12 GeV Upgrade
Future Science at Jefferson Lab

Electromagnetic Calorimeters (EC) for SoLID

The SoLID EC Working Group

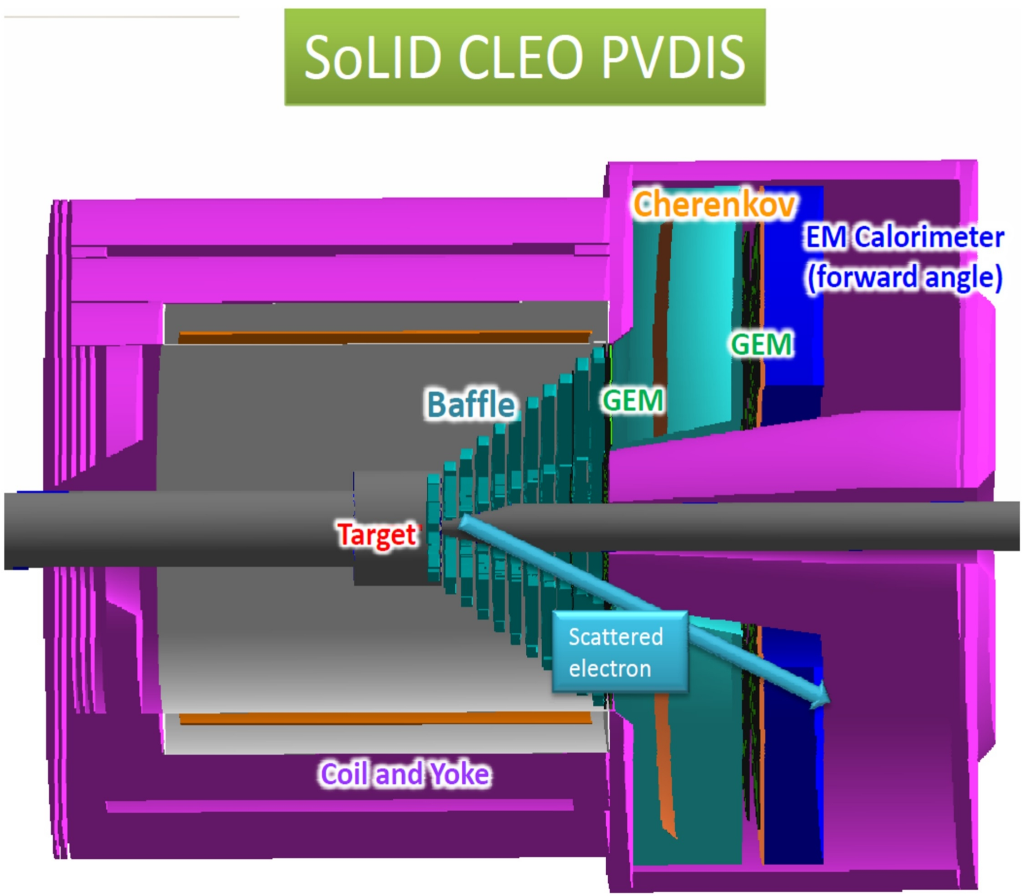
SoLID Collaboration Meeting

July 9-10, 2014

SoLID EC configuration

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

	θ (deg)	z (cm)	R(cm)	P (GeV/c)	Max π/e	Area (m^2)
PVDIS FAEC	22 - 35	(320,380)	(110,265)	2.3 - 6	~200	~ 18.3
SIDIS FAEC	7.5 - 14.85	(417,475)	(98,230)	1 - 7	~200	~ 13.6
SIDIS LAEC	16.3 - 24	(-65,-5)	(83,140)	3-6	~20	~ 4.0



EC Design Requirements — Physics

1. Electron- hadron separation:
   - >50:1 π rejection above Cherenkov threshold (~4) to 7GeV/c;
   - Electron efficiency > 95%;
   - (energy resolution: $\sigma(E)/E < 10\%/\sqrt{E}$)
2. Provide trigger:
   - PVDIS: coincidence with CC, suppress background;
   - SIDIS: identify beam bunch for PID thru TOF → timing $\sigma \sim 10^2$ps
3. Provide shower position to help tracking/suppress background
   - $\sigma \sim 1$ cm

EC Design Requirements — Other

4. Radiation resistance: > (4-5)x10^5 rad
5. B~1.5 T, high neutron background for SIDIS LAEC:
   - guide signals far from B field → PMTs
   - not silicone-based detector
6. Modules easily swapped and rearranged for PVDIS ↔ SIDIS; SIDIS needs 2-fold rotation (180^o) symmetry

SPD Design Requirements — Physics

1. Provide photon rejection (SIDIS only)

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	$2x10^4$	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	$4x10^5$	10^5	$3.5\%/E^{1/2}$

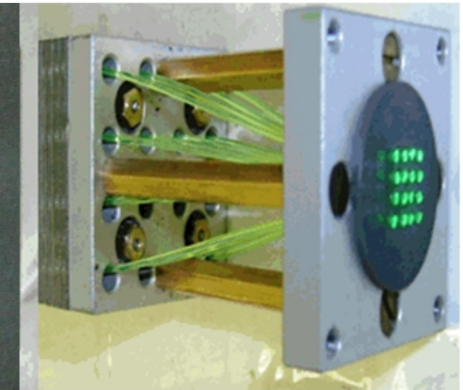
Choosing EC Type

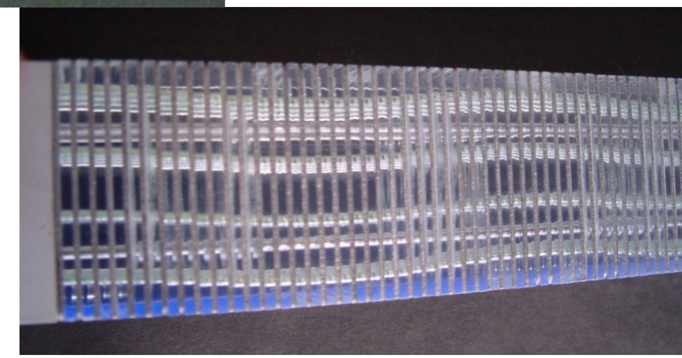
- SoLID radiation level (~400 krad per year) is too high for leadglass and CSI-like crystals (typically 1krad).
- Our ECs are large: 6-8m^3; Crystals: $PbWO_4$ (\$10/cc) and LSO (\$40/cc) can stand 10^6 rad, but to fill ~6m^3→ \$60M or \$240M .
- Both Shashlyk or SPACAL/SciFi (0.5-1Mrad) have enough 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
  - ϕ1mm fibers cost \$1/m: Total 6m^3 → **\$4M** for fiber alone.
  - Two orders of magnitude fibers more than Shashlyk, hard to read out, high PMT/DAQ cost.
- Shashlyk: total module production cost ~\$3.4M from IHEP, plus fiber/PMT/DAQ.

Shashlyk EC





- 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

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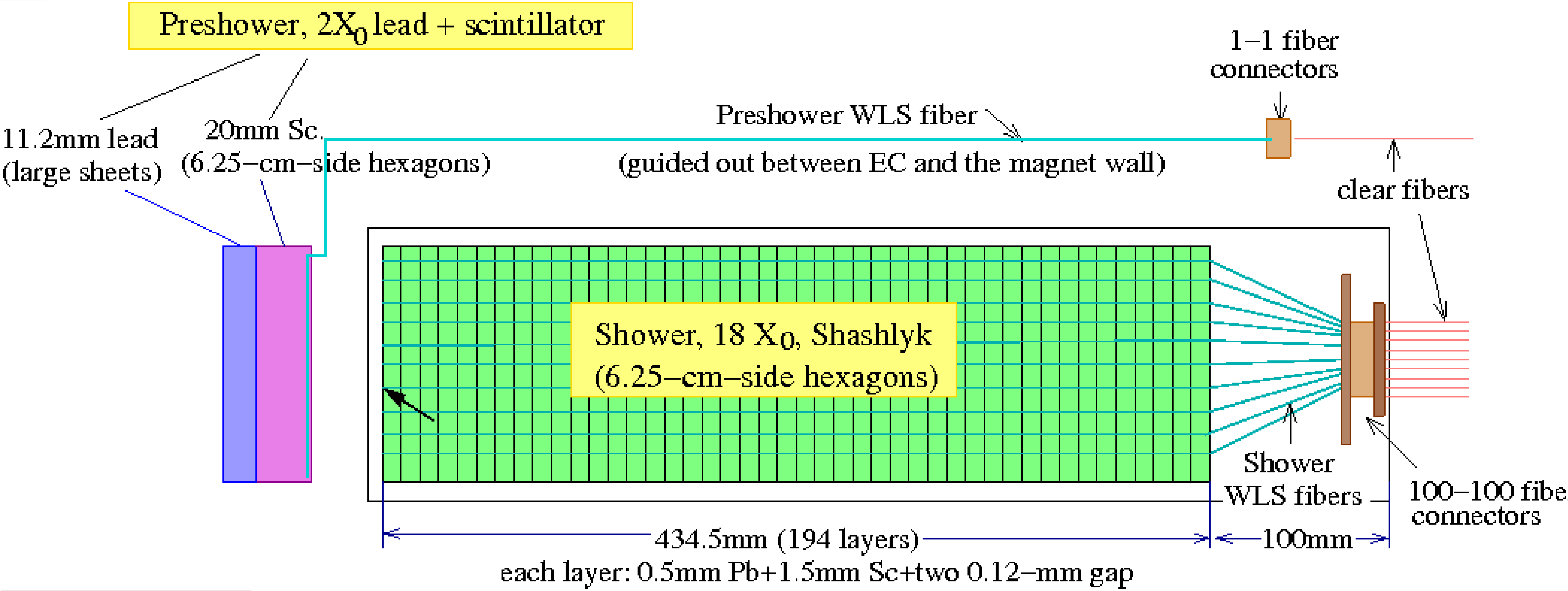
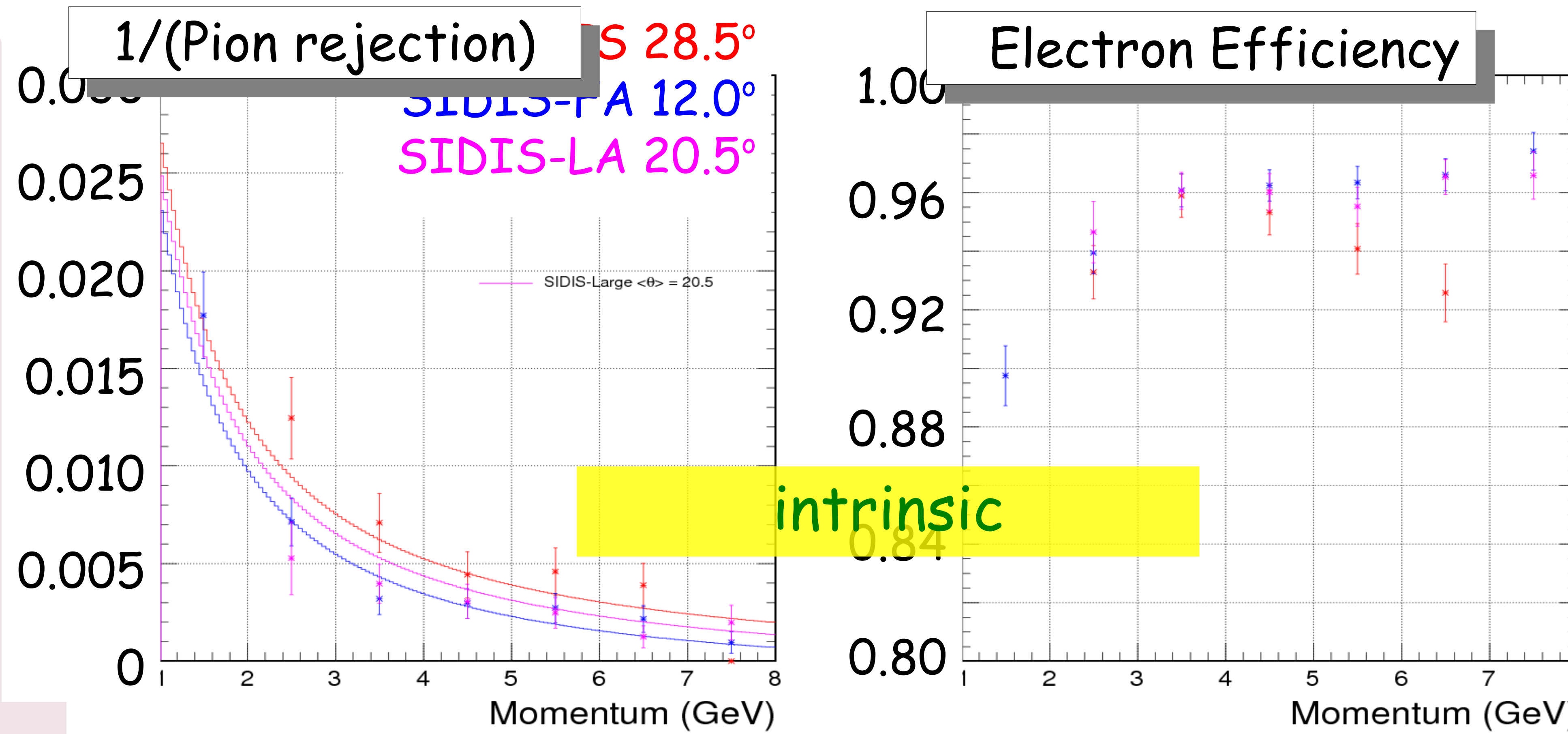
Design Consideration 1: Longitudinal

- Preshower: $2X_0$ lead + 20mm scintillator
- Preshower+Shower total length: $20X_0$
- Preshower and Shower have the same lateral design, otherwise totally detached



Design Consideration 1: Longitudinal

- Preshower: $2X_0$ lead + 20mm scintillator
- Preshower+Shower total length: $20X_0$
- Shower: 100:1 intrinsic pion rejection → 0.5mm Pb/1.5 mm Scint. (BASF143E) per layer. [4.5-5%/sqrt(E)]



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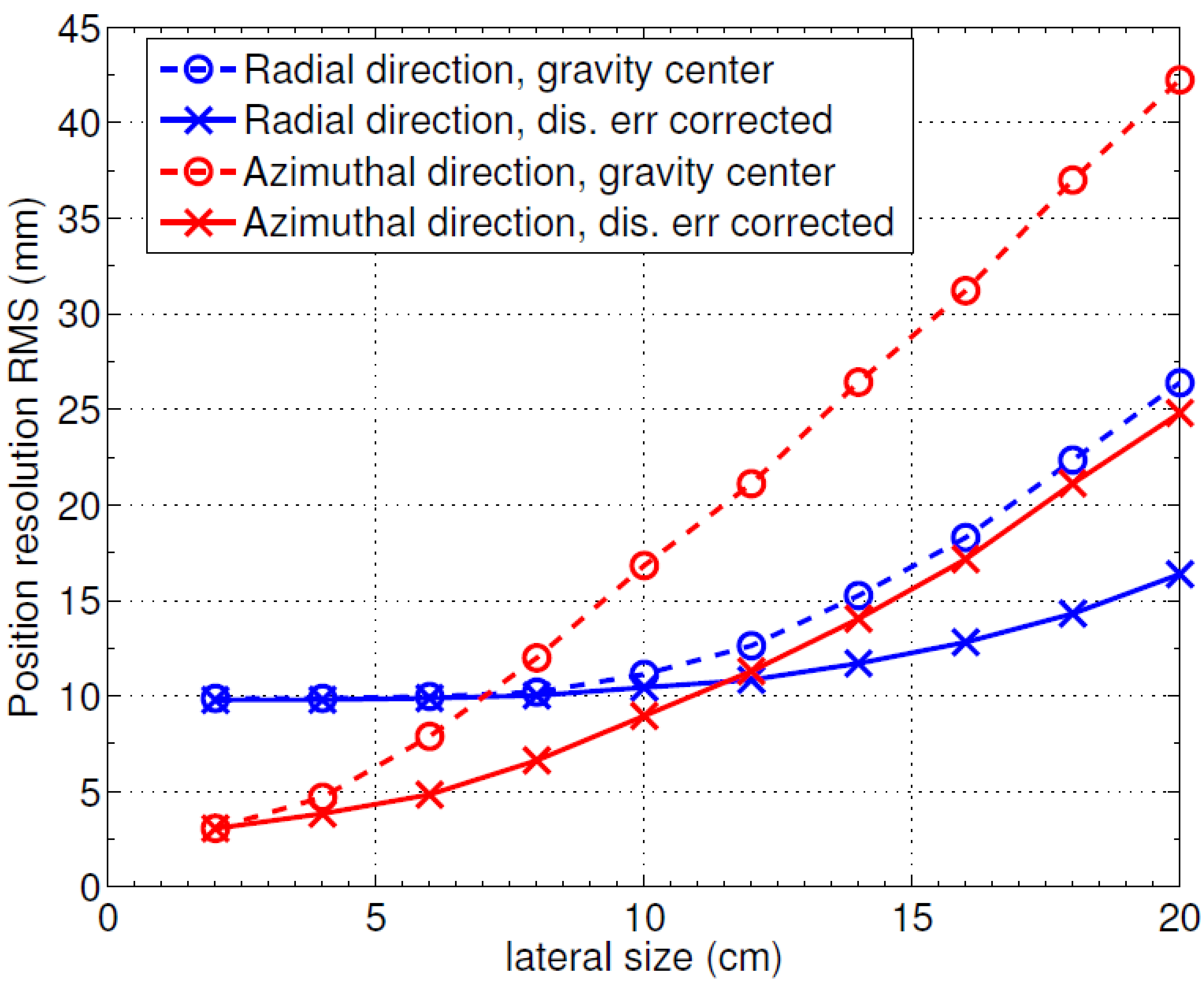
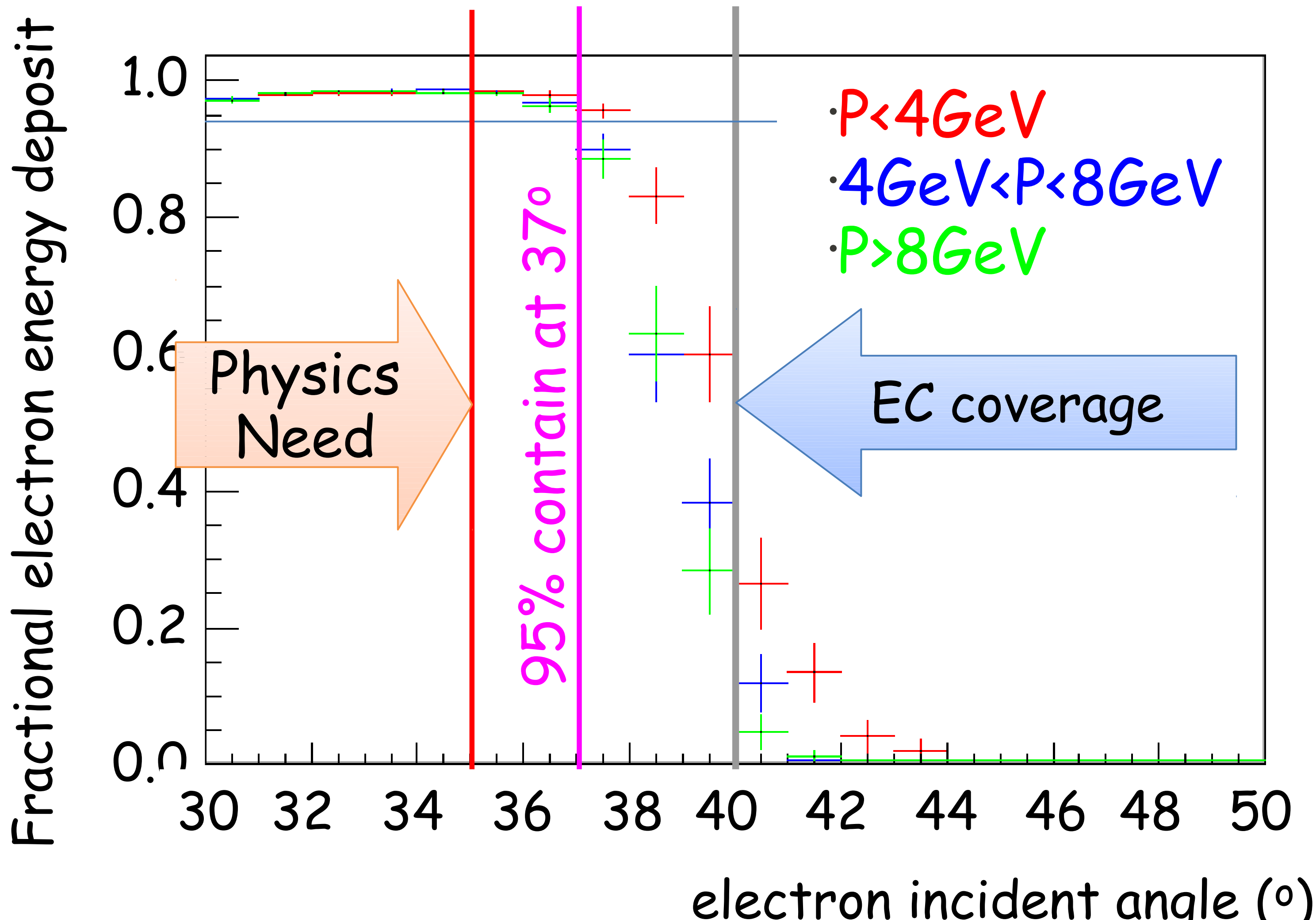
Design Consideration 2: Lateral



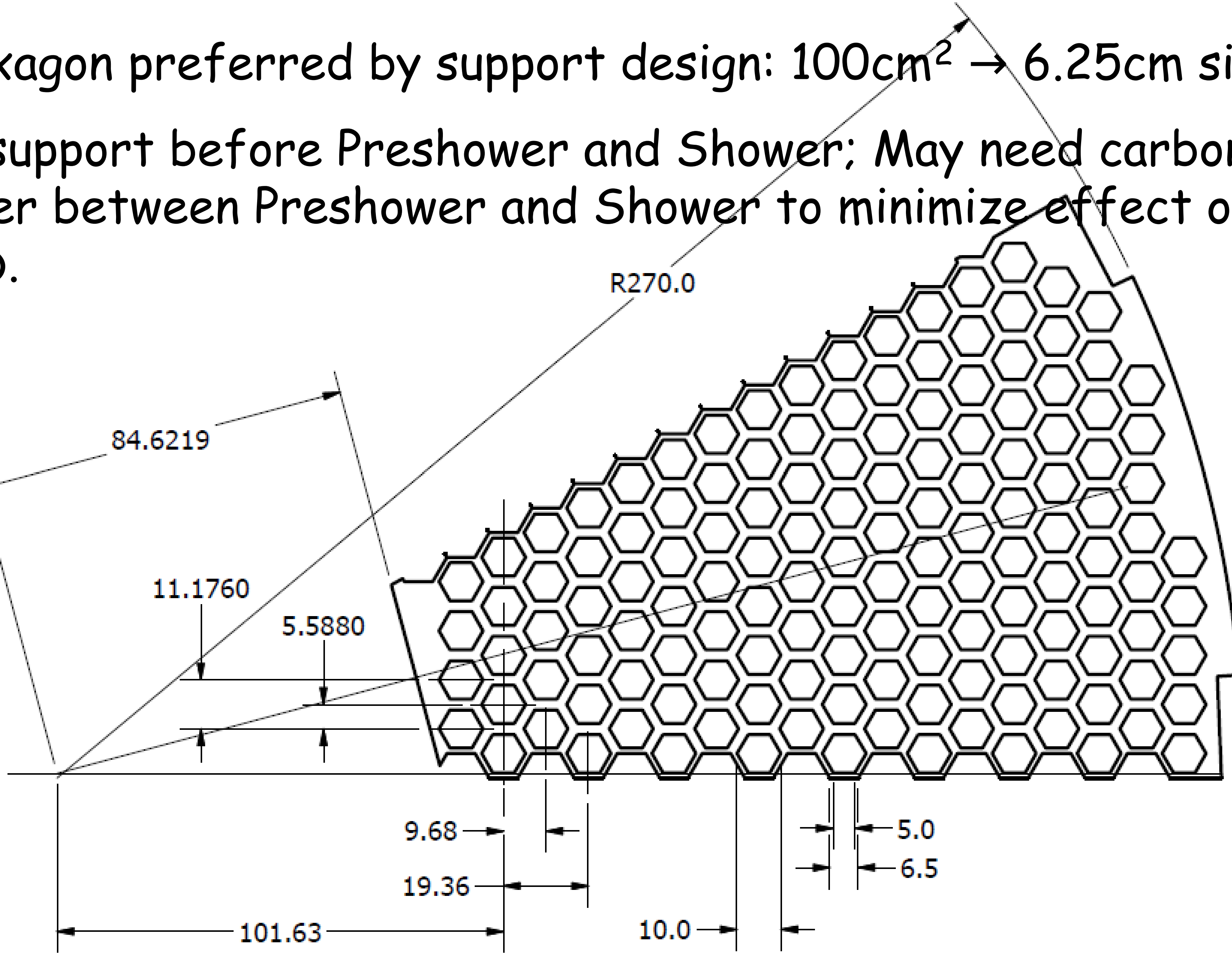
Design Consideration 2: Lateral

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



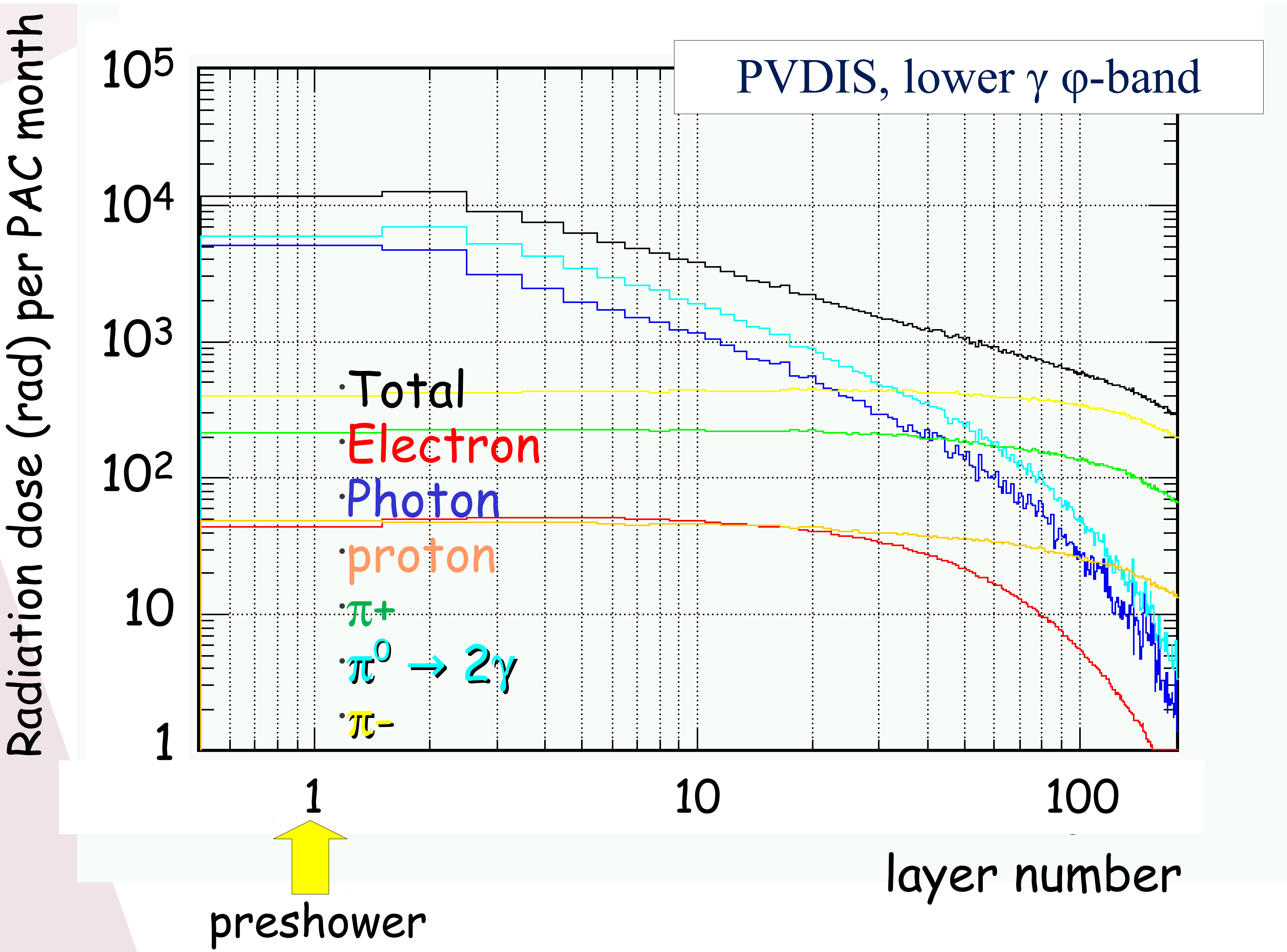
Design Consideration 2: Lateral

- Hexagon preferred by support design: 100cm^2 → 6.25cm side
- Al support before Preshower and Shower; May need carbon fiber between Preshower and Shower to minimize effect on PID.



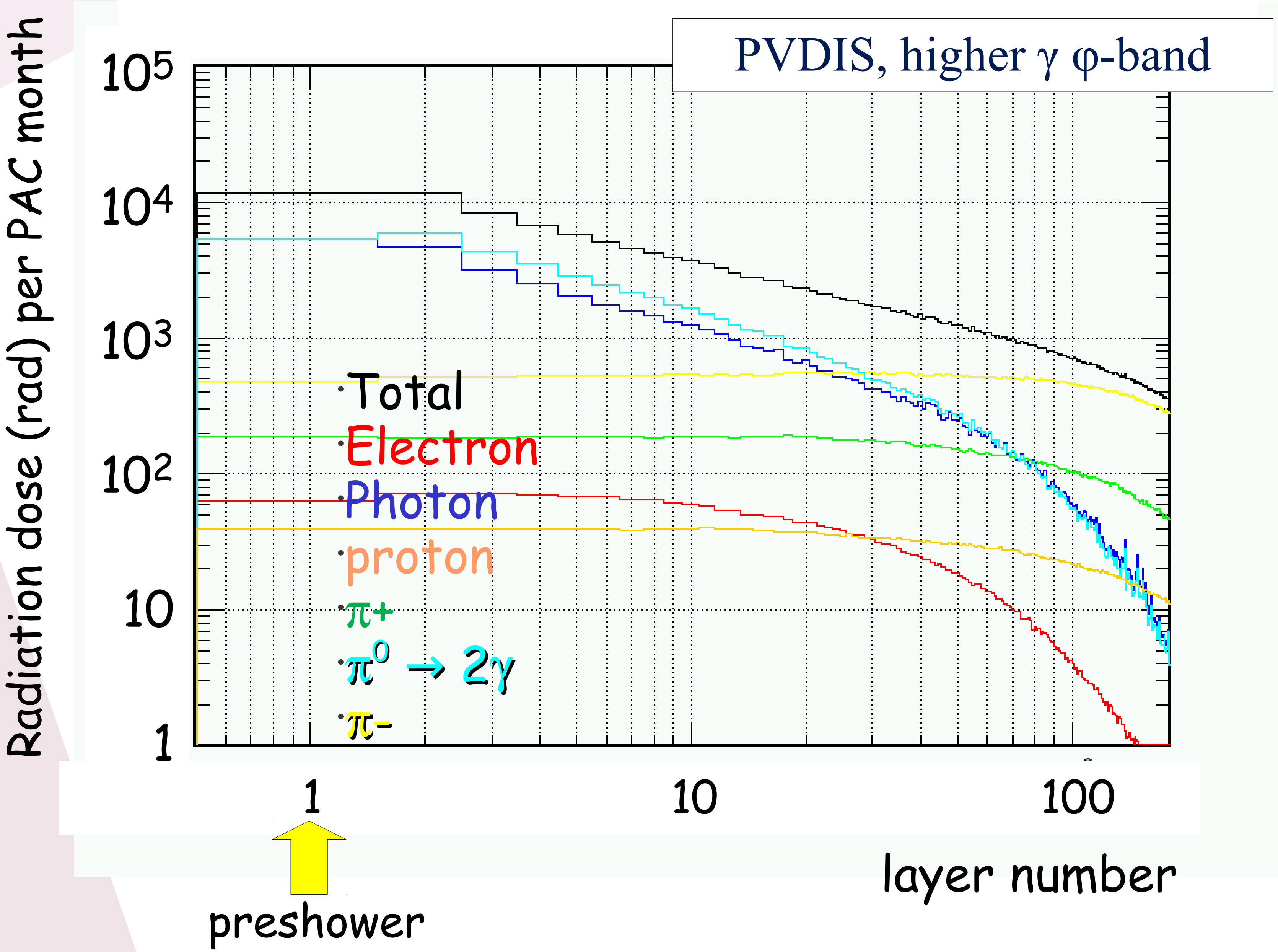
Design Consideration 3: Radiation Dose

- $2X_0$ lead efficiently block low energy photons



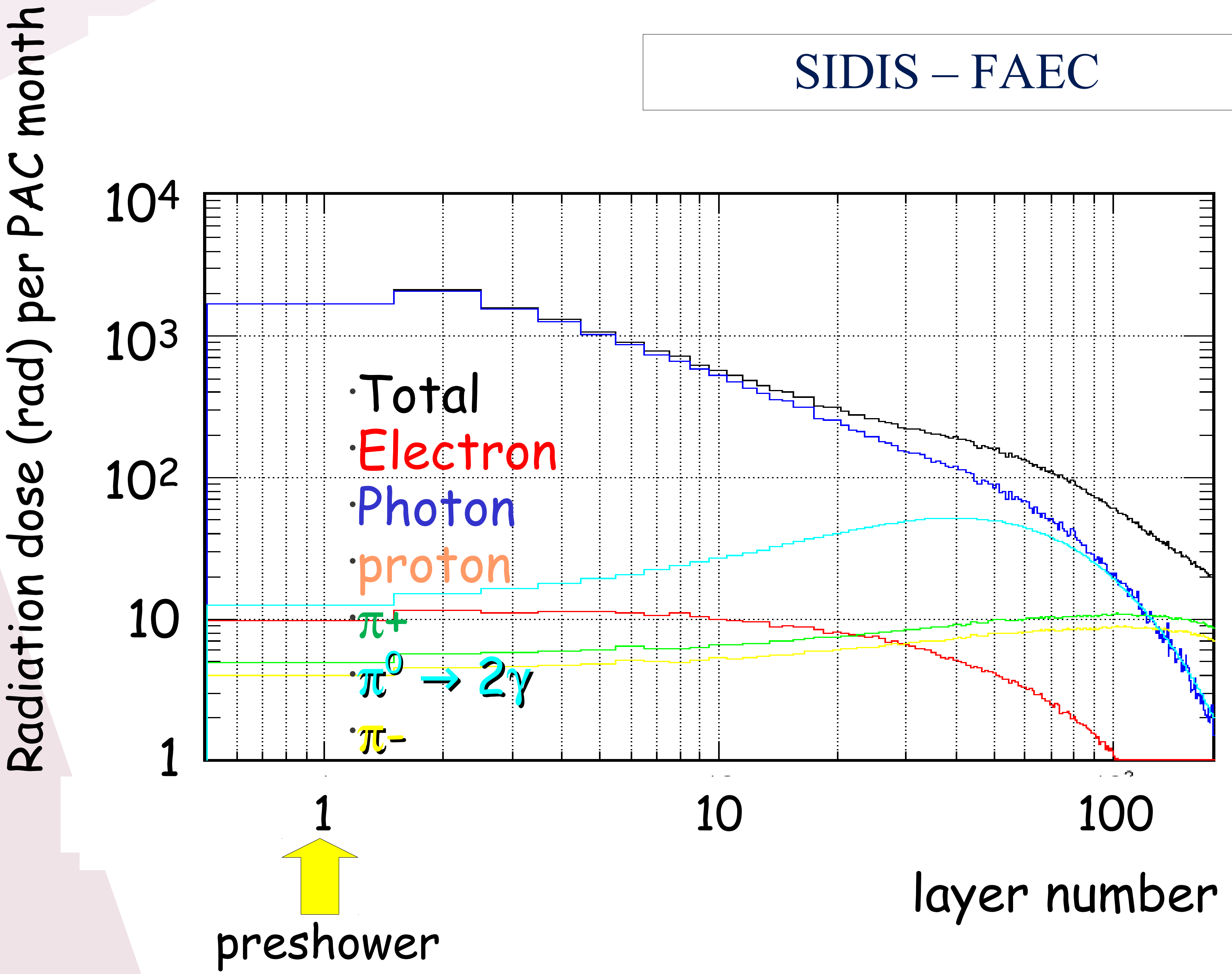
Design Consideration 3: Radiation Dose

- Photon blocker helps



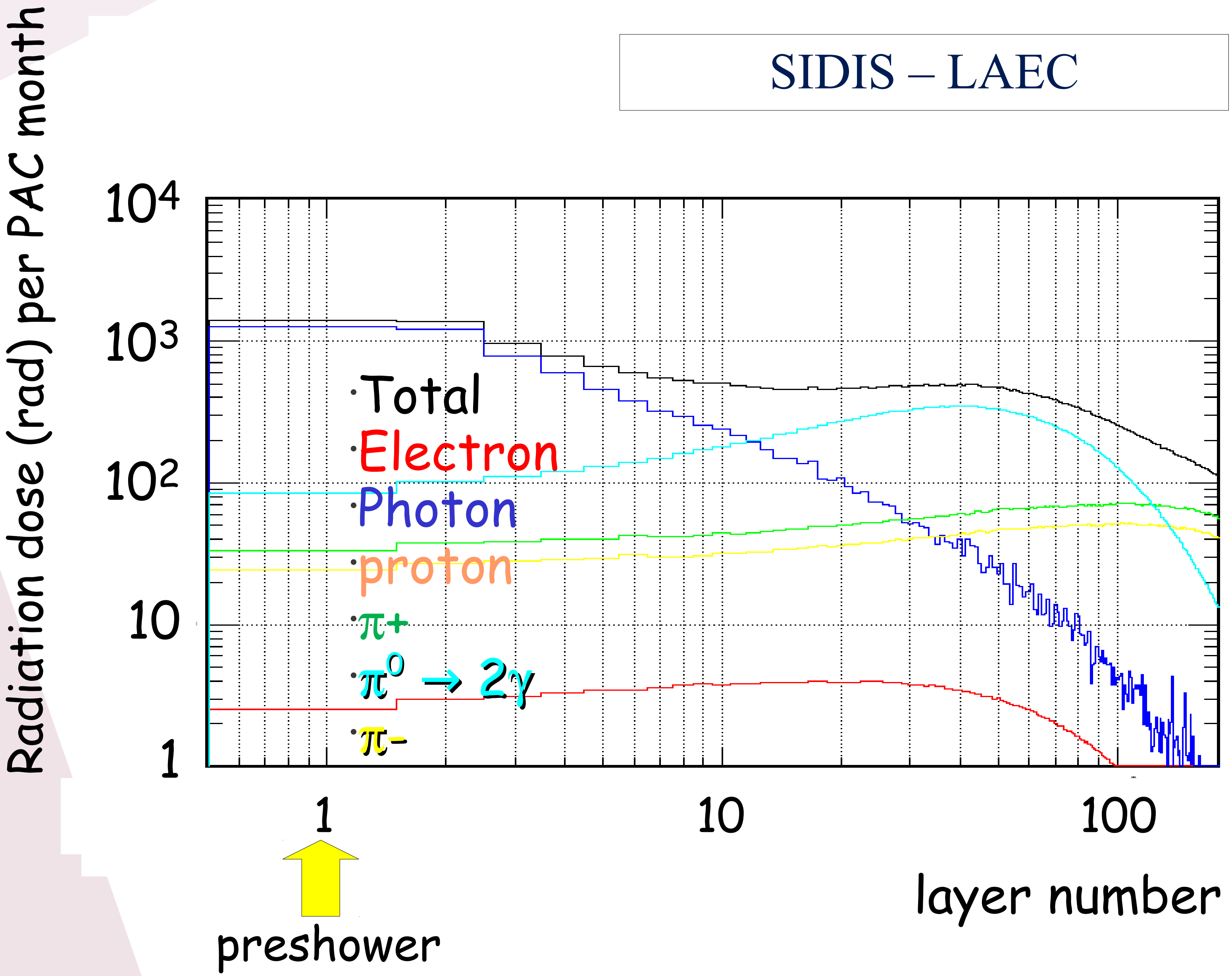
Design Consideration 3: Radiation Dose

- SIDIS: less of an issue

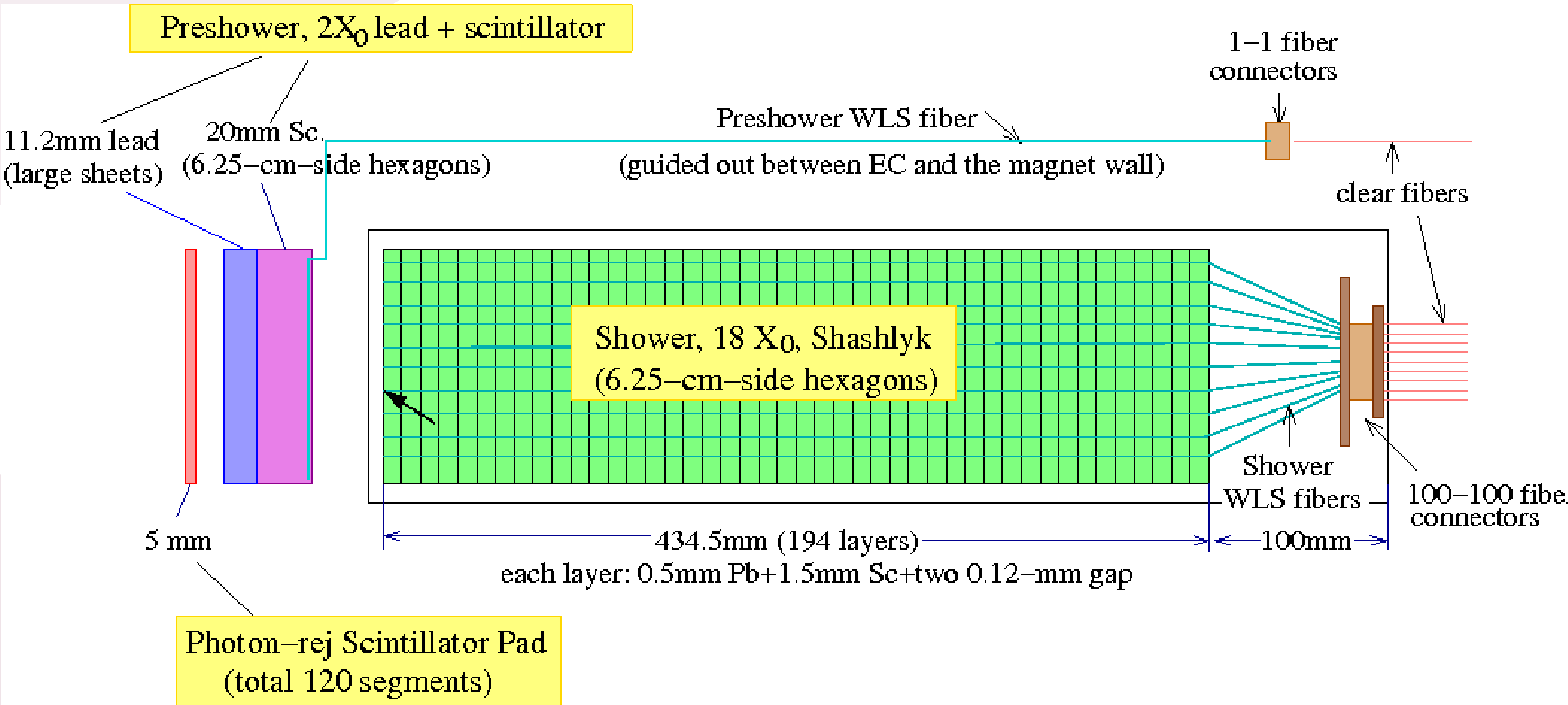


Design Consideration 3: Radiation Dose

- SIDIS: less of an issue



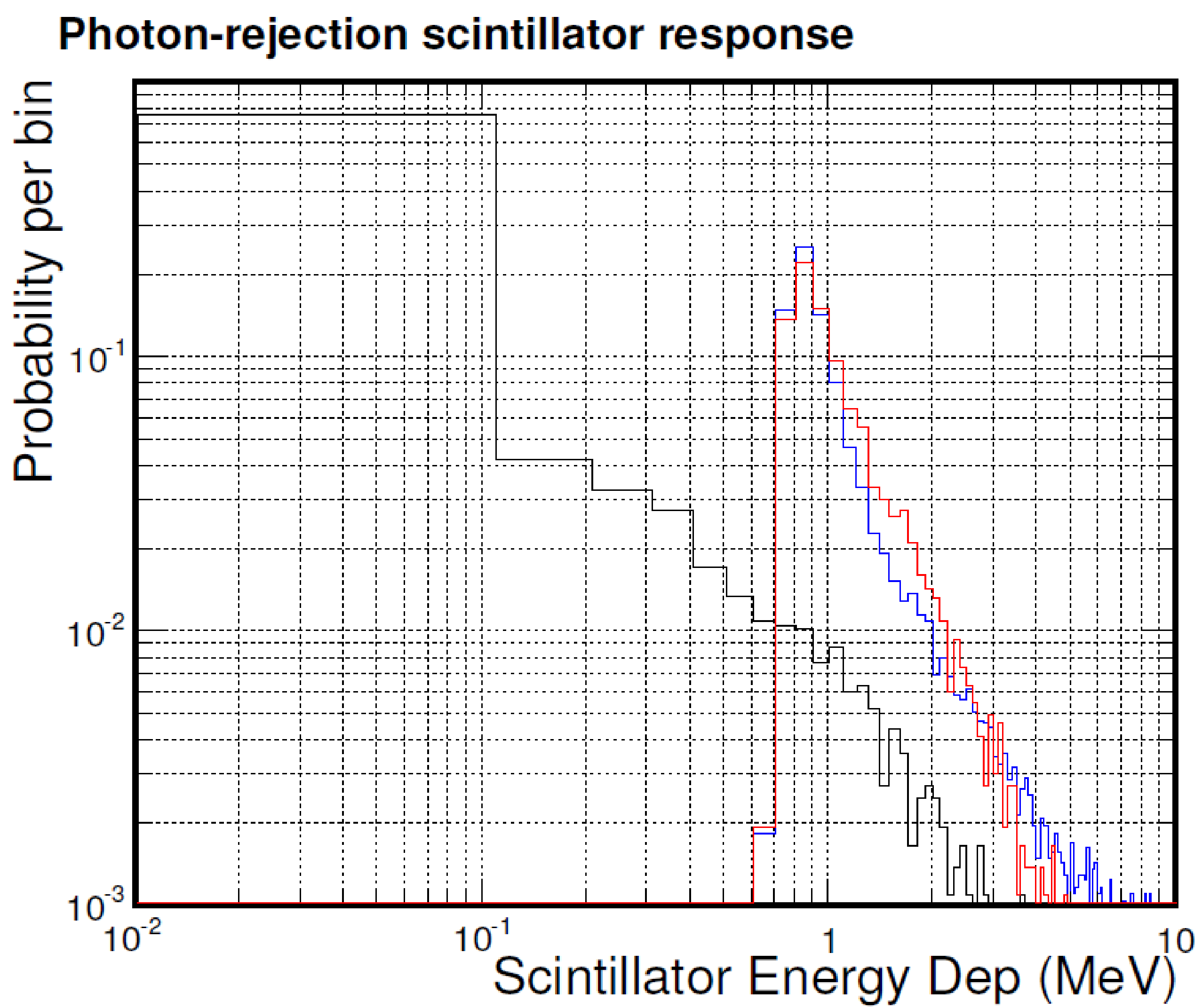
Design Consideration 4: SPD for SIDIS



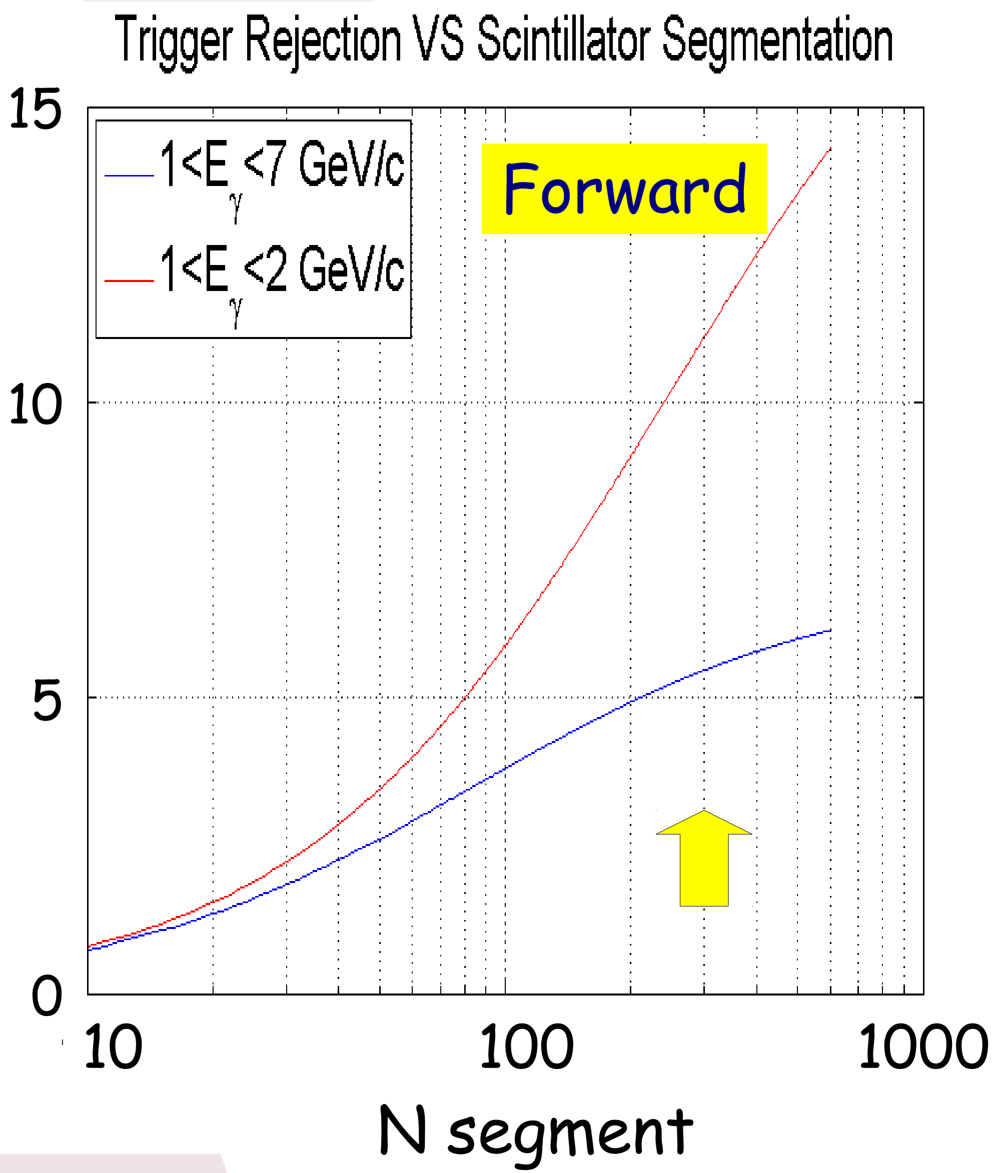
- Readout similar to Preshower
- Forward: between heavy gas and MRPC, 60 azimuthal x 4 radial
- Large angle: in front of EC, 60 azimuthal

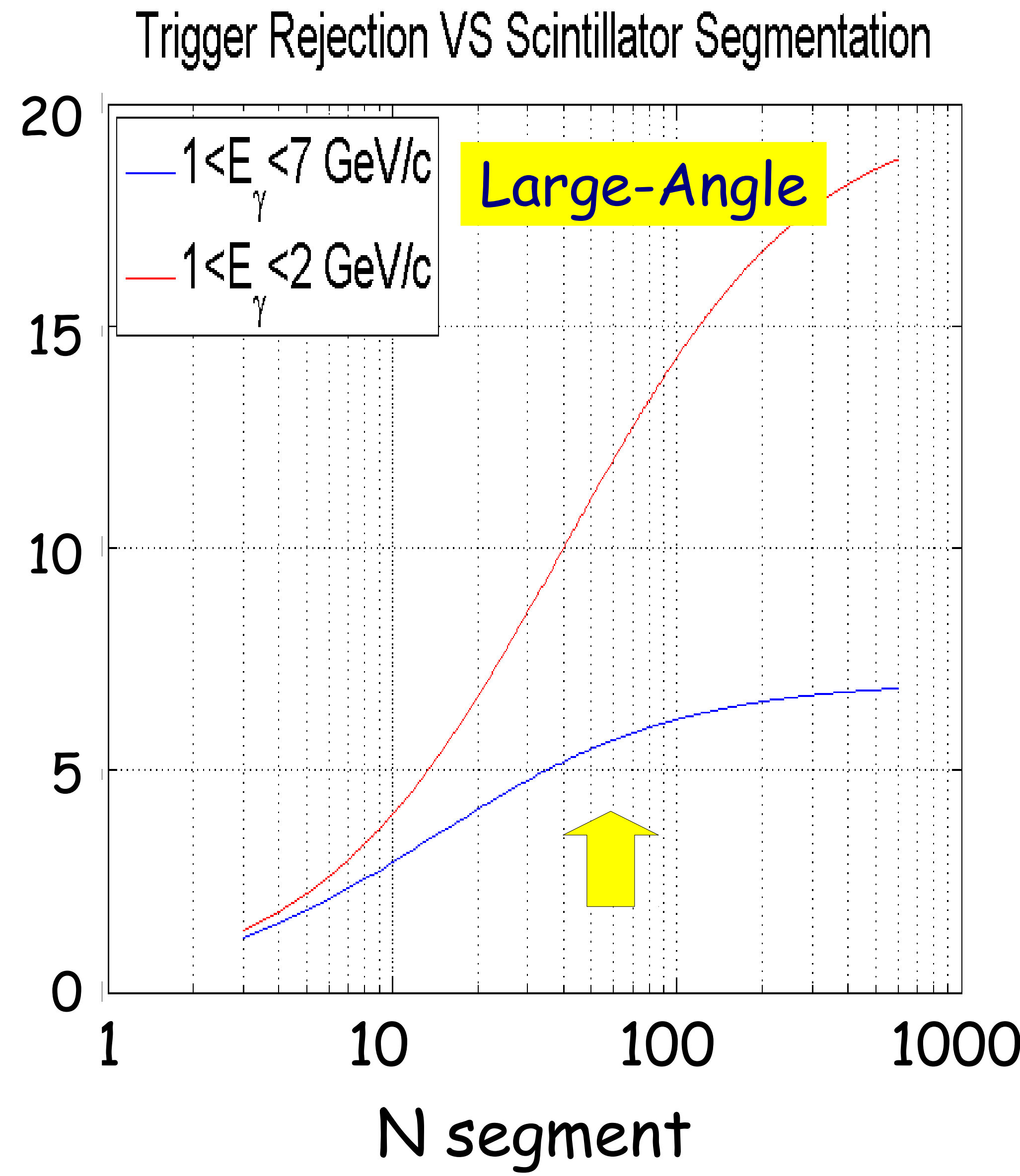
Design Consideration 4: SPD for SIDIS

Forward



Design Consideration 4: SPD for SIDIS





Design Consideration 4: Readout

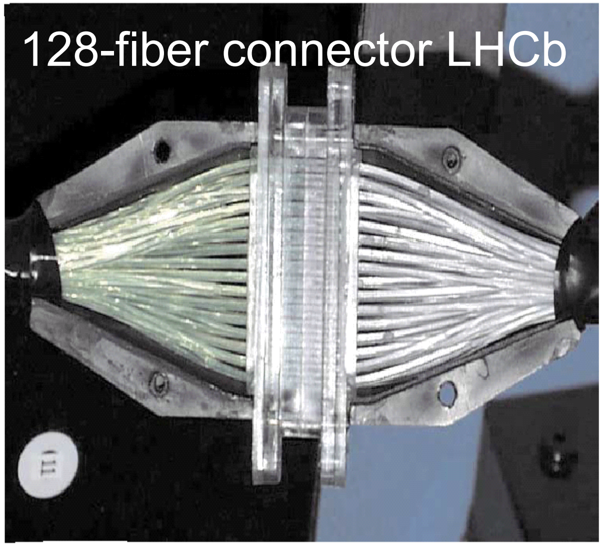
WLS fibers	Kuraray Y11	Saint Gobain BCF91A, BCF92 (faster)
wavelength	~420 → 494nm	~430 → 476nm
1/e length	>3.5m	>3.5m
mechanical property	better bending	
radiation hardness	13% light loss at 100krad (30% at 700krad)	15% light loss at 100krad (50% at 700krad)
light yield		2-3 times less than Y11
Clear fibers	Kuraray clear-PSM	Saint Gobain BCF98
cost	$$$$	$$

Will use Y11 for Preshower/SPD, BCF91A for Shower; Clear fiber yet to be tested.

Design Consideration 4: Readout

Fiber connector options:

- Preshower: 1-1 connector
- Shower: 100-100 connector
- Both can be made in-house using Delrin (as LHCb). Lab test shows 80% of light transmission



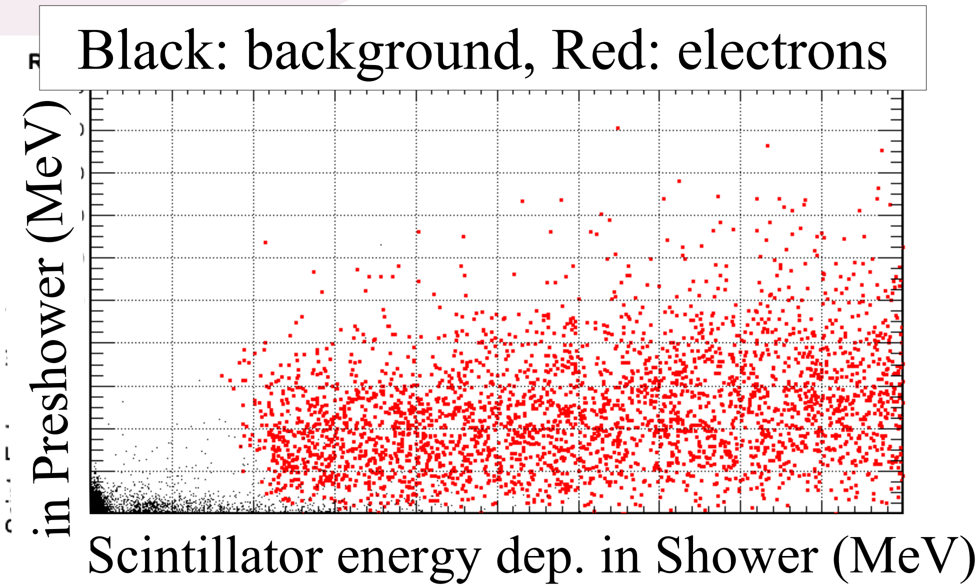
- fiber fusing possible, but switching SIDIS ↔ PVDIS difficult and can't be done locally
- Investigating other options (MINOS: DDK connectors

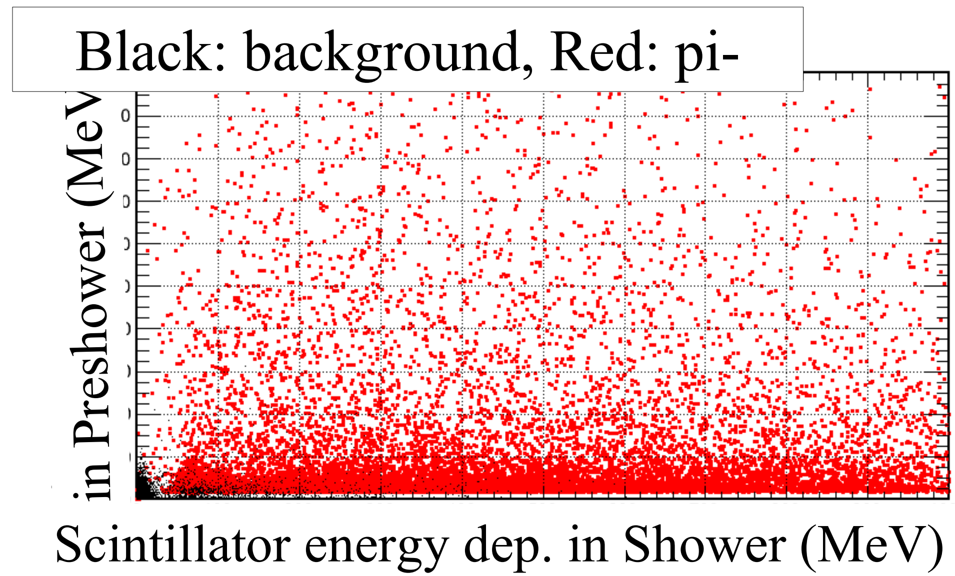
Design Consideration 4: Readout

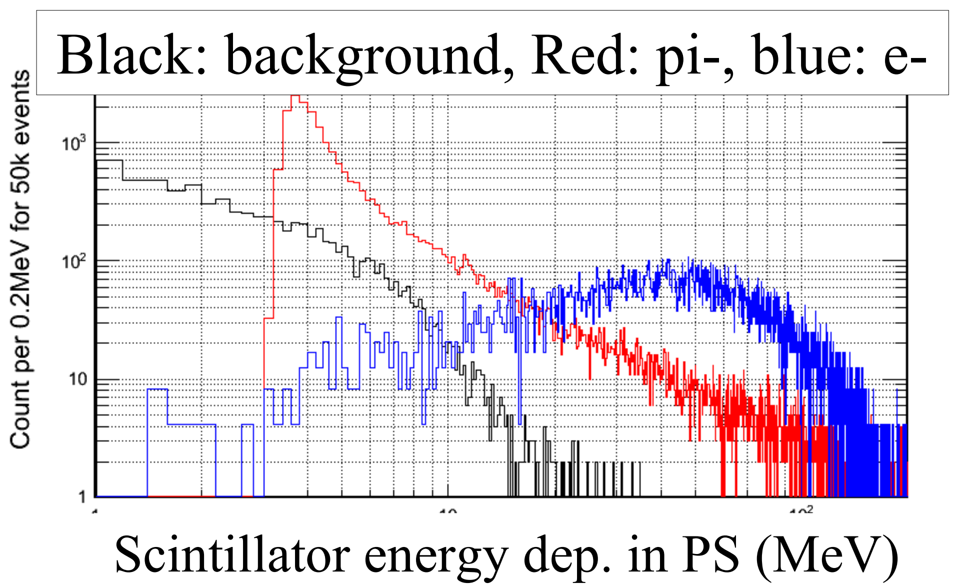
- SIDIS LAEC in high B field, high neutron background
- Silicon detectors expensive and won't stand the background.
- Guide light to low-B region to be read by PMTs
  - Shower: 100x ϕ–1mm fibers → ϕ-1in PMT (good area match), Hamamatsu R11102, x5 preamp gain, 5E4 PMT gain;
  - Preshower: (2-4)x ϕ–1mm fiber → 16-ch MAPMT, Hamamatsu R11265-100-M16, x50 preamp gain, 1E4 PMT gain
  - SPD: (2-4)x ϕ–1mm fiber → 16-ch MAPMT, Hamamatsu R11265-100-M16, x50 preamp gain, 1.6E5 PMT gain
- Working with JLab detector group on PMT base design

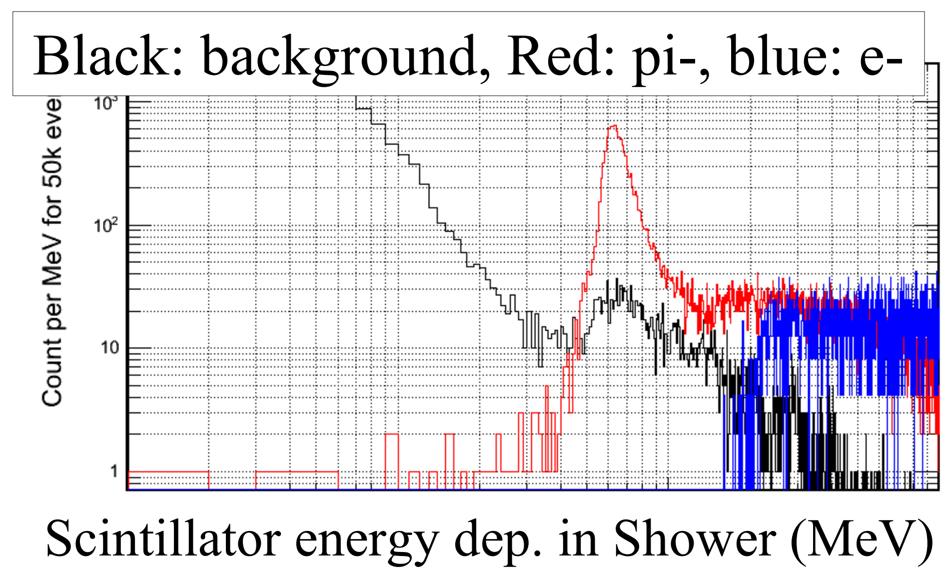
Performance — PID, SIDIS LAEC

- Background







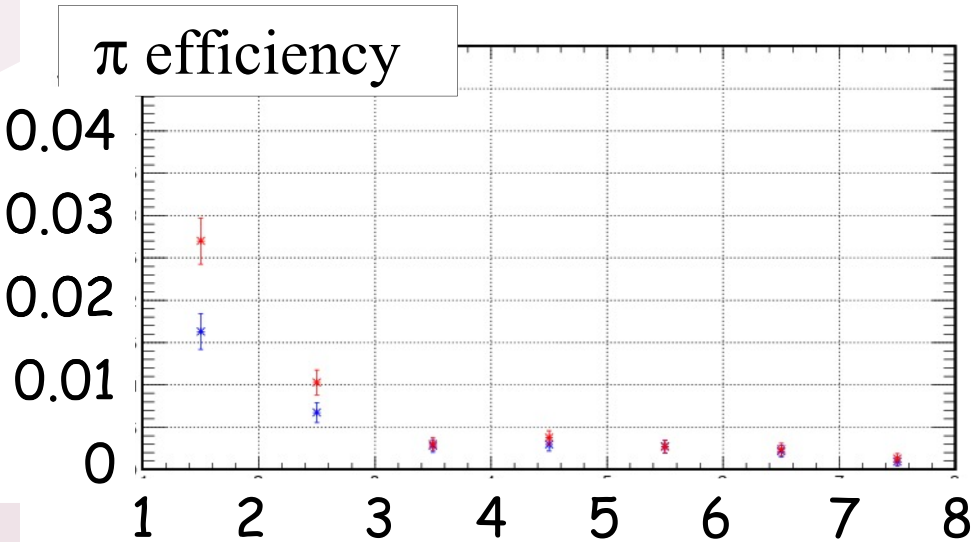


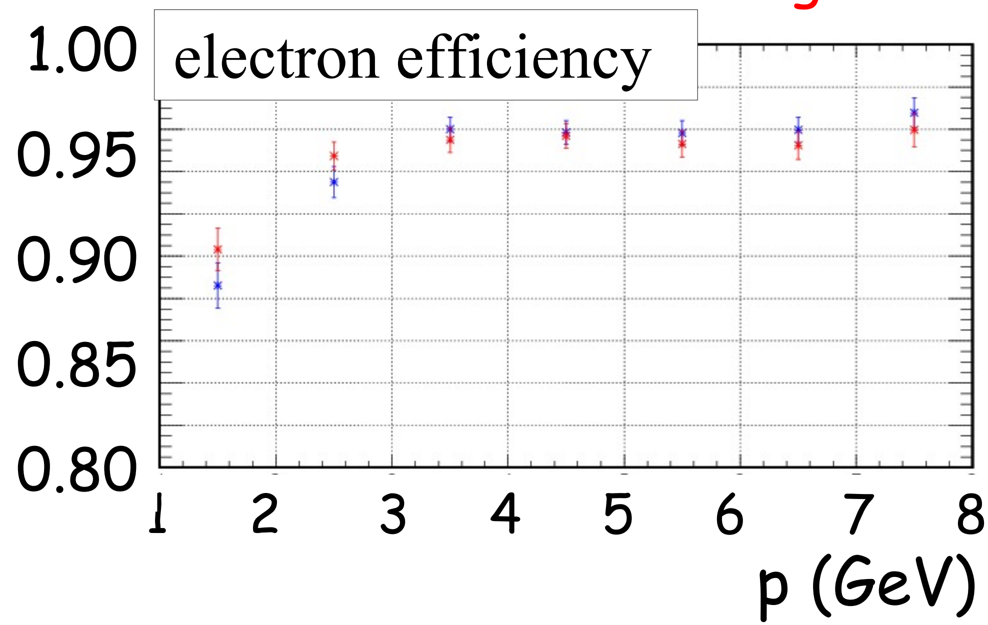
Performance — PID, SIDIS

Most inner radius region shown – worse case situation

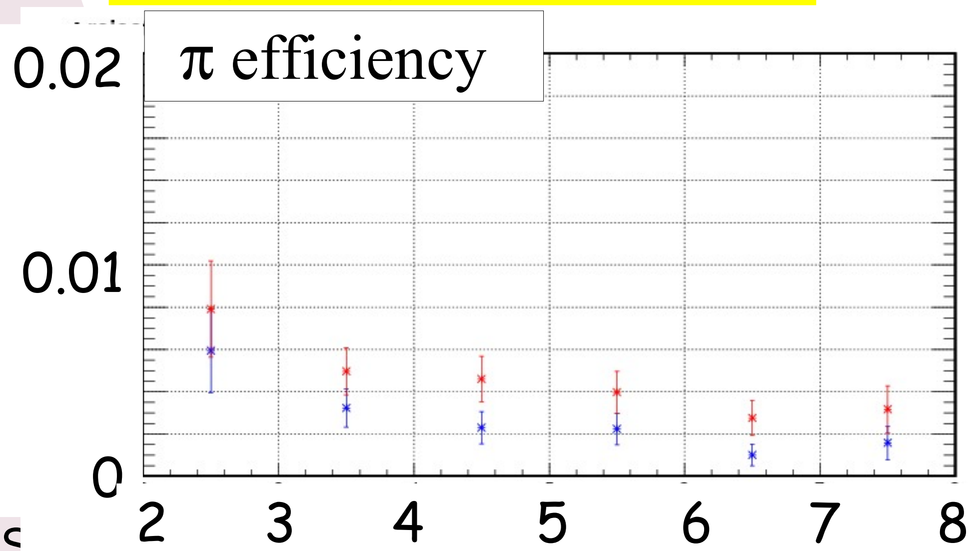
* Intrinsic
* W/ Background

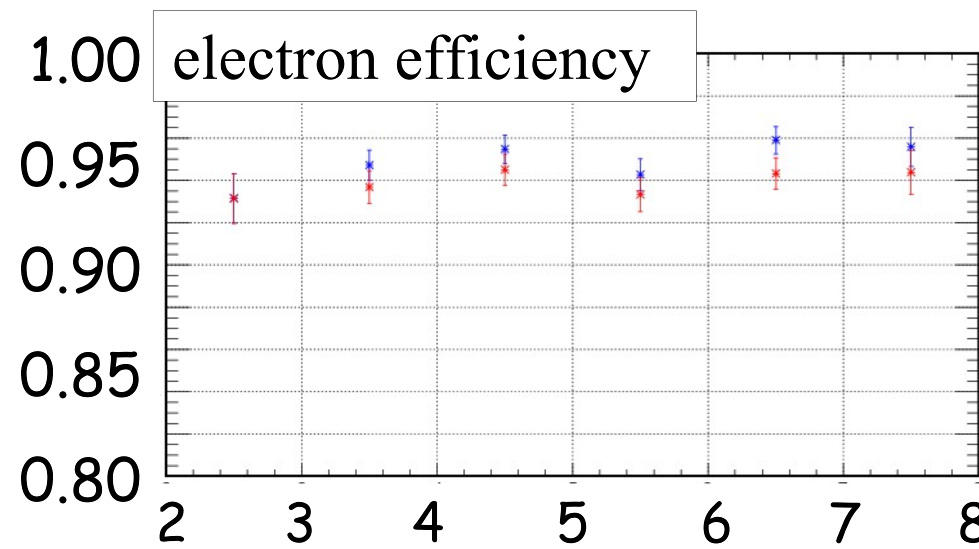
Forward Calorimeter





Large-Angle Calorimeter

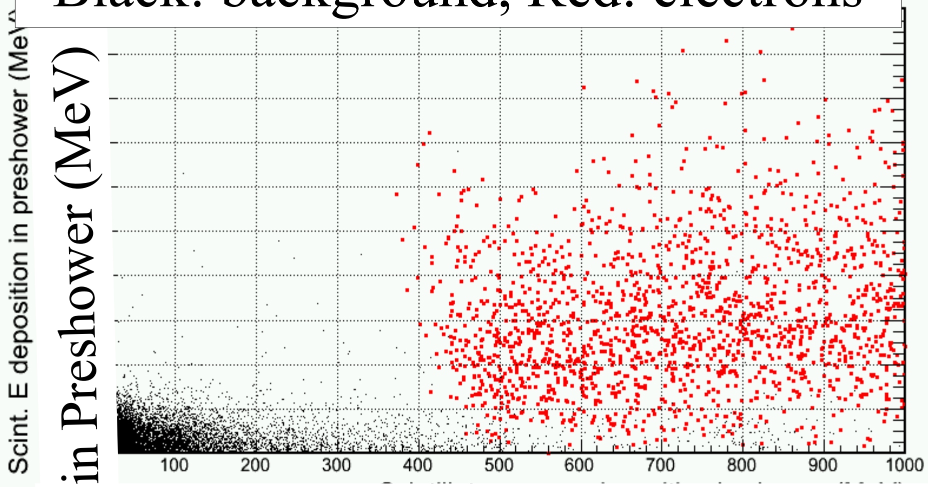




Performance — PID, PVDIS

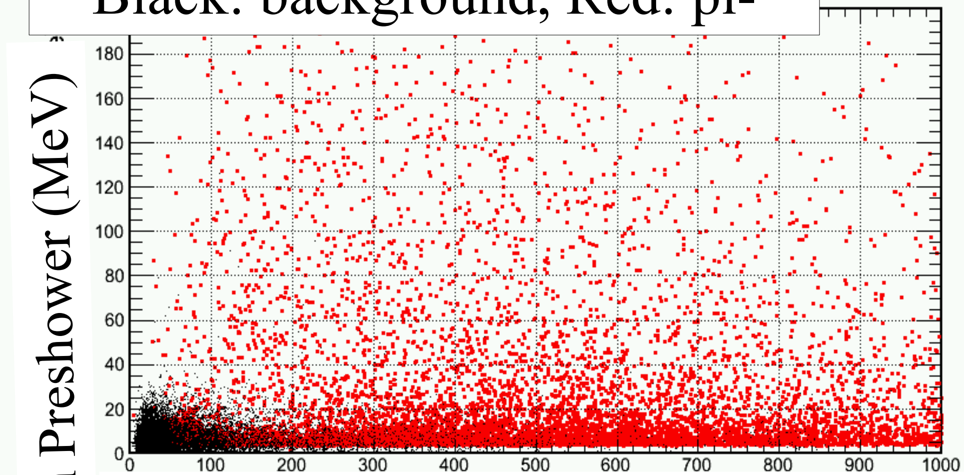
- Background

Black: background, Red: electrons



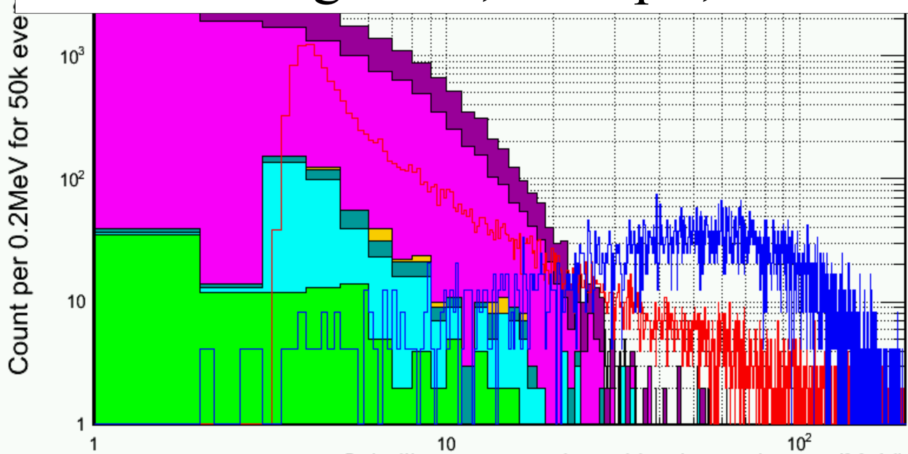
Scintillator energy dep. in Shower (MeV)

Black: background, Red: pi-



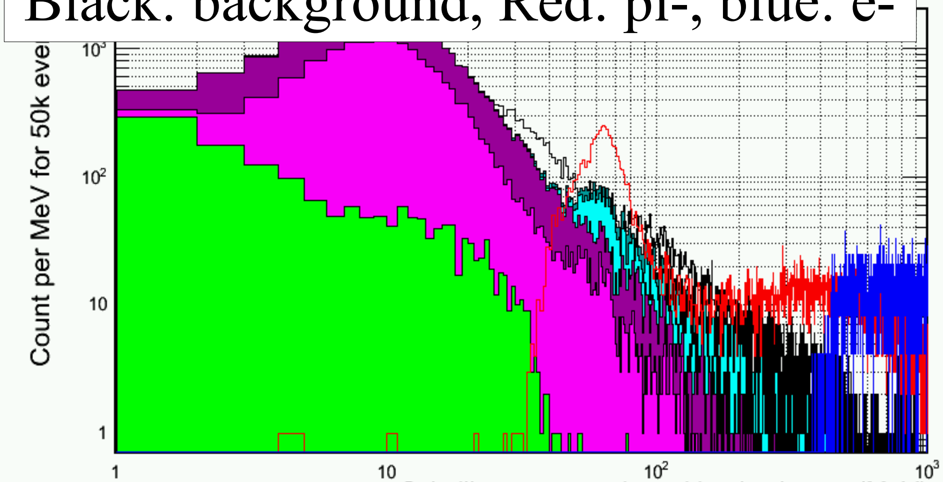
Scintillator energy dep. in Shower (MeV)

Black: background, Red: pi-, blue: e-



Scintillator energy dep. in PS (MeV)

Black: background, Red: pi-, blue: e-

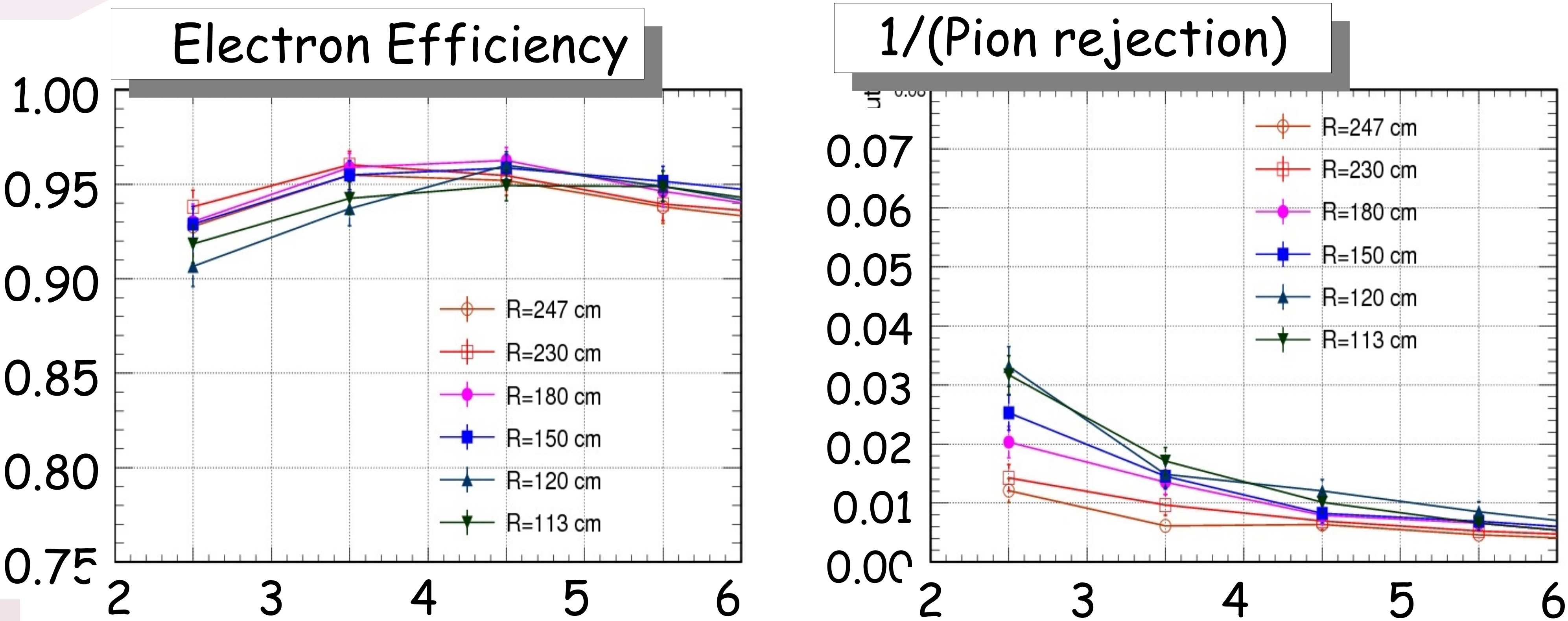


Scintillator energy dep. in Shower (MeV)

Photon Electron Pi- Pi+ Proton

Performance — PID, PVDIS (low γ)

- Background worsens PID. Will require full waveform recording if better PID is desired.

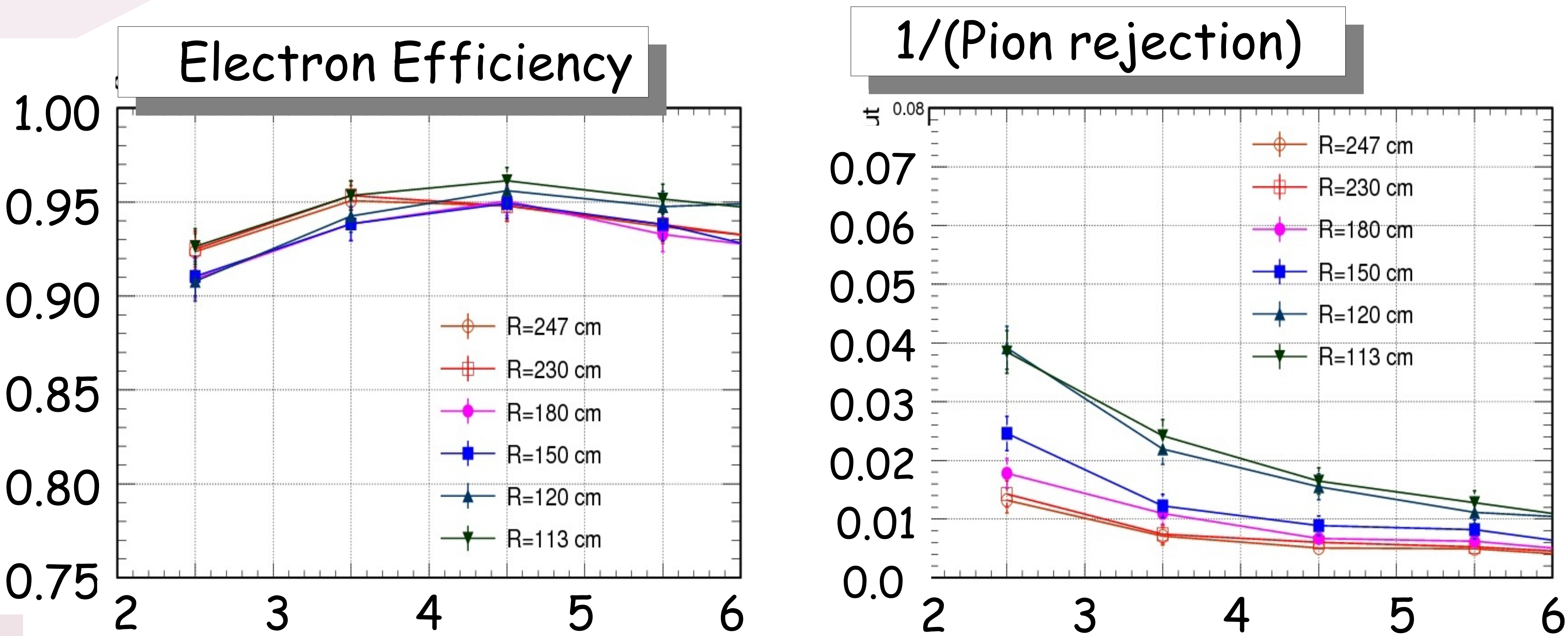


2D-cut PID, with latest background embedding

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

Performance — PID, PVDIS (high γ)

- Background worsens PID. Will require full waveform recording if better PID is desired.



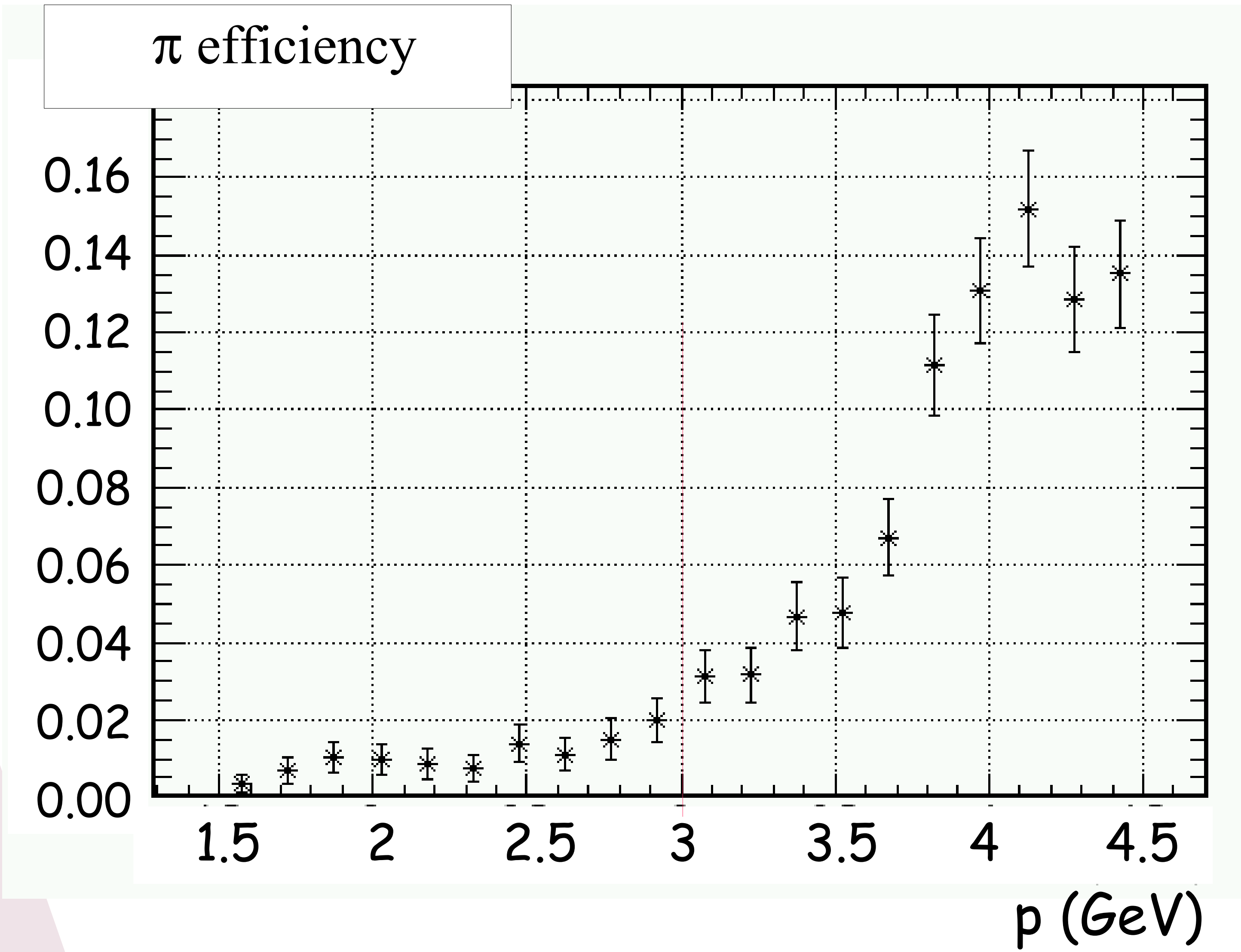
p (GeV)

2D-cut PID, with latest background embedding

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

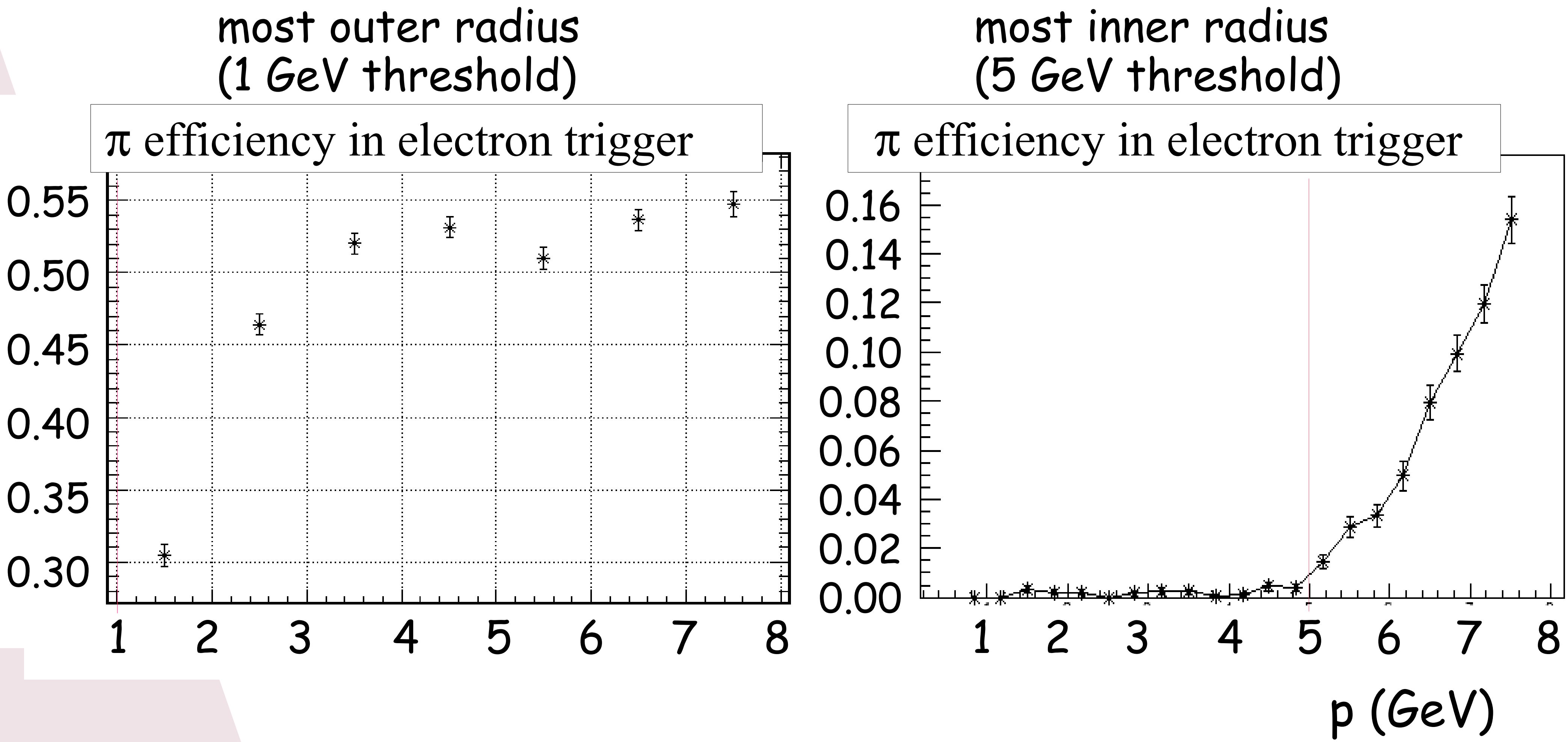
Performance — Triggering
SIDIS, large angle, electron trigger

Most inner radius region shown – worse case situation



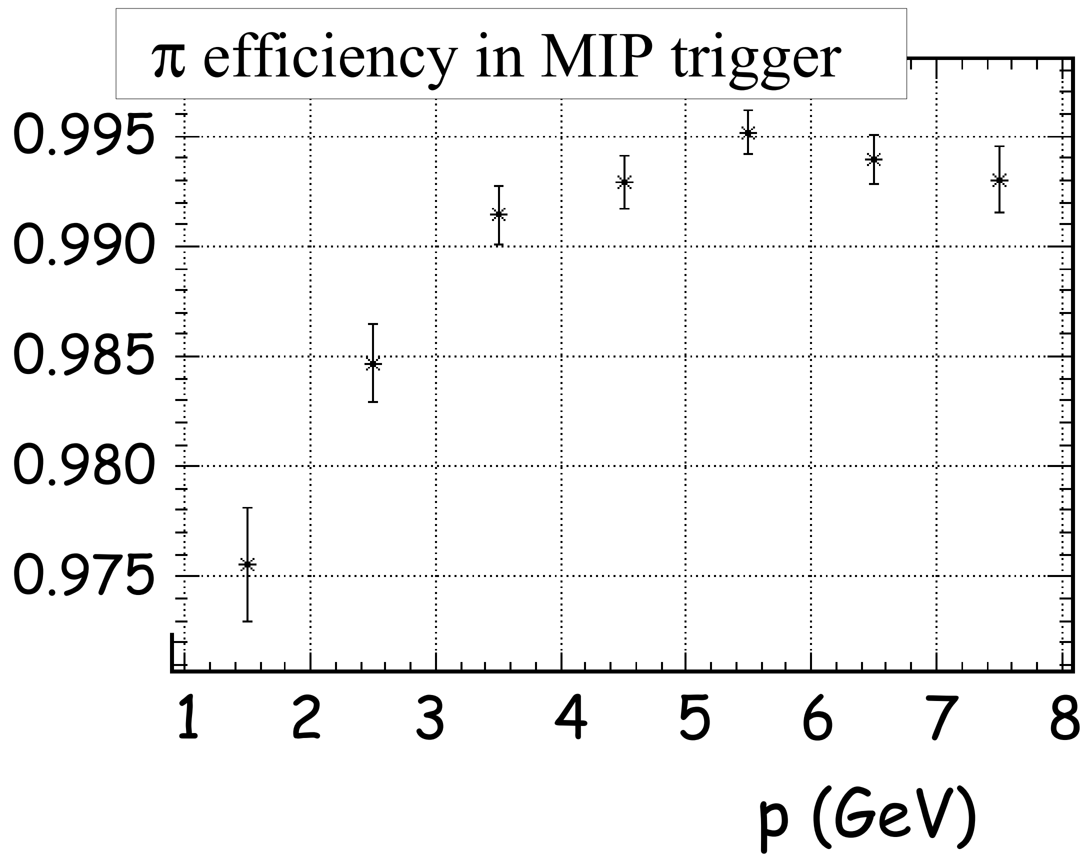
Performance — Triggering
SIDIS, forward

Electron trigger: Use radius-dependent trigger thresholds,



Performance — Triggering
SIDIS, forward MIP trigger

Pion trigger: 2-sigma below MIP

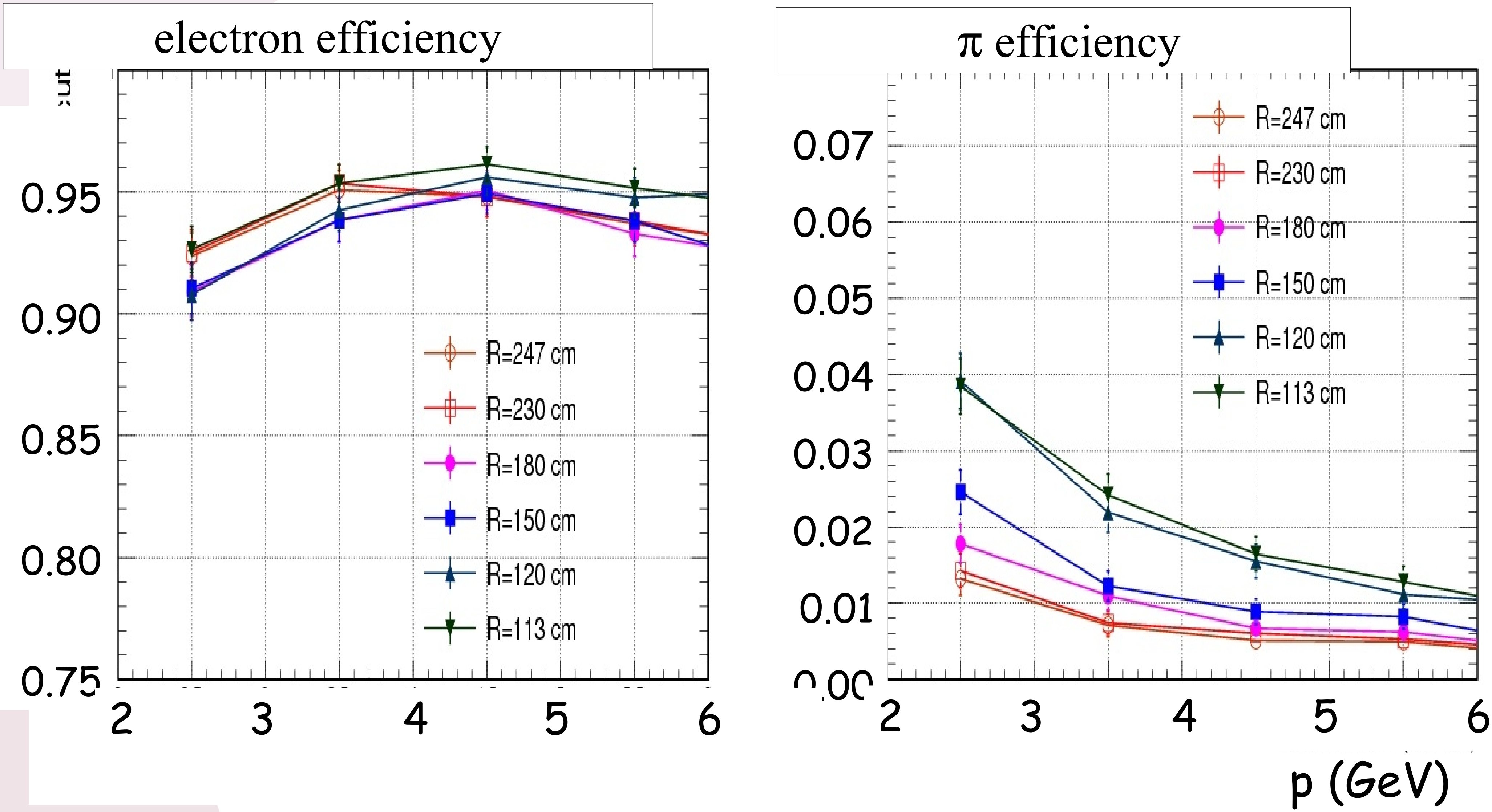


Performance — Triggering

SIDIS, trigger rates (whole EC)

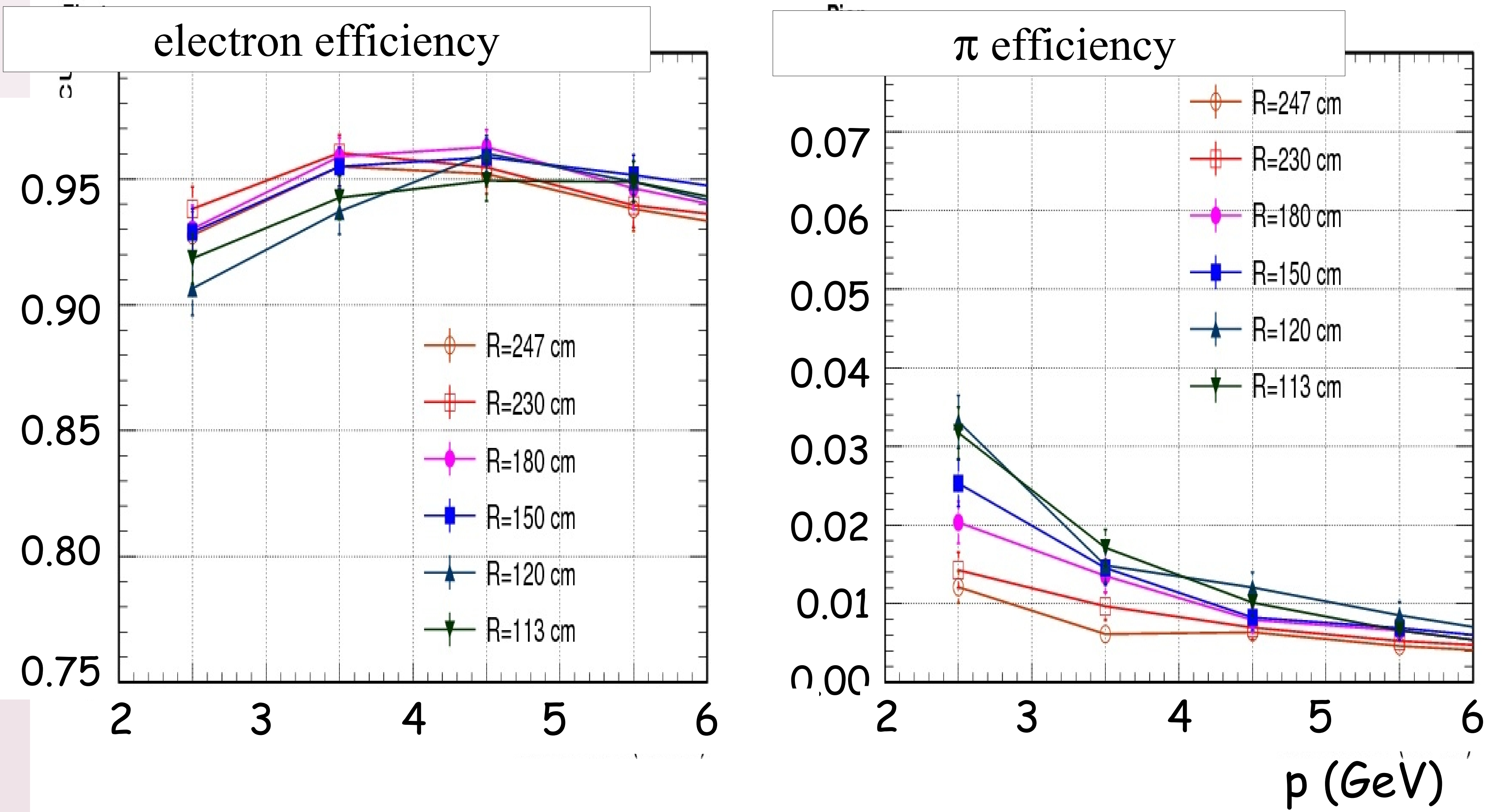
region	FAEC	LAEC
rate entering the EC (kHz)		
e^-	93.4	18.7
π^-	5.36×10^3	1.55×10^4
π^+	5.96×10^3	1.66×10^4
$\gamma(\pi^0)$	1.52×10^5	2.43×10^5
$e(\pi^0)$	6.52×10^3	2.04×10^3
p	1.86×10^3	6.16×10^3
electron trigger rate (kHz)		
e^-	74.2	11.68
π^-	500	5.16
π^+	548	5.12
$\gamma(\pi^0)$	896	12.5
$e(\pi^0)$	43	0.14
p	109	2.15
sum	2170	36.75
MIP trigger rate (kHz)		
e^-	93.4	
π^-	5240	
π^+	5800	
$\gamma(\pi^0)$	6760	
$e(\pi^0)$	772	
p	1732	
sum	2×10^4	

Performance — Triggering
PVDIS, higher photon background region



preserve DIS electron of x>0.35

Performance — Triggering
PVDIS, lower photon background region



preserve DIS electron of x>0.35

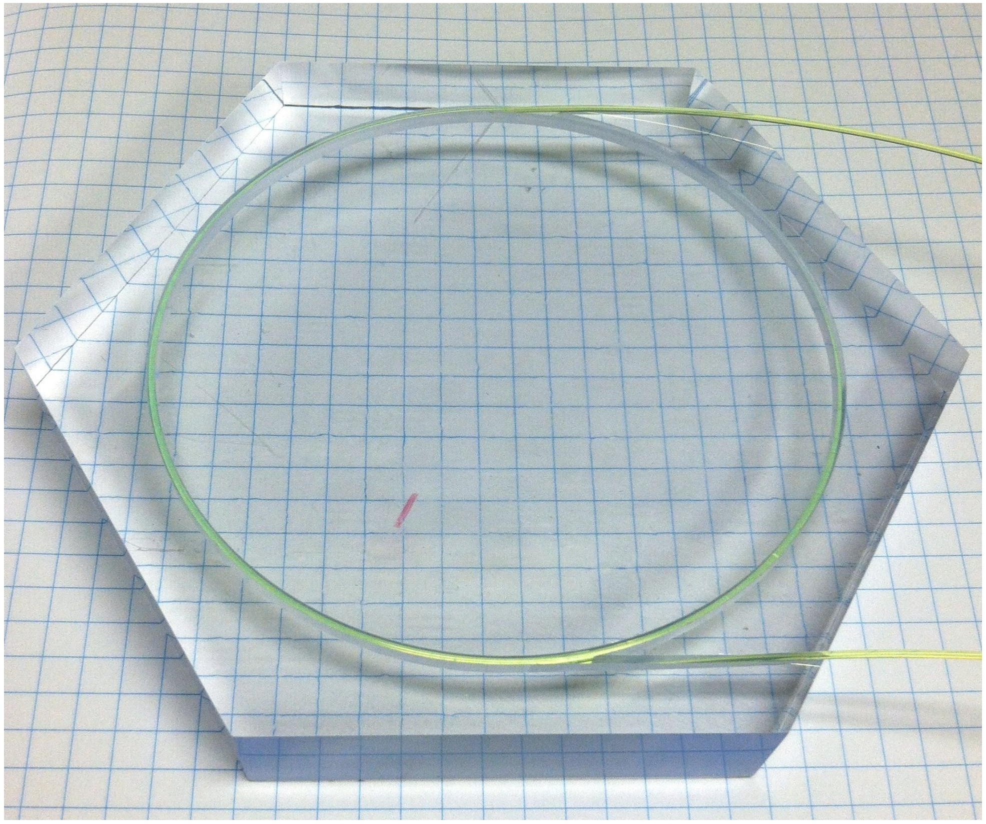
Performance — Triggering

PVDIS, trigger rates (whole EC)

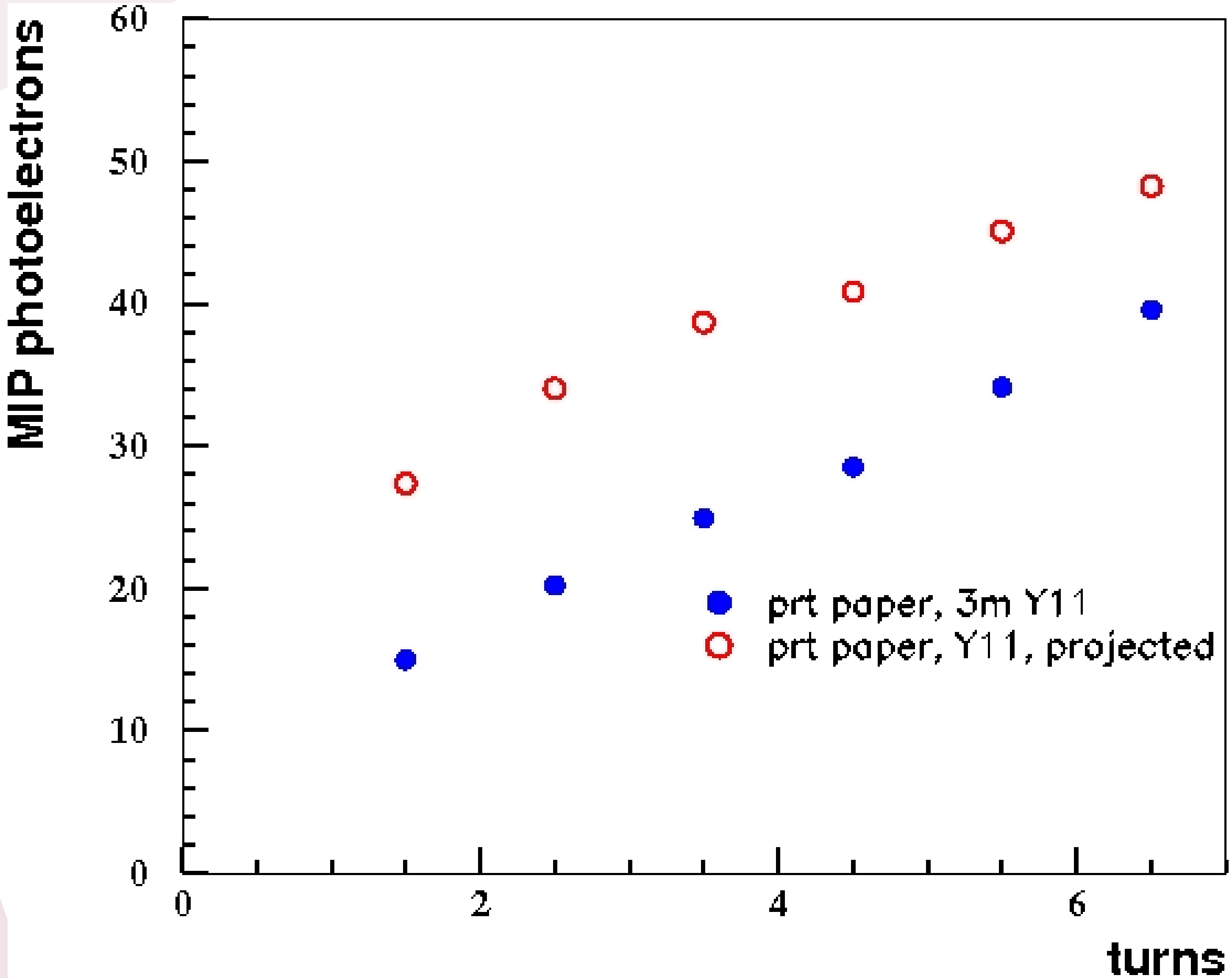
region	full	high	low
rate entering the EC (kHz)			
e^- (DIS)	413	148	265
π^-	5.1×10^5	2.7×10^5	2.4×10^5
π^+	2.1×10^5	1.0×10^5	1.2×10^5
$\gamma(\pi^0)$	8.4×10^7	4.2×10^7	4.3×10^7
p	5.5×10^4	2.4×10^4	3.1×10^4
sum	8.5×10^7	4.2×10^7	4.3×10^7
trigger rate for $p > 1$ GeV (kHz)			
e^- (DIS)	321	80	231
π^-	4.8×10^3	3.4×10^3	1.4×10^3
π^+	0.28×10^3	0.11×10^3	0.17×10^3
$\gamma(\pi^0)$	4	4	0
p	0.18×10^3	0.10×10^3	0.08×10^3
sum	5.6×10^3	3.7×10^3	1.9×10^3
trigger rate for $p < 1$ GeV (kHz)			
sum	$(3.1 \pm 0.7) \times 10^3$	$(1.6 \pm 0.4) \times 10^3$	$(1.5 \pm 0.4) \times 10^3$
Total trigger rate (kHz)			
total	$(8.7 \pm 0.7) \times 10^3$	$(5.3 \pm 0.4) \times 10^3$	$(3.4 \pm 0.4) \times 10^3$

Pre-R&D: preshower prototype testing

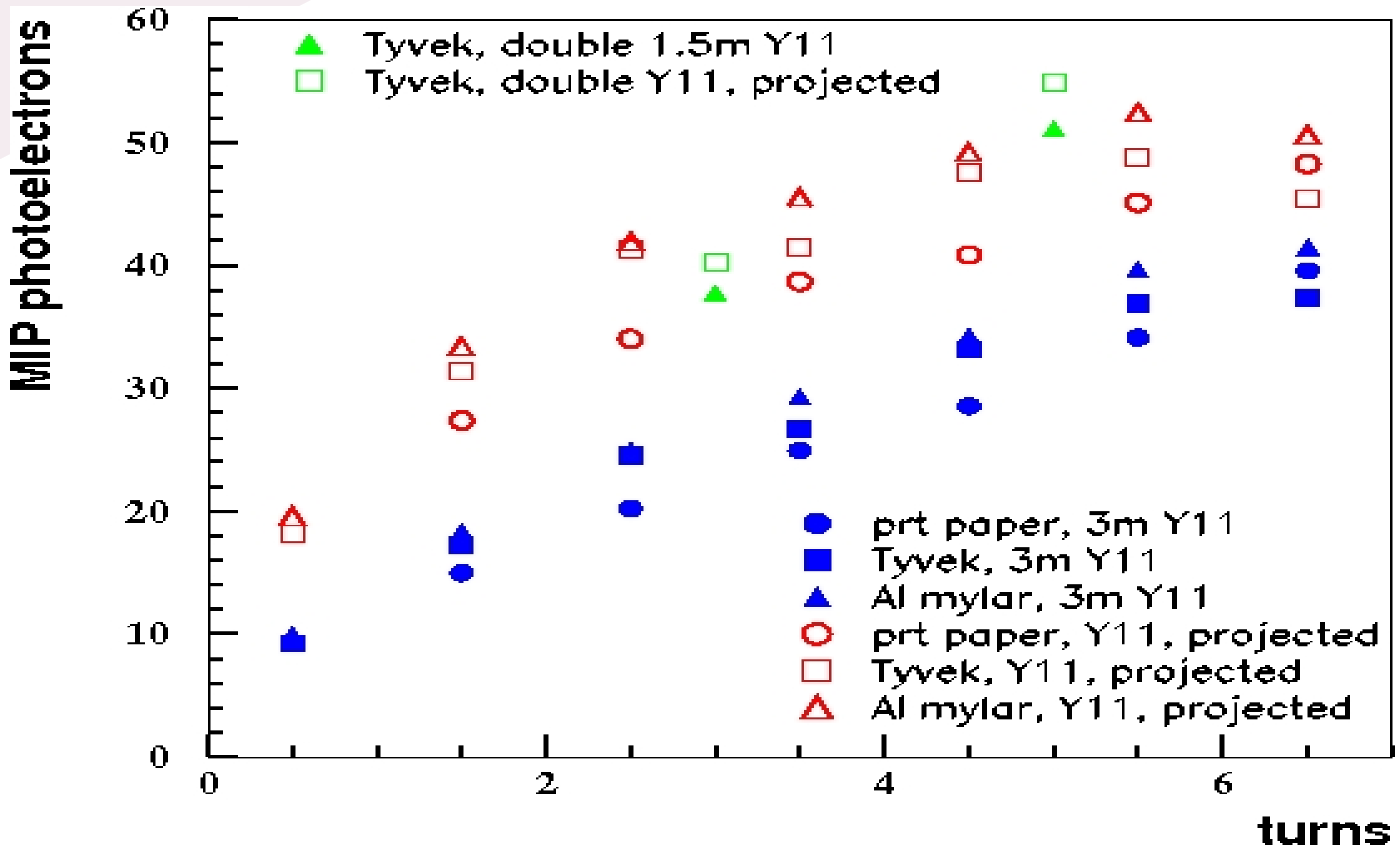
- Tested:
  - WLS fiber: Y11, BCF91A (55%), BCF92 (35%)
  - wrapping: printer paper, Tyvek homewrap (10% higher), aluminized mylar (17% higher)



Pre-R&D: preshower prototype testing



Pre-R&D: preshower prototype testing



- WLS fiber decay observed <3m: <2m or 3.50m w 6%/turn bending loss;
- best estimate: 26 for LAEC, 35 for FAEC - effect on PID to be simulated
- For SPD (3 turns fiber): 1/8 of Preshower yield – to be tested

Cost Estimation

- based on 1800 modules, IHEP cost includes 30% overhead

	Year-1	Year-2	Year-3	Year-4	Sum		Contrib	Request
Shower Modules	315	1870	655	132	2972			2972
PreShower Modules	80	180	100	30	390			390
SPD Mod-ules	30	30	5		65			65
WLS Fiber	80	100	39		219			219
Clear Fiber	150	250	126		526			526
Fiber Con-nectors	100	175	86		361			361
Shower PMTs	100	200	104	50	454			454
PS MAPMTs	80	120	34	30	264			264
SPD MAPMTs	30	30	6		66			66
Assembling and Testing	30	30	35	40	135			135
FTE	4	4	4	4	16		4	12
Shipping	10	20	10	10	50			50
Total-EC-cost	1005	3005	1200	292	5502			5502
Total-EC-FTE	4	4	4	4	16		4	12

To Do

- SPD embedding – 3mm and 5mm tiles ordered from SDU
- Shower: characterize MIP for COMPASS module, prototyping expensive!
- PMT/MAPMT testing: timing, base w/ preamp, UVa/JLab/SDU
- General fiber testing: rad hardness, connector prototype
- simulation PID: Preshower, SPD # of p.e. on PID
- simulation SPD: effect on MRPC, radial segmentation
- Support structure design (ANL/P.R.)

Backup

Preshower light collection simulation

- Simulation by Kai Jin: Dependence on # of turns agree with data; absolute efficiency seems to be reasonable
- Previously assumed SPD light yield to be 1/4 of Preshower (scale by thickness), but light collection efficiency only depend on fiber routing and # of turns → yield for SPD will be (1/4)*(1/2) of Preshower if using 3 turns of fiber and same groove density → readout needs careful study.
- 3mm and 5mm hexagons ordered (SDU) for testing SPD light collection

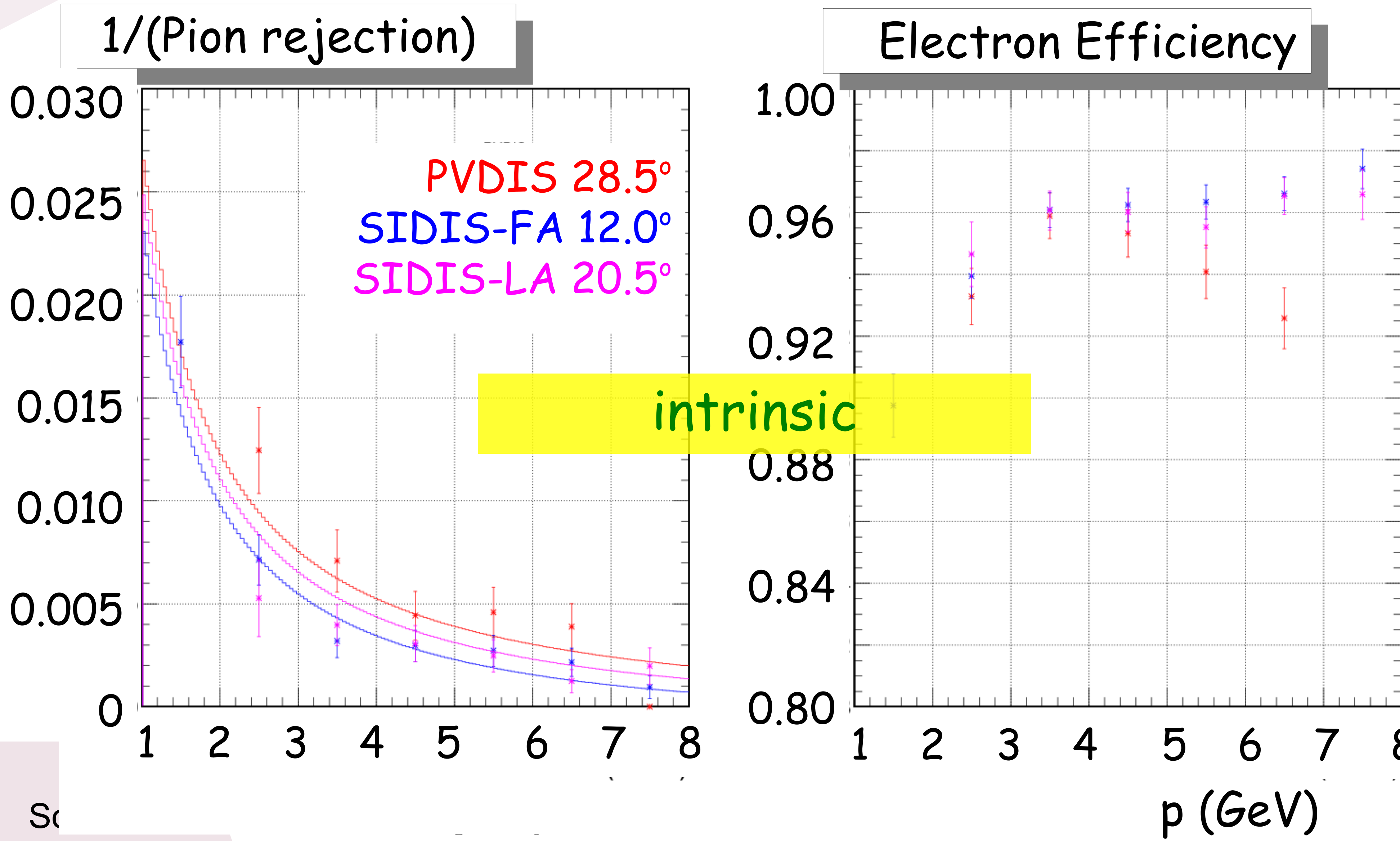
Design Consideration 1: Pb/scintillator ratio

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

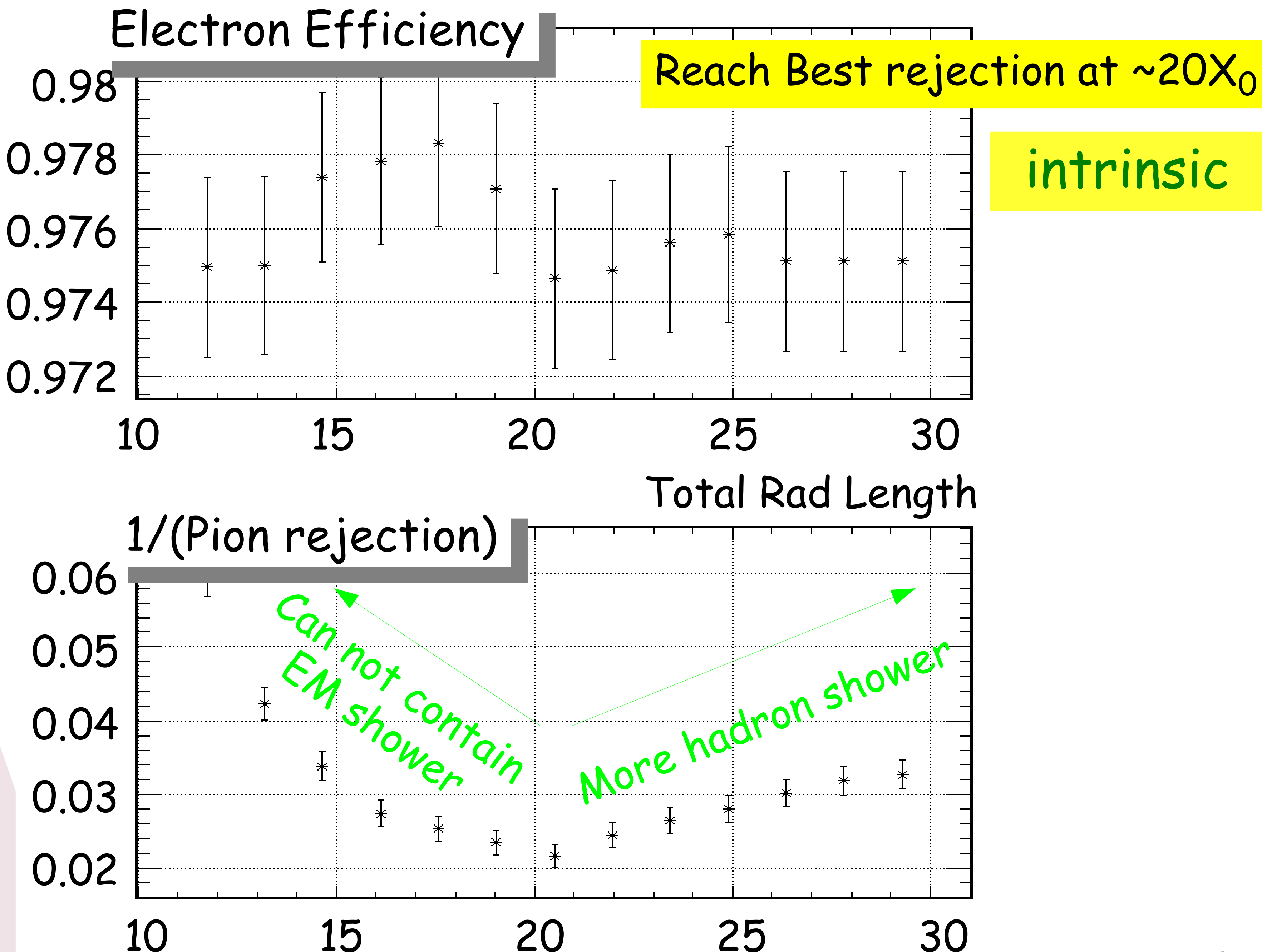
- Thinner Pb layers give better energy resolution, but requires more layers → Balancing between energy resolution and module length

Design Consideration 1.1: Pb/scintillator ratio

- Minimize scintillator ratio while reaching 100:1 intrinsic pion rejection → 0.5mm Pb/1.5 mm Scint. (BASF143E) per layer. [4.5-5%/sqrt(E)]

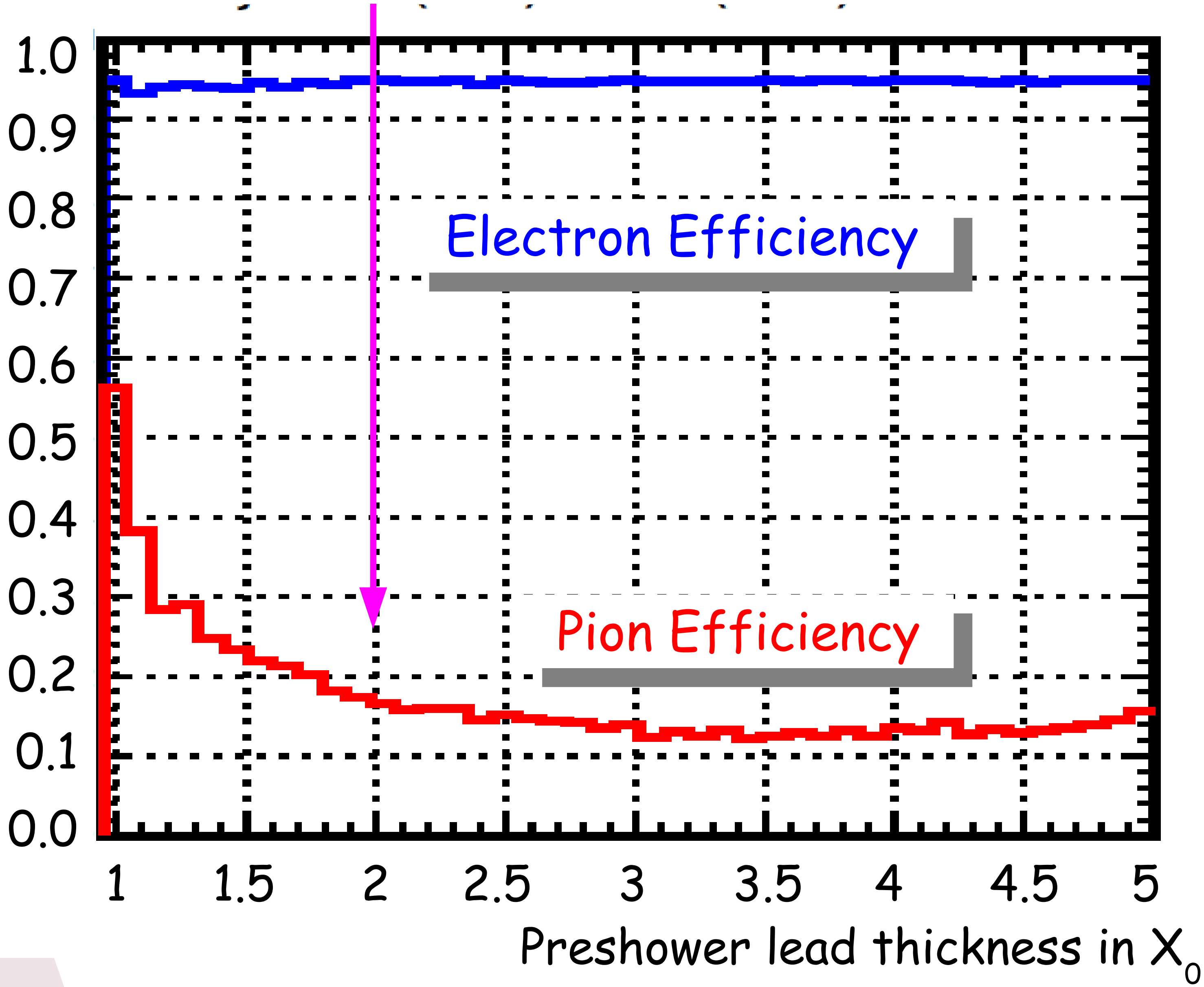


Design Consideration 1.3: Total Length

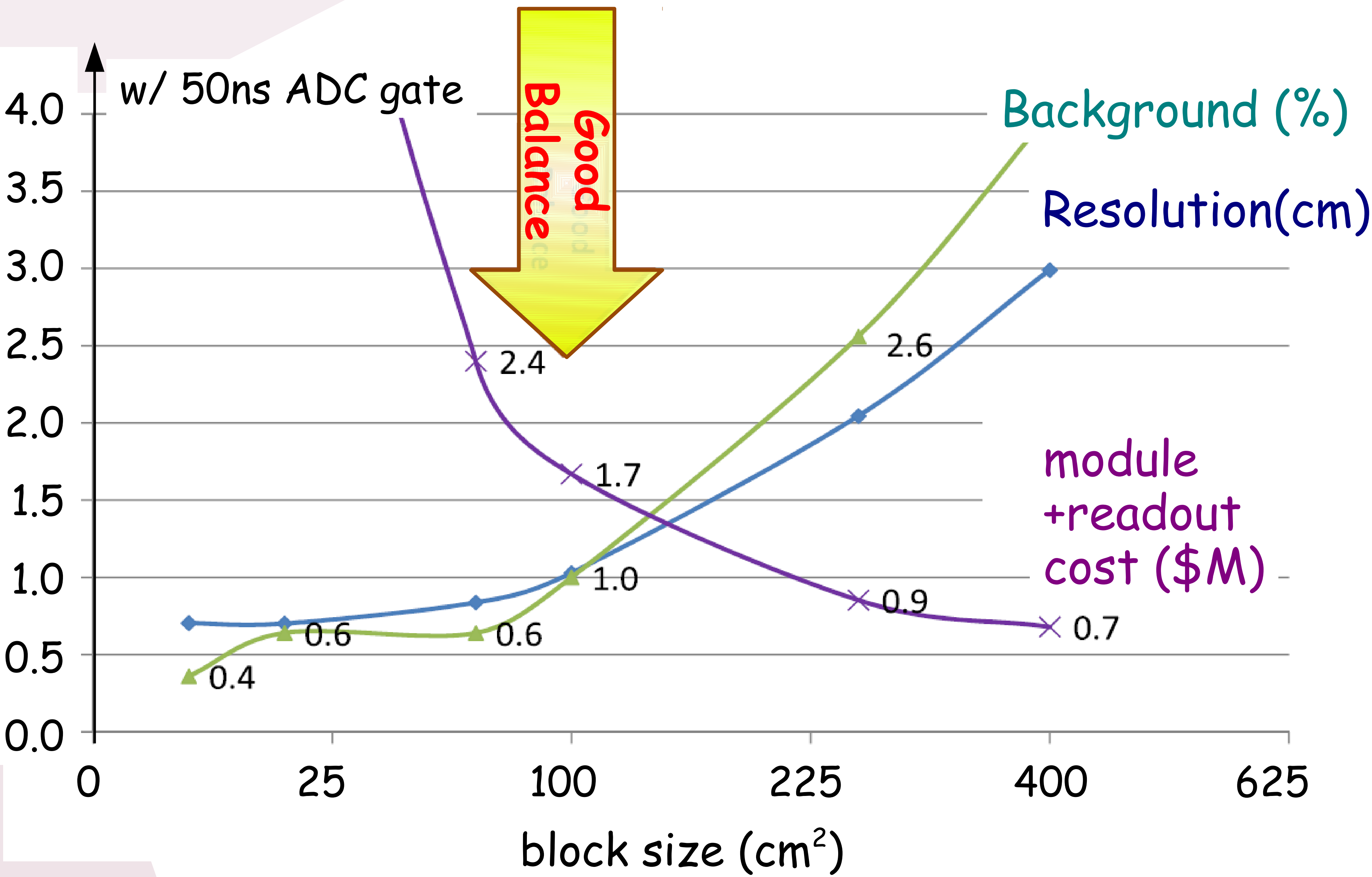


Design Consideration 1.4: Preshower Thickness

- $2X_0$ Pb efficiently reject pions and add to radiation hardness



Design Consideration 2: Lateral



Understanding Preshower light collection

- Typical scintillator efficiency: (10-15)% (google search), 2-3eV/photon → 5E7 photons/(GeV of energy deposit)
- light collection/absorption of WLS fiber from Kai's simulation: 0.02 for 4 turns, ϕ1mm, ϕ9cm-groove (200ppm) fiber, printer paper wrapping → 1E6 photos/GeV
- QE of Y11 dye: unknown, assume to be 100%
- WLS fiber trapping of emitted light: 3% for single-clad, 5% for multi-clad → 5E4 photons/GeV
- PMT QE: assume 20% → 1E4 photons/GeV
- WLS fiber attenuation: 3m gives 0.651 (if decay length 3.5m) or 0.472 (2.0m) → (5-6.5)E3 photons/GeV → (20-26) p.e. for MIP response of 20-mm thick Preshower hexagon (4MeV deposit), consistent with the observed 20-ish p.e. in the lab.