September 9, 2020

High Granularity Calorimetry for the ILC

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University of Oregon

Many contributions to this talk from colleagues, especially
J. Barkeloo, L. Braun, M. Breidenbach,
C. Gallagher, C. Potter, A. Steinhebel

ILC Physics

The physics opportunities of the ILC include:

- precision measurement of Higgs boson couplings
- search for exotic modes of Higgs boson decay
- search for dark matter particles and other invisible states
- search for heavy resonances through 2-fermion processes
- precision measurement of the top quark mass
- precision measurement of top quark electroweak couplings
- measurement of the triple Higgs boson coupling
- and more (eg. WW threshold and gigaZ)

Advantage of Higgs Studies at e+e−

Effects of new physics on the Higgs boson are expected to be small, of about a **few-percent at most.**

Typical LHC Higgs boson samples have large backgrounds. Furthermore, not all Higgs decay modes are observed.

At LHC, Higgs couplings are determined in a model-dependent way and precision is limited.

On the otherhand, the very low backgrounds and simple reactions in e^+e^- make higher precision, model-independent measurements feasible, if detectors are capable.

All major decay modes are observed in e^+e^-.

ILC Detector Energy Range

- Center-of-mass energies:
  - 200 GeV up to 1 TeV.
  - Special running at the Z-pole and WW threshold.
  - Higgs Factory, Giga-Z, Top Yukawa couplings, di-boson production, SUSY, other new physics motivated by alternative models.
  - Each physics topic creates a particular set of requirements.
- Detector designs developed for the full energy range.

ILC Experimental Advantages

- Radiation damage is mostly not an issue (except very forward)
  - collisions dominated by electroweak processes
- **Trigger-less operation - record every interaction** (< 6 Gb/sec)
- Bunch train structure allows **pulse power w/ gas cooling**

- Relatively low event rates
- Elementary interactions at known E_{cm} (e.g. $e^+e^- \rightarrow Z\,H$)
- Democratic Cross sections (e.g. $[e^+e^- \rightarrow ZH] \sim 1/2\,[e^+e^- \rightarrow d\bar{d}]$)
- Highly **Polarized Electron Beam** (~ 80% - & positron pol. 30%)
- Tunable center-of-mass energy

- Compared to LHC - trigger-less, ~no pileup, low occupancy, no rad.

- THESE FEATURES ENHANCE PRECISION MEASUREMENTS
- OPPORTUNITY FOR **DETECTOR OPTIMIZATION**

ILC Design Evolution

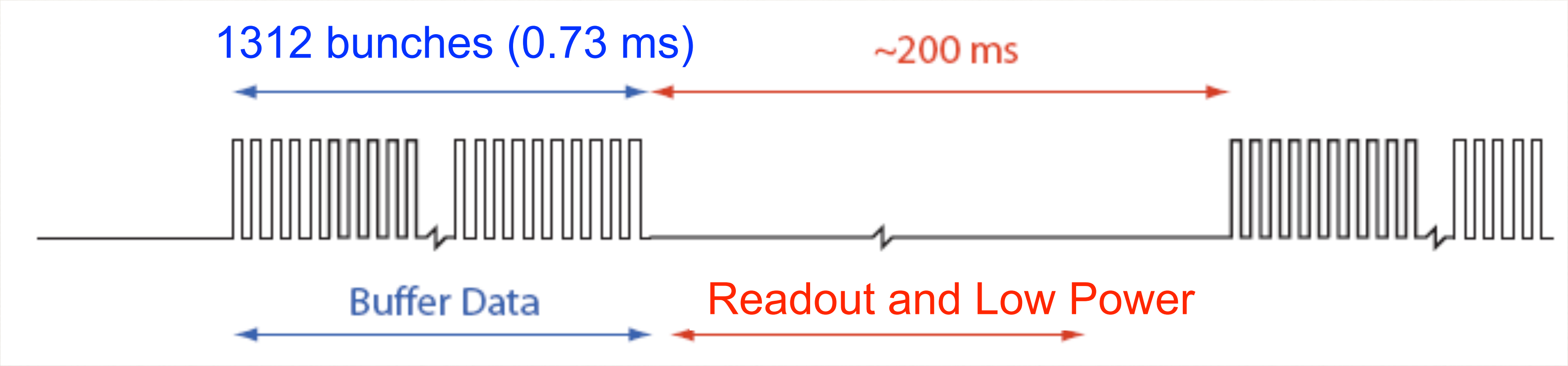
- ILC first designed for initial running at 500 GeV.
  - Technical Design Report.

arXiv:1306.6327 – Volume 1: Executive Summary
arXiv:1306.6352 – Volume 2: Physics
arXiv:1306.6353 – Volume 3.I: Accelerator R&D in the Technical Design Phase
arXiv:1306.6328 – Volume 3.II: Accelerator Baseline Design
arXiv:1306.6329 – Volume 4: Detectors

- Now, ILC250 proposed as first-stage with primary motivation to study Higgs-strahlung.
  - Many studies at 500 GeV - conditions milder at 250 GeV, but expect to eventually operate at 500 GeV, even higher.

ILC Beam Structure

- Beam structure important consideration in detector optimization.
- Bunch trains at 5 Hz.
- 1312 bunches / train in first-stage (ILC250)



- Duty cycle < 1%
- Average low power achieved by **power pulsing** during readout (also requires quiescent currents). Minimizes passive material and space.

Physics Drives Detector Requirements

Clean events with low backgrounds motivate unprecedented detector performance

Physics Process	Measured Quantity	Critical	Critical Detector	Required Performance
$H \to b\bar{b}, c\bar{c}, gg, \tau\tau$ $b\bar{b}$	Higgs branchin b quark charge			$\delta_b \sim 5\mu m \oplus 10\mu m/(p\sin^{3/2}\theta)$
ZH→$\ell^+\ell^-$X $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu} \to \mu^+\mu^- X$	Higgs Recoil M Lumin Weight BR (H →μμ)			$\sigma(p_t)/p_t^2 \sim few \times 10^{-5} GeV^{-1}$
ZHH $ZH \to q\bar{q}b\bar{b}$ ZH→ZWW* $\nu\bar{\nu}W^+W^-$	Triple Higgs C Higgs Mass BR (H → WW σ(e+e- → νν W+W-)			~3% for $E_{jet} > 100$ GeV $30\%/\sqrt{E_{jet}}$ for $E_{jet} < 100$ GeV
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum resolution, Hermiticity ⇒ Event Reconstruction	Maximal solid angle coverage

MOTIVATION FOR:
High granularity,
dense integration,
super light materials,
low power,
air cooling,
power pulsing

High granularity, dense integration, super light materials, low power, air cooling, power pulsing

Main ILC Detector Requirements

- Two-jet mass resolution comparable to the natural widths of W and Z for an unambiguous identification of the final states.
- Excellent flavor-tagging efficiency and purity (for both b- and c-quarks, and hopefully also for s-quarks).
- Momentum resolution capable of reconstructing the recoil-mass to di-muons in Higgs-strahlung with resolution better than beam-energy spread. Provides input to Particle Flow Calorimetry.
- Hermeticity (both crack-less and coverage to very forward angles) to precisely determine the missing momentum.
- Timing resolution capable of separating bunch-crossings to suppress overlapping of events .

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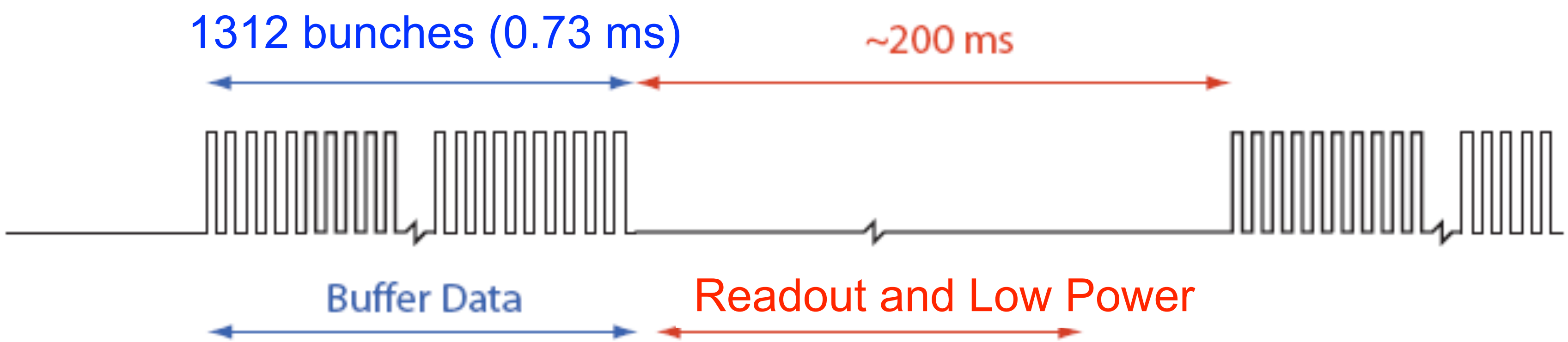

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- Two-j
  and Z
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- **Herm**
  angle
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- **Two-jet mas**
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  quarks, and
- Momentum
  di-muons in
  energy sprea
- **Hermeticity**
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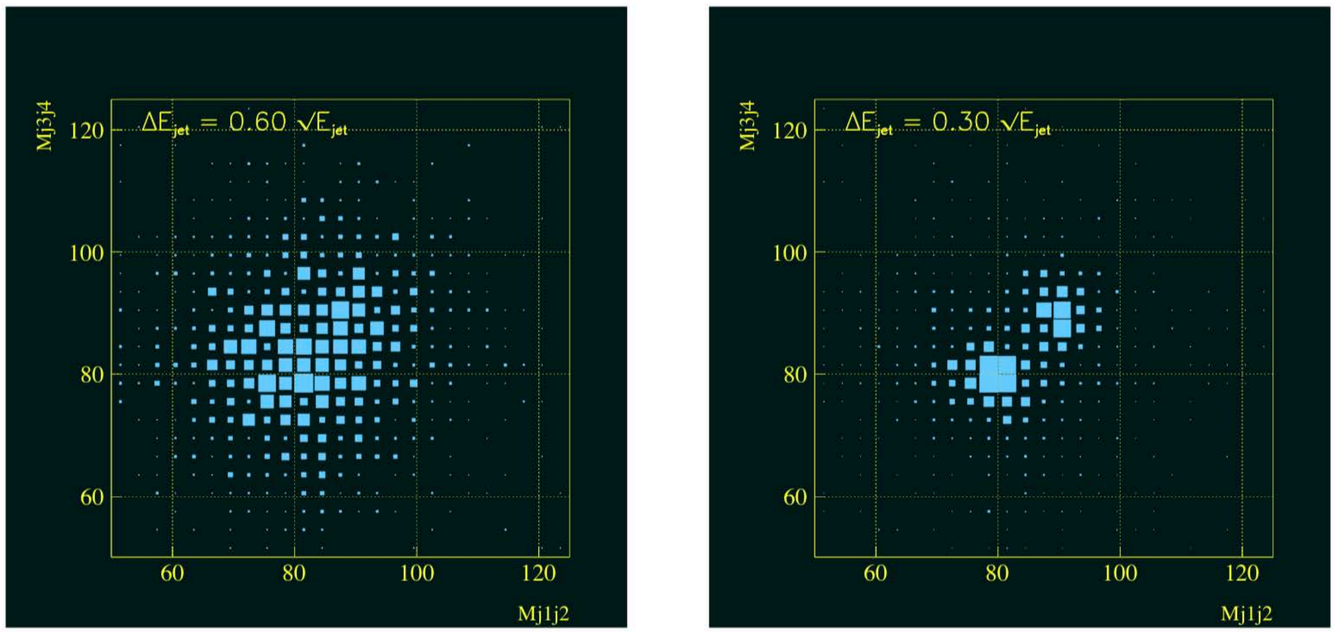
- **Timing reso**
  suppress ov

- Separate W&Z di-jet events.
- For 100 GeV jet - 3% resolution needed.

$$e^+e^- \rightarrow WW\nu\bar{\nu} \quad , \quad e^+e^- \rightarrow ZZ\nu\bar{\nu}$$



Brient & Videau, arXiv:0202004

Requirements Achieved in ILC Designs

- Clean events with low backgrounds enable unprecedented detector performance motivated by physics goals.
  - High granularity
  - Dense integration
  - Super light materials
  - Low/pulse power
  - Air cooling

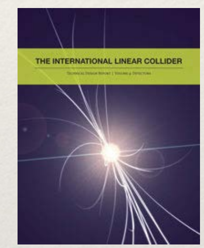
Documented and refined:

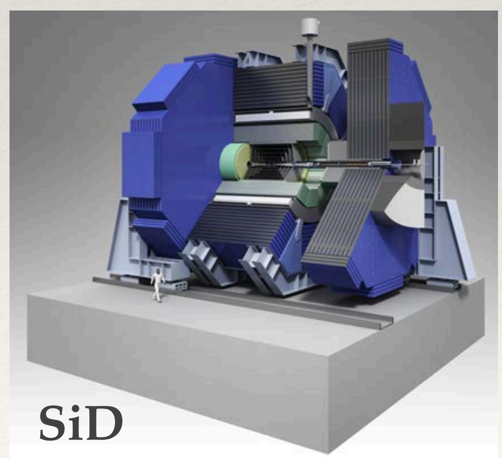
Reference Design Report - 2007
  arXiv:0712.2356

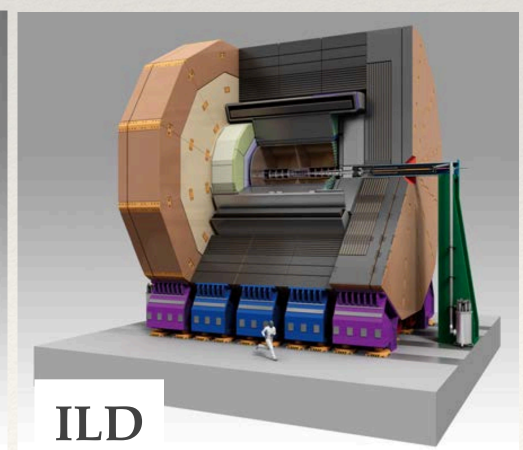
Leter of Intent to IDAG- 2009
  arXiv:0911.0006

Technical Design Report - 2013
  arXiv:1306.6329

Recent updates:
  arXiv:1903.01629, 1912.04601

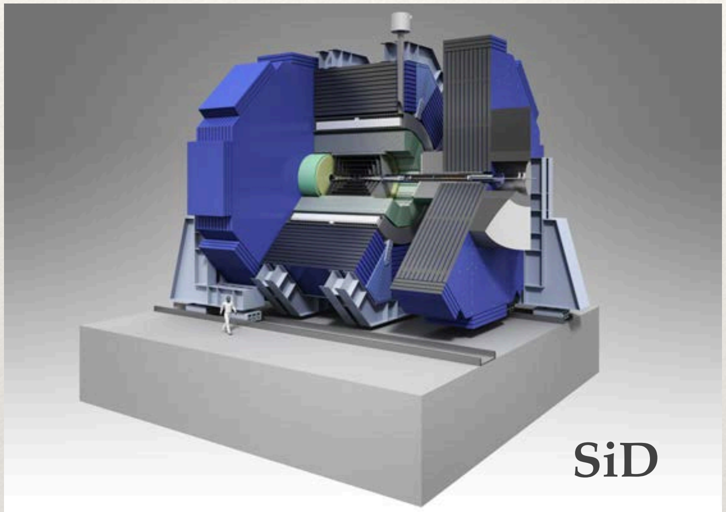


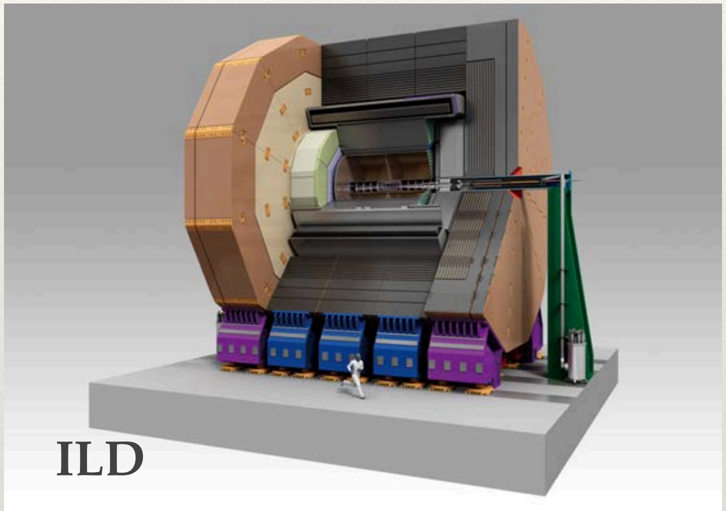




ILC Detectors

- Two Validated detector concepts.
- Complementary: tracking technology, magnetic field, calorimetry, etc.





SiD		ILD
Silicon	Tracking	TPC w/ silicon
6.0 m	Outer Radius	7.8 m
5 Tesla	B Field	3.5 Tesla

Design Goals: High efficiency
High resolution
Low fake rate
Control of systematics

Both employ particle flow calorimetry

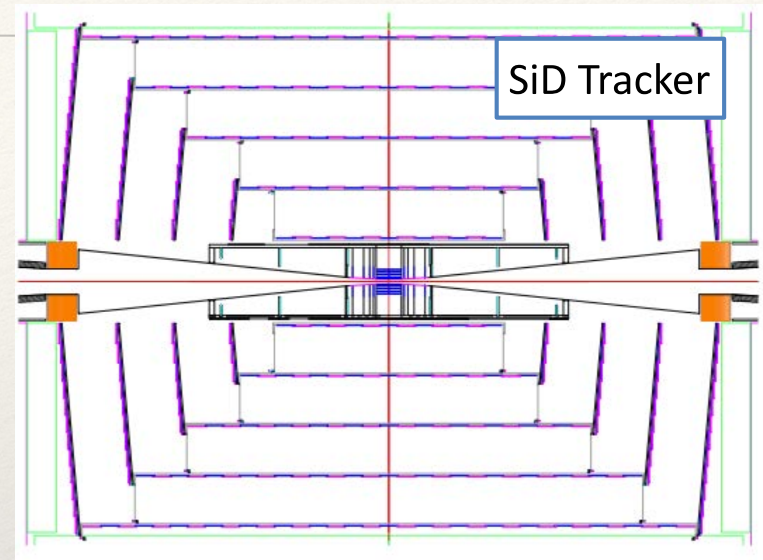
Particle Flow Depends on Tracking

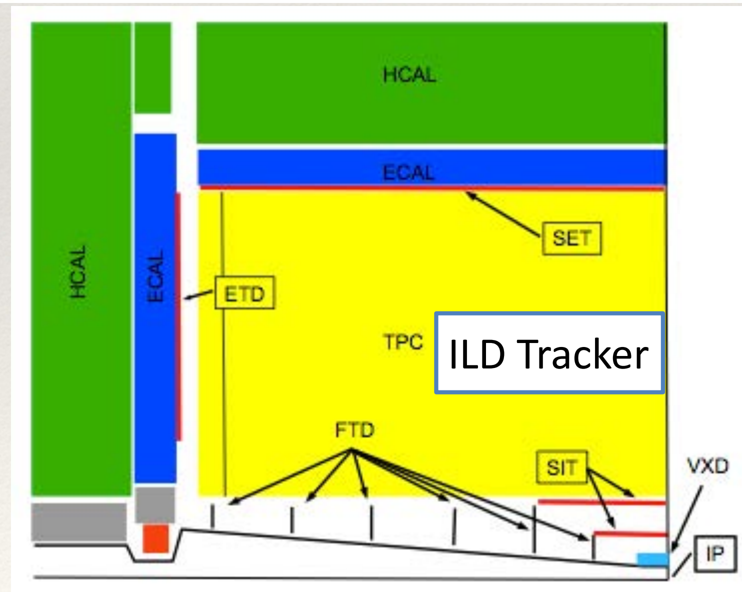
- Concepts use large BR^2/σ to achieve required very good momentum resolution:

$$\sigma\left(\frac{1}{p_T}\right) \leq 5\times10^{-5}\ (GeV^{-1})$$

- Silicon Tracking (SiD) - strips
  - 5 barrel layers, 4 forward disks
  - 1.2 m outer radius
  - Pixels being considered
  - B = 5T

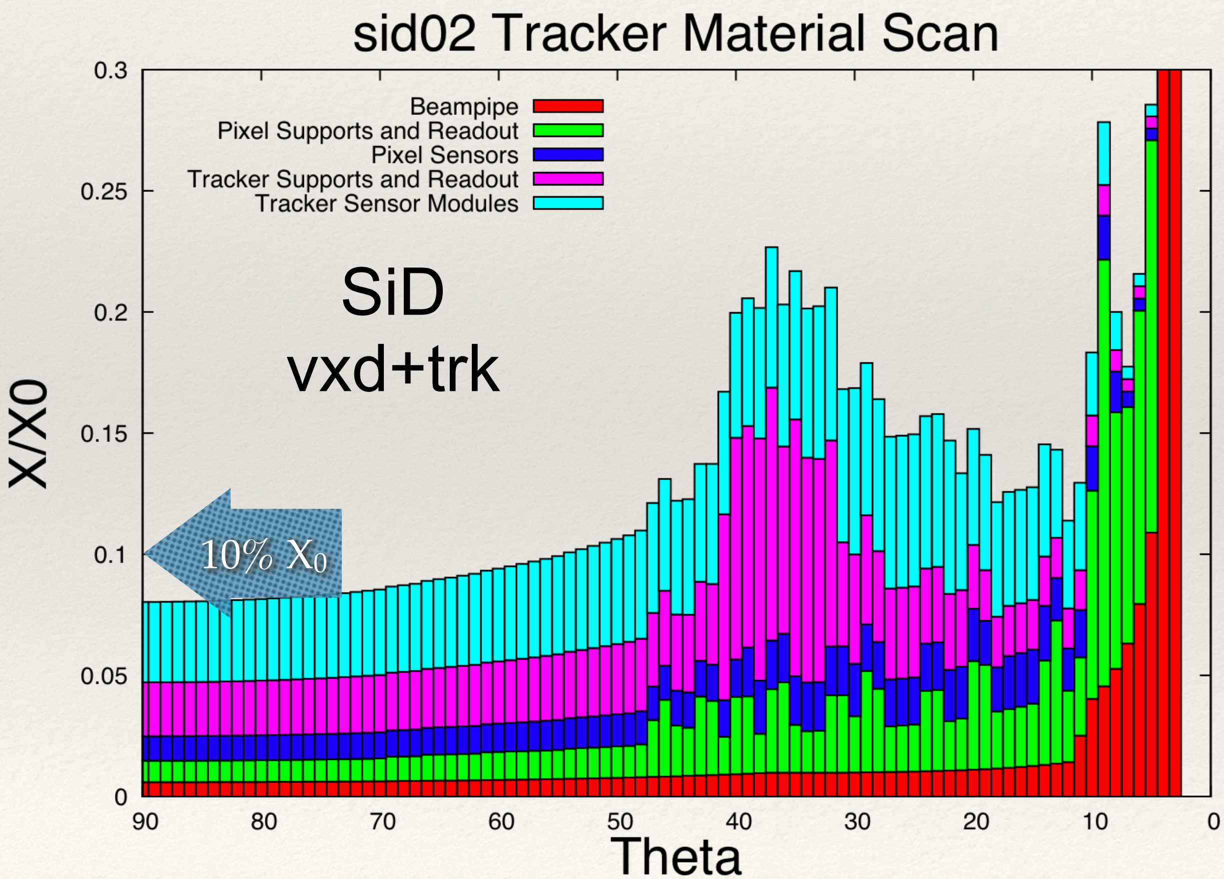
- TPC with silicon (ILD)
  - up to 228 hits per track
  - 1.8 m outer radius
  - B = 3.5 T

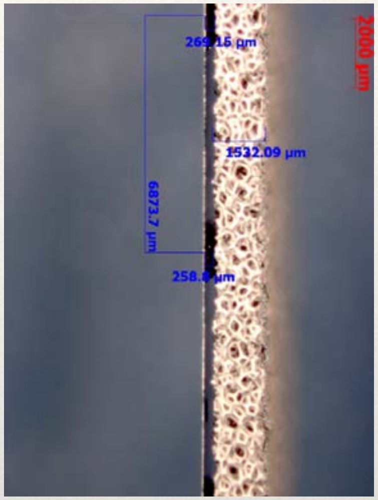




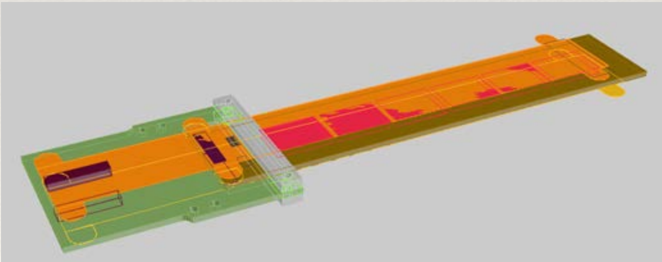
Silicon tracking w/ gas cooling → Low material

- Linkage between readout/mechanics/powering/cooling studies.
- Maintain low mass construction.
- Tracking material from SiD design:

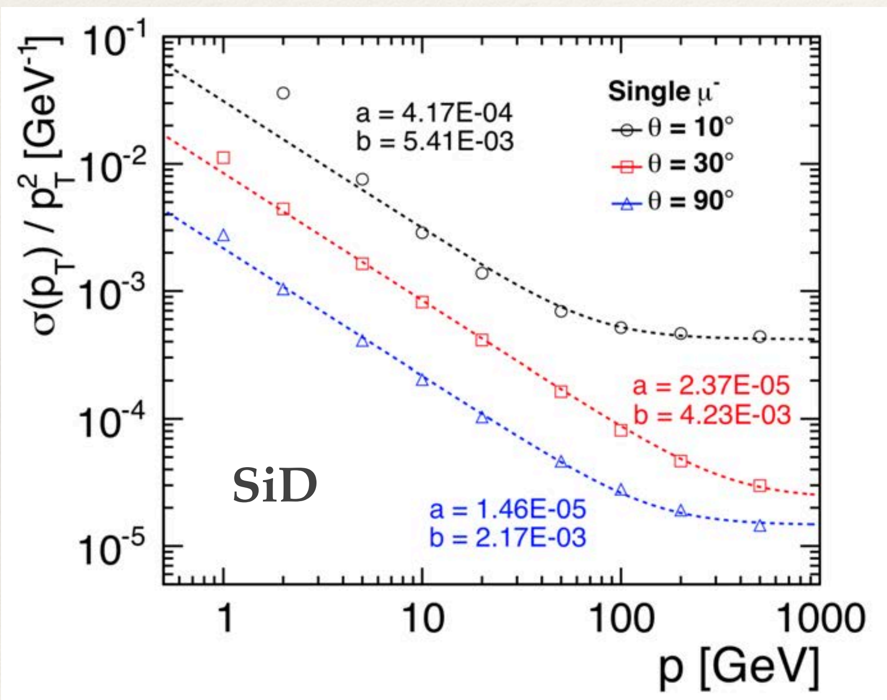


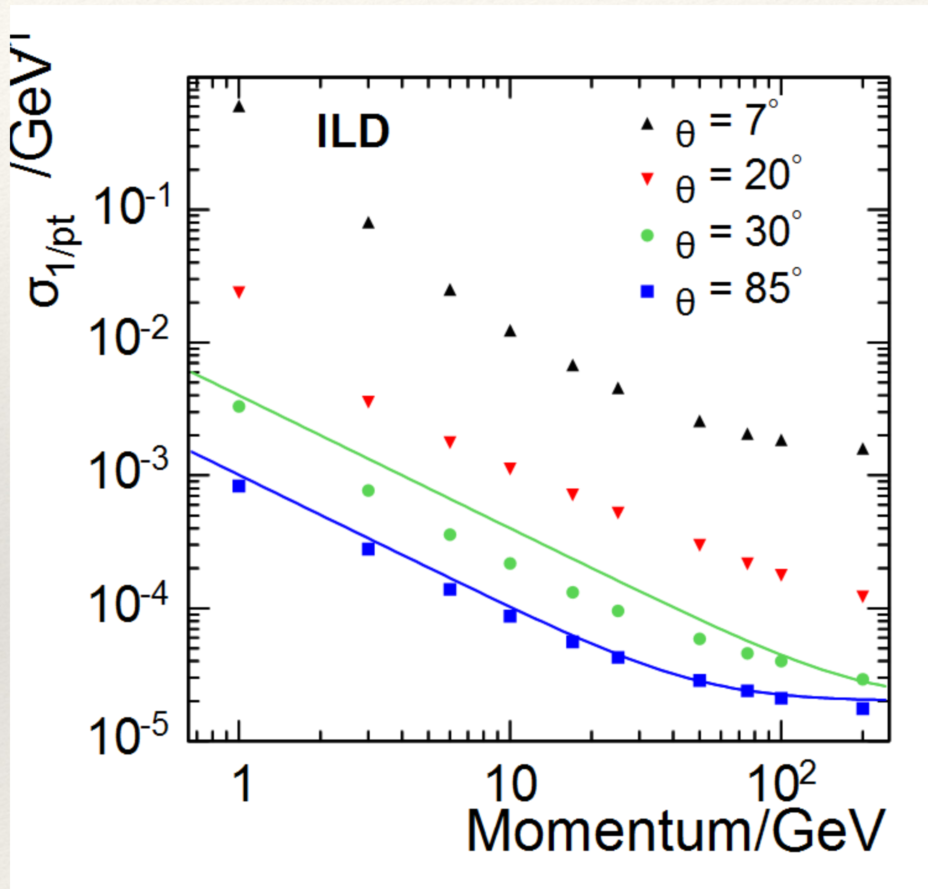


SiC foam,
J. Goldstein



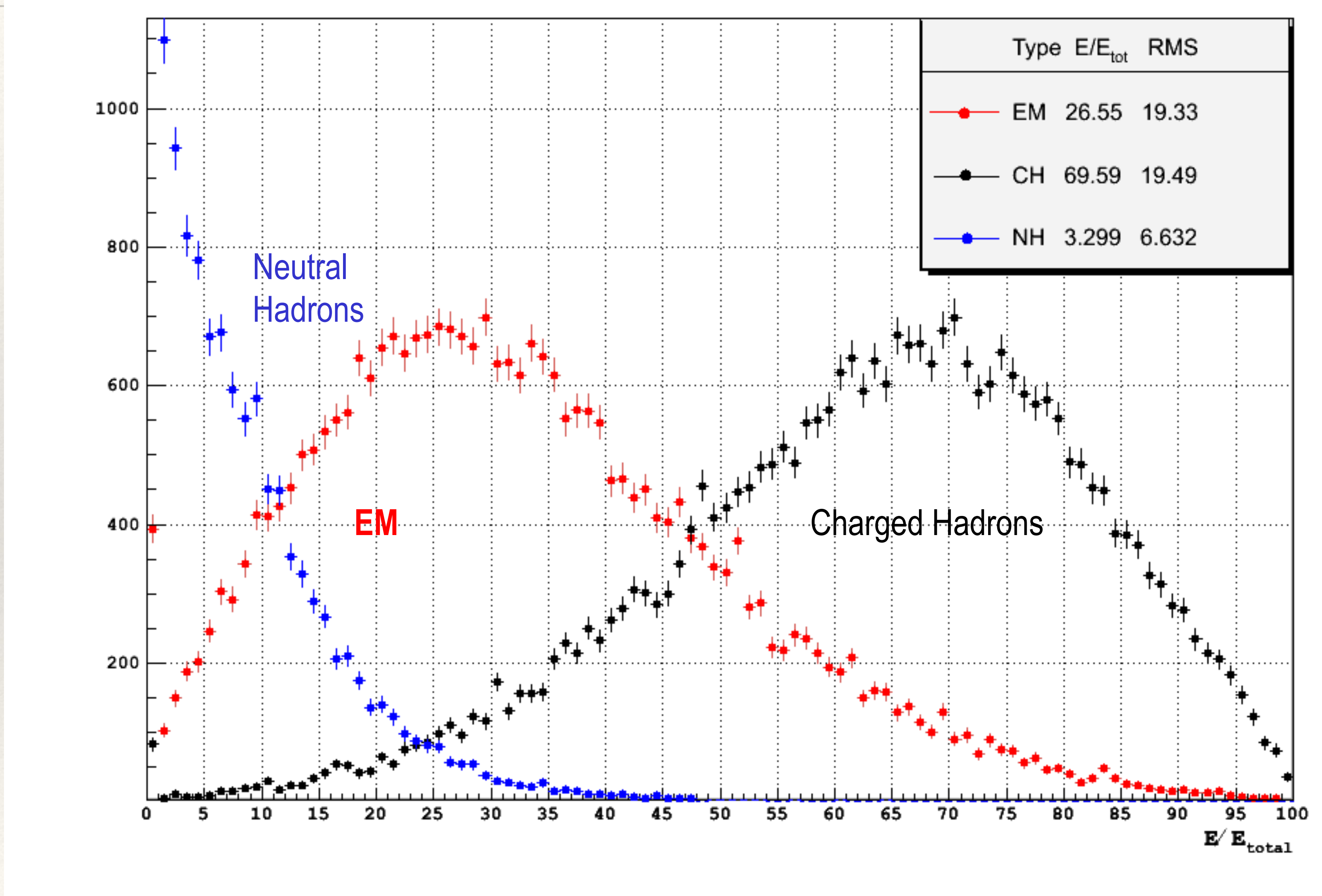
Tracking Performance starts PFA





arXiv:1306.6329

Typical Jet Fractions



ILC Calorimetry

- Typical hadronic jet energy
  - charged hadrons ~65%
  - photons ~25%
  - neutral hadrons ~10%

- Special conditions of ILC motivates particle flow approach for improved jet resolution (~3%) over traditional calorimetry. (inside coil).

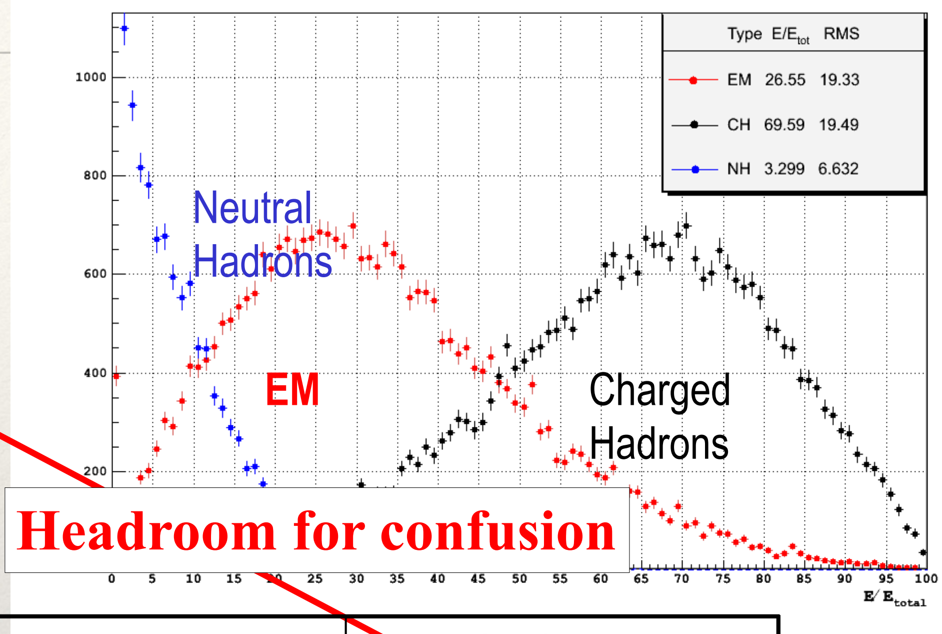
  - **Particle Flow (both validated detectors, ILD and SiD)**
    - use tracker momentum measurement
    - highly granular particle calorimeters to add neutral energy (EM + Had)

- Forward calorimeters (specialized) also needed
  - Measure luminosity via small angle Bhabha scattering
  - Provide fast feedback to machine via beamstrahlung remnants
    - in a higher radiation environment

Jet Energy Measurement via Particle Flow

Particle Flow:

- Jet resolution goal is 3-4% above 100 GeV
- In jet measurements, use the excellent resolution of tracker, which measures bulk of the energy in a jet
- Requires high granularity in calorimeter $\Rightarrow \sim 10^8$ cells



Particles in Jet	Fraction of Visible Energy	Detector	Resolution
Charged	~65-70%	Tracker	< 0.005% p_T negligible
Photons	~25-30%	ECAL	~ 15% / √E
Neutral Hadrons	~5-10%	ECAL + HCAL	~ 60% / √E

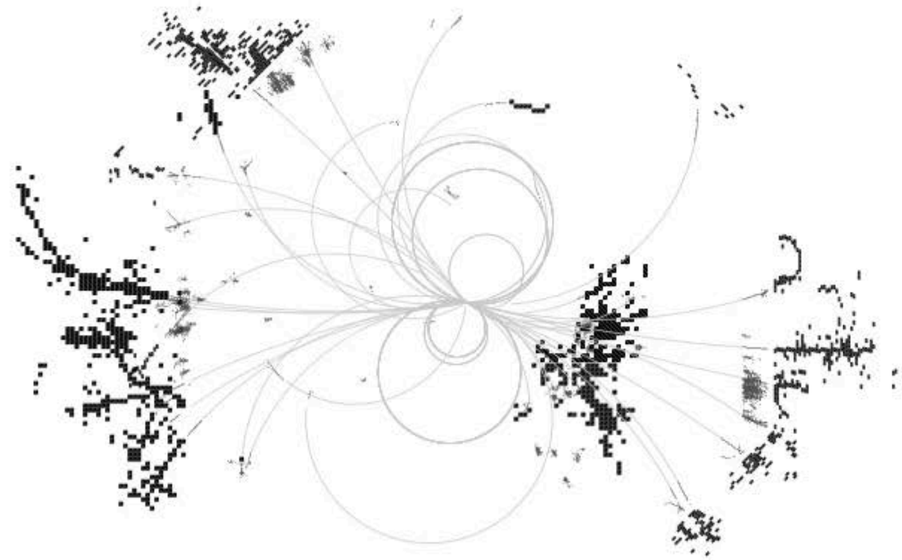
< 2% @ 100 GeV

Testing PFA Concept w/ Pandora

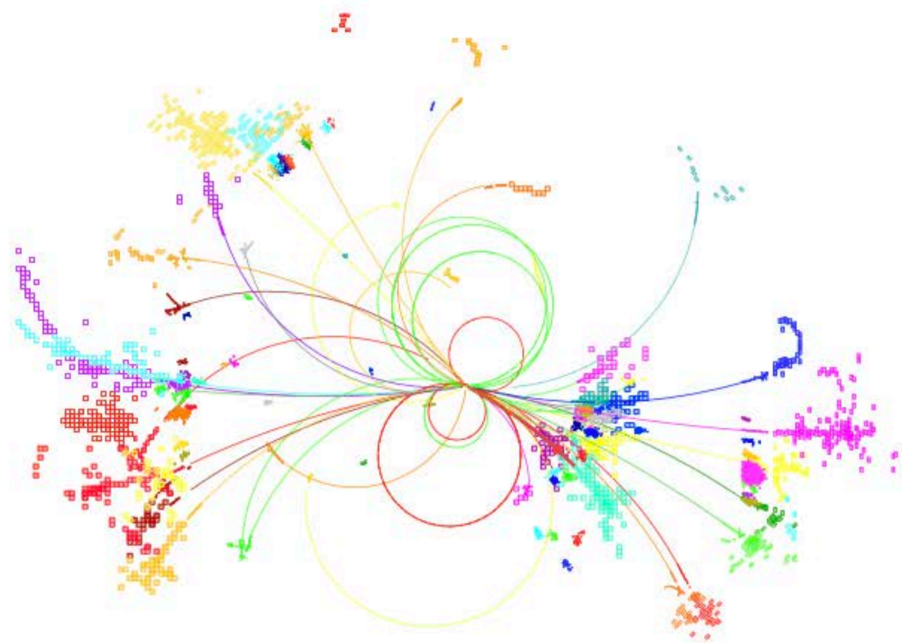
- Pattern recognition for particle flow calorimetry implementation for the ILC.
- Exploiting the fine granularity detectors.
- Reconstructs paths of individual visible particles.
- Identification of trajectories allows particle four-momenta from subdetector with best measurements.
- Unprecedented jet energy resolution.

- J. S. Marshall and M. A. Thomson, Eur. Phys. J. C75, 439 (2015), arXiv:1506.05348.

Four jet event at CLIC.



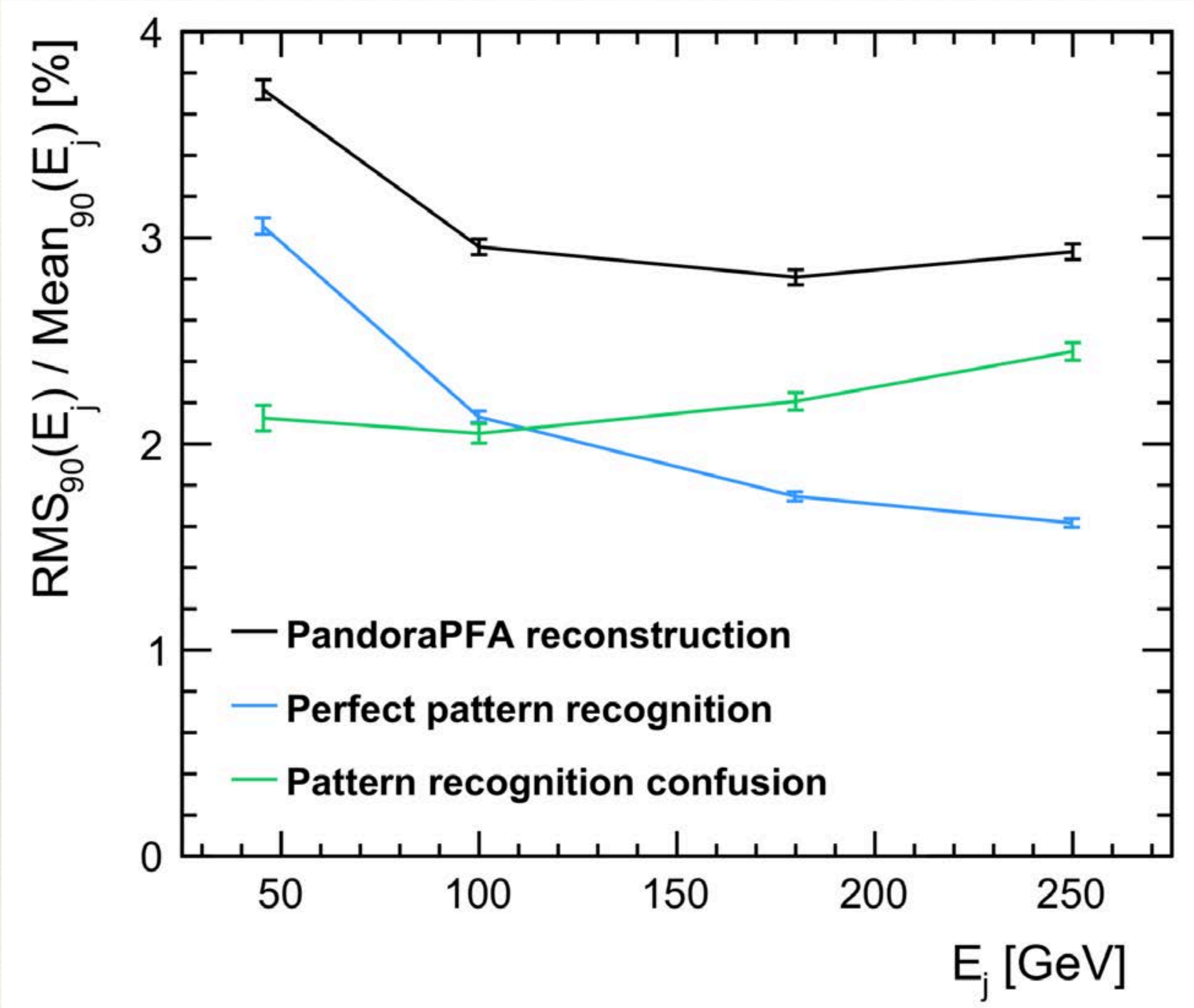
(a) Tracks and CaloHits.

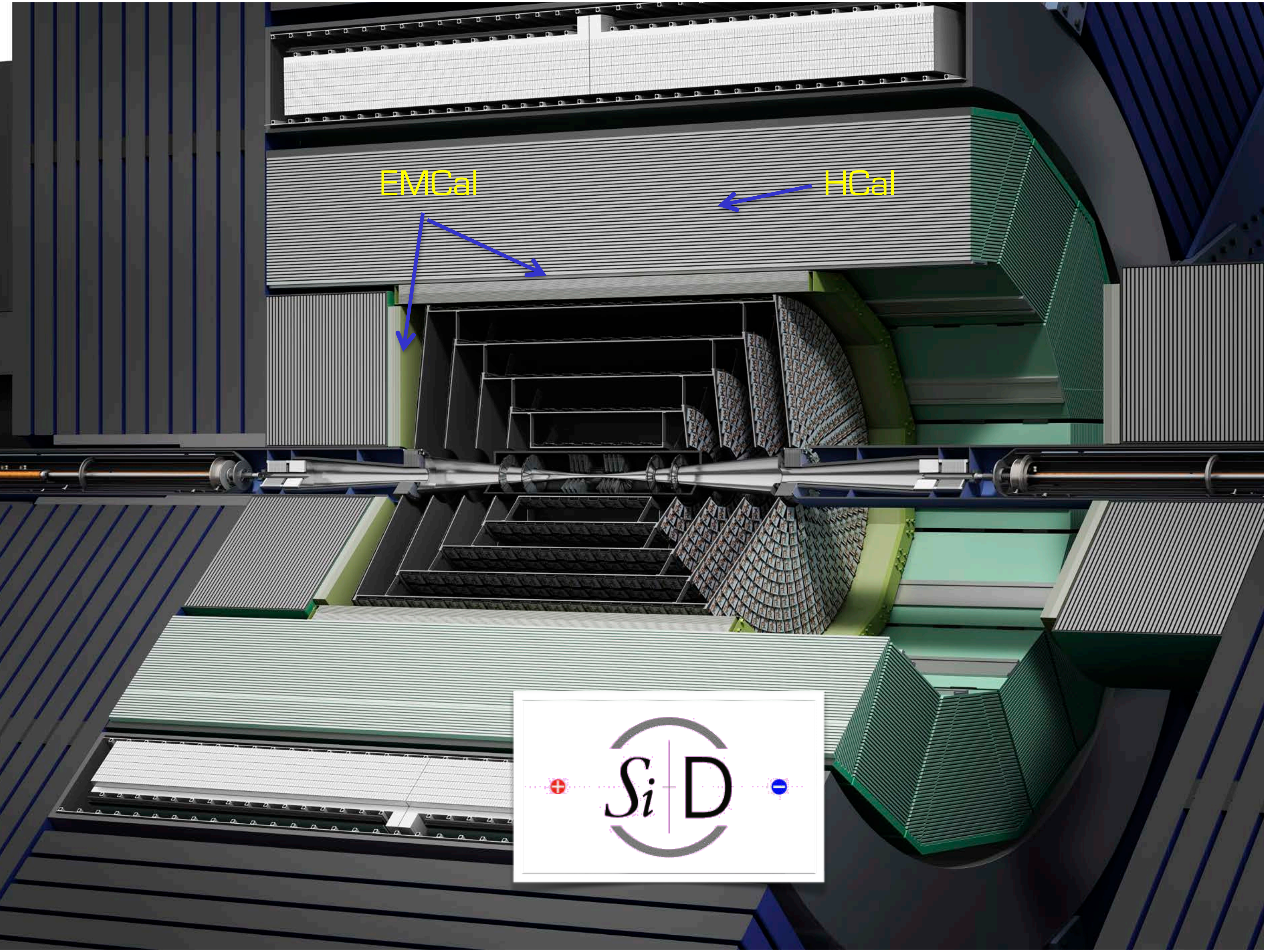


(b) Output PFOs.

PFA Jet Energy Resolution

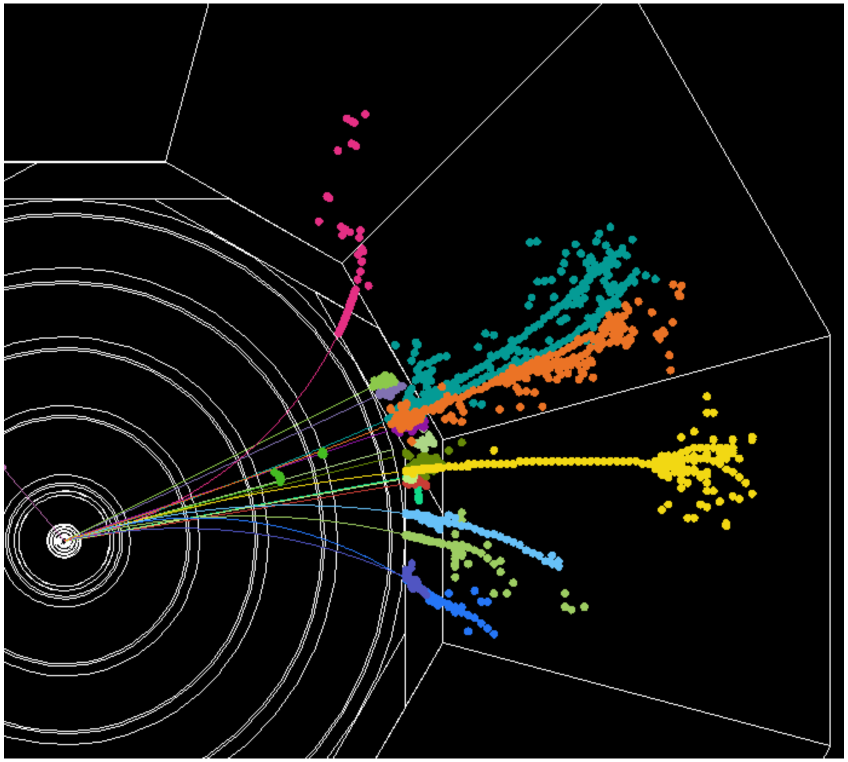
- Jet energy resolution (in %) for Z′ events as a function of jet energy in a realistic detector PandoraPFA.
- Also shown are effects of confusion and result assuming perfect PFA.
- J. S. Marshall and M. A. Thomson, Eur. Phys. J. C75, 439 (2015), arXiv:1506.05348.




EMCal
HCal
SiD

Calorimetry- Optimized for Particle Flow
Cost constrained!

- SiD Silicon-Tungsten ECAL
  - Tungsten absorber
  - 20 "thin"+10 "thick" layers
  - 20 x 0.64 X_0 + 10 x 1.3 X_0
    ~26 X_0
  - Baseline Readout
    - 13 mm^2 silicon pads
    - KPiX 1024 channel system bump bonded directly to large Si Sensors



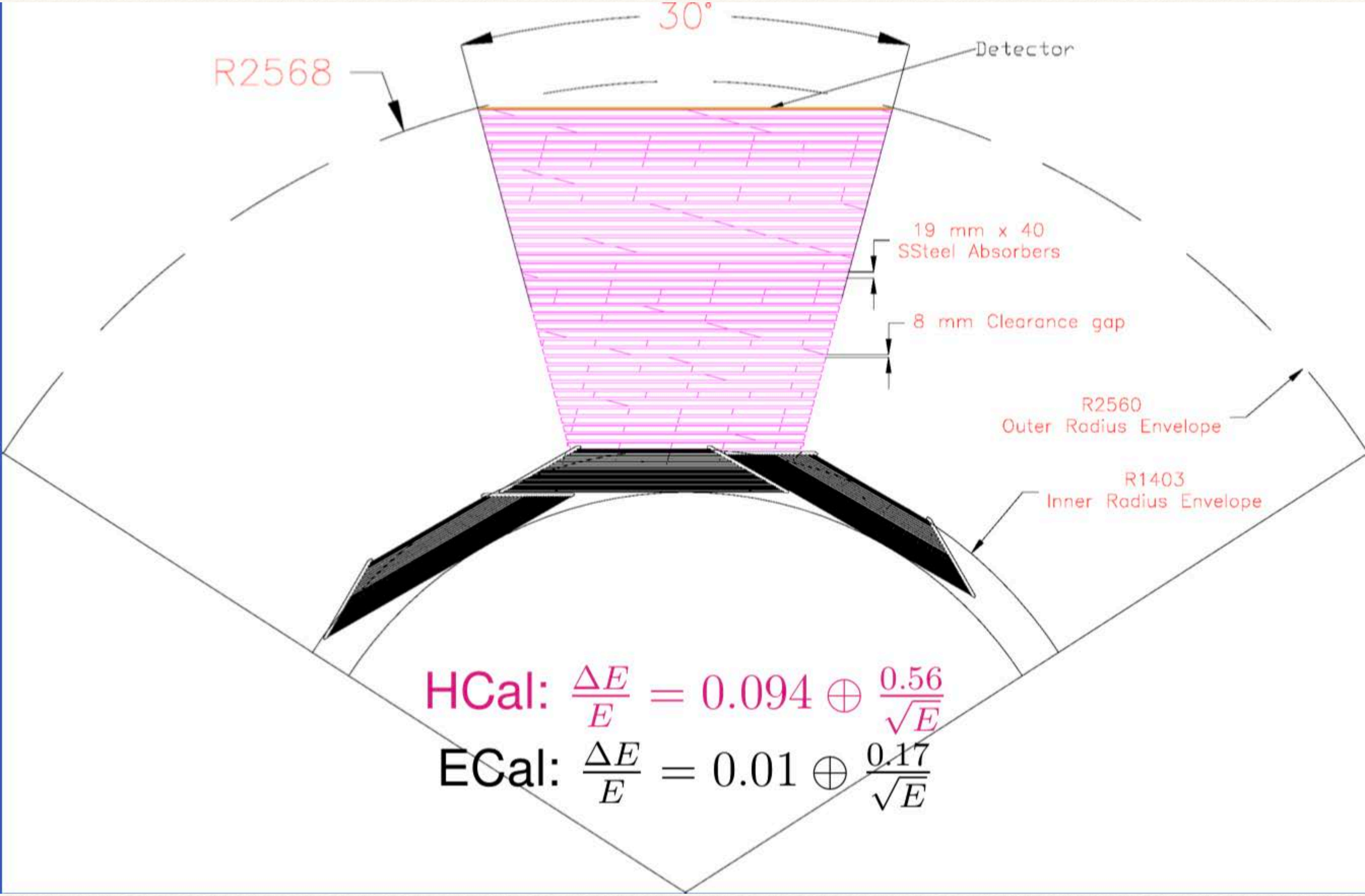
- SiD HCAL
  - 40 layers steel absorber (4.5 λ)
  - Proposed Readout
    - 3x3 cm scintillator w/ SiPM's

Particle flow significantly improves jets resolution by reducing contribution of hadron calorimeter resolution.

SiD ECal

- Measure energy of photons (~25% of jet energy)
- Identify charged tracks depositions in calorimeter by matching tracks with calorimeter depositions
- Measure initial depositions of neutral hadron interactions

- Each of these requirements done independently rely on high granularity to separate processes
    - Transverse spreading of showers (scaling with Moliere radius) compromises granularity

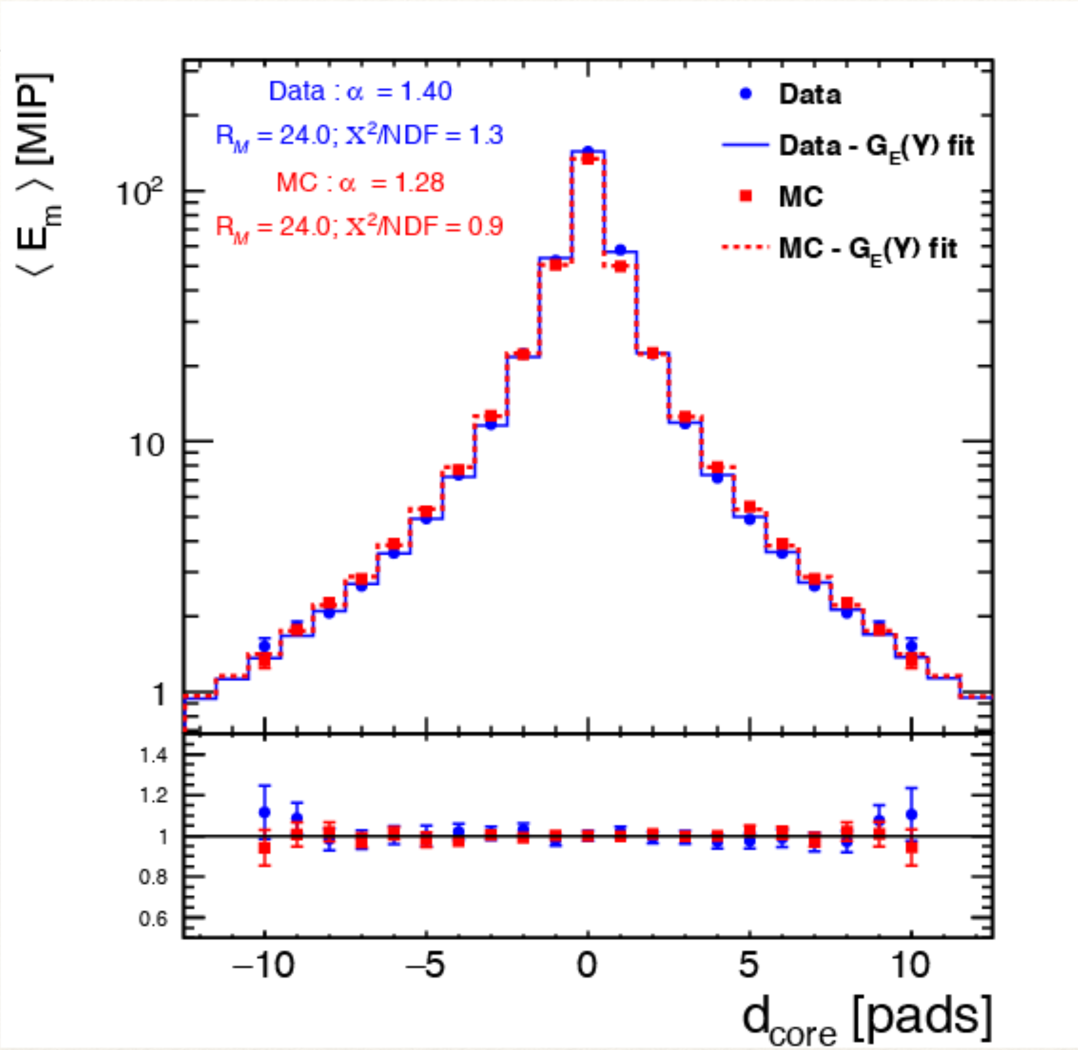


HCal: $\frac{\Delta E}{E} = 0.094 \oplus \frac{0.56}{\sqrt{E}}$

ECal: $\frac{\Delta E}{E} = 0.01 \oplus \frac{0.17}{\sqrt{E}}$

Transverse EM Shower Development Important

- Separation of "particles" in ECal depends on transverse shower profile
- Recent LumiCal beam test
  - 4 layers
  - 2 x 3.5 mm W
  - W/Si every 13.5 mm
  - Only instrumented four layers
- Measured R_M = 24 mm
  - Note: $R_M(W)$ = 9.3 mm

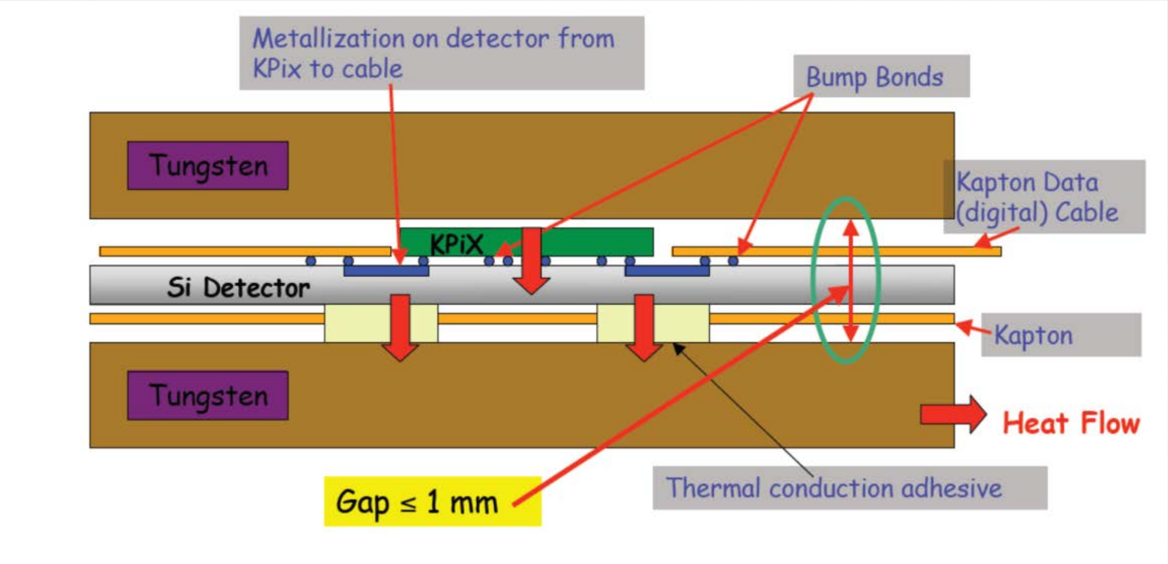


H. Abramowicz et al., Eur. Phys. J. C 78 (2018) 135

Transverse EM Shower Development

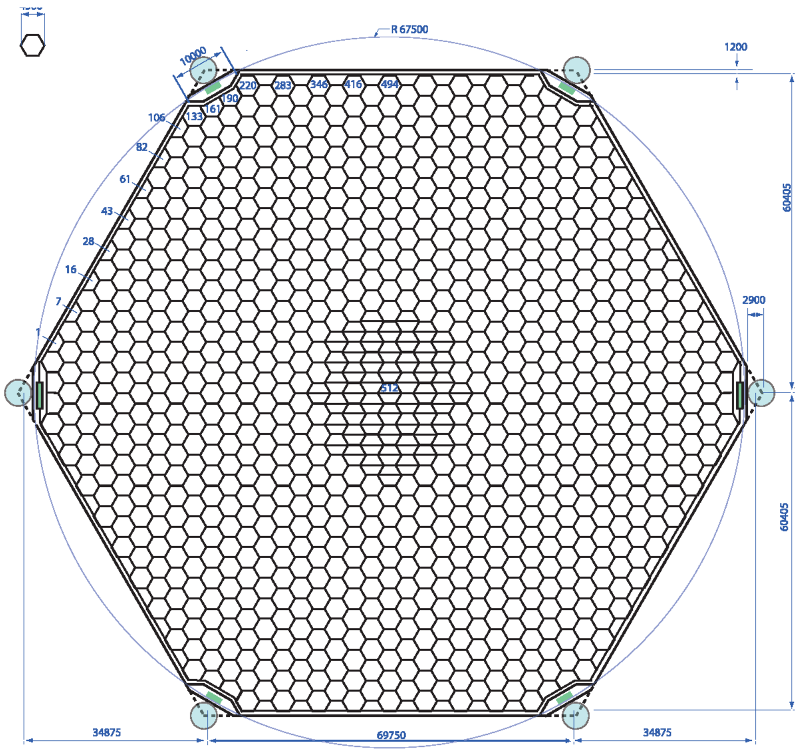
- Transverse shower development, and multiple “track” confusion, contained by maintaining small Moliere radius.

	LumiCal	Wide gap	Narrow gap	No gap
W(mm)	7	2.5	2.5	2.5
gap(mm)	6.5	2.5	1.0	0
R_M(cm)	2.4	1.86 †	1.30 †	0.93 †
	† Assumes pure W. Detail depends on alloy.			

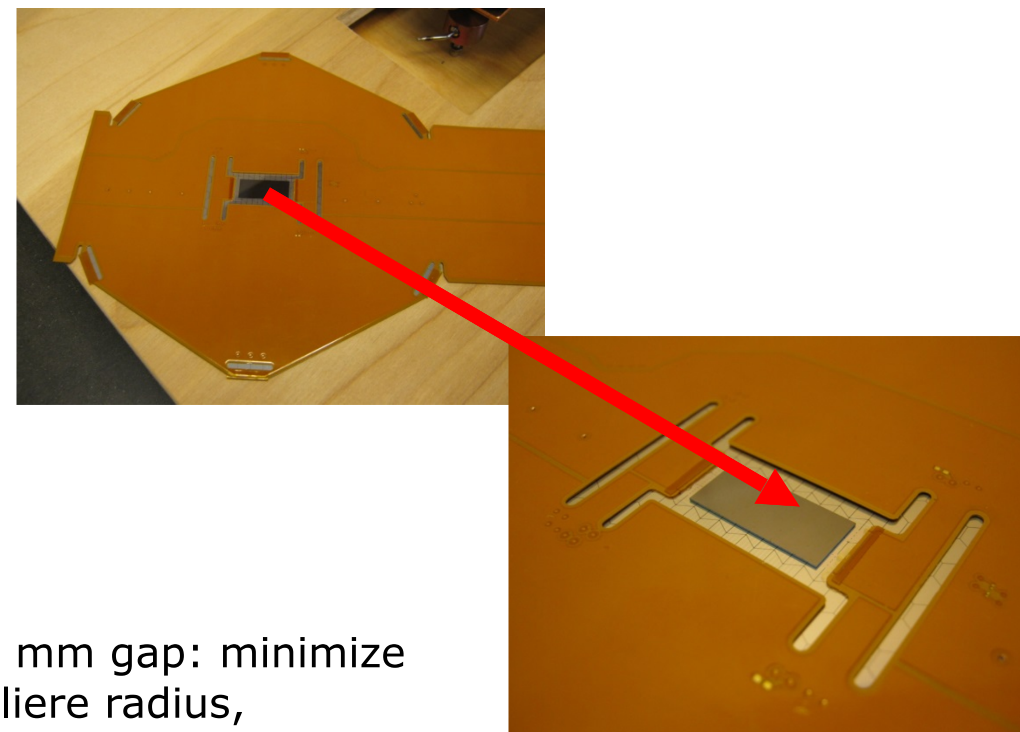


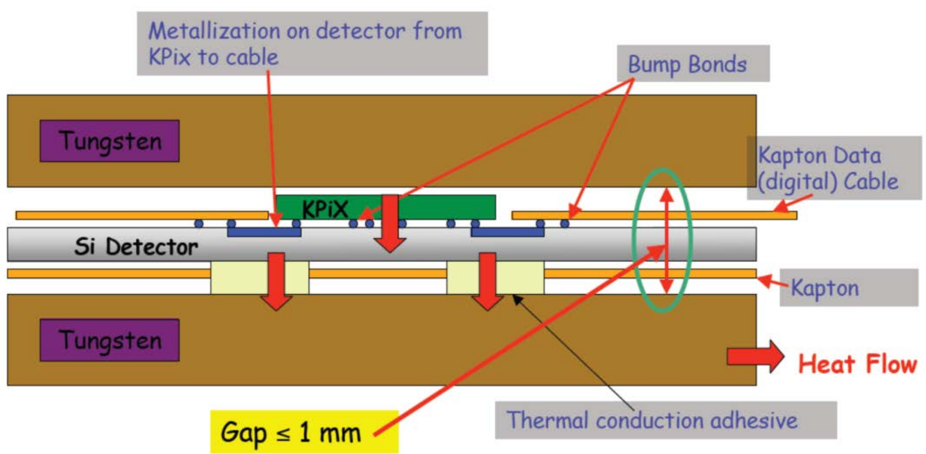
LumiCal from
H. Abramowicz et al.,
Eur. Phys. J. C 78 (2018) 135

Silicon sensors and KPiX ASIC



- 6 inch wafers, 1024 13 mm² pixels
- One 1024 channel KPiX ASIC on each wafer
- KPiX readout is bump-bonded directly to sensor

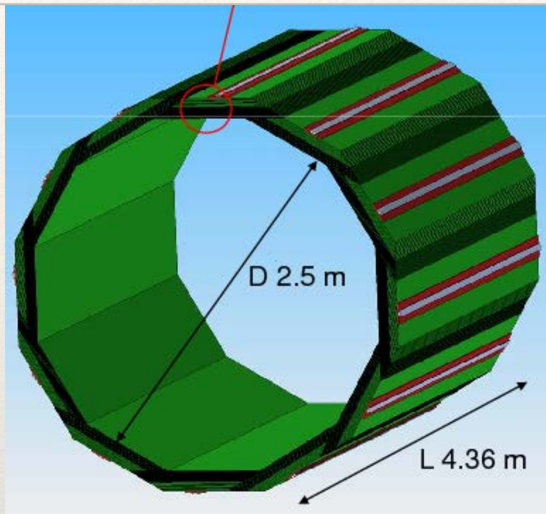


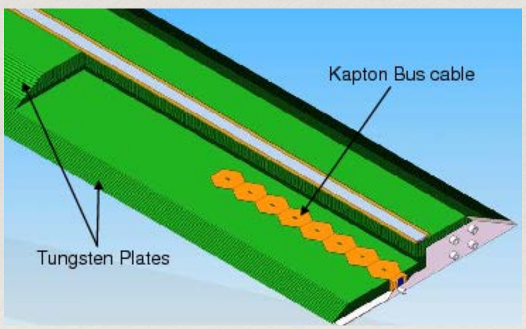


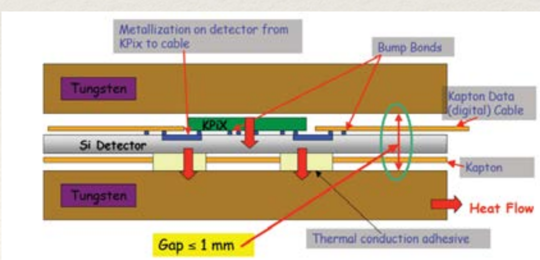
~1 mm gap: minimize Moliere radius, keep calorimeter compact

Tungsten plates thermal bridge to cooling on edge

Silicon-tungsten ECal - very high granularity

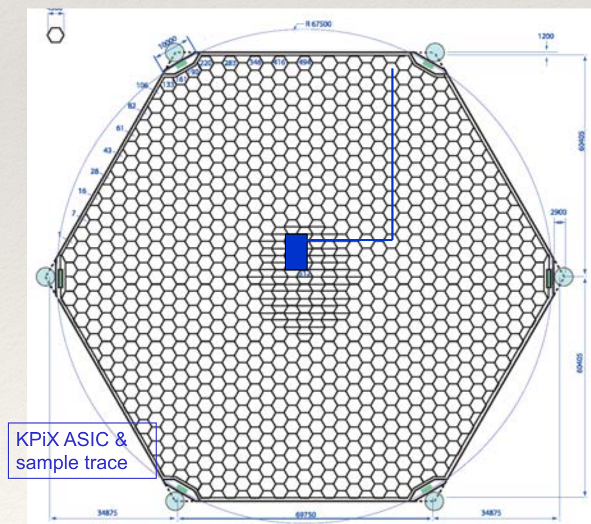


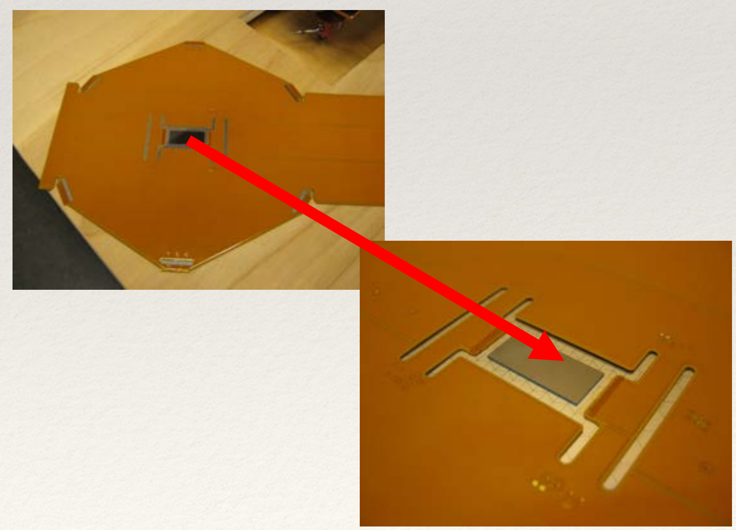




<u>SiD ECal Design</u>

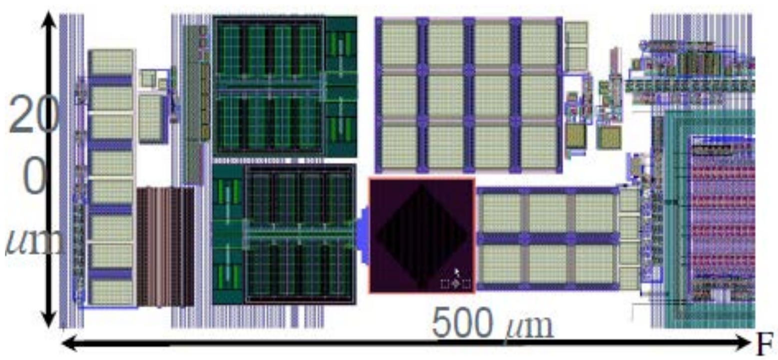
- 6 inch wafers
- 1024 13 mm^2 pixels
- KPiX readout and cable are bump-bonded directly to sensor
- 1 mm readout gaps -> 13 mm effective Moliere radius
- . Tungsten plates thermal bridge to edge cooling
- . Feeds Particle Flow (~3% jet resolution at 100 GeV)
- . EM resolution: 17%/sqrt(E)

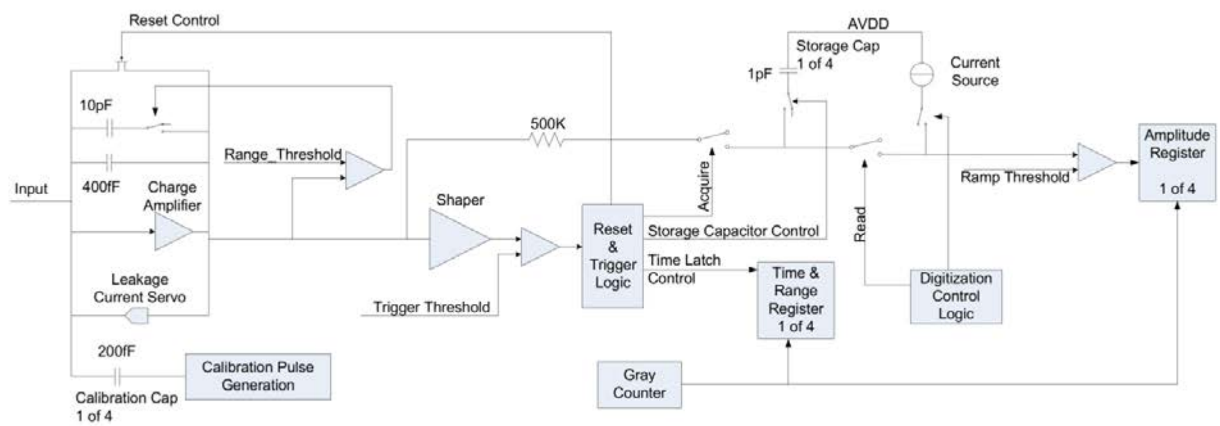




KPiX – a readout system on a chip

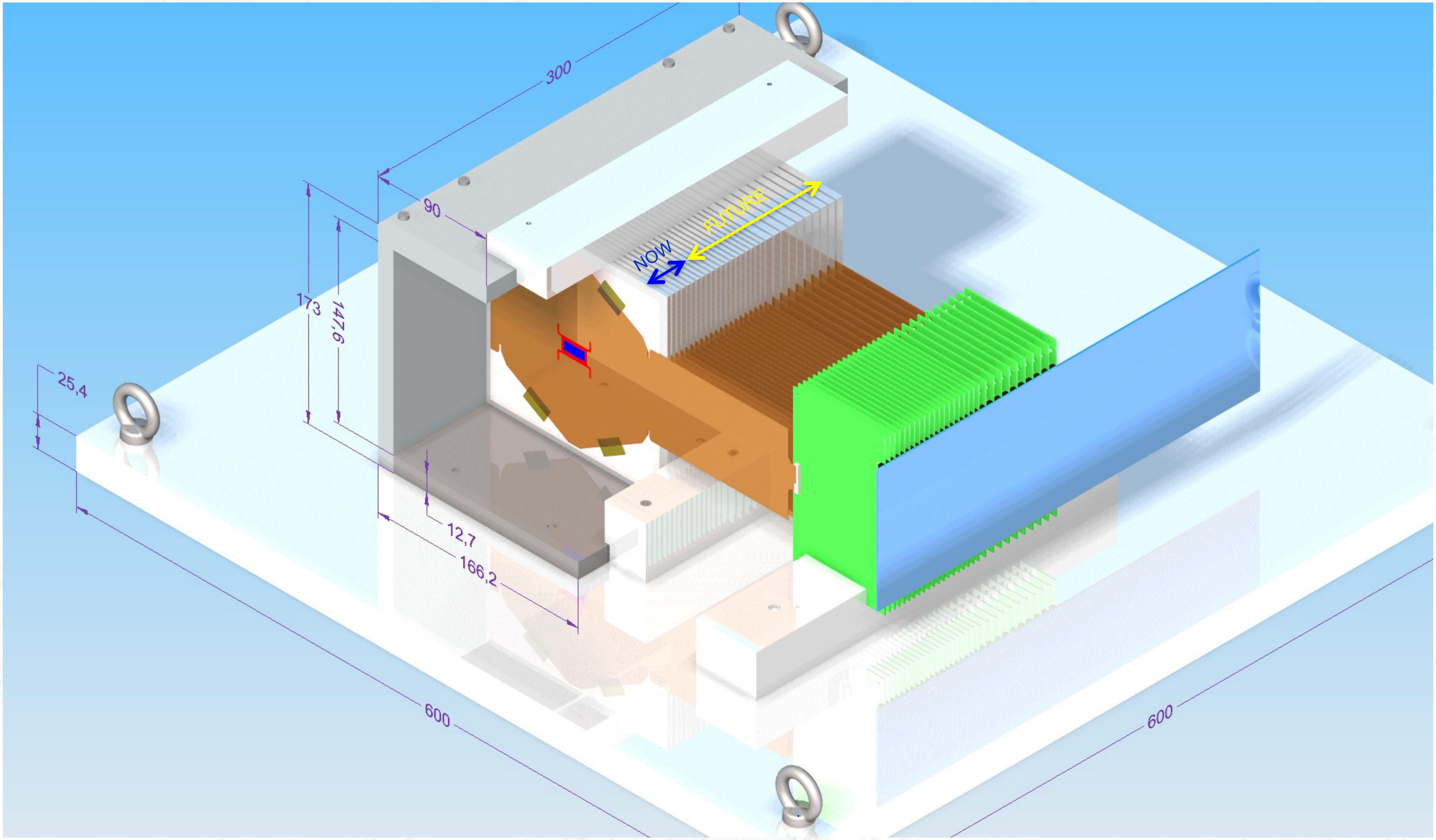
- A 1024 channel system to be bump bonded directly to large Si Sensors – enabling the Si Tracker and EMCal.
- Optimized for the ILC, with multi-hit recording during the train, and digitization and readout during the inter-train gap (199 ms).
- Front-end power down during inter-train gap. Mean power/channel <20 μW.
- Large dynamic range (for calorimetry) by dynamically switching the charge amp feedback cap.
- Pixel level trigger; trigger bunch number recorded.



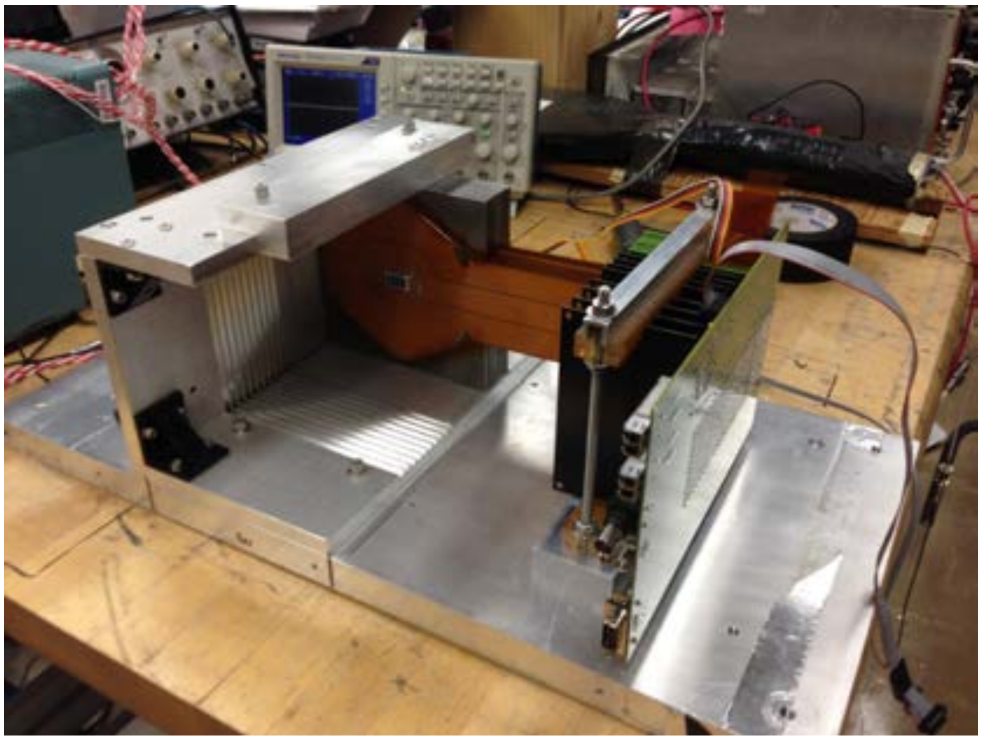


J. Brau et al., 2012 IEEE NSS and MIC Record N35-3, SLAC-PUB-15285.

Initial test beam module for T-511 only
9 Si + 8 W layers (~ 6 X_0)

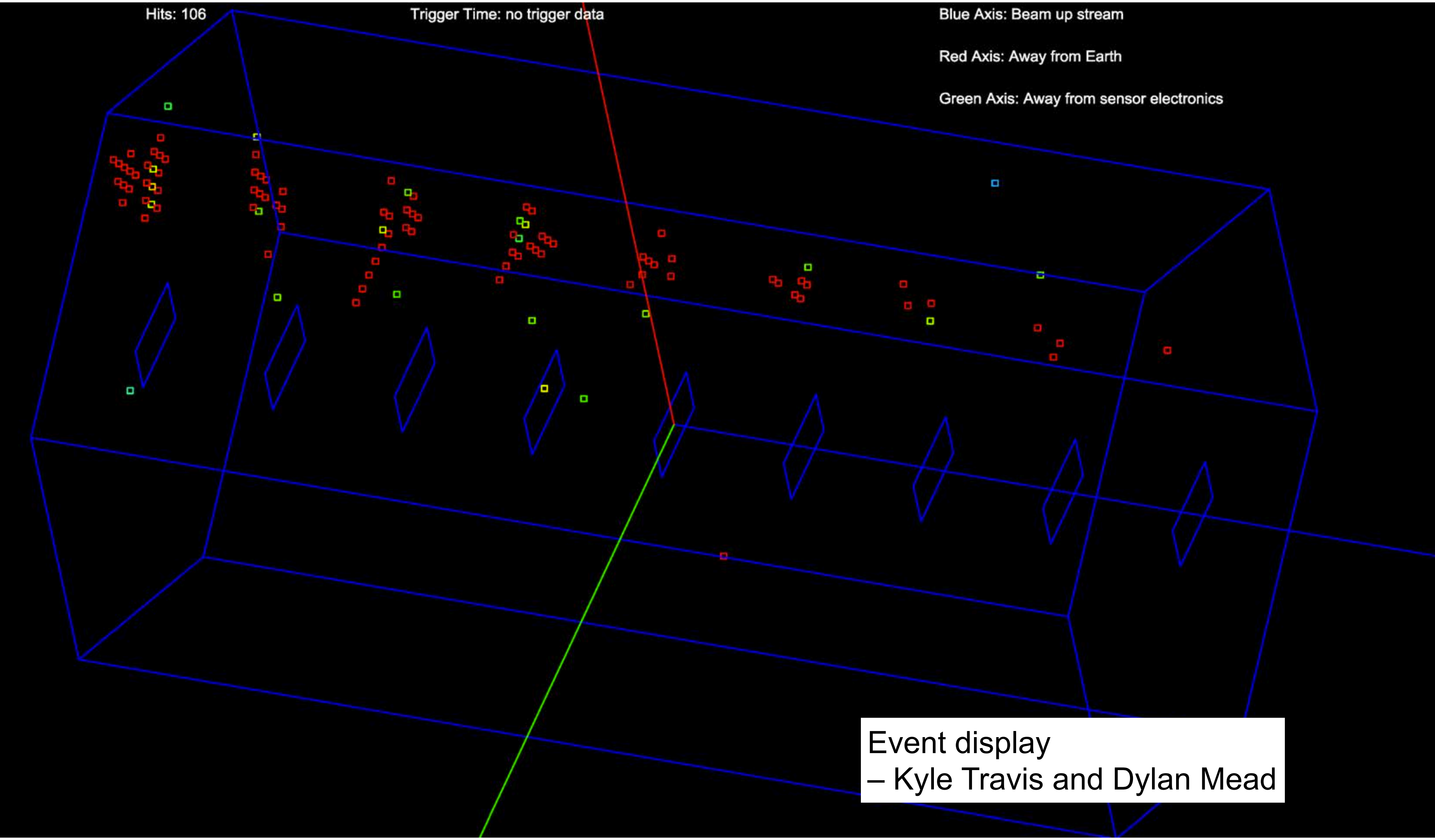


Test beam ECal prototype design – with SiD longitudinal profile

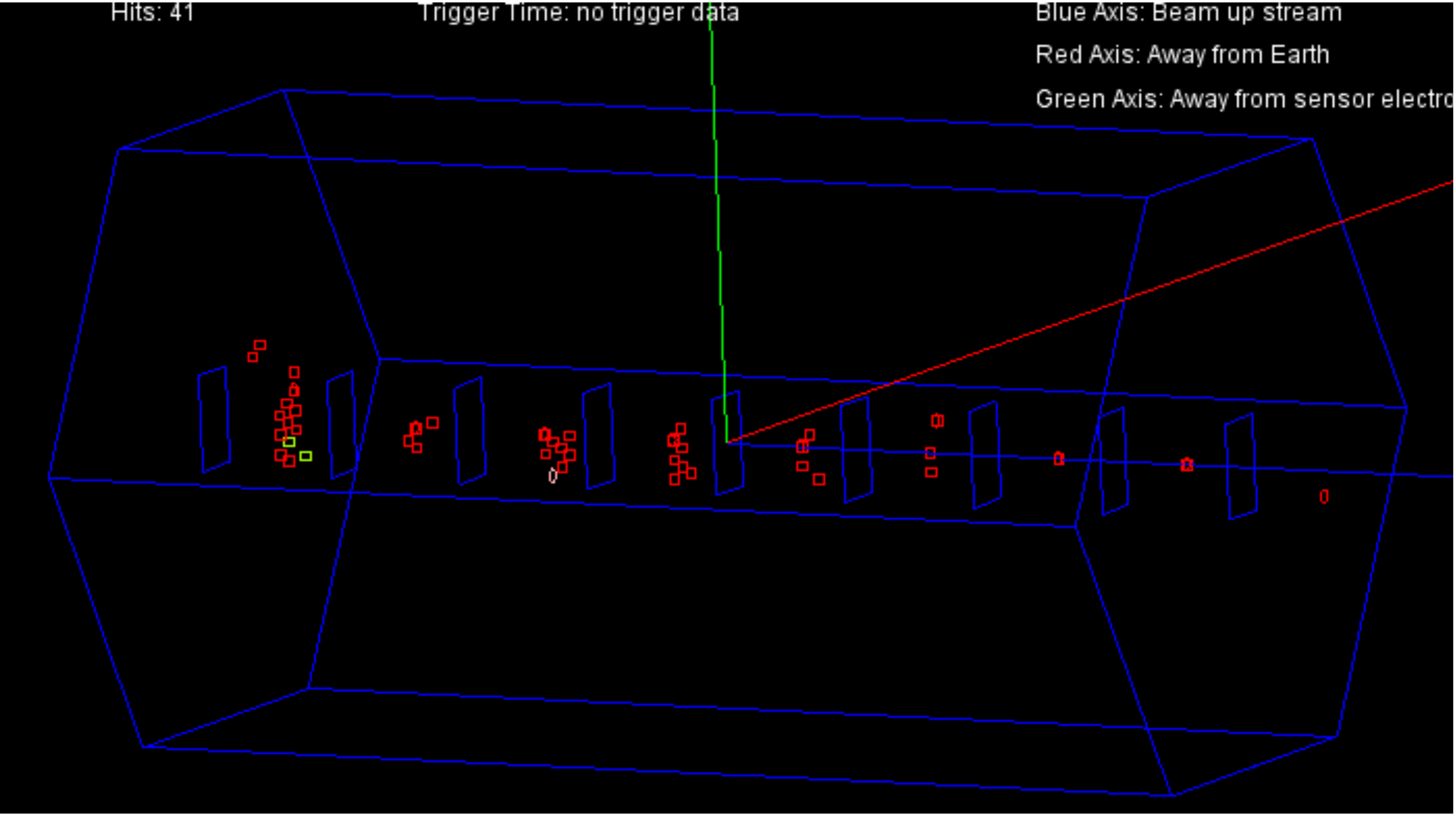


- First system test EMCal sensors in SLAC End Station A beam.
- 12.1 GeV electrons
- Utilized successfully bump bonded KPiX to sensor and sensor to cable.
- Uncovered issues related to many pixels triggered simultaneously. One part of solution may be on sensor:

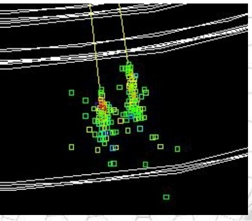
single-electron showers



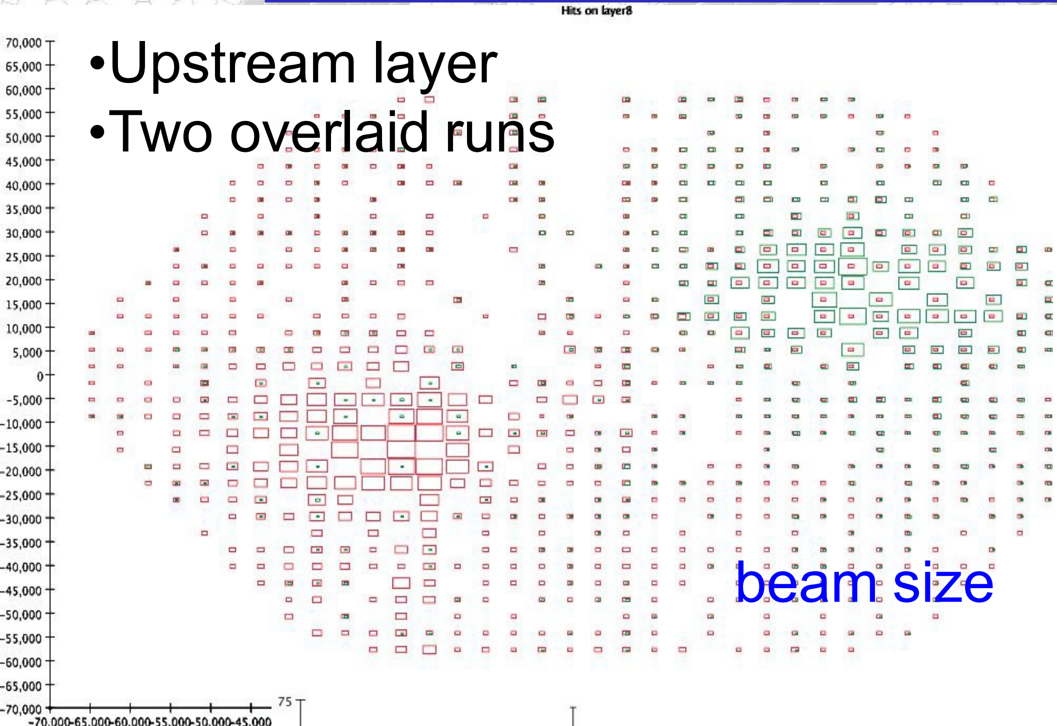
another one-electron event

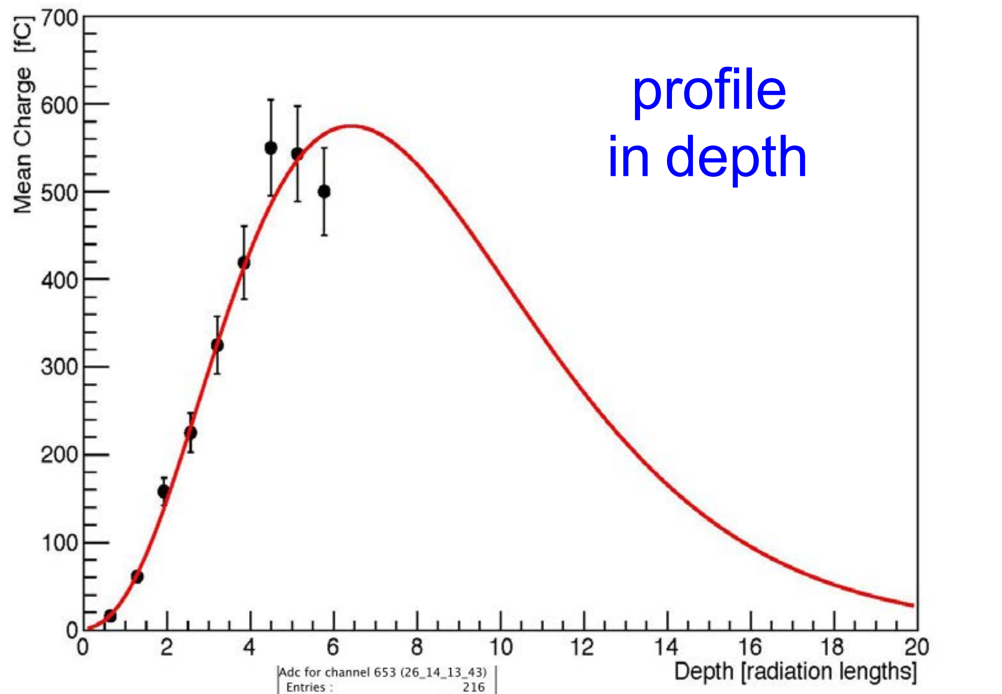


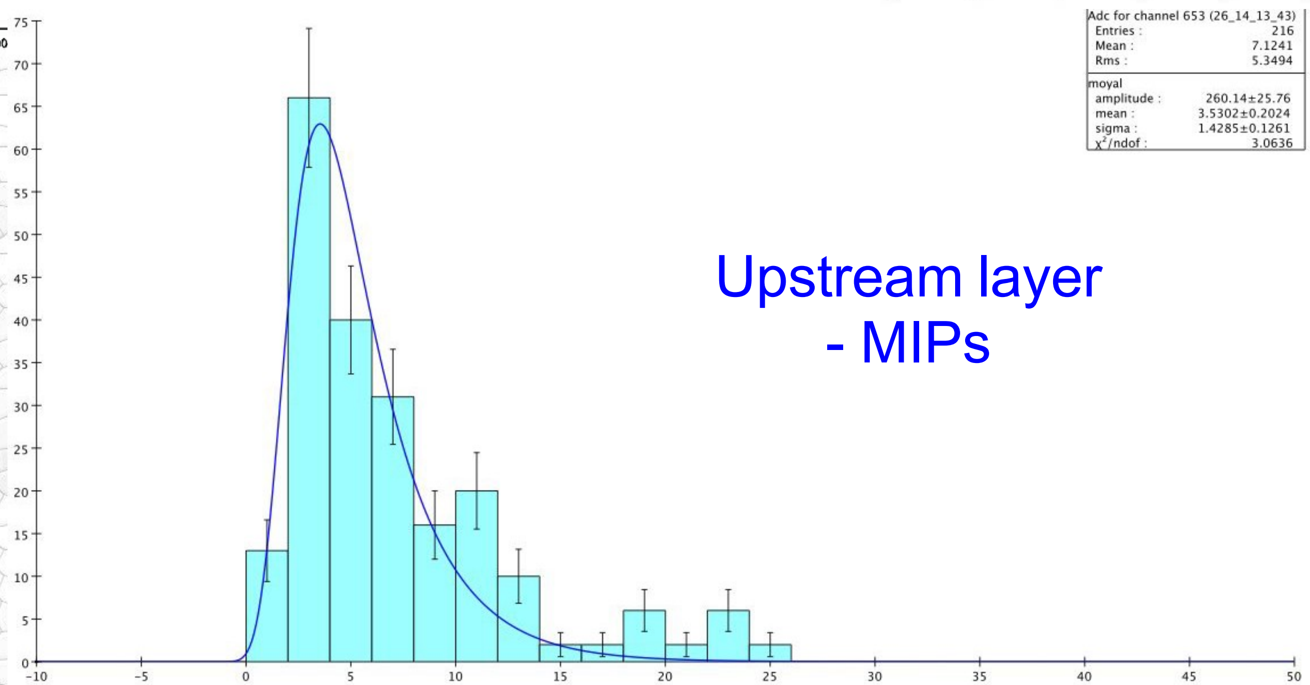
Test Beam Results



- Upstream layer
- Two overlaid runs



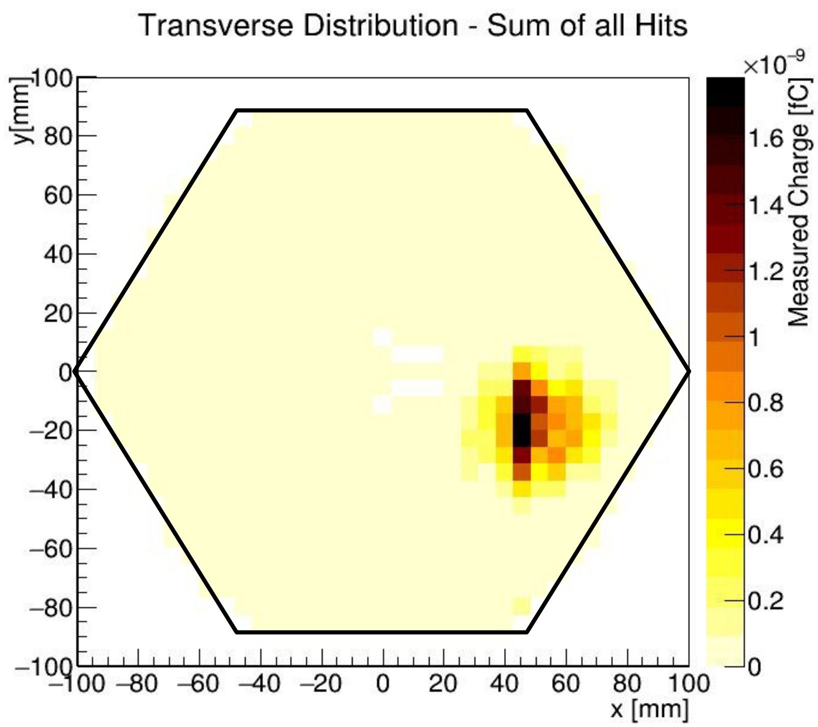




Upstream layer - MIPs

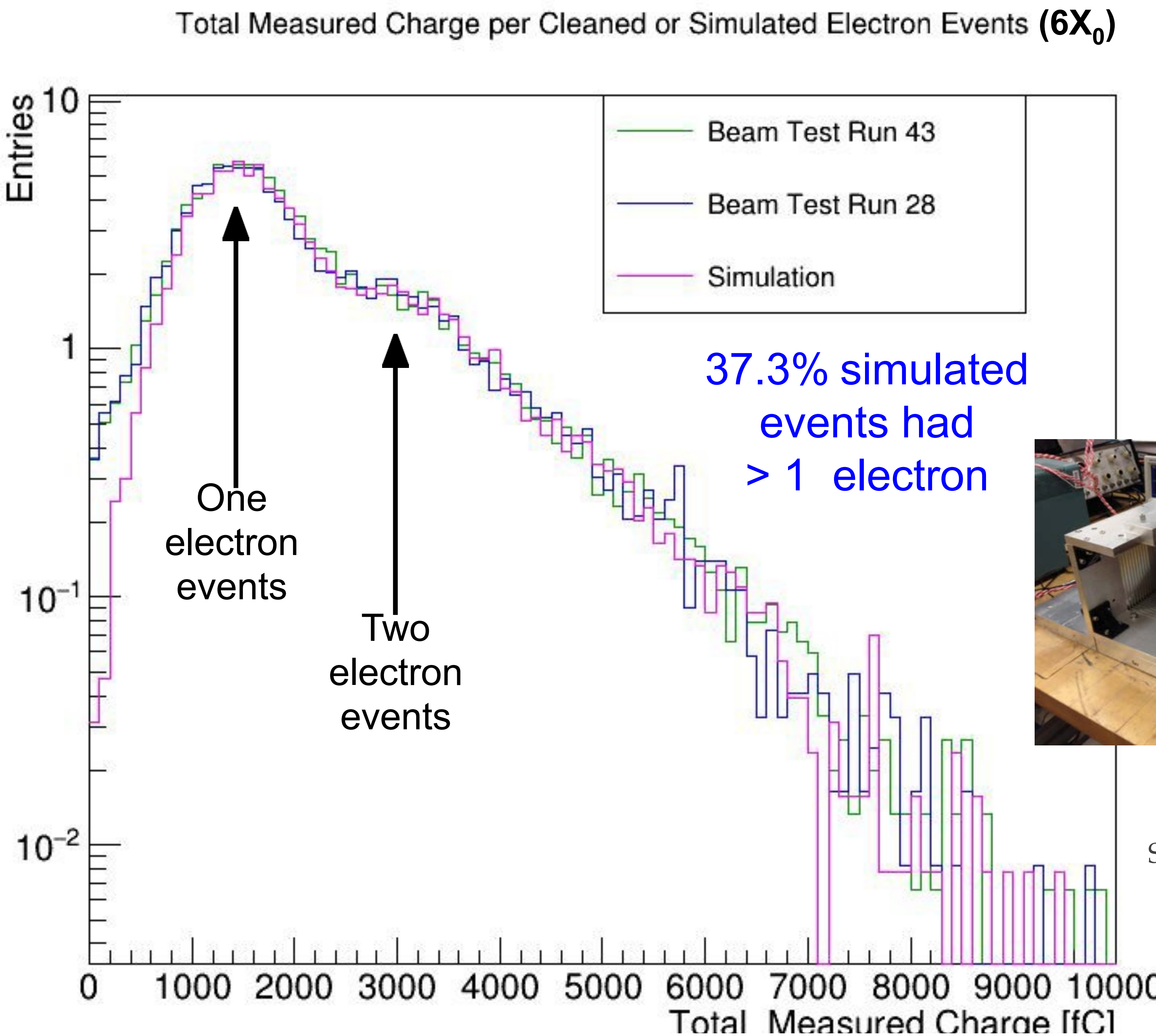
Simulation of Test Beam

- Geant4 - generated electron showers through 9 simulated Si layers (6 X_0 tungsten)
- Poisson distribution of events with 1, 2, 3, 4, or 5 simultaneous electrons
  - <n>=0.8725
- Random exclusion of "dead pixels"
- Normal distribution of events shifted from center

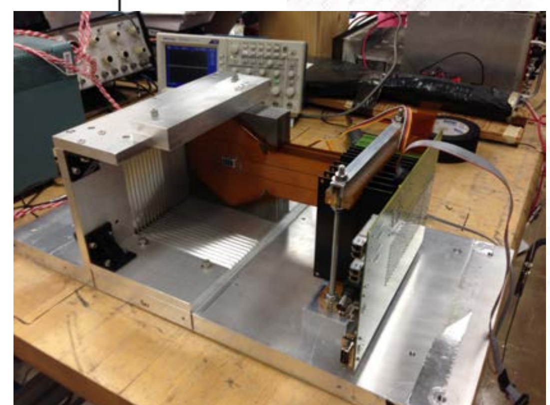


Work done at the University of Oregon: A. Steinhebel, J. Barkeloo, D. Mead

Simulation vs. Test Beam Data (6 X_0)



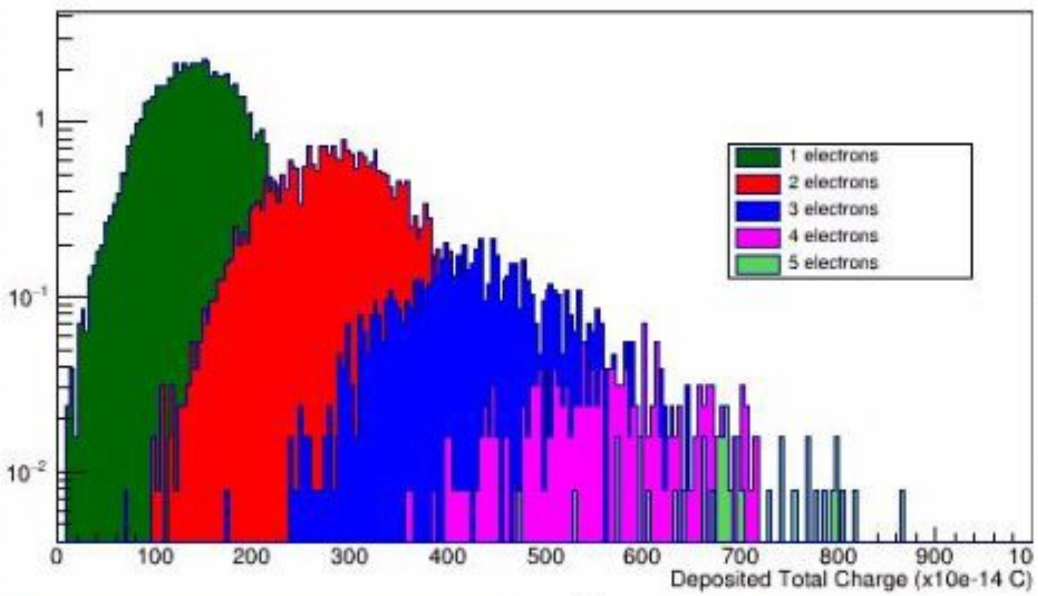
37.3% simulated events had > 1 electron



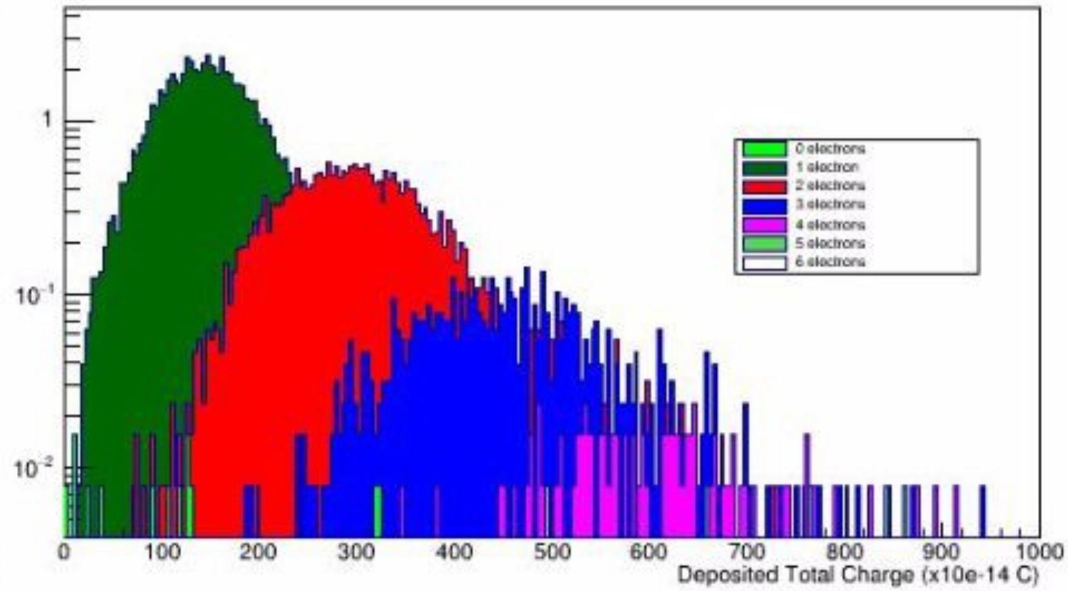
Steinhebel and J. Brau, arXiv:1703.08605

Test Beam - Counting Electrons in 6 X_0

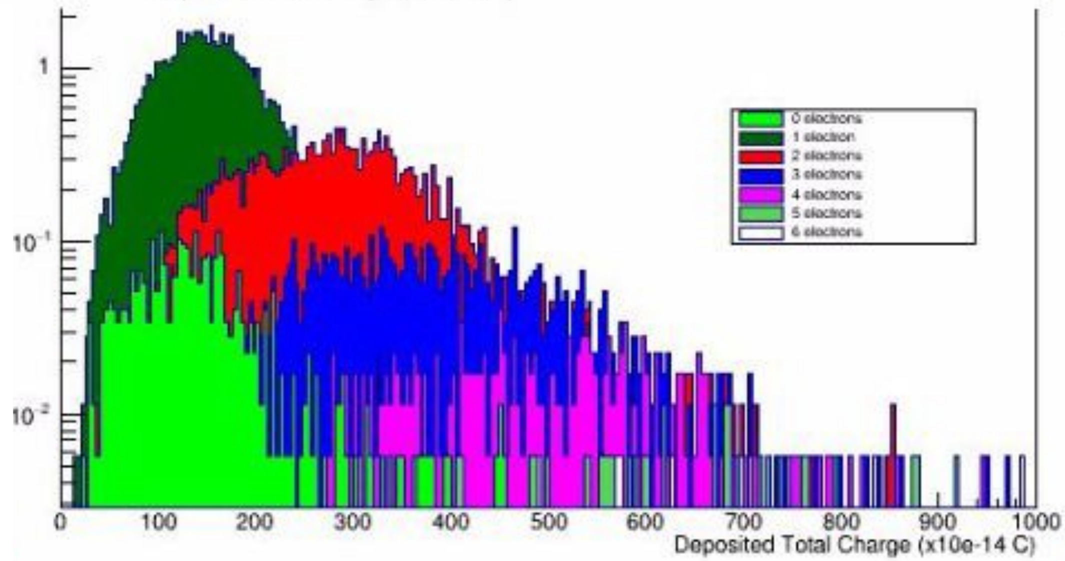
Electron Events -Simulation Truth



Electron Events -Simulation Tagged



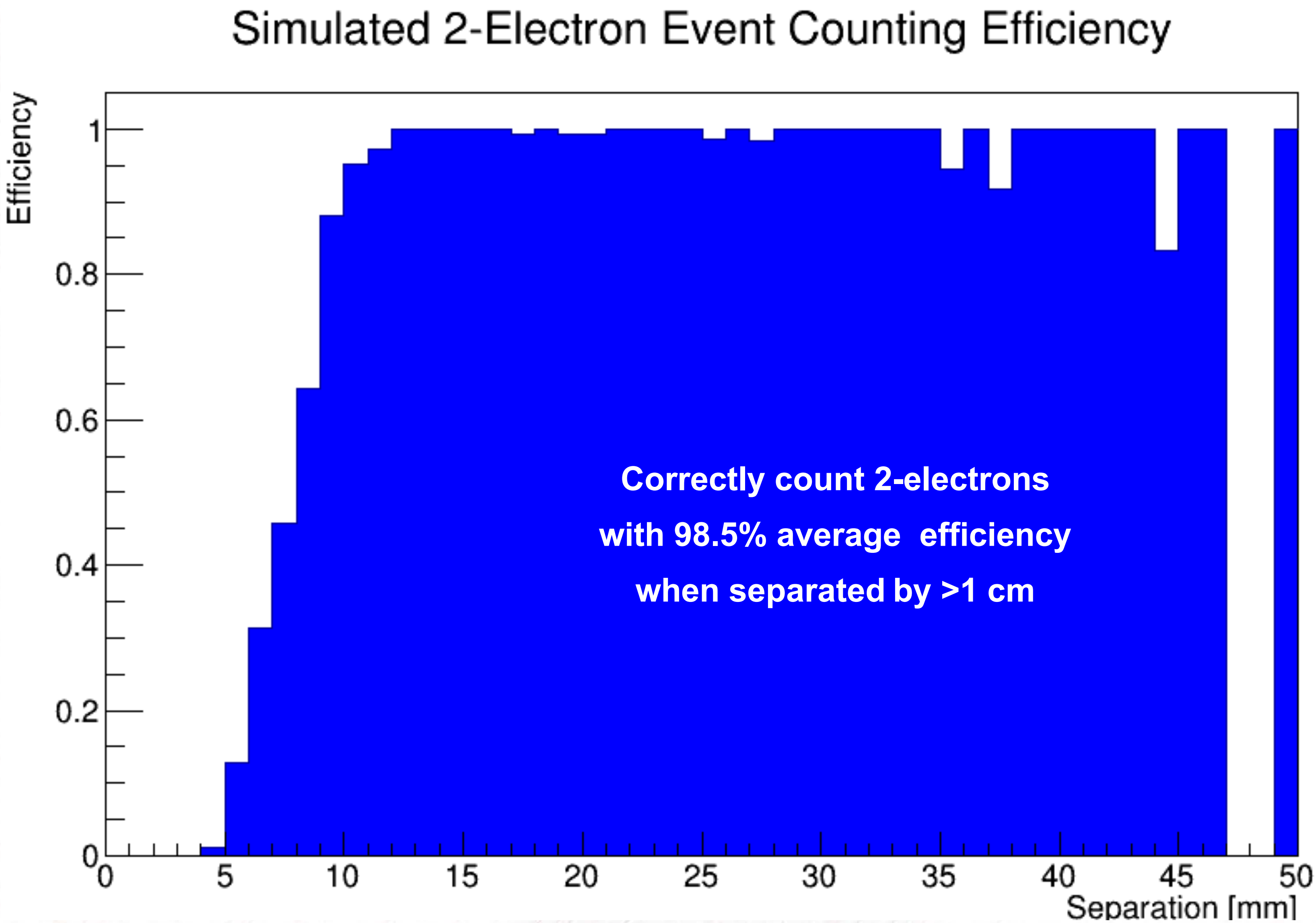
Electron Events - Test Beam Tagged



0 electrons
1 electron
2 electrons
3 electrons
4 electrons
5 electrons

Steinhebel and J. Brau, arXiv:1703.08605

Test Beam Results – Counting Electrons in 6 X_0



Steinhebel and J. Brau, arXiv:1703.08605

Simulation Studies

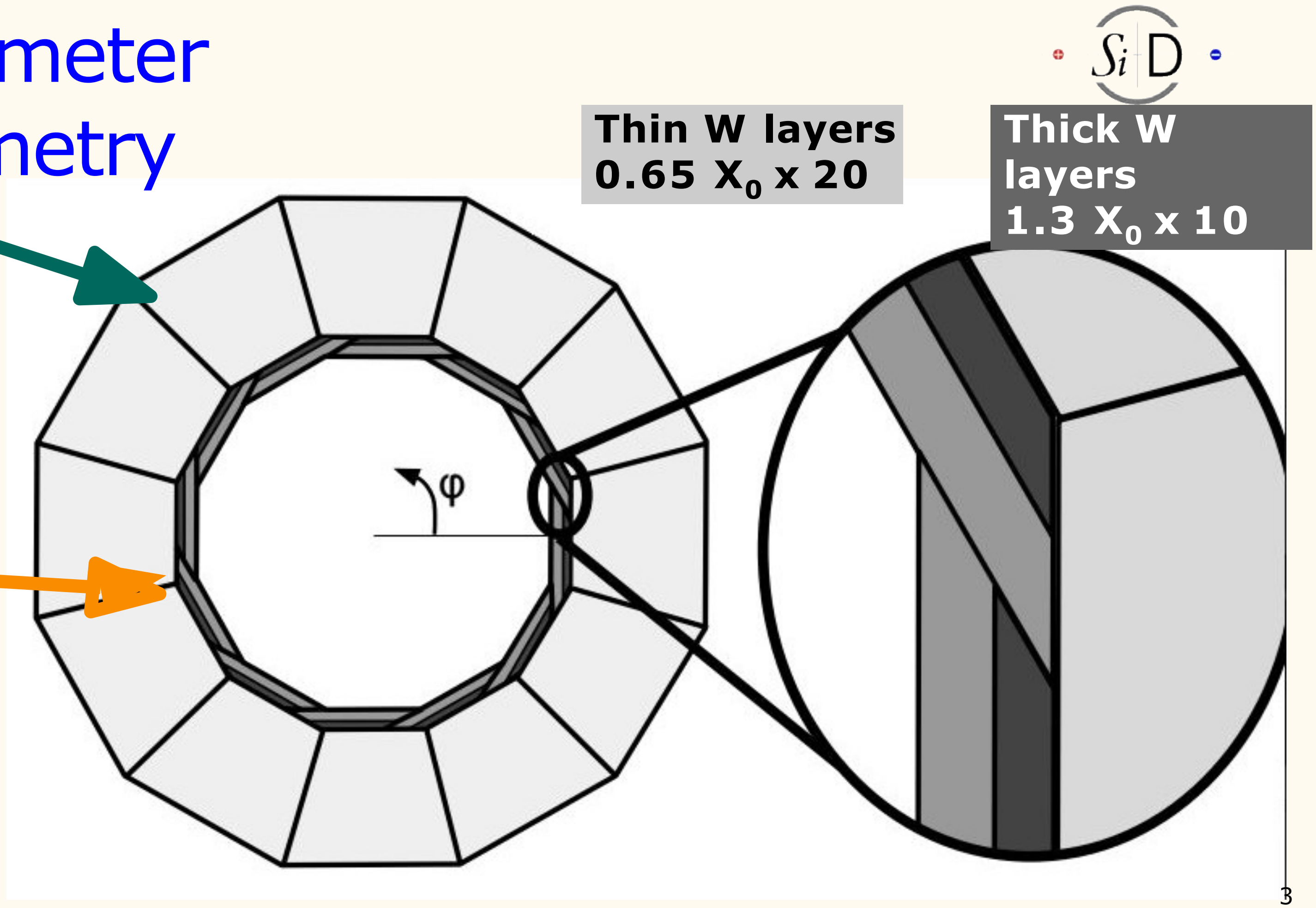
Calorimeter Geometry

HCal

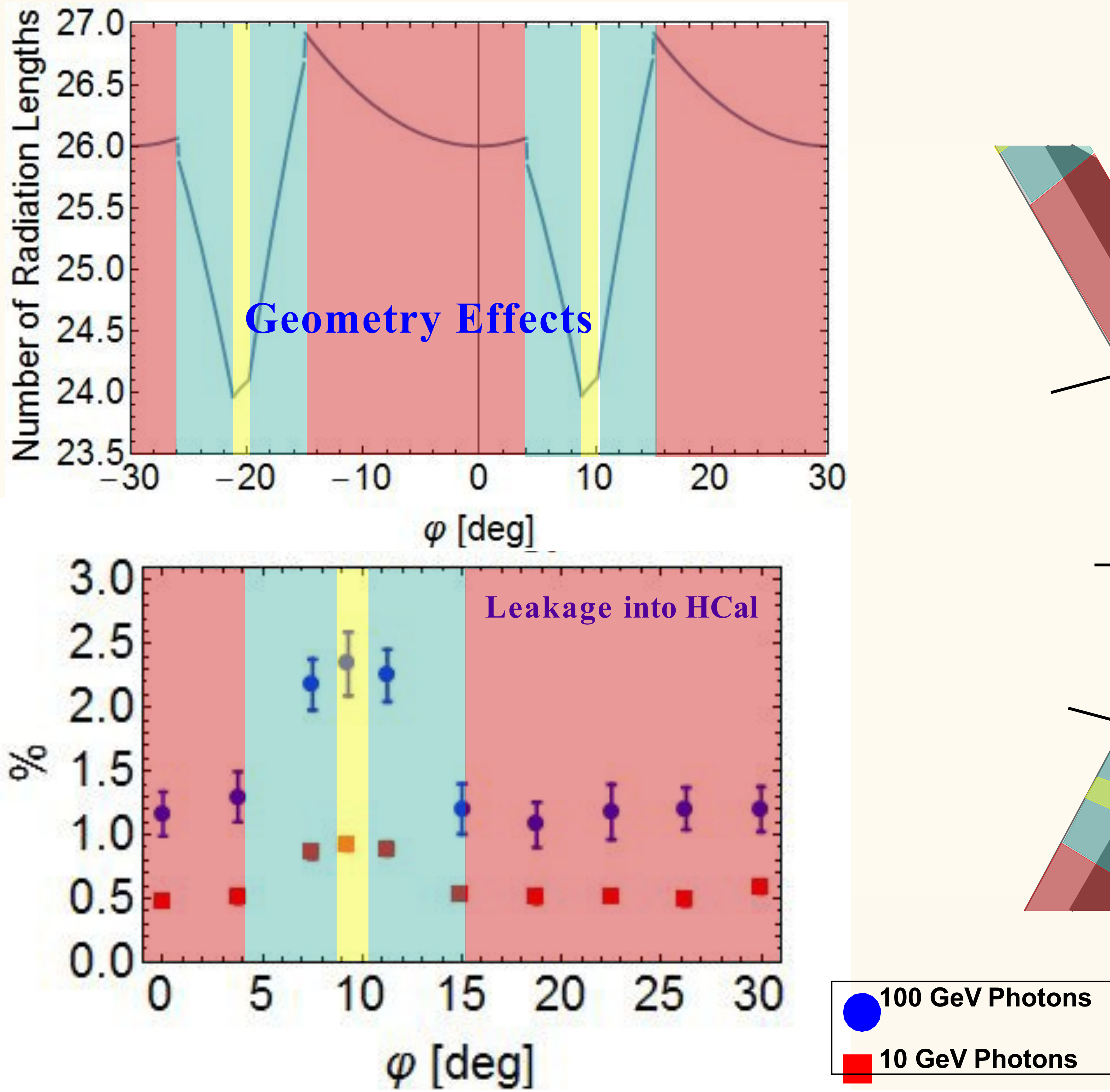
Scintillator sampling calorimeter Steel/ polystyrene

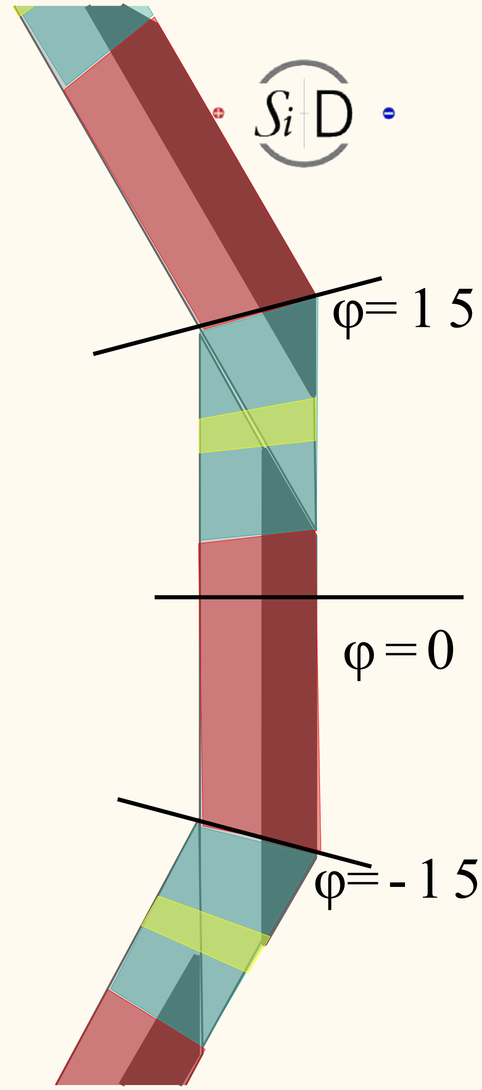
ECal

Solid state sampling calorimeter Tungsten alloy/ silicon

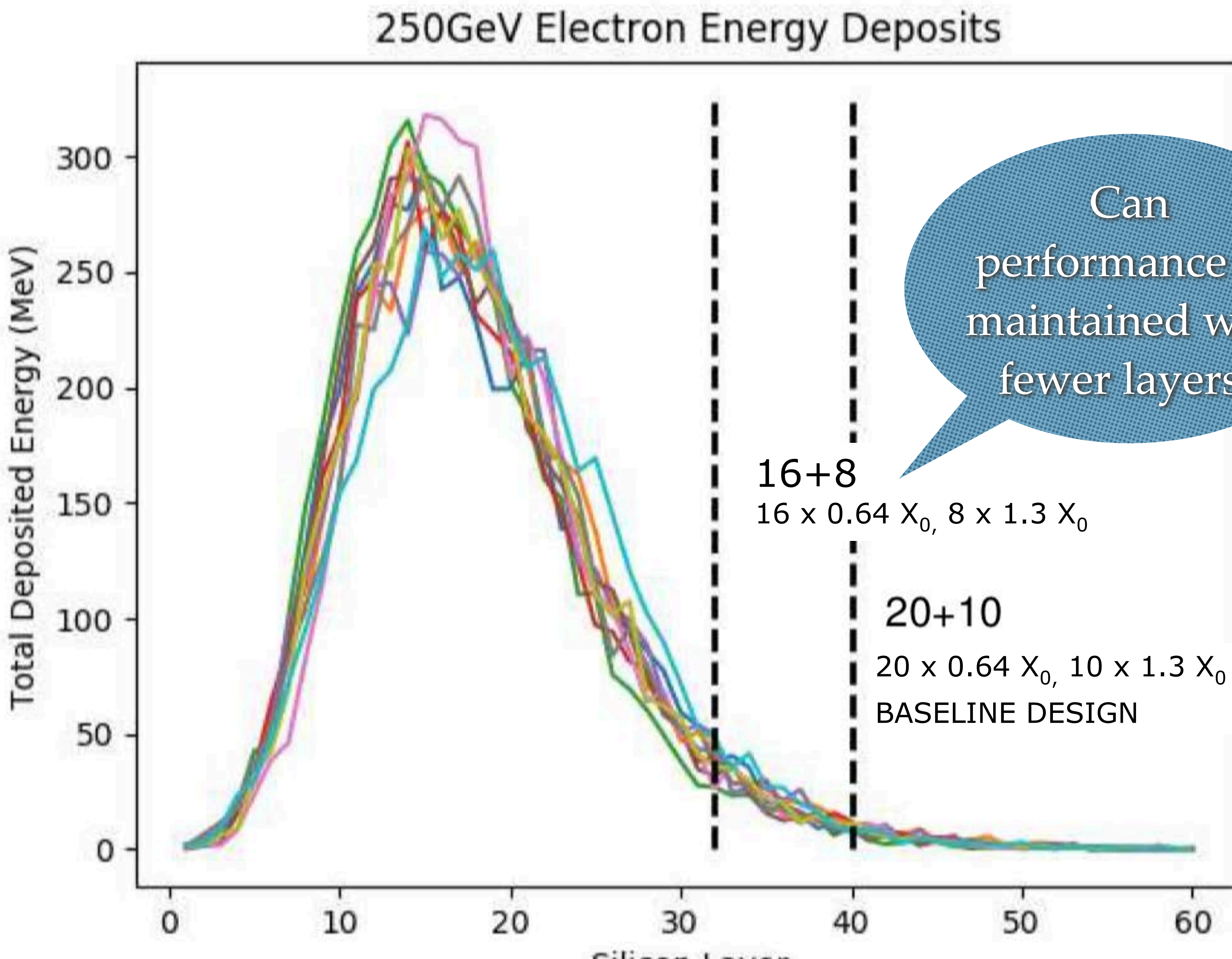


Steinhebel and J. Brau, arXiv:1703.08605

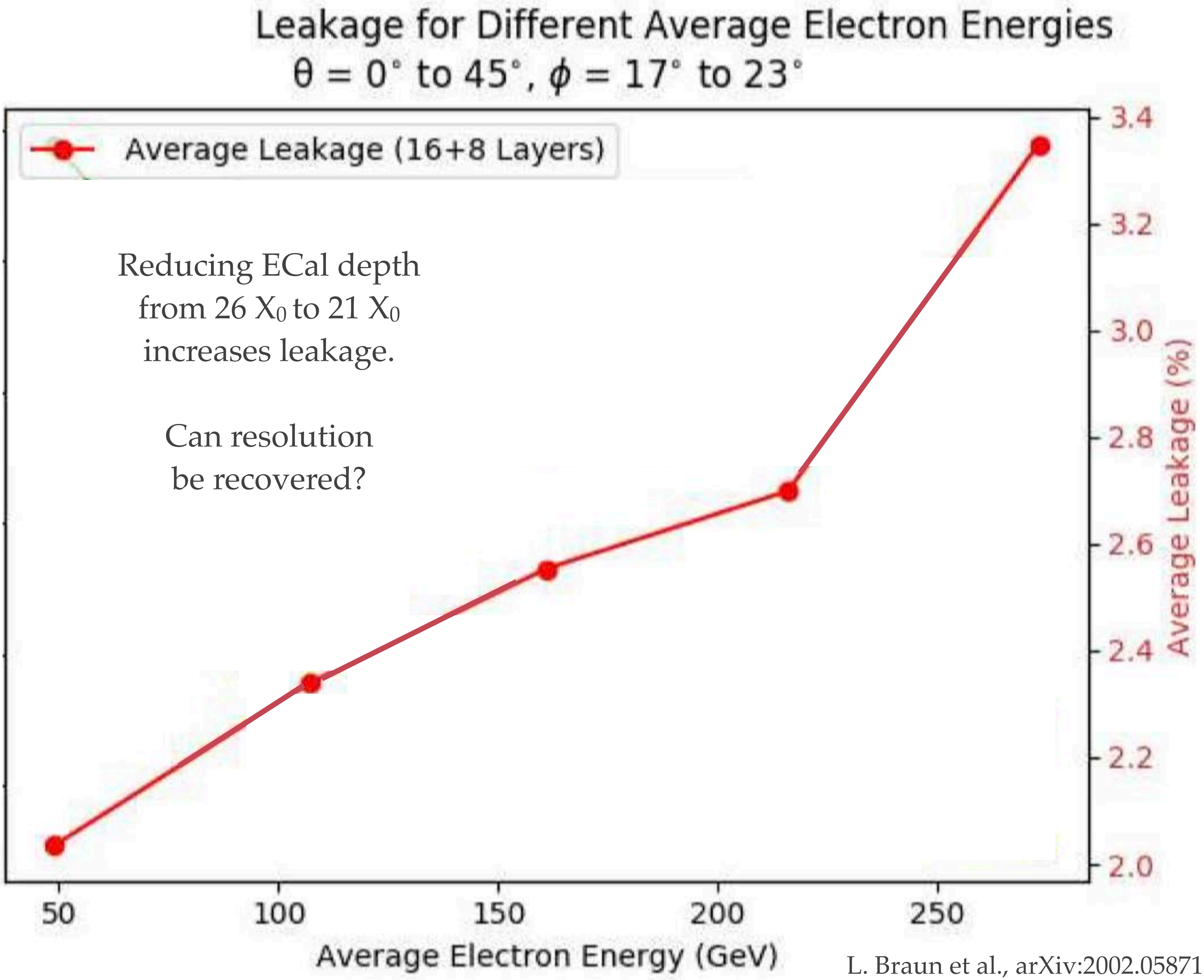




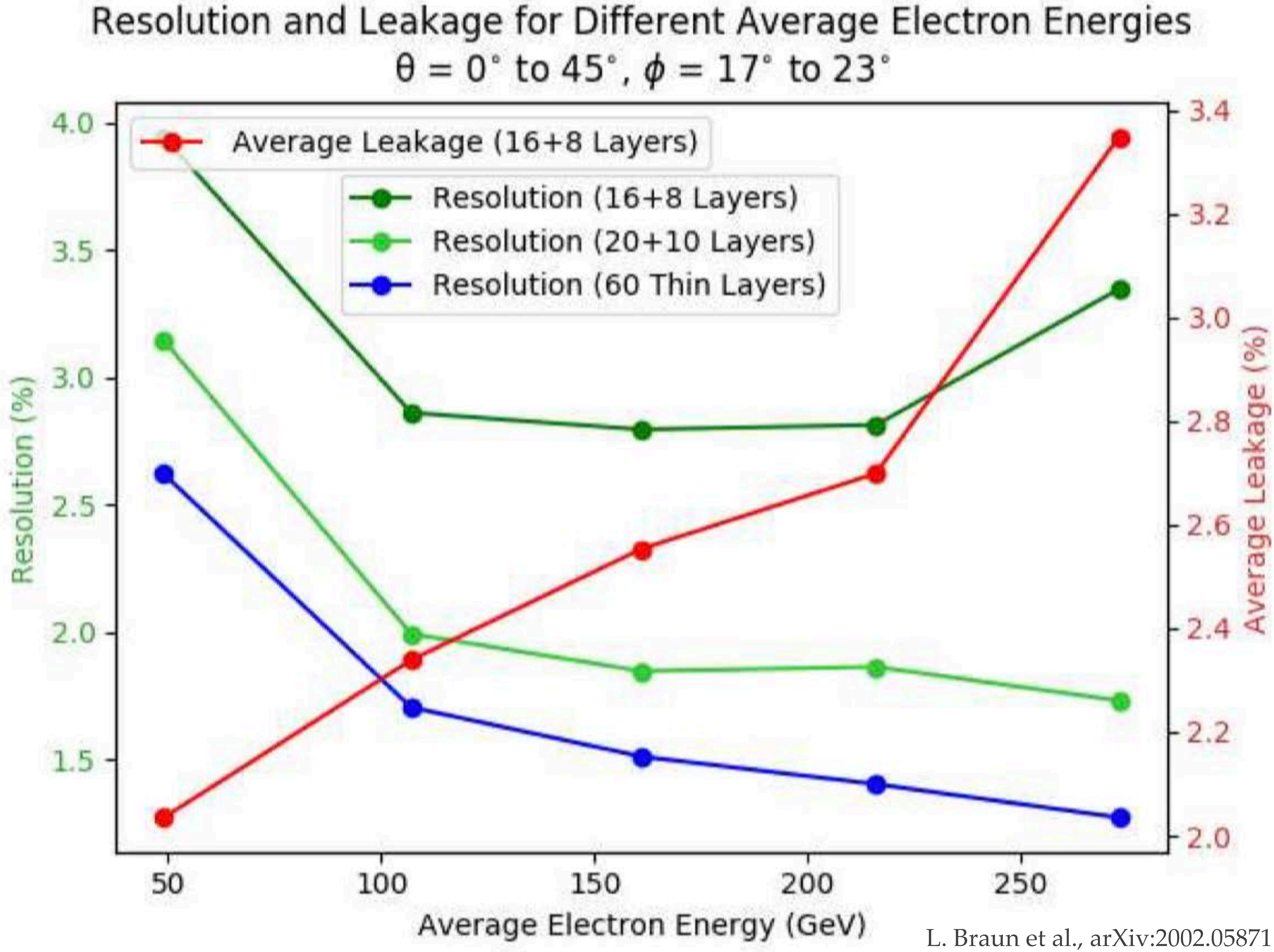
Steinhebel and J. Brau,
arXiv:1703.08605



250GeV Electron Energy Deposits
Total Deposited Energy (MeV)
Silicon Layer
Can performance be maintained with fewer layers?
16+8
16 x 0.64 X0, 8 x 1.3 X0
20+10
20 x 0.64 X0, 10 x 1.3 X0
BASELINE DESIGN

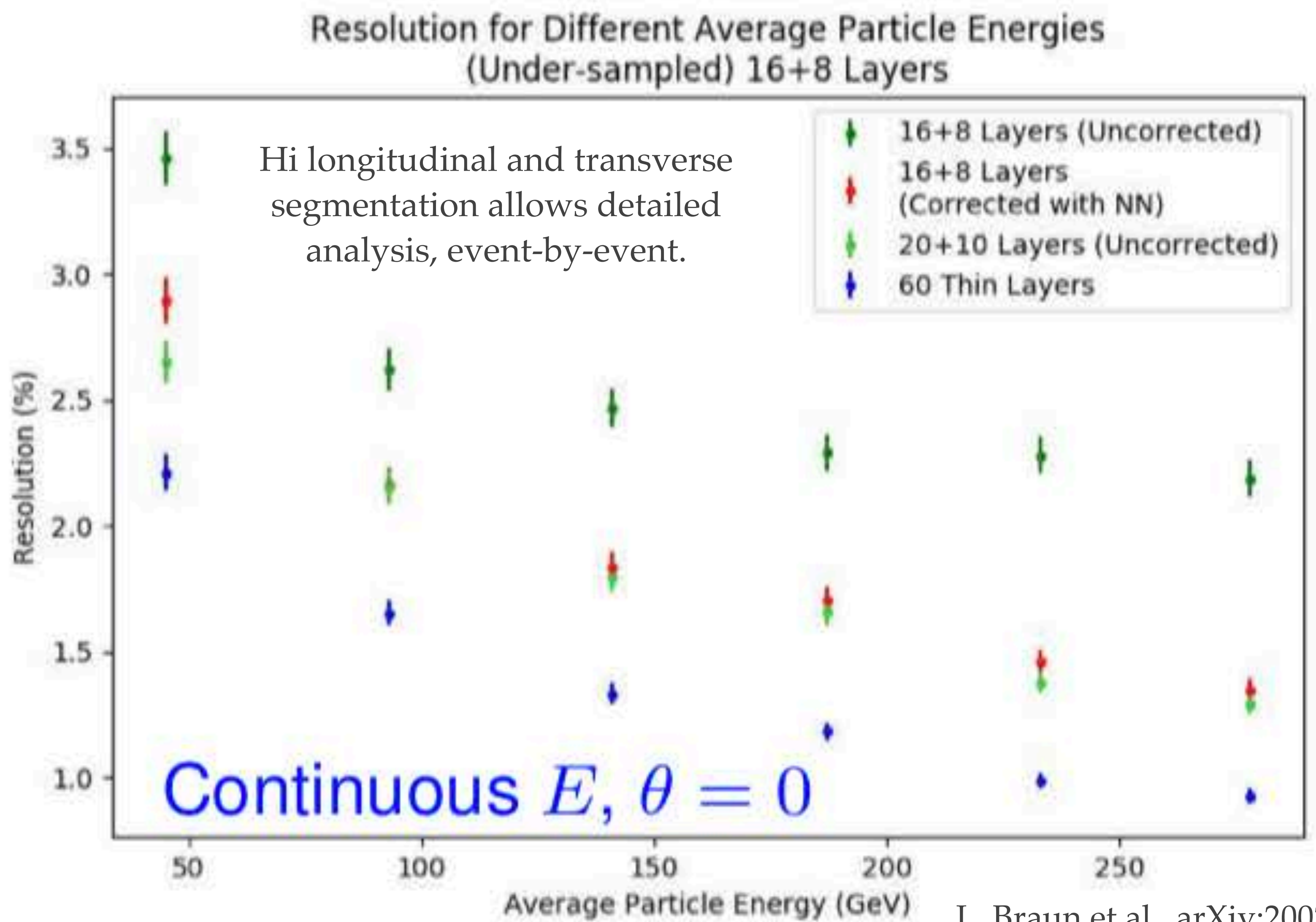


L. Braun et al., arXiv:2002.05871



L. Braun et al., arXiv:2002.05871

Neural Net Corrections for Energy

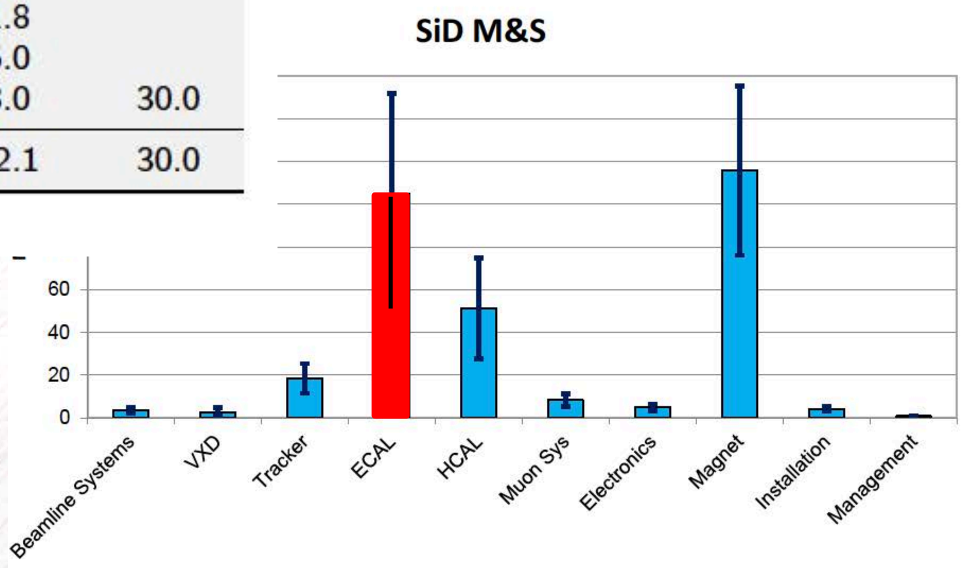


L. Braun et al., arXiv:2002.05871

SiD SiW ECal is Cost Constrained!

From the ILC TDR:

	M&S Base (M US-$)	M&S Contingency (M US-$)	Engineering (MY)	Technical (MY)	Admin (MY)
Beamline Systems	3.7	1.4	4.0	10.0	
VXD	2.8	2.0	8.0	13.2	
Tracker	18.5	7.0	24.0	53.2	
ECAL	104.8	47.1	13.0	288.0	
HCAL	51.2	23.6	13.0	28.1	
Muon System	8.3	3.0	5.0	22.1	
Electronics	4.9	1.6	44.1	41.7	
Magnet	115.7	39.7	28.3	11.8	
Installation	4.1	1.1	4.5	46.0	
Management	0.9	0.2	42.0	18.0	30.0
	314.9	126.7	186.0	532.1	30.0



M&S Cost (incl. contingency) =
~33M$ + ~2.4M$ (no. of layers)

The Future for SiW ECal is MAPS

- M. Breidenbach at SLAC is investigating this approach.
- Monolithic technologies have the potential to provide higher granularity, thinner, intelligent detectors at lower overall cost.
  - Significantly lower material budget
    - Eliminate the need for bump bonding or other challenging interconnect methods.
    - Can be thinned to less than 100 um.
  - Smaller pixel size.
    - Not limited by bump bonding.
  - Lower costs
    - Can be implemented in standard commiericla CMOS technologies (ATLAS estimated a savings in cost of about $35M switching to MAPS for the ITK upgrade.

Particle Flow Technologies

- **High granularity**
  - HCal ~ O(1 cm^3) - ECal ~ O(0.001 cm^3)
- **Scintillator**
  - strips or cells, read out by SiPMs
- **Gas**
  - glass RPC, either Digital or Semi-digital
  - MPGD (GEM, MicroMegas, …)
    - built-in suppression of sparks
    - tuning of resistivity allows variation of high rate capability
- **Semi-conductor diodes**
  - silicon for ECal
  - GaAs considered for radiation hardness requirements

CALICE COLLABORATION HAS DEVELOPED MANY TECHNOLOGIES

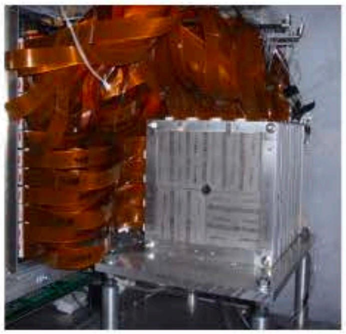
CALICE Technologies

Validation

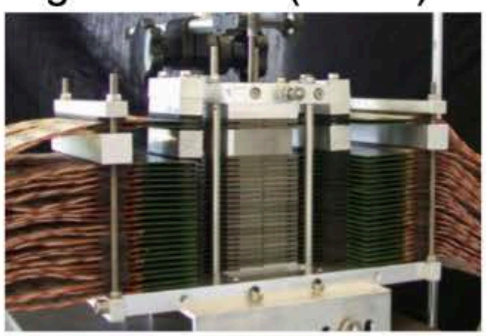
- A rich test beam program, with a variety of different prototypes

Electromagnetic - Tungsten absorbers

analog: Silicon and Scintillator/SiPM



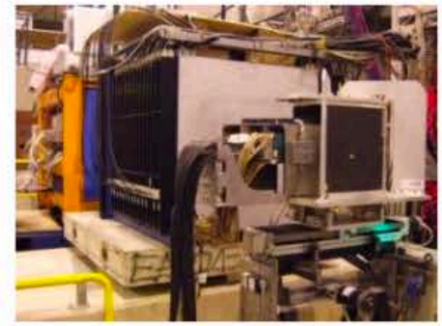
digital: Silicon (MAPS)



39 Mpixels in 160 cm^2

Hadronic - Steel and Tungsten absorbers

analog: Scintillator/SiPM (Fe and W)

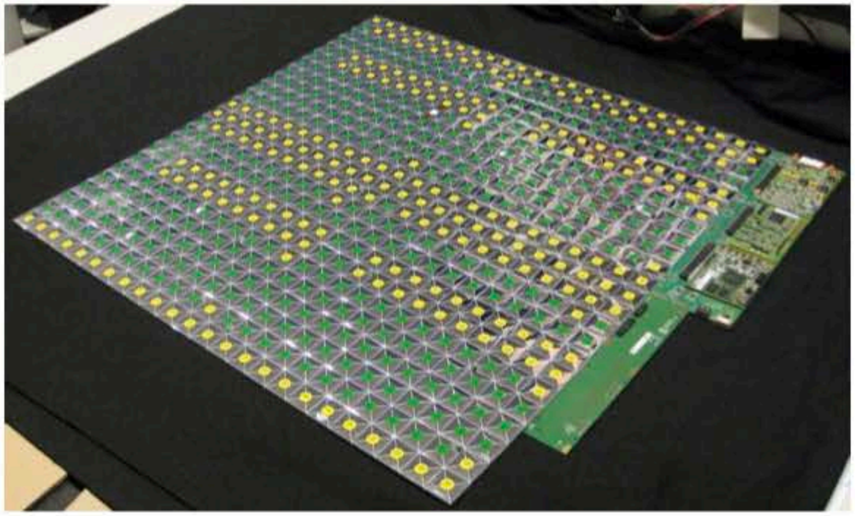


(Semi)digital: RPCs (Fe, W digital only)

+ few-layer SD prototype with Micromegas

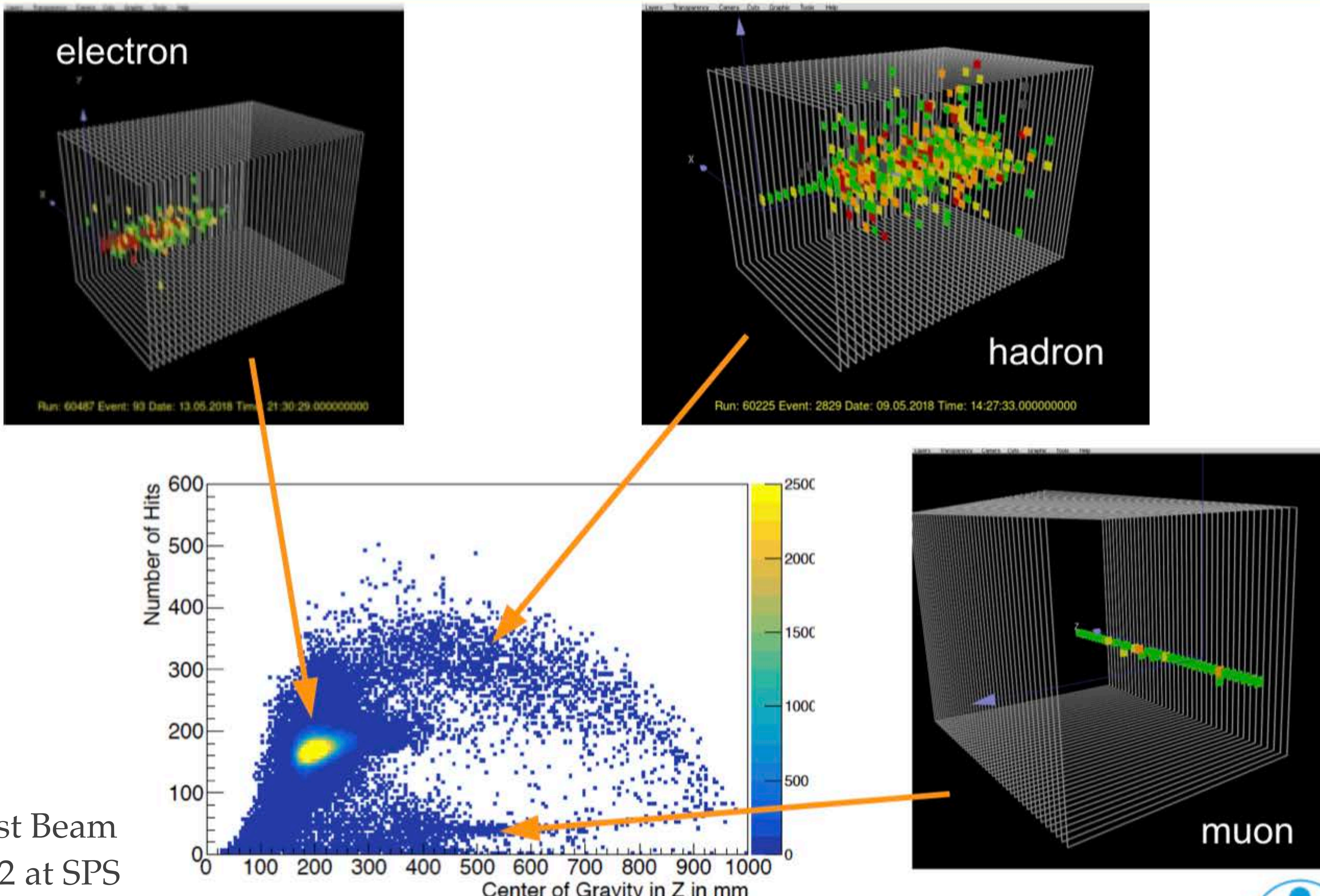
AHCAL testbeam prototype

- 38 active layers of 72*72 cm²
- 4 HBUs per module
  - 16 SPIROC 2E readout ASICs, 576 channels of 3*3 cm² tiles
  - in total: 608 ASICs, ~22000 channels
- all modules with surface-mount MPPCs
  - S13360-1325PE
  - 2668 pixels
  - operated at 5V overvoltage
  - nominal operation voltage within 200mV in a module -> use same voltage
- all modules are interchangeable, so positioning in stack according to quality (worst modules in the back)
- steel absorber stack corresponding to ~1% of ILD barrel



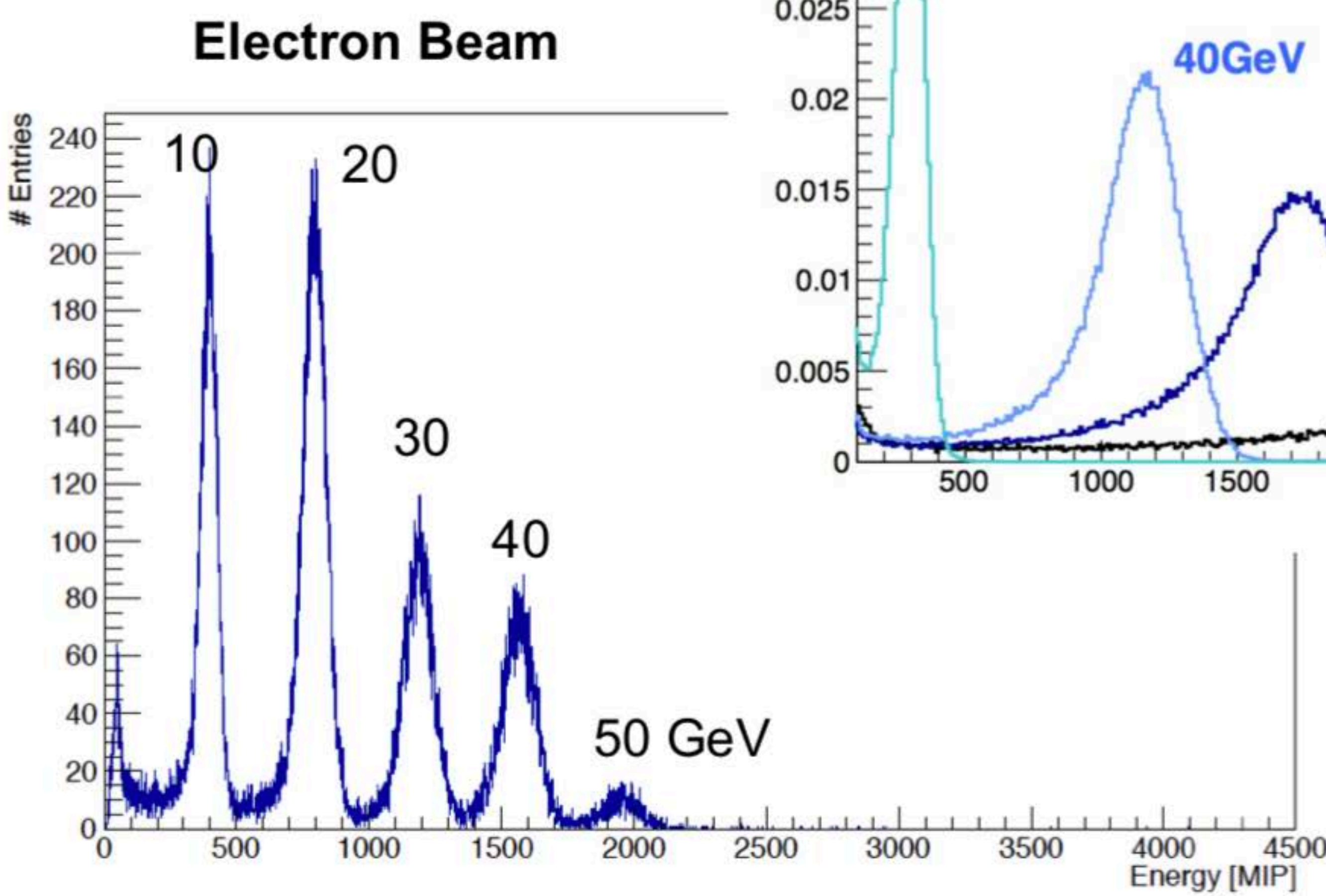
DESY.

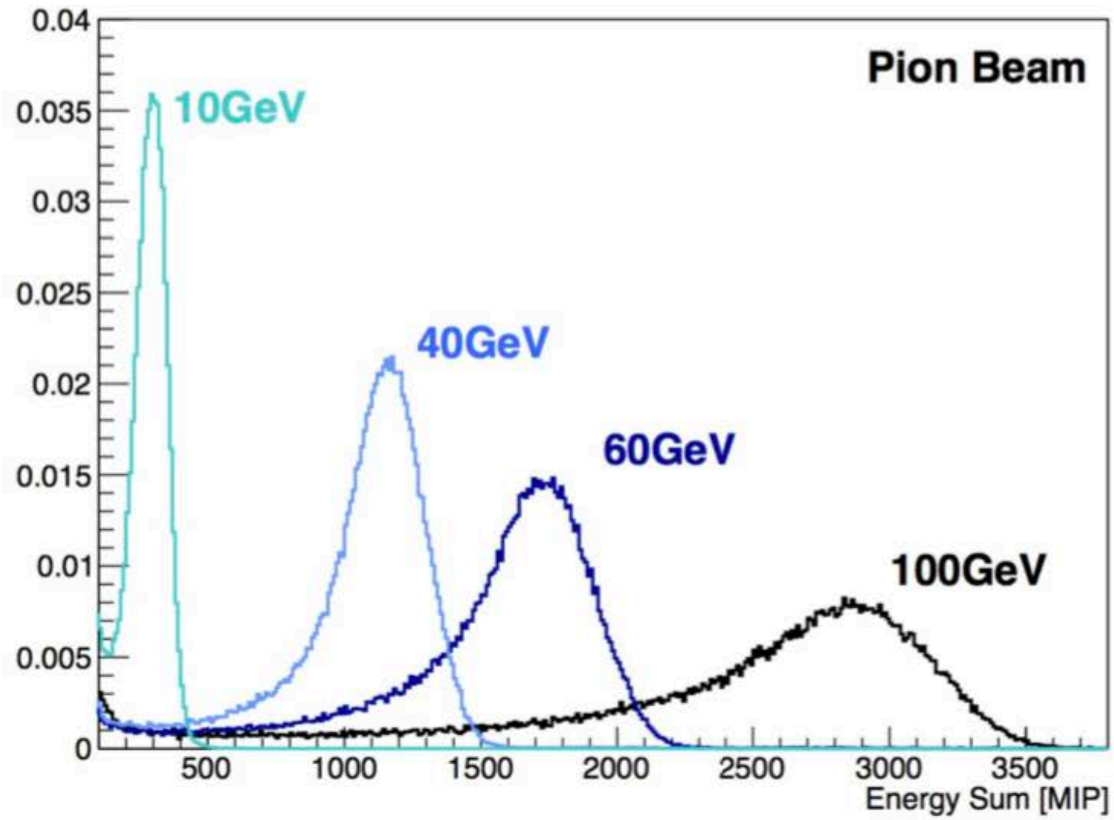
Event displays and online monitoring



Test Beam -H2 at SPS

Online Monitoring: Energy Sums





Selected CALICE Publications

- Hadronic Energy Resolution of a Combined High Granularity Scintillator Calorimeter System, JINST 13 (2018) P12022, e-print: arXiv:1809.03909 (physics.ins-det).
- Characterisation of different stages of hadronic showers using the CALICE Si-W ECAL physics prototype, G. Eigen et al., NIM A937 (2019) 41-52; e-print: arXiv:1902.06161
- Construction and Response of a Highly Granular Scintillator-based Electromagnetic Calorimeter, J. Repond et al., NIM A887 (2018), 150; e-print: arXiv:1707.07126
- Hadron shower decomposition in the highly granular CALICE analogue hadron calorimeter, G. Eigen et al., JINST 11 (2016) P06013, e-print: arXiv:1602.08578
- Analysis of Testbeam Data of the Highly Granular RPC-Steel CALICE Digital Hadron Calorimeter and Validation of Geant4 Monte Carlo Models, M. Chefdeville et al., NIM A937 (2019) 41-52; e-print: arXiv:1901.08818

Conclusion

- Highly granular calorimeters working with efficient tracking detectors offer excellent performance based on Particle Flow technique.
- The ILC detectors (SiD and ILD) have been conceived to achieve excellent performance based on this technique.
- Simulation and test beam studies of prototype calorimeters have achieve promising performance.
- Integration of chosen subsystems (tracking, calorimeters, solenoid) to realize overall performance with realistic engineering constraints has begun, but much needs to be completed.
- There's much still to be done to finalize detailed choices and performance optimization. SiD seeks colleagues to challenge assumptions and improve choices.

EXTRAS