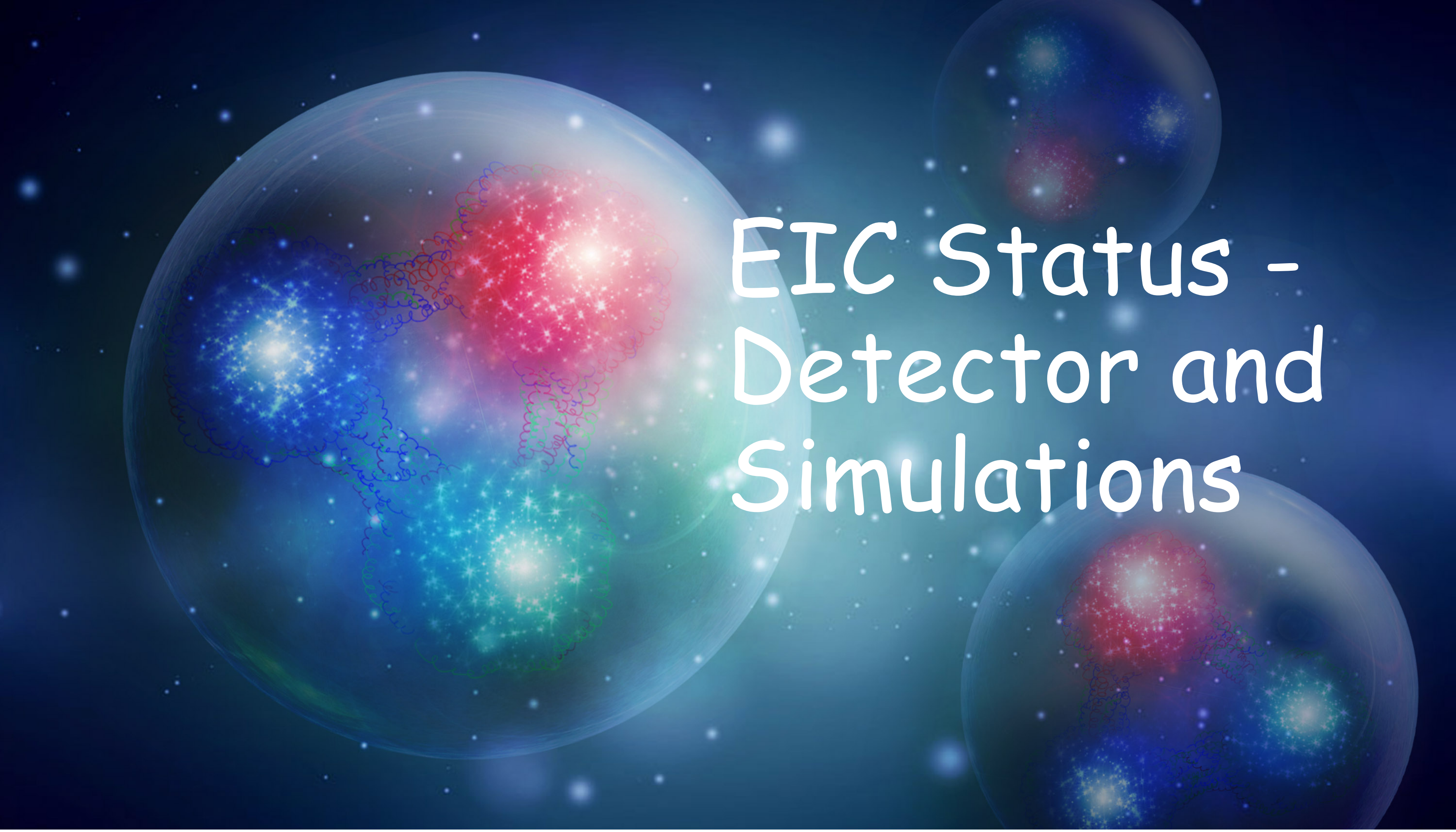


EIC Status - Detector and Simulations

Yulia Furletova

HUGS lectures

Outline

- Introduction to EIC
    - Highlights of EIC physics
    - EIC accelerators proposals
- Introduction to Deep Inelastic Scattering
    - DIS kinematic
- EIC detector design
    - Tracking
    - Vertex
    - Calorimeter
    - Particle Identification detectors
        - dE/dx
        - Time of flight
        - Cherenkov
        - Transition radiation
        - Muon detectors
    - Far-forward electron
    - Far-forward ion
    - Luminosity
    - Polarization
- Detector simulation and reconstruction

Outline

- Introduction to Electron Ion Collider
  - Highlights of EIC physics
  - US based EIC accelerators proposals
- Introduction to Deep Inelastic Scattering
  - DIS kinematic
- EIC detector design

Lecture-1

  - Tracking
  - Vertex

Lecture-2

  - Calorimeter
  - Muon detectors

Lecture-3

  - Particle Identification detectors
    - dE/dx
    - Time of flight
    - Cherenkov
    - Transition radiation

Lecture-4

- Detector simulation and reconstruction
- Conclusions

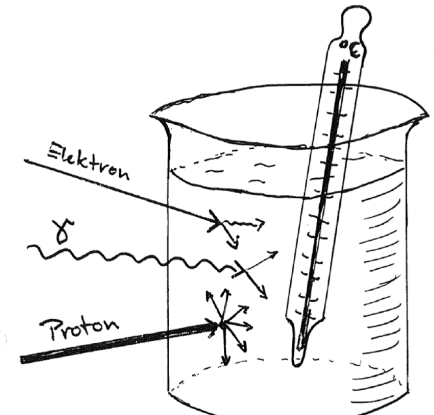
Lecture-5

Outline

- Motivation
- Calorimeter:
    - Electromagnetic calorimeter (EMCAL)
    - Hadronic calorimeter (HCAL)
    - Particle flow calorimeter
- Muon detectors
- Far-Forward

Motivation

- ✓ In nuclear and particle physics calorimeter refers to energy measurements of particles.



By Klaus Pretzl

We need 1kCal to change a temperature
on 1 °C for 1 liter of water

1kCal ~ $1000 \cdot 2.61 \cdot 10^{19}$ eV
~ $2.61 \cdot 10^{10}$ TeV

- ✓ In calorimeters the process of energy measurements is destructive: we must completely stop the particle in our detectors to measure its full energy :

  Unlike, for example, tracking chambers (straw, TPC, silicon, etc) , the particles are no longer available for detection once they path through a calorimeter.

  With just few exceptions: muons and neutrinos penetrate through with a minimal interactions

⇒ Calorimeter is the **outermost detector**

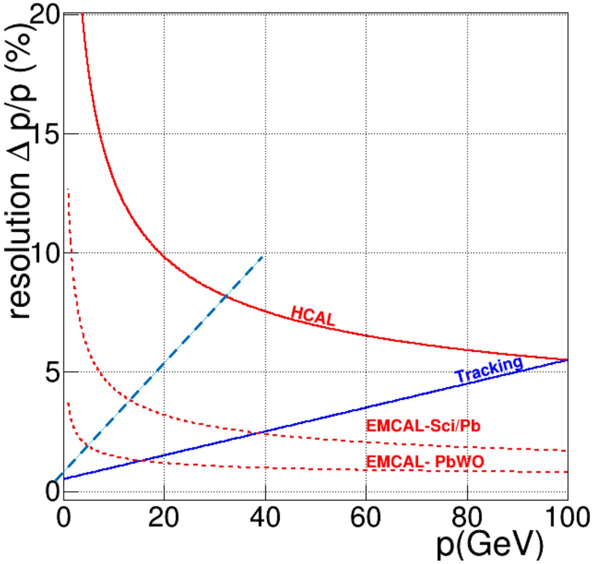
- ✓ At EIC we would like to provide close to 100% acceptance detector

Motivation

- ✓ Calorimeter measure charged + neutral particles
    - ➢ Scattered electron
    - ➢ Charged particles (electrons, hadrons)
    - ➢ Neutral particles (gammas, neutral hadrons)
    - ➢ Group of collimated particles moving into the same direction (Jets)

Motivation

- ✓ Why do we need a calorimeter ?
  - ✓ Use momentum measurements for charged particles: $E^2 = (p^2+m^2)$
    - ➢ Need to measure precise PID (or mass): not always possible.
    - ➢ Need to measure momentum precise: not always possible.
      - ❖ Momentum measurements are getting worse with increase of particle momenta ($\frac{\Delta p}{p} \sim p$)
      - ❖ BUT, Calorimeter measurements are getting better with increase of the energy ($\frac{\Delta E}{E} \sim \frac{1}{\sqrt{E}}$)
  - ✓ Need to measure neutral particles! Calorimeter is the ONLY detector for them.



Electromagnetic cascade

As electron or photon (high energy >1GeV) enters a thick absorber it produces a cascade of secondary electrons and photons.

Main processes: bremsstrahlung and pair production.

As the depth increases the number of secondary particles increases, but their mean energy decreases.

When the energies became below *critical energy* the multiplication process stops and energy via the processes of ionisation and excitation.

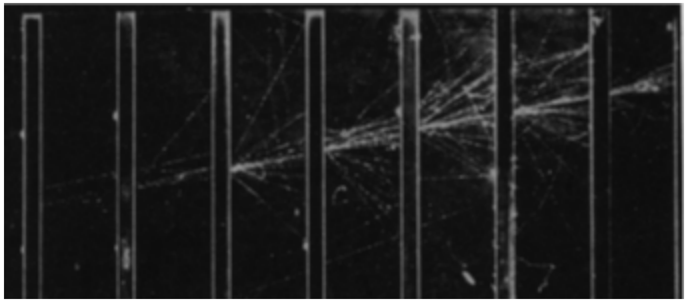
Calorimeter shower

Radiation length, X_0, is the distance in 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.

- ✓ 2^n particles 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 $n_{max} \sim \ln (E_0/E_c)$

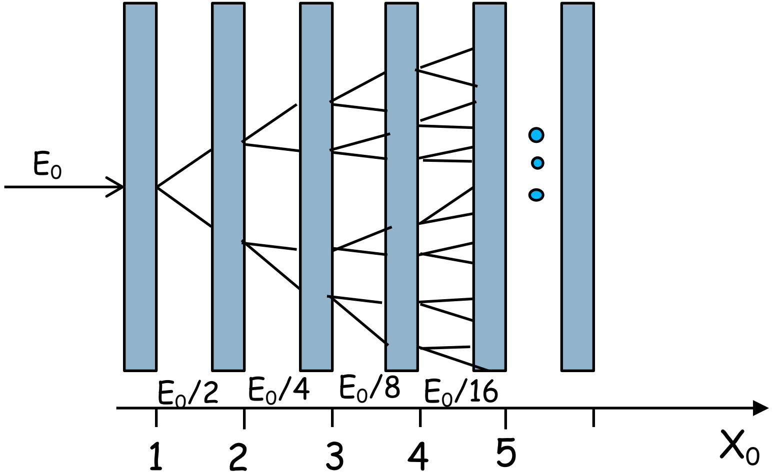
Lead absorbers in cloud chamber



- Number of particles in shower
- Location of shower maximum
- Transverse shower distribution
- Longitudinal shower distribution

Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle, i.e. calorimeters can be compact $L \sim \ln(E_0/E_c)$

Simple sketch of a shower development

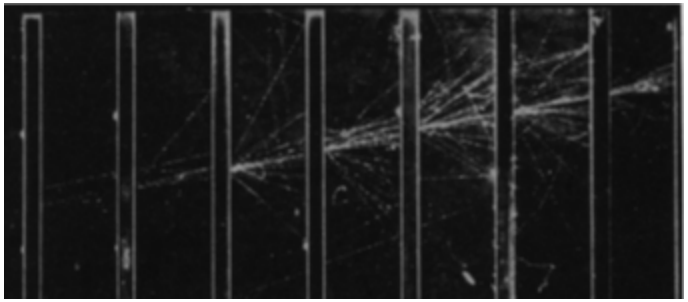


Calorimeter shower

Some examples:

E_c =10MeV
E_0= 1 GeV :
n_{max}= ln(100) =4.5 and N= $2^{n(max)}$=100
E_0=100 GeV :
n_{max} =ln(10000) =9.2 and N= $2^{n(max)}$=10000

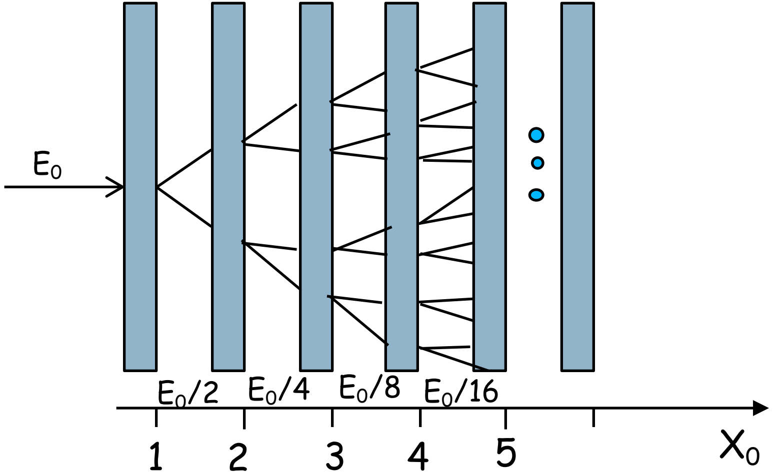
Lead absorbers in cloud chamber



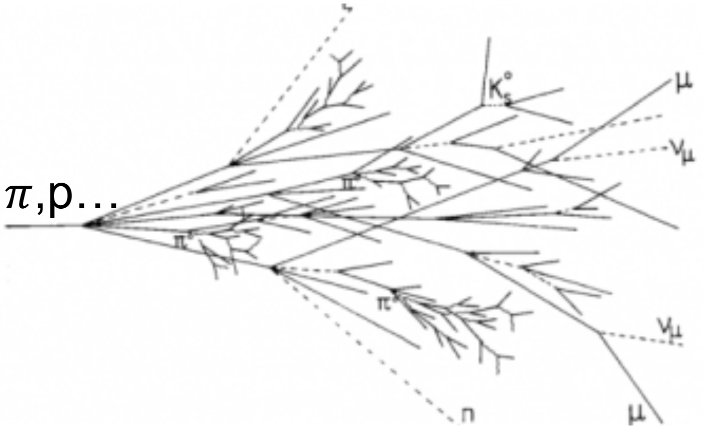
	LiAr	Fe	Pb	W	U
X_0 (cm)	14	1.76	0.56	0.35	0.32

For 100 GeV electron: 16 cm Fe or 5 cm Pb

Simple sketch of a shower development



Hadronic cascade (shower)

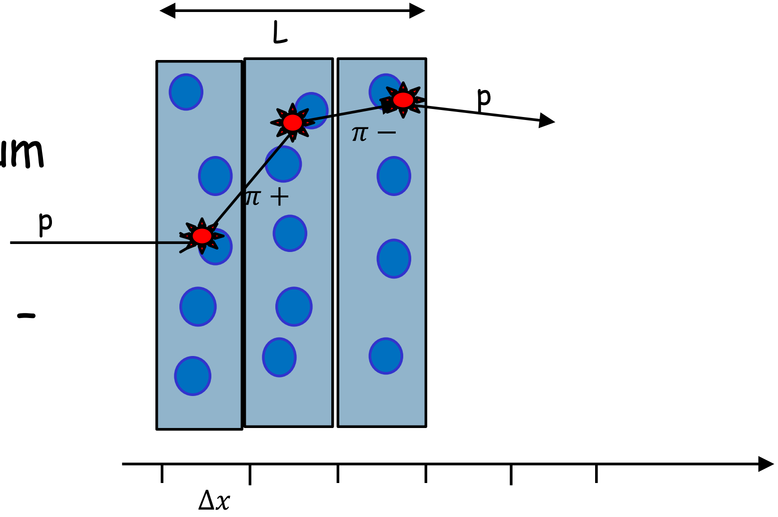


Similar to EM shower development, but more complex due to different processes involved:

- Includes Electromagnetic shower
- And Hadronic shower (the strong interaction with detector material):
  - Generation of pions, kaons, etc…
  - Breaking up nuclei
  - Creation of nun-detectable particles(neutrons, neutrinos, soft photons) => large uncetranties in Esum
  - Large fluctuations.

- Different scale: hadronic interaction length – determinates depth of the shower

Simple sketch of a hadronic interaction



The average distance between interactions

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

EM vs Hadronic cascade

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

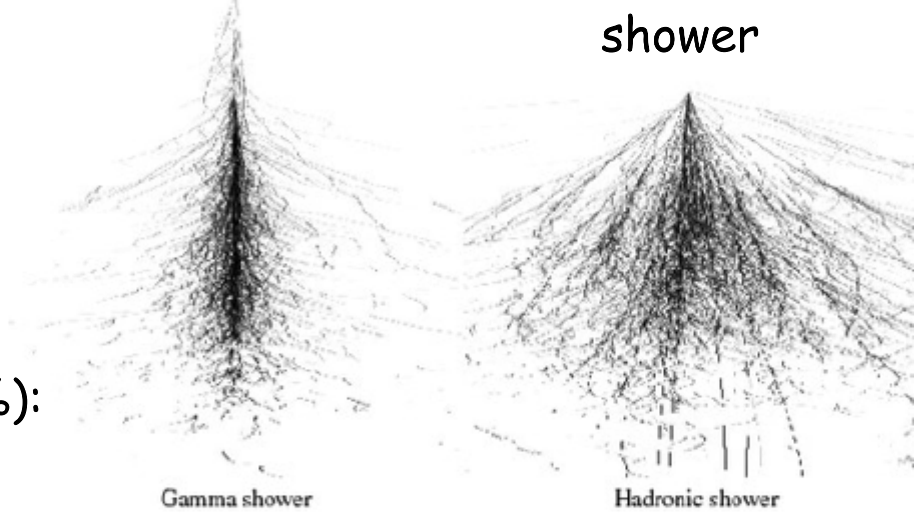
=> $\lambda_{int} \gg X_0$

- Number of particles ~ ln(E)

- Typical size for hadronic shower (95%):
  - ➢ Longitudinal: (6-9) λ_{int}
  - ➢ Transverse: $1 \cdot \lambda_{int}$

EM shower

Hadronic shower



	LiAr	Fe	Pb	W	U
X_0 (cm) radiation length	14	1.76	0.56	0.35	0.32
λ (cm) interaction length	86	16.8	17.6	9.95	11.03

Energy resolution

In ideal case: $E \sim N$, $\sigma(E) \sim \sqrt{N} \sim \sqrt{E}$

In real life:

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

a - **stochastic term:**

intrinsic statistical shower fluctuations, sampling fluctuations

b - **constant term:**

inhomogeneities, imperfections in construction (dimensional variations, etc.), non-linearity of readout electronics, energy lost in dead material, etc

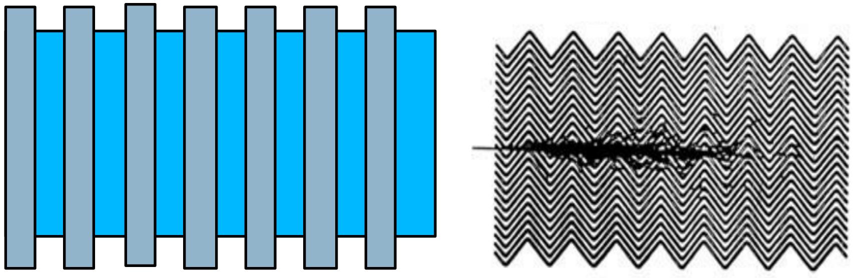
c- **noise term:**

readout electronic noise

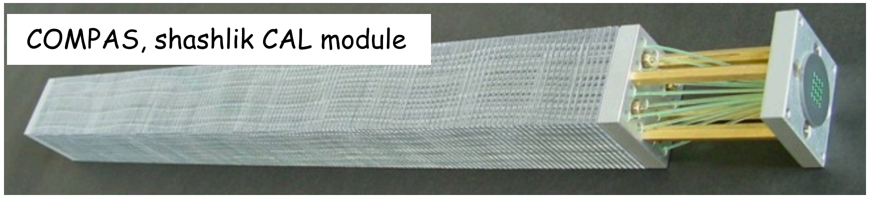
Types of calorimeter

- **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

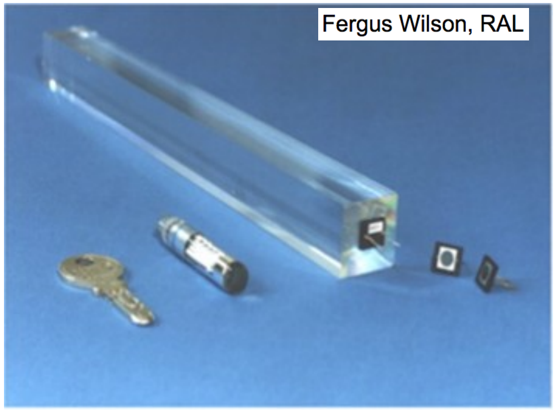


COMPAS, shashlik CAL module

- **Homogeneous calorimeter**

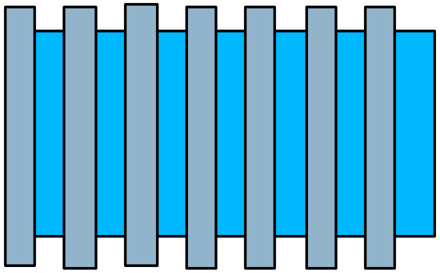
Monolithic material , serves as both absorber and detector material

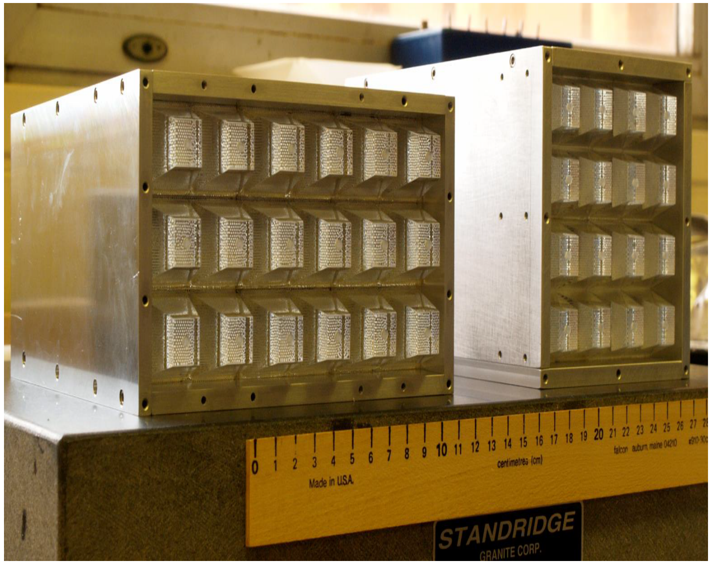
Liquid: Xe, Kr
Dense crystals: glass, crystals $PbWO_4$



Fergus Wilson, RAL

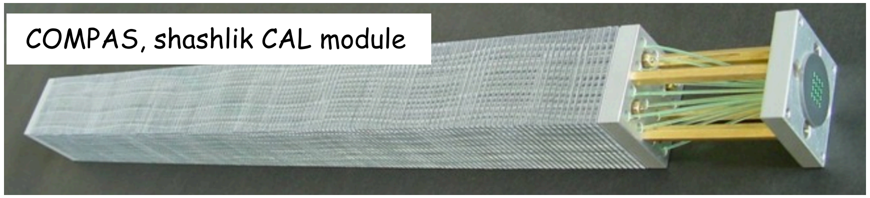
Sampling EM calorimeters





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

- Compact W-scifi calorimeter, developed at UCLA
- Sc. Fibers -SCSF78 Ø 0.47 mm, Spacing 1 mm center-to-center
- Resolution ~12%/√E
- On-going EIC R&D

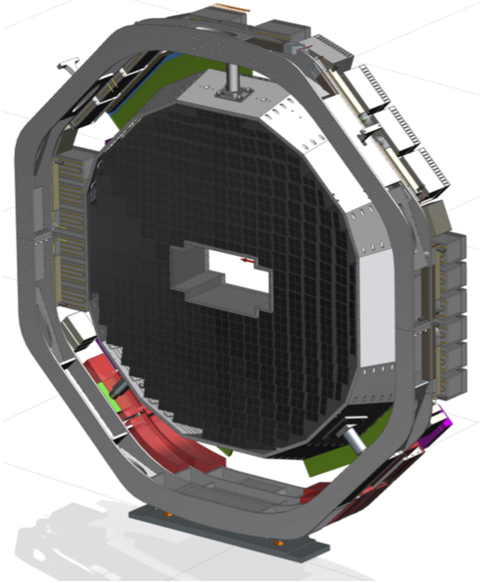


COMPAS, shashlik CAL module

$PbWO_4$ Crystal EM Calorimeter

Tungsten glass (CMS or PANDA)

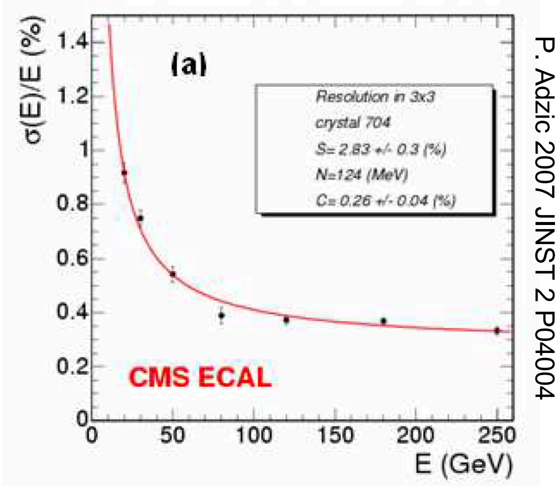
PANDA endcup



- Excellent energy resolution:
  $(1-3)\ \%/\sqrt{E(GeV)} + 1\%$
- Tower structure, fine transverse granularity
- Compactness, easy to assemble
- Time resolution: <2 ns
- Cluster threshold: 10 MeV

- Produced at two places (China, Russia)
- For CMS it took 10 years to grow all crystals !!!

CMS EMCAL



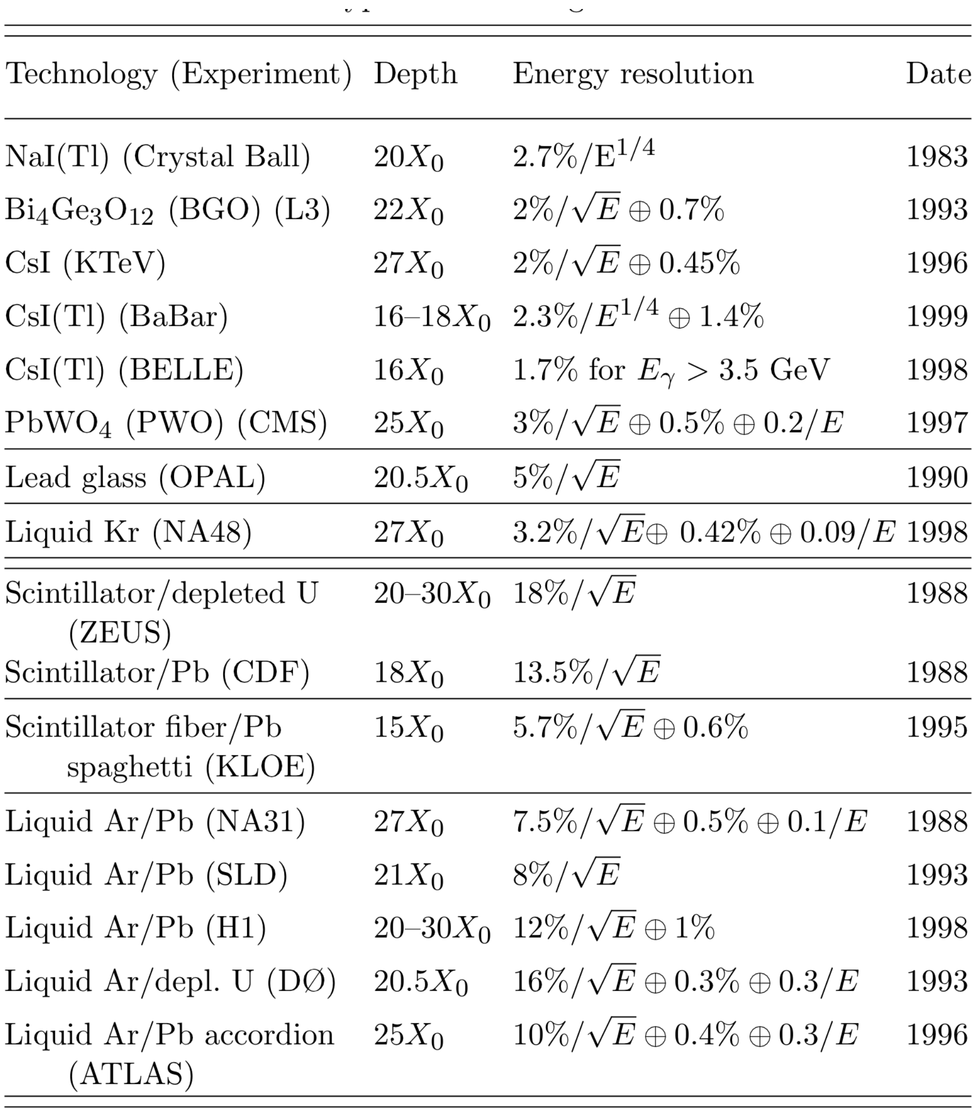
P. Adzic 2007 JINST 2 P04004

CMS EMCAL

CMS EMCAL facts:

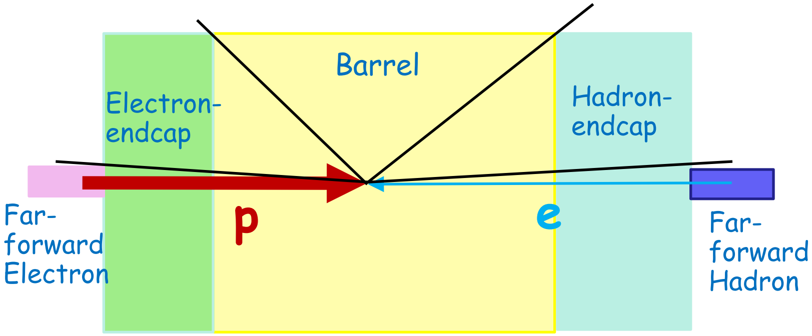
- crystals each weigh 1.5kg (but with a volume ~ small coffee cup)
- contains nearly 80,000 crystals (for each took two days to grow)

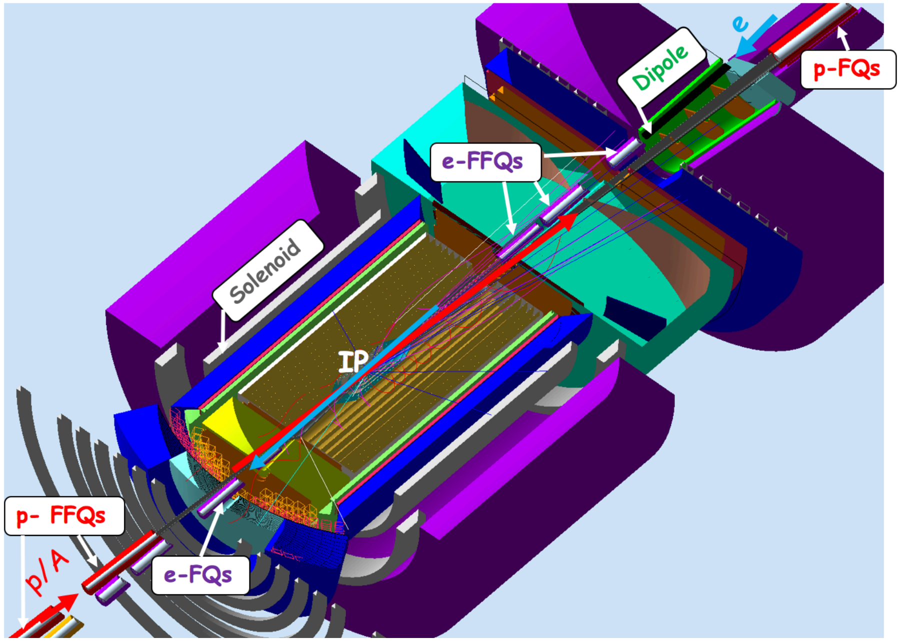
Other EM Calorimeter technology



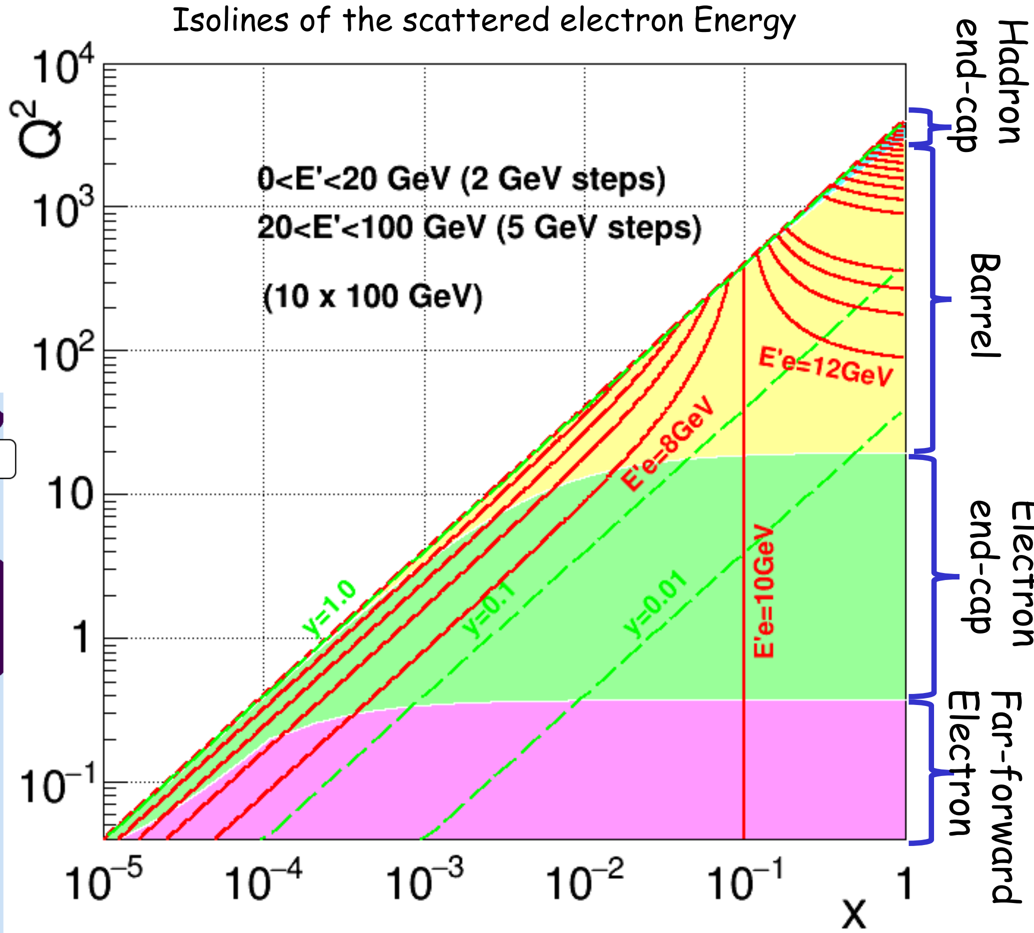
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (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 (D0)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

EMCAL at EIC requirements





Scattered electron


Isolines of the scattered electron Energy

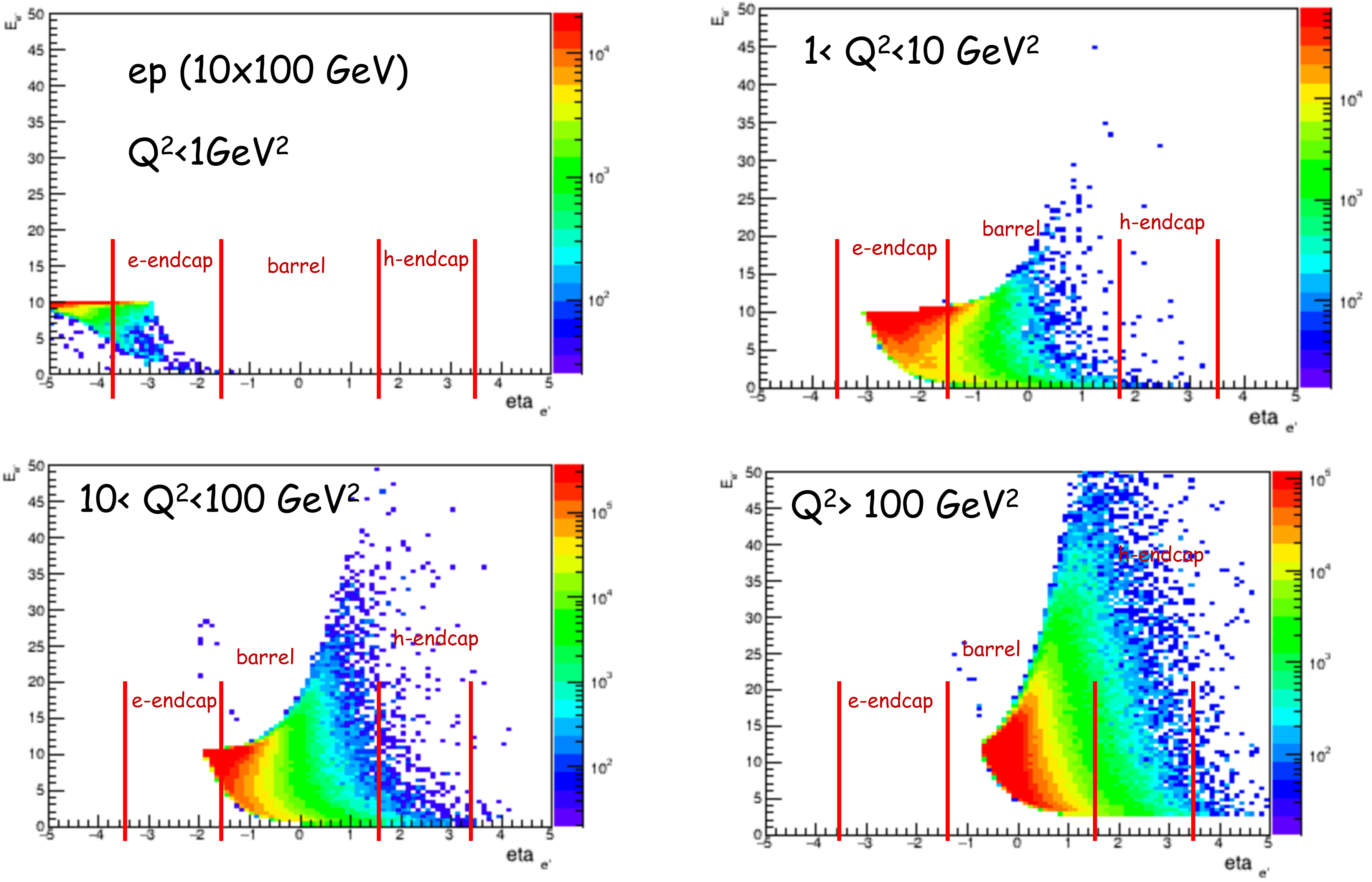
0<E'<20 GeV (2 GeV steps)

20<E'<100 GeV (5 GeV steps)

(10 x 100 GeV)

Scattered electron

Pythia6

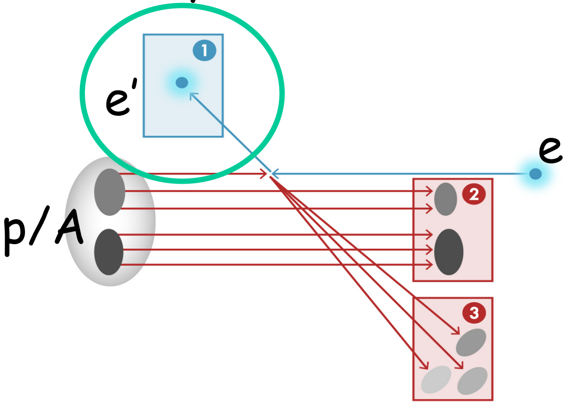


EMCAL requirements

Electrons:

-scattered electron

-secondary electrons (decay products (J/ψ))



Kinematic reconstruction

a) *Electron method* uses **information from scattered electron ONLY:**

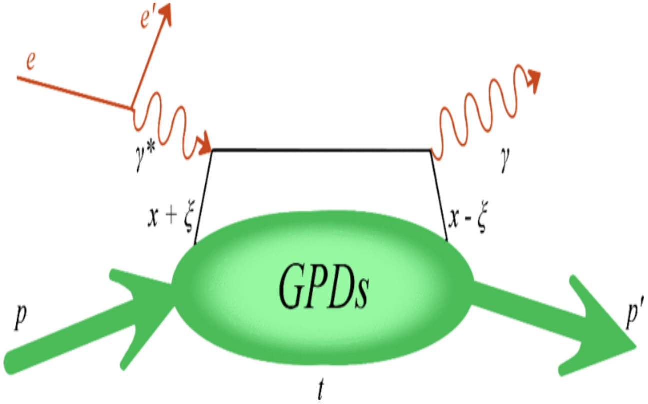
$$Q^2_{\mathrm{EM}} = 2E_eE_{e'}\left(1+\cos\theta_{e'}\right),$$

$$y_{\mathrm{EM}} = 1-\frac{E_{e'}}{2E_e}\left(1-\cos\theta_{e'}\right),$$

$$x = \frac{Q^2}{4E_eE_{\mathrm{ion}}}\,\frac{1}{y}$$

- Linear dependence on $E_{e'}$ of the Q^2

Gammas



- High granularity (azimuthal asymmetry)
- Background from π^0 -> $\gamma\gamma$ => high granularity

✓ 4π coverage for EM calorimeter for electrons and gammas

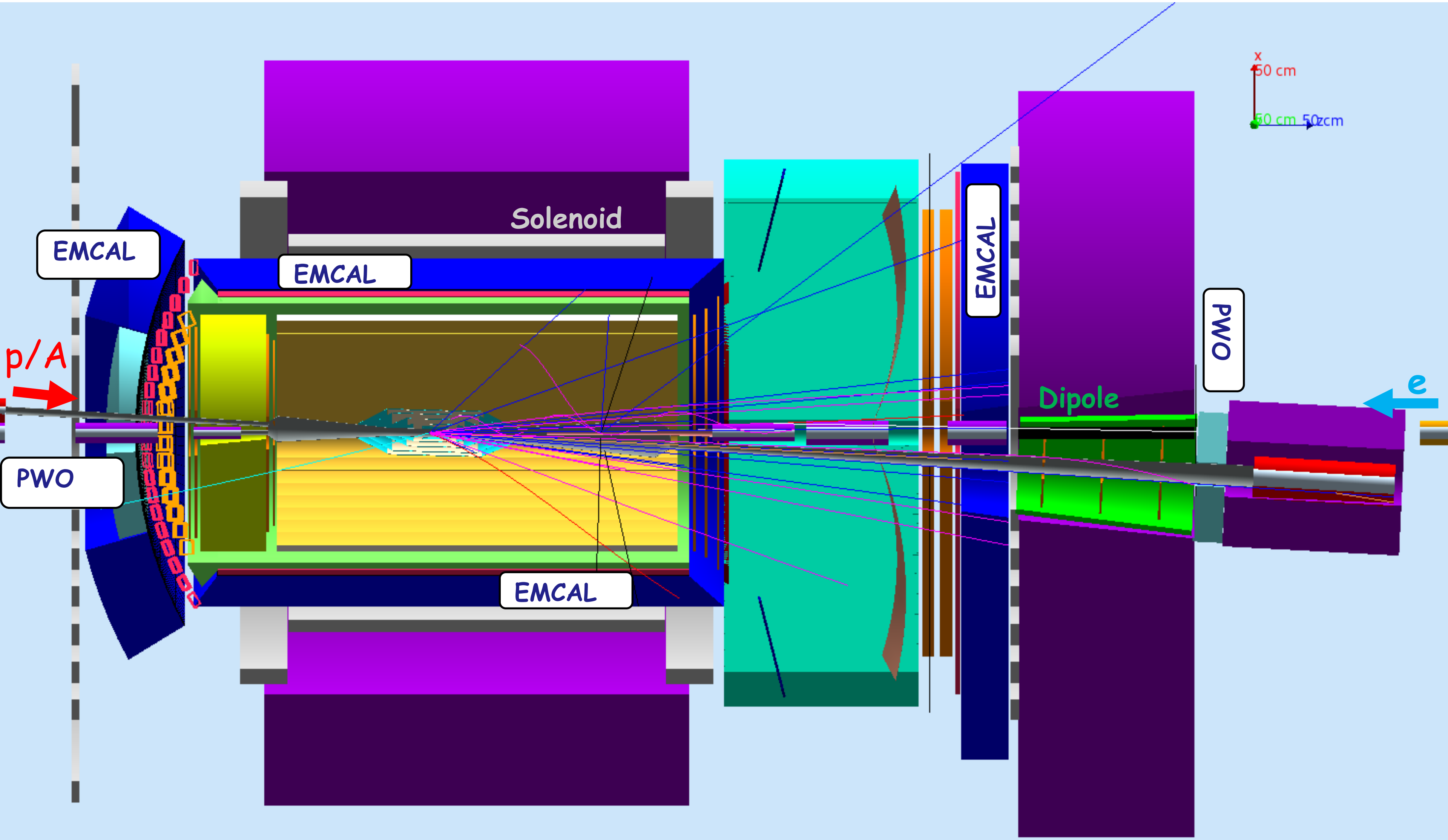
✓ High performance EM calorimeter is need in the electron endcap where scattered electron **has low energy**

✓ **High granularity** in the forward going direction

✓ very good **e-identification**

✓ Kinematic variables (x,Q^2) depend on $E_{e'}$

EMCAL at JLEIC



PWO

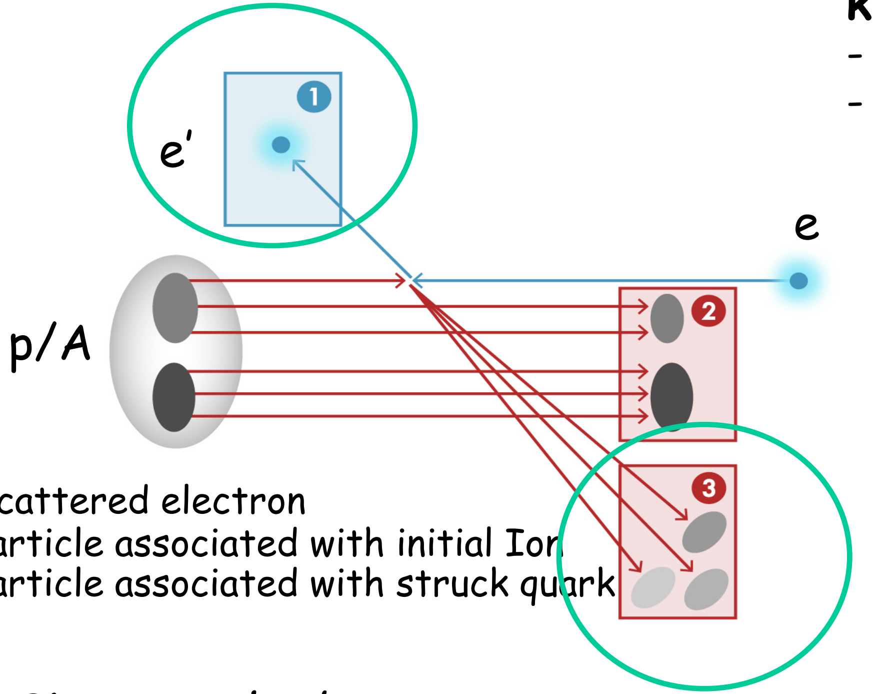
- PWO Close to the beam – more precise and more radiation hard calorimeter

Shashlyk

- Barrel and endcaps – less expensive

Is it enough to have only EM Calorimeter?

Hadronic final state



1. Scattered electron
2. Particle associated with initial Ion
3. Particle associated with struck quark

BUT… the Electron Method for kinematic reconstruction:

- Linear dependence on $E_{e'}$ of the Q^2
- This method could NOT be used for $y < 0.1$

All other methods require measurements of hadronic final states (particle associated with struck quark), here are just two examples

b) *Double angle method*

$$Q^2_{\mathrm{DA}} = \frac{4E_e^2 \sin\gamma_h\,(1+\cos\theta_{e'})}{\sin\gamma_h + \sin\theta_{e'} - \sin(\theta_{e'}+\gamma_h)},$$

$$y_{\mathrm{DA}} = \frac{\sin\theta_{e'}\,(1-\cos\gamma_h)}{\sin\gamma_h + \sin\theta_{e'} - \sin(\theta_{e'}+\gamma_h)},$$

Note: Does not require measurements of scattered electron energy, but require a good knowledge of hadronic final state :

$$\cos\gamma_h = \frac{P^2_{T,h} - \left(\sum_h (E_h - p_{z,h})\right)^2}{P^2_{T,h} + (\sum_h (E_h - p_{z,h}))^2}$$

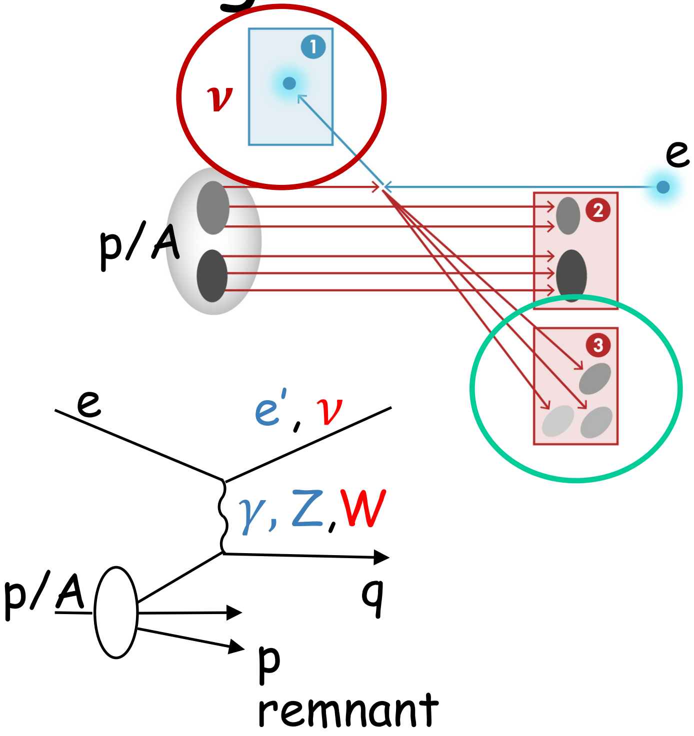
c) *Sigma method*

$$y_{e\Sigma} = \frac{\Sigma_h\,(E_h - p_{z,h})}{E - P_z},$$

$$Q^2_{e\Sigma} = \frac{(E_{e'}\sin\theta_{e'})^2}{1-y}.$$

Note: Does not depend on initial electron beam energy, less influenced by a initial state radiation

Charged current DIS



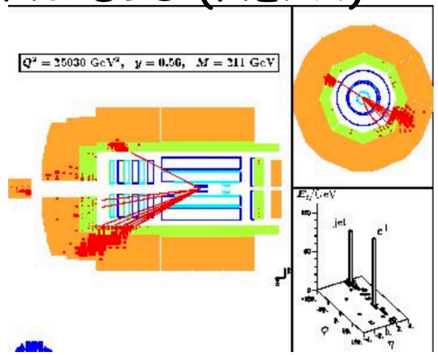
DIS kinematic could be reconstructed from hadronic final state only

d) Jacquet –Blondel method

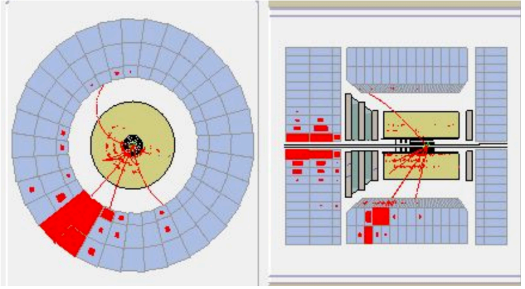
$$y_{\rm JB} = \frac{1}{2E_e} \sum_h \left(E_h - p_{z,h}\right),$$

$$Q^2_{\rm JB} = \frac{1}{1 - y_{\rm JB}} \left[\left(\sum_h p_{x,h} \right)^2 + \left(\sum_h p_{y,h} \right)^2 \right].$$

NC-DIS (HERA)

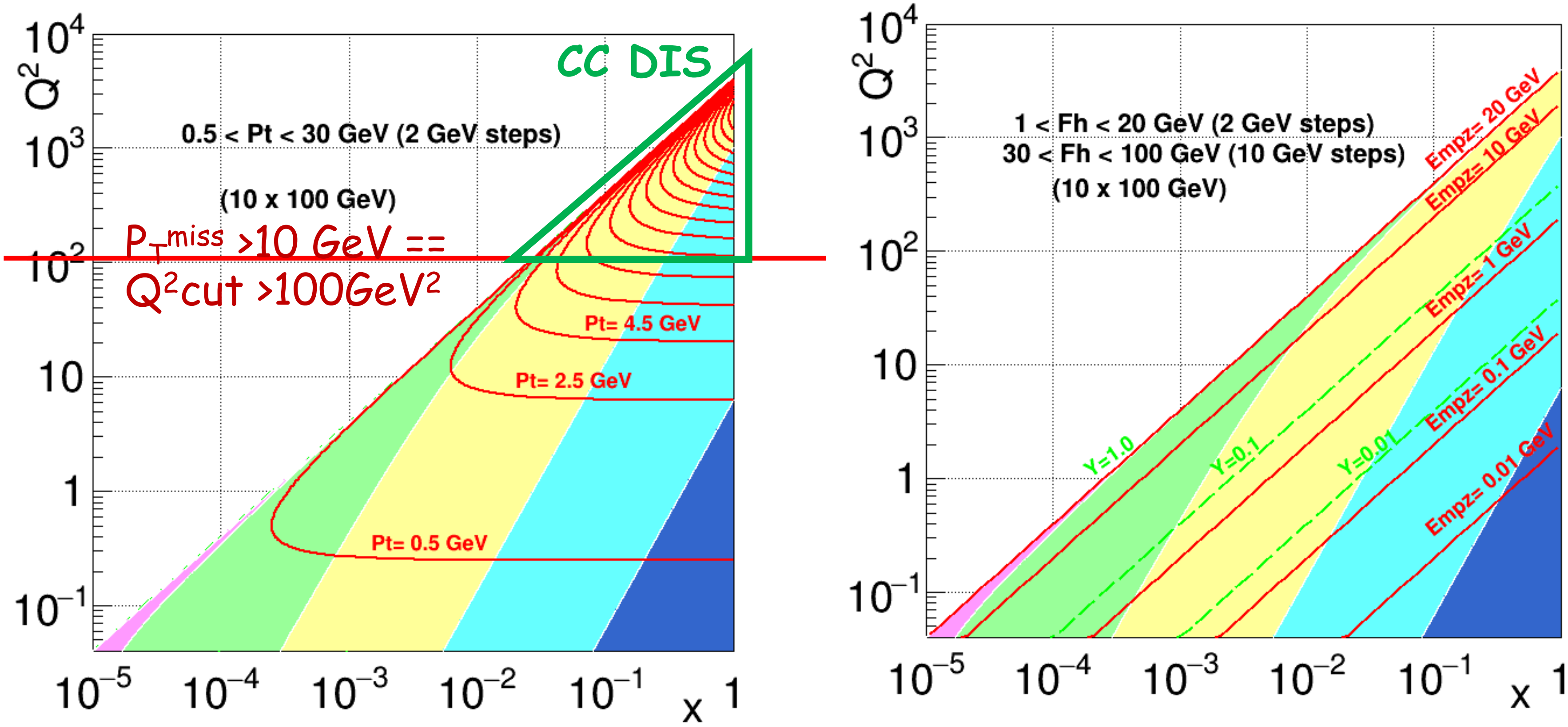


CC-DIS (HERA)



Note: poor resolution compare to other methods, but
this is the only method for Charged Current DIS events!!!

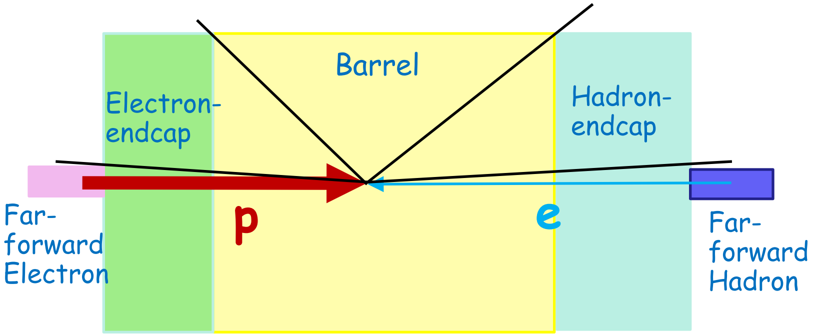
DIS kinematic: Charged Current



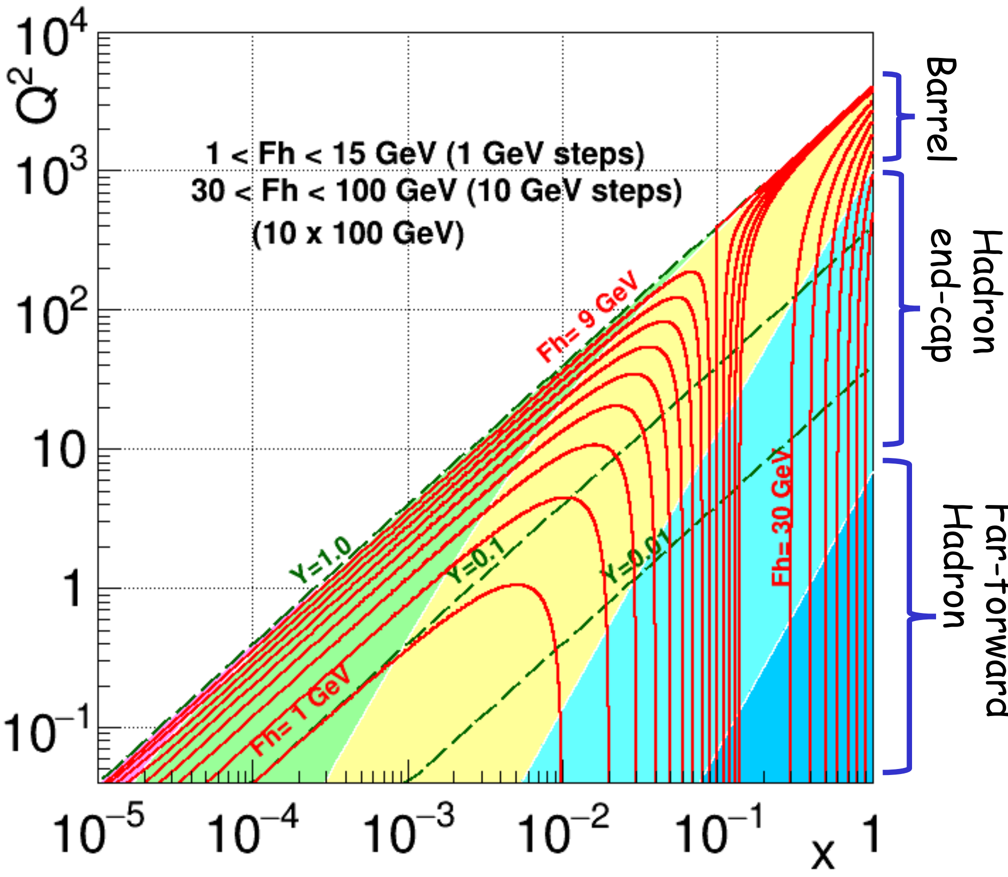
For CC-DIS -> only high P_T
P_T ^{miss} cut relates Q^2 cut
($E-p_z$)$_q$ relates to y

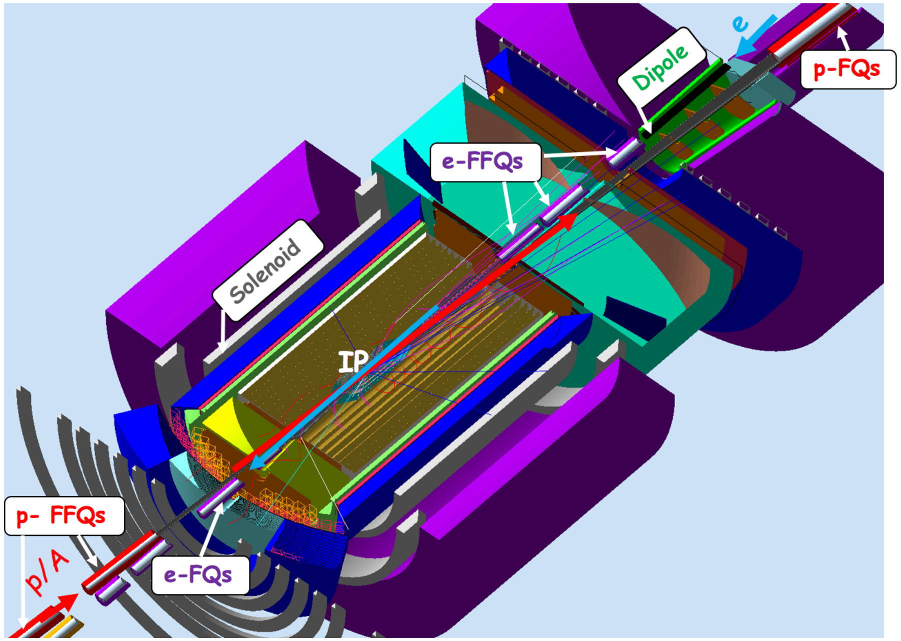
HCAL at EIC requirements

Struck quark



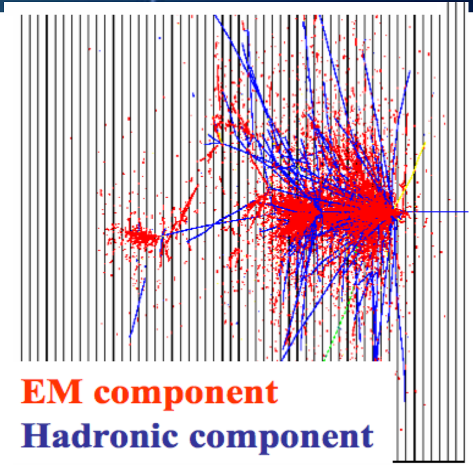
Isolines of thestruck quark





- need 4π coverage
- Electron endcap : mostly low energy <10GeV
- Hadron end-cap and Far-forward hadron : high energy > 50GeV

HCAL calorimeters



Hadronic calorimeters are usually sampling calorimeters

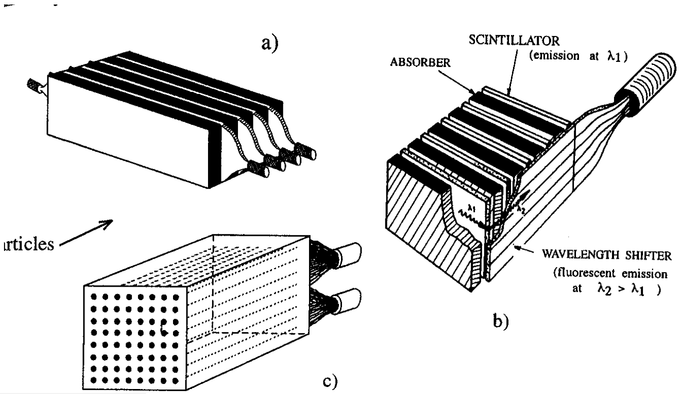
Has two components: Electromagnetic and Hadronic

The active medium made of similar material as in EMCAL:

→ Scintillator (light), gas (ionization chambers, wired chambers), silicon (solid state detectors), etc

The passive medium is made of materials with longer interaction length λ_I

→ Iron, uranium, etc

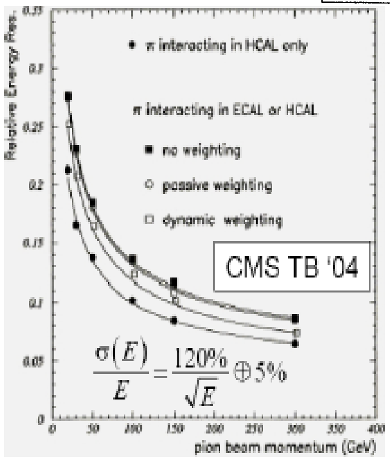


Resolution is worse than in EM calorimeters,usually in the range:

$$\frac{\sigma(E)}{E} \sim \frac{50\% - 100\%}{\sqrt{E}}$$

Uranium Calorimeter at ZEUS:

$\sigma_E/E \sim 35\%/\sqrt{E}$



16 scintillator 4 mm thick plates (active material)

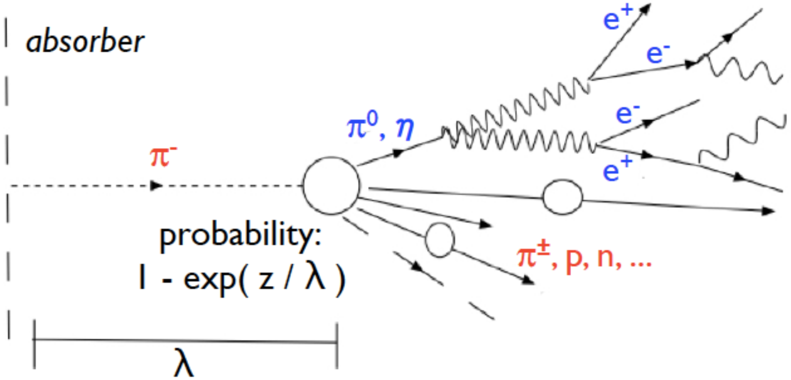
Interleaved with 50 mm thick plates of brass

EM fraction in hadronic shower

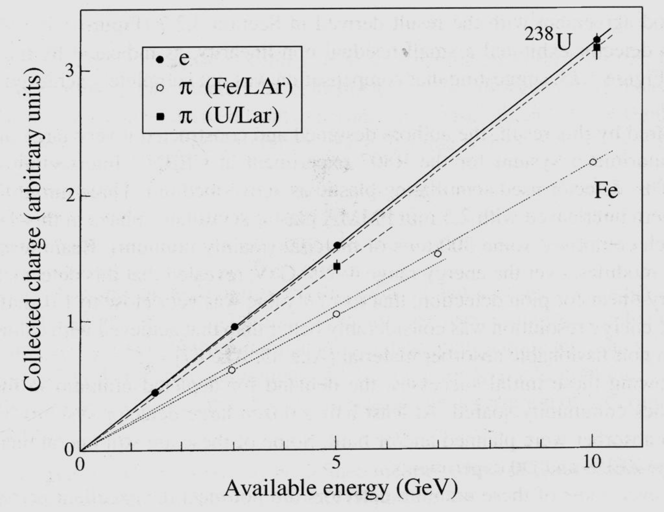
- $\pi 0, \eta$ production: all energy deposited via EM processes
- f_{EM} = fraction of hadron energy deposited via EM processes
  - Generally, f_{EM} increases with energy
- f_{had} = the strong interaction fraction
- Smaller calorimeter response to non-EM components of hadron showers than to EM components
- Need to compensate for the invisible energy (Lost nuclear binding energy, neutrino energy, Slow neutrons)
- e/h ≠1

$$\frac{e}{h} = \frac{1 - f_{em}(E)}{\pi/_{e}(E) - f_{em}(E)}$$

Compensation e/h = 1
Undercompensation e/h > 1
Overcompensation e/h < 1

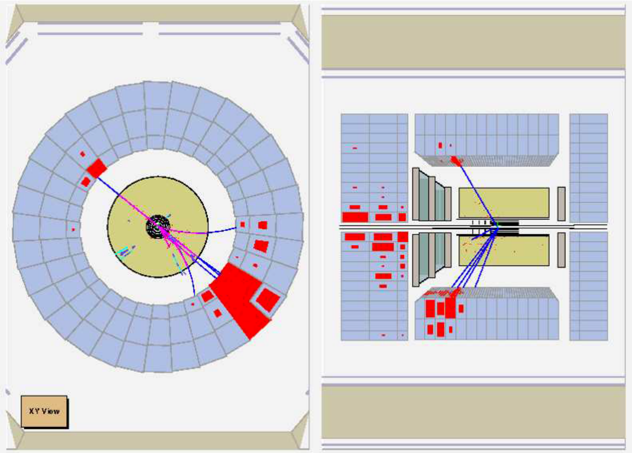


First uranium calorimeter by Fabjan and Willis: e/h ~ 1.1-1.2 hadro(nic shower increases due to more nuclear reactions)

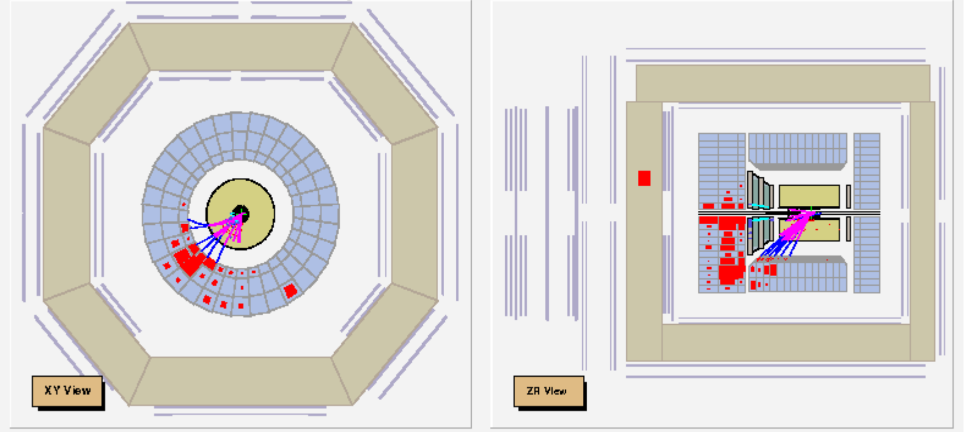


ZEUS calorimeter

Neutral current DIS



Charged current DIS



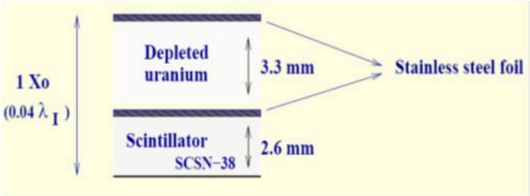
Sampling structure of the towers

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)

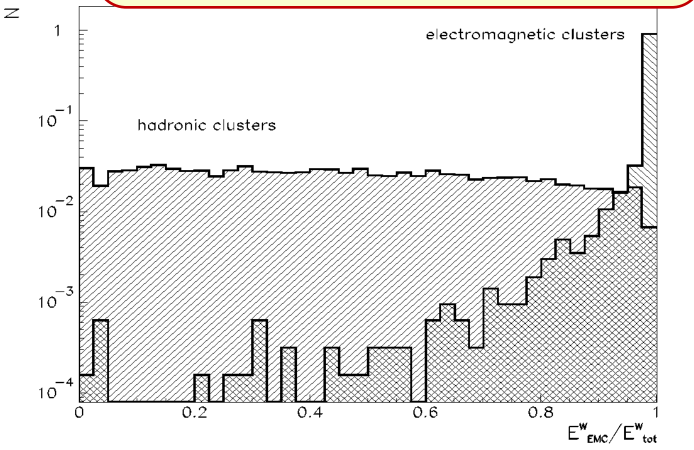
Longitudinal length of FCAL 6-7λ_{int} (Full containment of hadronic showers)

Neural network based electron identification

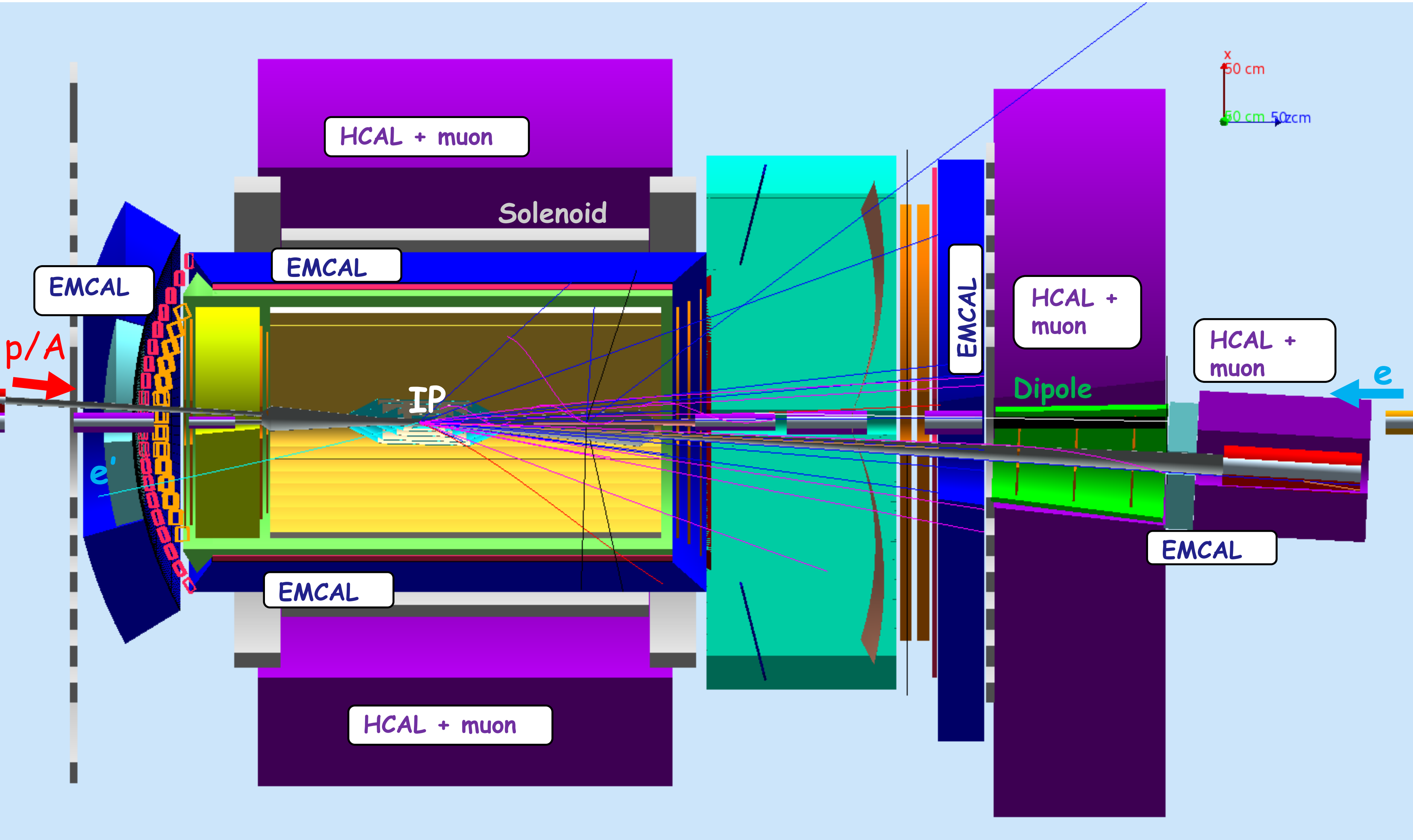


$$electrons: \frac{\sigma}{E} = \frac{18\%}{\sqrt{E}} \oplus 2\%$$

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



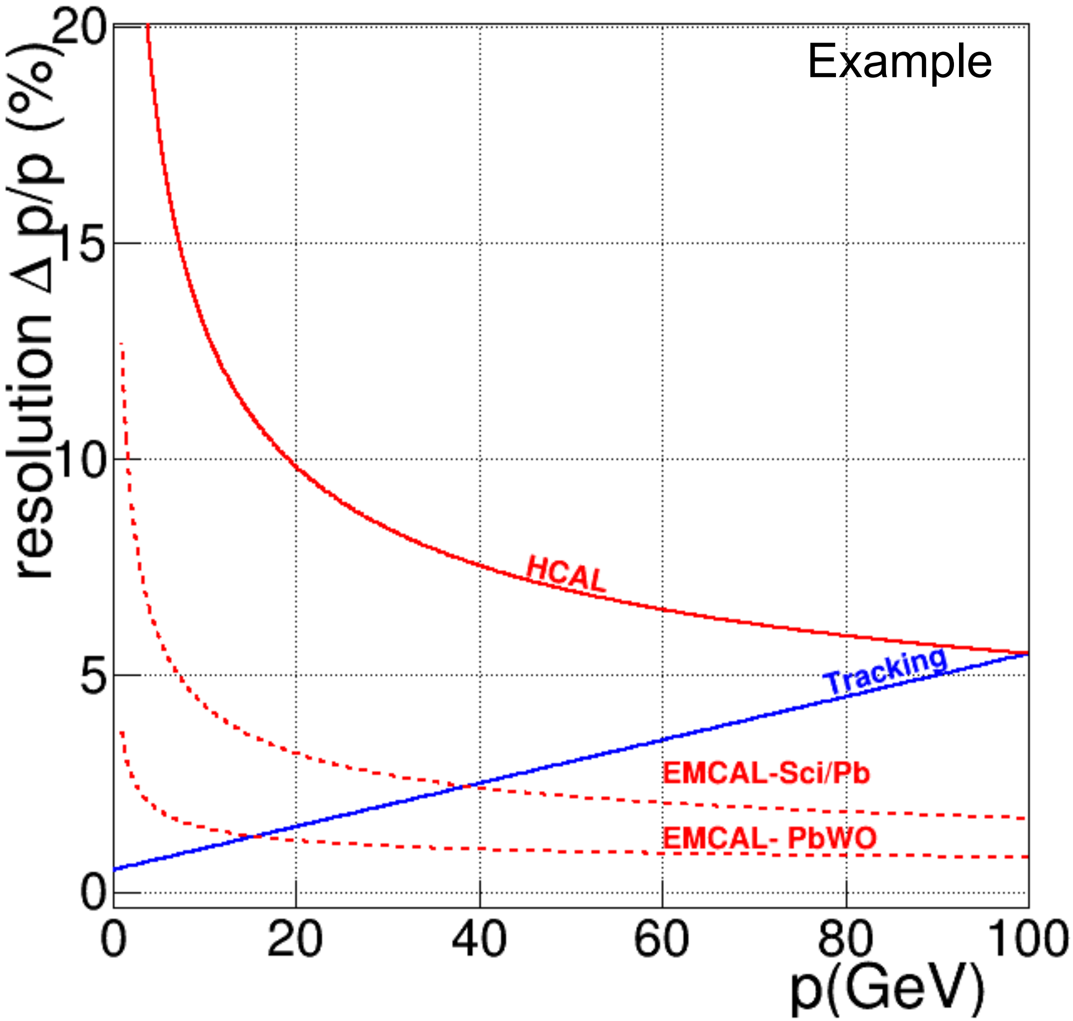
EIC Central detector overview



Modular design of the central detector

Yulia Furletova

Calorimeter vs tracking



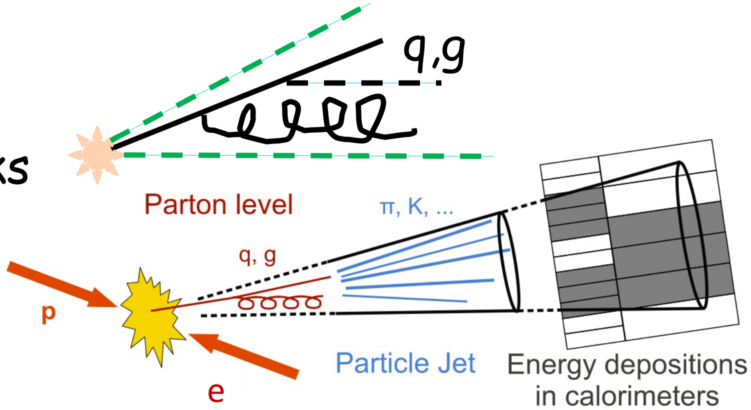
For charged particle one could choose the better method (E or p)

Jets

ask Google:

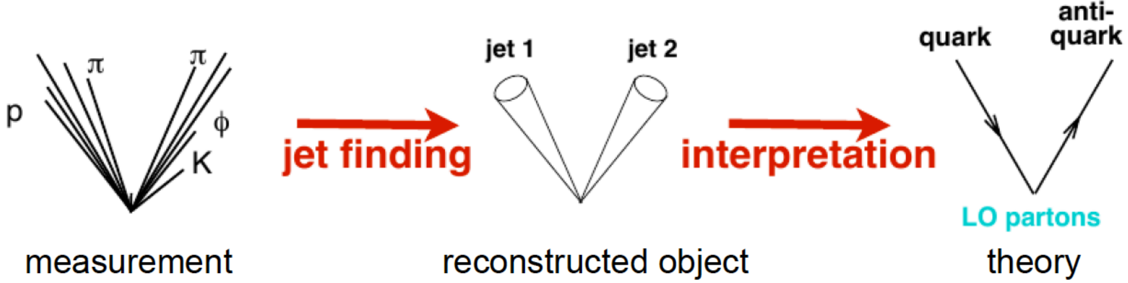
Jets for theorists: partons: gluons, quarks

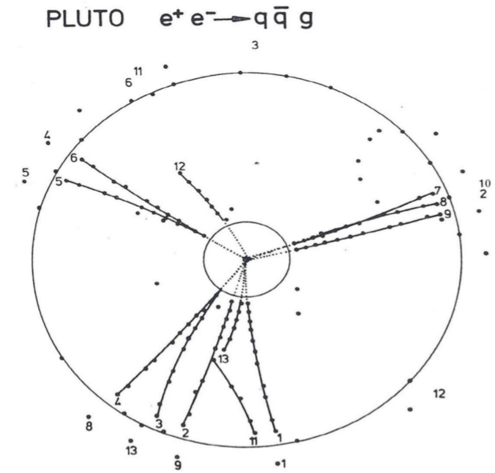
Jets for experimentalists:
number of collimated tracks which leaves energy in a calorimeter



K.Muller

Jet is a bunch of collimated particles (mostly hadrons), moving into direction of initial parton (quark, gluon)

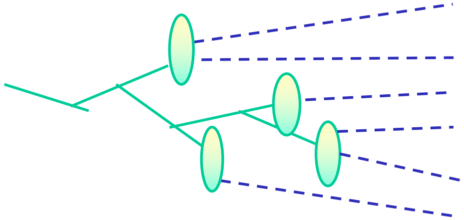




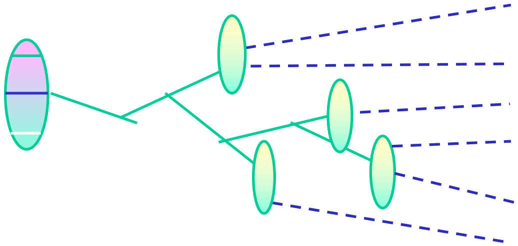
How well do we understand this transition?

Jets at EIC

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

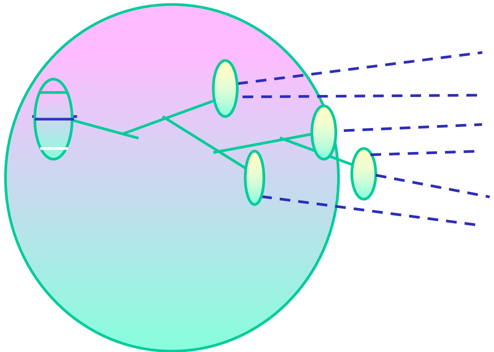


2) **Jets as a probe of partonic initial state**

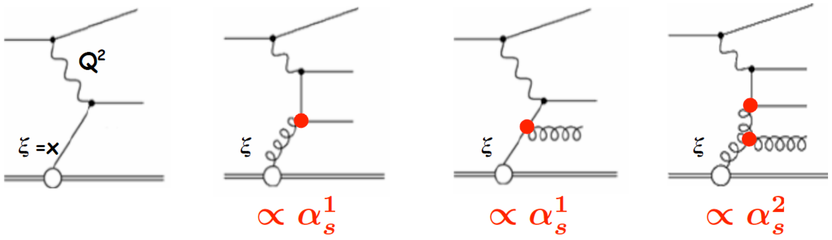


3) **Jets in medium (cold nuclear matter)**

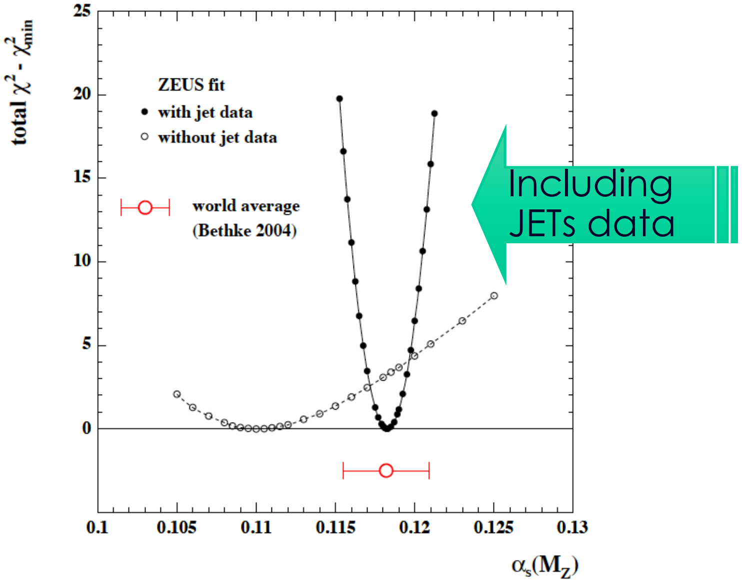
- ✓ energy loss, quenching
- ✓ broadening
- ✓ multiple-scattering.



Determination of α_s from the inclusive jet cross section in DIS

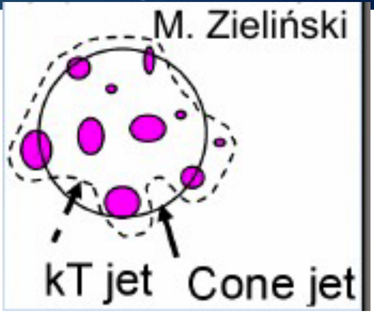


ZEUS/HERA



- High energy resolution calorimeter
- High granularity to study subjet structure

Jet Reconstruction



Jet is an object defined by an algorithm:

Two "categories" of jet algorithms:
1) Cone jets (Cone, SisCone, MidCone) traditionally for hadron colliders
-draw cone radius R around starting point (calorimeter towers with energy above threshold, "seeds").
-iterate position of cone until "stable" position is found

2) Clustering: sequential recombination (Jade, kT, anti-kT) traditionally e+e-,ep
- uses the knowledge that final state particles in a jet are largely collinear ie. have small transverse momentum between their constituent particles.
- algorithm begins to create a list of the momentum-space distance….

k_T algorithms (compared to cone algorithms) have the tendency to combine more energy into jets.

Jet is an object defined by an algorithm. If parameters are right it may approximate a parton. Physics results (particle discovery, masses, PDFs, coupling) should be independent of a choice of jet definition.

Particle flow calorimeters

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

Traditional calorimetric approach:
-Measure all components of jet energy in ECAL/HCAL
-70% of energy measured in HCAL with poor resolution : $\sigma_E/E \sim 60\%/\sqrt{E}$

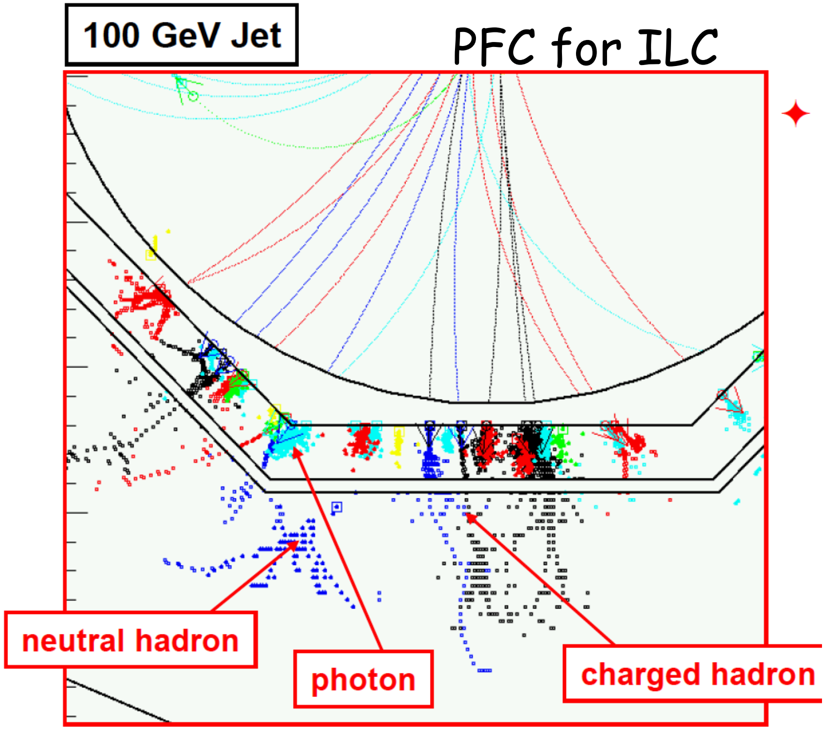
$\boxed{E_{JET}=EMCAL+HCAL}$

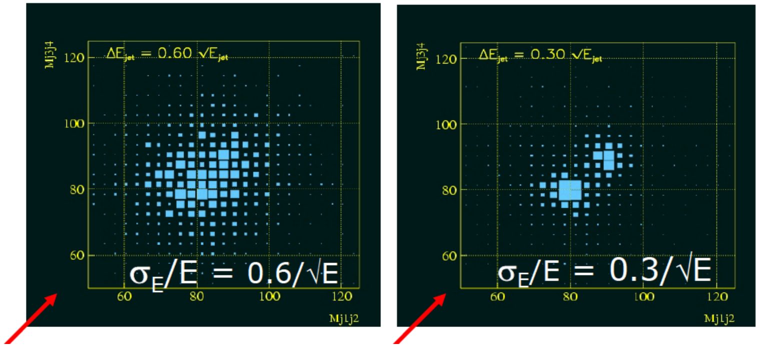
Particle Flow Calorimetry:
-charged particles measured in tracker (essentially perfectly)
-Photons in ECAL: : $\sigma_E/E \sim 2\text{-}10\%/\sqrt{E}$
-Neutral hadrons (ONLY) in HCAL =>
Only 10 % of jet energy from HCAL

$\boxed{E_{JET} = E_{track}+E_{\gamma}+E_n}$

much improved resolution!!!

PFC for ILC

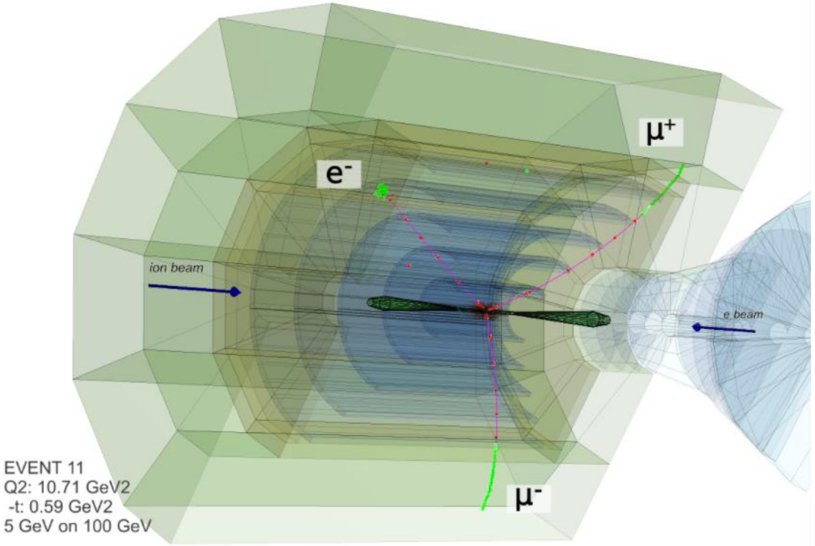


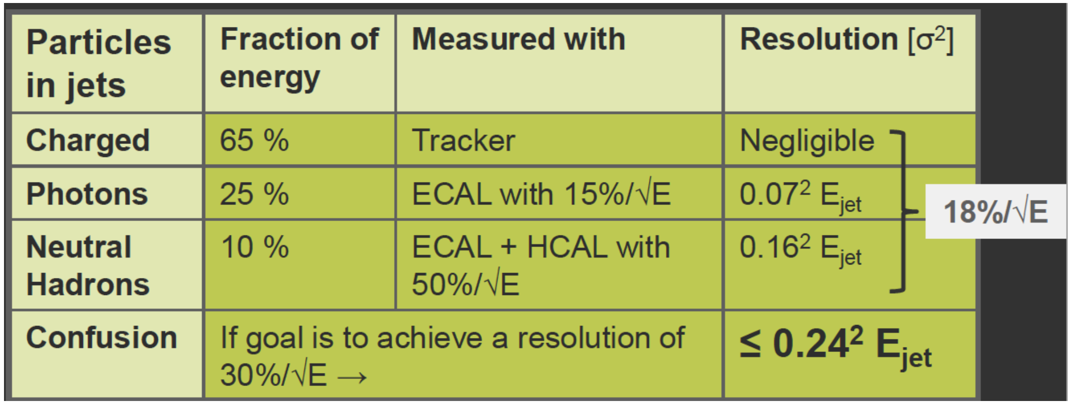


Mark Thomson

TOPSiDE (EIC detector concept)

Jose Repond





Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	0.07^2 E_{jet}
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	0.16^2 E_{jet}
Confusion	If goal is to achieve a resolution of 30%/√E →		≤ 0.24^2 E_{jet}

18%/√E

Factor of 2 better then previously achieved

- All silicon tracking
- Imaging calorimetry
- Ultra-fast silicon

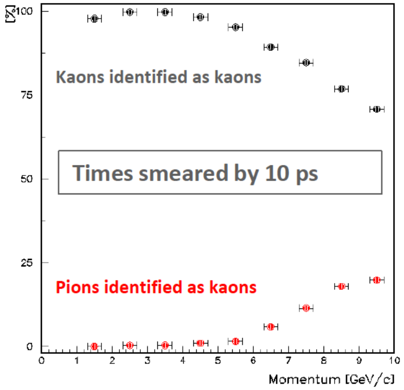
Of the order of 55 –80 M readout channels for EMCAL and HCAL:

Silicon pixels with an area of 0.25 cm^2
Total area about 1,400 m^2

Needed for 5D Concept (Measure E, x, y, z, t)

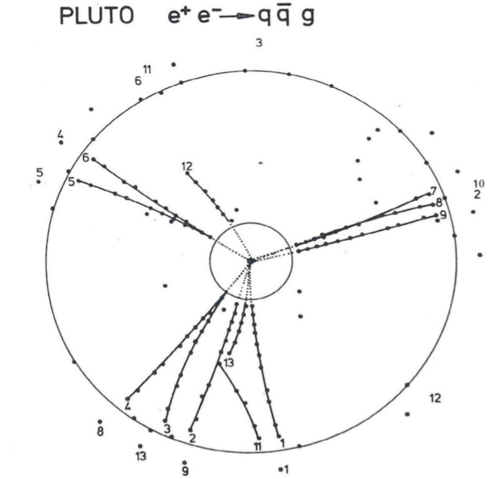
Implement in calorimeter and tracker for Particle ID (π-K -p separation)
Resolution of 10 ps→ separation up to ~ 7 GeV/c

Current status:
Best timing resolution about 27 ps

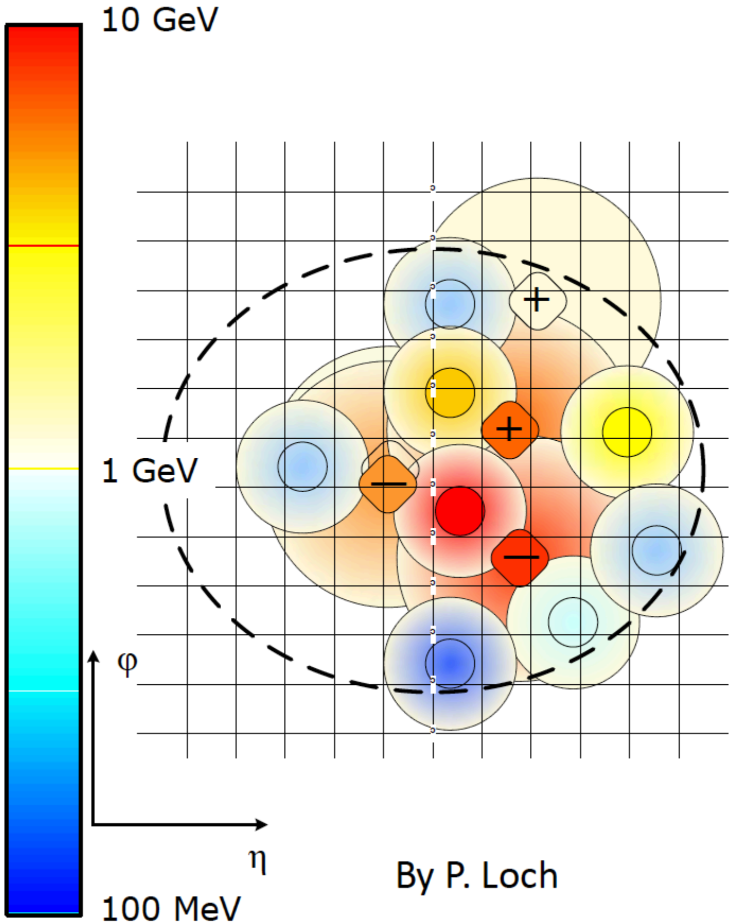


Reconstruction

Jet identification (q vs g vs heavy-q)



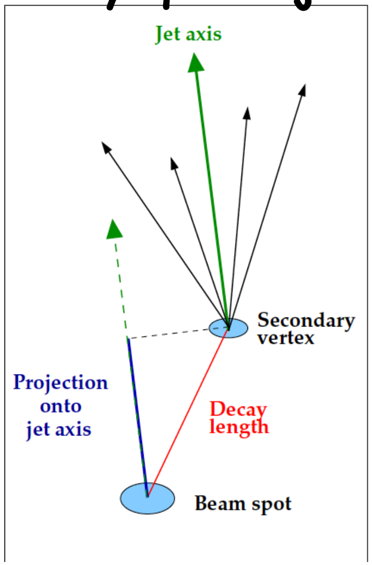
Sub-jets structure



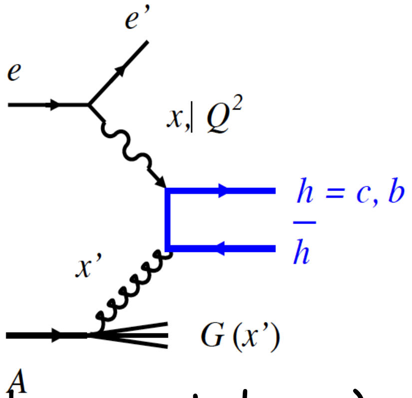
By P. Loch

Tau-Jets

Heavy quark jets



Heavy quark jets

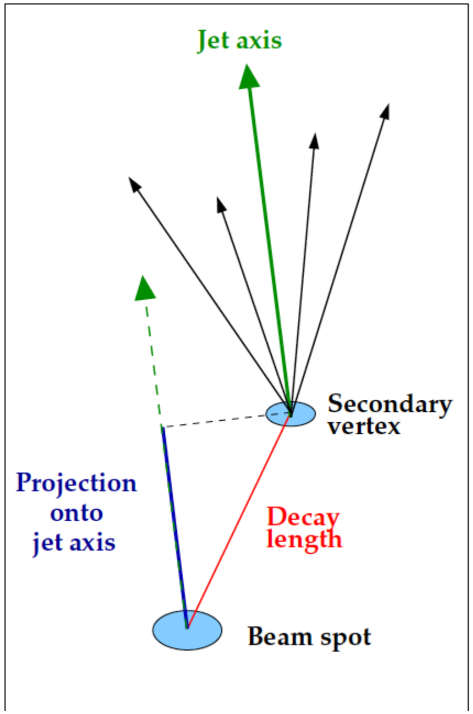


Jets initiated by a heavy quark!

Lifetime methods:

Exploit displaced vertices and/or tracks, both b-hadron or c-hadron decays (or subsequent decay)

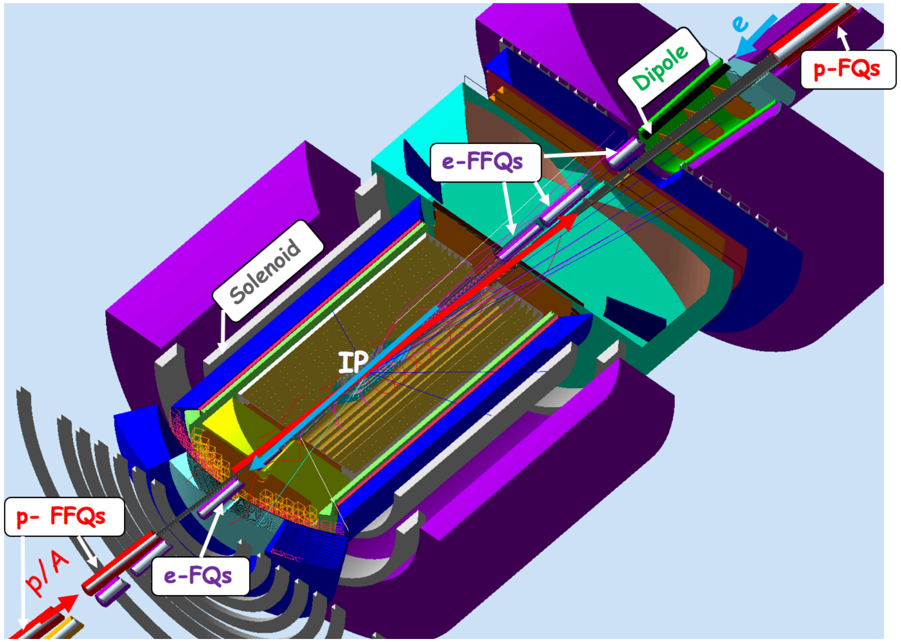
lepton tagging: μ or e inside the jet !



- Reconstruct jet
- Reconstruct vtx
- Decay length projection on jet axis
- (-) if in wrong semisphere
- Decay length significance S=d/δd
- M_{vxt} (assuming all tracks are charged pions)
- Subtract LF from wrong sign
- S in Mvtx bin

Calorimeter for EIC

Hermiticity;
- Very good energy resolution;
- Good position resolution;
- Fast response to avoid pile-up;
- Good timing resolution;
- Wide dynamical range;
- Good calibration precision;
- Uniform response;
- Good electron hadron separation;

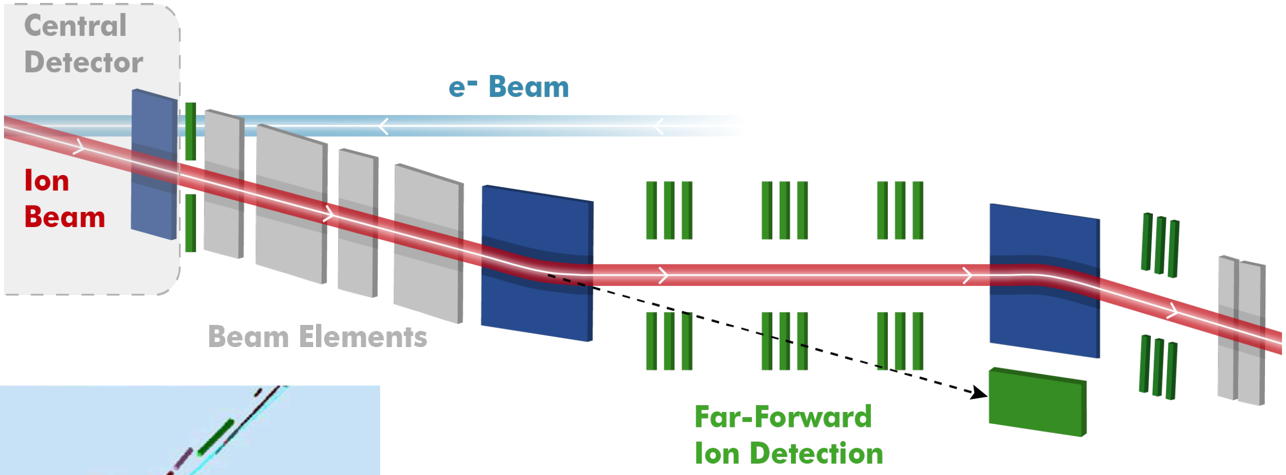


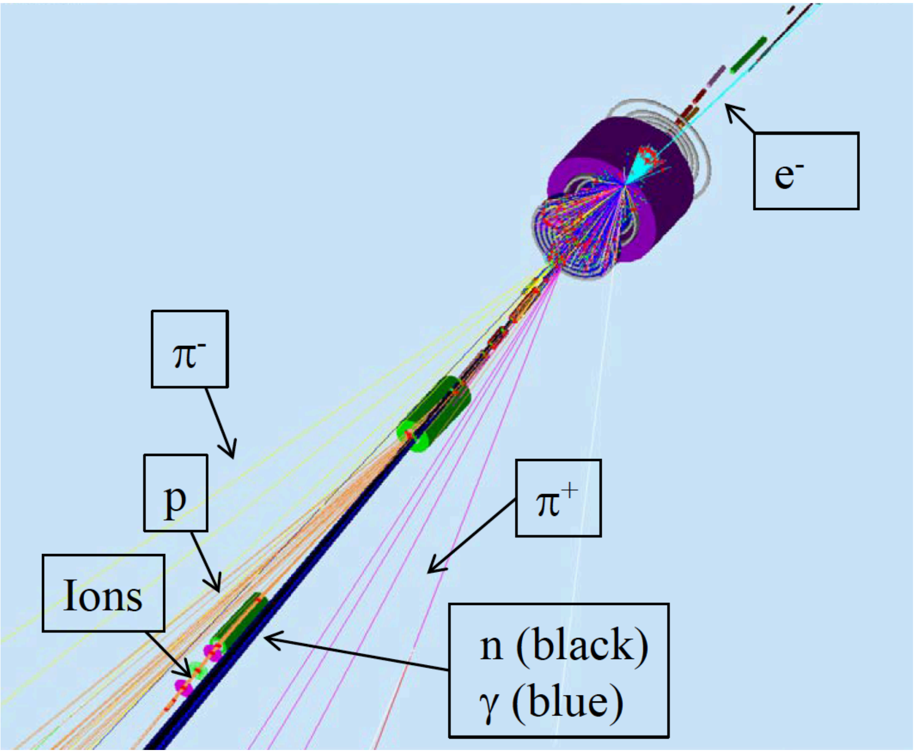
Particle's impact position is often estimated by using shower's center of gravity:

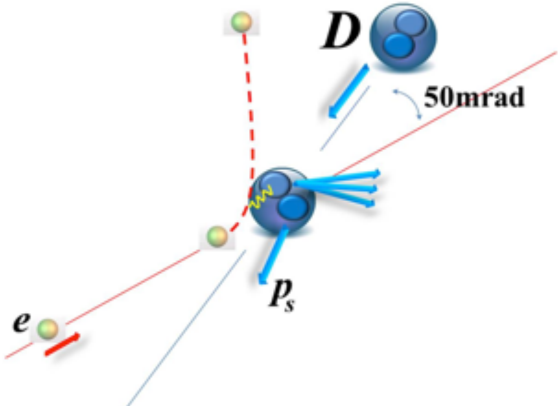
$$x = \frac{\sum_i x_i w(E_i)}{\sum_i w(E_i)}$$

Yulia Furletova

Far- forward detection







Zero-degree calorimeter:
Neutron tagging

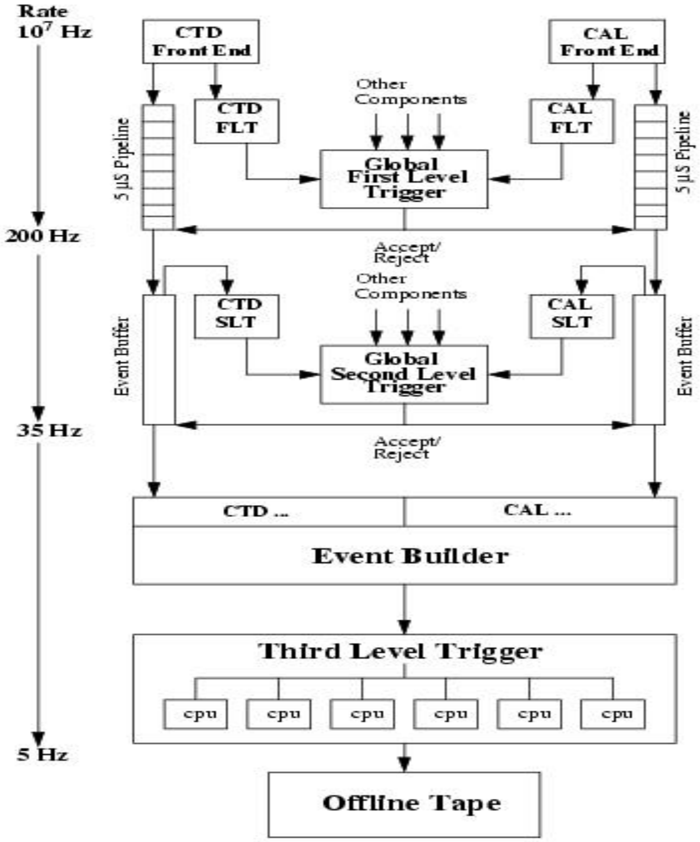
Trigger

ZEUS:

Sources of background

1. Beam related
    - synchrotron radiation
    - proton-beam background (vacuum)
    - Muons and neutrons
2. Physics related:
    - Low-Q^2 photoproduction

	Bunch crossing rate	**Physics rate**	**Total rate background**
ZEUS	10.4 MHz (96ns)	1-10 kHz	100 kHz
EIC	476 MHz (2ns)		?



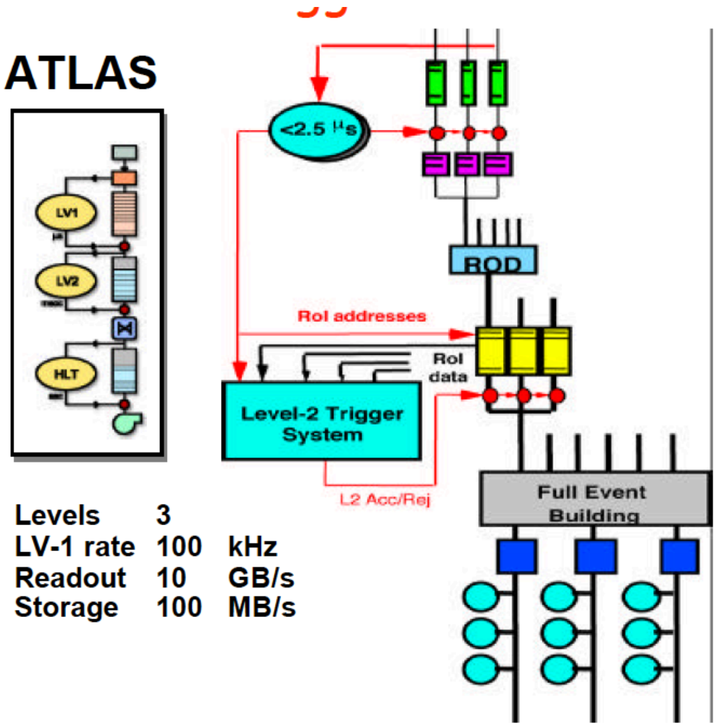
Storage speed limitation
Large improvements in FPGA size, speed and link bandwidth

A fast Calorimeter response is required for a trigger decision.

Trigger

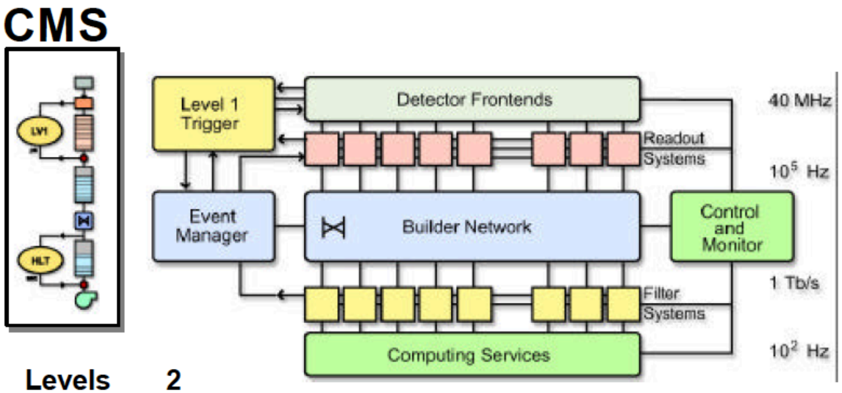
ZEUS:

ATLAS



Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

CMS



Levels	2	
LV-1 rate	100	kHz
Readout	100	GB/s
Storage	100	MB/s

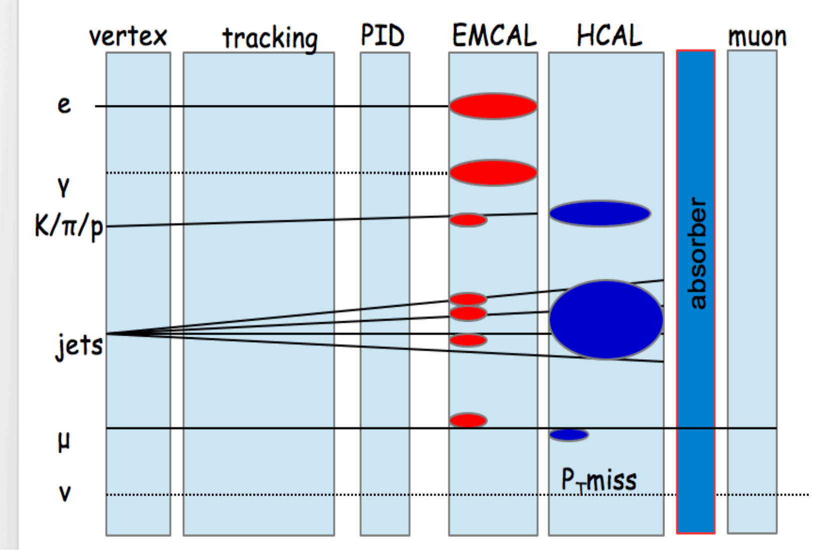
P.J. Wilson

Storage speed limitation is an issue for all particle physics experiments
Large improvements in FPGA size, speed
and link bandwidth

10GB/s -> reduced to -> 100 MB/s

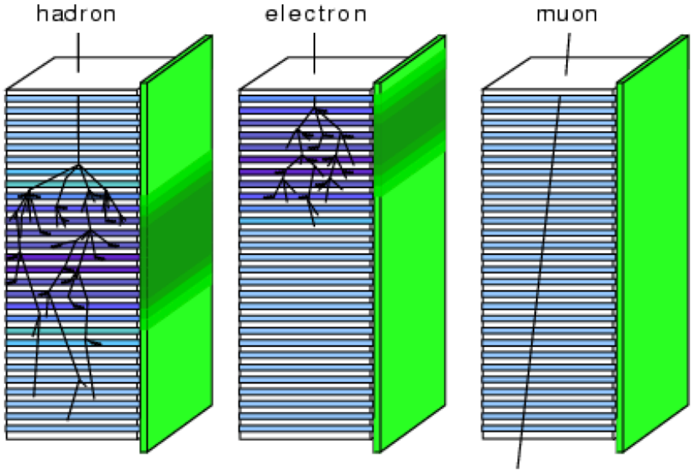
Calorimeter for particle identification

Electrons: track pointing to cluster in EMCAL
Gammas: no track but cluster in EMCAL
Neutral hadrons: no tracks, energy in HCAL
Neutrino: missing energy (E_T, p_T)
Muon: track, minimum energy in CAL
Charged hadrons: track+ energy in HCAL
(ratio EMCAL/HCAL)



Problems (misidentification):

e/hadron separation:
hadrons could develop shower in EMCAL
$\pi^0 \rightarrow \gamma\gamma$: cluster in EMCAL
Not possible to separate charged hadrons (π,K,p)



Erik Maddox

Muon chambers

Muon identification:
-Identification
-Energy/momentum measurements

For high energy (above a few GeV), muons identification is based on **low rate of interaction** of muons with matter…

If charged particle penetrates large amount of absorbers with minor energy losses and small angular displacement -- such particle is considered a muon

Muonlifetime is 2.2 msec (1GeV -> 7 km)

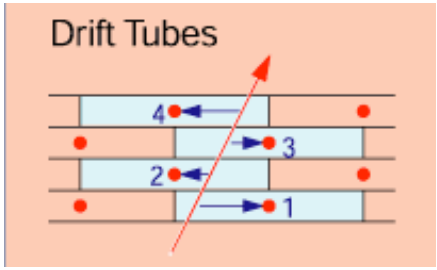
Hadrons create shower in absorber. If the absorber is too thin the shower can leak through, and such charged particle are detector after the absorber.

CMS- muon chambers

Eva Halkiadakis

Muon chambers are the outermost layer, but measurements are made combined with inner tracker.

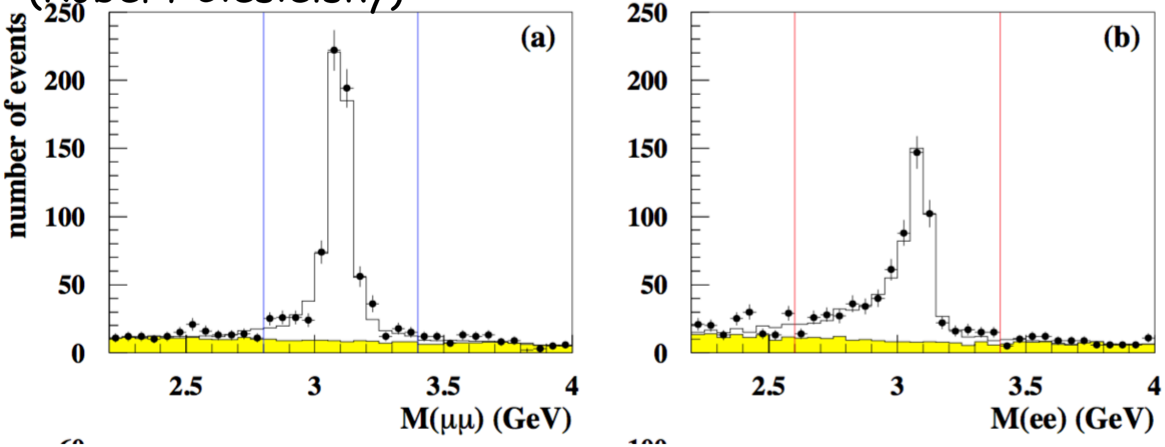
Larger volume (Drift Tubes)



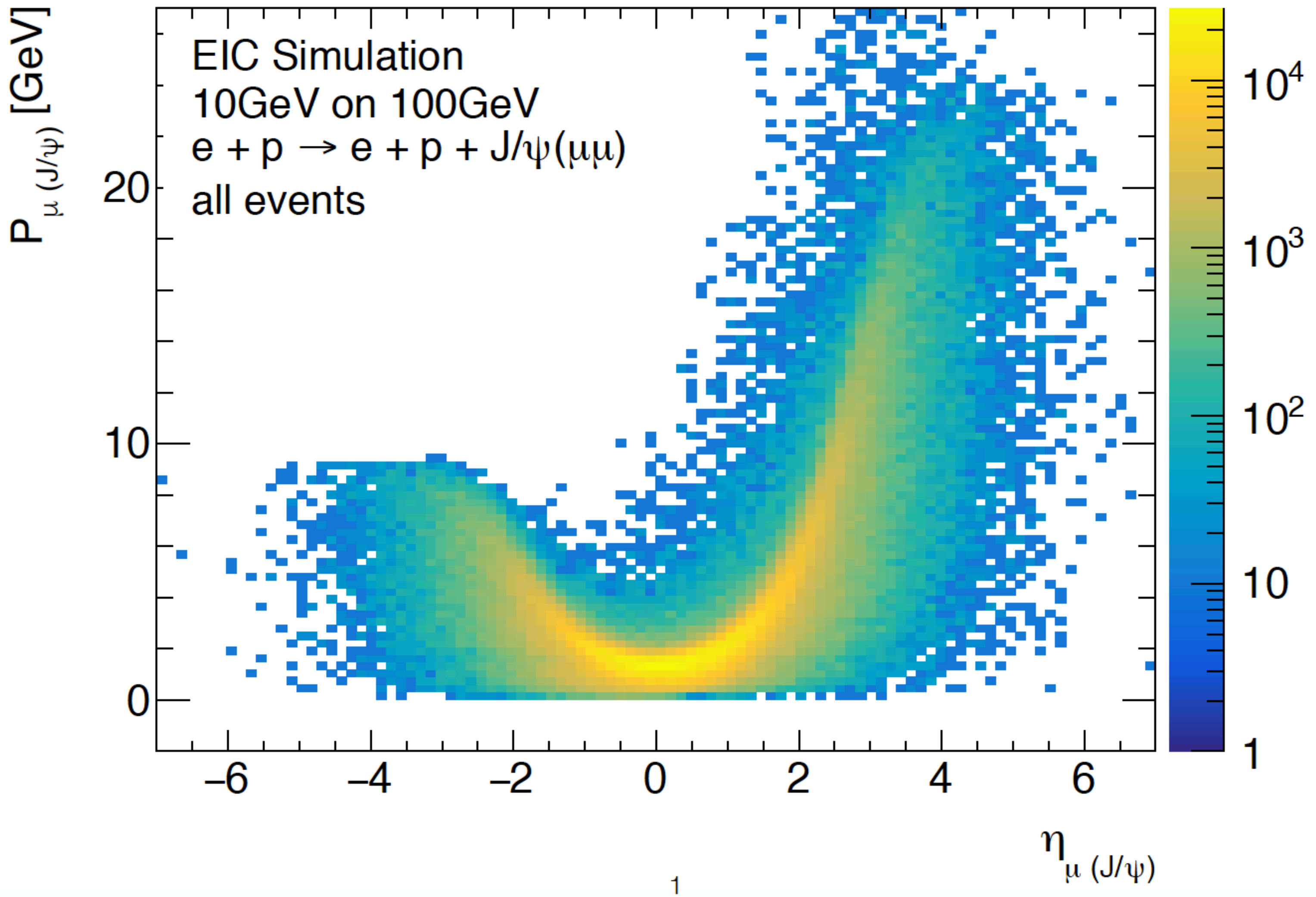
Muon identification

ZEUS/HERA data,
exclusive J/ψ
(Robert Ciesielsky)

Br (J/ψ->μ+μ-) ~6%

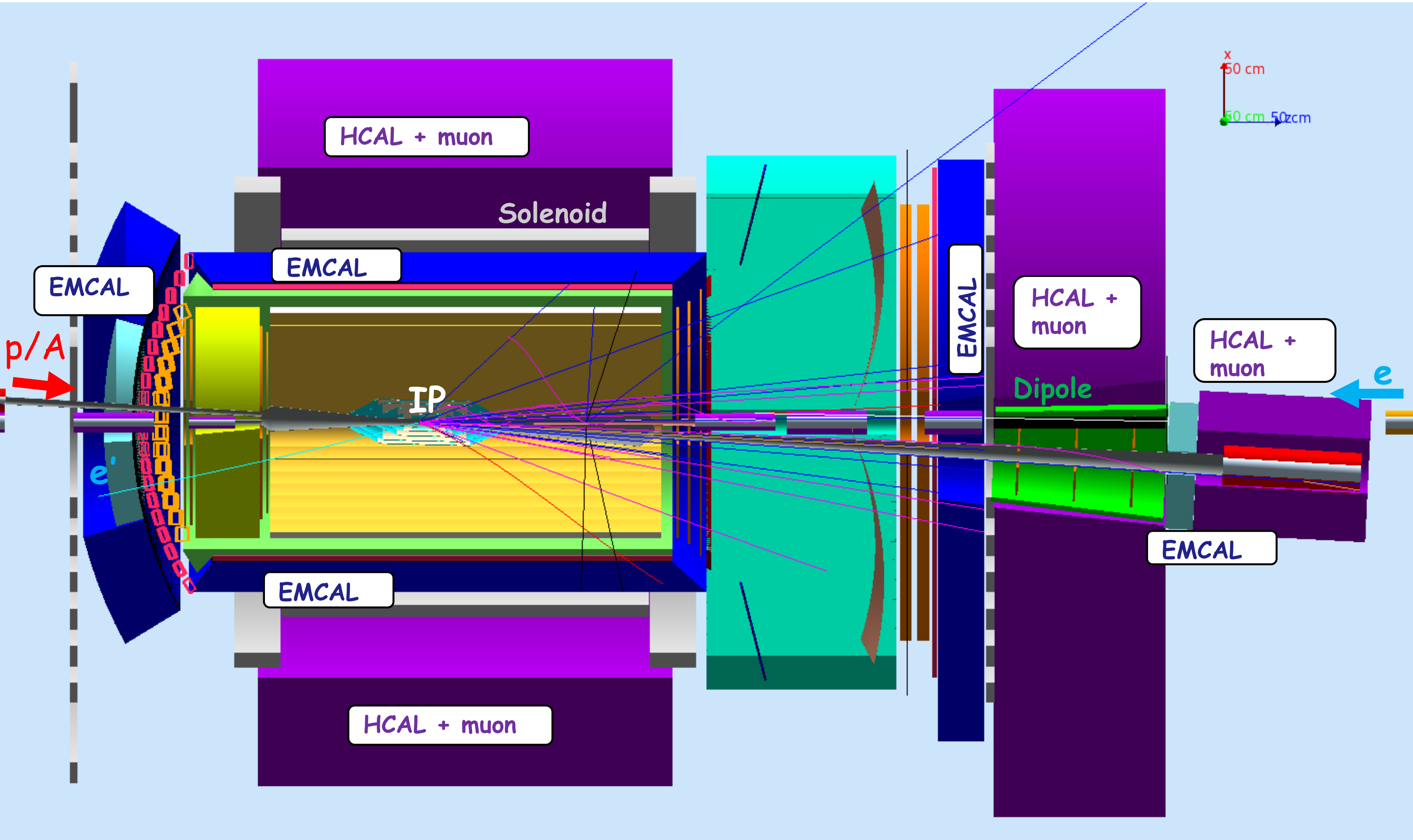


- Much cleaner sample from muon decay channel
- E_{emcal}/E_{tot} , for muons Min energy in EMCAL and HCAL
- p/E
- In addition (R&D needed) :
    - Need instrumentation: muon chambers.
    - dE/dx, cluster counting


EIC Simulation
10GeV on 100GeV
e + p → e + p + J/ψ(μμ)
all events
P_μ (J/ψ) [GeV]
0
10
20
−6
−4
−2
0
2
4
6
η_μ (J/ψ)
1
10
10^2
10^3
10^4
1

S. Joosten

EIC Central detector overview



Modular design of the central detector

Summary

Goals:

- → What kind of physics we would like to measure?
- → What are the typical particle energies (dynamic range)?
- → Cost?

Find a proper material:

- → fully contain the particle in the calorimeter (depth)
- → minimize fluctuations (better energy measurement)
- → low noise
- → minimize dead area
- → fast response
- → **radiation hard (especially near beampipe)**

Coverage: 4π solid angle

- Backup