Total Absorption Calorimetry

A path to superior jet energy resolution

Marcel Demarteau, Steve Magill, Adam Para, Hans Wenzel, Ren-Yuan Zhu

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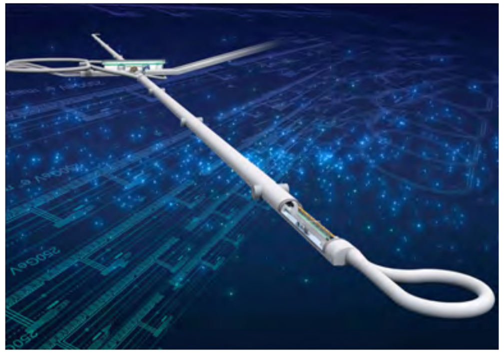
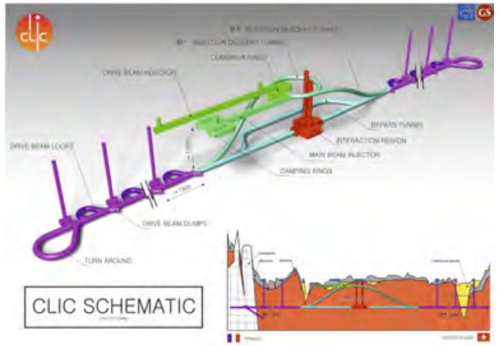
Particle Physics Strategy

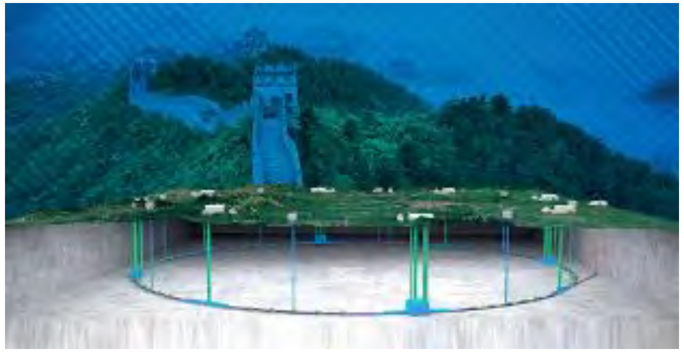
- P5 has identified five science drivers, one of which is:
  - ***Use the Higgs boson as a new tool for discovery.***
  - This science driver is currently mainly being pursued through the LHC program
- The unique position of the Higgs boson has recently been confirmed by the 2020 European Strategy Update:
  - ***An electron-positron Higgs factory is the highest-priority next collider.*** *For the longer term, the European particle physics community has the ambition to operate a proton-proton collider …*



International Linear Collider (ILC)
E_{cms} < 1 TeV



Compact Linear Collider (CLIC)
E_{cms} < 3 TeV

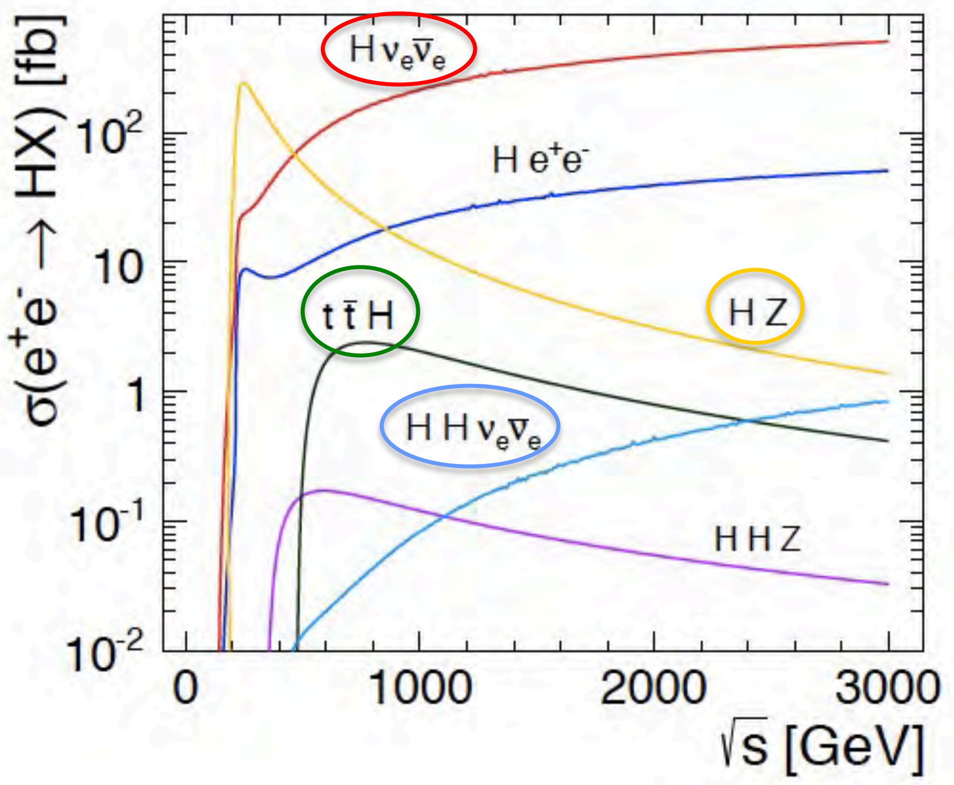


Circular Electron Positron Collider (CepC)
E_{cms} < 250 GeV

FCC-ee
E_{cms} ~365 GeV

Higgs at Electron-Positron Colliders

- Standard Model Higgs event signatures ($\sqrt{s}$ = 240 Gev)
  - **0-jets: ~3%:**
    - Z→ll, vv (30%); H→0 jets (~10%, ττ/μμ/γγ/γZ/WW/ZZ→leptonic)
  - **2 jets: ~32%**
    - Z→qq, H→0 jets (70%*10% = 7%)
    - Z→ll, vv; H→2 jets (30%*70% = 21%)
    - Z→ll, vv; H→WW/ZZ→semi-leptonic (3.6%)
  - **4 jets: ~55%**
    - Z→qq, H→2 jets (70%*70% = 49%)
    - Z→ll, vv; H→WW/ZZ→4 jets (30%*15% = 4.5%)
  - **6 jets: ~11%**
    - Z→qq, H→WW/ZZ→4 jets (70%*15% = 11%)
- **97% of the SM Higgsstrahlung signal has jets in the final state**



Manqi Ruan, LCWS 2019

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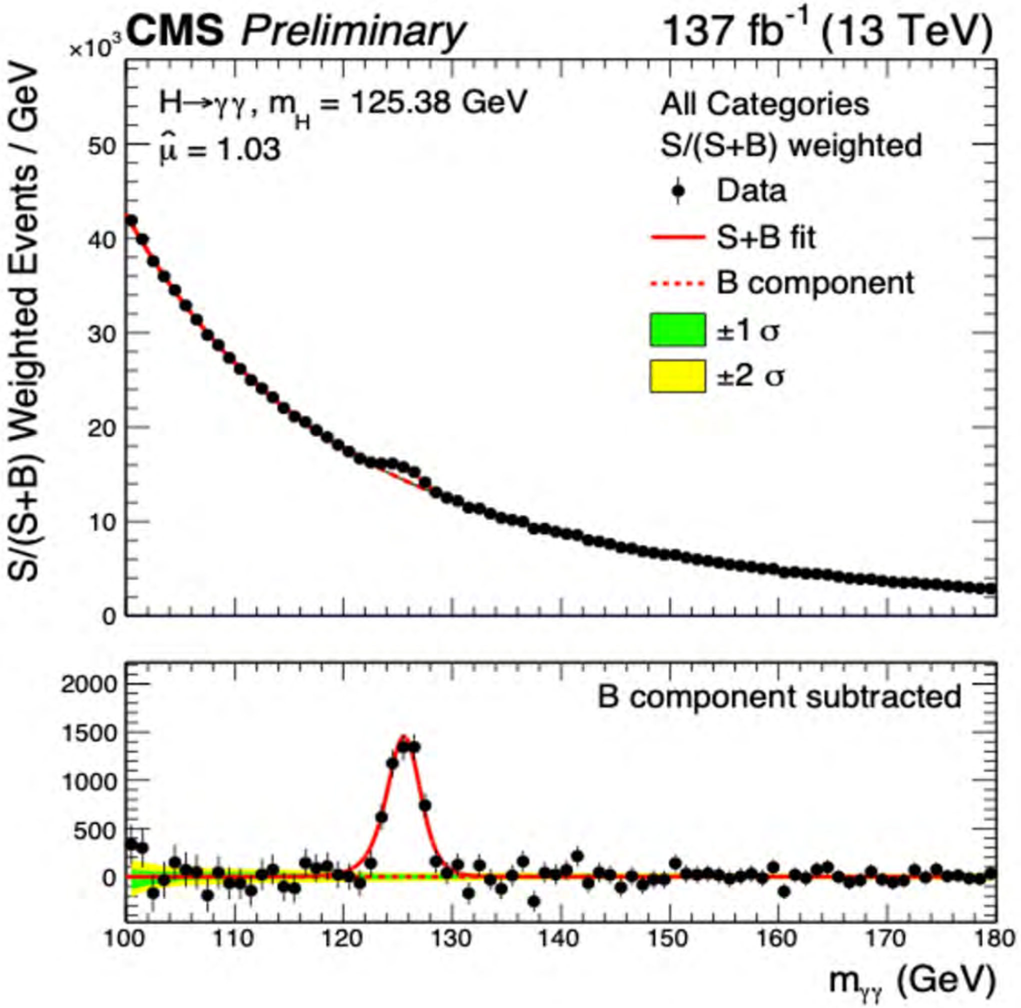
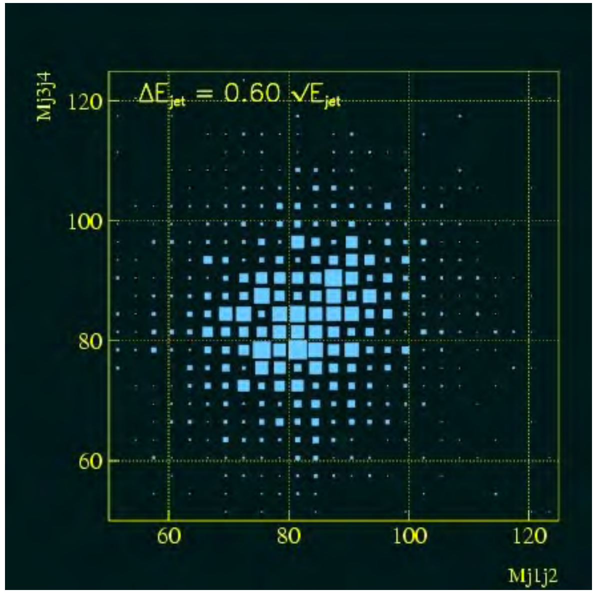
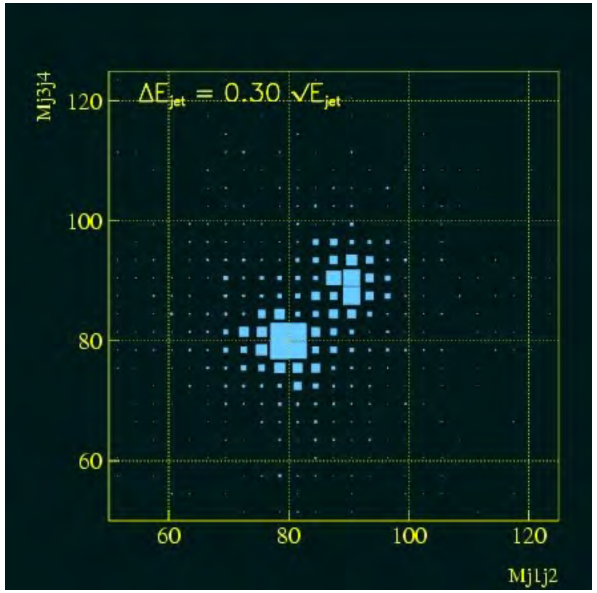
Jet Energy

- Great resolving power with excellent energy resolution



CMS ICHEP 2020





$$\frac{\sigma(E)}{E} = \frac{60\%}{\sqrt{E(GeV)}}$$

$$\frac{\sigma(E)}{E} = \frac{30\%}{\sqrt{E(GeV)}}$$

Limitations to Energy Resolution

- Electromagnetic calorimeters:
  - Obtain 1% energy resolution in total absorption media (crystals)
- Hadron calorimeters at best $50\%/\sqrt{E}$ for single particles;
- Limitations:
  - Sampling fluctuations (fluctuation of the energy sharing between passive and active materials)
  - Sampling fraction depends on the particle type and momentum, that is, ratio in the effective energy loss measured
  - Difference in the 'sampling fractions' between the different materials in sampling calorimeters
  - A fluctuating fraction of the hadron energy is lost to overcome nuclear binding energy and to produce mass of secondary particles
  - Leakage fluctuations due to neutrinos, muons and tails of the hadronic shower escaping the detector volume

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Approaches

- Compensating calorimeters (designed to have e/h=1)
  - Achieved by precisely tuning sampling fractions and media
- Offline re-weighting
  - Use shower profile information to give different weights to signals as a function of the shower depths in offline analysis
- Particle flow
  - Combined performance of tracker, to measure charged particles, and calorimeter, to measure neutrals.
- Total Absorption Calorimetry
  - Measurement of fraction of electromagnetic energy event by event by comparing two different signals in the same device: from scintillation light and Čerenkov light.

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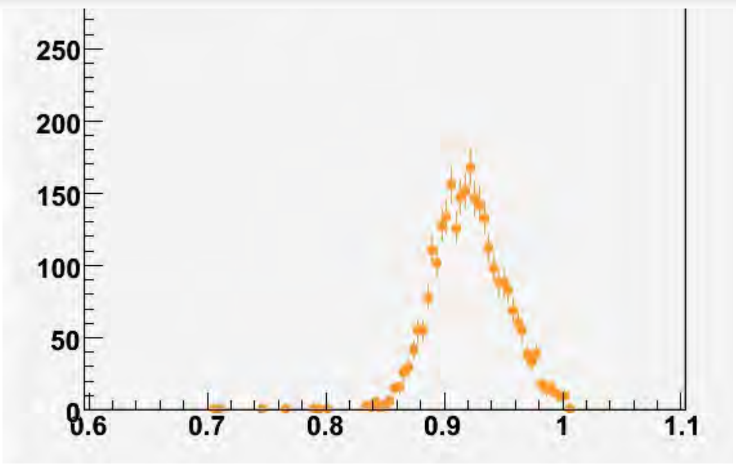
Total Absorption Calorimetry

- **Total absorption has no sampling fluctuations or other sampling–related contributions.**
- **Separate measurement of Scintillation light (S) and Čerenkov light (C) in the same device.**
- The dominant contribution to resolution: fluctuations of nuclear binding energy losses.
- Cherenkov-to-scintillation ratio a sensitive measure of the fraction of energy lost for binding energy/kinematics:
  - Electromagnetic (π^{o}) showers do not break nuclei and produce large amount of Cherenkov light (C/S~1)
  - Large amount of ‘missing’ energy – large number of broken nuclei – small amount of energy in the form of highly relativistic particles → small C/S ratio
  - Low amount of ‘missing’ energy – small number of broken nuclei – large amount of energy in the form of EM showers → C/S ratio close to 1
- Note: Cherenkov light is prompt and provides excellent timing.

Implementation

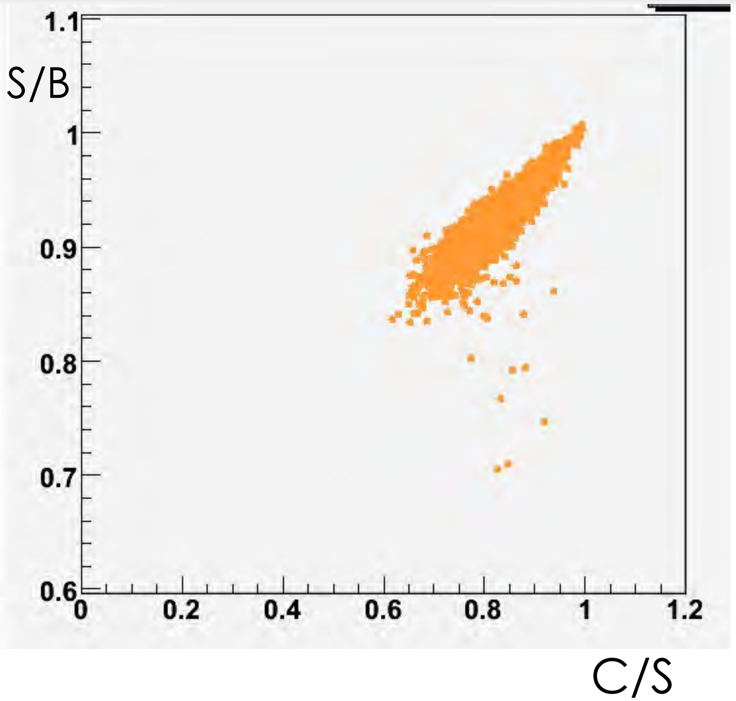
- Geant4 simulation of single 100 GeV π^-(B), total absorption calorimeter, measure scintillation (S) and Cherenkov (C) light

Scintillation Only



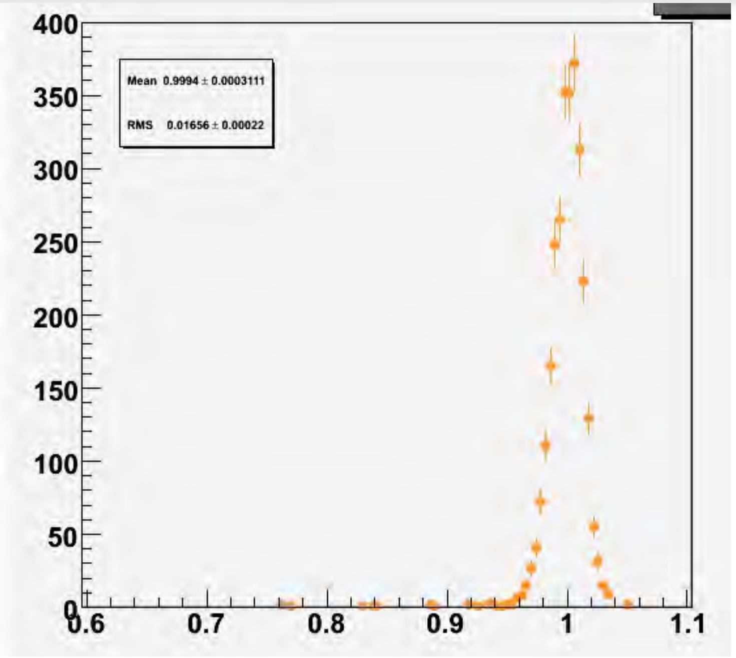
ΔE/E ~ 3.3% @ 100 GeV
Significant non-linearity: mean = 92 GeV

S – C Correlation



Use correlation to limit resulting resolution to the local width of the scatter plot

Corrected Response



ΔE/E = ~1.2-1.5% @ 100 GeV
Linear response

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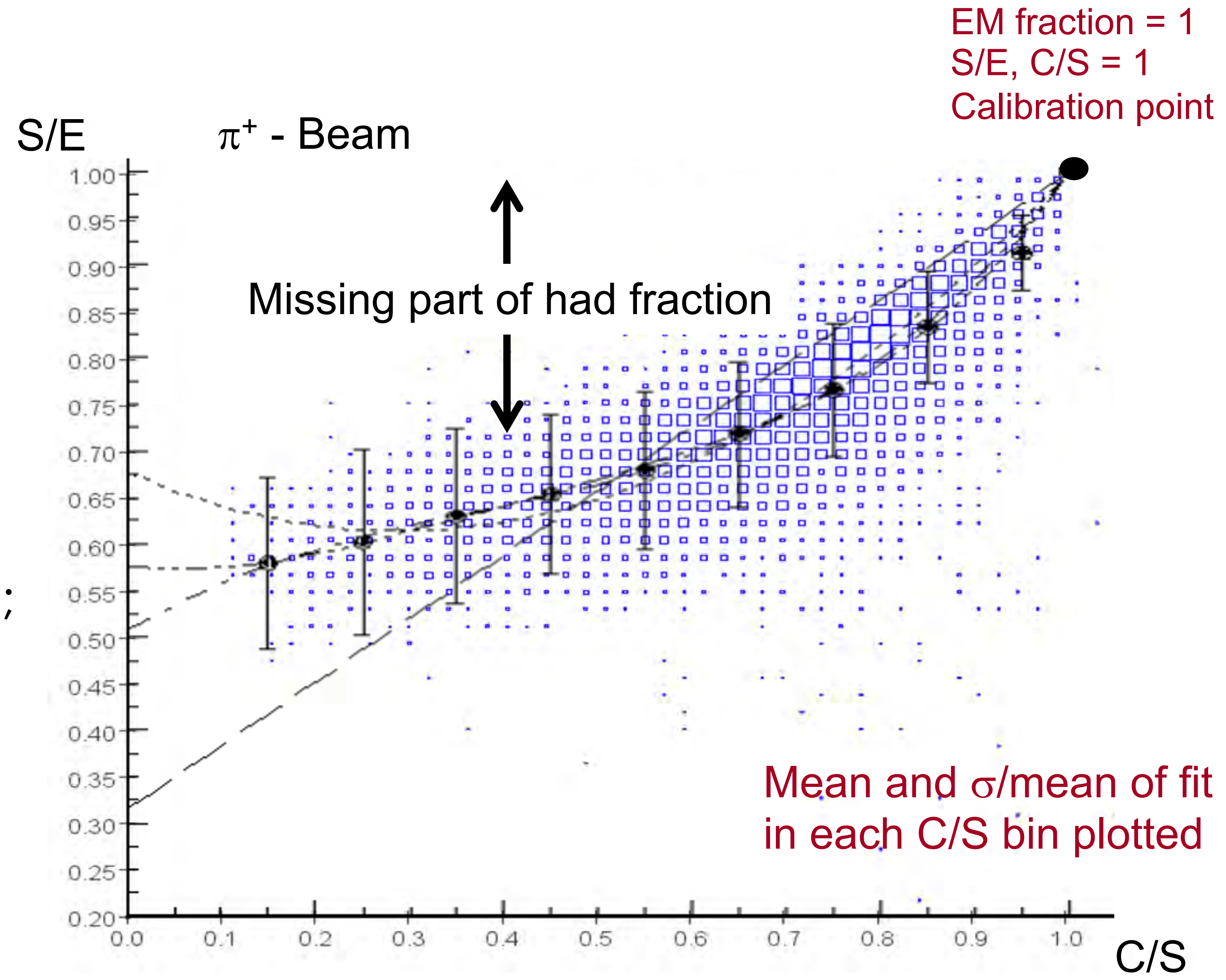
Implementation

- A total absorption calorimeter is uniformly sensitive to all particles

- Formalism:
  - Cherenkov response is sensitive to particles above Cherenkov threshold; all particles, including leading pions or muons, contribute.



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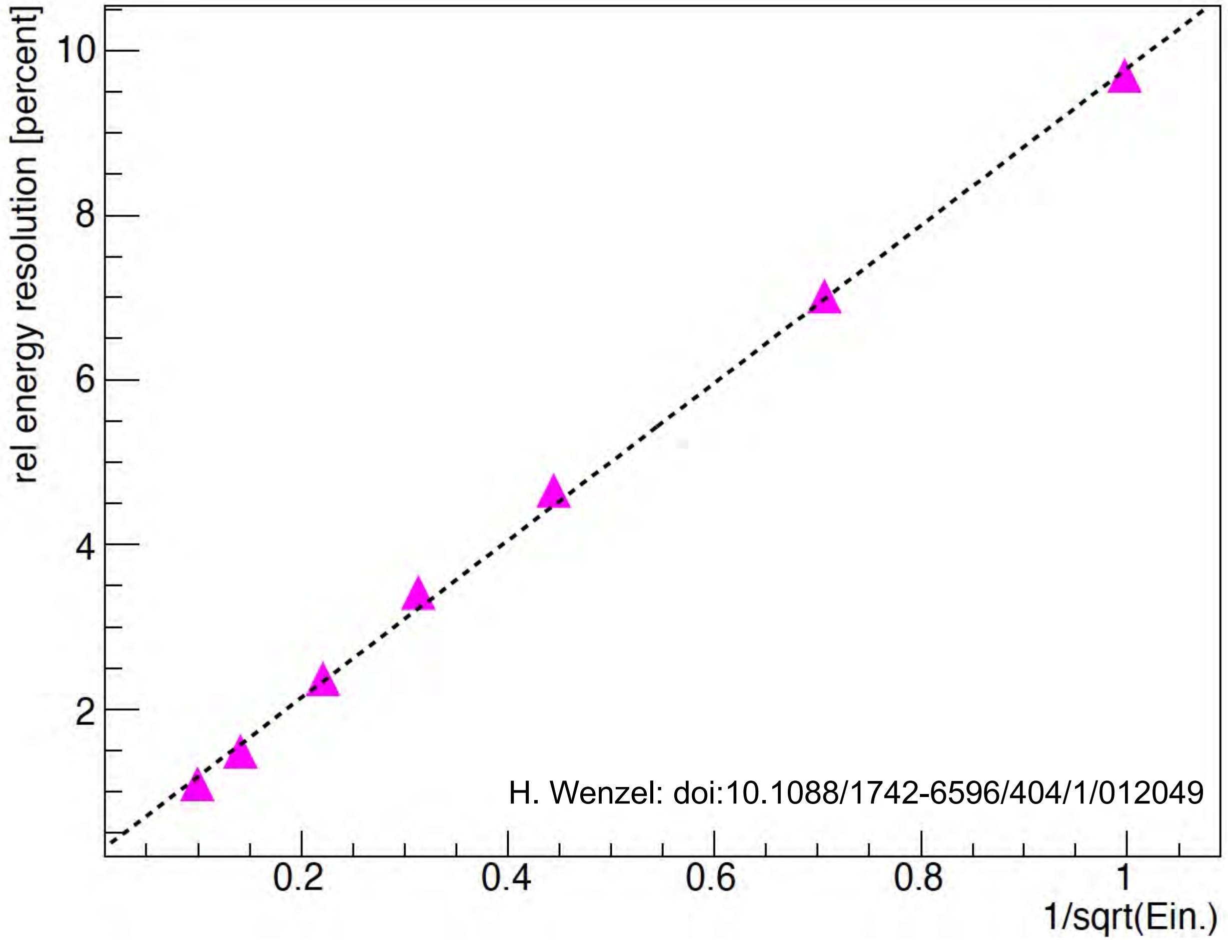
Implementation

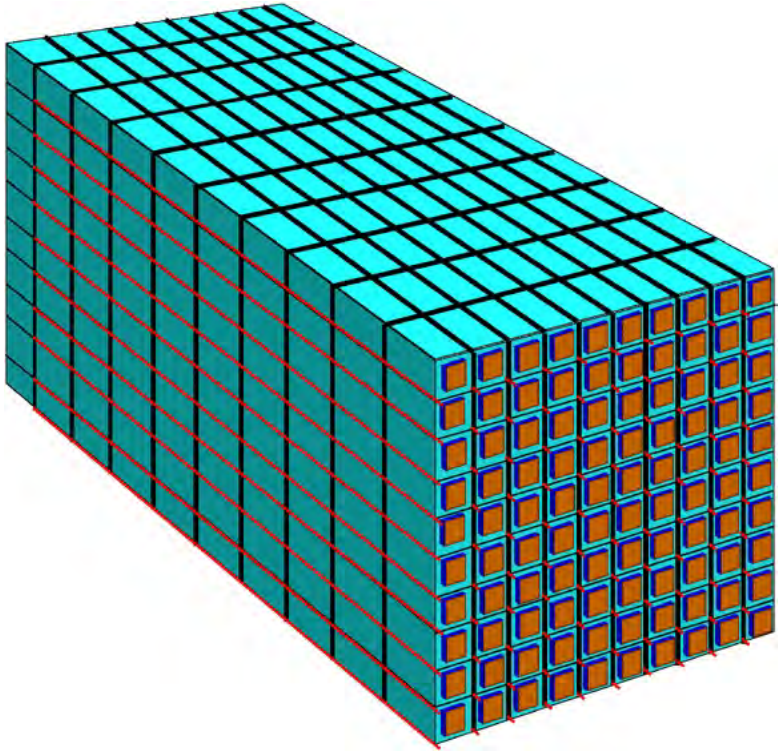
- Monte Carlo simulation of single particle response as demonstrator
  - BGO as calorimeter
  - Geant4, FTFP_BERT
  - Constant term: (0.23 ± 0.08)%
  - Sampling term: (9.55 ± 0.15)%
- This is single particle response in an ideal configuration; reality will raise the stochastic term to 15-20%.

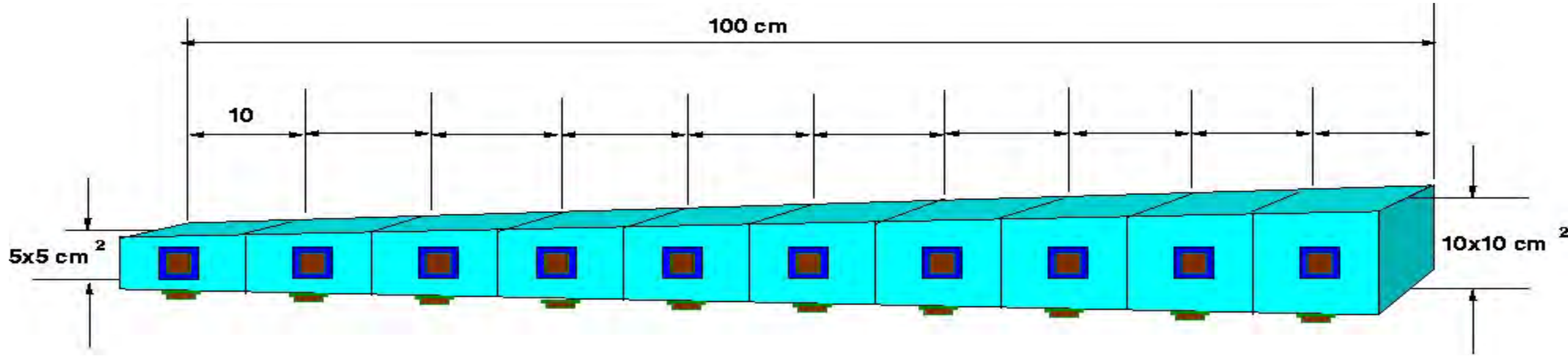


See talk by H. Wenzel for more details on status of simulation
This workshop

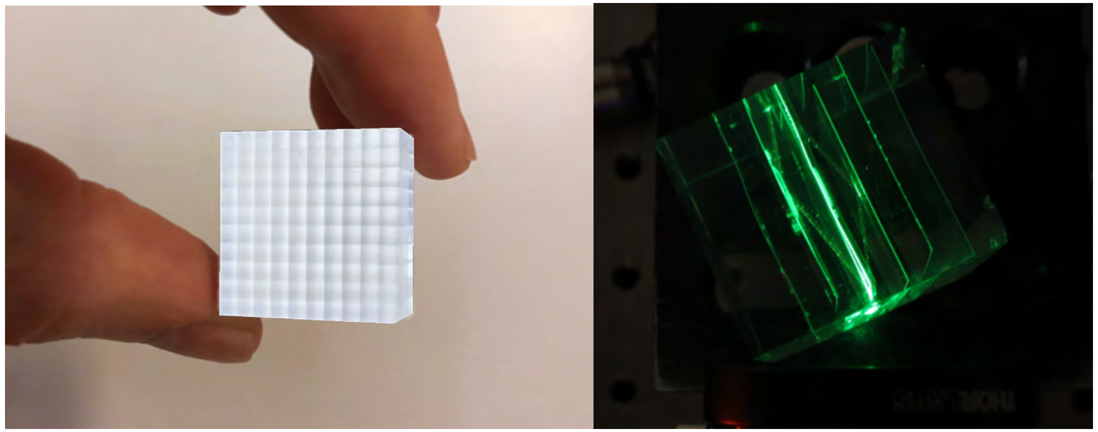
Technical Implementation

- Until recently the technical challenges were significant to even consider a homogenous calorimeter
- There have been tremendous technical advances that make this option viable with further R&D
  - Low form factor photo-detectors that can operate in a magnetic field (SiPM)
  - High density scintillating crystals/glasses (λ~20 cm)

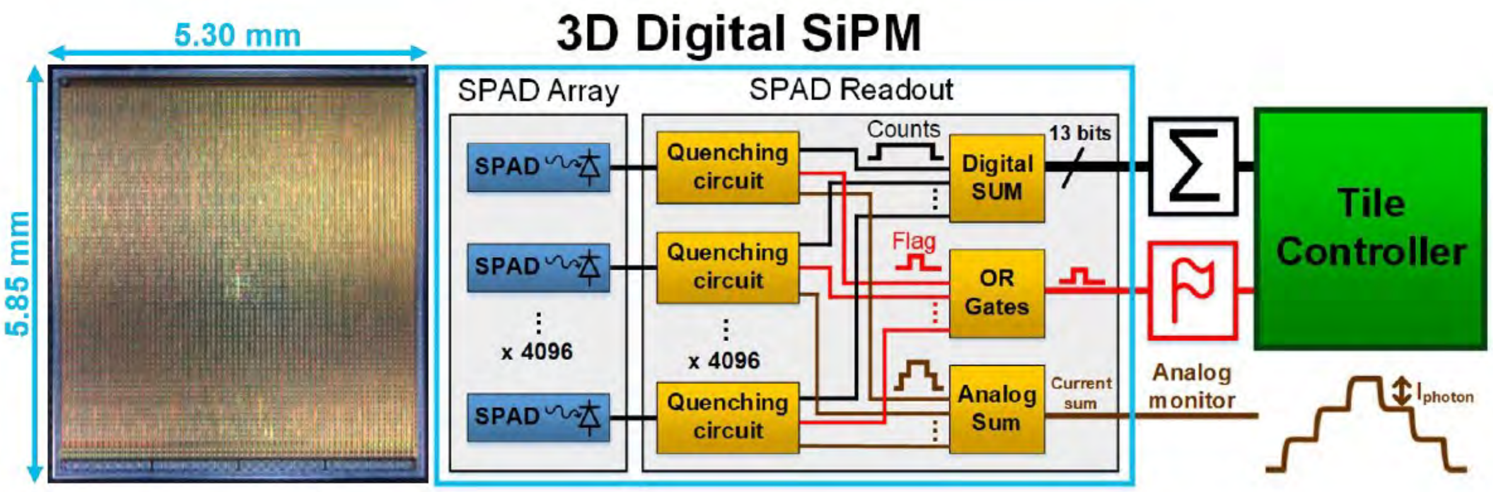




Some Developments



- Scintillator
  - Stereolithography 3D Printing of "Pulse-shape Discriminating plastic" with embedded reflector
  - M. Febbraro, photodetector session



- Readout
  - "Photon-to-digital converters"
  - SiPM with quench resistor by a transistor, never leaves digital domain
  - J-F. Pratte, cross-cut session

Cost-Effective Inorganic Scintillators

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	$BaO{\cdot}2SiO_2$ Glass[1]	HFG Glass[2]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	5.95
Melting point (°C)	1050	1030	1123	824	608	2040	980[3]	1420[4]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	425	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	1.50
Relative Light Output by PMT[a,c]	100	20	1.6 0.4	\	2.0	0.2 0.9	2.6	5.0 4.0	3.3 6.1
LY (ph/MeV)[d]	35,000	1,500	130	\	150	7,900	450	3,150	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	25 8
d(LY)/dT (%/°C)[d]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	?	?	?

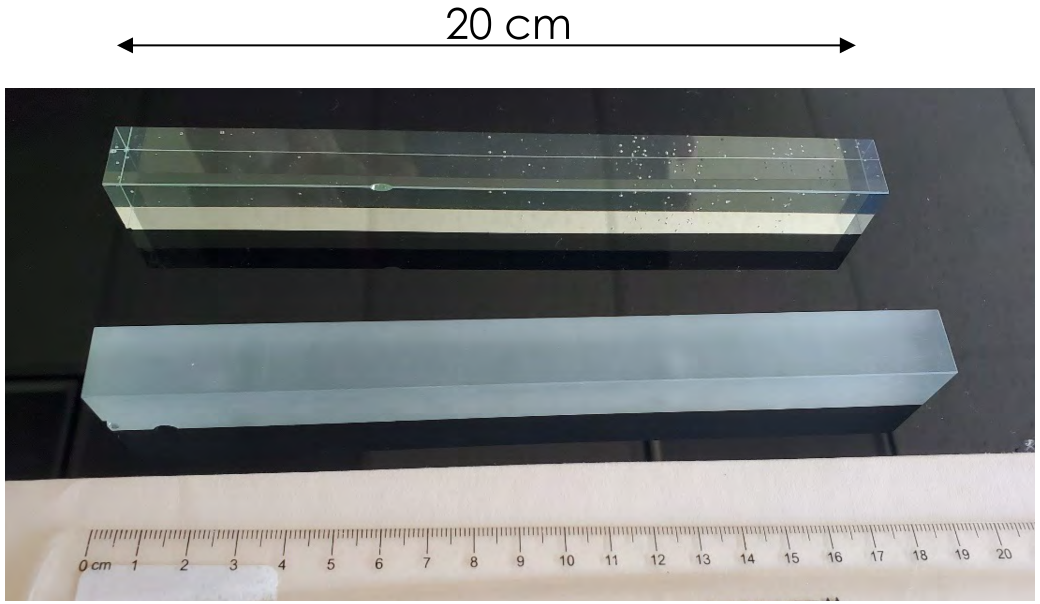
R-Y. Zhu
Chen Hu

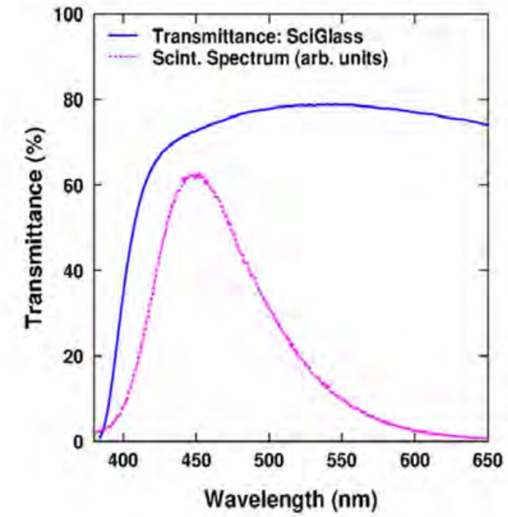
https://www.aforesearch.com/

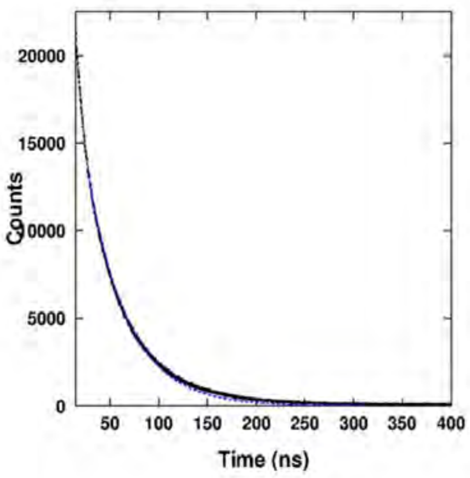
Glasses

- As part of the EIC R&D, good progress made on the development of glasses at the Vitreous State Lab at CUA and Scintilex.
- Production of 15-20 X0-long SciGlass blocks
  - simulations suggest resolutions comparable to PWO
- Anticipated cost of SciGlass ($2/cm^3)

- Also, R&D on Cherenkov-Scintillating glasses (CSglasses)
- Very high-density compared to nominal, emits at >550nm, good LY





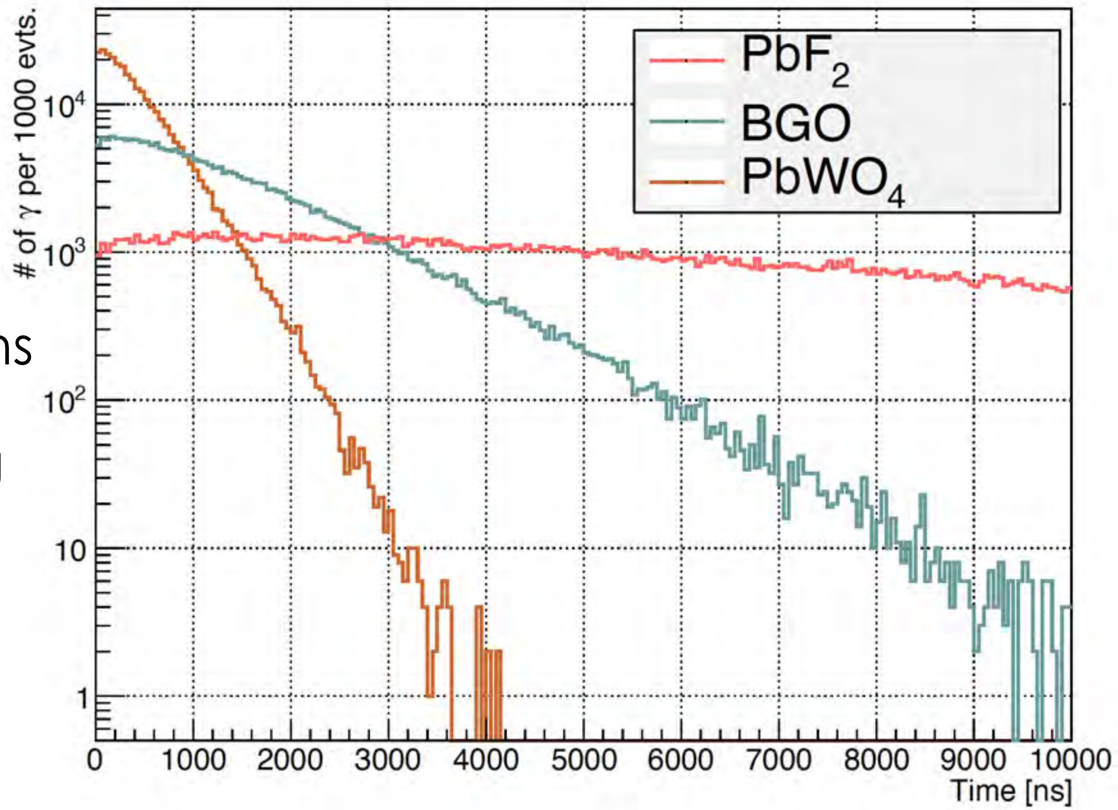


T. Horn

https://indico.phy.ornl.gov/event/38/timetable/#20210316

Additional Handles

- In a hadron shower there are ~20 neutrons ‘evaporated’ per GeV of a shower from nuclei with typical energies of 1-2 MeV, thus consuming ~15-20% of a hadron shower energy.
- In a sampling calorimeter with hydrogenous active medium these neutrons are observed via n-p reaction, thus recovering some of the total energy (1-2%)
- In a total absorption calorimeter these neutrons are thermalized and captured and ‘return’ all of their energy to the observed signal (on long timescale)
- A dual-gate provides a means to capture this energy.
- The magnitude of the correction depends on the gate time



Distribution of time of creation of photons created by the neutron capture process for different crystal materials (H. Wenzel, CHEF 2013)

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Summary

- To maximally exploit future facilities and advance our understanding of fundamental forces, major improvements in hadron calorimetry are required.
- Progress with development of dense scintillating materials and compact photodetectors enables construction of hadron calorimeters with energy resolution reaching10%/√E
- Significant progress in further understanding of the underlying physics of hadronic showers is being made.
- The potential return on a modest R&D investment could be very large.