Electromagnetic Barrel Calorimetry

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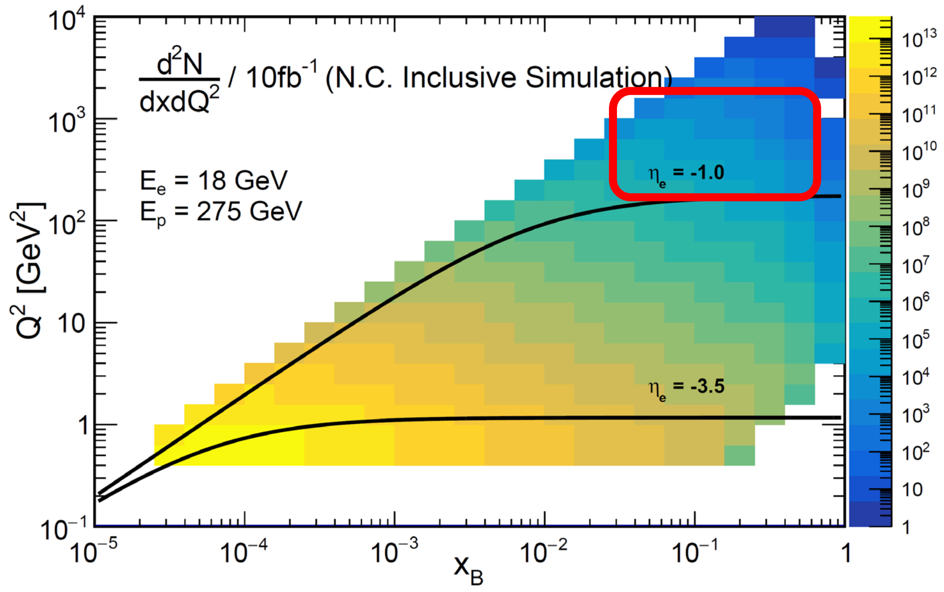
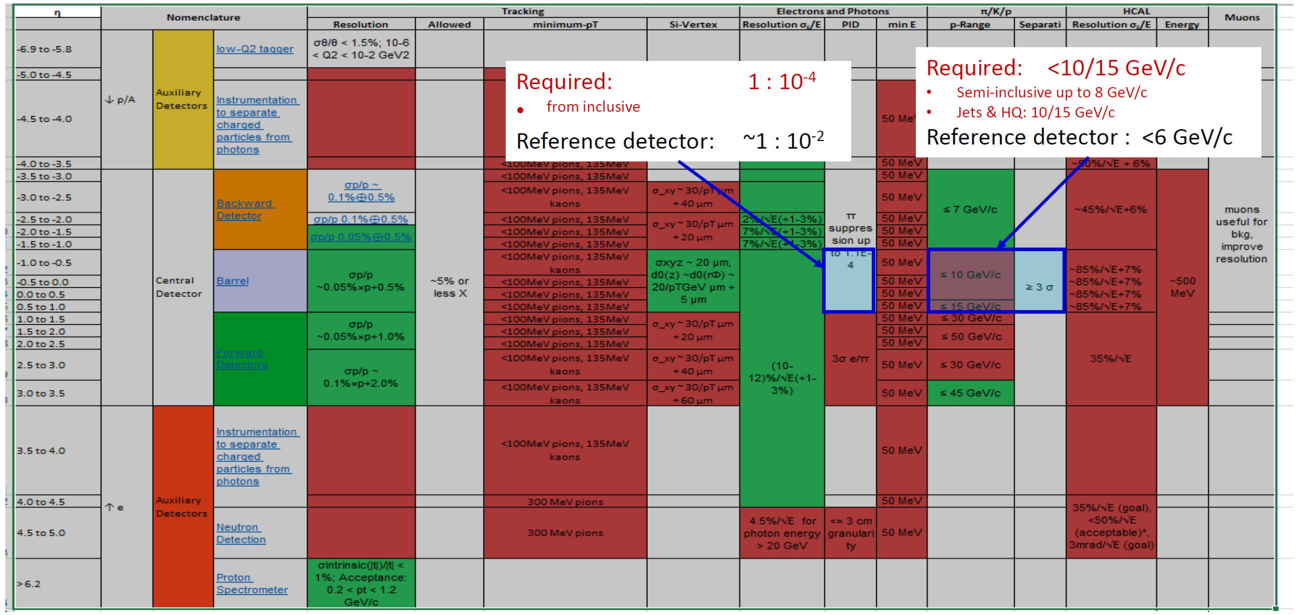
Introduction

Scattered electron kinematics measurement is essential at the EIC

- ☐ High precision, hermetic detection of the scattered electron is required over a broad range in η. Particularly in the backward-going direction over an energy range from 0.1 to tens of GeV
- ☐ In ECCE, we emphasize this also for the barrel EM calorimeter choice driven by high-x and high-Q^2 science drivers.
- ☐ Scintillating glass was chosen to provide comparable energy resolution to PbWO4 crystals at significant lower cost



From Yellow Report



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			~50%/√E + 6%		
-3.5 to -3.0		Central Detector	Backward Detector	σp/p ~ 0.1%⊕0.5%	~5% or less X	<100MeV pions, 135MeV			π suppression up to 1:1E-4	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%)		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			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	(10-12)%/√E(+1-3%)		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					
4.5 to 5.0			Neutron Detection			300 MeV pions		4.5%/√E for photon energy > 20 GeV	<= 3 cm granularity	50 MeV			35%/√E (goal), <50%/√E (acceptable)*, 3mrad/√E (goal)		
> 6.2			Proton Spectrometer	σintrinsic(|t|)/|t| < 1%; Acceptance: 0.2 < pt < 1.2 GeV/c											

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

Reference detector: ~1 : 10^{-2}

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

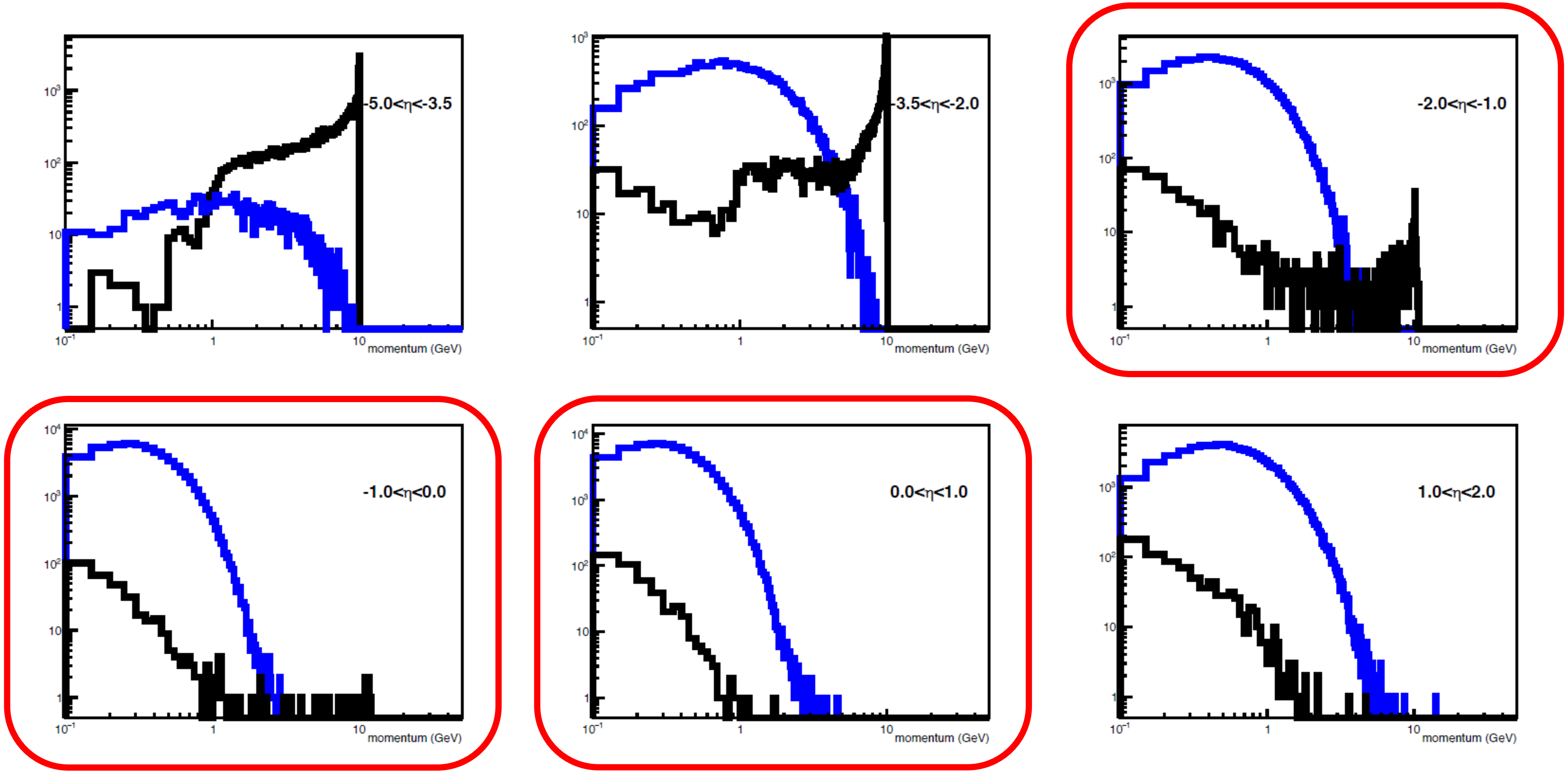
Reference detector : <6 GeV/c

Requirements
- ☐ Good energy resolution
- ☐ e/h separation up to 10^{-4}

e/π SEPARATION

NEEDS

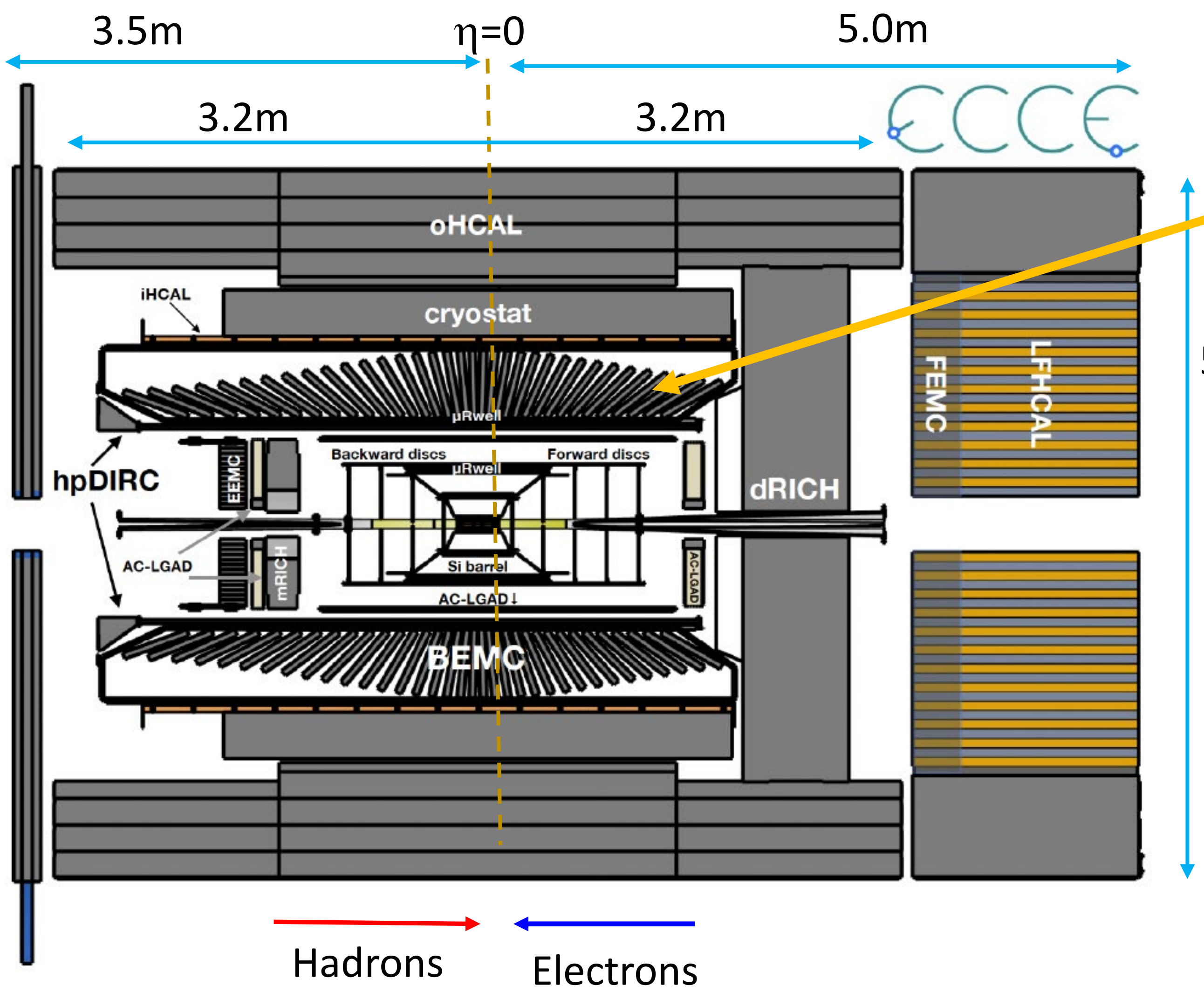
ΔG needs pi/e 10^{-3} , A_{PV} needs pi/e 10^{-4} in η bins -2 to 1



10 x 100 GeV Pion/e- Ratio (Work by **Hanjie Liu**)

3rd EIC Yellow Report Workshop (CUA), Sept 2020

The barrel EMCal in the ECCE Reference Detector



Barrel ECAL(BEMC)

Homogeneous, projective calorimeter based on SciGlass, cost-effective alternative to crystals

- The barrel is one of the largest sub-detectors with 8000 homogeneous scintillator blocks of 45.5cm length (and ~10cm radial readout space)
- It is extended in the negative rapidity direction (with η coverage from -1.7 to +1.3) to provide hermeticity with the backward ECal.
- In the backward direction hermeticity is provided by the combination of barrel, backward ECals, and mRICH complements (3σ e/h up to 2 GeV) . Readout and supply lines are included.
- In the forward direction the barrel EMCal faces much higher range of particle rates across the acceptance of the forward endcap

Overview of Barrel EMCal Specifications

- ☐ Coverage: $-1.7 < \eta < 1.3$
    - R_{min}=80cm
    - R_{max}=125.5cm (i.e., glass blocks are 45 cm long → 17 X0)
    - Electronics:125.5cm < R < 134cm
    - Outer support: 134cm < R < 140cm
    - Length along z= 445m (192.5cm(start) < z < 252.5cm (end))
- ☐ Egamma: 0.1 – 35 GeV
- ☐ Energy resolution (based on simulation): 2.5%/SqrtE + 2.7%/E + 1.5%
- ☐ Maximum Annual dose at top luminosity
    - EM: ~3 krad/year (30 Gy/year)
    - Hadron: 10^10 n/cm2
- ☐ Signal dynamics: 2 V dynamic range

Homogeneous Design based on PANDA

PANDA

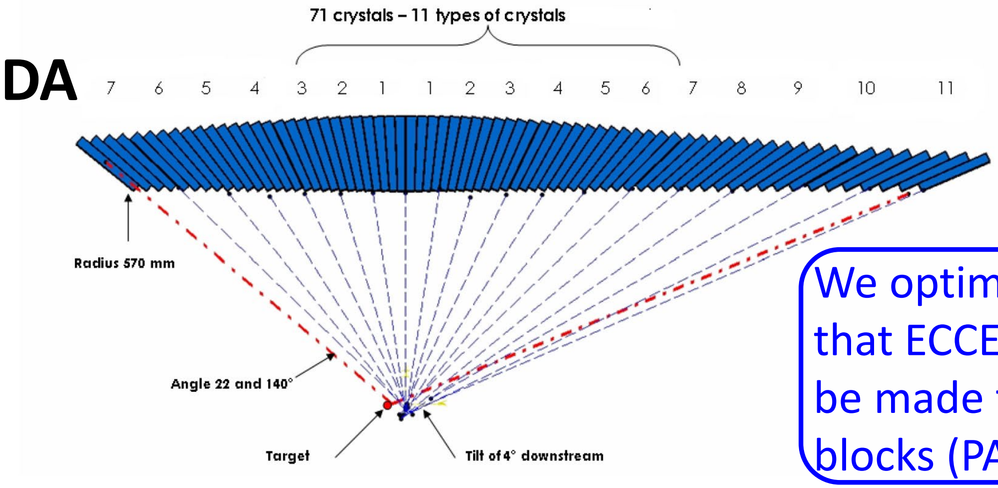
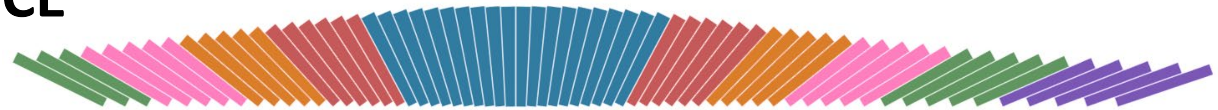


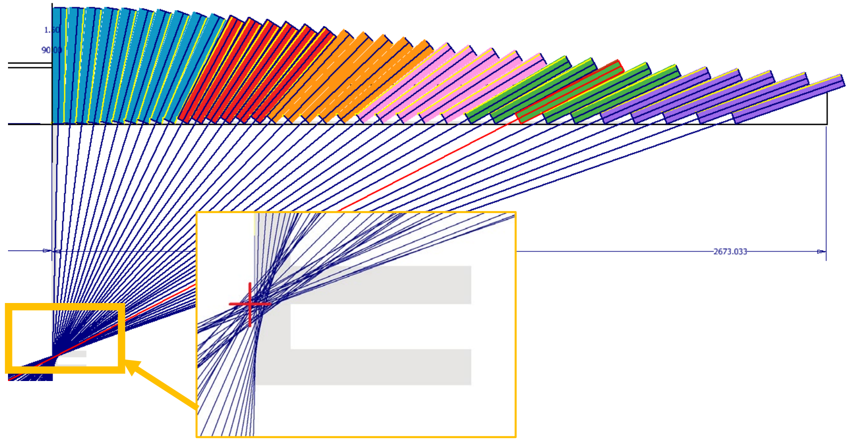
Figure 5.4: Crystal arrangement of the barrel along the beam axis. Positions of the different crystal types are indicated. Due to the mirror symmetry, 11 types are sufficient instead of 18.

ECCE

Based on realistic CAD design (CUA)



We optimized the geometry so that ECCE barrel calorimeter can be made from 6 families of blocks (PANDA has 11 families)



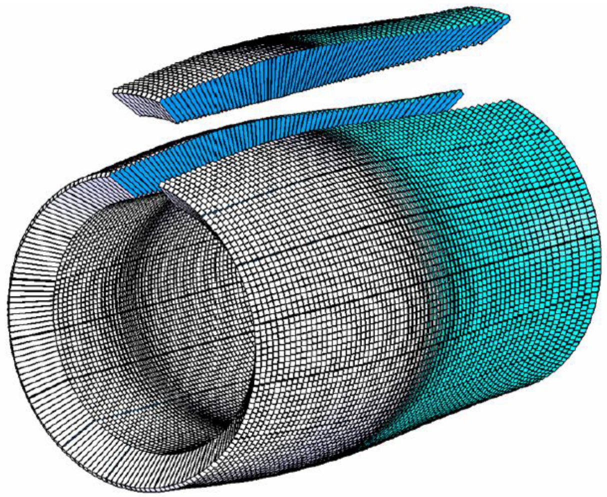
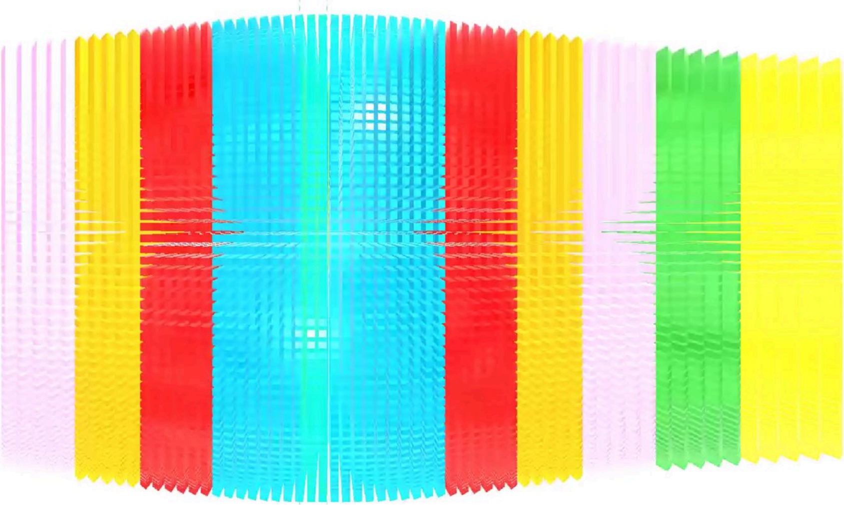
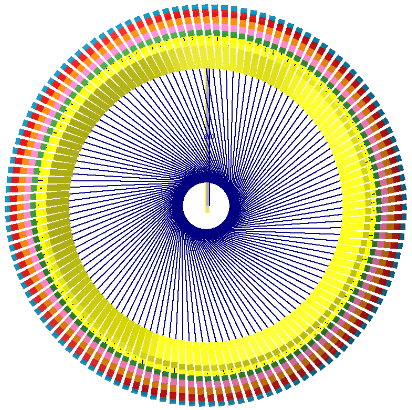


Figure 5.5: View of the total barrel volume with a separated single slice of 710 crystals. A slice covering 1/16 of the barrel volume.

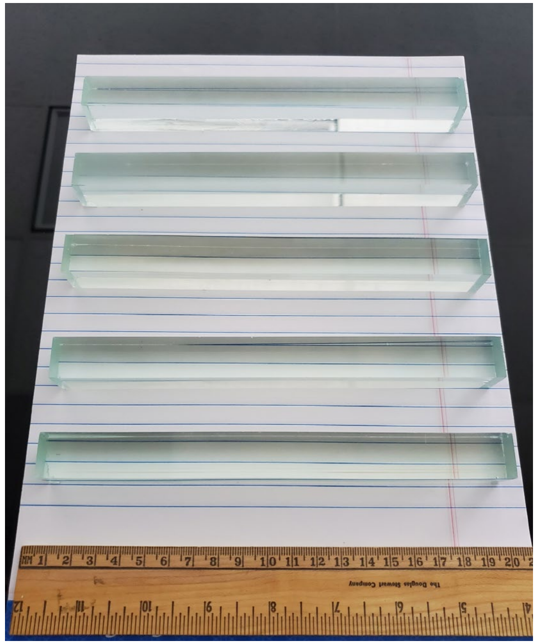




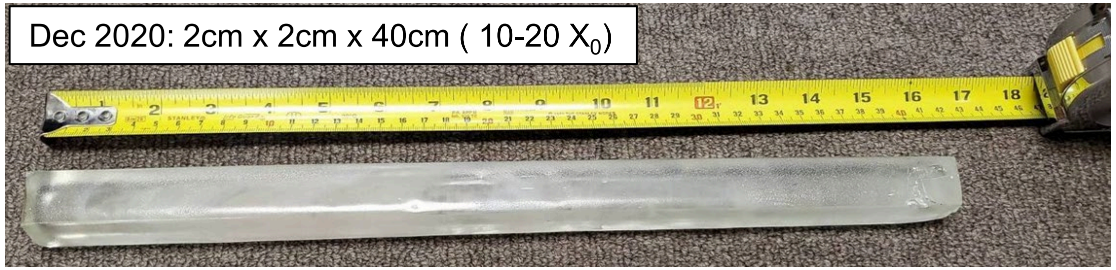
Homogeneous materials: Crystals and Glass

- High-resolution $PbWO_4$ (PWO) crystals are available from two vendors
- SciGlass 20cm has been produced reliably; We tested a 3x3 20 cm SciGlass prototype detector in beam and measured its performance as per simulation (ongoing R&D EEEMCAL consortium, eRD105)
- Received the first polished 40 cm SciGlass with more on the way
- We have an SBIR phase-II to start large-scale production (40+ cm, rectangular and projective shapes)

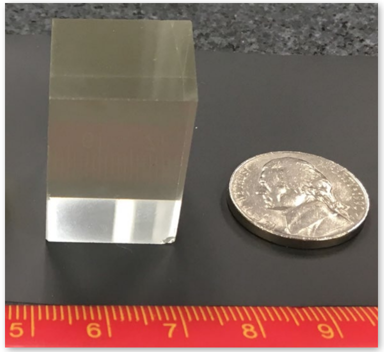
Example: G4 glass



Feb 2021: 2cm x 2cm x 20cm (7 X_0)



Dec 2020: 2cm x 2cm x 40cm (10-20 X_0)



2019: 2cm x 2cm x 4cm

2018: 1cm x 1cm x 1cm

Previous Scintillating Glass Calorimeters

Scintillating Glass of different formulation has been used for beam tests and as EMCal in the 1980s

https://inspirehep.net/literature/261664

Performance of a scintillating glass calorimeter for electromagnetic showers, 1988

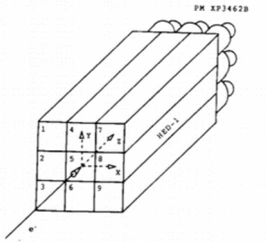


Fig. 3. Layout of the calorimeter setup in the test beam.

U. Buchner et al. / A scintillating glass calorimeter for electromagnetic showers 701

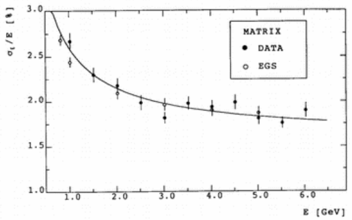


Fig. 12. Energy resolution as a function of the electron energy (black circles) and the EGS prediction (open circles). The line shows the parametrization (4) described in the text.

8x8x66 cm^3

1.46%/E+2.4%/sqrt(E)+1.63%

https://inspirehep.net/files/1299a6aa1e200e01f9d7f208800a81f6

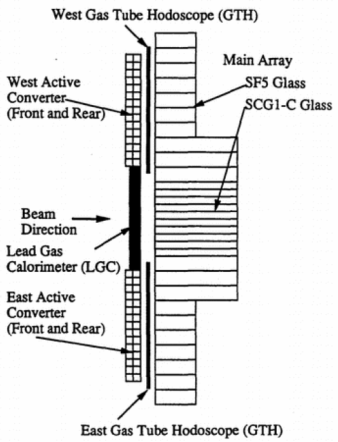
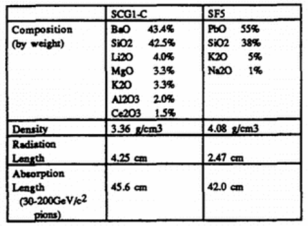


Figure 1. Plan view of the major components of the Experiment 705 calorimeter



	SCG1-C	SF5
Composition (by weight)	BaO 43.4% SiO2 42.5% Li2O 4.0% MgO 3.3% K2O 3.3% Al2O3 2.0% Ce2O3 1.5%	PbO 55% SiO2 38% K2O 5% Na2O 1%
Density	3.36 g/cm3	4.08 g/cm3
Radiation Length	4.25 cm	2.47 cm
Absorption Length (30-200GeV/c^2 pions)	45.6 cm	42.0 cm

Table 1. Properties of SCG1-C Scintillating and SF5 Lead Glass

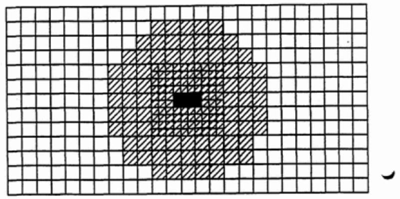


Figure 2. Beam view of the Main Array (SCG1-C scintillating glass is cross-hatched)

The Experiment 705 Electromagnetic Shower Calorimeter, 1993

15.x15.x89 cm^3
7.5x7.5x89 cm^3

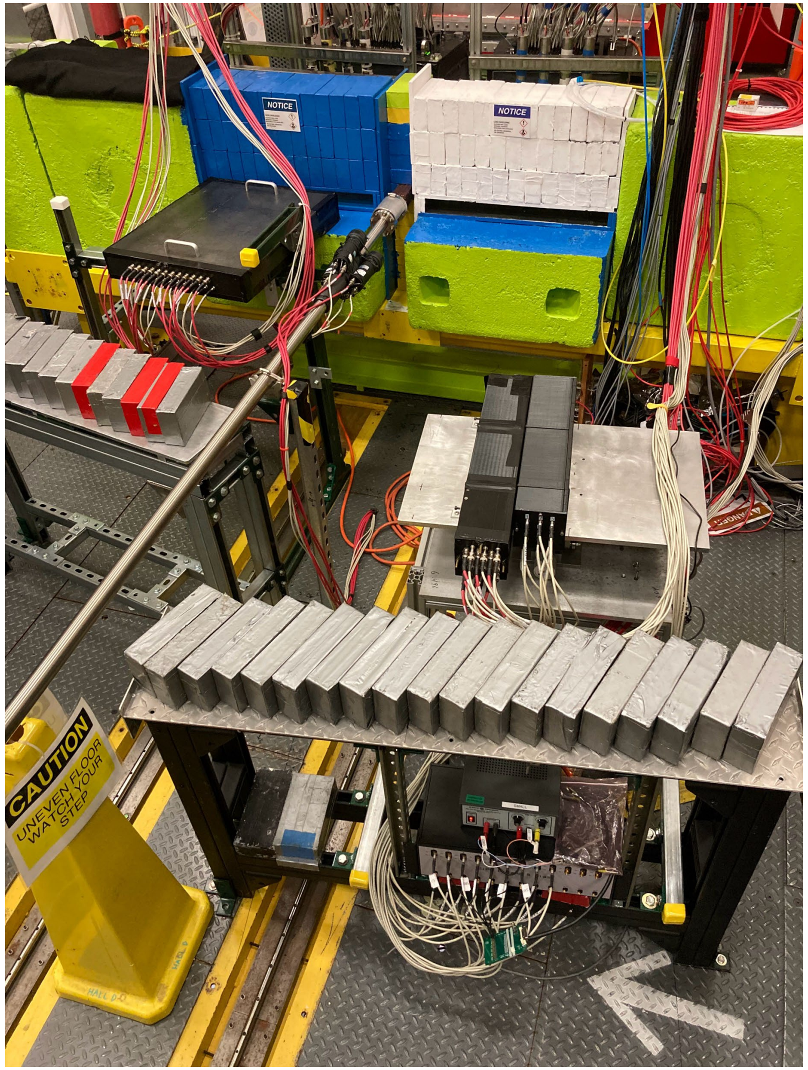
Rad. Length 20.9 X0

0.99%+4.58%/sqrt(E)

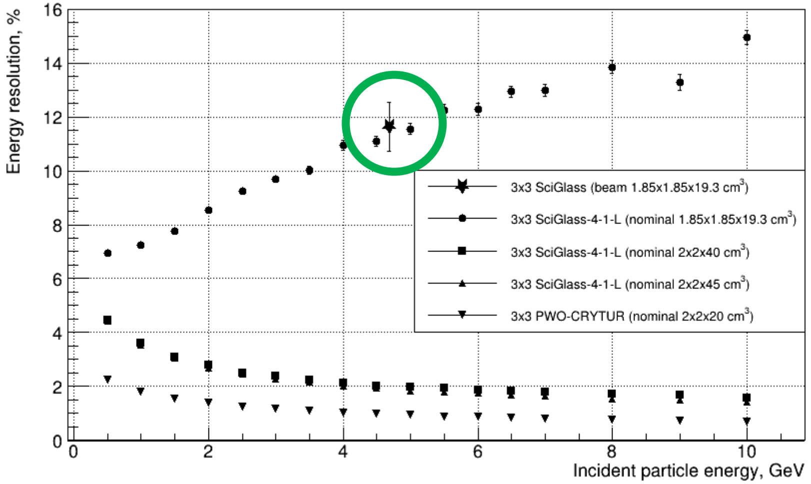
Resolution for mixed calorimeter (lead glass and SCG1-Glass)

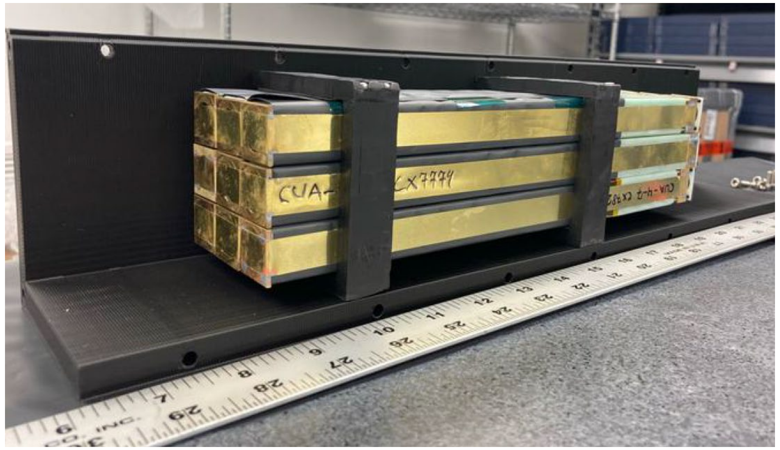
Results from 1980s scintillating glass calorimeters encouraging → Need to establish performance for SciGlass (different formulation)

Ongoing Beam Tests

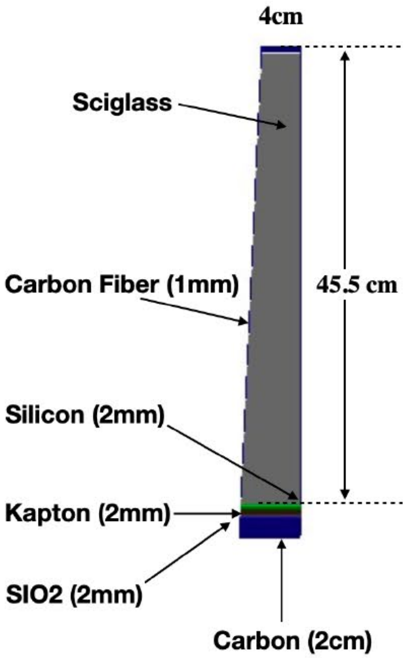


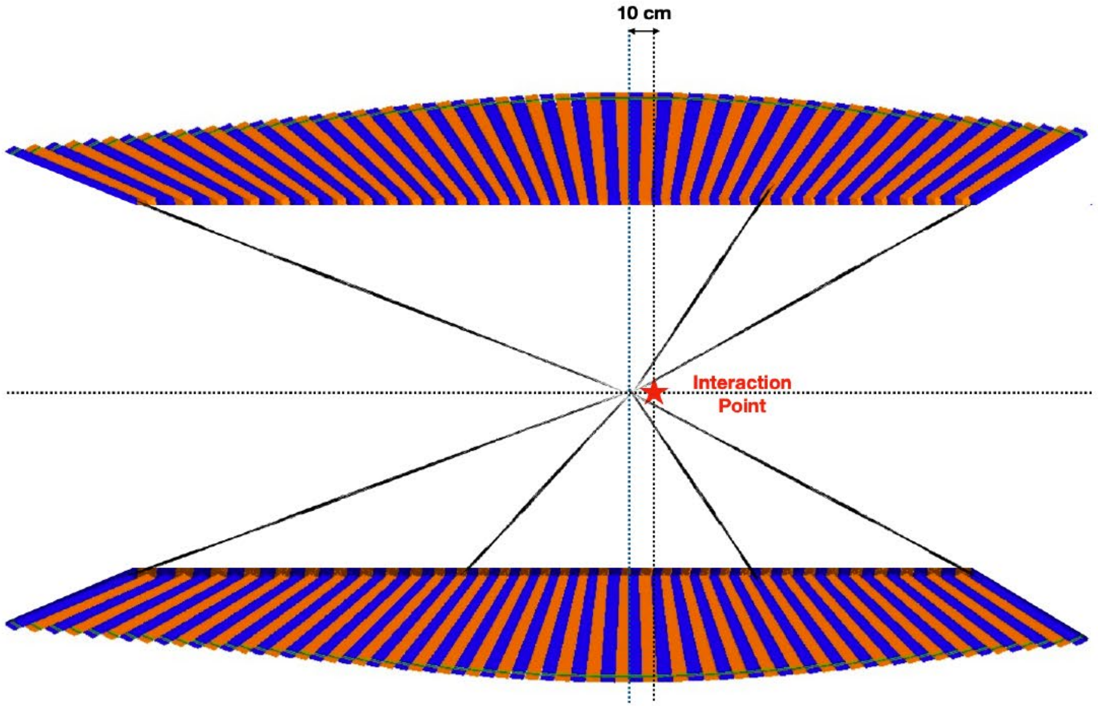
- Prototype 3x3 array installed and tested – energy resolution measured for three different beam energies
- Promising results for ~7 X_0 blocks – matches with Geant4
- **Plans for 2022: Test with ~15X_0 long blocks**

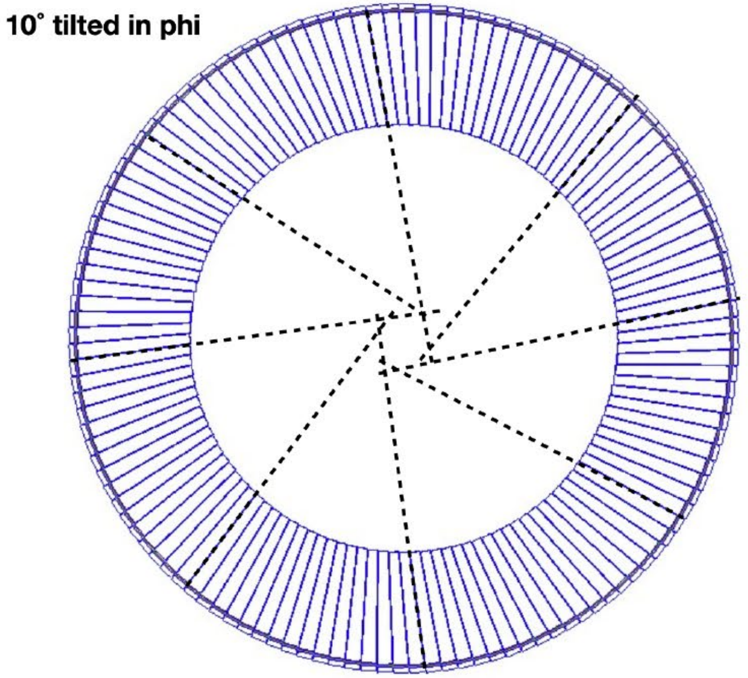


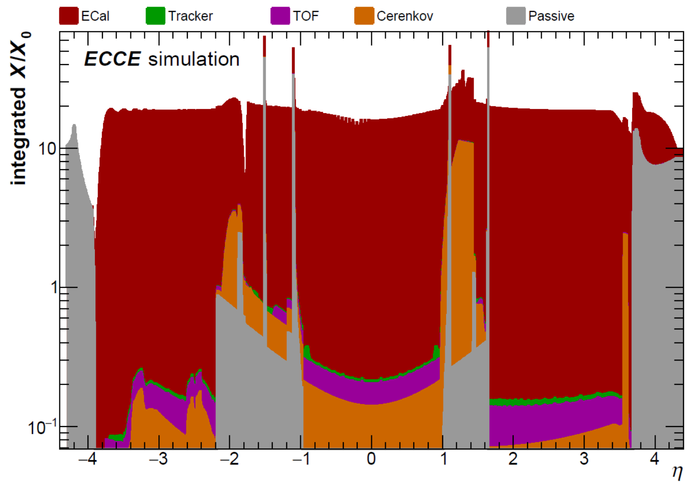


Barrel EMCal in Simulations





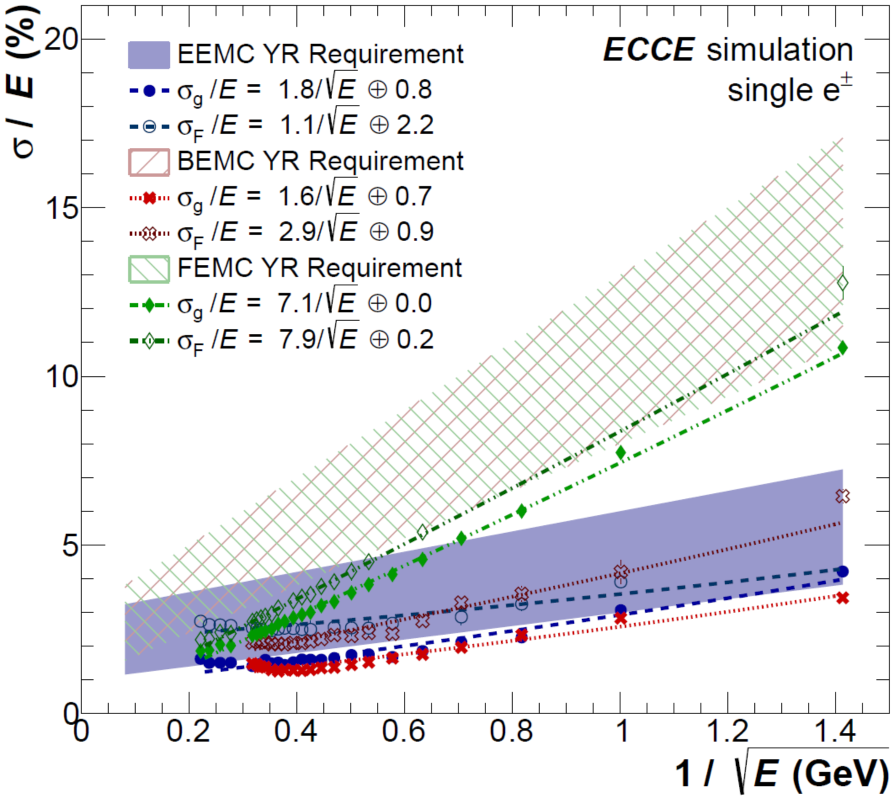




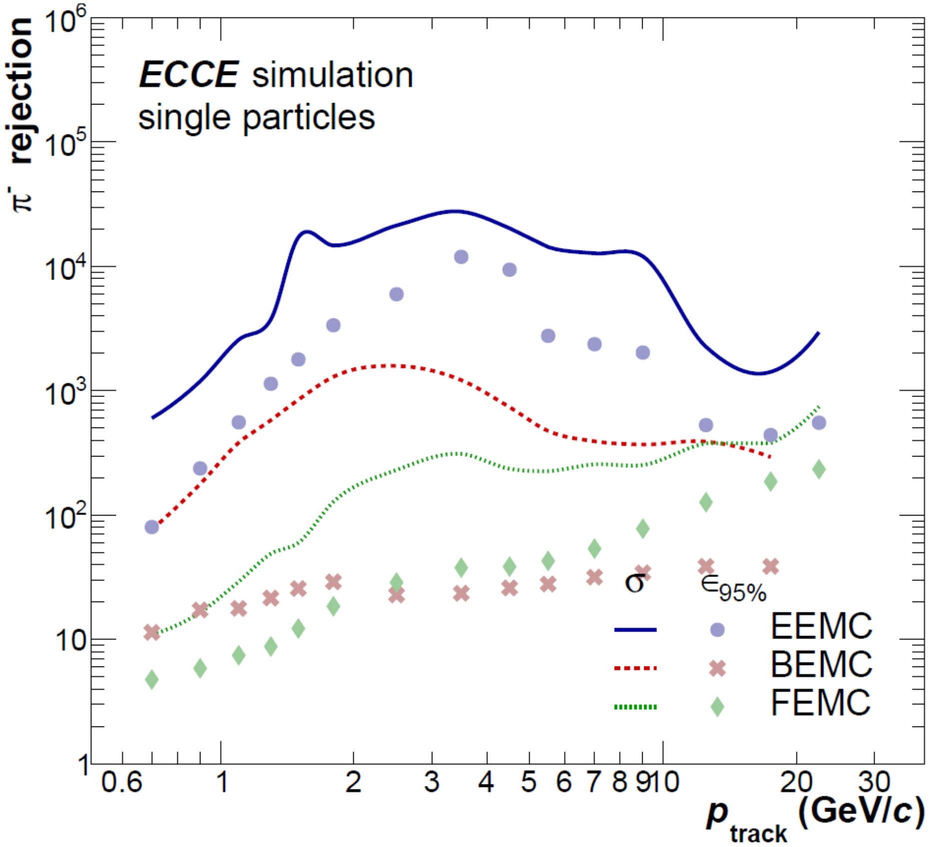
- ☐ Implemented with the active components and support structures
- ☐ Also important to consider materials in front of the EM calorimeter as it impacts performance (resolution, rejection, etc.)

Barrel EMCal Performance

Energy resolution



Pion Rejection



Exceeds requirements from Yellow Report

Mechanical Design based on PANDA

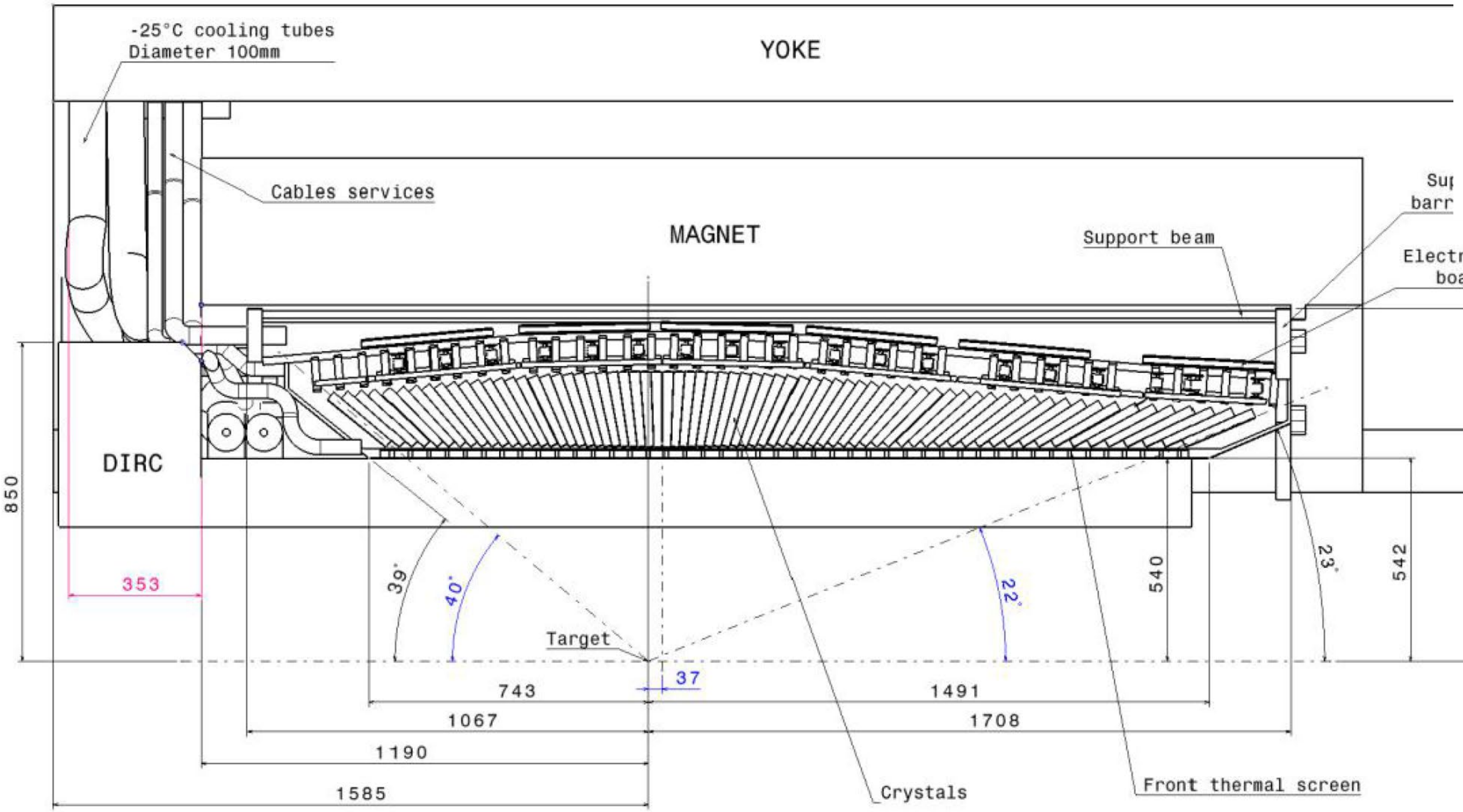


Figure 5.26: Dimensions of one slice.

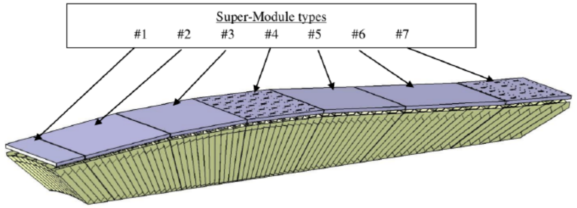
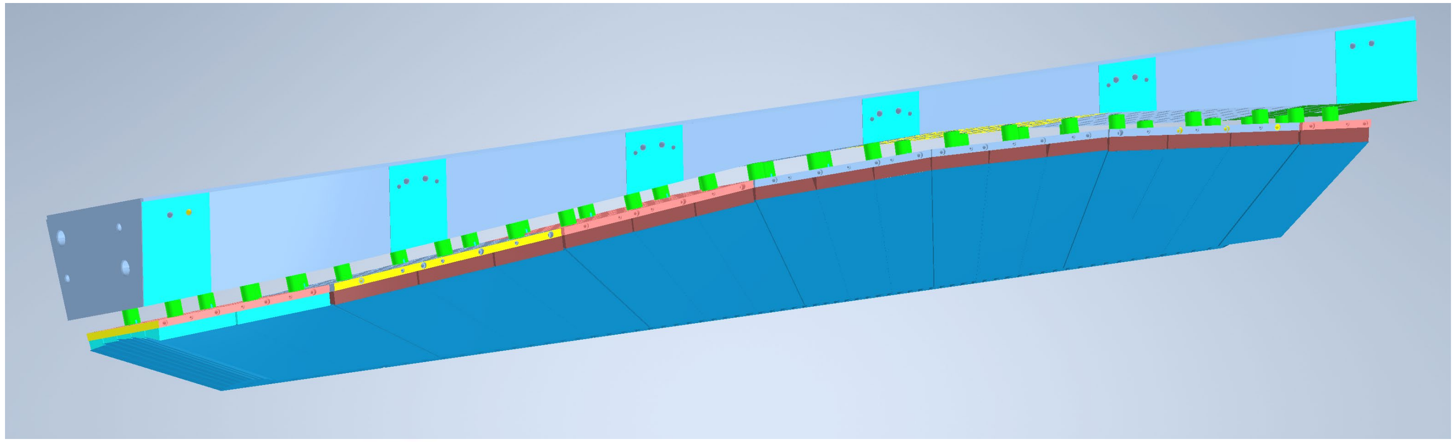
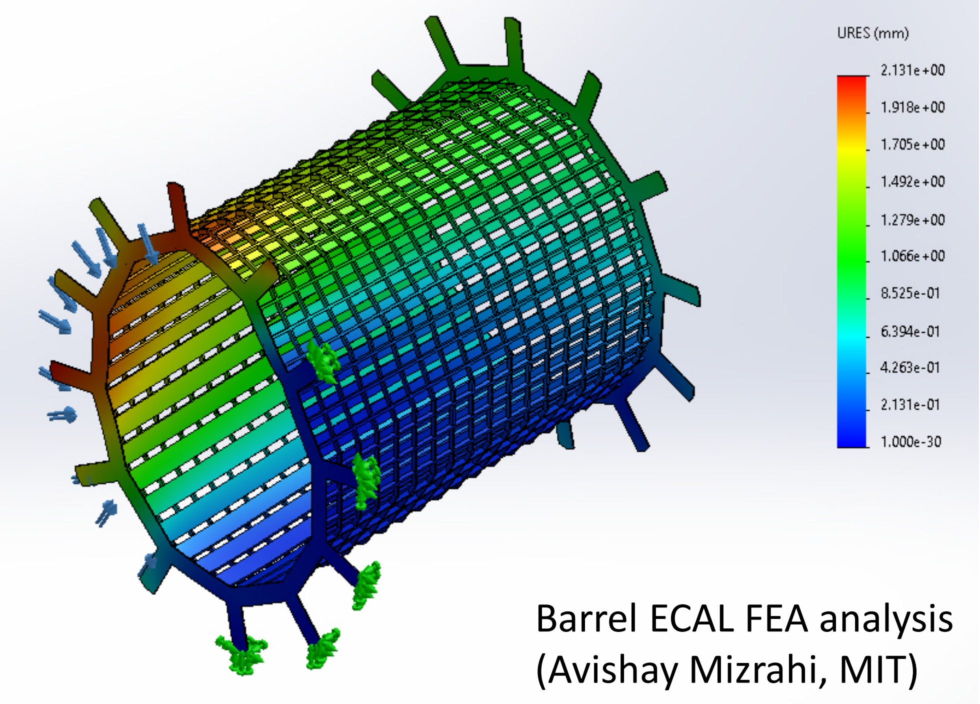


Figure 5.9: Modular structure of a slice.

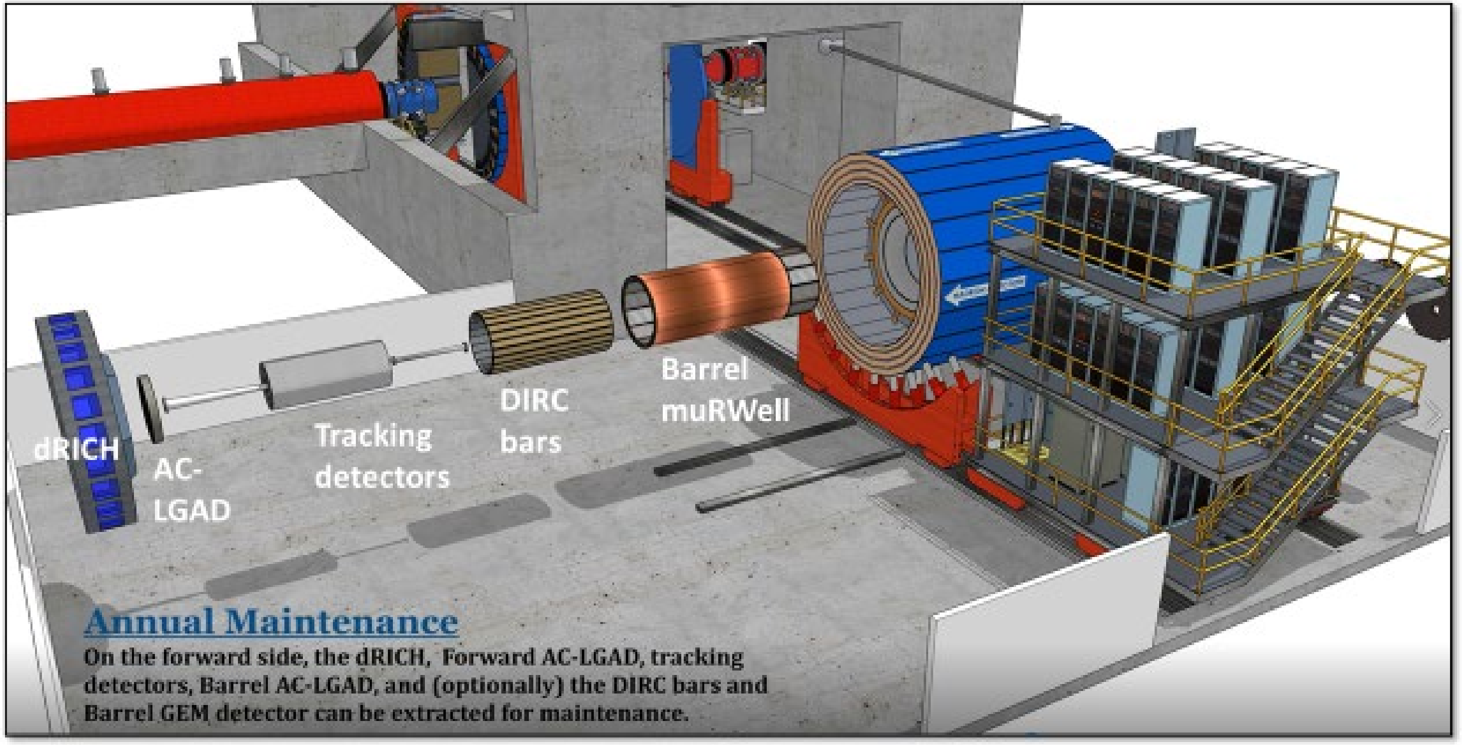
PANDA

Advancing the Design (making use of work already done at PANDA)





Barrel ECAL FEA analysis
(Avishay Mizrahi, MIT)



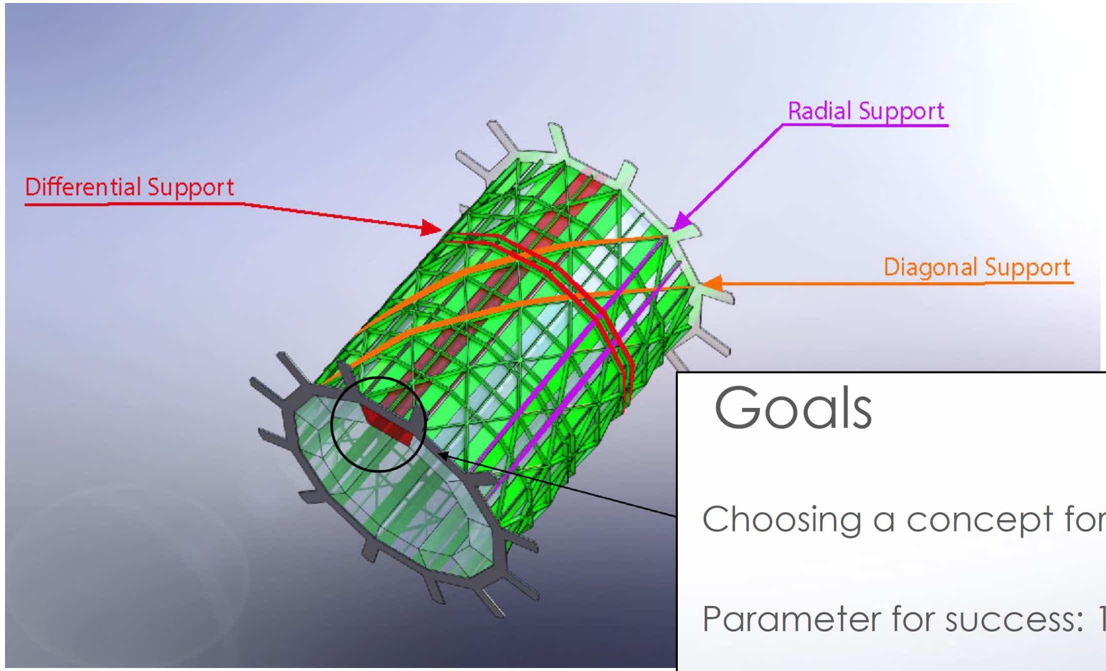
Annual Maintenance

On the forward side, the dRICH, Forward AC-LGAD, tracking detectors, Barrel AC-LGAD, and (optionally) the DIRC bars and Barrel GEM detector can be extracted for maintenance.

- ☐ Slice/supermodule details – also cooling, cabling, etc.
    - Ongoing studies (CUA/MIT)
- ☐ Support structure optimization
    - Ongoing studies (MIT)
- ☐ Access and maintenance

Advancing the Design – barrel support structure

Barrel ECAL support FEA analysis (Avishay Mizrahi, MIT)



Goals

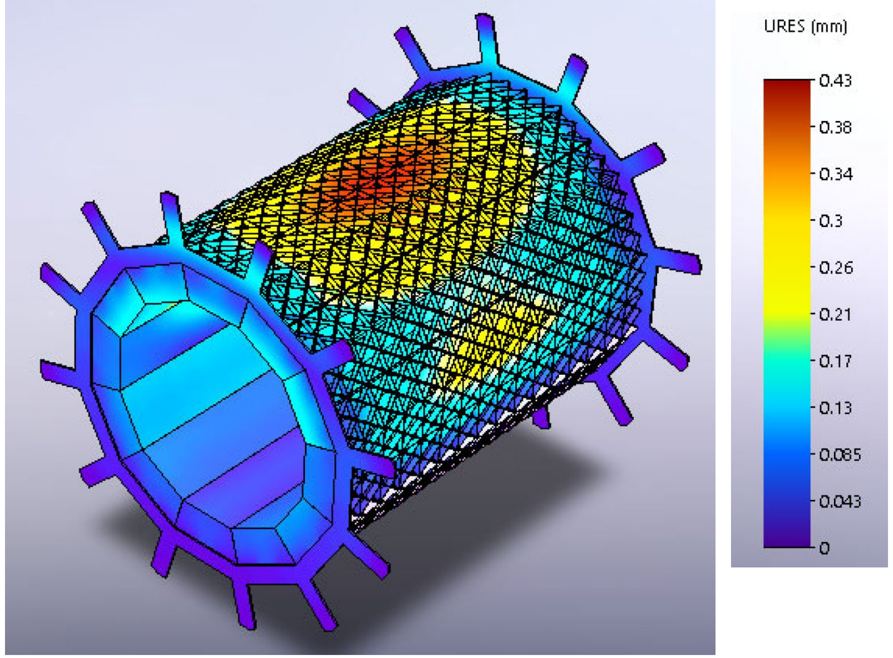
Choosing a concept for mesh design

Parameter for success: 1mm max Deflection.

Constraints:
- Paramagnetic material.
- 19mm max thickness for each beam.

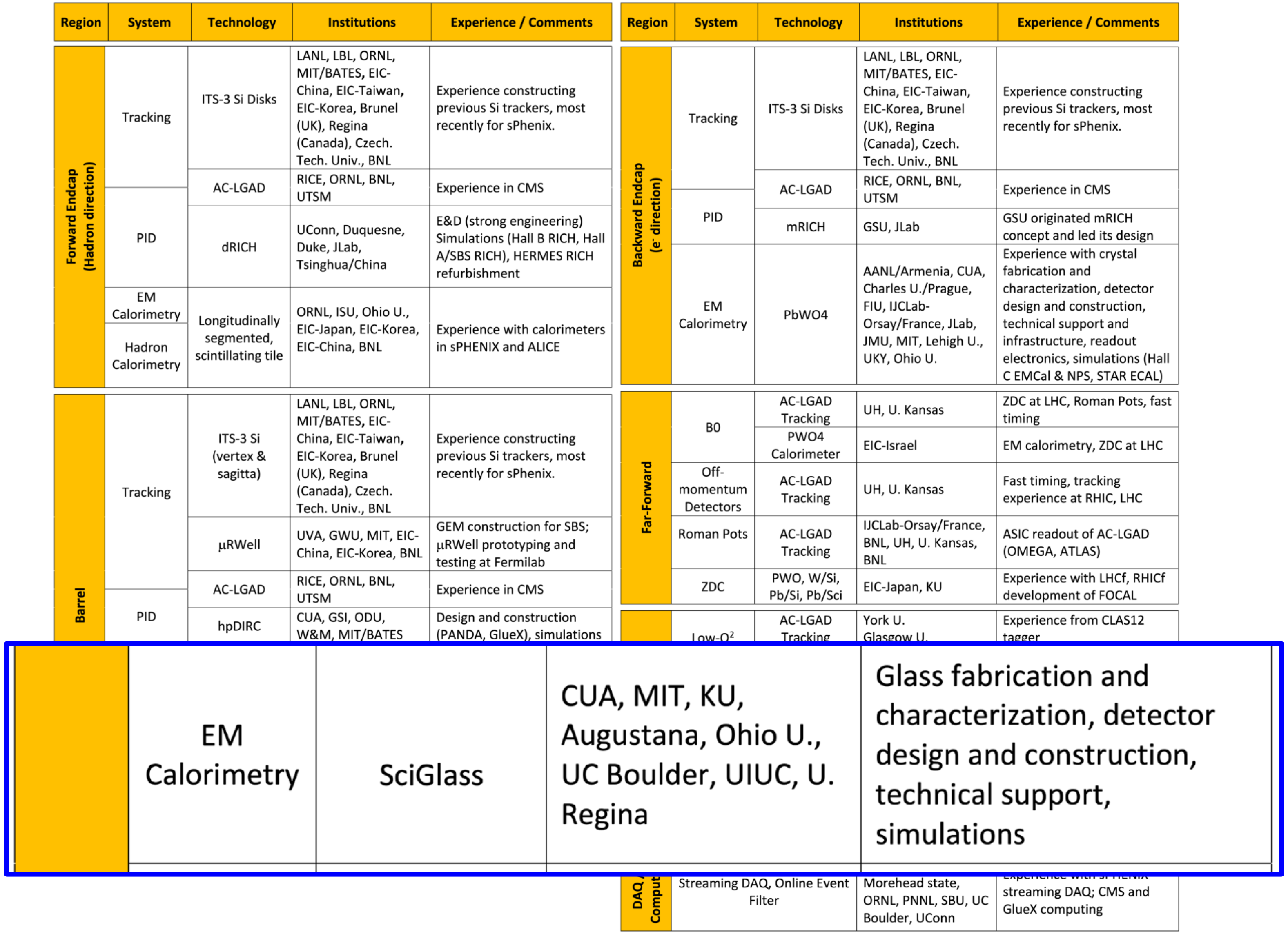
Nice to have:
- Lightweight
- Symmetric shape (easier to manufacture)

One promising option



- Volume: 0.571 m³.
- Works with Aluminum, Titanium and stainless-steel alloys.
- Uniform width to all beams (6.5mm).

BEMC Institutional Interest



Region	System	Technology	Institutions	Experience / Comments
Forward Endcap (Hadron direction)	Tracking	ITS-3 Si Disks	LANL, LBL, ORNL, MIT/BATES, EIC-China, EIC-Taiwan, EIC-Korea, Brunel (UK), Regina (Canada), Czech. Tech. Univ., BNL	Experience constructing previous Si trackers, most recently for sPhenix.
		AC-LGAD	RICE, ORNL, BNL, UTSM	Experience in CMS
	PID	dRICH	UConn, Duquesne, Duke, JLab, Tsinghua/China	E&D (strong engineering) Simulations (Hall B RICH, Hall A/SBS RICH), HERMES RICH refurbishment
	EM Calorimetry Hadron Calorimetry	Longitudinally segmented, scintillating tile	ORNL, ISU, Ohio U., EIC-Japan, EIC-Korea, EIC-China, BNL	Experience with calorimeters in sPHENIX and ALICE
Barrel	Tracking	ITS-3 Si (vertex & sagitta)	LANL, LBL, ORNL, MIT/BATES, EIC-China, EIC-Taiwan, EIC-Korea, Brunel (UK), Regina (Canada), Czech. Tech. Univ., BNL	Experience constructing previous Si trackers, most recently for sPhenix.
		µRWell	UVA, GWU, MIT, EIC-China, EIC-Korea, BNL	GEM construction for SBS; µRWell prototyping and testing at Fermilab
	PID	AC-LGAD	RICE, ORNL, BNL, UTSM	Experience in CMS
		hpDIRC	CUA, GSI, ODU, W&M, MIT/BATES	Design and construction (PANDA, GlueX), simulations

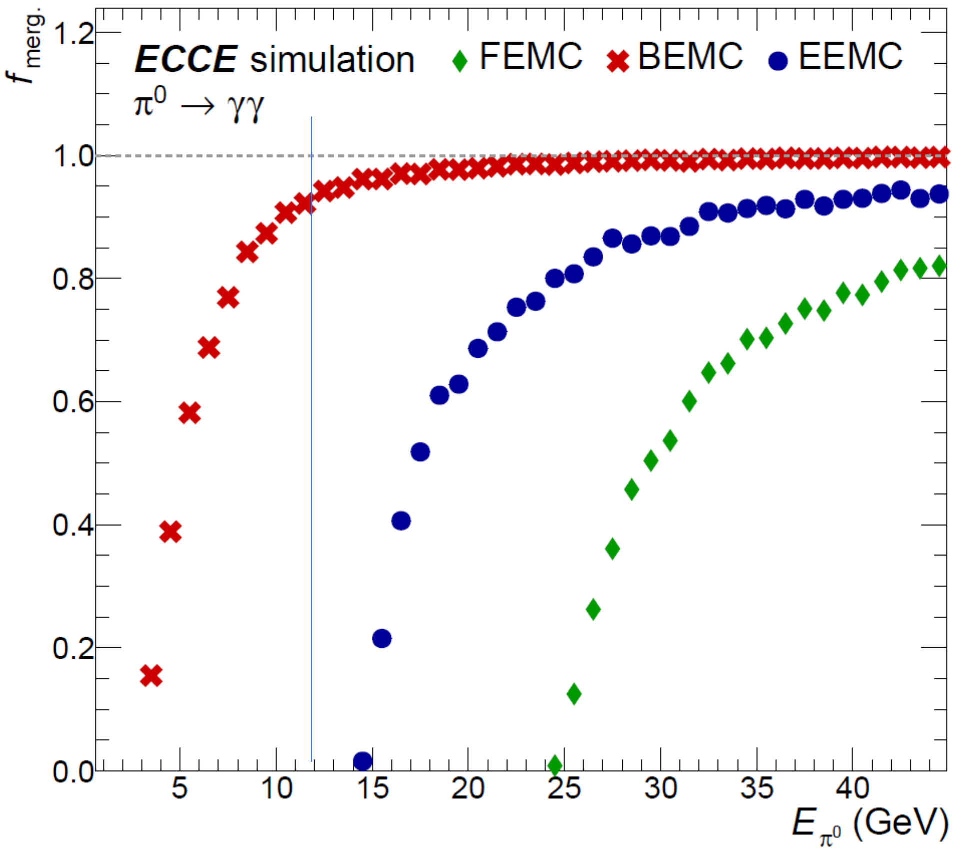
Region	System	Technology	Institutions	Experience / Comments
Backward Endcap (e⁻ direction)	Tracking	ITS-3 Si Disks	LANL, LBL, ORNL, MIT/BATES, EIC-China, EIC-Taiwan, EIC-Korea, Brunel (UK), Regina (Canada), Czech. Tech. Univ., BNL	Experience constructing previous Si trackers, most recently for sPhenix.
	PID	AC-LGAD	RICE, ORNL, BNL, UTSM	Experience in CMS
		mRICH	GSU, JLab	GSU originated mRICH concept and led its design
	EM Calorimetry	PbWO4	AANL/Armenia, CUA, Charles U./Prague, FIU, IJCLab-Orsay/France, JLab, JMU, MIT, Lehigh U., UKY, Ohio U.	Experience with crystal fabrication and characterization, detector design and construction, technical support and infrastructure, readout electronics, simulations (Hall C EMCal & NPS, STAR ECAL)
Far-Forward	B0	AC-LGAD Tracking	UH, U. Kansas	ZDC at LHC, Roman Pots, fast timing
		PWO4 Calorimeter	EIC-Israel	EM calorimetry, ZDC at LHC
	Off-momentum Detectors	AC-LGAD Tracking	UH, U. Kansas	Fast timing, tracking experience at RHIC, LHC
	Roman Pots	AC-LGAD Tracking	IJCLab-Orsay/France, BNL, UH, U. Kansas, BNL	ASIC readout of AC-LGAD (OMEGA, ATLAS)
	ZDC	PWO, W/Si, Pb/Si, Pb/Sci	EIC-Japan, KU	Experience with LHCf, RHICf development of FOCAL
	Low-Q^2	AC-LGAD Tracking	York U. Glasgow U.	Experience from CLAS12 tagger
DAQ / Comput	Streaming DAQ, Online Event Filter		Morehead state, ORNL, PNNL, SBU, UC Boulder, UConn	streaming DAQ; CMS and GlueX computing

	EM Calorimetry	SciGlass	CUA, MIT, KU, Augustana, Ohio U., UC Boulder, UIUC, U. Regina	Glass fabrication and characterization, detector design and construction, technical support, simulations

Figure 4.2: Planed responsibilities of the ECCE institutions for the production of different detector sub-systems.

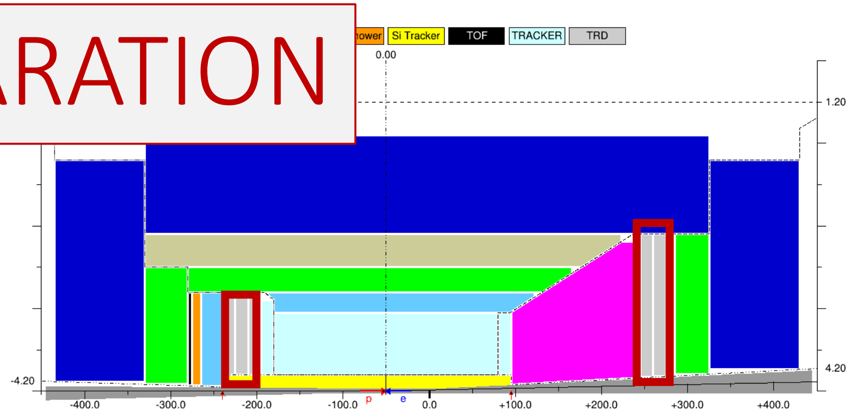
Barrel EMCal Complementarity

Pi0 merging fraction



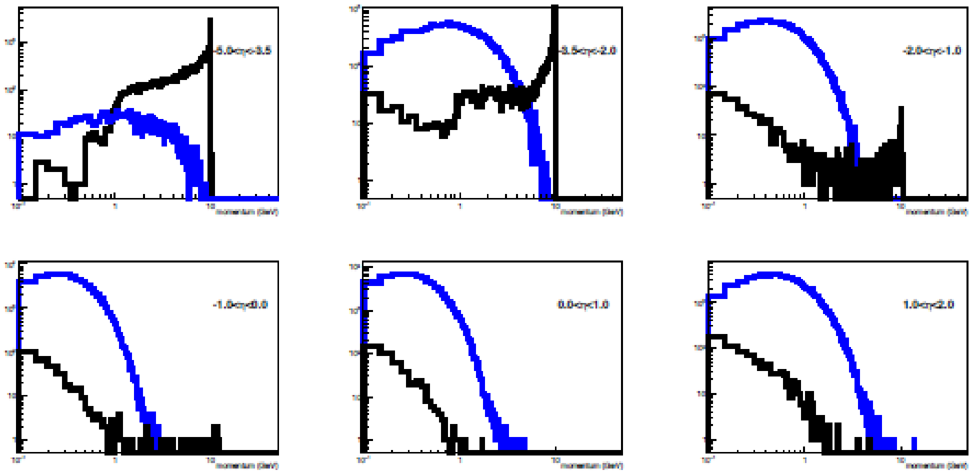
- ❑ ECCE emphasized electron detection from YR requirements
- ❑ Jet measurements might benefit from good 1photon/pi0 separation
- ❑ A good reason for 2 complementary EIC detectors

e/π SEPARATION



NEEDS

ΔG needs pi/e 10^{-3} , A_{PV} needs pi/e 10^{-4}.



10 x 100 GeV Pion/e- Ratio

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Catholic University of America
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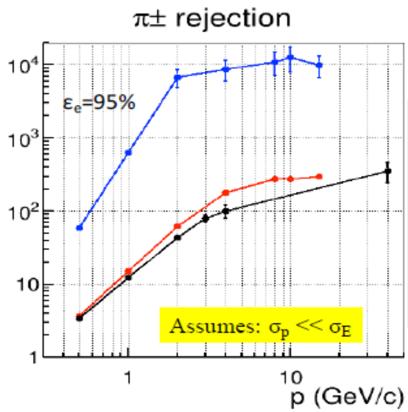
REFERENCE

- ECal as main actor
- Complemented by Cherenkov detectors
  - Backward, mRICH : e/π separation 3 σ up to 2 GeV/c
  - Forward, dRICH: e/π separation 3 σ up to 15 GeV/c
  - Barrel: no support from reference detector (DIRC)

π± rejection with E/p cut



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

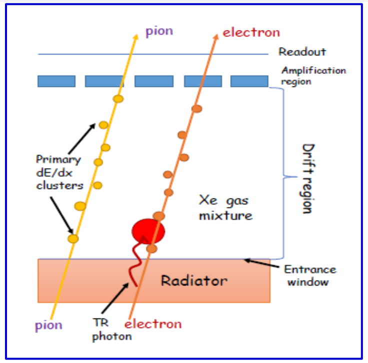
	$PbWO_4$ Crystal	W/SciFi	PbSc
Depth, X_0	20	~20	18
$\frac{\sigma_E}{E}$	$\frac{2.5\%}{\sqrt{E}} \oplus 1\%$	$\frac{13\%}{\sqrt{E}} \oplus 3\%$	$\frac{8\%}{\sqrt{E}} \oplus 2\%$
Depth, λ_I	0.87	~0.83	0.85
e/h	>2		<1.3

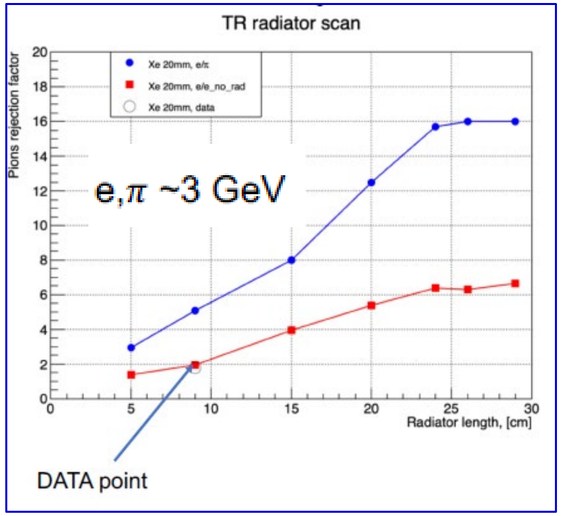
E/p > 1 - 1.6 · σ_{EMC} to keep ε_e=95%

ECal studies

GEM-TDR as specific detector to complement e/π SEPARATION

- Also precise tracker



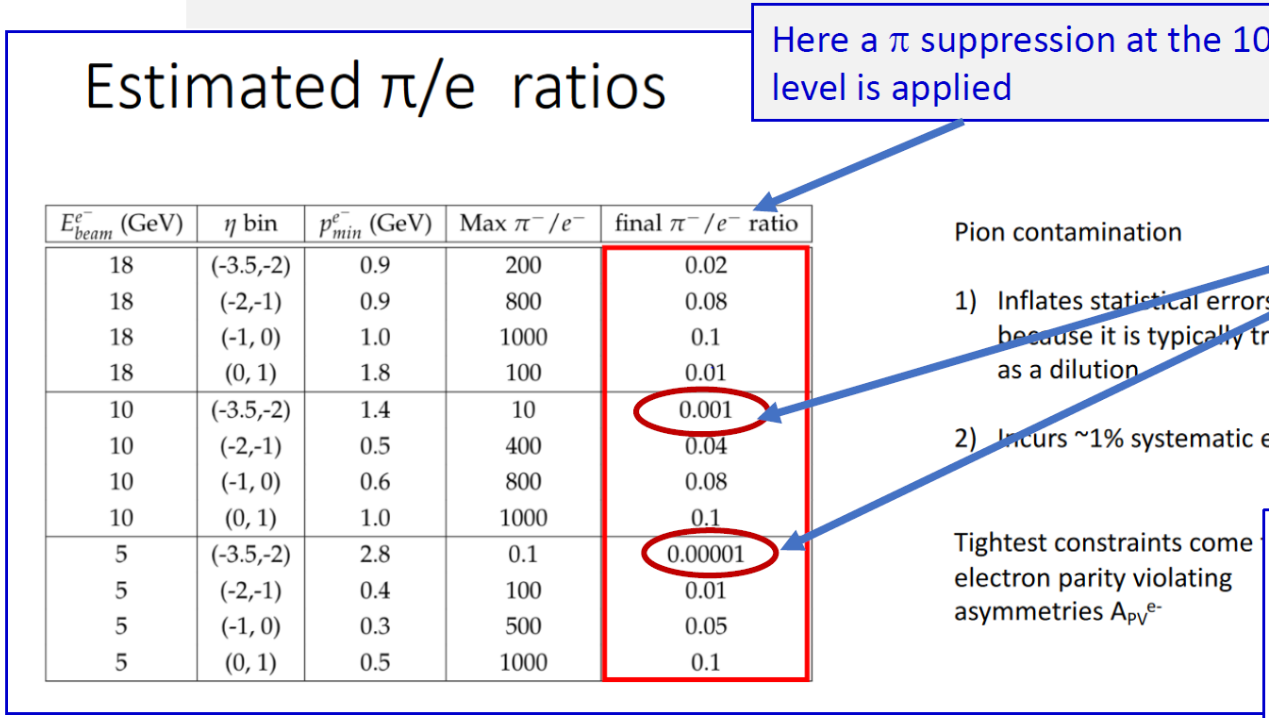


e,π ~3 GeV

DATA point

ABOUT π SUPPRESSION REQUIREMENTS

Here a π suppression at the 10^{-4} level is applied



Estimated π/e ratios

$E^{e^-}_{beam}$ (GeV)	η bin	$p^{e^-}_{min}$ (GeV)	Max π^-/e^-	final π^-/e^- ratio
18	(-3.5,-2)	0.9	200	0.02
18	(-2,-1)	0.9	800	0.08
18	(-1, 0)	1.0	1000	0.1
18	(0, 1)	1.8	100	0.01
10	(-3.5,-2)	1.4	10	0.001
10	(-2,-1)	0.5	400	0.04
10	(-1, 0)	0.6	800	0.08
10	(0, 1)	1.0	1000	0.1
5	(-3.5,-2)	2.8	0.1	0.00001
5	(-2,-1)	0.4	100	0.01
5	(-1, 0)	0.3	500	0.05
5	(0, 1)	0.5	1000	0.1

Pion contamination

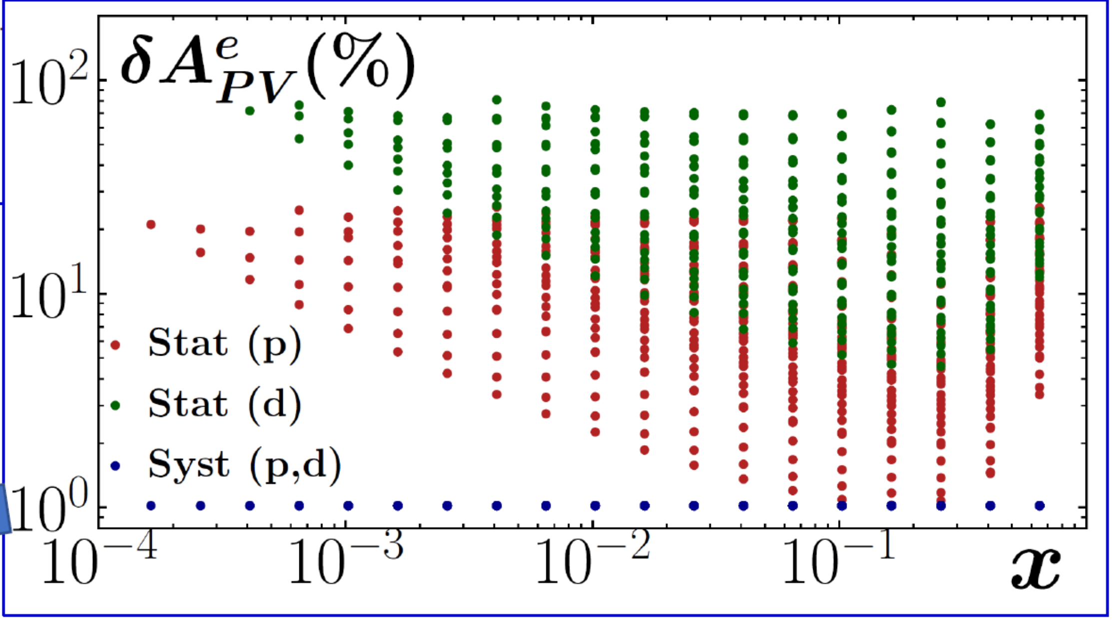
1) Inflates statistical errors because it is typically treated as a dilution

2) Incurs ~1% systematic error

Tightest constraints come electron parity violating asymmetries $A_{PV}^{e^-}$

Despite, the sever π rejection applied, the condition: "π/e at the 10^{-3} level" is satisfied only here

2 slides by Renee Fatemi, 12 Nov. 2020



the impact study of the detector performance is being repeated (Chris Concuzza)