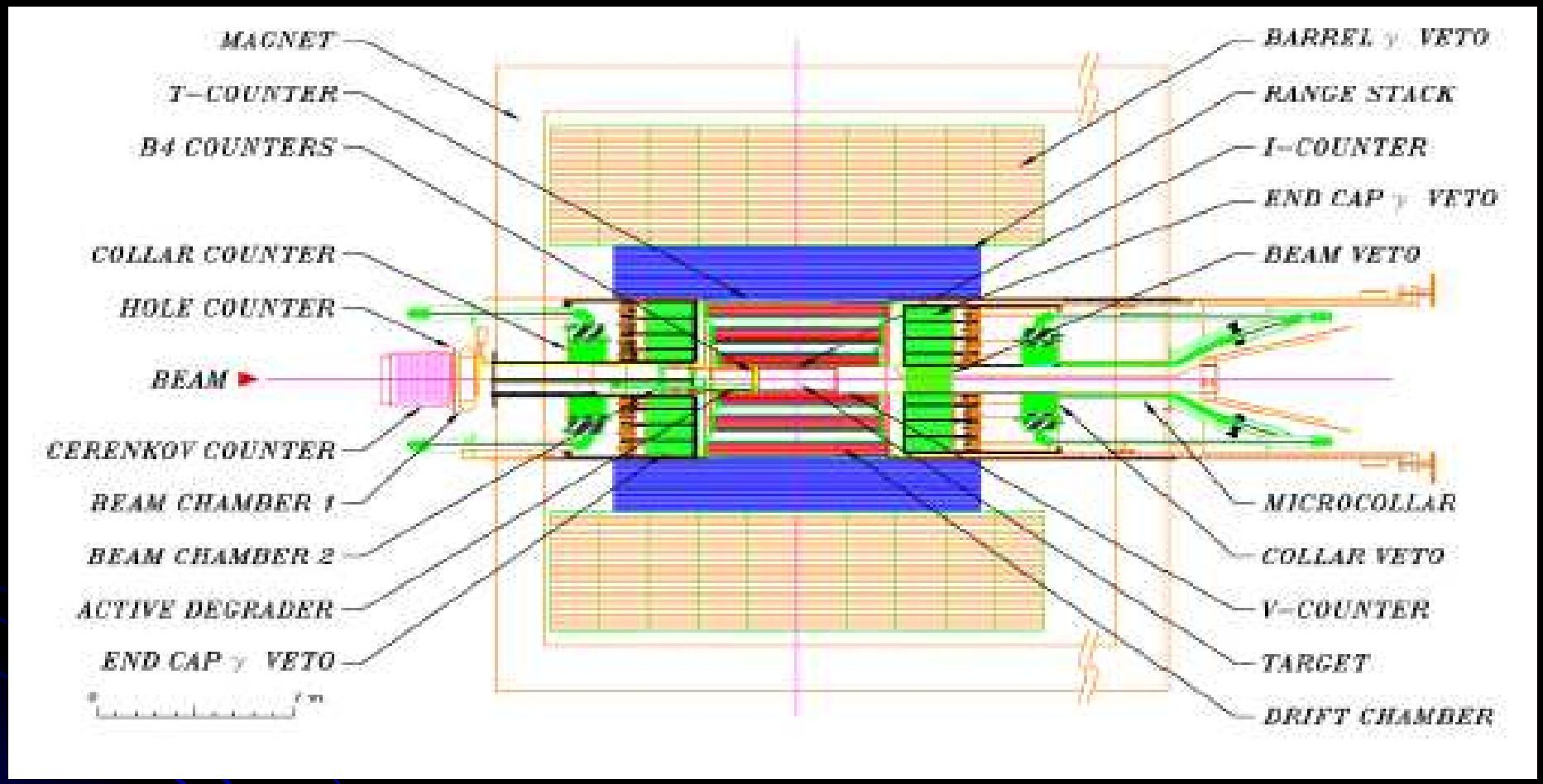
ORKA Calorimetry

Proposed Technologies

Corrado Gatto

INFN Napoli

Schematics of ORKA Calorimeter



- **Barrel technology:** Shashlyk/ADRIANO
- **Barrel**: R_{in}: R_{out}:L 70:145:240 cm³
- **Barrel Weigth**: 25-30 ton
- **Barrel segmentation:** 385 towers 32x25 cm² or 32-64 wedges

- **Endcap technology**: CsI (undoped)
- **Endcap size: dia:L**: 98cm:25cm
- **Endcap Weigth**: 1.13 ton
- **Endcap segmentation**: 24 6x5x25 cm³ + 119 8.5x7-8x25 cm³

Photon Veto or Calorimeter

It depends on the process!

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

Photon Veto or Calorimeter

Photon veto required here

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Photon Veto or Calorimeter

Energy measurement required here

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Preliminary

Requirements for ORKA

- π^0 rejection > 10^6-10^7 ⇨ γ inefficiency < 10^{-3}-10^{-4} above 20 MeV and for impinging angles 90° -20°. ***Desirable sensitivity down to few MeV***
- Depth > 20 X_0
- Accidentals rate: 0.011/MHz (in order to keep the same rate of accidentals as in E949)
- Max decay time for scintillator: 8 nsec (to keep the accidentals down)
- Energy resolution: 10-15% @ 200 MeV (from E949), but needs further studies
- Desirable: γ/n identification

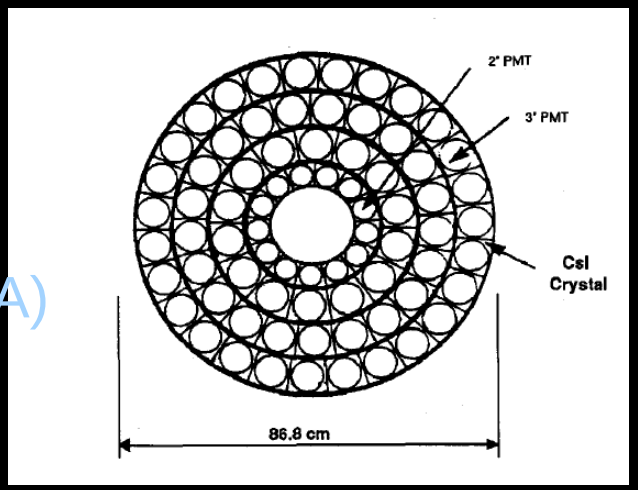
Dedicated discussion tomorrow

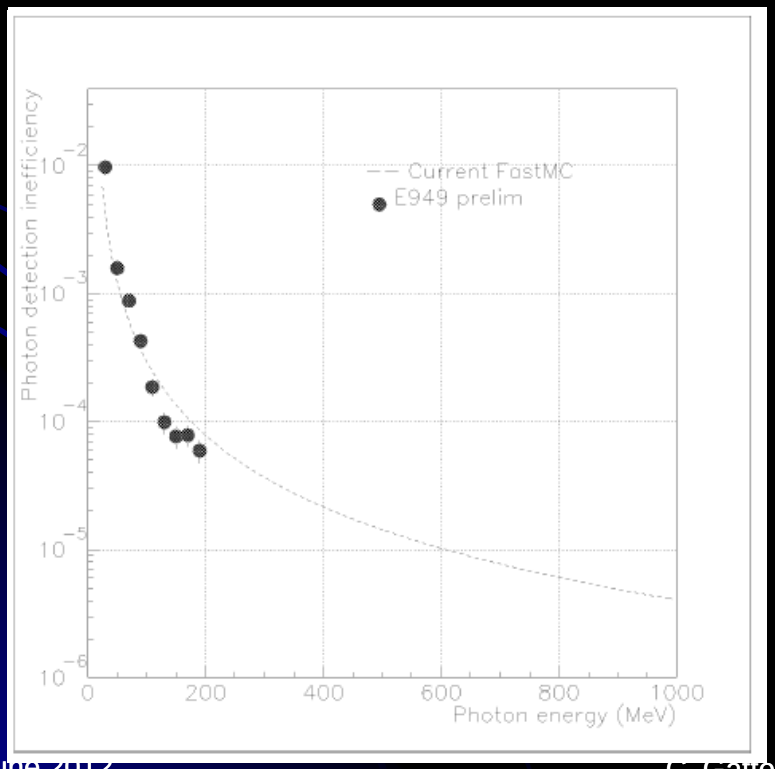
- Light yield ~ 1pe/MeV
- Xo < 3cm ; <ρ> > 3 gr/cm^3
- Threashold: compromise between low inefficiency & low accidentals
- Inhorganic scintillators and/or Cerenkov radiator
- Dual-readout calorimetry

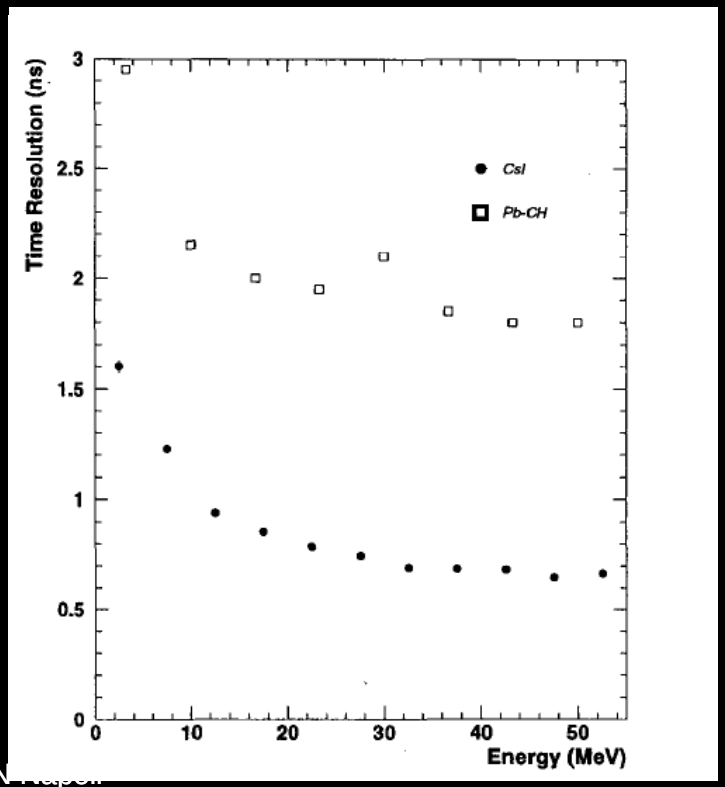
See A. Mazzacane's talk

ORKA Endcap Calorimeter

- Re-use E949 endcap calorimeter
- 25 cm CsI (undoped) crystals
- 13.5 Xo total depth (may be not enough at ORKA)
- 10 nsec decay constant (+ slower component)
- $\Delta E/E$ = 10.6% for π^0 from $K_{\pi 2}$ decays (245.6 MeV)







Technologies For Barrel

Shashlyk

- Pro
  - Cheap
  - Well established technology
  - Extensive test beam
- Cons
  - Sampling fluctuations
  - Inadequate for E_γ<50 MeV
  - Large inefficiency for low energy photon

ADRIANO with heavy glass or PbF_2

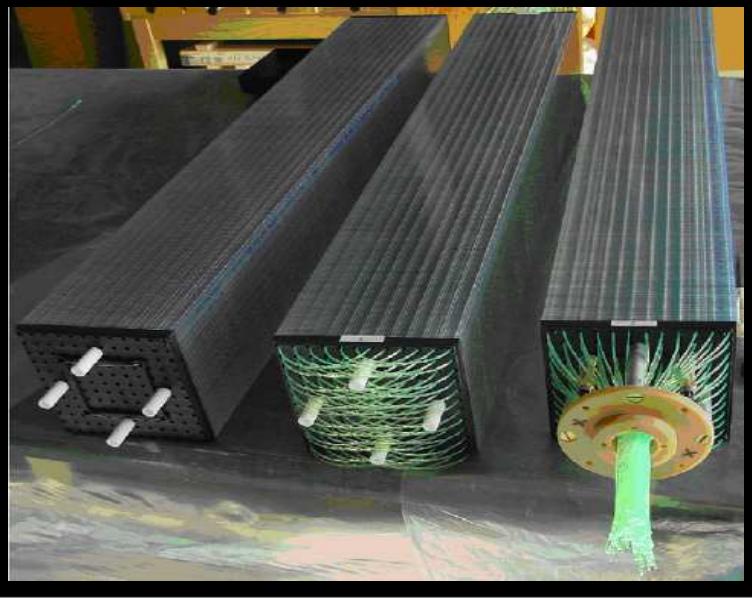
- Pro
  - Integrally active calorimeter
  - Higher detection efficiency
  - S vs C provides PID
- Cons
  - More expensive
  - Novel technology
  - Tested only at high energy (500 MeV)

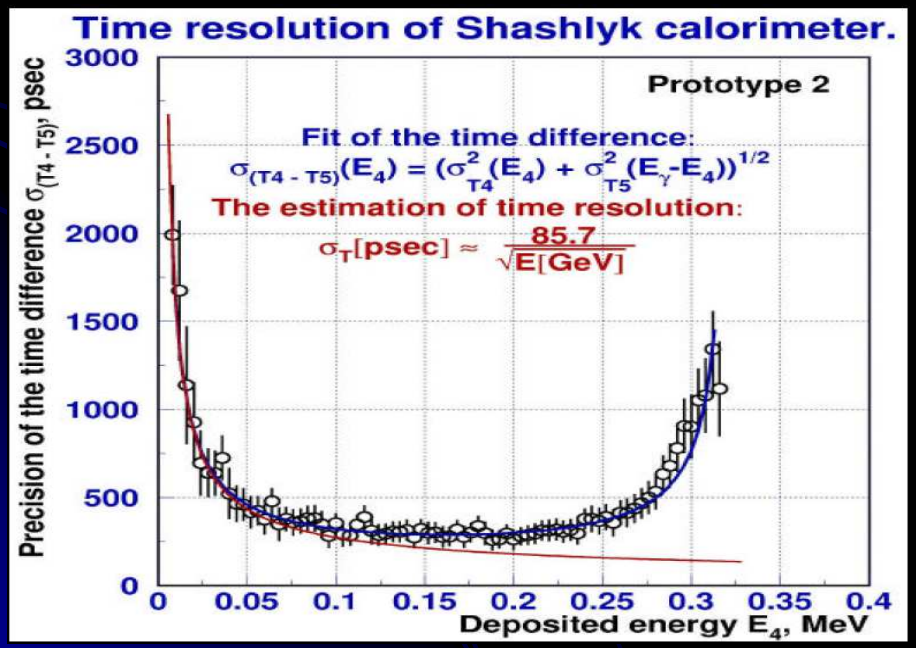
ADRIANO in single readout mode

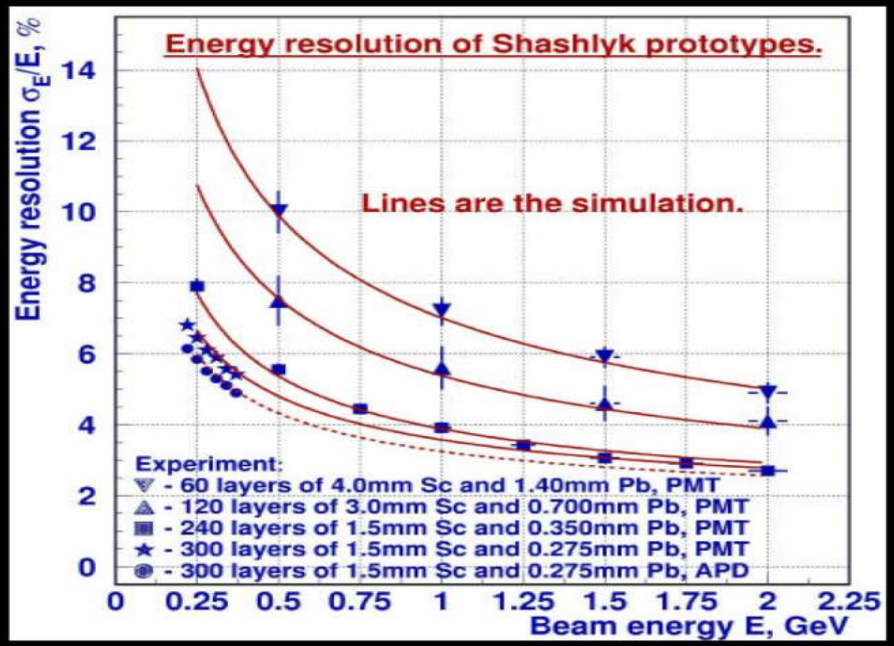
- Pro
  - Integrally active calorimeter
  - Highest detection efficiency
- Cons
  - Also expensive
  - Untested technology
  - No PID

Shashlyk Barrel Calorimeter

- 155 interleaved layers of 0.8-mm lead and 1.6-mm scintillator readout by 400 WLS
- Sampling fraction: 33%
- Xo = 1.2 cm; <ρ> ≈ 4 gr/cm^3
- L.Y.: 0.75-1.2 pe/MeV
- Energy resolution: 2.9-4.1%/ √E
- Time resolution: 90-100 psec/ √E



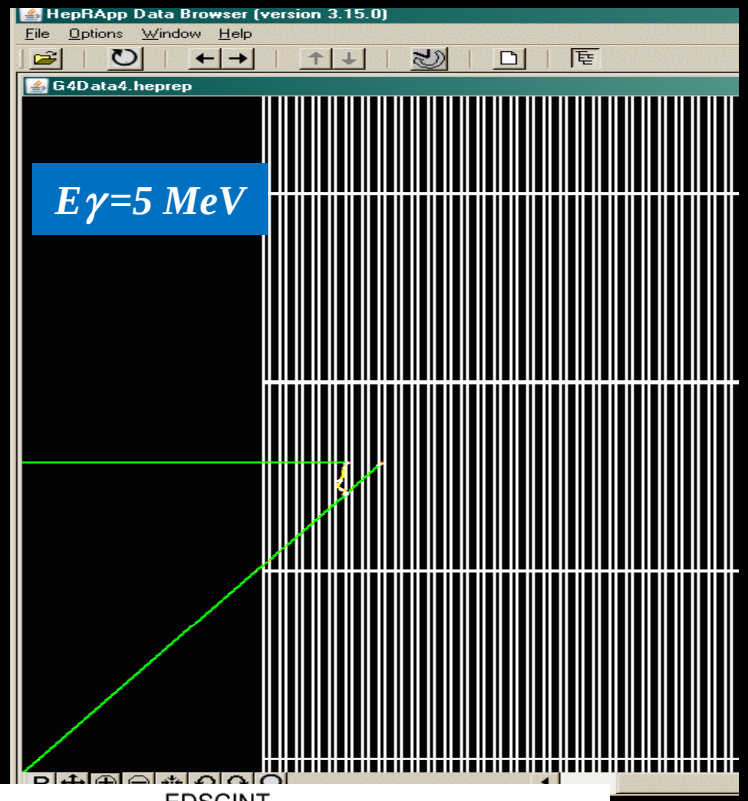


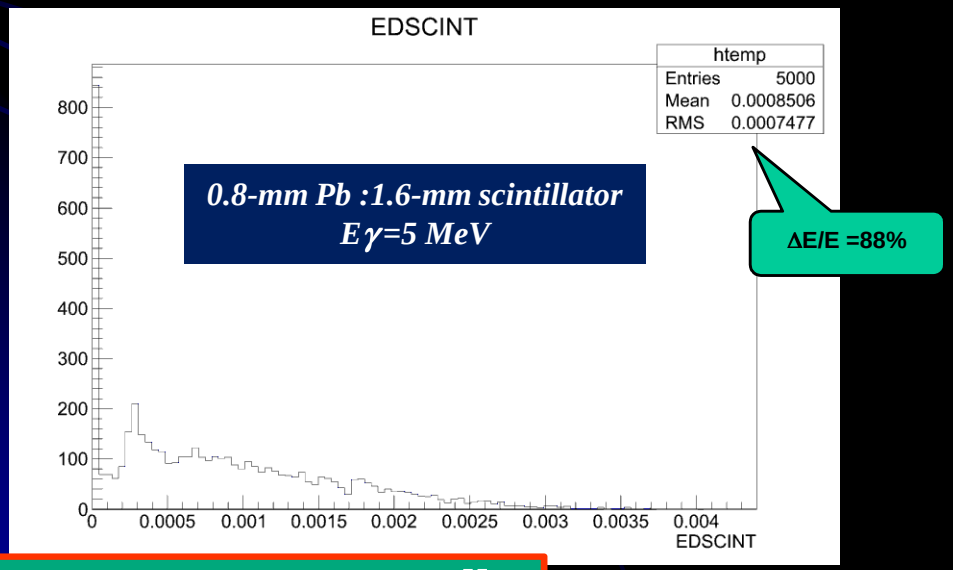


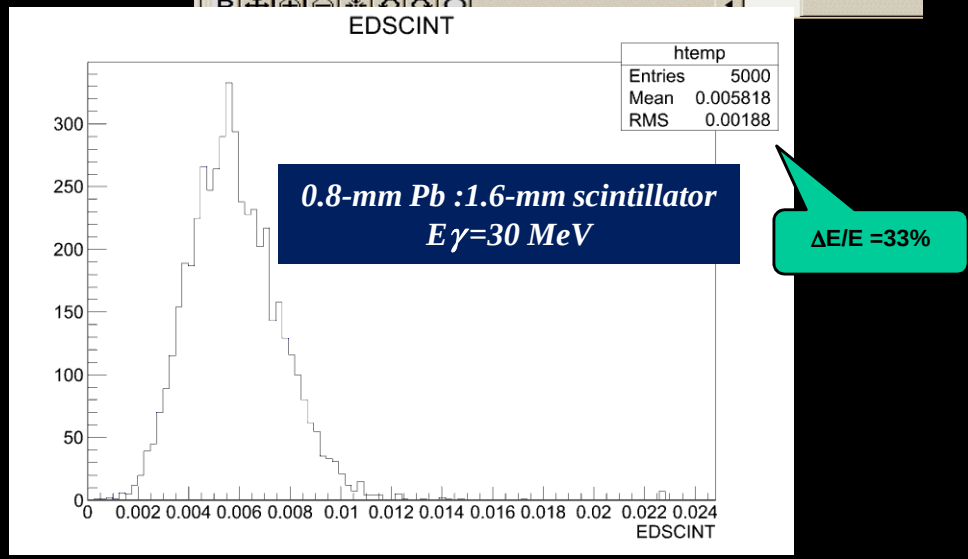
G.S. Atoian et al. / Nuclear Instruments and Methods in Physics Research A 584 (2008) 291–303

Shashlyk Potential Problems

- Range of Compton e^- in Pb from low energy γ is about 0.5 mm
- Effective absorber thickness changes as $tg^{-1}\theta$ (~2.75 at θ=20)
- WLS fibers have 1/10 light yield than scifi: potential crack from channeling in 0.9% volume (holes are 1.3 mm)
- Beam test of 300 layers of 0.275mm Pb/1.5mm scintillator
  - E_{beam}: 50-1000 MeV
  - 85% sampling fraction (rather than 33%)
  - Xo ~ 3.5cm ; $\langle\rho\rangle \approx 2.75$ gr/cm^3
  - Use Y11 (too slow for ORKA): expect a 30% lower l.y.
- Large sensitivity to neutrons with no PID
- Energy resolution is very poor for $E\gamma < 20$ MeV

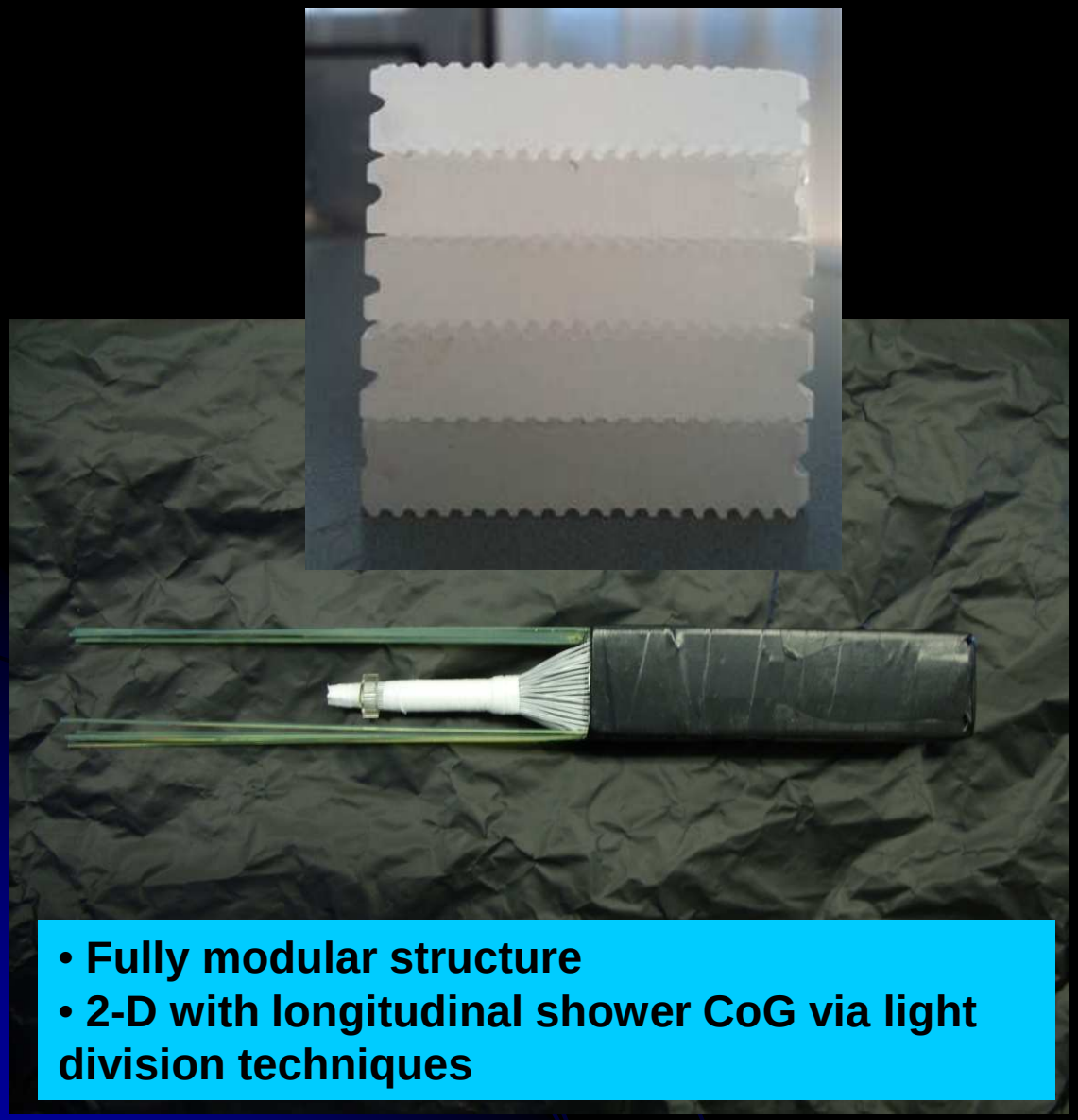






See A. Mazzacane's talk

ADRIANO: *A D*ual-*R*eadout *I*ntegrally *A*ctive *N*on-segmented *O*ption



- **Fully modular structure**
- **2-D with longitudinal shower CoG via light division techniques**

- **Cells dimensions**: 4x4x180 cm^3
- **Absorber and Cerenkov radiator**: lead glass or bismuth glass (ρ > 5.5 gr/cm^3)
- **Cerenkov light collection:** 10/20 WLS fiber/cell
- **Scintillation region**: scintillating fibers, dia. 1mm, pitch 4mm (total 100/cell) optically separated from absorber
- **Particle ID**: 4 WLS fiber/cell (black painted except for foremost 20 cm)
- **Readout**: front and back SiPM (Scifi only)
- **CoG z-measurement**: light division applied to SCSF81J fibers (same as CMS HF)
- **Small tg($\theta_{S/Q}$)**: due to WLS running longitudinally to cell axis ($\theta_{Cerenkov} < \theta_{Snell}$ for slower hadrons).

T1015 Collaboration at FNAL (32 Members)

Institution	Collaborator
INFN Trieste/Udine and University of Udine	Diego Cauz
	Anna Driutti
	Giovanni Pauletta
	Lorenzo Santi
	Walter Bonvicini
	Aldo Penzo
Fermilab	Erik Ramberg
	Paul Rubinov
	Eileen Hahan Anna Pla Greg Sellberg Donatella Torretta
	Hans Wenzel
	Gene Fisk
	Aria Soha Anna Mazzacane Benedetto Di Ruzza (now at BNL)
INFN Lecce	Corrado Gatto
	Vito di Benedetto Antonio Licciulli Massimo Di Giulio Daniela Manno Antonio Serra
INFN and University Roma I	Maurizio Iori
University of Salerno	Michele Guida
	NEITZERT Heinrich Christoph
	SCAGLIONE Antonio
	CHIADINI Francesco
University of Modena	Cristina Siligardi
	Monia Montorsi
	Consuelo Mugoni
	Giulia Broglia

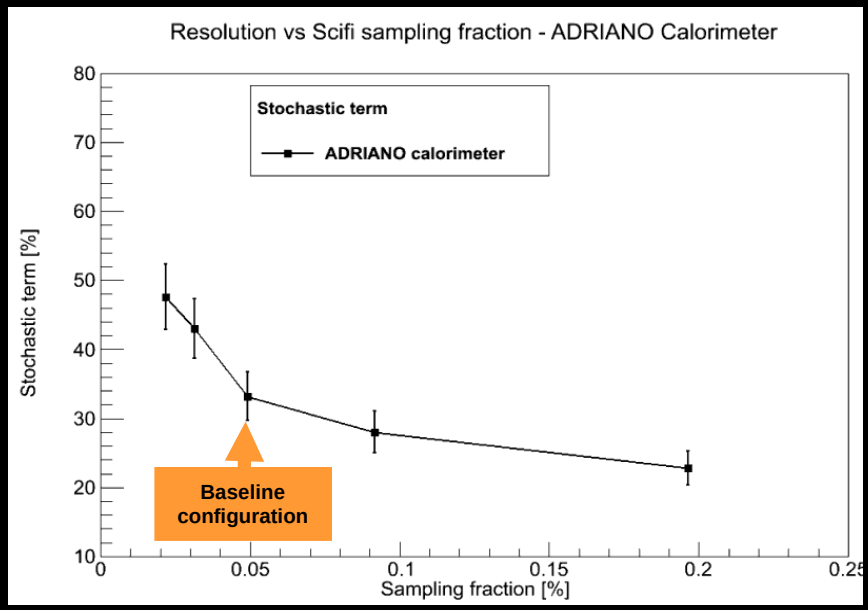
Fermilab
+
INFN
Collaboration

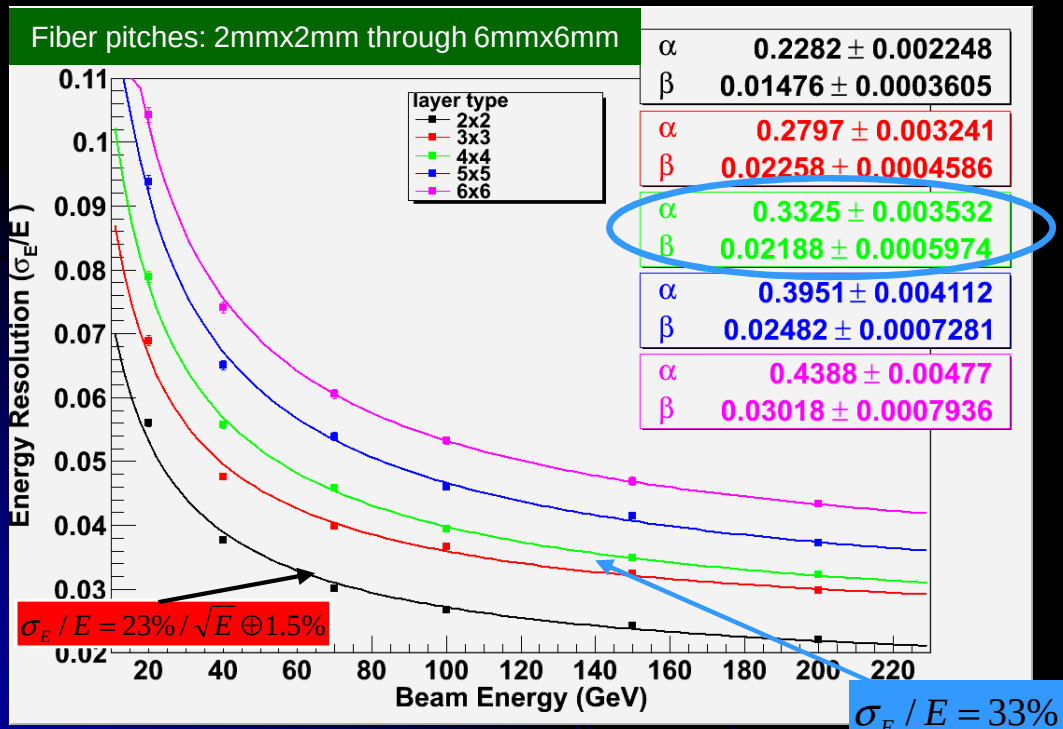
ADRIANO Light Yield and Hadr. Resolution

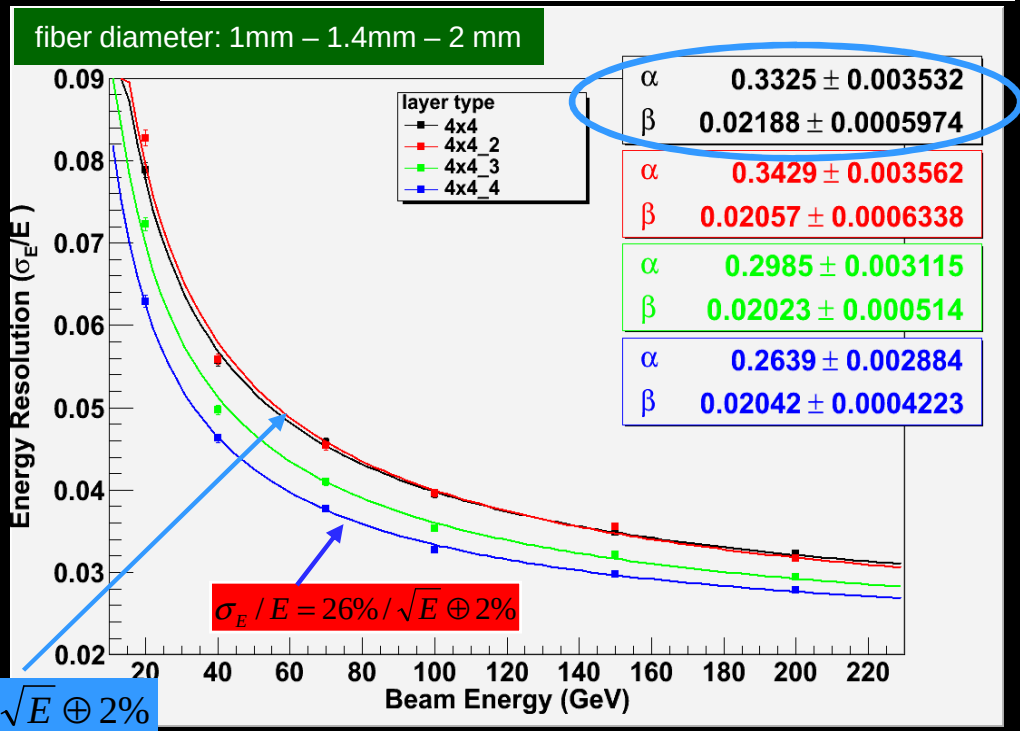
Integrally Active with Double side readout (*ADRIANO*)									Sampling
Pitch [mm²] Diameter	2x2 1mm	3x3 1mm	4x4 1mm	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillry	Sampling
<pe_S/GeV>	1053	430	254	163	124	500	110	250	200
<pe_C/GeV>	340	360	360	355	355	355	350	350	7.5

Baseline configuration

1-side readout







$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$

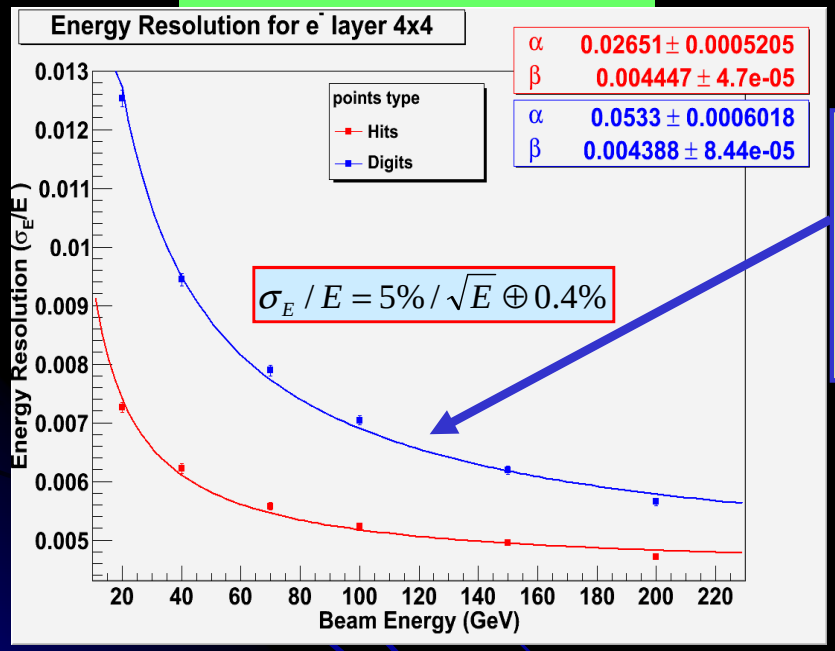
All numbers include the effect of photodetector QE

ILCroot simulations

ADRIANO EM Resolution (with and without instrumental effects)

- Compare standard Dual-readout method vs Cerenkov signal only (after electron-ID)
- Blue curve includes instrumental effects. Red curve is for perfect readout

Use only Cerenkov light

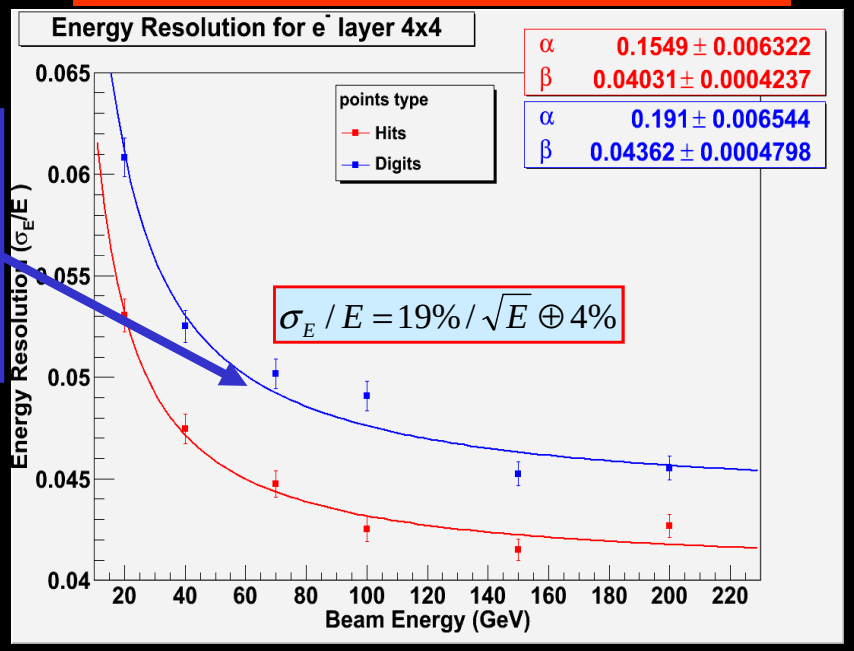


Blue curve includes:

- **SiPM's ENF**
- **Constant noise**
- **Fiber non-uniformity**
- **14 bit ADC**
- **3pe threshold**

ILCroot simulations

Dual-readout (scintillating+Cerenkov)



- Using Cerenkov signal only for EM showers gives **5%/√E** energy resolution while full fledged dual-readout gives only **19%/√E** (including FEE effects)

ADRIANO does not need a front EM section

If Cerenkov ligth yield is large enough

Preliminary

11 Prototypes Performance at Test Beam

Prototype	Glass	gr/cm^3	L. Y./GeV	Notes
5 slices, machine grooved, unpolished, white	**Schott SF57HHT**	**5.6**	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	**Schott SF57HHT**	**5.6**	84	SiPM readout
5 slices, precision molded, unpolished, coated	**Schott SF57HHT**	**5.6**	55	15 cm long
2 slices, ungrooved, unpolished, white	**Ohara BBH1 (BiO_2)**	**6.6**	65	
5 slices, scifi silver coated, grooved, clear, unpolished	**Schott SF57HHT**	**5.6**	64	15 cm long
5 slices, scifi white coated, grooved, clear, unpolished	**Schott SF57HHT**	**5.6**	120	
10 slices, white, ungrooved, polished	**Ohara PBH56**	**5.4**	30	DAQ problems
10 slices, white, ungrooved, polished	**Schott SF57HHT**	**5.6**	76	
5 slices, wifi Al sputter, grooved, clear, polished	**Schott SF57HHT**	**5.6**	30	2 wls/groove
5 slices, white, ungrooved, polished	**Schott SF57HHT**	**5.6**	158	Small wls groove
2 slices, plain, white	**Ohara BiO_2 experimental**	**7.5**	-	DAQ problem

- Analysis still ongoing
- Calibration problematic for DAQ issues and degrading of PMTs from He leaks
- Need further confirmation of the results

See C. Gatto talk at CALOR2012

ADRIANO for ORKA: baseline layout

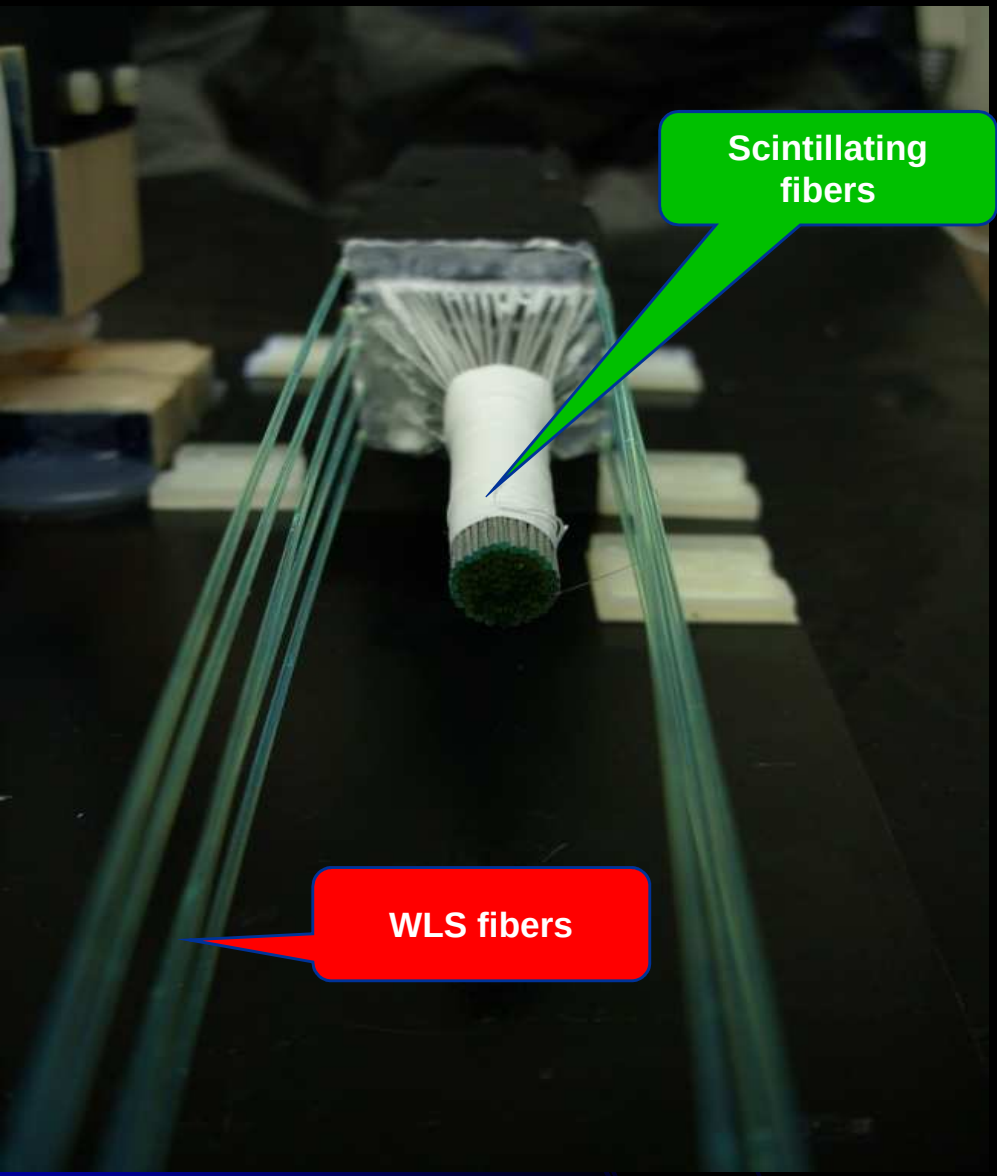
- **150 layers; 2mm PBH56/SF57 + 2mm fast scintillator (BC408 or SN88)**
  - X_o = 2.9 cm ; <ρ>=3.5 gr/cm^3 ; Depth = 21 X_o
- **Detector layout: 2.5m longitudinal layers with 2-sides readout in 64 azimuthl sectors (E949/KLOE approach)**
  - 5.6°/sector ; 9.5-13.5 cm sector width
  - Towers with back readout also considered, but potentially inefficient
- **Scintillator readout; 1mm BCF92 in grooves 1.6 cm apart**
  - λ(**BCF92)** = 350 cm ; 1000 fibers/sector bundlead in 10 units
- **Glass readout; 1mm BCF92 in grooves 1.6 cm apart**
  - λ(**BCF92)** = 350 cm ; 1000 fibers/sector bundlead in 10 units
- **Total density of fibers: 3.1/cm^2**
  - Compare to original ADRIANO: 6.2 fibers.cm^2

Needs Optimization For ORKA

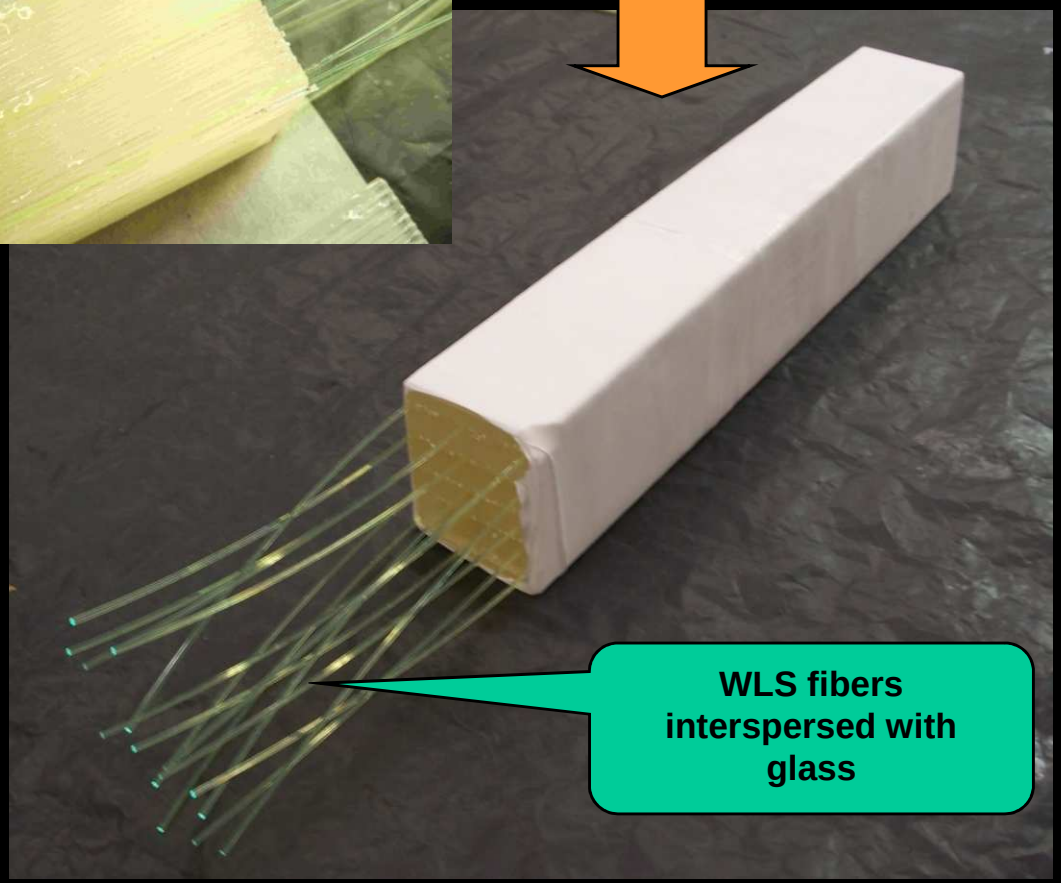
Lots of Cerenkov photons when n_D is about 1.9 or greater

ADRIANO Applications

Dual-readout Calorimetry
(compensate e/h fluactuations)



Imaging Calorimetry
(spatially resolve the shower in 3D)

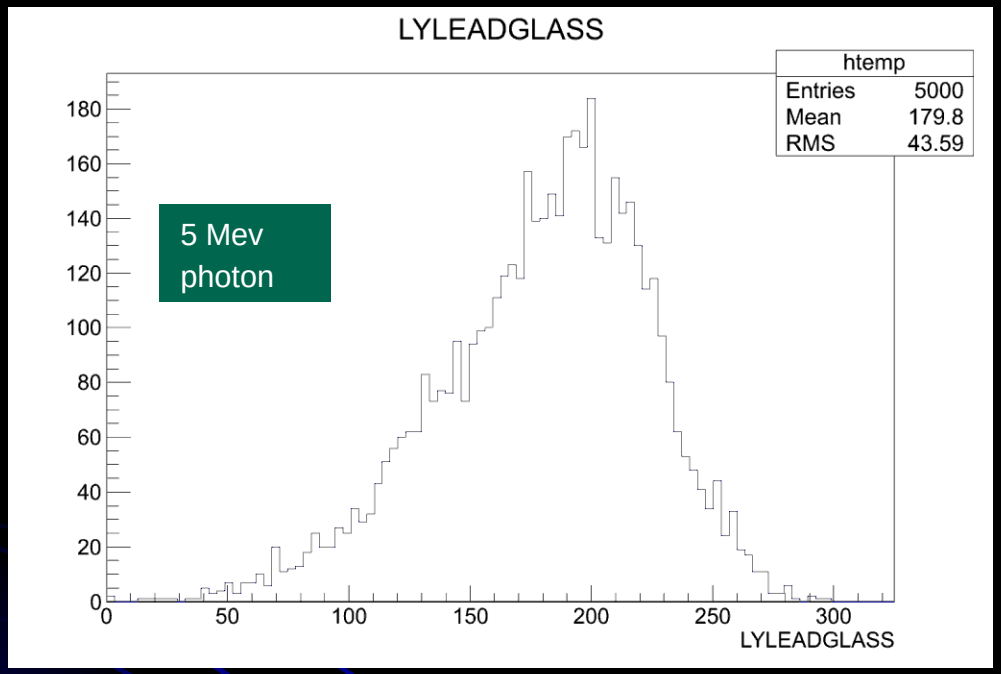


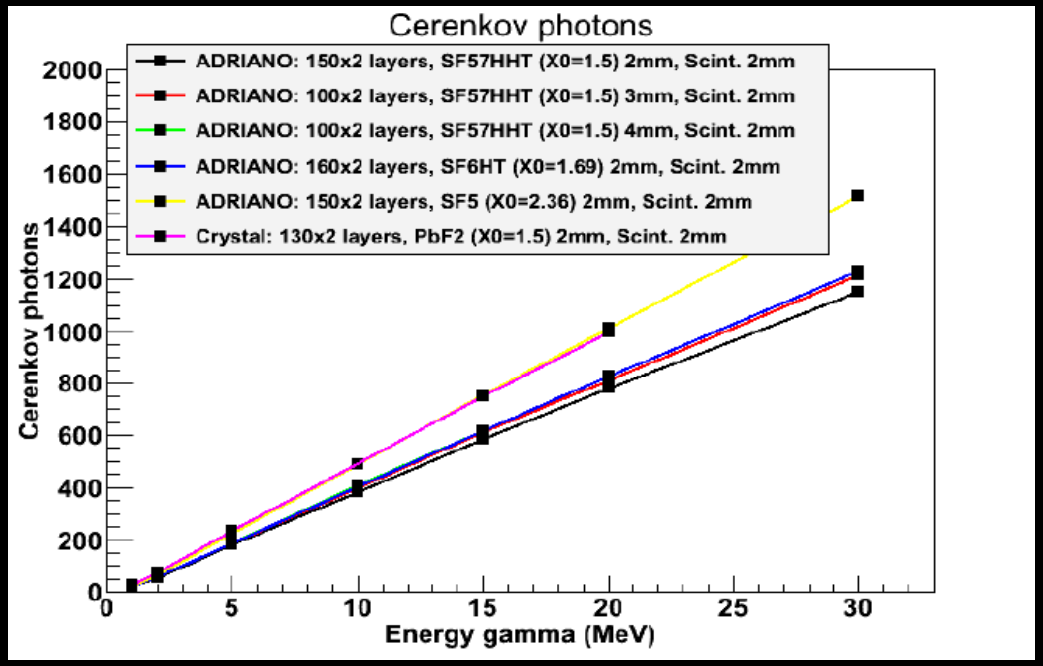
Glass vs Crystals

	Glass	Crystals
Light production mechanism	Only Cerenkov (minor fluorescence with some SF glasses)	Cerenkov + scintillation
Stability vs ambiental (temperature, humidity, etc)	Excellent	Poor
Stability vs purity	Very good if optical transmittance is OK	Very poor
Longitudinal size	Up to 2m	20-30 cm max
Cost	0.8 EUR/cm^3	10-100 EUR/ cm^3
Time response	prompt	Slow to very slow (with exceptions)
n_d	1.85-2.0 (commercilly available) 2.25 (experimental)	1.85-2.3
Density	6.6 gr/cm^3 (commercially available) 7.5 gr/cm^3 (experimental)	Up to 8-9 gr/cm^3
Radiation hardness	Medium (recoverable via UV annealing for Pb-glass) or unknown (for Bi-glass)	varies

Expected Cerenkov Light at Low Energy

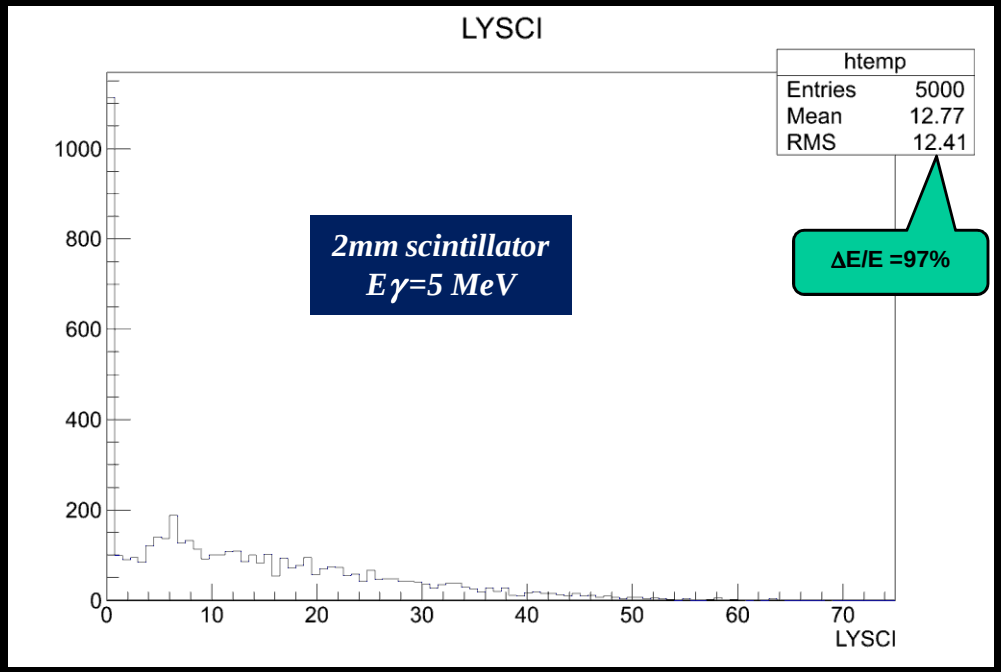
- **Cerenkov photons reaching the surface of 2mm optical glass are very aboundant**

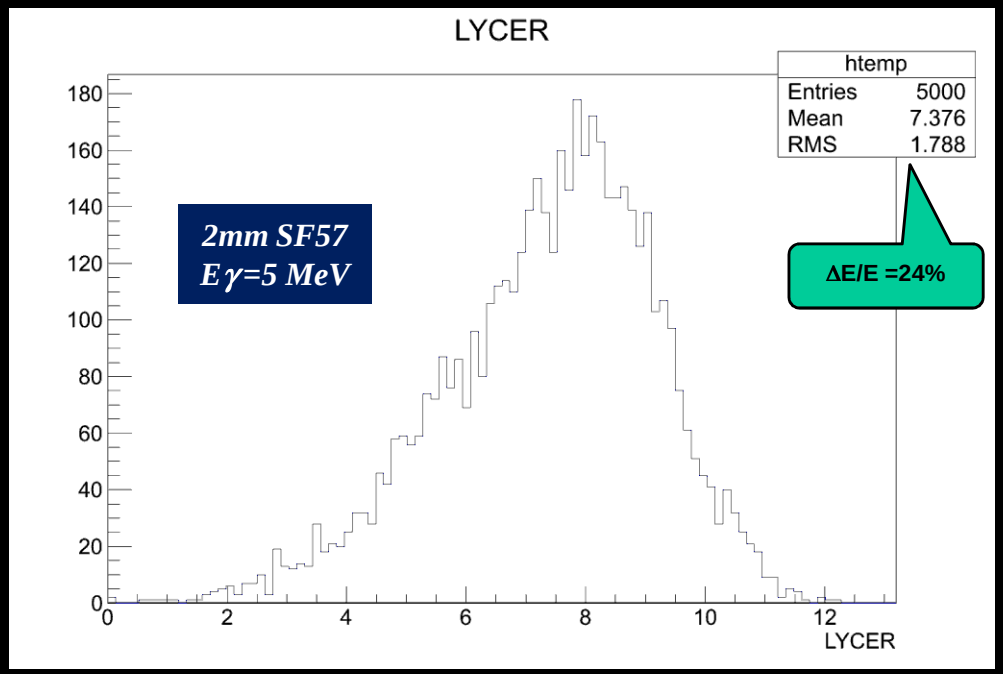


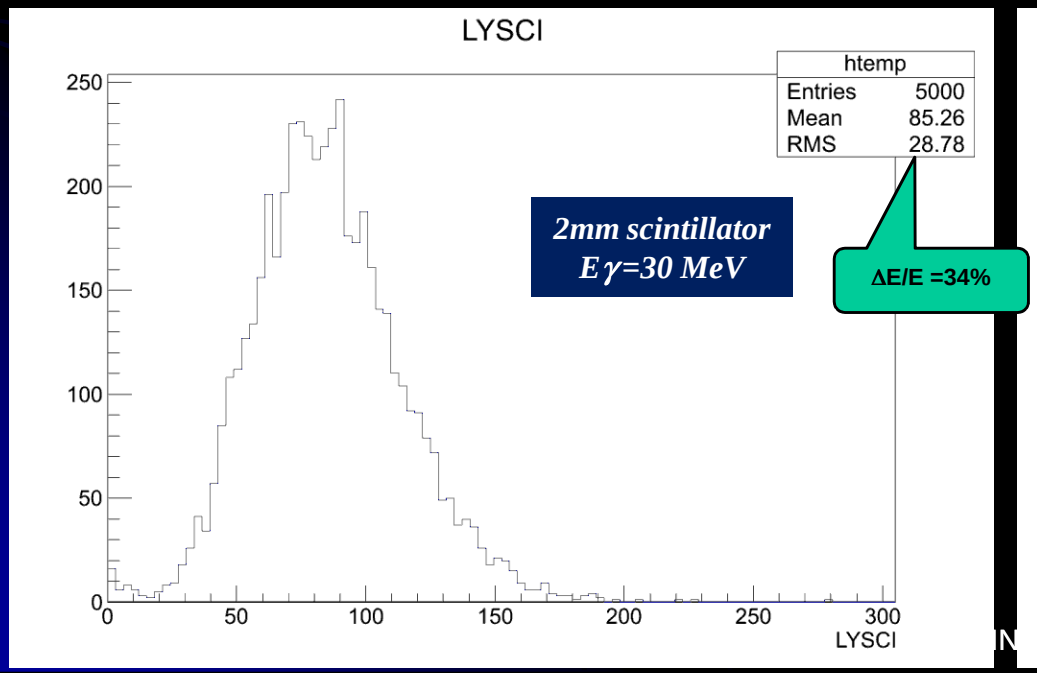


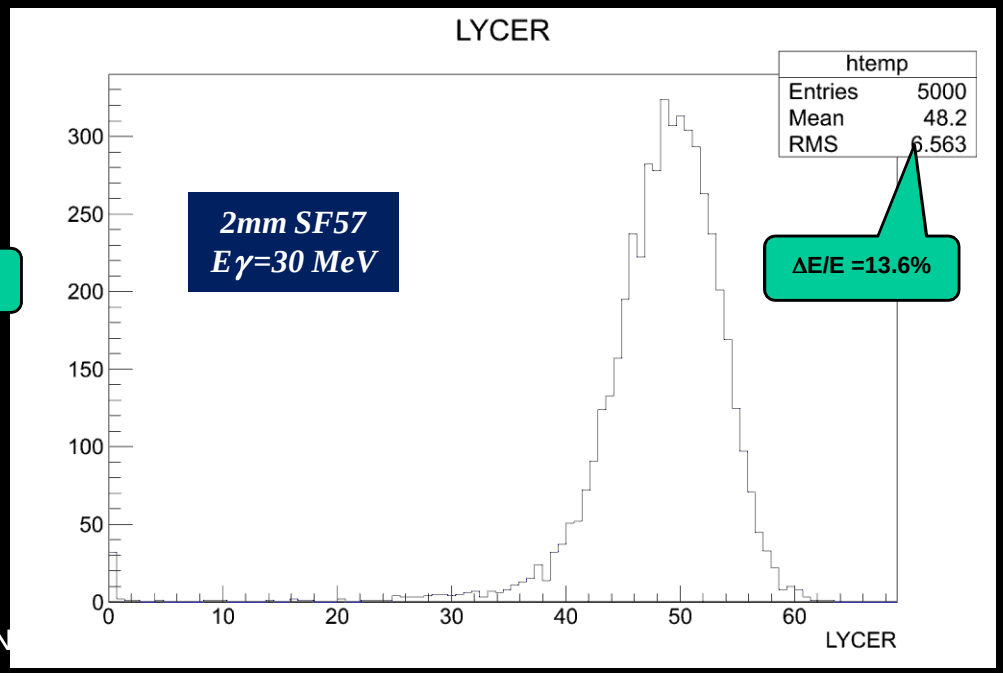
- **Use two techniques to capture them**
  - WLS fibers in longitudinal grooves (original ADRIANO approach for hadronic detectors)
  - WLS plates facing the glass (novel techniques under development for ORKA)

Simulated Light yield from Scintillator and Glass

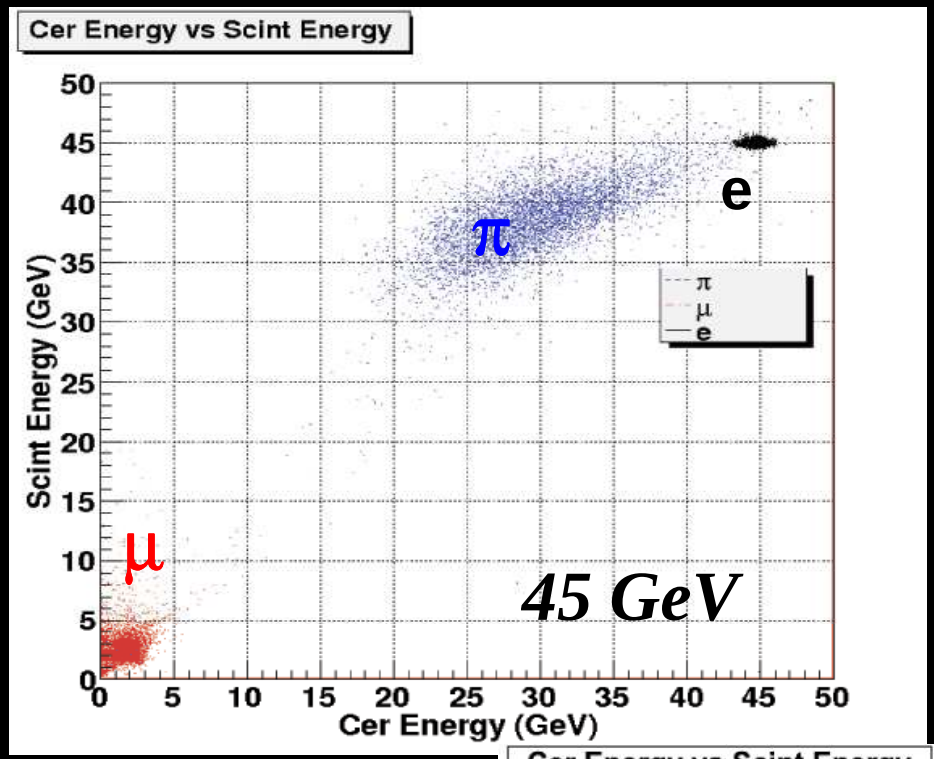


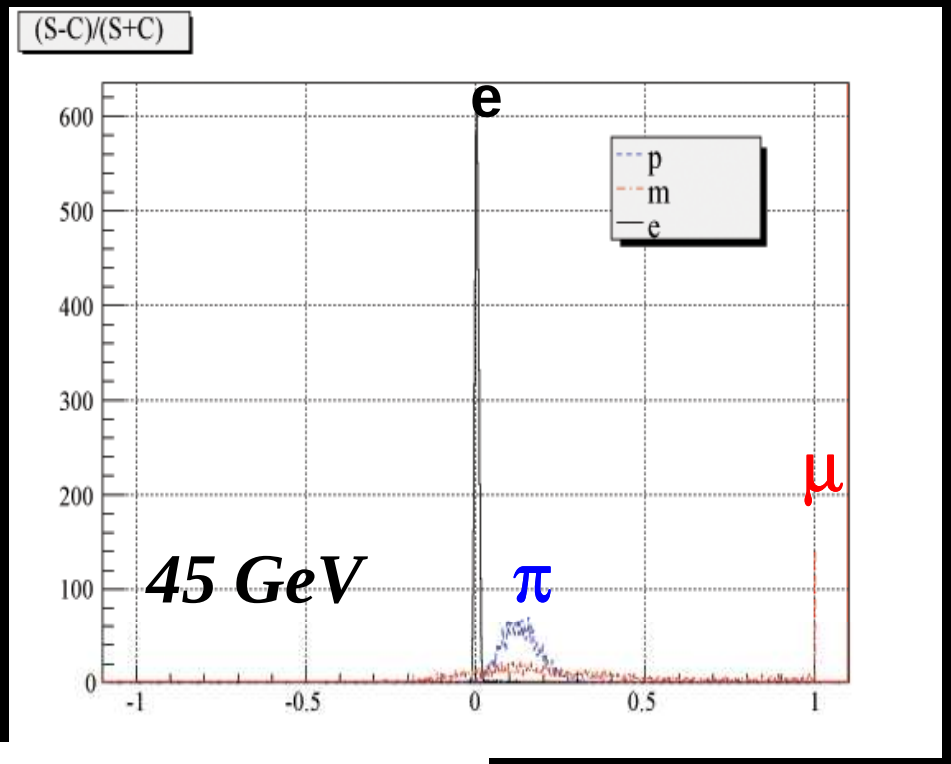


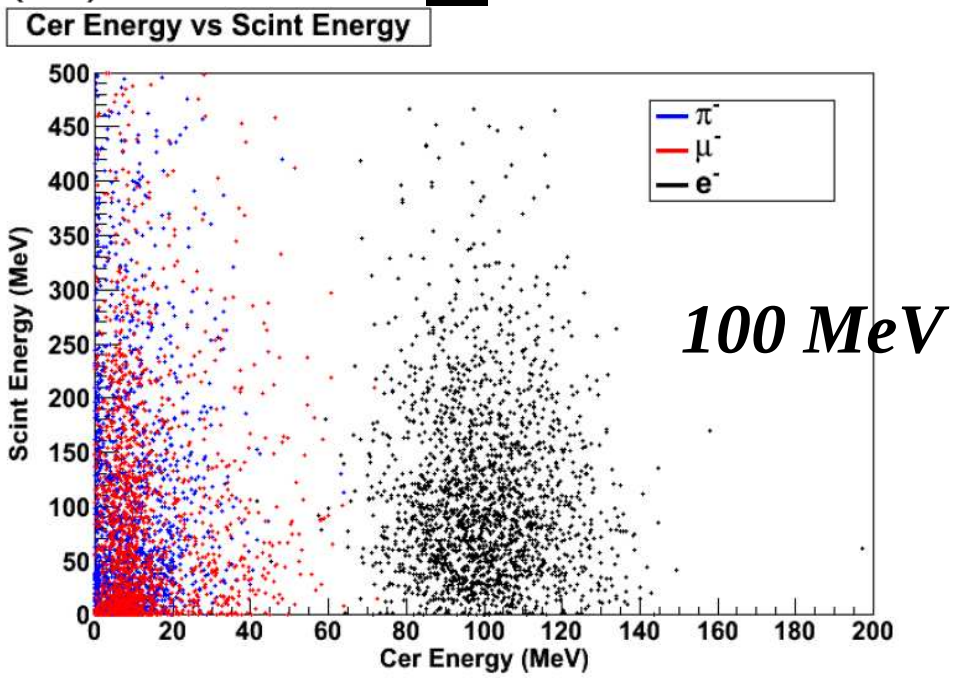




Particle Identification in Dual Readout Calorimeters







ADRIANO in Single-readout Mode

- Same layout as in dual-readout case, but put glass slices and scintillating plates in optical contact
- Dope the scintillator in a custom way so it is able to capture the Cerenkov light and WLS it (A. Pla)
- Transport the (two) WLShifted lights to the photo-sensor

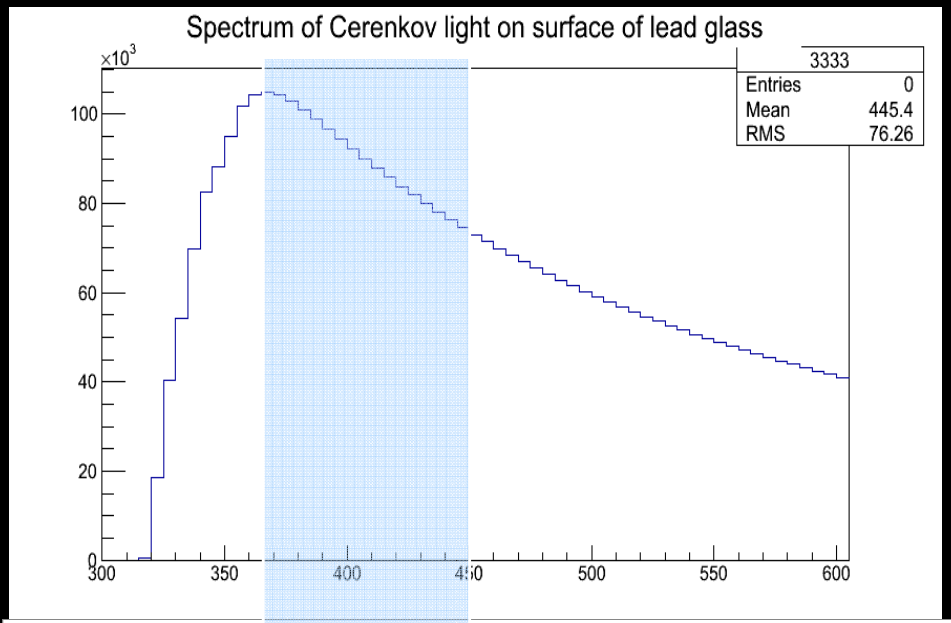
- Advantages:
  - Totally transparent detector, with no optical boundaries
  - If Cerenkov light is not captured by nearest WLS, there are 149 more chances to be captured by another

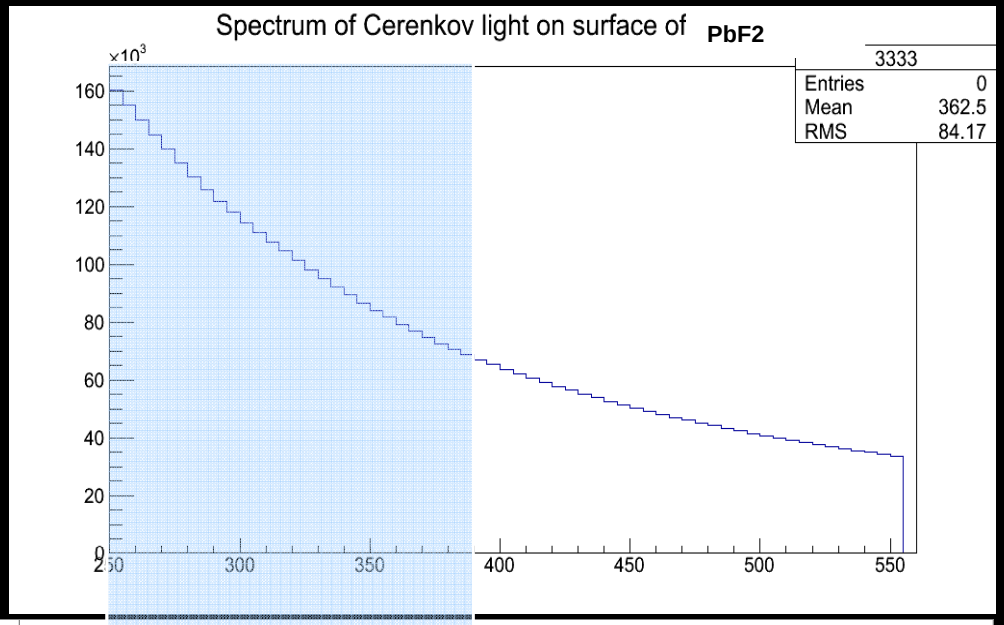
Make efficient use of plastic plates as scintillators and WLS for Cerenkov light

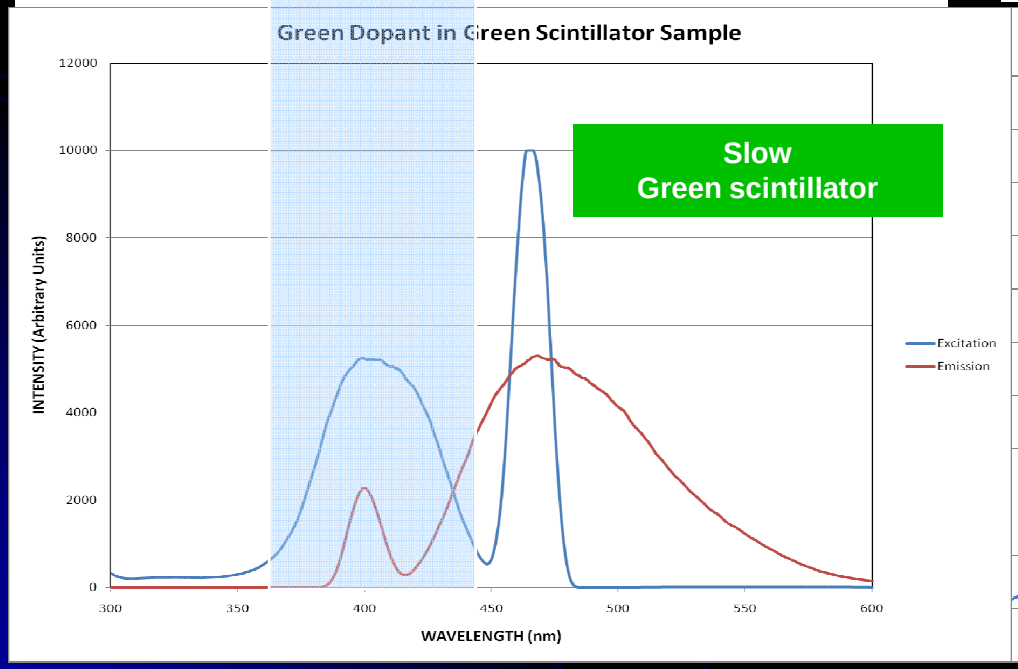
- Two light transport techniques under consideration

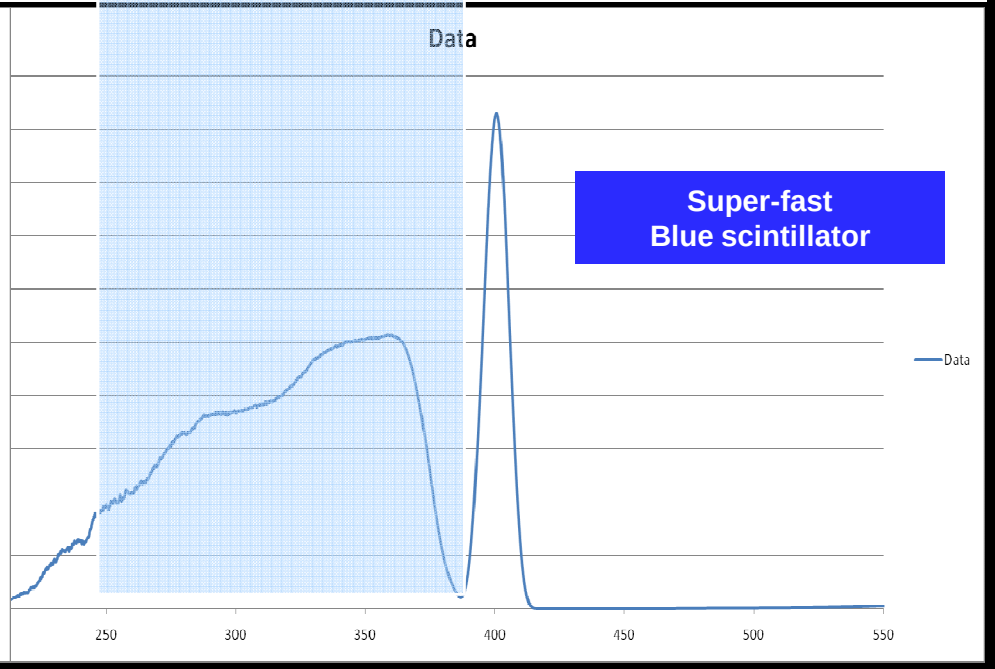
Anna Pla
E. Piacentino

Glass vs PbF_2



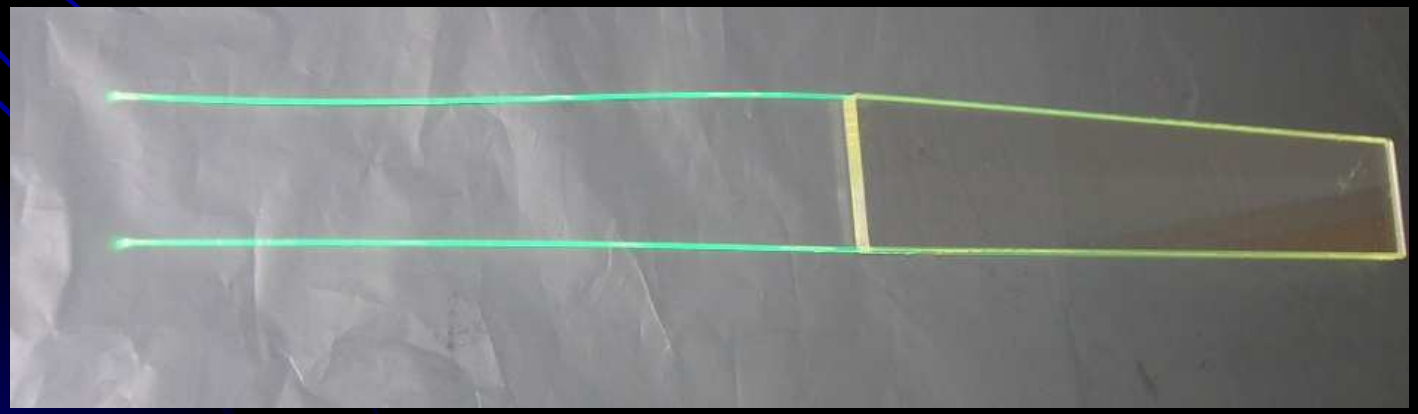






Main Issues

- PbF_2 version will use WLS fibers for light capture from scintillator
- Glass version use no fibers (a' la E949)
- Need to optimize:
  - Light transmission from glass to polystyrene
  - Already under development for ADRIANO at High Energies
  - Scintillating dye to better match Cerenkov spectrum
- LAPD will be a perfect complement when matched to the external surface of the barrel
- Novel technique: require extensive R&D
- **Caveat: green scintillators are slow (9 nsec or slower)**



Overcoming the Limitations of a 2-D Calorimeter

- ***ADRIANO* for ORKA is a 2-D calorimeter**
  - Easier to build and to calibrate
  - Fewer number of channels
  - No cracks nor unhomogeneities due to longitudinal segmentation

However, in principle, it misses the ability to determine the longitudinal shower profile

- ***Two possible solutions to measure z-coordinate***
  - Time difference measurement
  - Light division measurement

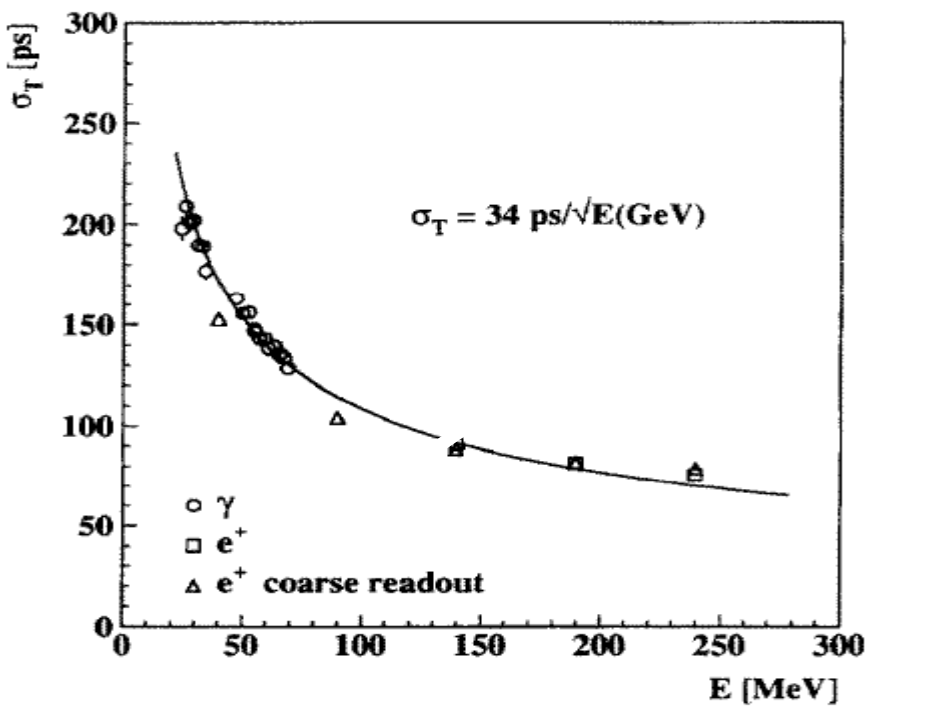
Adding the 3rd Dimension with time difference methods

- Already implemented for KLOE spacal (4.3m long, 0.5mm Pb, 15% sampling)
- Requires 25psec time measurement on both sides (TDC/WFD)
- Assume (pessimistically) the same resolution as KLOE and v_{fiber}=17.2 cm/nsec (for polistirene with n_D=1.58)

$$\sigma_z = \frac{6\ mm}{\sqrt{E}}$$

- Or: σ_z = 19 mm at 100 MeV
- Requires z-dependent time measurement corrections:

$$\sigma_T(z) = \sigma_T(0)\sqrt{\cosh(z/\lambda)}$$



Time resolution for KLOE calorimeter

J. Lee-Franzini et al. / Nucl. Instr. and Meth. in Phys. Res. A 360 (1995) 201–205

Adding the 3rd Dimension with light division methods

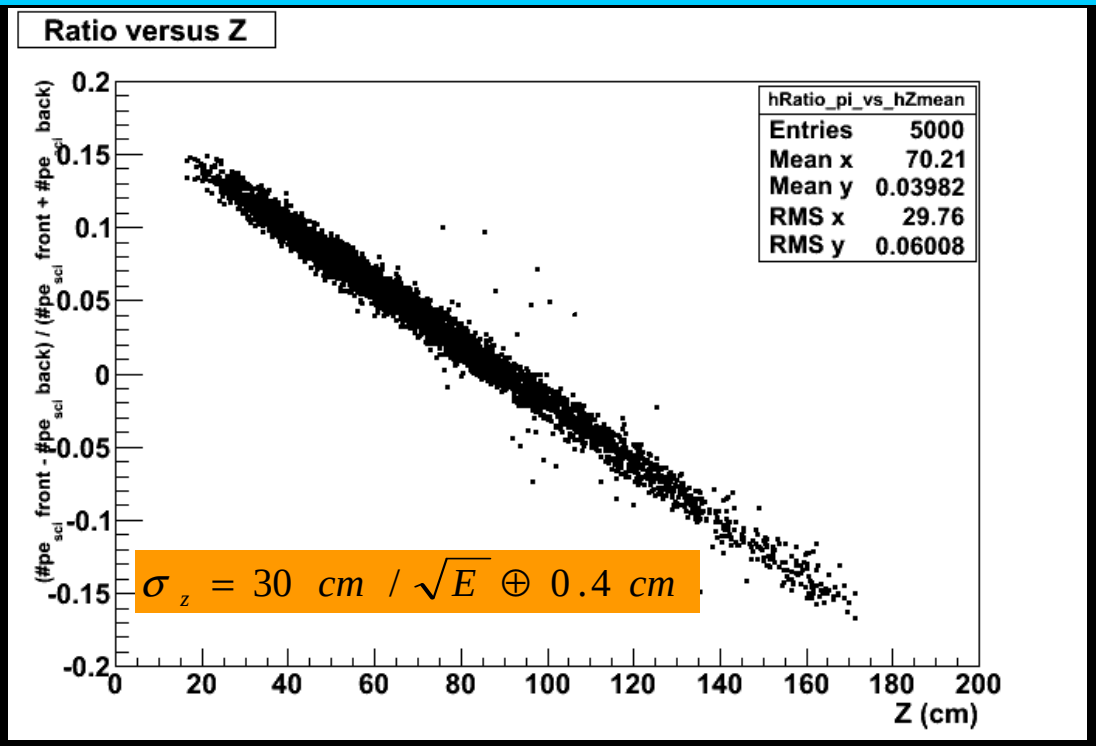
- Determine Center of Gravity of showers by ratio of front vs back scintillation light
- It works because λ_{81J} = 3.5m
- Similar to charge division methods in drift chambers with resistive wires
- A technique already adopted by UA1 and ZEUSS

100 Gev pions

Instrumental effects included in ILCroot :

- SiPM with ENF=1.016
- Fiber non-uniformity response = 0.6% (scaled from CHORUS)
- Threashold = 3 pe (SiPM dark current < 50 kHz)
- ADC with 14 bits
- Constant 1 pe noise.

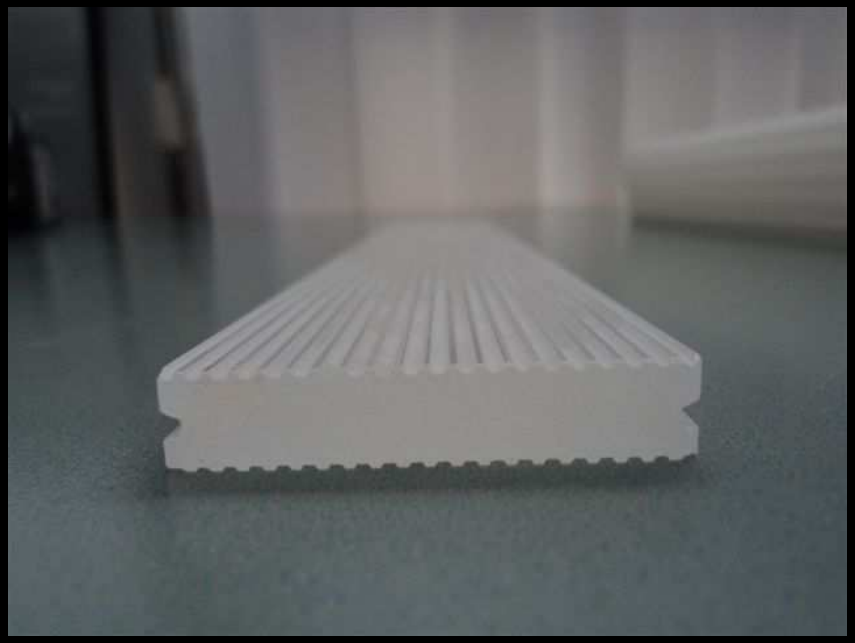
Front vs back Scintillation light vs true shower CoG



Fabrication Technology #1: Diamond tools machining

- Pro
  - Minimal R&D required
  - Room temp (min effect on n_D)
  - It allows construction of longer cells

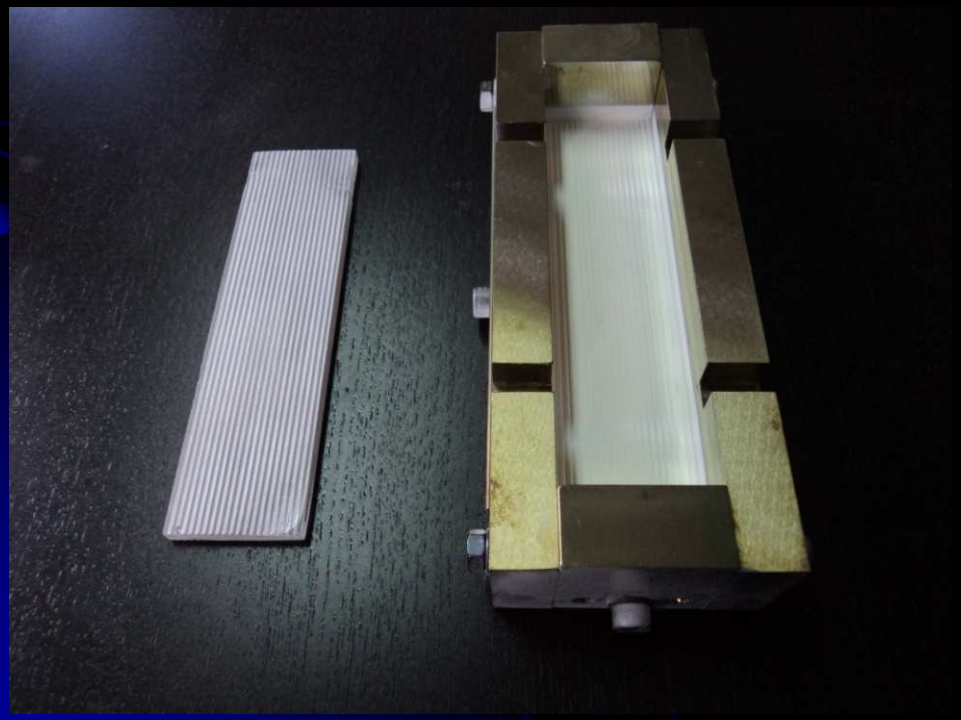
- Cons
  - Longer fabrication process
  - Large waste

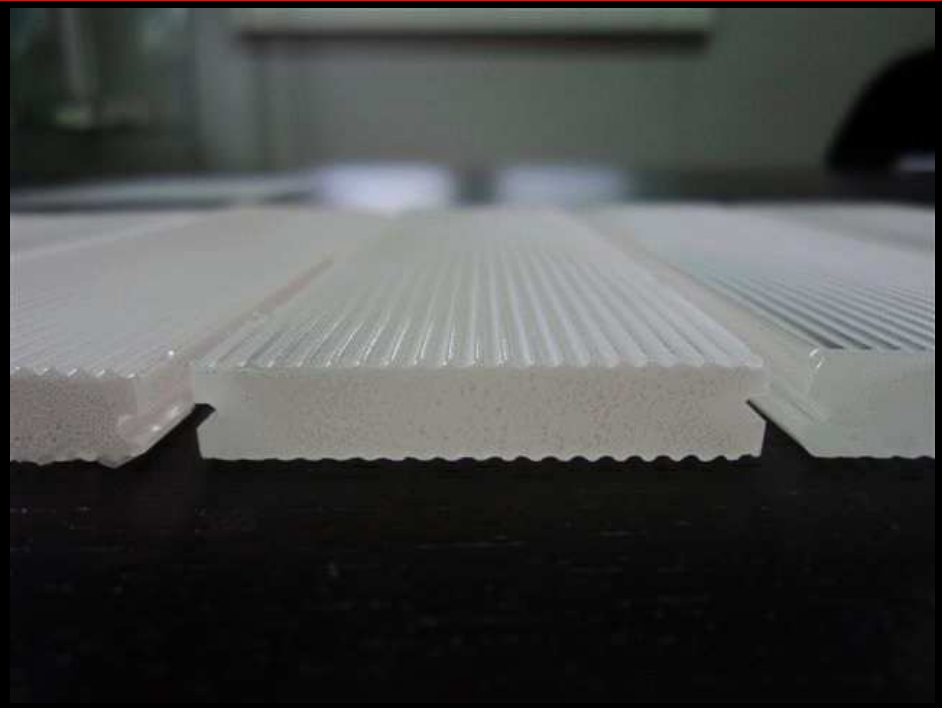


Fabrication Technology #2: Precision molding

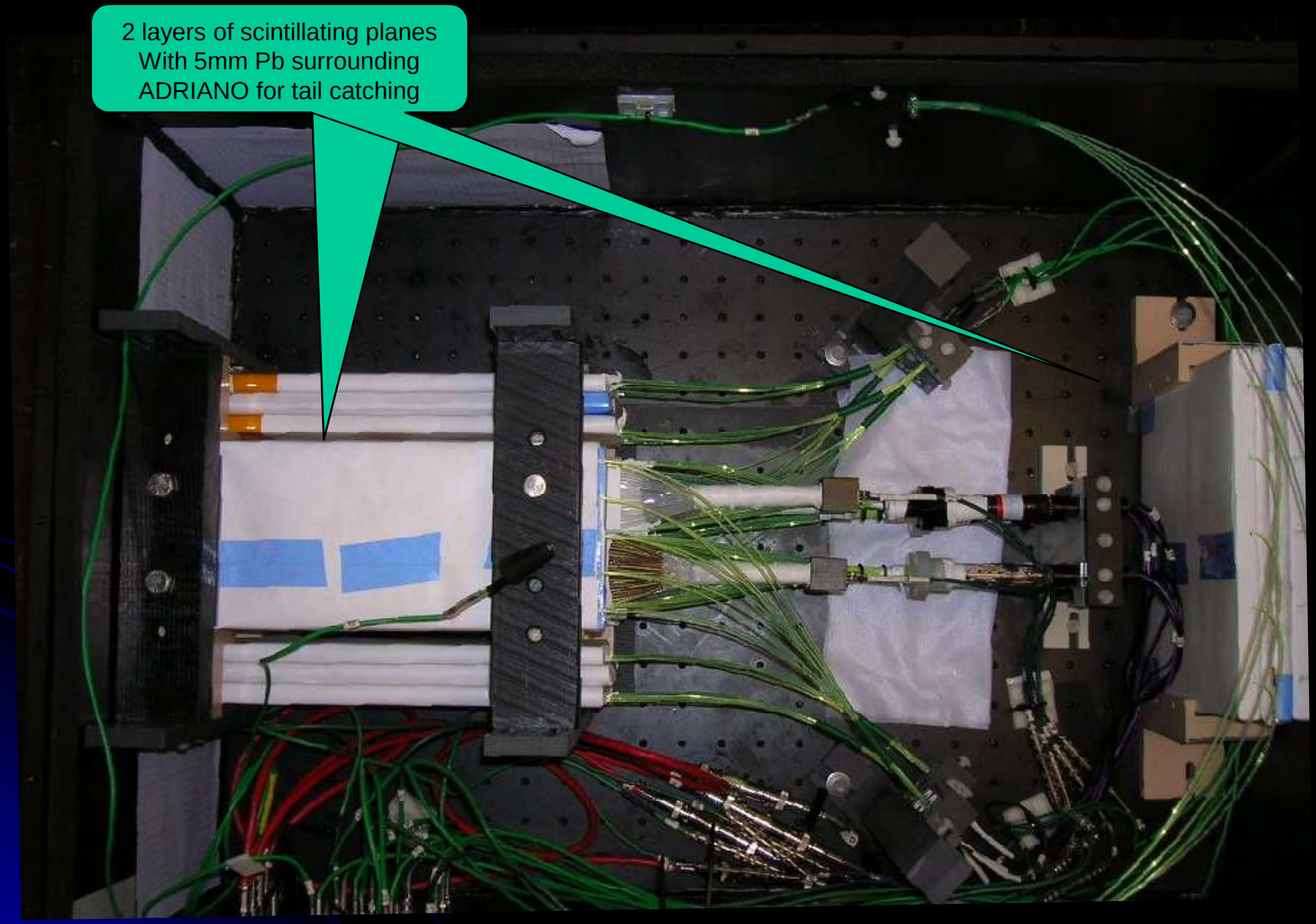
- Pro
  - Cheapest and fastest (15 min)
  - Optical finishing with no extra steps
  - Low temp cycle (min effect on n_D)

- Cons
  - Molds are expensives
  - Lots of R&D

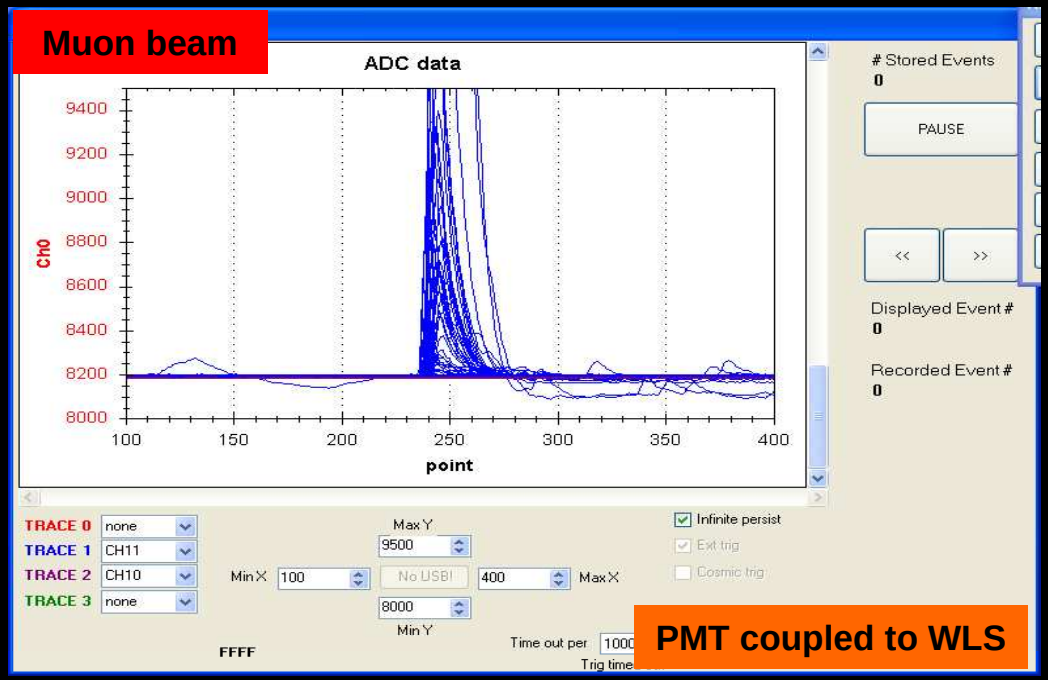


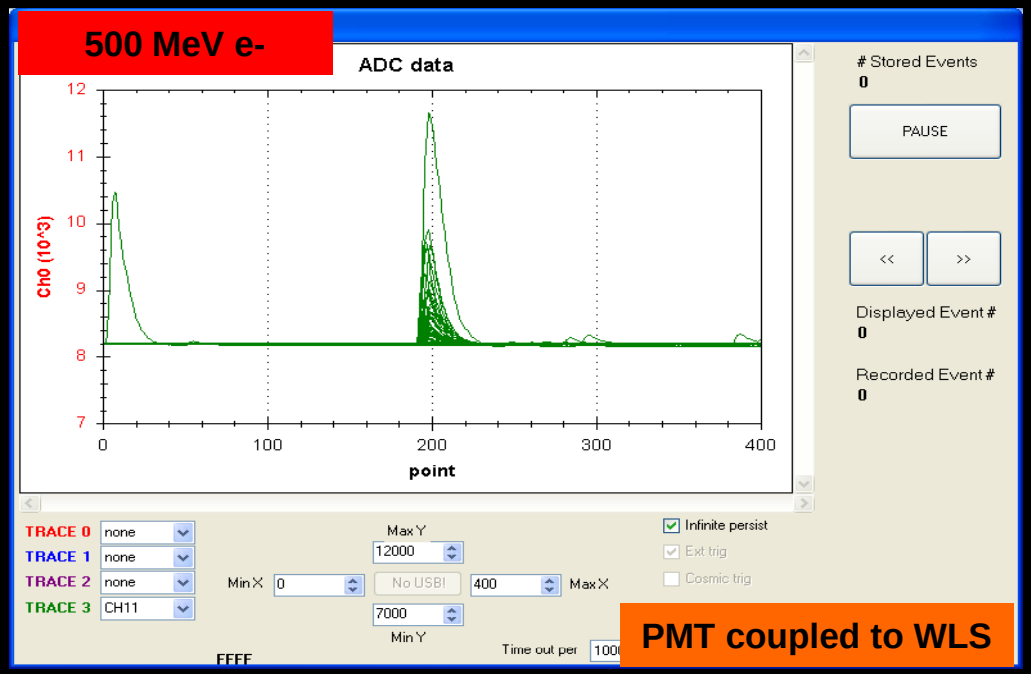


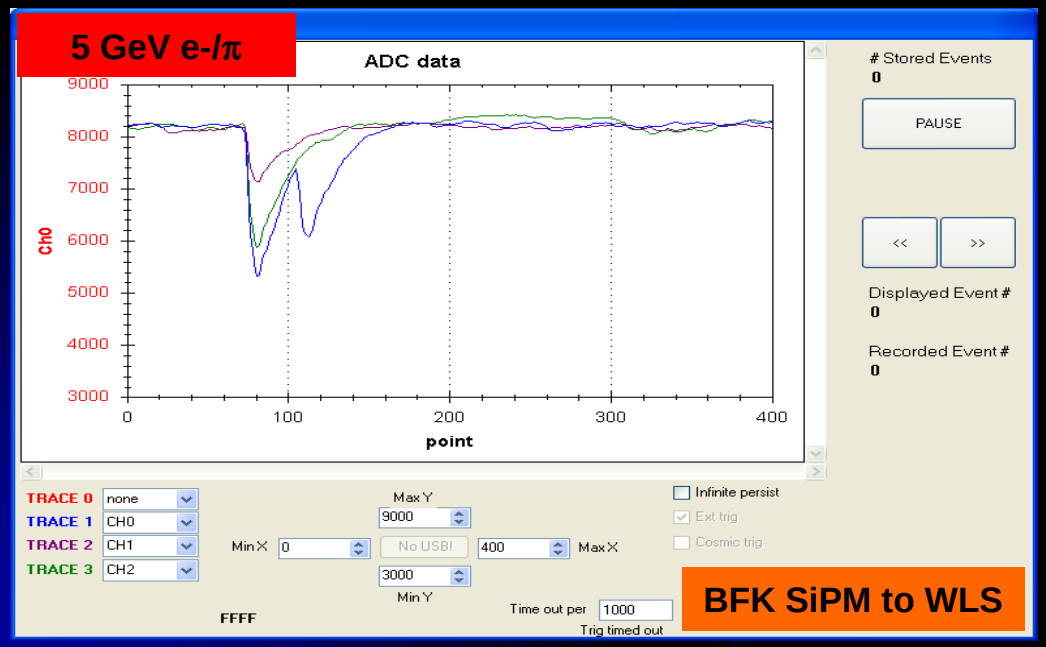
2012 Test Beam Setup at FTBF

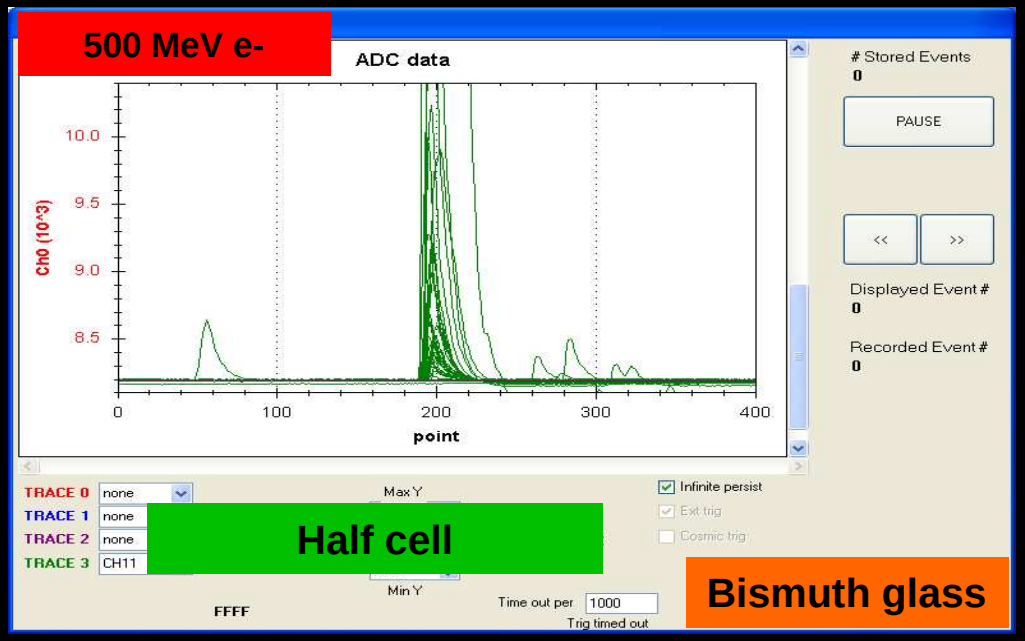


Waveforms from Test Beam FNAL







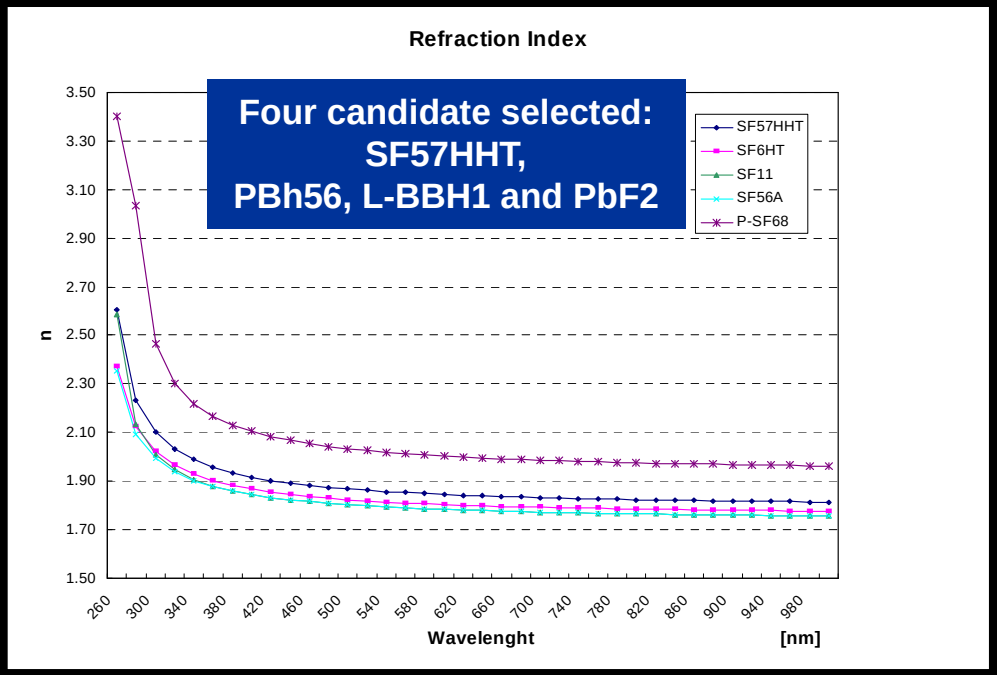


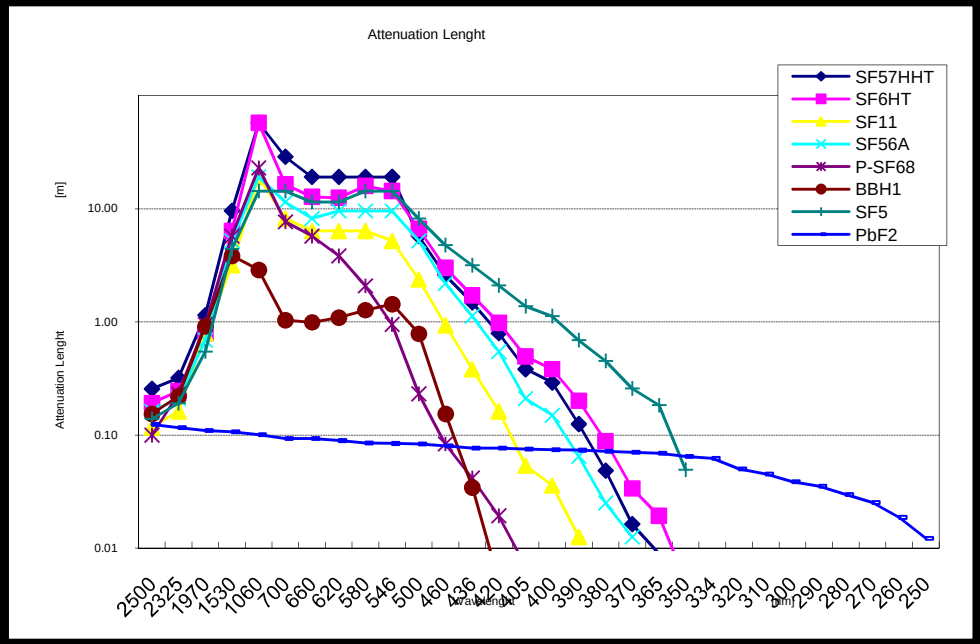
Conclusions

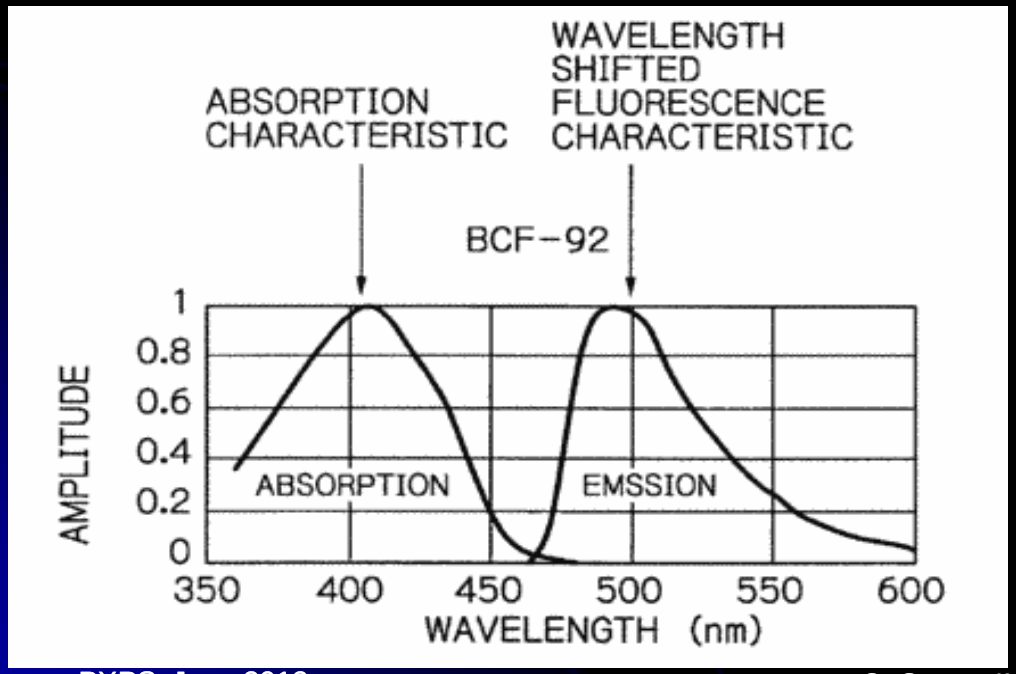
- *Three techniques are under consideration for a photon veto/calorimeter at ORKA: 1 sampling and two integrally active*
- *r-segmentation is preferred. Could swith to z-segmentation if light propagation time becomes an issue*
- **An integrally active calorimeter will easily provide at least 50% more light yield**
- Thin glass/crystals are employied as active absorber: require specific R&D
- R&D already under way under the auspices of T1015 collaboration (FNAL+INFN)
- ADRIANO technique already works for HEP: need dedicated optimization for lower energy experiment

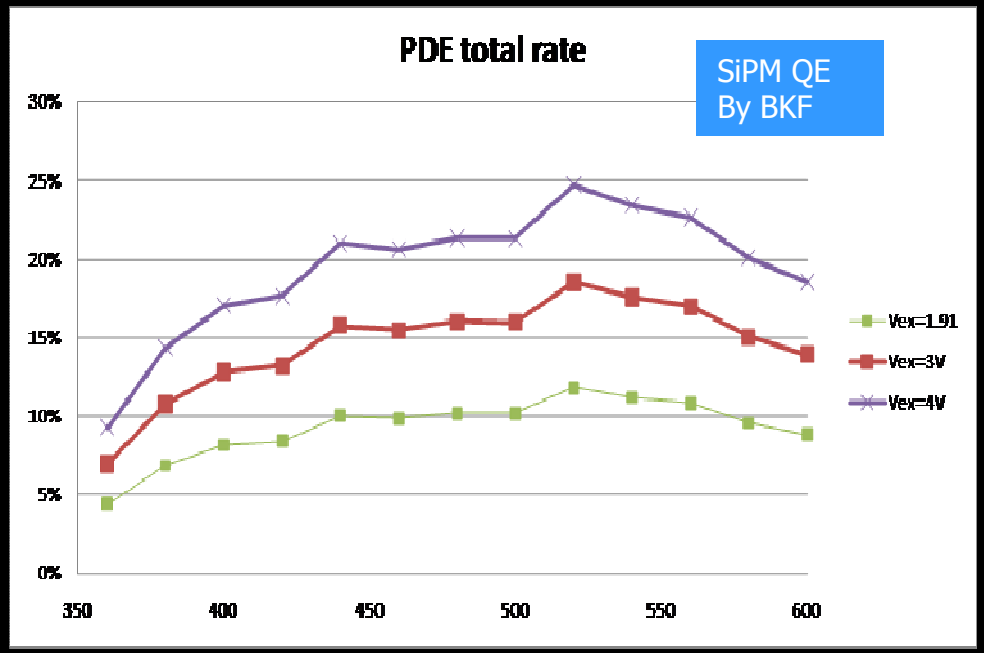
Backup Slides

Optical Spectra in *ADRIANO*







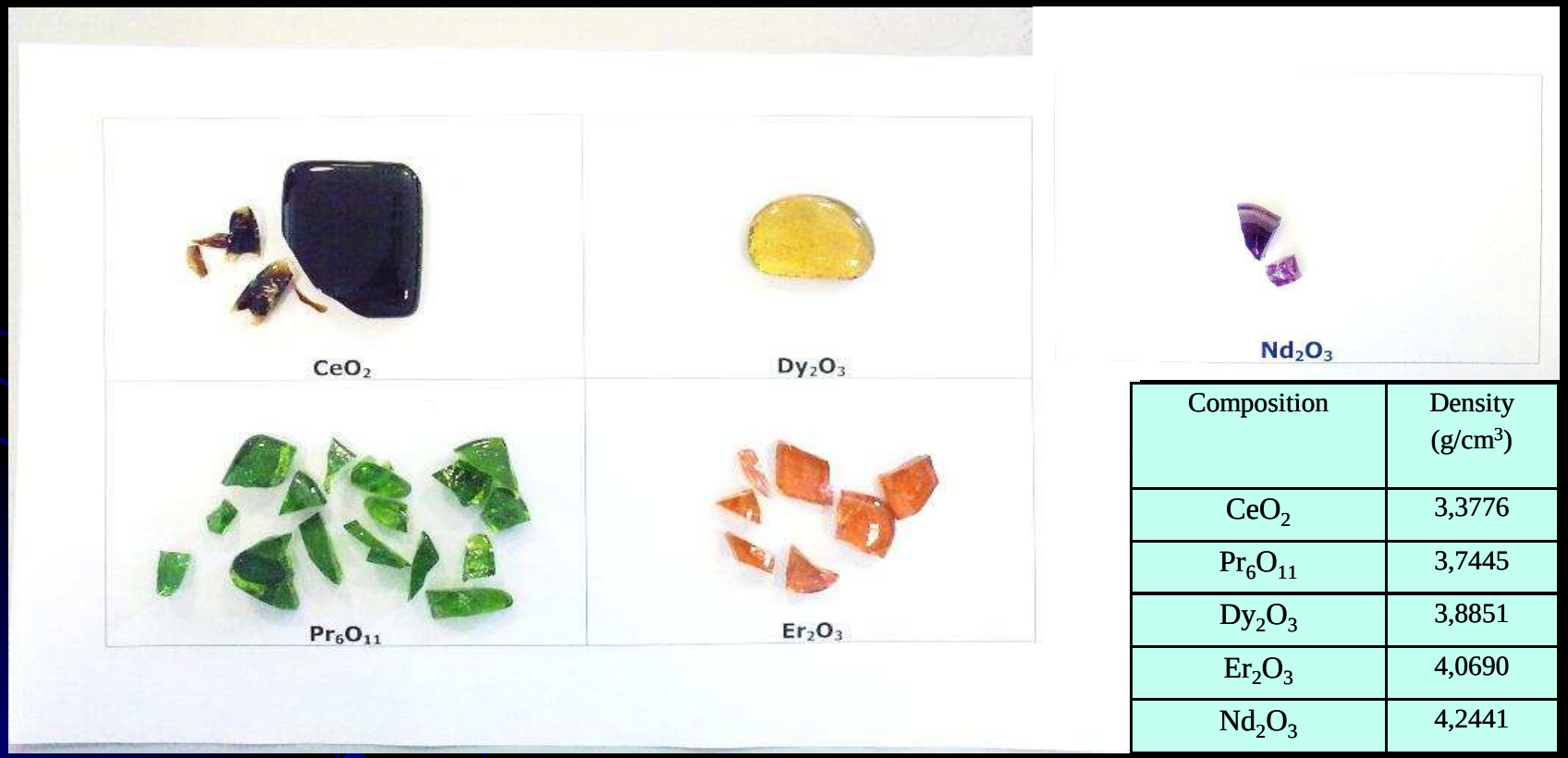


Scintillating Glass

- **Scintillation and Cerenkov at the same time in a totally homogeneous active absorber (not necessarely a good idea)**
- Major issues:
  - absorption lines in rare earths induce Č->S shift
  - Need high density glass
  - Slow scintillations (several tens ns)
- Separate the two problems:
  - Fix the optical problem by finding the correct ratio of oxides
  - Increase the density with proper vetrous matrix (BiO2 and WO2 under consideration)
- Current status:
  - Several rare earth oxides tested: Dy_2O_3 promising
  - BiO2 glass OK (6.6 gr/cm^3), WO2 unsuccesful (need high temp furnace)

Rare Earth Heavy Glasses

- Rare earths oxides + Ho_2O_3 + ZnO + P_2O_5+B_2O_3+SiO_2
- R.e. considered: CeO_2, Dy_2O_3, Nd_2O_3, Pr_6O_{11}, Er_2O_3



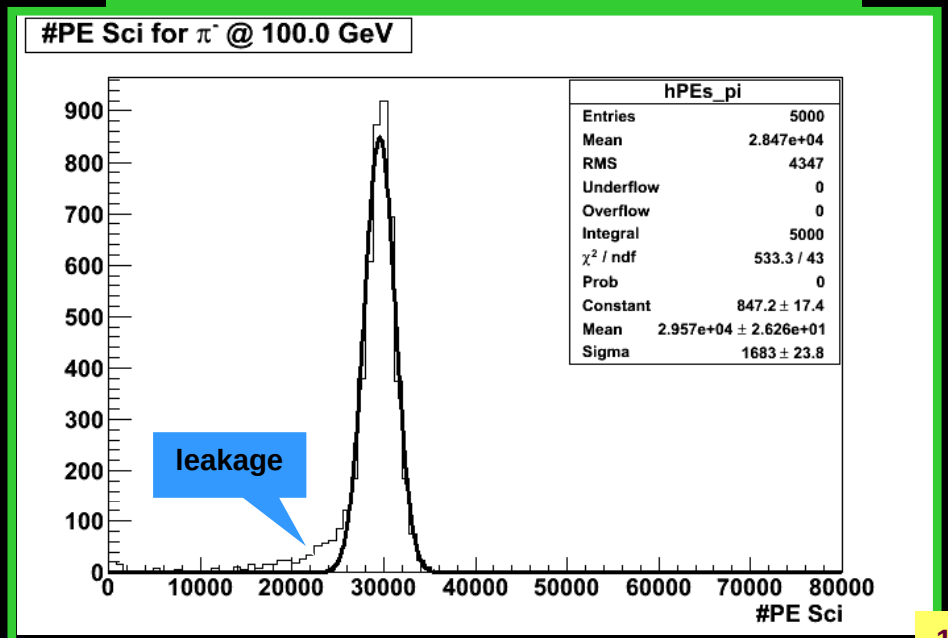
Composition	Density (g/cm^3)
CeO_2	3,3776
Pr_6O_{11}	3,7445
Dy_2O_3	3,8851
Er_2O_3	4,0690
Nd_2O_3	4,2441

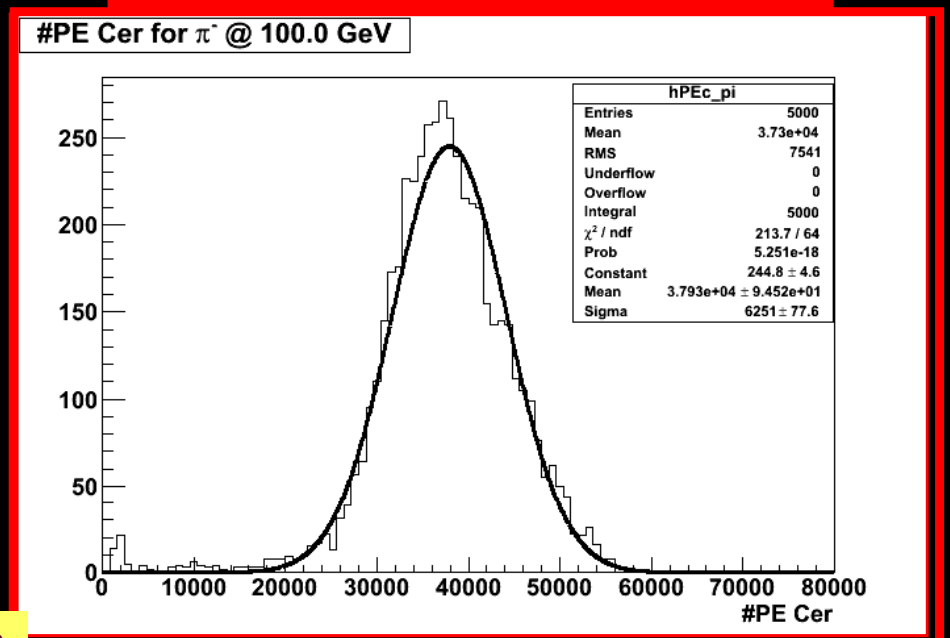
Department of Materials and Environmental Engineering

Leakage in 180 cm long *ADRIANO* module

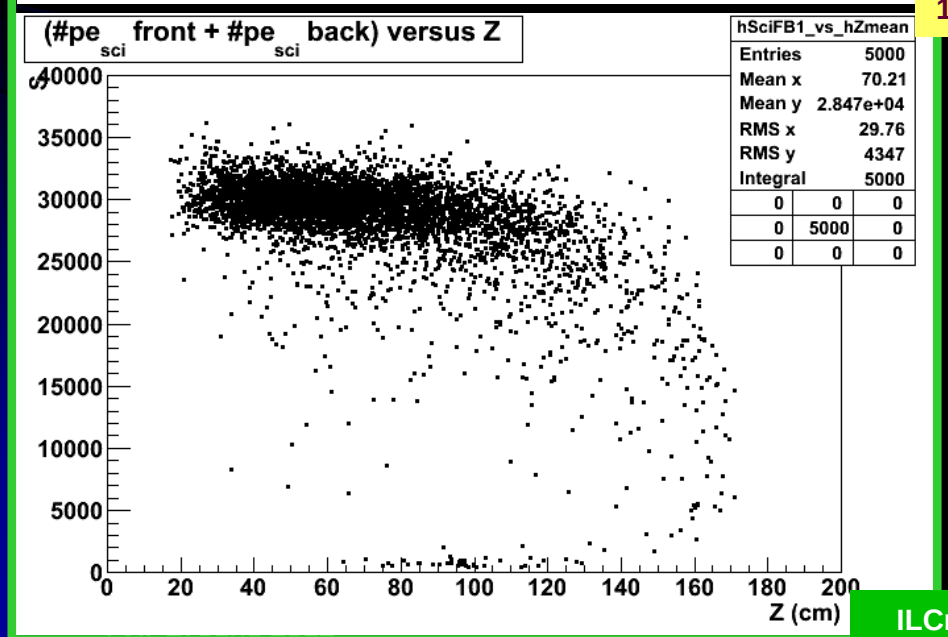
Uncorrected scintillating signal

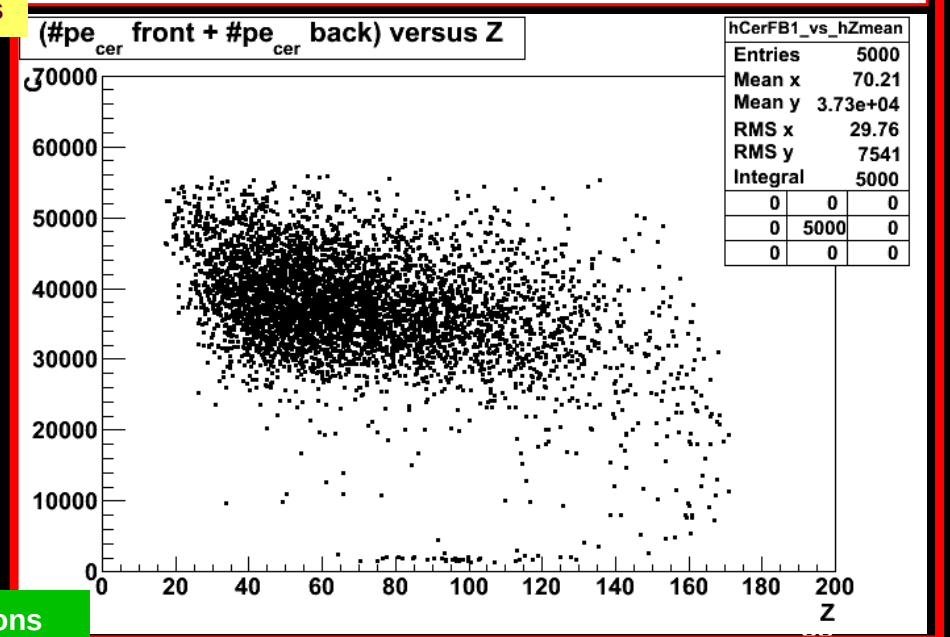
Uncorrected Cerenkov signal





100 Gev pions

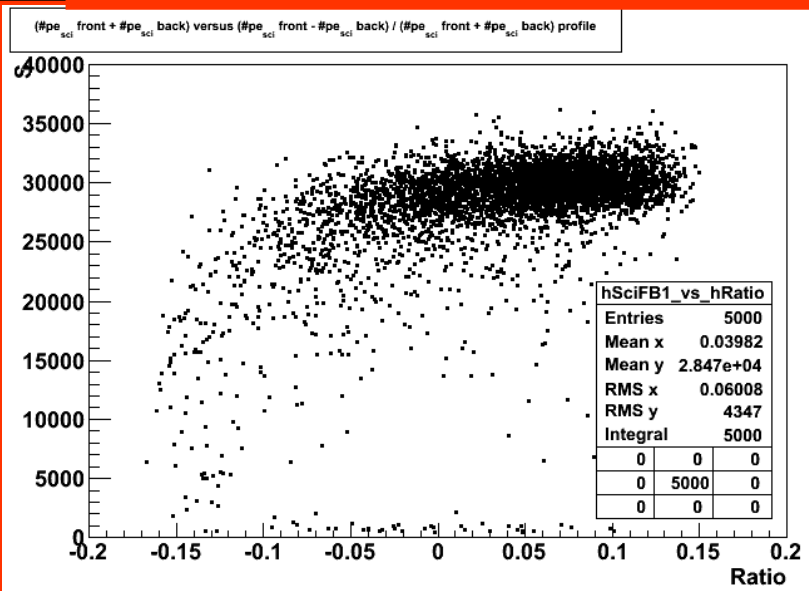


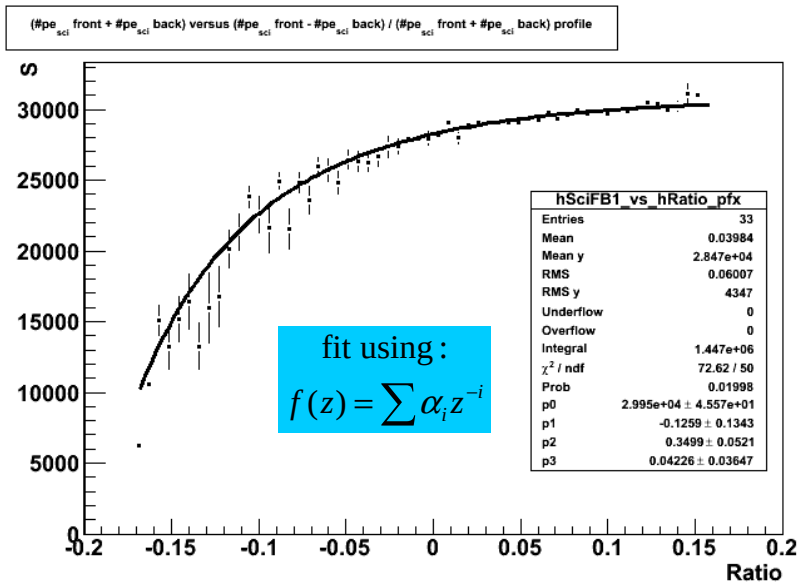


ILCroot simulations

Applying leakage corrections from CoG measured with a light division

Uncorrected scintillating signal

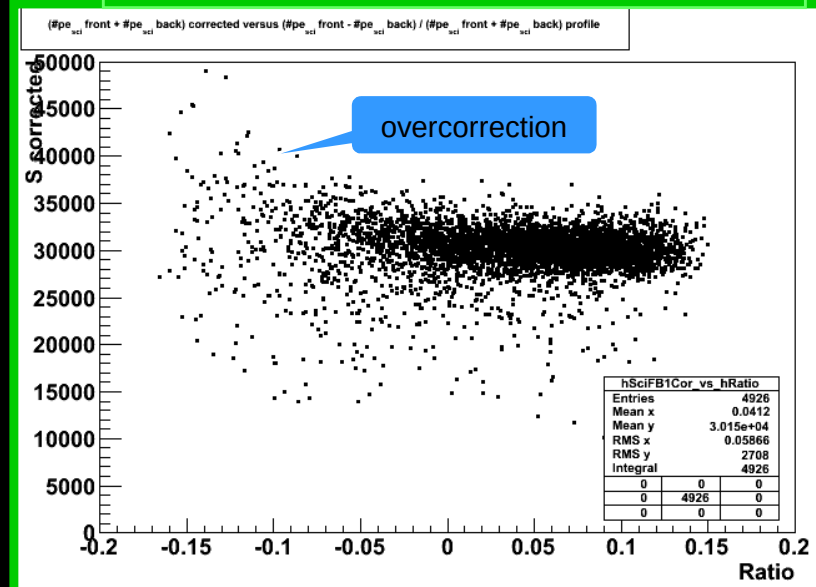


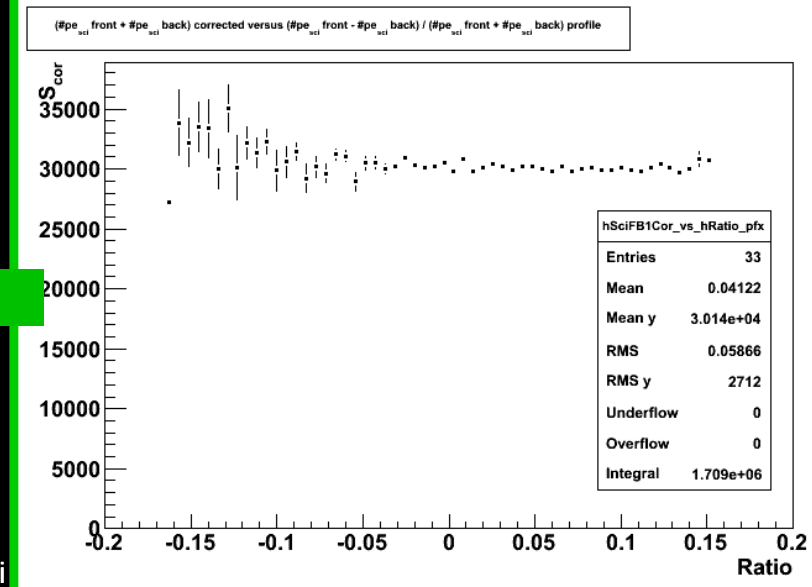


100 Gev pions

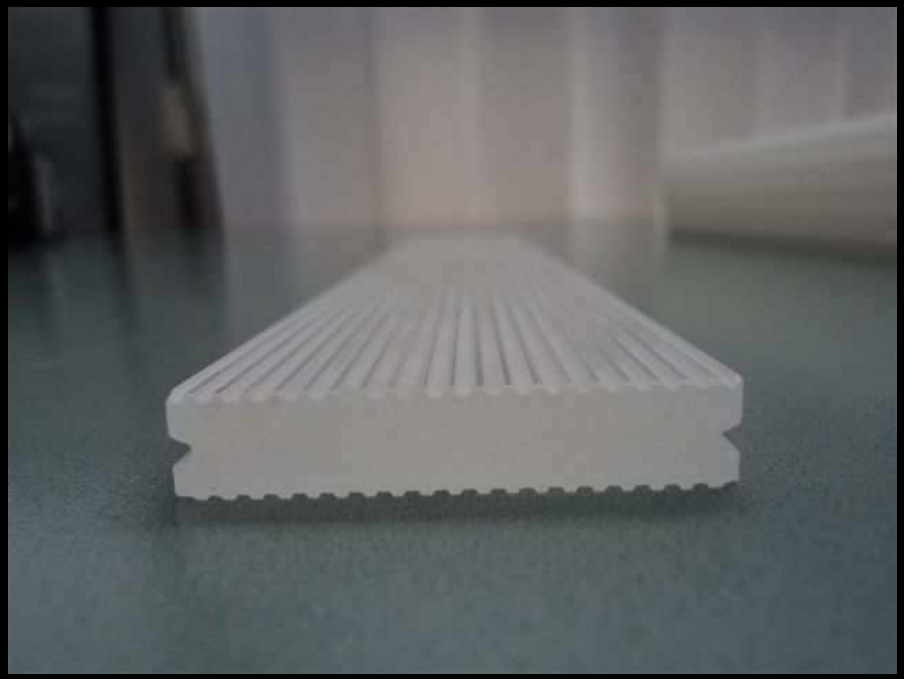
ILCroot simulations

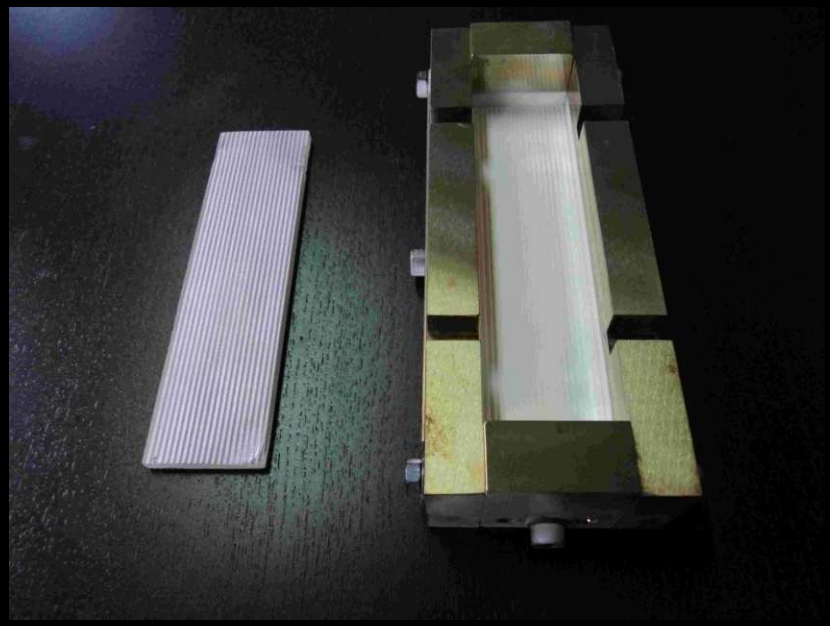
Corrected scintillating signal

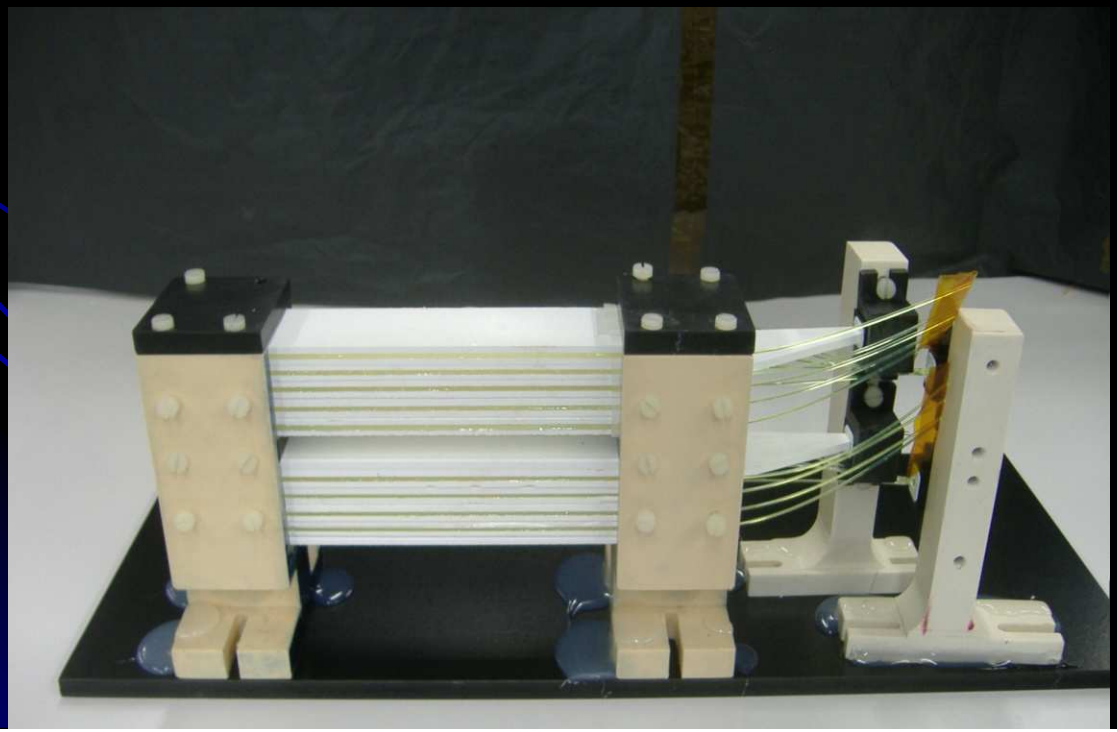




TiO2 Coated Variant

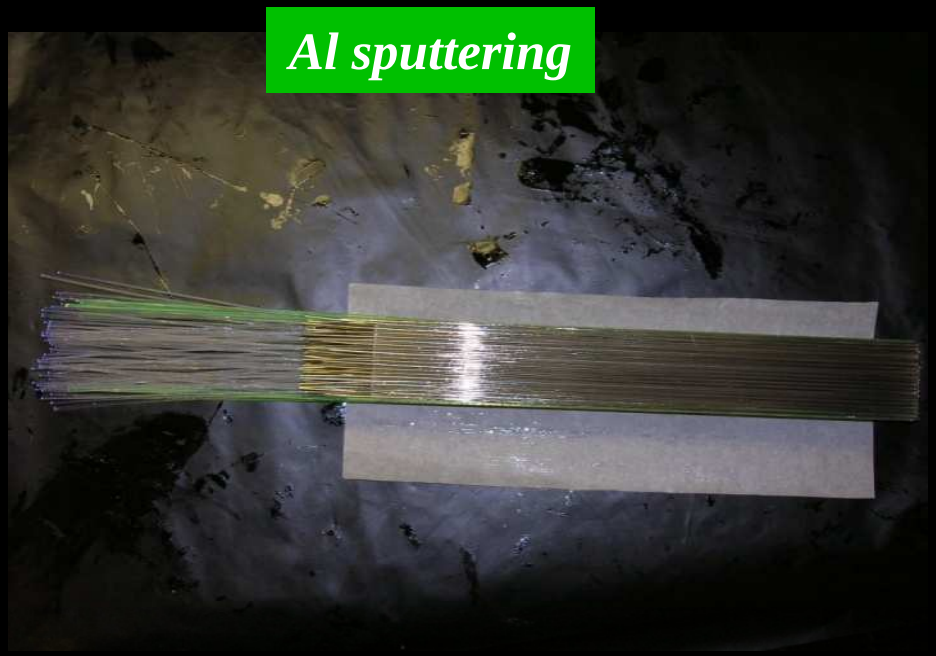


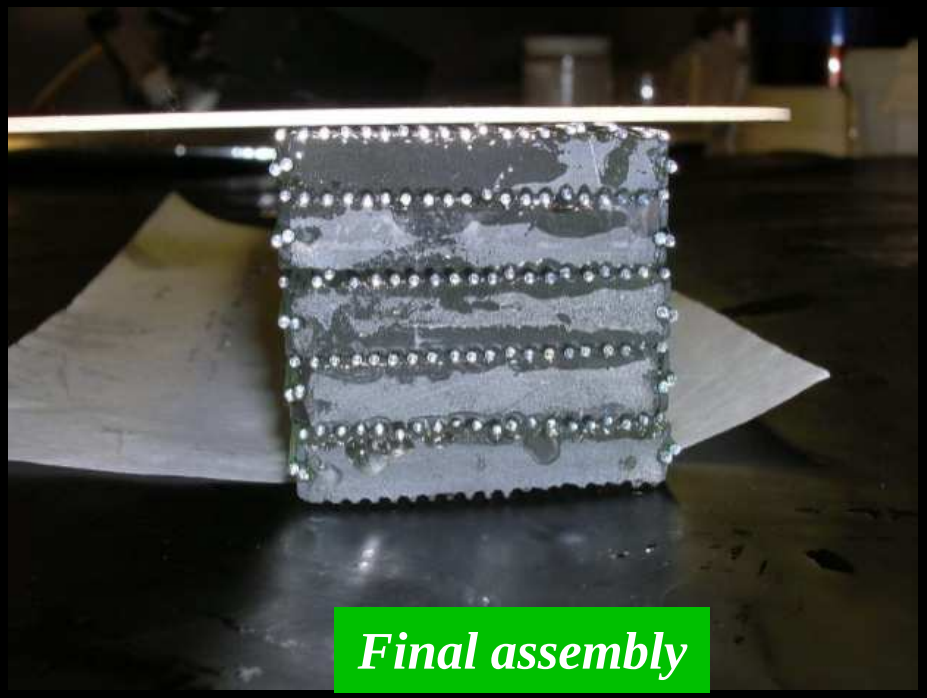




Also tried silver coating (with poorer results)

Aluminized Scifi Variant

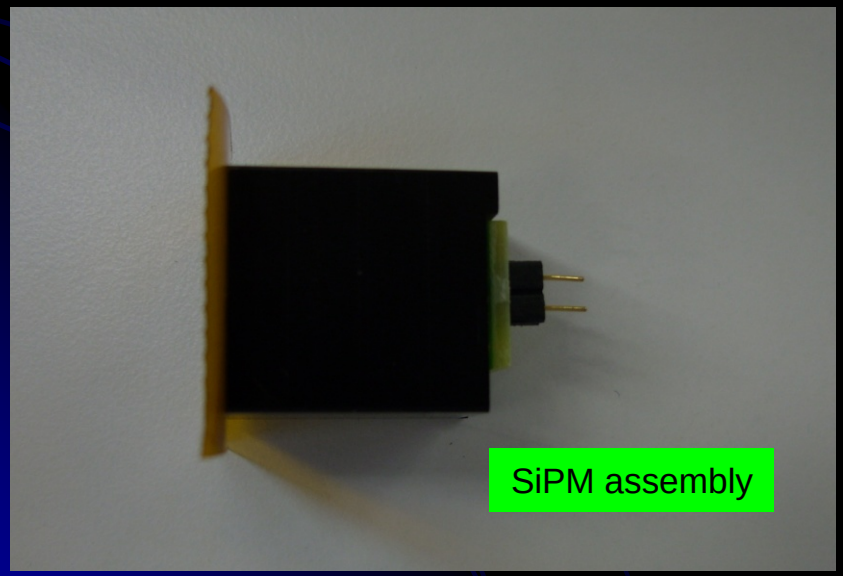




Ligth Readout R&D

Trieste concentrators

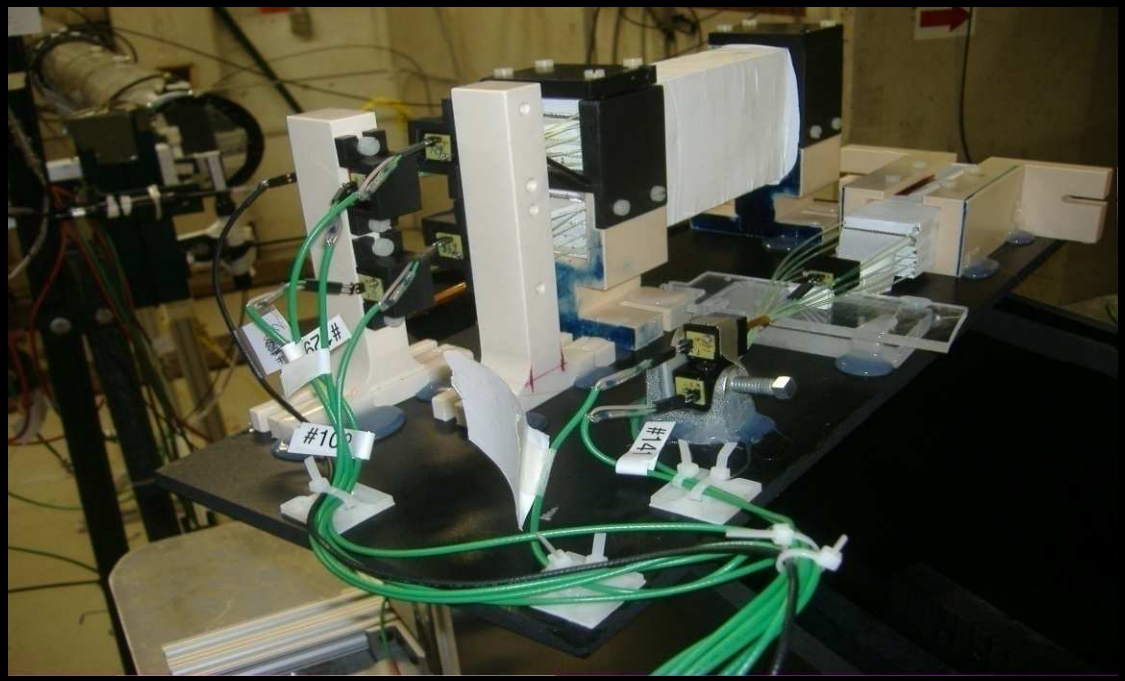
Winstone Cone concentrator
(G. Sellberg & E. Hahn)

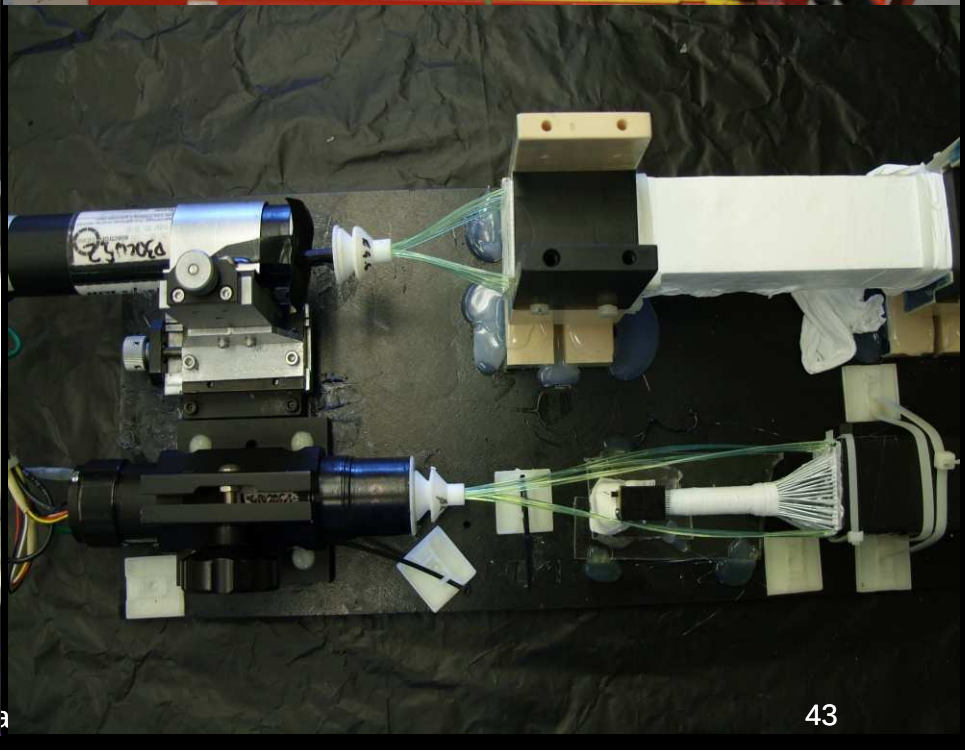


SiPM assembly

Light concentrator + fibers:
SiPM side

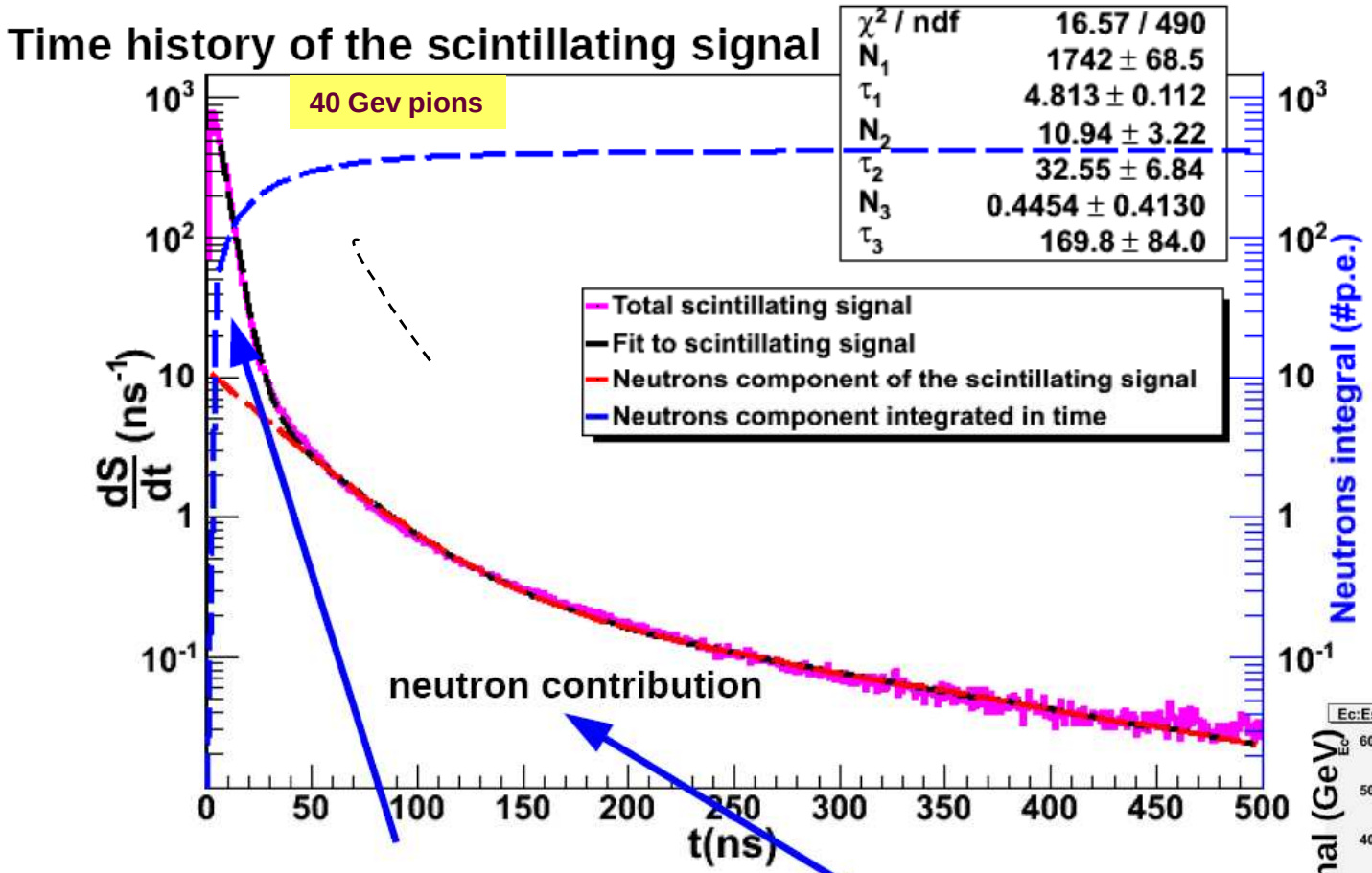
2011 Test Beam Setup at FTBF





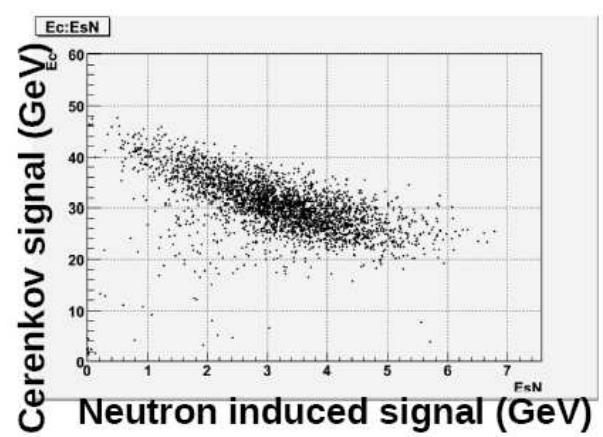
From Dual to Triple Readout

Disentangling neutron component from waveform

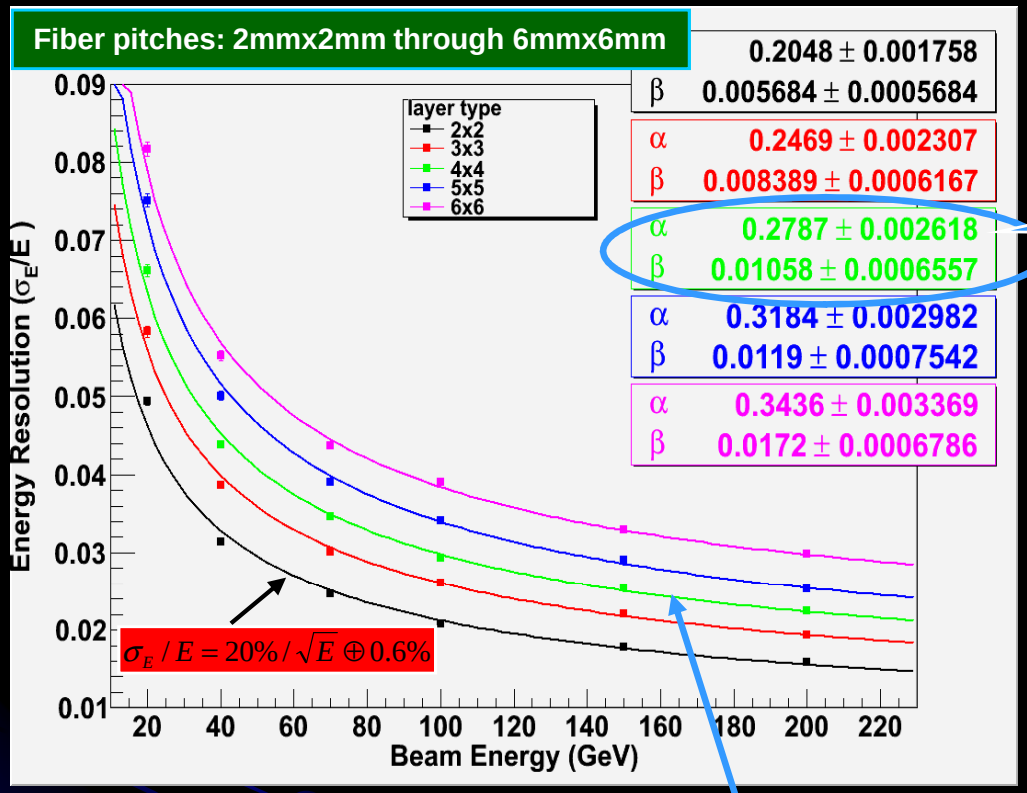


- The distribution has been fitted with a triple exponential function.
- After 50 ns only neutrons contribute to the signal.

$$E_{shower} = \frac{S_{fast} - \chi C}{1-\chi} + \xi S_{slow}$$

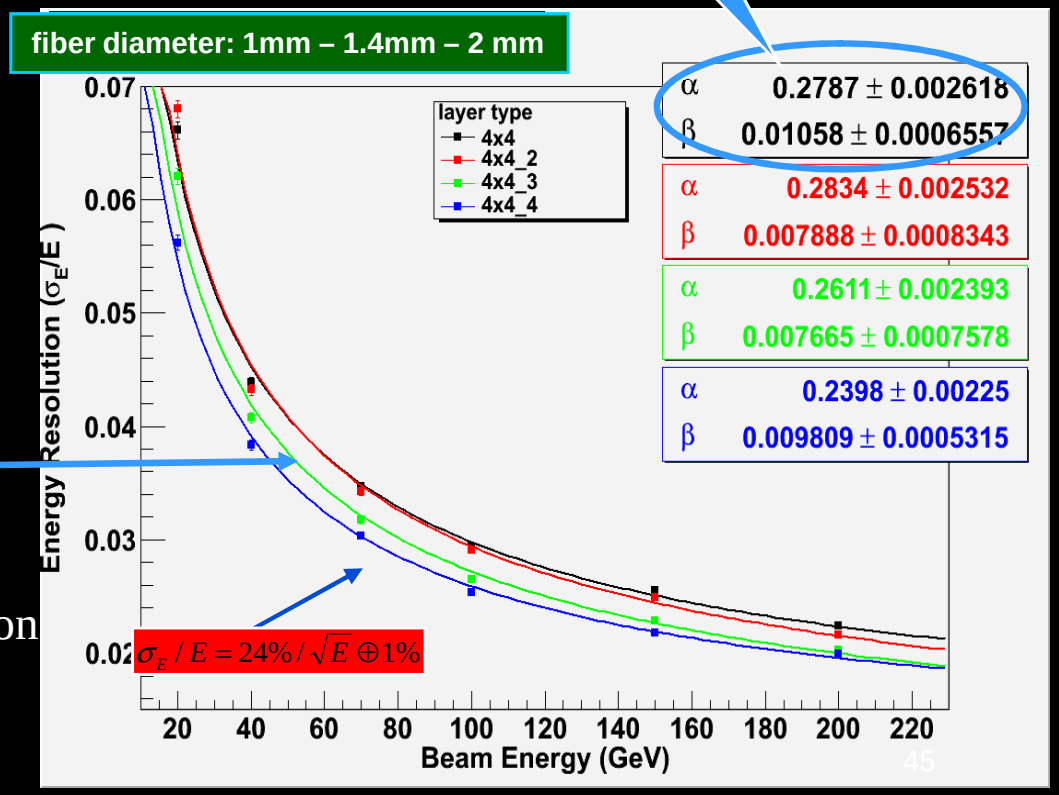


ADRIANO in Triple Readout configuration



Baseline configuration

Pion beams



$$\sigma_E / E = 28\% / \sqrt{E} \oplus 1\%$$

Compare to ADRIANO in Double Readout configuration

$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$$

Future Prospects

- First 2 year R&D on fabrication techniques already producing clear directions
- Precision molding technique is preferred (*ADRIANO*)
- Starting in year 2012 we will exploit
  - Laser-based technique coupled with diamond milling
  - Dedicated, high speed (< 30 min) molding machine with Pt-Ir coated (Ra ~ 5-10 nm) molds
  - Photo-etching techniques
- Ohara sponsorship/partership for bismuth optical glass (6.6 gr/cm^3, n_d = 2.0) in progress: two strips (total 1.4 Kg) provided at no cost
- New Ohara heavy glass just tested at FNAL
  - 7.54 gr/cm^3 ; n_d = 2.24
- *ADRIANO*2 (Cerenkov + scintillating glass)

  R&D just starting. First results: >600 pe/GeV
- Rare earth-doping tests under way at DIMA
- Heading toward a large prototype
  - 1,800 PMT appropriated from CDF
  - New experiments adopting *ADRIANO* (next slide)