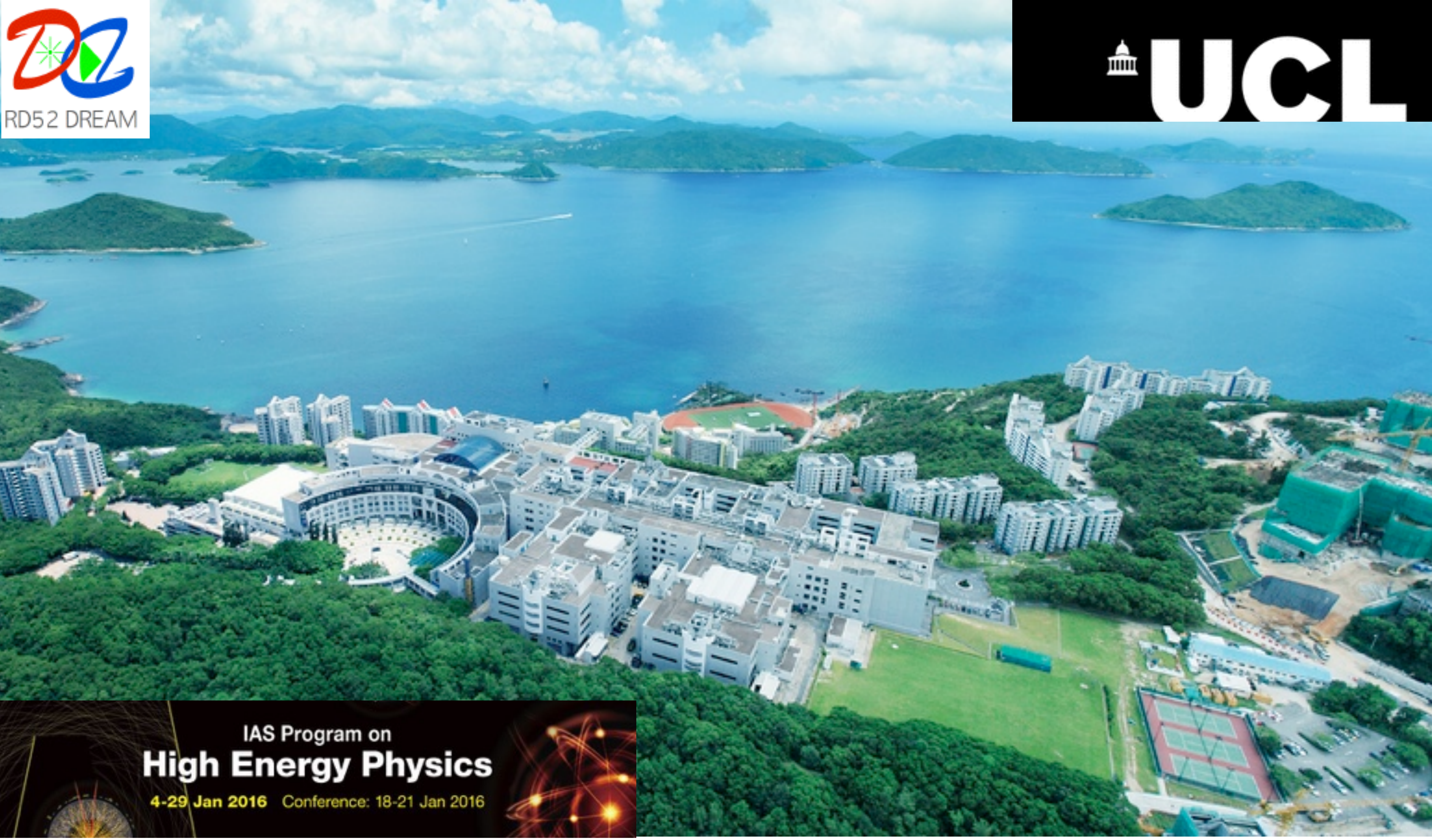

Time Structure in Dual Readout Calorimeters

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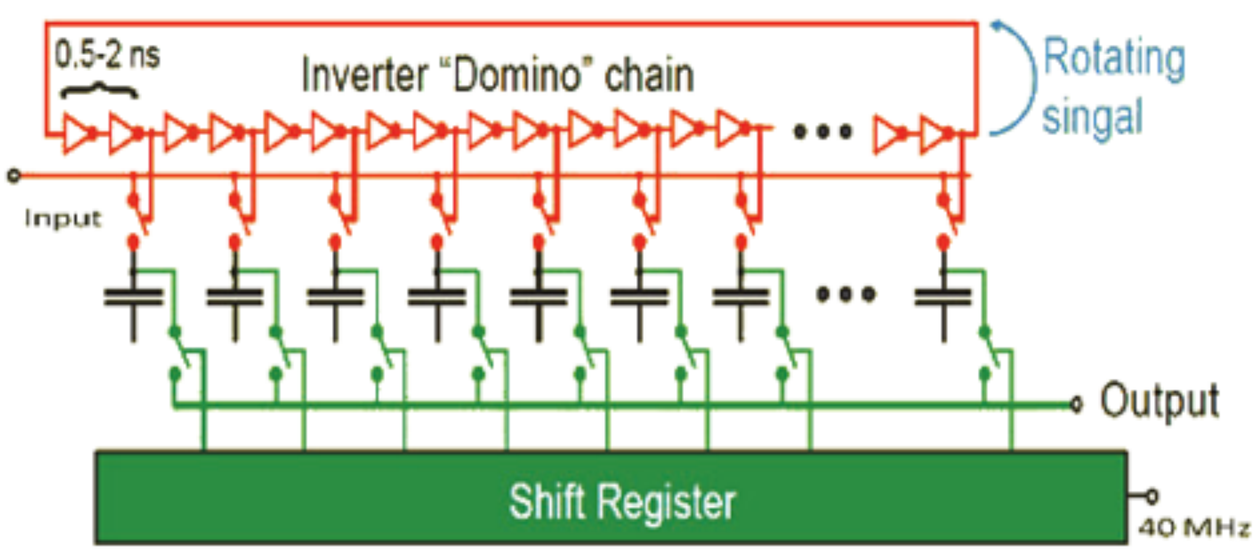
Motivation

- Sehwook should have convinced you that dual readout is a good idea
- You need to separate Scintillation and Cherenkov light
- If you have a crystal the timing structure of the signal is a way to disentangle the two components
- Even with a fibre calorimeter the timing structure gives you a lot of interesting information

Electronics

- Oscilloscope
- DRS-4: a fast and relatively cheap sampler made in PSI
  - But simple dedicated electronics is enough to implement what follows in a collider experiment



High Z scintillating crystals

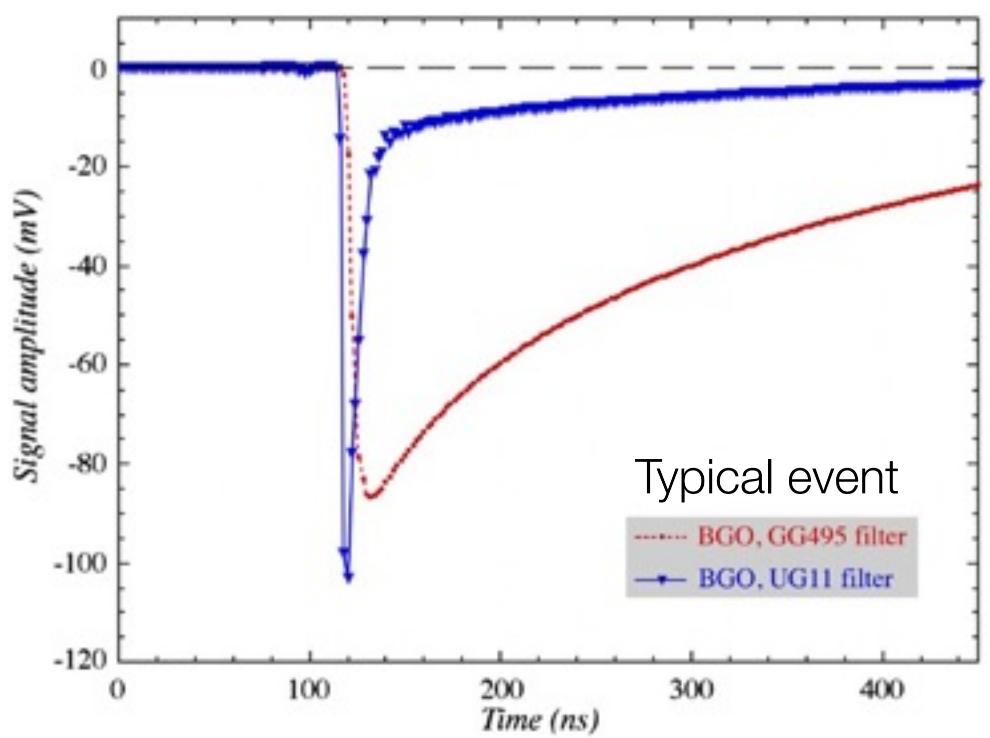
- Fantastic for e/γ (3%$E^{-1/2}$)
  - Good response
  - Completely avoid sampling fluctuations
- BUT typical response to hadrons is low -> large non linearity -> they'll compromise hadronic resolution
- Can we apply dual readout?

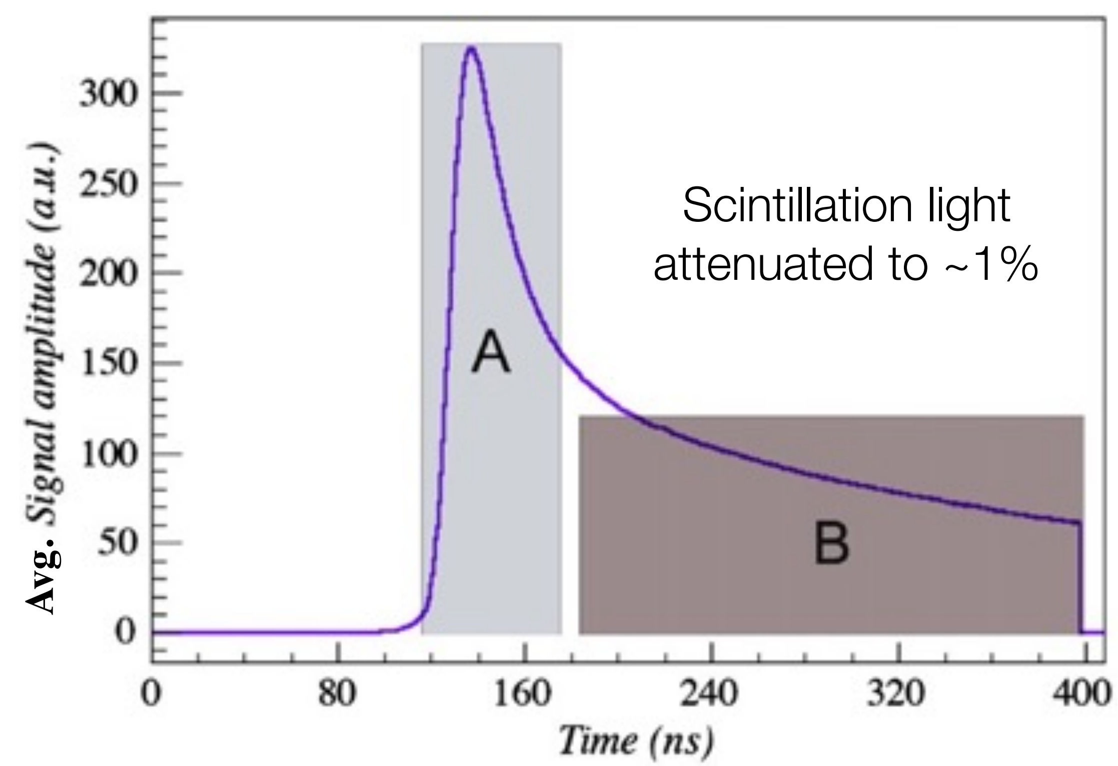
	Cherenkov	Scintillation
Time	prompt	exponential
Wavelength	1/λ	peak
Direction	Cone	isotropic
Polarization	polarised	unpolarised

- Timing analysis + filtering to extract the C and S components

The BGO matrix

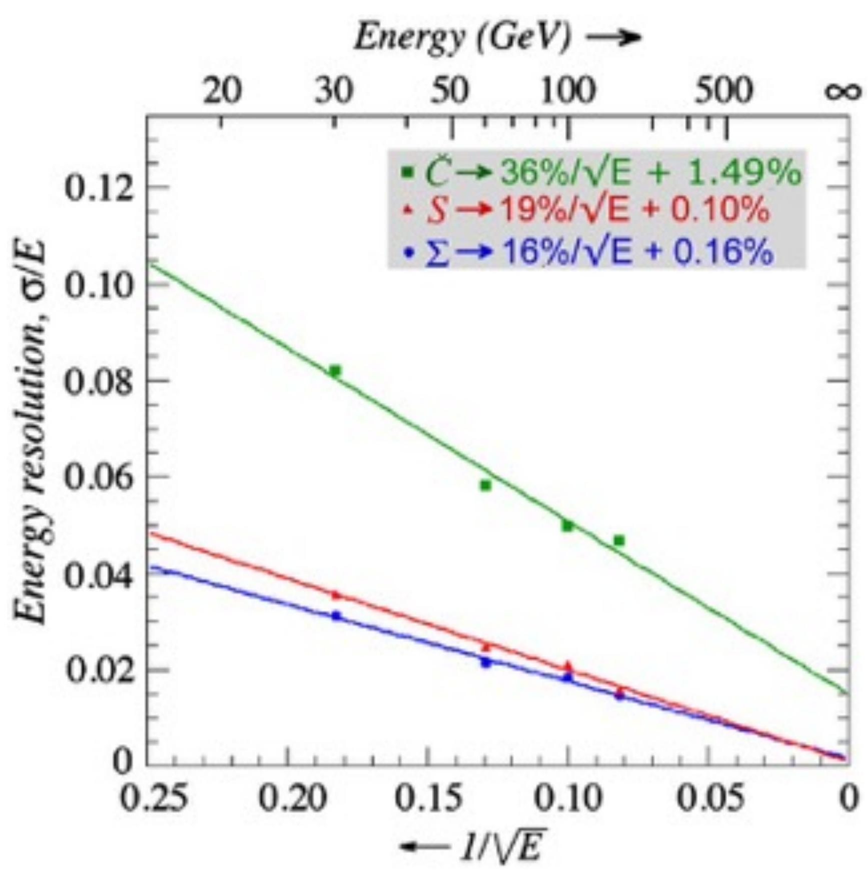
- The light output of the matrix is filtered to enhance the C component
- Two gates are used to measure the C and S signal separately

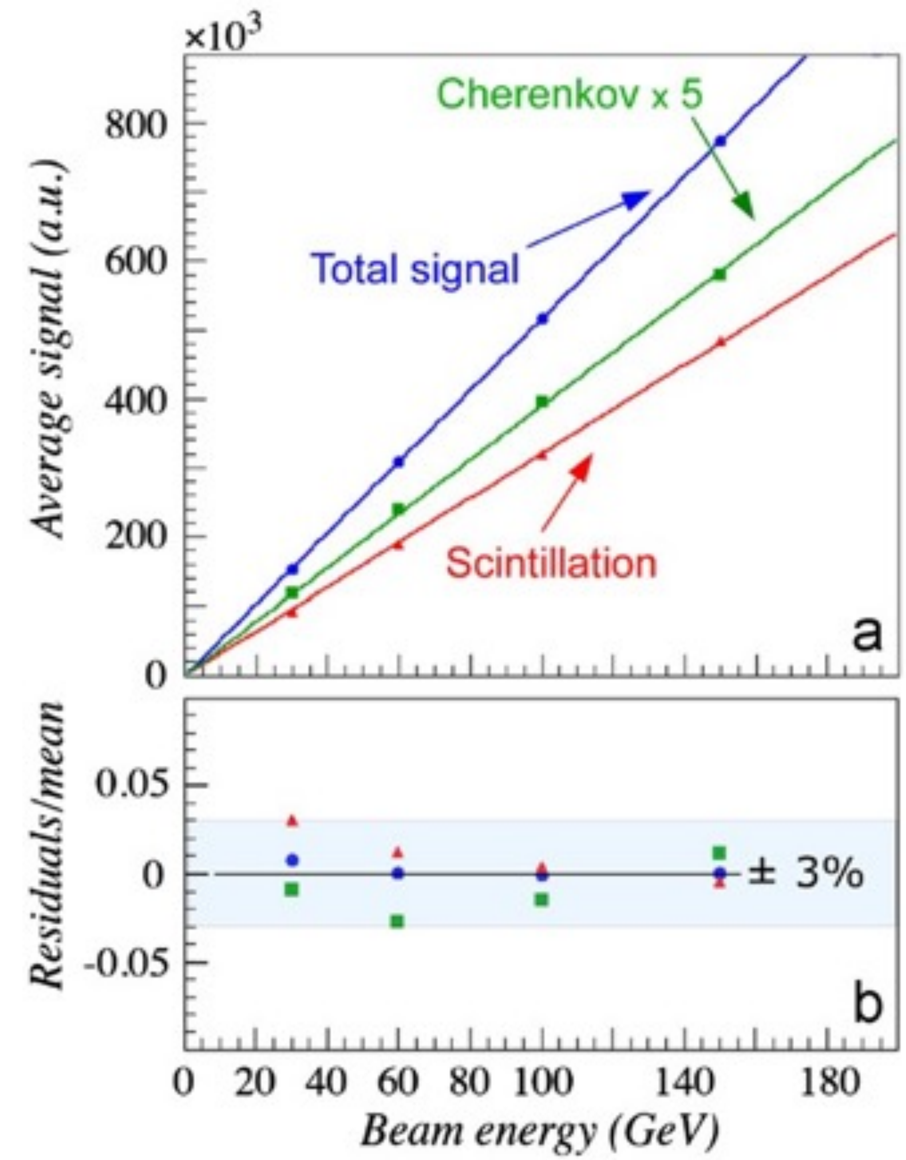




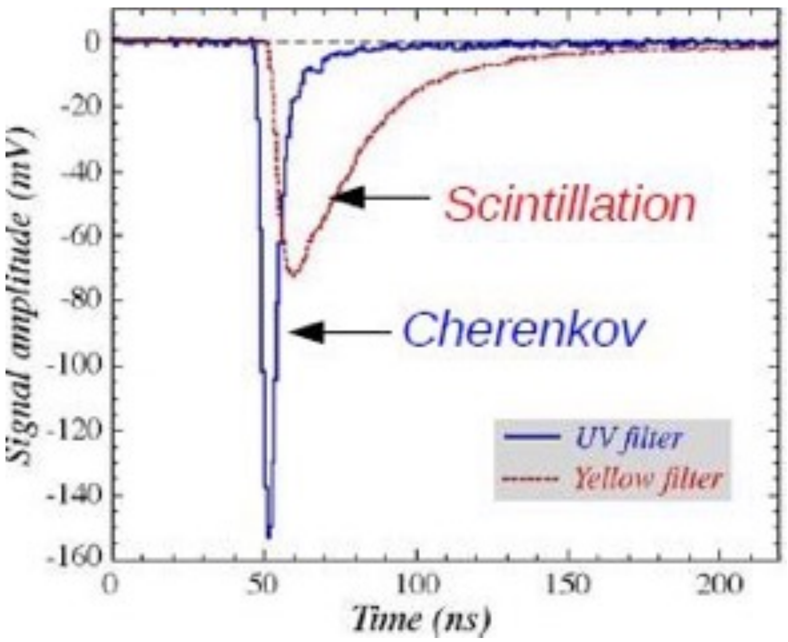
The BGO matrix, em performance

- Linearity within 3%
- Ok resolution, but far from ideal
  - S resolution affected by strong attenuation
  - Low C light yield



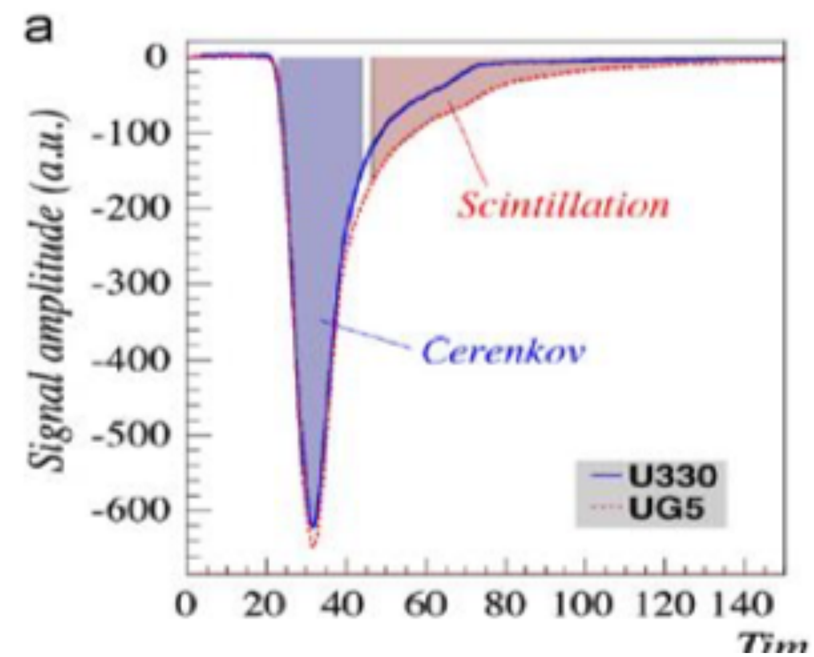


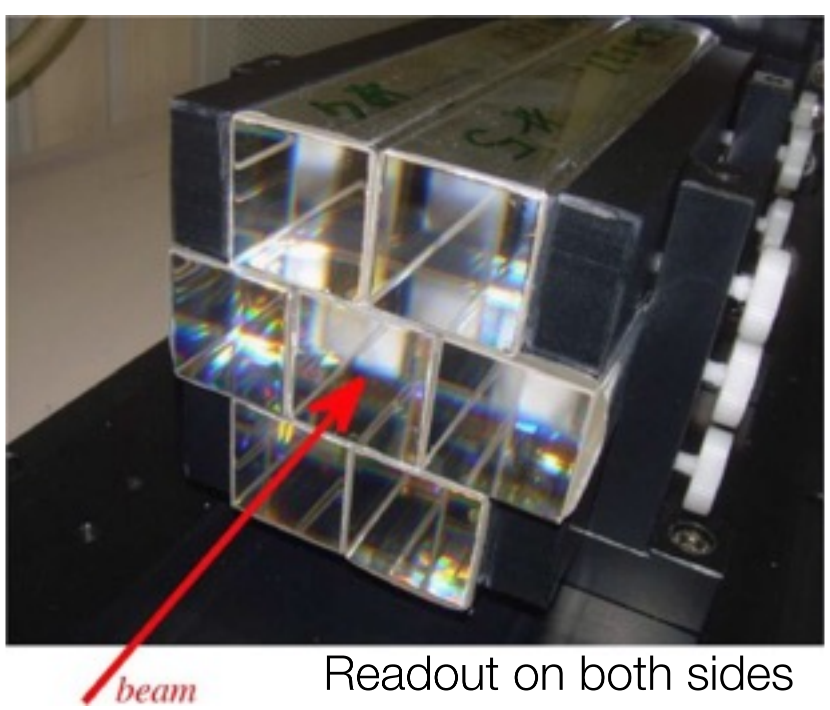
PWO matrix



PbWO4 (0.3% Mo)

- Single side and dual side readout tested
- Use a combination of filters and timing analysis

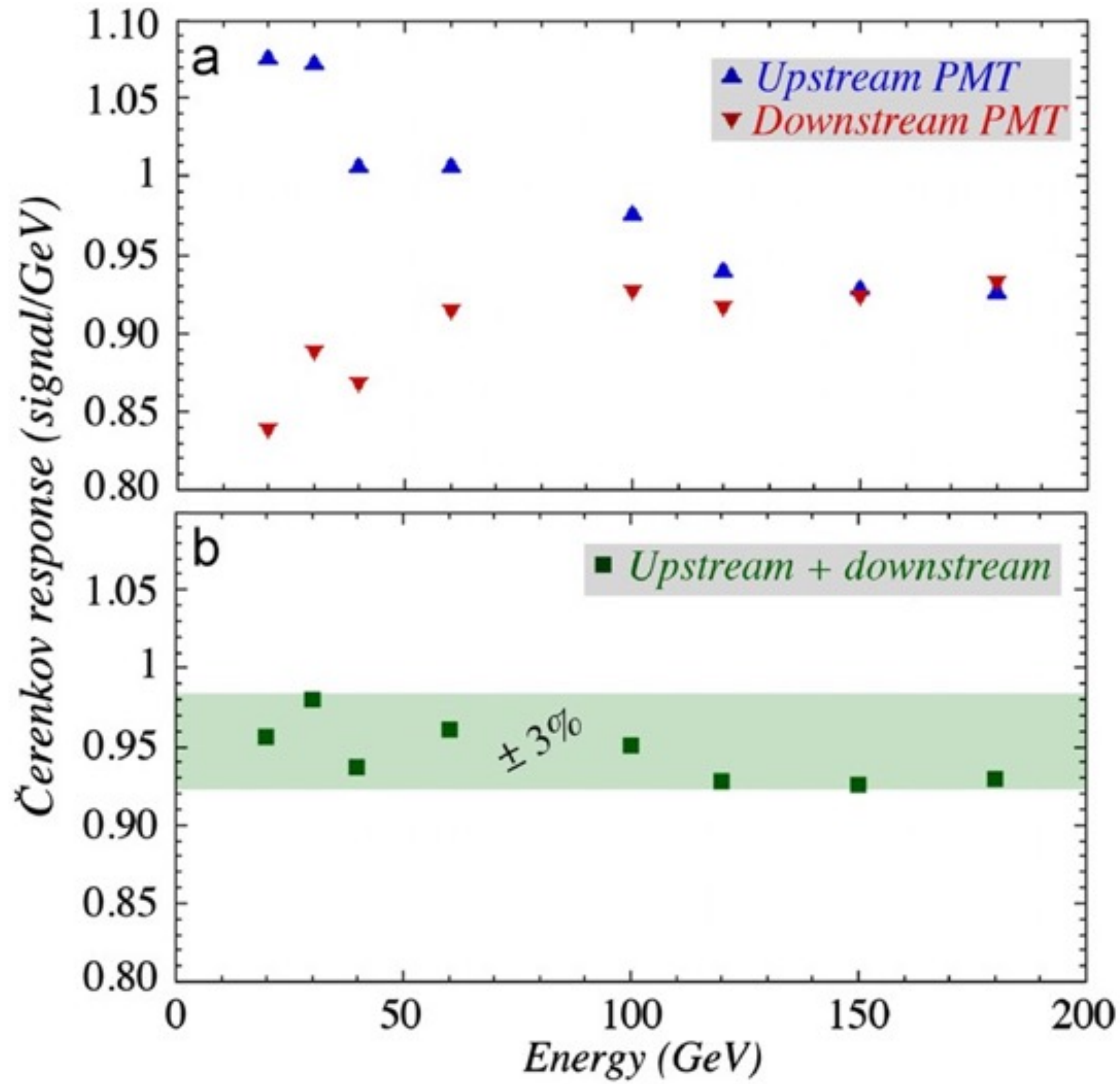




Readout on both sides

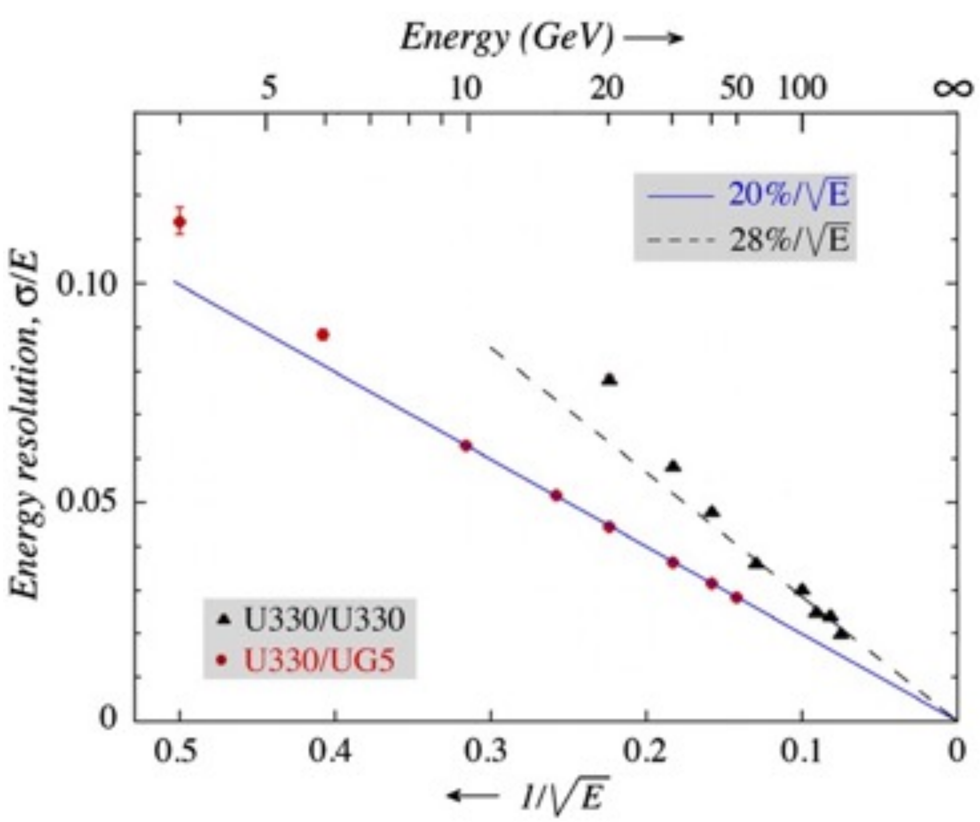
PWO matrix em performance

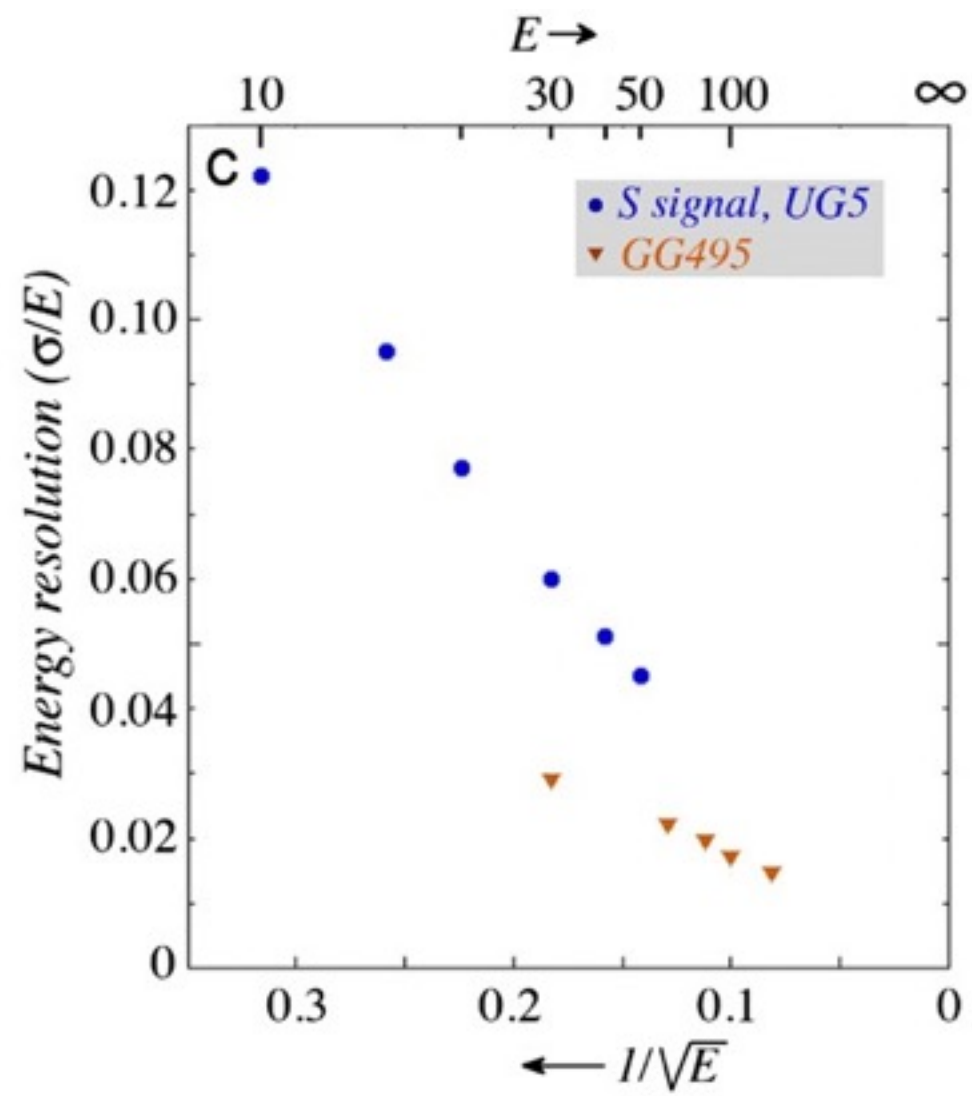
- Position dependent response in single side mode due to UV self absorption
- Single side readout cannot be used



PWO matrix em performance

- C Resolution improves as we collect more UV photons
- Visible noise component at low E

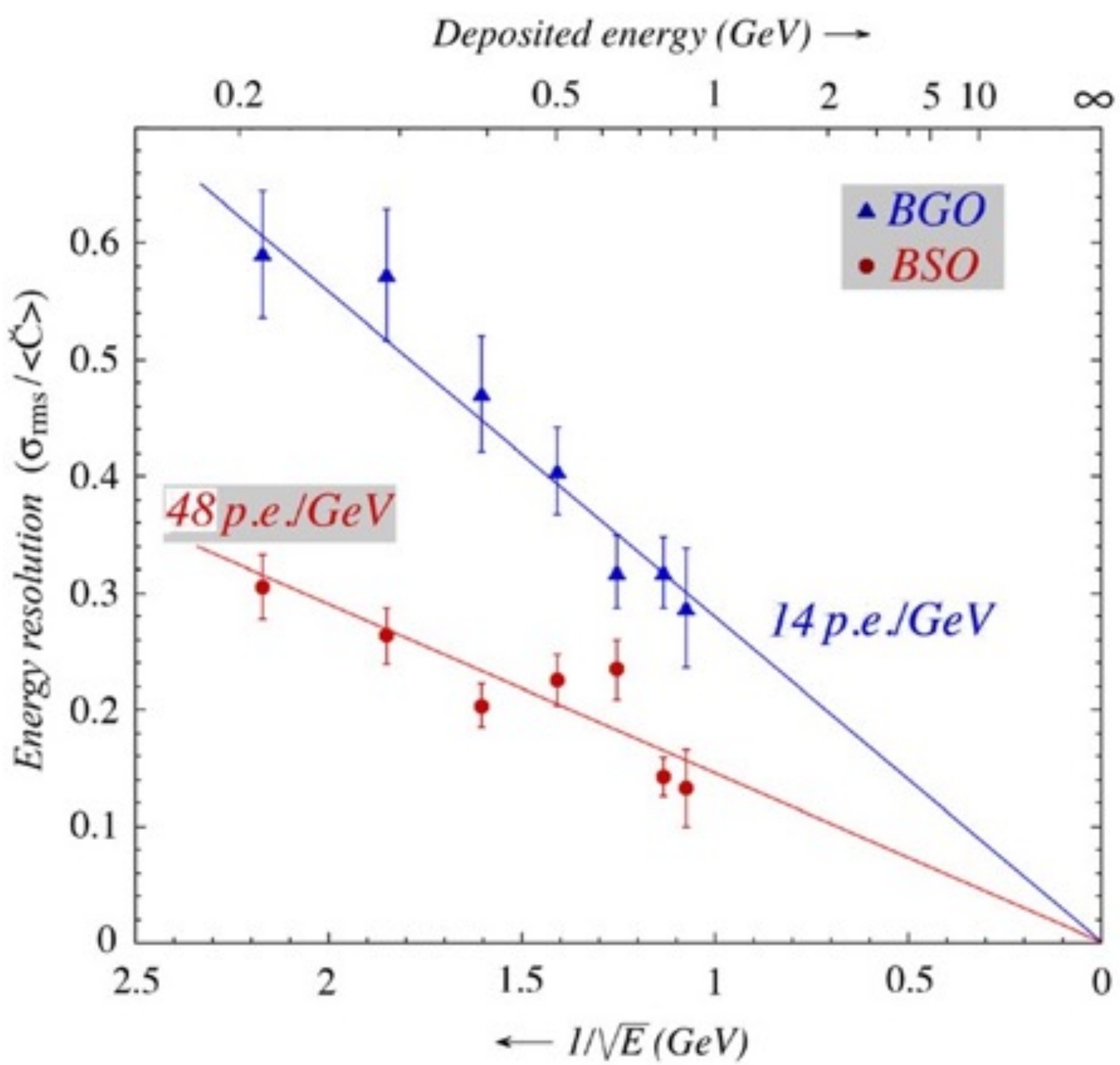


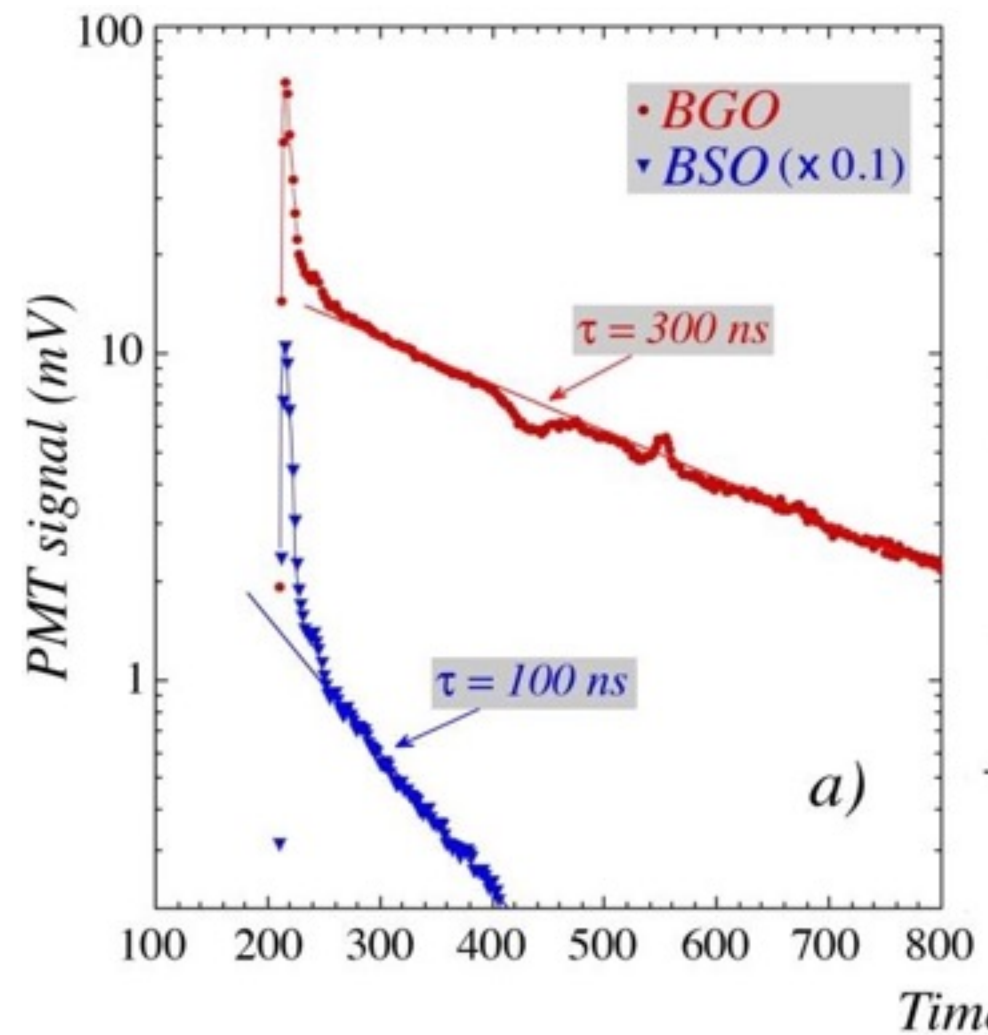


- S resolution is impacted severely by UV filters

Comparison of a BGO and a BSO crystal

- Better UV transparency
  - 3x light yield, no position dependence





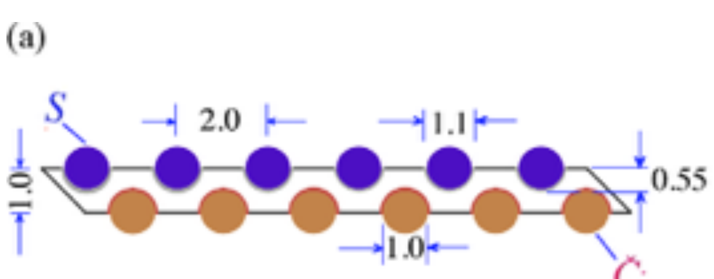
- Slower scintillation
  - better separation in single side mode

Conclusions (crystals)

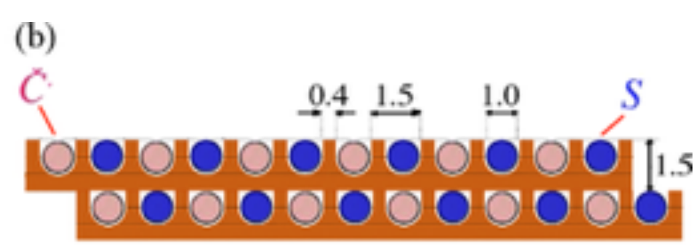
- Non conventional readout compromises em resolution
  - Optical filters severely reduce scintillation resolution
  - Beware of self absorption
  - No sensitivity to neutrons
- We believe we can obtain a better em resolution with a fibre calorimeter
- We can get a better C light yield in a fibre calorimeter
  - A better dual readout calorimeter (copper, higher sampling fraction)

The RD52 fibre calorimeters

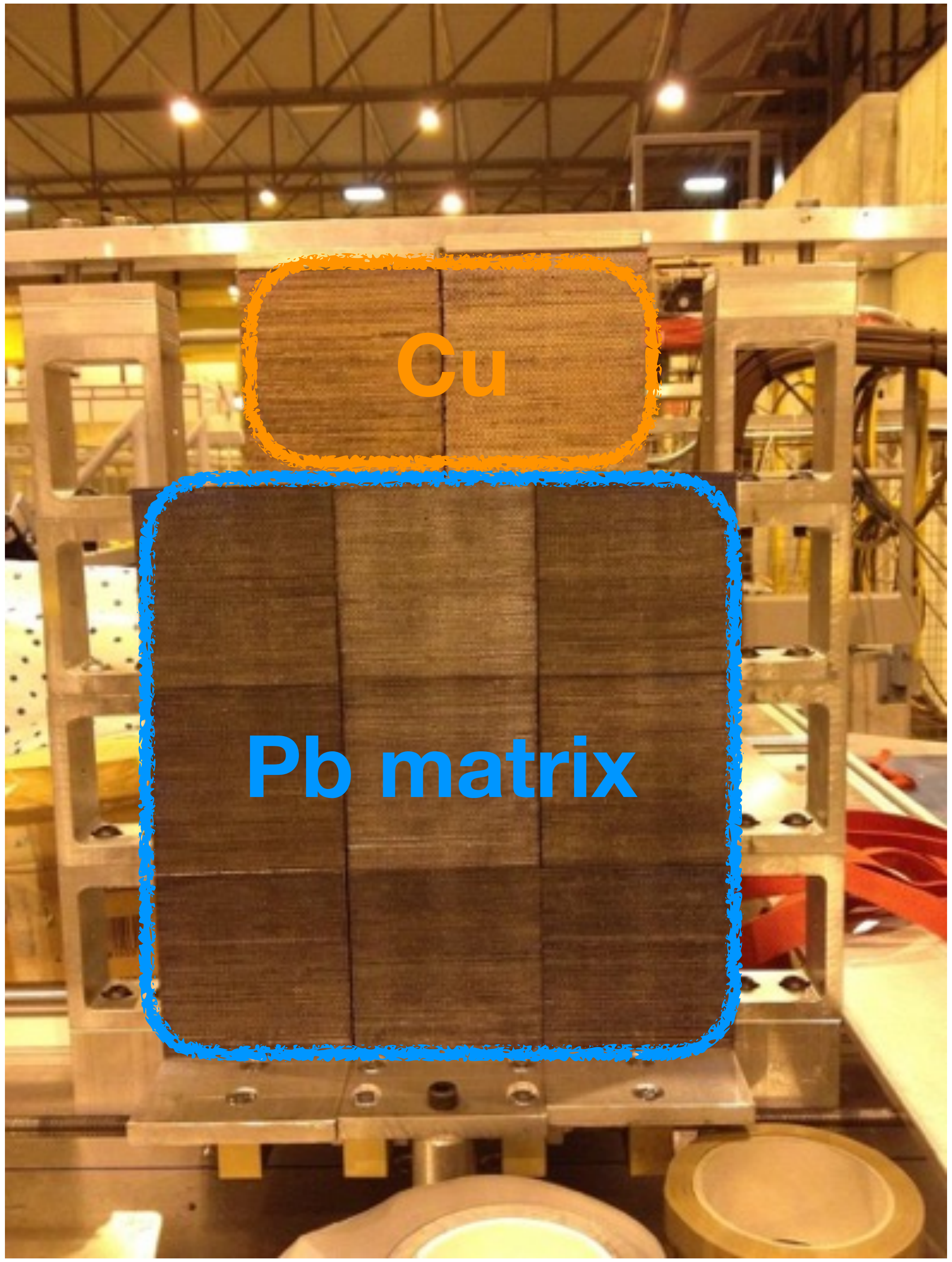
- We will show extremely powerful e/pi separation despite the lack of longitudinal segmentation
- In addition to the lateral profile we use the C/S ratio and the timing profile of the shower to characterise each event



Pb

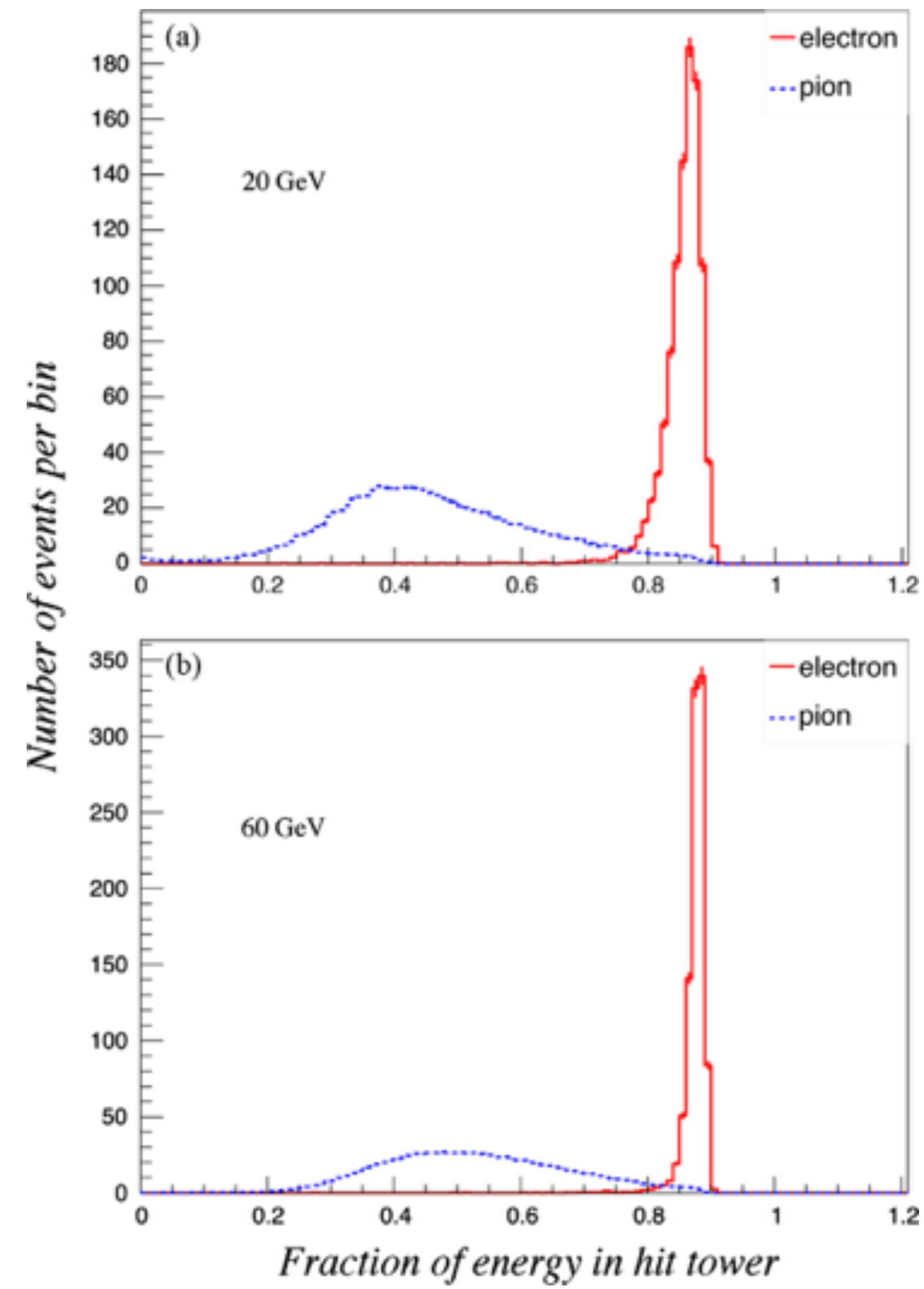


Cu

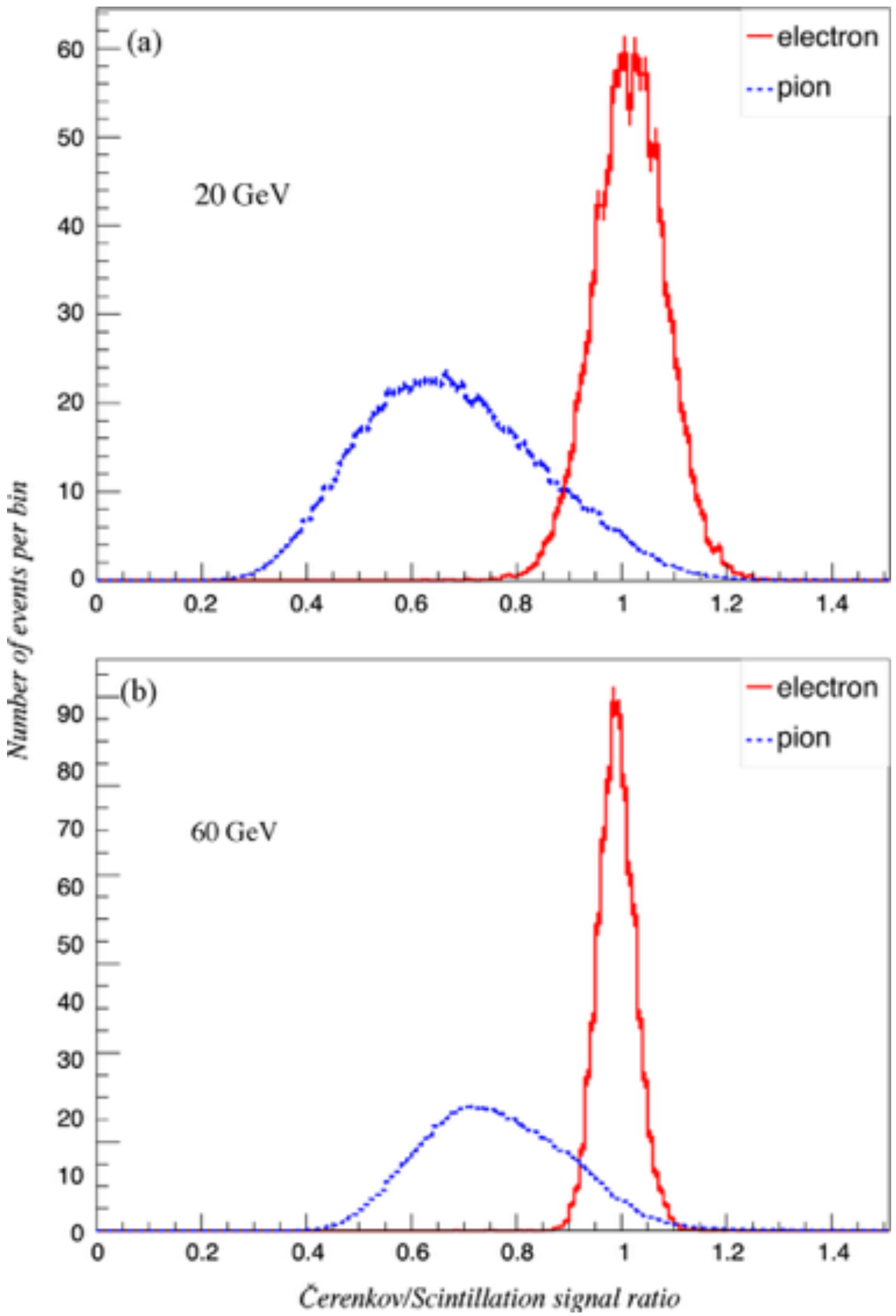


Lateral shower profile

- The RD52 calorimeter lacks a high-Z em stage
- But its lateral granularity is small (1.6 Moliere radii) and can be increased at will just by regrouping the fibres

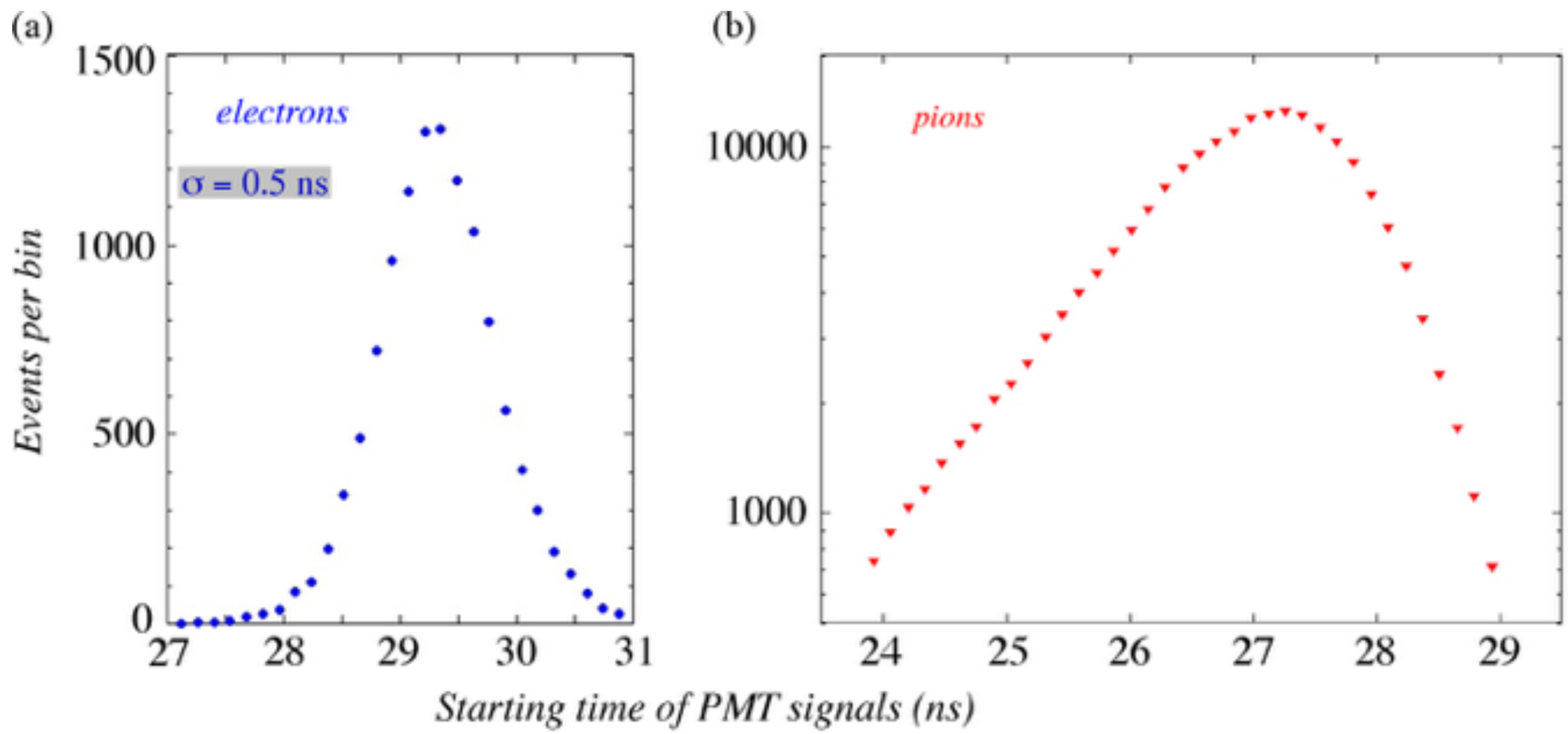


C/S ratio

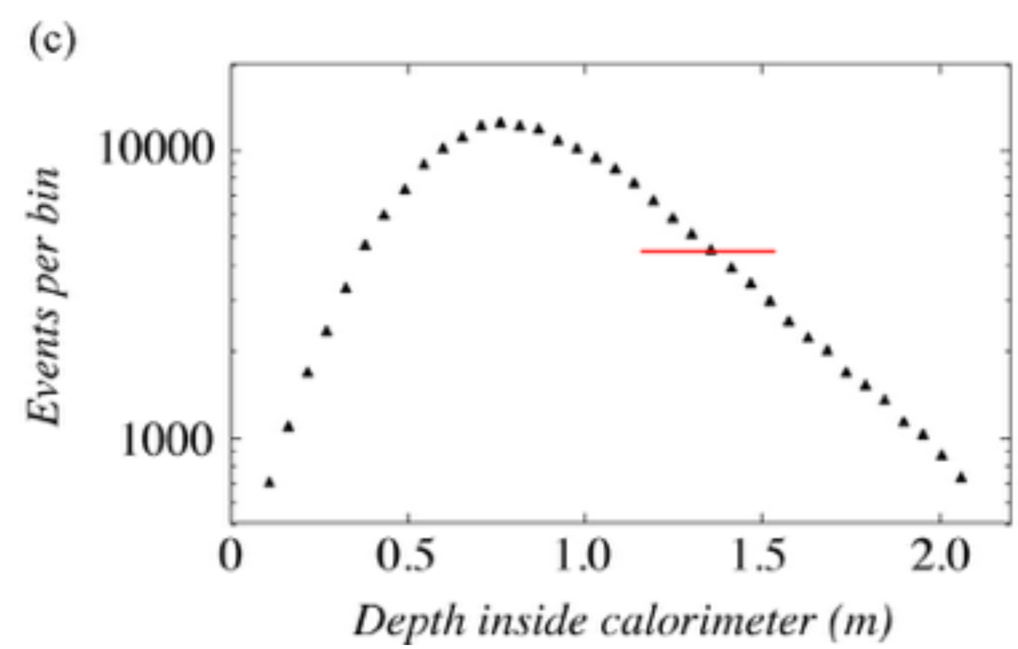


- C/S ~ 1 for electrons
- the electron distribution gets narrower at higher energies
- C/S slowly grows with energy for hadrons as f_{em} increases

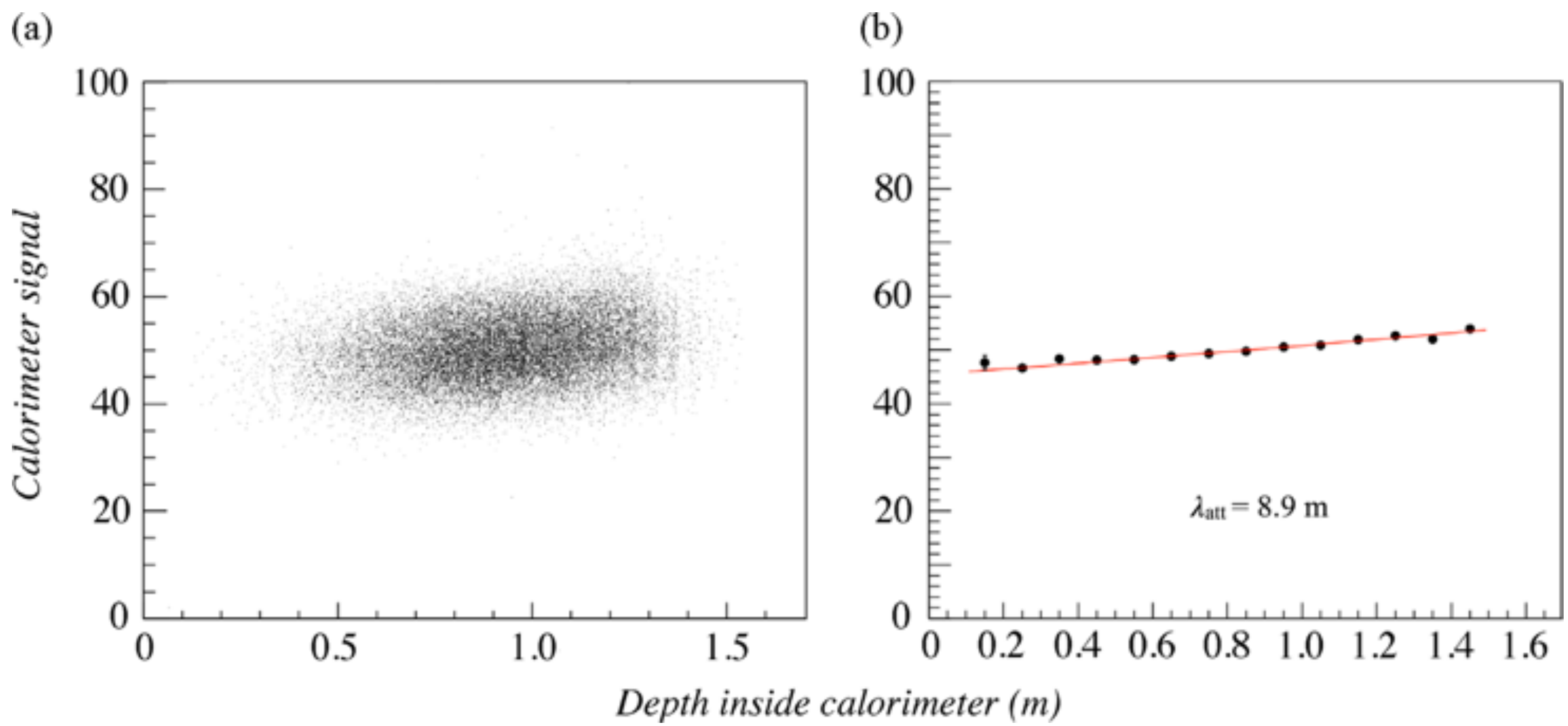
Time structure (delay)



- The delay of the PMT signal is correlated with the starting position of the shower



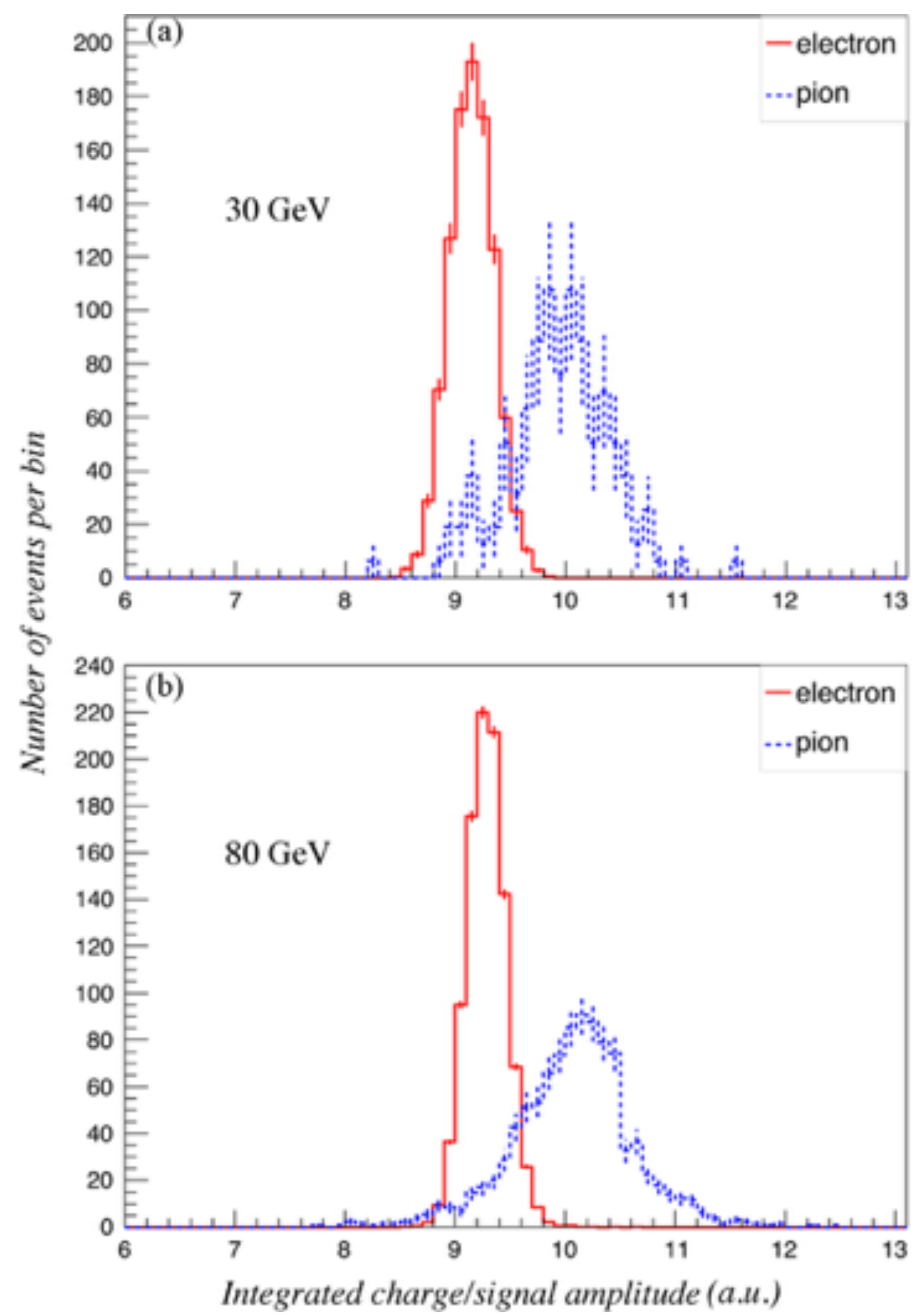
Time structure (delay)



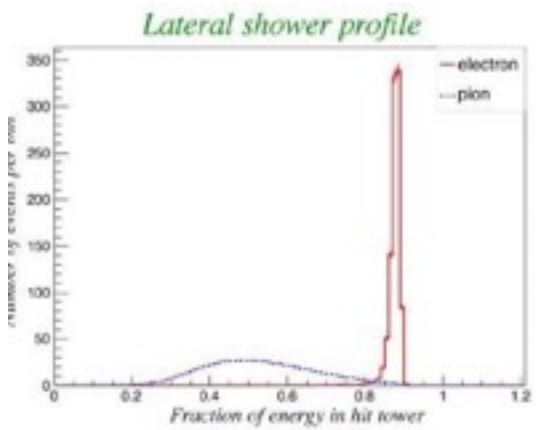
- Depth measurements can also be used to correct for the attenuation of light in the fibres.

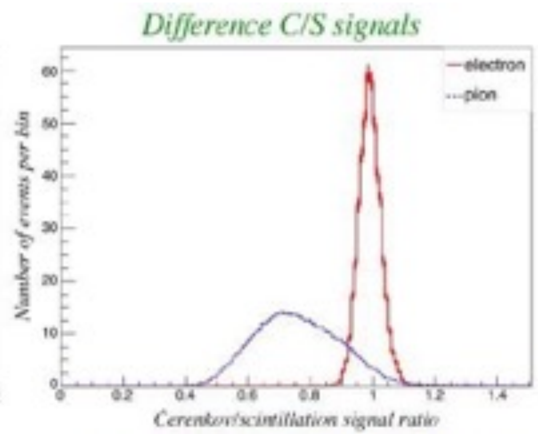
Timing structure (pulse width)

- The width of the light distribution is an indicator of the shower longitudinal development
- pions, of course, have much wider showers than e
- This is from a different dataset

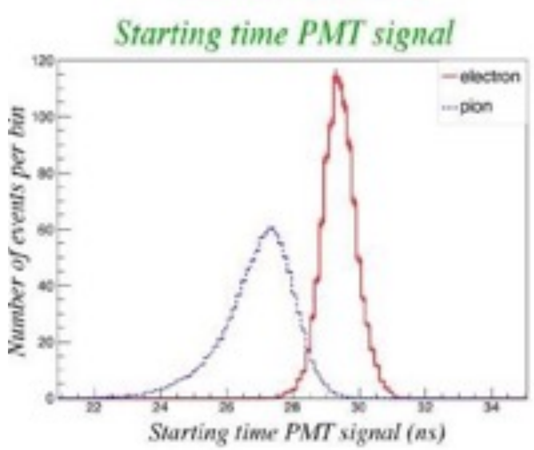


Unity is strength

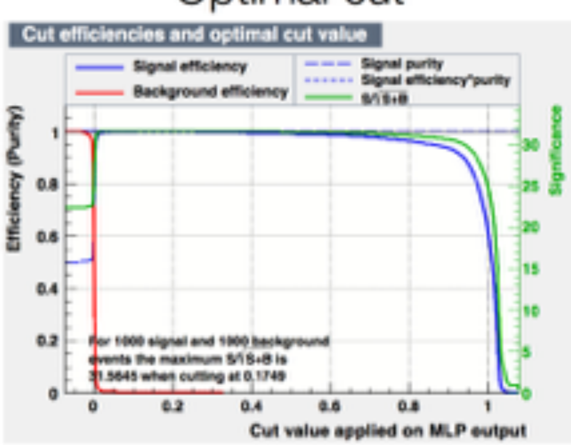


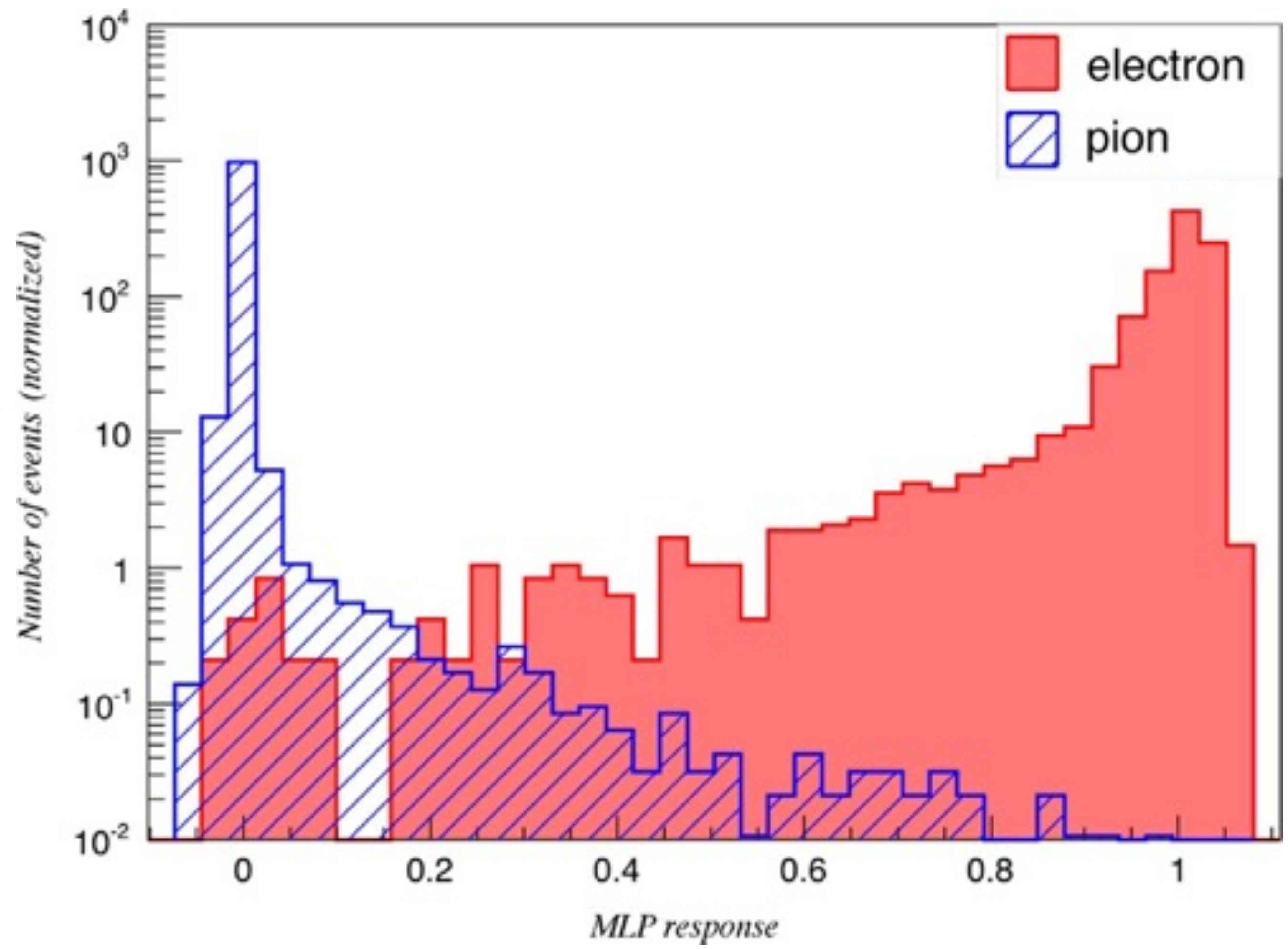


99.8 % electron ID,
0.2 % pion mis-ID
for MLP > 0.17



Optimal cut



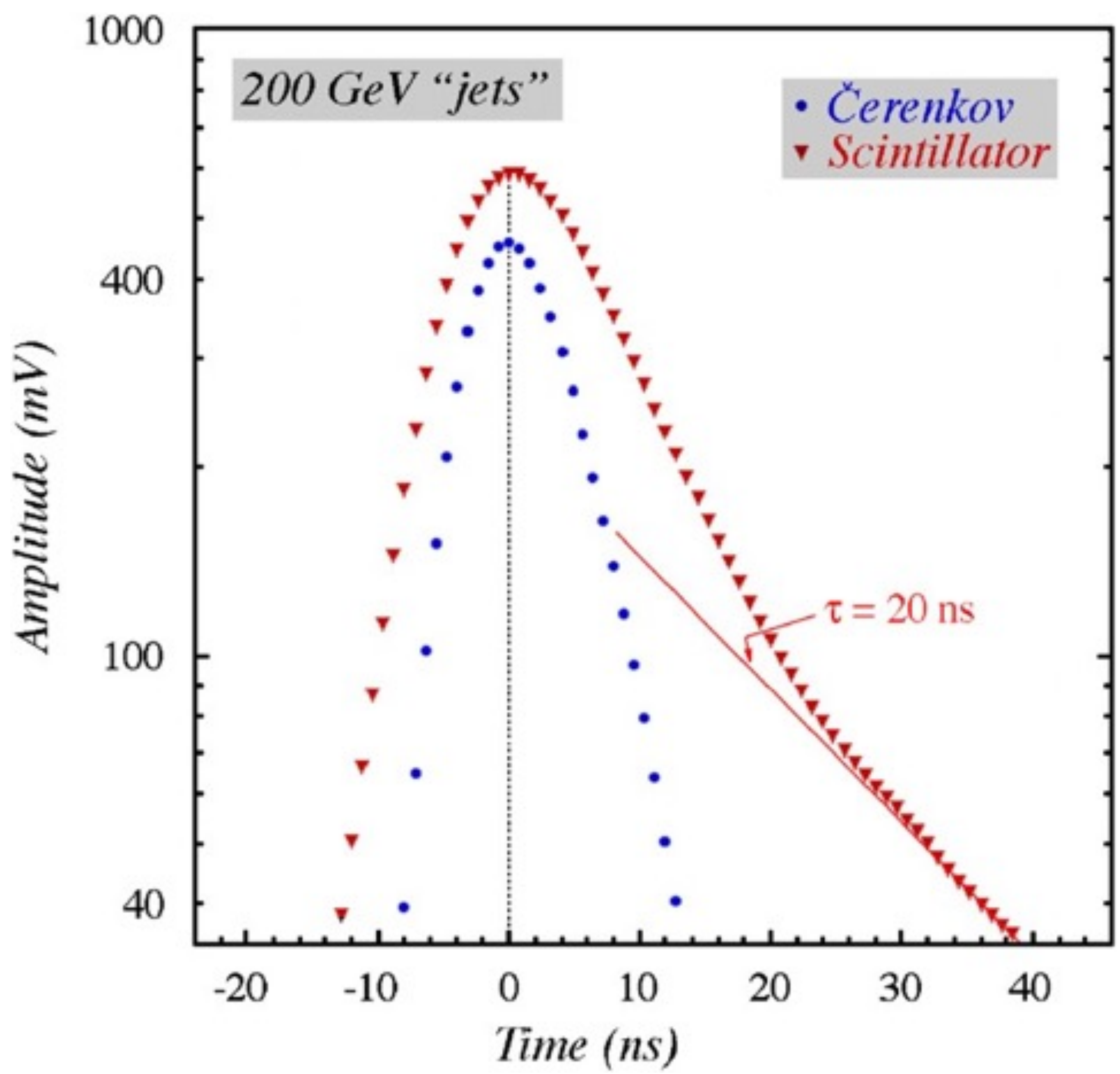


Invisible energy

- Fluctuations in visible energy: the *final limit* of hadronic resolution
- 30-40% of the hadronic energy is released in nuclear breakup, mainly as evaporation neutrons
- What if we could measure them?

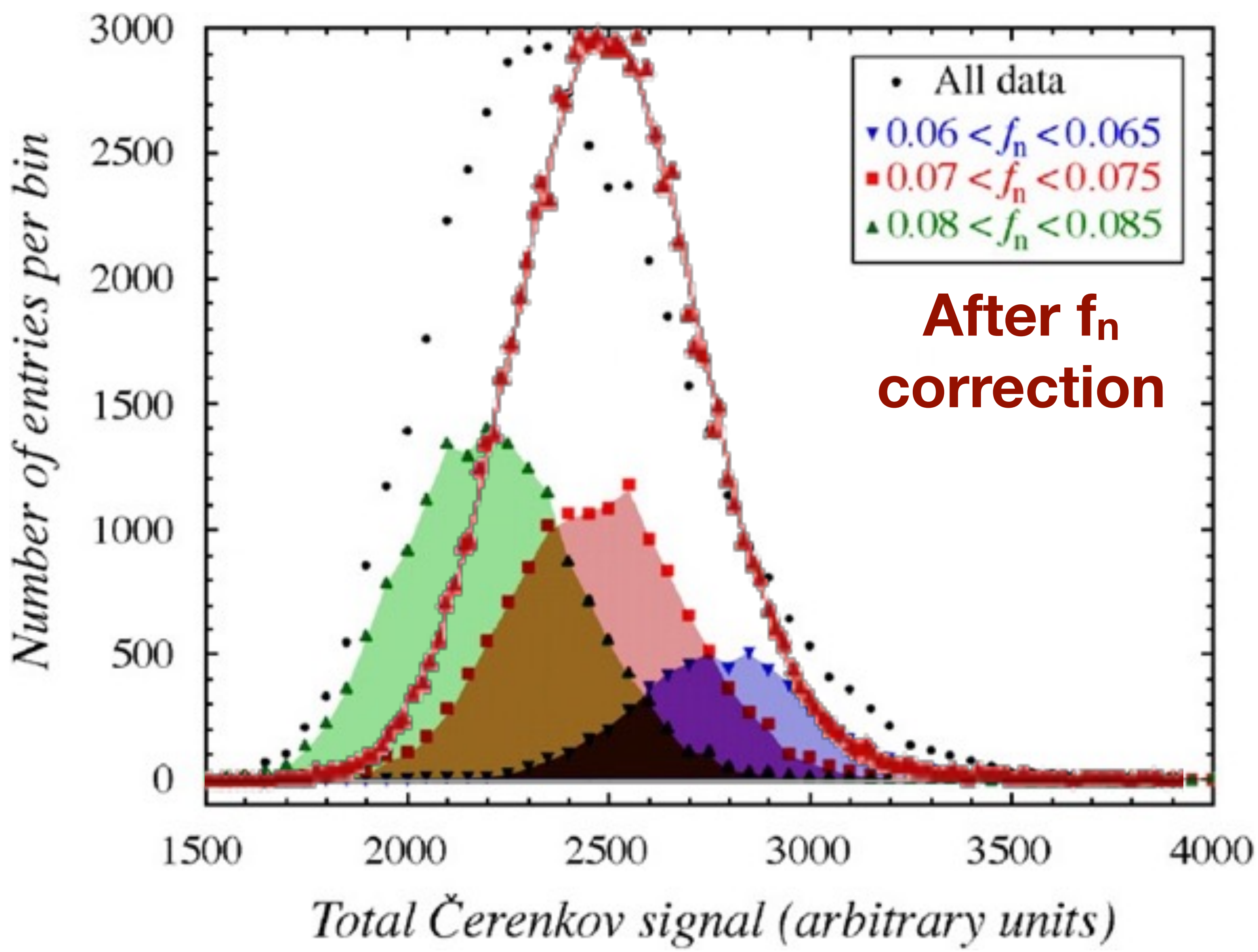
The neutron fraction

- Waiting for the neutron to be absorbed takes too long
- Elastic scattering of n on H in plastic fibres (exponential signal with τ~20ns)



Triple readout

- We cal the relative size of this tail f_n
- f_n is complementary to f_{em}, we can use it to further improve the had resolution



After f_n correction

Summary

- Crystal studies
- Particle ID
- Measurement of the neutron fraction

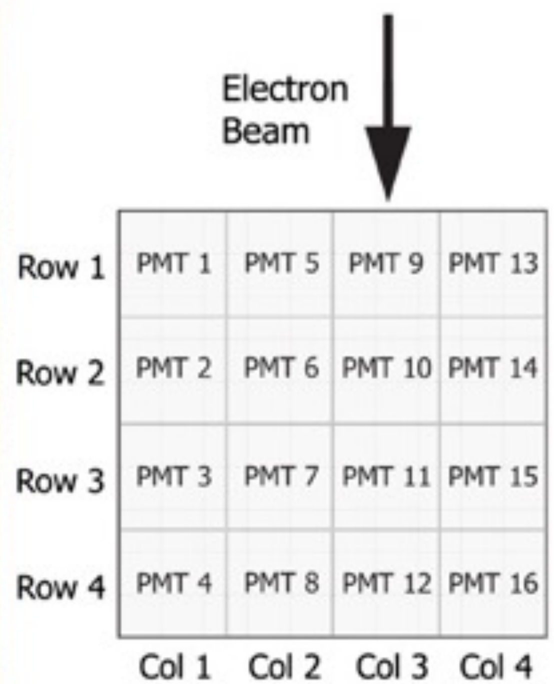
Thank you!

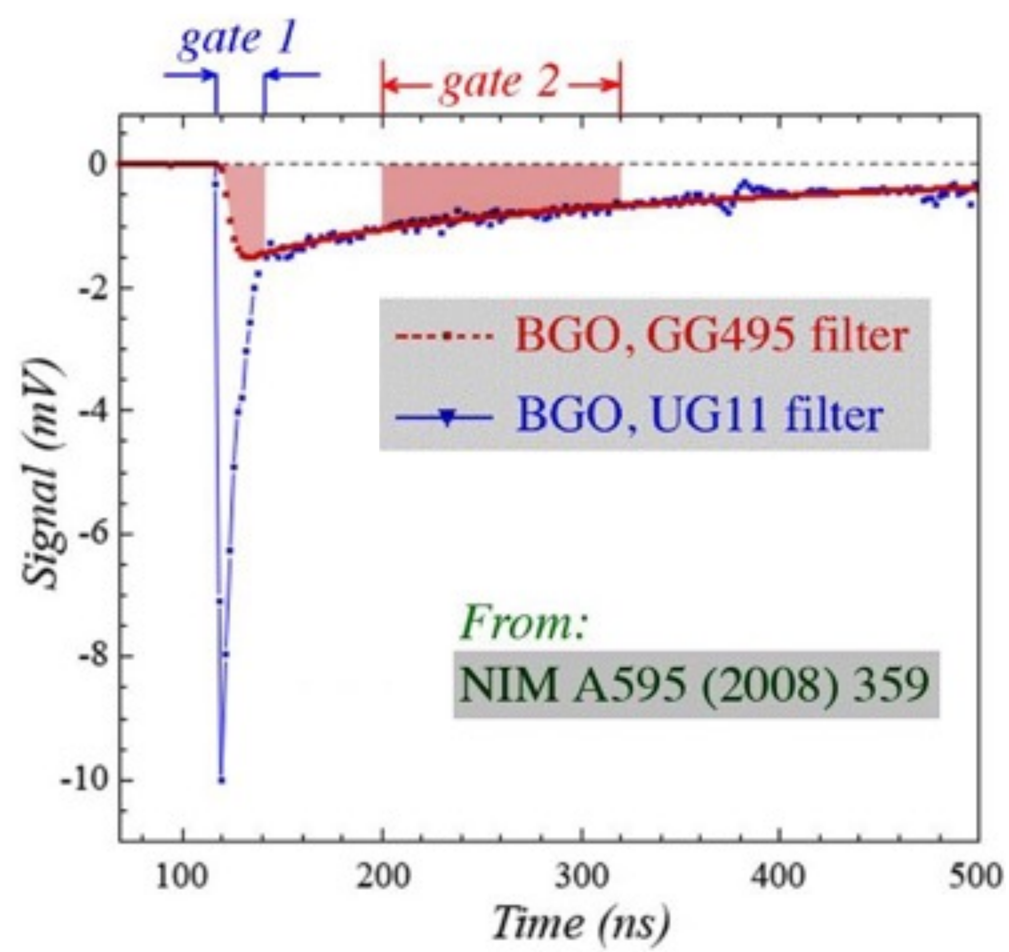
Questions?

Separate C and S in high Z scintillating crystals

	Cherenkov	Scintillation
Time	prompt	exponential
Wavelength	1/λ	peak
Direction	Cone	isotropic
Polarization	polarised	unpolarised

- Timing analysis can extract the two components from one signal





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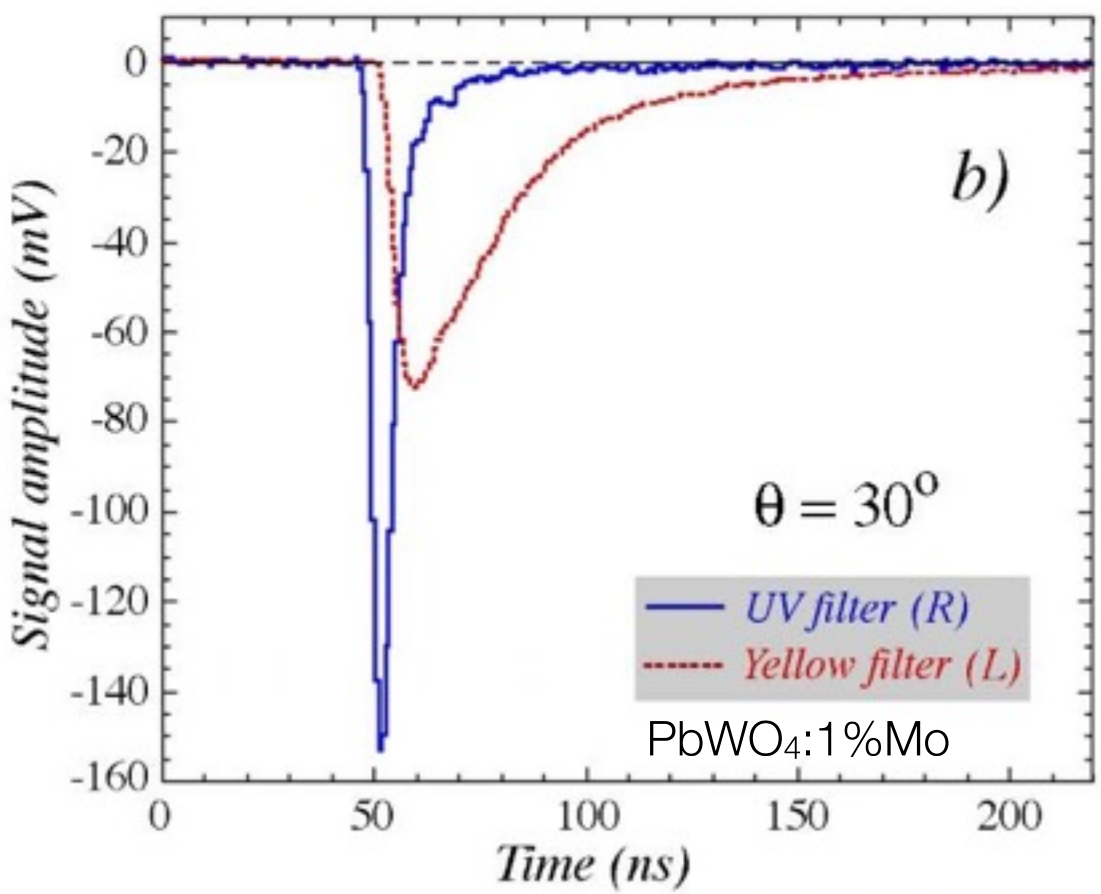
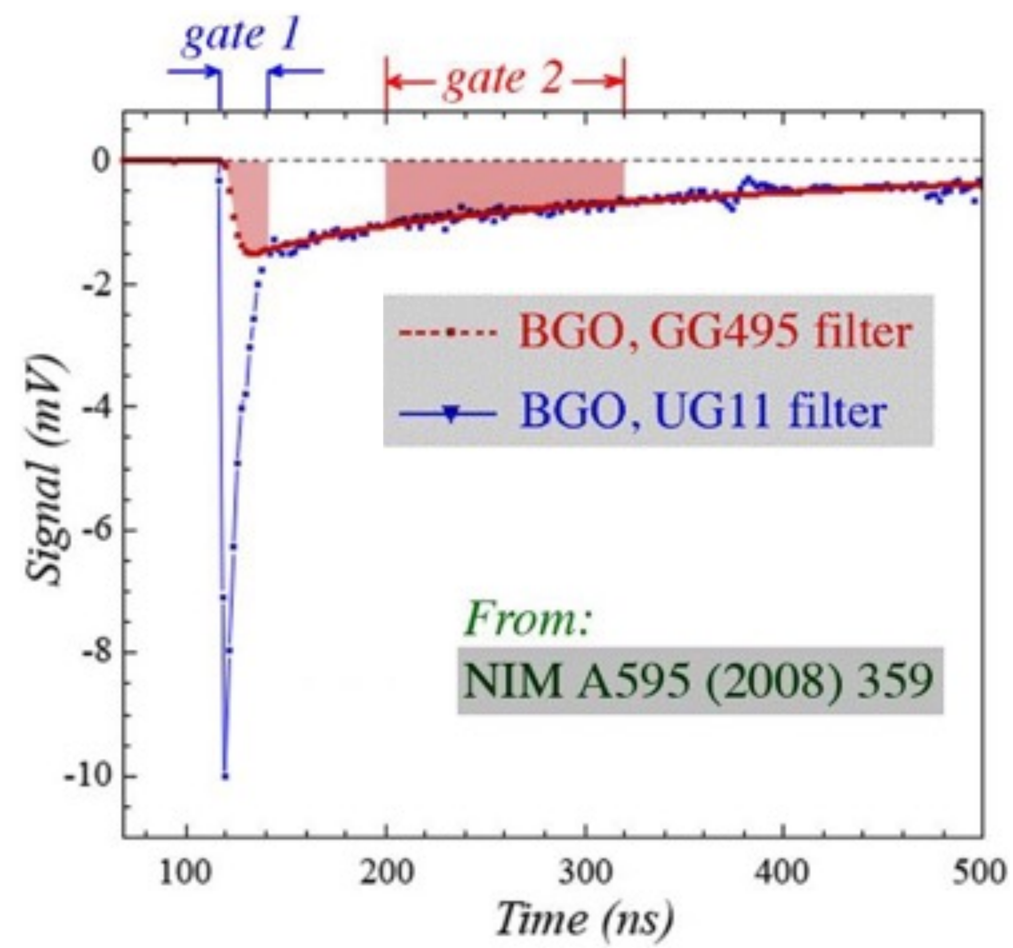
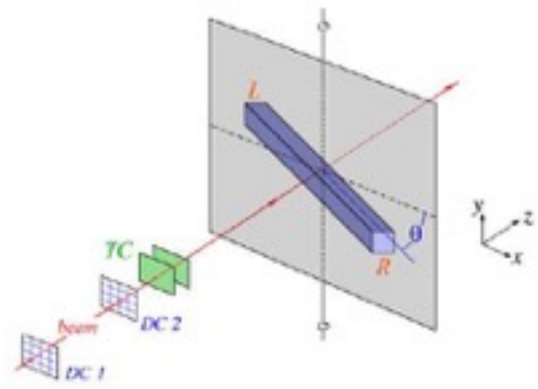


PbWO4:1%Mo

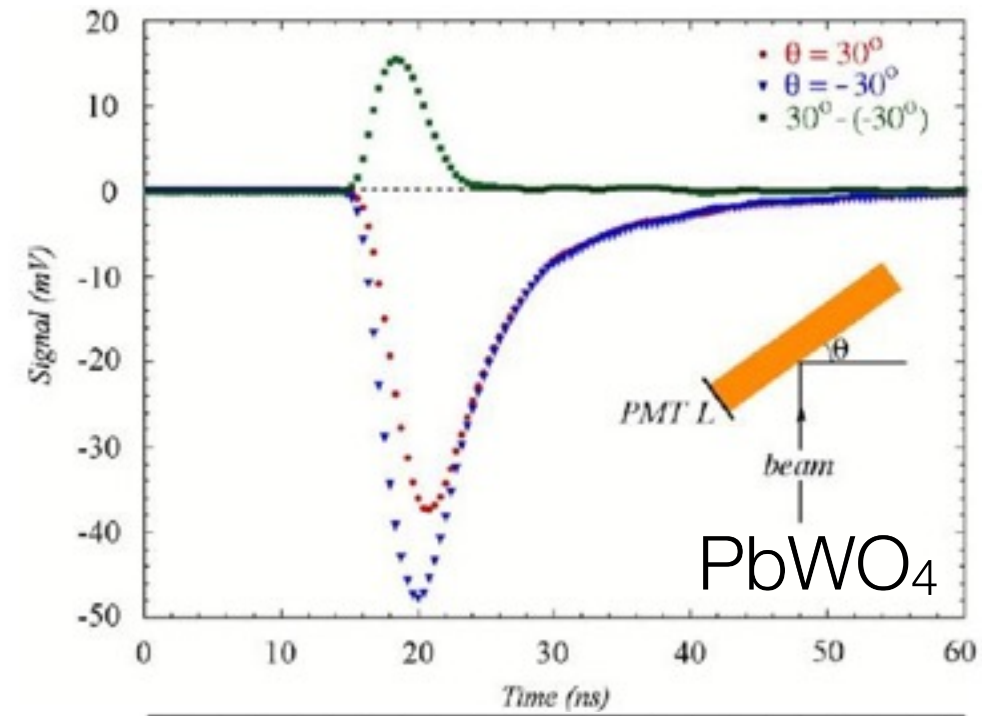


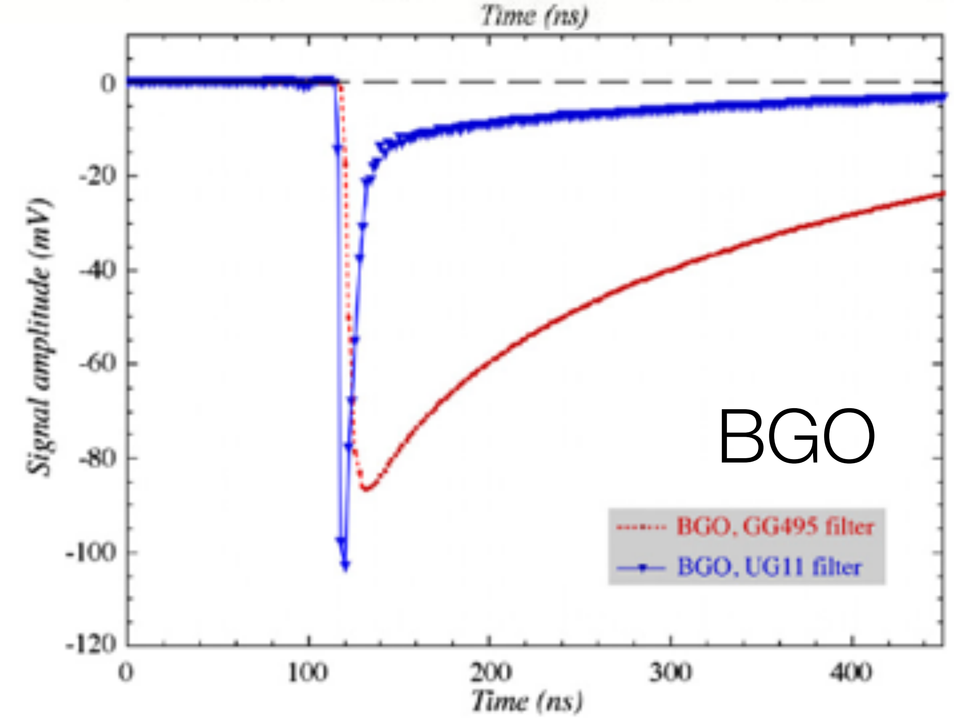
Single crystal studies



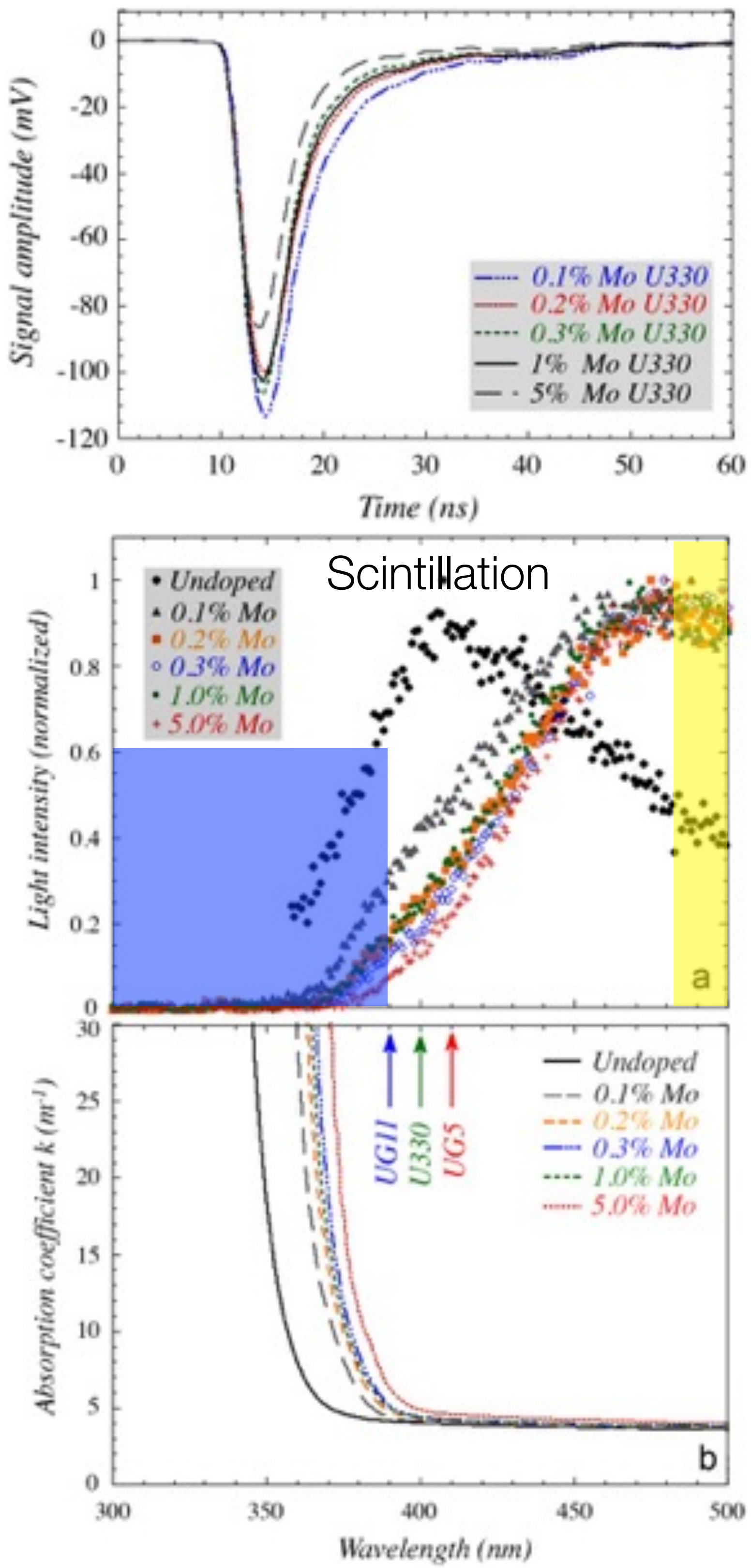
- Directionality used to detect Cherenkov

- Average 30 pe/GeV
- BGO provides better separation
  - Long S tail
  - well separated spectrum
- C component is still a small compared to S

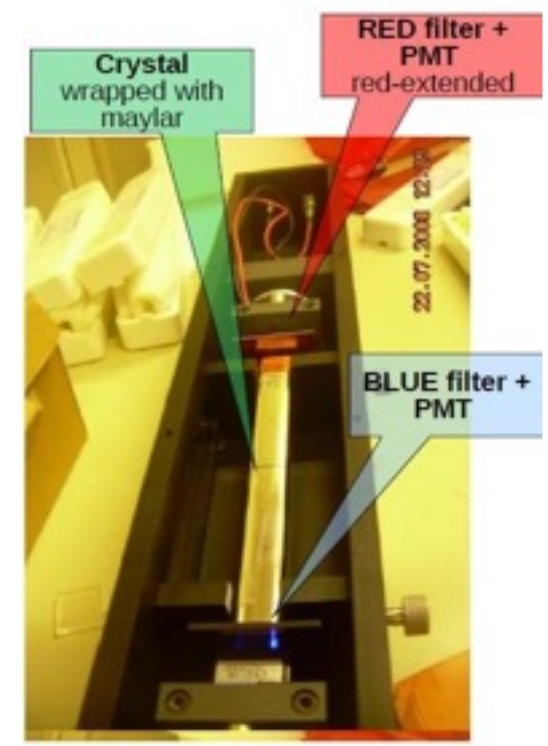




PWO crystals optimizaion

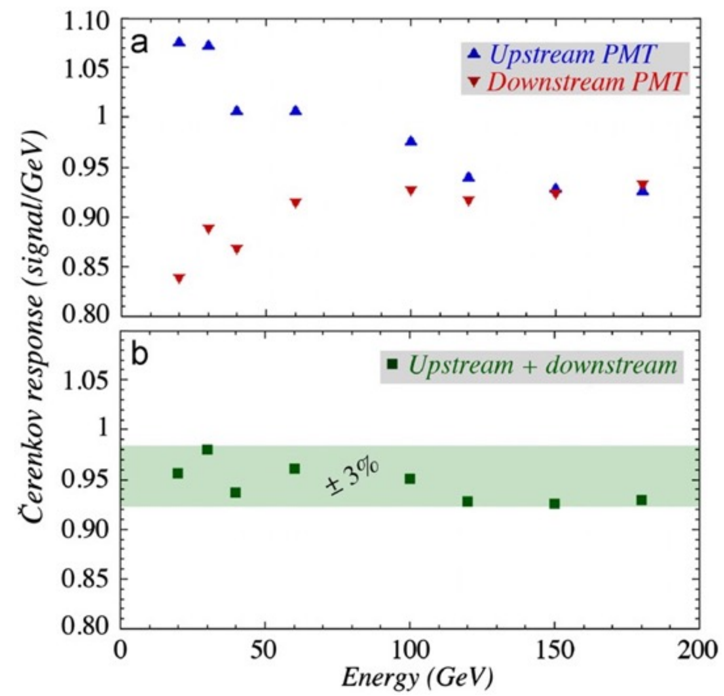


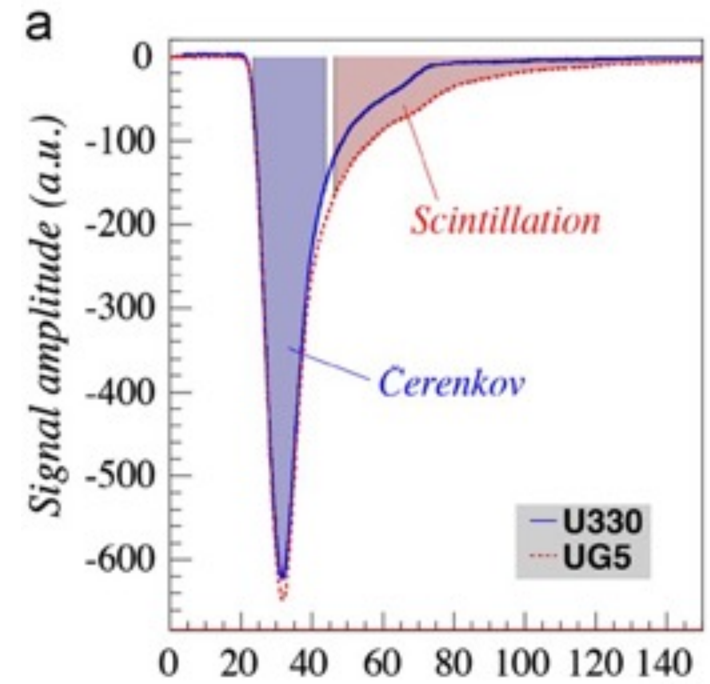
- Mo/Pr doping to better separate C and S
  - Shift emission spectrum towards visible
  - Slower decay time (better C/S separation)
  - But increased UV self absorption
- 0.3%Mo selected

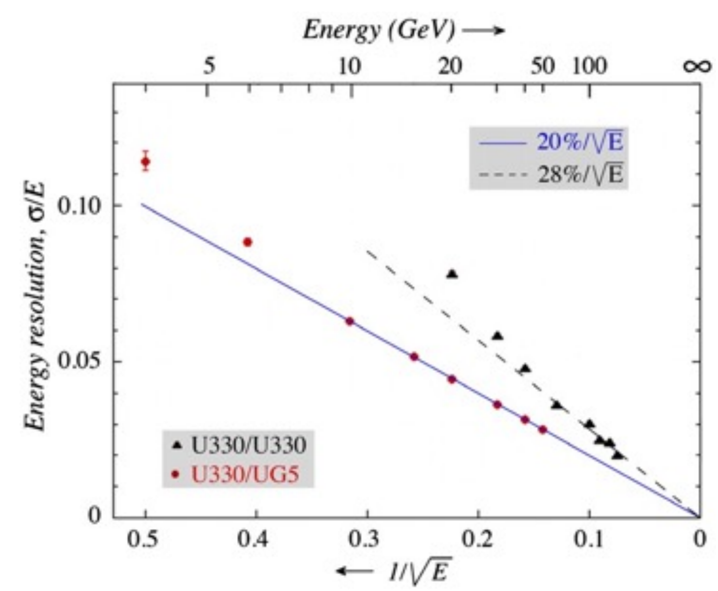


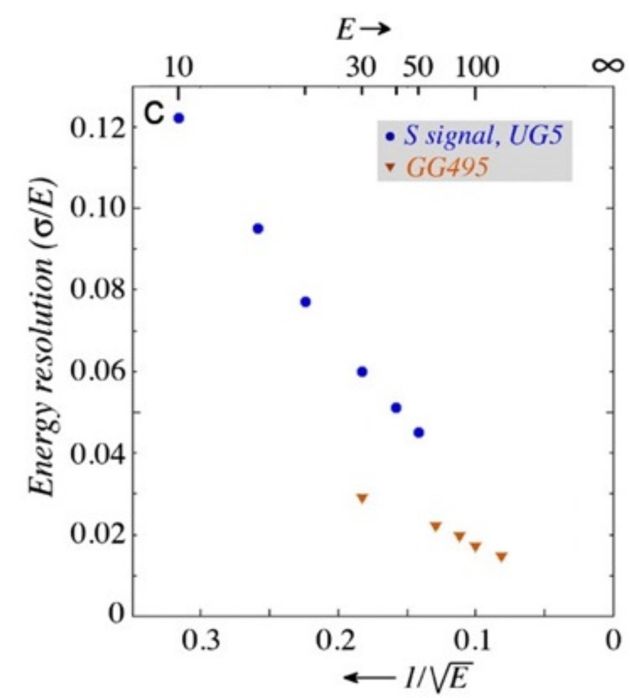
PWO matrix em performance

- Position dependent response in single side mode due to UV self absorption
- We use a combination of
- C Resolution improves as we collect more UV photons









Limits of the crystal approach

- In inorganic scintillators h/e_{sci} is too low and the intrinsic variance of the Cherenkov hadronic response severely limits dual readout resolution (cfr. arxiv: 1210.2334)

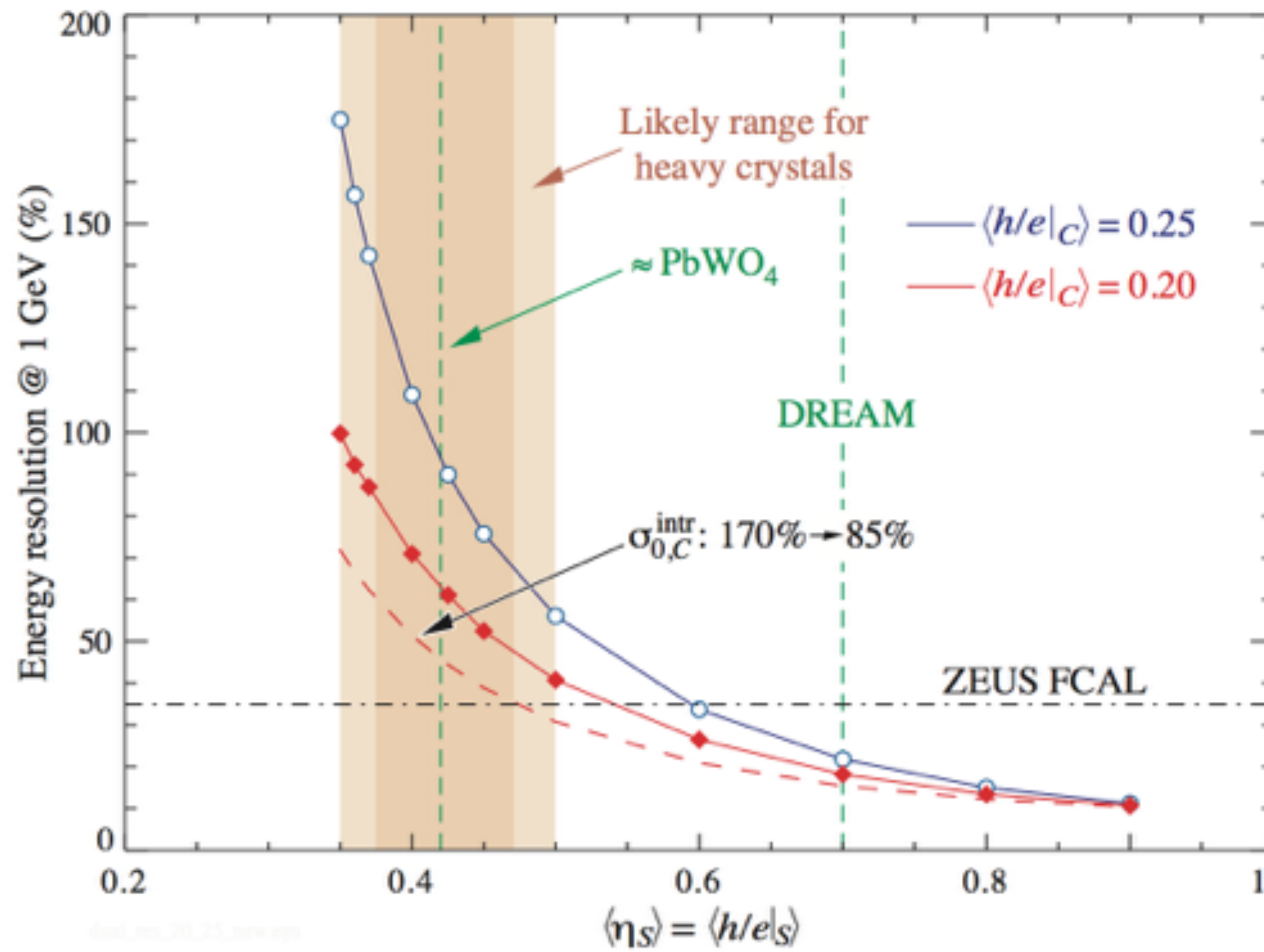


Figure 6: Dependence of resolution on η_S at two values of $\eta_C \equiv h/e|_C$. The results for $\eta_C = 0.20$ are essentially those for $\eta_C = 0.25$ displaced to the left by 0.05; it is the *contrast* between η_C and η_S that determines the resolution. The dashed line shows the effect of halving the width of the η_C p.d.f.

- Increase h/e_{sci} by enhancing response to hadrons?

Particle ID

	Electron	Pion	
Lateral shower profile (S15/∑S)	85%	40 - 50 %	Tower size: 1.6x1.6 R_M, 0.2x0.2 λ_{int}
C/S	1 (EM particles are relativistic)	Large fluctuations of the em component	
Start time of the PMT signals	The light is produced at: ~12 cm (10X_0) (on average)	The light is produced at: 60 cm (~2 λ_{int}) (on average)	Time between Trigger and the PMT signal
PMT Pulse (Int. charge/amp.)	relatively small and constant	Large fluctuations	The depth at which light is produced and the em comp. fluctuation