EIC Detectors: Calorimeters and glass scintillator development

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CFNS Summer School 2019

Center for Frontiers in Nuclear Science,
August 1-2, 2019

Outline Lecture 2

- ❑ Electron-Ion Collider (EIC) – Imaging the Gluons and Sea Quarks of Nucleons and Nuclei

- ❑ Detector Design

- ❑ Central Detector

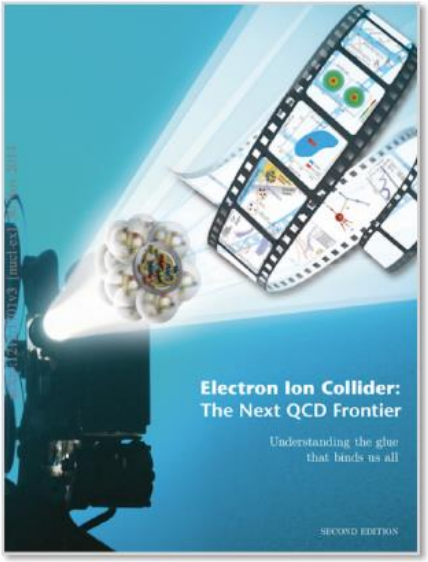
- ❑ Detector example: calorimeter
    - ➢ Overview calorimeter concepts
    - ➢ Inorganic scintillators
    - ➢ Glass scintillators as alternative active material in calorimetry

Why EIC?

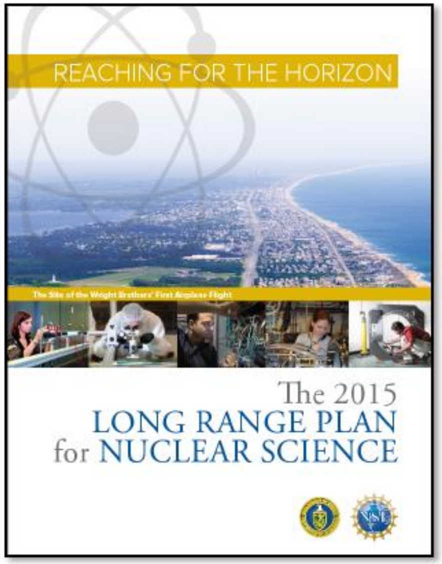
Right tool:

- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

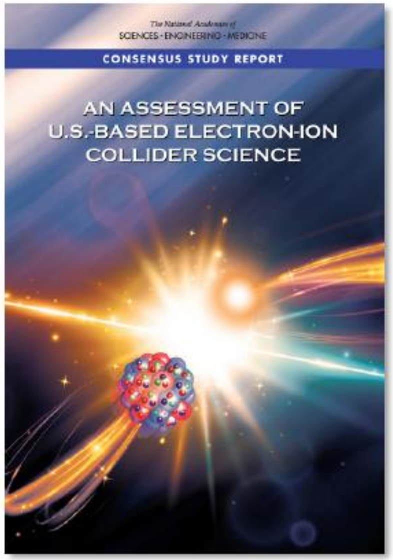
Understanding of nuclear matter is **transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.



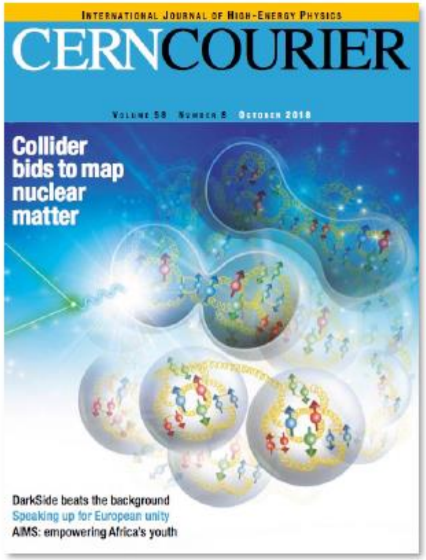
Electron Ion Collider:
The Next QCD Frontier
Understanding the glue that binds us all
SECOND EDITION



REACHING FOR THE HORIZON
The Site of the Wright Brothers' First Airplane Flight
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

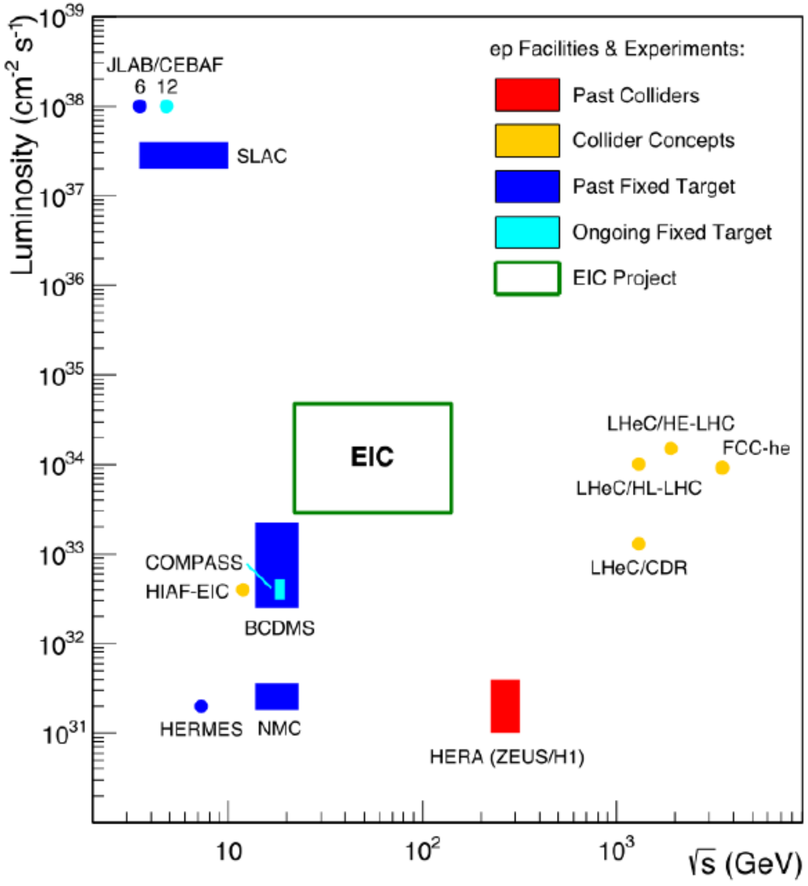


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 58 NUMBER 8 OCTOBER 2018
Collider bids to map nuclear matter
DarkSide beats the background
Speaking up for European unity
AIMS: empowering Africa's youth

The EIC



Frontier accelerator facility in the U.S.

World's first collider of

- polarized electrons and polarized protons/light ions (d, ^{3}He)
- electrons and nuclei

Versatile range of

- beam energies: $\sqrt{s}_{ep}$ range ~20 to ~100 GeV upgradable to ~140 GeV
- beam polarizations for electrons, protons and light ions (longitudinal, transverse, tensor), at least ~70% polarization
- ion beam species: D to heaviest stable nuclei

High luminosity

- 100 to 1000 times HERA luminosity

EIC Requirements

Requirements from Physics:

- ❑ High Luminosity: $10^{33\text{-}34}$ $cm^{-2}s^{-1}$ and higher → nucleon/nuclei imaging
- ❑ Flexible center of mass energy → wide kinematic reach
- ❑ Electrons (0.8) and protons/light nuclei (0.7) highly polarized → study of spin structure
- ❑ Wide range of nuclear beams (D to Pb/U) → high gluon densities
- ❑ Room for a wide acceptance detector with good PID (e/h & π, K, p) → flavor dependence
- ❑ Full (or large) acceptance for tagging, exclusivity, protons from elastic reactions, neutrons from nuclear breakup → target/nuclear fragments

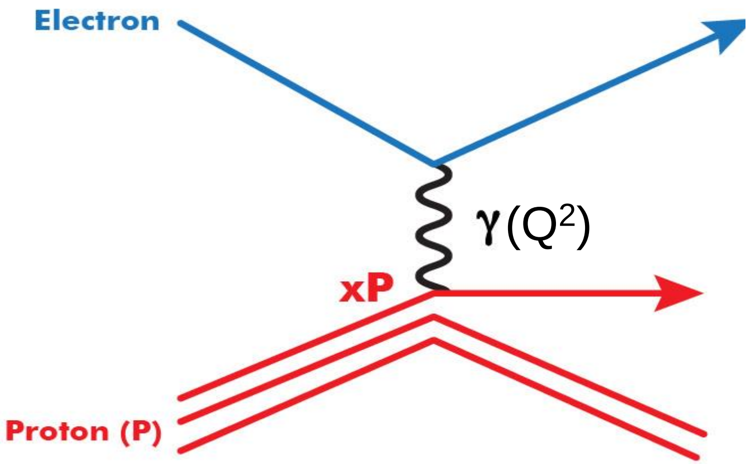
The “sweet spot” for the EIC parameters is a balance of

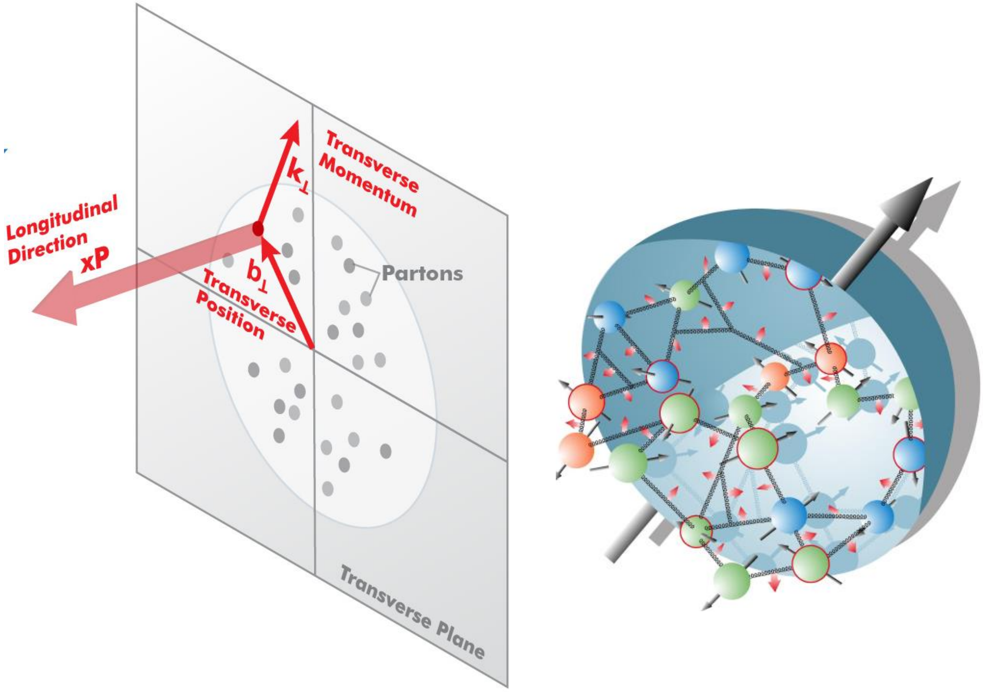
- ➢ High enough energies to reach high Q^2 (up to ~1000 GeV^2)
- ➢ Low enough proton energy to measure transverse scale of ~100 MeV well.
- ➢ High enough energy to explore collective effects towards saturation.
- ➢ High enough luminosity for the nucleon/nuclei imaging.
- ➢ IR and Detector with acceptance and performance to fully measure the relevance processes

Detector Design

Mapping position and motion of quarks and gluons

$s=xyQ^2$, $s=4E_eE_p$



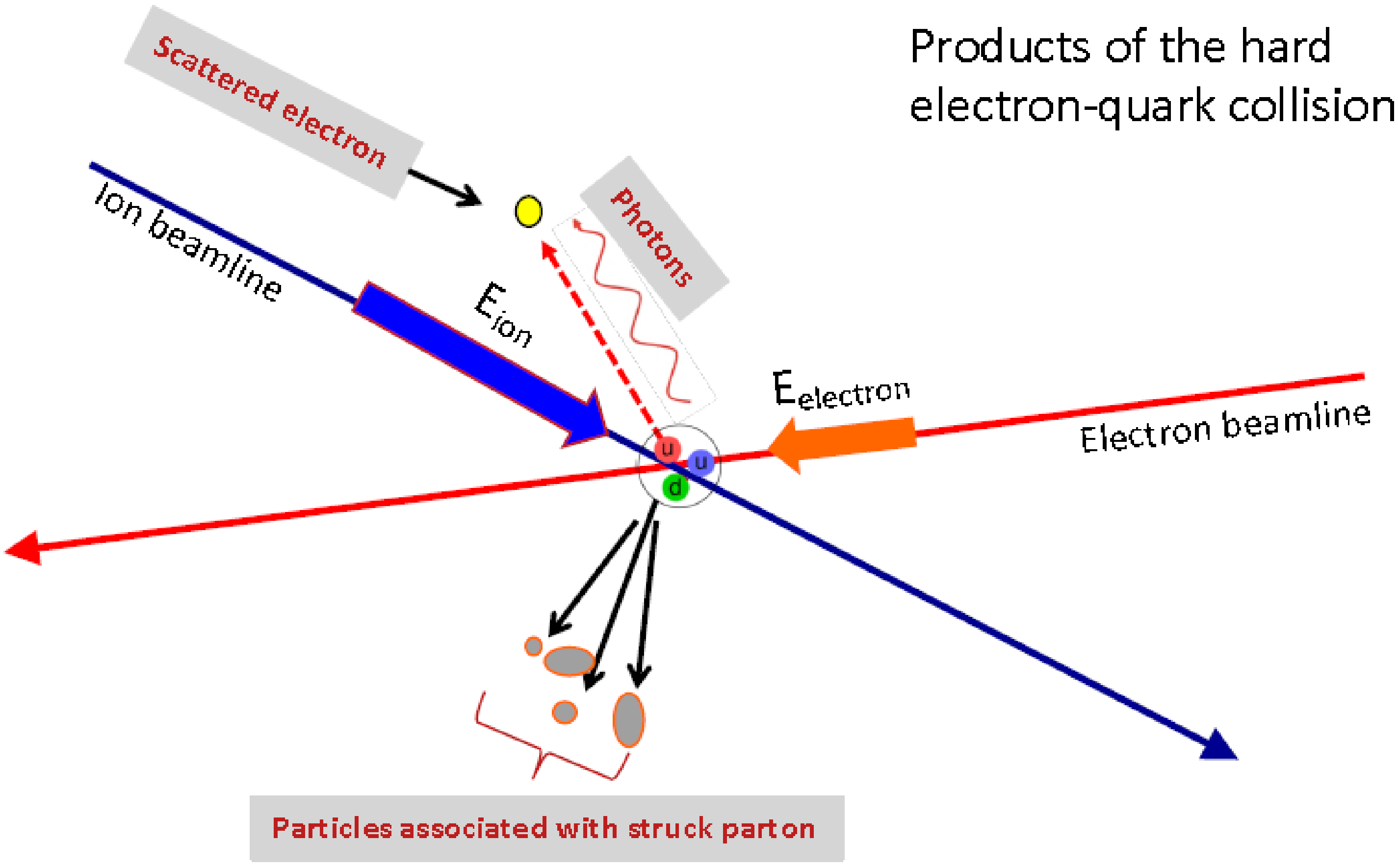


On one hand: need high beam energies to resolve partons in nucleons. Q^2 needs to be up to ~1000 GeV^2

On the other hand: need to resolve quantities (k_t, b_t) of order a few hundred MeV in the proton. Limits the proton beam energy & High Lumi needed.

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

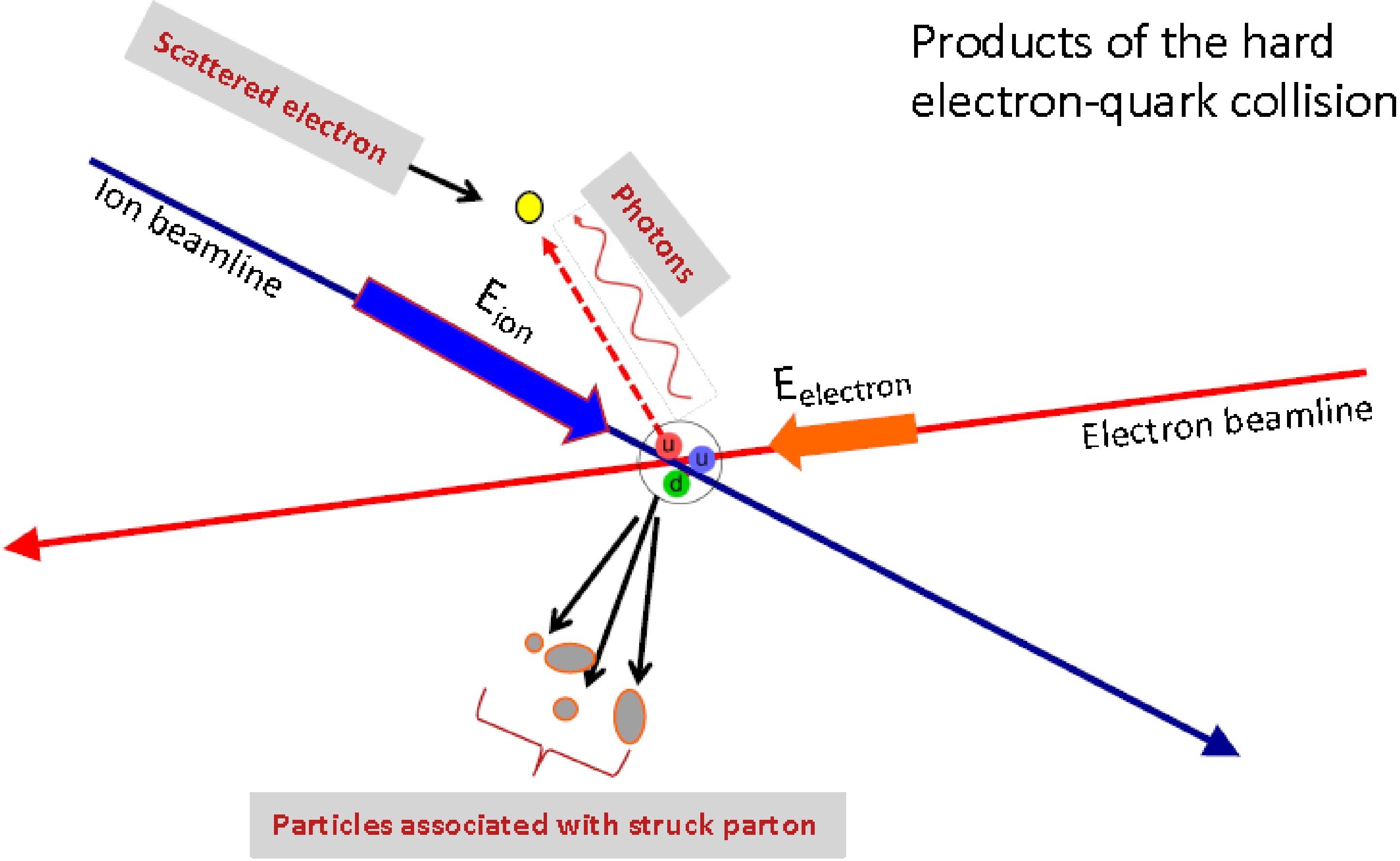
Particle Identification



Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA** colliders.

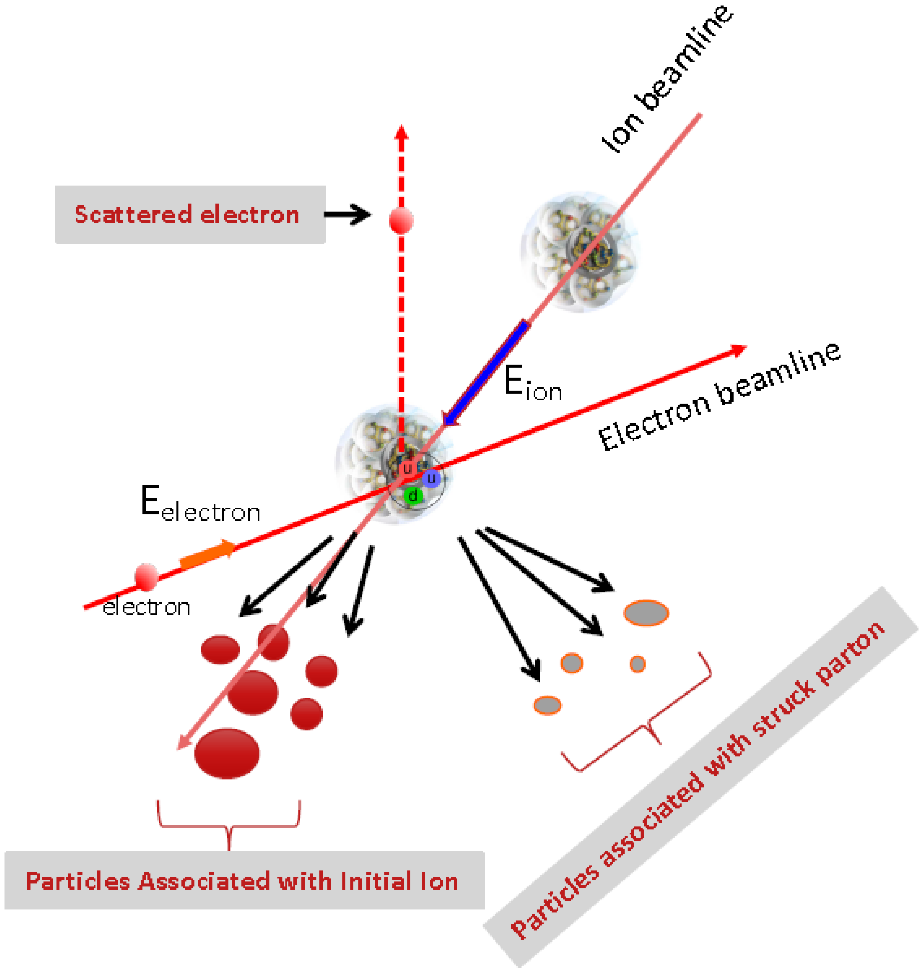
Final-state particles in central rapidity



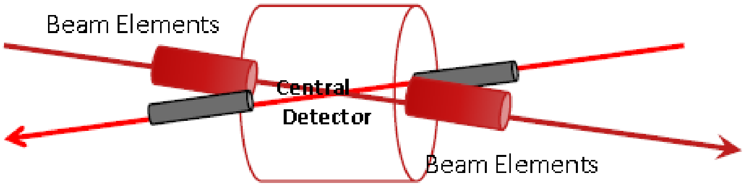
Products of the hard electron-quark collision

Asymmetric collision energies will boost the final state particles in the ion beam direction: **Detector requirements change as a function of rapidity.**

Final-state particles



The aim is to get **~100% acceptance** for all final state particles, and measure them with good resolution.

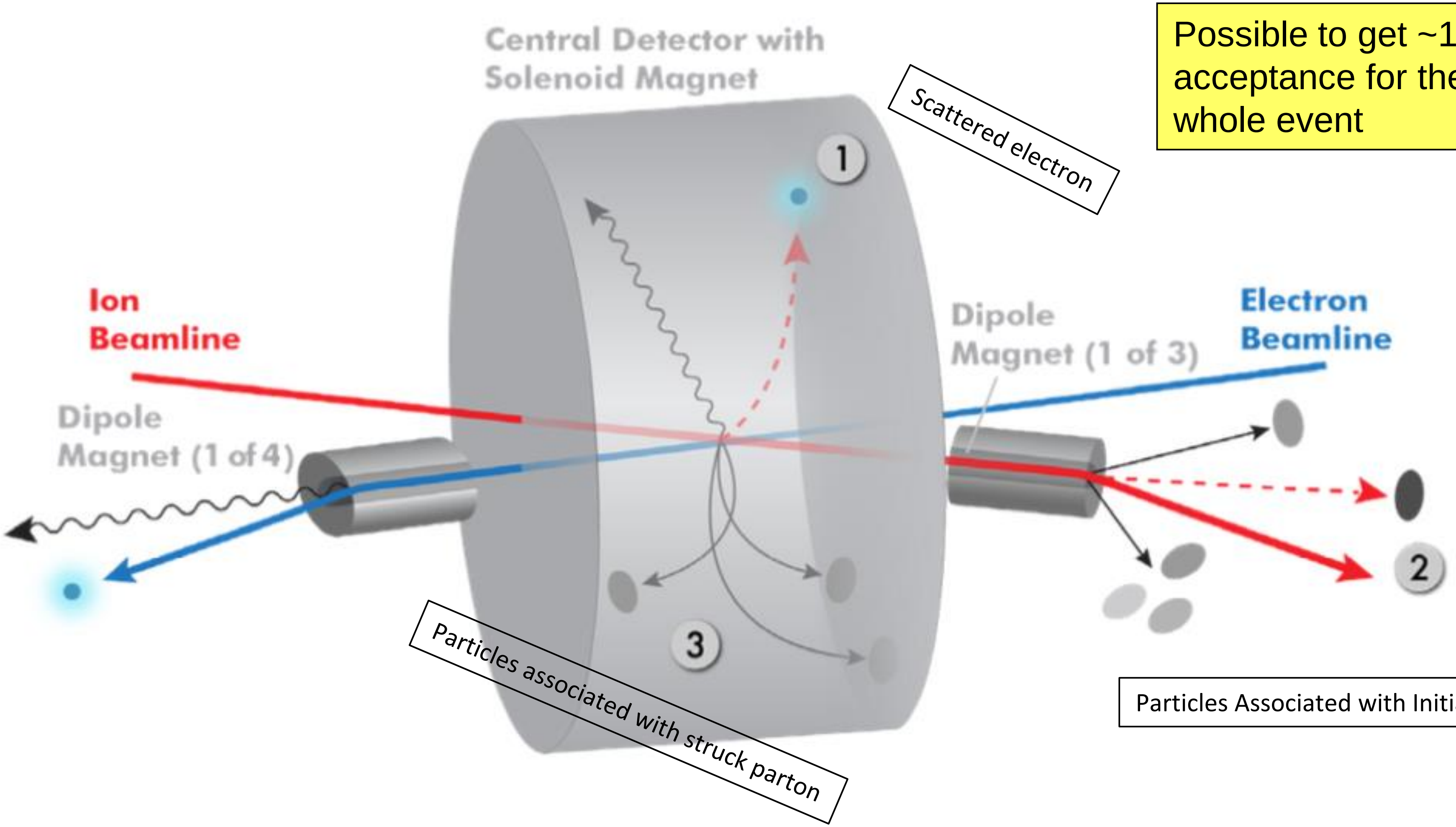


Experimental challenges:

- beam elements limit forward acceptance
- central Solenoid not effective for forward

Interaction Region Concept

Possible to get ~100% acceptance for the whole event



Scattered electron

Particles associated with struck parton

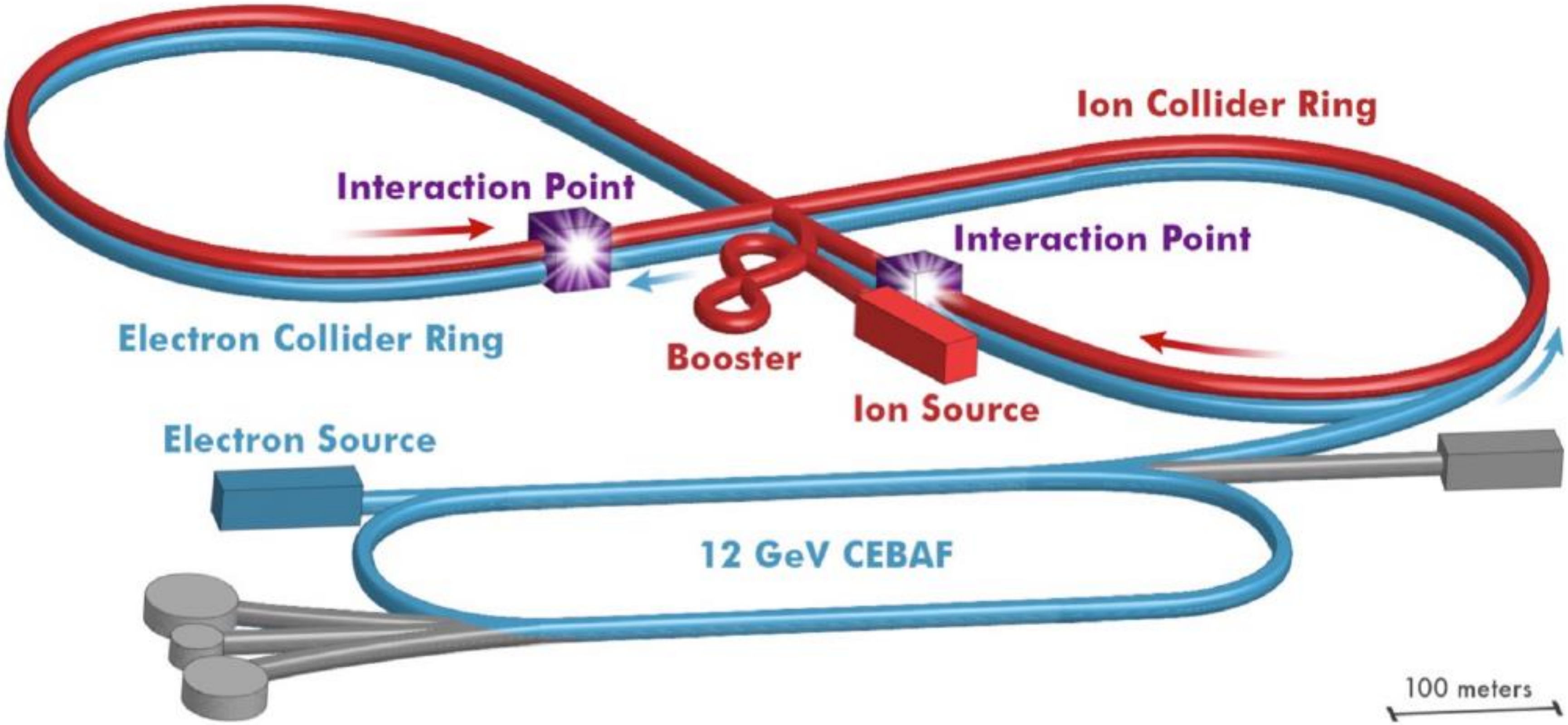
Particles Associated with Initial Ion

Relatively large crossing angle (50 mr) combined with large aperture final focus magnets, and forward dipoles are keys to this design - this crossing angle creates room for forward dipoles and gives a space for detectors in the forward regions

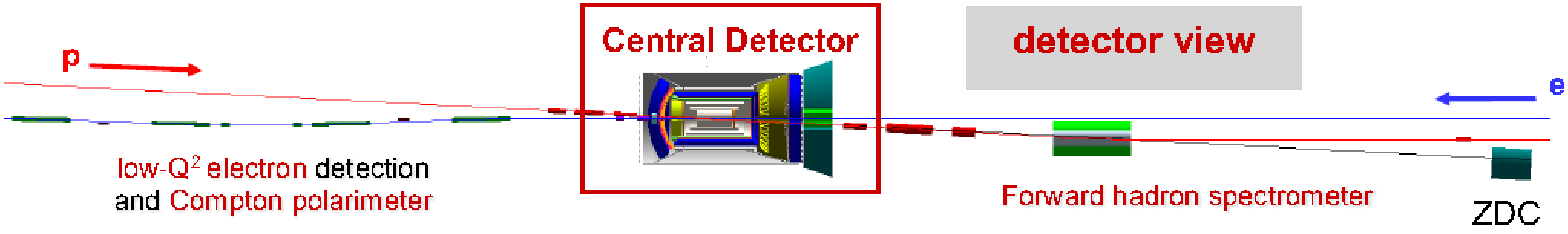
Interaction Region Design: Interaction Points

Background reduction

- far from electron bending magnets (**synchrotron radiation**)
- close to proton/ion bending (**hadron background**)



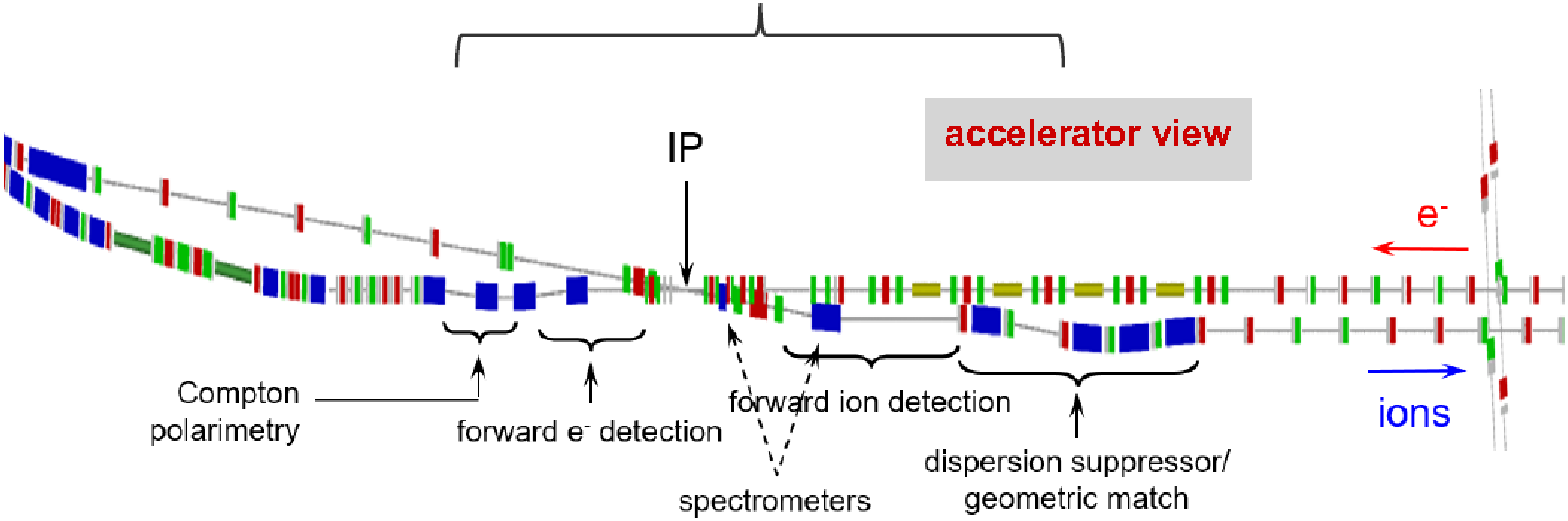
Detector and Interaction Region



Extended detector: 80m

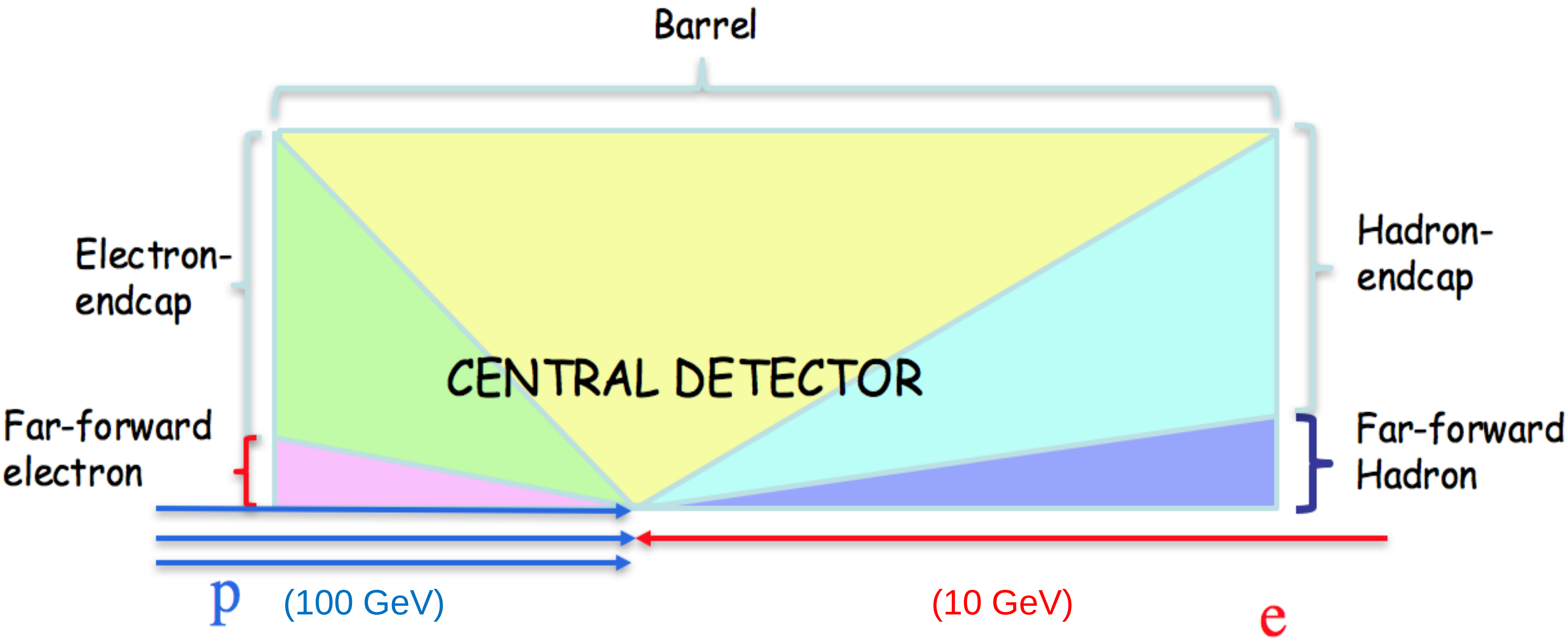
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer

fully integrated with accelerator lattice

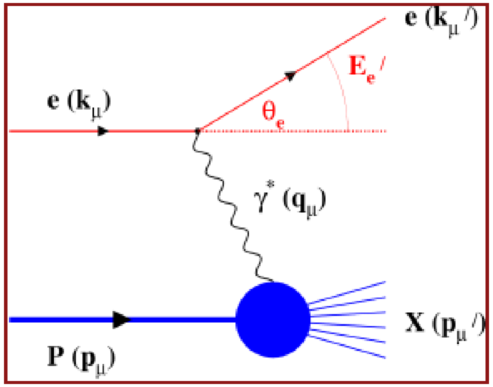


Central Detector

Detector Coverage



Basic Kinematic Reconstruction

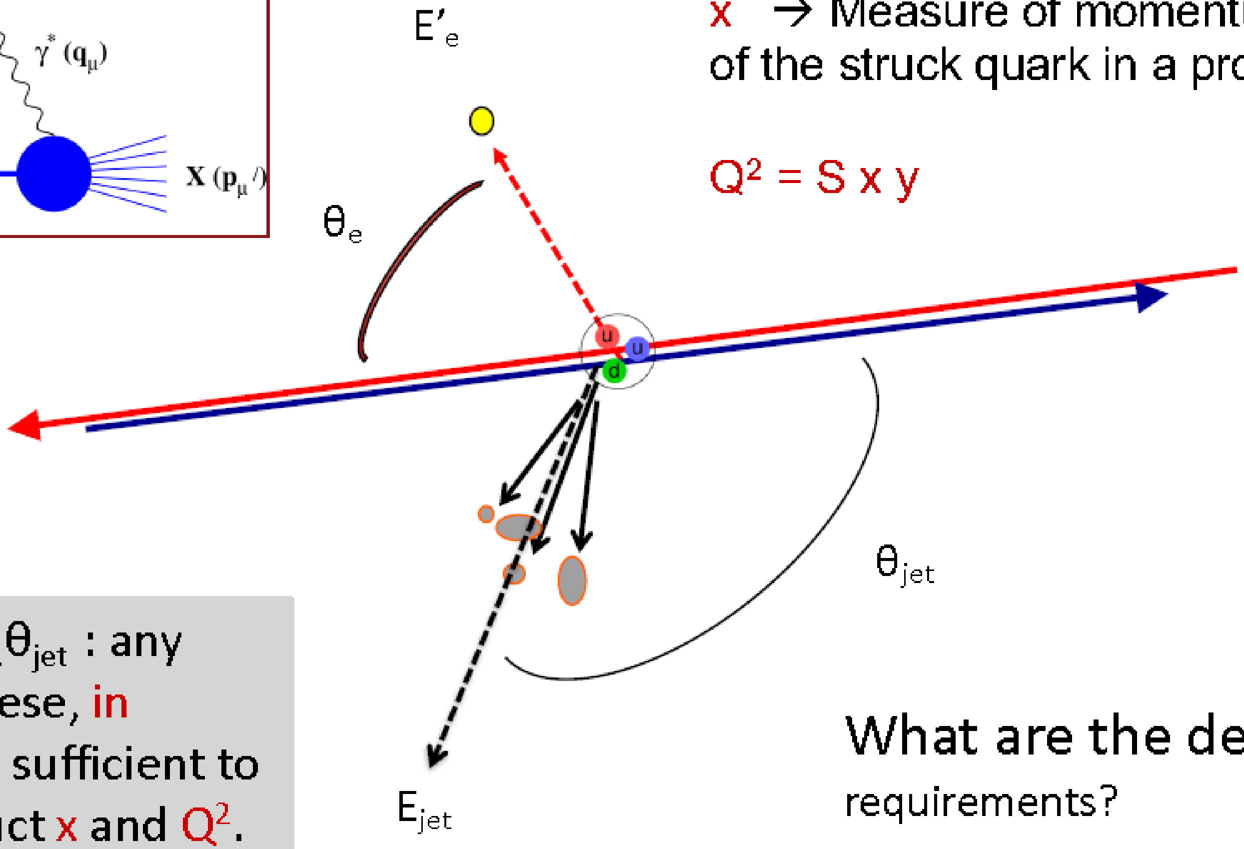


Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\ x\ y$



$E'_e, \theta_e, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct x and Q^2.

What are the detector requirements?

Particle Detection and Identification

Stable particles only 27 (13) particles in PDG have $c\tau > 1\mu m$ ($500\mu m$)

- Electrons/positrons ($e^{\pm}$)
- Gammas (γ)
- Individual hadrons ($\pi^{\pm}$, $K^{\pm}$,p)
- Neutral hadrons (n,K^0_L)
- Muons ($\mu^{\pm}$)
- Neutrinos (ν)

Measurements

- Charge and Momentum measurements
- Energy measurements
- Vertex origination
- Particle ID

Position, origination and direction (x,y,z) → Tracking detectors

Momentum (p) → Tracking detectors in magnetic field

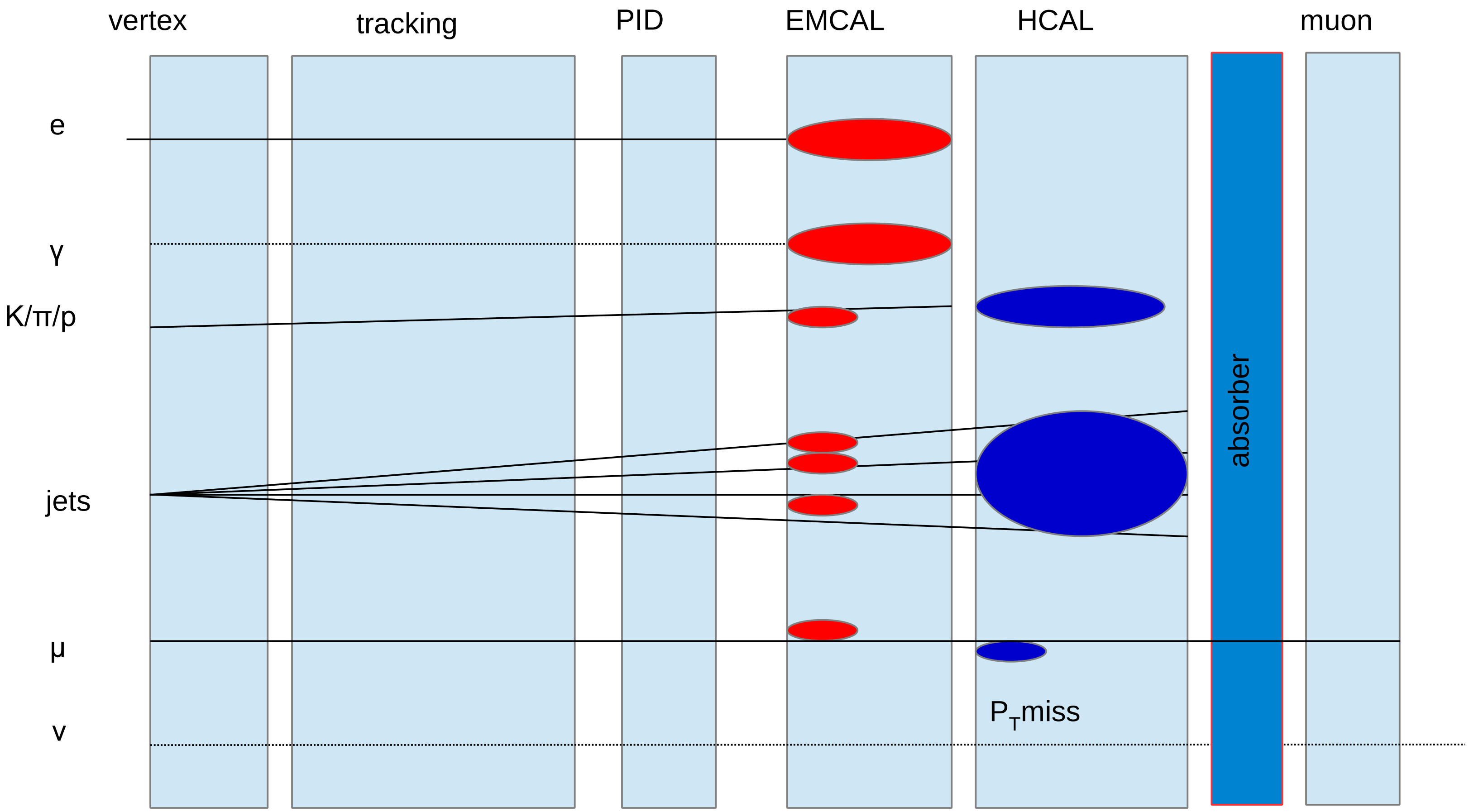
Energy (E) → Calorimeter

Mass (m)
Velocity (β) → Time of flight
Cherenkov radiation
Transition radiation

General Structure of Detectors

Stable particles (e,μ,π,K,p, jets(q,g), gamma, ν - Pt^{miss}):

Momentum/Energy, Type(ID), Direction, vertex



Electromagnetic Calorimetry

Electromagnetic Calorimeters measure EM showers and early hadron showers:
Energy, position, time

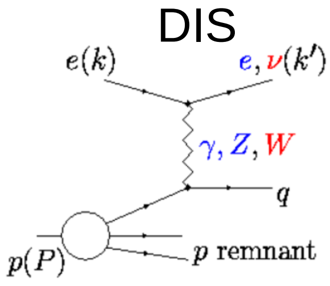
$PbWO_4$ Crystal EM Calorimeter

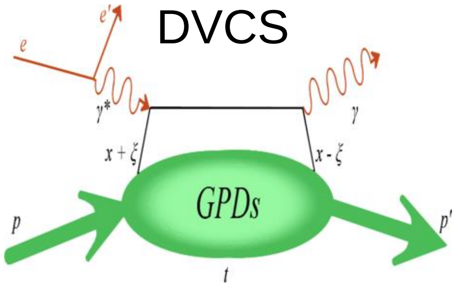
- Tungsten glass, similar to CMS or PANDA
- Time resolution: <2 ns
- Energy resolution: <2%/√E(GeV) + 1%
- Cluster threshold: 10 MeV
- Produced at two places (China, Czech R.)
- Ongoing EIC R&D (CUA, Orsay, …)
- R&D ongoing also for JLab detectors

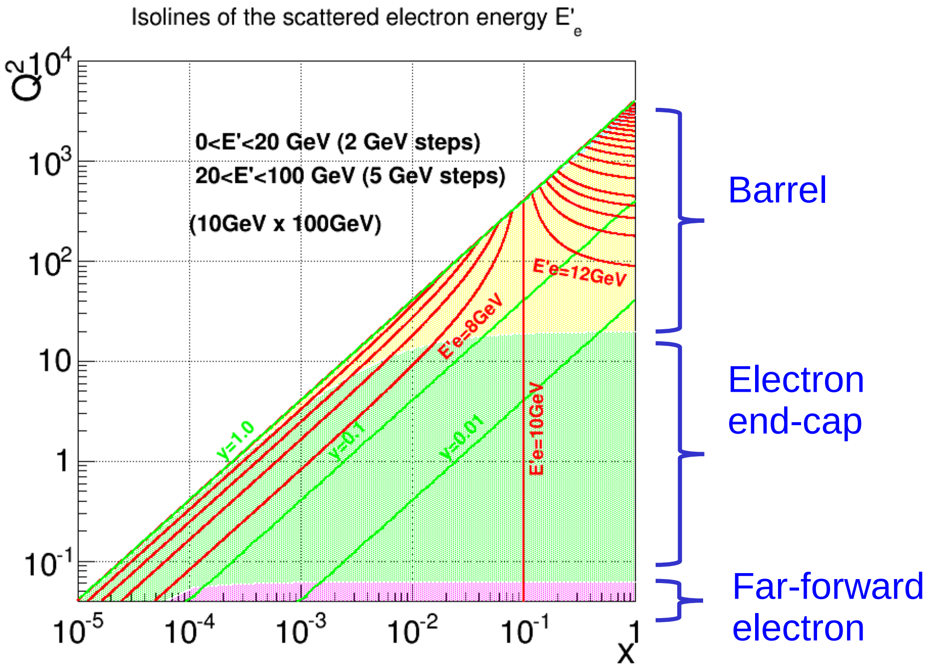
Sampling EM Calorimeter

- Shashlyk (scintillators +absorber)
  - WLS fibers for readout
  - EM(SPACAL):

- Compact W-scifi calorimeter, developed at UCLA
- Spacing 1 mm center-to-center
- Resolution ~12%/√E
- On-going EIC R&D







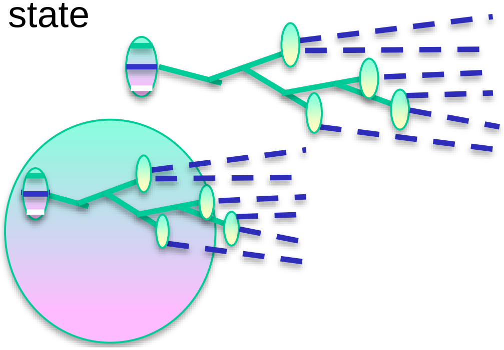
- $PbWO_4$ for e-endcap - close to the beam – need energy precision and radiation hardness (but not like CMS).
- Glass, shashlyk for barrel? – less expensive

Jets at EIC and Hadronic Calorimetry

1) Jets evolution and dynamics (jet == struck quark)

2) Jets as a probe of partonic initial state

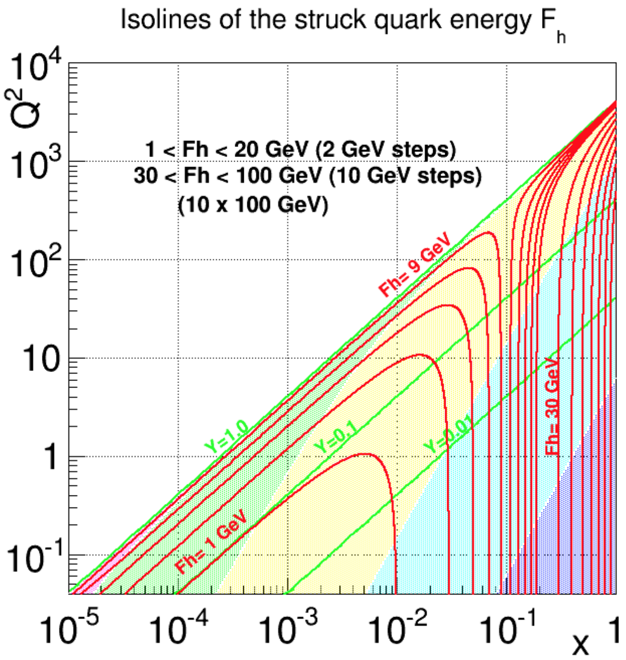
3) Jets in medium
(cold nuclear matter)
- ✓ energy loss, quenching
- ✓ broadening
- ✓ multiple-scattering.



At EIC for the first time will be able to study in-medium propagation and hadronization of heavy quarks (charm & beauty)

Charged current DIS

Neutrino in the final state →
- Could use only jets to reconstruct (x, Q^2) kinematics
- Need 4π HCAL coverage for $P_T$miss



In a typical jet :
60 % of jet energy in charged hadrons
30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)
10 % in neutral hadrons (mainly n, K_L)

Traditional calorimetric approach:
-E_{JET}=EMCAL+HCAL
-70% of energy measured in HCAL with poor resolution : $\sigma_E/E \sim 60\%/\sqrt{E}$
Uranium Calorimeter at ZEUS:
$\sigma_E/E \sim 35\%/\sqrt{E}$

Particle Flow Calorimetry:
$E_{JET} = E_{track} + E\gamma + E_n$
-charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: : $\sigma_E/E \sim 2\text{-}10\%/\sqrt{E}$
- Neutral hadrons (ONLY) in HCAL →
Only 10 % of jet energy from HCAL
much improved jet resolution…

Tracking

Main purpose of tracking:

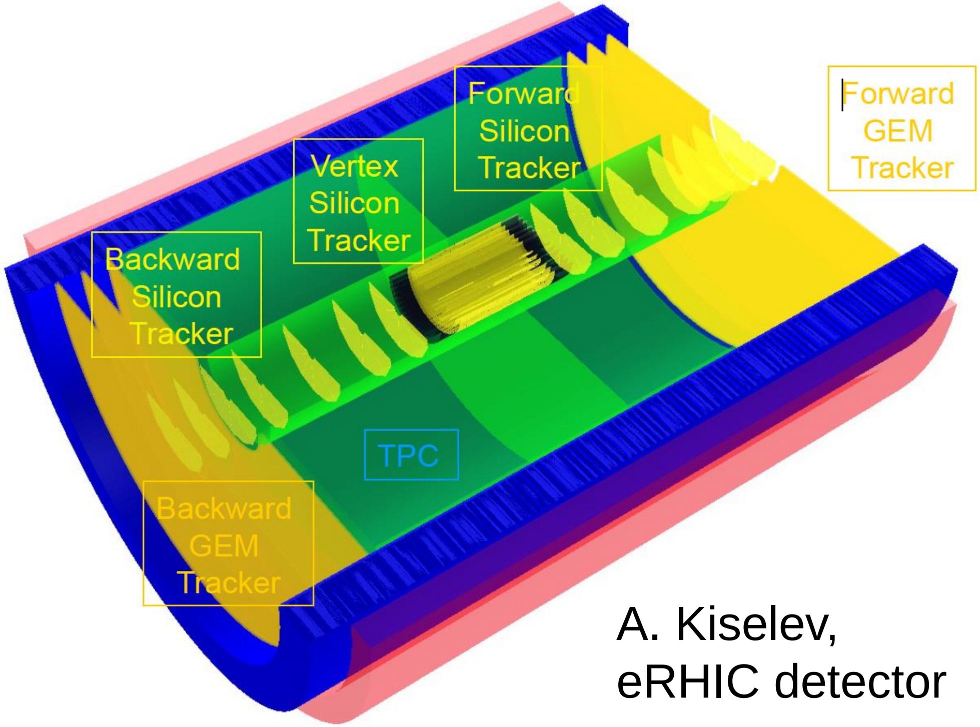
- reconstruct charged tracks and measure their momenta precisely (~few %)
- dE/dx (PID) for low momentum tracks.

Barrel: TPC or drift chambers

- relatively fast detector,
- minimal multiple scattering
- limited PID

Endcaps: Gas Electron Multiplier (GEM)

- High multiplicity in forward region – we need a high granularity tracker resolution ~50 μm.
- Radiation hardness



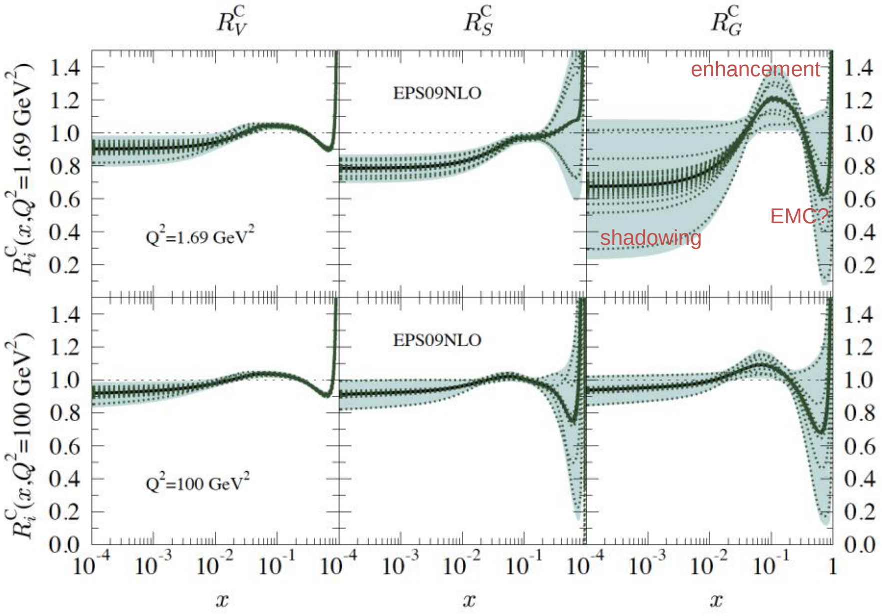
A. Kiselev, eRHIC detector

Vertex Detector

Main purpose of vertex detector:

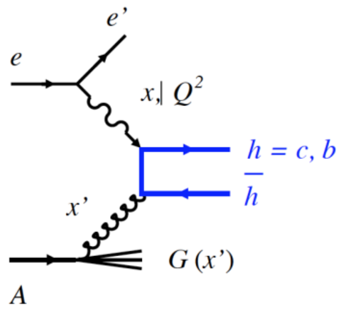
- Reconstruction of a primary vertex
- Reconstruct secondary vertex:
  - Tagging of c and b quarks
  - (decay length ~100-500 µm)
- improve momentum resolution of outer tracker
- provide stand-alone measurements
  - of low-Pt particles
- dE/dx measurements for Particle IDentification

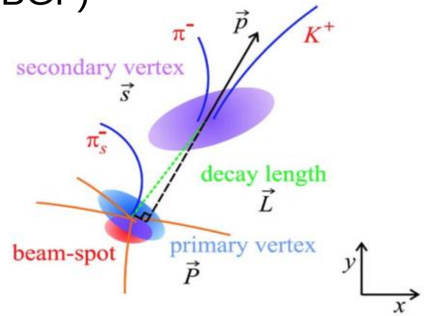
Nuclear PDF parametrization EPS09 Eskola et al. 2009



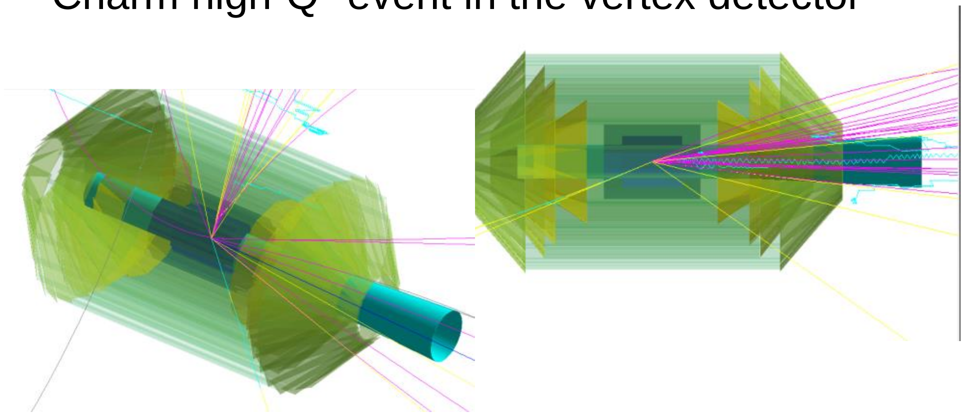
Heavy quarks

Boson (photon)- Gluon Fusion (BGF)





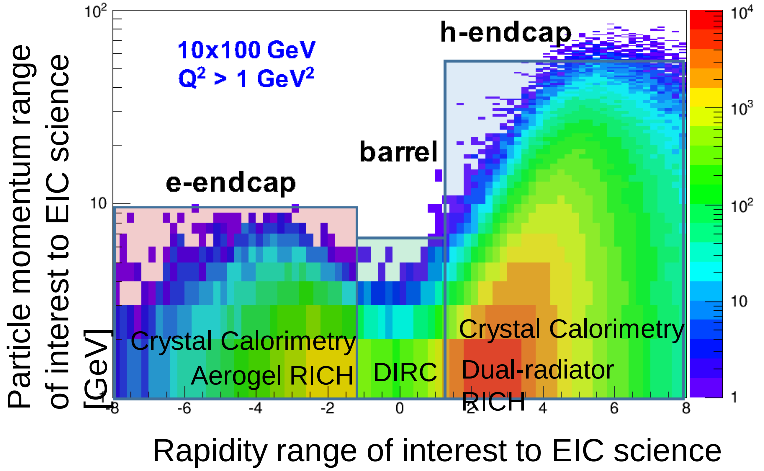
Charm high-Q^2 event in the vertex detector



- Vertex detector is detector closest to IP, and background increases occupancy.
- High granularity detector is needed (pixels)
- Beam related background can also cause radiation damage.

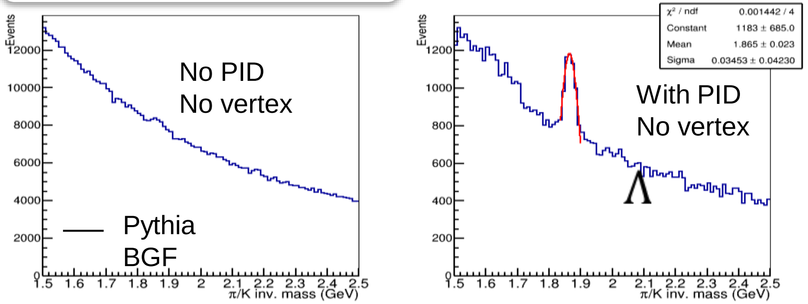
Hadron Identification

Semi-inclusive DIS: involves measurements of one or more final-state hadrons in addition to the detection of the scattered lepton.



Exclusive processes:

D0 mass plots: $D^o \rightarrow K^- \pi^+$



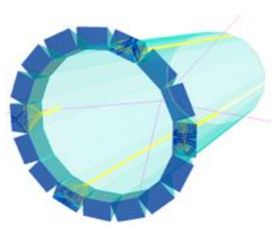
Time of Flight: MRPC

Multi-gap Resistive Plate Chamber (MRPC) R&D: achieved ~18 ps resolution with 36-105 μm gap glass MRPC π/K <3.5GeV

Electron end-cap: Modular RICH

- Modular aerogel RICH (eRD14 detector R&D)
- π/K separation up to ~10 GeV

Barrel: DIRC



- radially compact (2 cm)
- Particle identification (3σ) p/K < 10 GeV, π/K < 6 GeV, e/π < 1.8 GeV

Hadron end-cap: dual-radiator RICH

- JLEIC design geometry constraint: ~160 cm length
- Aerogel in front, followed by CF4
- covers energy for π/K up to 50GeV
- Sensitive to magnetic field → Envisioned 3T solenoid with minimized field in RICH region

Electron Identification

Physics:

- ✓ For rare physics, based on electron identification
- ✓ Charmonium, light vector mesons (ρ,ω,φ)
- ✓ Tetraquarks and Pentaquarks (and other XYZ states)
- ✓ Open Charm and Beauty physics
- ✓ Di-lepton production
- ✓ Scattered electron identification at Large-x, large-Q2

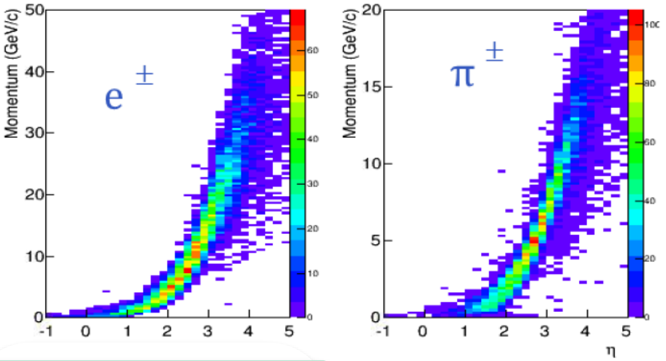
Transition radiation detector (TRD) under consideration for enhanced electron/hadron rejection: GEM/TRD

- combined high granularity tracker and PID.
- cover energy range 1-100 GeV.
- provide additional e/hadron rejection factor 10-100.

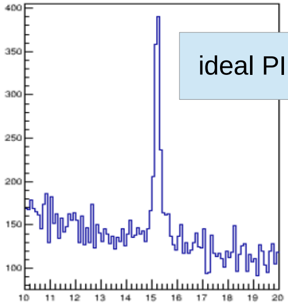
σ(Zc[3900]) ~ 5 nb

σ(PhP, Q^2<1GeV) ~ 10000 nb

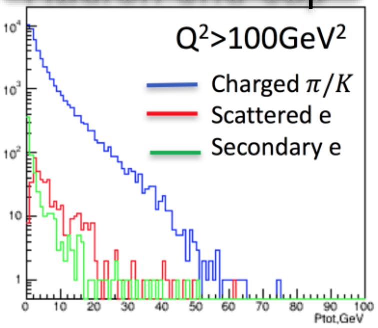
New XYZ stage Zc[3900]



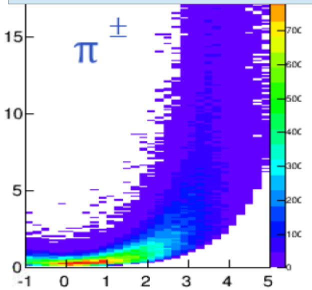
Zc[3900] m^2 (e+e-π+)

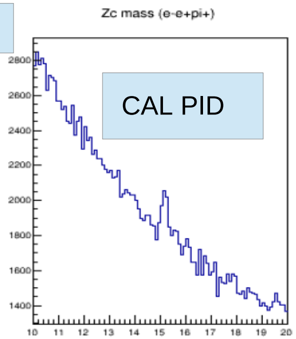

ideal PID

Hadron end-cap



PhP background

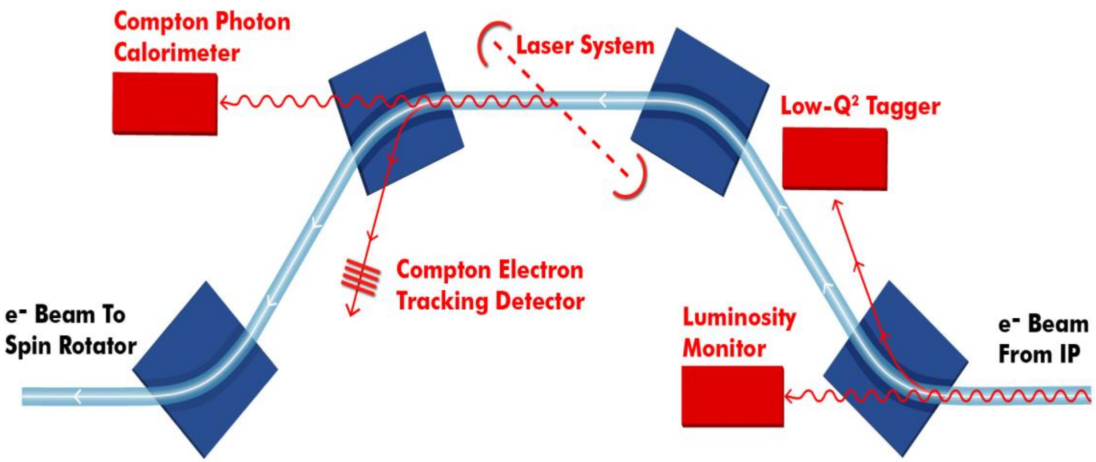



Zc mass (e-e+pi+)

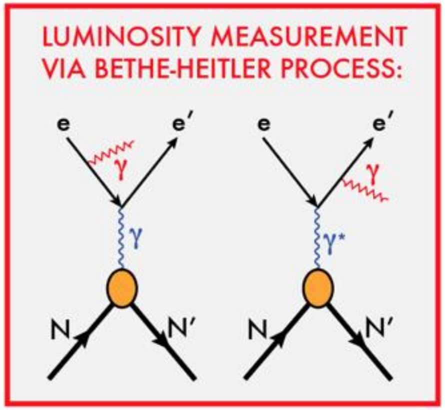
CAL PID

Excellent e/π PID in the hadron endcap region is needed for electrons with energy 1-100GeV

Chicane for Forward Electron Detection



Example from JLEIC design

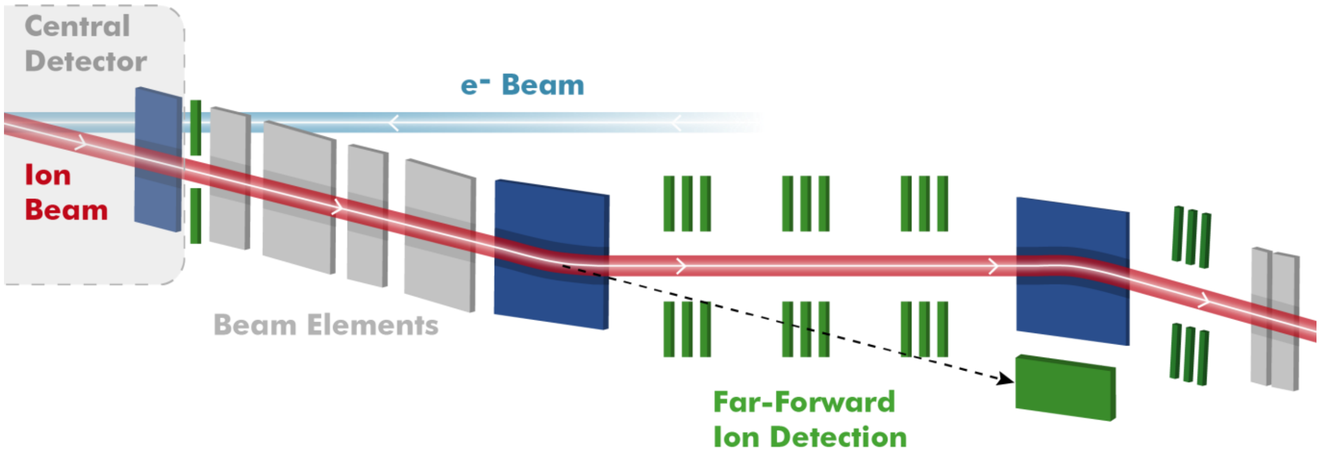


- ☐ Low Q^2 tagger
- ✓ For low Q^2 electrons

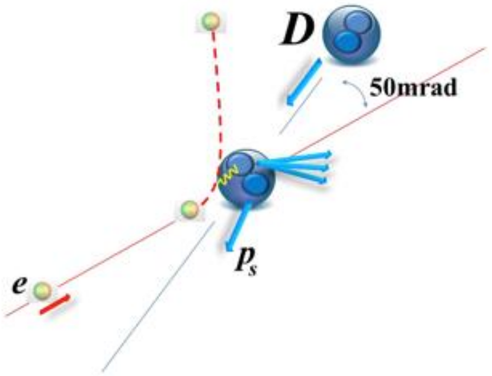
- ☐ Luminosity monitor:
- ✓ Luminosity measurements via Bethe-Heitler process
- ✓ First dipole bends electrons
- ✓ Photons from IP collinear to e-beam

- ☐ Polarization measurements
- ✓ First two Dipoles compensate each other
- ✓ The same polarization as at IP
- ✓ Minimum background and a lot of space.
- ✓ Measurements of both Compton photons and electrons

Far-Forward Ion Detection



Ion remnant/Tagging

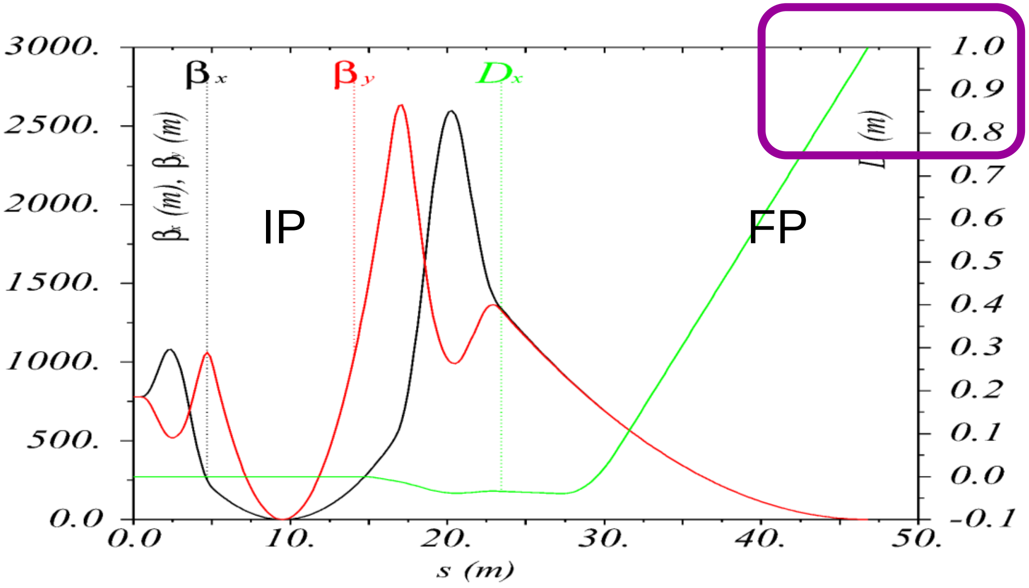


e.g., tagging nucleon (p, n) structure function from e-d

Hadron detection in three stages

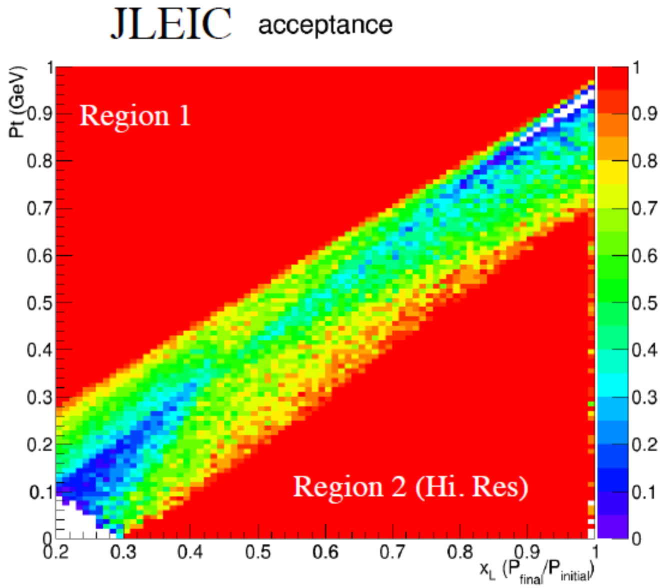
- ❑ Endcap with 50 mrad crossing angle
- ❑ Small dipole covering angles to a few degrees, detect down to 0.5 degree before ion final-focus quads
- ❑ Ultra-forward up to >0.5 degree, for particles passing accelerator quads

Beamline functions as spectrometer: $dp/p < 3\times10^{-4}$ (i.e., at 50 GeV/u, Δp = 150 MeV/c ~ Fermi momentum)

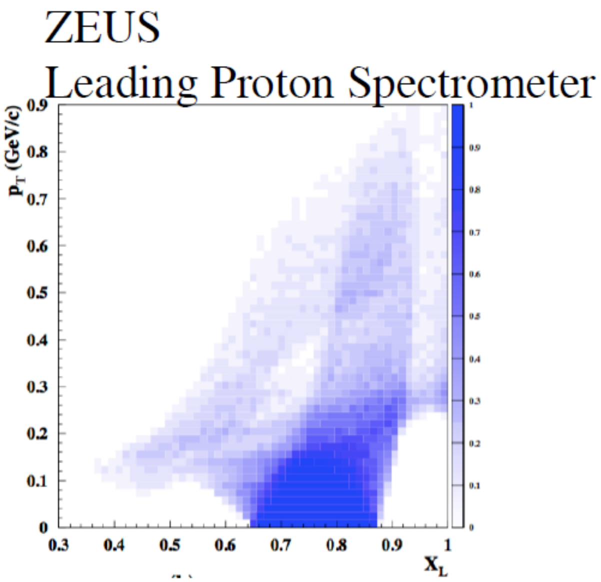


Full Acceptance for Forward Physics!

Example: acceptance for p’ in e + p → e’ + p’ + X



Zhiwen Zhao (Duke)

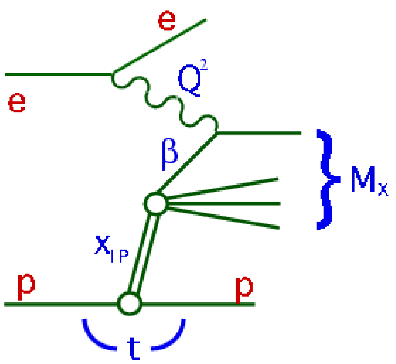


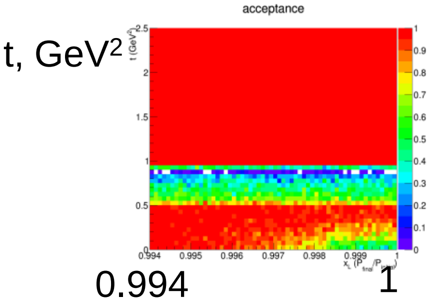
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than ZEUS)

Diffraction

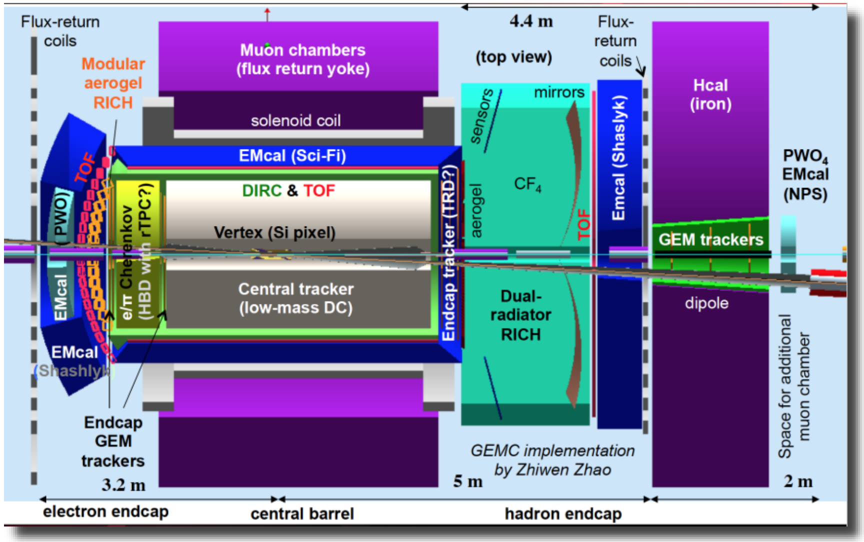




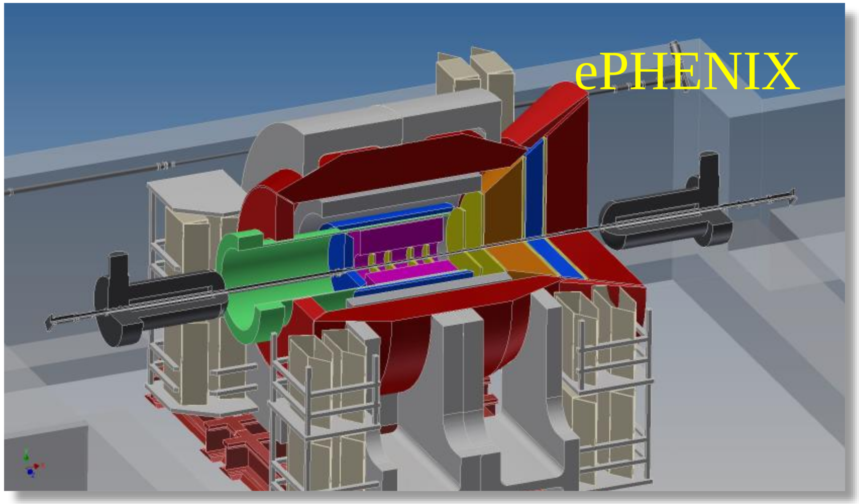
Huge gain in acceptance for diffractive physics and forward tagging to measure F_2^n!!!

Detector Concepts

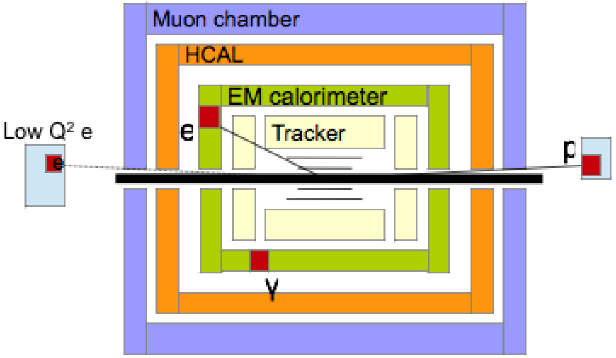
Jefferson Lab (JLEIC Detector)



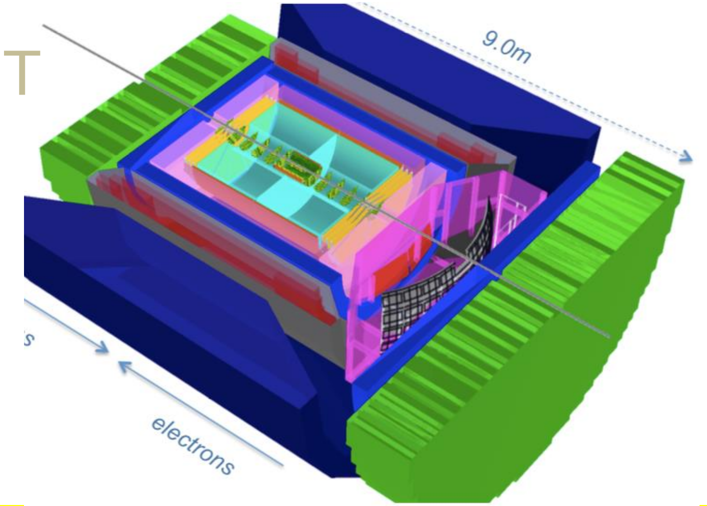
Brookhaven



2nd IP for jets



BeAST



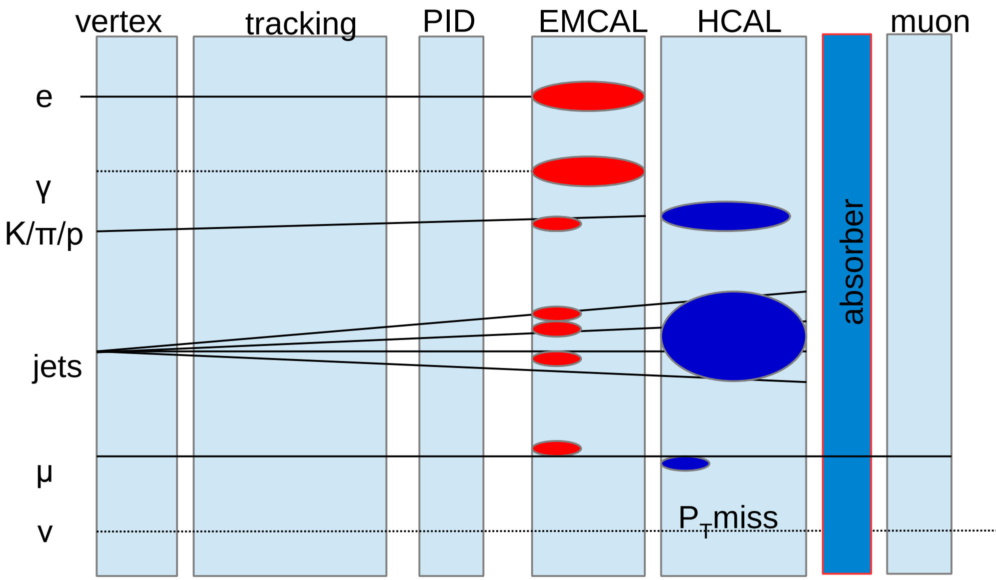
Modular design of the central detector

Detector Example: Calorimeter

Calorimetry in Nuclear Physics

- ☐ Energy measurements of charged and neutral particles
  - ➢ Electromagnetic: Electrons and photons
  - ➢ Charged and neutral hadrons
  - ➢ Group of collimated particles moving in the same direction (jets)

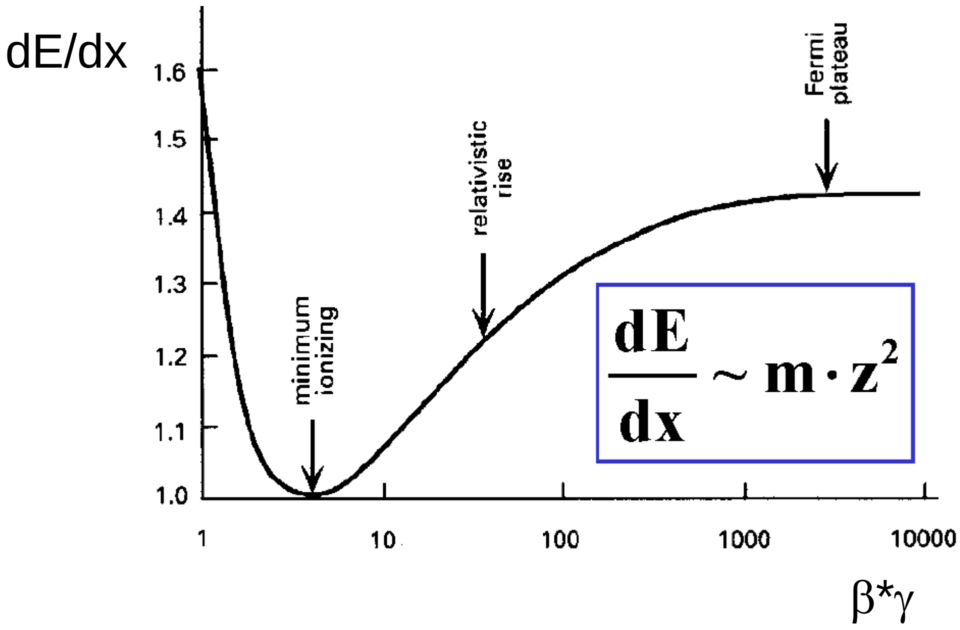
- ☐ The process of energy measurements is destructive: must completely stop the particle to measure its full energy
  - ➢ Unlike, e.g., tracking detectors, the particles are no longer available for detection after they pass through a calorimeter



- ☐ Calorimeters are the outermost detectors
  - ➢ Note that muons and neutrinos pass through calorimeters with nearly no interaction

Detection and Identification of Charged Hadrons

- ☐ Energy
  - ➢ Complete stopping
  - ➢ Energy loss – Minimum Ionizing
- ☐ Position
  - ➢ Limited by size of individual detector modules
- ☐ Velocity
  - ➢ Time-of-flight for low-energy particles
- ☐ Particle IDentification (PID)
  - ➢ Intrinsic sensitivity (pulse shape)
  - ➢ ΔE-E method

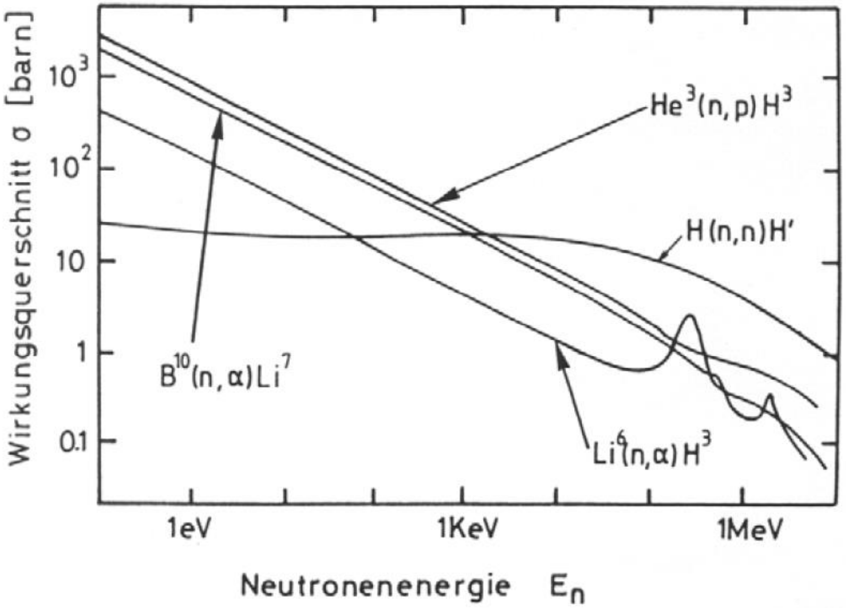


$$\frac{dE}{dx} \sim m \cdot z^2$$

Limited due to large hadronic interaction length

$$\lambda \gg X_0$$

Detection and Identification of Neutral Hadrons



- ☐ Energy < 20 MeV: (n,γ) capture

$$n + {}^{6}Li \rightarrow \alpha + {}^{3}H$$

$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li$$

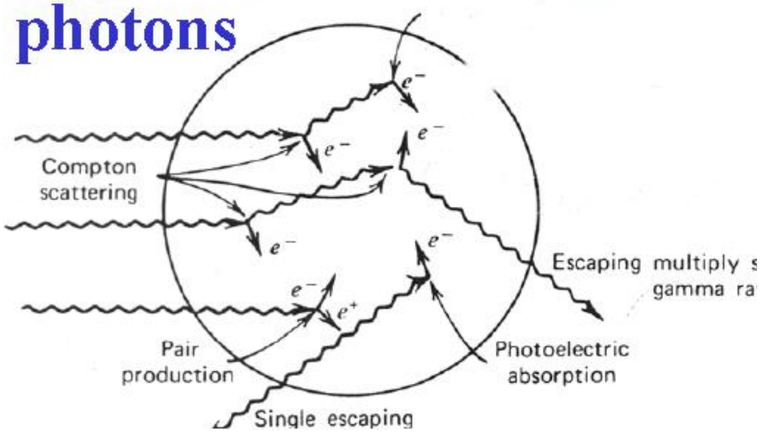
$$n + {}^{3}He \rightarrow p + {}^{3}H$$

- ☐ Energy > 20 MeV: (n, p)

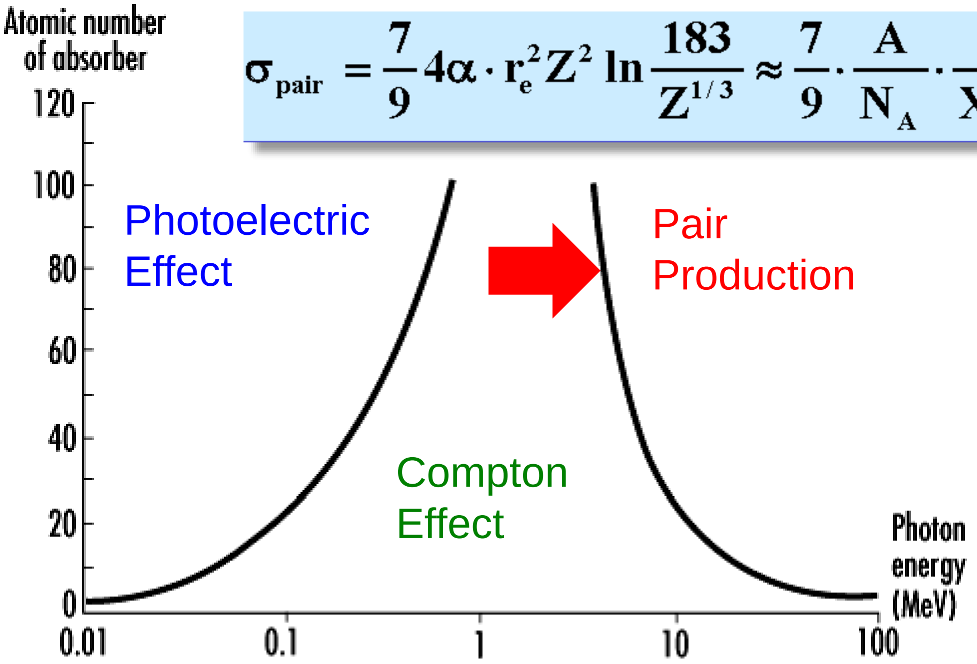
- ☐ Energy > 1 GeV: hadronic shower

Electromagnetic Probes

photons



$$\sigma_{\text{pair}} = \frac{7}{9} 4\alpha \cdot r_e^2 Z^2 \ln \frac{183}{Z^{1/3}} \approx \frac{7}{9} \cdot \frac{A}{N_A} \cdot \frac{1}{X_0}$$



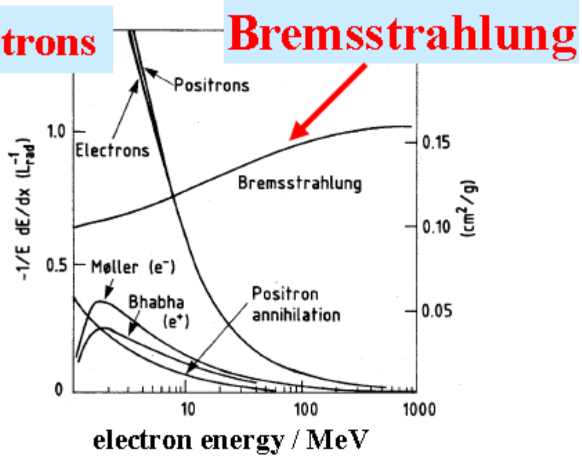
Photoelectric Effect

Pair Production

Compton Effect

electrons

Bremsstrahlung



$$-\frac{dE}{dx} = \frac{E}{X_0}$$

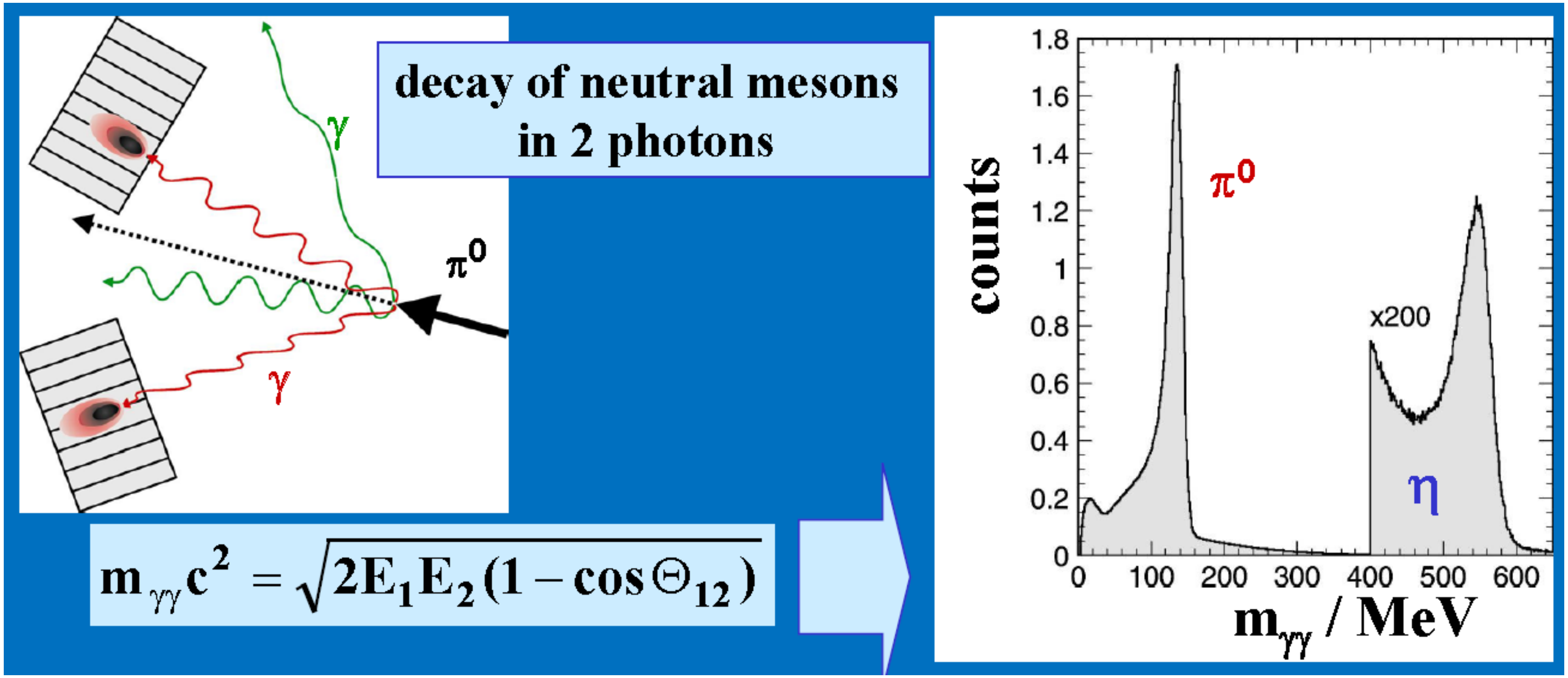
EM shower

radiation length $X_o \sim \frac{1}{Z^2}$

Requirements on EM Calorimetry

- ☐ Energy and position measurement for electrons, positrons, and photons

Invariant mass reconstruction



decay of neutral mesons in 2 photons

$$m_{\gamma\gamma}c^2 = \sqrt{2E_1E_2(1-\cos\Theta_{12})}$$

Electromagnetic Cascade (Shower)

- When an electron or photon with energy > 1GeV enters a thick absorber it produces a cascade of secondary electrons and photons
  - For energies >1 GeV, the main processes are bremsstrahlung and pair production

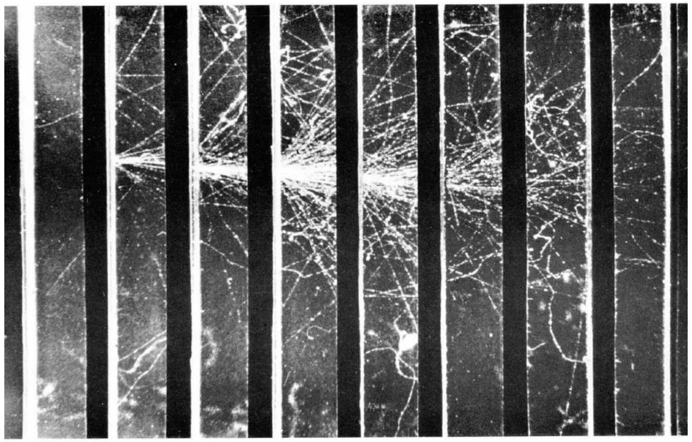
- As the depth increases, the number of secondary particles increases as well, but their mean energy decreases

- When the energies fall below the critical energy the multiplication process stops

Electromagnetic Shower

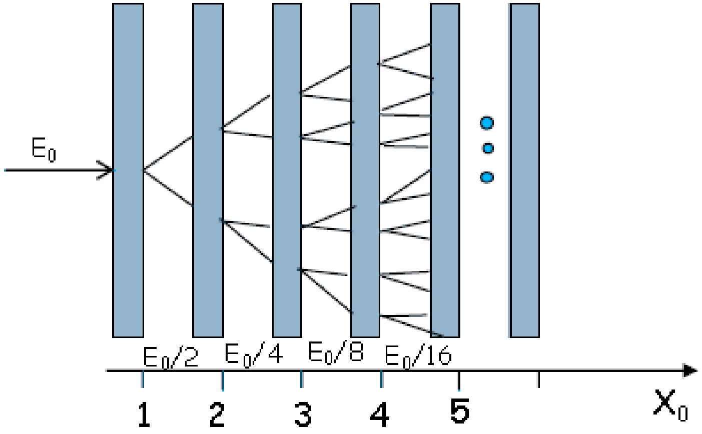
- Radiation length, X_0, is the distance over which, on average:
  - An electron loses all but 1/e of its energy (1-1/e)=63%
  - Photon has a pair conversion probability of 7/9

Lead absorbers in a cloud chamber



- Shower characteristics
  - Secondaries after $n[X_0]$, each with energy $E_0/2^n$
  - Stops if $E <$ critical energy E_c
  - Number of particles $N=E/E_c$
  - Maximum at $n_{max} \sim \ln(E_0/E)$

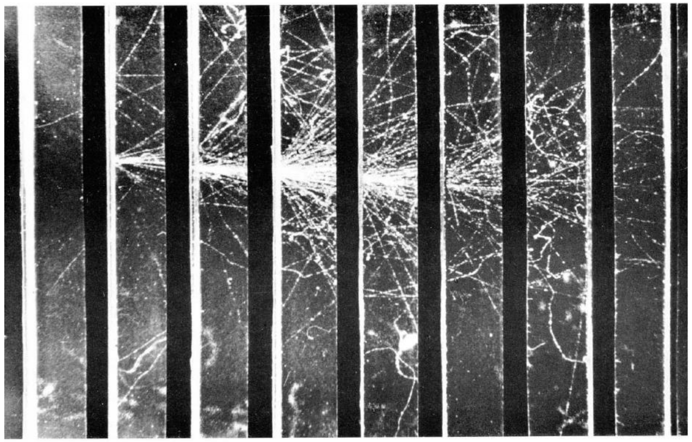
Simple sketch of a shower development



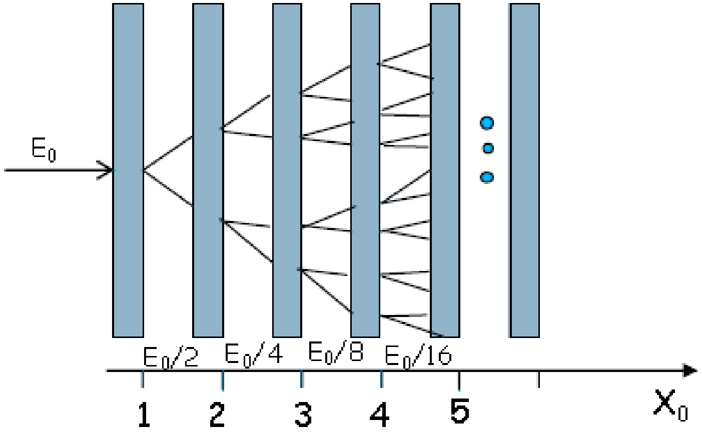
- Important for design and material selection:
  - Longitudinal shower development
  - Transverse shower development
  - Location of shower maximum and number of particles

Electromagnetic Shower

- ☐ Examples for E_c=10 MeV
  - ○ E_0=1 GeV
    - ➢ N_{max}=ln(100)=4.5 and N=2^{nmax}=100
  - ○ E_0=100 GeV
    - ➢ N_{max}=ln(10000)=9.2 and N=2^{nmax}=10000

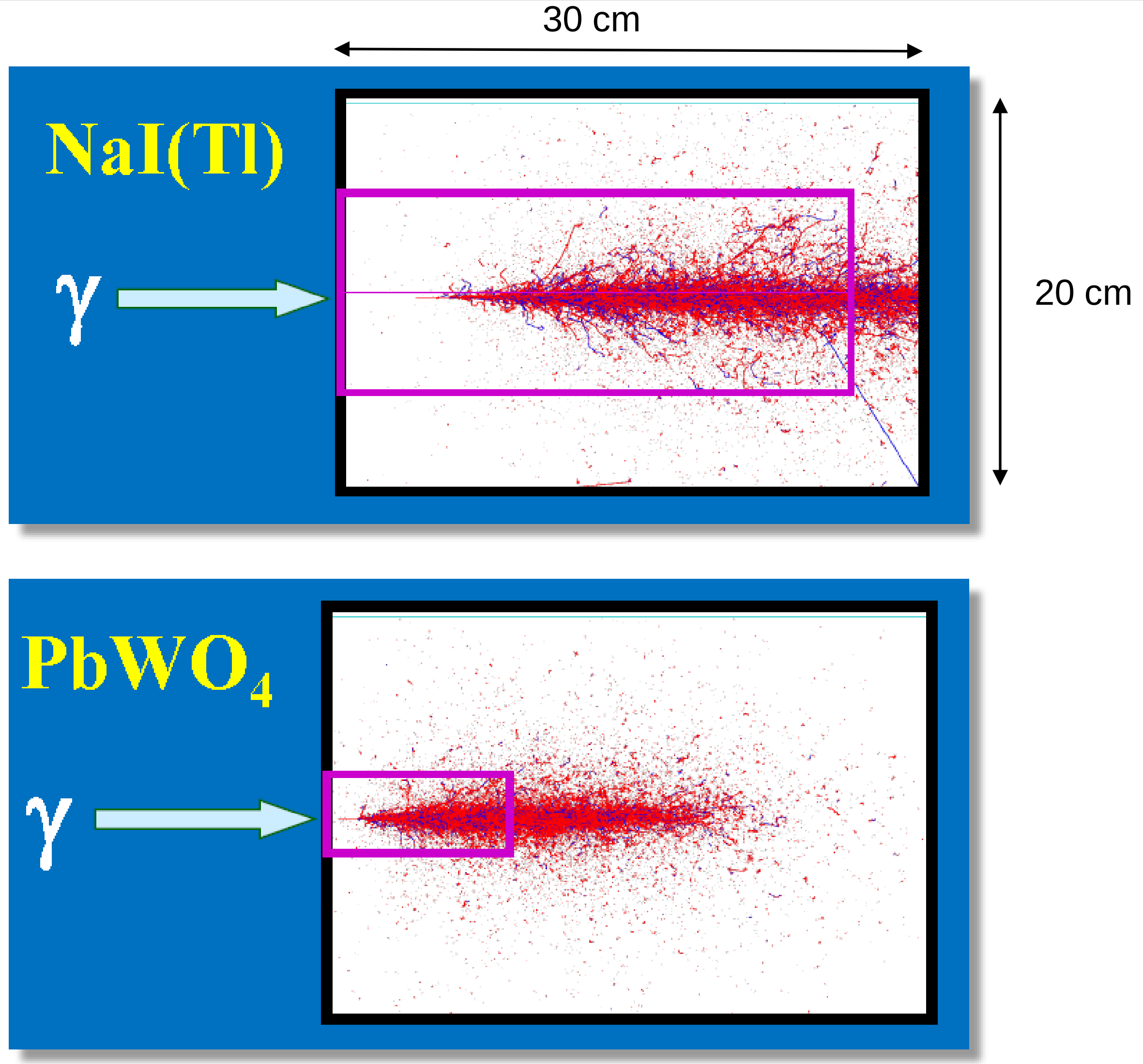

Lead absorbers in a cloud chamber

	Fe	**Pb**	**NaI(TI)**	**$PbWO_4$**
X_0 (cm)	1.76	0.56	2.6	0.89

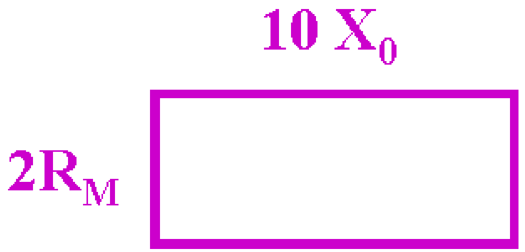

Simple sketch of a shower development

- ➢ For 100 Gev electrons: 16cm Fe or 5cm Pb

EM calorimeter material selection– stopping power



Photon Energies:
50 MeV – 50 GeV

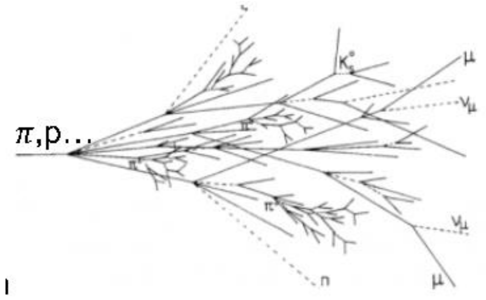


$$X_0 = \frac{716.4 \times A}{Z(Z+1)\ln(\frac{287}{\sqrt{Z}})}\frac{1}{\rho}$$

Small Moliere radius good to contain shower

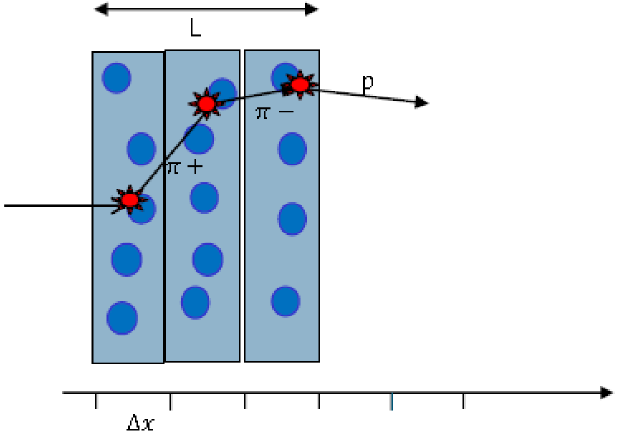
- Disadvantage: more sensitive to mismatches of tracking

Hadronic Cascade (shower)



- ☐ Similar to EM shower development, but more complex due to different processes involved
  - ➢ Includes electromagnetic shower
  - ➢ And hadronic shower (strong interaction with materials)
    - ○ Generation of pions, kaons, etc.
    - ○ Breakup of nuclei
    - ○ Creation on non-detectable particles (neutrons, neutrinos, soft photons) – large uncertainties in E_{sum}
    - ○ Fluctuations

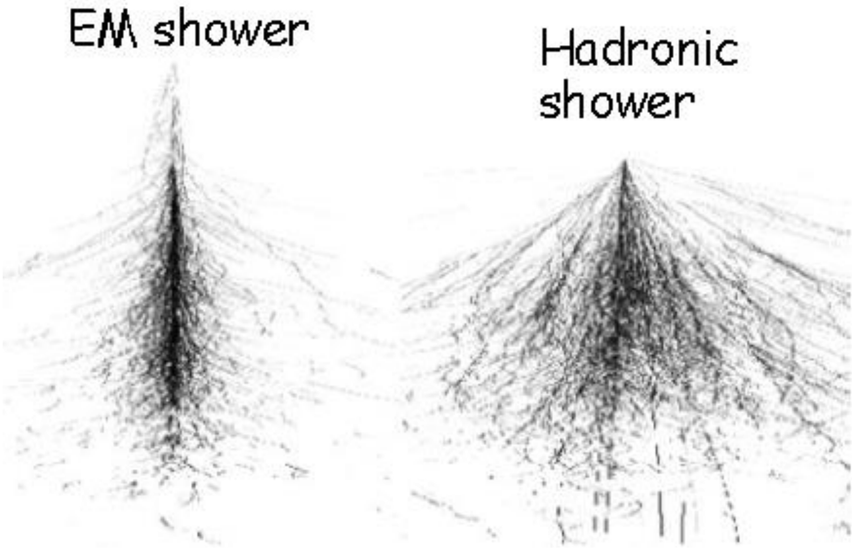
Simple sketch of a hadronic interaction



- ☐ Different scale: hadronic interaction length determines depth of the shower
  - ➢ Average distance between interactions

$$\lambda \sim \frac{L}{N_{int}} \sim 1/(\rho\,\sigma_{el})$$

EM vs Hadronic Cascade



- Material dependence
  - EM: $X_0 \sim A/Z^2$
  - HAD: $\lambda_{int} \sim A^{1/3}$

Λ_{int} >> X_0

- Typical size of hadronic shower (95%):
  - Longitudinal: (6-9) λ_{int}
  - Transverse: 1 λ_{int}

	Fe	**Pb**	**NaI(Tl)**	**$PbWO_4$**
X_0 (cm)	1.76	0.56	2.6	0.89
l_{int} (cm)	16.8	17.6	42.3	20.3

Energy Resolution

- Ideal case: E ~ N, $\sigma(E) \sim \mathrm{sqrt}(N) \sim \mathrm{sqrt}(E)$

- In real life:

$$\boxed{\sigma(E) \sim a\sqrt{E} \oplus b \cdot E \oplus c} \quad \text{or} \quad \boxed{\frac{\sigma(E)}{E} \sim \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}}$$

a – stochastic term: intrinsic statistical shower fluctuations, sampling fluctuations

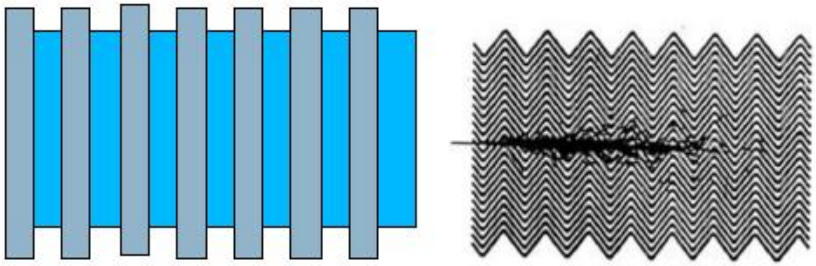
b – noise term: readout electronics noise

c – constant term: inhomogeneities, imperfections in construction (e.g. dimensional variations), nonlinearity of readout electronics, energy loss, etc.

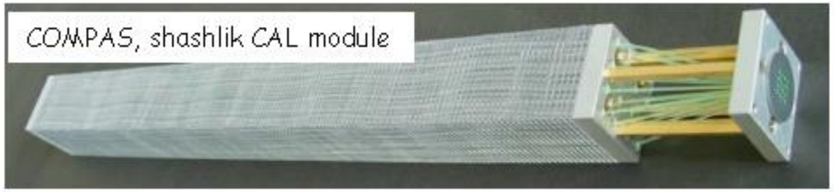
Calorimeter types

- **Sampling calorimeter:**

Layers of absorber alternate with active(sensitive) detector volume (sandwich, shashlik, accordion structures)



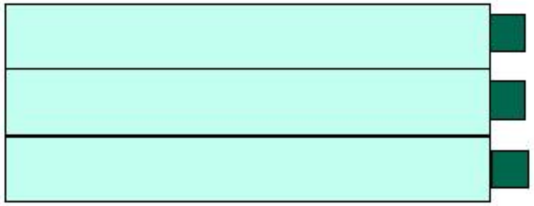
Absorber: Pb, etc
Sensitive (solid or liquid):
Si, scintillator, LiAr



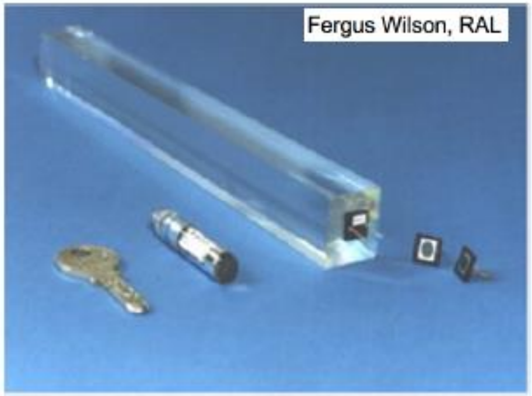
COMPAS, shashlik CAL module

- **Homogeneous calorimeter**

Monolithic material , serves as both absorber and detector material

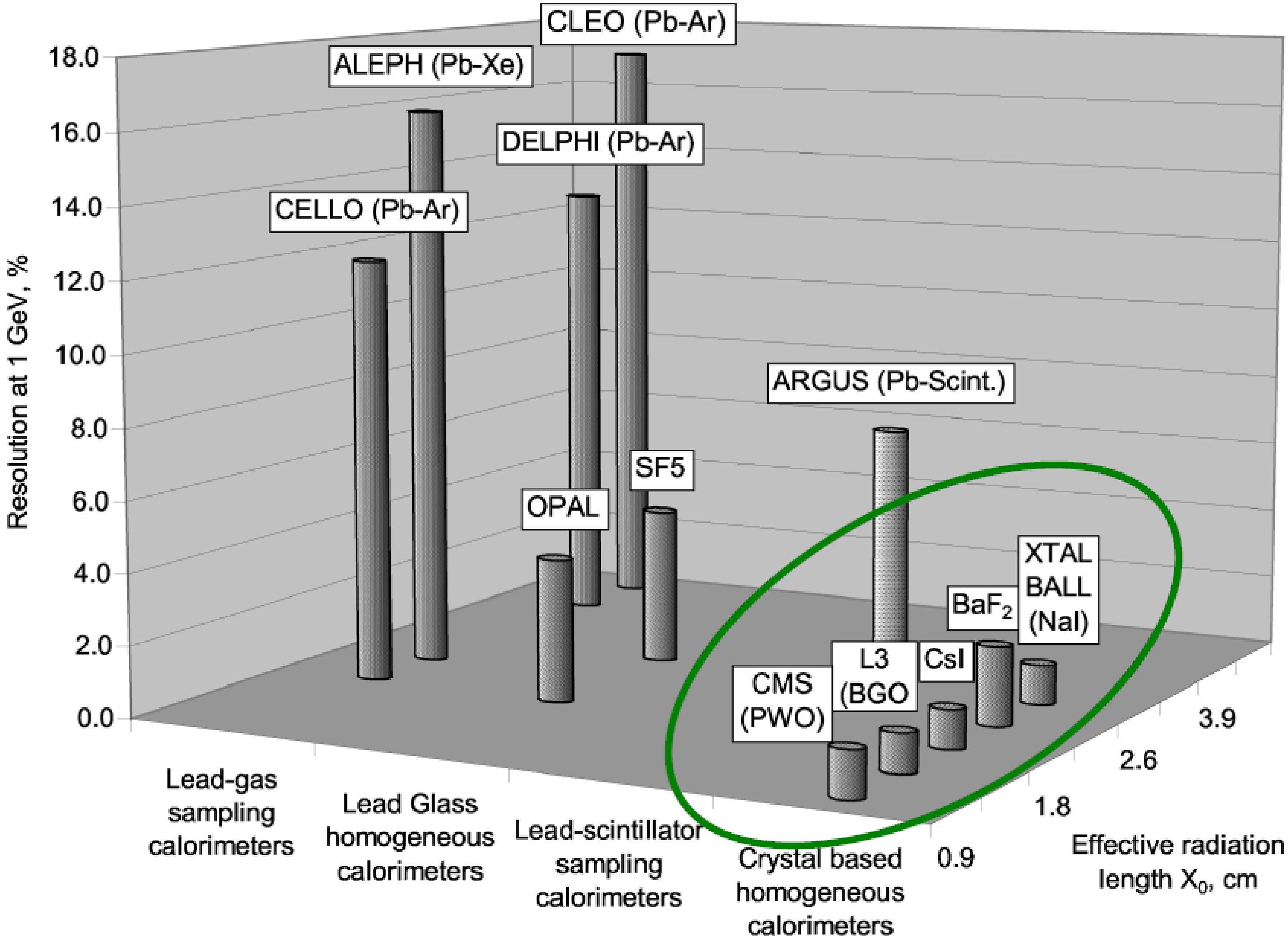


Liquid: Xe, Kr
Dense crystals: glass, crystals $PbWO_4$



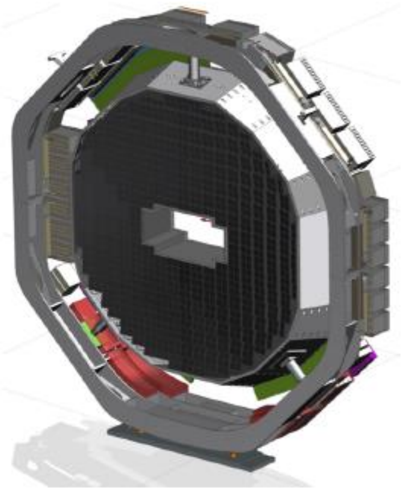
Fergus Wilson, RAL

Advantage of homogeneous calorimeters

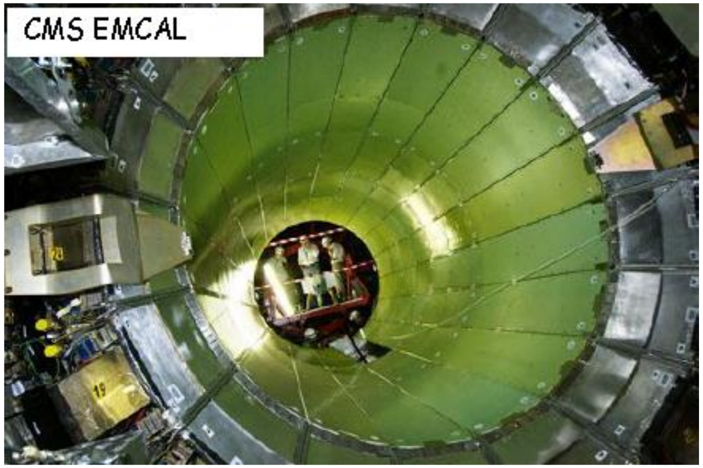


$PbWO_4$ homogeneous EM Calorimeters

- ❑ Lead tungstate ($PbWO_4$) used at CMS and PANDA
  - ➢ Excellent energy resolution
  - ➢ Compact
  - ➢ Time resolution < 2ns
  - ➢ Cluster threshold: 10 MeV

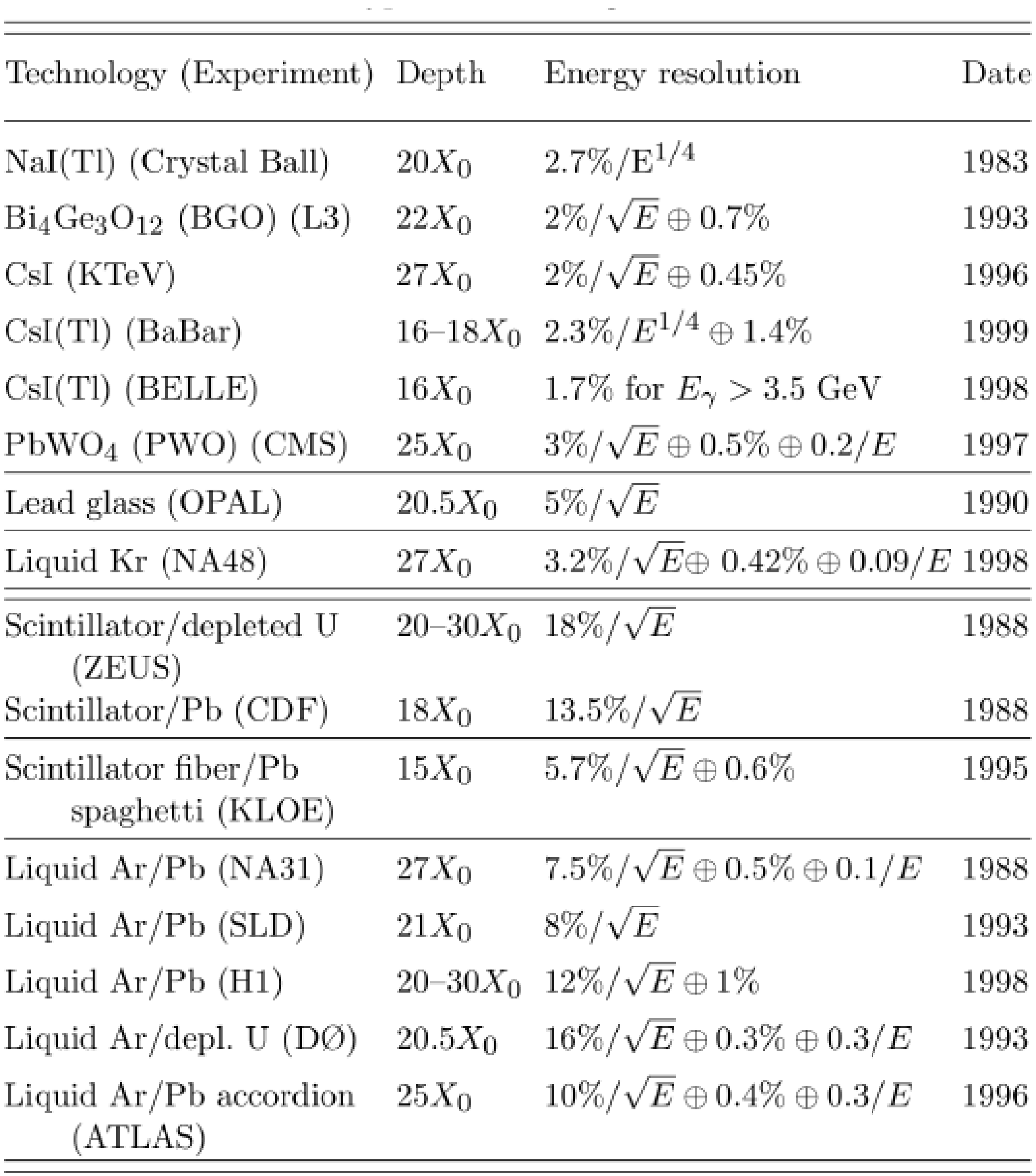


- ❑ Produced at two vendors (China, Russia)



- ❑ CMS EMCAL facts:
  - ➢ Contains nearly 80,000 crystals
  - ➢ Each crystal weighs 1.5 kg
  - ➢ It took 10 years to grow all the crystals!!

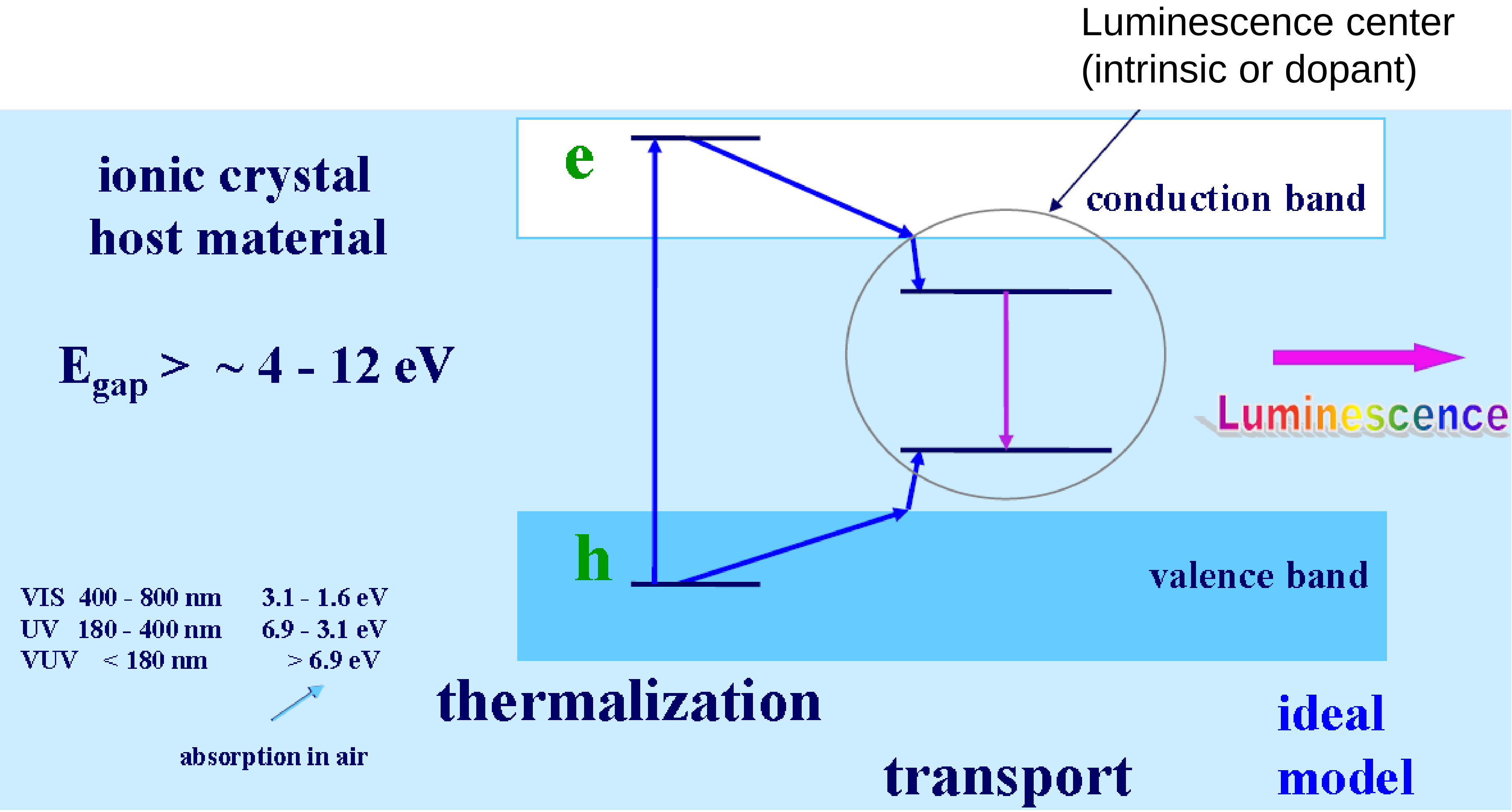
Other calorimeter technologies



Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Inorganic Scintillator Basics

Fundamental processes in inorganic scintillators



Luminescence center (intrinsic or dopant)

ionic crystal host material

$E_{gap} > \sim 4 - 12$ eV

VIS 400 - 800 nm 3.1 - 1.6 eV
UV 180 - 400 nm 6.9 - 3.1 eV
VUV < 180 nm > 6.9 eV

absorption in air

thermalization

transport

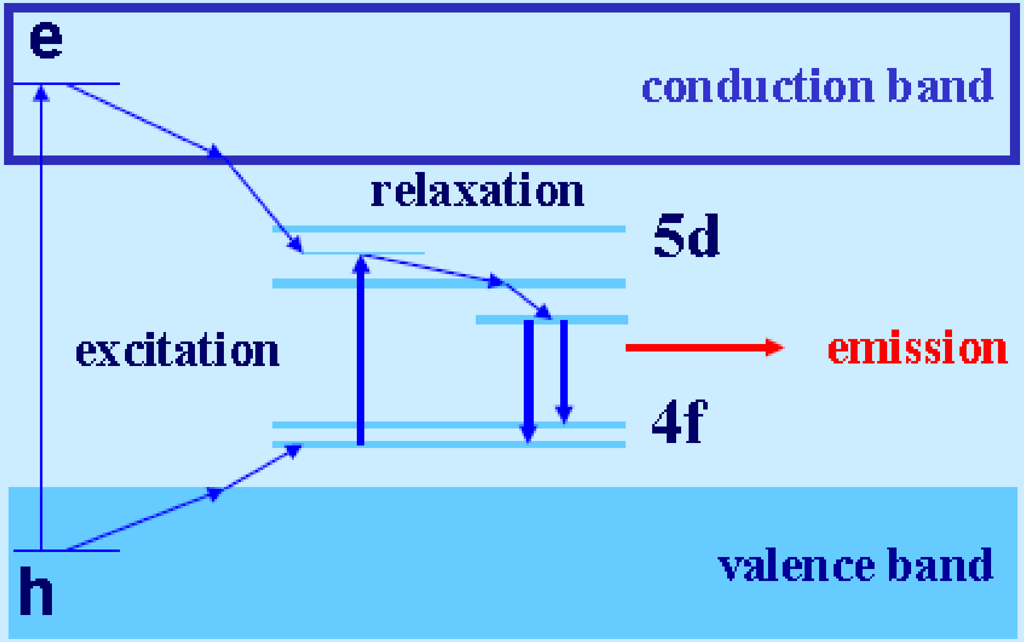
ideal model

Advantage of Ce^{3+} luminescence

why Ce^{3+} ?

core ⇨
and 1 electron in
4f state

Ce^{3+} luminescence center



5d → 4f allowed dipole transition

fast response $\tau \sim 20$ ns

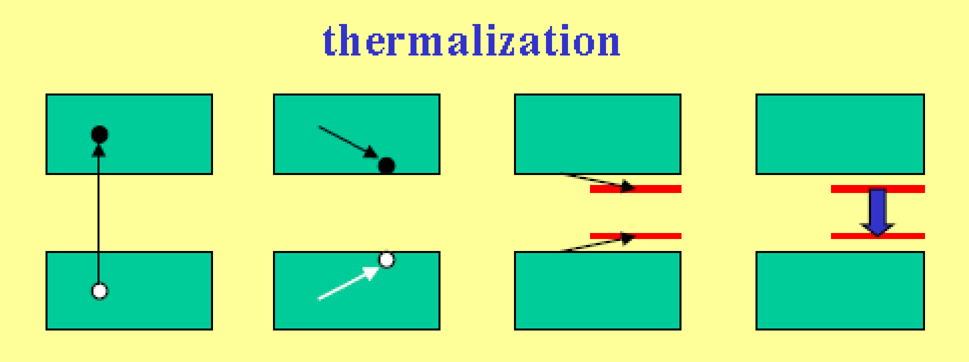
Scintillator Basics – photons from scintillation

relative light output: $L_R = \frac{N_{ph}}{E_{dep}}$

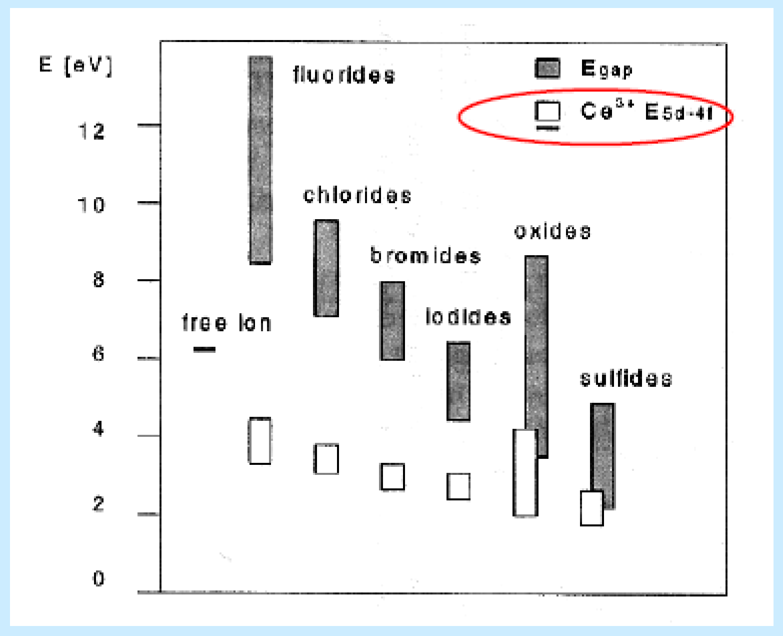
energy to generate an e/h-pair: $\xi_{eh} = \beta \cdot E_g \quad E_g : \text{band} - \text{gap}$

$\beta = 1.5 - 2 : \text{ionic crystals}$

$\beta = 3 - 4 : \text{covalent binding}$



$$N_{ph} = \frac{E_\gamma}{\beta \cdot E_{gap}} \cdot S \cdot Q$$

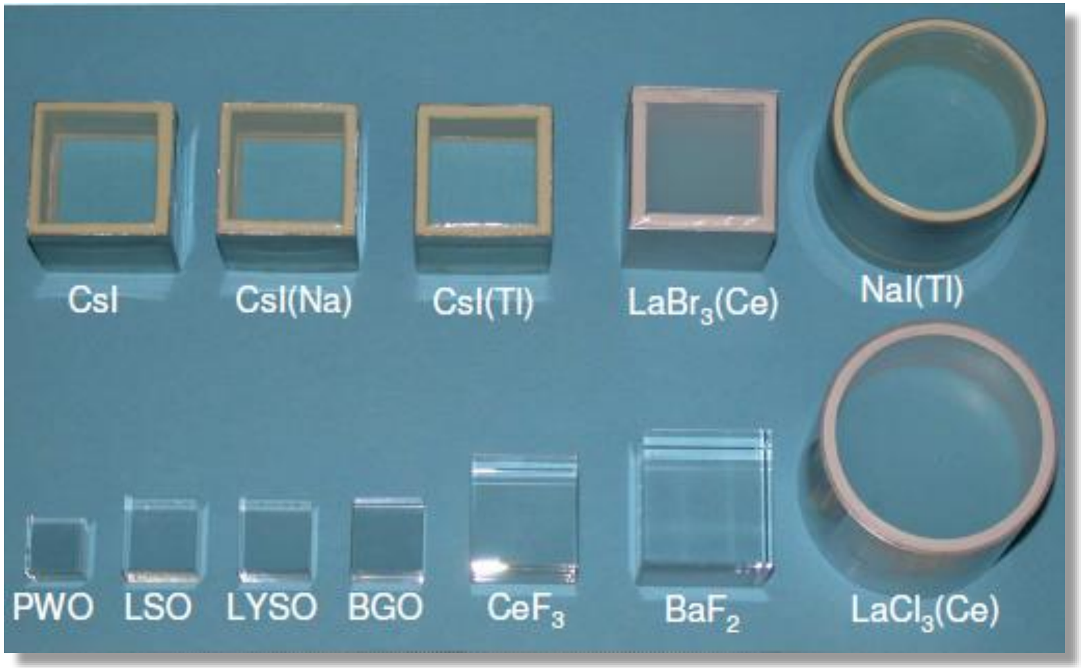


C.W.E. van Eijk, NIM A460 (2001) 1

Selection of Inorganic Scintillators

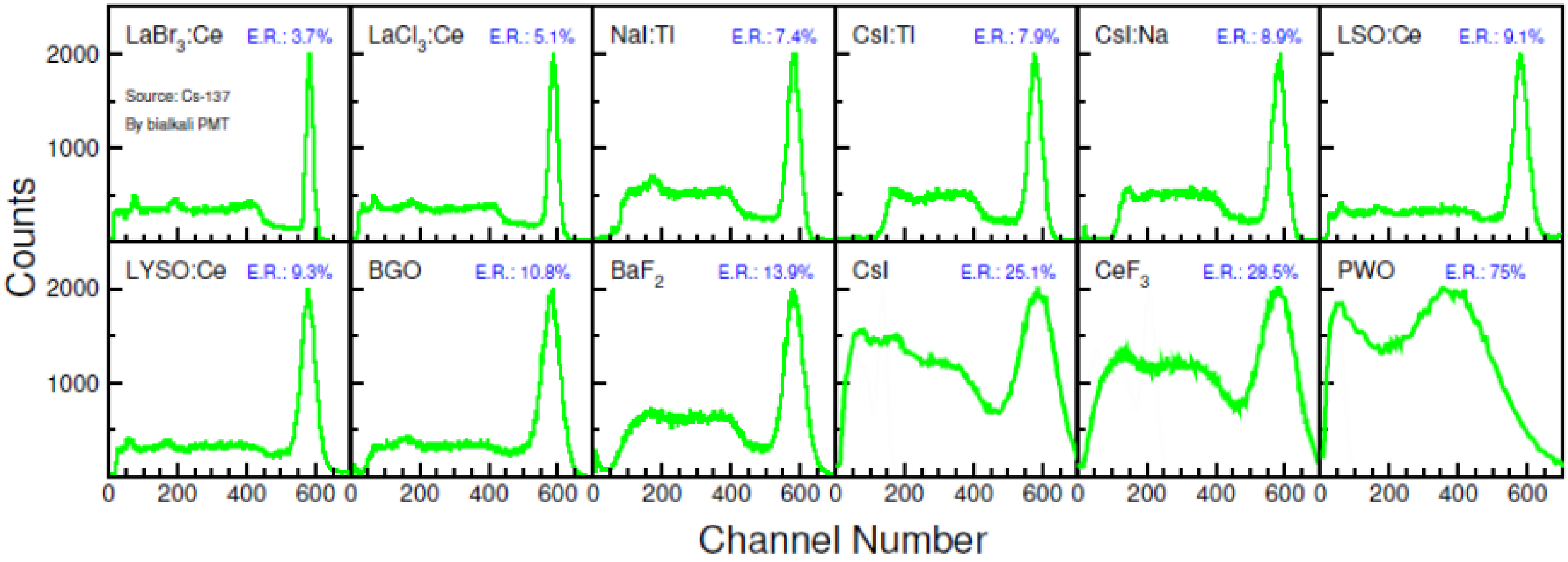
Material/ Parameter	Density (g/cm^3)	Melt. Point (℃)	Rad. Length (cm)	Moliere Radius (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
BaF_2	4.89	1280	2.03 2.06	3.10 3.40	1.50	300 220	650 0.9	16000 2000	>50	Scint.	52.7
CeF_3	6.16	1460	1.70 1.68	2.41 2.60	1.62 1.68	340 300	5 30	2800	>100	Scint.	50.8
(BGO)$Bi_4Ge_3O_{12}$	7.13	1050	1.12	2.23 2.30	2.15	480	300	8000 4000	>1000	.98 scint, .02 Č	83
(PWO)$PbWO_4$	8.30	1123	0.89 0.92	2.00	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
PbF_2	7.77	824	0.93	2.21	1.82	280 310	<30	2-6	50	Pure Č	77
(BSO):Ce$Bi_4Si_3O_{12}$	6.80	1030	1.85	≈5	2.06	470 505	≈100	1000 4000	>10	Scint.	75
(LSO):CeLu_2SiO_5	7.40	2050	1.14	2.07	1.82	420	40	30000	>1000	.98 sint ..02 Č	64.8
(LYSO):Ce$[LuY]_2SiO_5$	7.40	2050	1.14	2.07	1.82	420	40	30000	>1000	.98 scint. .02 Č	64.8

Properties of Inorganic Scintillators



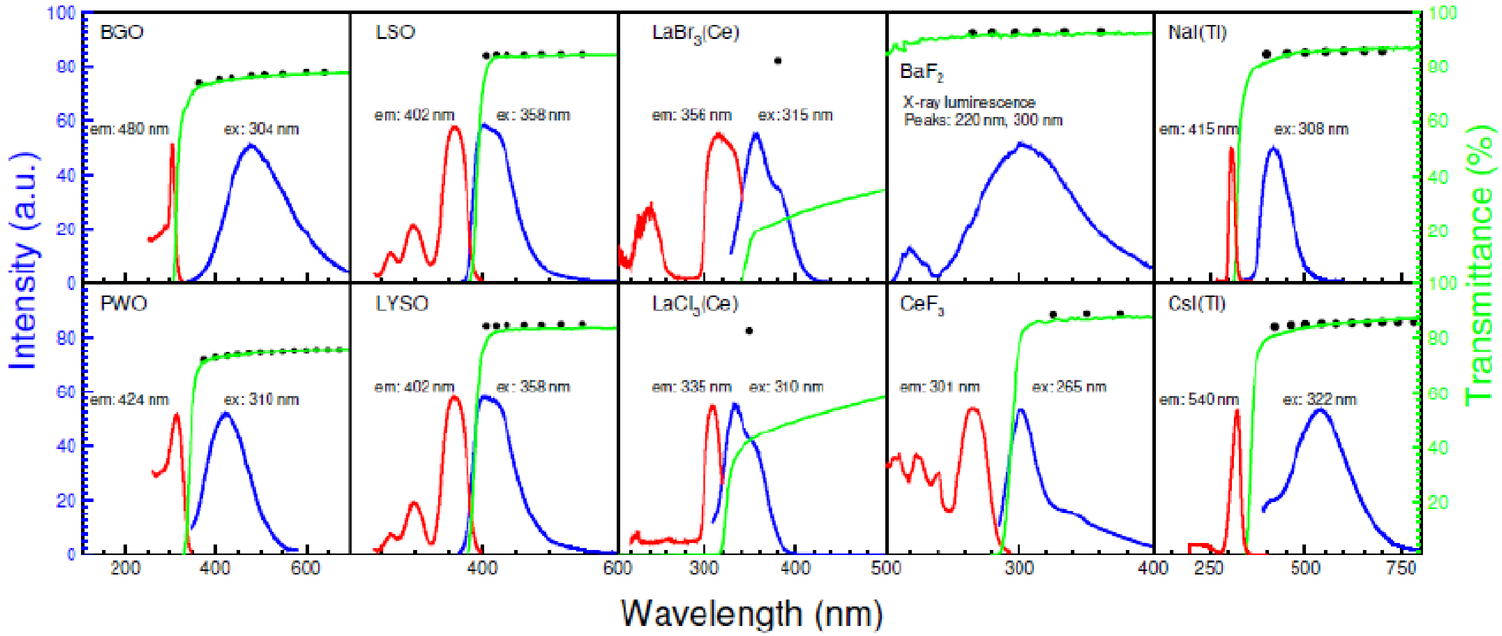
Identical Volume: X_0^3

Energy resolution

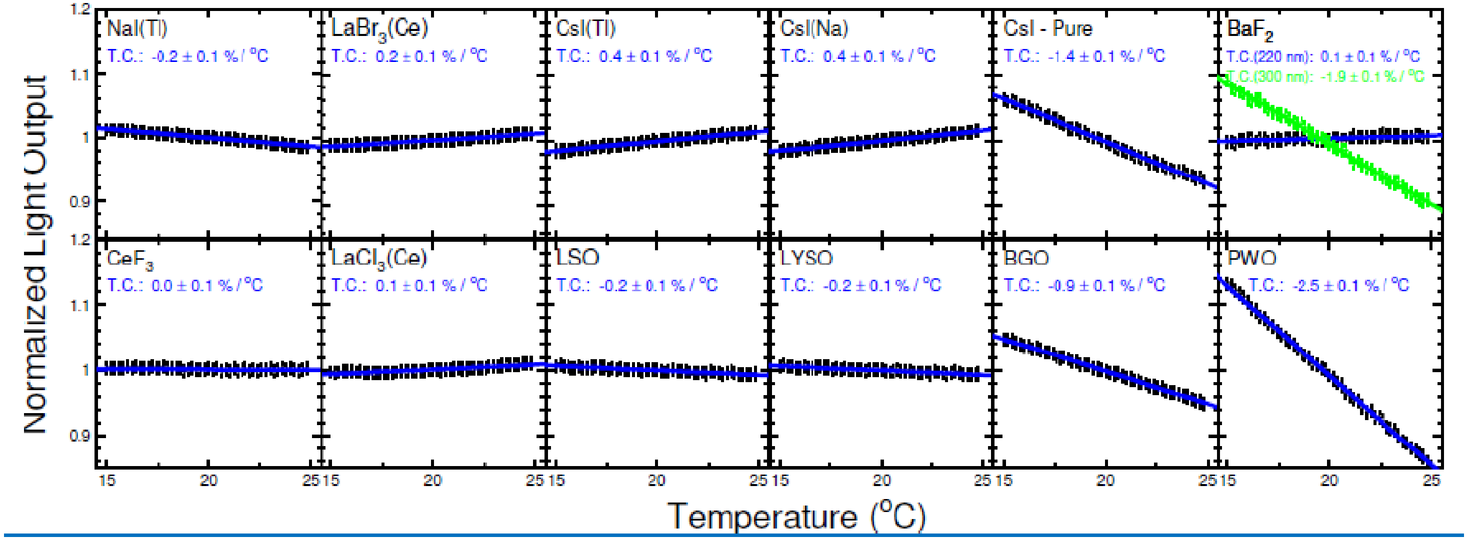


Properties of Inorganic Scintillators

Emission and transmittance



Temperature dependence



New Materials for EIC Calorimeters

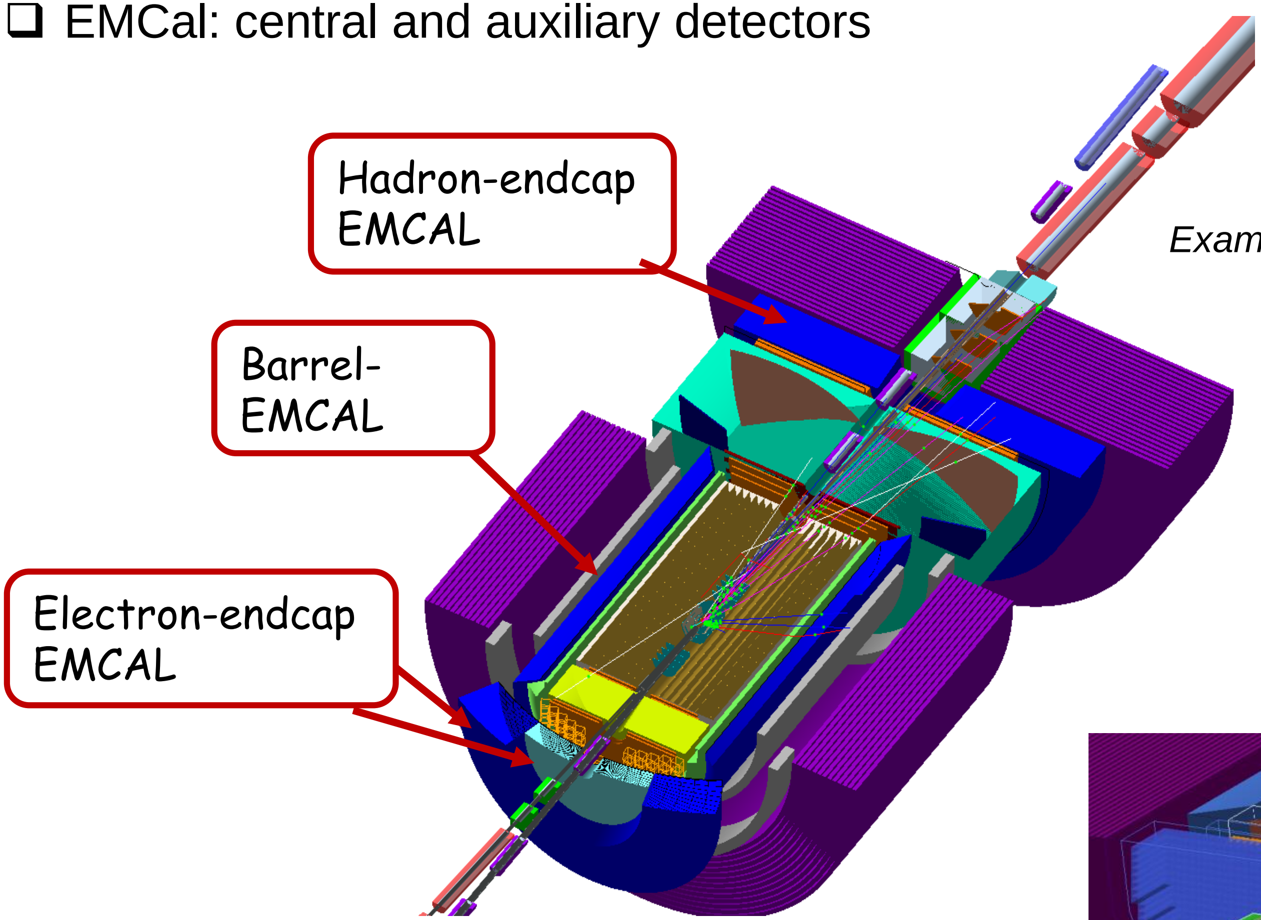
V. Berdnikov, T. Horn, I.L. Pegg

and the EIC Homogeneous Calorimetry eRD1 Consortium

The Catholic University of America
IPN Institut de Physique Nucléaire Orsay
A. Alikhanyan National Laboratory
SCINTILEX
Jefferson Lab Thomas Jefferson National Accelerator Facility
California Institute of Technology 1891
INFN
Brookhaven National Laboratory

EIC EM Calorimetry

- ☐ EMCal: central and auxiliary detectors

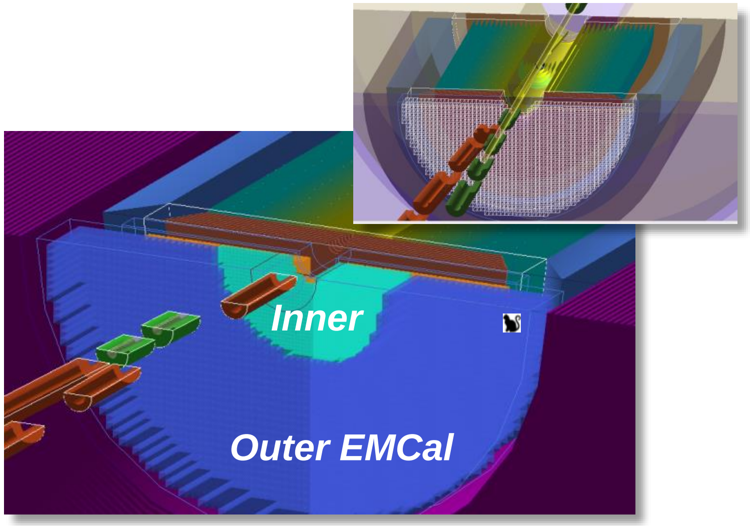


Hadron-endcap EMCAL

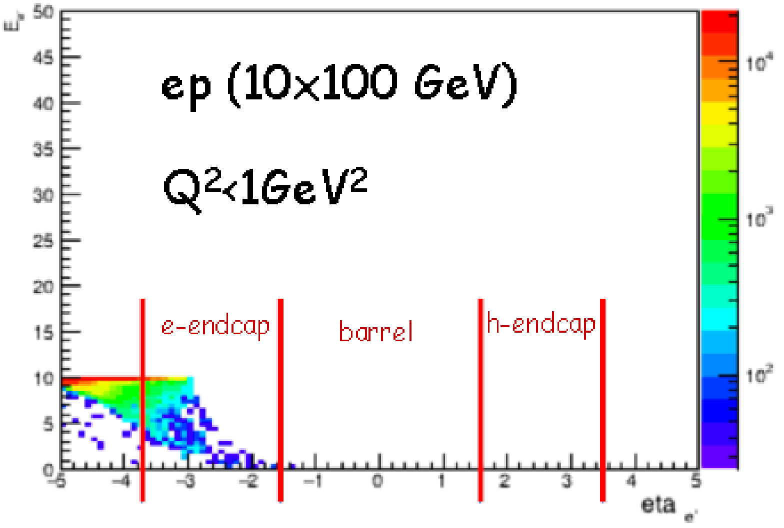
Barrel-EMCAL

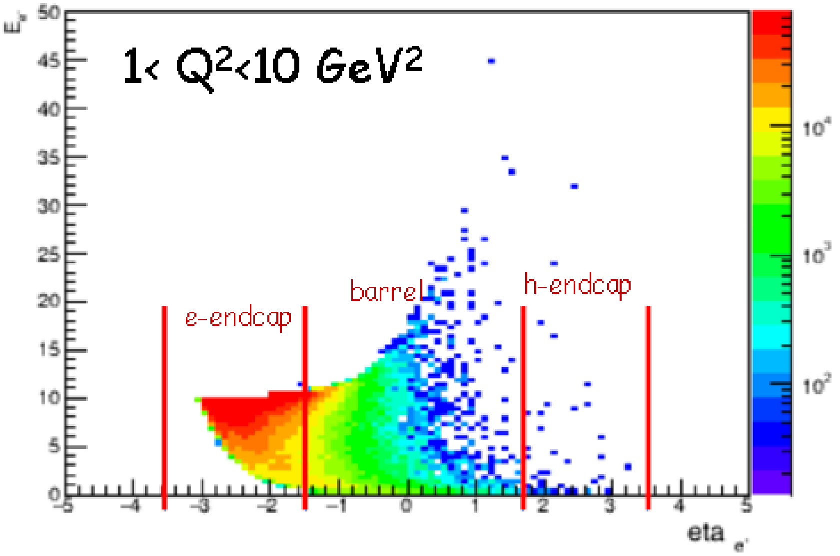
Electron-endcap EMCAL

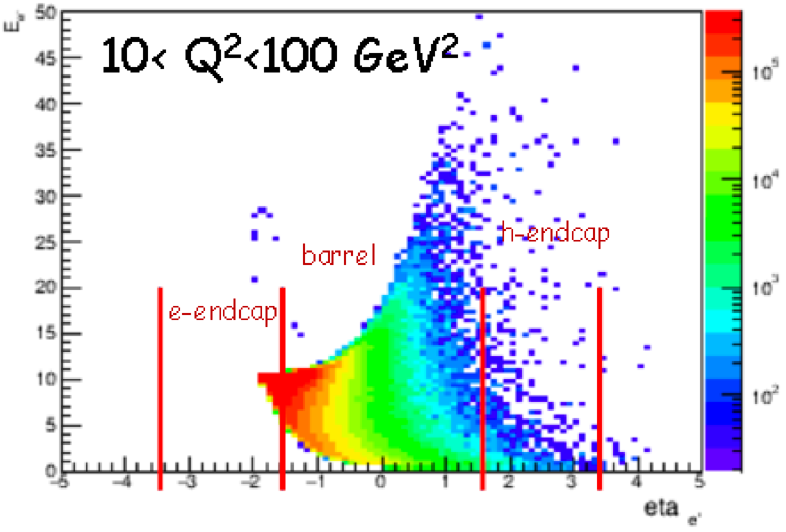
Example: JLEIC detector

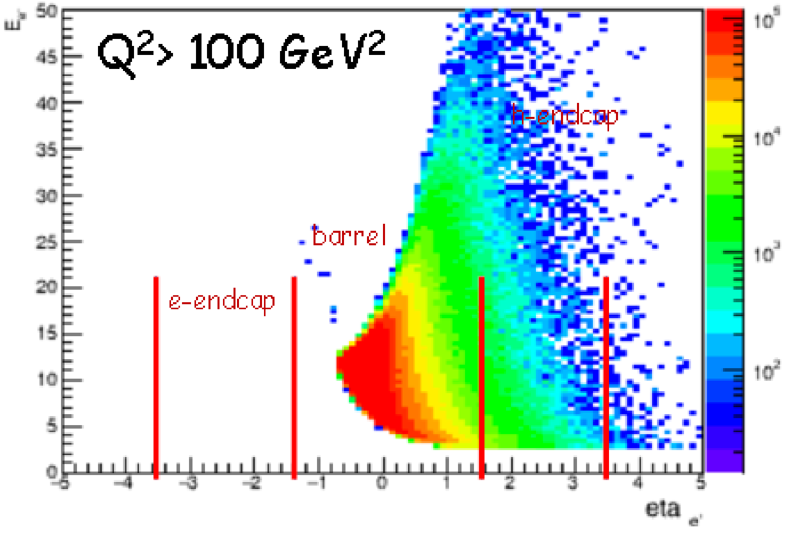


Scattered electron kinematics





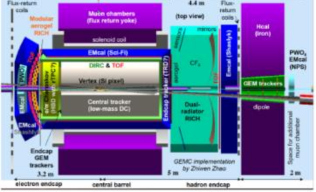




Regions and Physics Goals	Calorimeter Design
Lepton/backward: EM Cal ○ Resolution driven by need to determine (x, Q^2) kinematics from scattered electron measurement ○ Prefer $1.5\%/\sqrt{E} + 0.5\%$	**Inner EM Cal for for $\eta < -2$:** ➢ Good resolution in angle to order 1 degree to distinguish between clusters ➢ Energy resolution to order ($1.0\text{-}1.5\ \%/\sqrt{E}+0.5\%$) for measurements of the cluster energy ➢ Ability to withstand radiation down to at least 2-3 degree with respect to the beam line. **Outer EM Cal for $-2 < \eta < 1$:** ➢ Energy resolution to $7\%/\sqrt{E}$ ➢ Compact readout without degrading energy resolution ➢ Readout segmentation depending on angle
Ion/forward: EM Cal ○ Resolution driven by deep exclusive measurement energy resolution with photon and neutral pion ○ Need to separate single-photon from two-photon events ○ Prefer $6\text{-}7\%/\sqrt{E}$ and position resolution < 3 mm	
Barrel/mid: EM Cal ○ Resolution driven by need to measure photons from SIDIS and DES in range 0.5-5 GeV ○ To ensure reconstruction of neutral pion mass need: $8\%/\sqrt{E} + 1.5\%$ (prefer 1%)	**Barrel, EM calorimetry** ➢ Compact design as space is limited ➢ Energy resolution of order $8\%/\sqrt{E} + 1.5\%$, and likely better
Ion/Forward: Hadron Cal ○ Driven by need for x-resolution in high-x measurements ○ Need Δx resolution better than 0.05 ○ For diffractive with ~50 GeV hadron energy, this means $40\%/\sqrt{E}$	**Hadron endcap:** ➢ Hadron energy resolution to order $40\%/\sqrt{E}$, ➢ EM energy resolution to < ($2\%/\sqrt{E} + 1\%$) ➢ Jet energy resolution < ($50\%/\sqrt{E} + 3\%$)

Requirements on calorimeter materials

- Light Yield – Conversion of energy into visible light
- Attenuation Coefficient – Radiation length
- Scintillation Response – emission intensity
- Emission spectrum matching between scintillator and photo detector – emission peak
- Chemical stability and radiation resistance
- Linearity of light response with incident photon energy
- Moliere radius for lateral shower containment
- Temperature stability



Regions and Physics Goals	**Calorimeter Design**
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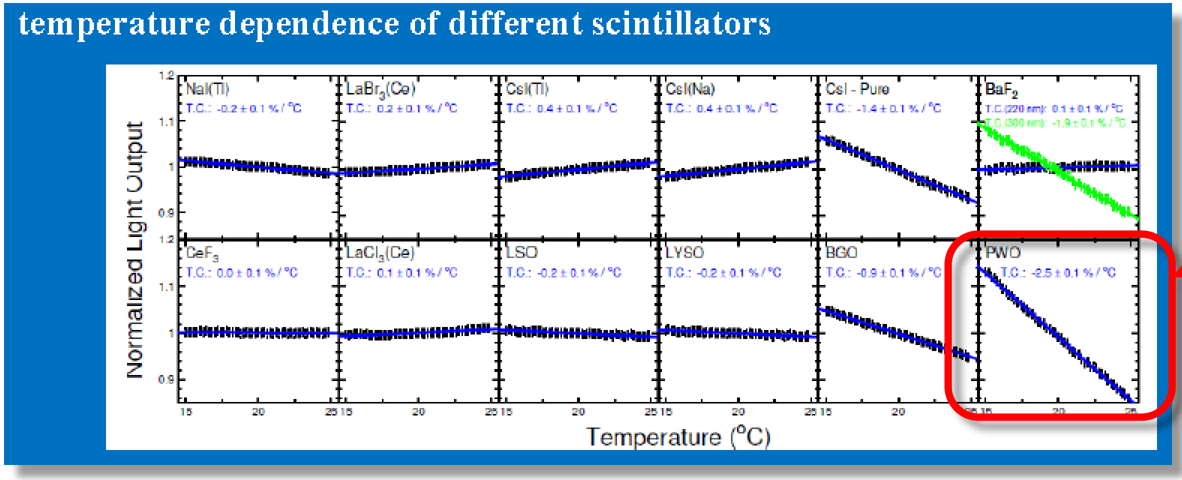
Ion/forward: EM Cal ○ Resolution driven by deep exclusive measurement energy resolution with photon and neutral pion ○ Need to separate single-photon from two-photon events ○ Prefer 6-7%/√E and position resolution < 3 mm	

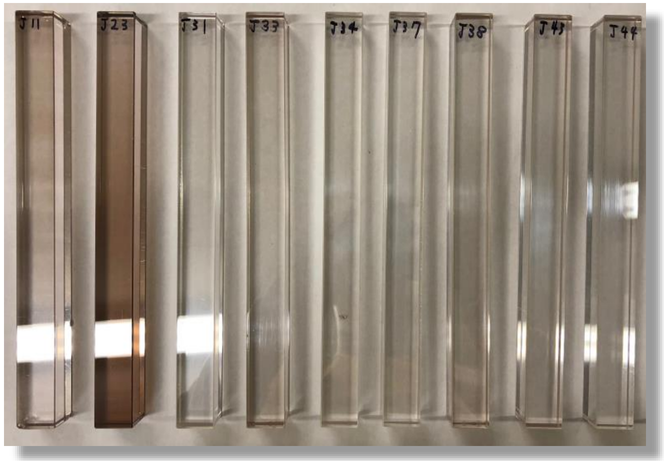
Backward/lepton Inner EM Cal – most demanding for high resolution

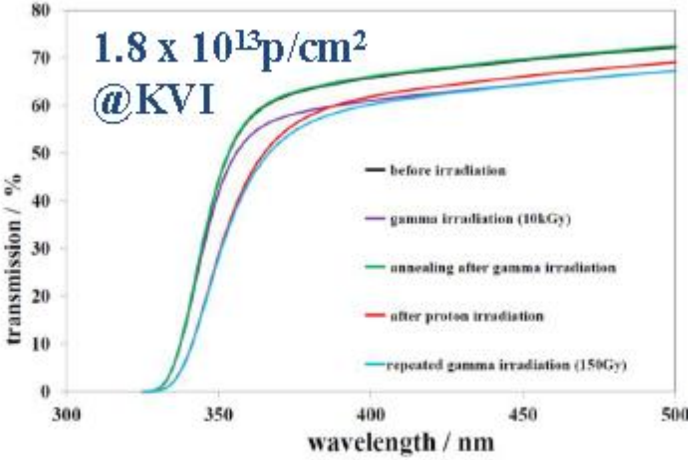
Crystals in EMCal: $PbWO_4$

$PbWO_4$ optimal for EMCal, e.g. CMS, PANDA detectors – stopping power, fast response, etc., but also limitations, e.g. hadron radiation damage, low Light Yield



$PbWO_4$ light yield temperature dependence: **2%/°C**



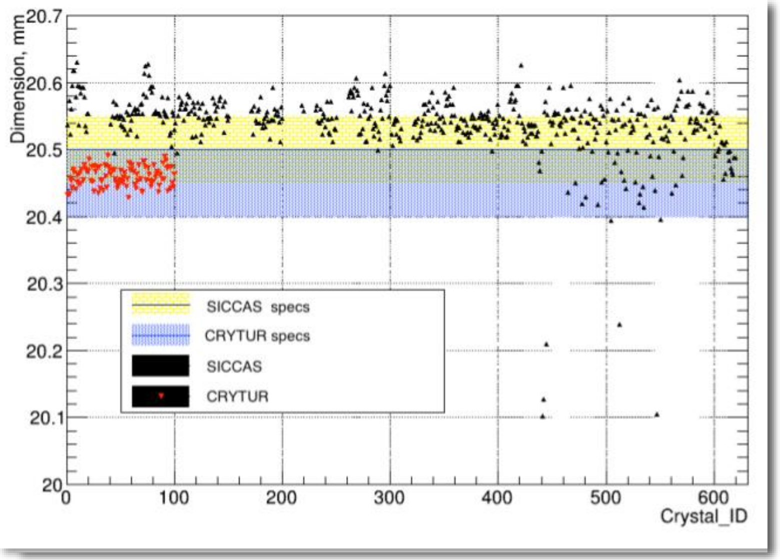


$PbWO_4$ radiation damage

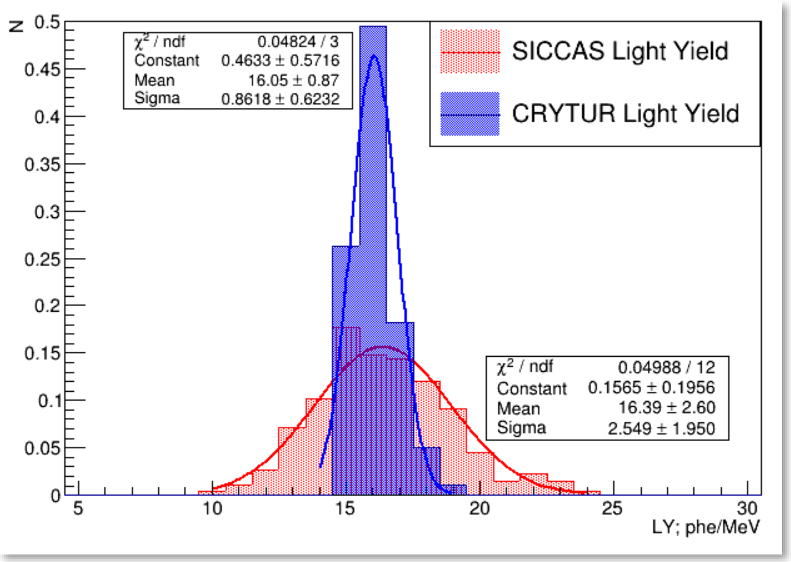
Crystals in EMCal: $PbWO_4$

- ☐ **Expensive (\$15-25/cm^3)** – barrel EMCal not affordable
- ☐ Another consideration: manufacturing uncertainty
  - ➢ SICCAS: failure rate ~35% for crystals received 2017-19 due to major mechanical defects – an additional 15% are questionable
  - ➢ CRYTUR: Strict quality control procedures – so far 100% of crystals accepted, but limited raw material

Quality analysis:



Dimensions



Light yield

Regions and Physics Goals	Calorimeter Design
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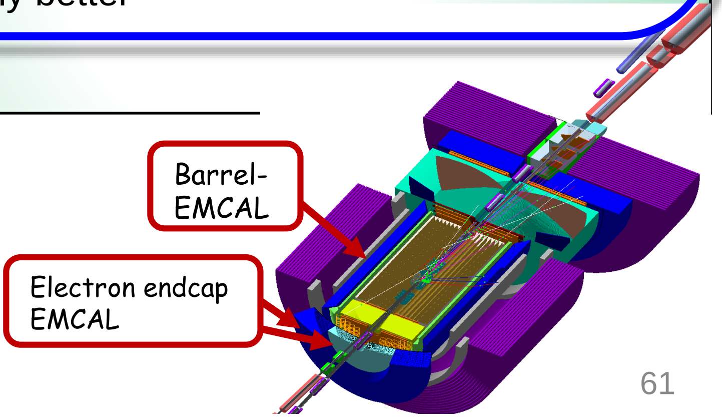
Backward/lepton Outer EM Cal and barrel region – more relaxed on resolution requirements



Glass-based Scintillators for Detector Applications

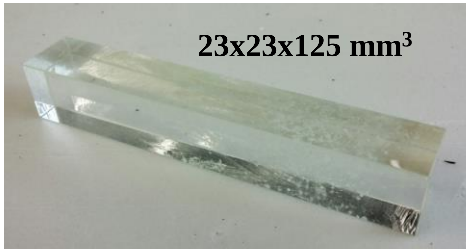
An alternative active calorimeter material that is more cost effective and easier to manufacture than, e.g. crystals

Material/ Parameter	**Density (g/cm^3)**	**Rad. Length (cm)**	**Moliere Radius (cm)**	**Interact Length (cm)**	**Refr. Index**	**Emission peak**	**Decay time (ns)**	**Light Yield (pe/MeV)**	**Rad. Hard. (krad)**	**Radiation type**	**Z_{Eff}**
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	450, 540	10 20-200 ~500	17-22	10	.90 scint. .10 Č	75.6
$(BaO*2SiO_2)$:Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	>2000 *(no tests >2Mrad yet)*	Scint.	51
$(BaO*2SiO_2)$:Ce glass w/ Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	>2000 *(no tests >2Mrad yet)*	Scint.	58

Also: $(BaO*2SiO_2)$:Ce shows no temperature dependence

Shortcomings of earlier work:

- Macro defects, which can become increasingly acute on scale-up
- Sensitivity to electromagnetic probes



The Vitreous State Laboratory – unique expertise

Premier materials science facility with unique capabilities and expertise in glass R&D

- ☐ Current R&D program includes
  - Nuclear and hazardous waste stabilization
  - Glass and ceramic materials development
    - Formulation optimization
    - Characterization
    - Property-composition models
  - Materials corrosion and characterization
  - Off-gas treatment
  - Water treatment, ion exchange
  - Cements, flyash
  - Geopolymers
  - Biophysics
  - Nano-materials
  - Thermoelectrics
  - Spintronics
  - Scintillation detectors

The Vitreous State Laboratory – unique facility

- ☐ Designing, constructing and testing large glass production systems
  - VSL Joule Heated Ceramic Melter (JHCM) Systems:
    - The largest array of JHCM test systems in the US
    - The largest JHCM test platform in the US

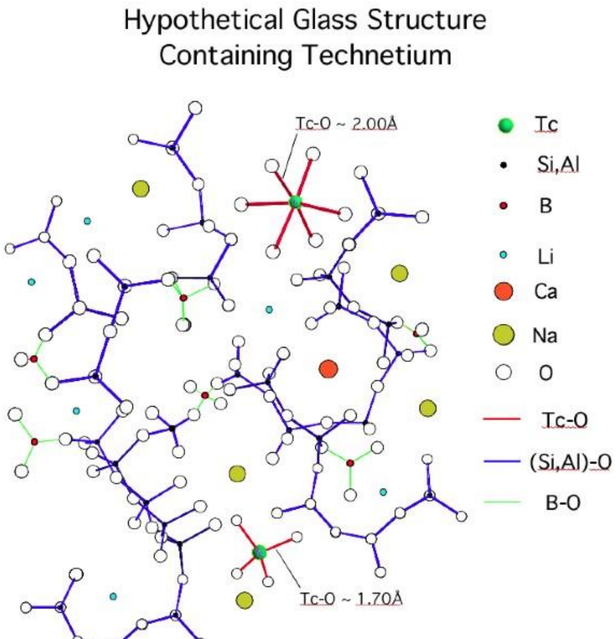
PILOT SYSTEM SCALE-UP

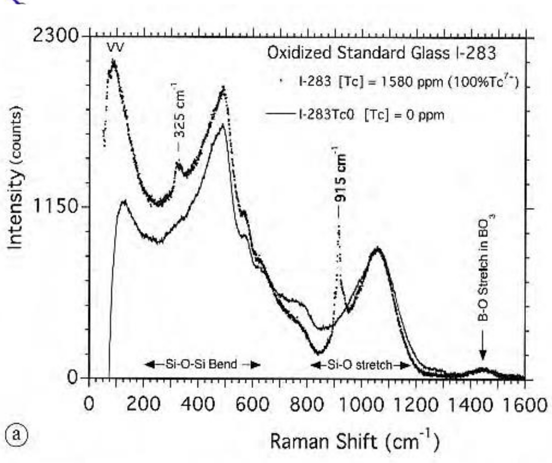
DM10 and DM100 JHCM Systems at VSL

VSL DM1200 HLW Pilot Melter System

About 400,000 kg glass made from about 1 million kg feed

XAS Studies on Silicate Glasses





- Na: $Na^{+}O_{3-7}$: Na-O = 2.30 -2.60 Å
- Mn: $Mn^{2+}O_{4-5}$: Mn-O = 2.07 Å, Mn-Mn = 3.48 Å
- Cu: $Cu^{2+}O_4$: Cu-O = 1.96 Å, Cu-Cu = 2.98 Å
- Sr: $Sr^{2+}O_{4-5}$: Sr-O = 2.53 Å
- Zr: $Zr^{4+}O_{6-7}$: Zr-O = 2.08 Å
- Mo: $Mo^{6+}O_4$: Mo-O = 1.75 Å
- Ag: $Ag^{+}O_2$: Ag-O = 2.10 – 2.20 Å
- I: $I^{-}(Na,I)_4$: I-Li = 2.80 Å, I-Na = 3.04 Å
- Re: $Re^{7+}O_4$: Re-O = 1.74 Å
- Bi: $Bi^{3+}O_3$: Bi-O = 2.13 Å
- S: $S^{6+}O_4$ surrounded by network modifiers; S^{2-}; S-S
- Cl: Cl-O = 2.70 Å; Cl-Cl = 2.44 Å; Cl-Na; Cl-Ca
- V: $V^{5+}O_4$; minor $V^{4+}O_5$ under reducing conditions
- Cr: redox sensitive: $Cr^{6+}O_4$ Cr-O = 1.64 Å; $Cr^{3+}O_6$ Cr-O = 2.00 Å; $Cr^{2+}O_4$ Cr-O ~ 2.02 Å
- Tc: redox sensitive, $Tc^{4+}O_6$ Tc-O = 2.00Å; $Tc^{7+}O_4$ Tc-O = 1.75 Å; evidence of Tc-Tc = 2.56 Å in hydrated, altered glass
- Sn: $Sn^{4+}O_6$ (minor $Sn^{2+}O_4$) Sn-O = 2.03 Å; Sn-Sn = 3.50 Å
- Al: $Al^{3+}O_4$: Al-O: 1.77 Å
- Si: $Si^{4+}O_4$: various polymerizations
- Zn: $Zn^{2+}O_4$: Zr-O: 1.96 Å, Zn-Si 2nd nearest-neighbor evidence

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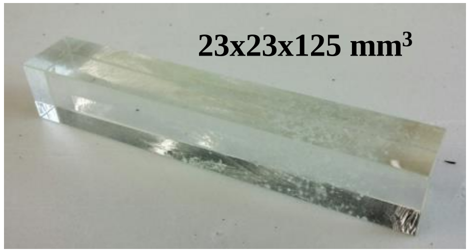
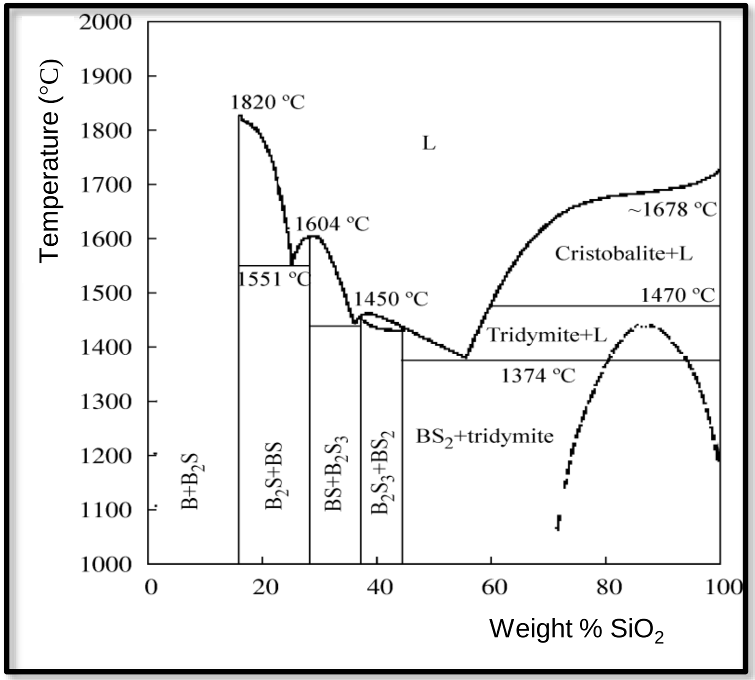


Material Overview

Technology: Glass production combined with successive thermal annealing (800 – 900^{o}C)

Phase diagram of the BaO*SiO$_2$ system

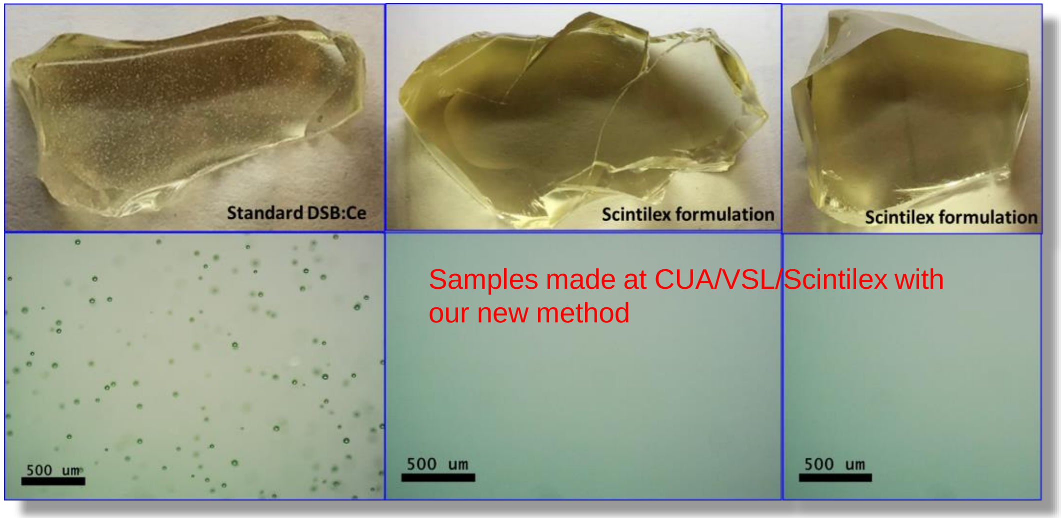


Ba-Si system allows to incorporate trivalent ions: **Lu, Dy, Gd, Tb, Yb, Ce**

New Glass Scintillator Material

- Glass scintillators being developed at *VSL/CUA/Scintilex*

Progress with new method to eliminate defects



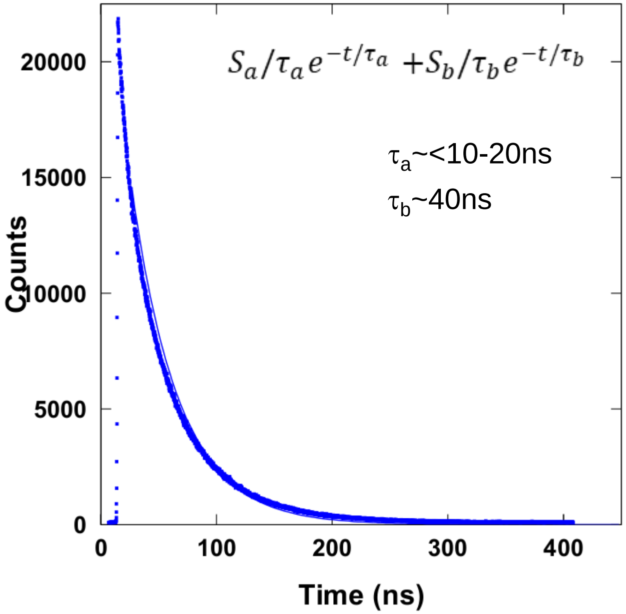
Samples made at CUA/VSL/Scintilex with our new method

Optical properties comparable or better than $PbWO_4$

Light Yield

Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

Scintillation decay time



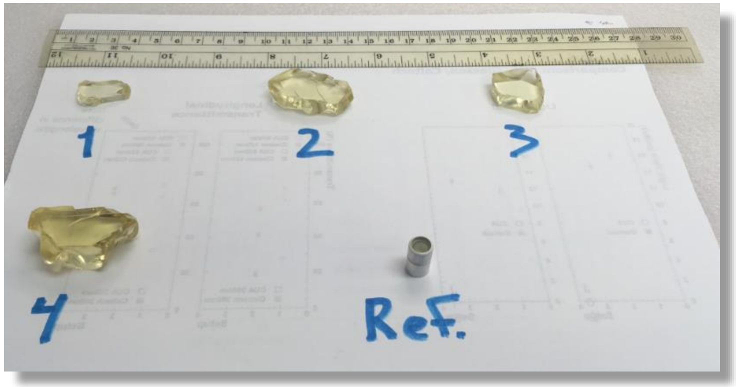
τ_a~<10-20ns

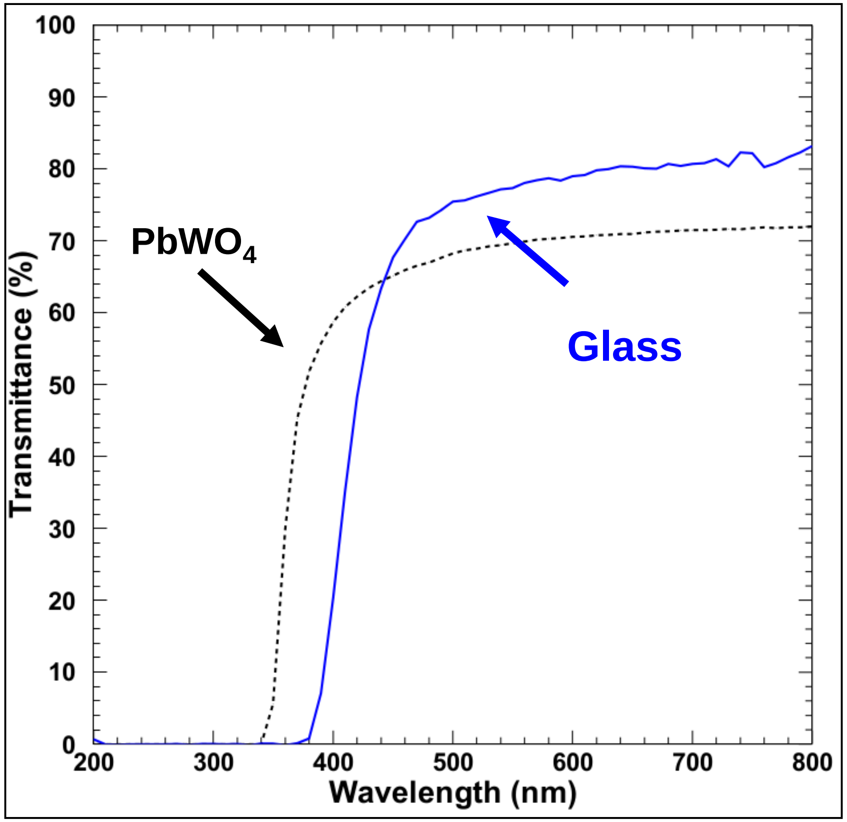
τ_b~40ns

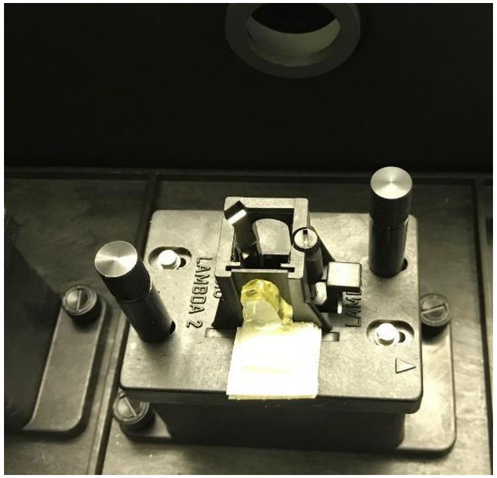
Decay time measured with single photon counting

New Glass Scintillator Material

- **Transmittance** of small samples comparable and sometime better than PbWO4





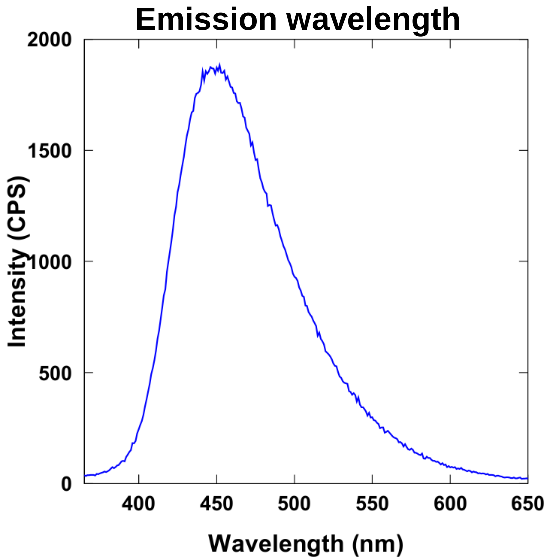


Glass Scintillator – formulation optimization

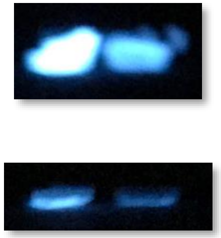
❑ Two glass formulations for calorimeter application

VSL-Scintilex-G4 (nominal)

VSL-Scintilex-T1



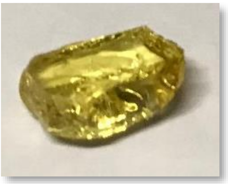
Scintillation light



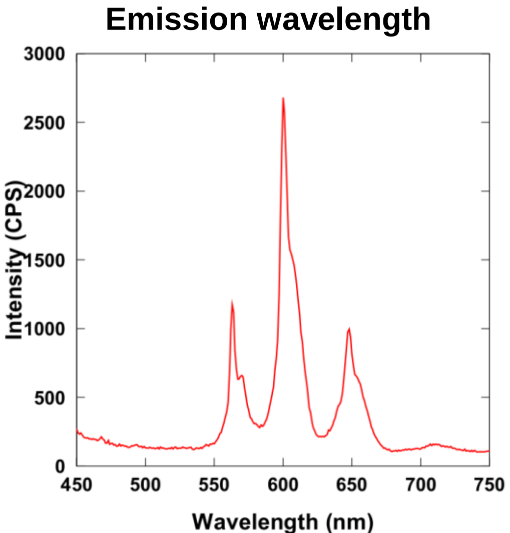
- ➢ Nominal: optimized LY, timing, radiation hardness, etc. ✓
- ➢ Increased density compared to nominal, lower LY, but still higher than PWO

❑ Formulations with initial emission wavelength tuning

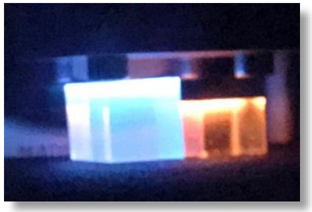
VSL-Scintilex-SC1



VSL-Scintilex-EC1



Scintillation light

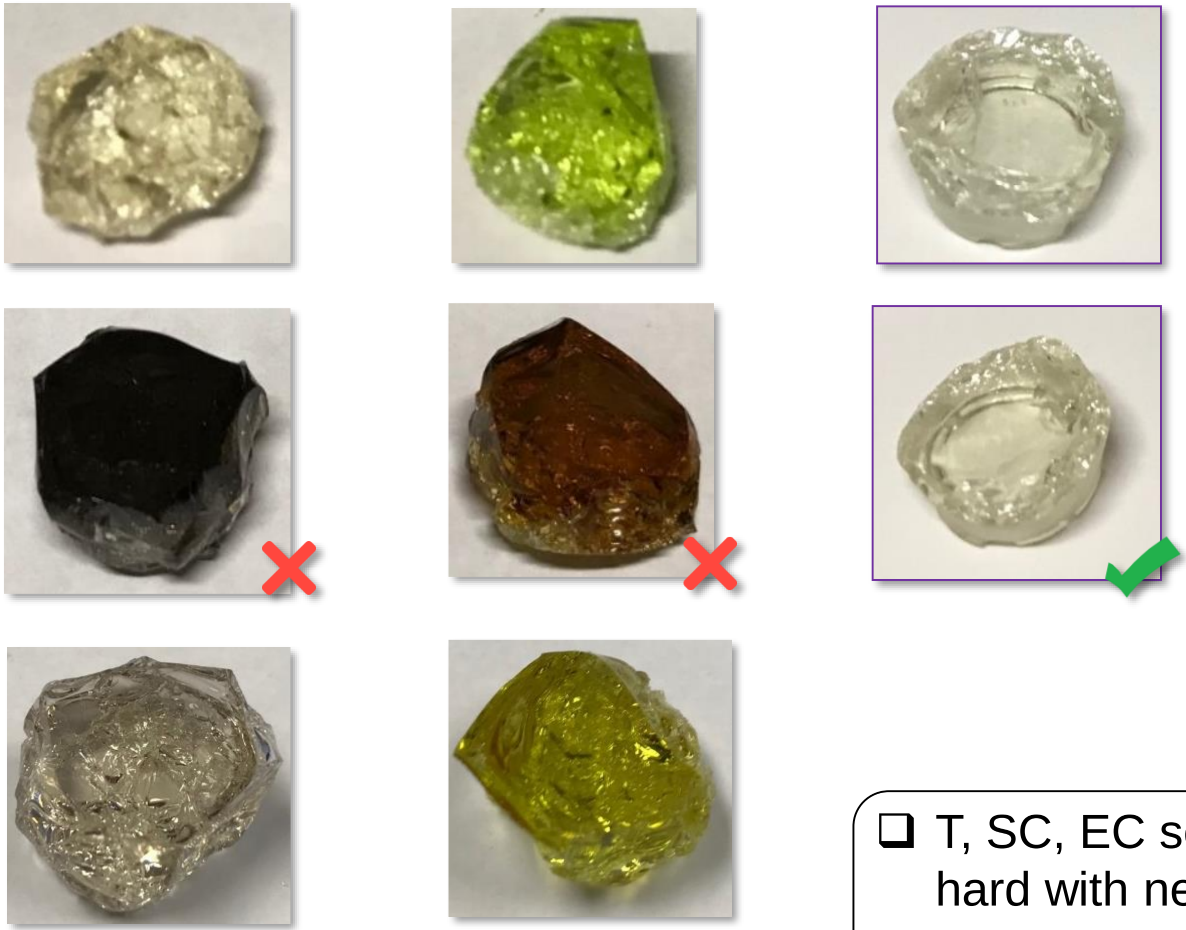


- ➢ Can have higher density compared to nominal, emits at >550nm, good LY

Glass Scintillator – Radiation Hardness

SCINTILEX

- ☐ High dose radiation tests – progress with new method at CUA/VSL/Scintilex



VSL-Scintilex-S1

VSL-Scintilex-S2

VSL-Scintilex-G4 (nominal)

Before irradiation

After 2min 160KeV
Xray at >3k Gy/min

After curing

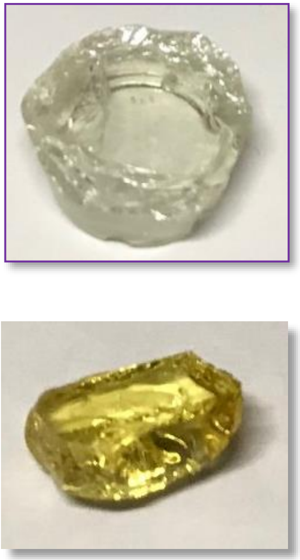
- ☐ T, SC, EC series are EM radiation hard with new method too
- ☐ Hadron irradiation test planned

Glass Scintillator – Initial Scale-Up

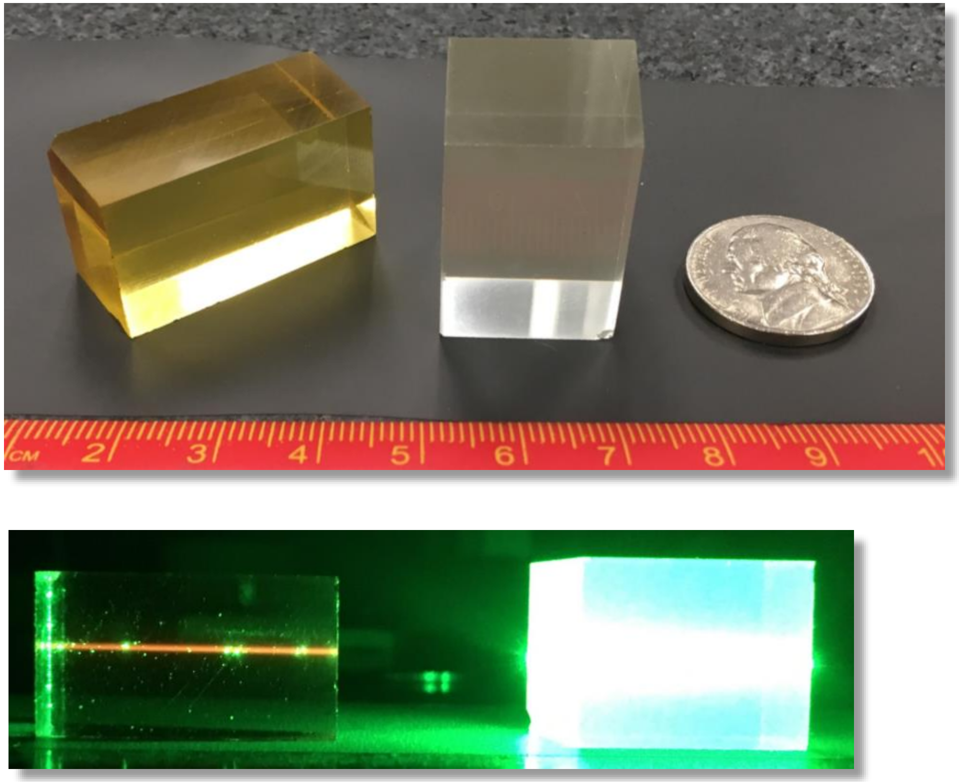
- ❑ Progress with scale-up – medium-size samples produced, issues associated with further scale-up identified, solutions are being implemented and tested

Example: G4 (nominal), SC1 glass

1cm x 1cm x 0.5cm (test size)



2cm x 2cm x ~3cm (medium size)



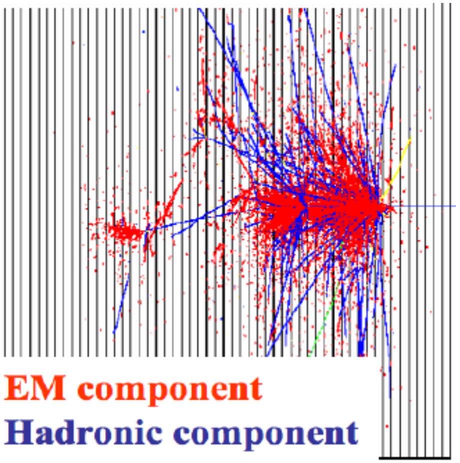
Summary EMCal

- ☐ $PbWO_4$ crystals are ideal for precision EMCal, but also have limitations and are expensive – large volume detectors are unaffordable

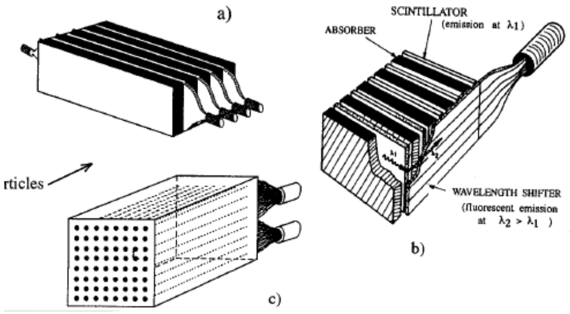
- ☐ Glass-based scintillators are cost-effective alternative to crystals, in particular EMCal regions with relaxed resolution requirements
  - Small samples produced at CUA/VSL/Scintilex have a factor of ten or higher light yield compared to $PbWO_4$
  - Initial scale-up successful – medium-size samples produced without defects
  - Ongoing optimization
  - Beam test program expected to start this fall

Hadronic Calorimeters

Hadronic Calorimeters

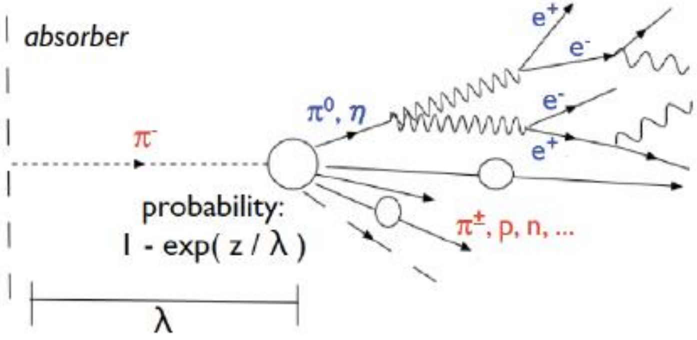


- Usually sampling calorimeters
- Showers have two components: EM and hadronic
- Active medium made of similar material as EMCal
    - Scintillator (light), gas (ionization/wire chambers), silicone (SSD)
- Passive medium is a material with longer interaction length
    - Iron, uranium, …
- Resolution is worse than in EMCals, e.g. ZEUS Uranium calorimeter: 35%/sqrt E



EM fraction in hadronic shower

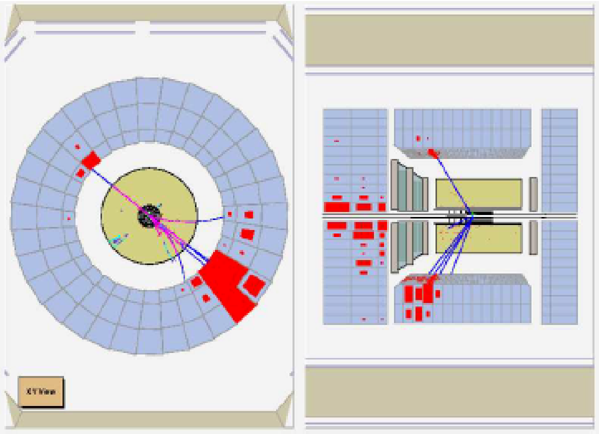
- ❑ π^0, eta production: all energy deposited through EM processes
- ❑ f_{EM}=fraction of hadron energy deposited via EM processes
  - ➢ In general f_{EM} increases with energy



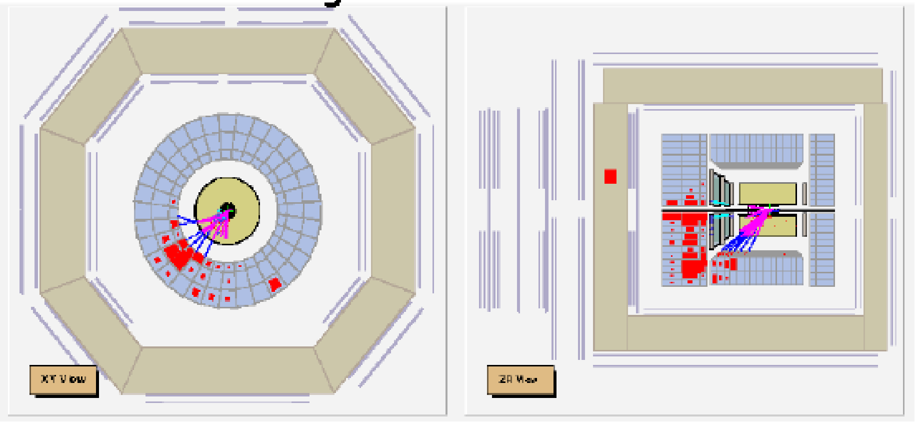
- ❑ f_{had} = the strong interaction force
- ❑ Smaller calorimeter response to non-EM components of hadron showers than to EM components
- ❑ Need to compensate for the invisible energy (lost nuclear binding energy, neutrino, slow neutrons)

ZEUS calorimeter

Neutral current DIS



Charged current DIS



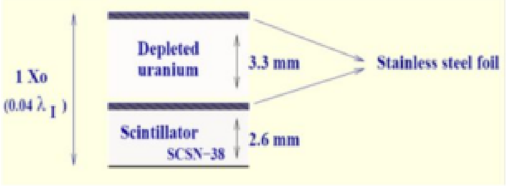
Sampling structure of the towers

Depleted Uranium alloy(98.1% U_{238},1.7% Nb, 0.2% U_{235})

Longitudinal length of EMC is $1\lambda_{int} = 25X_0$. (Almost complete containment of EM showers)

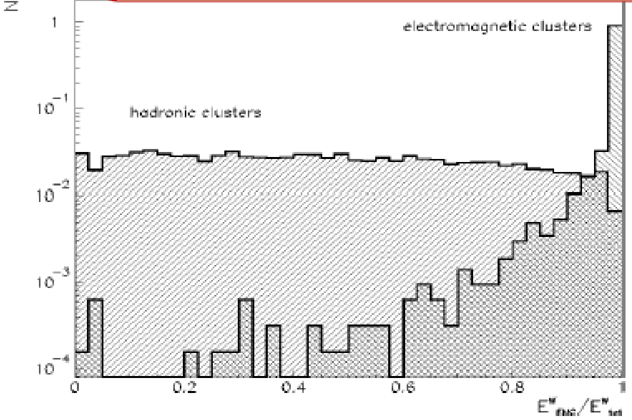
Longitudinal length of FCAL $6\text{-}7\lambda_{int}$ (Full containment of hadronic showers)

Neural network based electron identification

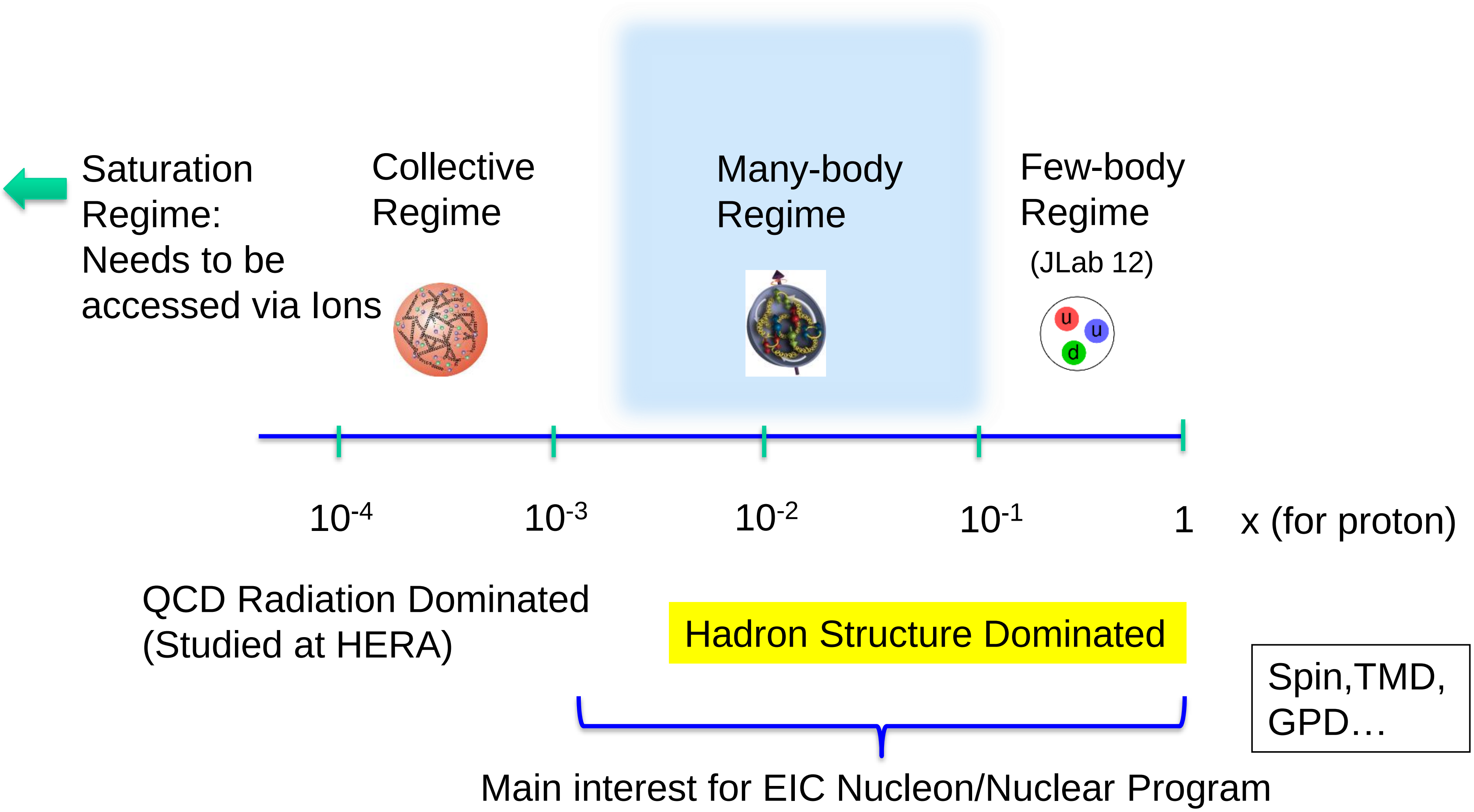


$$electrons: \frac{\sigma}{E} = \frac{18\%}{\sqrt{E}} \oplus 2\%$$

$$hadrons: \frac{\sigma}{E} = \frac{35\%}{\sqrt{E}} \oplus 2\%$$



Where EIC Needs to be in x (nucleon)



Saturation Regime: Needs to be accessed via Ions

Collective Regime

Many-body Regime

Few-body Regime

(JLab 12)

10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 x (for proton)

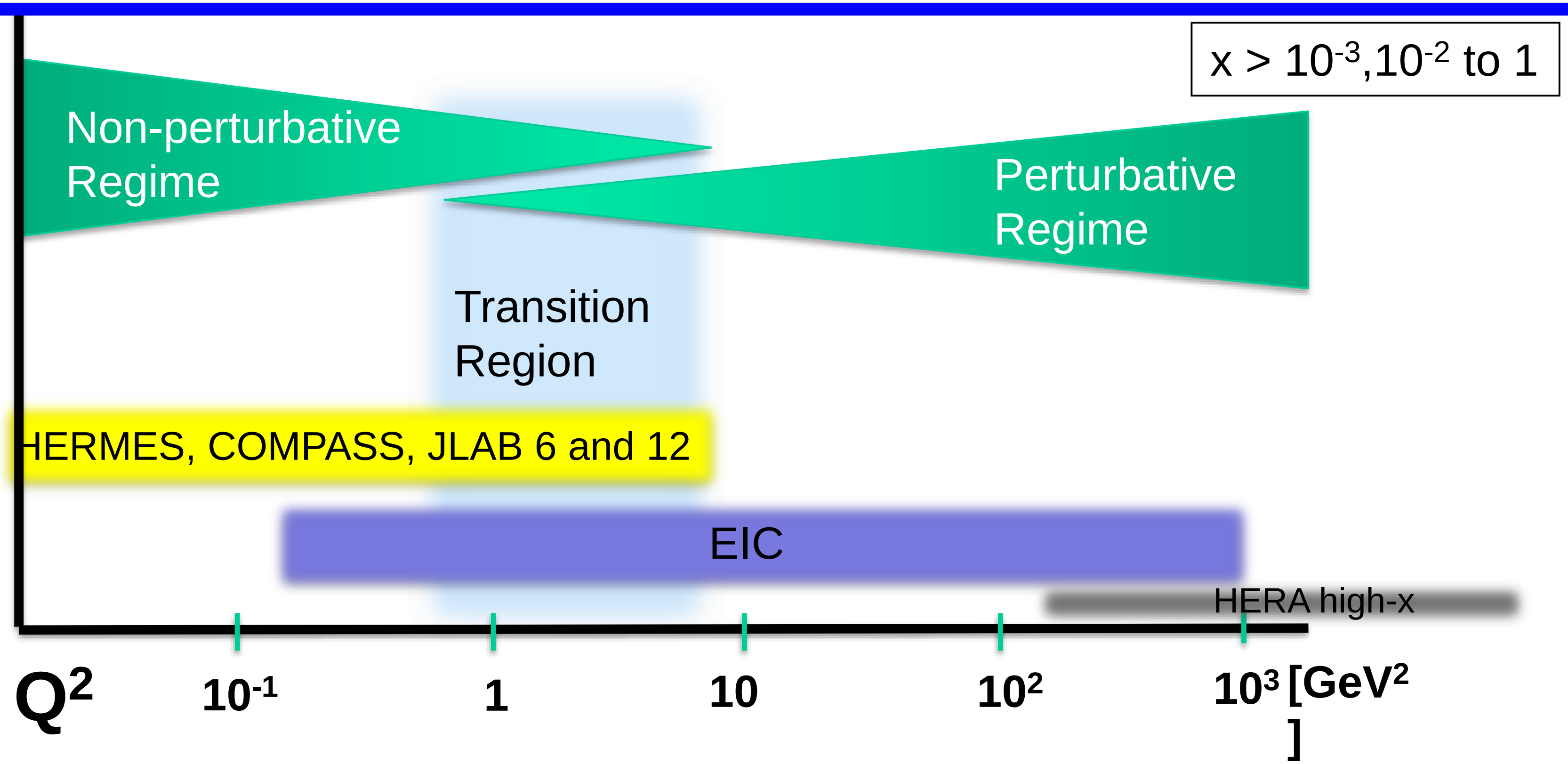
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Spin,TMD, GPD…

Main interest for EIC Nucleon/Nuclear Program

Where EIC needs to be in Q^2



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Perturbative/Non-perturbative, Leading Twist/Higher Twist