EM Calorimetry for an EIC Detector

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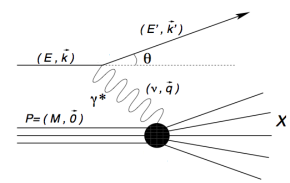
YR-Calorimetry WG conveners: V.Berdnikov and E.Chudakov

EMCal for an EIC Detector

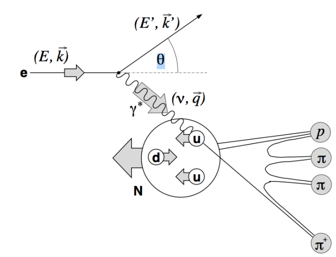
Electron/photon PID, energy, angle/position:

Coverage (in rapidity and energy), resolution, granularity, projectivity

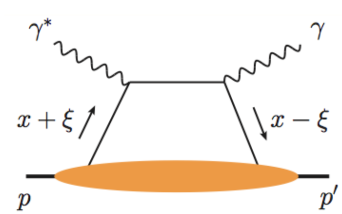
Inclusive DIS: scattered electron



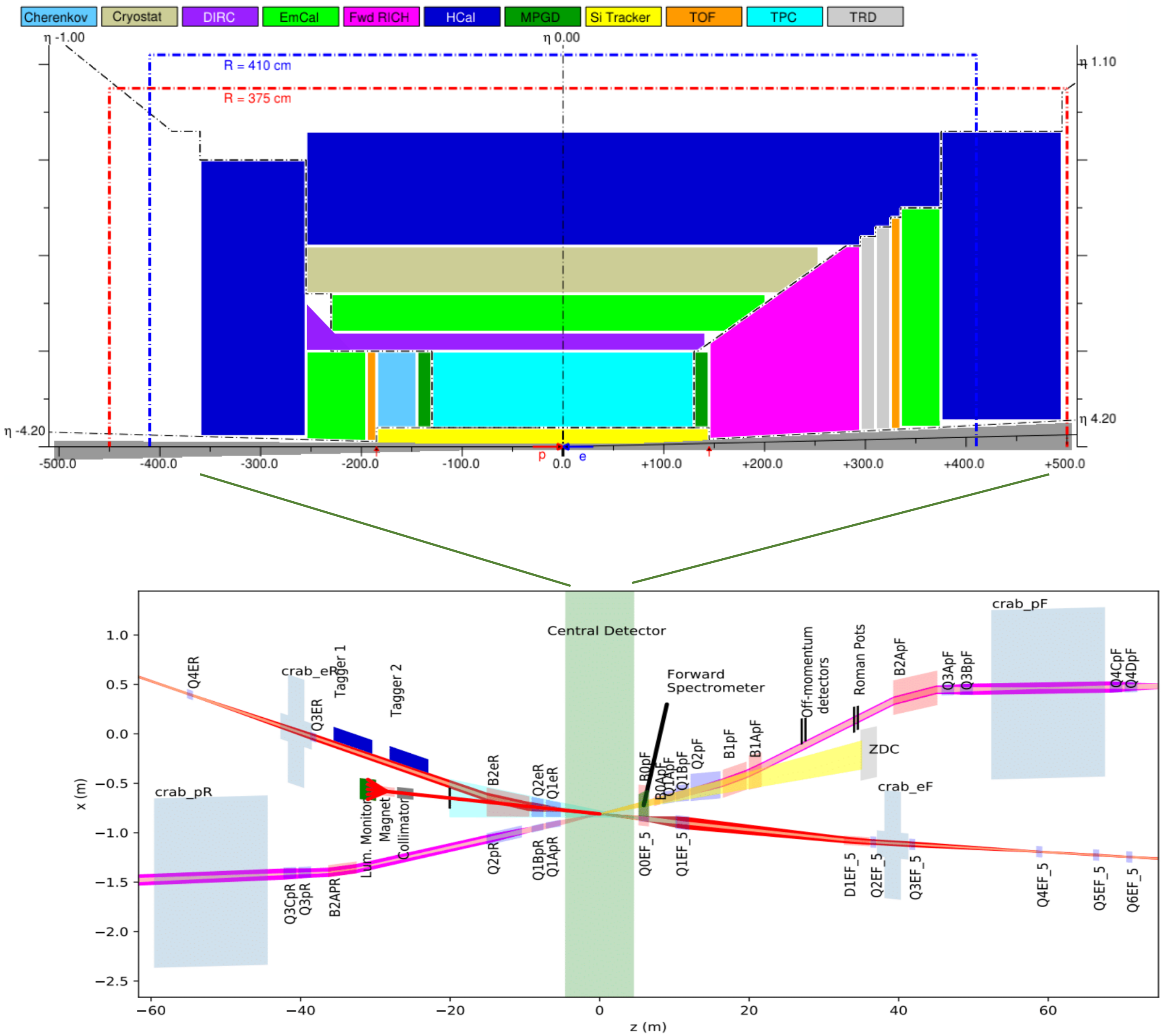
Semi-Inclusive DIS: $\pi 0 \rightarrow \gamma\gamma$, HF $\rightarrow$ e



Exclusive DIS: DVCS photons, J/ψ→ee etc.



EMCal in an EIC Detector



Central Detector:

EMCal: |η|<4

Far-Backward:

EMCal for low Q^2 tagger

EMCal for lum. det

Far-Forward:

ZDC: EMCal&HCal

EMCal/PS at B0?

Space is at premium everywhere

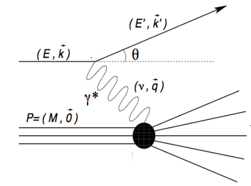
Key Characteristics

- **Depth (long. size)** **=>Compactness**
  Defined by X_0 and energy range ($L \sim 20X_0$)
- **Granularity** **=> $\sigma_{X,Y}$, e/π, γ/π0**
  Defined by R_m ($\sim X_0 \cdot 21\text{MeV}/E_{crit}$)
- **Projectivity** **=> $\sigma_{X,Y}$, e/π, γ/π0**
- **Minimal detectable energy** **=> Decays**
  Defined by noise level
- **Resolution** **=> Precision, kin. reach**

$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \oplus \frac{c}{E}$$

a: defined by syst. effects (non-uniformity, calibration, leakage)
b: defined by sampling fraction, light yield
c: noise term

Energy Resolution and eID



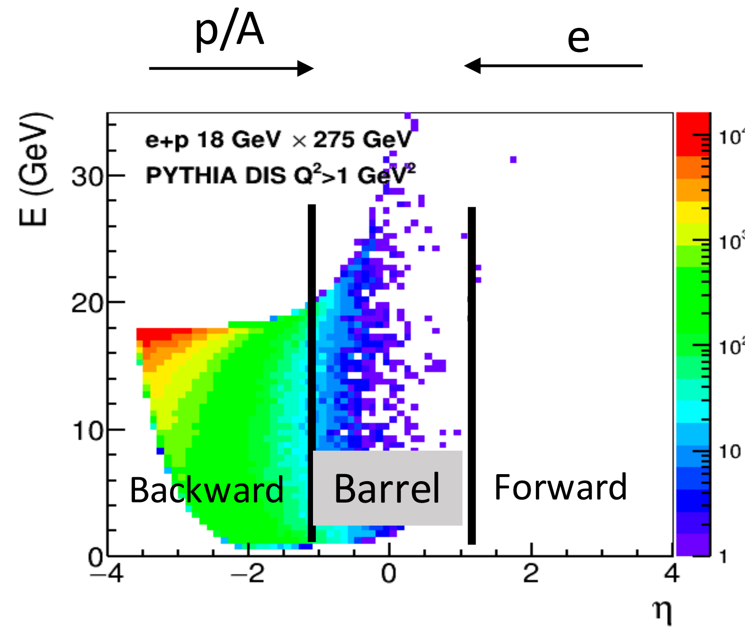
DIS kinematics through electron measurements

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

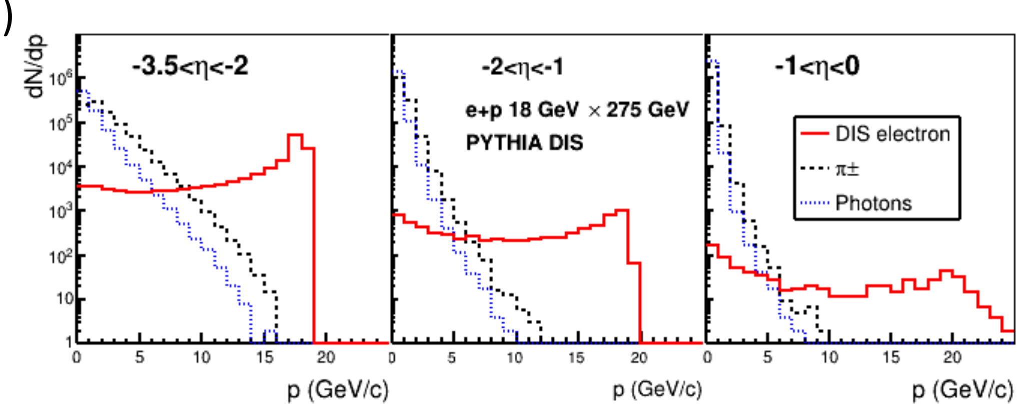
- Mainly barrel and backward
- Energy/Momentum measurement is critical: $\frac{\sigma_{Q2}}{Q^2} \sim \frac{\sigma_{E'}}{E'}$; $\frac{\sigma_x}{x} \sim \frac{1}{y}\frac{\sigma_{E'}}{E'}$
- Enhanced role at higher electron energies (tracking at lower energies)

  Minimize const term in σ_E
- Highest resolution EMCal in the most backward region (due to degraded tracking mom. res.)
- Lowest material budget (to minimize Bremsstrahlung)

Need to suppress pions



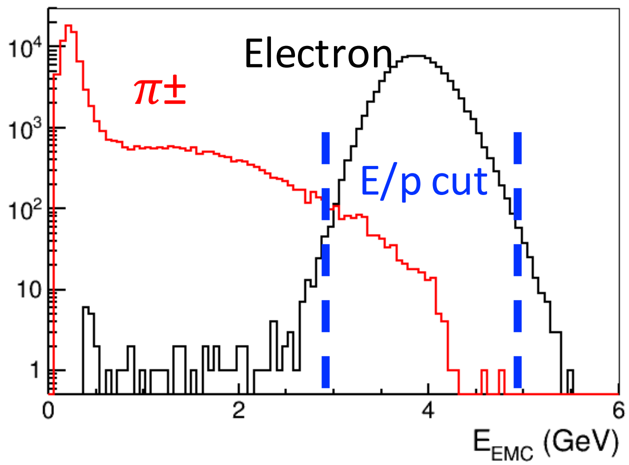
dN/dp vs p



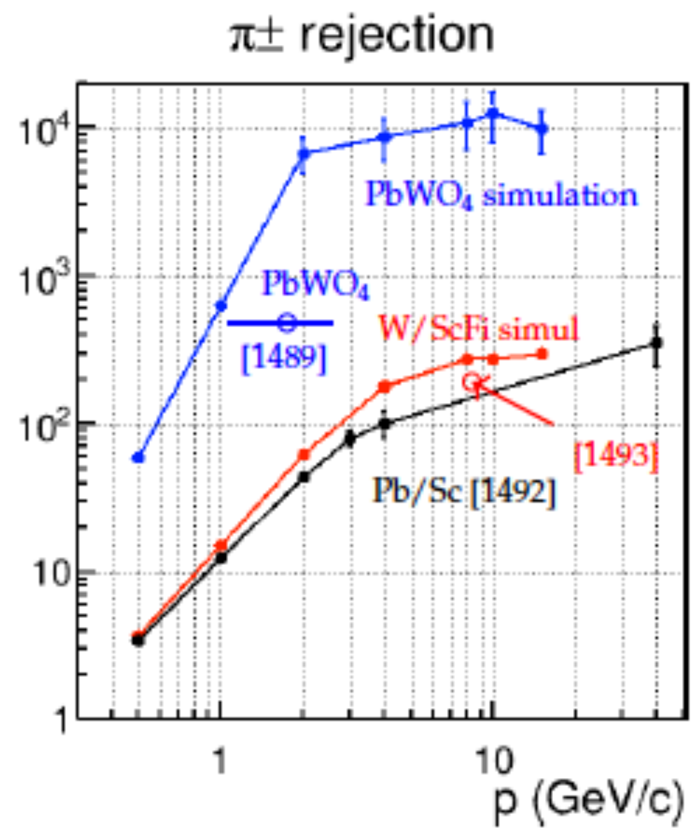
e/π Separation

E/p matching cut

EMCal response to p=4 GeV/c
(GEANT4 for SPACAL-like EMCal)



Additional ×(2-4) suppression from lateral shower profile



Strongly depends on EMCal technology:

- The smaller X_0/λ_{int} the better (smaller prob to initiate had. shower)
- The larger e/h the better (smaller response to had. shower energy)
- The higher energy res. the better (tighter E/p and shower profile cut)
- The higher granularity the better (shower profile)

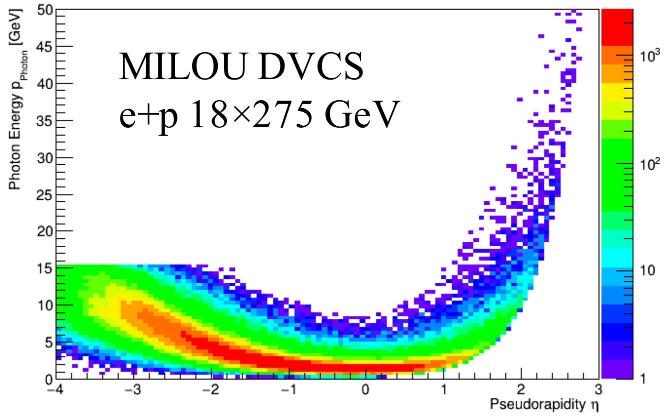
Granularity

$$\theta_{min} = \frac{2m_{\pi 0}}{E_{\pi 0}}$$

γ/π0 discrimination

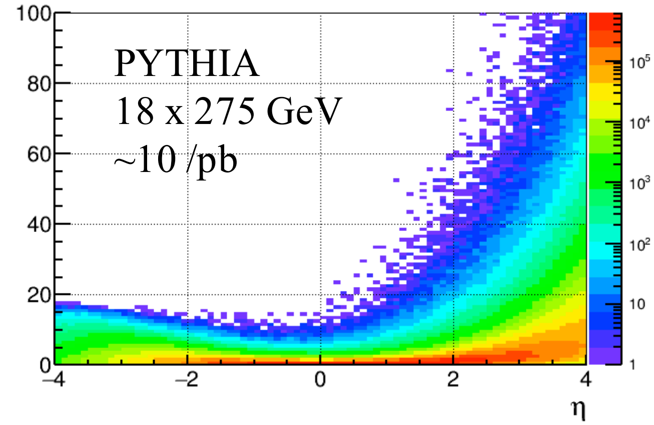
DVCS photons

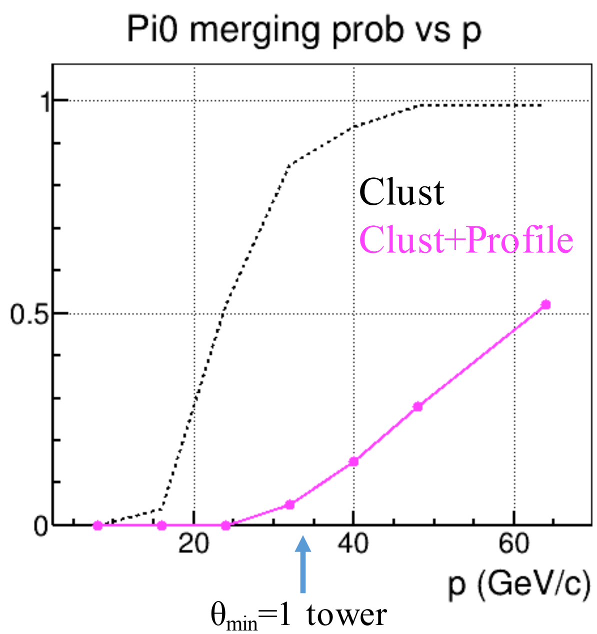
p (GeV/c) vs η



SIDIS π0

p (GeV/c) vs η



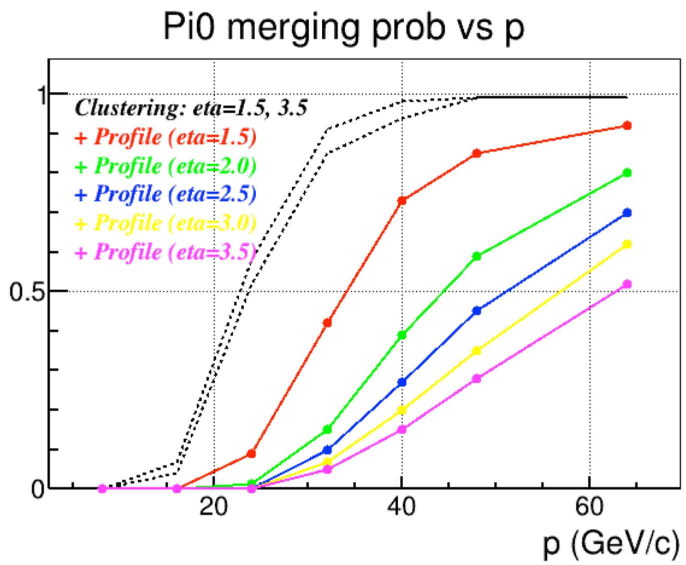


GEANT4:
Forward EMCal with granularity ~0.008 (2.5×2.5 cm² at z=3m)

Scalable with tower size d and location Z:

$$p \sim Z/d$$

Projectivity



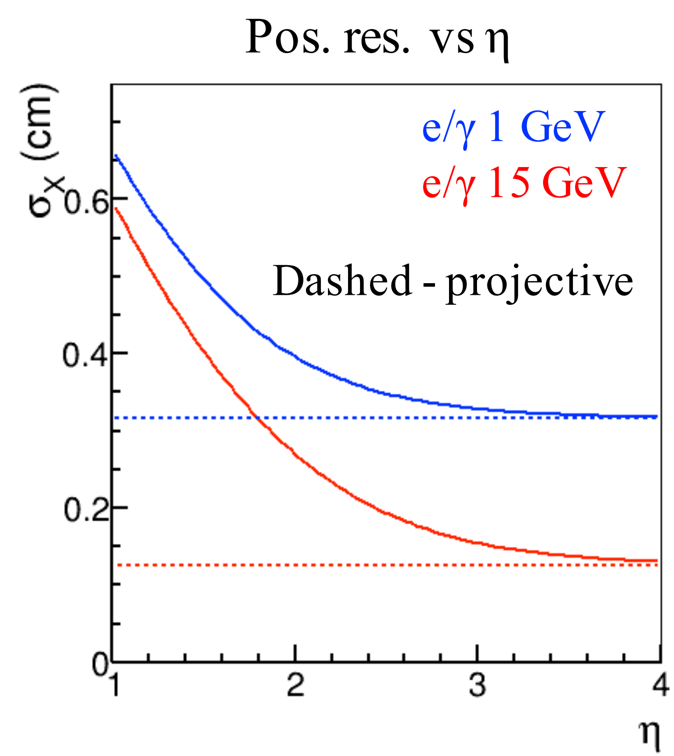
GEANT4:
Forward EMCal with granularity ~0.008 (2.5×2.5 cm^2 at z=3m)

Significant loss of $\gamma/\pi0$ discrimination power at lower rapidity in non-projective EMCal

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

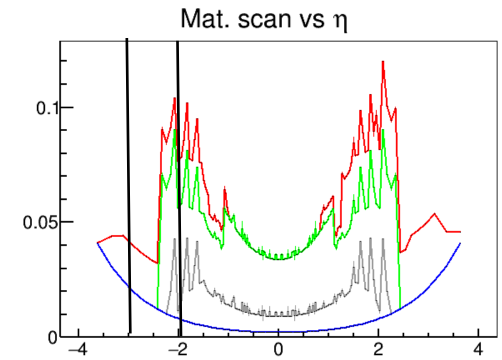
For projective geometry

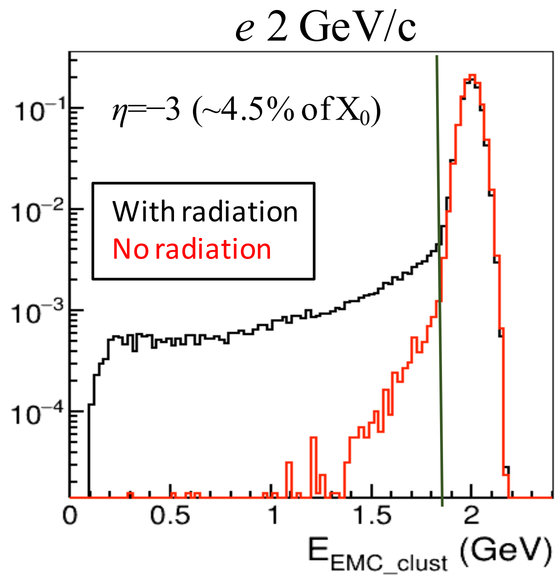
"Non-projectivity" term (from long. shower fluct.) $d \sim X_0$



Position resolution is dominated by "non-projectivity" term

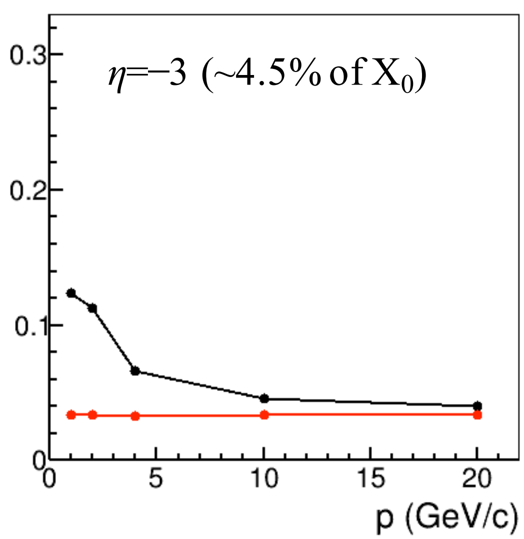
Effect of Material Upfront

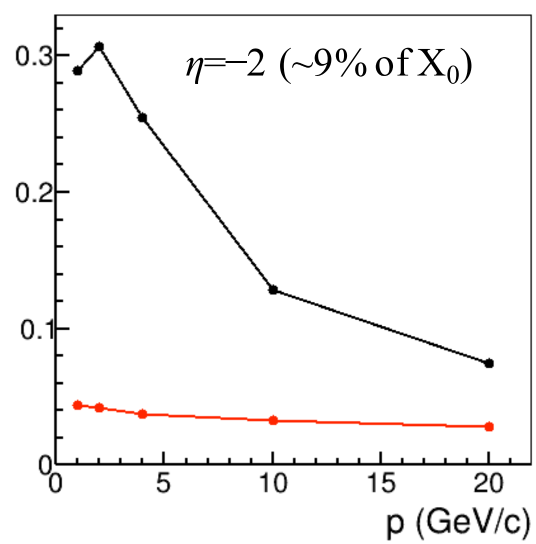




Eff: $E_{EMC} > E_{nom} - 2\ \sigma_{EMC}$

Losses vs p (GeV/c)





2.3% for a pure Gaussian response

E/p matching performance for eID will be significantly affected!

Material effect may neutralize the power of high resolution EMCal and tracking for e/π separation

We'd better know when we measure *e* vs *e*+*γ* in the EMCal

Preshower?

- May address a number of issues raised above
- Will relax the requirements for the EMCal

2-3 X0 absorber + MIP detector

- ➢ High probability to initiate EM shower
  Compared to hadronic shower
- ➢ Small shower transverse size (~1mm)
  A few cm in the EMCal

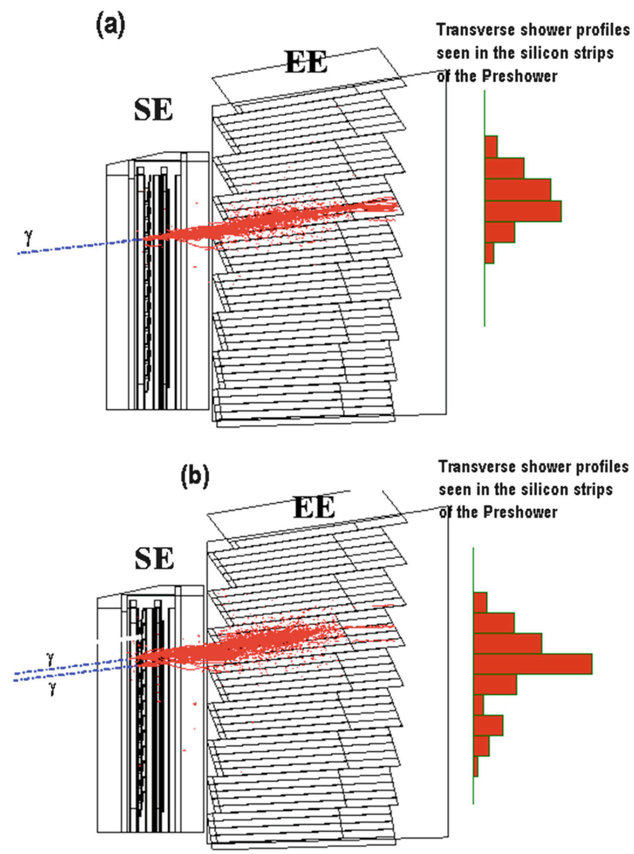
***e/π* separation**
Additional π± suppression factor of 4-10 is expected

γ/π^0 discrimination
In proposed geometry and *p* range (<50 GeV/c), the minimal distance between decay photons is ~1.5cm
=> 0.5 cm granularity may be enough

***e / e+γ* separation**
Will mitigate the material effect (e.g. in E/p matching)

***e&γ* position resolution improved**
Particularly vs non-projective EMCal

CMS preshower+PWO EMCal



YR: Detector Requirements (from Physics WG)

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														~50%/√E+6%	
-3.5 — -3.0		Central Detector	Backwards Detectors		σ_p/p ~ 0.1%×p+2.0%				2%/√E+(1-3)%						
-3.0 — -2.5							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	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				≥ 3σ	~500 MeV	~85%/√E+7%	Useful for bkg, improve resolution
0.0 — 0.5											≤ 10 GeV/c				
0.5 — 1.0				135 MeV K							≤ 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										

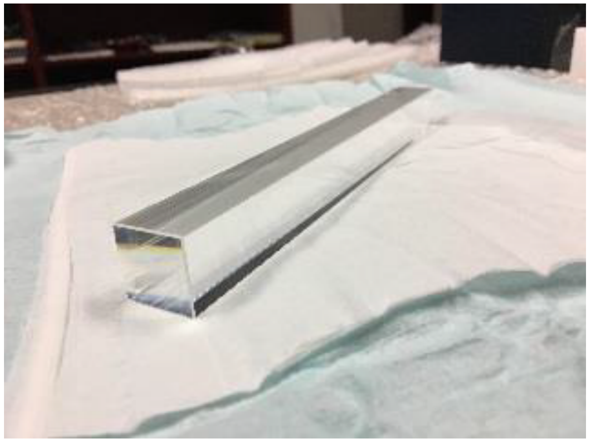
YR: Detector options (from Detector WG)

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



Scintillating light => photo sensor

$X_0 = 0.9$cm => Compactness

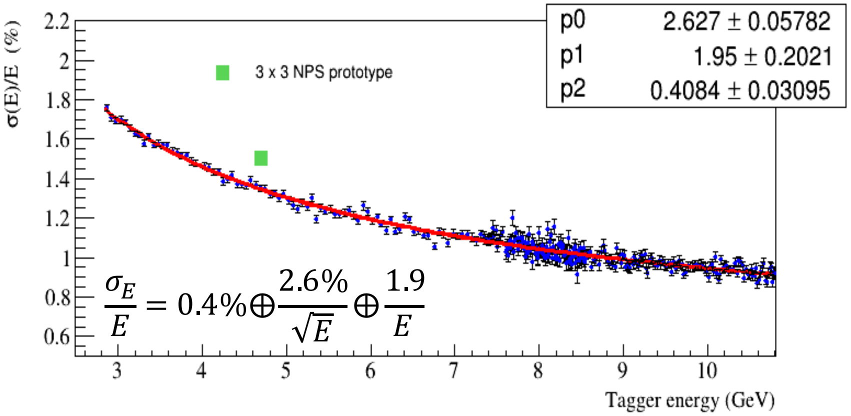
$R_m = 2$cm => High granularity

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

>1000 krad => Radiation hard

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

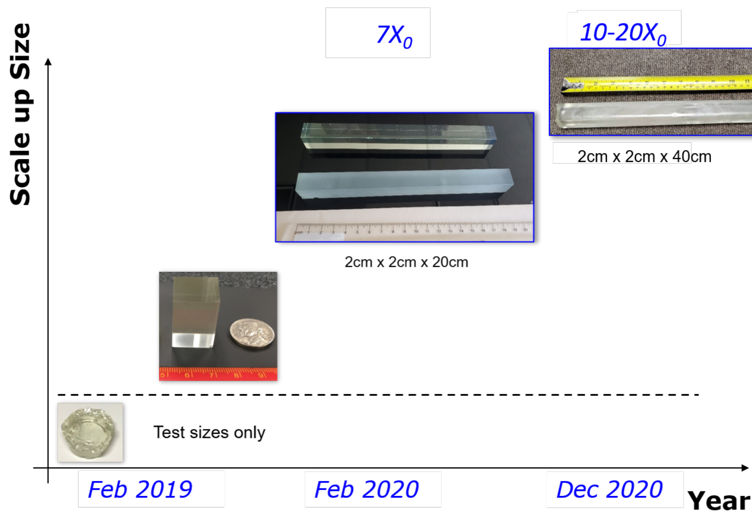
Jlab-PrimEx eta/NPS PWO EMCal prototype



An ideal EMCal for EIC Detector

Homogeneous EMCal: SciGlass

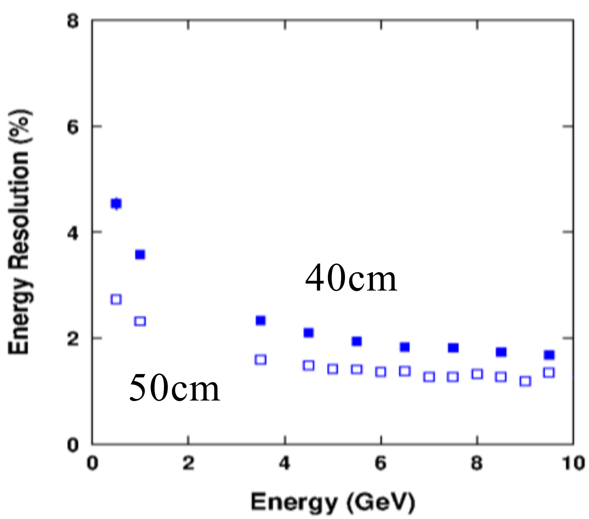
eRD1: T.Horn



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

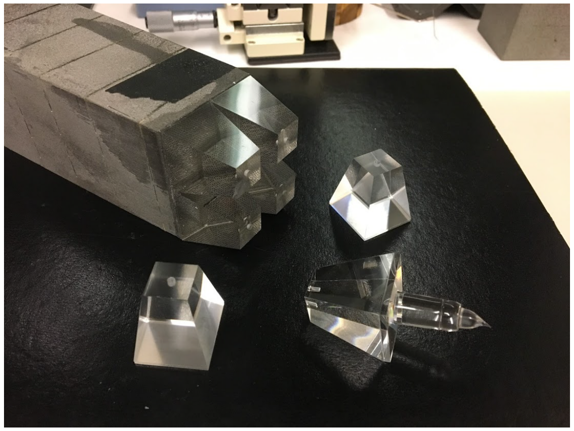


Alternative to high resolution (expensive) EMCal

	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, %/℃	2-3	0

Sampling EMCal: W/SciFi

eRD1: C.Woody & O.Tsai



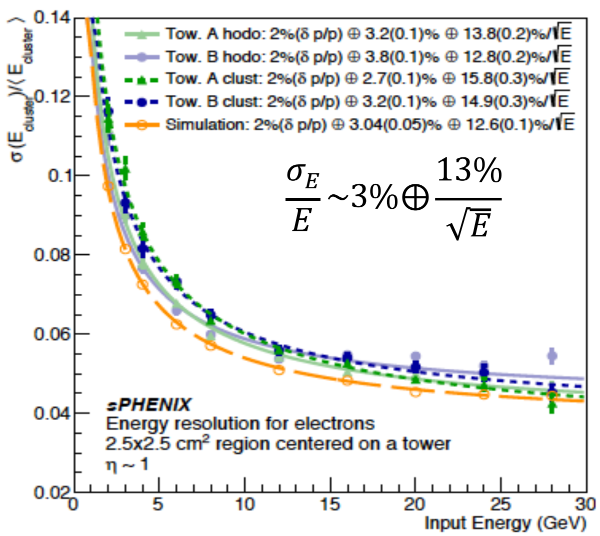
Light generated in scintillating fibers, embedded in an absorber (W/epoxy mix), is transported to photo sensor

sPHENIX barrel EMCal:

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

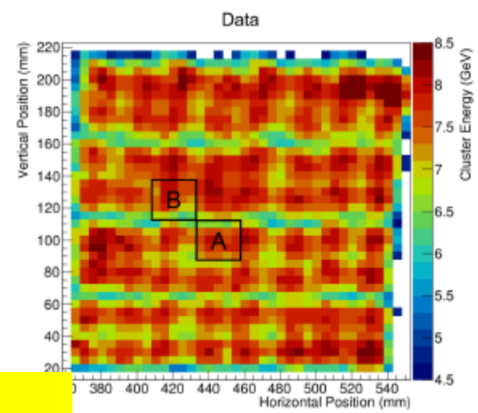
  Can be improved by increasing the sampling fraction, at the expense of larger X_0 and R_m

BNL-sPHENIX: W/SciFi



R&D:

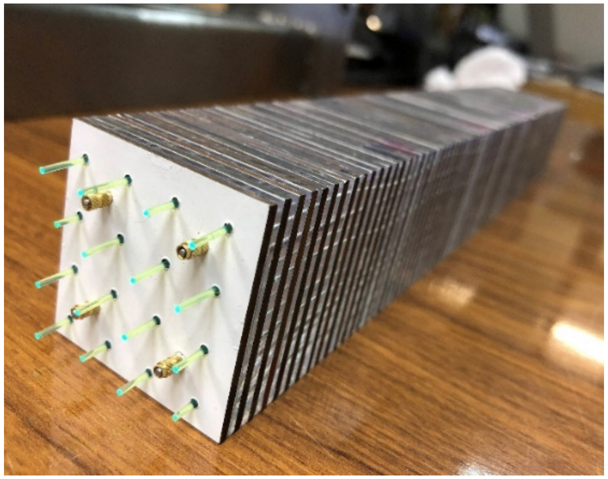
Improve light collection eff. and uniformity



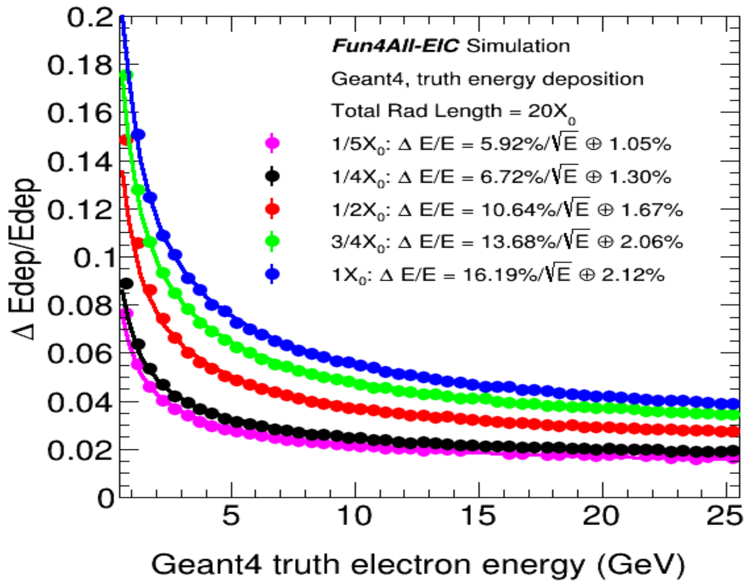
Close to satisfy EIC Detector requirements in barrel and forward region

Sampling EMCal: W/Sc shashlik

eRD1: C.Woody&E.Kistenev



$X_0 \sim 0.9\text{cm}$ $R_m \sim 2\text{cm}$



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

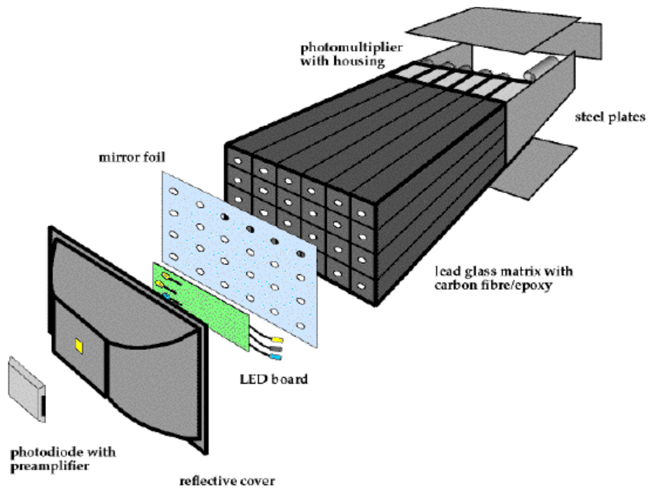
- Each fiber readout by its own SiPM
- More detailed info on shower development within a tower
  - Improve position resolution
  - Improve energy res. (const term)
  - May improve γ/π0 discrimination
- Tunable resolution through the change of sampling fraction and/or frequency:

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

- 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-endcup (η>-2)

PbSc-Shashlik

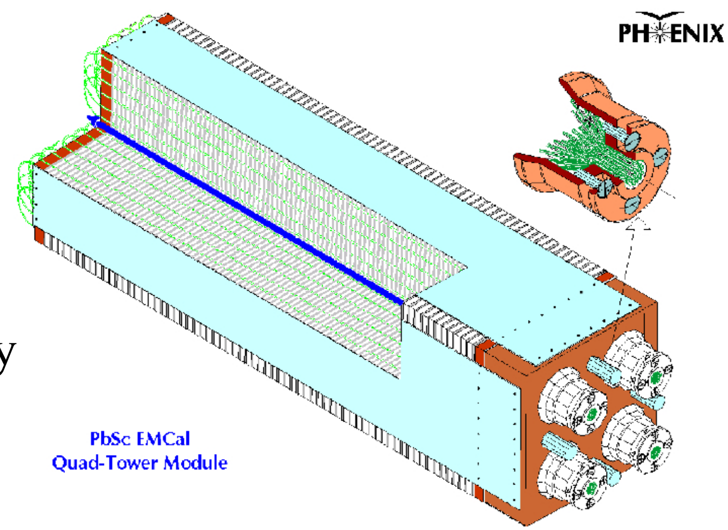
~15k towers from PHENIX (5.5×5.5 cm^2)

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

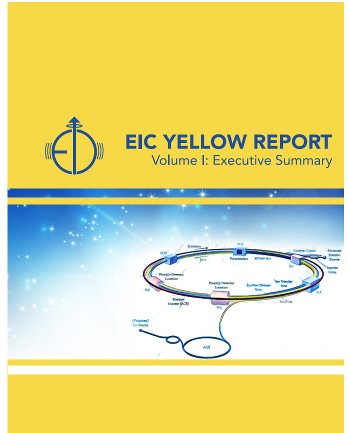
Each fiber readout would make it of high granularity

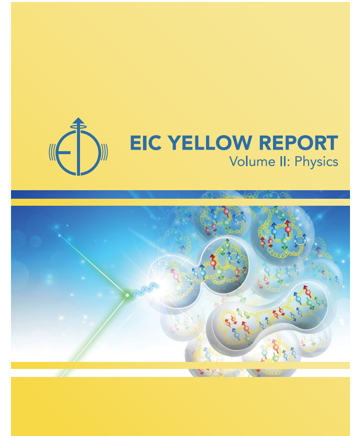
Shower core is << R_m !

=> Good candidate for h-endcup



Summary





- 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 options (from Detector WG)

From YR Wiki

Table.5 **Calorimetry for EIC**

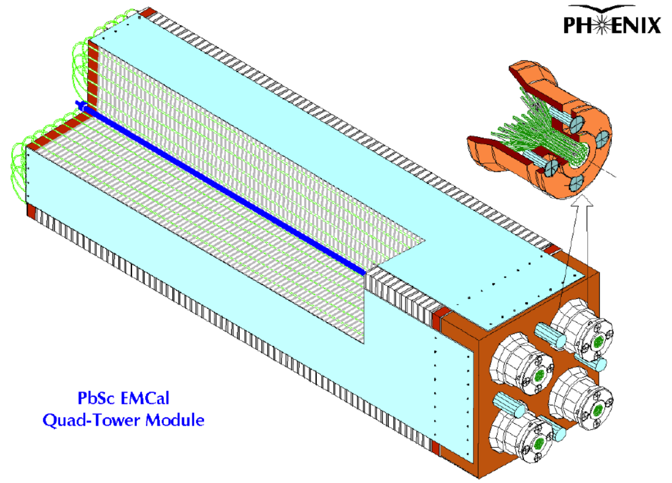
η	ECAL								HCAL				
	Total depth, cm	**Depth, RL**	**Energy resolution σE/E, %**	**Spacial resolution σX, mm**	**Granularity, mm^2**	**Min. photon energy, MeV**	**PID e/π, π suppression**	**Technology examples***	**total depth, cm**	**Energy resolution σE/E, %**	**Spacial resolution σX, mm**	**Granularity, mm^2**	**Technology examples**
-4.0:-2.0	38	22	1.0⊕2.2/√E⊕1.0/E	3/√E⊕1	20×20	20	1000	$PbWO_4$ crystals	105	50/√E⊕10	50/√E⊕30	100×100	Fe/Sc
-2.0:-1.0	38 38 50 50 (65)**	20 20 22 13* 16*	1.5⊕8.0/√E⊕2/E 2⊕12/√E⊕2/E 1.5⊕(7-8)/√E⊕2/E ? 1.5⊕4.0/√E⊕2/E	3/√E⊕1 3/√E⊕1 6/√E⊕1 6/√E⊕1 6/√E⊕1	25×25 25×25 40×40 40×40 40×40	50 50 50 30 30	300	W/Sc Shashlyk W powder/ScFi Pb/Sc Shashlyk SciGlass SciGlass	105	50/√E⊕10	50/√E⊕30	100×100	Fe/Sc
-1.0:1.0	30 30 38 65 *	18 18 22 16*	2⊕12/√E⊕2/E 3⊕14/√E⊕2/E 1.0⊕2.2/√E⊕1.0/E 1.5⊕4.0/√E⊕2/E	3/√E⊕1 3/√E⊕1 3/√E⊕1 6/√E⊕1	25×25 25×25 20×20 40×40	100 100 20 30	300 300 1000 300	W/Sc Shashlyk W powder/ScFi PWO SciGlass	110	100/√E⊕10	50/√E⊕30	100×100	Fe/Sc
1.0:4.0	38 38 (50)** (65)**	20 20 22 16*	1.5⊕8.0/√E⊕2/E 2⊕12/√E⊕2/E 1.5⊕10.0/√E⊕2/E 1.5⊕4.0/√E⊕2/E	3/√E⊕1 3/√E⊕1 6/√E⊕1 6/√E⊕1	25×25 25×25 40×40 40×40	100 100 100 30	300	W/Sc Shashlyk W powder/ScFi Pb/Sc Shashlyk SciGlass	105	50/√E⊕10	50/√E⊕30	100×100	Fe/Sc

All technologies are either mature or a part of ongoing R&D

EMCal in Central Detector

	E-endcup -4<η<-2	E-endcup -2<η<-1	Barrel |η|<2	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

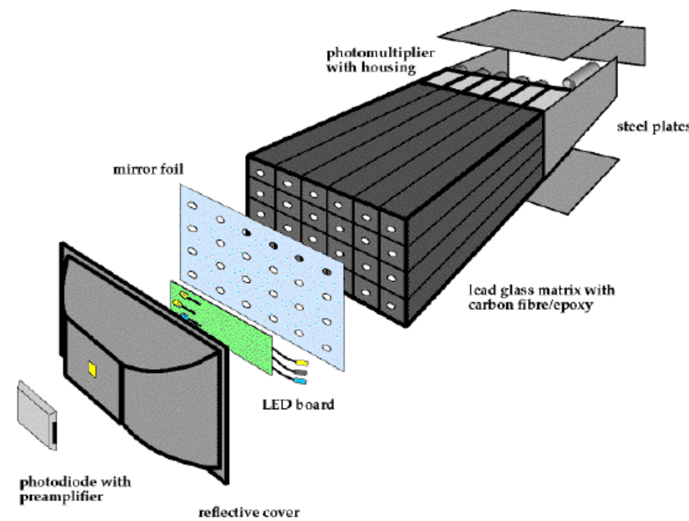
Available options



PHENIX PbSc
18X0 (X0 ~ 2cm)
5.5 x 5.5 x 37.5 cm3

PHENIX PbGl
14.4X0 (X0 ~ 2.8cm)
4 x 4 x 40 cm3

Many other PbGl modules are available at BNL and JLab



e/π separation

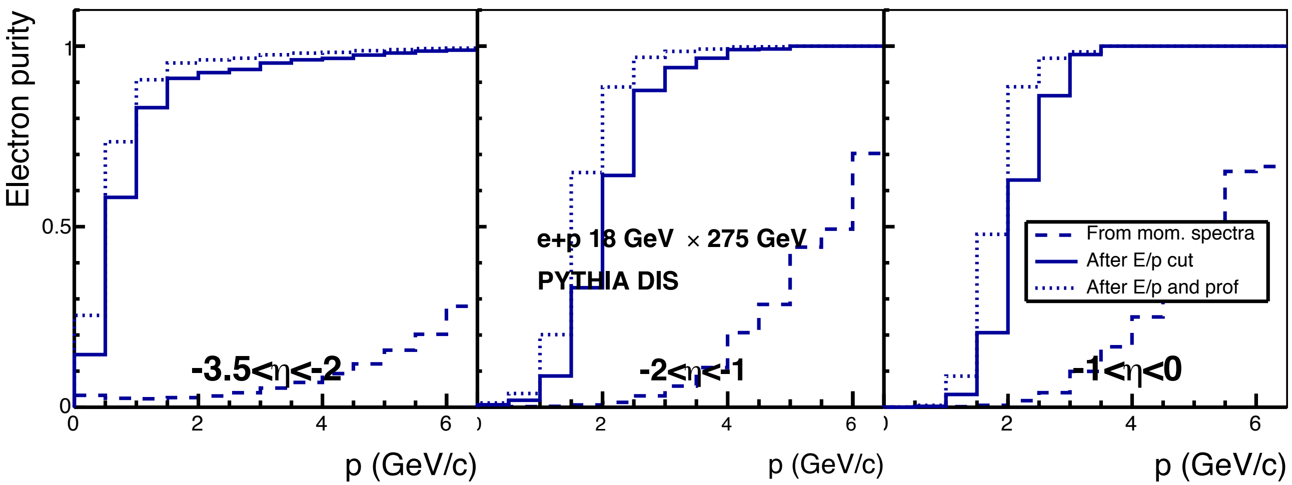
For DIS electron

-3.5<η<-2	-2<η<-1	-1<η<1
$\frac{\sigma_E}{E} = \frac{2.5\%}{\sqrt{E}} \oplus 1\%$	$\frac{\sigma_E}{E} = \frac{7\%}{\sqrt{E}} \oplus 2\%$	$\frac{\sigma_E}{E} = \frac{12\%}{\sqrt{E}} \oplus 2\%$

Ideal case:

- No material on the way to EMCal
- Perfect EMCal (no gaps/cracks)
- Gaussian response to electron

Purity = e / (e+h)

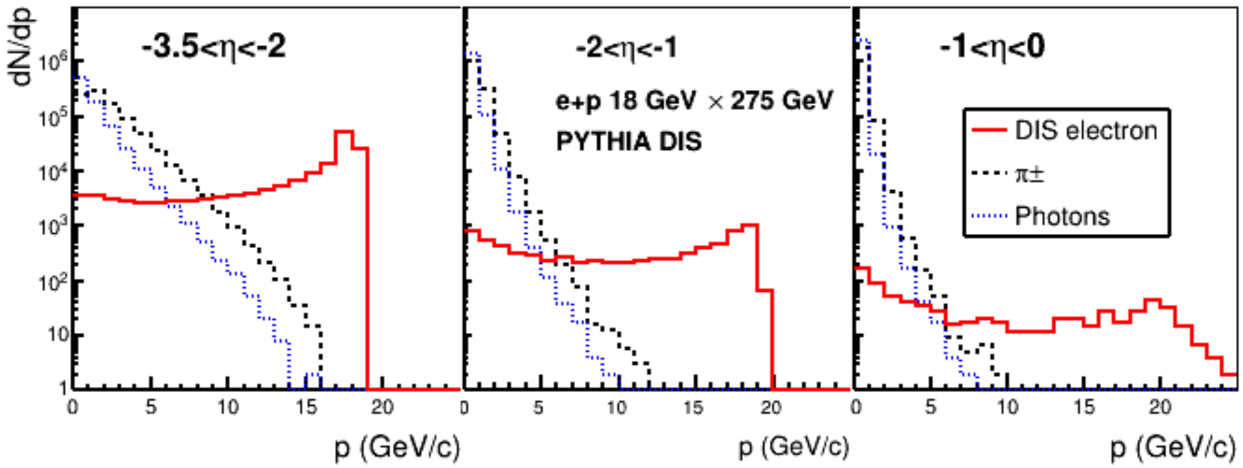


Expect to get high *e* purity at >4 GeV/c for 18 GeV electron beam

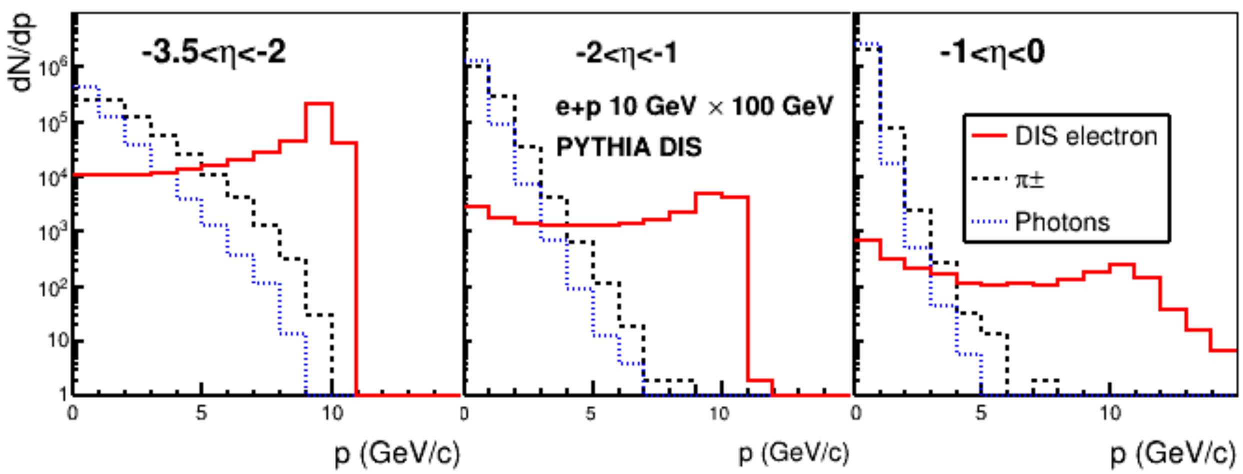
(>3 GeV/c for 10 GeV electron beam)

e-endcup: p<2 GeV/c will be covered by mRICH
barrel: p<1.3 GeV/c will be covered by DIRC

Additional eID capabilities for 1-2<p<4 GeV/c would be highly desirable

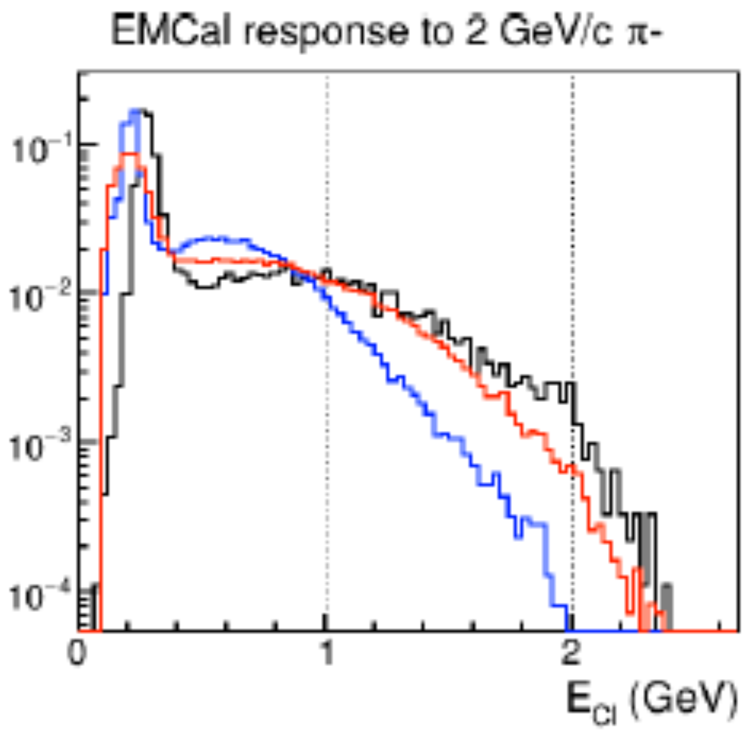


18x275 GeV

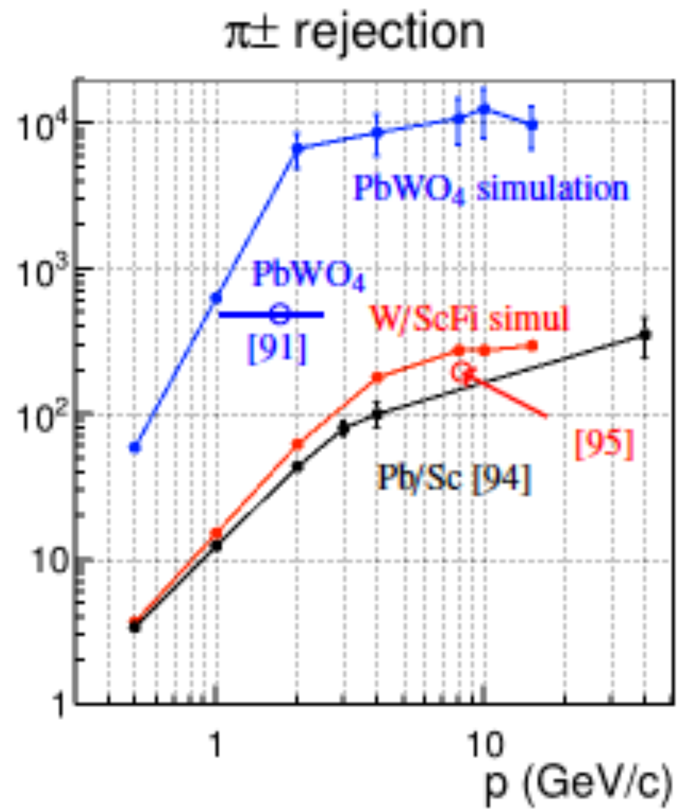


10x100 GeV

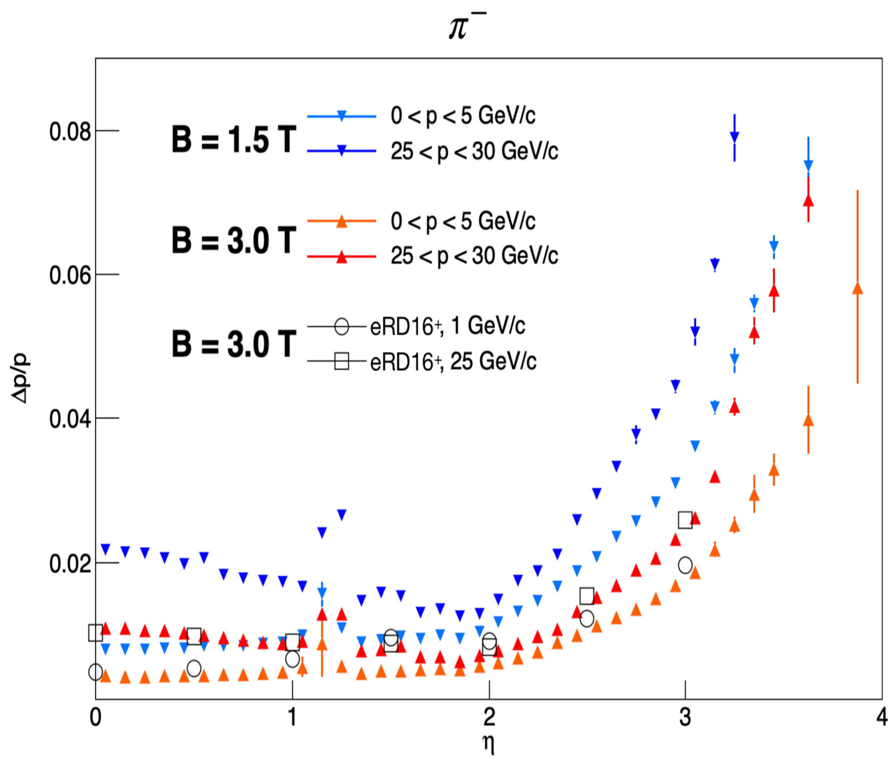
Clean measurements at higher momenta
Huge background at lower momenta



EMCal response to 2 GeV/c π-
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
E_{Cl} (GeV)



π± rejection
10^4
10^3
10^2
10
1
PbWO$_4$ simulation
PbWO$_4$
[91]
W/ScFi simul
[95]
Pb/Sc [94]
1
10
p (GeV/c)



BaBar-based Tracking model:
TPC (barrel), Si +GEM (forw)
(Fun4All-GEANT4 simulation)