

Tile Dual Readout and Beyond

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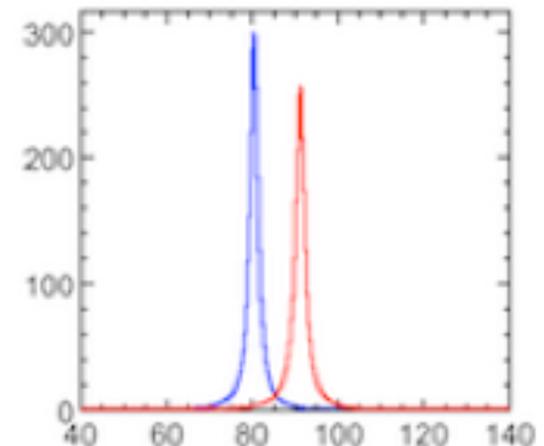
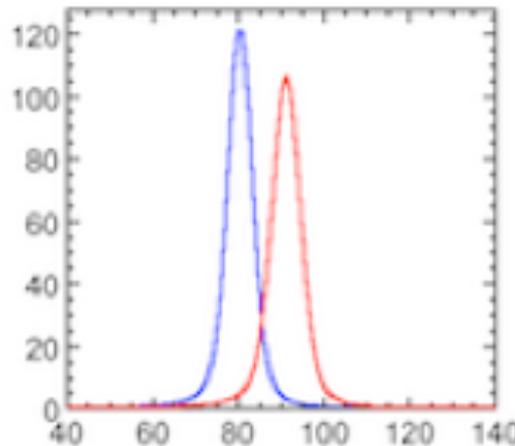
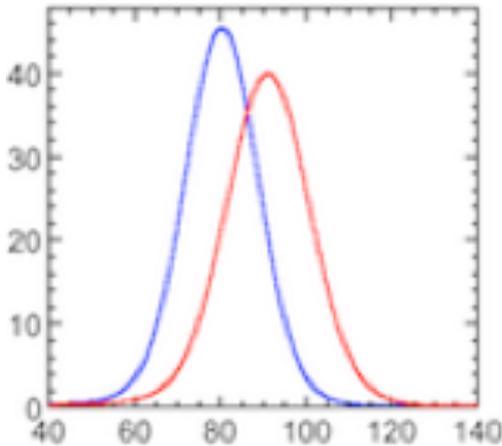
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A Physics Example: Calo Precision jets



- - **Jet-Jet masses:** Goal for future experiments: Z->jetjet vs W->jetjet
- Ratio W,Z->jj : W,Z->leptons \sim 6-7
- Reconstruct AND Separate (E_{Miss} , jet tags, V-V scattering, BSM, W' , Z' ...)
- Separation of W from Z: $\sigma_{E_{\text{jet}}}/E_{\text{jet}} \sim 3\%$ necessary at 100 GeV, with typical single particle energies ~ 10 GeV [*ASIDE: during collision crossing times which may be as small as ~ 10 's of ns, pileup events ~ 200 /crossing and raddam exceeding 50-100MRad.] A 3%-4% jet energy resolution from 50-500 GeV gives 2.6-2.3 σ W/Z separation. J-J mass resolution is important in searches for heavy W'/Z' , vector boson scattering, triple VVV....*



- W/Z->jet-jet separation: **Left** - calorimeter $\sigma_E/E=60\%/VE$; **Middle** σ_E/E 22%/VE (3% @ 50 GeV) $\sim 2.6\sigma$ separation; **Right** -perfect resolution: $\sim 4.5\sigma$ separation. (from M. Terwort)

Dual Readout: Cerenkov Compensation

First form of multiple readout

- 1st Quantitative MC Study:
 - GEANT MC in 1988 [*Compensating Hadron Calorimeters with Cerenkov Light, D.R. Winn, W.Worstell, IEEE Trans. Nuc. Sci.,V1 NS-36, 334(1989)*]
 - Idea: Use differences in response to e-m fluctuations between
 - Cerenkov Medium(transparent – LAr, H₂O, SiO₂) vs
 - Ionization Medium (scintillator, LAr ion collection,..)to reduce hadron shower fluctuations and make e/h-> 1
- DREAM Collaboration/Richard Wigmans et al.
 - Parallel Scintillating+Quartz Fibers
 - Excellent progress in test beams
 - Thorough Analysis of Dual Parallel Fiber Calorimeters
- MC: 18%/√E possible....But DREAM: ≥30%/√E:



Parallel Fiber Deficits - 1



- **1. Constant Term—unavoidable issue** – scintillator light attenuation in $\sim 2+$ m fibers.
- **2. Pointing/Projective Geometry problematic** in a practical parallel fiber calorimeter over a substantial solid angle. The mechanics + fiber packing of fully projective (θ, φ) very difficult for (pitch, yaw) more than $\sim 5^\circ$. Streaming down fiber holes lowered the resolution in DREAM, even at a 2° pitch. Packing extra fibers from the back or conical fibers: \rightarrow Constant term, \rightarrow Calibration Issues
- **3. Scintillator Fiber & Photodetector Raddam:** At present, there are no good examples of scintillator fibers which have proven sufficient raddam resistance or speed to be useful for hadron calorimetry at many future colliders or high flux.
- **4. Fiber Bundle & Photodetector Punchthrough:** Huge fiber bundles, $>33\%$ of the back of the fiber dual calorimeter area, are directly behind the calorimeter. Large punchthrough backgrounds are generated by these fibers, photodetectors ($\sim 1/800$ incident π/K quasi-elastic scatter through a $10 L_{\text{int}}$ calorimeter).



- **4. E-M and Hadronic Components of Incident Jets:** Parallel fibers: ~little ability to detect + separate *incident direct e-m component inside of a jet - no full longitudinal segmentation.*
- **5. High Resolution EM Front End.** The parallel fiber dual readout jet calorimeter: ~no compensated high-Z high sampling EM front end.
- **6. Calibration:** Parallel fiber geometry difficult to calibrate, as radiation damage & attenuation varies w/ length. (Contrast w/ longitudinally segmented calorimeters)
- **7. Timing & Pileup:** Longitudinal fibers store the information of jet/em showers: the signal is over the time for the light to traverse the fibers. The light generated *at the back of the calorimeter arrives at the photodetector first.* Thus Fiber calorimeters measure the falling edge of the shower, a less precise measurement

- **8. Longitudinal Segmentation:** Fiber dual readout is incompatible with true longitudinal segmentation, even with waveform electronics, and cannot be easily rebuilt for front readout or implement 4,5 above.
- **9. Radiation Damage: No ability to Repair front end damage.**
- **10. Cerenkov Fiber Index of Refraction:** High Radiation Resistant Cerenkov fibers are limited to quartz, with $n=1.46$ yield an $h/e_C \sim 0.25-0.20$ – limiting resolution. Lower index $n < 1.4$ fibers yielding a lower h/e_C ratio are not conveniently available (Ex: silica aerogels, Teflon AF, Siloxanes, fluoride glass)
- **11. Cost:** the cost of tiles is significantly less per mass or volume of sensitive material than that of fibers, and the cost of a fabricated tile absorber matrix is considerably less than the parallel fiber Swiss cheese absorber.

12. No Particle Flow/Energy Flow Calorimetry:

Parallel Fibers are incompatible with high granularity - improving jet $\Delta\theta/\theta$, core ID of jets, isolation/ID of leptons/photons in jets and pileup, and neutral particle (K^0 , n) ID, especially under pileup. Waveform analysis may provide some longitudinal segmentation as the history is stored in the fibers, but complicated. **Tile readout:** fully compatible with highly granular calorimetry, easily added to particle flow calorimeters

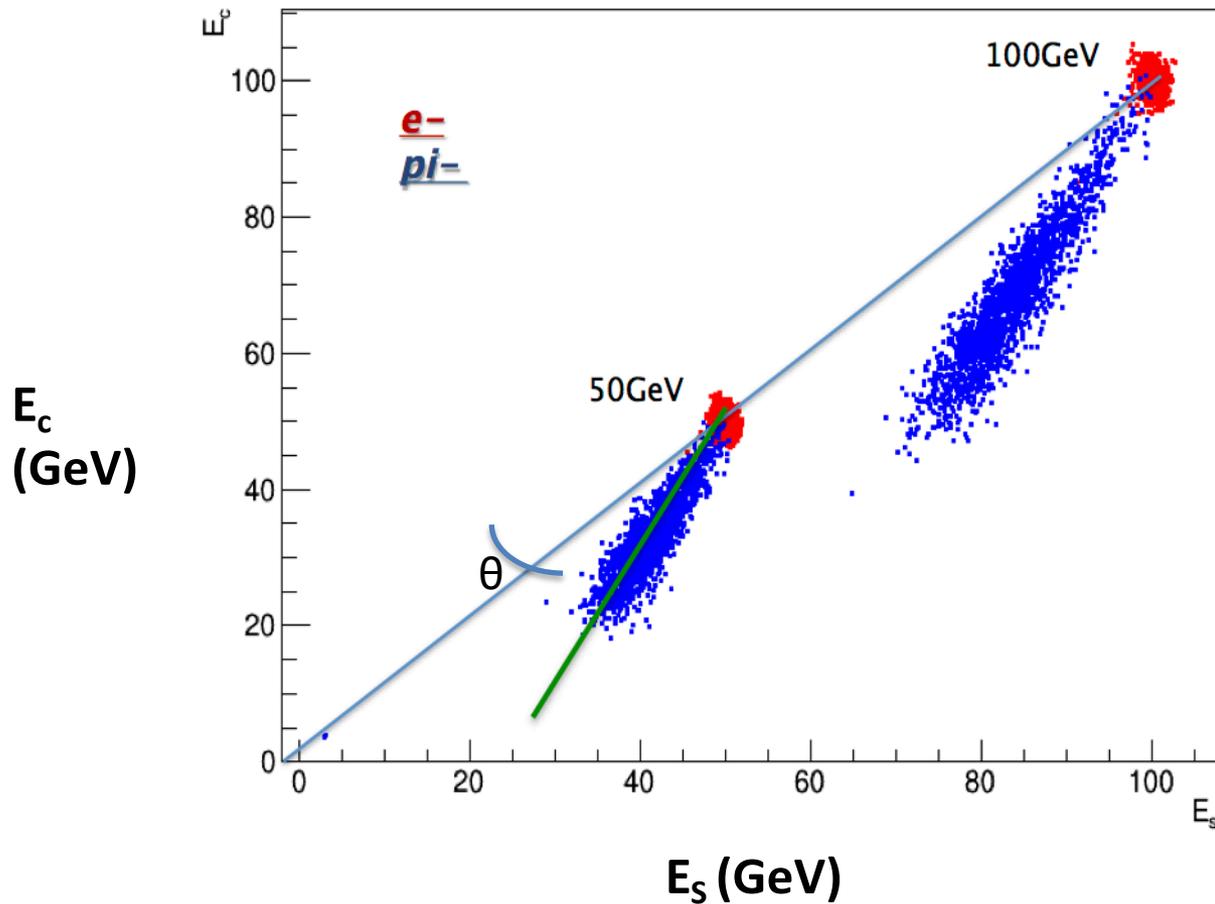
13. No Alternate Convenient Fiber Sensor Types for Dual Readout ...or Triple or Multiple Readouts:

Parallel fibers do not have other convenient fiber sensors which could further separate e-m and hadronic components

Ionization detectors

- Solids – Si, Diamond, GaAs,..;
- Liquids- LArgon, Liq. Scintillators
- Gasses – micromegas, TRD
- β ->1 sensitive detectors such TRD, or ultra-low-index materials(aerogels $n\sim 1.1$, MgF_2 , water $n\sim 1.33$, perfluoro-, silicones,..);
- Secondary Emission sensors with higher response to slow particles β ->0 and minimal response to minimum ionizing energy (new large MCP);
- Inorganic non-hydrogenous scintillators (LYSO, $PbWO_4$, ZnO:Ga et al.),
- Neutron-Enhanced: 6Li , ^{10}B , 3He , fissionable... containing materials.

- **GEANT4 MC on a simple fine grained tile calorimeter:**
 - **0.5 cm thick each of quartz Cherenkov, plastic scintillator, and Cu absorber tiles.**
 - Two energies (50, 100 GeV) each of 1000 **electrons (red dots)** and of ~800-1000 **pions (blue dots)**] were sent into a 50x50 cm calorimeter, 12.2 Lint deep (8 Lint of Cu, 1.5 Lint polystyrene, 2.7Lint Quartz = 12.2 Lint Length ~ 3.6m)
 - Simple MC: Photons 325-650nm generated in the Cerenkov tiles and in the scintillator tiles were counted by GEANT4. Then 0.5% at random were assigned as converted to p.e., a conservative estimate based on existing calorimeters using WLS fibers and PMT photocathodes.
 - Electrons and Pions of 50 GeV, 100 GeV were simulated – the numbers of Cerenkov and of Scintillator photons were converted to E_C and E_S ->
 - Means of histograms of the electron shower p.e. in quartz and in scintillator were used to normalize the number of collected p.e. in Cerenkov light and in Scintillator light to normalized energies $E_{Cerenkov}$ and $E_{Scintillator}$, - plotted as a scatter plot of E_C vs E_S for each electron (next slide)
 - Scintillator photons ~120x Cerenkov photons; photostatistics are not limiting factors.



Electrons: E_c vs E_s (red points) lie along line shown schematically as $E_c = E_s$.

Pions: E_c vs E_s scatter-plotted (blue points) lie mainly below the $E_c = E_s$ electron line with correlation between E_c vs E_s fitted as a line (green, 50 GeV points at an angle θ).

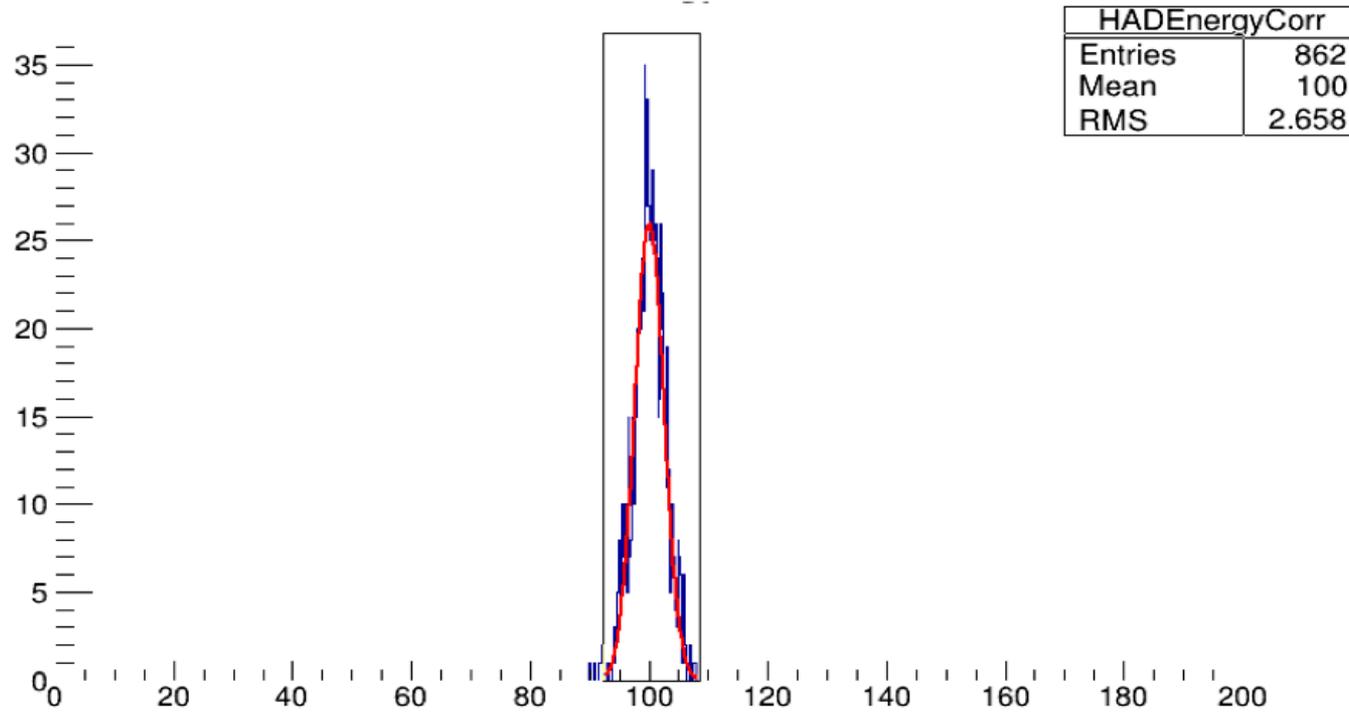
As the shower fluctuates more to hadrons, E_c falls faster than E_s

Dual Correction

- **A Simple analysis:** Linear fit to hadron scatter points (Green line), with slope R , corrects the energy: Project the scatter points as a histogram perpendicular to the linear correlation, the energy distribution becomes Gaussian & narrower.

- Pion Energy E (*first order*): $E = E_s + [\text{a correction term proportional to the difference } (E_s - E_c)]$:
 $E = E_s + \alpha(E_s - E_c)$ with α given by slope R as $R = (1 + \alpha)/\alpha$ or $\alpha = 1/(1 - R)$.
 - The angle between the line $E_c = E_s$ and fitted π scatter plot line: $\theta = \arctan(R) - \pi/4$.
- $(E_s - E_c)$ grows as shower fluctuates into nuclear/hadronic energies.
- As slope R gets steeper, the correction term $\alpha(E_s - E_c)$ becomes more important.
 - When Cerenkov E_c is the same as scintillation E_s (example: e 's or π 's exchange to π^0 's),
then $(E_s - E_c) \sim 0$, $E = E_s = E_c$
- **This analysis can be easily shown to be equivalent to that of Wigmans using D.Groom's analysis of dual or Cerenkov readout.**

Dual Correction - II



Cherenkov-Corrected Energy (GeV)

(mean, rms) = (100, 2.66) GeV

σ_E/E enables $W \rightarrow$ jet-jet separated from $Z \rightarrow$ jet-jet

Future Work:

- **Higher order terms-** $\alpha_2(E_s - E_c)^2 + \alpha_3(E_s - E_c)^3 + \dots$ & energy dependent α_n –
 - \rightarrow **Continuous mapping**(vector field) of the points in E_c vs E_s space to line $E_c = E_s = E$

– Rules of Thumb:

- (0) An intrinsic limit of normal hadron calorimetry: $\sigma_E/E > 11-13\%/VE$, given by the ratio of detectable neutron energy to the fluctuations in lost nuclear binding energy.
- (1) Contrast between h_i/e_i (i =ionization) and h_c/e_c (C =Cerenkov) for hadrons h and e-m energy: the ratio of ratios $[h_i/e_i]/[h_c/e_c] \geq 4$ in order to reach incident hadron energy resolutions below $30\%/VE$, with $18\%/VE$ being a reasonable target to achieve using plastic scintillator and low index materials;
- (2) h_i/e_i : as large as possible \rightarrow hydrogenous or n-sensitized ionization detection media.
- (3) e-m energy resolution in Cerenkov light $< 70\%/VE$ to achieve $< 20\%/VE$;
- (4) Resolution scales $\sim \sqrt{f_{\text{sample}}/f_{\text{frequency}}}$.
- (5) Compensation achieved by enhancing neutron(hydrogenous/ n-absorbing) & ion fragment sensitivity

FUTURE Dual Readout

- **Adding sensor tiles** relatively insensitive to MIPs, more sensitive to $\gamma\beta \rightarrow 0$
 - increases the contrast between e-m and hadronic energy (enhancing the low energy hadronic signal)
- **Secondary Emission:** Signal scales $\sim dE/dx$,
 - MIP SE signal $\sim 100x$ less than that of the energy of the peak signal (peak signal for protons occurs at $\sim 200\text{KeV}$ - $n+p \rightarrow p+n$ knock-on protons).
- **Homogeneous dense inorganic scintillators** (LYSO, PbWO_4 , CeF_3 , LAr, LXe...)...
 - $h_i/e_i \sim 0.4$ and $h_c/e_c \sim 0.25$, or $[h_i/e_i]/[h_c/e_c] \sim 1.6$:
 - > *Homogeneous calorimeters cannot achieve dual readout compensation better than $\sim 50\%/ \sqrt{E}$ on hadrons, even with perfect separation between scintillator light & Cerenkov light in the homogeneous detector. [LAr/Ch4 ions instead of Scintillator]*

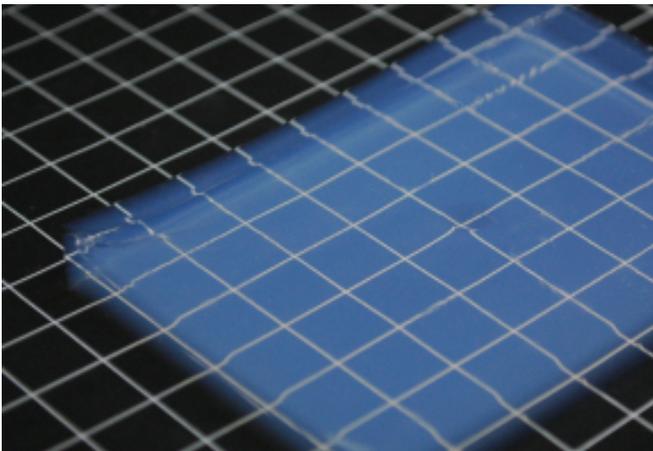
$\sigma_E/E \sim 15\%-18\%/ \sqrt{E}$ on jets: scintillator sensors with $h_i/e_i \sim 0.6-0.8$ and Cerenkov sensors with $h_c/e_c \leq 0.2$ are needed. To achieve $h_c/e_c < 0.2$, lower n Cerenkov radiators are required ($\beta_{\text{thresh}} \rightarrow 1$),. Requires photons for e-m resolution $< 70\%/ \sqrt{E}(\text{GeV})$ or $N_{pe} > 2$ pe/GeV .

Extend E-M Response by higher sensitivity to $\beta \rightarrow 1$
Results in high contrast ratio with $h_c/e_c > 0.15$ (i.e. $e_c/h_c > 6-7$)
(Lessens low energy Hadron, n, and nuclear fragment Sensitivity)

(A) TRD Example: Straw tubes,..... Low mass issue for calorimetry

(B) Low index n Tiles ($1.1 < n < 1.35$) tiles Note: thickness for sufficient photons..

- silica aerogels ($n=1.05-1.3$)
- TeflonAF ($n=1.29$, 12 Mrad) (amorphous form; water-clear)
- polysiloxanes ($n=1.35$, 100 Mrad)
- MgF_2 (1.37)
-



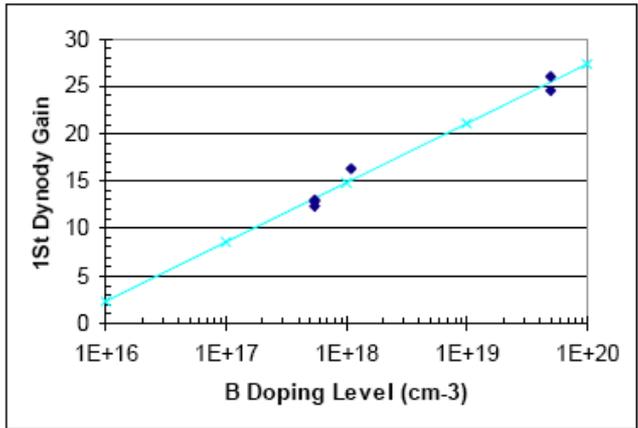
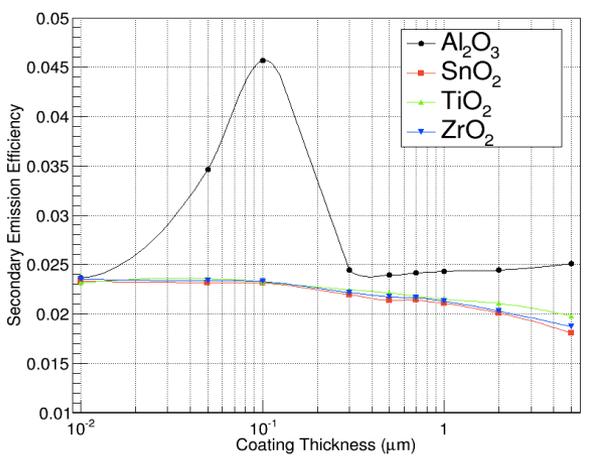
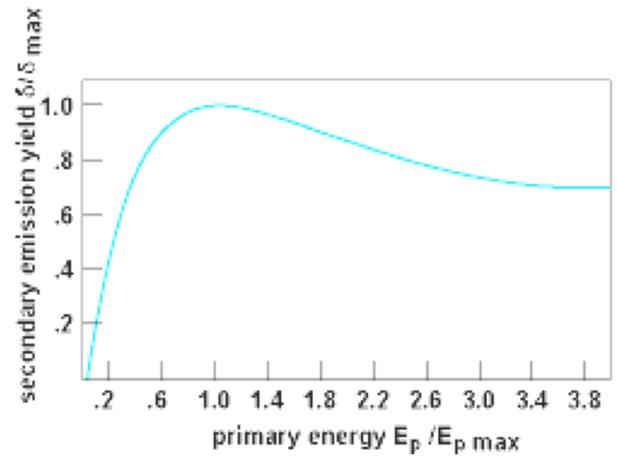
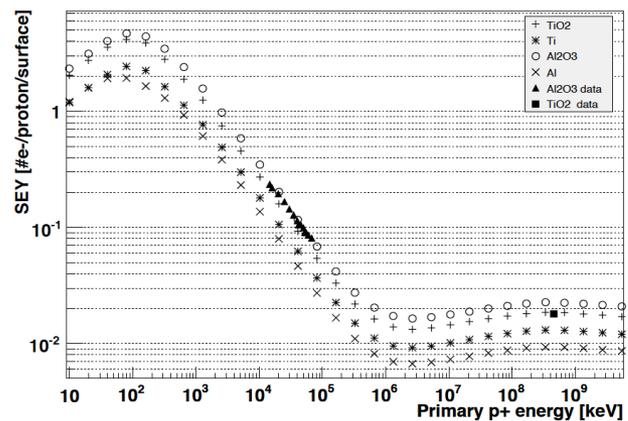


Beyond: Multiple Particle Flow Readout -2



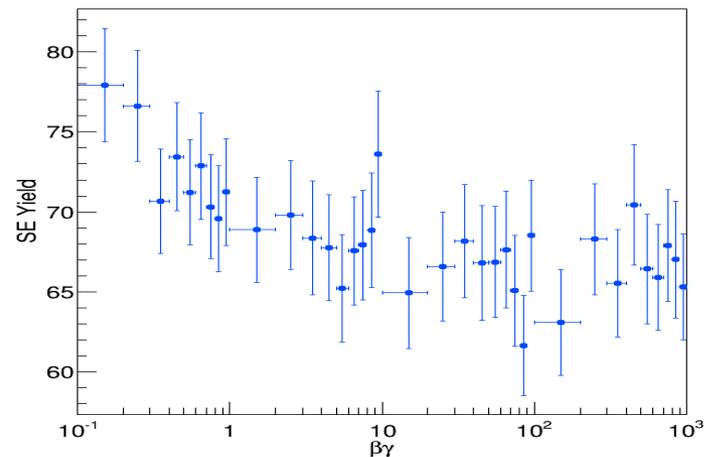
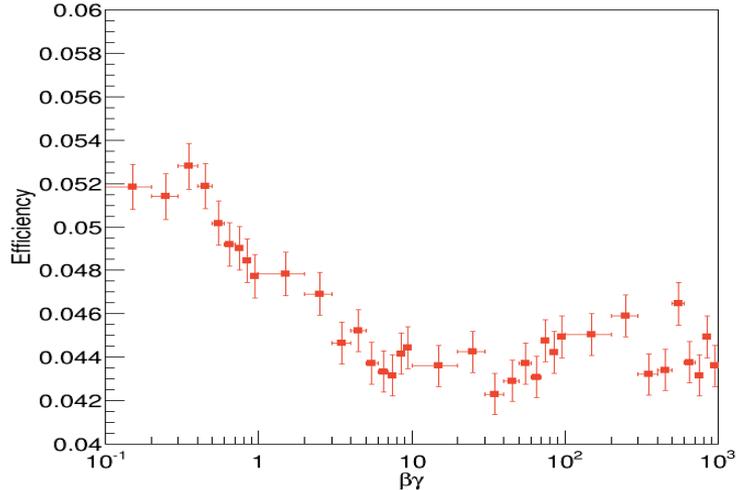
- **Secondary Emission (SE).** Secondary Emission(SE) tiles are more sensitive to $\gamma\beta \rightarrow 0$ particles than to MIPs - scales as dE/dx . MIP SE signal $\sim 100-200x$ less than at peak $\gamma\beta$ SE signal – **the opposite of Cerenkov light**. SE tiles for correction for heavy fragments, lost neutron energies, slow hadrons. (triple/quadruple readout.) 1-2 MeV alpha particle: Max SE yield.

LHC SE Monitors:
SE Yield vs E_p (KeV)
 10^{20} p/cm²

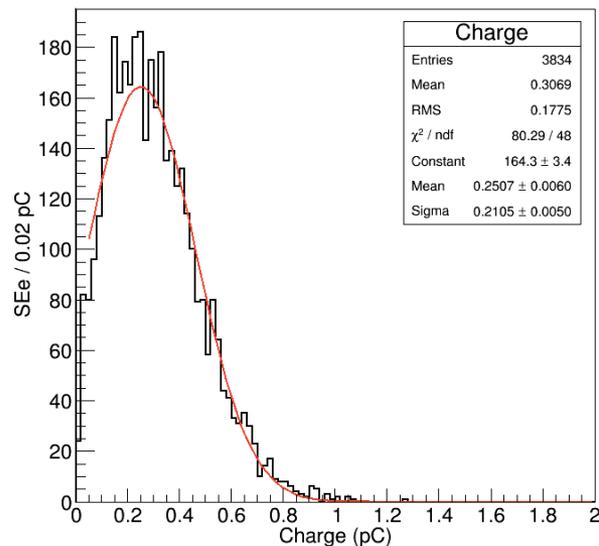


B-doped
Nanoxstal
Diamond
1 μ m thick
On dynode

Secondary Emission

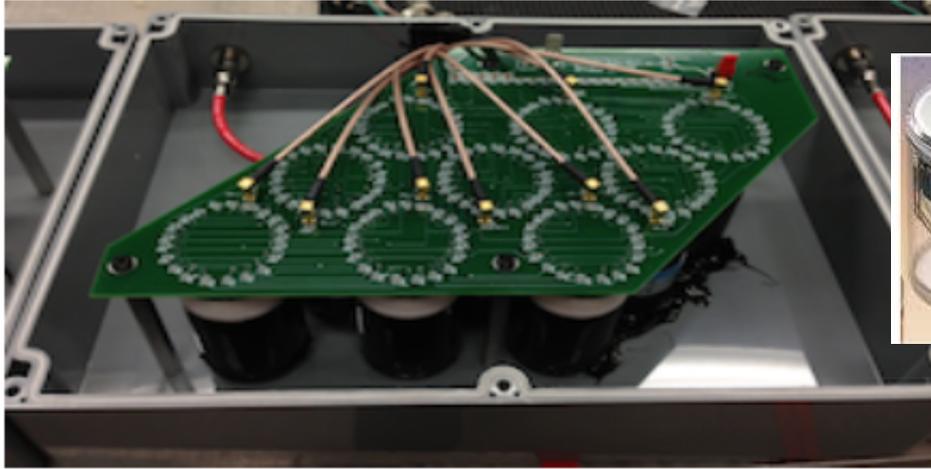


(L) Secondary electron emission efficiency (L) of a single Cu cathode coated with 100 nm of Al_2O_3
 (R) SEe yield vs $\beta\gamma$ of 100-nm Al_2O_3 cathode and SE yield of 9 stages of dynode.



The generated charge in a 9-stage secondary emission device as a result of an efficient secondary emission at the cathode.

Secondary Emission



12x12 MCP
FNAL Test
Beam

2-cm iron absorbers:

$X_0 = 1.75$ cm

Molière Radius: 1.72 cm

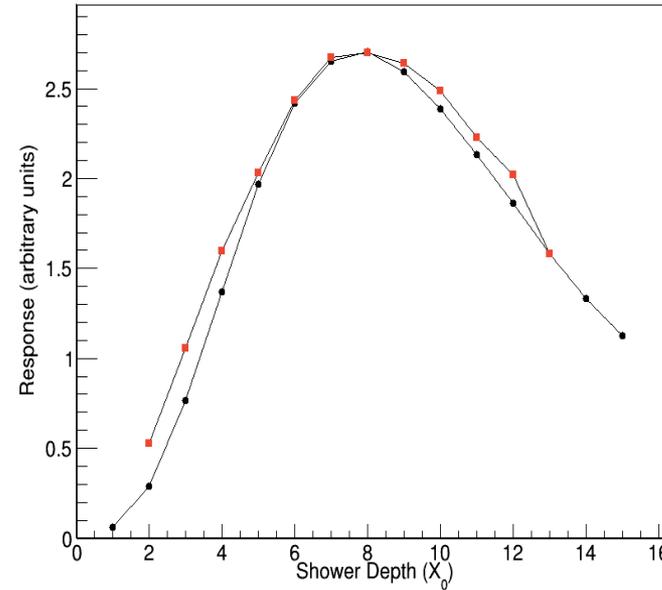
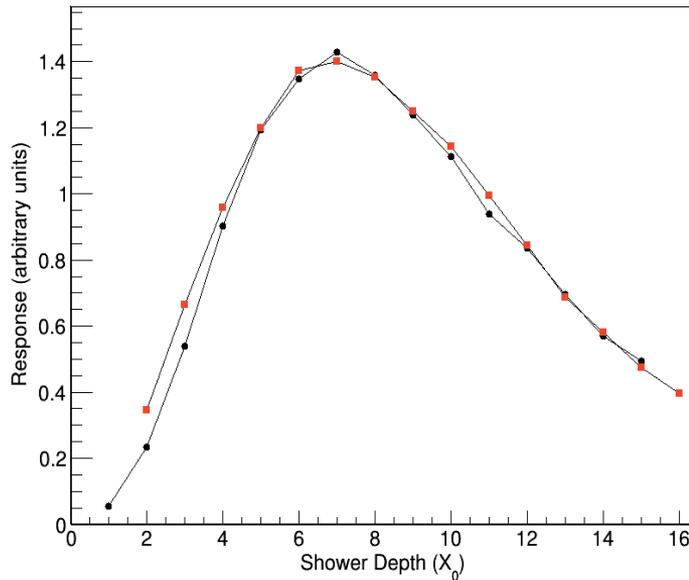
80 GeV e^- Beam
→



$0 - 9 X_0$

Shower not contained laterally or longitudinally
→ Results require estimates and approximations

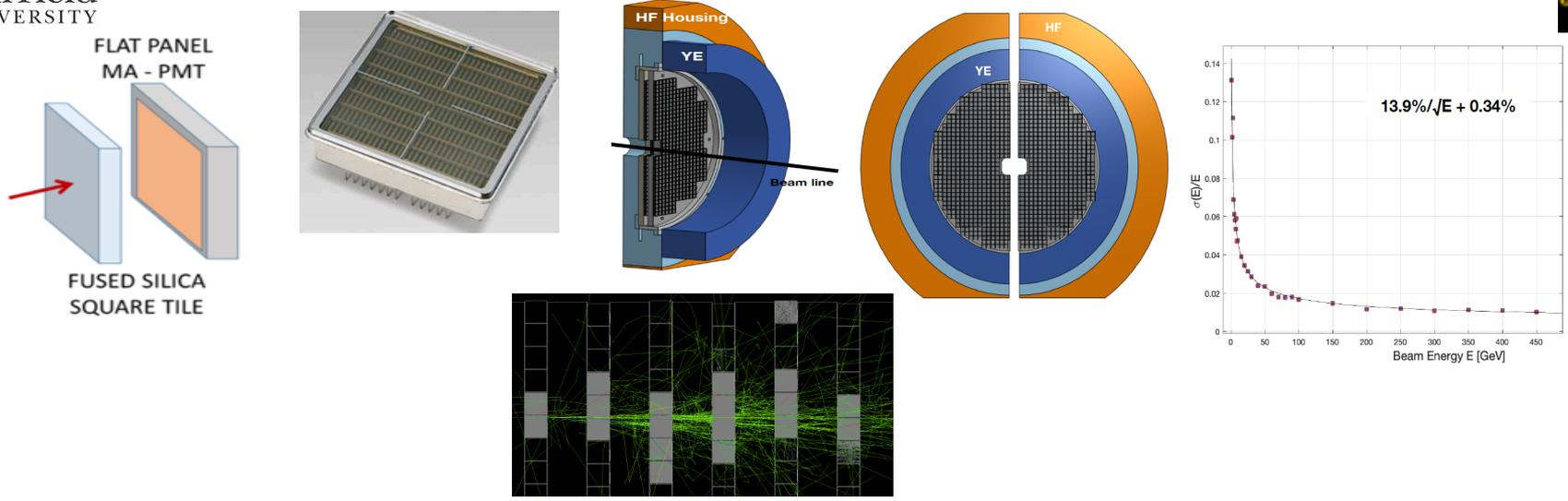
Secondary Emission



Response of the SE module to 8 (left) and 16 GeV (right) electrons with tungsten absorbers. Data are shown in black and MC simulation results are shown in red.

We emphasize that SE is essentially unconditionally rad hard for any anticipated uses

SE+Cerenkov In-Situ Calorimeter Sensor



- Use a PMT as a direct calorimeter sensor!
- A proposed high transverse segmented forward e-m stub-preshower calorimeter in front of CMS forward calorimeter at $3 \leq \eta \leq 5.5$
 - Cerenkov from Window + added tile
 - SE ionization from dynodes
 - Self-compensating from dynode signal adding low-E signal



- **Triple Readout and beyond:** 3+ tiles to improve dual readout:
 - non-hydrogenous scintillator,
 - hydrogenous/neutron-sensitive scintillator,
 - 2 indices of Cerenkov tile(s), SE tiles....
 - Compare less n-sensitive scintillators [non-hydrogenous] to more n-sensitive H or n-converting scintillator tiles.
- **Combined Dual/Triple Readout with Particle Flow:** Add Cerenkov tiles, TRD tiles, SE tiles, or others to existing Particle/Energy flow calorimeter prototypes.
- **Neutron-enhanced detecting scintillator tiles** thin film coatings - ^{10}B , ^6Li , hydrogenous materials [^6LiH] – thin clear film, buffered w/ alumina films; interesting: $\text{Li}^6\text{B}^{10}\text{H}_4$ which would be transparent if deposited as thin films between clear buffers. ^{10}B SE yield dynodes.
- **Liquids:** very large homogeneous detectors: LB, cosmic neutrinos or proton decay
 - 1) water “tiles” ($n=1.29-1.31$ TeflonAF light pipe) + LS tiles – no absorber
 - 2) LArgon drifted ions + Cerenkov light detection. The index n good e/h contrast; scintillation light at 128nm will not penetrate PMT windows.
 -

Multiple Tile Readout

- MTR can be tuned for best $\sigma E/E$, timing, rate, and radiation resistance
- MTR can enhance Energy, Intensity, and Cosmic Experiments
- MTR enables Radiation-Resistance
- MTR compatible with Energy Flow high granularity calorimetry.
- MTR can be added to Calice or the CMS endcap HGCal and other existing calorimeters
- MTR can be selected with Rad Resistant tiles.