Tile Multiple Readout and Beyond

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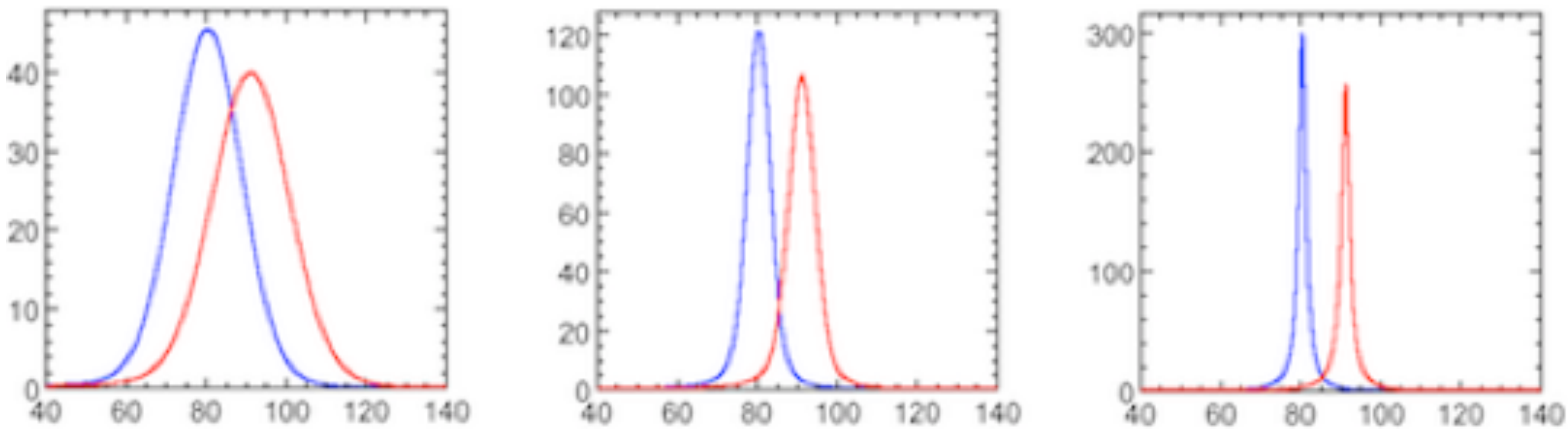
One Physics Example: Precision jets

- ***- Jet-Jet masses:*** Goal for future experiments: SM Z->jetjet; W->jetjet
- Ratio W,Z->jj to W,Z->leptons ~ 6-7
- Reconstruct AND Separate(+SM, E_{Tmiss}, jet tags, V-V scattering, BSM, W', Z'…)
- Separation of W from Z: σ_{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 very important In searches for heavy W'/Z', vector boson scattering, triple VVV….



- W/Z->jet-jet separation: ***Left*** - calorimeter σ_E/E=60%/√E; ***Middle*** σ_E/E 22%/√E (3% @ 50 GeV*) ~2.6σ separation*; ***Right*** -perfect resolution: ~4.5σ separation.

Dual Readout: Cerenkov Compensation
First form of multiple readout

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- 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,..)

      to reduce hadron shower fluctuations and make e/h-> 1
- DREAM Collaboration/Richard Wigmans et al.
  - Excellent progress in real tests!
  - Thorough Analysis of Dual Parallel Fiber Calorimeters!
- MC: 18%/√E seems possible….But DREAM: 30%/√E: Parallel Scintillating+Q Fibers

Parallel Fiber Deficits - 1

- ***1. Constant Term–unavoidable issue*** – scintillator light attenuation in ~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 ~5°. Streaming down fiber holes lowered the resolution in DREAM, even at a 2° pitch. Packing extra fibers from the back or conical fibers: ->Constant term, ->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 (~1/800 incident π/K quasi-elastic scatter through a 10 L_{int} calorimeter).

Parallel Fiber Deficits - 2

- ***4. E-M and Hadronic Components of Incident Jets:*** Parallel fibers: ~no ability to detect + separate *incident direct e-m component inside of a jet, since there is no longitudinal segmentation.*

- ***5. High Resolution EM Front End.*** The parallel fiber dual readout jet calorimeter: *~no ability to make a 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

Parallel Fiber Deficits - 3

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- ***8. Longitudinal Segmentation:*** Fiber dual readout is incompatible with true longitudinal segmentation, even with waveform electronics, and cannot be easily rebuilt for front raddam 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 ~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.

Parallel Fiber Deficits – 4

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^O, n) ID, especially under pileup. ***Tile* readout**: fully compatible with highly granular calorimetry, easily added to particle flow calorimeters

13. No Other Sensors for Dual Readout, Triple or Multiple Readouts:

Parallel fibers cannot use other 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~1.1, MgF_2, water n~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: ^{6}Li, ^{10}B, ^{3}He, fissionable… containing materials.

MC Study: Tile Dual Readout

- GEANT4 MC on a simple tile calorimeter: 0.5 cm thick each of quartz, plastic scintillator, and Cu absorber tiles.

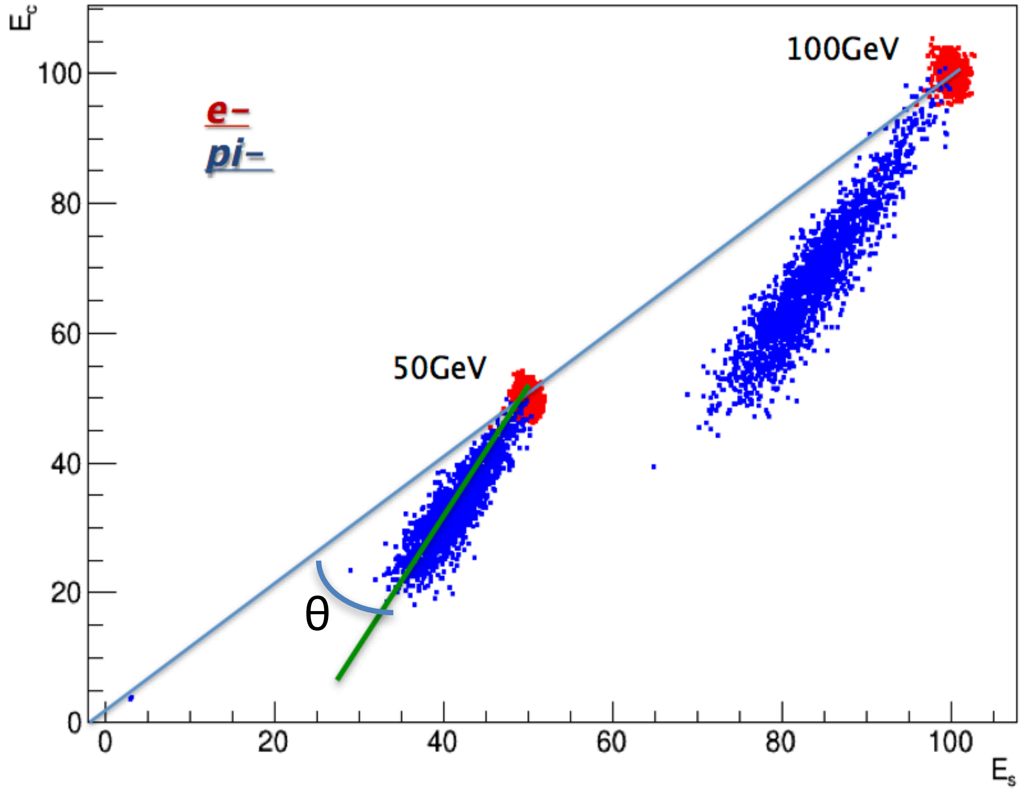
- Two energies (50, 100 GeV) each of 1000 electrons (red dots) and of ~800-1000 pions (blue dots)] were sent into the 50x50 cm calorimeter, 12.2 Lint deep (8 Lint of Cu, 1.5 Lint polystyrene, 2.7Lint Quartz = 12.2 Lint Length ~ 3.6m)

- $N_{photons}$ 325-650nm generated in the Cerenkov and in the scintillator tiles were counted. 0.5% at random were assigned as converted to p.e.

- Scintillator photons ~120x Cerenkov photons; photostatistics not limiting factors.
- Means of histograms of the electron shower p.e. in quartz and in scintillator were used to convert/normalize the number of collected p.e. in Cerenkov light and in Scintillator light to normaized energies $E_{Cerenkov}$ and $E_{Scintillator}$, and then plotted as a scatter plot of E_C vs E_S for each electron.

- Pions of 50, 100 GeV were then simulated, converted to E_C vs E_S

E_c GeV



- **Scatter plots:** **E_S GeV**

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

Pions: E_c vs E_s scatter-plotted (blue) 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.

- 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.

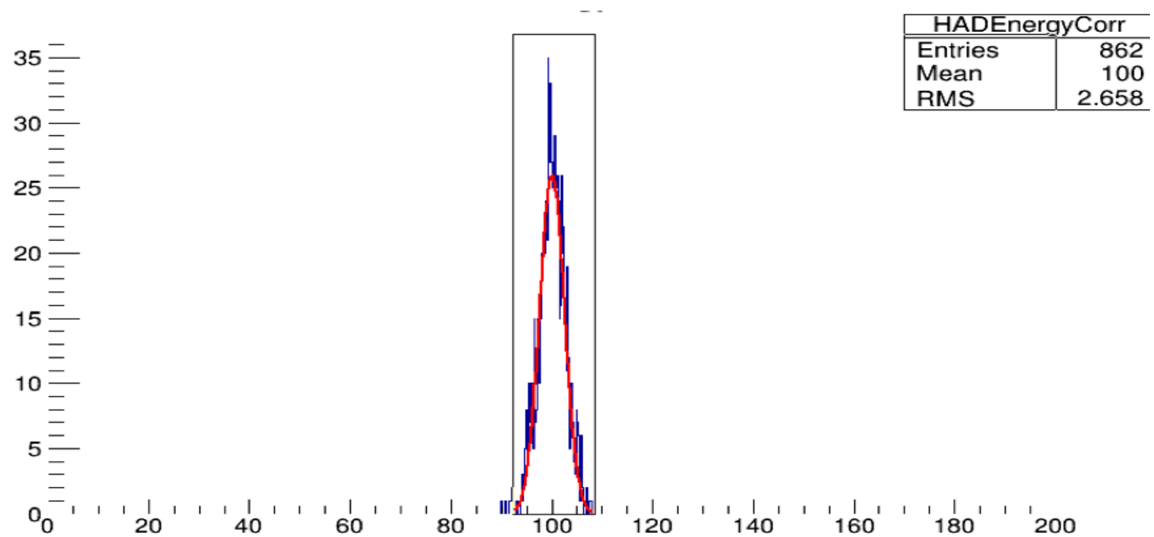
Dual Correction

- 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 (e's or π's exchange to π^o's), then $(E_s-E_c)\sim 0$, $E=E_s=E_c$



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

➔ ***σE/E that enables W -> jet-jet separated from Z -> jet-jet***

- **Higher order terms**- $\alpha_2(E_s-E_c)^2 + \alpha_3(E_s-E_c)^3$ +.. and energy dependent α_n – there is a continuous mapping(vector field) of the points in E_c vs E_s space to the line $E_c=E_s$ = E.

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Tile Dual Summary/Discussion

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– **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 can be achieved by enhancing neutron(hydrogenous or n-absorbing) or ion fragment sensitivity and/or by suppression electromagnetic component by tuning the absorber thickness relative to sampling media (f_{sample} typically ~1/10 but at a loss of potential ultimate resolution).

FUTURE

- ***Adding sensor tiles*** relatively insensitive to MIPs, OR more sensitive to $\gamma\beta$->0 increases the contrast between e-m and hadronic energy (enhancing the low energy hadronic signal) – one such sensor is Secondary Emission; its signal scales as dE/dx, with a 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 non-hydrogenous dense inorganic scintillators** (LYSO, $PbWO_4$,CeF_3)

  - 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 ~50-60%/√E on hadrons, even with perfect separation between scintillator & Cerenkov light in the homogeneous detector*. [Note: LAr/Ch4]

Theoretical ~15%-18%/√E on jets: *scintillator sensors with h_i/e_i ~ 0.6-0.8 (likely hydrogenous & n-sensitive), and Cerenkov sensors with $h_C/e_C \leq 0.2$ are needed. To achieve $h_C/e_C < 0.2$, lower n(index of refraction) Cerenkov radiators are required(i.e. β_{thresh} ->1), but require enough photons to achieve an e-m resolution < 70%/√E(GeV) or N_{pe}> 2 pe/GeV.*

Beyond: Multiple Particle FlowReadout -1

Extend E-M Response by higher sensitivity to β ->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)

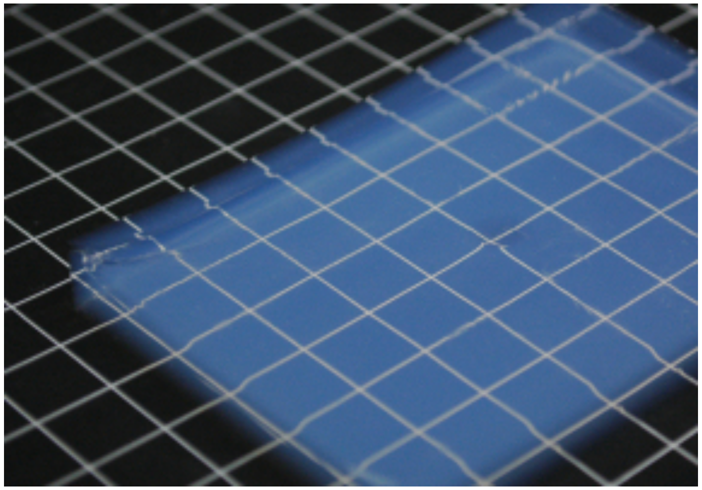
(A) TRD

- Straw tubes,…… Low mass issue for calorimetry)

(B) Low *index Tiles*

(1.1<n<1.35) tiles :

- 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);

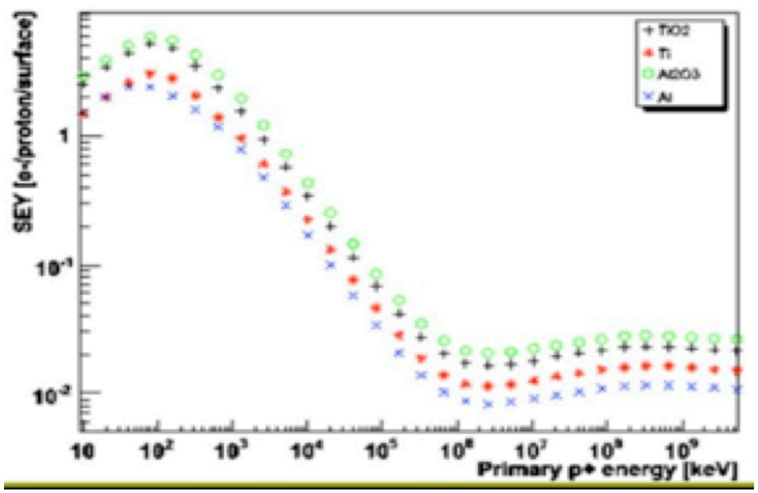


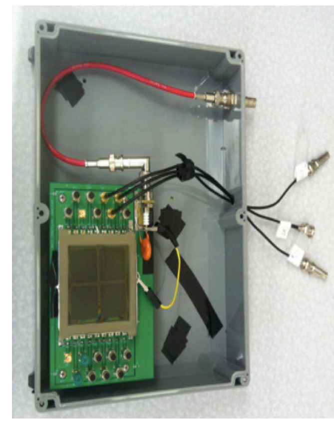
Beyond: Multiple Particle Flow Readout -2

- ***Secondary Emission (SE).*** Secondary Emission(SE) tiles are more sensitive to γβ->0 particles than to MIPs - scales as dE/dx. MIP SE signal~100-200x less than at peak gb 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: secondary yield ~at max.

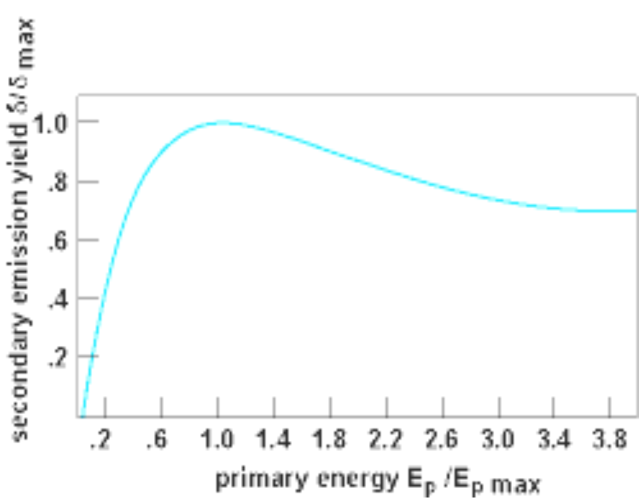
LHC SE Monitors: SE Yield vs Ep (KeV)

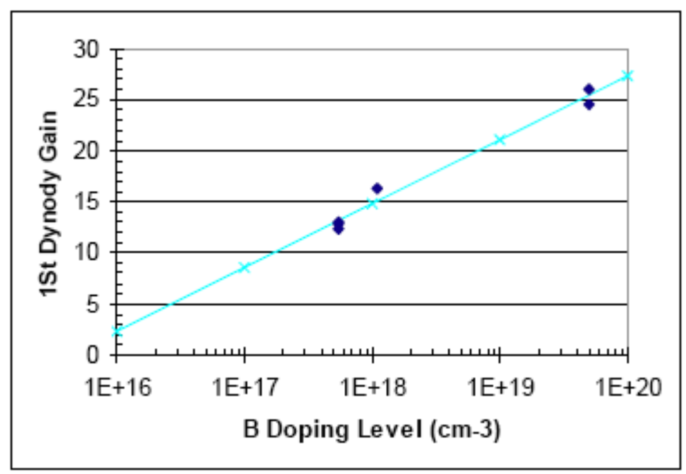
10^{20} p/cm^2 !





12x12 MCP FNAL Test Beam





B-doped Nanoxtal Diamond 1μm thick On dynode

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-sensitive neutron scintillators [non-hydrogenous scintillators; inorganic and perfluorcompounds] to more neutron-sensitive H or n-absorbing/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.

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Multiple Readout

- Multiple Readout can be tuned for best σE/E, timing, rate, and radiation resistance
- Multiple Tile Readout can enhance Energy, Intensity, and Cosmic Experiments
- Multiple Tile Readout enables Radiation-Resistance
- Multiple Tile Readout compatible with Energy Flow high granularity calorimetry.
- Multiple Readout can be added to Calice or the CMS endcap HGCal and other existing calorimeters