from Newark Airport (EWR) depending on arrival and departure times. Perhaps PHL depending on need.

[Shuttle Request Form]

Please let us know by **June 7** so we can plan (and let you know if we can pick you up/drop you off)

Once shuttle arrangements are done, forms for people to rideshare will be provided.

Getting around Bethlehem

All conference events are a convenient walk from one another, nothing is further than 0.5 miles (0.8 km).
Parking is free at the Comfort Suites
Parking at the Event Venue can be arranged

Comfort Suites Hotel cost → $85/day (free breakfast)
Trembley Apartments cost → $55/day

Priority for Trembley Apartments will be given to Early Career Scientists – however there is room for others
3 Bedroom, 1 bath + kitchen/living room
[Housing Form]
[Virtual Tour]

Venue – Rauch Business Center

Rauch has indoor collaborative seating
Coffee shop open from 9 am – 3 pm
Outdoor eating area
Indoor eating area

Additional classroom spaces available, let me know your needs!
(Day/Time + number of people, resources)

200 people, built in mics, cameras

95 people

65 people

Social Dinner – Zest Restaurant

Outline of Lectures

- Lecture 1: Particle Physics Detectors and Intro to ePIC
  - Interaction of Particles with Matter
  - Detector requirements at the EIC
  - The design of the ePIC Detector
  - Tracking Detectors
- Lecture 2: ePIC Detector and the EIC Science Case
  - Calorimetry
  - Particle Identification
  - Far forward/Far backwards
  - Physics observables
  - Interaction Region Considerations

Quantum Chromodynamics and Nuclear Matter

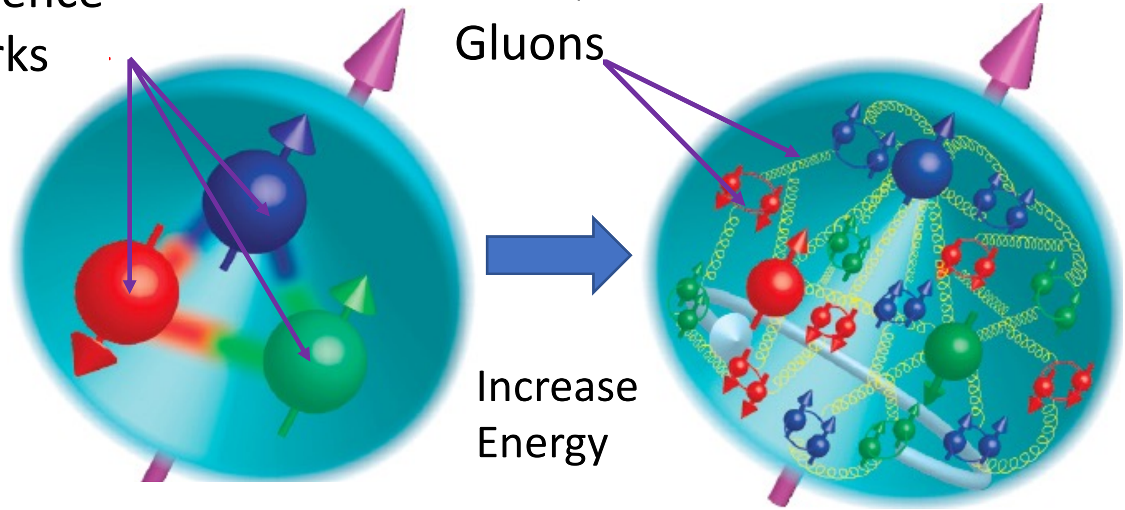
The study of Nuclear Physics is the quest to understand the origin, evolution, and structure of the matter of the universe

- How do the **properties of the proton** such as **mass** and **spin** emerge from the sea of quarks, gluons, and their underlying interactions?
- What is the **configuration and motion** of quarks and gluons located within the nucleon?
- What happens to the **gluon density** in nucleons and nuclei at small x?
- How do **quarks and gluons interact** with a nuclear medium?
- How do the **confined hadronic states** emerge from quarks and gluons?

Properties of the Proton

3 Valence Quarks

Sea Quarks and Gluons



Increase Energy

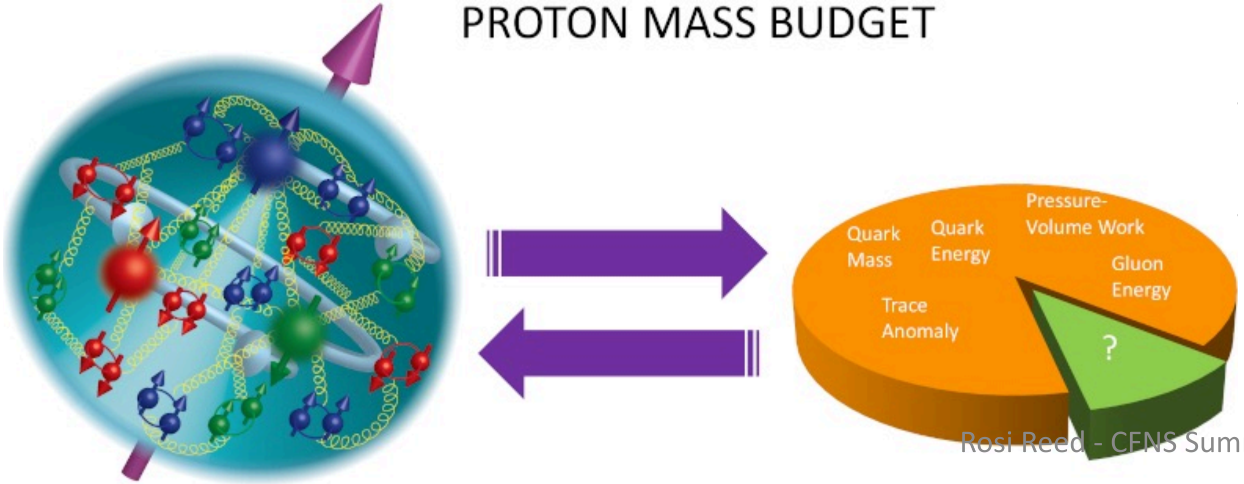
quarks gluons

Proton spin: $\frac{1}{2} = \frac{1}{2}\Sigma_q \Delta q + \Delta G + L_{g,q}$

Orbital angular momentum

Only 20-30% comes from the quarks!

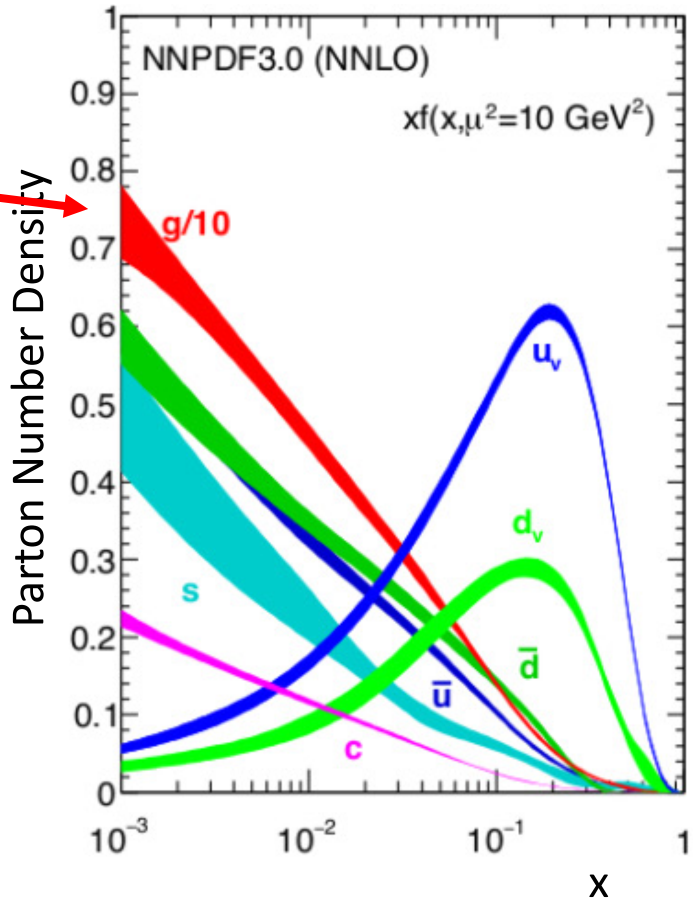
PROTON MASS BUDGET

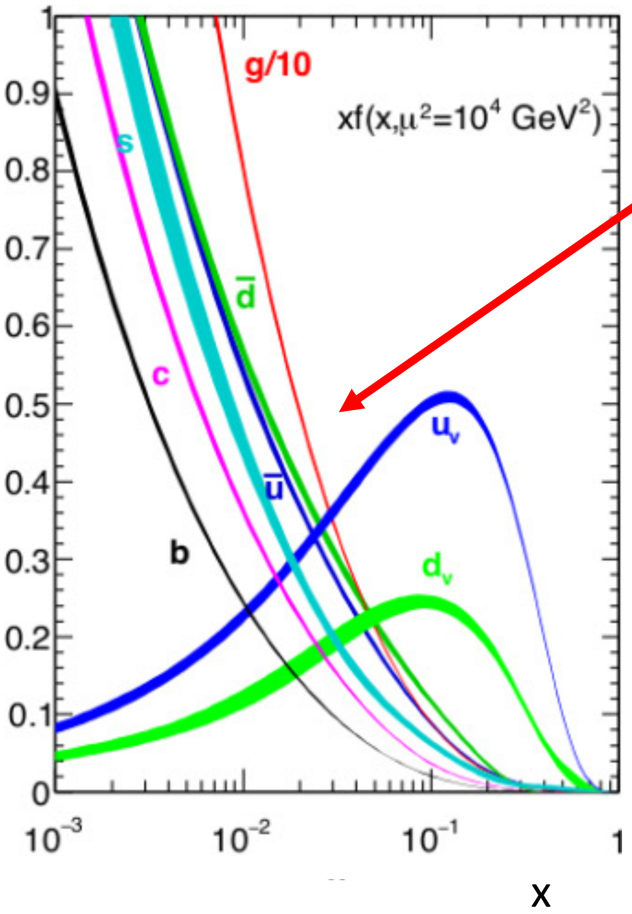


Mass is driven by a complicated sum of various QCD interactions!

Quarks and Gluons Structure and Motion

Where does this saturate?



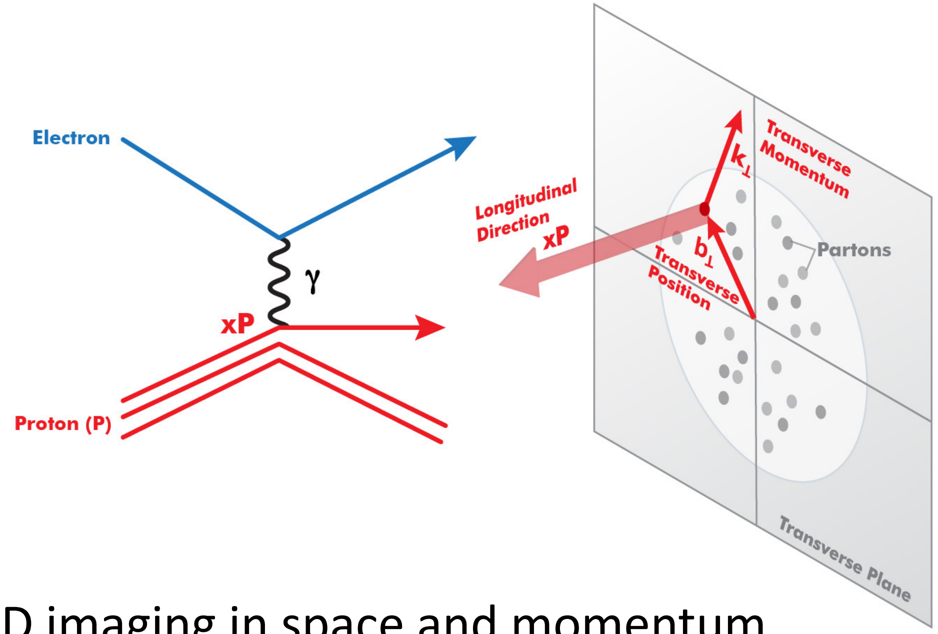


What do these distributions look like for protons in a nucleus?

Fraction of Proton Momentum Carried by Parton

3D Imaging in Space and Momentum

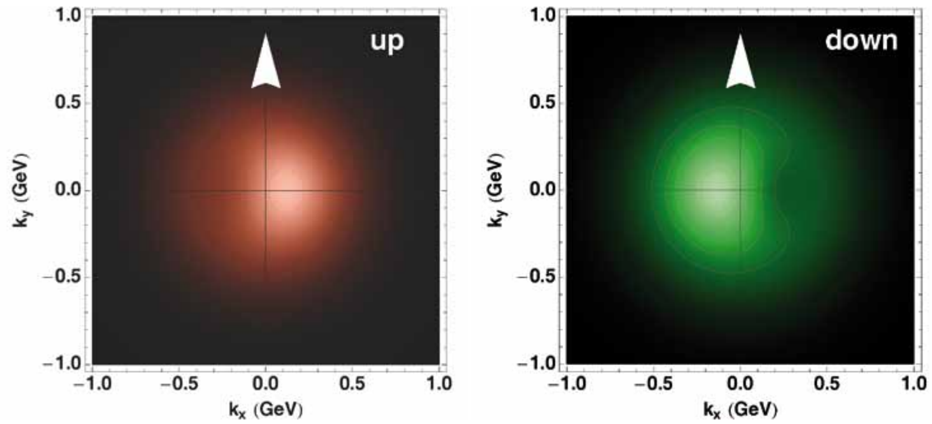
RHIC is the only polarized hadron collider in the world → EIC polarization capabilities



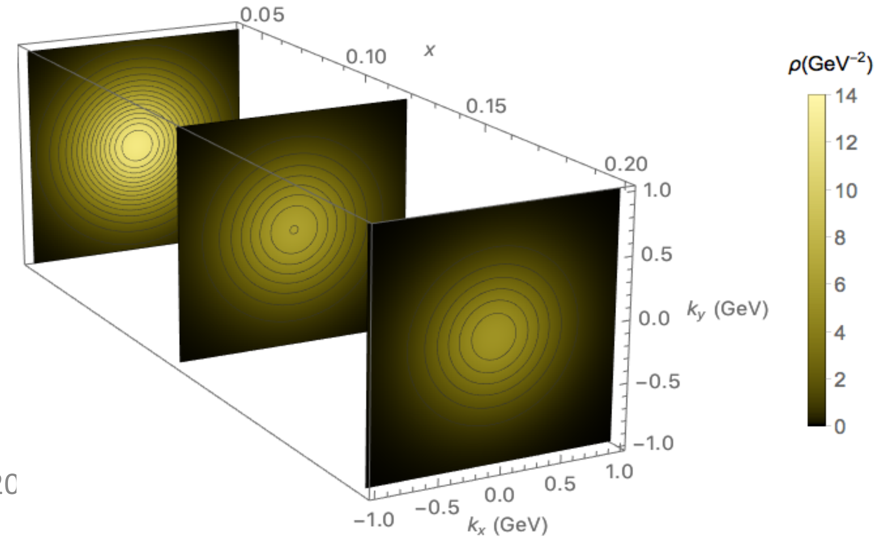
3D imaging in space and momentum

longitudinal structure (PDF)
+ transverse position Information (GPDs)
+ transverse momentum information (TMDs)

Transversely polarized nucleon



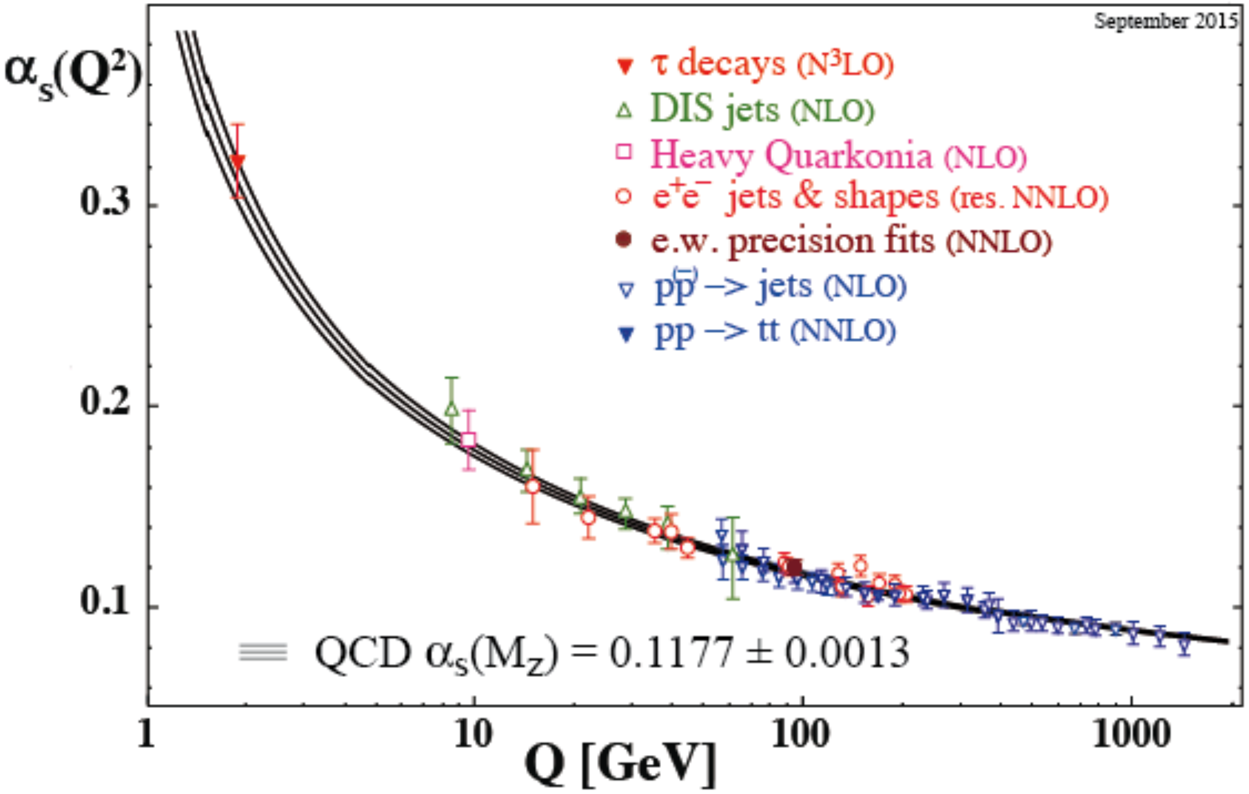
Unpolarized nucleon



Quantum Chromodynamics

Another interesting aspect of QCD:

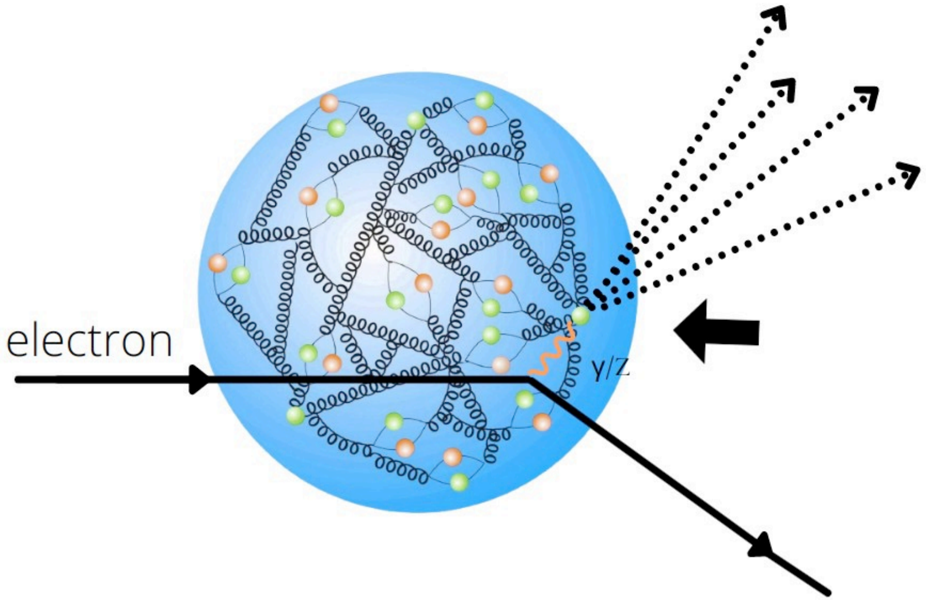
- Gluons can interact with themselves!
  - Leads to a coupling constant in QCD which varies with energy
  - At high energy (short distance), coupling is small and quarks are essentially free → perturbative
  - At low energy (long distance), coupling is large → non-perturbative



QCD constant runs from ~1 to 0.1 which results in complex nuclear structures and dynamics

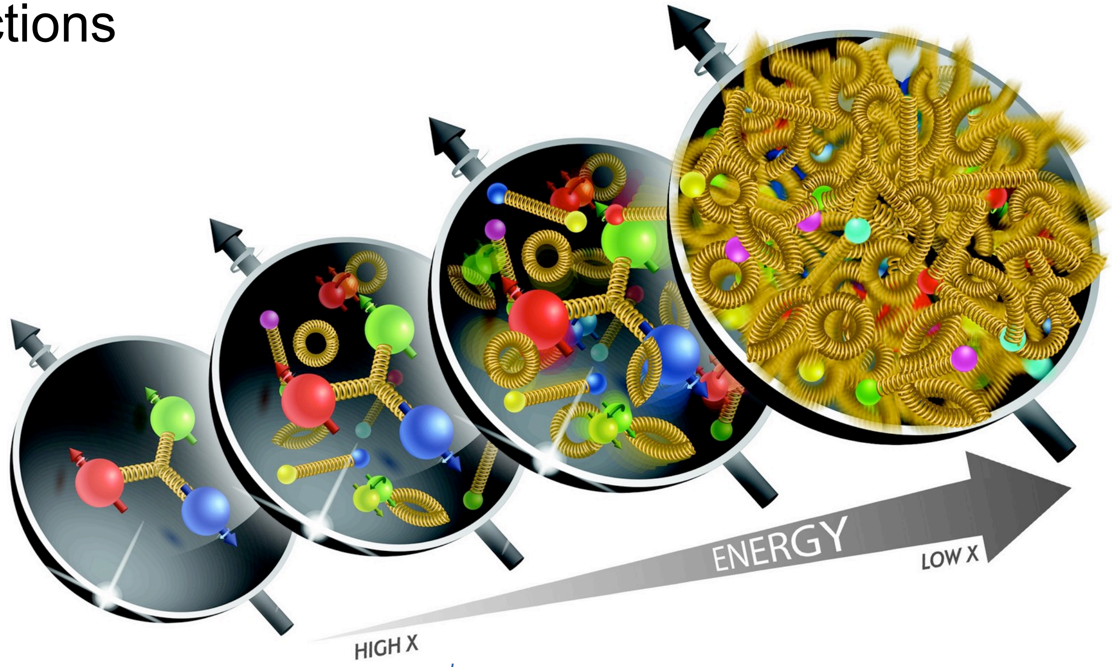
How do we study the complicated structure of QCD?

How Do You Study the Structure of Matter?



Deep Inelastic Scattering: e + p → e' + X

- **Golden process to probe nucleons and nuclei** with electron beams providing the unmatched precision of EM interactions

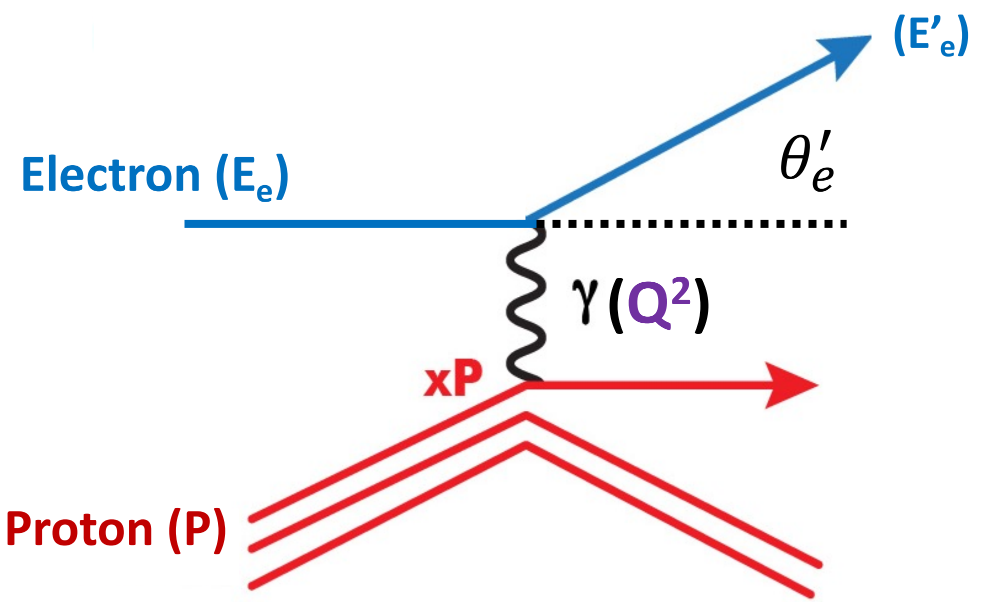


Q^2 – resolution power (virtuality of the photon)
s – center-of-mass energy squared
x - the fraction of the nucleon's momentum carried by the struck quark
y – inelasticity

Center-of-mass energy √s: 20 – 140 GeV

- Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

Deep Inelastic Scattering (DIS)

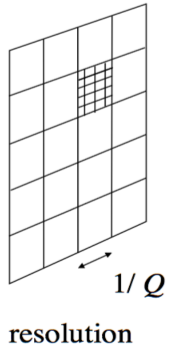


$$Q^2 = 2E_e E_e'(1 - \cos\theta_e')$$

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

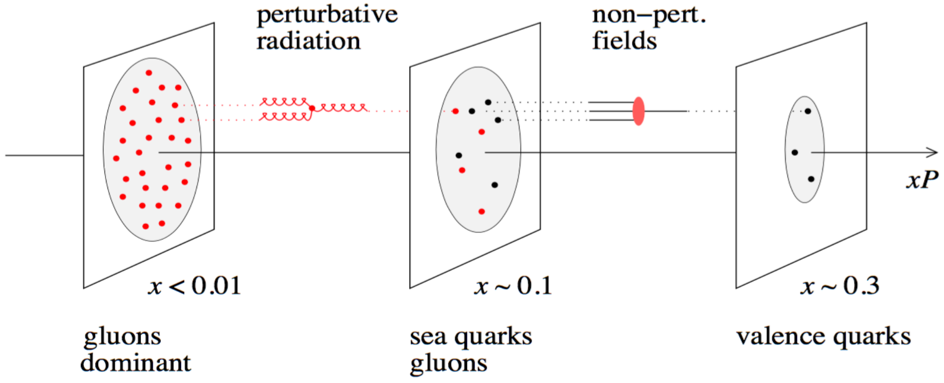
Measure of momentum fraction of struck parton

Changing Q^2 changes the resolution scale

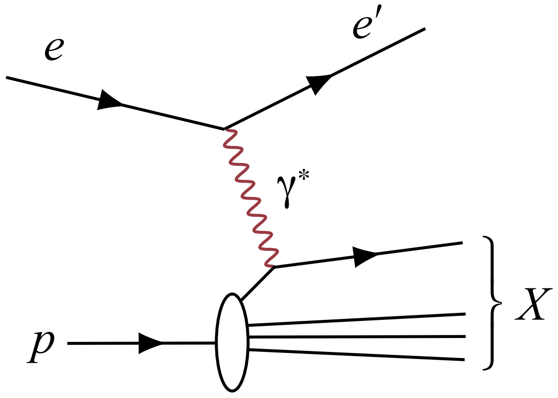


$Q^2 = 400$ GeV^2
=> $1/Q = 0.01$ fm

Changing **x** projects out different configurations where different dynamics dominate



Deep Inelastic Scattering (DIS)
Different Processes



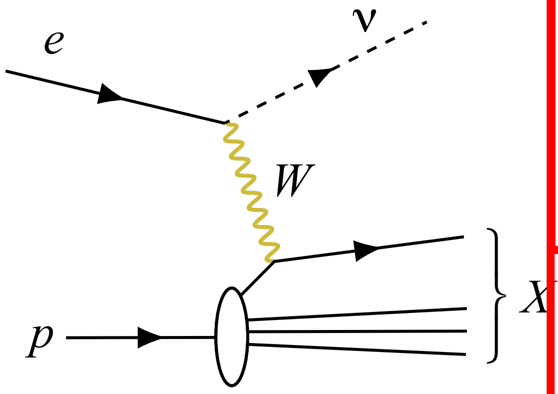
$$e + p/\mathrm{A} \longrightarrow e' + X$$

Neutral-current Inclusive DIS

Spin and Flavor structure of nucleons and nuclei

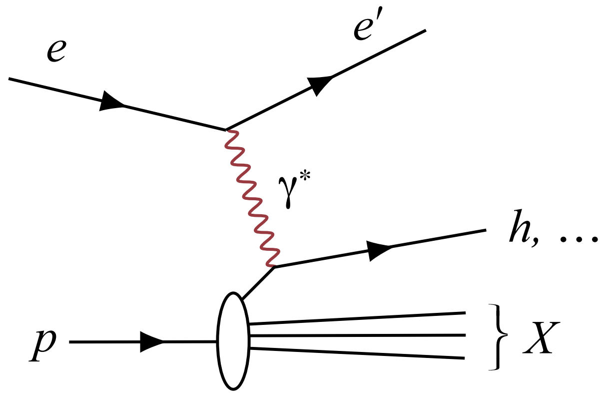
Tomography Transverse Momentum Dist.

Parton Distributions in nucleons and nuclei



$$e + p/\mathrm{A} \longrightarrow \nu + X$$

Charged-current Inclusive DIS



$$e + p/\mathrm{A} \longrightarrow e' + h^{\pm,0} + X$$

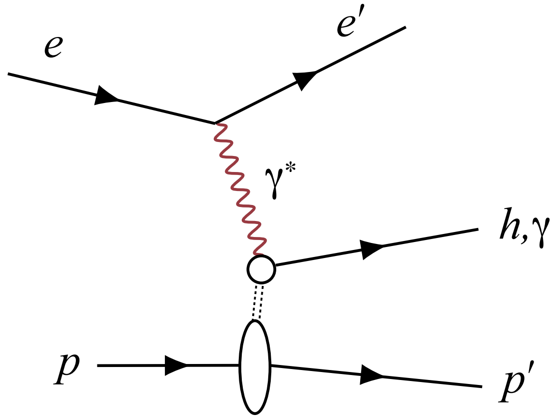
Semi-inclusive DIS

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

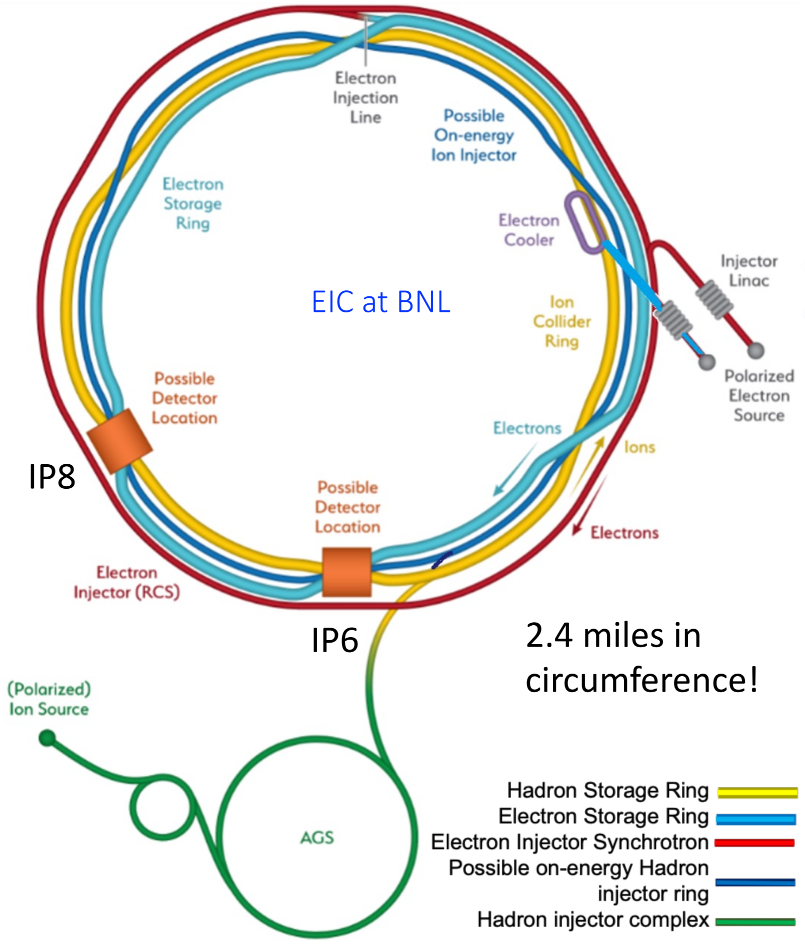
Tomography Spatial Imaging

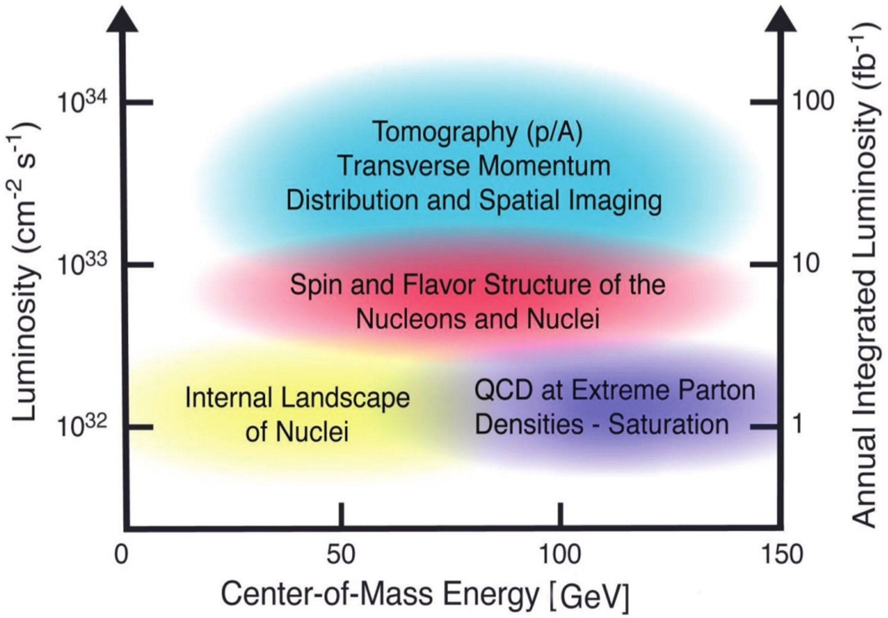


$$e + p/\mathrm{A} \longrightarrow e' + p'/A' + \gamma/h^{\pm,0}/VM$$

Exclusive DIS

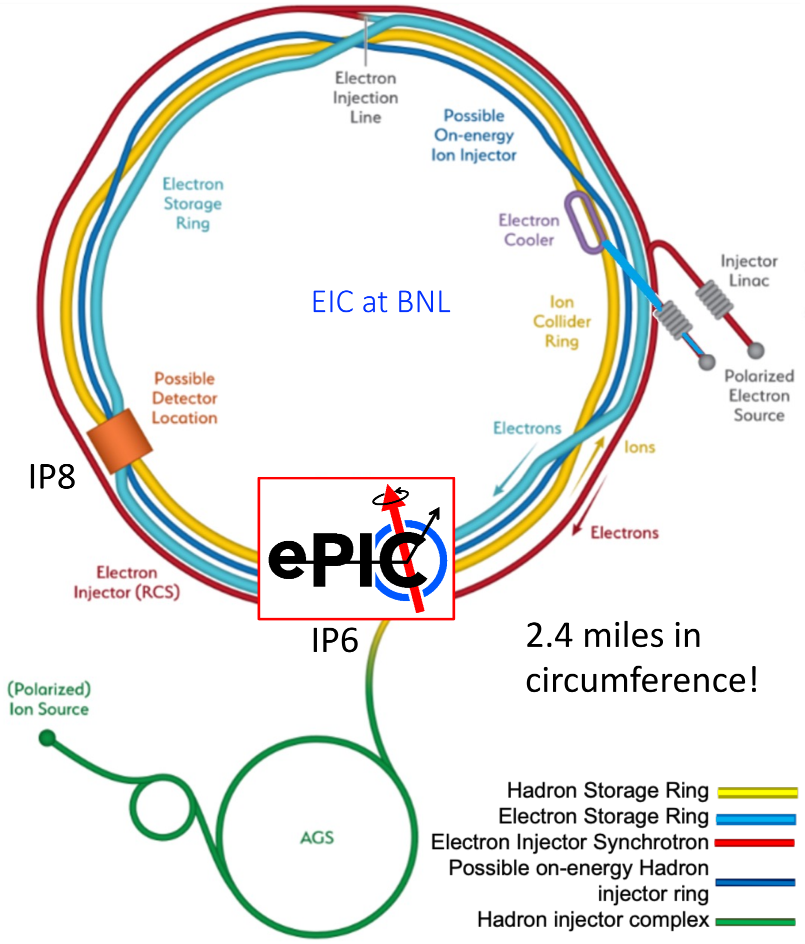
EIC Machine Parameters

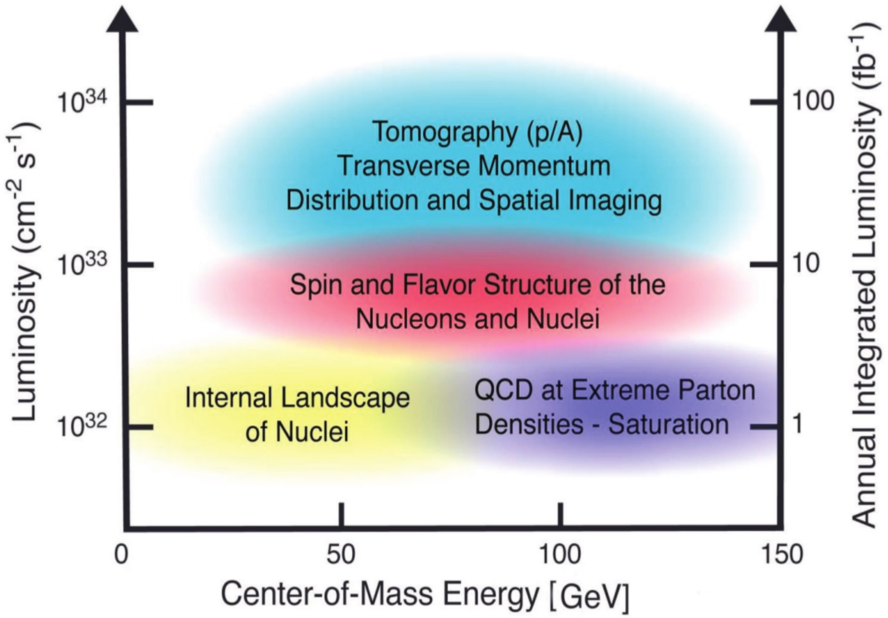




- Center of mass energy: 20 – 140 GeV
  - Electrons: 2.5 – 18 GeV
  - Protons: 40 – 275 GeV (ions: $Z/A \times E_{proton}$)
- Luminosity: 10^{34} /cm^2/sec
- Polarization: <70% (both electron and ion)
- Ion Species: proton - Uranium
- Detectors: up to 2 interaction regions with (almost) complete coverage

EIC Machine Parameters





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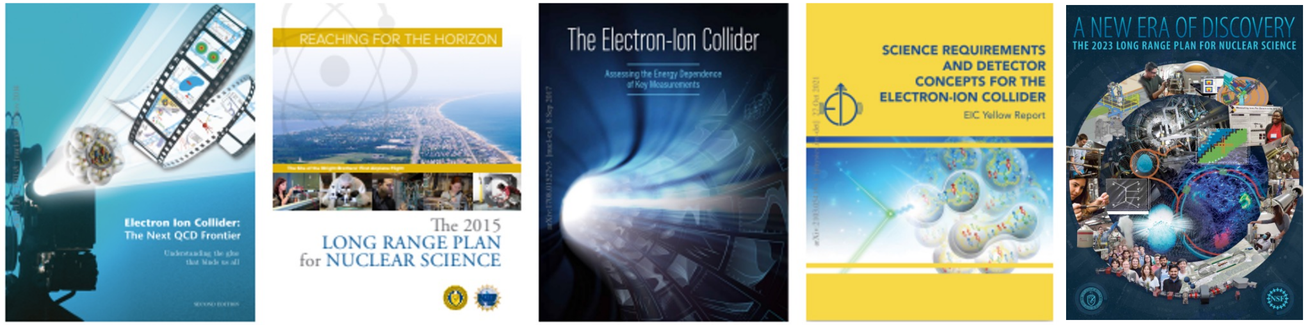
The EIC Yellow Report

The EIC yellow report was an enormous community exercise to quantify the *physics and detector requirements* to be able to purse EIC physics.

https://arxiv.org/abs/2103.05419

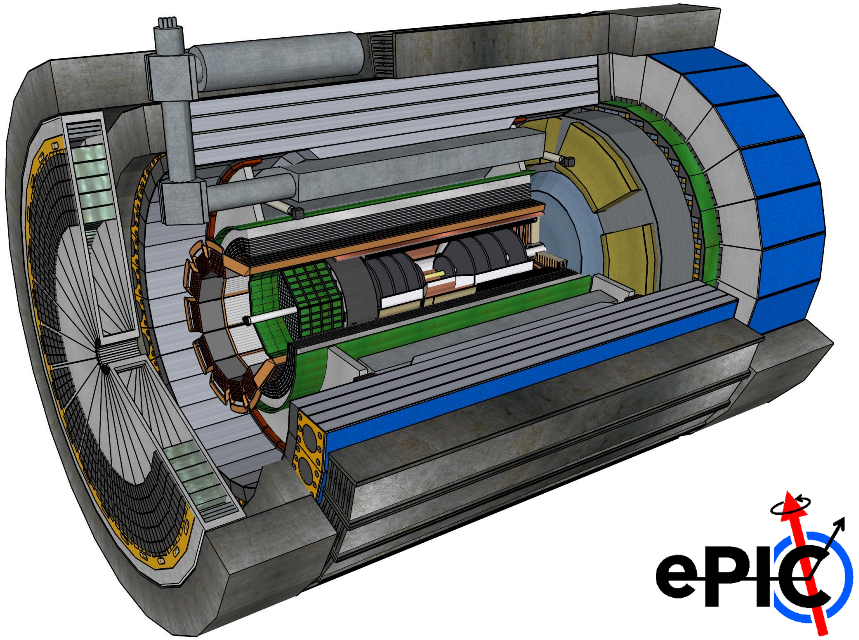
Detector Design Process Timeline
electron-Proton and Ion Collider (ePIC) Experiment



2012 2015 2017 2020 2023

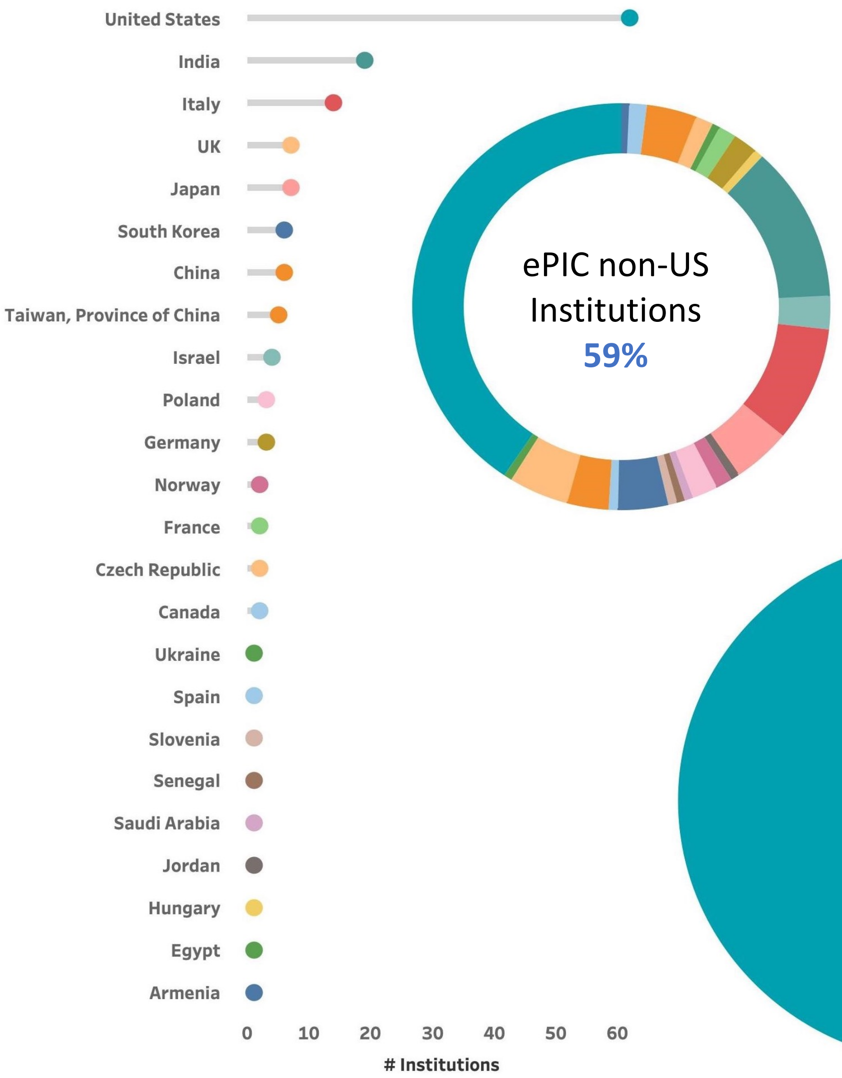
Detector and machine design parameters driven by physics objectives

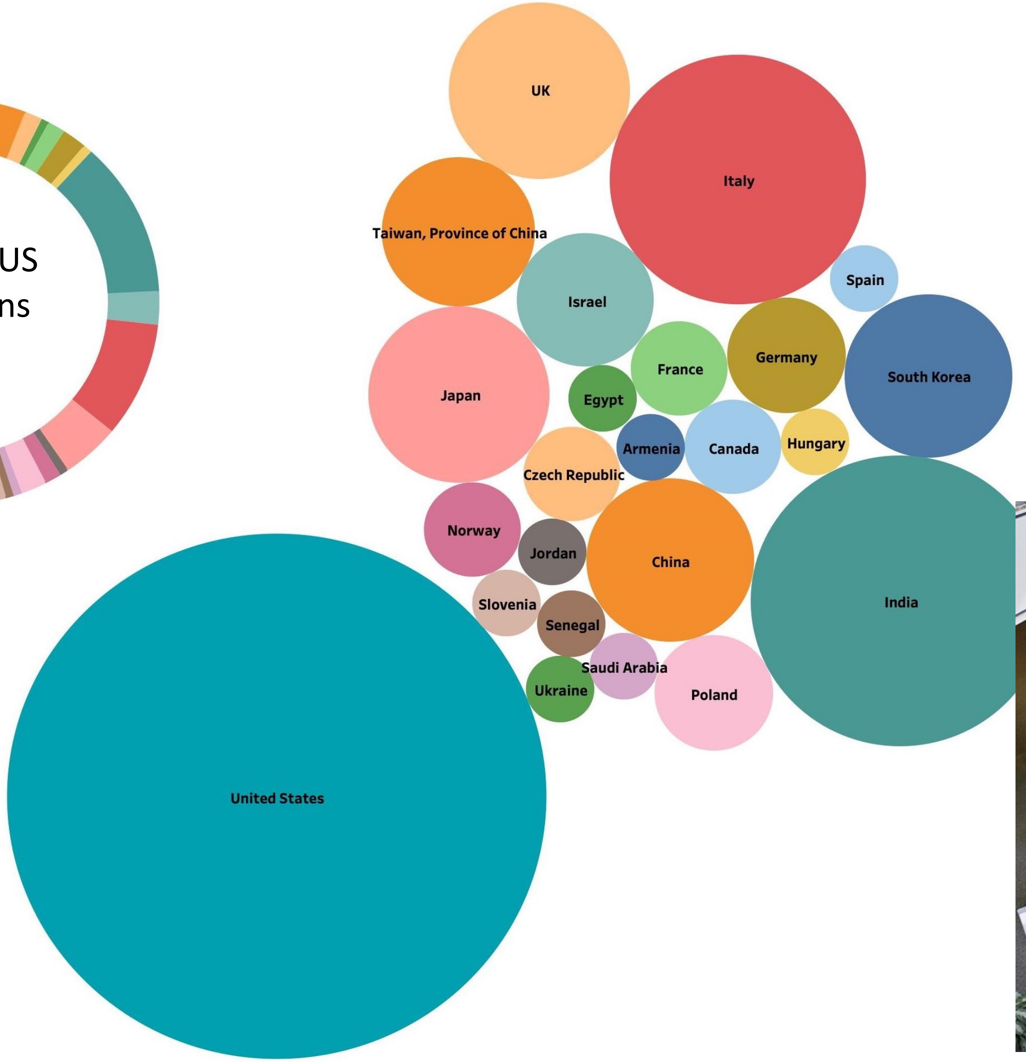
- Call for proposals issued jointly by BNL/JLab **March 2021** (Due Dec 2021
  - ATHENA, CORE and ECCE proposals submitted
- DPAP closeout **March 2022**
  - ECCE proposal chosen as basis for 1st EIC detector reference design
- **Spring/Summer 2022** – ATHENA and ECCE form joint leadership team
  - Joint WG's formed and consolidation process undertaken
  - Coordination with EIC project on development of technical design
- Collaboration formation process started **July 2022**
- Charter ratified & elected ePIC Leadership Team **February 2023**
- **Working towards TDR!**



ePIC

The ePIC Collaboration

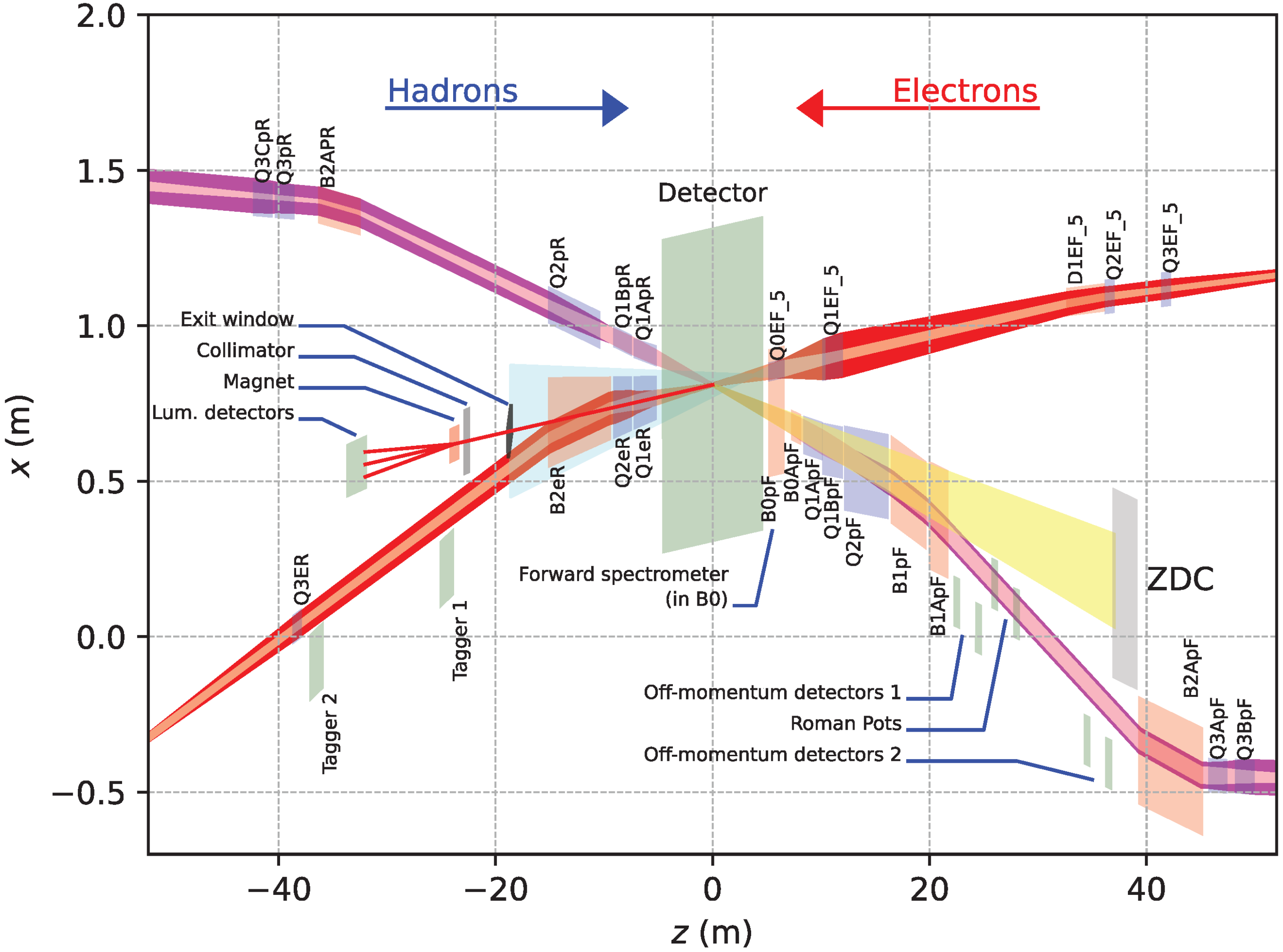




500+ participants

A truly global pursuit for a new experiment at the EIC!

ePIC Detector Extent



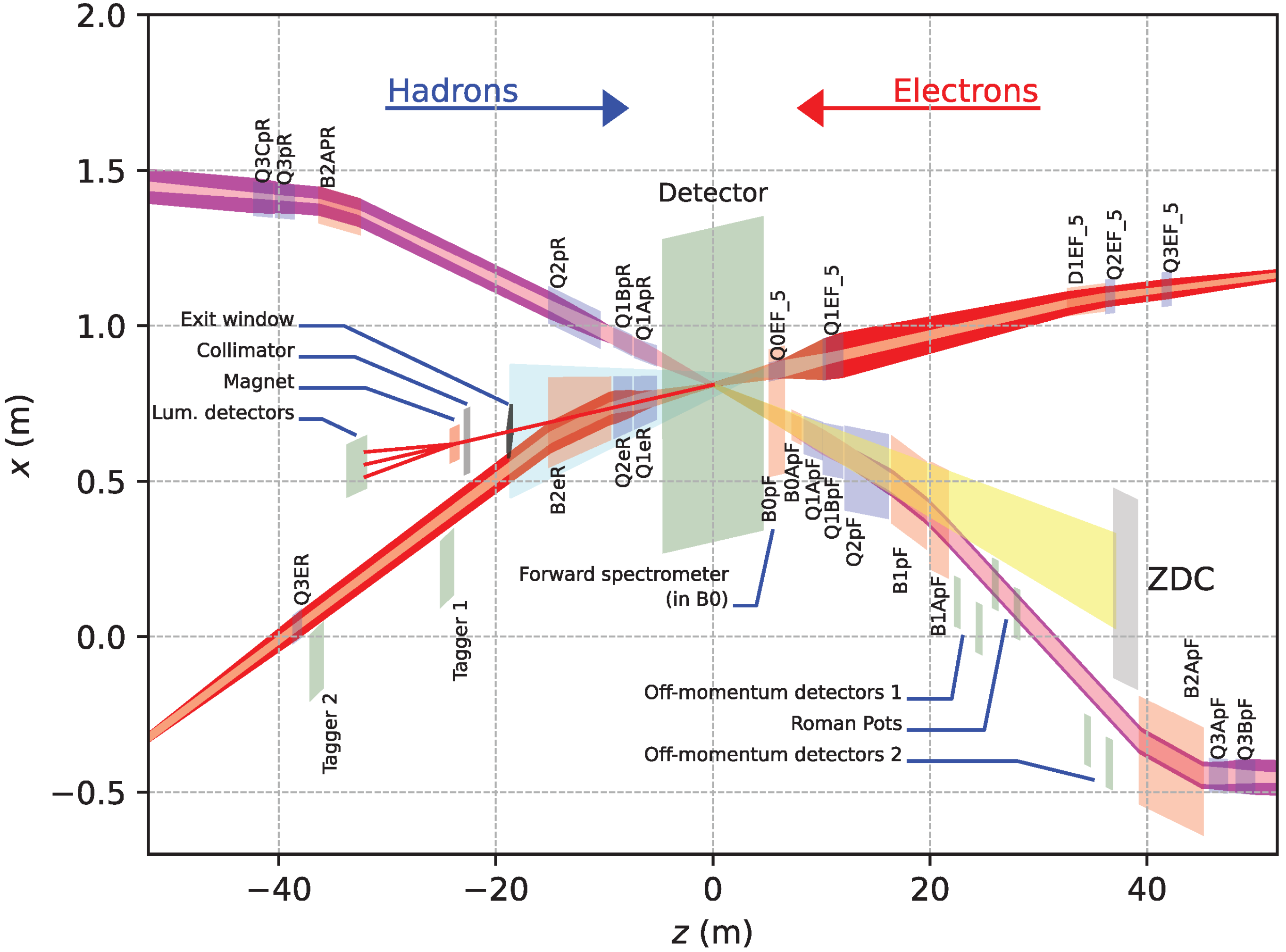
Total Length of the Detector: ~75m

Central Detector: ~10m

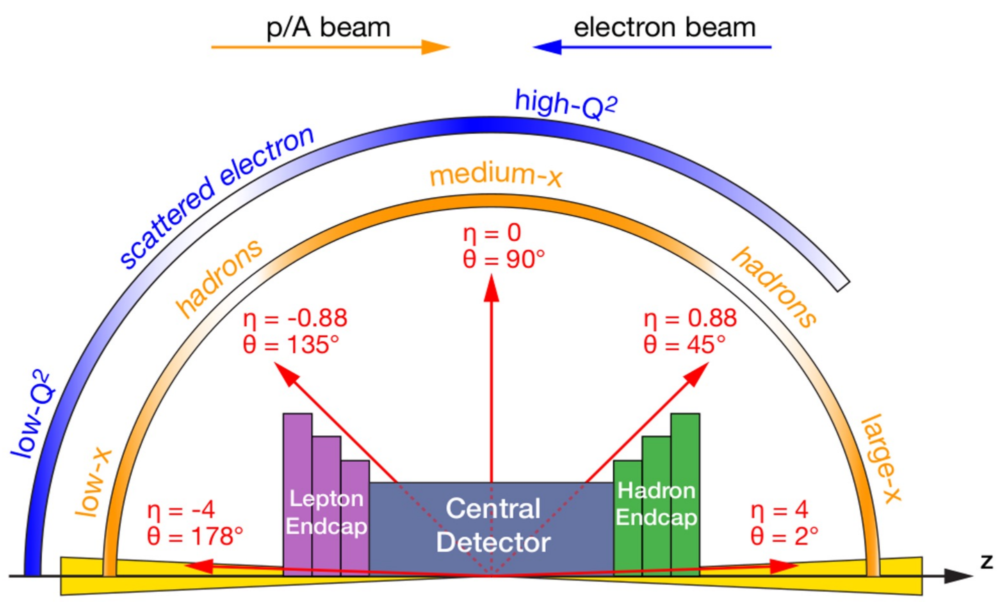
Far Backward Electron detection: ~35m

Far Forward Hadron Spectrometer: ~40m

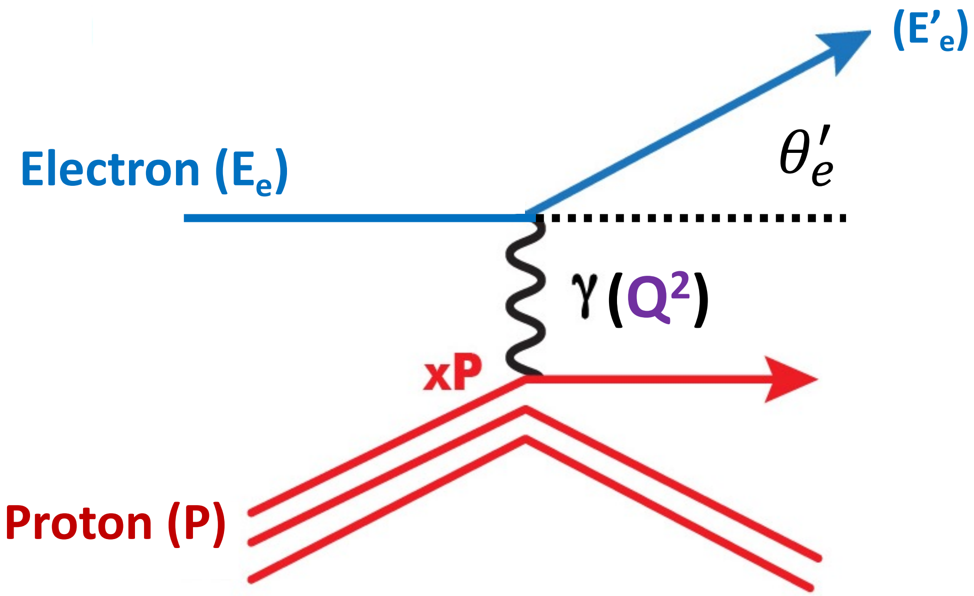
ePIC Detector x and Q^2



$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



Deep Inelastic Scattering (DIS)



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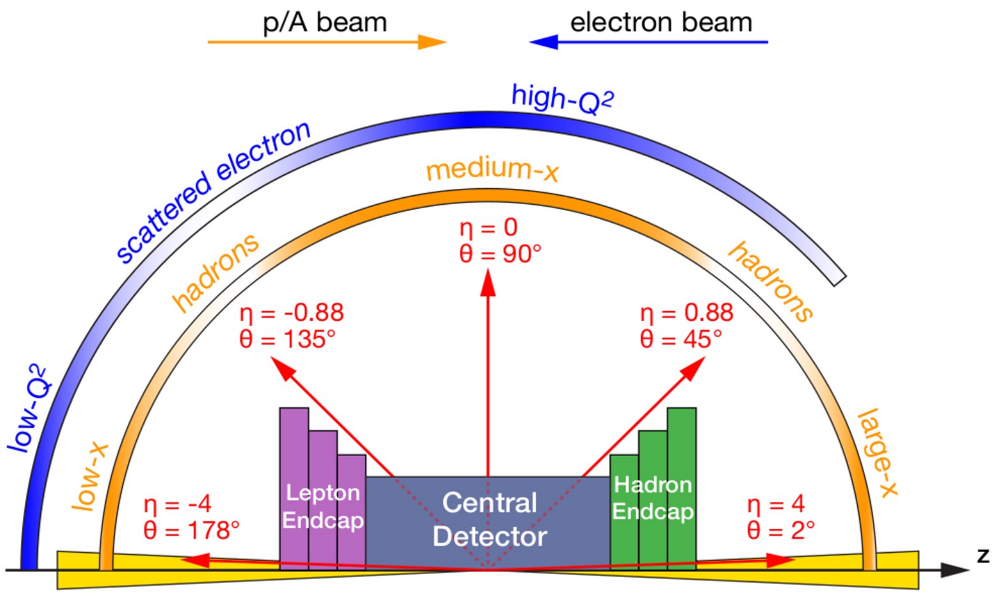
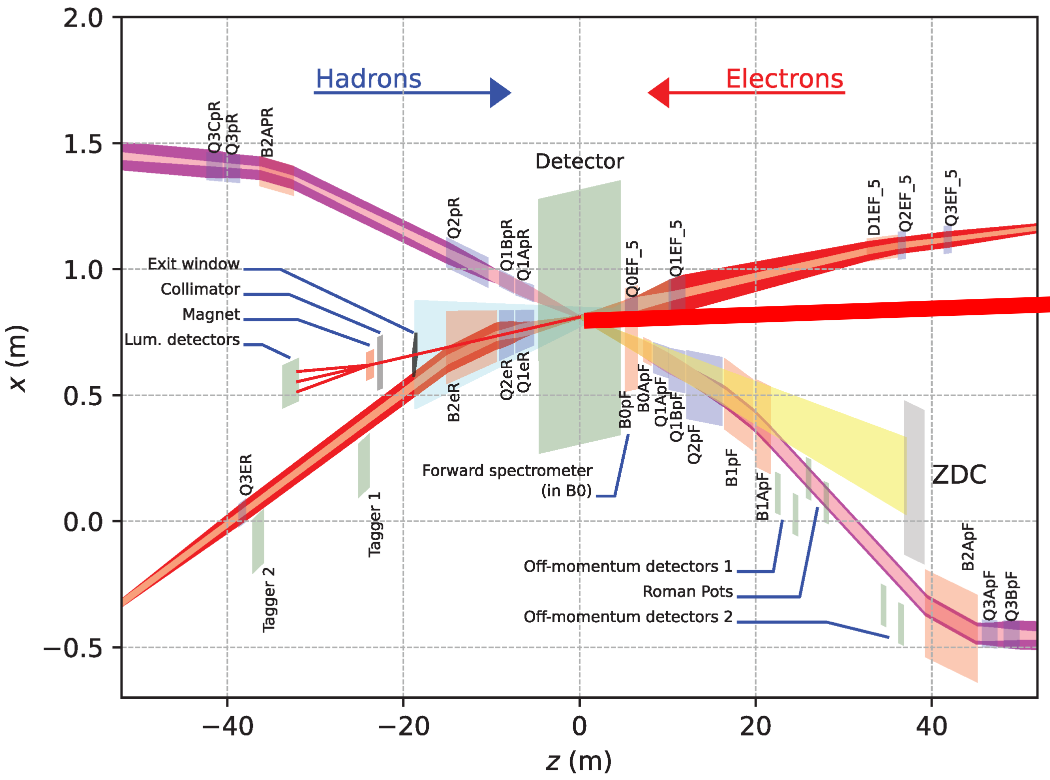
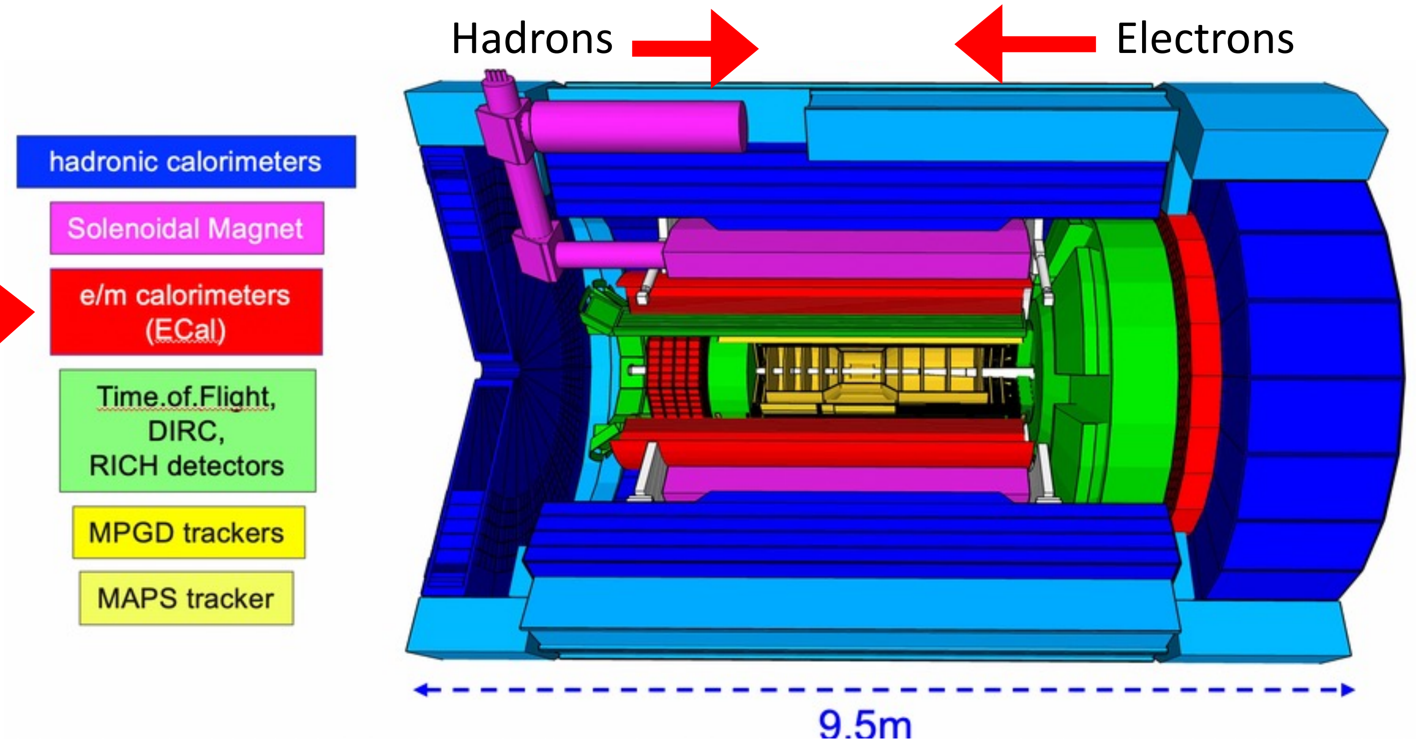
Changing **x** projects out different configurations where different dynamics dominate



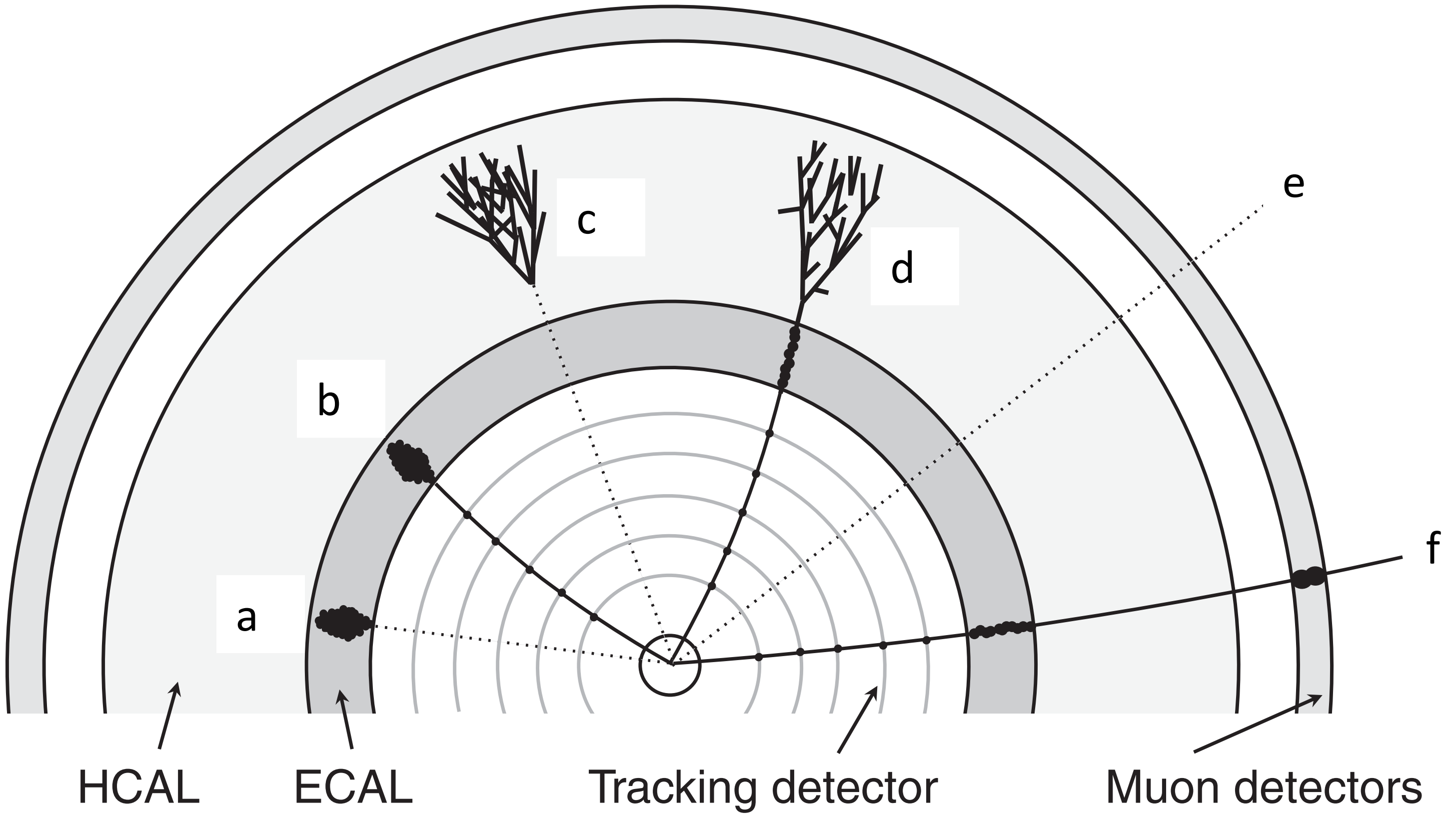
ePIC Detector → Barrel



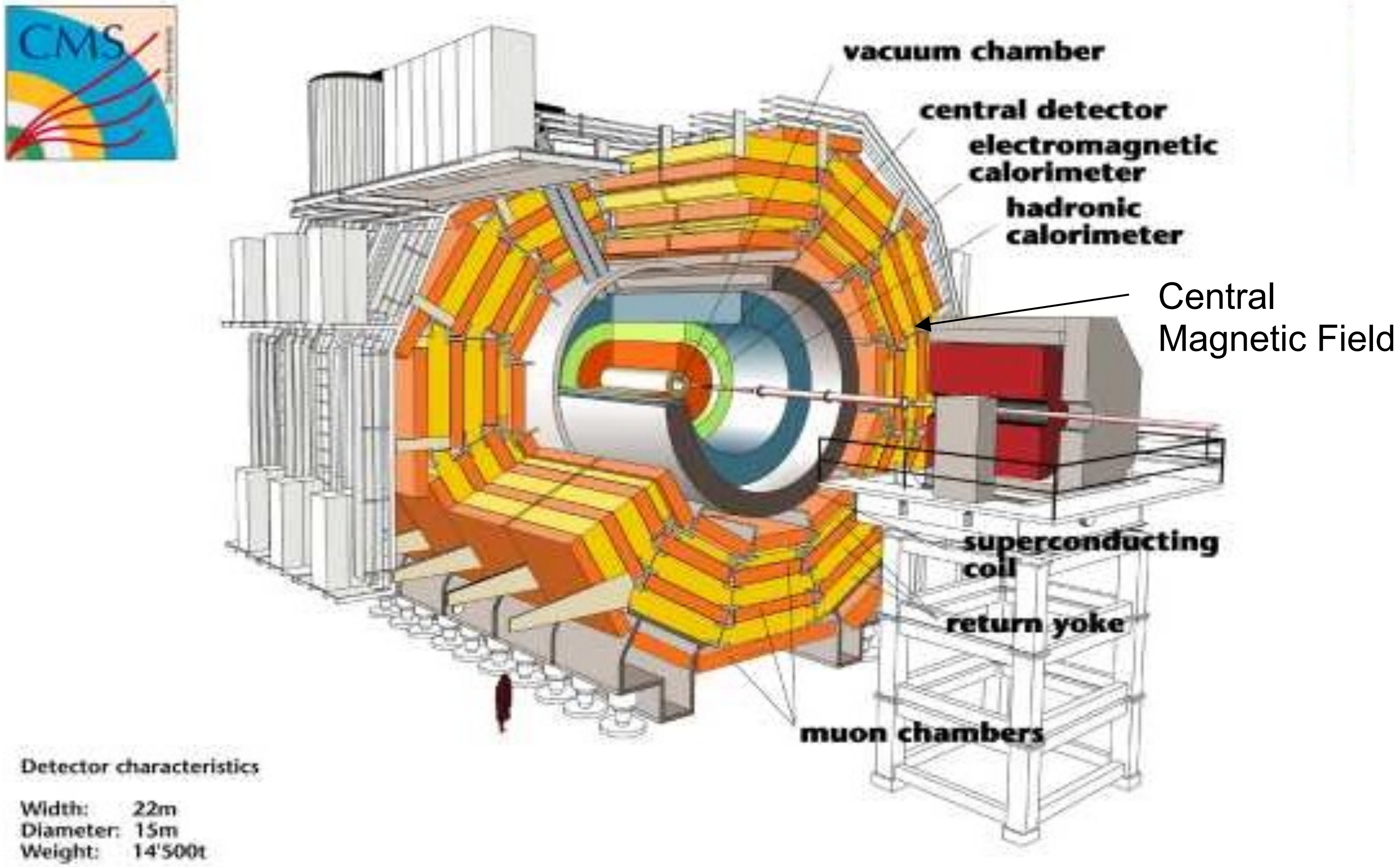


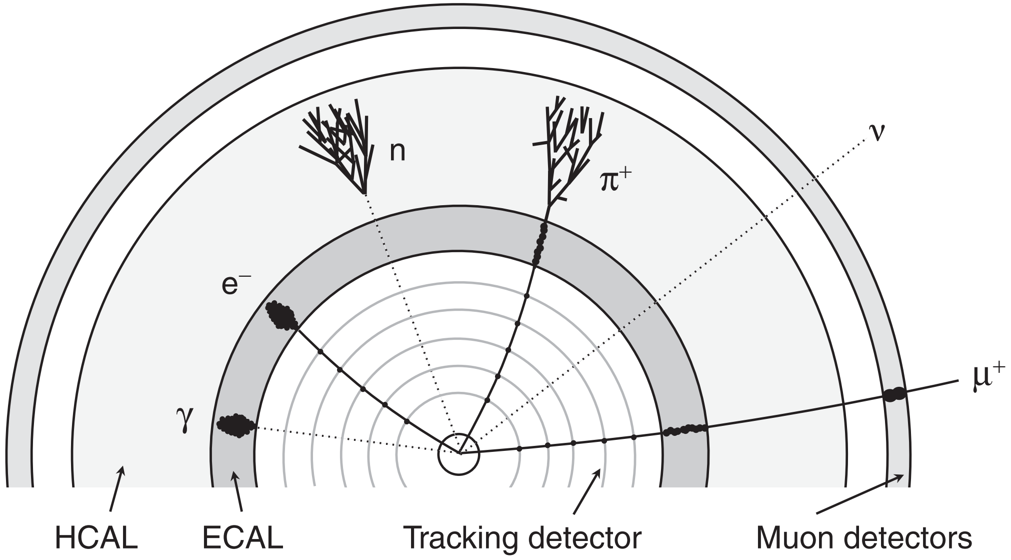
Auxiliary detectors needed to tag particles with very small scattering angles both in the outgoing lepton and hadron beam direction (B0-Taggers, Off-momentum taggers, Roman Pots, Zero-degree Calorimeter and low Q2-tagger).

Modern Particle Physics Experiments Basics



Modern Particle Physics Experiments Basics





Many common features in modern NP and HEP detectors – inner tracking, magnetic field, EM and hadronic calorimetry, outer muon chambers.

Want to determine particle track, charge, momentum, energy, type (id) ….

Interaction of Radiation with Matter

(Heavy Particles, Low Density Matter)

- Heavy Charged Particles (p, α, etc)
  - When a charged particle passes through matter, it interacts primarily with atomic electrons
  - Conservation of energy/momentum for a heavy particle M incident on a light particle m gives:
  - $\Delta T = T\left(\frac{4m}{M}\right)$ Kinetic energy lost by M
    - Elastic, head-on collision – this is the maximum energy loss
  - <u>Example</u>: For a 5MeV α particle, $m_\alpha \sim 4m_n$ $\Delta T = 5MeV\left(\frac{4m_e}{4m_n}\right) \cong 2.6keV$
- A typical particle will undergo thousands of collisions before it loses all its energy!
- A heavy particle is deflected by a small amount in a collision
- The Coulomb force has an infinite range, so a particle interacts simultaneously with many electrons and effectively loses energy *continuously* along its path
- The energy required to ionize atoms is a few 10's of eV, so many collisions will liberate atomic electrons
  - Known as "δ rays"

Bethe-Block Equation

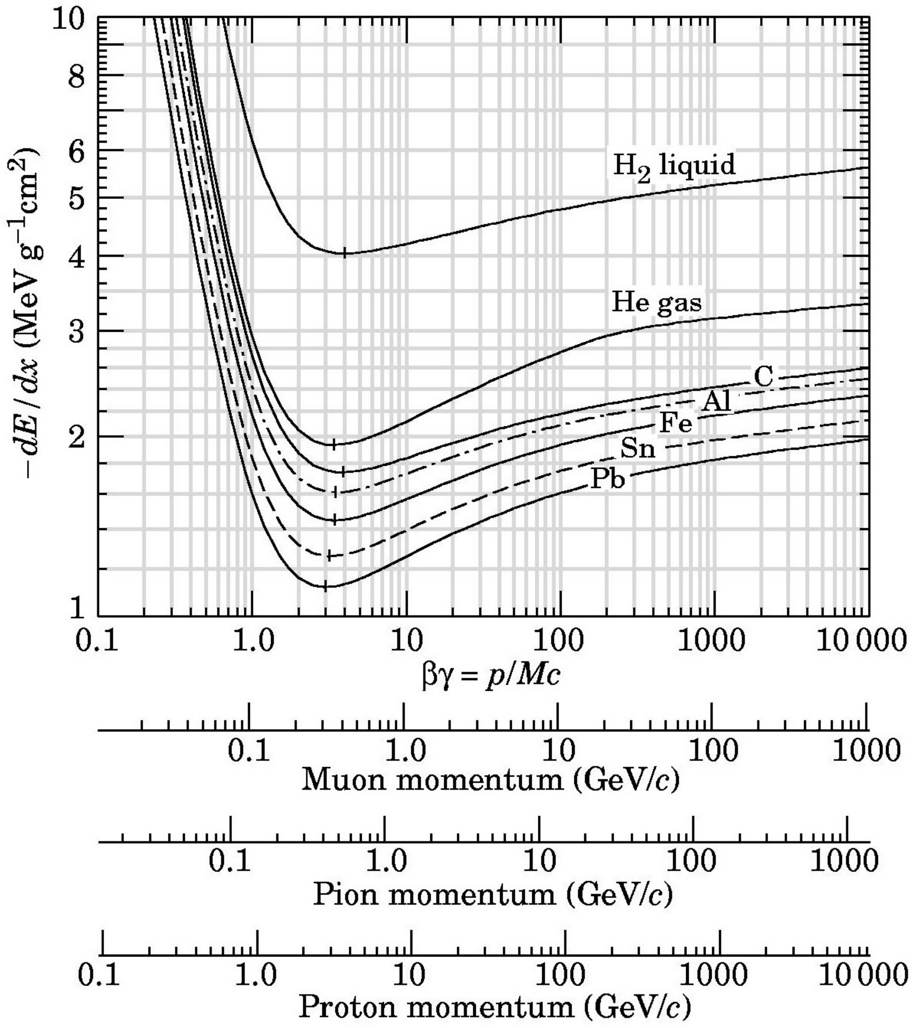
- The original calculation for energy loss of a charged particle is due to Hans Bethe (1930)
  - **Bethe-Block Equation**
    - For a particle of charge *ze*, velocity *v*:

$$-\frac{dE}{dx} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi}{m_e c^2} \frac{n_e z^2}{\beta^2} \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

  - The electron density is given by:

$$n_e = \frac{N_A \cdot Z \cdot \rho}{A}$$

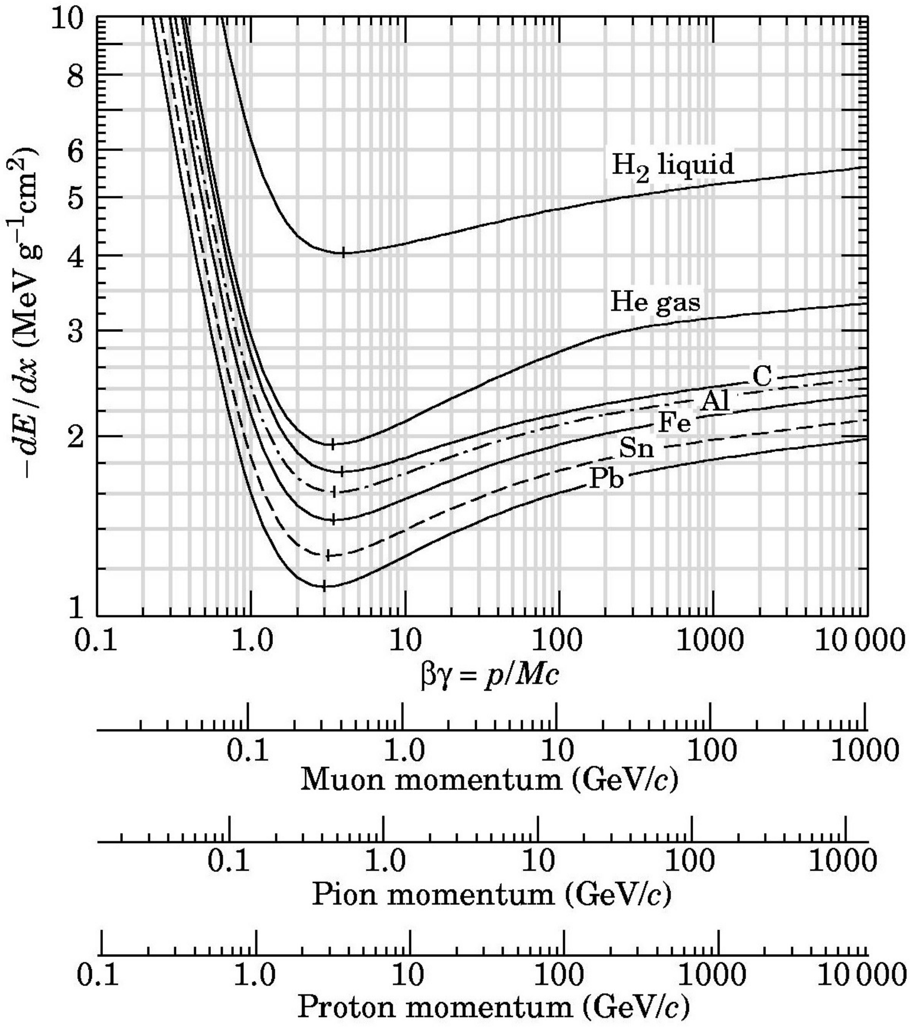
  - *I* is the *mean ionization energy* for the material
    - In principle it is an average over all ionization and excitation processes $I_{AIR} = 86 eV \qquad I_{Al} = 163 eV$
    - Approximately *I/Z* ~ 10 eV



Bethe-Block (II)

$$-\frac{dE}{dx}=\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\frac{4\pi}{m_ec^2}\frac{n_ez^2}{\beta^2}\cdot\left[\ln\left(\frac{2m_ec^2\beta^2}{I\cdot\left(1-\beta^2\right)}\right)-\beta^2\right]$$

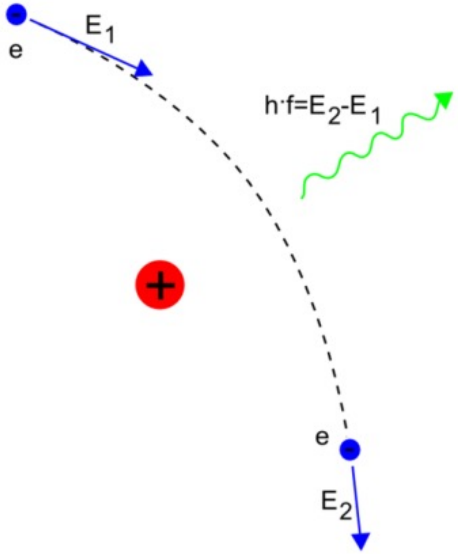
- Energy loss depends quadratically on *v* and *z*, but not on its mass *M*
- For low energies (β << 1), the energy loss decreases as ~$1/v^2$
- Reaches a minimum for $E \sim 3Mc^2$
  - $dE/dx \sim 2MeV\ g^{-1}\ cm^2$ (note – divided by density!)
- For $\beta \sim 1$ the energy loss rises logarithmically
  - Referred to as “relativistic rise”
  - Relativistic deformation of Coulomb field of incident particle increases effective impact parameter cutoff (semiclassical)



Energy Loss by Electrons and Positrons

- Electrons/Positrons travelling through matter also collide w/atomic electrons
  - They will lose energy faster and scatter at larger angles
  - They can lose energy via *bremmstrahlung*
    - Accelerated charge radiates energy!
  - Energy loss (also due to Bethe):

T = kinetic energy of electron/positron



$$-\frac{dE}{dx}\bigg|_{collisions} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{2\pi}{m_e c^2}\frac{n_e}{\beta^2}\cdot\left[\ln\left(\frac{T(T+m_e c^2)\beta^2}{2I^2 m_e c^2}\right) - (1-\beta^2)\right]$$

$$-\frac{dE}{dx}\bigg|_{bremm.} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{Z^2 n_e (T+m_e c^2)}{137\cdot m_e^2 c^4}\cdot\left[4\ln\left(\frac{2(T+m_e c^2)}{m_e c^2}\right) - \frac{4}{3}\right]$$

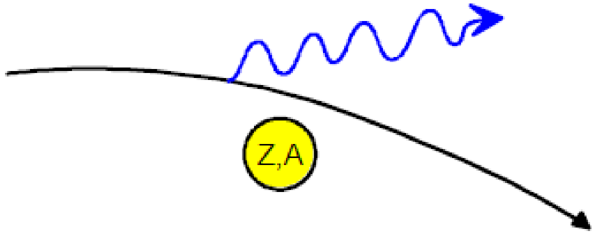
  - Which term dominates for electrons/positrons depends on the incident energy of the lepton

$$\frac{\left(\frac{dE}{dx}\right)_{bremm}}{\left(\frac{dE}{dx}\right)_{collisions}} \approx \frac{(T+m_e c^2)}{m_e c^2}\frac{Z}{1600}$$

Radiation Length

Parametrize bremsstrahlung energy loss as:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0} \quad \Rightarrow \quad \mathrm{E} = E_0 e^{-x/X_0}$$



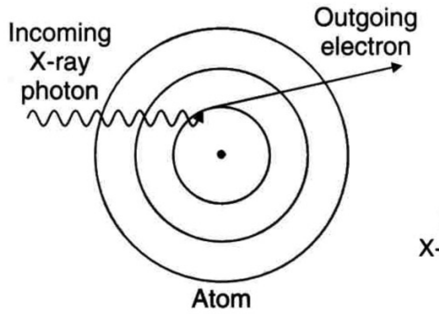
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}} \sim 180\, A/Z^2 \ [\mathrm{g\ cm^{-2}}]$$

Example: for Pb (Z=82, A=208), X_0 ~ 5.0mm

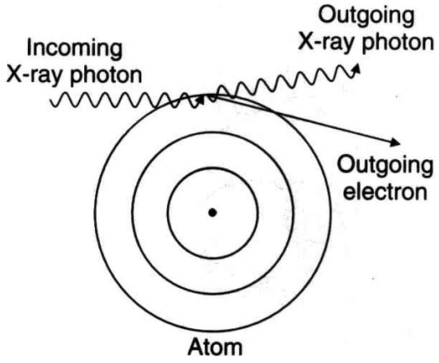
A radiation length (X_0) is a very convenient quantity to characterize a medium where bremsstrahlung dominates (high energy > ~ 10 MeV).

Photons

- There are three relevant processes for the interaction of photons with matter:
  - Photoelectric Effect, Compton Scattering, Pair Production
- <u>Photoelectric Effect</u>
  - Absorption of a photon by an atomic e^-
  - Difficult to calculate but easily measured
  - Most important at low E_γ



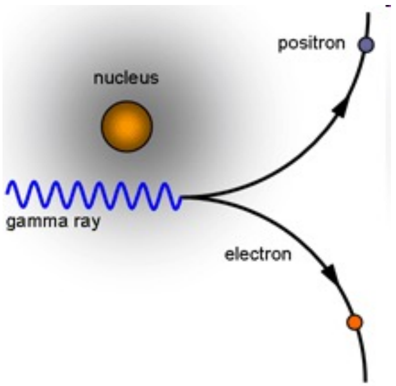
- <u>Compton Scattering</u>
  - Scattering of a photon off an atomic e^-
  - Probability depends on scattering angle



- <u>Pair Production</u>
  - Photon converts to an e^+/e^- pair
  - Presence of nucleus required for momentum conservation (Recoil negligible

$$E_\gamma = T_{e^+} + m_e c^2 + T_{e^-} + m_e c^2$$

  - Threshold at $2m_e c^2$
    - Important at higher energies
    - Mean free path before pair production: $\lambda_{pair} = 9/7 X_0$

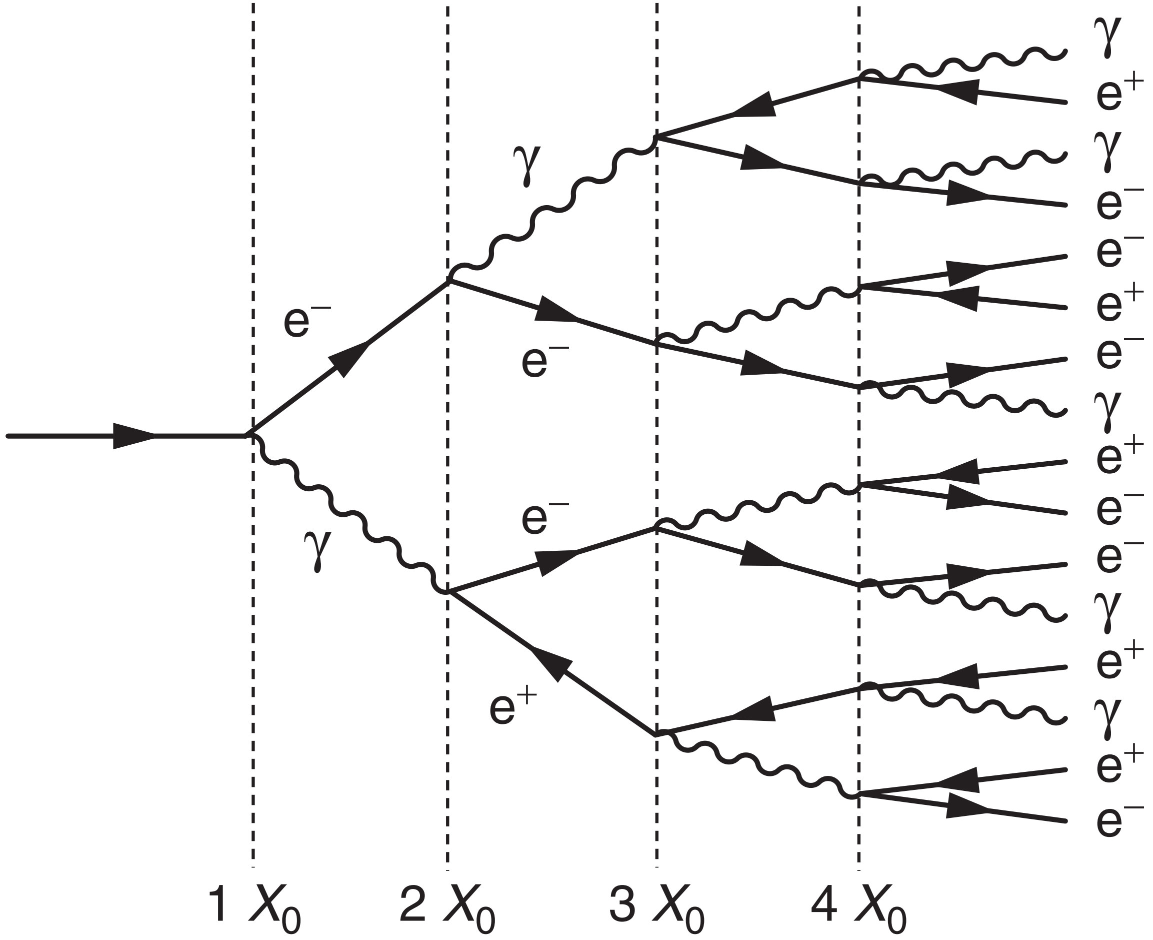


Electromagnet Showers

Resolution of EM Calorimeters

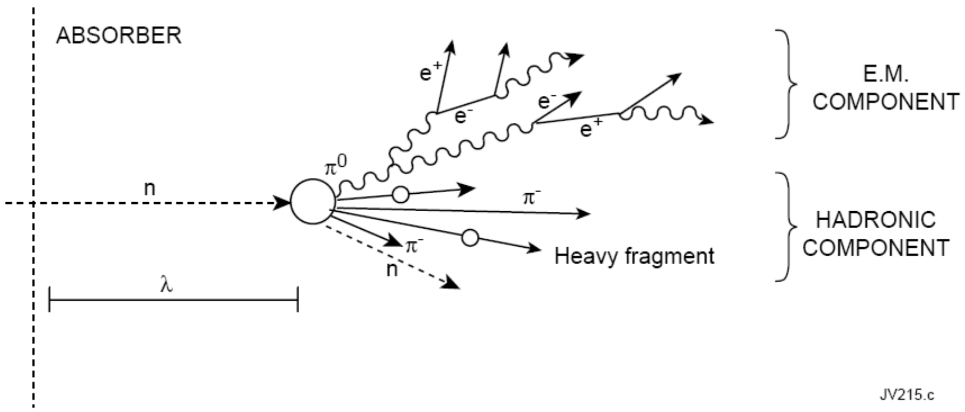
$$\frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E/\mathrm{GeV}}}.$$

- Number of EM particles essentially doubles every radiation length
- Light is collected to determine energy
- Shower develops until E_{ave} falls below the critical energy E_c
  - Electrons and positrons then lose energy by ionization

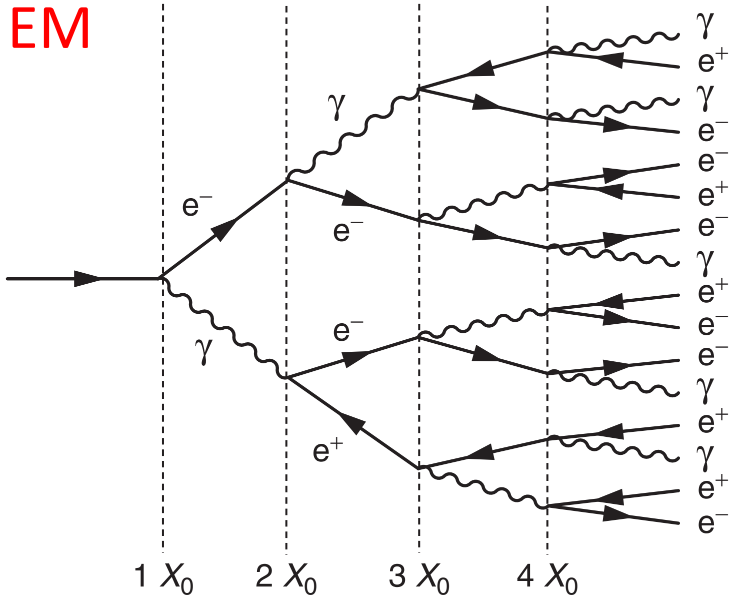


Hadronic Showers

Hadronic



EM



- Hadronic showers are messier and larger than EM showers
- Electromagnetic component due to $\pi^0 \rightarrow \gamma\gamma$
- Nuclear interaction interaction length λ_n → mean distance between hadronic interactions
  - Much larger than radiation length!

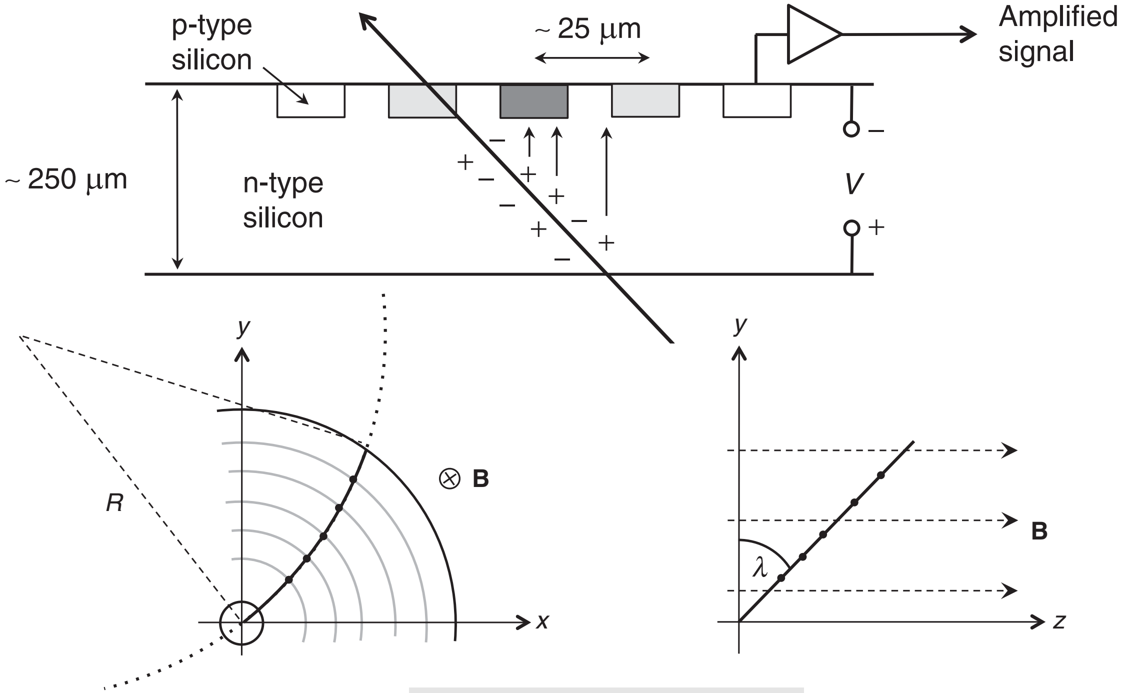
Resolution of Hadronic Calorimeters

$$\frac{\sigma_E}{E} \gtrsim \frac{50\%}{\sqrt{E/\mathrm{GeV}}}$$

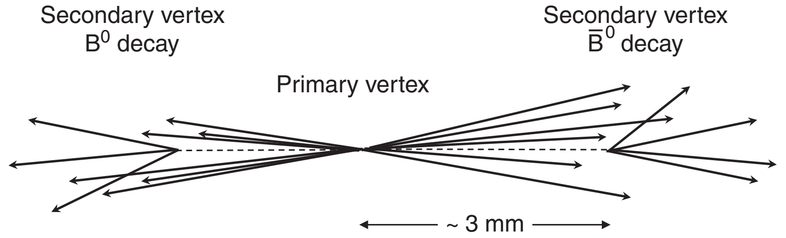
material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Tracking Basics

- Charged particles leave a trail of ionized atoms and liberated electrons when traveling through matter
  - This ionization allows us to reconstruct the trajectory
- 2 main tracking detector technologies:
  - Large gaseous tracking volume where the liberated electrons drift in a strong electric field towards sense wires where the signal can be recorded
  - Semiconductor technology using silicon pixels or strips



$$p \cos \lambda = 0.3\, B R,$$

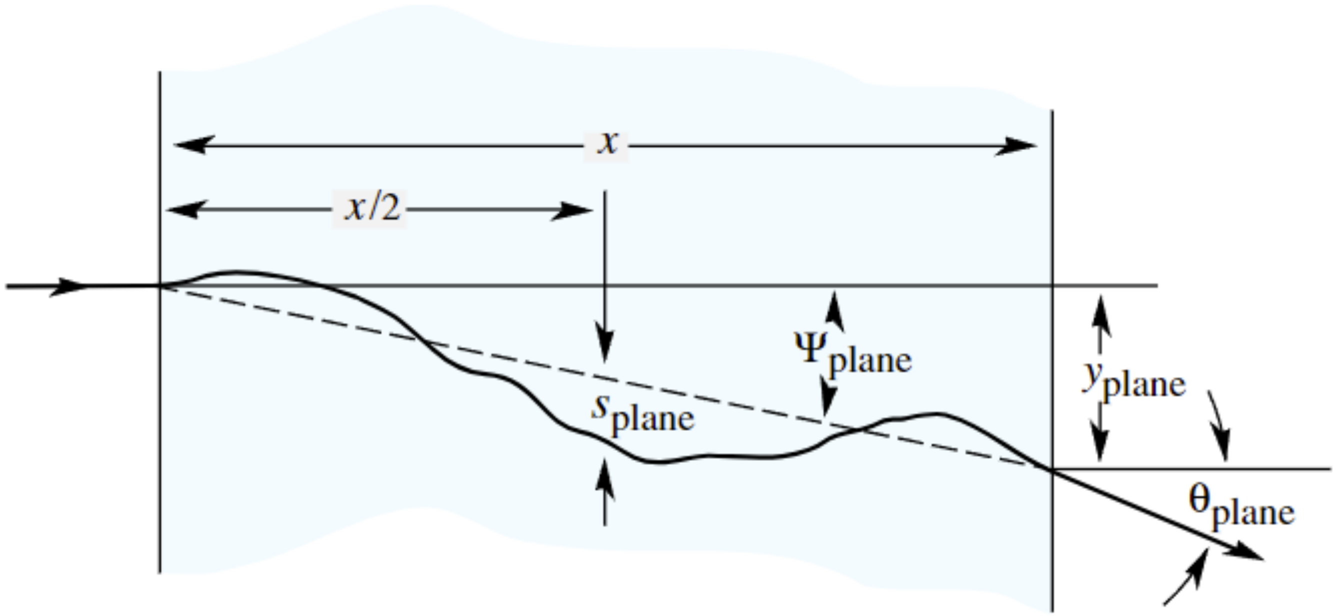


Multiple Scattering

- Particles passing through matter can also undergo scattering from the atomic nuclei (Rutherford scattering). This will deflect the direction of the particle through many small-angle scatters:

Thickness of material in radiation lengths

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10}\left(\frac{x z^2}{X_0 \beta^2}\right)\right]$$
$$= \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x z^2}{X_0 \beta^2}\right)\right]$$



Many small scatters leads to an approximately Gaussian distribution with tails

$$\frac{1}{2\pi\,\theta_0^2} \exp\left(-\frac{\theta_{\text{space}}^2}{2\theta_0^2}\right) d\Omega,$$

$$\frac{1}{\sqrt{2\pi}\,\theta_0} \exp\left(-\frac{\theta_{\text{plane}}^2}{2\theta_0^2}\right) d\theta_{\text{plane}}$$

For tracking detectors, you want it all - high precision, large signal, low mass, …

Momentum Resolution

Momentum measurement uncertainty:
$$\frac{\sigma_p}{p} = \frac{L^2}{8Rs}\cdot\frac{\sigma_s}{s} = \frac{L^2}{8R}\cdot\frac{\sigma_s}{L^4/64R^2} = \frac{\sigma_s}{L^2}\cdot 8R = \frac{\sigma_s}{L^2}\cdot\frac{8p}{eB} \sim p\cdot\frac{\sigma_s}{BL^2}$$

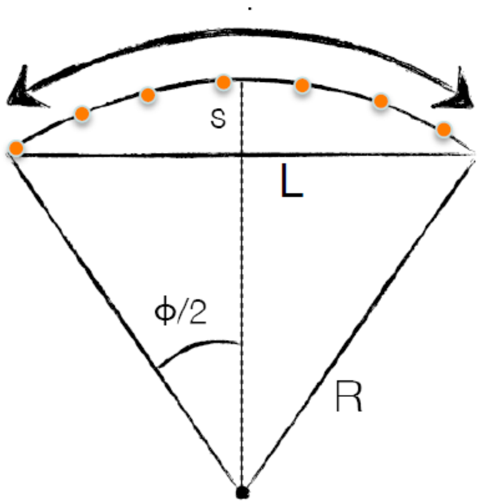
Uncertainty σ_s depends on number and spacing of track point measurements; for equal spacing and large N:

$$\sigma_s = \frac{\sigma_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$

see: Glückstern, NIM 24 (1963) 381 or
Blum & Rolandi, Particle Detection ...

Good
momentum resolution:

- large path length L
- large magnetic field B
- good Sagitta measurement



For
momentum p:

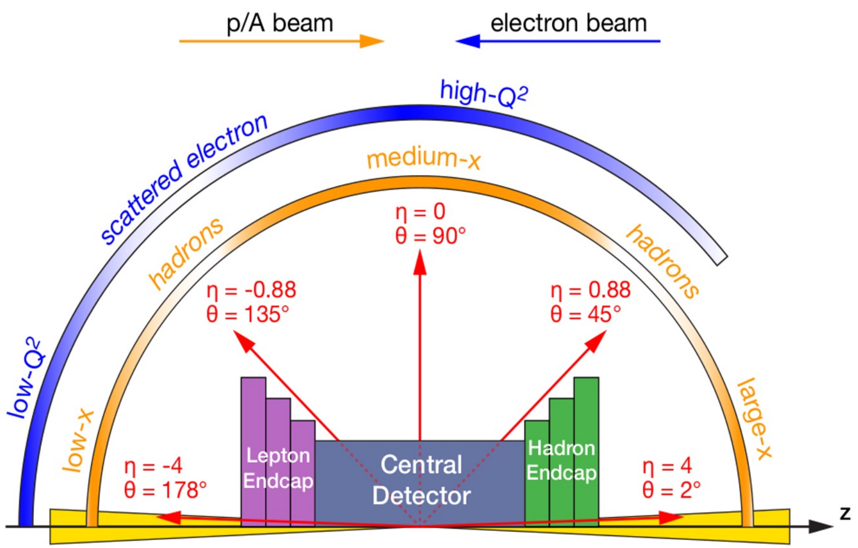
generally in experiment measure p_t

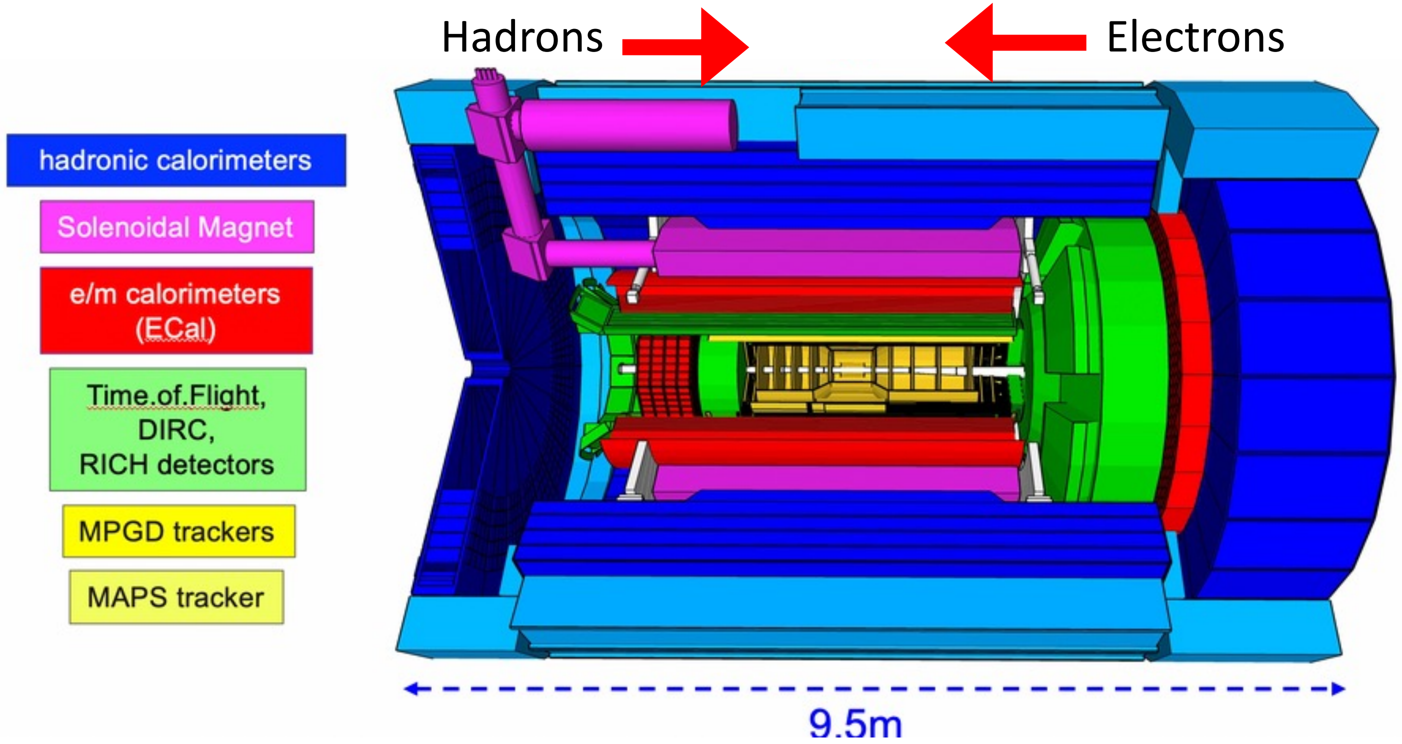
$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_t}}{p_t}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

multiple scattering term conts. in p_t

using $p = \frac{p_t}{\tan\theta}$

ePIC Detector → Tracking





EIC Detector Requirements Tracking

Vertex detector → Identify primary and secondary vertices,
- Low material budget: 0.05 X/X_0 per layer
- High spatial resolution: 10 mm pitch CMOS Monolithic Active Pixel Sensor

Central and Endcap tracker → High precision low mass tracking
- MAPS – tracking layers in combination with micro pattern gas detectors

ePIC Tracking Challenges and Strategies

Challenges

- Efficient pattern recognition
- Very low material budget for the central tracking region not exceeding 5% X/X_0 (p resolution!)
- Solenoidal magnetic field
  - Fine ∫ B· dl in the barrel
  - Limited ∫ B· dl in the endcaps
- Limited lever arm
  - Solenoid and overall detector design constrains in the barrel
  - IR design in the endcaps
- "low" interaction rate (< 0.5 GHz), but significant background!

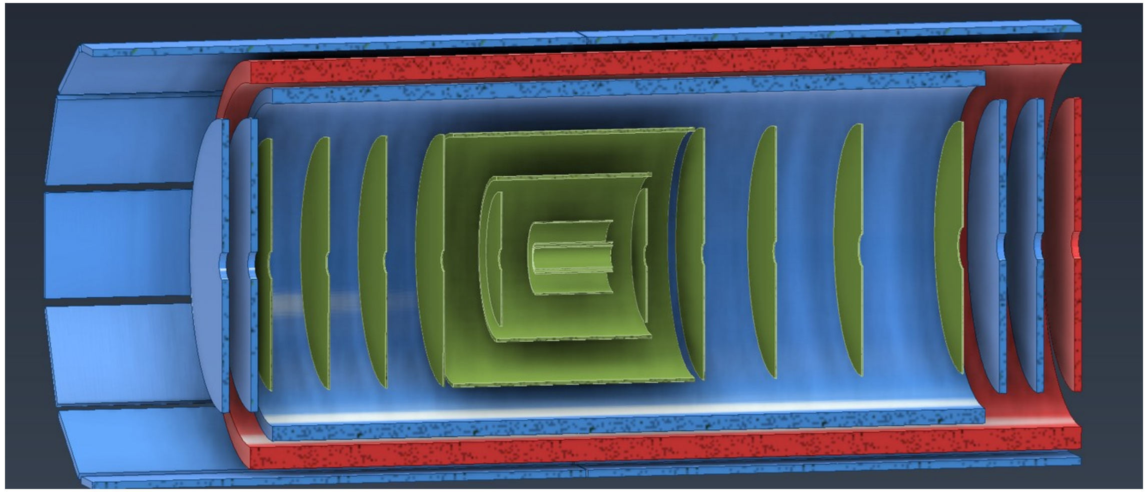
Strategies

- Redundancy of the measured space point coordinates
- Monolithic Active Pixel Silicon (MAPS)
  - Guiding example: the inner tracking in ALICE (ALPIDE chip, also used in sPHENIX)
- Fine space resolution – fine granularity Si sensors
- Synergies among detector components (backward ECal, barrel ECal, RICH counters)
- Good time res. to disentangle signal from background → additional MicroPattern Gaseous Detector layers (MAPS cannot provide)

The ePIC Central Tracking Detector

Hybrid detector based on silicon + gaseous technologies for barrel region

- Silicon Vertex Tracker (SVT):
  - SVT Inner Barrel (IB) L0, L1, L2 and Outer Barrel (OB) L3, L4
  - Monolithic Active Pixel Sensors (MAPS) based on 65 nm CMOS technology being developed by ALICE
- MPGD (Micro-Pattern Gas Detectors)
  - Gaseous detectors to cover a large outer tracking volume
  - Provides a good timing performance (Provide ~ 10 – 30 ns timing resolution) for pattern recognition
- AC-LGAD Sensors
  - Excellent time resolution for the particle identification by time-of-fight method
  - Provides an extra hit for pattern recognition and tracking
- Forward region: Five MAPS silicon disks followed by two MPGD (Micro-Pattern Gas Detectors) layers and a TOF layer Backward region: Five MAPS silicon disks followed by two MPGD layers



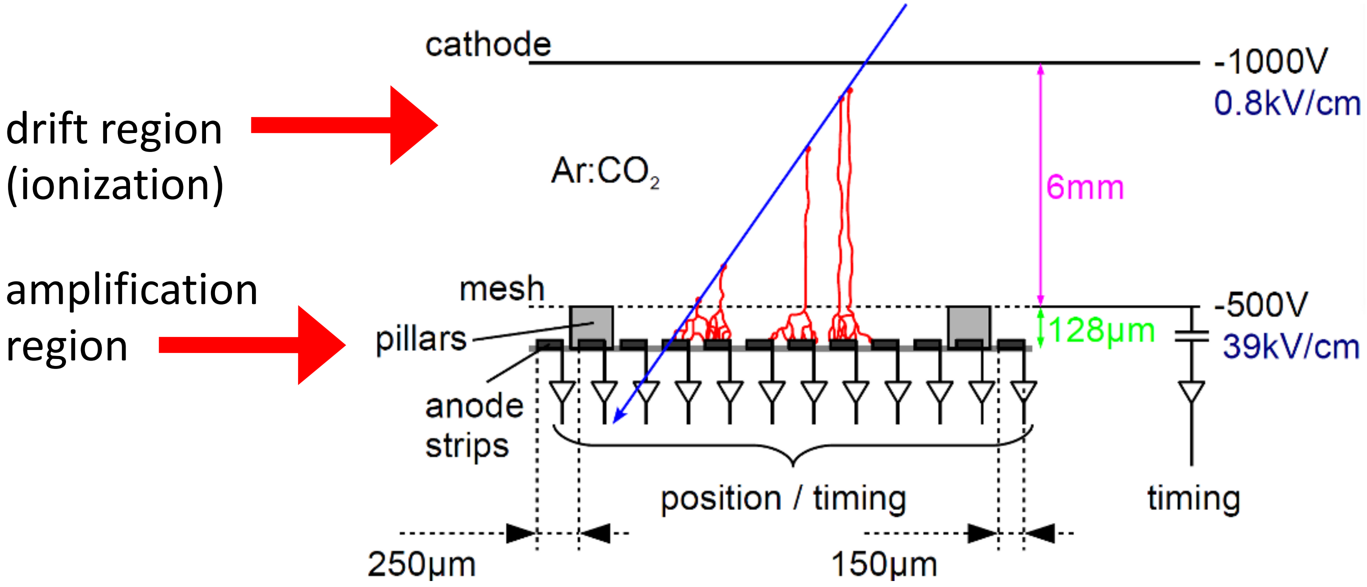
SVT IB, OB and Disks (MAPS)

MPGD Barrels and Disks

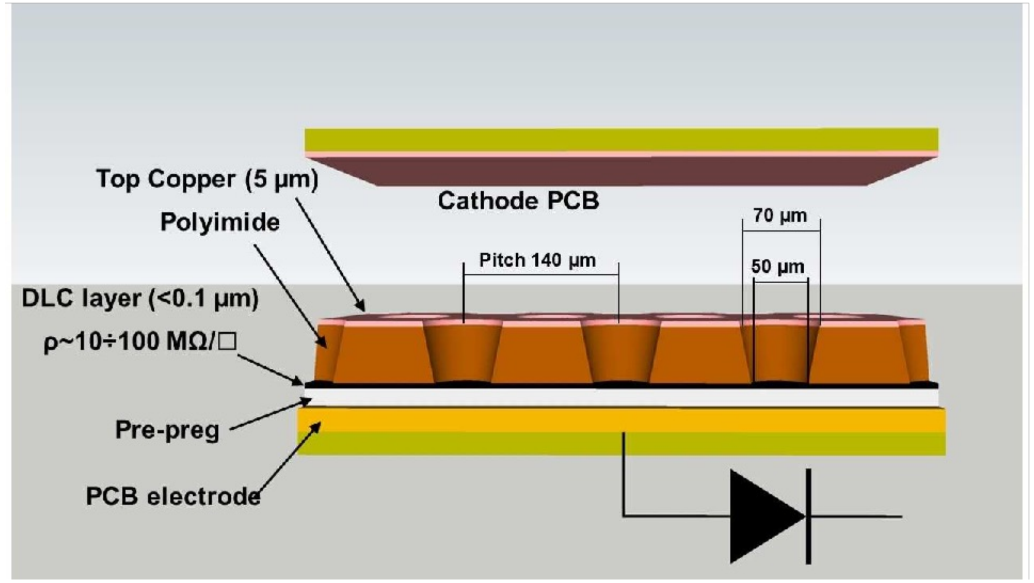
AC-LGAD TOF

Micro Pattern Gas Detectors (MPGD)

- Both have good spatial resolution of order ~150μm with a fast time response (<10ns).
- μMega detectors have been demonstrated in a cylindrical geometry



Micromegas (Micro-Mesh Gaseous Structure)

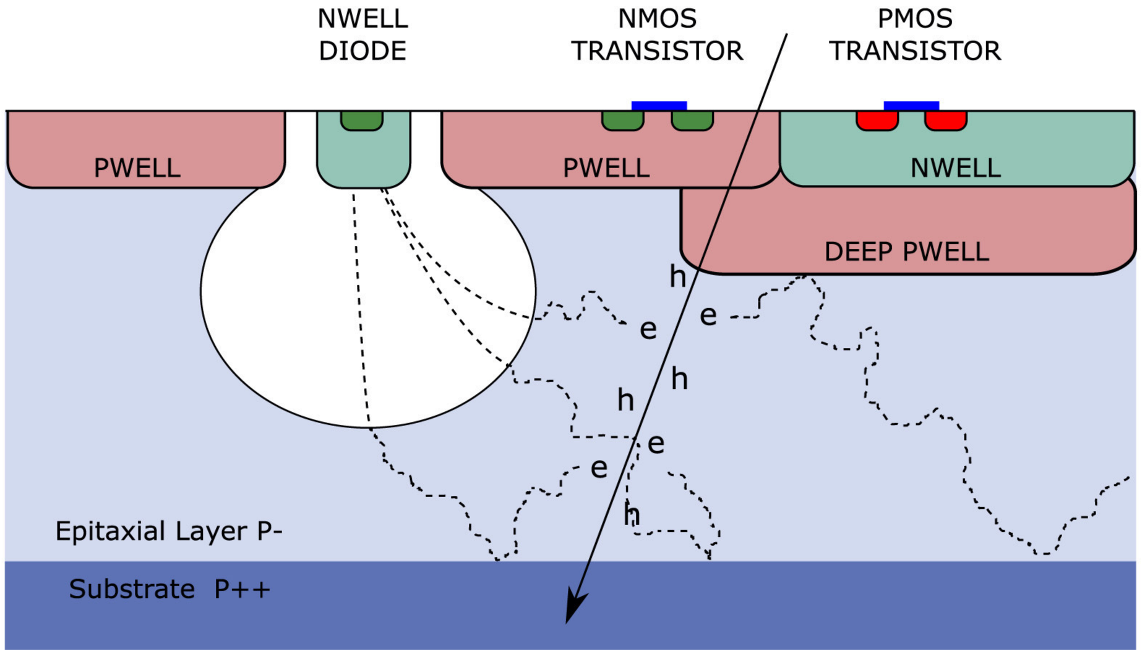


Micro-RWELL (Micro-Resistive WELL)

Resistive Layer above the readout electrodes
Amplification occurs in a single stage, where a WELL structure replaces the separate micro-mesh+ amplification gap

MAPS (Monolithic Active Pixel Sensor)

- Sensor and the readout electronics are integrated on a single piece of silicon (monolithic)
- Each pixel in a MAPS detector is an active element
- Very small pixel sizes (~micrometers)
  - High spatial resolution
  - High density of pixels → excellent granularity
- Thin Sensors → Low material budget
- Radiation hard
- Fast



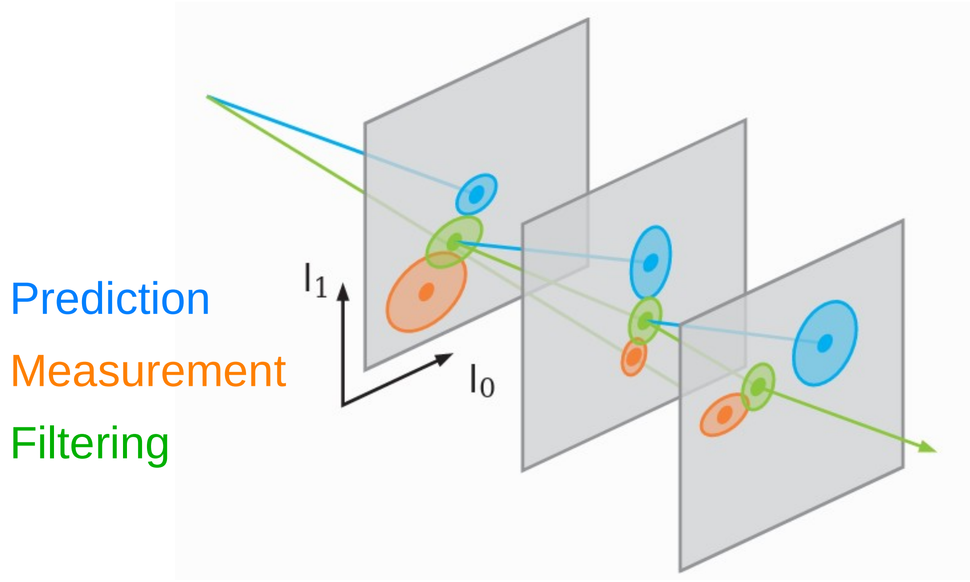
https://doi.org/10.1016/j.nima.2015.09.057

Complementary metal-oxide semiconductor (CMOS)

- Semiconductor technology used in most of today's integrated circuits

Tracking in the ePIC Experiment

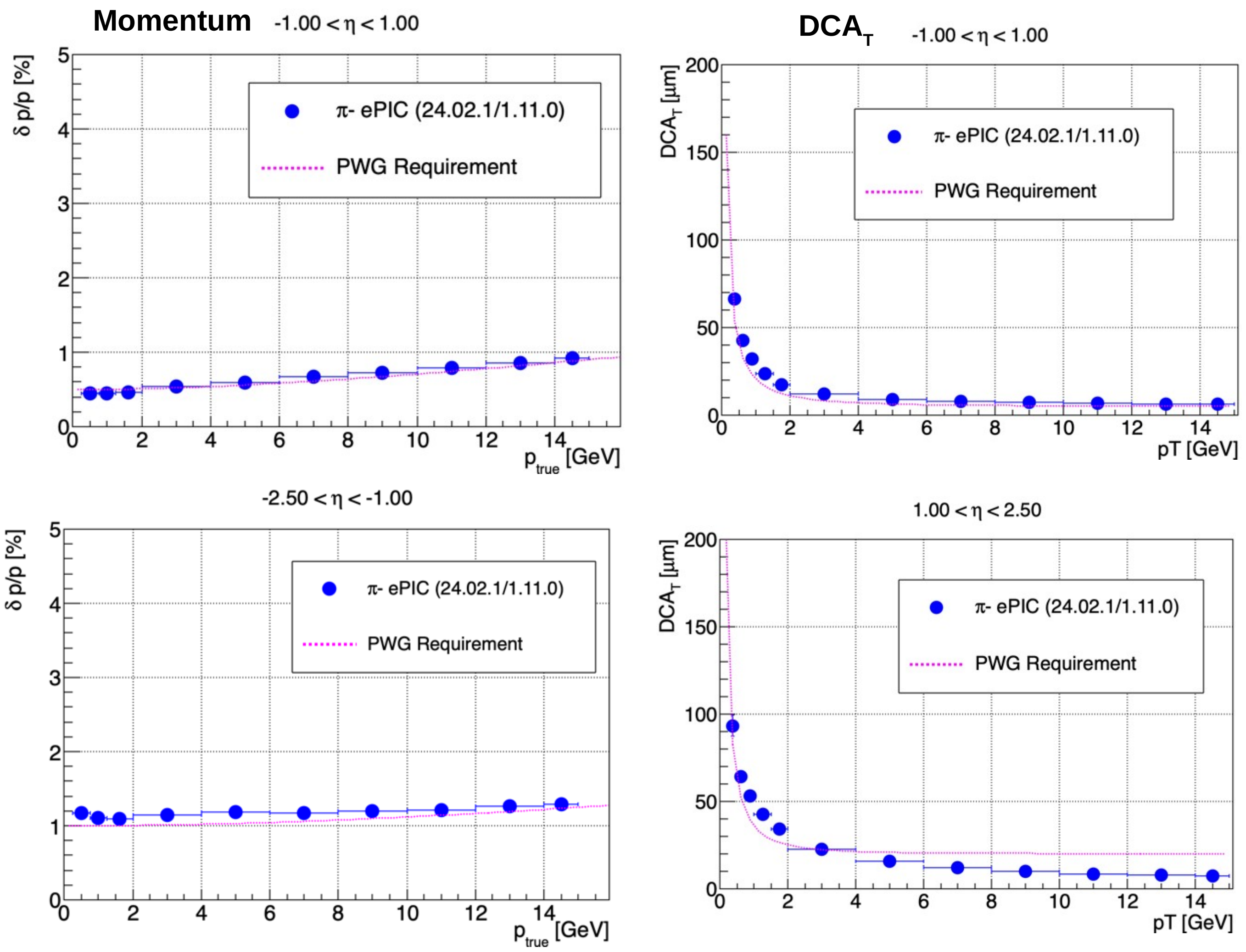
- Reconstruction of particle trajectory (with B-field, material effects, background)-4D tracking Tracking:
- Track finding and fitting using combinatorial Kalman Filter (CKF): ACTs (A Common Tracking Software)
- Track Parameters: (l_0 , l_1 , ϕ, θ, 1/p, t)
  - l_0,l_1 - local parameters describing the sensor surface
  - ϕ: Azimuthal angle in global coordinates
  - θ: angle w.r.t. z axis in global coordinates
  - p: Momentum of the track
  - t: time of hit (important due to background)



Three Steps (Kalman Filter)

1. Extrapolation
2. Filtering
3. Smoothing

Preliminary Tracking Performance



- Momentum and Distance of Closest Approach (DCA_T) Resolutions
- Requirements are met in the central region
- Requirements are substantially met in the forward/hadron and backward/electron region

S. Kumar, 16th Pisa Meeting on Advanced Detectors

Conclusions

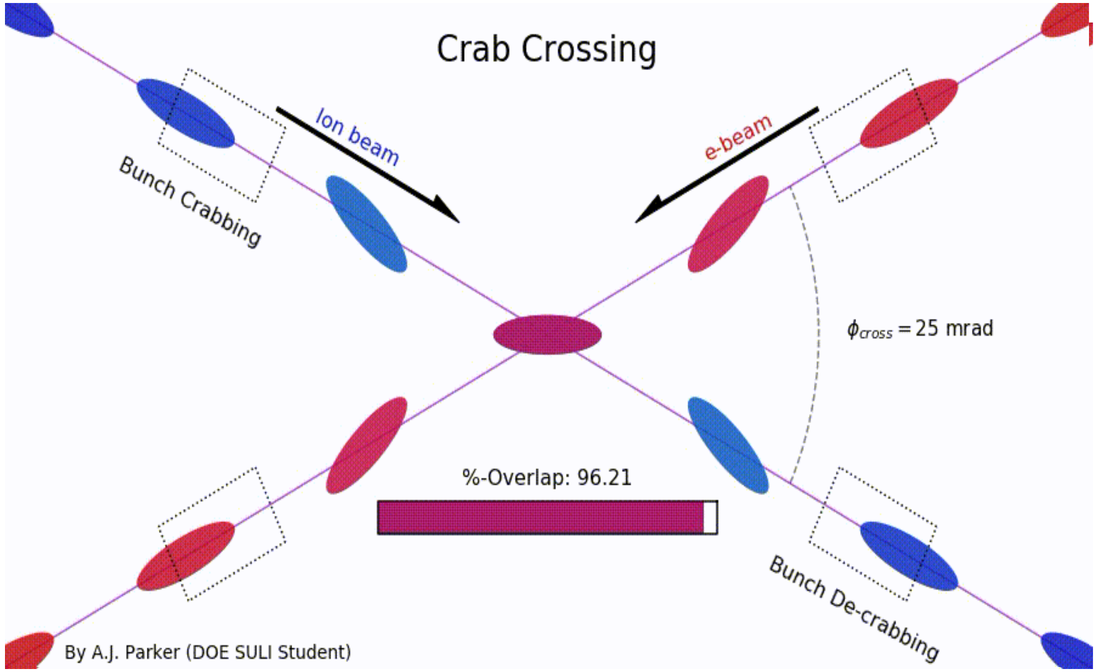
- Detectors use the basic properties of particles traveling through matter to determine kinematics and flavor of those particles
- A modern collider detector is a combination of detector technologies designed to work in concert to achieve a specific set of physics goals.
- Tracking is at the heart of all modern nuclear and HEP experiments
  - Need to know the precise kinematics of any particle
  - Decay vertices
  - Removal of background

End Lecture 1

Why a Crossing Angle?

- Brings focusing magnets close to IP
  → high luminosity
- Beam separation without separation dipoles
  → reduced synchrotron radiation background

But significant loss of luminosity!



Solution: Crab crossing

- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction