EIC Detector

HUGS2023

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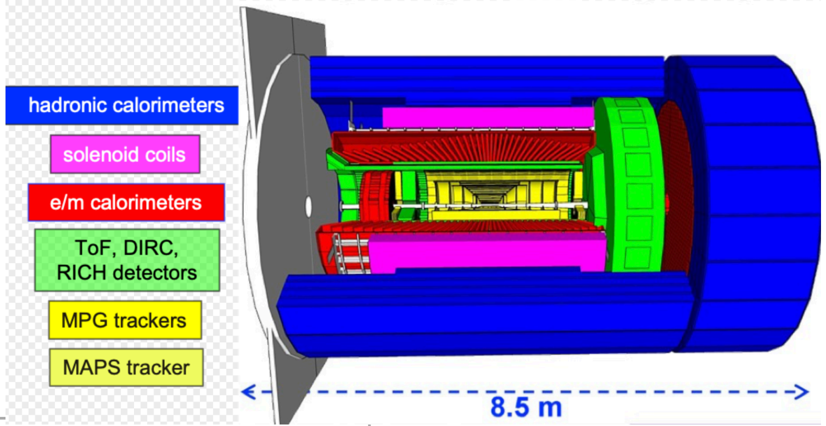
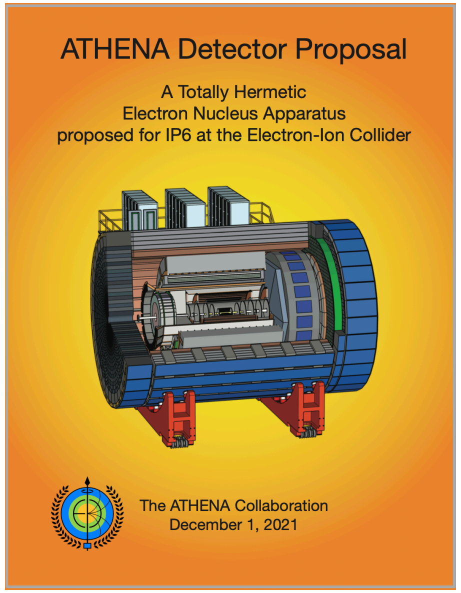
Outline

- Detector acceptance, location, size , global integration
- Central detector:
  - Tracking detectors, PID, Calorimeter …
- Far-forward/backward detectors
- Background

Materials for slides come from various EIC community efforts: Yellow Report, EIC Project, ECCE/ATHENA proposals, ePIC collaboration, etc
Many thanks to all collaborators!

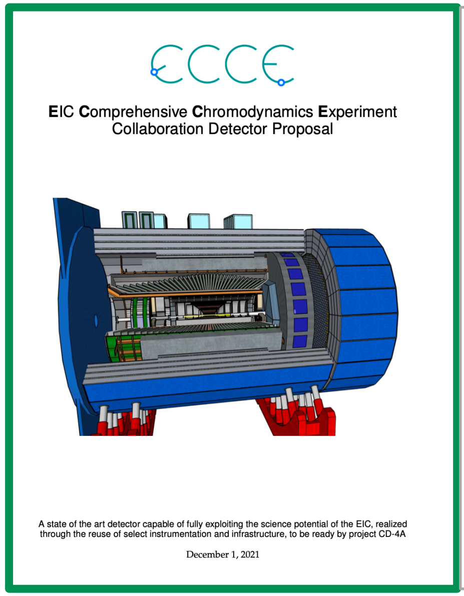



EIC YELLOW REPORT
Volume III: Detector


ATHENA Detector Proposal

A Totally Hermetic
Electron Nucleus Apparatus
proposed for IP6 at the Electron-Ion Collider

The ATHENA Collaboration
December 1, 2021


ECCE

EIC Comprehensive Chromodynamics Experiment
Collaboration Detector Proposal

A state of the art detector capable of fully exploiting the science potential of the EIC, realized through the reuse of select instrumentation and infrastructure, to be ready by project CD-4A

December 1, 2021

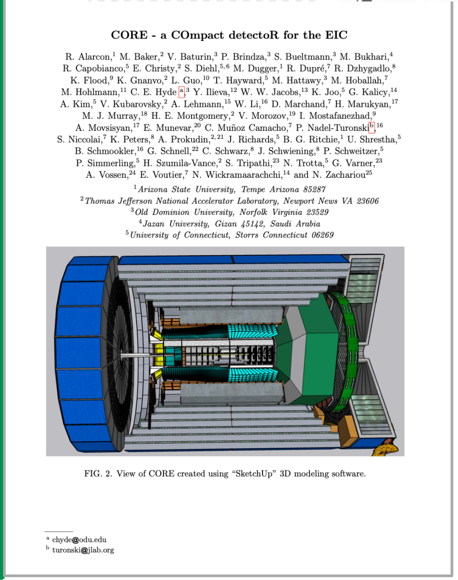

CORE - a COmpact detectoR for the EIC

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FIG. 2. View of CORE created using "SketchUp" 3D modeling software.

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ePIC

Number of events

$$\boxed{N = \sigma \cdot L \cdot \epsilon \cdot a}$$

Where L is a luminosity

σ is a cross section

a is an acceptance,

ε is a detector efficiency

Statistical uncertainties: $\sim \frac{1}{\sqrt{N}}$

($d\sigma^{tot}_{measured} = \sqrt{N_{obs}}\frac{\sigma^{tot}_{measured}}{N^{obs}}$)

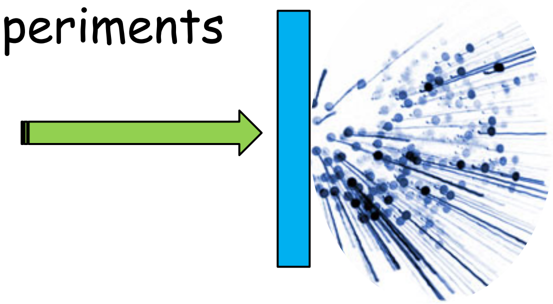
✓ As high luminosity as possible

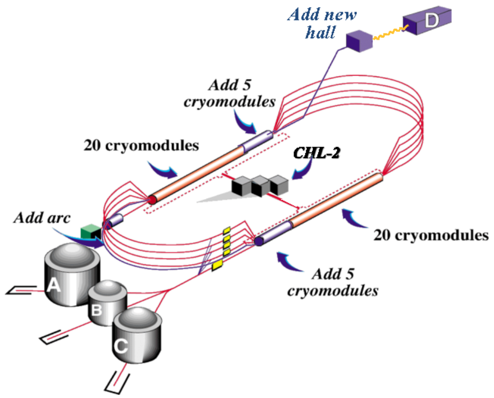
✓detector efficiency at 100% => no dead-time for detectors

✓full acceptance (100%) => detect all particles

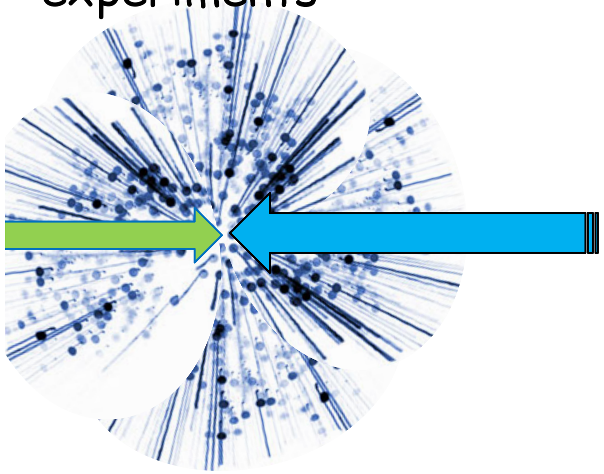
Acceptance and event kinematics :
fixed target vs collider ?

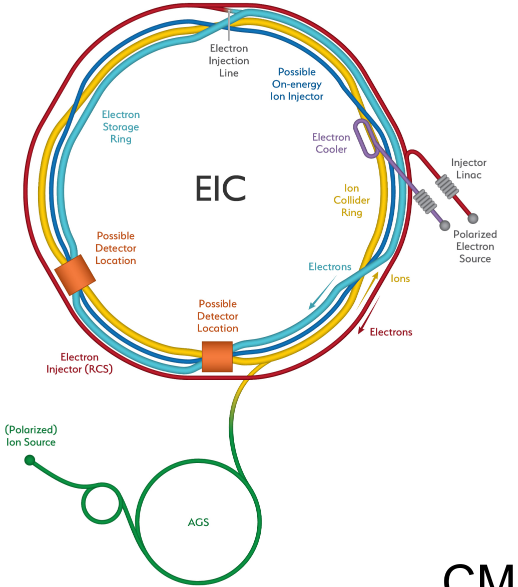
Fixed target
experiments





Collider
experiments



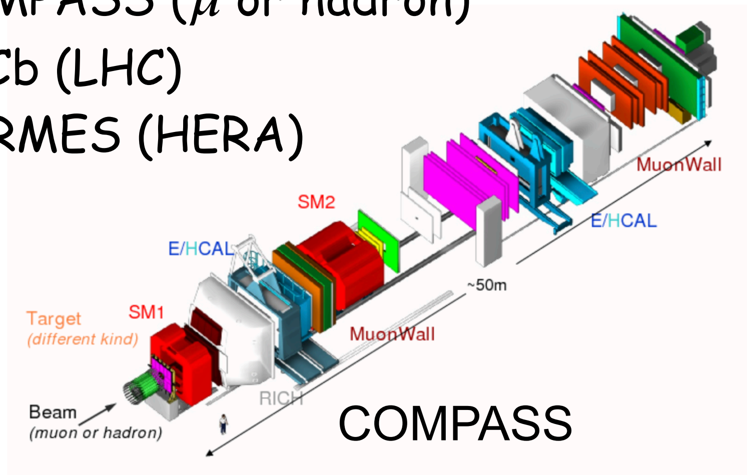


CEBAF/JLAB (e)

COMPASS (μ or hadron)

LHCb (LHC)

HERMES (HERA)



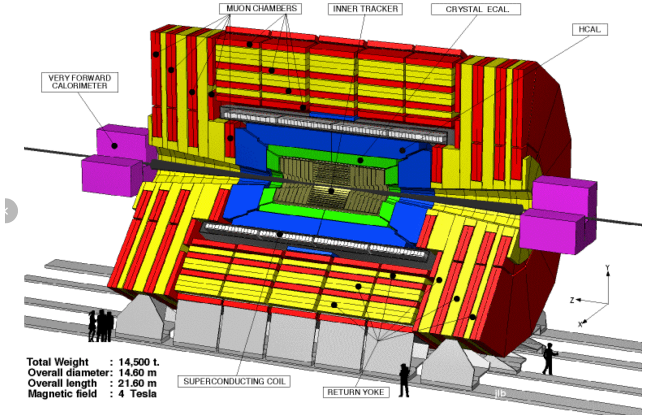
COMPASS

(pp) - ATLAS, CMS (LHC)

(e+e-) - KEK (Belle-II)

(e- p/A) - H1,ZEUS (HERA) , **EIC**

CMS



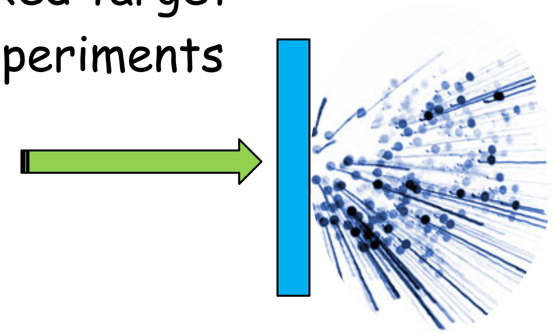
$Q^2 = s \bullet y \bullet x$

$$s = 4 \cdot E_e \cdot E_p$$

Homework question:

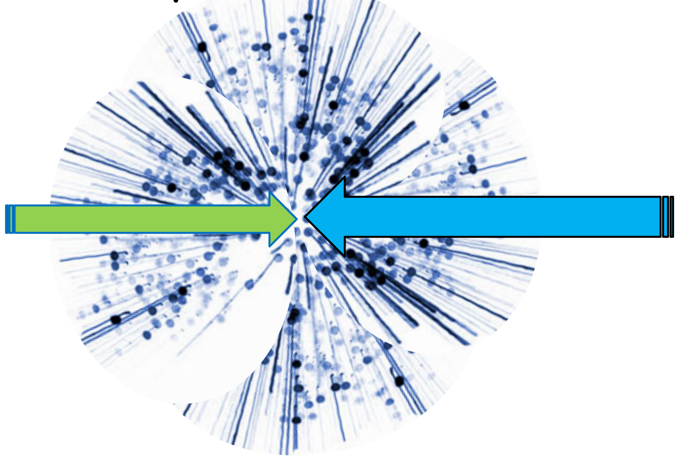
At EIC, electrons with energy of 18 GeV will collide with protons with energy of 275 GeV . Calculate the center-of-mass energy of this accelerator.
Consider an experiment, where protons are at rest (fixed target). What electron energy would be needed to obtain the same center-of-mass energy as at EIC collider ?

Fixed target experiments



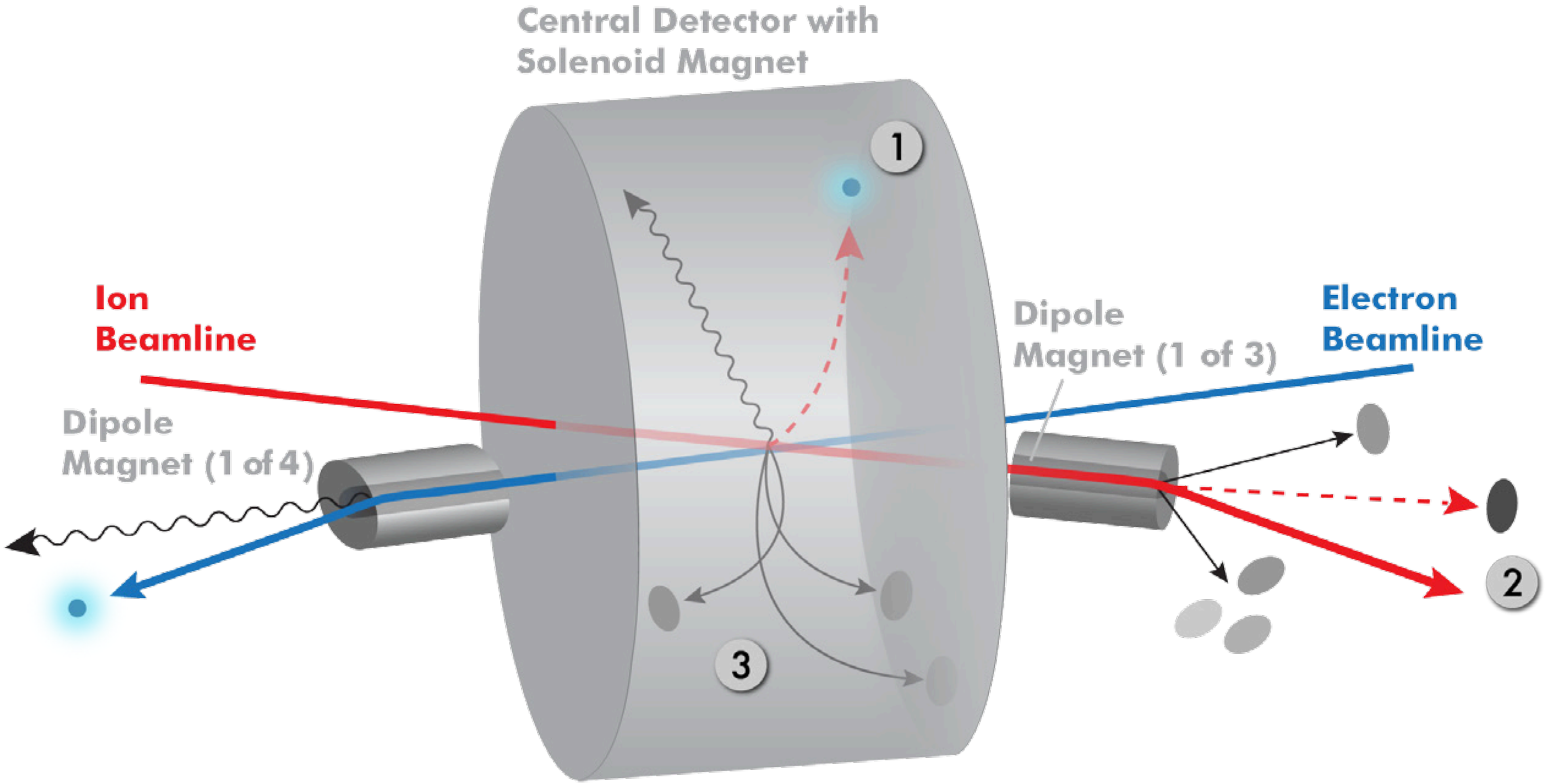
vs

Collider experiments



Collider: Total acceptance detector

- In ideal case – we want to have 4π coverage for the detector.



But, beam elements **limit a forward acceptance**

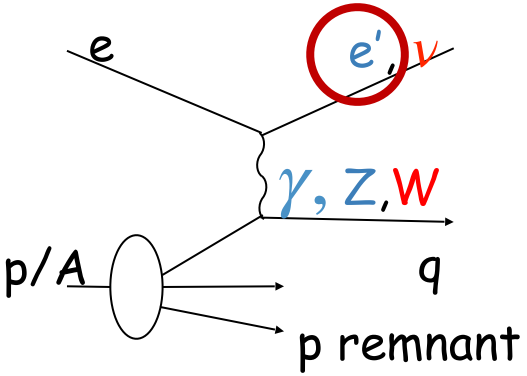
Detection of forward going particles are particularly challenging

- not usual concern at colliders
- Higher the Ion Beam energy, more difficult to achieve.

=> Integration with accelerator is very important

=> eP collider=> forward and backward directions have different functions.

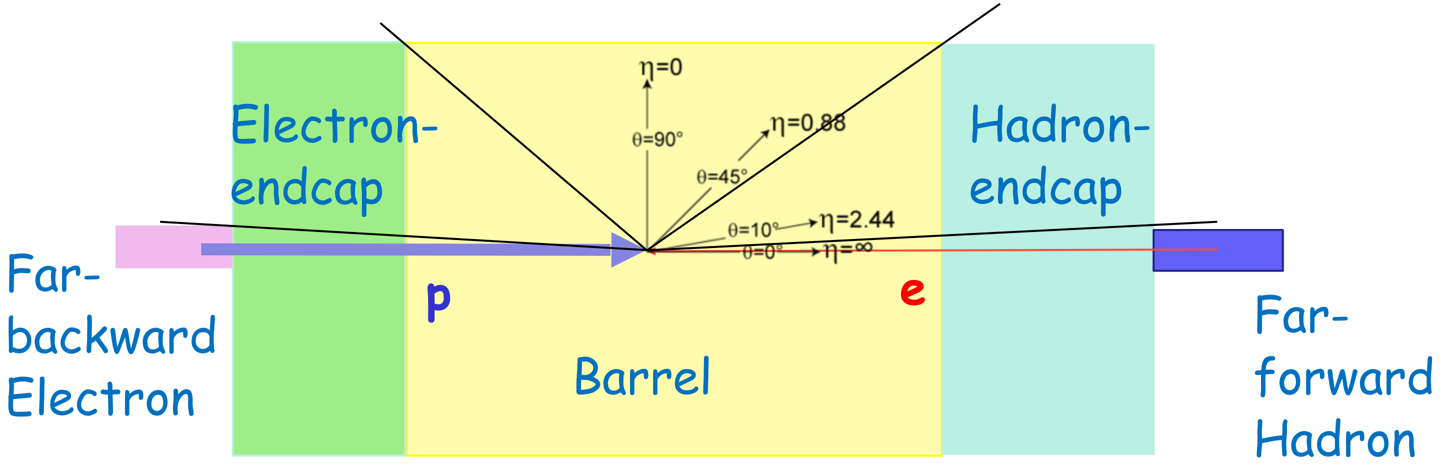
Why endcaps and forward areas are important at EIC?

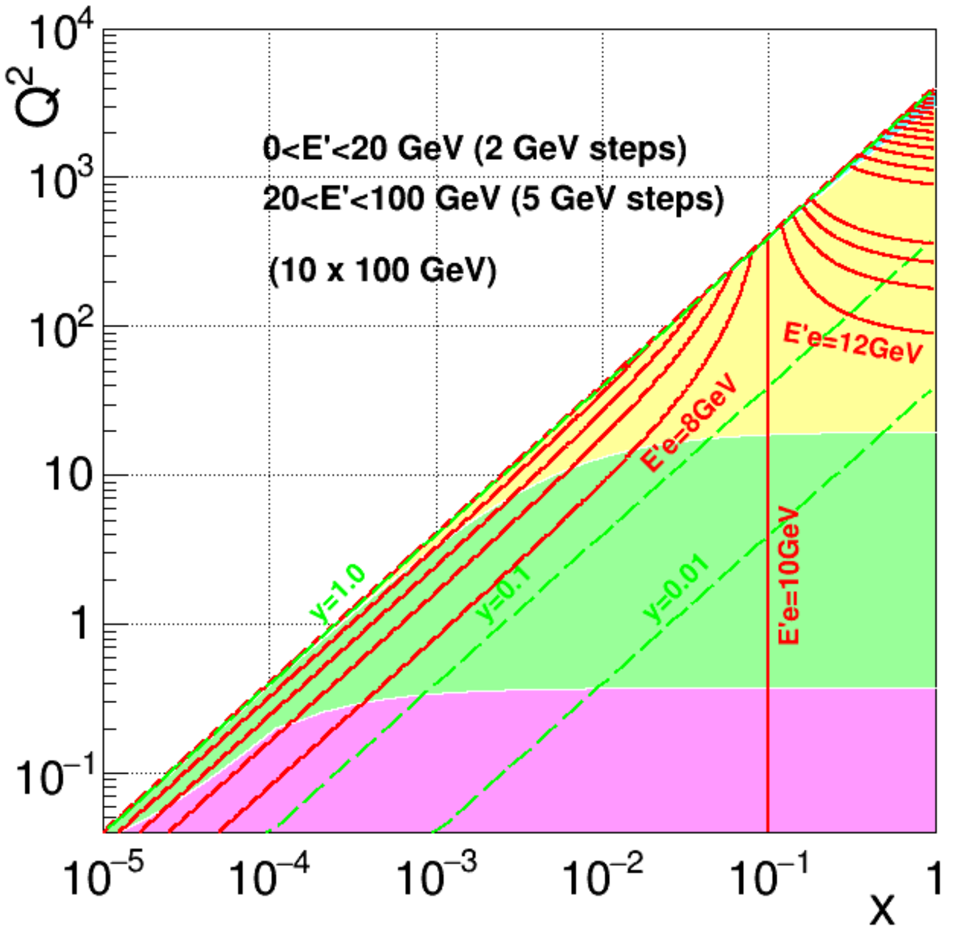


$$Q^2_{\mathrm{EM}} = 2E_eE_{e'}\,(1+\cos\theta_{e'})\,,$$

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

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



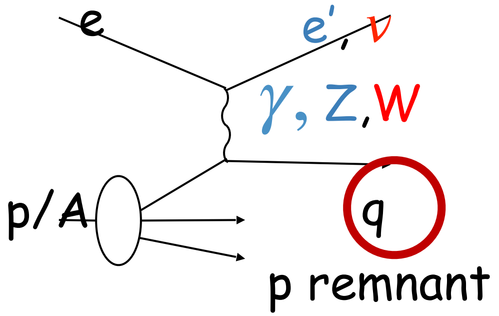


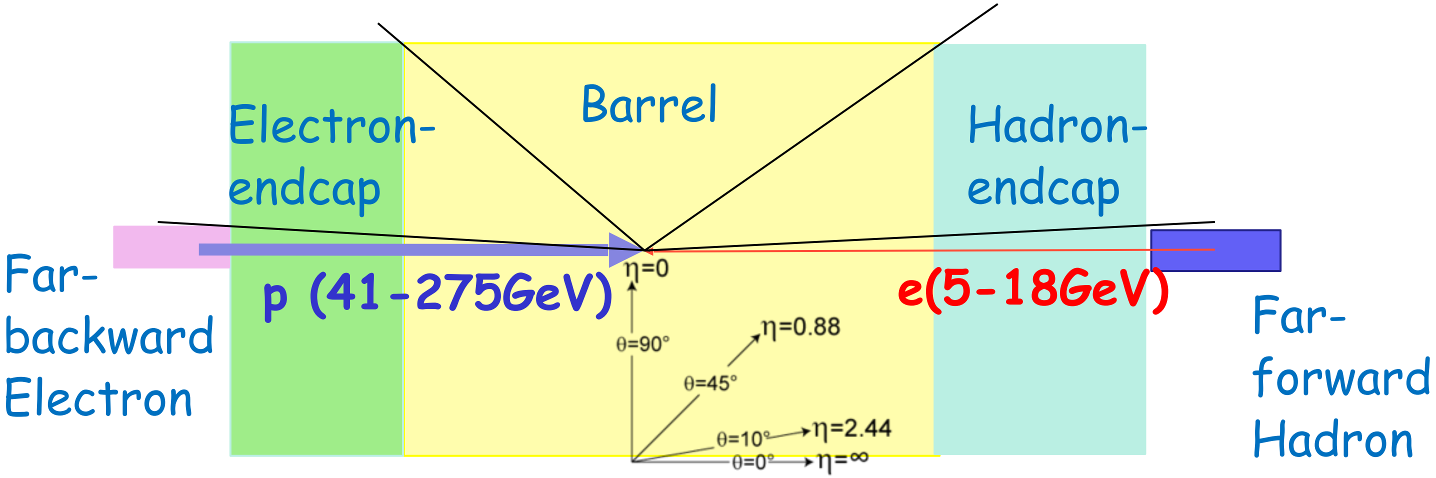
Pseudorapidity:

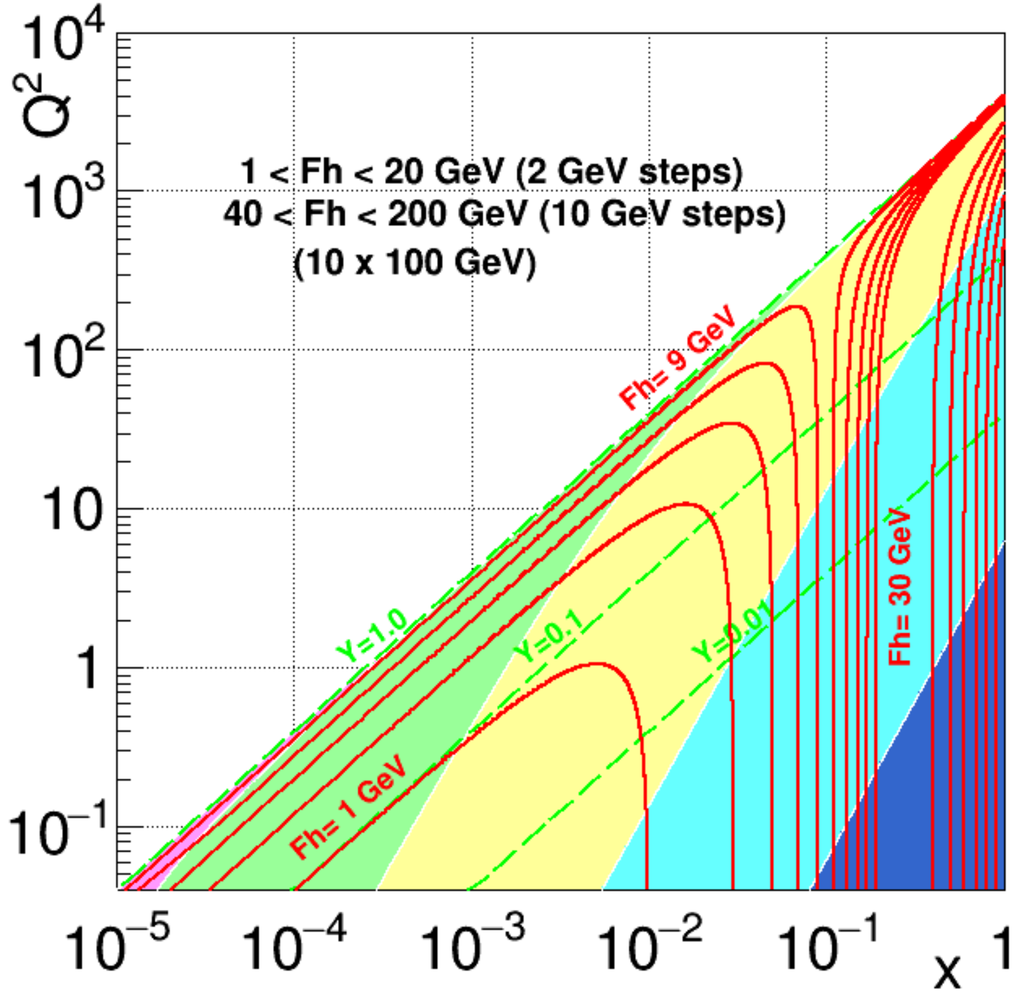
$\eta = -\ln(\tan(\theta/2))$

Transition area from DIS to Photoproduction (Q^2<5GeV)

Why endcaps and forward areas are important at EIC?



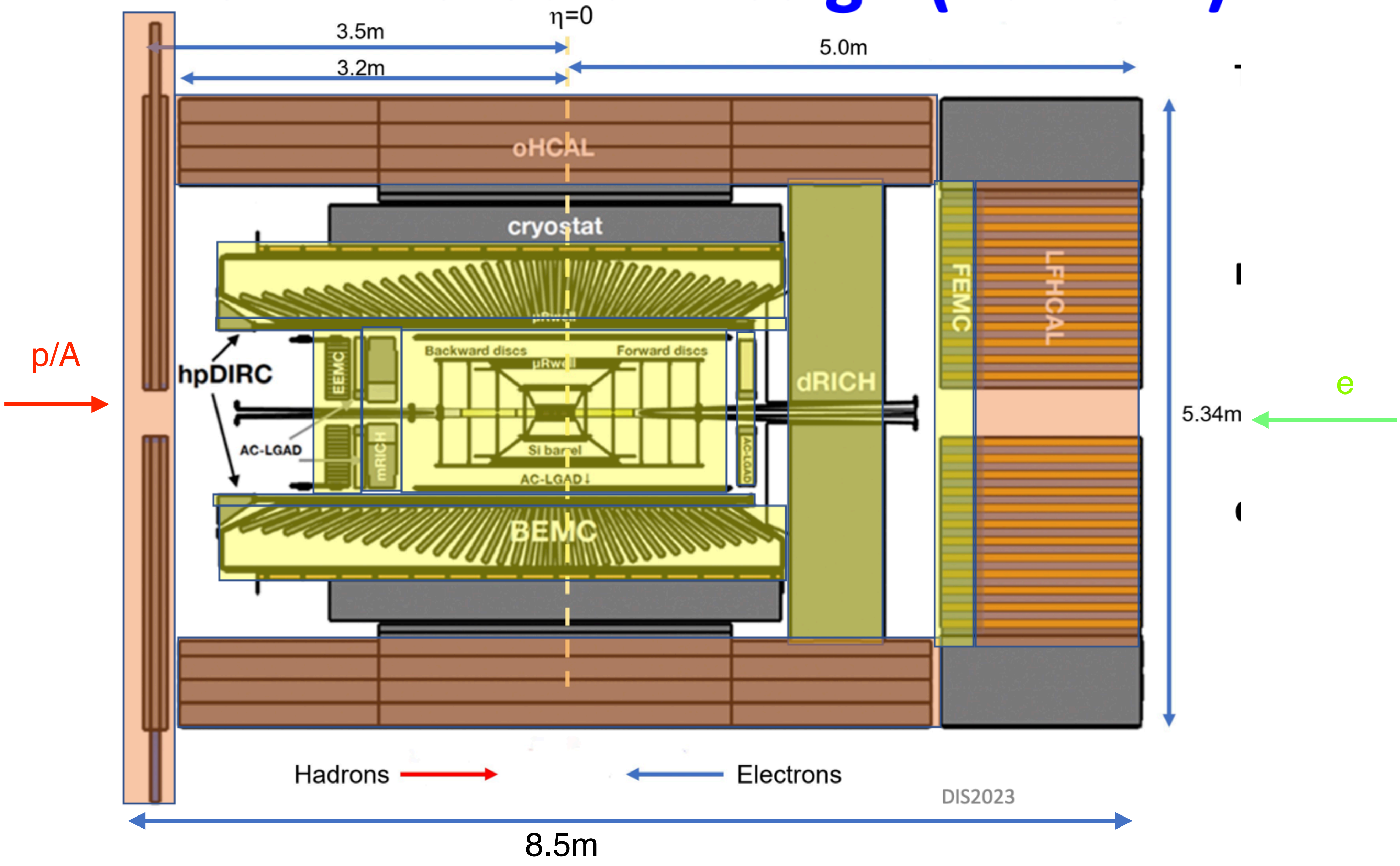




- All hadrons are boosted towards hadron-endcap due to asymmetric beam energies
- Proton/Ion Remnant
- Diffractive/exclusive physics in the Far-forward area

ePIC Detector Design (Current)

Central detector



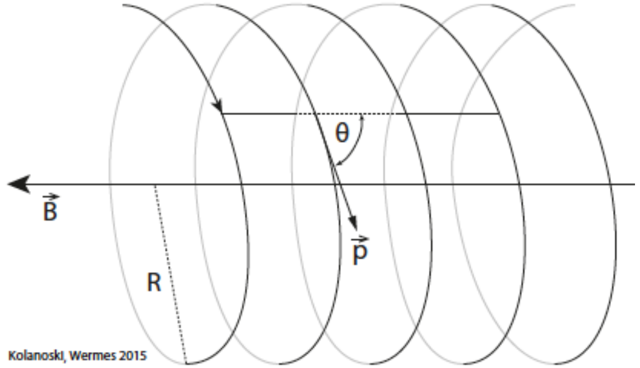
Why do we need a magnetic field?

Magnetic field to measure momentum and charge

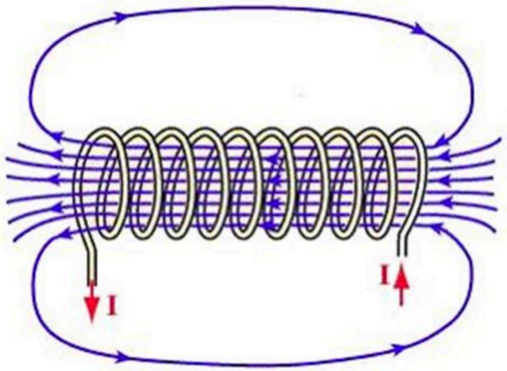
Solenoid:

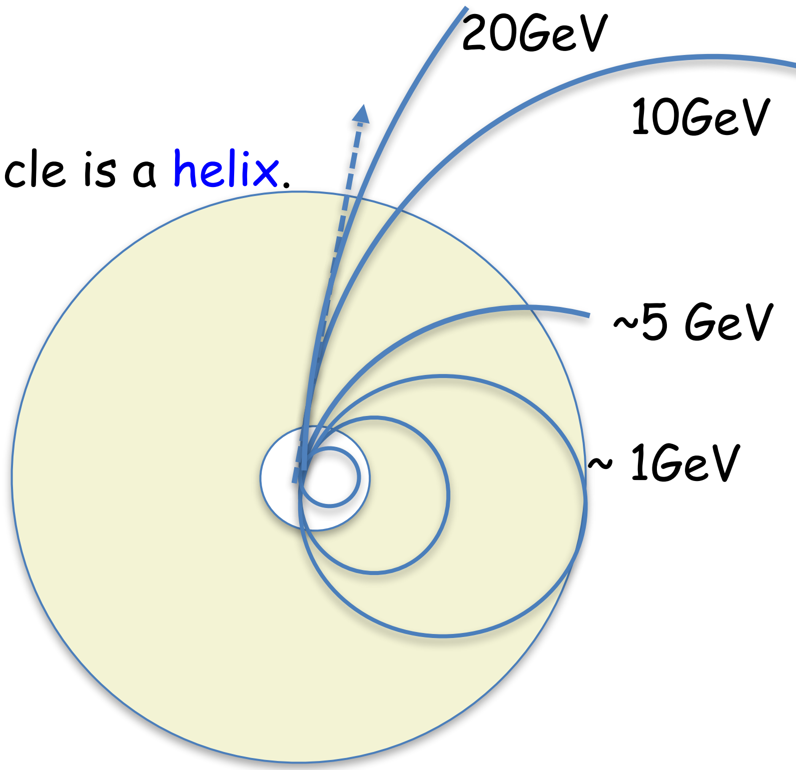
In a homogeneous B-field the motion of a charged particle is a helix.

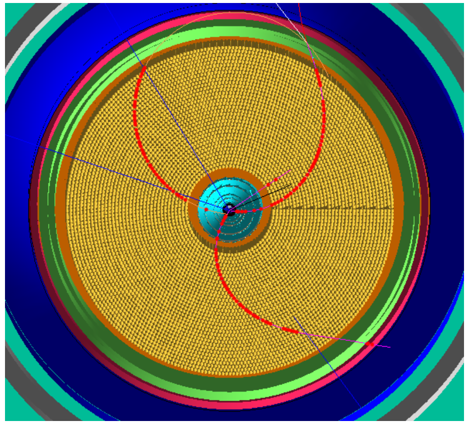
$$pT[\text{GeV}] = 0.3 \cdot B\,[\text{T}] \cdot R\,[\text{m}]$$



Kolanoski, Wermes 2015

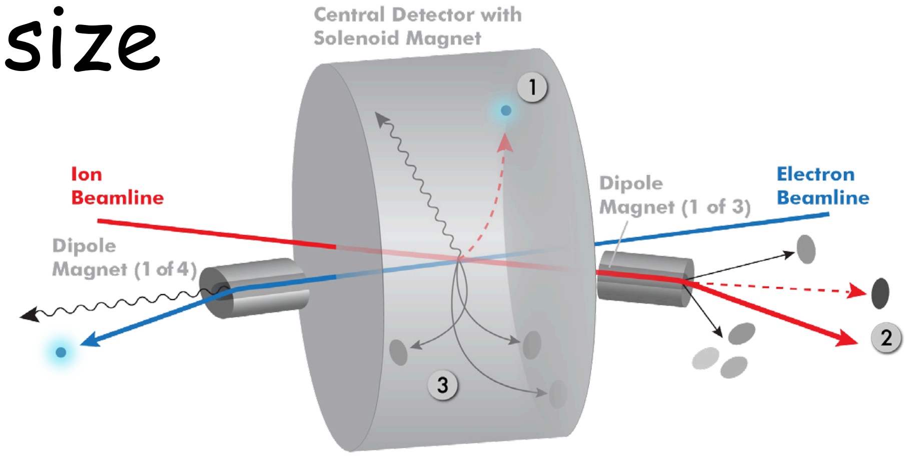






- Need high magnetic field to reconstruct bending radius: for high momentum particles, otherwise straight segment (no momentum measurements, no charge) – depends on resolution of tracker.
- Also we need higher magnetic field for particles going at the shallow angle (along a beampipe)
- **BUT** Too high magnetic field: low momentum particles could bend/fly inside a beampipe without detection

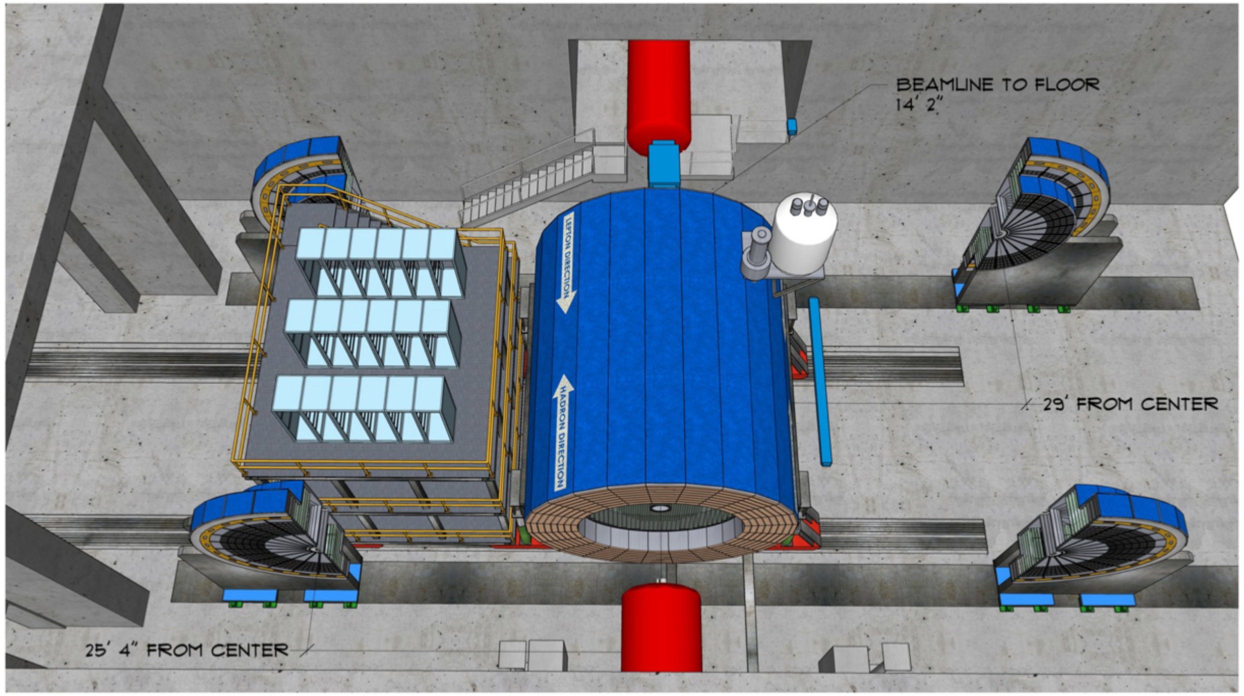
Total acceptance detector: Detector size



Detector needs a **Solenoid** to measure particle momenta =>

- We need it only for our detector system ! The accelerator could function without it! => Solenoid field **needs to be compensated by accelerator**
- Optimize/change a magnetic field - depending on the beam energy configuration we use ?

- **limitation in size:** for the central detector (in R and Z) due to the radius/length of solenoid magnet =>
  - how it fits into the HALL?
  - how to do assembly, installation, maintenance ?

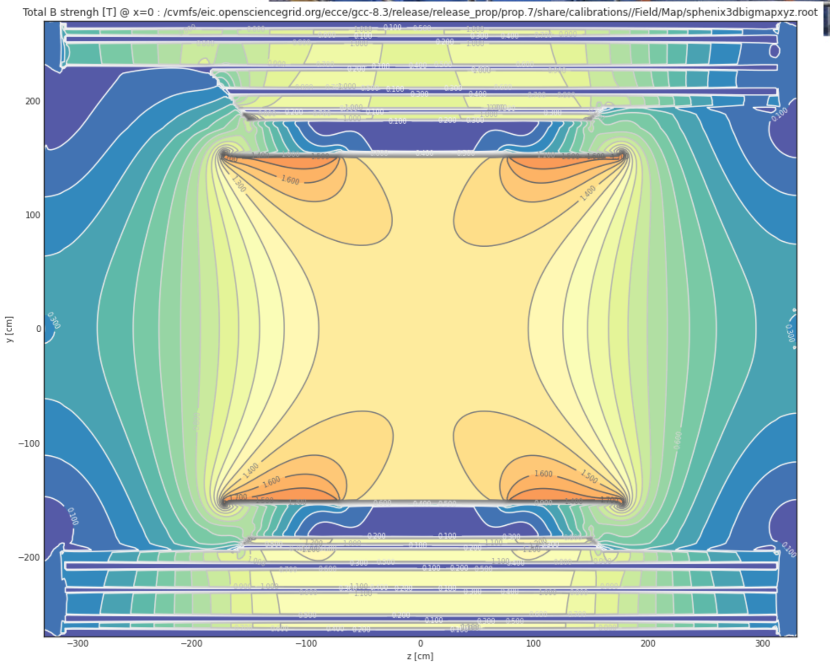


The Solenoid

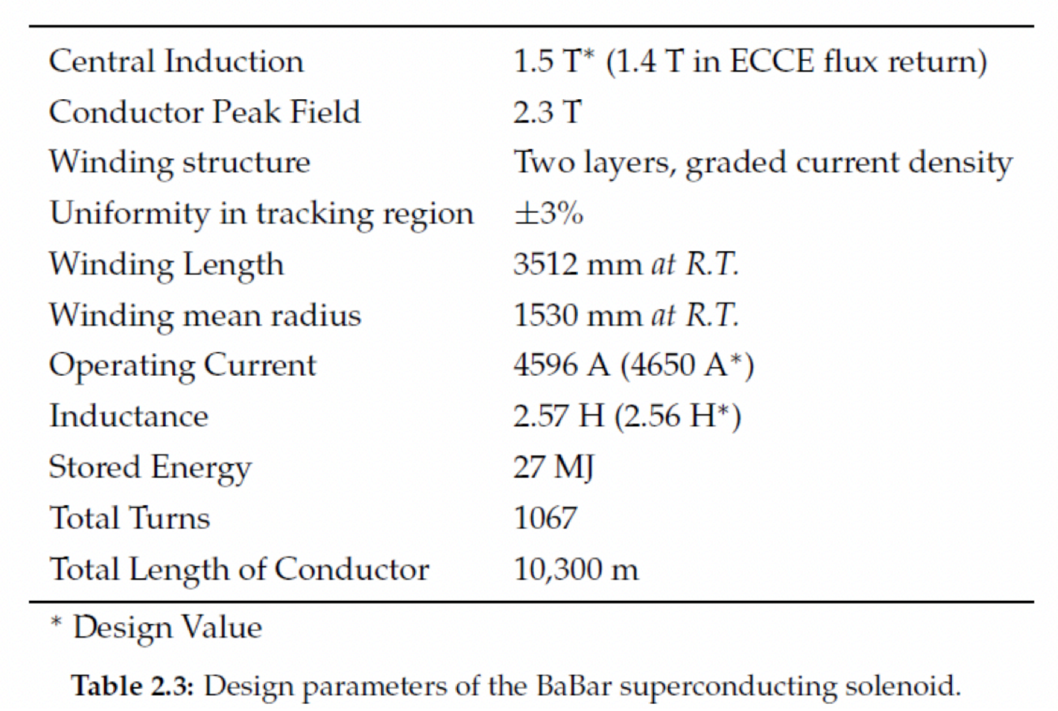
The BaBar superconducting solenoid for the EIC detector (sPhenix) could be reused -provides the 1.4 T field

A design of a new solenoid with similar parameters are on-going (1.7T , unto 2T)

The warm bore diameter of 2.84m and coil length of 3.512 m



planing to reuse the surrounding hadronic calorimeter and flux containment system

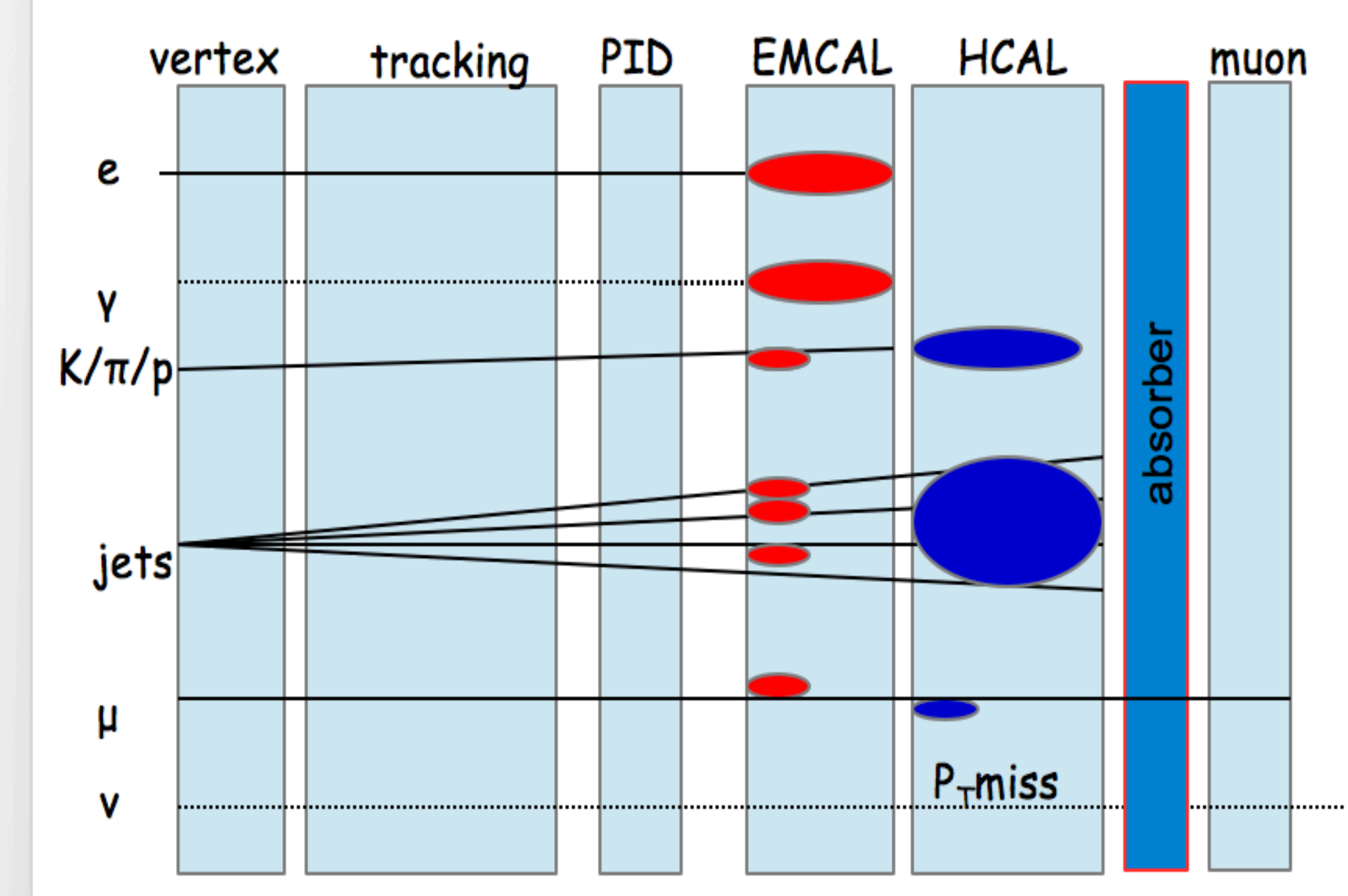


Central Induction	1.5 T* (1.4 T in ECCE flux return)
Conductor Peak Field	2.3 T
Winding structure	Two layers, graded current density
Uniformity in tracking region	±3%
Winding Length	3512 mm *at R.T.*
Winding mean radius	1530 mm *at R.T.*
Operating Current	4596 A (4650 A*)
Inductance	2.57 H (2.56 H*)
Stored Energy	27 MJ
Total Turns	1067
Total Length of Conductor	10,300 m

* Design Value

Table 2.3: Design parameters of the BaBar superconducting solenoid.

Central detector layout (General purpose detector)



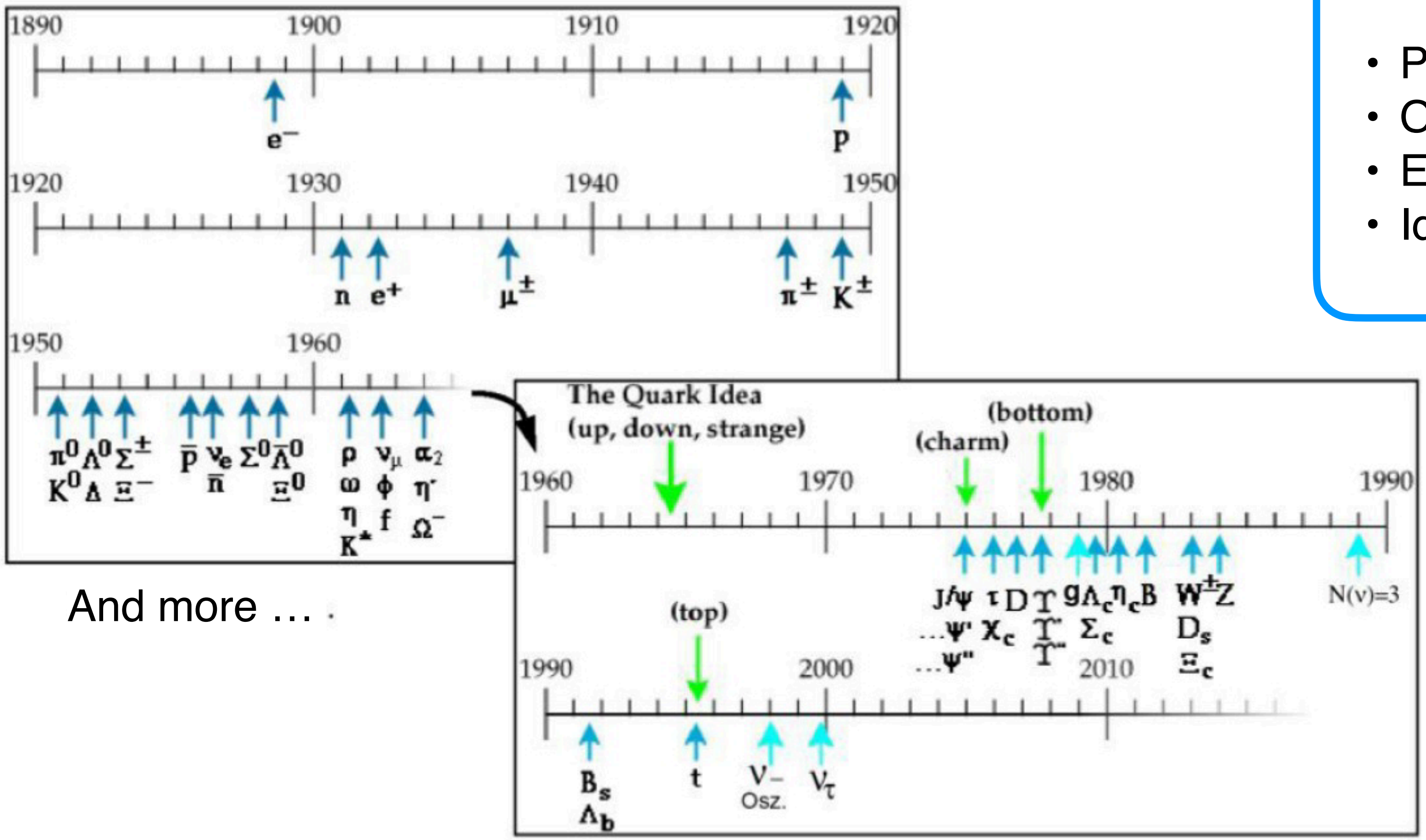
Particles

Today more then 200 particles listed in Particle Data Group (PDG)

But only 27 have cτ > 1μm
and only 13 have cτ > 500μm

For all particles we want to measure:

- Particle momentum
- Origination (vertex)
- Energy
- Identification (Mass) : type of the particle



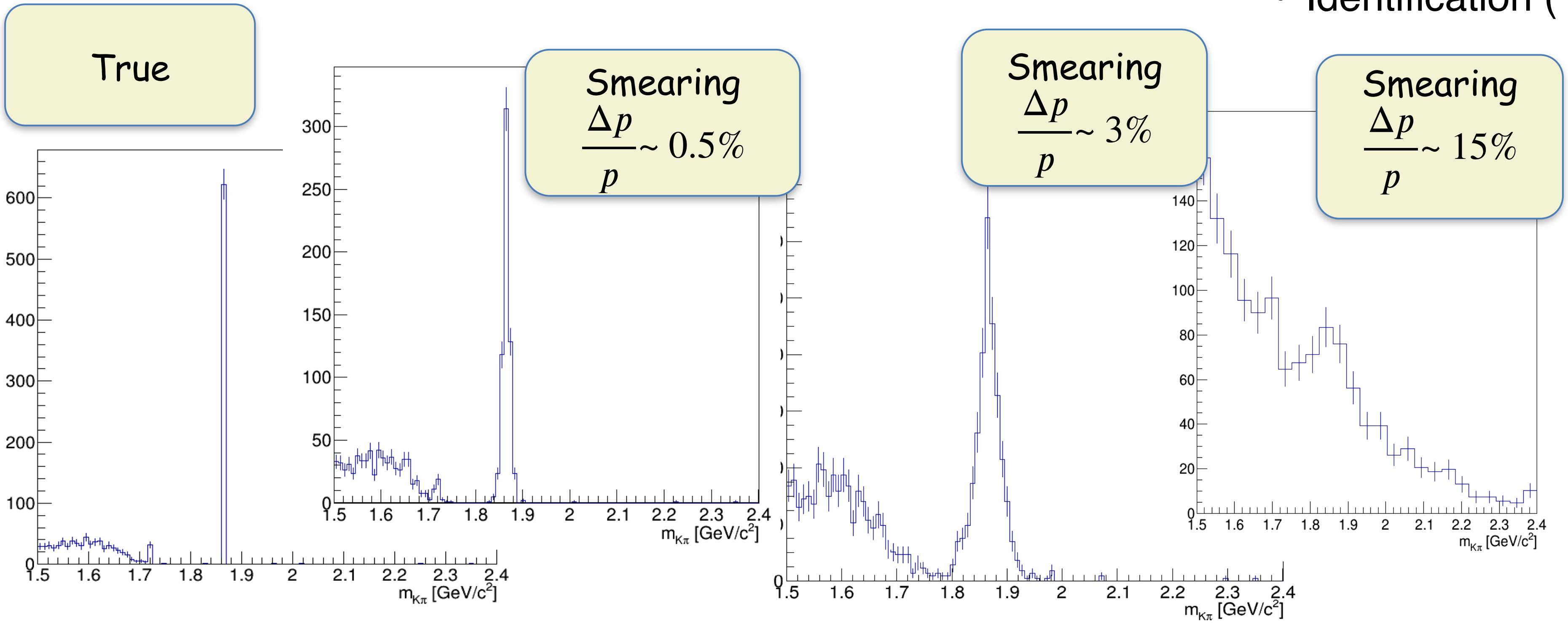
And more … .

Why do we need precision measurements of particle momentum?

For all particles we want to measure:

- **Particle momentum or Particle trajectory or Track => Tracking detectors**
- **Origination (vertex)**
- Energy
- Identification (Mass) : type of the particle

For example, $D^0 \rightarrow \pi^- K^+ (\pi^+ K^-)$



True

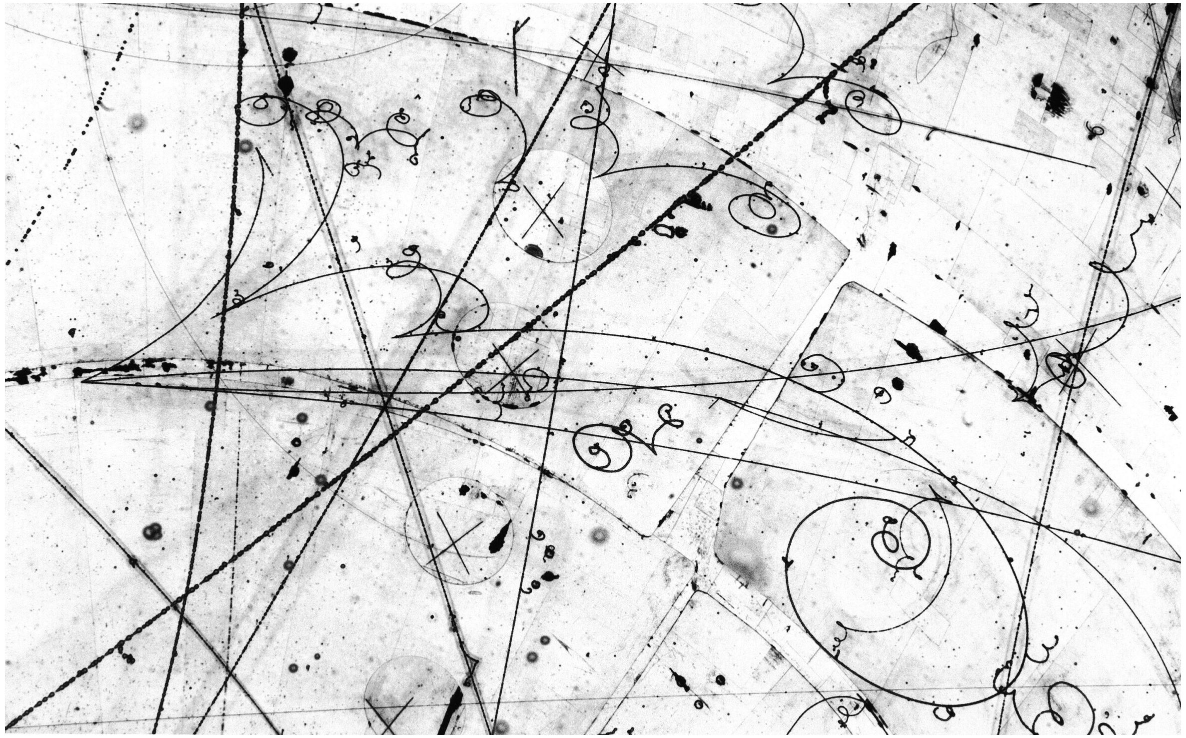
Smearing $\frac{\Delta p}{p} \sim 0.5\%$

Smearing $\frac{\Delta p}{p} \sim 3\%$

Smearing $\frac{\Delta p}{p} \sim 15\%$

Tracks

Tracks in particle physics

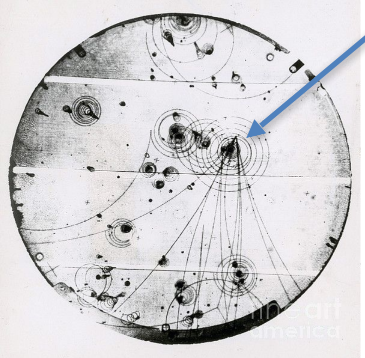


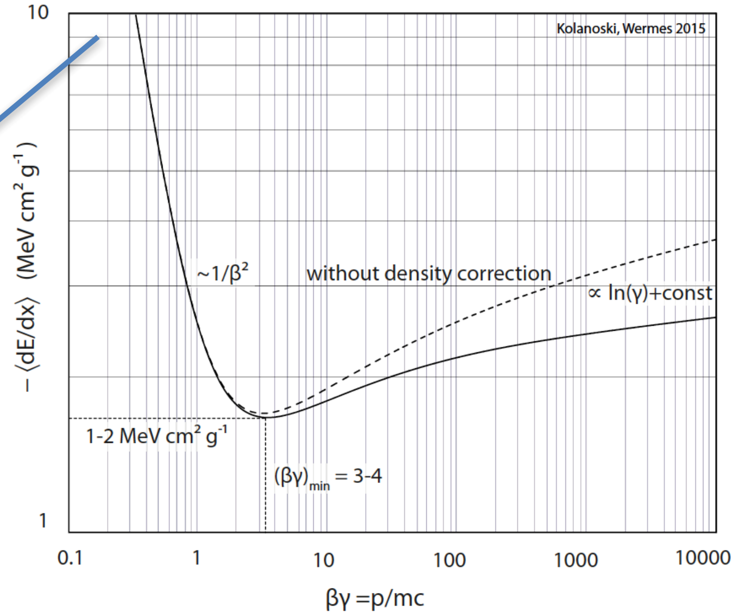
- ➢ Particles have to interact with material of detector

Tracking detectors (position sensitive detectors)

- Particles have to interact with material of detector

- Electronically recordable hits/tracks
- Provide precise space point coordinates/trajectory of charged particles
- Provide momentum measurements in magnetic (B) field
- Provide angle measurements
- Provide measurements of primary and secondary vertices
- Provide a multitrack separation
- Provide a particle identification (if possible)
- Keep a minimum of material along the path of particles to minimize scattering and secondary interactions.





Bethe-Bloch formula:

$$-\left\langle \frac{dE}{dx} \right\rangle = K \frac{Z}{A} \rho \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \frac{2\, m_e\, c^2\, \beta^2\, \gamma^2\, T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma,\, I)}{Z} \right]$$

- Almost does NOT depend on material (Z/A ~ $\frac{1}{2}$)
- Proportional to z^2
- Depends on $\beta\gamma$ = p/E *E/m = p/m
- The same curve for all z=1 particles when plotted as a function of $\beta\gamma$)
- Have a minimum at $\beta\gamma$ =3-4
- Plateau at high $\beta\gamma$

Momentum resolution

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\text{meas}} + \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\text{MS}}}$$

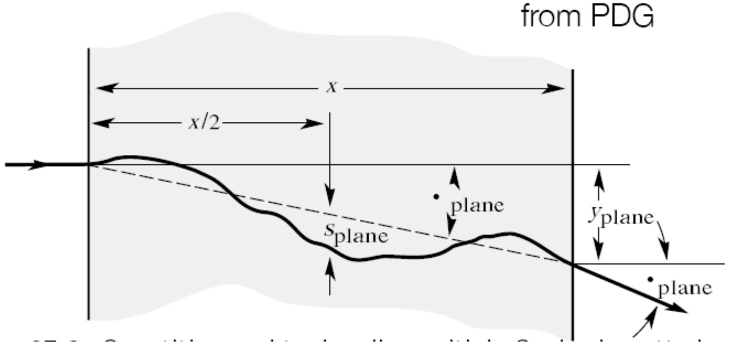
Position resolution (N>10) :

$${\frac{\sigma(p_T)}{p_T}}_{\text{meas}} = \frac{\sigma(x)\cdot p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

Multiple scattering:

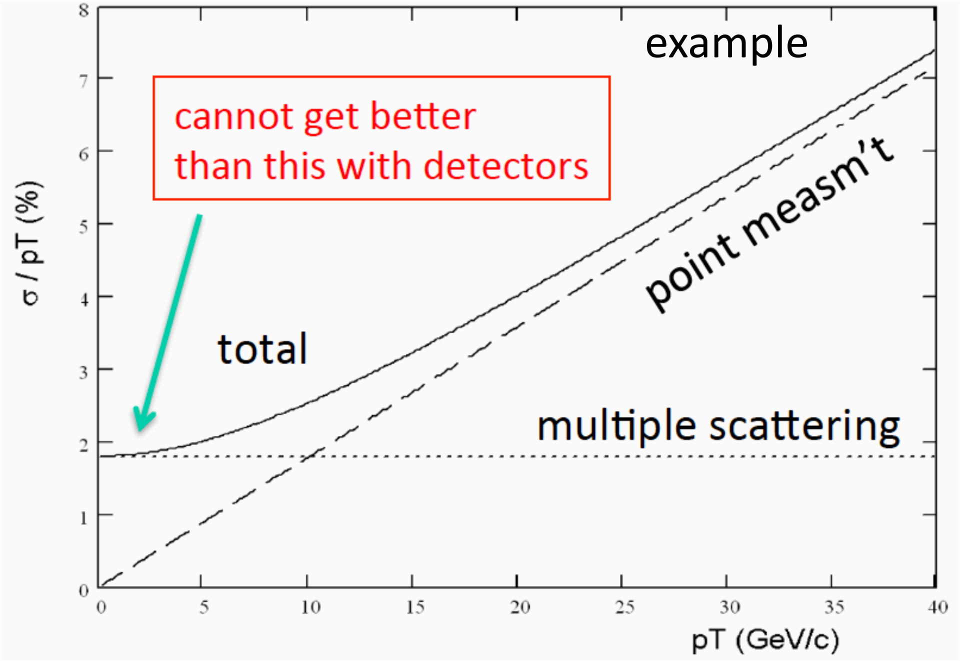
$$\frac{\sigma(pT)\text{MS}}{pT} \approx \frac{1}{\sqrt{LX0B}}$$

from PDG



At small momenta this limits resolution of momentum measurement ...

p_T [GeV] = 0.3• B [T] • R [m]



cannot get better than this with detectors

-Optimize material effects (multiple scattering)
optimize amount of material along particle track (sensitive area (Si), support structure, cables..)

-Place first plane as near as possible to IP

-P_T is linearly better with B-field, but…

-Increase N (but only as 1/$\sqrt{N}$)

-Improve hit point resolution (σmeas)

Tracking detectors/Vertex

For example,

$D^+ \rightarrow \pi^- K^+ \pi^+$

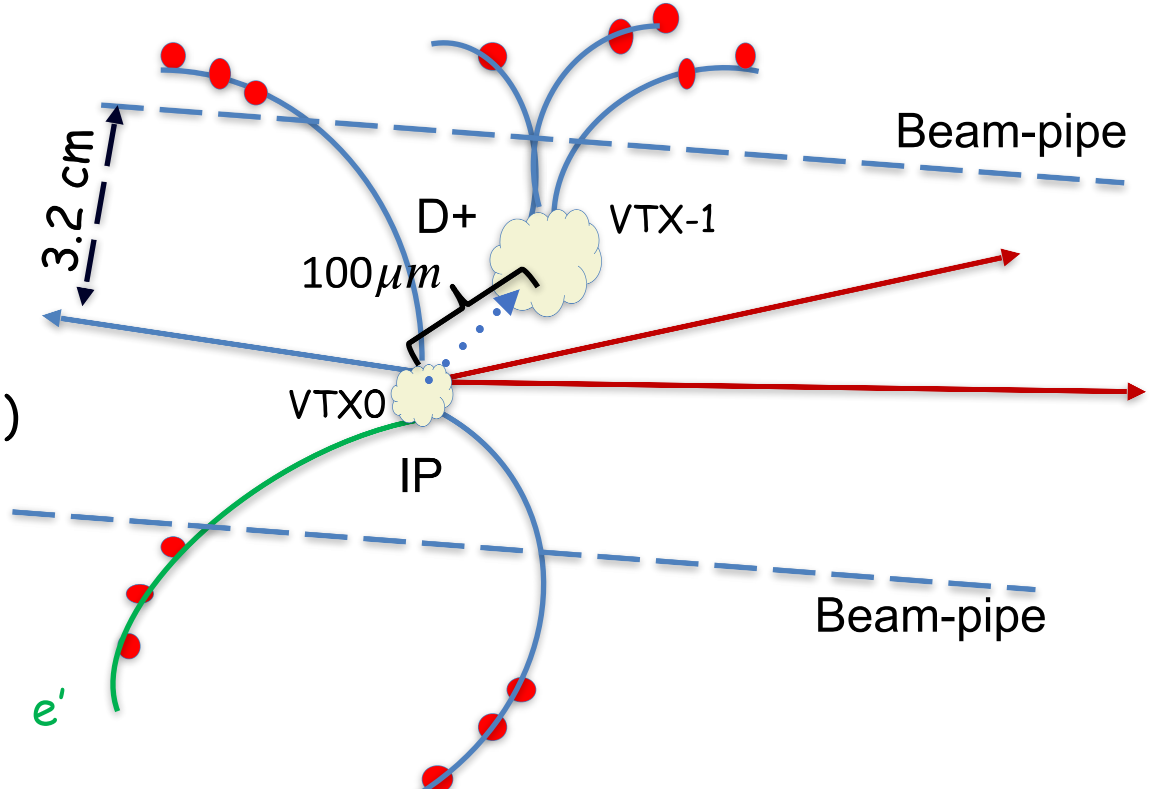
Challenge: How to measure a displaced vertex ?!

-Secondary vertices: D-mesons (lifetime) ca 100-300μm

(our hair 50-150 μm)

=> Need to place high granularity and precision detector as close as possible to IP (to beam-pipe)

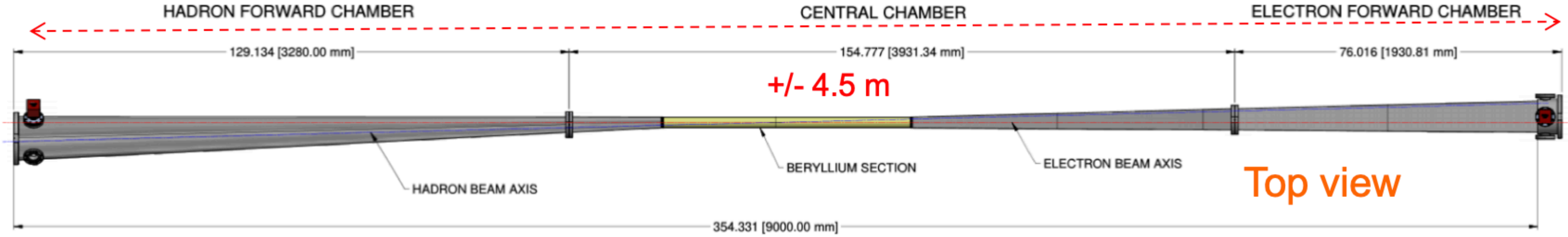
BUT a beam pipe needs to be large enough to allow beam (with beam halo) to path through (depends on bunch sizes)



EIC central beam-pipe

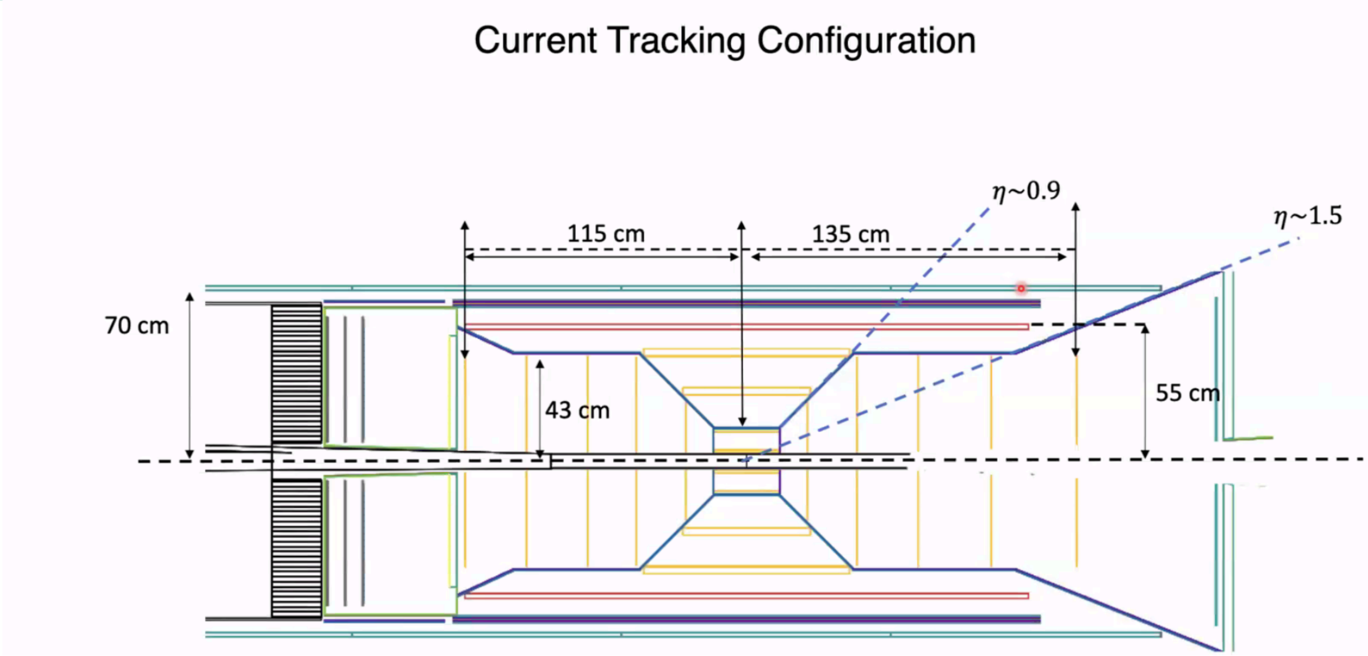
-Inner section: 1.5 m Beryllium to minimize multiple scattering

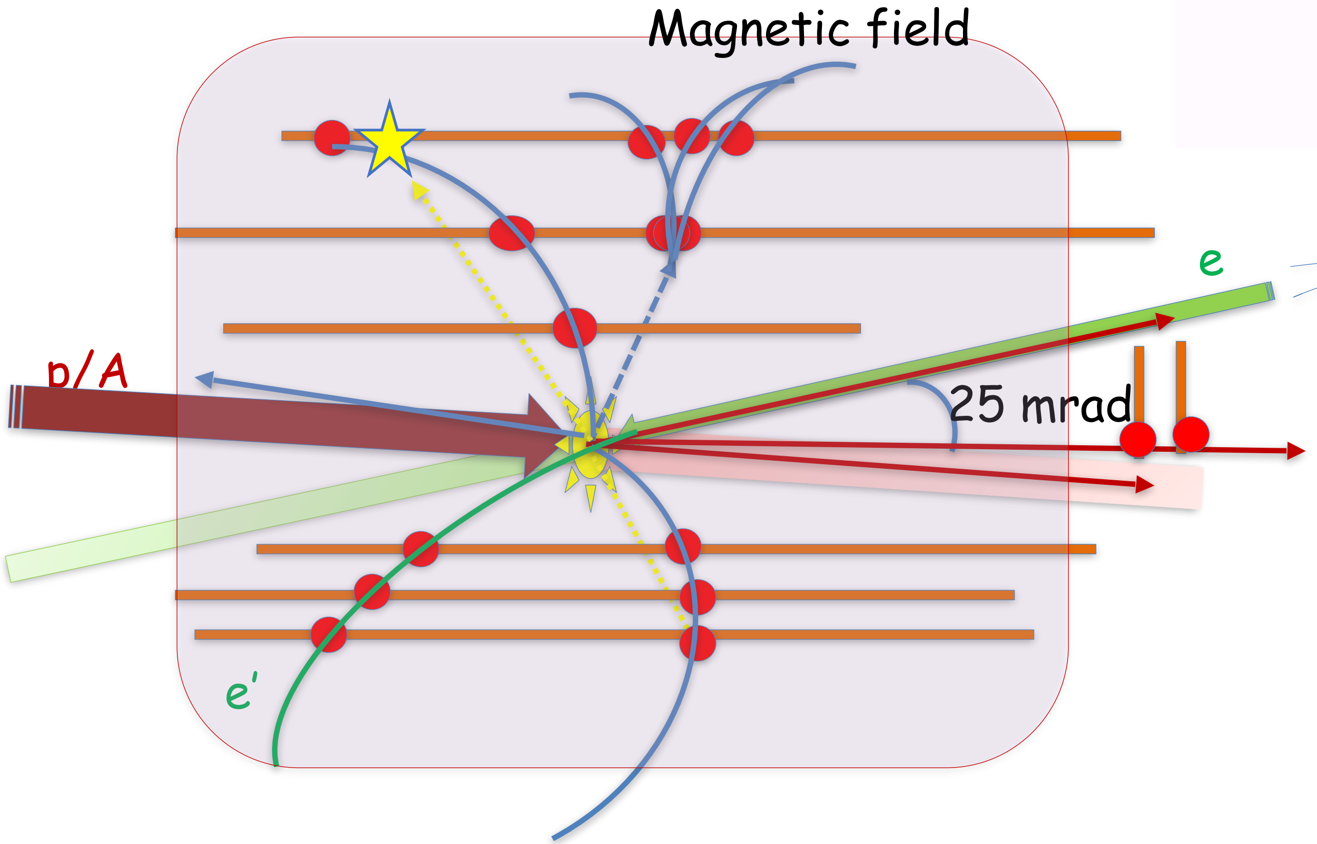
-2um Gold coating to absorb soft photons from synchrotron radiation



Tracking at EIC

Hybrid tracking detector design: Monolithic Active Pixel Sensor (MAPS, ITS3) based silicon vertex/ tracking subsystem, the muRWELL tracking subsystem and the AC-LGAD outer tracker, which also serves as the ToF detector.



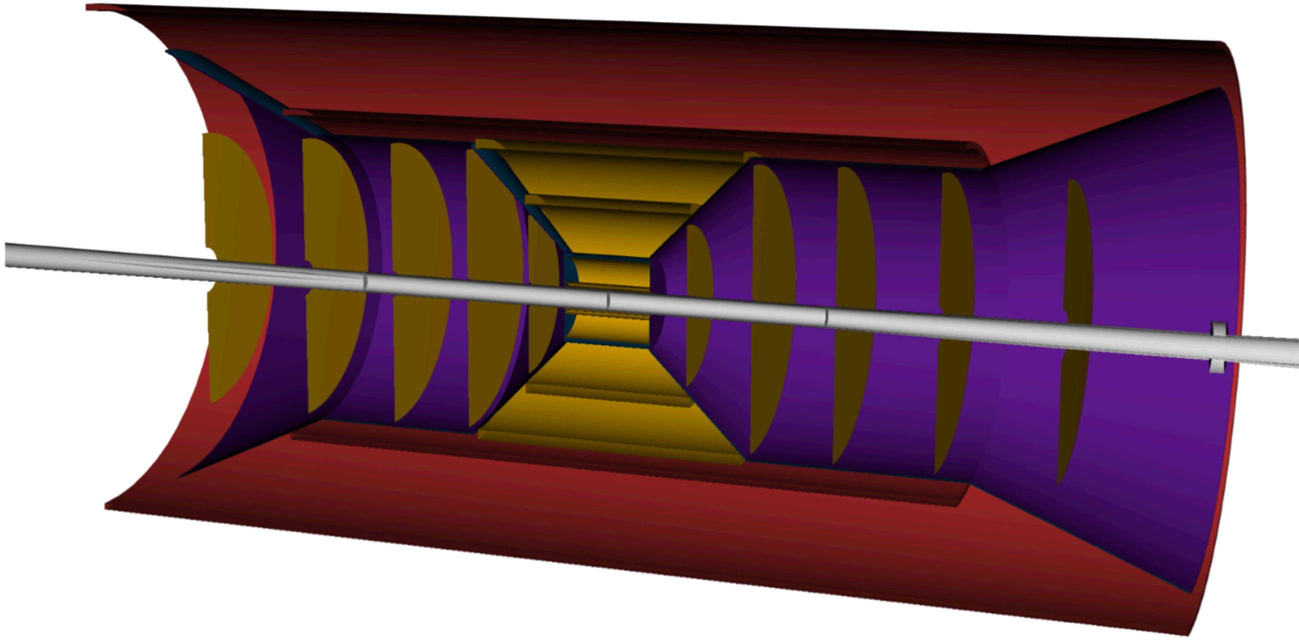


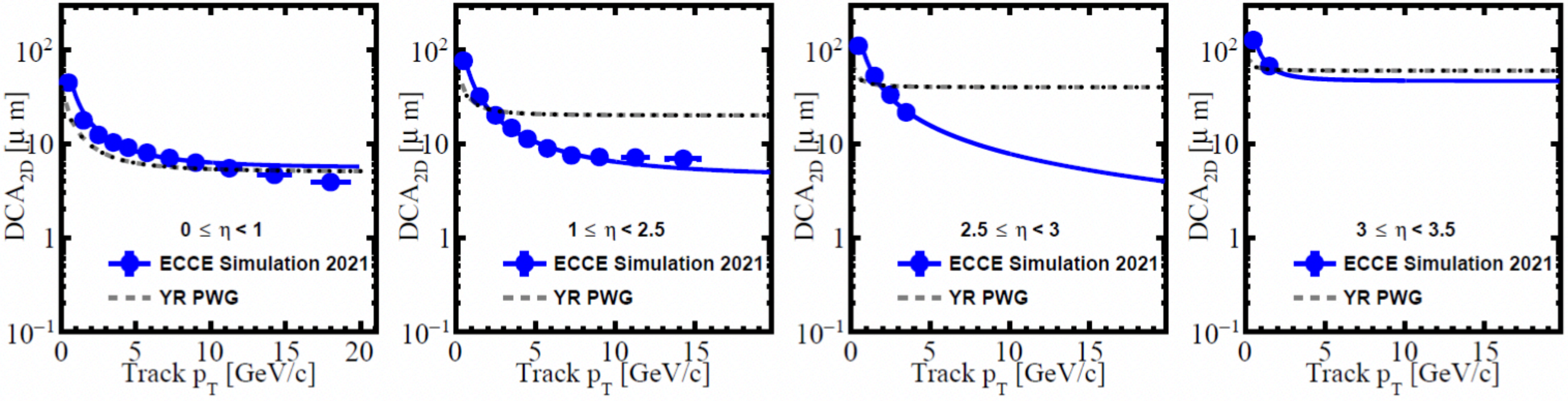
Magnetic field to measure momentum and charge (bended curves)
Particles have to interact with material of detector:

- ✓ Charged particles: leave energy along the track (hits) (dE/dx)
- ✓ Photons/Gammas- depending on energy (*): no tracks (no hits or just a single hit)

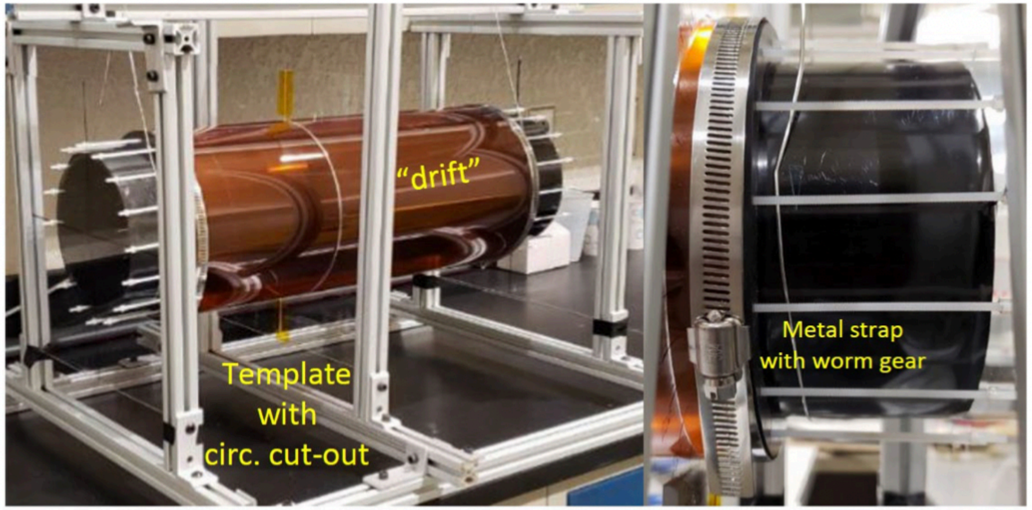
Tracking detectors/Vertex

- Low material budget: 0.05% X/X0 per layer
- High spatial resolution: 20 µm pitch MAPS (Alice ITS3)
- TowerJazz 65nm technology (ongoing R&D Si Consortium)
- Configuration: Barrel + Disks for endcaps
- IηI<3.5 with full azimuth coverage





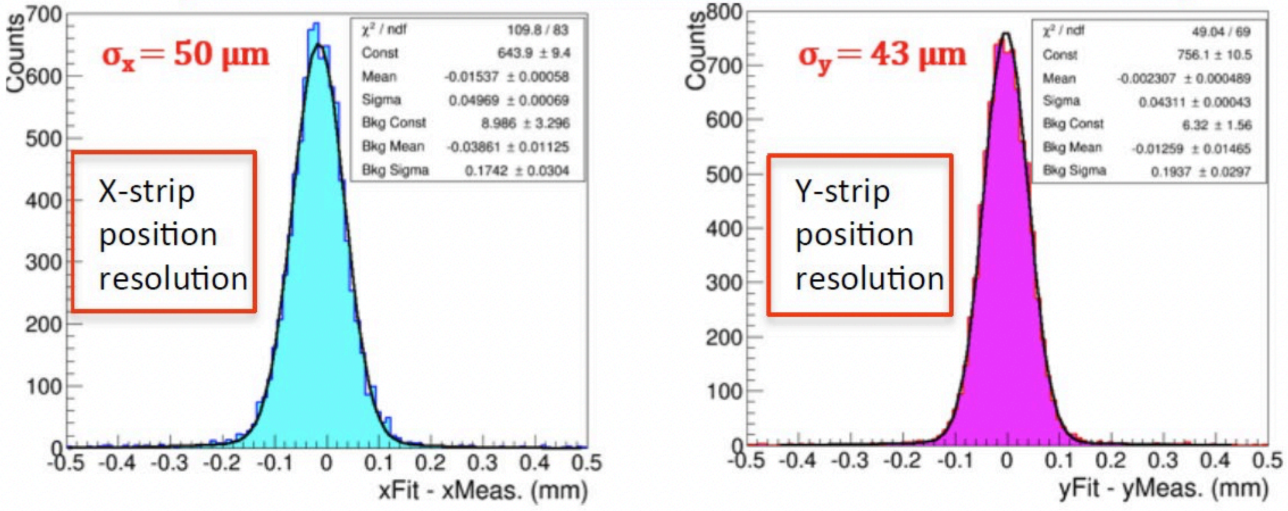
Tracking detectors/Vertex

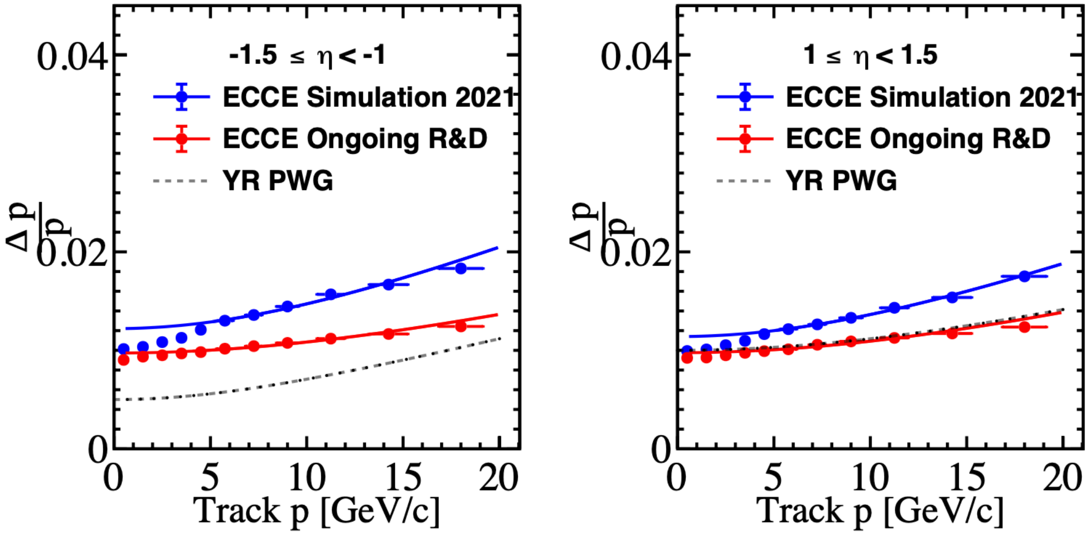


For the larger/outer layers :

- MPGD technology
- spatial resolution well below 100 um for curved geometry
- Large-area detectors possible - cost efficient compared to silicon large surface detectors

Preliminary µRwell results from Fermilab test beam





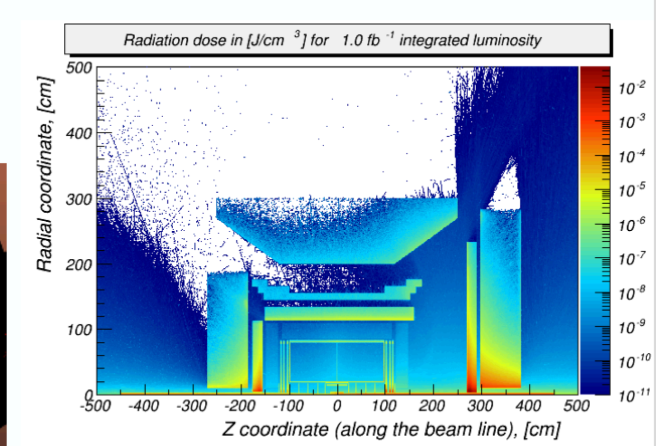
Background/radiation

- ➢ The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance

- ➢ There are main background/radiation sources :
  - ❖ primary collisions
  - ❖ beam-gas induced
  - ❖ synchrotron radiation

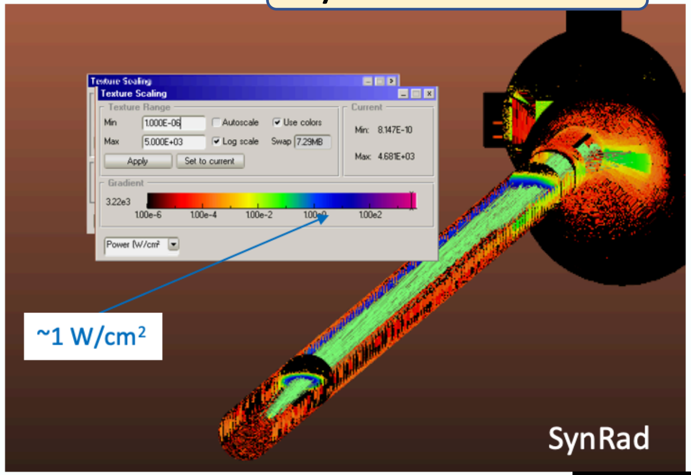
- ➢ The design of absorbers and masks must be modeled thoroughly

Primary collisions/ionizing radiation

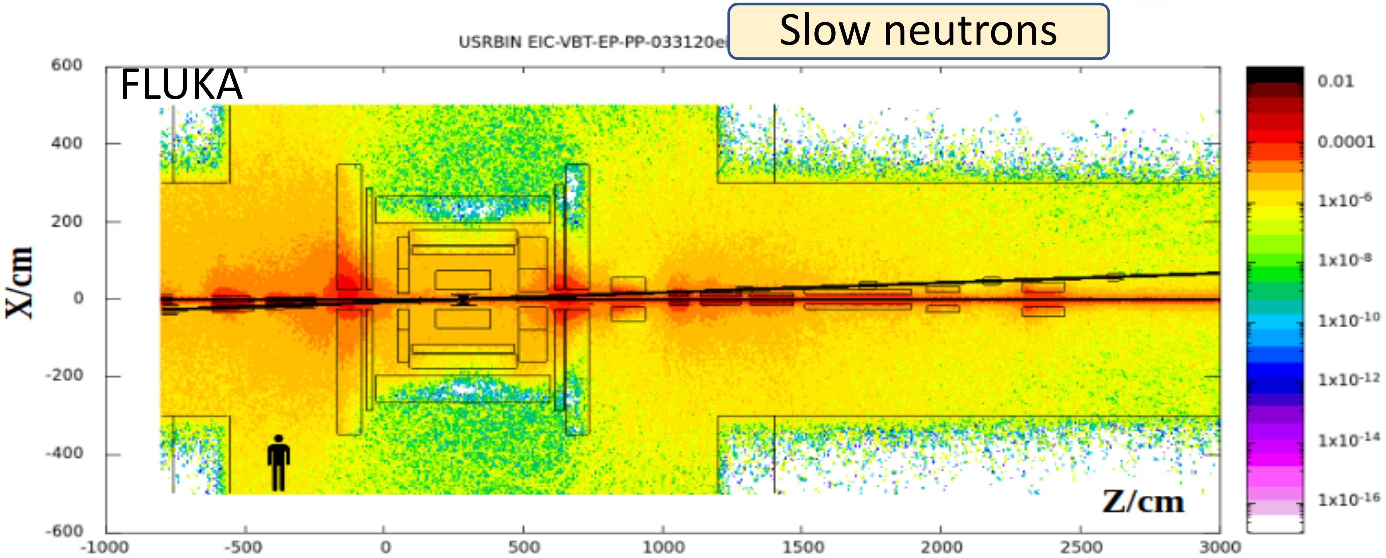


-> backward EmCal: ~250 rad/year
(at a “nominal” luminosity
~10^{33} cm^{-2} s^{-1})

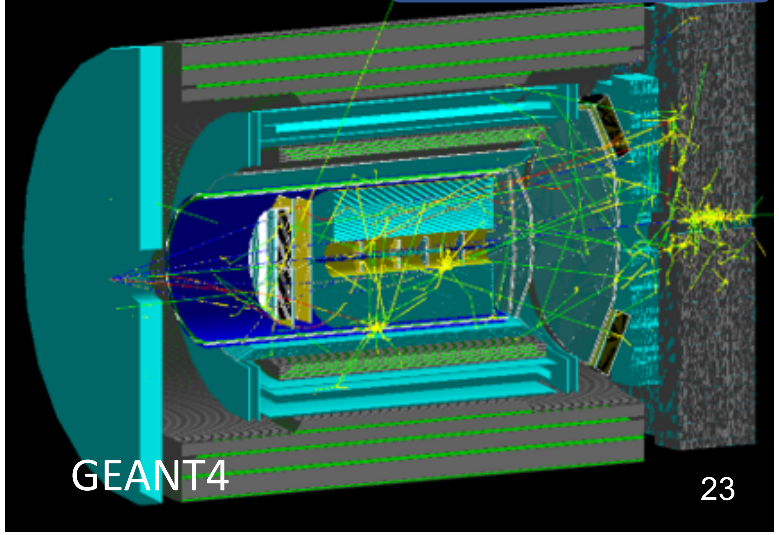
Synchrotron rad.



Slow neutrons



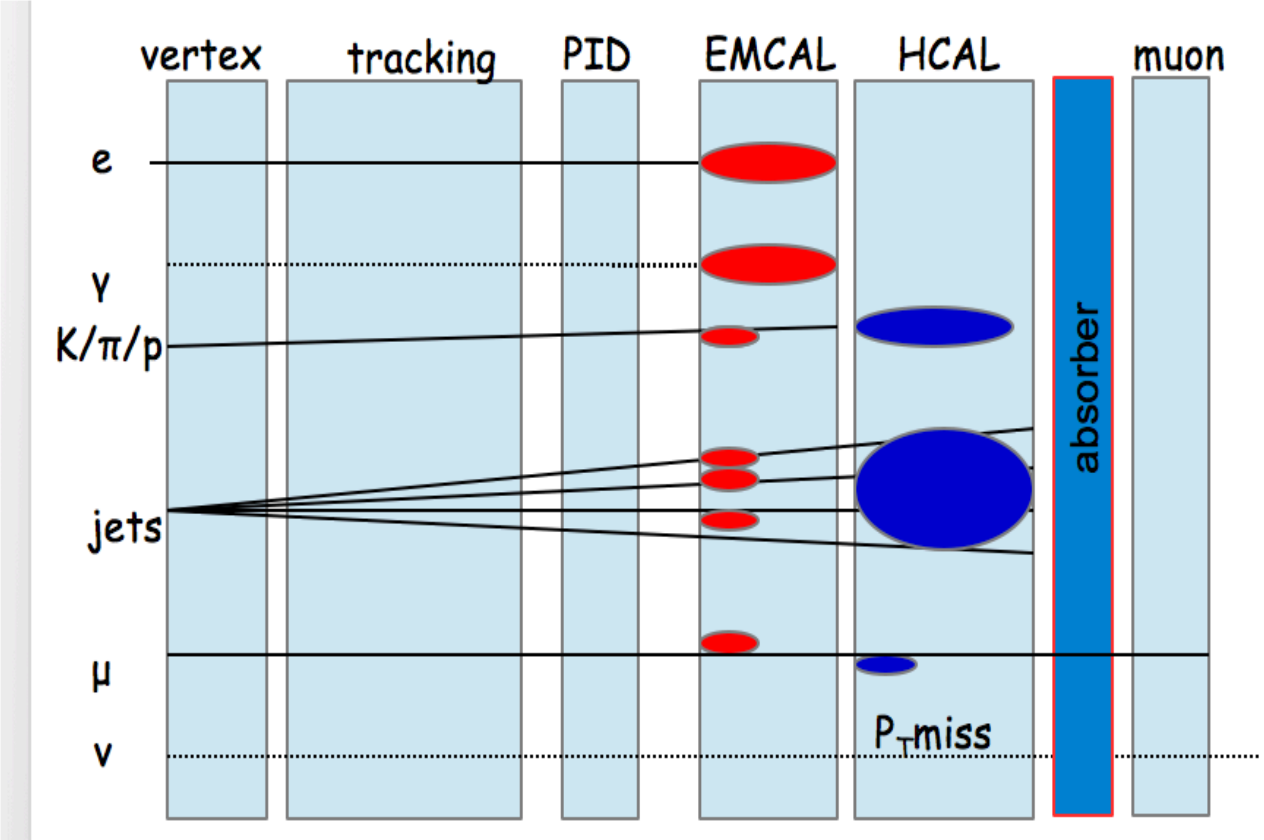
Beam-gas event



Particle Identification

Limited number of "stable" final state particles: only 13 have cτ > 500μm

- Electrons /positrons
- Gammas
- Jet/Jets
- Individual hadrons ($\pi\pm$, K±,p)
- Muons (absorber and muon chamber)
- Neutrinos (missing PT in EM+HCAL)
- Neutral hadrons (n,K^0_L) (HCAL)

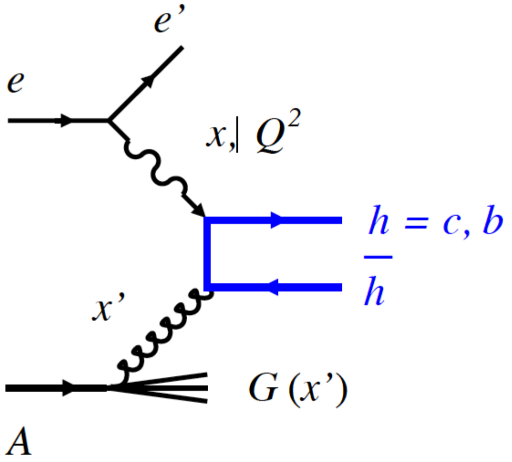


- Electrons: EMCAL cluster + track pointing to cluster
- Gammas (γ): EMCAL cluster, no track pointing to cluster
- Neutrinos (ν): missing P_T
- Muons: track, min. energy in EMCAL, min. energy in HCAL, track in muon det.
- Charged pions, kaons and protons from each other -> **Cherenkov detectors**

Short lived particles: hadron identification

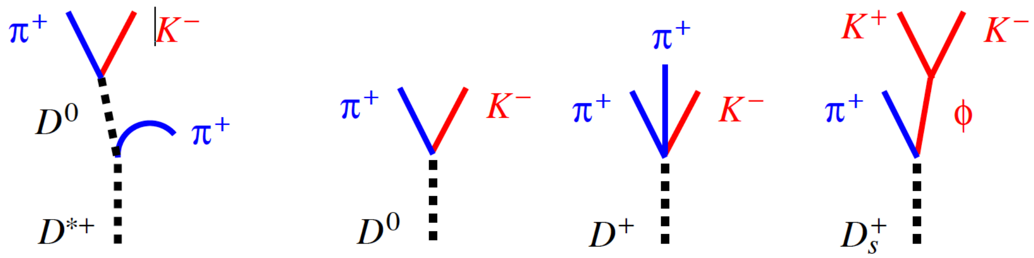
Example: charm -> (fragmentation)-> D-mesons ->(decay) -> hadrons,leptons…

Invariant mass reconstruction



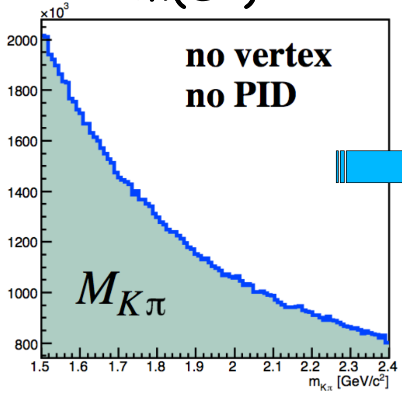
D^{-*} -> π^-_s D^0

↳ $\pi^- K^+$

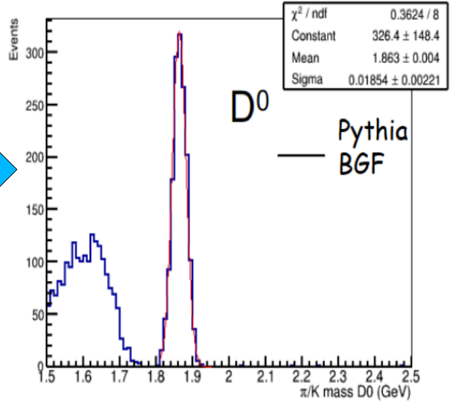


- high combinatorial background without PID

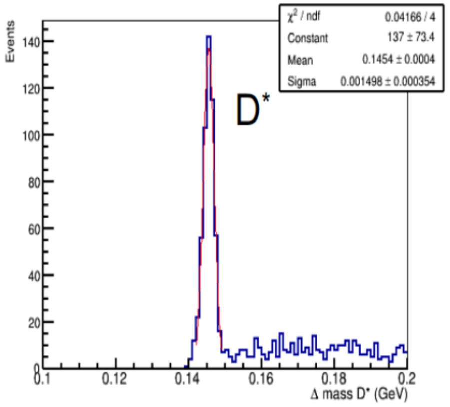
m(D^0)



m(D^0)

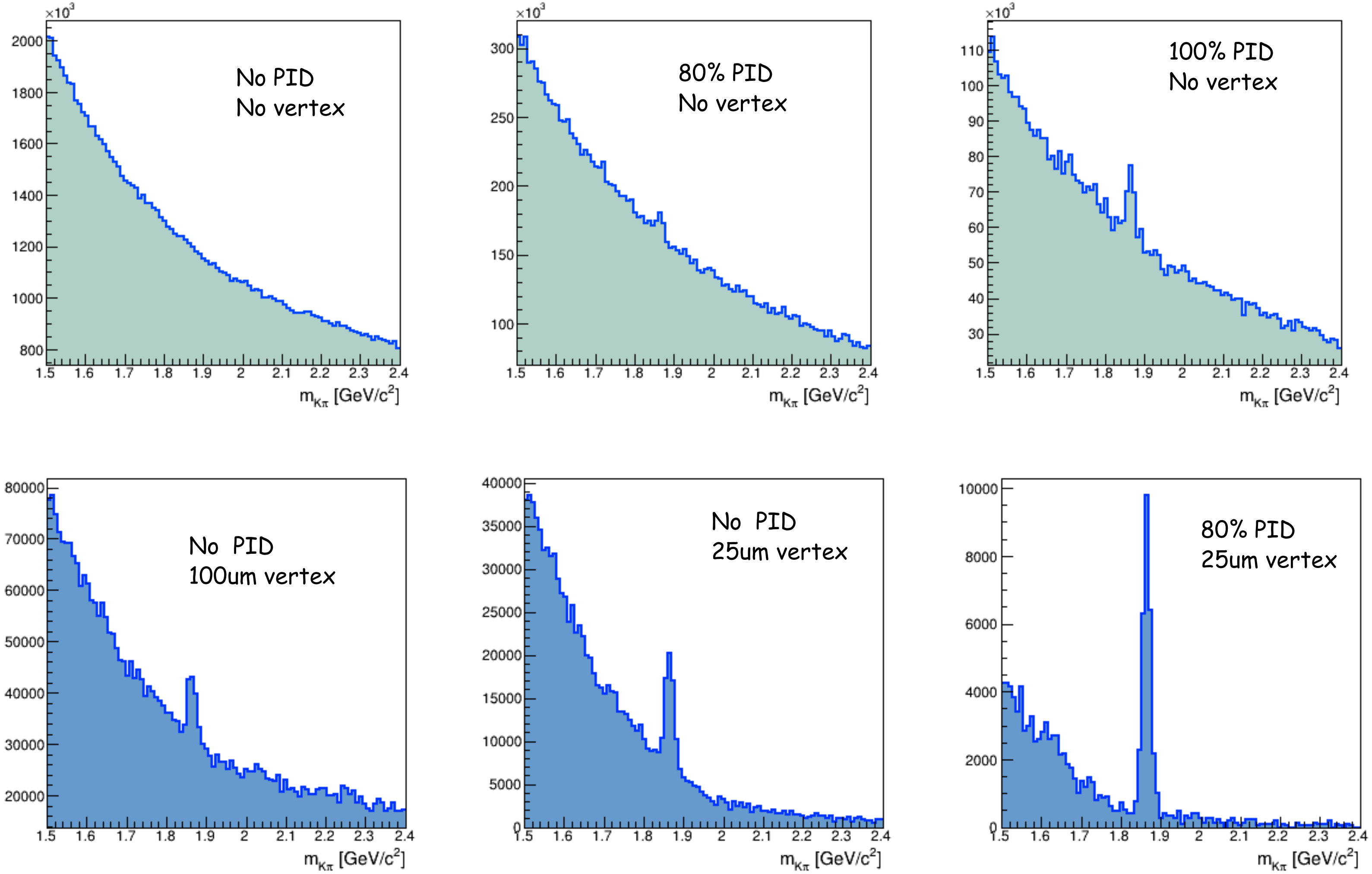


m(D*) – m(D^0)= m (π^-_s)



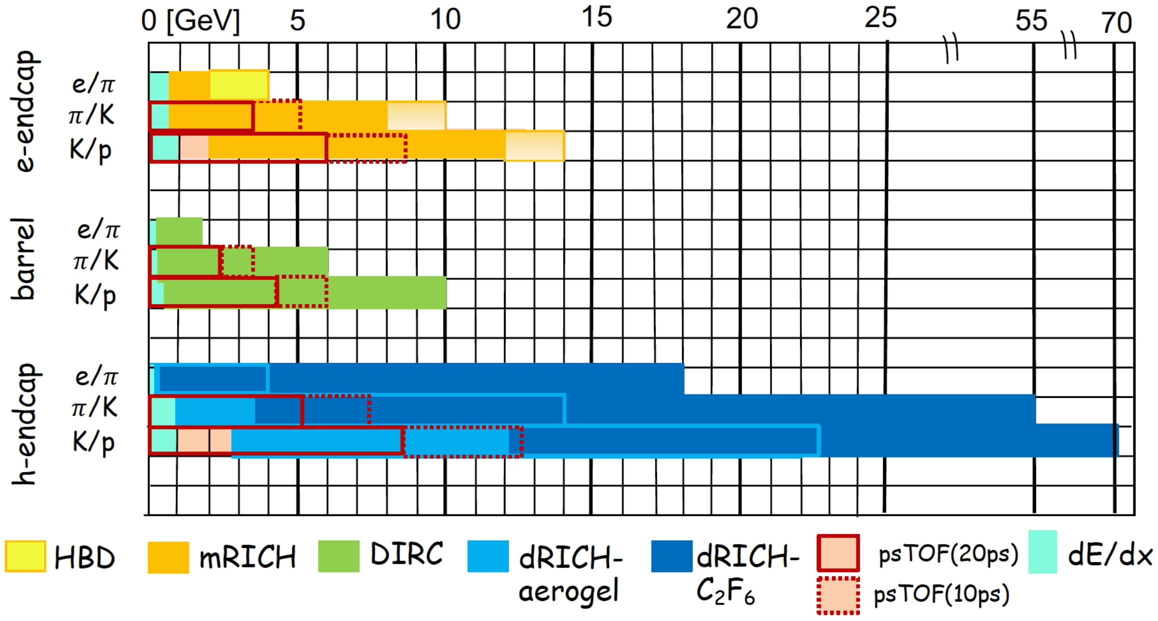
Individual charged hadrons(π, K, p)

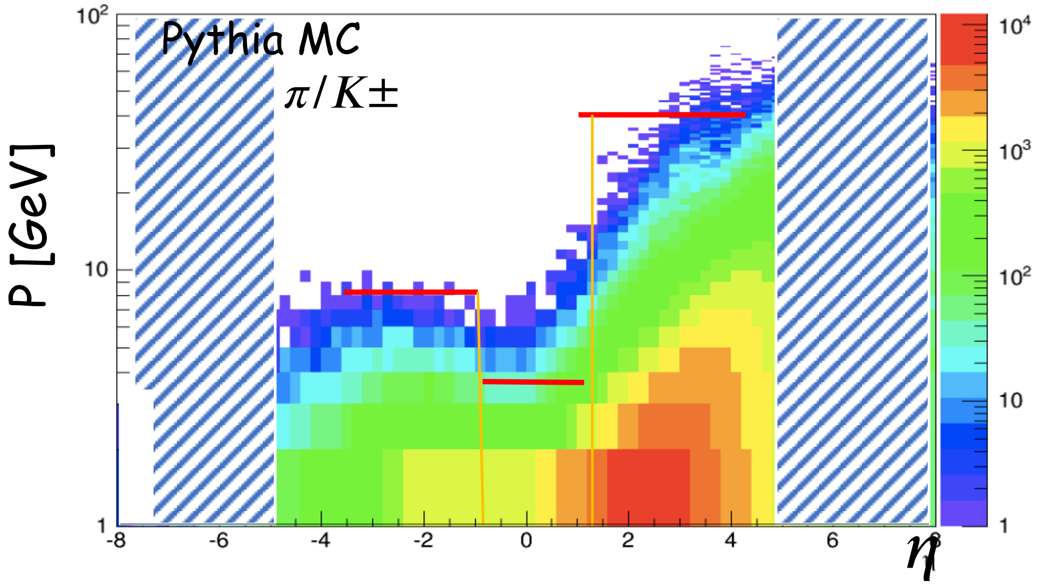
$D^0 \rightarrow \pi K$ mass spectrum, on the top of DIS background

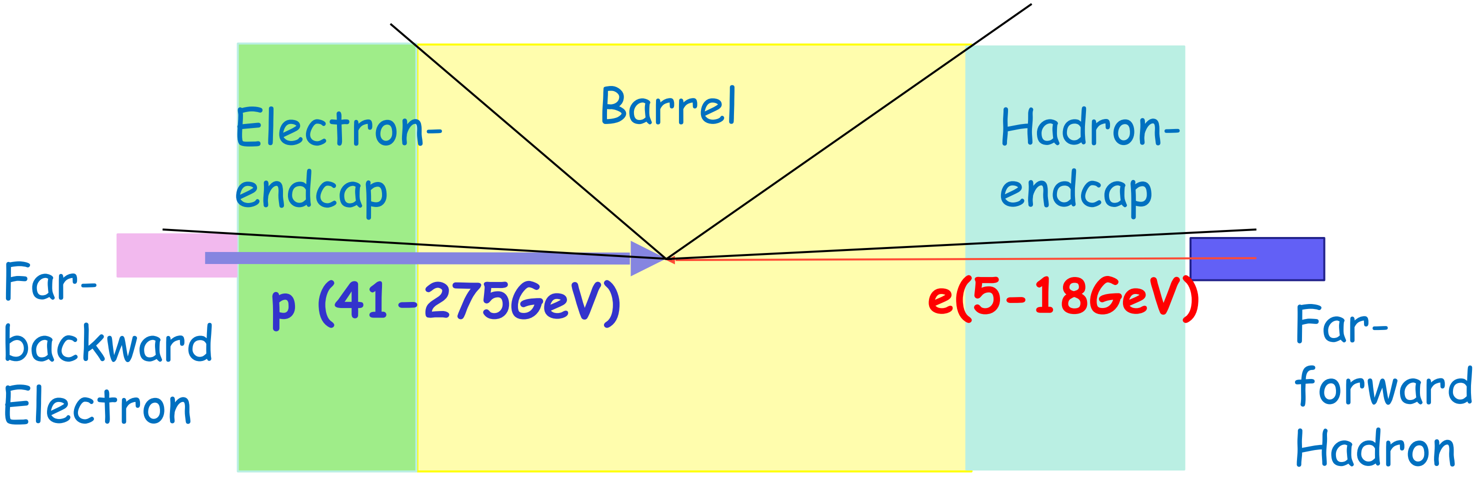


In order to select/identify specific reaction (for example, D0 production) one need to apply certain criteria/cuts to extract such events from the minbias events (DIS background).

Particle identification: charged hadrons(π, K, p)







Cherenkov detectors, complemented by other technologies at lower momenta (TOF)

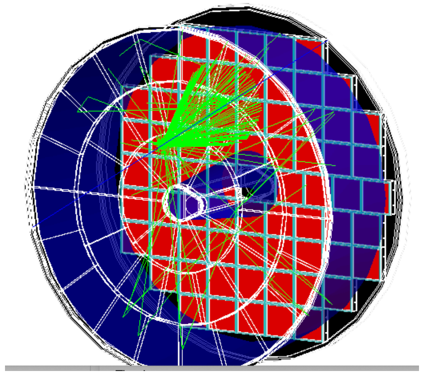
Need 4π coverage

Particle Identification detectors

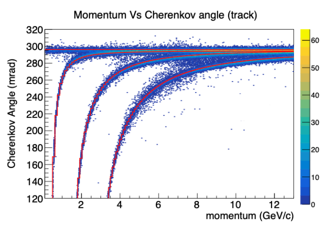
Backward PID

A Proximity-Focusing RICH for the ePIC Experiment

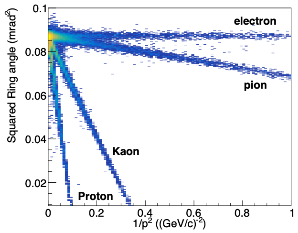
- Aerogel radiator
- threshold-based electron ID
- Requires expansion volume



π/K up to 10 GeV



(a) Reconstructed Cherenkov angle for particles as a function of particle momentum

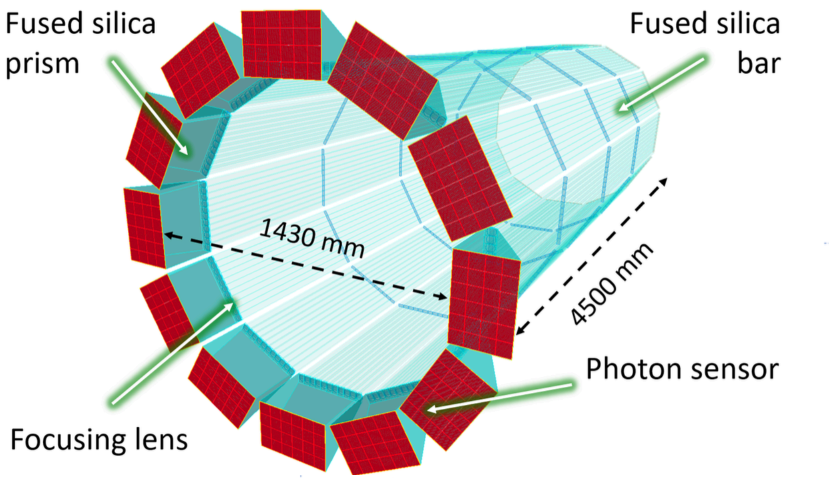


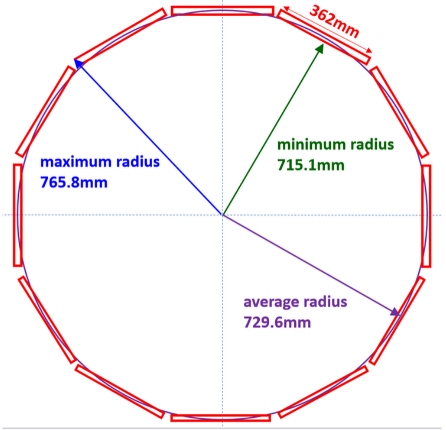
(b) Reconstructed squared Cherenkov angle for particles as a function of inverse squared momentum

Barrel PID

A High-performance DIRC
-radially compact (~5cm)
-better optics and <100ps timing

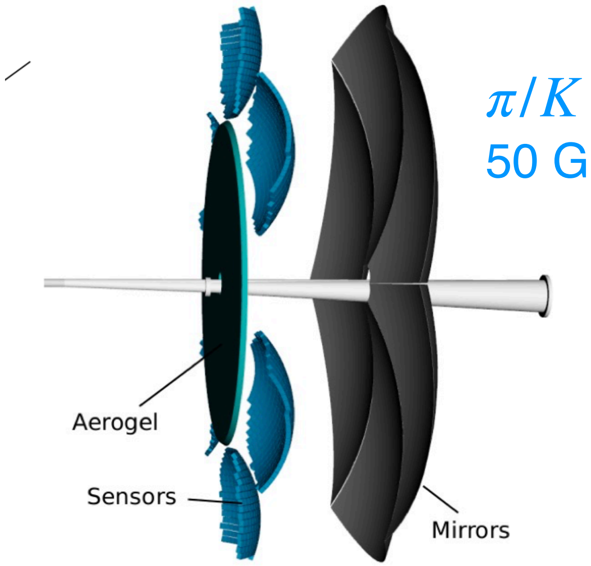
π/K up to 6 GeV





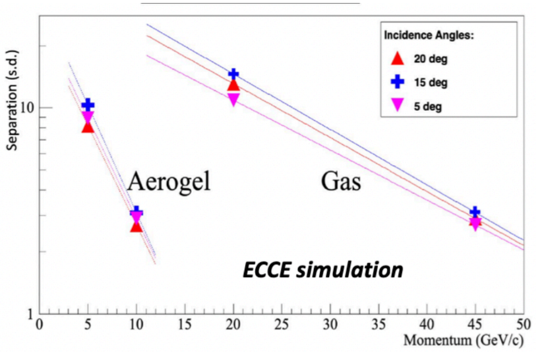
Forward PID

Dual-Radiator RICH (dRICH)



π/K up to 50 GeV

Aerogel and Gas radiators

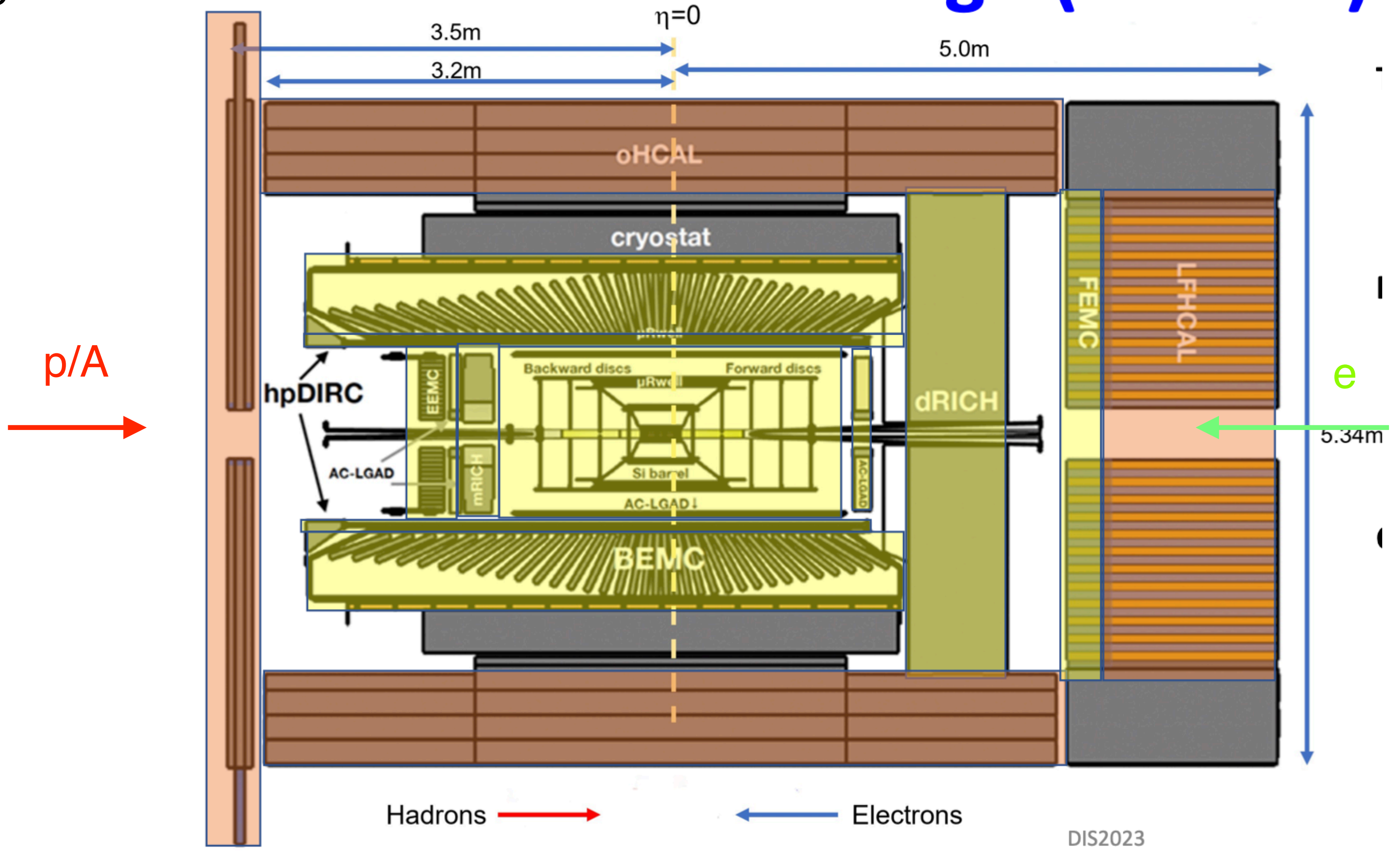


Particle Identification detectors

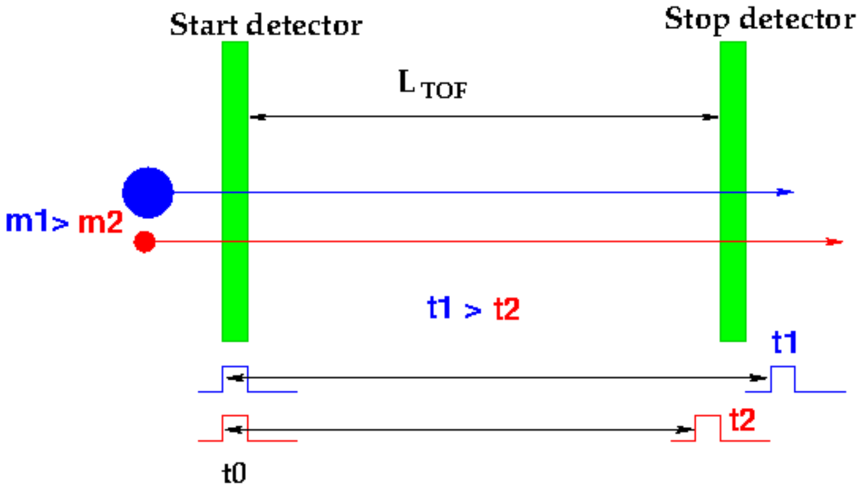
PID technologies are based on the outcome of the EIC generic R&D (eRD14)

- Backward: Proximity-Focusing RICH(**pfRICH**)
- Barrel: Radially compact with flexible design high-performance DIRC **(hpDIRC)**
- Forward: Double-radiator RICH **(dRICH)**
- TOF (*) AC-LGAD based time-of-flight (TOF) system for hadronic PID in momentum range below the thresholds of the Cherenkov detectors

ePIC Detector Design (Current)

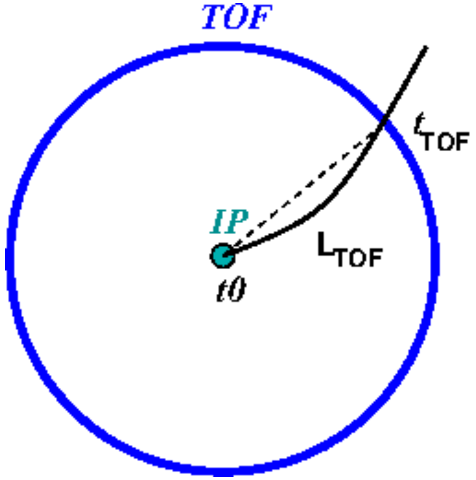


Timing detectors: AC-LGAD

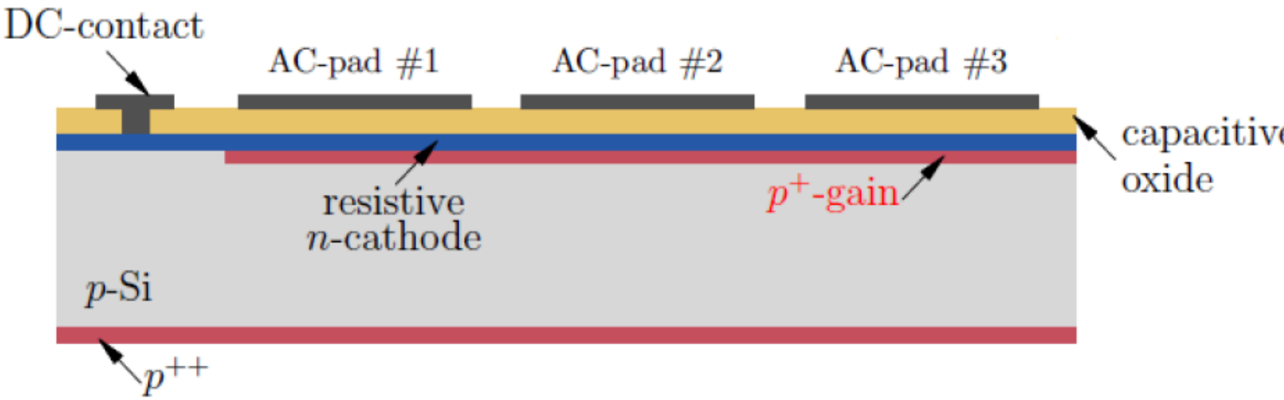


$$\Delta t_{TOF} = \frac{cL_{TOF}}{2p^2}(m_1^2 - m_2^2)$$

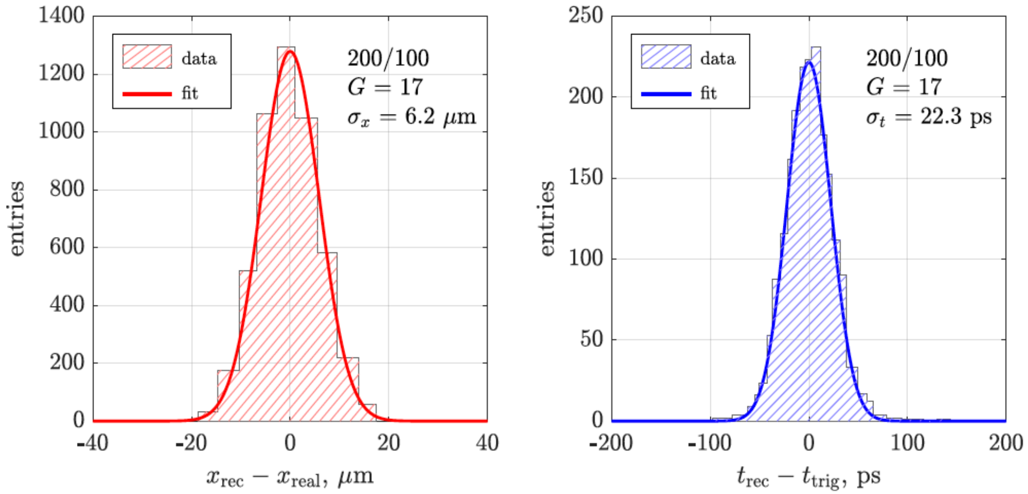
$$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right).$$



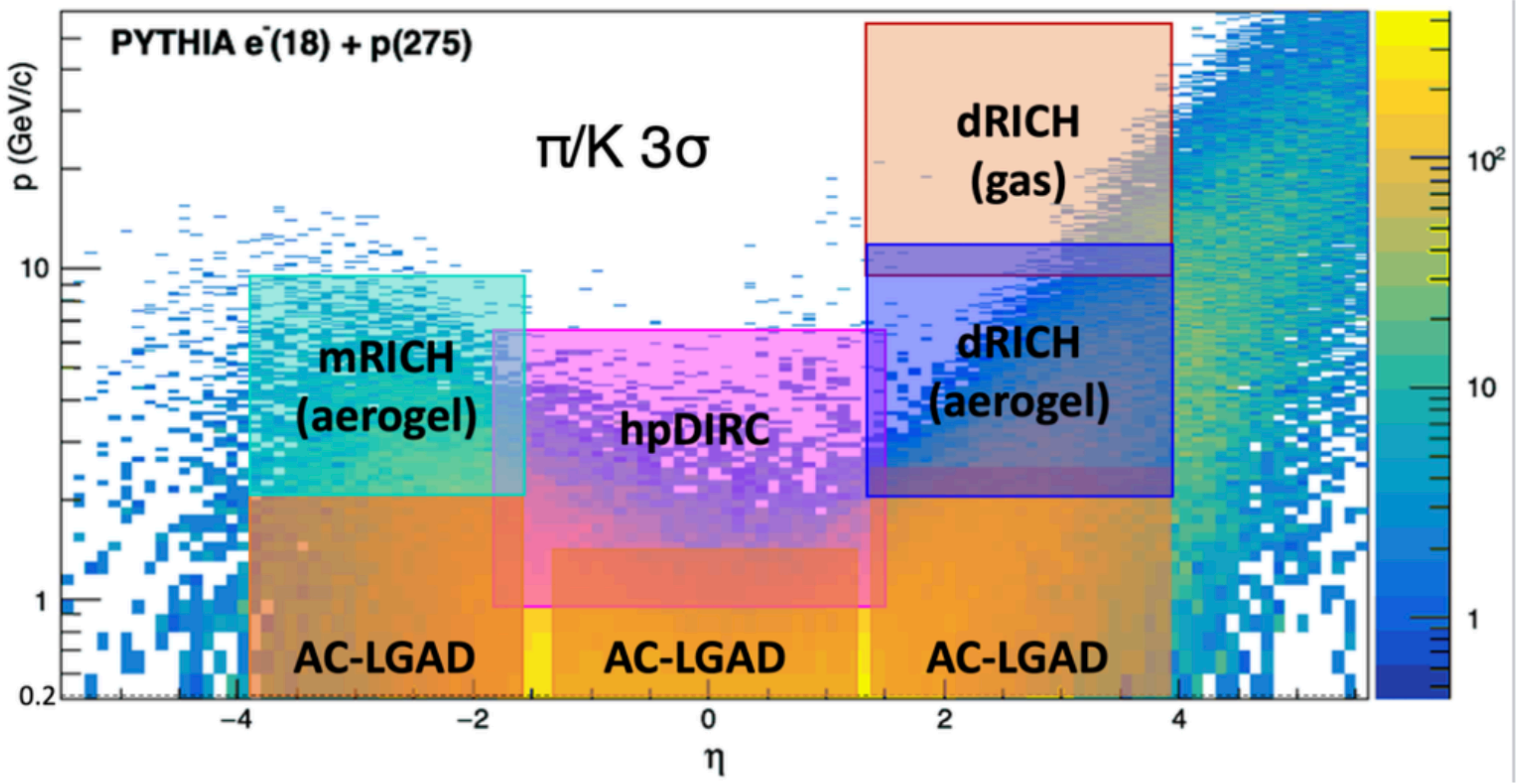
- ➢ In barrel - limited space L_{TOF} < 1 m
- ➢ No space for "Start detector" - t0
- ➢ Need to know **vertex position** more precisely to **measure L_TOF** precise (total particle length/curvature)
- ➢ high timing resolution of TOF detector (10-20 ps)



- For TOF or Far-Forward/Backward area
- Detectors can provide <20ps / layer
- AC-coupled variety gives 100% fill factor and potentially a high spatial resolution (dozens of microns) with >1mm large pixels

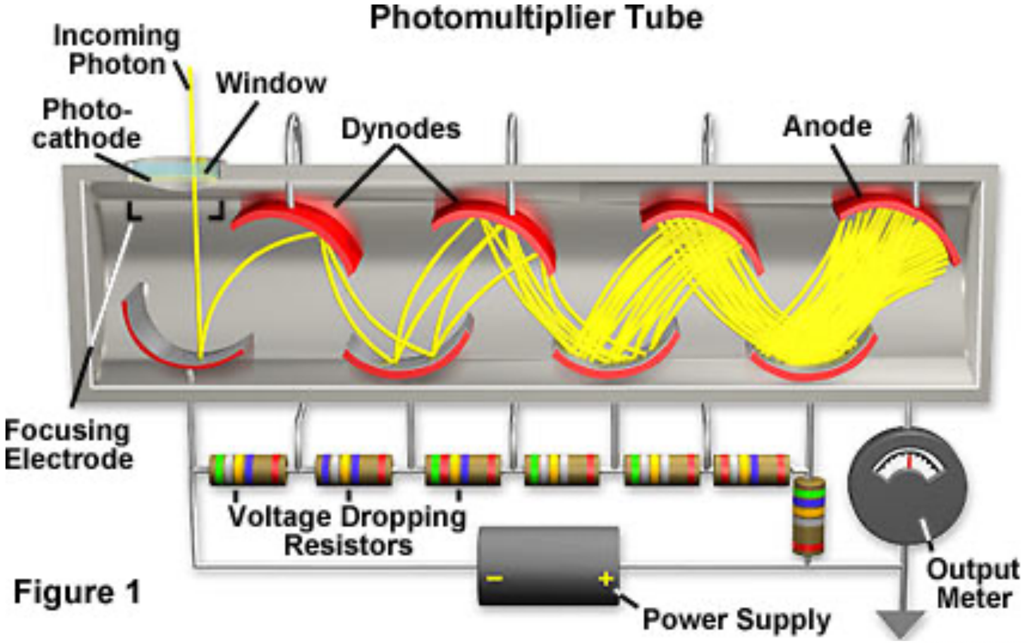


Particle identification: charged hadrons(π, K, p)



Readout: PMT vs SiPM

PMT

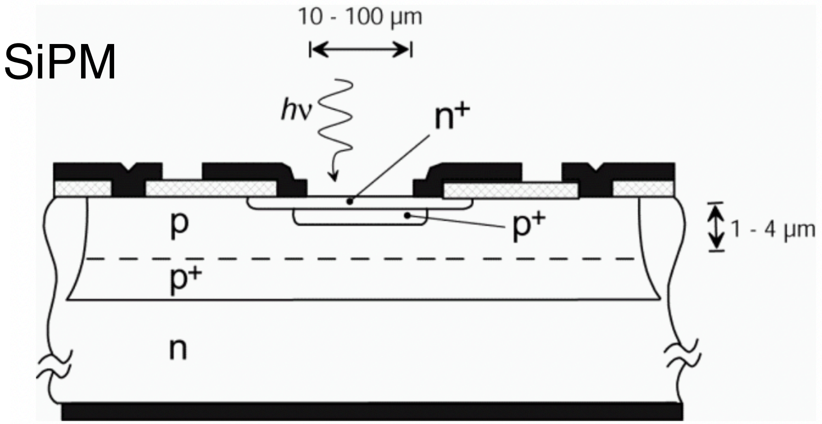


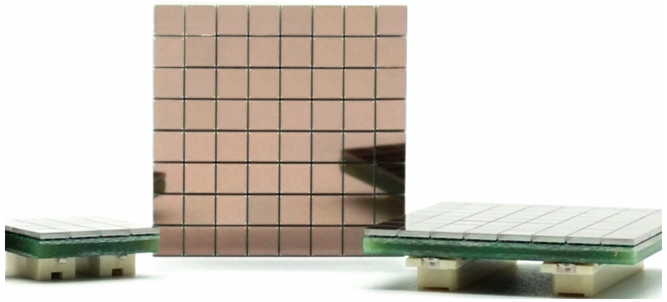
Good linearity in large dynamic range

Very sensitive to the magnetic field

Typical Gain $=10^4 - 10^7$

SiPM





Compactness

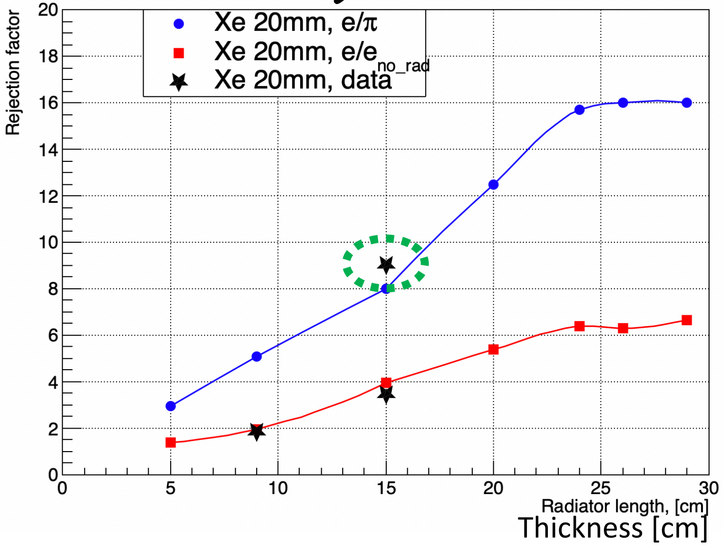
Single photon sensitive

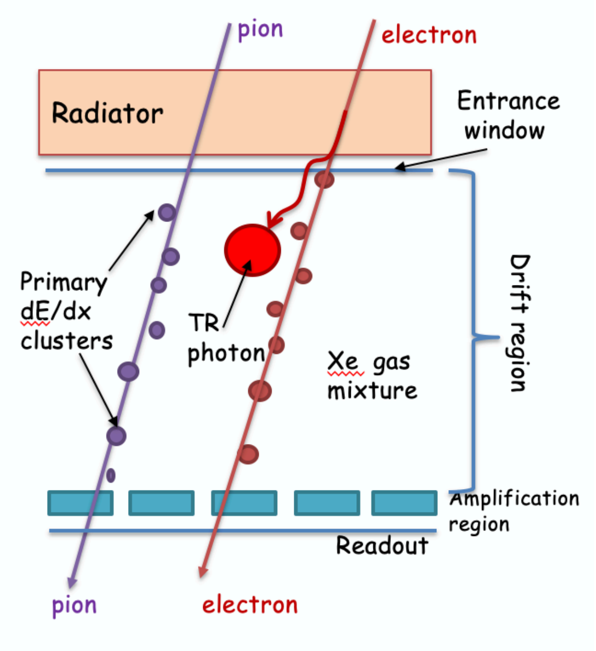
Huge dark noise rate (temperature dependent)

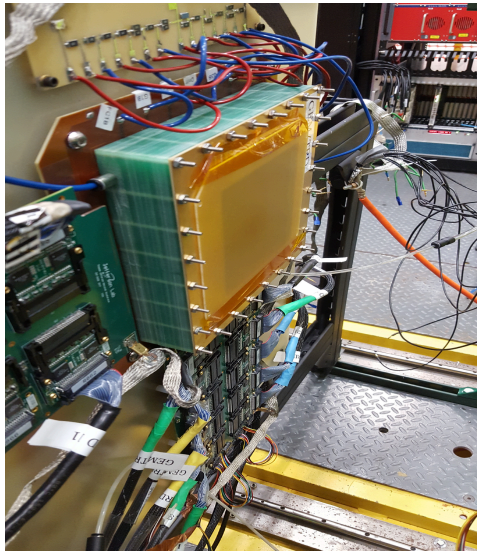
> 100kHz/mm2 @ 25C

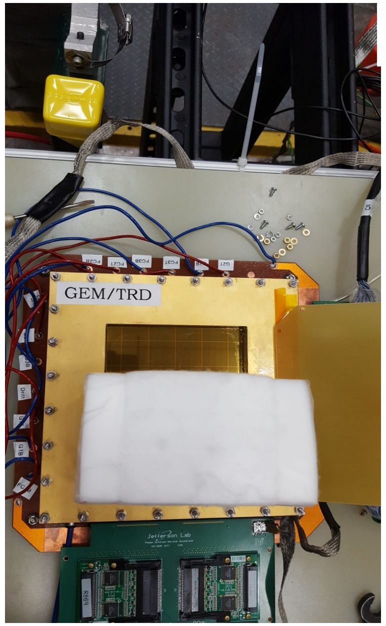
Additional e- ID : GEM based TRD (part of generic R&D) for future update or 2nd Detector

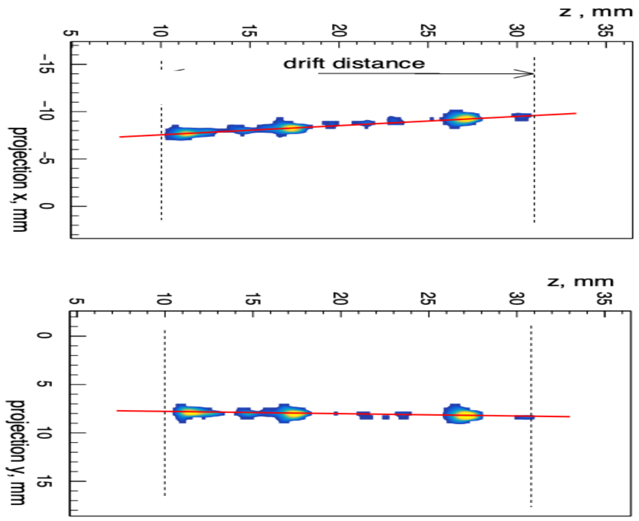
- To improve e-identification for leptonic/semi-leptonic decays.
- In addition to Calorimeters and Cherenkov detectors in the hadron-endcap considering TRD.
- GEM -TRD/Tracker :
  - e/π rejection factor ~10 for momenta between 2-100 GeV/c from a single ~15cm thick module.











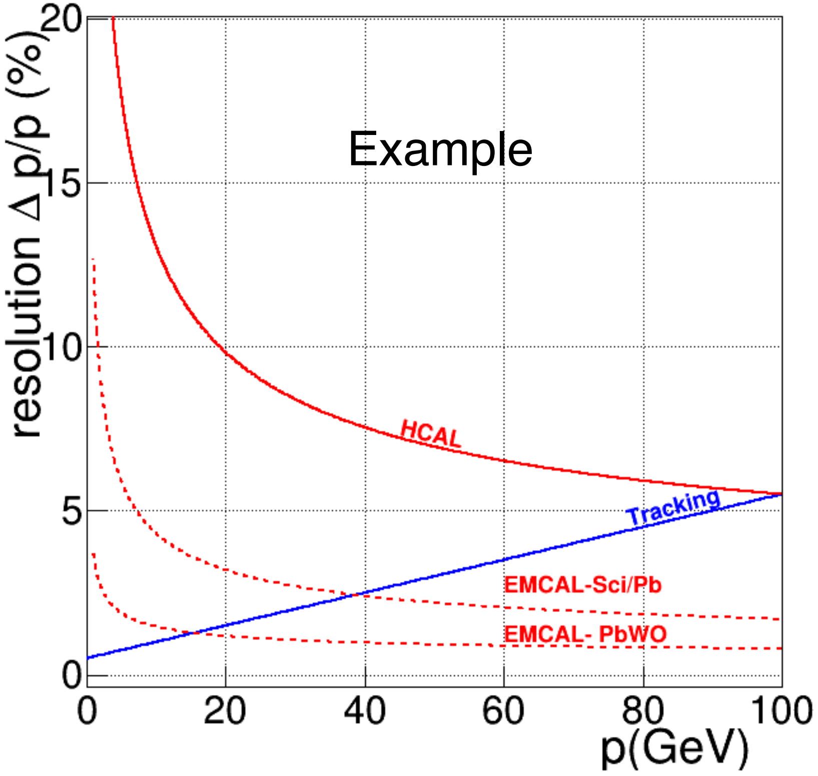
- Very precise Tracking segment behind dRICH.
- Could be used as the EIC detector upgrade

Why do we need a calorimeter ?

✓ Use momentum measurements for charged particles: $E^2 = (p^2+m^2)$

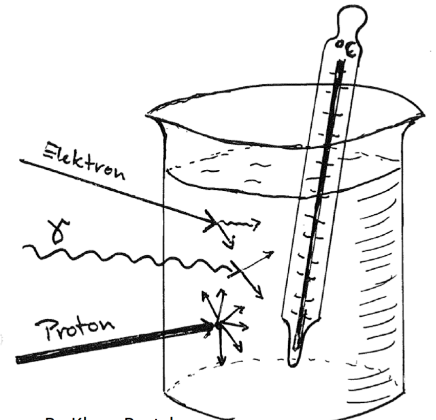
- ➢ Need to identify a particle (or mass): not always possible.
- ➢ Need to measure momentum precise: not always possible.
  - ❖ Momentum measurements are getting worse with increase of particle momenta ($\frac{\Delta p}{p} \sim p$)
  - ❖ BUT, Calorimeter measurements are getting better with increase of the energy ($\frac{\Delta E}{E} \sim \frac{1}{\sqrt{E}}$)

✓ Need to measure neutral particles! Calorimeter is the ONLY detector for them.



Calorimetry

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



By Klaus Pretzl

We need 1kCal to change a temperature on 1 ℃ 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 (silicon, gaseous, 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

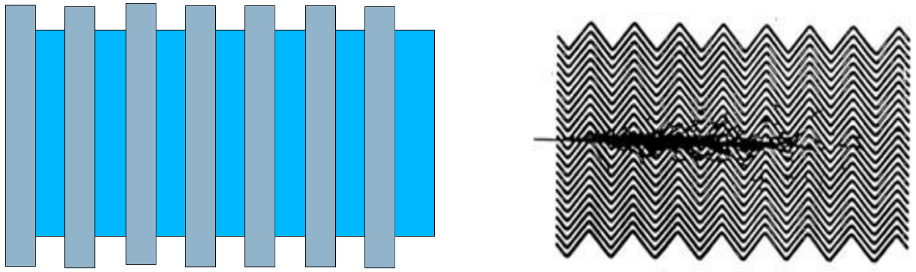
  ⇒ Calorimeter is the **outermost detector**

- ✓ Calorimeter measure charged + neutral particles

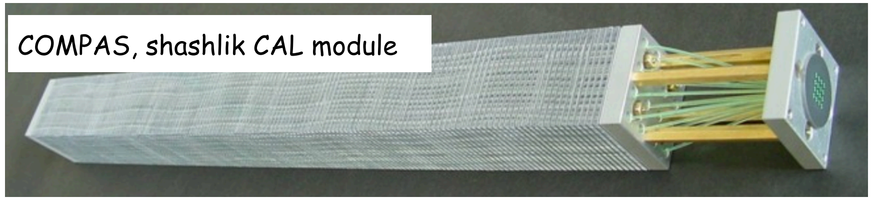
Types of calorimeter

- **Sampling calorimeter:**

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



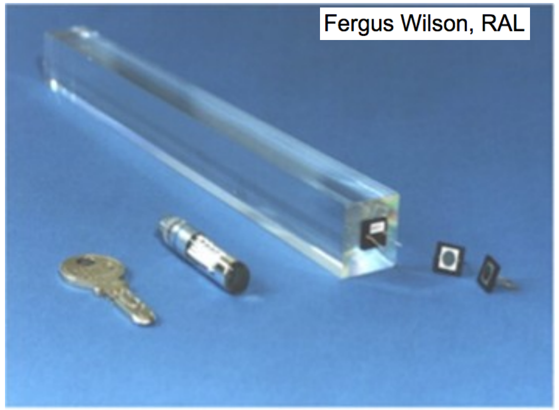
Absorber: Pb, etc
Sensitive (solid or liquid):
Si, scintillator, LiAr


COMPAS, shashlik CAL module

- **Homogeneous calorimeter**

Monolithic material , serves as both absorber and detector material

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

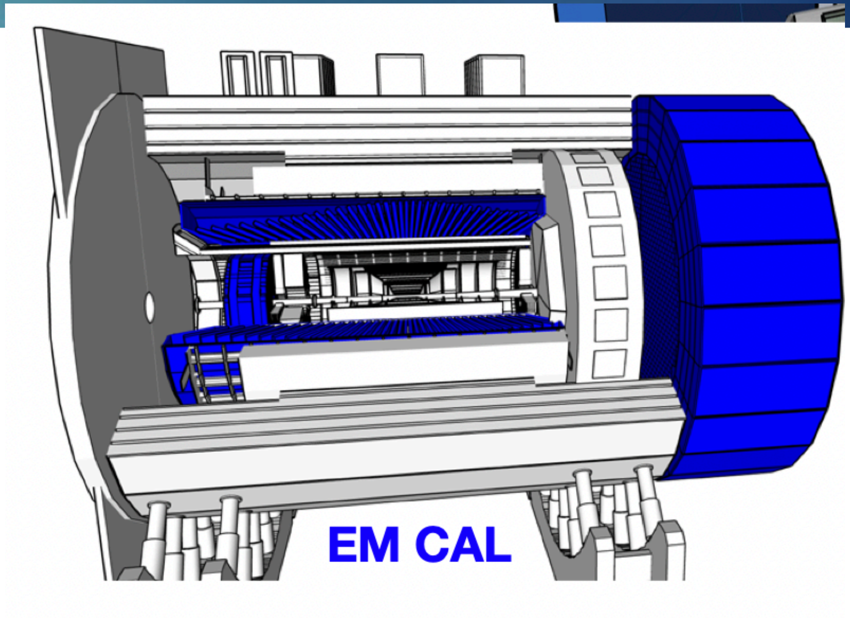

Fergus Wilson, RAL

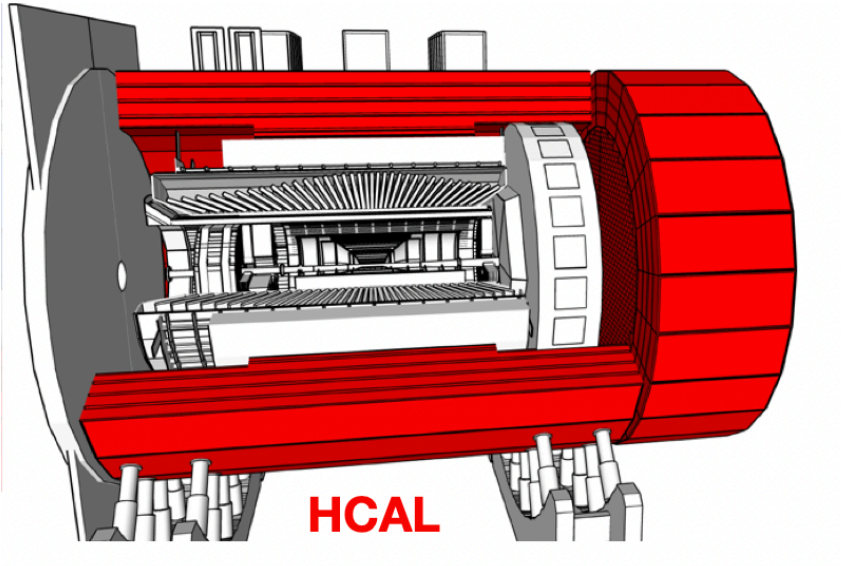
Calorimetry at EIC

Close to 4π coverage
calorimeters need to perform

- Scattered electron kinematics measurement
- Photon detection and energy measurement
- e/h separation (via E/p & cluster topology)
- π0/γ separation

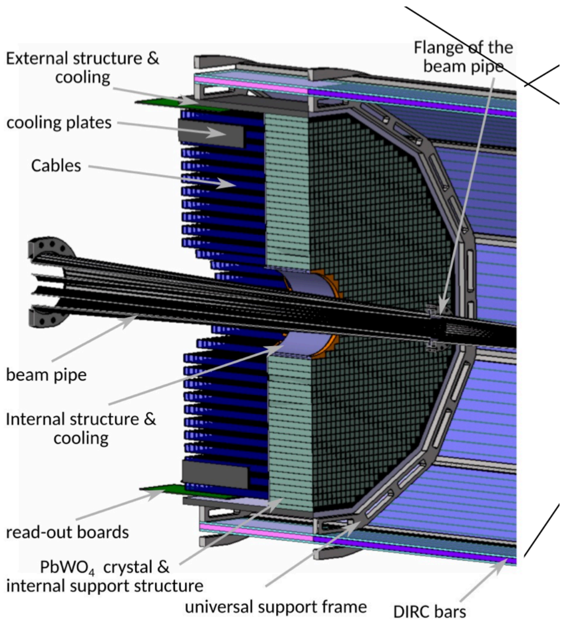
EMCAL technologies are based on the outcome of the EIC generic R&D (eRD1)





Electromagnetic calorimeter

Backward EMCAL



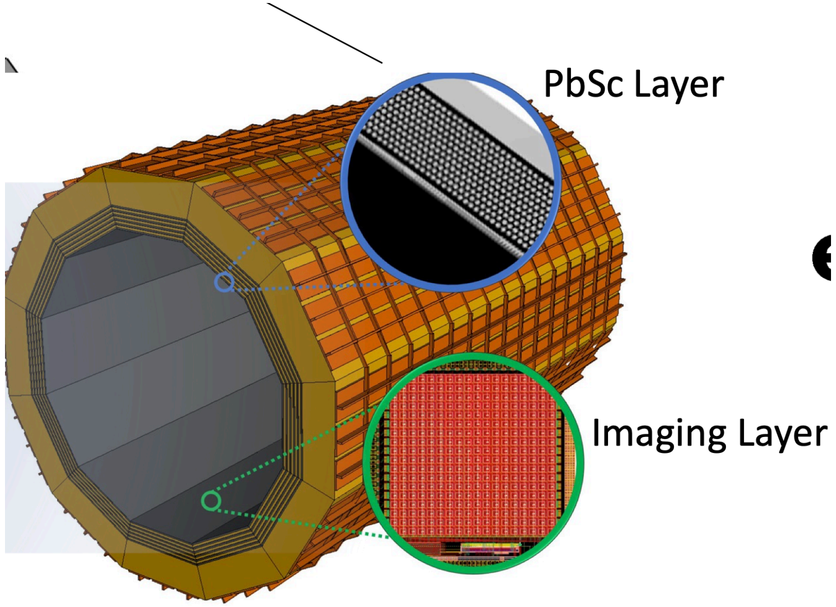
Backwards EMCal
PbW04 crystals

Figure from the EIC EEEMCAL Consortium design report

	Backward ECAL
η	[-4 .. -1.8]
σ_E/E	2%/√E+1%*

*Based on prototype beam tests and earlier experiments

Barel EMCAL

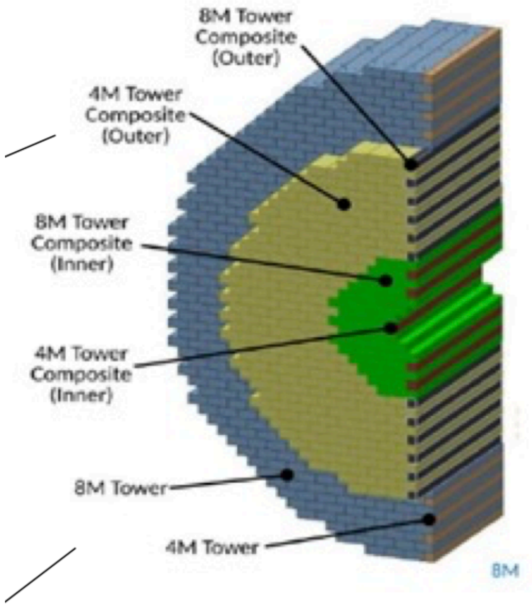


Imaging PbSc calorimeter

Astropix-based imaging layer

Alternative: SciGlass

Forward EMCAL



High granularity
W/SciFi EMCal
Longitudinally separated
HCAL with high-η insert

	Barrel ECAL	Forward ECAL
η		[1.3 .. 4]
σ_E/E		7.1%/√E+0.3%

*Based on prototype beam tests and earlier experiments

Crystals

Tungsten glass (CMS or PANDA)

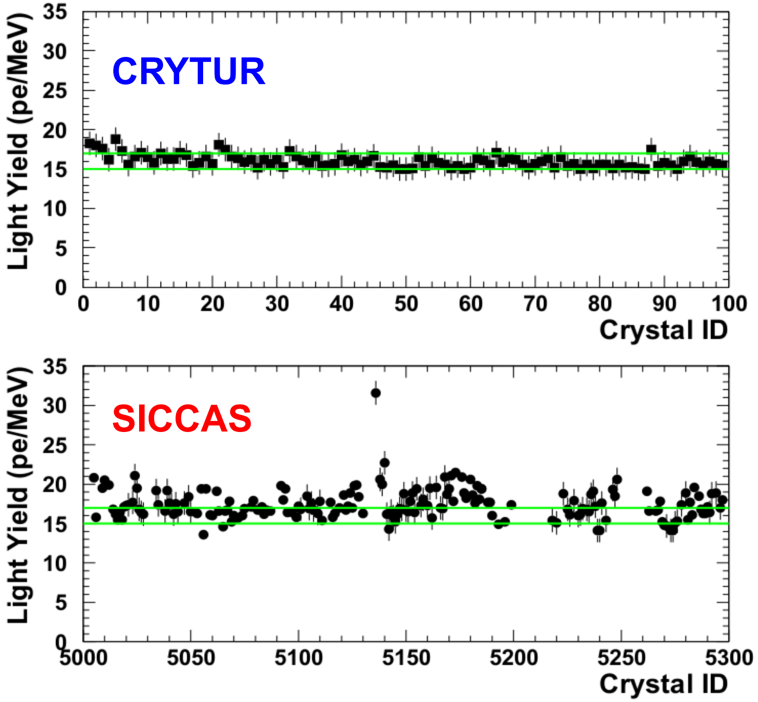
- Excellent energy resolution:

  $(1-3)\ \%/\sqrt{E(\mathrm{GeV})} + 1\text{-}1.5\ \%$
- Tower structure, fine transverse granularity
- Compactness, easy to assemble
- Time resolution: <2 ns
- Cluster threshold: 10 MeV

- are available from two vendors
- Each crystal each weigh 1.5kg
- Each crystal needs ca two days to grow

- For CMS it took 10 years to grow all crystals !!!

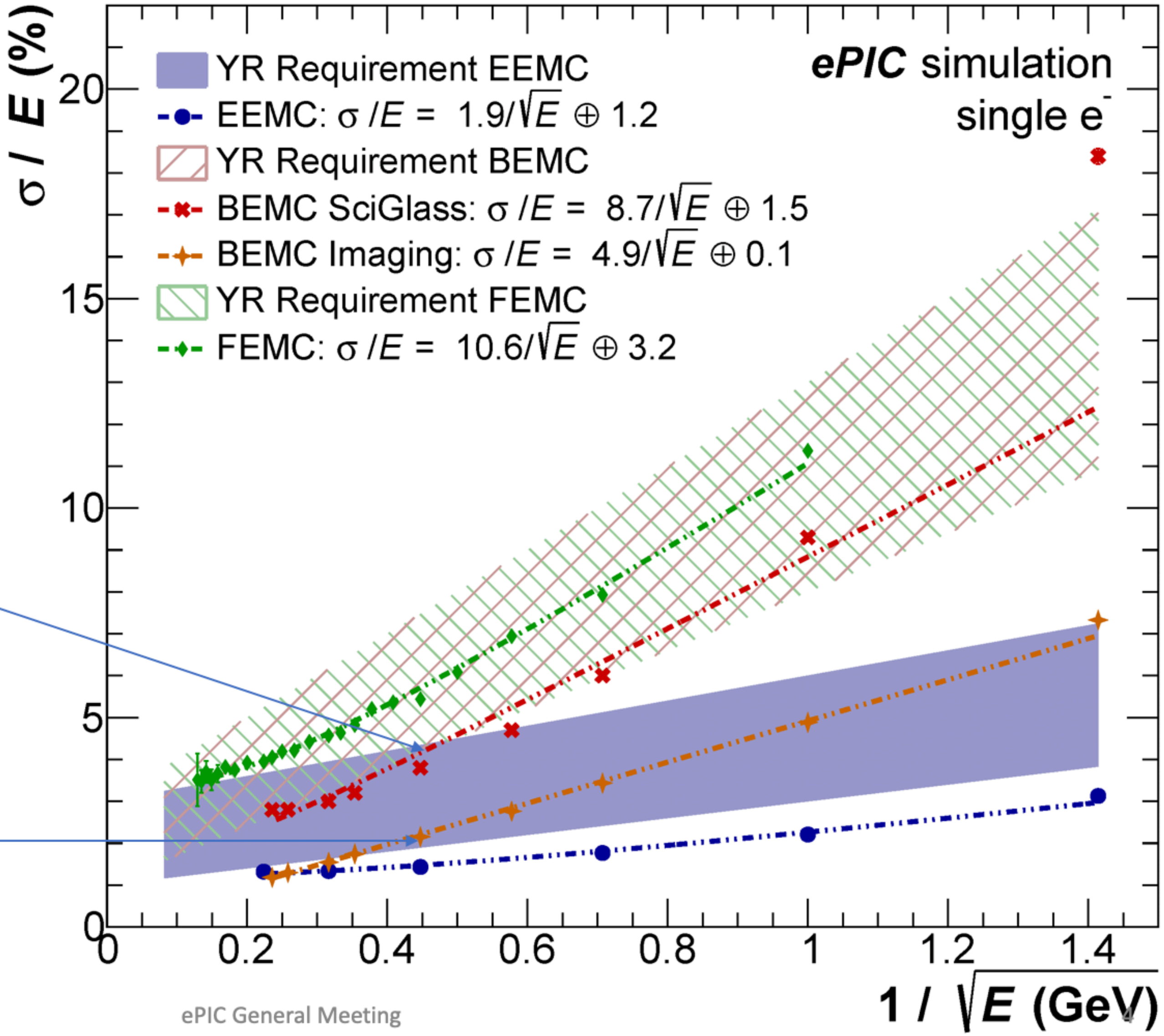
PWO: vendor characterization



ePIC electromagnetic calorimeters

EMCal energy resolution plot from Fredierike Bock 3/30/2023

Both calorimeters meet the YR energy resolution requirement

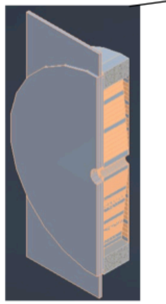


SciGlass easily meets the YR requirement

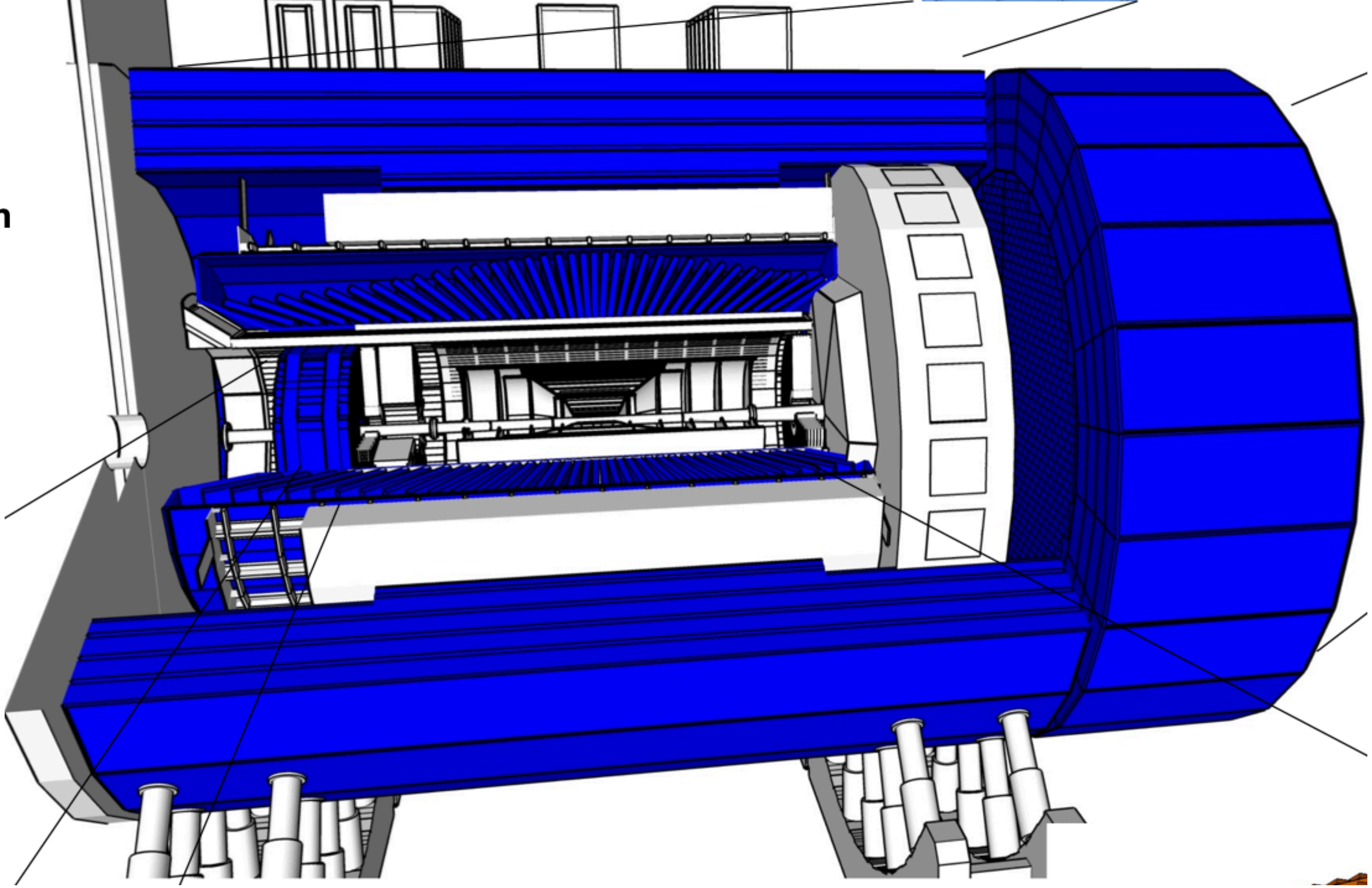
Imaging EMCal does substantially better than the YR requirement

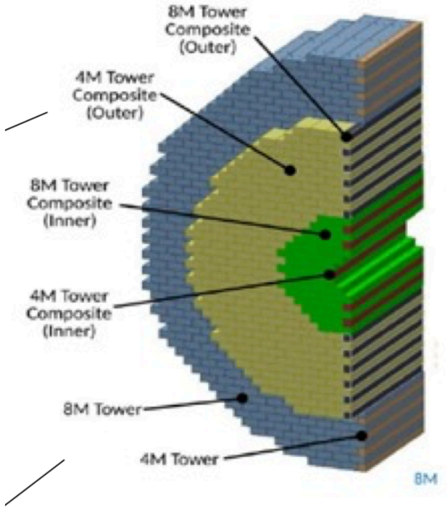
Hadronic calorimeter

Barrel HCAL (sPHENIX re-use)



Backwards HCal Steel/Sc Sandwich tail catcher

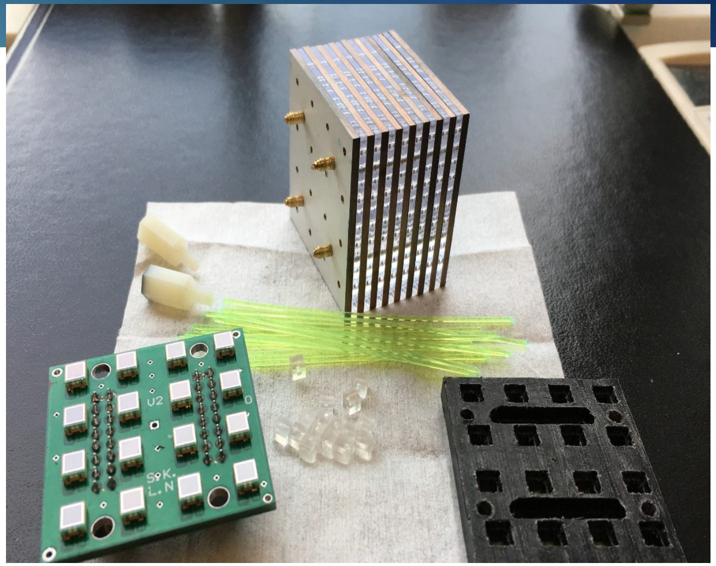


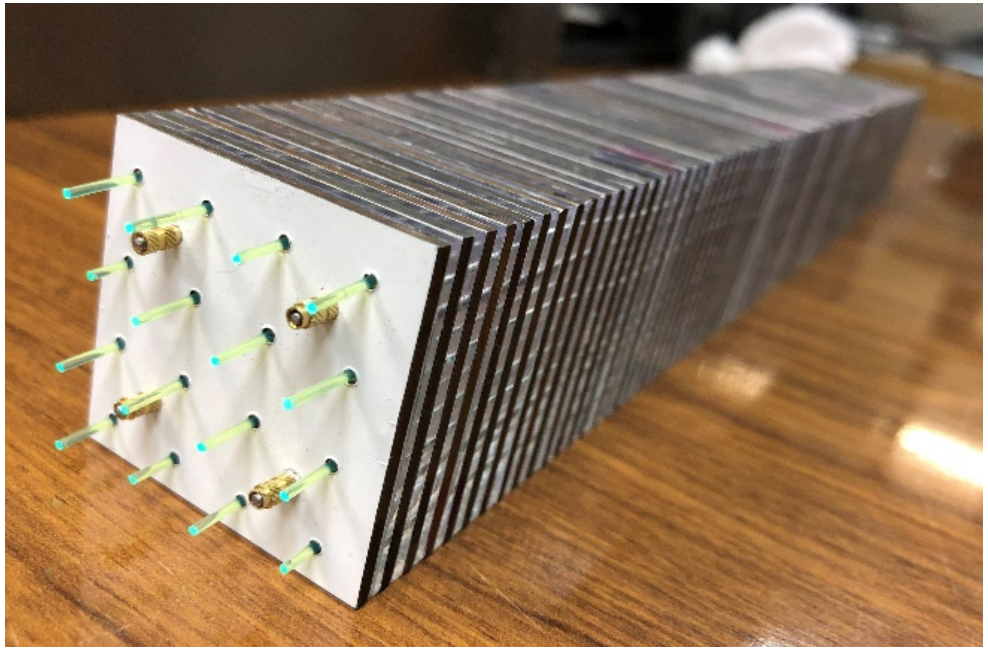


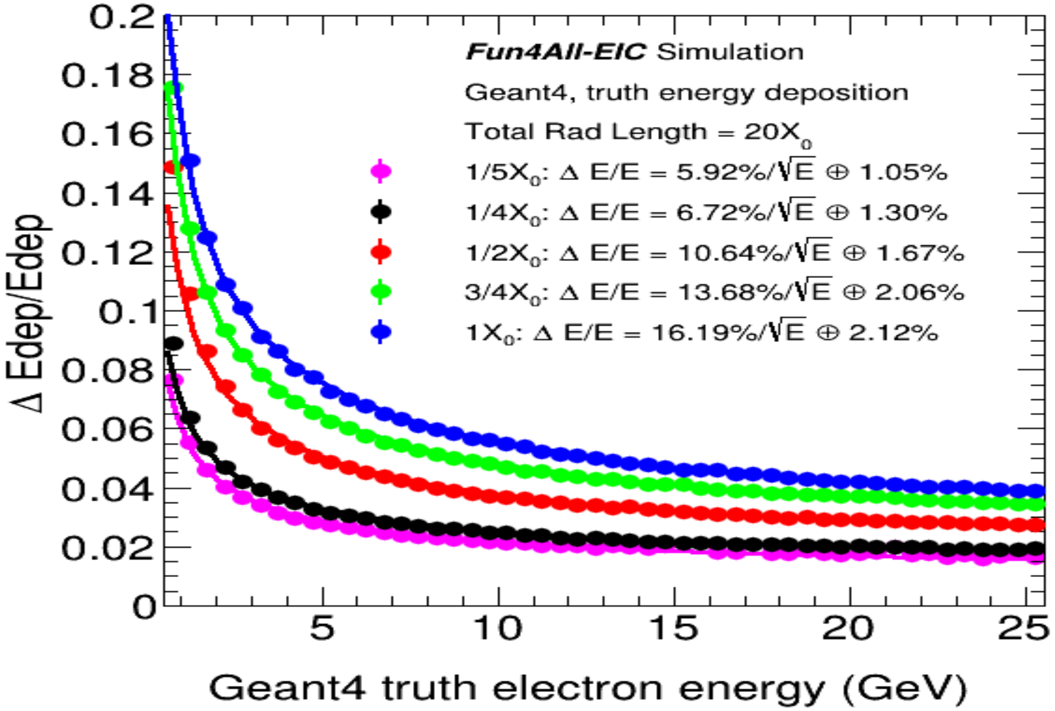
High granularity W/SciFi EMCal Longitudinally separated HCAL with high-η insert

Sampling calorimeter: EMCAL

- Well established technology
  - HERA-B, ALICE, PHENIX, PANDA, …
- Medium energy resolution ~7..13%/√E
- Compact (X_0 ~7mm or less), cost efficient
- Pb/Sc shashlyk

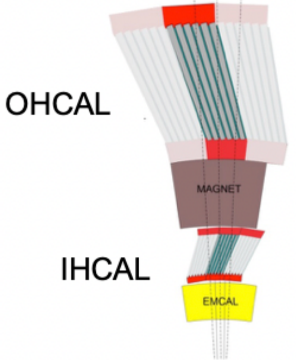




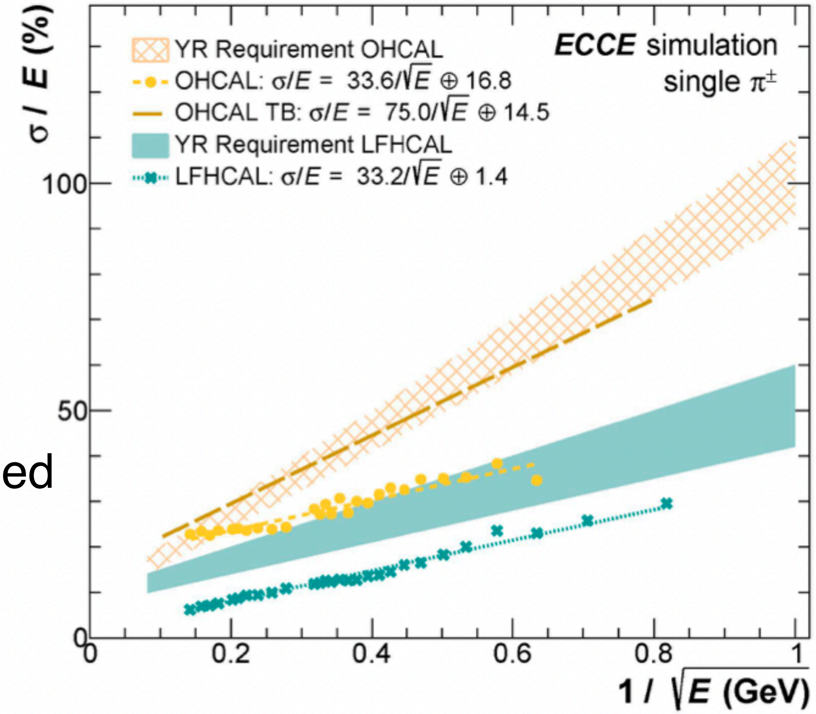


Sampling calorimeter: HCAL

Barrel HCAL (OHCAL+IHCAL)

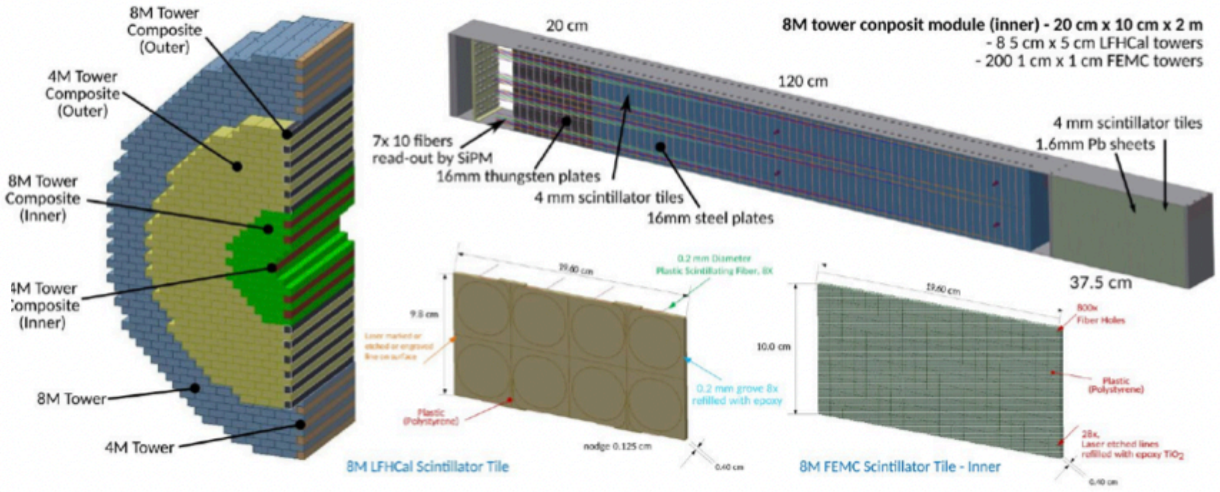


Sampling calorimeter based on Fe/SC tiles



Forward HCAL (LFHCAL)

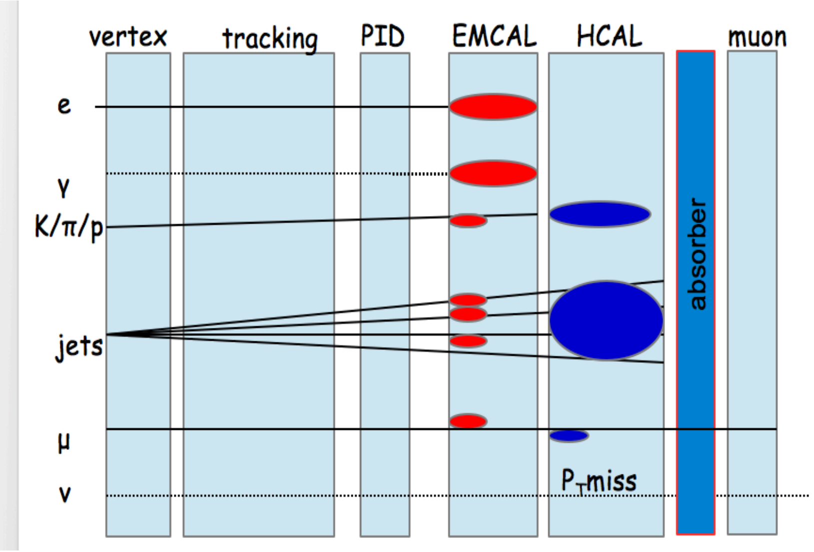
Integrated ECAL+HCAL longitudinally segmented sampling calorimeter based on Fe/SC, W/Sc and last segment W (tailcatcher)



	Barrel HCAL	Forward HCAL
η	[-1 .. 1]	[1 .. 4]
σ_E/E	$\sim 75\%/\sqrt{E} + 15\%$*	$\sim 33\%/\sqrt{E} + 1.4\%$
depth	$\sim 4\text{-}5\ \lambda_I$	$\sim 7\text{-}8\ \lambda_I$

*Based on prototype beam tests and earlier experiments

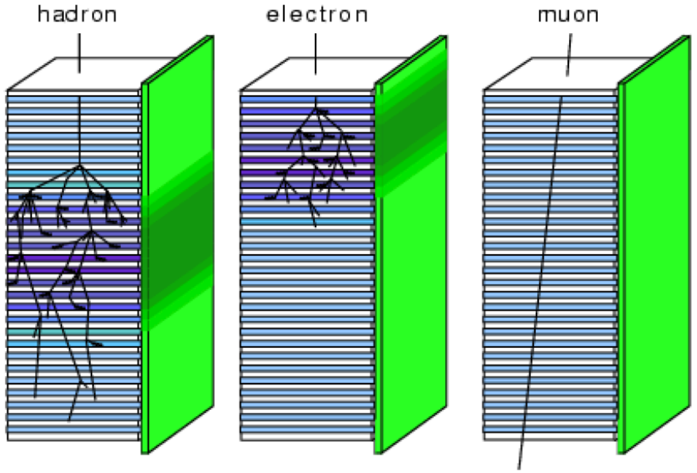
Calorimeter for particle identification



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):

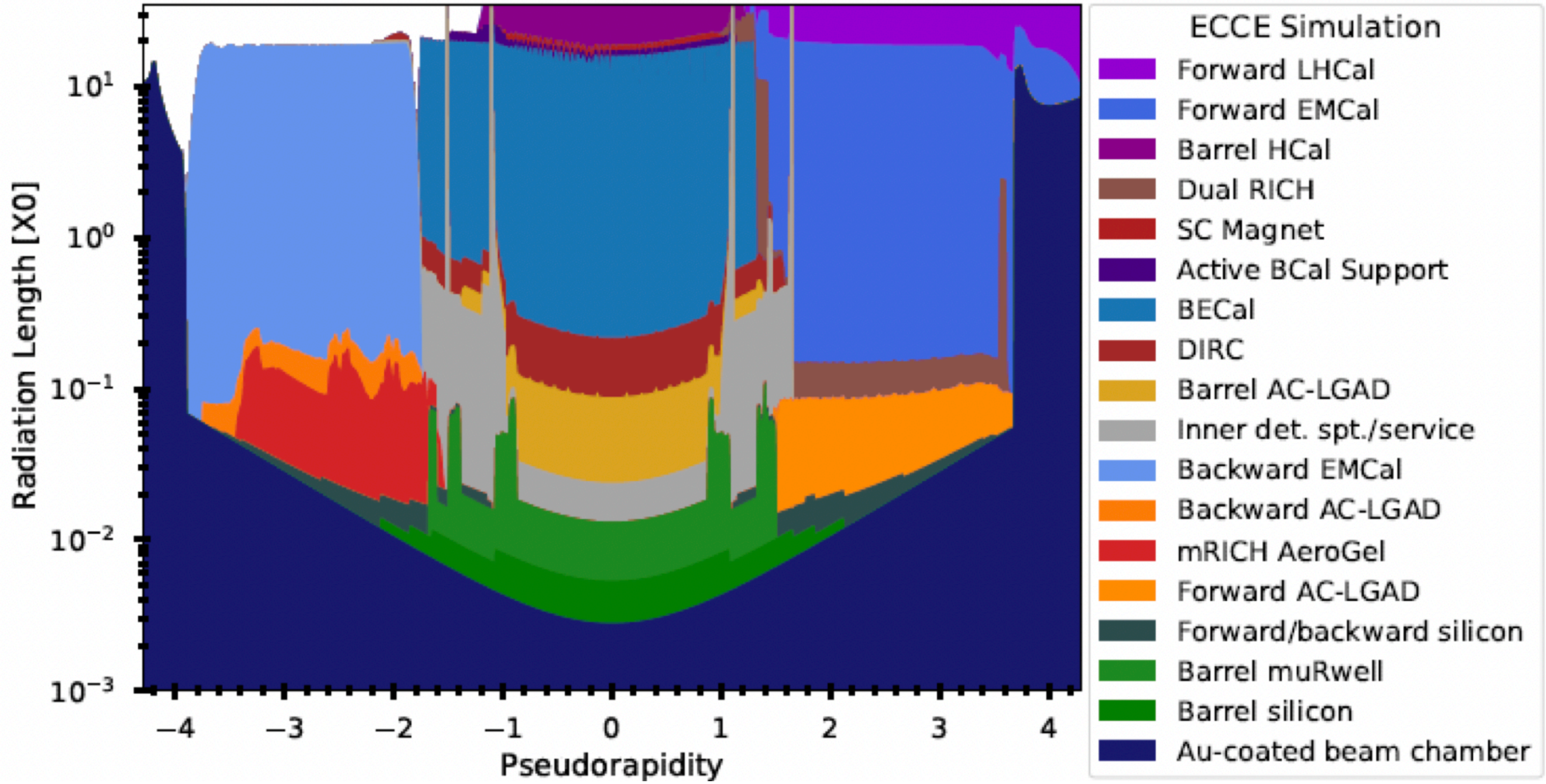
e/hadron separation:
hadrons could develop shower in EMCAL
$\pi 0 \rightarrow \gamma\gamma$: cluster in EMCAL
Not possible to separate charged hadrons (π,K,p)



Erik Maddox

Material budget

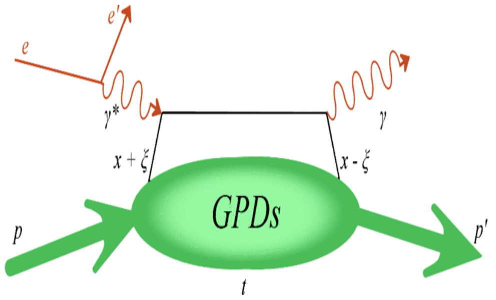
- ❑ Low material budget
  - ❑ Minimize bremsstrahlung and conversions for primary particles
  - ❑ Improve tracking performance at large |η| by minimizing multiple Coulomb scattering
  - ❑ Minimize the dead material in front of the high-resolution EM calorimeters



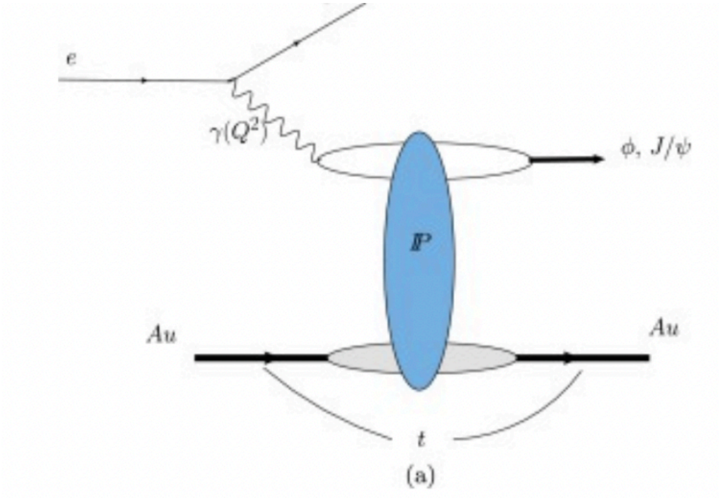
Physics motivation: exclusive reactions

- ➢ DVCS, (p -> p')

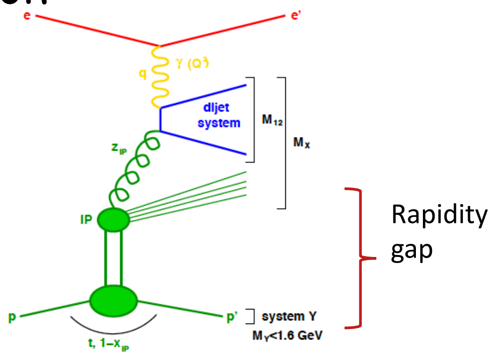
$$e + p \rightarrow e' + \gamma + p'$$



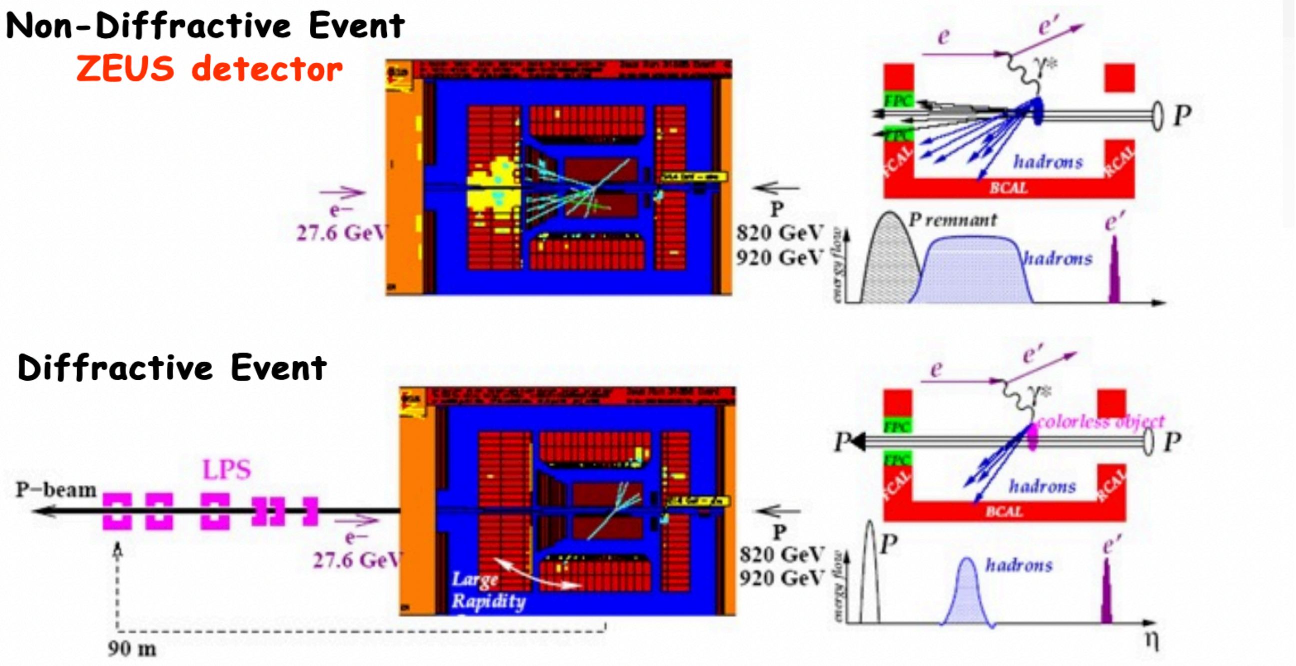
- ➢ (p -> n) , (D-> D')
- ➢ Vector Meson production (J/Psi)



➢ Diffraction



Example from HERA/ZEUS

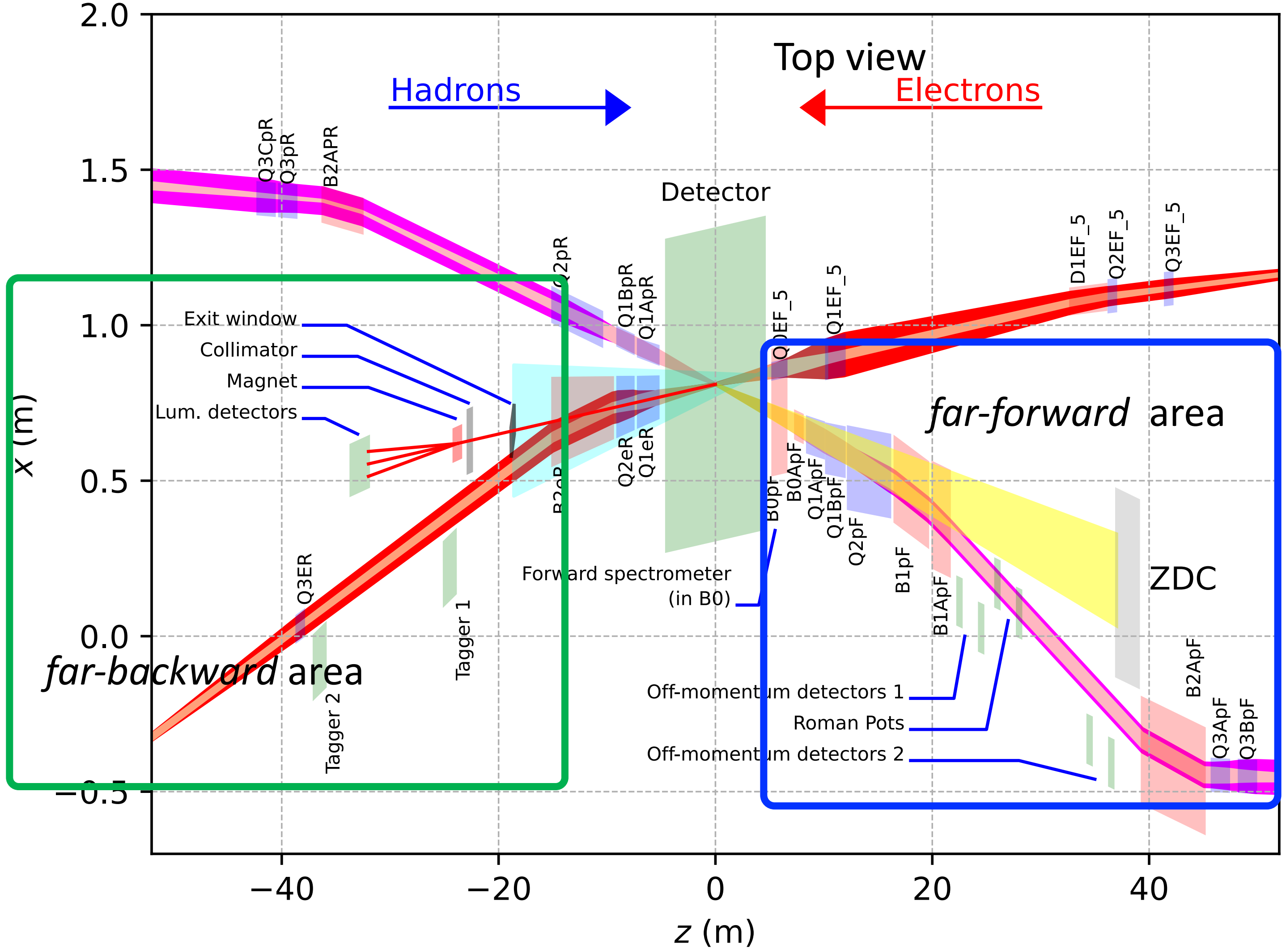


M_X - invariant mass of all particles seen in the central detector

t - momentum transfer to the diffractively scattered proton

t - conjugate variable to the impact parameter

EIC interaction region layout (IP6)

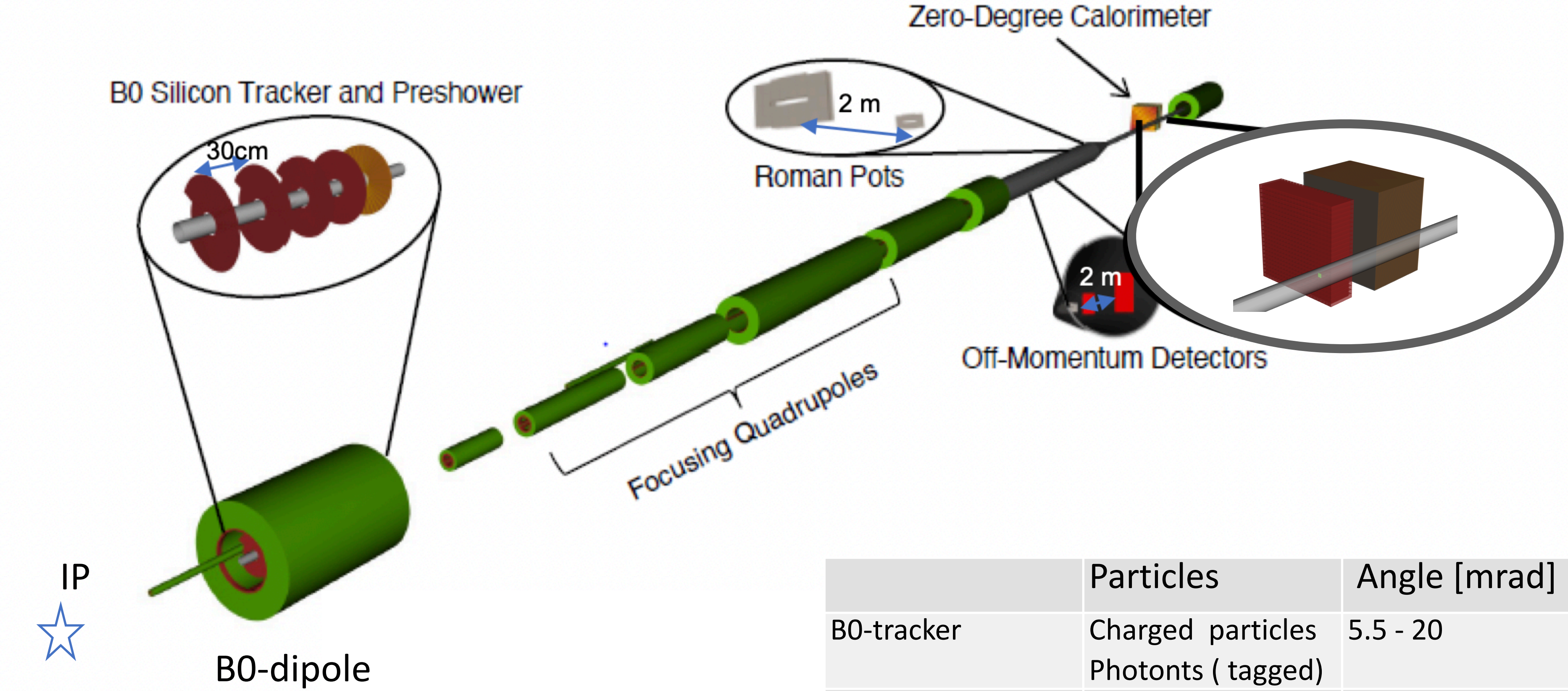


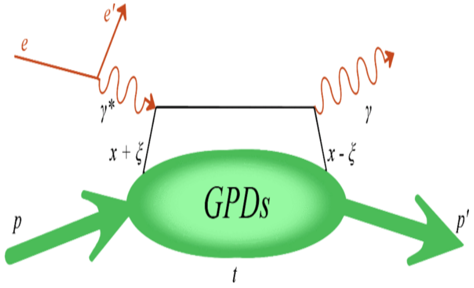
- ~9.5 m around the IP is reserved for the *central* detector
- Crossing angle provides beam separation and space for detector placements
- Apertures of FFQs and dipoles are designed to allow forward going particles to go through

- *Far forward* and *far backward* detector components are distributed along the beam line within ±40 m
- Design should be able to operate **with different beam energy and high luminosity**
- We are keeping a full detector integration in sync with the accelerator design from the early stages on

Far-forward detectors (hadron-going)

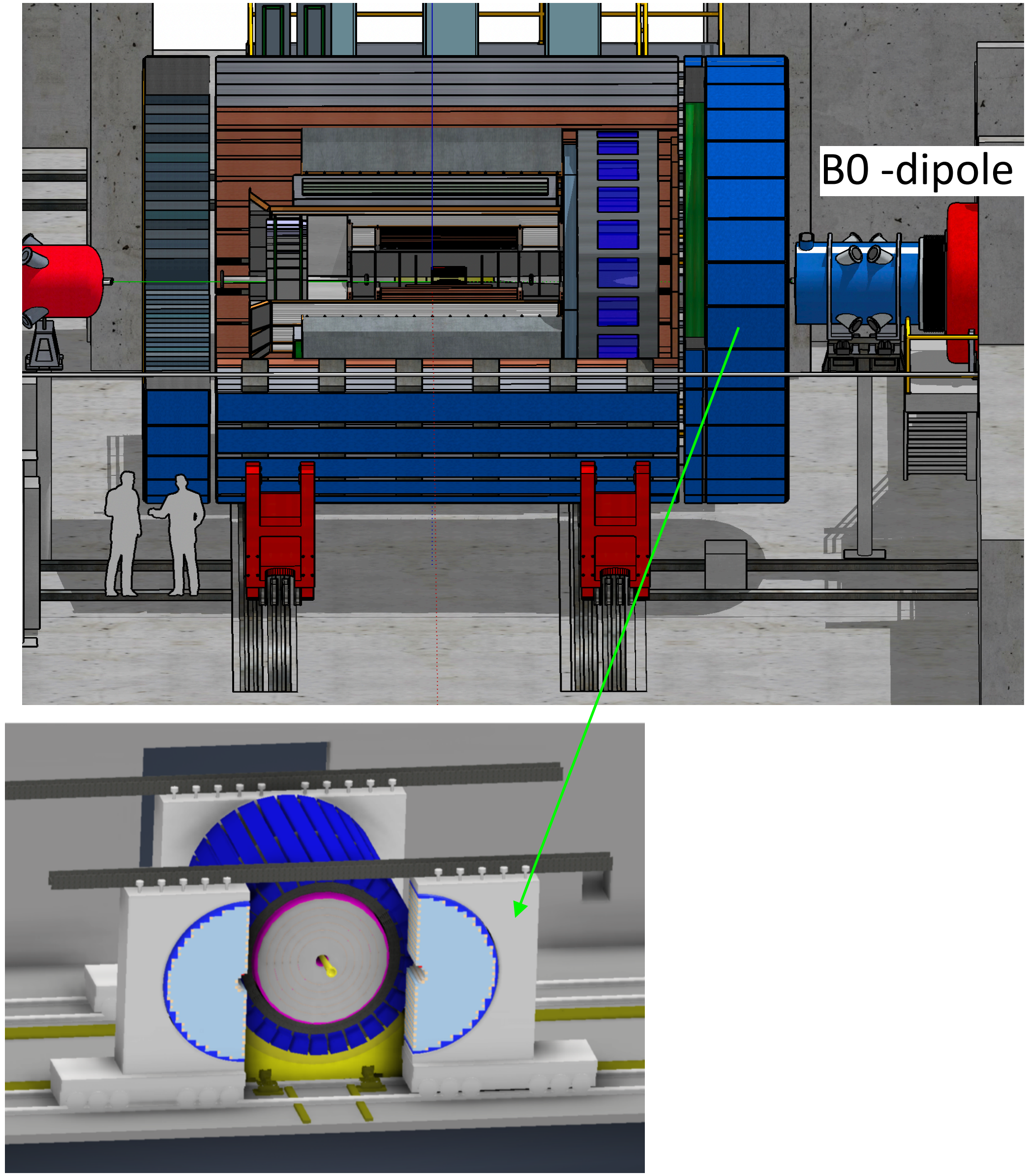
Geant4 implementation of IP6 Far-forward area

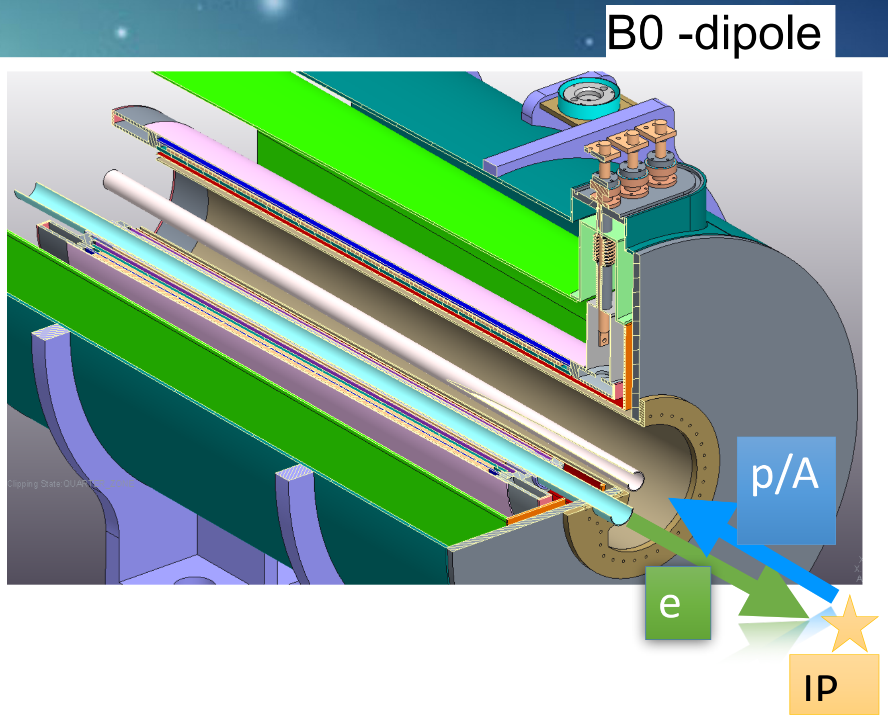




	Particles	Angle [mrad]	$p/p_{beam}(x_L)$
B0-tracker	Charged particles Photonts (tagged)	5.5 - 20	
Off-momentum	Charged particles	0-5.0	0.4< xL< 0.65
Roman Pots	Protons Light nuclei	0 * - 5.0 $(*)10\sigma$ cut	0.6 < xL< 0.95
ZDC	Neutrons Photons	0-4.0 (5.5)	

B0-detectors





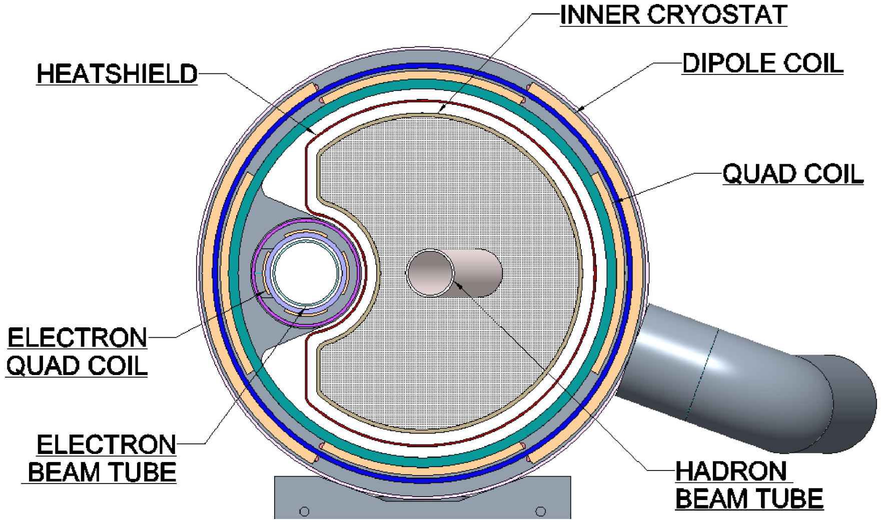
- ➡Dipole field 1.3T: for momentum reconstruction. Design still ongoing (most likely B0 will be shorter 1.8m -> ~1.5m)
- ➡B0 placement - after HCAL
  - ✦ Limited space
  - ✦ Access to B0-detectors only from one side (after opening HCAL)
  - ✦ Vacuum pumps
  - ✦ Beam-pipes: crossing angle

- ➢ B0 placement: high background area => high granularity detectors needed in this area

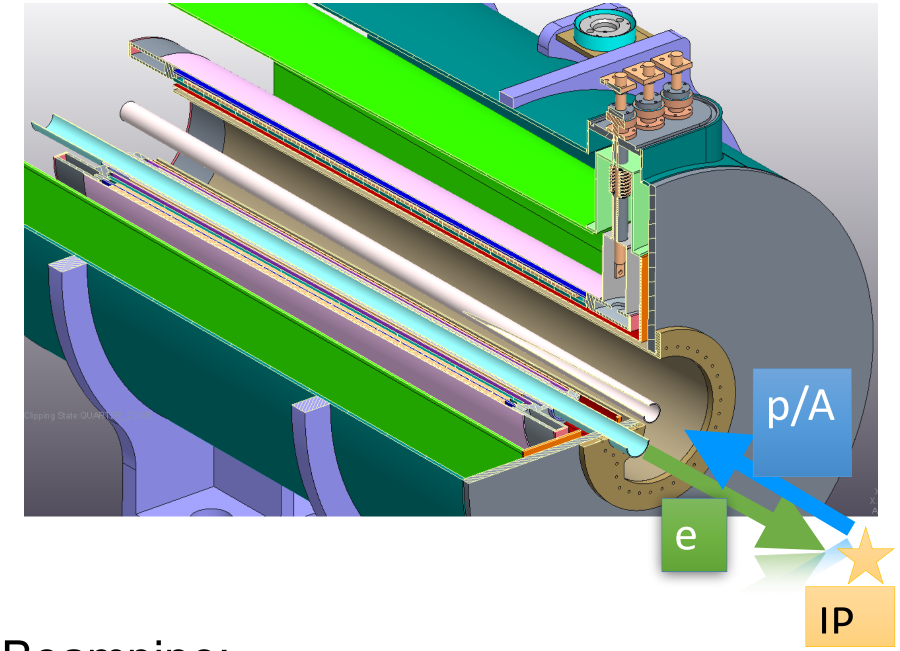
B0-detectors

($5.5 < \theta < 20.0$ mrad) ($4.6 < \eta < 5.9$) -- large |t| value

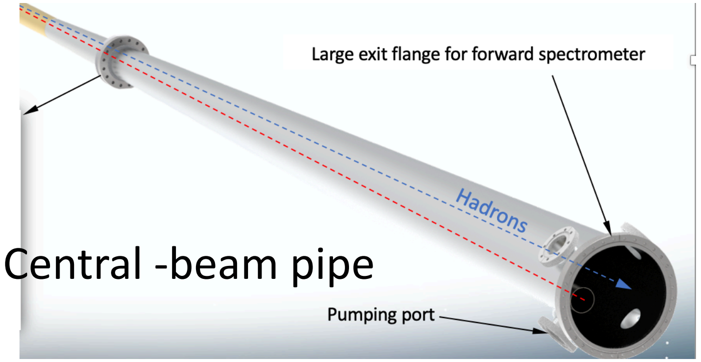
- Create zero field line at electron beam axis.
- Warm space for detector package insert located inside a vacuum vessel to isolate from insulating vacuum.



B0 -dipole



- ➢ Beampipe:
  - ❖ Near IP - common beam pipe
  - ❖ Beams are separation into two independent beam-pipes in front of B0
  - ❖ Low-mass **exit window** for far-forward particles

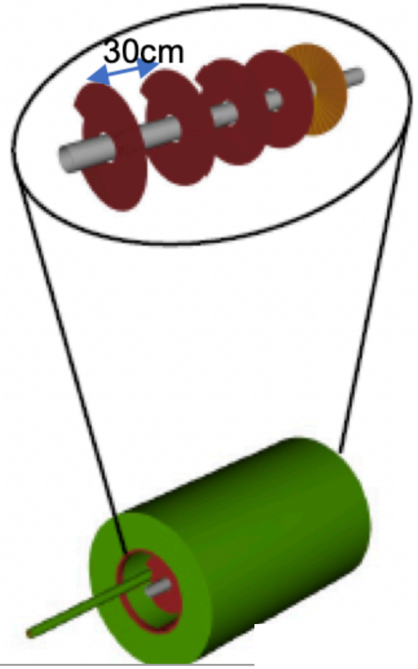


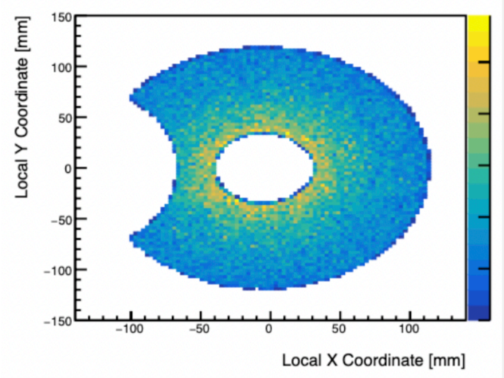
Central -beam pipe

=> B0 detector mechanical integration

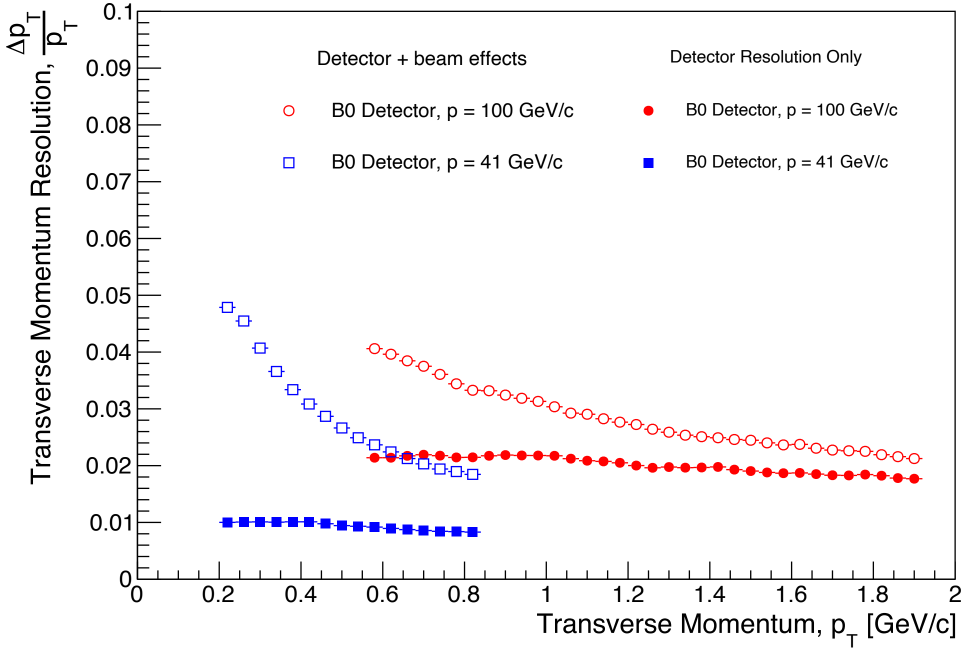
B0-detectors

(5.5 < θ < 20.0 mrad)





- ✓ **Tracker for charged particles**: High granularity detectors needed in this area with layers of fast-timing detectors due required p_T, beam effects, high background.
- ✓ B0-dipole length is ca 1.5m
- ✓ Combination of high spatial resolution and good timing spaced evenly by 30cm inside (~20 cm in diameter)

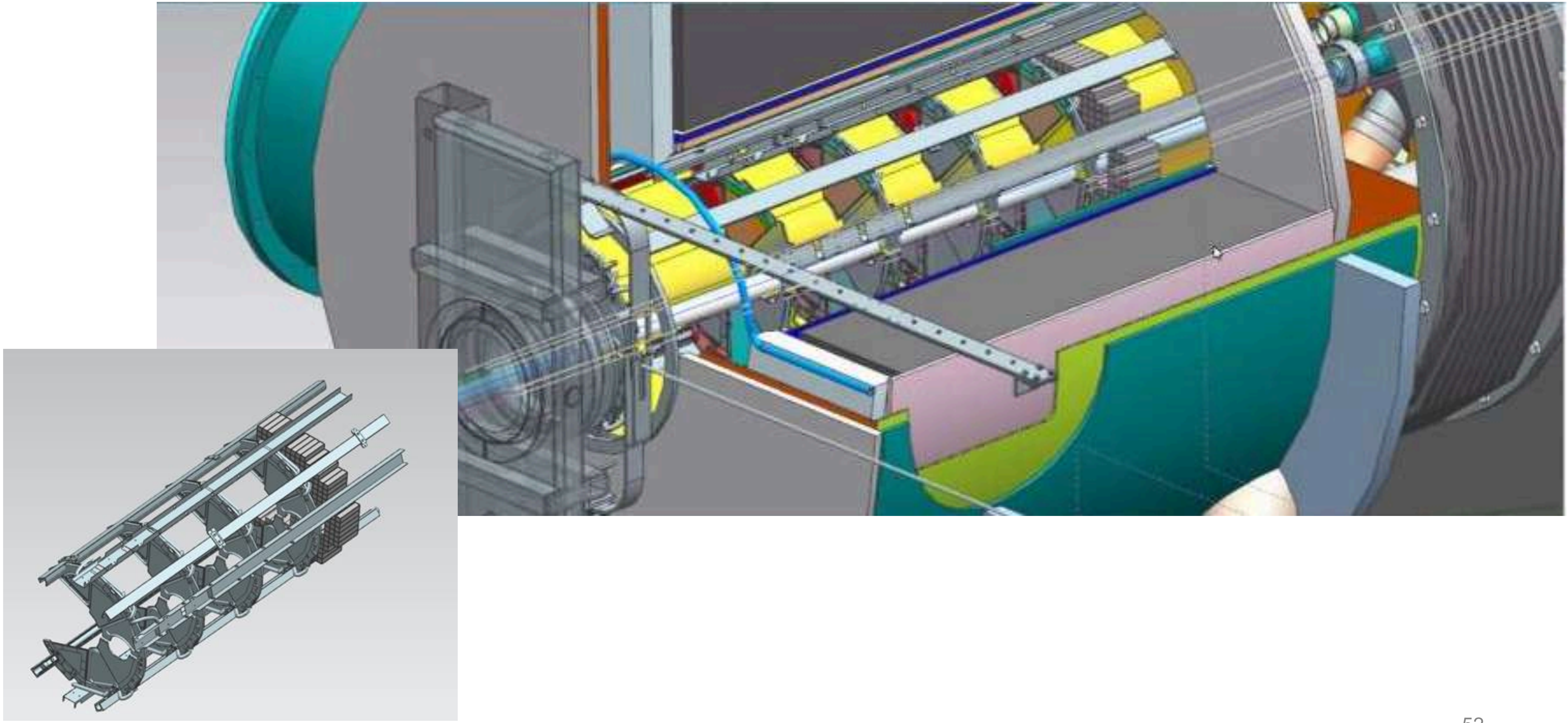


For photon detection: A simple photon tagger or EMCAL (for energy measurements) will be needed. As an example: for $\gamma + \gamma$ from π^0 separation to clearly isolate u-channel DVCS

- ➡ $PbWO_4$ (11.2 r.l.) behind the tracking layers: each 10 cm long with a surface area of 2x2 cm^2 (ECCE)
- ➡ or 2 radiations lengths of **Pb converter**, followed by a layer of **AC-LGADs** (ATHENA)

=> Work in progress

B0-detectors integration



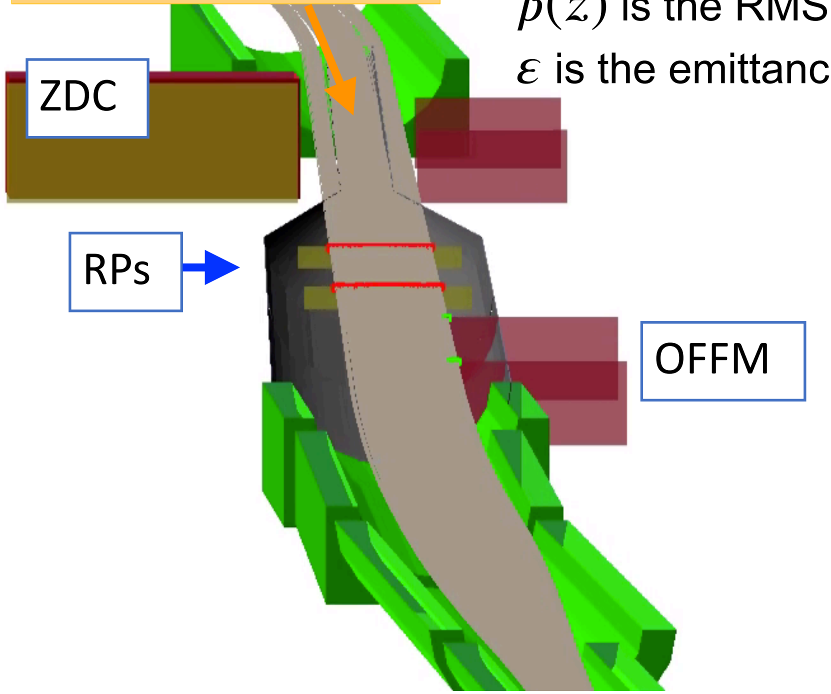
Roman-Pots

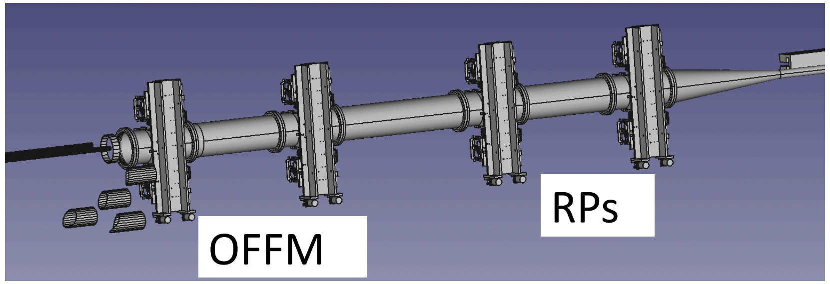
0.0* (10σ cut) < θ < 5.0 mrad

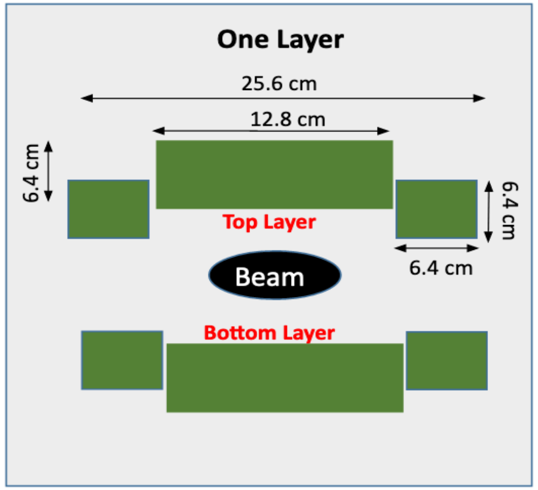
$$\sigma(z) = \sqrt{\varepsilon \bullet \beta(z))}$$

Geant4 setup:
5mrad particle cone

$\sigma(z)$ is the Gaussian width of the beam,
$\beta(z)$ is the RMS transverse beam size.
ε is the emittance.

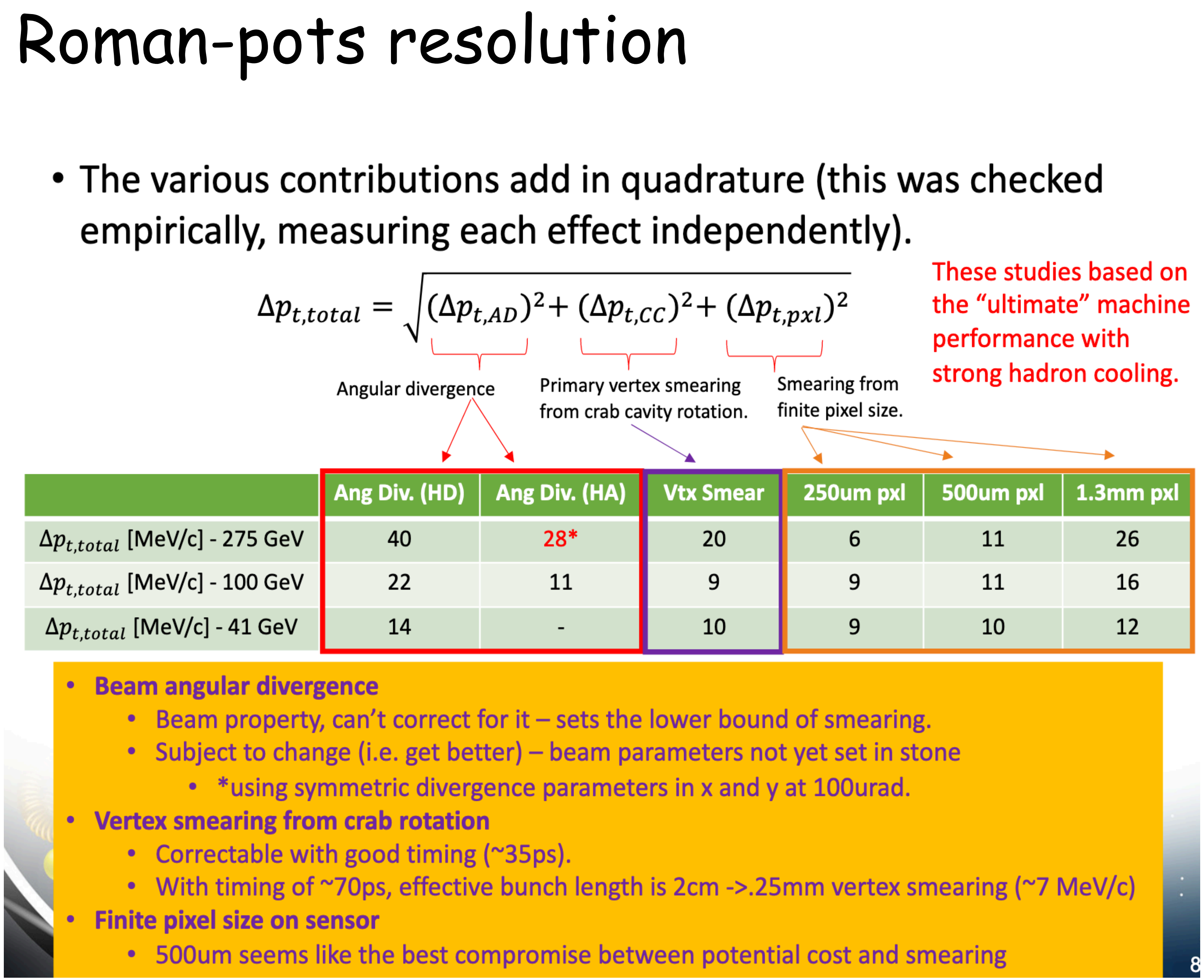






- ✓ **Movable** (as close as 10σ away from the beam (depends on beam energy and beam configuration: high divergence or high acceptance).
- ✓ Move out during an injection.
- ✓ RPs needs to be **integrated into the vacuum system**
- ✓ Insertion from top and bottom - need to minimize space in front of ZDC.
- ✓ Preliminary concept of a mechanical setup.
- ✓ **Very close contact with accelerator** to avoid negative impacts on the machine operation

Alex Jentsch



Roman-pots resolution

- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{\underbrace{(\Delta p_{t,AD})^2}_{\text{Angular divergence}} + \underbrace{(\Delta p_{t,CC})^2}_{\text{Primary vertex smearing from crab cavity rotation.}} + \underbrace{(\Delta p_{t,pxl})^2}_{\text{Smearing from finite pixel size.}}}$$

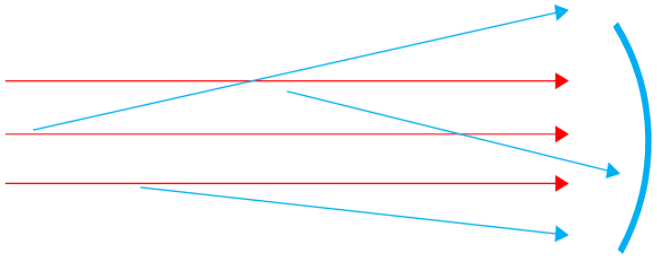
These studies based on the “ultimate” machine performance with strong hadron cooling.

	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250um pxl	500um pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

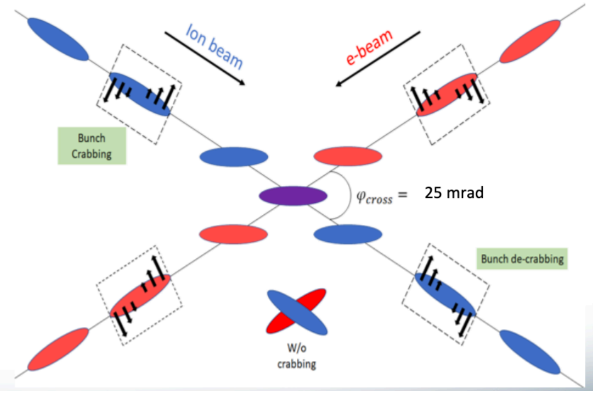
- **Beam angular divergence**
  - Beam property, can’t correct for it – sets the lower bound of smearing.
  - Subject to change (i.e. get better) – beam parameters not yet set in stone
    - *using symmetric divergence parameters in x and y at 100urad.
- **Vertex smearing from crab rotation**
  - Correctable with good timing (~35ps).
  - With timing of ~70ps, effective bunch length is 2cm ->.25mm vertex smearing (~7 MeV/c)
- **Finite pixel size on sensor**
  - 500um seems like the best compromise between potential cost and smearing

8

Angular divergence

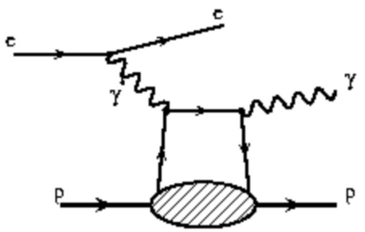


Primary vertex smearing from crab cavity rotation

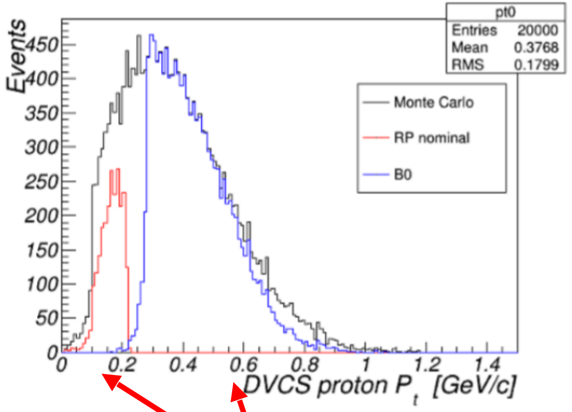


Forward proton acceptance

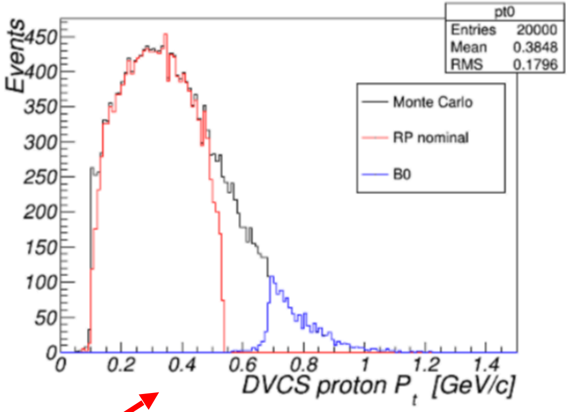
Alex Jentsch



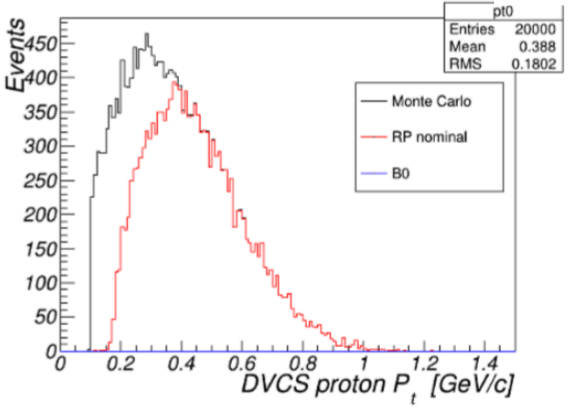
5 GeV x 41 GeV



10 GeV x 100 GeV



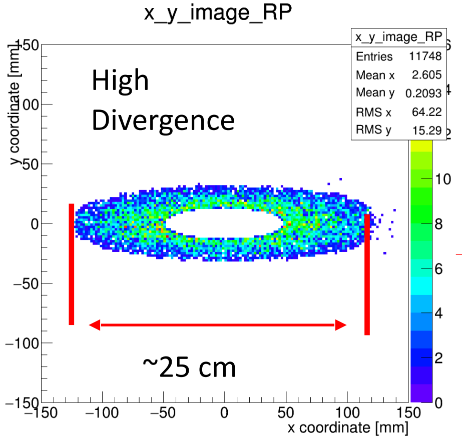
18 GeV x 275 GeV

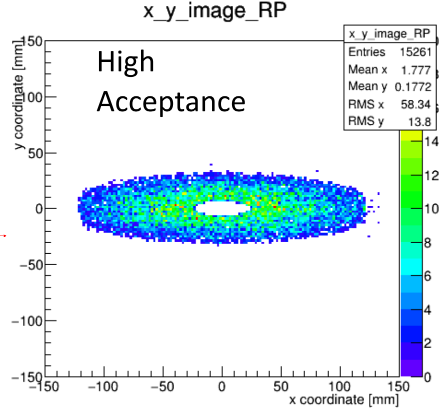


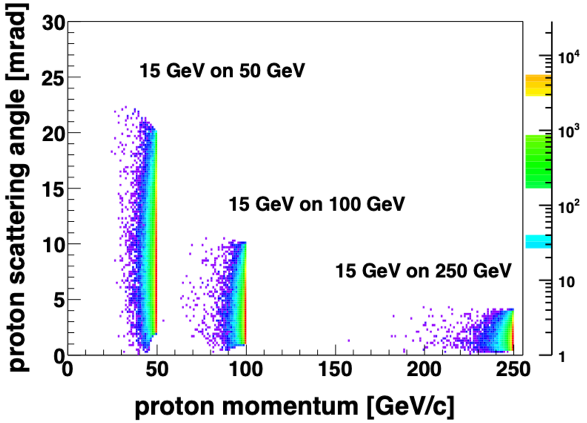
Need both detector systems together here!

High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

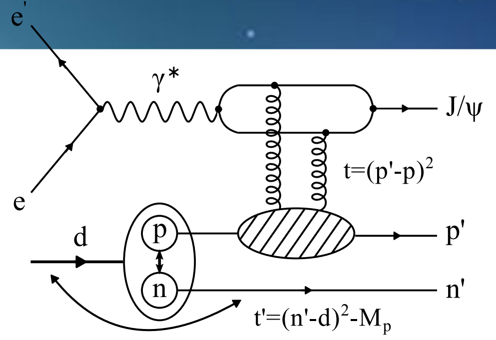
High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP



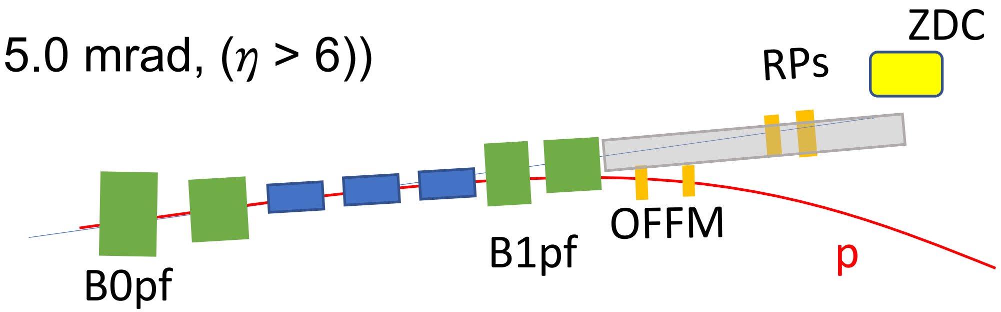




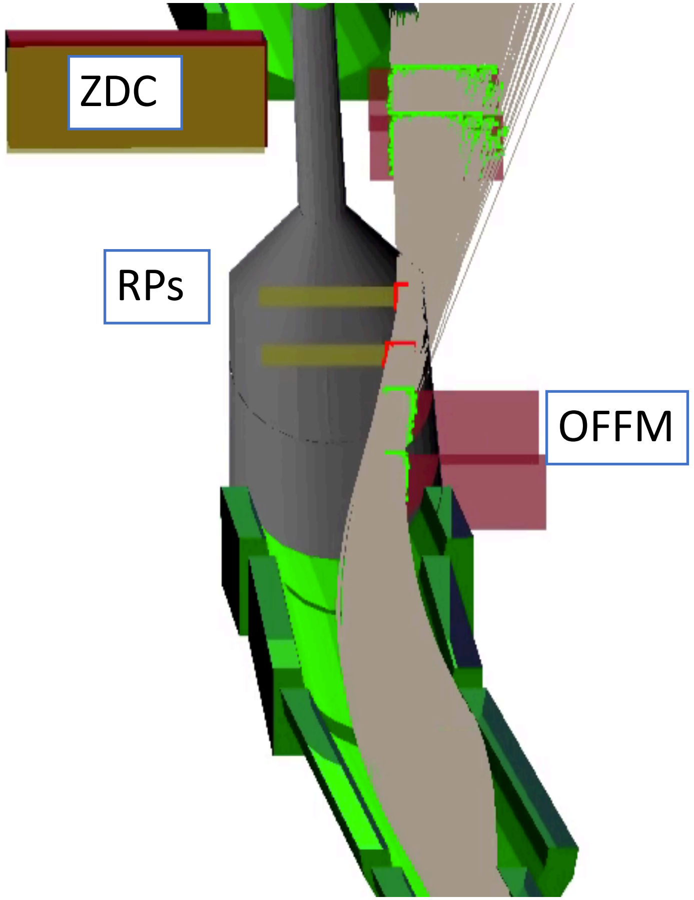
Off-momentum detectors



(0.0 < θ < 5.0 mrad, (η > 6))

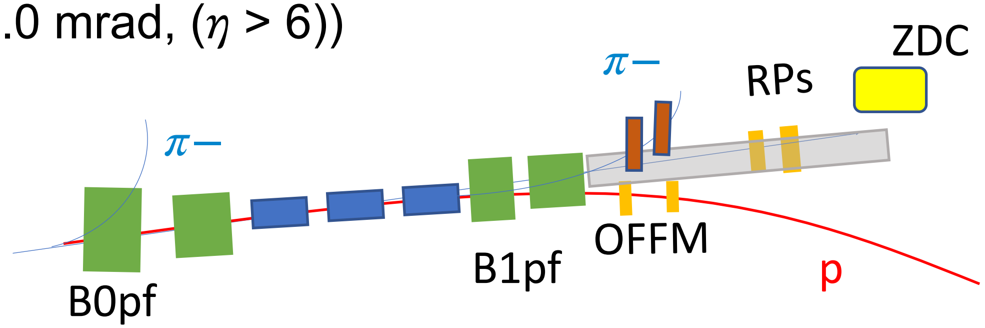


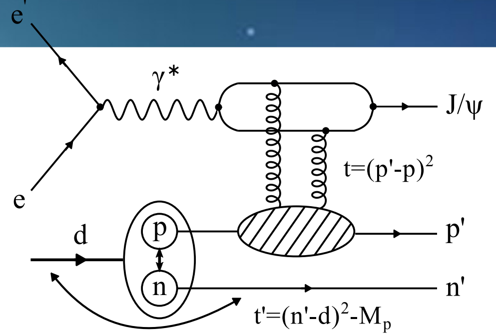
- Protons that come from nuclear breakup have a different magnetic rigidity than their respective nuclear beam ($x_L<1$)
- This means the protons experience more bending in the dipoles.
- As a result, small angle ($\Theta < 5$mrad) protons from these events will not make it to the Roman Pots, and will instead exit the beam pipe after the last dipole.
- Detecting these requires “off-momentum detectors”.
- Movable, beam pipe integration.



Off-momentum detectors

($0.0 < \theta < 5.0$ mrad, ($\eta > 6$))

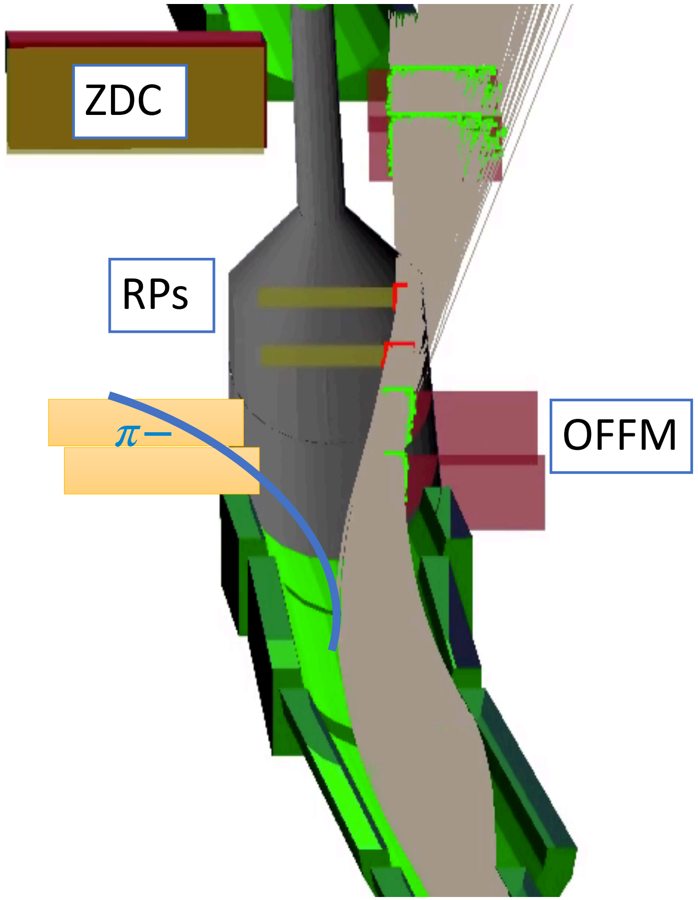




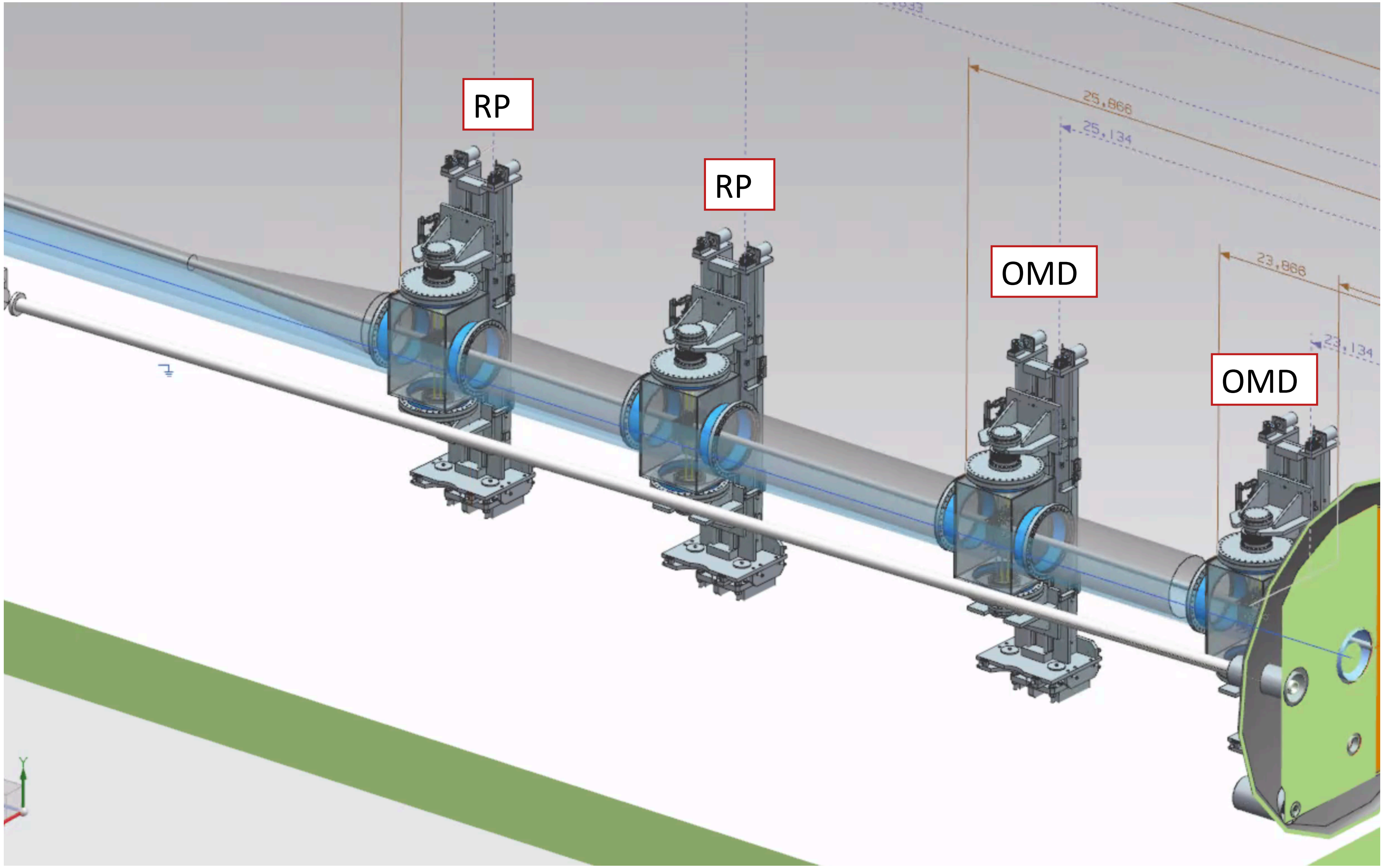
e p -> (K) -> e’ + Λ + X

↳ p + $\pi-$(Br~64%)

- ➢ Detecting Lambda’s decays in the target fragmentation area is very hard, due to a very large decay length (meters).
- ➢ Would require in addition detection of negative charged particles (pi-) at the OFF-momentum detector location



Roman Pots/ OMDs integration



Zero Degree Calorimeter (ZDC)

For detection of neutrons and photons

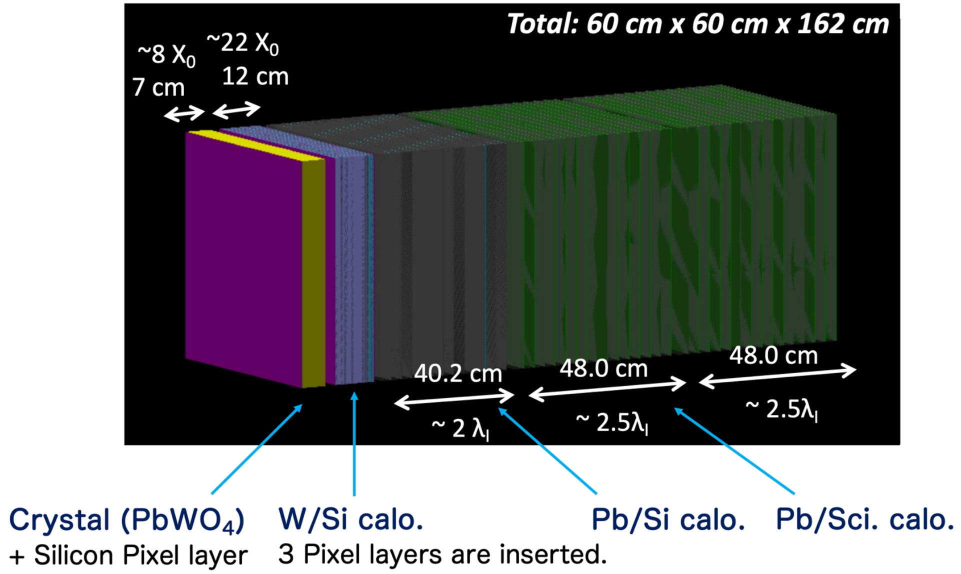
<u>Acceptance:</u>

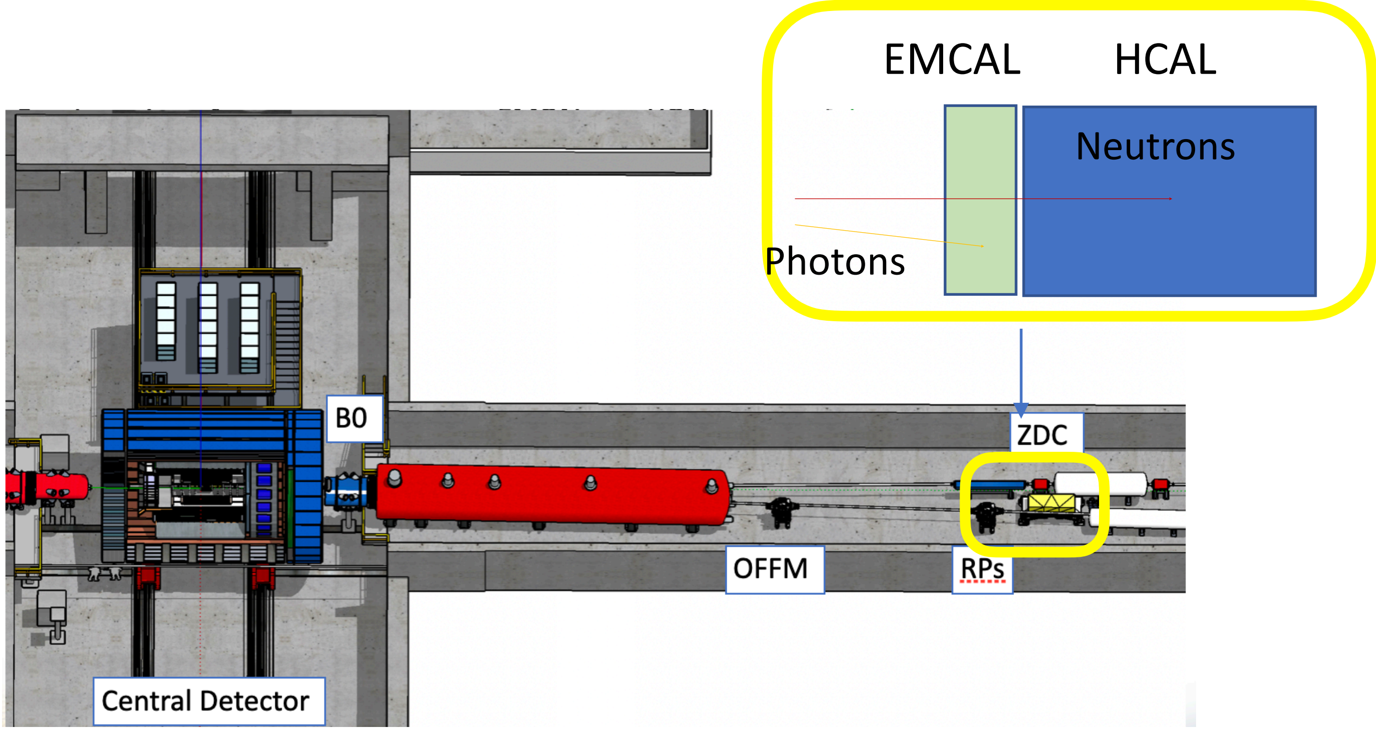
0<θ<5.5 mrad

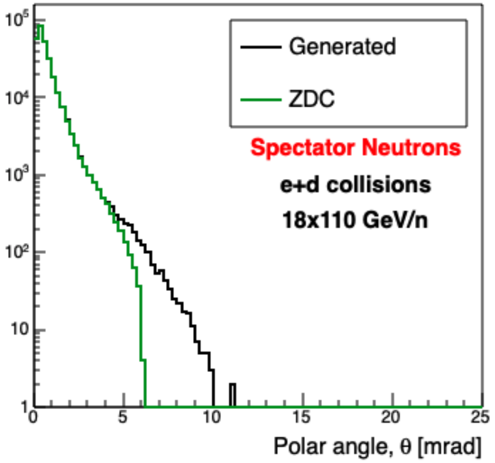
(Limited by bore of magnet where the neutron cone has to exit)

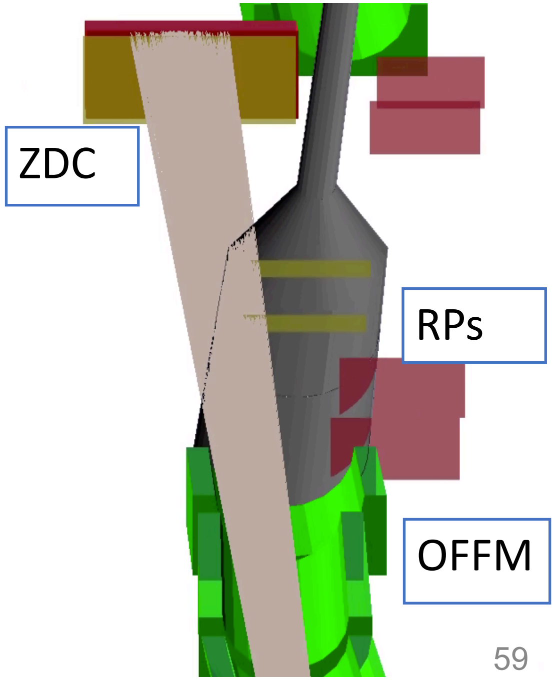
High resolution ZDC, based on ALICE FoCAL

*note: space for readout may extend the longitudinal length.

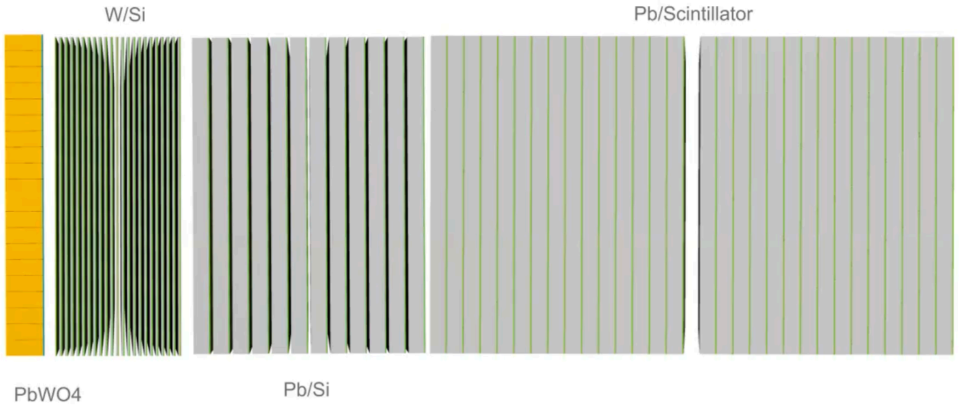


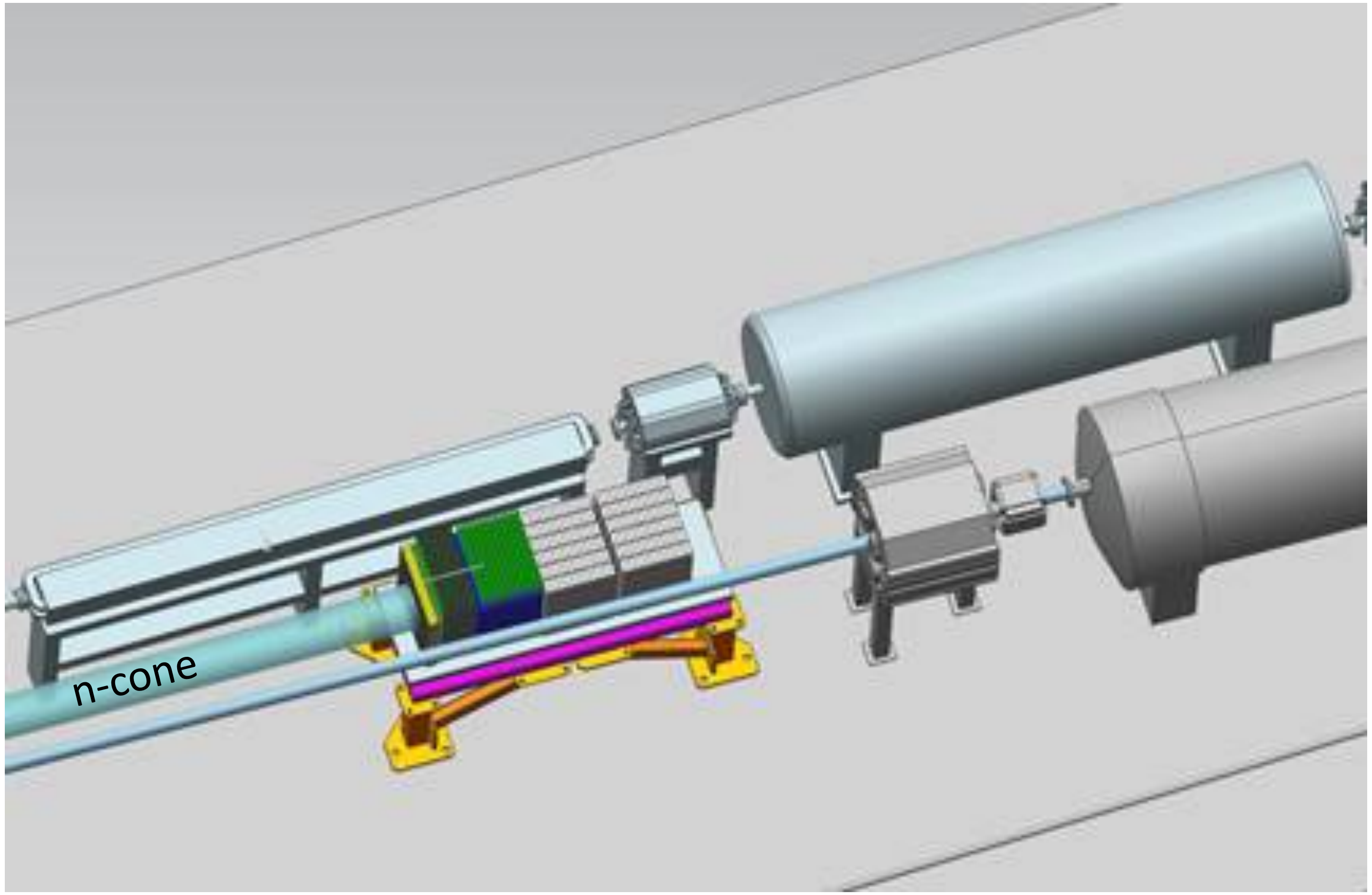


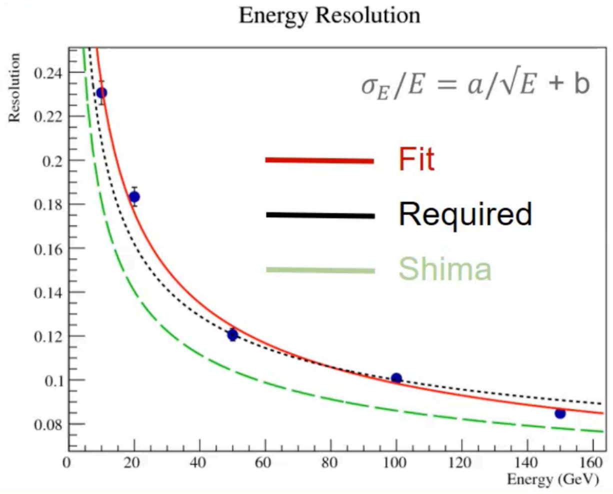




ZDC integration

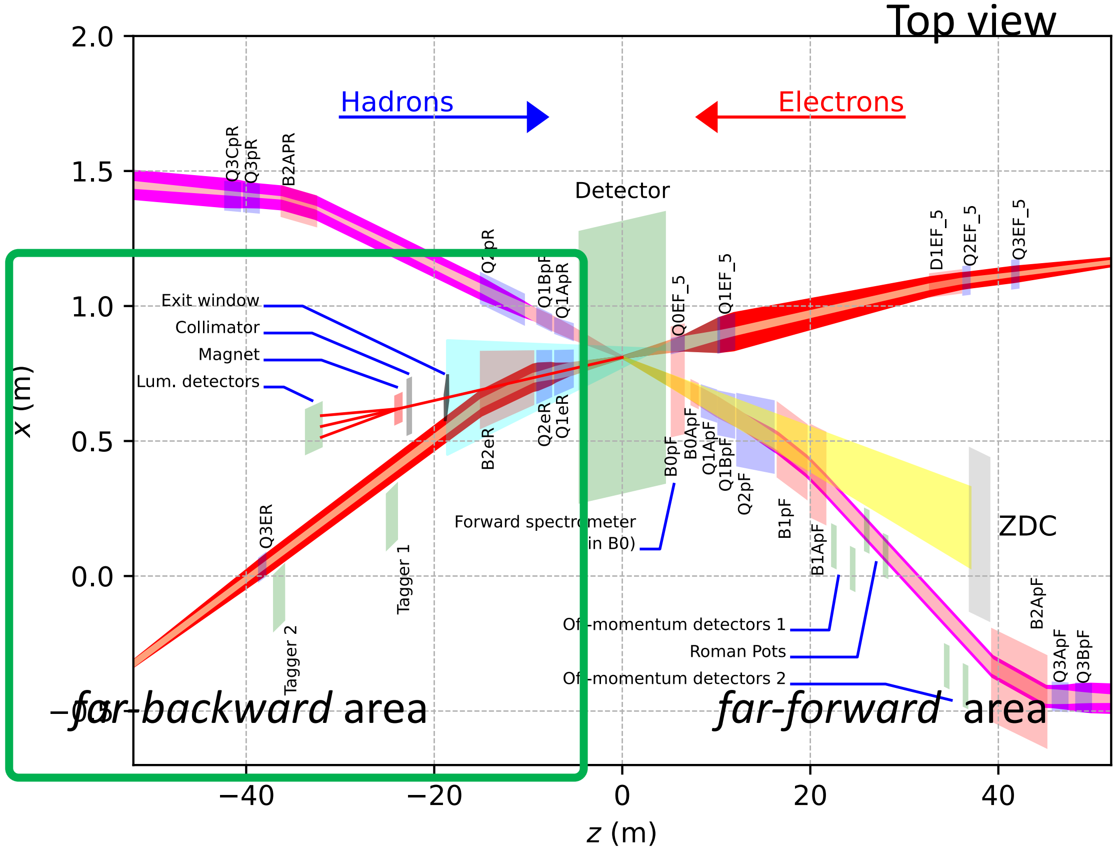






- Fit: $\frac{63\%}{\sqrt{E}} + 3.6\%$
- Required: $\frac{50\%}{\sqrt{E}} + 5\%$
- Shima: $\frac{44\%}{\sqrt{E}} + 4.2\%$

Far-backward (electron-going) region



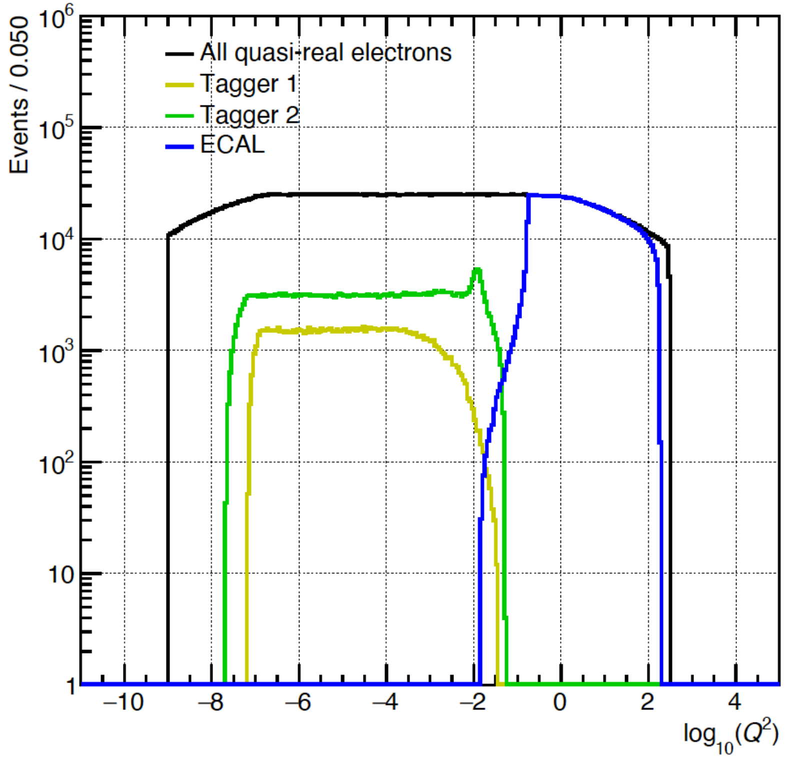
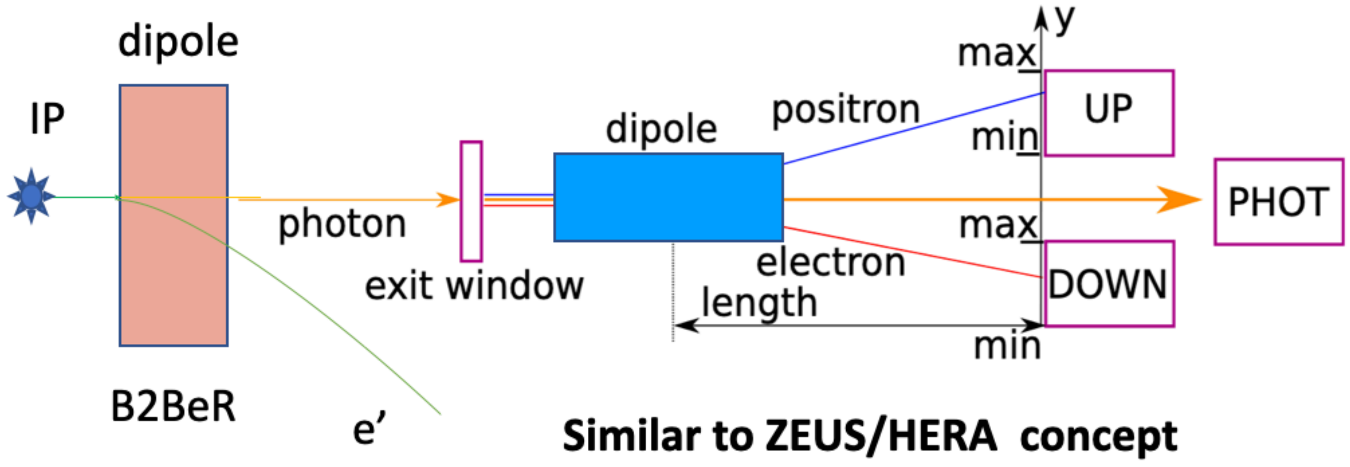
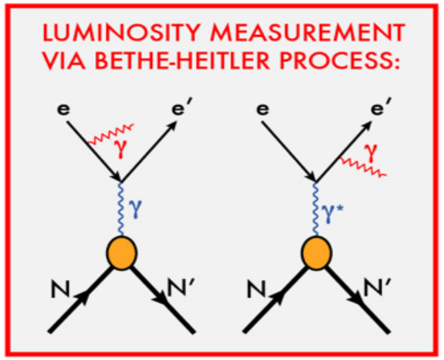


FIG. 16: Coverage in Q^2 for tagger detectors and ECAL.

- ➢ This area is designed to provide coverage for the low-Q² events (photoproduction, $Q^2 < \sim 1 GeV^2$). Need to measure the scattered electron position/angle and energy.
- ➢ And luminosity detector (ep -> e’pγ bremsstrahlung photons)
- ➢ Beam-pipe design ongoing

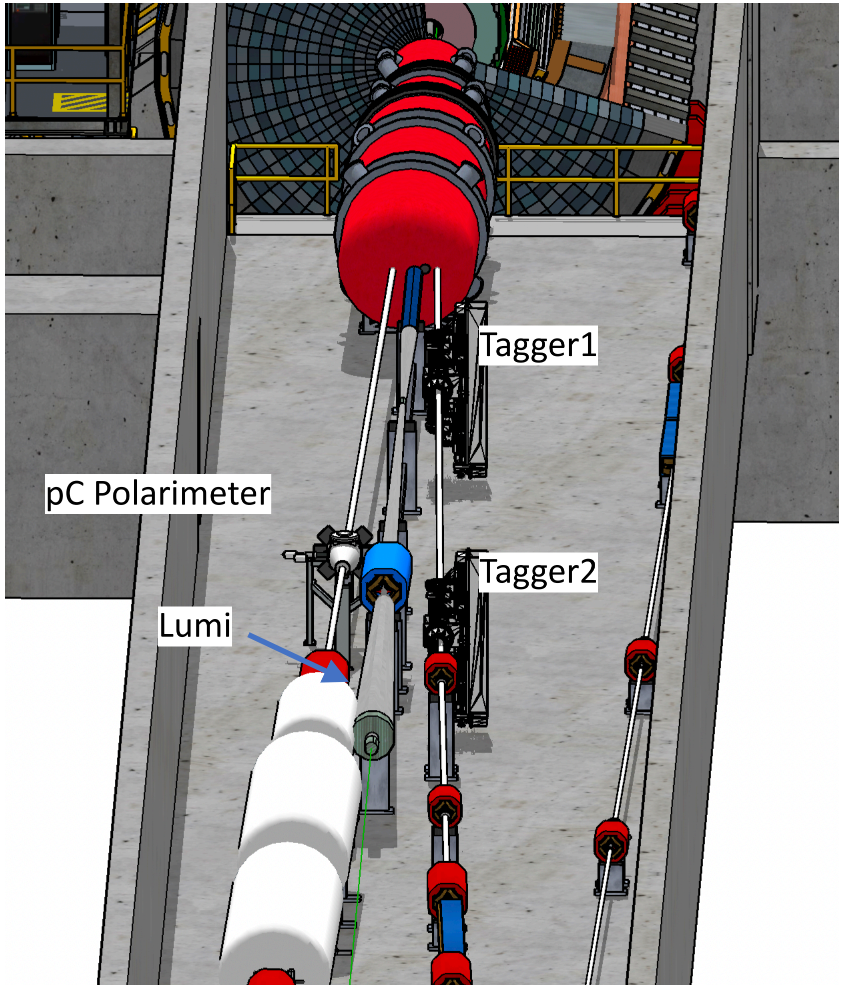
Luminosity monitor



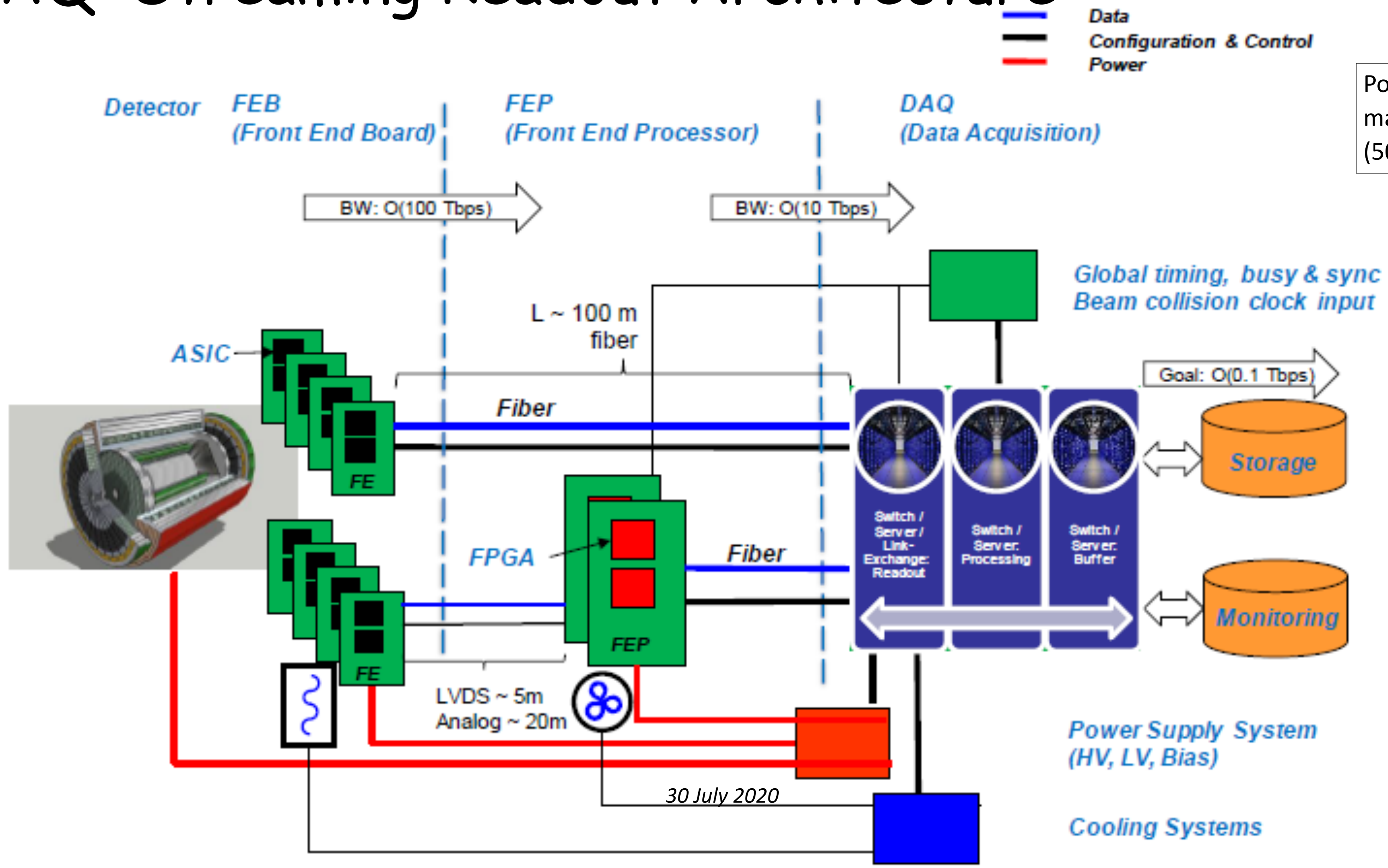


Goals for Luminosity Measurement:
Integrated luminosity with precision δL/L< 1%

- Luminosity measurements via Bethe-Heitler process
- Photons from IP collinear to e-beam
- First dipole bends electrons
- Photon conversion to e-/e+ pair
- Pair-spectrometer
- Synchrotron photons collimation scheme needs to be further refined



DAQ: Streaming Readout Architecture



30 July 2020

Possible at EIC as data rates manageable
(500 kHz, O(100) Gbps)

EIC Yellow Report – Readout and DAQ *FJ Barbosa, K Chen, J Huang*

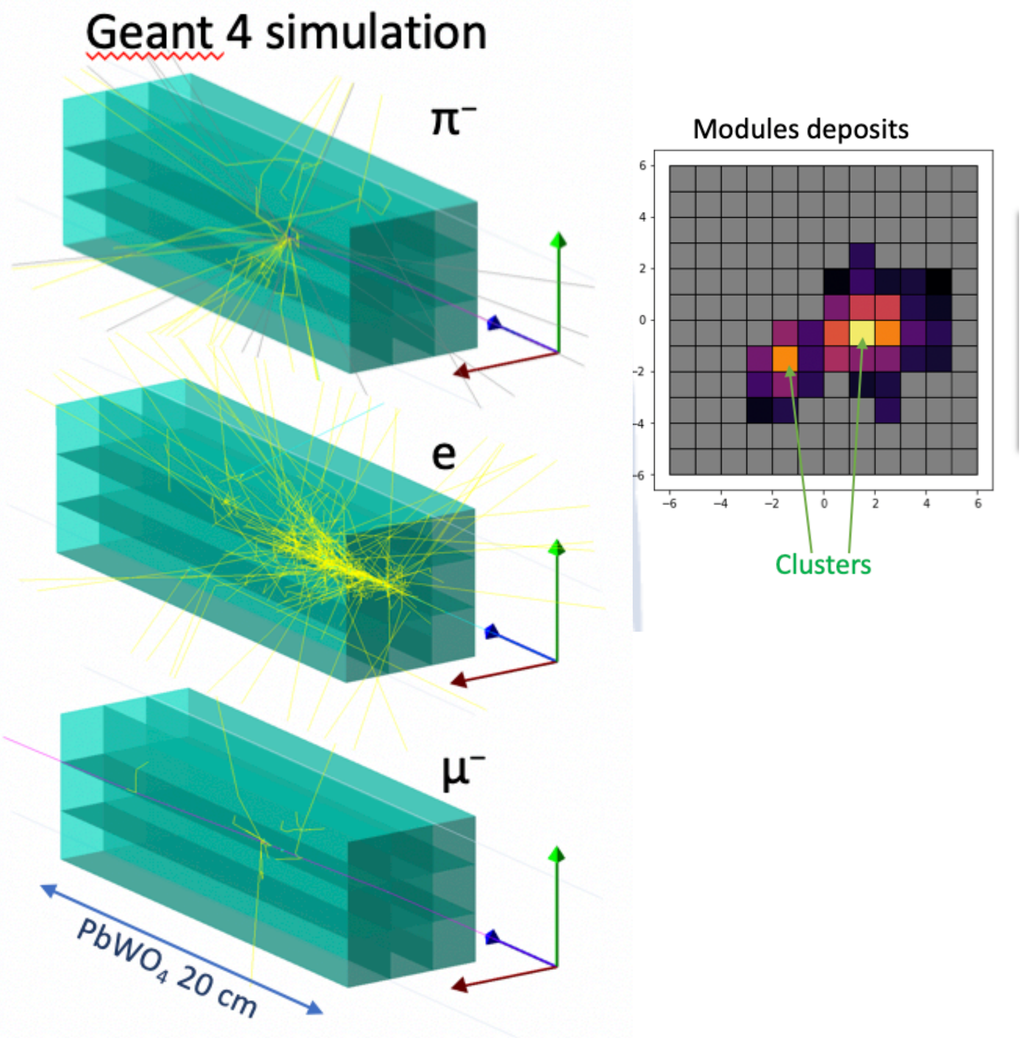
D. Romanov

AI/ML for EIC

- For Calorimeter : clustering, energy reconstruction
- For Tracking: Clustering/ pattern recognition / track fitting
- For particle identification (from a single detector or from multiple)

- For detector optimization
- For online data processing (FPGA)

- For physic event selection
- For background suppression
- … and many others

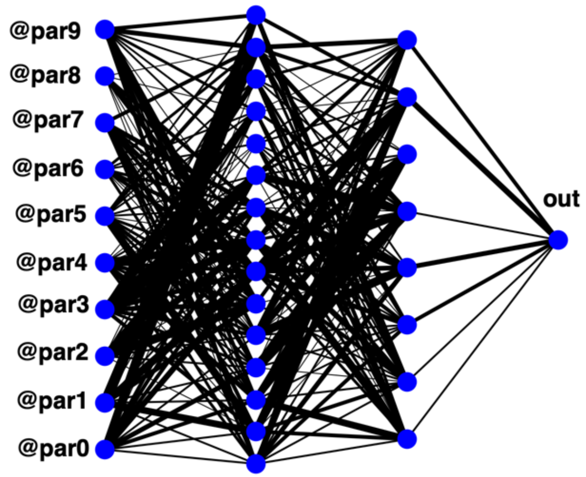


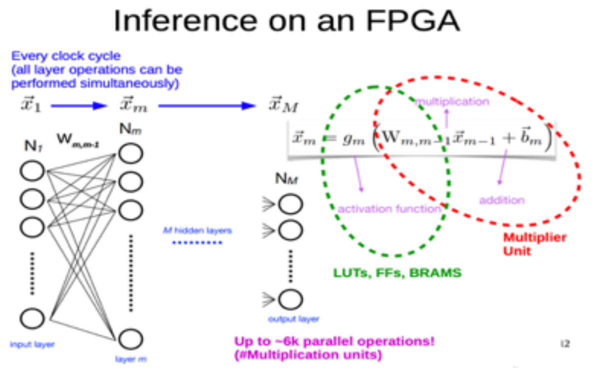
Examples of events with e and π^- showers and μ^- passing through.

ML on FPGA

https://ieeexplore.ieee.org/document/10079189

Low latency

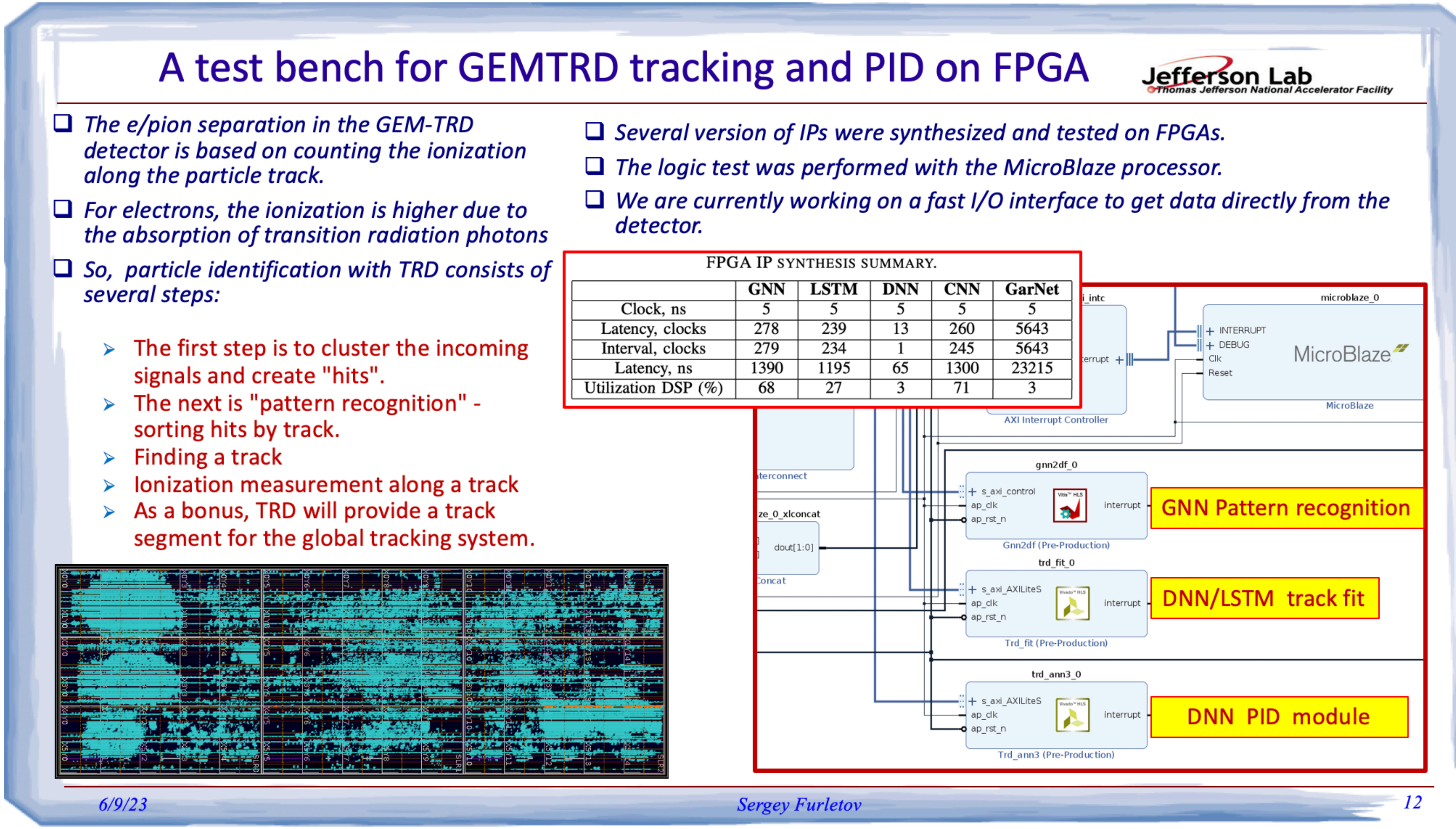




Inference on an FPGA

Every clock cycle
(all layer operations can be performed simultaneously)

Up to ~6k parallel operations!
(#Multiplication units)



A test bench for GEMTRD tracking and PID on FPGA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

- ❑ *The e/pion separation in the GEM-TRD detector is based on counting the ionization along the particle track.*
- ❑ *For electrons, the ionization is higher due to the absorption of transition radiation photons*
- ❑ *So, particle identification with TRD consists of several steps:*
  - ➢ The first step is to cluster the incoming signals and create "hits".
  - ➢ The next is "pattern recognition" - sorting hits by track.
  - ➢ Finding a track
  - ➢ Ionization measurement along a track
  - ➢ As a bonus, TRD will provide a track segment for the global tracking system.
- ❑ *Several version of IPs were synthesized and tested on FPGAs.*
- ❑ *The logic test was performed with the MicroBlaze processor.*
- ❑ *We are currently working on a fast I/O interface to get data directly from the detector.*

FPGA IP SYNTHESIS SUMMARY.

	GNN	LSTM	DNN	CNN	GarNet
Clock, ns	5	5	5	5	5
Latency, clocks	278	239	13	260	5643
Interval, clocks	279	234	1	245	5643
Latency, ns	1390	1195	65	1300	23215
Utilization DSP (%)	68	27	3	71	3

GNN Pattern recognition

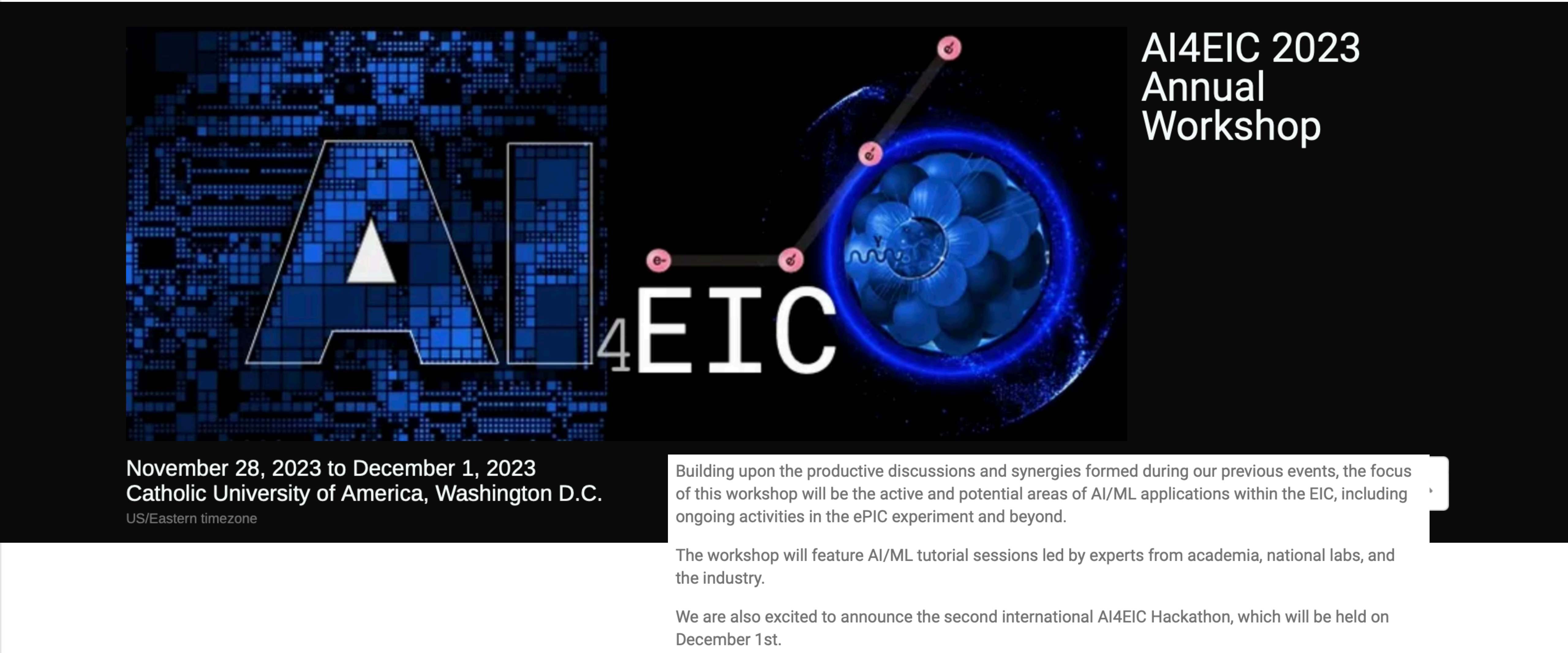
DNN/LSTM track fit

DNN PID module

6/9/23 Sergey Furletov 12

https://indico.bnl.gov/event/19560/

AI4EIC



AI4EIC 2023 Annual Workshop

November 28, 2023 to December 1, 2023
Catholic University of America, Washington D.C.
US/Eastern timezone

Building upon the productive discussions and synergies formed during our previous events, the focus of this workshop will be the active and potential areas of AI/ML applications within the EIC, including ongoing activities in the ePIC experiment and beyond.

The workshop will feature AI/ML tutorial sessions led by experts from academia, national labs, and the industry.

We are also excited to announce the second international AI4EIC Hackathon, which will be held on December 1st.

Summary

- The EIC detector (ePIC) - a physics-driven design
- It is a general purpose detector.
- It is also a balance between the reuse of equipment, the mature state of art technology and detector technologies that are at the near-end of an extensive R&D effort
- AI was used to optimize detector choices, locations, and materials.
- We are continue to improve the design on the way to CD2

Following movies are made by
Miguel Arratia and **Sean Preins**

Backup

Solutions:

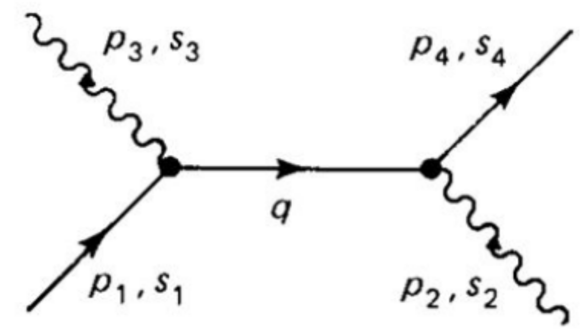
$$\sqrt{s} = \sqrt{(4E_e E_p)} = \sqrt{4 \cdot 18 \cdot 275} \sim 141 GeV \sim \sqrt{2E_A m_B}$$

$$s = (p_A + p_B)^2 = m_A^2 + m_B^2 + 2 \cdot E_A \cdot m_B \sim 2 \cdot E_A \cdot m_B$$

$$\sqrt{s} = 141 GeV \sim \sqrt{2E_A m_B}$$

$$E_A = \frac{141^2}{2 \cdot m_B} \sim 10\ TeV$$

Electron polarization measurements

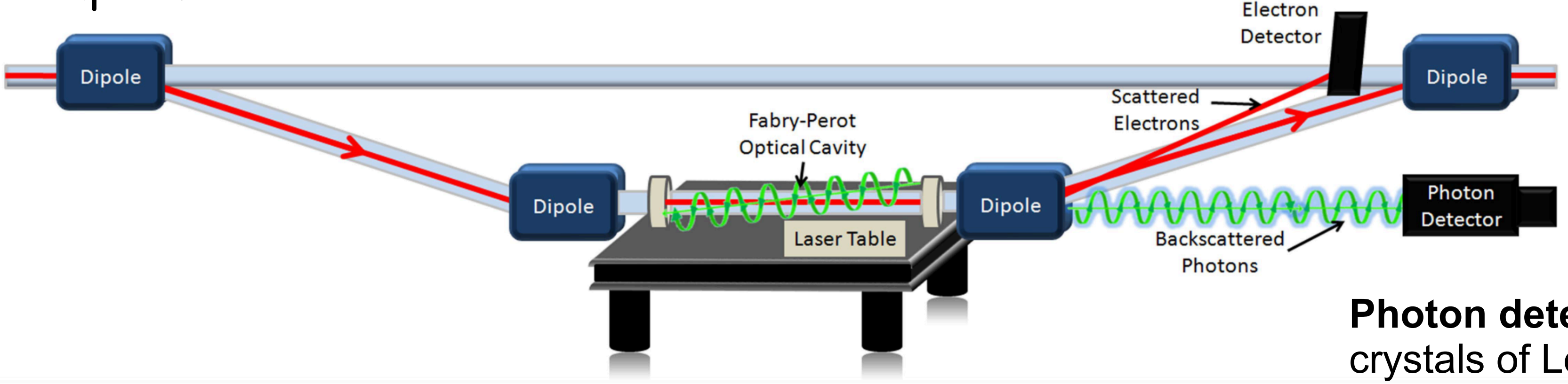


Compton Scattering

Compton polarimeter:

- Used to determine a polarization of electron beam
- Incoming photons scatters off electron

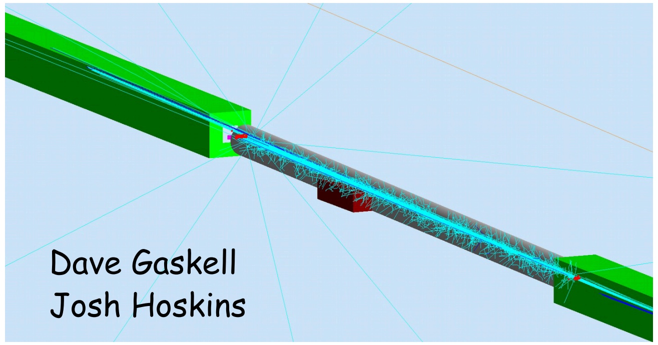
Setup in Hall C



Photon detector (calorimeter) a matrix of four crystals of Lead Tungstate (P bW O_4) scintillating crystals with dimensions of 3 × 3 × 20 cm to detect the backscattered photons.

~1% electron beam polarization measurements

Simulation for EIC is ongoing



Dave Gaskell
Josh Hoskins

Electron detector (Diamond micro-strip detector)

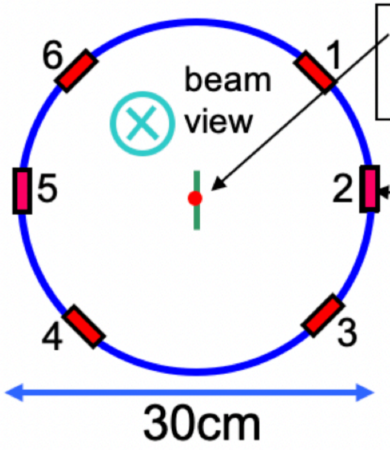
The detectors are made from 21 mm× 21 mm × 0.5 mm plates of Chemical Vapor Deposition (CVD) diamond . Each diamond plate has 96 horizontal metallized electrode strips with a pitch of 200 μm

Hadron Polarization (RHIC, EIC)

Elke Aschenauer
Vadim Ptitsyn

Existing p Polarization in RHIC achieved with “Siberian snakes”
- Near term improvements will increase proton polarization in RHIC from 60% to 80%

Polarimetry exploits left-right asymmetry in elastic scattering due to spin orbit interaction

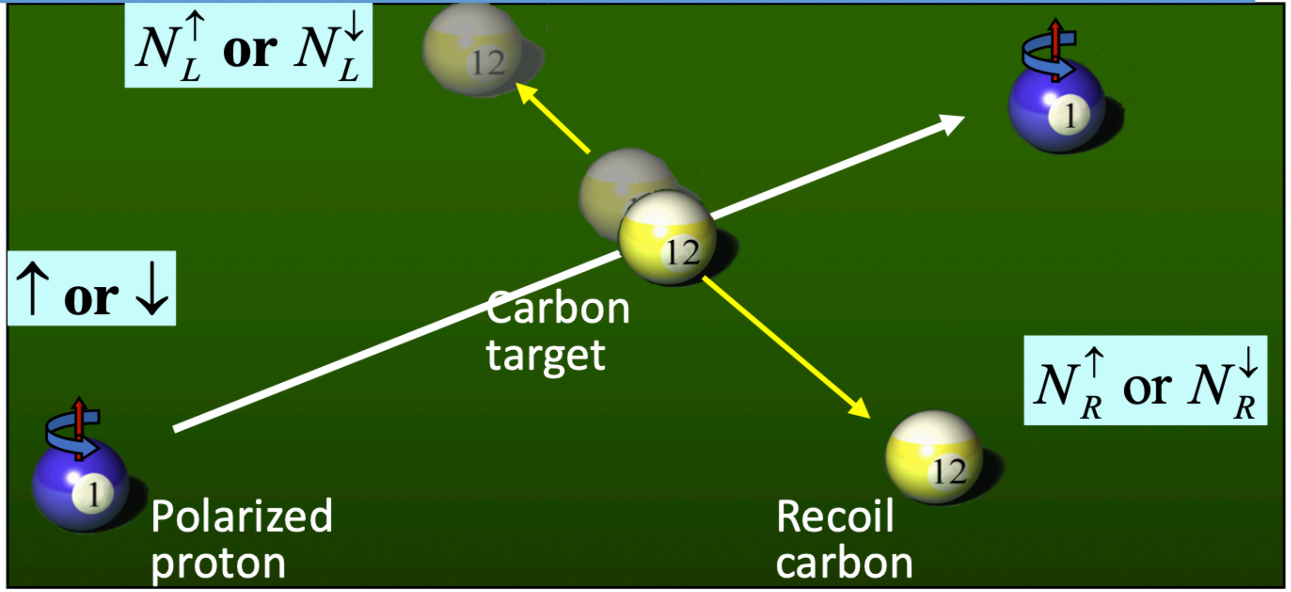


Ultra-thin carbon ribbon target ~ 100 mono-layers think, 10µm wide

Si strip detectors for recoil carbon (TOF, E_C)

$$p^{\uparrow}C \rightarrow p^{\uparrow}C$$

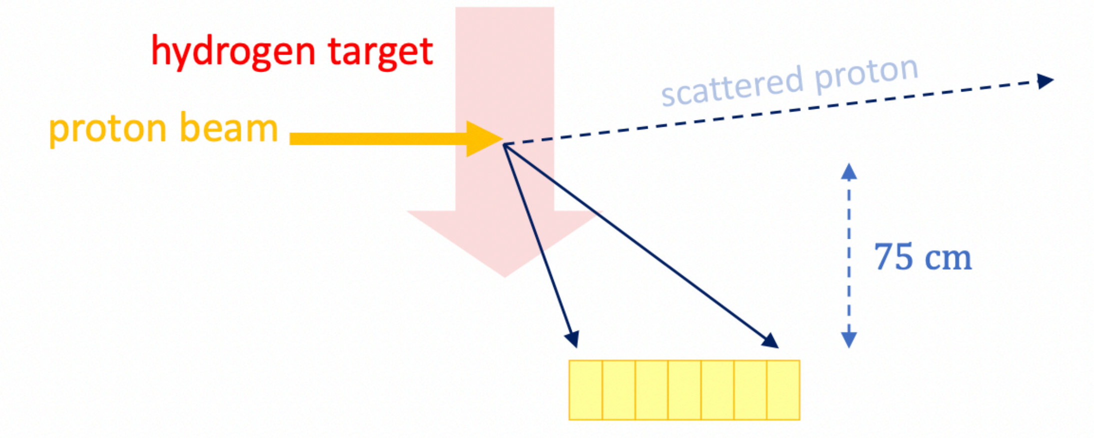
$$P_B = \frac{\varepsilon_{LR}}{A_N}, \quad \varepsilon_{LR} = \frac{N_L - N_R}{N_L + N_R}$$

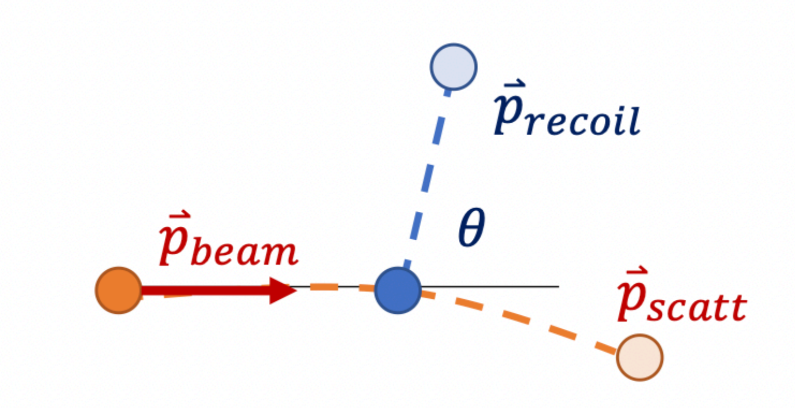


- Proton-Carbon Polarimeter (pC): very fast and high precision, but needs to be normalized

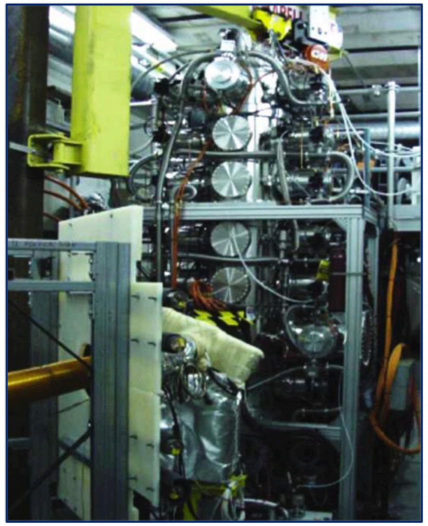
Hadron Polarization (RHIC, EIC)

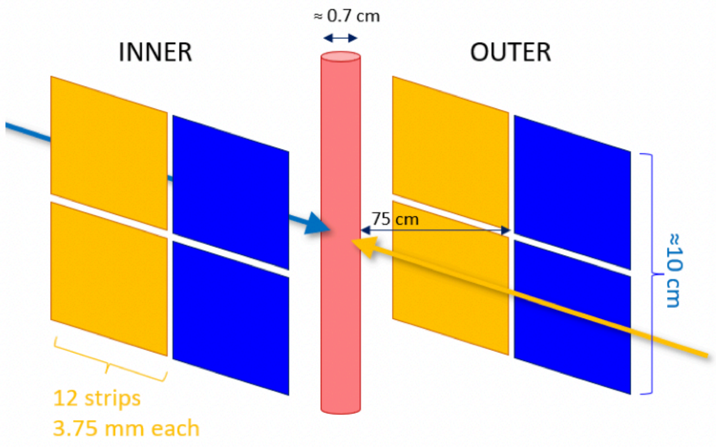
K. Oleg Eyser





HJET: Polarized atomic hydrogen jet target





- Polarized hydrogen Jet Polarimeter (HJet): absolute polarization, but slow.

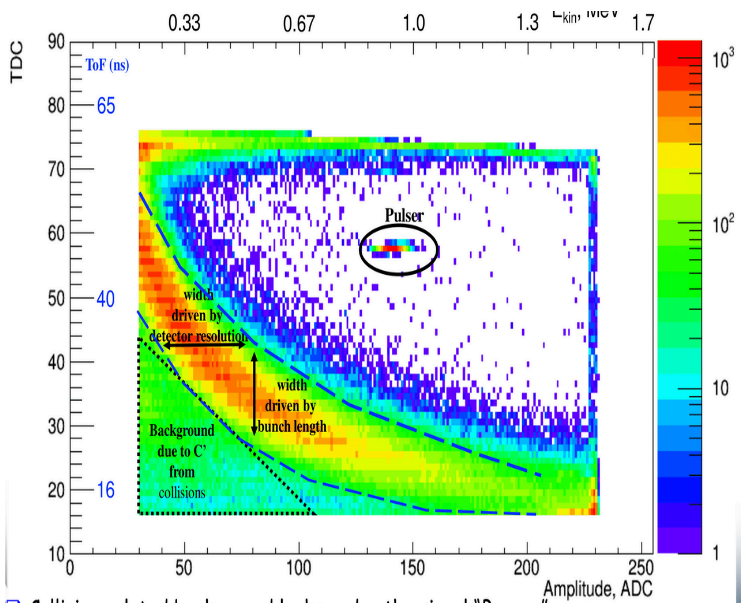
Hadron Polarization

Elke Aschenauer

Hadron polarimetry at EIC

At RHIC:

- Polarized hydrogen Jet Polarimeter (HJet): absolute polarization, but slow.
- Proton-Carbon Polarimeter (pC): very fast and high precision, but needs to be normalized

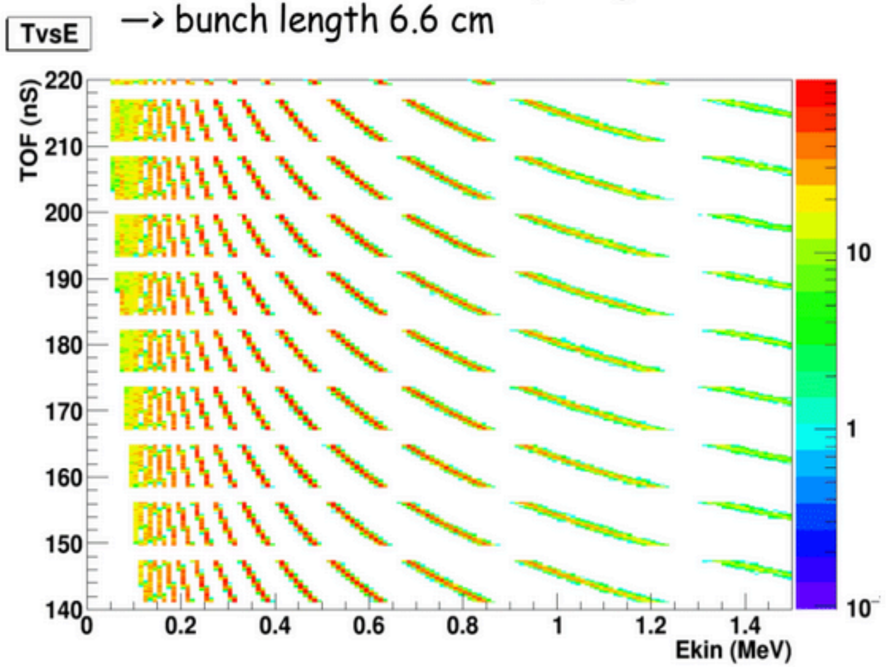


RHIC vs EIC

BUT EIC is not RHIC!

- Higher bunch frequency and current.
- Background?

1320 bunches —> bunch spacing 8.7 ns
—> bunch length 6.6 cm

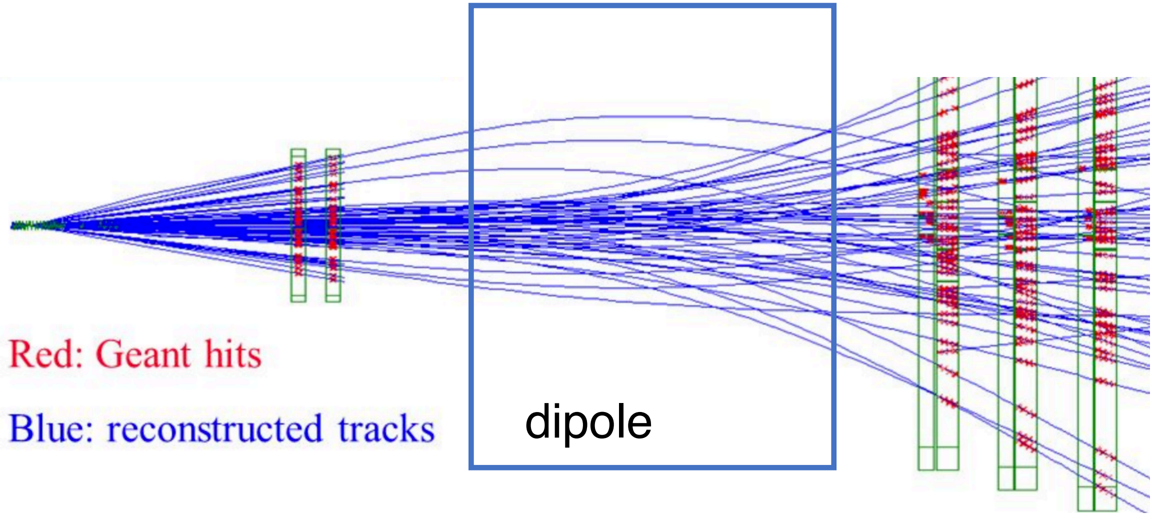


New detector technology (fast ~ 10ps Si?)
Reduce TOF ?
Polarized D and He-3

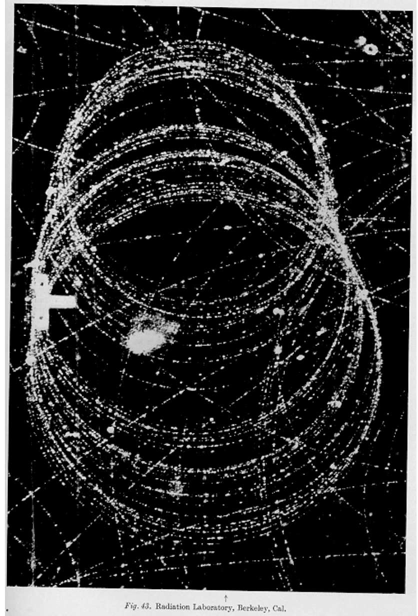
Why do we need a magnetic field?

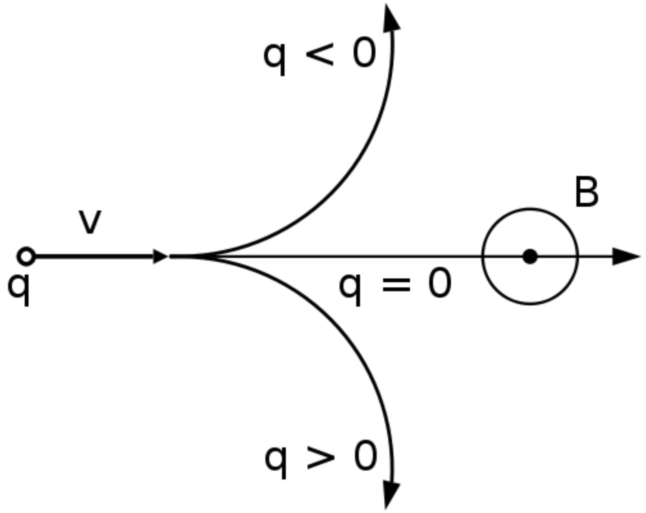
-bending radius depends on a particle momentum

-charge (right, left)



$p[\text{GeV}] = 0.3 \cdot B\,[\text{T}] \cdot R\,[\text{m}]$





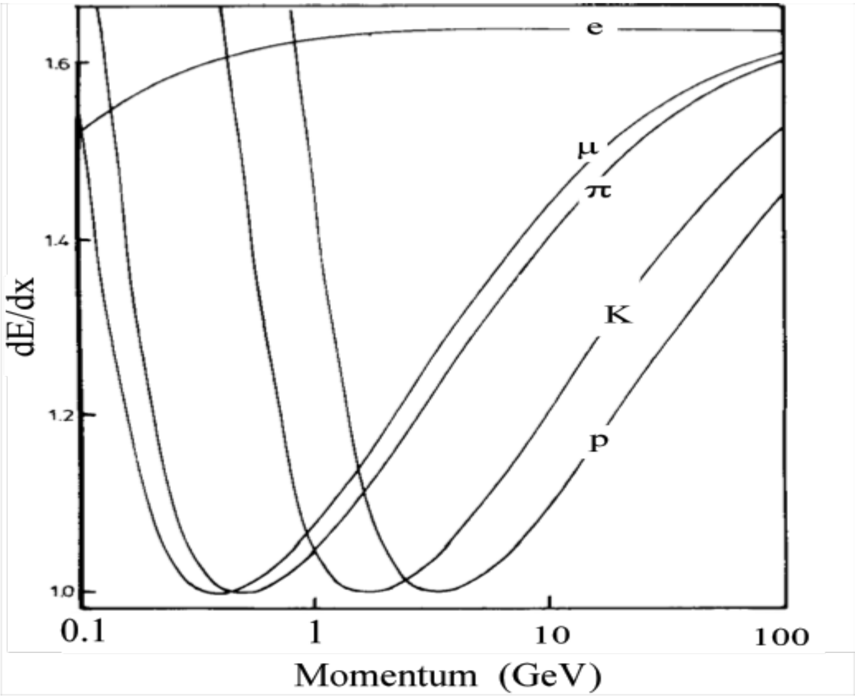
Electron in a magnetic field at the Bevatron, 1940

Energy loss

Most tracking detectors are ionization detectors

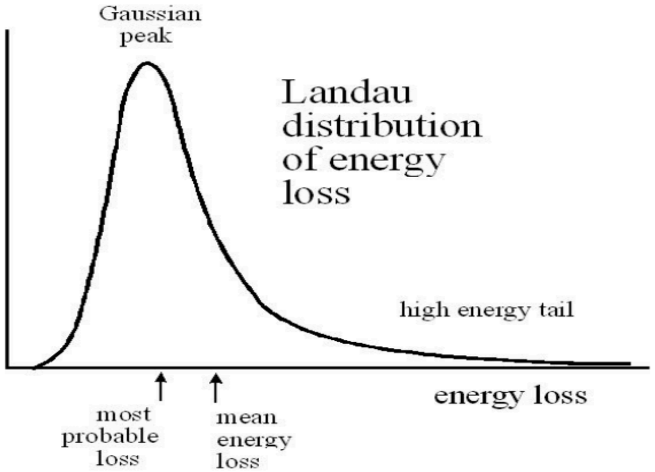
$$-\left\langle \frac{dE}{dx} \right\rangle = K \boxed{\frac{Z}{A}} \rho \boxed{\frac{z^2}{\beta^2}} \left[\frac{1}{2} \ln \frac{2\, m_e\, c^2\, \beta^2\, \gamma^2\, T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma,\, I)}{Z} \right]$$

same curve plotted vs. momentum for different particles => could be used for PID

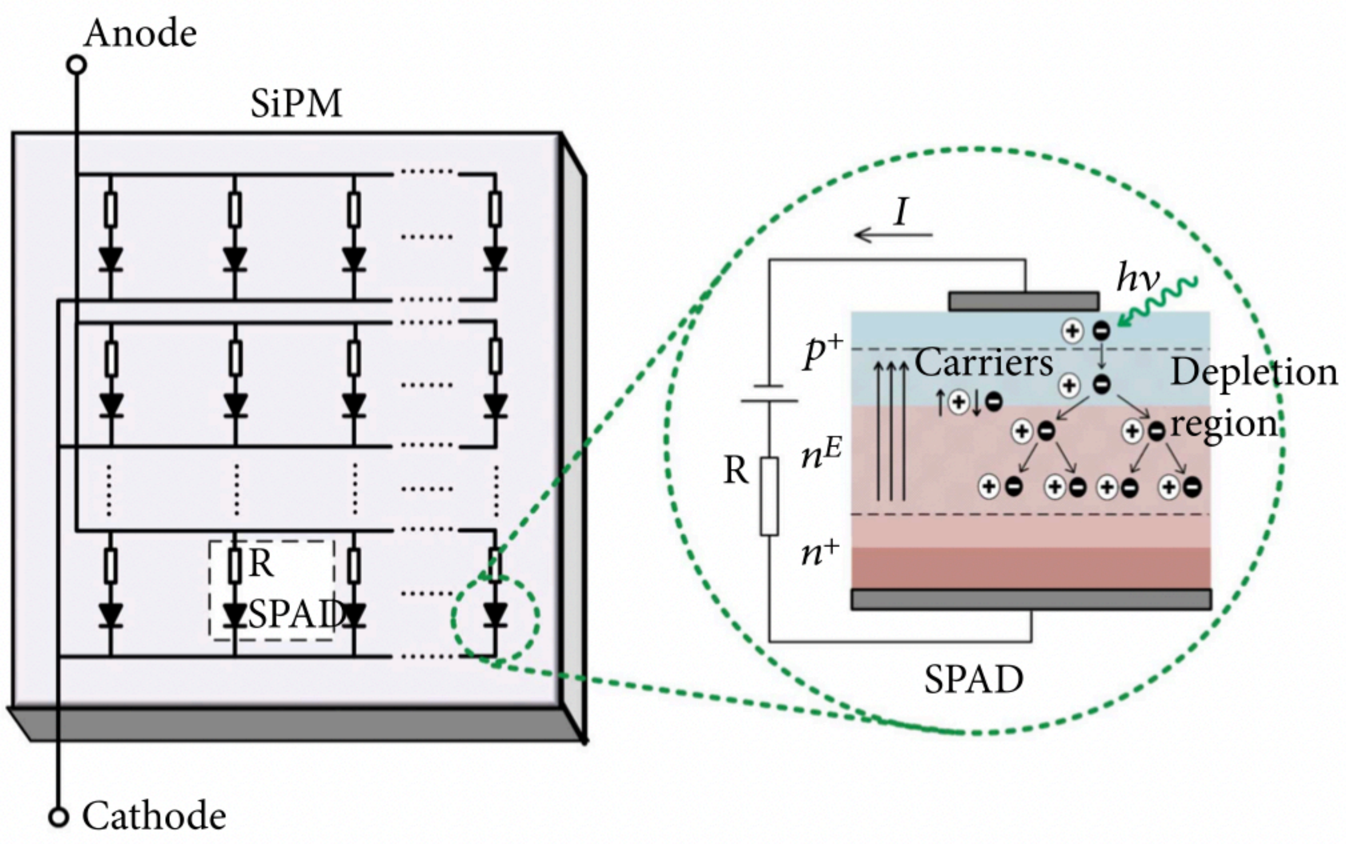


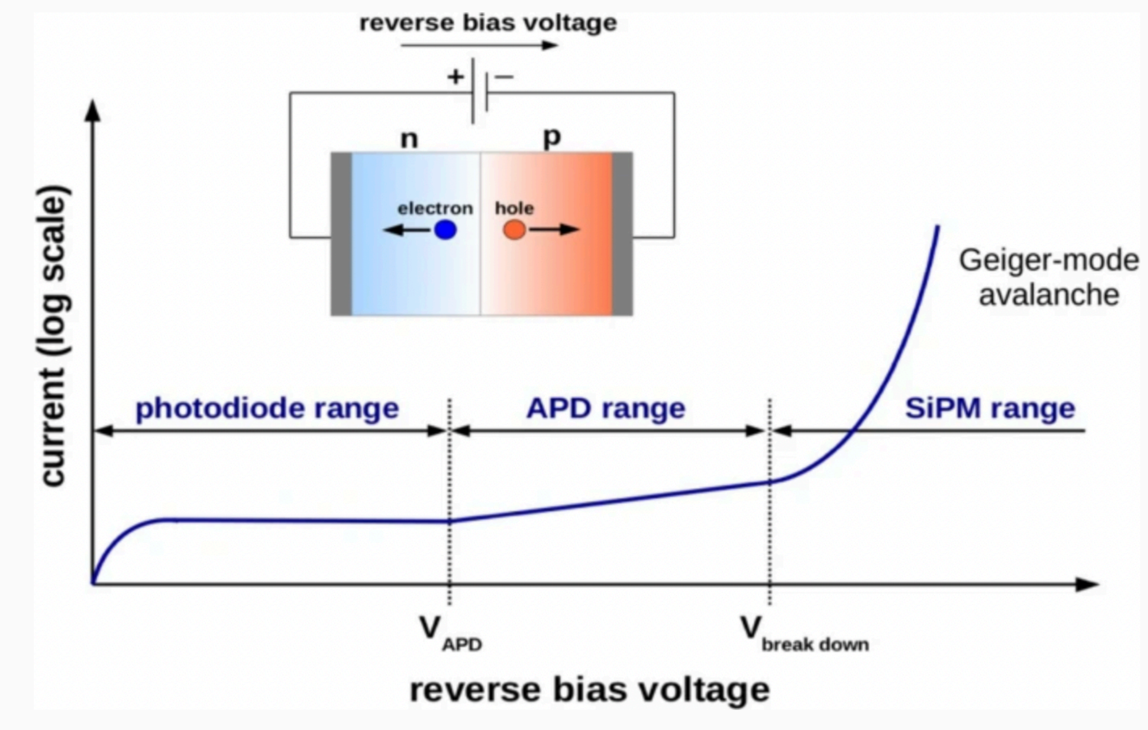
- Examples of typical energy loss at minimum ionizing:
  - ✓ 1 meter air: 0.22 MeV
  - ✓ 300μm Si: 0.12 MeV
  - ✓ 1mm iron: 1.1 MeV

- Energy loss is a stochastic process (app described by Landay distribution) with infinitely" long tail.



Readout: SiPM





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