Electron-Ion Collider

(Machine & Detectors – An Overview)

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IFJ PAN
EIC PL UG Seminar
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WASHINGTON, D.C. – Today (Jan. 9, 2020), the **U.S. Department of Energy (DOE)** selected Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

Design and construction of an EIC was recommended by the National Research Council of the National Academies of Science, noting that such a facility "would maintain U.S. leadership in nuclear physics" and "help to maintain scientific leadership more broadly." Plans for an EIC were also endorsed by the federal Nuclear Science Advisory Committee.

Secretary Brouillette approved Critical Decision-0, "Approve Mission Need," for the EIC on Dec. 19,2019.

"The Department is excited to be moving forward with an Electron Ion Collider at BNL," stated Office of Science Director Dr. Chris Fall. "**However, participation from many parts of the DOE laboratory complex will be essential if the EIC is to be a success.**"
Thomas Jefferson National Accelerator Facility in Newport News, VA will be a major partner in realizing the EIC, and several other DOE laboratories are expected to contribute to EIC construction and to the groundbreaking nuclear physics research program that will be accomplished there.

The EIC will be a game-changing resource for the international nuclear physics community. American researchers have benefited from DOE participation in international collaborations such as CERN and the international community is currently contributing to our construction of the Long Baseline Neutrino Facility and the Deep Underground Neutrino Experiment.
DOE looks forward to conversations with our international partners about contributions to the EIC effort.

Funding for the EIC is subject to annual appropriations by Congress.

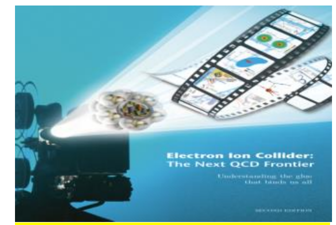
The Electron Ion Collider

A microscope to investigate QCD at various scales, energies and colour field stregths

For e-N collisions at the EIC:

- **Polarised beams**: e (~80%), p, d/^{3}He (~70%) flexible polarisation patterns (all possible) use of snakes and spin rotators
- e beam 5-10(20) GeV
- **Variable √s**: 20-100 (140) GeV
- **Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}**
  100-1000 times HERA!

Nucleon spin,
TMDs – confined q & g motion,
GPDs – confined spatial correlations

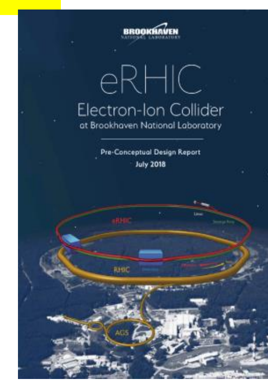


1212.1701.v3
A. Accardi et al.
Eur. Phy. J. A, 52 9(2016)

For e-A collisions at the EIC:

- **Wide range of nuclei (d→Pb)**
- **Polarised light ions (d and ^{3}He)**
- Variable centre of mass energy
- Luminosity/nucleon same as e-p

Low x, saturation,
High g density (nlQCD),
Hadronisation,
Energy losses,
Nucl. struc. fun.



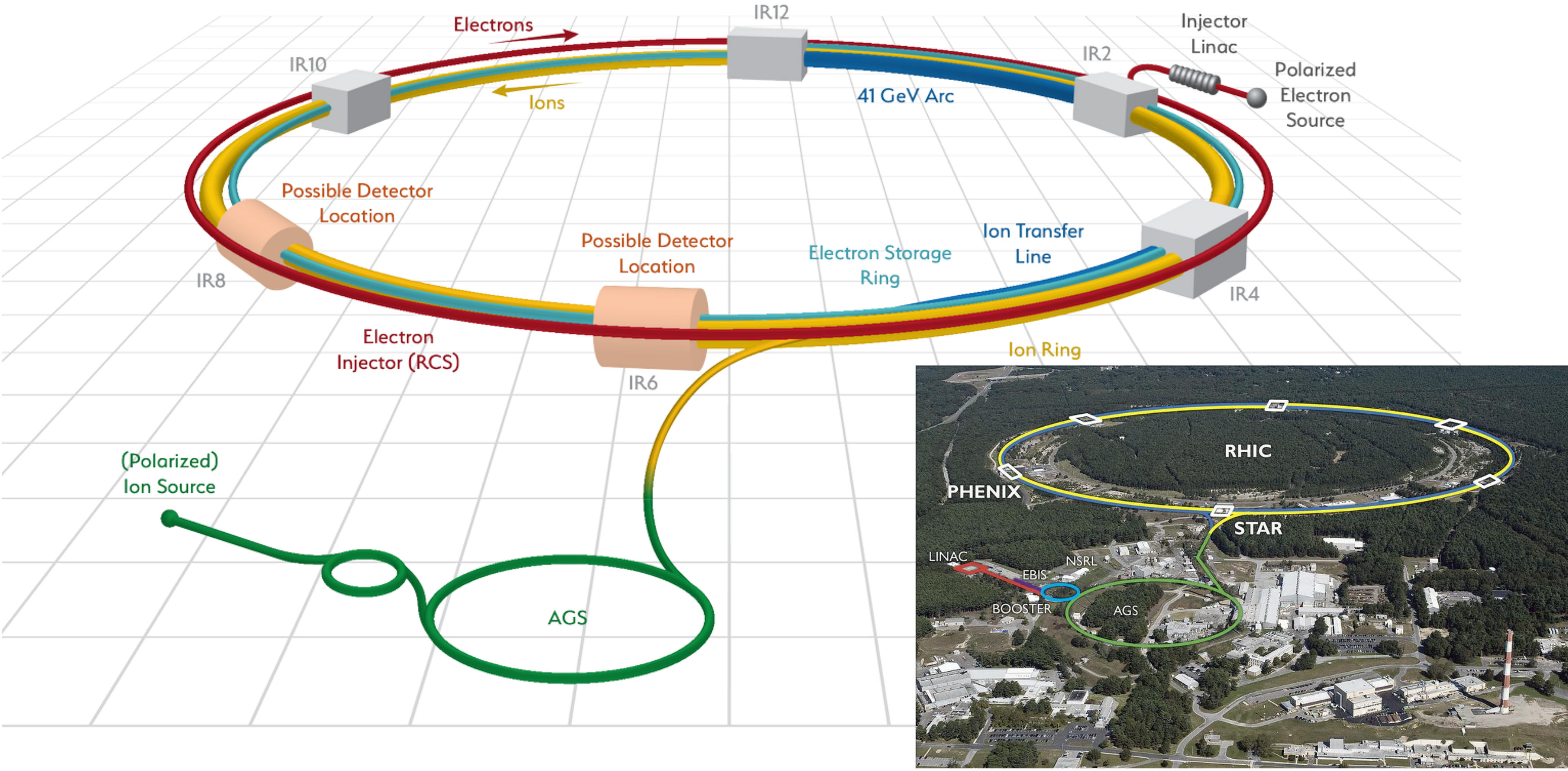
World's first polarised electron-proton/ligh ion **(work on heavy ion polarised beams has been started)**
and
electron-nucleus collider

The Electron Ion Collider

Cook's receipe for the EIC

- Take one of the RHIC rings (yellow) to become the EIC hadrong ring
- Modify it to match the EIC specification
- To lower emittance and IBS use the electron cooling
- Add a lepton storage ring (in the same tunel, cost effective)
- Use a spin-transparent rapid-cycling synchrotron as a full-energy polarized electron injector for rapid bunch replacement to counteract depolarisation
- Build a high luminosity interaction region that fulfills acceptance requirements

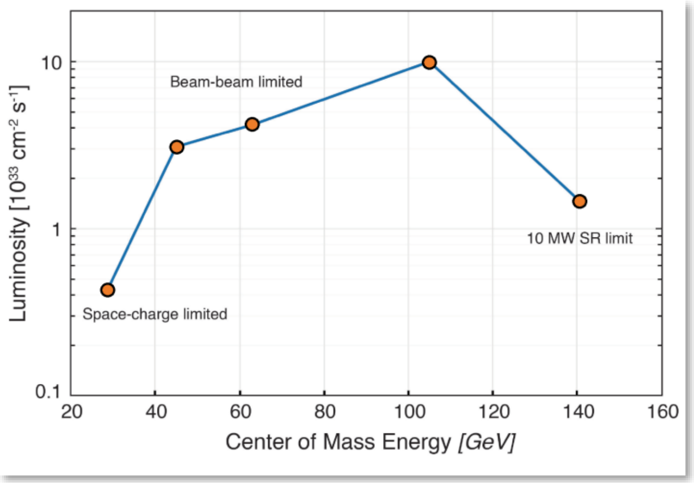
Resulting layout



RHIC tunnel will host also the lepton ring – cost effective solution

Highest Luminosity Parameters

	proton	electron
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} hor./vert. [nm]	9.6/1.5	20.0/1.2
$\beta^*_{x,y}$ [cm]	90/4	43/5
b.-b. param. hor./vert.	0.014/0.007	0.073/0.100
σ_s [cm]	6	2
$\sigma_{\mathrm{d}p/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} long./transv. [h]	3.4/2.0	N/A
L [$10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	10.05	

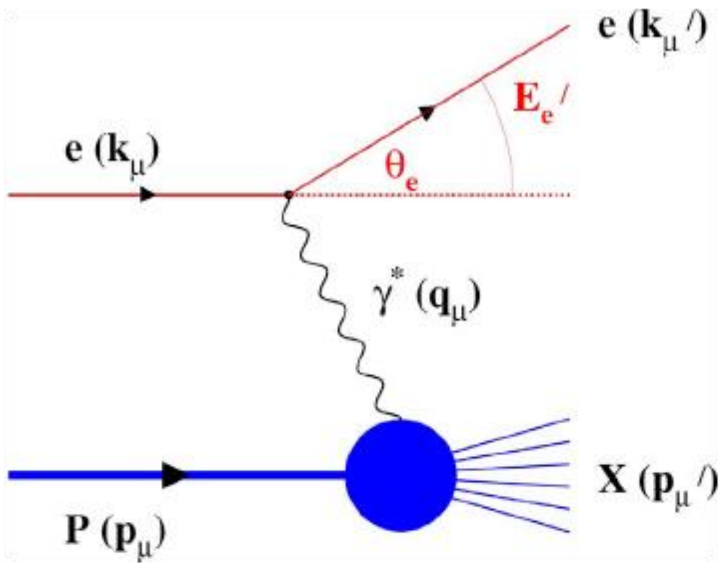


- **Hadron beam**:
  - resembles RHIC, however smaller vertical emittance and ~10 times more bunches
  - requires strong hadron cooling or frequent beam injection (2 h IBS growth time)
- **Electron beam**:
  - Spin up and down bunches stored simultaneously (physics programme)
  - Polarisation via Sokolov-Ternov effective only anti-parallel to the main dipole (limit: 92.4%)
  - Inject bunches with required polarisation pattern(s) at full collision energy
  - Frequent replacement of the beam to escape S-T influence and spin diffusion

Machine parameters optimised for high instantaneous luminosity at high energy
Alternative optimisation schemes are possible e.g. high lumi at low energy

How and what do we measure?

Deep Inelastic Scattering delivers precision and control – study the matter structure with a pin



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

Resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Inelasticity

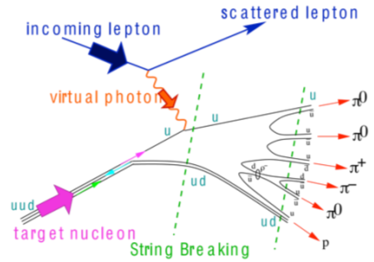
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Momentum fraction of a struck quark

Hadron :

$$z = \frac{E_h}{\nu}; p_t$$

With respect to the exchanged photon



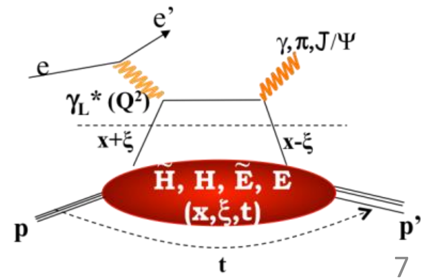
Measurement types:

Inclusive events: e+p/A → e'+X

Semi-inclusive events: e+p/A→e'+h(π, K, p, jet)+X

Exclusive events: e+p/A→e'+p'/A'+h(π, K, p, jet)

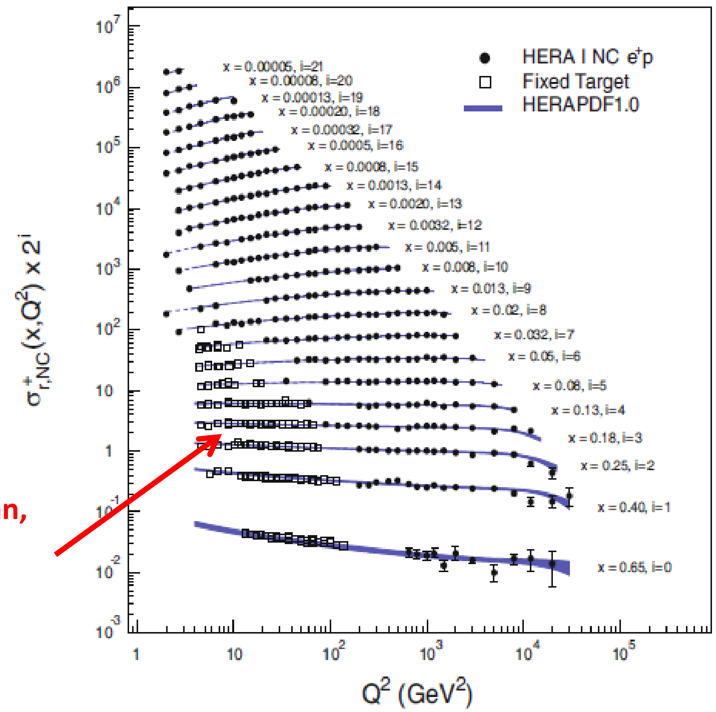
Whole final state is recorded!



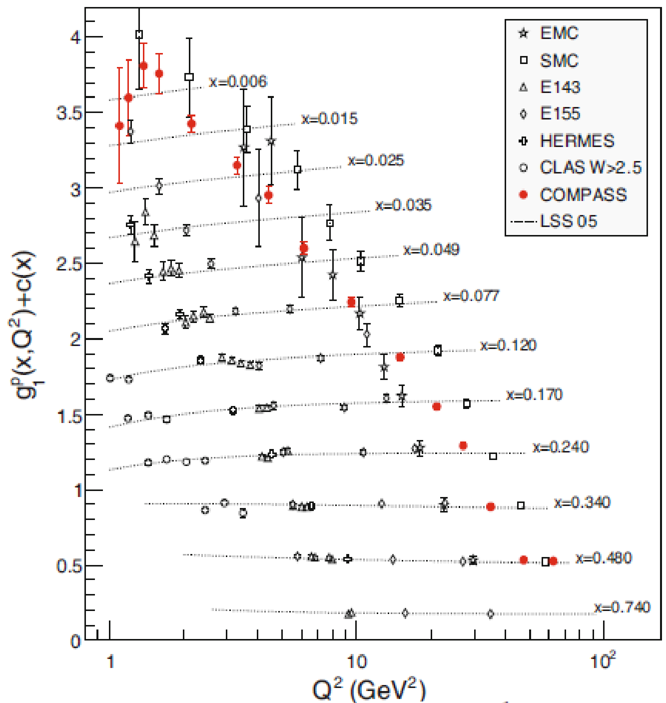
DIS Legacy

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

$$\frac{1}{2}\left[\frac{d^2\sigma^{\leftrightarrows}}{dx\,dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4}y(2-y)g_1(x,Q^2)$$



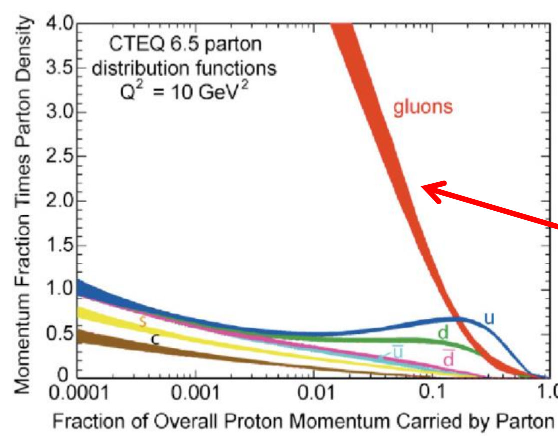
Friedman,
Kendall,
Taylor



$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

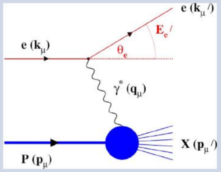
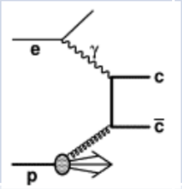
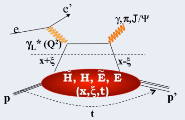
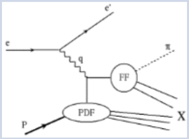
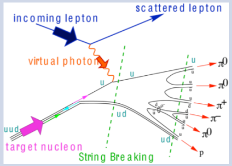
$$F_2(x,Q^2) = x\sum e_q^2\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$\sigma_r = \left(\frac{d^2\sigma}{dx\,dQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]}$$
$$= F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

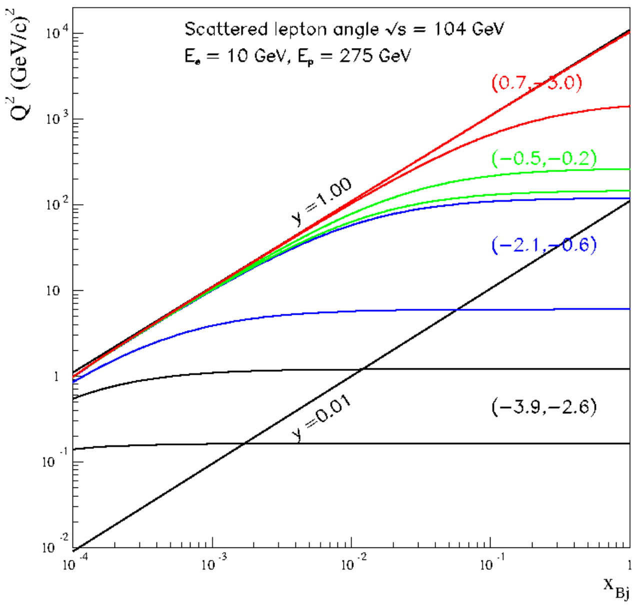


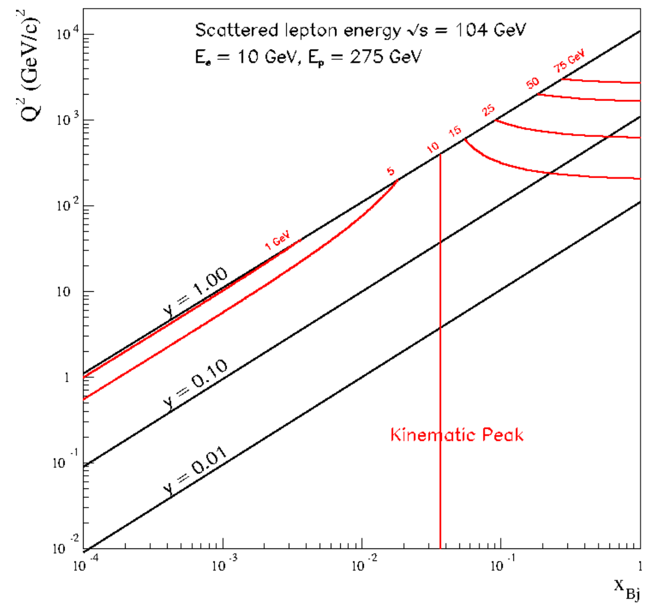
At HERA xG(x) behaviour was a surprise
(not the only one)

Measurements to be performed

Physics goal	Process/Meas. type	Experimental challenges
Structure functions F_2, F_L	Inclusive scattering 	Electron measurement (id, E, polar angle) Hadron system, Background rejection, Luminosity precision
Spin structure functions	Inclusive scattering	**Polarisation**, π/K separation
Gluon density	Heavy quark production, Di-jets 	Secondary vertices, π/K/p separation Jet measurement
GPDs	DVCS 	Forward proton, e, γ meas. Background rejection, Exclusivity
TMDs	Semi-inclusive DIS  	π/K/p separation
Nuclear PDFs	Scattering off various nuclei d – U	Nuclear debris
…..		

Neutral Current DIS Kinematics – Lepton



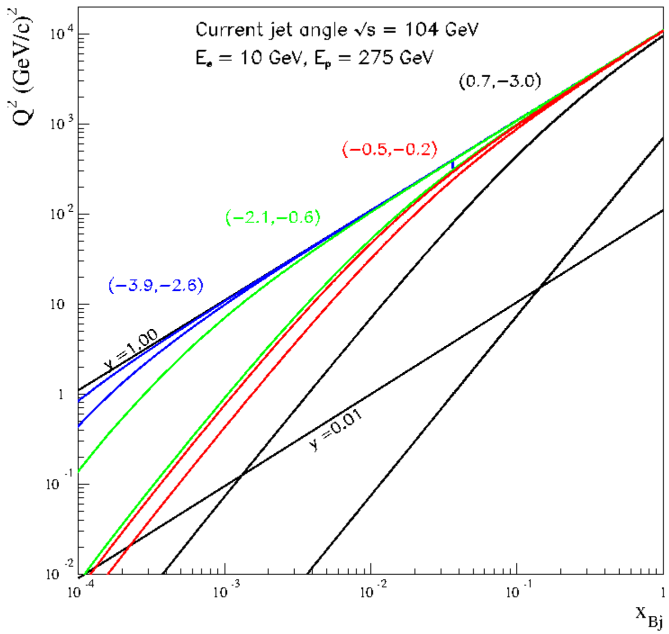


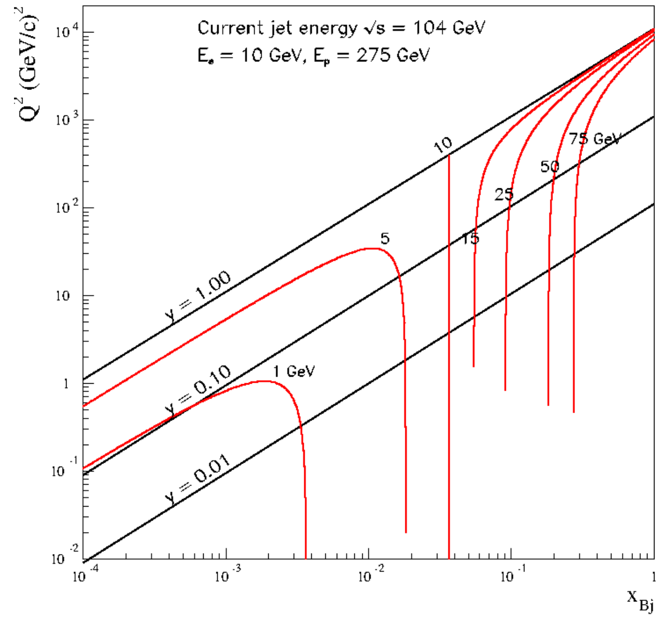
- Scattered electron angle well estimates Q^2
- Above the kinematic peak electron energy is poor at the y estimation

Needs that impact the experimental appratus:

- **Precise measurement of the scattered electron in large η range (large coverage)**
- **Good electron ID**

Neutral Current DIS Kinematics – Quark





At smalll y the jet energy well is a good estimator of x_{Bj}

Precise measurement of the hadron jet is requested -- experimental implications

Kinematics reconstruction using:

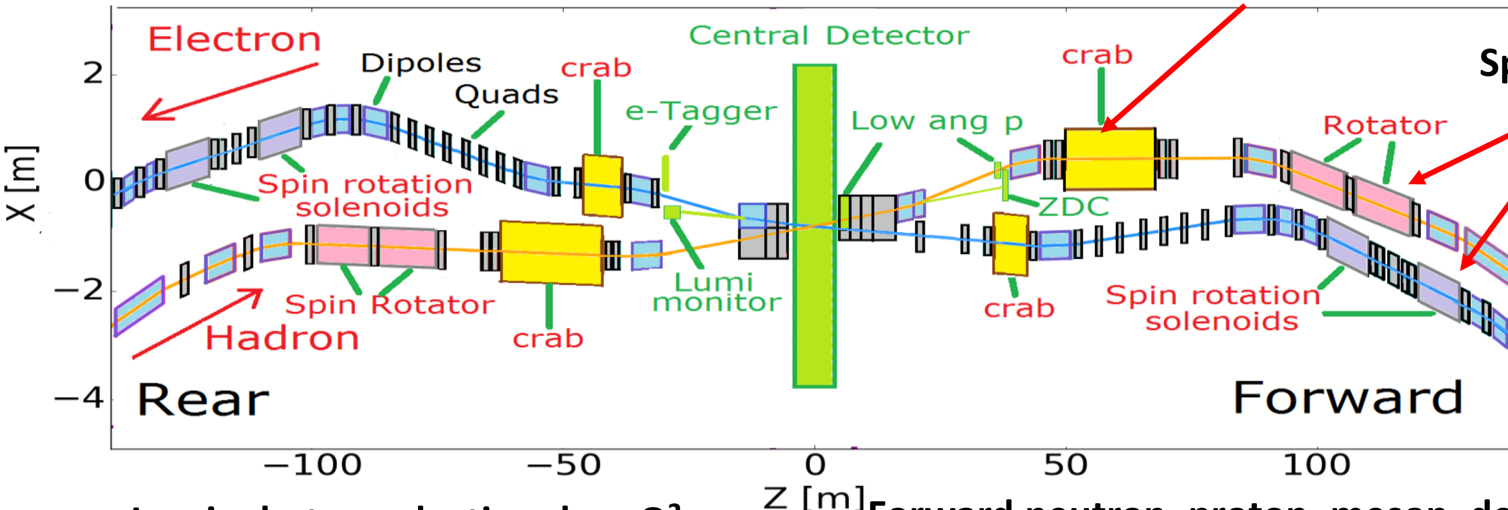
- Jacquet-Blondel: system of hadrons
- Double Angle: combining electron and hadrons
- Electron

Detector(s)

A complicated Iteraction Region structure

Maximise luminosity

Spin physics



Lumi, photoproduction, low-Q^2

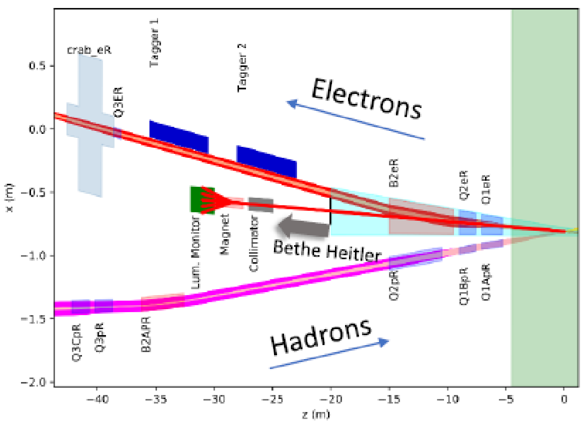
Forward neutron, proton, meson, debris

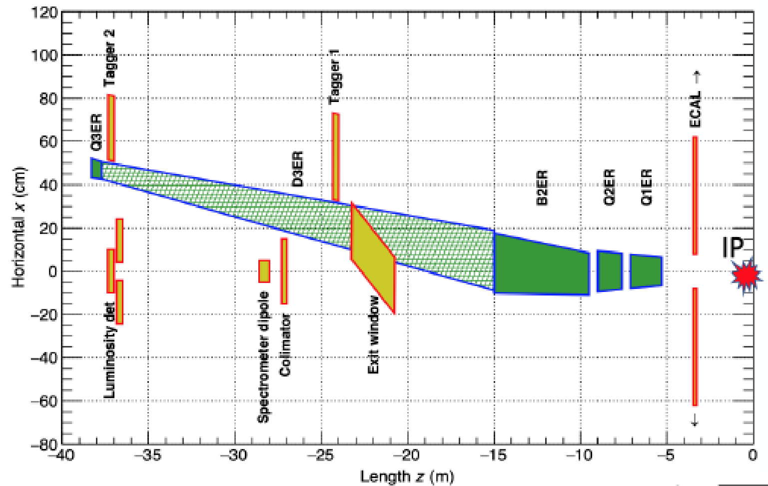
Central detector

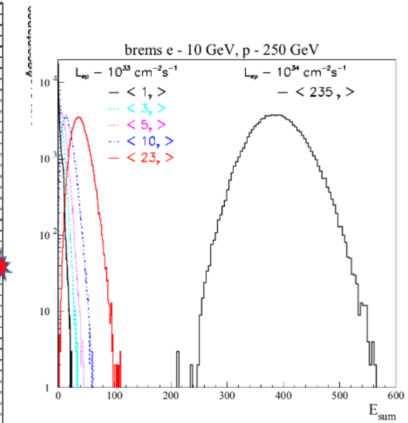
- +/- 4.5 m space at the Interaction Point to accomodate central detector
- Total crossing angle of 25 mrad (centred on the lepton beam, fan out synch. rad.)
- Transverse momentum acceptance down to 200 MeV/c
- Peak magnetic fields below 6T (NbTi sufficient)
- Important issue of synchrotron radiation of 2.5 A electron beam (E_C ~45 keV)

Lepton hemisphere

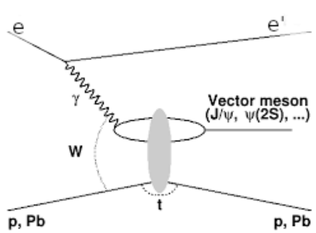
- **Luminosity/lepton beam diagonostics**:
  - Use the Bethe-Heitler (bremsstrahlung) proces: (un)converted photons, Z^2 enhancement for A-beam, energy, position



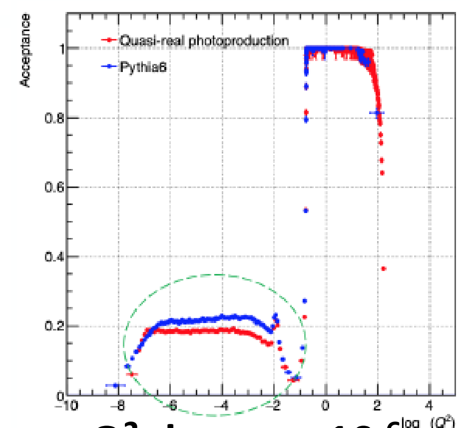




- Synchrotron radiation monitor



- **Photoproduction/low-Q^2**:
  - Lepton tagging: impact position (trajectory), energy

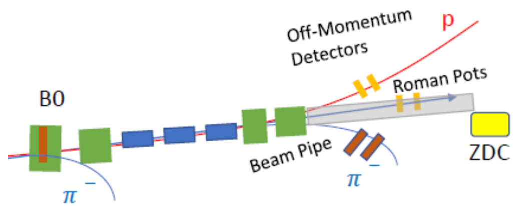


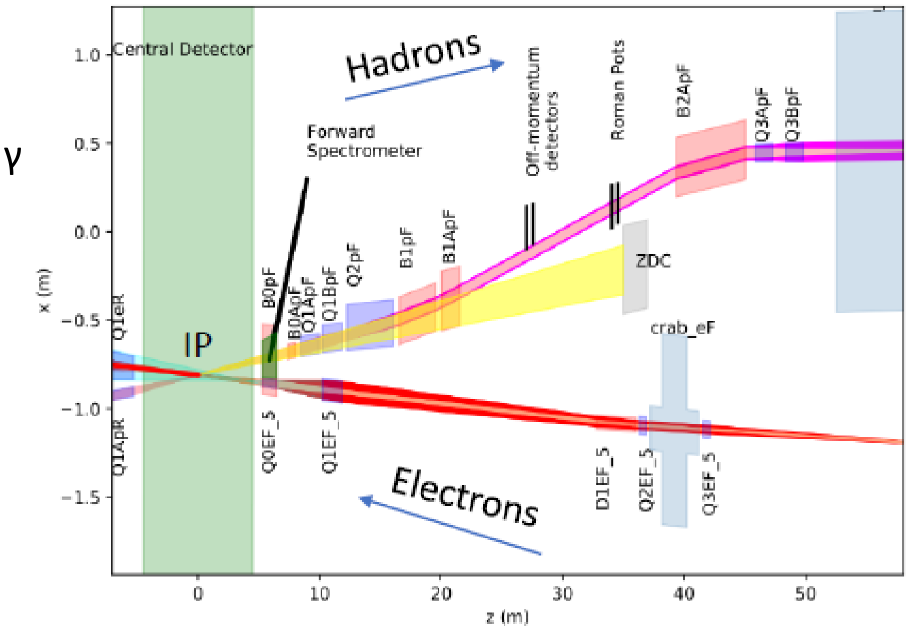
Q^2 down to 10^{-6}

Hadron hemisphere

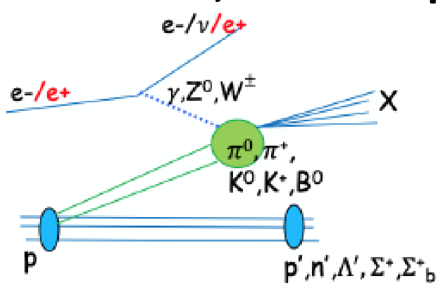
- **Far Forward Detectors**:
  - Zero Degree Calorimeter (ZDC): forward n, γ
  - Roman Pots: forward p, mesons, debris

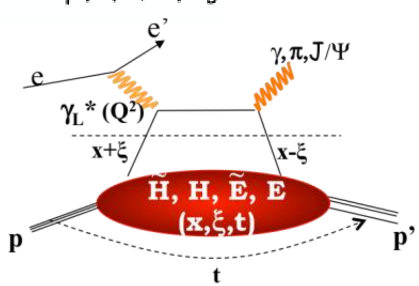
  e p → e’ + Λ (p,π^-) + X



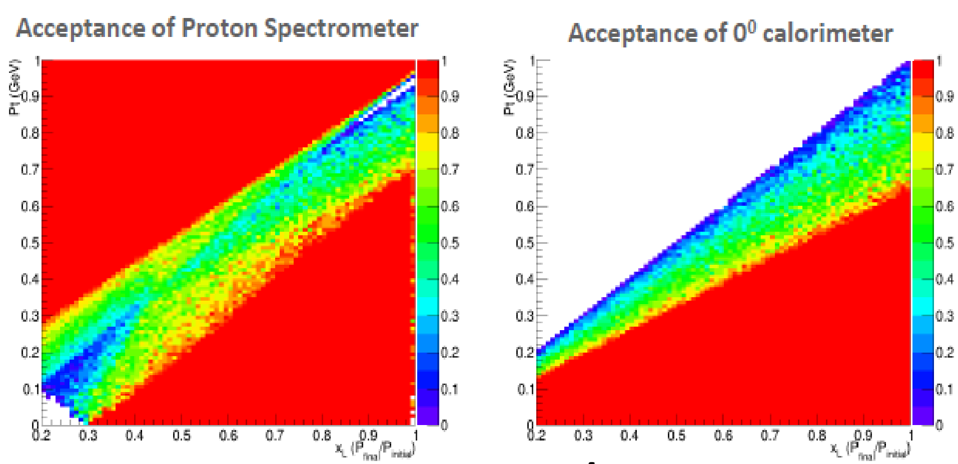


- **Diffraction, exclusive processes, DVCS, …**





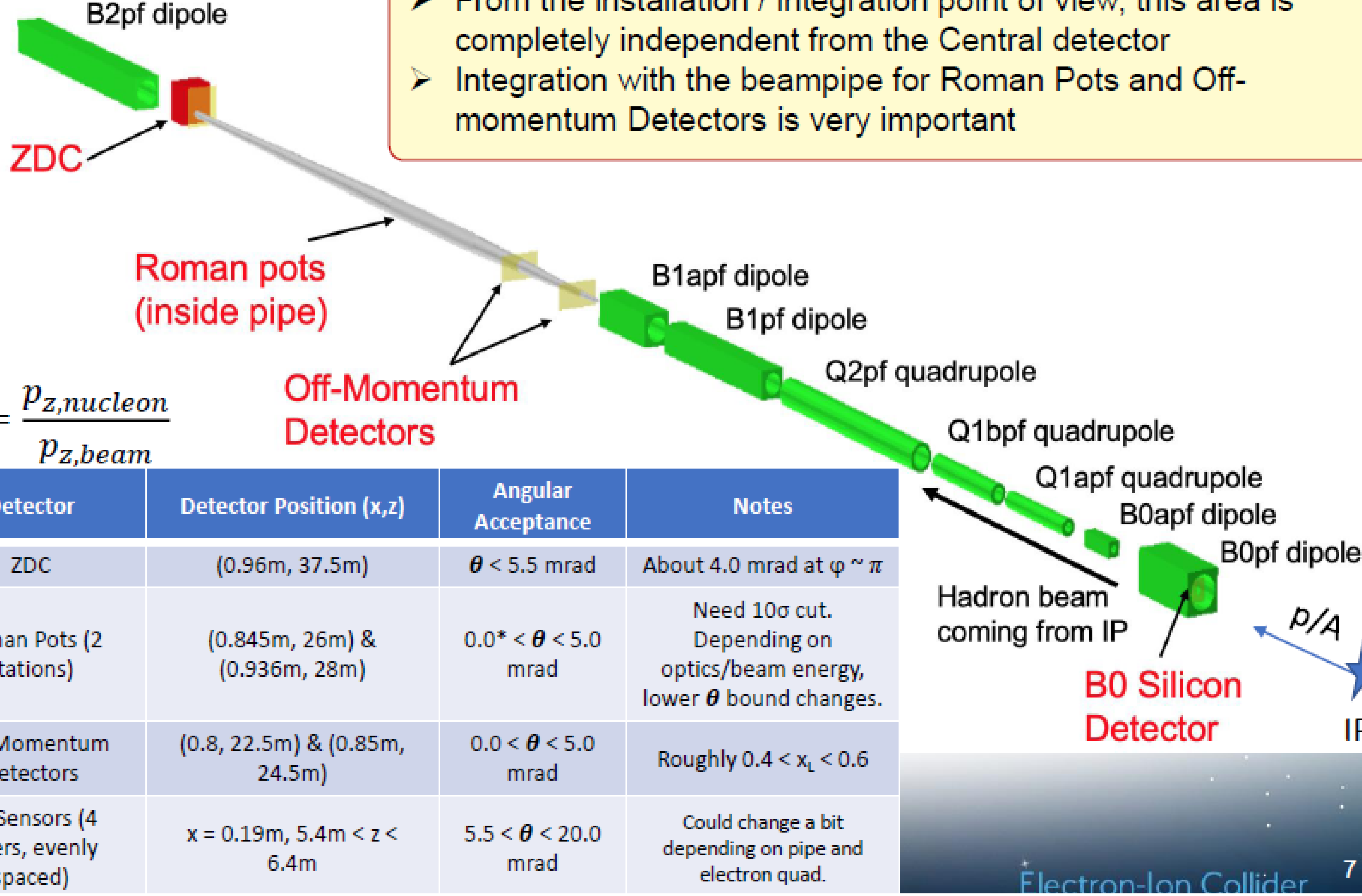
p_T



$x_L = p_{final}/p_{initial}$

Far forward (hadron going) region

- From the installation / integration point of view, this area is completely independent from the Central detector
- Integration with the beampipe for Roman Pots and Off-momentum Detectors is very important

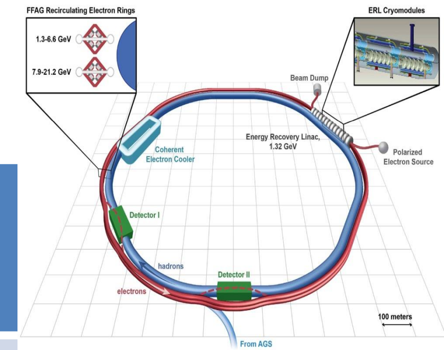


$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

Detector	Detector Position (x,z)	Angular Acceptance	Notes
ZDC	(0.96m, 37.5m)	$\theta < 5.5$ mrad	About 4.0 mrad at $\varphi \sim \pi$
Roman Pots (2 stations)	(0.845m, 26m) & (0.936m, 28m)	$0.0^* < \theta < 5.0$ mrad	Need 10σ cut. Depending on optics/beam energy, lower θ bound changes.
Off-Momentum Detectors	(0.8, 22.5m) & (0.85m, 24.5m)	$0.0 < \theta < 5.0$ mrad	Roughly $0.4 < x_L < 0.6$
B0 Sensors (4 layers, evenly spaced)	x = 0.19m, 5.4m < z < 6.4m	$5.5 < \theta < 20.0$ mrad	Could change a bit depending on pipe and electron quad.

Coutersy of Y. Furletova, EIC 2020, Cockroft Meeting

Central Detector Requirements

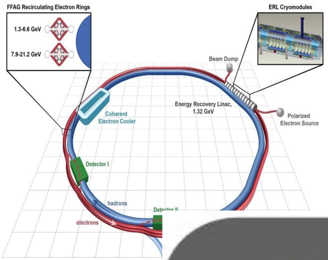


Tracking: Particle momentum+charge Event+secondary vertices	Central tracker+solenoid Vertex detector
Electron ID+measurement $\|\eta\|<4$, good energy resolution	Tracker+solenoid+calorimetry
Hadron jet measurement v. good energy resolution, kinematics	Tracker+solenoid+calorimetry
π/K/p separation (PID) Central for p<7 GeV/c Forwarf p<50GeV/c	Tracker+solenoid, forward dipole/toroidal B ToF, Cerenkov
Forward proton, meson/barion D=decay products	Si Pixels+Timing in Roman Pots
Forward neutron, gamma	ZDC
Muons?	Muon chambers

Which type?

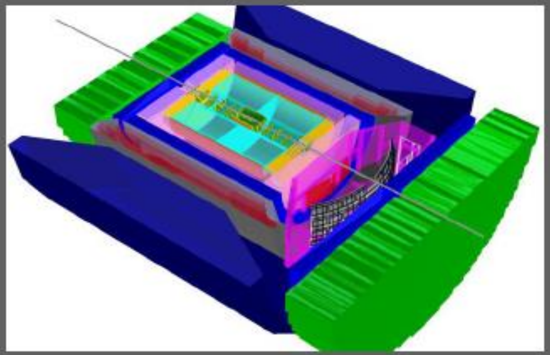
general purpose (ATLAS/CMS, ZEUS/H1) or a ``dedicated'' (LHCb) detector or a mixture
symmetric versus asymmetric? (H1 lessons @ HERA, impact on the solenoid)

In any case prepare a full acceptance detector!!!

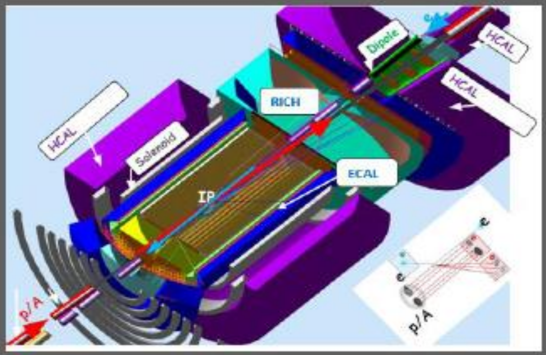


Current Concepts of the EIC Detector

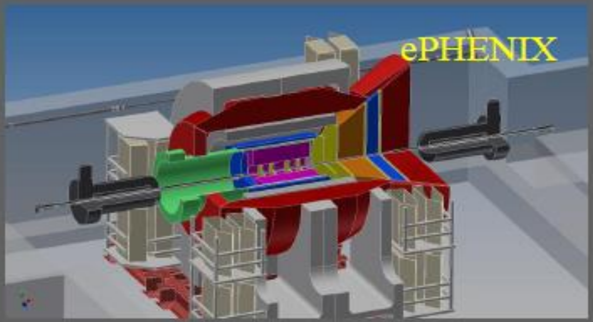
Brookhaven concept: BEAST



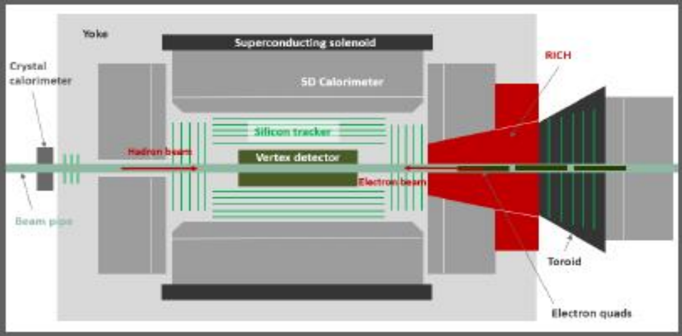
Jefferson lab concept: JLEIC



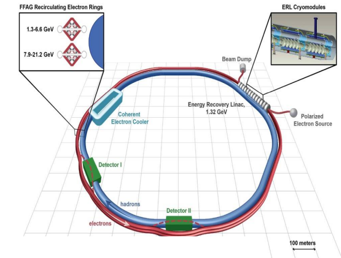
sPhenix → ePhenix

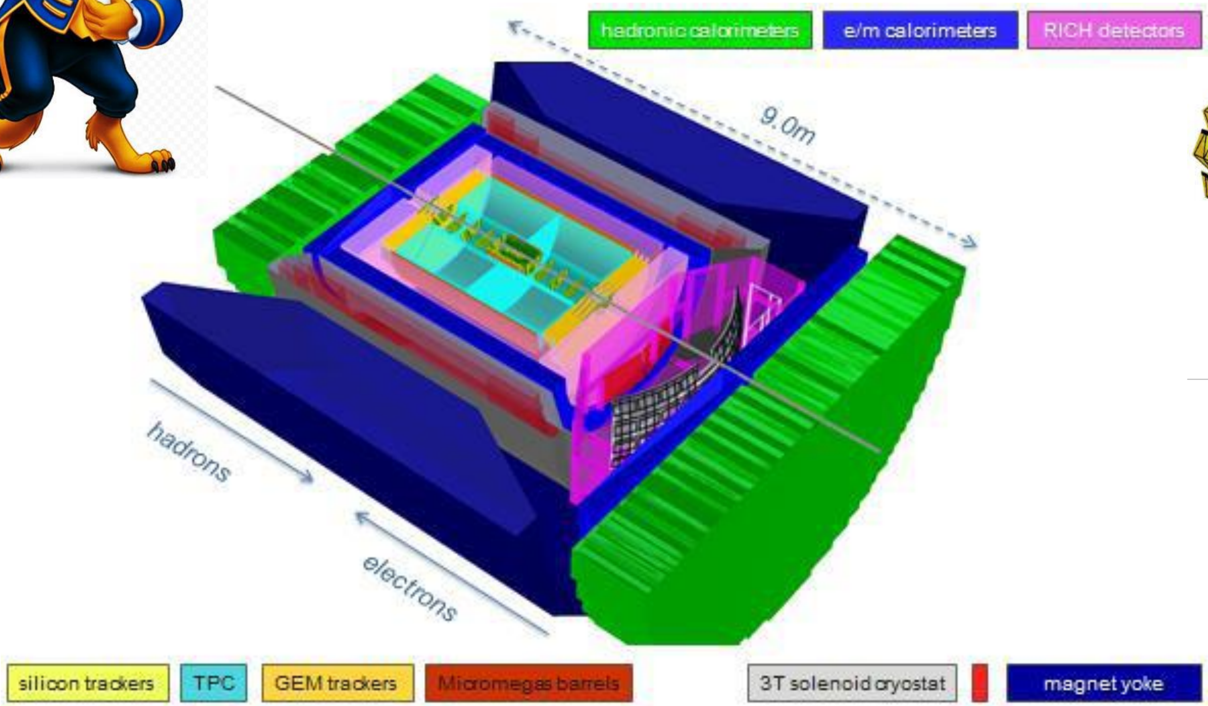


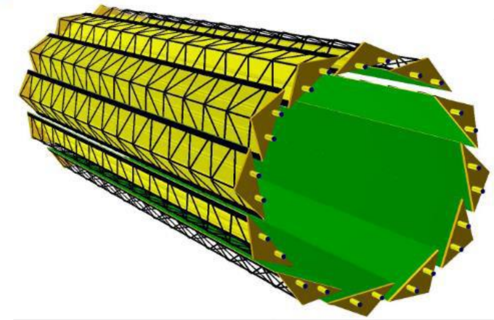
Argonne concept: TOPSiDE

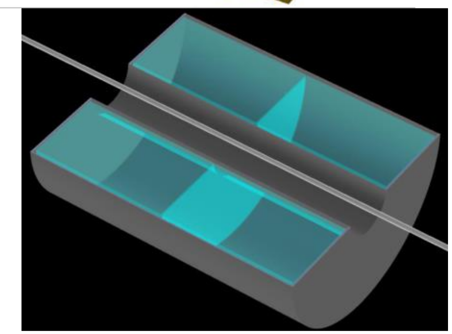


BEAST – Brookhaven eA Solenoidal Tracker









Si vertex: MAPS 20x20 μm^2 based; only binary hit info;4 layers in barrel 0.3% X_0 each, Endcap: 3 discs

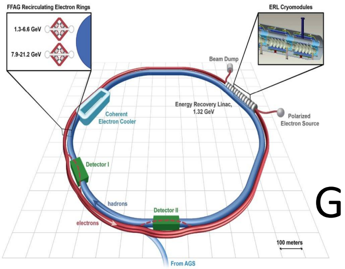
Central 2m long TOC; R:22.5-77.5 cm, ~6% X_0 (barrel) ~15% X_0 (endcap); GM readout, 5 mm pads, 50μm

+Micromegas inside and outside of the TPC – track seeding

EM CAL: η < -2: $PbWO_4$ ~2%/√E; barrel+forward (-2 < η <3.5) W powder+sc. fibres 7-10%/√E

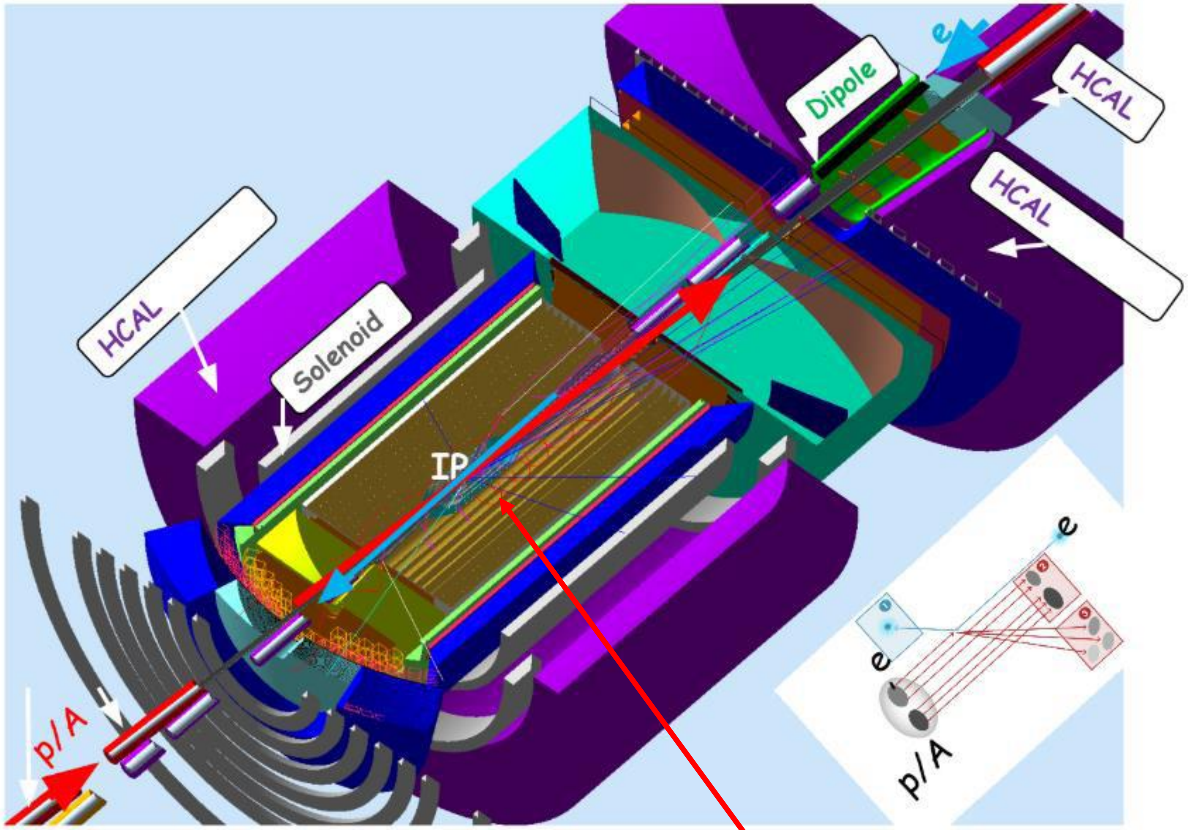
HAD CAL: only forward (meas. hadrons) and backward (e PID); Pb/Sc ~50 %/√E;
Lack in barrel: no need; precision? (EIC aims at the 1% level!; $E_{neutr.}$ Fluct., e ID, DA kinem., bckg reject.)

PID: p<1 GeV/c – dE/dx (tracker) or ToF (moderate resolution); 1<p<3-4 GeV/C – RICH Aerogel (n~1.05) in front of the CAL; 10<p<50 GeV/c Gas (~1m) RICH – practically only in forward direction



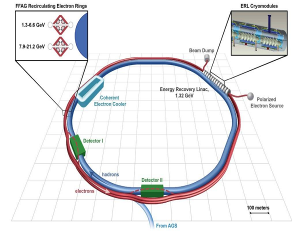
Jefferson Lab Detector: JLEIC

General purpose detector with emphasis on forward/backward detectors



- Similar to BEAST
- However. foresees **barrel HAD CAL**
- Uses **muon chambers**

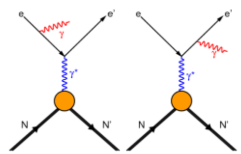
Central tracking – TPC?

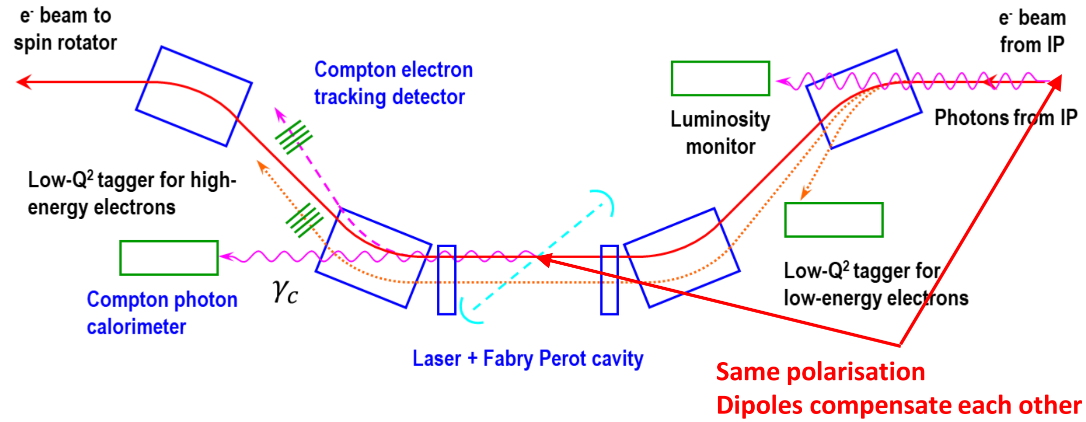


Jefferson Lab Detector: JLEIC – Forward/Backward

Electron direction:

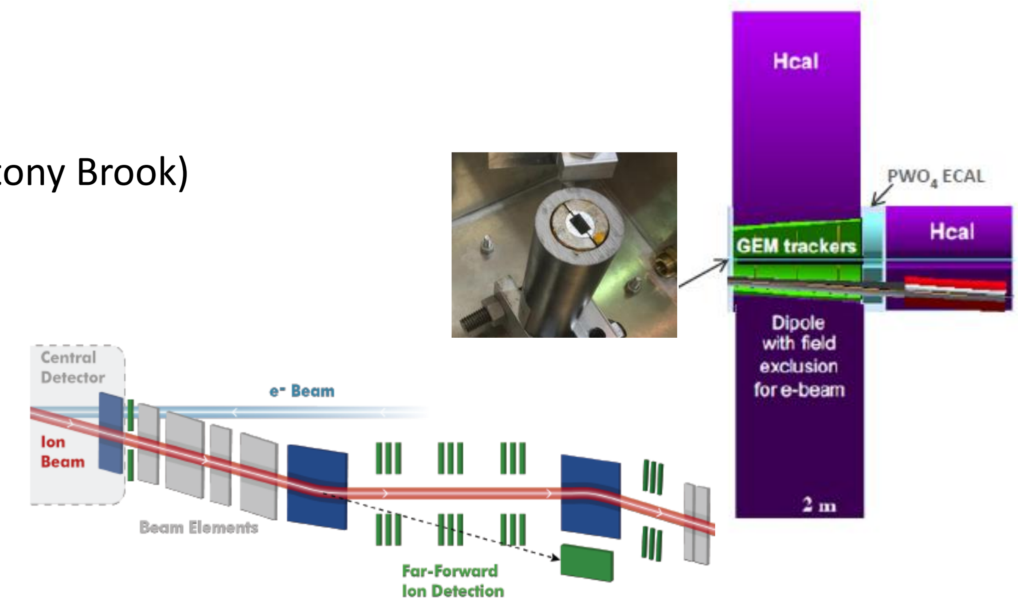
- **Lumi** via BH process
- **Low-Q^2 tagger** for e measurement
- **Polarisation**:
  Laser+Compton γ-cal+e-tracker

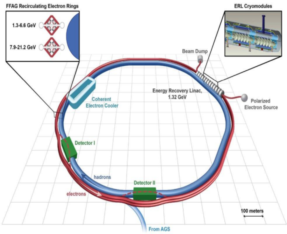




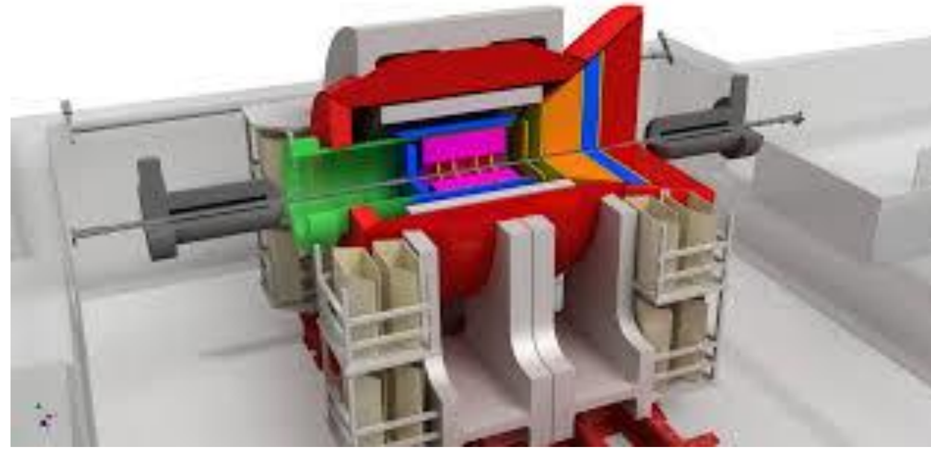
Proton/ion direction:

- **Dipole B:** cannot interfere with e-beam (Stony Brook)
- **Tracking:** GEM (inside the dipole B)
- **RPs:** acceptance ~100% for $x_L > 0.98$
- **ZDC:** large acceptance

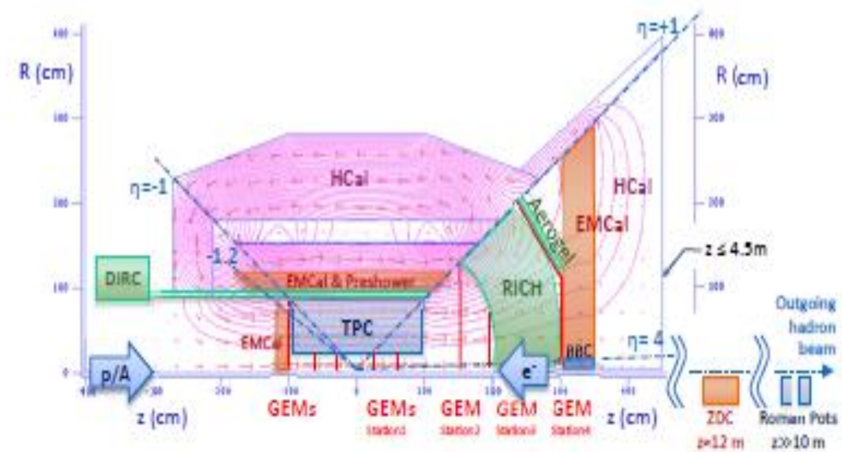




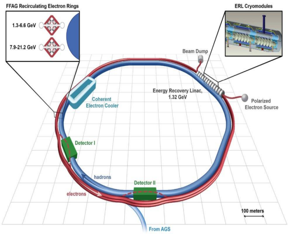
ePHENIX Detector



- PHENIX→sPHENIX→ePHENIX
- **SC 1.5 T BABAR solenoid**
- **Central:**
  - Compact TPC
  - RICH+DIRCs
    PID
  - EMCAL: W-fiber shashlik ~12%/√E
  - Barrel HCAL: Sc-steel ~100%/ √E
- **Forward:**
  - Crystal cals
  - RPs
  - ZDC



Could be ready for the D DAY!!!



Argonne TOPSiDE Detector

Timing Optimised Pid Silicon Detector for the EIC

Topside: "The upper part of a ship's side, above the waterline."

Although the TOPSIDE is one of the most visible parts, it isn't anywhere near the entirety of the ship!

XXIst century idea: get from a detector an event in a form of a list:

DIS event

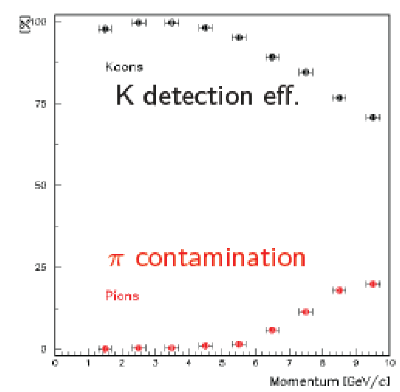
Particle ID	P_x	P_y	P_z
11 (e^-)	-0.743	-0.636	-4.842
321 (K^+)	0.125	0.798	6.618
-211 (π^-)	0.232	0.008	3.776
-211 (π^-)	0.151	-0.007	4.421
211 (π^+)	0.046	0.410	2.995
111 (π^0)	-0.093	0.048	1.498
2112 (p)	0.115	-0.337	31.029
211 (π^+)	0.258	0.145	6.336
310 (K_s^0)	0.385	-0.408	3.226

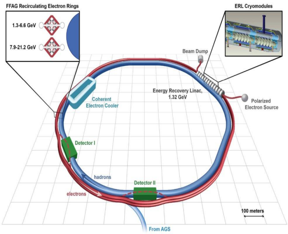
Symmetric central detector, $|\eta| < 3$, covers nearly 4π

Ultra-fast Si trackers and highly granular *Imaging CAL*

Full PID over $-5 < \eta < 3$

Dedicated PID detectors in the forward region

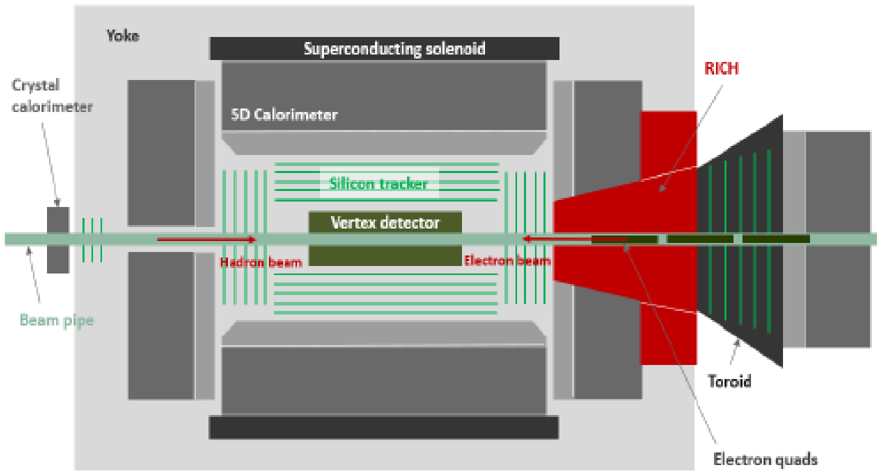




Argonne TOPSiDE Detector

TOPSiDE: The 5D Concept

Measure (E,x,y,z,t) for (every) hit in tracker + calorimeter



Silicon pixel vertex + **strip tracker**
Imaging em calorimeter
Imaging hadron calorimeter
Superconducting solenoid (3T)
Forward gaseous RICH
Forward dipole + cloak or toroid w/out cloak
Forward silicon disks
Forward calorimetry
Backward silicon disks
Backward crystal calorimeter

Particle identification (pion – kaon – proton separation)

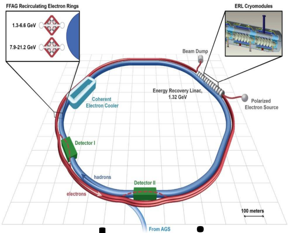
Particle momenta < 7 GeV/c for most of the solid angle from tracker + calorimeter
Requires **silicon sensors with time resolution of about 10 ps**

Best to date 18 ps for 35 μm thick Si

Eliminates

The need for preshower counters, TRDs, TOF or Čerenkov (in front of the calorimeter), muon chambers (in back of calorimeter)

J. Repond, @ 13th Int. Workshop on high-p_T physics in the RHIC/LHC Era,19-23/3/2019



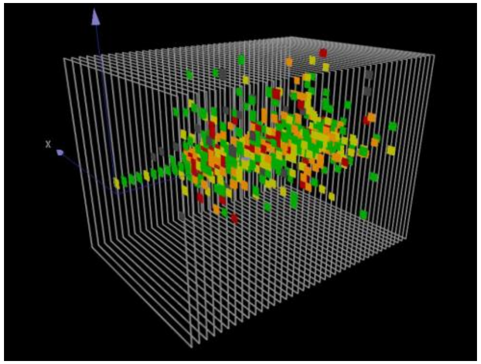
Argonne TOPSiDE Detector

Imaging calorimetry:

replace traditional towers structure with fine lateral and longitudinal granularity

go from O(10^5) to O(10^8) cells

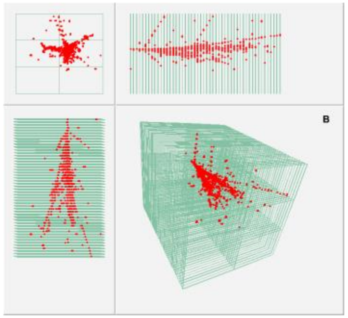
one may reduce resolution to few bits(1,2)/cell



Technologies:

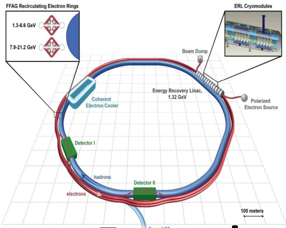
use large (O(1cm^2) pixels(Si), pads(Sc, GEM, Micormegas) or strips (Sc)

Review article by *F. Sefkov et al.,*
Experimental Tests of Particle Flow Calorimetry,
Rev. Mod. Phys. 88 (2016) 15003, arXiv: 1507.05893 [physics.ins-det]



PID: e, μ, hadrons - ``easy''
Muon system not necessary any longer

Software compensation for e/π
Leakage corrections: long. shower development + measurement of leaking charged particles
Use MIPS to monitor gain
Use Particle Flow Algorithms (PFA) to reconstruct the jet energy – improvement in resolution



Argonne TOPSiDE Detector

Example of the **EM imaging calorimetry**: **PENTACAL** – prototype 5D EM CAL

20 layers of W/Si

W has smallest Molière radius

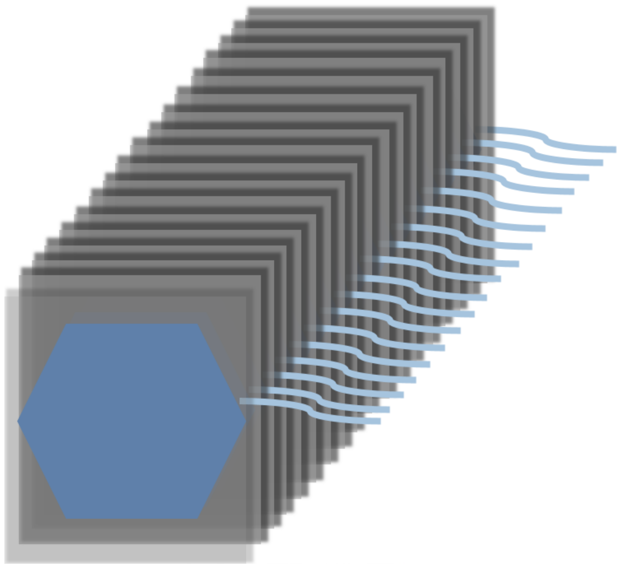
on output: coordinates (x,y,z), energy, precision time

Use 8” Si wafers:

area: ~324 cm^2

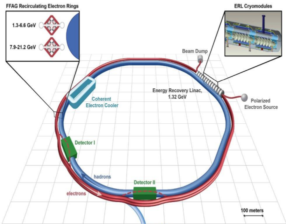
pixel: 1 mm^2 → ~32 400 channels/wafer

total numer of channels close 650 000



Interested parties:

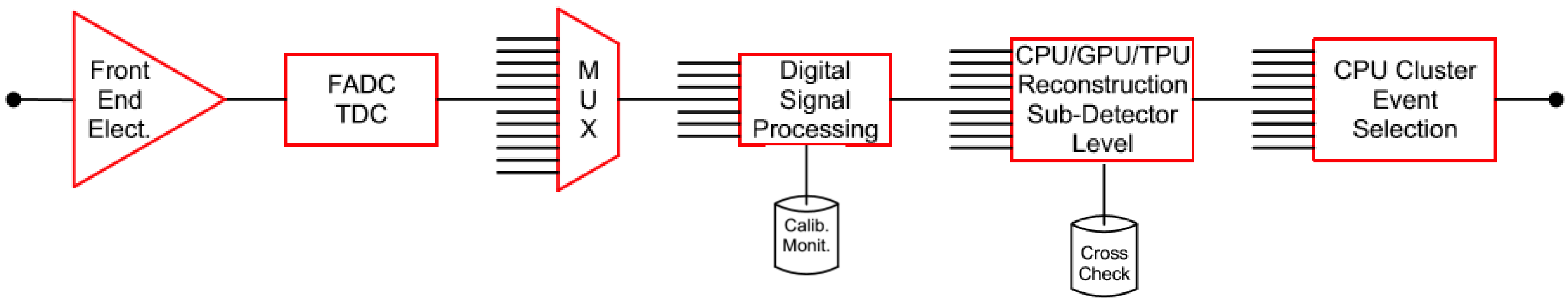
TOPSiDE, AMBER, JLAB, ...



EIC Detector Readout

Idea: **Go streaming**

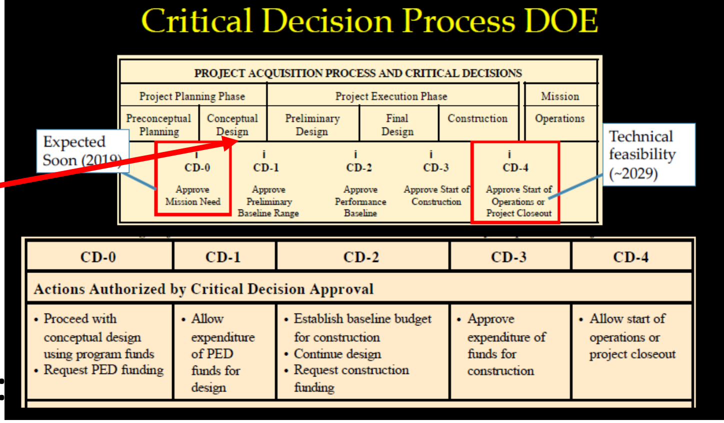
- **Event selection based on access to the full information from all detectors**:
  - without relying on hardware triggers
  - software controlled selection – adaptable algorithms
  - on-line calibration, aligment, monitoring, reconstruction



- **Upgraded LHCb: about 0.7 GB/s → disk**

Summary

- **The EIC will happen** some day



CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

We are somewhere here

- **EIC machine&physics implies challenges for a detector:**

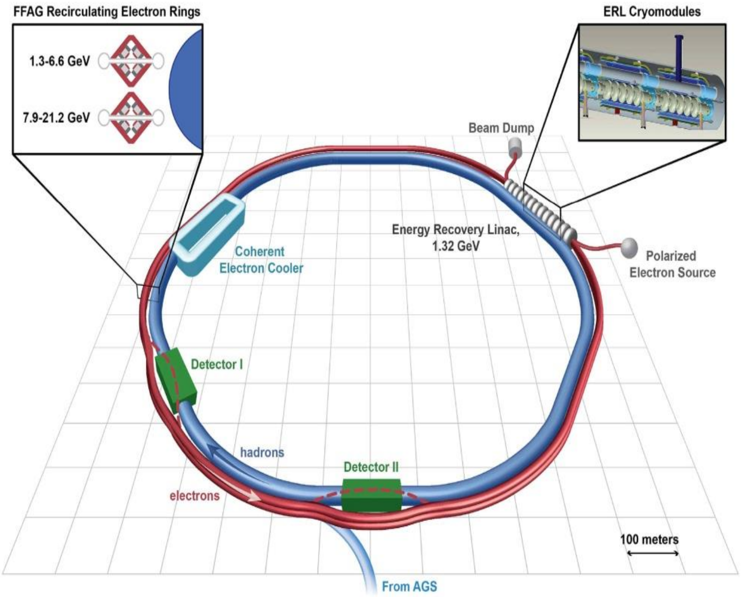
detection of forward p/n/mesons/debris
measurement of e scattered at low angles
measurement of the final state (nearly exclusive, 4π coverage)
extensive PID: π/K/p seperation over large solid angle
kinematic reconstruction of CC events

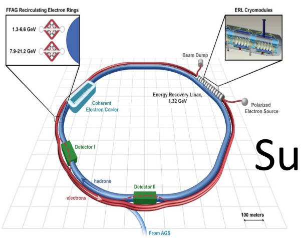
addressed by BEAST, sPHENIX, JLEIC, TOPSiDE

- **Include novel ideas**:

forward dipole with B-field masking (electron beam)
forward RICH
streaming readout
5D concept

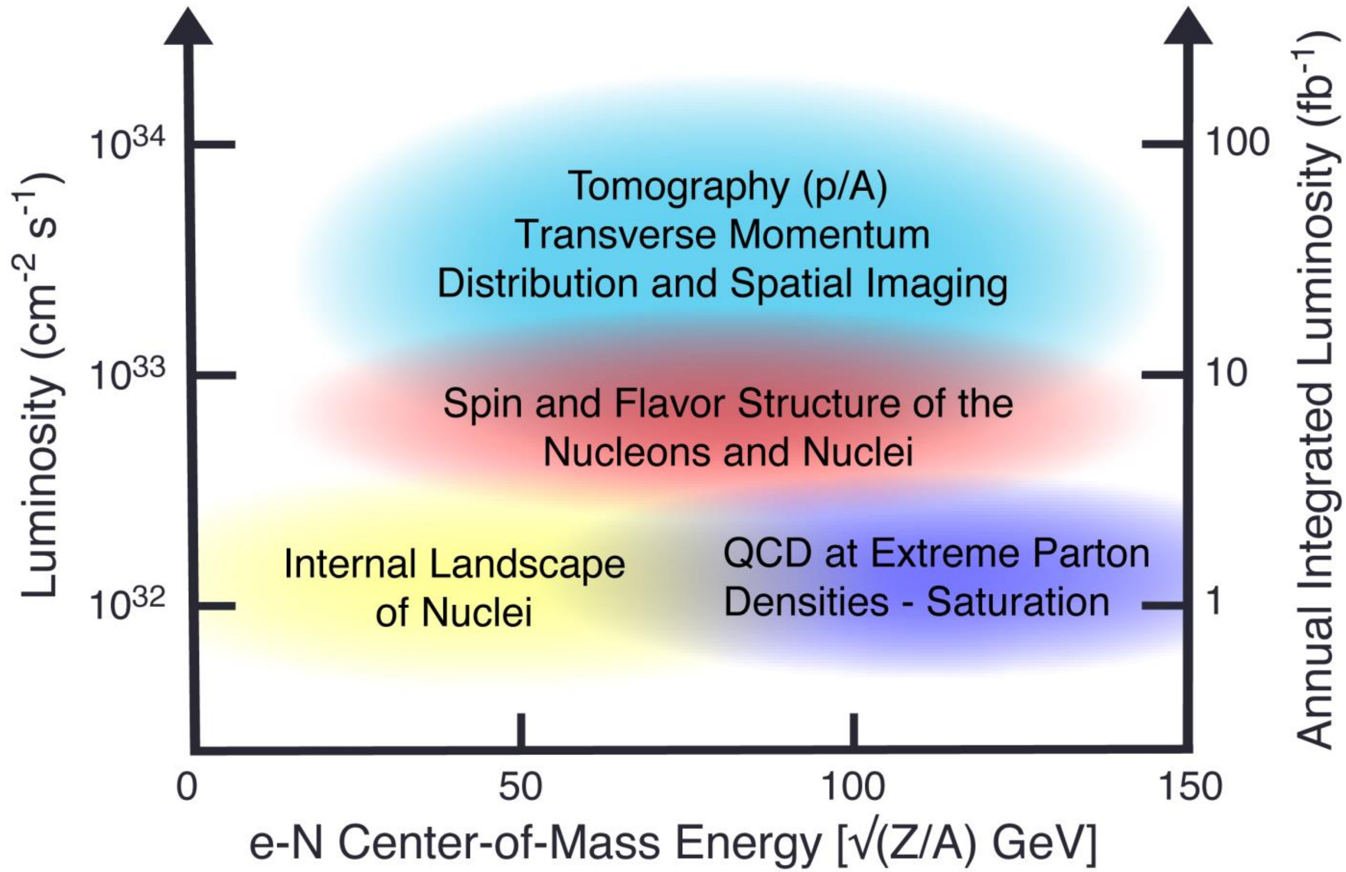
- **There is a place for a one(two) detector(s)**





Summary

Summary of EIC physics vs. CM energy vs. Luminosity vs. Integrated luminosity



Special thanks to W. Amstrong, A. Deshpande Y. Furletova, Ch. Montag, J. Repond from whom I took some materials