EIC Physics & Experimental Equipment

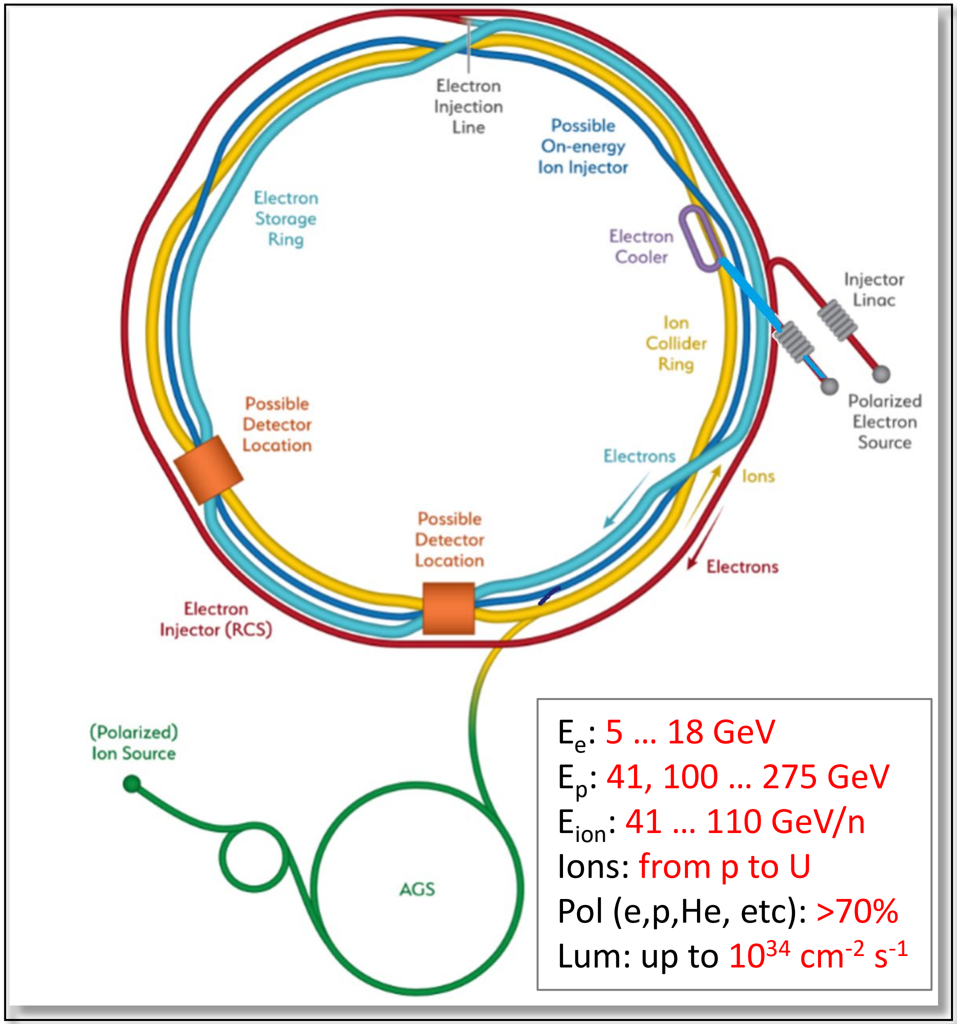
Tanja Horn

Credits: Material by the EICUG Yellow Report Initiative, Physics WG & Detector WG

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab

National Academy of Science Report: AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE:



"An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:

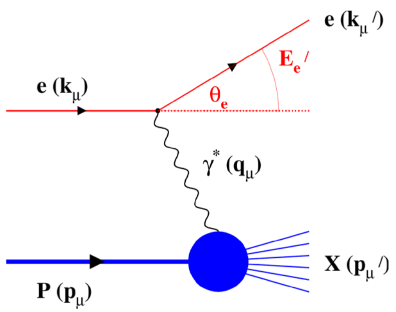
- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?"**

THE CATHOLIC UNIVERSITY OF AMERICA Jefferson Lab

Overview EIC Physics and Measurements

machine & detector requirements →

Parton Distributions in nucleons and nuclei | QCD at Extreme Parton Densities - Saturation | Spin and Flavor structure of nucleons and nuclei | Tomography Transverse Momentum Dist. | QCD at Extreme Parton Densities - Saturation | Tomography Spatial Imaging



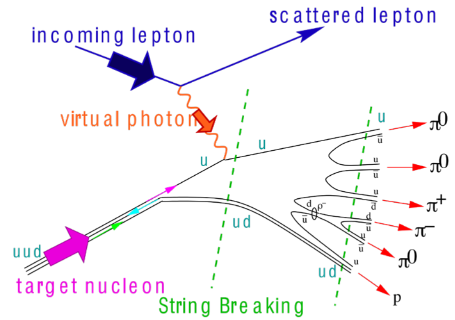
Inclusive DIS

- measure scattered lepton
- multi-dimensional binning: x, Q^2

→ reach to lowest x, Q^2 impacts Interaction Region design

→ low mass detectors, excellent e/h separation

$\int Ldt$: 1 fb^{-1}

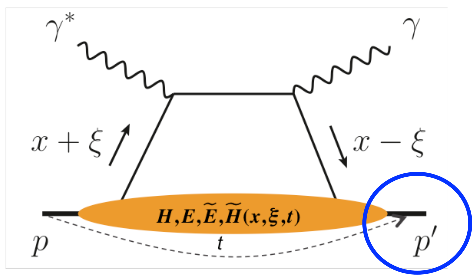


Semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, ϕ

→ particle identification over entire region is critical

10 fb^{-1}



Exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, ϕ
- proton p_T: 0.2 - 1.3 GeV

→ Not detected in main detector

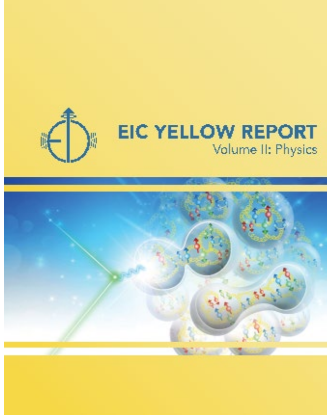
→ strong impact on Interaction Region design

10 - 100 fb^{-1}

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab

EICUG: Yellow Report (YR) Initiative



http://www.eicug.org/web/content/yellow-report-initiative

Detector requirements and design driven by EIC Physics program and defined by EIC Community

Physics Topics → Processes → Detector Requirements

Physics Working Group:

Inclusive Reactions
Semi-Inclusive Reactions
Jets, Heavy Quarks
Exclusive Reactions
Diffractive Reactions & Tagging

Detector Working Group:

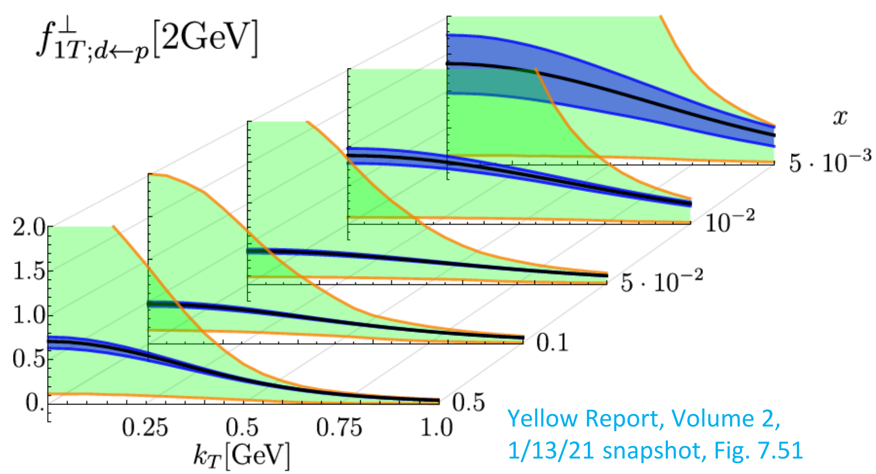
Tracking + Vertexing
Particle ID
Calorimetry
Far-Forward Detectors
DAQ/Electronics
Polarimetry/Ancillary Detectors
Central Detector: Integration/Magnet
Forward Detector: IR Integration

Handoff between Physics & Detector Working Groups in "**interactive detector matrix**":
Collects physics requirements "real time", lists all technologies for a given region, and links to studies that established the numbers

Example of EIC Measurements: Origin of Nucleon Spin

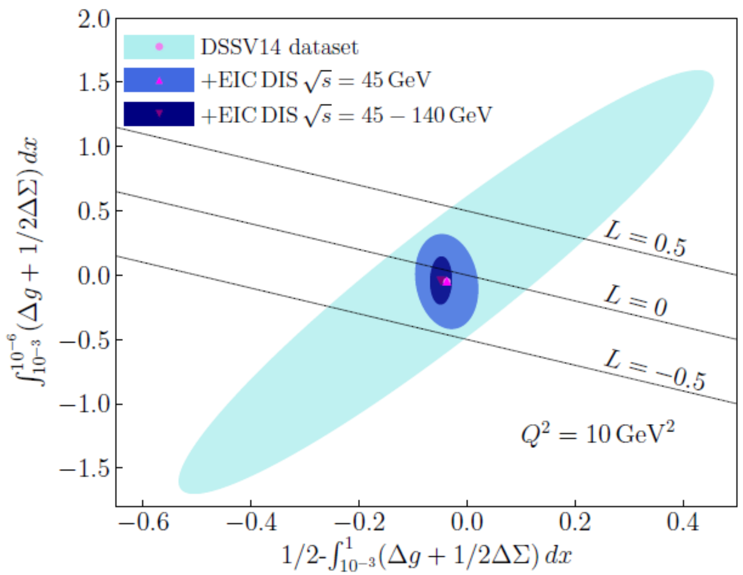
- Understanding the nucleon spin in terms of contributions from quark and gluon spin and angular momentum contributions has been an essential goal for several decades.
- EIC will put the nucleon spin decomposition's phenomenology on firm ground, and by inference well constrain the parton angular momenta contribution

Yellow Report, Volume 2, Chapter 7



Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.51

Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.17 and 8.11



Physics WG (https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Physics_Common)

→ Also see talk by C. Bissolotti on Transverse Momentum Distributions at EIC

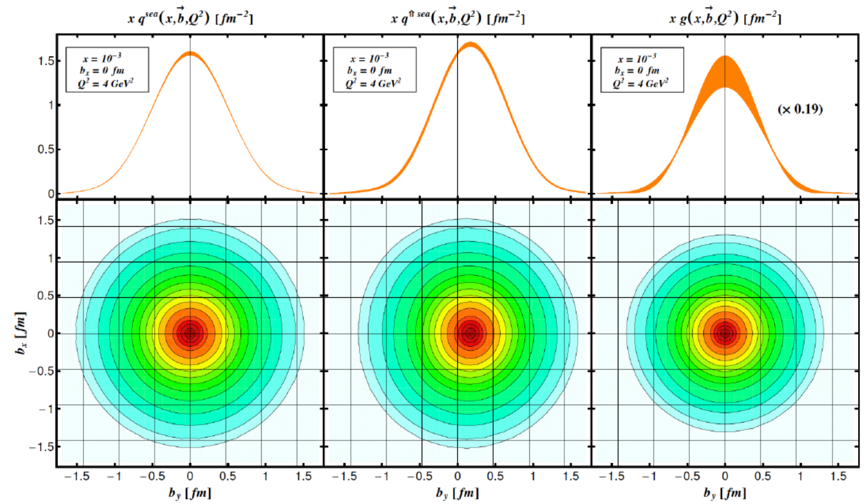
THE CATHOLIC UNIVERSITY OF AMERICA Jefferson Lab

Examples of EIC Measurements: Origin of Hadron Mass

- More than 99% of the mass of the visible universe resides in atomic nuclei, whose mass, in turn, is primarily determined by the masses of the proton and neutron.
  - Therefore, it is of utmost importance to understand the origin of the proton (and neutron) mass, particularly how it emerges from the strong interaction dynamics.

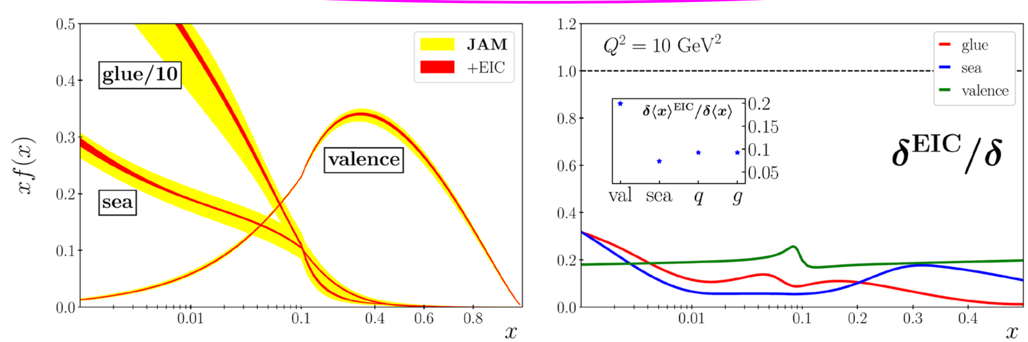
- Another way to address the emergence of hadron mass is through chiral-symmetry features that manifest in the lightest mesons, the pion and kaon.
  - The properties of the nearly massless pion are the cleanest expressions of the mechanism that is responsible for the emergence of the mass and have measurable implications for the pion form factor and meson structure functions

Extract densities of quarks and gluons from DVCS



Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.44

Large reduction in pion (structure) pdfs through EIC



[Arrington et al., J. Phys. G 48 (2021) 7, 075106]

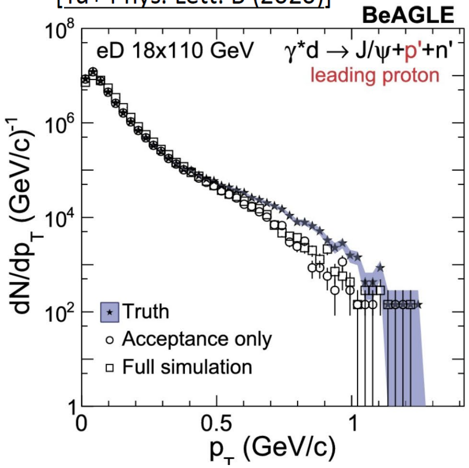
THE CATHOLIC UNIVERSITY OF AMERICA

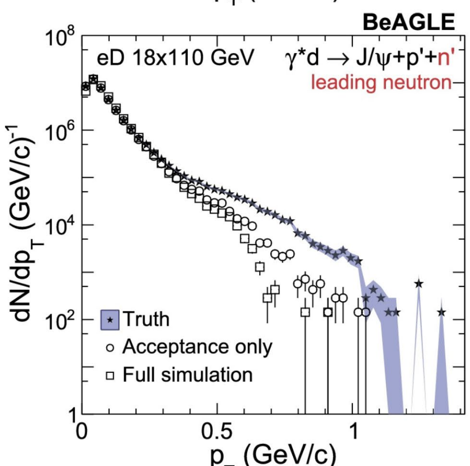
Jefferson Lab

Examples of EIC Measurements: Nuclei

Incoherent diffractive J/Ψ production in e-d tagging

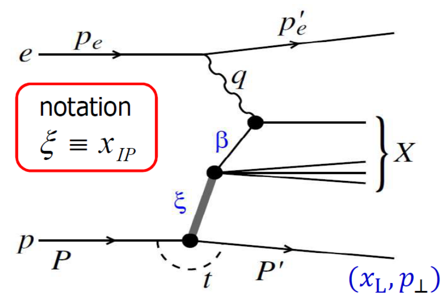
[Tu+ Phys. Lett. B (2020)]

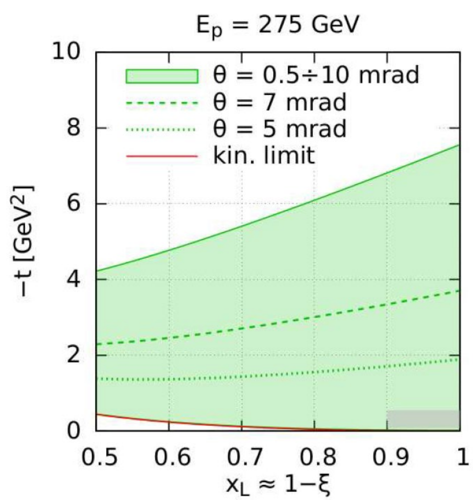




Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.73

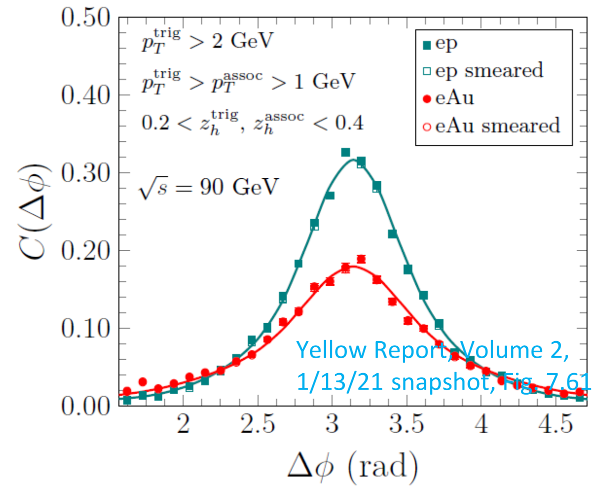
Inclusive diffraction in e-A



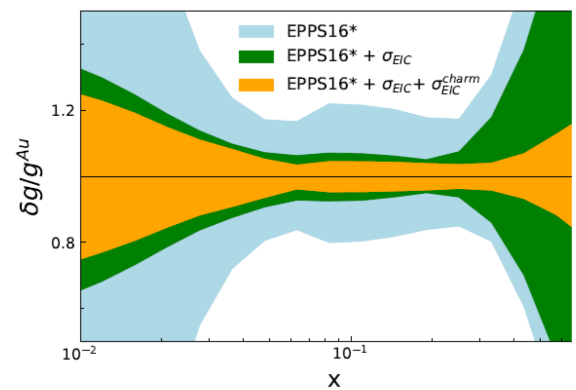


Yellow Report, Volume 2, 11/16/20 snapshot, Fig. 7.29

di-hadron azimuthal angle correlation, nuclear glue ratio through inclusive and open charm



Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.61

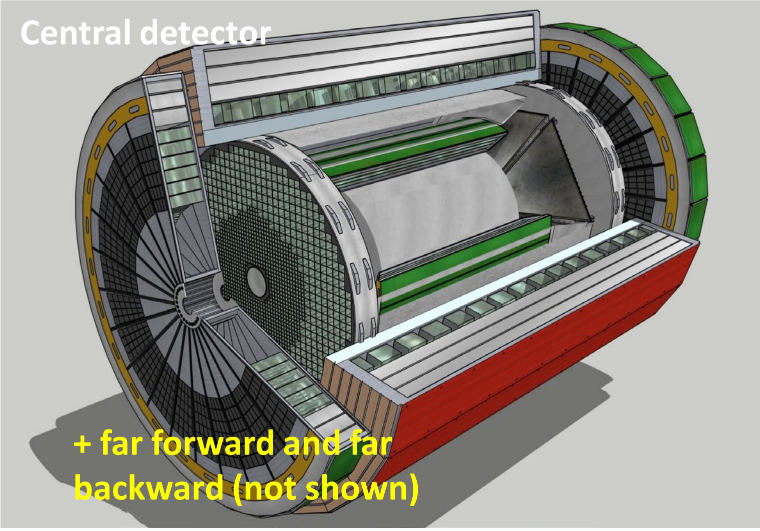


Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.67

→ Also see talks by A. Tadepalli, S. Li, Z. Tu, F. Salazar, W. Chang on EIC Physics Opportunities

EIC Detector General Requirements

EIC physics measurements require a detector with unique capabilities

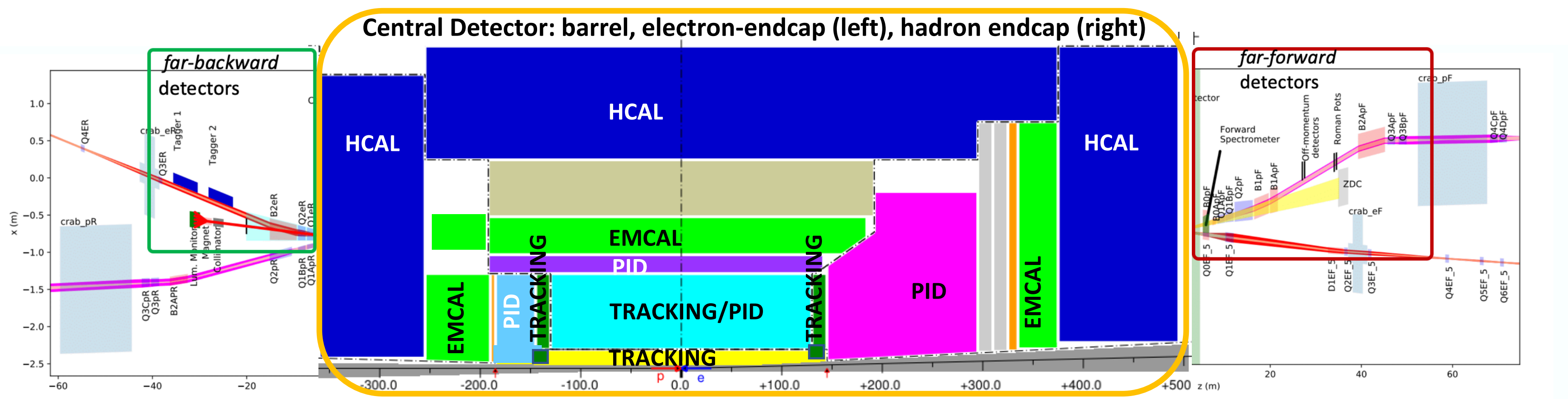


- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EMCal
- High performance PID to separate p, K, π
  - also need good e/π separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

➢ **Integration into Interaction Region is critical**

EIC detector – general features

EIC Central Features Detector 2D: 3 integrated regions: Far-backward, Central, Far-forward

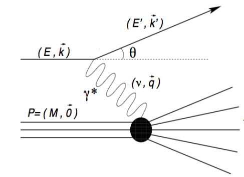


Detector Technologies from Yellow Report (Table 11.49)

system	system components	reference detectors	detectors, alternative options considered by the community		
tracking	vertex	MAPS, 20 um pitch	MAPS, 10 um pitch		
	barrel	TPC	TPC[a]	MAPS, 20 um pitch	MICROMEGAS[b]
	forward & backward	MAPS, 20 um pitch & sTGCs[c]	GEMs	GEMs with Cr electrodes	
	very far-forward & far-backward	MAPS, 20 um pitch & AC-LGAD[d]	TimePix (very far-backward)		
ECal	barrel	W powder/ScFi or Pb/Sc Shashlyk	SciGlass	W/Sc Shashlyk	
	forward	W powder/ScFi	SciGlass	PbGl	Pb/Sc Shashlyk or W/Sc Shashlyk
	backward, inner	$PbWO_4$	SciGlass		
	backward, outer	SciGlass	$PbWO_4$	PbGl	W powder/ScFi or W/Sc Shashlyk[e]
	very far-forward	Si/W	W powder/ScFi	crystals[f]	SciGlass
h-PID	barrel	High performance DIRC & dE/dx (TPC)	reuse of BABAR DIRC bars	fine resolution TOF	
	forward, high p	double radiator RICH (fluorocarbon gas, aerogel)	fluorocarbon gaseous RICH	high pressure Ar RICH	
	forward, medium p		aerogel		
	forward, low p	TOF	dE/dx		
	backward	modular RICH (aerogel)	proximity focusing aerogel		
e/h separation at low p	barrel	hpDIRC & dE/dx (TPC)	very fine resolution TOF		
	forward	TOF & areogel			
	backward	modular RICH	adding TRD	Hadron Blind Detector	
HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc	
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	very far-forward	quartz fibers/ scintillators			

Inclusive DIS

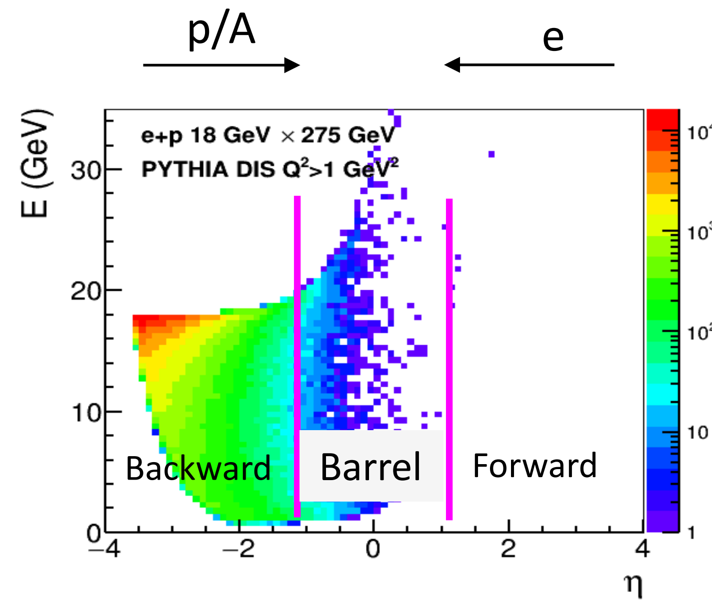
$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right) \qquad y = 1 - \frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right) \qquad x = \frac{Q^2}{sy}$$



DIS kinematics through electron measurements

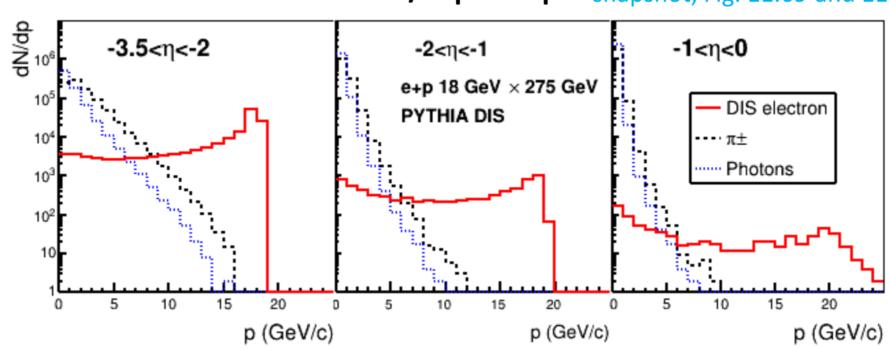
EMCal + Tracking + Electron ID

- Mainly barrel and backward
- Hadron suppression up to a factor of 10^4
- Energy/Momentum measurement is critical:
  $\frac{\sigma_{Q^2}}{Q^2} \sim \frac{\sigma_{E'}}{E'}$; $\frac{\sigma_x}{x} \sim \frac{1}{y}\frac{\sigma_{E'}}{E'}$
- Highest resolution EMCal in the most backward region (due to degraded tracking mom. res.)
- Lowest material budget (to minimize Bremsstrahlung)



dN/dp vs p

Yellow Report, Volume 3, 1/13/21 snapshot, Fig. 11.69 and 11.70

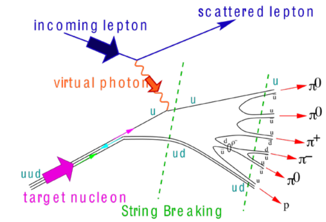


Low Q^2 tagger

(far backward EMCal+Tracking)

- To measure reactions with $Q^2 < 0.1$ GeV^2
- **Minimize the gap with central detector**

Semi-Inclusive DIS (SIDIS)



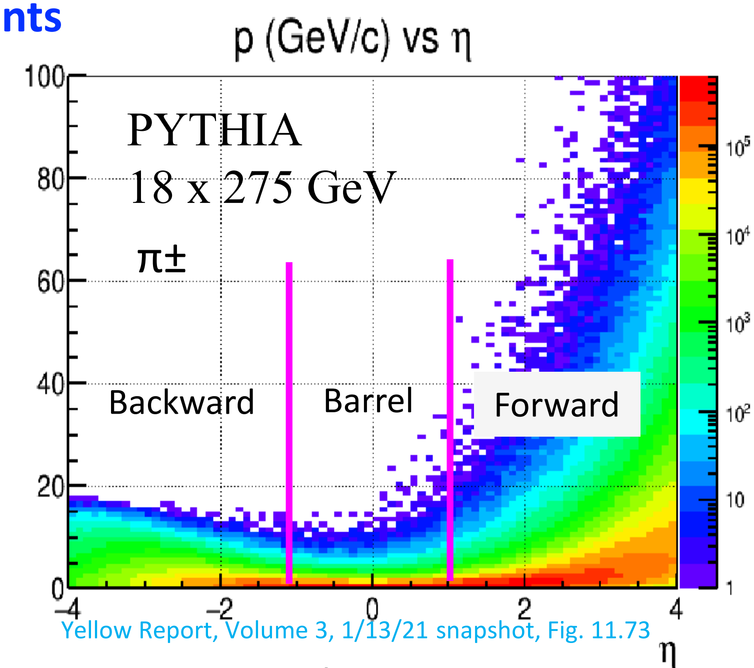
Flavor tagging through identified hadron measurements

EMCal + Tracking + Particle ID

- Coverage at least |η|<3.5
- Charged PID: π/K/p, e/h
- π^0/γ discrimination → EMCal granularity
- Particle decays (e.g. Λ→πp) => Minimal momentum threshold

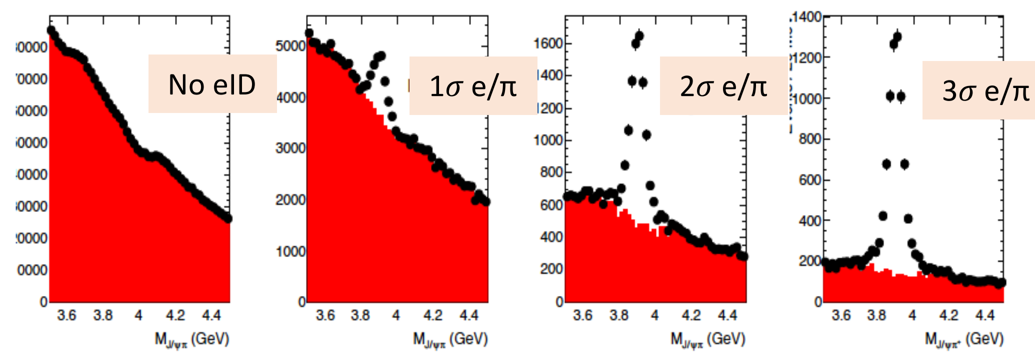
Rapidity	π/K/p and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

Yellow Report, Volume 2, 1/13/21 snapshot, Table 8.2



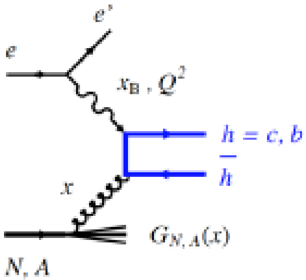
Yellow Report, Volume 3, 1/13/21 snapshot, Fig. 11.73

e/h impact on $Z_c^+ \rightarrow J/\psi$+π

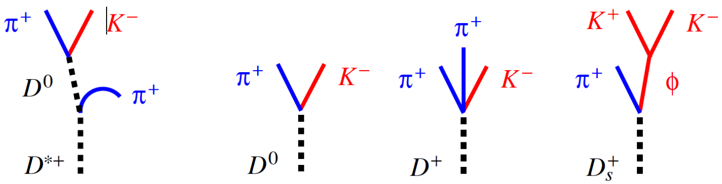


Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 8.38

Heavy Quarks



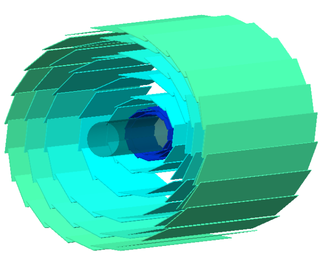
Gluon tagging

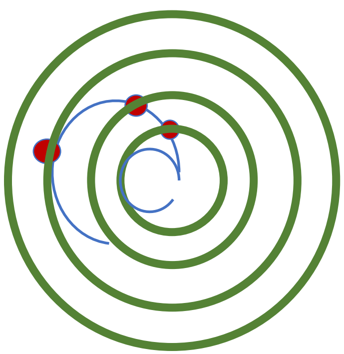


	Mass	$c\tau$
D0	1864,8 MeV	123 μm
D*	2010.2 MeV	-
D+	1869.5 MeV	315 μm
Ds+	1967 MeV	147 μm
Λc	2286.5 MeV	60μm

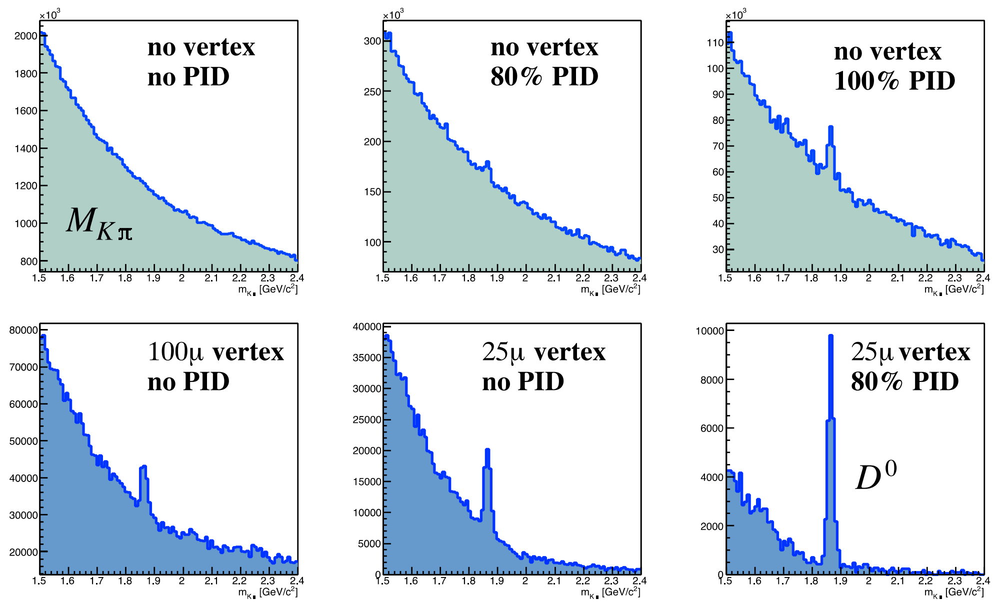
+ Vertex tracker

- Resolution ~20 µm
- Also, provides stand-alone measurements of low p_T particles





$D^0 \rightarrow K\pi$

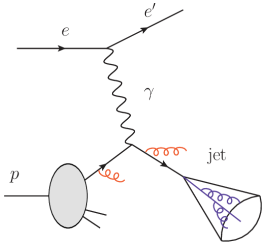


Jets/HF WG (https://wiki.bnl.gov/eicug/index.php/Yellow_Report_Physics_Jets-HF)

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab

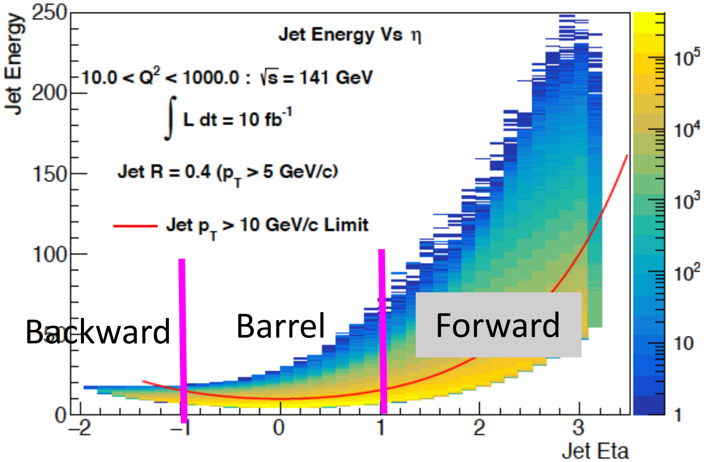
Jets



Hadronization in vacuum and in nuclear medium

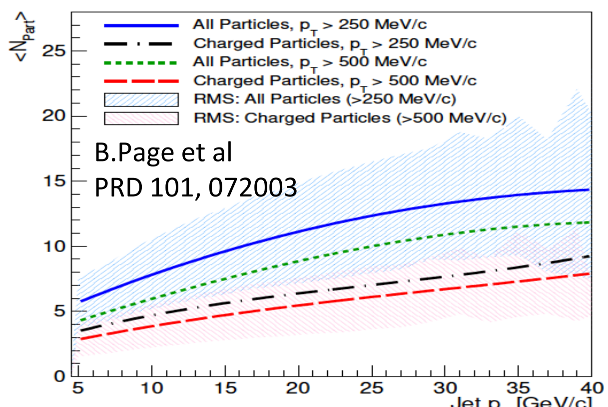
+ Hadron Calorimetry

- Continuous coverage at least |η|<3.5
  - Minimize gap between barrel and endcap
- Important to measure neutral hadrons (n, K_L)
- Important for DIS kin. reconstruction with JB approach (via hadronic final state)
  - The only method for CC events
- Tag jets with no neutrals
  - Significantly improve jet resolution
- Would benefit from higher HCal energy resolution at η>2.5 for charged hadron measurements
  - Because of degraded track momentum res.

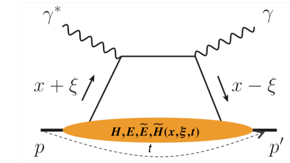


Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 8.41

Particle multiplicity in a Jet



Exclusive Reactions

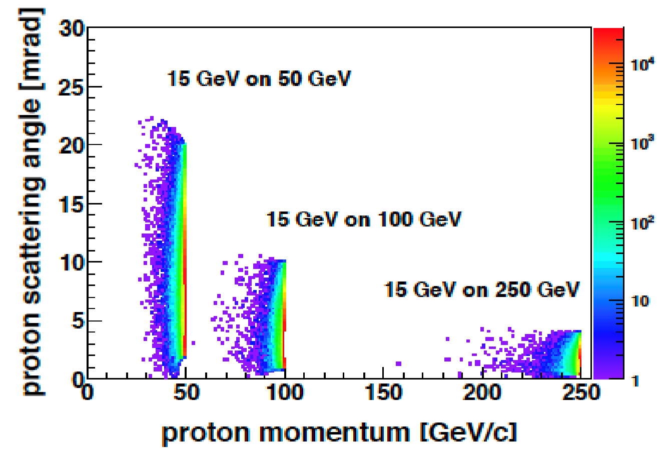


Multidimensional Parton tomography

+ Far-Forward proton tagger (Roman Pots)

- Dedicated detector(s) close to the beam line is required
- Need to cover at least $0.18<p_T<1.3$ GeV/c
- Integration in the Interaction Region is critical
- Exclusiveness => hermetic coverage from central to far-forward (see next slide)

DVCS: scattered proton



Fourier Transform

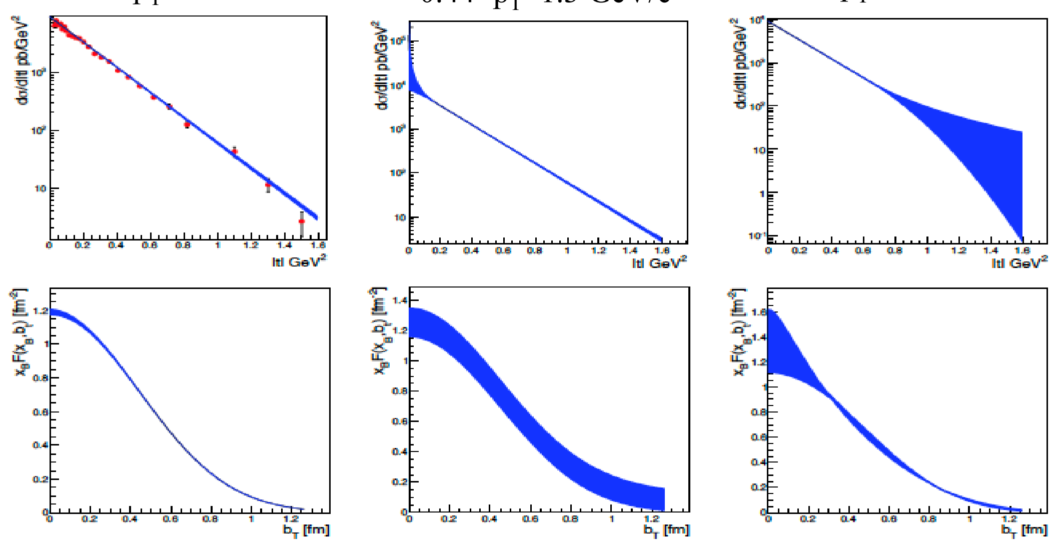
DVCS $\sigma(t)$

PDF(b_T)

$0.18<p_T<1.3$ GeV/c

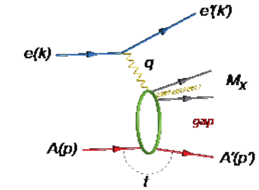
$0.44<p_T<1.3$ GeV/c

$0.18<p_T<0.8$ GeV/c

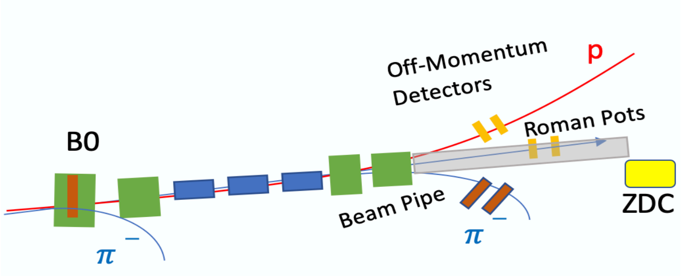


Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 7.46

Diffractive Reactions & Tagging



Free neutron structure and nuclear modification
Meson structure
High gluon density matter

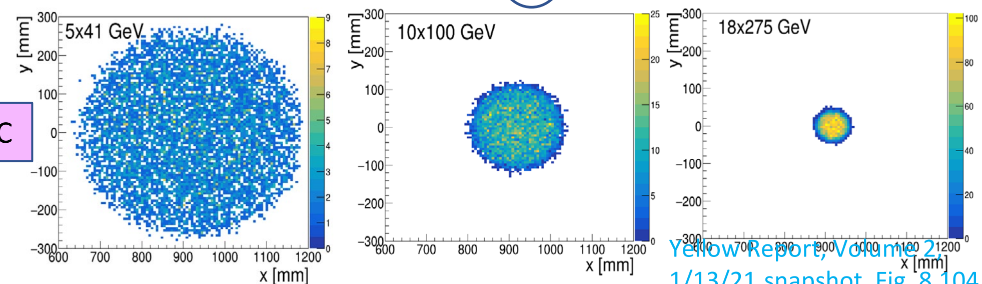


+ Zero Degree Calorimeter

- Neutrons from nuclear break up, nucleon tagging in light ion reactions, and $p \to n$ processes
- HCal+EMCal: Coverage 60x60 cm^2

$$e + p \to e' + X + n \text{ (for pion structure)}$$

ZDC



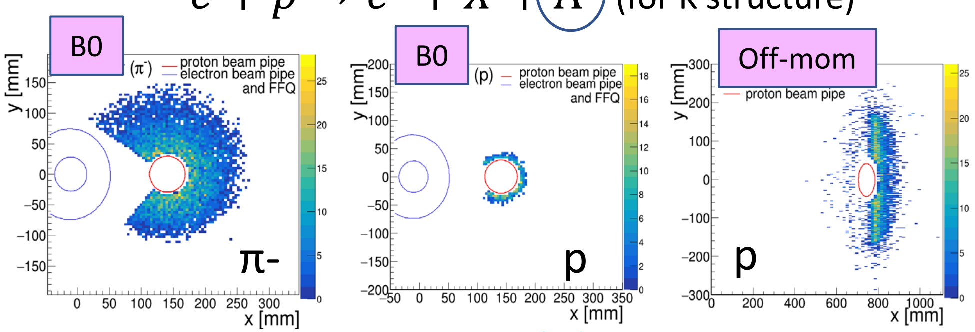
Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 8.104

+ Additional tracker(s) between central detector and proton tagger

("B0" and "OFF mom")

- Rapidity Gap measurements
- Forward decay products
- Hermetic coverage from central to far-forward region

$$e + p \to e' + X + \Lambda \text{ (for K structure)}$$

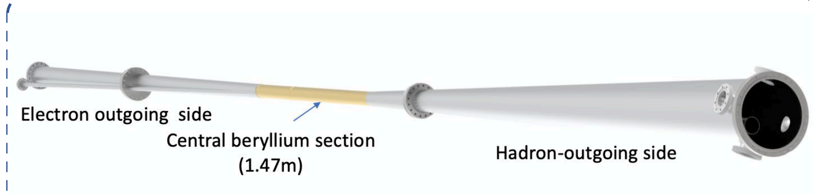


Yellow Report, Volume 2, 1/13/21 snapshot, Fig. 8.106

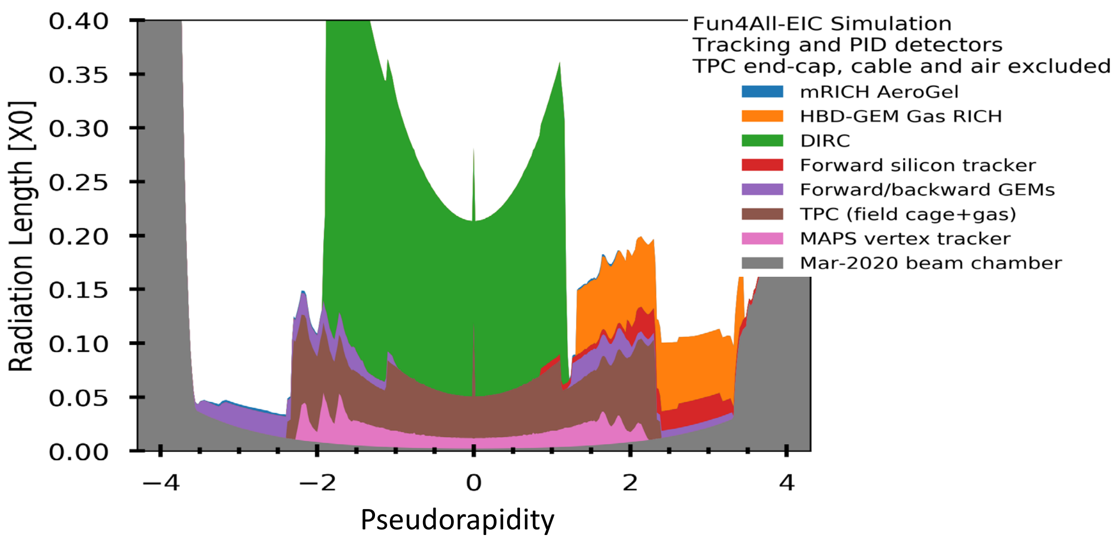
Integration in the Interaction Region is critical

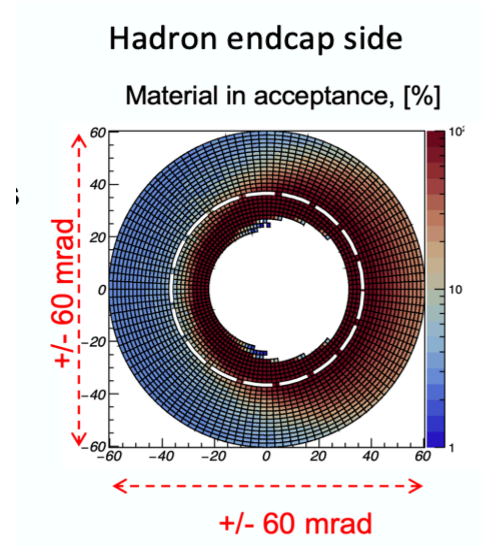
Tracking/Material Budget

- ❑ Vertex + central + forward / backward tracker layout (moderate momentum resolution, vertex resolution ~20 μm)
- ❑ At most 3T central solenoid field (maximize B*dl integral at high |η|)
- ❑ 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



- ❑ Central area of beampipe (around IP):
  ~1.5m of beryllium to minimize multiple scattering for low P_T particles
- ❑ Low-mass exit window for far-forward particles
- ❑ Few % radiation length material thickness for the required angular range (low angle)





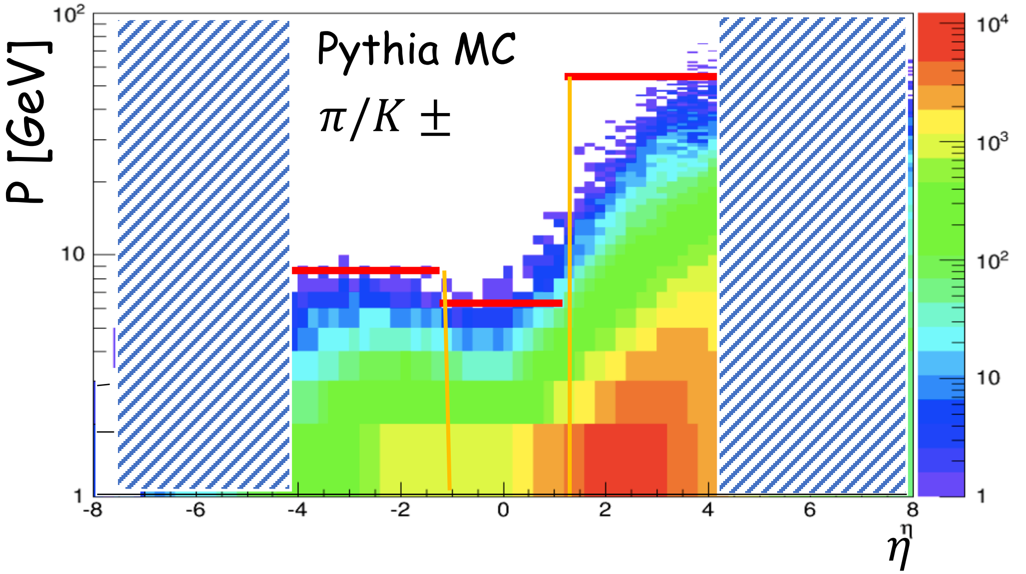
Particle ID

- In general, need to separate:
  - Electrons from photons -> 4π coverage in tracking
  - Electrons from charged hadrons -> mostly provided by calorimetry
  - Charged pions, kaons and protons from each other -> Cherenkov detectors

Physics requirements:

Rapidity	π/K/p and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

Illustration of PID detectors achievements:



Cherenkov detectors, complemented by other technologies at lower momenta

Electromagnetic Calorimeter

- Applications
  - Scattered electron kinematics measurement at large |η| in the e-endcap
  - Photon detection and energy measurement
  - e/h separation (via E/p & cluster topology)
  - π^0/γ separation -> may also consider a highly segmented preshower

- Anticipated stochastic term in energy resolution & π suppression

η	[-4 .. -2]	[-2 .. -1-2	[-1 .. 1]	[1 .. 4]
σ_E/E	~2%/√E	~(4-8)%/√E	~(12-14)%/√E	~(4*-12)%/√E
π suppression	Up to 1:10^{-4}	Up to 1:10^{-3}-10^{-2}	Up to 1:10^{-2}	3σ e/π

- Other considerations
  - Fast timing
  - Compactness (small X_0 and R_M)
  - Tower granularity
  - Readout immune to the magnetic field

#	Type	sampling, mm	f_{samp}	X_0 mm	R_M mm	λ_I mm	cell mm^2	$\frac{X}{X_0}$	ΔZ cm	σ_E/E, % α	β
1	W/ScFi**	⊘0.47 ScFi W powd.	2%	7.0	19	200	25^2	20	30	2.5	13
2	$PbWO_4^{***}$	-	-	8.9	19.6	203	20^2	22.5	35	1.0	2.5
3	Shashlyk***	0.75 W/Cu[a] 1.5 Sc	16%	12.4	26	250	25^2	20	40	1.6	8.3
4	W/ScFi** with PMT	0.59^2 ScFi W powd.|	12%	13	28	280	25^2	20	43	1.7	7.1
5	Shashlyk***	0.8 Pb 1.55 Sc	20%	16.4	35	520	40^2	20	48	1.5	6
6	TF1 Pb glass***	-	-	28	37	380	40^2	20	71	1.0	5-6
7	Sc. glass*[b]	-	-	26	35	400	40^2	20	67	1.0	3-4

EIC Yellow Report

Yellow Report, Volume 3, 1/13/21 snapshot, Table 11.28

→ Also see talk by A. Bazilevsky on EIC Calorimeters

Hadron Calorimeter

- Main purpose: hadron/jet energy measurement
  - Particle Flow Algorithm usage anticipated (where HCal role is identification and energy measurements of the neutral hadrons, namely neutrons and K_L)

- "Conventional" hadronic calorimetry has been considered as default

  -> Alternatives, e.g., dual readout were mentioned as well

- Anticipated stochastic term in energy resolution & depth

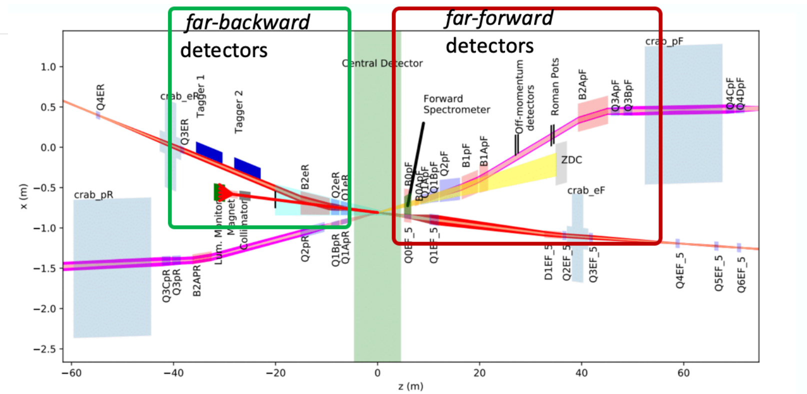
η	[-4 .. -1]	[-1 .. 1]	[1 .. 4]
σ_E/E	~50%/√E + 10%	~100%/√E + 10%	~50%/√E + 10%
depth	~5 λ_I	~5 λ_I	~6-7 λ_I

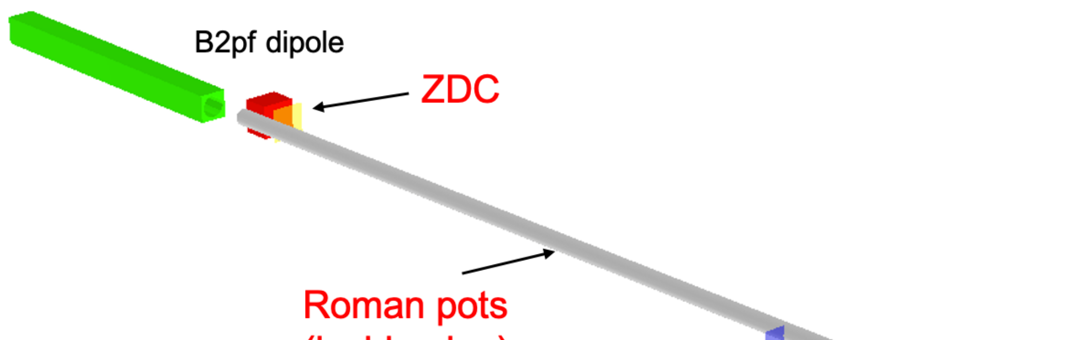
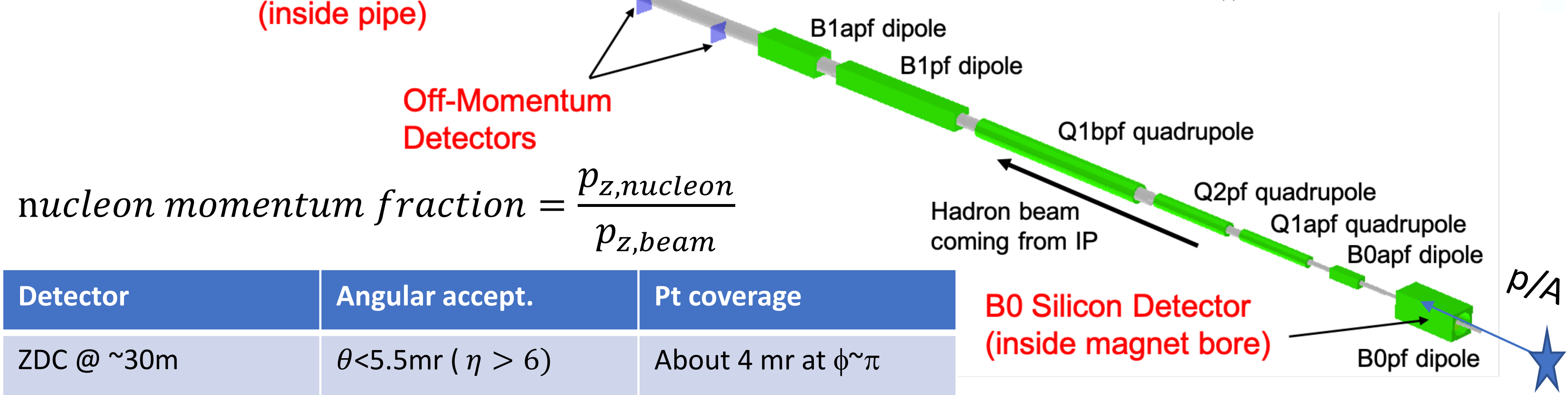
- Other considerations
  - Space!
  - Interplay with EmCal in a "binary" EmCal+HCal configuration
  - Tower granularity (~10 x 10 cm^2 suffices)
  - Readout immune to the magnetic field

→ Also see talk by A. Bazilevsky on EIC Calorimeters

Far forward (hadron going) region

→ Also see talk by A. Jentsch on EIC Far Forward Detectors



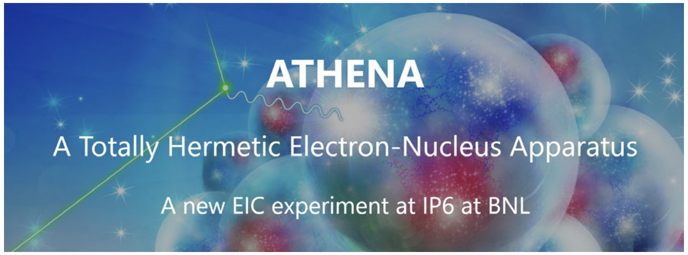



$$nucleon\ momentum\ fraction = \frac{p_{z,nucleon}}{p_{z,beam}}$$

Detector	Angular accept.	Pt coverage
ZDC @ ~30m	θ<5.5mr ($\eta > 6$)	About 4 mr at ϕ~π
Roman Pots (2 stations)	0*<θ<5.0 mr ($\eta > 6$)	0.65<$\frac{p_{z,nucleon}}{p_{z,beam}} < 1.0$ *10σ cut
Off-Momentum Detectors	0.0< θ < 5.0 mr ($\eta > 6$)	Roughly 0.3<$\frac{p_{z,nucleon}}{p_{z,beam}} < 0.6$
B0 forward spectrometer	$5.5 < \theta < 20.0$ mr (4.6< $\eta < 5.9$)	Also looking at γ tagging via EMCal

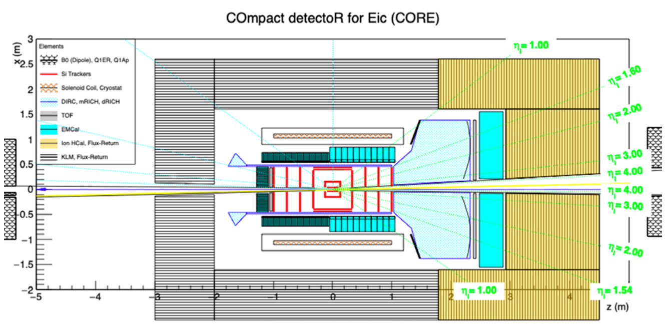
Yellow Report, Volume 3, 1/13/21 snapshot, Fig. 9.4 and 11.83

EIC Detector Proposals:



https://sites.temple.edu/eicatip6/

See talk by Yulia Furletova

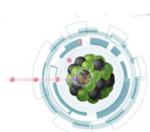


https://userweb.jlab.org/~hyde/EIC-CORE/

See talk by Charles Hyde

ECCE

EIC Comprehensive Chromodynamics Experiment



ECCE shares the vision of the Nuclear Physics community that the EIC science mission is best served by two complementary detectors. In pursuit of that goal, ECCE is investigating a detector based on a 1.5T solenoid in both EIC interaction regions, ready for the beginning of EIC accelerator operation.

https://www.ecce-eic.org/

See talk by John Lajoie

Summary

- The NAS Report on the EIC Science Case, along with the EIC White Paper, provide the fundamental framework for EIC experiments.
- The EIC Yellow Report and CDR established the detector requirements and design driven by EIC Physics program and defined by EIC Community
- YR and CDR defined a reference detector (integrated, including central detector and far forward and far backward regions) and panorama of detector technologies
- EIC detector proposal efforts are ongoing – building on the EIC YR and CDR and further developing the concepts for experimental equipment best suited for science needs as documented in NAS Report and EIC White Paper

EIC YR Physics Working Group

- Conveners: Adrian Dumitru (Baruch), Olga Evdokimov (UIC), Andreas Metz (Temple U.), Carlos Munoz-Camacho (IJCLab-Orsay)

- Five Working groups
  - **Inclusive Reactions:** to join this group and its mailing list, contact R. Fatemi
    - **Conveners:** Renee Fatemi (Kentucky), Nobuo Sato (JLab), Barak Schmookler (Stony Brook)
  - **Semi-inclusive Reactions:** to join this group and its mailing list, contact R. Seidl
    - **Conveners:** Ralf Seidl (RIKEN), Justin Stevens (W&M), Alexey Vladimirov (Regensburg), Anselm Vossen (Duke), Bowen Xiao (CCNU, China)
  - **Jets, Heavy Quarks:** to join this group and its mailing list, contact L. Mendez
    - **Conveners:** Leticia Mendez (ORNL), Brian Page (BNL), Frank Petriello (ANL & Northwestern U.), Ernst Sichtermann (LBL), Ivan Vitev (LANL)
  - **Exclusive Reactions:** to join this group and its mailing list, contact S. Fazio
    - **Conveners:** Raphaël Dupré (Orsay), Salvatore Fazio (BNL), Tuomas Lappi (Jyvaskyla), Barbara Pasquini (Pavia), Daria Sokhan (Glasgow)
  - **Diffractive Reactions & Tagging:** to join this group and its mailing list, contact W. Cosyn
    - **Conveners:** Wim Cosyn (Florida), Or Hen (MIT), Doug Higinbotham (JLab), Spencer Klein (LBNL), Anna Stasto (PSU)

- Webpage: http://www.eicug.org/web/content/yellow-report-physics-working-group

EIC YR Detector Working Group

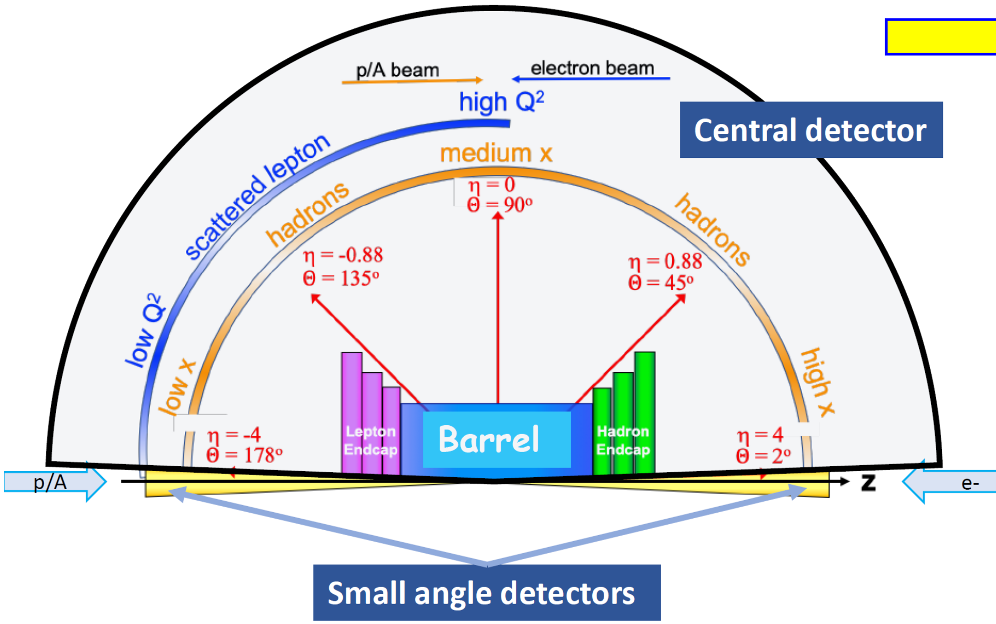
- Conveners: Ken Barish (UC Riverside), Tanja Horn (CUA), Peter Jones (U. Birmingham), Silvia Dalla Torre (Trieste/INFN), Markus Diefenthaler (Jlab, ex-officio)

- Eight Working groups
  - **Tracking (+vertexing),** Conveners: Kondo Gnanvo (UVA), Leo Greiner (LBNL), Annalisa Mastroserio (INFN), Domenico Elia (INFN)
  - **Particle ID**, Conveners: Tom Hemmick (SBU), Patrizia Rossi (JLab)
  - **Calorimetry (EM and Hadronic),** Conveners: Vladimir Berdnikov (CUA), Eugene Chudakov (JLab)
  - **Far-Forward Detectors**, Conveners: Alexander Jentsch (BNL), Michael Murray (Kansas)
  - **DAQ/Electronics**, Conveners: Andrea Celentano (INFN), Damien Neyret (CEA Saclay)
  - **Polarimetry/Ancillary Detectors**
    - Conveners: Elke Aschenauer, Dave Gaskell
  - **Central Detector/Integration & Magnet,** Conveners: Willliam Brooks, Alexander Kiselev (BNL)
  - **Forward Detector/IR Integration,** Convener: Yulia Furletova (JLab)
  - **Infrastructure and Installation,** Convener: TBA
  - **Detector Complementarity,** Conveners: Elke Aschenauer (BNL), Paul Newman (Birmingham)

- Webpage: http://www.eicug.org/web/content/yellow-report-detector-working-group

THE CATHOLIC UNIVERSITY OF AMERICA Jefferson Lab

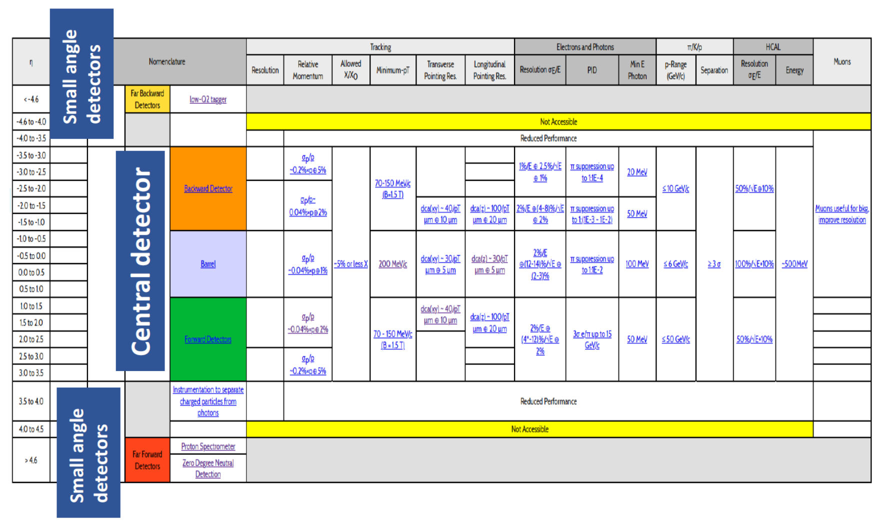
EIC YR Detector Requirements Overview: Interactive Matrix



Yellow Report, Volume 3, 1/13/21 snapshot, Fig. 9.1

Covers entire region with central and "small angle" detectors

Collects physics requirements "real time", lists all technologies for a given region, and links to studies that established the numbers



https://physdiv.jlab.org/DetectorMatrix/

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab