12 GeV Upgrade

Future Science at Jefferson Lab

Electromagnetic Calorimeters (EC) for SoLID

The SoLID EC Working Group

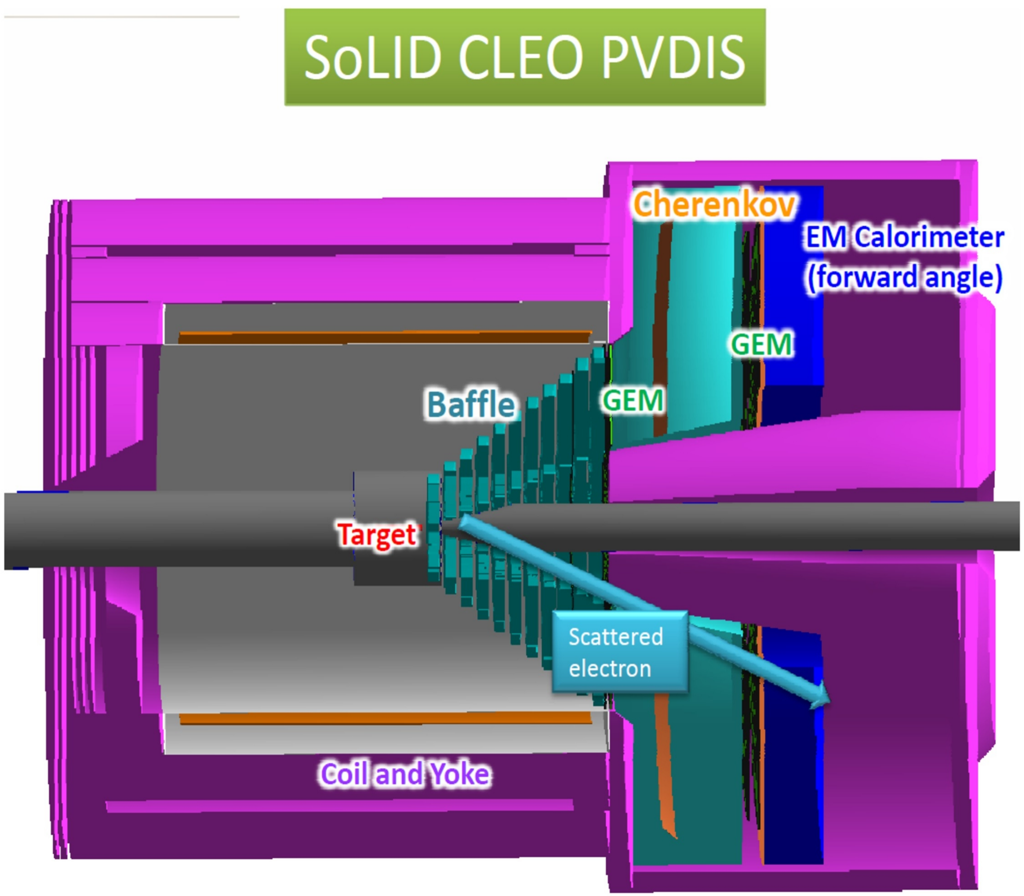
SoLID Collaboration Meeting

November7-8, 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

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;
3. Provide shower position to help tracking/suppress background
   - σ ~ 1 cm
4. Radiation resistance: > $(4\text{-}5)\times10^5$ rad
5. B~1.5 T, high neutron background
6. Modules easily swapped and rearranged for PVDIS ↔ SIDIS; SIDIS needs 2-fold rotation (180^o) symmetry

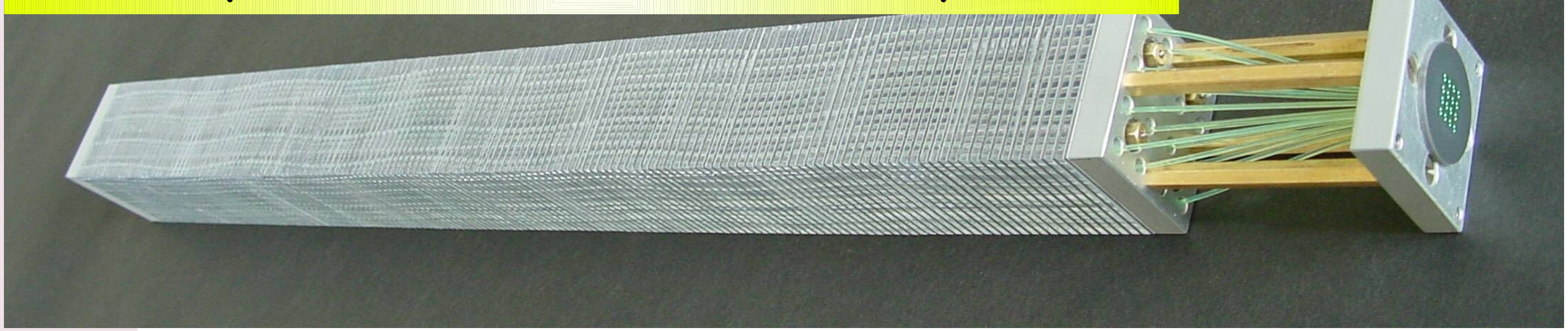
SPD Design Requirements (SIDIS only)

1. LASPD: Provide primary photon rejection 5:1; combine with RF bunch to provide primary TOF (150ps preferred)
2. FASPD: Provide photon rej 5:1, secondary to MRPC

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

- 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; use of crystals: $PbWO_4$ ($10/cc) or LSO ($40/cc) is cost prohibitive;
- SciFi type needs half volume being scintillating fibers, cost of fiber alone ($4M if 1mm dia, $1/m) exceed total cost of Shashlyk type. Cost of PMT/HV also too high.
- Shashlyk: Fairly robust technique, moderate cost, tunable energy resolution, radiation 500krad tested by IHEP



IHEP, COMPASS Shashlik, 2010

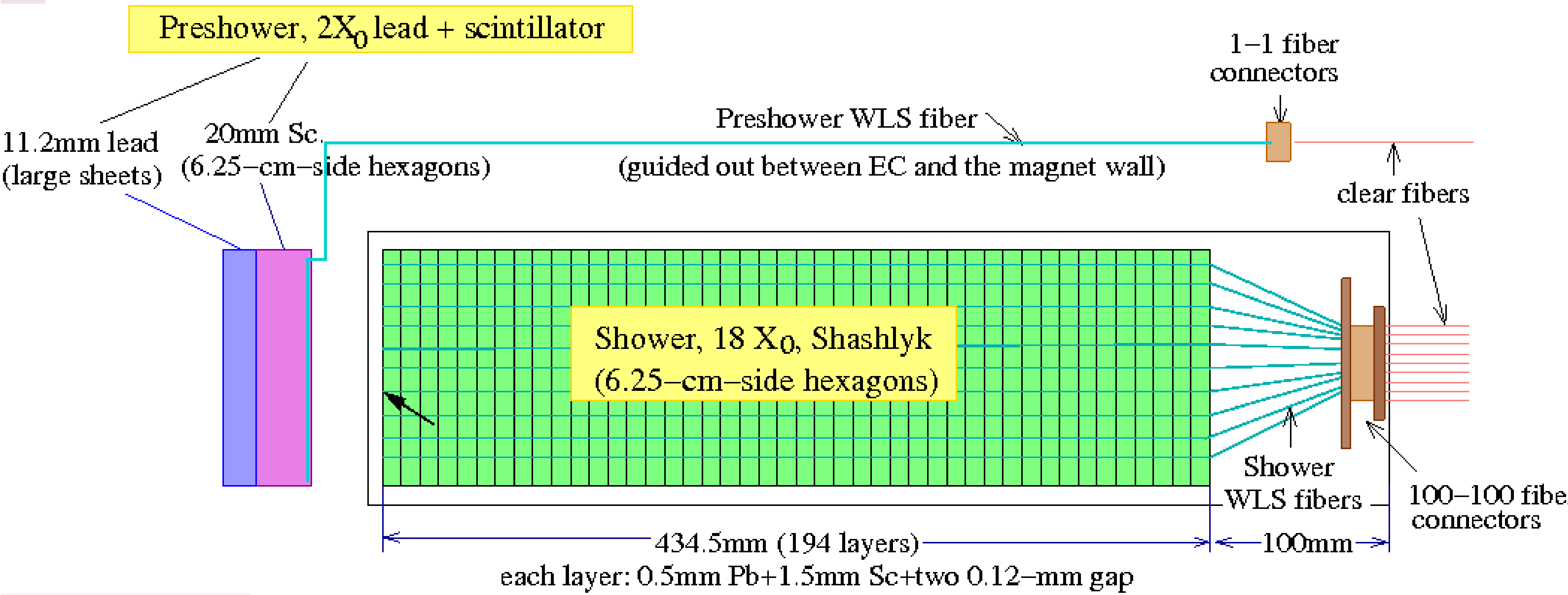
IHEP Scintillator Facilities

www.ihep.ru/scint/index-e.htm

- Polysterene based, injection molding cuts cost drastically, production 200 modules/month possible.

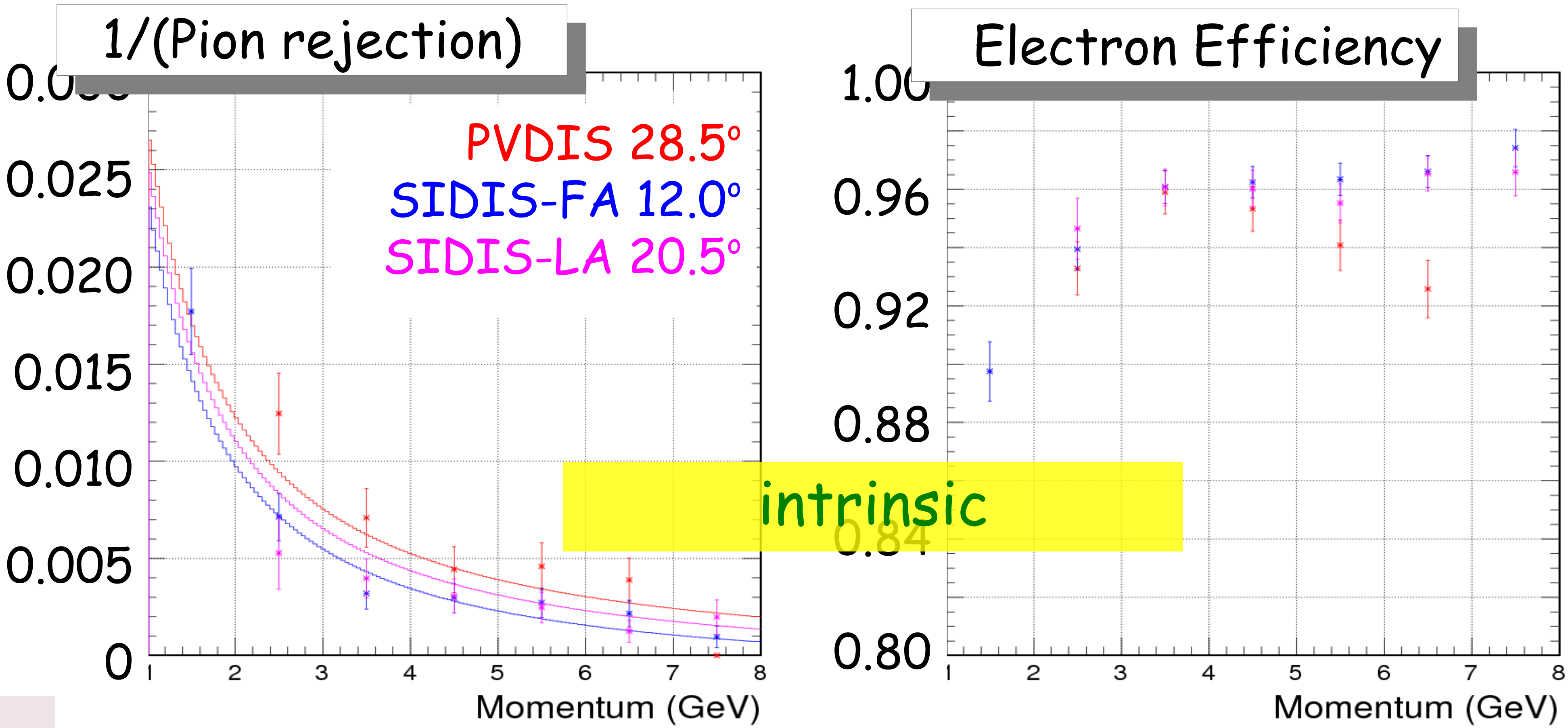
Design Consideration 1: Longitudinal

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

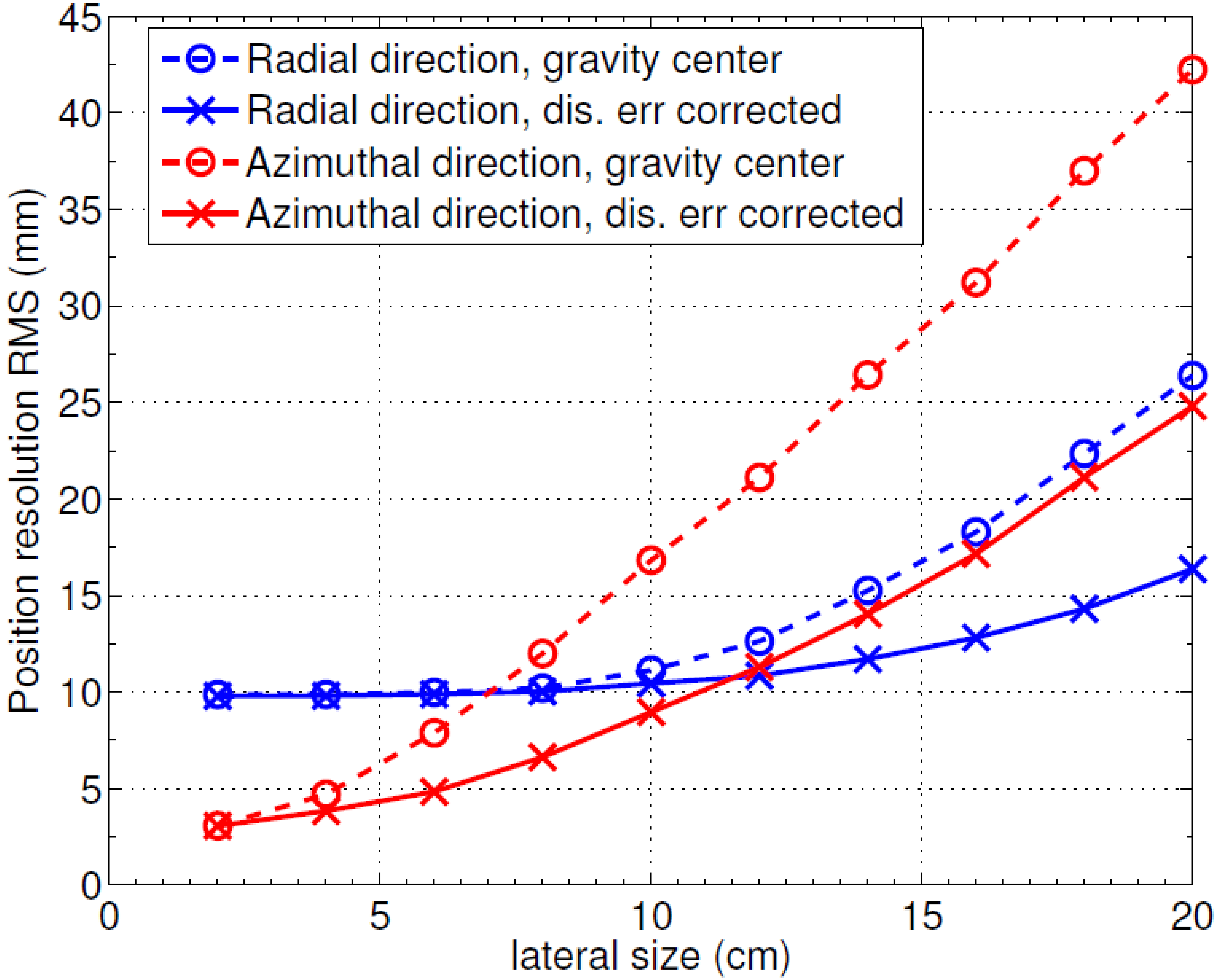


Design Consideration 1: Longitudinal

- Shower: 100:1 intrinsic pion rejection → 0.5mm Pb/1.5 mm Scint. (BASF143E polysterene) per layer. [4.5-5%/sqrt(E)]

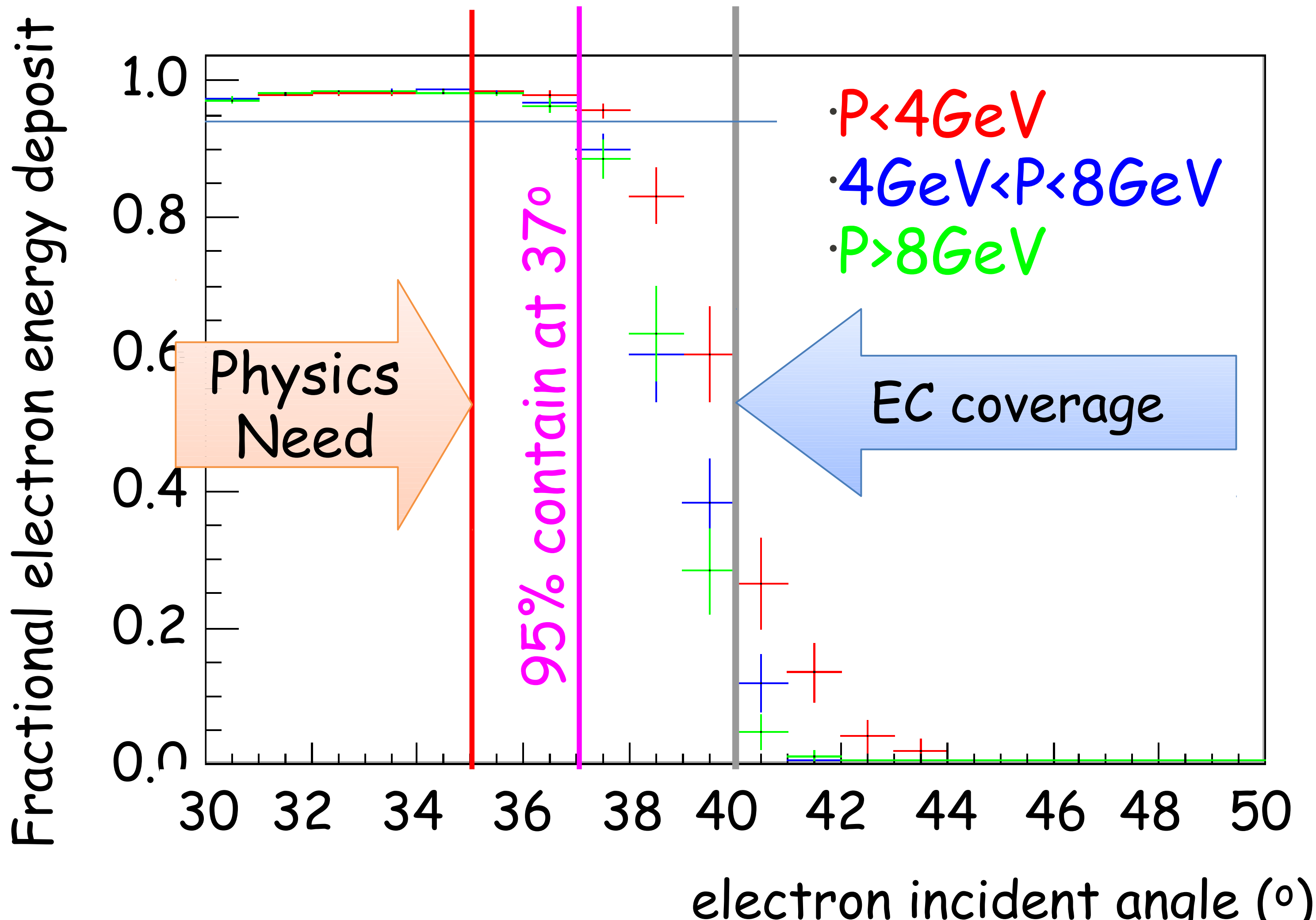


Design Consideration 2: Lateral



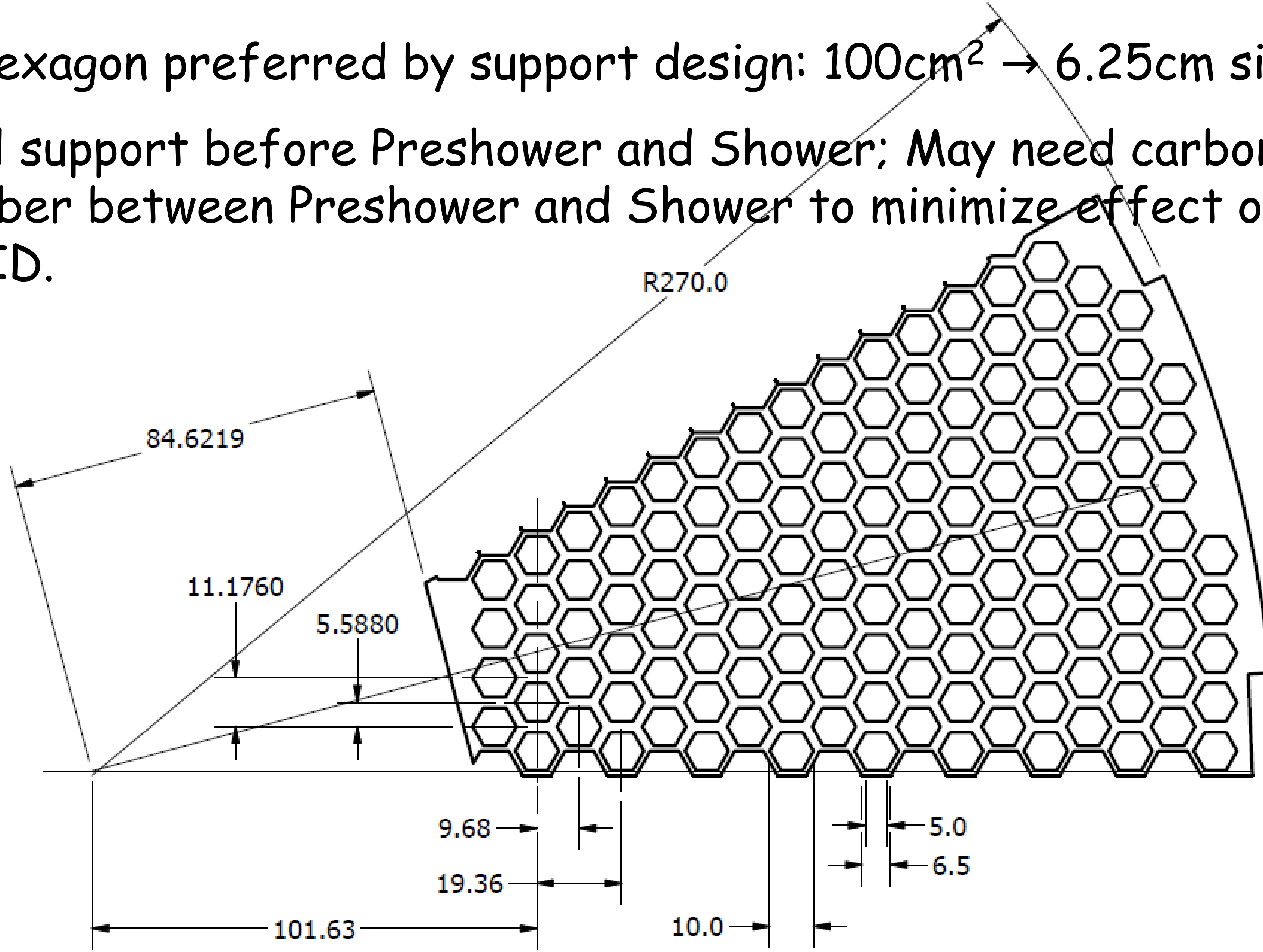
Design Consideration 2: Lateral

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



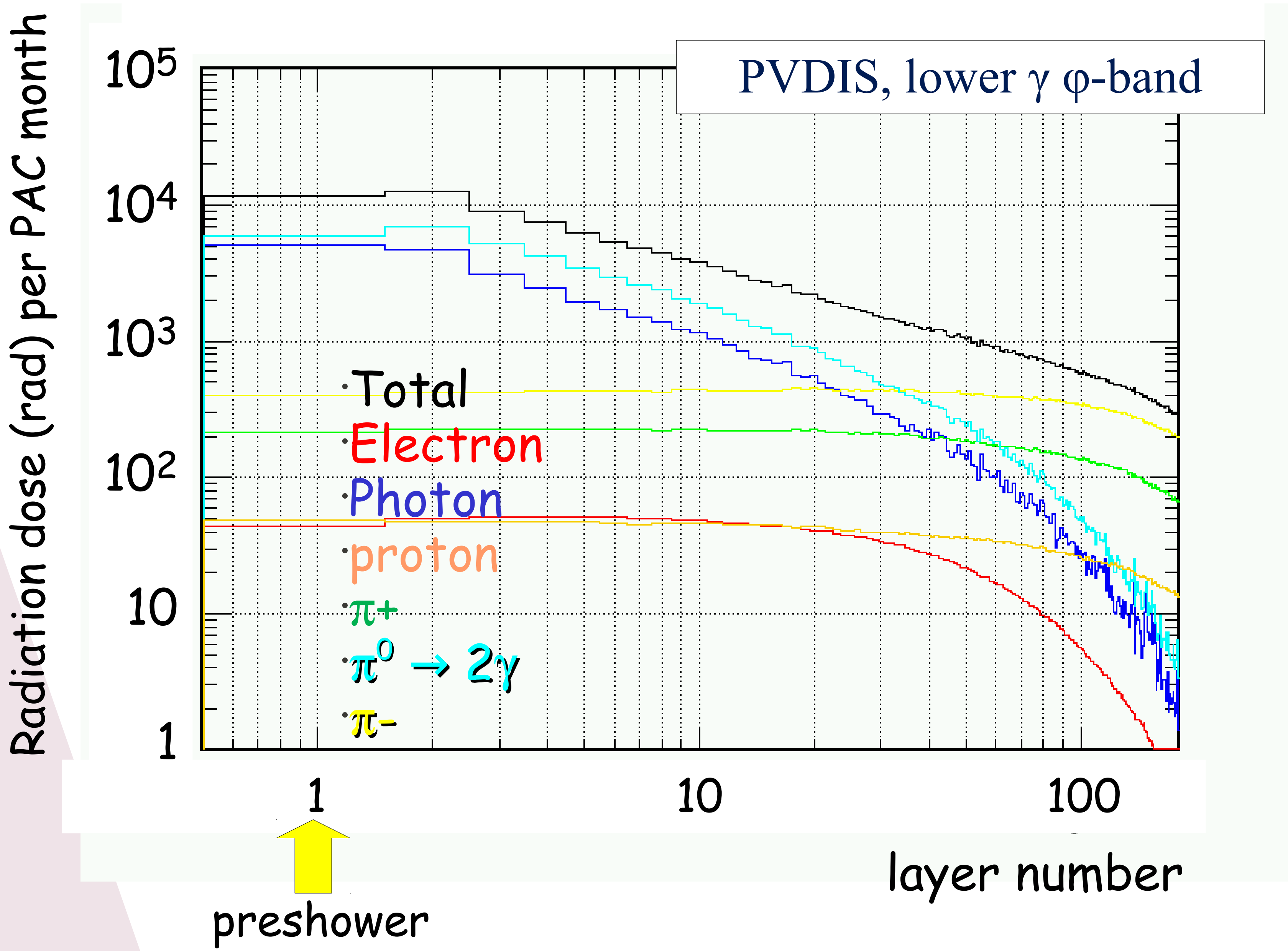
Design Consideration 2: Lateral

- 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.



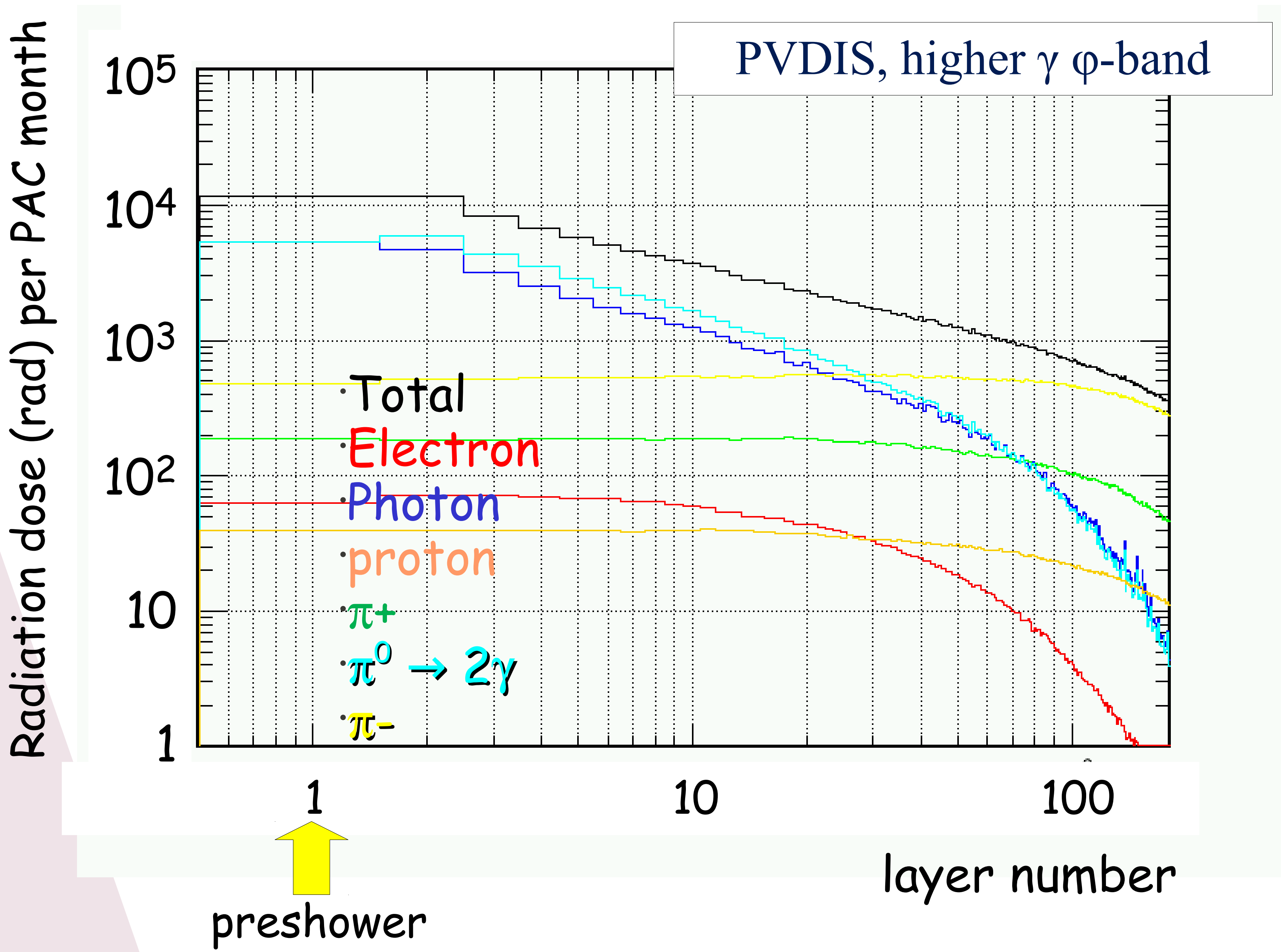
Design Consideration 3: Radiation Dose

- $2X_0$ lead efficiently block low energy photons



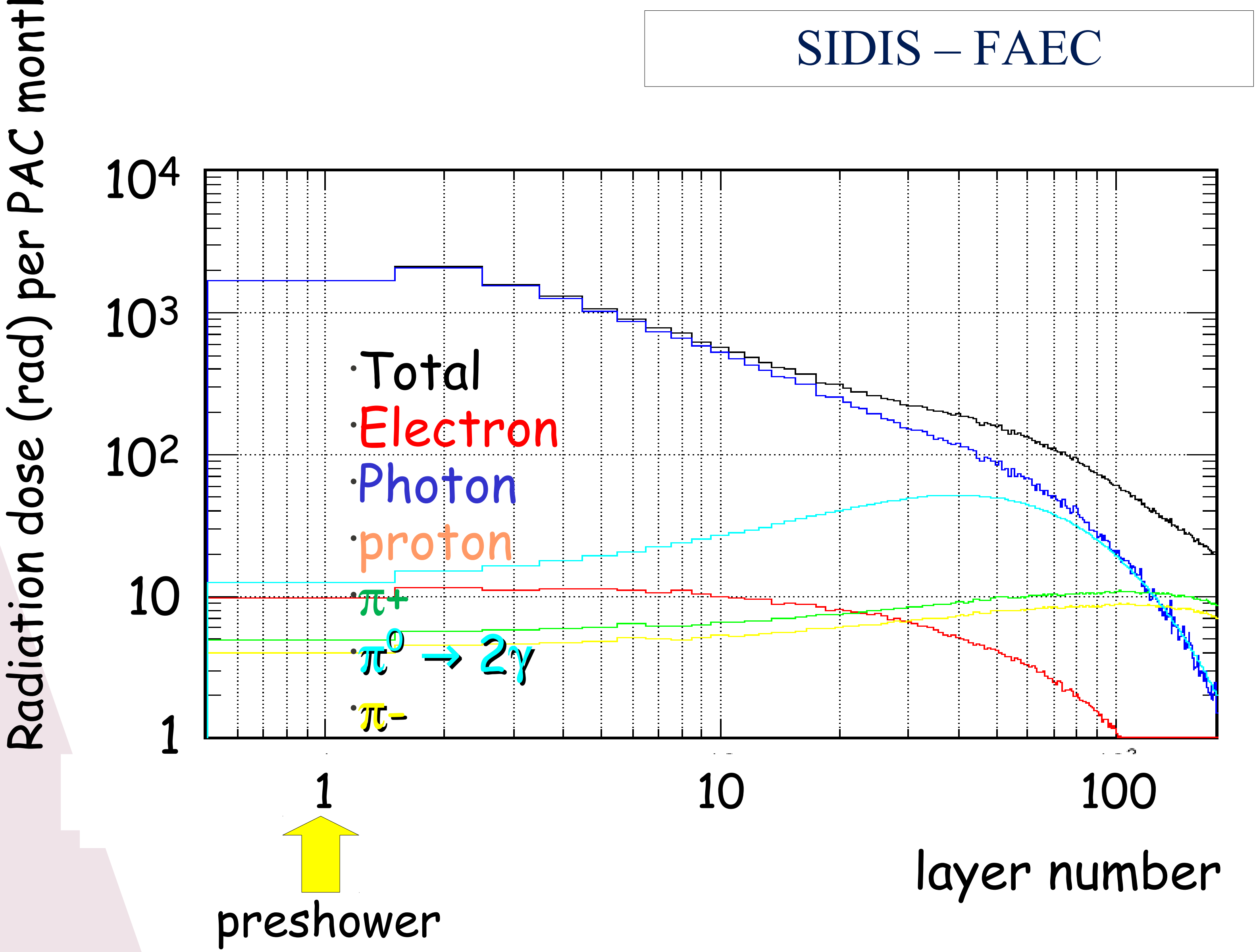
Design Consideration 3: Radiation Dose

- Photon blocker helps



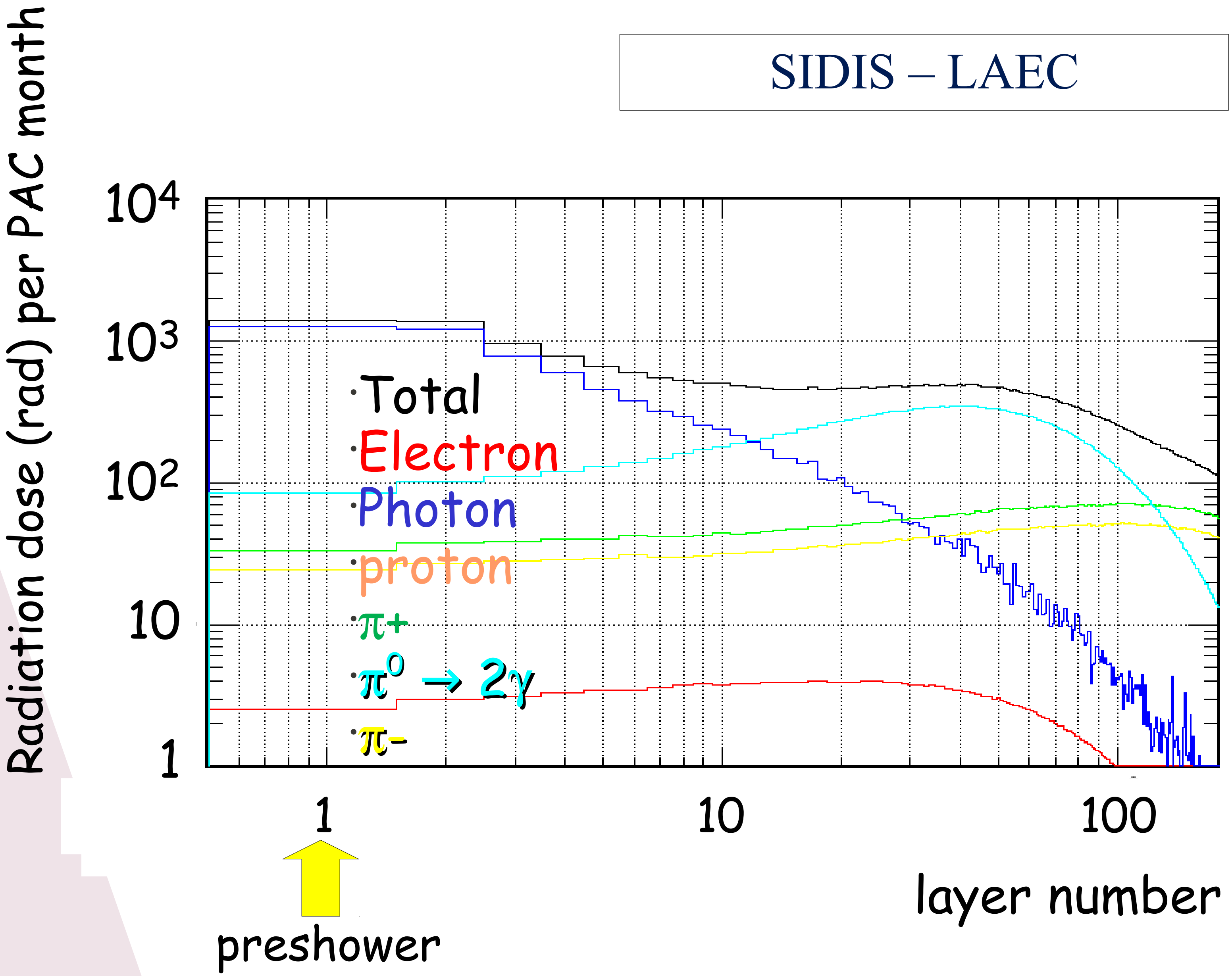
Design Consideration 3: Radiation Dose

- SIDIS: less of an issue



Design Consideration 3: Radiation Dose

- SIDIS: less of an issue



Design Consideration 4: Fiber Choice

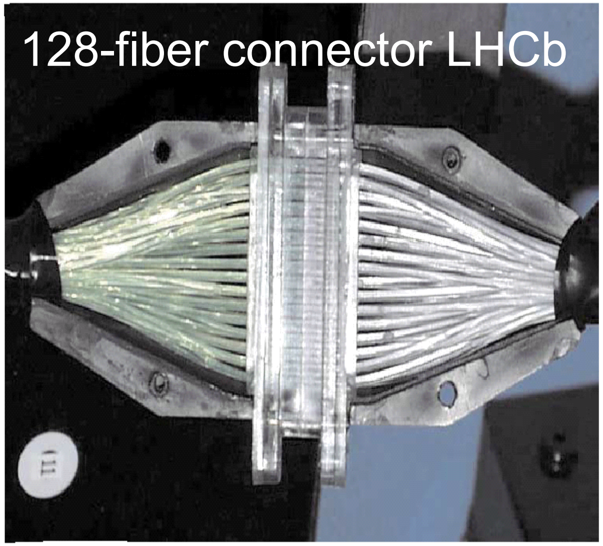
WLS fibers	Kuraray Y11	Saint Gobain BCF91A, BCF92 (faster)
wavelength	~420 → 494nm	~430 → 476nm
1/e length	>3.5m	>3.5m
mechanical property	less bending loss	
radiation hardness	13% light loss at 100krad (30% at 700krad)	15% light loss at 100krad (50% at 700krad)
light yield		2-3 times less than Y11
Clear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

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

Design Consideration 4: Fiber Choice

Fiber connector options:

- Preshower: 4-4 connector
- Shower: 100-100 connector
- Both can be made in-house using Delrin (as LHCb). Also investigating DDK connectors (Japan, used at Fermilab), sample received

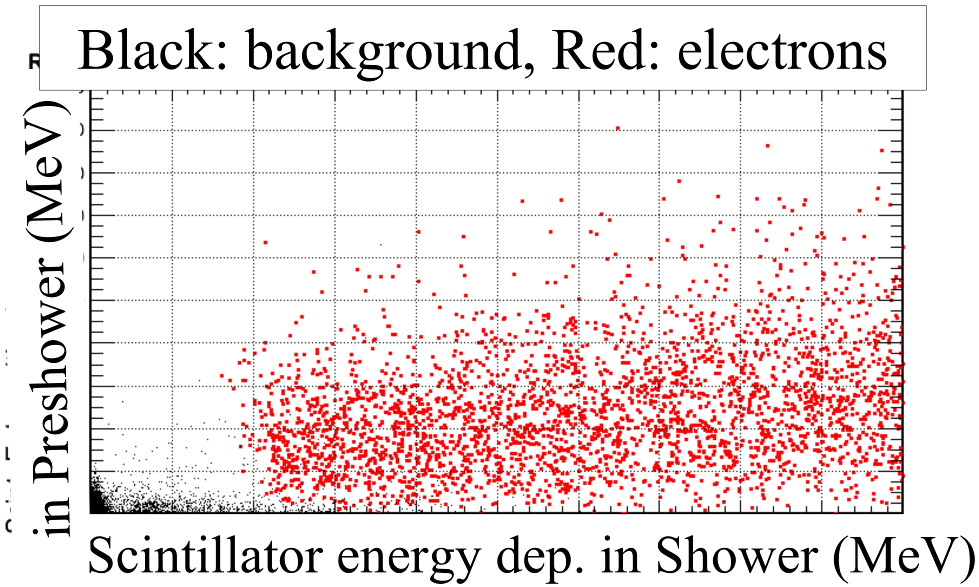


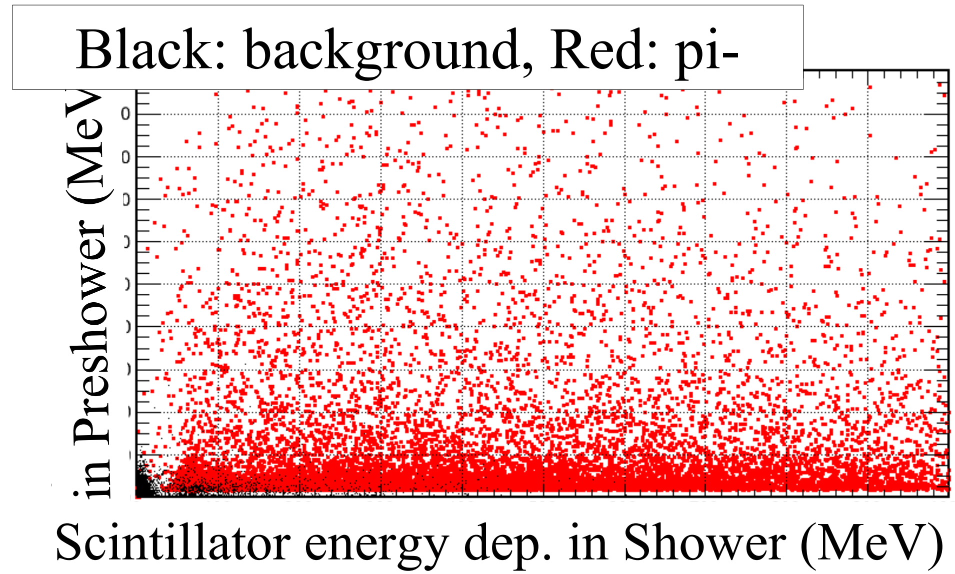
- fiber fusing possible, but switching SIDIS ↔ PVDIS difficult and can't be done locally

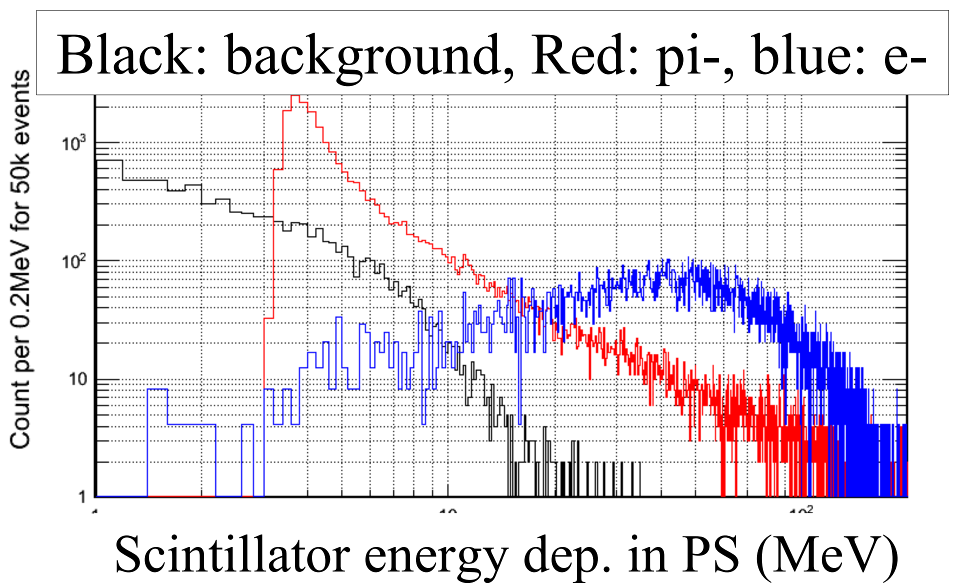
- Transfer light to outside Solenoid to PMTs (PMT info → later).

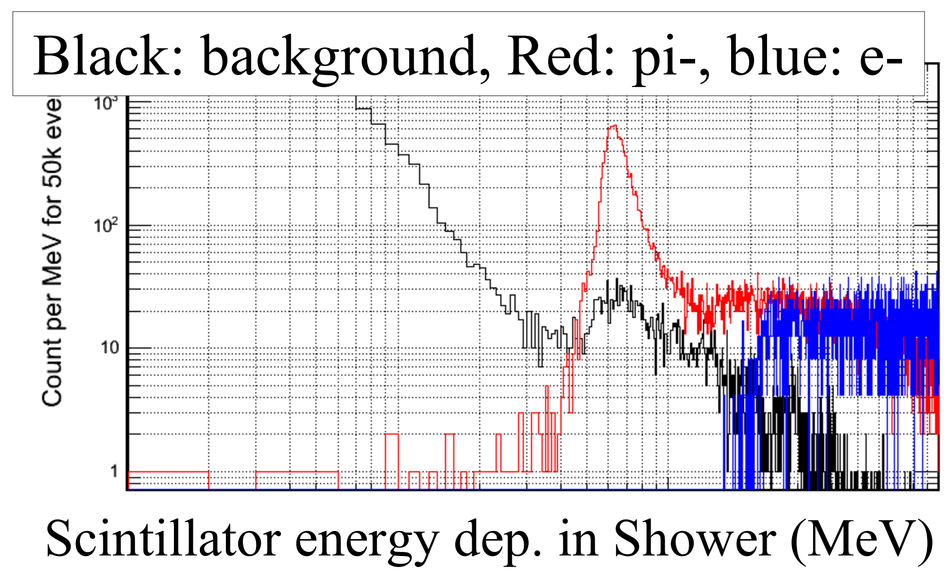
Performance — PID, SIDIS LAEC

- Background



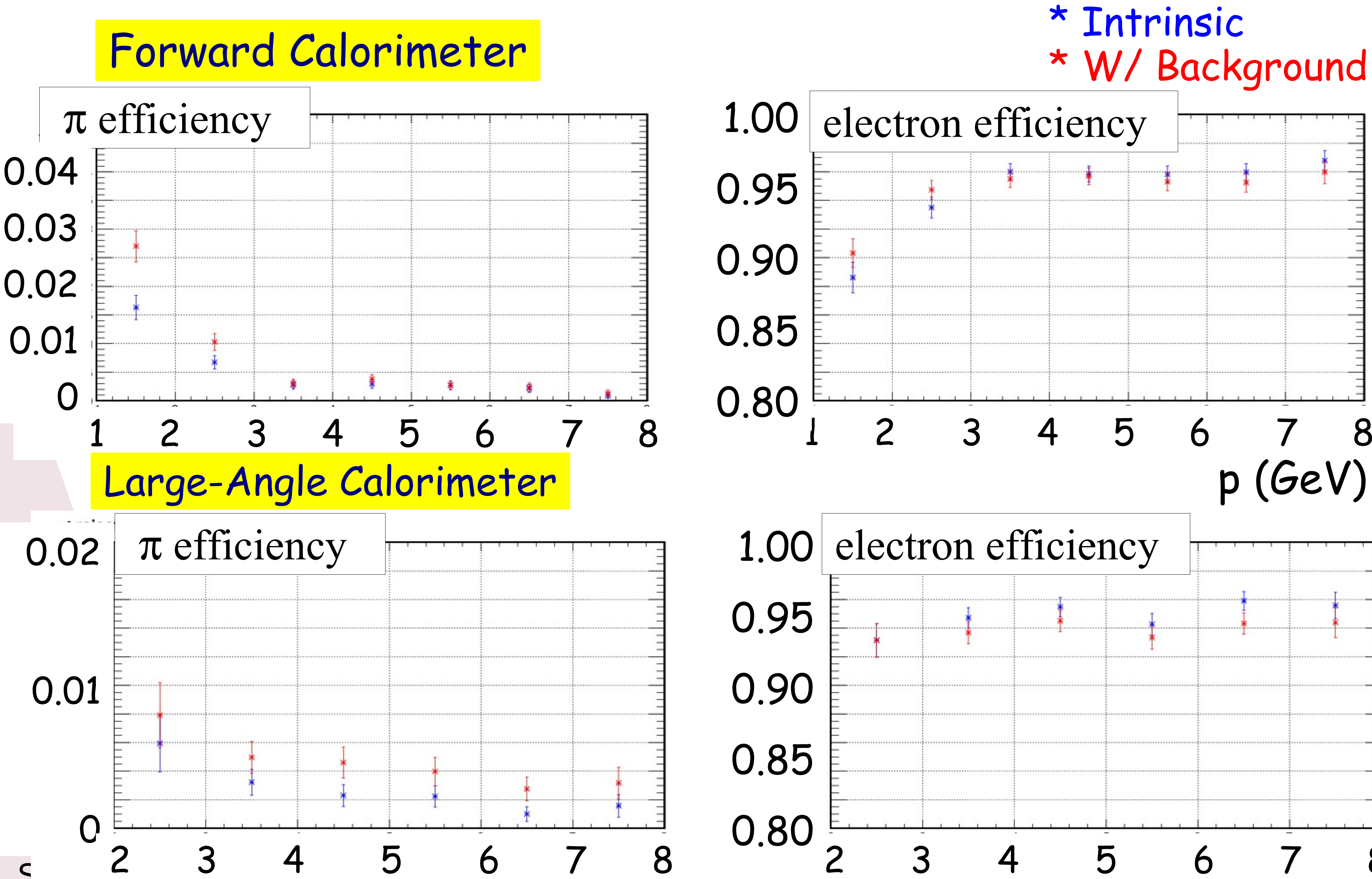






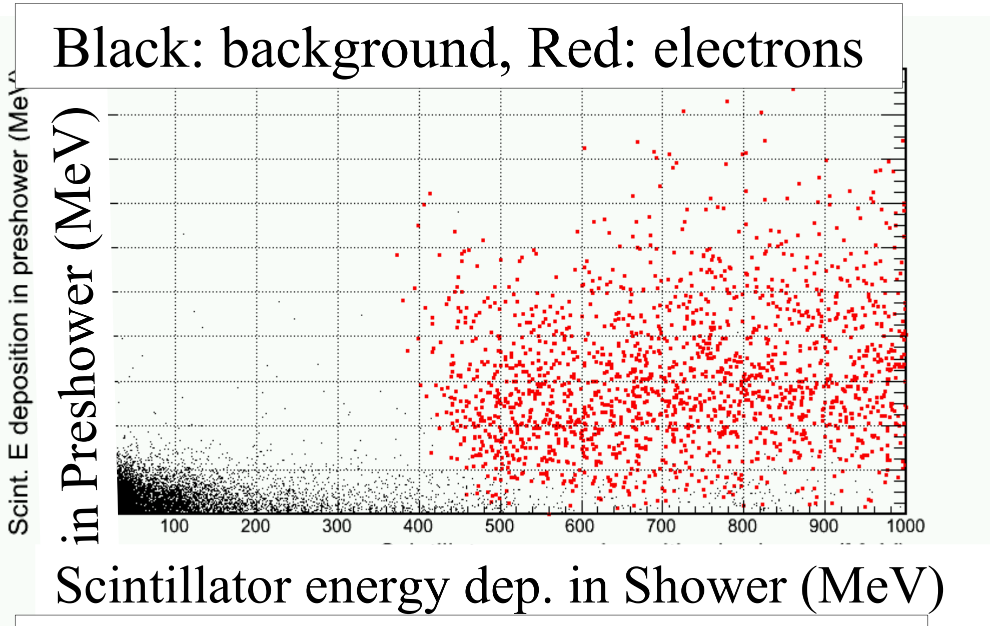
Performance — PID, SIDIS

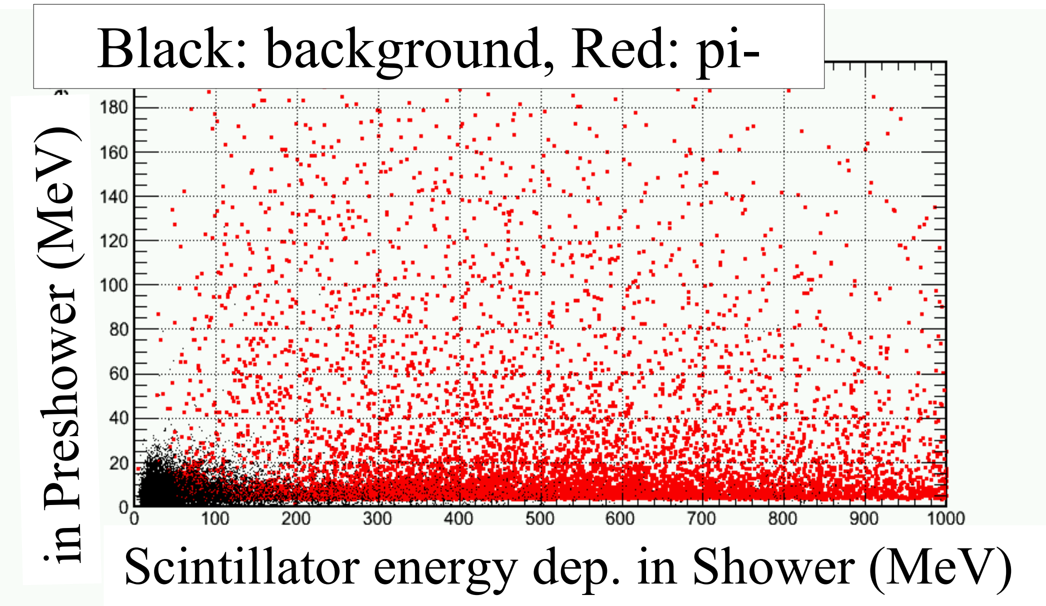
Most inner radius region shown – worse case situation

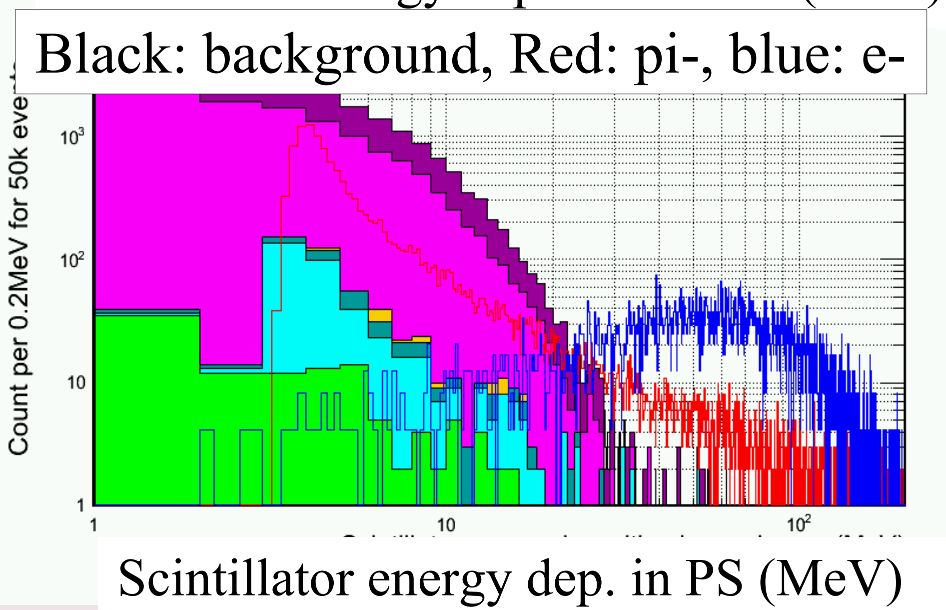


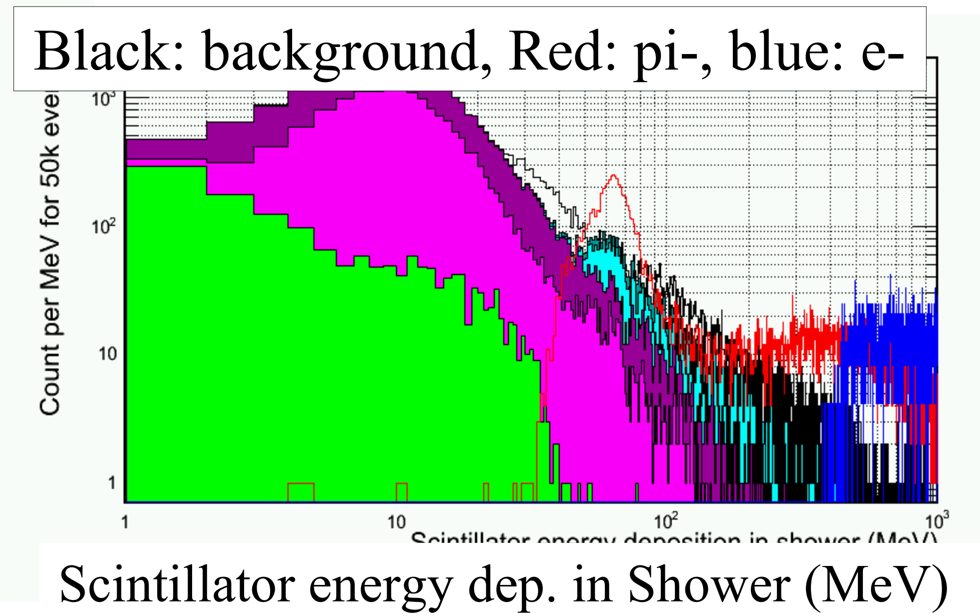
Performance — PID, PVDIS

- Background





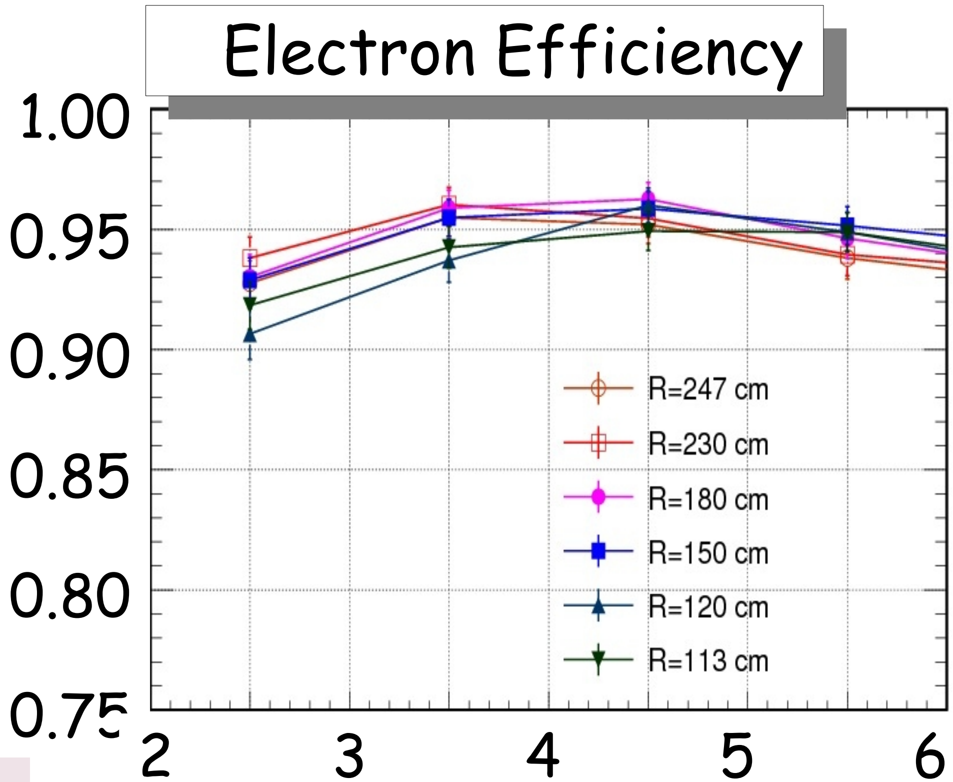


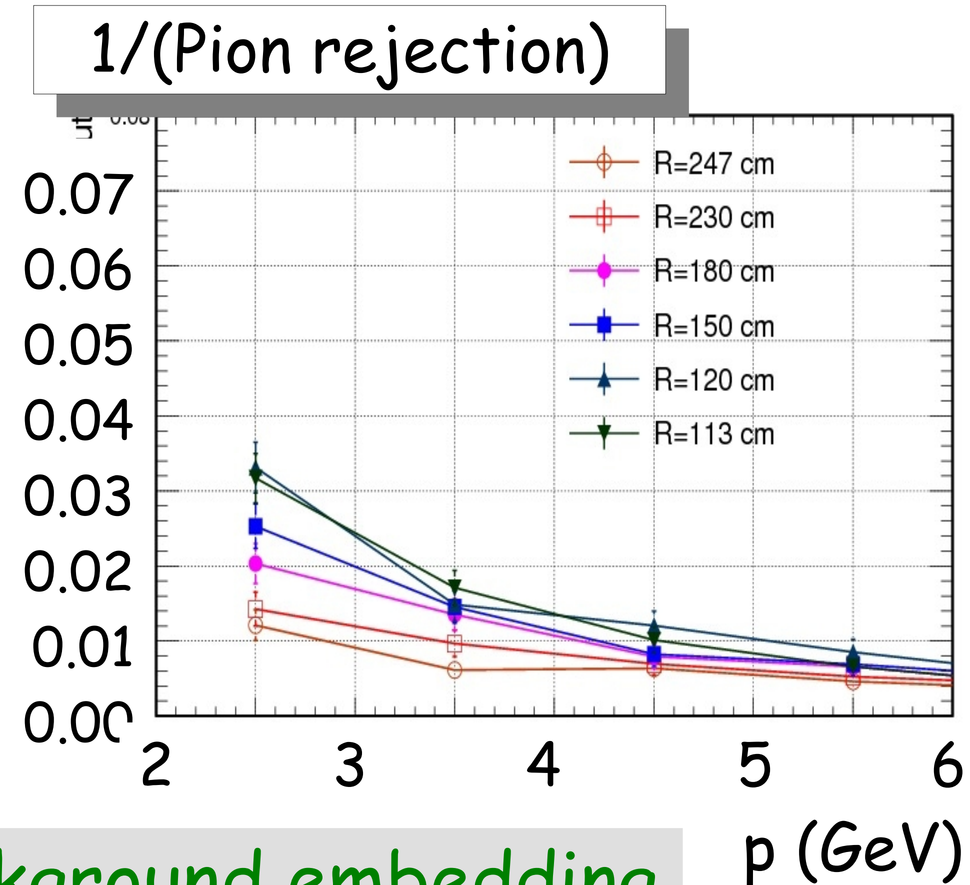


Photon Electron Pi- Pi+ Proton

Performance — PID, PVDIS (low γ)

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



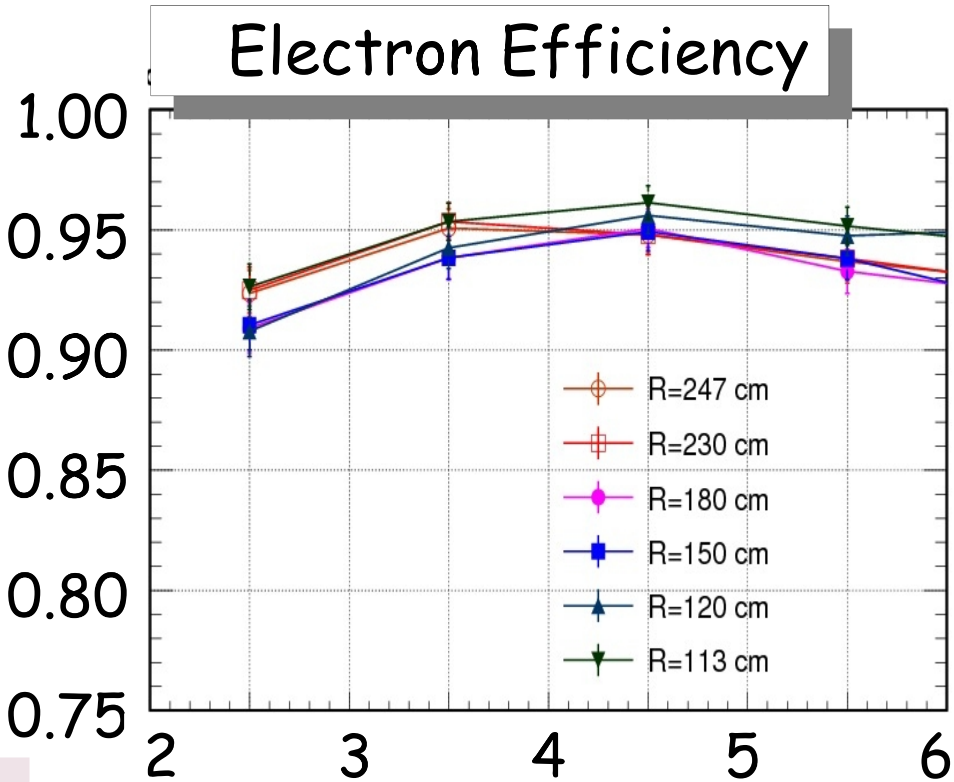


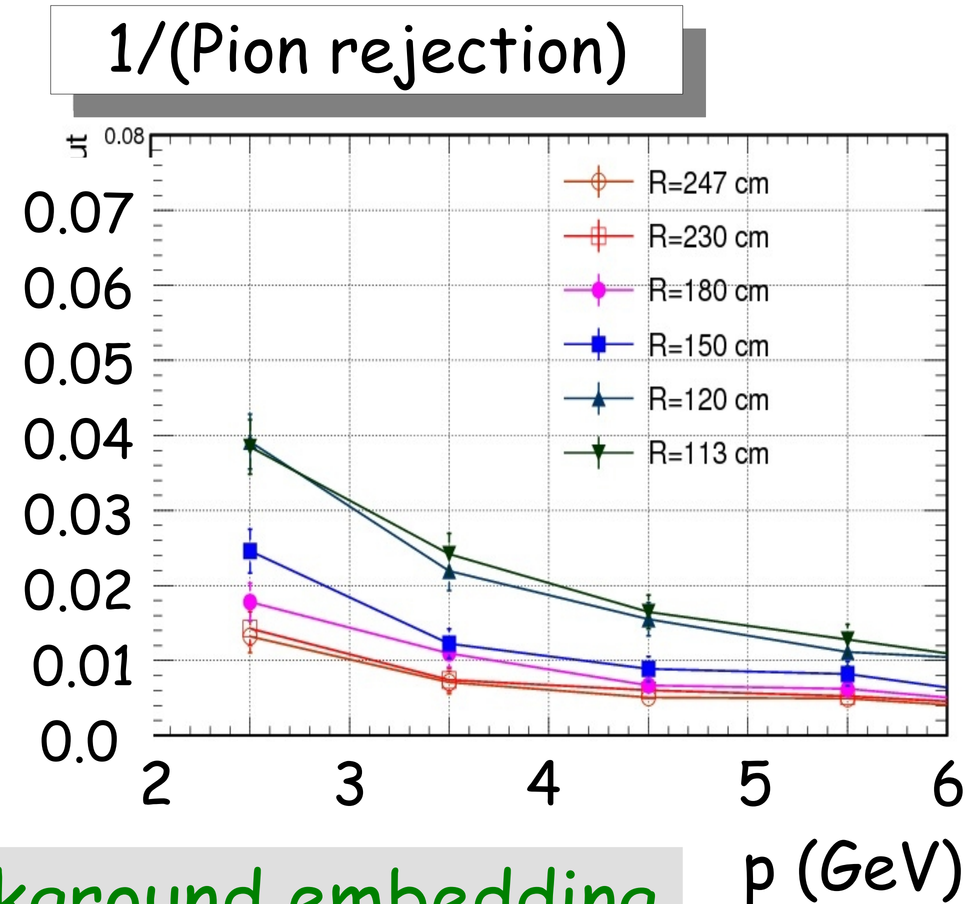
2D-cut PID, with latest background embedding

PVDIS: p=2.3~6 GeV

Performance — PID, PVDIS (high γ)

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



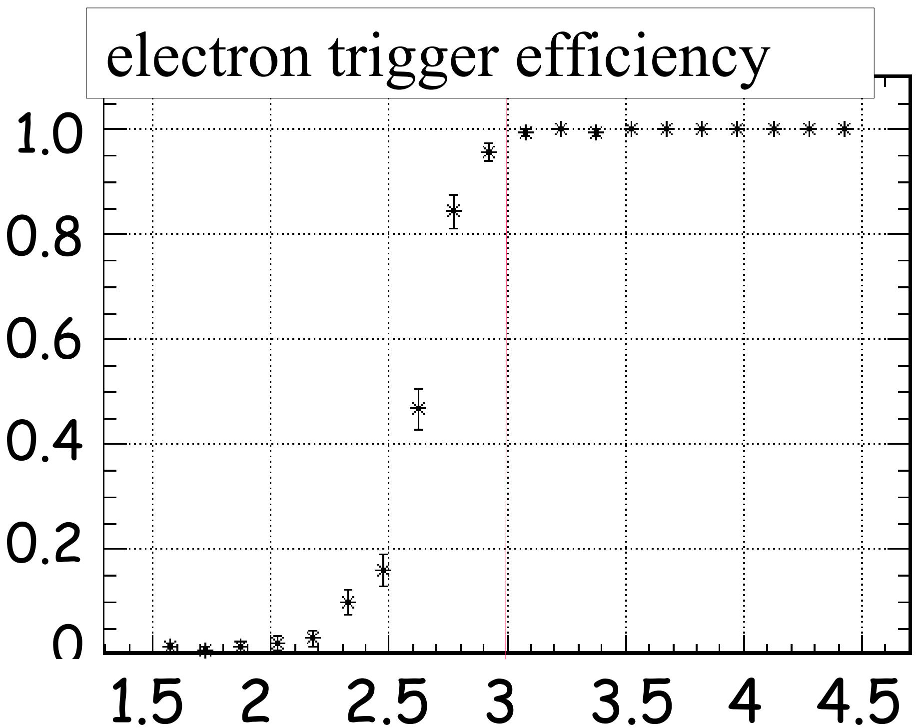


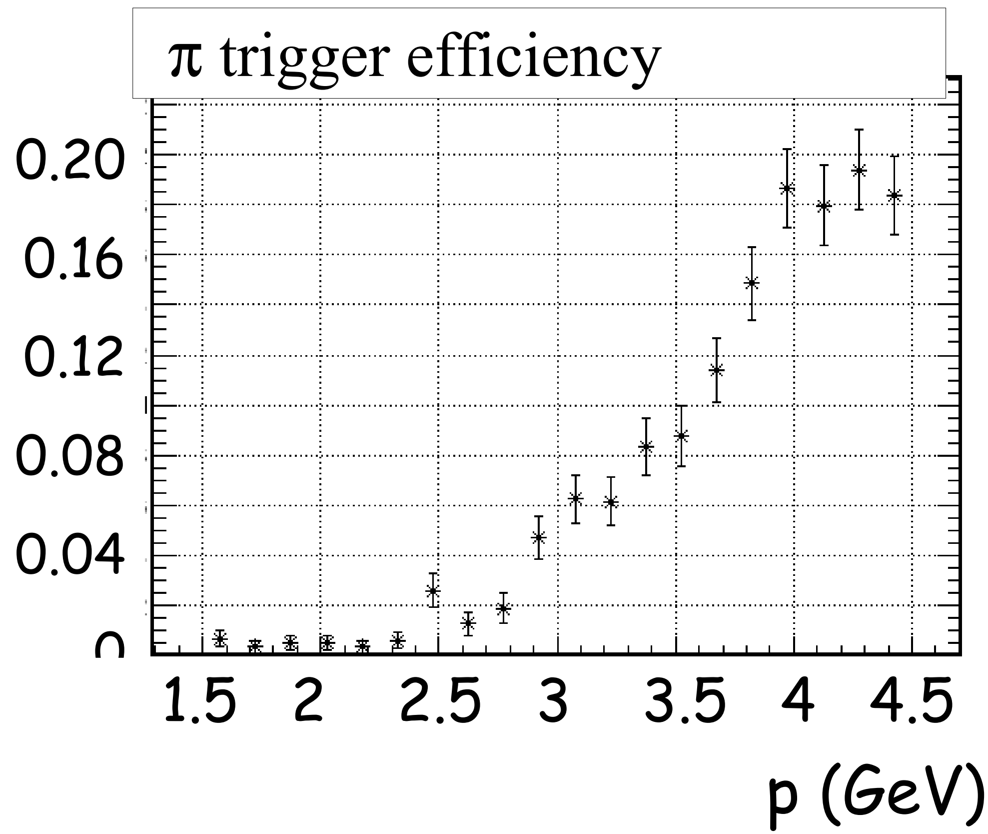
2D-cut PID, with latest background embedding

PVDIS: p=2.3~6 GeV

Performance — Triggering
SIDIS, large angle, electron trigger

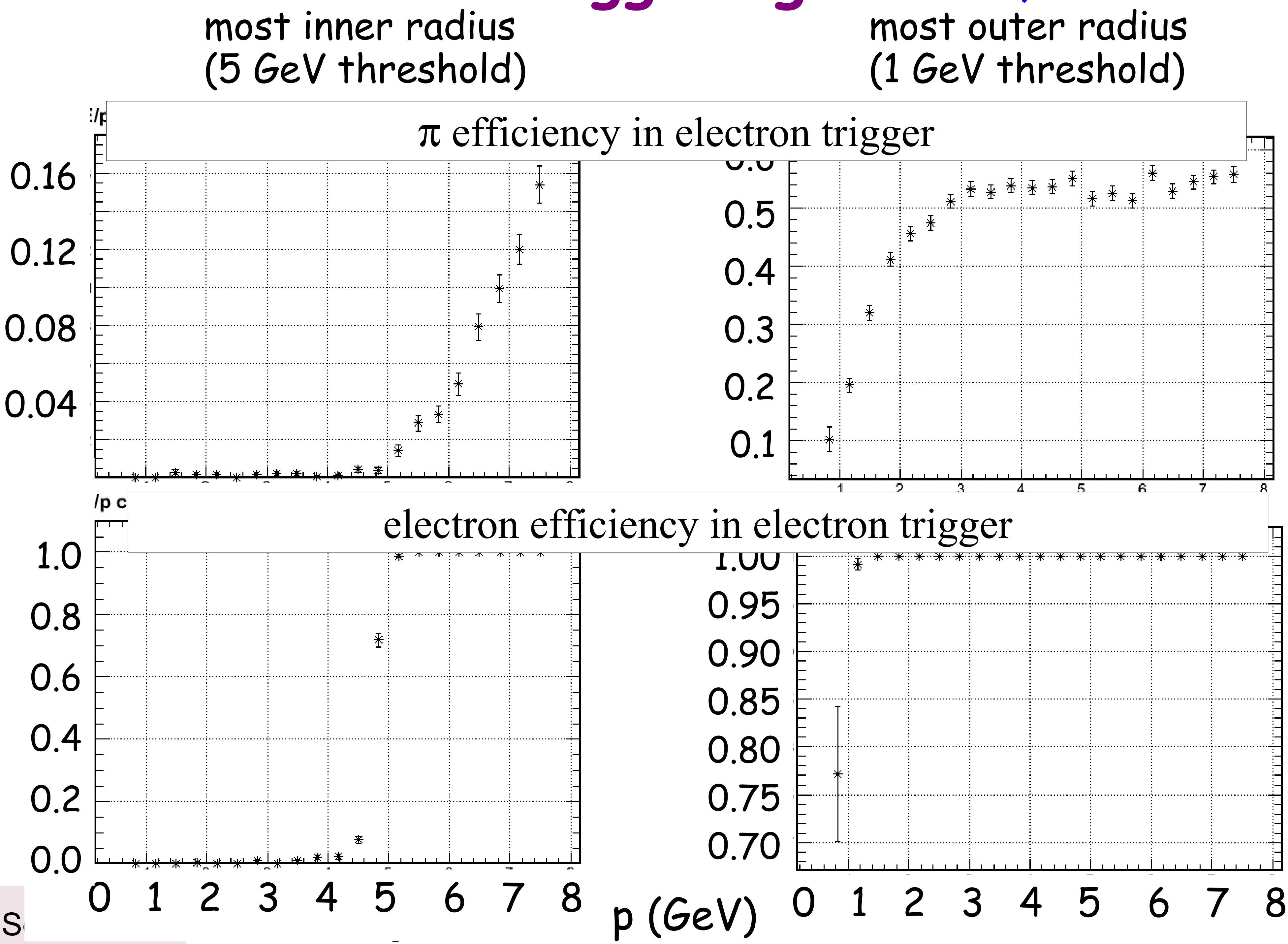
Most inner radius region shown – worse case situation





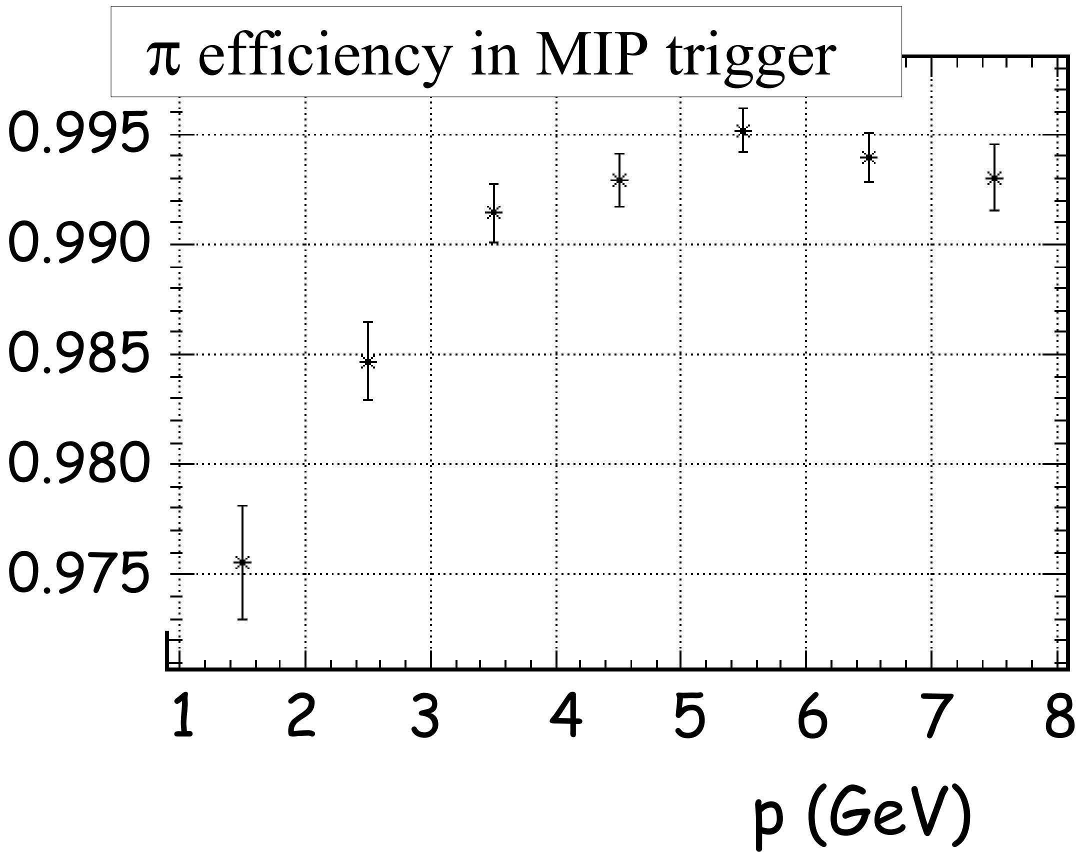
threshold: 2.6 GeV → 3 GeV momentum

Performance — Triggering SIDIS, forward



Performance — Triggering
SIDIS, forward MIP trigger

Pion trigger: 2-sigma below MIP



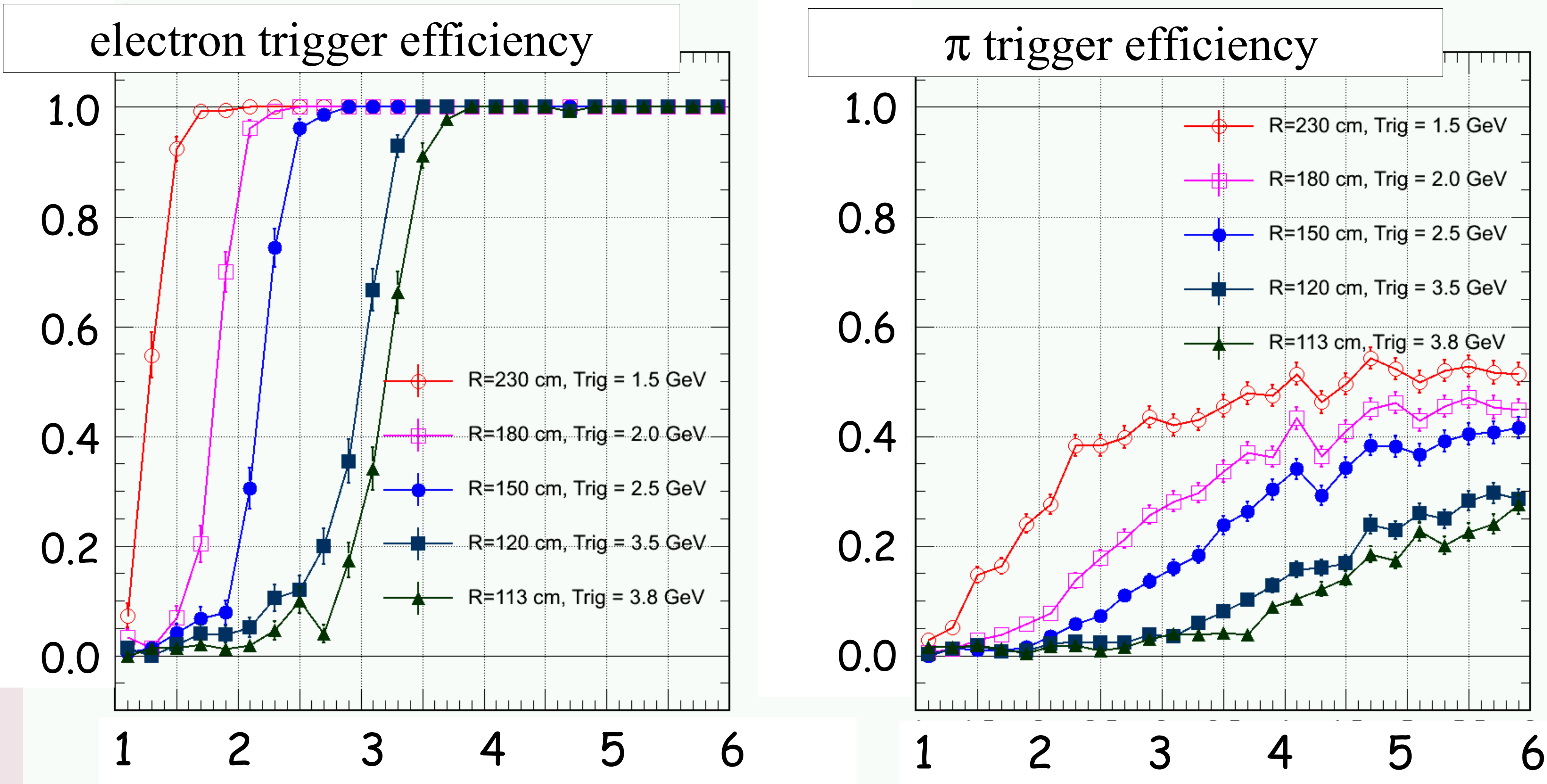
Performance — Triggering

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, trigger rates (whole EC)

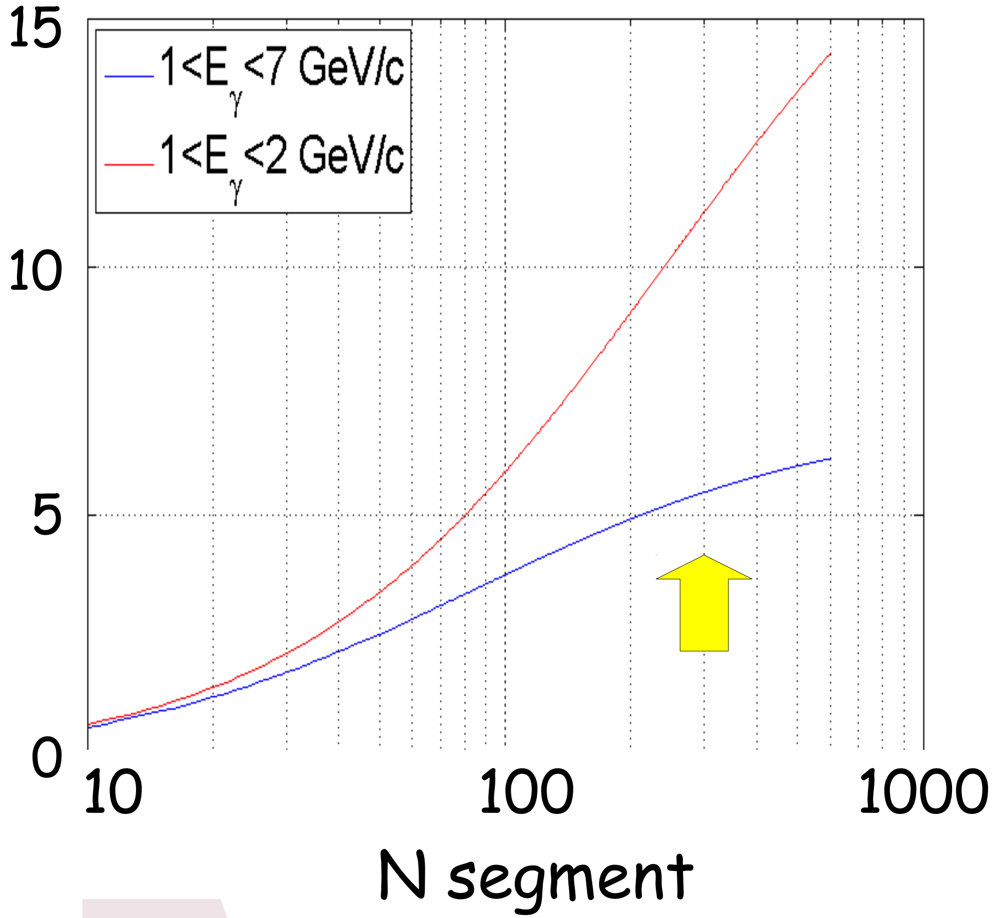
region	full	high	low
rate entering the EC (kHz)			
e^- (DIS)	413	148	265
π^-	5.1×10^5	2.7×10^5	2.4×10^5
π^+	2.1×10^5	1.0×10^5	1.2×10^5
$\gamma(\pi^0)$	8.4×10^7	4.2×10^7	4.3×10^7
p	5.5×10^4	2.4×10^4	3.1×10^4
sum	8.5×10^7	4.2×10^7	4.3×10^7
trigger rate for $p > 1$ GeV (kHz)			
e^- (DIS)	321	80	231
π^-	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	$(8.7 \pm 0.7) \times 10^3$	$(5.3 \pm 0.4) \times 10^3$	$(3.4 \pm 0.4) \times 10^3$

SPD Design for SIDIS

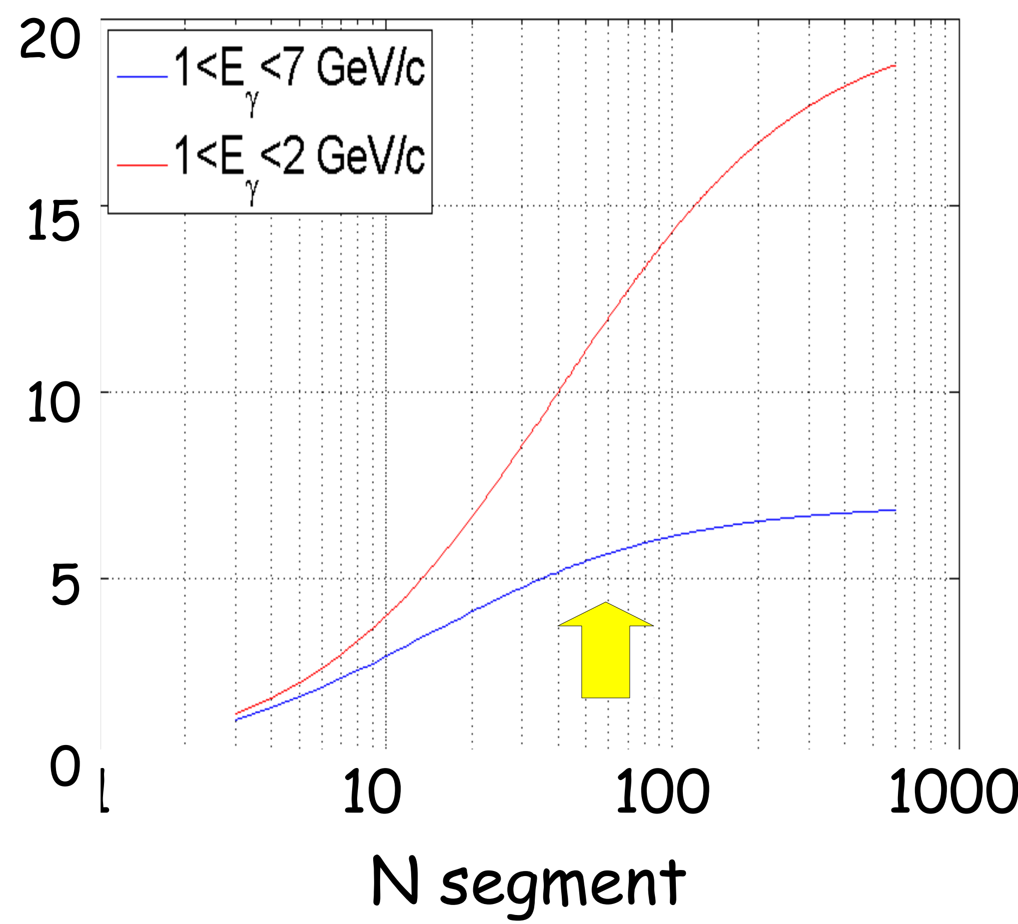
SPD Design for SIDIS

- Starting point: 5mm LASPD (60 azimuthal) provides 10:1 photon rej; 5mm FASPD (60 azimuthal x 4 radial) provides 5:1;

Forward photon rejection

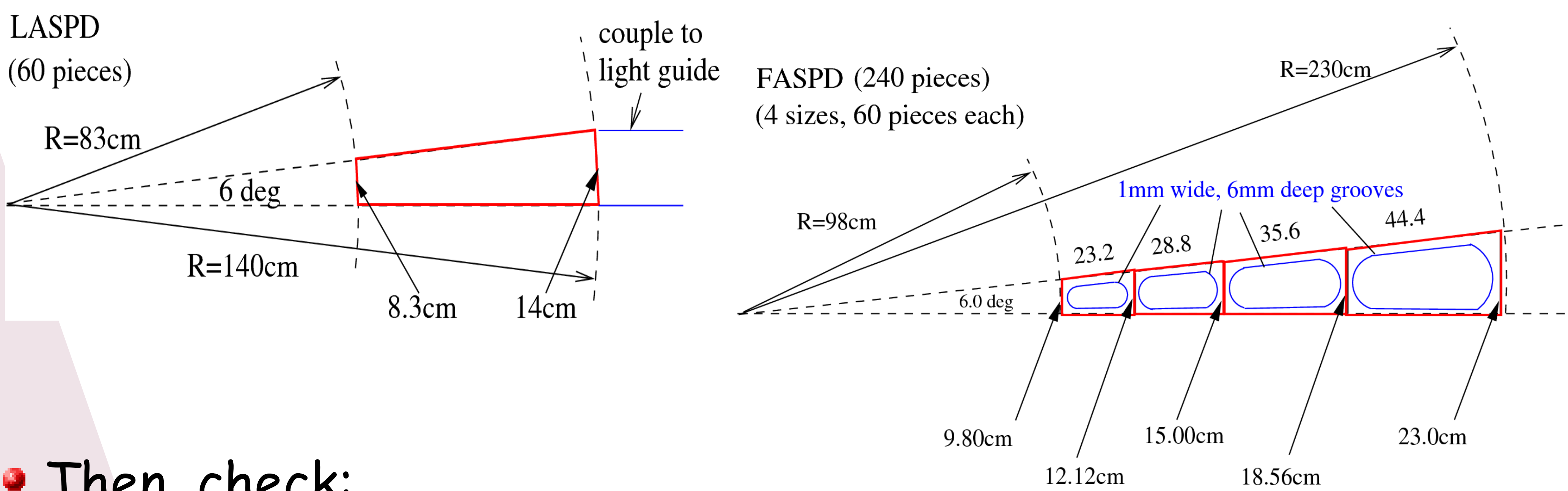


Large-Angle photon rejection



SPD Design for SIDIS

- Starting point: 5mm LASPD (60 azimuthal) provides 10:1 photon rej; 5mm FASPD (60 azimuthal x 4 radial) provides 5:1;

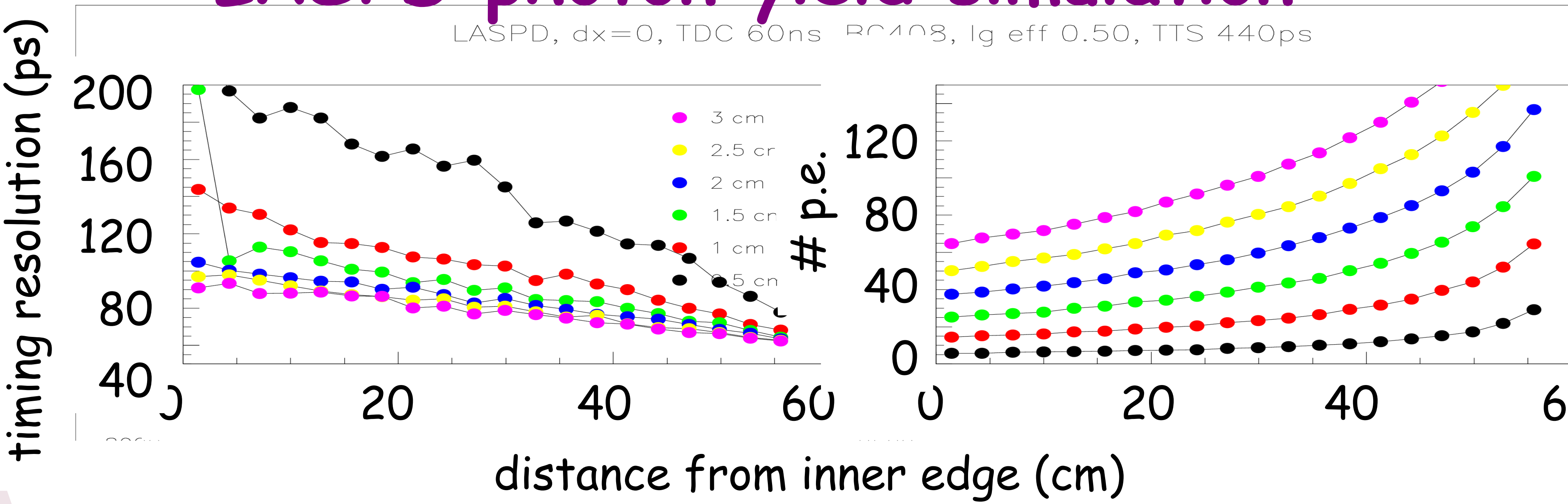


- Then, check:
  - feasibility: with x50 preamp, require (20-40)p.e./MIP to keep 1/2MIP at 20mV and anode current below 1/2 of maximum
  - LASPD timing resolution < 150ps

SPD photon yield simulation

- 3E3 photon/MeV scintillator efficiency as obtained from Preshower data (1/3 of Eljen EJ200 or BC408 and 1/2 of expected polysterene-based material);
- Propagate down SPD, use 0.95 reflectivity and add scintillator decay (use BC408);
- Assuming 50% light guide efficiency
- Good agreement with data for: HRS S2 (300ps), CLAS12TOF (2 sizes, 35ps, 55ps), moderate for CLAS6TOF (120ps).
- For SPD, timing resolution dominated by PMT TTS, also affected by TDC channel setting

LASPD photon yield simulation



- LASPD: 15-20 mm thickness needed for both yield and timing, direct light readout required;
- FASPD: Too long for direct readout, use WLS fiber embedding, 1cm → 20p.e., 1.3ns timing spread; 2cm → 40 p.e., 1.0ns timing spread.
- prototype test to be done to check simulation (LASPD ordered, FASPD still being designed)
- effect on photon rejection being studied.

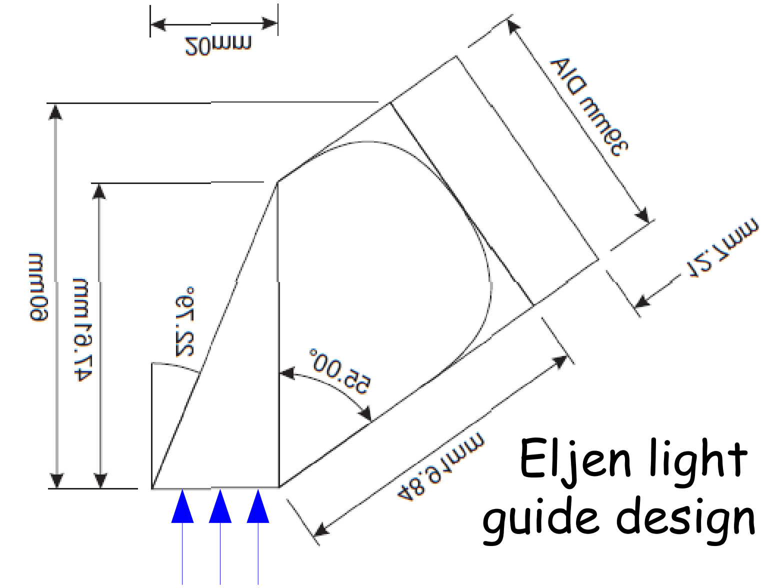
EC & SPD PMT Choice

- Guide light to low-B region to be read by PMTs
  - Shower: 100x ϕ–1mm fibers → ϕ-1in PMT (good area match), Hamamatsu R11102, custom divider with x5 preamp, 5E4 PMT gain;
  - Preshower: (4)x ϕ–1mm fiber → 16-ch MAPMT, Hamamatsu R11265-100-M16, 2E4 PMT gain limited by anode current (1/10 of max), require x50 preamp;
  - FASPD: (4)x ϕ–1mm fiber → 16-ch MAPMT, Hamamatsu R11265-100-M16, require half-MIT=20mV, need 1.6E5 PMT gain to combine with the max x50 preamp gain. Anode current 50uA total (1/2 of max).

- Working with JLab detector group on PMT base/preamp design

LASPD readout by Fine-Mesh PMTs

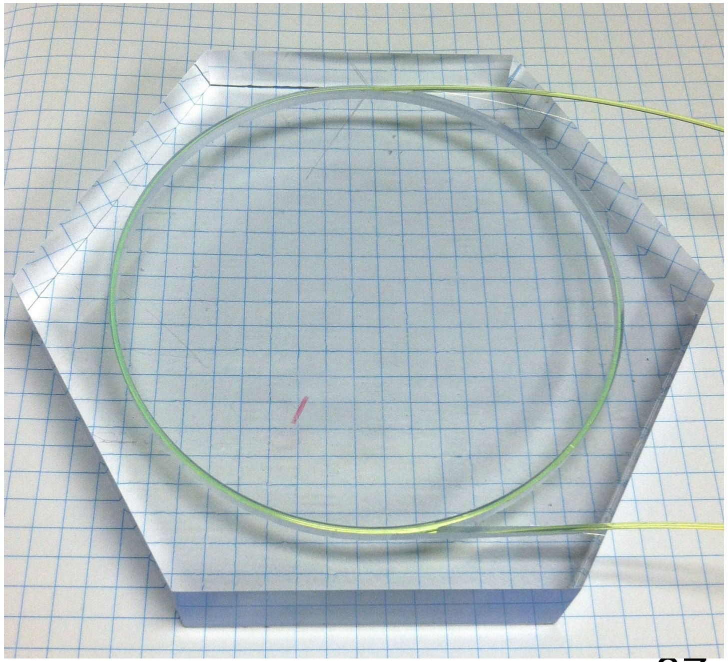
- FMPMT and APD both are field resistant, similar radiation hardness, but APD gain is much lower.
- Existing data on FMPMT (INFN, FIU) show
  - gain drops by 100 at 1.2T, 0 deg, 10-30 at 30 deg. Above a critical angle (45-55 deg) FMPMT is unusable.
  - timing worsens (30%-100% larger) at 0deg, but nearly independent of field at 30 deg, up to 1.2T.
  - → Indicate the use of 55-deg bending light guides.
- Will use Hamamatsu R5924-70 FMPMT (2in) due to higher Ianode limit (100uA vs. 10uA), but will test all 3 FMPMTs (under SoR) using a 5-in 5T solenoid in the test lab.
- Cost: $3k*60



Eljen light guide design

Pre-R&D: preshower prototype testing

- Tested: IHEP, CHN#1 (similar yield)
- WLS fiber: Y11, BCF91A(55% rel.), BCF92(35% rel.)
- wrapping: printer paper, Tyvek 1055B(10% higher), al mylar (17% higher)
- Fiber routing: optimized to double fiber, 2.5 turns each
- Max output: 71p.e. at WLS fiber end, expect 40 at PMT
- To do: test CHN#2; parallel testing UVa/SDU; fiber connector; clear fiber; PID simulation with 40 p.e.



Preshower Prototyping and Production

Vendor	polymer base	light yield anthracene	Price for mass production (20mm)
IHEP	polysterene	40% from CERN data	$216k tot + 30%, or $156 each
Chn #1 高能科迪科技有限公司？		40% from UVa data	$100*1800=$180k
Chn#2 中核控制系统工程有限公司	ST401 phenylethene	40%	$100*1800=$180k
Eljen Technology	EJ200 polyvinyltoluene	64%	[$77 (no groove)/$204 (grooved)] *1800; or $212/$418x3
Saint Gobain Crystal	BC408 polyvinyltoluene	64%	$430x2 no groove

? Chinese: subject to 20% transverse (横向) overhead or not?

LASPD Prototyping and Production

Vendor	polymer base	light yield % anthracene	Price for mass production (20mm)
IHEP (material only)	polysterene	40% from CERN data	$10k total, 5mm, no light guide, +30%
Chn #1 高能科迪科技有限公司 ?		40% from UVa data	$533*60, $32k tot (1/3 SPD, 2/3 l.g.)
Chn#2 中核控制系统工程有限公司	ST401 phenylethene	40%	$420EA, $25k total, no l.g.(?)
Eljen Technology	EJ200 polyvinyltoluene	64%	$578*60, $35k tot (1/3 SPD, 2/3 l.g.)
Saint Gobain Crystal	BC408 polyvinyltoluene	64%	$1062*60, no groove, no l.g.

? Chinese: subject to 20% transverse (横向) overhead or not?

FASPD Prototyping and Production

Vendor	polymer base	light yield % anthracene	Price for mass production (20mm)
IHEP (material only)	polysterene	40% from CERN data	$40k total, 5mm; +30%
Chn #1 高能科迪科技有限公司？		40% from UVa data	
Chn#2 中核控制系统工程有限公司？	ST401 phenylethene	40%	($1500)*60=, $90k total
Eljen Technology	EJ200 polyvinyltoluene	64%	$1160*60=$66k tot
Saint Gobain Crystal	BC408 polyvinyltoluene	64%	$1062 EA, no groove, no l.g.

? Chinese: subject to 20% transverse (横向) overhead or not?

Shashlyk Production (IHEP)

- Mold: $30k x 2 (scintillator), $15k (lead); plus
- $1270 per module, see below
- Same prototyping and mass production
- Not including 30% overhead

Component	Cost per module
Scintillator	$200
Lead	$240
flanges, nuts	$230
assembly	$320
add fiber mirror, testing	$110

Prototyping (8 modules): $55k+30%, plus fiber ($2,961)

Mass production: $2,361k + 30% = $3,069k, plus fiber

Shashlyk Production (Alternate)

Component	3 modules	8 modules	1800 modules
scintillator (CHN#1)	$10k	$27k	$1kx1800=$1.8M
lead (Kolgashield)	$7,776	$17k	$488k
paper (Kolgashield)	$1,152	$2.5k	$130k
flanges, nuts, rods	$600	$1.6k	$150x1800=$270k
fiber mirror, testing	?		
Total w/o assembly	$19.5k	$48.1k	$2,688k

CHN: only #1 can do injection molding

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
$100k	SPD Modules	30	30	5		65			65
	WLS Fiber	80	100	39		219			219
	Clear Fiber	150	250	126		526			526
	Fiber Connectors	100	175	86		361			361
	Shower PMTs	100	200	104	50	454			454
	PS MAPMTs	80	120	34	30	264			264
$180k	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

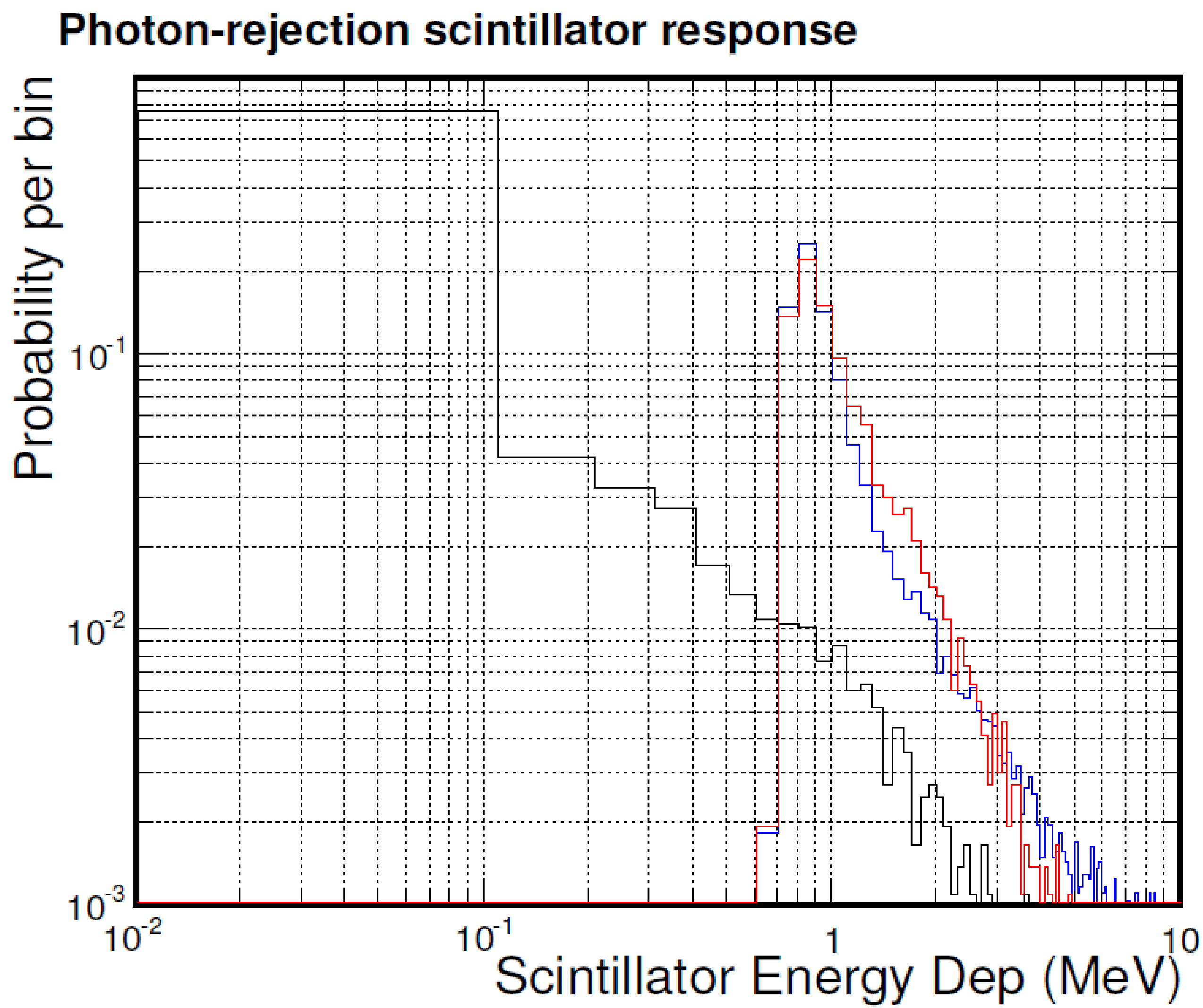
To Do

- Preshower: CHN#1 prototype, SDU/UVa parallel testing;
- LASPD: Test Eljen prototype with both R9779 and FMPMT;
- FASPD: same as LASPD, with fiber embedding;
- Fiber connector test, DDK custom design;
- Shower: look for prototype funding, engineering support.

- Simulation PID: Preshower with 30-40 p.e.
- Simulation SPD: photon rejection at 10-20mm
- Support structure design (ANL/P.R.)

Backup

Forward



Photon-rejection scintillator response
Probability per bin
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
Scintillator Energy Dep (MeV)

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

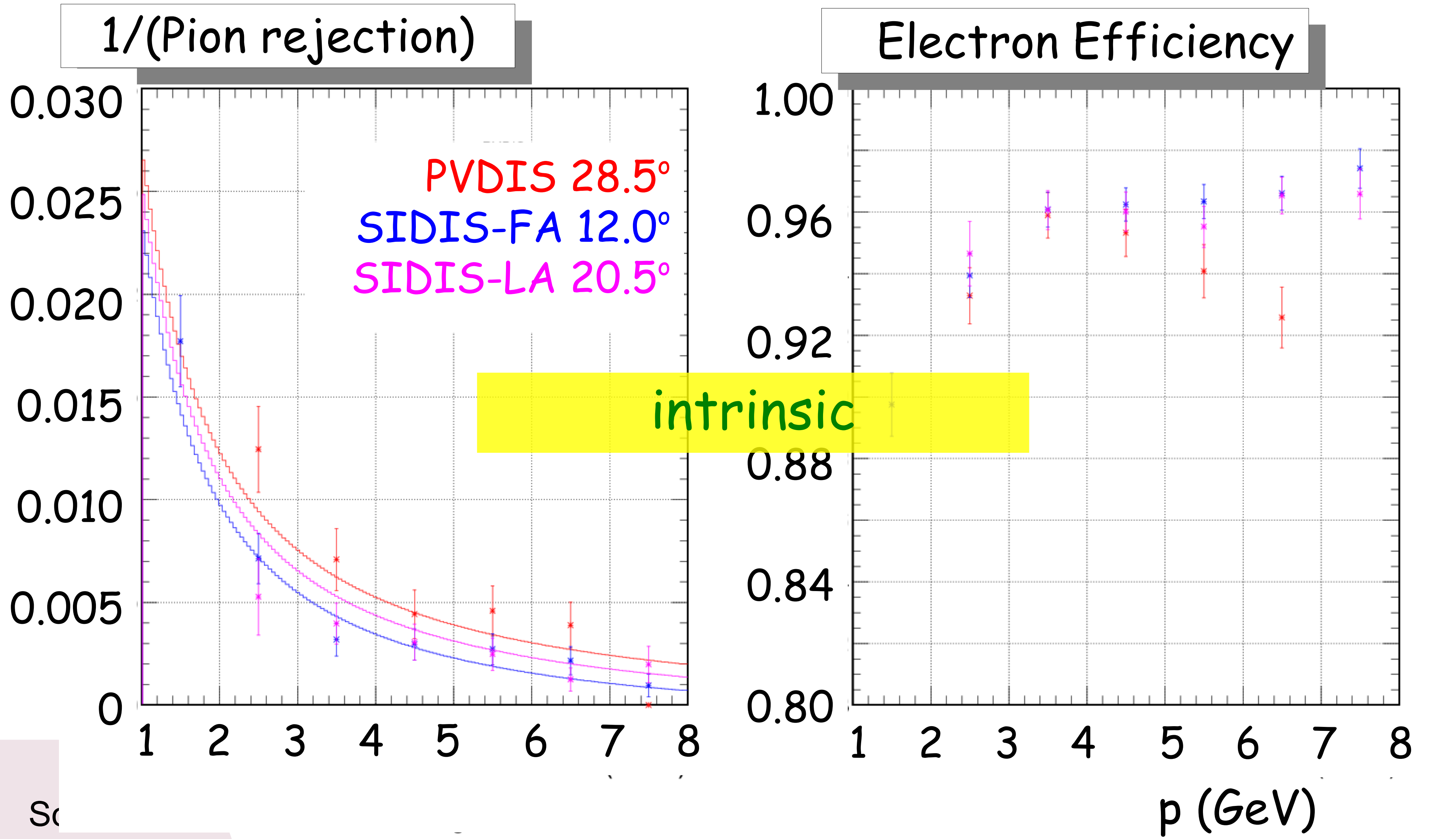
Design Consideration 1: Pb/scintillator ratio

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

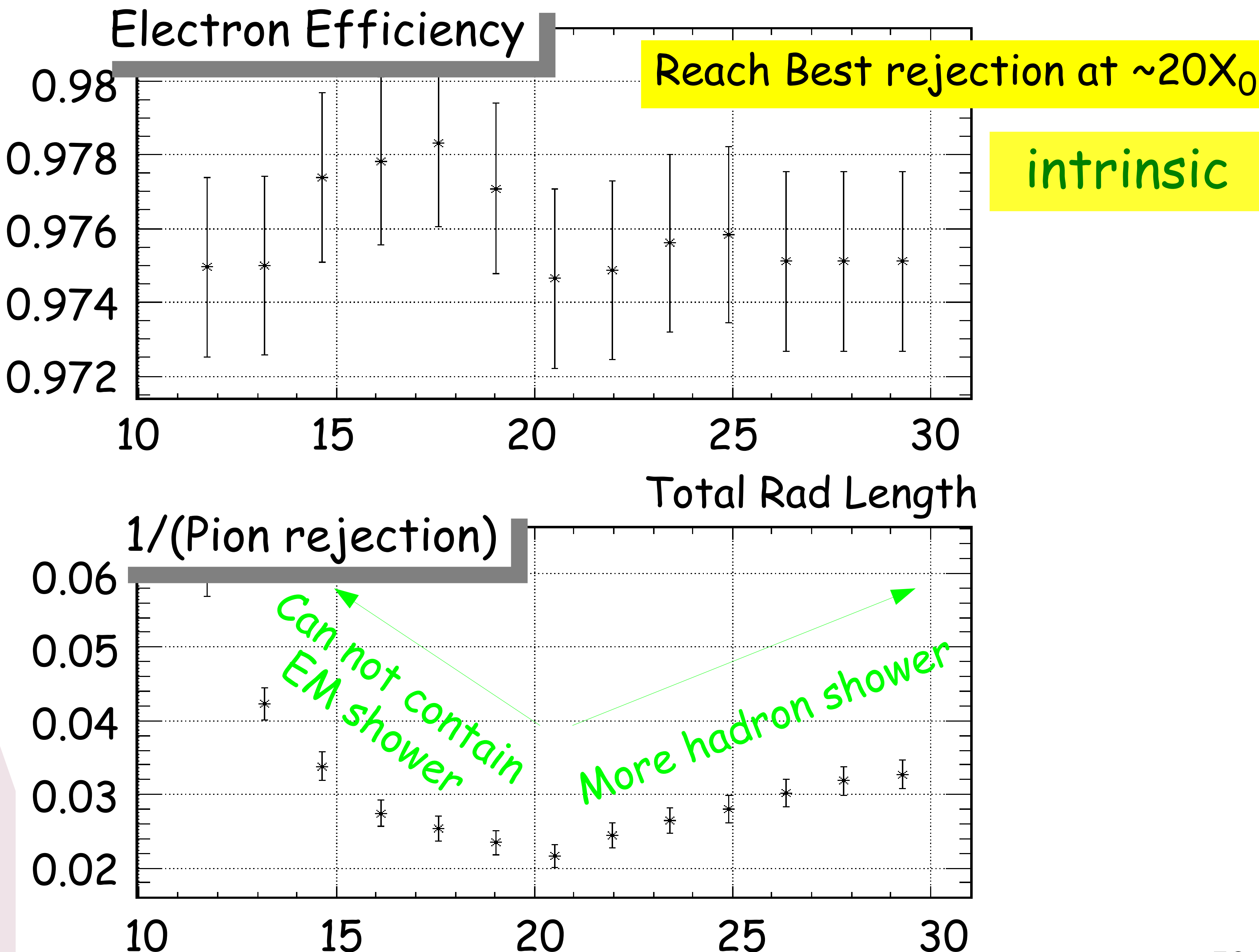
- Thinner Pb layers give better energy resolution, but requires more layers → Balancing between energy resolution and module length

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)]

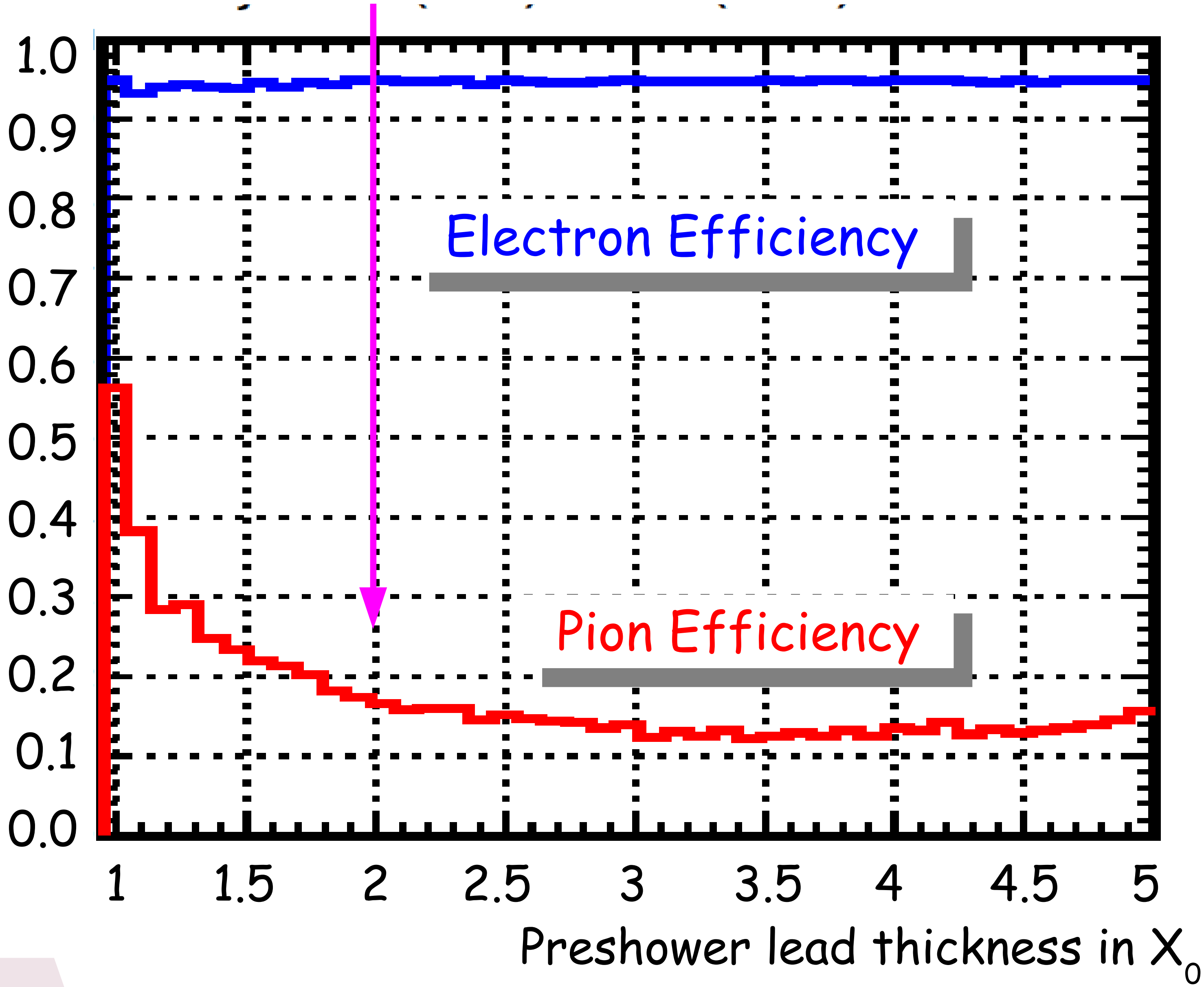


Design Consideration 1.3: Total Length

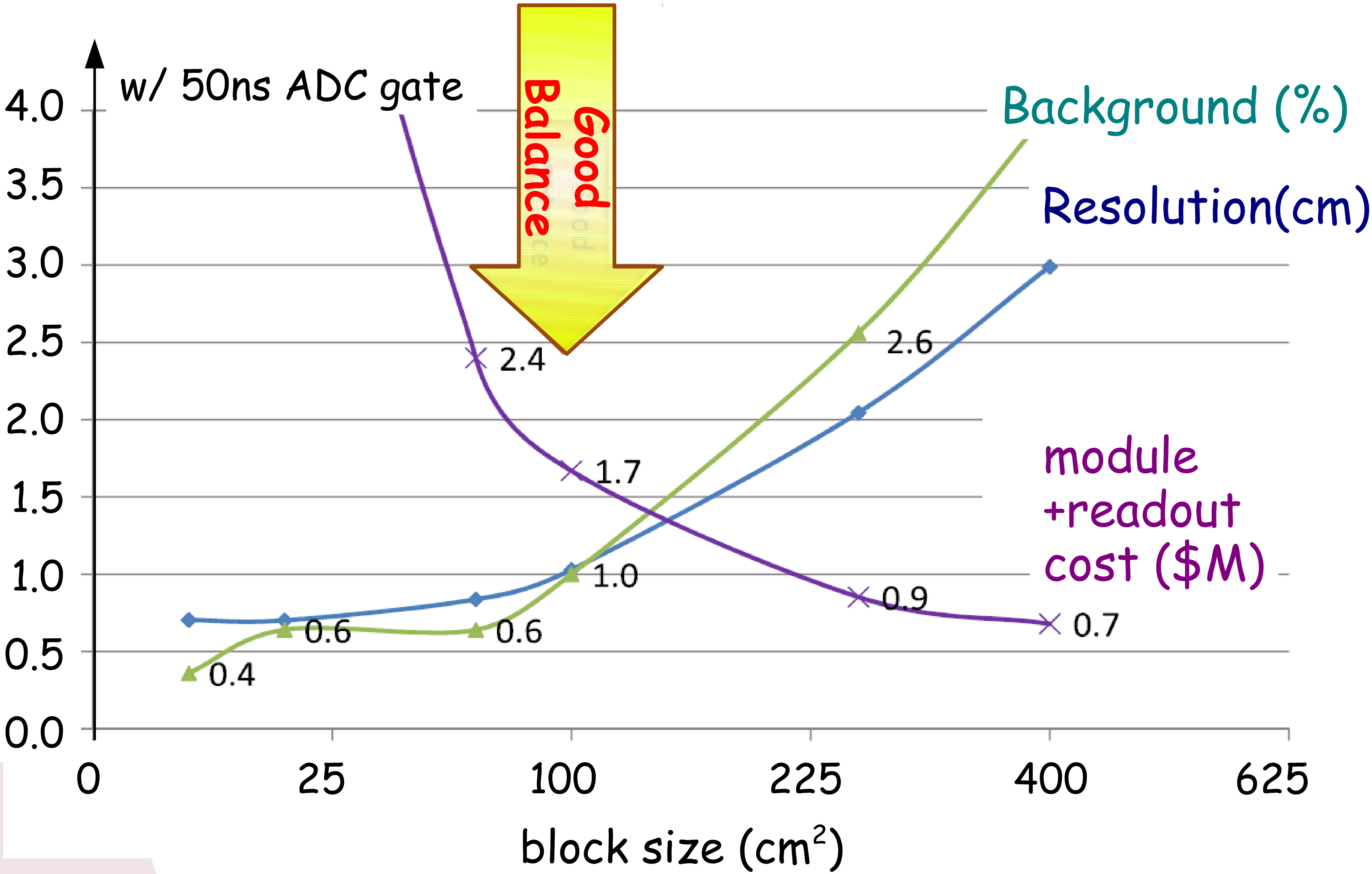


Design Consideration 1.4: Preshower Thickness

- $2X_0$ 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.