Energy Resolution and Timing Performance Studies of a W-CeF_3 Sampling Calorimeter prototype with a Wavelength-Shifting Fiber Readout

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on behalf of the W-CeF_3 R&D group

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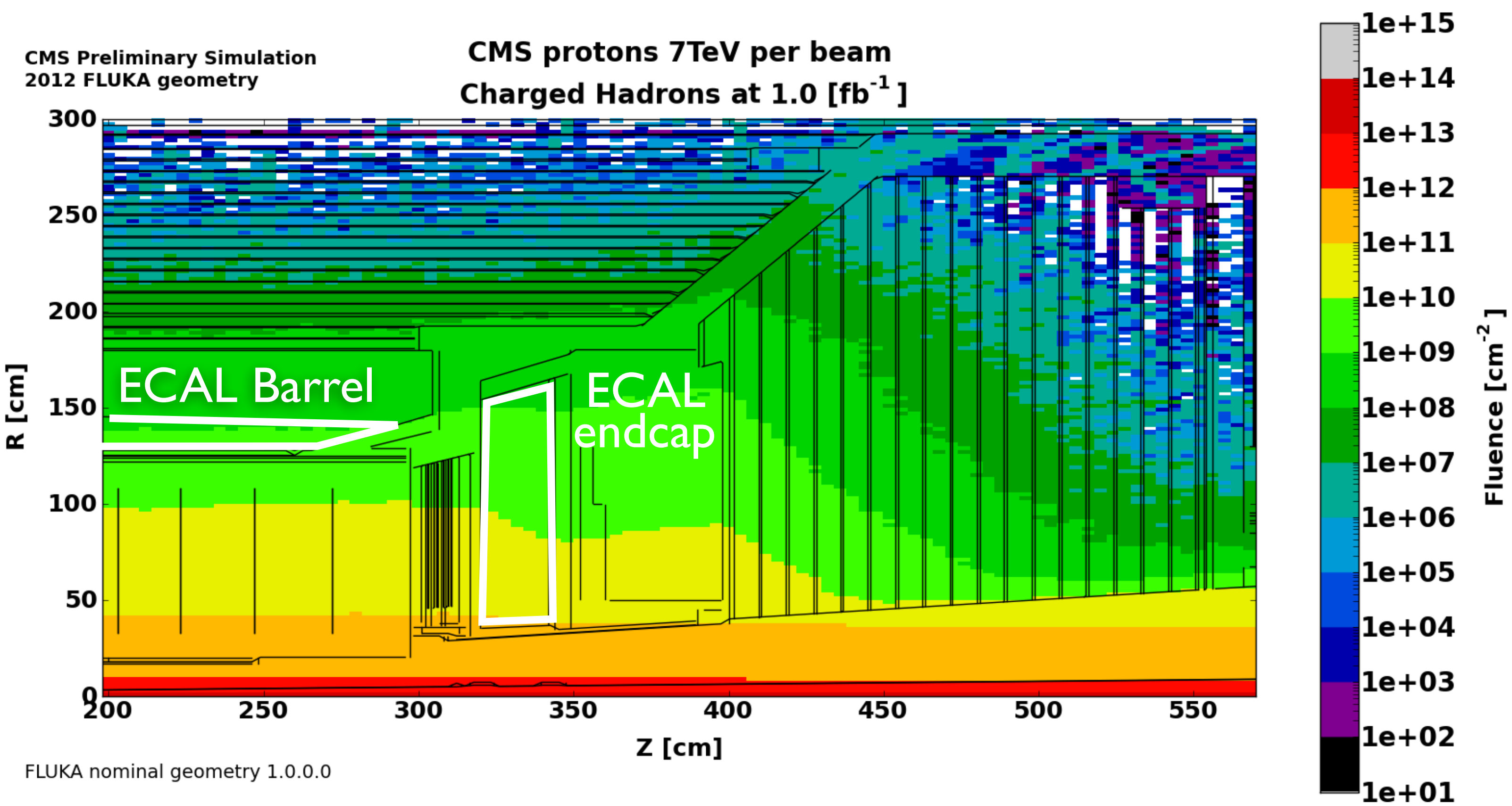
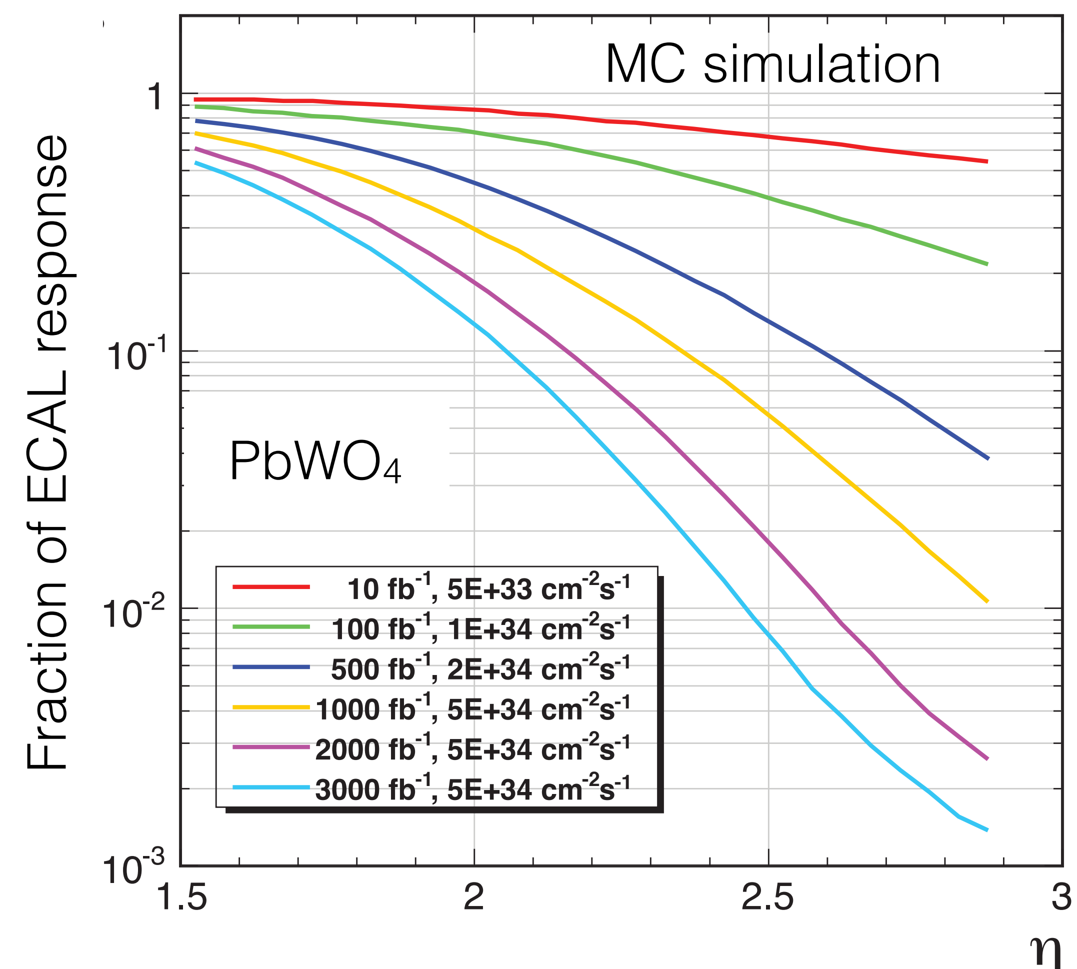
Int. Conf. on Technology and Instrumentation in Particle Physics 2017 *Beijing, May 25th, 2017*

Original motivation: HL-LHC radiation environment in CMS

- HL-LHC (~2025): a harsh environment for electromagnetic calorimetry (ECAL)
  - γ dose rate up to 50 Gy/h, dose up to ~1 MGy (at $\eta = 3$)
  - Hadron fluences up to ~4×10^{14} cm^{-2} (average energy a few GeV)
  - Neutron fluences up to ~5×10^{15} cm^{-2} (average energy 1 MeV)
  - Radiation-induced transparency losses in $PbWO_4$ resulting in an energy resolution degradation
  - Upgrade for HL-LHC: complete replacement of ECAL endcaps + partial ECAL barrel upgrade

Hadron fluence [cm^{-2}] , 14 TeV pp, 100 fb^{-1}





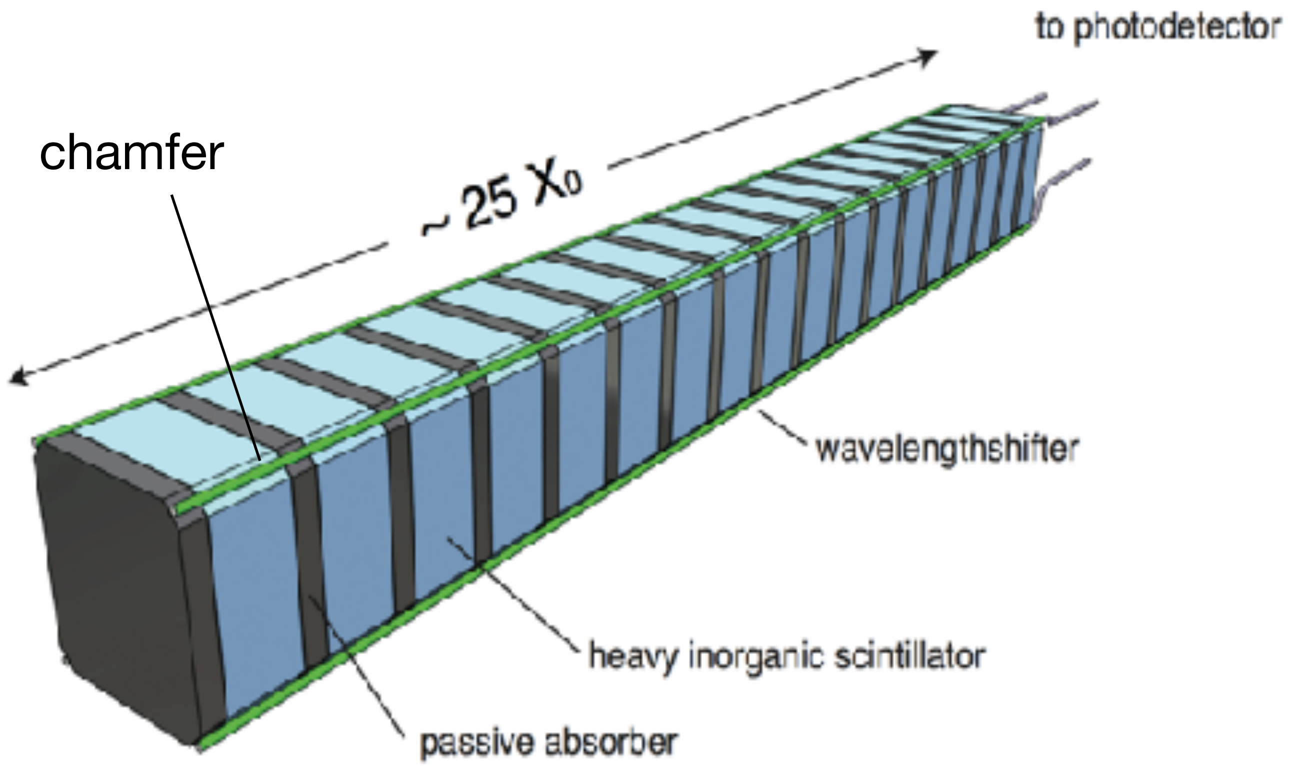
CMS Coll., CMS DP-2013/028

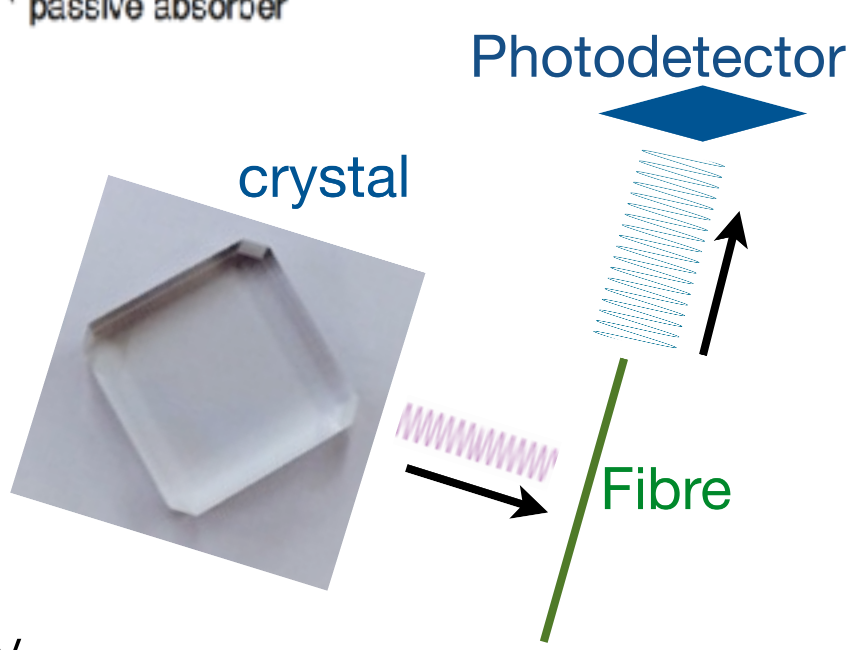
CMS Coll., CERN-LHCC-2015-010

Strategy: a simple geometry

F. N.-T. et al., CALOR 2014, JoP Conf. Ser. 587 (2015) 012039

- Use an inorganic scintillator that is adequately radiation-tolerant
- Build a sampling calorimeter
- Extract the light by WLS fibers running along depolished chamfers
  - minimising the machining and construction complexity, thus saving on costs
  - minimising the light path, thus reduces radiation damage effects
  - optimising the Molière radius, thus cell size, for pile-up mitigation





- Two setups:
  - **Single-channel prototype** → energy resolution, uniformity
  - **5 x 3 channel matrix** → angular dependence

CeF_3 crystal scintillator

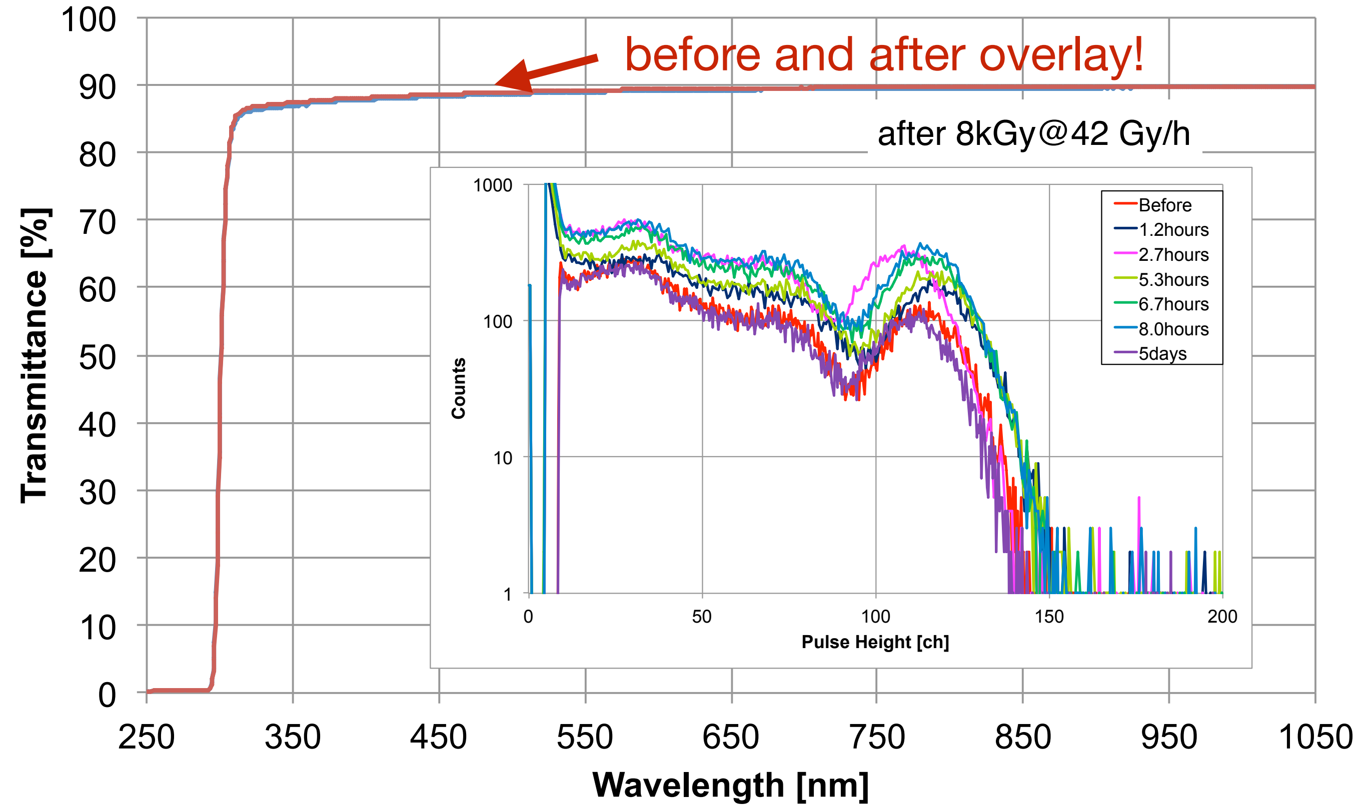
Density [g/cm³]	6.16
Refractive index	1.62
Peak luminescence [nm]	340
Decay time [ns]	~30
dLY/dT [%/°C]	0.14

UV

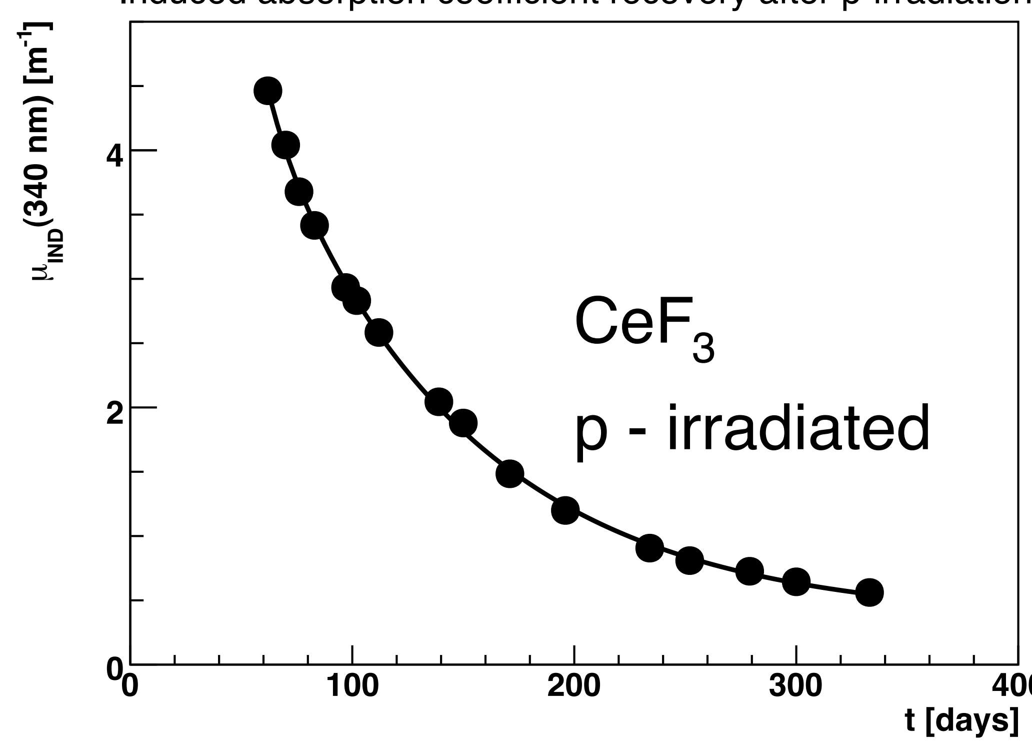
fast

- **Ionising radiation:**
  - Can be made to recover
  - Studied in the ’90 for CMS[1)]
  - Studies performed on new crystals from Tokuyama, Japan[2)]
- **Hadron fluences:**
  - Can be made to recover — no build-up
  - Proven on 20 y old crystal[3)]

Tokuyama CeF_3 transmission and 60Co LY spectrum (inset) after γ-irradiation



Induced absorption coefficient recovery after p-irradiation



1) E. Auffray (CERN) et al., NIM A 383 (1996) 367-390

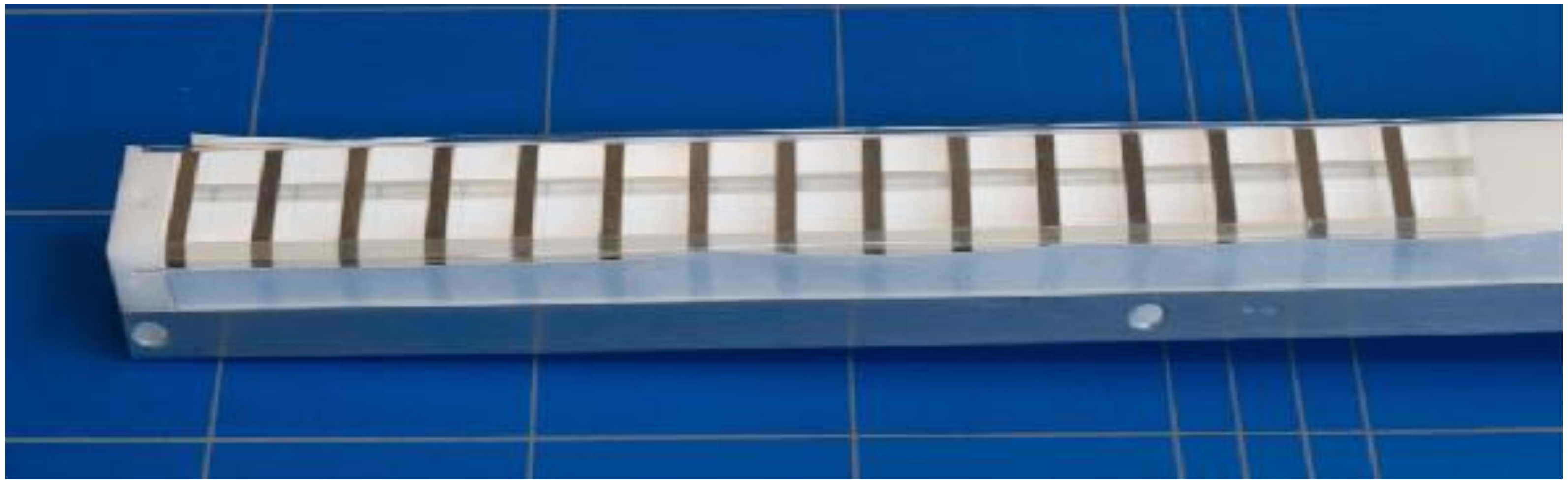
2) F. N.-T. et al. , SCINT 2015, Berkeley (USA)

3) G. Dissertori et al., NIM A 622 (2010) 41-48

Single-channel prototype

★ Dimensions chosen within CMS ECAL $PbWO_4$ crystals envelope

- (10 mm CeF_3 + 3 mm W) x 15 layers = 19.5 cm = 25 X_0
- depolished chamfers, 3 mm wide, accomodate 1 mm ∅ fibers
- Effective R_M = 23 mm, transverse dimensions 24 mm x 24 mm, SF = 38%
- For the tests in beam, surrounded by BGO crystals for shower containment
- Kuraray 3HF-SC (1500) plastic fibers as WLS
- Each WLS fiber read out independently by a PMT
- Energy resolution and uniformity studies



Intrinsic energy resolution

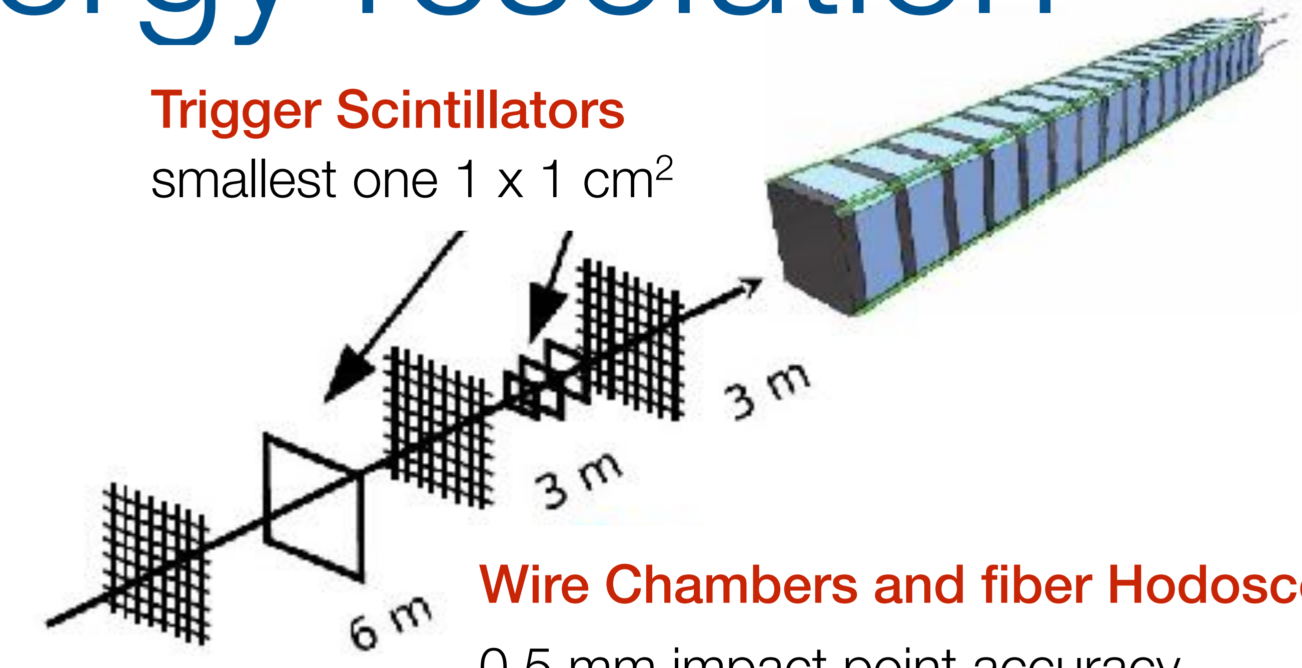
CERN SPS, October 2014

H4 electron beam

20 - 150 GeV

Trigger Scintillators

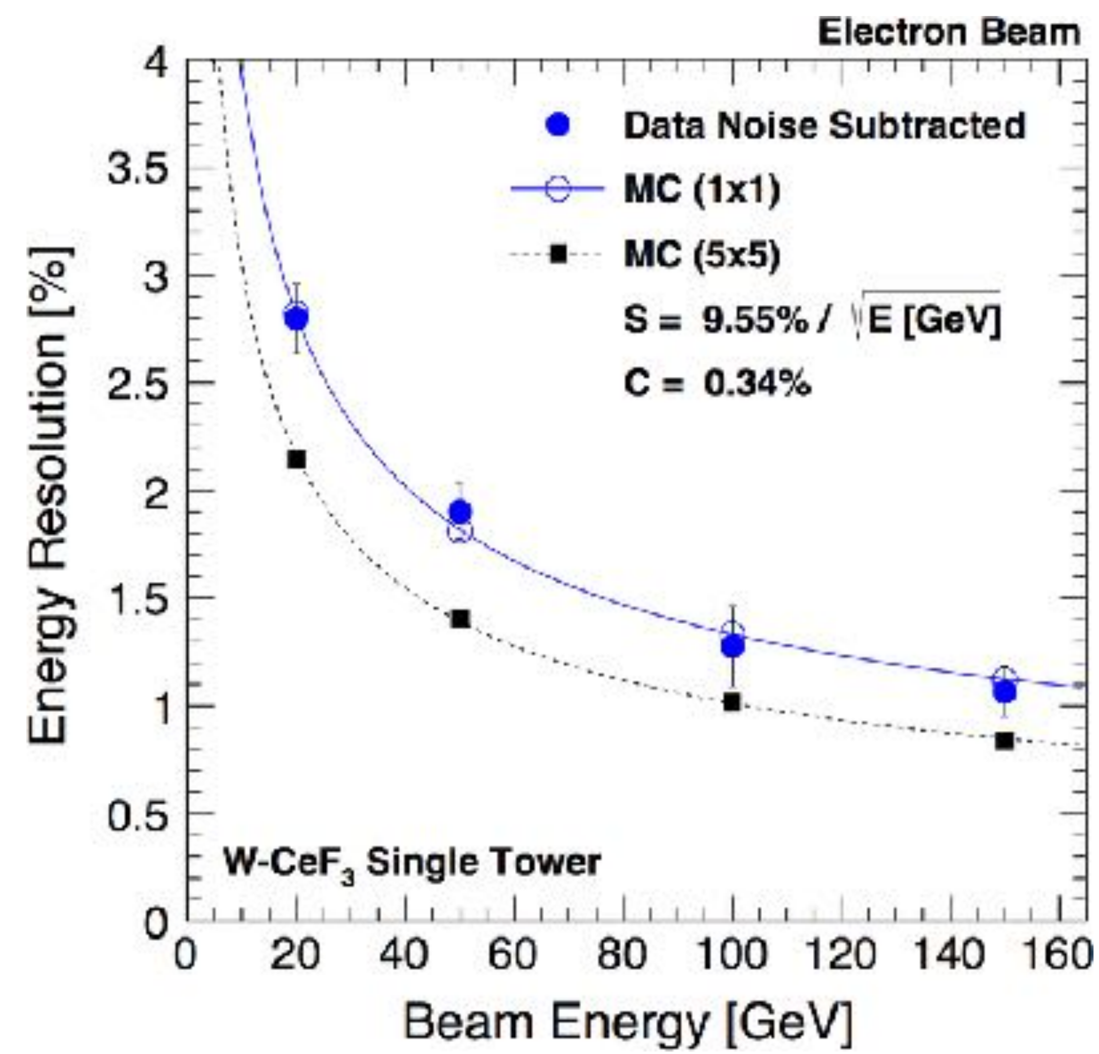
smallest one 1 x 1 cm^2



Wire Chambers and fiber Hodoscopes

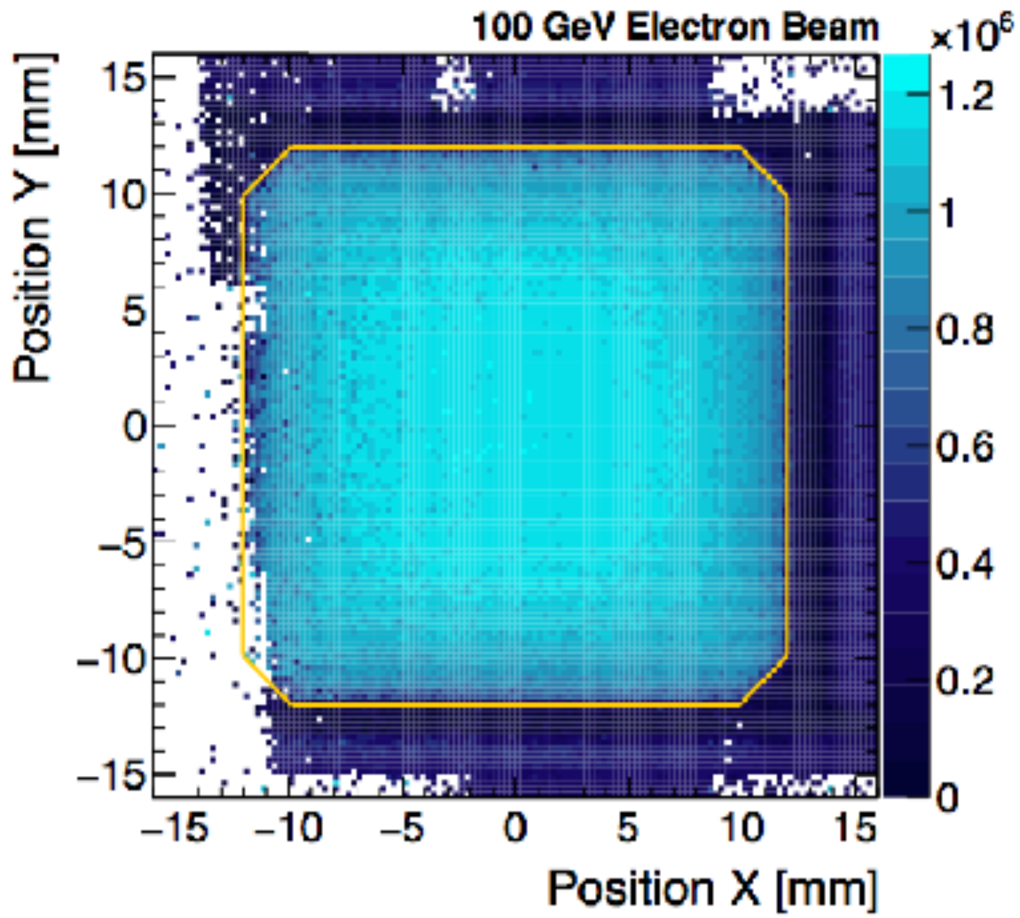
0.5 mm impact point accuracy

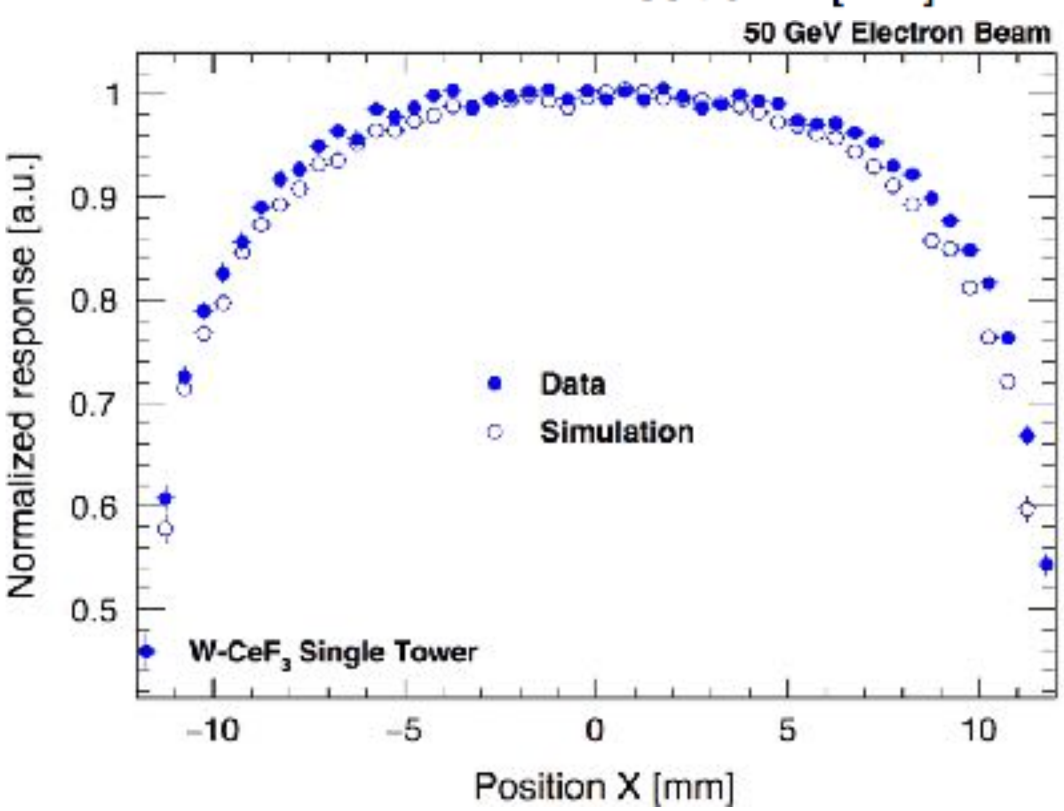
- ★ Central events selection:
  - 6 x 6 mm^2 of front face
  - Energy resolution measured
- ★ Single channel energy resolution dominated by lateral containment
  - Good agreement between data and Monte Carlo
- ★ The Monte Carlo extrapolation to a **5 x 5 channel matrix** shows that an **energy resolution stochastic term < 10% is achievable**



R. Becker et al., NIM A 804 (2015) 79 - 83

W/CeF$_3$ channel Response Uniformity



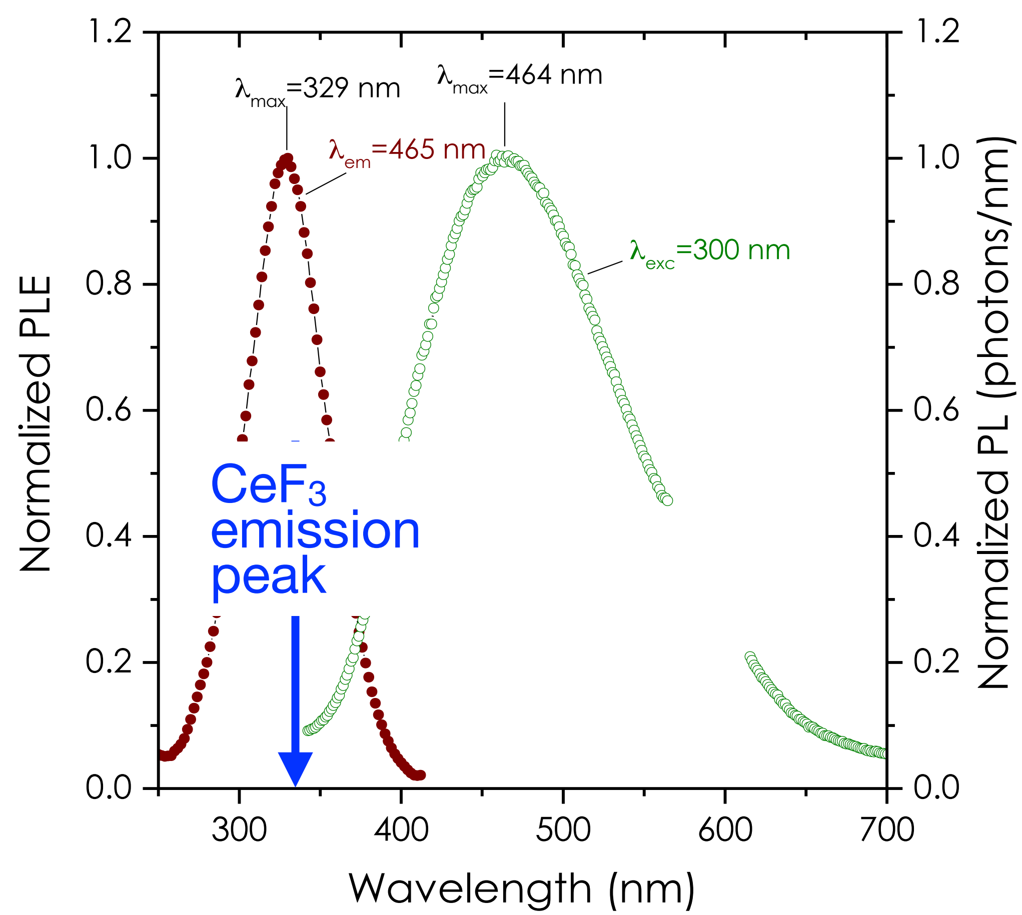


- ✦ Response vs impact point can be studied through precise electron tracking. Although Light Collection effects are not corrected for, we observe:
  - **Uniform response** across central part of the channel
  - **Lateral non-uniformities** dominated by shower non-containment
- ✦ Data/simulation in good agreement (within 5%)
- ✦ Agreement on non-central region can be improved:
  - Light collection being included in the simulation

R. Becker et al., NIM A 804 (2015) 79 - 83

WLS: Ce-doped quartz fibres

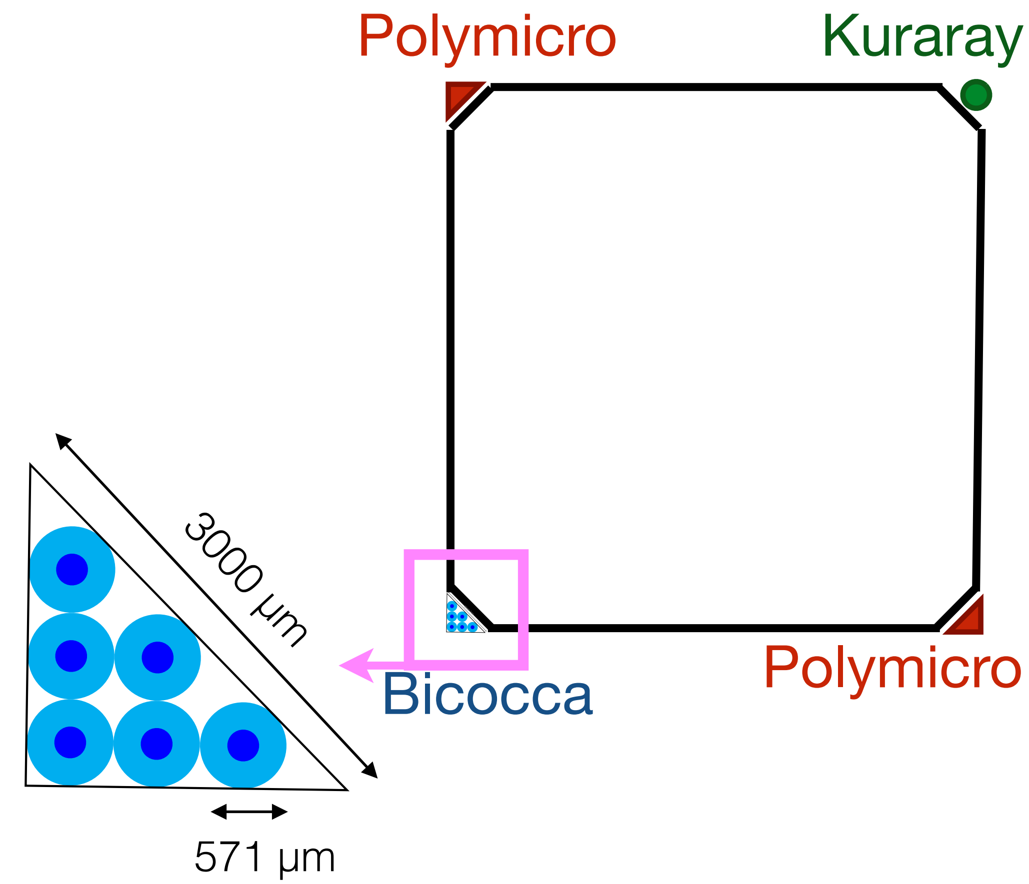
- Ce-doped photoluminescent quartz ($Ce:SiO_2$) is a good WLS candidate with CeF_3:
  - $Ce:SiO_2$ core (where light is produced) + cladding for light transport
- $Ce:SiO_2$ fibres developed for application to dosimetry[1)]:
  - Radiation hardness anticipated up to fluences $>10^{15}$ cm^{-2}
  - Absorption spectrum matches CeF_3 emission
  - Suitable as a WLS with CeF_3
  - Fast time response (30 ns), **green** emission
  - Development of rad-hard $Ce:SiO_2$ in progress



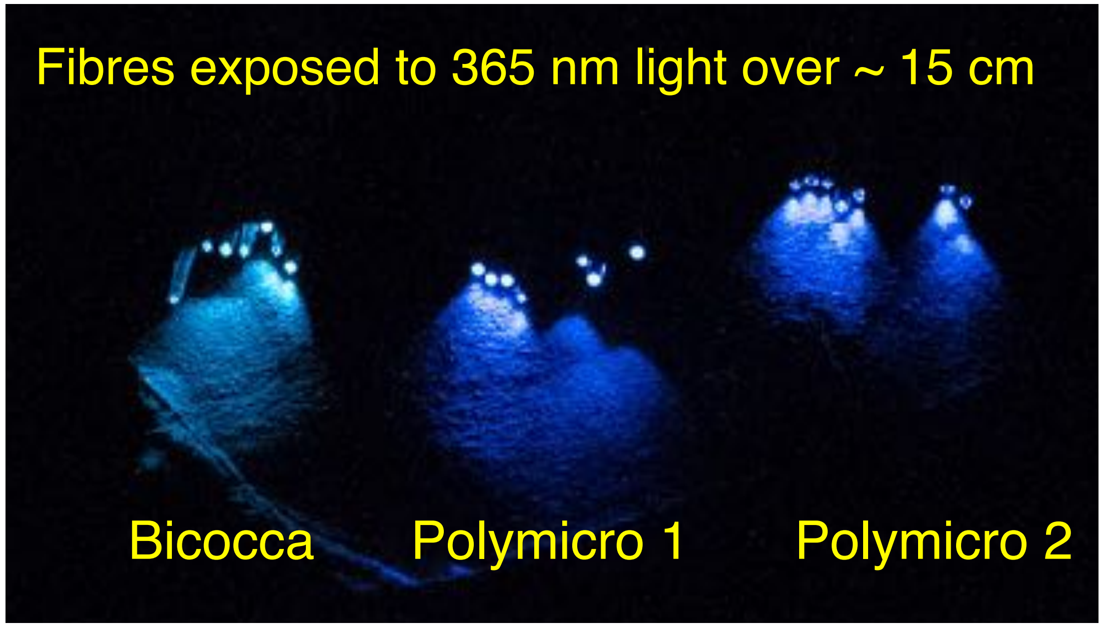
1) *A. Vedda, N. Chiodini, M. Fasoli et al., Appl. Phys. Lett., Vol. 85 (2004) 6356 and priv. comm. (U. Milano Bicocca)*

Tests with Ce:SiO_2 fibres

- **CERN SPS H4 beam, June 2015**
- A bundle of SiO_2:Ce fibres in each of 3 corners:
  - 1 bundle from U. Milano-Bicocca[1)]
  - 2 bundles from Polymicro/Texas Tech [2)]
- One Kuraray 3HF plastic fibre as reference



- WLS efficiency is lower wrt Kuraray fibres:
  - bundle of Ce-doped quartz fibres: factor **~10 less light** than a plastic fibre
  - smaller diameter fibres: bundle of 6 SiO_2:Ce fibres in each corner

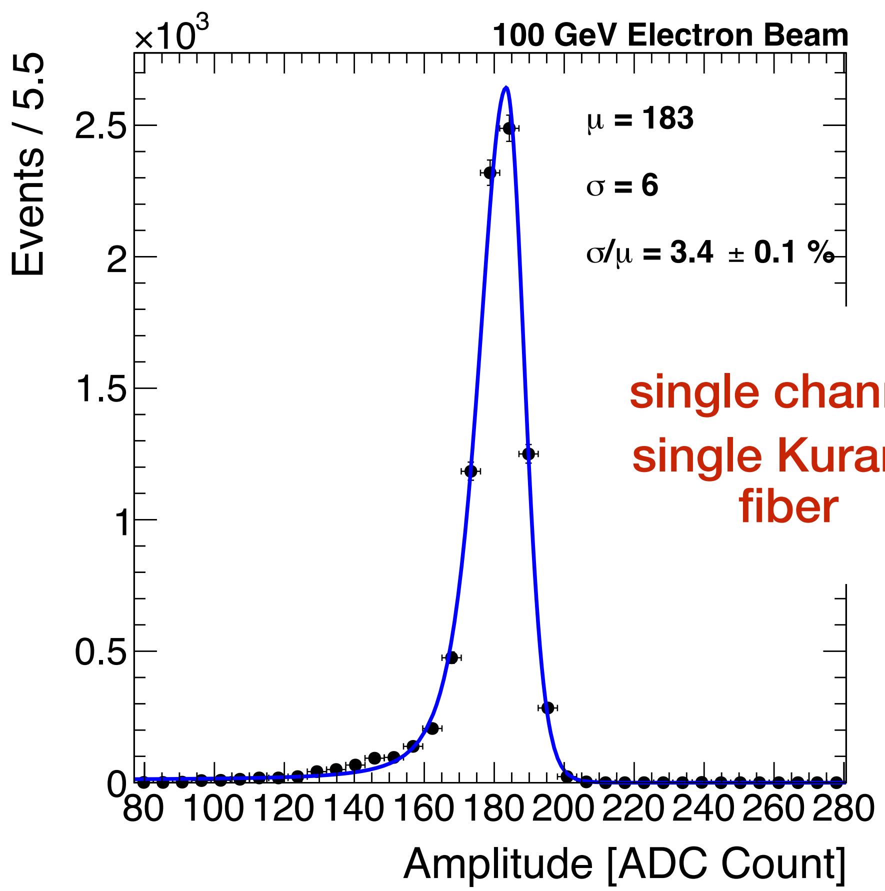


1) *A. Vedda, N. Chiodini, M. Fasoli et al., Appl. Phys. Lett., Vol. 85 (2004) 6356 and priv. comm.*

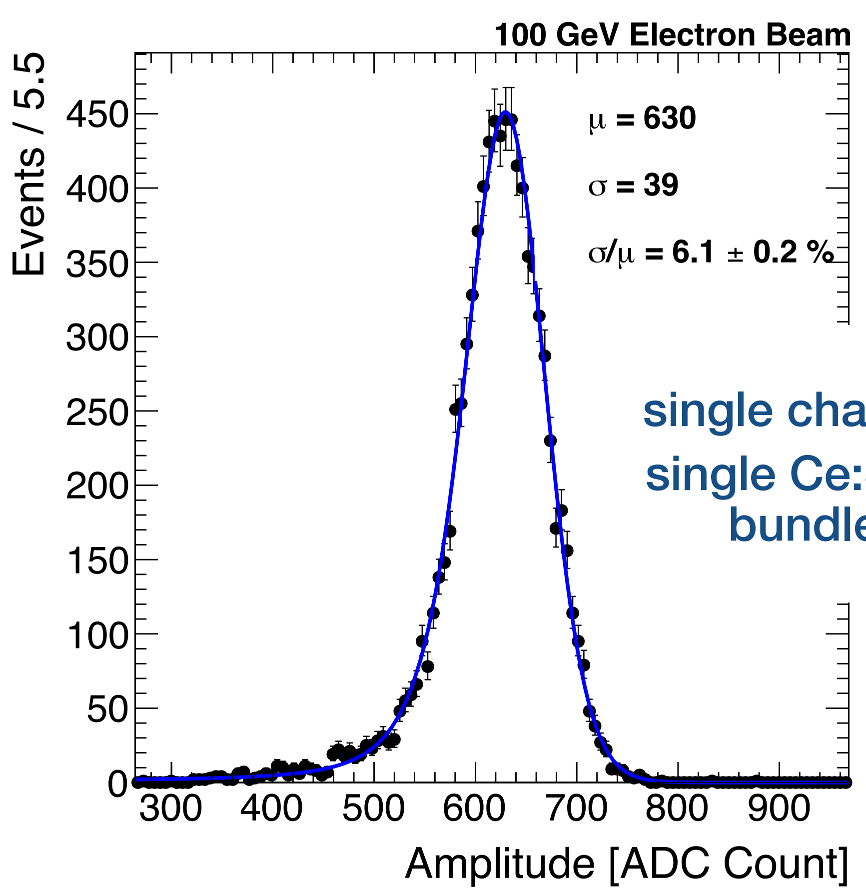
2) *Jordan Damgov, N. Akchurin et al., SCINT2015, Berkeley (USA)*

Energy resolution with $Ce:SiO_2$ WLS fibres

- Central events selection: 3 x 3 mm^2 of front face
- Slightly different energy resolution for the different bundles of $Ce:SiO_2$ fibres
- Worse resolution compared to plastic fibres, consistent with ratio of photoluminescent light yields



σ/E=3.4% @ 100 GeV

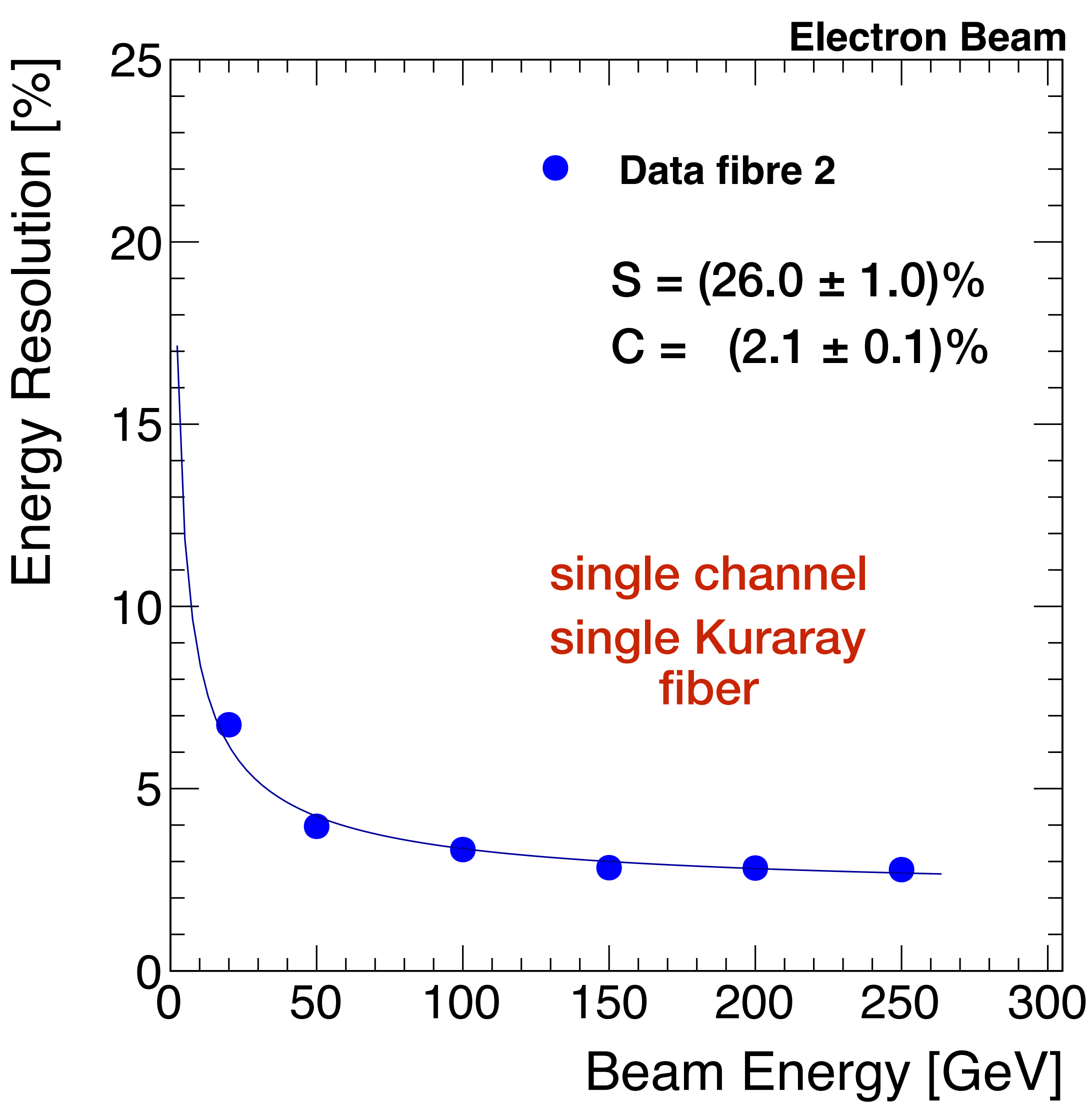


σ/E=6.1% @ 100 GeV

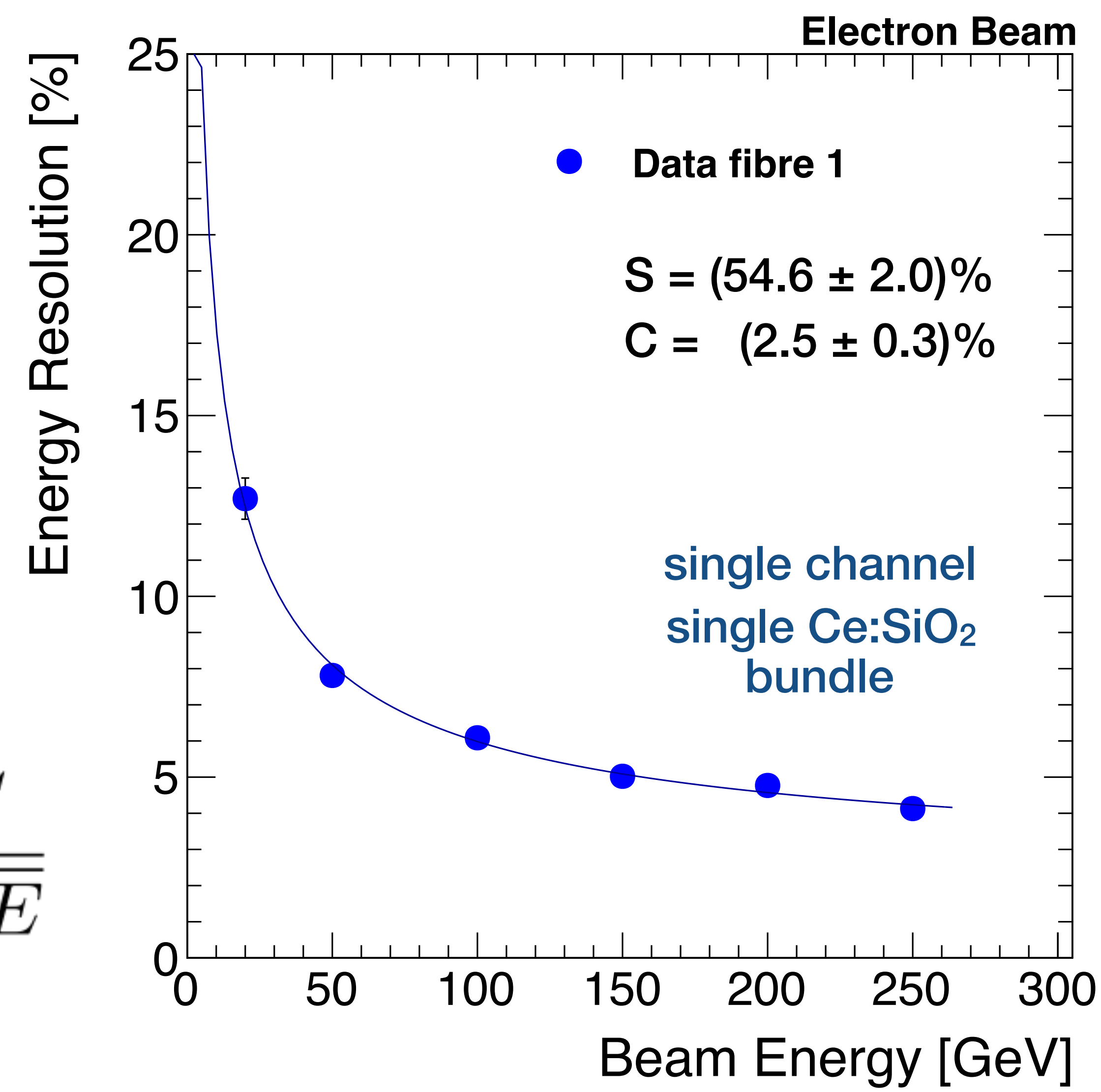
F. Micheli et al., IEEE NSS 2015, San Diego (USA)

Energy resolution vs. energy

- Resolution with Ce:SiO_2 WLS fibres
- Dominated by the photoluminescent light yield, a factor ~10 lower than for Kuraray plastic fibers
- **Higher light-yield fibres would improve the energy resolution**



$$\frac{\sigma}{E} = C \oplus \frac{S}{\sqrt{E}}$$

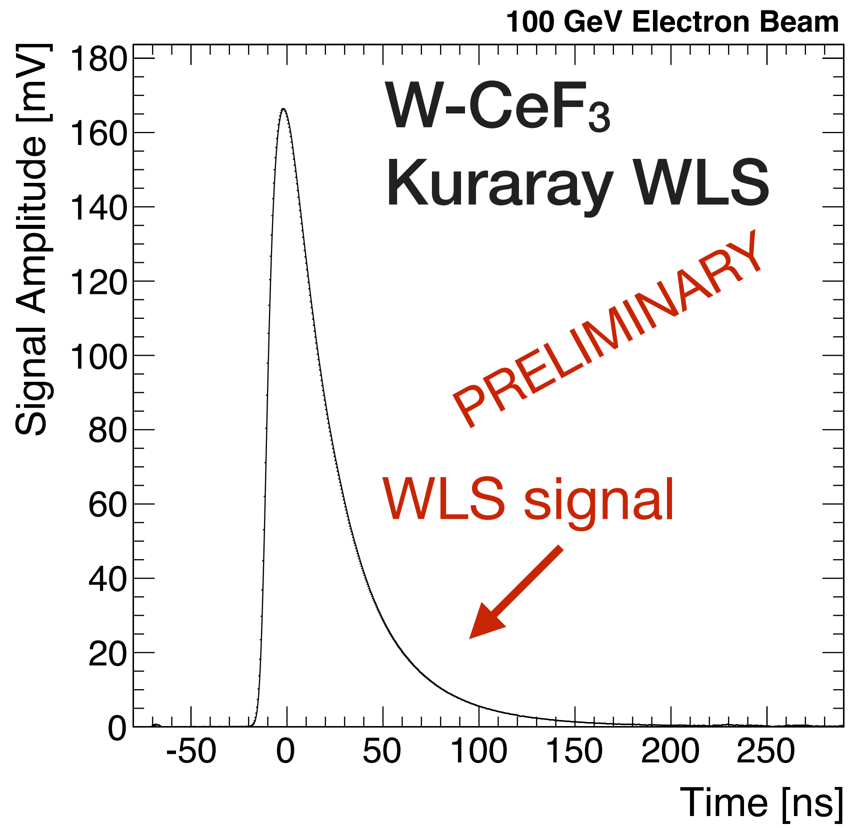


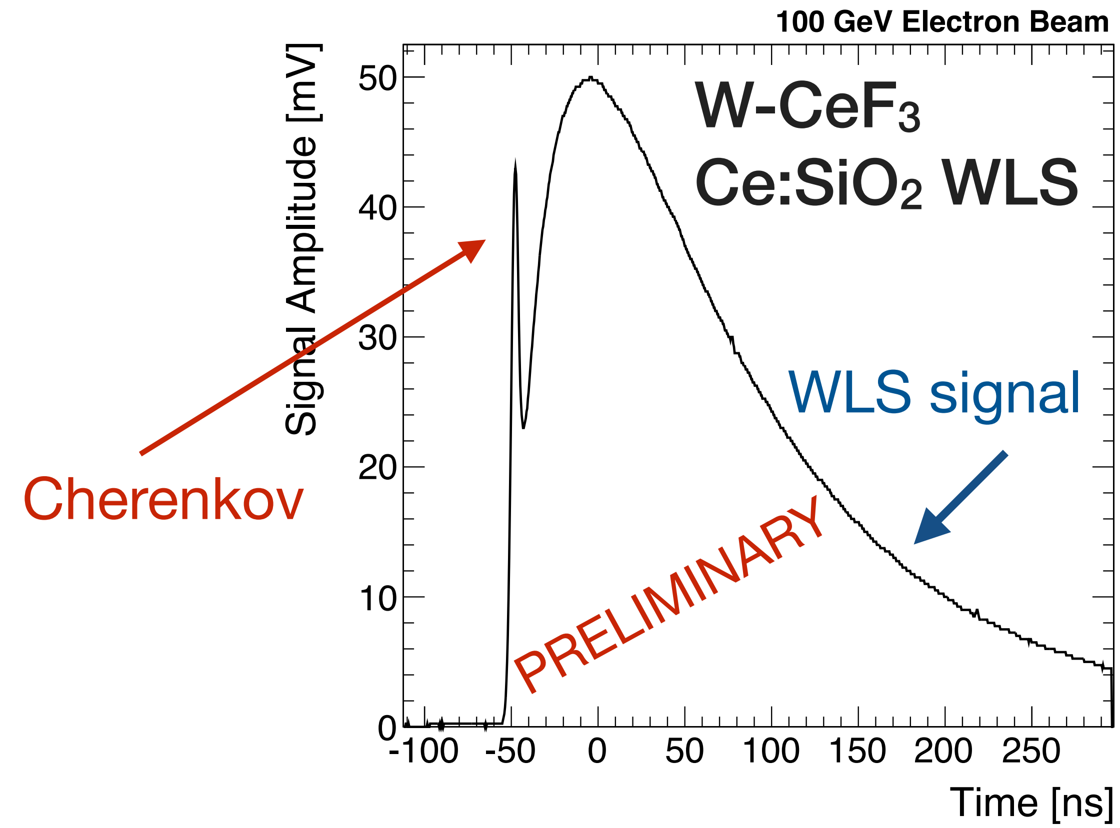
F. Micheli (ETH) et al., IEEE NSS 2015, San Diego (USA)

Signal shape characteristics

- PMT + Digitiser @ 2.5 GHz (400 ns window) → full waveform acquired
- SiO_2:Ce fibres exhibit:
  - WLS emission time constant typical of Cerium (folded in twice!)
  - a fast, Cherenkov component with a rise time of a few ns (dominated by PMT response time)

→ applications in timing measurements? Perform dedicated timing studies

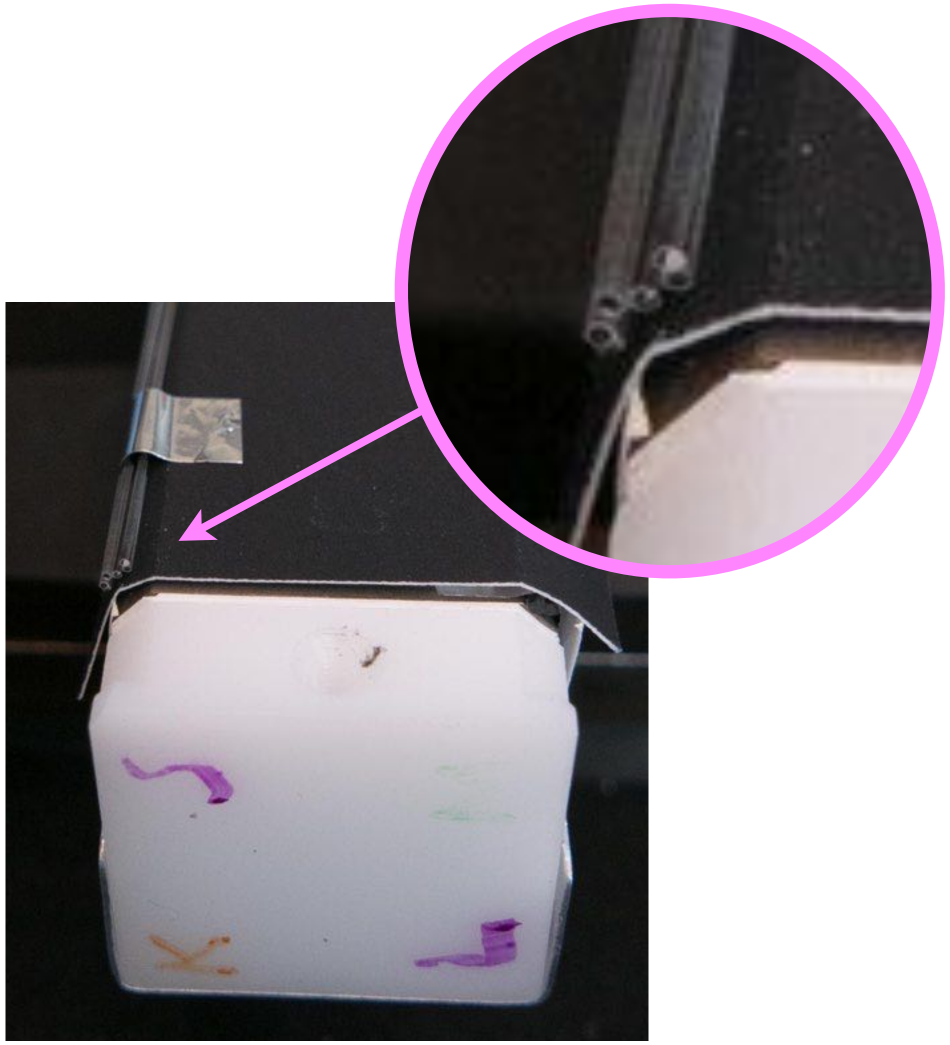


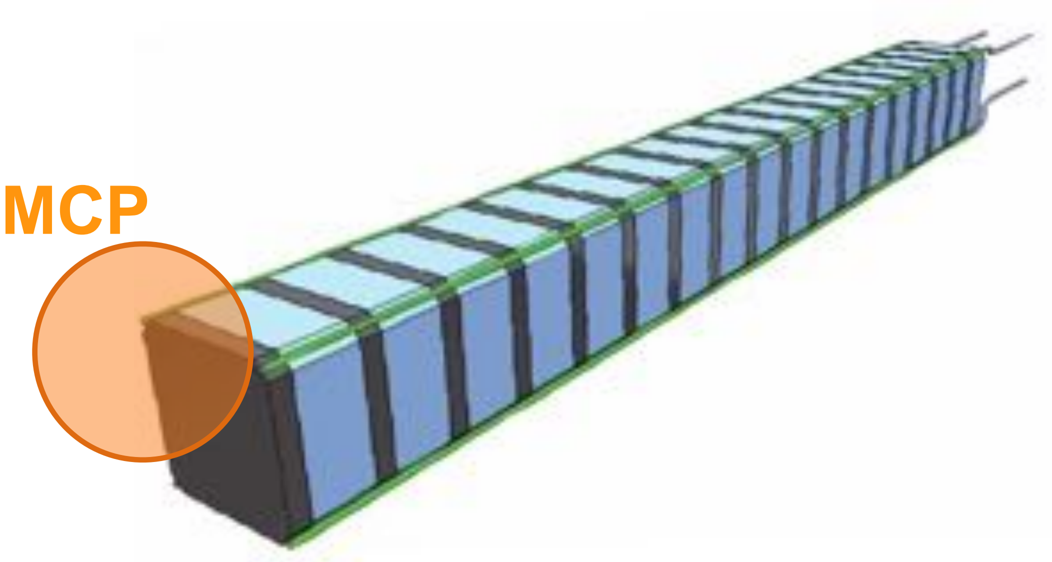


F. Micheli (ETH) et al., IEEE NSS 2015, San Diego (USA)

Timing studies with $Ce:SiO_2$

- ★ **CERN SPS H4 beam, October 2015**
- ★ One "**blind**" bundle of $Ce:SiO_2$ fibers: black paper inserted between it and the W-CeF_3 stack
  - No WLS signal, collect just **Cherenkov** and **direct scintillation signal from the fiber**
  - Fiber bundle read out with a Hamamatsu **SiPM**
  - Reference time from **MicroChannelPlate (MCP)** device[1] in front of channel, which has time resolution 20 - 30 ps, negligible

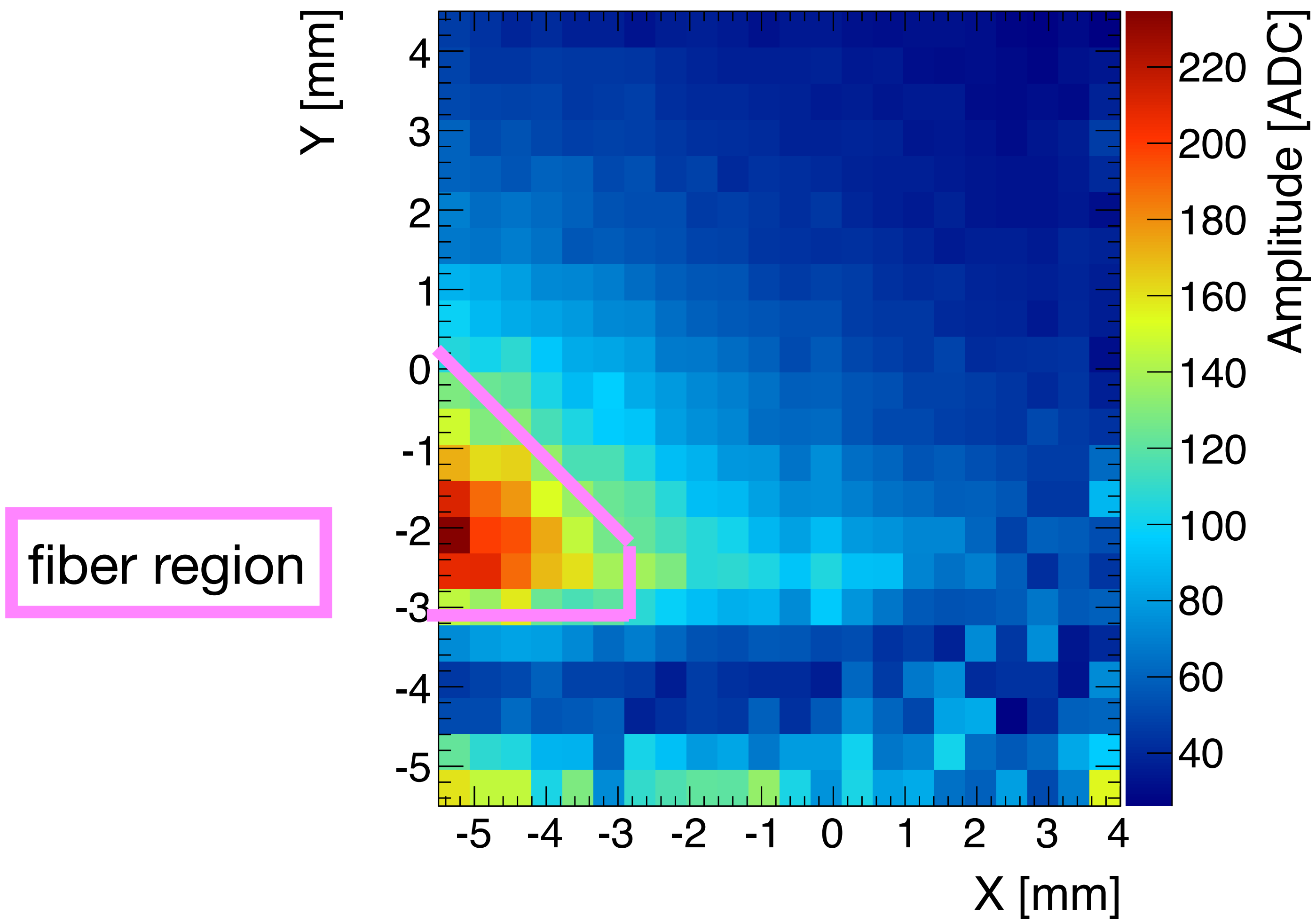


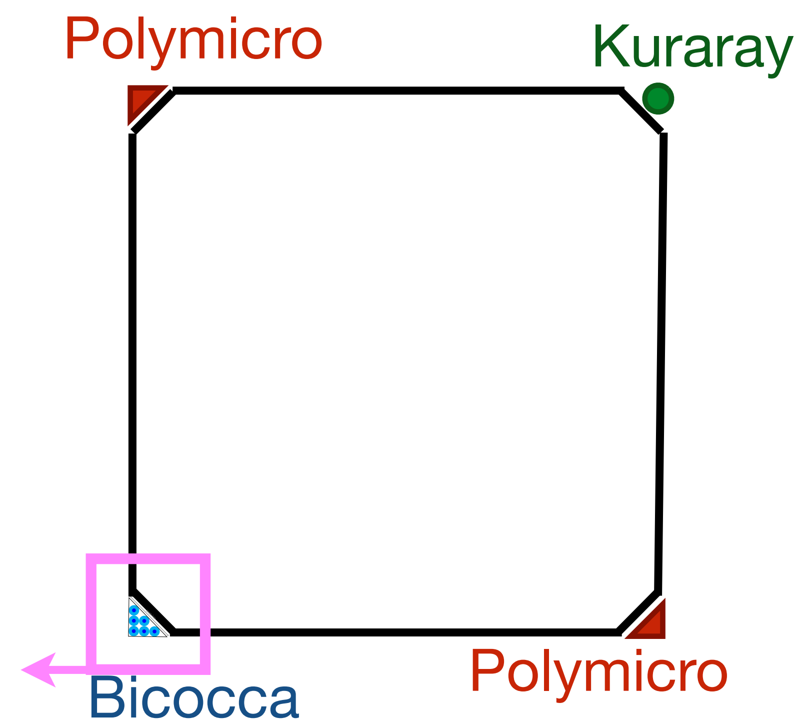


1) L. Brianza et al., Nucl. Instr. Meth. A797 (2015) 216-221

Ce:SiO$_2$ signal amplitude map

- Data taken with beam centred on blind Ce:SiO$_2$ fiber bundle, 1 x 1 cm^2 trigger
- Ce:SiO$_2$ fibers pulse amplitude map using impact point coordinates from beam hodoscope

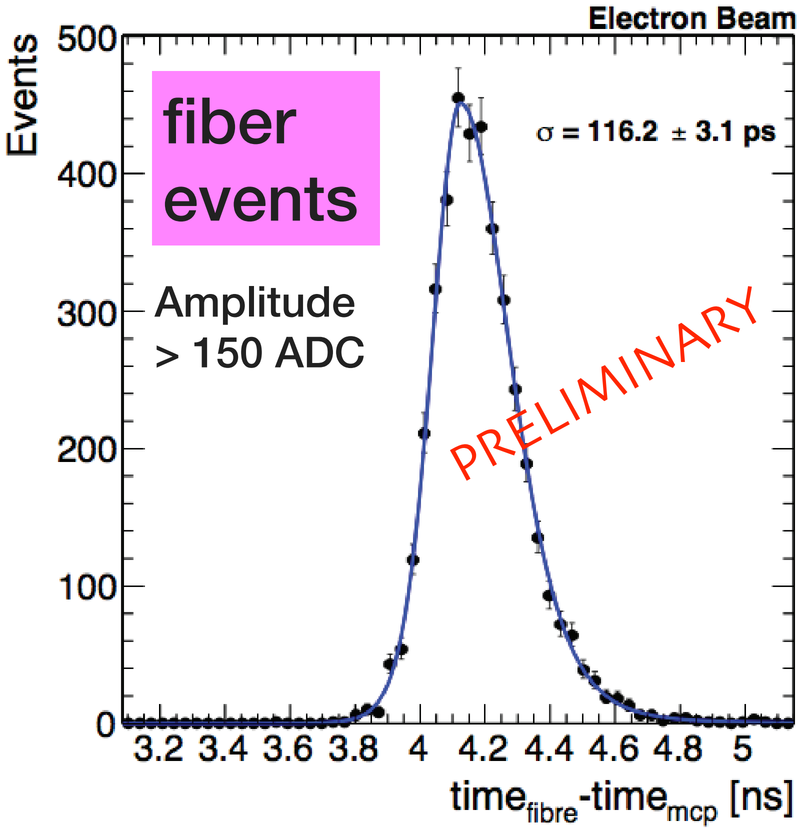




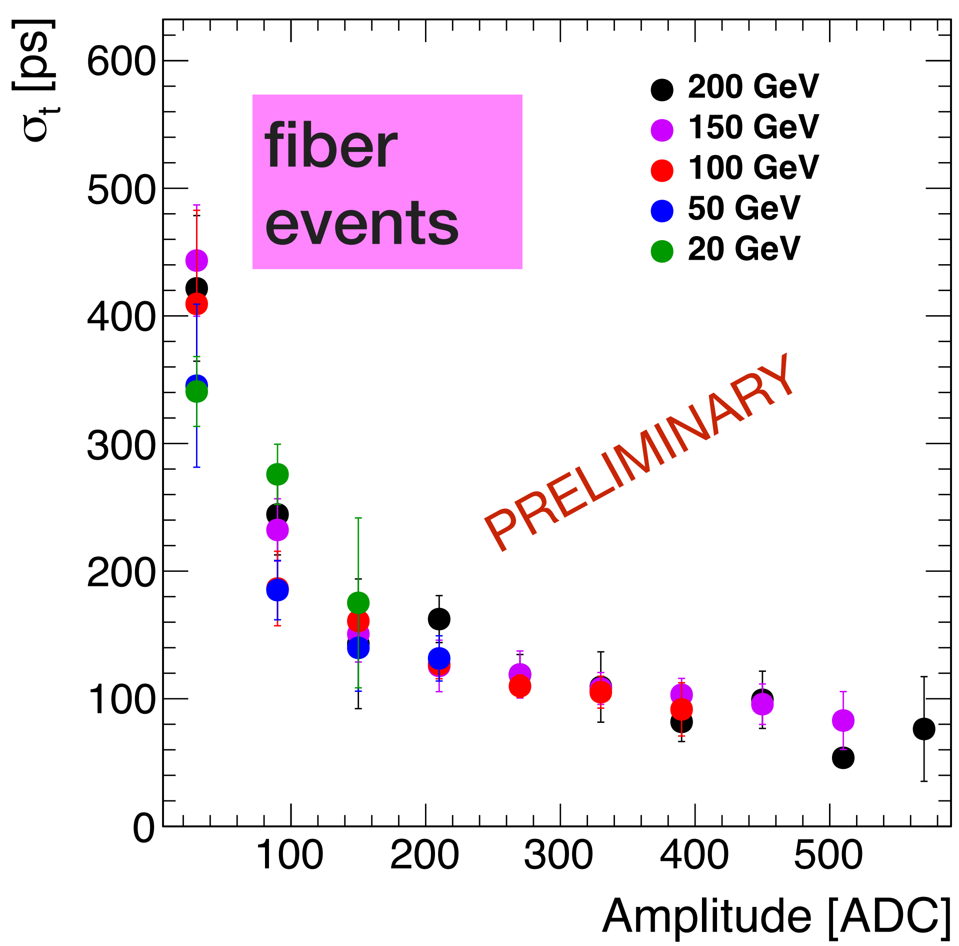
★ Amplitude of pulses used to identify event category:

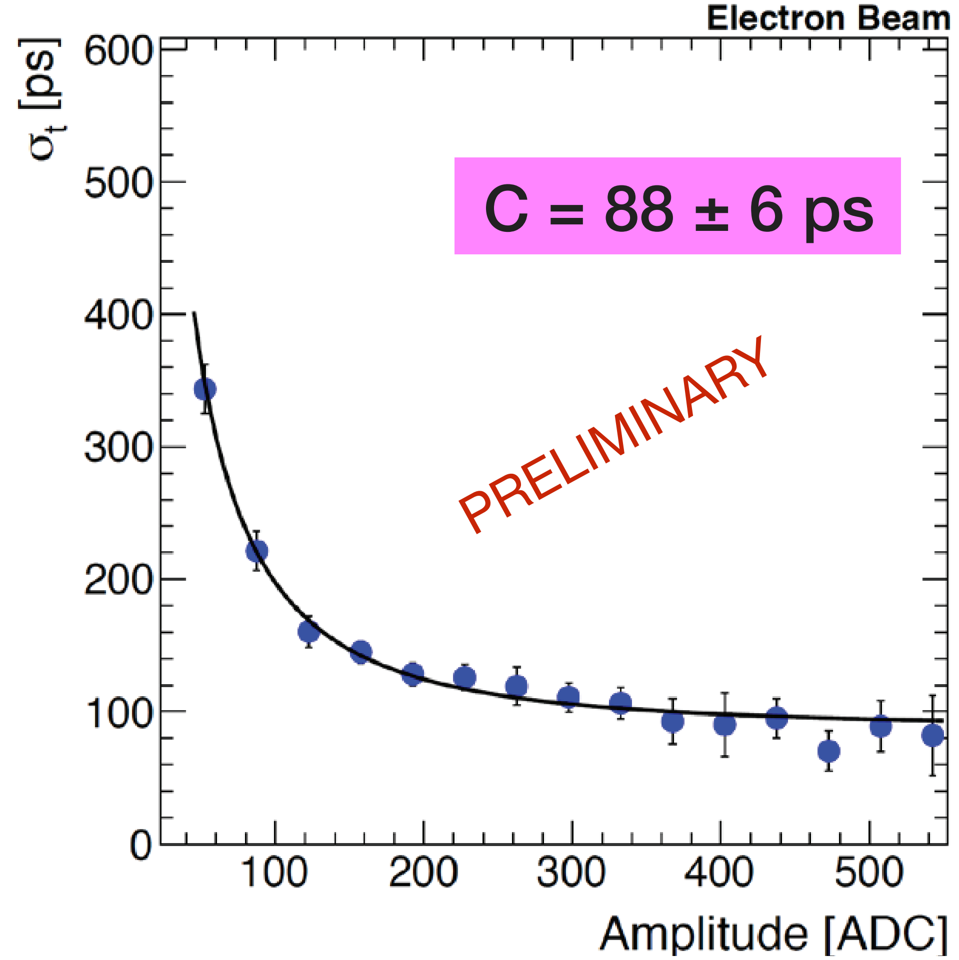
“Fiber” event: beam in fiber region, while signal from **Kuraray** fiber < threshold

Timing resolution



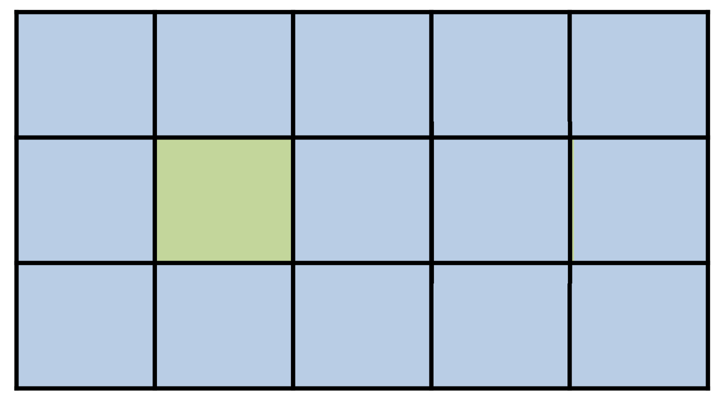
- The timing resolution depends on amplitude
- The beam energy is irrelevant
- Merge time resolution data for all energies and estimate the resolution for events on fiber and events on channel
- For amplitude > 100 ADC counts, timing resolution **σ_t ~ 100 ps**

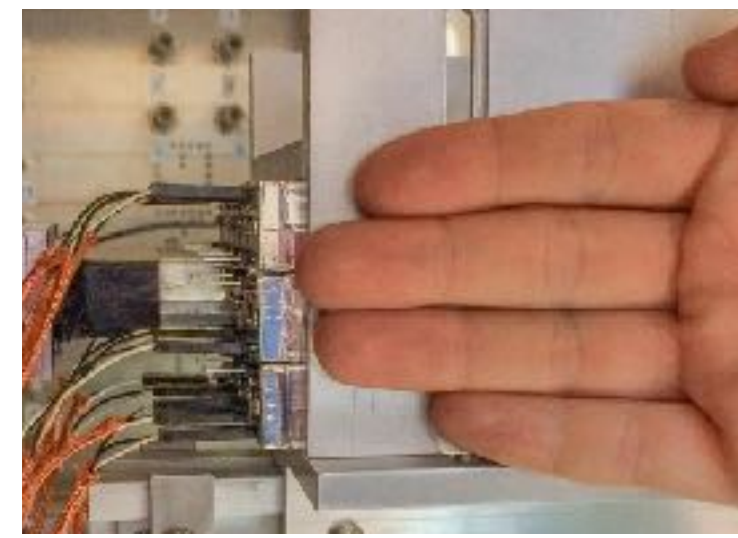




W-CeF_3 prototype matrix

- 5 x 3 channel matrix built, for ultimate energy and angular resolution studies
- 12x(6 mm CeF_3 + 6 mm W) ≃ $25X_0$ (= 144 mm)
- High granularity: effective R_M = 17 mm (for pile-up rejection), transverse dimensions 17 mm x 17 mm, SF = 22%

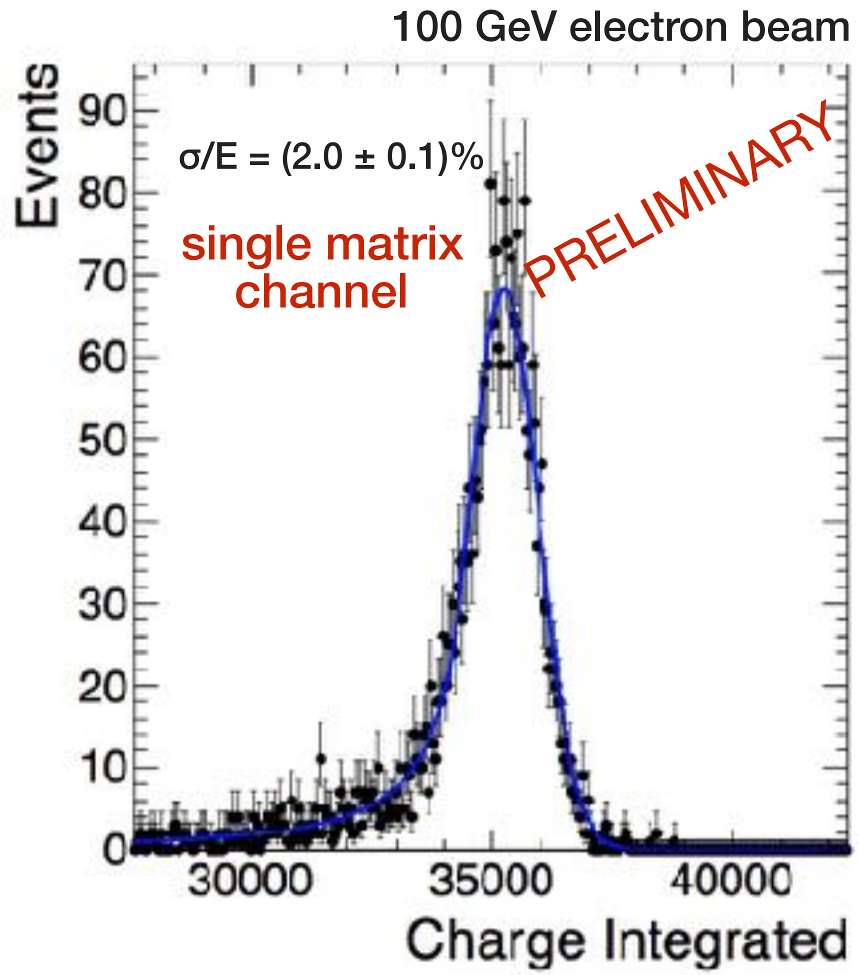




- 3 mm-wide, depolished chamfers as before, to favour scintillation light escape towards WLS, dimensioned to accommodate fibres
- WLS Kuraray 3HF-SC fibres for readout
- 4 fibres signals onto one photodetector but for one inner channel, where they are read out independently
- APD readout, Hamamatsu S8664-55, 5 x 5 mm^2, as for CMS ECAL barrel

First results

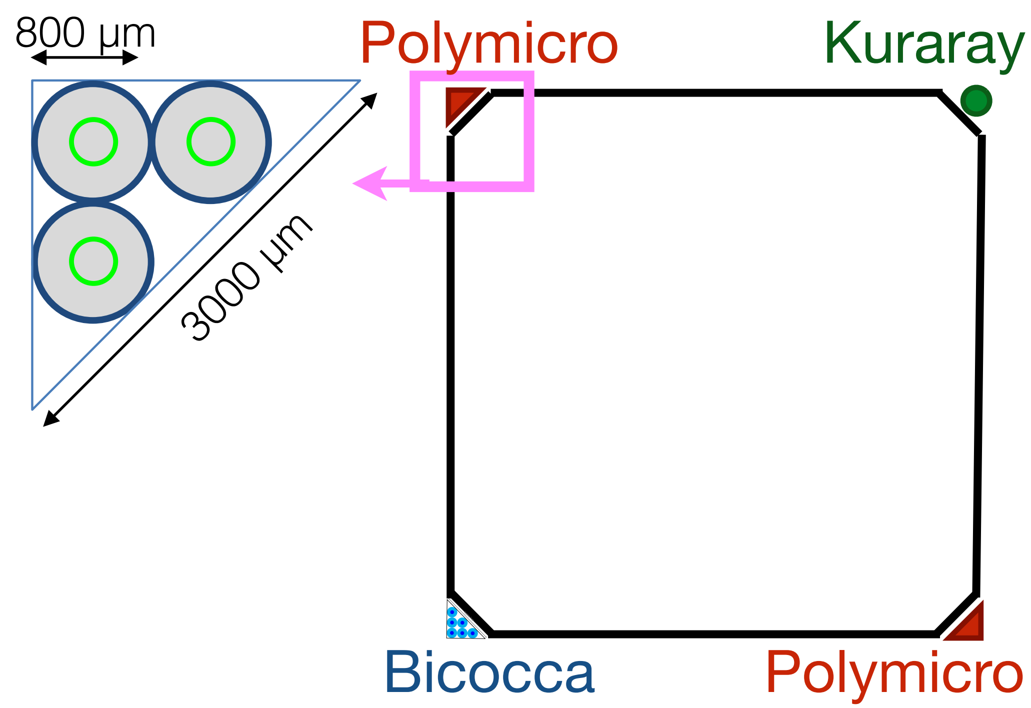
- **CERN SPS H4 beam, June 2016**
- Energy resolution studied for central events (4 x 4 mm^2)
- Single channel resolution **2% at 100 GeV**
- Result scales as expected with the sampling fraction wrt single-channel prototype

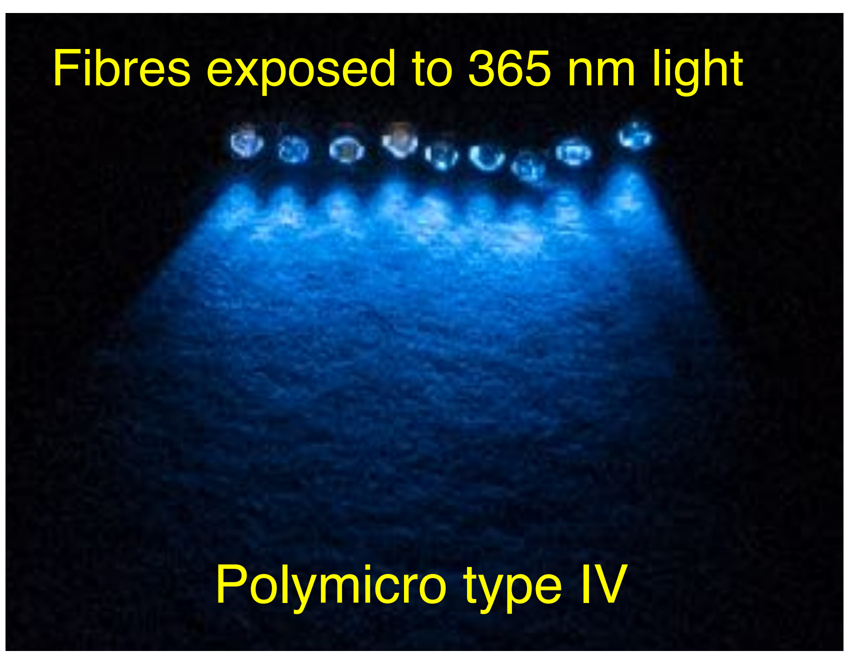


- Single-channel stochastic term compatible with **20%/√E**
- Considerable electronic noise would require new readout

2017 Tests with new $Ce:SiO_2$ fibres

- **CERN SPS H4 beam, June 2017**
- A bundle of SiO_2:Ce fibres in each of 3 corners:
  - 1 bundle from U. Milano-Bicocca[1)]
  - 2 bundles of type IV fibers from Polymicro/ Texas Tech [2)]
- One Kuraray 3HF plastic fibre as reference





- Polymicro type IV fibers:
  - different Ce-distribution (on a ring)
  - higher WLS efficiency expected through optimised light transport

1) A. Vedda, N. Chiodini, M. Fasoli et al., Appl. Phys. Lett., Vol. 85 (2004) 6356 and priv. comm.
2) N. Akchurin, this conference

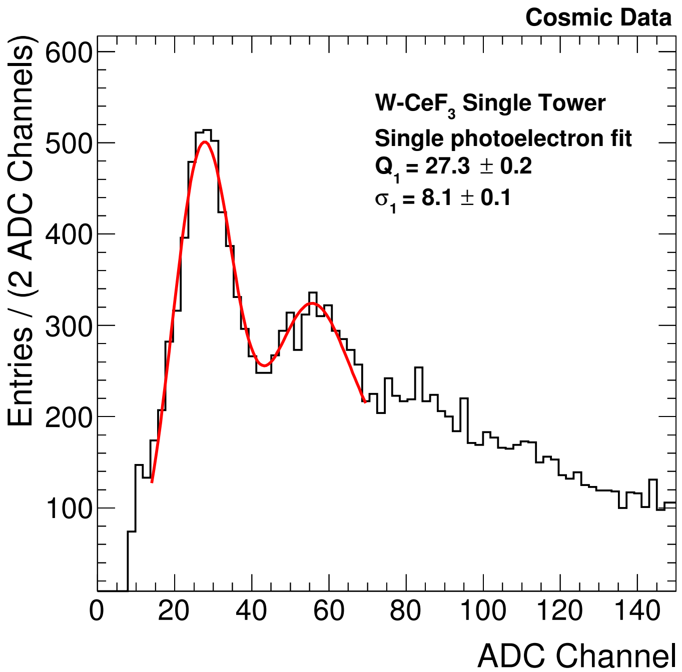
Conclusions

- An innovative sampling calorimeter geometry has been built and exposed to particle beams up to 150 GeV
- Materials used (Cerium Fluoride, Ce-doped quartz) potentially suitable for HL-LHC running in response time, radiation hardness, signal amplitudes, granularity
- For cell dimensions as in present CMS ECAL (24 x 24 mm^2, R_M=23 mm), and sampling fraction **38%**, 5x5 energy resolution: **~10%/$\sqrt{E}$**
- For high-granularity cell dimensions (17 x 17 mm^2, R_M=17 mm) and sampling fraction **22%**, analysis is in progress
- Timing resolution **<100 ps (preliminary)**
- Further results using new generation Ce:SiO_2 fibers expected on energy resolution

Backup

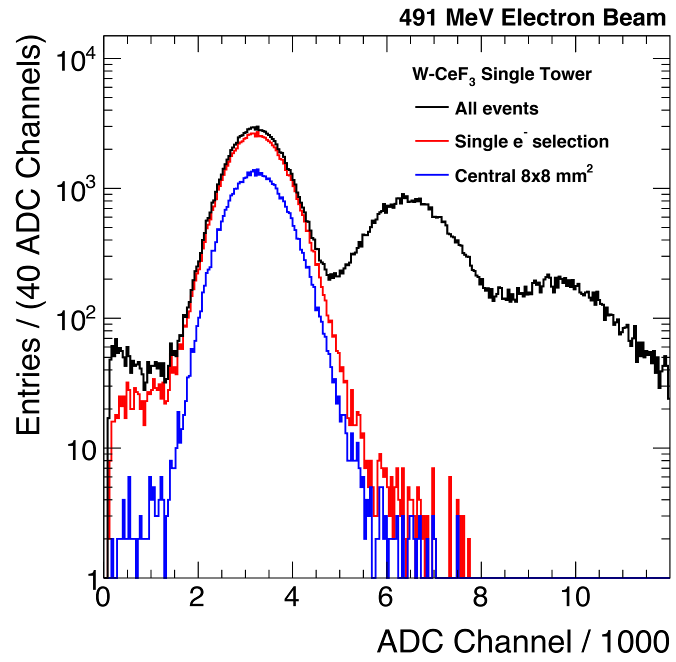
Frascati W/CeF_3 results

Cosmic runs

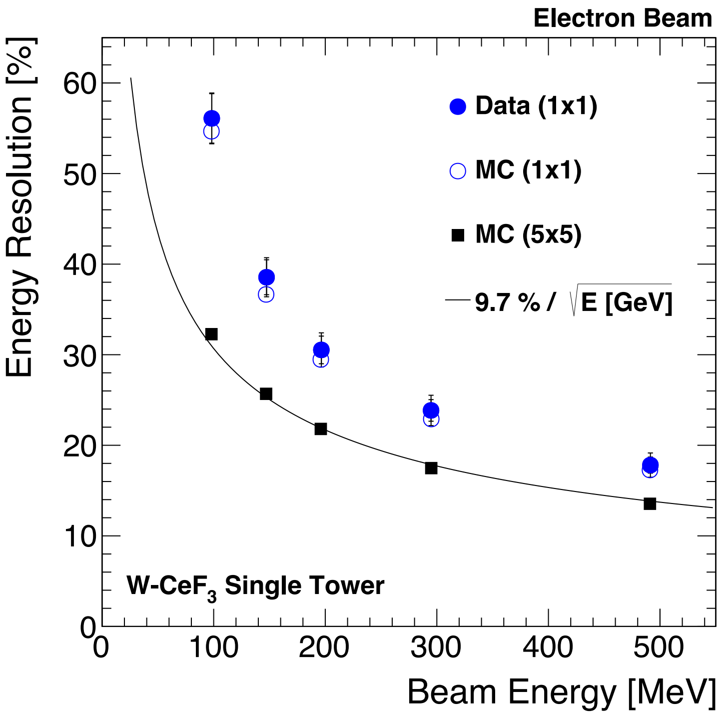


(a) For cosmic muons: pedestal-subtracted ADC spectrum for one fiber signal of the W-CeF_3 tower. Q_1 is the fitted position of the single photoelectron peak, σ_1 is its width.

Event selection



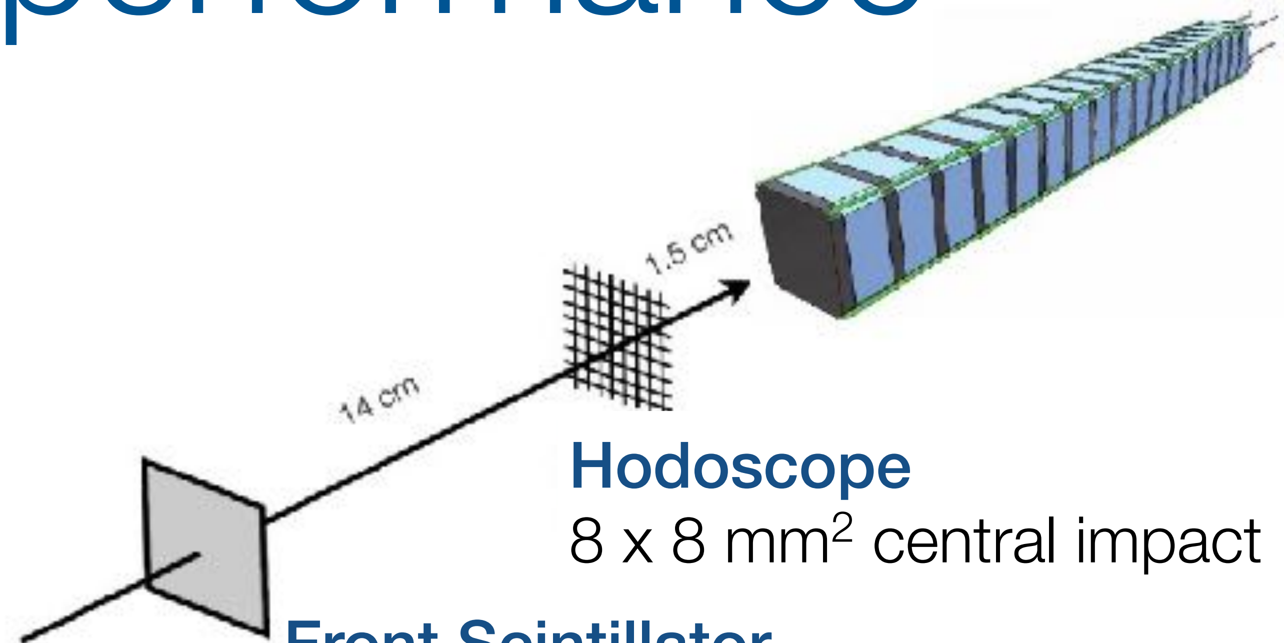
Resolution



1) *R. Becker, F. N.-T. et al., 2015 JINST 10 P07002*

Low-energy performance

Frascati **B**eam **T**est **F**acility
Bunched electron beam
98 - 491 MeV



Hodoscope
8 x 8 mm^2 central impact

Front Scintillator
single e- selection

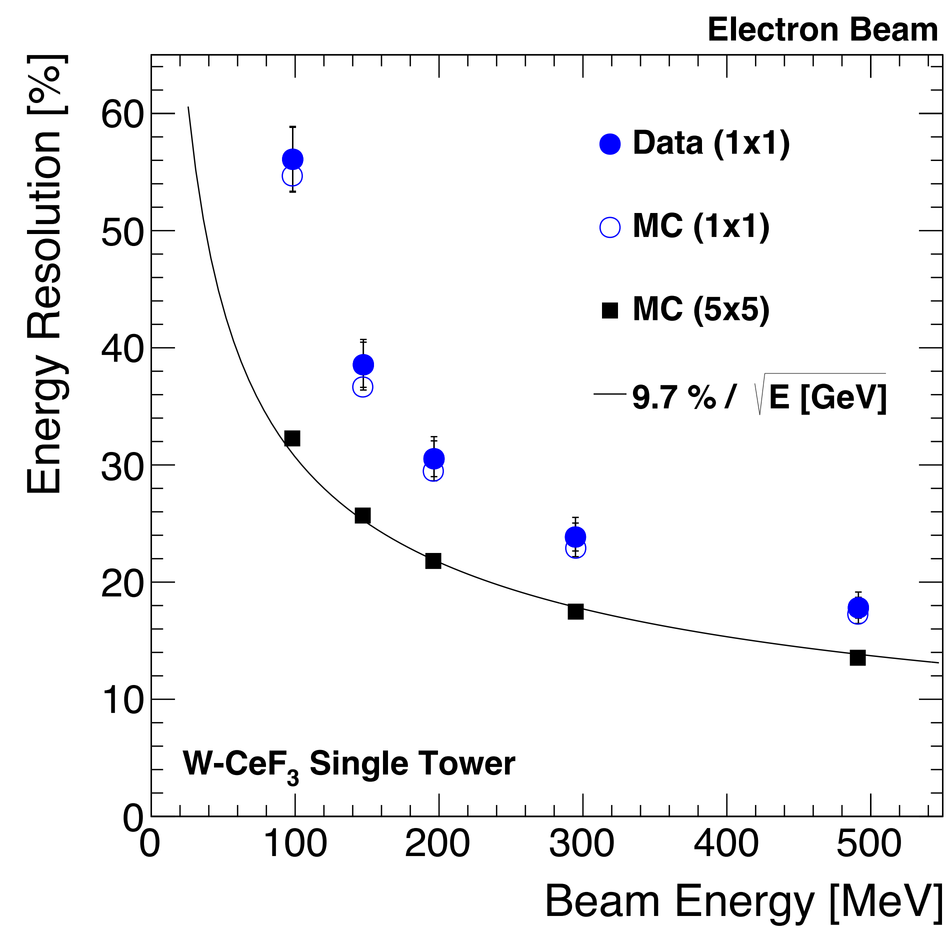
★ Single channel prototype:

- Channel surrounded by BGO crystals
- Kuraray 3HF-SC (1500) fibers
- Hamamatsu R1450 PMT
- Fibers read out individually

★ Single channel energy resolution dominated by lateral containment

- Good agreement between data and Monte Carlo
- No sensitivity to constant term

- Monte Carlo extrapolation to 5 x 5 channel matrix shows that **resolution better than 10%/√E is achievable**



R. Becker et al., 2015 JINST 10 P07002