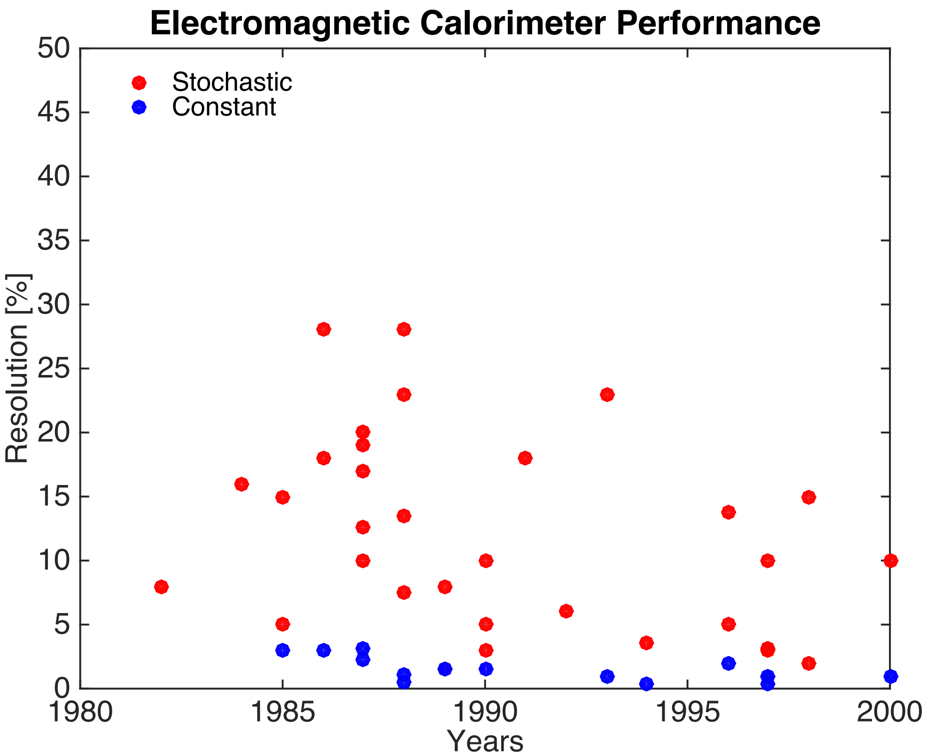
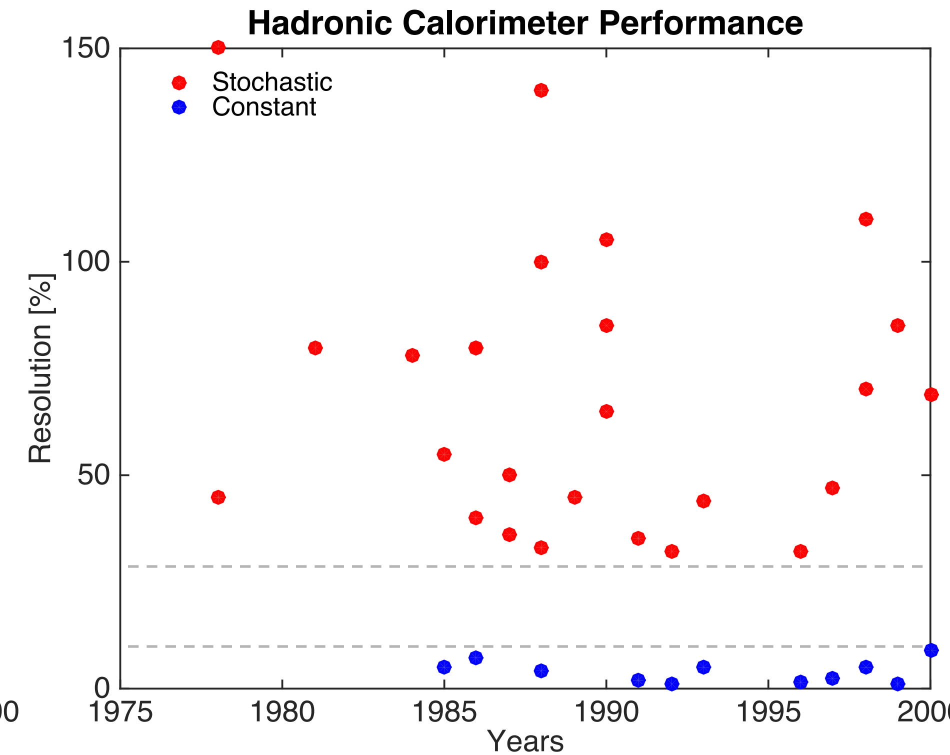
Dual-readout Calorimetry
(for the FCC-hh)

N. Akchurin
Texas Tech University

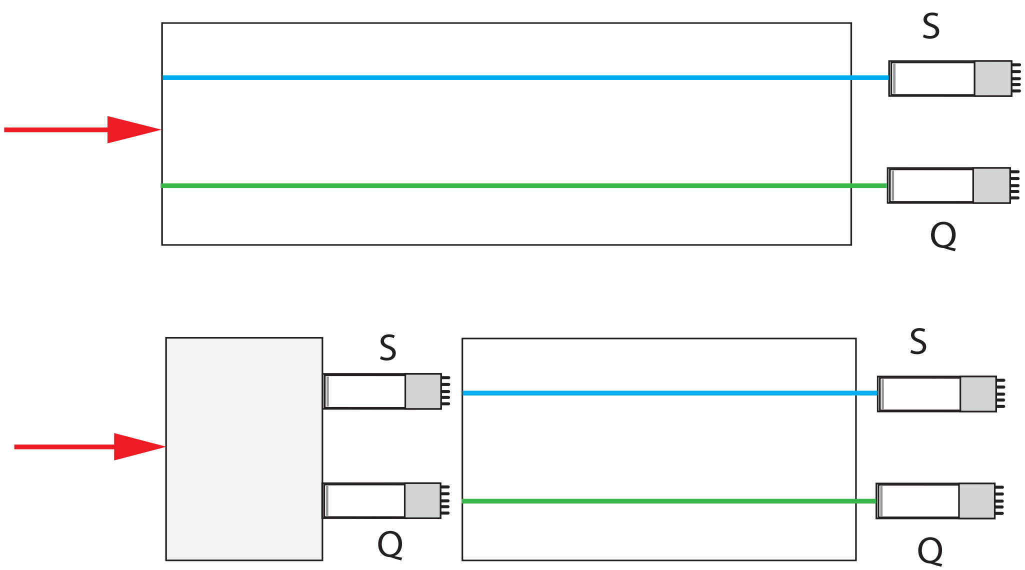
Evolution of Calorimeter Energy Resolutions

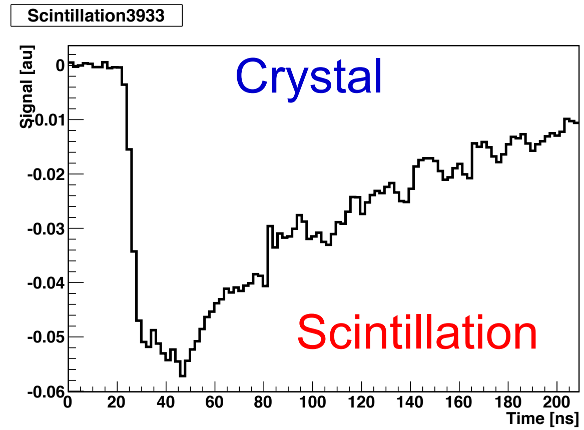


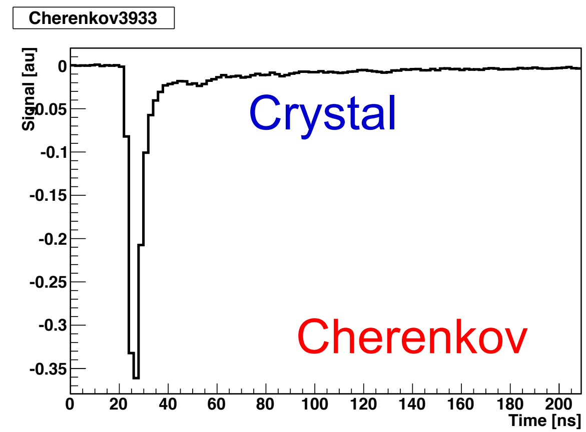


- Sample above includes Fermilab (fixed-target and Tevatron), CERN (SppS, SPS, LEP and LHC)
- There is an improvement in the EM performance of most major calorimeters over time
- The HAD performance has not markedly changed in the two to three decades

Multi-readout Technique





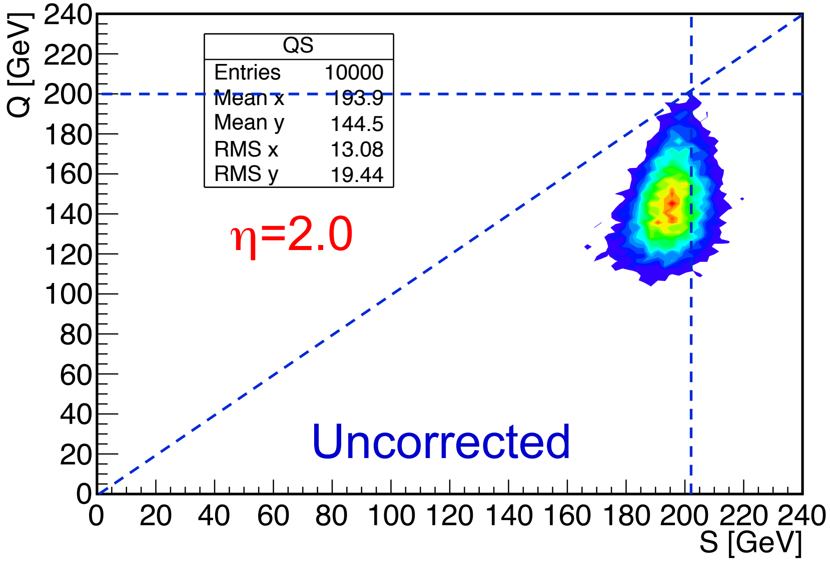


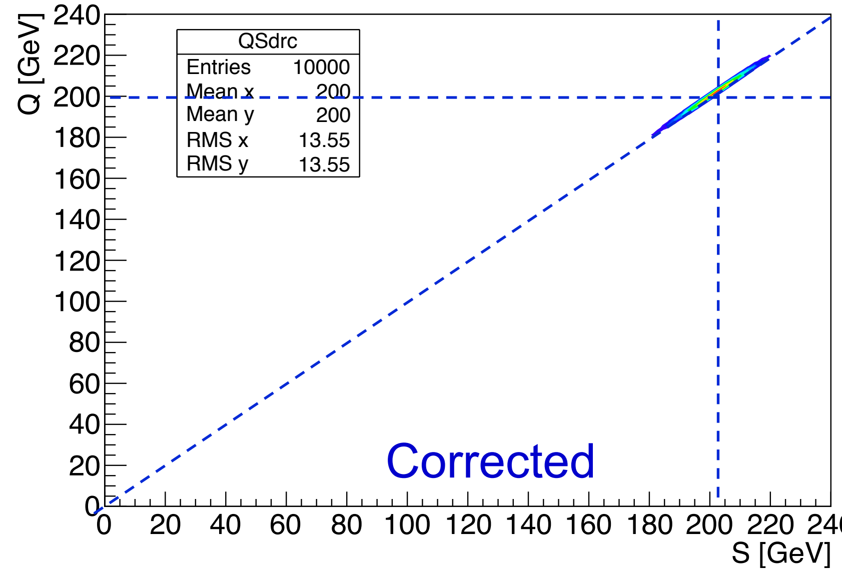
In a dual-readout system, we consider *Q* and *S* signals. The signal separation can be accomplished either physically (as schematically shown above) or by taking advantage of the different characteristics between the scintillation and Cherenkov light in wavelength, directionality, speed of response, or polarization. These signals provide a wealth of information *S, Q,* f_{em}*, PID, z(t), etc* for feature extraction algorithms NIM A537 (2005) 537

Scintillation = Ionization + bremsstrahlung + pair production

Cherenkov = bremsstrahlung + pair production

Dual-readout Technique (Brass – 2.4 mm Fiber Spacing)



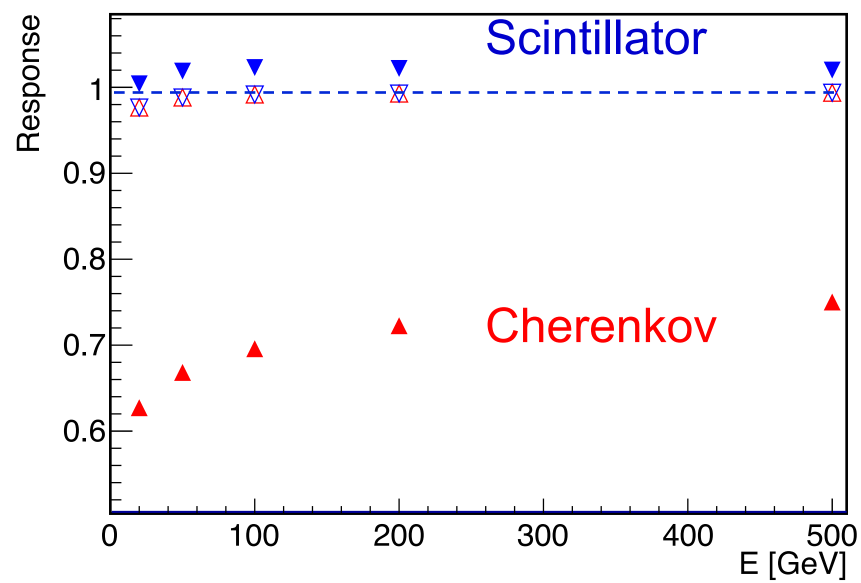


$$\left(\frac{e}{h}\right)_Q = 3.2 \quad \left(\frac{e}{h}\right)_S = 0.9$$

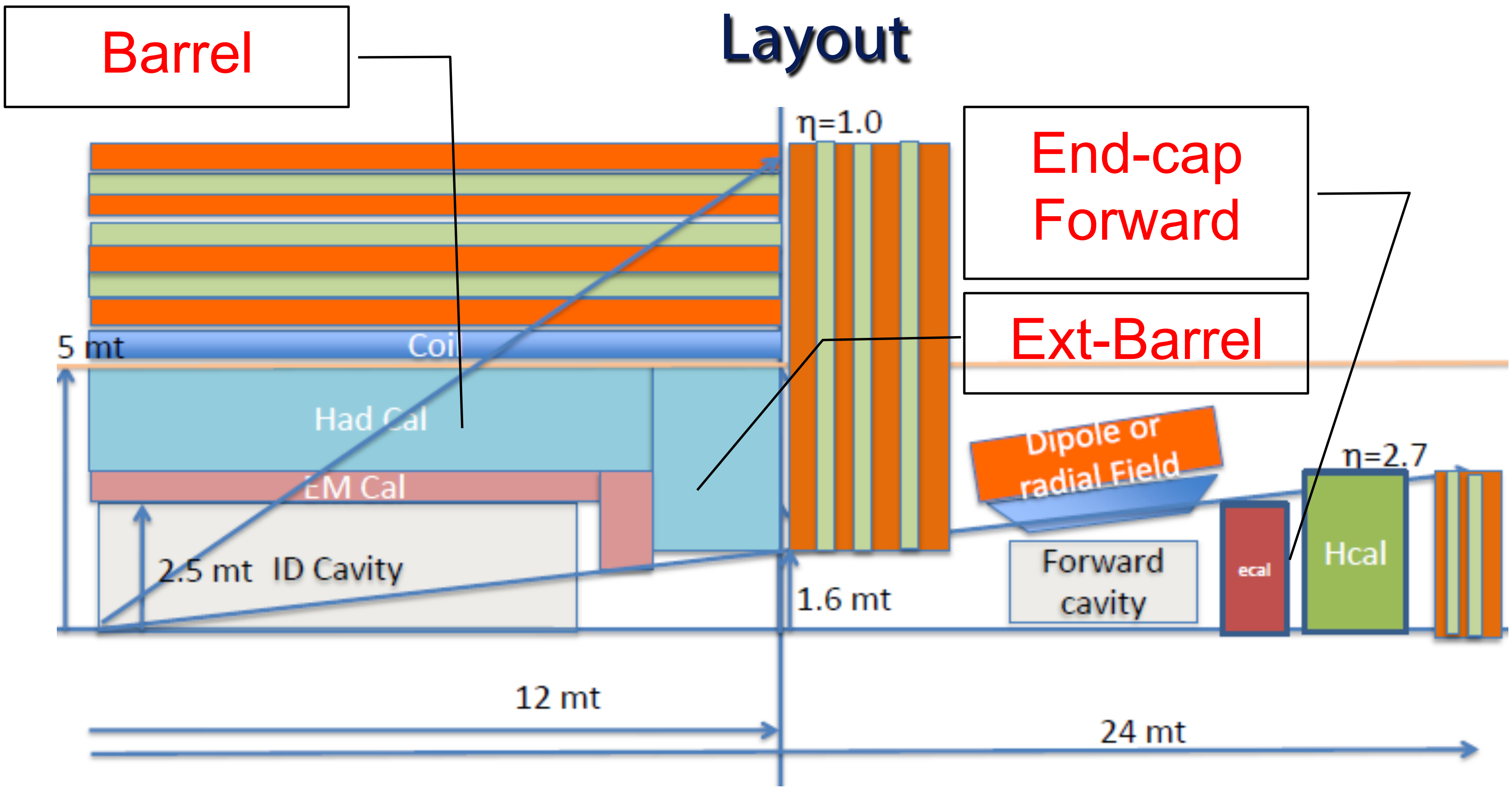
$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$\frac{Q}{S} = \frac{f_{em} + 0.31(1 - f_{em})}{f_{em} + 1.11(1 - f_{em})}$$



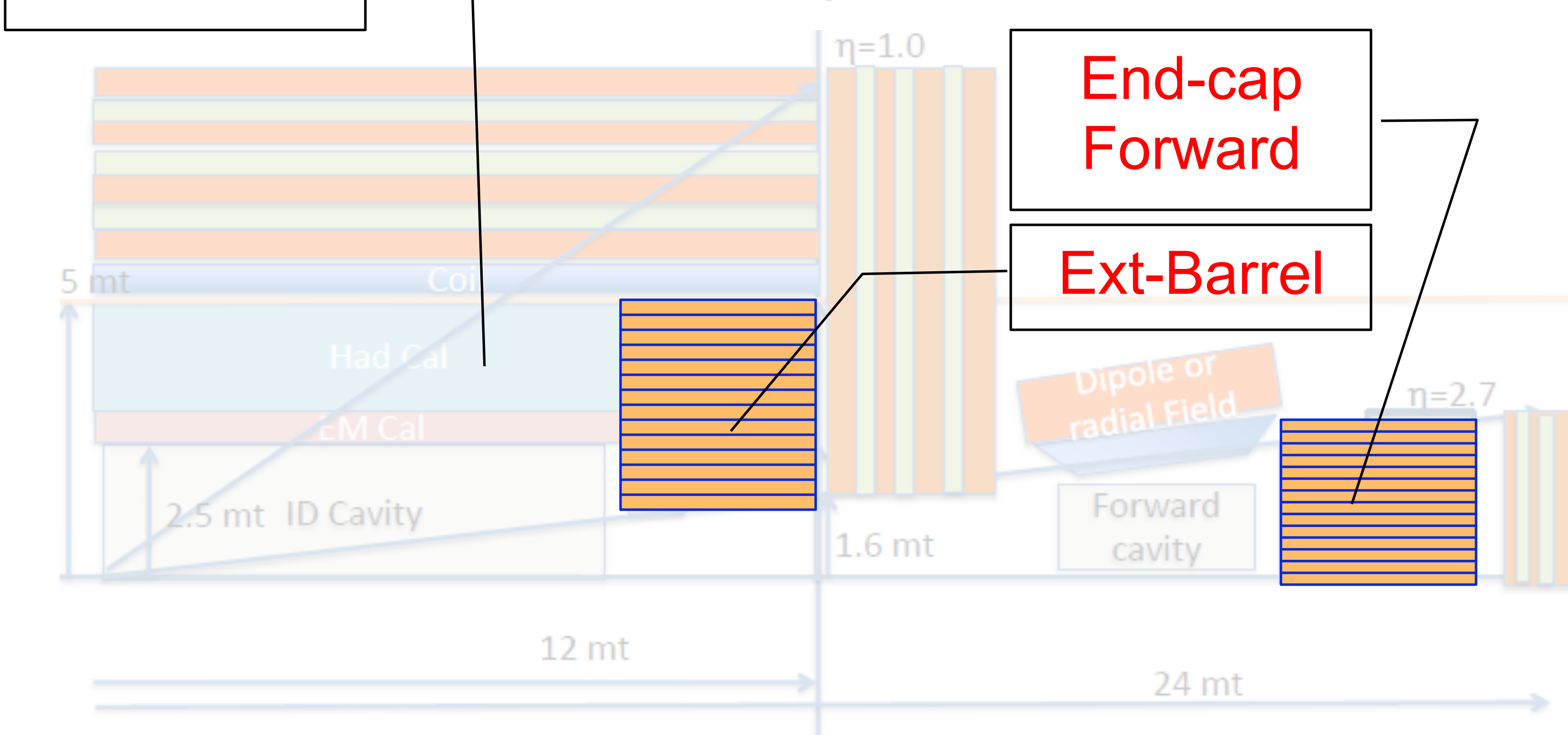
Layout



Four Approximate Geographical Regions

Barrel	(0 < |η| <1.5)	16 m long, 2.5 m radius
Ext-Barrel	(1.5< |η| <2.7)	
End-Cap	(2.7< |η| <4)	3 m outer radius
FCAL	(4 < |η| <6)	1 m outer radius

Layout



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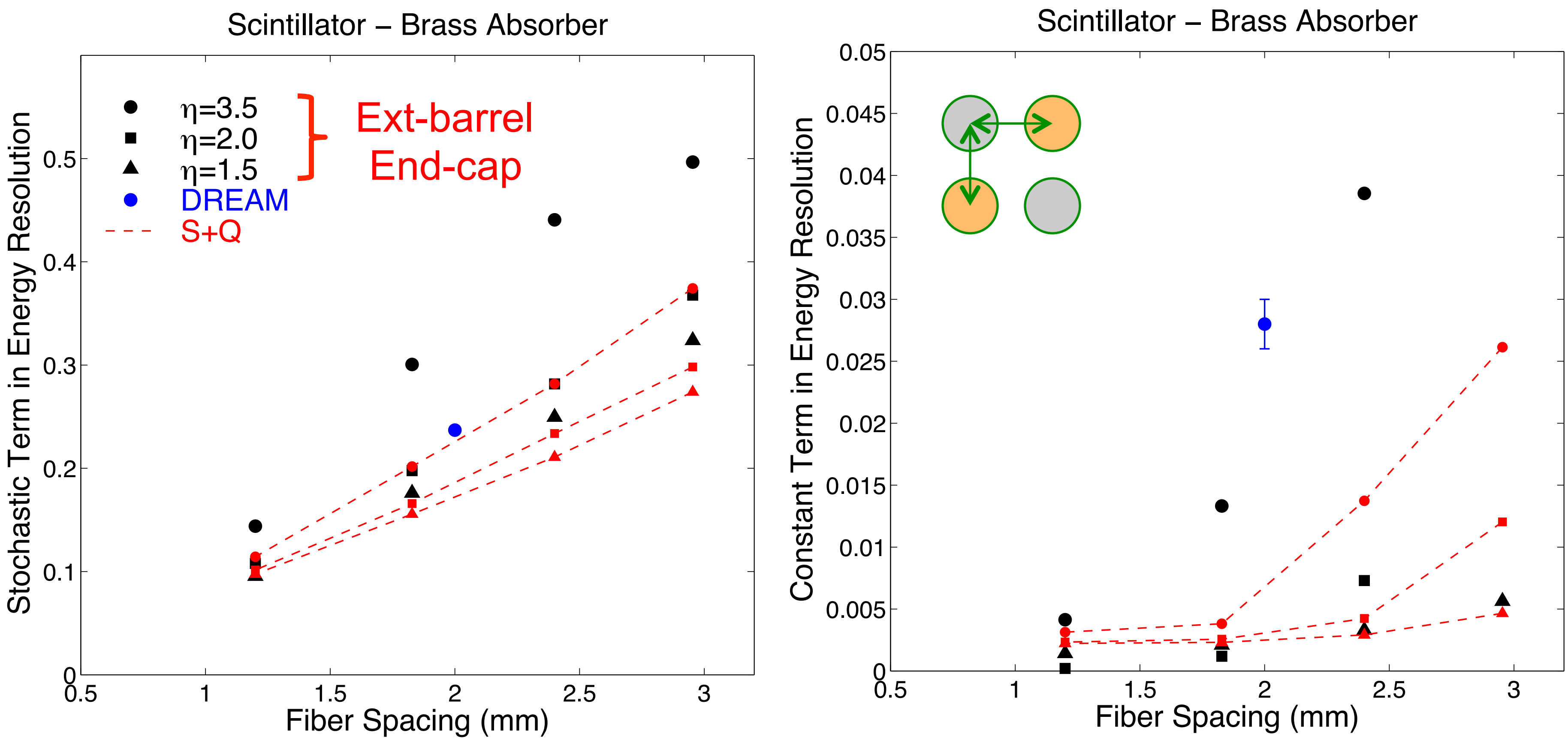
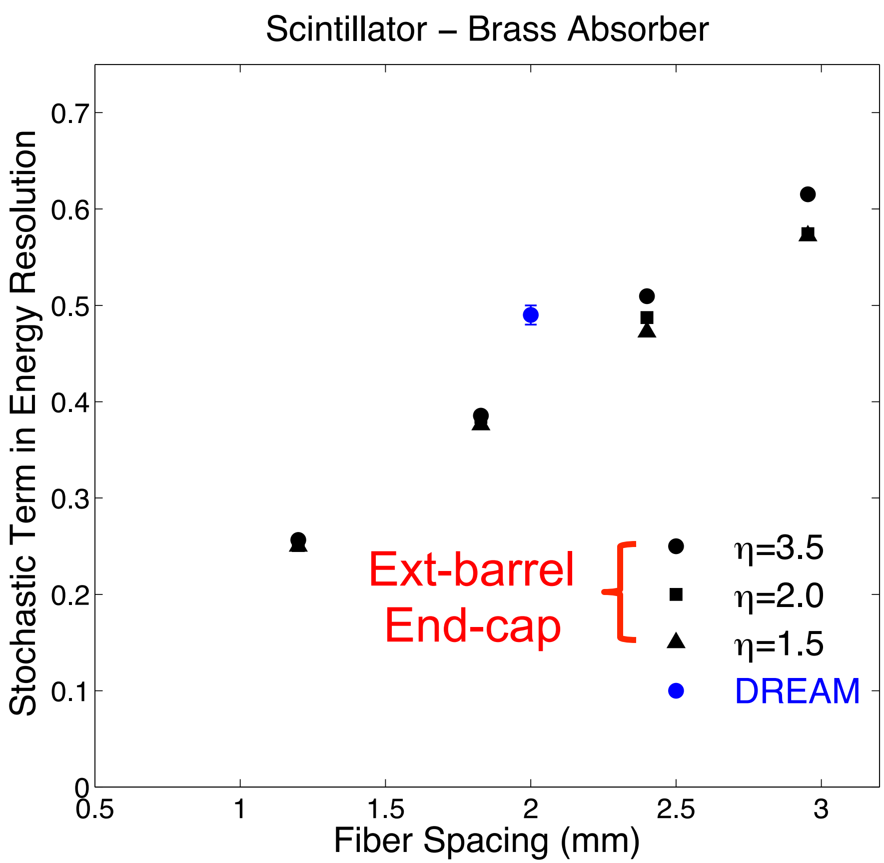
EM Energy Resolution *vs* Fiber Spacing

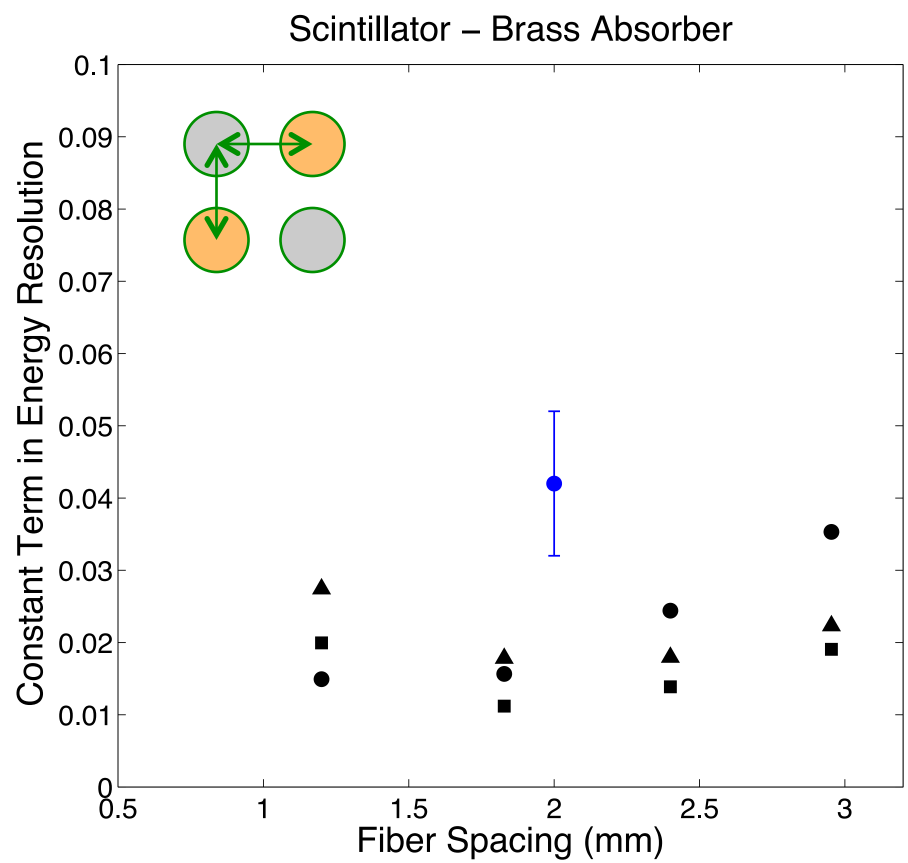


Simulations show that EM energy resolution is ~20%/√E for 2 mm fiber spacing, consistent with expectations based on DREAM data

The constant term is better than 2%

Raw HAD Energy Resolution *vs* Fiber Spacing

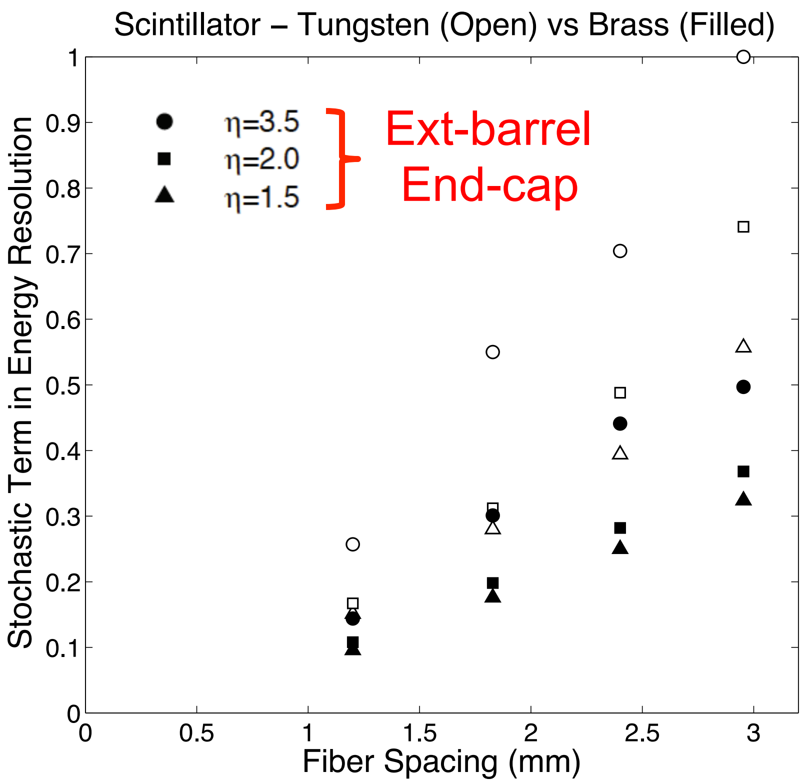


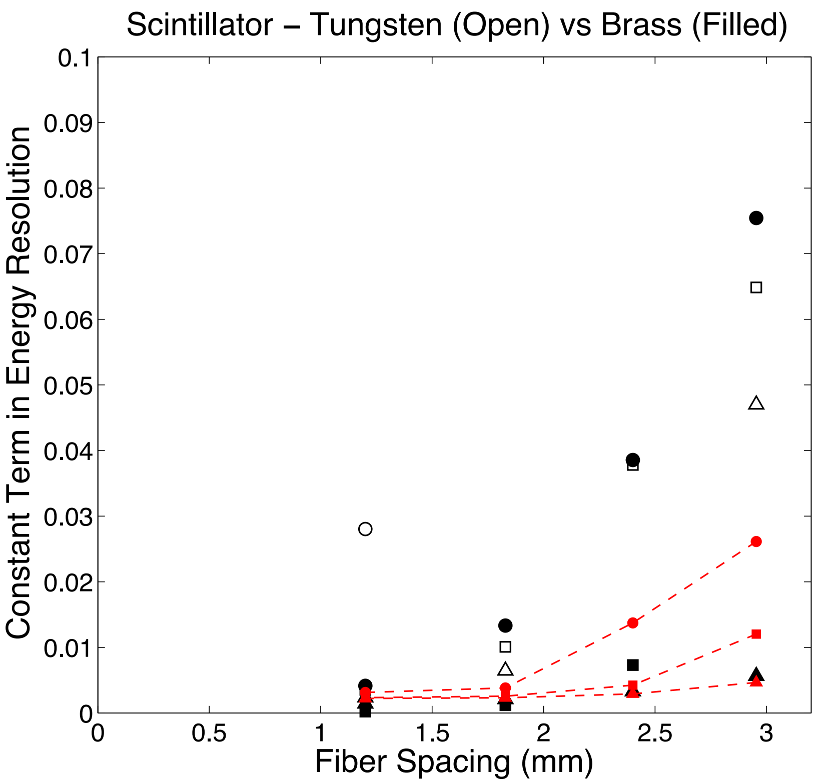


Simulations show that the raw HAD energy resolution is better than ~40%/√E for 2 mm fiber spacing without dual-readout correction, consistent with expectations based on DREAM data

The constant term is <4%

Comparison between Tungsten and Brass (EM)

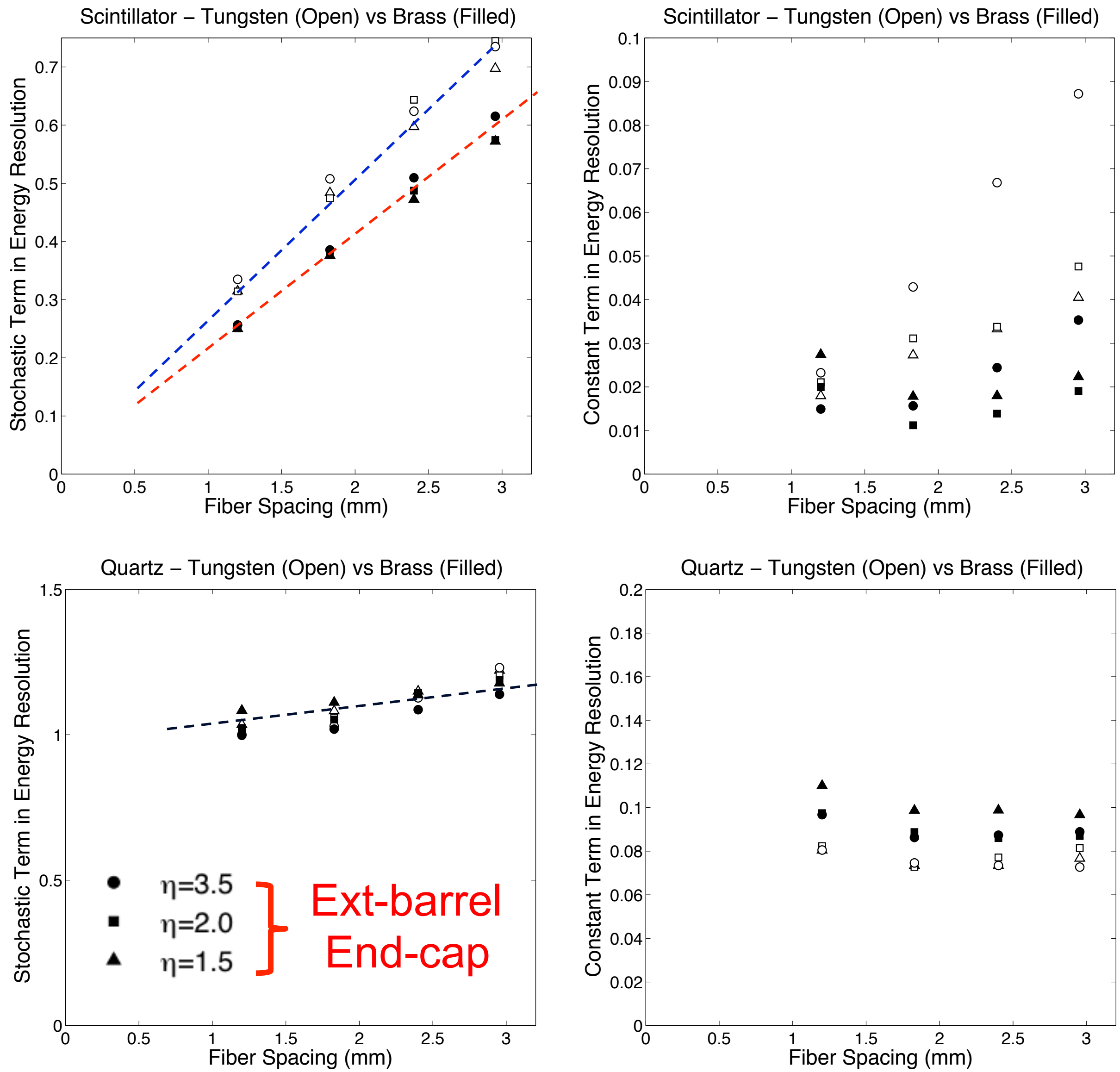




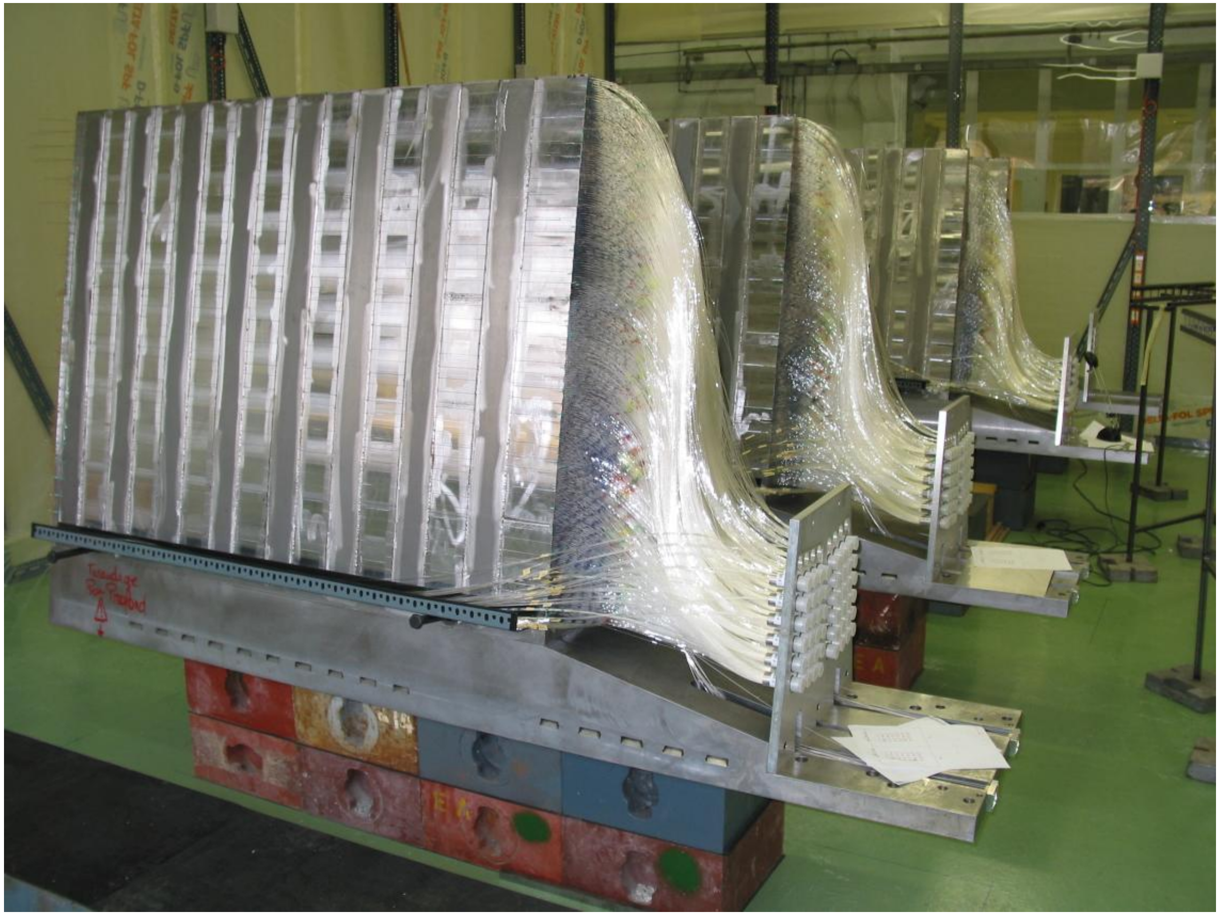
Simulations suggest that EM energy resolution is ~30%/√E for 2 mm fiber spacing in tungsten

Large constant term variations in tungsten are due to impact point/angle

Comparison between Tungsten and Brass (HAD)

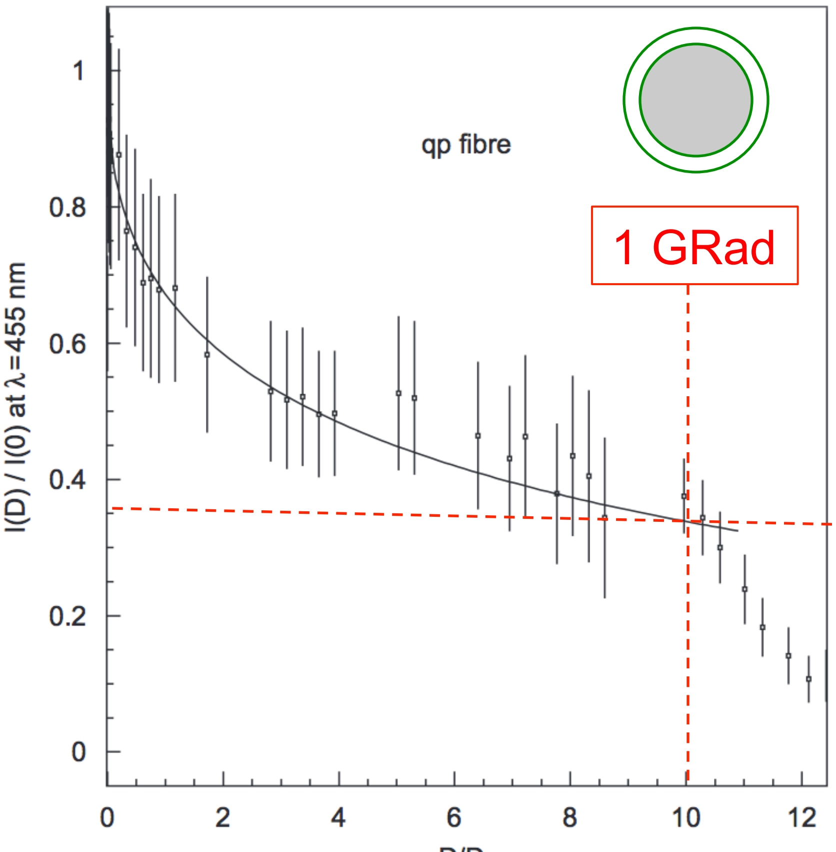


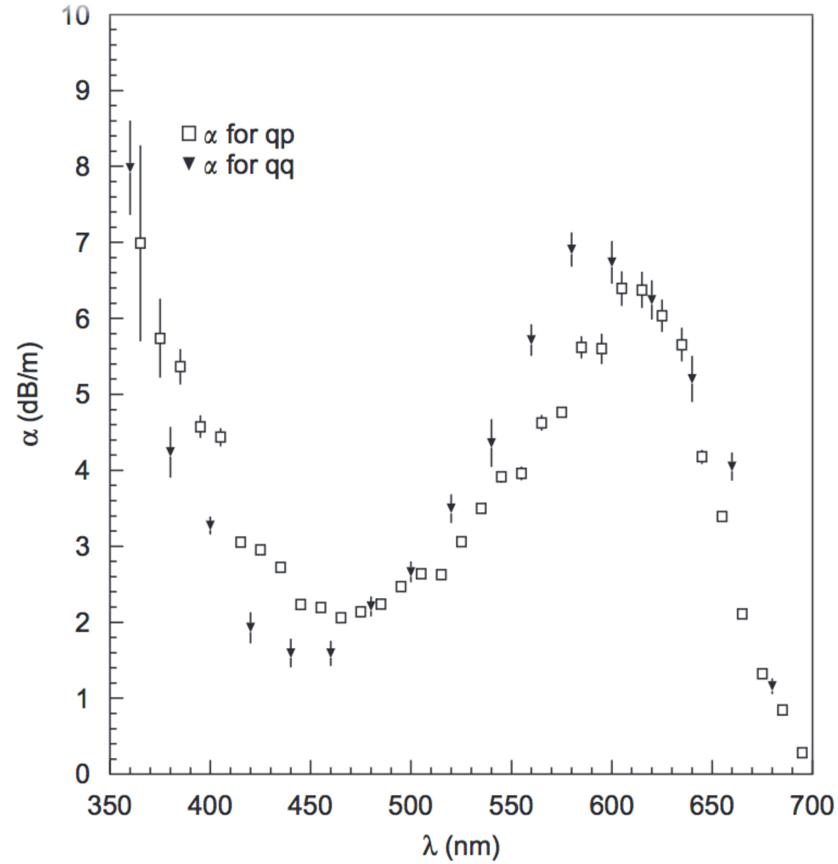
An Example: CMS Forward (Quartz Fiber) Calorimetry



- CMS Forward Calorimeter consists of steel absorber and quartz fibers in high radiation are ($3<|\eta|<5$)
- Extensive R&D effort on the radiation-hardness properties of quartz fibers
- Developed a good understanding of quartz fiber calorimeters (large *e/h*) and experience in operations
- EPJC 53 (2008) 139-166

Quartz Fibers are Radiation-hard



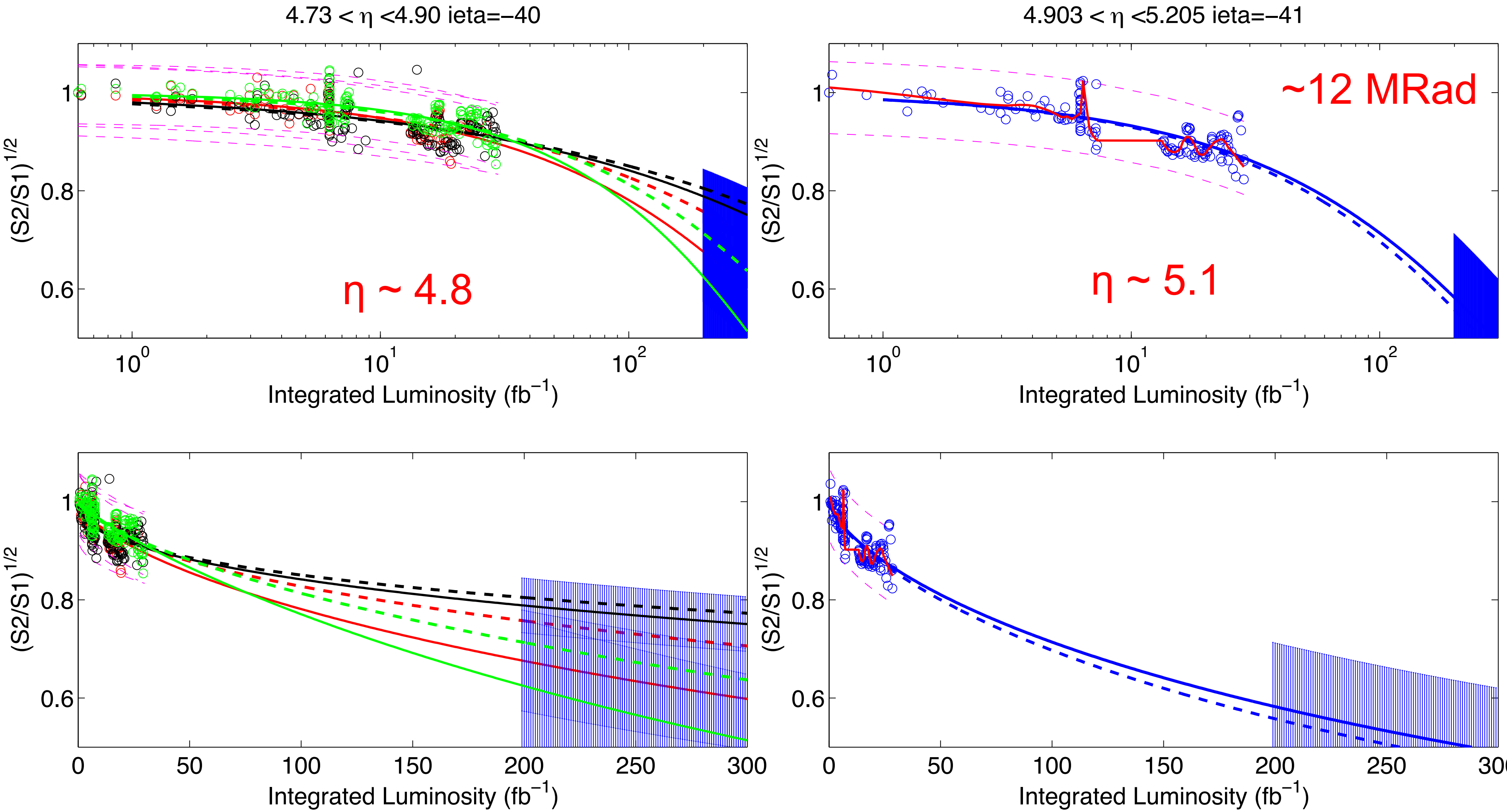


Several radiation hardness tests carried out on quartz fibers during the R&D phase of the CMS forward calorimeter using gammas, electrons and hadrons

Hard-polymer-clad/high OH- fused-silica core fibers (QP) show significant radiation-hardness and can be deployed in forward and end-cap calorimeters

PRL 71(1993)1019, NIM A490(2002)444, NIM A585(2008)20

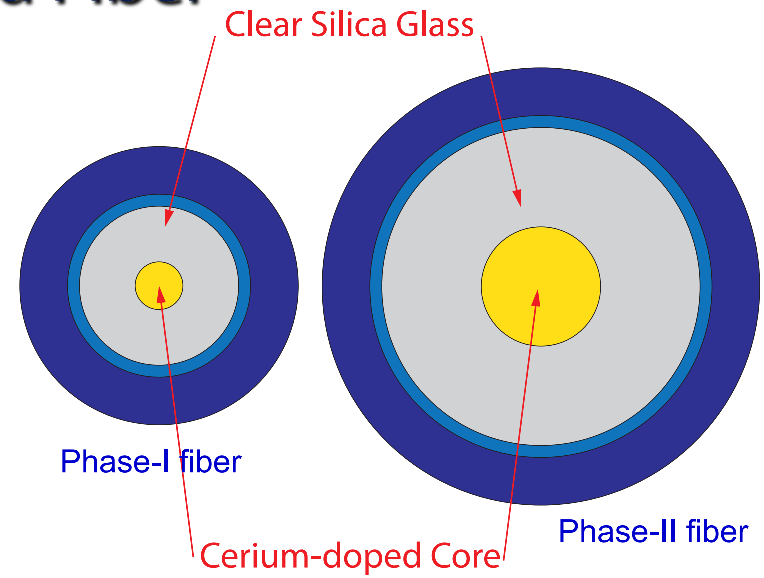
Quartz Fibers and Projections to 300 fb^{-1} at LHC

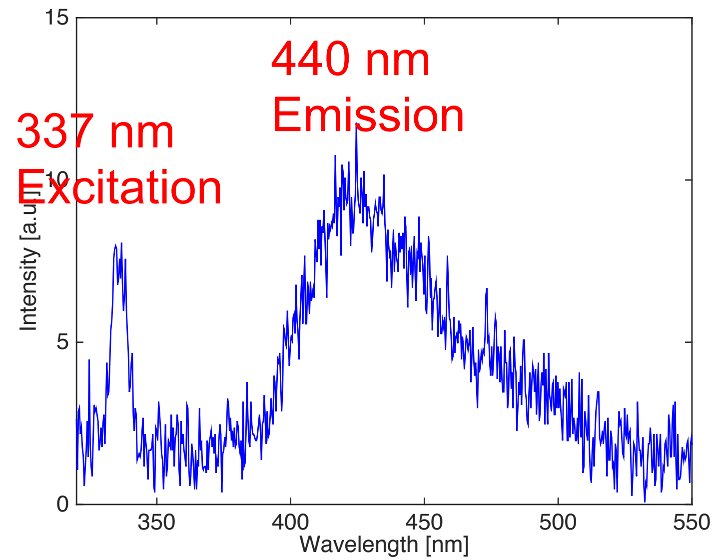


$$T(D,\lambda,z) = \exp\left[-\frac{\alpha L}{4.343}(D(z)/D_0)^{\beta}\right]$$

Scintillation/Cherenkov Light in a Single Radiation-hard Fiber

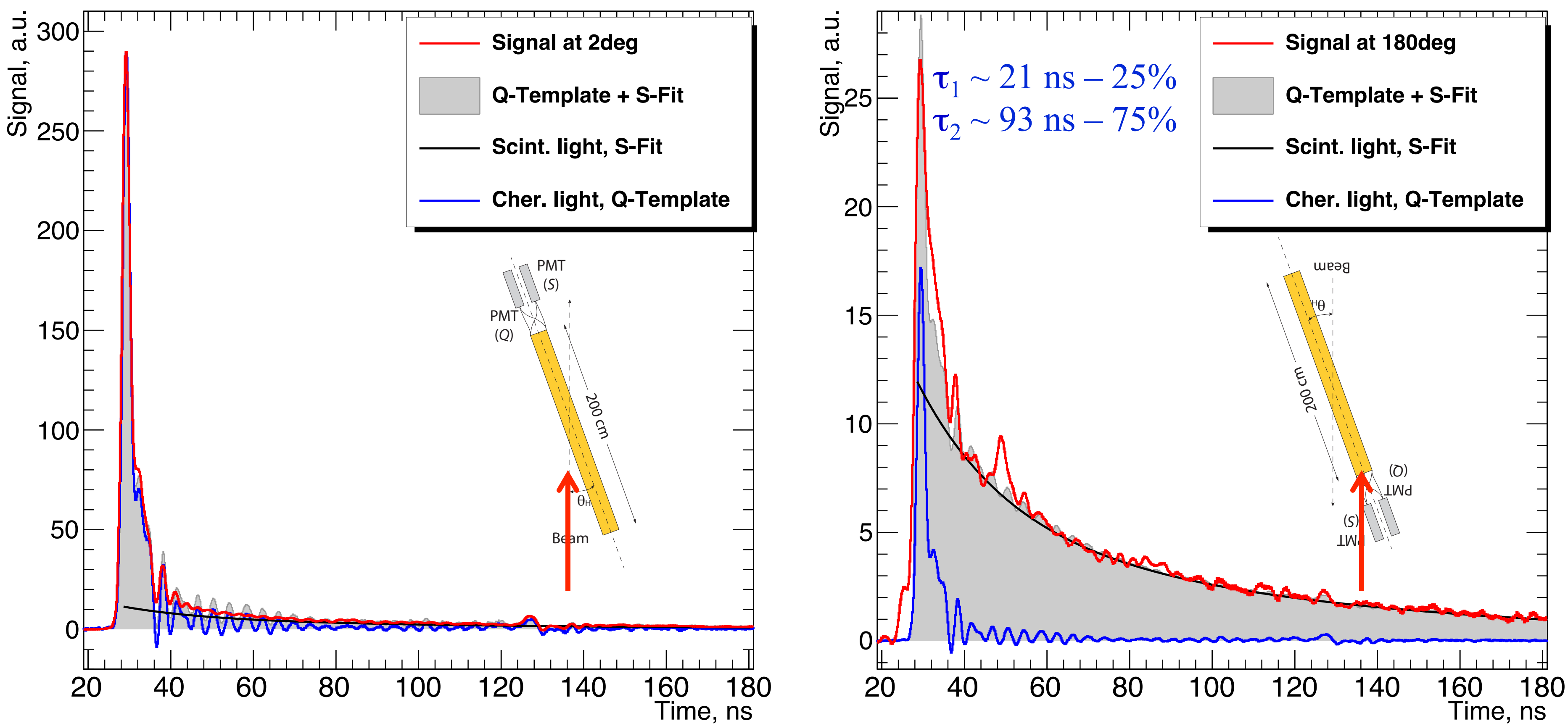
- Several R&D projects are underway investigating cerium-doped fused-silica fibers ($SiO_2:Ce^{3+}$) and a number of prototype fibers have been produced
- It may be possible to use a single fiber (*e.g*. $SiO_2:Ce^{3+}$) to extract both Cherenkov and scintillation light at the same time reducing the number of readout channels by a factor of 2 in dual-readout
- Preliminary results on radiation hardness are encouraging



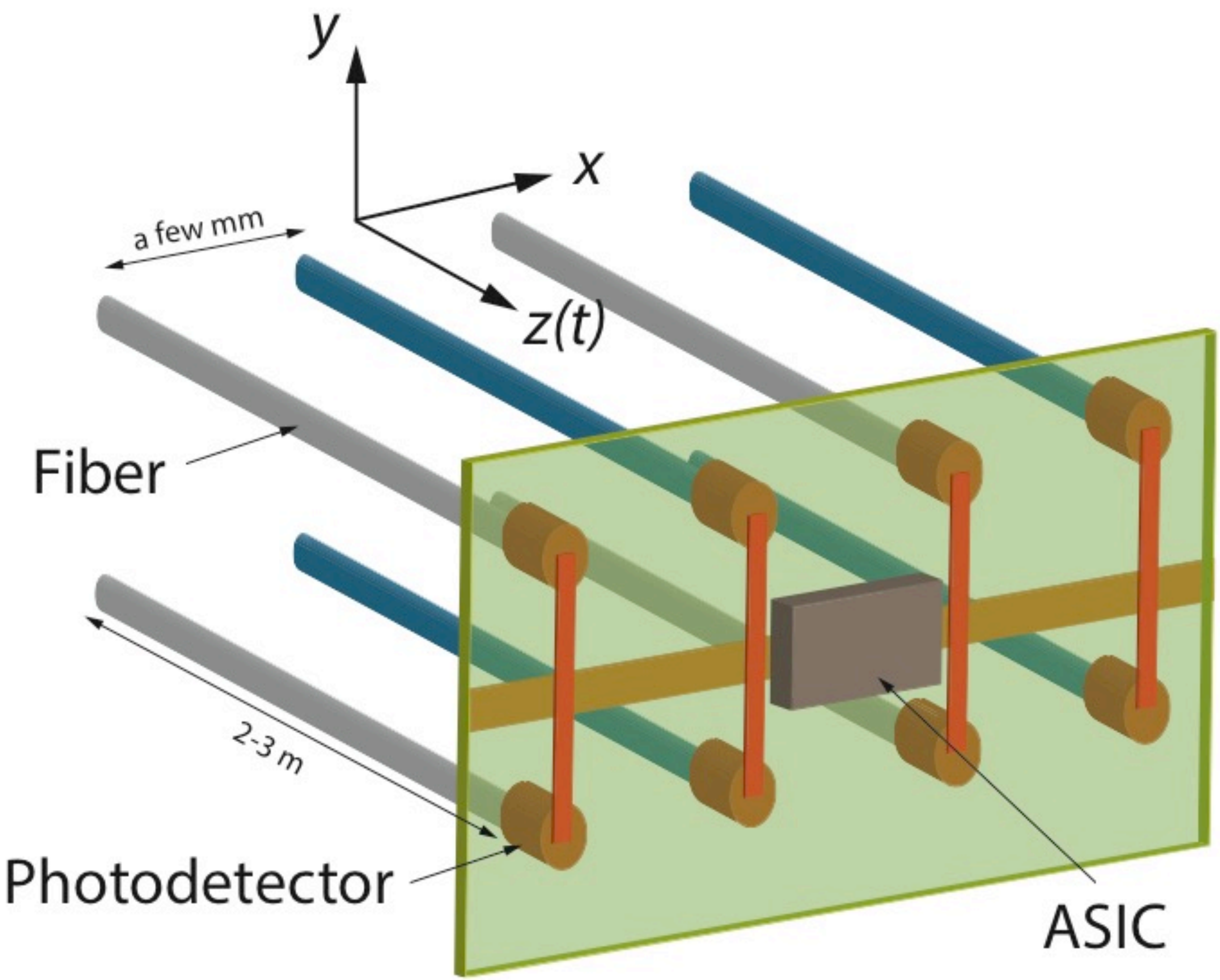


Scintillation/Cherenkov Light in a Single Radiation-hard Fiber - II

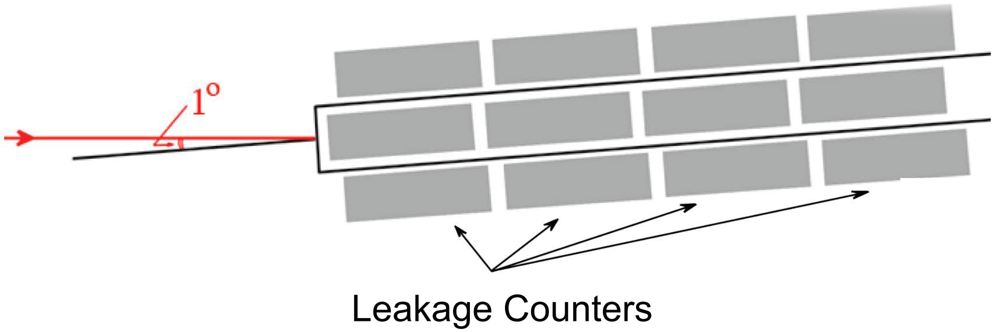
The Cherenkov (SiO_2) and scintillation ($SiO_2:Ce^{3+}$) light coexist in a single fiber and the balance between the two types of light can be "tuned" by geometry

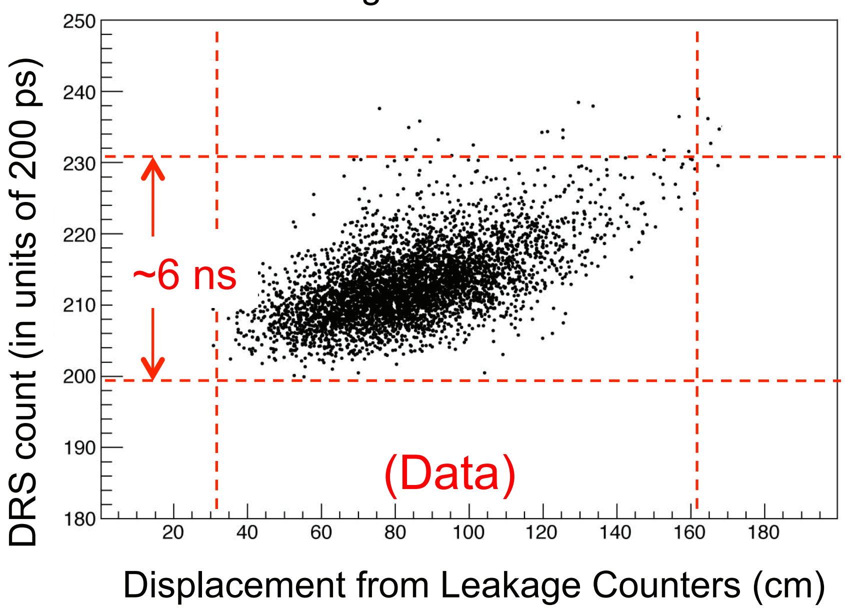


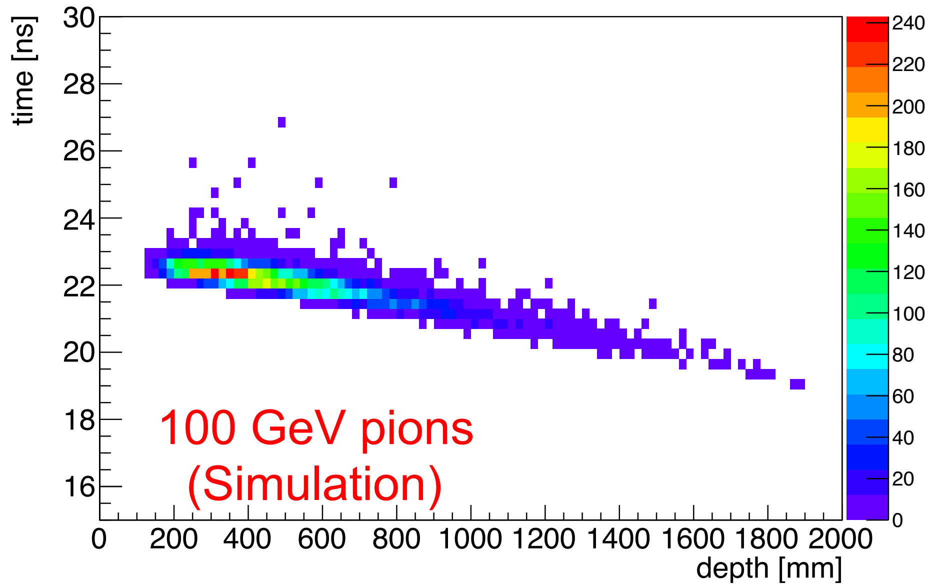
Transverse/Longitudinal Granularity



DRS *vs* Position Measurements with Beam

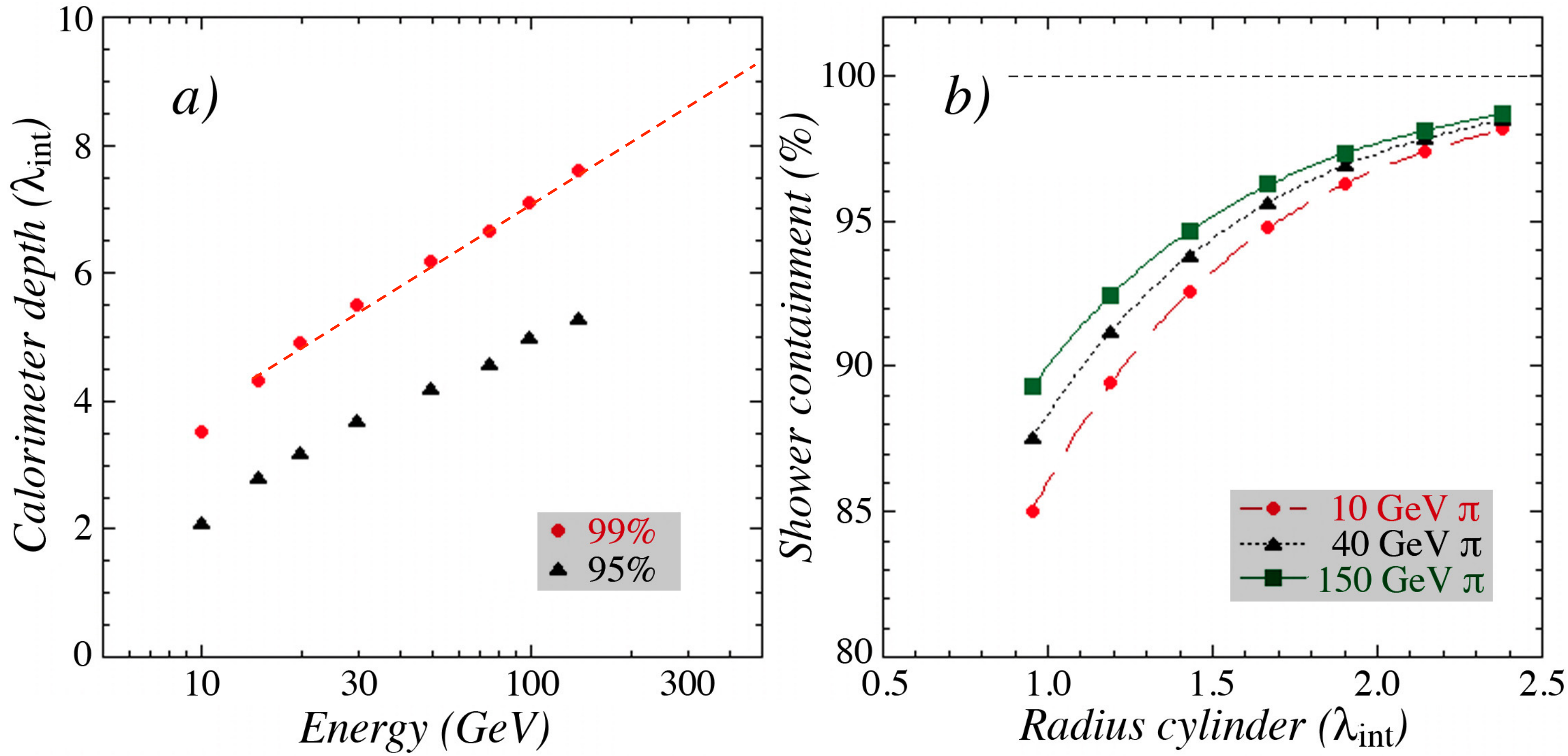






DREAM/RD52 measured the correlation between the gravity of 'light' in a calorimeter and the time of arrival of photons. The precision by which the signal shape is measured determines the effective longitudinal segmentation

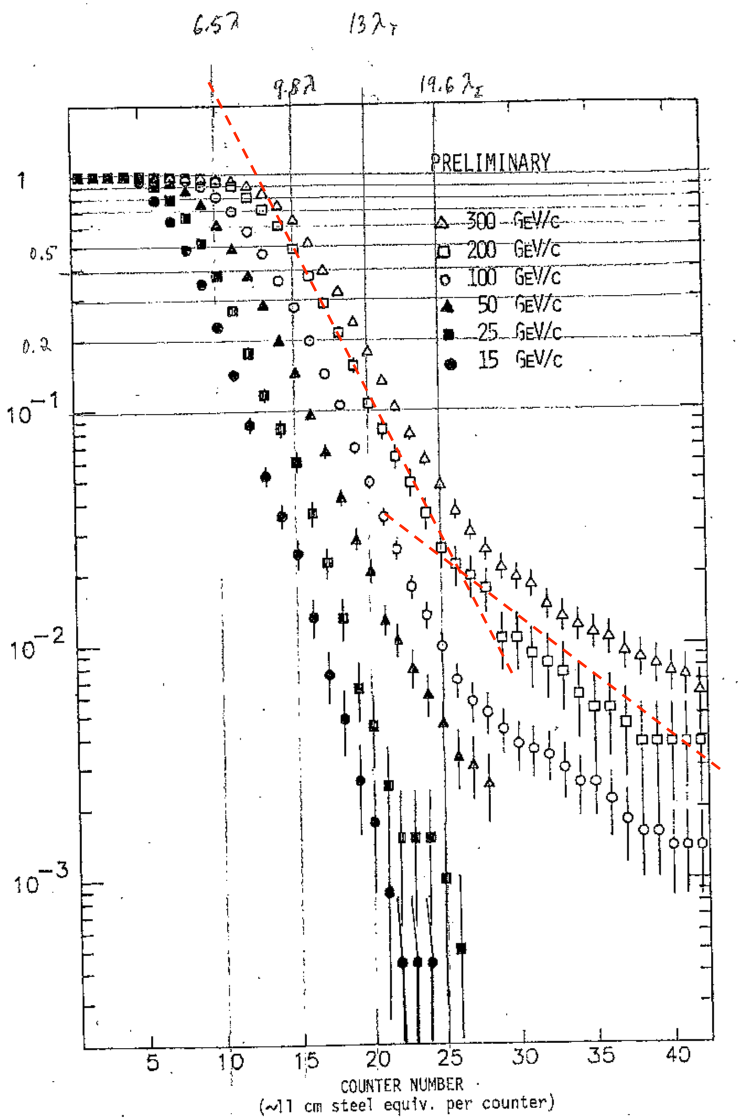
Longitudinal and Transverse Containment for Hadron Showers - I



a) Iron-based calorimeter longitudinal shower containment is 99% at <10 λ_I for 500 GeV charged pions NIM 180 (1981) 429, NIM A666 (2012) 80-97

b) Lead-based calorimeter transverse shower containment is ~99% in less than 2.5 λ_I NIM A606 (2009) 362-394

Longitudinal and Transverse Containment for Hadron Showers - II



- Probability for at least one MIP to occur at a depth of steel for different hadron incident energies
- There is an irreducible component in hadronic showers due to decay muons in the absorber. Enlarging the calorimeter from 10 to 13 λ_I will reduce this type of a leakage by a factor ~2.5 for high energy (~200 GeV) hadrons

R&D Areas for Dual-Readout for FCC

Dual-readout technique may offer unique capabilities for the FCC experiments

R&D activities may include:

1. Fast, bright, and radiation-hard scintillating fibers (Ce, Pr, …)
2. Innovative waveguide structures accommodating Cherenkov and scintillating light
3. Crystals for ECAL and dual-readout
4. Multi-GHz, low power, compact waveform digitizers
5. Fast, miniature and radiation-hard photodetectors
6. 3D metal printing technologies for calorimetry applications
7. …

Absorbers

	Z	Density (g/cm^3)	E_c (MeV)	X_o (mm)	Moliere (mm)	λ_{int} (mm)	$(dE/dx)_{MIP}$ (MeV/cm)
Fe	26	7.87	22.0	17.6	16.9	168	11.4
Cu	29	8.96	20.0	14.3	15.2	151	12.6
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5