Two detectors at EIC – cross checks

(Summary of the key measurements highlighted in the Yellow Report and thereby motivate baseline requirements of a 2nd detector)

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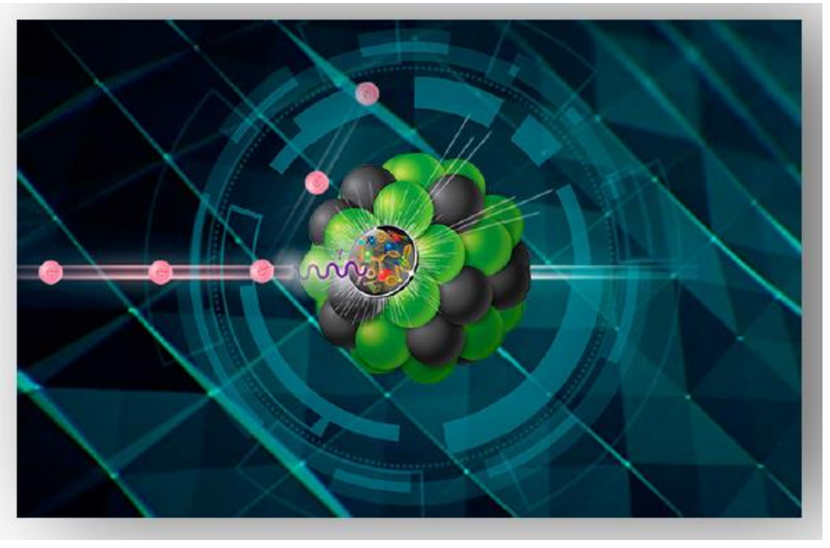
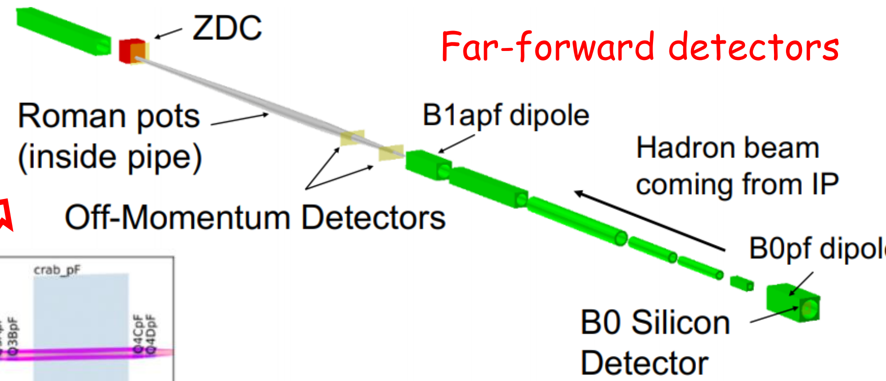
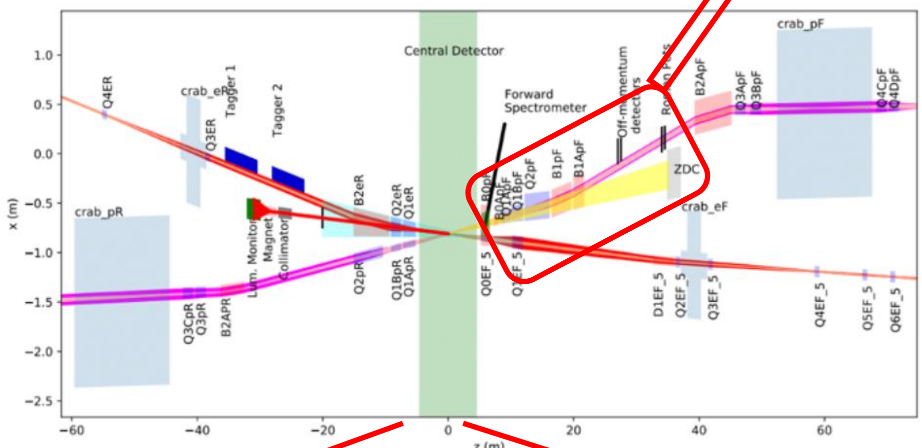
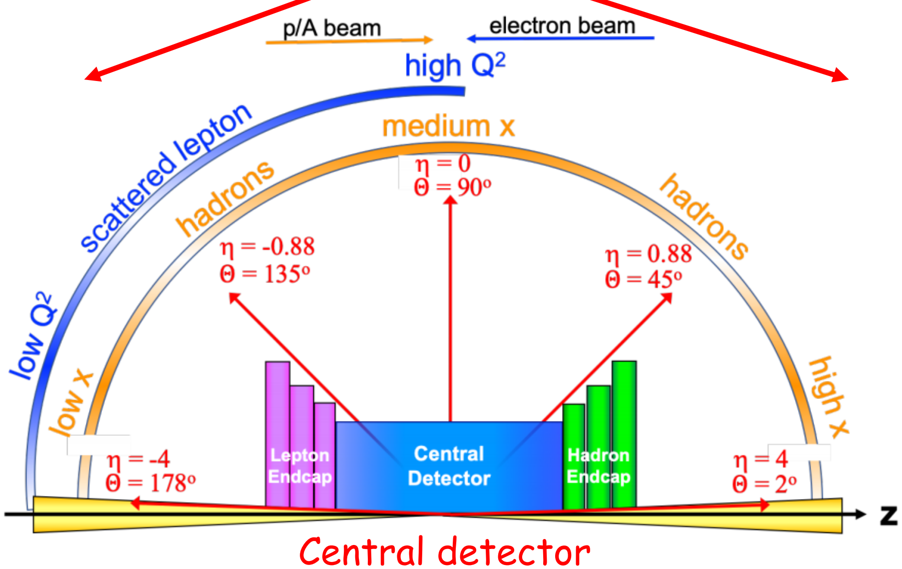
EICUG 2nd detector meeting
Dec 6-8, 2022
CFNS



EIC detector layout



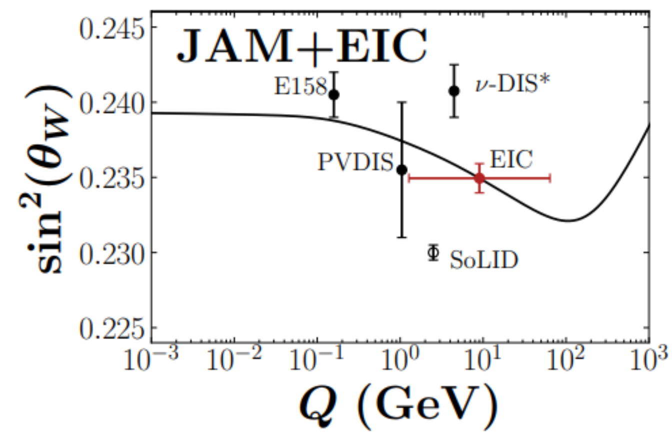


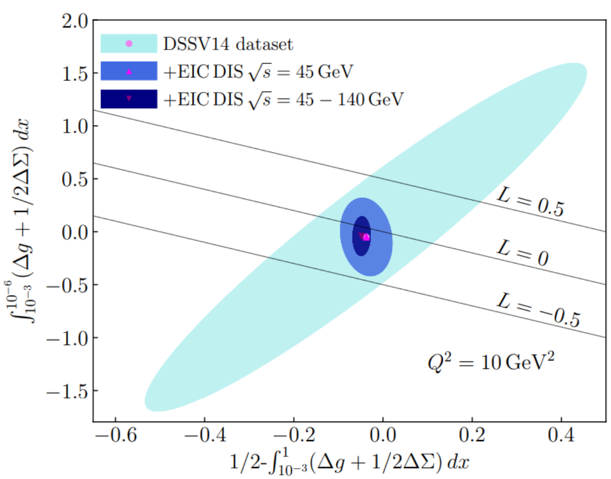


- Asymmetric detector configuration
- Far-forward region critical to many key processes

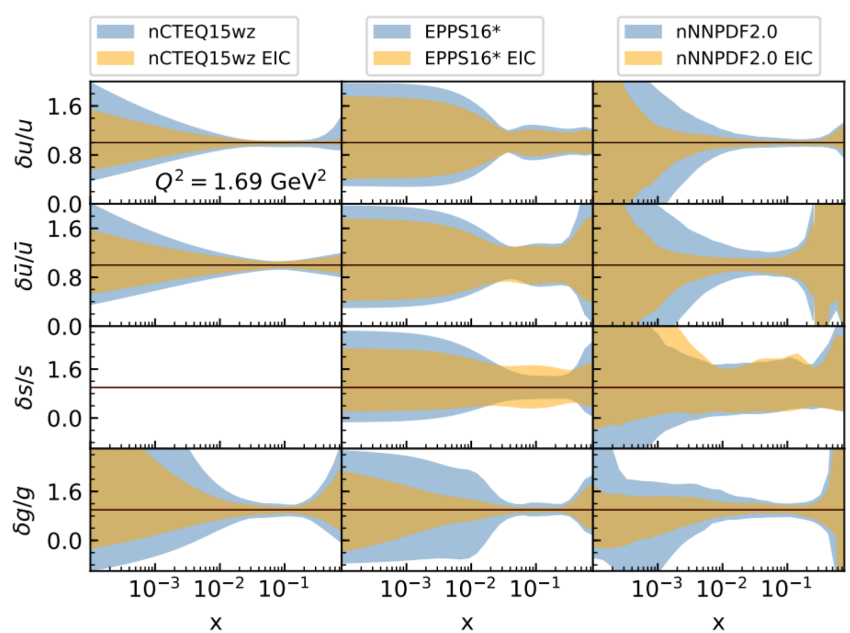
WG 1 - Inclusive reactions: physics topics

- 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

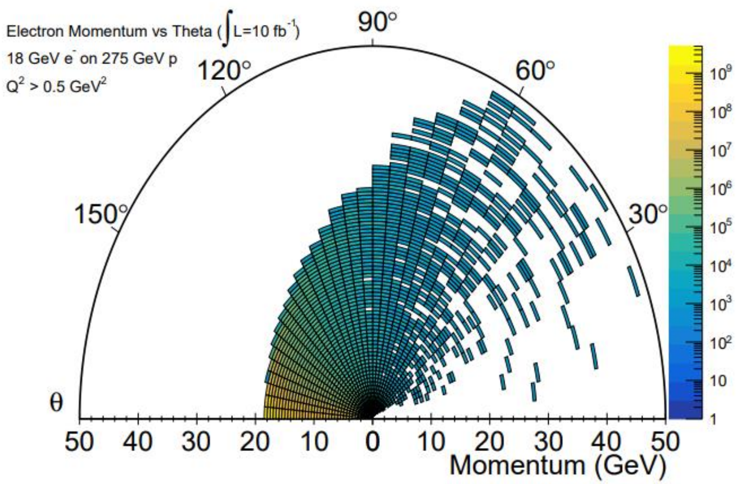


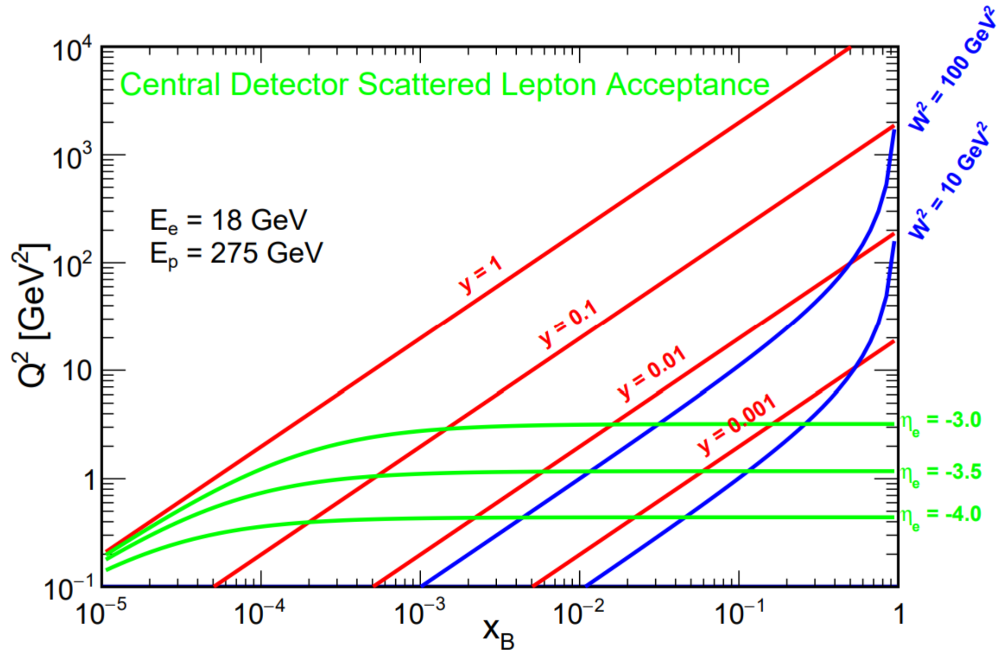


Gold nucleus



WG 1 - Inclusive reactions: acceptance

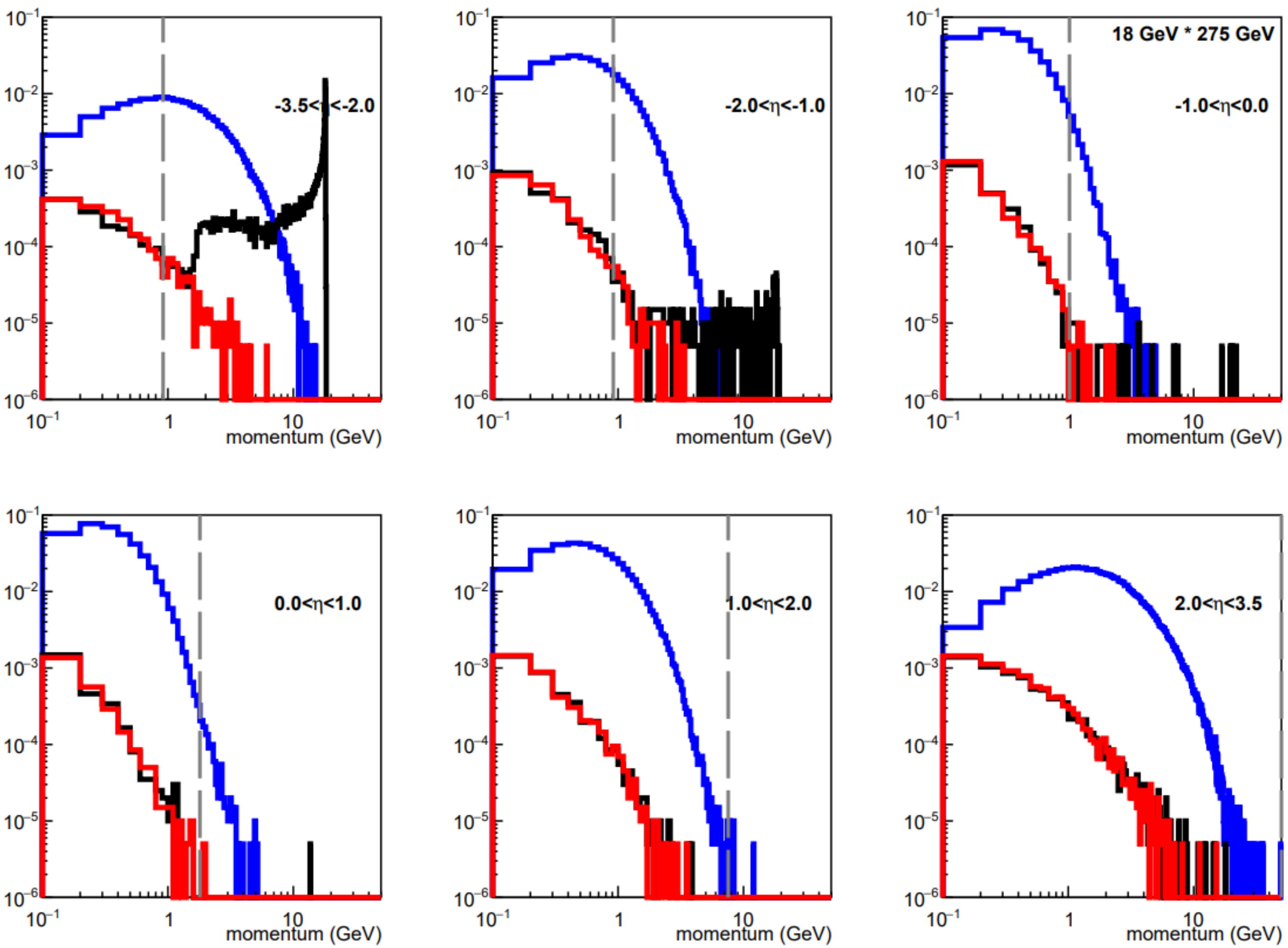




pQCD: $Q^2 > 1$ GeV^2 & $W^2 > 4$ GeV^2 $\rightarrow$

-3.5< η <3.5 coverage sufficient

WG 1 - Inclusive reactions: PID



Electrons
Negative Pions
Positrons

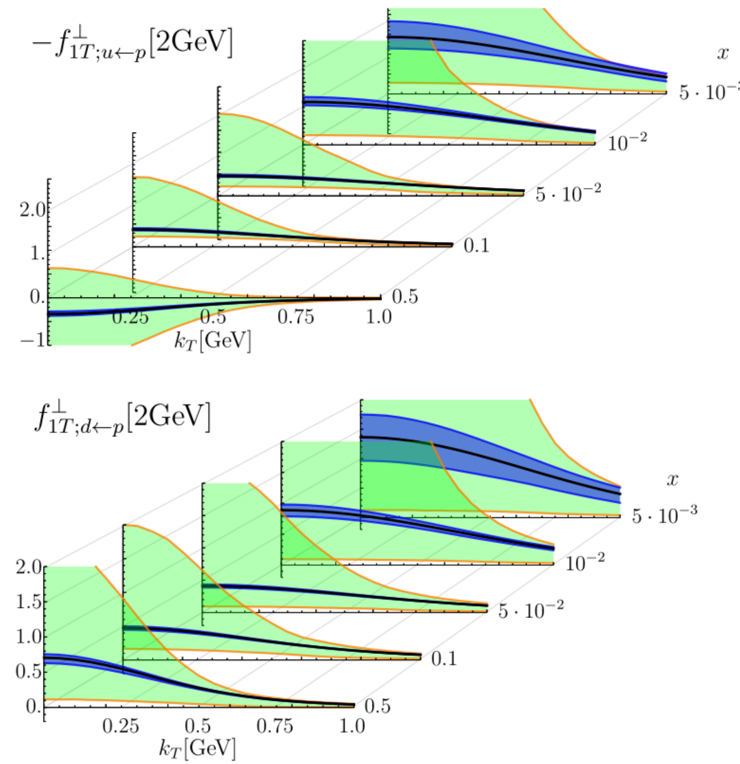
π^- contamination inflates statistical errors

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

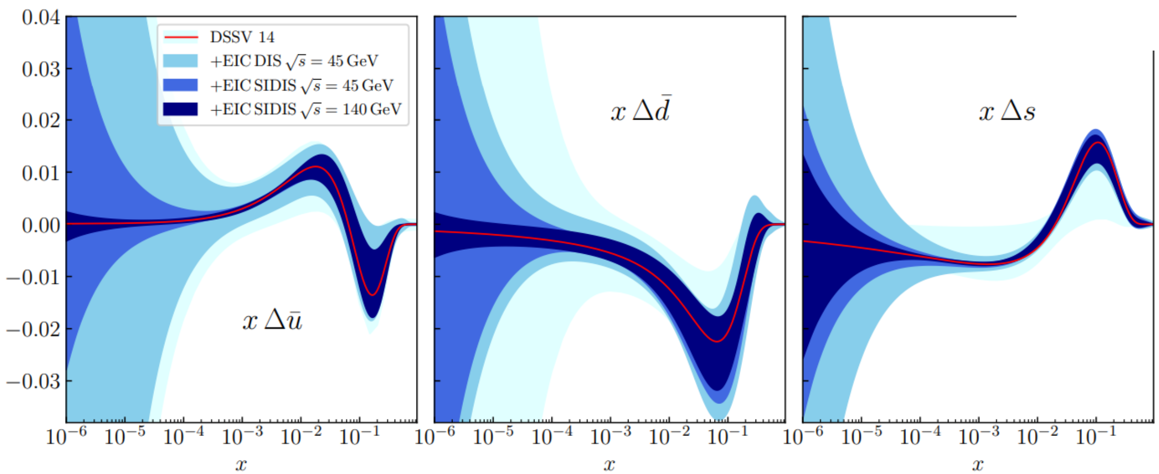
10^4 π^- suppression required

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

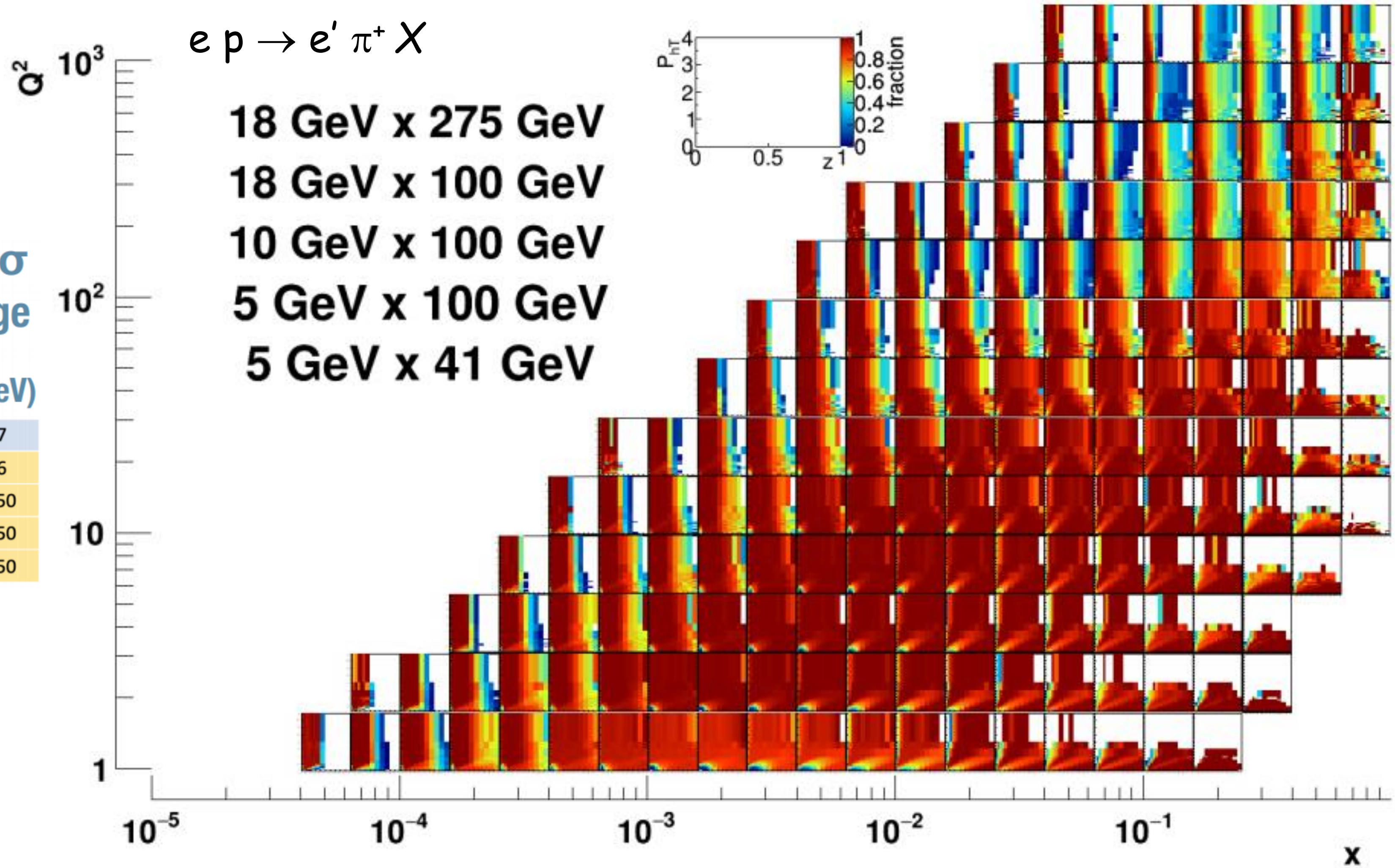


Sea quark helicities from SIDIS at EIC

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

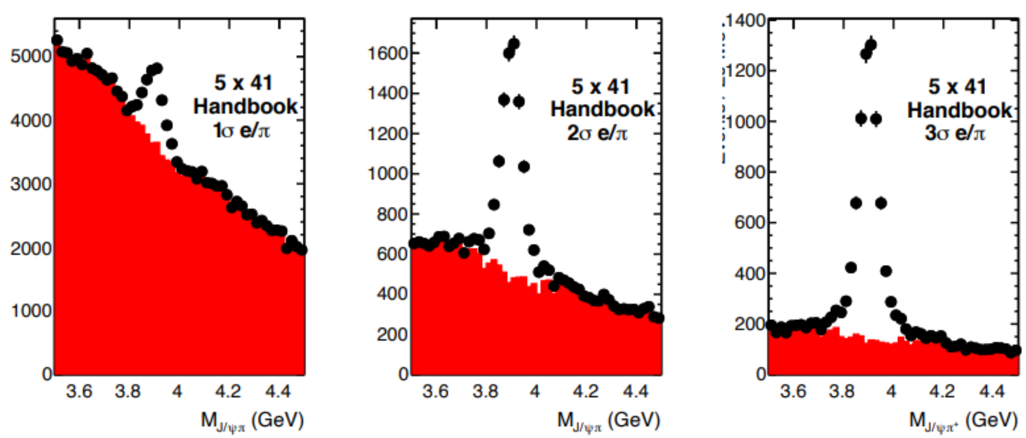


- High z/p_T limited in some cases by barrel PID p<6 GeV
- Impact at intermediate x-Q2 compensated by different beam energies, when using existing models for TMD extraction

WG 2 – Semi-inclusive reactions: Electron PID

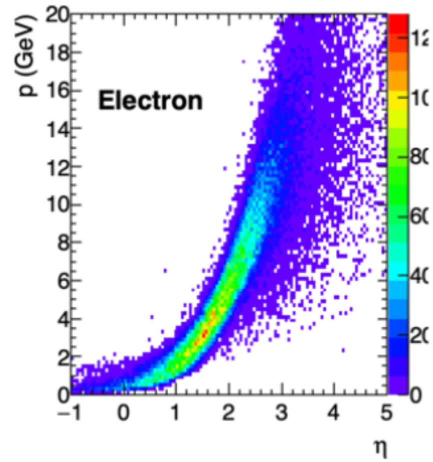
$$\gamma p \to Z_c^+ n, \;\; Z_c^+ \to J/\psi \pi^+$$

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

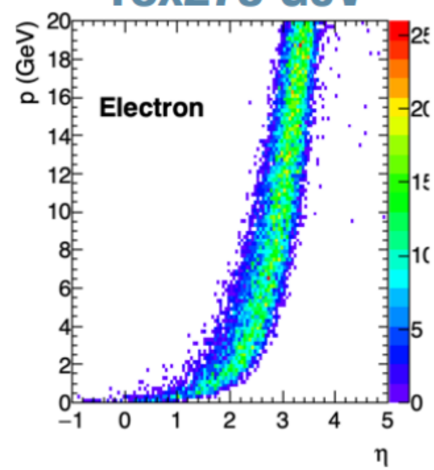


$$J/\psi \to e^+e^-$$

5x41 GeV

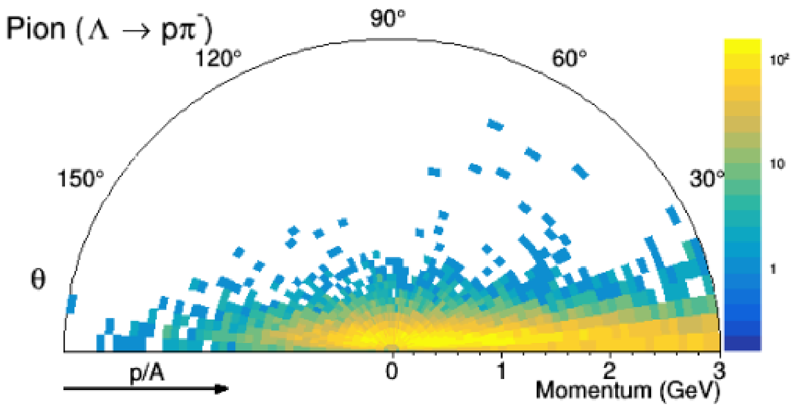


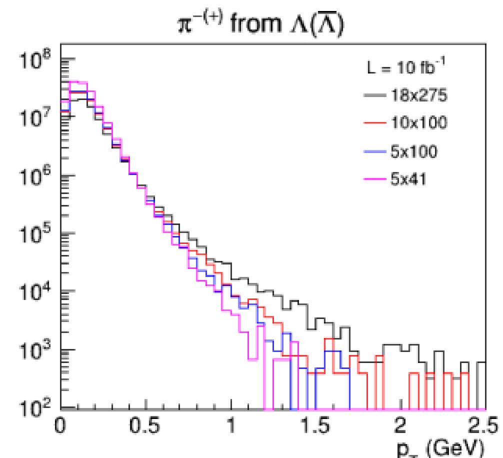
18x275 GeV



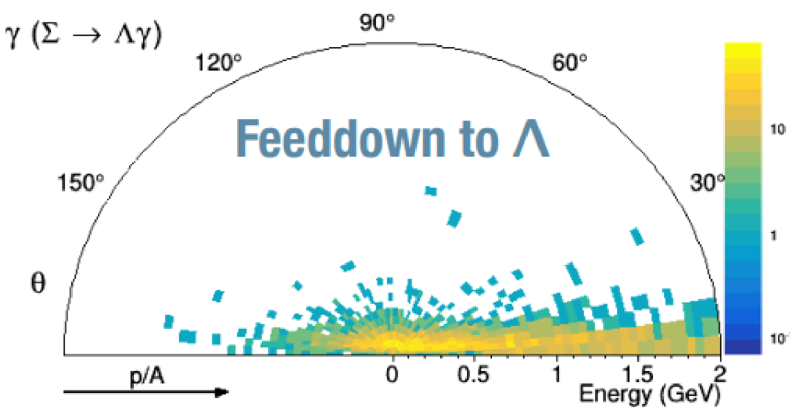
WG 2 – Semi-inclusive reactions: Minimum p_T

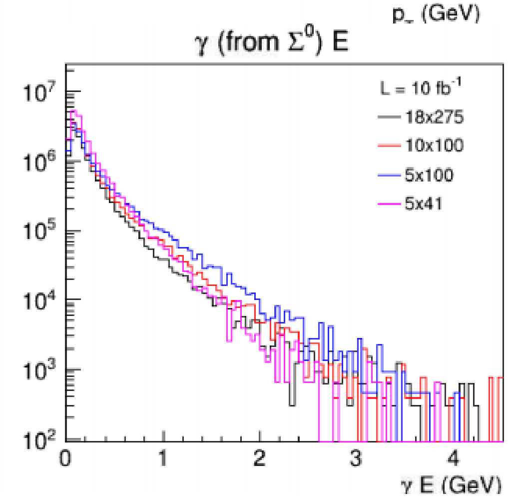
$$ep \rightarrow e'\Lambda X$$





18x275 GeV



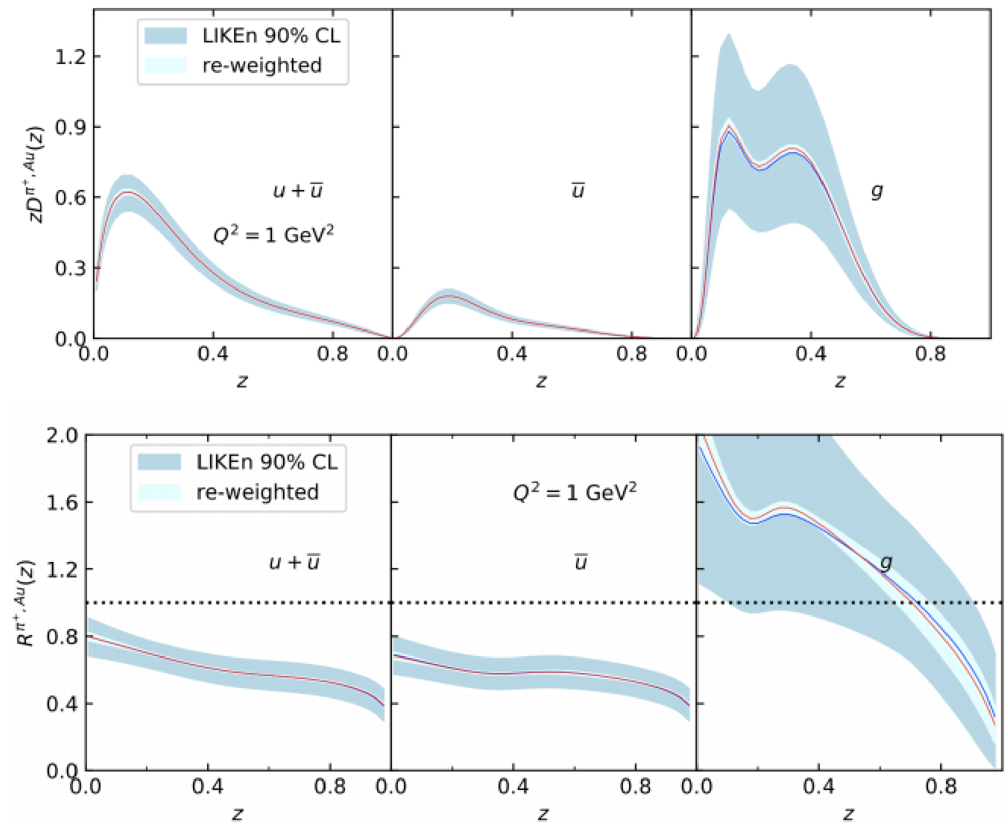


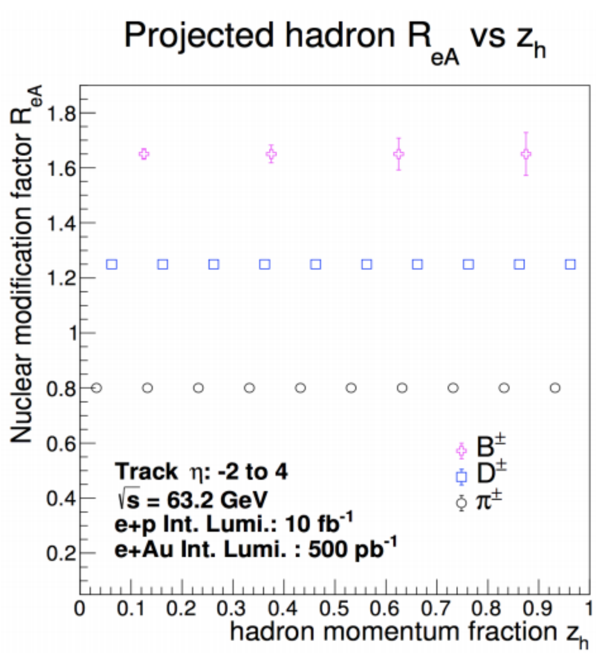
- 100 MeV p_T detection required for efficient Λ detection
- Σ feeddown rejection requires $E\gamma$>200 MeV for η<3 and $E\gamma$>400 MeV for η>3

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



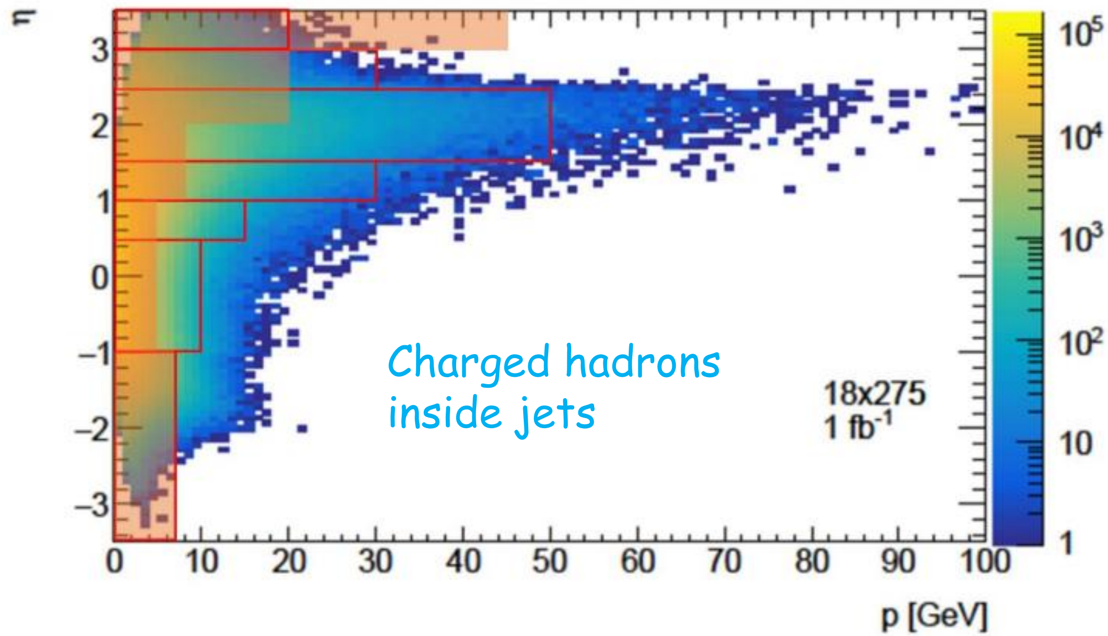


WG 3 – Jets and Heavy Quarks: PID

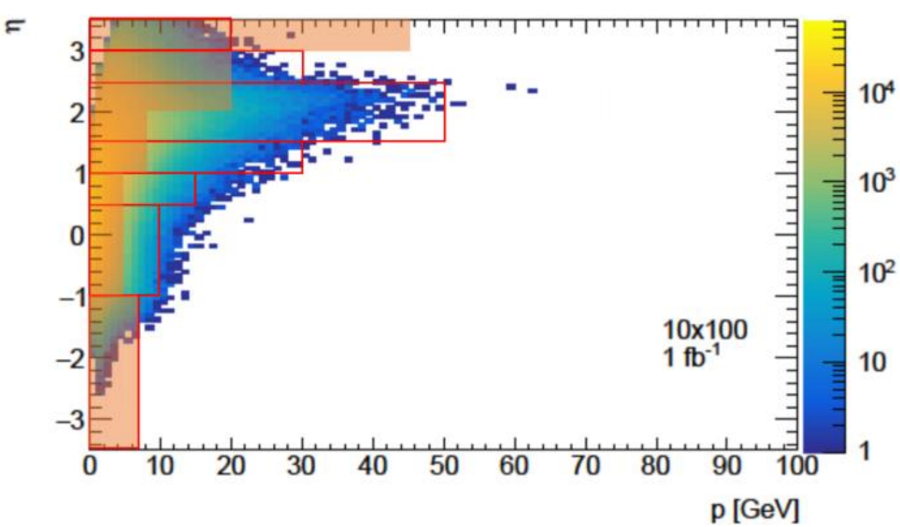
PID Momentum Coverage

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



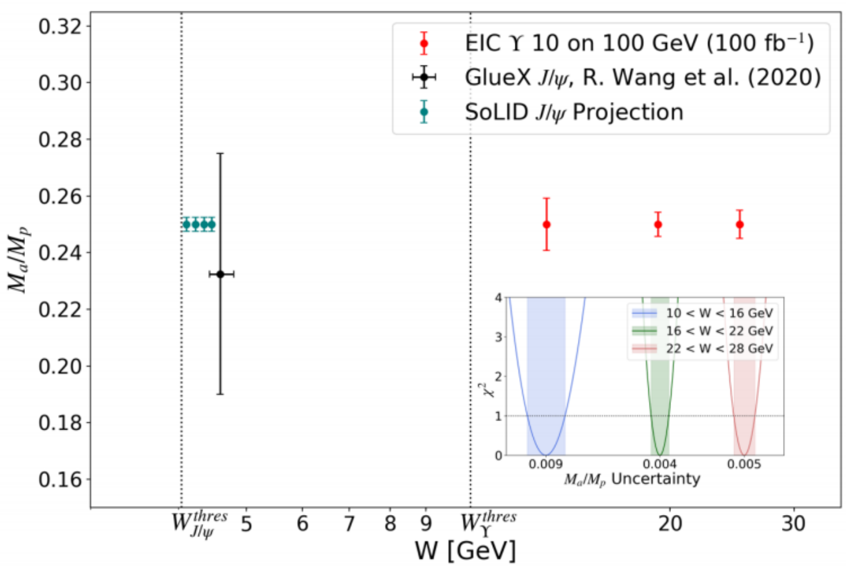
Reduction of particle momenta at highest (and lowest) eta are due to jet radius

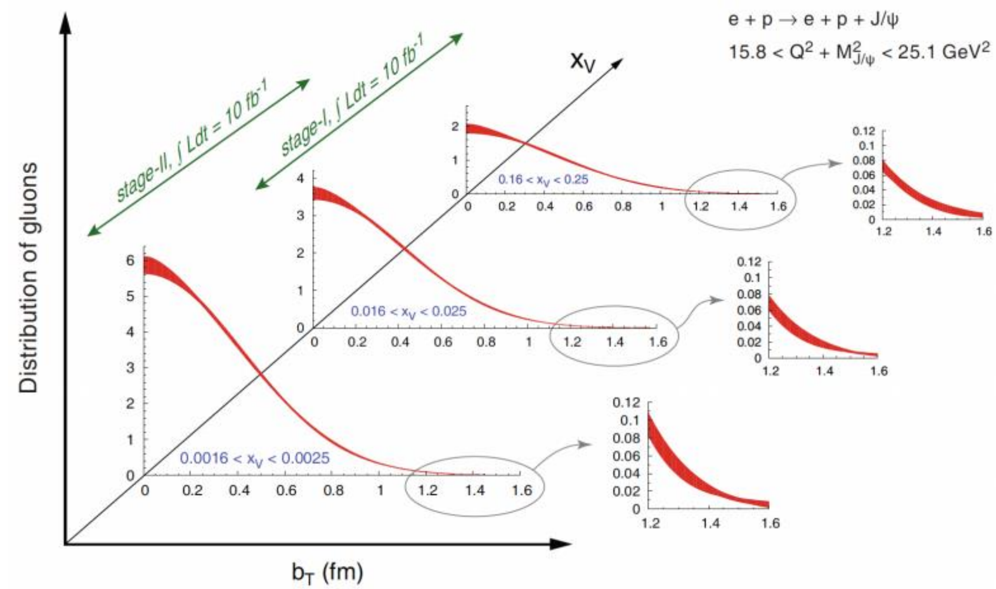
Hadron PID required up to large values of momenta

WG4 – Exclusive reactions: physics topics

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

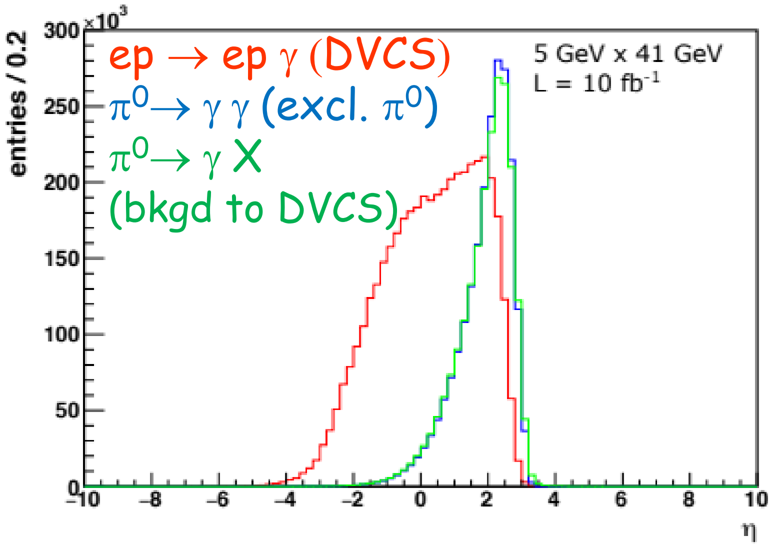
Trace anomaly contribution to the proton mass (Υ production)

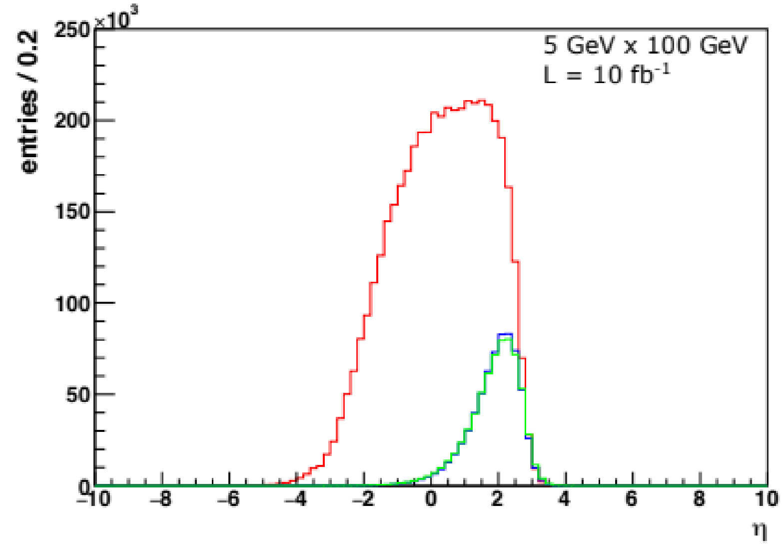




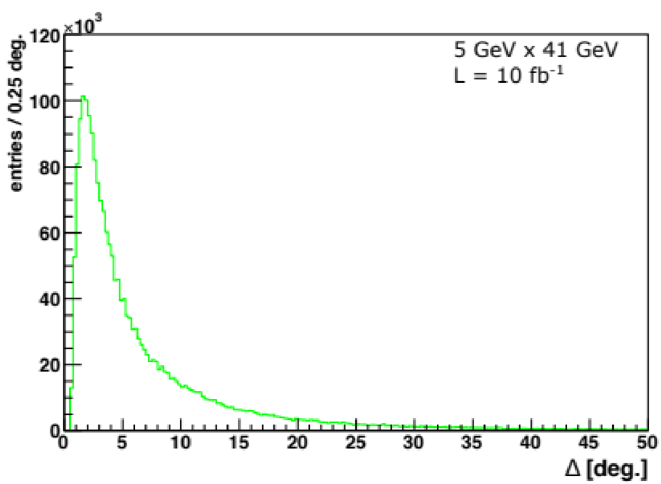
Gluon 3D imaging from J/ψ production

ECAL granularity

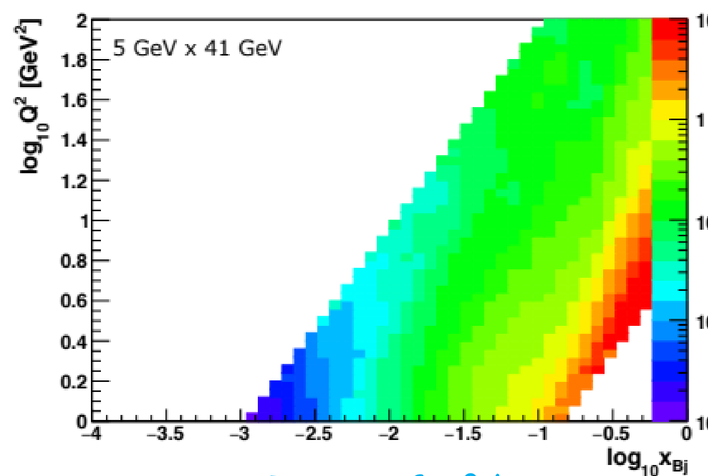




Separation of photons from π^0 decays is crucial for DVCS



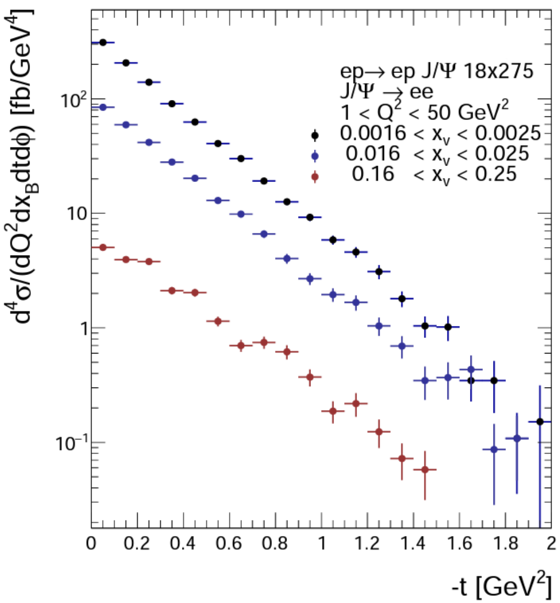
Opening angle $\pi^0 \rightarrow \gamma\gamma$



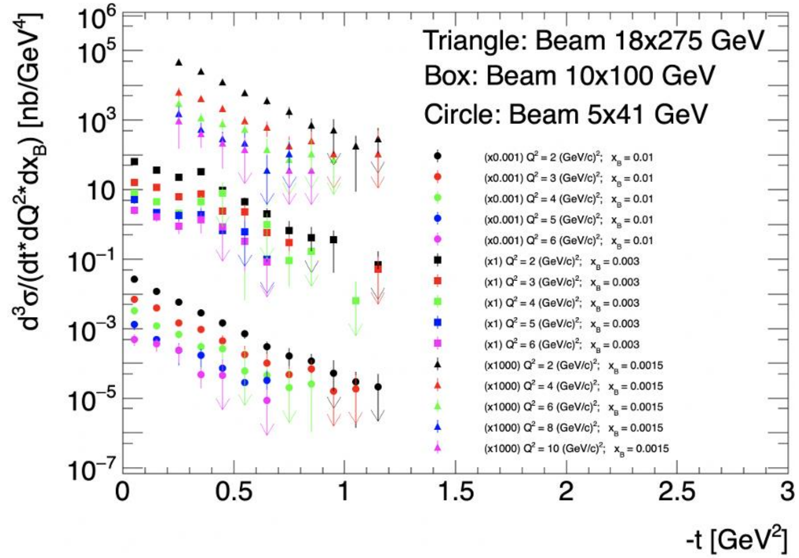
Ratio of π^0/γ

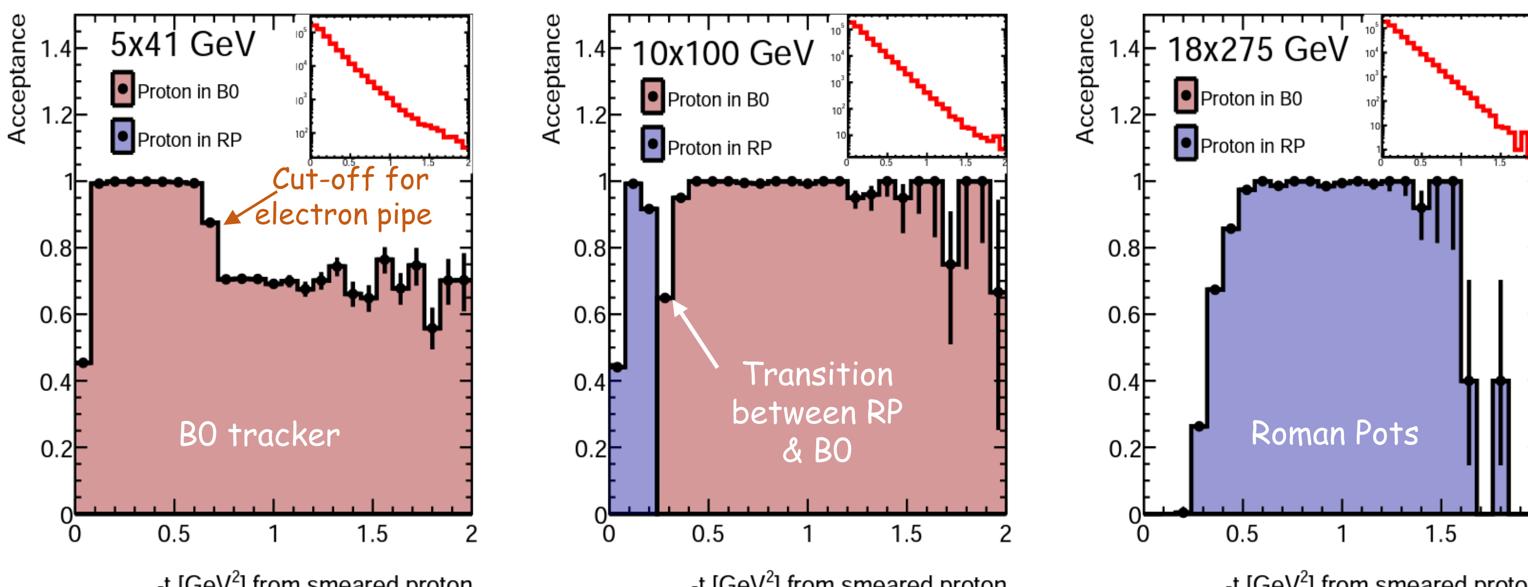
B0 & Roman Pots

Exclusive J/ ψ production

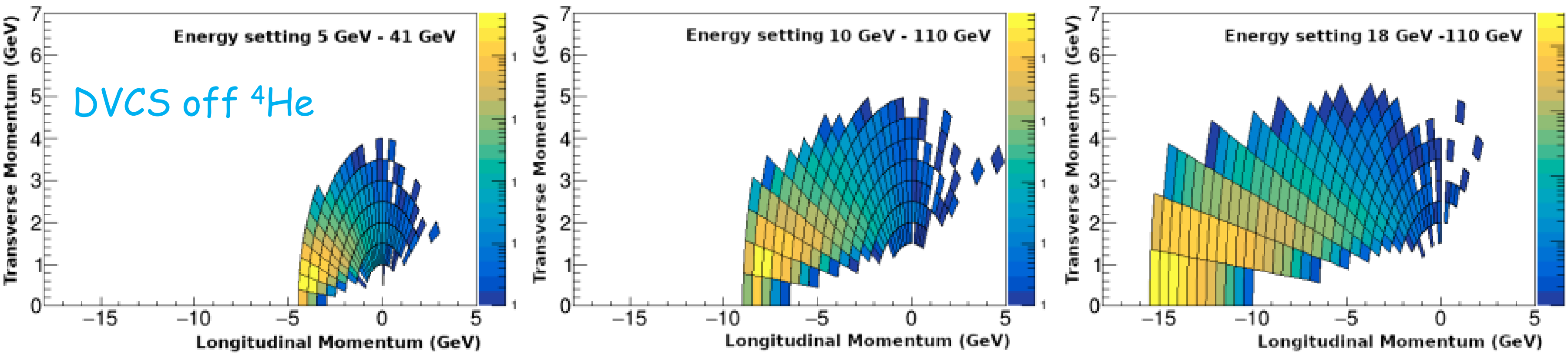


t-dependence of DVCS cross section

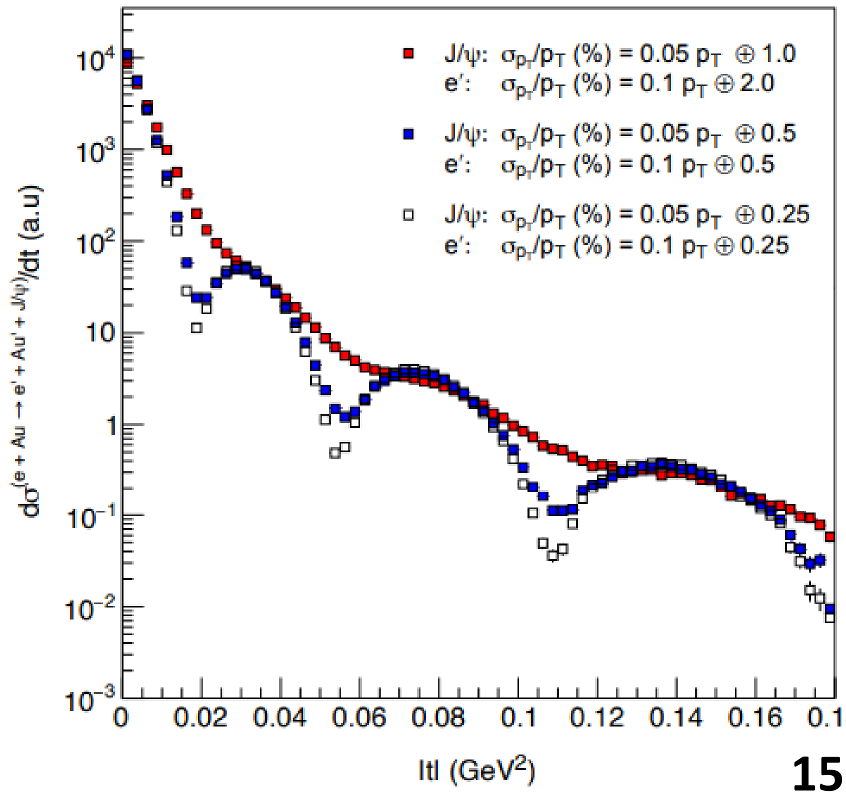




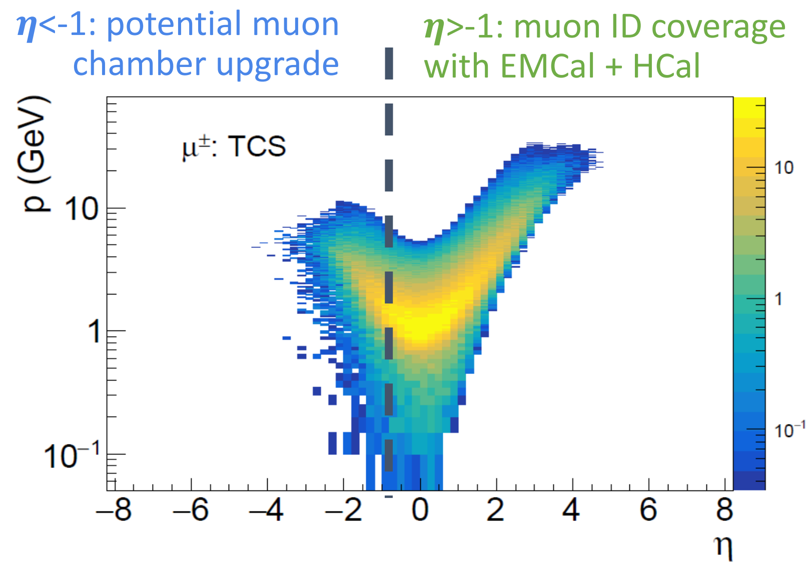
WG 4 – Exclusive reactions: far-forward acceptance



- 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



TCS and muon detection



EPIC will have a complete EMCal + HCal coverages in the central and forward calorimeter stacks

- Total hadron interaction length:
  6-7 λ_0 for central and 7-8 λ_0 for forward
  Pion punch through probability: 10^{-2} to 10^{-3} level
- Pion rejection quantified with full detector simulation, reconstruction, and AI-based classifier in following slides

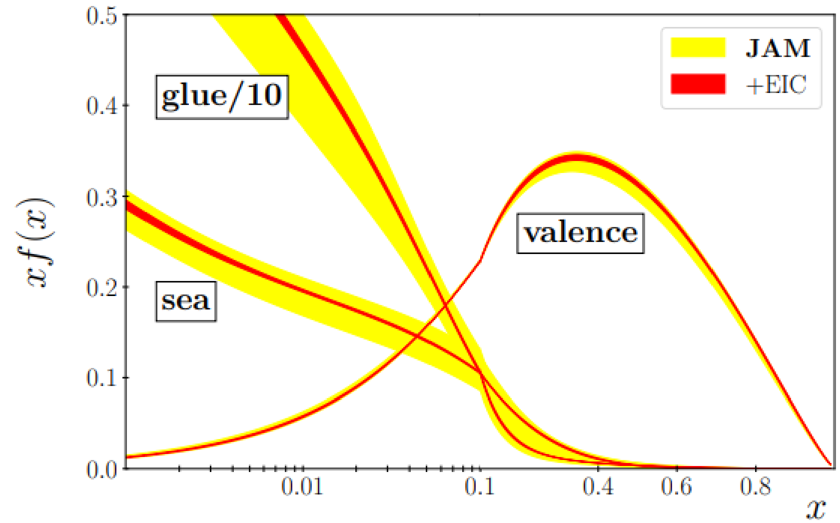
In the backward region, the YR did not show a compelling case for an HCAL:

- There will be a field return steel which can be used as pion absorber followed by a muon chamber as upgrade. Total thickness 3-5 λ_0 , pion punch through prob.: 10^{-1} to 10^{-2}
- steel which can be used as pion absorber followed by a muon chamber as upgrade. Total thickness 3-5 λ_0 , pion punch through prob.: 10^{-1} to 10^{-2}

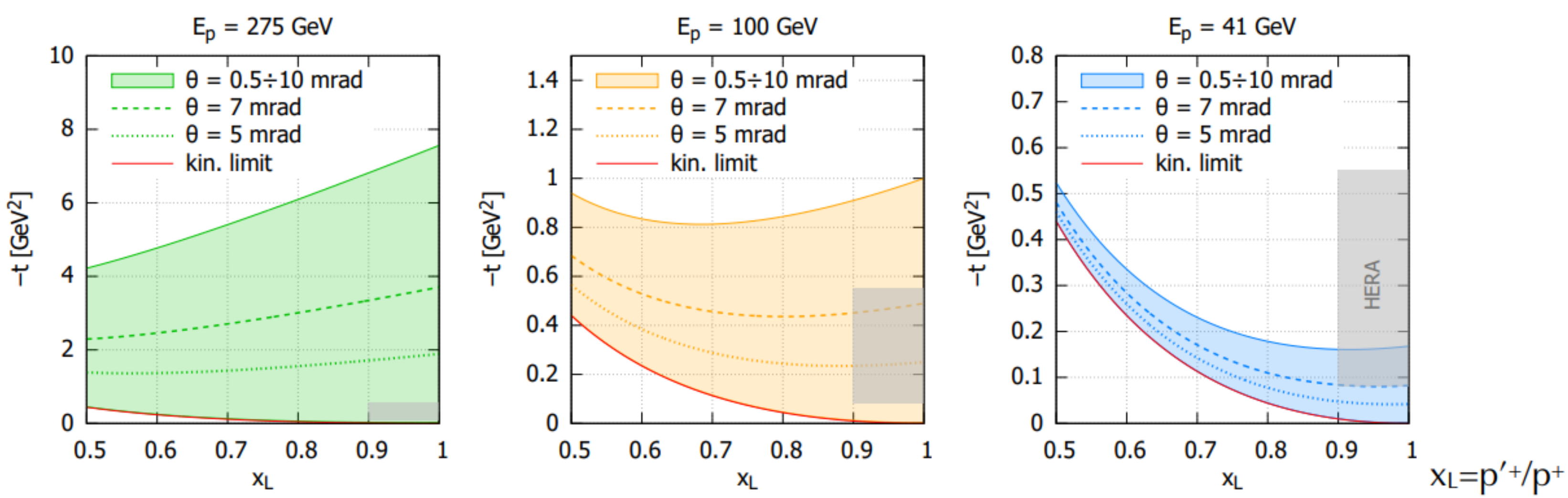
WG 5 – Diffractive & Tagging: physics topics

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

Pion PDFs



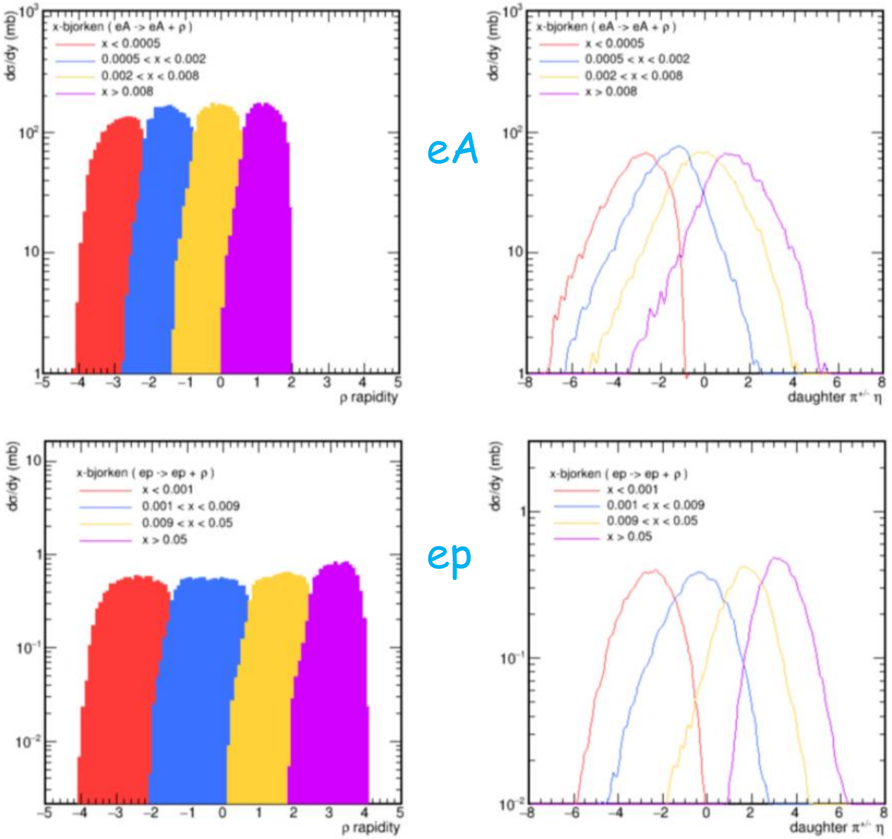
Inclusive diffraction



HERA range

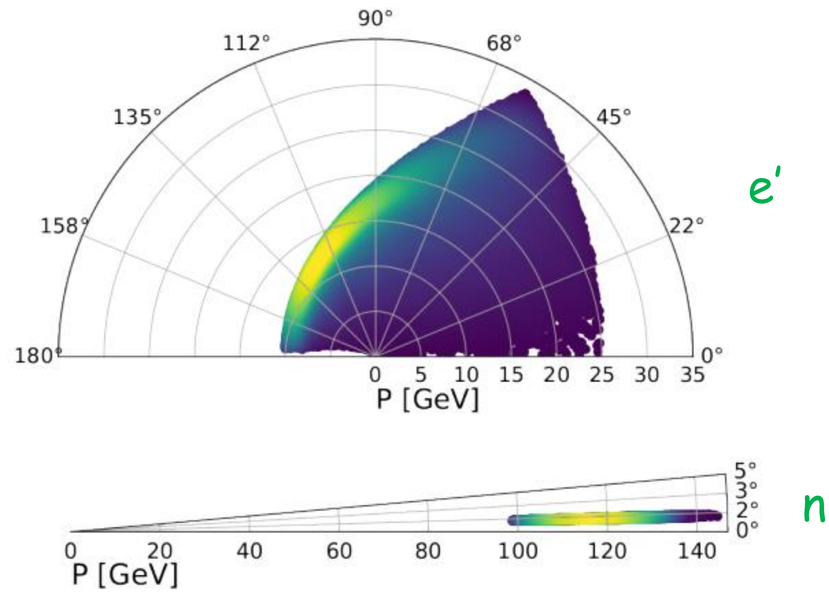
WG 5 – Diffractive & Tagging: hermeticity

Coherent ρ photoproduction



Sullivan process for pion structure:

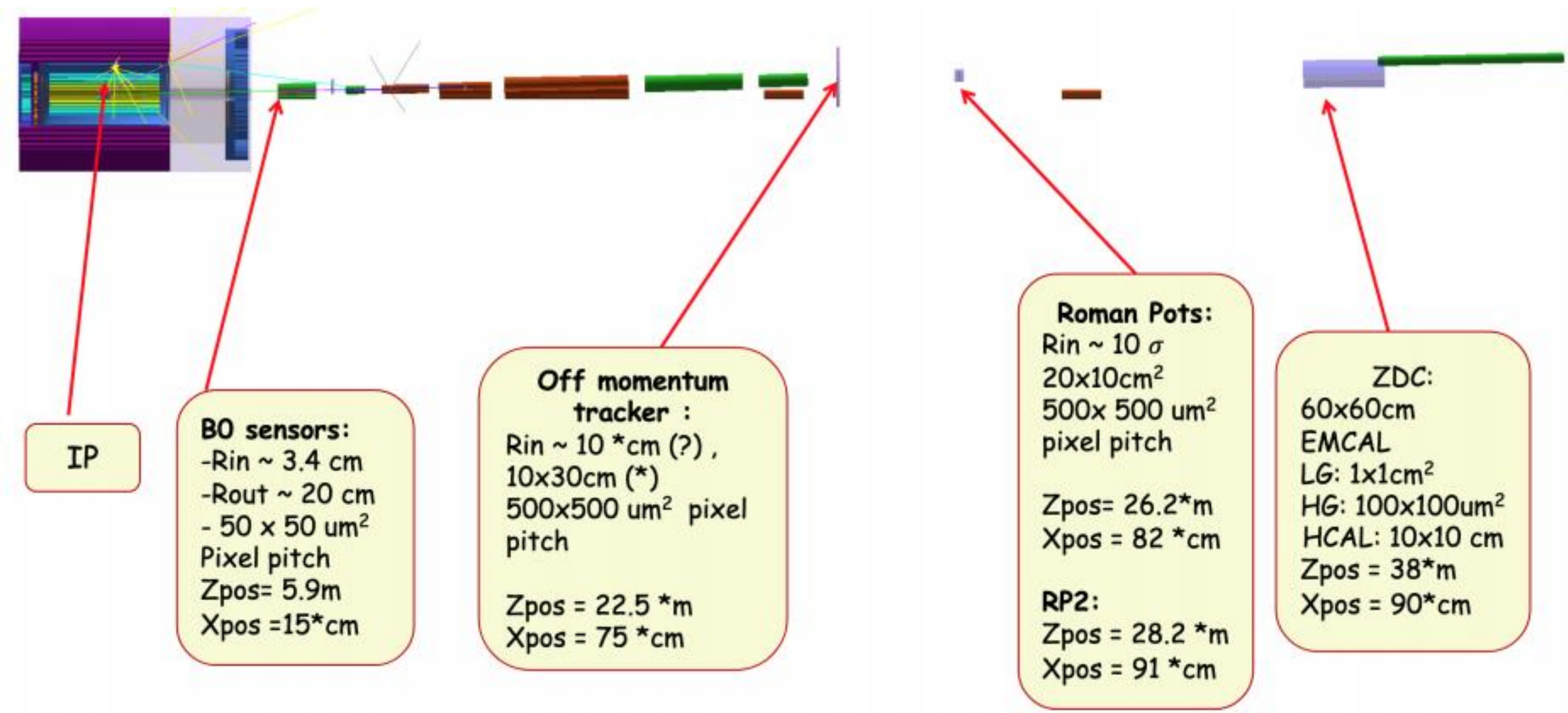
$$e + p \to e' + X + n$$



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

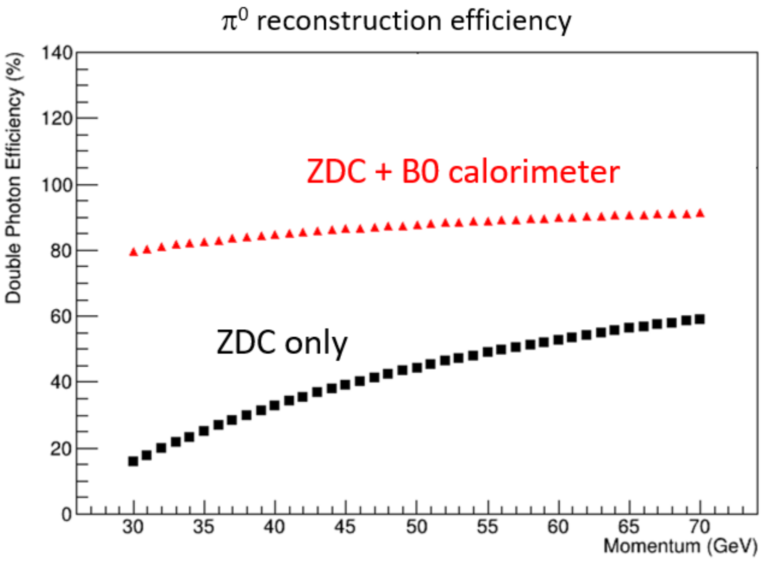
Meson structure: far-forward region

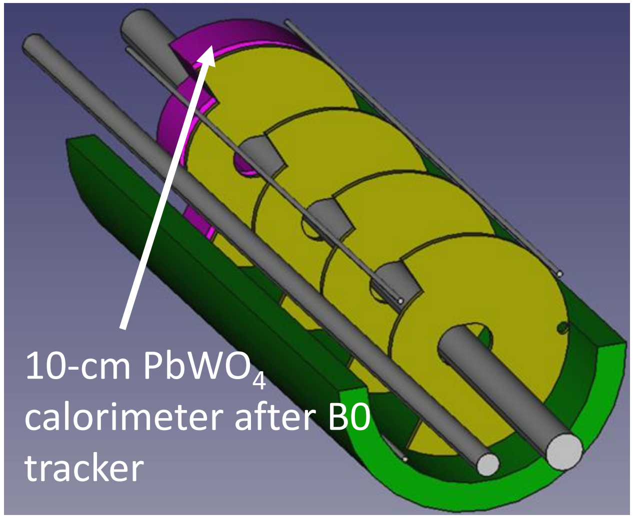
Detailed acceptance and resolution requirements driven by meson structure physics :



U-channel DVCS

- Access to nucleon *Transition Distribution Amplitudes* (TDA): light-cone matrix elements complementary to GPDs
- Bethe-Heitler is suppressed in the *u*-channel, but π^0 background suppression is needed via an EMCal at very forward rapidity (B0 magnet)





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						$\sim 50\%/\sqrt{E}+6\%$	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p+2.0\%$	~5% or less				π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~500 MeV	$\sim 45\%/\sqrt{E}+6\%$	Useful for bkg, improve resolution
-3.0 — -2.5							$\sigma_{xy}\sim 30\mu m/p_T + 40\mu m$								
-2.5 — -2.0					$\sigma_p/p \sim 0.05\% \times p+1.0\%$		$\sigma_{xy}\sim 30\mu m/p_T + 20\mu m$								
-2.0 — -1.5									$7\%/\sqrt{E}+(1\text{-}3)\%$						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p+0.5\%$		$\sigma_{xyz} \sim 20\ \mu m$, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV $\mu m + 5\ \mu m$		$(10\text{-}12)\%/\sqrt{E}+(1\text{-}3)\%$		≤ 10 GeV/c			$\sim 85\%/\sqrt{E}+7\%$	
-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			$\sim 35\%/\sqrt{E}$	
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										

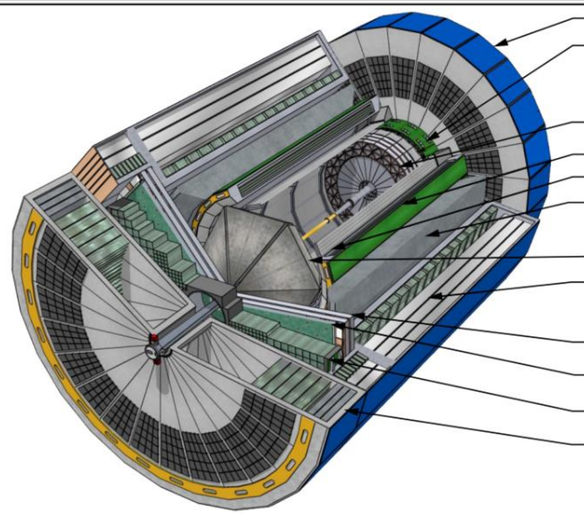
Summary of requirements

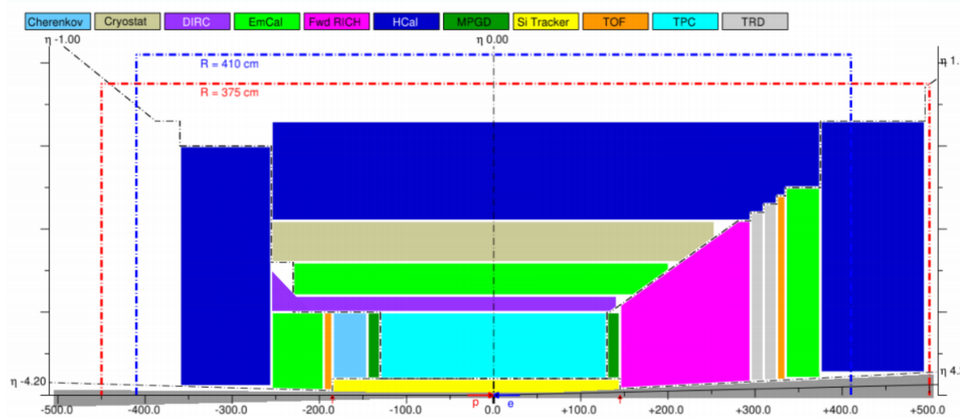
- Hermeticity: $-4 < \eta < 4$ in the central detector is crucial (exclusive & diffractive channels)
- Momentum resolution in central region:
  DIS and SIDIS channels that use the hadronic state to reconstruct kinematics
- Miminum p_T: 100 MeV for pions, 135 MeV for kaons
- Vertex resolution: driven 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			





Back up

Processes / Topics	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.