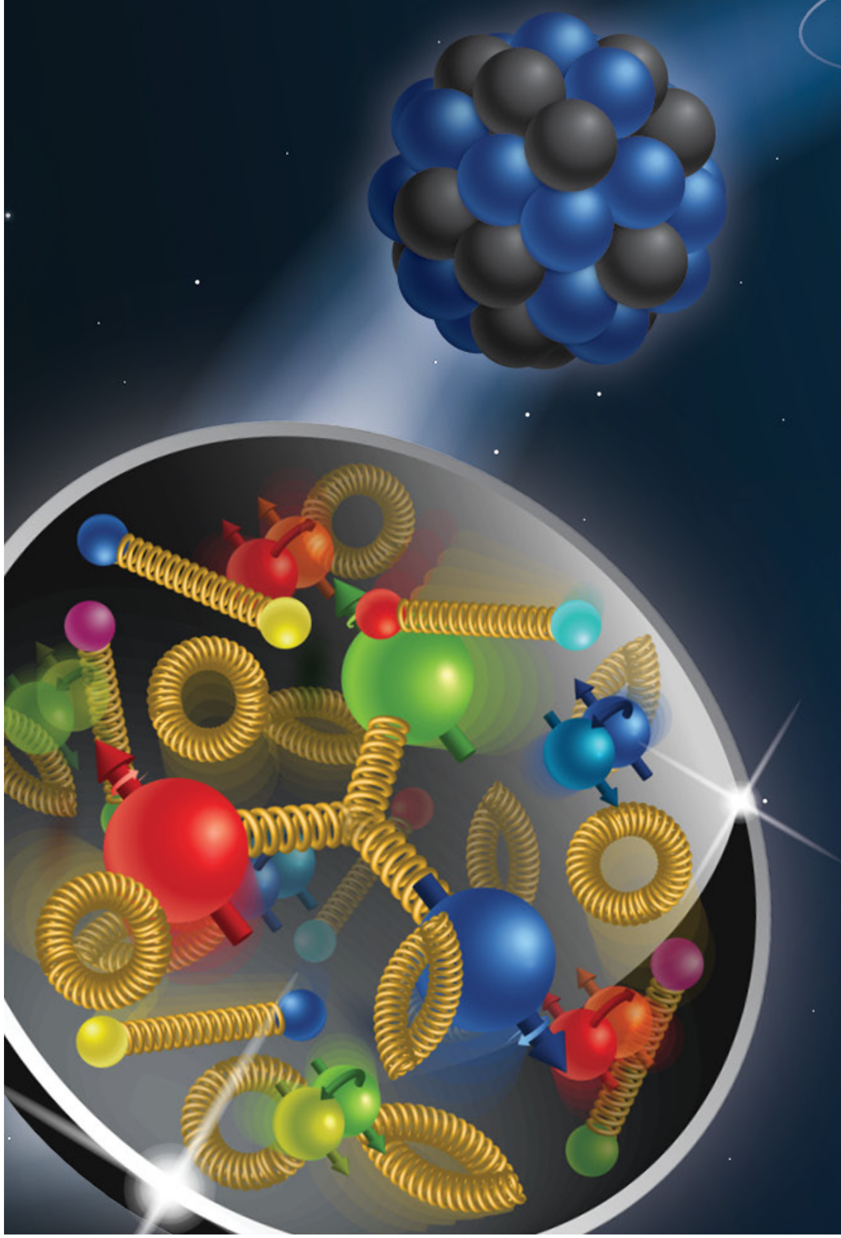
YR: arXiv: 2103.05419



Calorimetry for an EIC Detector

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RHIC & AGS Annual Users' Meeting

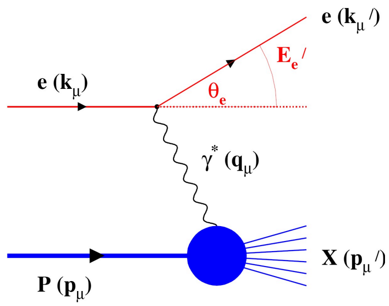
June 8-11, 2021

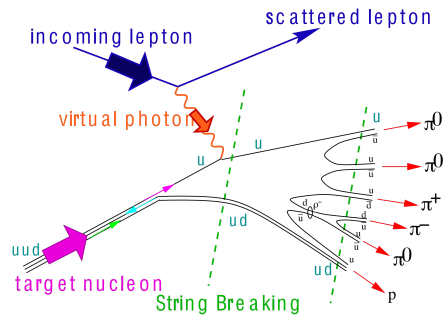
Electron-Ion Collider

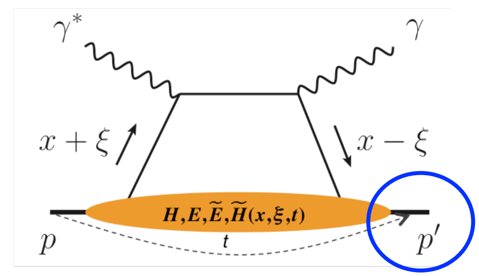
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

Experimental Measurement Categories to address EIC Physics

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

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

exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, φ
- proton p_t: 0.2 - 1.3 GeV
  - → cannot be detected in main detector
  - → strong impact on Interaction Region design

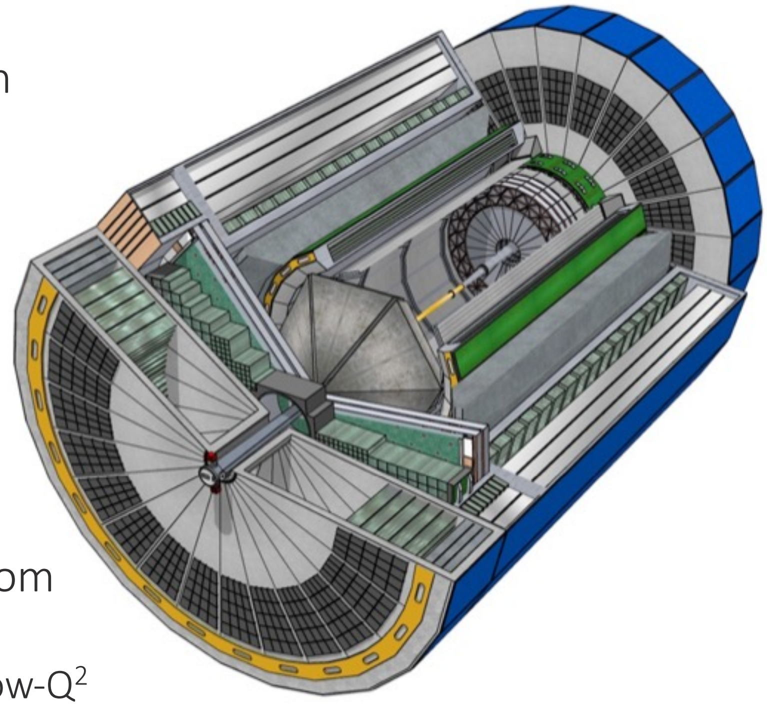
∫Ldt: 1 fb^{-1} — 10 fb^{-1} — 10 - 100 fb^{-1}

machine & detector requirements

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 (μ-vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - 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

EMCal

Goals:

- DIS kinematics
  (through scattered electron)
- Decay electrons
  (e.g. from vector mesons and HF)
- Photons
  (e.g. from DVCS)
- π0
  (e.g. from SIDIS or exclusive DIS)

Challenges:

- Dynamic Range
- Energy resolution
  (particularly at high $|\eta|$, high p)
- Charged hadron suppression for eID
- γ/π0 discrimination
  (Granularity, projectivity)

Limited space => dense, high granularity, high resolution EMCal

HCal

Goal:

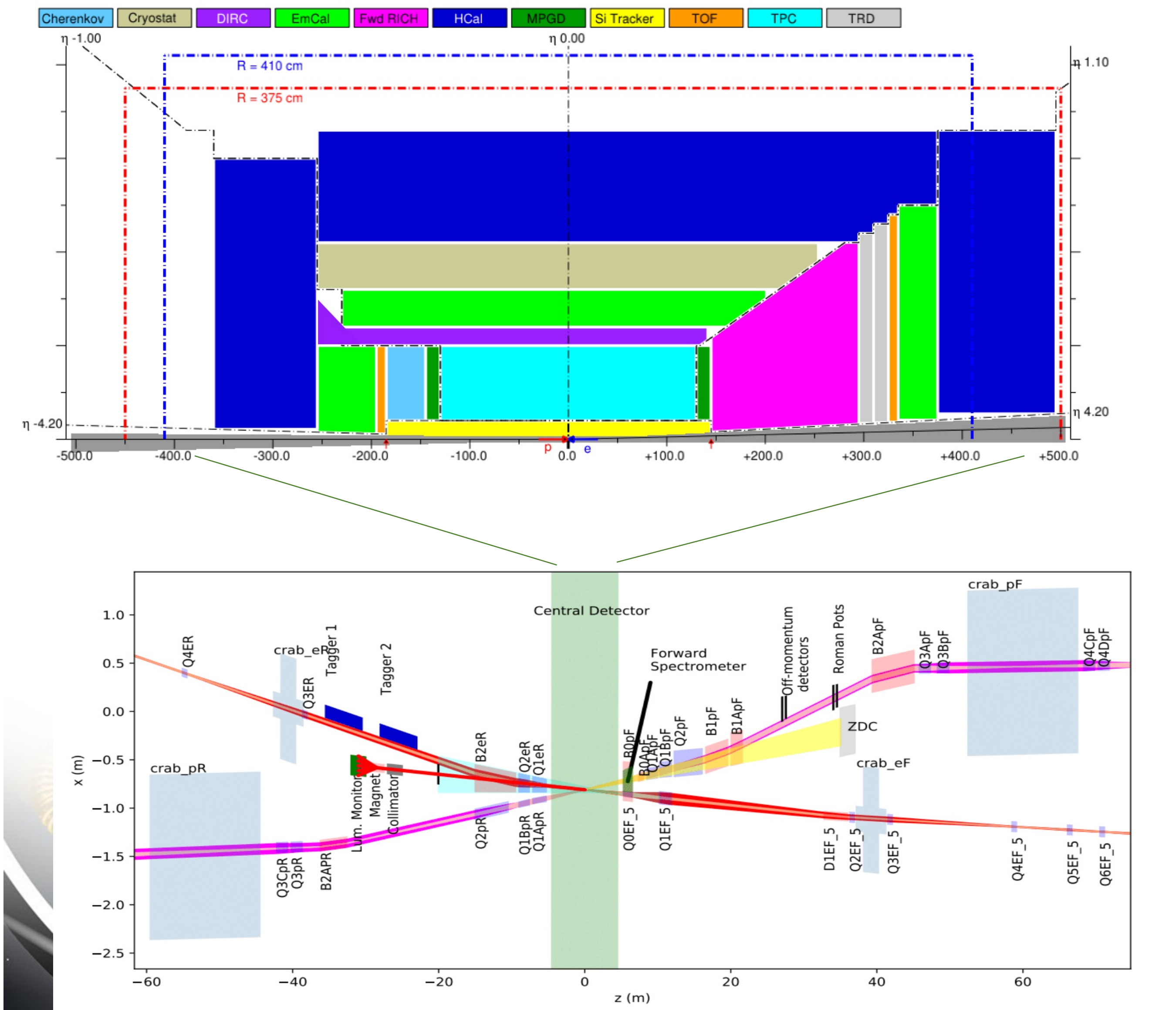
- Jet measurements
- Hadron measurements
- Rapidity gap
  (tag diffractive events)

Challenges:

- Energy resolution
  (particularly at high $|\eta|$)
- Neutral/Charged cluster discrimination
  (with help of tracking)

Limited space <=> Resolution

Calorimetry in EIC Detector



Central Detector:

EMCal&HCal: |η|<4

Far-Backward:

EMCal for lum. det

EMCal for low Q^2 tagger

Far-Forward:

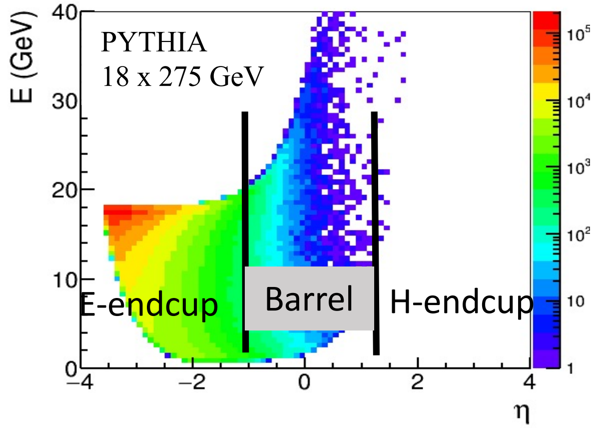
ZDC: EMCal&HCal

EMCal/PS at B0?

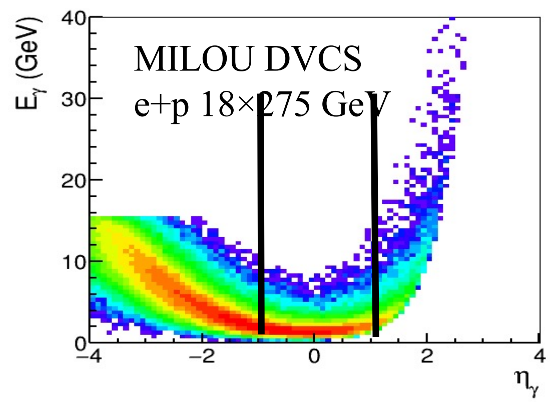
Space is at premium everywhere

EMCal in Central Detector

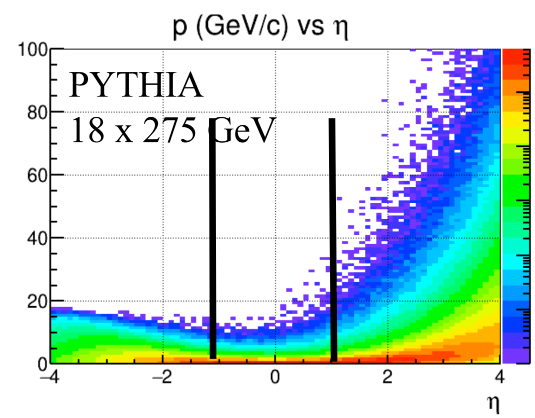
DIS e



DVCS photons



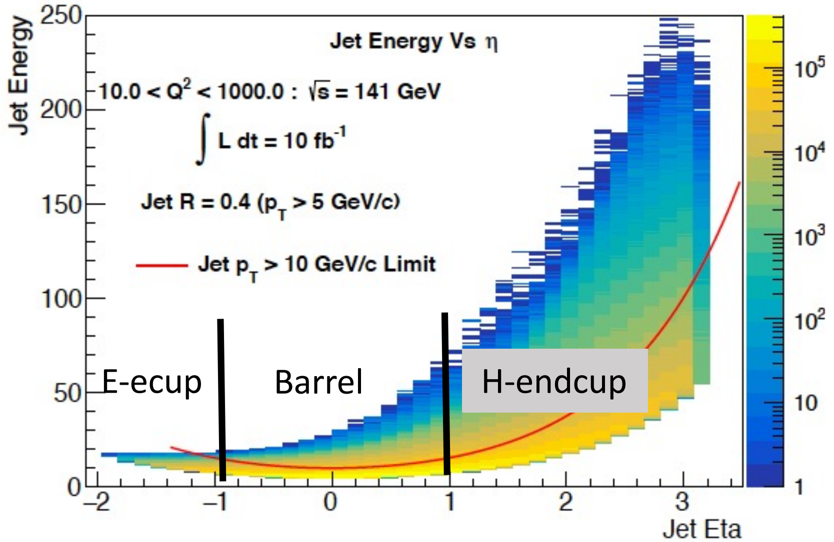
SIDIS π0



	E-endcup -4<η<-2	E-endcup -2<η<-1	Barrel |η|<1	H-endcup 1<η<4	
Resolution , $\frac{\sigma_E}{E}$	$\frac{2\%}{\sqrt{E}} \oplus$(1-3)%	$\frac{7\%}{\sqrt{E}} \oplus$(1-3)%	$\frac{10-12\%}{\sqrt{E}} \oplus$(1-3)%	$\frac{10-12\%}{\sqrt{E}} \oplus$(1-3)%	Important to minimize const term
Min E, GeV	0.1	0.1	0.1	0.1	To measure decays
Granularity, Δθ	<0.02	<0.02	<0.025	<0.01	Defines γ/π0 discr., helps for e/π
Projectivity	Desirable	Desirable	Yes	Desirable	Affects γ/π0 discr and pos. res
Avail. space	Δz=60cm	Δz=60cm	Δr=30cm	Δz=40cm	Including all services

HCal in Central Detector

Jets



Jacquet-Blondel for DIS kinematics

$$Q^2_{JB} = \frac{p^2_{T,h}}{1 - y_{JB}} \qquad p^2_{T,h} = \left(\sum_h p_{x,h}\right)^2 + \left(\sum_h p_{y,h}\right)^2$$

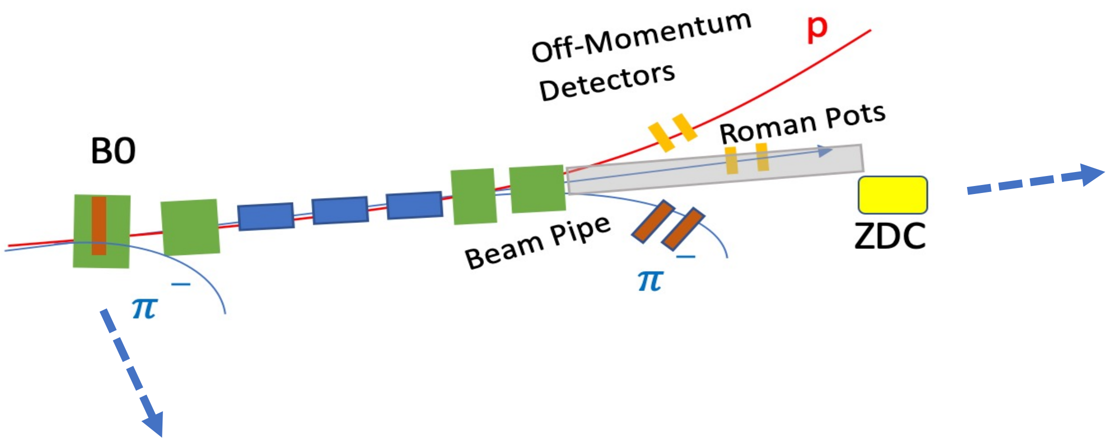
$$y_{JB} = \frac{(E - p_z)_h}{2E_e} \qquad (E - p_z)_h = \sum_h (E_h - p_{z,h})$$

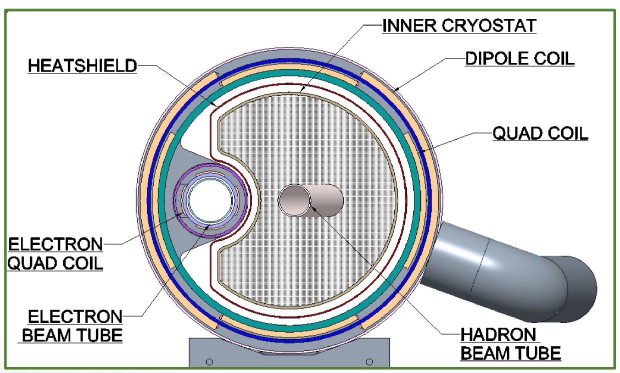
$$x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$

- All hadrons need to be reconstructed
- n and K_L only in HCal

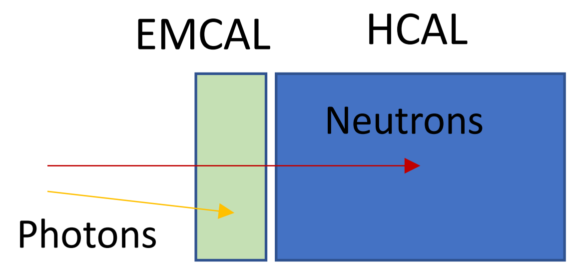
	E-endcup -4<η<-1	Barrel |η|<1	H-endcup 1<η<2.5	H-endcup 2.5<η<4	
Resolution , $\frac{\sigma_E}{E}$	$\frac{50\%}{\sqrt{E}} \oplus 6\%$	$\frac{85\%}{\sqrt{E}} \oplus 7\%$	$\frac{50\%}{\sqrt{E}} \oplus 6\%$	$\frac{35\%}{\sqrt{E}} \oplus 5\%$?	
Min E, GeV	0.5	0.5	0.5	0.5	To minimize bias in jets, and JB kinematics reco
Granularity, cm²	10×10	10×10	10×10	10×10	To separate charged from neutrals
Avail. space	Δz=~100cm	Δr=120cm	Δz=120cm	Δz=120cm	Including all services

EMCal & HCal in Far-Forward





5.5 < θ < 20 mrad
Tracking
EMCal/PS



θ < 5.5 mrad

$0.6 \times 0.6 \times 2\ m^3$

HCal: $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 5\%$

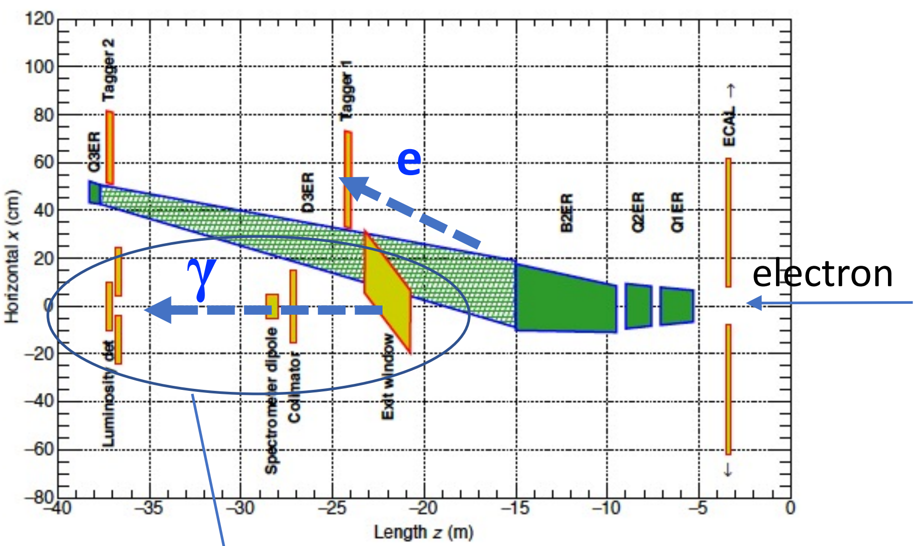
$\sigma_\theta \sim \frac{3\ mrad}{\sqrt{E}}$

EMCal: γ down to 0.1 GeV

High res, e.g. PWO

~Continuous coverage from central to far-forward region is anticipated

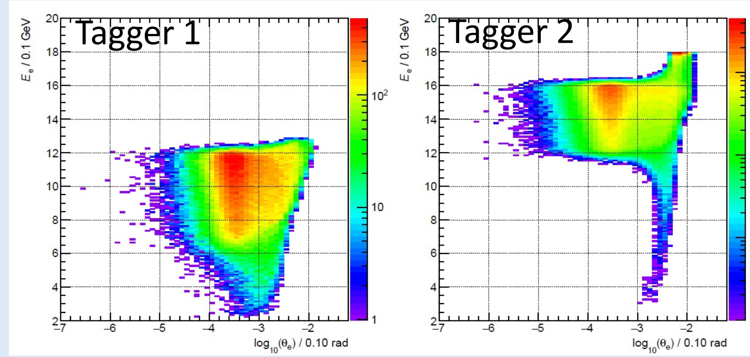
EMCal in Far-Backward



Low Q2 tagger

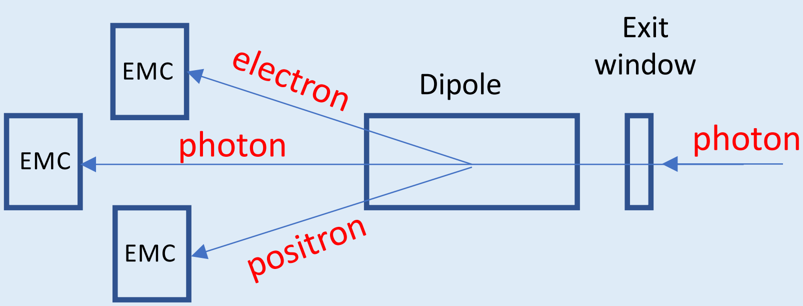
EMCal: High granularity

High precision energy&position for *e*

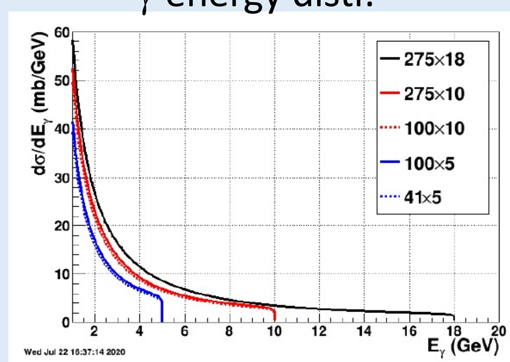


Luminosity Detector: $e + p \rightarrow e + p + \gamma$

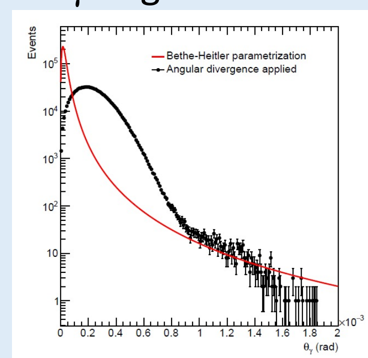
EMCal: energy&position for γ, *e*- and *e*+



γ energy distr.



γ angular distr.



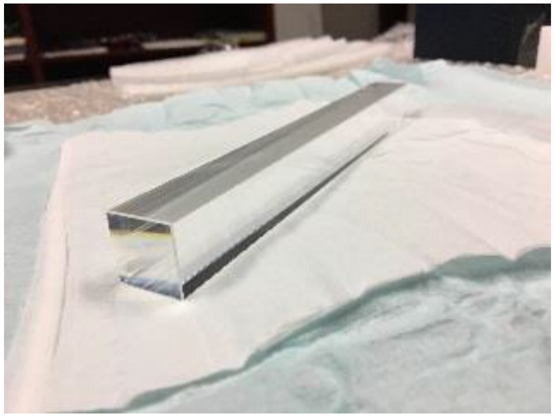
YR: Detector options

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			

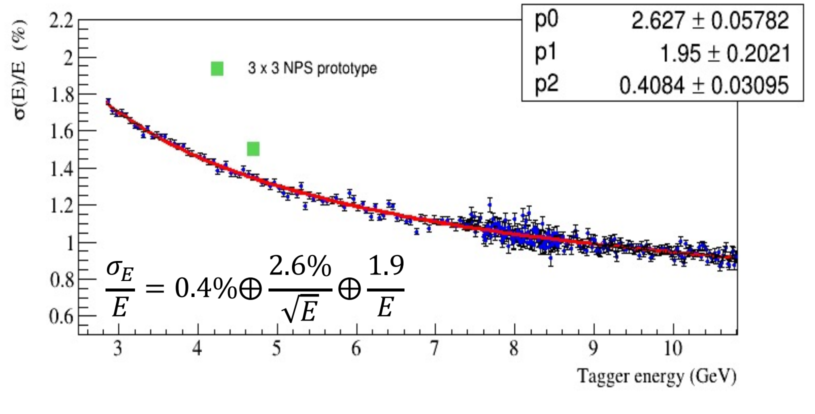
[a] TPC surrounded by a micro-RWELL tracker
[b] set of coaxial cylindrical MICROMEGAS
[c] Small-Strip Thin Gas Chamber (sTGC)
[d] MAPS for B0 and off-momentum poarticles, LGAD for Roman Pots
[e] also Pb/Sc Shashlyk
[f] alternative options: $PbWO_4$, LYSO, GSO, LSO

Homogeneous EMCal: $PbWO_4$

eRD1: T.Horn



Jlab-PrimEx eta/NPS PWO EMCal prototype



Scintillating light => photo sensor

$X_0 = 0.9$cm => Compactness

$R_m = 2$cm => High granularity

$\frac{\sigma_E}{E} = (0.4 - 1)\% \oplus \frac{(2-3)\%}{\sqrt{E}}$ => High resolution

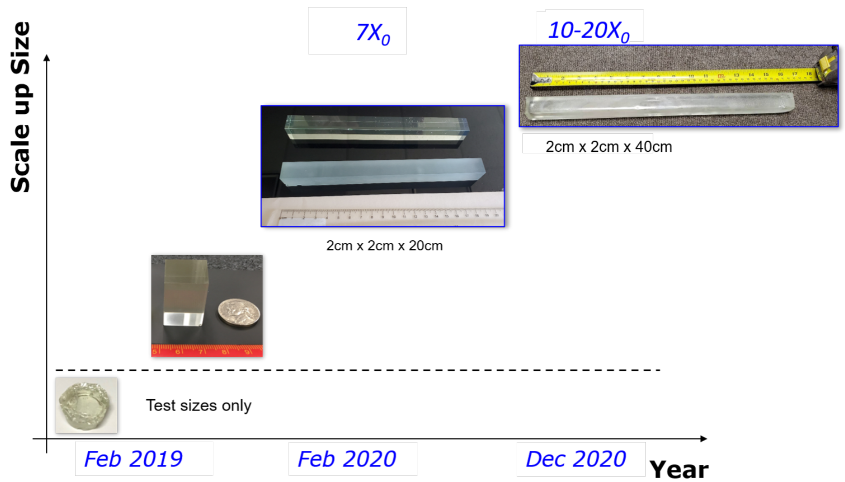
>1000 krad => Radiation hard

d(LY)/dT = -(2-3)%/°C => Temperature sensitive

An ideal EMCal for EIC Detector

Homogeneous EMCal: SciGlass

eRD1: T.Horn

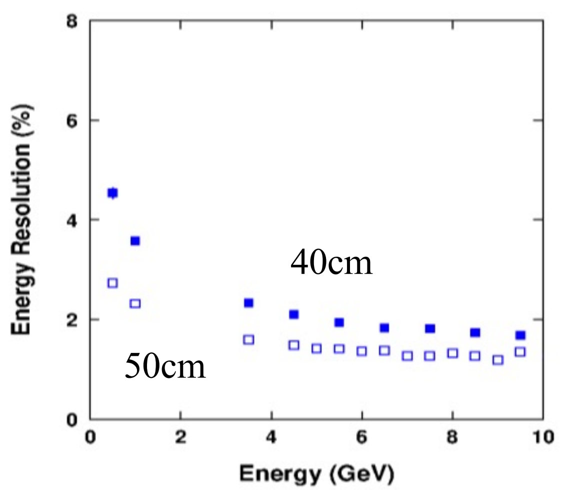


Scintillating light => photo sensor

- Scaling up to ~$20X_0$ in 2021

  With acceptable mechanical and optical properties
- Test beam in 2021
- Prepare for the large scale production

Simulation

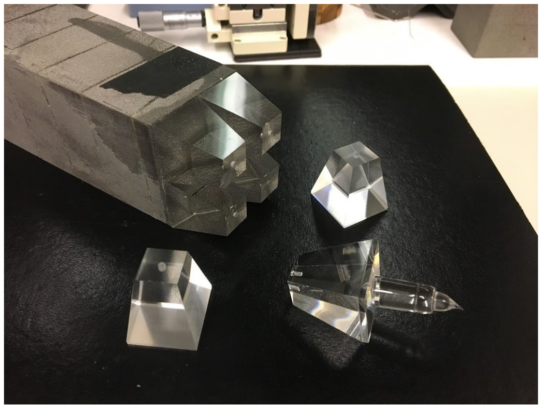


Alternative to high resolution (expensive) EMCal

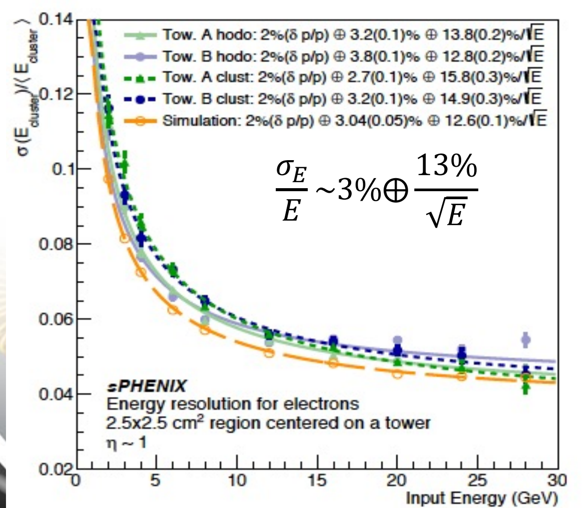
	PWO	SciGlass
X0, cm	0.9	2-3
Rm, cm	2.0	2.2 – 2.8
$\frac{\sigma_E}{E}$, %	$(0.4-1)\%\oplus\frac{(2-3)\%}{\sqrt{E}}$	Similar for the same length in X_0
Rad. Tolerance, krad	>1000	>1000
d(LY)/dT, %/°C	2-3	0

Sampling EMCal: W/SciFi

eRD1: C.Woody & O.Tsai



BNL-sPHENIX: W/SciFi



Light generated in scintillating fibers, embedded in an absorber (W/epoxy mix), is transported to photo sensor

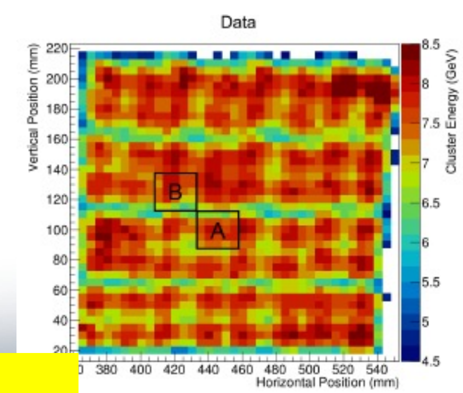
sPHENIX barrel EMCal:

- Compact: X_0 = 0.7cm
- High granularity: R_m = 2cm
- Sampling fraction: ~2.3%
- Modest resolution

Can be improved by increasing the sampling fraction, at the expense of larger X_0 and R_m

R&D:

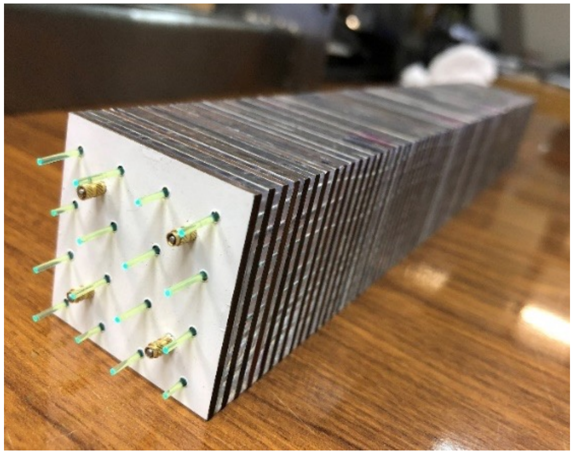
Improve light collection eff. and uniformity



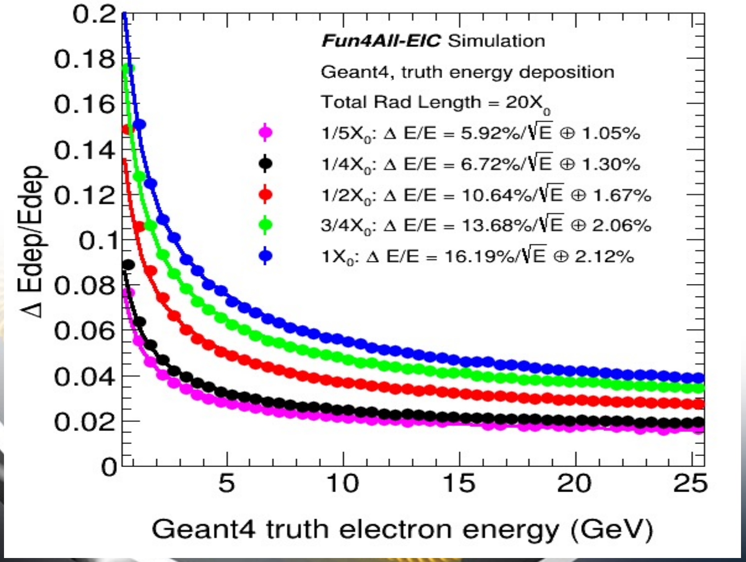
Close to satisfy EIC Detector requirements in barrel and forward region

Sampling EMCal: W/Sc shashlik

eRD1: C.Woody&E.Kistenev



$X_0 \sim 0.9$cm $R_m \sim 2$cm



Light generated in scintillating tiles transported through the WLS fibers to photo sensors

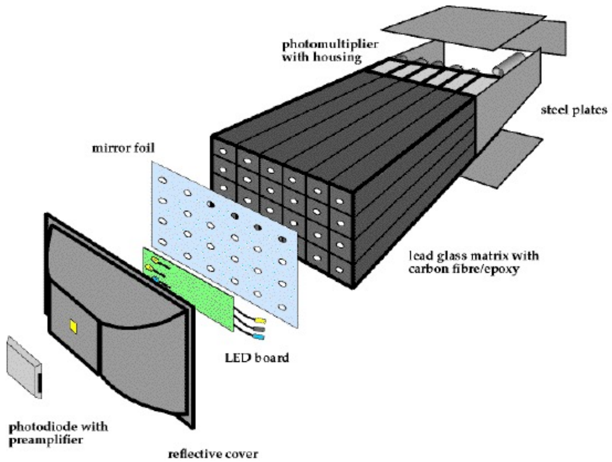
- Each fiber readout by its own SiPM
- More detailed info on shower development within a tower
  - Improve position resolution
  - Improve energy res. (const term)
  - May improve γ/π0 discrimination
- Tunable resolution through the change of sampling fraction and/or frequency:

$$\frac{\sigma_E}{E} = (1-2)\% \oplus \frac{(6-16)\%}{\sqrt{E}}$$

- Test beam data in 2021

Satisfies EIC Detector requirements everywhere except for the most backward region

Refurbish existing EMCals



PbGl

A lot of modules from previous experiments:

$$\frac{\sigma_E}{E} \sim \frac{6\%}{\sqrt{E}} \oplus 1\%$$

Good e/π separation

=> Good candidate for e-endcap (η>-2)

PbSc-Shashlik

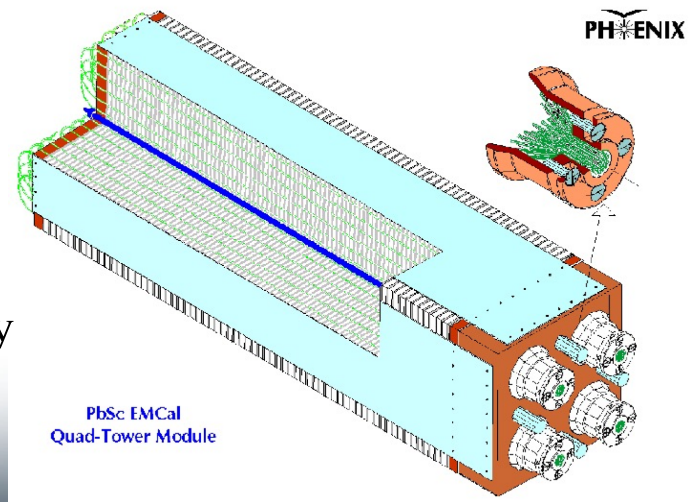
~15k towers from PHENIX (5.5×5.5 cm^2)

$$\frac{\sigma_E}{E} \sim \frac{8\%}{\sqrt{E}} \oplus 2\%$$

Each fiber readout would make it of high granularity

Shower core is << R_m !

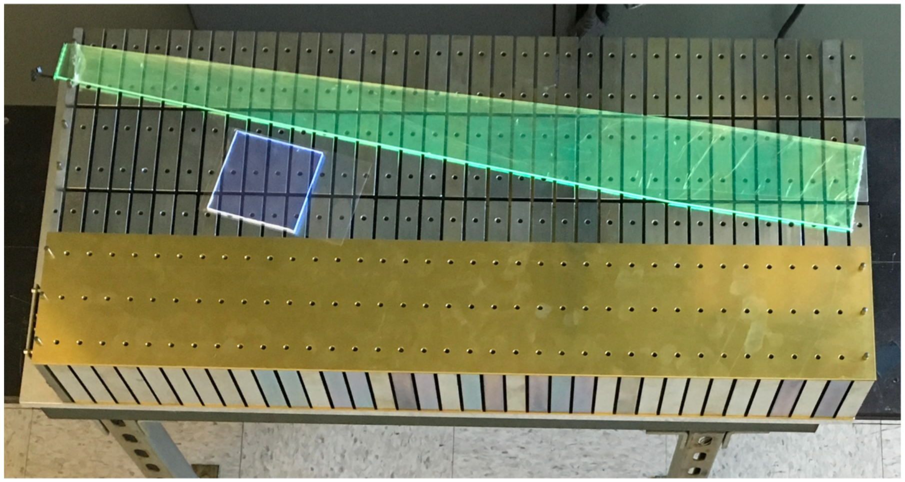
=> Good candidate for h-endcap



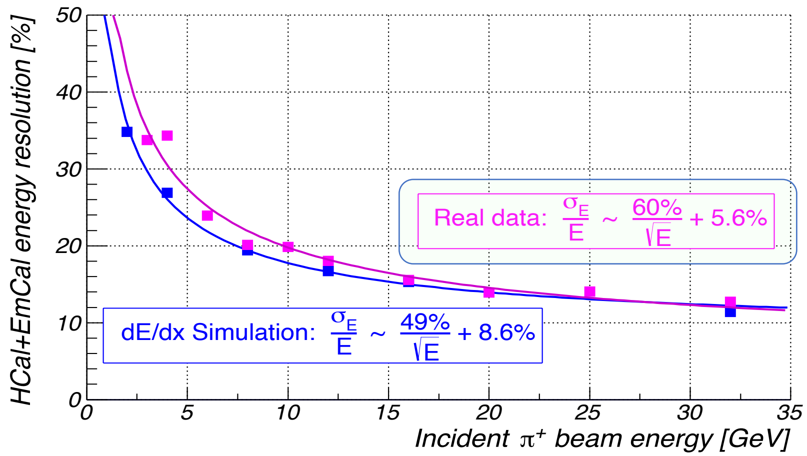
Sampling HCal for endcup

eRD1: O.Tsai

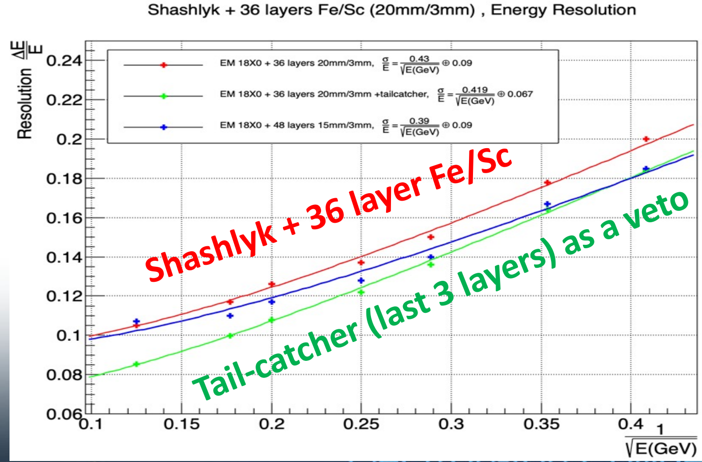
BNL-fSTAR: Fe/Sc HCal (20mm/3mm)



Close to satisfy EIC Detector requirements everywhere except for the most forward region



Tail-Catcher as a veto



Tail-Catcher

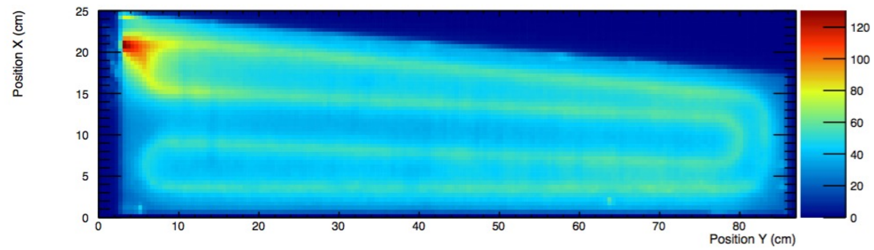
(to mitigate long. leakage fluctuations)

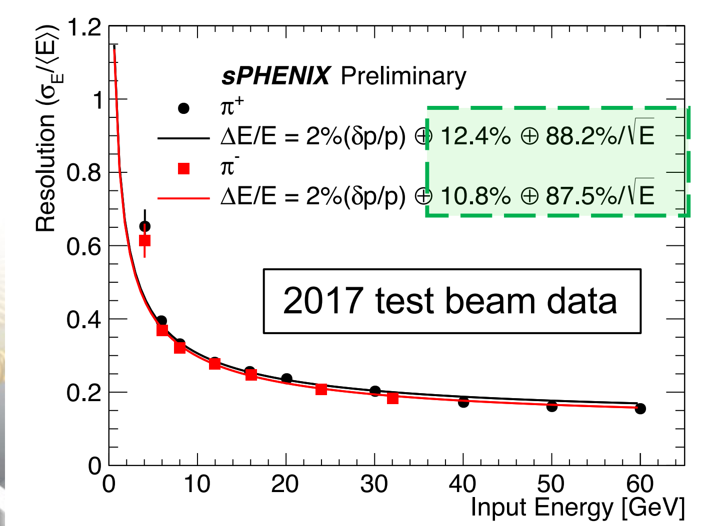
- Improves the energy resolution
- Detection efficiency loss
  - 10% loss for 6 GeV pions
  - 50% loss for 60 GeV pions

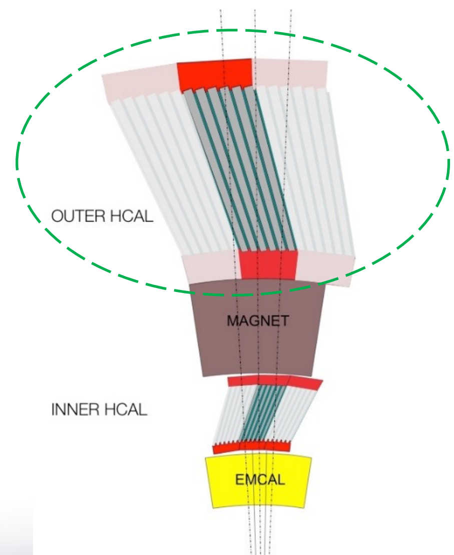
Sampling HCal for barrel

BNL-sPHENIX: Fe/Sc HCal

Scintillator plate with embedded WLS fiber



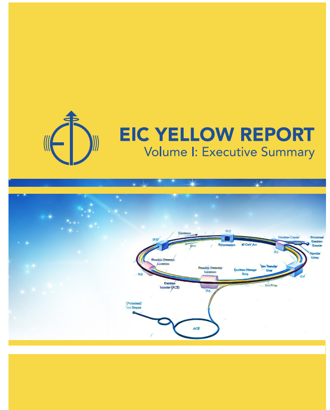


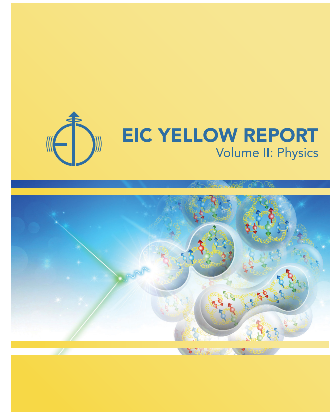


Close to satisfy EIC Detector requirements in barrel

Summary

arXiv:2103.05419



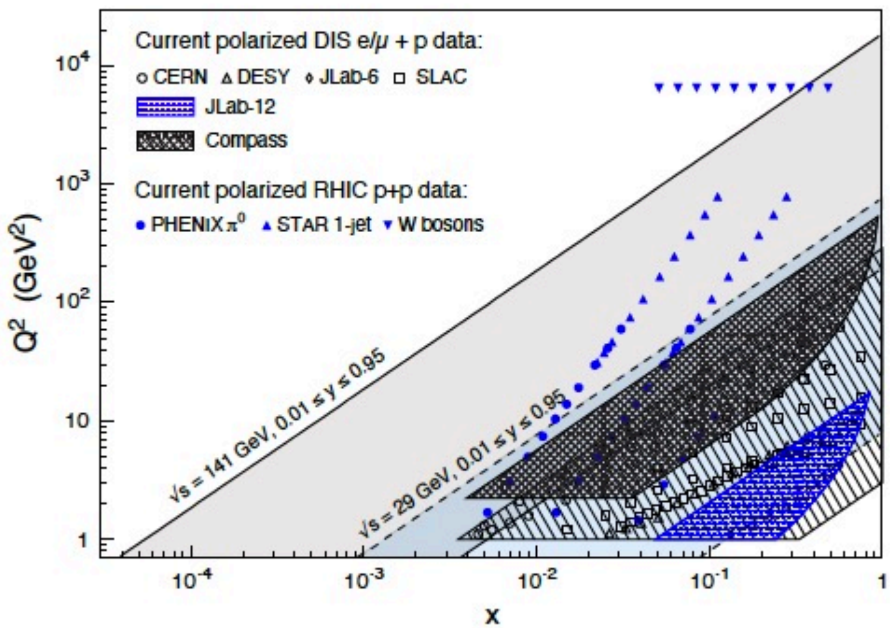


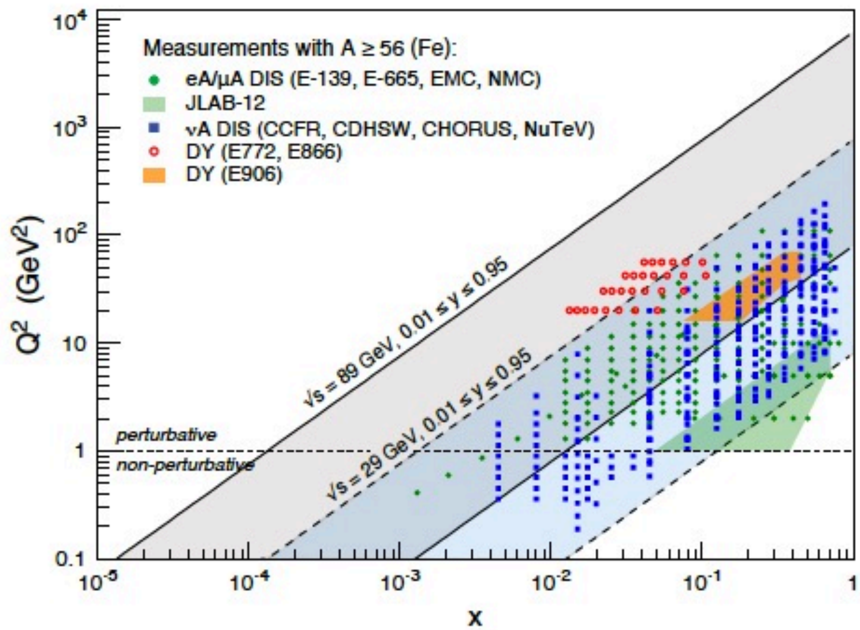
- Detector requirements defined by YR Physics Working groups
- All requirements initially defined for EMCal can be satisfied with the existing technologies
  - Different technologies can be used in each kin. regions
  - Space is at premium; larger space would allow more options
  - Active R&D for different technologies
  - Existing EMCals to refurbish
  - Preshower may help to enhance EMCal capabilities

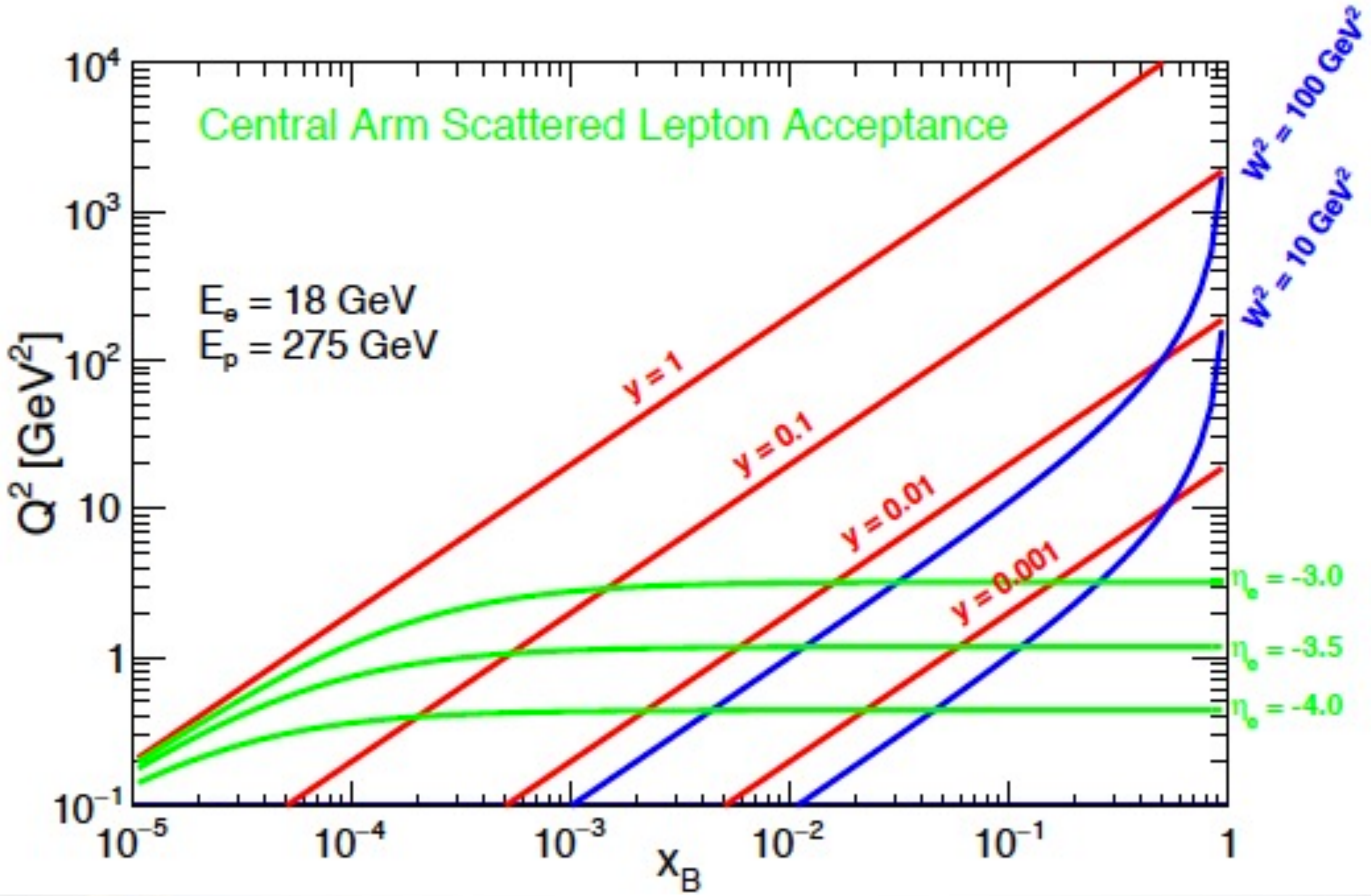
Backup

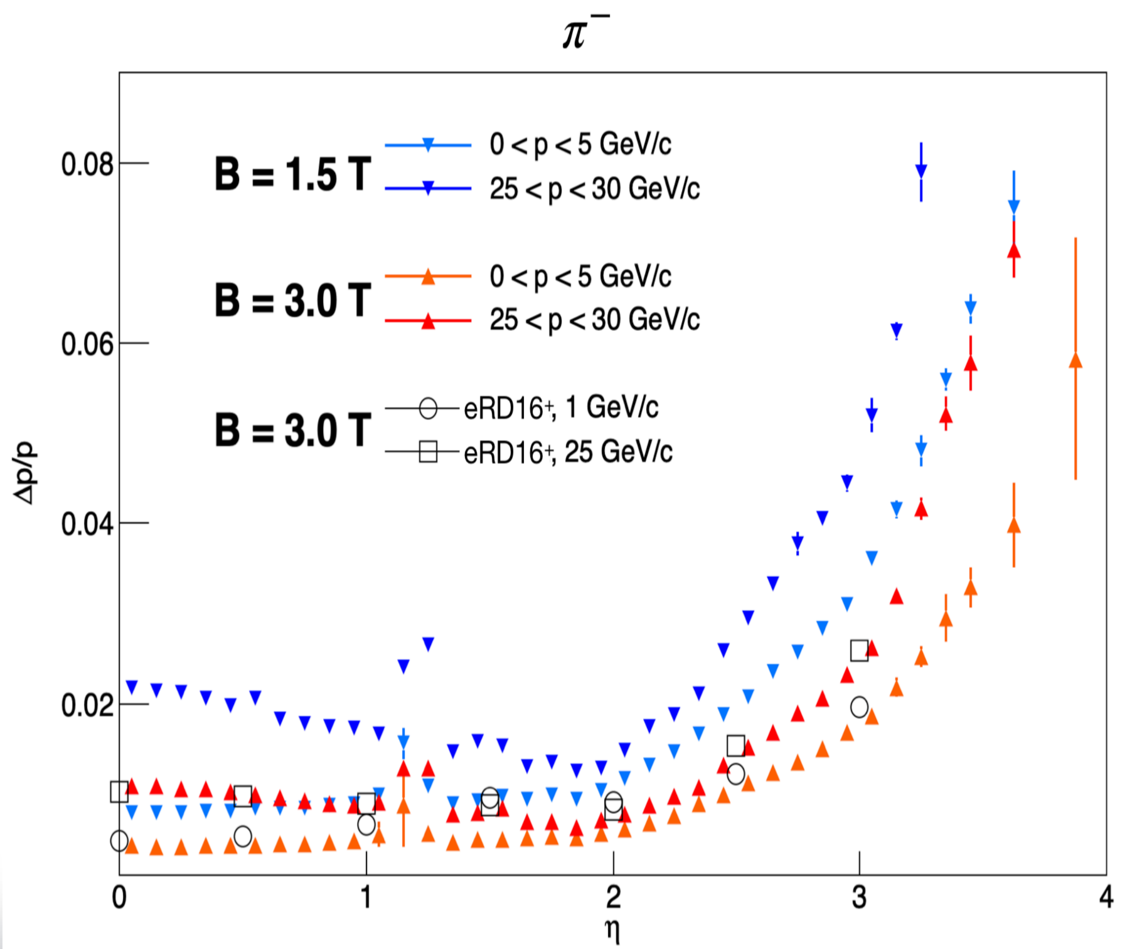
YR: Detector Requirements

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												
-4.0 — -3.5									2%/√E+(1-3)%					~50%/√E+6%	
-3.5 — -3.0		Central Detector	Backwards Detectors												
-3.0 — -2.5					σ_p/p ~ 0.1%×p+2.0%		σ_{xy}~30μm/p_T+40μm								
-2.5 — -2.0														~45%/√E+6%	
-2.0 — -1.5					σ_p/p ~ 0.05%×p+1.0%		σ_{xy}~30μm/p_T+20μm		7%/√E+(1-3)%	π suppression up to 1:10^4	≤ 7 GeV/c				
-1.5 — -1.0															
-1.0 — -0.5			Barrel												
-0.5 — 0.0				100 MeV π											
0.0 — 0.5				135 MeV K	σ_p/p ~ 0.05%×p+0.5%	~5% or less	σ_{xyz} ~ 20 μm, $d_0(z)$ ~ $d_0(r\varphi)$ ~ 20/p_T GeV μm + 5 μm	50 MeV			≤ 10 GeV/c	≥ 3σ	~500 MeV	~85%/√E+7%	Useful for bkg, improve resolution
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors						(10-12)%/√E+(1-3)%		≤ 30 GeV/c				
1.5 — 2.0					σ_p/p ~ 0.05%×p+1.0%		σ_{xy}~30μm/p_T+20μm								
2.0 — 2.5										3σ e/π	≤ 50 GeV/c			~35%/√E	
2.5 — 3.0					σ_p/p ~ 0.1%×p+2.0%		σ_{xy}~30μm/p_T+40μm				≤ 30 GeV/c				
3.0 — 3.5							σ_{xy}~30μm/p_T+60μm				≤ 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		$\sigma_{intrinsic}(\|t\|)/\|t\|$ < 1%; Acceptance: 0.2< p_T <1.2 GeV/c										


Current polarized DIS e/μ + p data:
○ CERN △ DESY ◇ JLab-6 □ SLAC
JLab-12
Compass
Current polarized RHIC p+p data:
● PHENIX π⁰ ▲ STAR 1-jet ▼ W bosons
√s = 141 GeV, 0.01 ≤ y ≤ 0.95
√s = 29 GeV, 0.01 ≤ y ≤ 0.95
Q² (GeV²)
x
10⁴
10³
10²
10
1
10⁻⁴
10⁻³
10⁻²
10⁻¹
1

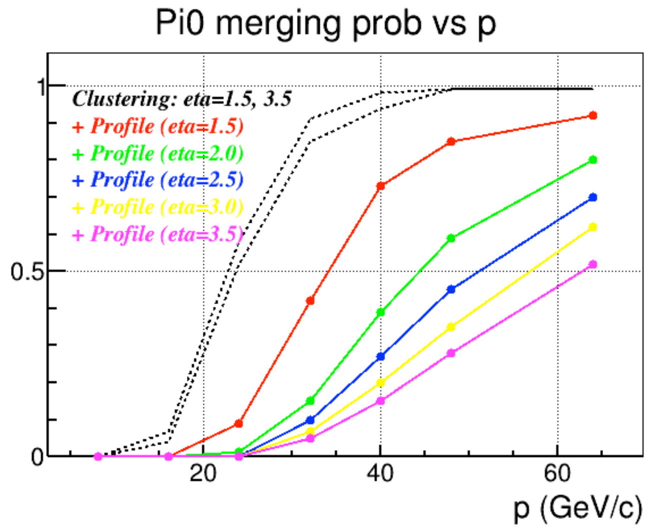

Measurements with A ≥ 56 (Fe):
eA/μA DIS (E-139, E-665, EMC, NMC)
JLAB-12
νA DIS (CCFR, CDHSW, CHORUS, NuTeV)
DY (E772, E866)
DY (E906)
√s = 89 GeV, 0.01 ≤ y ≤ 0.95
√s = 29 GeV, 0.01 ≤ y ≤ 0.95
perturbative
non-perturbative
Q² (GeV²)
x
10⁴
10³
10²
10
1
0.1
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
1


Central Arm Scattered Lepton Acceptance
E_e = 18 GeV
E_p = 275 GeV
y = 1
y = 0.1
y = 0.01
y = 0.001
W^2 = 100 GeV^2
W^2 = 10 GeV^2
η_e = -3.0
η_e = -3.5
η_e = -4.0
Q^2 [GeV^2]
x_B
10^{-1}
1
10
10^2
10^3
10^4
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1



π⁻
B = 1.5 T
0 < p < 5 GeV/c
25 < p < 30 GeV/c
B = 3.0 T
0 < p < 5 GeV/c
25 < p < 30 GeV/c
B = 3.0 T
eRD16+, 1 GeV/c
eRD16+, 25 GeV/c
Δp/p
0.08
0.06
0.04
0.02
0
1
2
3
4
η

EMCal: Projectivity



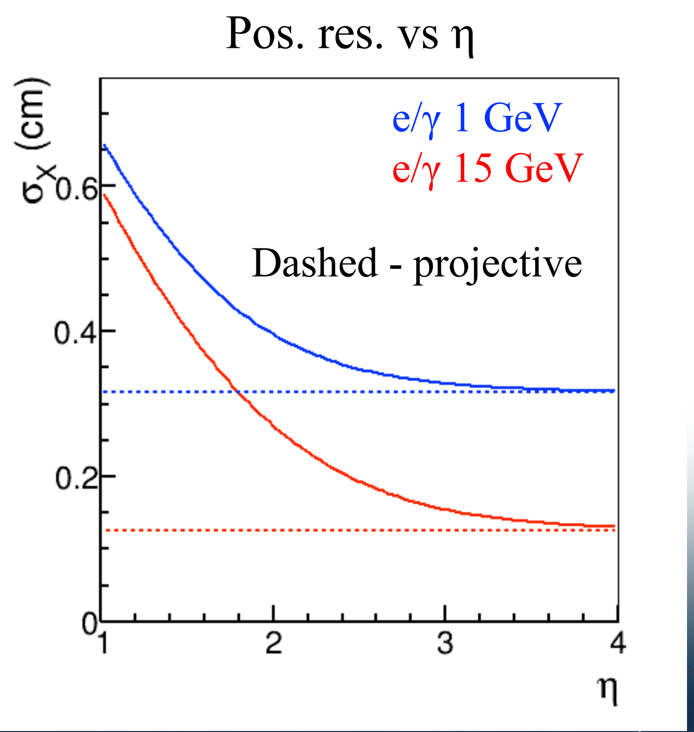
GEANT4:
Forward EMCal with granularity ~0.008 (2.5×2.5 cm^2 at z=3m)

Significant loss of $\gamma/\pi 0$ discrimination power at lower rapidity in non-projective EMCal

$$\sigma_X(E,\theta_X) = \sigma_X(E,0^0) \oplus d\sin(\theta_X)$$

For projective geometry

"Non-projectivity" term (from long. shower fluct.) d~X_0



Position resolution is dominated by "non-projectivity" term