# Calorimetry R&D Directions
# Needs in the Next 3-5 Years

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**Princeton Muon Collider Organizational Workshop**

# Importance of Order of Magnitude Leaps

- **Past Three Decades**
  - Tens of microseconds to tens of nanoseconds
  - Thousands of channels to millions
  - kRad to MRad tolerances
  - 100kBytes to GBytes of per event data
  - Trigger based on a handful of scalar sums to thousands of individual particle tag quantities
  - …many firsts with every new calorimeter
- **With each leap, we create opportunities for invention and innovation in the physics program and deliver more events, max out resolution within constraints, high granularity, and lower backgrounds for more sensitivity to new physics**

# Muon Collider Era

- **We have to be even more impressive than before**
  - Sub-nanosecond tags for each individual particle region
  - Multi-signal/multi-dimensional discrimination to further particle identification for all particles
  - Tens to hundreds of millions of channels
  - Tens of Mrad tolerances
  - Tens of GBytes of per event data
  - Triggers based on all real-time reco particles in the event
  - First AI/ML fully optimized detector design
- **Above all, the great leap for the muon collider detector calorimeter is to deliver new order of magnitude advances across the board while fully cleaning each event of beam-induced-background**

# Calorimeter R&D Directions

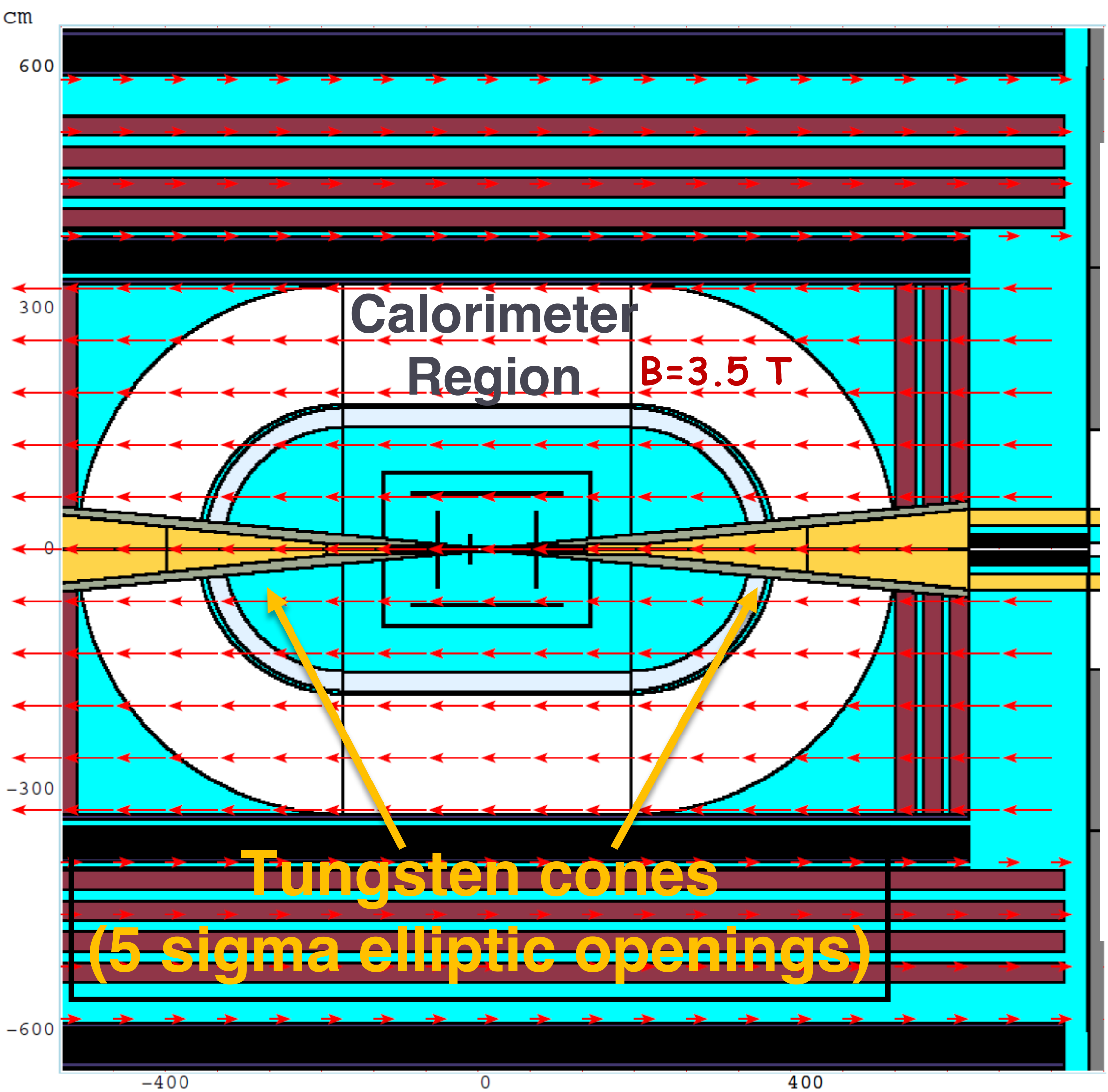
- **Complex landscape of potential technologies**
  - Si-W based on-detector/MAPS readout
  - Cryo/Noble Liquid/LAr high granularity with cold readout
  - Optical calorimetry with Dual-Readout/hybrid crystals
  - Emerging timing-centric approaches/Fast glass/Crillin
- **Time-domain important and pervasive dimension**
  - (AC-)LGAD/silicon
  - Fast glass/Crillin
  - LYSO/Fast Scint/SiPM
  - And several evolving 10's to 100's of picosecond leading-edge discrimination for many of the full-detector calorimeter technologies

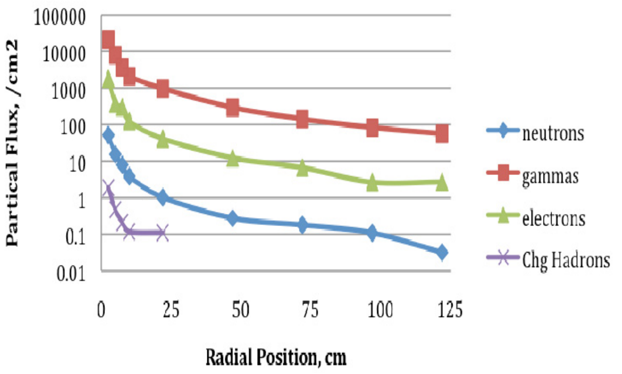
# Calorimeter R&D Future

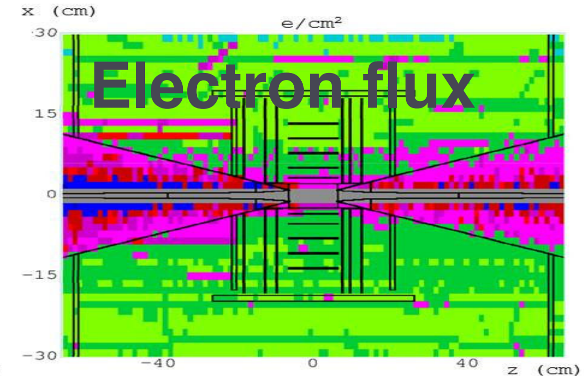
- **Maximize information content**
  - Measure and identify particles and event - and parameters needed to maintain calibration and remove backgrounds
  - Dig deep: high quality local data, but save frugally/intelligently
- **A strong guiding paradigm is Particle-Flow, but previous incarnations were hardly well-implemented**
  - In fact, PF is largely, at this time, based on a lot of assumptions
  - Energy “Flow”:  assumes time is measured at different points along the trajectories – few examples of that
  - Assembly of particles out of the parts collected from vertex/tracking/calorimeter/muon – not fail safe
  - Calorimetry – often downgraded to minimum performance, driving many of the mistakes made in the algorithm

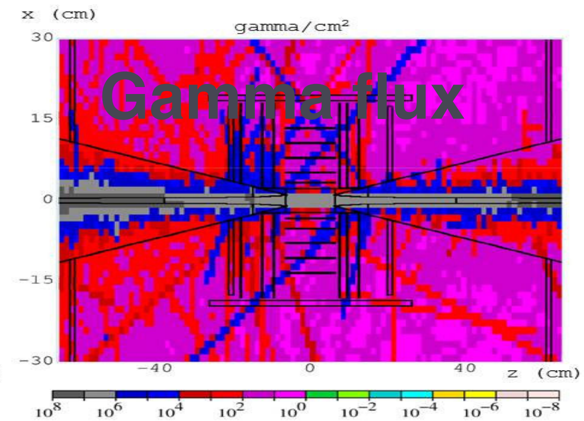
https://arxiv.org/abs/1204.5739
https://accelconf.web.cern.ch/ipac2012/papers/moppc037.pdf

# Example Muon Collider Outline



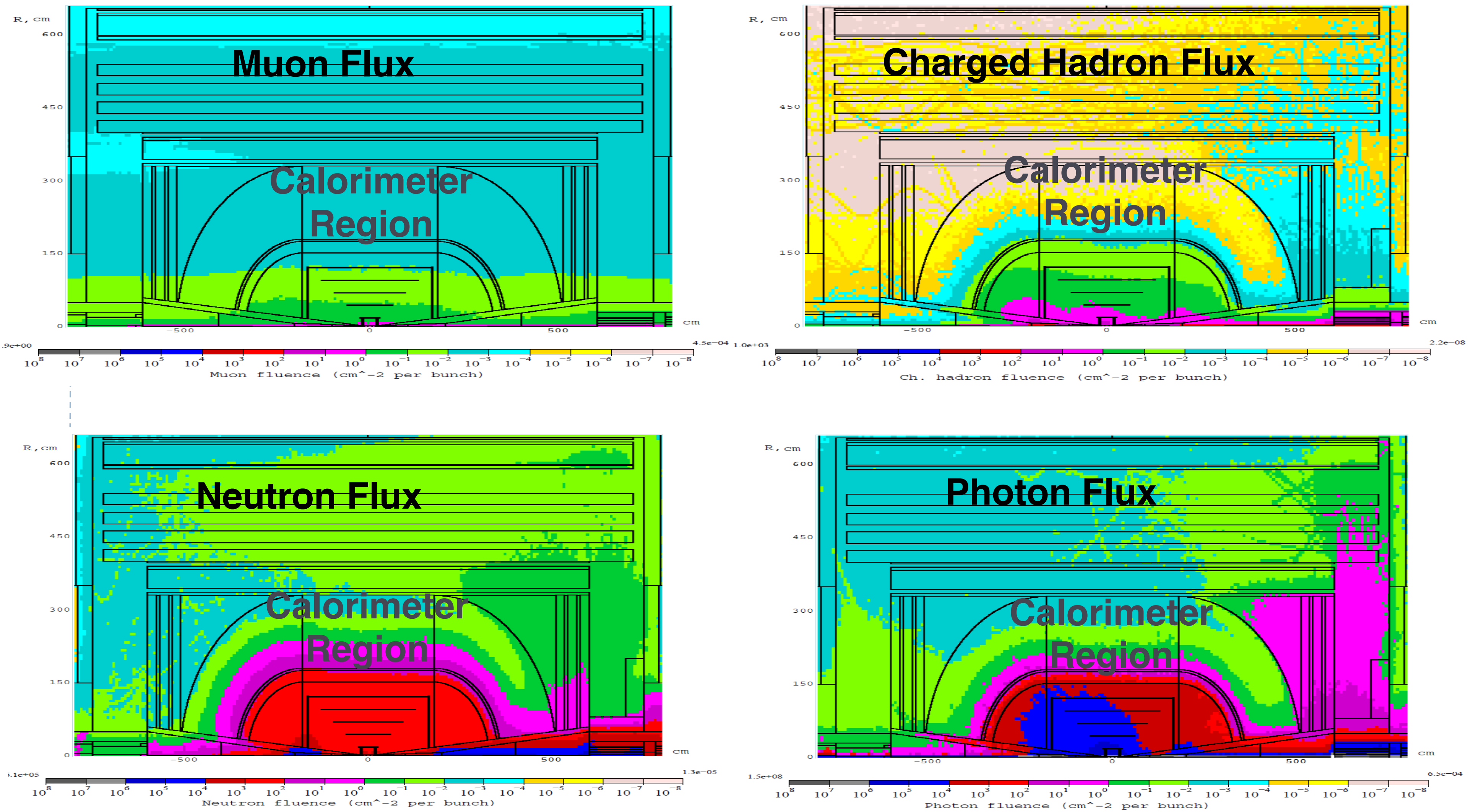





N. Mokhov (FNAL)

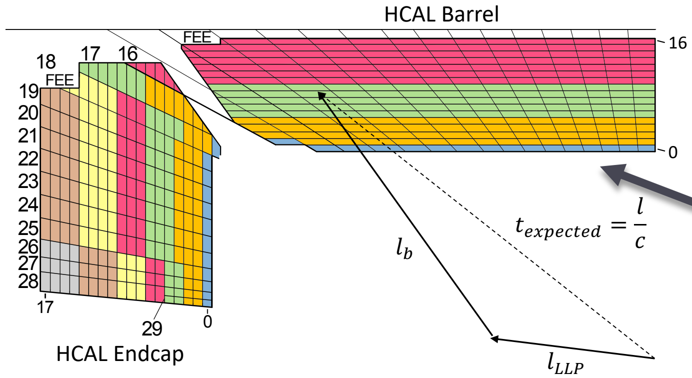
# Expected Flux Through Calorimeters



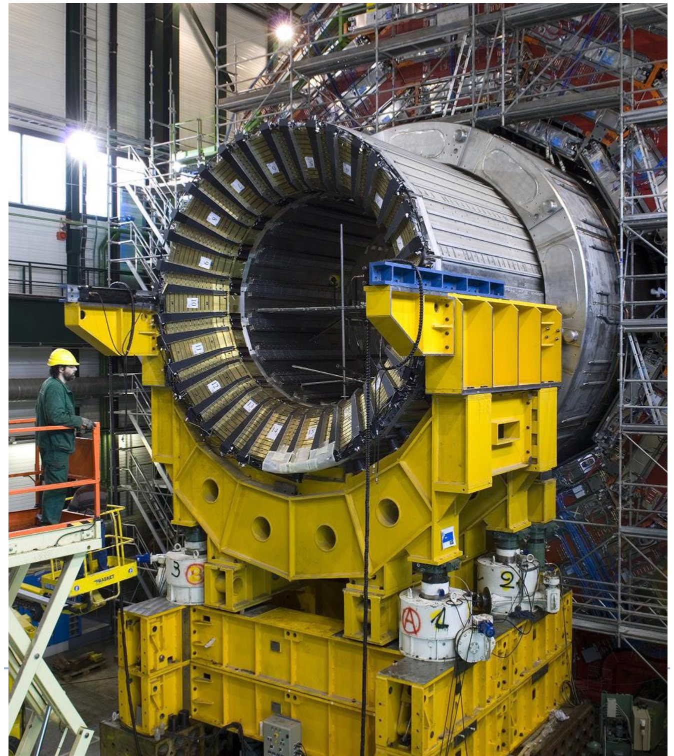
# Time-domain is different than HL-LHC/muC

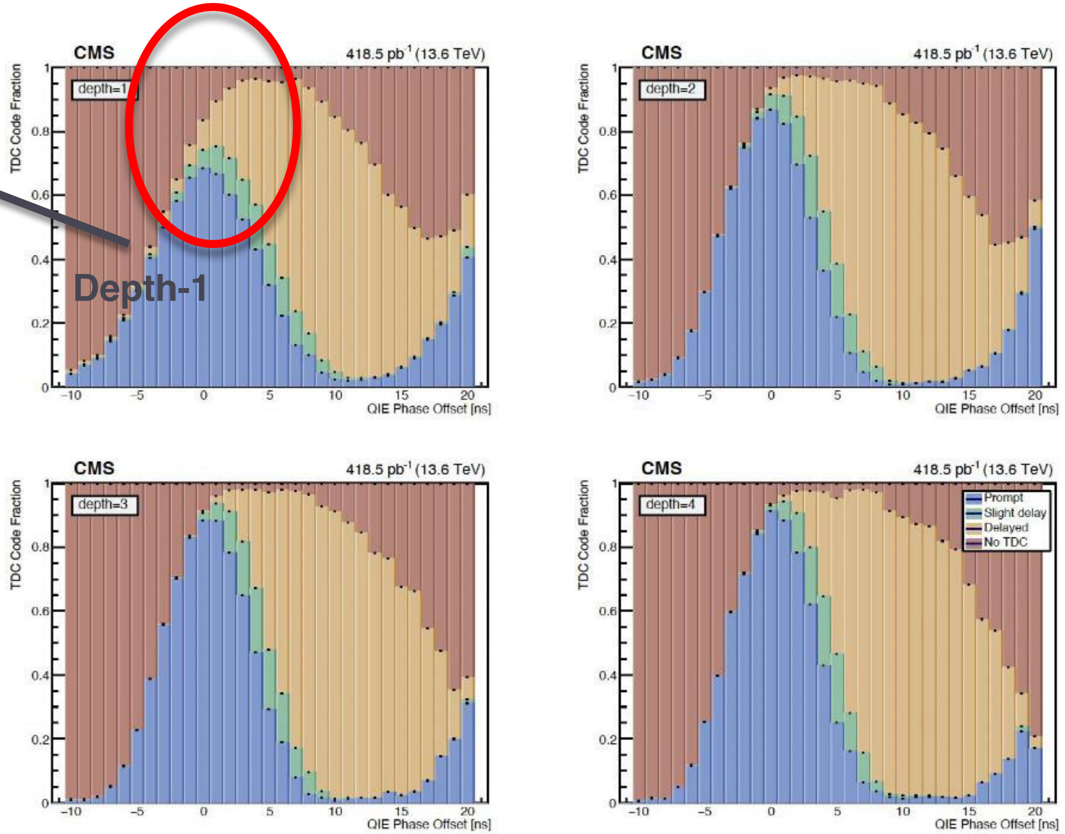
- HL-LHC has a class of backgrounds that are from inelastic proton-proton interactions from the beam (sub-ns spread) – Much less of this in muC
- There is significant ambient neutron flux from hadron interactions in neutron rich materials in the calorimeters (diffuse in time) – More from collimators upstream and tungsten nose
- Significant low energy flux from tungsten nose
- Beam halos (muons produced in secondary lost beam interactions) – large flux from off-momentum electron-initiated showers upstream
- Cosmics (grow in rate when there is random overlap in broad time window for collecting events) – narrower IP time windows help here

# Example hadron calorimeter time-alignment




$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$






Distributions used to derive TDC based alignments. X-axis corresponds to pulse alignment; y-axis is measured TDC time

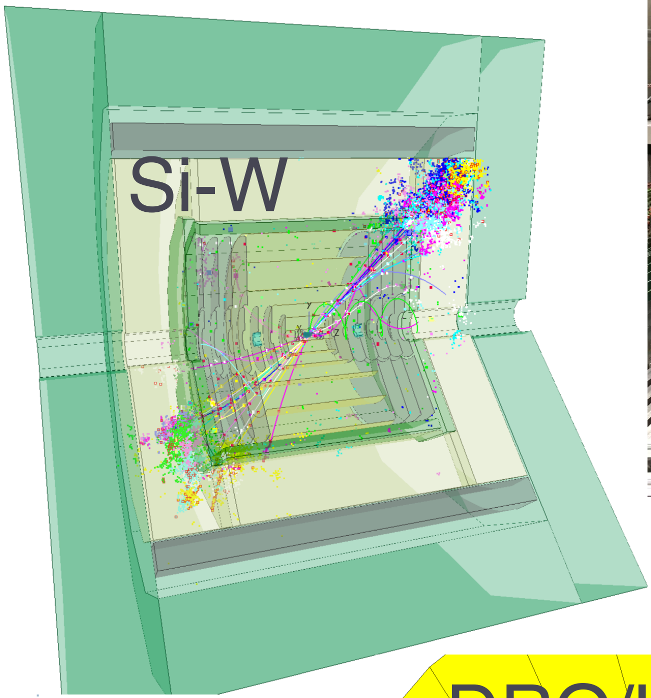
Blue: prompt (0-6ns)
Green: slightly delayed (6-7ns)
Orange: delayed (7-25ns)
Red: invalid TDC bit

**2007-2020**

# Muon Collider Calorimetry

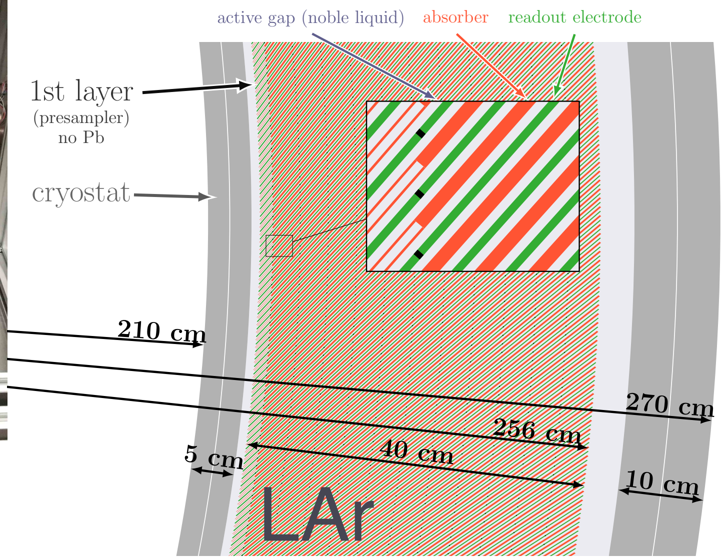
- **Need to drop some assumptions**
  - Measure hit times along trajectories
  - Track from IP outward and from Beam Collimators inward
- **Standard geometries are designed to be hermetic and uniform – tunnel vision on IP**
  - Locations of calorimeter surfaces influences the separation power on beam backgrounds
  - Prompt time of arrival distributions should not peak at background arrival times – and overlap should be suppressed by multiple times along trajectories leading up to calorimeter
  - Timing layers/walls should be arranged to efficiently catch beam backgrounds and maintain high event quality
  - Projective to the IP is for signal

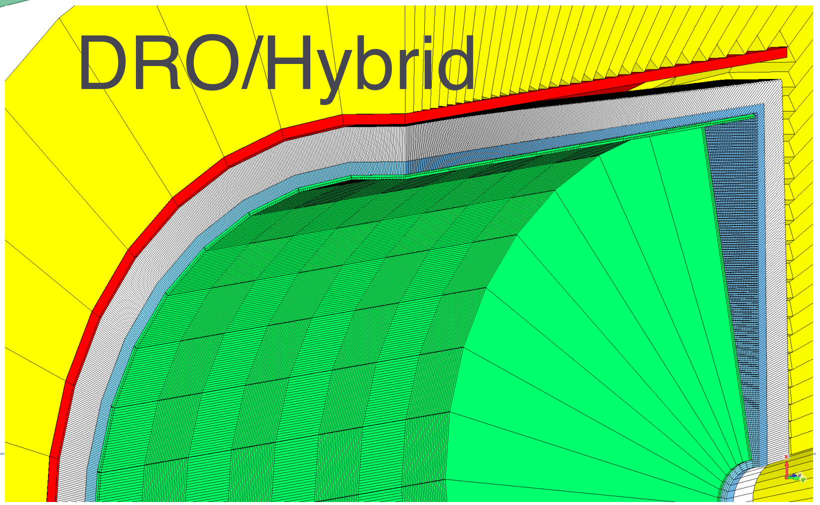
# Optimize w/ Simulation and Test Beam



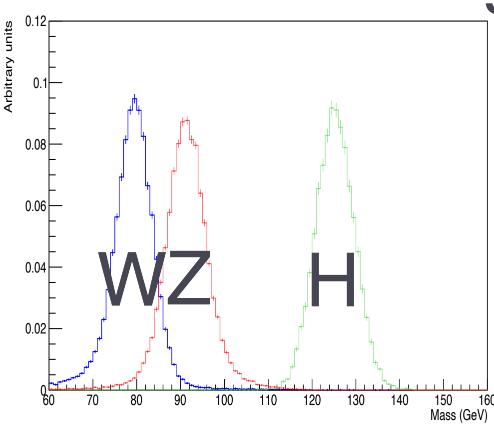


https://arxiv.org/abs/2109.00391




Benchmarking



# Summary Table of Energy Resolutions

https://arxiv.org/abs/2109.00391

| Detector technology (ECAL & HCAL) | E.m. energy res. stochastic term | E.m. energy res. constant term | ECAL & HCAL had. energy resolution (stoch. term for single had.) | ECAL & HCAL had. energy resolution (for 50 GeV jets) | Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets) |
|---|---|---|---|---|---|
| Highly granular Si/W based ECAL & Scintillator based HCAL | $15-17\,\%$ [12,20] | $1\,\%$ [12,20] | $45-50\,\%$ [45,20] | $\approx 6\,\%$ ? | $4\,\%$ [20] |
| Highly granular Noble liquid based ECAL & Scintillator based HCAL | $8-10\,\%$ [24,27,46] | $< 1\,\%$ [24,27,47] | $\approx 40\,\%$ [27,28] | $\approx 6\,\%$ ? | $3-4\,\%$ ? |
| Dual-readout Fibre calorimeter | $11\,\%$ [48] | $< 1\,\%$ [48] | $\approx 30\,\%$ [48] | $4-5\,\%$ [49] | $3-4\,\%$ ? |
| Hybrid crystal and Dual-readout calorimeter | $3\,\%$ [30] | $< 1\,\%$ [30] | $\approx 26\,\%$ [30] | $5-6\,\%$ [30,50] | $3-4\,\%$ [50] |

If the focus is mainly jets, then high-granularity with PFA delivers 4% at 50 GeV – often called "PFA calorimetry"

Noble Liquid is a better calorimeter across the board, but needs PFA studies

Higher EM performance with Noble Liquid or Fibers – Highest with Crystals

Best Intrinsic Hadron Performance with Dual-Readout Fibers

Hybrid Dual-Readout Crystals+Fibers attempts to maximize all performances

# Many small projects

WP1 - Sandwich calorimeters with fully embedded electronics

WP2 - Liquified Noble Gas Calorimeters

WP3 - Optical calorimeters

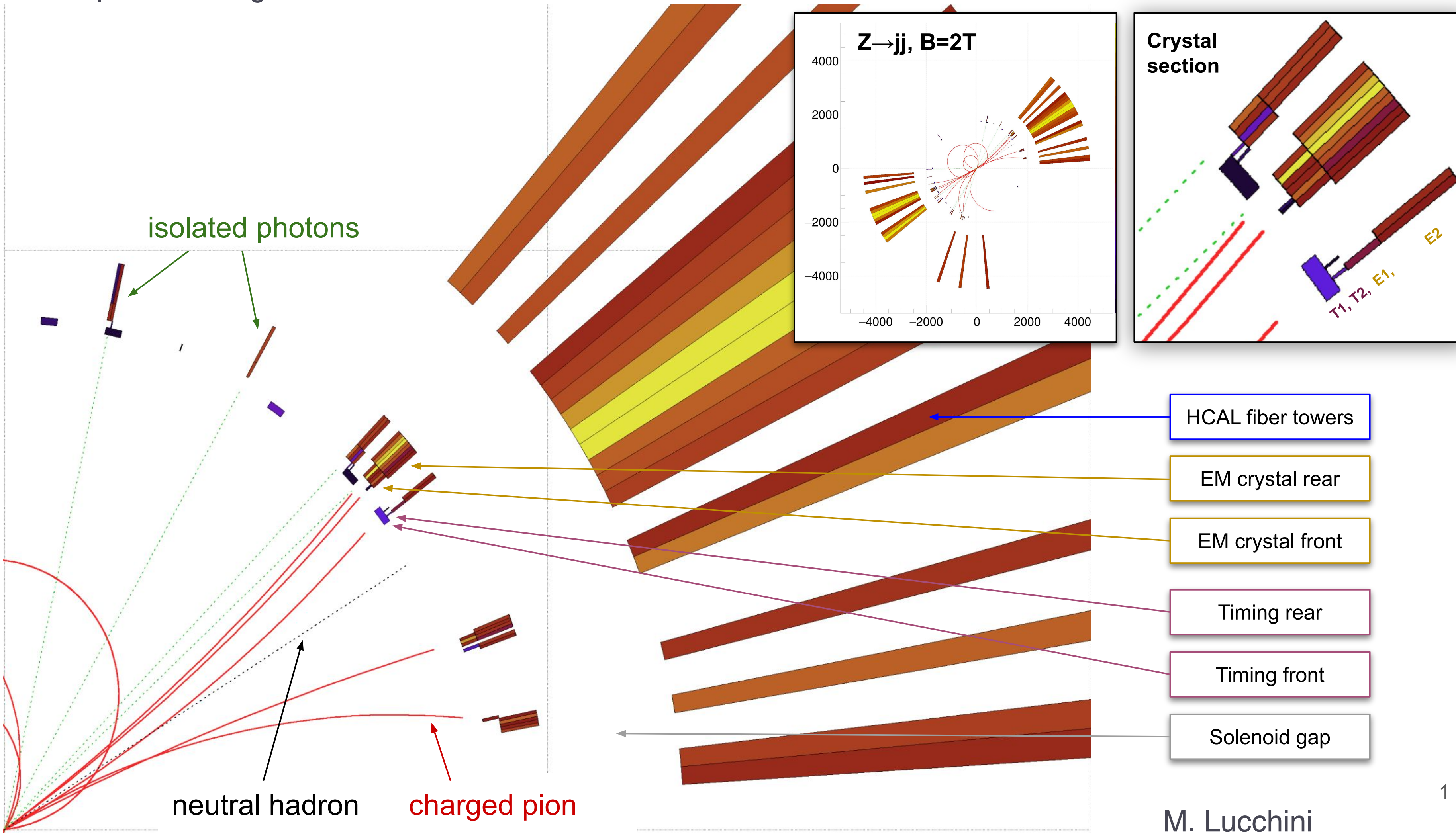
WP4 - Electronics and readout

- Task 3.1.1 HGCCAL
- Task 3.1.2 MAXICC ¶
- Task 3.1.3 Crilin
- Task 3.2.1 GRAiNITA
- Task 3.2.2 SpaCal
- Task 3.2.3 RADiCAL
- Task 3.3.1 DRCal
- Task 3.3.2 TileCal
- Task 3.4.1 ScintCal
- Task 3.4.2 CryoDBD Cal

Limited full detector optimization and performance benchmarking

# Hybrid Dual-Readout Crystals+Fibers

https://arxiv.org/abs/2008.00338

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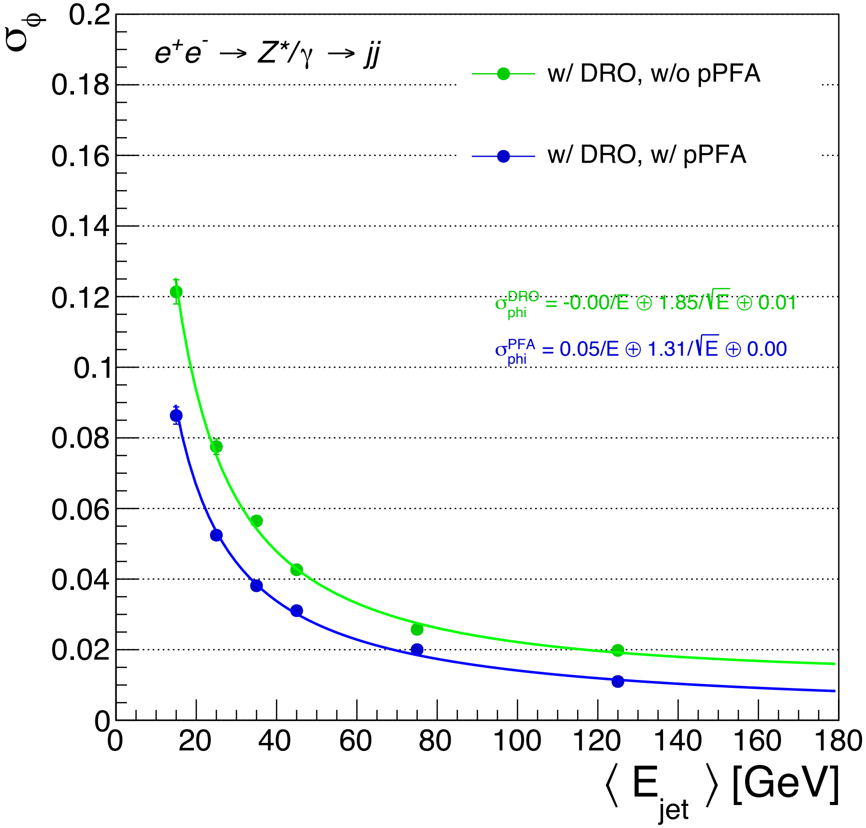
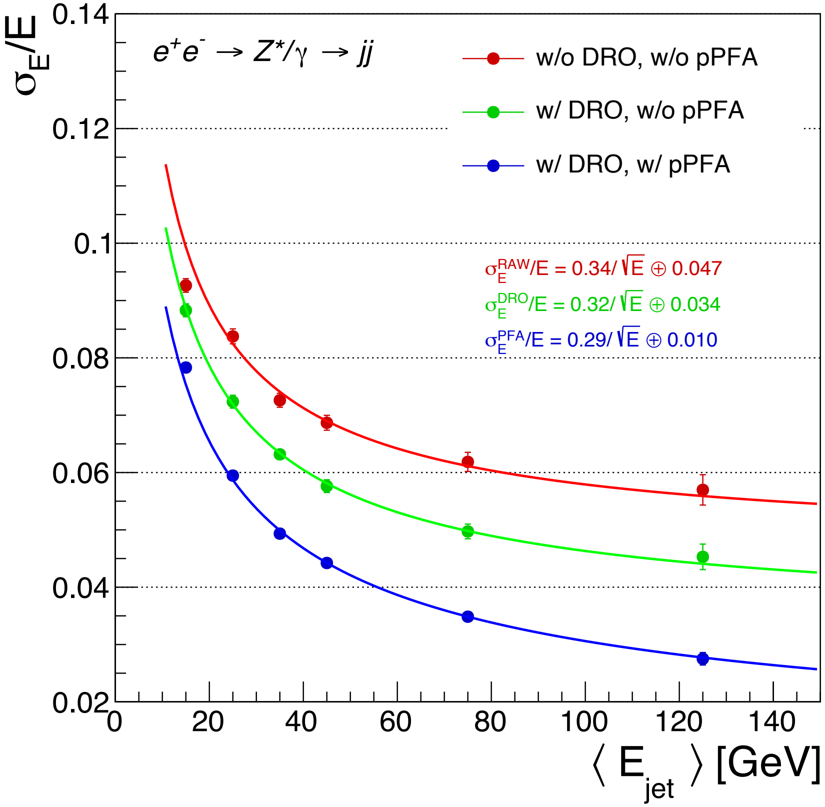
M. Lucchini

# Dual-Readout PFA

Jet angular resolution (φ)



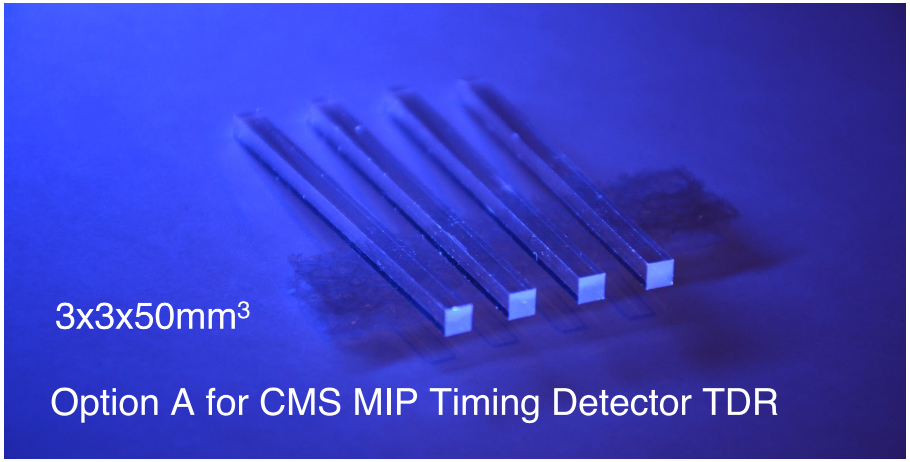

Jet energy resolution



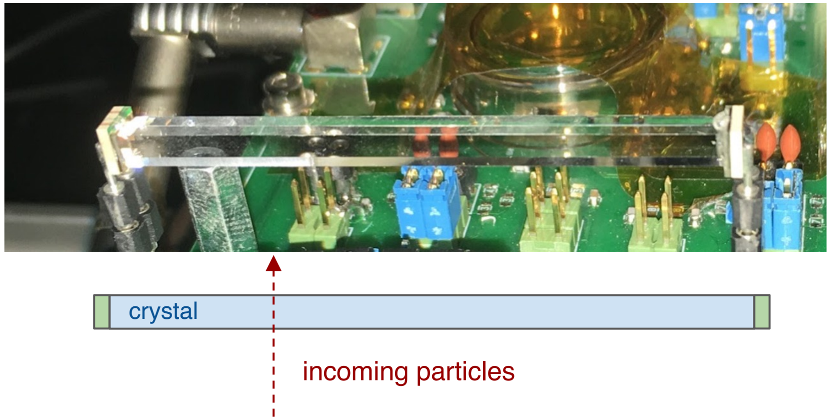

M. Lucchini

# Importance of Timing Layers (in front of calorimeter)

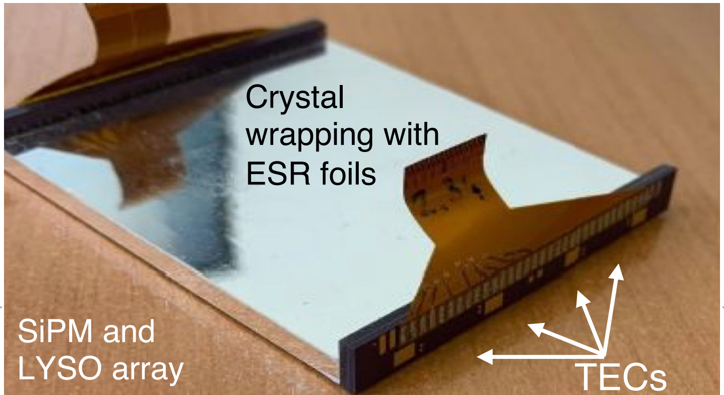
- **New era of MIP timing**
  - ~25ps resolution per hit (1/c = 33ps/cm)




**Non-wrapped crystal bar with 2 SiPMs attached at each end**




Low occupancy timing layer timing for ~0.3-1 X0
Transverse orientation w/ stereo readout

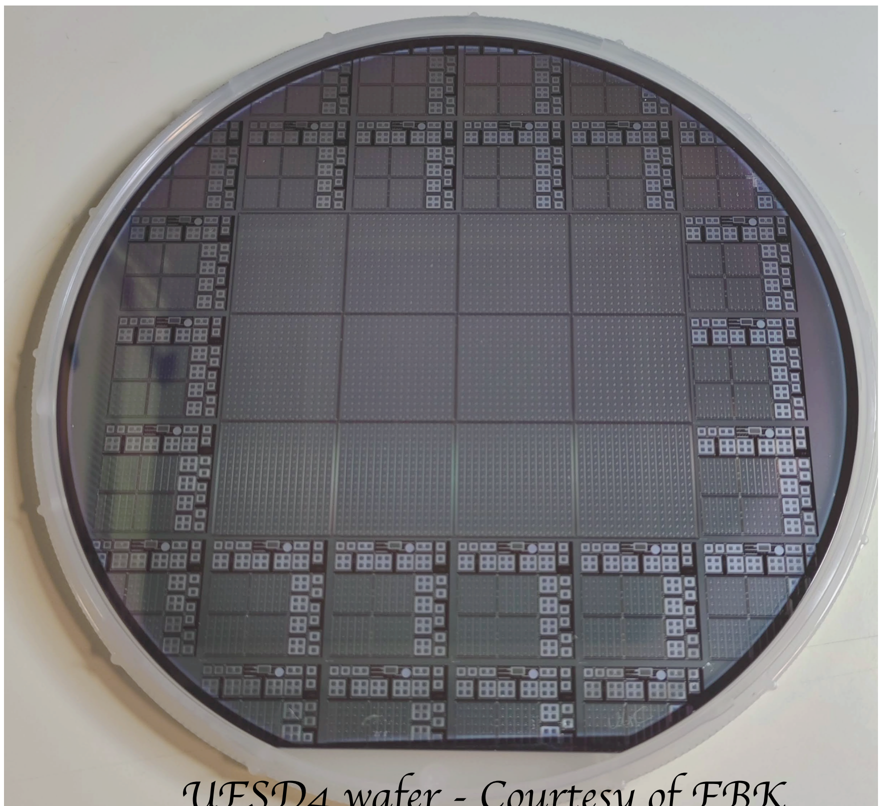



**Hermetic 30 ps timing layers a first-ever**

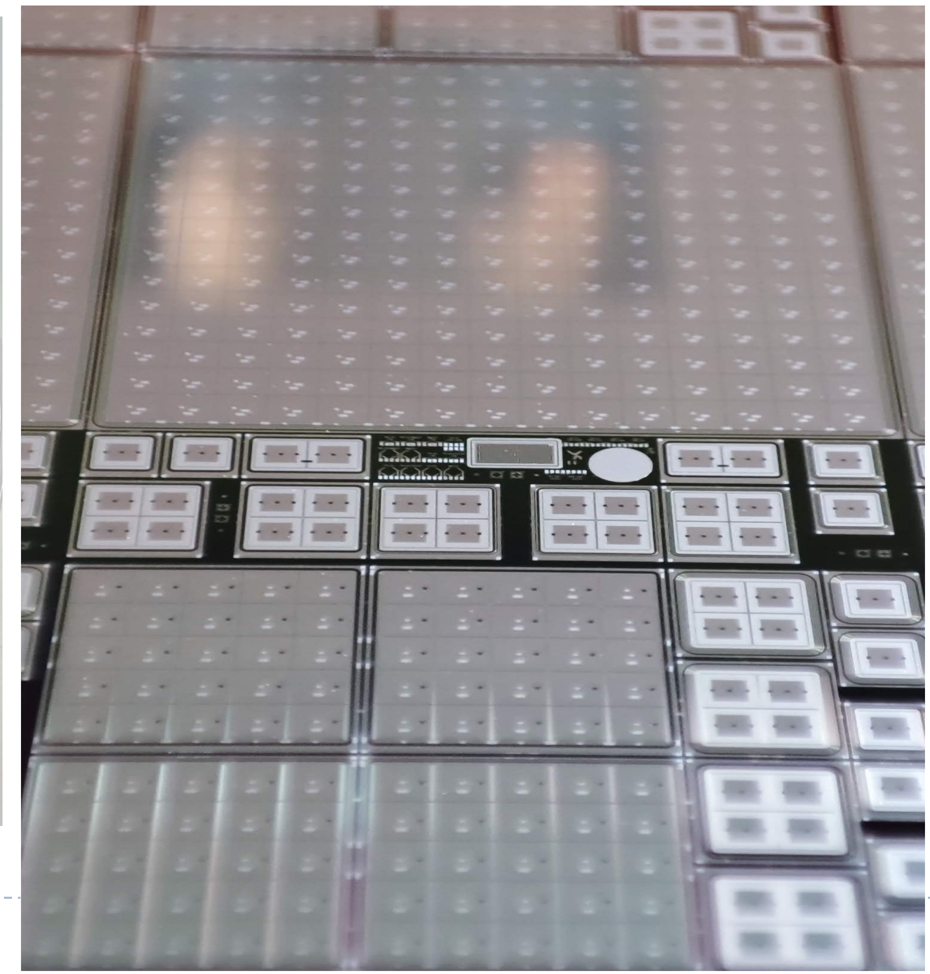
# Importance of Timing Layers in tracker

- **New era of MIP timing**
  - ~40ps resolution per hit per layer

**Future direction:**
**AC-Coupled with Doping Concentration RadHard Compensation**



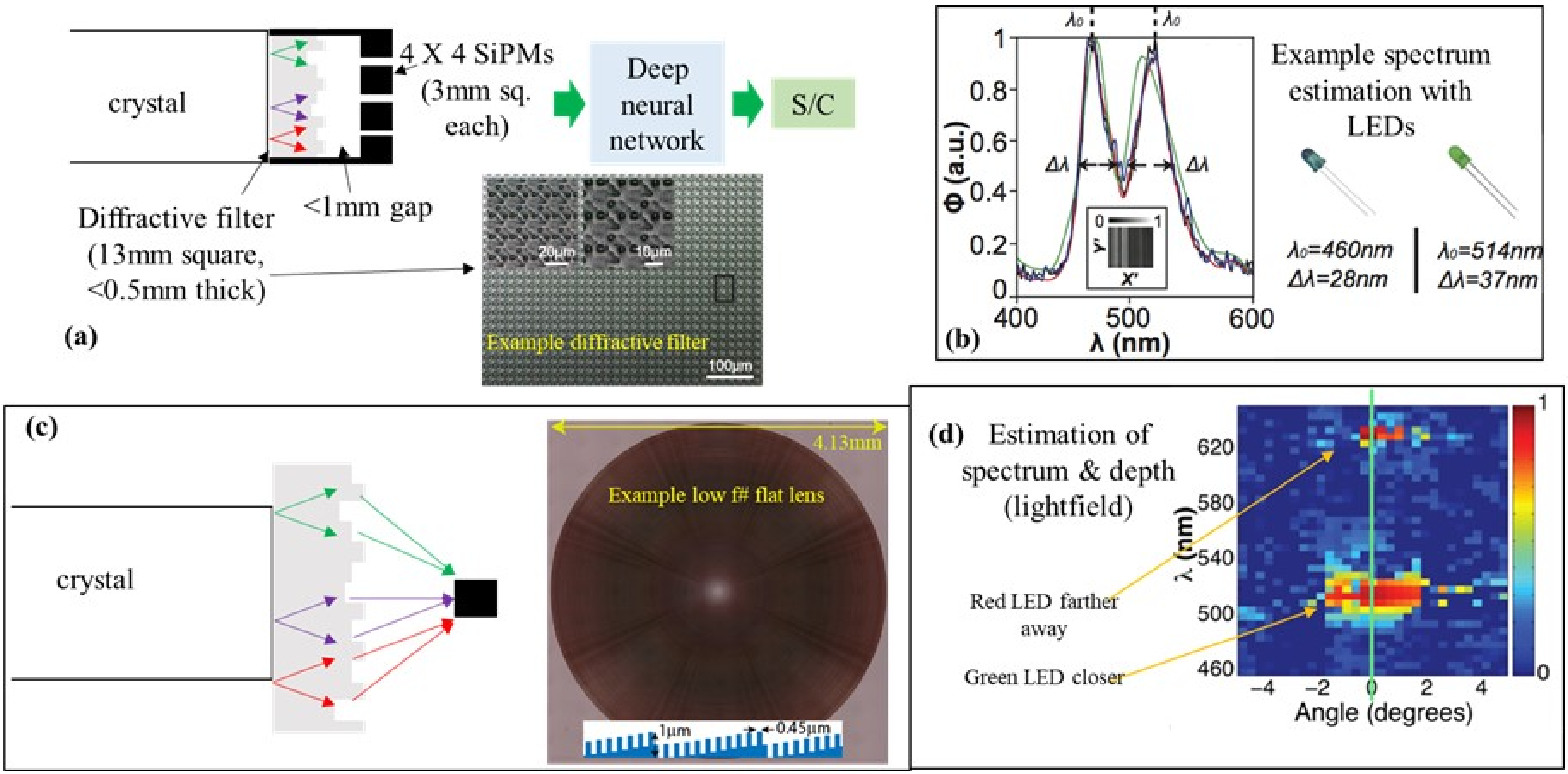
*UFSD4 wafer - Courtesy of FBK*



# Sparks of New Ideas

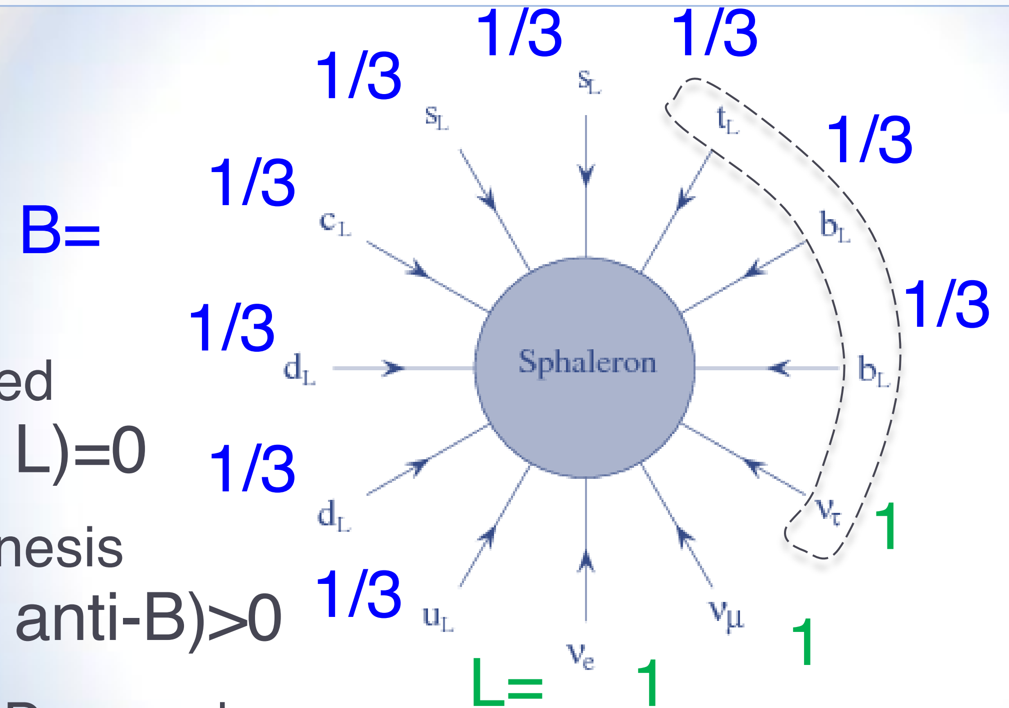
## Dual-Readout Blue Sky R&D

**Look for these from all technologies** (CalVision Proposal, H. Newman)



# 10 TeV has to the potential to observe the "God Process" of matter creation in the Universe

**Sphaleron corresponds to an unstable configuration of fields, which, after a small perturbation, decays to the vacuum by emission of many particles.**




Conserved

Δ(B - L)=0

Baryogenesis

Δ(B - anti-B)>0

Balance Drowned in Relic Neutrinos

Δ(L - anti-L)>0

The sphaleron solution is known explicitly and its energy is

$$E \sim \frac{m_W}{\alpha_W} \sim 9\,TeV$$

$$\begin{pmatrix} u_L^{2/3} \\ \; \end{pmatrix} \begin{pmatrix} \; \\ d_L^{-1/3} \end{pmatrix} \begin{pmatrix} \; \\ d_L^{-1/3} \end{pmatrix} + \begin{pmatrix} \nu_L \\ \; \end{pmatrix}$$

$= 0$

**Major Calo Benchmark: 9 jets and 3 leptons (or neutrinos)**

# Summary

- **Importance of Order of Magnitude Advancement**
  - Sub-nanosecond for every corner of the calorimeter
  - Multi-signal evaluation concurrent with energy measurement
  - Real time-domain information
  - Energy flow in and out of calorimeter cells
  - On detector reconstruction from pulse shapes to multi-signal to regional and event reconstruction – the whole range of fast and precise on-detector evaluation
  - Orders of magnitude in cleanup and robustness against BIB
  - State-of-the-art New ASICs
  - First AI/ML optimized detector

# Final Remarks

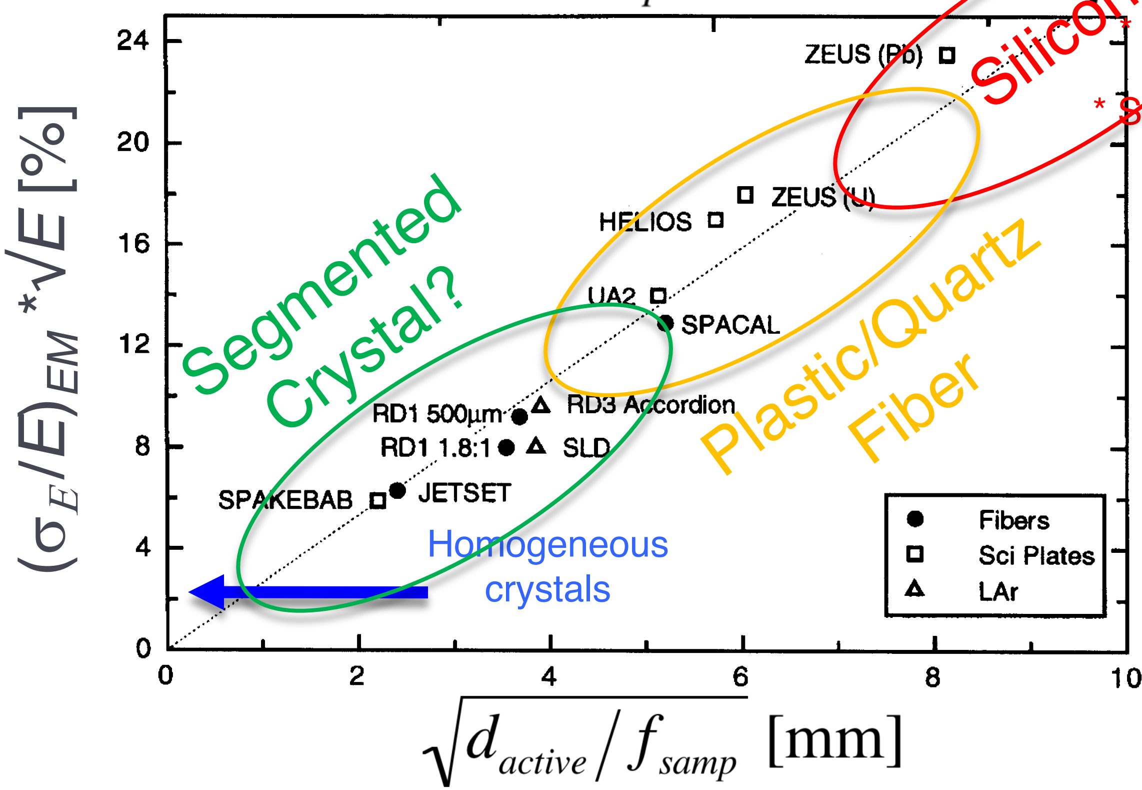
- **Simulation is absolutely central to optimizing the calorimeter in concert with PFA/PID performance**
  - Many options are open, but the software needs to be able to cycle through them and compare
- **Timing layers at ~20-40ps resolution will quickly be indispensable**
- **Physical self-cleaning demonstrator essential as a focus of Detector R&D (CASTOR-table like env)**
- **Calorimeter R&D should continue to be impressing, pushing on ASICs, PID, and novel detector signals** (look for very new ideas)
  - Once even proposed a SQUID sampling array to estimate electron longitudinal polarization from statistical sampling of the EM shower
  - Embedded spatially distributed arrays of entangled coherent states for correlated decoherence signals
  - …

# Additional slides

# Three Regimes of EM Resolution

- **For EM showers in a sampling calorimeter, the energy resolution is dominated by the sampling fluctuations:**

$$(\sigma_E/E)_{EM} \cdot \sqrt{E} \approx (\sigma_E/E)_{samp} \cdot \sqrt{E} = 2.7\% \sqrt{d_{active}/f_{samp}}$$

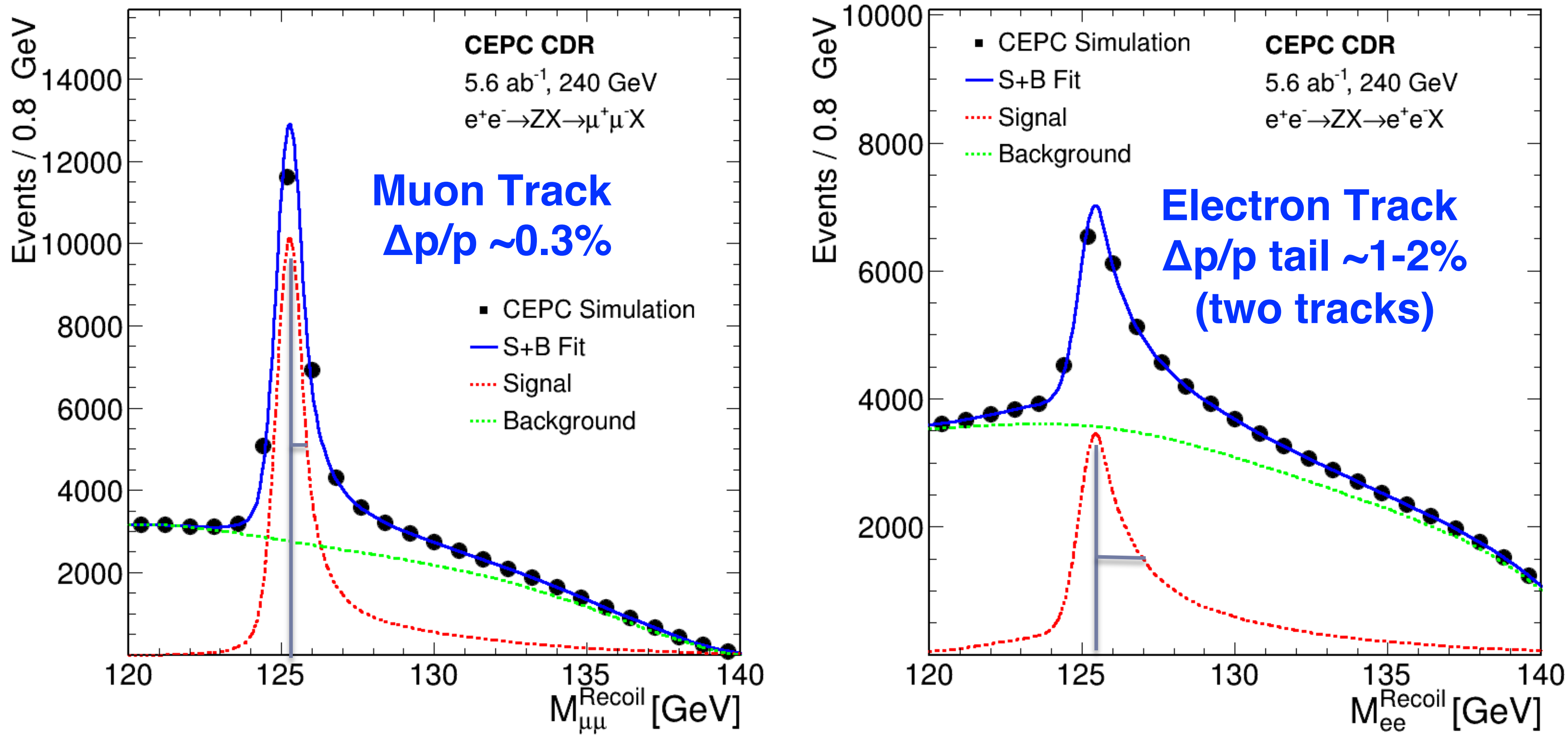



$X_0(Si)/X_0(W)=27$

(Courtesy of R. Wigmans)

# Recoil Analysis – Single Most Important Unbiased Sample of Higgs Boson Decays

- **$Z \rightarrow \mu^+\mu^-$ Recoil**
- **$Z \rightarrow e^+e^-$ Recoil**




Example from CDR reference design
(electron tracks with no Brem. recovery)

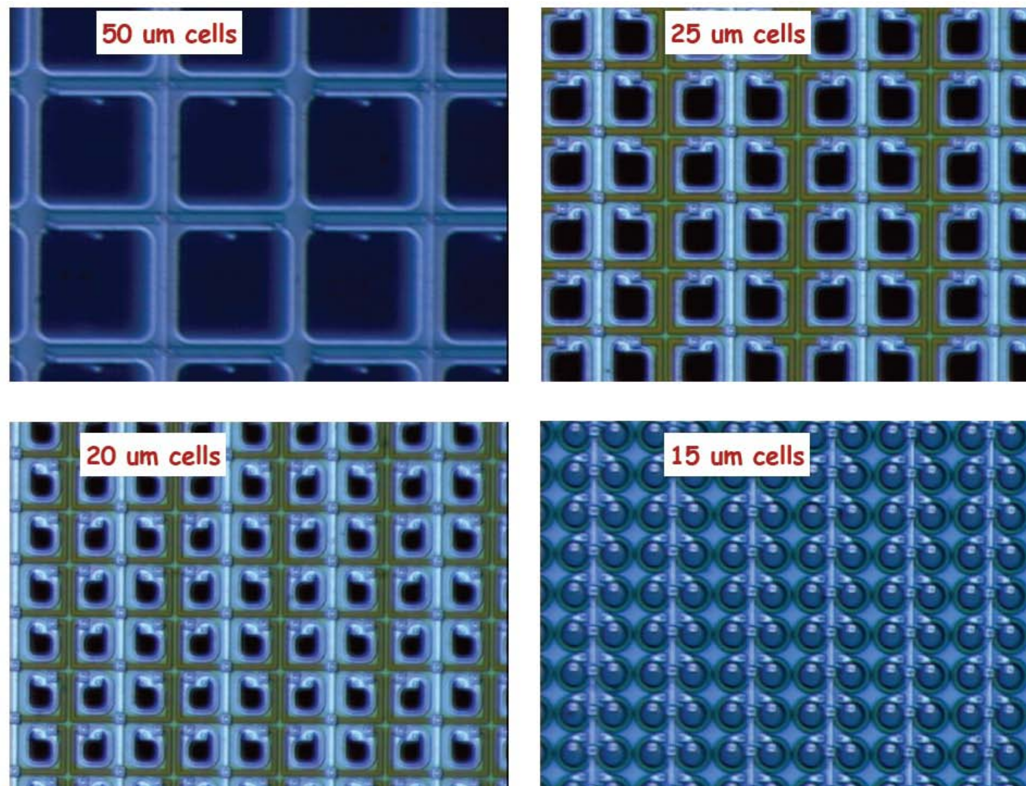
**→ ~80% of Resolution Recovery with 3%/√E**

# Silicon Photomultiplier (SiPM) Cells

- **Typical dynamic range customization for SiPM**
  - More (small) SPADS to count more photons (50→15µm)
  - Bright crystal (LYSO, GAGG) and high photodetection efficiency (PDE) and light collection efficiency (LCE)

Currently:
Large device ~6x6mm$^2$
CMS MTD ~4.5 m$^2$ of SiPMs (of 3x3mm$^2$)

Segmented Crystal ECAL:
~200 m$^2$ of crystal surface (3-4 layers)
Which SiPM device?



# Further Possibilities for SiPMs with High Dynamic Range and Packing Density

- **Large pixel count w/ large gain leads to current output limitations for large area devices**
  - Multiple analog outputs per device
    - Regional lumped analog sums - split output currents per region and sum (1/128, 1/32,1/8,1/2)
    - Multi-gain SPADs (5, 15, 50μm) for different cell sizes and fill factors – dynamic range built into SPAD layout
  - On-chip ADC with regional serializers
  - Commercial market for LIDAR advances is growing rapidly – many new developments expected