The Electron-Ion Collider Yellow Report

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DIS2021
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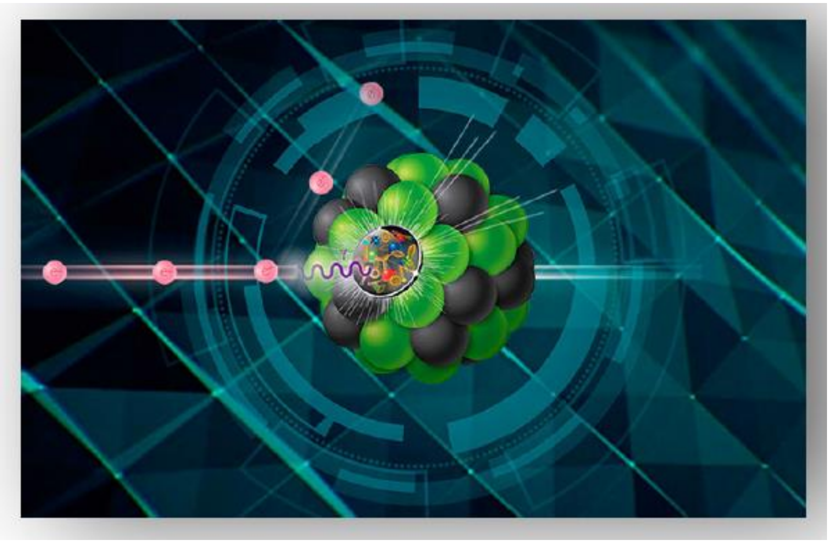
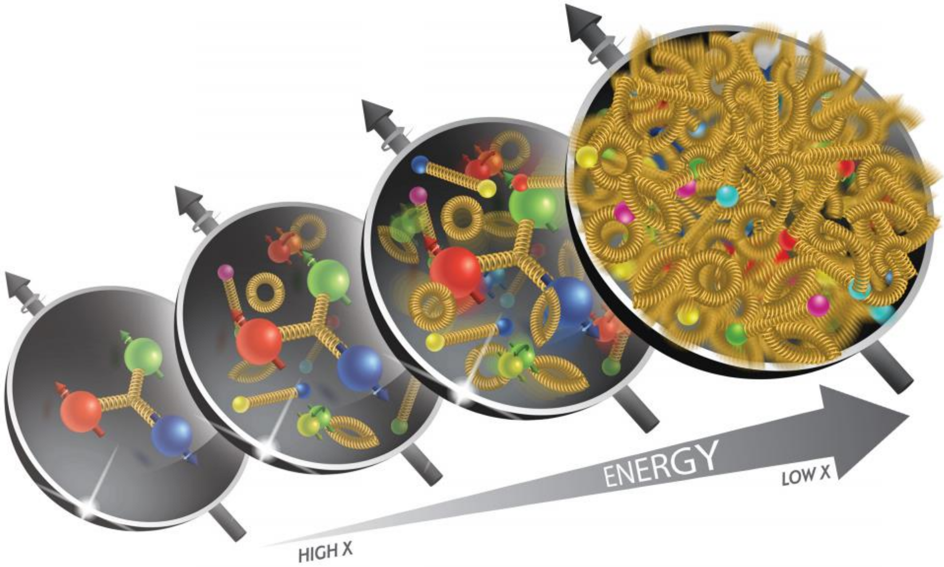


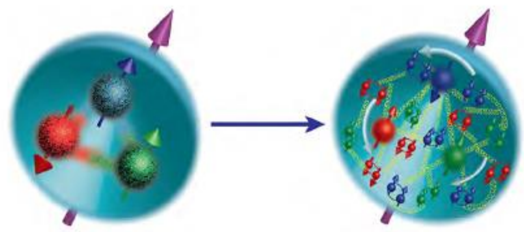
Outline



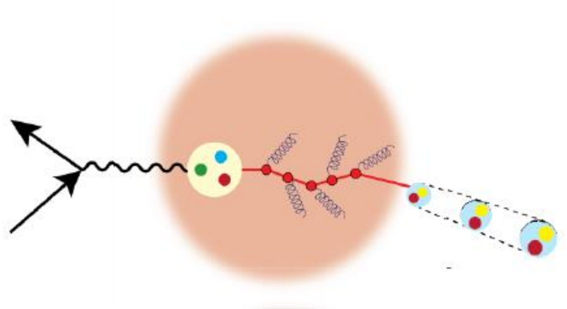
- The Electron Ion Collider
- Recent developments
- The Yellow Report initiative
- Detector requirements from physics
- The EIC reference detector
- Conclusion and outlook

Motivation – the EIC science program

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



How do the nucleon properties emerge from them and their interactions?



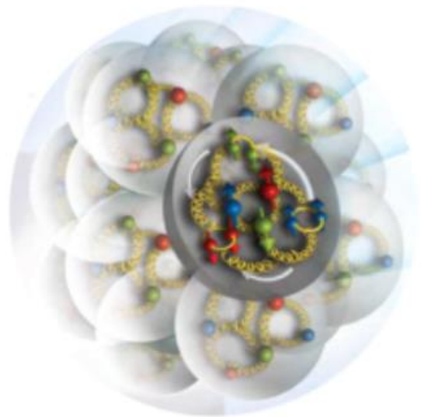
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

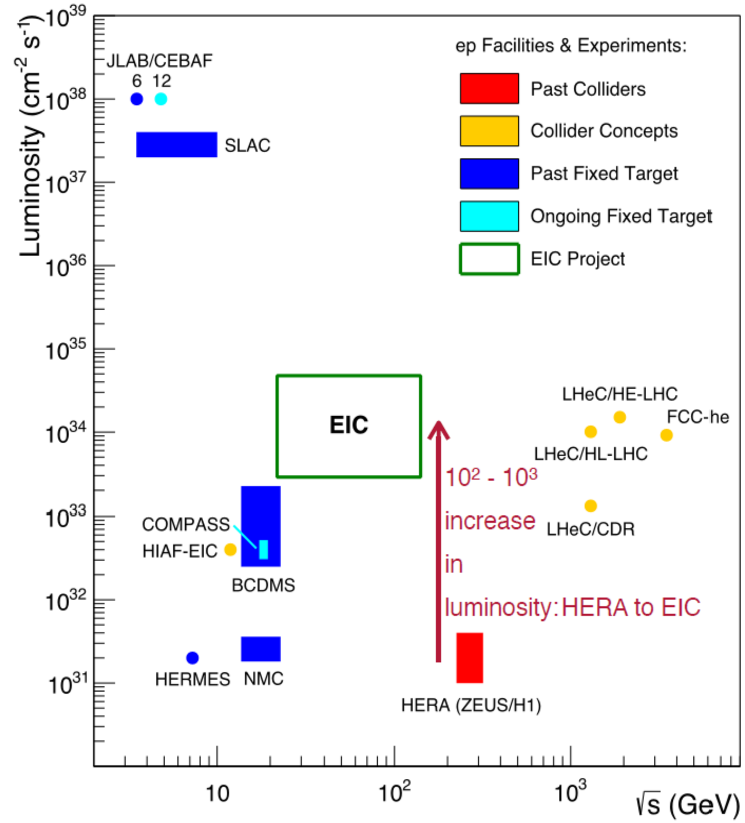
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

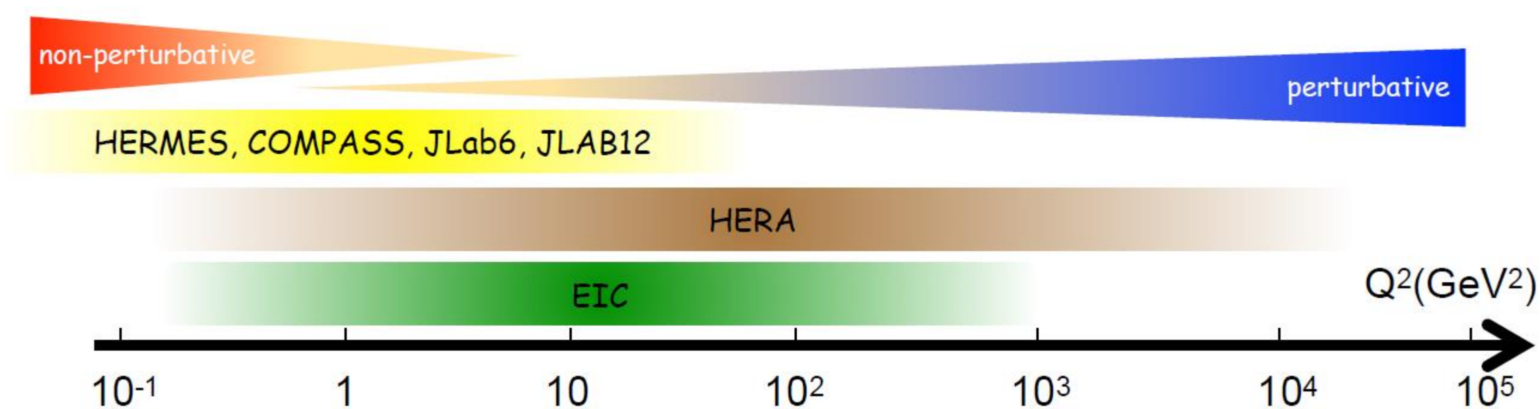
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



EIC machine requirements

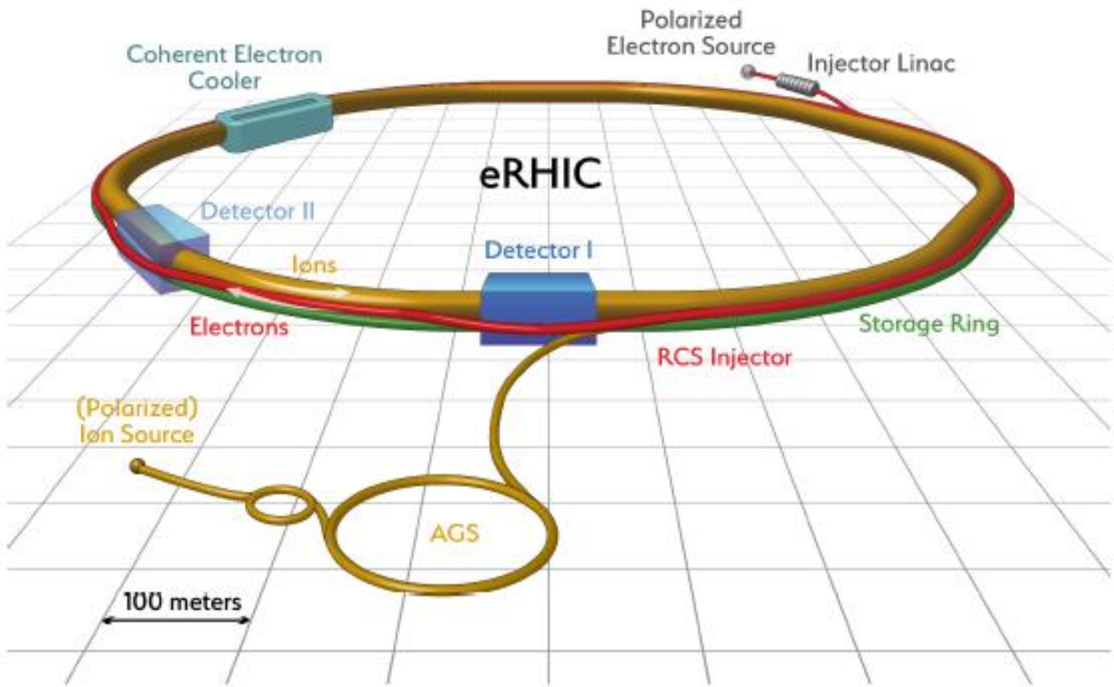
- High luminosity: 10^{34} cm^{-2} s^{-1}
- Flexible center-of-mass energy $\sqrt{s} = \sqrt{4E_eE_p}$: wide kinematic range $Q^2 = s \times y$
- Highly polarized electron (0.8) and proton/light ion (0.7) beams: spin structure studies
- Wide range of nuclear beams (d to Pb/U): high gluon density





EIC Facility

- Highly polarized electron / Highly polarized proton and light ions /Unpolarized heavy ions
- CME: ~ 20-100GeV
- Luminosity: ~ $10^{33-34}cm^{-2}s^{-1}$



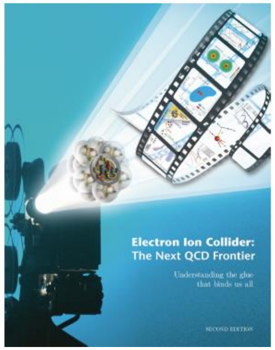
- ❑ Polarized electron source and 400 MeV injector linac
- ❑ Polarized proton beams and ion beams based on existing RHIC facility
- ❑ 2 detector interaction points capability in the design

EIC development

- 2012: White paper, updated in 2014
- 2015: Long-range plan:

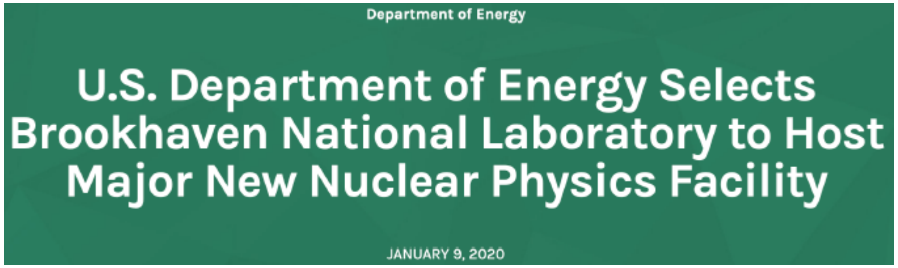
"Construct a high-energy high-luminosity polarized electron-ion collider as the highest priority for new construction"

arXiv:1212.1701



Understanding the glue that binds as all!

- 2017: Review of the EIC Science Case by the US National Academy of Sciences (NAS)
- 2018: Report by the NAS
- 2019: CD-0 (mission need) from the US Department of Energy
- 2020: Site selection (Brookhaven National Laboratory)



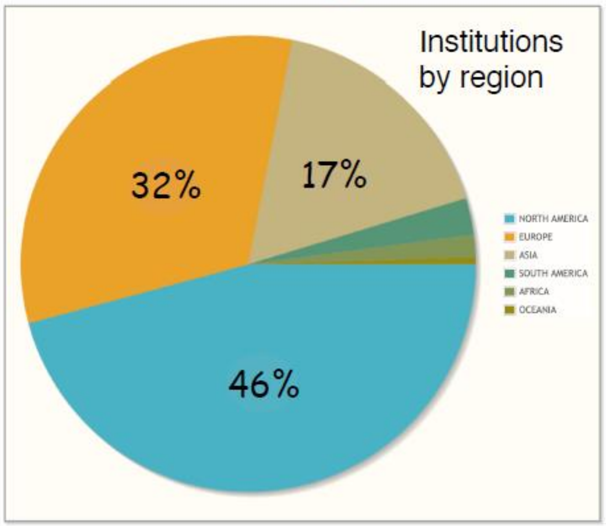
Current project goal:
Start of operations in ~2030

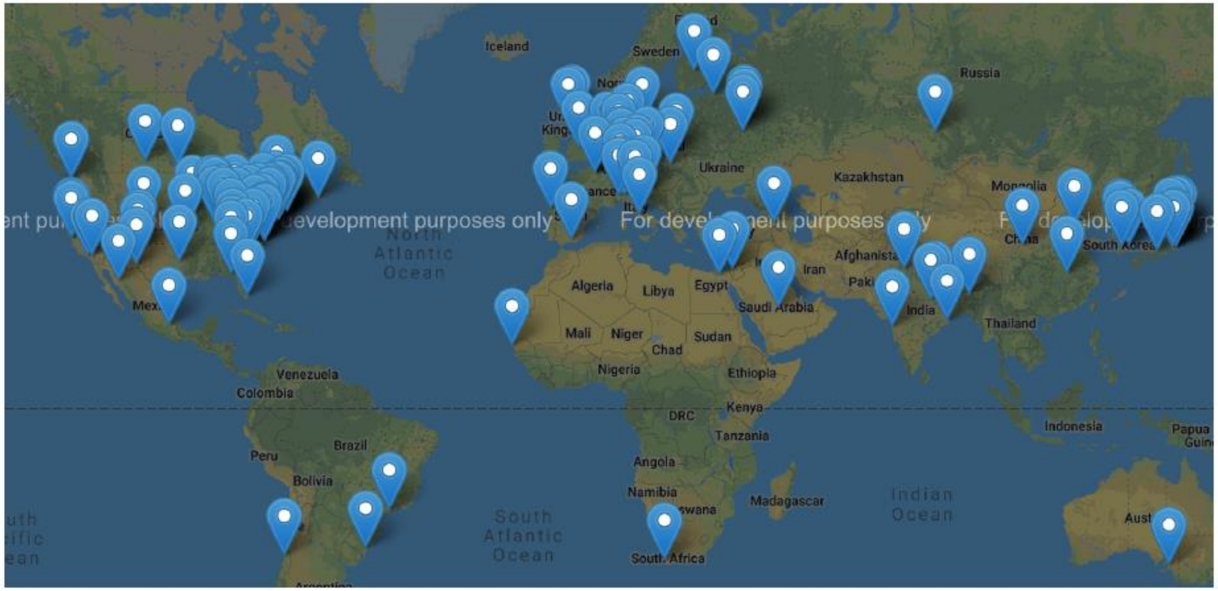
The EIC Users Group

- EIC User Group and R&D activities

WWW-page: www.eicug.org

  - EIC User Group:
    - EICUG organization established in summer 2016
    - In numbers….: 1275 members, 255 institutions in 34 countries (6 world regions)
    - World map:





  - R&D activities:
    - EIC Detector R&D program operated by BNL with ~$1M / year
    - EIC Accelerator R&D with ~$7M / year

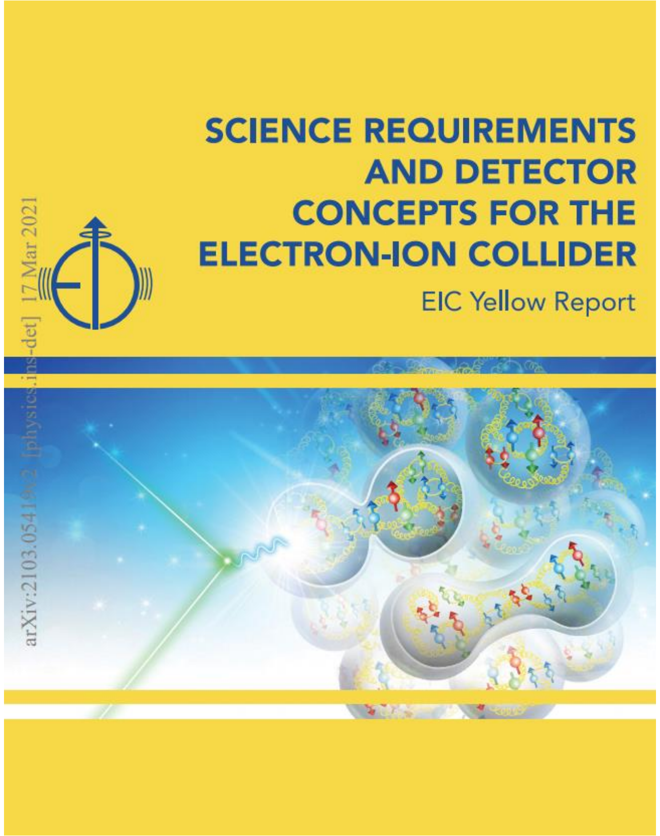
The Yellow Report Initiative

The purpose of the Yellow Report Initiative is to advance the state and detail of the documented physics studies (White Paper, INT program proceedings) and detector concepts in preparation for the realization of the EIC.

- Work started in January 2020
- Report released in March 2021: arXiv:2103.05419
- Enormous community effort: 902 pages, 415 authors, 151 institutions

Organization:

- Physics Working Group
  - Inclusive Reactions
  - Semi-inclusive Reactions
  - Jets & Heavy Quarks
  - Exclusive Reactions
  - Diffractive & Tagging
- Detector Working Group
  - Tracking
  - PID
  - Calorimetry
  - Far-forward detectors
  - DAQ/Electronics
  - Central Detector/Integration & Magnet
  - Forward Detector/IR integration
  - Polarimetry/Ancillary detectors
  - Detector Complementarity



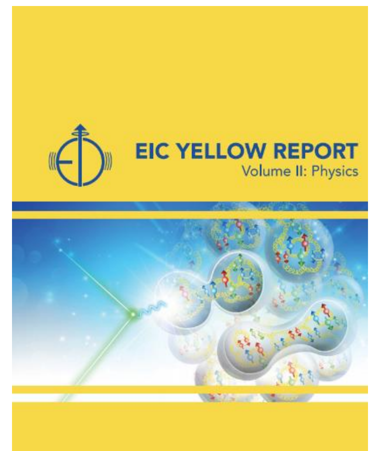
The Yellow Report Outline

Volume I: Executive Summary

Volume II: Physics

- The EIC Physics Case
- EIC Measurements and Studies
- Detector Requirements

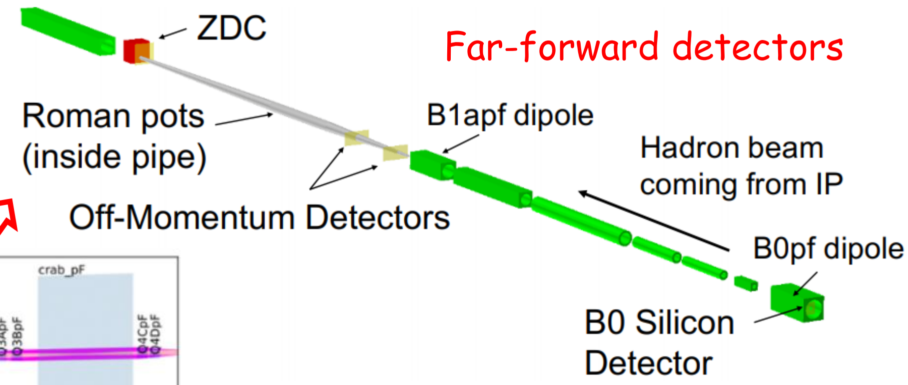
Focus of this talk

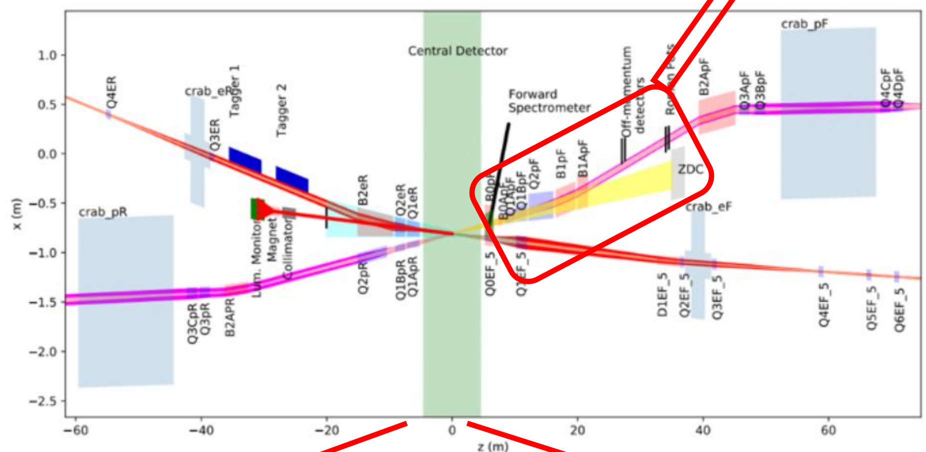


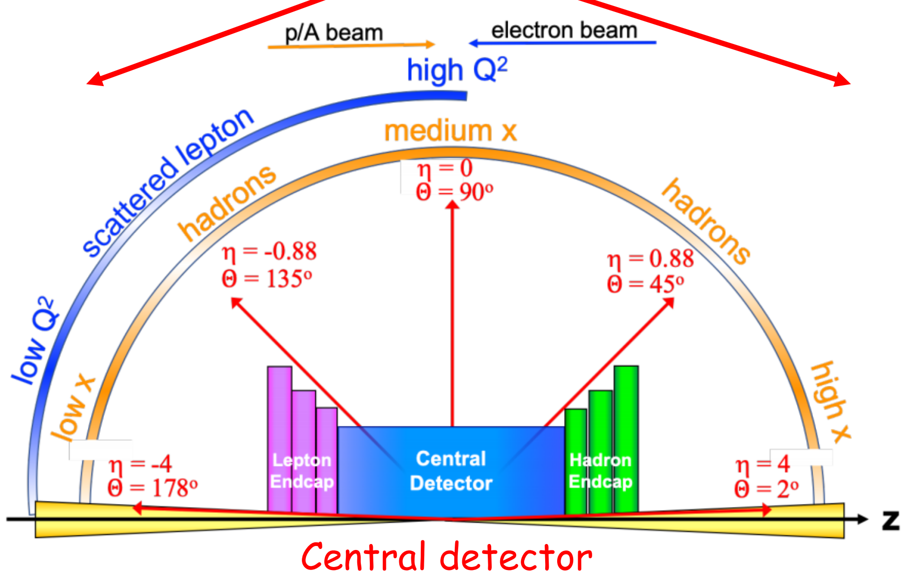
Volume III: Detector

- Detector Challenges & Performance Requirements
- Detector Aspects
- The Case for Two Detectors
- Integrated EIC Detector Concepts
- Detector R&D Goals and Accomplishments

EIC detector layout



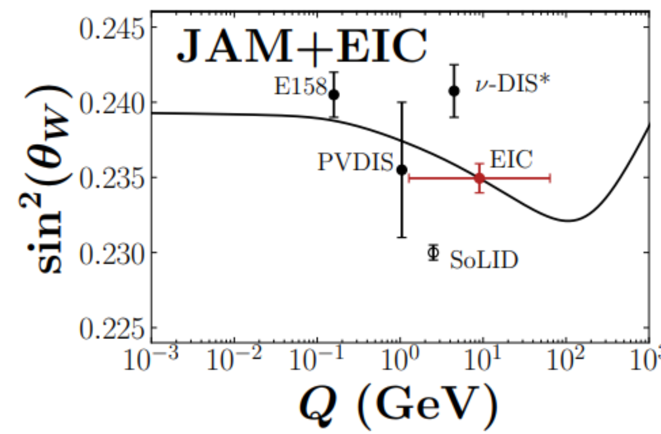


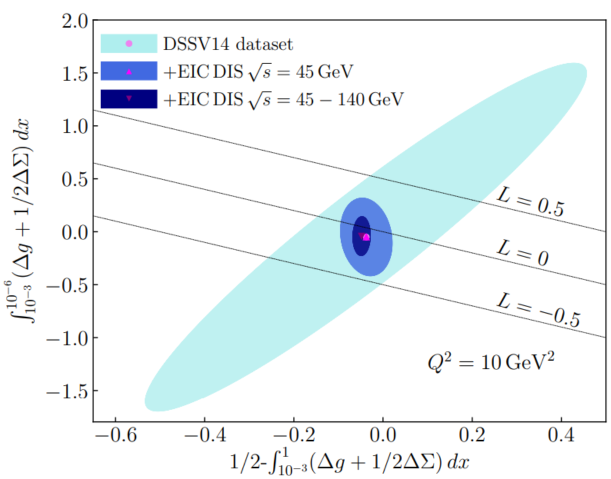


- Asymmetric detector configuration
- Far-forward region critical to many key processes

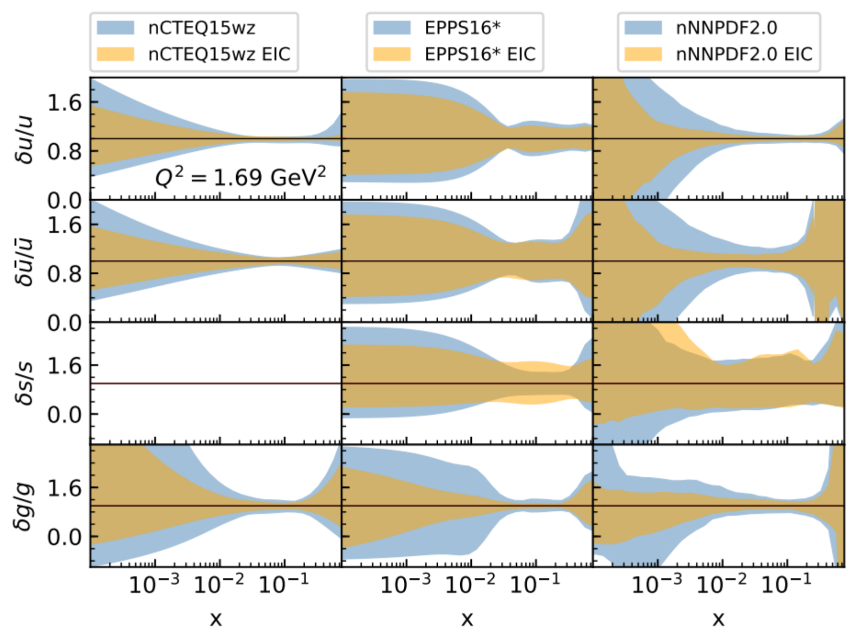
WG 1 - Inclusive reactions: physics topics

- Global properties and parton structure of hadron: unpolarized & polarized PDFs
- Nuclear medium: nuclear PDFs
- Multi-parton correlations: twist-3 PDF $g_T^q(x)$
- Electroweak and BSM physics: weak neutral current measurements

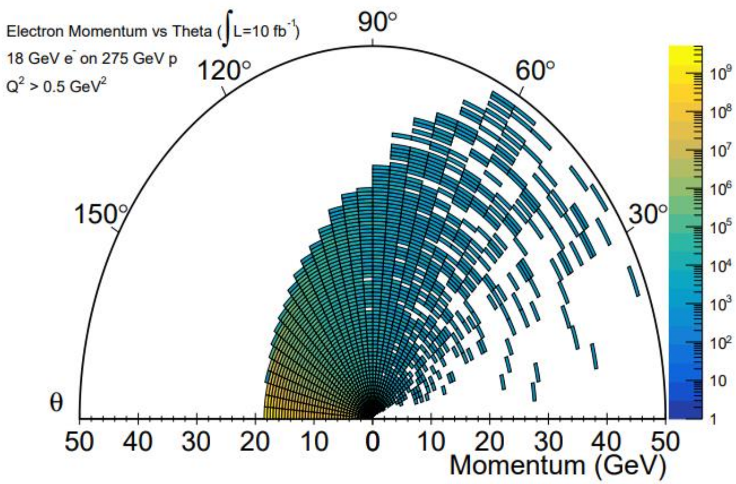


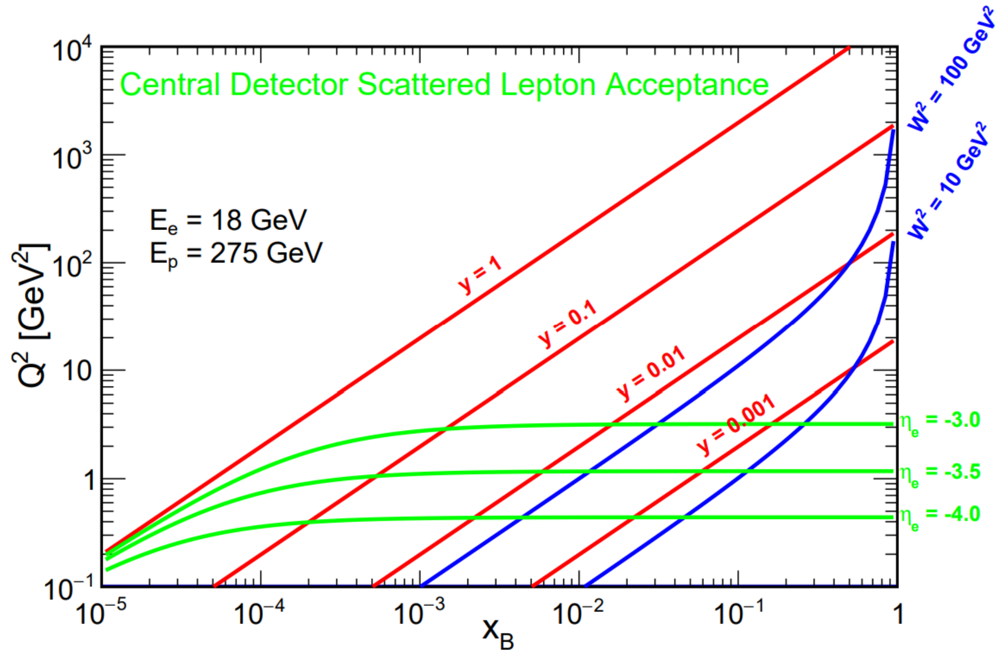


Gold nucleus



WG 1 - Inclusive reactions: acceptance

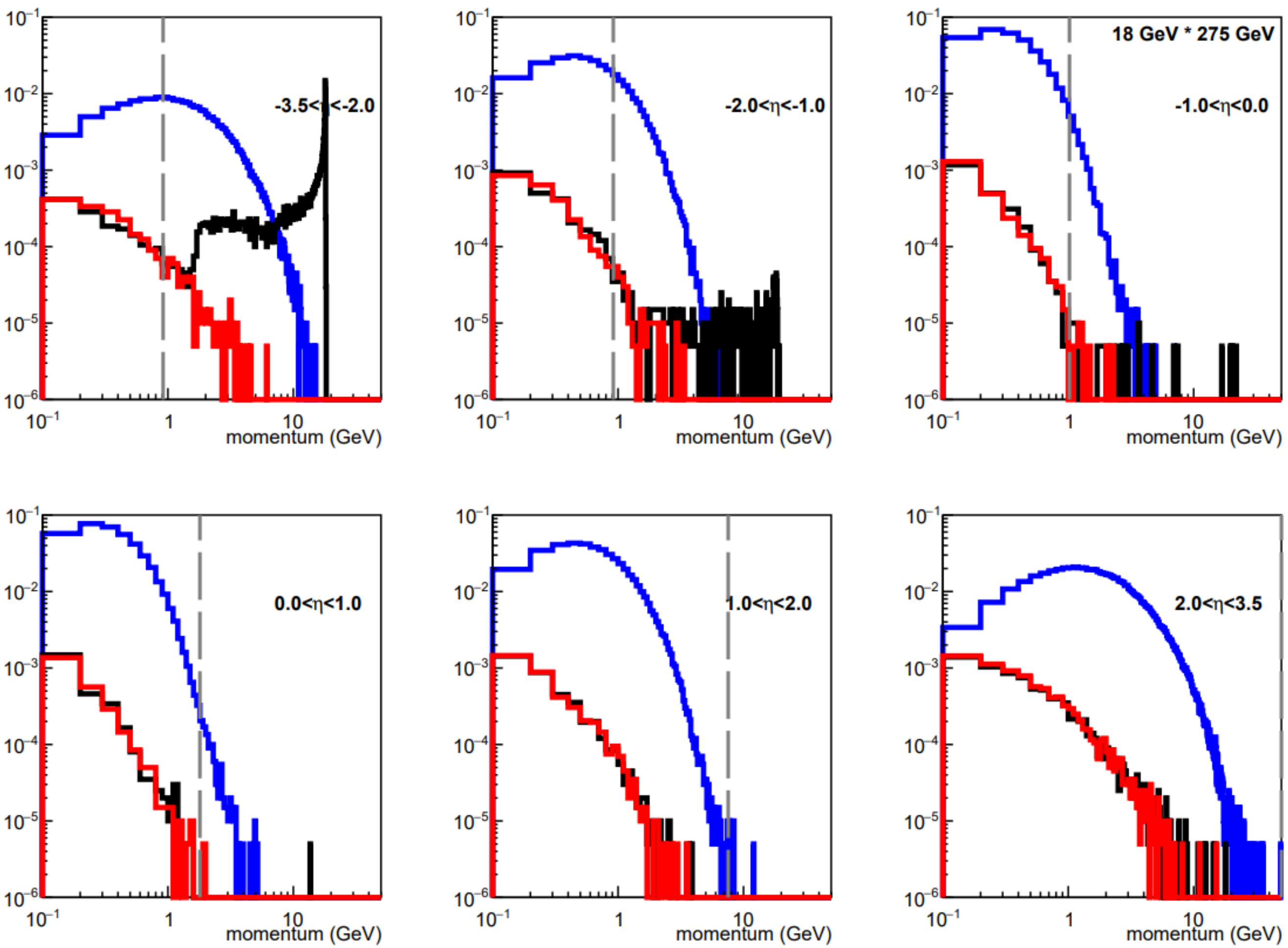




pQCD: $Q^2 > 1\ GeV^2$ & $W^2 > 4\ GeV^2 \rightarrow$

$-3.5 < \eta < 3.5$ coverage sufficient

WG 1 - Inclusive reactions: PID



Electrons
Negative Pions
Positrons

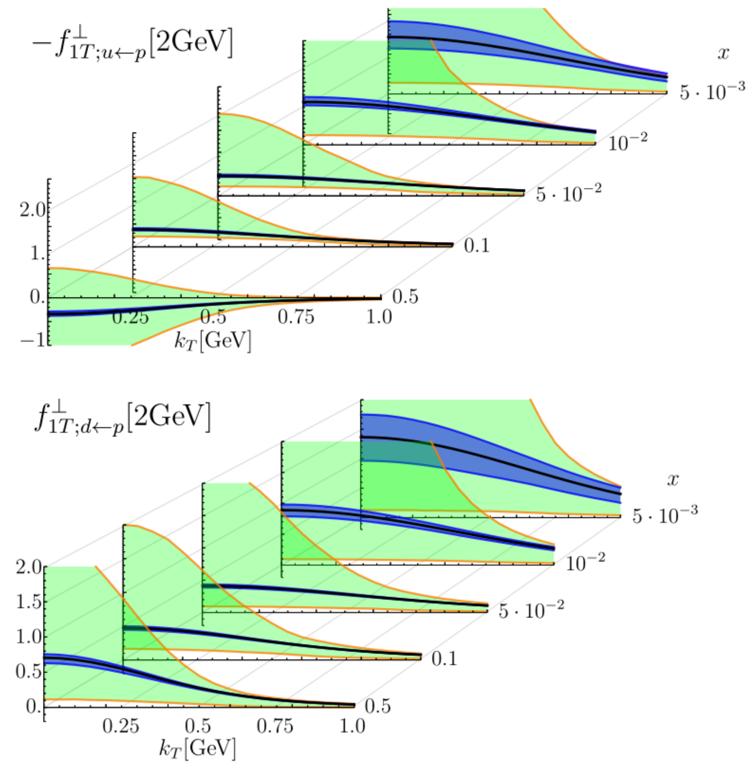
π^- contamination inflates statistical errors

Tightest constraint on PID from parity violating asymmetries A^{e-}_{PV}

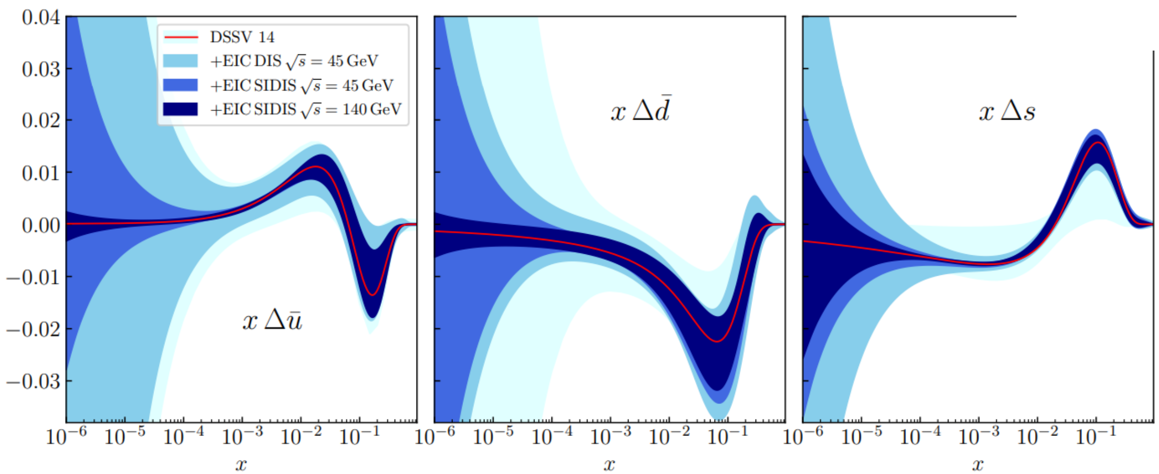
10^4 π^- suppression required

WG 2 – Semi-inclusive reactions: physics topics

- Sea quark PDFs
- Sea quark helicities
- 3D Imaging of the nucleon and nuclei: TMDs
- Photoproduction mechanisms for X,Y,Z states in ep & eA
- X,Y,Z state spectroscopy

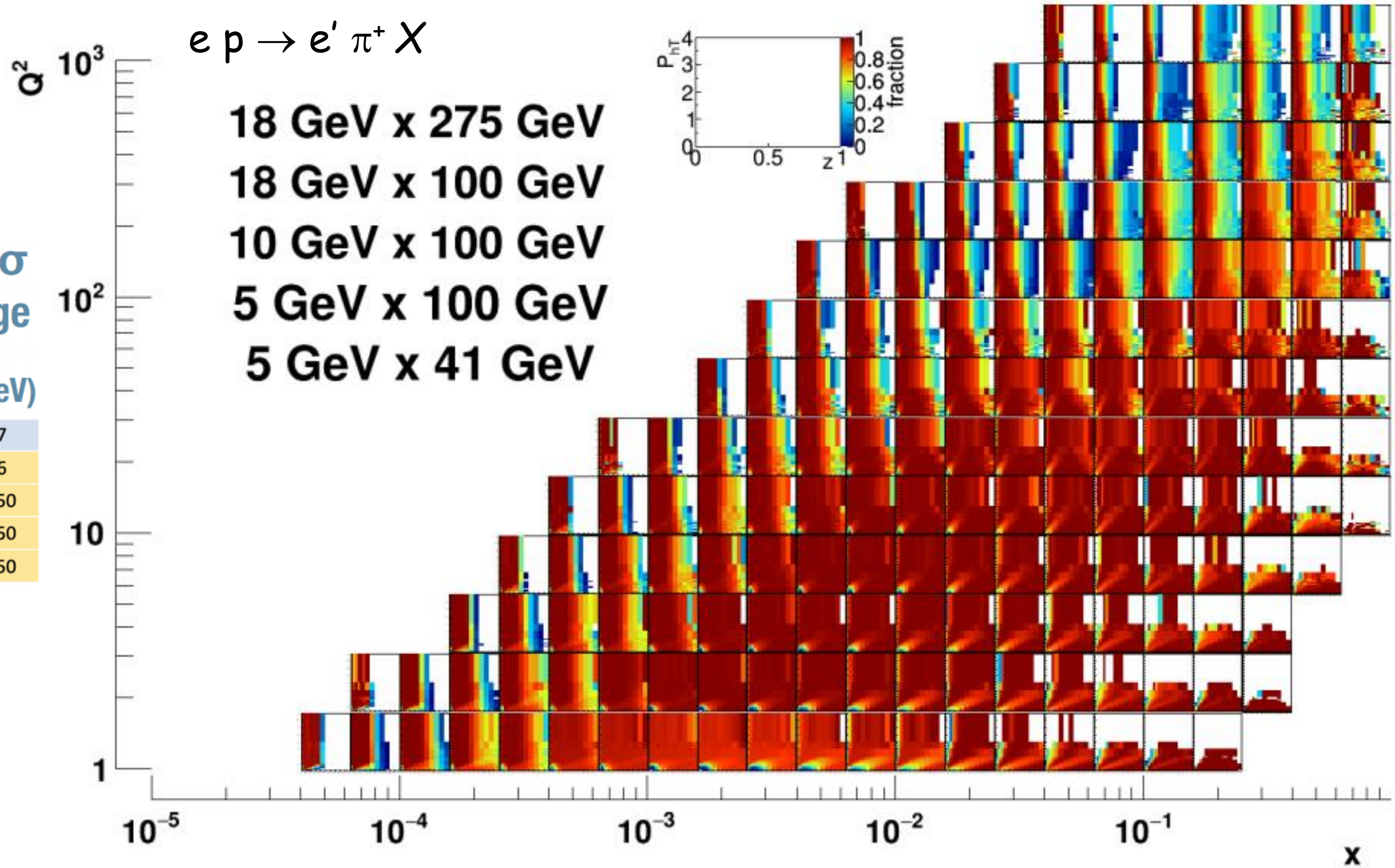


Quark Sivers and Collins measurements



Sea quark helicities from SIDIS at EIC

WG 2 – Semi-inclusive reactions: Hadron PID



Assumed 3σ PID coverage

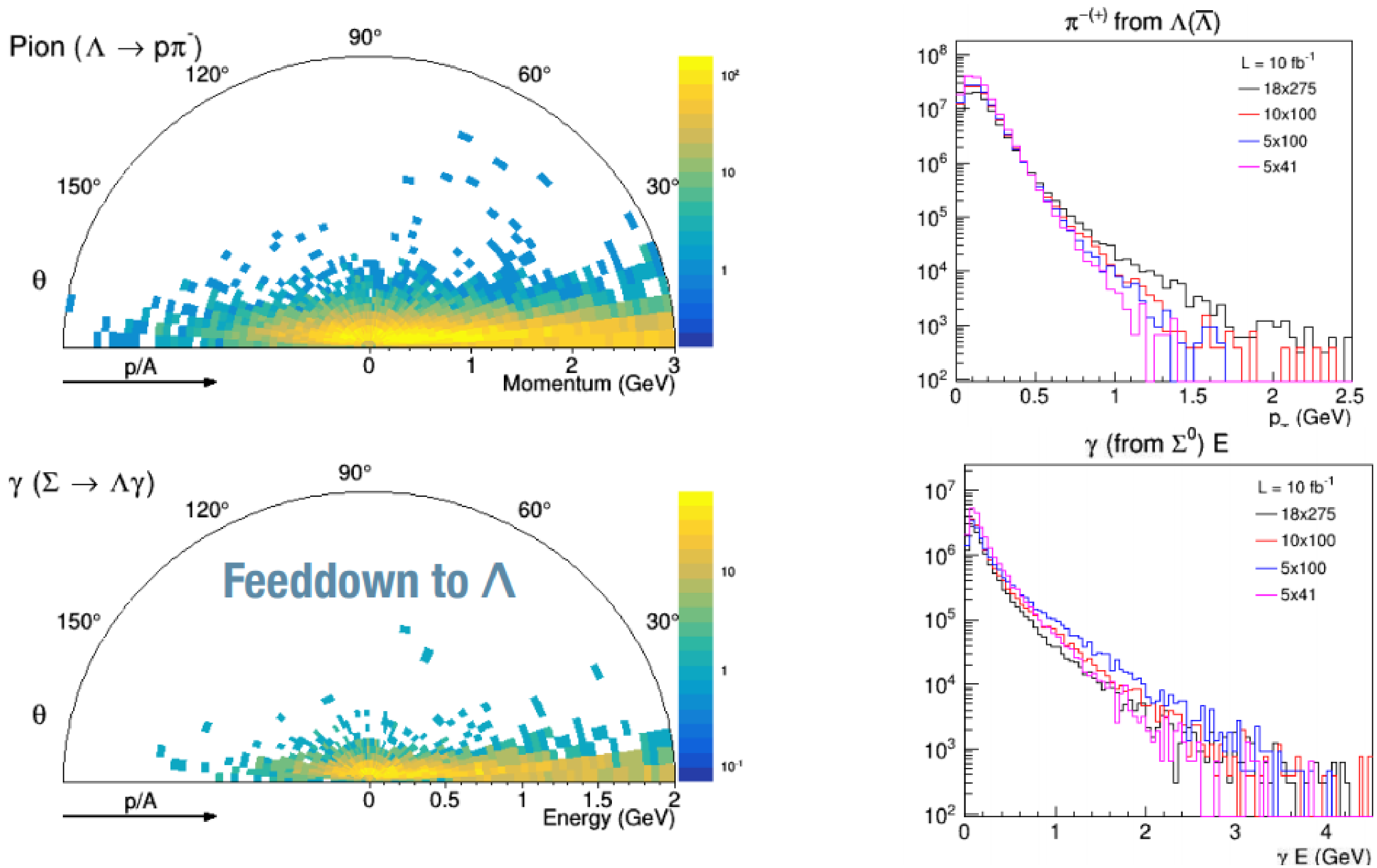
η	p (GeV)
-3.5 - -1.0	0.2 - 7
-1.0 - 1.0	0.2 - 6
1.0 - 2.0	0.2 – 50
2.0 - 3.0	0.5 – 50
3.0 - 3.5	0.5 – 50

- High z/p_T limited in some cases by barrel PID p<6 GeV
- Impact at intermediate x-Q2 compensated by different beam energies, when using existing models for TMD extraction

WG 2 - Semi-inclusive reactions: Minimum p_T

$$ep \rightarrow e'\Lambda X$$

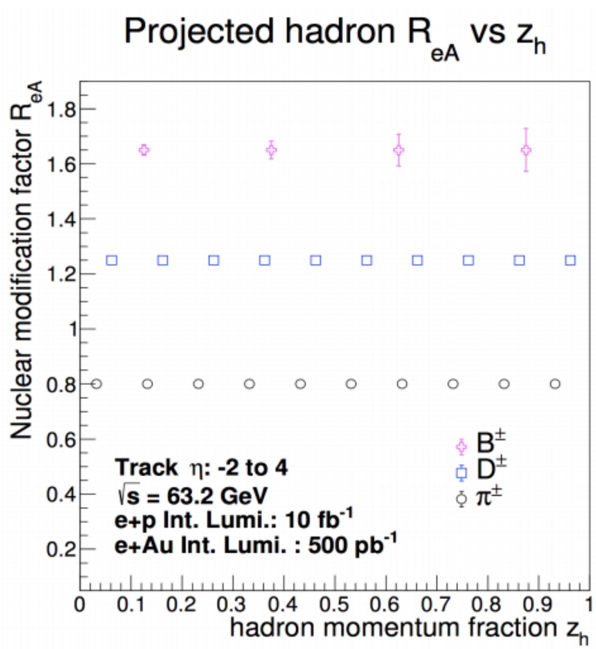
18x275 GeV



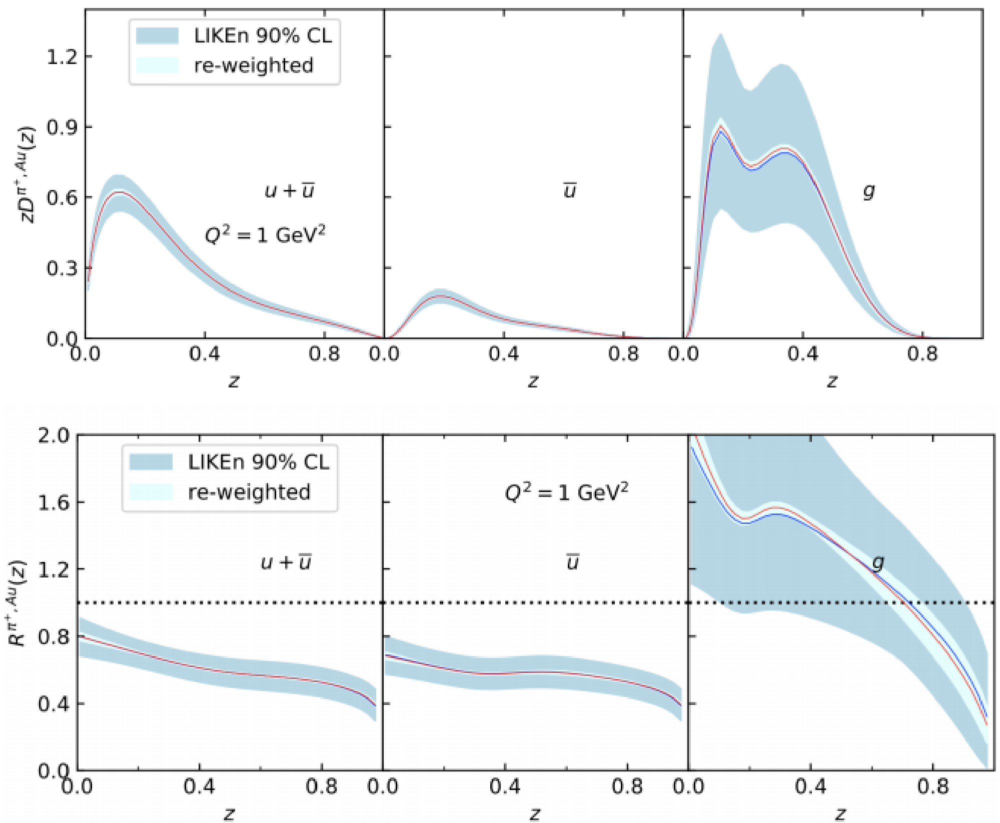
- 100 MeV p_T detection required for efficient Λ detection
- Σ feeddown rejection requires $E\gamma$>200 MeV for η<3 and $E\gamma$>400 MeV for η>3

WG 3 – Jets and Heavy Quarks: physics topics

- Helicity dependence in charm production
- Particle propagation through matter
- Hadronization in the vacuum and in the nuclear medium
- Quarkonia
- Gluon saturation
- Jet production in polarized DIS
- Jet-based TMD measurements



Nuclear fragmentation functions:
effect of 10 fb^{-1} at EIC

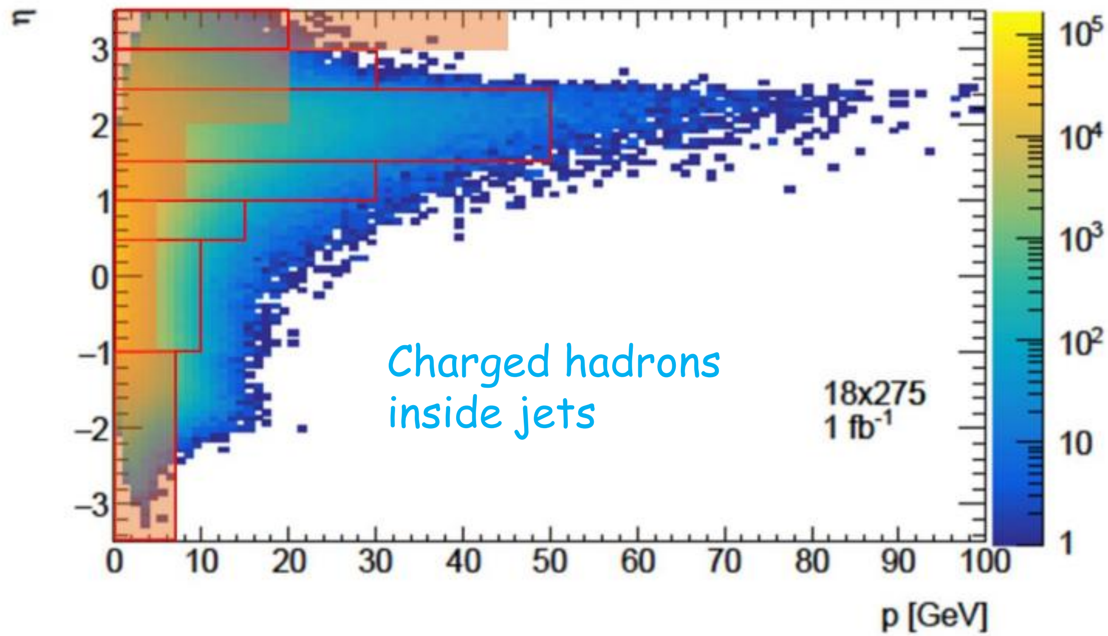


WG 3 – Jets and Heavy Quarks: PID

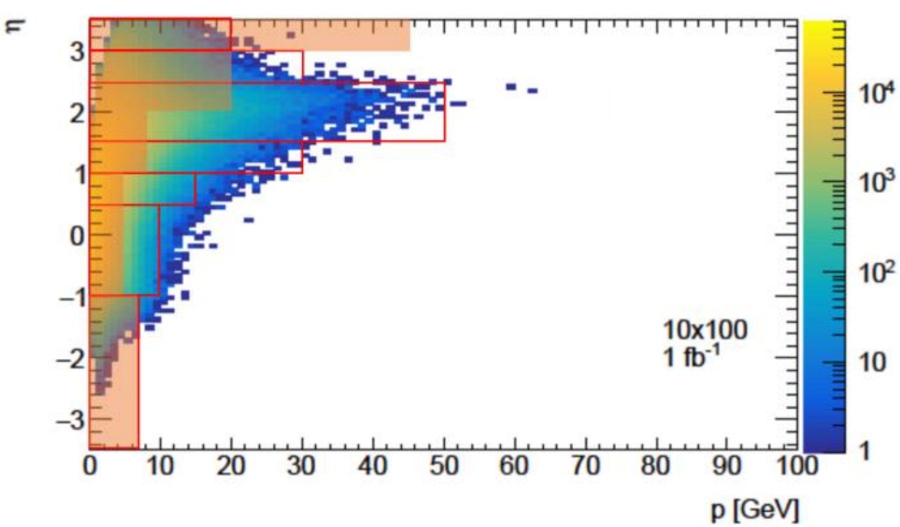
PID Momentum Coverage

Eta Range	Default Momentum Coverage	Requested Momentum Coverage
-3.5 < η < -1.0	≤ 7 GeV	Same
-1.0 < η < 0.0	≤ 5 GeV	≤ 10 GeV
0.0 < η < 0.5		
0.5 < η < 1.0		≤ 15 GeV
1.0 < η < 1.5	≤ 8 GeV	≤ 30 GeV
1.5 < η < 2.0		≤ 50 GeV
2.0 < η < 2.5	≤ 20 GeV	
2.5 < η < 3.0		≤ 30 GeV
3.0 < η < 3.5	≤ 45 GeV	Can tolerate ≤ ~20 GeV

18x275



10x100

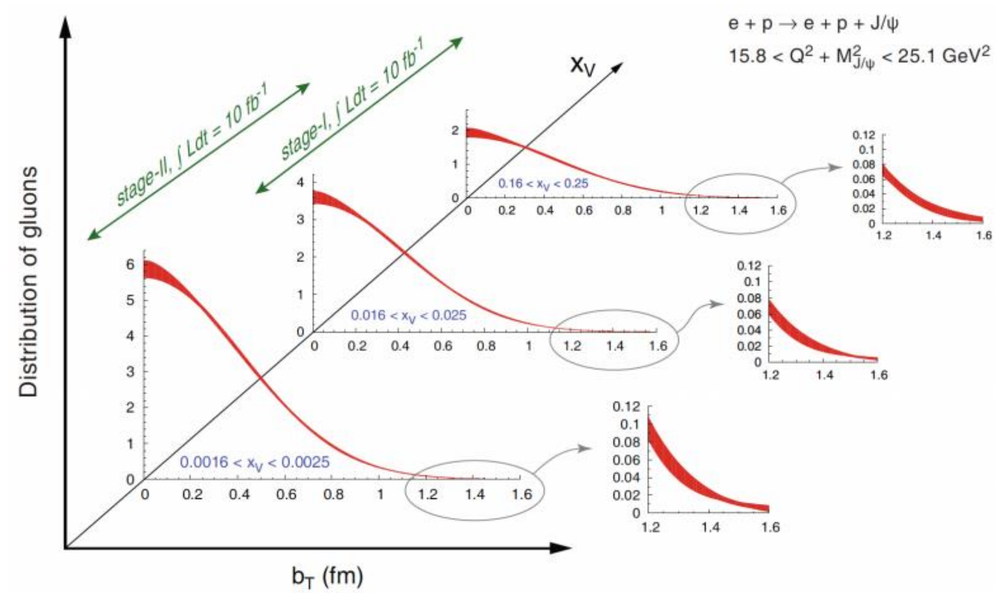


Reduction of particle momenta at highest (and lowest) eta are due to jet radius

Hadron PID required up to large values of momenta

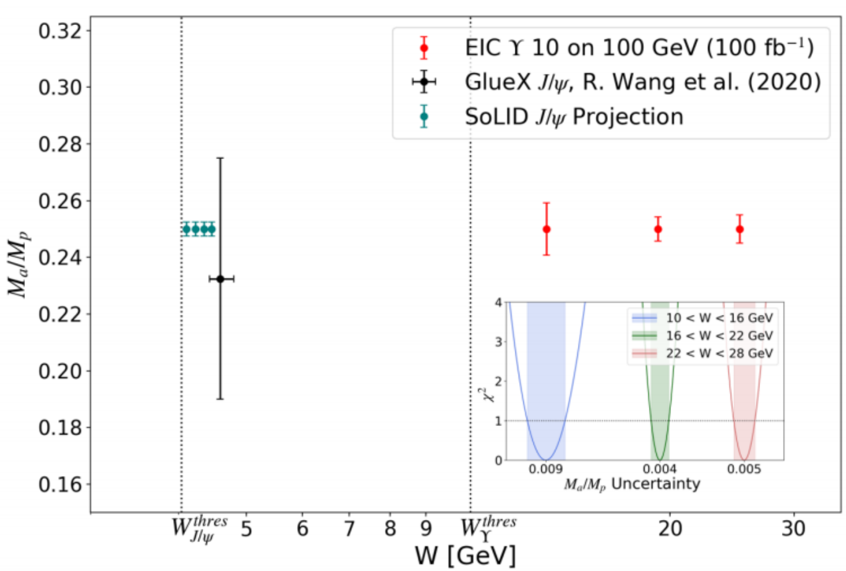
WG 4 – Exclusive reactions: physics topics

- 3D imaging of the nucleon and nuclei: GPDs
- Origin of nucleon mass
- Wigner functions

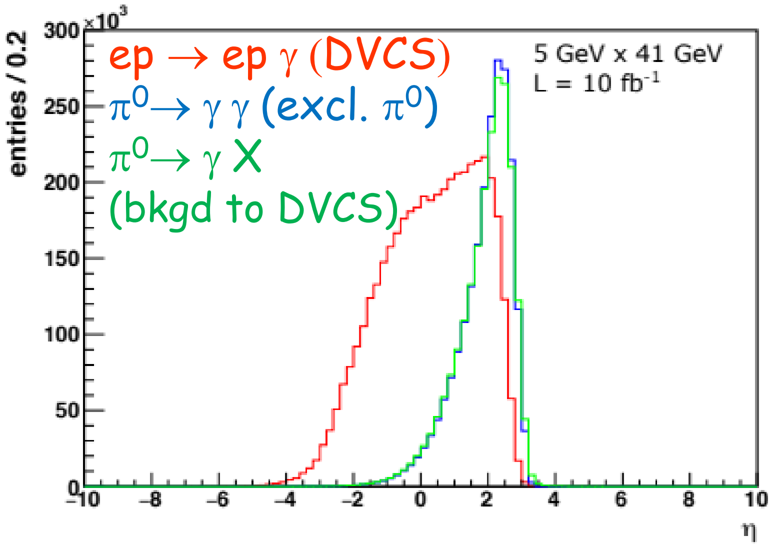


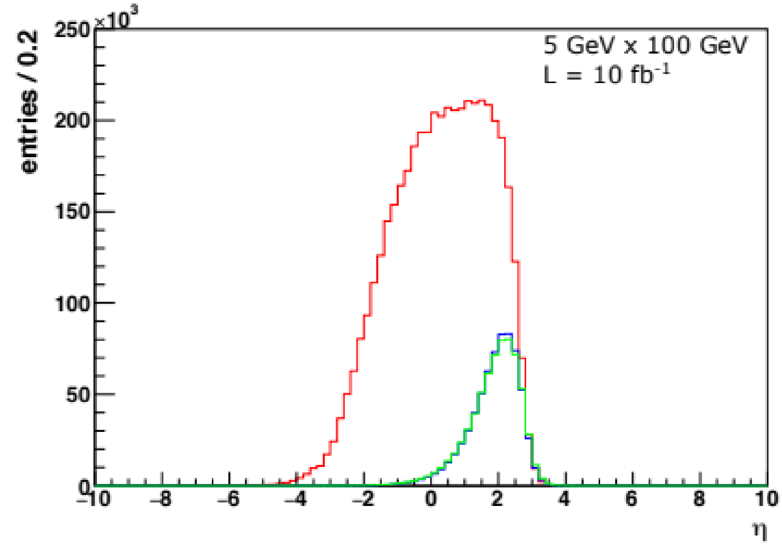
Gluon 3D imaging from J/ψ production

Trace anomaly contribution to the proton mass (Υ production)

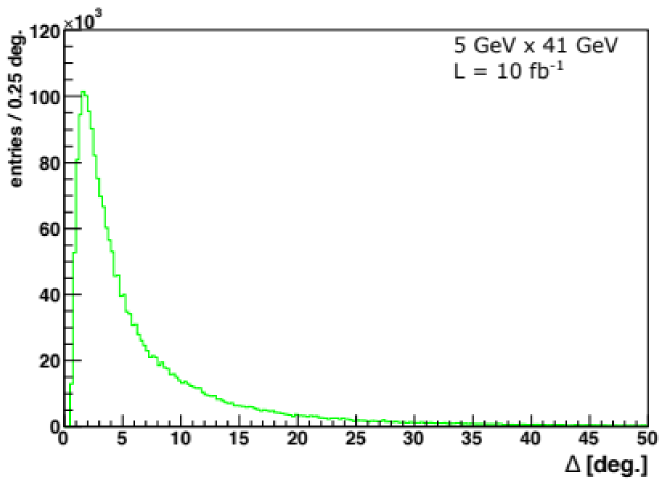


WG 4 – Exclusive reactions: ECAL granularity

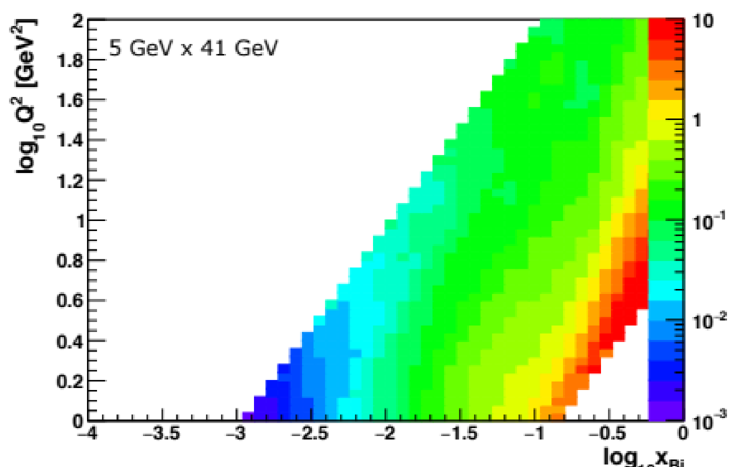




Separation of photons from π^0 decays is crucial for DVCS

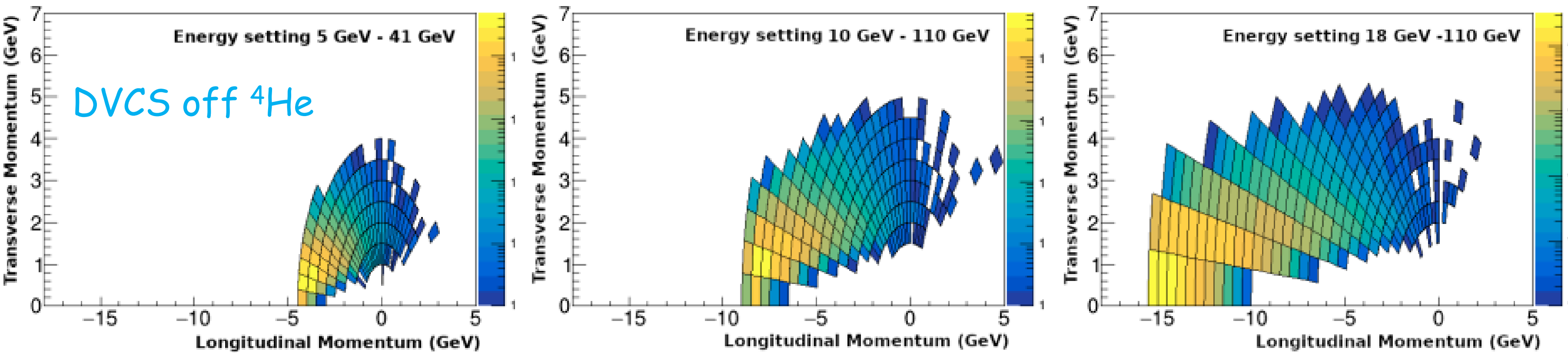


Opening angle $\pi^0 \to \gamma\gamma$

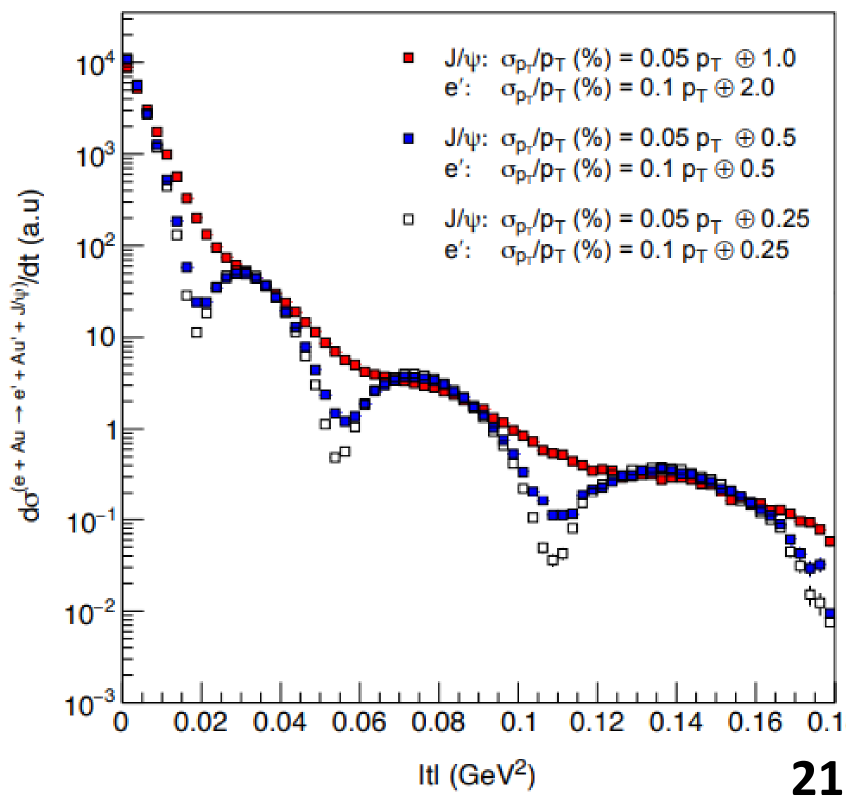


Ratio of π^0/γ

WG 4 – Exclusive reactions: far-forward acceptance



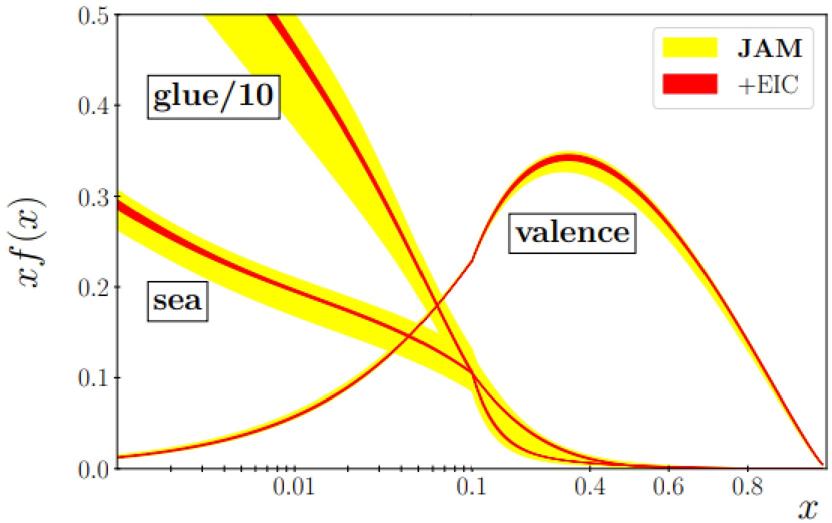
- Excellent hermeticity required: $-4<\eta<4$ in central detector
- p_T measured at Roman Pots down to 0.2 GeV required for DVCS (even less for exclusive vector meson production)
- High resolution tracking: $\sigma_{pT}/p_T(\%) < 0.05\ p_T \oplus 0.5$
- Muon detection useful for vector meson production and Time-like Compton Scattering (combinatorial background reduction)
- Photon detection in ZDC required to suppress incoherent processes



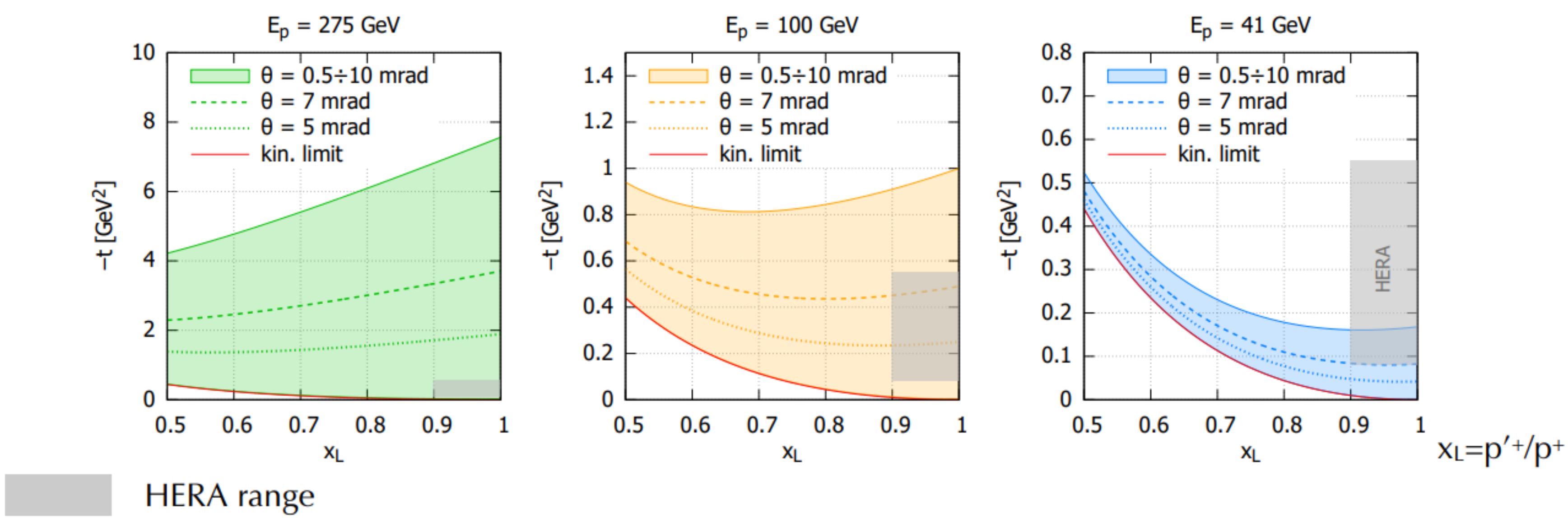
WG 5 – Diffractive & Tagging: physics topics

- Meson structure
- Structure of light nuclei
- Short-range correlations

Pion PDFs

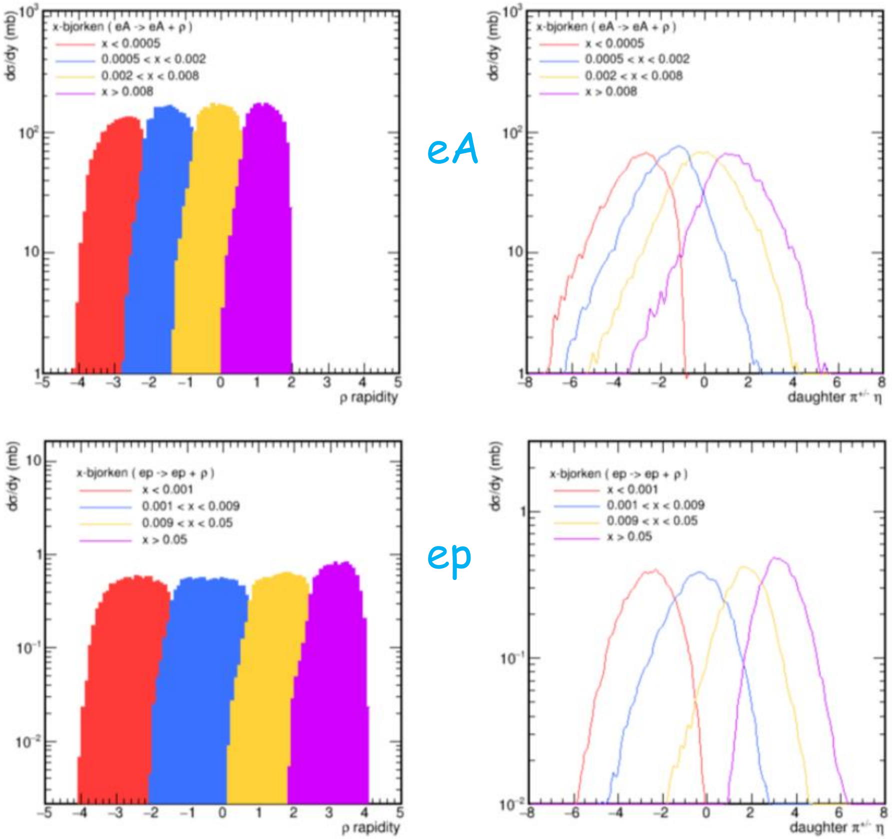


Inclusive diffraction



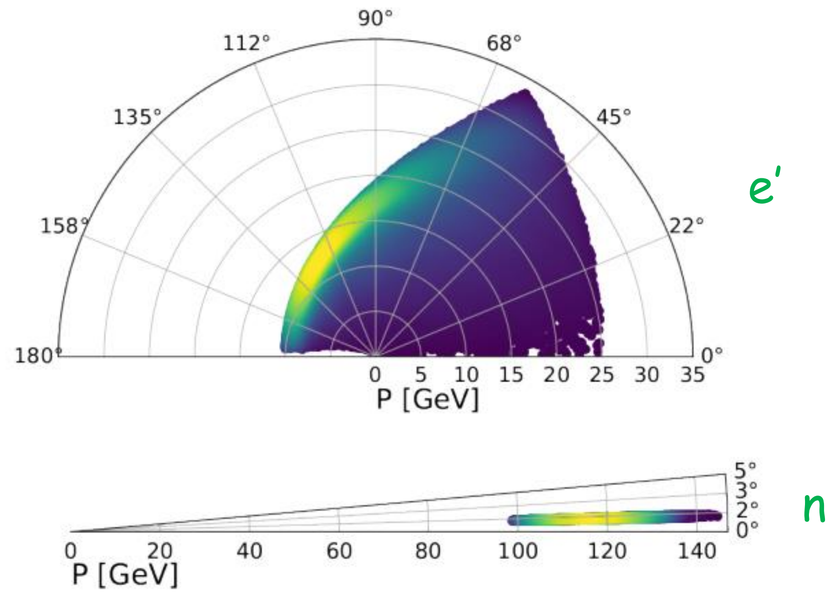
WG 5 – Diffractive & Tagging: hermeticity

Coherent ρ photoproduction



Sullivan process for pion structure:

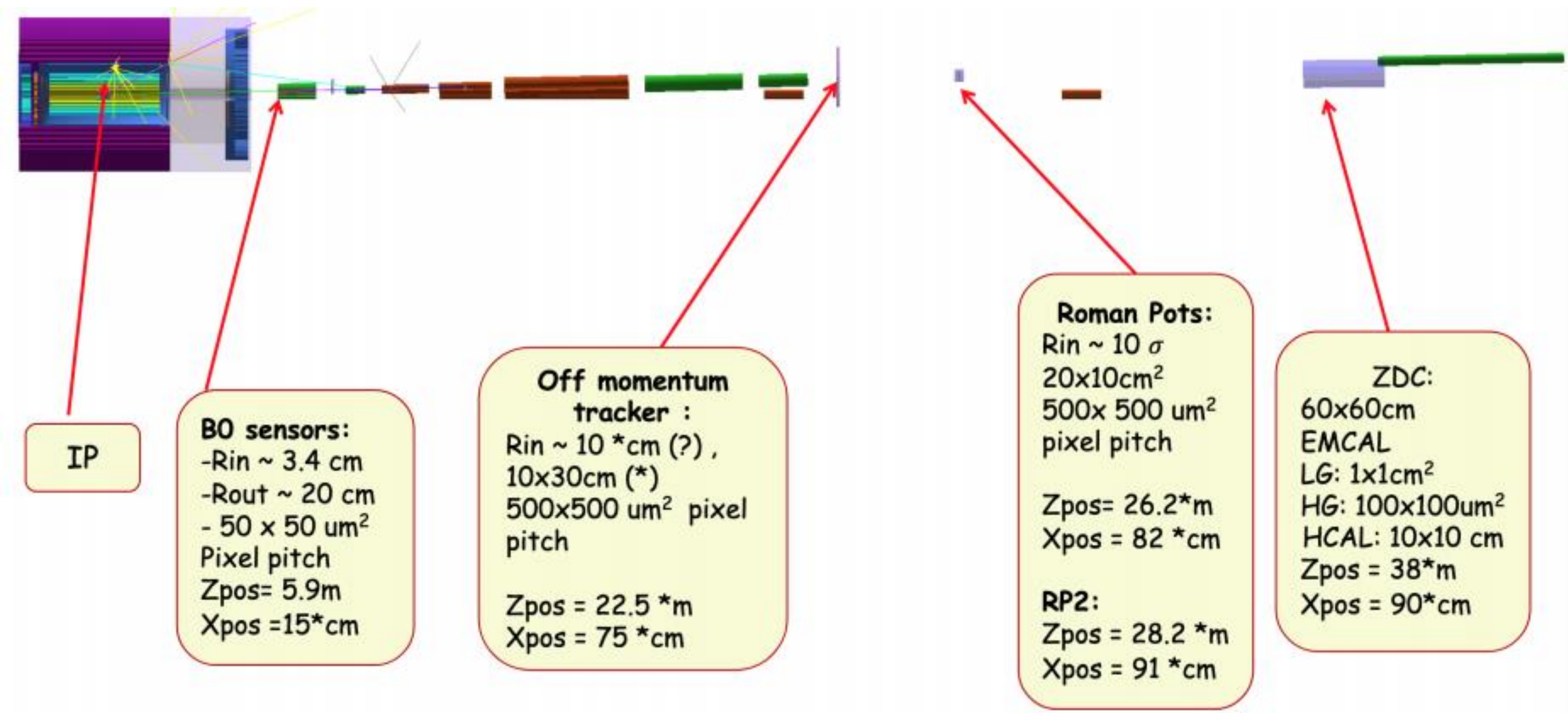
$$e + p \rightarrow e' + X + n$$



- Pseudorapidity coverage directly matches into x_B acceptance
- Separating coherent & incoherent reactions require detection of low enegy photons (>50 MeV) from some nuclear deexcitations

WG 5 – Diffractive & Tagging: far-forward region

Detailed acceptance and resolution requirements driven by meson structure physics :



Summary of requirements

η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2										
…															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						$2\%/\sqrt{E}+(1\text{-}3)\%$						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						~$50\%/\sqrt{E}+6\%$	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p + 2.0\%$	~5% or less	$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$			π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~500 MeV	~$45\%/\sqrt{E}+6\%$	Useful for bkg, improve resolution
-3.0 — -2.5															
-2.5 — -2.0															
-2.0 — -1.5					$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$		$7\%/\sqrt{E}+(1\text{-}3)\%$						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p + 0.5\%$		$\sigma_{xyz} \sim 20$ µm, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV µm + 5 µm		$(10\text{-}12)\%/\sqrt{E}+(1\text{-}3)\%$		≤ 10 GeV/c			~$85\%/\sqrt{E}+7\%$	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$			3σ e/π	≤ 30 GeV/c			~$35\%/\sqrt{E}$	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p + 2.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$				≤ 30 GeV/c				
3.0 — 3.5							$\sigma_{xy} \sim 30\mu m/p_T + 60\mu m$				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
…															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c										

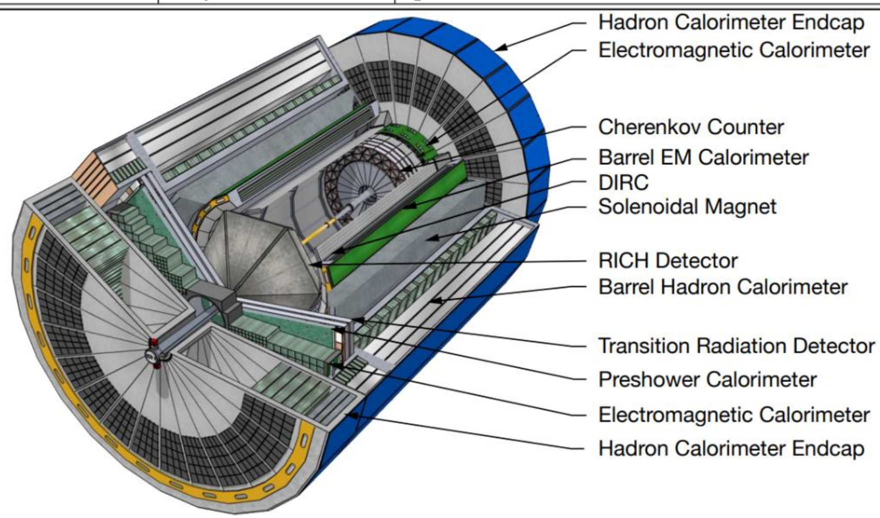
Summary of requirements

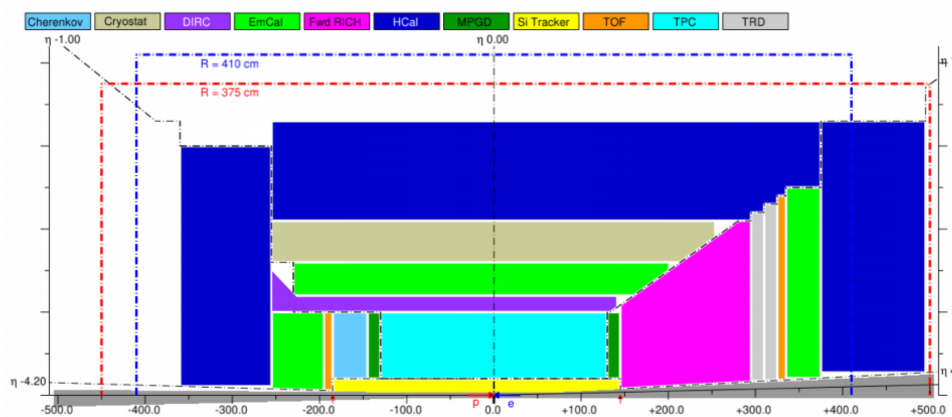
- Hermeticity: $-4 < \eta < 4$ in the central detector is crucial (exclusive & diffractive channels)
- Momentum resolution in central region:
  DIS and SIDIS channels that use the hadronic state to reconstruct kinematics
- Miminum p_T: 100 MeV for pions, 135 MeV for kaons
- Vertex resolution: driven by heavy flavor reconstruction (σ_{xy}~20 μm /$p_T \oplus$ 5 μm)
- Electron ID: π suppression of 10^4 for eg. PVDIS. 3σ e/π separation for spectroscopy
- γ detection threshold:
  driven by need to separate coherent/incoherent in vector meson production
- Hadron ID: required over a large momentum range for SIDIS/TMD measurements
- ECAL: 10-12%/$\sqrt{E}\oplus$1-3% in central region for jets, 1-2%/$\sqrt{E}\oplus$1-3% at backwards rapidities (DIS electron reconstruction)
- HCAL: 50%/$\sqrt{E}\oplus$10% (jets), with a minimum threshold of 500 MeV

In addition: far-forward requirements mentioned before

The EIC reference detector

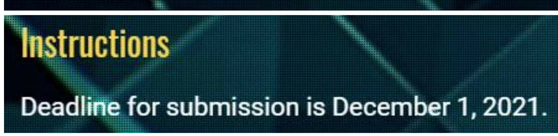
system	system components	reference detectors	detectors, alternative options considered by the community		
tracking	vertex	MAPS, 20 um pitch	MAPS, 10 um pitch		
	barrel	TPC	TPC[a]	MAPS, 20 um pitch	MICROMEGAS[b]
	forward & backward	MAPS, 20 um pitch & sTGCs[c]	GEMs	GEMs with Cr electrodes	
	very far-forward & 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			





Conclusion and Outlook

- ✓ The EIC User Group initiated an enormous effort during 2020 to define the requirements of a future EIC detector
- ✓ The EIC Yellow Report released last month details the studies that led to the outline of a "Reference Detector" that will address the physics of the future EIC



Back up

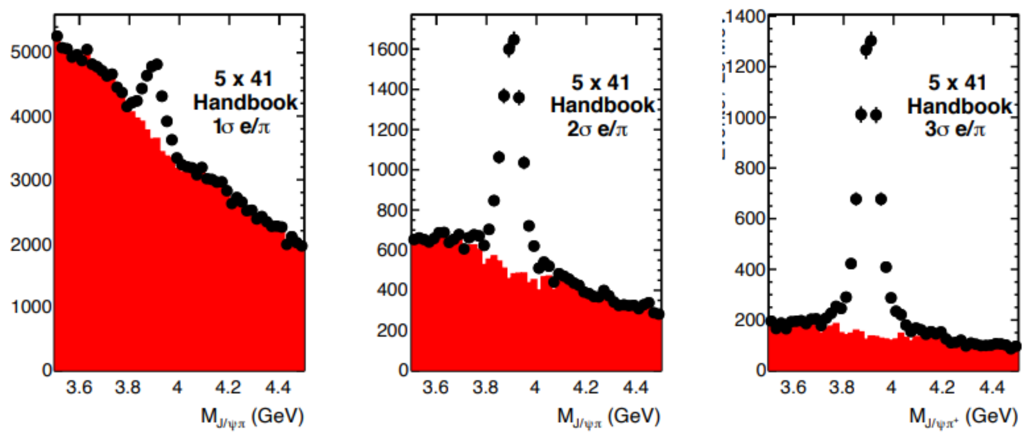
Topics \ Processes	Inclusive	Semi-Inclusive	Jets, Heavy Quarks	Exclusive	Diffractive, Forward Tagging
Global properties & parton structure	**incl. SF**	**h, hh**	**jet, Q**	**excl. $Q\overline{Q}$**	**incl. diffraction, tagged DIS on D/He**
Multidimensional Imaging		**h**	**jet, di-jet, jet+h, Q, $Q\overline{Q}$**	**DVCS, DVMP, elast. scattering**	
Nucleus	**incl. SF**	**h, hh**	**jet, di-jet, Q, $Q\overline{Q}$**	**coh. VM, di-jet, h, hh, D/He FF**	**diffr. SF, incoh. VM, di-jet, h, hh, nucl. fragments**
Hadronization		**h, hh, jet+h**	**jet, Q, $Q\overline{Q}$**		
Other fields	**incl. SF with e^+, $\sigma_{\gamma A}^{tot}$**	**charged curr. DIS, $\sigma_{\gamma A \to hX}$**		$\sigma_{\gamma A}^{elast}$	$\sigma_{\gamma A}^{diffr}$

Table 6.1: Relationship between the EIC science topics (rows) and the categories of measurements (columns). Measurements already discussed in the White Paper [2] or the NAS Report [1] are highlighted in red. Various additional measurements and physics ideas that have emerged since are also included in this table, but the table is not meant to be exhaustive. "Other fields" refers to neutrino, cosmic-ray and high-energy physics. The acronym "SF" refers to structure function, "FF" to form factor, "h" to identified hadrons, Q to heavy quarks; $Q\overline{Q}$ to heavy-quark bound states (quarkonium), and "VM" to vector mesons.

WG 2 – Semi-inclusive reactions: Electron PID

$$\gamma p \rightarrow Z_c^+ n, \;\; Z_c^+ \rightarrow J/\psi \pi^+$$

- Central detector coverage impacts acceptance at lower energies
- 3σ e/π separation for η>1 required to achieve desired purity



$$J/\psi \rightarrow e^+ e^-$$

5x41 GeV

18x275 GeV