Performance in electron beams of a tungsten-CeF_3 prototype for radiation-resistant high-energy physics calorimetry

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on behalf of the W-CeF_3 R&D group:

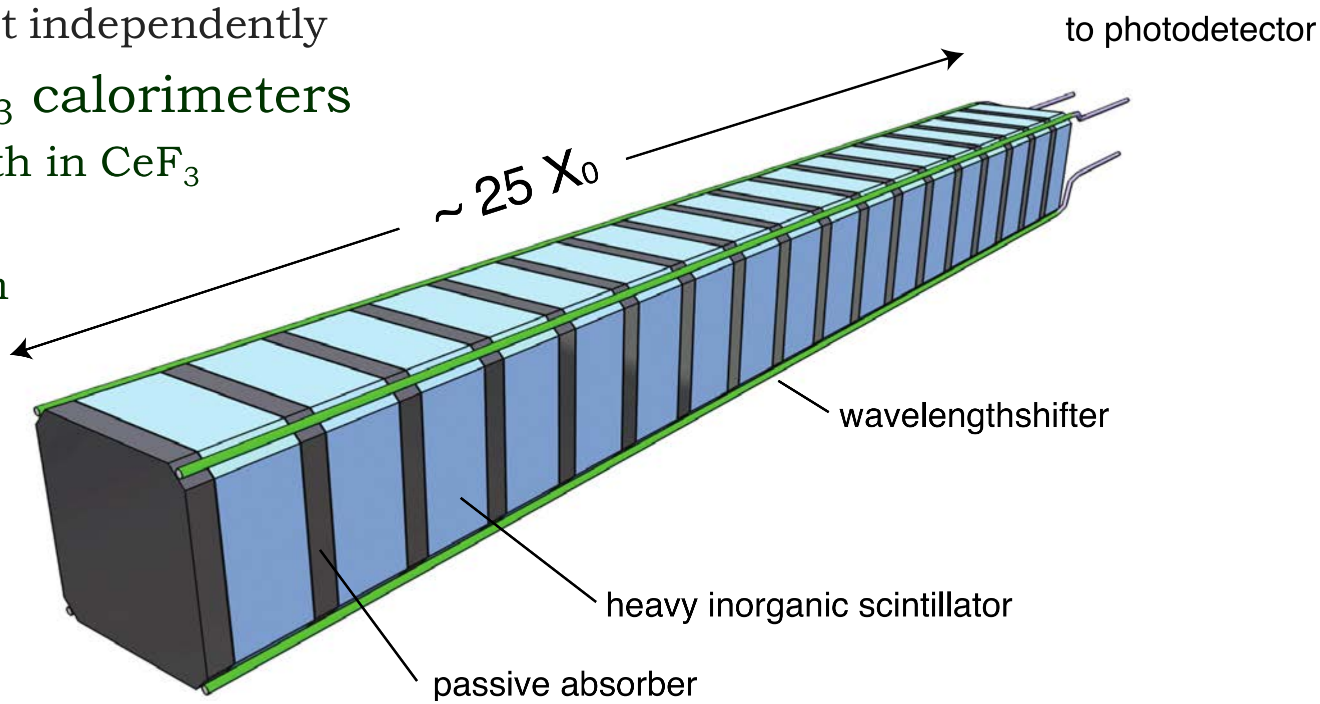
- ETH Zurich
- Roma, University "Sapienza" and INFN
- Milano, University "Bicocca" and INFN
- Torino, University and INFN
- Trieste, University and INFN
- Texas Tech University, Lubbock, Texas

Outline

- A new R&D: the W/CeF_3 calorimeter prototype
  - high precision/high granularity/radiation tolerant EM calorimeter technology for future hadron colliders (harsh environment)
- 2014 beam tests @ Frascati Beam Test Facility and Cern SPS H4 beam facility
  - Intrinsic energy resolution and response uniformity
- June 2015 beam test @ H4
  - Ce:SiO_2 quartz fibers and photodetector characterization
- October 2015 beam test @ H4
  - New optimized Ce:SiO_2 fibers and timing studies
- 2016 Plans @ H4
  - Beam test with 5x3 W/CeF_3 matrix
  - Energy resolution vs impact angle and containment studies

The concept: a simple geometry

- Explore a concept that is mechanically simple, as it might help minimizing the costs and the construction complexity.
- Light extraction by WLS fibers running along depolished chamfers
  - 3 mm-wide depolished chamfers to accommodate fibers
  - Each fiber readout independently
- Sampling W/CeF_3 calorimeters
  - minimize light path in CeF_3
  - very compact
  - X_0 less than 8 mm
  - R_M = 23 mm can be reduced to 15 mm

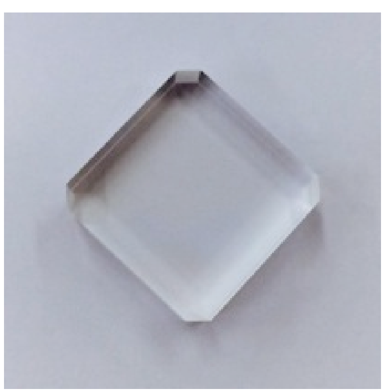


CeF_3 crystals

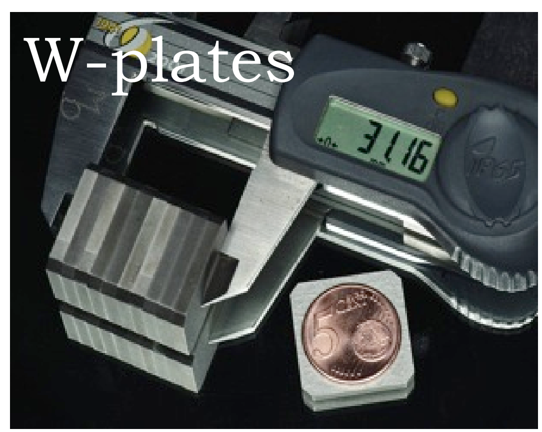
CeF_3 very well suited scintillator for HEP calorimetry applications:

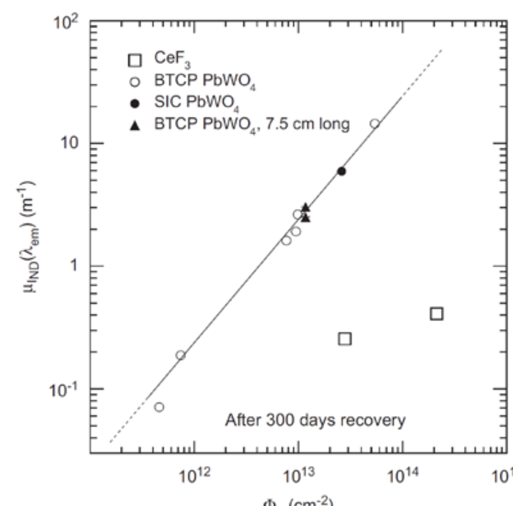
- fast
- resistant to ionizing radiation
  - *E. Auffray et al. NIM A 383 (1996) 367-390*
- able to recover from hadron damage
  - *G. Dissertori et al. NIM A 622 (2010) 41-48*
- suitable for readout via wavelength shifting (WLS)

Density [g/cm^3]	6.16
Refractive Index	1.62
Peak Luminescence [nm]	340
Decay Time [ns]	~20
dLY/dT [%/C^{-1}]	0.14



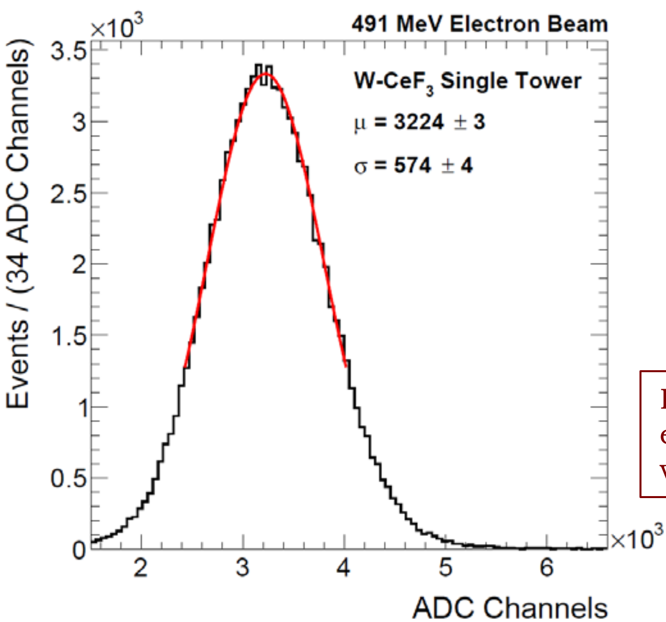
CeF_3 samples produced by Tokuyama



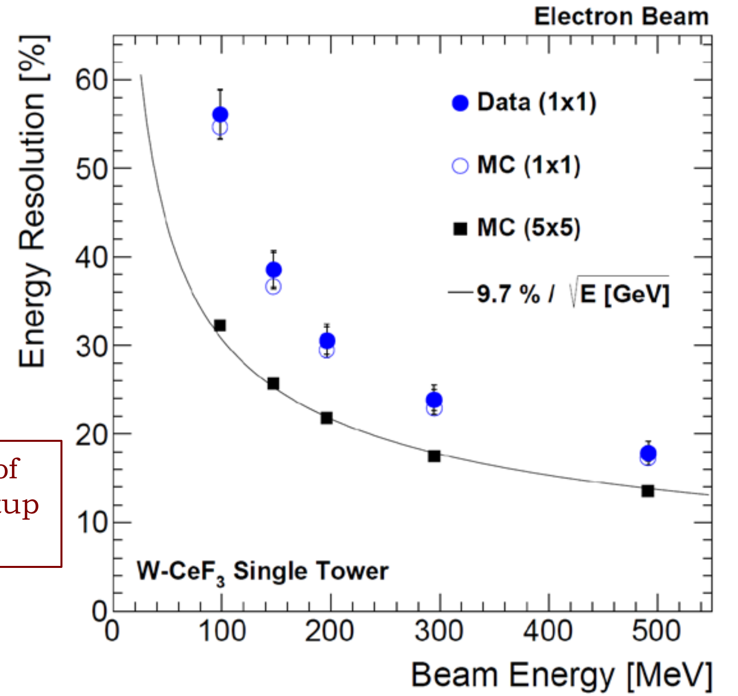


Energy resolution

- Frascati BTF electron beam: $100 < E_e < 500$ MeV
  - 10 x (3.1 mm W + 10 mm CeF_3) = 131 mm ~ 17 X_0
  - Readout by 3HF single-clad Kuraray WLS plastic fibers and PMTs (each fiber read out independently)
  - L3 BGO crystals added to form a 3x3 matrix for containment and alignment purposes
- 10% stochastic term achievable



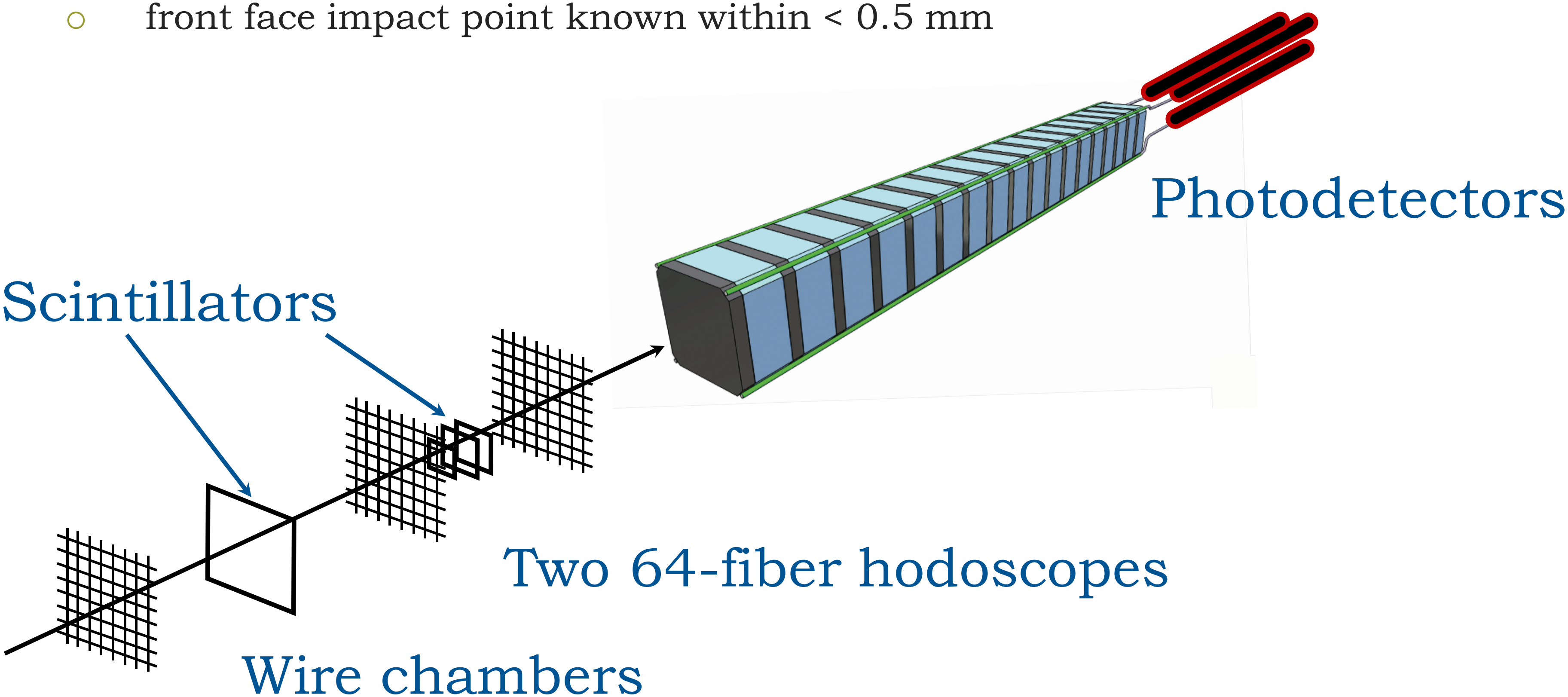
Full simulation of experimental setup with GEANT4.



R. Becker, et al., 2015 JINST 10 P07002

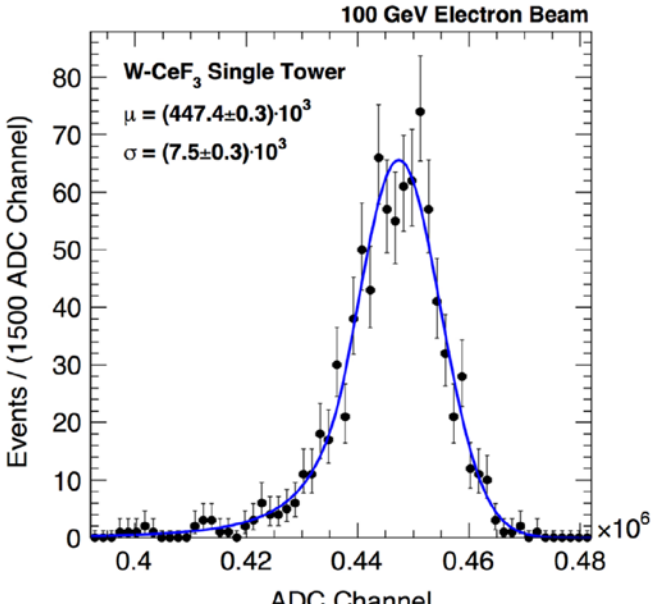
H4 beam test line

- High energy electron beam: $20 < E_e < 250$ GeV
- Precise electron tracking:
  - front face impact point known within < 0.5 mm

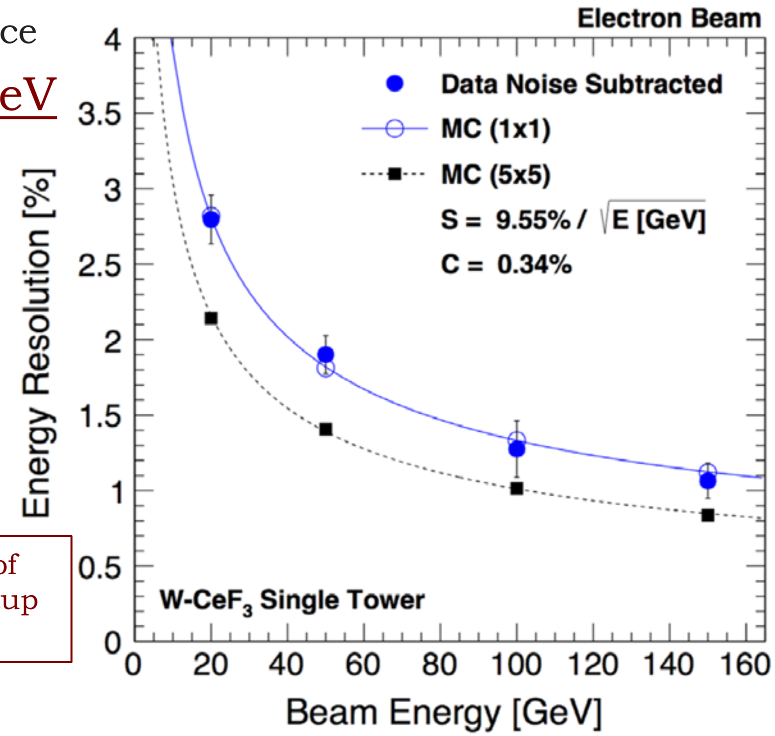


Energy resolution (2)

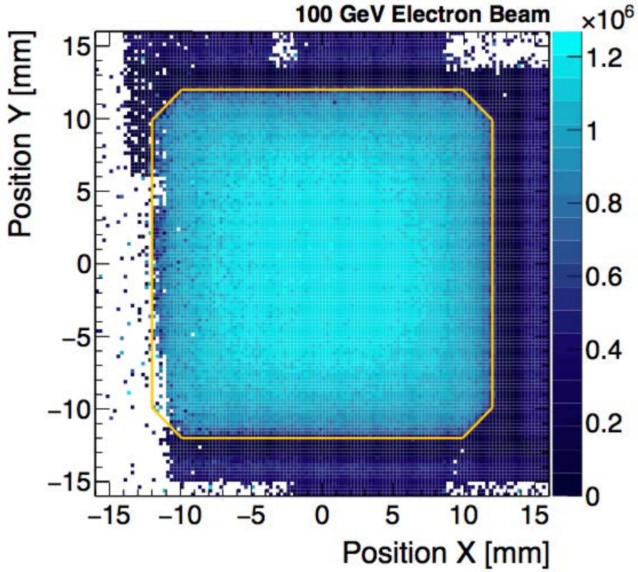
- Setup @ H4:
  - 15 x (3.1 mm W + 10 mm CeF_3) = 197 mm ~ 25 X_0
  - Readout by 3HF single-clad Kuraray WLS plastic fibers and PMTs (each fiber read out independently)
  - L3 BGO crystals added to form a 5x5 matrix for containment and alignment purposes
  - Central events selection: 3x3mm^2 of front face
- Energy resolution of 1% at 100-150 GeV



Full simulation of experimental setup with GEANT4.



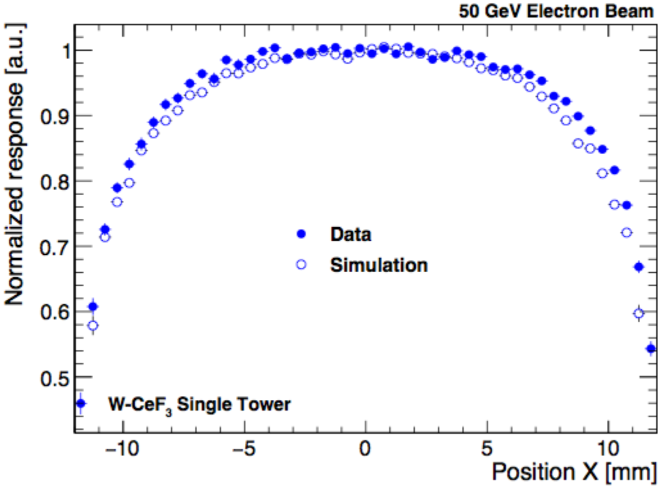
Response uniformity



Channel response vs impact point (measured with the electron tracking).

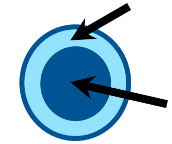
- Very uniform response in the central part of the channel.
- Lateral non-uniformity due to shower containment effect.

- Data/simulation agreement within 5%
- Light collection not yet included in the simulation

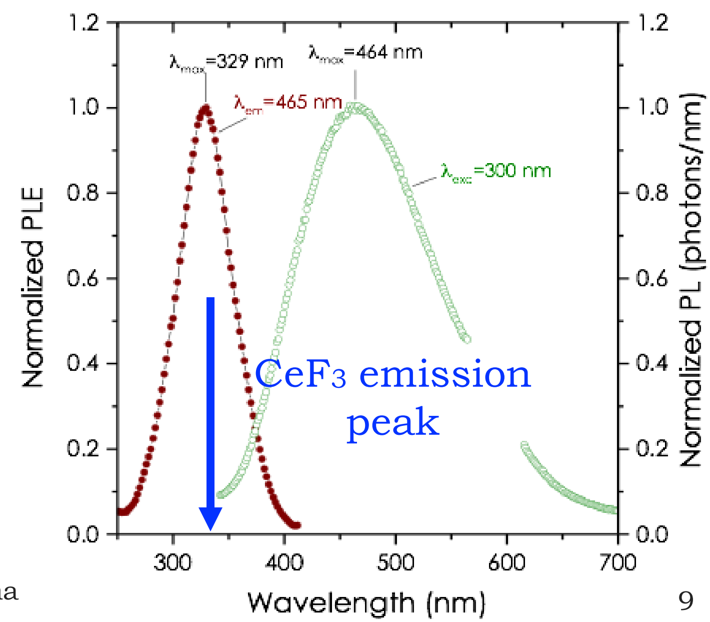


R. Becker, et al., NIM A 804 (2015) 79 - 83

Ce-doped quartz fibers



- Previous results with plastic fibers (NOT radiation-hard)
- Photoluminescent quartz (Ce doped) fibers ($Ce:SiO_2$) good candidates:
  - $Ce:SiO_2$ core (where light is produced)+ multiple cladding for light transport
- Basic properties of $Ce:SiO_2$ fibers in studies for application to dosimetry:
  - Radiation hardness to hadron fluences ($>10^{15}$ cm^{-2}) and e.m. radiation
  - Suitable for WLS
  - Absorption spectrum matches CeF_3 emission
  - Fast time response



- *A. Vedda, N. Chiodini, M. Fasoli et al., Appl. Phys. Lett., Vol. 85 (2004) 6356 and priv. comm.*
- *Jordan Damgov, SCINT2015 presentation*

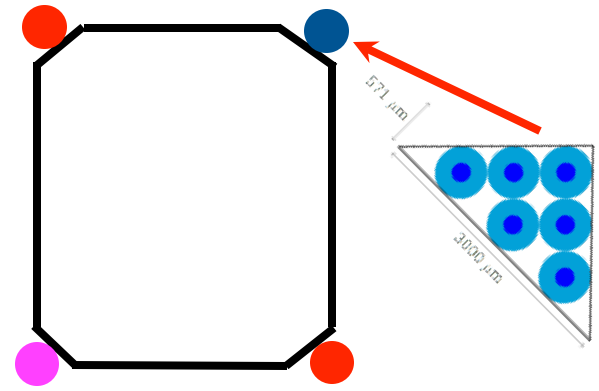
Quartz fiber setup

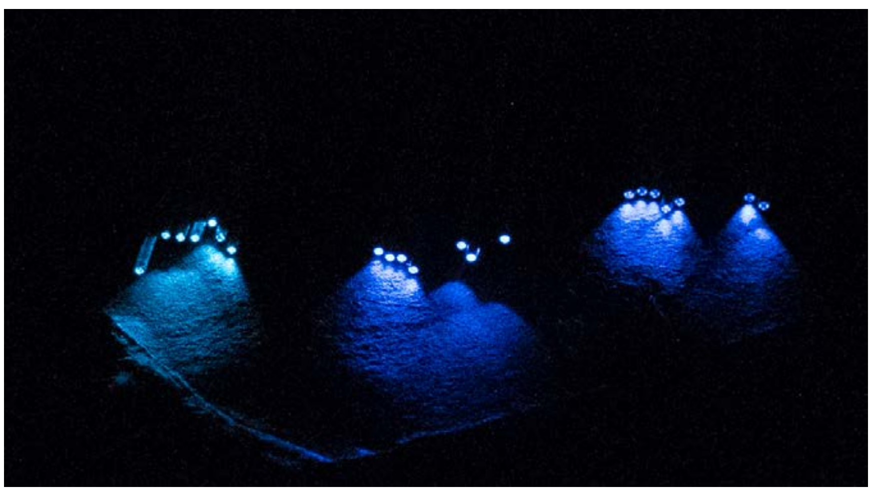
June 2015: beam test with quartz fibers

- 3 bundles of $Ce:SiO_2$ fibers
  - 1 bundle from U. Milano-Bicocca

    A. Vedda, N. Chiodini, M. Fasoli et al., Appl. Phys. Lett., Vol. 85 (2004) 6356 and priv. comm.
  - 2 bundles from Polymicro/Texas Tech

    Jordan Damgov, SCINT2015 presentation
- One plastic fiber as reference



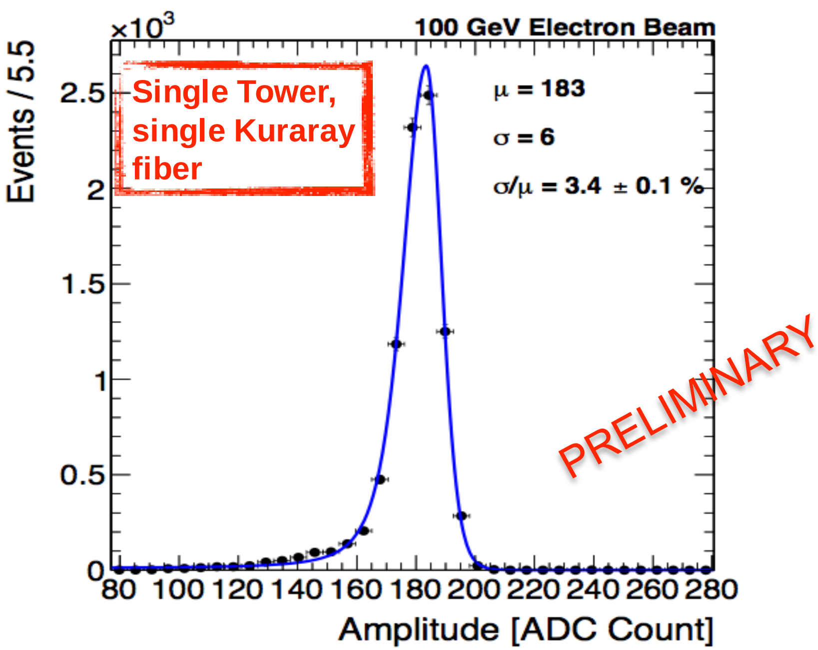


WLS efficiency is lower wrt plastic fibers:

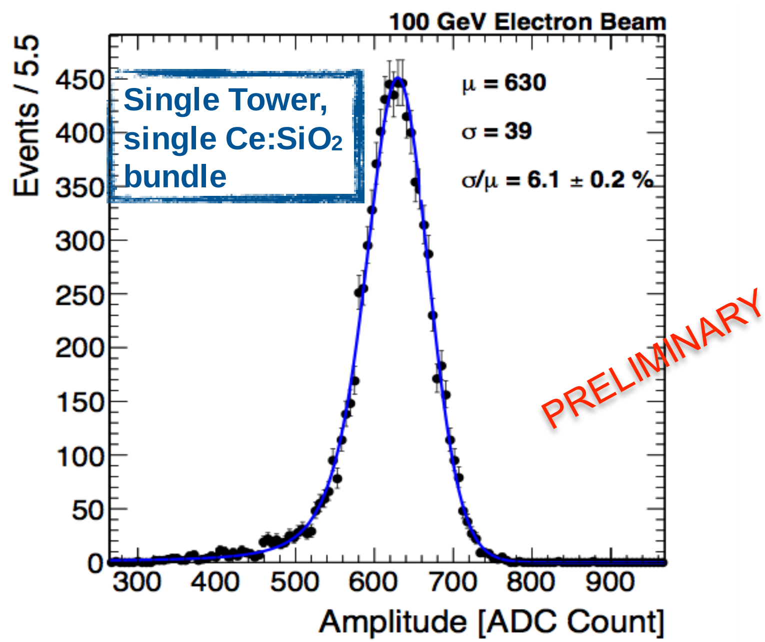
- Ce-doped quartz fibers ~ factor 10/20 less light than plastic fibers
- smaller size fibers: bundle of 6 $Ce:SiO_2$ fibers in each corner

Plastic vs $Ce:SiO_2$ fibers

- Different energy resolutions for the different bundles of $Ce:SiO_2$ fibers
- Worse resolution wrt plastic fibers (consistent with factor ~10 less light)



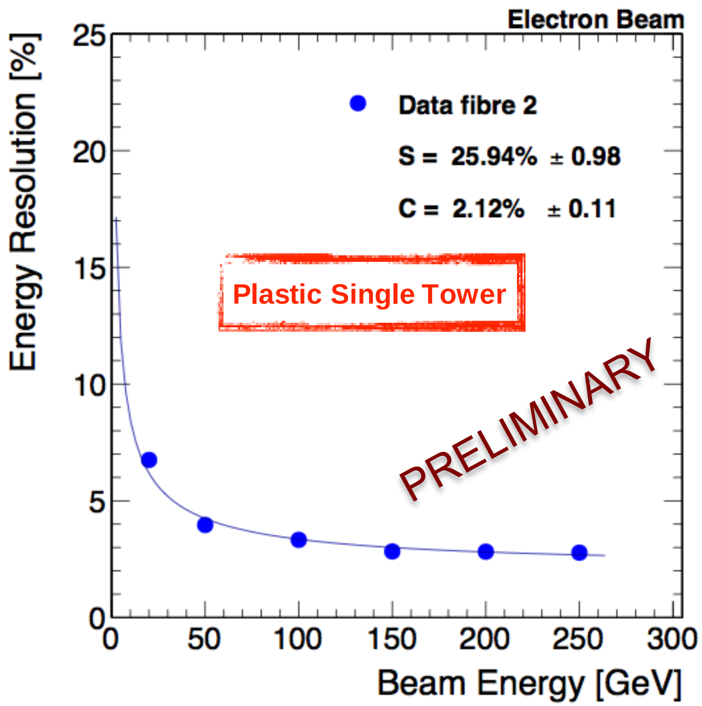
σ = 3.4% @ 100 GeV

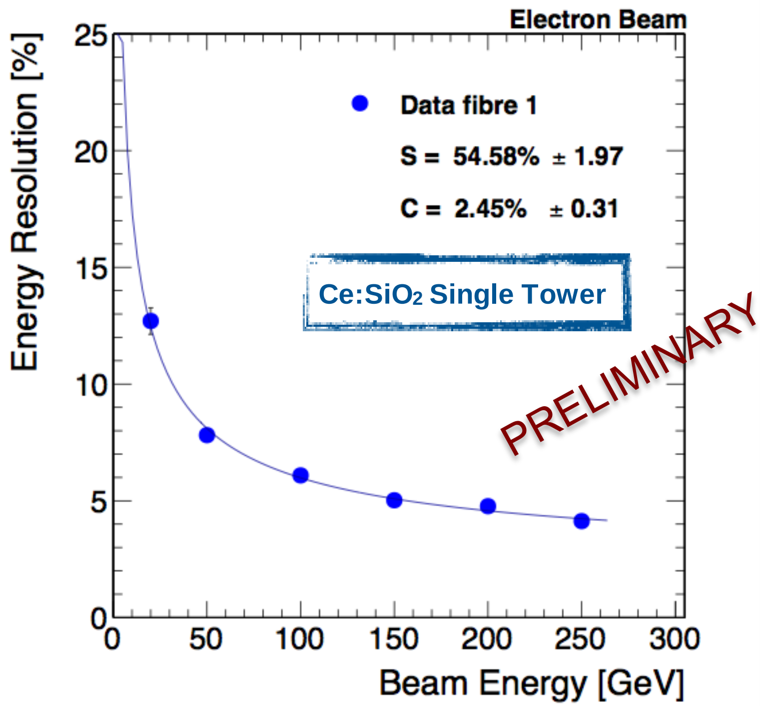


σ = 6.1% @ 100 GeV

Energy Resolution

- Resolution (noise subtracted) for Ce:SiO_2 fibers:
  - dominated by photostatistics, compatible with factor 10 to 20 (depending on bundle) less light produced wrt plastic fibers
- Higher light yield Ce:SiO_2 fibers would improve resolution

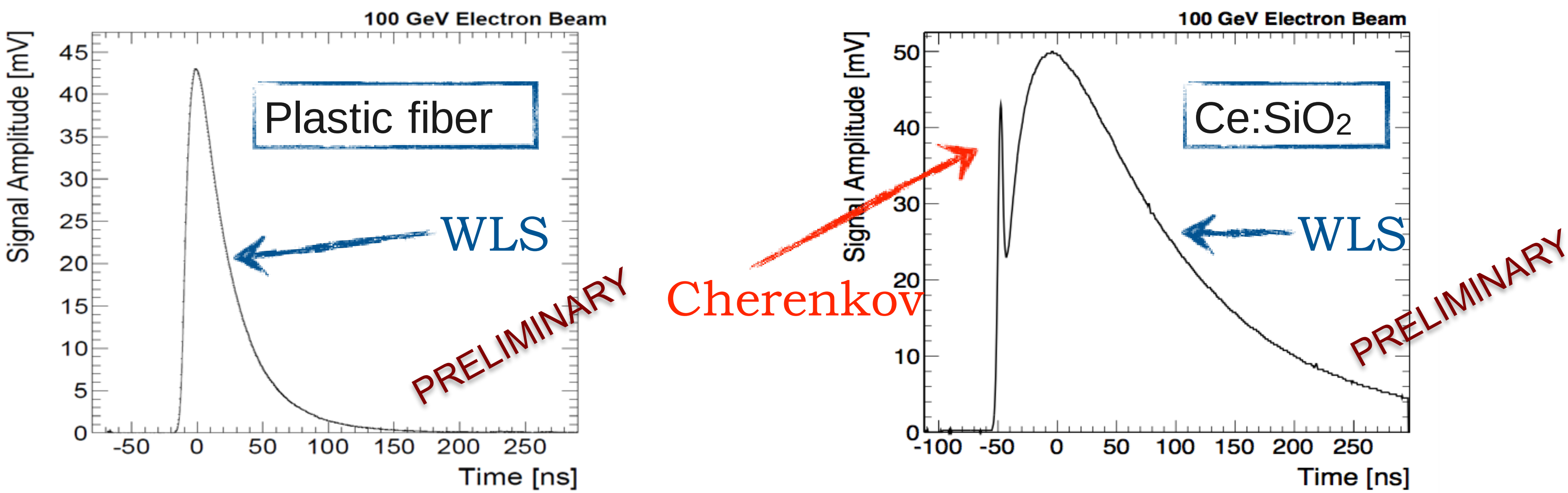




Plastic vs $Ce:SiO_2$ fibers

fibers read by PMT + Digitizer @ 2.5 Gs/s (400ns window) → full waveform acquired

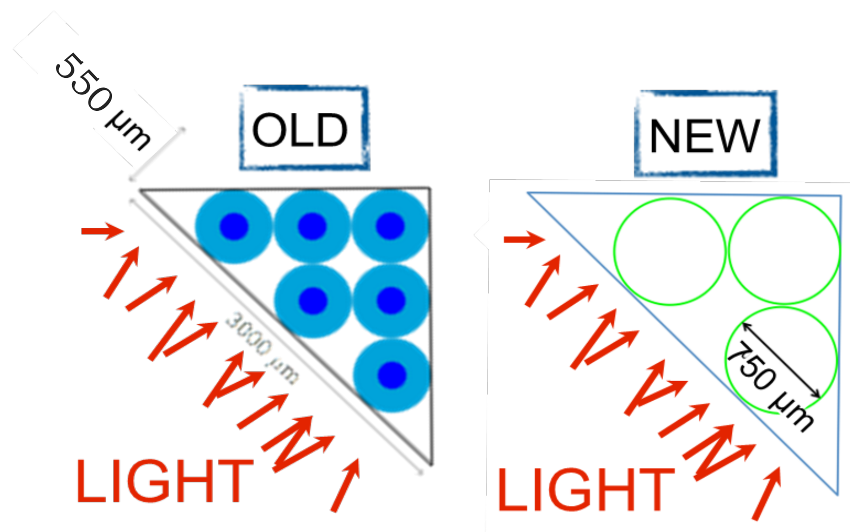
- $Ce:SiO_2$ fibers:
  - Slower WLS re-emission
  - Fast Cherenkov component:
  - Rise time few ns (dominated by PMT response time)



October beam test - fibers

- Results of summer test beams gives two main research paths:
  - Better Ce:SiO_2 fibers for better energy resolution (WLS)
  - Use of fast Cherenkov component for timing purposes
- Dedicated setup: initial study of these possibilities
- New fibers with bigger core (U. Milano-Bicocca) → higher light yield
- Active volume (core) x1.4 wrt June beam test and increased direct exposure

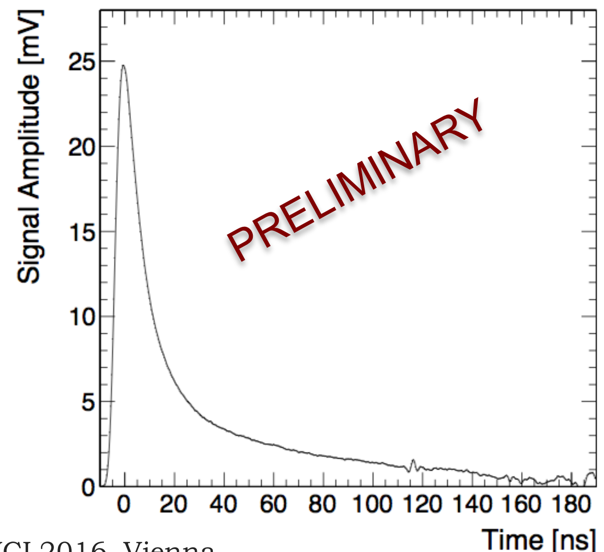
old Ce:SiO_2 | new Ce:SiO_2 | Plastic

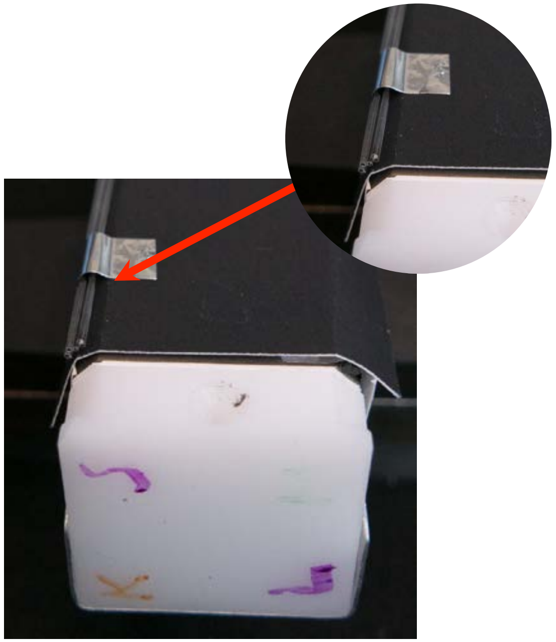


Timing studies

Motivation: timing information will be crucial for pileup-suppression in detectors for HL-LHC

- One bundle of Ce:SiO_2 has been "blinded" with black paper
- No WLS, pure Cherenkov and direct scintillation
- Readout with Hamamatsu SiPM and ETH preamplifier board.

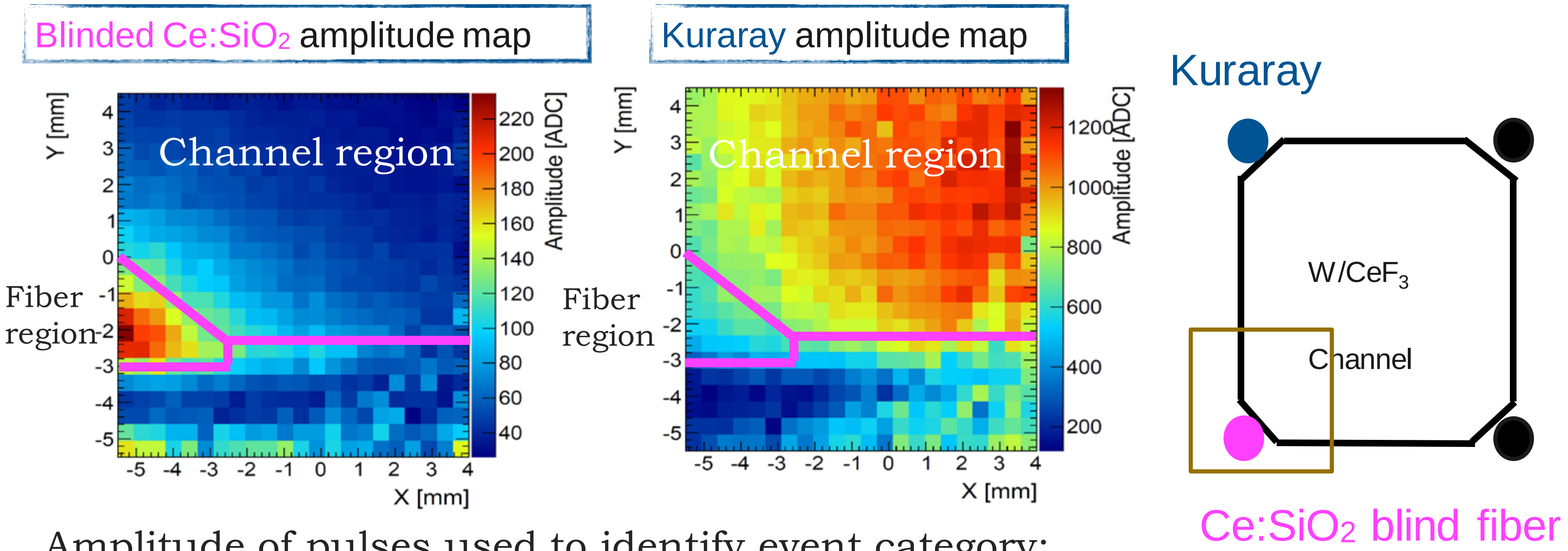




- Rapid rise time: 3-4 ns encouraging for timing
- Exponential direct scintillation

Timing studies

- Data taken with beam centered on the blinded $Ce:SiO_2$ fiber (rather than on the centre of the channel): trigger 1x1 cm scintillator.
- Pulse amplitude as a function of hodoscope coordinates.



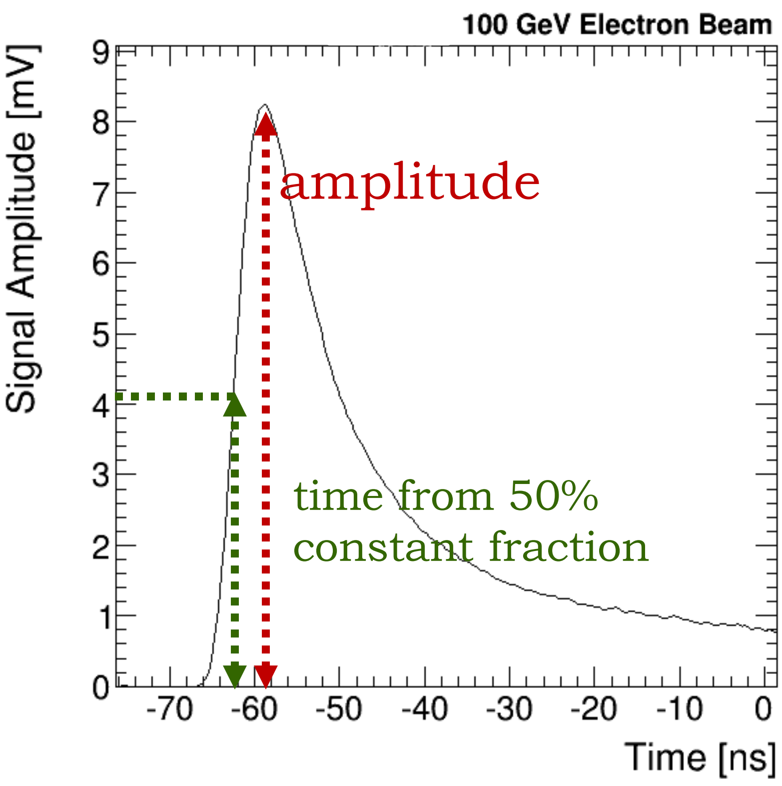
Amplitude of pulses used to identify event category:

- Fiber: beam in fiber region & Kuraray signal < thresh.
- Channel: beam in channel region & Kuraray signal > thresh.

Timing studies

- Pure Cherenkov and direct scintillation
- Time from 50% constant fraction
- Interpolation of the 5 samples around this point

- Reference timing from a MicroChannelPlate device in front of the CeF_3 channel.
- MCP time resolution: 20-30 ps (almost negligible in the following)
- Above procedure for MCP timing determination.

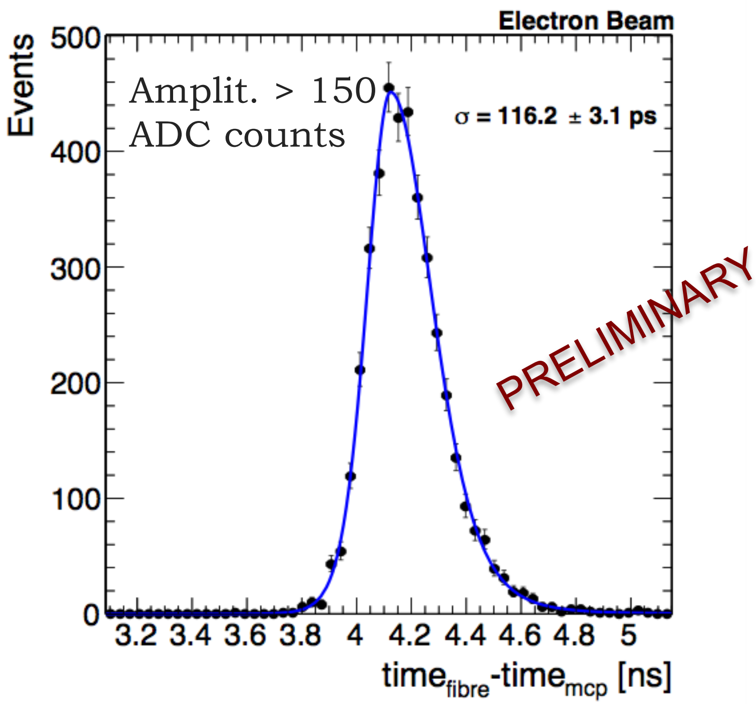


L. Brianza et al. NIM A 797 (2015) 216-221

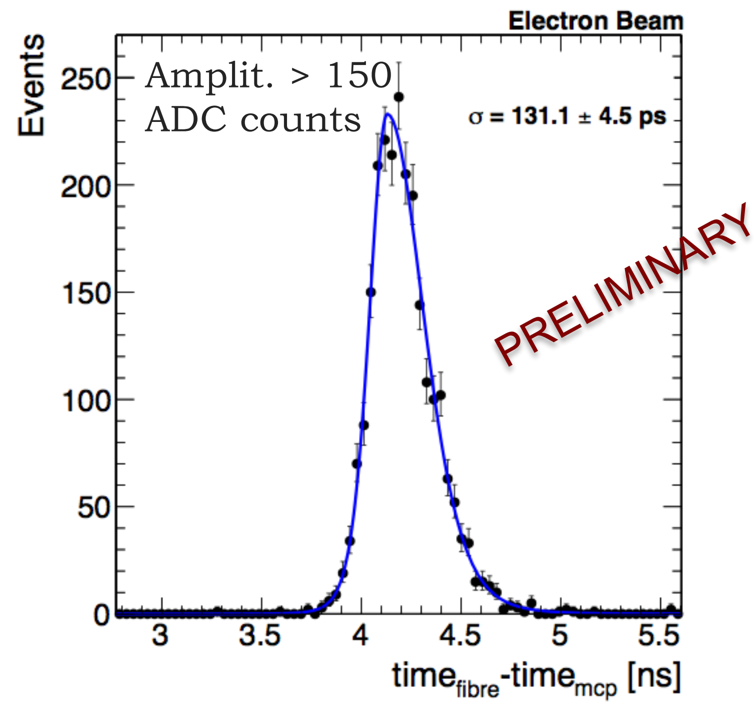
Timing resolution

- Resolution estimated with the fiber – MCP time difference for $Ce:SiO_2$ blind fiber.

fiber event selection



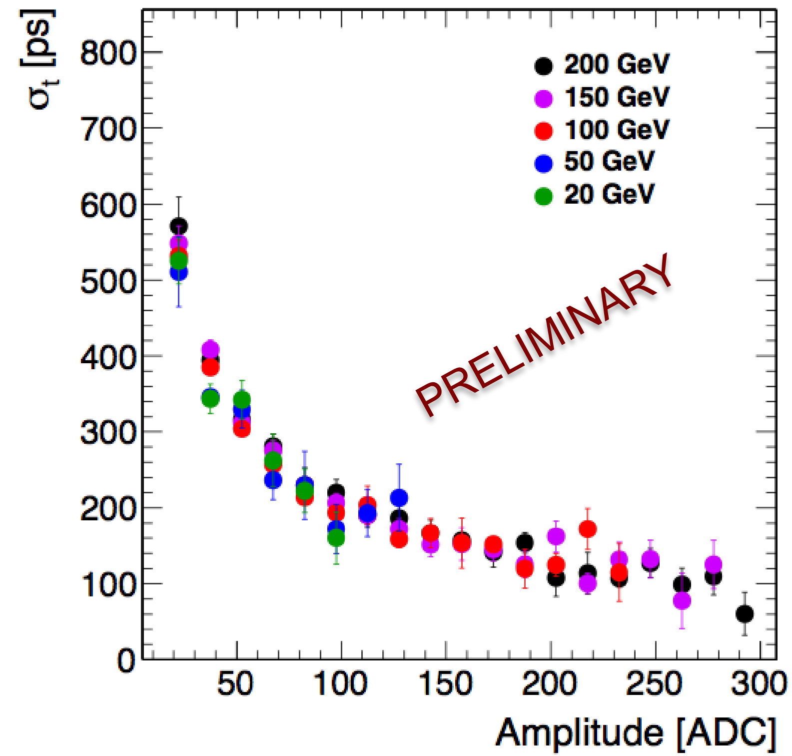
channel event selection



Timing resolution

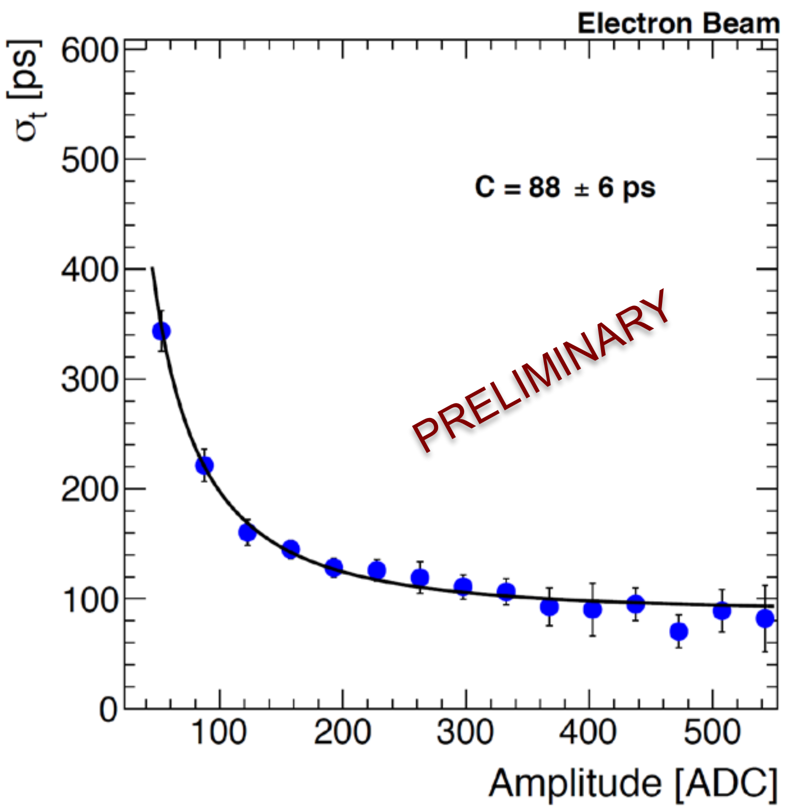
Resolution is amplitude dependent. Beam energy is irrelevant.

- Beam impact on channel (events passing channel selection)
- For amplitude >100 ADC counts resolution σ_t~100 ps
- Merge timing resolution for all energies together and estimate the resolution for events on fiber and events on channel

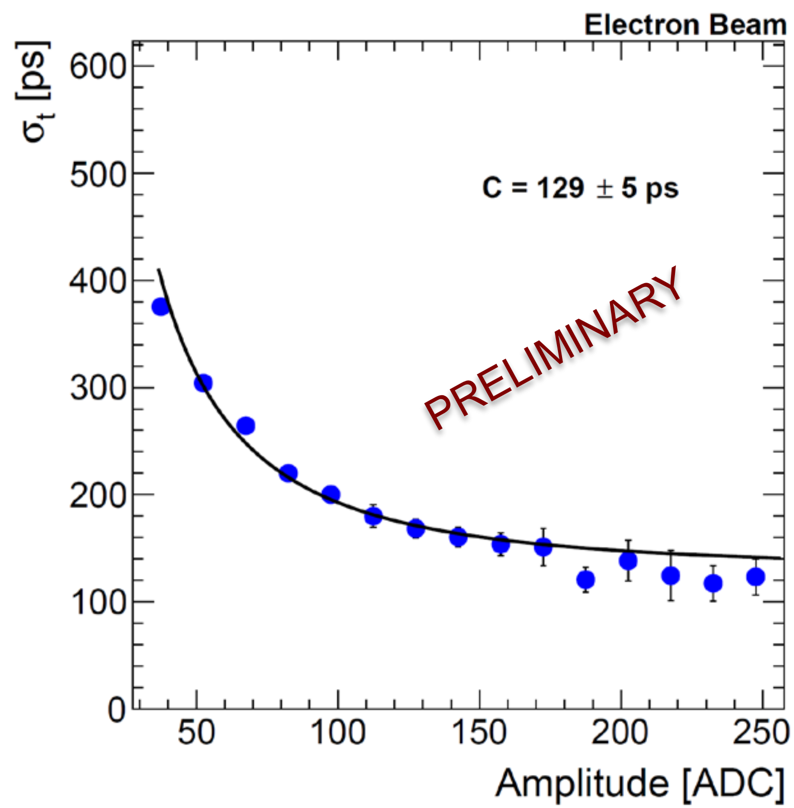


Timing resolution

fiber event selection

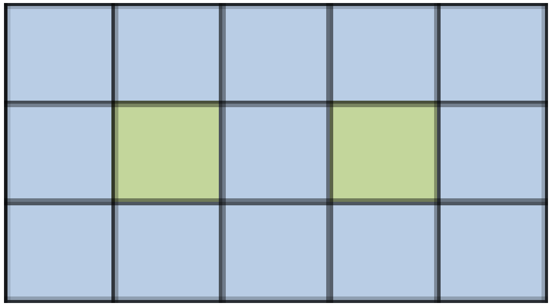


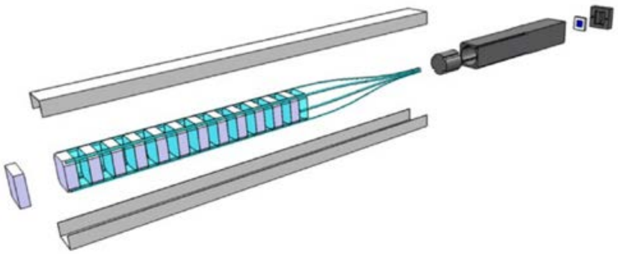
channel event selection



2016 Beam Test

- 5x3 channel matrix for energy resolution (vs impact angle) and containment studies.
- 12 x (6 mm CeF_3 + 6 mm W) ≃ $25X_0$ (≃ 14.5 cm), transverse dimension 17 mm
- High granularity: R_M = 17 mm
- WLS fibers for readout: Kuraray 3HF-SC
- 4 fibers signals onto one photodetector, but read out independently for two inner channels (in total 21 channels)
- APD readout since PMTs dimensions not suitable for this configuration





Conclusions

- W/CeF_3 energy resolution: stochastic term < 10% and constant term well below 1%.
- Good energy resolution is also achievable with radiation resistant quartz fibers.
- Timing result with SiPM read out by ETH preamplifier board: resolution <100 ps achievable.
- W/CeF_3 matrix will be on beam this summer for ultimate energy resolution and containment studies.

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