Status of ADRIANO R&D in T1015 Collaboration

Corrado Gatto

On behalf of

T1015 Collaboration

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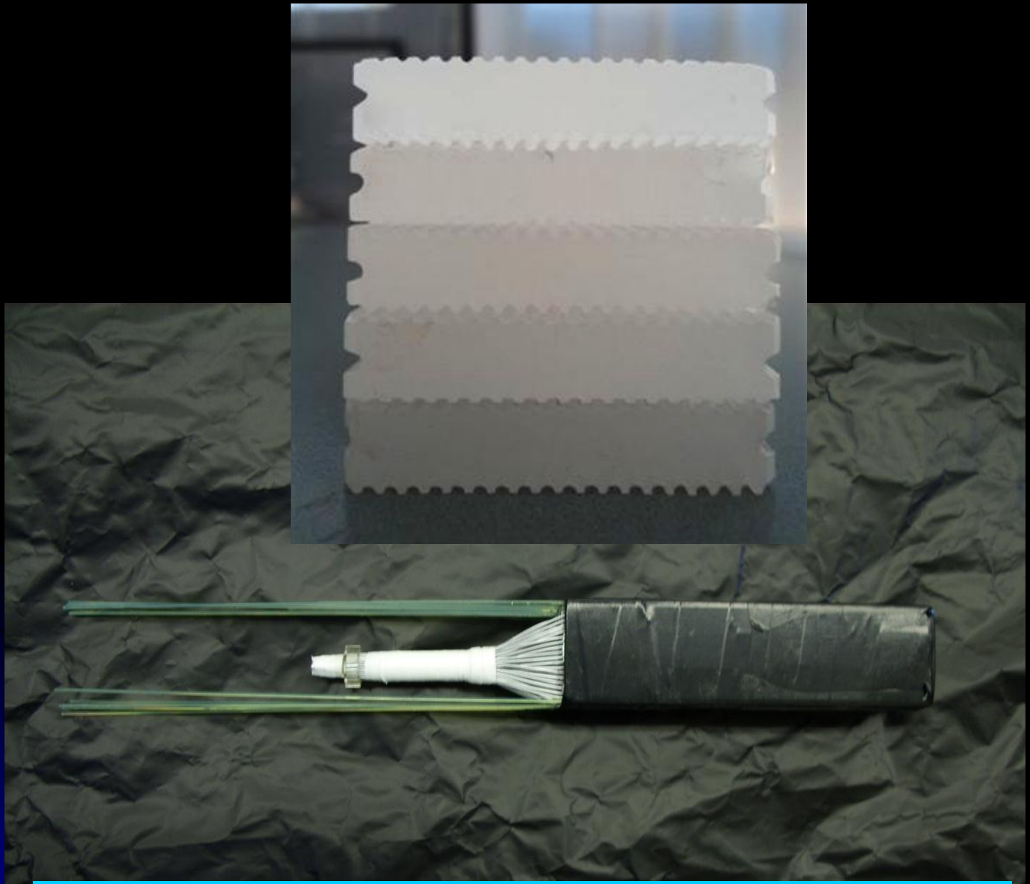
Fermilab
+
INFN Collaboration

Why Dual-Readout Calorimetry?

- Energy resolution $\propto 1/\sqrt{E}$
- Particle ID (from S vs C)
- ~ 10^5 channels
- Can be calibrated with e^- only
- Integrally active version (ADRIANO and ADRIANO II) works as EM and Hadronic calorimeter at the same time

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

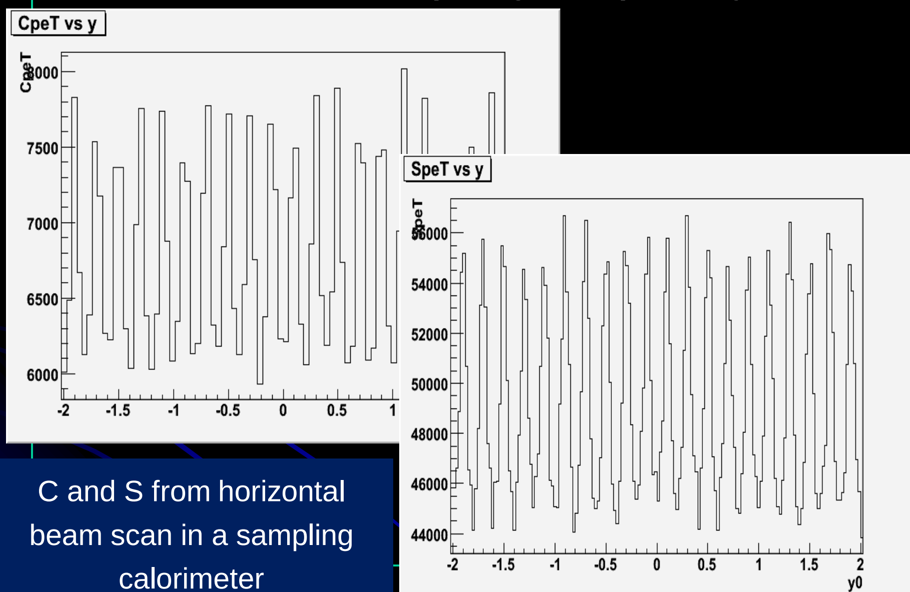


- **Fully modular structure**
- **2-D with longitudinal shower CoG via light division techniques**

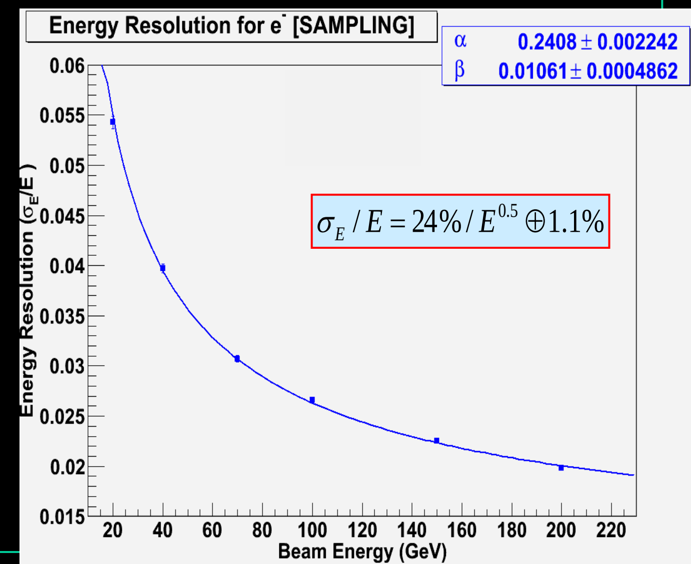
- **Cells dimensions**: 4x4x180 cm^3
- **Absorber and Cerenkov radiator**: lead glass or bismuth glass (ρ > 5.5 gr/cm^3)
- **Cerenkov light collection:** 10/20 WLS fiber/cell
- **Scintillation region**: scintillating fibers, dia. 1mm, pitch 4mm (total 100/cell) optically separated from absorber
- **Particle 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 ($\theta_{Cerenkov}$ < θ_{Snell} for slower hadrons).

Rationale #1 for *ADRIANO*

- **Integrally Active Calorimeter with transparent, high n_D absorber**
  - Use homogeneous medium as **an *ACTIVE ABSORBER***
  - It generates the Cerenkov component of dual-readout at the same time
  - Lots of Cerenkov photons when n_D is about 2.0 or greater
  - Avoid sampling frequency fluctuations for EM showers



C and S from horizontal beam scan in a sampling calorimeter



Cerenkov and Scintillating signal produced by e^- @ 45 GeV beam in sampling dual readout calorimeter with 1mm pitch between fibers as function of e^- impact point.

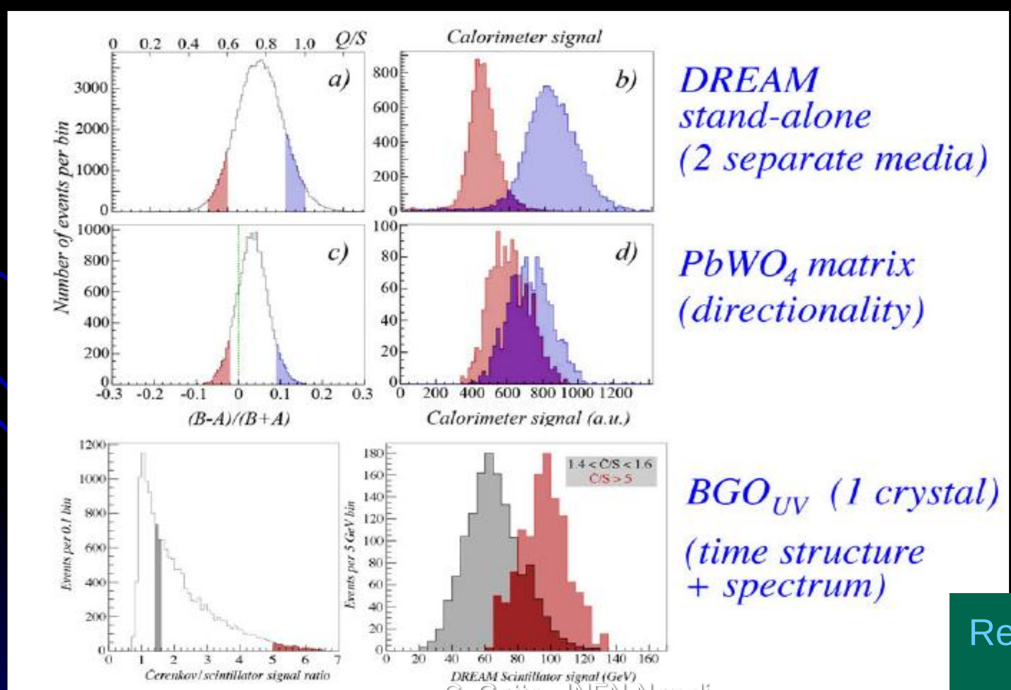
ADRIANO does not need a front EM section

Rationale #2 for *ADRIANO*

- **Scintillating and Cerenkov light in *OPTICALLY SEPARATED MEDIA:* ->non-homogeneous detector**
  - Use the absorber as Cerenkov component of dual-readout
  - Use scintillating fibers for the second component
  - Control the scintillation/Cerenkov with appropriate pitch between fibers

Hydrogen in plastic important element for neutron

Separation efficiency between S & C components



Report form DREAM Collaboration studies.

Rationale #3 for *ADRIANO*

- Use heavy glasses rather than crystals

	Glass	Crystals
Light production mechanism	Only Cerenkov (minor fluorescence with some SF glasses)	Cerenkov + scintillation
Stability vs ambiental (temperature, humidity, etc)	Excellent	Varies, but generally poor
Stability vs purity	Very good if optical transmittance is OK	Very poor
Longitudinal size	Up to 2m	20-30 cm max
Cost	0.4-0.8 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

Rationale #4 for *ADRIANO*

- Keep **the number of fibers to as manageable level** for a 4π calorimeter
- Define Γ = total area of photodetector/total external calorimeter area.
- Γ takes into account:
  - The needed photodetector area to read circular fibers with optimum packing
  - The crowdiness of your FEE
- At present:
  - Γ_{DREAM} = ~24%; $\Gamma_{4th\ Concept}$ = ~ 21; Γ_{Spacal} = ~ 21

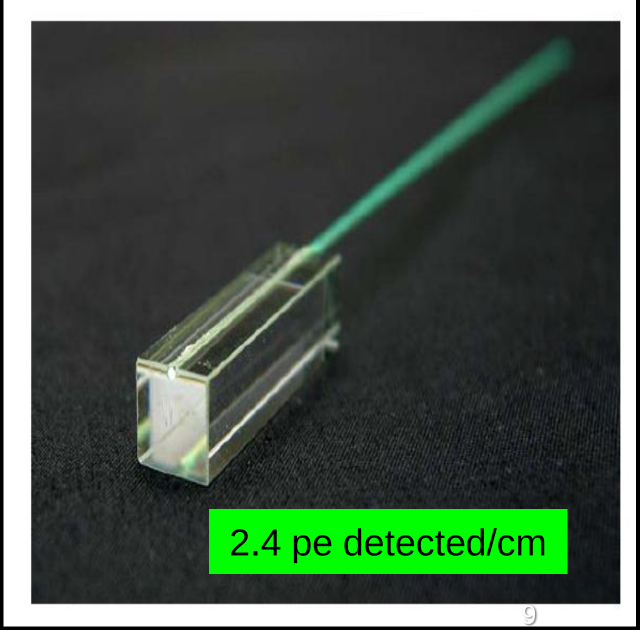
Quite large

- **In its baseline configuration $\Gamma_{Adriano}$ = 8%**

ADRIANO Simulations in ILCroot

- **ILCroot: C++ Software architecture based on root, VMC & Aliroot**
  - G3, G4, Fluka + all ROOT tools (I/O, graphics, PROOF, data structure, etc)
  - **Single framework, for generation, simulation reconstruction and analysis**
- *ADRIANO* is a melting pot of well established experimental methodologies
- All algorithms are implemented parametrically
- Use known experimental setups to normalize the overall results:
  - **DREAM** for scintillating light production (fiber calorimeter is OK, BGO+fibers not quite there)
  - **CHORUS** for instrumental effects with sci-fibers
  - **R. Dollan Thesis** for WLS light collection with SF57

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.



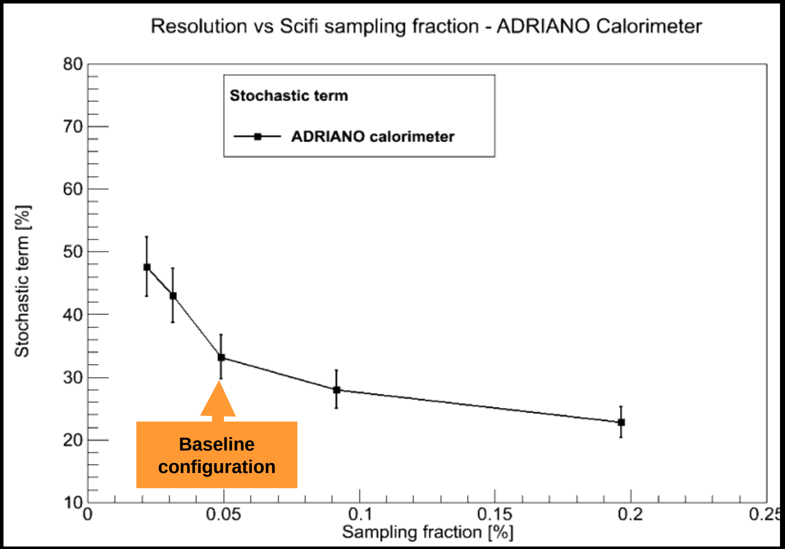
ILCroot simulations

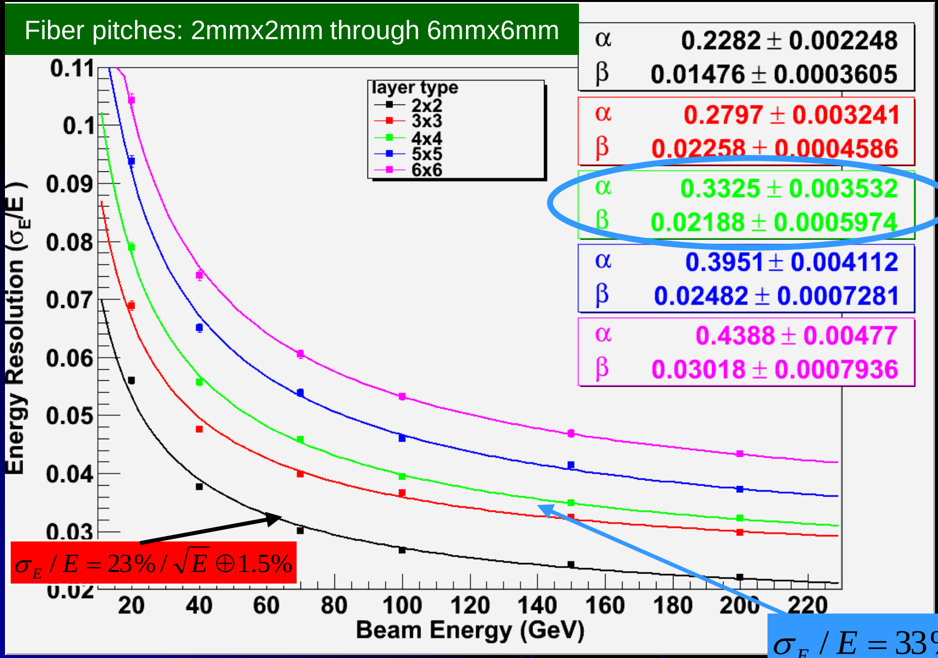
ADRIANO Light Yield and Resolution

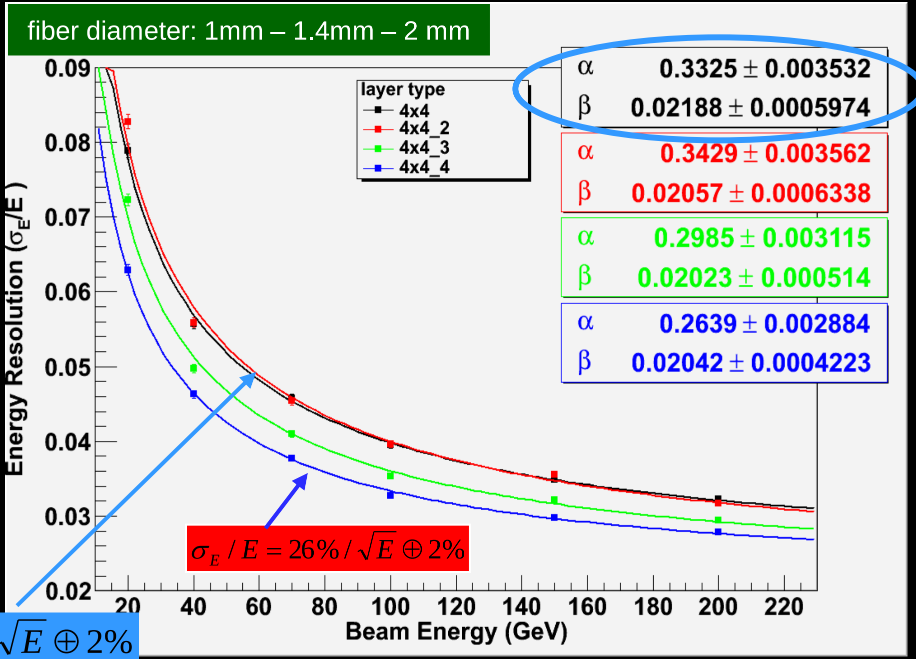
Integrally Active with Double side readout (*ADRIANO*)									Sampling
Pitch [mm²] Diameter	2x2 1mm	3x3 1mm	**4x4 1mm**	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillry	Sampling
<pe_S/GeV>	1053	430	**254**	163	124	500	110	250	200
<pe_C/GeV>	340	360	**360**	355	355	355	350	350	7.5

Baseline configuration (4x4 1mm)

1-side readout (Sampling)







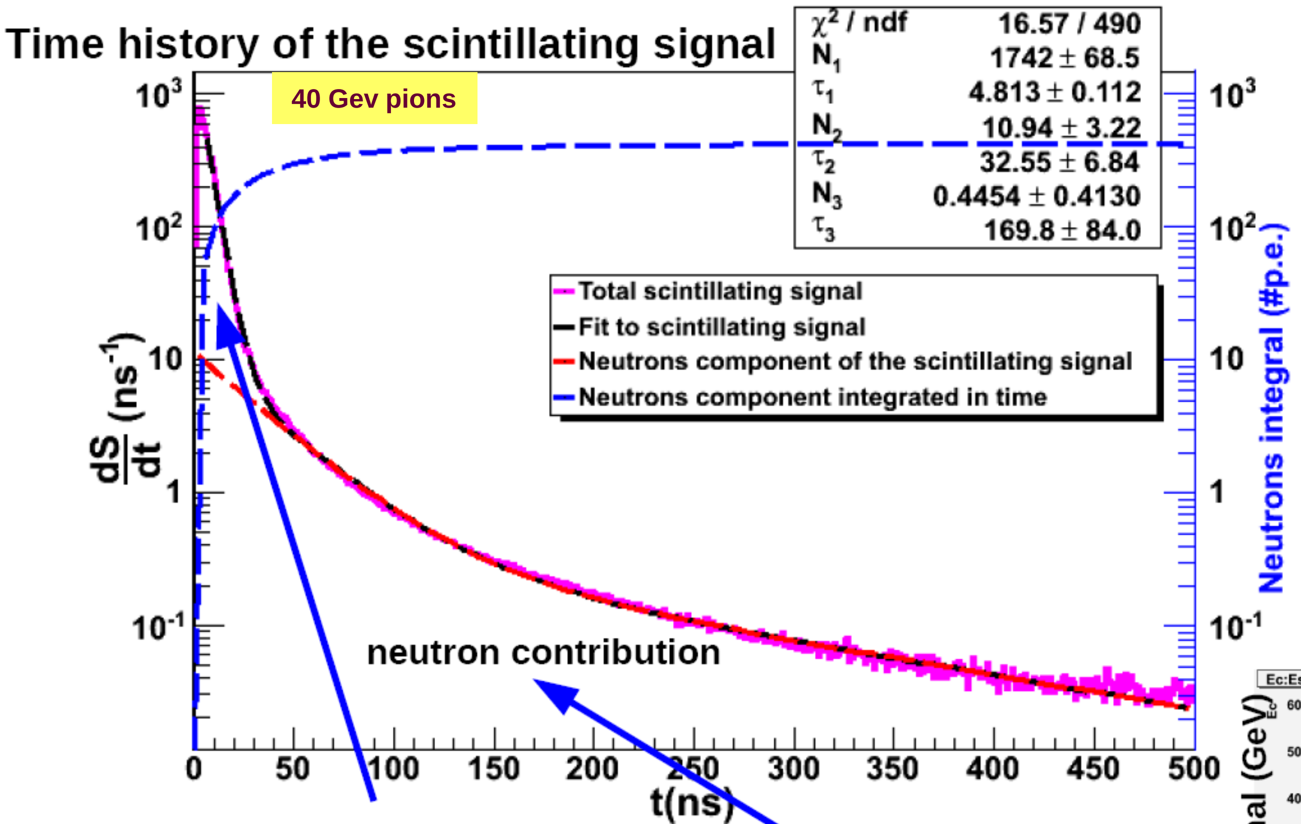
$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$

All numbers include the effect of photodetector QE

ILCroot simulations

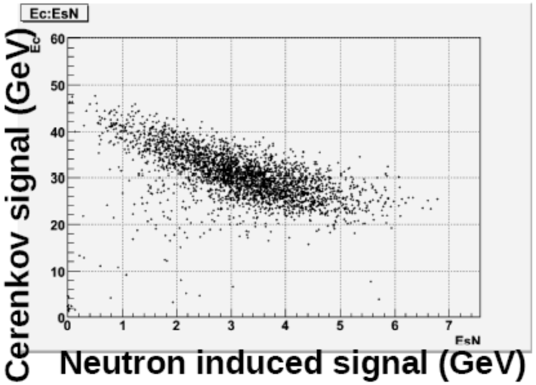
From Dual to Triple Readout

Disentangling neutron component from waveform

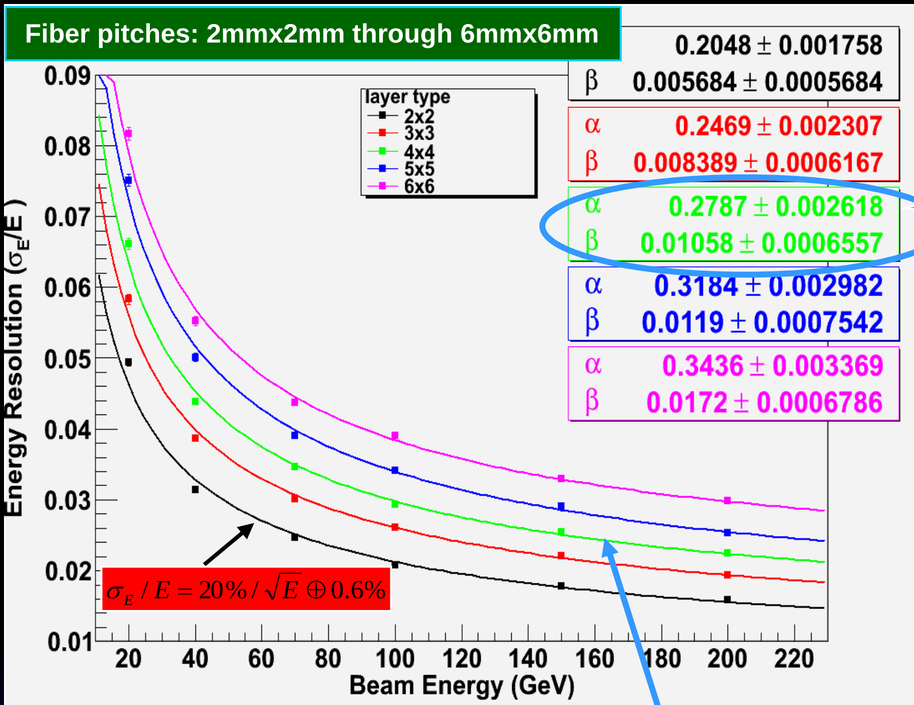


$$E_{shower} = \frac{S_{fast} - \chi C}{1 - \chi} + \xi S_{slow}$$

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

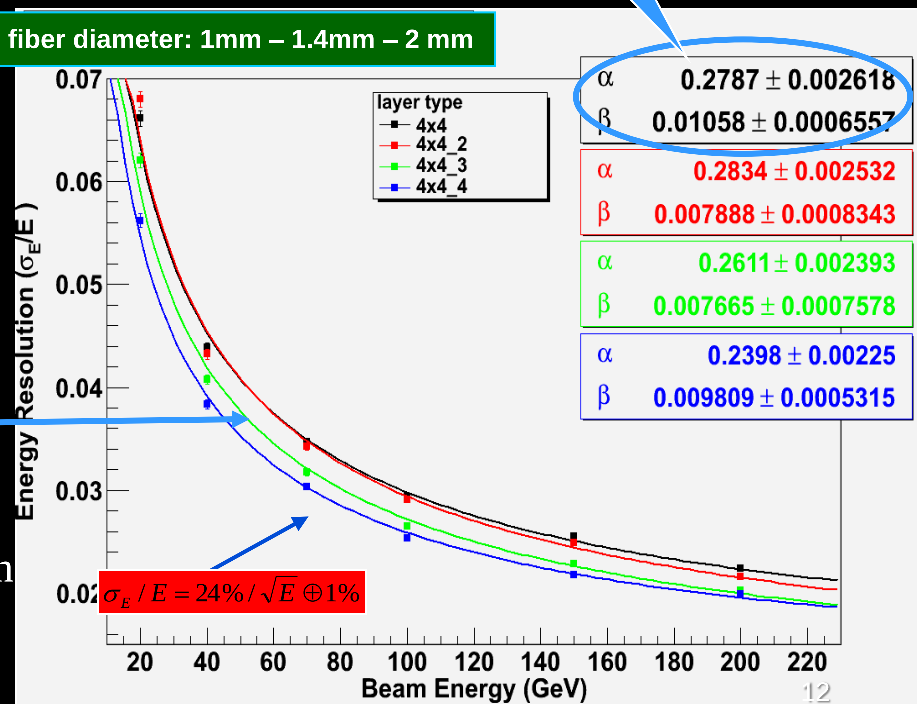


ADRIANO in Triple Readout configuration



Baseline configuration

Pion beams



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

Compare to ADRIANO in Double Readout configuration

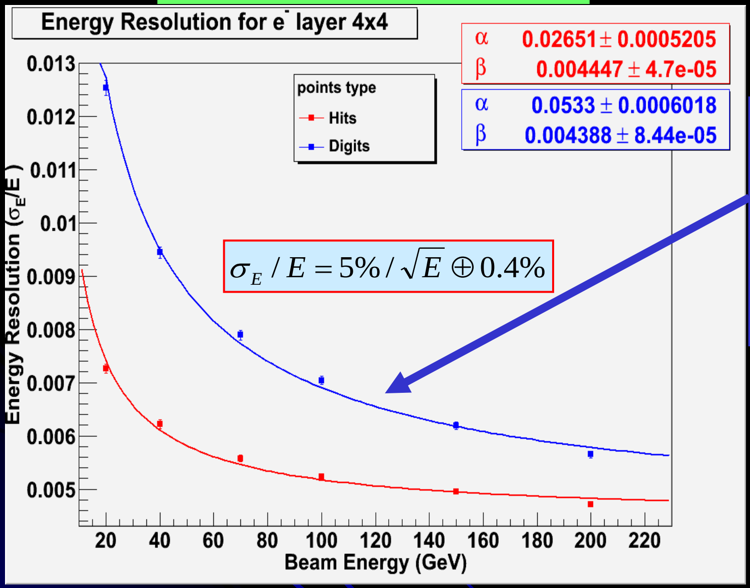
$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$$

ILCroot simulations

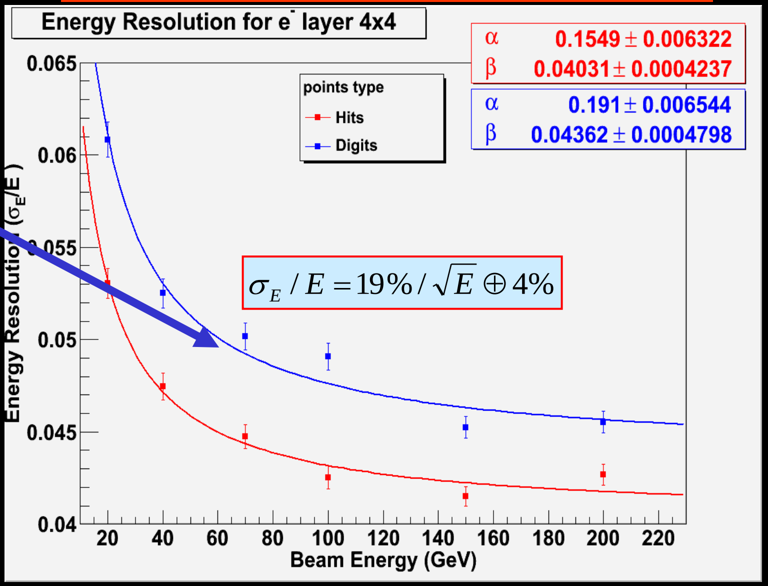
ADRIANO EM Resolution (with and without instrumental effects)

- 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



Dual-readout (scintillating+Cerenkov)



Blue curve includes:

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

ILCroot simulations

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

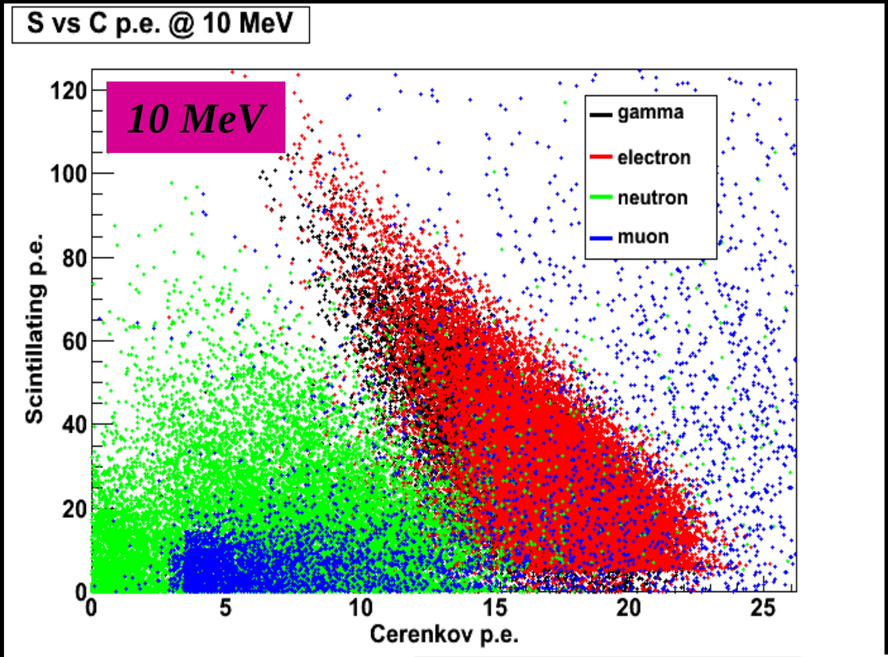
ADRIANO does not need a front EM section

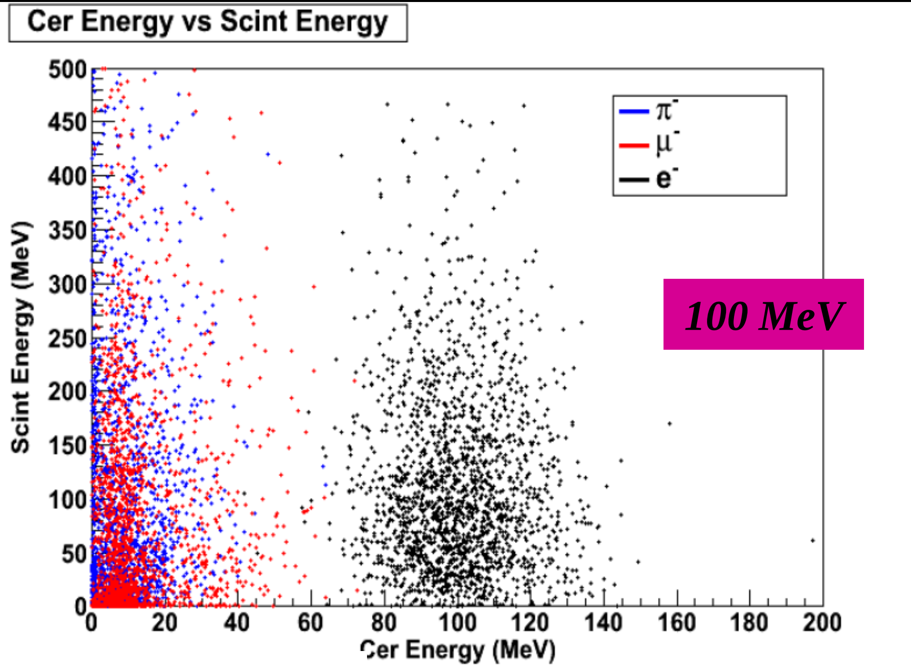
If Cerenkov ligth yield is large enough

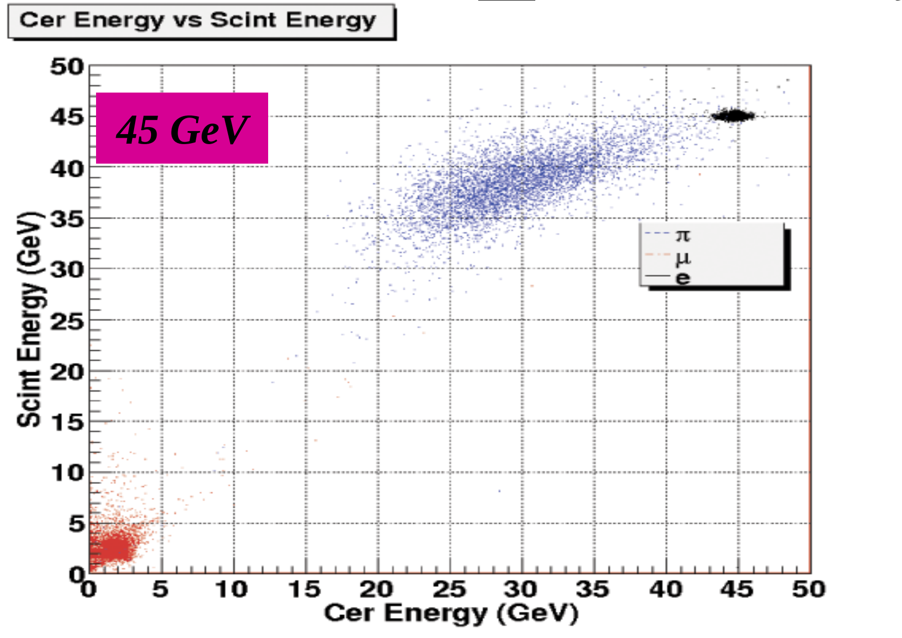
Anna Mazzacane
Vito Di Benedetto

ILCroot simulations

Particle ID with ADRIANO



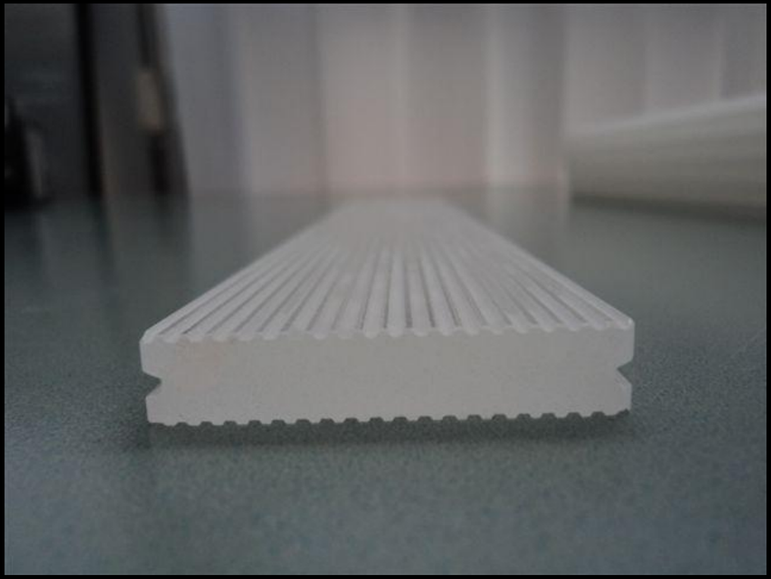




Fabrication Technology #1: Diamond tools machining

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

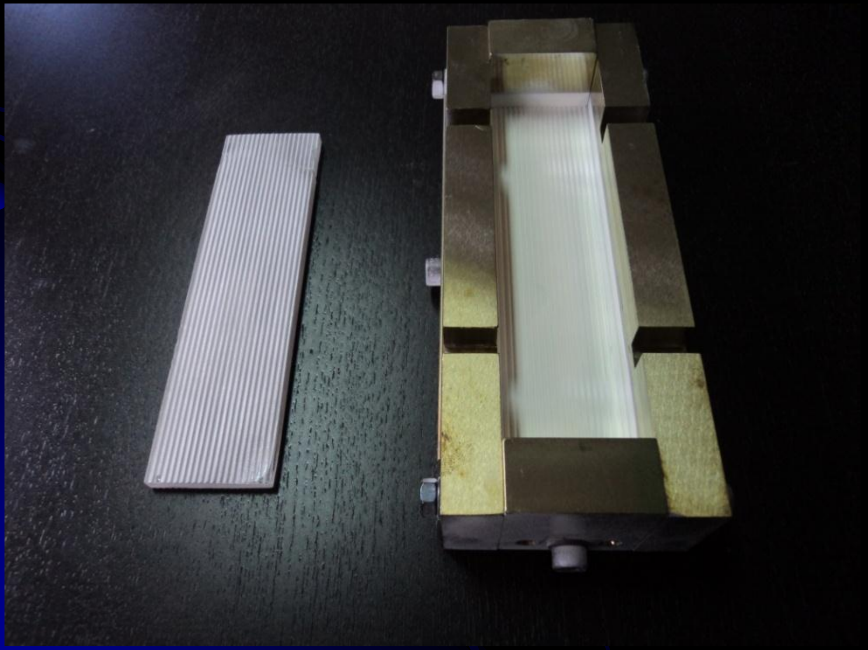
- **Cons**
  - Longer fabrication process
  - Large waste

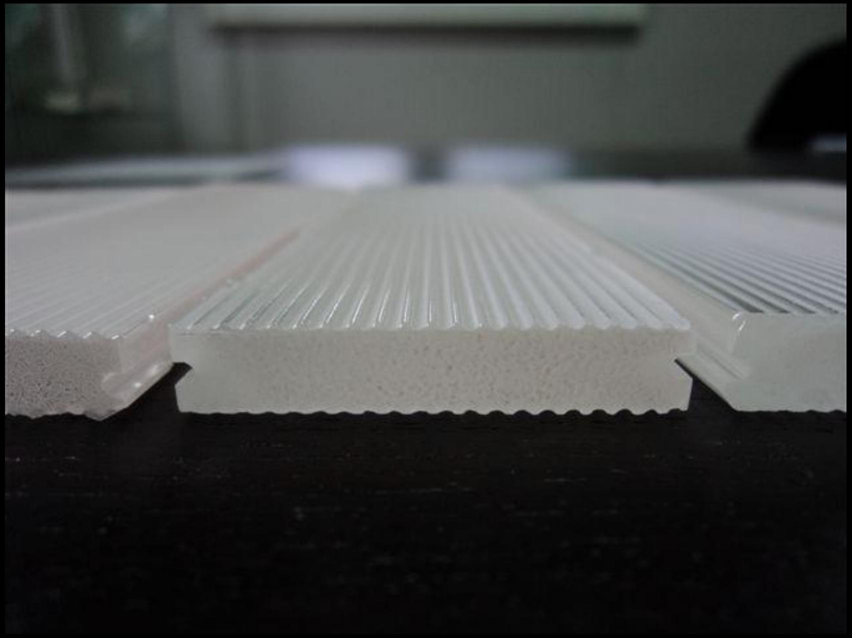


Fabrication Technology #2: Precision molding

- 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

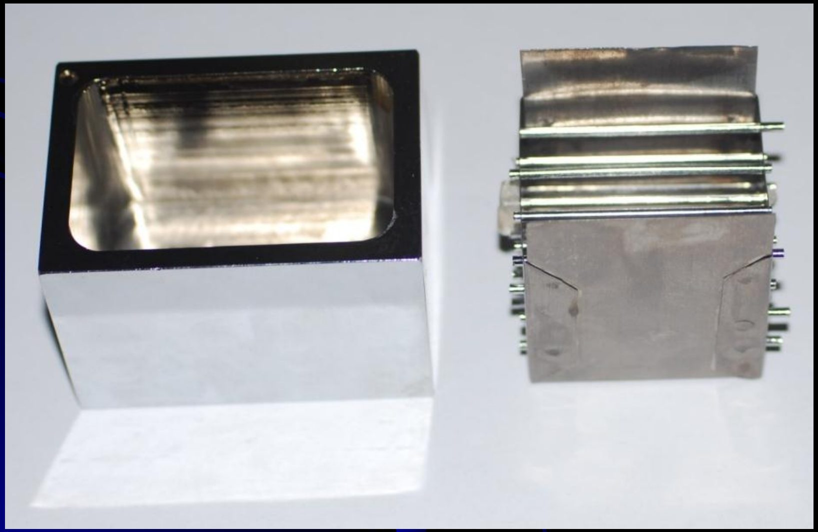




Fabrication Technology #3: Glass melting

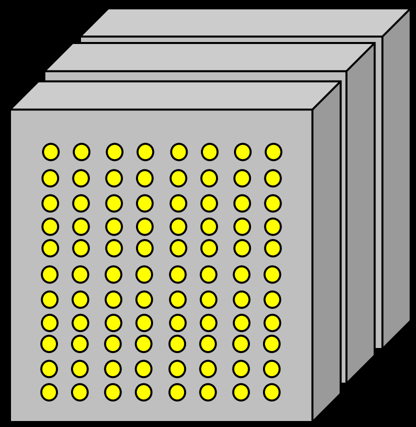
- Pro
  - Build entire cell in one step
  - Very robust mechanical structure

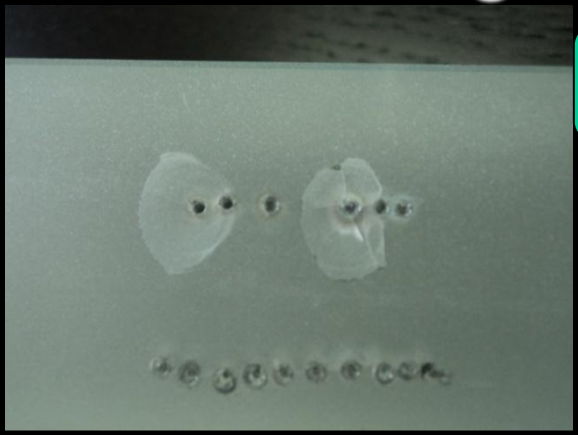
- Cons
  - High temperature cycle
  - Extra passive material
  - Easy to get glass defects



Early stages of R&D

Fabrication Technology #4: Laser + diamond drilling

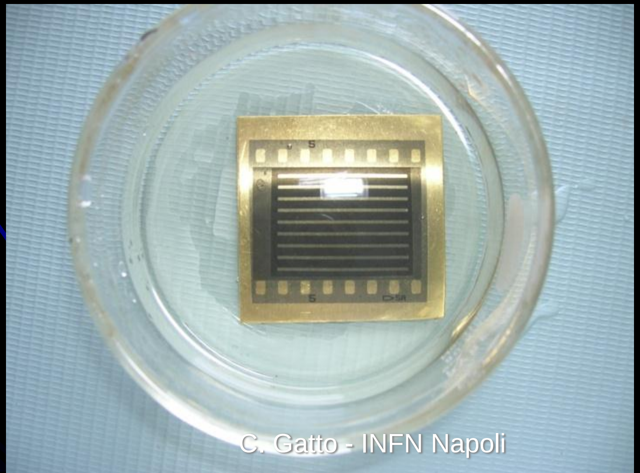




Nd-YAG laser

SALENTEC advanced technologies

Fabrication Technology #5: Photo-etching



T1015 R&D Program

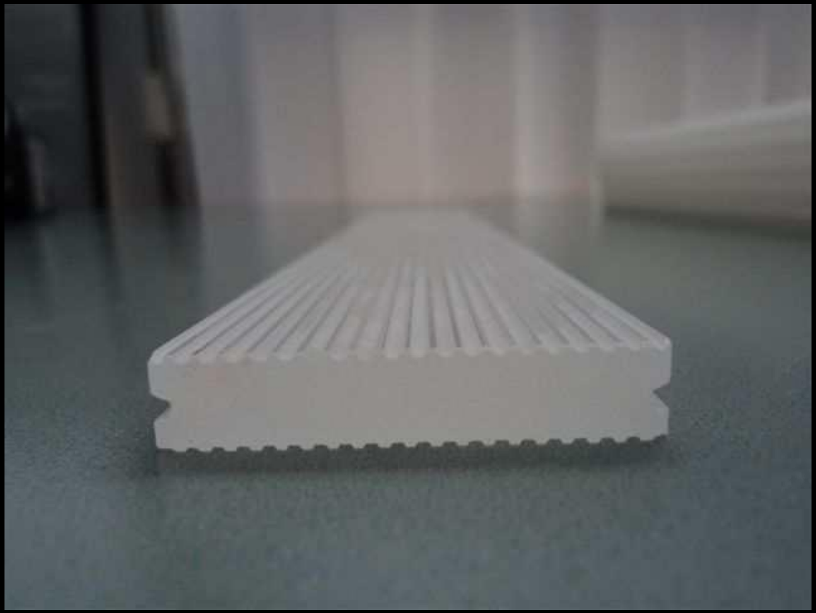
- Four test beam at FTBF by the spring of 2012: several cells in different configurations (40x40x250 mm^3)
- 4 glass type: lead and bismuth based + scintillating Ce doped glass
- 3 glass coatings: TiO2, Silver paint, clear acrylic
- 3 WLS fibers: Y11 (1.2mm) & BCF92 (1.0, 1.2 mm)
- 1 Scintillating fiber: SCSF81
- 4 scifi coating: TiO2, BasO4, Silver paint, Al sputter
- Several optical glues (mostly homemade)
- 5 photodetectors: 2 SiPM (2.8 round and 4.3x4.3 square) & 2 PMT (P30CW5 , R647, H3165)
- 4 light coupling systems: direct glass + direct WLS + 4 light concentrators

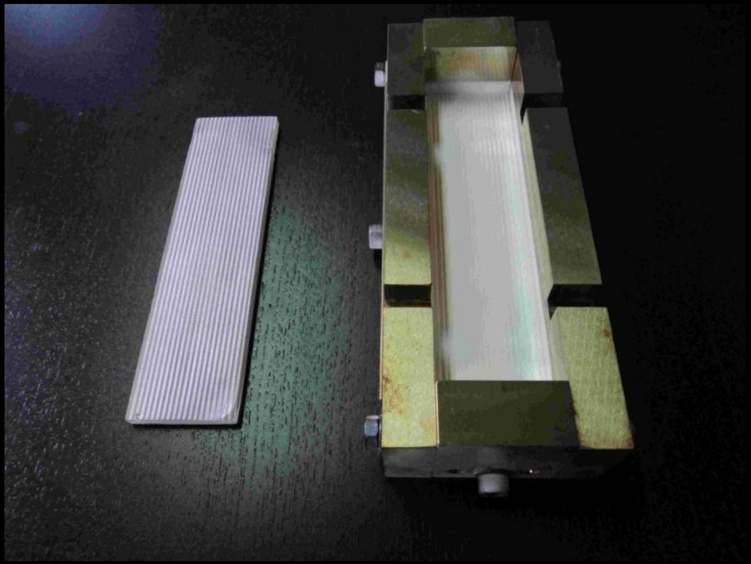
Goals are:

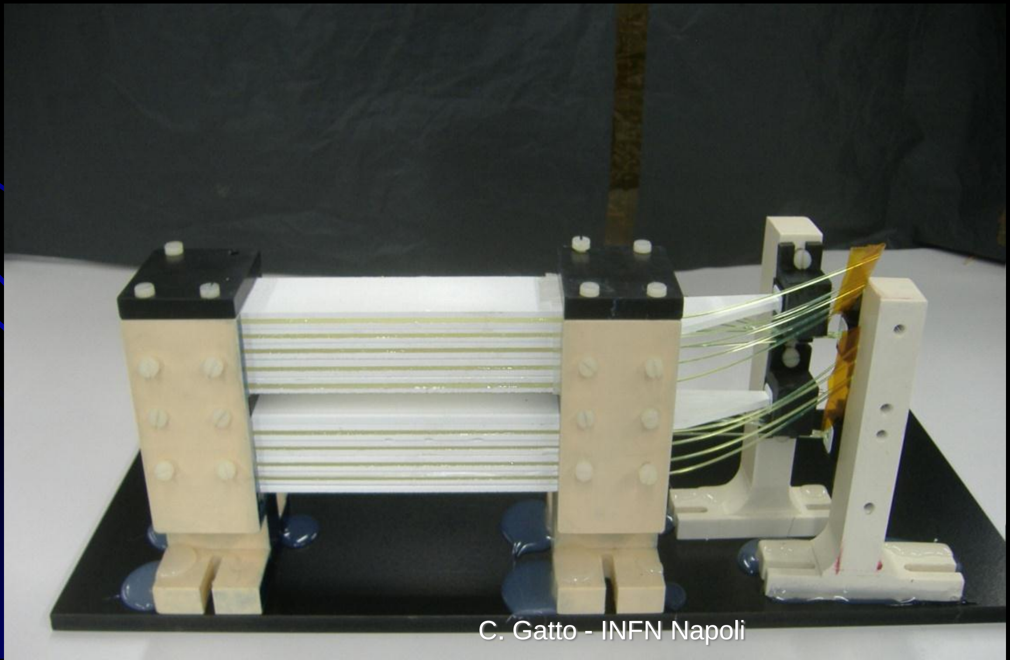
- ***Maximize light yield (Cerenkov)***
- ***Measure parameters for Montecarlo simulations***

Unlikely to be able to test the dual-readout concept (size limited)

TiO2 Coated Variant

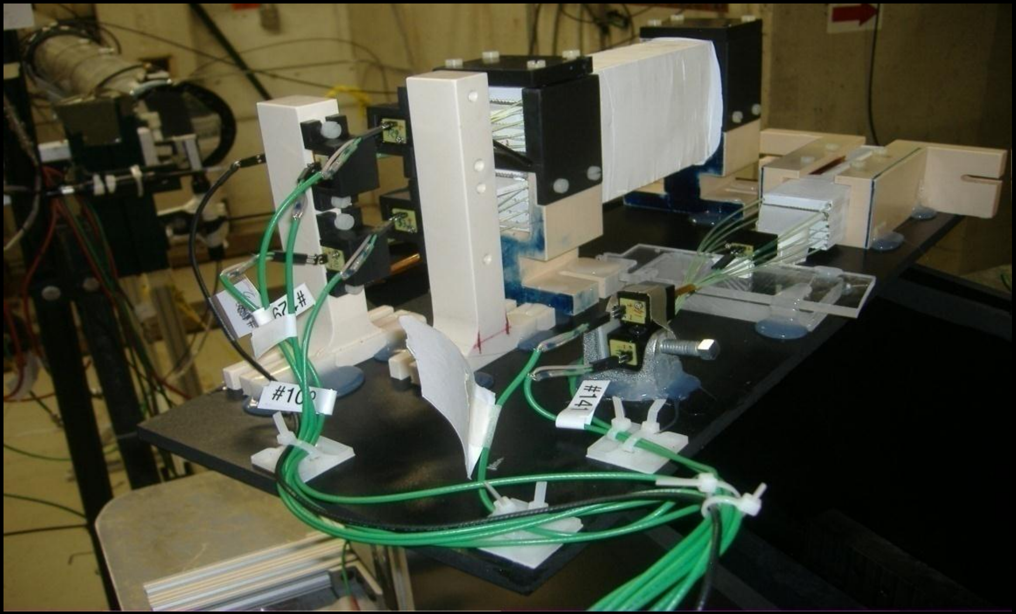


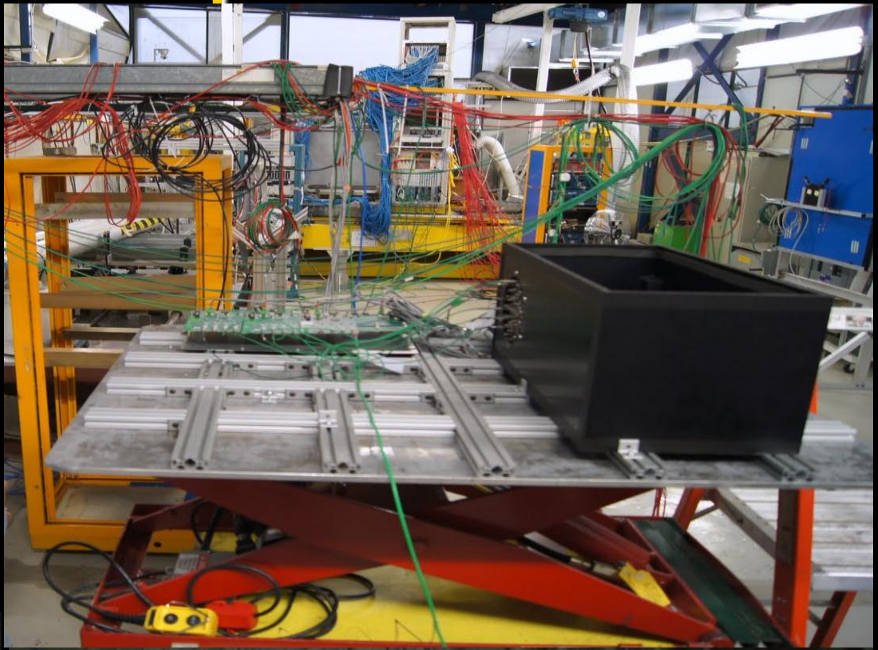


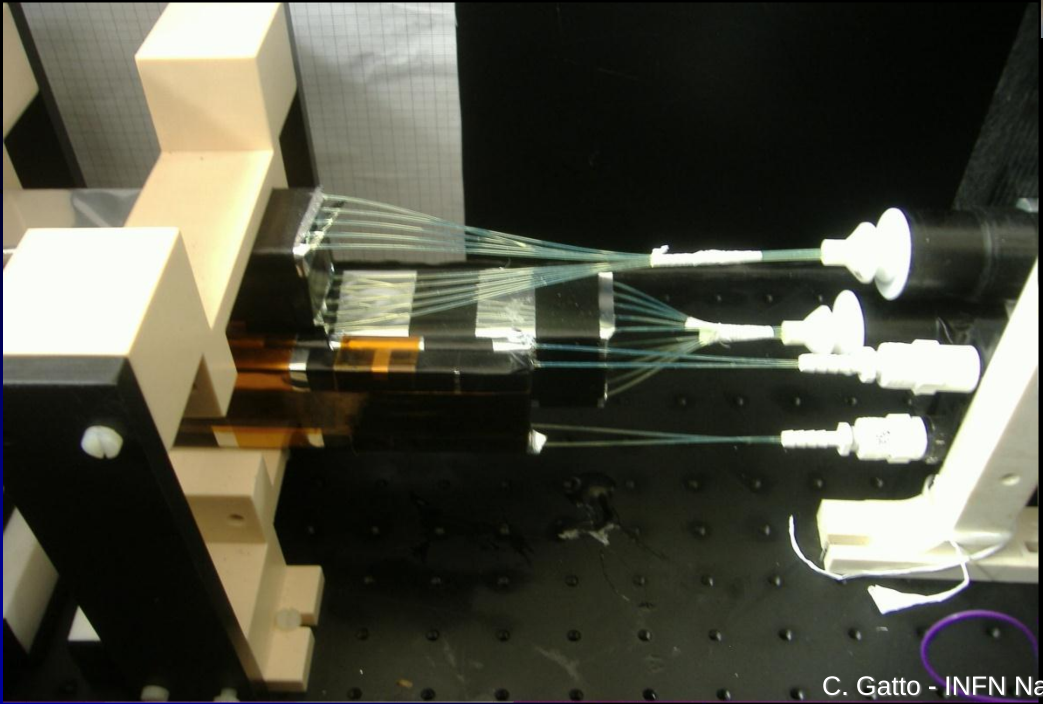


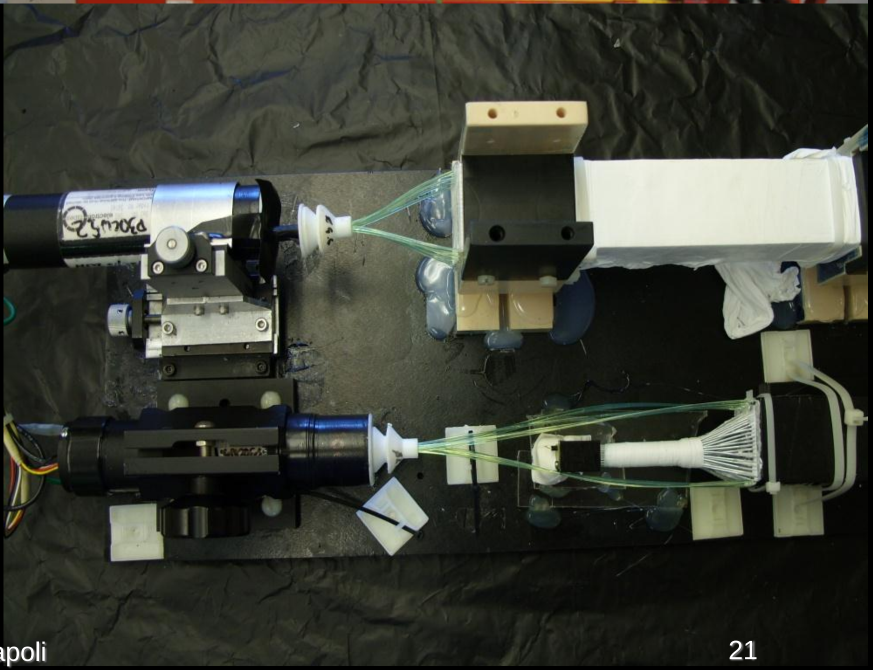
Also tried silver coating (with poorer results)

2011 Test Beam Setup at FTBF

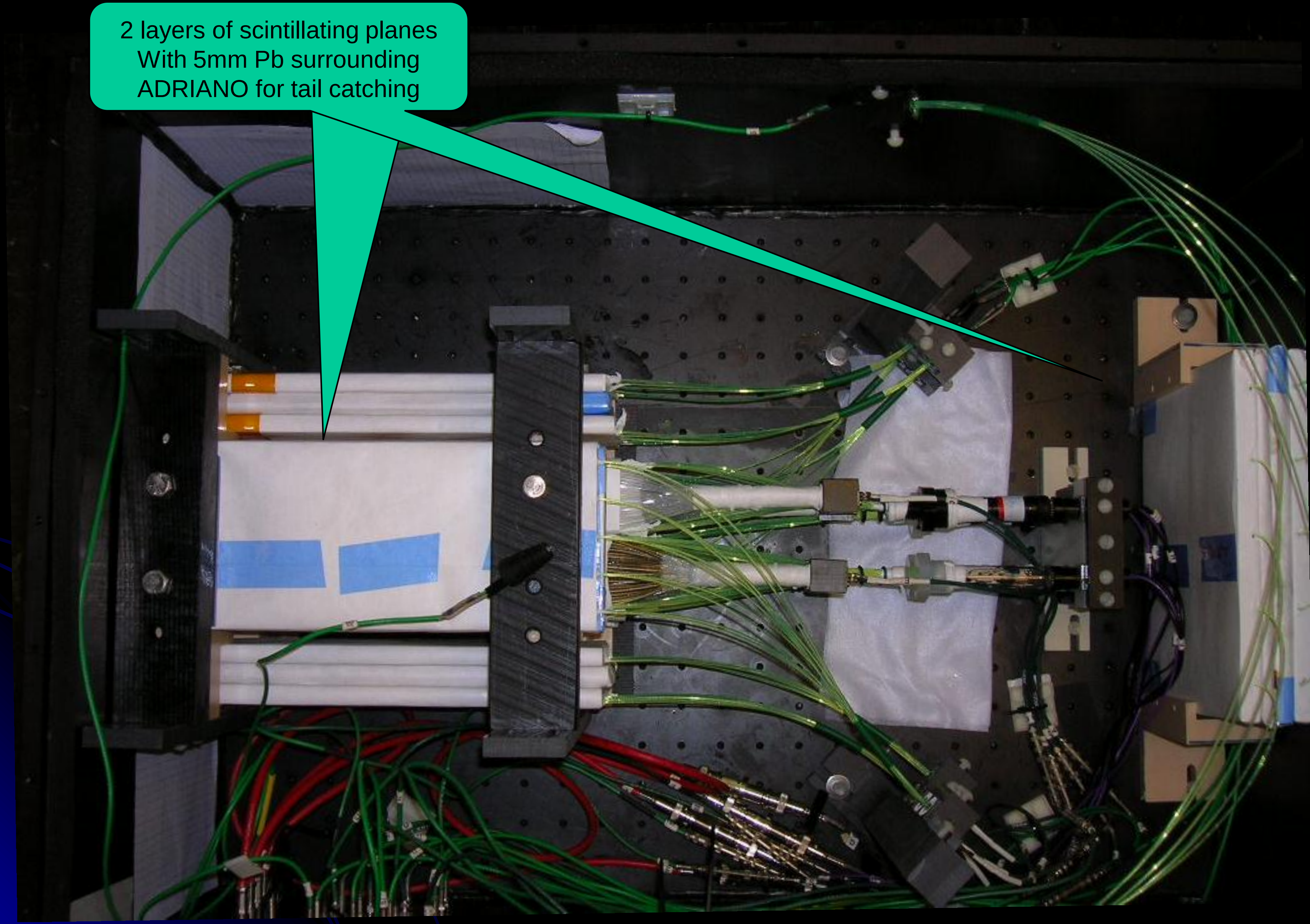




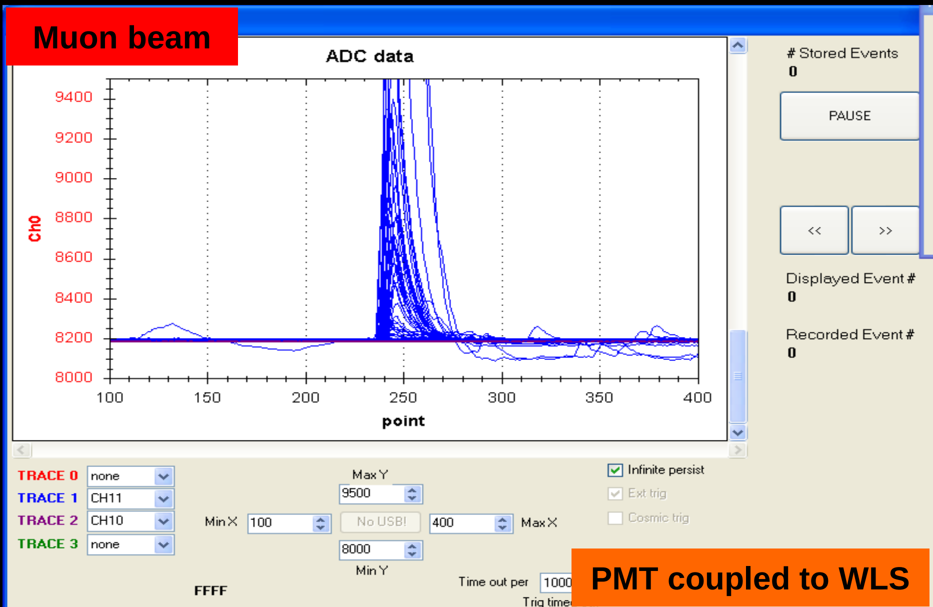


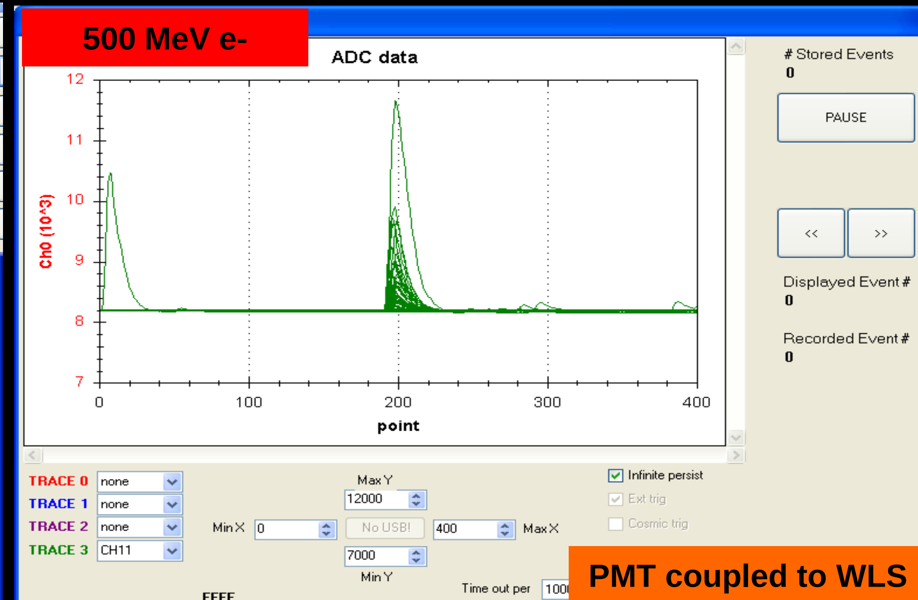


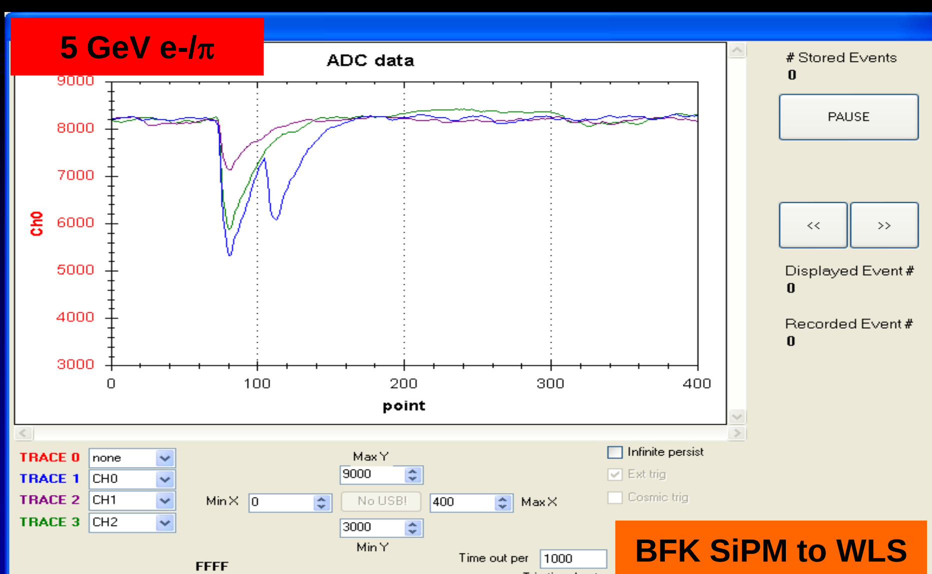
2012 Test Beam Setup at FTBF

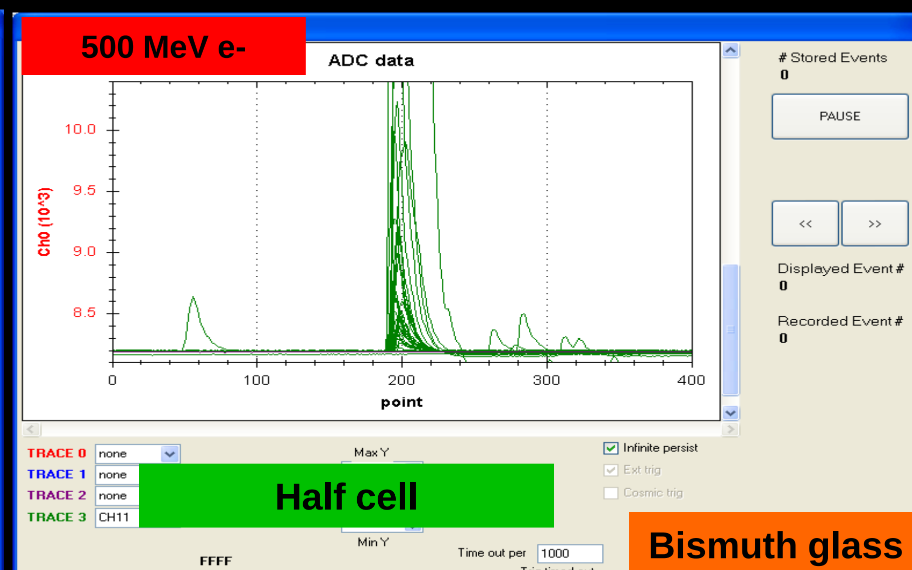


Waveforms from TB4 DAQ (FNAL)



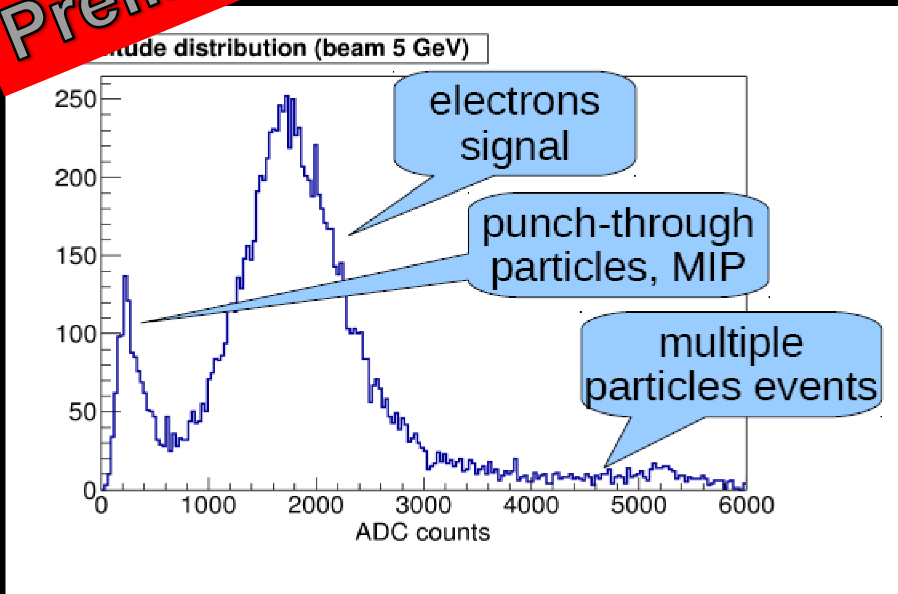


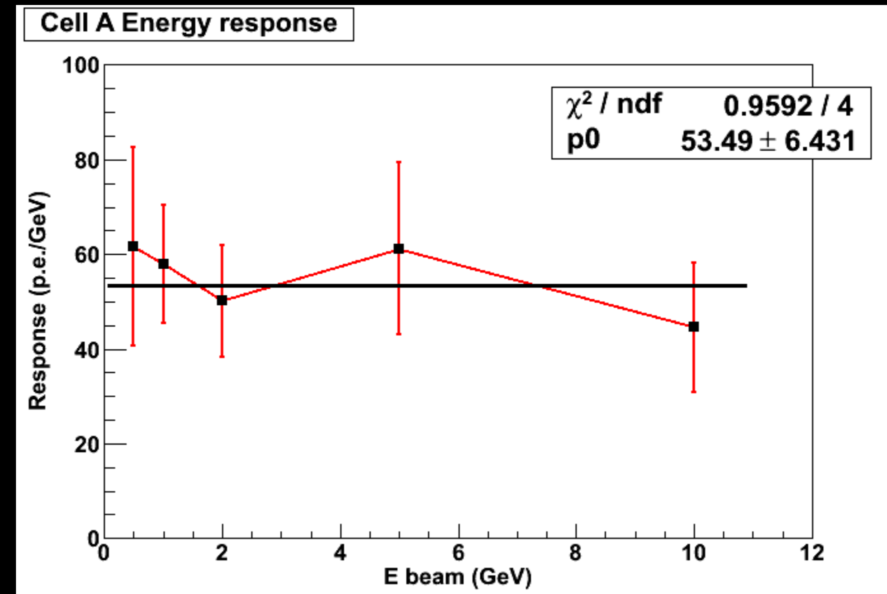


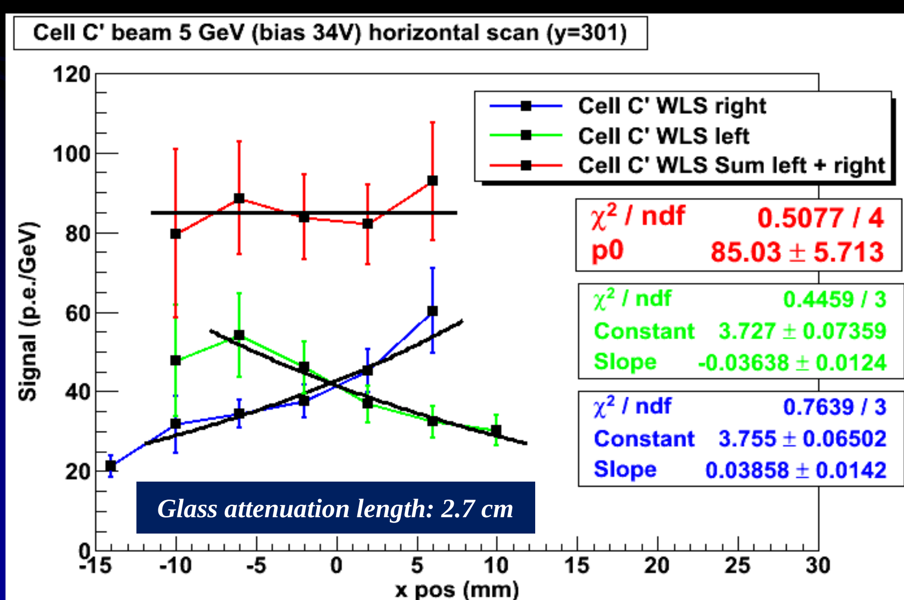


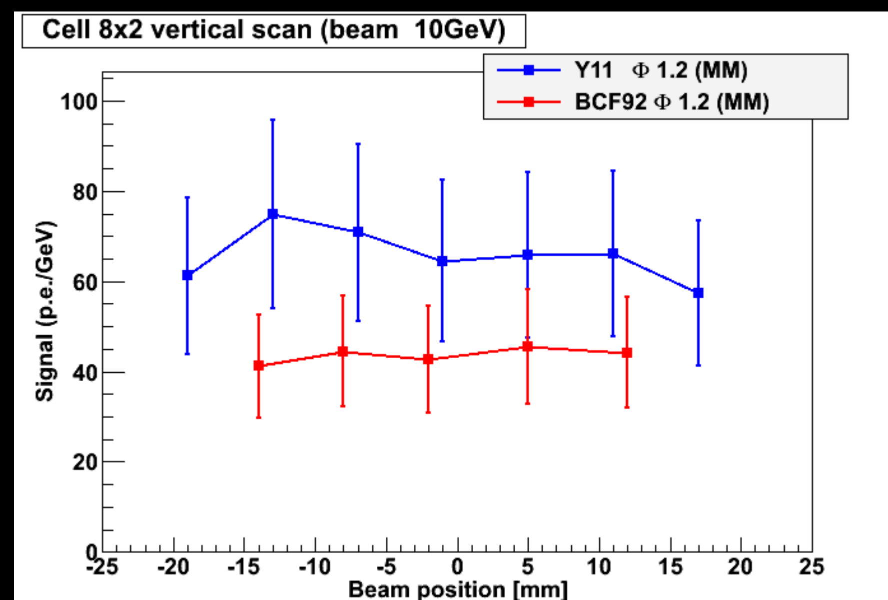
Detector Response Uniformity

Preliminary









Preliminary

11 Prototypes Performance Summary

Prototype	Glass	gr/cm^3	L. Y.	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 wrap	**Ohara BBH1**	**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 wrap, ungrooved, polished	**Schott SF57HHT**	**5.6**	158	Small wls groove
2 slices, plain, white wrap	**Ohara 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

Next: New Glasses R&D in T1015

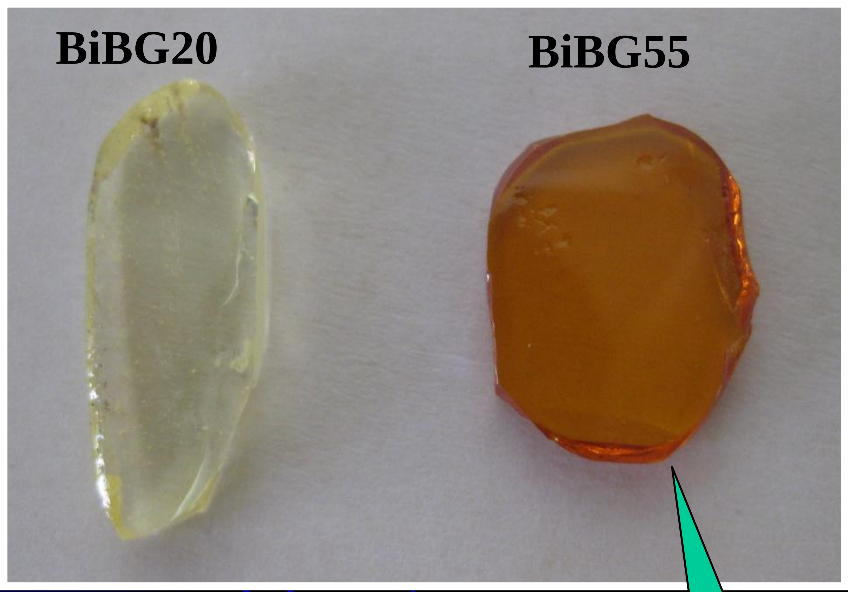
- **Research mostly carried at Department of Materials and Environmental Engineering at Uni-Modena (Italy)**
- Heavy glasses with ***no-Pb*** (Cerenkov only)
  - Mostly ***Bi*** based (heavier, less environmental issues, higher n_D, lower softening point for molding)
  - WO_2 under study (just purchased a 1600 °C furnace)
  - Goal is >8 gr/cm^3
- Rare earths doped scintillating heavy glasses:
  - Ba-Bi-B matrix to accomodate Ce_2O_3 :
  - Density achieved up to now: 7.5 gr/cm^3 (see next slide)
  - Several rare earth oxides tested: Dy_2O_3 promising
  - Lithium content for neutron sensitivity
- Organic scintillator doped heavy glasses:
  - Requires low melting point glass matrix (< 500 °C)
  - Currently under R&D at DIMA: P-T-F-P glass (up to 5.8 gr/cm^3)

See D. Groom talk at CALOR2012

Bismuth Borate Glasses BiB-G

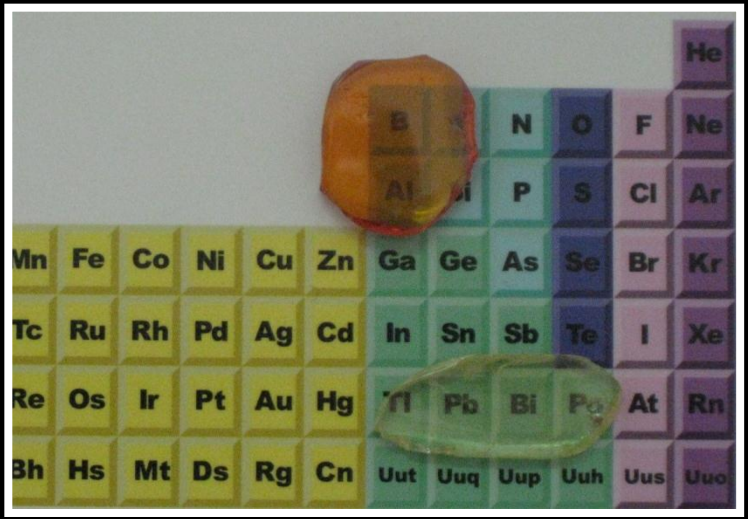
Goal *High density glasses by melt quench method*

- *Two compositions (BiBG20 and BiBG55) with different Bi_2O_3 content*



Bi_2O_3 mol% →

Dark color due to Bi_2O_3 not pure enough



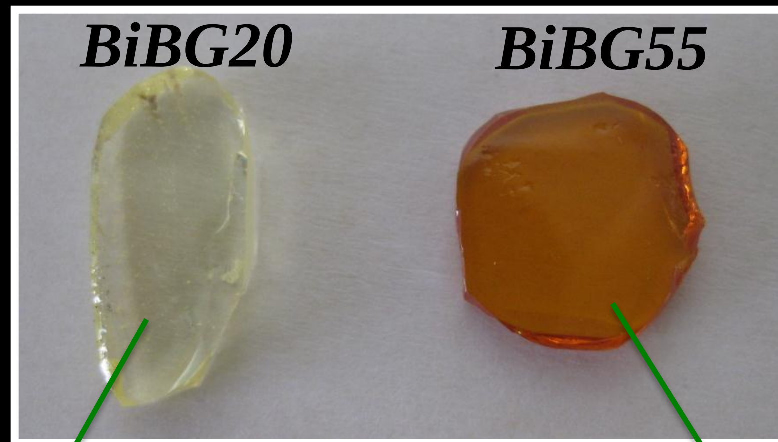
DENSITY

Glass	ρ (g/cm³)
BiBG 20	4.57
BiBG 55	7.48

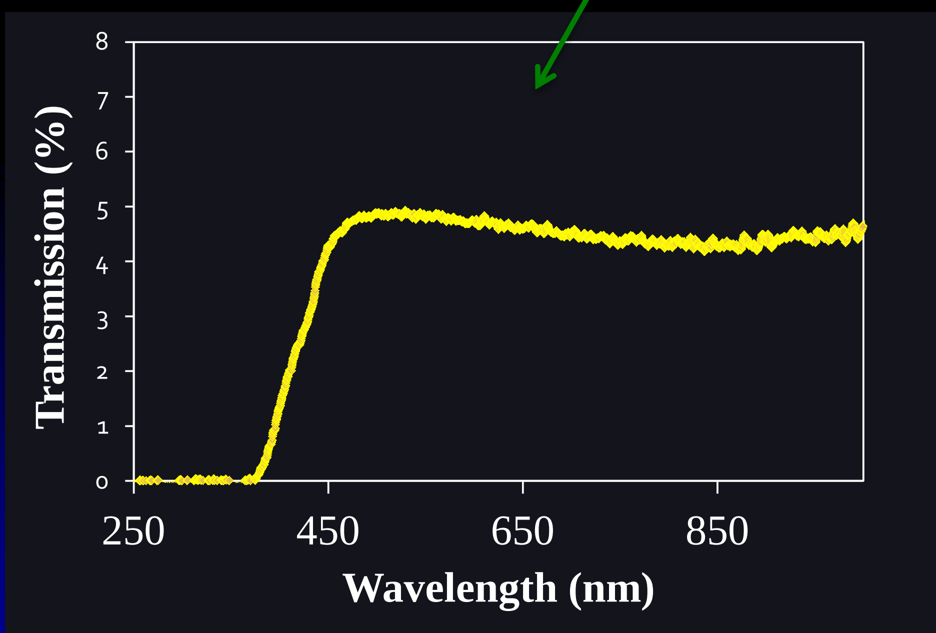
exp.error ± 0.01

Consuelo Mugoni

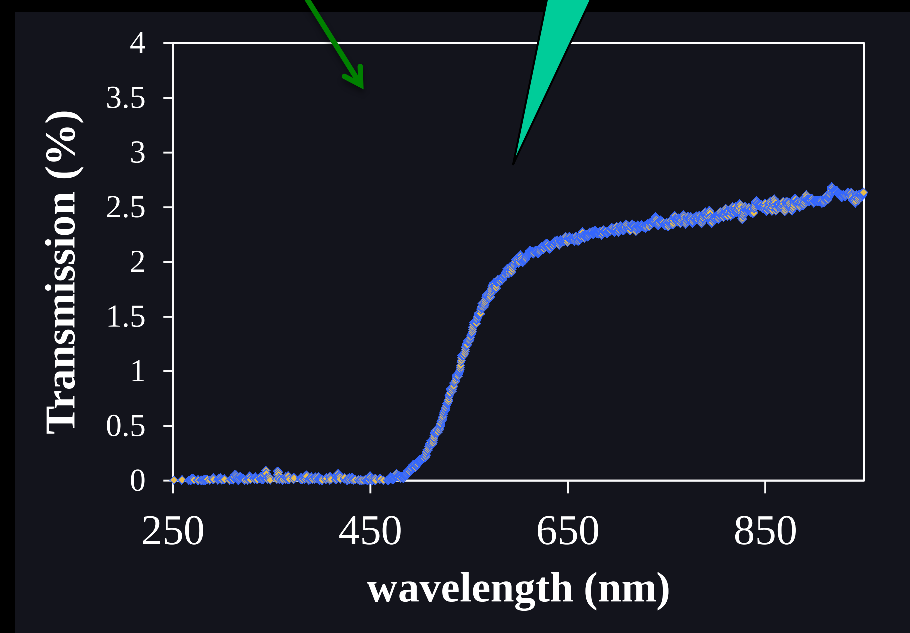
Transmission Spectra



No absorption bands



thickness c.a 0.3 cm

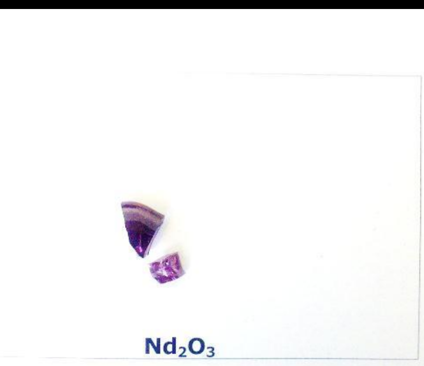


thickness c.a 0.3 cm

Consuelo Mugoni

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

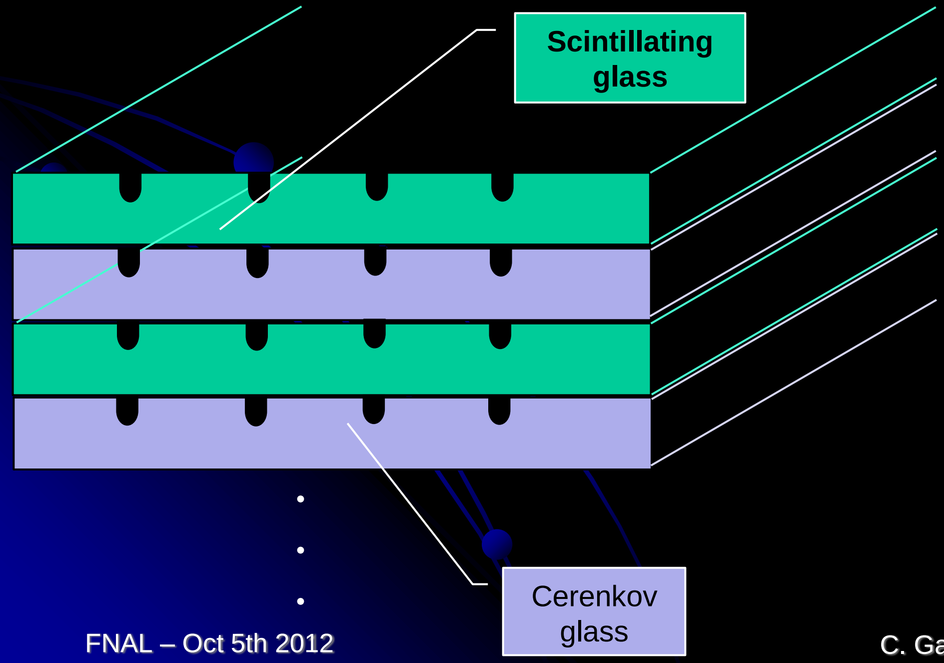


Composition	Density (g/cm^3)
CeO_2	3,3776
Pr_6O_{11}	3,7445
Dy_2O_3	3,8851
Er_2O_3	4,0690
Nd_2O_3	4,2441

Department of Materials and Environmental Engineering

ADRIANO II: aka Glass-only ADRIANO

- Advantages:
  - No density dilution from scifi plastic
  - **Excellent EM calorimeter**
  - Easier to build
  - Cheaper (scifi are expensive!)
  - Requires Li or H in the glass (see D. Groom talk at CALOR2012)



SCG1- tested at FTBF

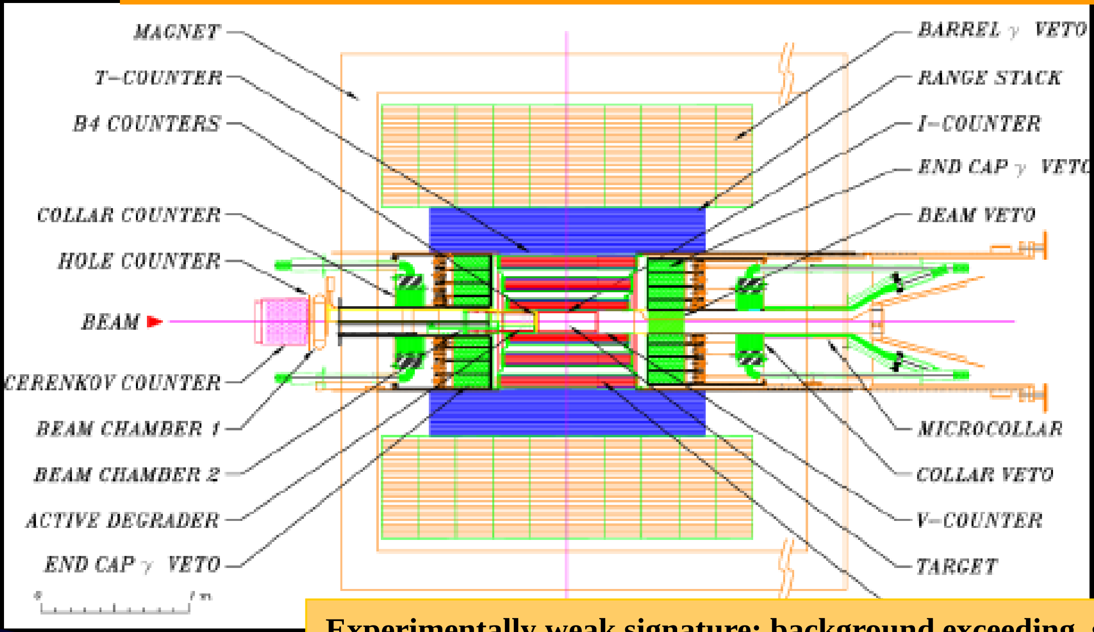
Light yield: > 600 pe/Gev (FEE saturating)

Future Prospects & Conclusions

- **Cerenkov ligth yield more than adequate for 30%/sqrt(E) calorimetry. Our goal is to make it even better for EM calorimetry**
- Precision molding is (at present) the preferred construction technique: two molds (37 cm long) under construction (flat and grooved)
- **Year 2013 program:**
  - 14cm x 14cm x 74cm ADRIANO module (total 18 cells)
  - 9.2 cm x 4.6 cm x 37 cm module with scintillanti plates
  - 9.2 cm x 4.6 cm x 37 cm S+C module (for ORKA experiment)
  - Test beam of scintillating glass module
- **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 tested in 2012 at FNAL
  - 7.54 gr/cm^3 ; n_d = 2.24
- ***ADRIANO*2 (Cerenkov + scintillating glass)**
- **Heading toward a large prototype**
  - 1,800 PMT appropriated from CDF
  - 2 ton SF57 left from NA62 calorimeter construction

ADRIANO for ORKA: 50T Prototype

$K^+ \rightarrow \pi^+ \nu\nu$ decay at Main Injector with 1000 events sensitivity



- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in range stack
- Veto photons, charged tracks

Experimentally weak signature: background exceeding signal by $>10^{10}$

ORKA Critical Experimental Issue

- Proposed Photon Veto based on Shashlik calorimeter
  - About 2/3 of energy lost in Pb absorber
  - Need to set threshold at 1pe
  - No energy measurement

- Estimated accidental losses based on E949:

$$\mathcal{S} = e^{\lambda(R_{\mathrm{ORKA}} - R_{\mathrm{E949}})}$$

- Using: λ = -0.345/MHz, R_{ORKA}=, 26.2 MHz R_{E949}=8.4MHz

$\mathcal{S} = 0.54$ with respect to E949

Backup Slides

Overcoming the Limitations of a 2-D Calorimeter

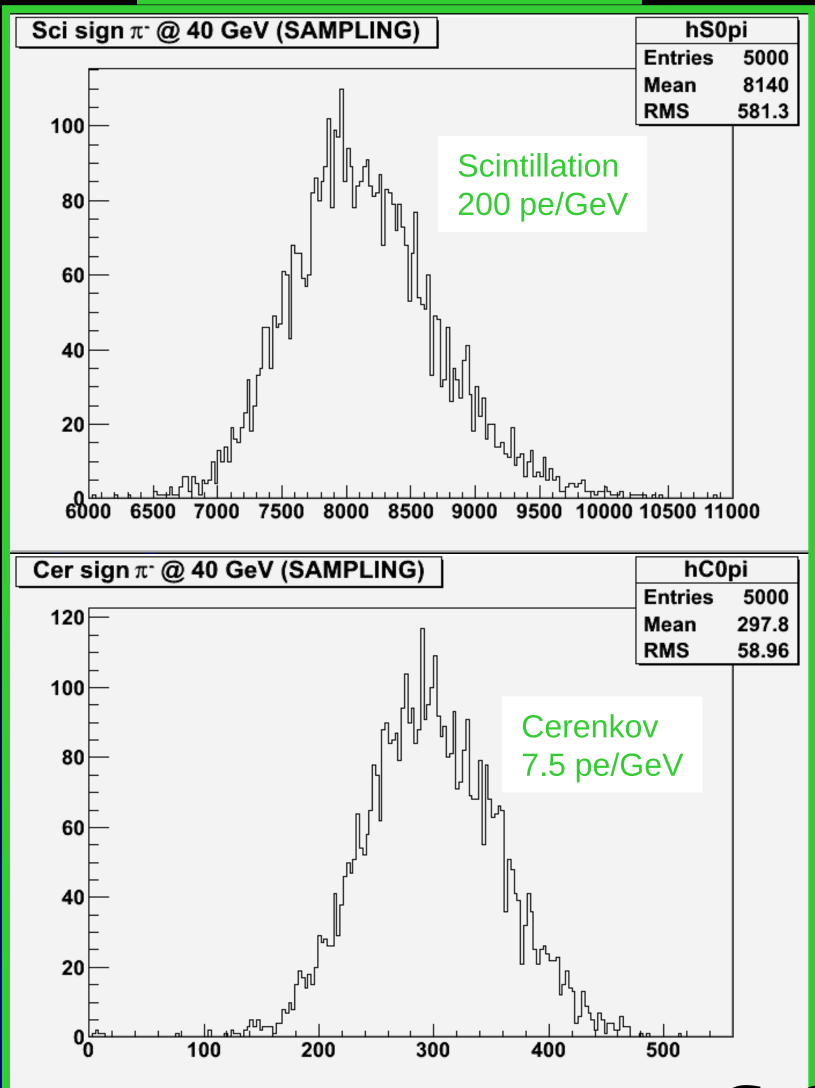
- ***ADRIANO* is a 2-D calorimeter**
  - Easier to build and to calibrate
  - Fewer number of channels
  - No cracks nor unhomogeneities due to longitudinal segmentation

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

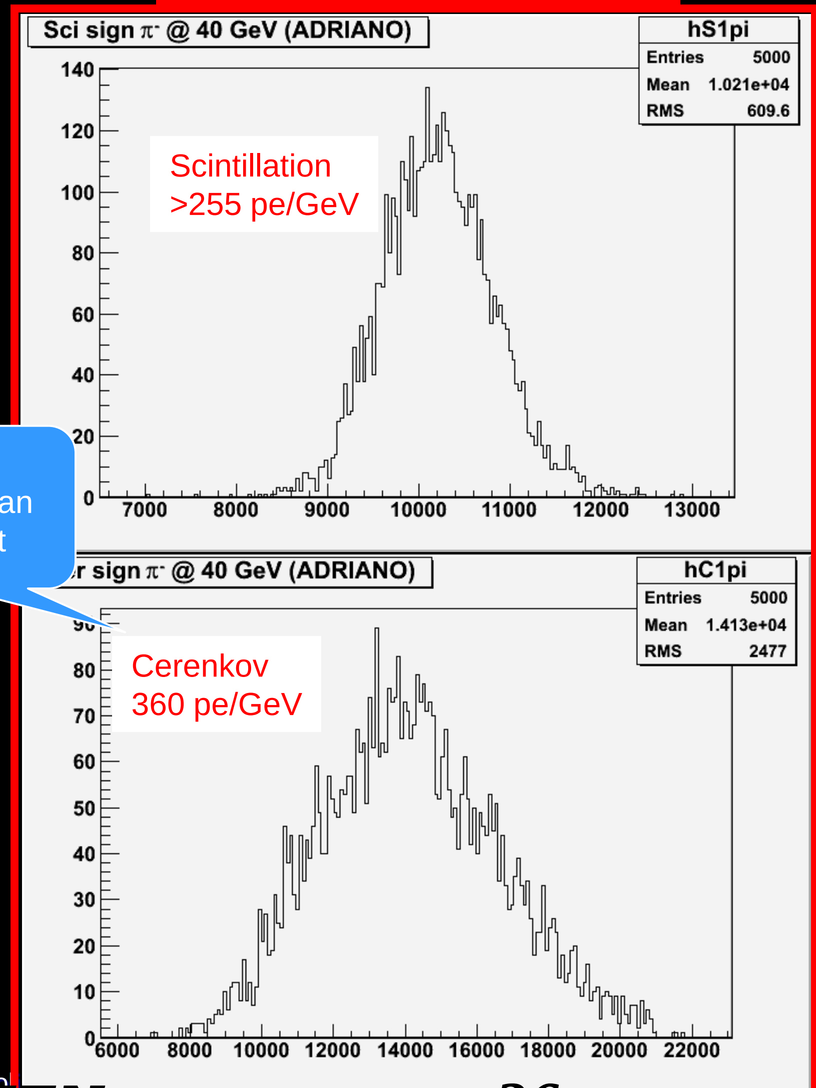
ILCroot simulations

Photon yield:
Sampling vs Integrally Active

Sampling Calorimeter



ADRIANO Calorimeter



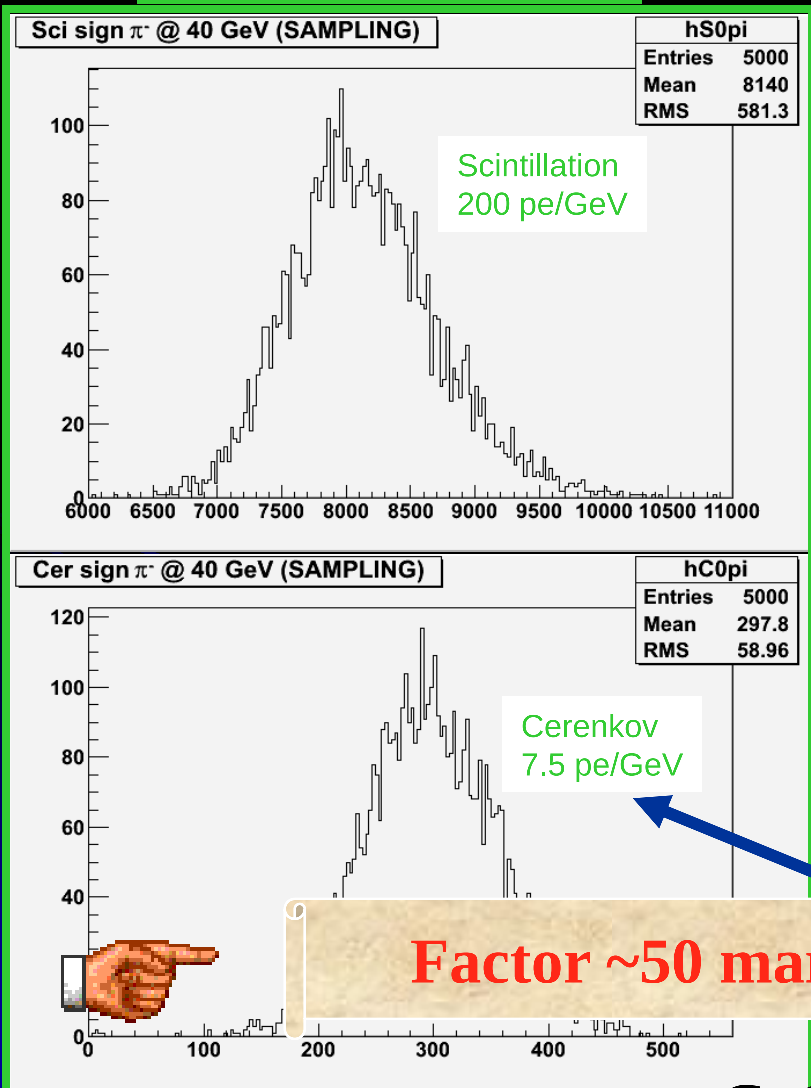
To be considered an upper limit

40 Gev pions

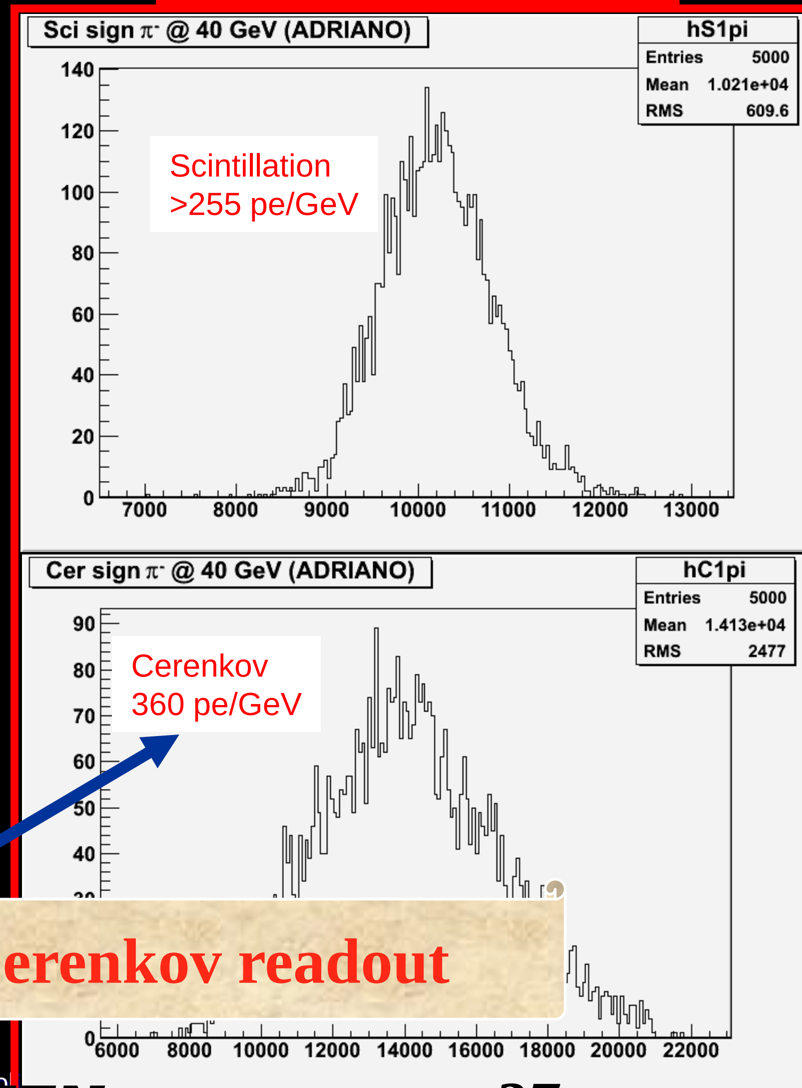
ILCroot simulations

Photon yield:
Sampling vs Integrally active

Sampling Calorimeter



ADRIANO Calorimeter



40 Gev pions

Factor ~50 margin in Cerenkov readout

Adding the 3rd Dimension info with light division methods

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

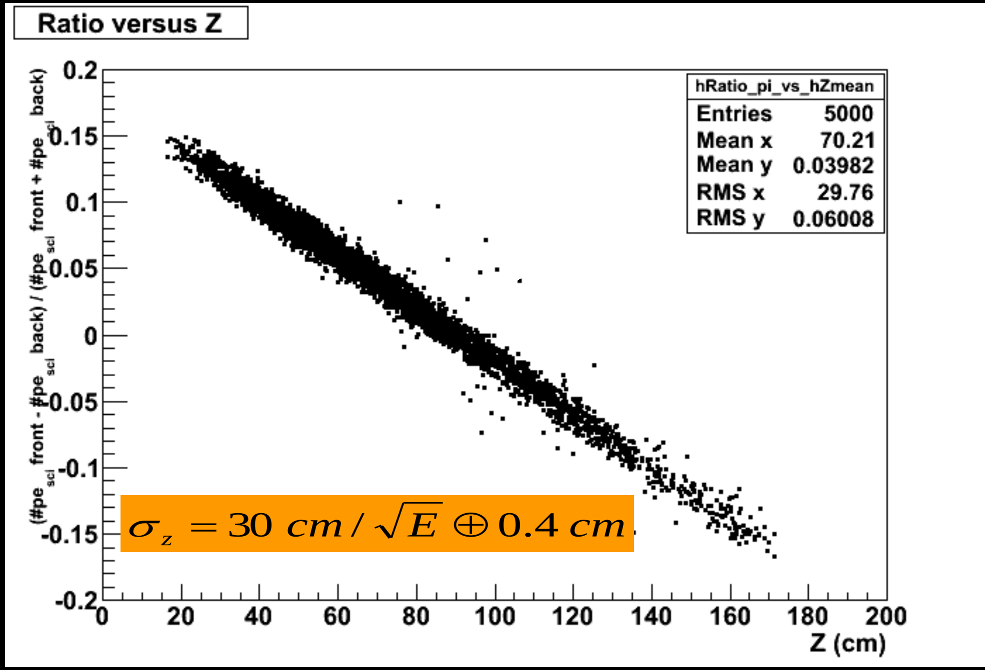
Instrumental effects included in ILCroot :

- 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.

ILCroot simulations

100 Gev pions

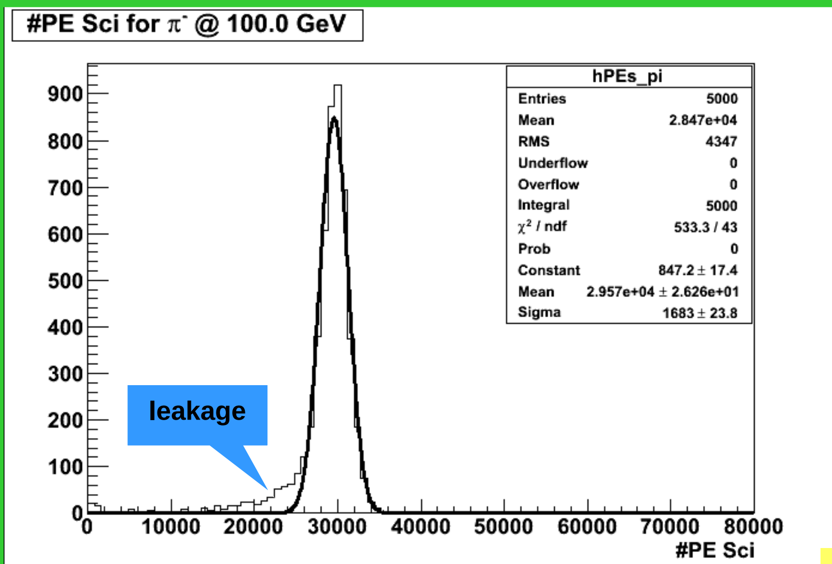
Front vs back Scintillation light vs true shower CoG

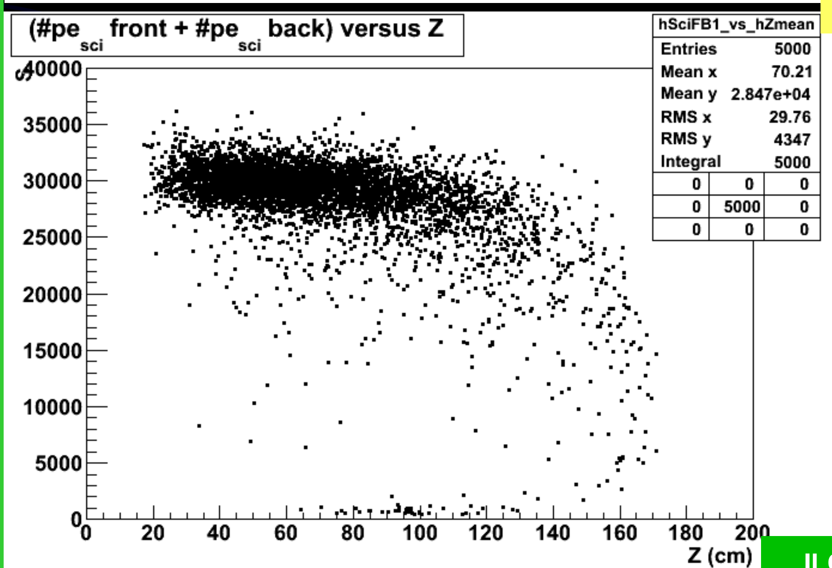


$$\sigma_z = 30\ cm / \sqrt{E} \oplus 0.4\ cm$$

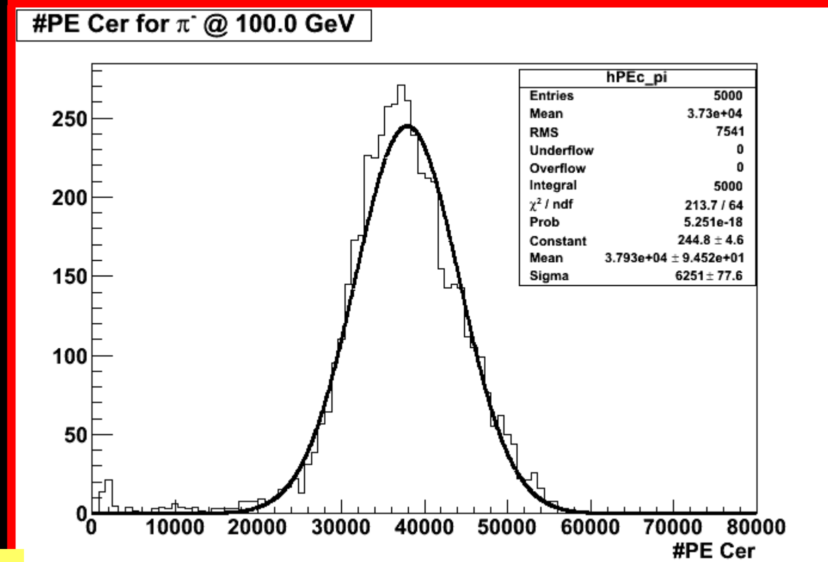
Leakage in 180 cm long *ADRIANO* module

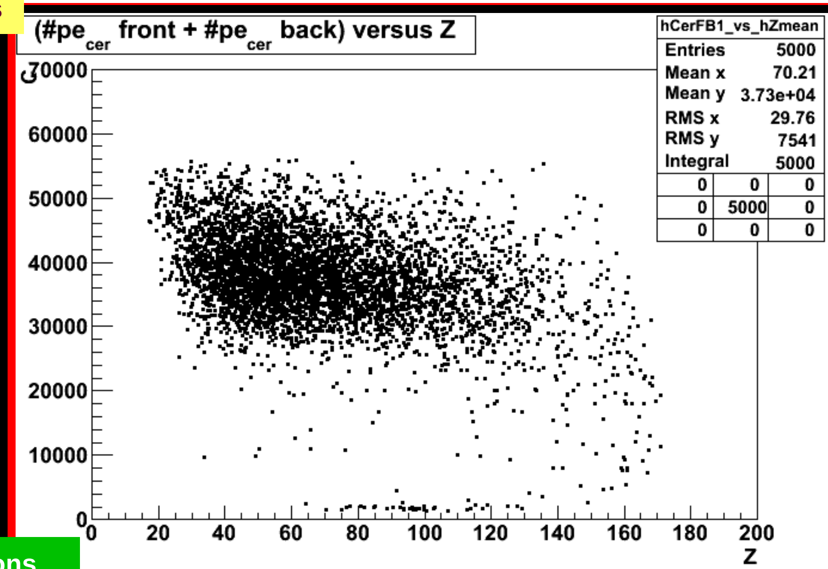
Uncorrected scintillating signal





Uncorrected Cerenkov signal



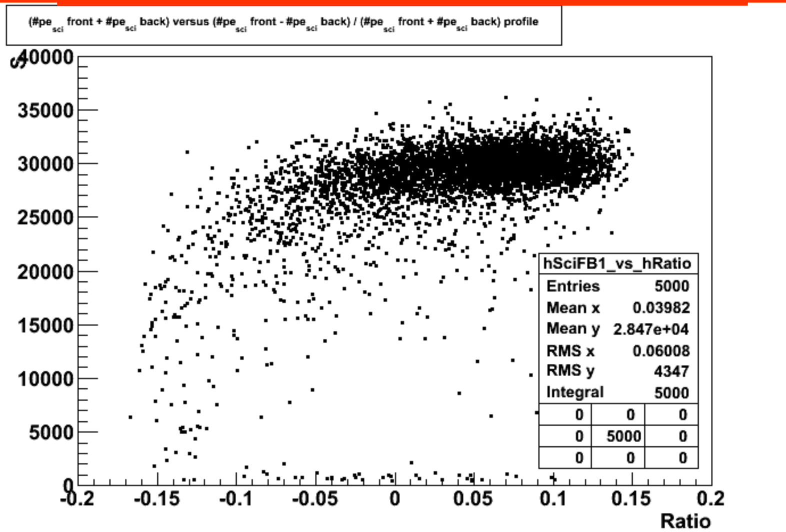


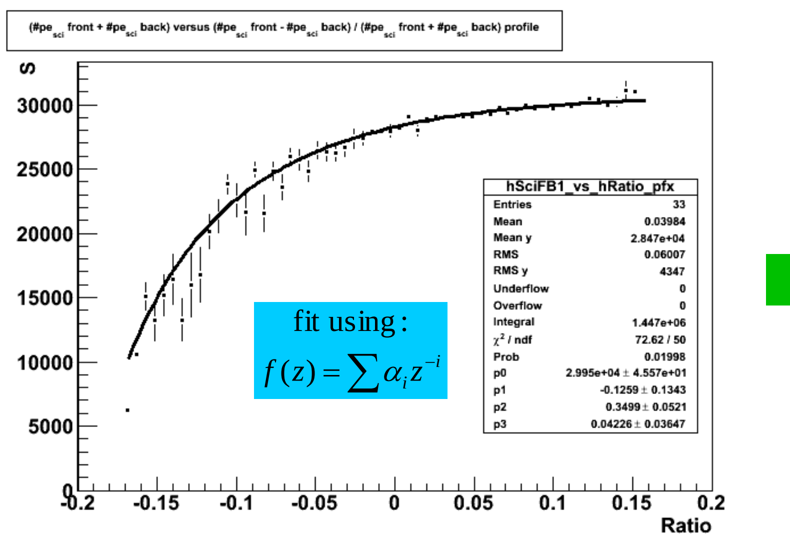
100 Gev pions

ILCroot simulations

Applying leakage corrections from CoG measured with a light division

Uncorrected scintillating signal

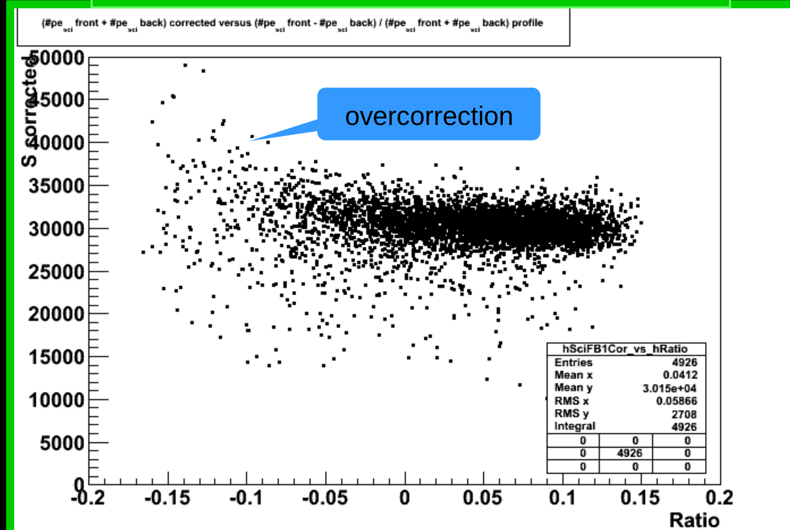


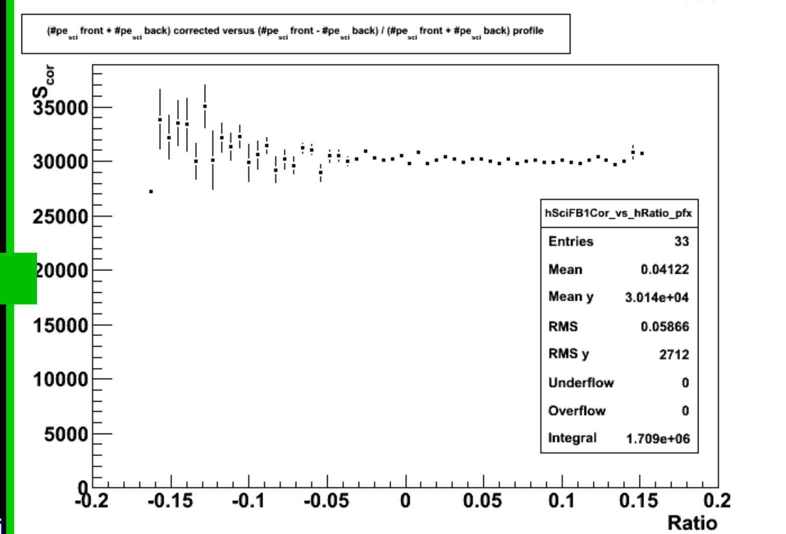


100 Gev pions

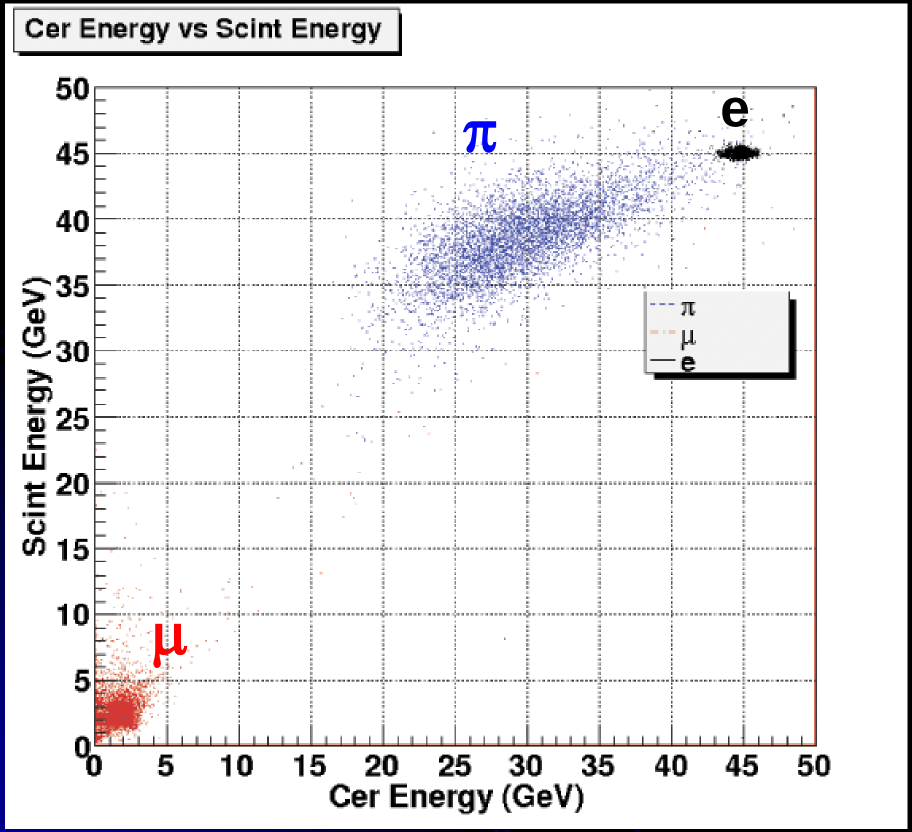
ILCroot simulations

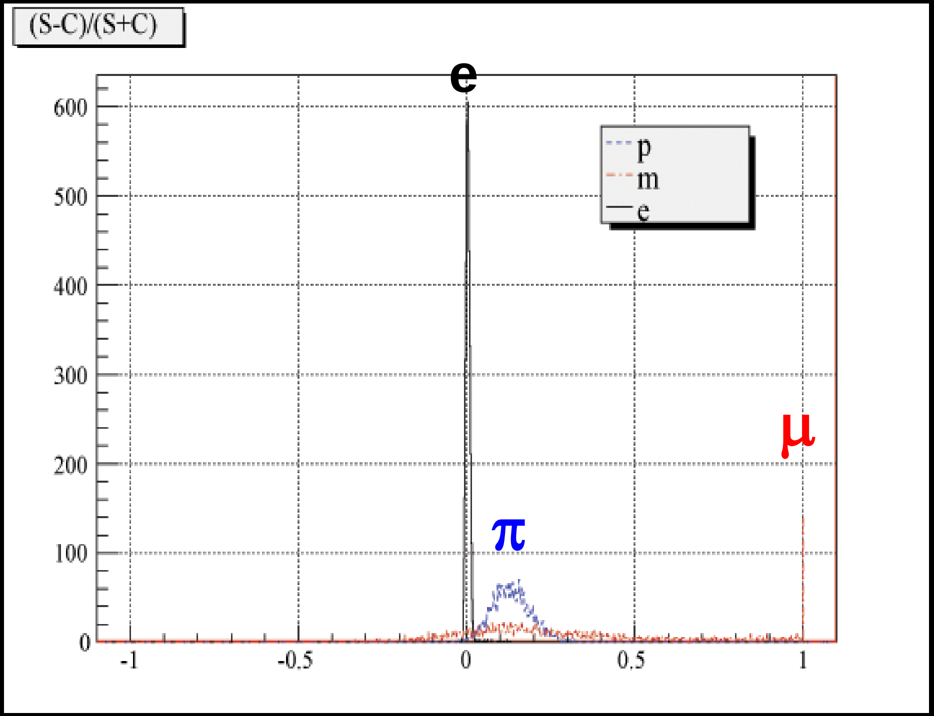
Corrected scintillating signal





Particle Identification in Dual Readout calorimeters

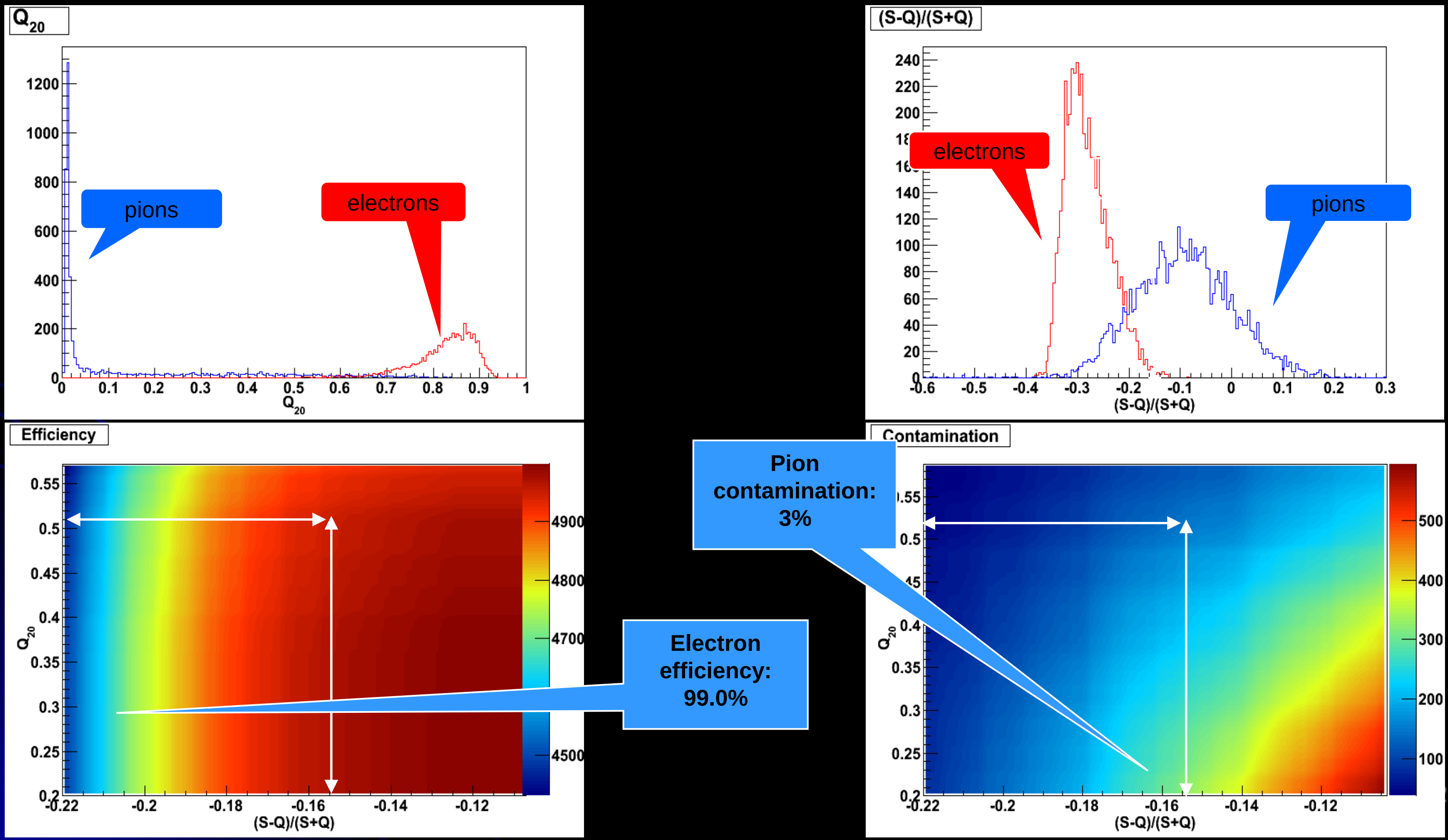




- 45 GeV particles

Identifying EM Showers in *ADRIANO*

- Use Q_{20} fibers and (S-Q)/(S+Q) to disentangle EM particles from hadrons
- Use $E_{Cerenkov}$ from heavy glass ONLY for EM showers



Calibration à la DREAM

- E_S and E_C for electron beam is equivalent to pion beam when *fem*=1

Step 1

$$\begin{cases} E_S = \left[fem + \dfrac{(1-fem)}{\eta_S} \right] \cdot E_{HCAL} \\ E_C = \left[fem + \dfrac{(1-fem)}{\eta_C} \right] \cdot E_{HCAL} \end{cases}$$

for electrons →

$$\begin{cases} E_S = E_{HCAL} \\ E_C = E_{HCAL} \end{cases}$$

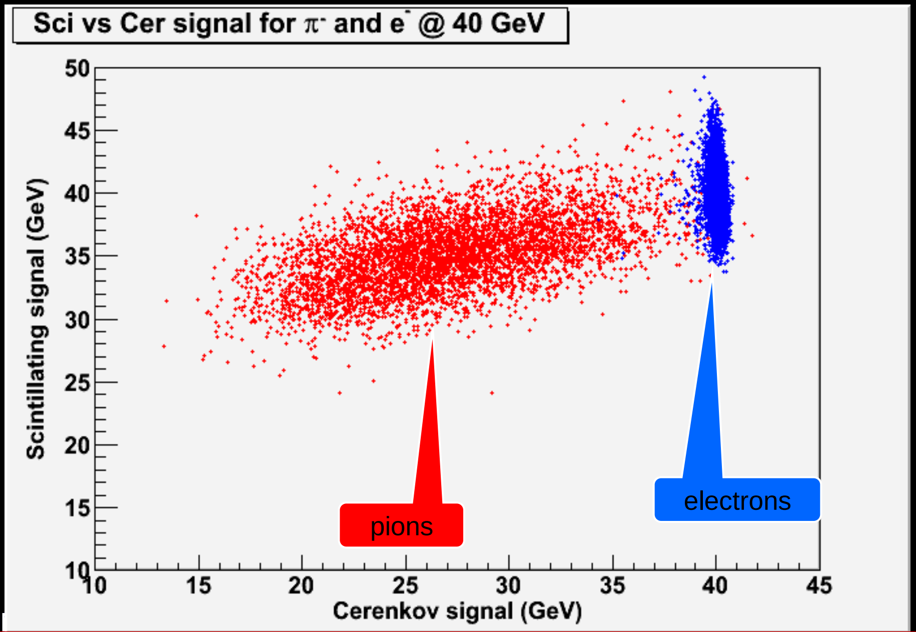
- Final calibration with pions:

  minimize

Step 2

$\chi^2(E_{HCAL} - E_{beam})$

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$



Calibration à la TWICE

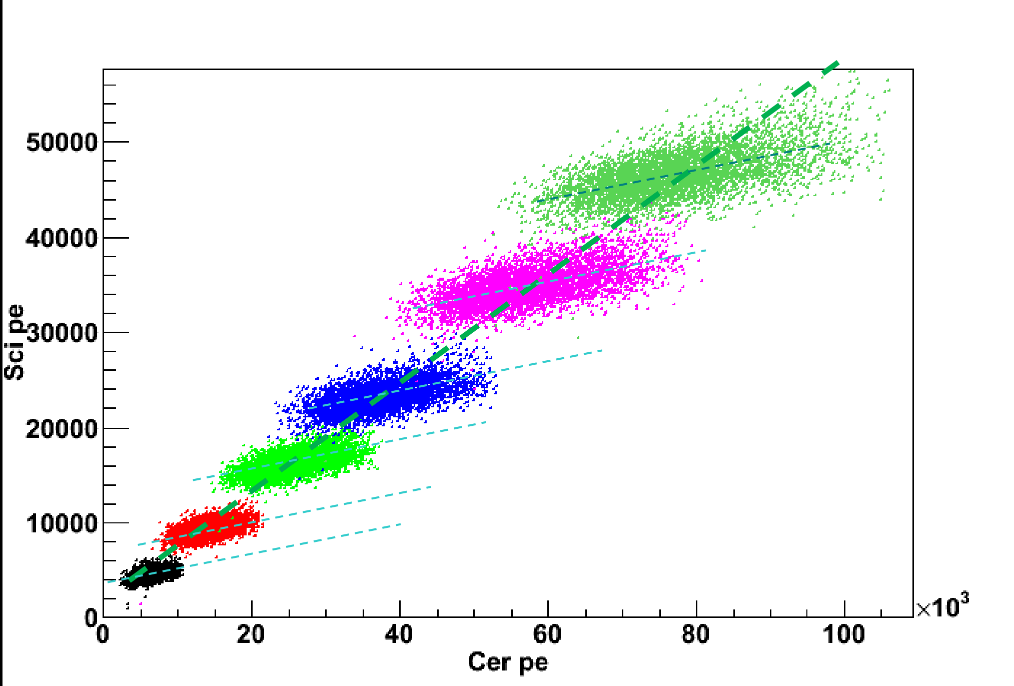
- Take advantage of the fact that η_S and η_C are expected to be (almost) energy independent
- Use a sample of *n* pions of **ANY** known energy
- For the *i-th* pion rewrite the dual readout equation as:

$$\frac{\hat{S}_i}{E_i} = \alpha - \beta\frac{\hat{Q}_i}{E_i}.$$

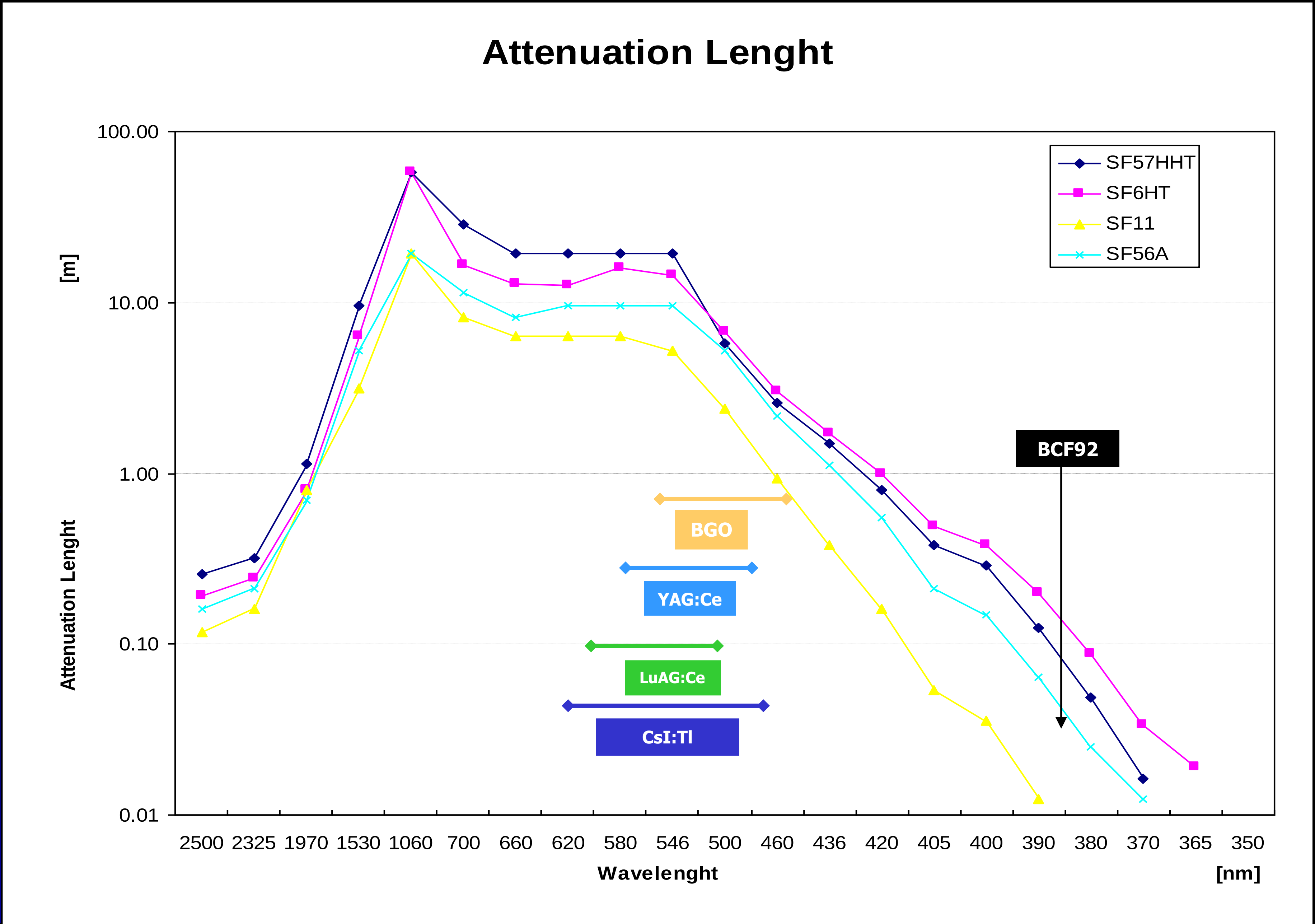
- Then, from LR analysis

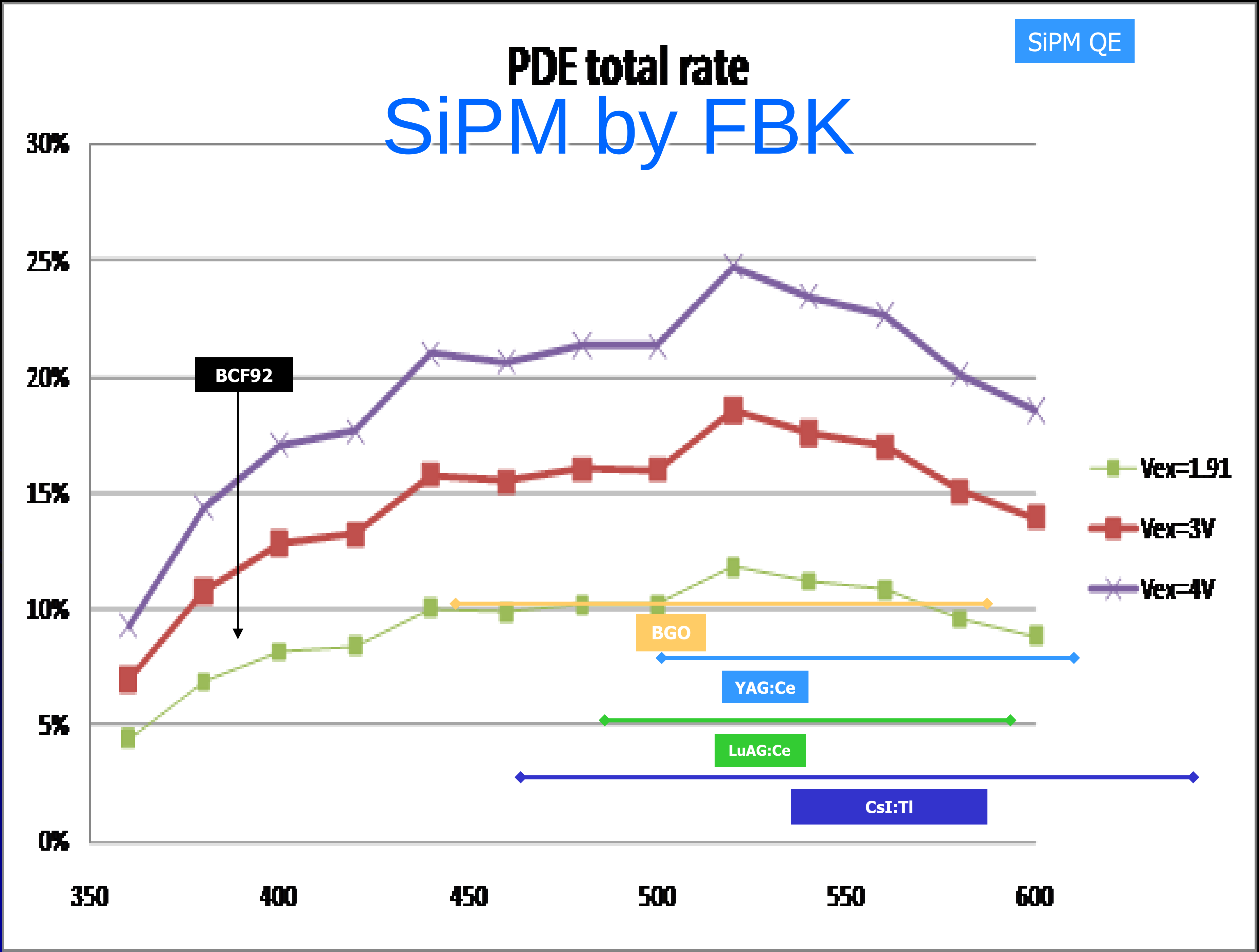
$$\beta = \frac{\sum_1^n(\hat{Q}_i/E_i)(\hat{S}_i/E_i) - 1/n\sum_1^n(\hat{Q}_i/E_i)\sum_1^n(\hat{S}_i/E_i)}{\sum_1^n(\hat{Q}_i/E_i)^2 - 1/n(\sum_1^n\hat{Q}_i/E_i)^2}$$

$$\alpha = 1/n\sum_1^n(\hat{S}_i/E_i) - \beta/n\sum_1^n(\hat{Q}_i/E_i)$$



Integrally absorbing calorimetry with SF glass and crystals

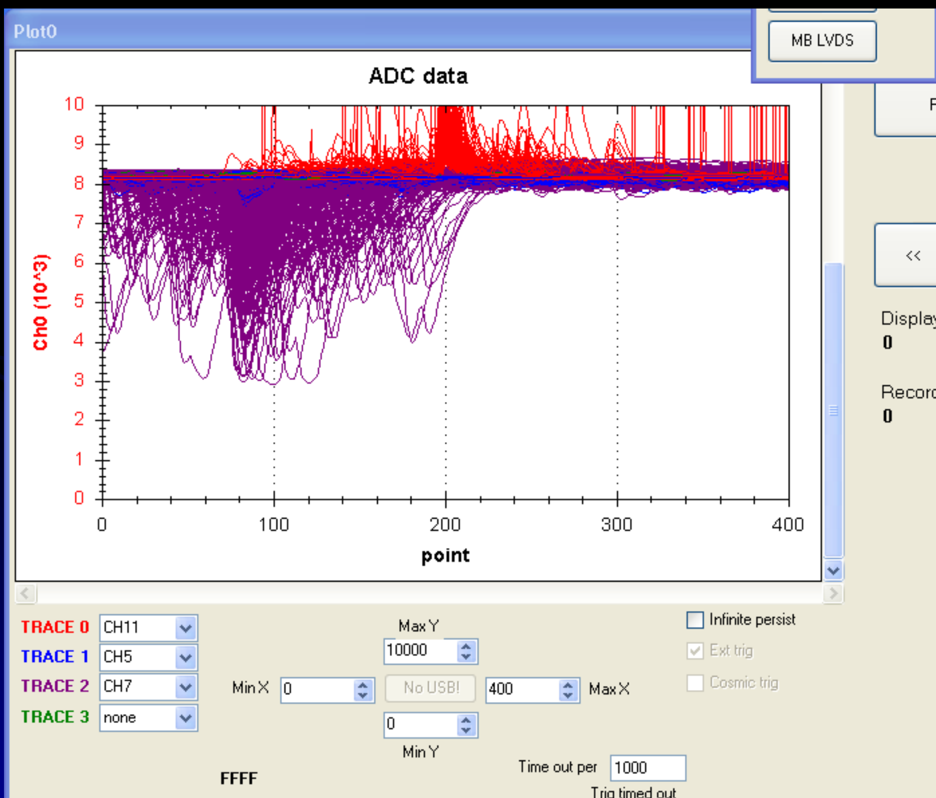


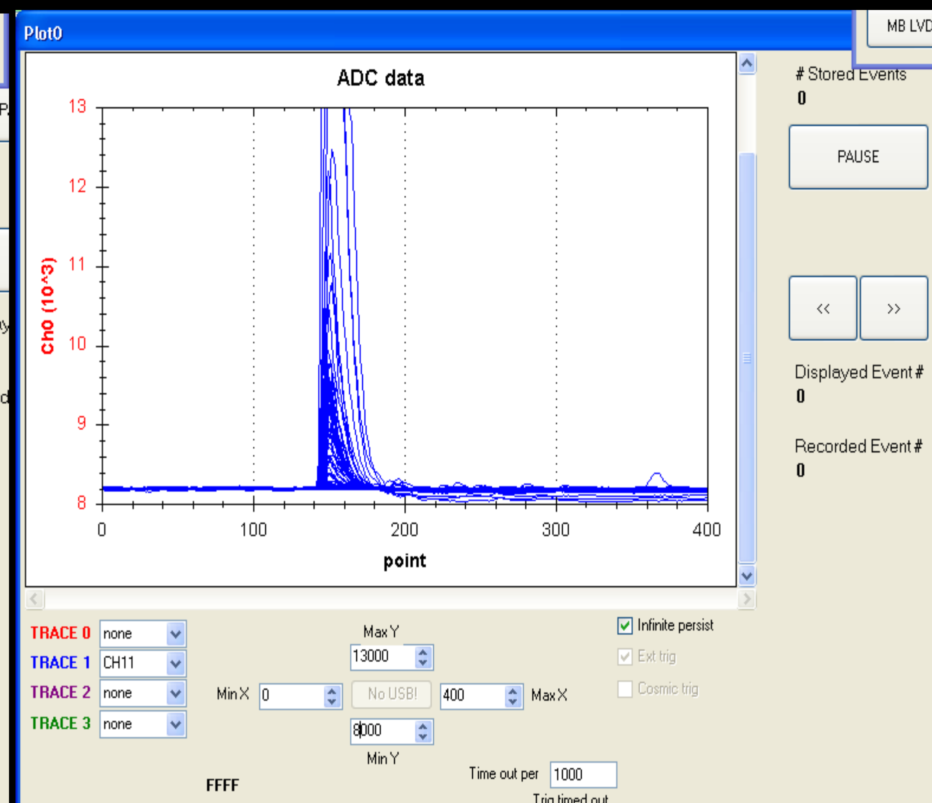

SiPM QE
PDE total rate
SiPM by FBK
30%
25%
20%
15%
10%
5%
0%
350
400
450
500
550
600
BCF92
BGO
YAG:Ce
LuAG:Ce
CsI:Tl
Vex=1.91
Vex=3V
Vex=4V

Waveforms from TB4 DAQ:

SiPM with W.C. light concentrator (by G. Sellberg) vs PMT

5 Gev e/π beam



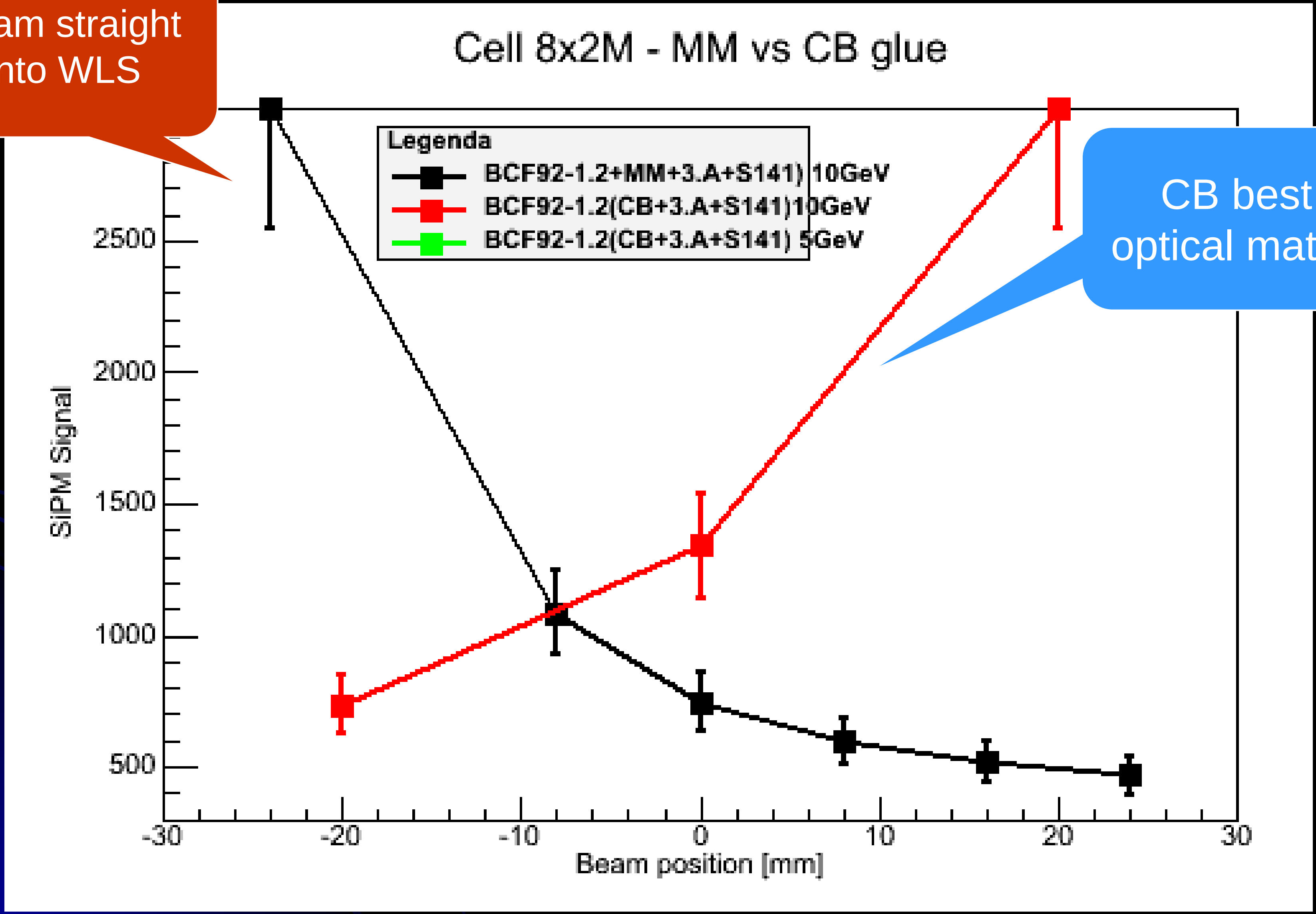


Preliminary results

Comparing different glues

Beam straight into WLS

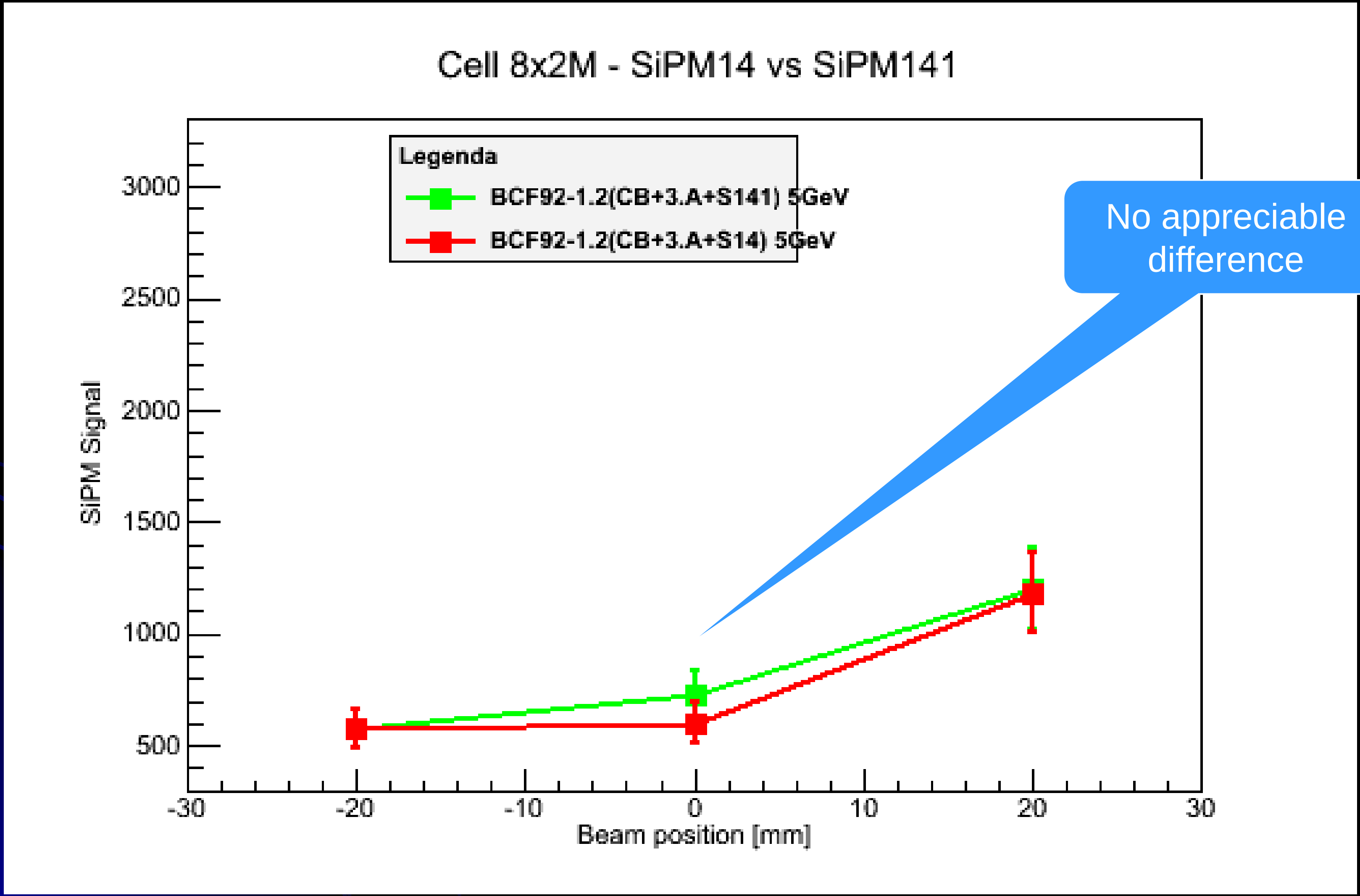
CB best optical match



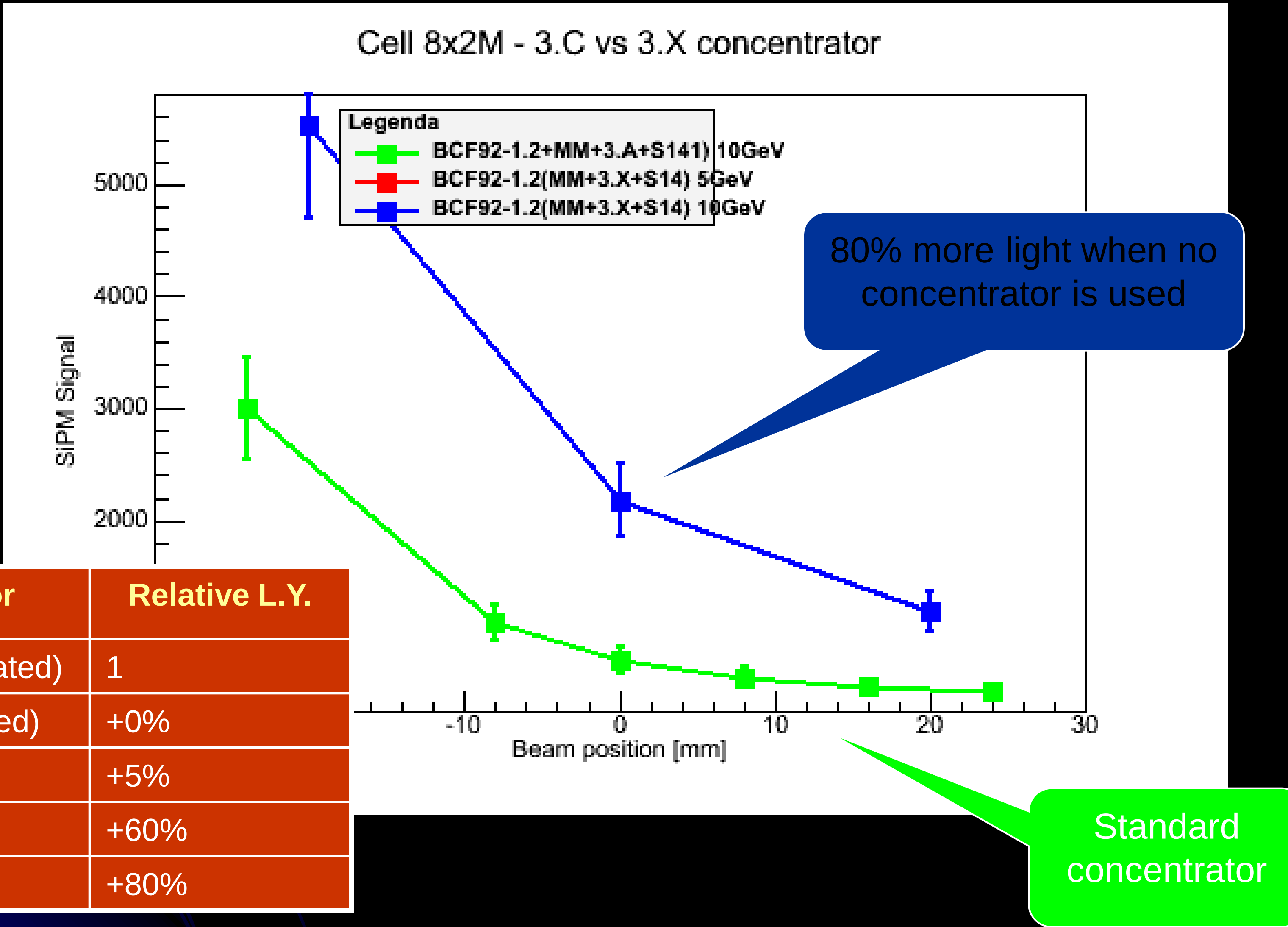
Preliminary results

Comparing different SiPM

2.8 mm round vs 4x4mm^2 square



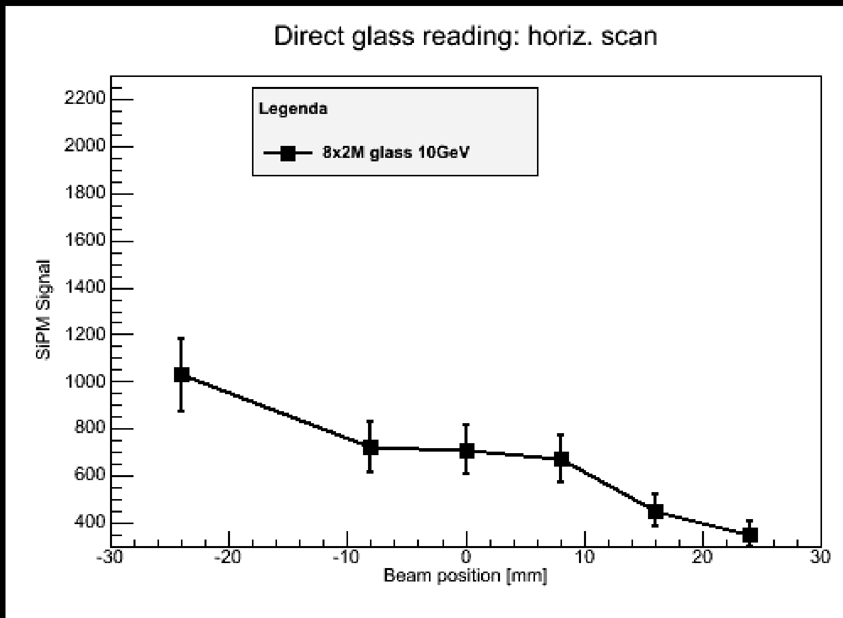
Comparing different Light Concentrators

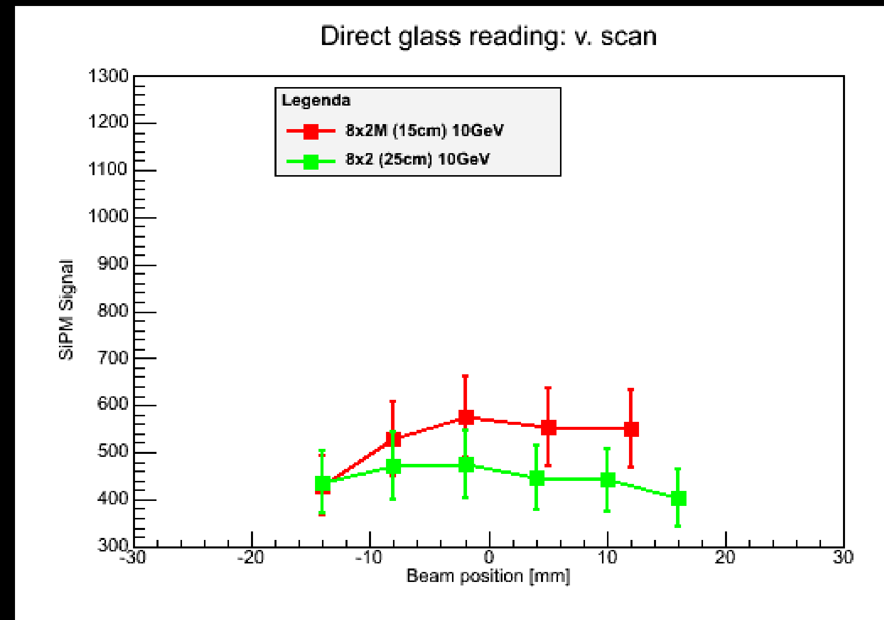


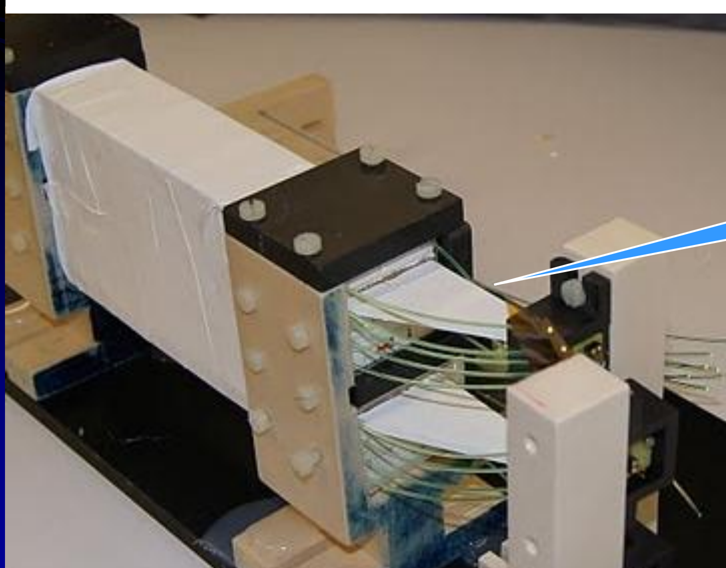
Concentrator	Relative L.Y.
Original (TiO_2 coated)	1
Original (Ag coated)	+0%
super polished	+5%
Winstone cone	+60%
none	+80%

Preliminary results

Fiber Readout vs Direct Glass Readout





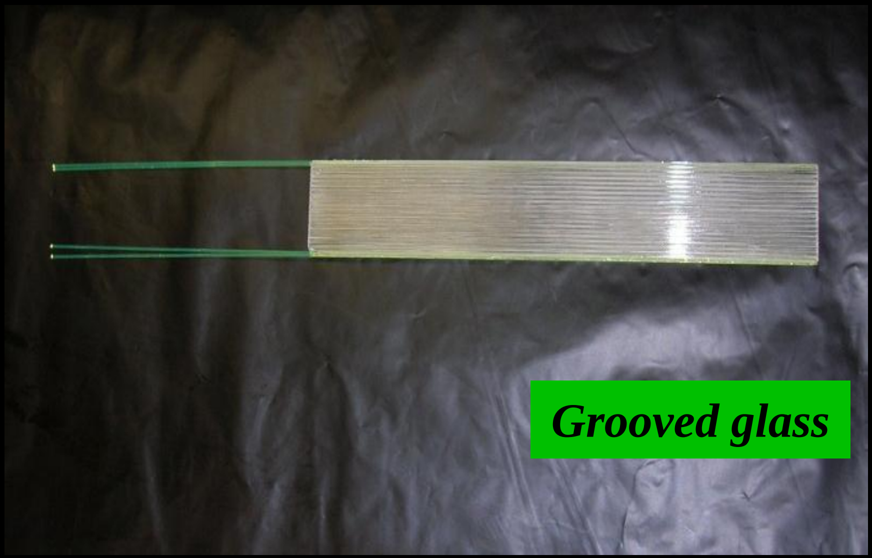


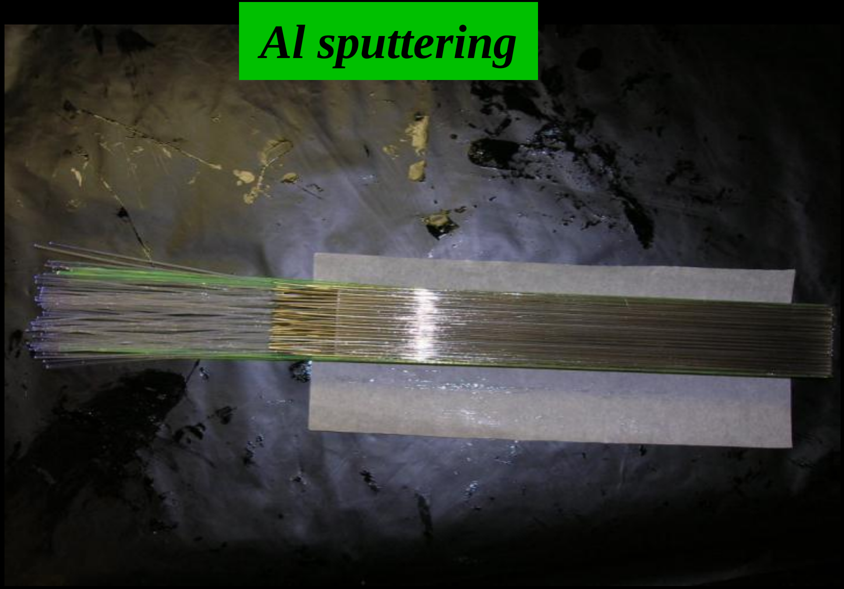
Only ~16% of Cerenkov light is collected

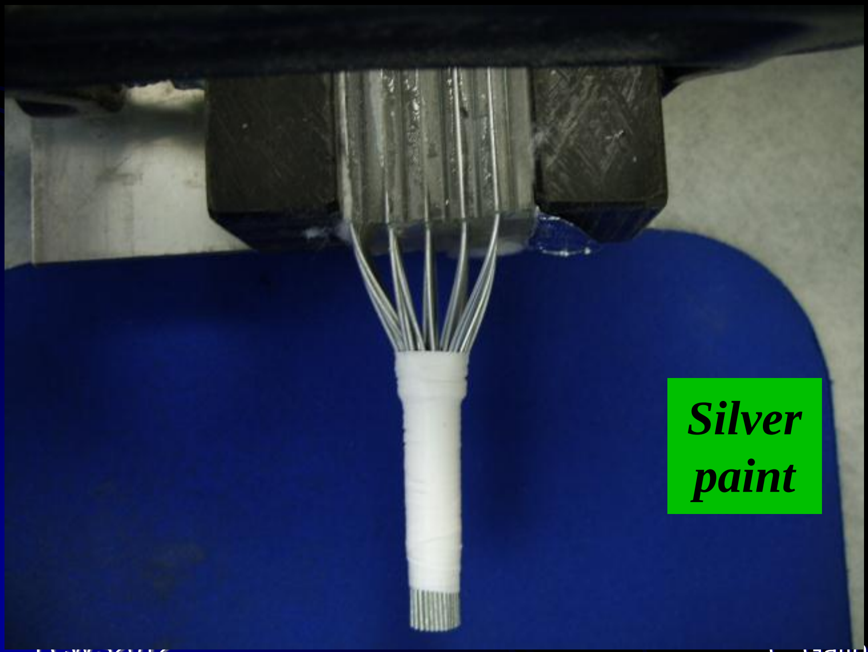
~73% more light collected by directly reading the glass

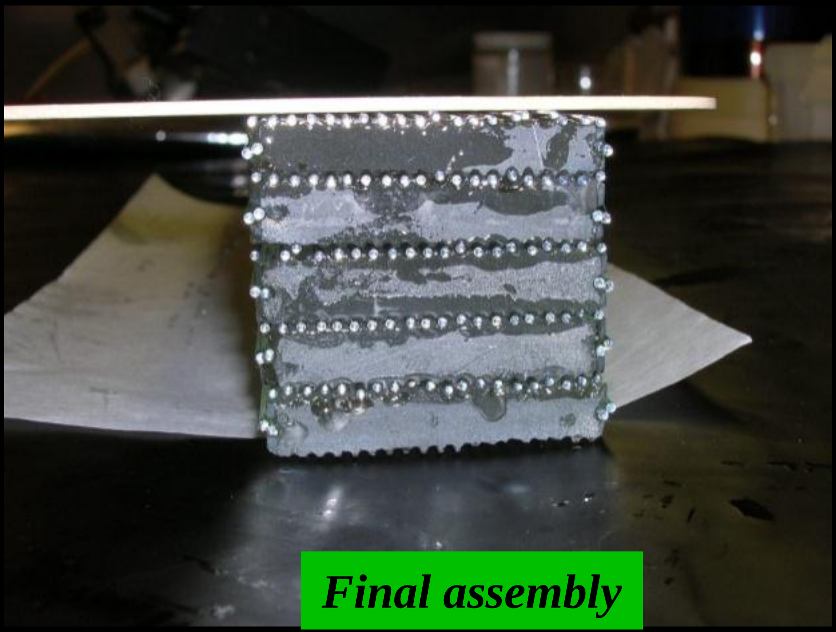
~2 cm longitudinal attenuation length

Aluminized Scifi Variant

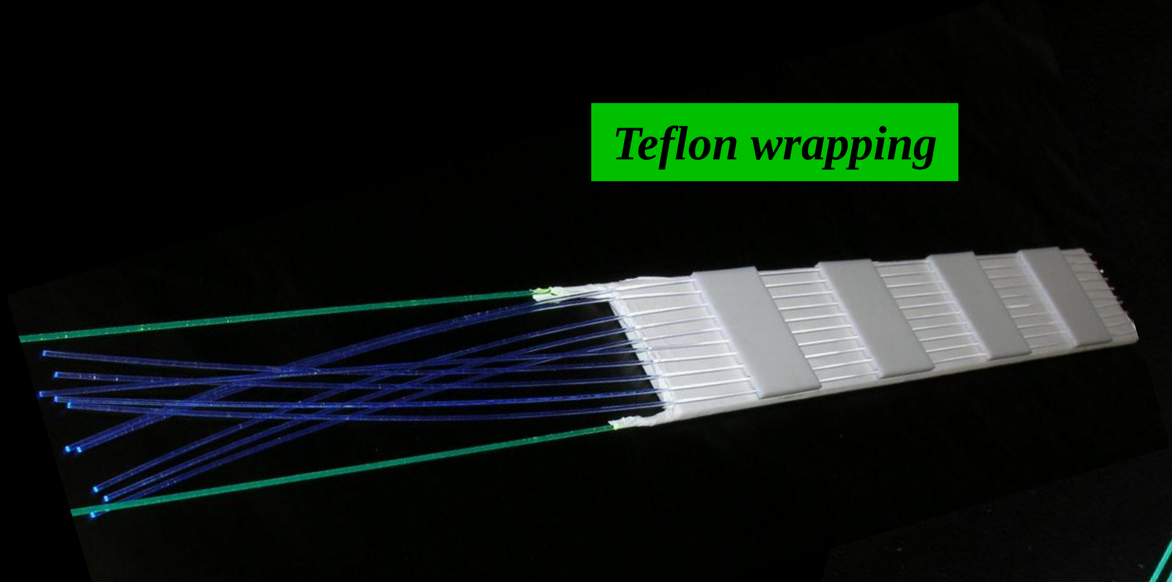




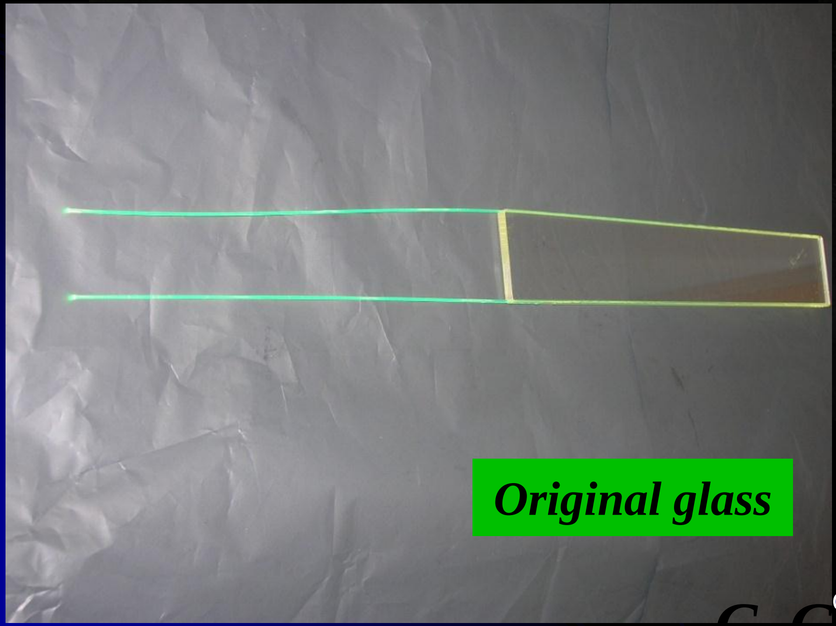




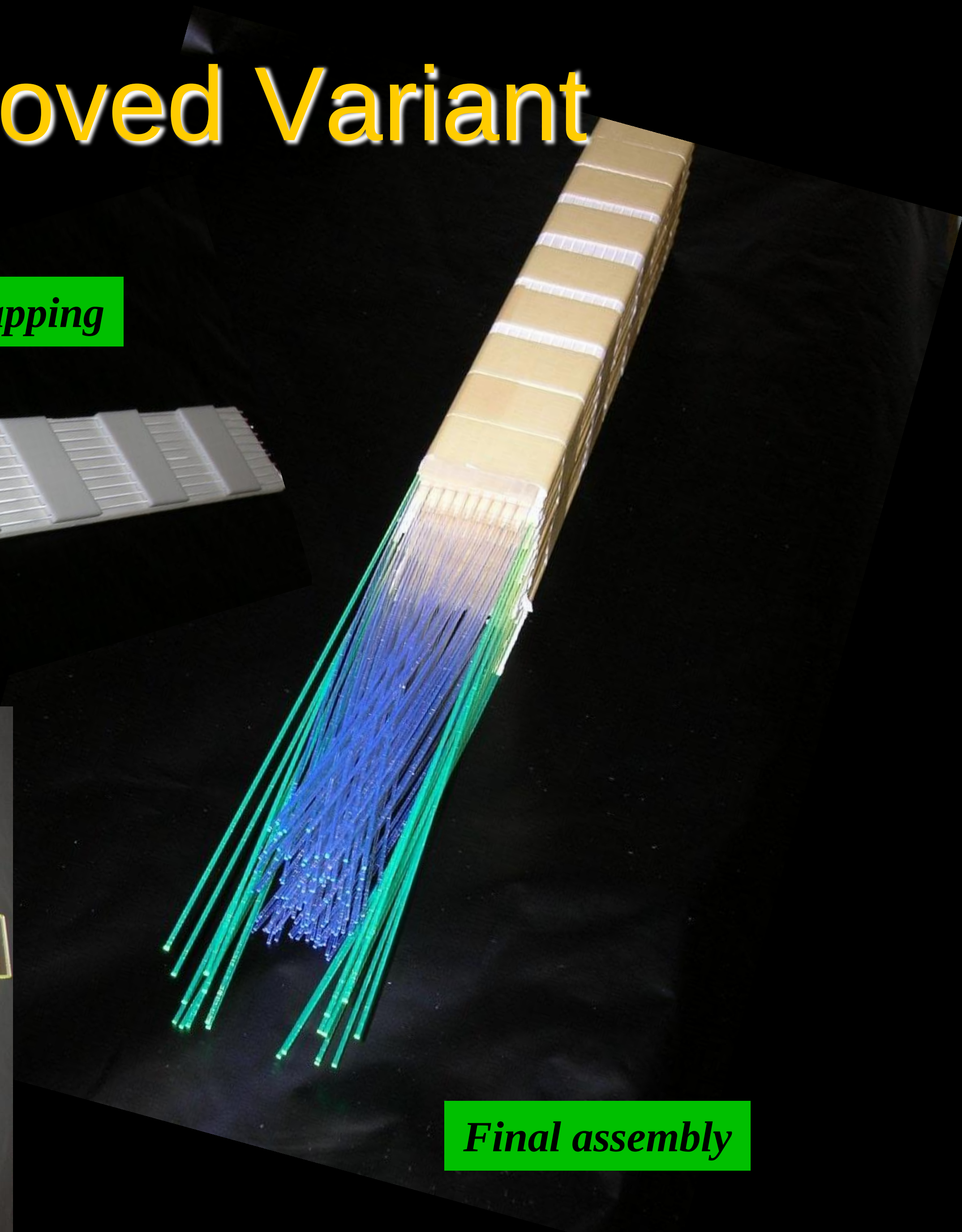
Non-grooved Variant



Teflon wrapping



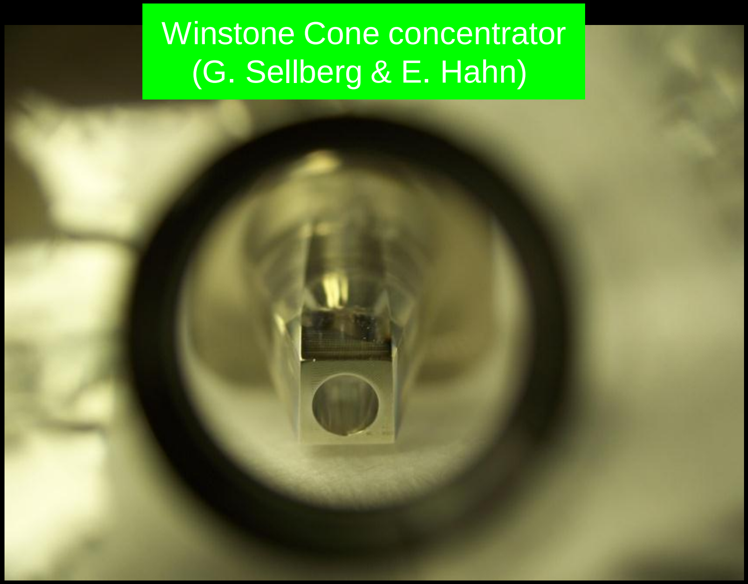
Original glass



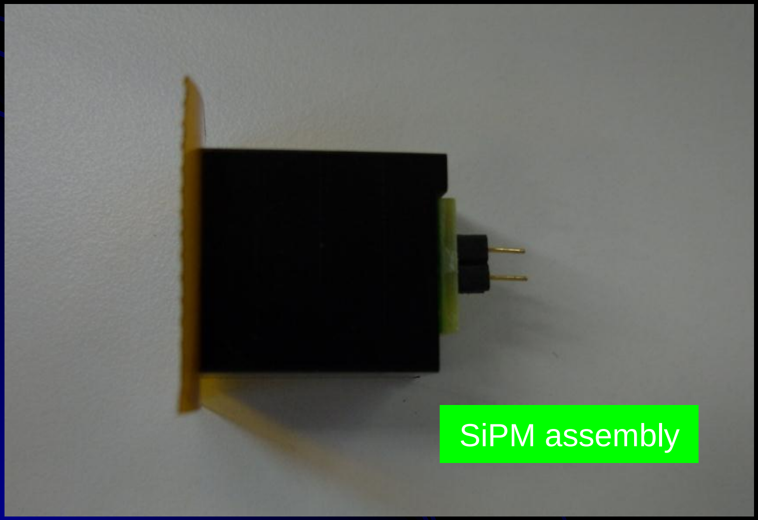
Final assembly

Ligth Readout R&D

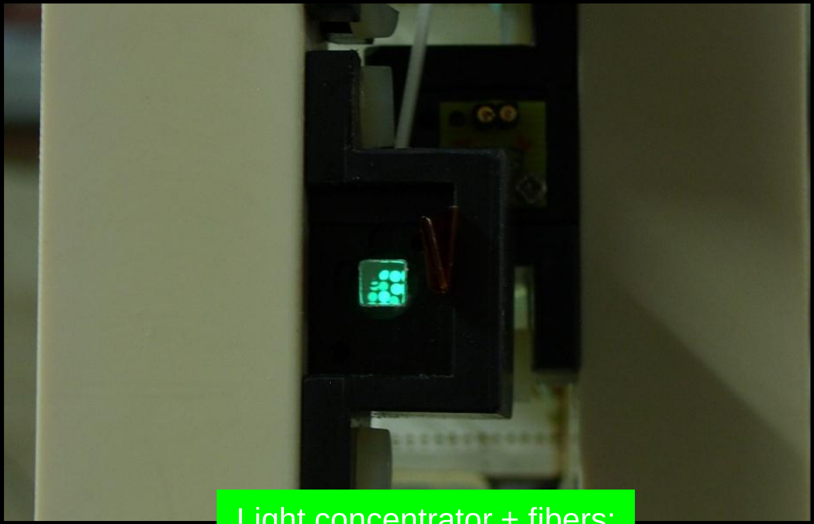
Trieste concentrators



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

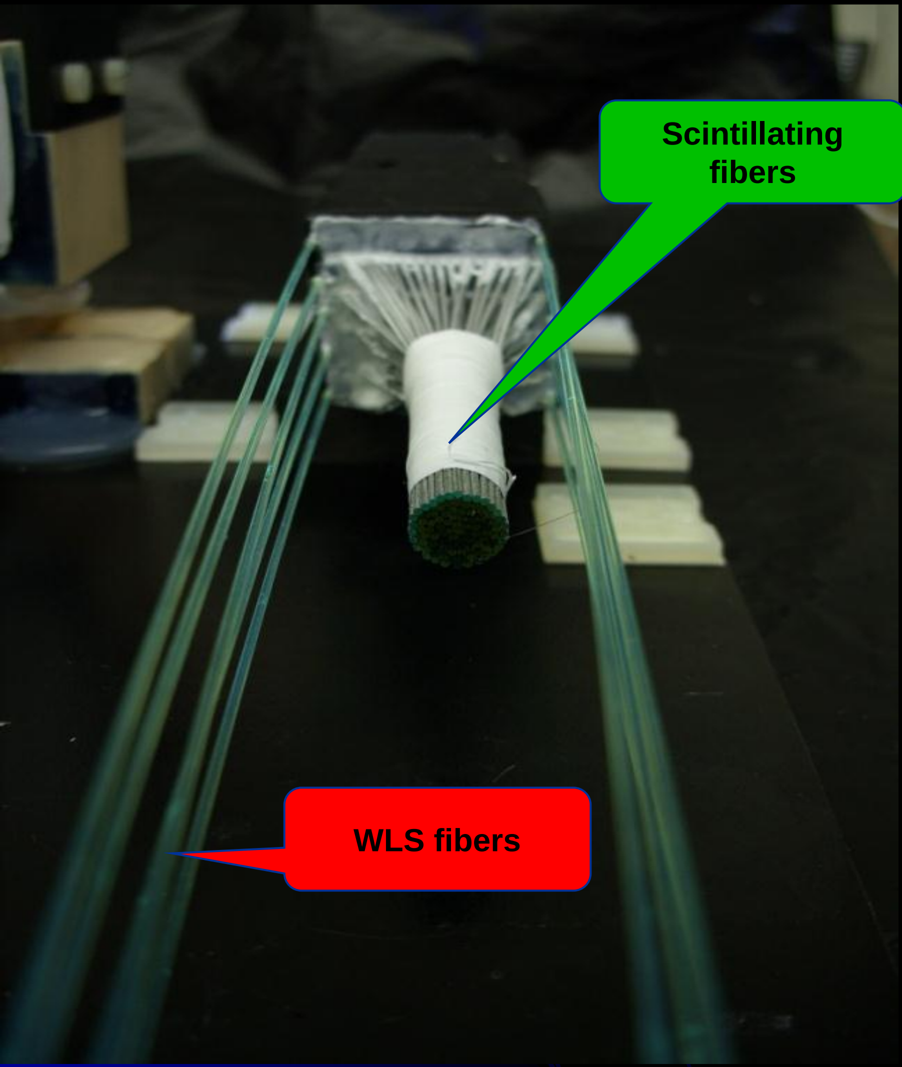


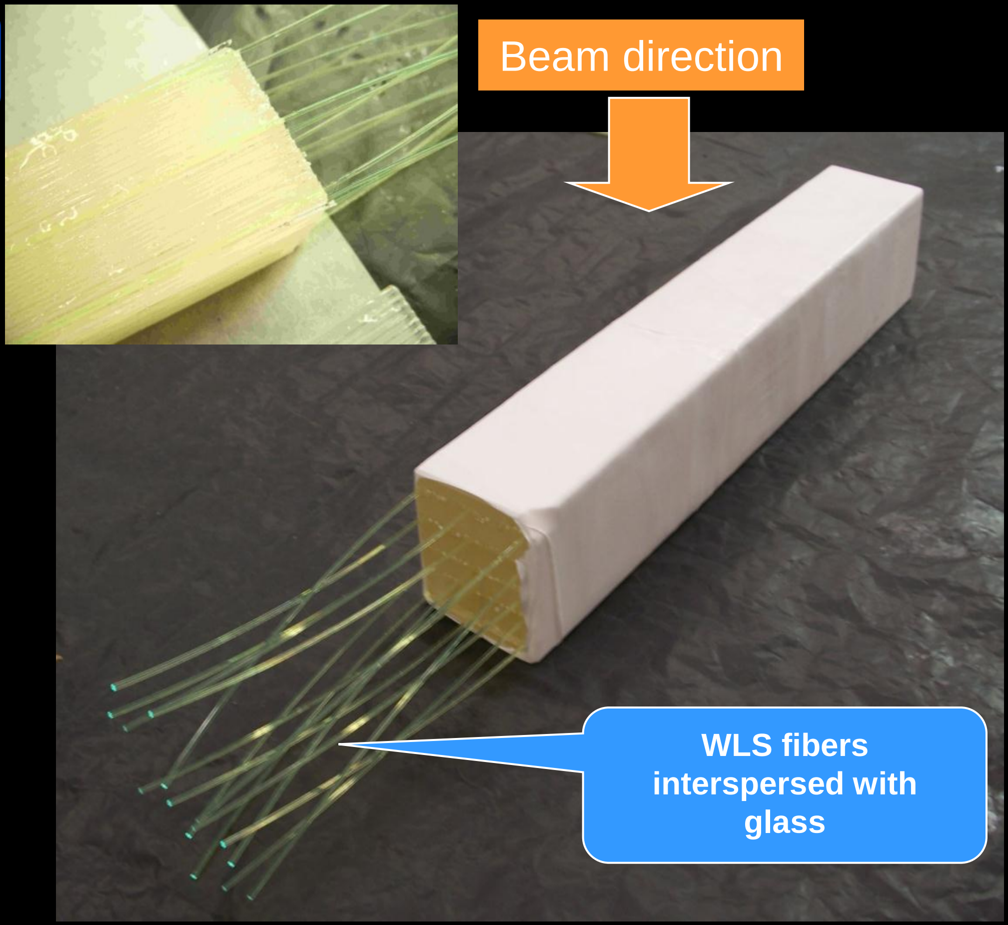
SiPM assembly



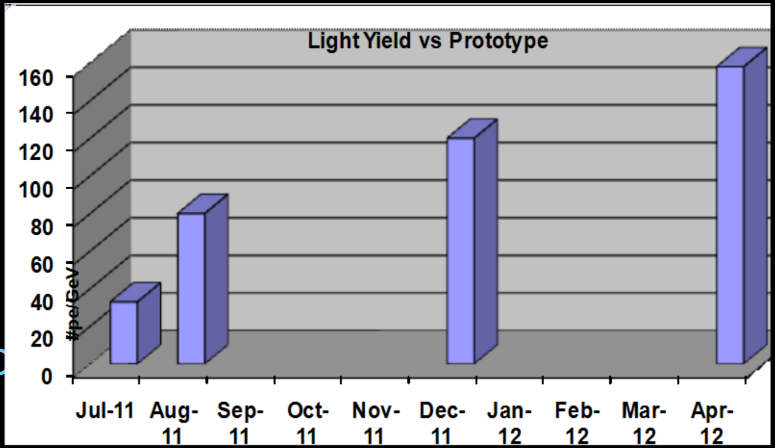
Light concentrator + fibers:
SiPM side

ADRIANO Applications





Summary of Preliminary Analysis of 2011/12 Test Beam Data

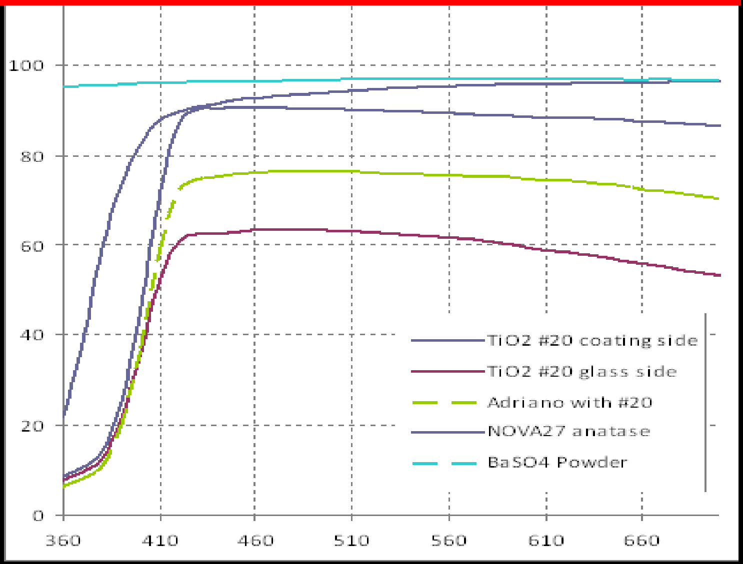


- Light yield constantly improving with new prototypes; current limit ~160 pe/GeV
- April 2012 test beam yielded ~1/2 of the expected (from simulations) light yield
- Light attenuation length critically depends on coating type and surface finishing of glass
- Coupling of fibers to SiPM is critical: air gap between light concentrator and SiPM more than halves the light yield
- Y11 fibers produce almost 50% more light than BCF92 with Cerenkov light
- Different glues produce up to a factor of 2 in light yield
- Cold vs hot glass construction methods make no appreciable difference
- Direct reading from glass at back of cell yields less light than reading fibers
- SiPM and PMT produce comparable signals. However, large noise from present version of SiPM make them hard to use in low energy applications

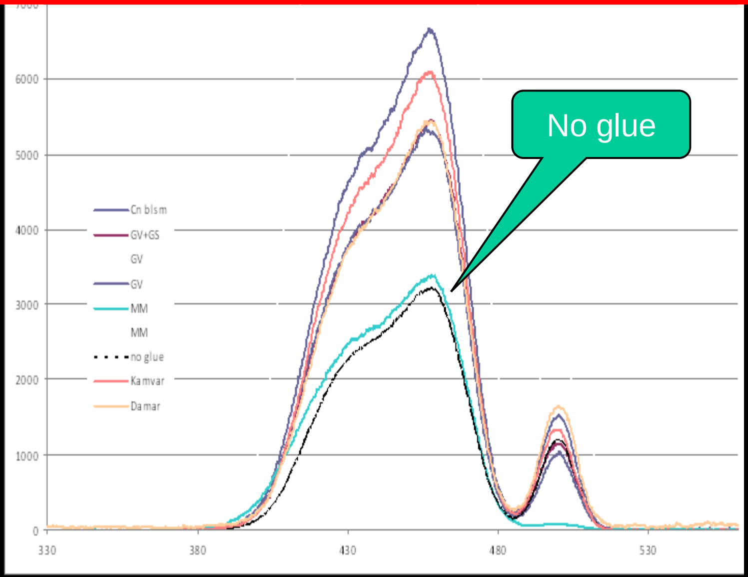
Spectroscopy Measurements

A. Pla

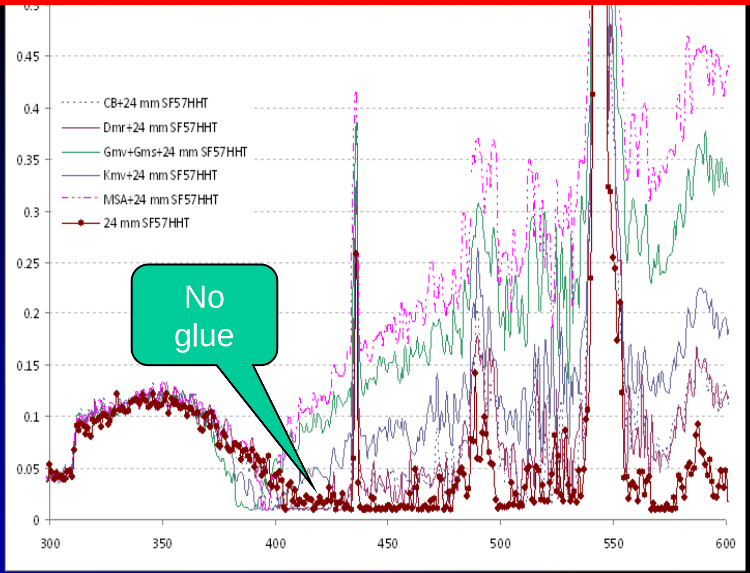
Spectral reflectivity of various coatings



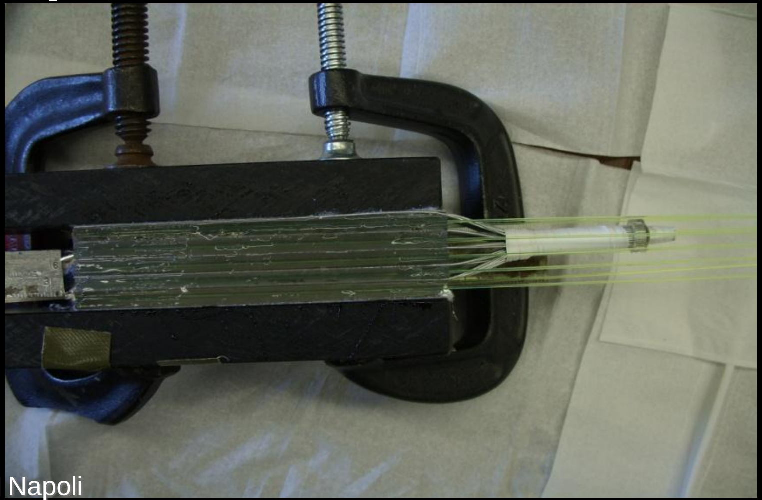
Spectral excitation curves of glass+WLS+optical glues



Spectral transmission curves of glues+glass



Best coating and optical glue is from an homemade mix



Consuelo Mugoni

Transmission Spectra of Rare Earth glasses