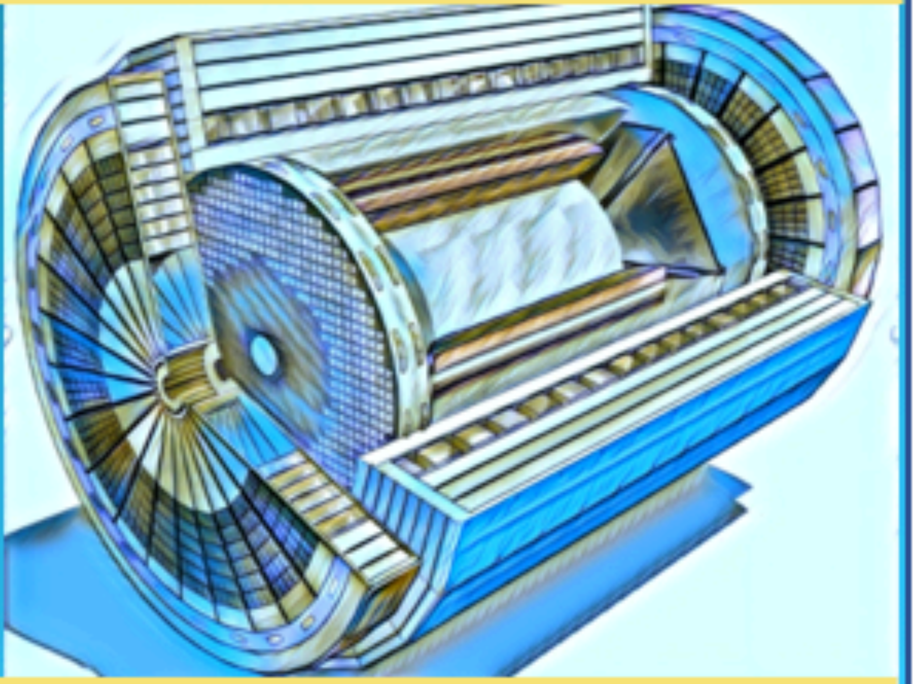
EIC Yellow Report

Volume II: Detector



2nd Interaction Region at the EIC Workshop (prep meeting)

Kenneth N. Barish
UC Riverside

Dec 15, 2020

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Detector Working Group

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

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

Technologies Matrix

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	GEMs	GEMs with Cr electrodes	sTGC
	far forward & far backward	MAPS, 20 um pitch			
	very far forward & far backward	MAPS & AC-LGAD	TimePix (very far backward)		
ECal	barrel	Pb/Sc Shashlyk	SciGlass	W powder/ScFi	W/Sc Shashlyk
	forward	W powder/ScFi	SciGlass	PbGl	Pb/Sc or W/Sc Shashlyk
	backward, inner	$PbWO_4$	SciGlass	PbGl	
	backward, outer	SciGlass	$PbWO_4$	W powder/ScFi	W/Sc Shashlyk [c]
	very far forward	Si/W	W powder/ScFi	crystals [d]	SciGlass
h-PID	barrel	High performance DIRC & dE/dx (TPC)	reuse of BABAR DIRC bars	fine high 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 focussing RICH (aerogel)		
e/h separation at low p	barrel	hpDIRC & dE/dx (TPC)			
	forward	TOF & areogel	adding TRD		
	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			

[a] surronded by a microR-WELL tracker
[b] set of coaxial cylindrical MICROMEGAS
[c] also Pb/Sc Shashlyk
[d] alternative options: $PbWO_4$, LYSO, GSO, LSO

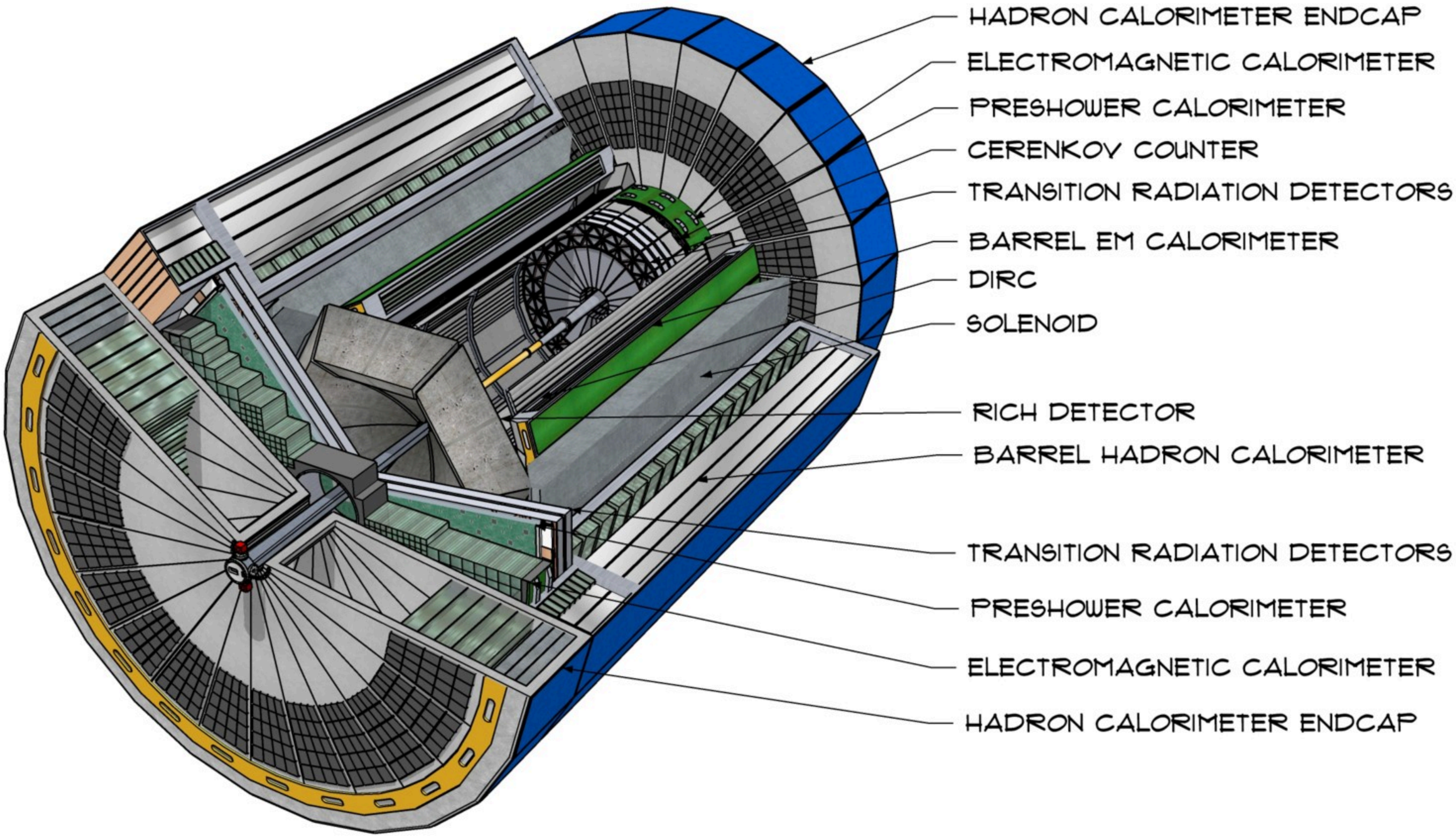
Example (gas detector technologies)

	TPC + Fast MPGD Layer	Cylindrical MPGD (Micromegas, µRWELL)	Drift Chambers / Straw Tubes	Planar MPGDs (GEM, Micromegas, µRWELL)	Small TGCs	MPGD-TRDs
Barrel region	Pros: - momentum res.; - additional dE/dx; - cost - Low material in barrel Cons: - End cap material - calibration space charge distortion	Pros: - Space & angular res. - Time resolution (< 10 ns) - Low mat. in end cap - Cost & robustness Cons: - Momentum res. - Fabrication challenges - Material budget in barrel	Pros: - momentum res.; - additional dE/dx; - cost - Low mat. in barrel Cons: - End cap material - calibration - Stability issues	Pros: - Alternative to cylindrical MPGDs arrangement in polygons - Easier fabrication Cons: - Momentum res. - Detector space barrel - Material budget in barrel	N/A	N/A Radiator size
Hadron End Cap	N/A Only planar option		Pros: - momentum res.; - additional dE/dx; - cost Cons: - Material budget - calibration - Stability issues	Pros: - Momentum & angular res. - Low material (< 0.4X/X0 - Cost & robustness Cons: - N/A	Pros: - Momentum & angular res. - Cost & robustness Cons: - Material budget	Pros: - Additional tracking - Angular res. for RICH - Additional e/π PID Cons: - Available space i.e. radiator thickness
Electron End Cap	N/A Only planar option		N/A	Pros: - Momentum & angular res. - Low material (<0.4%) - Cost & robustness Cons: - N/A	N/A Mainly because of material budget	Pros: - Additional tracking - Complement e PID in electron end cap Cons: - Available space i.e. radiator thickness

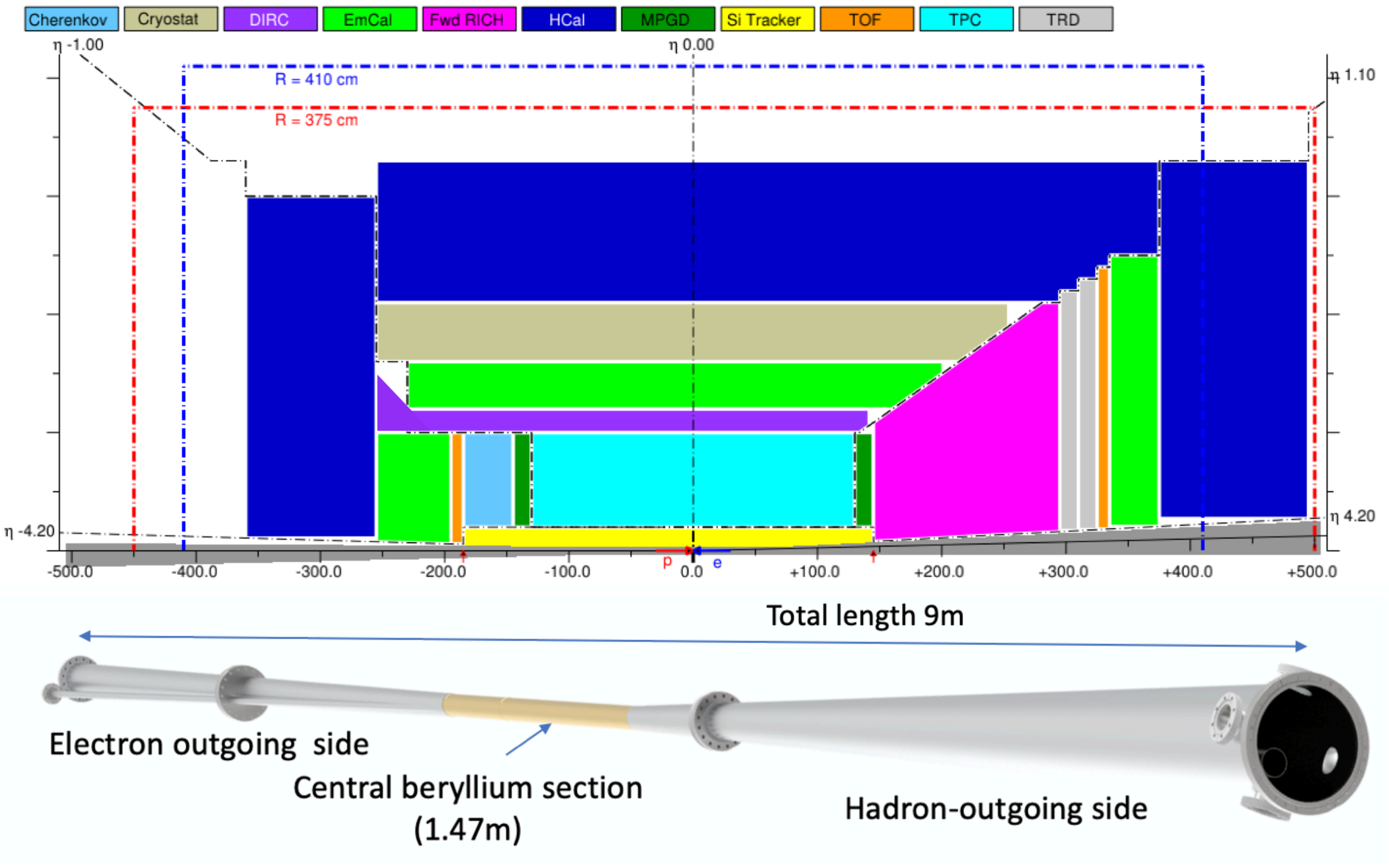
Figure 11.7: Comparison of different gaseous detectors technologies for tracking in EIC.

K. Barish

An Integrated EIC Detector Concept



An Integrated EIC Detector Concept

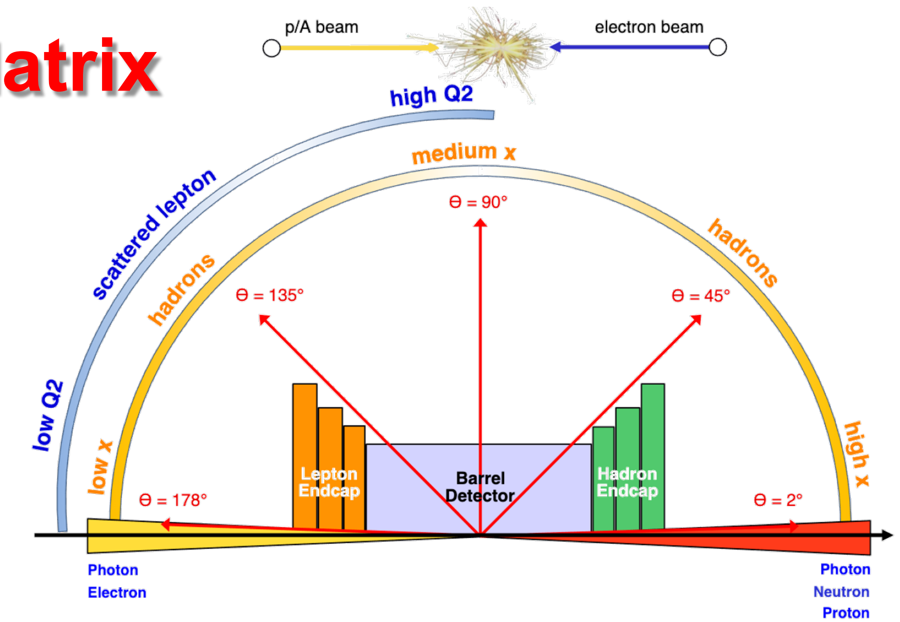


K. Barish

The Interactive Detector Matrix

Interactive table of detector requirements for each region of physics

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



<table>
<tr><th rowspan="2">η</th><th rowspan="2">θ</th><th rowspan="2" colspan="3">Nomenclature</th><th colspan="6">Tracking</th><th colspan="3">Electrons and Photons</th><th colspan="2">π/K/p</th><th colspan="2">HCAL</th><th rowspan="2">Muons</th></tr>
<tr><th>Resolution</th><th>Relative Momentum</th><th>Allowed X/X_0</th><th>Minimum-pT</th><th>Transverse Pointing Res.</th><th>Longitudinal Pointing Res.</th><th>Resolution σ_E/E</th><th>PID</th><th>Min E Photon</th><th>p-Range (GeV/c)</th><th>Separation</th><th>Resolution σ_E/E</th><th>Energy</th></tr>
<tr><td>< -4.6</td><td></td><td rowspan="3">↓ p/A</td><td>Far Backward Detectors</td><td>low-Q2 tagger</td><td colspan="14"></td></tr>
<tr><td>-4.6 to -4.0</td><td></td><td rowspan="2"></td><td rowspan="2"></td><td colspan="14">Not Accessible</td></tr>
<tr><td>-4.0 to -3.5</td><td></td><td></td><td colspan="12">Reduced Performance</td><td rowspan="10">Muons useful for bkg, improve resolution</td></tr>
<tr><td>-3.5 to -3.0</td><td></td><td rowspan="14"></td><td rowspan="14">Central Detector</td><td rowspan="5">Backward Detector</td><td rowspan="2"></td><td rowspan="2">σ_p/p ~0.2%×p⊕5%</td><td rowspan="14">~5% or less X</td><td rowspan="5">70-150 MeV/c (B=1.5 T)</td><td rowspan="3"></td><td></td><td rowspan="3">1%/E ⊕ 2.5%/√E ⊕ 1%</td><td rowspan="3">π suppression up to 1:1E-4</td><td rowspan="3">20 MeV</td><td rowspan="5">≤ 10 GeV/c</td><td rowspan="14">≥ 3 σ</td><td rowspan="5">50%/√E⊕10%</td><td rowspan="14">~500MeV</td></tr>
<tr><td>-3.0 to -2.5</td><td></td><td></td></tr>
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<tr><td>-2.0 to -1.5</td><td></td><td rowspan="2">dca(xy) ~ 40/pT µm ⊕ 10 µm</td><td rowspan="2">dca(z) ~ 100/pT µm ⊕ 20 µm</td><td rowspan="2">2%/E ⊕(4-8)%/√E ⊕ 2%</td><td rowspan="2">π suppression up to 1:(1E-3 - 1E-2)</td><td rowspan="2">50 MeV</td></tr>
<tr><td>-1.5 to -1.0</td><td></td></tr>
<tr><td>-1.0 to -0.5</td><td></td><td rowspan="4">Barrel</td><td rowspan="4"></td><td rowspan="4">σ_p/p ~0.04%×p⊕1%</td><td rowspan="4">200 MeV/c</td><td rowspan="4">dca(xy) ~ 30/pT µm ⊕ 5 µm</td><td rowspan="4">dca(z) ~ 30/pT µm ⊕ 5 µm</td><td rowspan="4">2%/E ⊕(12-14)%/√E ⊕ (2-3)%</td><td rowspan="4">π suppression up to 1:1E-2</td><td rowspan="4">100 MeV</td><td rowspan="4">≤ 6 GeV/c</td><td rowspan="4">100%/√E+10%</td></tr>
<tr><td>-0.5 to 0.0</td><td></td></tr>
<tr><td>0.0 to 0.5</td><td></td></tr>
<tr><td>0.5 to 1.0</td><td></td></tr>
<tr><td>1.0 to 1.5</td><td></td><td rowspan="5">Forward Detectors</td><td rowspan="3"></td><td rowspan="3">σ_p/p ~0.04%×p⊕2%</td><td rowspan="5">70 - 150 MeV/c (B = 1.5 T)</td><td rowspan="2">dca(xy) ~ 40/pT µm ⊕ 10 µm</td><td rowspan="3">dca(z) ~ 100/pT µm ⊕ 20 µm</td><td rowspan="5">2%/E ⊕ (4*-12)%/√E ⊕ 2%</td><td rowspan="5">3σ e/π up to 15 GeV/c</td><td rowspan="5">50 MeV</td><td rowspan="5">≤ 50 GeV/c</td><td rowspan="5">50%/√E+10%</td><td></td></tr>
<tr><td>1.5 to 2.0</td><td></td><td></td></tr>
<tr><td>2.0 to 2.5</td><td></td><td rowspan="3"></td><td></td></tr>
<tr><td>2.5 to 3.0</td><td></td><td rowspan="2"></td><td rowspan="2">σ_p/p ~0.2%×p⊕5%</td><td></td><td></td></tr>
<tr><td>3.0 to 3.5</td><td></td><td></td><td></td></tr>
<tr><td>3.5 to 4.0</td><td></td><td rowspan="3">↑ e</td><td rowspan="2"></td><td>Instrumentation to separate charged particles from photons</td><td></td><td colspan="12">Reduced Performance</td><td></td></tr>
<tr><td>4.0 to 4.5</td><td></td><td></td><td colspan="13">Not Accessible</td><td></td></tr>
<tr><td>> 4.6</td><td></td><td>Far Forward Detectors</td><td>Proton Spectrometer
Zero Degree Neutral Detection</td><td colspan="14"></td></tr>
</table>

Tensions: Barrell PID Requirements

η	Nomenclature			Tracking: Resolution	Tracking: Allowed	Tracking: minimum-pT	Tracking: Si-Vertex	Electrons and Photons: Resolution σ_E/E	Electrons and Photons: PID	Electrons and Photons: min E	π/K/p: p-Range	π/K/p: Separati	HCAL: Resolution σ_E/E	HCAL: Energy	Muons
-6.9 to -5.8	↓ p/A	Auxiliary Detectors	low-Q2 tagger	σθ/θ < 1.5%; 10-6 < Q2 < 10-2 GeV2											
-5.0 to -4.5															
-4.5 to -4.0			Instrumentation to separate charged particles from photons							50 Me					
-4.0 to -3.5						<100MeV pions, 135MeV				50 MeV			~[illegible]0%/√E + 6%		
-3.5 to -3.0		Central Detector	Backward Detector	σp/p ~ 0.1%⊕0.5%	~5% or less X	<100MeV pions, 135MeV				50 MeV	≤ 7 GeV/c		~45%/√E+6%	~500 MeV	muons useful for bkg, improve resolution
-3.0 to -2.5						<100MeV pions, 135MeV kaons	σ_xy ~ 30/pT µm + 40 µm			50 MeV					
-2.5 to -2.0				σp/p 0.1%⊕0.5%		<100MeV pions, 135MeV	σ_xy ~ 30/pT µm + 20 µm	2%/√E(+1-3%)	π suppression up to 1:1E-4	50 MeV					
-2.0 to -1.5				σp/p 0.05%⊕0.5%		<100MeV pions, 135MeV		7%/√E(+1-3%)		50 MeV					
-1.5 to -1.0						<100MeV pions, 135MeV		7%/√E(+1-3%)		50 MeV					
-1.0 to -0.5			Barrel	σp/p ~0.05%×p+0.5%		<100MeV pions, 135MeV kaons	σxyz ~ 20 µm, d0(z) ~d0(rΦ) ~ 20/pTGeV µm + 5 µm	(10-12)%/√E(+1-3%)		50 MeV	≤ 10 GeV/c	≥ 3 σ	~85%/√E+7%		
-0.5 to 0.0						<100MeV pions, 135MeV				50 MeV			~85%/√E+7%		
0.0 to 0.5						<100MeV pions, 135MeV				50 MeV			~85%/√E+7%		
0.5 to 1.0						<100MeV pions, 135MeV				50 MeV	≤ 15 GeV/c		~85%/√E+7%		
1.0 to 1.5			Forward Detectors	σp/p ~0.05%×p+1.0%		<100MeV pions, 135MeV	σ_xy ~ 30/pT µm + 20 µm		3σ e/π	50 MeV	≤ 30 GeV/c		35%/√E		
1.5 to 2.0						<100MeV pions, 135MeV				50 MeV	≤ 50 GeV/c				
2.0 to 2.5						<100MeV pions, 135MeV				50 MeV					
2.5 to 3.0				σp/p ~ 0.1%×p+2.0%		<100MeV pions, 135MeV kaons	σ_xy ~ 30/pT µm + 40 µm			50 MeV	≤ 30 GeV/c				
3.0 to 3.5						<100MeV pions, 135MeV kaons	σ_xy ~ 30/pT µm + 60 µm			50 MeV	≤ 45 GeV/c				
3.5 to 4.0	↑ e	Auxiliary Detectors	Instrumentation to separate charged particles from photons			<100MeV pions, 135MeV kaons				50 MeV					
4.0 to 4.5						300 MeV pions				50 MeV			35%/√E (goal), <50%/√E (acceptable)*, 3mrad/√E (goal)		
4.5 to 5.0			Neutron Detection			300 MeV pions		4.5%/√E for photon energy > 20 GeV	<= 3 cm granularity	50 MeV					
>6.2			Proton Spectrometer	σintrinsic(|t|)/|t| < 1%; Acceptance: 0.2 < pt < 1.2 GeV/c											

Required: $1 : 10^{-4}$
- from inclusive

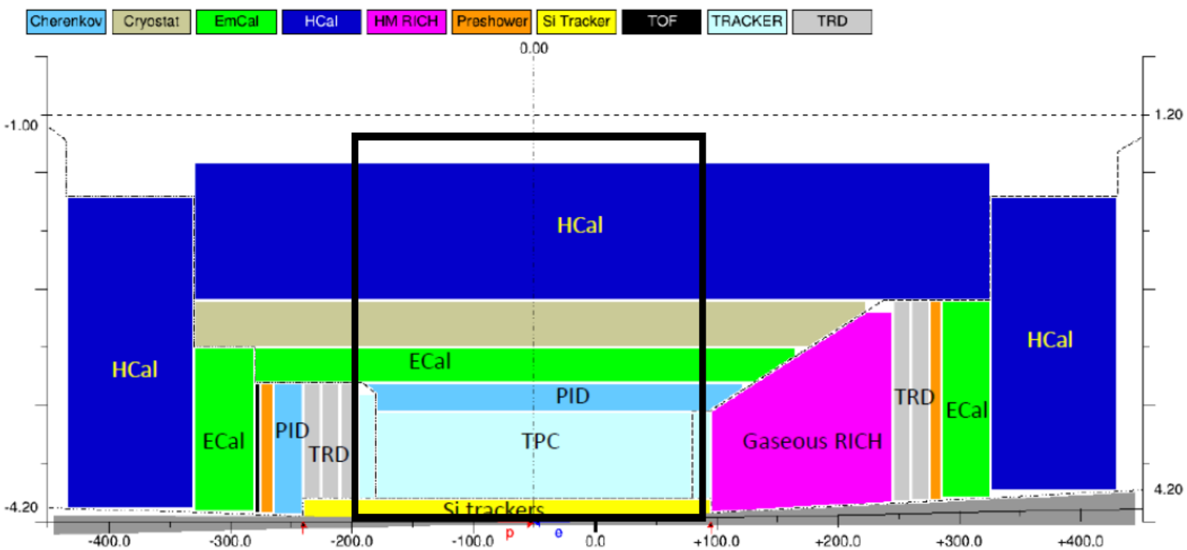
Reference detector: $\sim 1 : 10^{-2}$

Required: <10/15 GeV/c
- Semi-inclusive up to 8 GeV/c
- Jets & HQ: 10/15 GeV/c

Reference detector : <6 GeV/c

Tensions: Barrell PID Requirements

SPACE CONSTRAINS



A possible "option"

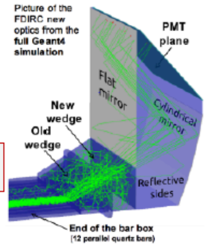
- radially, ~30 cm more if TPC→ full Si tracking
- What for? Alternative possibilities:
  - h-PID
  - e/π sep.
  - Improved Ecal

Tensions: Barrell PID Requirements

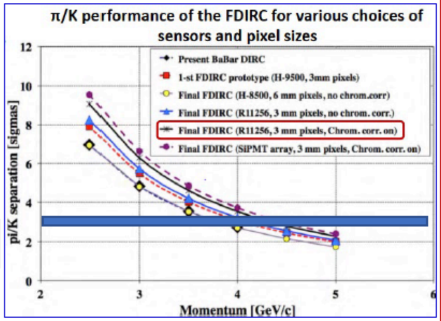
BARREL PID: ALTERNATIVE OPTIONS

alternatives

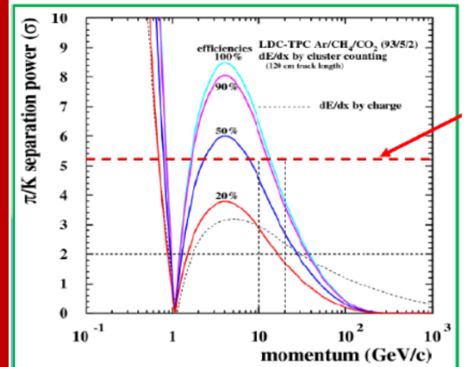
F-DIRC (super B)



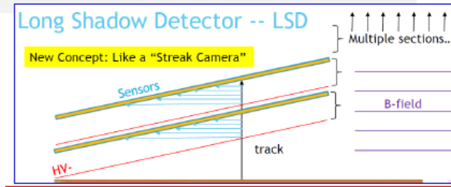
π/K separation: 4.5 GeV/c (3σ)



dE/dx → cluster counting



Long Shadow Detector -- LSD



Assuming 40 cm available and scaling results from literature

- If ~ 90% efficiency, 3σ at ~ 10 GeV/c

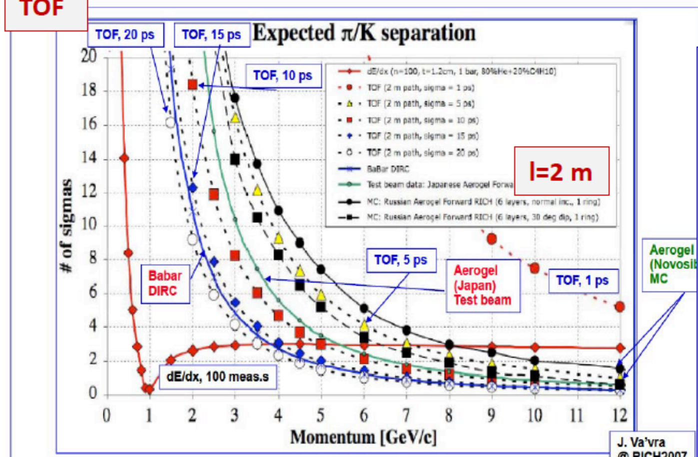
BUT

Complement of DIRC/TOF needed at small p

Which cluster detectors?

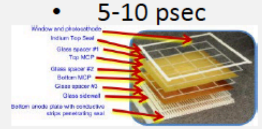
All this only speculative so far

TOF

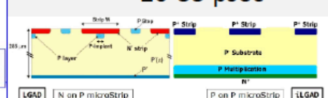


TOF, 2 options

- LAPPD, Cherenkov in window
  - 5-10 psec



- LGAD, Silicon Avalanche
  - 20-35 psec

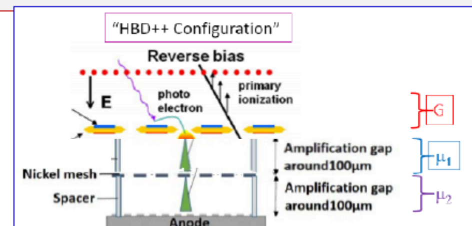


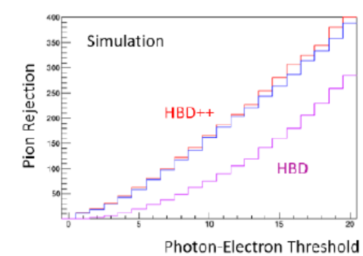
For π rejection only: **empowered HBD**

- By decreasing the MIP signal with minimum gas gap between multiplication stages (HBD ++)
- By 2 HBDs, each one with half length; reduced probability to have MIP signal in both!

BUT

- **No test so far**





Tensions: Forward HCAL Resolution

η	θ (mrad)	Nomenclature		Tracking (B = 1.5 T): Resolution	Relative momentum	Allowed X/X_0	minimum-pT	Trasverse pointing res.	Longitudinal pointing res.	Electrons and Photons: Resolution σ_E/E	PID	min E photon	π/K/p: p-Range (GeV/c)	Separation	HCAL: Resolution σ_E/E	Energy	Muons
-4.0 to -3.5			Backward Detector		reduced performance												
-3.5 to -3.0		Central Detector			σp/p ~ 0.2%×p ⊕ 5%	~5% or less X	to be determined			1%/E⊕2.5%/√E⊕1% (for 40 cm space)	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ	50%/√E⊕10% (Better resolution required more space and R&D)	~500 MeV	muons useful for bkg, improve resolution
-3.0 to -2.5																	
-2.5 to -2.0					σp/p ~ 0.04%×p ⊕ 2%												
-2.0 to -1.5								dca(xy) ~ 40/pT μm ⊕ 10 μm	dca(z) ~ 100/pT μm ⊕ 20 μm	2%/E⊕(4-8)%/√E⊕2% (Upper limit achievable with 50 cm space *Better resolution requires ~65 cm space allocated)	π suppression up to 1:(1E-3 - 1E-2)	50 MeV					
-1.5 to -1.0																	
-1.0 to -0.5			Barrel		σp/p ~ 0.04%×p ⊕ 1%		100 MeV/c with 50% acceptance (similar for pi and K)	dca(xy) ~ 30/pT μm ⊕ 5 μm	dca(z) ~ 30/pT μm ⊕ 5 μm	2%/E⊕(12-14)%/√E⊕(2-3)% for 30 cm space A better stochastic term can be achieved with more space: 2.5% with crystals 35cm 10% sampling 40cm 4% SciGlass 65cm	π suppression up to 1:1E-2	100 MeV (50 MeV if higher resolution)	≤ 6 GeV/c		100%/√E+10%		
-0.5 to 0.0																	
0.0 to 0.5													≤ 6 GeV/c				
0.5 to 1.0																	
1.0 to 1.5			Forward Detectors		σp/p ~ 0.04%×p ⊕ 2%		to be determined	dca(xy) ~ 40/pT μm ⊕ 10 μm	dca(z) ~ 100/pT μm ⊕ 20 μm	2%/E⊕(4*-12)%/√E⊕2% Upper limit achievable with 40cm space *Better resolution requires ~65 cm space allocated	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c (worse approaching 3.5)		50%/√E +10% (35%/√E not achievable)		
1.5 to 2.0																	
2.0 to 2.5					σp/p ~ 0.2%×p ⊕ 5%												
2.5 to 3.0																	
3.0 to 3.5																	
3.5 to 4.0	↑ e			Reduced performance													

Forward HCAL performance seems not aligned with physics requirements

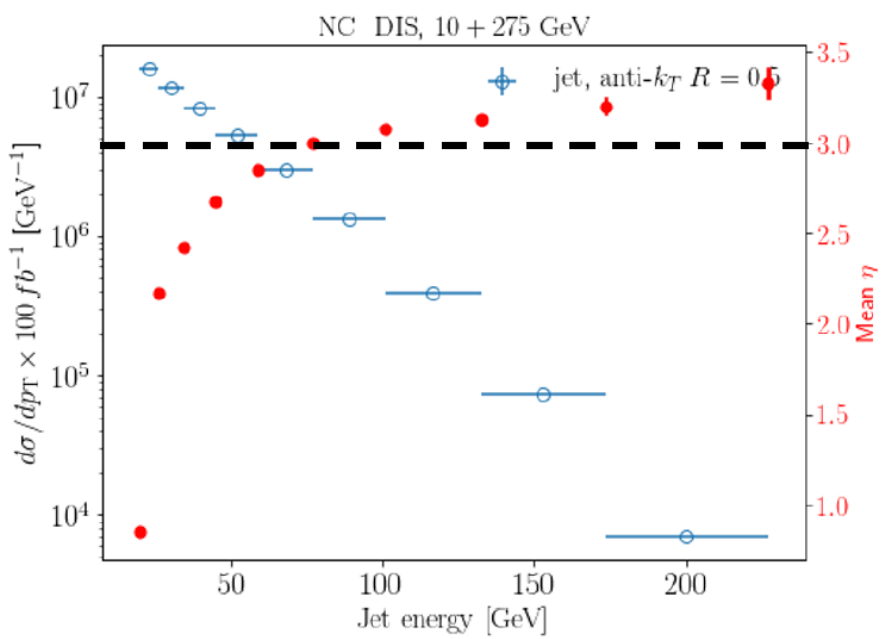
Tensions: Forward HCAL

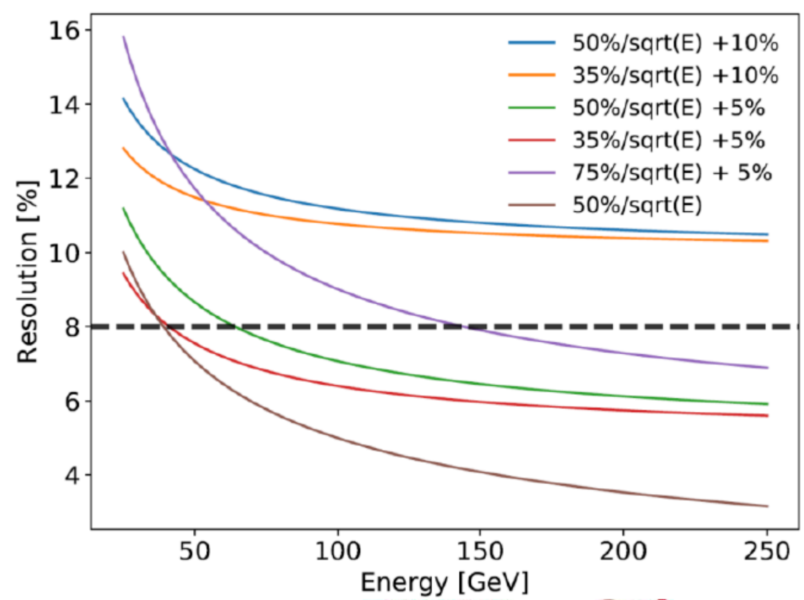
HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
-3.5 < η < -1.0	50%/√E	Same (~10% constant term is acceptable)
-1.0 < η < 1.0	N/A	85%/√E + 10%
1.0 < η < 3.0	50%/√E	50%/√E + 10%
3.0 < η < 3.5	50%/√E	50%/√E + 5%
3.5 < η < 4.0	N/A	50%/√E + 5%

For η > 3, a constant term of ~5% is needed as jet energies rapidly increase in this region while tracking resolution significantly degrades

- ➢ energy resolution is important
- ➢ energy resolution dominated by the constant term





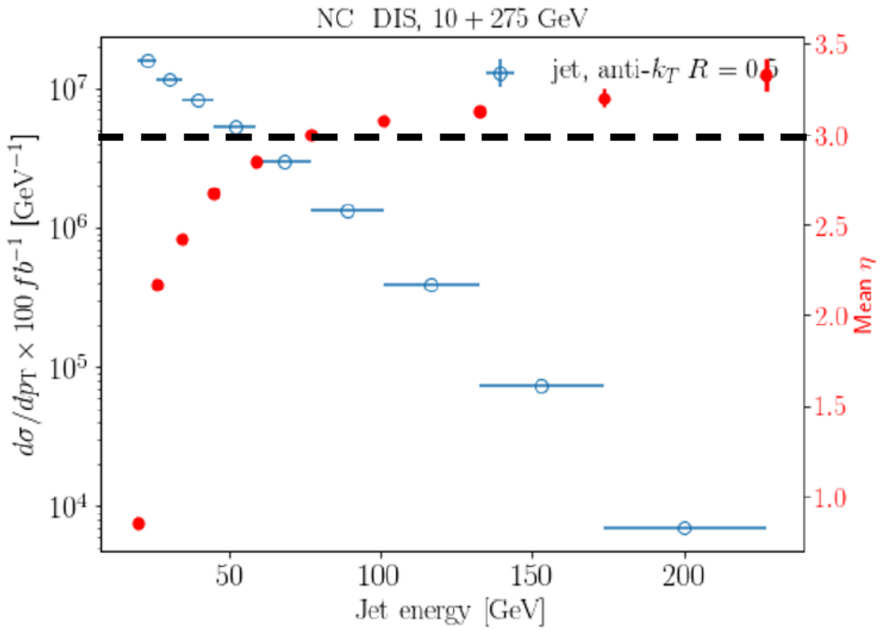
Tensions: Forward HCAL

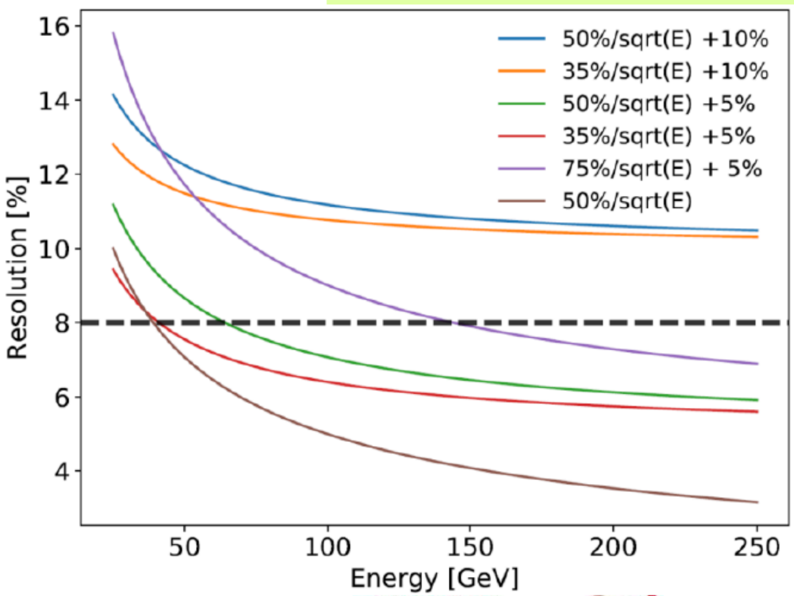
HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
-3.5 < η < -1.0	50%/√E	Same (~10% constant term is acceptable)
-1.0 < η < 1.0	N/A	85%/√E + 10%
1.0 < η < 3.0	50%/√E	50%/√E + 10%
3.0 < η < 3.5		50%/√E + 5%
3.5 < η < 4.0	N/A	

As tracking will be absent for η > 3.5, good HCal resolution will be imperative for good overall jet energy resolution.

- differential TMD measurements with jets, e.g. electron-jet Sivers asymmetry in the valence region and mid to high Q^2.





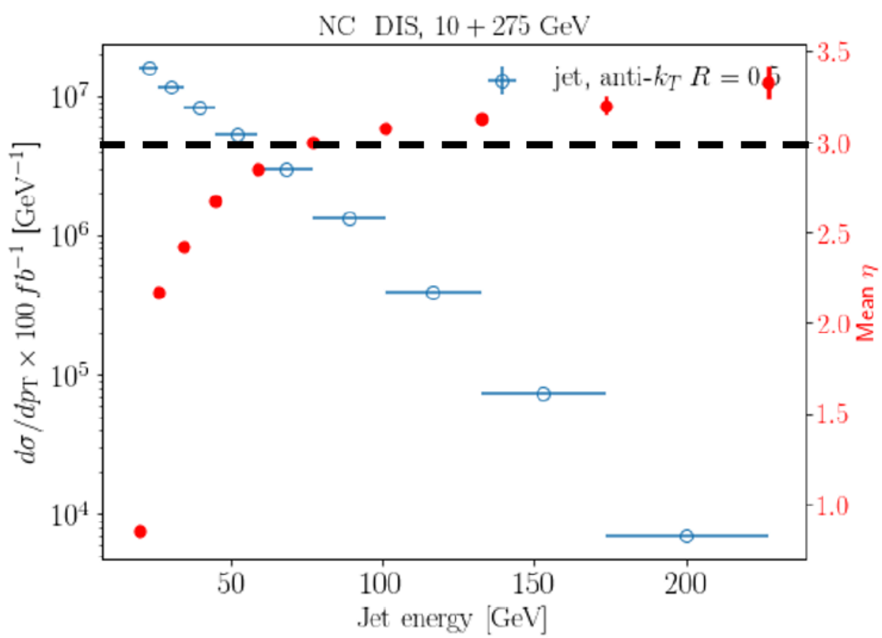
Tensions: Forward HCAL

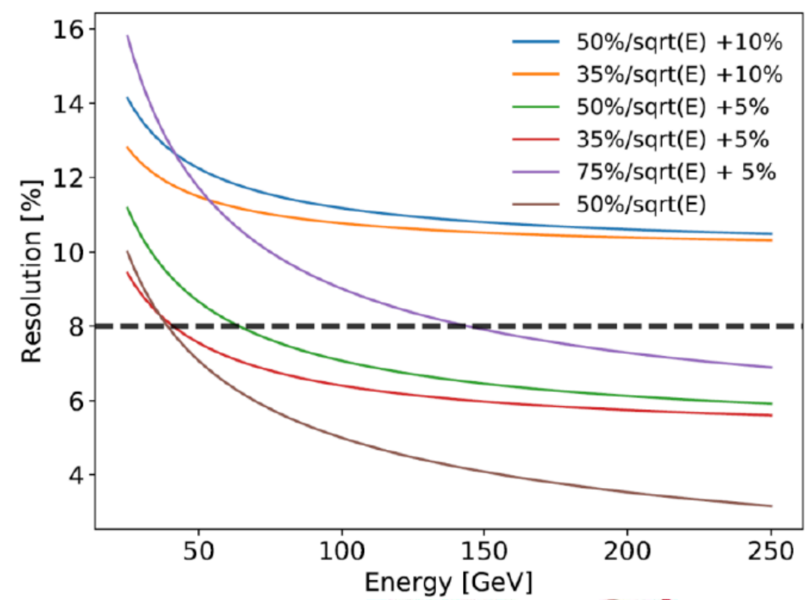
HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
-3.5 < η < -1.0	50%/√E	Same (~10% constant term is acceptable)
-1.0 < η < 1.0	N/A	85%/√E + 10%
1.0 < η < 3.0	50%/√E	50%/√E + 10%
3.0 < η < 3.5		35%/√E
	N/A	

For large-x processes need delta x < 0.1, where HCAL resolution determines delta x

- For a 50 GeV hadron/jet energy and 35%/√E → delta x=0.05





Tensions: Forward HCAL

HCal Energy Resolution

Eta Range	Default Resolution (σE/E)	Requested (σE/E)
$-3.5 < \eta < -1.0$	50%/√E	Same (~10% constant term is acceptable)
$-1.0 < \eta < 1.0$	N/A	85%/√E + 10%
$1.0 < \eta < 3.0$	50%/√E	50%/√E + 10%
$3.0 < \eta < 3.5$		35%/√E
	N/A	

For large-x processes need delta x < 0.1, where HCAL resolution determines delta x

- For a 50 GeV hadron/jet energy and 35%/√E → delta x=0.05

- ❑ EIC requirements up to η~3 may be achieved with existing technologies tried by eRD1 consortium and STAR Forward upgrade with some additional R&D efforts to improve on performance of STAR like forward calorimeter system.

- ❑ A high resolution HCal insert for η>3 will require additional R&D efforts, e.g. to develop high density fiber calorimeter with SiPM readout.

Detector YR Status Summary

- A wide array of detector technology solutions were explored.
- An integrated detector concept that addresses most physics requirements has been developed.
- Some tension points between physics requirements and detector technologies persist
  - Further development and R&D needed.
- Purpose of YR Efforts:
  - Advance the state and detail of the documented physics studies and detector concepts. 👍
  - Provide the basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors towards future Technical Design Reports (TDRs). 👍