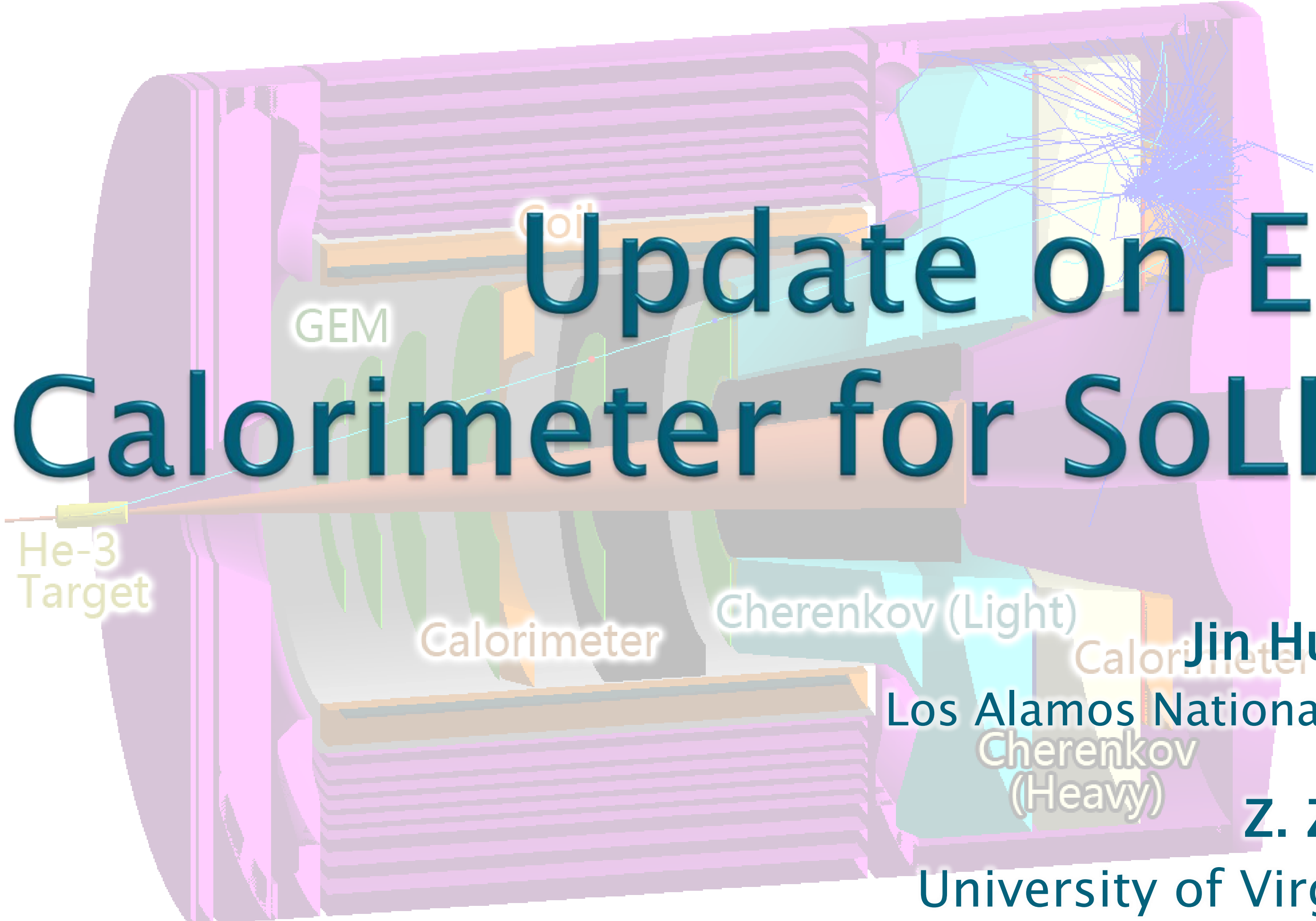
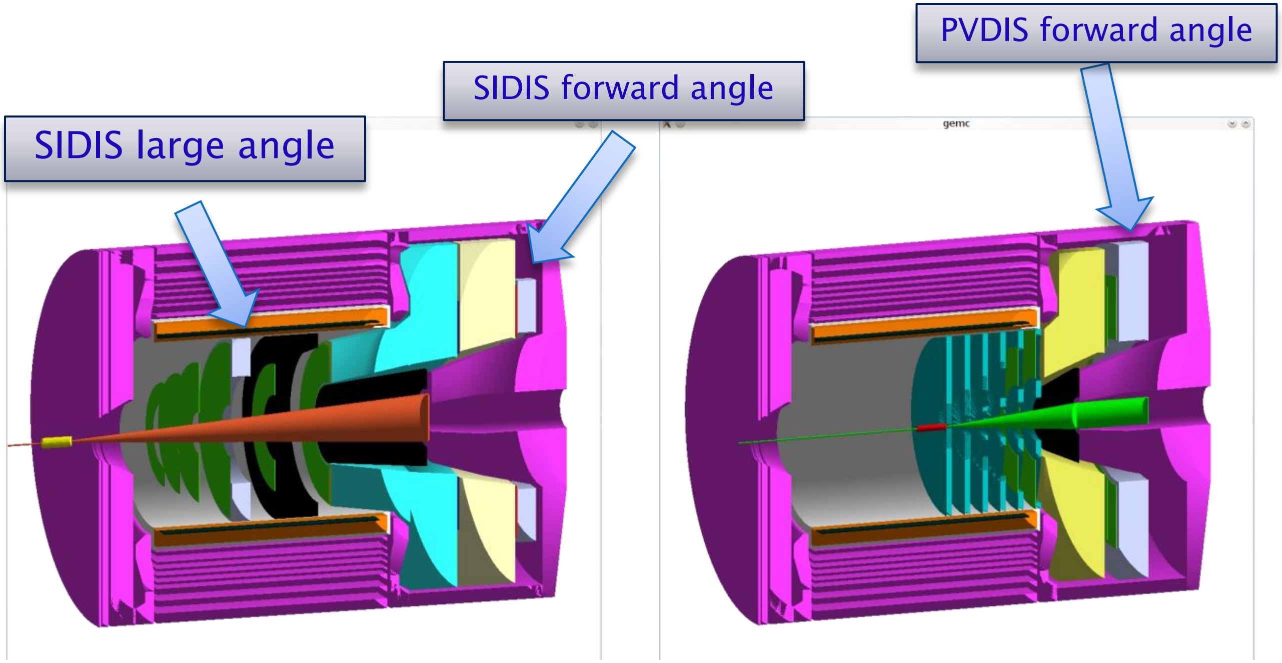
Update on EM Calorimeter for SoLID



Jin Huang
Los Alamos National Lab

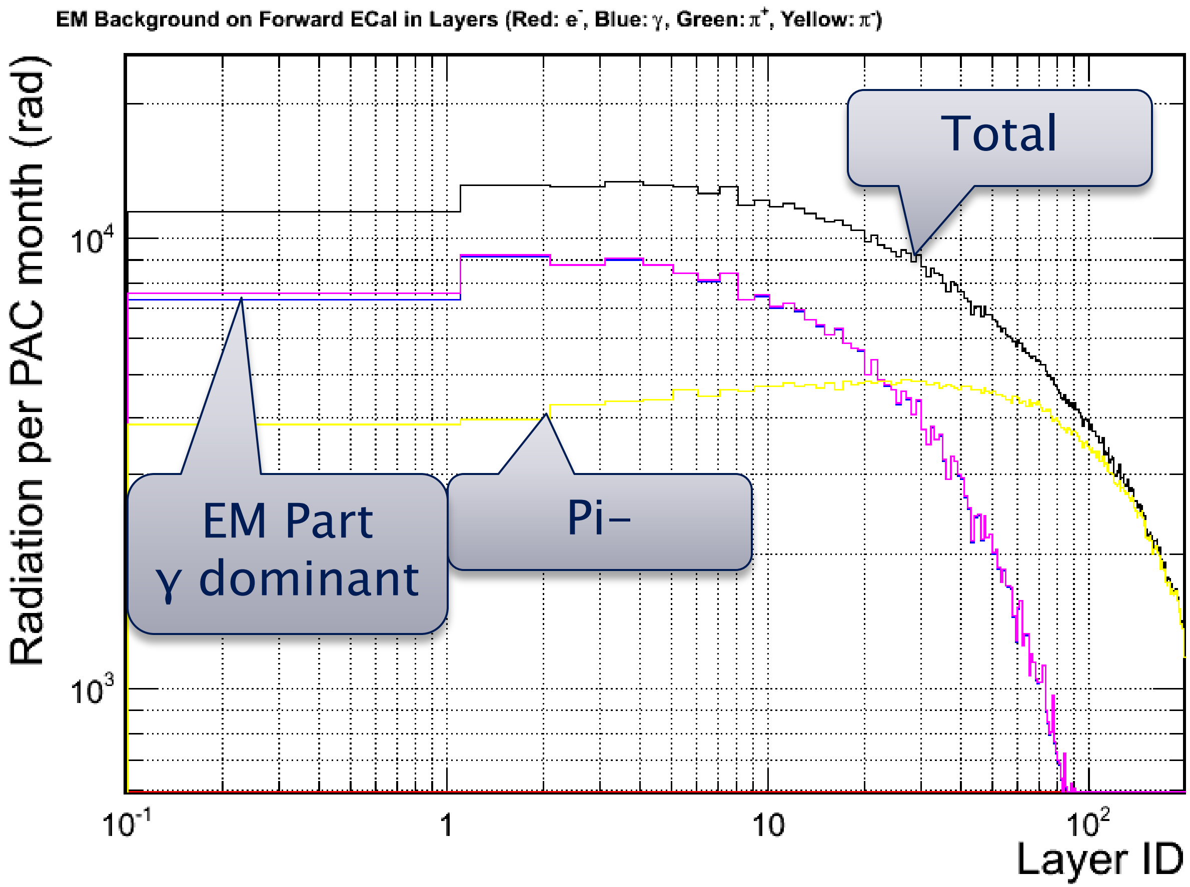
Z. Zhao
University of Virginia

SoLID Calorimeter Overview



- Electron-hadron separation
  - ~100:1 pion rejection in electron sample
  - Energy resolution: $\sigma(E)/E \sim 5\%/\sqrt{E}$
- Provide shower Position
  - $\sigma \sim 1$ cm, for tracking initial seed / suppress background
- Time response
  - $\sigma <\sim$ few hundreds ps
  - provide trigger/identify beam bunch (TOF PID)

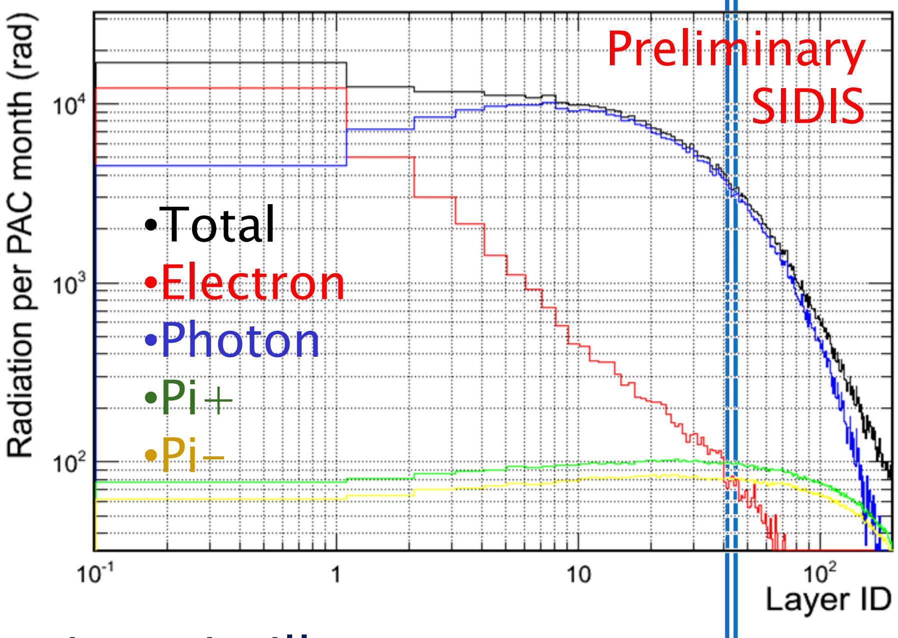
Radiation dose update for PVDIS



Updated dose with baffle made of Pb
Similar level to SIDIS now

Radiation on fiber path

Preshower



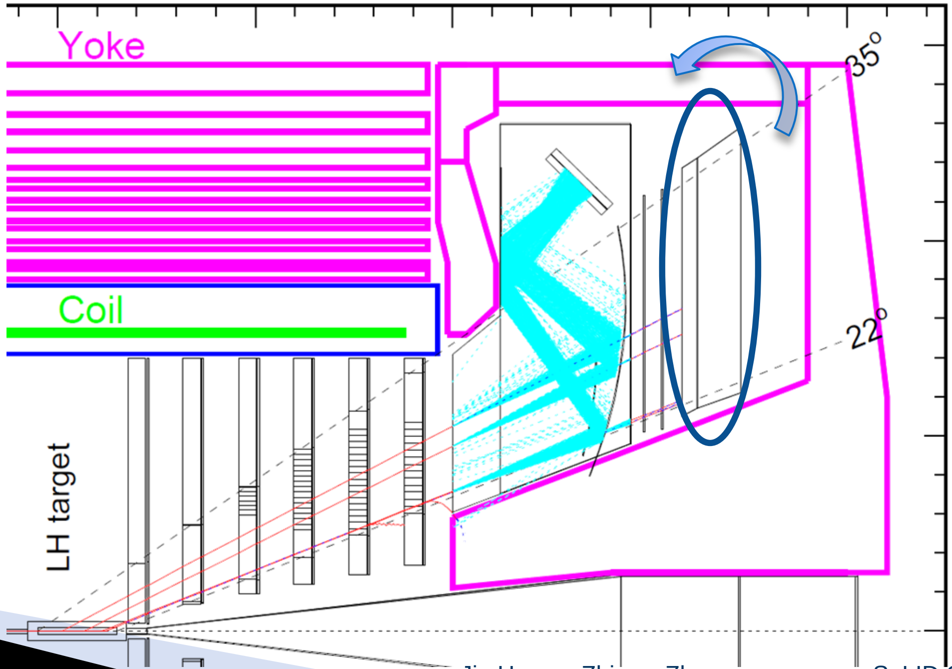
- Two dominant effects:
- Radiation effect
  - Worse case: before calorimeter ~10^4 rad similar to 1st layer of scintillator, Y11 take to 10^5
- False signal in fiber
  - Wavelength shifting fiber change scintillator photo, not effective scintillator
  - Main signal are constant background from low energy electron/photon, -> shifting in pedestal
  - Should try beam tests
- Can run fiber from backside of calorimeter and avoid direct view of target

Radiation on preshower

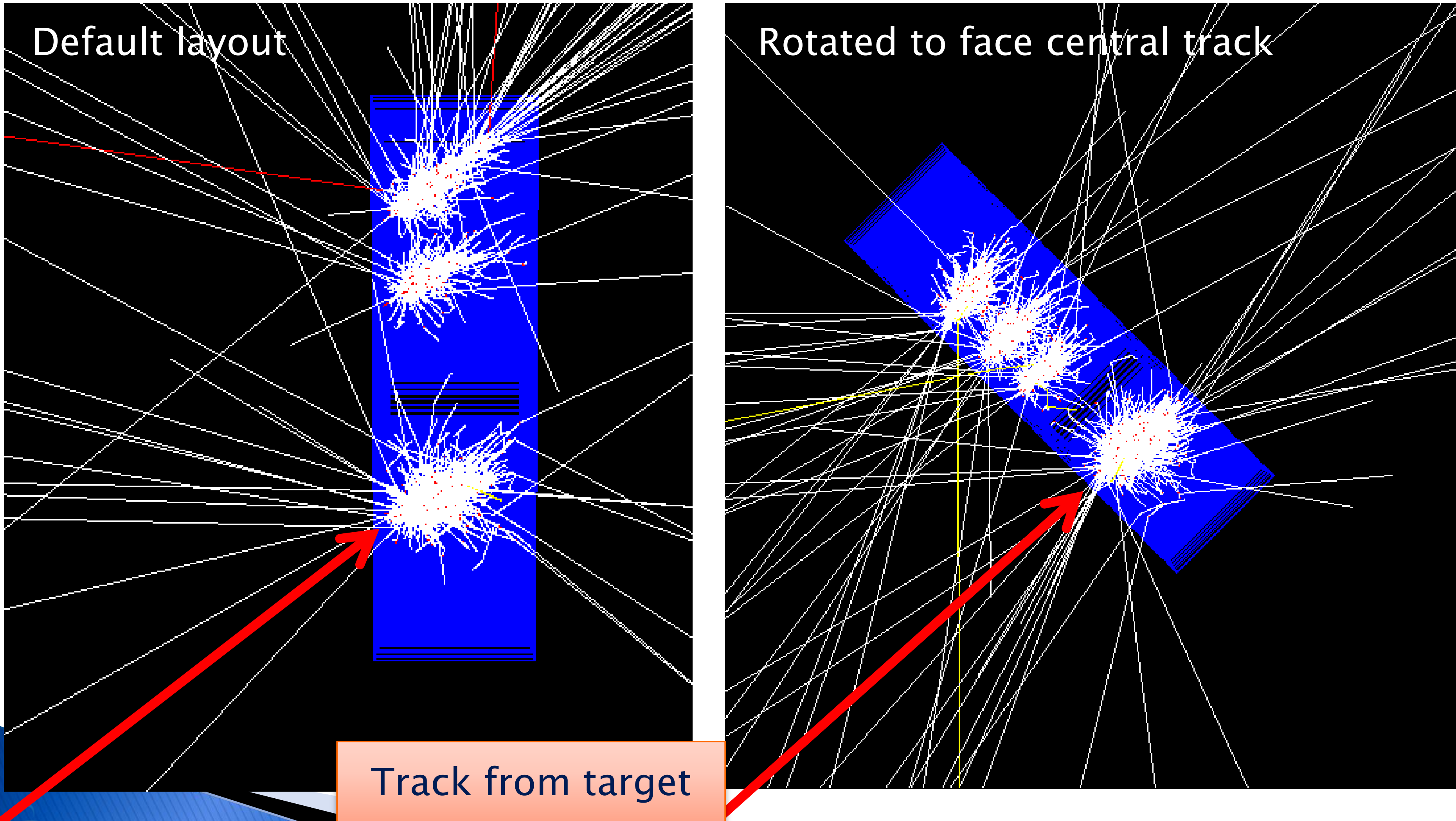
- Reaching radiation limit (30% reduction in light output) for current approved experiments
- A few possible solutions
  - Swapping modules between large R-inner R
    - Radiation dose varies by factor of ~10
  - Keep searching for high radiation-resistant fiber/scintillator
  - Replacing the preshower part of calorimeter
  - Redesign preshower with $PbWO_4$ crystal with wavelength shifting fiber read out

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



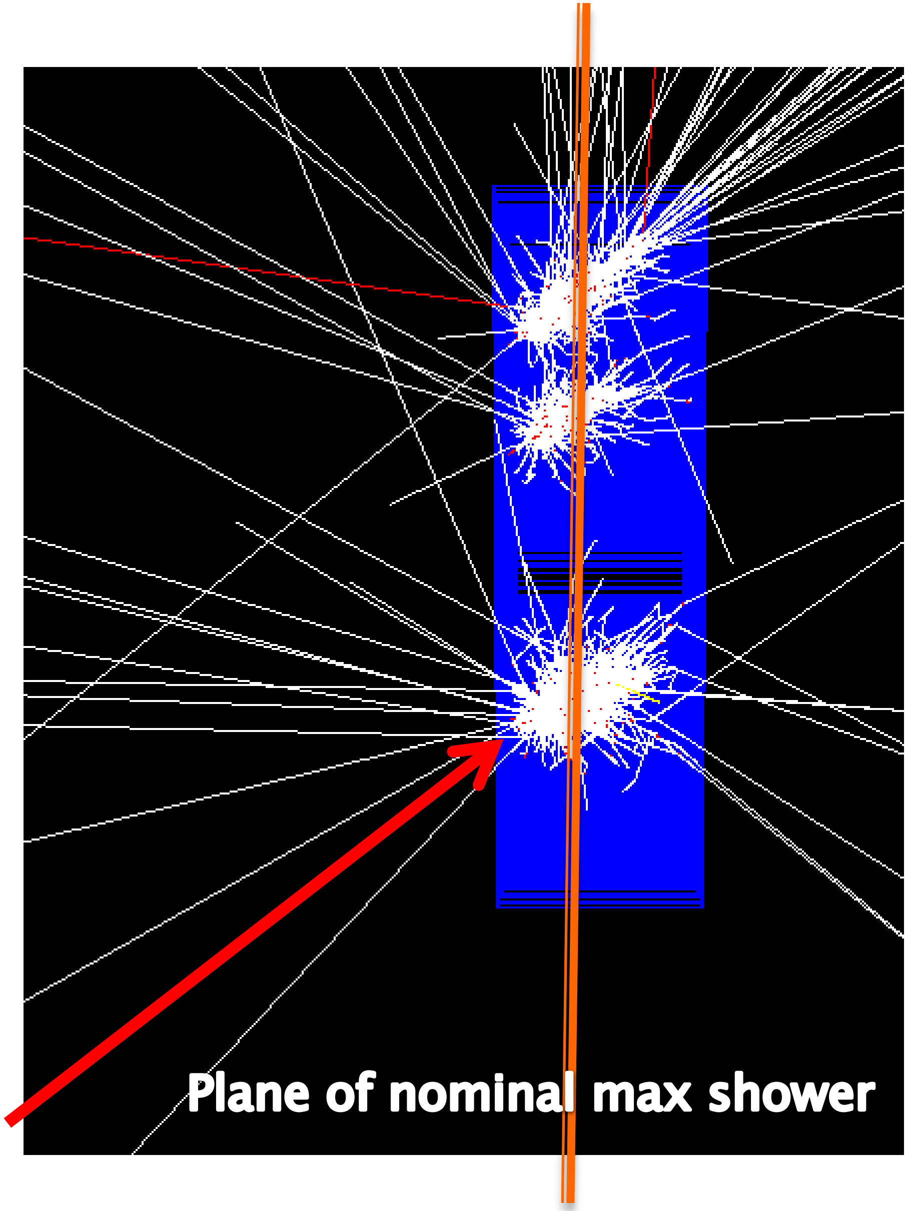
Tested in specialized Geant4 simulation with SIMC inputs of realistic tracks



Corrections

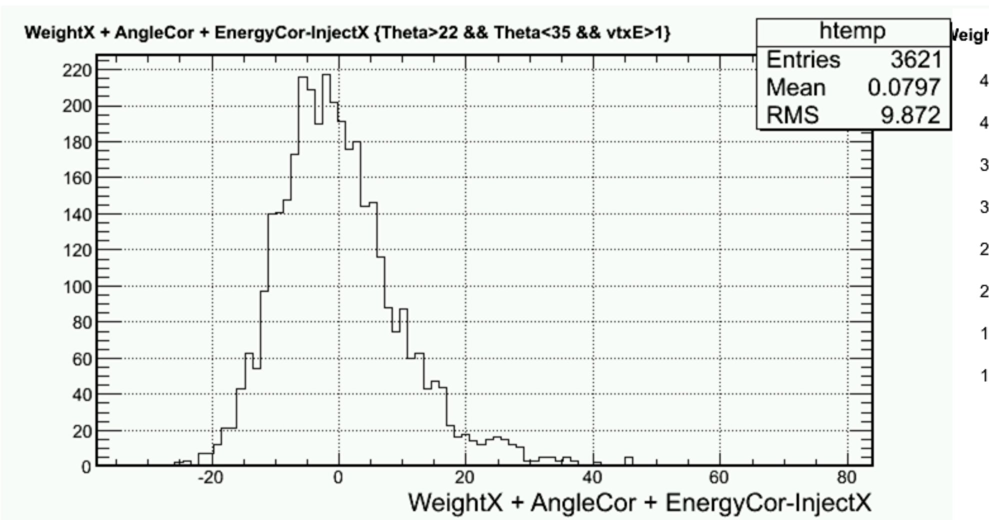
Shower location at predefined plane of nominal max shower =

- 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)



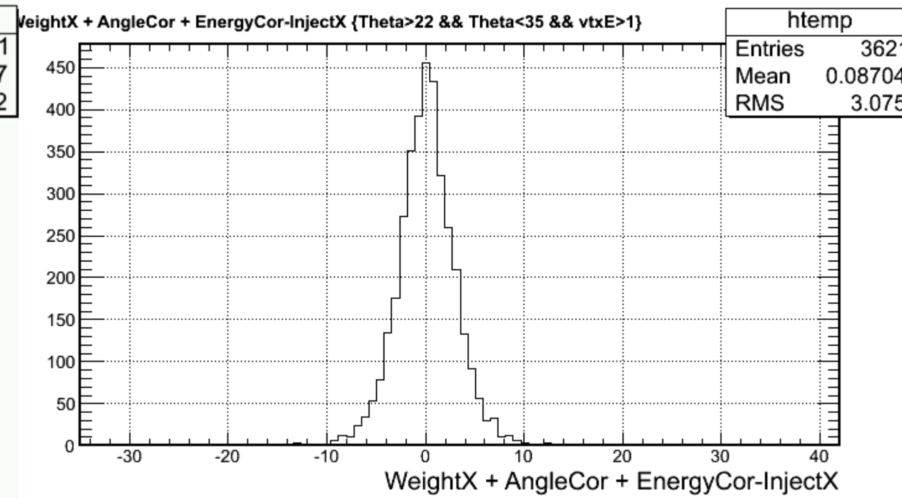
Effect 1: Probing shower longitudinal size effect w/ very fine segmentation

Nominal layout



Residual for corrected shower position (mm)

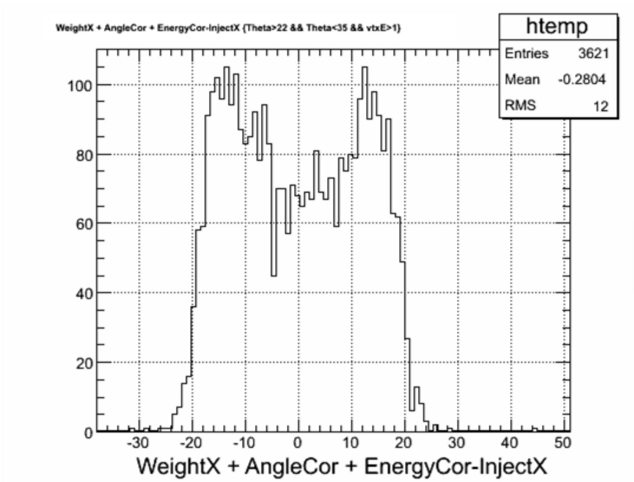
Facing track



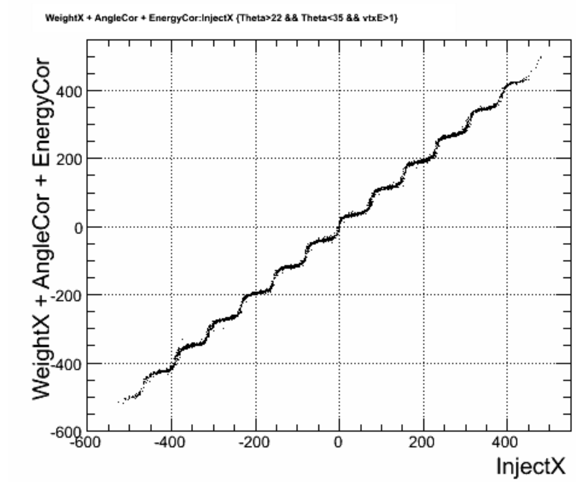
Residual for corrected shower position (mm)

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

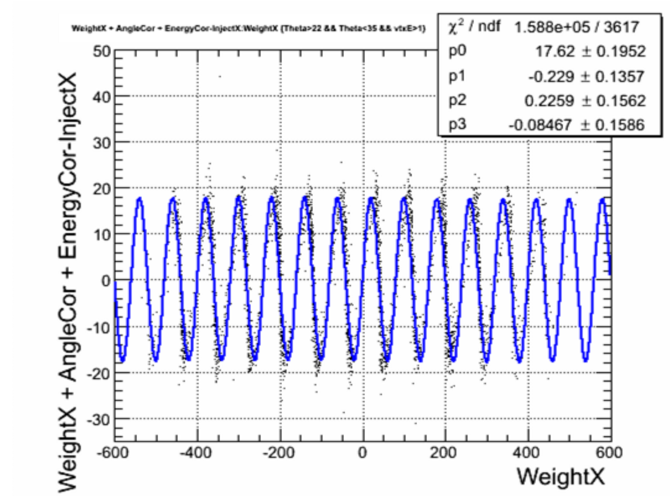
Effect 2: Probing shower longitudinal size effect w/ very fine segmentation



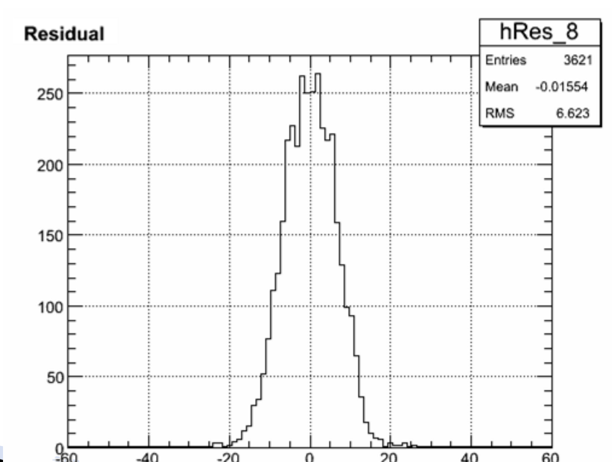
Residual (mm) of center of of gravity for 8x8 cm module = 12 mm



Reconstructed location VS track projection



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



Corrected residual, improved by 2

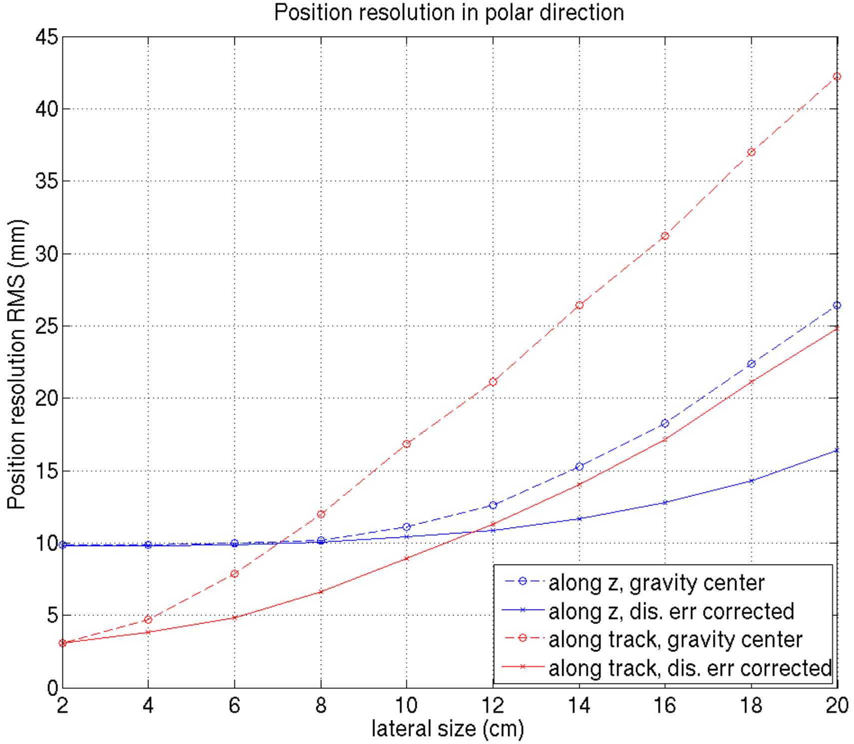
Los Alamos NATIONAL LABORATORY EST.1943

Jefferson Lab

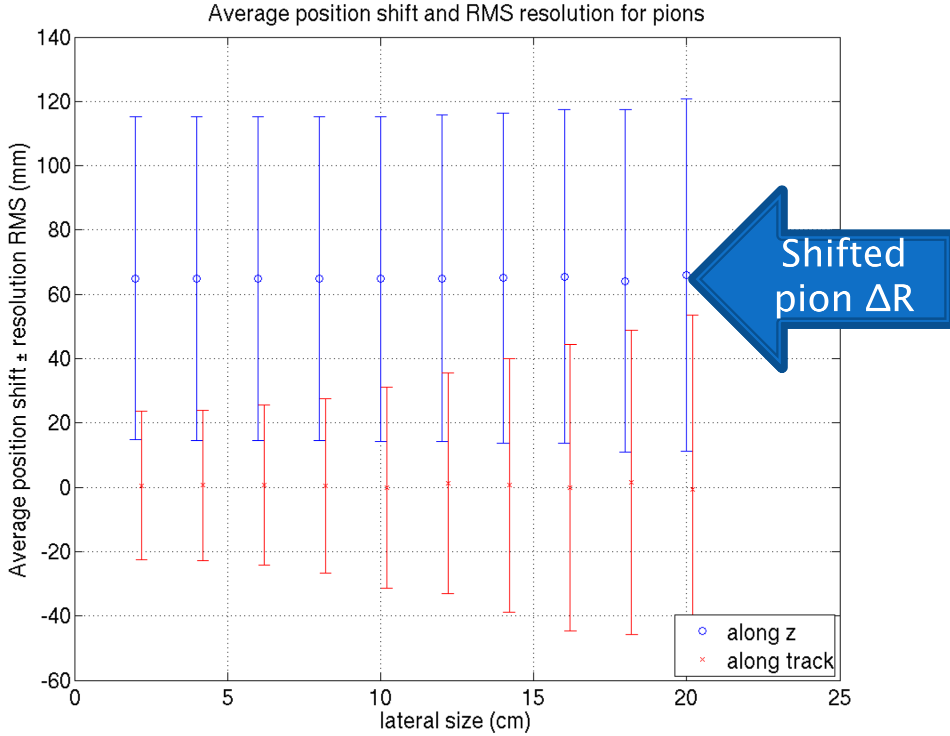
Position resolution VS lateral size

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

Electron



Hadron



Comparison between two choise

- No show stopper in either case

Nominal layout (along z)

- Simple to support
- Less discretization error

Rotated to face track

- Better resolution after correction
- Better pion reconstruction
- Smaller size in R
- Personal preferable

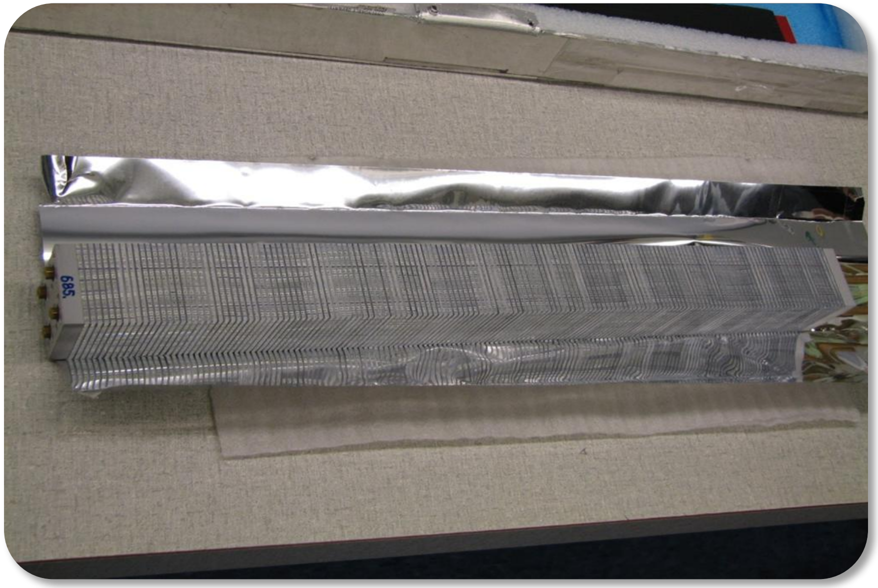
Discussions

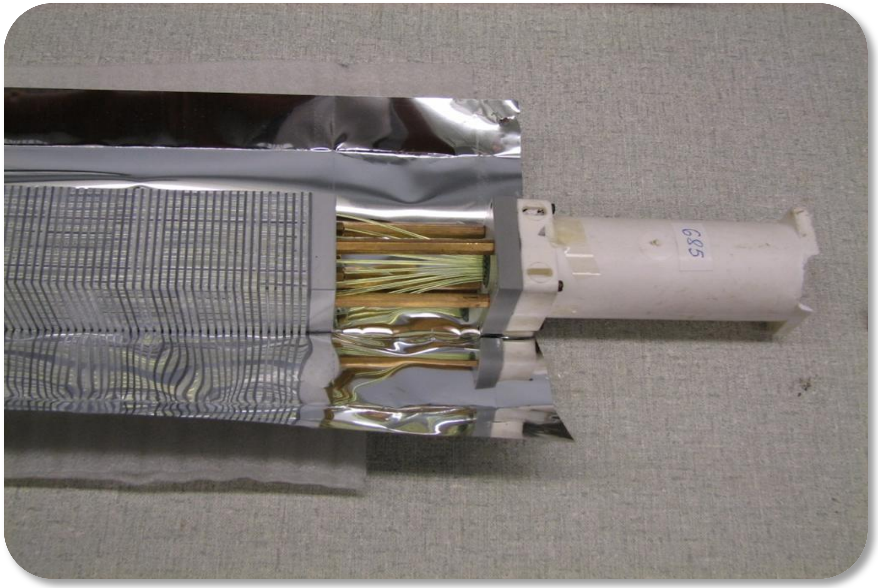
- More discussions
  - Cable layout
    - Need R&D on WLS-clear fiber connector
  - EM energy measurement
    - 5%/Sqrt(E) as baseline + constant term (calibration, etc.)
    - Constant online calibration with electrons of known momentum
  - Pion rejection w/ Cherenkov detector
    - Finalizing pi/e ratio map in CLEO geometry
    - How much Cherenkov can deliver?
- Radiation dose is challenging
- Prefer rotated calorimeter to track direction for PVDIS
- Next stage of simulation to come w/ background, tower searching
- Calorimeter test in the following section

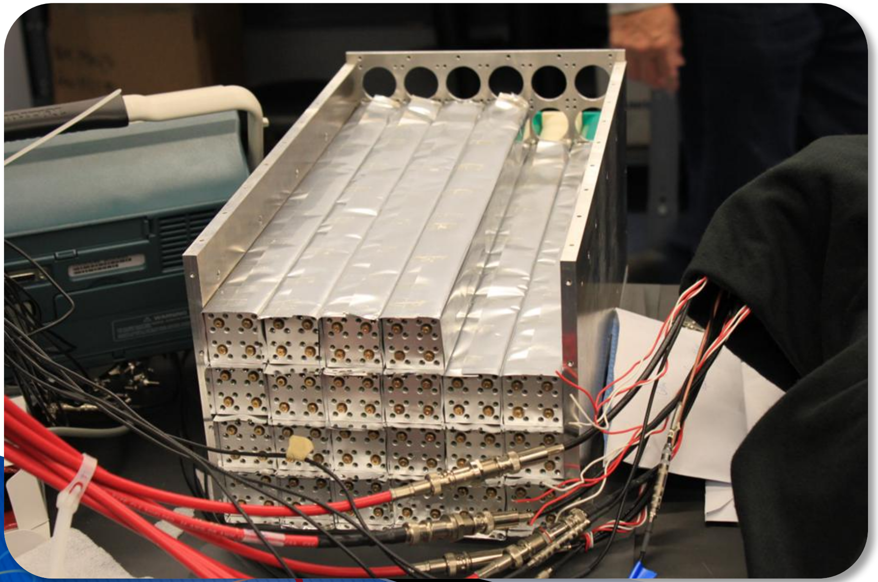
COMPASS Shashlik Module Test

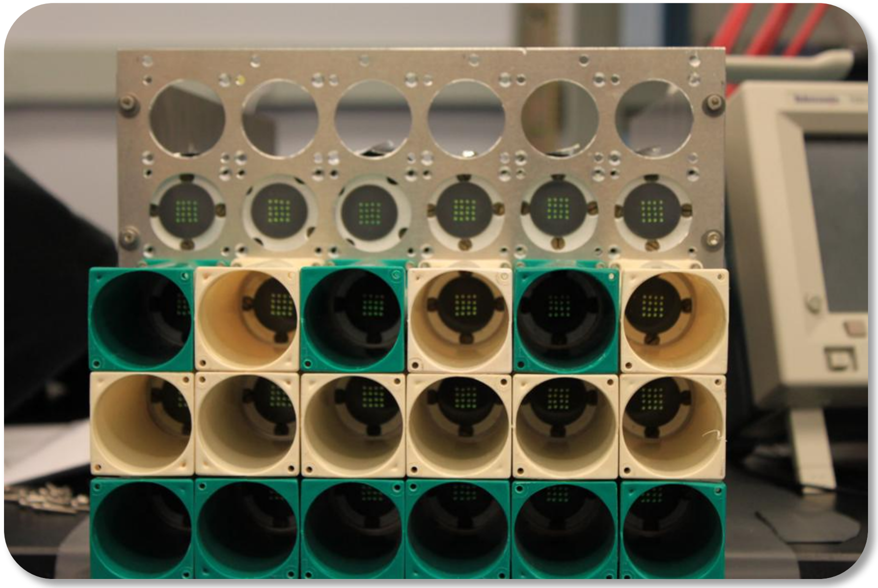
- Gain experience with the COMPASS Shashlik module.
- Determine energy resolution at different energies and different impact angles.
- Determine position resolution at different energies and different impact angles.
- Anchor simulation with data.

COMPASS modules used for TPE@CLAS







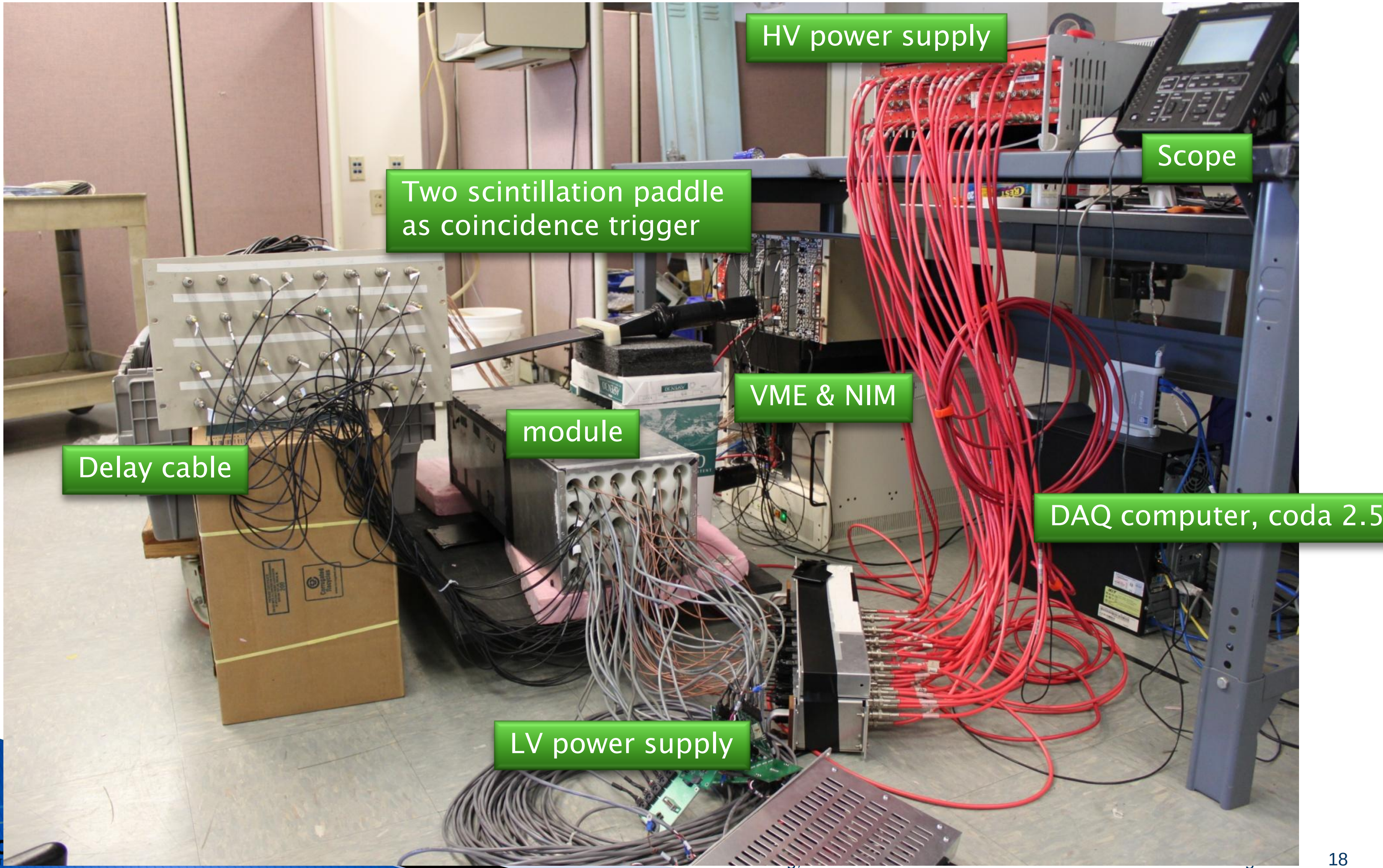


Module and readout

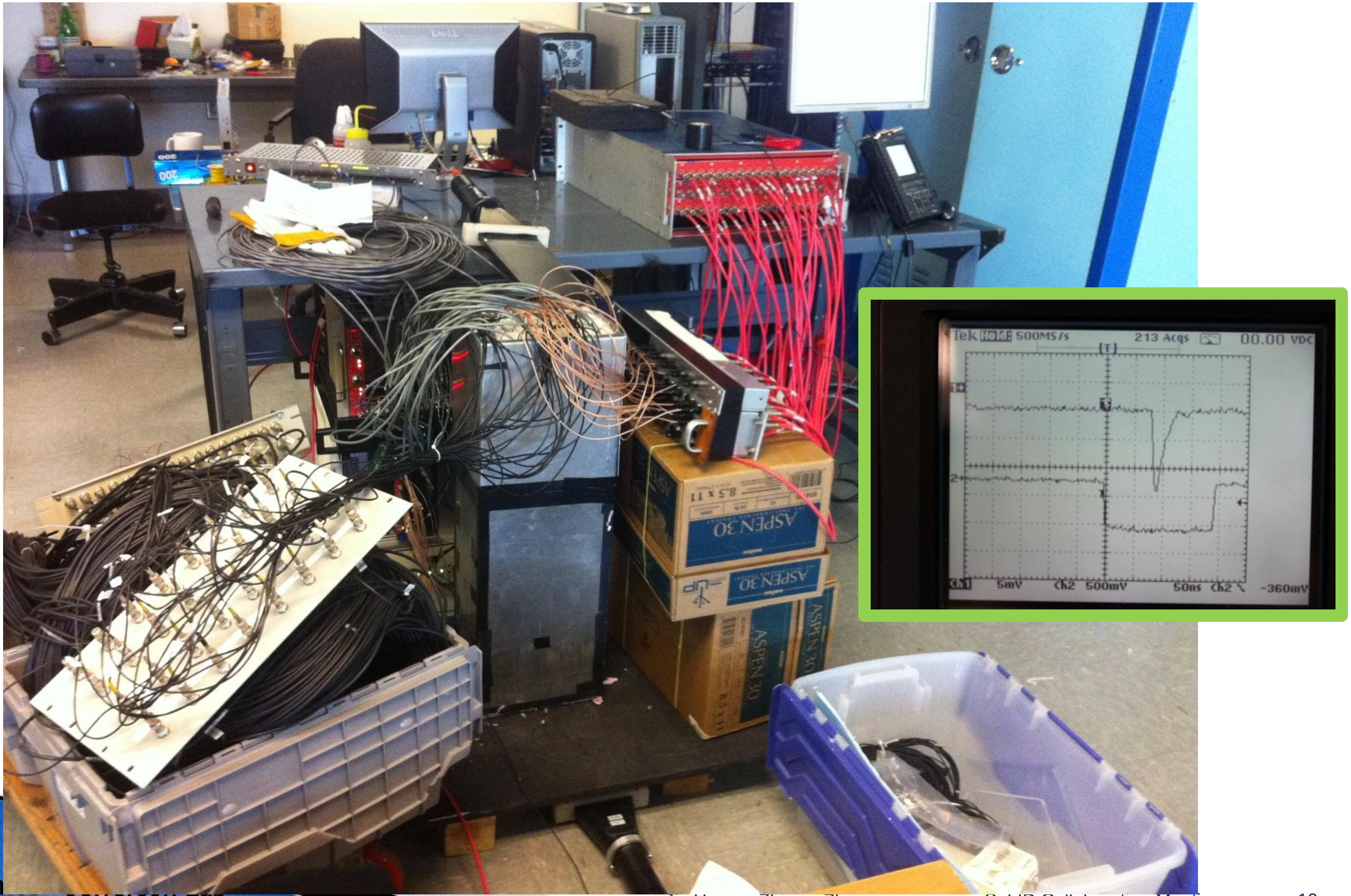
- Module is in TPE frame with original PMT removed. 30 of 3.8x3.8cm modules in 6x5 array.
- Readout: 1.1"D Photonis XP2972 PMTs, used in HallA DVCS proton array.

Mounting the two

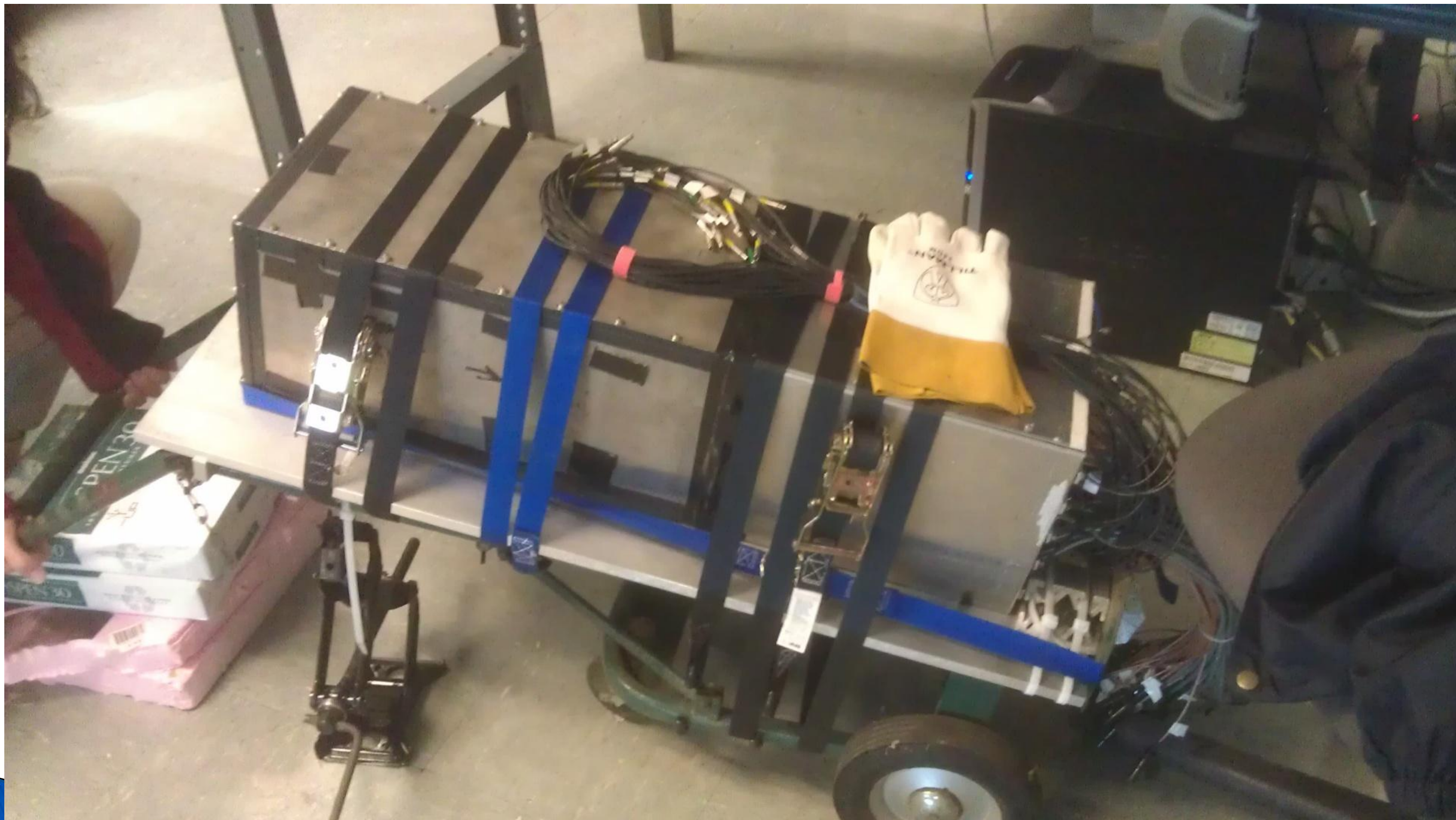
Cosmic ray test (horizontal setup)



Cosmic ray test (vertical setup)

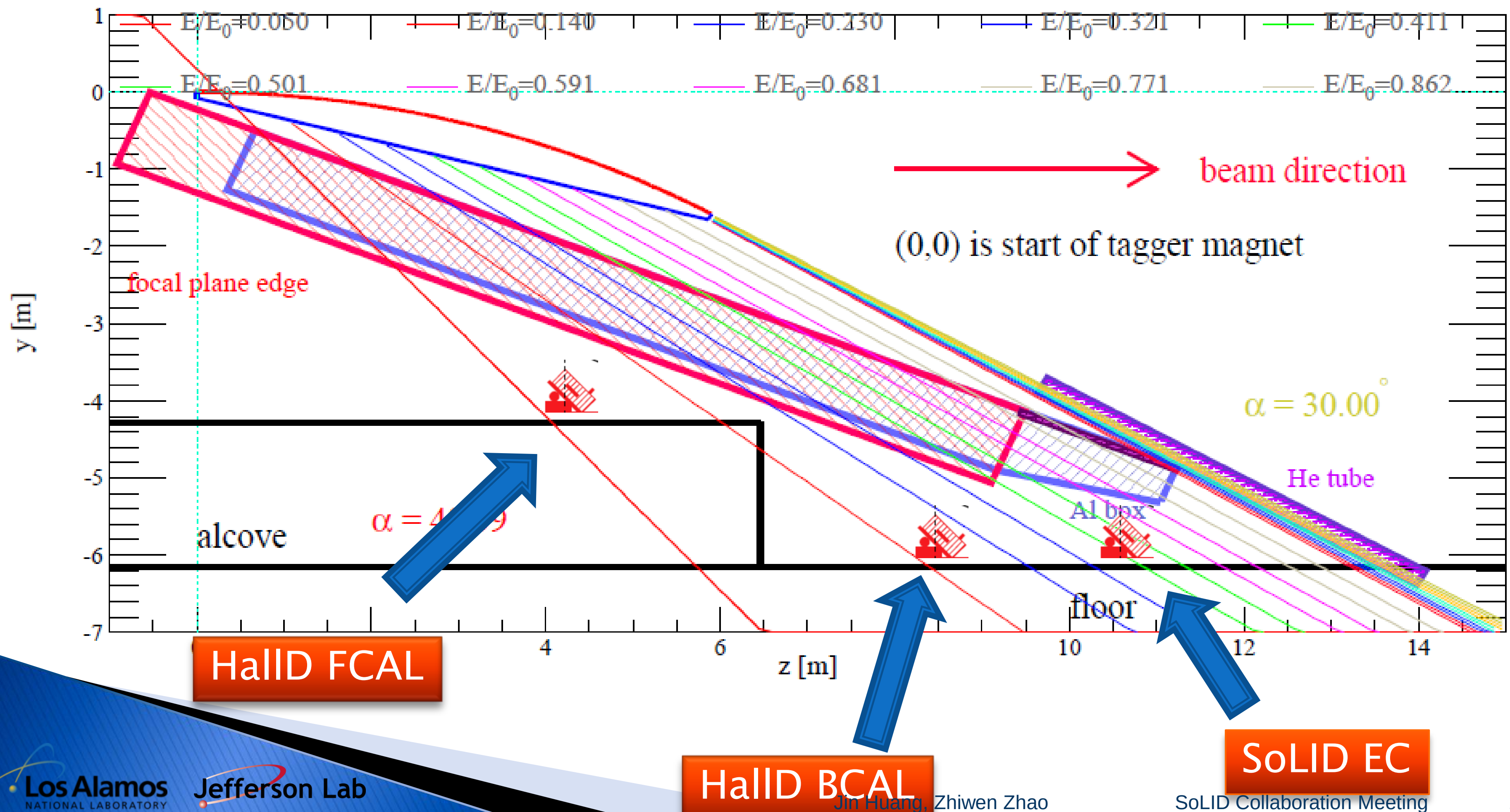


Moving and Support

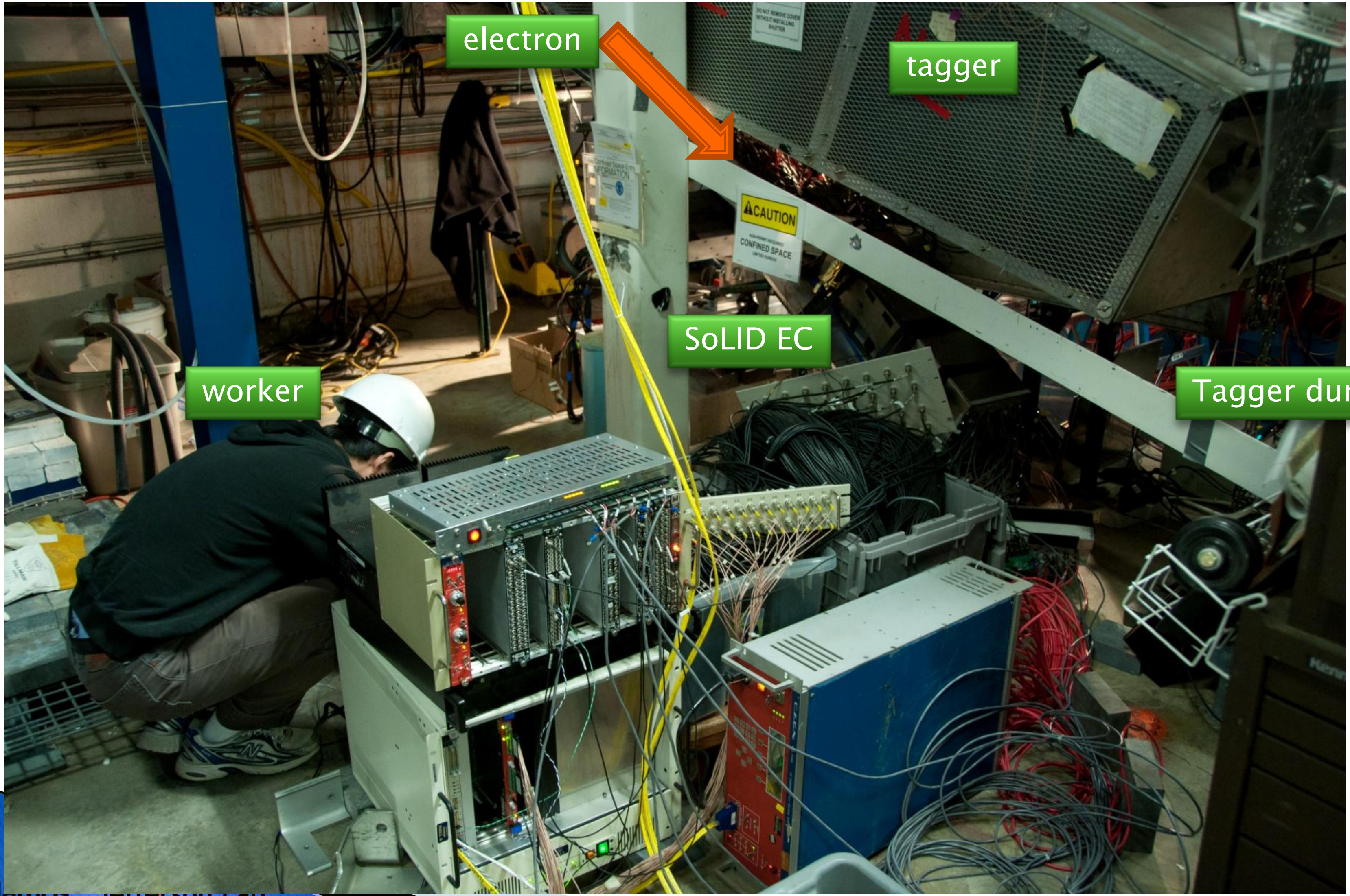


Test under CLAS photon tagger

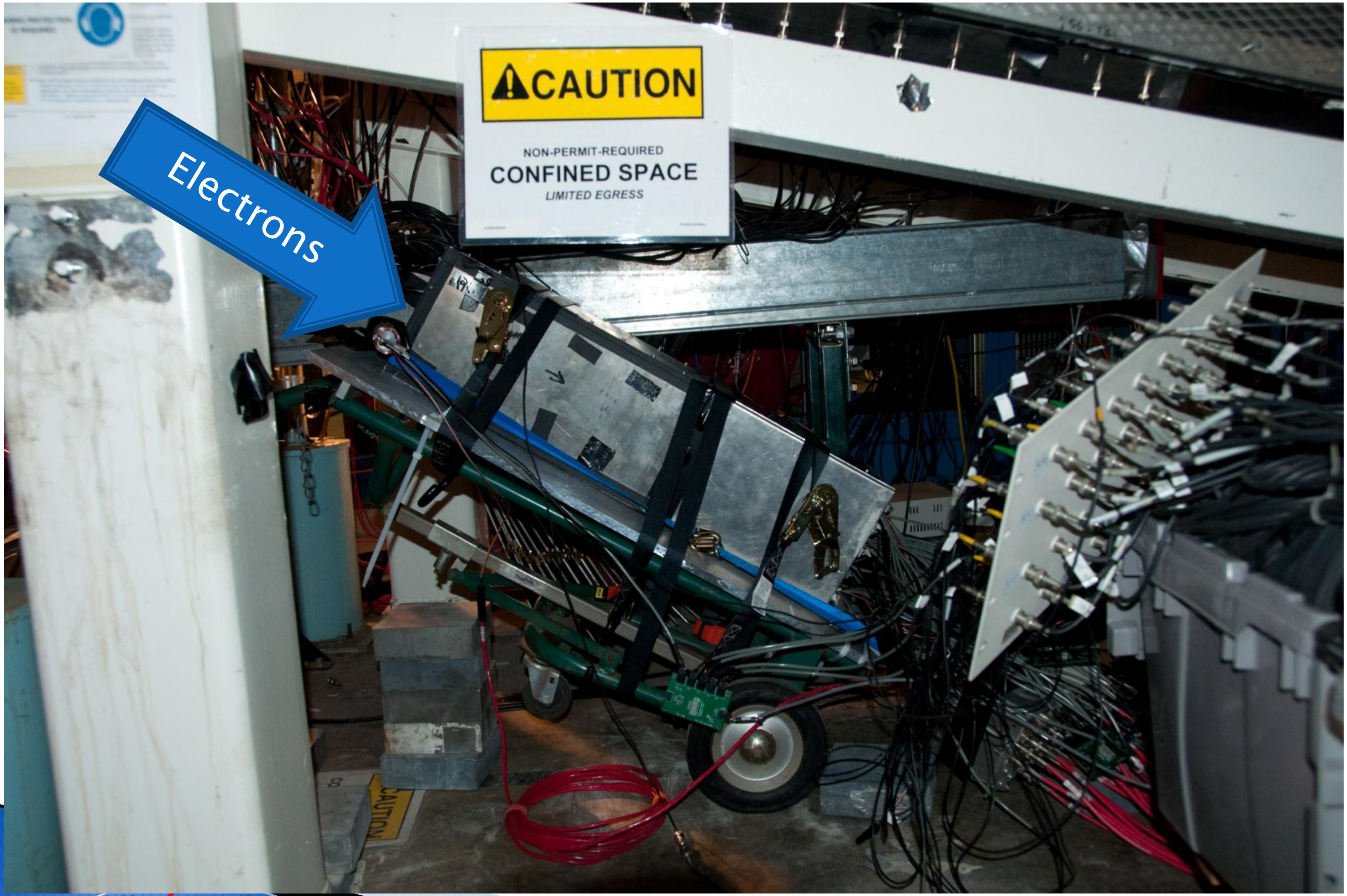
- Electron with known energy and impact angle
- Variable energy, variable impact angle
- Possibility to use Hall B DAQ resource



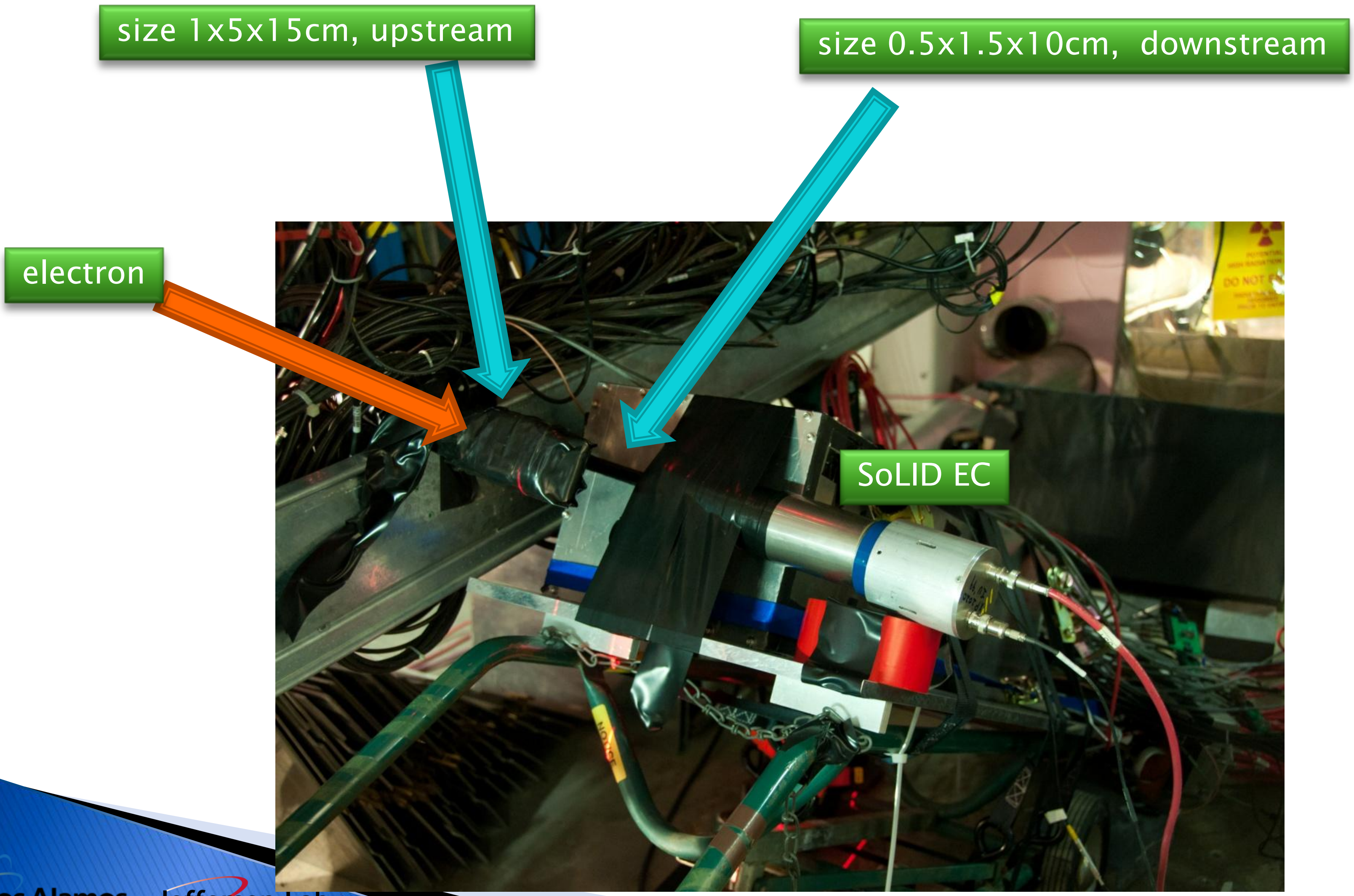
In HallB, under Photon Tagger



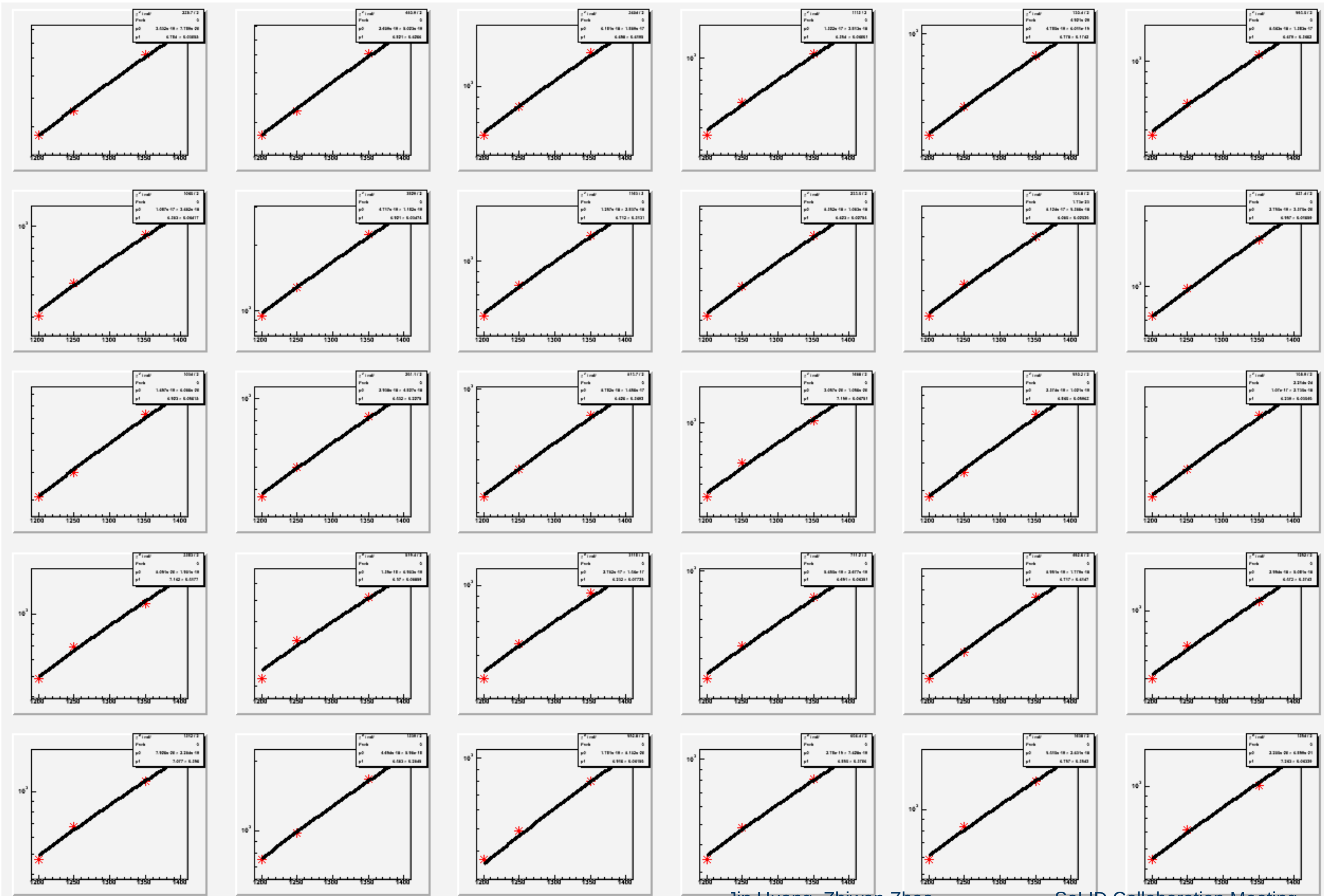
Tilting at about 32 degree to start with small angle beam impact



Two small scintillatiors as coincidence trigger

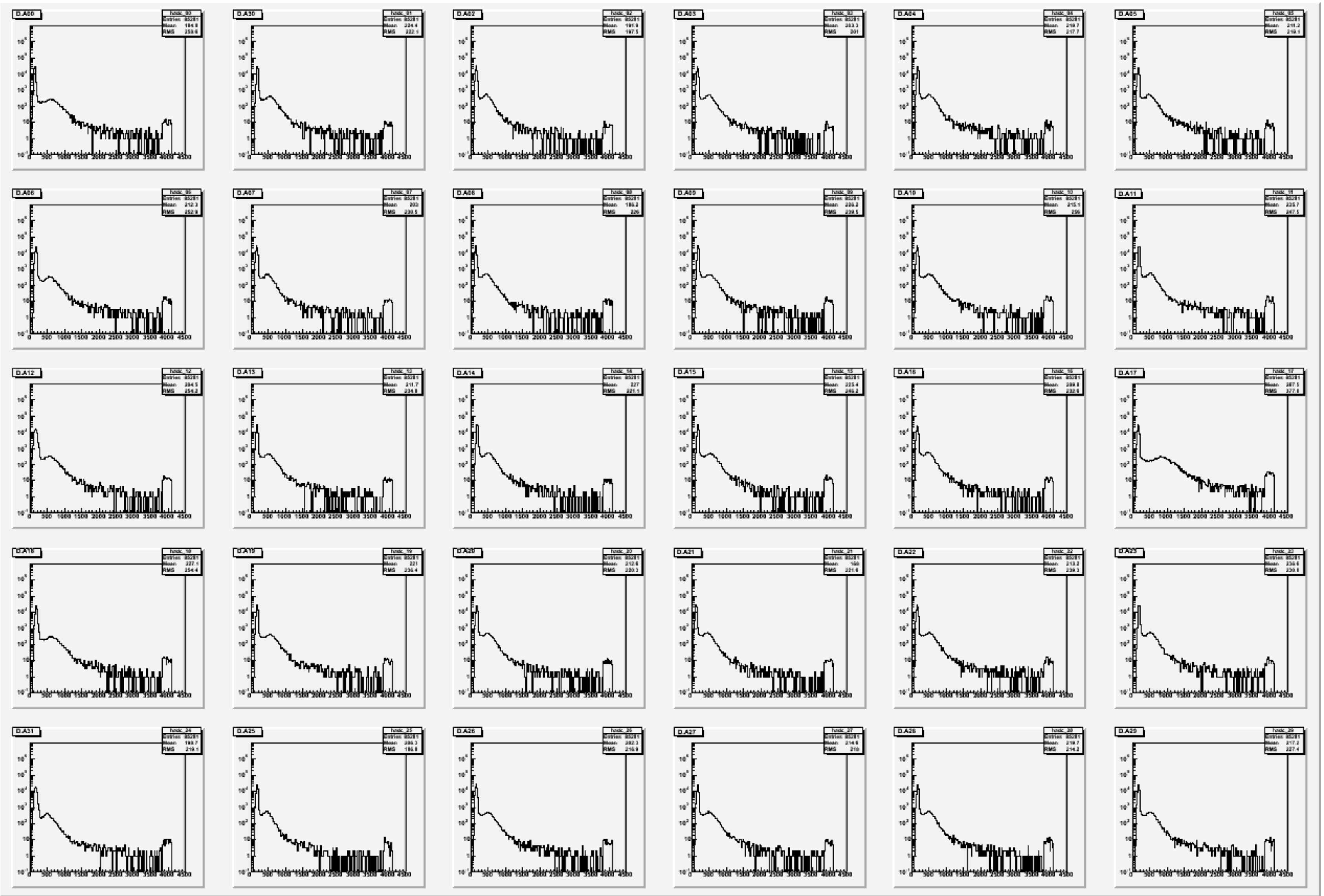


Cosmic ray gain match (ADC-Ped : Voltage)



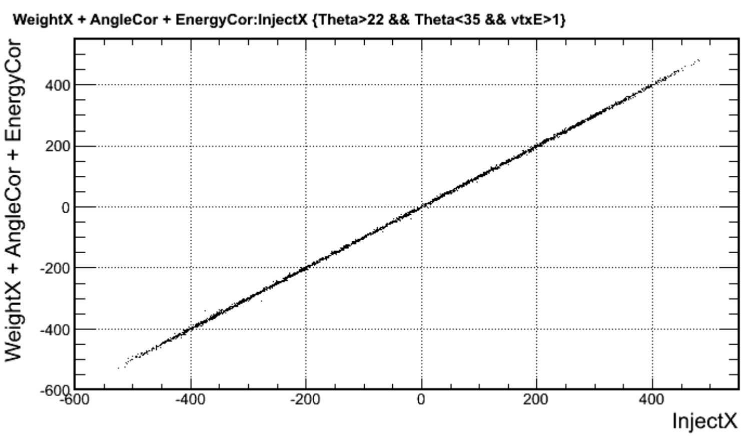
Cosmic ray gain match

after matching, most signals are within factor of 0.7-1.5

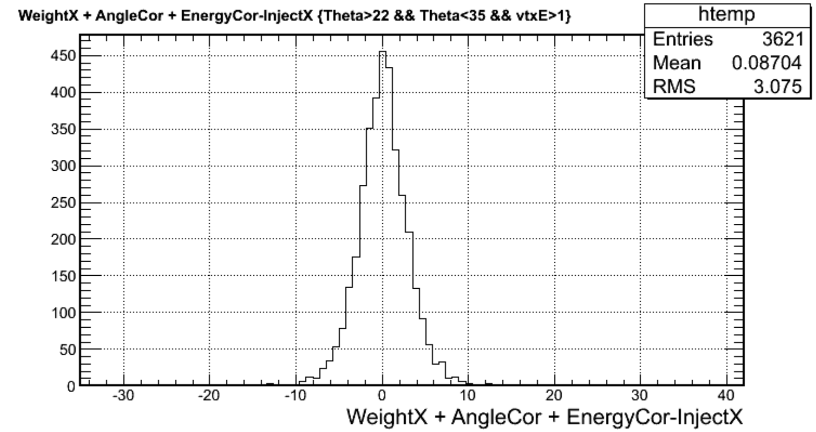


Backup Slides

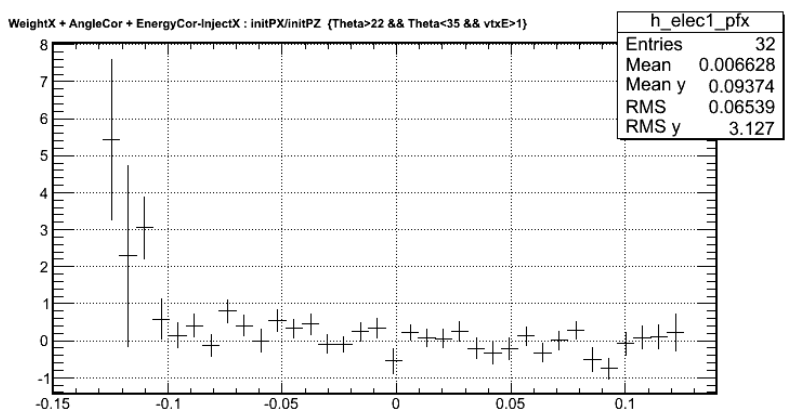
- (summary on page 13)



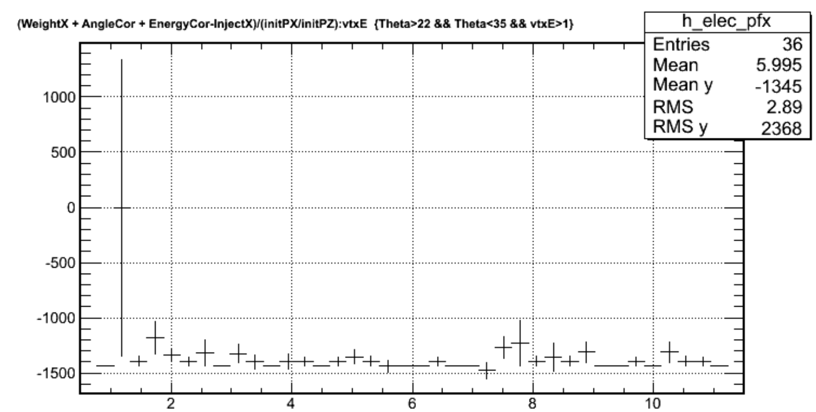
WeightX + AngleCor + EnergyCor:InjectX {Theta>22 && Theta<35 && vtxE>1}
WeightX + AngleCor + EnergyCor
InjectX



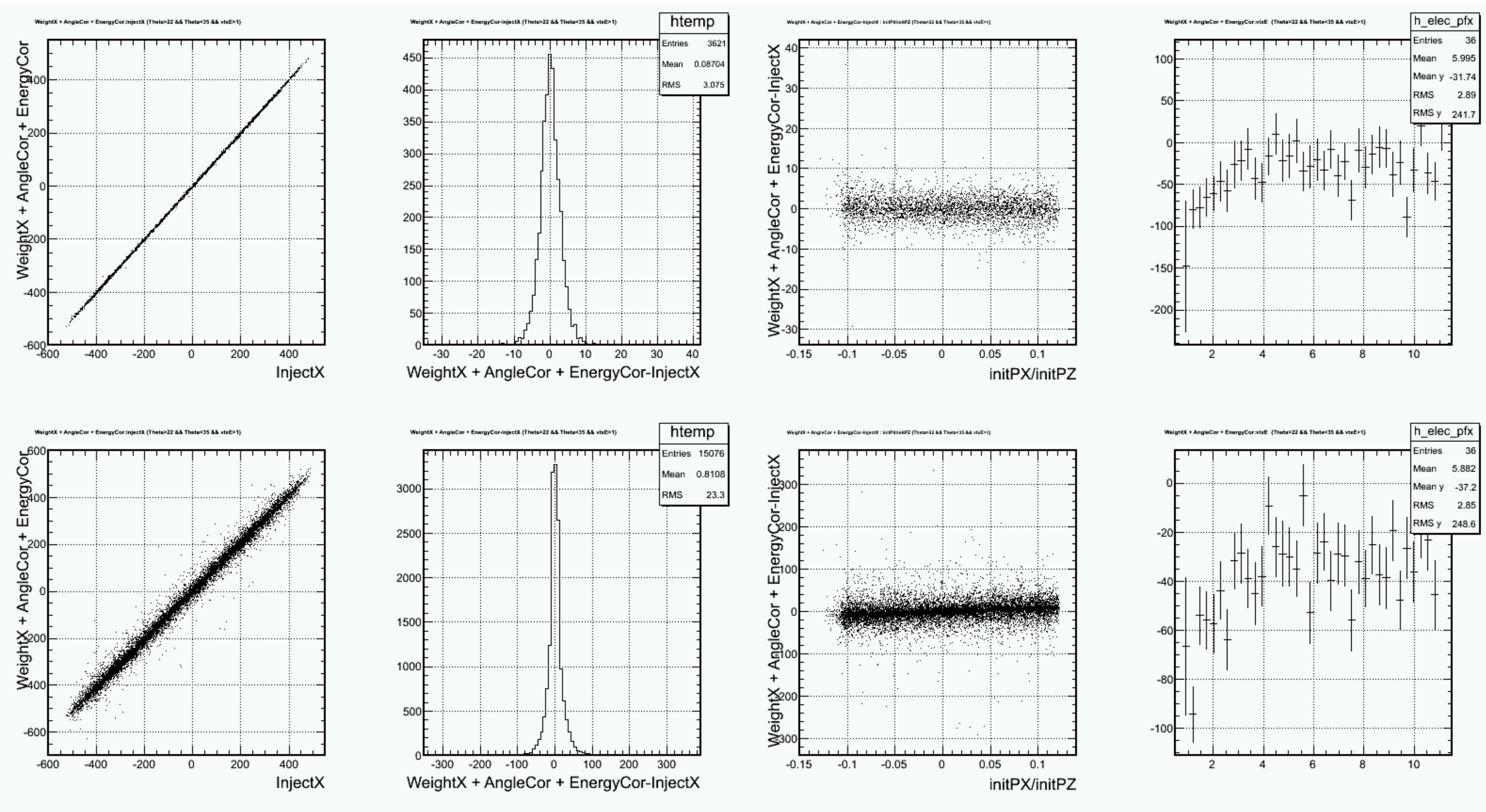
WeightX + AngleCor + EnergyCor-InjectX {Theta>22 && Theta<35 && vtxE>1}
htemp
Entries 3621
Mean 0.08704
RMS 3.075
WeightX + AngleCor + EnergyCor-InjectX

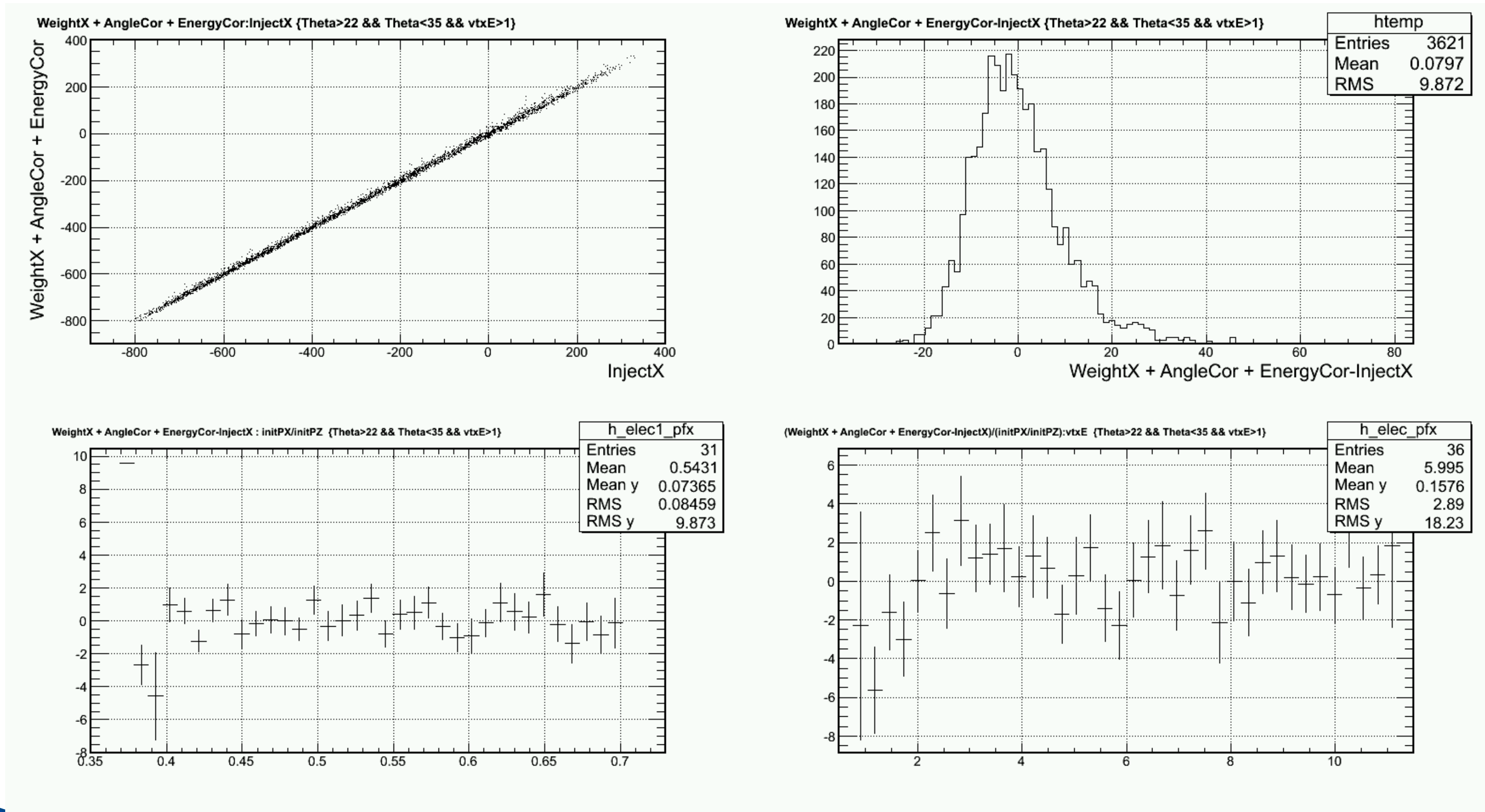


WeightX + AngleCor + EnergyCor-InjectX : initPX/initPZ {Theta>22 && Theta<35 && vtxE>1}
h_elec1_pfx
Entries 32
Mean 0.006628
Mean y 0.09374
RMS 0.06539
RMS y 3.127

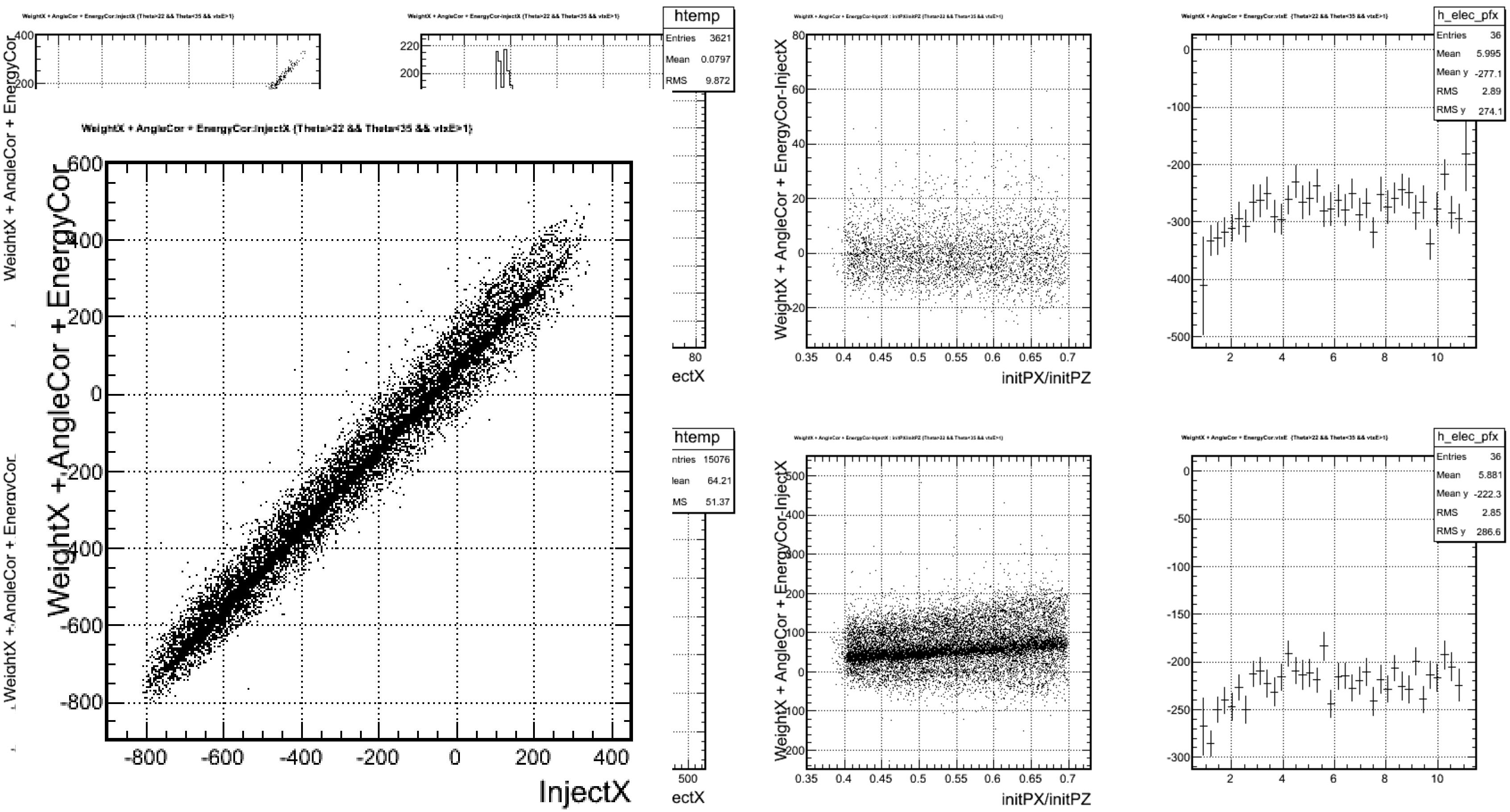


(WeightX + AngleCor + EnergyCor-InjectX)/(initPX/initPZ):vtxE {Theta>22 && Theta<35 && vtxE>1}
h_elec_pfx
Entries 36
Mean 5.995
Mean y -1345
RMS 2.89
RMS y 2368


WeightX + AngleCor + EnergyCor
InjectX
htemp
Entries 3621
Mean 0.08704
RMS 3.075
WeightX + AngleCor + EnergyCor-InjectX
WeightX + AngleCor + EnergyCor-InjectX
initPX/initPZ
h_elec_pfx
Entries 36
Mean 5.995
Mean y -31.74
RMS 2.89
RMS y 241.7
WeightX + AngleCor + EnergyCor
InjectX
htemp
Entries 15076
Mean 0.8108
RMS 23.3
WeightX + AngleCor + EnergyCor-InjectX
WeightX + AngleCor + EnergyCor-InjectX
initPX/initPZ
h_elec_pfx
Entries 36
Mean 5.882
Mean y -37.2
RMS 2.85
RMS y 248.6



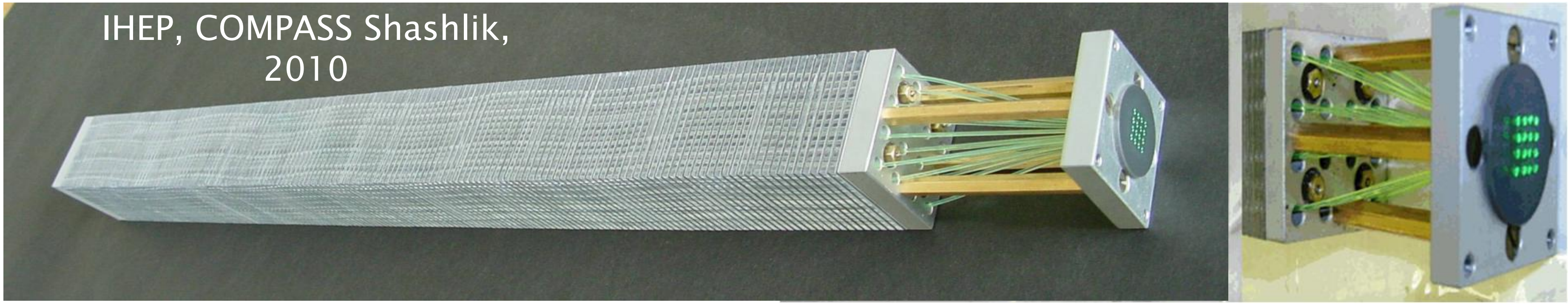
WeightX + AngleCor + EnergyCor:InjectX {Theta>22 && Theta<35 && vtxE>1}
WeightX + AngleCor + EnergyCor
InjectX
WeightX + AngleCor + EnergyCor-InjectX {Theta>22 && Theta<35 && vtxE>1}
htemp
Entries 3621
Mean 0.0797
RMS 9.872
WeightX + AngleCor + EnergyCor-InjectX
WeightX + AngleCor + EnergyCor-InjectX : initPX/initPZ {Theta>22 && Theta<35 && vtxE>1}
h_elec1_pfx
Entries 31
Mean 0.5431
Mean y 0.07365
RMS 0.08459
RMS y 9.873
(WeightX + AngleCor + EnergyCor-InjectX)/(initPX/initPZ):vtxE {Theta>22 && Theta<35 && vtxE>1}
h_elec_pfx
Entries 36
Mean 5.995
Mean y 0.1576
RMS 2.89
RMS y 18.23


WeightX + AngleCor + EnergyCor:InjectX {Theta>22 && Theta<35 && vtxE>1}
WeightX + AngleCor + EnergyCor
InjectX
htemp
Entries 3621
Mean 0.0797
RMS 9.872
htemp
Entries 15076
Mean 64.21
RMS 51.37
WeightX + AngleCor + EnergyCor-InjectX
initPX/initPZ
h_elec_pfx
Entries 36
Mean 5.995
Mean y -277.1
RMS 2.89
RMS y 274.1
h_elec_pfx
Entries 36
Mean 5.881
Mean y -222.3
RMS 2.85
RMS y 286.6

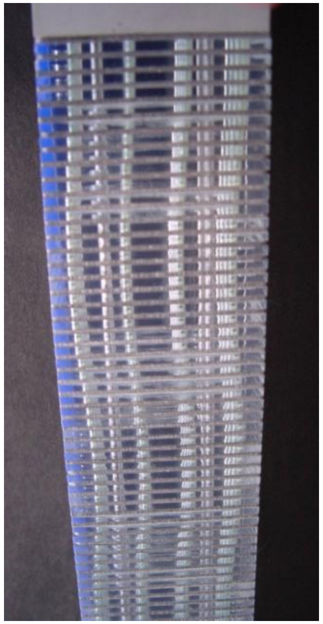
Requirement

- Radiation resistant
  - PVDIS forward angle
    - EM <=2k GeV/cm^2/s + pion (GeV/cm^2/s), total ~<60 krad/year
      Depending on baffle design
  - SIDIS forward angle
    - EM <=5k GeV/cm^2/s + pion , total, total ~<100 krad/year
  - SIDIS large angle
    - EM <=20k GeV/cm^2/s + pion, total, total ~<400 krad/year
  - Overall dose shown above, better inspected
- The Layout need to satisfy 2-fold rotation symmetry for SIDIS.
- Modules can be easily swapped and rearranged for different configuration.
- Photonsensors located outside of magnet yoke, fiber connection is one solution.
- A reasonable cost, strongly affected by the number of modules/channels, to cover the same acceptance area, we need the module transverse size not too small.

Best option: Shashlyk Calorimeter



- Shashlyk calorimeter
  - Lead-scintillator sampling calorimeter
  - WLS Fiber collects and reads out light
- Satisfy the SoLID requirement
  - Good energy resolution (tunable)
  - Radiation hardness ~ 500kRad (improvable)
  - Good time resolution (100ps)
- Easier to collect and read out the light
- Well developed technology, used by many experiments
- IHEP production rate about 200 per month

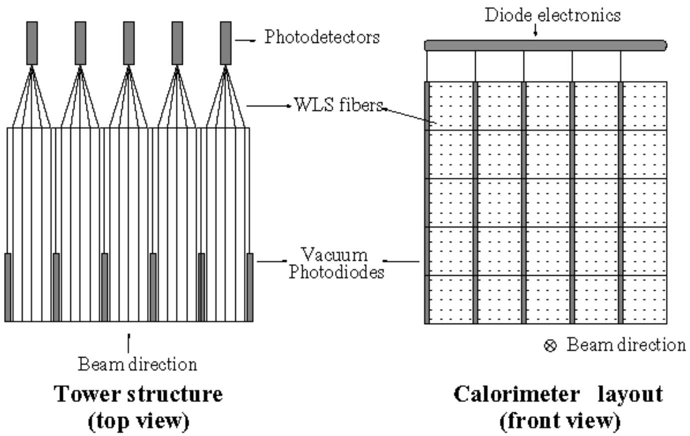


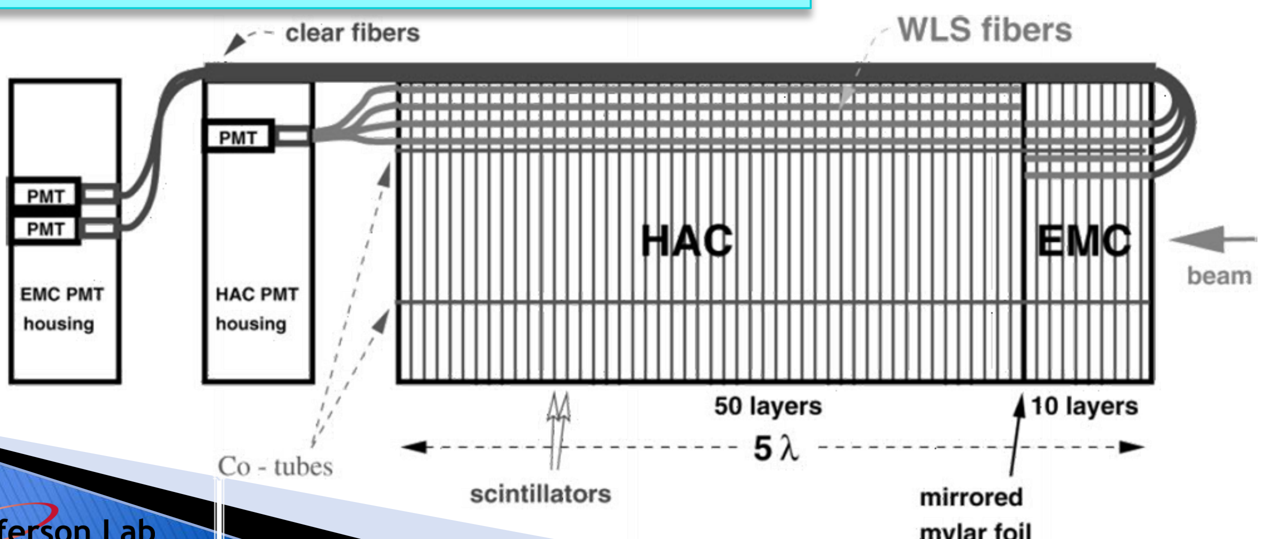
Preshower/shower

- Preshower-shower separation for better electron PID
- 4 RL as preshower, 16 RL as shower

Readout option 1, separate readout

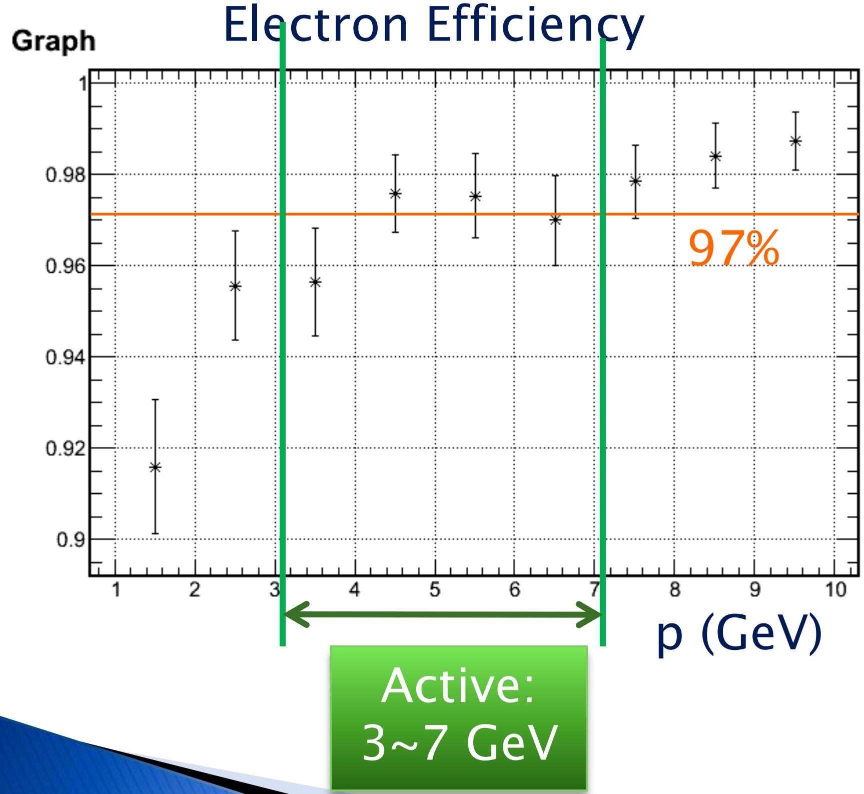
1. Run preshower fiber through shower part with light-protection
2. Run preshower fiber (separately) to outside magnetic field
3. Curve fiber from front, ZEUS example below
4. Readout preshower by photodiode, example on right.

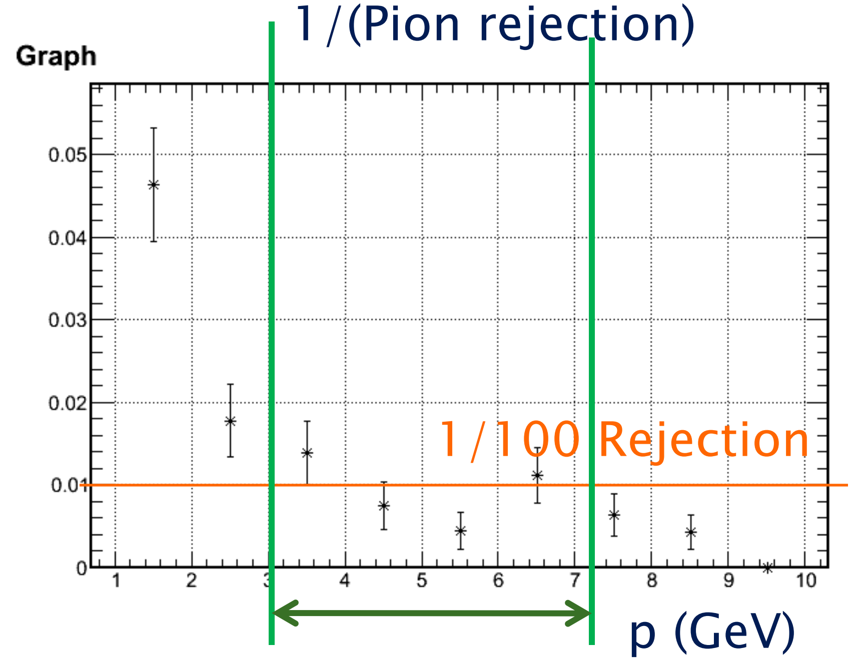




Pion rejections leads the design

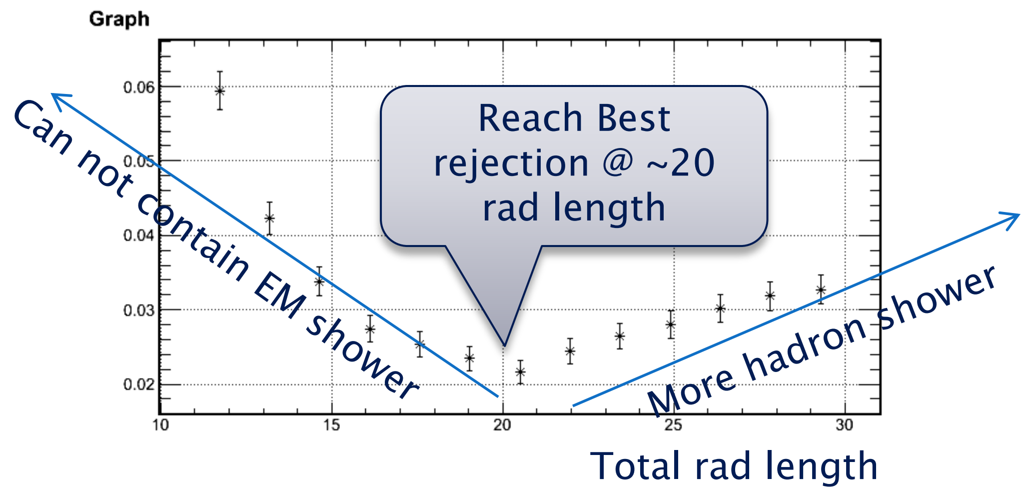
- Reach 100:1 pion rejection
- 0.6mm lead/1.5mm scintillator
  200 layers, 42cm in length (20 X_0)



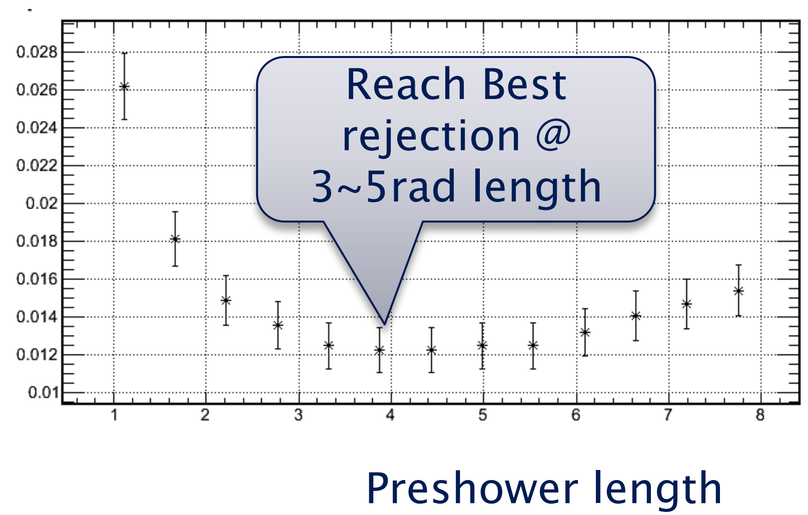


Thickness optimized

Preshower + Shower



Preshower part

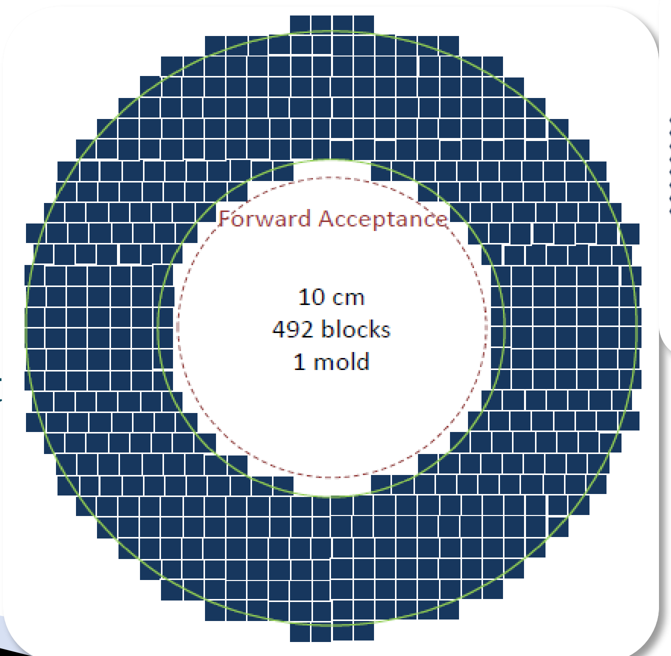


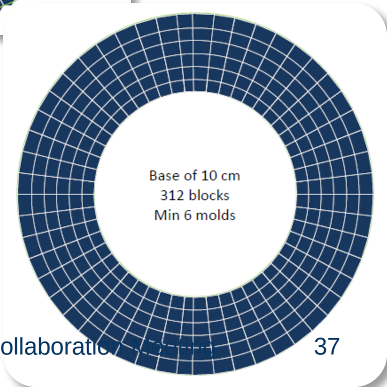
MIP energy deposition:
~60MeV (preshower)
300 MeV (TotalShower)

ECAL Design: Layout

	Hexagon		Square		Sector	
	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
Total	1398 blocks 1 mold ~ $1.4M		1400 blocks 1 mold ~ $1.4M		888 blocks 15 molds ~ $1.64M	

❖ Preferred **Square**
- Easy assembly
- Mature production
- Easier rearrangement





Calorimeter Design: Fibers

- **Fibers:**
  - Wave Length Shifting fibers (WLS): KURARAY Y11, ~150 fibers/module
  - Clear Fibers: KURARAY clear PS, Super Eska…,
- **Connectors**
  - Optical WLS/clear fiber connector, used in previous experiments (LHCb, Minos) light loss studies and design well documented
  - Clear Fiber in 24 wide ribbon cables by Mitsubishi, coated with black Tedlar for protection and light tightness
  - 24 wide connectors from DDK to link WLS and clear fiber ribbon cables
  - Fibers are fly cut and polished with diamond fly cutter, possible use of an optical couplant to reduce light loss.
  - Fiber bunch diameter for one module 10 mm
    For 1500 modules, min. length of WLS: ~100 km!
    Clear fiber length depends on the readout option ~500km?
  - Ongoing work: study of the fiber bundling design

Preliminary Budget Estimate

Experiment	Angle (degree)	Radius (cm)	Area(m^2)	Number of modules	Module cost (M$)	Fiber Extension (M$)	PMT+ support (M$)	Total cost
PVDIS (forward angle)	22-35	110-258	~10	1000? ~Baffle design	1.5	0	0.6	2.1
SIDIS (forward angle)	9-15	107-202	11	908				
SIDIS (large angle)	17-24	82-141	5	492	0.8	0.3(?)	0.3	1.4

+ **Support structure: 0.2M$ (?)**

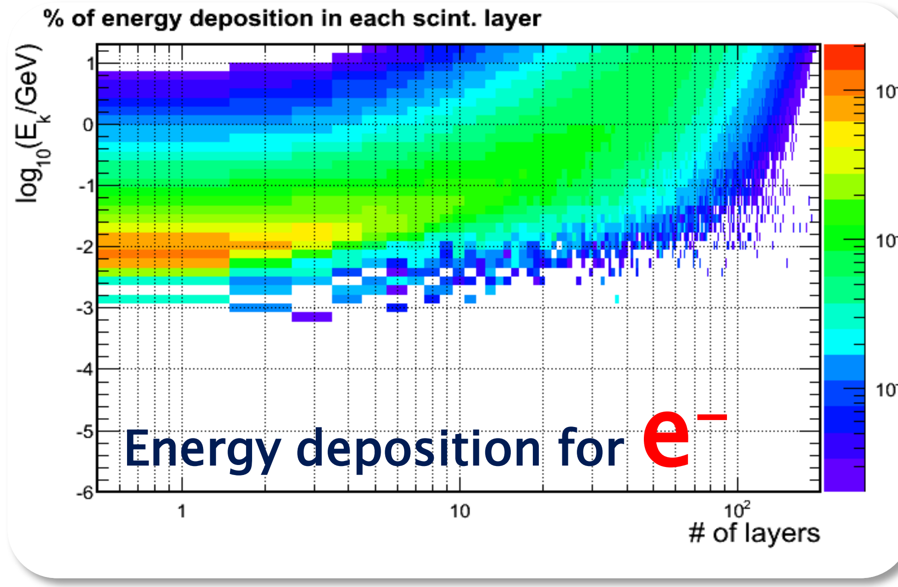
- **10x10cm Shashlyk module costs about $1~1.5K each**
- **Rearrangement of modules between PVDIS & SIDIS large angle calorimeters**

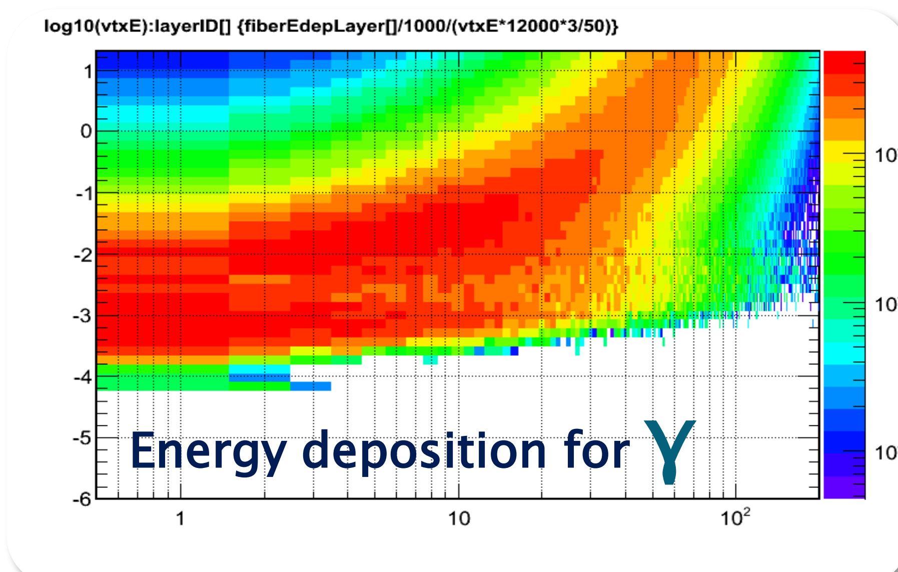
PVDIS : factor 0.5 reduction due to only covers ~half of azimuthal angle

Los Alamos NATIONAL LABORATORY EST. 1943 Jefferson Lab

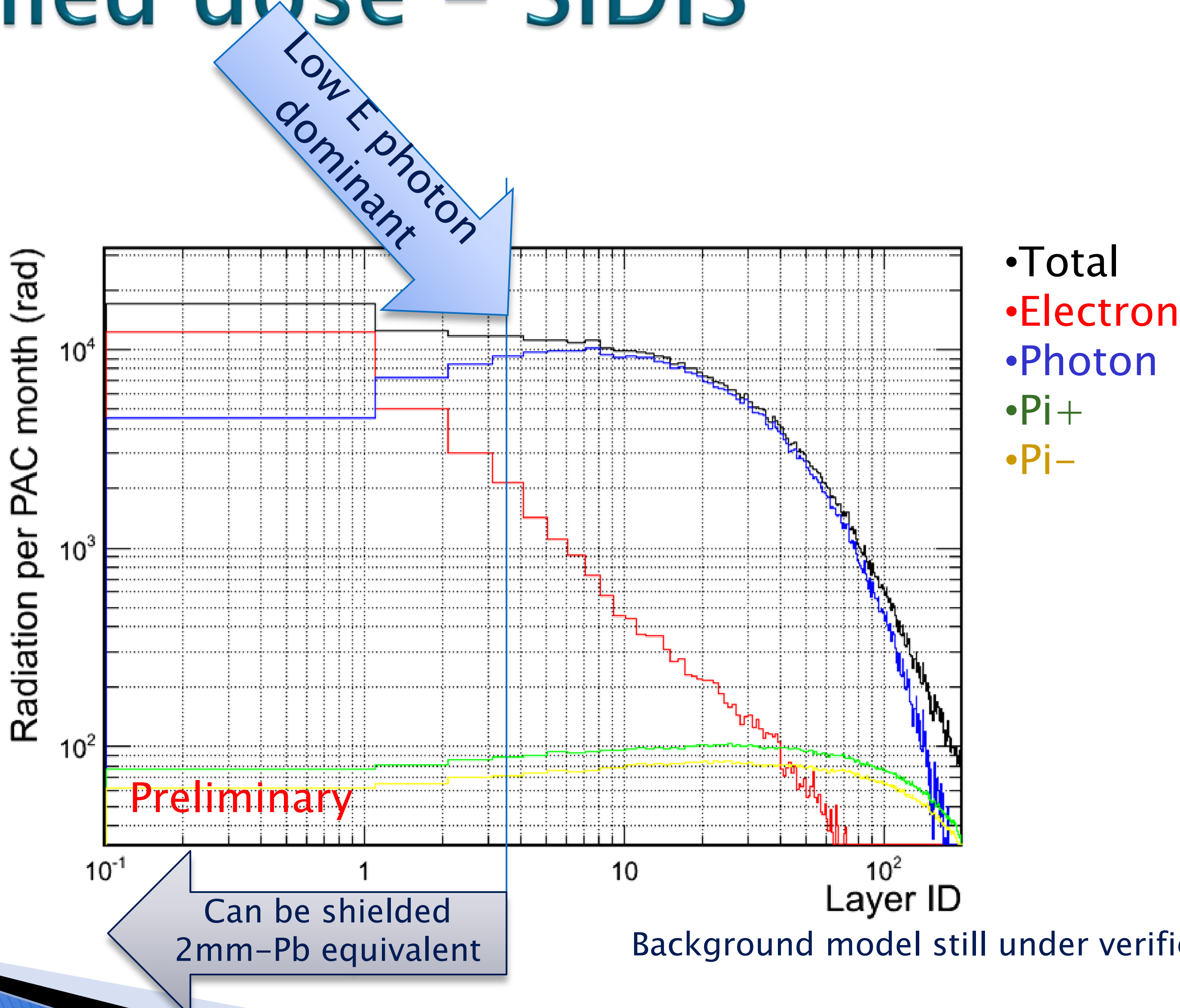
Simulate the radiation level

- 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



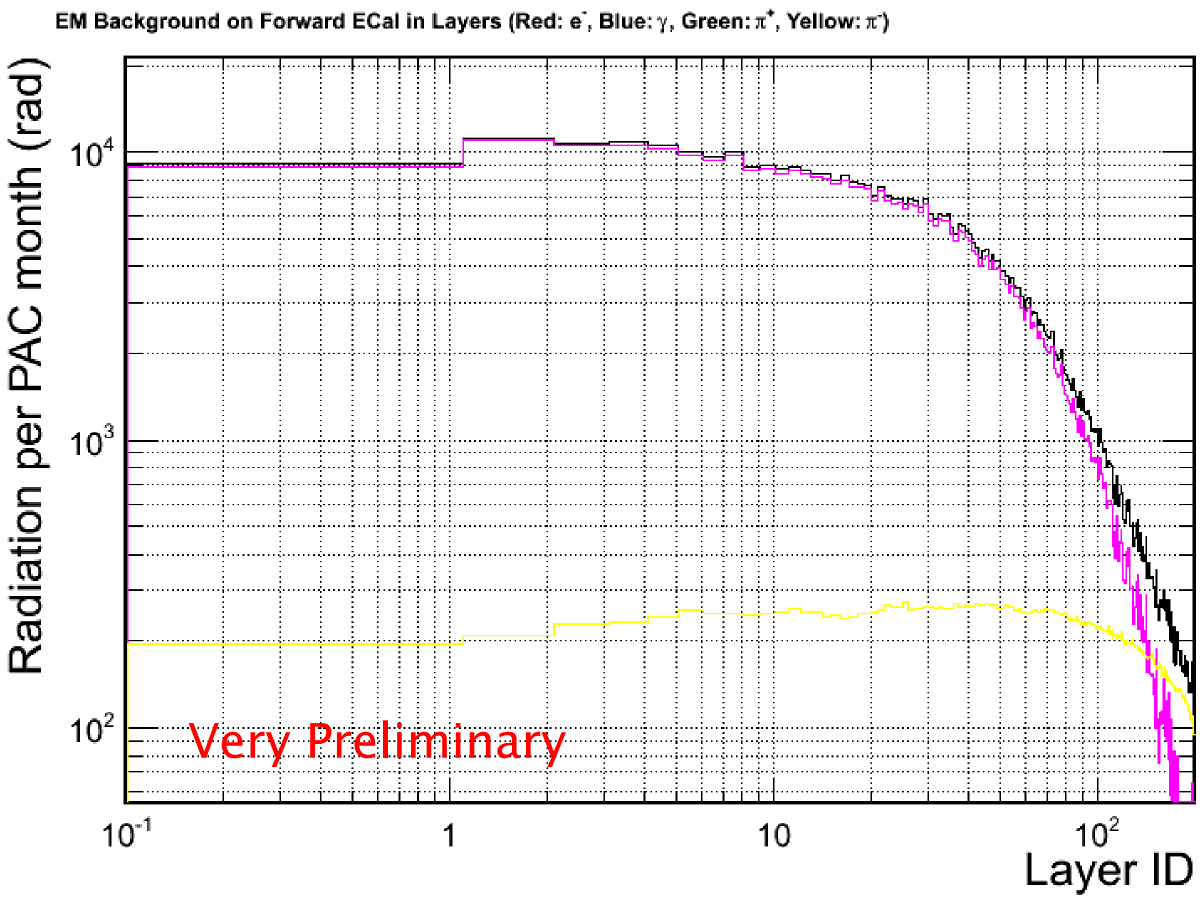


Detailed dose – SIDIS



Background model still under verification

Detailed dose – PVDIS

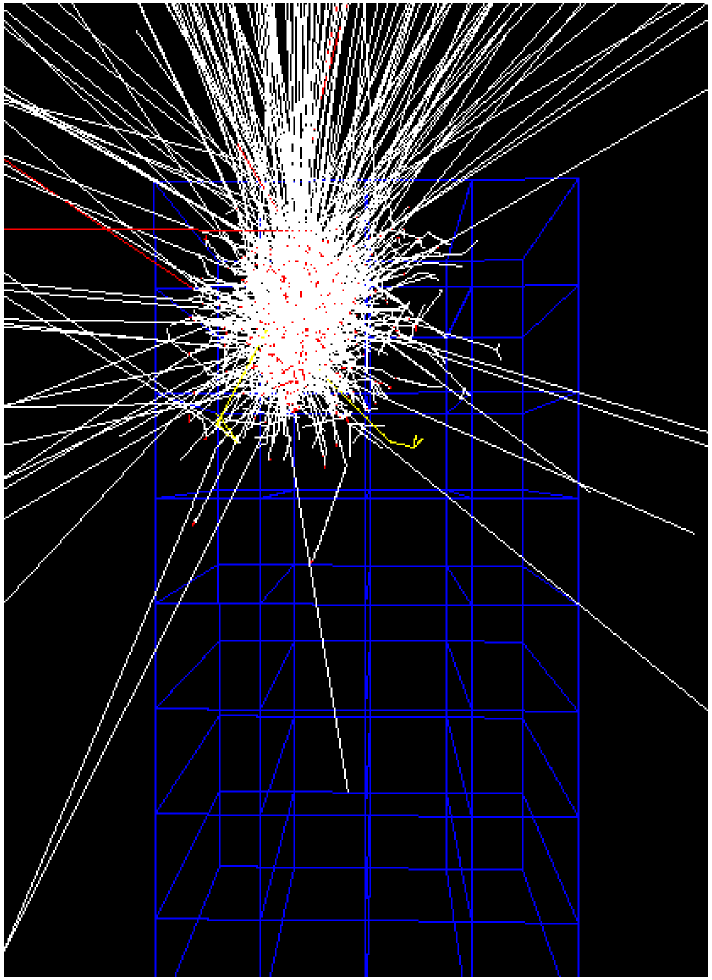


- Total
- Total EM
- Pi-

Background and baffle model still under verification

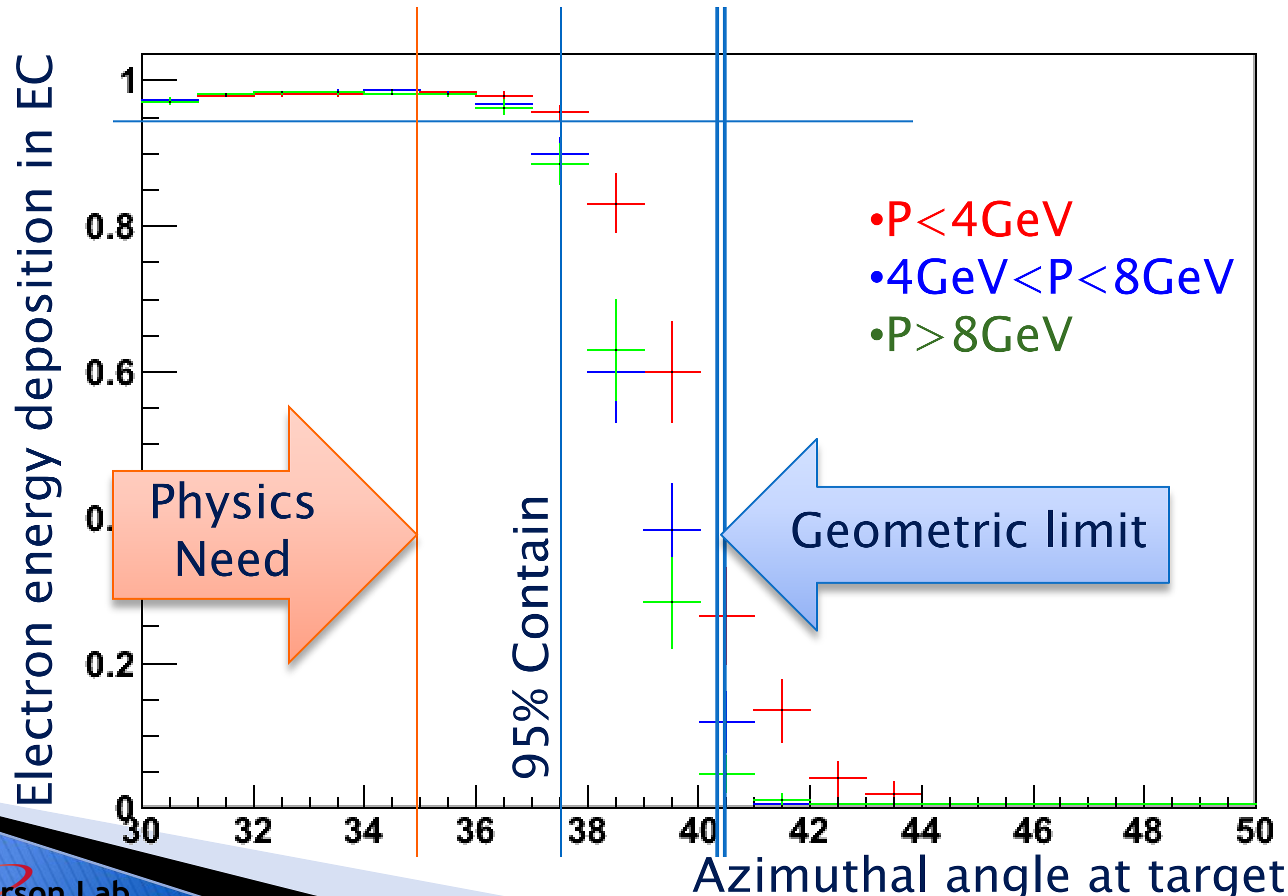
Simulate edge effect

- 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?

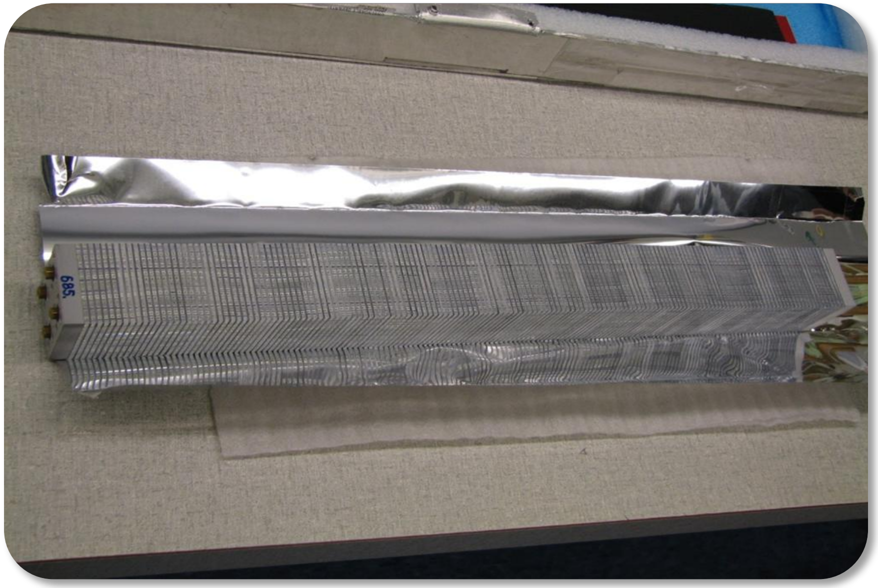


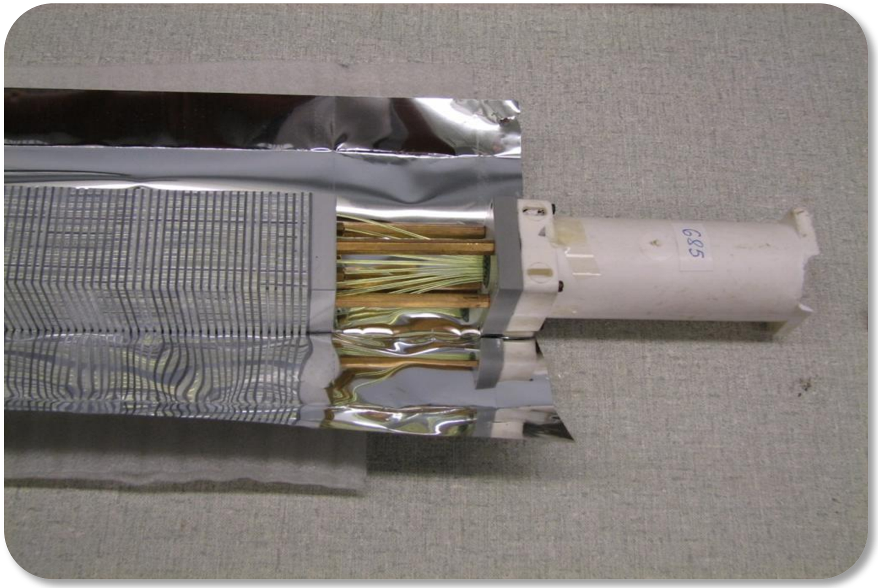
The edge effect – PVDIS

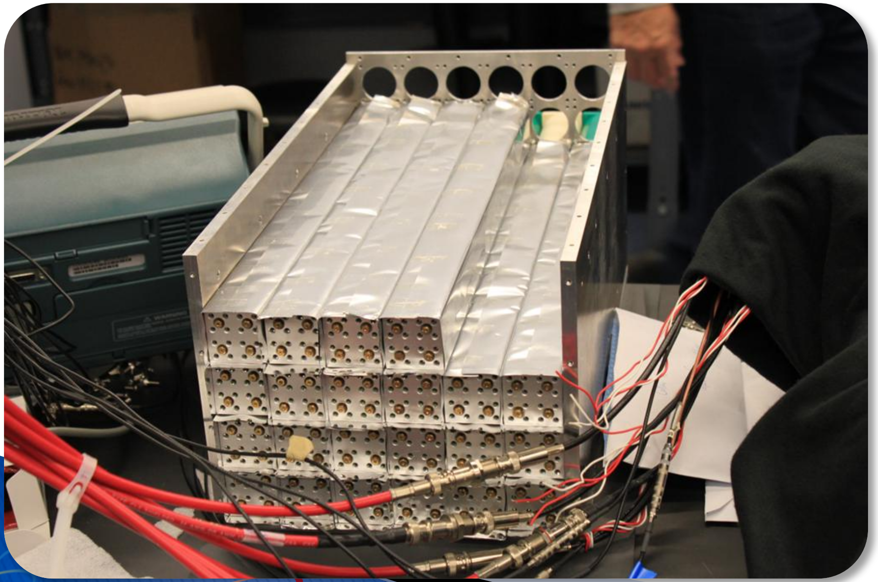
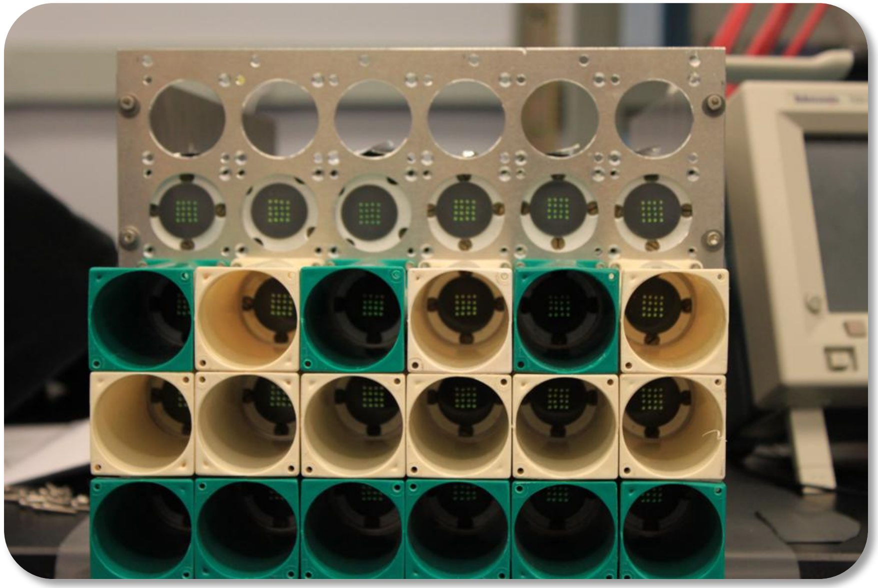
- Have largest indenting angle
  - Calorimeter edge to target center -> 40 degree



COMPASS modules used for TPE@CLAS





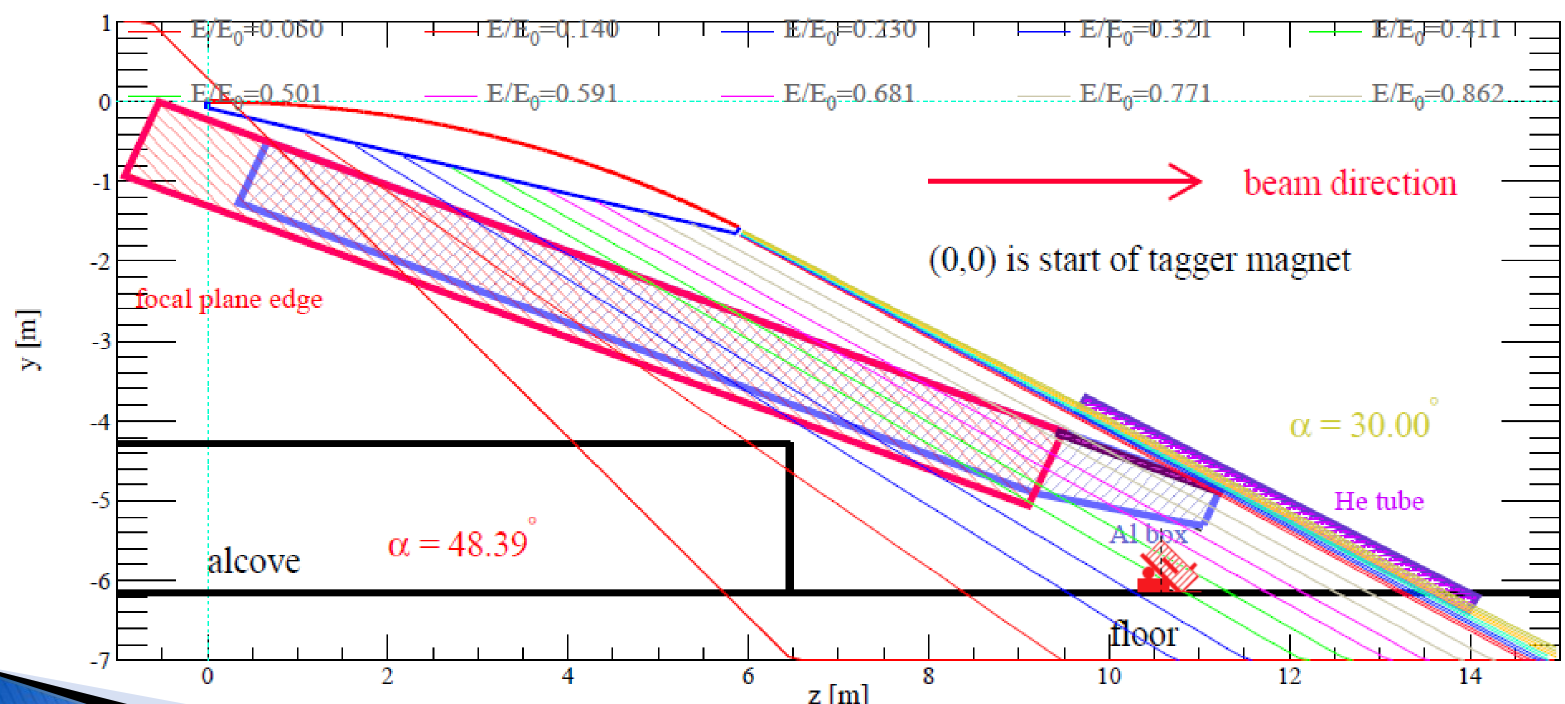
COMPASS Calorimeter in the Shashlik produce line

Experiment	COMPASS	PANDA	KIPIO
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 (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

- Close to the layer configuration that we need
- Less sampling and worse energy resolution
- Finer lateral size

Proposed floor Plan
@ Hall B photon tagger

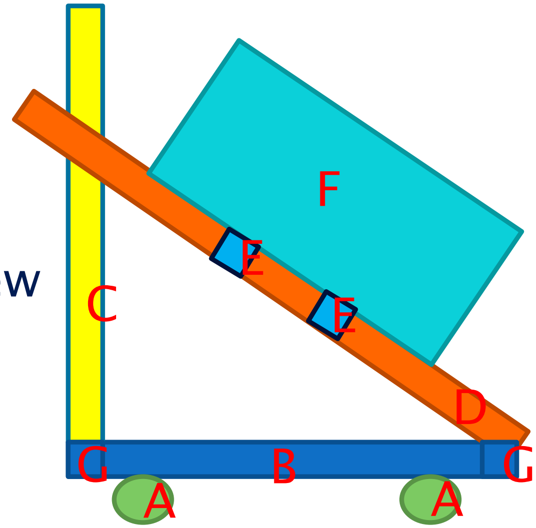
- Electron with known energy and impact angle
- Variable energy
- Possibility to use Hall B DAQ resource



Beam Test Status
Thanks to the hard work of Z. Zhao

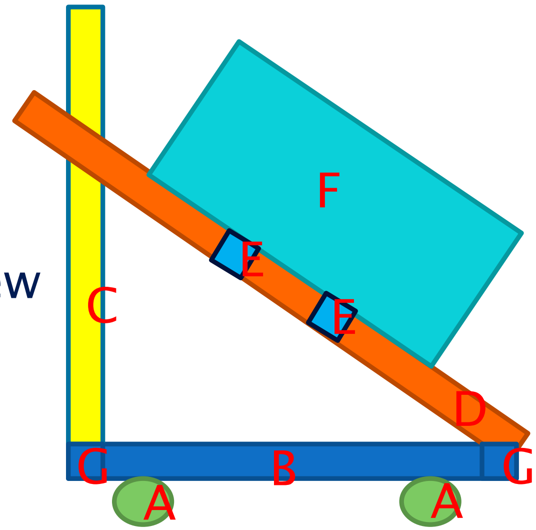
- Module and readout (PMT, base etc) are in Jlab
- Working on connecting PMT to module
- Working on supporting structure by using Unistruct parts
- Bench test and move into HallB around March.
- Take advantage of the experience of other calorimeter test under the CLAS tagger.

Side view

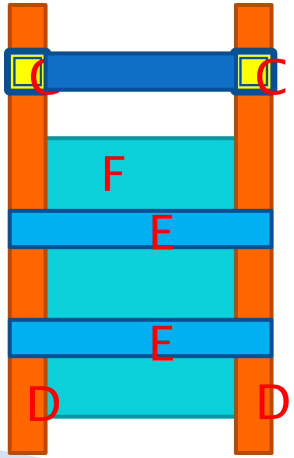


Calorimeter box and support

Side view



Bottom view



A: 4 wheels to move around
B: 2 long bars for bottom support
G: 2 short bars for bottom support
C: 2 bars for vertical support
D: 2 bars to lift the box
E: 2 bars to connect the box
F: the box with size about (30x25x80cm) and weight about 250lb)

The main features of the support:

1. It can support the box and be stable
2. D can move along C, so the box can be tilted at different angles.

Conclusion

- Keep pursuing the Shashlyk calorimeter design
  - Studied sampling/thickness/size/layout
  - Budget ~ 3.5 M$
- Beam test on the way
  - Hands-on experience.
  - Anchor the simulation to finalize parameters
- Many open questions
  - Finalize background radiation simulation
  - Preshower and shower segmentation
  - Fiber connectors
  - Detecting pi-0? $$ needed
  - Fund the detector!

Choosing EC Type

- PVDIS and SIDIS radiation level (400krad per year) is too high for lead glass and crystals (1krad), both Shashlyk or SPACAL/SciFi (0.5-1M rad) will work.
- Both Shashlyk and SciFi have good energy, position and time resolution.
- ***SciFi costs more***
  - SciFi needs about half volume being scintillation fibers for good energy resolution.
  - 1mm diameter fibers cost $1/m.
  - Forward angle EC (10m^2 area, 0.4m depth), Large angle EC (5m^2 area, 0.4m depth)
  - SciFi , total **$4M** for the *fiber alone.*
  - Shashlyk , total from **$1.5M to $2.2M** for **produced modules** of 10x10cm from IHEP.

EM calorimeters with optical readout

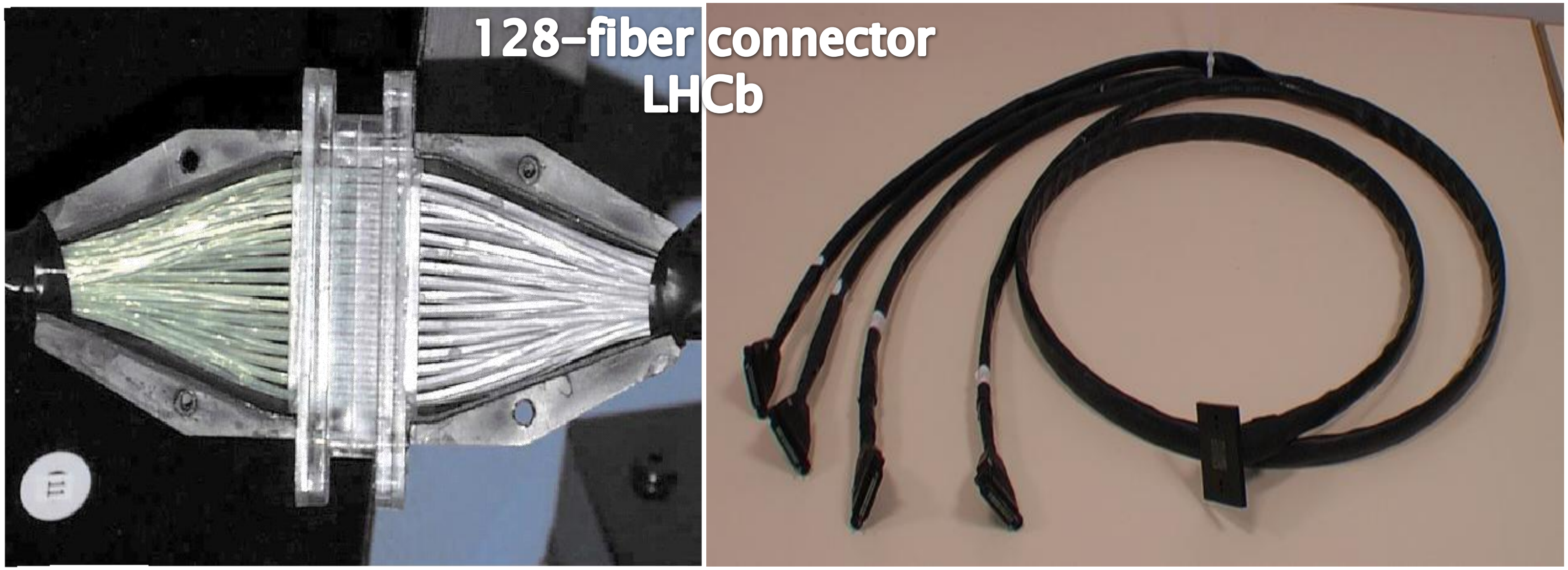
Material	Density g/cm^3	X_0 cm	R_M cm	λ_I cm	Refr. index	τ ns	Peak λ nm	Light yield	$\frac{N_{p.e.}}{GeV}$	rad	$\frac{\sigma E}{E}$
Crystals											
NaI(Tl)**	3.67	2.59	4.5	41.4	1.85	250	410	1.00	10^6	10^2	$1.5\%/E^{1/4}$
CsI *	4.53	1.85	3.8	36.5	1.80	30	420	0.05	10^4	10^4	$2.0\%/E^{1/2}$
CsI(Tl)*	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	$2.\%/E^{1/2}$
$PbWO_4$	8.28	0.89	2.2	22.4	2.30	5/39% 15/60% 100/01%	420 440	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	$1.5\%/E^{1/2}$
PbF_2	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		1.647	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF-5	4.08	2.54	4.3	21.4	1.673	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF57	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	$2 \cdot 10^4$	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	$4 \cdot 10^5$	10^5	$3.5\%/E^{1/2}$

$*$ - hygroscopic

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

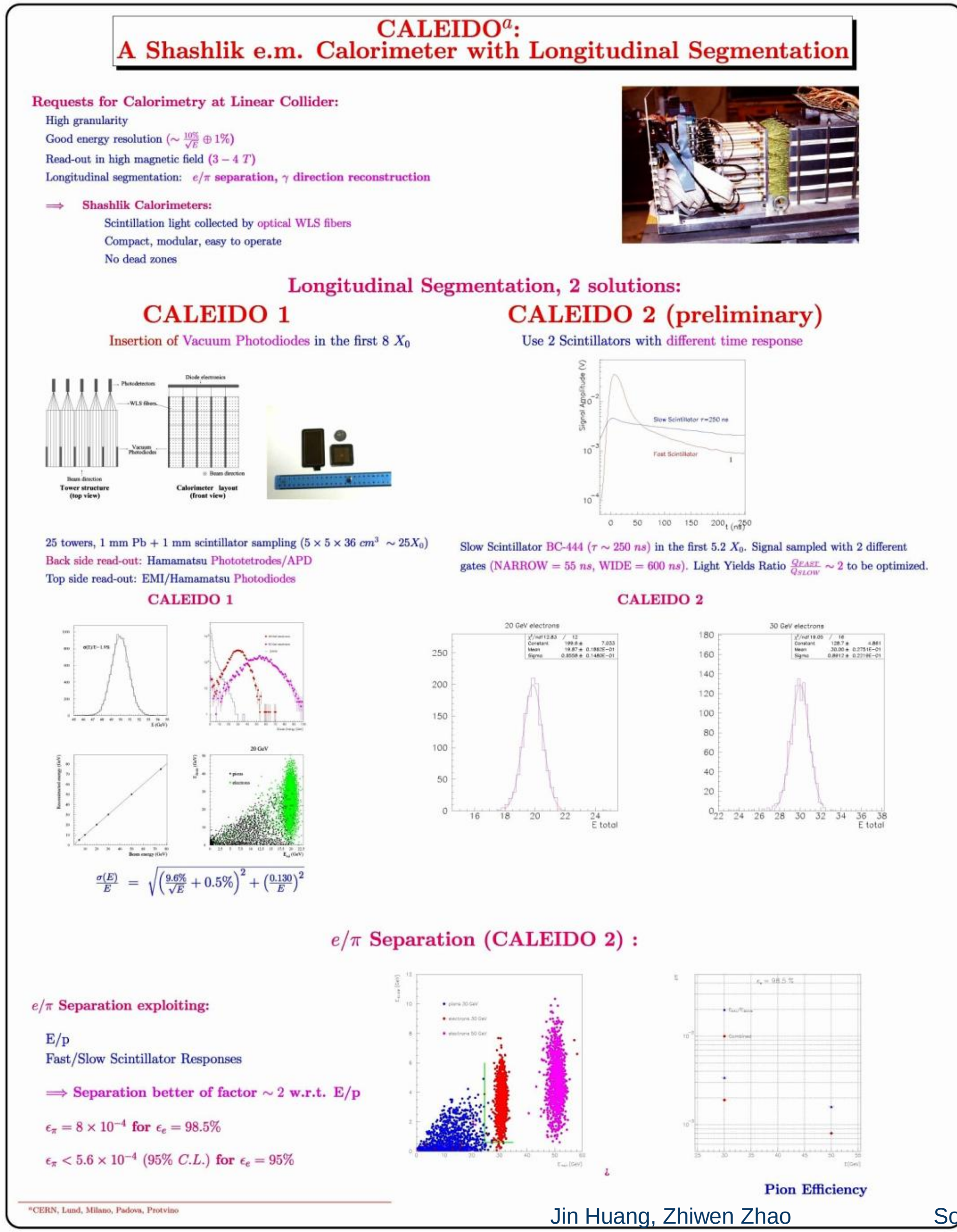
- **Option 3:**

  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

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

https://hedberg.web.cern.ch/hedberg/home/caleido/caleido.html



PVDIS rate

Process	Geometry	
	Open	baffles
DIS total	2500 kHz	110 kHz
DIS $W > 2$ GeV, $X > 0.20$	1500 kHz	110 kHz
DIS $W > 2$ GeV, $X > 0.55$	35 kHz	12 kHz
DIS $W > 2$ GeV, $X > 0.65$	8 kHz	3 kHz
π^- $p > 0.3$ GeV	2300 MHz	140 MHz
π^- $p > 1.0$ GeV	460 MHz	70 MHz
π^- $p > 2.0$ GeV	26 MHz	8 MHz
DIS $X > 0.20$ $E_{CALOR} > E_{thr}(R)$	680 kHz	102 kHz
π^- $E_{CALOR} > E_{thr}(R)$	540 kHz	120 kHz
π^- $E_{CALOR} > E_{thr}(R)$ pileup	$\sim$10 kHz	<2 kHz

Table 3.3: Calculated DIS and pion rates in the spectrometer.

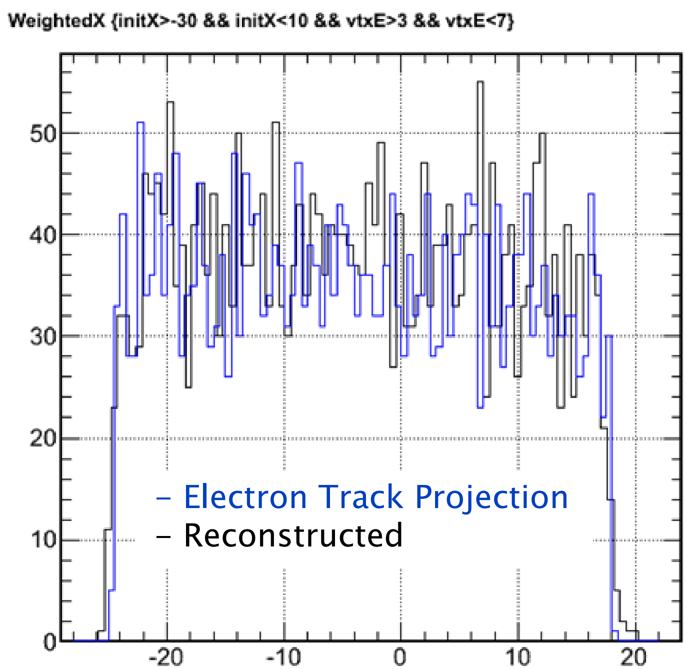
SIDIS rate

Process	Rate Forward angle 11 GeV	Rate Large angle 11 GeV	Rate Forward angle 8.8 GeV	Rate Large angle 8.8 GeV
(e,eπ^+)	1467 Hz	192 Hz	810 Hz	117 Hz
(e,eπ^-)	1010 Hz	120 Hz	554 Hz	73 Hz
single e^-	88.5 kHz	11.0 kHz	151 kHz	16.5 kHz
high energy photon	623 kHz	51.5 kHz	596 kHz	37 kHz
single π^+	2.90 MHz	20.2 kHz	2.5 MHz	13.4 kHz
single π^-	1.77 MHz	14.5 kHz	1.47 MHz	9.2 kHz
single K^+	226 kHz	5.9 kHz	185 kHz	4.1 kHz
single K^-	54.6 kHz	1.2 kHz	39.9 kHz	0.6 kHz
single proton	1.15 MHz	13.8 kHz	0.99 MHz	9.4 kHz
low energy photon	200 MHz	-	200 MHz	-

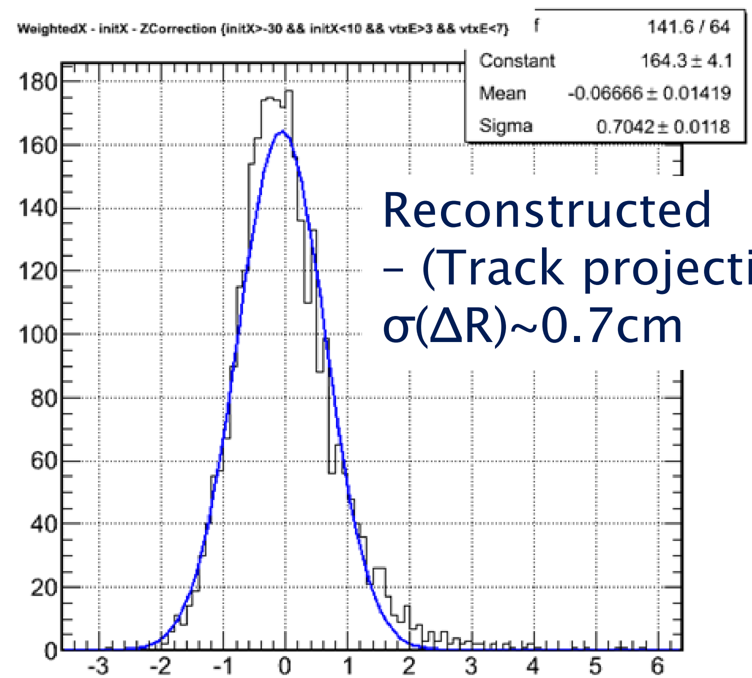
Transverse Size

- Larger Transverse Size means
  - Less position resolution, position become discrete
  - More background
  - Less Cost

Illustration w/ 2x2cm model (intrinsic res.)
Energy deposition weighted position average
Integrated over working momentum range



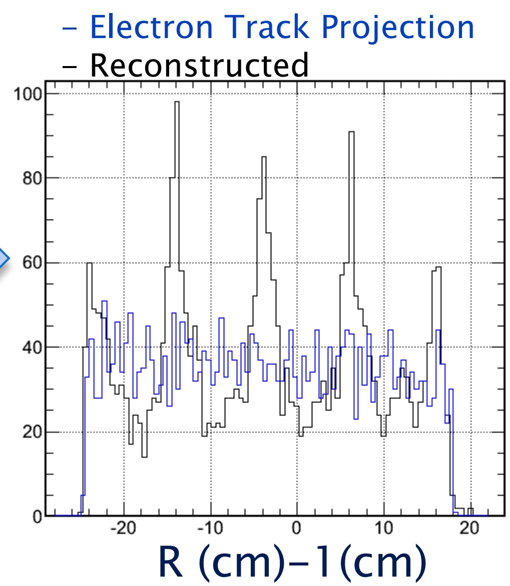
R (cm)−1(cm)

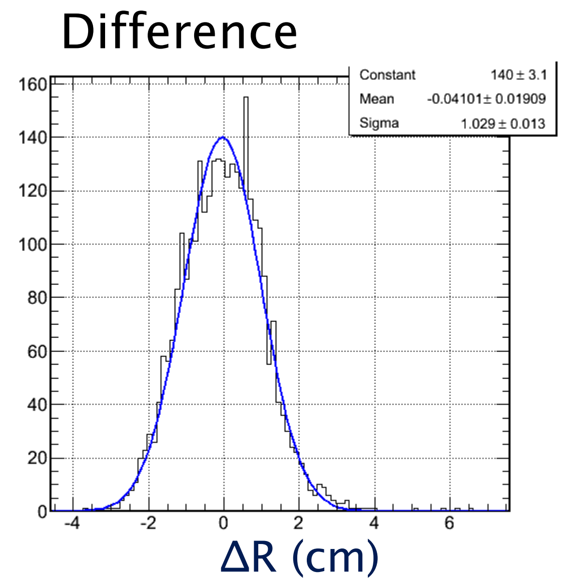


Reconstructed
– (Track projection)
σ(ΔR)~0.7cm

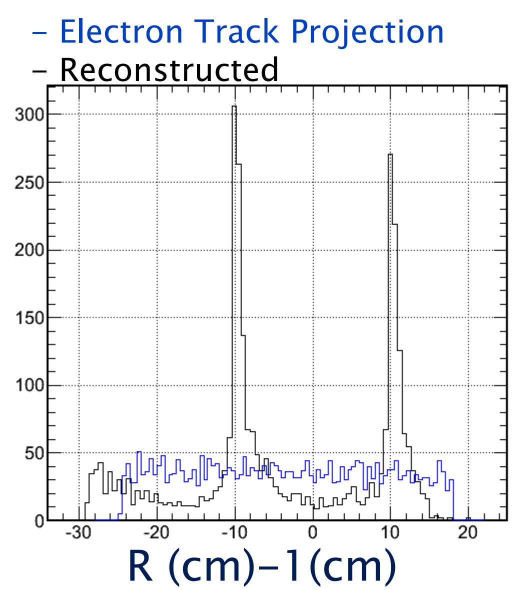
ΔR (cm)

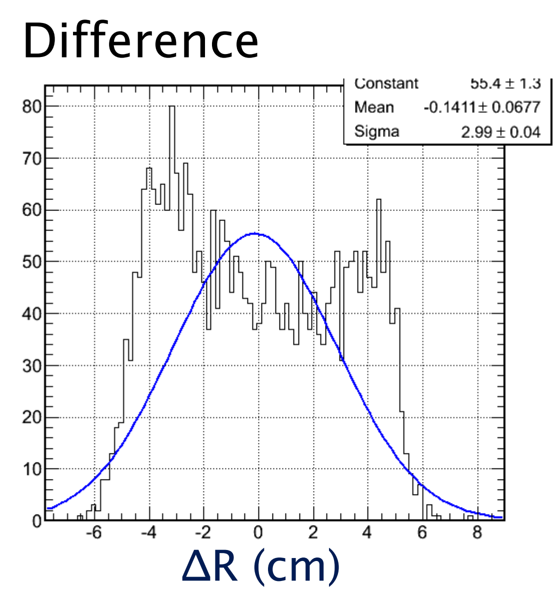
- •10x10 cm block size
- •Noticeably discrete
- •σ(ΔR)~1.0cm





- •20x20 cm block size
- •Discrete effect dominant
- •σ(ΔR)~3.0cm





More consideration on transverse size
Rough numbers only