EIC Detector Design

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Outline

- **Introduction**
- **EIC detector concepts**
- **Tracking**

Wednesday

- **Calorimetry**
- **Particle identification**
- **Summary**

Thursday

*Input from E.Aschenauer, M.Chiu, R.Erbacher, Y.Furletova, K.Gnanvo, T.Horn, U.Langenegger, V.Manzari, P.Nadel-Turonski, B.Page, D.Pitzl, J.Repond, L.Ruan, F.Sefkow, M.Stanitzki, B.Surrow, M.Vandenbroucke, H.Wennloef, P.Wintz, C.Woody, R.Yoshida and other colleagues used in this lecture

Calorimetry

Calorimetry basics

- **Calorimeter measures energy of incoming particle**
  - Stopping the particle
  - Converting the energy into something detectable (light, charge)
  - Basic mechanism: e/m and hadronic showers
  - The measured output is proportional to the particle energy

- **It also measures the location of energy deposit**
  - Showers are relatively well localized
  - Calorimeter readout is segmented
  - Therefore (provided primary vertex location is known) one can determine *directional information* for neutral particles (photons, neutrons)

Particles seen by calorimeters

- **Charged hadrons (π, K, p)**
  - Track & hadronic shower
- **Electrons**
  - Track & e/m shower
- **Photons**
  - e/m shower
- **Neutral hadrons (n, K_L)**
  - Hadronic shower
- **Muons**
  - Track

All other particles are too short-lived

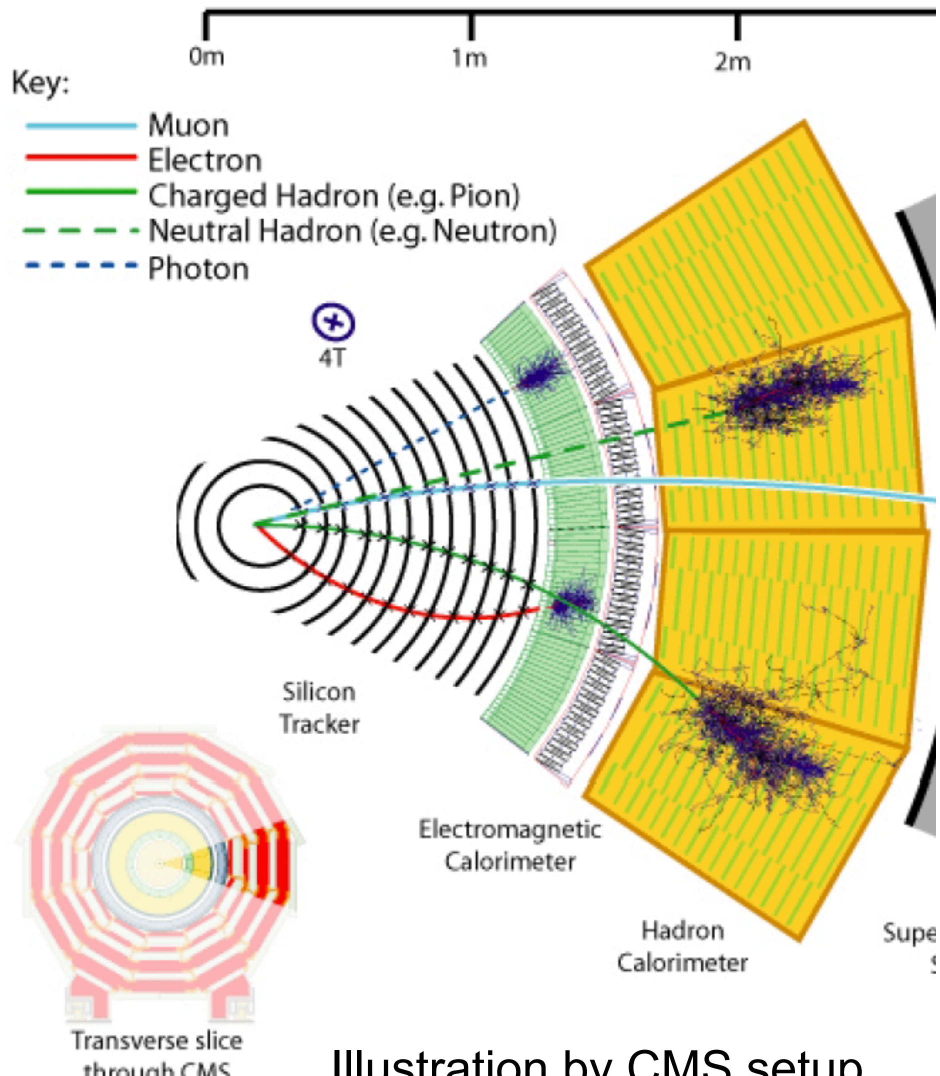
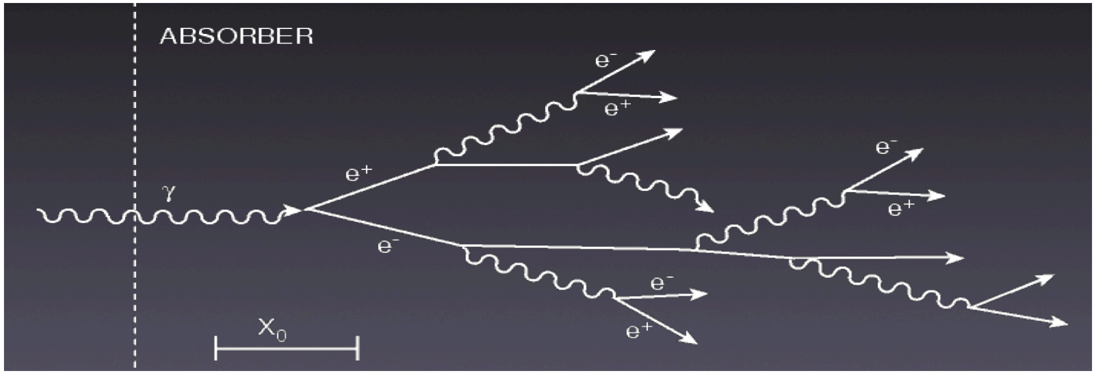


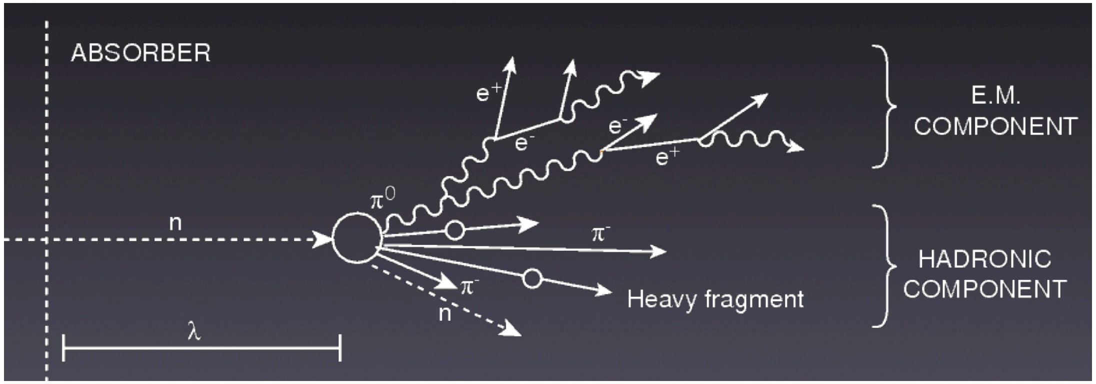
Illustration by CMS setup

e/m and hadronic showers

- **e/m showers: QED, clean & simple**



- **Hadronic showers: nuclear interactions + e/m component**

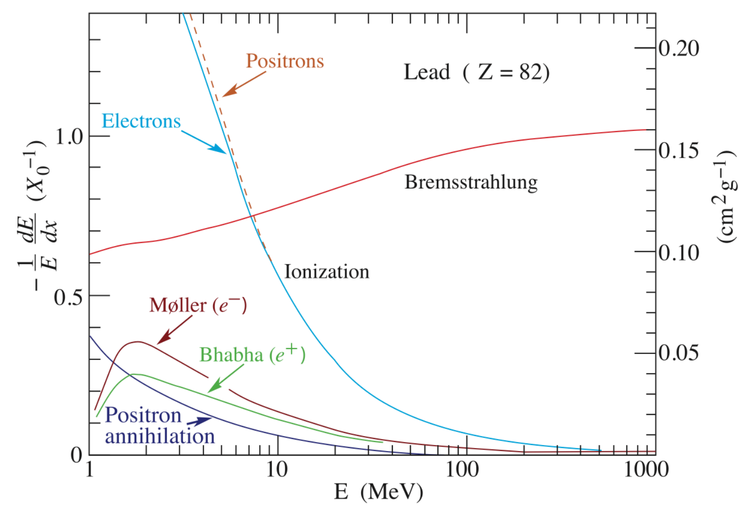


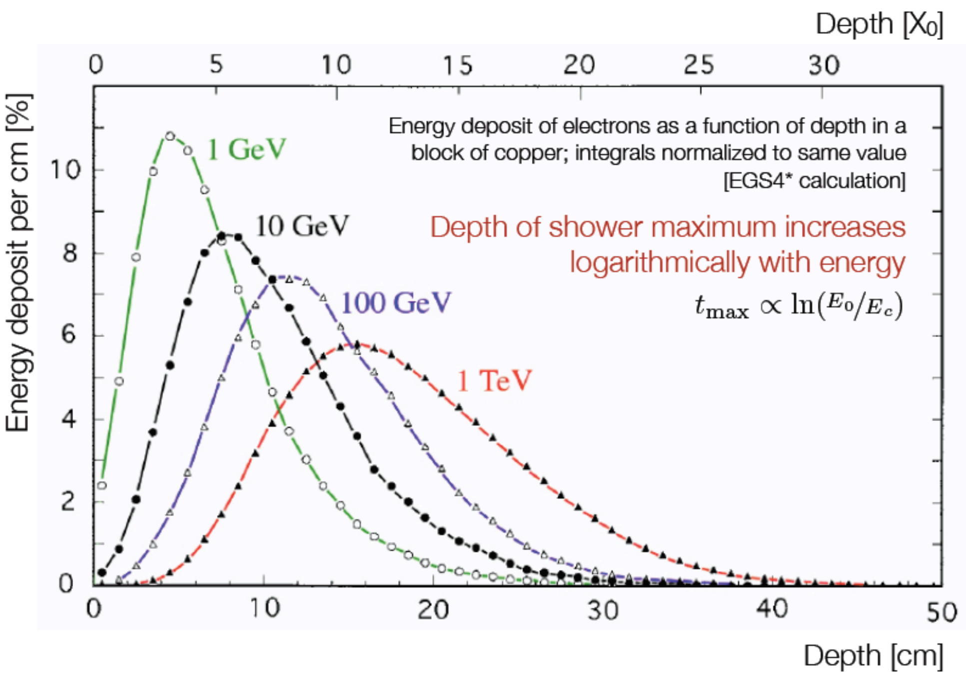
-> Note: event-to-event fluctuation of e/m component and different response to the e/m and hadronic components is the main reason of hadronic calorimeter performance degradation

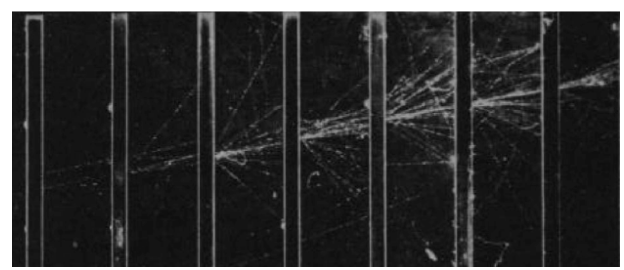
Electron and γ interaction with matter

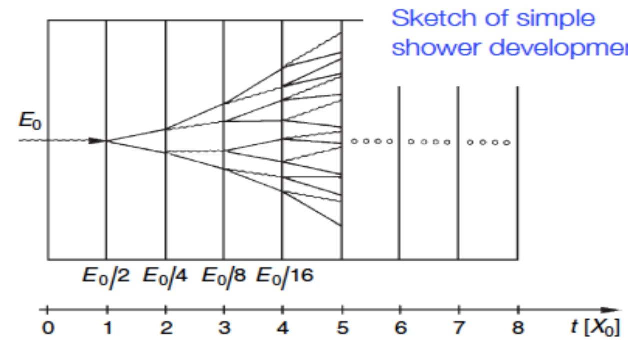
- At higher energies dominated by bremsstrahlung (electrons) and pair production (photons) -> shower particle contents grows exponentially
- At lower energies ionization dominates and shower starts "dying out"
- Critical energy: E_c, where ionization and radiation processes have ~equal weights

Fractional energy loss per radiation length









Sketch of simple shower development

e/m calorimetry cheat sheet

- Radiation length (X_0)
  - When the energy has been reduced to 1/e
  - Characterizes the shower depth

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

- Critical Energy (E_C)
  - Energy, where Ionization takes over

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

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

- Moliere Radius ($r_{Moliere}$)
  - Radius which contains 90 % of the shower
  - Characterizes the width of the shower

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

- Shower Max(imum)
  - The peak of the shower

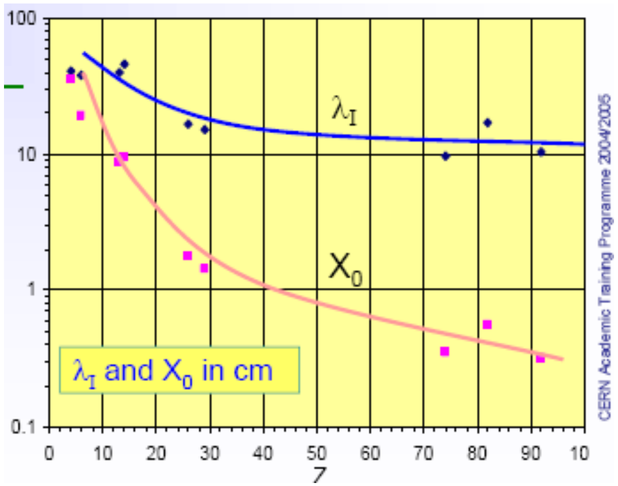
$$S_{max} = \ln\left(\frac{E_{Incoming}}{E_C}\right)$$

-> Note: shower depth only grows logarithmically with energy

X_0 (e/m) vs λ_I (nuclear)

λ_{int}: mean free path between nuclear collisions

$$\lambda_{int}\ (\mathrm{g\ cm^{-2}}) \propto A^{1/3}$$



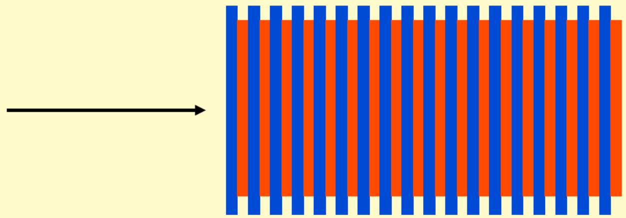
-> Note: apparently $\lambda_I \gg X_0$, therefore hadronic calorimeters are typically much bigger than the e/m ones in order to fully contain the hadronic shower

Material	Z	A	Z/A	X_0 (cm)	λ_I (cm)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	866	718	0.0708
He	2	4.002	0.500	756	520	0.125
C	6	12.01	0.500	18.8	38.1	2.27
Al	13	26.98	0.482	8.9	39.4	2.70
Cu	29	63.55	0.456	1.43	15.1	8.96
Pb	82	207.2	0.396	0.56	17.1	11.4
W	74	183.8	0.403	0.35	9.58	19.3
U	92	238.0	0.387	0.32	10.5	19.0
Scint.			0.538	42.4	81.5	1.03

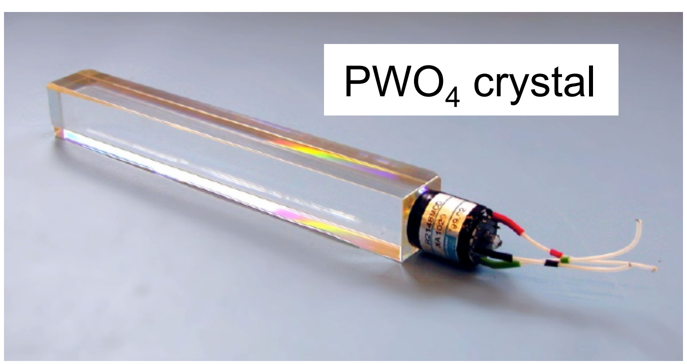
Sampling and homogeneous types

- **Two main calorimeter types:**

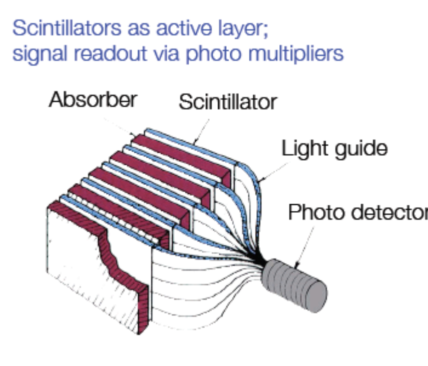
Sampling calorimeters:
Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon

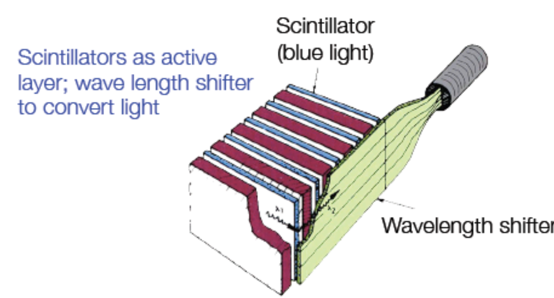


Homogeneous calorimeters:
A single medium serves as both absorber and detector, eg: liquified Xe or Kr, dense crystal scintillators (BGO, $PbWO_4$ …….), lead loaded glass.



Example sampling configurations





Calorimeter resolution

- **Typically parameterized as**

$$\left(\frac{\sigma_E}{E}\right) = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term

Constant term

Noise term (e.g. electronic noise)

- **Stochastic term:**
  - Photon statistics, sampling fluctuations
- **Constant term:**
  - Non-uniform detector response
  - Channel-to-channel mis-calibration
  - Longitudinal leakage (calorimeter too short to contain the shower)

-> Note: resolution improves with energy, as long as the constant term does not start dominating

EIC e/m calorimetry: use case & requirements

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%/√E + 0.5% 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	Inner EM Cal for for $\eta < -2$: ➢ Good resolution in angle to order 1 degree to distinguish between clusters ➢ Energy resolution to order (1.0-1.5 %/√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%/√E ➢ Compact readout without degrading energy resolution ➢ Readout segmentation depending on angle
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%/√E +1.5% (prefer 1%)	Barrel EM Cal: ➢ Compact design as space is limited ➢ Energy resolution of order 8%/√E +1.5%, and likely better Hadron endcap EM Cal: ➢ EM energy resolution to < (12%/√E + 1%)

07/26/18 EIC R&D Meeting: the most complete "consensus" table at this time

Disclaimer

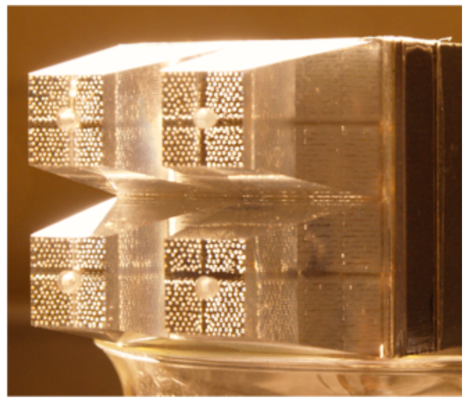
- **These “requirements” are a combination of**
  - Limited amount of modeling studies
  - Past experience
  - Present and/or near future state of the (calorimetry) art
  - Progress within the EIC Detector R&D Program
  - Common sense & educated guesses
  - Trade-offs coming from budget constraints

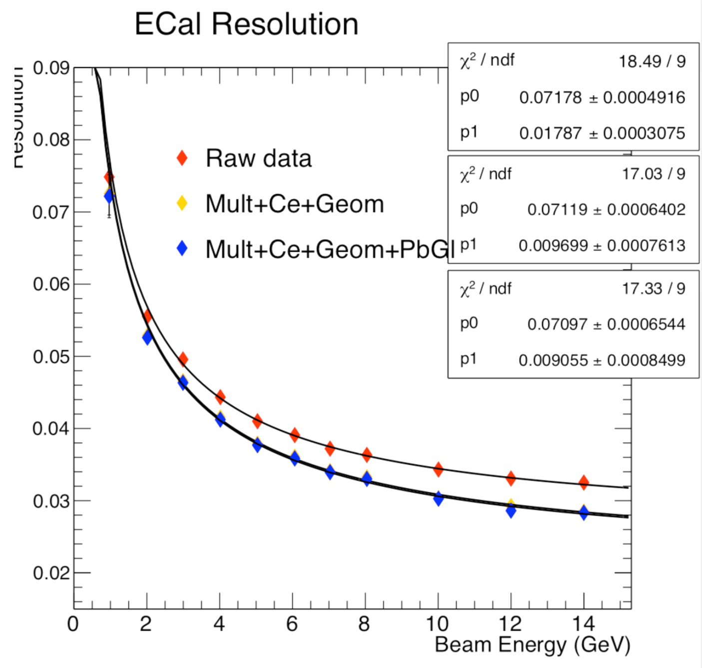
-> We believe they are good enough as a guidance and as a starting point for various types of physics analyses

W/SciFi EIC calorimeter R&D: early days

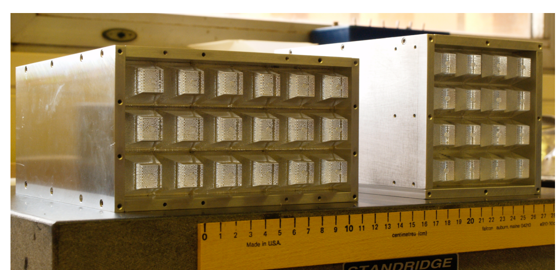
- Scintillating fibers embedded in a composite absorber (tungsten power + epoxy)
- Round and square fibers tested

Detector	Fibers SCSF 78	Absorber
"Old" High sampling frequency	Round, 0.4mm	75% W 25% Sn
"Square" High sampling fraction	Square, 0.59 x 0.59 mm^2	100% W



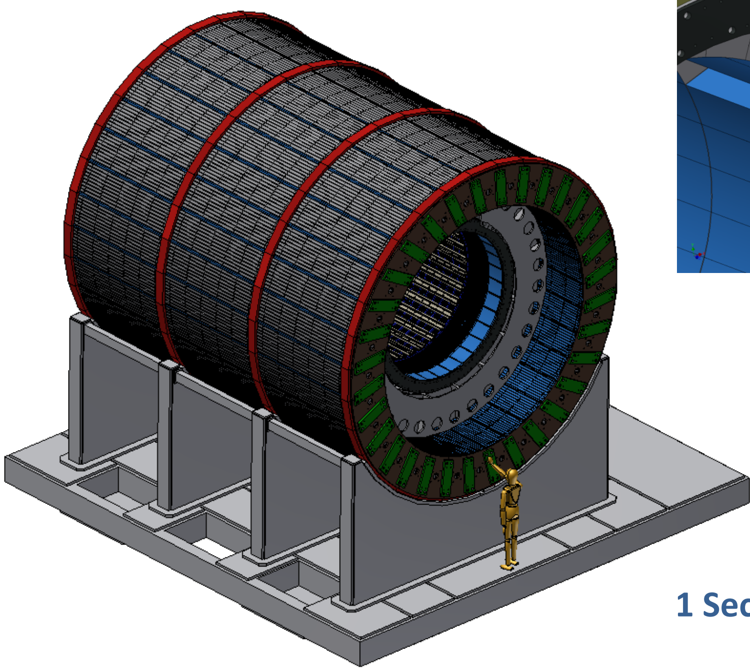


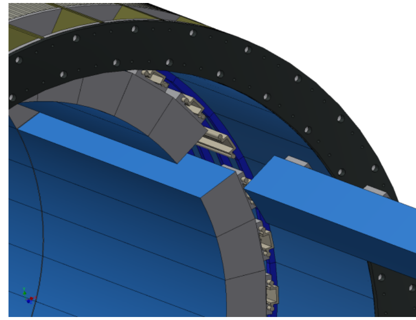
- Several test beam campaigns in 2012 .. 2016
- Achieve 7-12%/√E (variable by design), with ~1% constant term at 10°, ~3% at 4°
- PMT and SiPM implementations
- Beam installation at RHIC in 2017



W/SciFi design: sPHENIX implementation

2(±η) x 32 (ϕ) = 64 Sectors

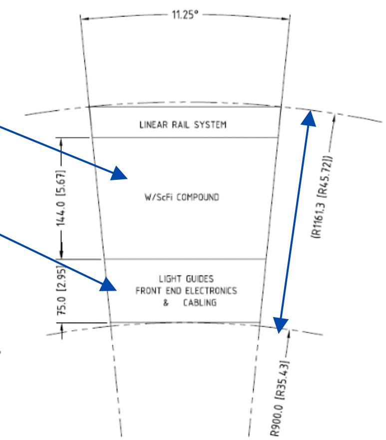


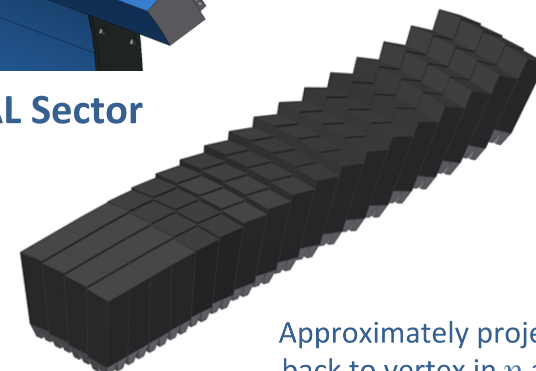


EMCAL Sector

~14 cm absorber (η=0)

7.5 cm readout

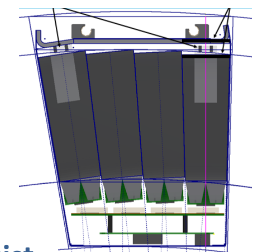




Approximately projective back to vertex in η and ϕ

1 Sector = 72 Blocks
= 288 towers

Module = Block/Reflector/Light Guides/SiPMs

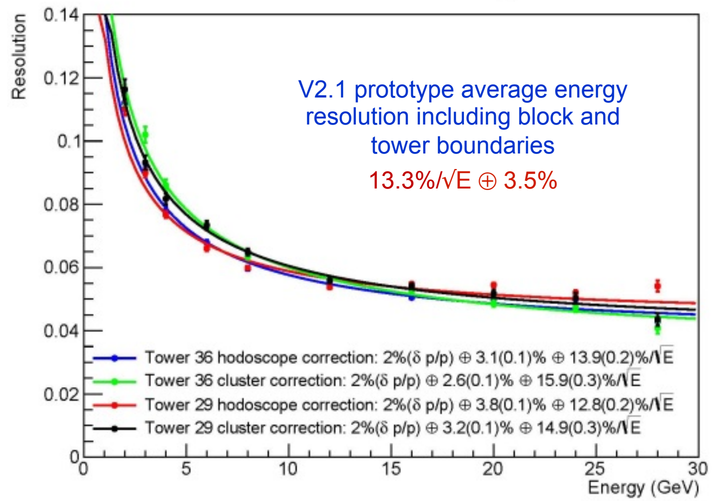


Blocks consist of 2x2 towers

- Coverage: ± 0.85 in η, 2π in ϕ
- Segmentation: $\Delta\eta \times \Delta\varphi \approx 0.025 \times 0.025$
- Readout channels (towers): 72x256 = 18432
- Energy Resolution: $\sigma_E/E < 16\%/\sqrt{E} \oplus 5\%$
- Provide an e/h separation > 100:1 at 4 GeV
- Approximately projective in η and ϕ
- Compact, works inside 1.4T magnetic field and reduces cost of HCAL

W/SciFi design: sPHENIX implementation

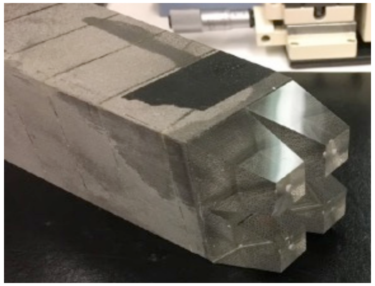
- **The EMCAL has undergone 4 rounds of prototyping and beam tests at Fermilab and is in a very mature stage.**
- **Results have shown that the detector can meet the requirements for the sPHENIX physics program.**
- **A detailed engineering design has been developed for the complete detector.**



- Construction of the first pre-production prototype sector (Sector 0) is under way. All blocks have been produced at UIUC and are being installed in the sector at BNL.

Readout End
Scintillating Fibers

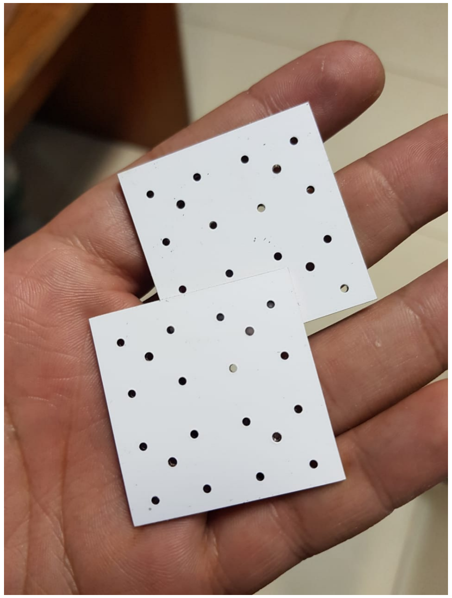
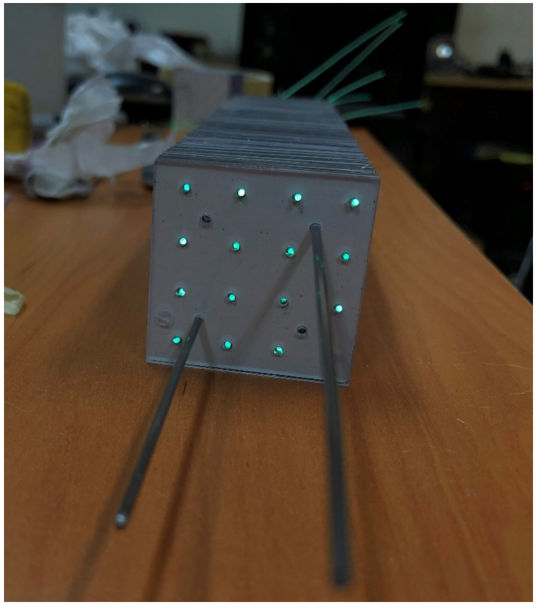
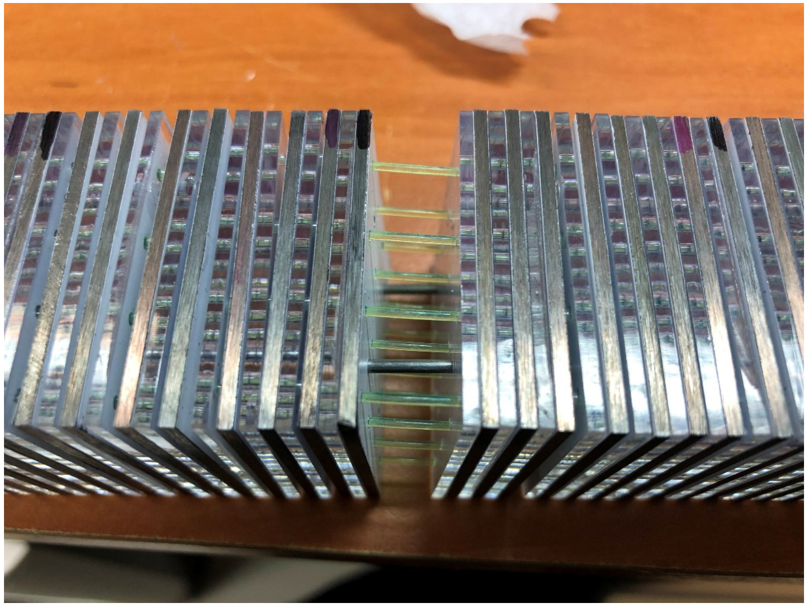
Light Guides
4 towers/block



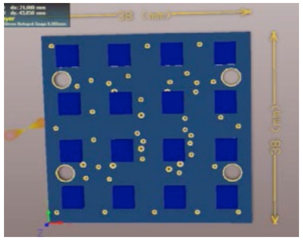
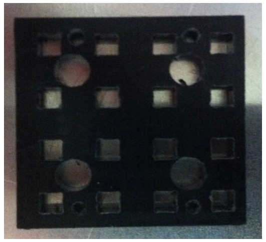
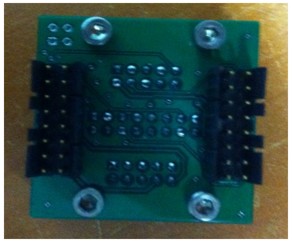
W/SciFi Absorber Block

Blocks installed in Sector 0 at BNL

W/Cu/SciTile shashlik calorimeter

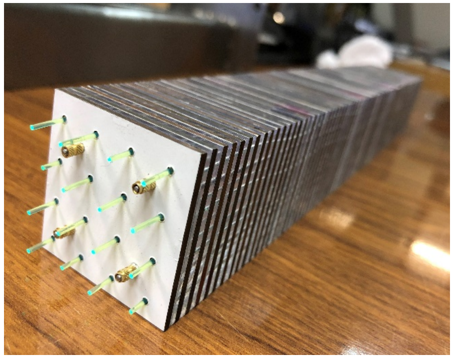
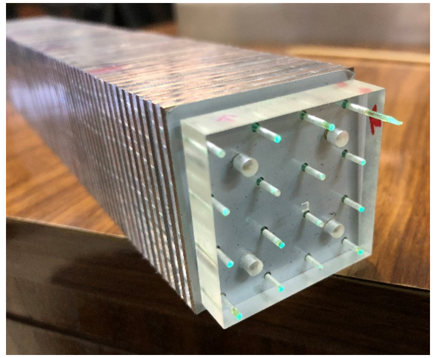
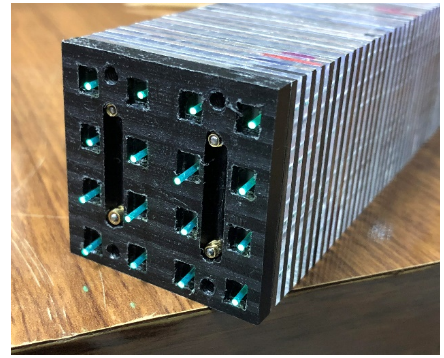
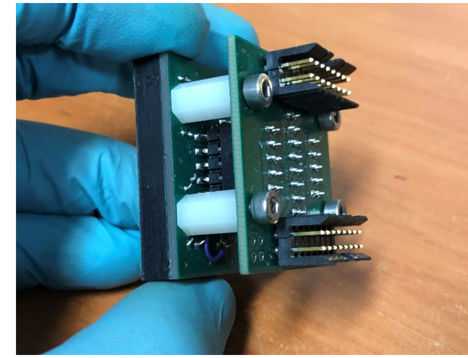




- Use W80/Cu20 alloy as absorber
- Read out each WLS fiber with an individual SiPM

- A viable alternative solution to W/SciFi calorimeter ...
- ... potentially with a better light collection uniformity in a compact design

W/Cu/SciTile shashlik calorimeter

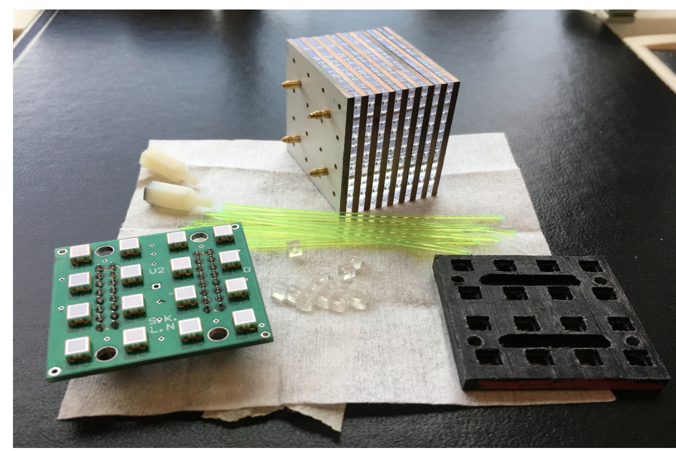





Stack of seventy 38 x 38 x 1.5 mm W80Cu20 absorber plates and 1.5 mm scintillator plates

Readout consists of 16 WLS fibers each read out with its own 3x3mm^2 SiPM

- First module completed at UTFSM
- LED and cosmic tests are ongoing (light yield, uniformity, timing)

- A short stack is shipped to BNL for light collection uniformity studies

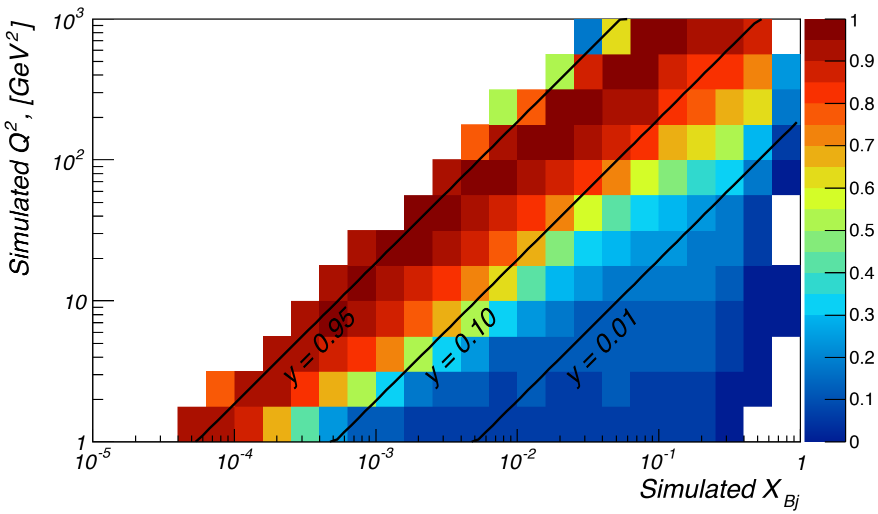


Scattered electron kinematics reconstruction

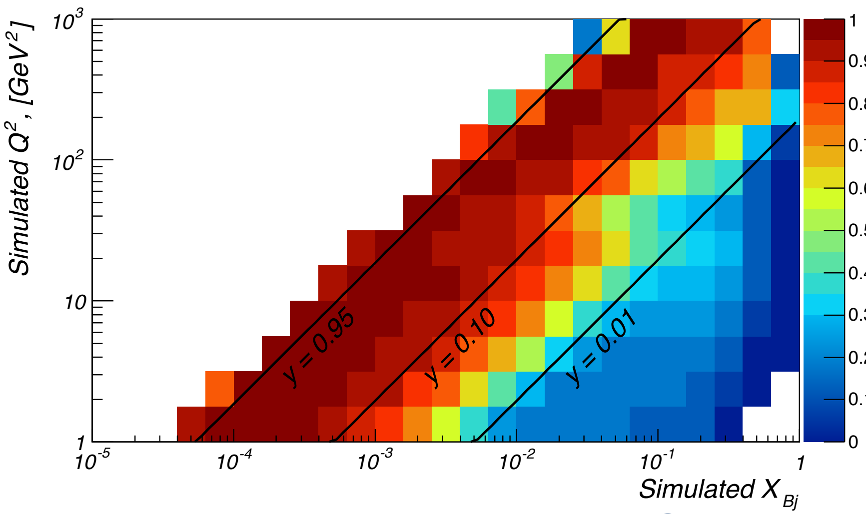
$$Purity = \frac{N_{gen} - N_{out}}{N_{gen} - N_{out} + N_{in}}$$

- Describes migration between kinematic bins
- Important to keep it close to 1.0 for successful unfolding

- A possible way to increase ***y*** range: use e/m calorimeter in addition to tracking
  - ~2%/√E energy resolution (and ~0 constant term) for $\eta < -2$ (PWO crystals)
  - ~7%/√E energy resolution for $-2 < \eta < 1$ (W/SciFi sampling towers)



Lepton tracking only

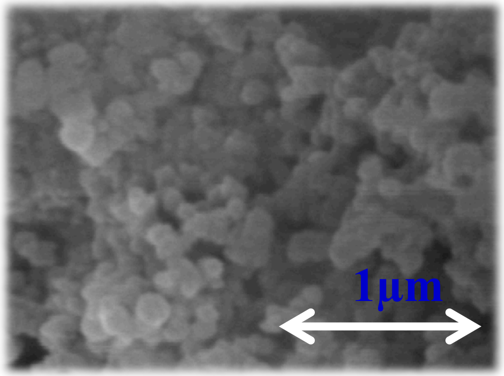


Lepton tracking + EmCal

- Apparently, the high-resolution crystal EmCal at very backward rapidities can help increasing the available ***y*** range ...
- ... but only if it has a very small constant term and is “radiation hard”

New materials for EIC calorimetry

- **Ceramic glass as active calorimeter material:**
  - More cost effective that PWO
  - Easier to manufacture
  - Better optical properties (?)
  - Technology: glass production combined with successive thermal annealing (800 – 900°C)



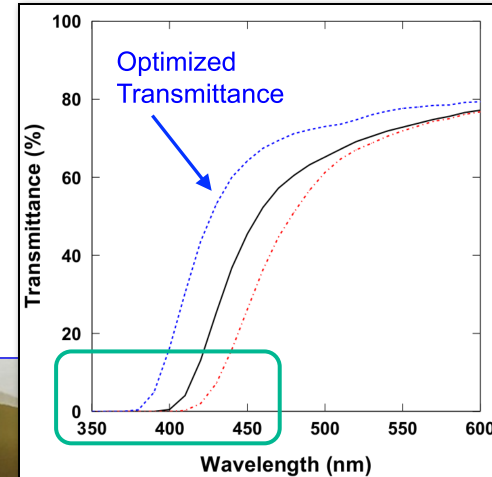
SEM image of recrystallized $BaO*2SiO_2$ at 950°C

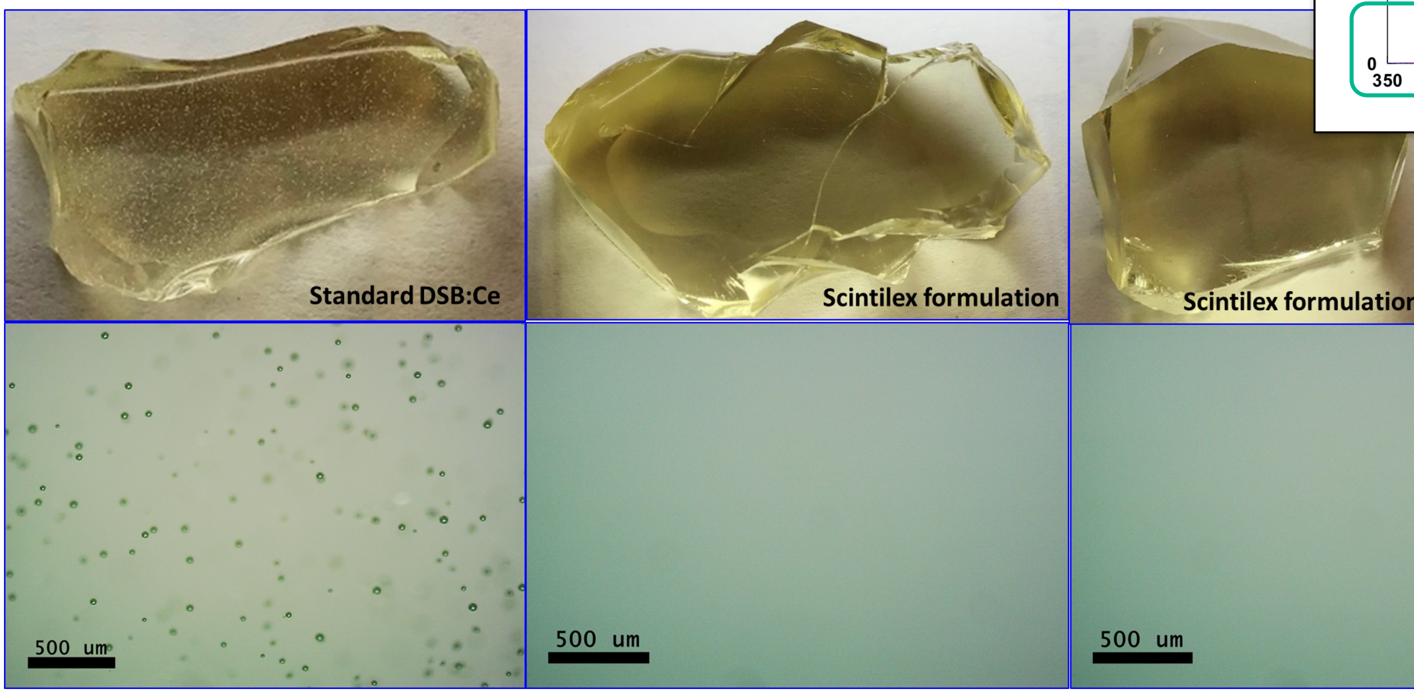
Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
($BaO*2SiO_2$):Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass loaded with Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

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

Glass ceramic: optical property tuning

- Uniformity remains a concern – manufacturing process requires optimization – progress with new method at CUA/VSL/Scintilex



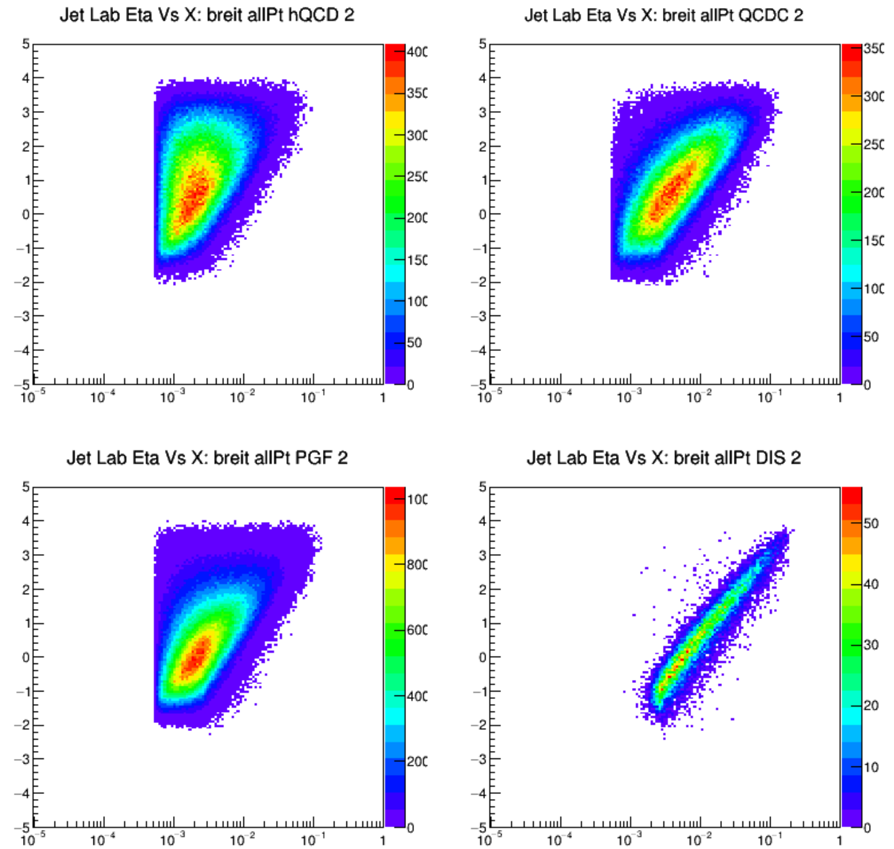


Better transparency, less cracks, higher light yield

Hadronic calorimetry for EIC

- Hadronic energy resolution, especially in the forward endcap, is important for several EIC physics measurements
- Requirements:
  - Compactness
  - Immunity to the magnetic field
  - High (enough) energy resolution
  - Reasonable cost
  - Other (minimal neutron flux, etc)
- Pending questions:
  - Should one stick to the compensated calorimeter design (which by the way never showed high energy resolution for jets) or consider other options (dual-readout or dual-gate concepts, high-granularity calorimetry)?
  - How at all one can get a decent performance out of a 5-7λ deep HCal?

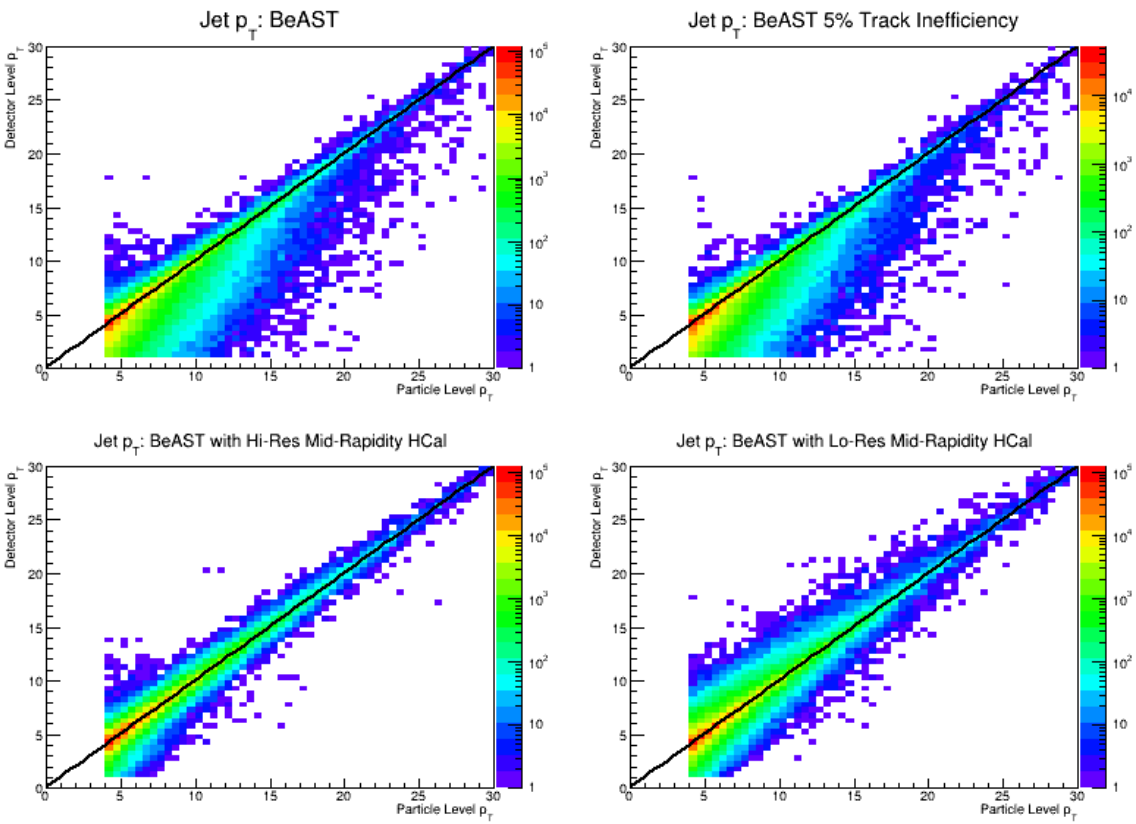
Jet kinematics for various MC processes

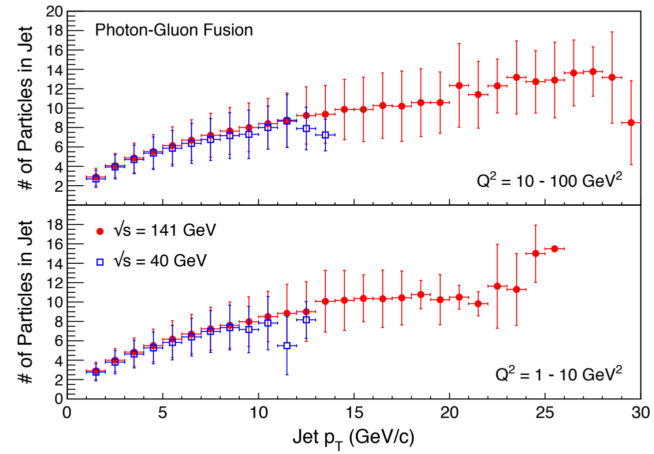


Hadronic calorimeter in the barrel

Jet study for BeAST: ep-events, 20 x 250 GeV, $10 < Q^2 < 100$ GeV^2

- eic-smear pass in a PFA-like fashion (check P_t reconstruction quality)

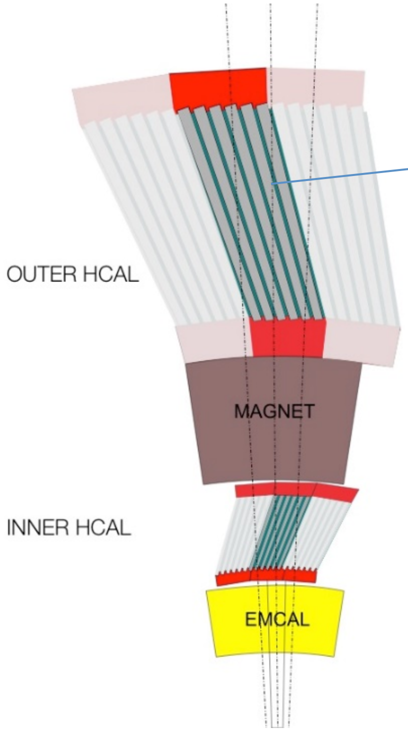


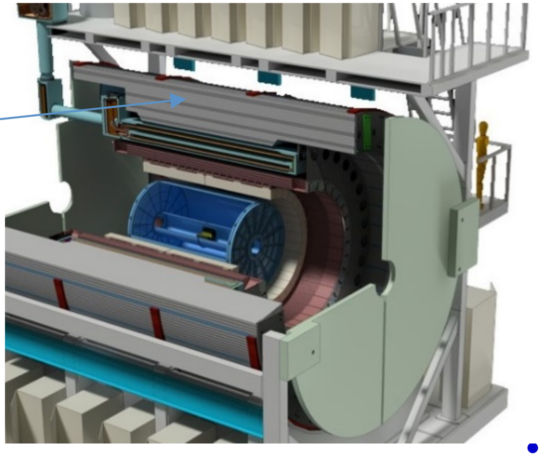


- Here Hi-Res HCal is ~35%/√E + 2% (ZEUS) ...
- ... and Lo-Res HCal is ~85%/√E + 7% (CMS)

-> So it does make a difference

sPHENIX Hadron Calorimeter



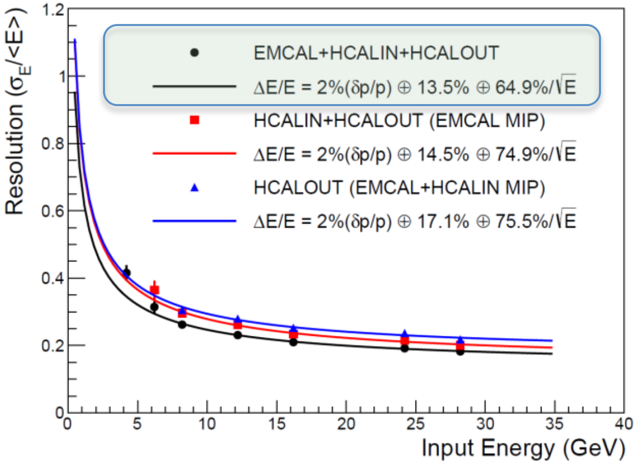


HCAL steel and scintillating tiles with wavelength shifting fiber

- **Outer HCal (outside the solenoid)**
- **$\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$**
- **1,536 readout channels**

SiPM Readout

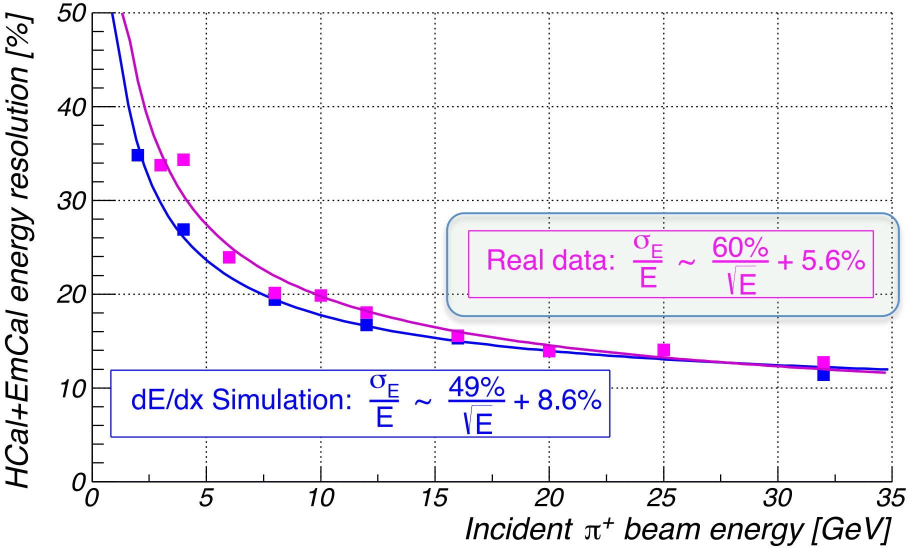
- Uniform fiducial acceptance $-1<\eta<1$ and $0<\varphi<2\pi$; extended coverage $-1.1<\eta<1.1$ to account for jet cone

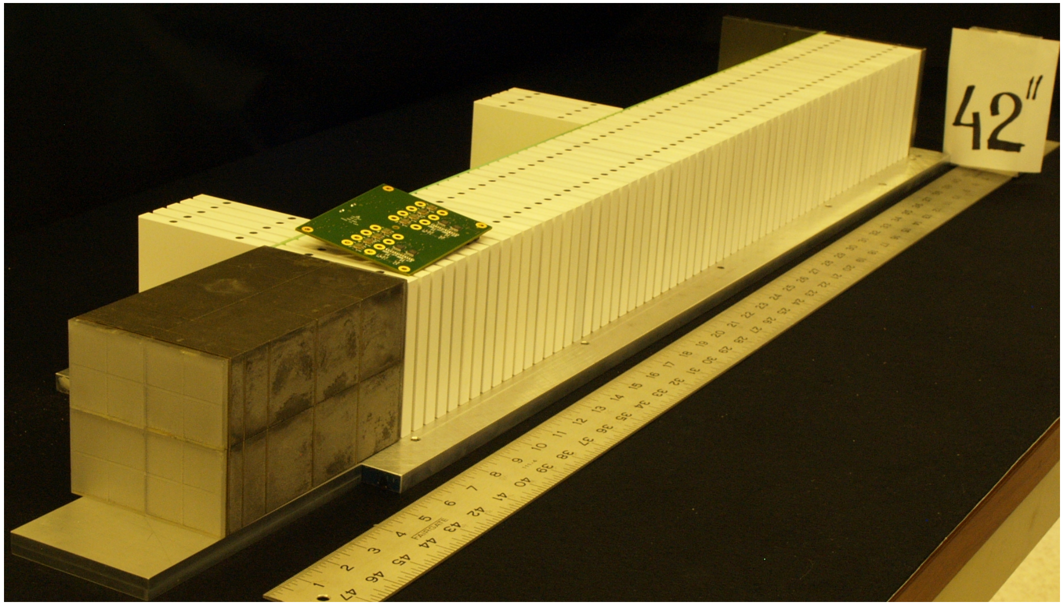


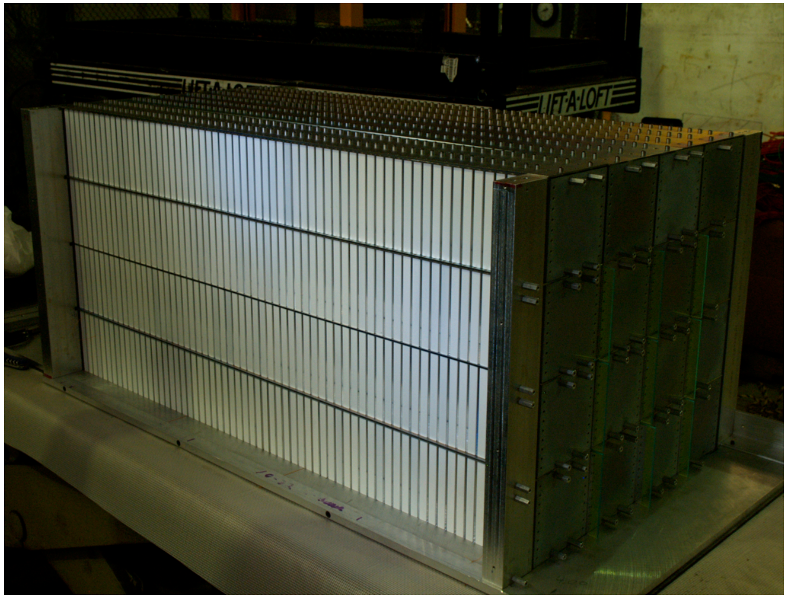
- Outer HCAL $\approx 3.5\lambda_I$
- Magnet $\approx 1.4X_0$
- Frame $\approx 0.25\lambda_I$
- EMCAL $\approx 18X_0 \approx 0.7\lambda_I$

Pb/SciTile EIC calorimeter R&D: early days

- Scintillating tiles interleaved with Pb plates (compensated)
- WLS
- SiPM readout
- Achieve ~60%/√E energy resolution, with ~6% constant term







Dual readout hadronic calorimetry?

The idea:

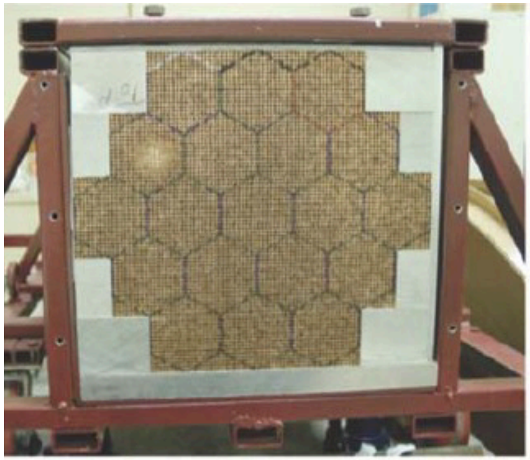
- Abandon built-in compensation (and raise sampling fraction)
- Use two types of fibers as active media (scintillating and clear ones)
- Measure Cherenkov light in addition to the scintillation one and use the ratio of two to correct for the f_{em} fluctuations on event-by-event basis

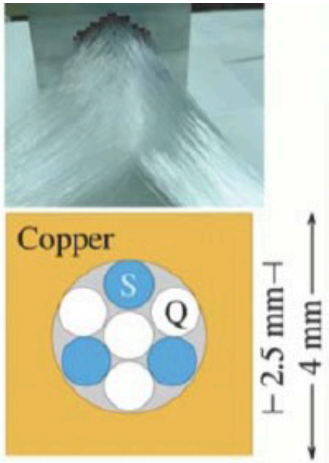
Performance attained so far:

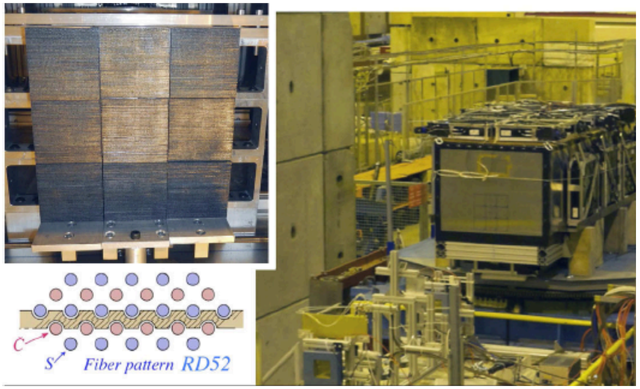
- DREAM (Cu/fiber): ~65%/√E + 0.6%
- RD52 (Pb/fiber): ~70%/√E

Applicability at EIC is problematic:

- Cumbersome construction process
- So far only a PMT configuration (although a small prototype with SiPMs was tried out already)







Dual-gate hadronic calorimetry?

- Large fluctuations in ‘invisible’ energy (nuclear binding energy) main cause of poor resolution
- Main mechanism of production of **n** is spallation (except for U), can be thought as evaporating nucleons from excited nuclei
- Kinetic energy of **n** correlated with ‘invisible’ energy

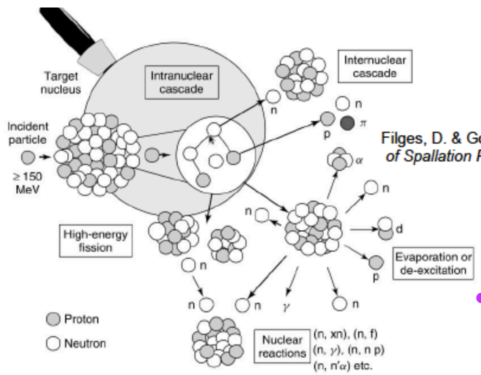
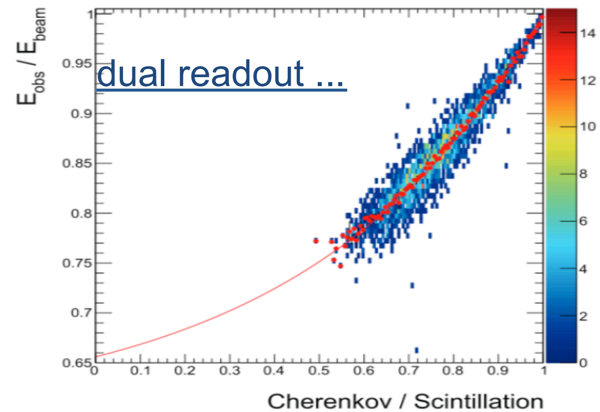


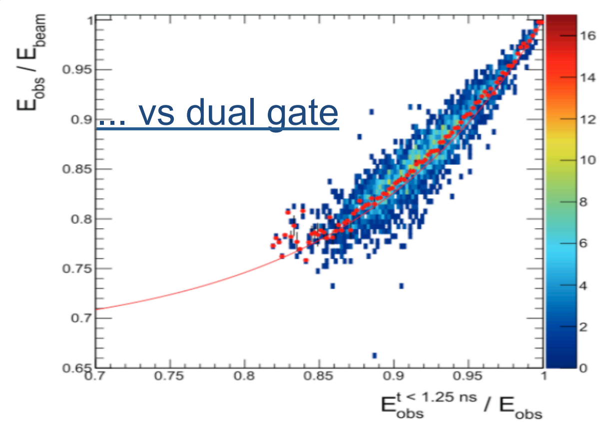
Fig. 1.12 The principal scheme of spallation.

Filges, D. & Goldenbaum, *Handbook of Spallation Research*, Wiley, 2010

90% between 0.1 and 10 MeV

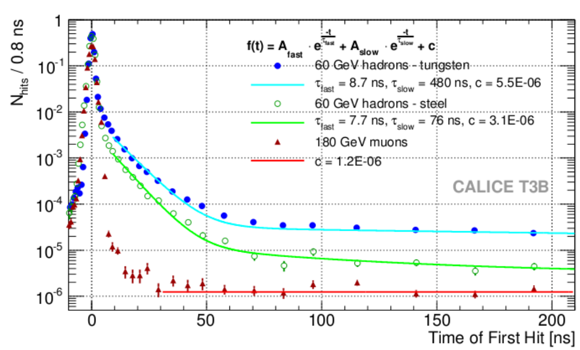
- Thermalization is mainly due to elastic scattering on hydrogen
- Mean free path ~ 20 cm, t ~ 15ns





First measurements by ZEUS in the 90-th; Recently repeated by

- DREAM
- RD52 Collaboration
- CALICE Collaboration

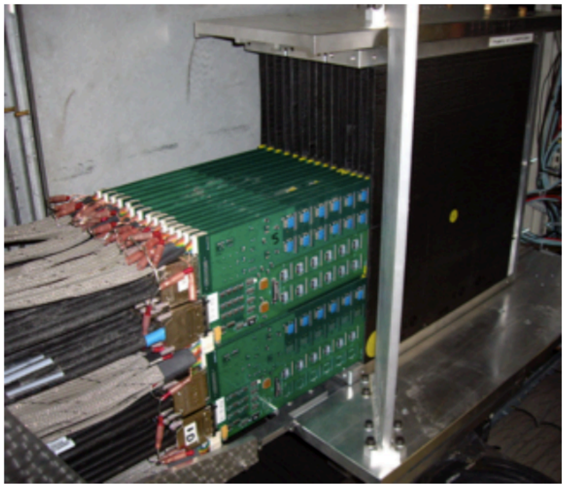


CALICE (Fe/Sc; ~8ns fall-down)

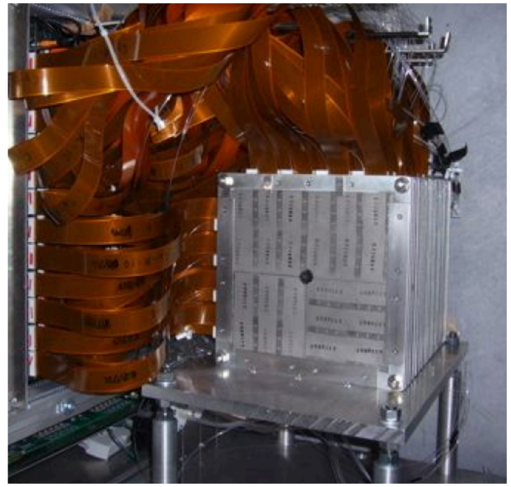
High granularity calorimetry?

-> active community; rapidly developing field; large-scale prototypes

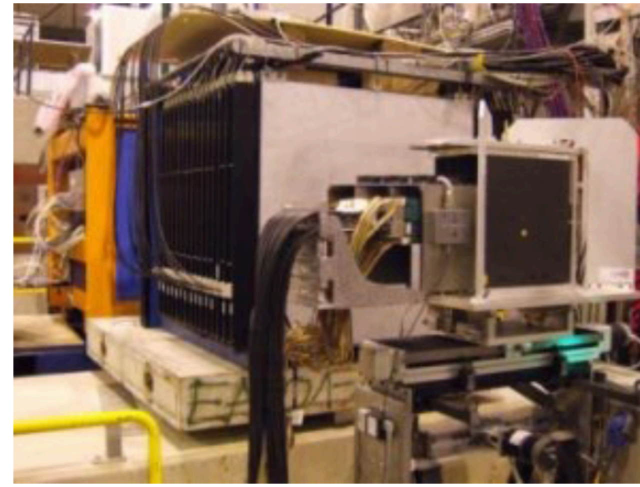
SiW ECAL



ScintW ECAL

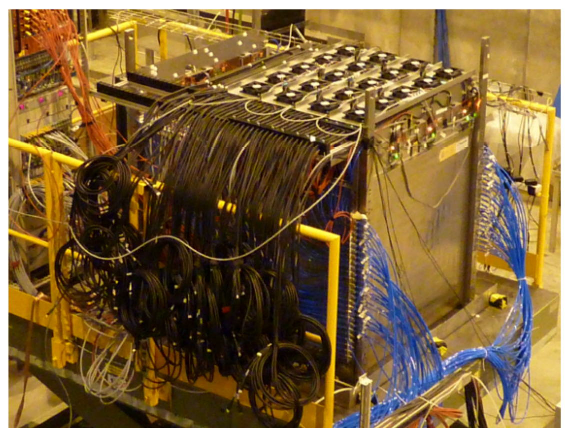


Scint AHCAL, Fe & W



RPC DHCAL, Fe & W

RPC SDHCAL, Fe



plus tests with small numbers of layers:

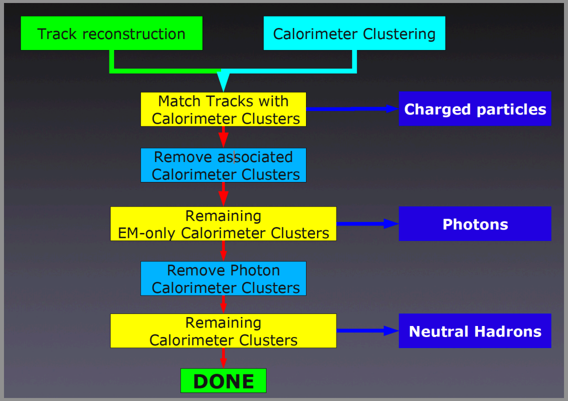
- ECAL, AHCAL with integrated electronics

- Micromegas and GEMs

CALICE

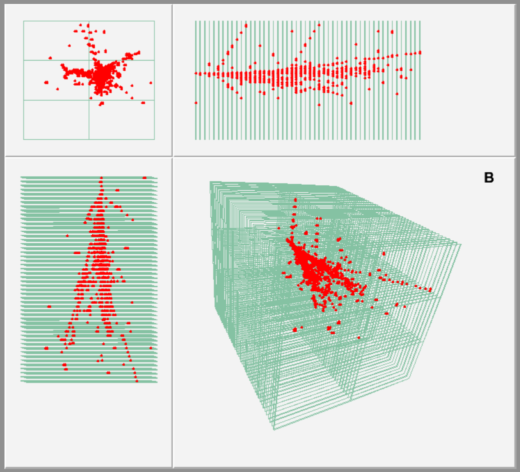
High granularity calorimetry & PFA

Attempt to measure the energy/momentum of each particle in a hadronic jet with the detector subsystem providing the best resolution



The idea

Replace the traditional tower structure with very fine granularity
Few 1,000 channels → few 10,000,000 channels
Option to reduce resolution on single channels to 1 – 2 bits (digital readout)



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 ~2 better jet energy resolution than previously achieved
EIC environment: particularly suited for PFAs, due to low particle multiplicity and low momenta

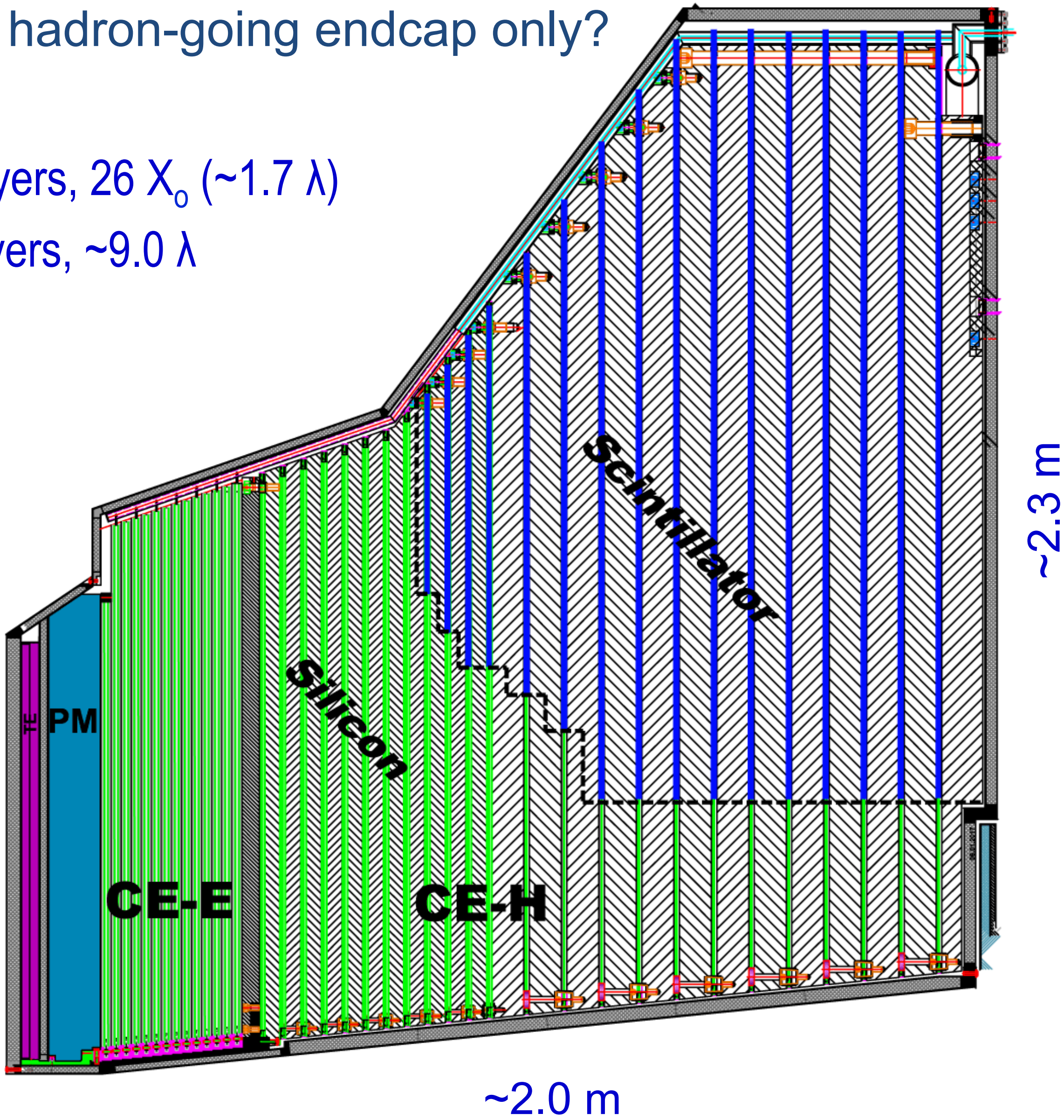
CMS forward calorimeter upgrade

- Use this technology in the hadron-going endcap only?

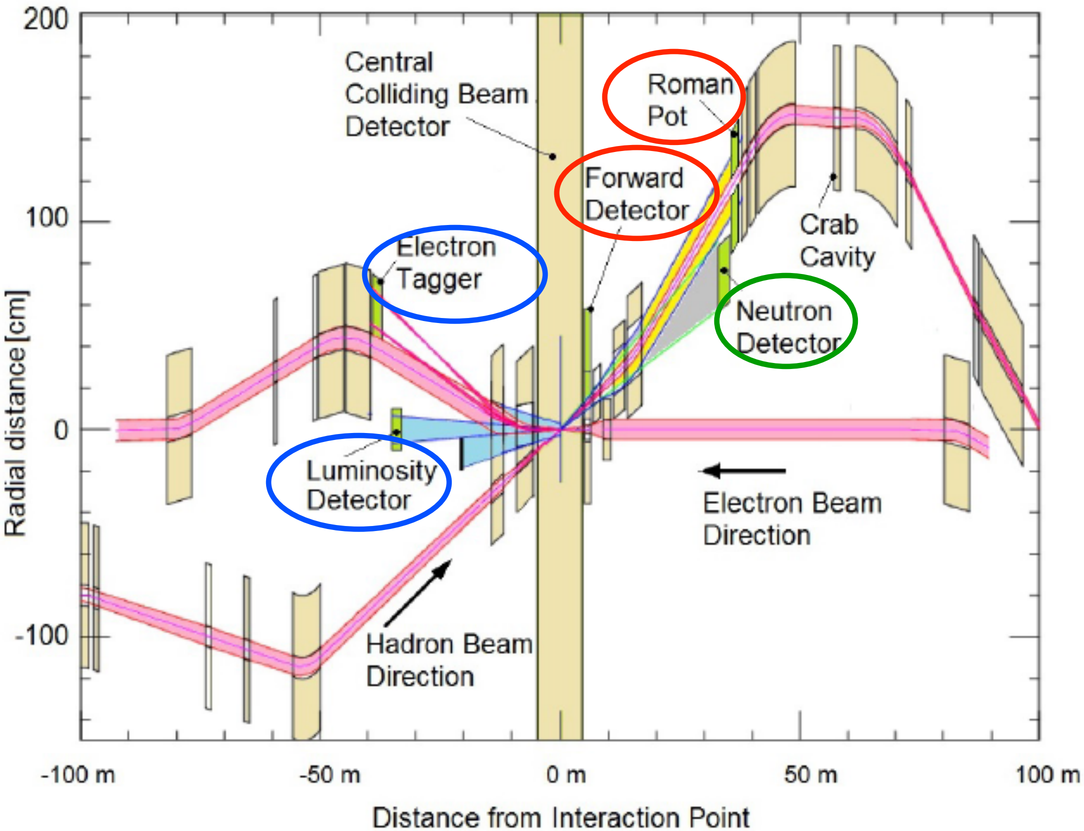
- **CE-E**: Si and Cu/CuW/Pb, 28 layers, 26 X_o (~1.7 λ)
- **CE-H**: Si+Scint and Steel, 24 layers, ~9.0 λ

- $1.5 < \eta < 3.0$
- ~600 m^2 of Si,
- ~500 m^2 of scintillator
- ~6M Si channels

-> this would be pretty much the size of the EIC "ideal" endcap calorimeter!

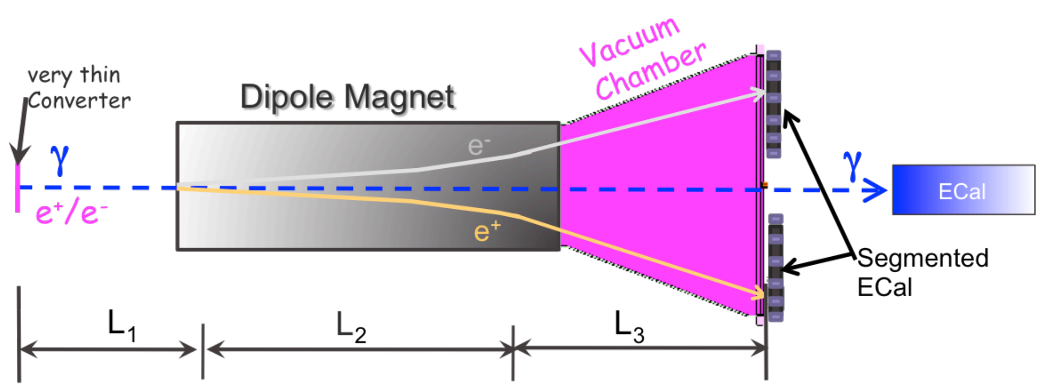


Auxiliary detector calorimeters



- Radiation hardness (both against neutrons and ionizing radiation)
- Highest possible levels of performance (small systems, can be unique)

- Electromagnetic calorimeters
  - Luminosity monitor
  - Low Q^2 tagger
- Hadronic calorimeters
  - Zero-Degree Calorimeter



Luminosity monitor a la ZEUS

Particle Identification

Particle Identification (PID) objectives

In this talk focus on electron and charged hadron identification

- **In general, need to separate**
  - Electrons from photons
  - Electrons from charged hadrons
  - Charged pions, kaons and protons from each other

- **Use any available physics process and detector arrangement to do so:**
  - Energy loss dE/dx
  - Cerenkov radiation
  - Transition radiation

  - Time of flight measurement
  - Longitudinal segmentation of the calorimeter setup

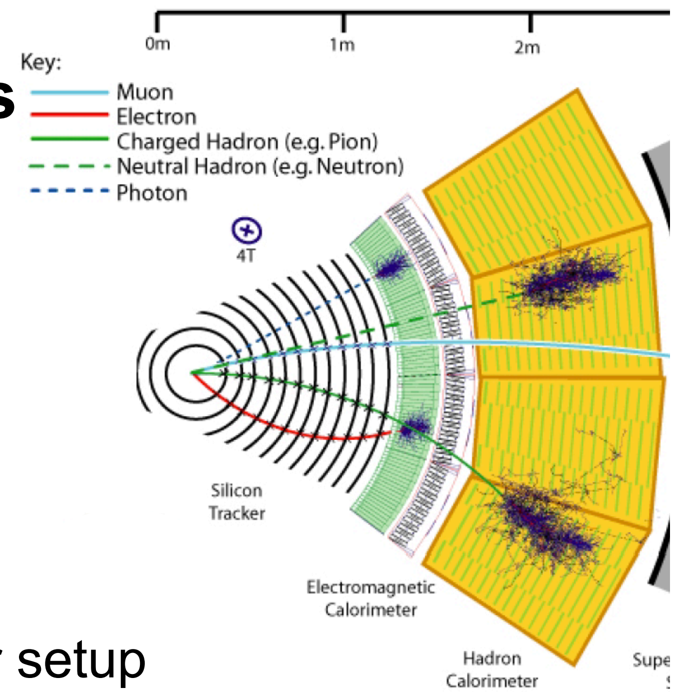


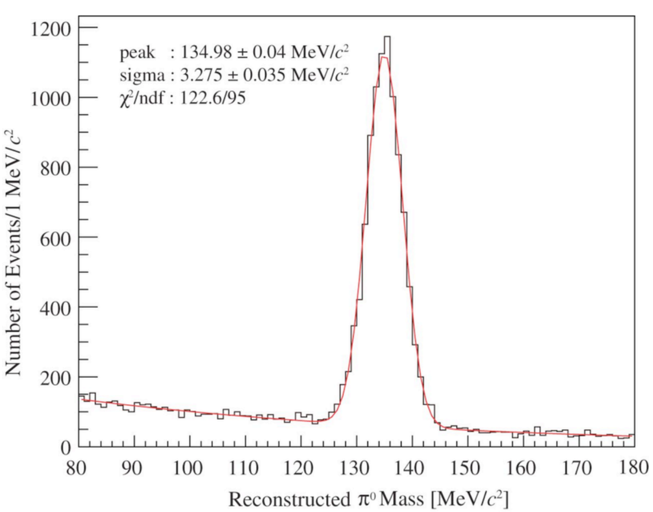
Illustration by CMS setup

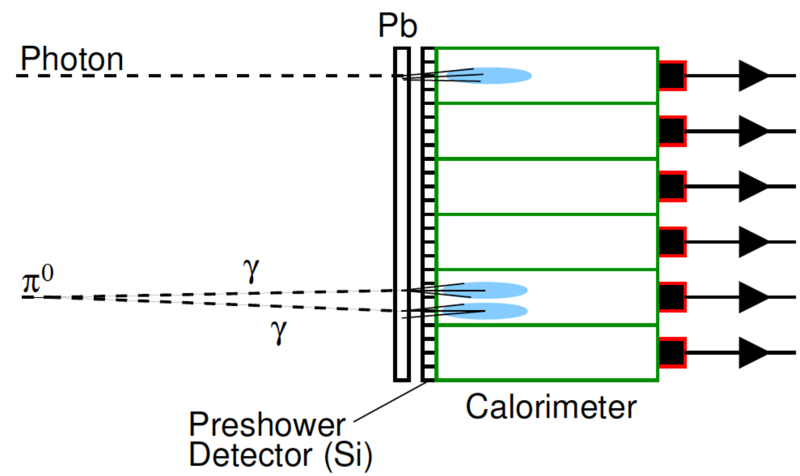
Side remark on π^0 identification

A short-lived particle, so use $\pi^0 \to \gamma\gamma$ decay channel and build invariant mass of the 2γ system

-> Note: decay photons are detected by e/m calorimeter, which provides not only energy, but also *location* measurement; therefore (using primary vertex location, reconstructed via charged particle tracks) one can build 4-momenta required for M_{inv} calculation

- **But what if the 2γ opening angle too small?**
  - Use high granularity preshower in front of e/m calorimeter

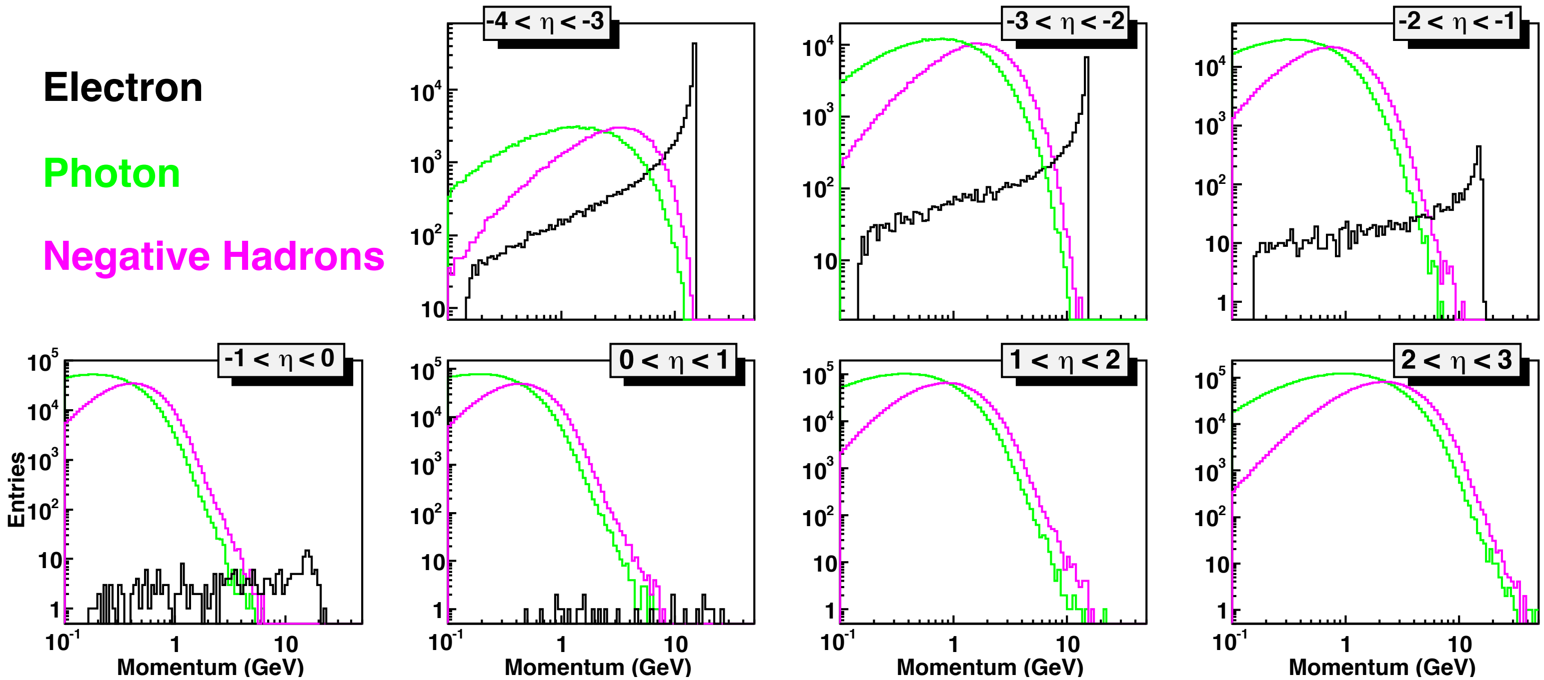


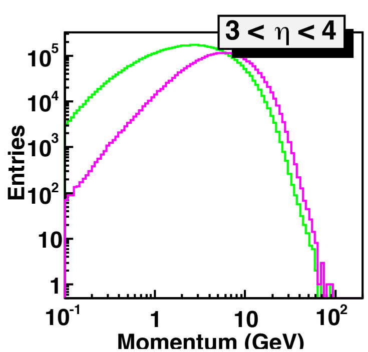


-> Note: preshower also helps to distinguish electrons from charged hadrons

Relative electron/photon/h⁻ yields

15x250 GeV configuration; particle yields versus momentum in the 4 < η < 4 range:





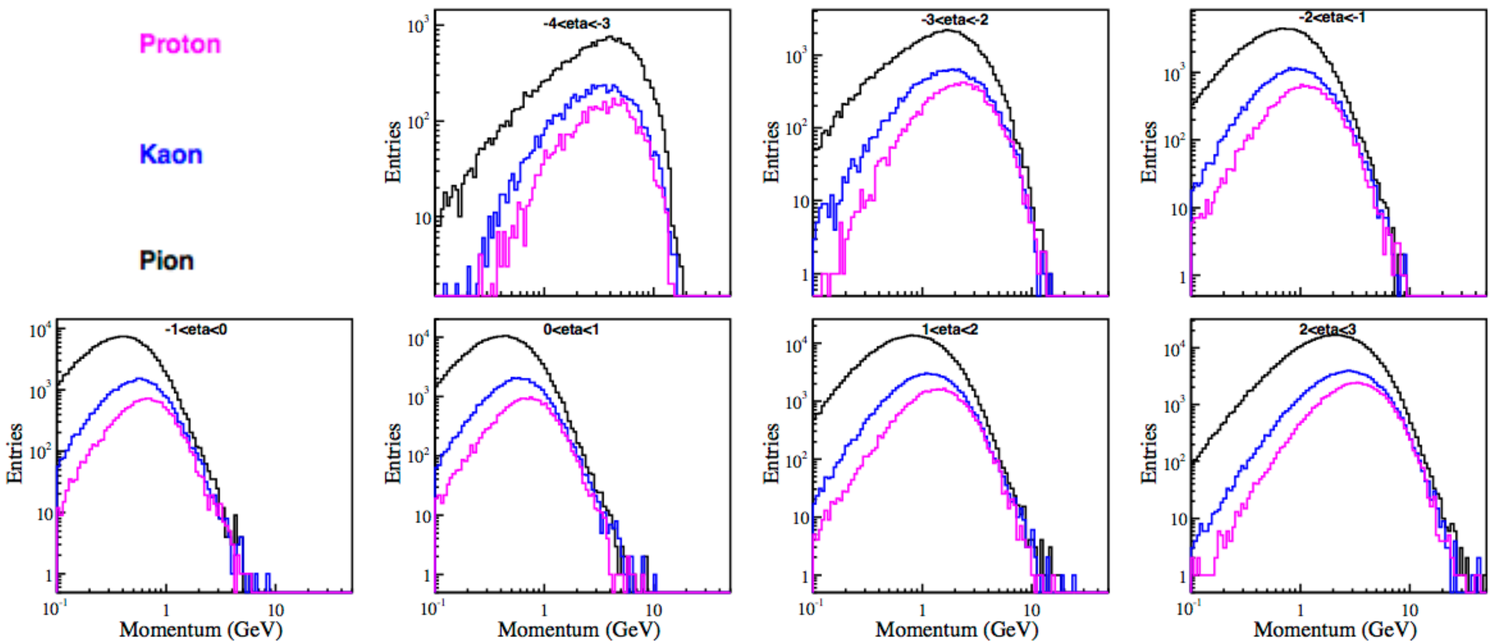
γ suppression:
the same η coverage for
tracking & Ecal

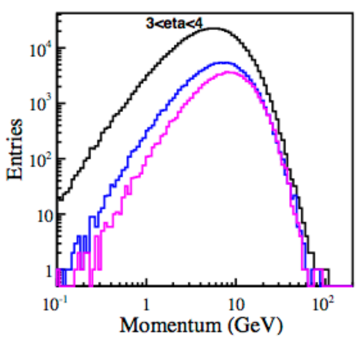
h^- suppression through E/p
-3.5<η<-1: 10:1 to 10^3:1
−1<η <1: 10^4:1

- η range [-1.0 .. -3.5] is also covered by the hadronic calorimeter

Relative pion/kaon/proton yields

20x250 GeV configuration; yields versus momentum in the 4 < η < 4 range:



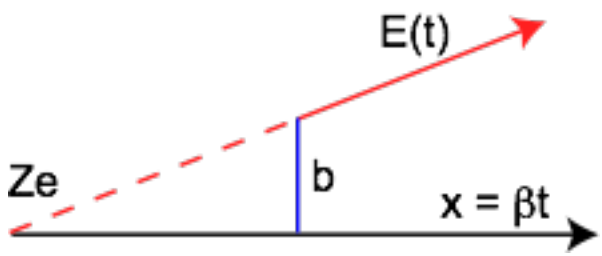


- π/K/p distributions at the same η look similar
- π/K ratio is about 3:1 -> depending on the desired efficiency and contamination this defines the required suppression factors

Energy loss dE/dx

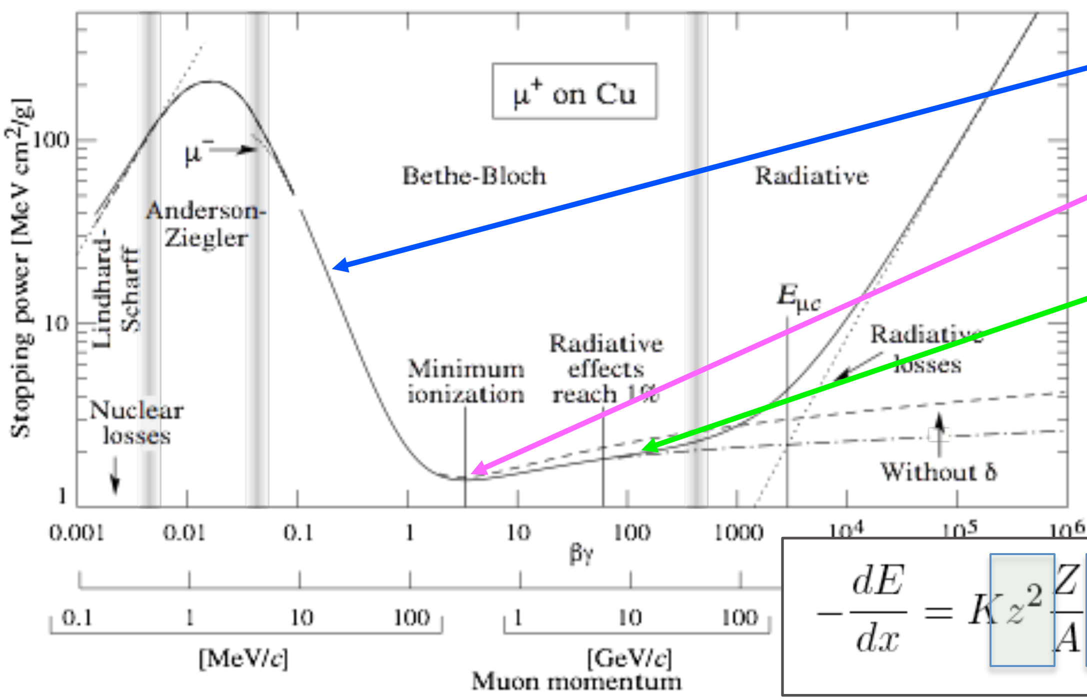
- Elementary calculation of energy loss:

  Charged particles traversing material give impulse to atomic electrons



$$p_y^e = e\int E_y(t)dt = e\int E_y(t)\frac{dx}{\beta} = \frac{2Ze^2}{\beta b}$$

$$\text{Energy transfer} = \frac{(p_y^e)^2}{2m_e} \propto \frac{1}{\beta^2}$$



- $\langle dE/dx \rangle \sim 1/\beta^2$ region
- MIP: $\beta\gamma \sim 3\text{-}4$
- relativistic rise: $\langle dE/dx \rangle \sim \ln\gamma^2\beta^2$

Bethe-Bloch Formula

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

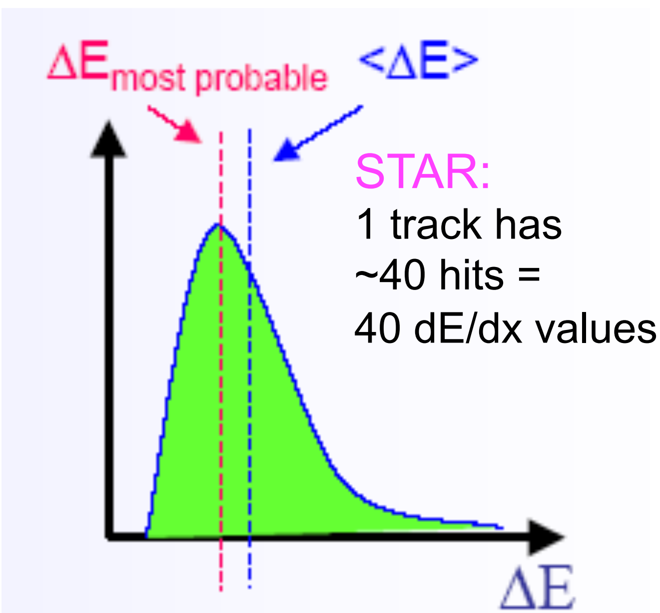
Energy loss dE/dx: STAR TPC

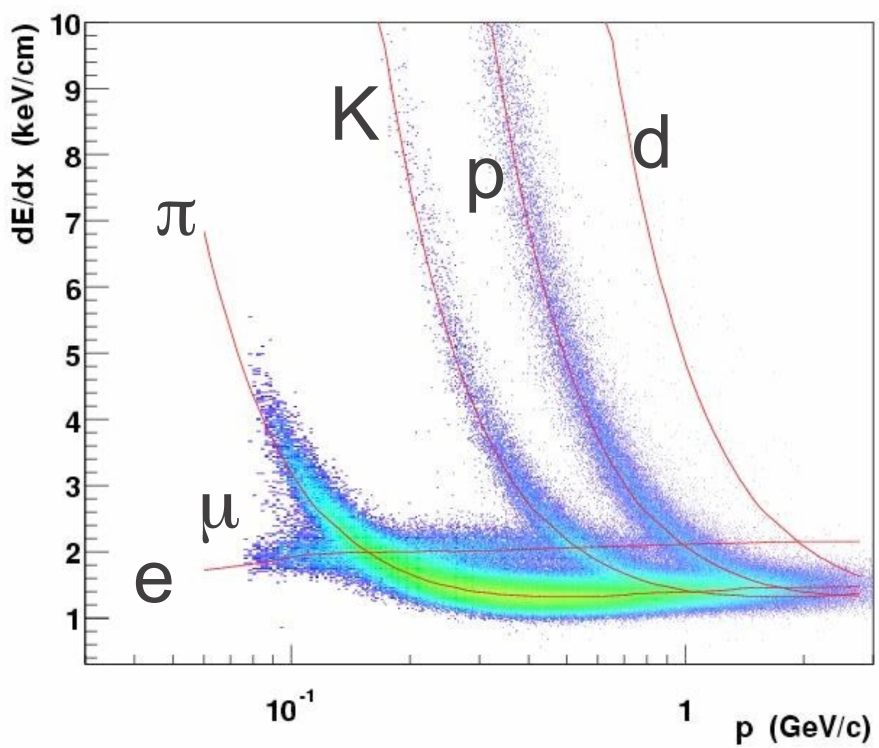
$$p = mv = m_0 \beta \gamma c$$

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

Simultaneous measurement of p and dE/dx defines mass m_0 ⇒ particle ID

- But: real detector (limited granularity) can not measure <dE/dx> !
- It measures the energy ΔE deposited in a layer of finite thickness δx
- Thin layers or low density materials: few collisions, some with high energy transfer
- Energy loss distributions show large fluctuations towards high losses: "Landau tails"

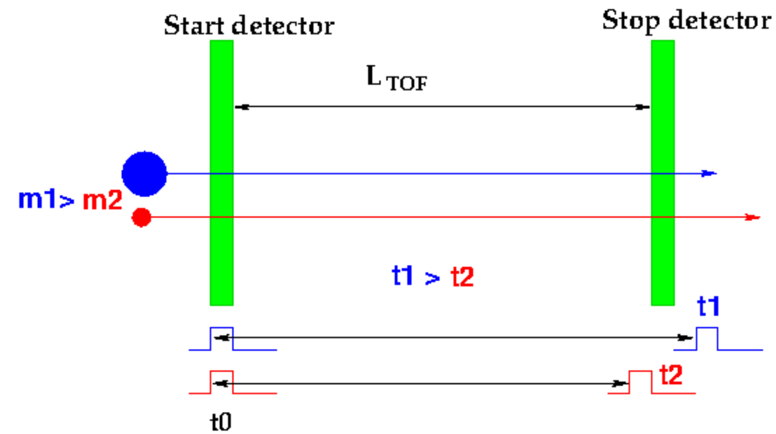




Time of Flight

Simplified scheme:

- For a given momentum a more massive particle has smaller *velocity*, therefore it will spend more *time* to travel a given distance L between two detectors



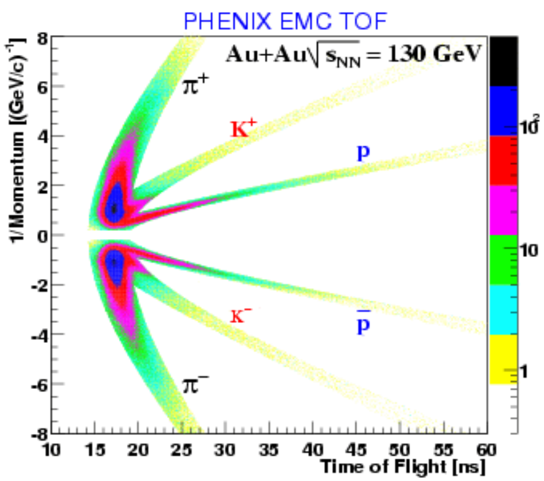
So in the experiment: assuming that particle momentum is known from tracking, derive particle *mass* by measuring its velocity

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

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

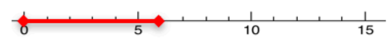
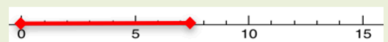
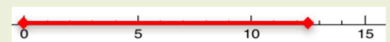
-> Note: the technique works best for large detectors and low momenta

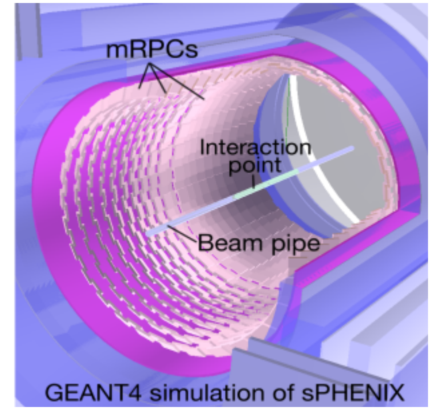
- **Caveats**
  - For a compact detector need very high timing resolution for this to work above few GeV/c
  - Providing a high resolution T_{start} measurement is not trivial at an EIC (electron bunches have finite, ~1cm length; installing ~10ps timing detectors around IP adds material, etc)



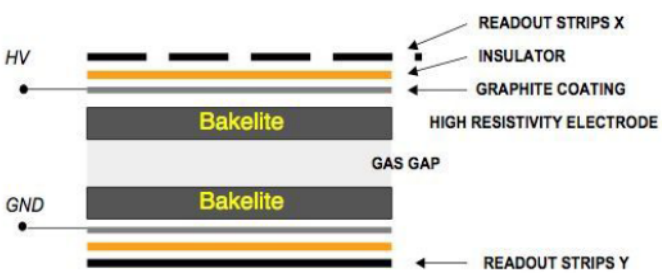
Time of Flight for EIC

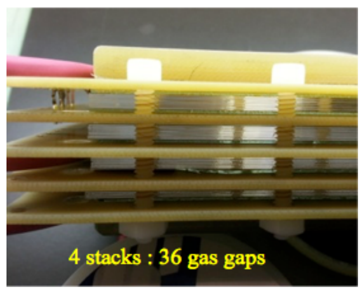
In "sigma" units, for 10ps timing: **pion/kaon** & **kaon/proton** separation

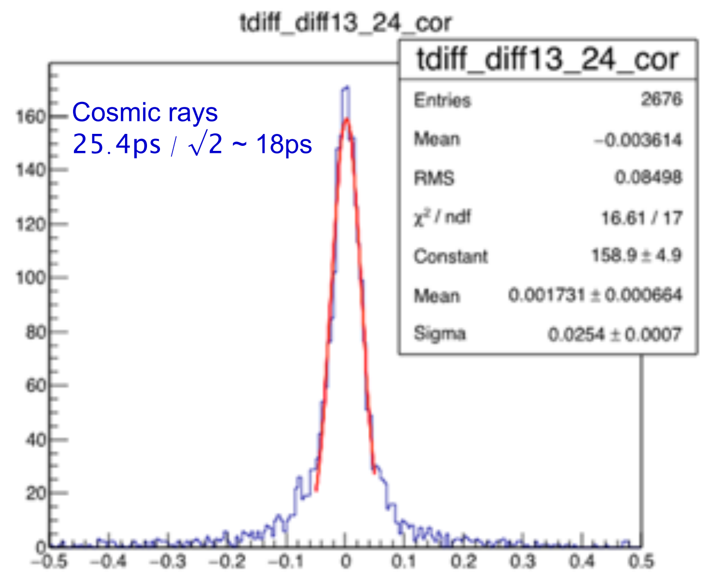
σ_{tot}=10 ps	1m (Barrel)		
σ_{tot}=10 ps	4m (Hadron)		



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



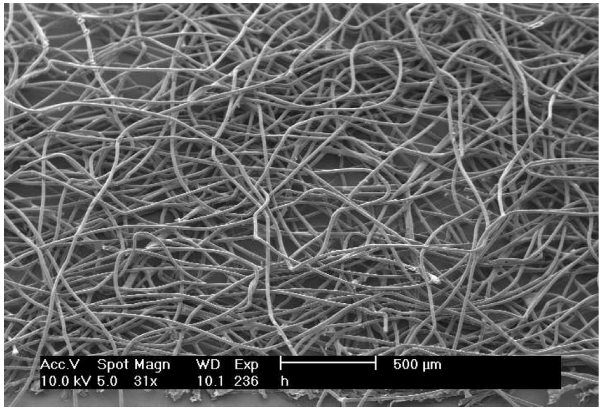


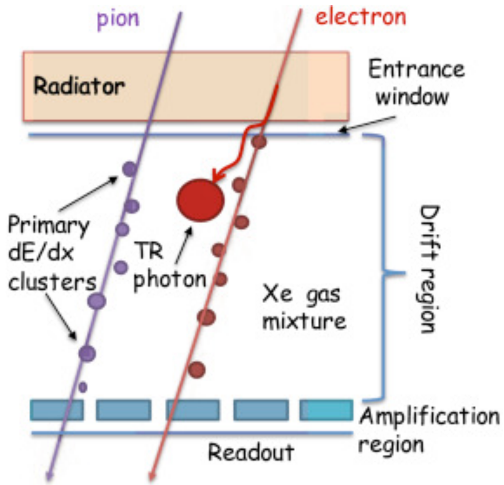


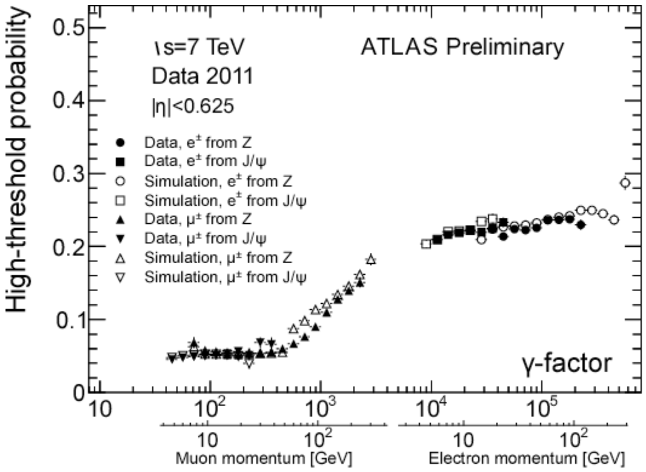
a charged particle passing through causes local discharge which induces signals in the readout strips

Transition radiation

- Transition radiation(TR) is produced by a charged particles when they cross the interface of two media of different dielectric constants
- The probability to emit one TR photon per boundary is of order α~1/137, therefore multilayer dielectric radiators are used to increase the transition radiation yield, typically few hundreds of mylar foils or a fleece
- Energy of TR photons are in X-ray region (2 - 40 keV)



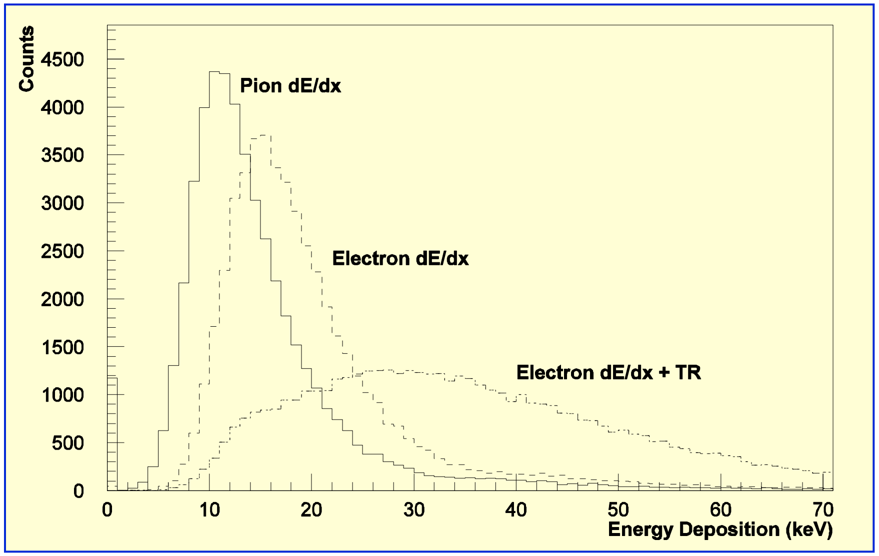


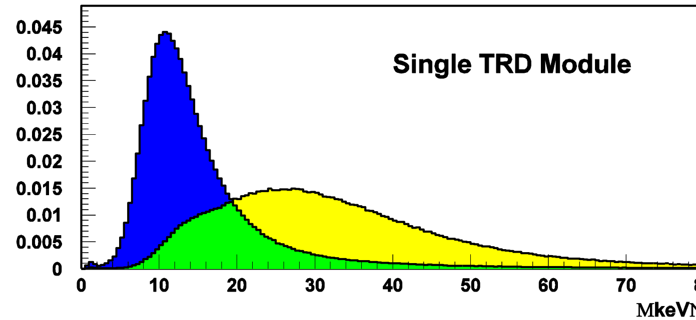


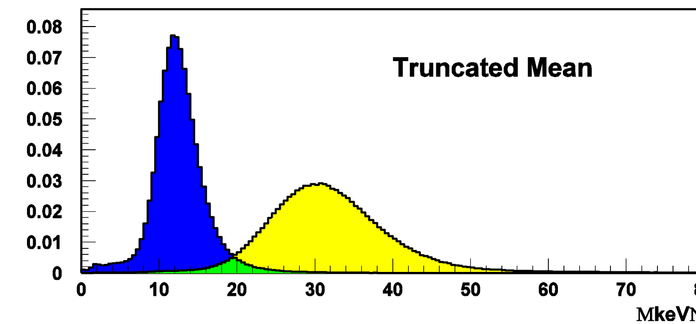
- The onset of TR starts at about γ ~ 1000 (so electrons will produce a measurable signal starting from ~1-2 GeV/c momenta while pions will not emit TR up to a few hundred GeV/c) -> this is the basis for electron/pion separation
- Total TR Energy is proportional to the γ factor of the charged particle

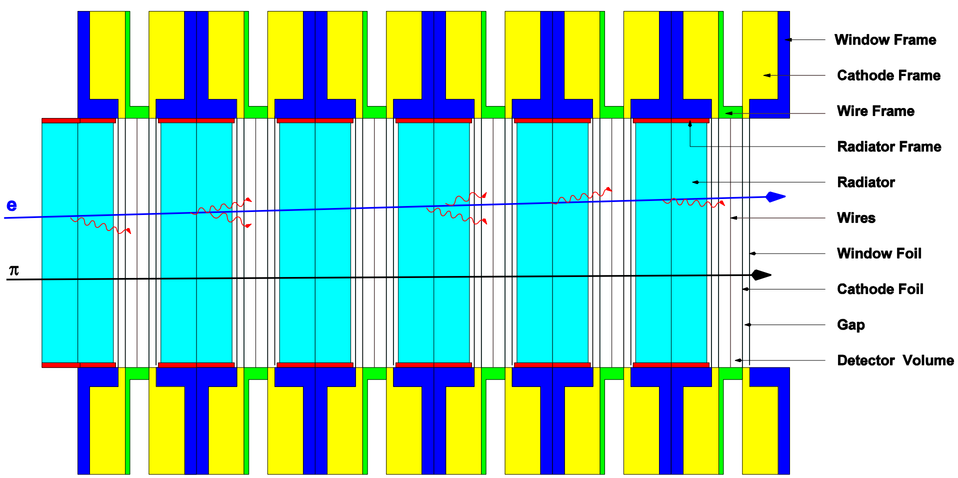
HERMES TRD

Single module response expectation





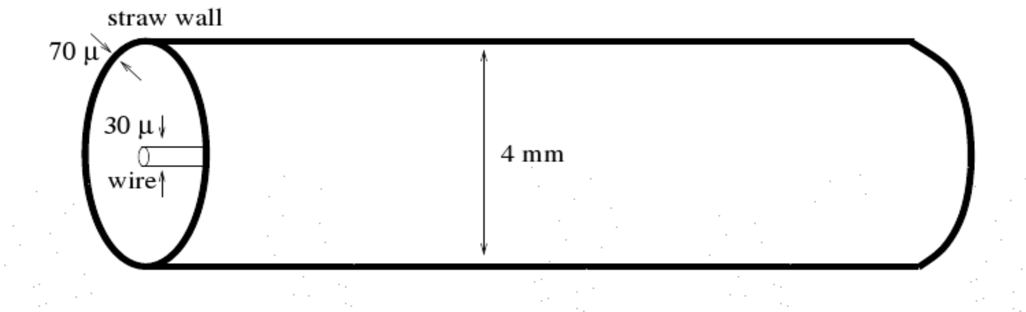


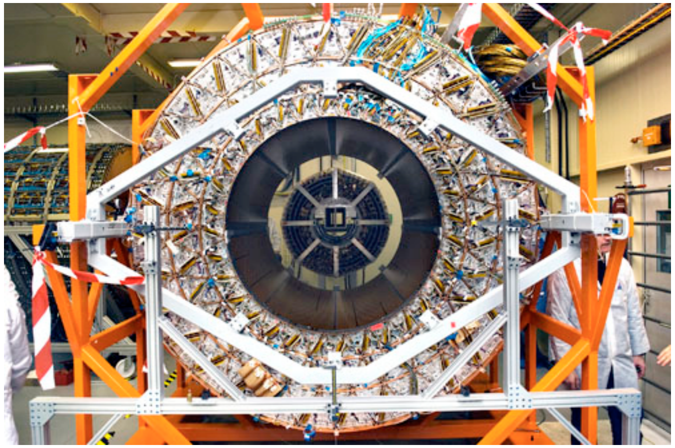


- Perhaps the first routinely working TRD in a NP experiment
- Pion rejection factor of ~130 for HERMES electron energy range (27.5 GeV HERA beam)

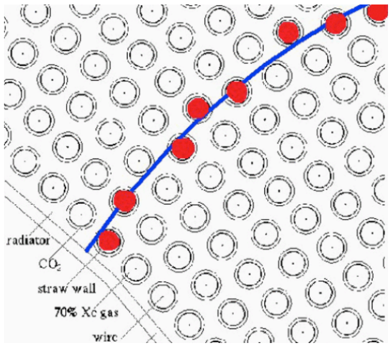
Six flat modules; Xe-based mixture; MWPC readout

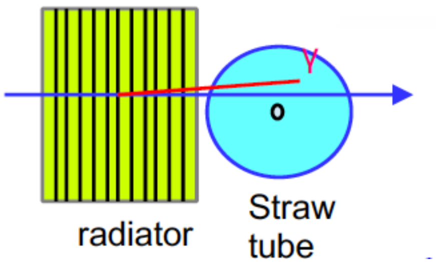
ATLAS Transition Radiation *Tracker*

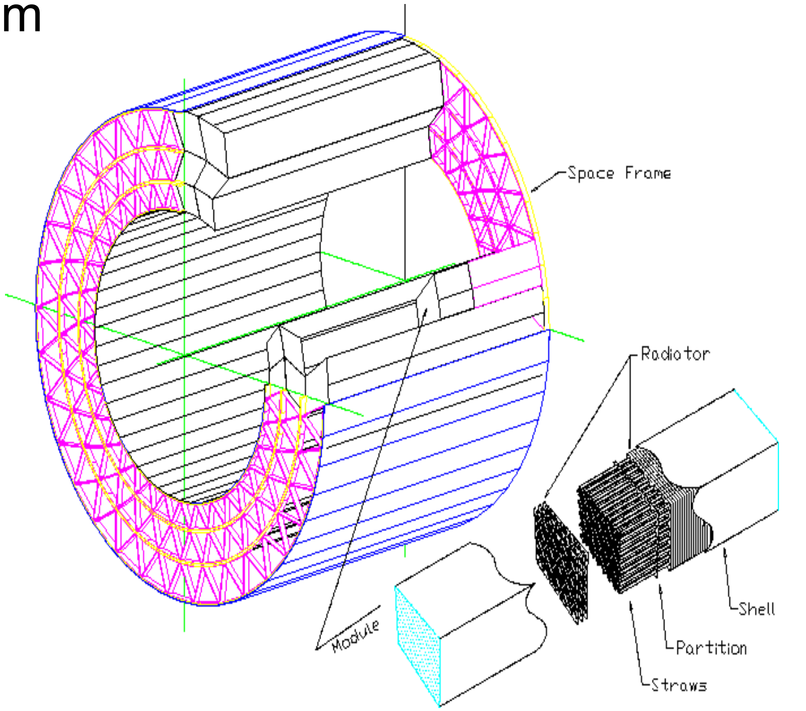




- Built of straw tubes
- Radiator foils are placed between the straws
- In addition to TR: spatial resolution ~130μm



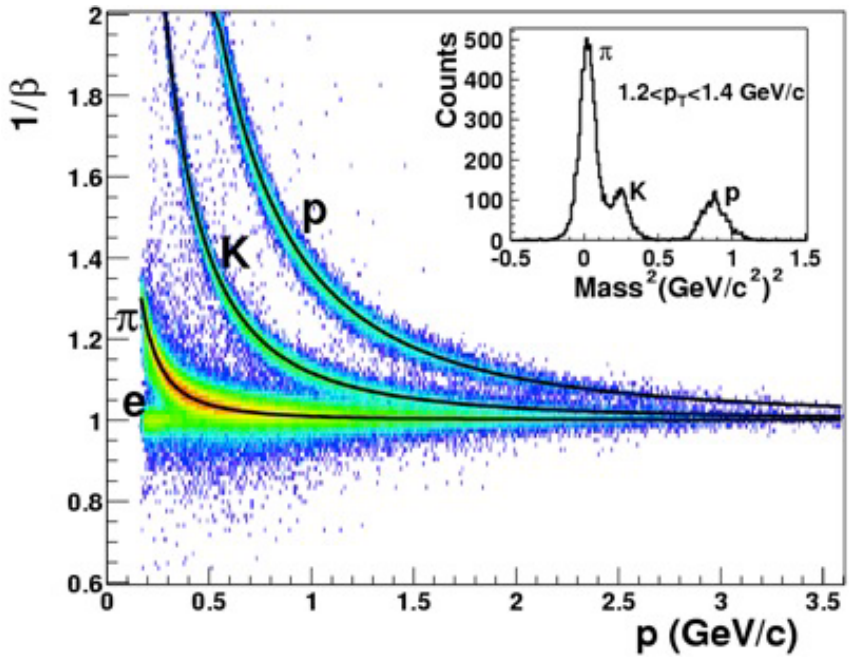




- Straw gas mixture Xe(70%) CO2(27%) O2(3%)

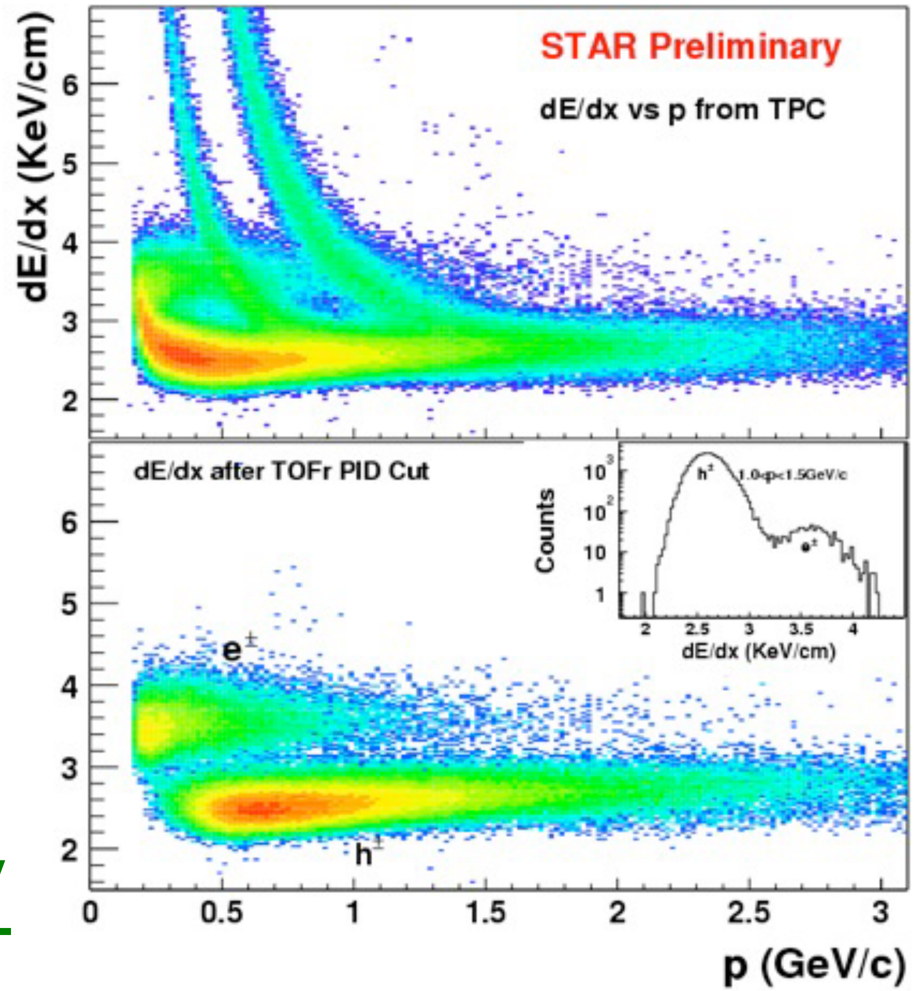
Combination: time of flight & dE/dx @ STAR

Time of Flight alone



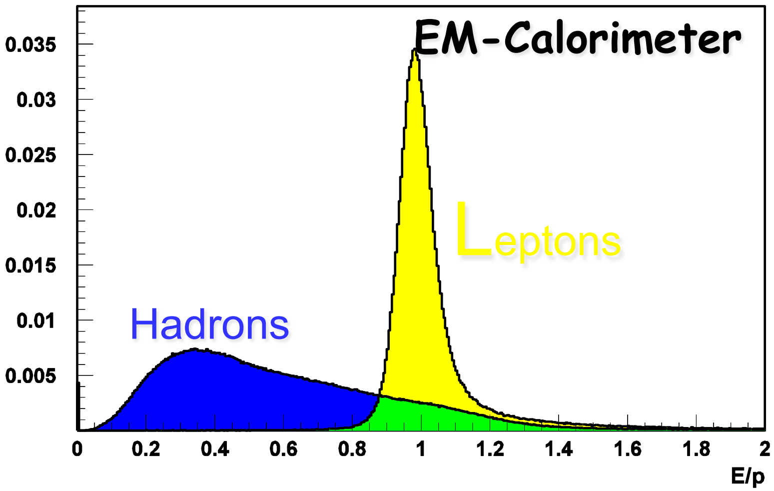
-> Note: combining information from several independent PID detectors can drastically improve the selection quality (in this example provides clear electron-hadron separation up to ~3 GeV/c

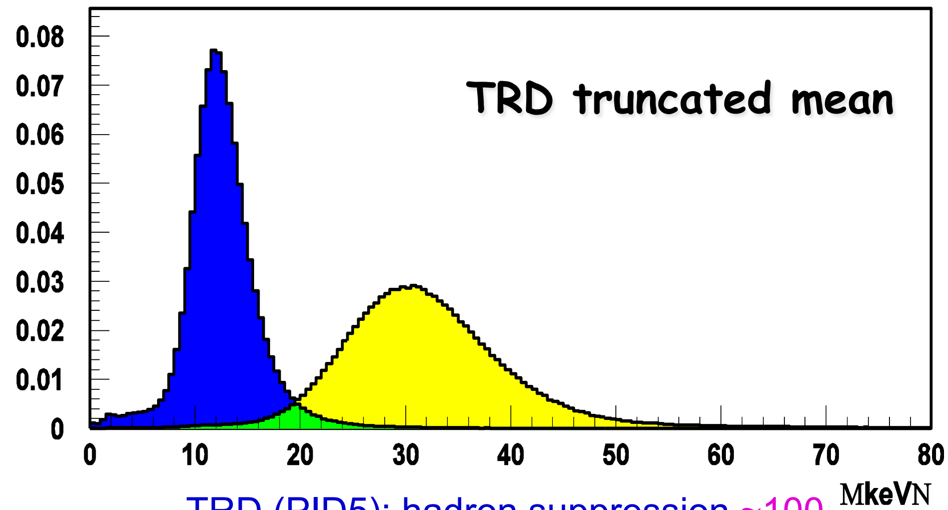
dE/dx alone



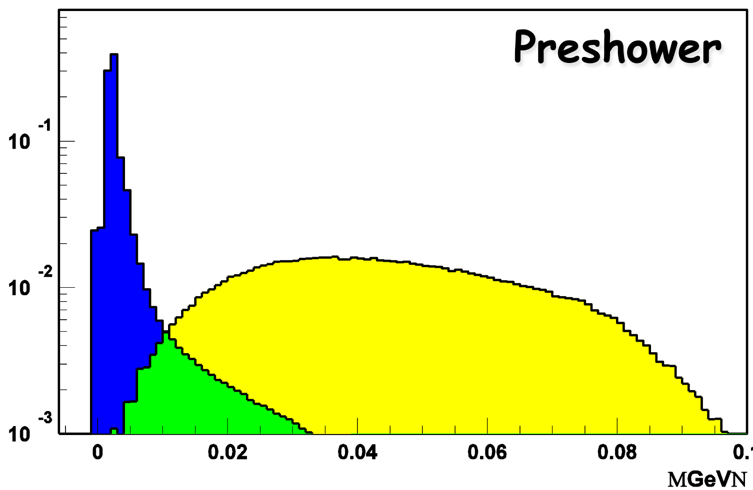
dE/dx with a hard ToF cut

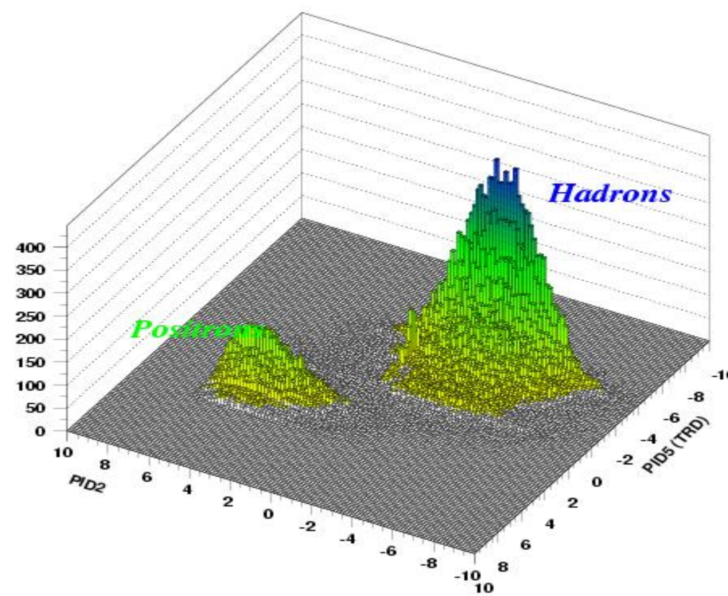
Combination: electron ID @ HERMES





TRD (PID5): hadron suppression ~100





Both together (PID2): hadron suppression ~1000

-> Note: overall suppression up to ~10^5

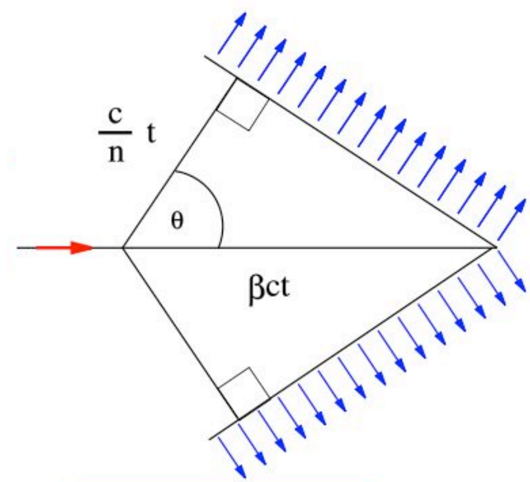
Cerenkov radiation

- Cherenkov radiation arises when a charged particle in a material moves faster than the speed of light in that same medium:

$$\beta c = v = c/n$$

- It is emitted at an angle θ_c, defined by particle velocity β and medium refractive inde

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



$\cos\theta_c = 1/\beta n$

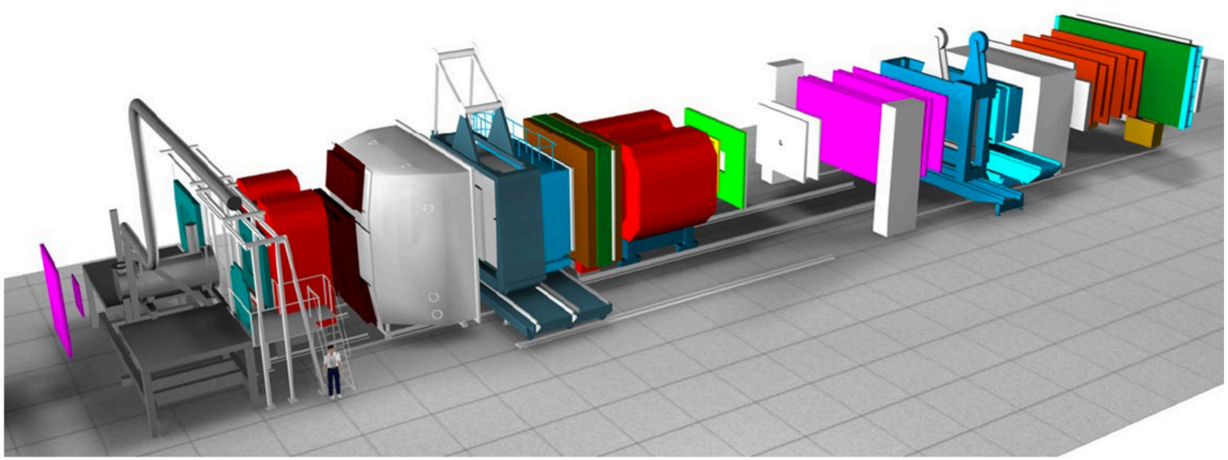
- Condition for Cherenkov radiation to occur: $\beta > c/n$
- Energy emitted per unit path length:

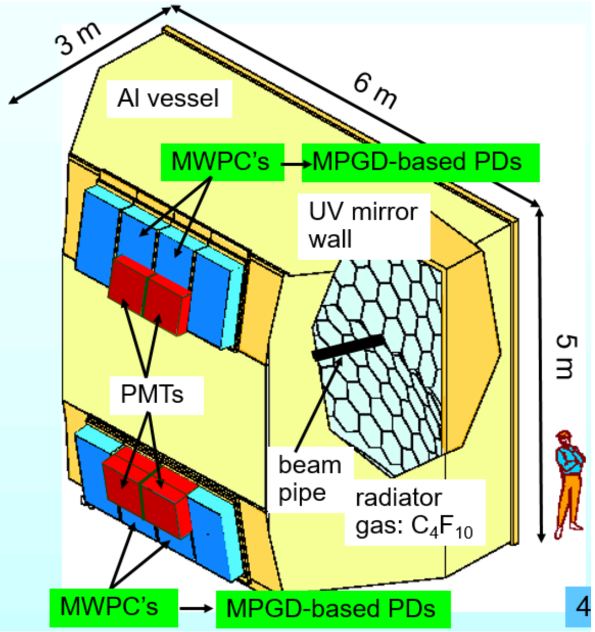
$$\frac{dE}{dx} = 4\pi^2 e^2 \int_{\beta n > 1} \frac{1}{\lambda^3}\left(1 - \frac{1}{\beta^2 n^2}\right) d\lambda$$

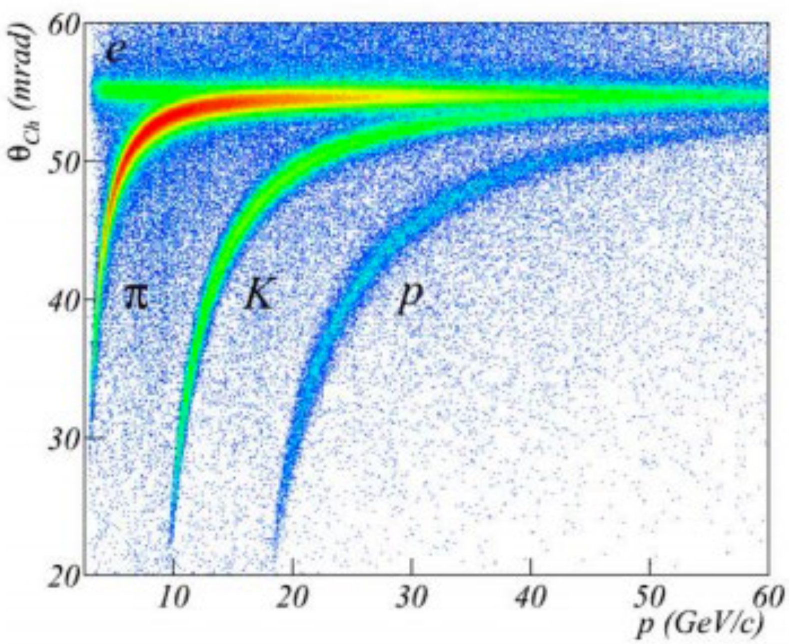
- Two main types of Cerenkov detectors: threshold and ring-imaging ones

-> Note: Ring-Imaging CHerenkov (RICH) detectors are assumed to be the main tool for hadron PID for an EIC detector

Illustration: COMPASS RICH#1



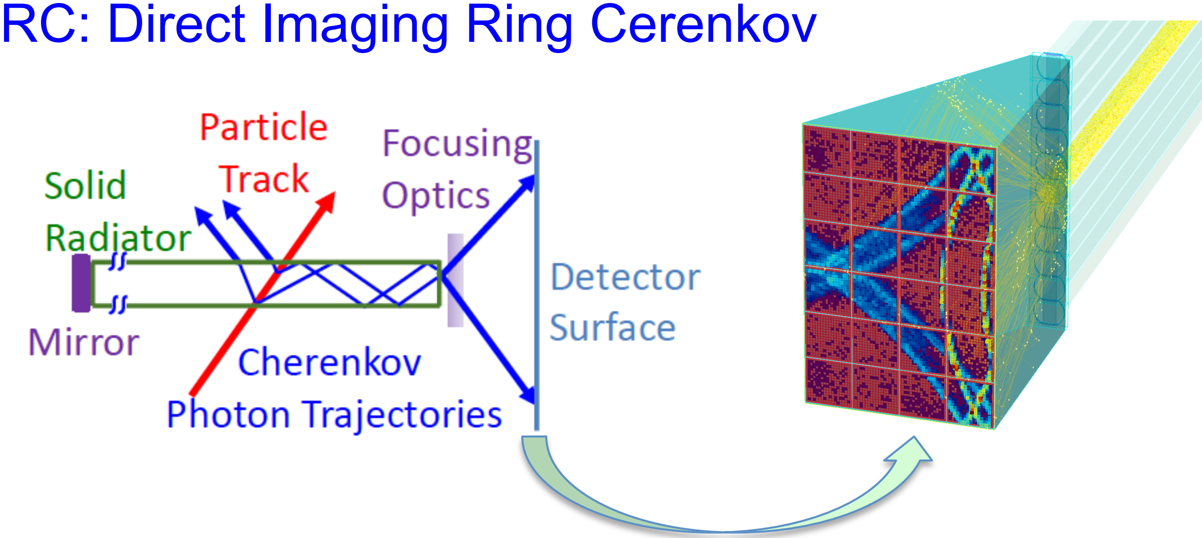


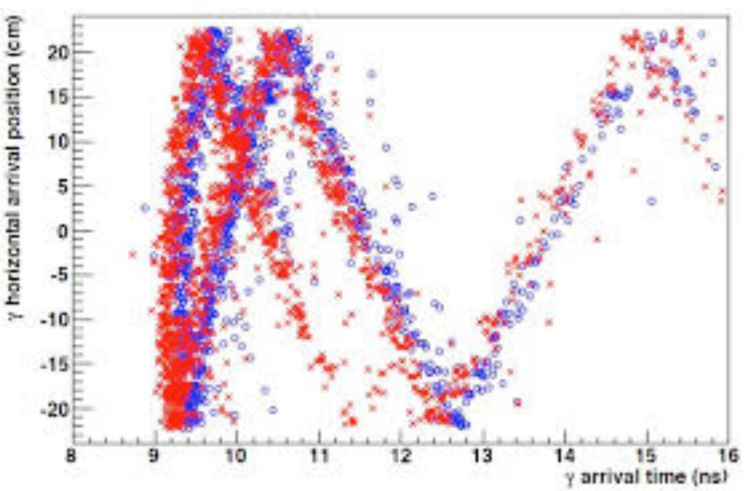


- A single-radiator design with the relatively heavy C_4F_{10} radiator
- After upgrade: UV range, CsI-coated THGEM-based photon detectors
- A detector like this would fit EIC needs provided a lighter radiator (with the π/K separation up to ~50 GeV/c) is used

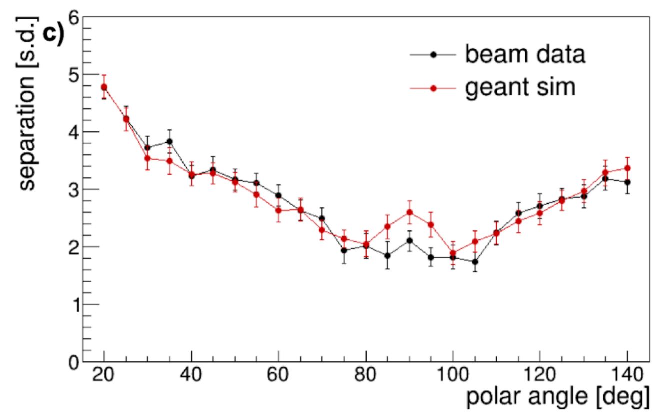
Barrel: DIRC with high resolution timing

DIRC: Direct Imaging Ring Cerenkov





Correlation between photon coordinate and arrival time for Belle II barrel DIRC

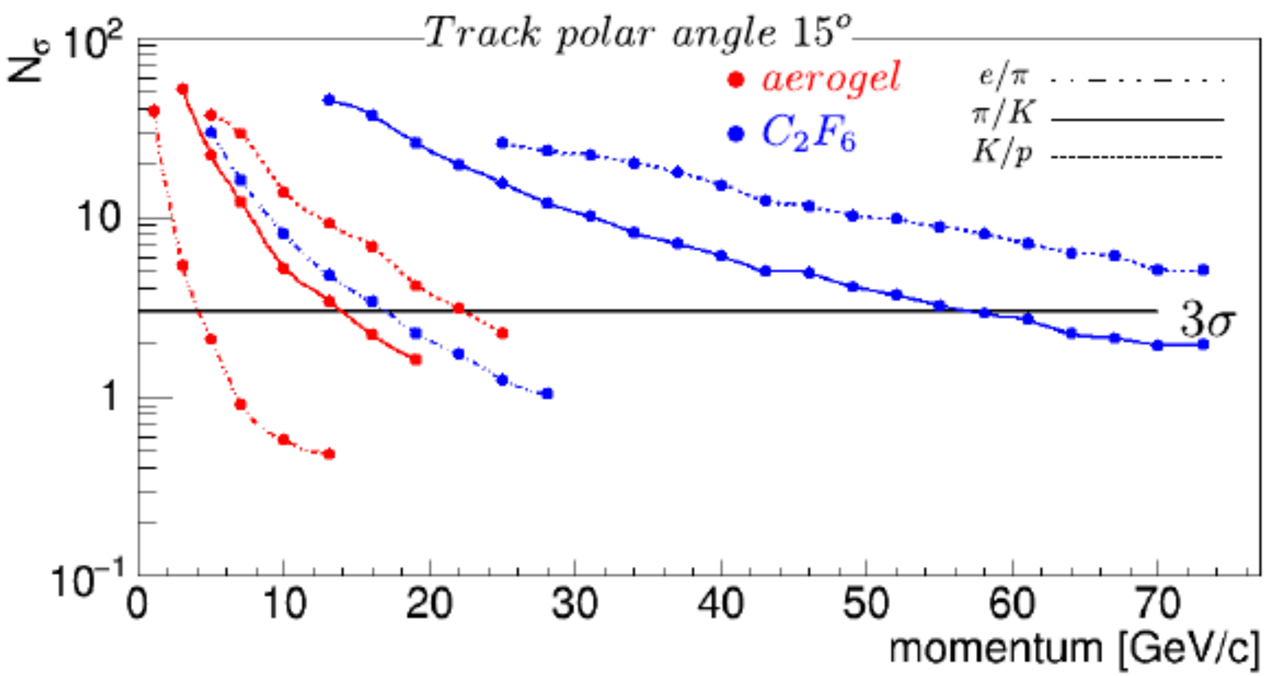


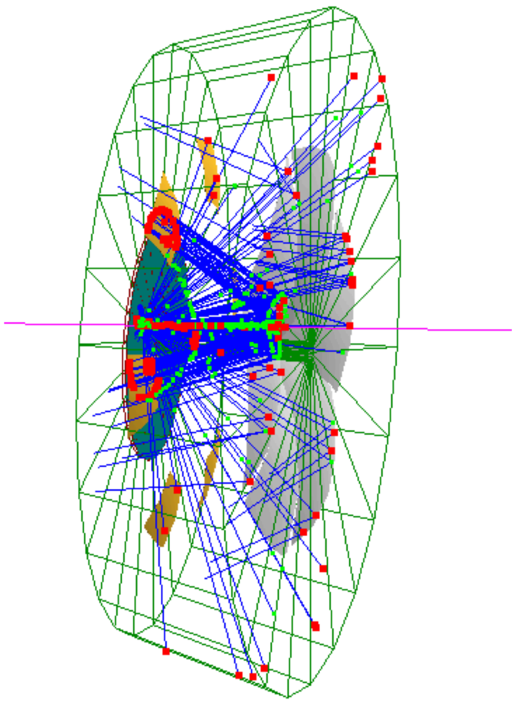
Projected π/K separation at 7 GeV/c for EIC barrel DIRC

-> Note: modeling shows that by using high-resolution timing one can extend π/K 3σ separation range to up to ~6 GeV/c, sufficient for EIC needs

Hadron endcap: dual radiator RICH

dRICH: use very successful HERMES-like configuration with two radiators (here: n=1.02 aerogel and C_2F_6 gas) in order to provide continuous coverage with >3σ π/K separation in the whole required EIC hadron-going endcap momentum range, so from lowest momenta up to ~50 GeV/c





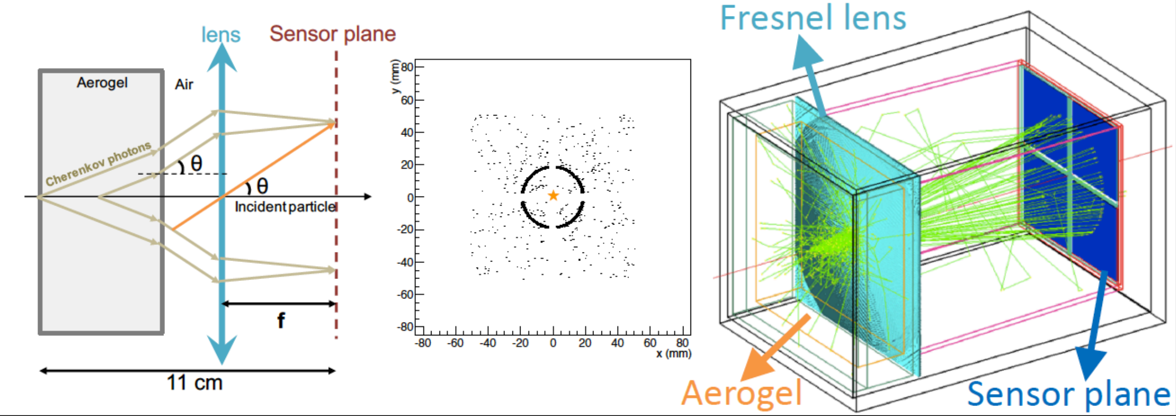
-> Note: one can also consider a pair of independent RICH detectors, where gaseous RICH may also work in UV range

-> In any case the biggest problem for gaseous RICH with ~1m long radiator is to work at all in the strong solenoid fringe field (tracks are bent!)

Lower momenta: modular RICH

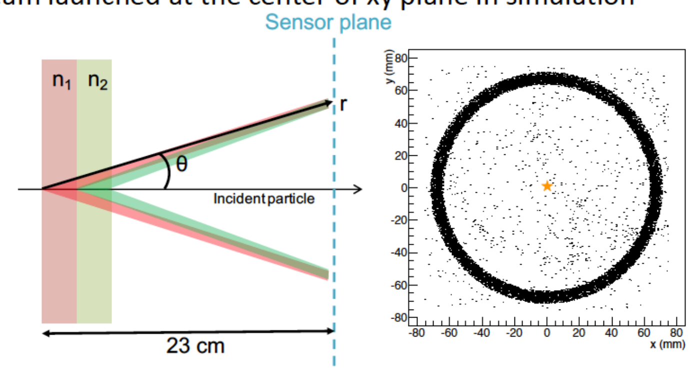
mRICH: use aerogel (low density transparent radiator with n ~ 1.2 .. 1.5) in a configuration with a Fresnel lense rather than Belle II – like proximity focusing configuration

Lens-Based mRICH Design

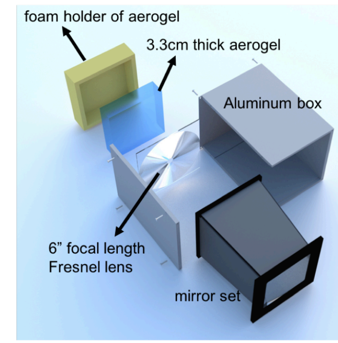


9 GeV/c pion beam launched at the center of xy plane in simulation

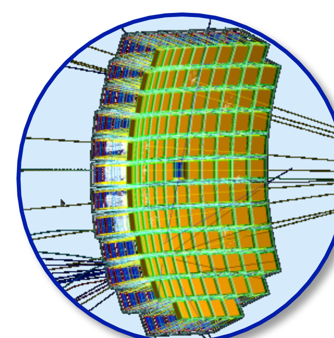
Two-Layer Proximity Focusing Design (BELLE-2 ARICH)



- EIC mRICH designed for K/pi ID up to 10 GeV/c
- BELLE-2 ARICH aims to separate pion and kaon up to 4 GeV/c



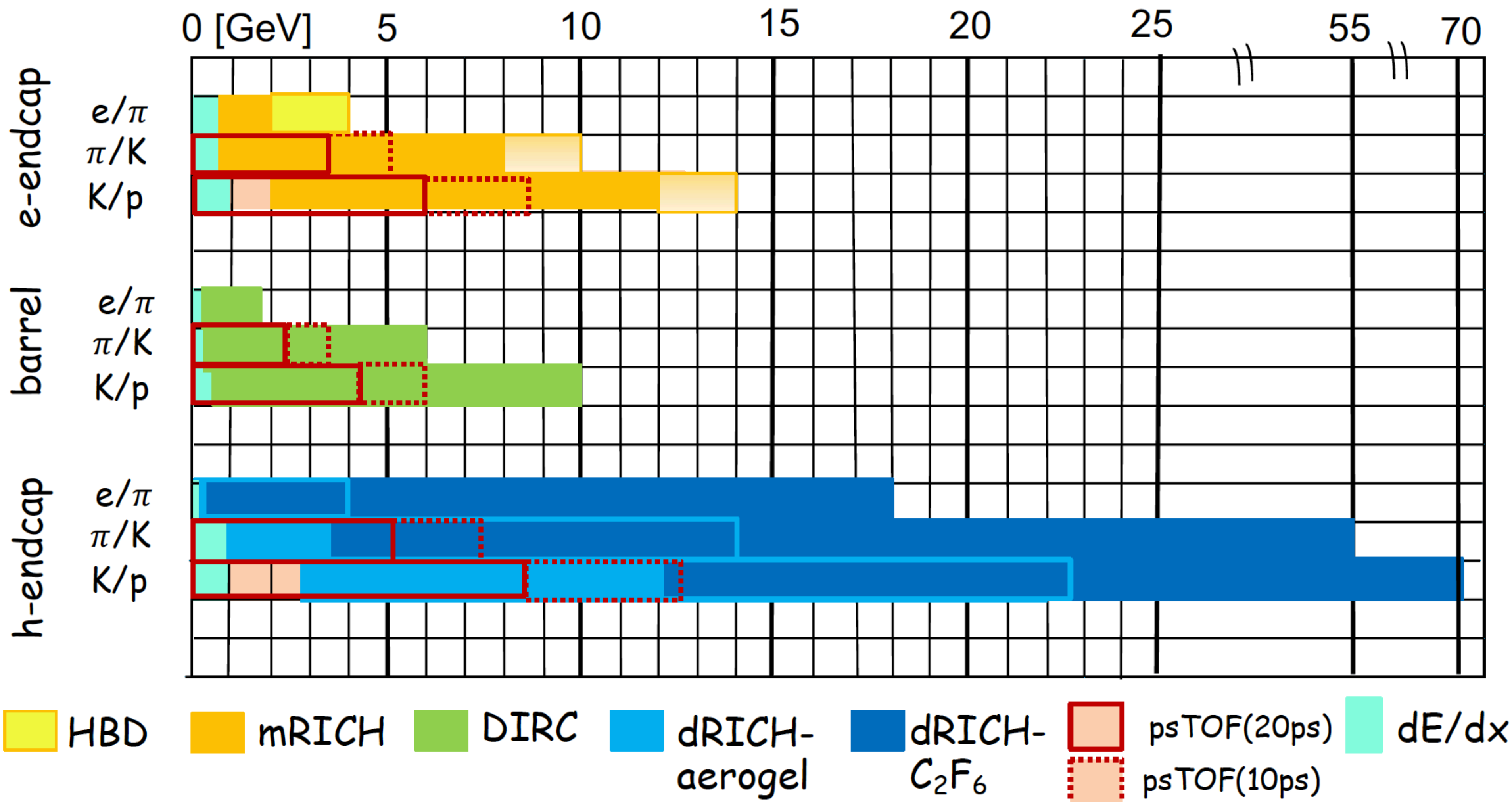
Single module



EIC endcap matrix

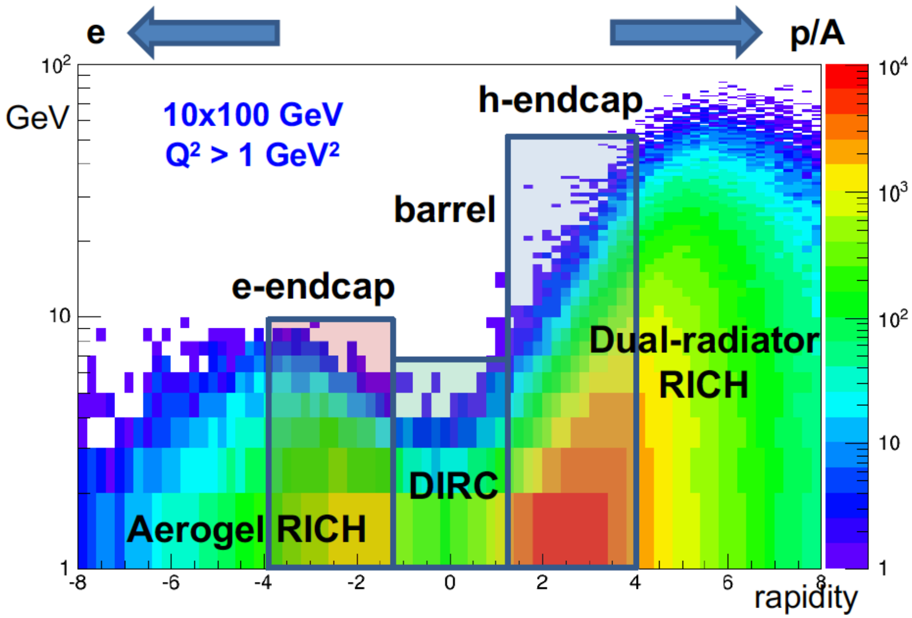
-> allows to extend the momentum range, save linear space as well as minimize the size of the photosensor assembly

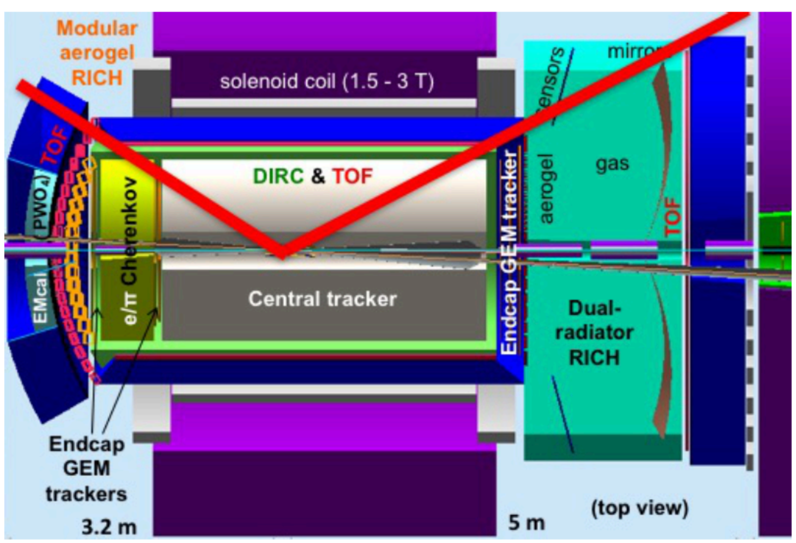
Expected particle ID performance



-> Note: electron/pion separation will be mostly provided by e/m calorimetry (and possibly Transition Radiation Detectors)

Hadron PID solution for EIC





- **h-endcap:** a RICH with two radiators (gas + aerogel) is needed for π/K separation up to ~50 GeV/c
- **e-endcap:** A compact aerogel RICH which can be projective π/K separation up to ~10 GeV/c
- **barrel:** A high-performance DIRC provides a compact and cost-effective way to cover the area π/K separation up to ~6-7 GeV/c
- TOF and/or dE/dx in a TPC can cover lower momenta

That’s all, guys!