# Photomultipliers: In-Situ High Rate Radiation-Resistant Calorimeter Sensors Cerenkov Light+Secondary Emission

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# Forward Region Calorimety at future Colliders
## $6 \geq \eta \geq 3$

- Rates: 40-100 MHz beam crossing (+ gas of n, $\gamma$)
- Hysteresis: <2% pulse-pulse for resolution
- Occupancy: High! 100% per 1cm$^2$ cells/towers
  - e, $\gamma$ <1 GeV, n~ MeV's … multiplicity >10/cell
  - Cells at ~100 MHz – *or higher depending on* $E_{thresh}$
- Dynamic range/cell: ~$10^4$ (mip-> TeV jets)
- Radiation: 100-1,000 MRad, $10^{16}$-$10^{17}$ n/cm$^2$
- Timing: ≤30ps pileup mitigation (100's/crossing)
- Identify/Measure: jet e-m component, $\mu$

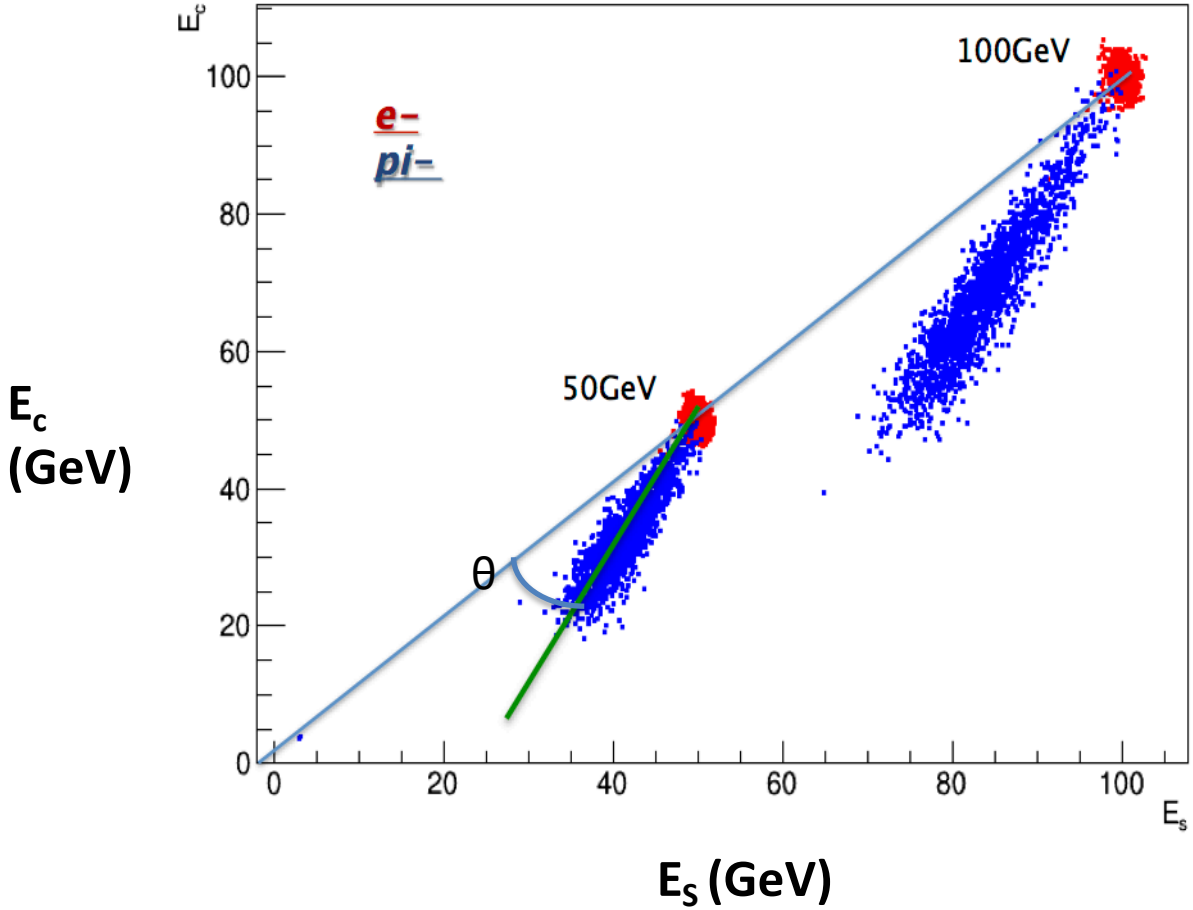
# Calorimetry Detector Issues at large $\eta$

- RC time constants: **rate limitation**
  - Devices with $\sigma_T$<30ps ….. can have low rate capability
- MCP-PMT: inherently resistive ~ PMT resistive base
  - Typically limited by 30ns recovery
  - MCP Raddam? Yes. Lifetime? Not long enough
- SiPM: *Inherently resistive*
  - *Excellent* for low rate, low light level optical pulse timing, B.
    - But Typ Performance: 30 ns dead-time @ 3 p.e.
  - Cross-talk >10% at large light levels-> hysteresis issues.
  - Radiation Damage
  - Cooling issues limit compactness near the beam-pipe
- Si diodes: no or low gain
  - Fast pulse risetimes - but capacitance can limit rate
  - Hysteresis from e/hole polarization at highest rates
  - Raddam at highest dose regions
  - Requires on-detector amplifier - raddam issues inside showers

# Dual/Multiple Readout: 2 *or more* sensors with different Responses to shower fluctuations.

## 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, $H_2O$, $SiO_2$ ….) vs
      - Ionization Medium (scintillator, LAr ion collection,..)
  - DREAM Collaboration/Richard Wigmans et al.
    - Parallel Scintillating+Quartz Cherenkov Fibers
    - Excellent progress in test beams - DREAM: ≥30%/√E
    - Thorough Analysis of Dual Parallel Fiber Calorimeters
- Present state of GEANT MC: 18%/√E possible….




**Use different Responses to Correct Calorimeter Energy…**
**We propose Cherenkov vs Secondary emission Via PMT dynodes.**

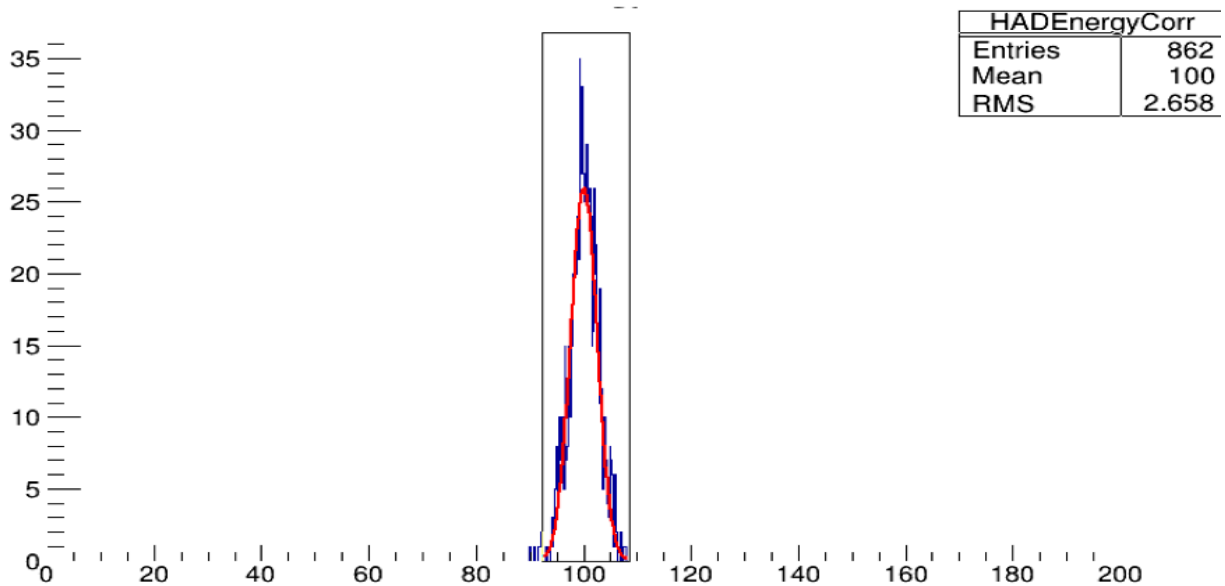
***Electrons:*** $E_c$ vs $E_s$ (red points) lie along line shown schematically as $E_c = E_s$.

***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).

Project the points along the fitted line

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

# Dual Tile Correction –
# *Tiles* 1cm thick each Plastic Scint, Quartz, Cu




***Cherenkov-Corrected Energy (GeV) (mean, rms) = (100, 2.66) GeV***

***$\sigma_E/E$ enables W -> jet-jet separated from Z -> jet-jet at ~2.5$\sigma$***

*Future Work:*

- **Multiple Readout Tile types (aerogel low n, TRD, Secondary Emission, ….)**
- **Higher order terms**- $\alpha_2(E_s-E_c)^2 + \alpha_3(E_s-E_c)^3 + ..$ & energy dependent $\alpha_n$ –
  - > **Continuous mapping**(vector field) of the points in $E_c$ vs $E_s$ space to line $E_c=E_s = E$

# Tile Dual Summary/Discussion

– **Rules of Thumb:**

- (0) An intrinsic limit of normal hadron calorimetry: $\sigma_E/E > 11\text{-}13\%/\sqrt{E}$, 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 $30\%/\sqrt{E}$, with $18\%/\sqrt{E}$ being a reasonable target to achieve using plastic scintillator and low index materials;

- (2) $h_i/e_i$: as large as possible -> hydrogenous or n-sensitized ionization detection media.

- (3) e-m energy resolution in Cerenkov light $< 70\%/\sqrt{E}$ to achieve $<20\%/\sqrt{E}$;

- (4 ) Resolution scales $\sim\sqrt{(f_{sample}/f_{frequency})}$.

- (5) Compensation achieved by enhancing neutron(hydrogenous/ n-absorbing) & ion fragment sensitivity

# FUTURE Multiple Readout

- ***Adding sensor tiles*** relatively insensitive to MIPs, more sensitive to γβ->0
  - increases the contrast between e-m and hadronic energy (enhancing the low energy hadronic signal)
- **Secondary Emission:** Signal scales ~ dE/dx,
  - MIP SE signal ~100x less than that of the energy of the peak signal (peak signal for protons occurs at ~200KeV - n+p->p+n knock-on protons).
- **Homogeneous dense inorganic scintillators** (LYSO, $PbWO_4$,$CeF_3$, LAr, LXe..)…

  - $h_i/e_i$ ~ 0.4 and $h_c/e_C$ ~ 0.25, or $[h_i/e_i]/[h_c/e_C]$ ~1.6:

-> *Homogeneous calorimeters cannot achieve dual readout compensation better than ~50%/√E on hadrons, even with perfect separation between scintillator light & Cerenkov light in the homogeneous detector*. [LAr/Ch4 ions instead of Scintillator]

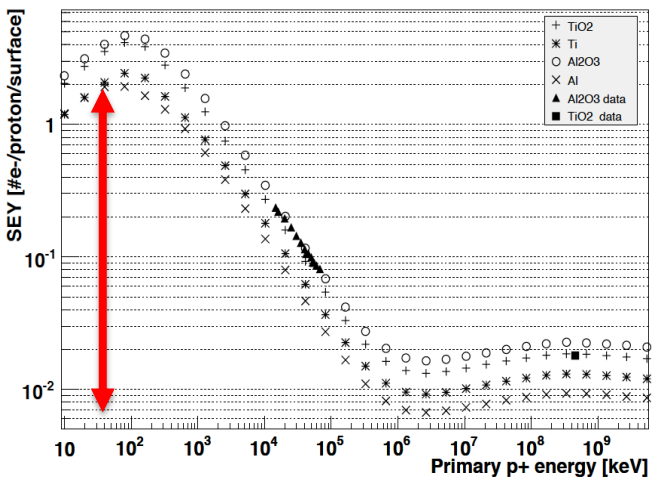
***$\sigma_E/E$ ~15%-18%/√E on jets:*** *scintillator sensors with $h_i/e_i$ ~ 0.6-0.8 and Cerenkov sensors with $h_C/e_C \leq 0.2$ are needed. To achieve $h_C/e_C < 0.2$, lower n Cerenkov radiators are required($\beta_{thresh}$ ->1),. Requires photons for e-m resolution < 70%/√E(GeV) or $N_{pe}$> 2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

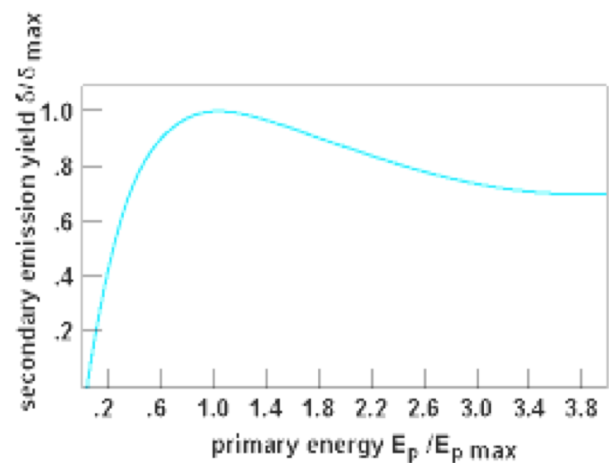
# Secondary Emission as a Calorimeter Sensor

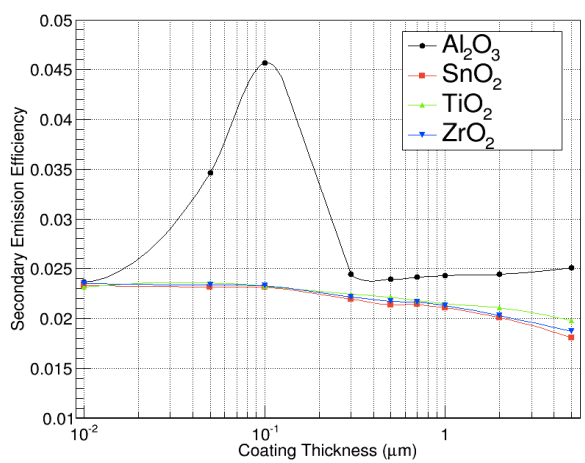
- ***Secondary Emission (SE).*** Secondary Emission(SE) tiles are more sensitive to γβ->0 particles than to MIPs - scales as dE/dx. MIP SE signal~100-200x less than at peak γβ SE signal ***– the opposite of Cerenkov light***. SE tiles for correction for heavy fragments, lost neutron energies, slow hadrons.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

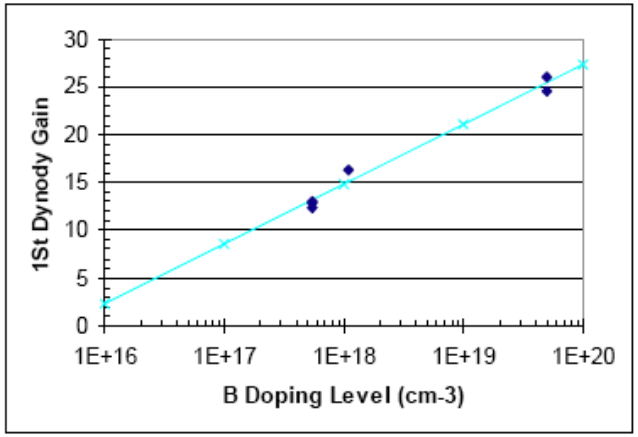
**LHC SE Monitors: SE Yield vs Ep (KeV)**

**$10^{20}$ p/cm² !**



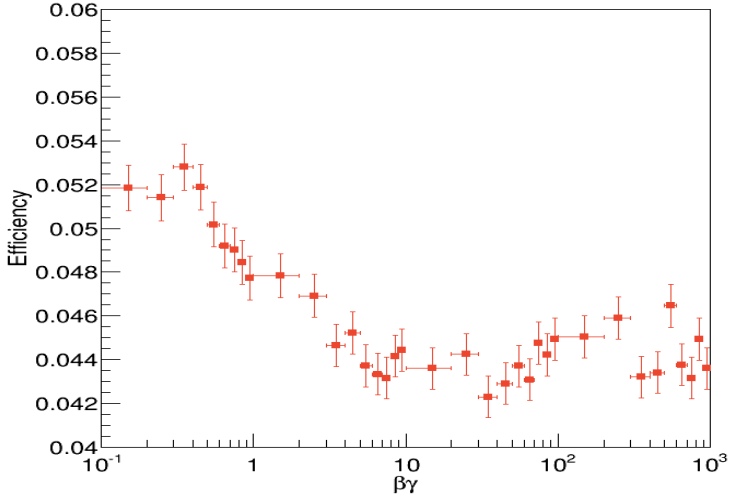



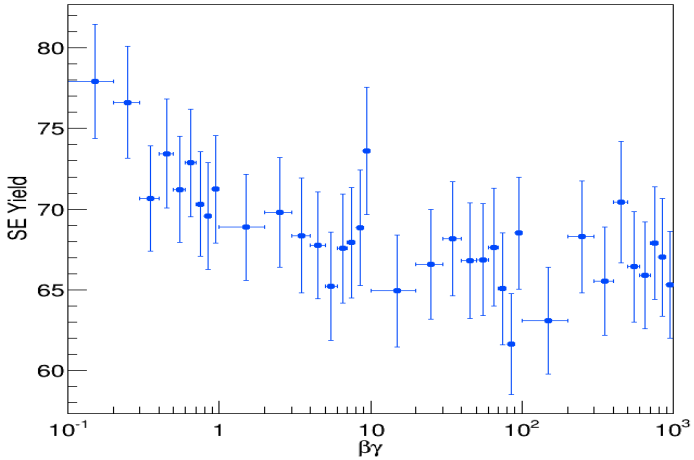



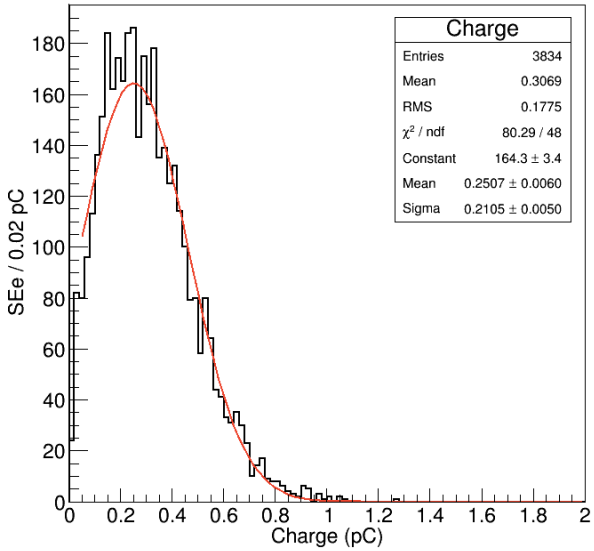

B-doped
Nano-xtal
Diamond
1μm thick
On dynode

# Secondary Emission



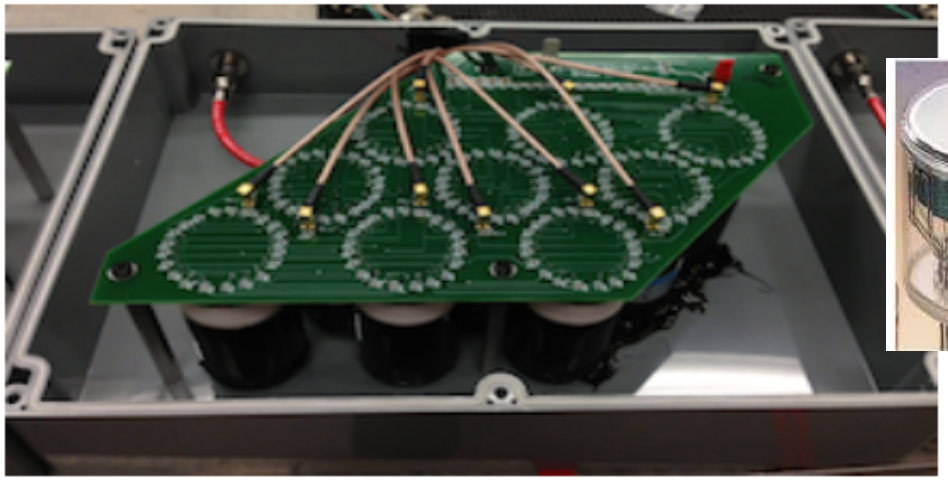



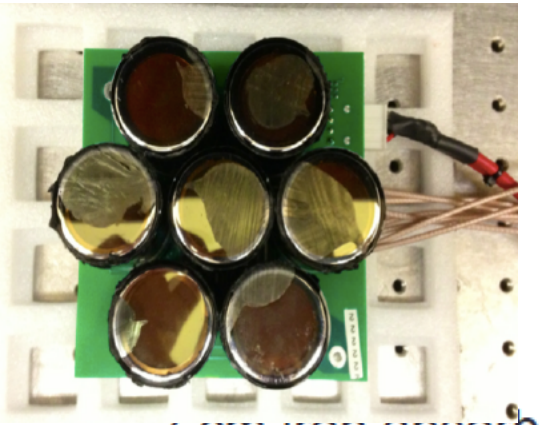

*(L) Secondary electron emission efficiency (L) of a single Cu cathode coated with 100 nm of Al2O3*
*(R) SEe yield vs βγ of 100-nm $Al_2O_3$ cathode and SE yield of 9 stages of dynode.*




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

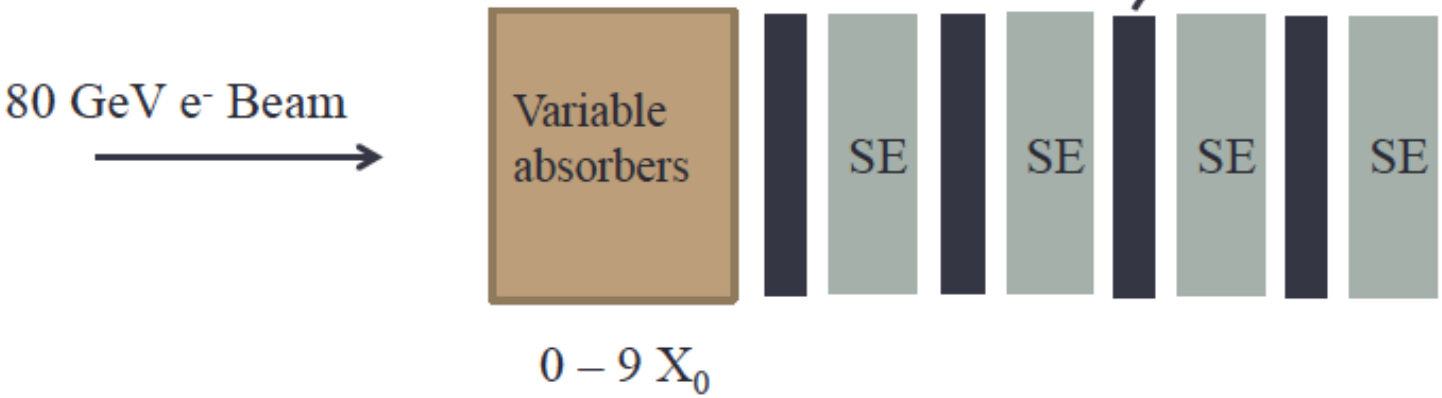
# Secondary Emission





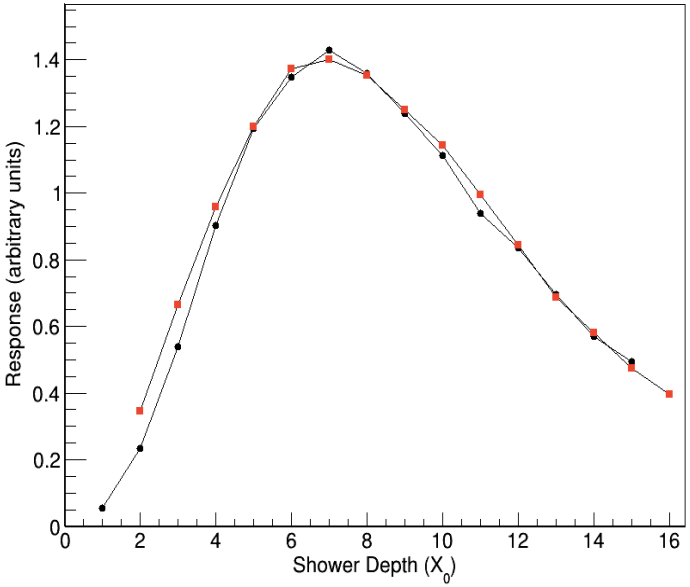
2-cm iron absorbers:

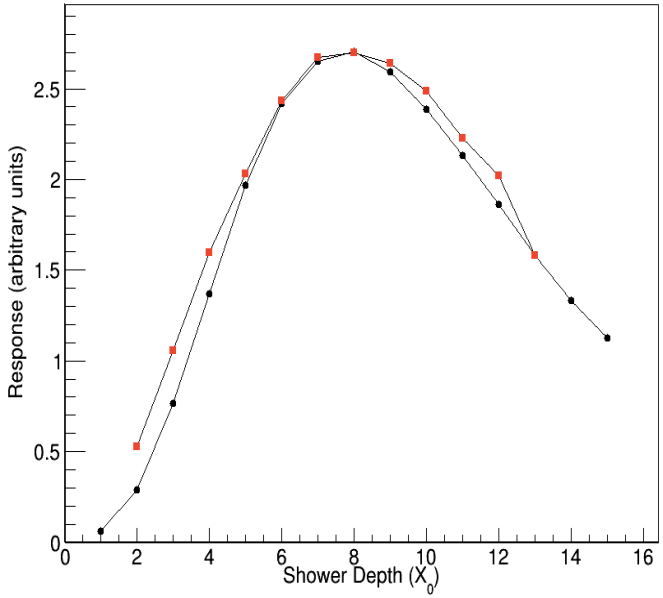
$X_0$ = 1.75 cm
Molière Radius: 1.72 cm




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

# Secondary Emission



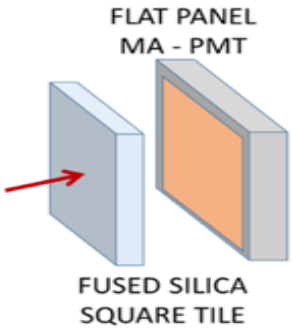

Response of the SE module to 8 (left) and 16 GeV (right) electrons with tungsten absorbers. Data are shown in **black** and MC simulation results are shown in **red**.

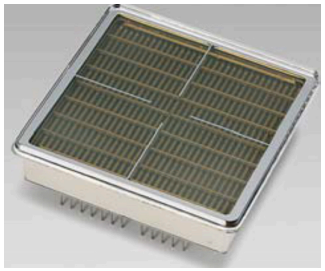
We emphasize that SE is essentially unconditionally rad hard for any anticipated uses

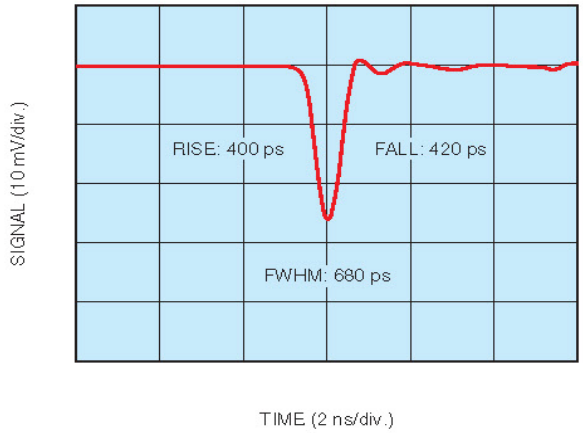
# PMT for time/rate application requirements/properties:

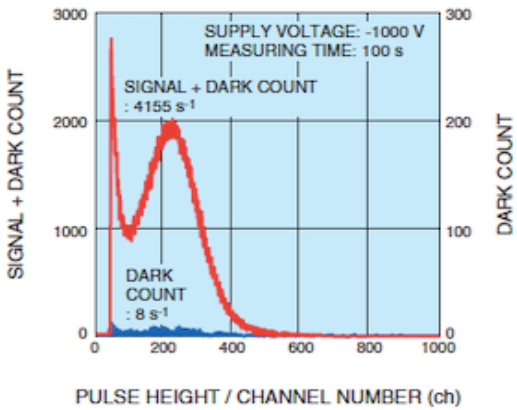
- RADDAM: Metal Vacuum Envelopes + Quartz, Sapphire window PMT
  - ***Dynodes:*** metal oxide secondary emission > 10 GRAD
  - ***Photocathode:*** 10 nm film – energy loss ≤ 1 eV/mip.
  - no excess noise from RADDAM in metal-envelope/*quartz etc* window PMT.
    - Studies of glass-based PMT by ATLAS and NASA: Increased dark current entirely from glass induced phosphorescence
    - PMT survive > 20 years in satellites in the n-dose and solar wind in near-earth orbit.
- Radiation Resistant, Thin (≤3mm) Windows: quartz ($SiO_2$), $MgF_2$, or sapphire ($Al_2O_3$)
- Gain: $G_{eff} \sim 5 \times 10^4$: low gain to avoid dynode Ohmic heating @ 100 MHz. $G_{max} \leq 2 \times 10^6$
- Inductance, Capacitance of anode plane to ground L < 5pH; C <0.2pF
- B-Field: Secondary Emission (SE) mesh/metal dynodes: ≥5% max Gain @1T (forward calo)
- Compact Longitudinal Dimensions: Glass window-to-Anode pins thickness ≤ 1.5cm
- Multi-Anode Pixel Size: ≤ 3x3 mm
- Single p.e. timing: **$T_{rise} \leq 0.5$ ns; $T_{fall} < 0.5$ns; Slew Rate >10 mV/ns into 300 Ω;**
- Latency/Transit Time: $T_{trans}$<3 ns enables rate ≥ $(2 \times T_{trans})^{-1}$ ~200 MHz
- Quantum Efficiency: (QE) for Ultra bi-alkali photocathodes ~35%-40% (competes w/ SiPM?)
- Tileable: square or hex shapes

# SE+Cerenkov In-Situ Calorimeter Sensor



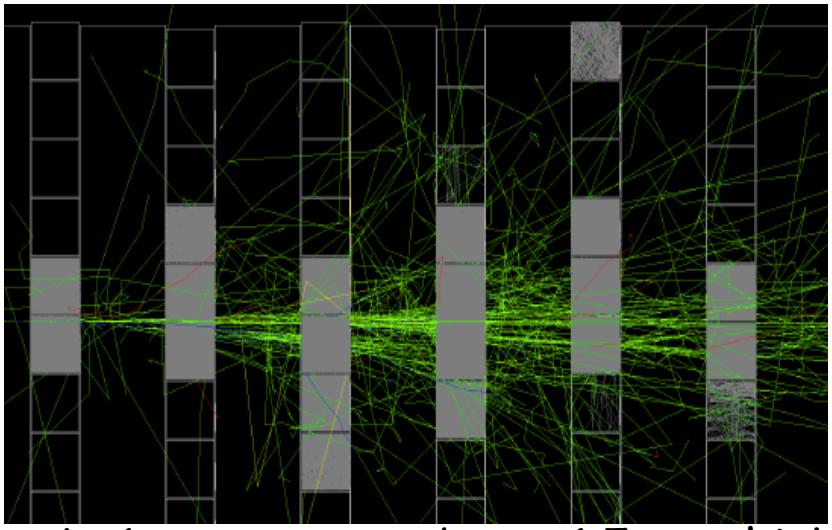


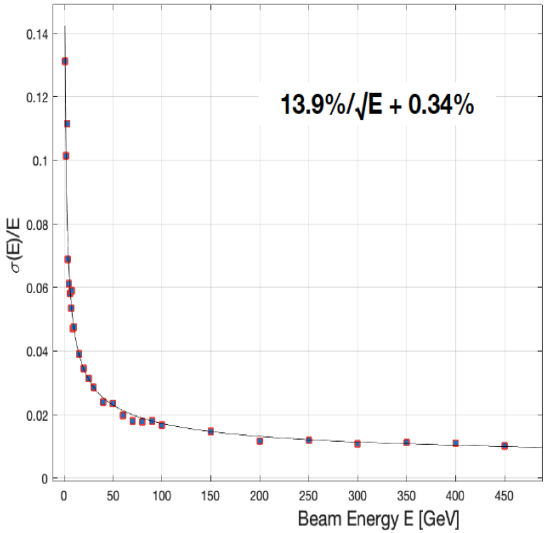




- PMT: quasi-compensated calorimeter sensor
  - Cerenkov from Cerenkov tile+PMT Window
  - SE ionization from dynodes
  - Self-compensating: dynode signal adds low-E particles
  - High transverse segmented forward e-m stub-preshower calorimeter in front of CMS forward calorimeter at $3 \leq \eta \leq 5.3$?

# Monte Carlo of Cerenkov radiator+PMT+ Absorber (No Dynode S.E. included… yet)

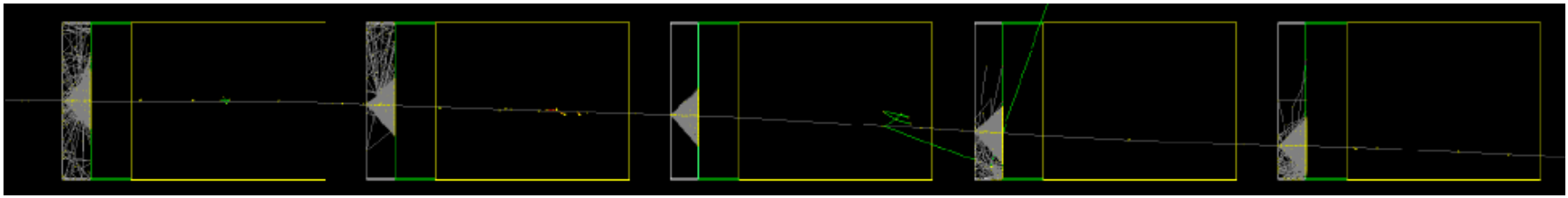
**100 GeV π**






Calorimeter: L: 1 cm quartz cubes + 1.5 cm thick PMT + 3mm W plates. R: e-m resolution

**μ**

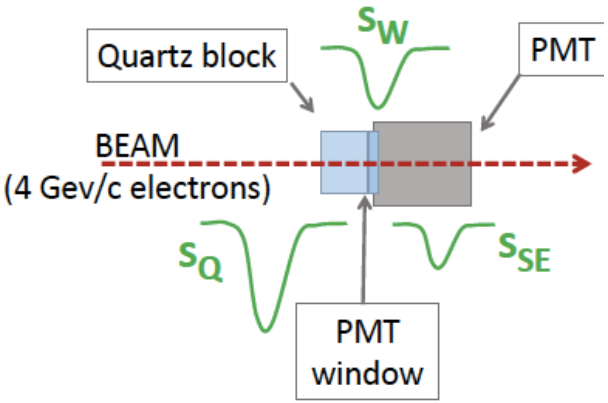


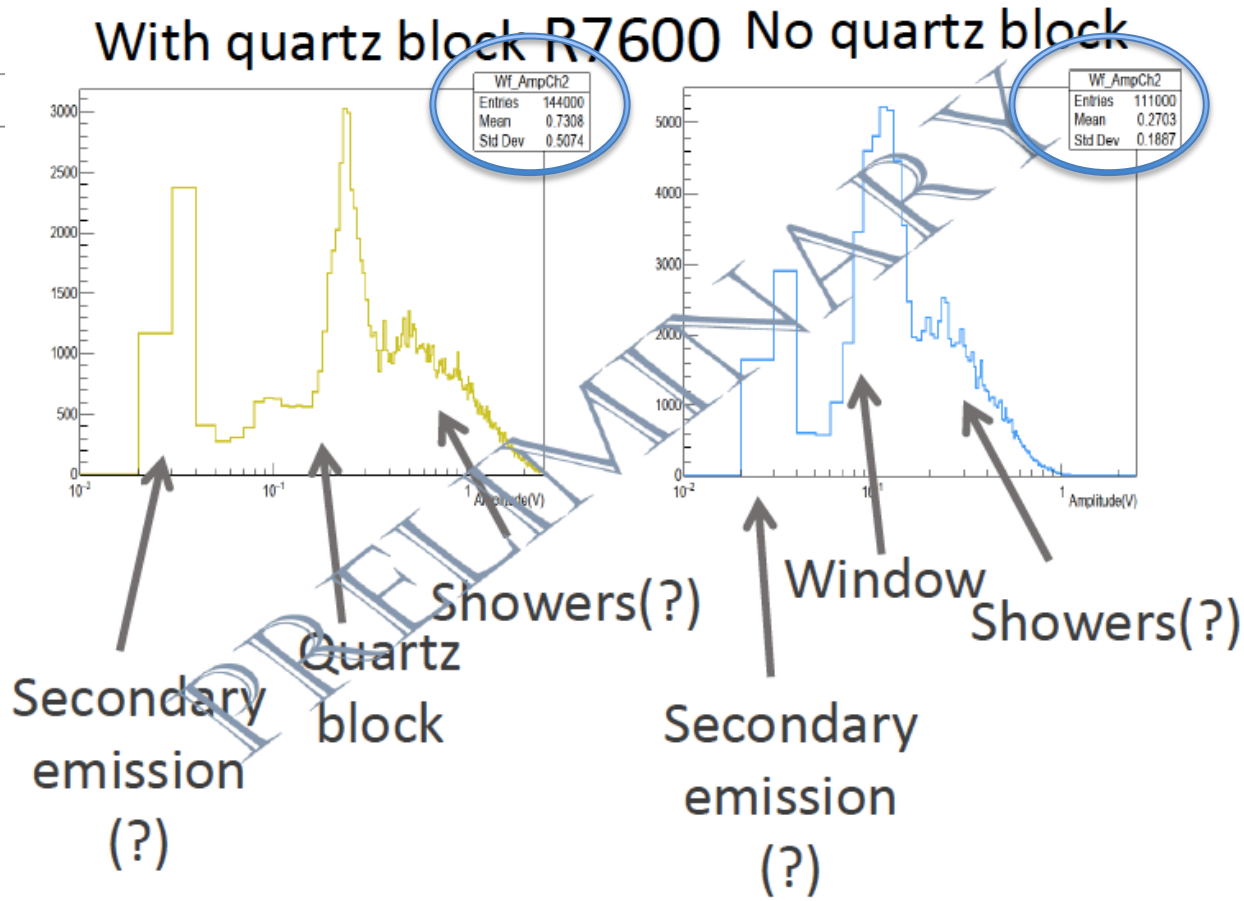
*Stub Tracker/E-M PreRadiator: 5 quartz 1cm thick quartz tiles mated to 5 MAPMTs + 2 λ of Fe absorber tiles: Muon Cerenkov light trajectories/Cerenkov cones*

Fairfield UNIVERSITY

University of Iowa

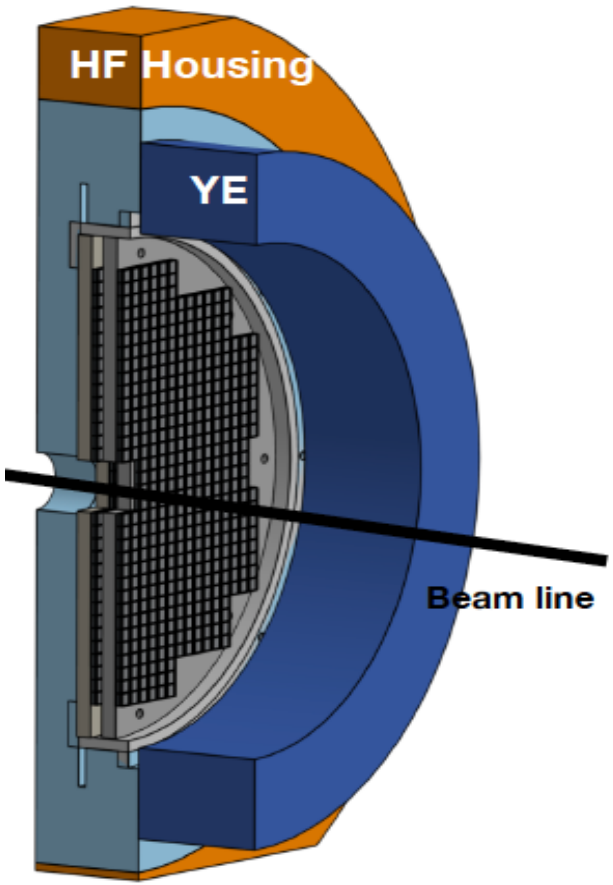
# Preliminary Tests from DESY test beam
# R7600 PMT with and without quartz block

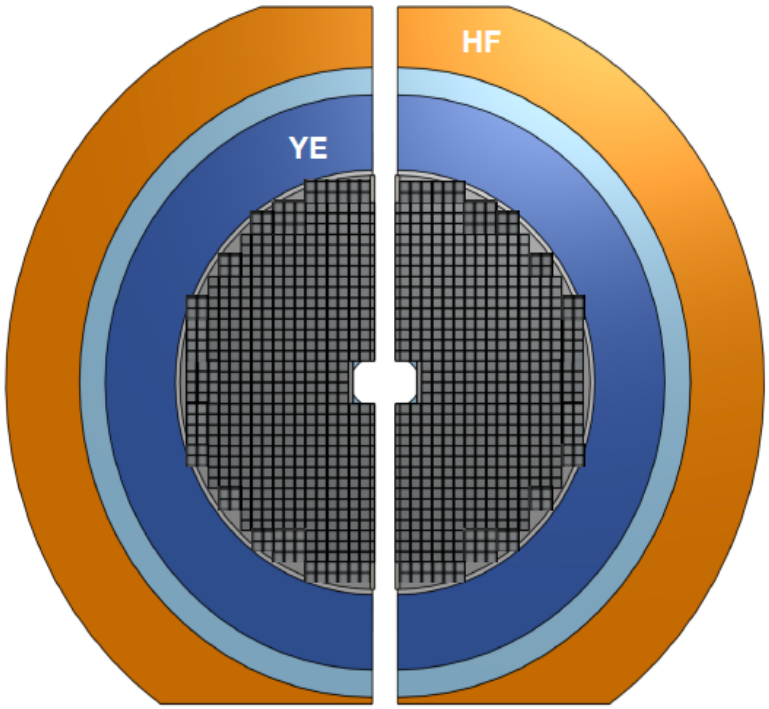



**Secondary Emission likely from μ-halo, γ or n sky-shine in the beam(?)**

# Possible Application: CMS HF Forward Calorimeter
Stub Pre-Radiator/μ-Tag/Timing:30-40ps
Protects HF from Raddam
1x1 cm cells PMT+Quartz, ~1 λ thick W absorber, ~3m diameter



# Extra Slides

# 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= $E_s$ + [a correction term proportional to the difference ($E_s$-$E_c$)]:**

  $E = E_s + \alpha(E_s - E_c)$ with a 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 $\pi^o$'s),

    **then ($E_s$-$E_c$)~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.**

# Multiple Tile Readout

- MTR can be tuned for best σE/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.

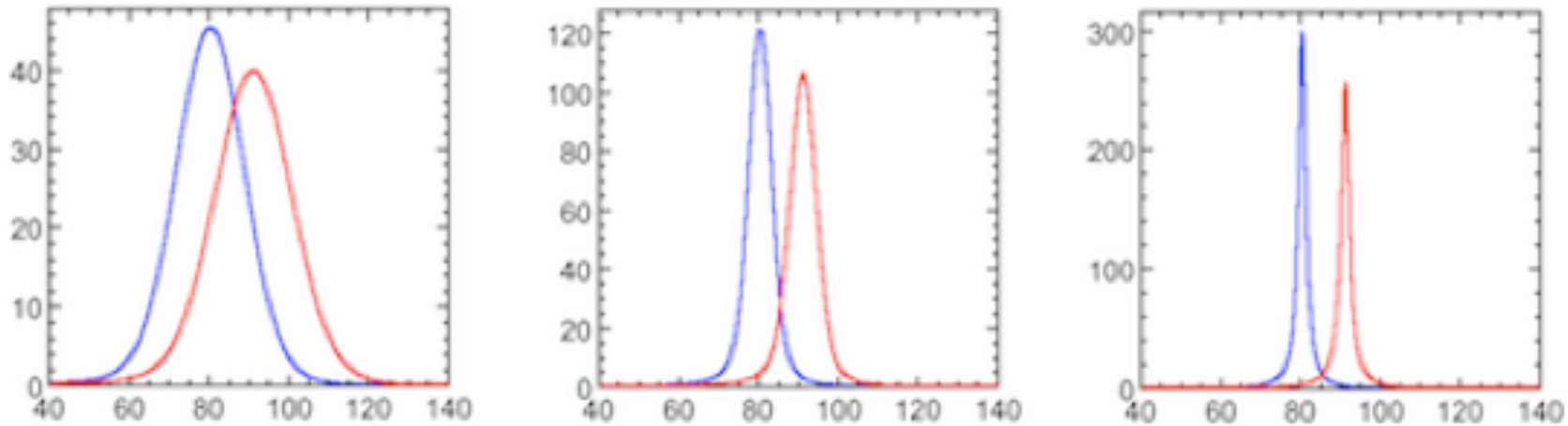
# Beyond: Multiple Particle Flow Readout -3

- ***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 - $^{10}B$, $^{6}Li$, hydrogenous materials [$^{6}LiH$] – thin clear film, buffered w/ alumina films; interesting: $Li^{6}B^{10}H_4$ 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.
-

# 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 ~ 6-7
- Reconstruct AND Separate ($E_{Tmiss}$, jet tags, V-V scattering, BSM, W', Z'…)
- Separation of W from Z: $\sigma_{Ejet}/E_{jet}$ **~**3% necessary at 100 GeV, with typical single particle energies ~10 GeV [*ASIDE: during collision crossing times which may be a 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 2.6-2.3σ 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%/√E; ***Middle*** $\sigma_E/E$ 22%/√E (3% @ 50 GeV*) ~2.6σ separation*; ***Right*** -perfect resolution: ~4.5σ separation. (from M. Terwort)