Asia Pacific Center for Theoretical Physics

Nuclear Physics School
25—29 June 2018

Electron Ion Collider Interaction Region Designs and Detector Concepts

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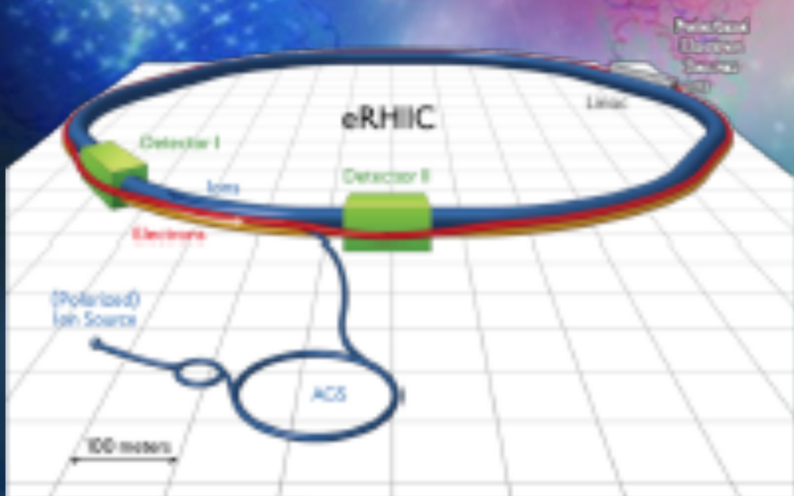
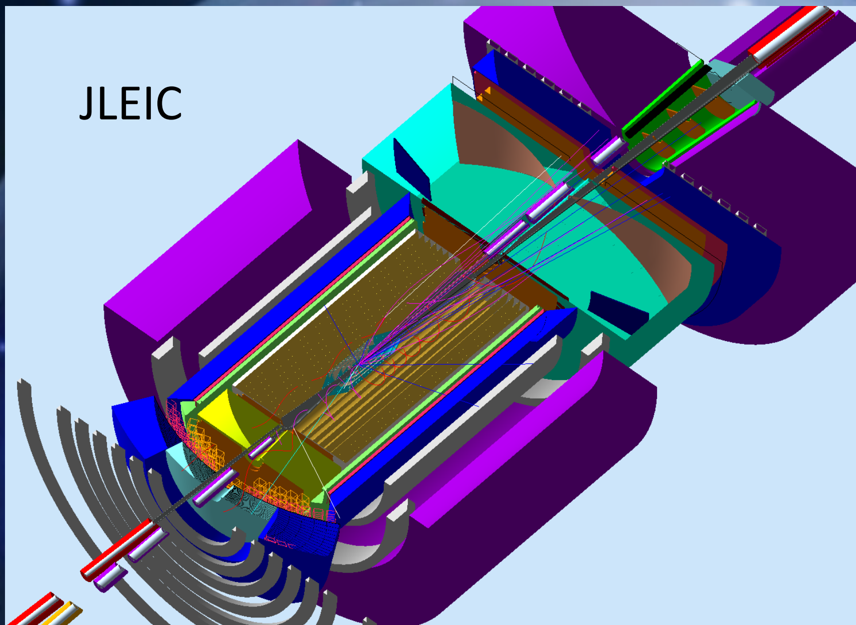
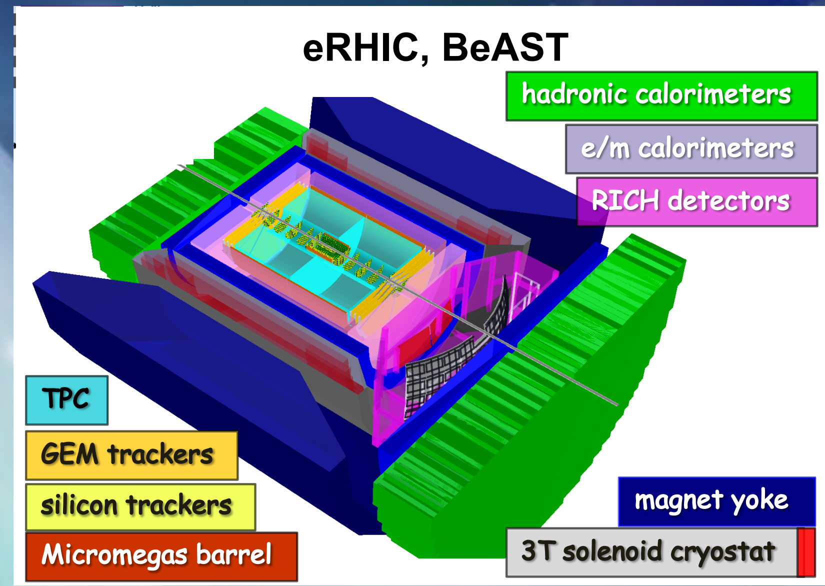
OLD DOMINION UNIVERSITY

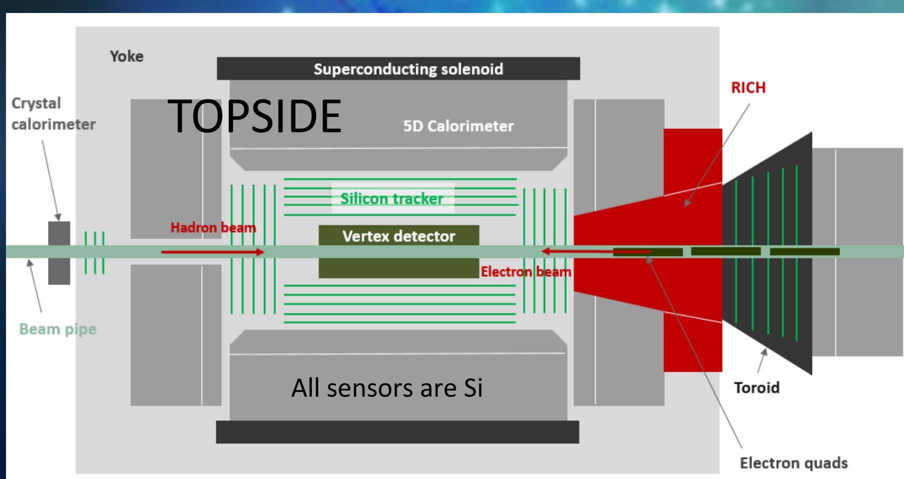
- My talk is JLEIC-centric.
  - Most concepts are general to JLEIC/eRHIC
  - Most slides from Y.Furletova Jlab Users Group Annual Meeting: www.jlab.org/conferences/ugm/program.html

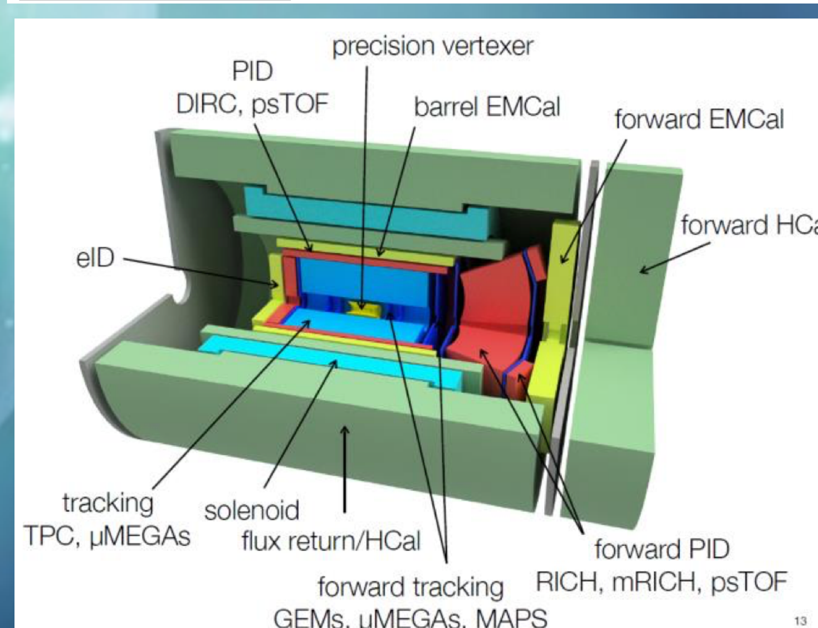


EIC Detector Concepts









Interaction Region (IR) Requirements: I. Beam

- Focused beam
  - Gaussian profiles σ_x, σ_y ≈ 10 μm
  - N_e, N_i = particles per micro-bunch ≈ 10^{10}
  - f = bunch collision frequency (50 to 500) •10^6 / sec
- Luminosity: $L = \frac{N_e N_i f}{4\pi\sigma_x\sigma_i} \sim 10^{33} \cdots 10^{34}\ \frac{1}{cm^2 sec}$
  - Event Rate for a process of cross section σ (integrated over a kinematic bin): $R = L\,\sigma$
- Non-zero crossing angle
  - JLEIC: 50 mrad (beam bunches 60 cm apart)
  - eRHIC: 25 mrad

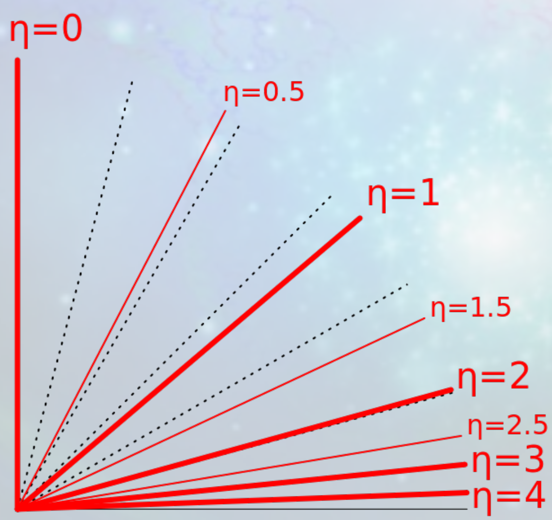
JLEIC Parameters (3T option)

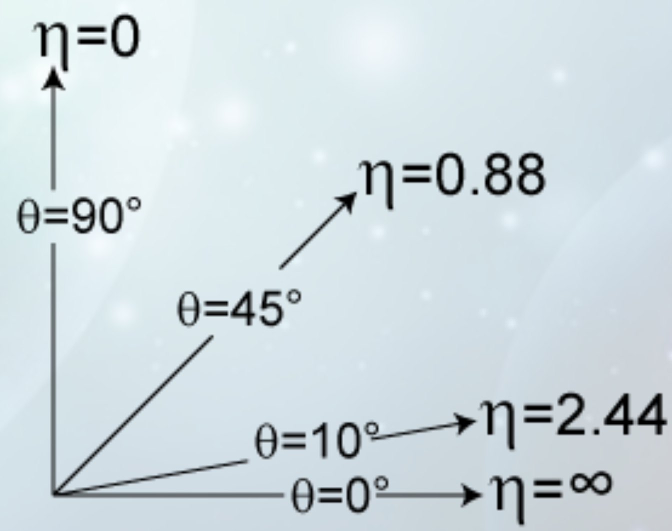
CM energy	**GeV**	**21.9 (low)**		**44.7 (medium)**		**63.3 (high)**	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		**476**		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	**0.98**	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	**80%**	**80%**	**80%**	**80%**	**80%**	**75%**
Bunch length, RMS	cm	3	1	**1**	1	2.2	1
Norm. emittance, hor / ver	μm	0.3/0.3	24/24	**0.5/0.1**	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β*	cm	8/8	13.5/13.5	**6/1.2**	5.1/1.0	10.5/2.1	4/0.8
Ver. beam-beam parameter		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**2.5**		**21.4**		**5.9**	

Kinematic Definitions

$\cos\theta = P_z/P$

- Rapidity: $\eta = \frac{1}{2}\ln\left[\frac{E+P_z}{E-P_z}\right] \rightarrow \ln\left[\frac{E+P}{M}\right]$ for $\theta=0$.
- Pseudo-Rapidity "η" $= -\ln\left[\tan\frac{\theta}{2}\right]$
  - Prove: "η"$\approx\eta$ for $P/M \gg 1$ and $\theta \gg M/P$
  - Graphs of pseudo-rapidity





eRD14: Particle ID Consortium

https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

- Dual RICH: C2F6 (n~1.001 + Aerogel (n=1.02)
  - Two rings formed by spherical mirror only photo-sensors
- Modular RICH: Aerogel + Fresnel Lens (compact)
- Detection of Internal Reflected Cherenkov light (DIRC)
- Multi-gap Resistive Plate Chamber
  - Goal: 10 ps Time-of-Flight (TOF)

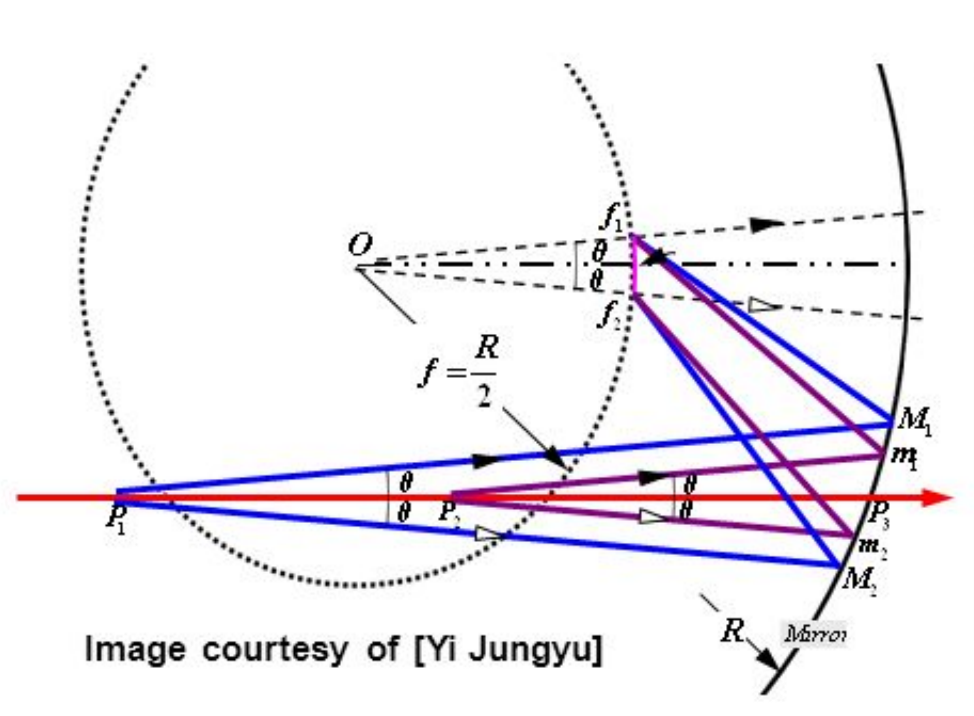
- Other R&D
  - $PbWO_4$ crystals for e,gamma Energy measurement
  - Transition Radiation (good for e/hadron separation)
  - 10 ps TOF with Si

Particle Identification: Cherenkov Detectors

- Measure particle momentum via tracking in B-field
  - Radius of curvature of track: $R = (p_\perp c)/(eBc)$
    - Units: [pc] = GeV = 10^9 eV
    - [B] = Tesla = Volt•s/m^2
    - [eBc] = eV/m ➔ if B=1 Tesla, then *eBc = 0.3* GeV/m
- Cherenkov radiation sensitive to velocity
  - v>c/n ➔ $\cos\theta_C = c/(nv) = 1/(n\beta)$
  - Intensity: $\frac{dN}{dL} = \alpha_{QED} Z^2 \int \frac{d\lambda}{\lambda^2} \epsilon(\lambda) \left[1 - \frac{1}{[n(\lambda)\beta]^2}\right]$
  - Threshold Cherenkov: CO_2 gas at STP:
    - n(400nm) = 1.00046 ➔ $\beta_{Threshol} = 1/n = 0.99954$
    - Only electrons radiate for p ≤ 3.46 GeV/c
      (pions, muons, protons are too slow)

Ring Imaging Cherenkov Detectors

- Solid Cone of light focused to ring.
  - $r_C \approx f\, \theta_C$ (small angle approximation)



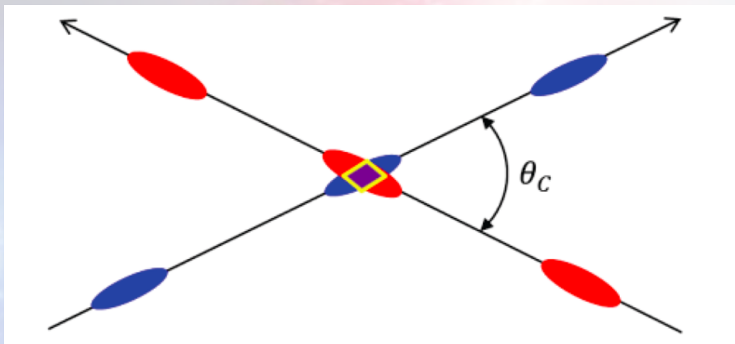
- Center of ring predicted by track
- Each photon detected provides a measure of radius *r*.
- Resolution of Cherenkov angle

$$\sigma(\theta_C) = \frac{1}{\sqrt{N_\gamma}} \frac{\sigma(r)}{f}$$

- $\beta = 1/[n \cos\theta]$
- m = p/(β$\boldsymbol{\gamma}$) ➔ Identify particle species

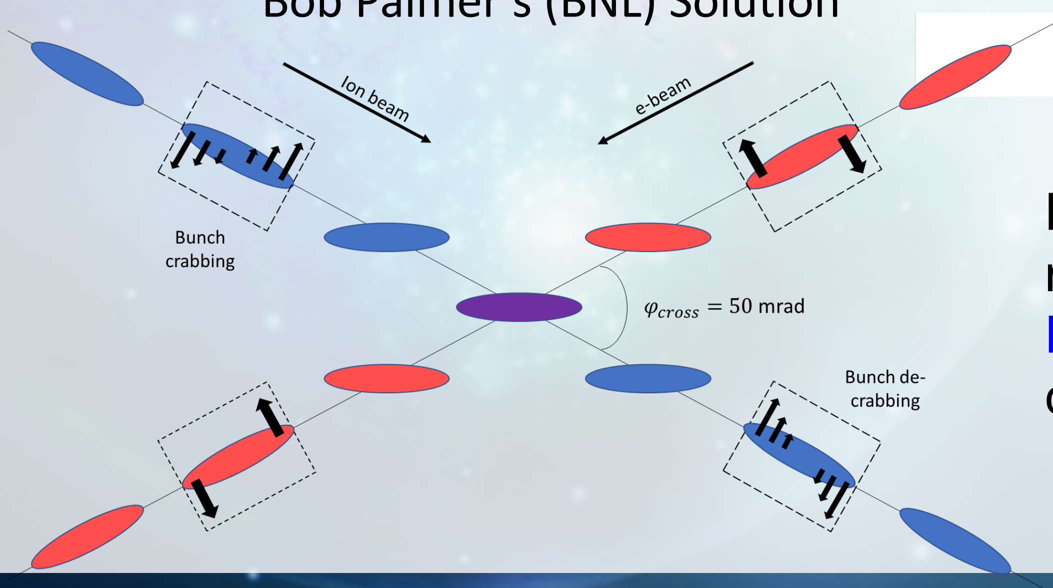
Beam Crabbing

- Beam crossing angle is necessary to avoid parasitic collisions due to short bunch spacing, make space for machine elements, improve detection and reduce detector background



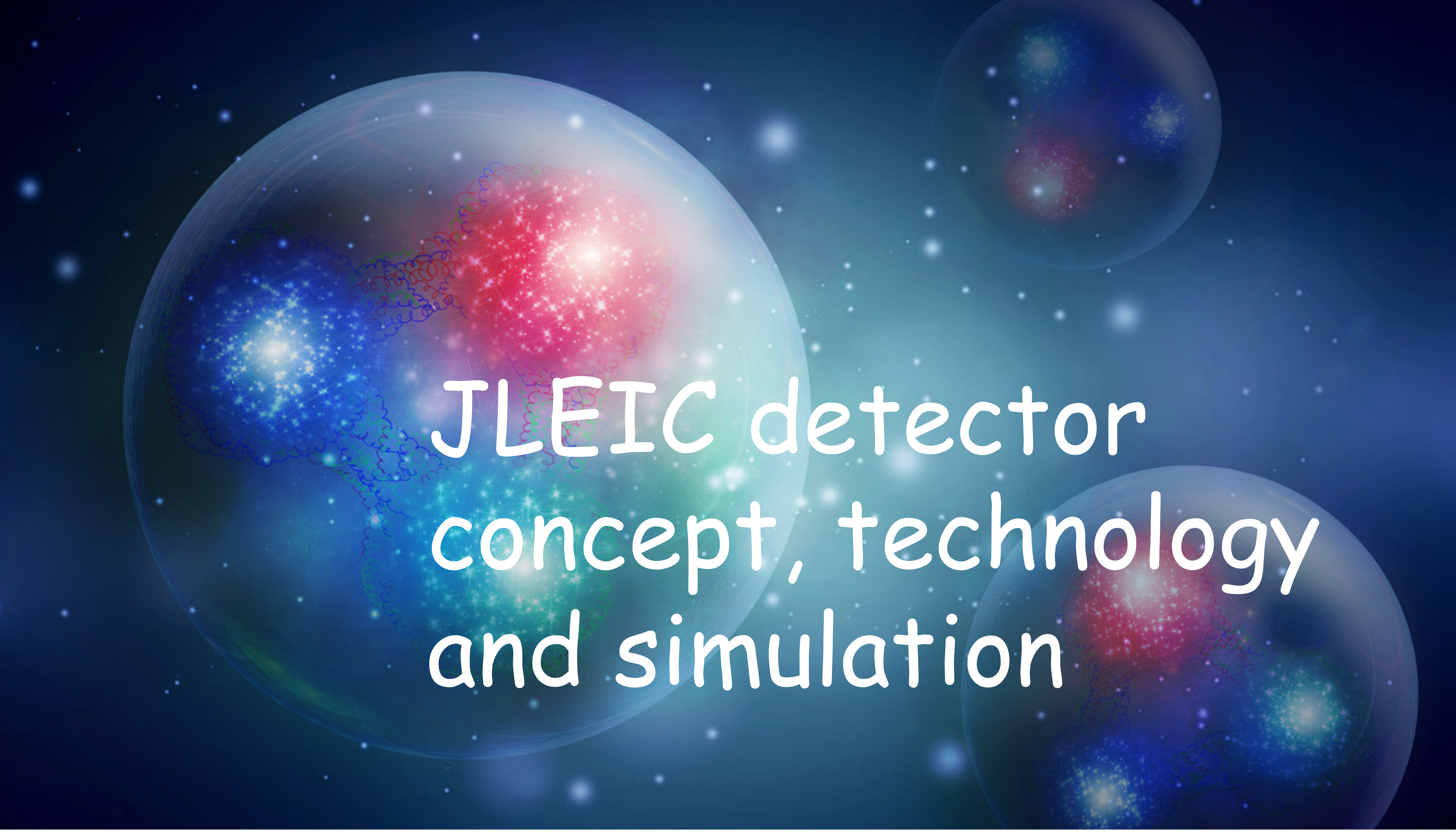
Low luminosity
Beam dynamics issues

Bob Palmer's (BNL) Solution



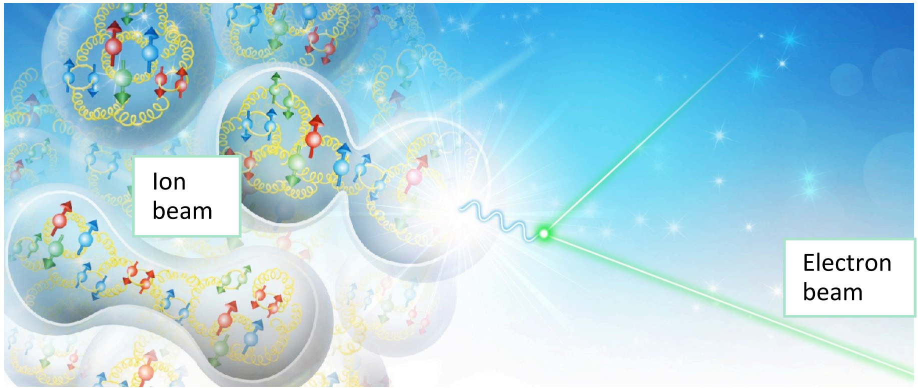
Effective head-on collision restored
Factor of 10 luminosity increase compared to uncorrected case

JLEIC detector concept, technology and simulation



Yulia Furletova, on behalf of JLEIC detector/software working group

DIS: Many complementary probes in a single facility



✓ **Inclusive**

$e+p/A \to e' + X$

Analyze only scattered electron
(modern Rutherford experiment)

✓ **Semi-inclusive**

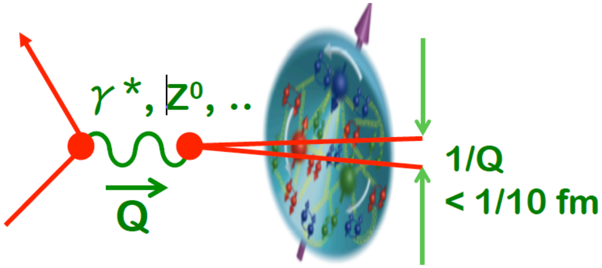
$e + p/A \to e' + h\ (\pi, K, p, \text{jet}, \ldots) + X$

Detect scattered electron in coincidence with hadrons/jets (much cleaner then in h-h collisions)

✓ **Exclusive**

$e + p/A \to e' + h\ (\pi, K, p, \text{jet}, \ldots) + p'/A'$

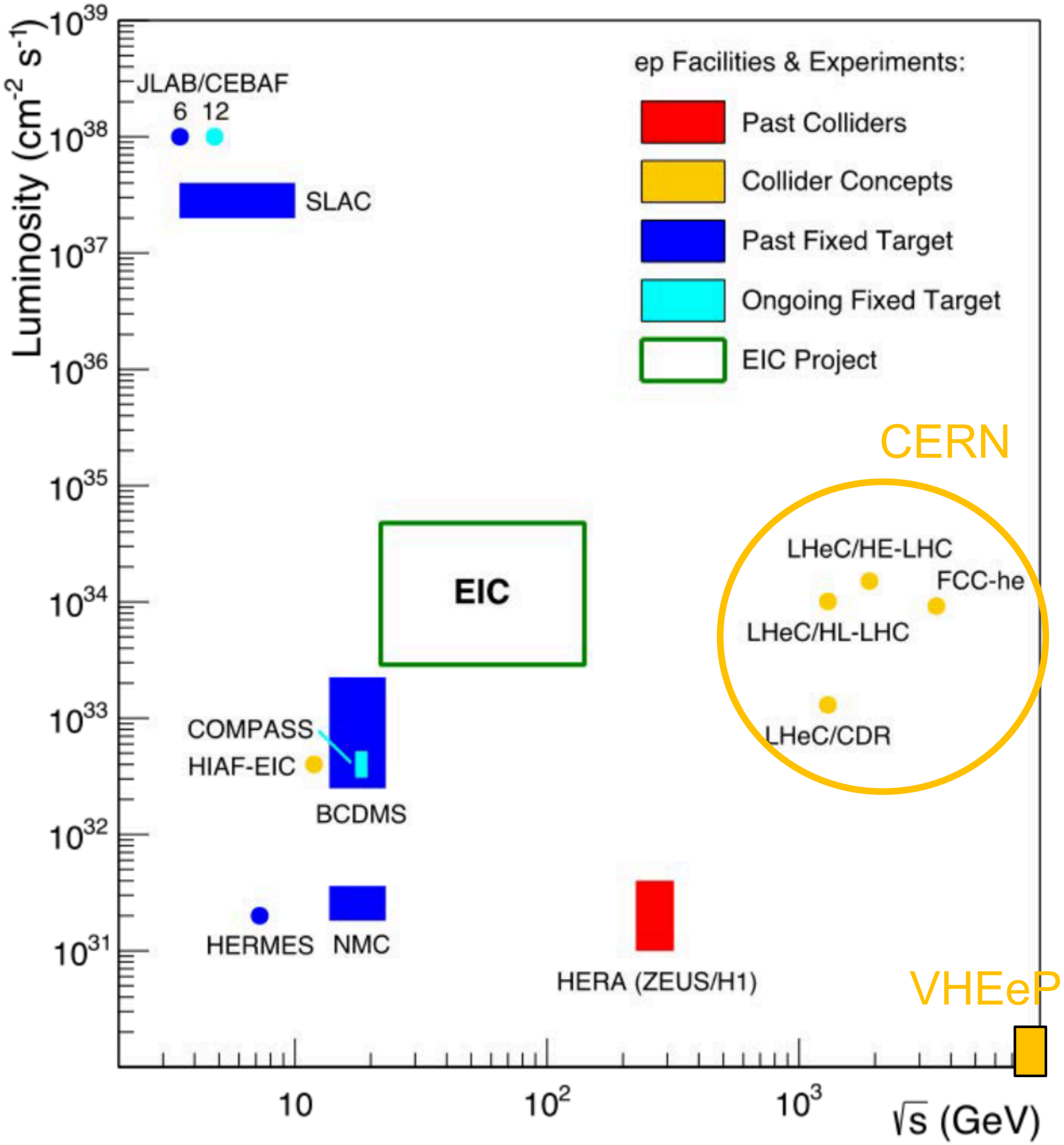
Detect everything, including scattered proton/nucleus (or fragments)



From 12 GeV to EIC:

Imaging -> Markus Diehl
Tagged physics -> Tanja Horn
GPDs -> Charles Hyde
QCD in nuclei -> Christian Weiss
Color propagation -> Taisiya Mineeva
.....

Past, existing and proposed DIS facilities



All DIS facilities in the world.

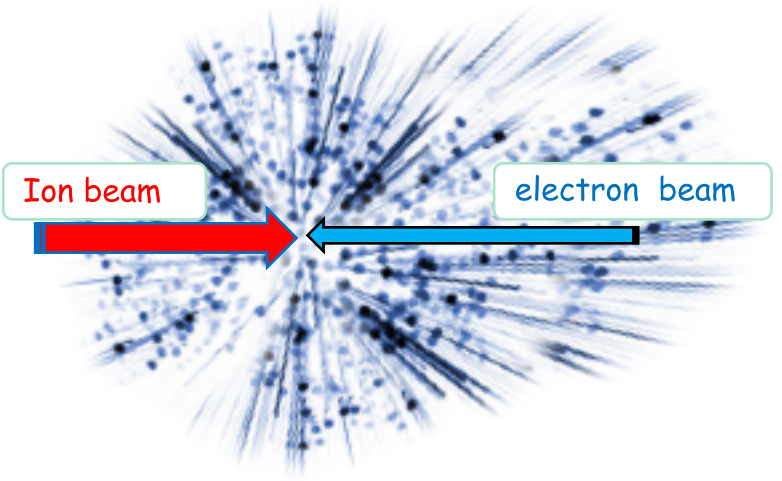
JLab has highest Luminosity ever!

- Higgs coupling
- Very low-x (saturation?)

EIC: JLEIC or eRHIC
- Only polarized e, p, d, 3He DIS Collider (ep, eA)
- First ever eA collider (no nuclei in HERA)
- Only DIS facility with full reconstruction of projectile final state (proton or nuclear remnants, excitations…)

Detector design for EIC

Collider experiments



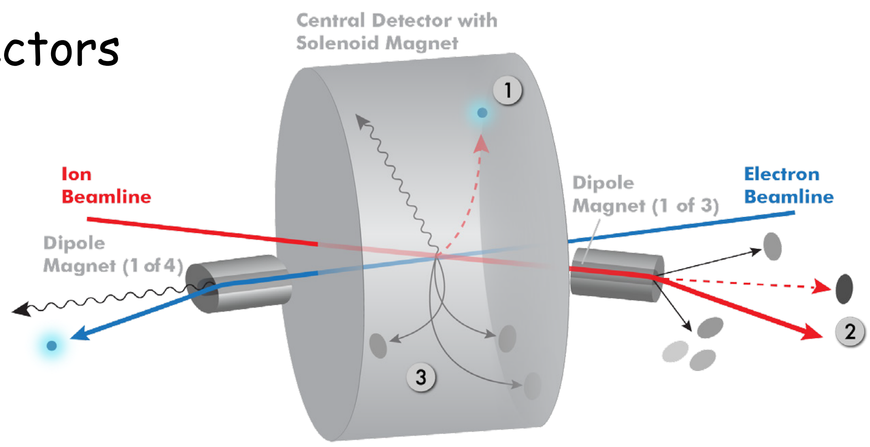
-Total acceptance coverage (4π) including far-forward/rear detection

-Integration with accelerator

-High precision measurements:
- statistics (~100fb^{-1}/measurement)
- minimize systematic uncertainties (<1%)

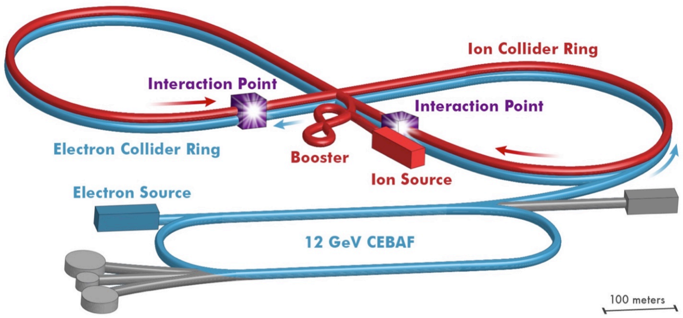
-Advanced detector technology:
High resolution tracking and vertex detectors
High energy resolution calorimeter
Particle identification ,etc..

-Minimize background

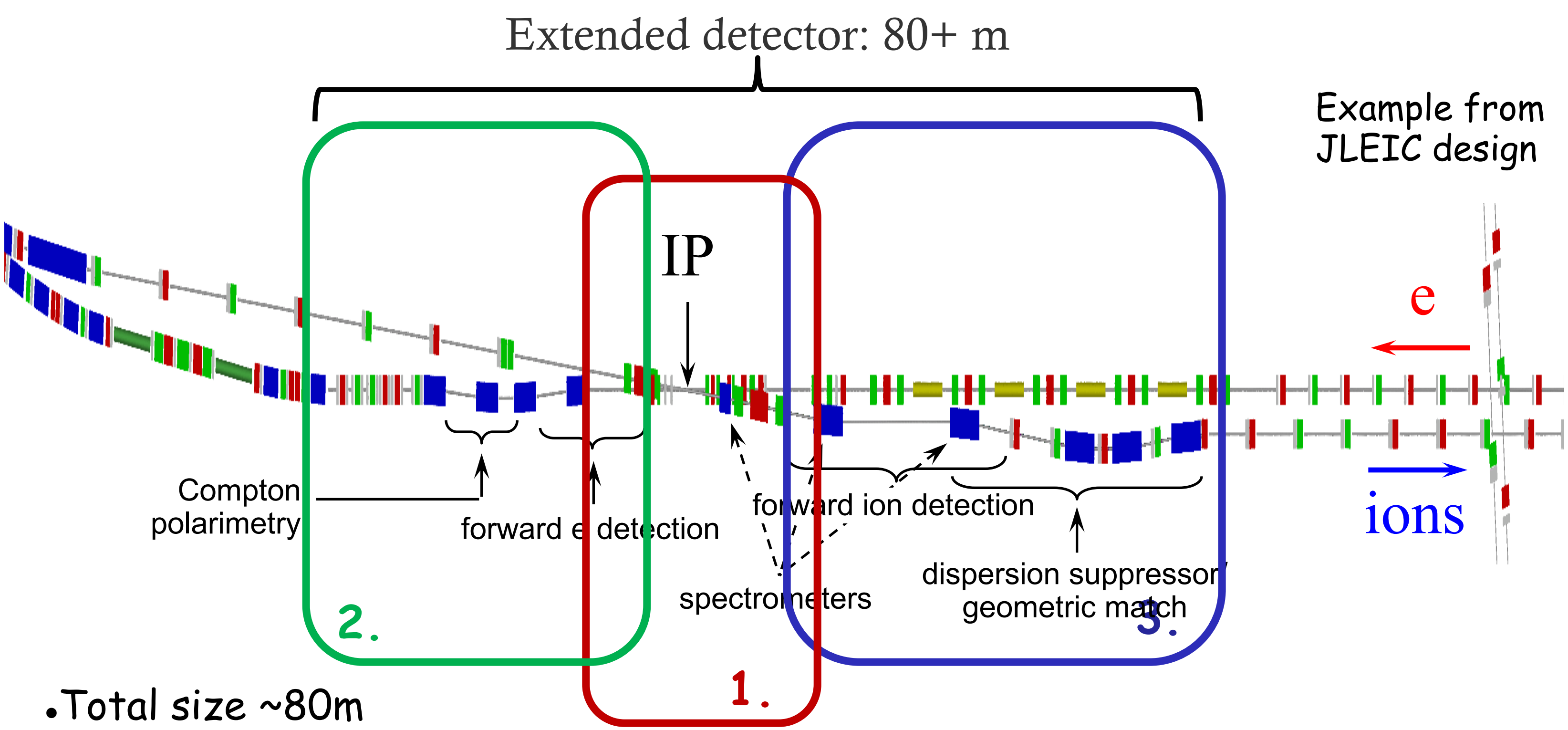


Integration with accelerator

- IP placement to reduce a background
  - synchrotron radiation
  - beam gas events
  - neutrons
- Crossing angle (50mrad) to create a room for forward detection



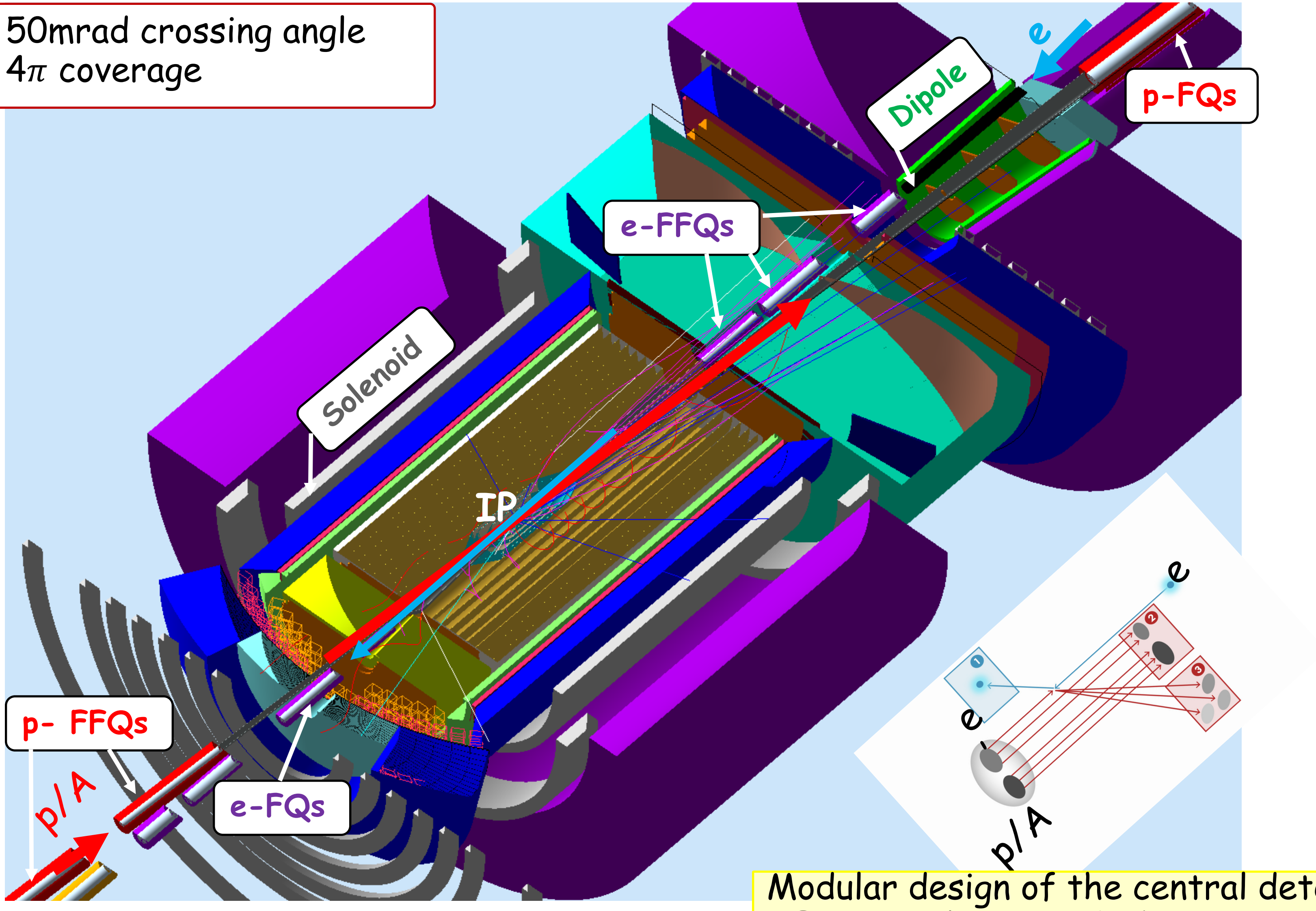
Example from JLEIC design



- Total size ~80m
1. Central detector ~10m
2. Far-forward electron detection ~30m
3. Forward hadron spectrometer ~40m

EIC Central detector (top view)

- ✓ 50mrad crossing angle
- ✓ 4π coverage



Modular design of the central detector
GEMC simulation in docker

GEMC with docker

Getting started

Similar instructions for
- eicROOT : Alex Kiselev BNL
- ePHENIX: Nils Feege Stony Brook U.

1. Install Docker

2. Run container

   docker run -p 6080:6080 -v /my/data/dir:/data -it --rm electronioncollider/jleic:1.0. *4*

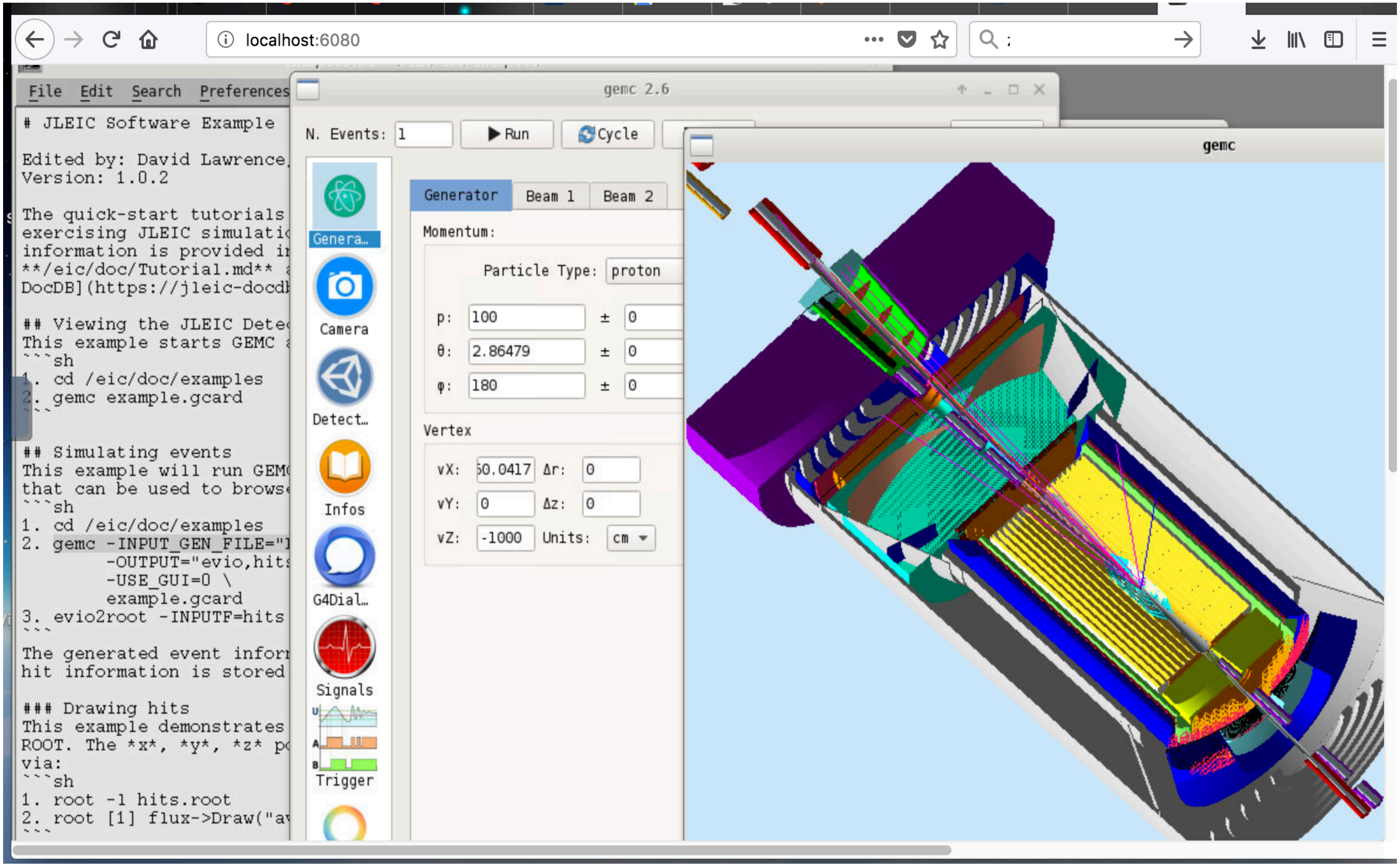
3. Point browser to:

   http://localhost:6080

For tests on ifarm:
> singularity shell shub://electronioncollider/jleic:1.0.4

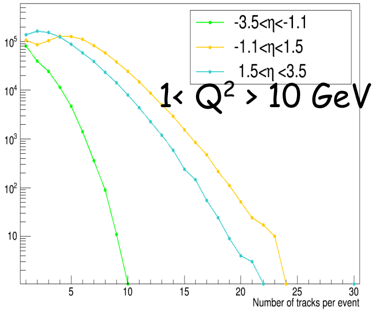
requires :
> setenv https_proxy https://jprox.jlab.org:8082
> module load singularity-2.5.1

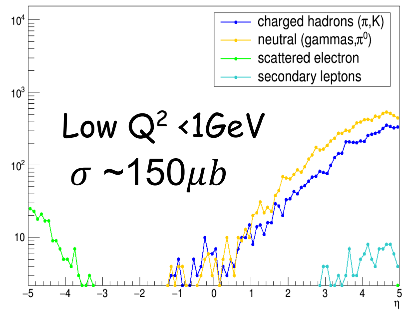
GEMC with docker

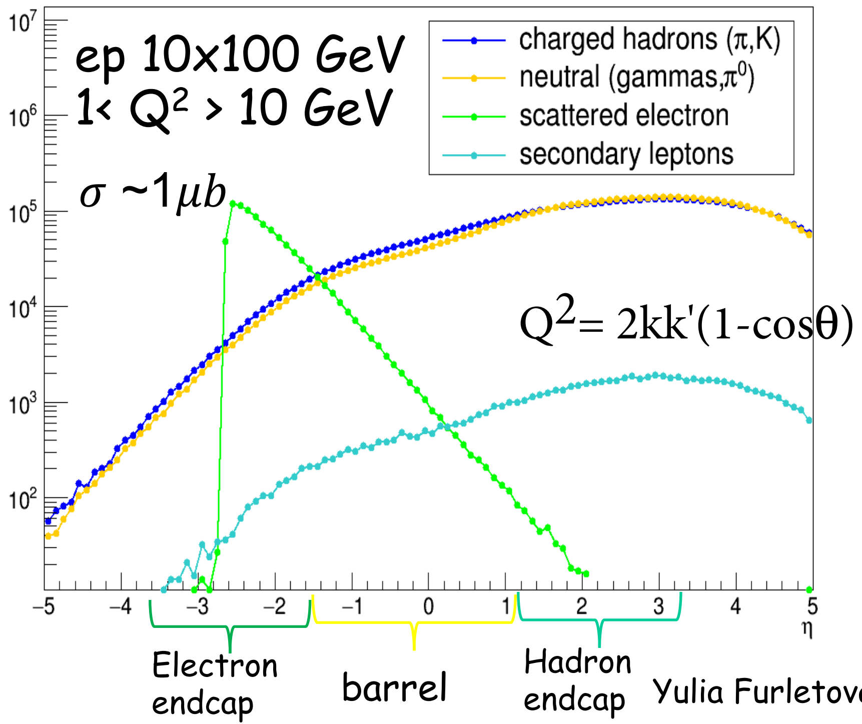


Tracking detectors

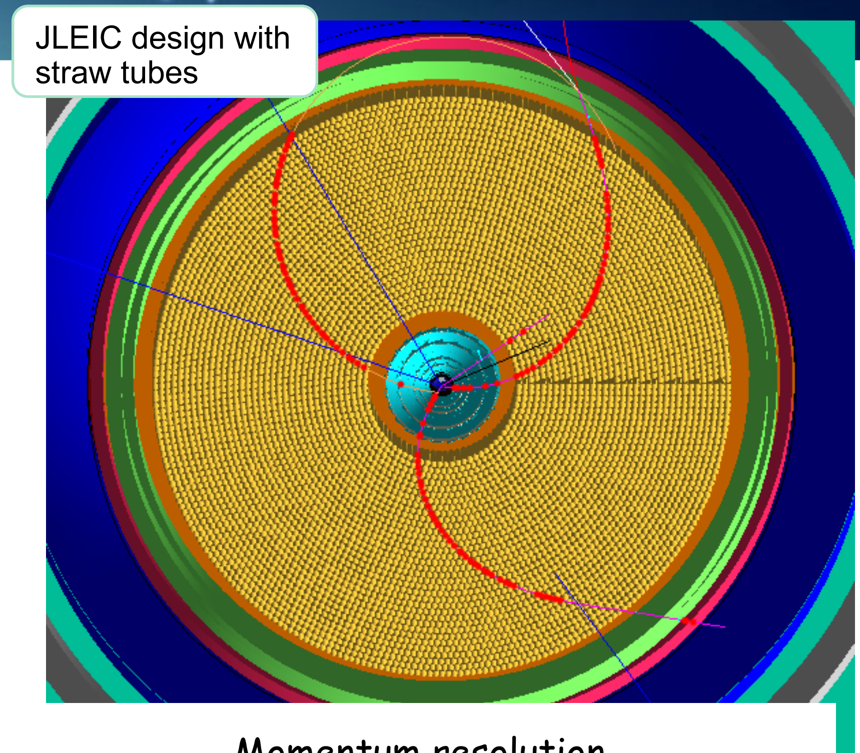
- Several options for central tracking: (TPC, straw tubes, Drift chambers, Si)
- At EIC, momentum resolution below few % is required

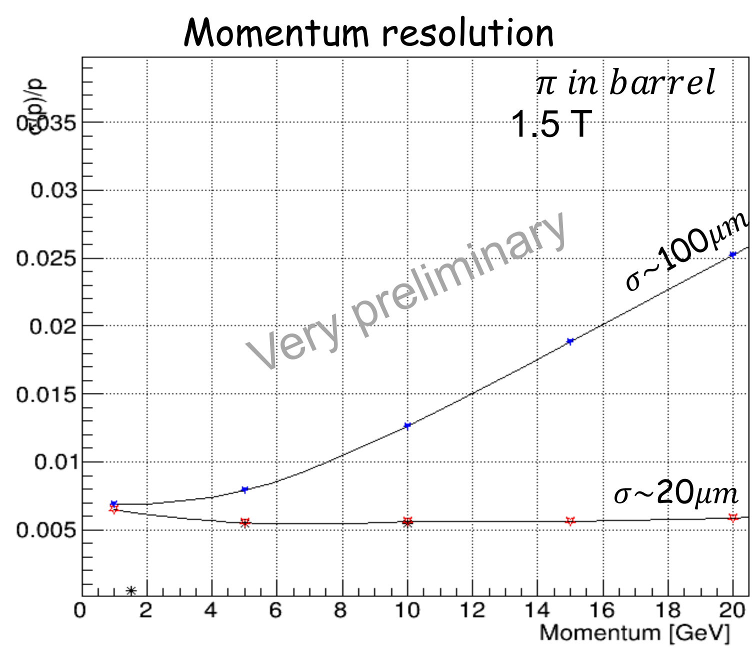






Yulia Furletova





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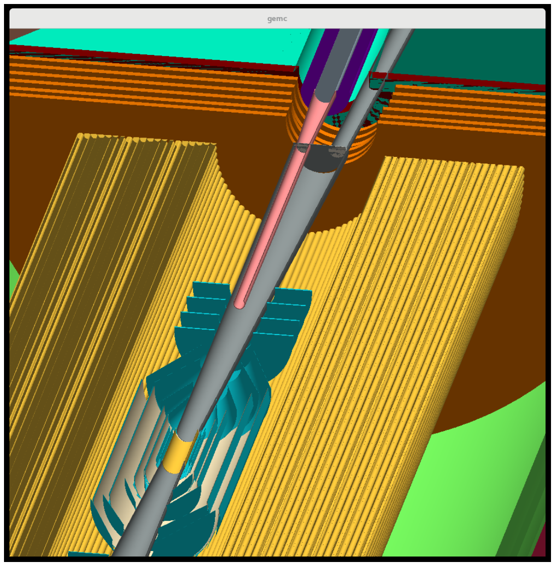
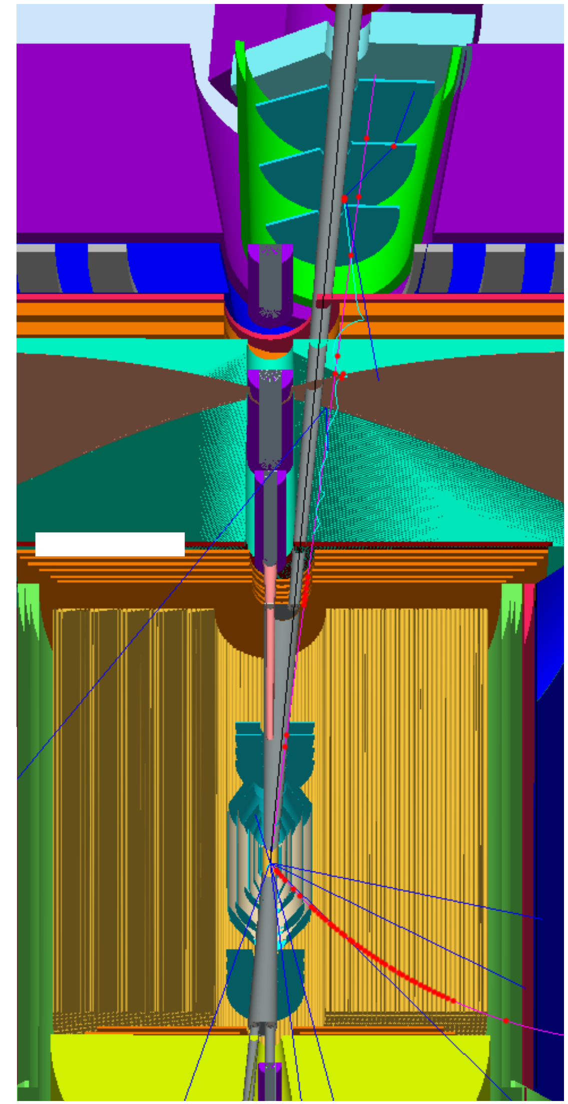
Tracking

Vertex detector
 (MAPS, DEPFET,DS Si)

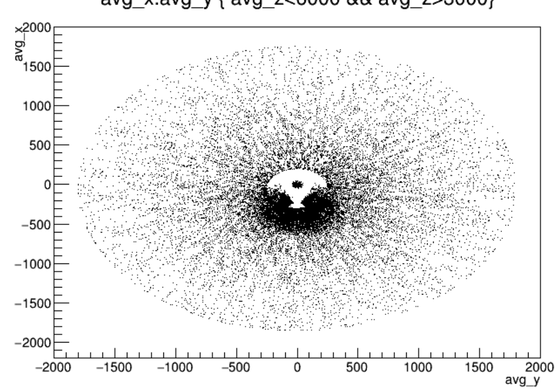
- Number of layers, granularity
- Endcaps



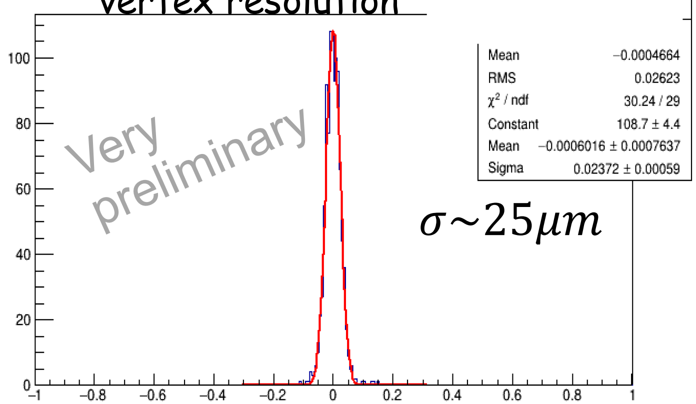
Forward Dipole at JLEIC to improve momentum reconstruction



Occupancy, detector coverage

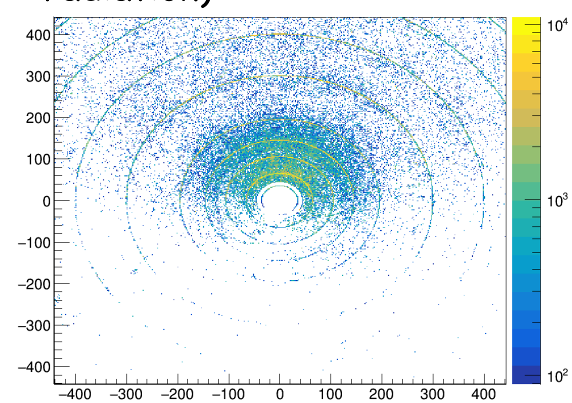


vertex resolution



$\sigma \sim 25\mu m$

Occupancy with background (here with synchrotron radiation)



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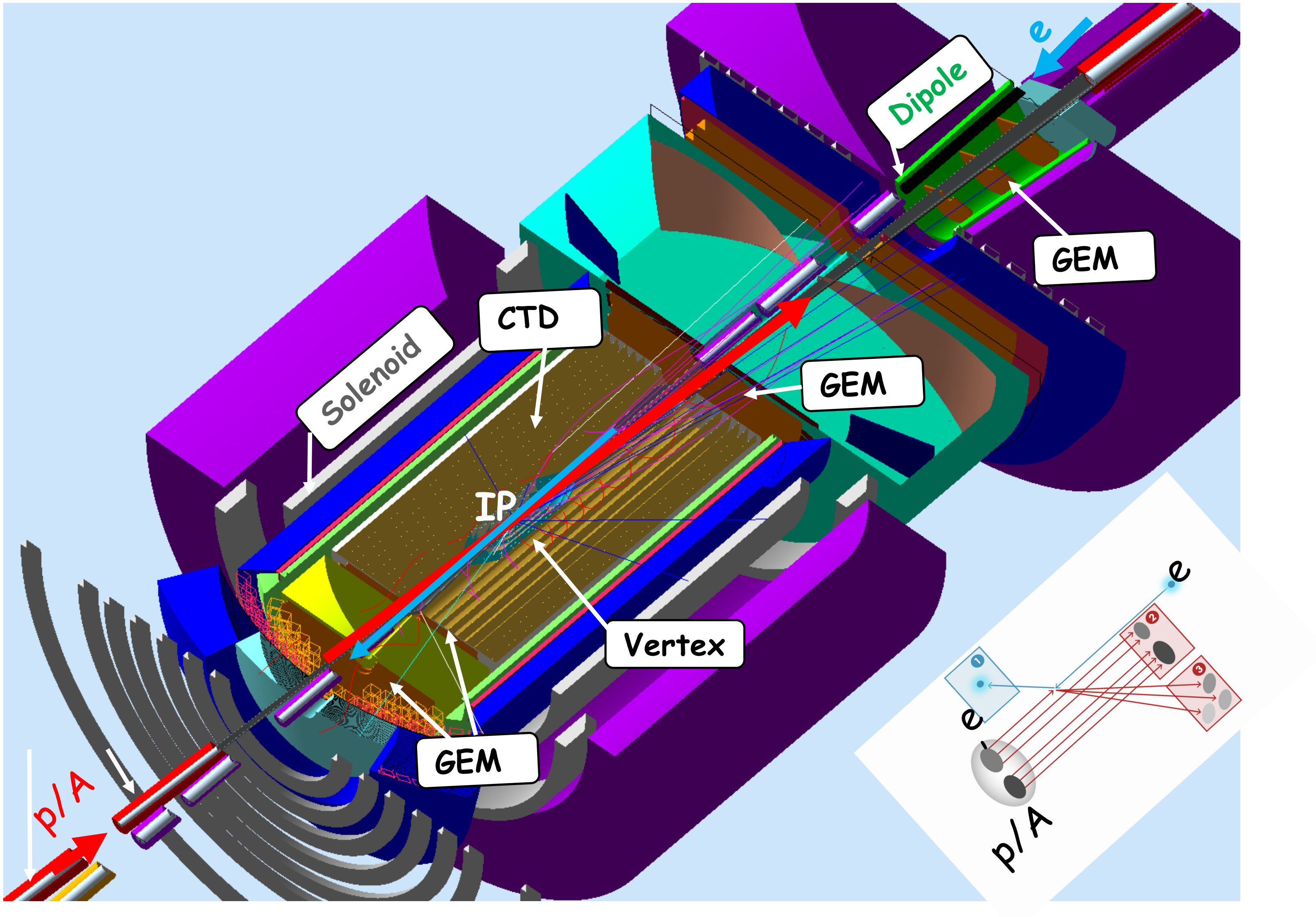
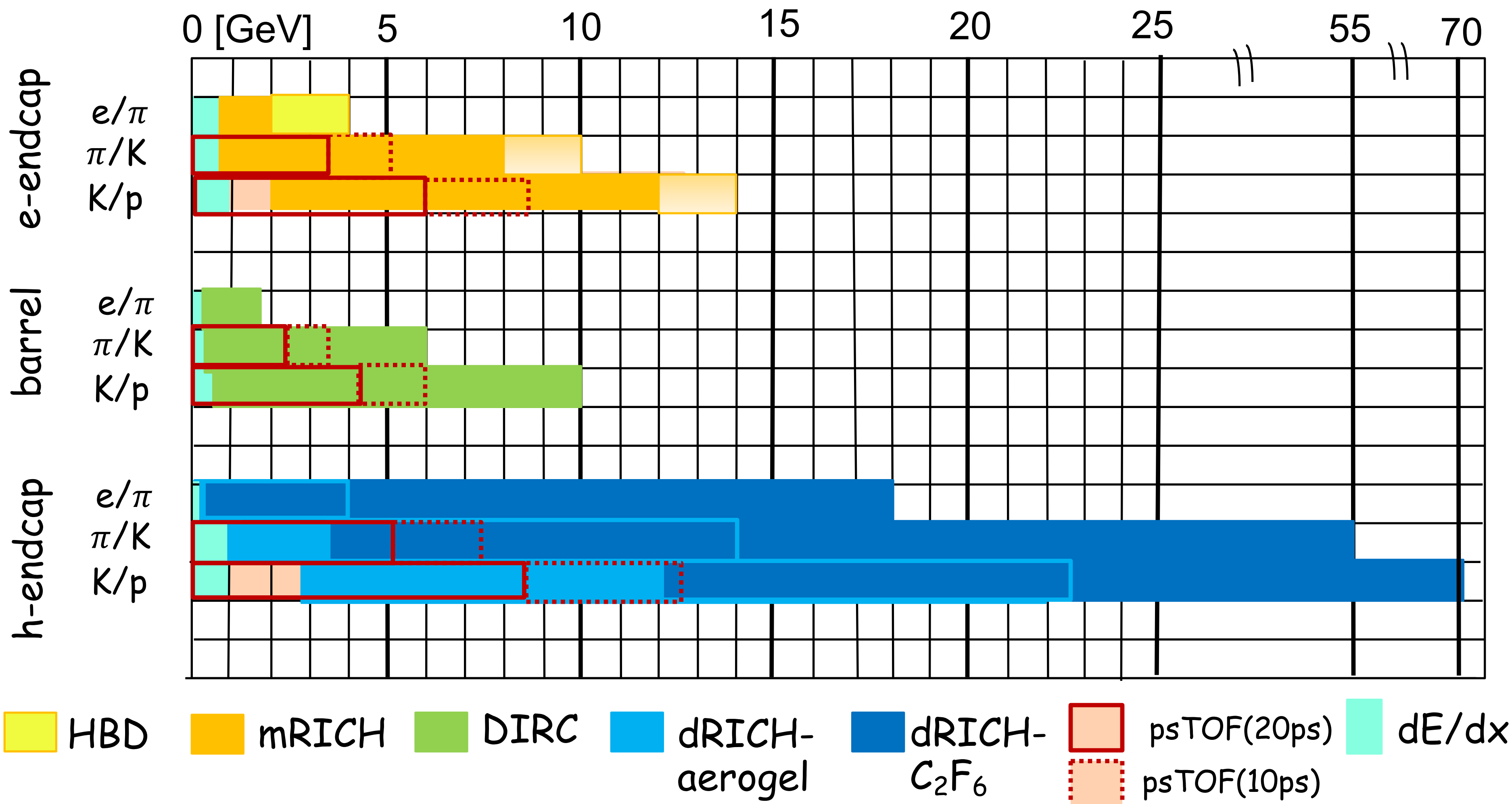
Tracking

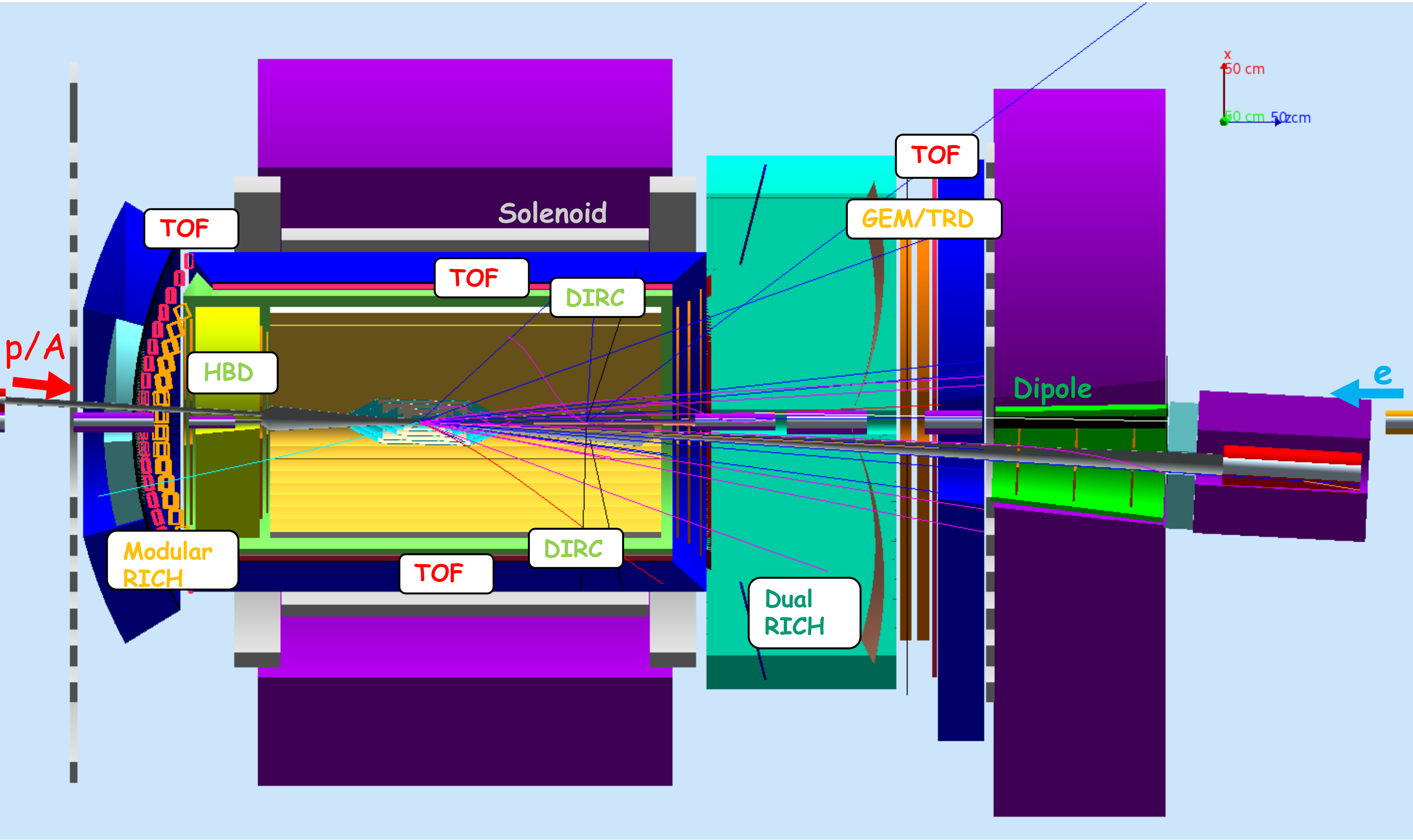


Individual hadrons (π, K, p): Cherenkov, TOF

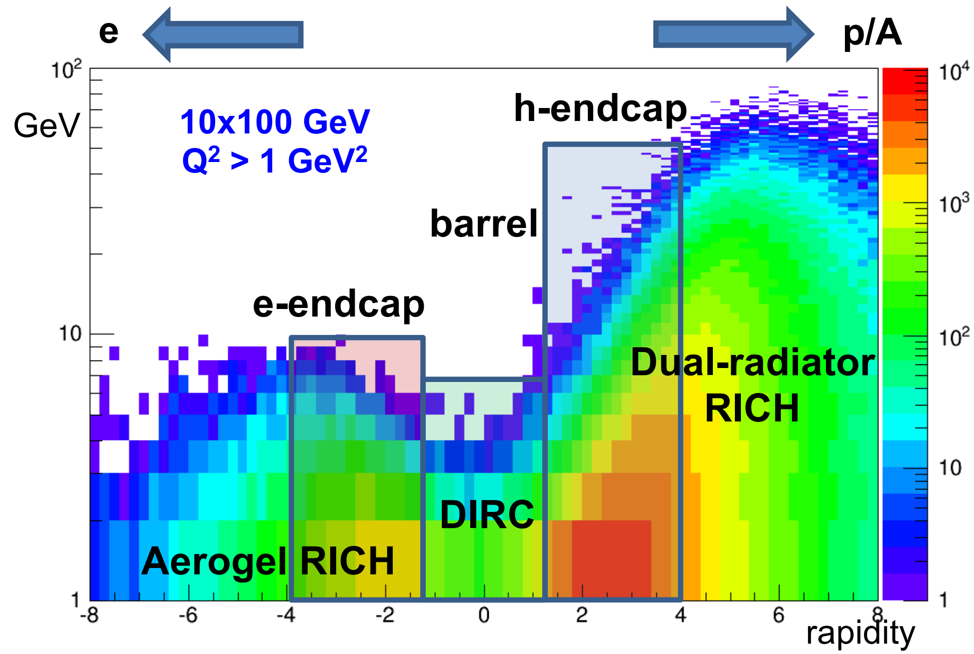


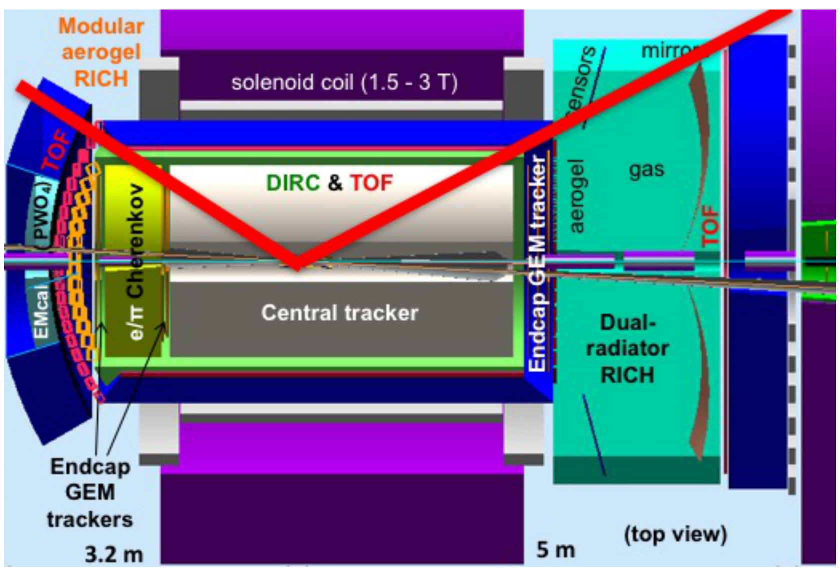
** Here, electron/hadron separation only from Cherenkov detectors is shown. Main e/h rejection is done by calorimeters (+TRD).

JLEIC central detector(top view) /PID



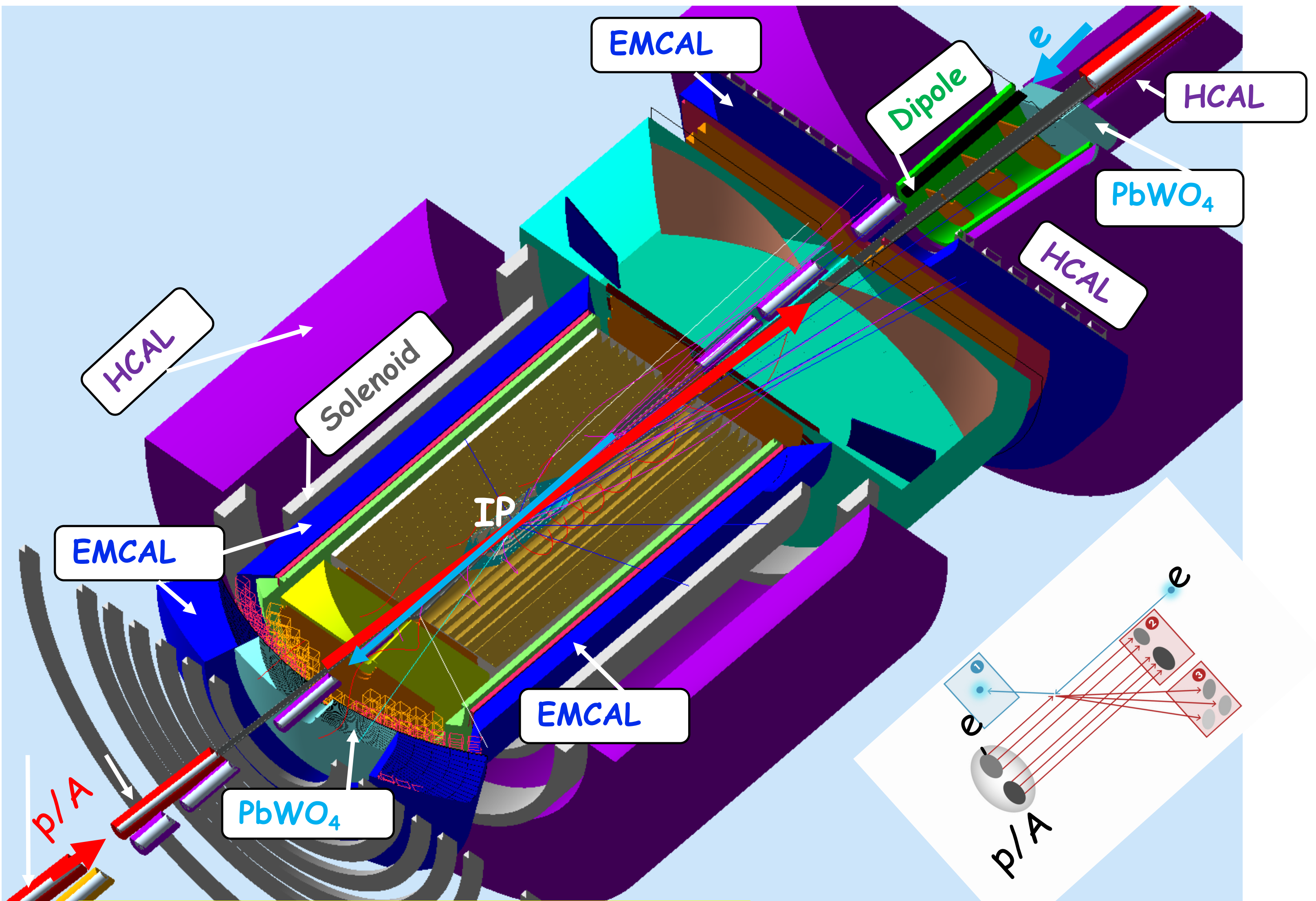
A PID solution for the EIC - implementation





- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  π/K/p separation up to ~50 GeV/c
- **e-endcap**: A compact aerogel RICH which can be projective
  π/K/p separation up to ~10 GeV/c
- **barrel**: A high-performance DIRC provides a compact and cost-effective way to cover the area.
  π/K/p separation up to ~6-7 GeV/c
- **TOF (and/or dE/dx in TPC)**: can cover lower momenta.
- **Photosensors and electronics**: need to match the requirements of the new generation devices being developed – both for the final system and during the R&D phase

Calorimeter



$PbWO_4$

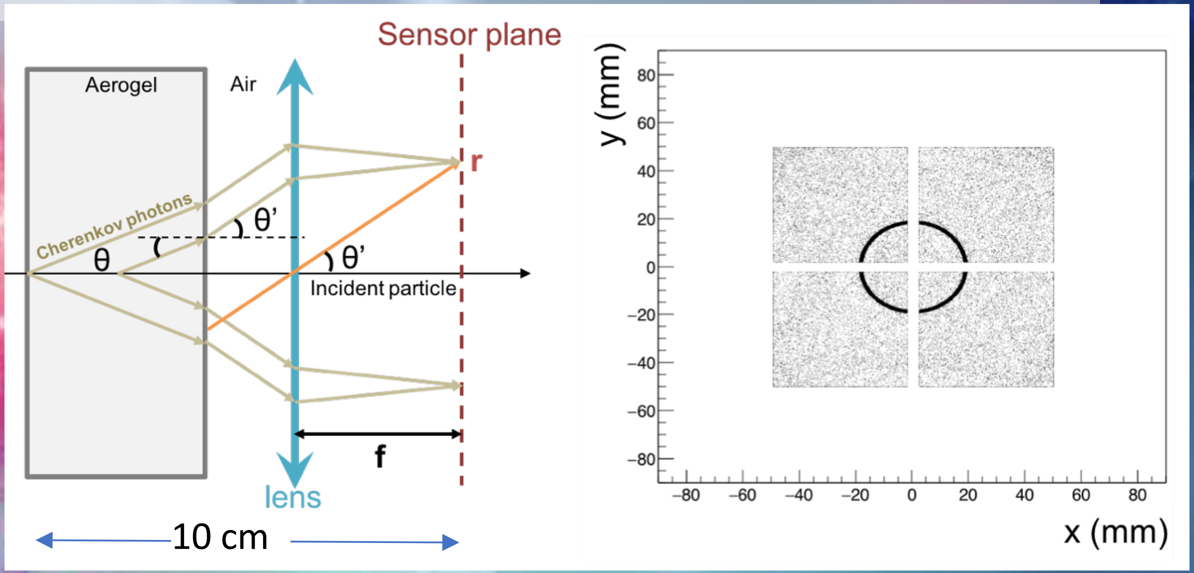
- $PbWO_4$ Close to the beam – more precise and more radiation hard calorimeter

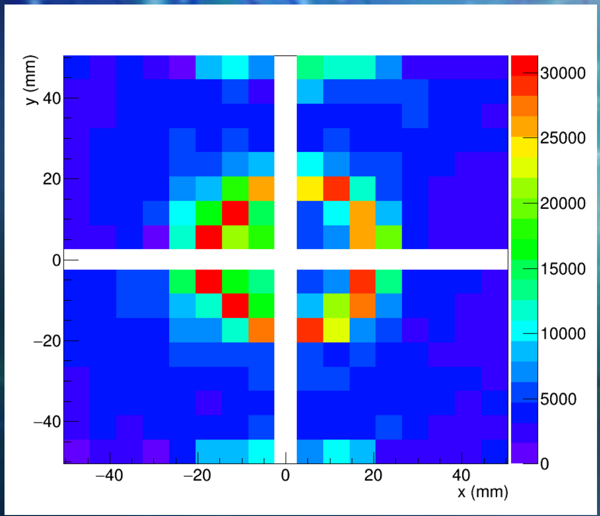
Shashlyk

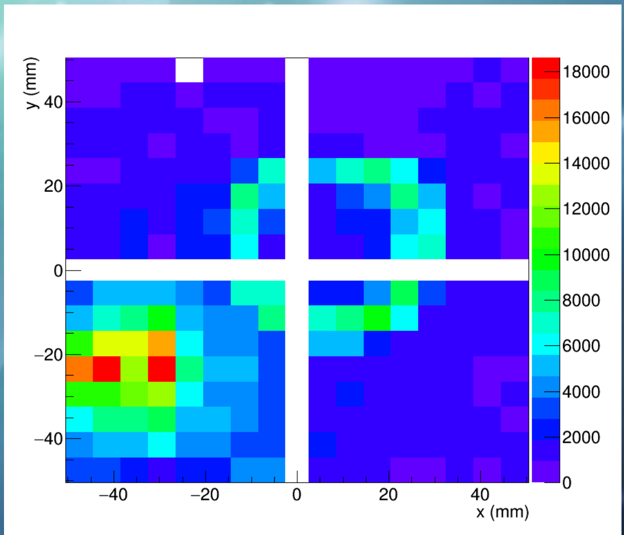
- Barrel and endcaps – less expensive

Modular RICH: Aerogel + Fresnel Lens

- Fresnel lens creates circle centered at origin, regardless of particle impact position
- Reduces required size of photo-sensor array
- Multi-anode PMT (pixels)

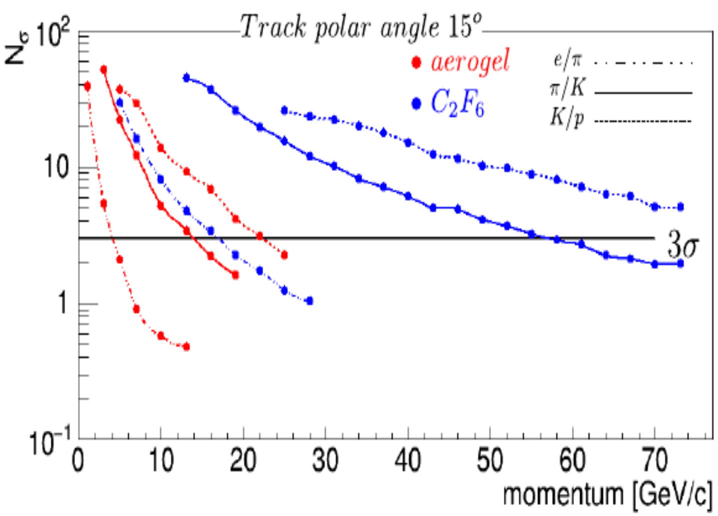


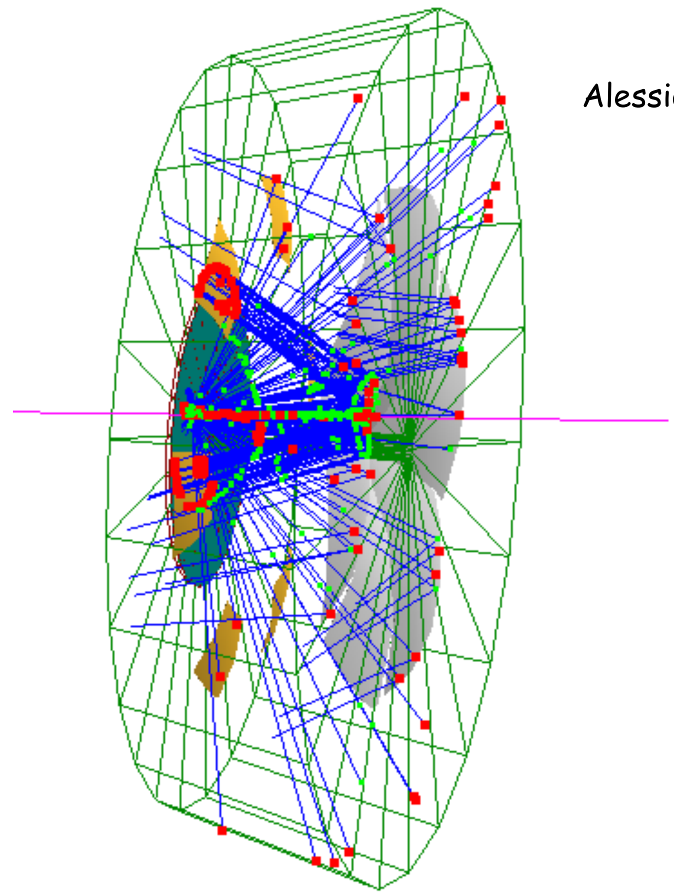




Dual Radiator RICH : Aerogel (thin) + 160 cm C_2F_6

- Sensitive to magnetic field=> New 3T solenoid minimized a field in RICH region
- Outward reflecting mirror
- Aerogel drives the detector to be solid state (e.g. SiPMs, LAPPDs)
- Focal plane away from the beam, reduced background





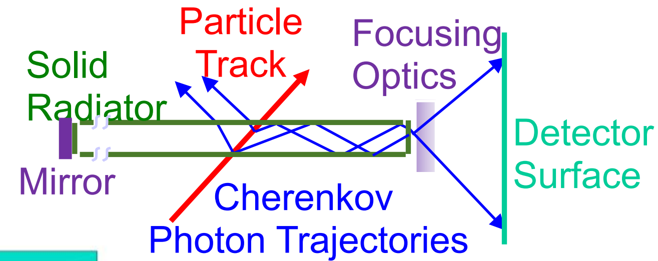
Alessio Del Dotto

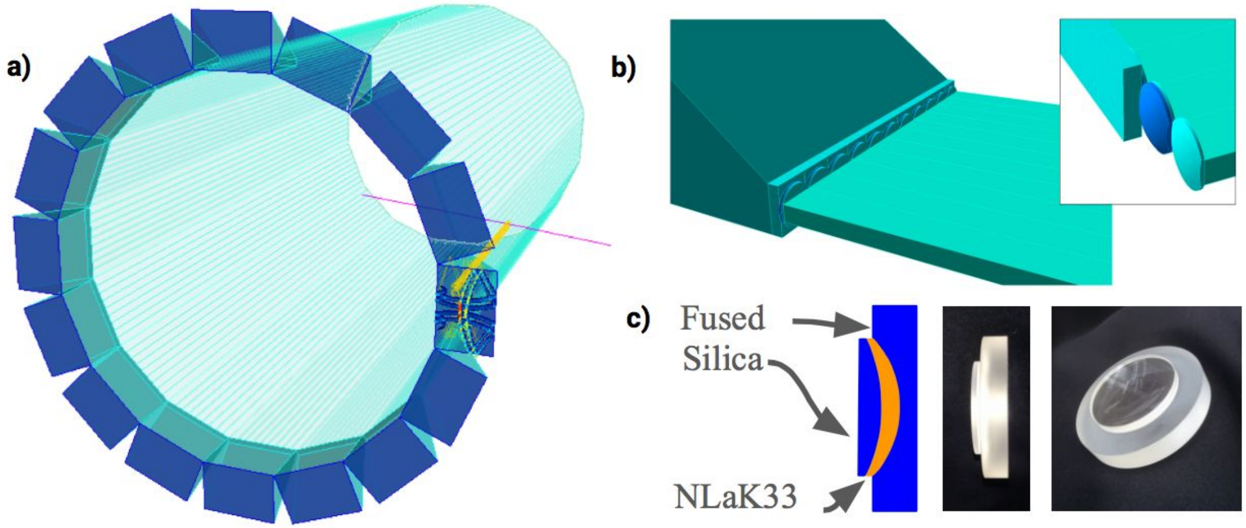
- Particle identification:

0.003(0.8) < e/π < 4 GeV 0.01 (3.48) < e/π < 18 GeV
0.8 (2.84) < π/K < 14 GeV 3.48(12.3) < π/K < 55 GeV
2.84(5.4) < p/K < 22 GeV 12.3 (23.4) < p/K < 70 GeV

Individual hadrons (π, K, p)

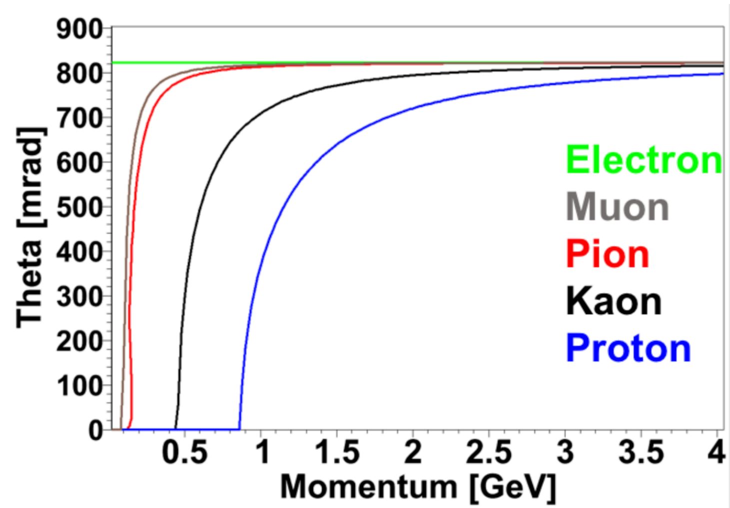
Barrel: DIRC •radially compact 5 cm)





Current design based on narrow synthetic fused silica bars arranged in 16 barboxes, coupled to solid prisms with custom made 3-layer lens, read out by arrays of MCP-PMTs.

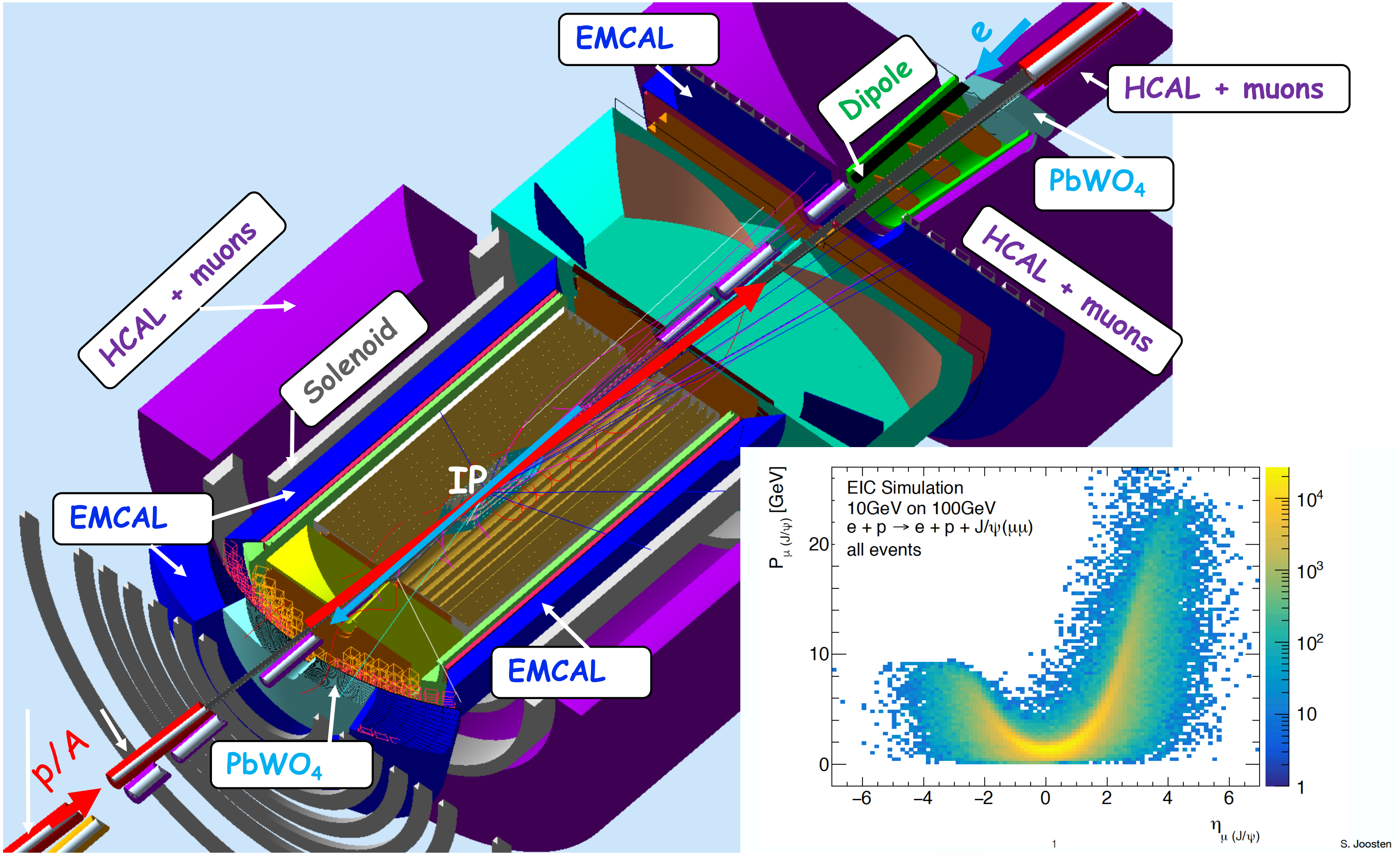
20 - 100 photons detected per incident track



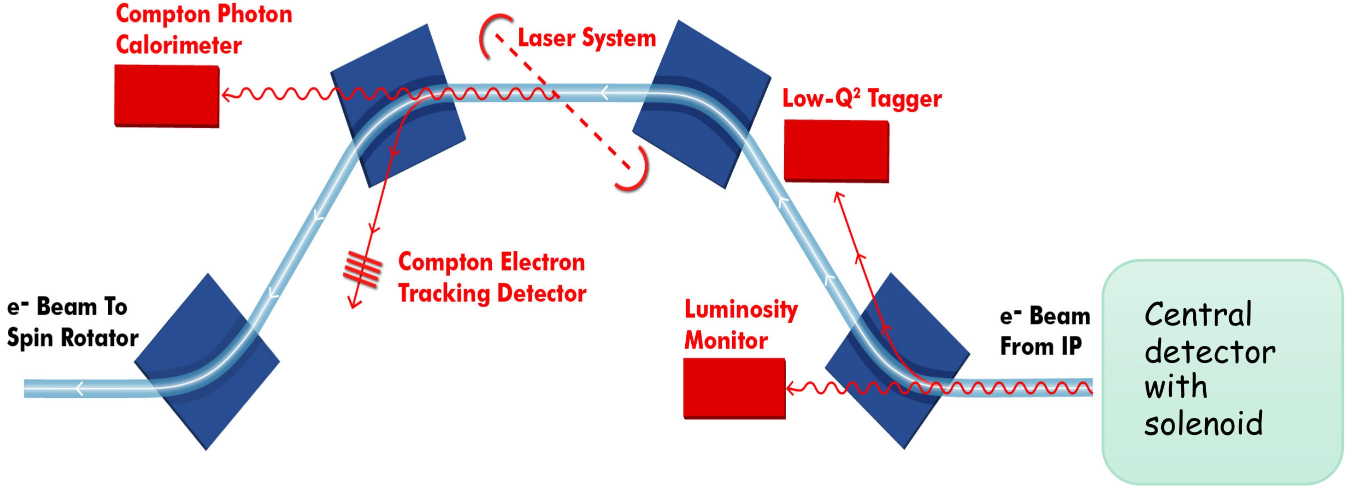
- Simulation for particle identification (3σ):

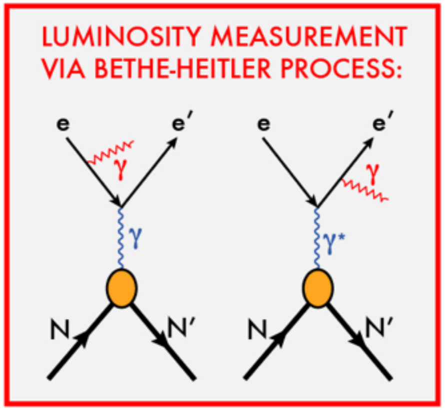
0.15 < e/π < 1.8 GeV
0.15 (0.45) < π/K < 6 GeV,
0.45 (0.8) < p/K < 10 GeV,

Muon detection



Chicane for Electron Far-Forward Area





- **Low Q2 tagger**

✓ For low Q^2 electrons

- **Luminosity monitor:**

✓ Luminosity measurements via Bethe-Heitler process

✓ First dipole bends electrons

✓ Photons from IP collinear to e-beam

- **Polarization measurements (similar to JLAB/Hall-A/C chicane)**

✓ First two Dipoles compensate each other

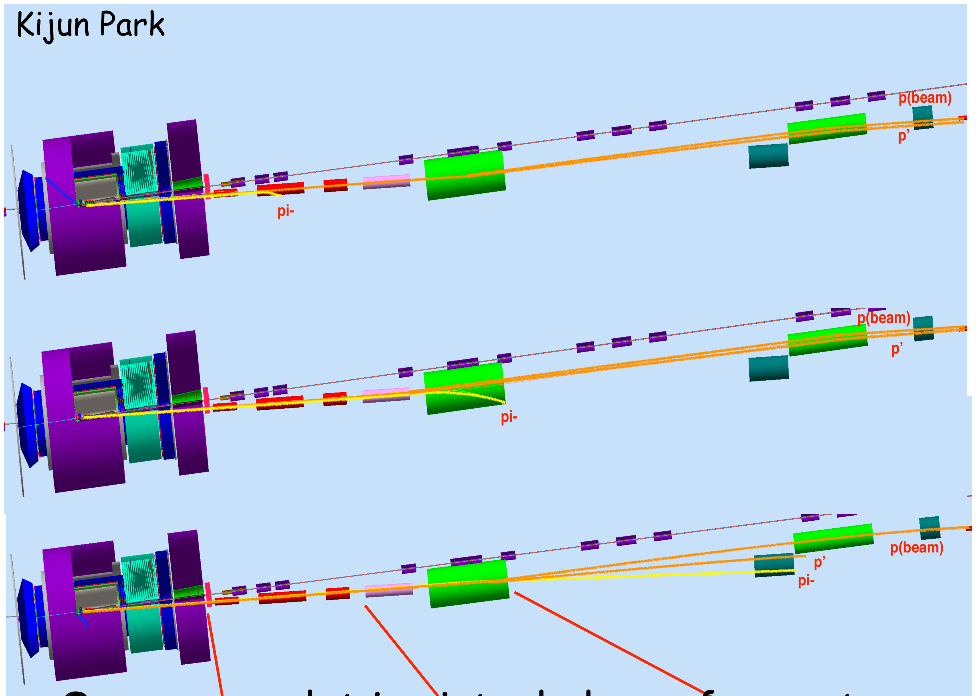
✓ The same polarization as at IP

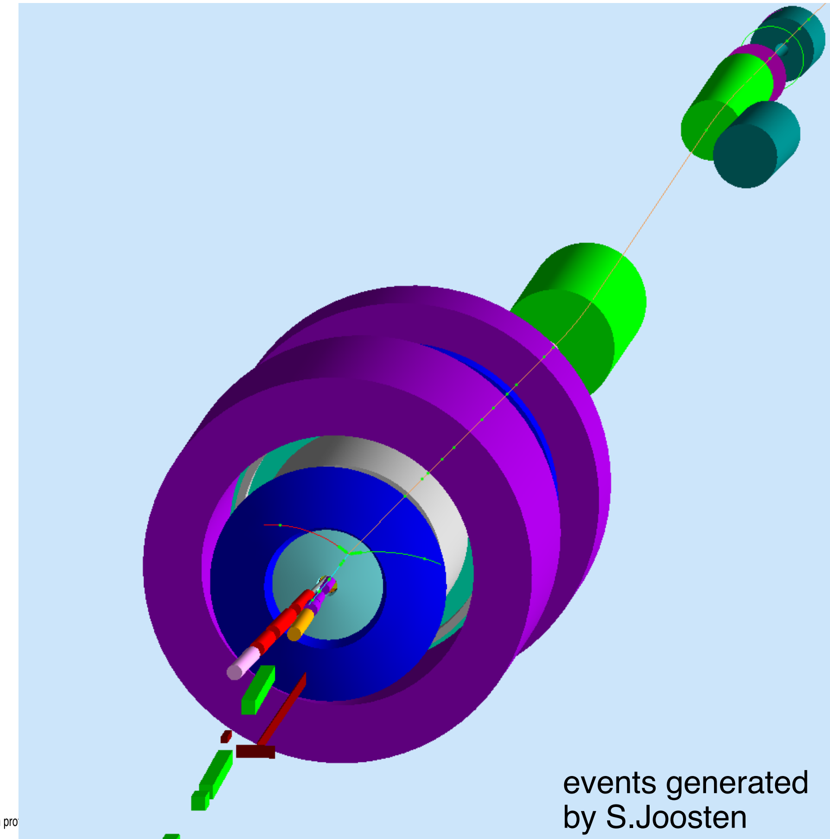
✓ Minimum background and a lot of space.

✓ Measurements of both Compton photons and electrons

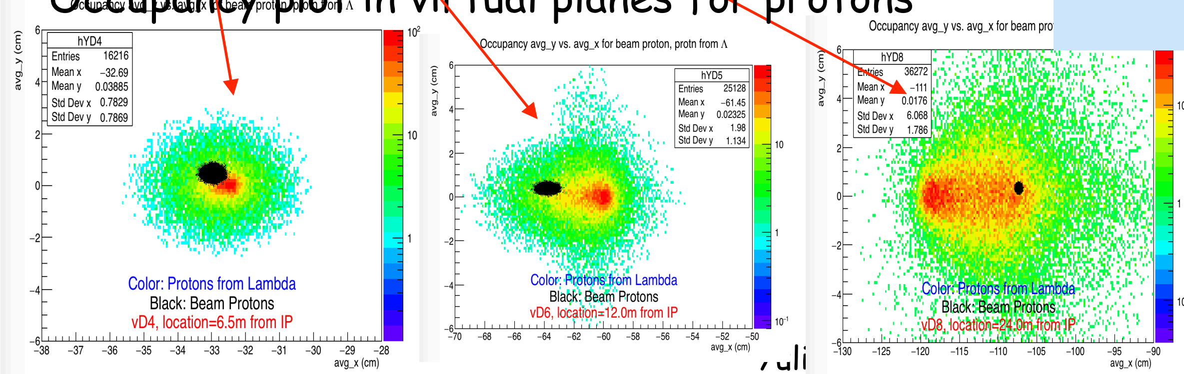
Far-forward ion direction area

- Tracking for Tagged DIS events
- $\Lambda \to p + \pi$
- Exclusive J/ψ

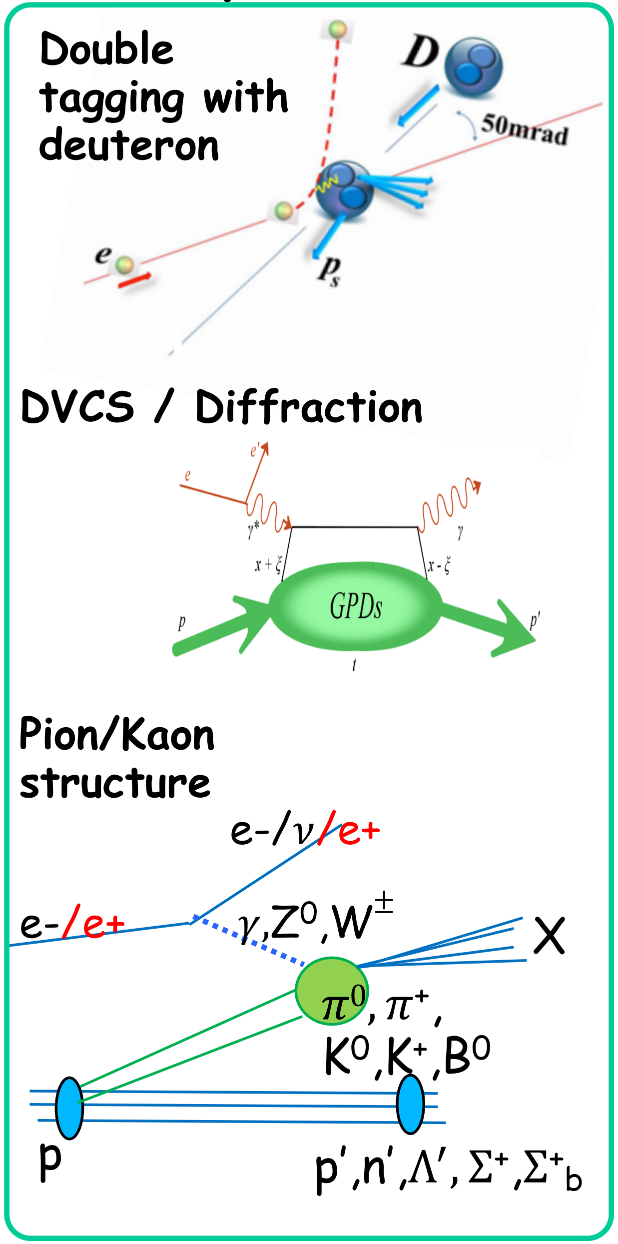


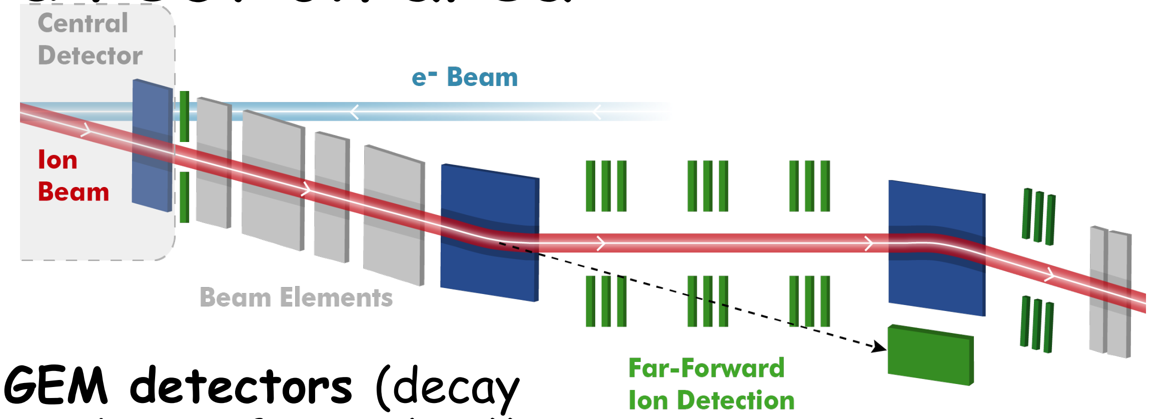


Occupancy plot in virtual planes for protons

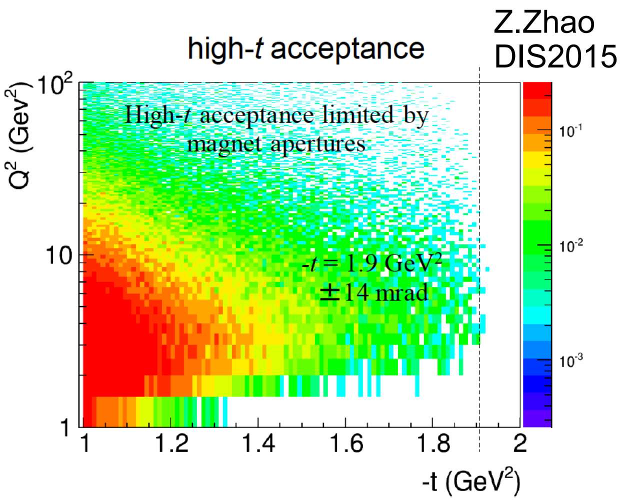


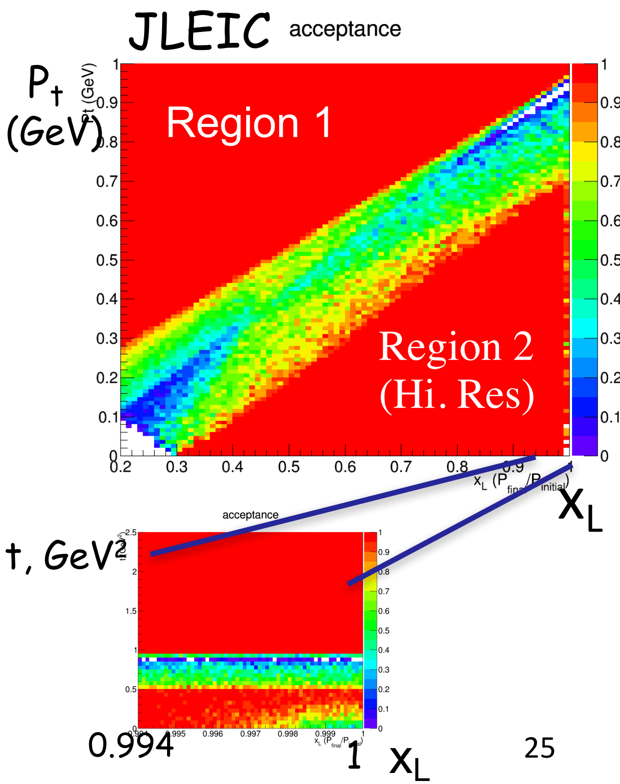
Far-forward ion direction area





- **GEM detectors** (decay products of Λ', Σ (π, K))
- **Roman-pots** for (p)-tagging
- **Zero degree calorimeter** for (n)-tagging
- **Double tagging**





EIC Detector R&D

- Calorimeter Consortium — CUA, Orsay, Giessen
  - PbWO4 Crystal R&D (synergy with JLab/NPS)
- Tracking Consortium — Saclay, Temple, UVA
- Particle Identification Consortium
  - DIRC — ODU, CUA, GSI, …
  - Dual RICH — Duke, INFN, W&M
  - Modular RICH — INFN, …
  - Sensors in high B field — USC, Jlab
- Compton Polarimetry Electron Detector — JLab, W&M (collaborating w Kansas)
- Software Consortium — JLab, ANL, SLAC, W&M..
- GEM-Based TRD (new since 2017) — JLab, Temple, UVA
- Background Simulations (new since 2017) — JLab, UConn, SLAC, …
- Streaming readout Consortium (new, 2018 proposal) — SBU, INFN Genova,CUA, MIT, Jlab

List likely incomplete …

Summary

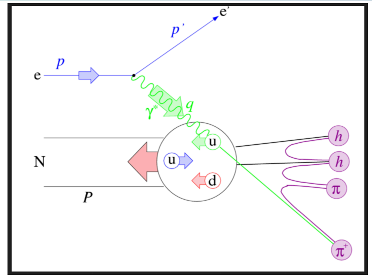
- Physics of nucleon and nuclear structure must drive the accelerator and detector design.
- JLEIC detector design is based on a *total* acceptance detector and particle identification concept. This means excellent forward/rear coverage in addition to the central coverage, as well as on identification of individual particle species.
- **Machine parameters**, **interaction region** and **detector design** must go hand in hand, paying close attention to the emerging **physics program** of the EIC (a good collaboration among Accelerator Physicists, Experimentalists, and Theoreticians)

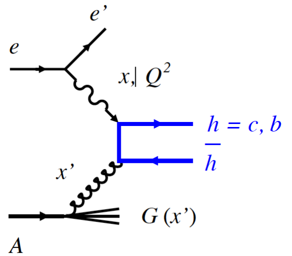
Thank you!

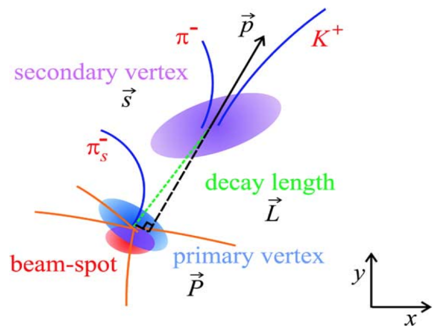
PID and Vertex detectors

- Semi-inclusive DIS
- Charm/Beauty identification : access to gluons
  - exclusive decay ($D^0 \to K^- \pi^+$)
  - inclusive decays (D mesons-> K+X)
- Spectroscopy

- high combinatorial background

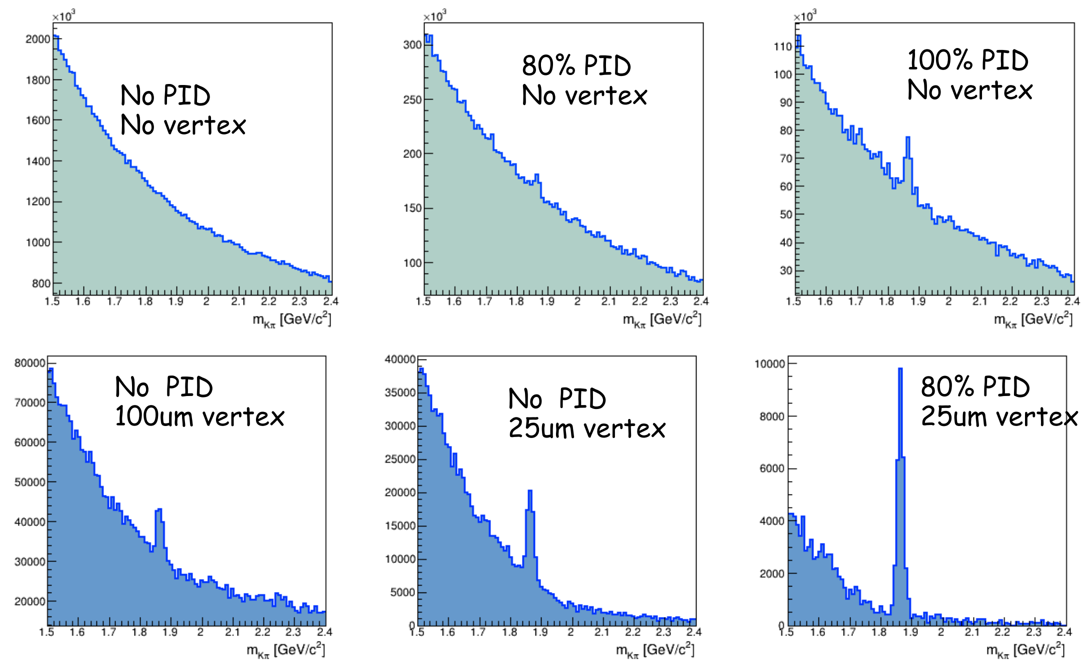




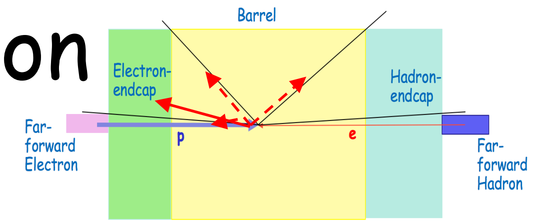


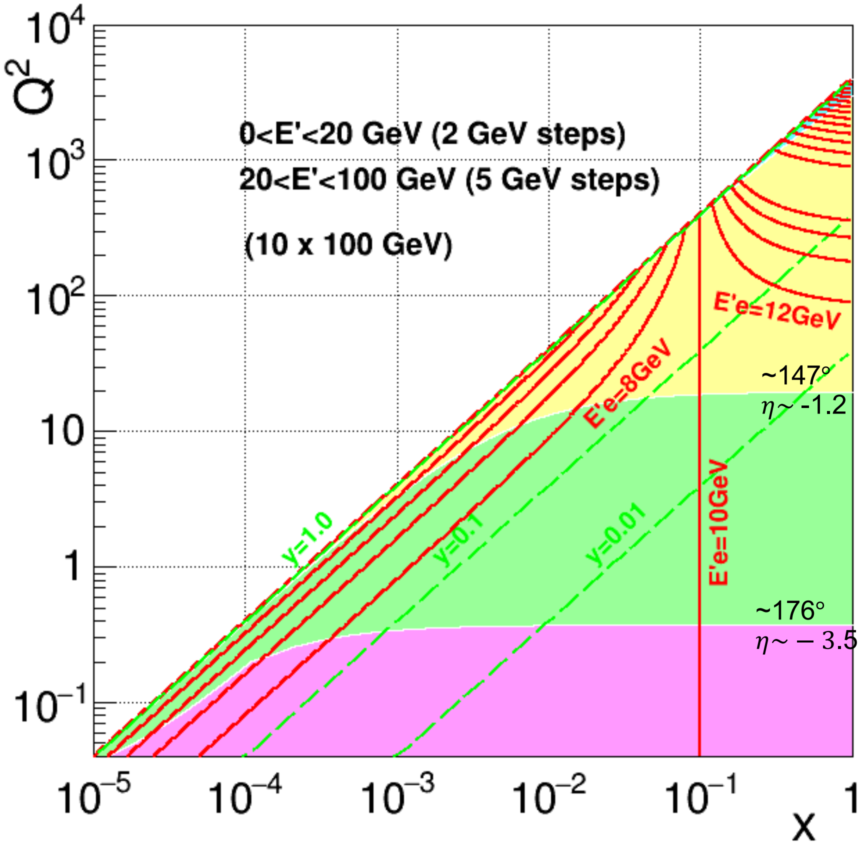
- Momentum
- Particle identification (PID)
- Vertex origin (high precision tracking and Vertex detector)

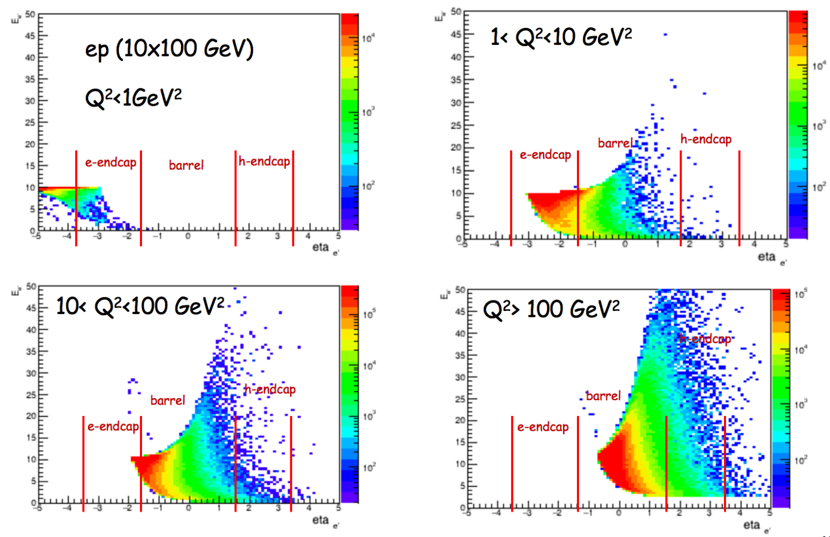
$D^0 \to \pi K$ mass spectrum
ep 10x100 GeV



Event kinematic: scattered electron







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

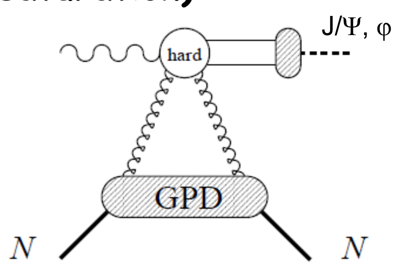
$$y_{\mathrm{EM}} = 1 - \frac{E_{e'}}{2E_e}\left(1-\cos\theta_{e'}\right),$$

$$x = \frac{Q^2}{4E_e E_{\mathrm{ion}}}\frac{1}{y}$$

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

Electron identification (e/hadron separation)

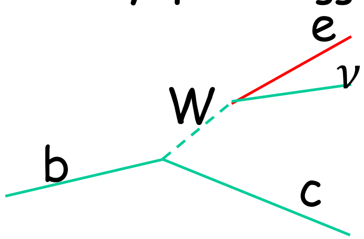
- GPD and Coherent Exclusive Diffraction (saturation)



Br ($J/\psi \to e^+e^-$) ~6%

Br ($J/\psi \to \mu^+\mu^-$) ~6%

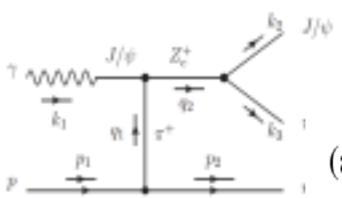
- Heavy quark tagging



Br ($D^{\pm} \to e+X$) ~16%

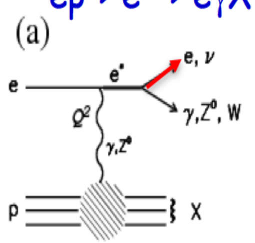
Br ($B^{\pm} \to e+\nu+X_c$) ~10%

- Exotic spectroscopy

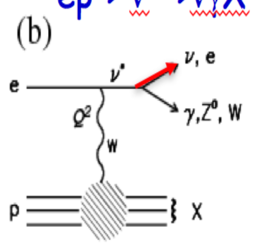


- Other BSM physics

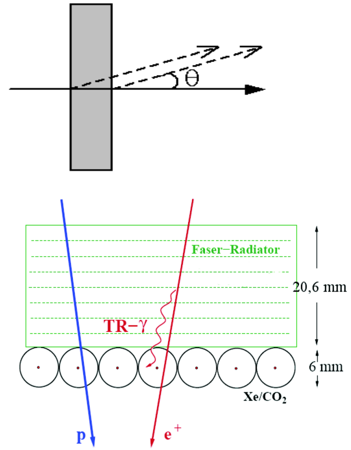
ep-> e*-> eγX

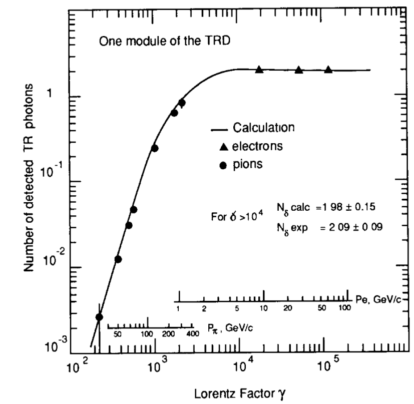


ep-> ν*->νγX



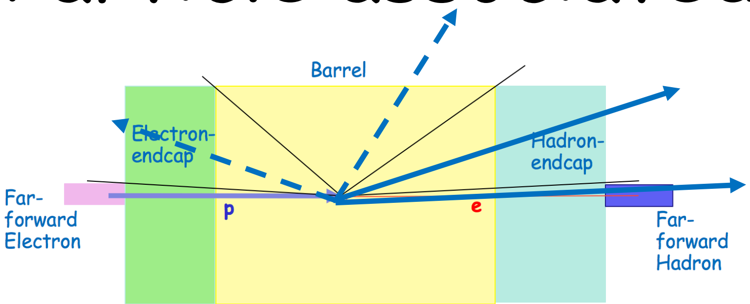
Transition radiation



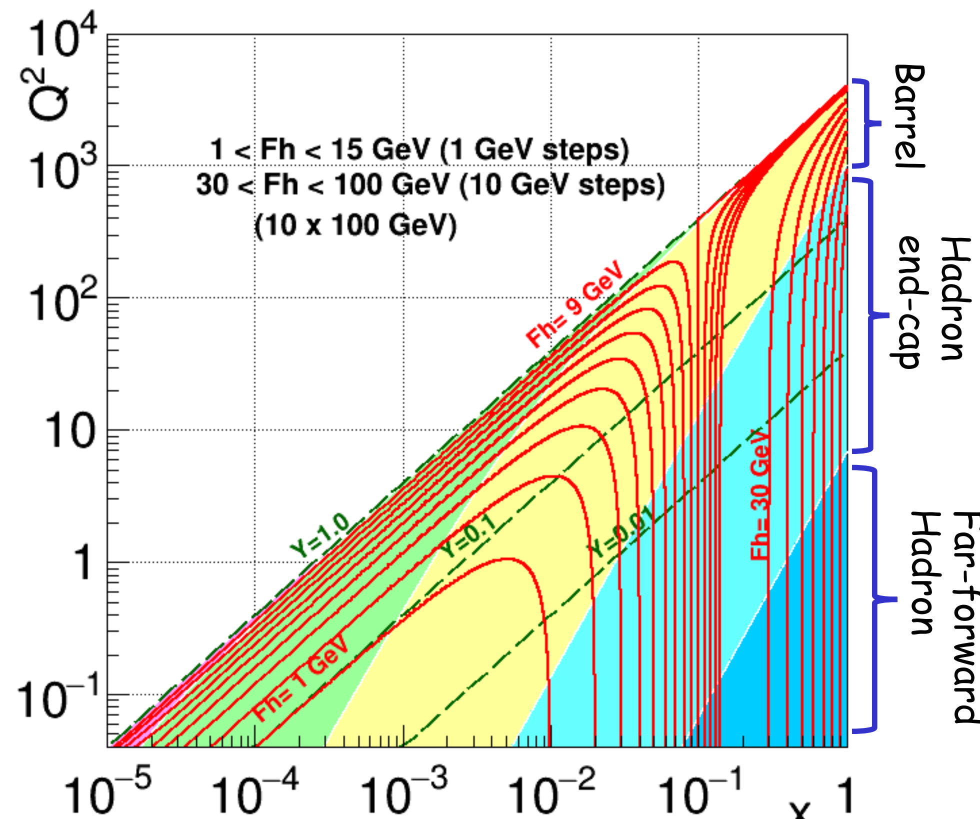


- Provides e/π separation 1-100GeV
- It is a tracking device (could be combined with tracker)
- Provides also dE/dx high precision (heavy gas), could also work in a cluster counting mode.
- Depending on configuration provides additional e/π rejection 10-100
- GEM/TRD detector R&D is ongoing

Particle associated with struck quark



Isolines of the struck quark Energy



All other methods of kinematic reconstruction require measurements of hadronic final states (particles associated with struck quark)

Double angle method

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

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

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

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

Sigma method:

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

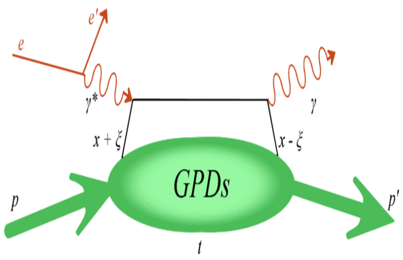
$$Q^2_{e\Sigma} = \frac{(E_{e'} \sin\theta_{e'})^2}{1-y}.$$

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

- Electron endcap : mostly low energy <10GeV
- Hadron end-cap and Far-forward hadron : high energy > 50GeV
- Hadron energy measurements at high-x refers to measurements of x

EM Calorimeter

Electrons:
-scattered electron
-secondary electrons (decay products (J/ψ))
Gammas:
-DVCS process
azimuthal asymmetry



- ✓ 4π coverage for EM calorimeter
- ✓ High performance EM calorimeter is need in the electron endcap where scattered electron **has low energy**
- ✓ **High granularity** in the forward going direction: high background from $\pi^0 \to \gamma\gamma$
- ✓ very good **e-identification and e/π rejection**

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

$PbWO_4$ Crystal EM Calorimeter (at small angles, electron endcap)

-Tungsten glass, similar to CMS or PANDA
- Time resolution: <2 ns
- Energy resolution: <2%/√E(GeV) + 1%
- Cluster threshold: 10 MeV

Sampling EM Calorimeter

- **Shashlyk** (scintillators +absorber)

-WLS fibers for readout
-**Sci-fiber EM(SPACAL):**

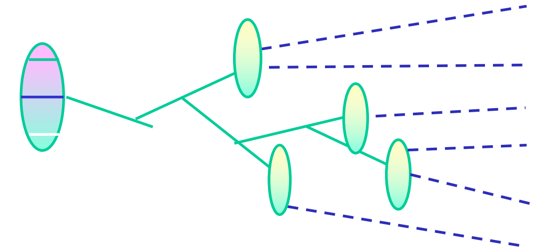
- Compact W-scifi calorimeter, developed at UCLA
- Spacing 1 mm center-to-center
- Resolution ~12%/√E
- On-going EIC R&D

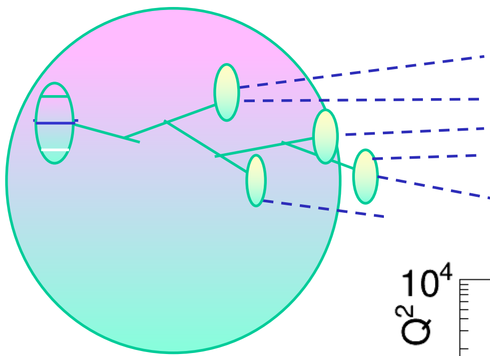
Jets and neutral hadrons (n,K^0_L)

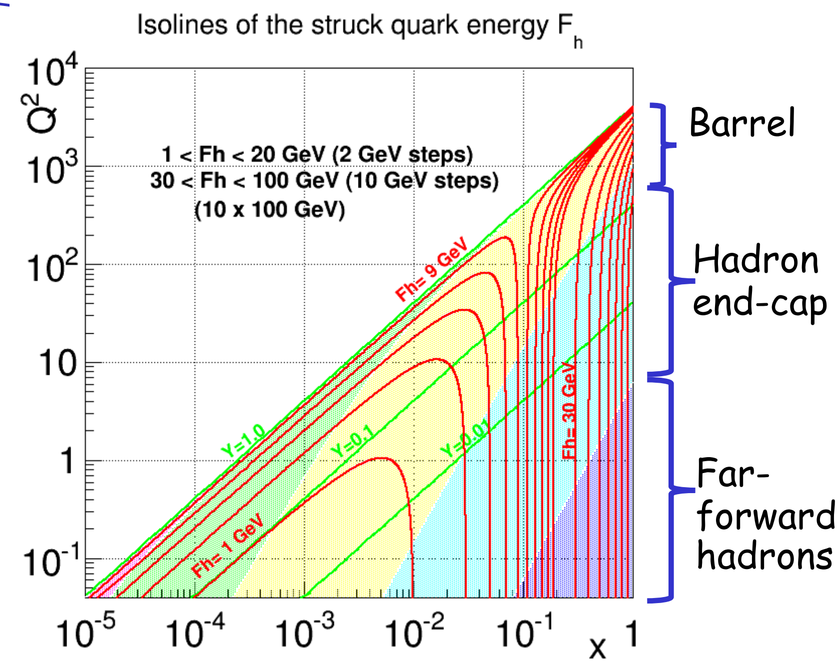
1) **Jets evolution and dynamics** (jet == struck quark)

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

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

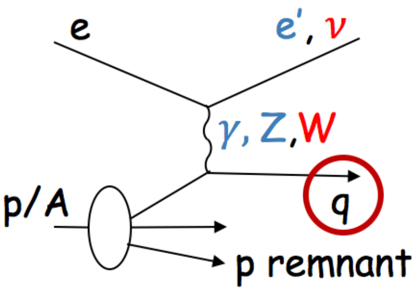






- 4π coverage for HCAL is required for CC DIS!
- High resolution calorimeter (energy measurements)
- High granularity to study subjet structure

Charged Current DIS

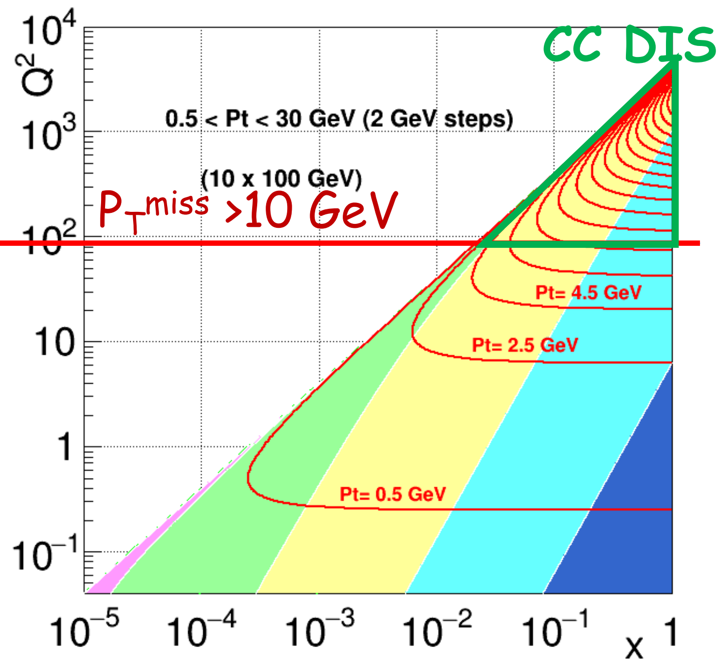


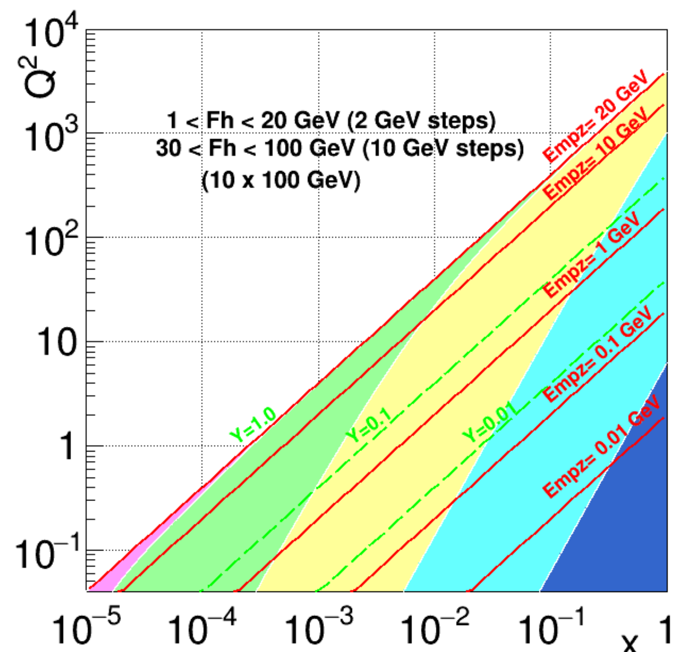
DIS kinematic will be reconstructed from hadronic final state only

d) Jacquet –Blondel method

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

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





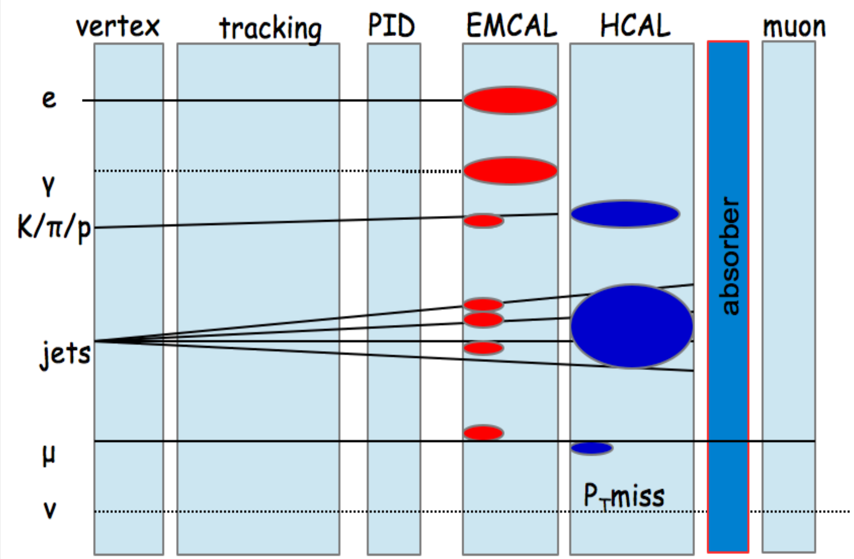
Note: poor resolution compare to other methods, but
this is the only method for Charged Current DIS events!!!

Yulia Furletova

Particles associated with a struck quark

Limited number of “stable” final state particles:

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



Methods for PID (mass difference):

-dE/dx: (p<1GeV)
-Time-of-Flight: (p<3-6GeV)
-Cherenkov radiation: p < 5 (50) GeV)
-Transition radiation: (e/h separation)
1 < p < 100GeV

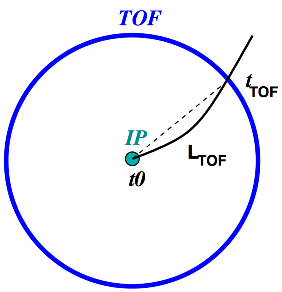
Energy Loss Measurements dE/dx

No extra detector required:
use information from tracking/vertex detectors

- Limitation : p<1GeV
- Could be used for higher momentum due to he relativistic rise of the Bethe-Bloch curves
- Depending on available electronics a **cluster counting** method could be used to improve momentum coverage

Individual hadrons (π, K, p)

Time-of-flight (psTOF)

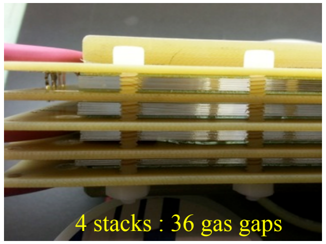


- **Limit in space** (barrel) => PID momentum limitation => could be improved by high precision timing measurements <10psec
- Radial space needed: ~10cm.

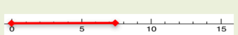
- **t0: self-determined =>** need to know a **vertex origination** to **measure L_TOF** precise (total particle length/curvature)

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

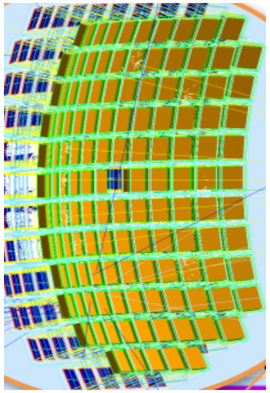
Barrel (1m) for 20ps (10ps):
π/K < 2.5 (3.5) GeV,
K/p < 4.2 (6) GeV
End-caps (4m):
π/K < 5 (7.3) GeV,
K/p < 8.5 (12.5) GeV



Mickey Chiu

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

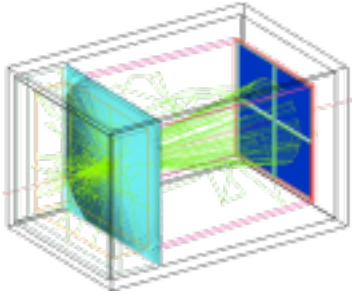
Electron end-cap: Modular RICH

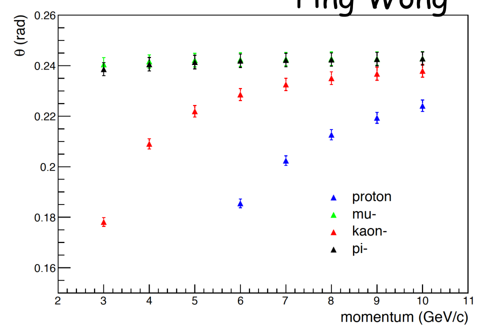


- Modular aerogel RICH: compact, using lens-based design to **reduce ring size and sensor plane area**

- Separation (3σ):
  0.56 GeV < e/π < 2 GeV ,
  0.56 (2.0) GeV < π/K < 8 (10) GeV,
  2.0 (3.8) GeV < K/p < 12 GeV

Ping Wong





Hadron blind detector (HBD)

- Threshold cherenkov detector for e/π separation
- Limited momentum coverage