12 GeV Upgrade
Future Science at Jefferson Lab

Electromagnetic Calorimeters (EC) for SoLID

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SoLID Collaboration Meeting

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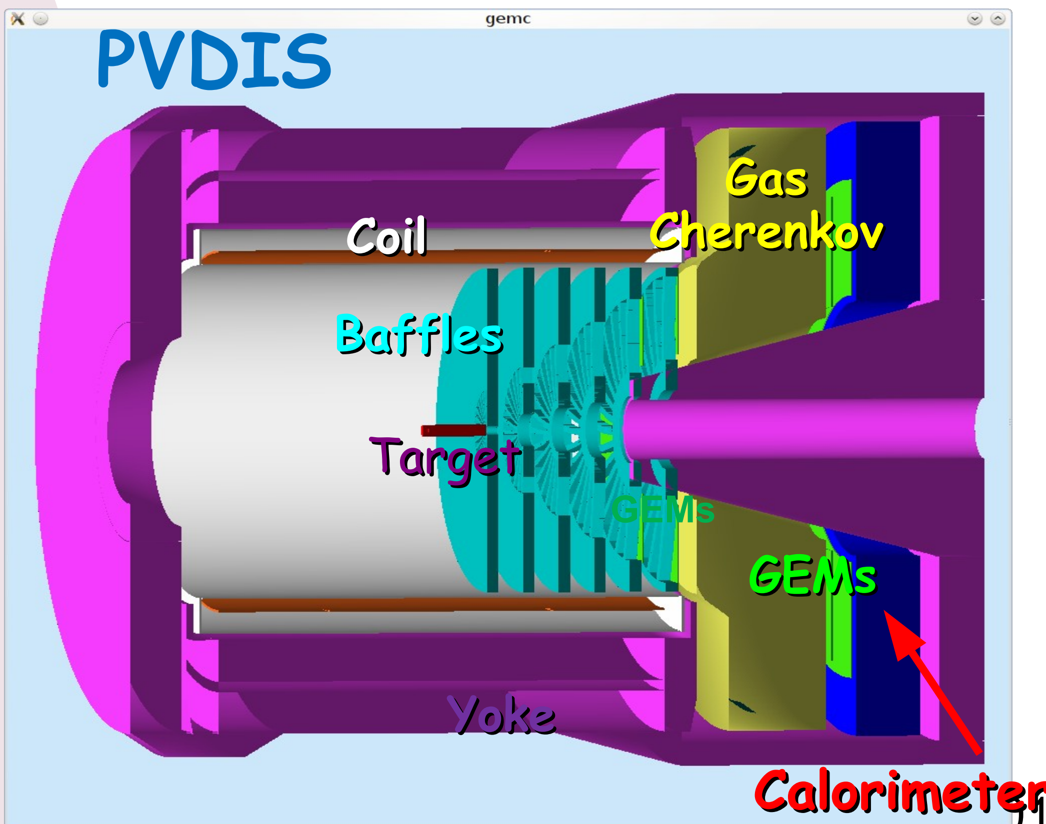
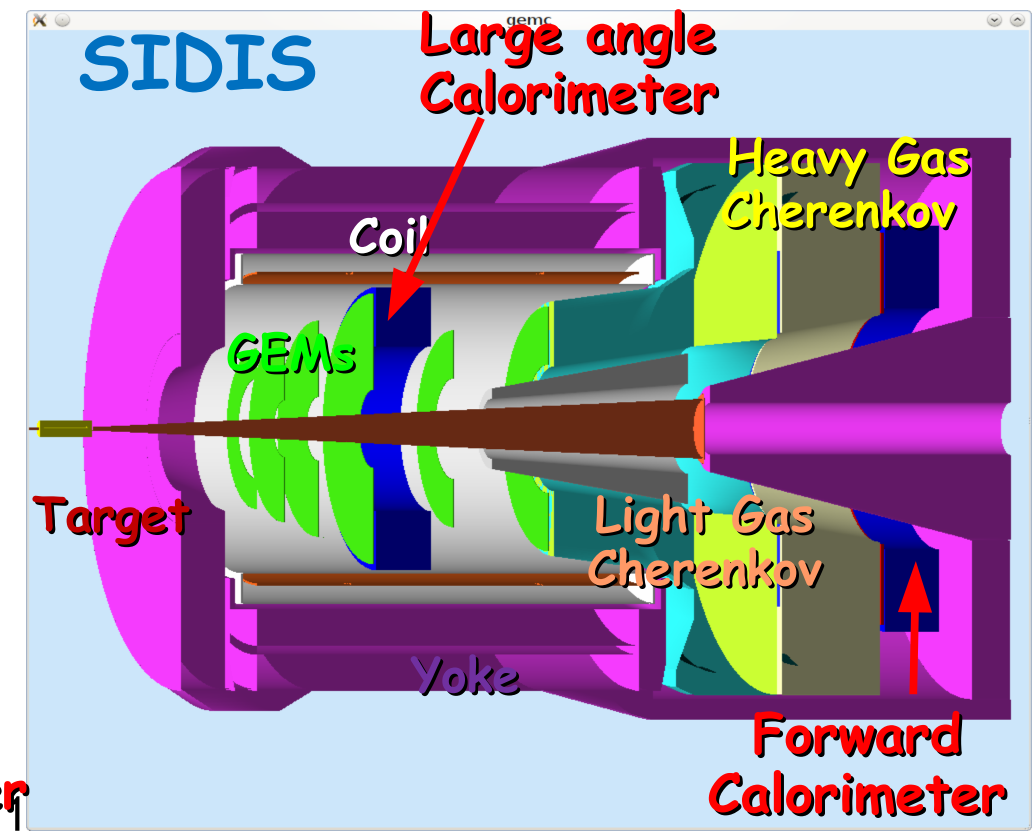
SoLID EC configuration

Provide key e/π separation, modules shared between PVDIS & SIDIS

EC	θ (deg)	P (GeV/c)	Max π/e	Area (m^2)
PVDIS forward angle EC	22 - 35	2.3 - 6	~200	~ 20
SIDIS forward angle EC	9 - 17	1 - 7	~200	~ 10
SIDIS large angle EC	17 - 24	3-6	~20	~ 5





EC Design Requirements

1. Electron- hadron separation:
   - 20:1 - 100:1 pion rejection within p= 1 – 7GeV/c
   - Energy resolution: $\sigma(E)/E \approx 5\%/\sqrt{E}$
2. Time response: provide trigger, identify beam bunch for PID through coincidence TOF (SIDIS only);
   - σ <~ a few hundreds ps (CEBAF beam bunch ~2ns)
3. Provide shower position to help tracking/suppress background
   - σ ~ 1 cm
4. Radiation resistance: 5×10^5 rad for one PAC year
5. Magnetic field 1.5 T for SIDIS large angle EC: Silicon based photon-sensors (field-resistant) can't survive high neutron environment and expensive; PMTs work but need to be away from high magnetic field.
6. Modules easily swapped and rearranged for PVDIS ↔ SIDIS
7. SIDIS needs 2-fold rotation (180^o) symmetry

Material	ρ g/cm^3	X_0 cm	R_M cm	λ_I cm	n refrac.	τ ns	peak λ nm	light yield	Npe /GeV	rad	$\delta E/E$
Crystals											
NaI(Tl)	3.67	2.59	4.5	41.4	1.85	250	410	1.00	10^6	10^2	$1.5\%/E^{1/4}$
CsI	4.53	1.85	3.8	36.5	1.80	30	420	0.05	10^4	10^4	$2.0\%/E^{1/2}$
CsI(Tl)	4.53	1.85	3.8	36.5	1.80	1200	550	0.40	10^6	10^3	$1.5\%/E^{1/2}$
BGO	7.13	1.12	2.4	22.0	2.20	300	480	0.15	10^5	10^3	$2\%/E^{1/2}$
PbWO4	8.28	0.89	2.2	22.4	2.30	15/60%	420	0.013	10^4	10^6	$2.0\%/E^{1/2}$
LSO	7.40	1.14	2.3		1.81	40	440	0.7	10^6	10^6	$1.5\%/E^{1/2}$
PbF2	7.77	0.93	2.2		1.82	Cher	Cher	0.001	10^3	10^6	$3.5\%/E^{1/2}$
Lead glass											
TF1	3.86	2.74	4.7		1.65	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF-5	4.08	2.54	4.3	21.4	1.73	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF-57	5.51	1.54	2.6		1.89	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
Sampling: lead/scintillator											
SPACAL	5.0	1.6				5	425	0.3	2×10^4	10^6	$6.0\%/E^{1/2}$
Shashlyk	5.0	1.6				5	425	0.3	10^3	10^6	$10\%/E^{1/2}$
Shashlyk(K)	2.8	3.5	6.0			5	425	0.3	4×10^5	10^5	$3.5\%/E^{1/2}$

Choosing EC Type

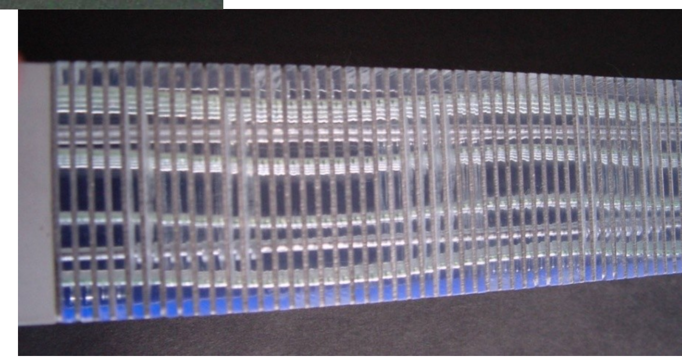
- PVDIS and SIDIS radiation level (~400 krad per year) is too high for leadglass and CSI-like crystals (typically 1krad).
- Our ECs are large: Forward angle EC ($10m^2$x0.4m depth), Large angle EC ($5m^2$x0.4m), or PVDIS EC ($20m^2$x0.4m) → Total 6-$8m^3$
- Crystals like $PbWO_4$ (\$10/cc) and LSO (\$40/cc) can stand 10^6 rad, but too expensive: Total ~$3m^3$→ \$30M or \$120M .
- Both Shashlyk or SPACAL/SciFi (0.5-1Mrad) have enough radiation hardness and good energy, position and time resolution.

SciFi vs. Shashlyk:

- SciFi needs about half volume being scintillation fibers to reach good energy resolution, 1mm-diameter fibers cost \$1/m: Total $6m^3$ → **\$4M** for fiber alone.
- Compare to Shashlyk: total module cost from <**\$3M** from IHEP.
- Two orders of magnitude fibers than Shashlyk, hard to read out.

Shashlyk EC

IHEP, COMPASS Shashlik, 2010



- Lead-scintillator sampling calorimeter
- WLS fibers [$1/(9.5mm)^2$] collect and guide out light → one PMT per module.
- Good and tunable energy resolution
- Radiation hardness: ~ 500 krad tested by IHEP
- transverse size can be customized
- Light collection and readout straightforward
- Well developed technology, used by many experiments, IHEP production rate about 200/month

IHEP Scintillator Facilities
www.ihep.ru/scint/index-e.htm

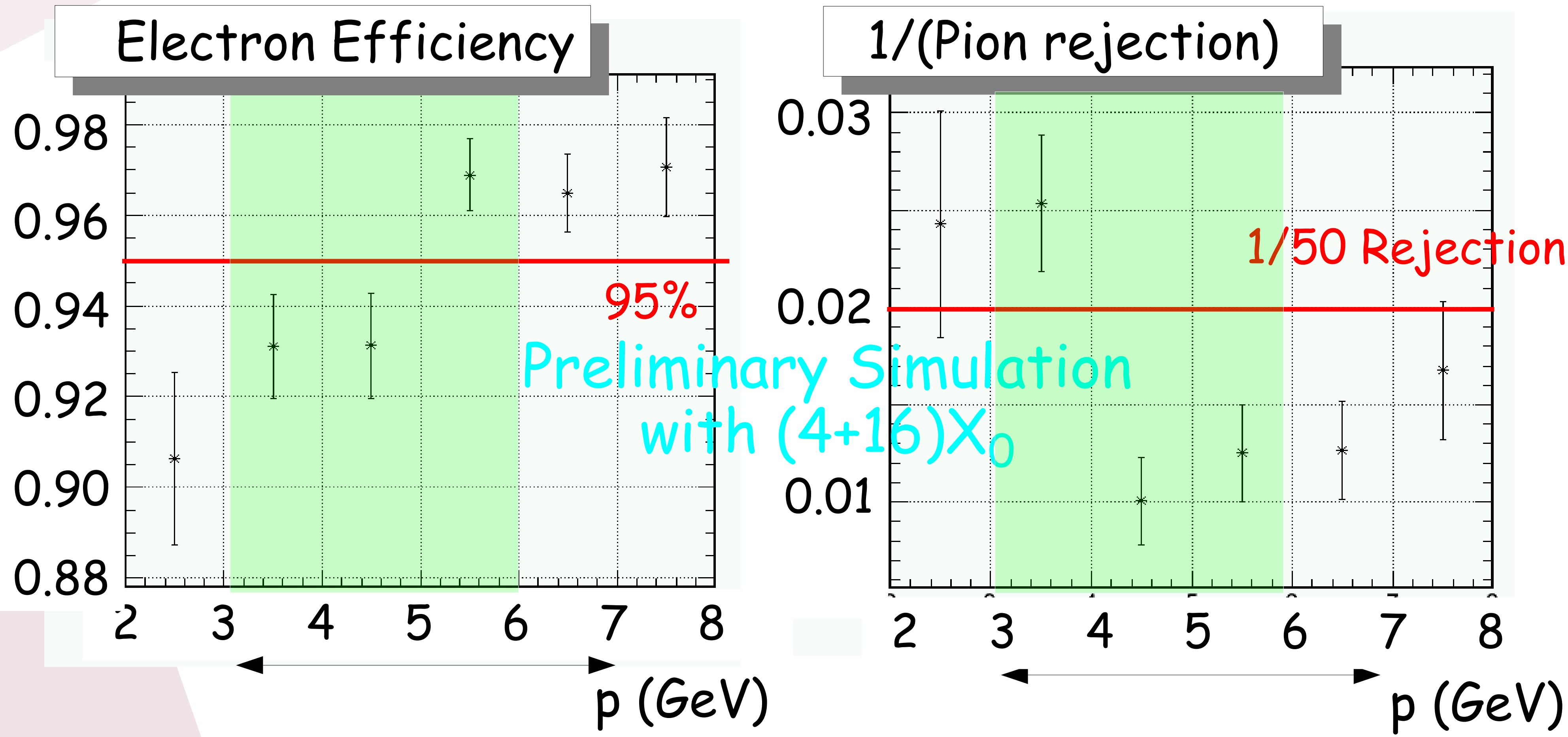
Design Consideration 1: Pb/scintillator ratio

Experiment	COMPASS	PANDA	KOPIO
Pb Thick/Layer (mm)	0.8	0.3	0.28
Sci Thick/Layer (mm)	1.5	1.5	1.5
Energy Res. a/sqrt(E)	6.5%	~3%	~3%
Rad. length, X_0 (mm)	17.5	34	35
Total rad length in X_0	22.5	20	16
Moliere radius (mm)	36	59	60
Typical Detecting Energy	10^1~10^2GeV?	<10GeV	<1GeV
Lateral Size (cm)	~4x4	11x11	11x11
Active depth(cm)	400	680	555

- Thinner Pb layers give better energy resolution, but requires more layers → Balancing between energy resolution and module length

Design Consideration 1: Pb/scintillator ratio

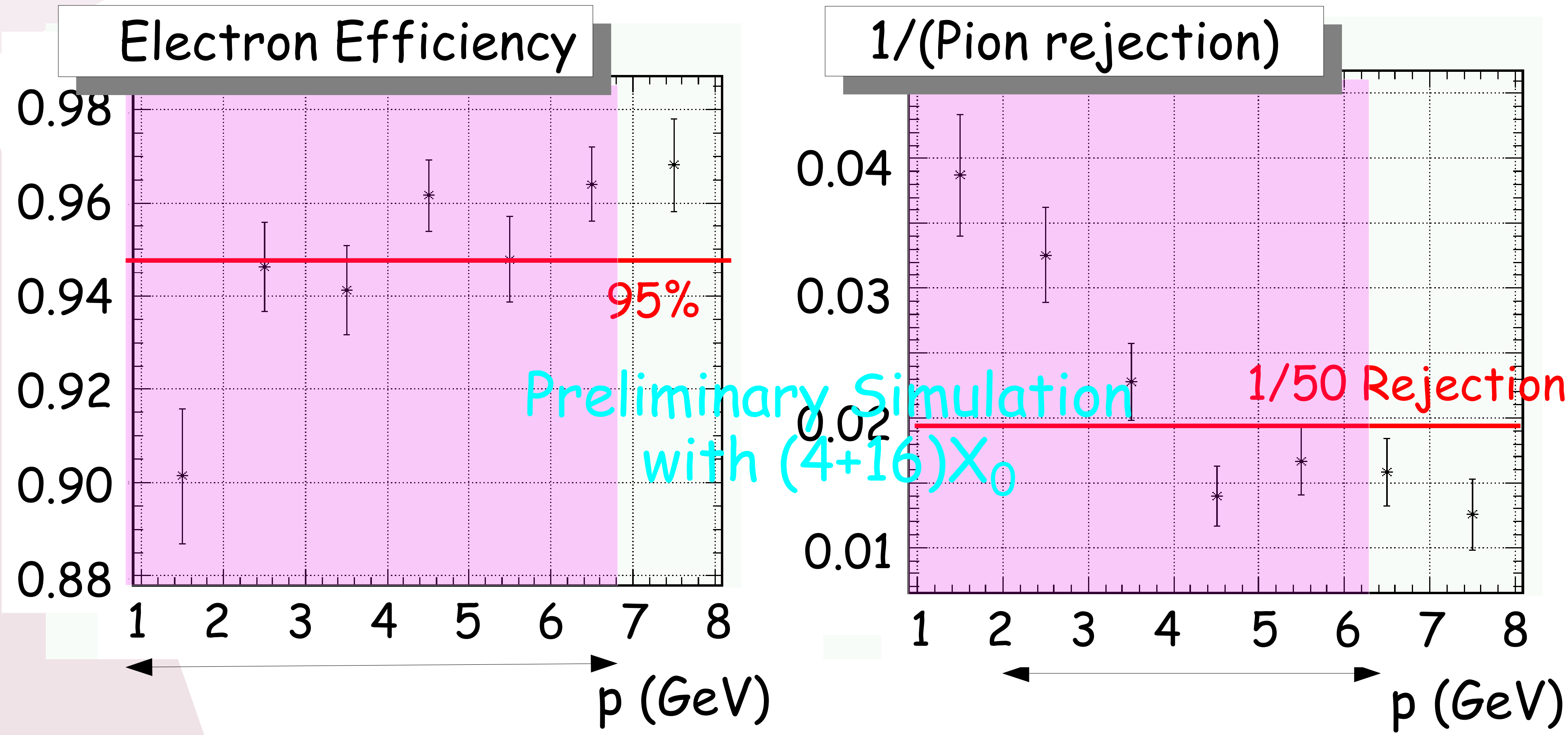
- Minimize scintillator ratio while reaching 100:1 pion rejection → 0.5mm Pb/1.5 mm Scint. (BASF143E) per layer.



SIDIS large angle: p=3~6 GeV

Design Consideration 1: Pb/scintillator ratio

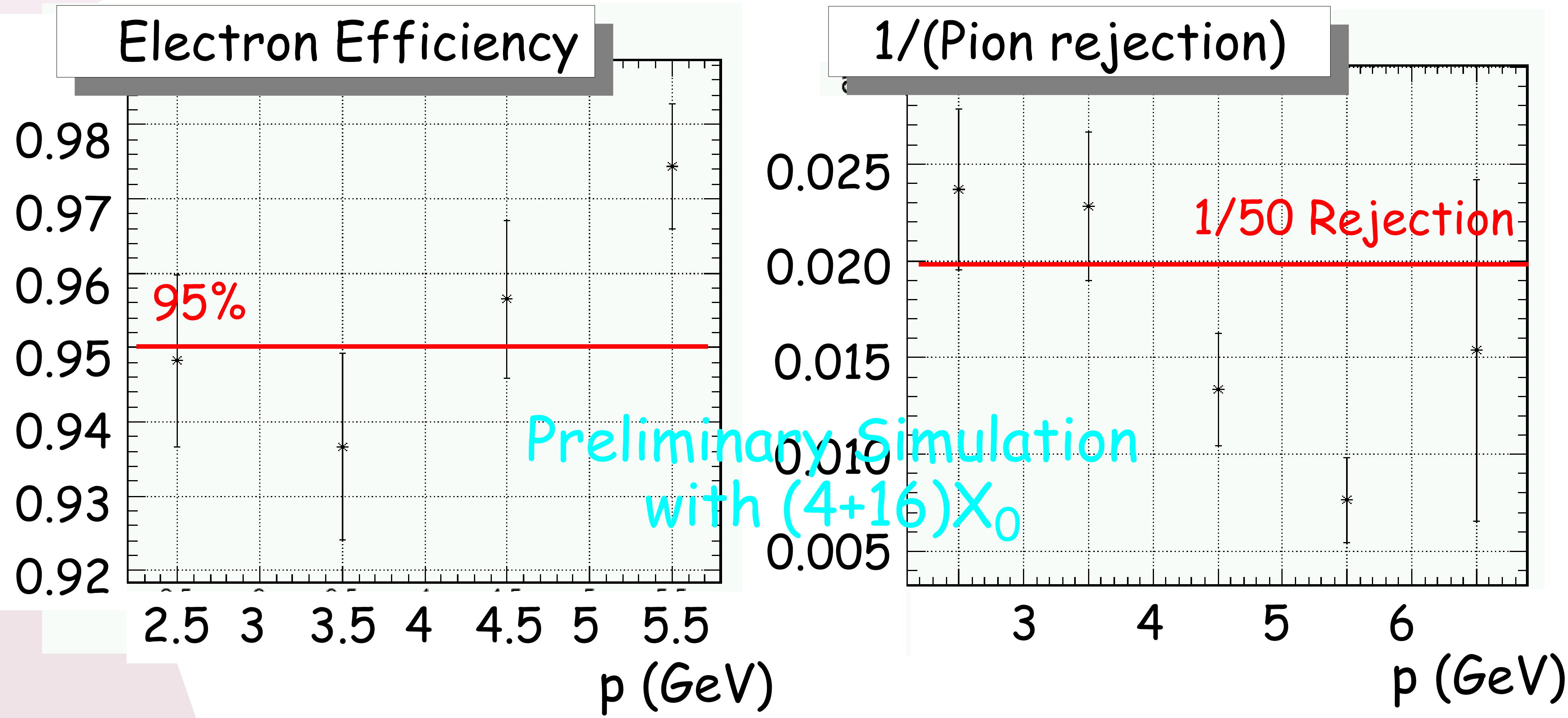
- Minimize scintillator ratio while reaching 100:1 pion rejection → 0.5mm Pb/1.5 mm Scint. (BASF143E) per layer.



SIDIS forward angle: p=1~7 GeV

Design Consideration 1: Pb/scintillator ratio

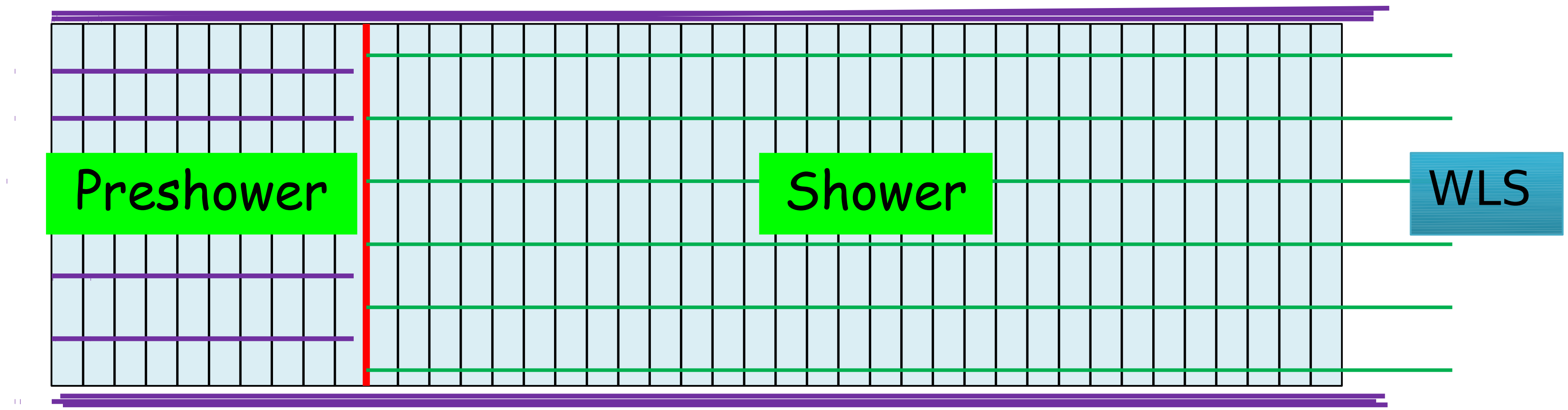
- Minimize scintillator ratio while reaching 100:1 pion rejection → 0.5mm Pb/1.5 mm Scint. (BASF143E) per layer.



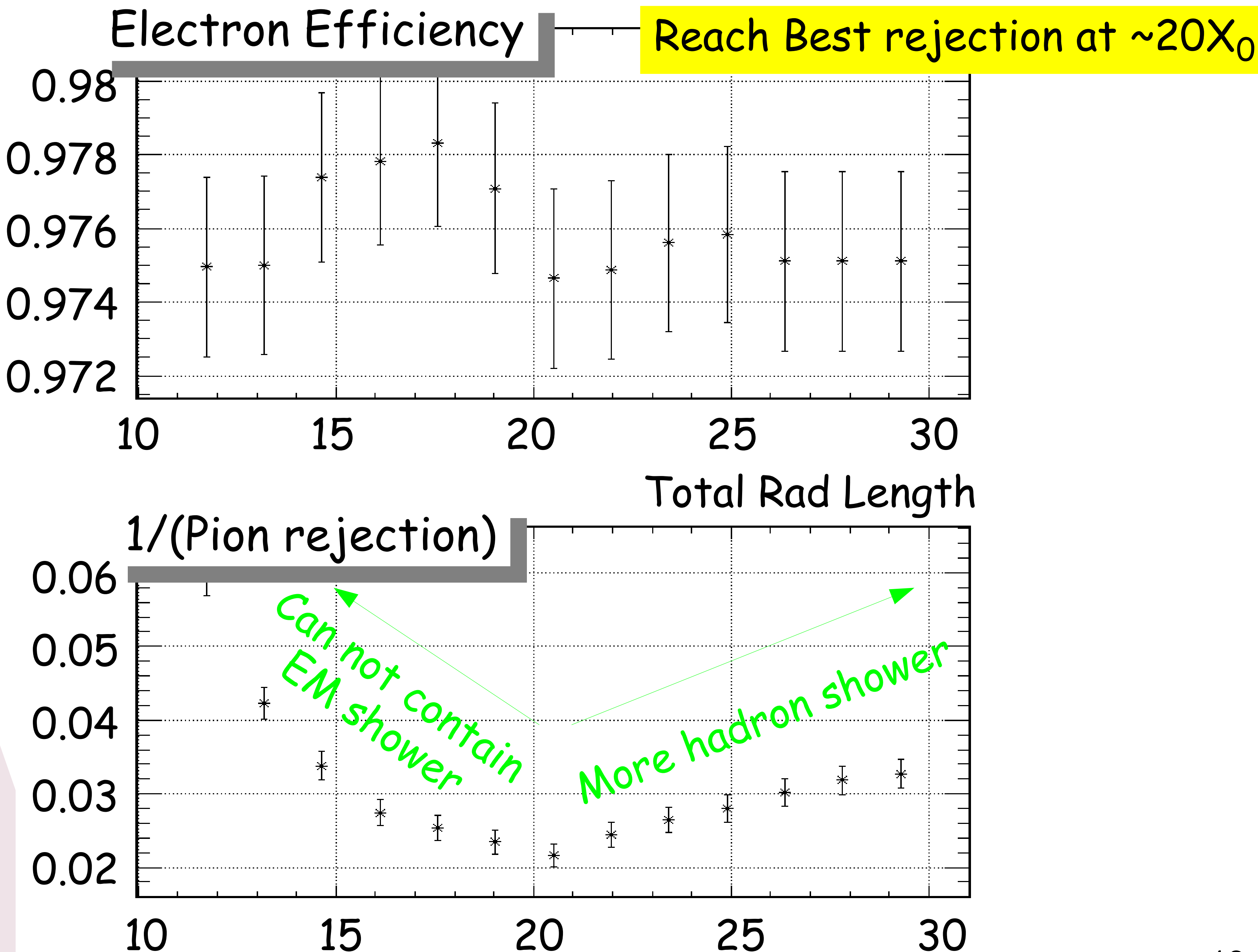
PVDIS (forward angle): p=2.3~6 GeV

Design Consideration 2.0: Preshower/Shower

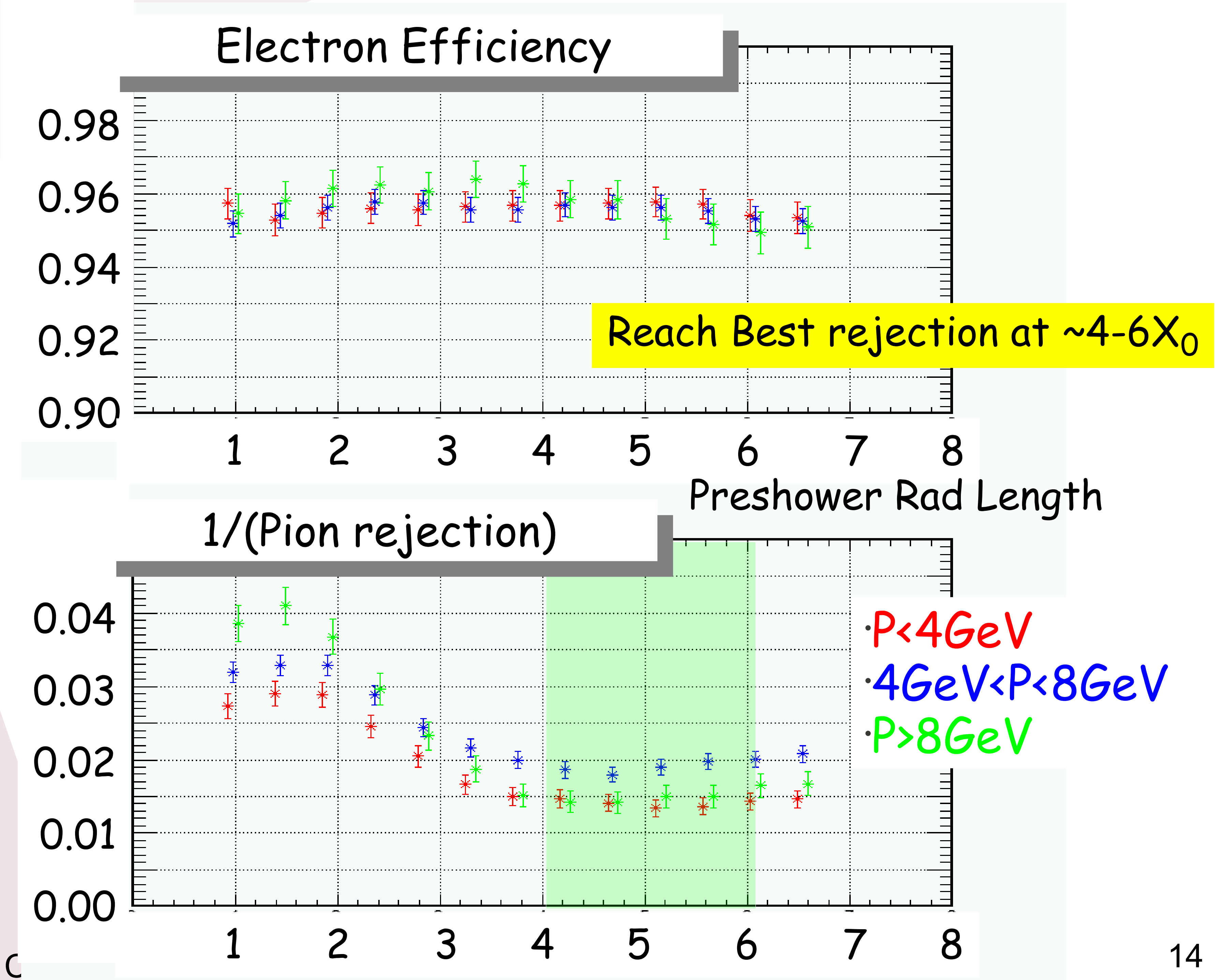
Preshower and shower have separate WLS readout in the current design:



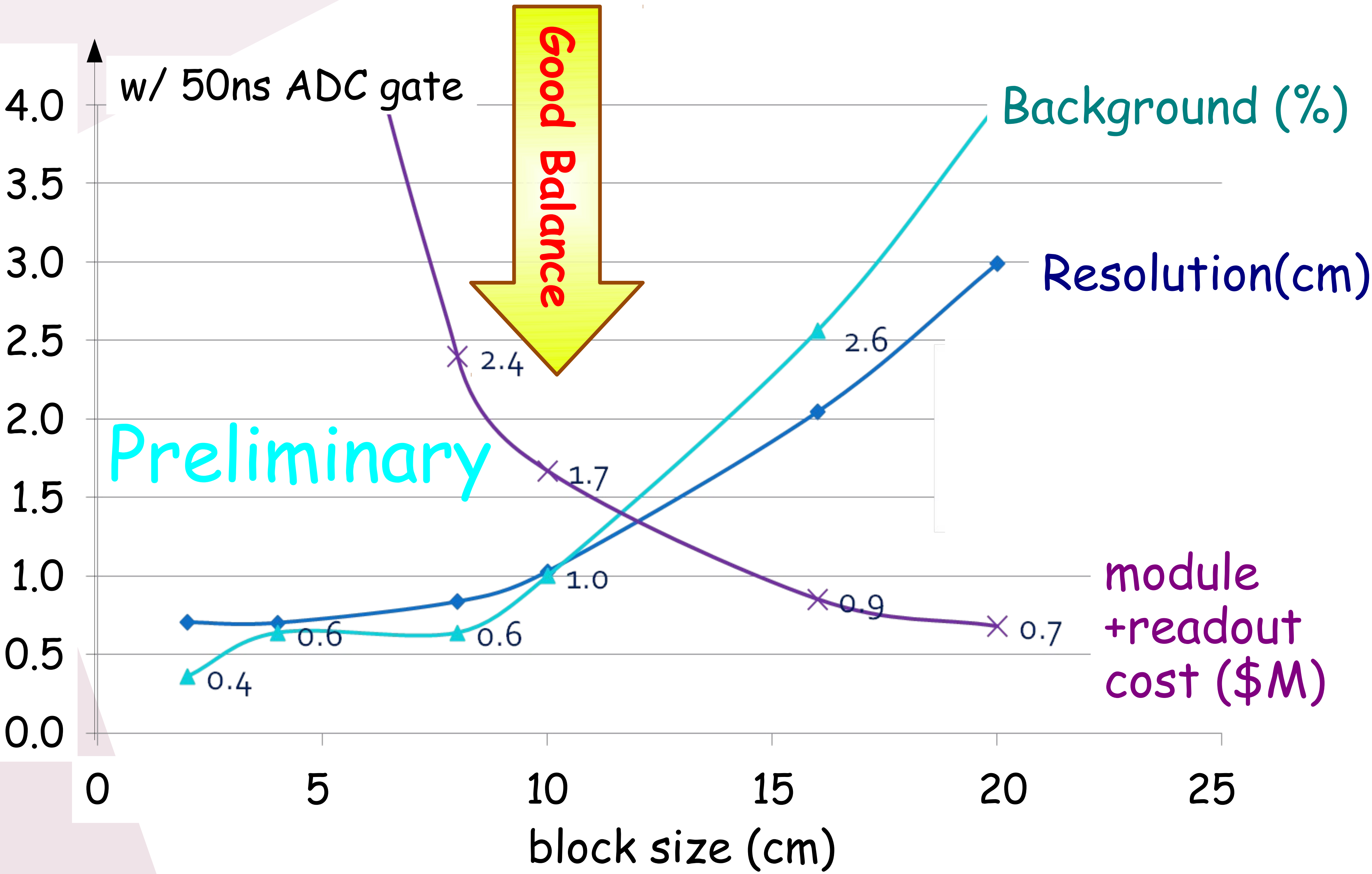
Design Consideration 2.1: Total Length



Design Consideration 2.2: Preshower Length

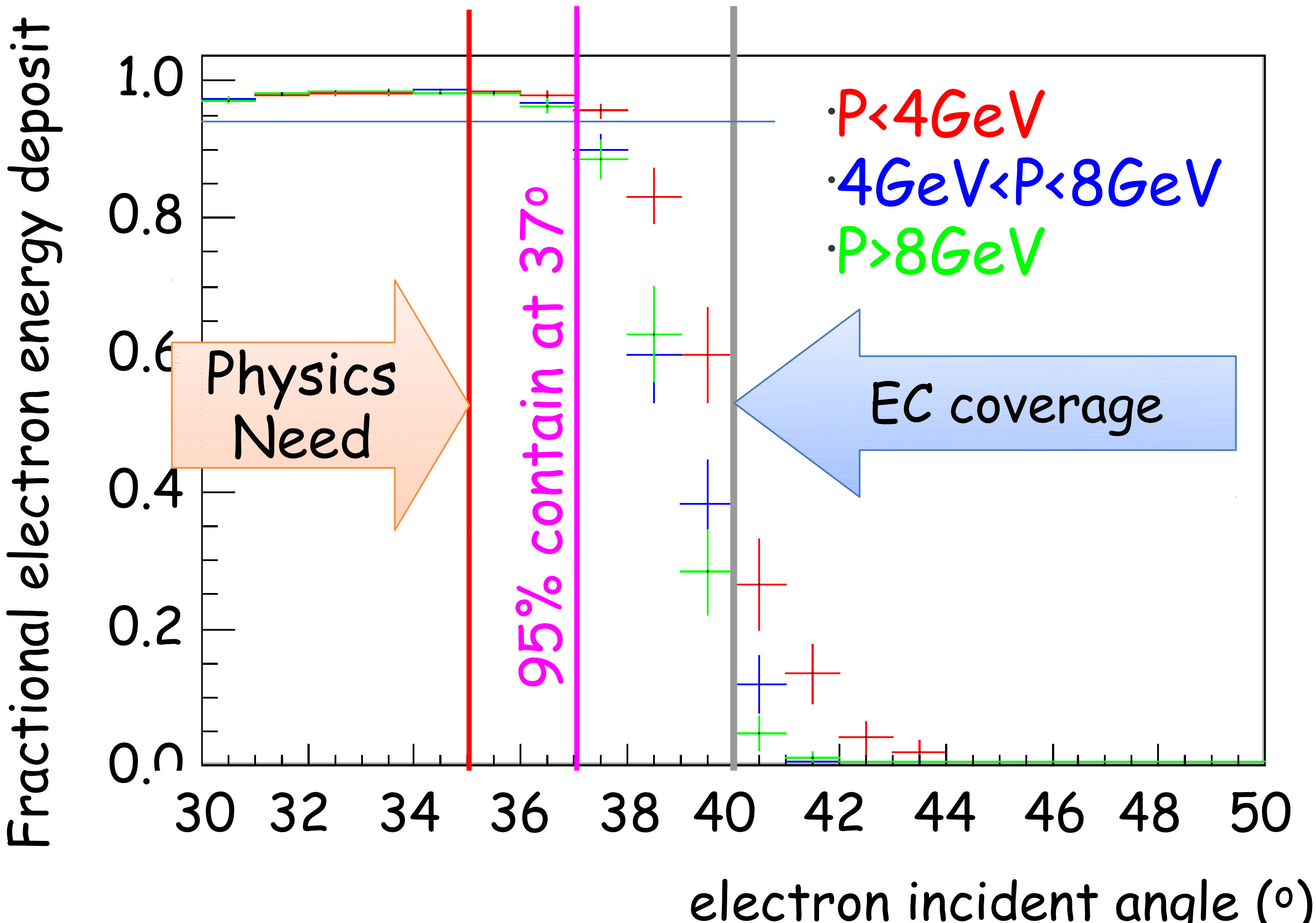


Design Consideration 3: Lateral Size

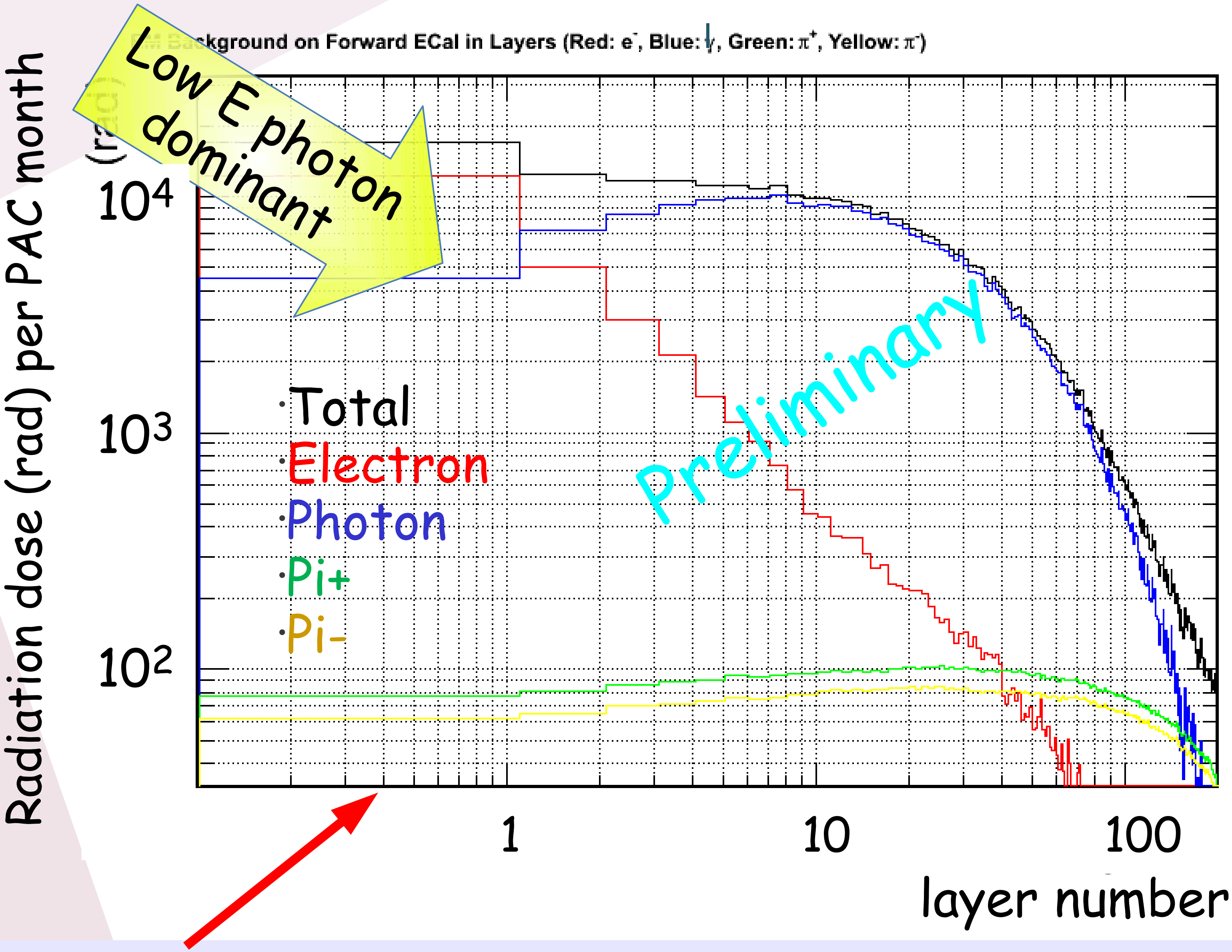


Design Consideration 4: Edge Effect

PVDIS physics requires the largest incident angle (35^0 from target center, 37^0 from downstream target); Calorimeter covers up to ~40^0.



Design Consideration 5: Radiation Dose



Can be shielded with 2mm Pb; Effect on energy resolution ~0.1%/sqrt(E) worse, no obvious effect on pion rejection (EM shower not yet developed in the first few layers)

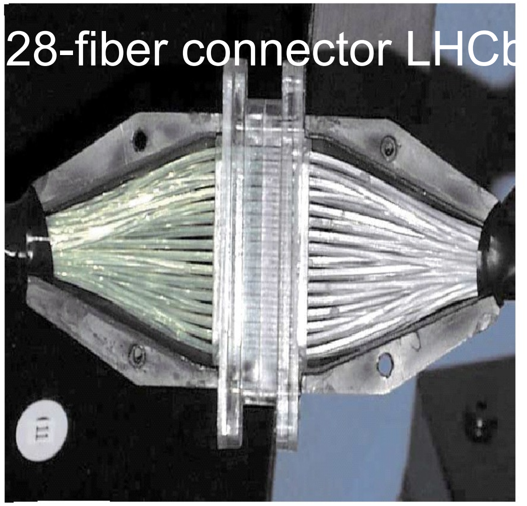
Design Consideration 6: Fibers & Connectors

Fibers:

- Wave Length Shifting fibers: KURARAY Y11
  - Radiation hardness: 13% light loss at 0.1Mrad, 30% light loss at 0.7Mrad (manageable with scintillator BASF143E)
  - Attenuation length ~3m, okay for PVDIS or SIDIS forward angle, but not for SIDIS large angle
  - Difference between PVDIS and SIDIS large angle complicates re-arrangement.
- Clear Fibers (3-5m from SIDIS large angle to readouts): KURARAY, clear PS, Super Eska;

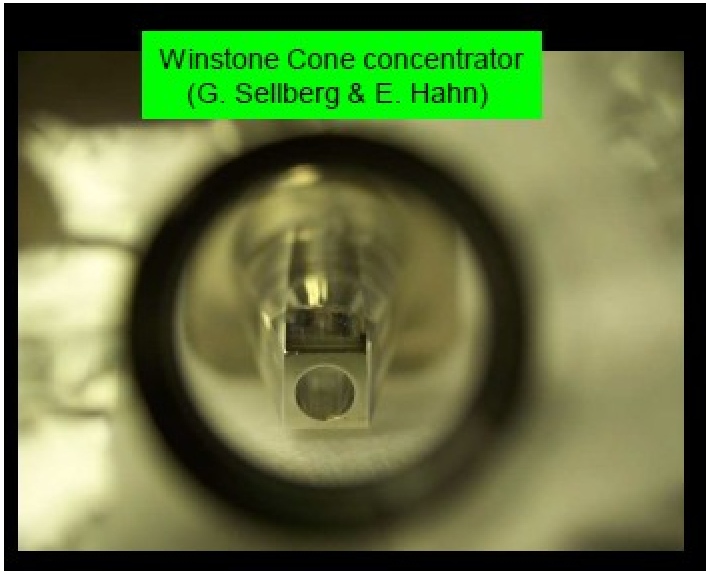
Design Consideration 6: Fibers & Connectors

Fiber connector options:



- One to one WLS/clear fiber connector: used in previous experiments (LHCb, Minos,...), light loss studies and design well documented, but costly and must run 2x50000 fibers to readouts for SIDIS large angle alone;

- Lucite rod would reduce the cost, but rigid and no information on light loss.

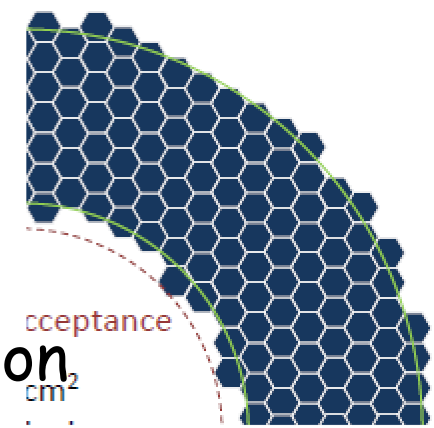


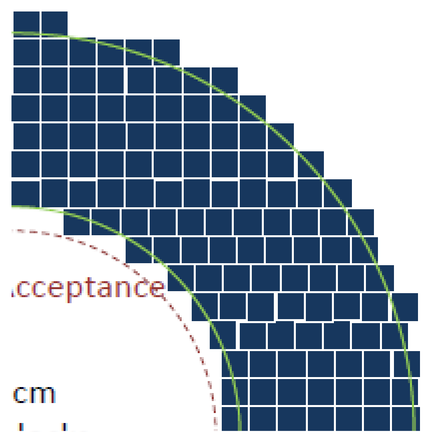
- Winstone cone concentrator from Fermi Lab (~20 fibers to ϕ3-mm, read out by 9 clear fibers): need 5000 cones + clear fibers (SIDIS large angle alone); larger clear fibers?

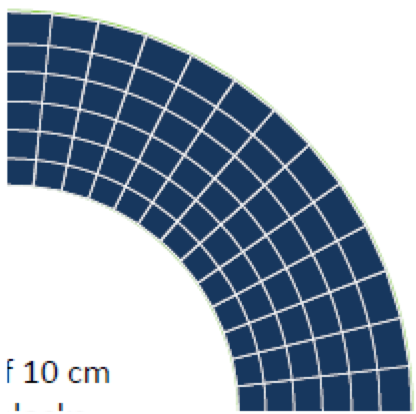
- Searching for other fiber bundle to bundle connection.

Design Consideration 7: Shape & Layout

Module shape	Hexagon		Square		Sector	
EC (SIDIS angle)	Small	Large	Small	Large	Small	Large
Size(cm)	10	10	10	10	10.5	9.95
#Blocks	912	486	908	492	576	312
#Molds	Min 1	Min 1	Min 1	Min 1	Min 9	Min 6
Overall	1398 blocks 1 mold ~$1.4M		1400 blocks 1 mold ~$1.4M		888 blocks 15 mold ~$1.64M	







Prefer Square

- easy assembly
- mature production
- easier rearrangement

Sol

Cost Estimation

Total ~ $5M + clear fiber

- Based on module $1500EA, PMT~$500EA;
- Table not including clear fibers and connectors, and DAQ.

EC	# modules	Total module cost ($)	# PMTs	Total PMT cost ($)	Total cost ($)
SIDIS large angle	500	0.75M	2x500	0.5M	1.25M
SIDIS forward angle	1000	1.5M	2x1000	1M	2.5M
PVDIS (assuming 100% coverage)	2000	3.0M	2x2000	2M	5 M

Overview of Current Design

Based on COMPASS Shashlyk module design.

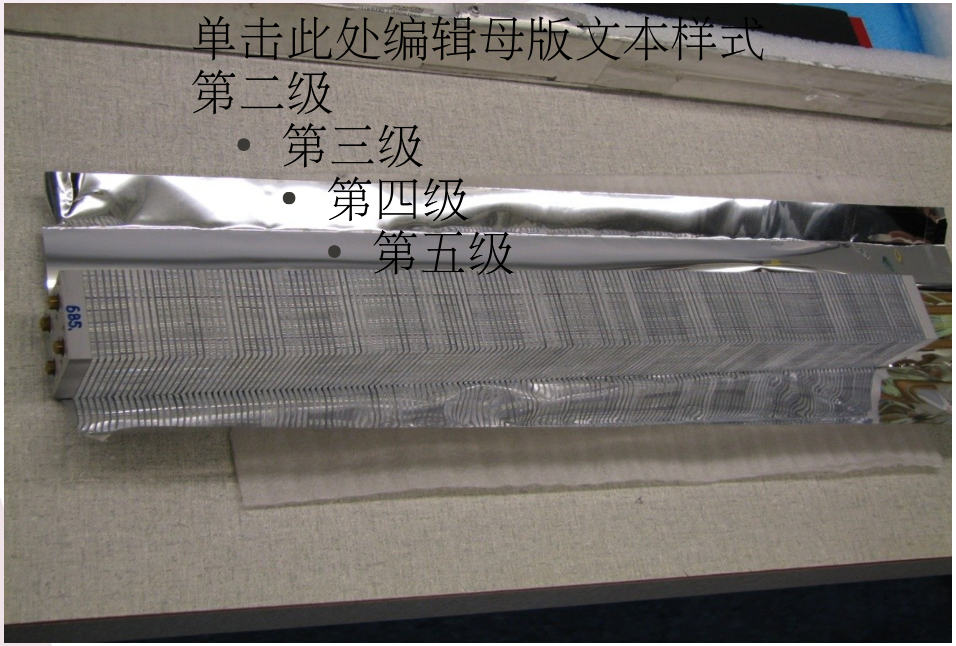
- 0.5mm Pb/1.5mm scintillator, 240 layers
- 48cm long (20 X_0), 4X_0 preshower, 16X_0 shower.
  - Balance between longitudinal size and pion rejection
  - 20:1 - 100:1 pion rejection with 95% electron efficiency (depending on momentum)
- 10x10cm^2 square shape modules ← balance between cost and position resolution/background
- 100 WLS fibers per module (1/cm^2, KURARAY Y11)
- Total 1500(SIDIS) ~ 2000(PVDIS) modules
- Fiber connection still being studied

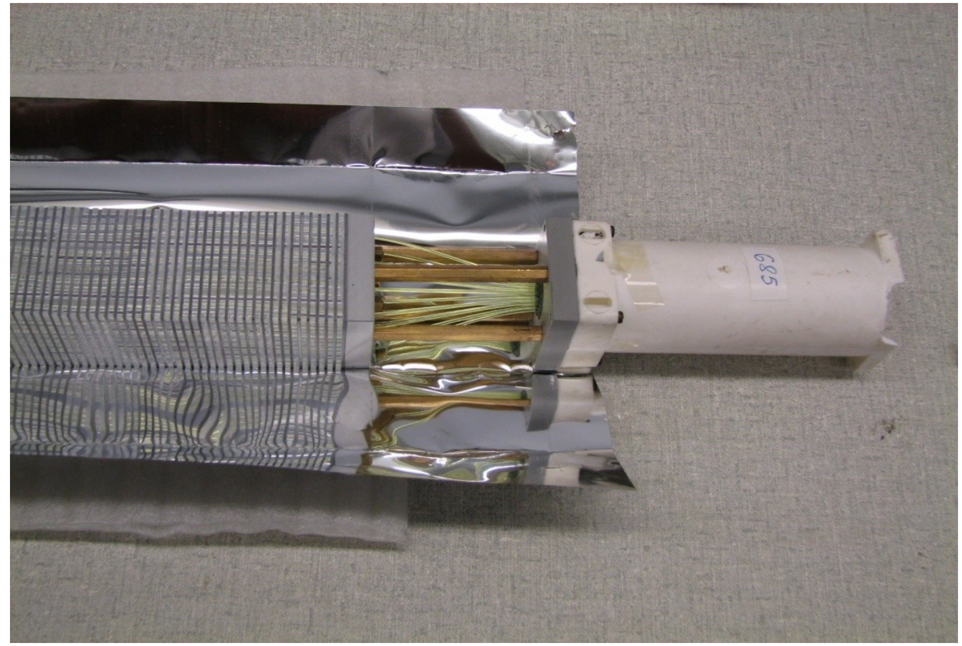
Summary

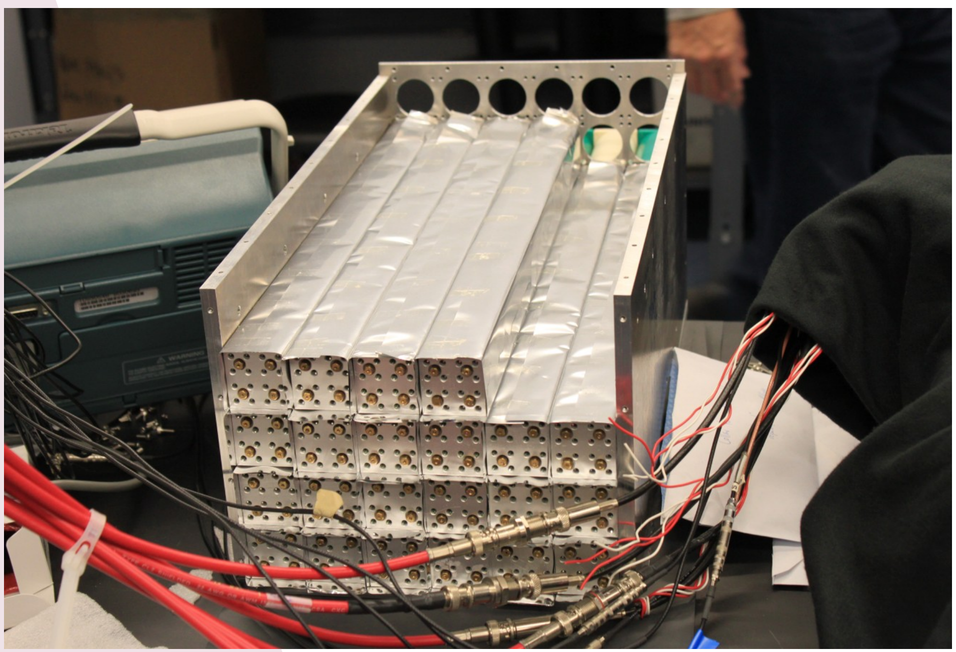
- EC is the key detector for electron-hadron separation in SoLID.
- The challenges:
  - reach good pion rejection
  - operate in high radiation environment
  - and strong magnetic field.
- Preliminary design is on-going.
- We will collaborate with IHEP on prototyping and production.

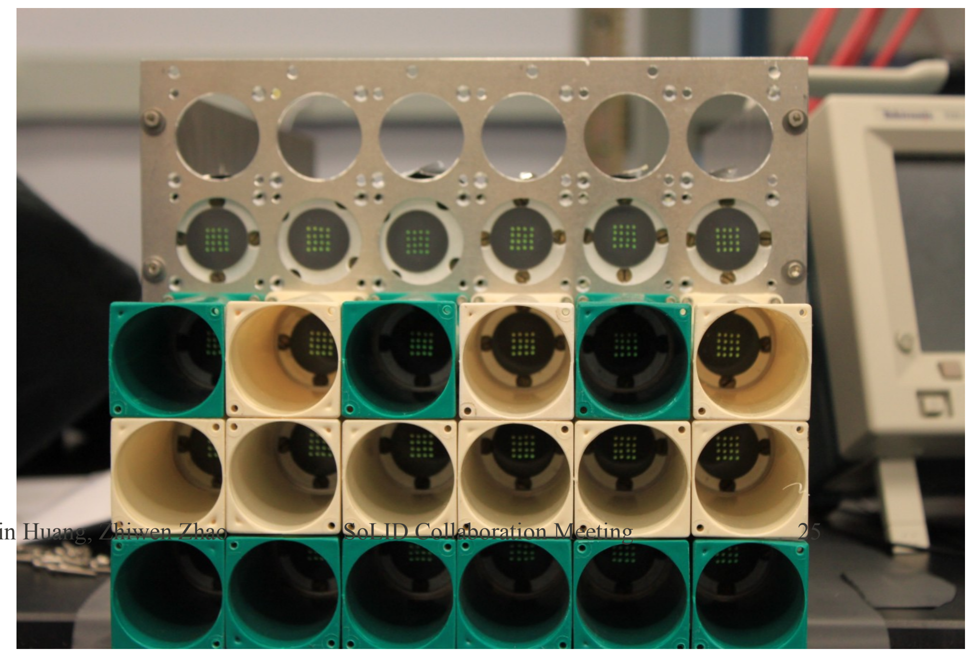
Backup for beam test in Hall B

COMPASS modules used for TPE@CLAS









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EC 4/2012 beam test: Modules and readout

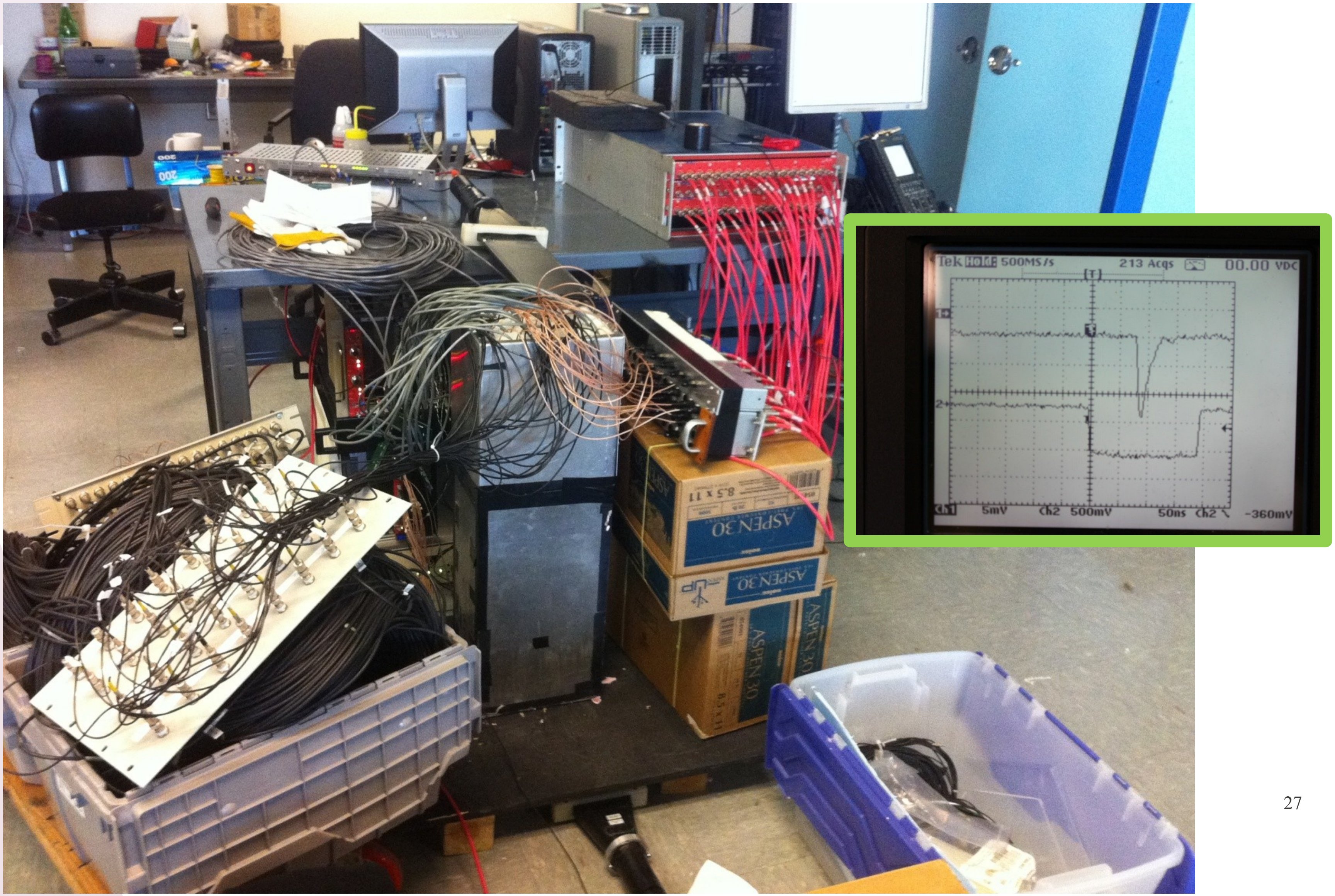
Module is in TPE frame with original PMT removed.
30 of 3.8x3.8cm modules in 6x5 array.

Readout: 1.1"D Photonis

XP2972 PMTs, used in HallA

DVCS proton array.

Cosmic ray test (vertical setup) on 2nd floor counting house



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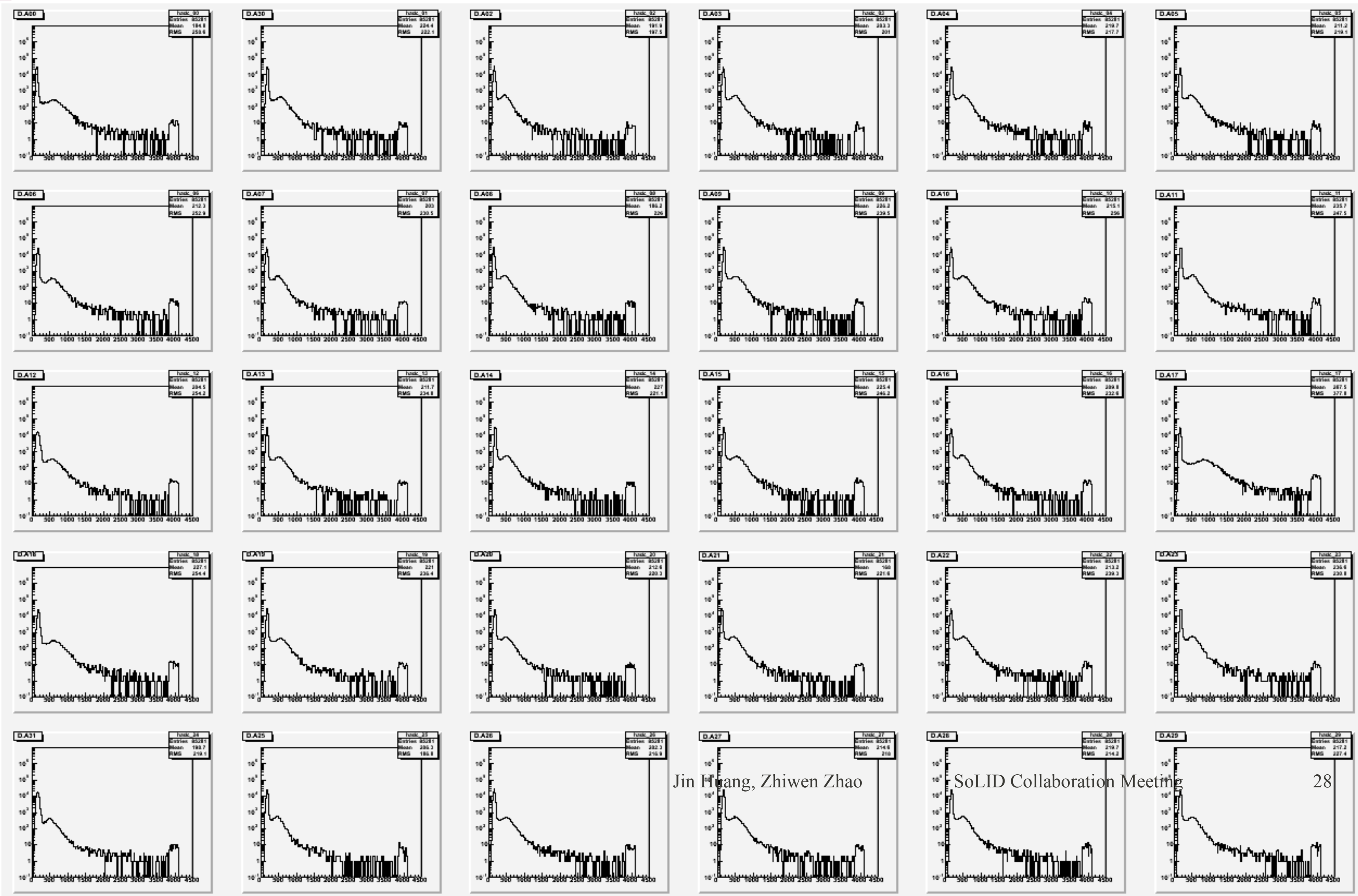
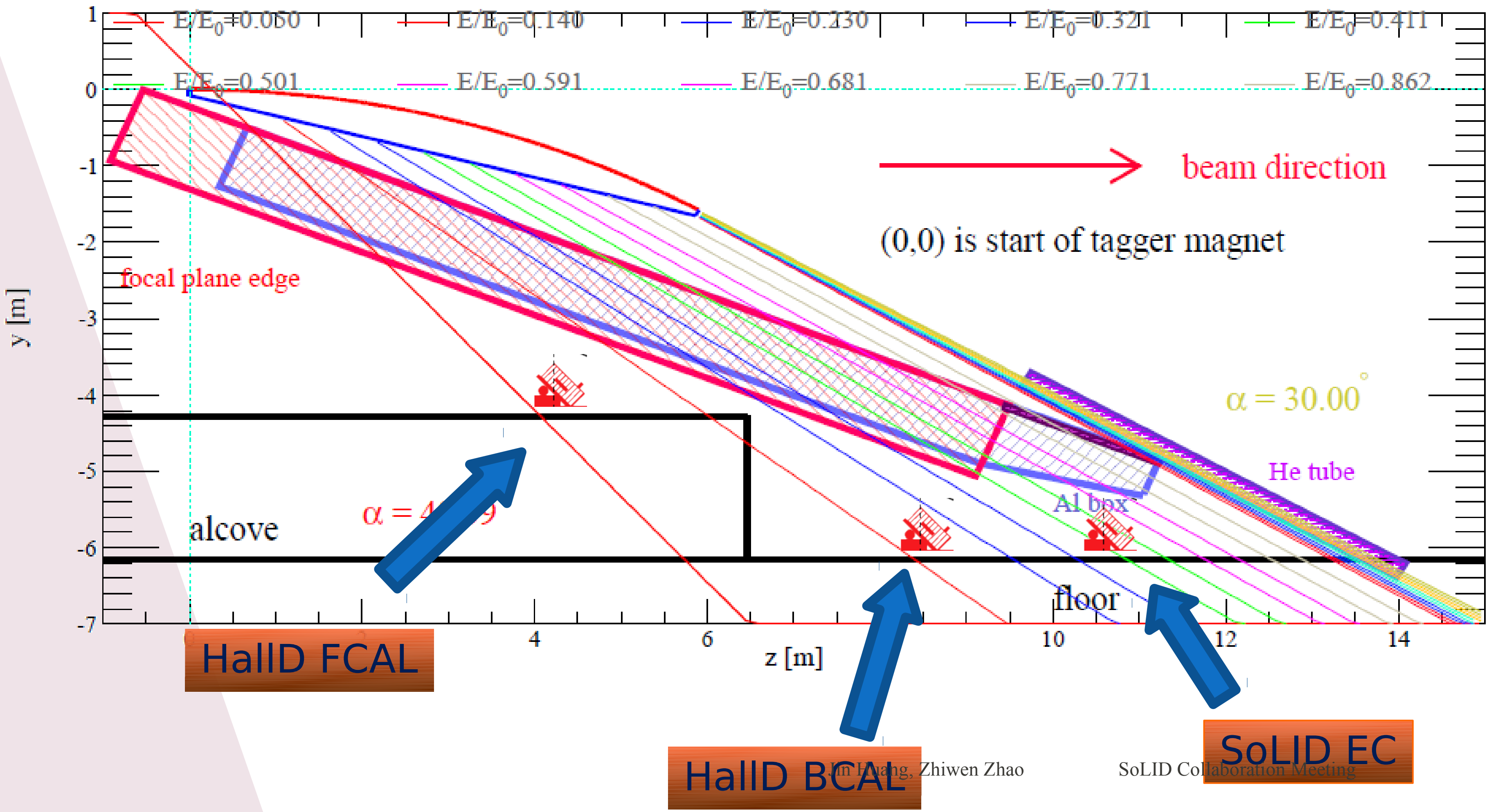
Cosmic ray gain match
after matching, most signals are within factor of 0.7-1.5

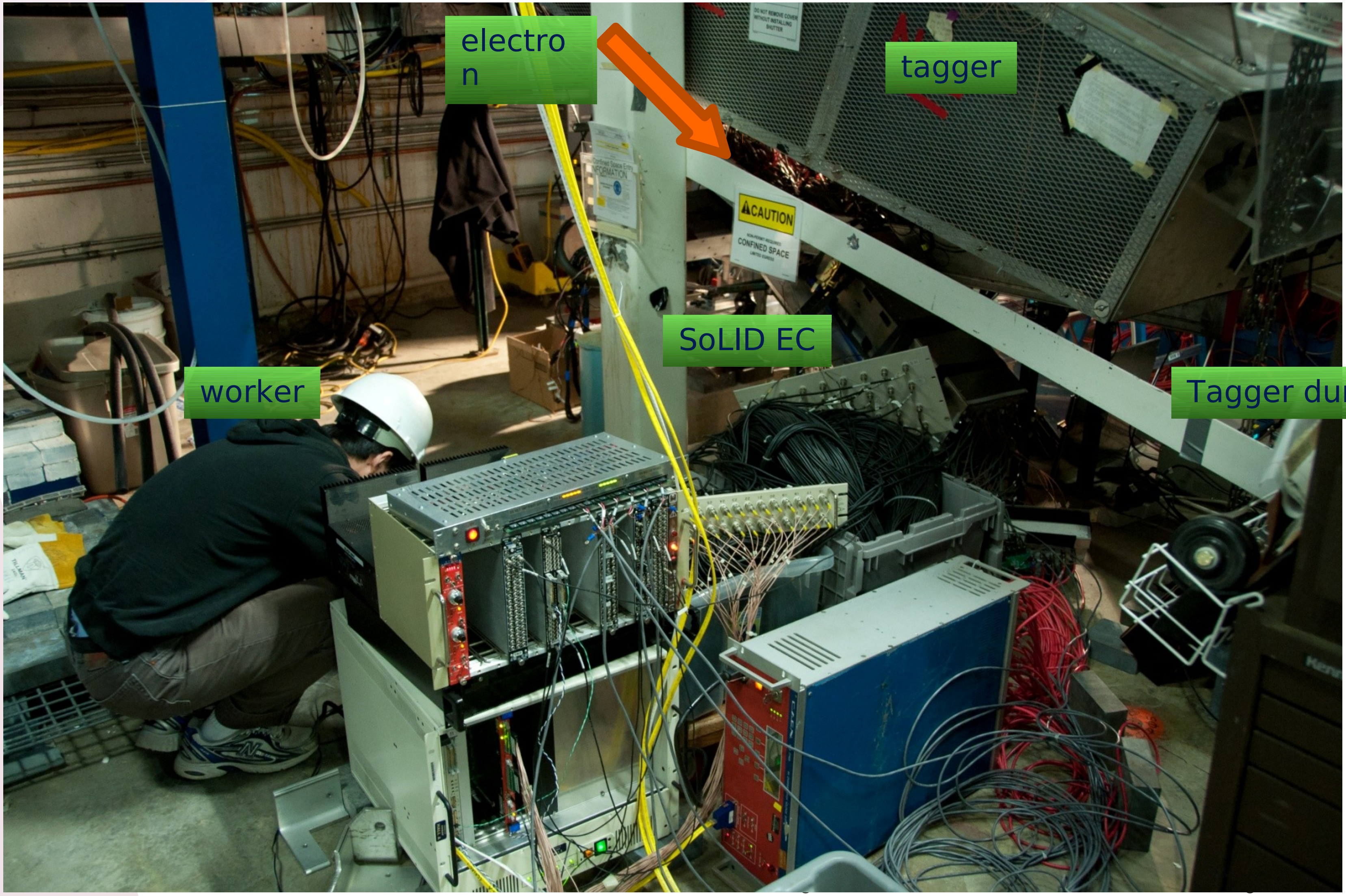


4/2012 Test under CLAS photon tagger

Electron with known energy and impact angle
Possibility to use Hall B DAQ resources



In HallB, under Photon Tagger



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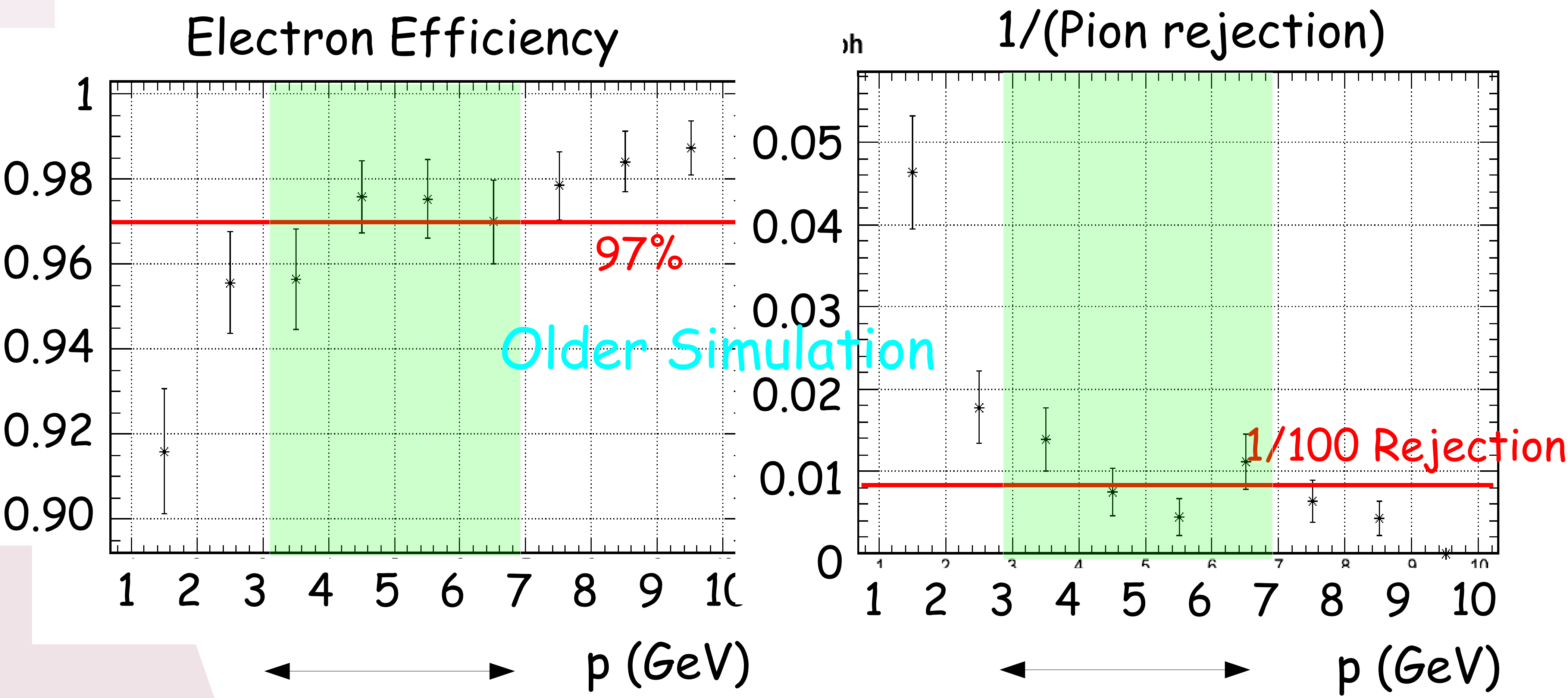
Backup

Clear/Extension fiber cost

- One-one connection:
  - SIDIS forward WLS: 2x1000 modules x 100 fibers/module x 1m x \$1.5/m = \$800k
  - SIDIS large angle clear: 2x 500 modules x 100 fibers/module x 4m x \$2/m = \$300k
  - PVDIS: +1000 modules in forward → \$800k+\$800k (changing fibers) or \$800k+\$400k+\$300k (keep clear fibers)
  - Total: \$1.6M + 200,000(?) connectors
- Winstone cone:
  - # fibers reduce by factor 2.2 (or more) → \$0.73M (or less) +10,000 Winstone cones.

Design Consideration 1: Pb/scintillator ratio

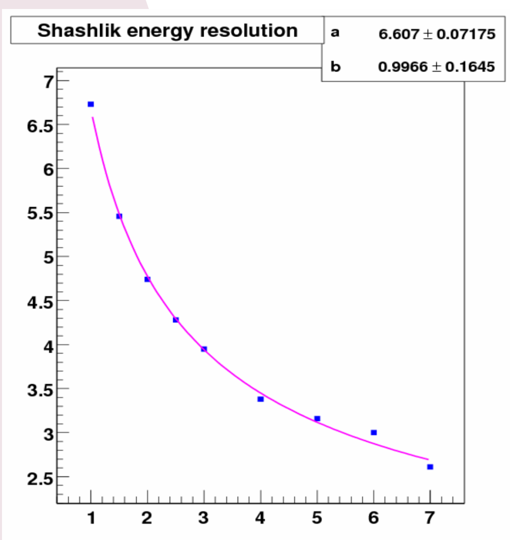
- Minimize scintillator ratio while reaching 100:1 pion rejection → 0.6mm Pb/1.5 mm Scint. (BASF143E) per layer.

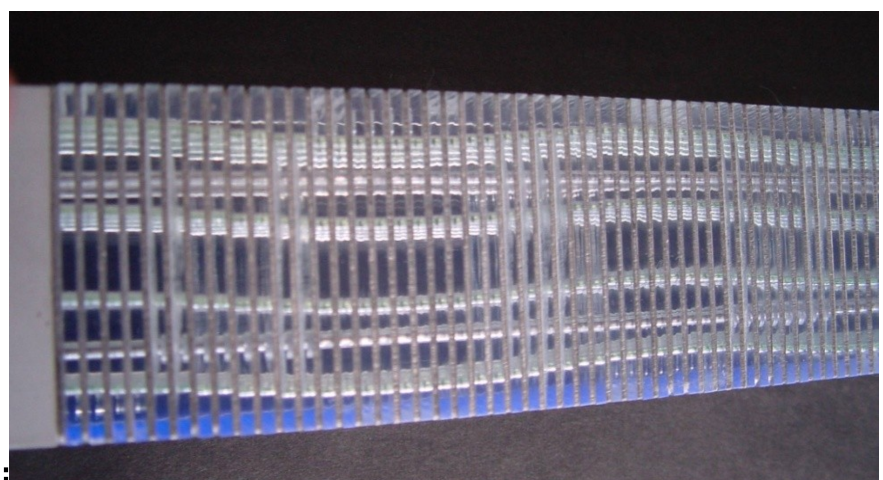


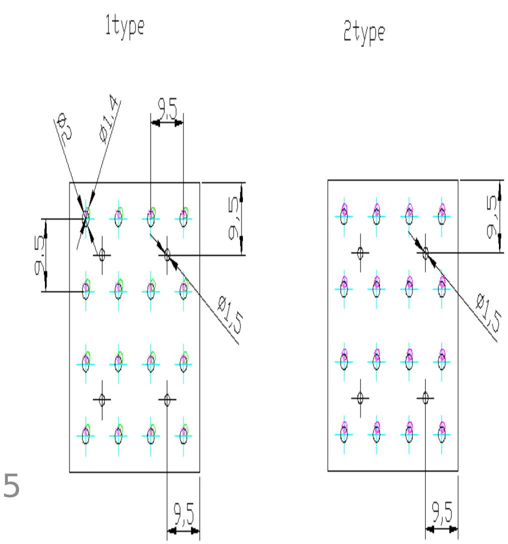
SIDIS large angle: 3~7 GeV

ECAL *Shashlik*

- Dimensions 38.2x38.2 mm2
- Radiation length 17.5mm
- Moliere radius 36mm
- Radiation thickness 22.5 X0
- Scintillator thickness 1.5mm
- Lead thickness 0.8mm
- Radiation hardness 500 krad
- Energy resolution 6.5%/√E 1%





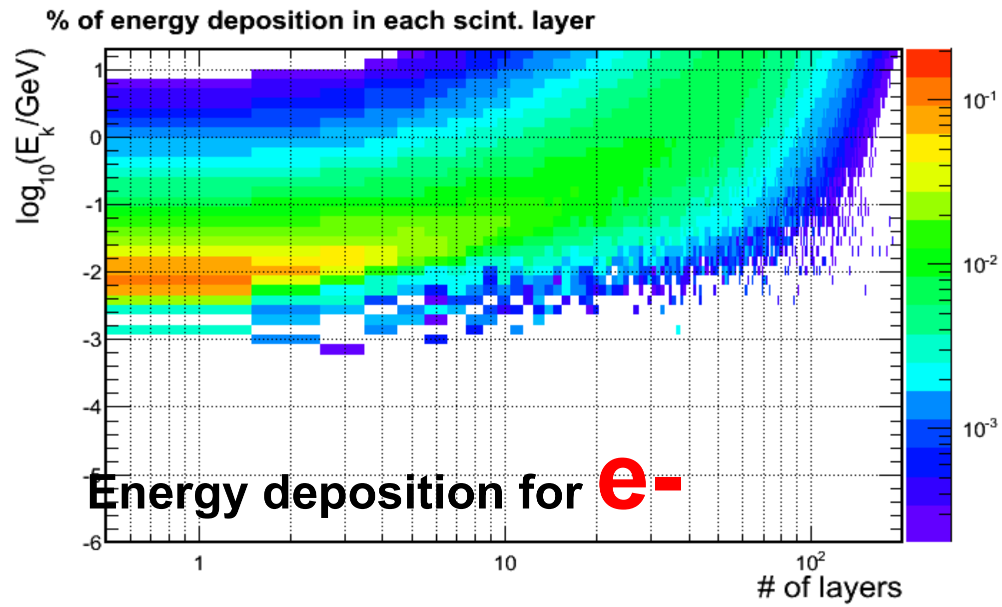


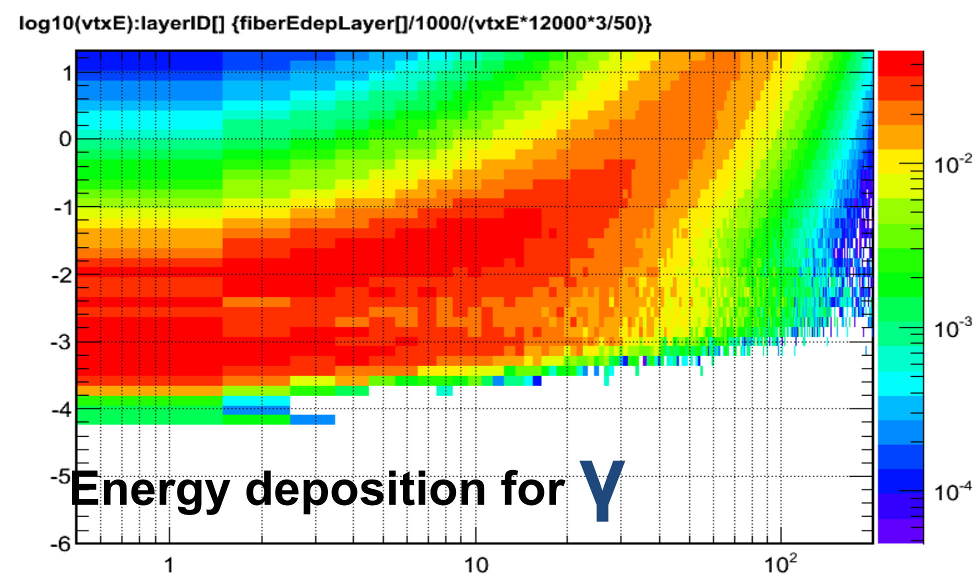
Radiation on preshower

- Reaching radiation limit (30% reduction in light output) for current approved experiments (about 300 PAC days)
- A few possible solutions
  - Swapping modules between large R-inner R
    - Radiation dose varies by factor of ~10
  - Keep searching for high radiation-resistant fiber/scintillator
  - Replacing the preshower part of calorimeter
  - Redesign preshower with PbWO4/LYSO crystal with wavelength shifting fiber read out

Simulate the radiation level

- Overall dose close the calorimeter limit
  ->
  inspect radiation inside calo.
- The radiation dose for scintillators is 100krad~2Mrad (material dependent)
- Use Geant3/Wiser tools to simulate radiation background
- Use Geant4 simulate energy deposition in each layer for various background





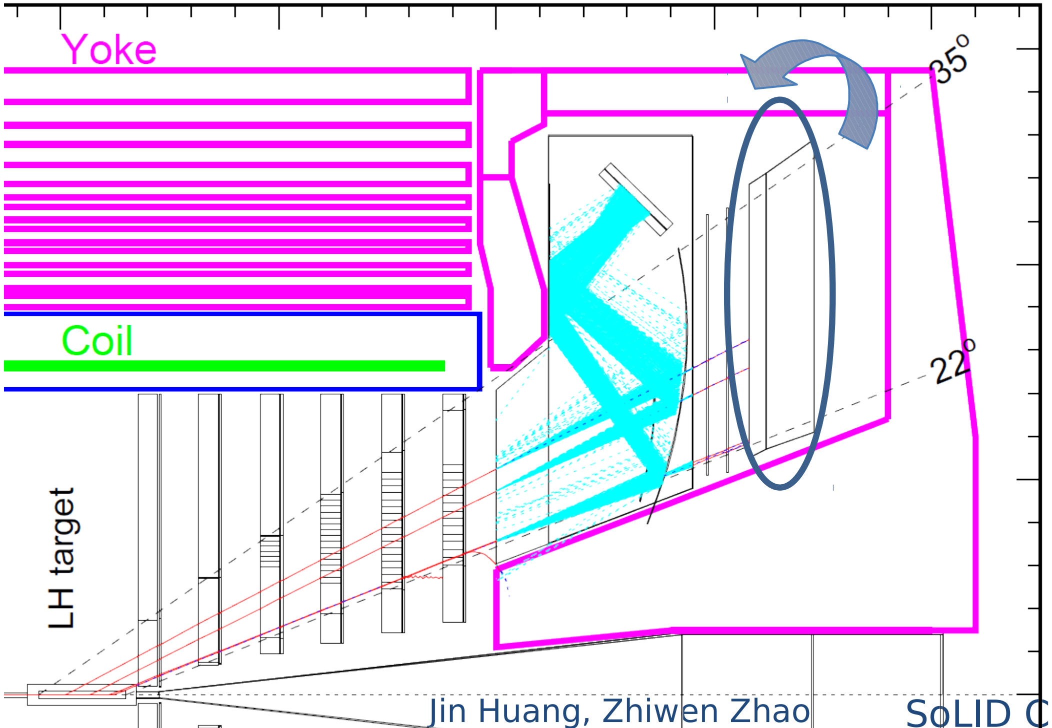
Positioning calorimeter for PVDIS

PVDIS calorimeter have largest polar angle

- 22 – 35 degree
- Not full azimuthal coverage, possible to rotate

Two main factor relates resolution with larger indenting angle

1. Variation in shower position along track translates into transvesre position
2. Spread charge into more module -> less discretization effect



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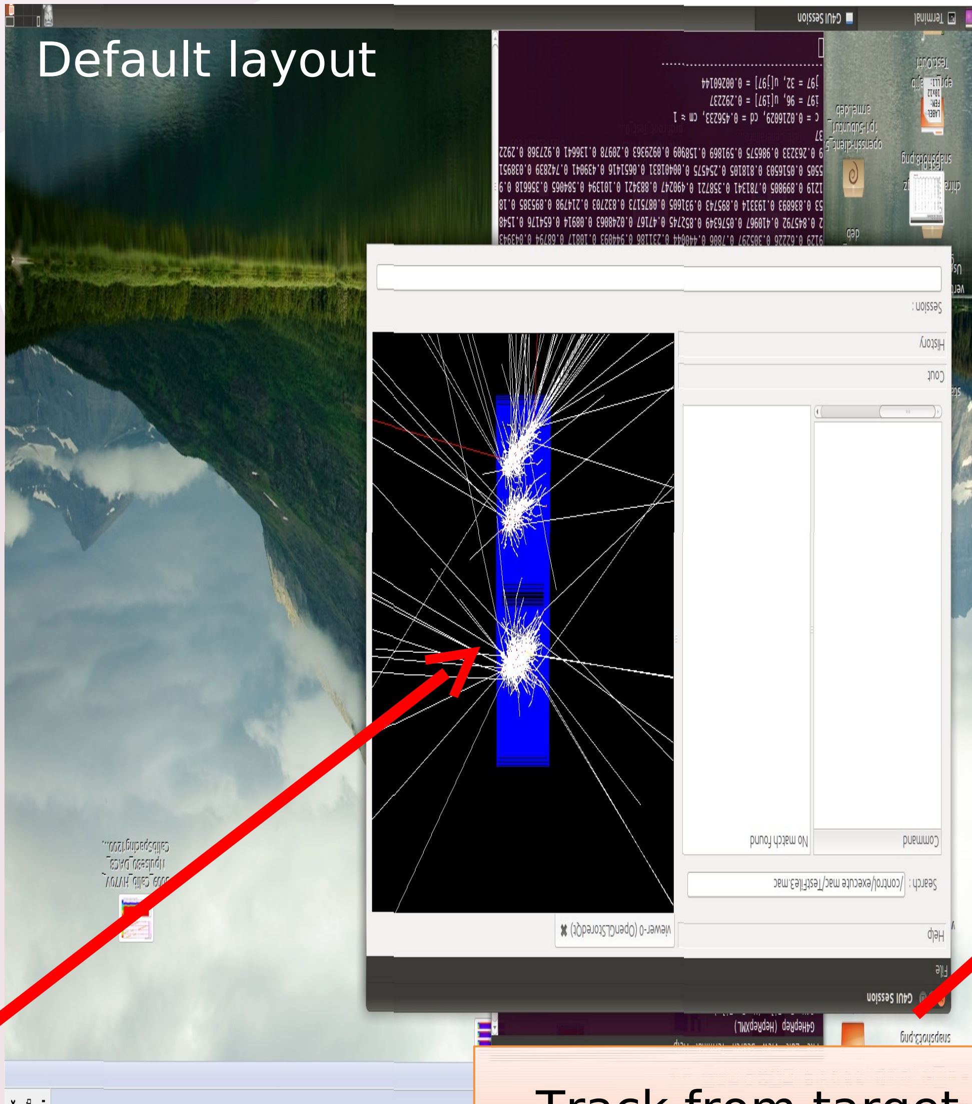
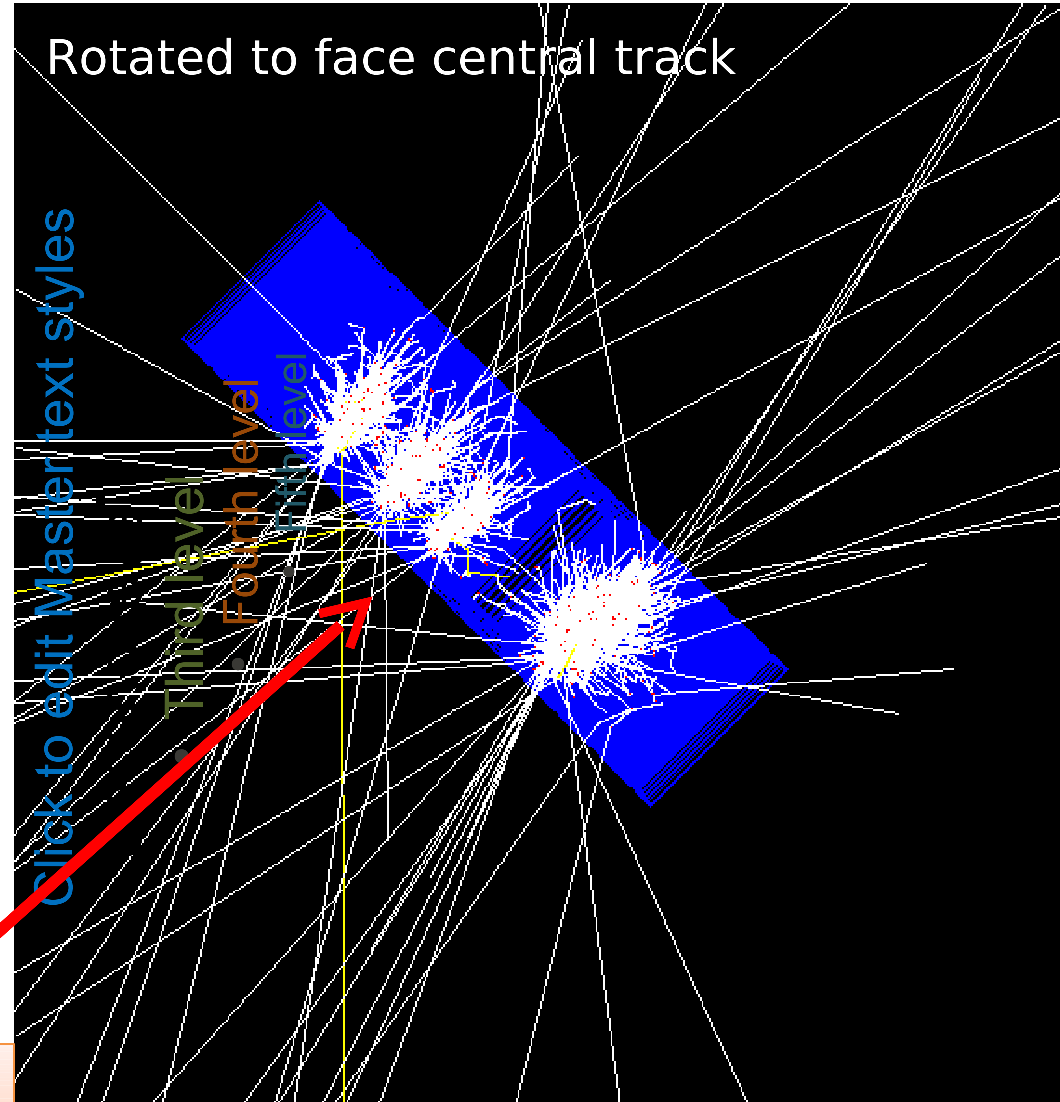
Tested in specialized Geant4 simulation with SIMC inputs of realistic tracks





Track from target

Corrections

Shower location at predefined plane of nominal max shower =

Center of gravity

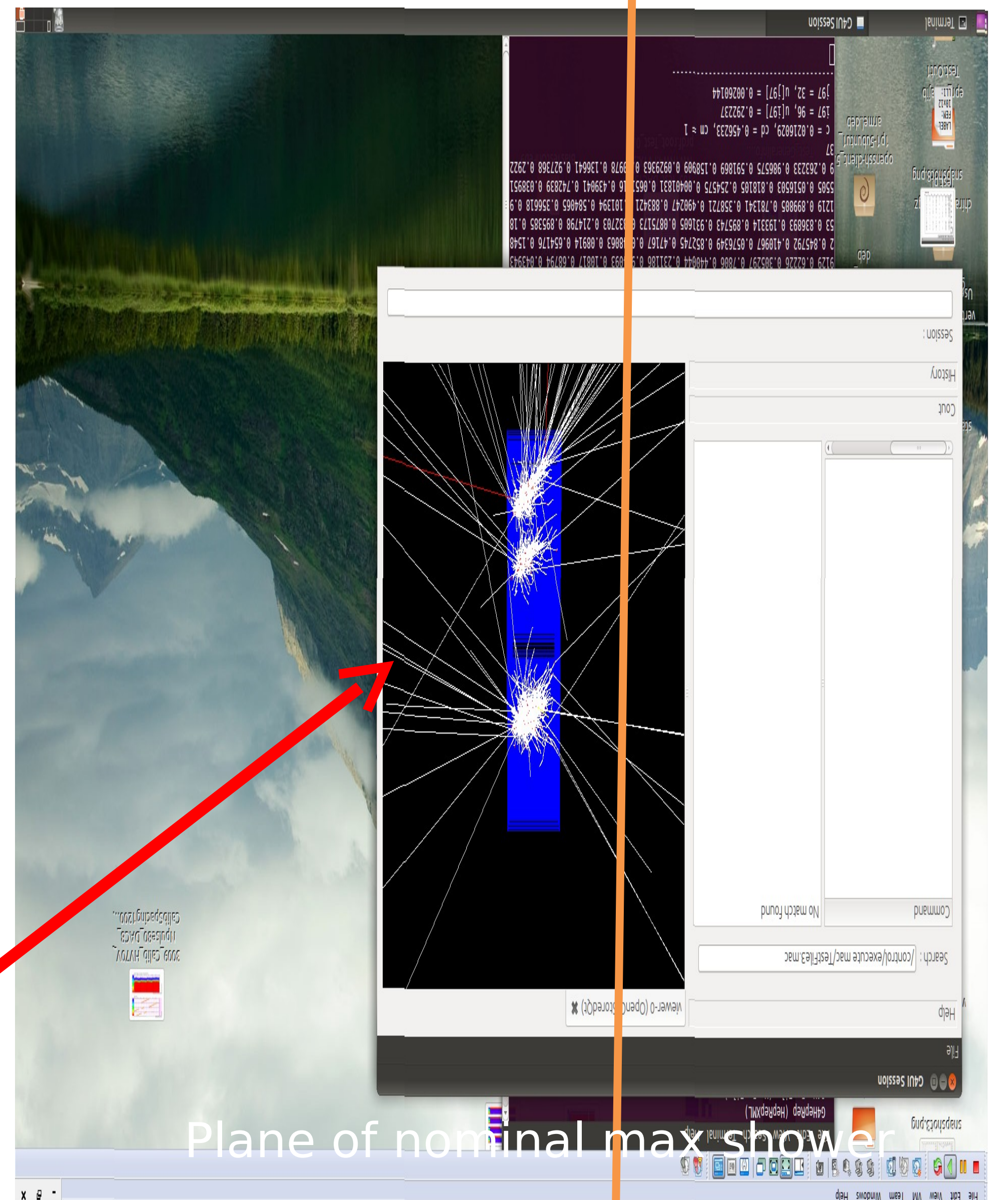
- Average position with energy weighting

Energy/slope correction

- Shifting of shower center with energy, fitted from simulation
- Information available from calorimeter only

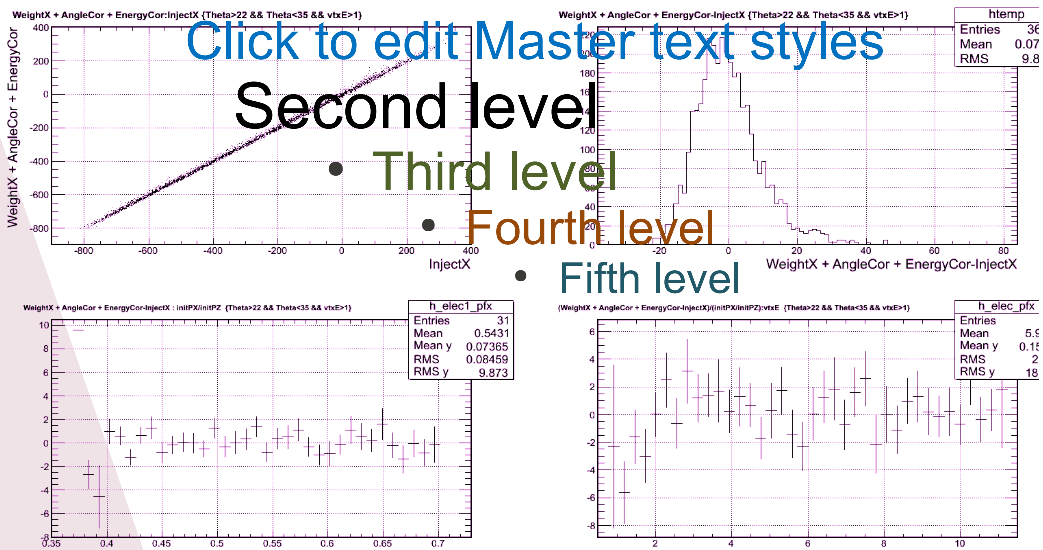
Discretization correction

- Position readout discredited to center of each module
- Can be corrected to some extent (see later slides)



Effect 1: Probing shower longitudinal size effect w/ very fine segmentation

Nominal layout



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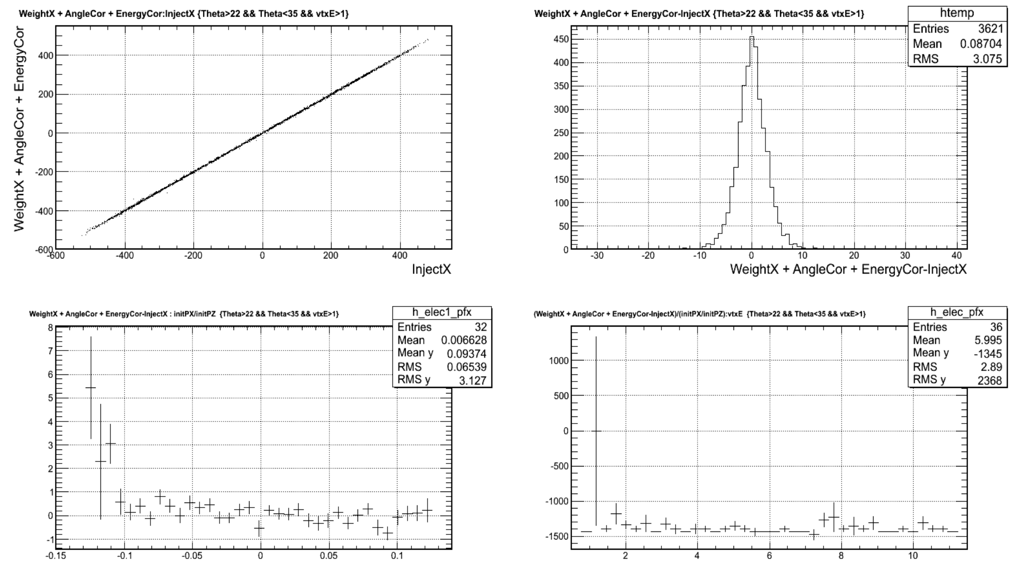
Second level

- Third level
  - Fourth level
    - Fifth level

Residual for corrected shower position (mm)

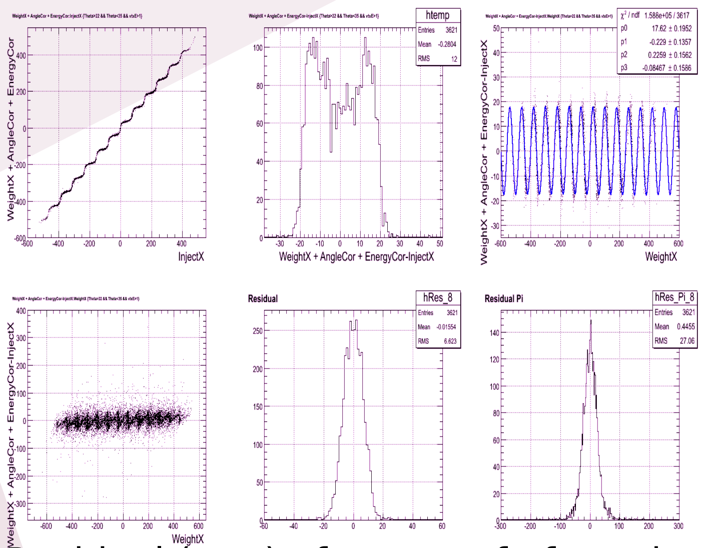
Facing track



Residual for corrected shower position (mm)

- At nominal of 28 degree, variation of shower translate to 1 cm of uncertainty from the detector intrinsic best ~0.3 cm

Effect 2: Probing shower longitudinal size effect w/ very fine segmentation

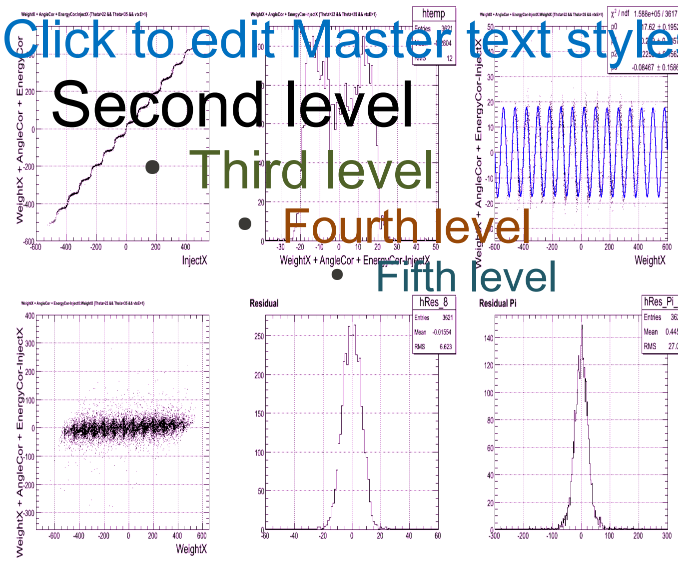


Residual (mm) of center of of gravity
for 8x8 cm module = 12 mm

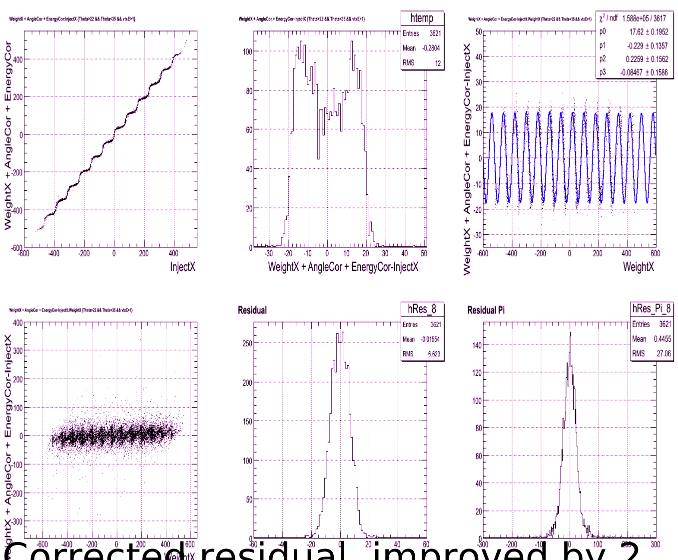
Click to edit Master text styles

Second level

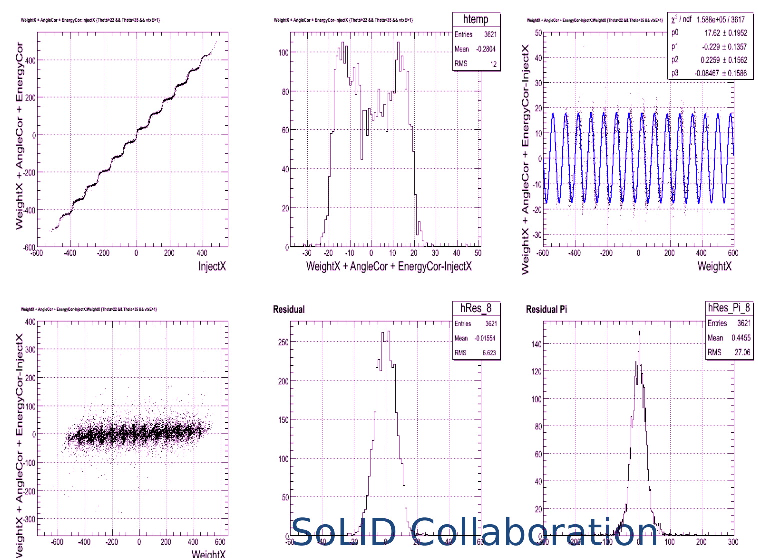
- Third level
  - Fourth level
    - Fifth level



Reconstructed location
VS track projection



Corrected residual, improved by 2



Fit and correct discretization effect
(Based on calorimeter response only)

Position resolution VS lateral size

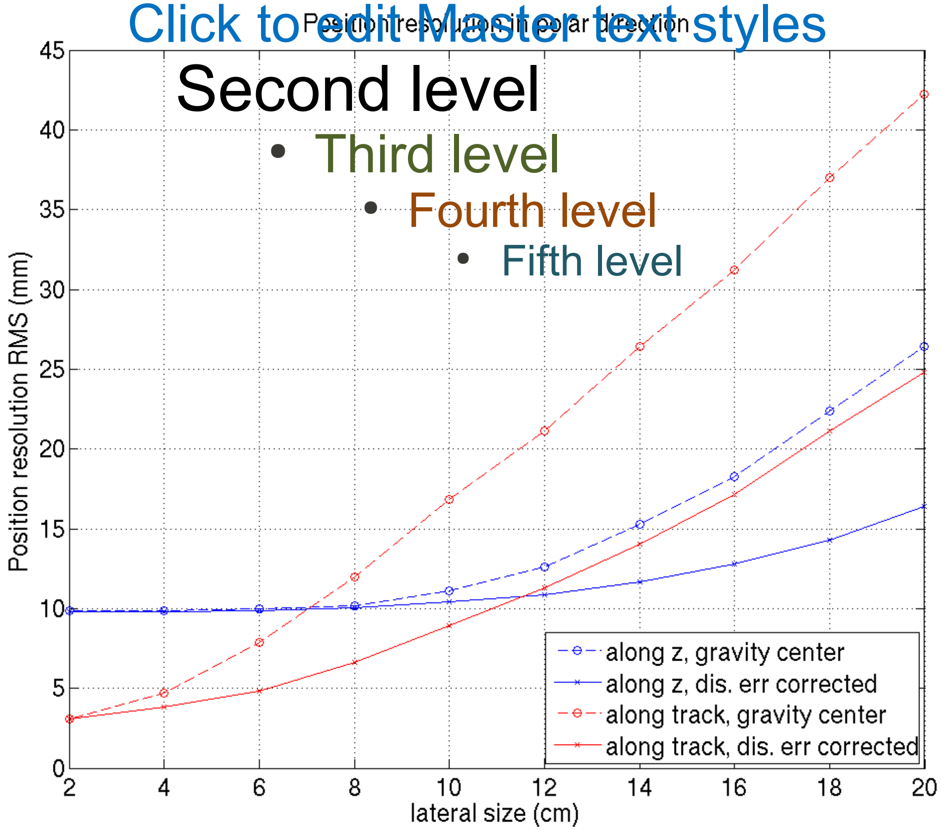
- Blue: calorimeter modules along z axis
- Red: calorimeter modules along central track

Electron

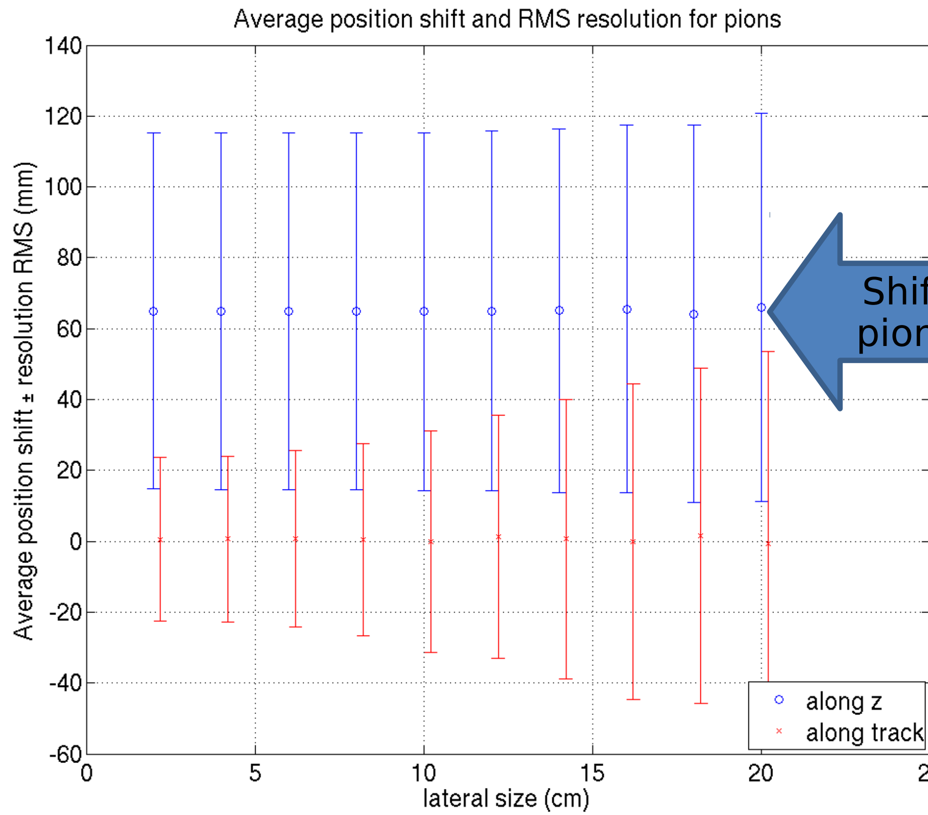
Click to edit Master text styles

Second level

- Third level
  - Fourth level
    - Fifth level



Hadron



Shifted pion ΔR

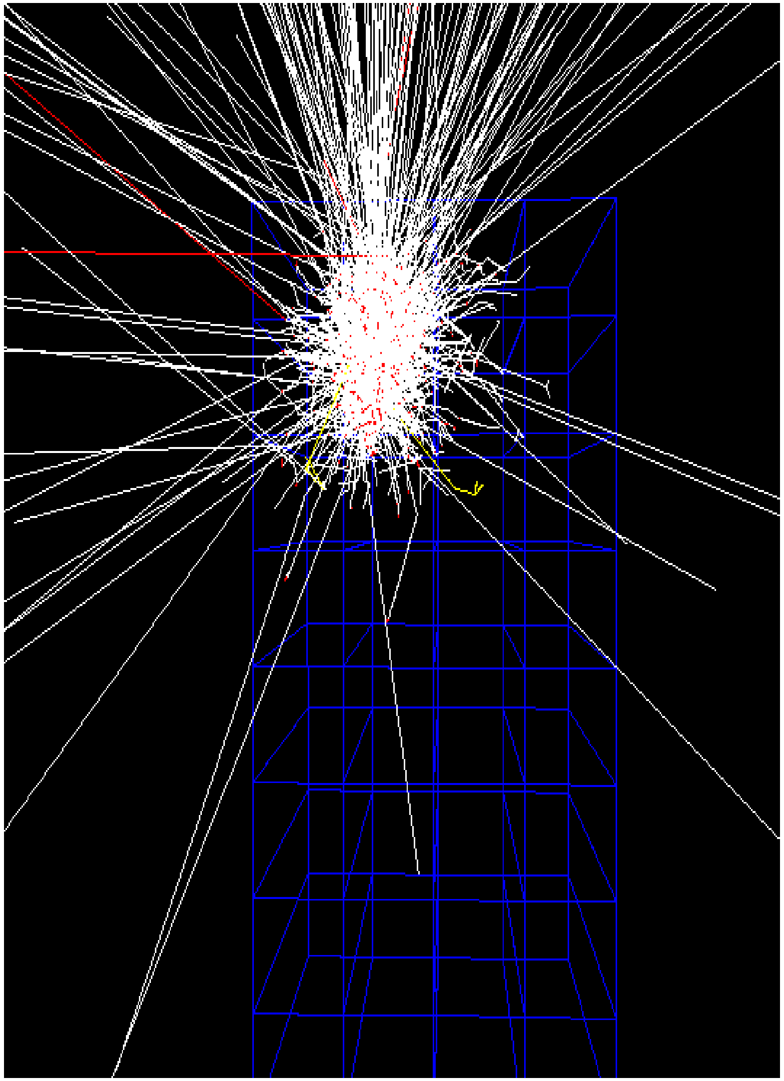
Comparison between two choise

- No show stopper in either case

Nominal layout (along z)	**Rotated to face track**
Simple to support Less discretization error	Better resolution after correction Better pion reconstruction Smaller size in R Personal preferable

Simulate edge effect

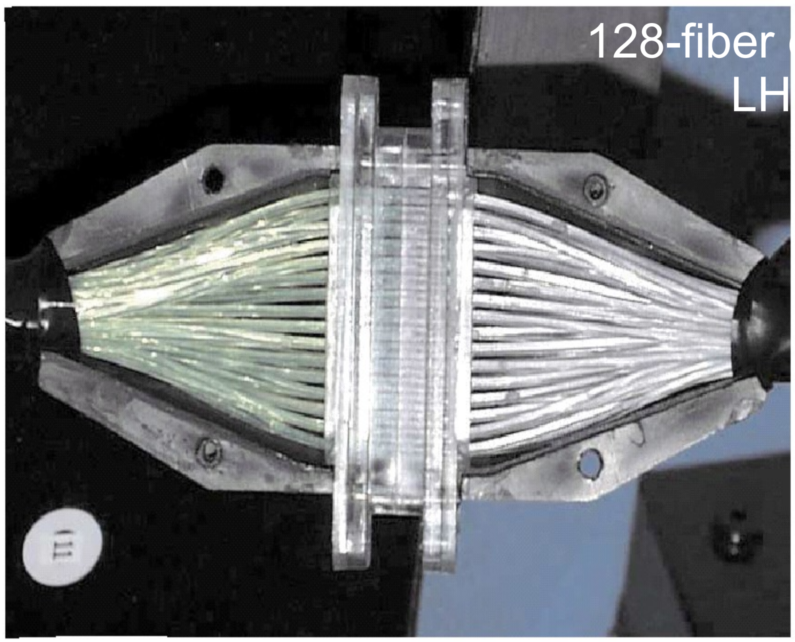
- Calorimeter module laid long z direction
- Particle impacts to calorimeter with an angle to normal direction
- Edge event can not be fully contained in calorimeter
- How wide is this edge region?



Calorimeter Design: Connectors

Option 1:

One to one WLS/clear fiber connector,
used in previous experiments (LHCb, Minos)



Calorimeter Design: Connectors

- **Option 2:**

Thermal fusion: splice the WLS and clear fiber.

Giorgio Apollinari et al NIM in Phys. Research. A311 (1992) 5211-528

- **Option 3:**

Glue the WLS fibers to a lucite disk coupled to a lucite Rod with optical grease or Si gel "cookie".

Would reduce the cost significantly

ed more R&D to decide what is the best option.