Future Detectors

Top and Higgs Physics at Future Colliders
and Imaging Calorimeters for Colliders & Beyond

MPP Project Review
December 2017

Frank Simon
Max-Planck-Institute for Physics

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The Future Detectors Group 2017

The Core Group

funded by Excellence Cluster

- *Post-Docs*

  Naomi van der Kolk (until 07/2017), Marco Szalay (since 07/2017)
- *PhD Students*

  Miroslav Gabriel, Christian Graf, Yasmine Israeli, Marco Szalay (until 06/2017), Hendrik Windel (since 03/2017 - also in Belle II group)
- *Master Students*

  Lorenz Emberger (since 04/2017), Daniel Heuchel, Hendrik Windel (until 02/2017)
- *Technical Students*

  Guia Resina (since 12/2017)
- *Group Leader*

  Frank Simon

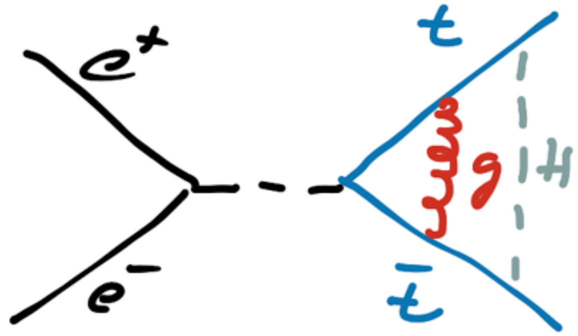
- Close collaboration with:
  - Belle / Belle-II group
  - And **the technical departments**!

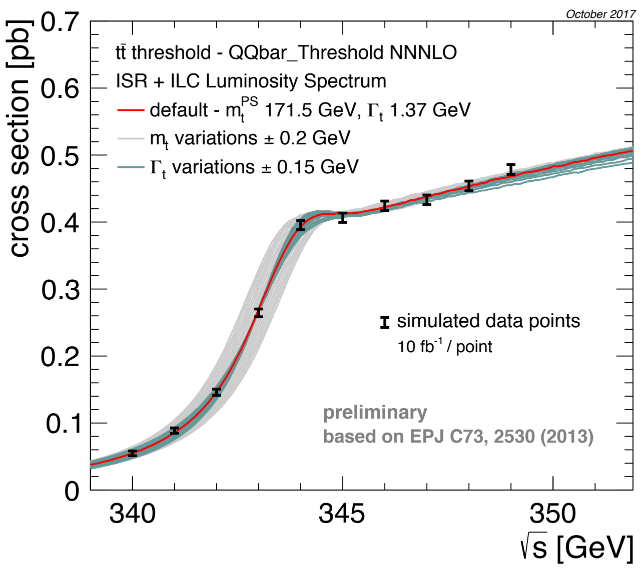
With key roles in collaborations and projects, among them:

- Spokesperson of the CALICE collaboration
- Member of the CLICdp Executive Team
- Member of the ILC Physics Group

The Projects in the Group

Physics at future e^+e^- colliders





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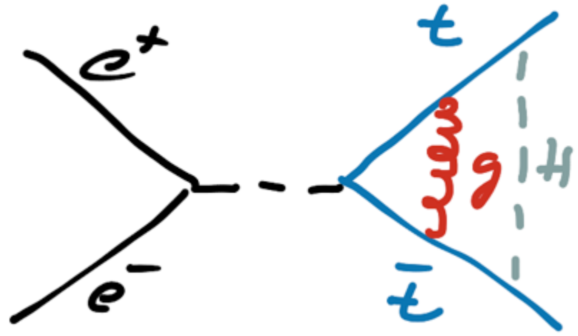
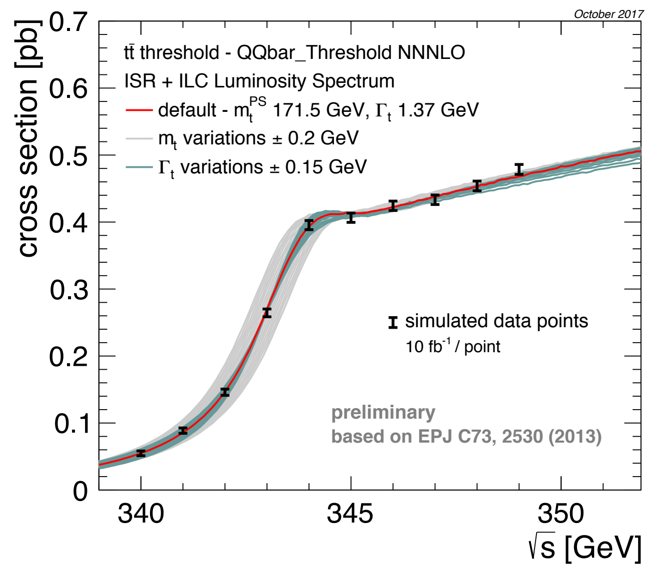
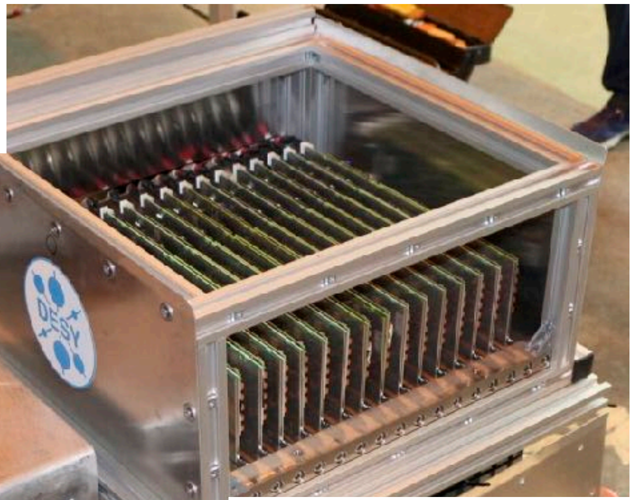
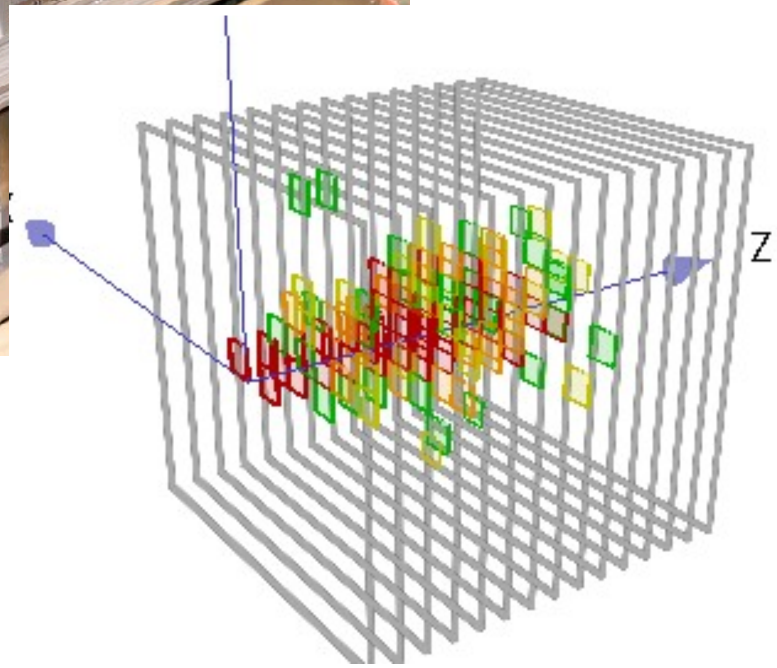
Physics at future e+e- colliders





Highly granular calorimeters





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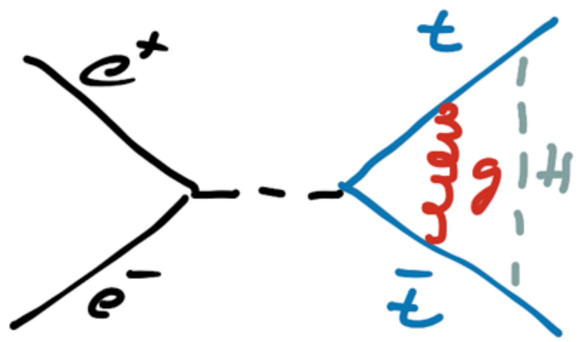

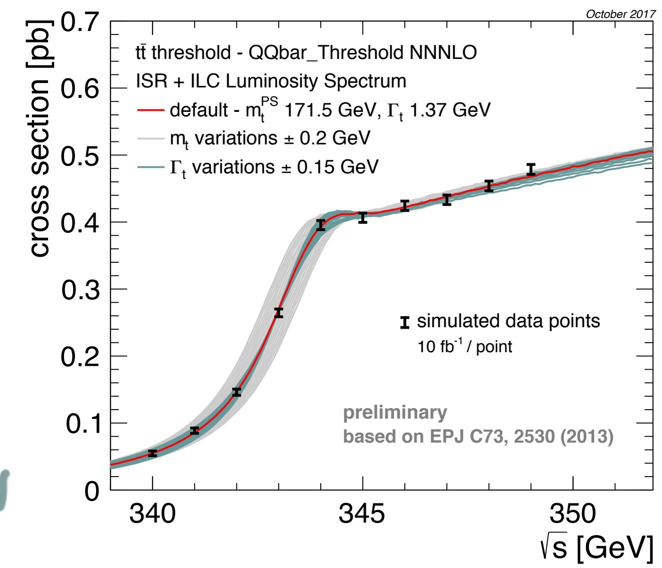

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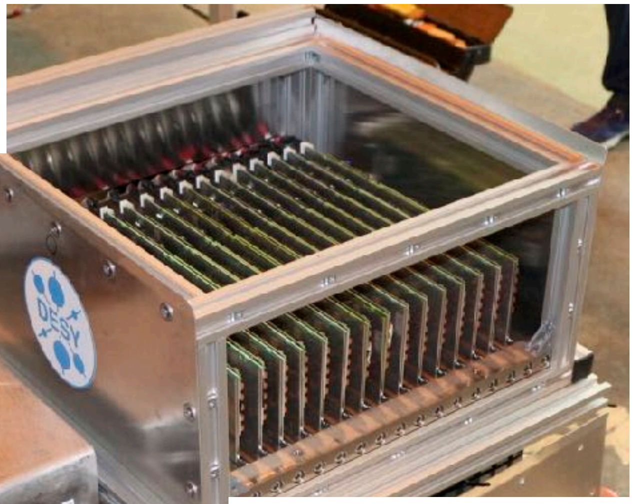
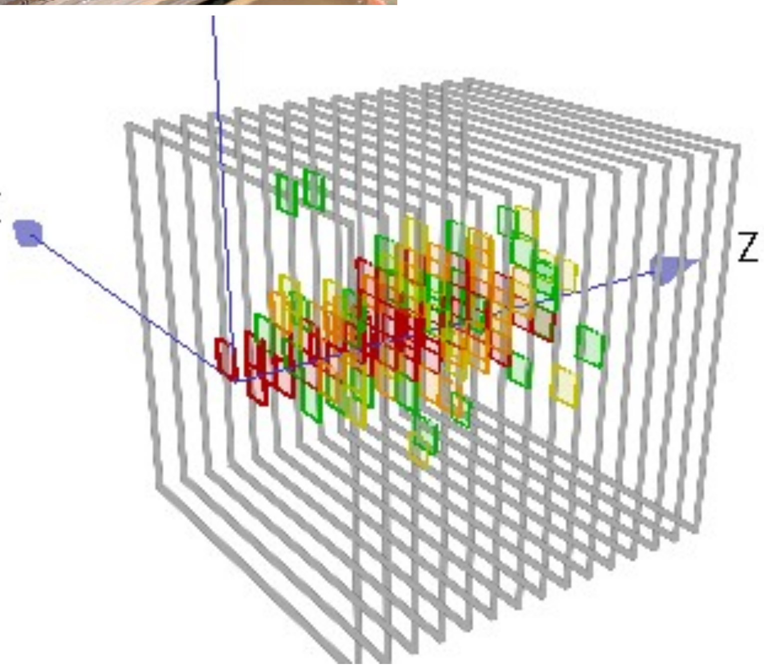
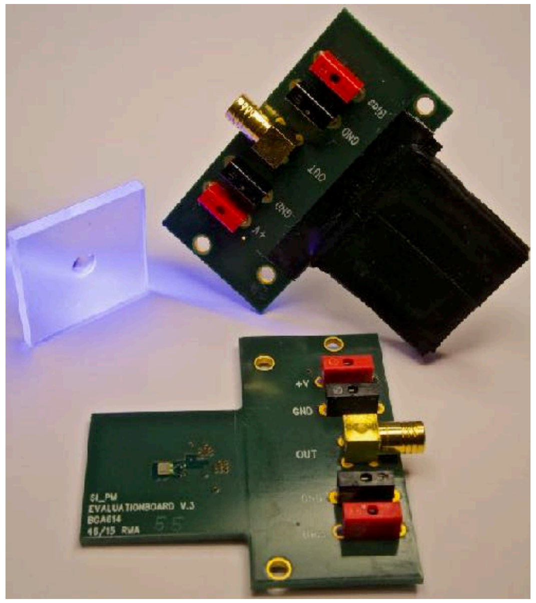


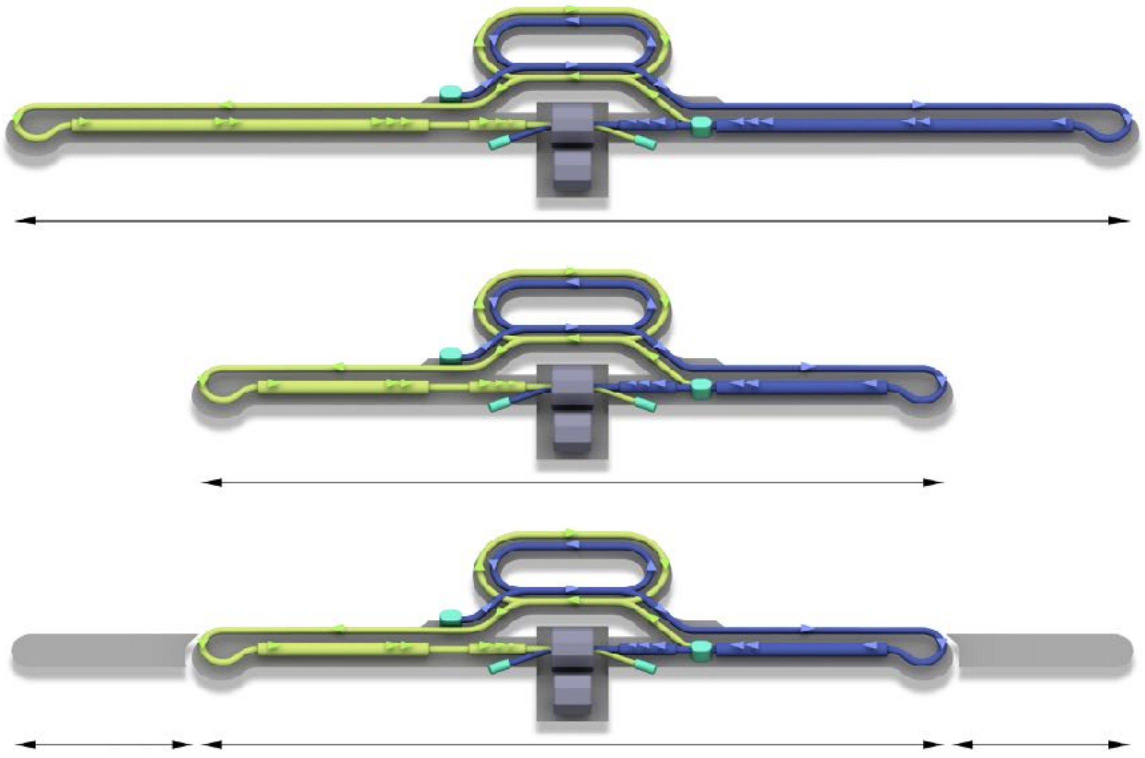


Applications of CALICE technologies



The Main Driver: Linear Colliders

- Two possibilities discussed in international contexts:



ILC, now as a staged machine starting at 250 GeV

- Stage 1: Precision Higgs physics, SM physics, BSM searches
- Top physics, substantially extended Higgs and BSM program after energy upgrade

still in discussion in Japan

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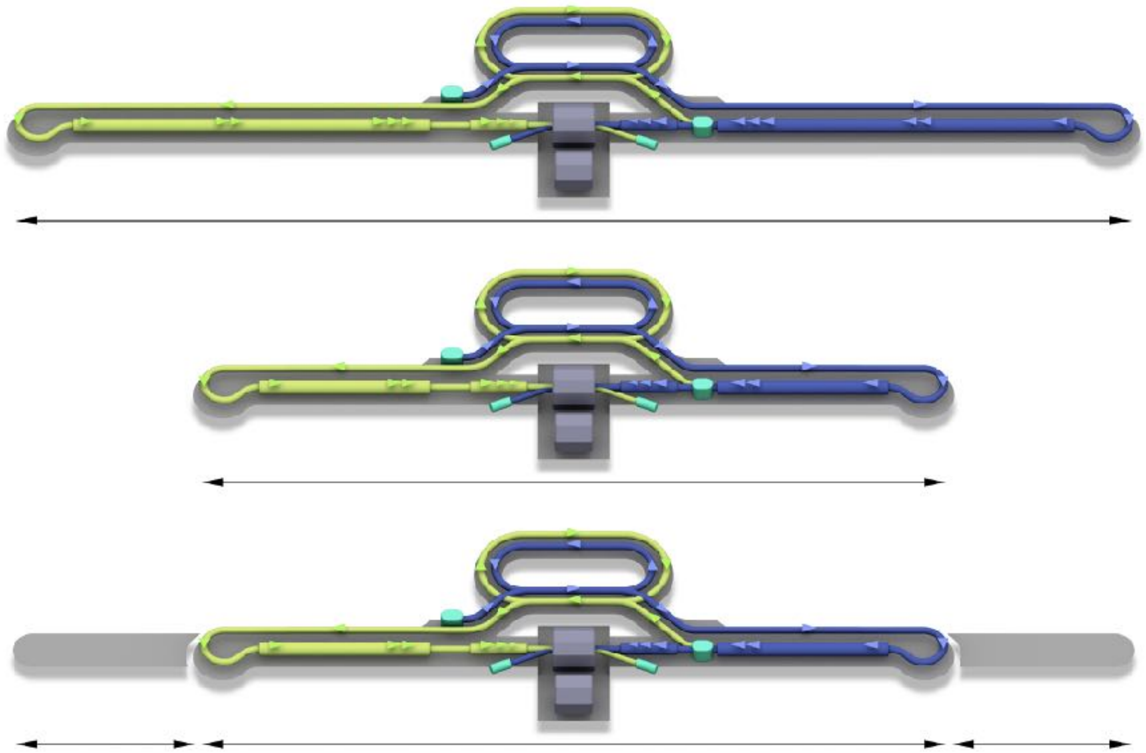

ILC, now as a staged machine starting at 250 GeV

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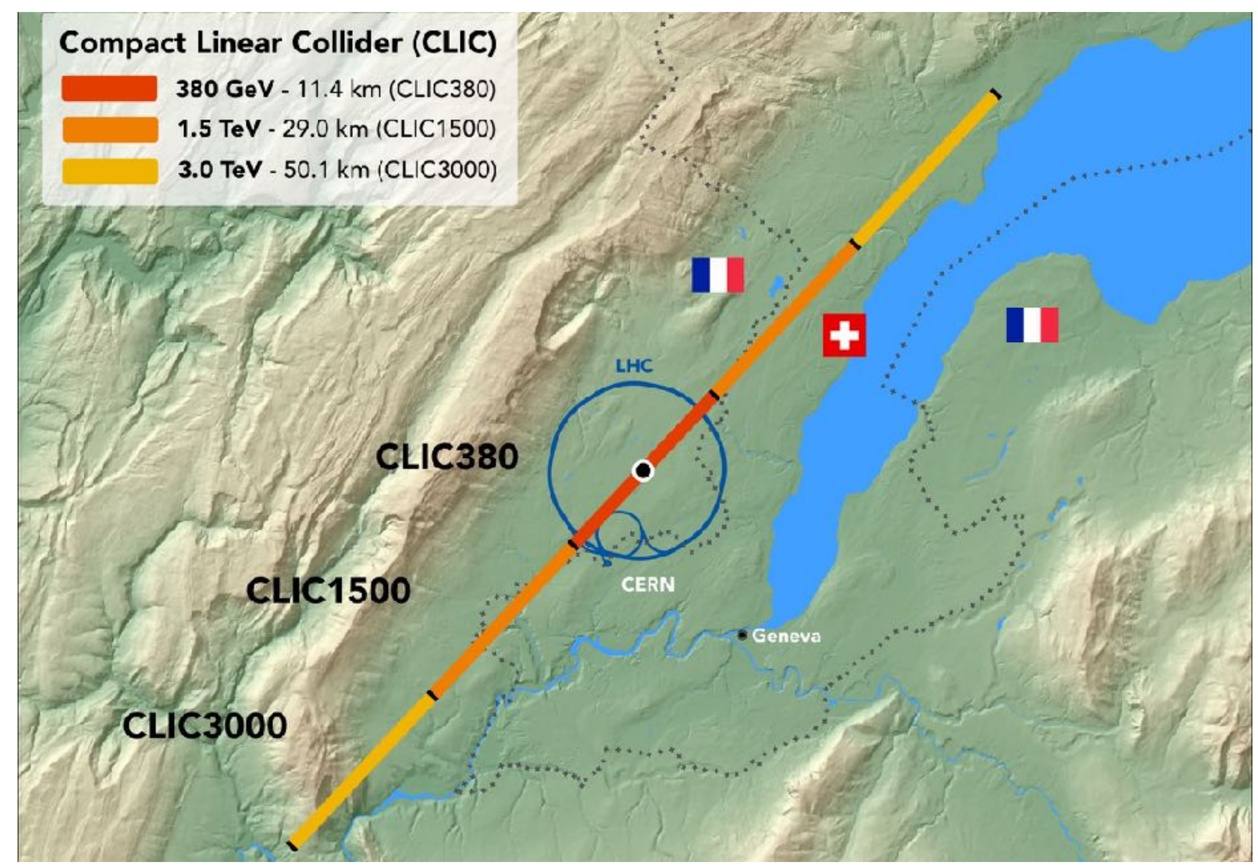
CLIC, a staged machine reaching into the multi-TeV region
starting at 380 GeV

- Stage 1: Broad precision Higgs, top and SM program, BSM searches in stage 1
- Extended BSM and Higgs program with energy upgrades, up to 3 TeV

one of the options for CERNs future

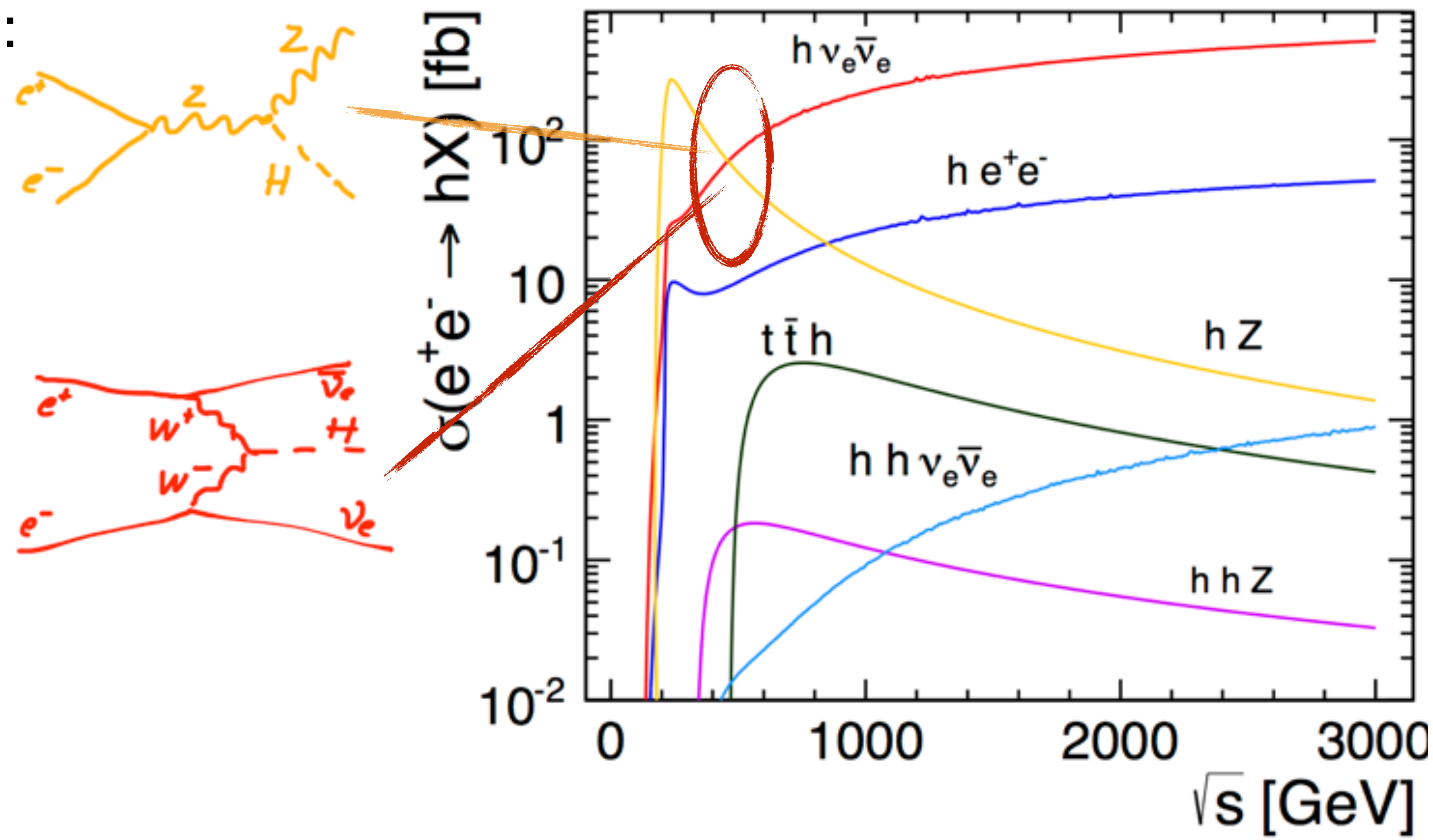


Physics: Higgs @ CLIC

- Understanding the potential for precision Higgs physics
  the study here (CLIC @ 350 GeV):

Hadronic decays of the
Higgs boson:
H -> bb, cc, gg

hard or even impossible
at the LHC



PhD Thesis Marco Szalay

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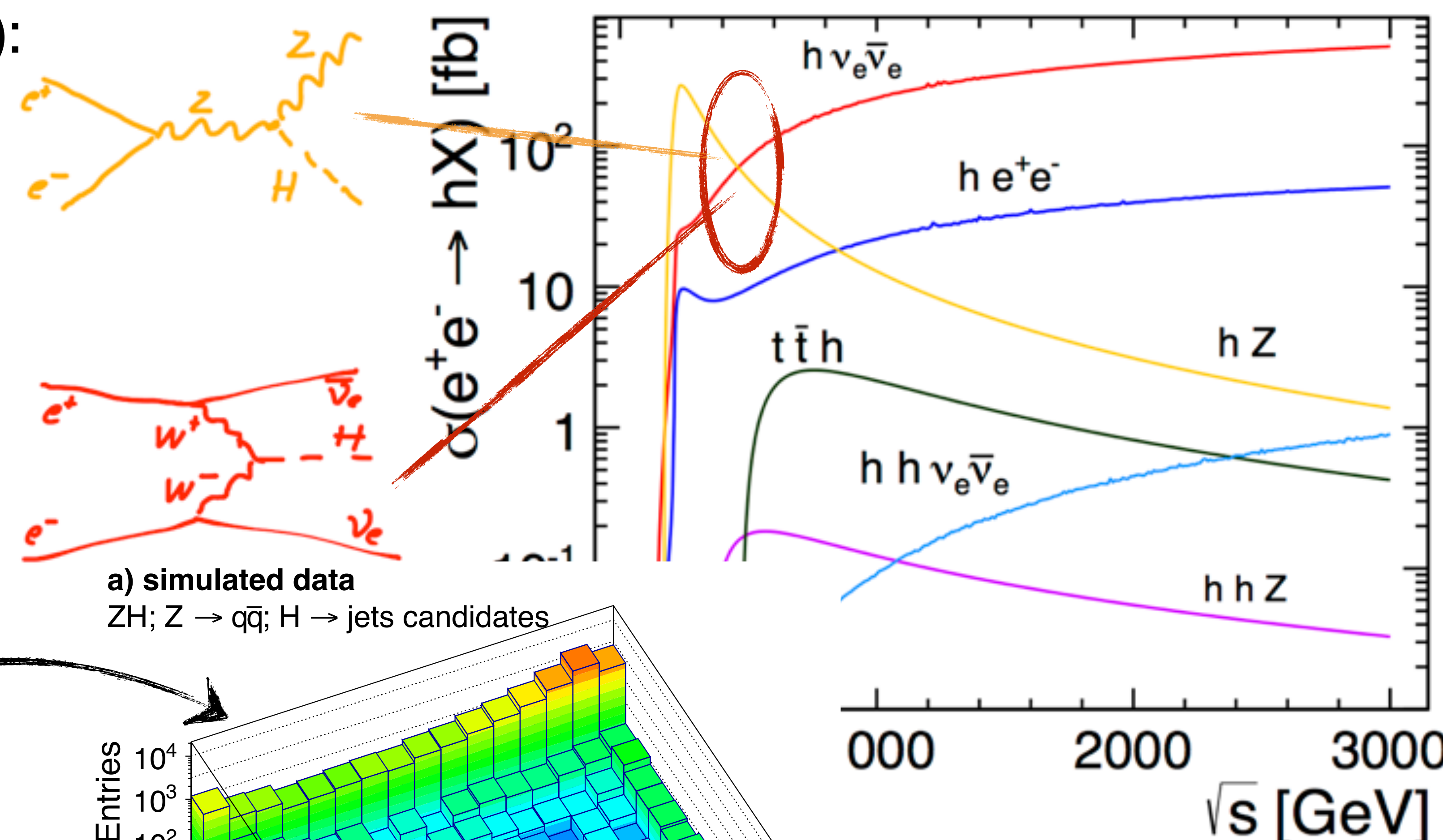

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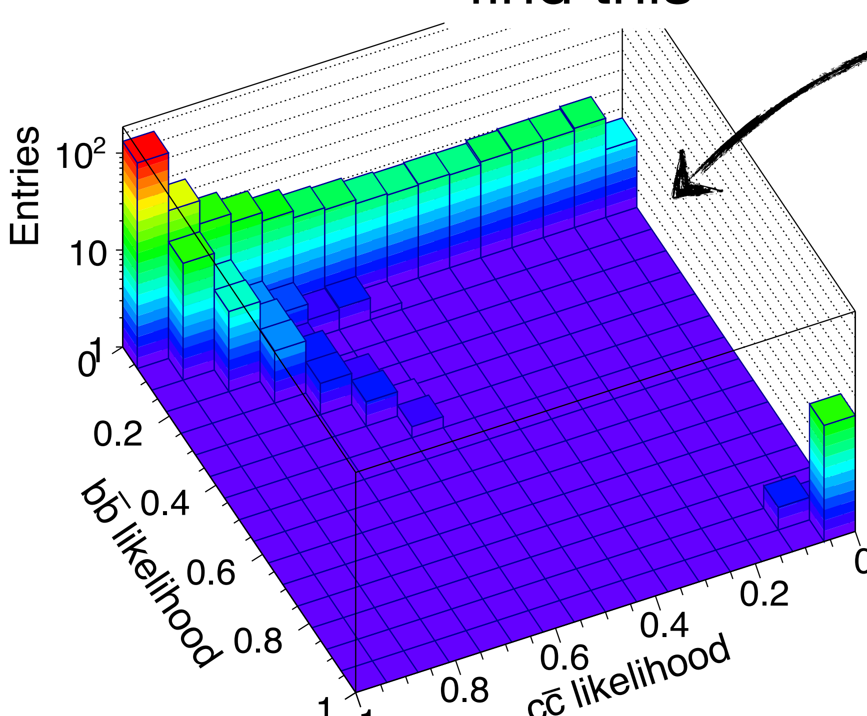
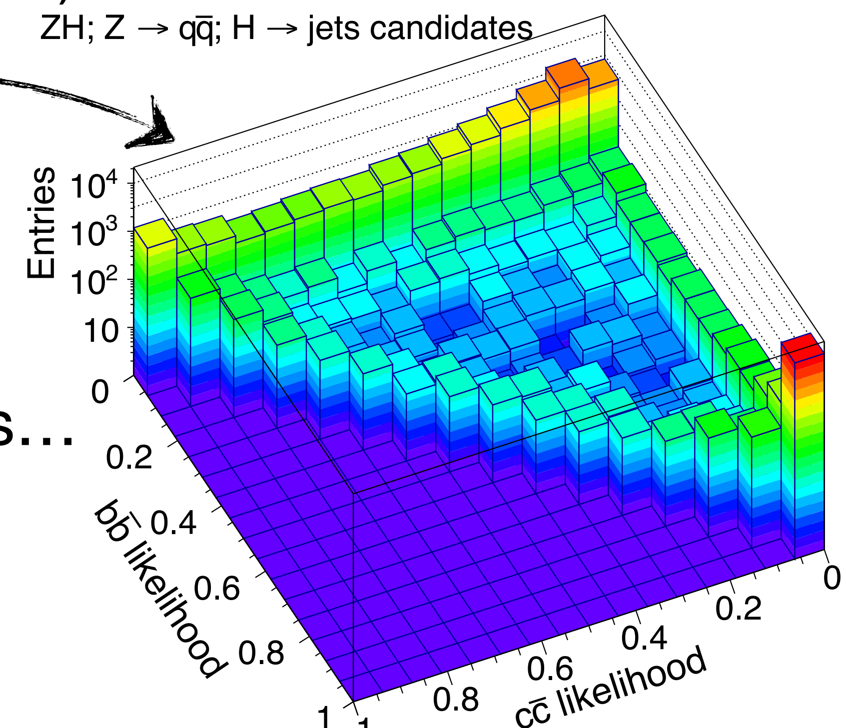
c) fit template: $c\bar{c}$
ZH; $Z \to q\bar{q}$; $H \to c\bar{c}$

find this



in this…

a) simulated data
ZH; $Z \to q\bar{q}$; $H \to$ jets candidates



PhD Thesis Marco Szalay

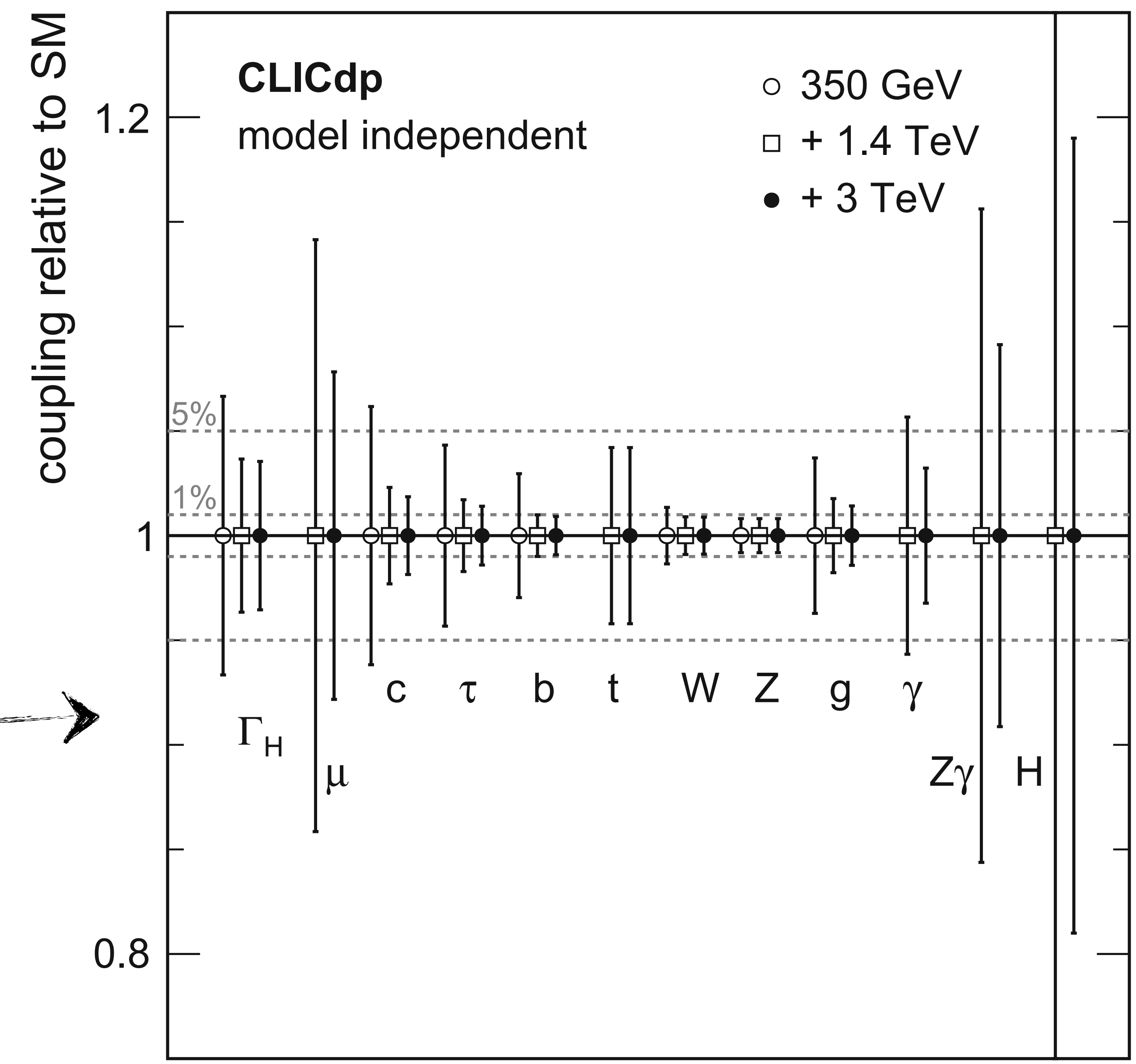
Physics: Higgs @ CLIC

- Taking projected uncertainties from full detector simulations

Decay	Statistical uncertainty	
	Higgsstrahlung (%)	WW-fusion (%)
$H \to b\bar{b}$	0.86	1.9
$H \to c\bar{c}$	14	26
$H \to gg$	6.1	10

350 GeV

… and combining them with many other studies at the three CLIC energy stages in a global fit



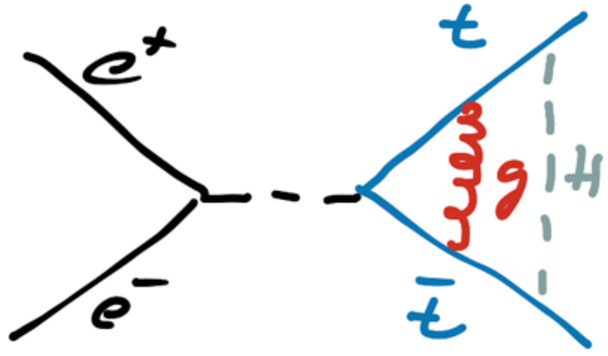
results in sub-1% - level precision for key couplings in a model-independent framework

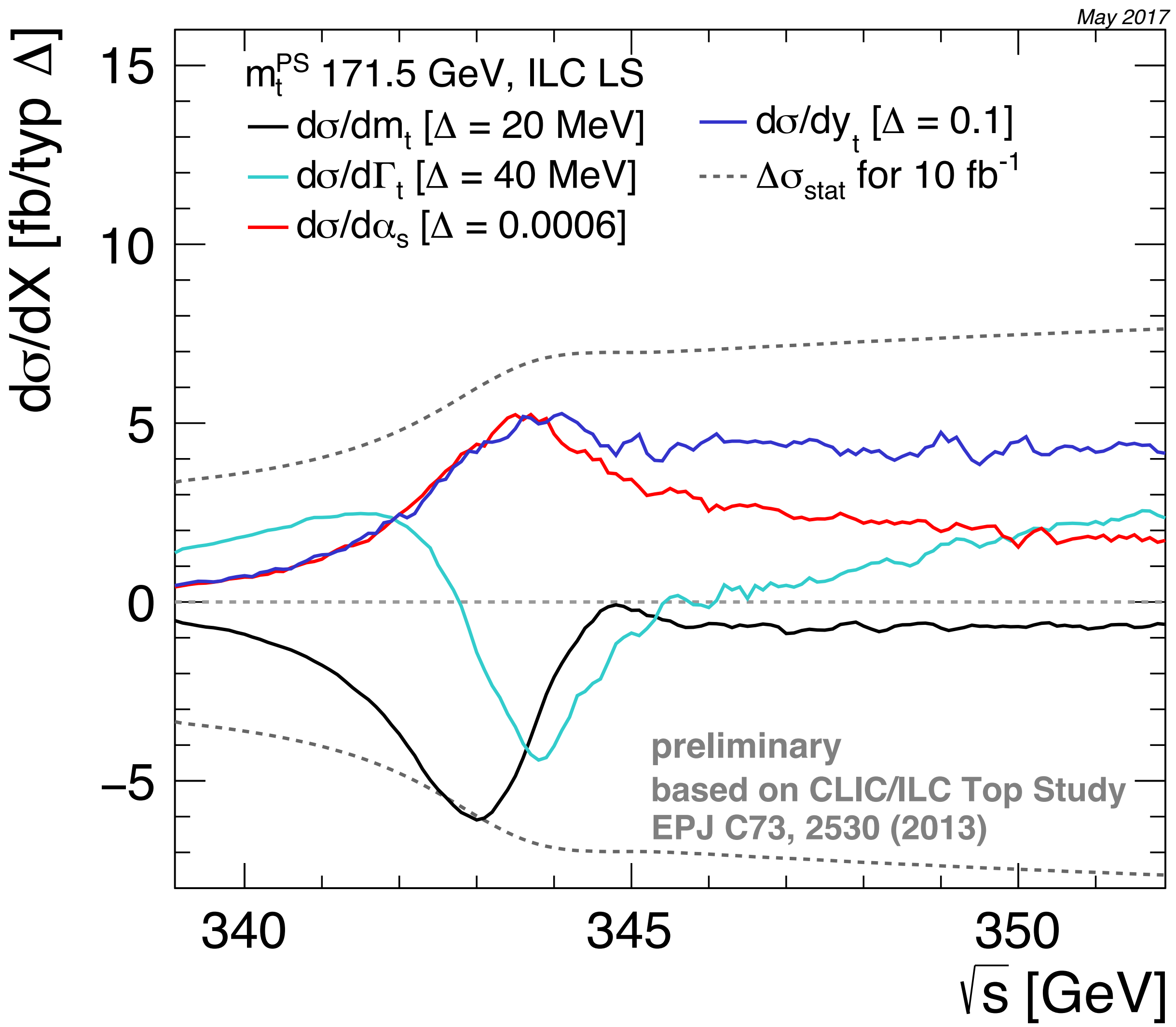
few per-mille when using the “kappa framework”

Higgs Physics at CLIC: EPJC 77, 475 (2017)

Physics: The Top Threshold

- Understanding the physics potential of a top threshold scan in e^+e^- colliders - taking into account latest theory uncertainties





top mass with ~ 10 - 20 MeV (stat)
with reasonable luminosity assumptions

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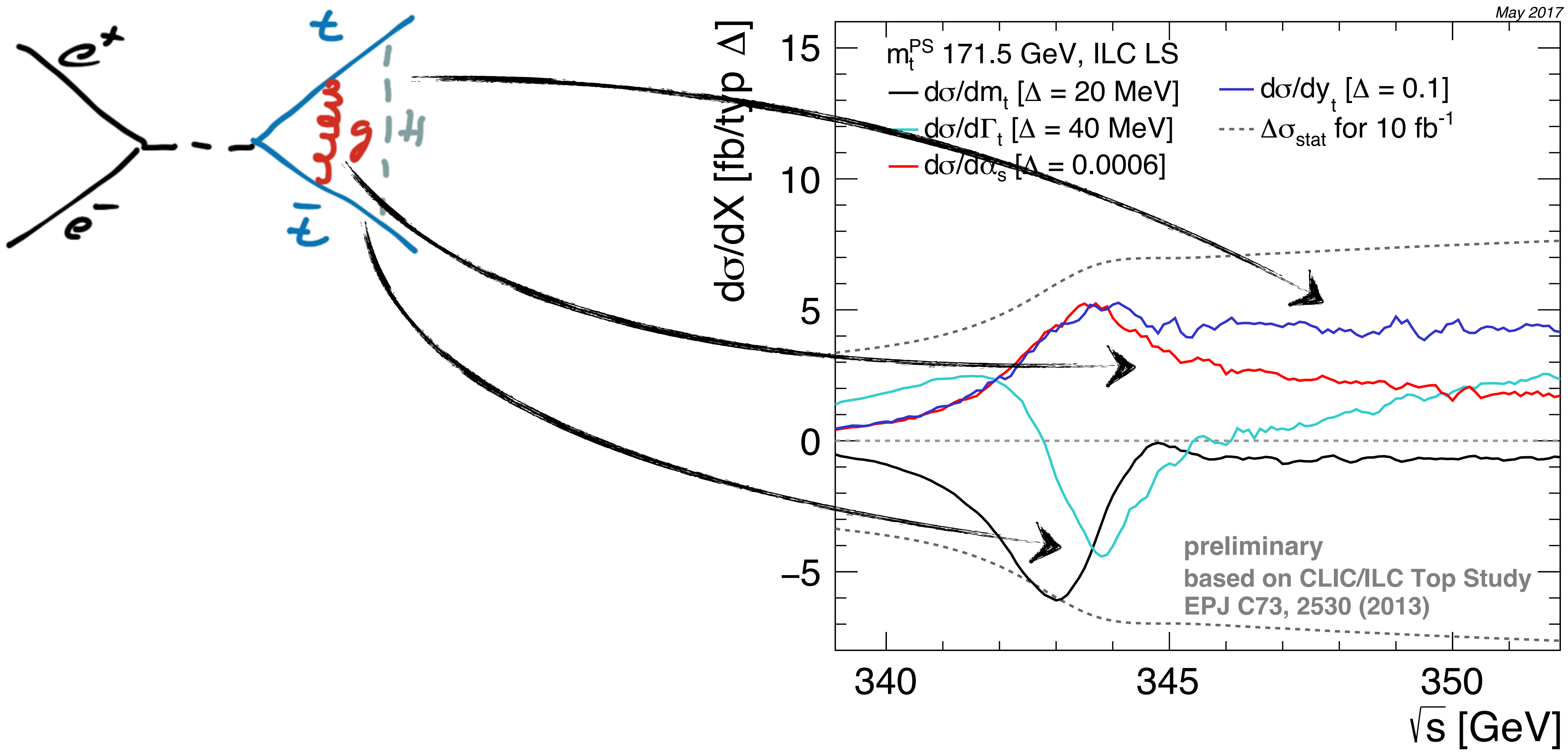

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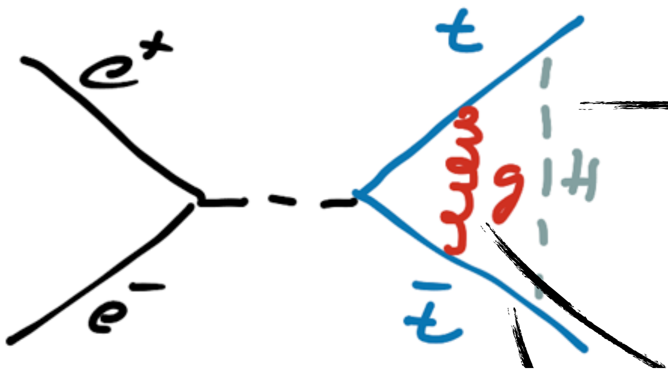

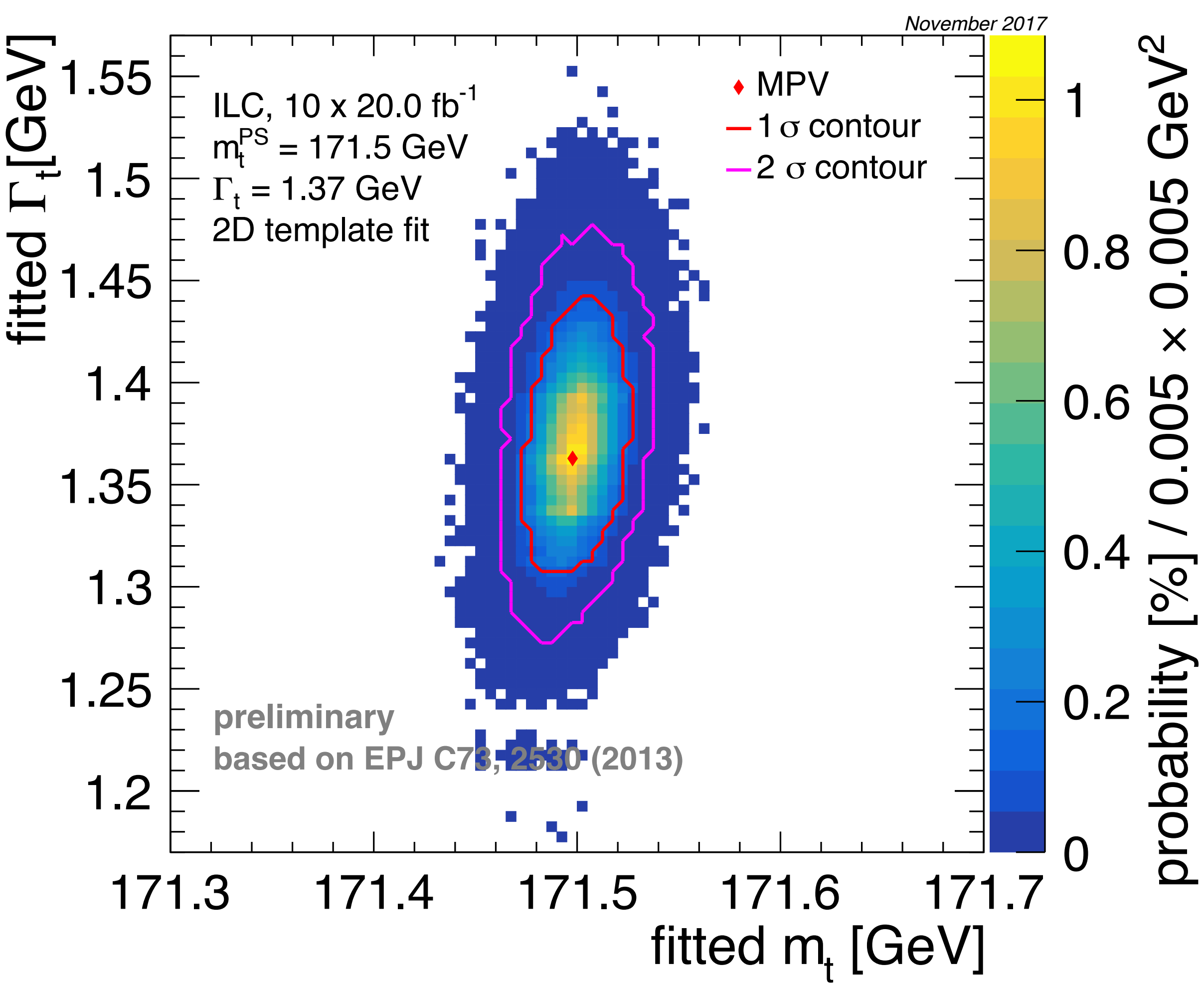

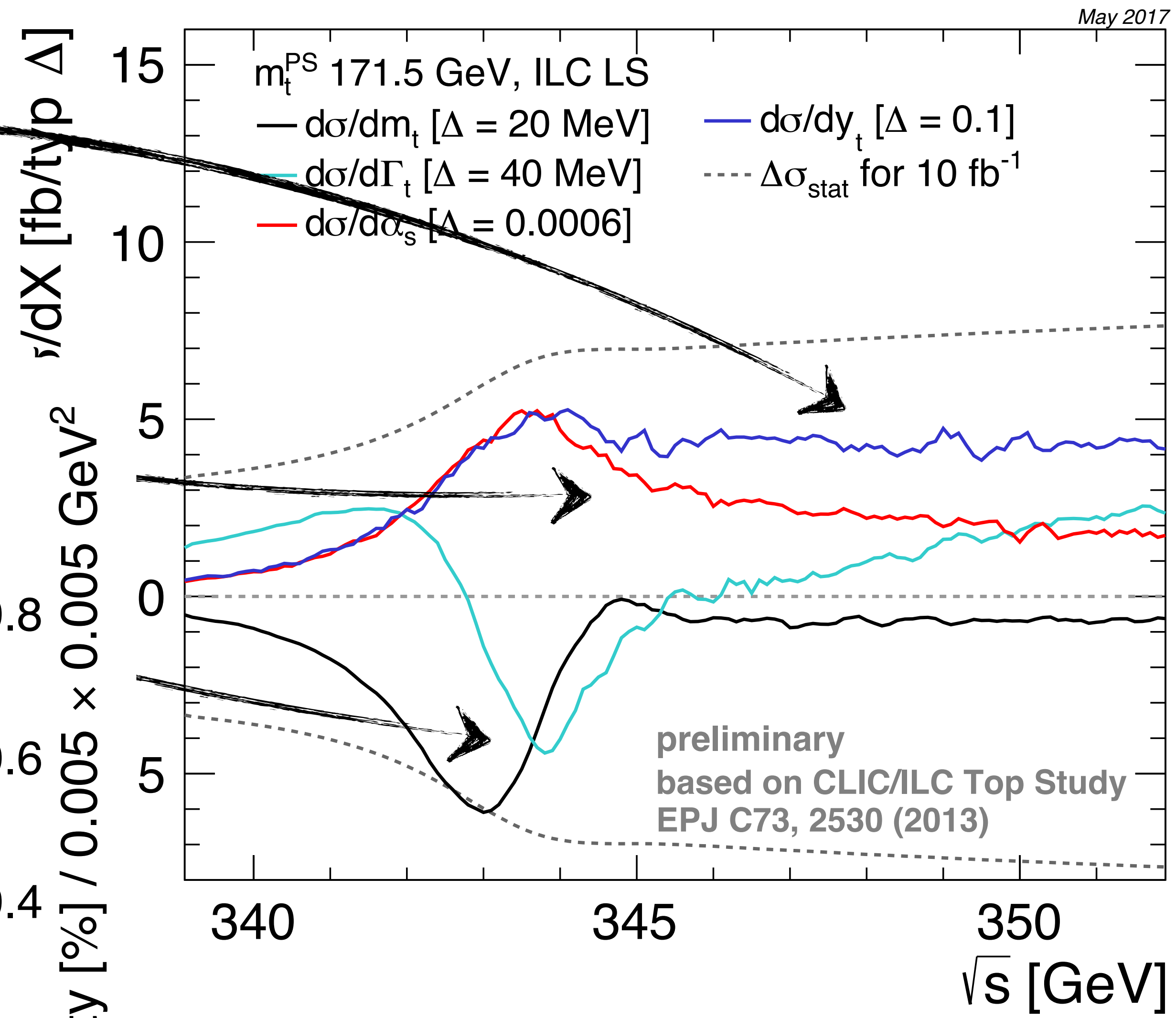

top mass with ~ 10 - 20 MeV (stat) with reasonable luminosity assumptions

2D extraction of parameters (m_t, Γ_t) also possible from cross section alone

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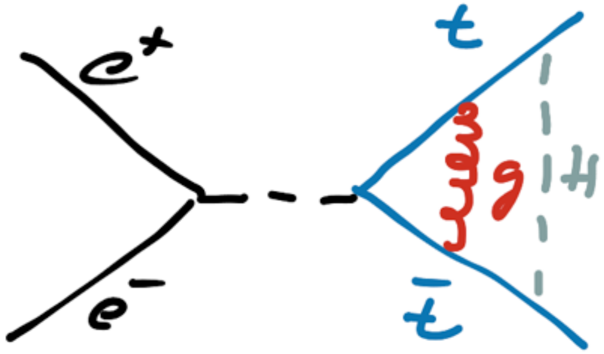
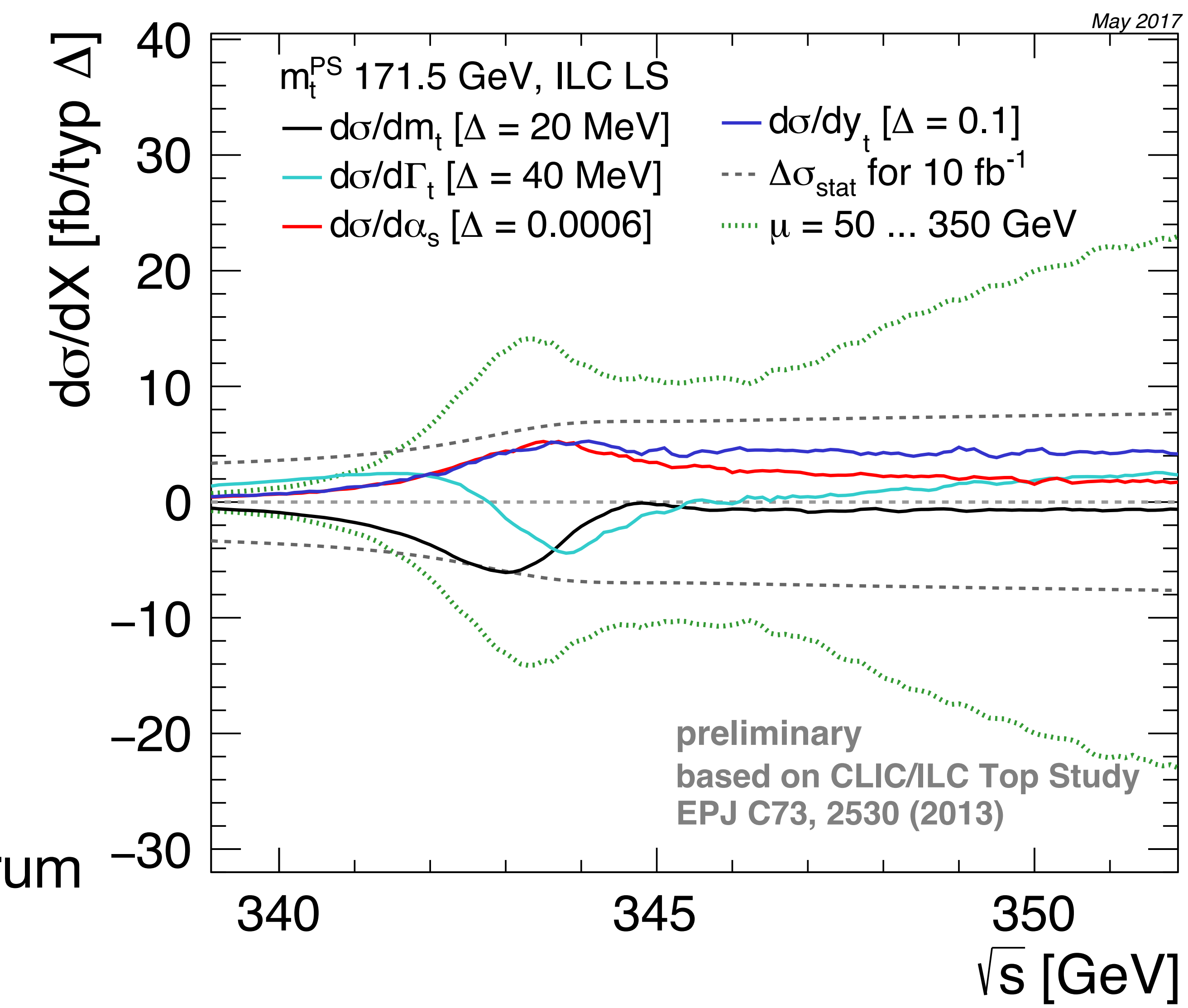


NNNLO QCD scale uncertainties (collaboration with M. Beneke et al.) change the picture a bit:

Scale uncertainties introduce a ~ 40 MeV uncertainty on the mass, that is largely independent of the collider luminosity spectrum



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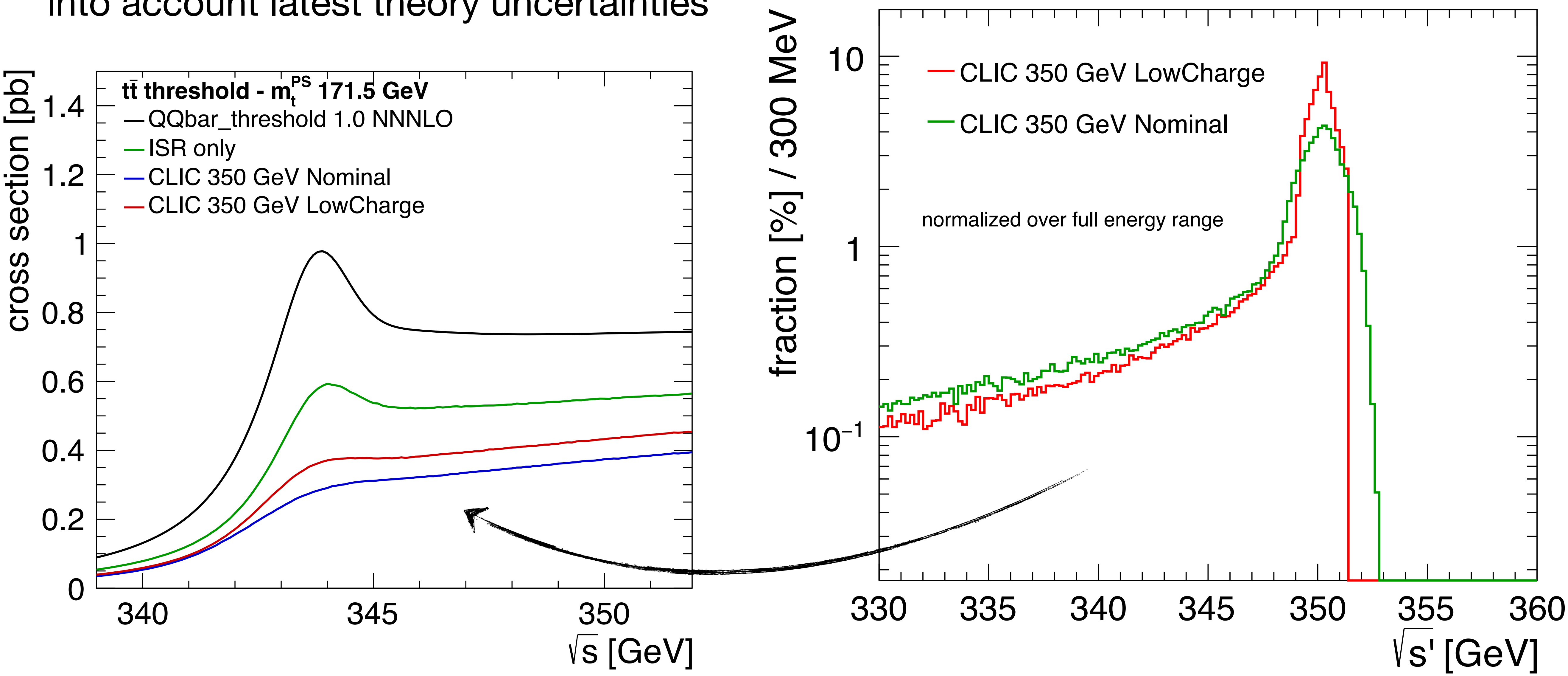

Not entirely true for extreme broadening - and high lumi quality also important for multi-parameter measurements: Advantage for rings, re-examining possibilities for a tuning of the luminosity spectrum of CLIC

ongoing study with CLIC machine group for CLIC top physics paper

CALICE: Towards a Technological Prototype

- Years of development on various technological details of scintillator-based highly granular hadronic calorimeters are now being put to a concrete test:
  The CALICE AHCAL Technological prototype

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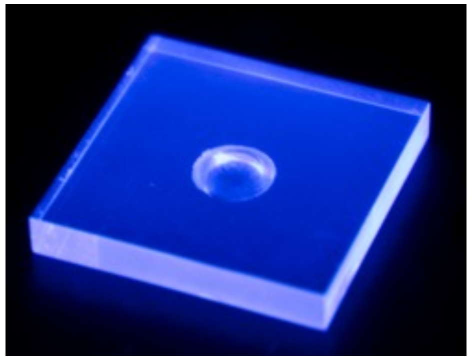

Scintillator tiles for direct readout with SiPMs
original developments at MPP, then Mainz
detailed tests at MPP

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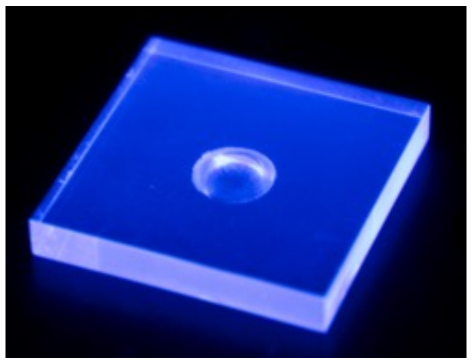

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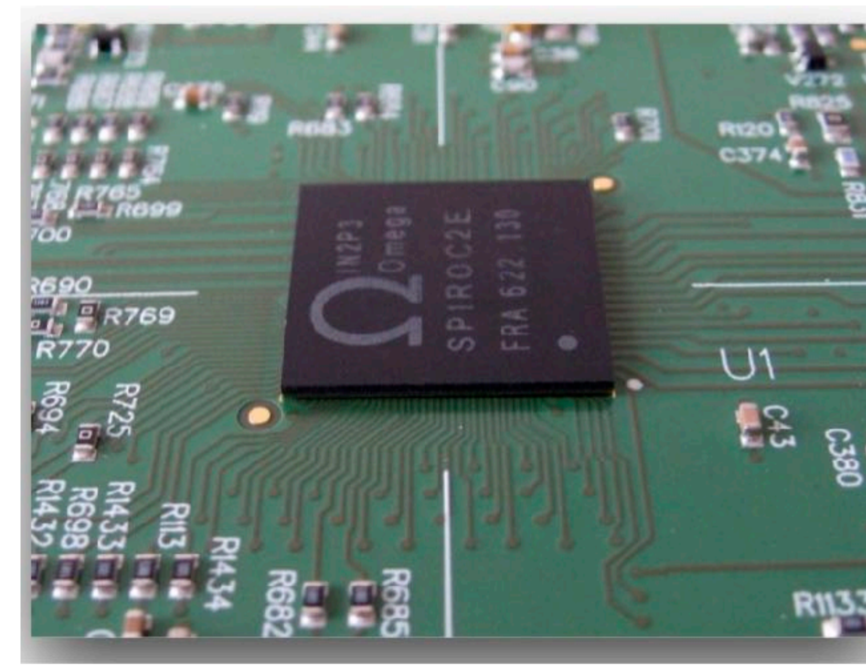
Combined with integrated electronics
(DESY, ASICs from OMEGA)



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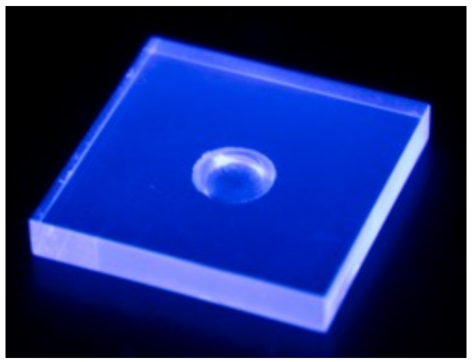

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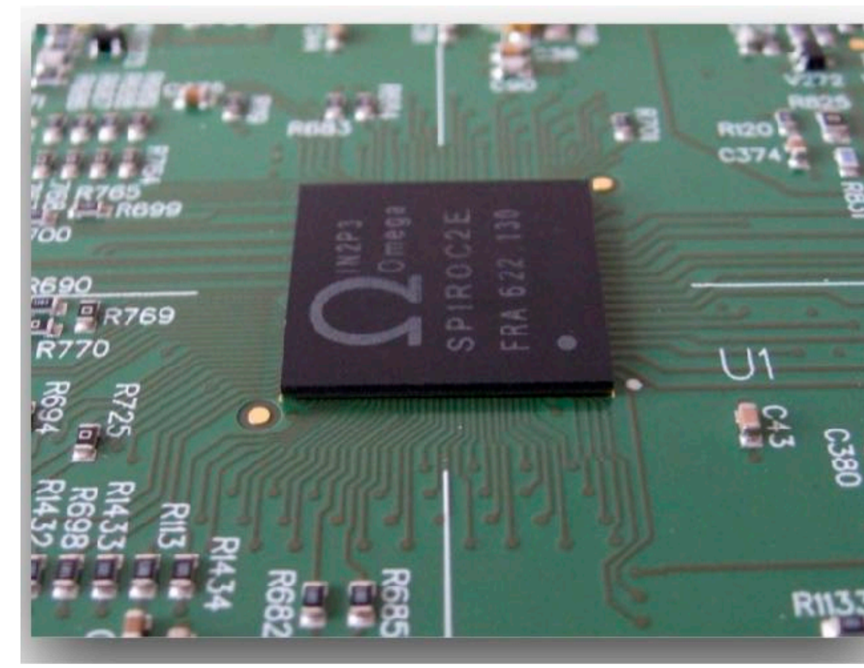

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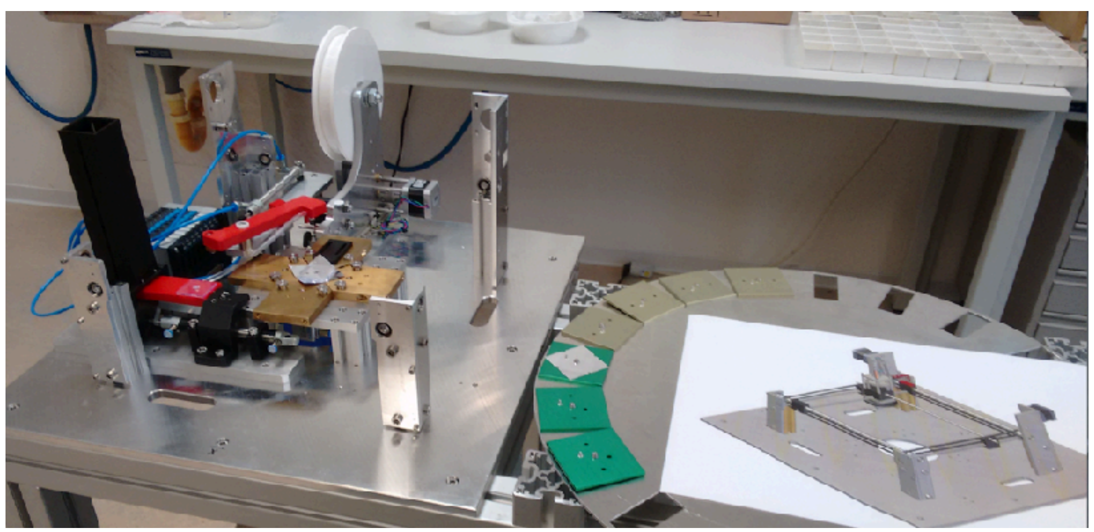

Automatic wrapping
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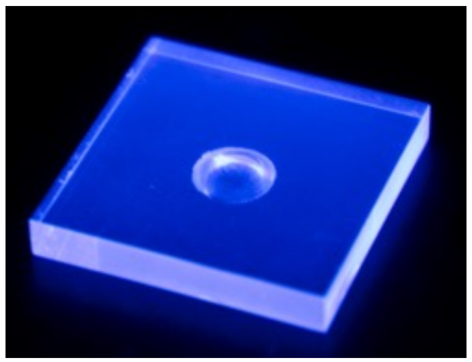

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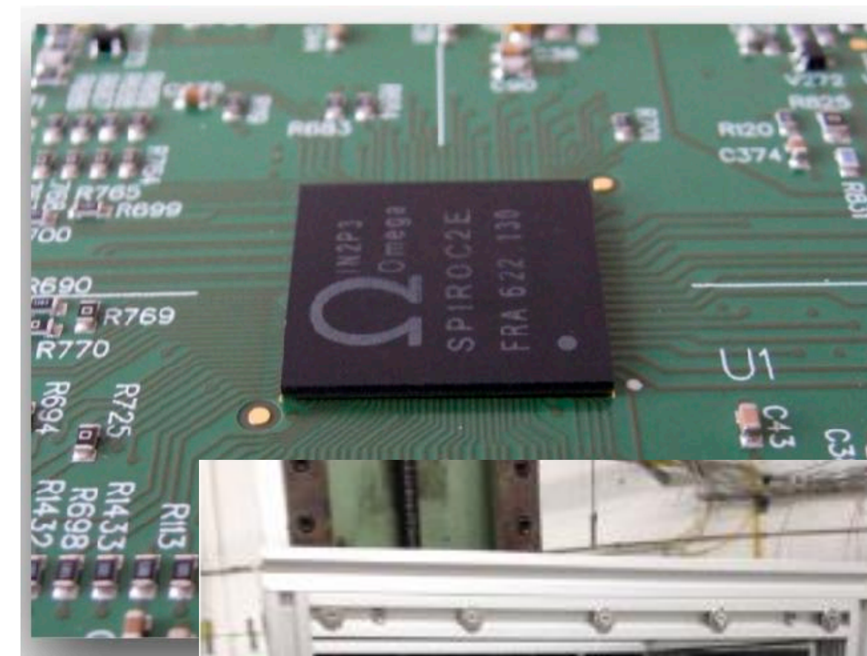

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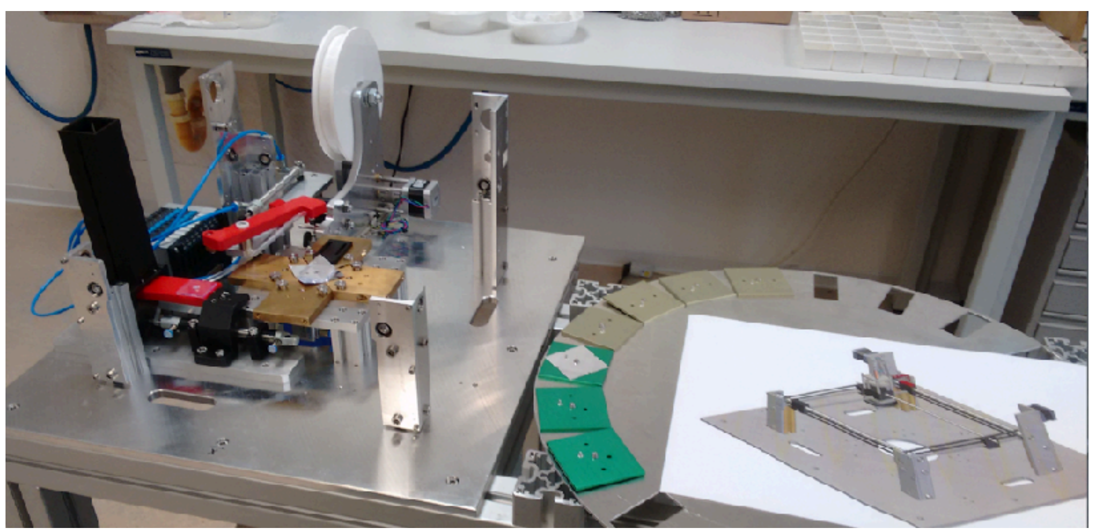
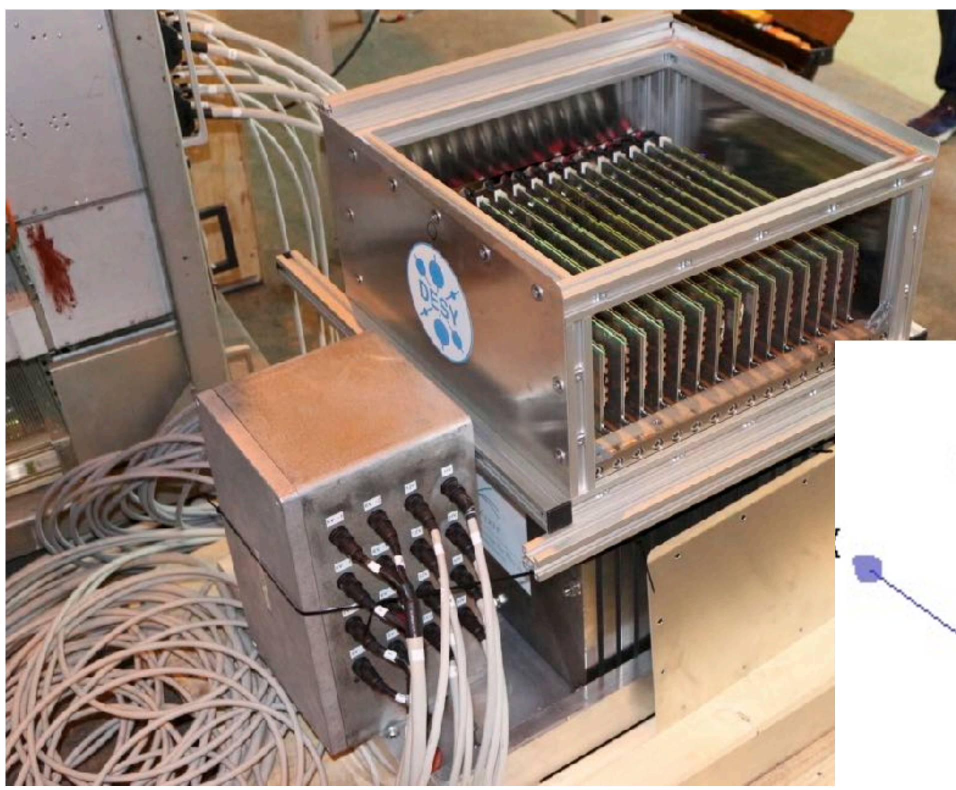


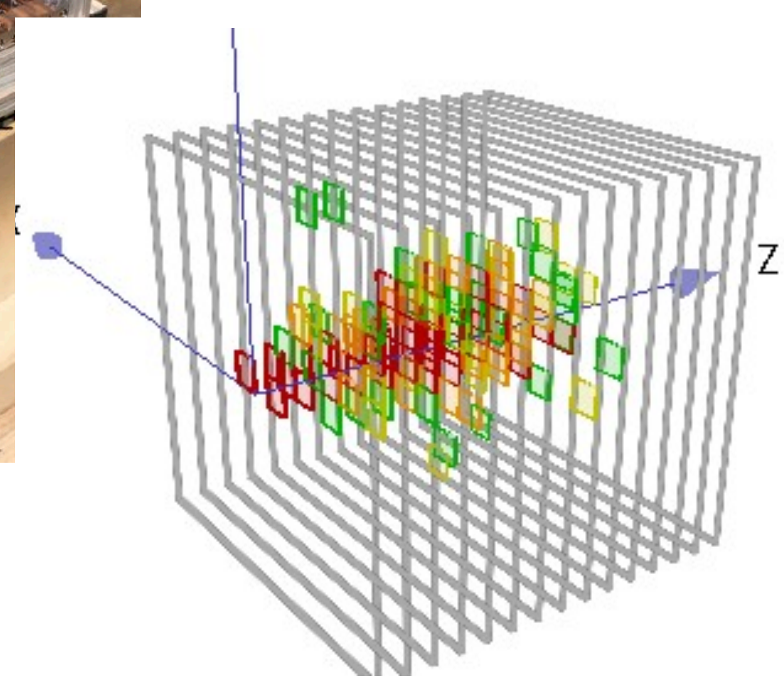
Automatic wrapping and placing of tiles (UHH, Mainz)

Inserted in non-magnetic precision absorber structures (MPP)

CALICE: Test Beams, Test Beams, Test Beams…

- Tests of a compact “em prototype) with electrons in fields up to 3T in summer
    - Proof of principle of power pulsing in strong magnetic fields: Involved the construction of “magnet-safe” power distribution at MPP





Christian Graf

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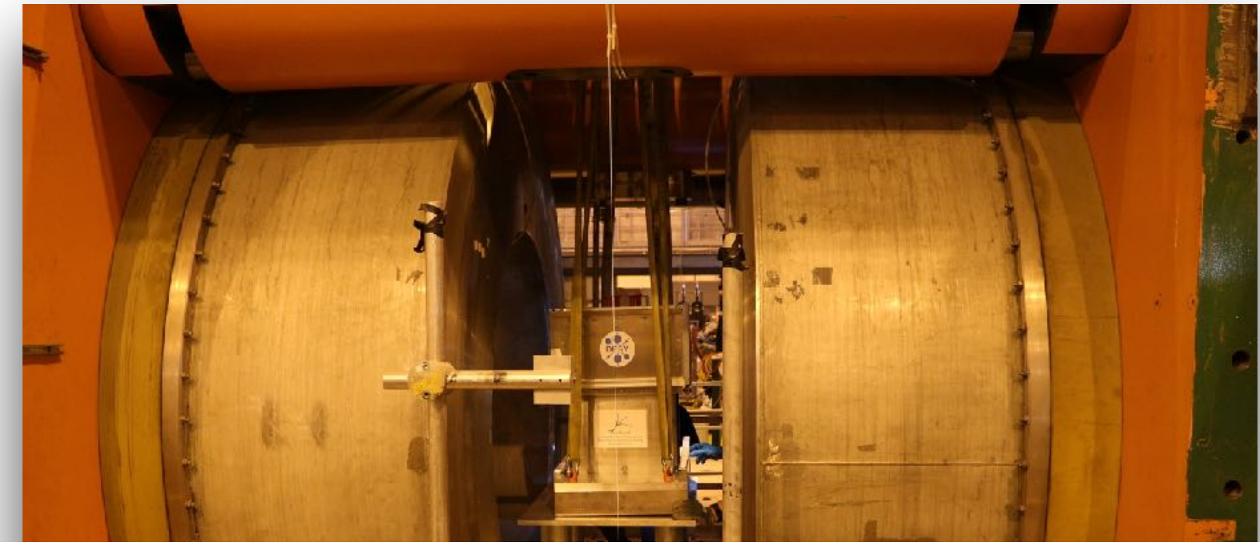

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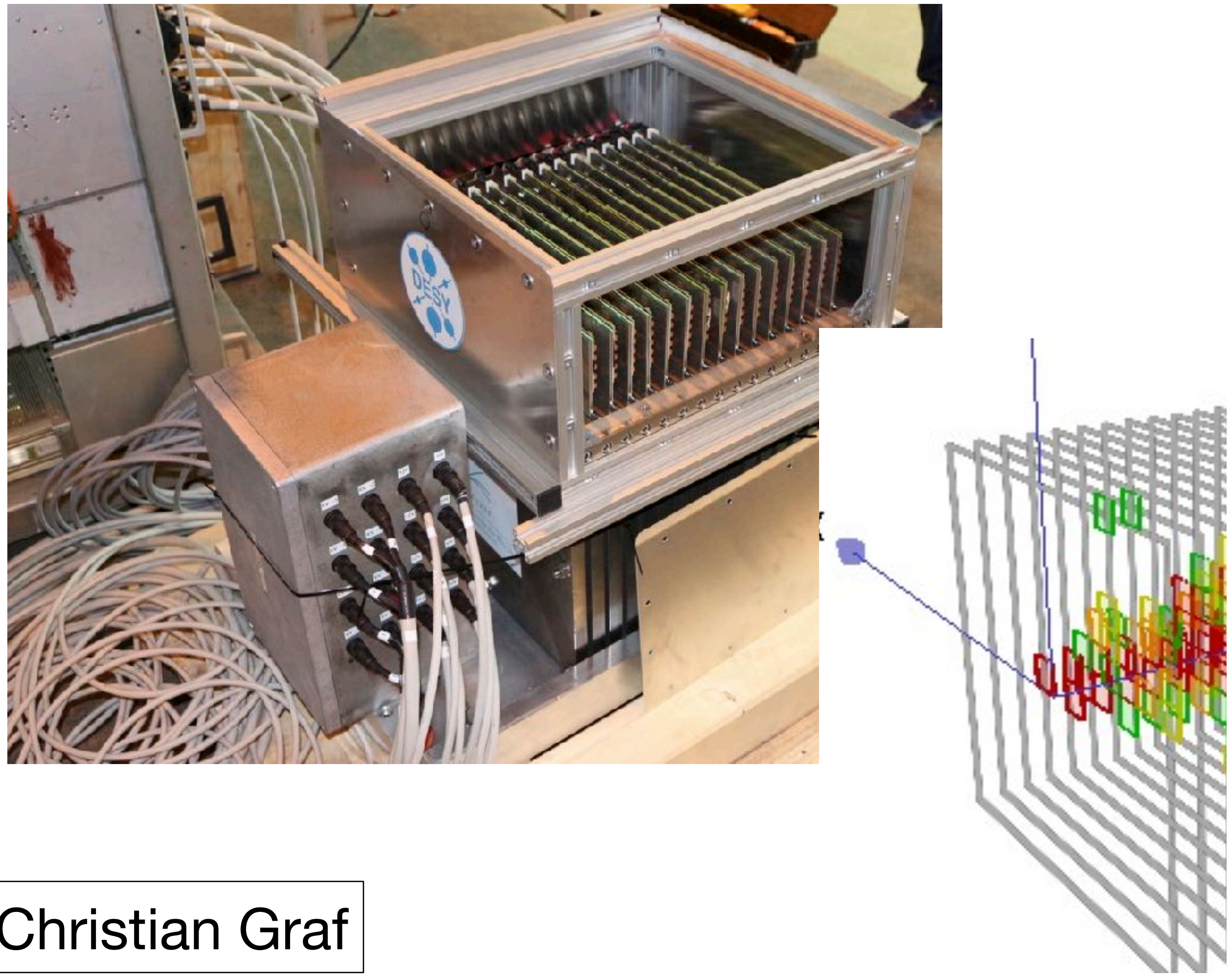

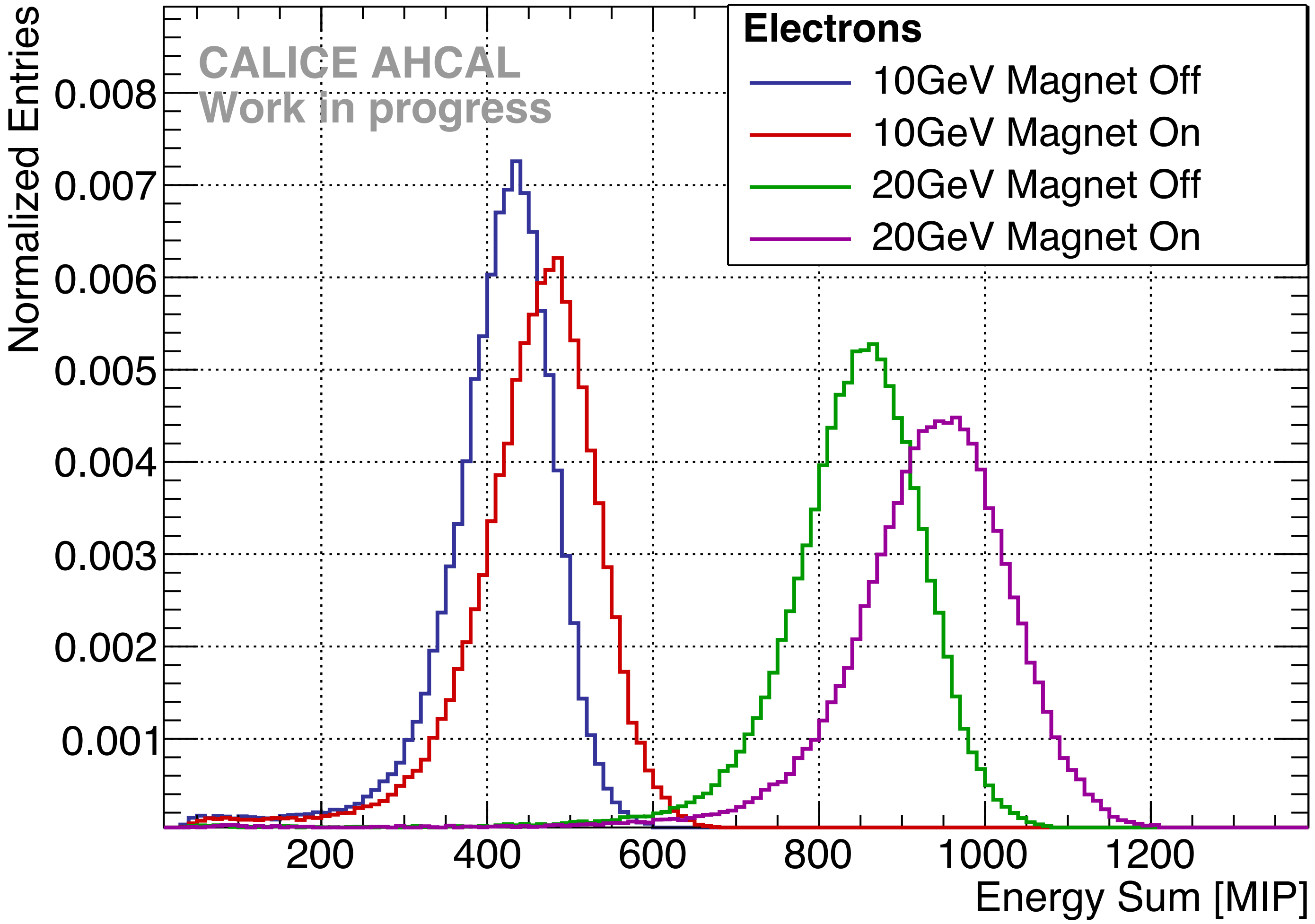

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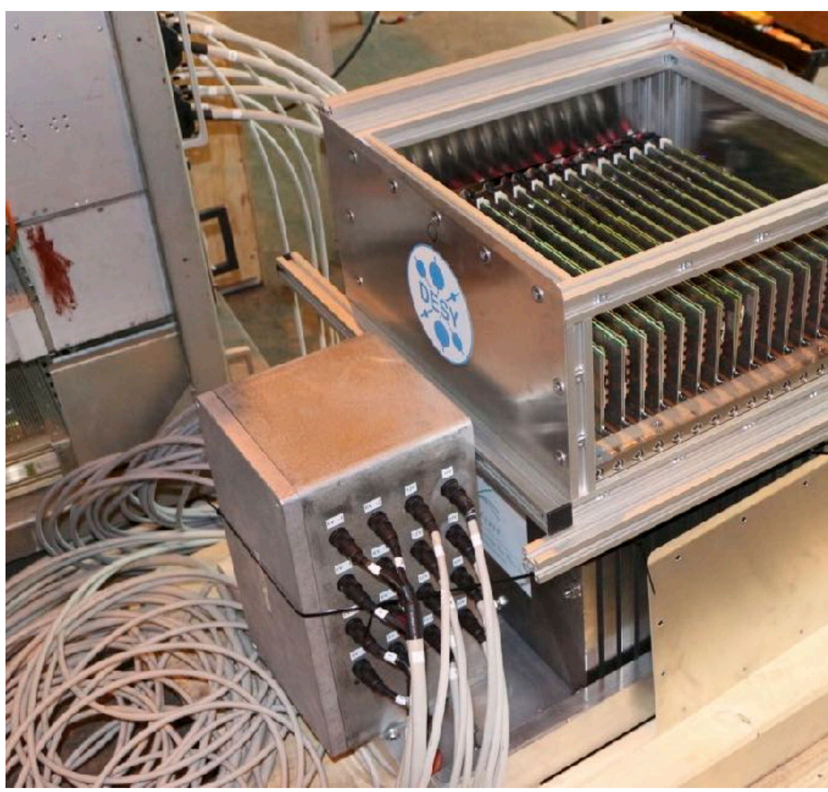

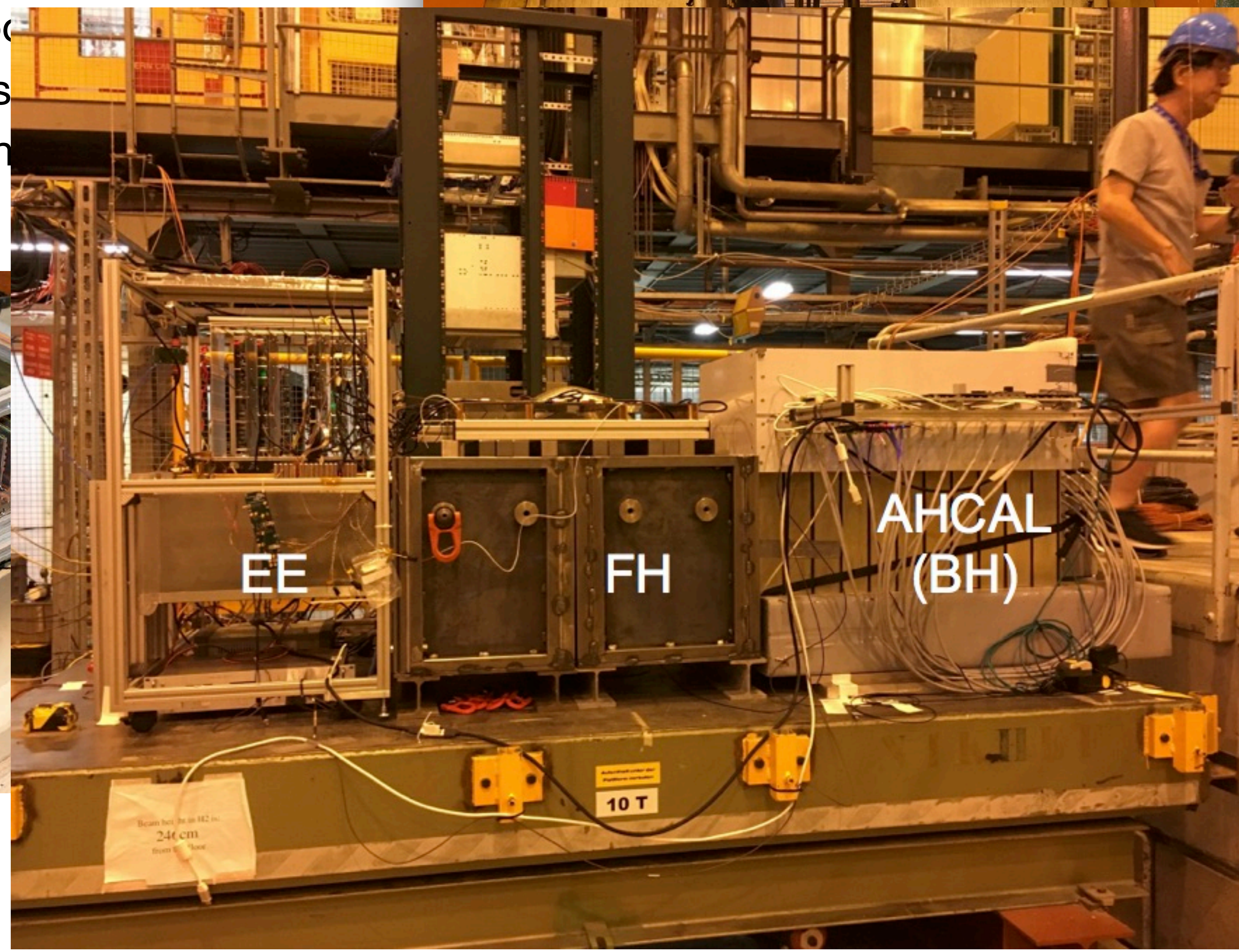

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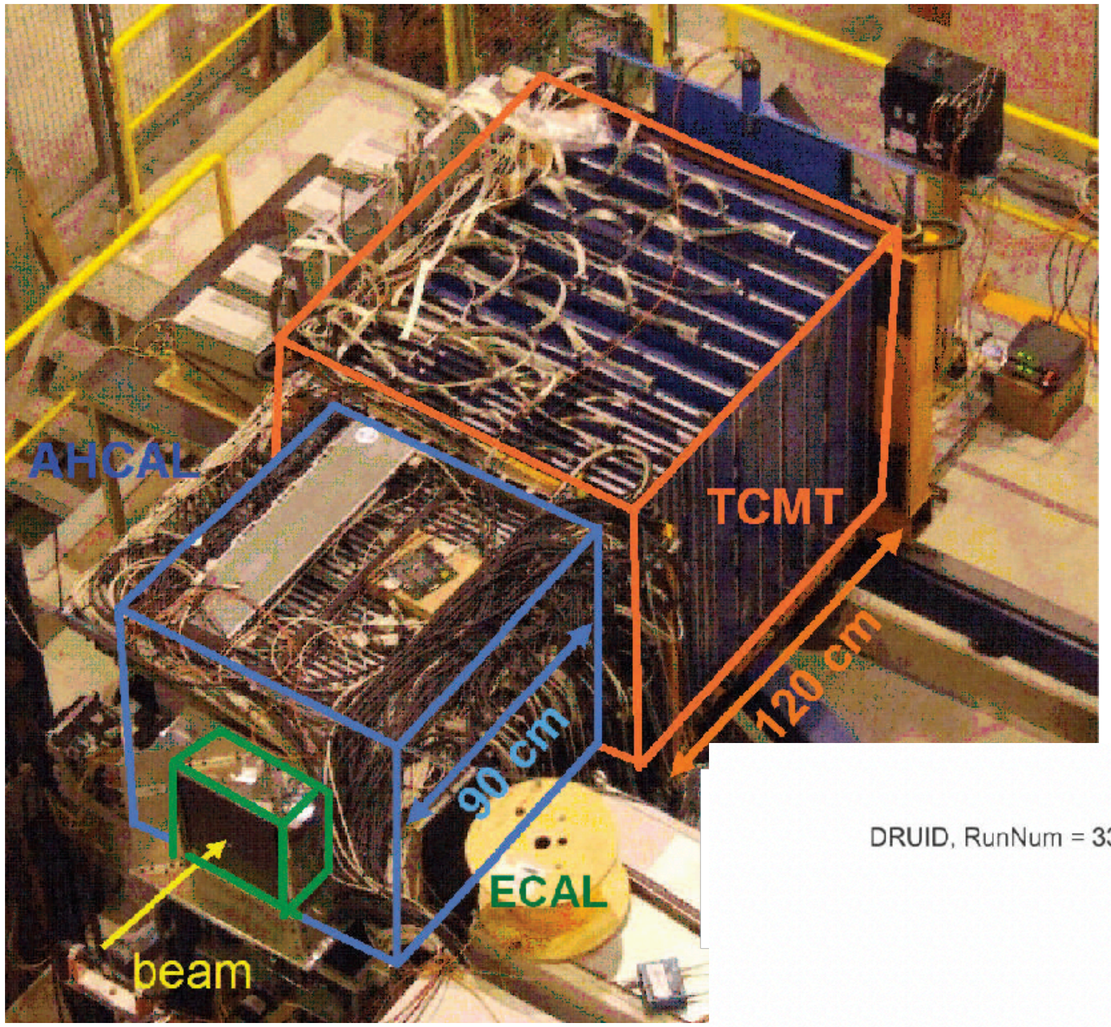
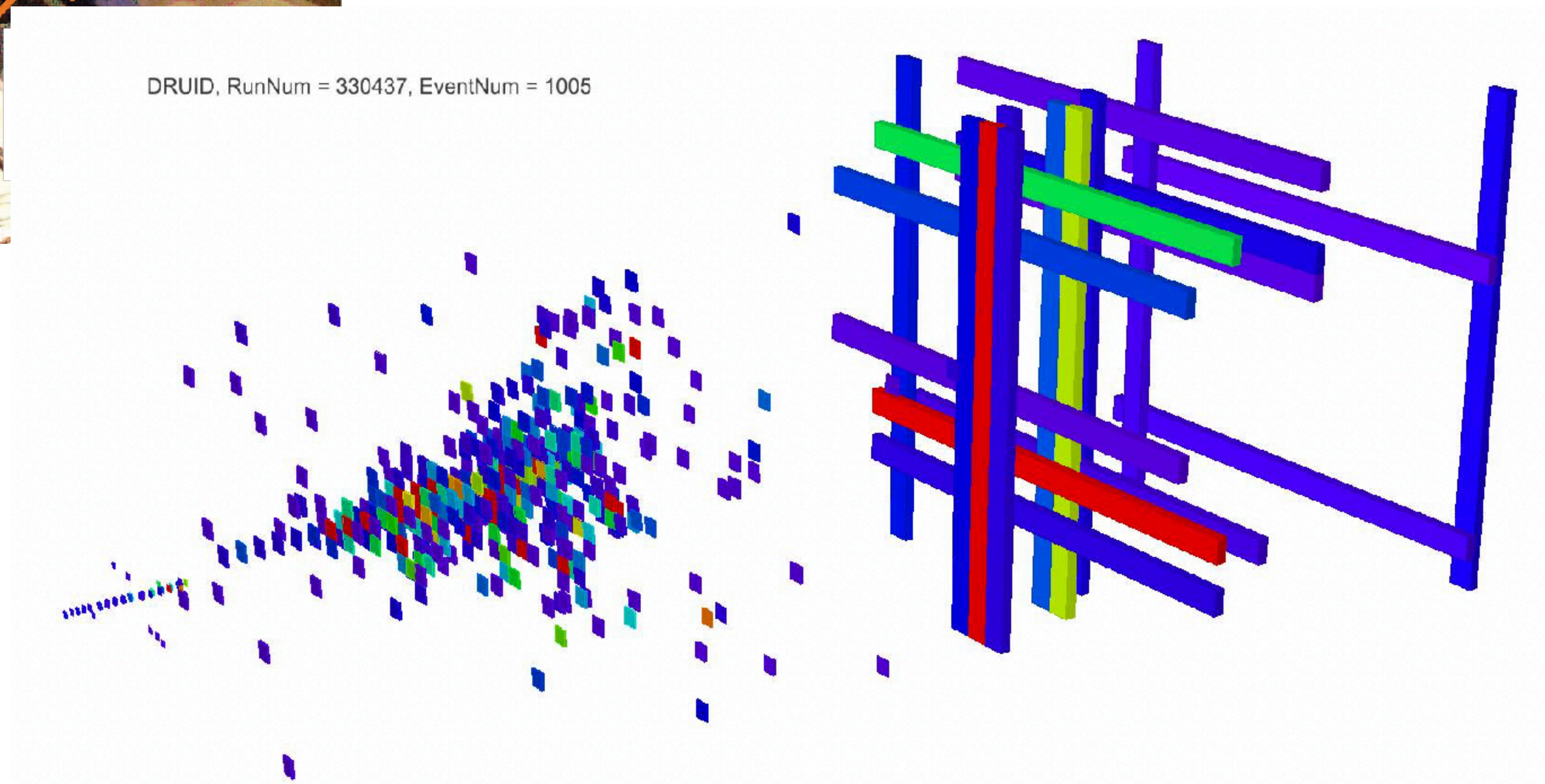
CALICE: Energy Reconstruction & PFA



- Studying energy resolution in a “real-world” setting: A combined system of SiW ECAL, Scintillator/FE HCAL, Tail Catcher
- Exploiting granularity: Local energy density can be used to improve energy resolution with software compensation methods



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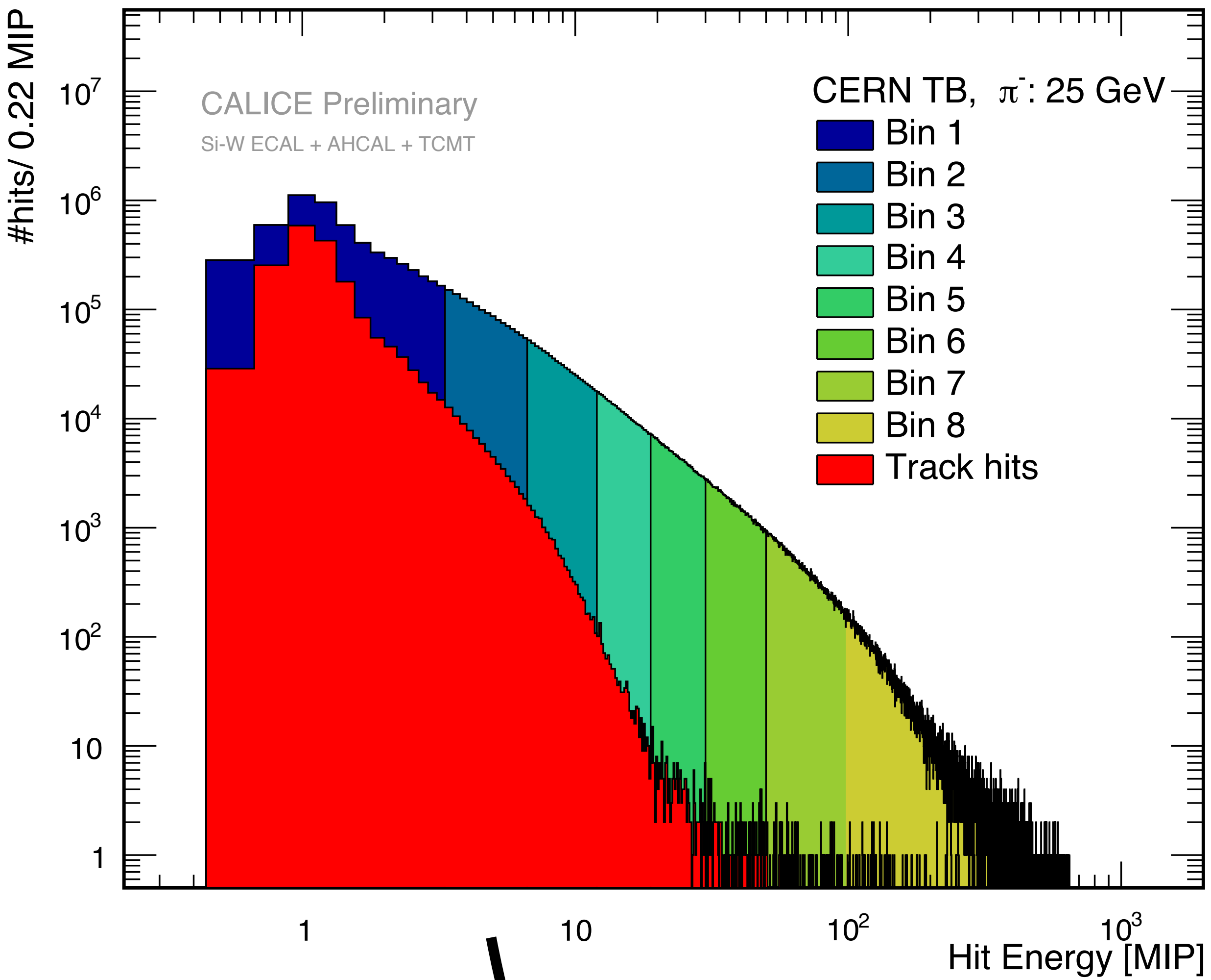
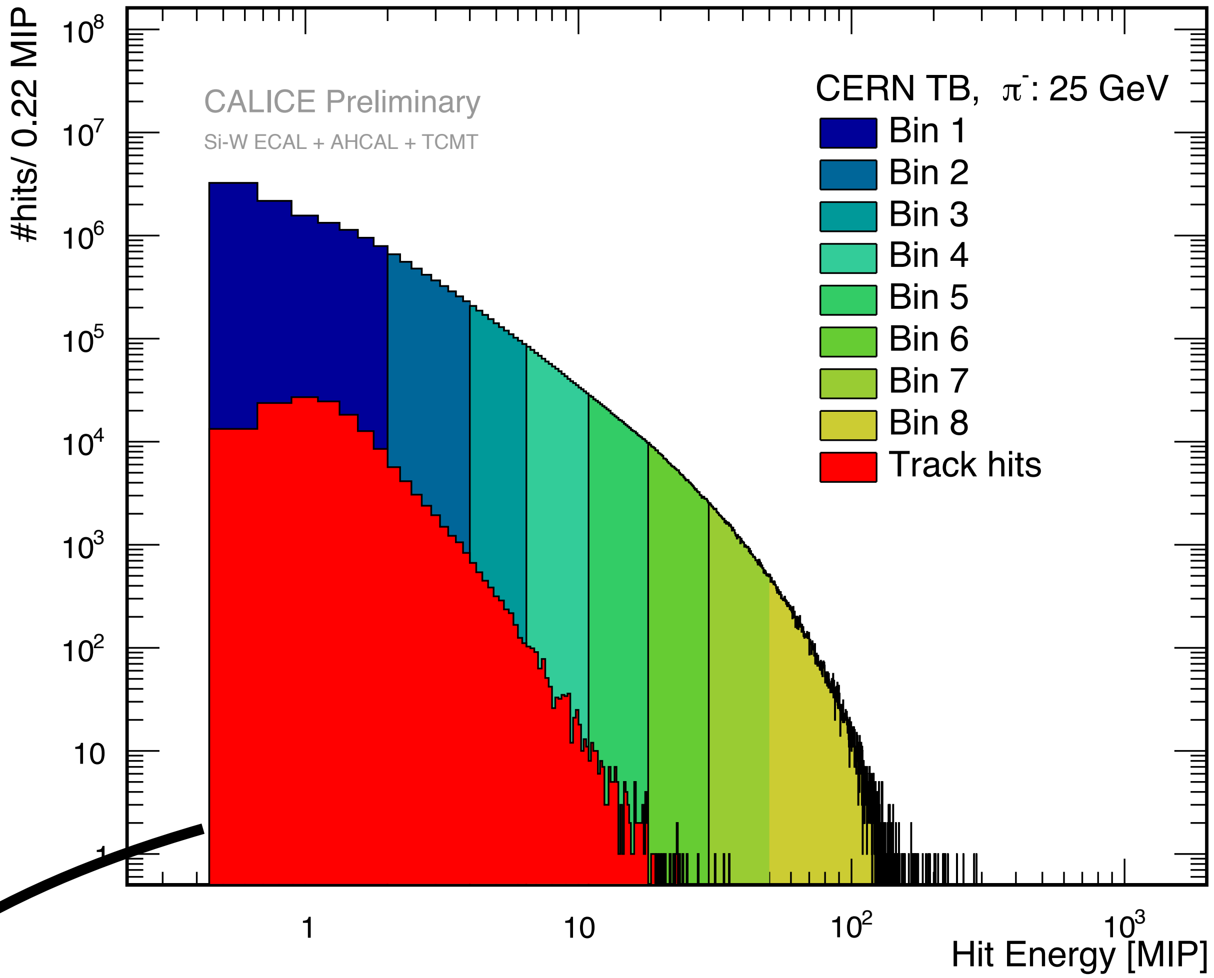
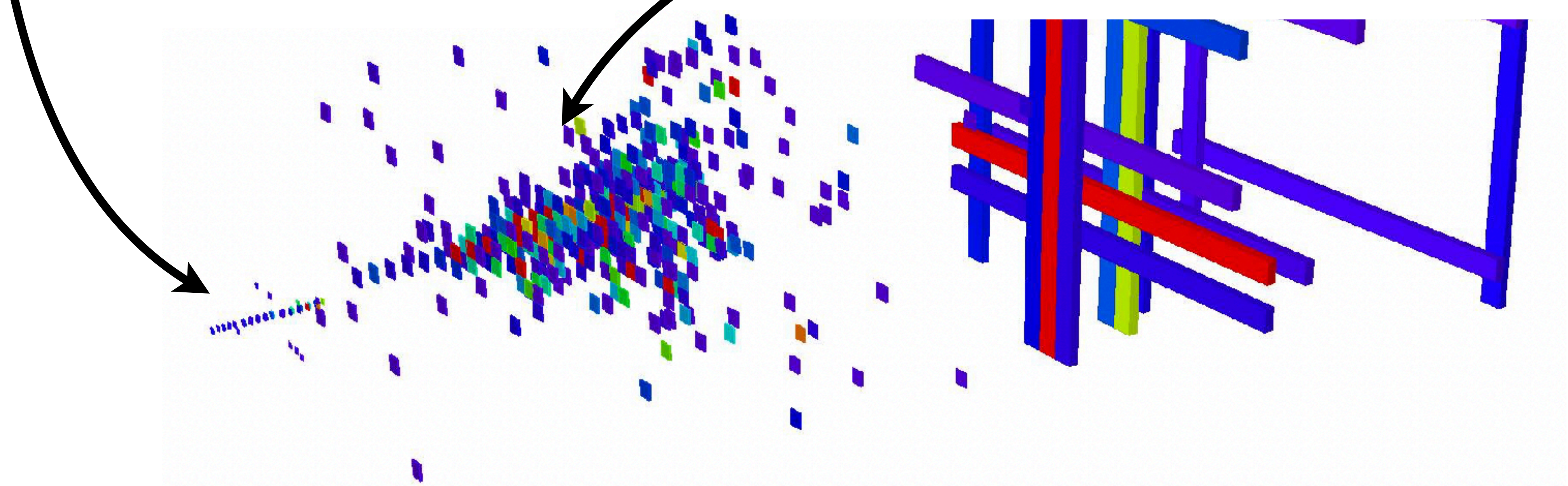


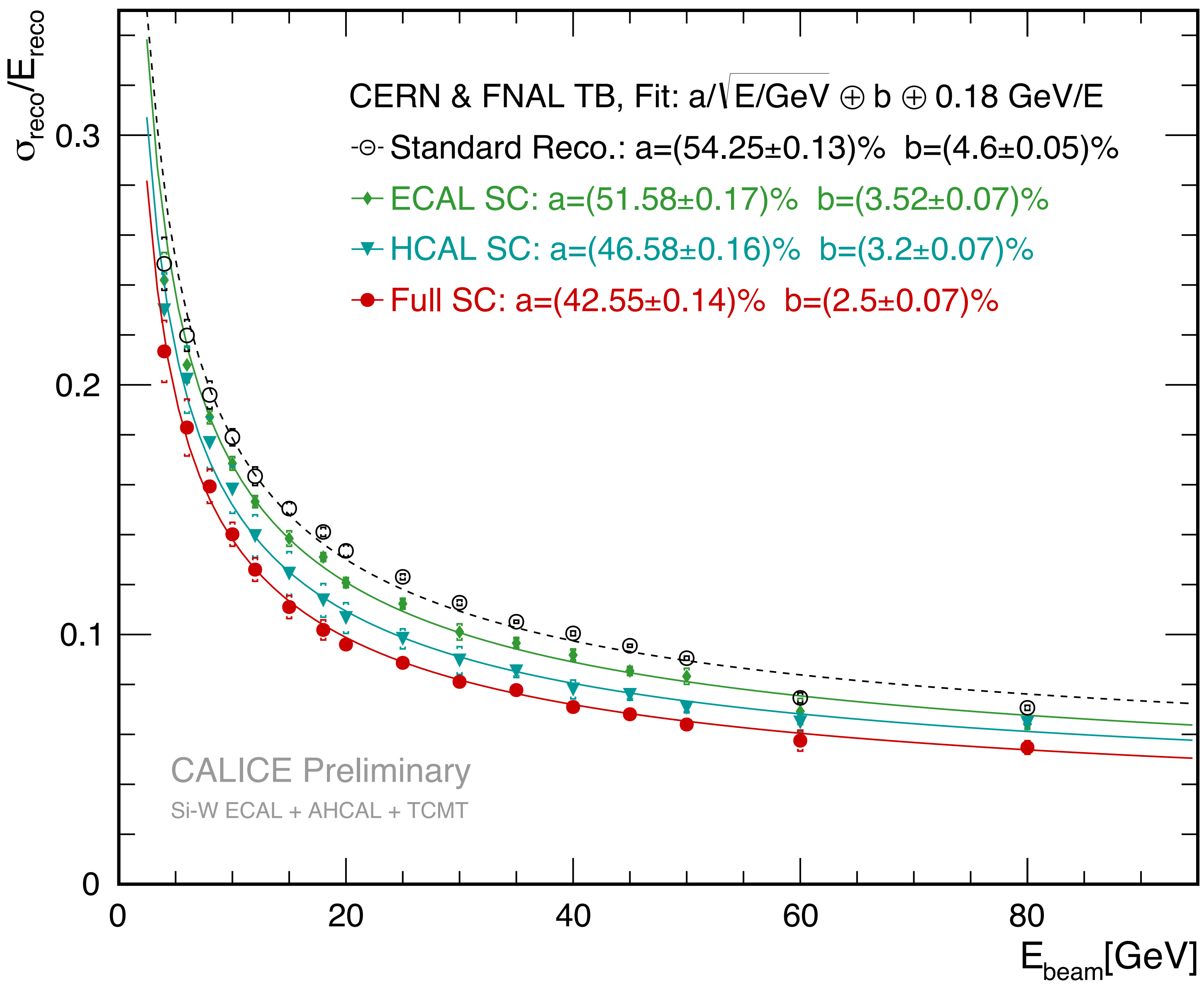




CALICE: Energy Reconstruction & PFA

- Local software compensation: each "hit" is weighted according to its amplitude
  - weights are energy dependent: Needs first estimate of cluster energy determined w/o SC methods

JINST 7 P09017 (2009)



- New study with full detector system (SiW ECAL + AHCAL + TCMT)
- ▸ SC in ECAL alone up to 8% improvement
- ▸ SC in HCAL alone up to 23% improvement
- ▸ Full SC up to 30% improvement, for a stochastic term of 42.5% and a constant term of 2.5%

Yasmine Israeli, CAN-058 (2017)

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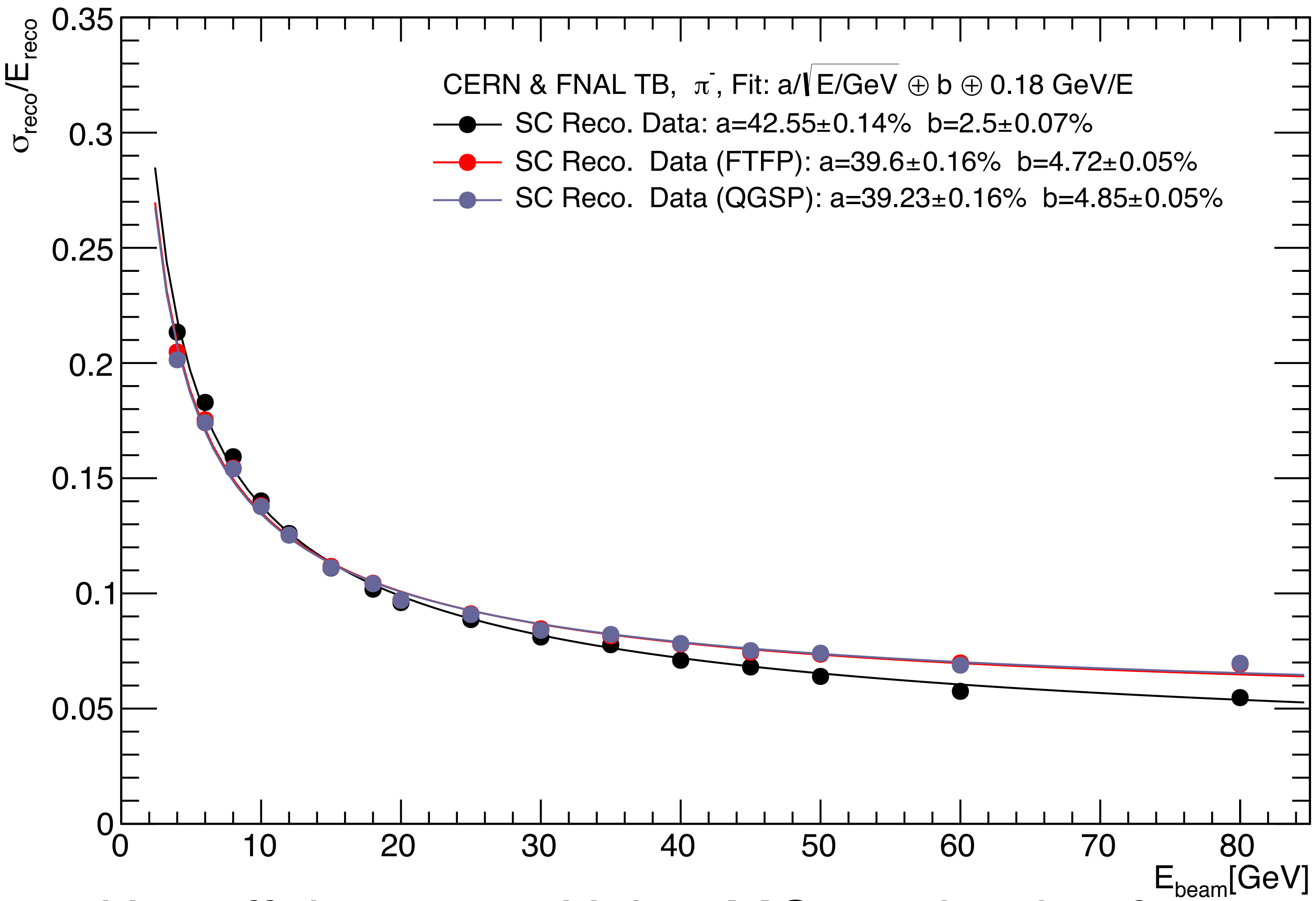

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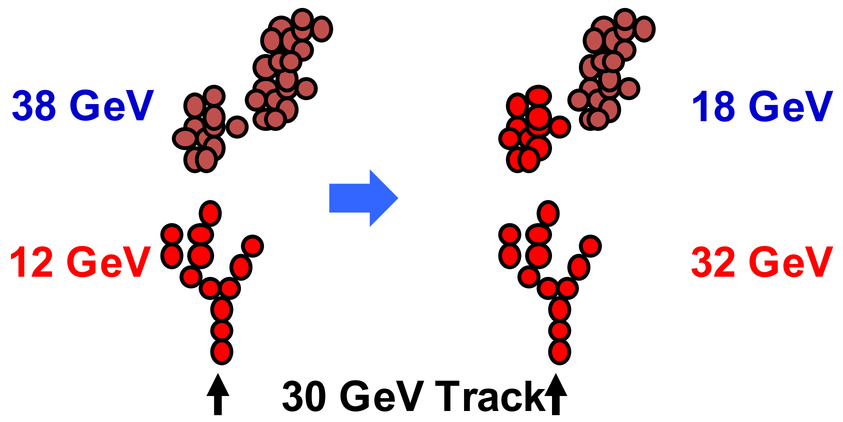
Hot off the press: Using MC - trained software compensation on data - discrepancy at higher energy reflects issue in reproduction of resolution in simulations without software compensation

Yasmine Israeli, CAN-058 (2017)

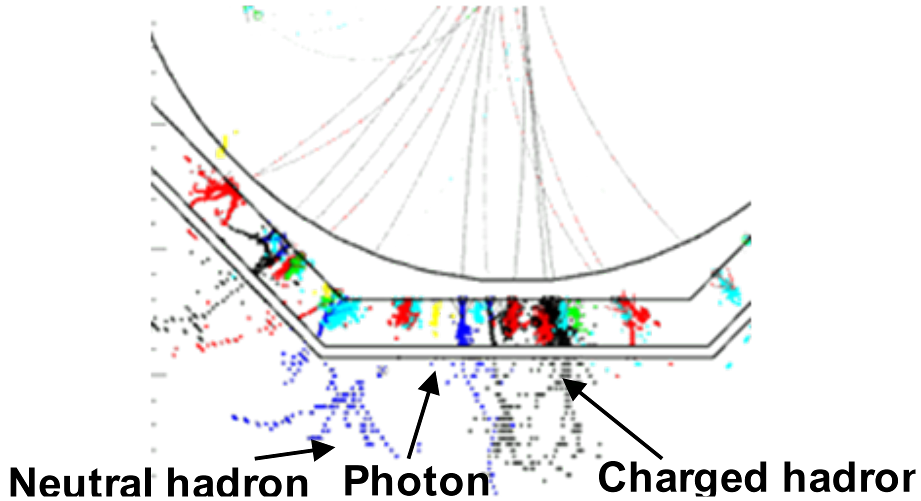
CALICE: Energy Reconstruction & PFA

- Integrating software compensation in particle flow reconstruction
  - Full simulations using the ILD detector concept for GEANT4
    - Areas of possible benefits:



Reclustering: association of calorimeter energy to charged tracks, making use of track and cluster energy - profits from better energy estimates

Final energy sum: Profits from improved measurement of neutral hadrons



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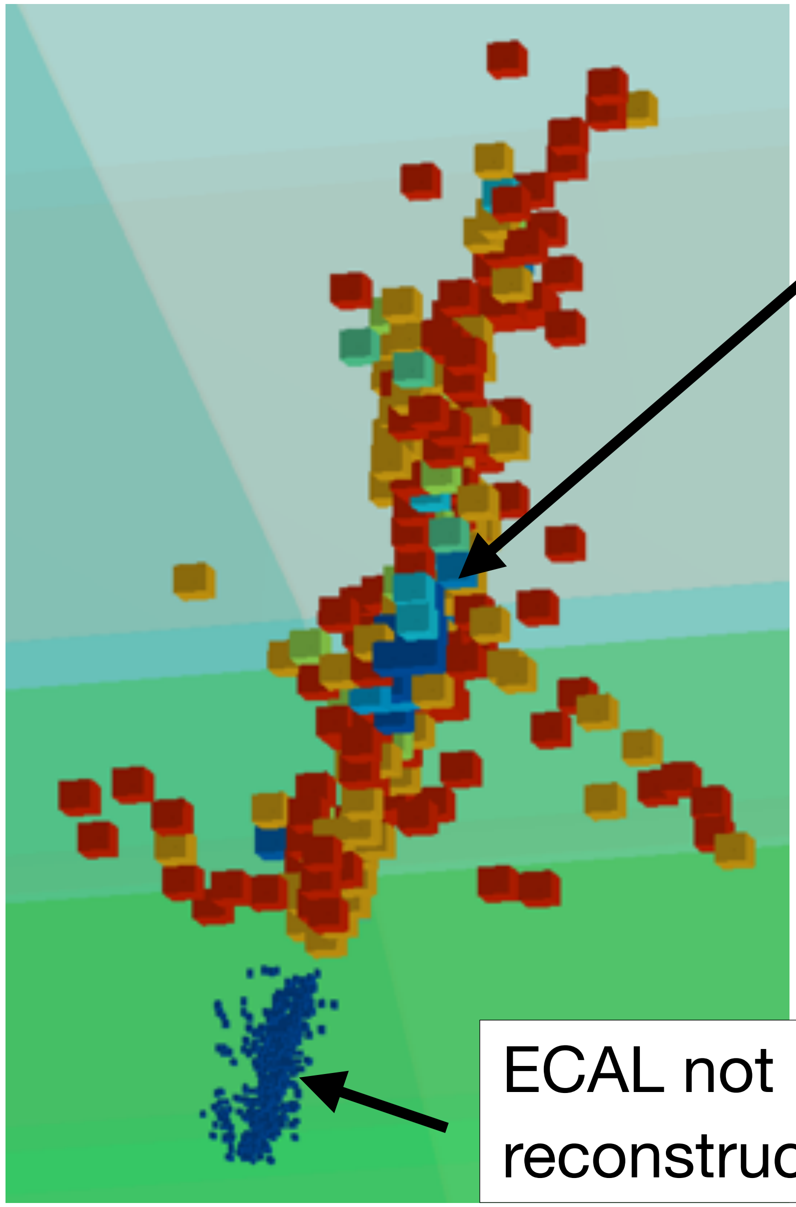


transfer software compensation algorithm and training strategies from CALICE to full ILD detector simulations

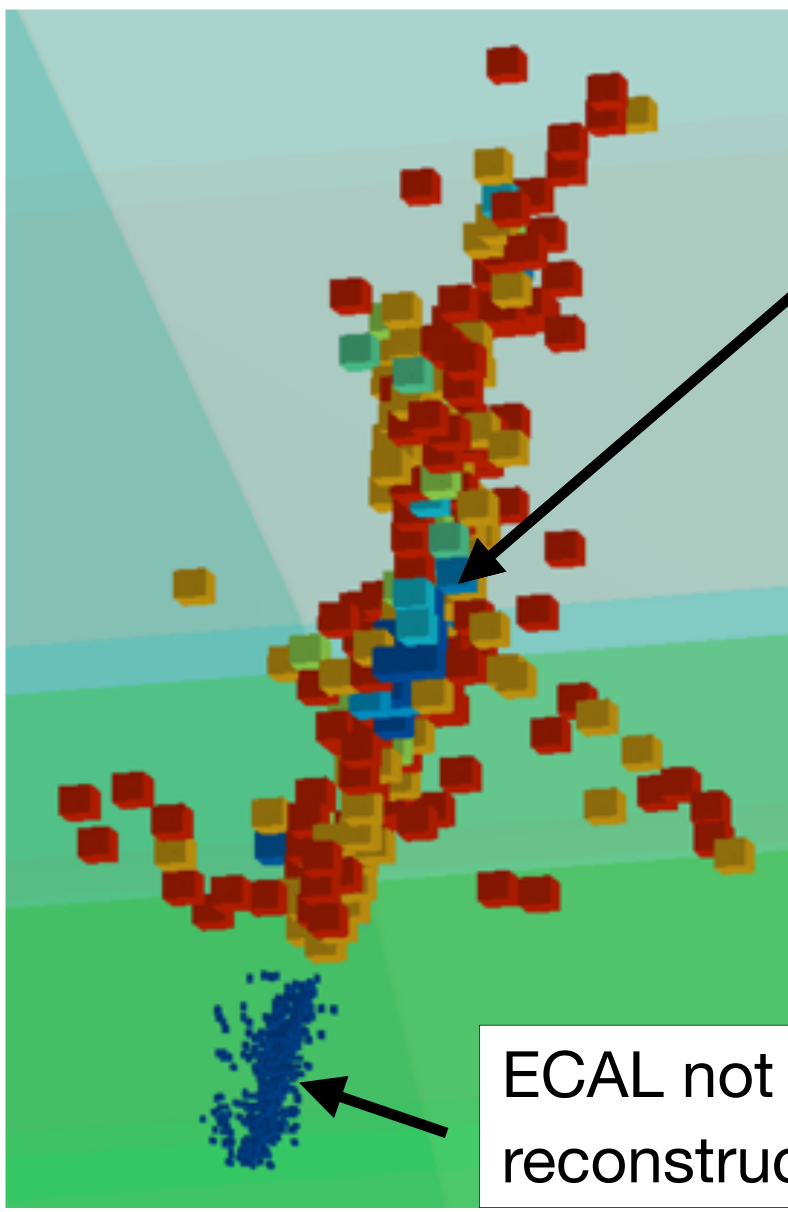
em sub showers (in shower core) weighted less than hadronic periphery

ECAL not included: standard reconstruction used

CALICE: Energy Reconstruction & PFA

- Integrating software compensation in particle flow reconstruction
  - Full simulations using the ILD detector concept for GEANT4

transfer softv
strategies f



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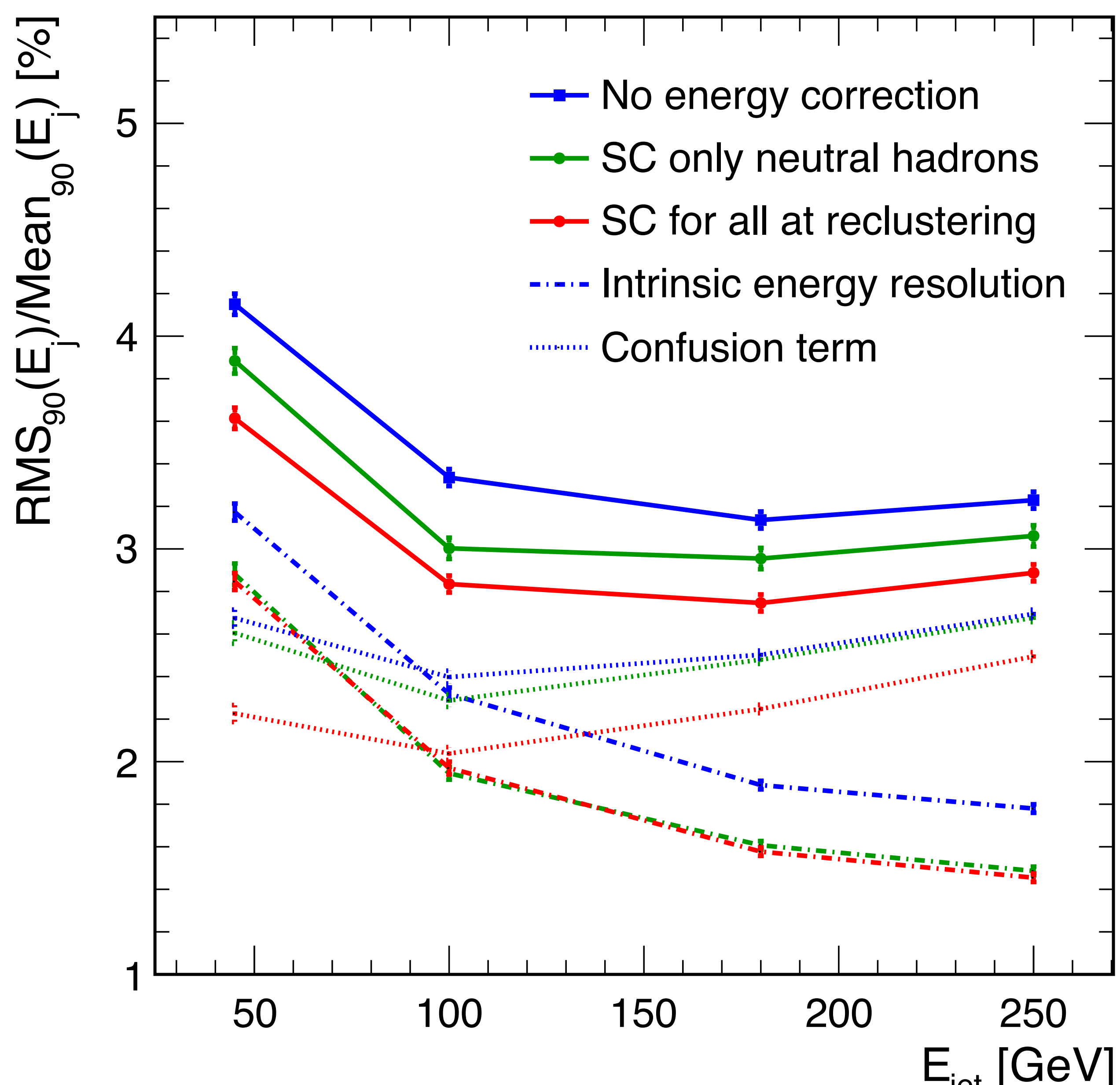
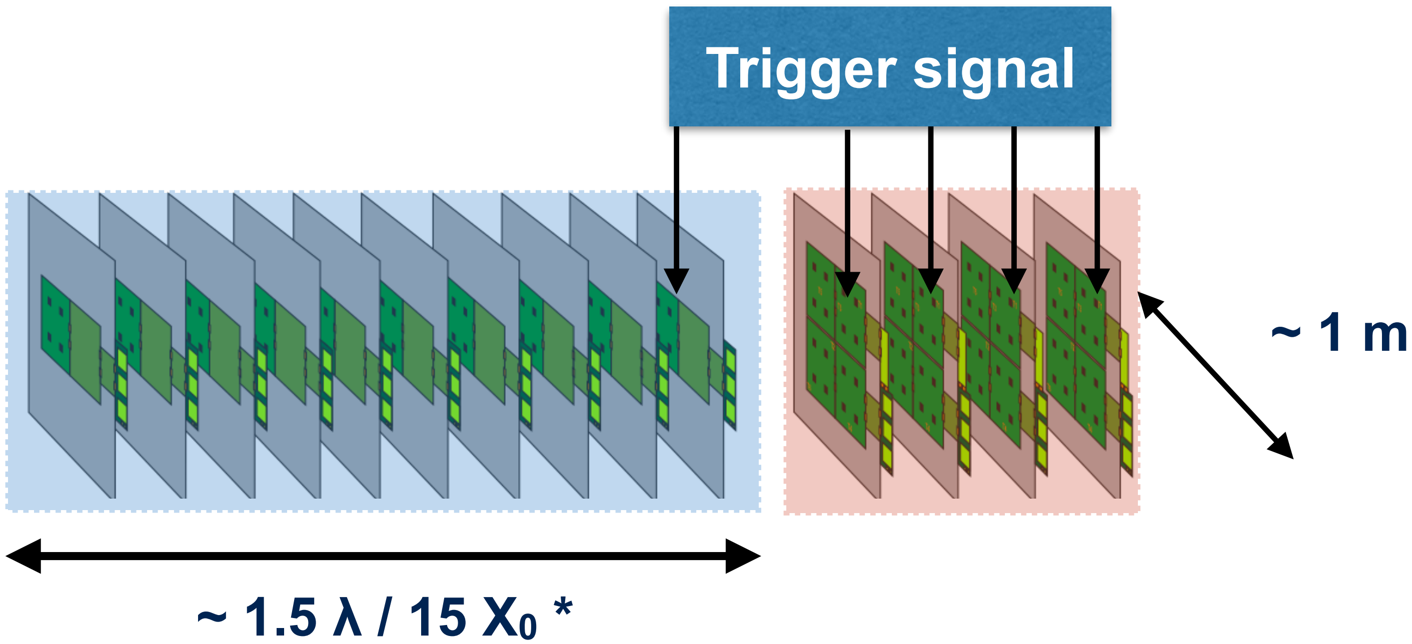
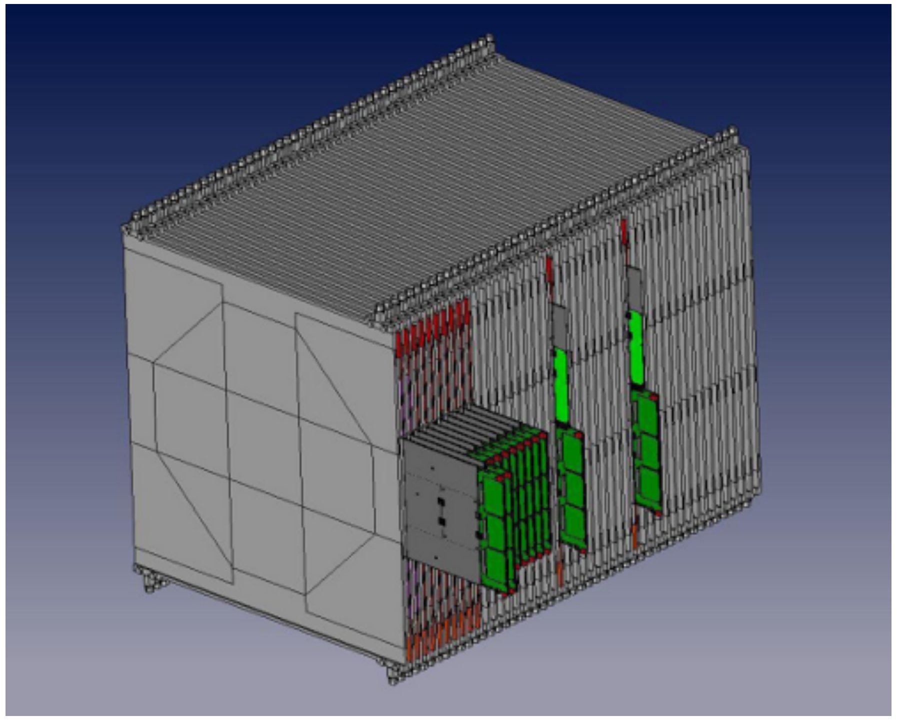


EPJ C77, 698 (2017)

CALICE: Exploiting New Capabilities: Timing

- First tests of timing feature of new AHCAL electronics: partially instrumented tungsten absorbers, prototype detector elements with different scintillator designs





Christian Graf

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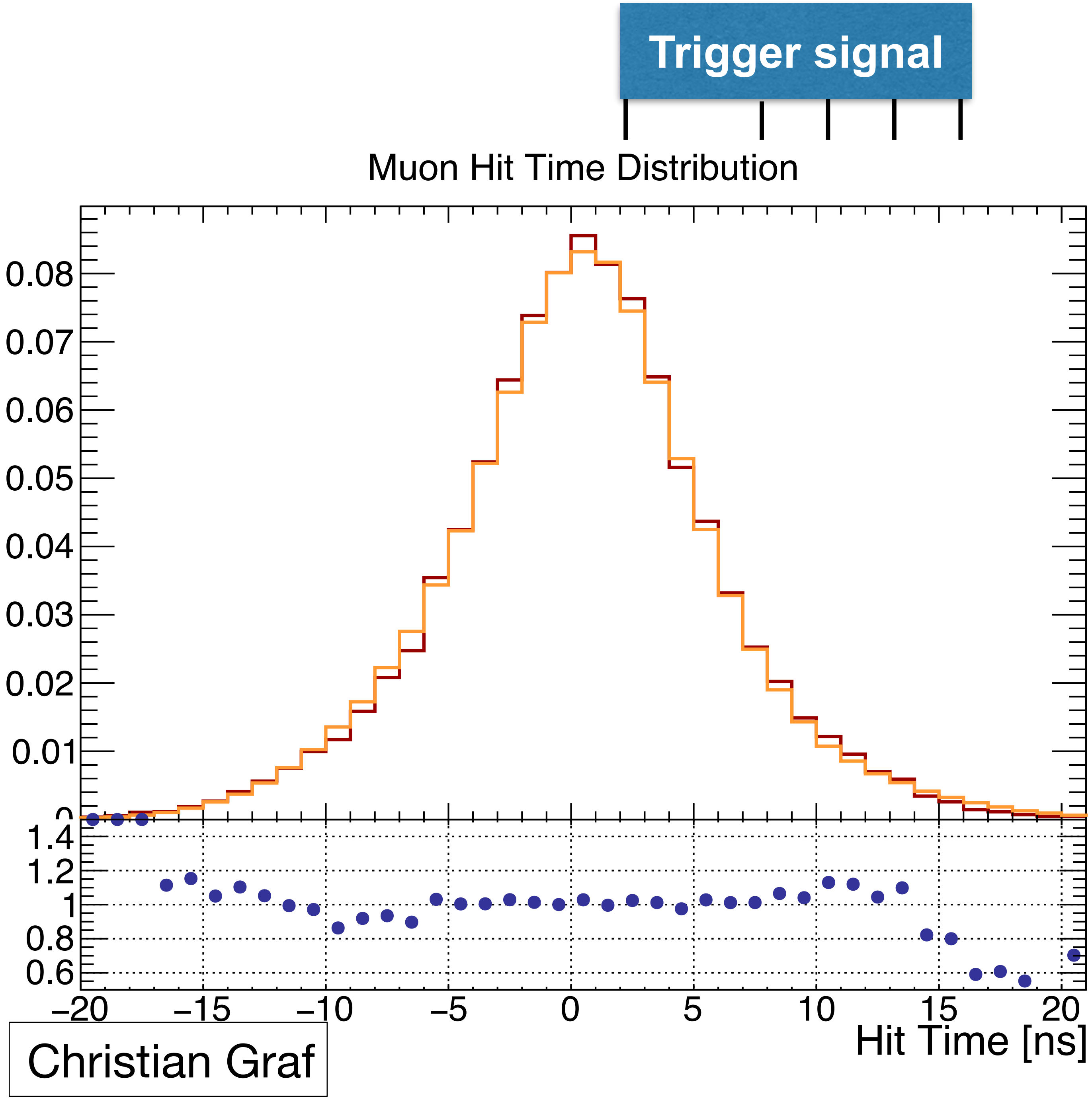

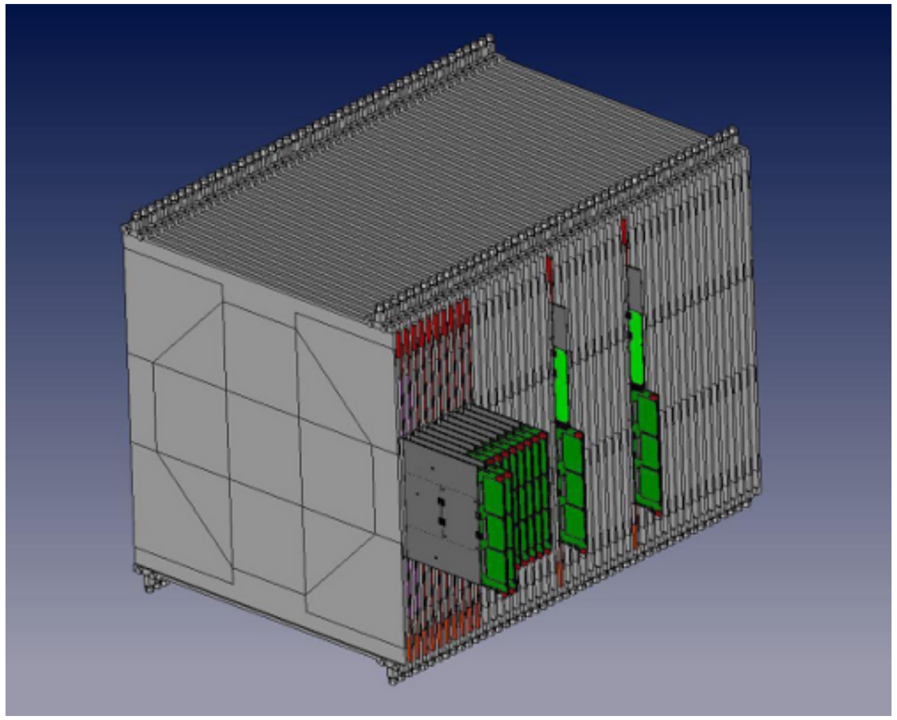

MIP time stamping on the 5.5 ns level per cell (given by limitations of test beam mode of electronics)

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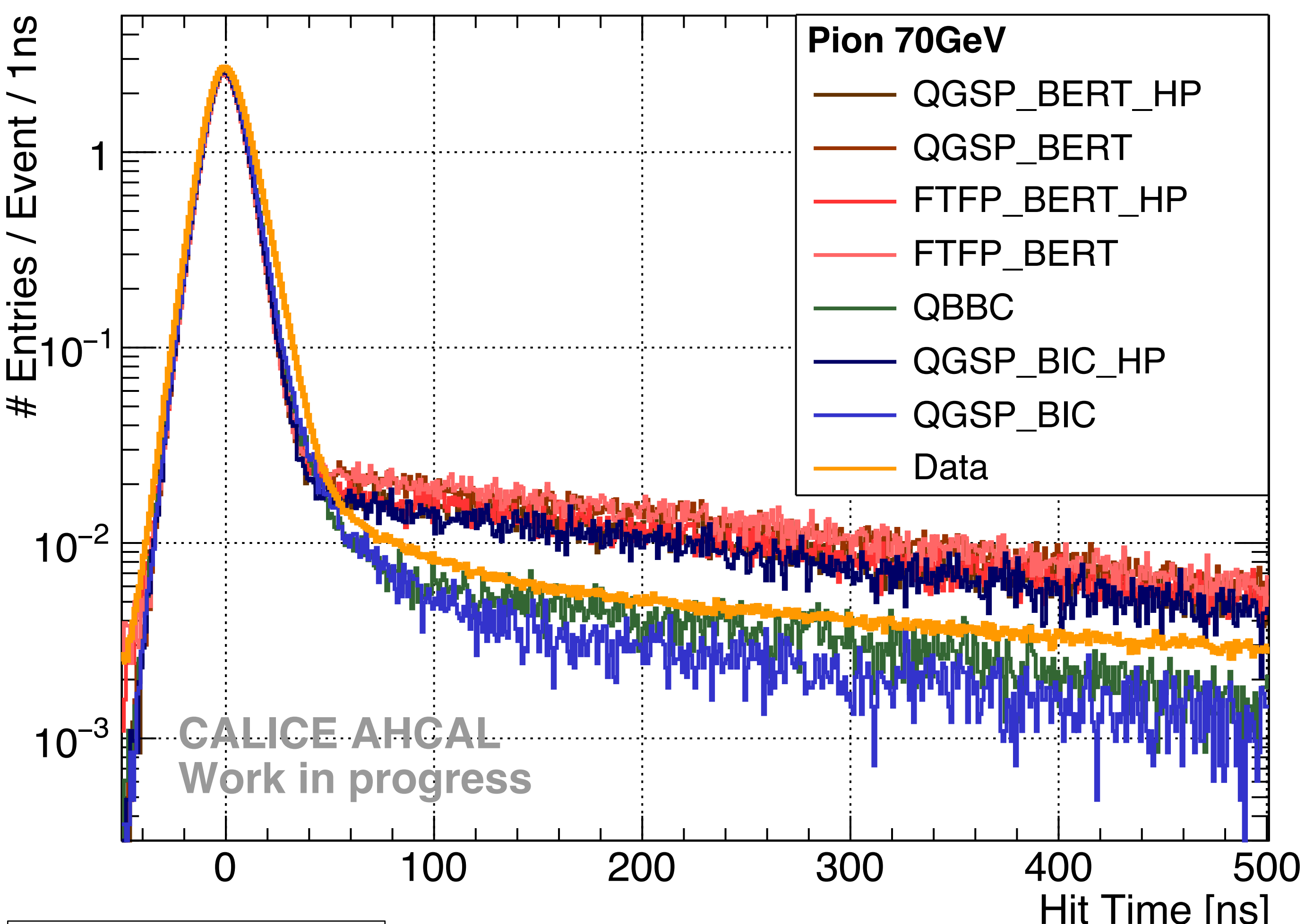
Hittime - T0 time, normalized to event



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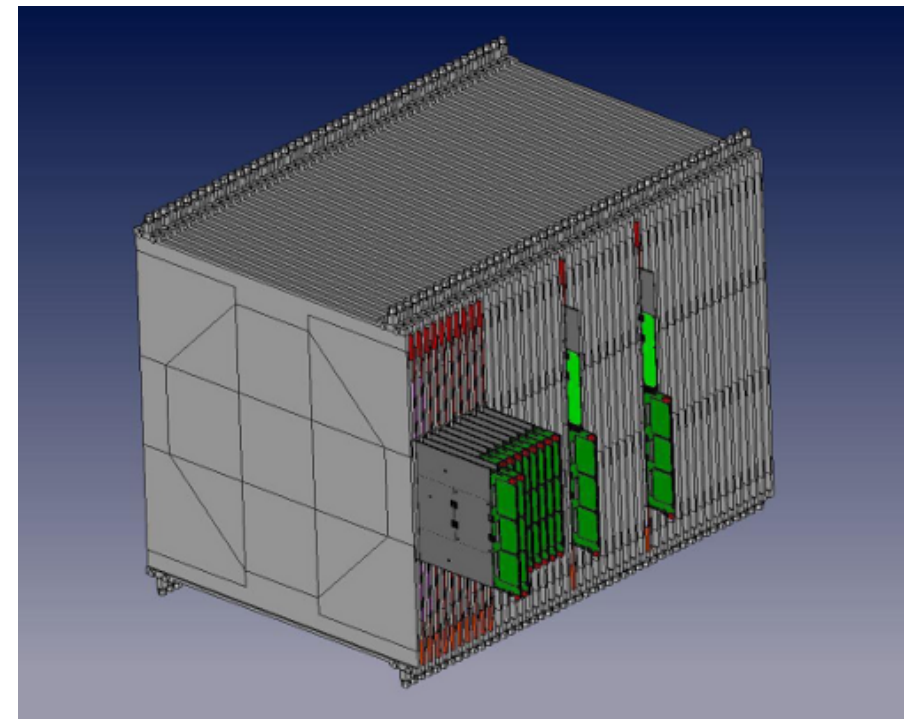


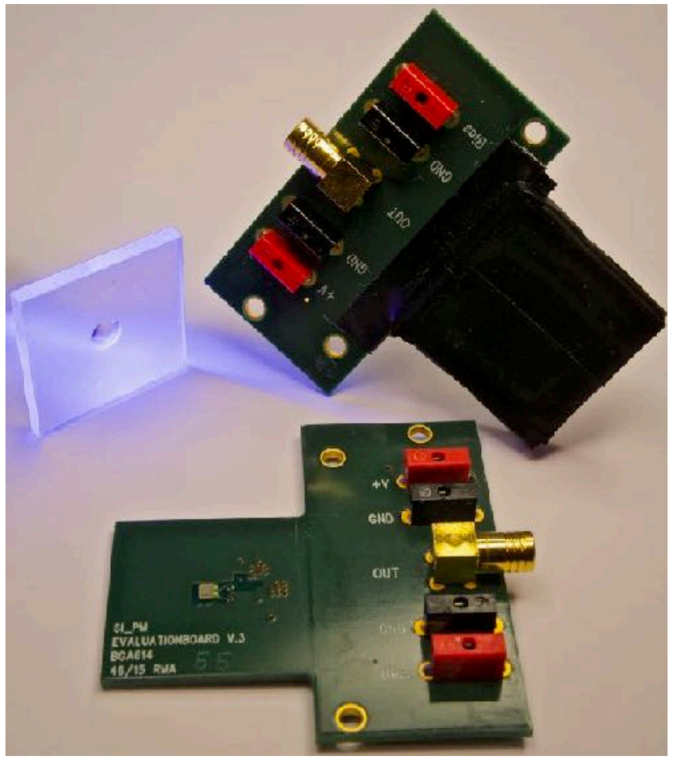
MIP time stamping on the 5.5 ns level per cell (given by limitations of test beam mode of electronics)

Extended time structure in hadronic showers - primarily due to neutrons: Can this be exploited in software compensation?

Commissioning of SuperKEKB: CLAWS

- Scintillator tiles developed for CALICE, coupled to fast sampling readout with very deep buffers used to monitor injection background in SuperKEKB

Phase I:
Took data Feb - June 2016 during first commissioning of accelerator



Miroslav Gabriel, Hendrik Windel

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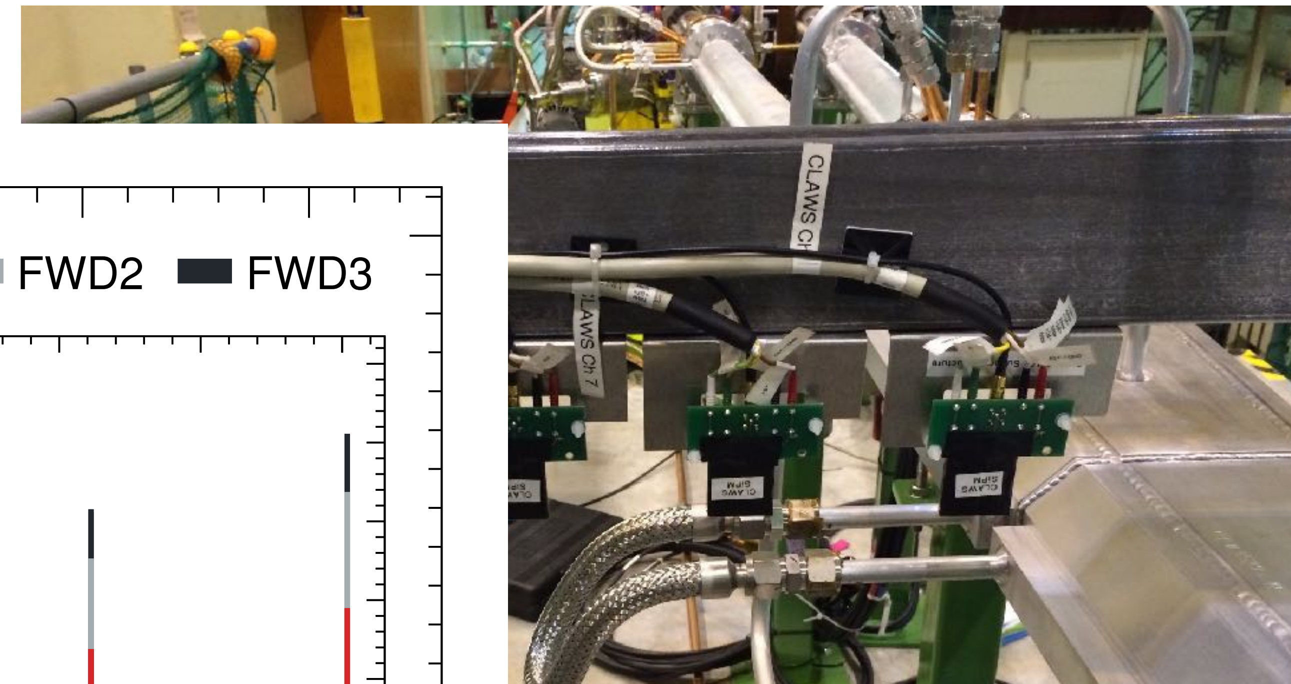

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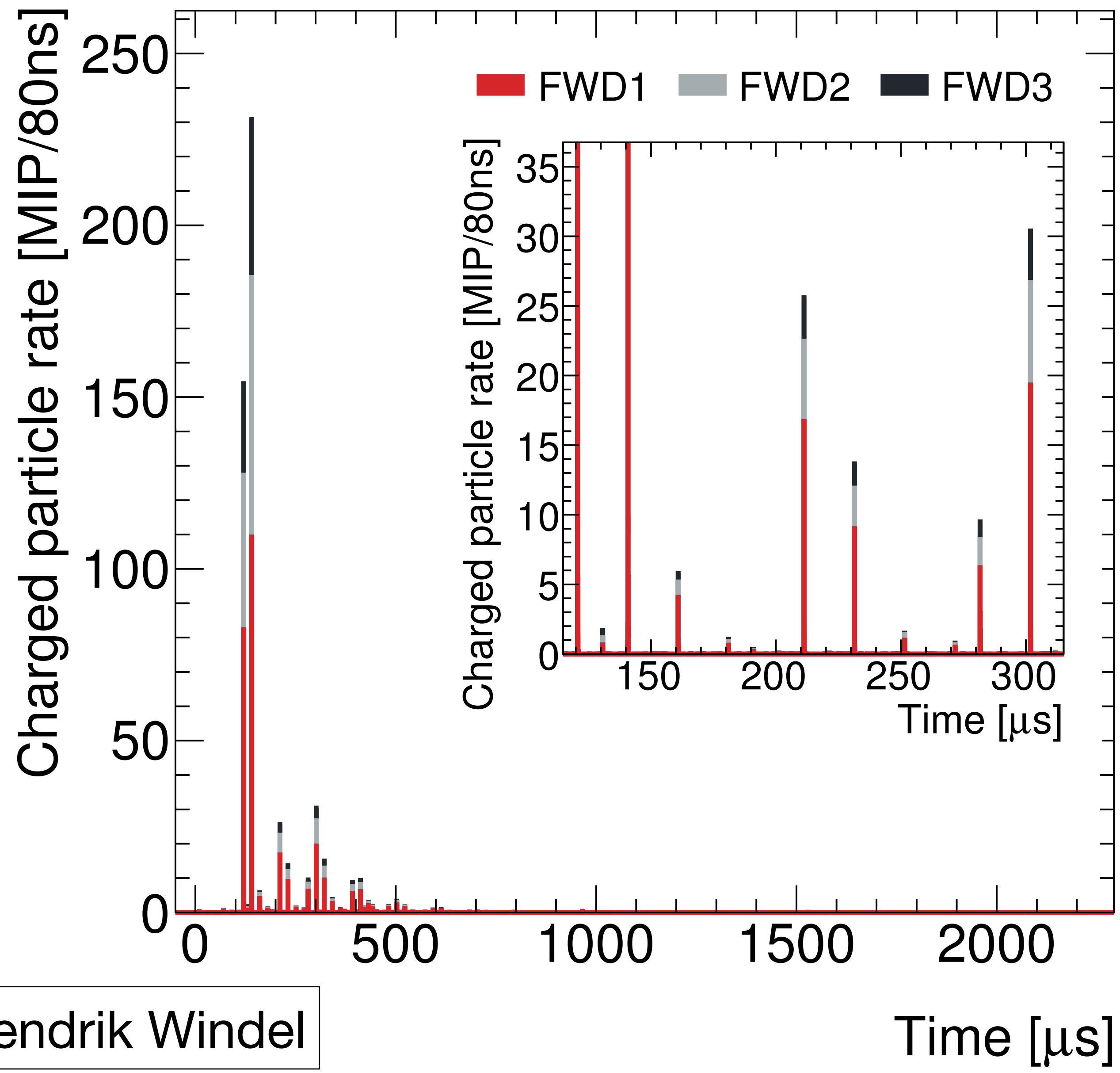

Machine-lattice induced time structure observed, overlaying decay of background over ~ 0.5 ms

Miroslav Gabriel, Hendrik Windel

CLAWS: Towards the Second Phase

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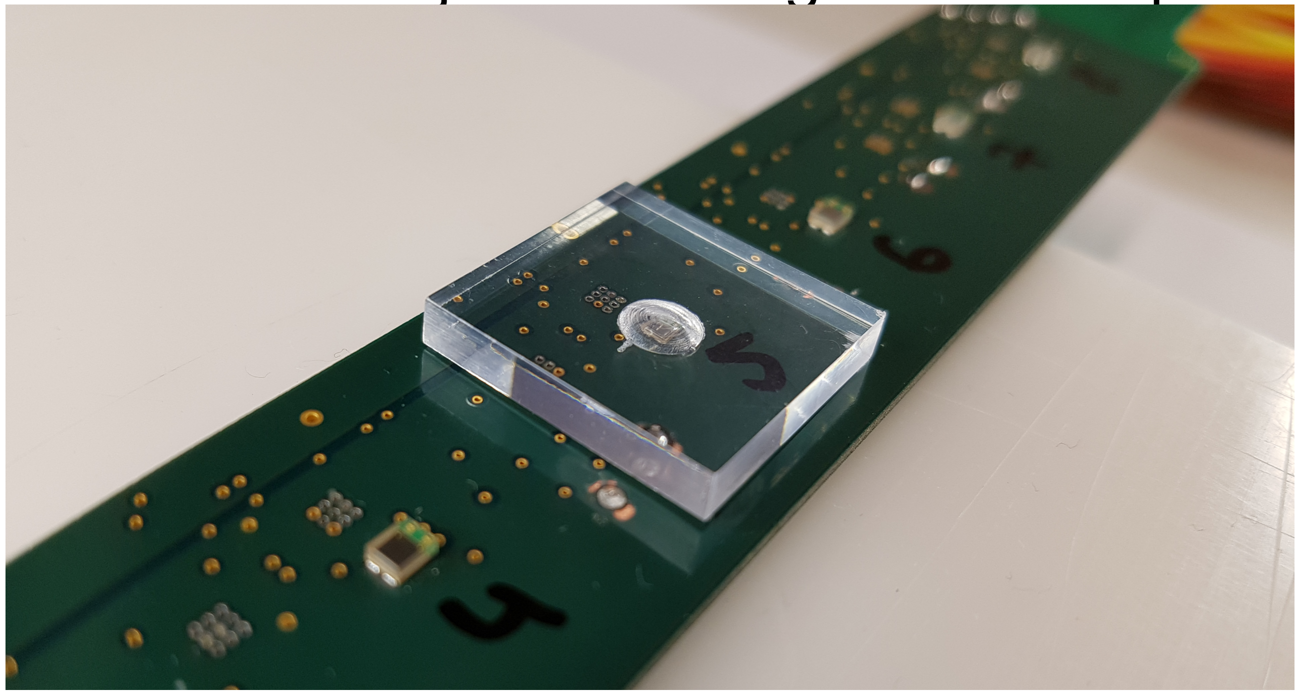
Phase II:
From March 2018, with colliding beams



Phase I CLAWS system adapted to the requirements for installation as part of the BEAST II vertex detector

Miroslav Gabriel, Daniel Heuchel, Hendrik Windel

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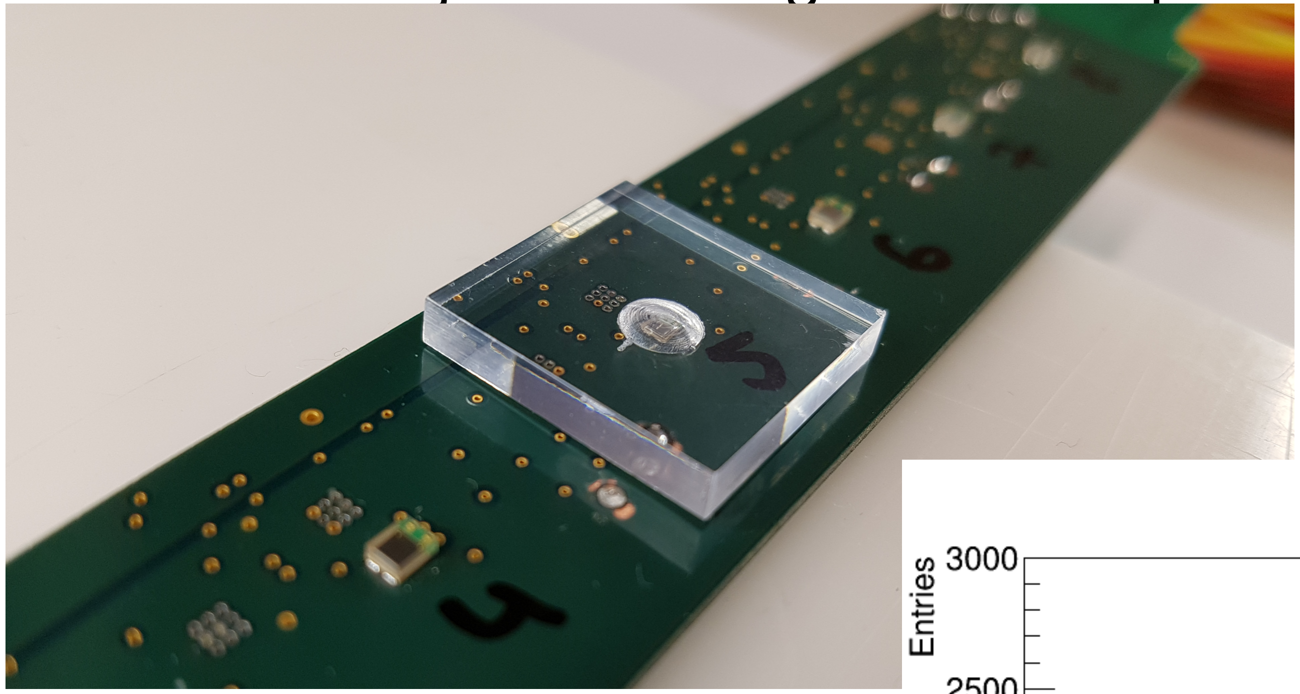

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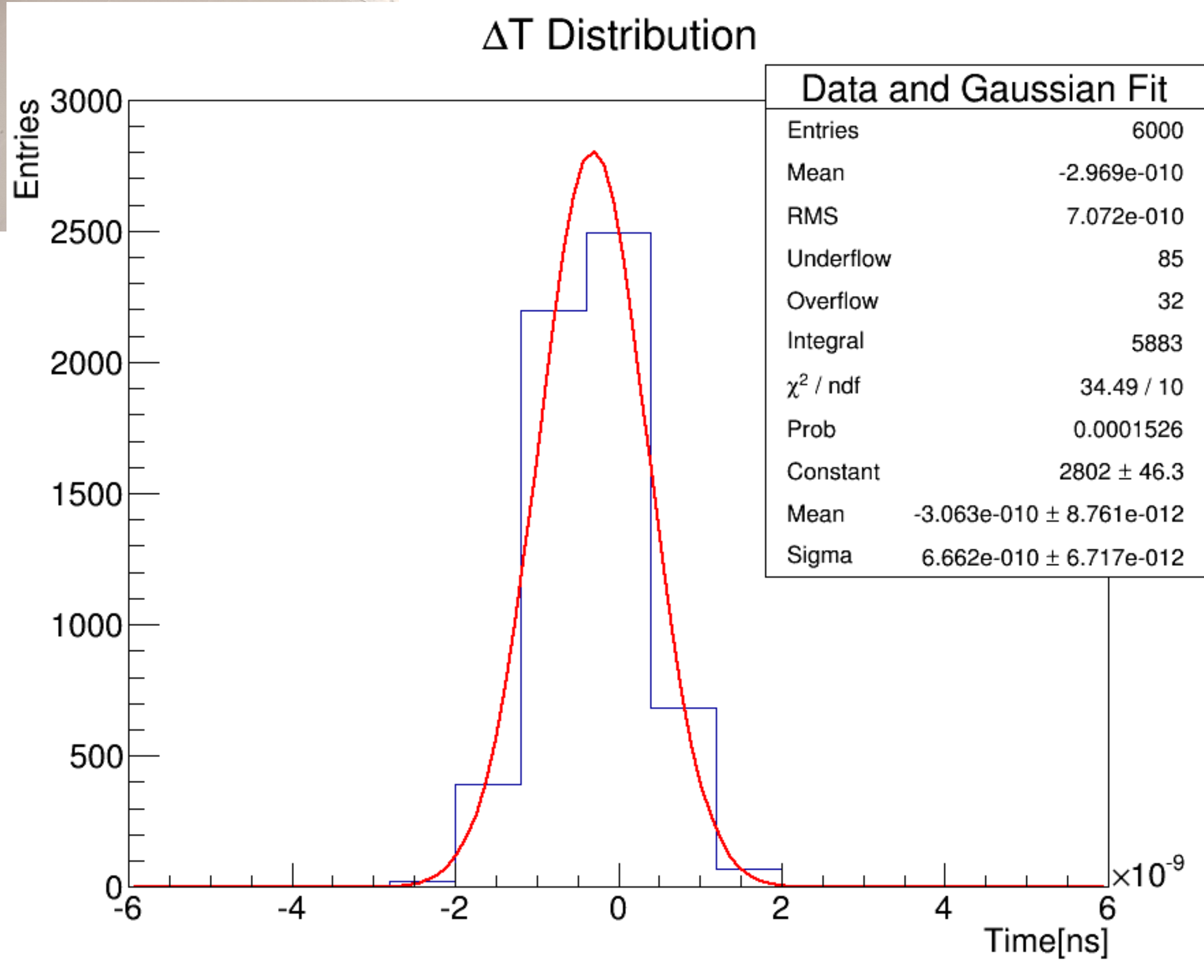

Extensive calibration: 4 ladders with 8 sensors each calibrated, MIP time resolution ~ 400 ps

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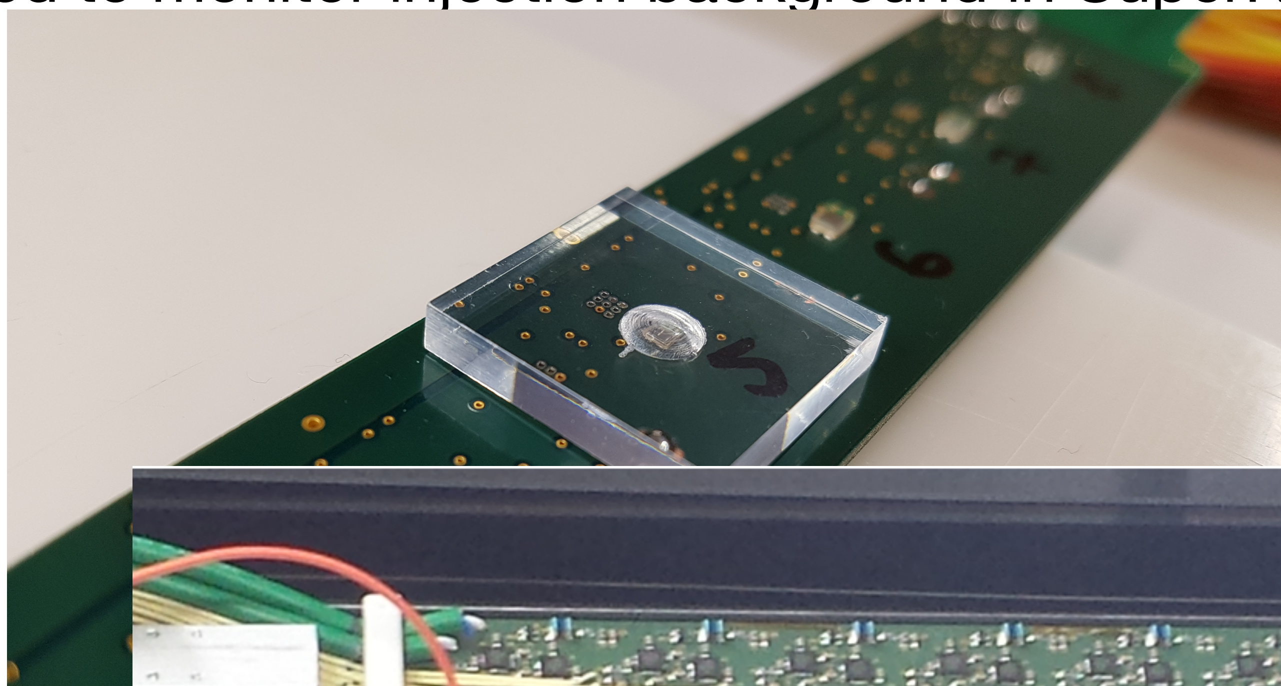

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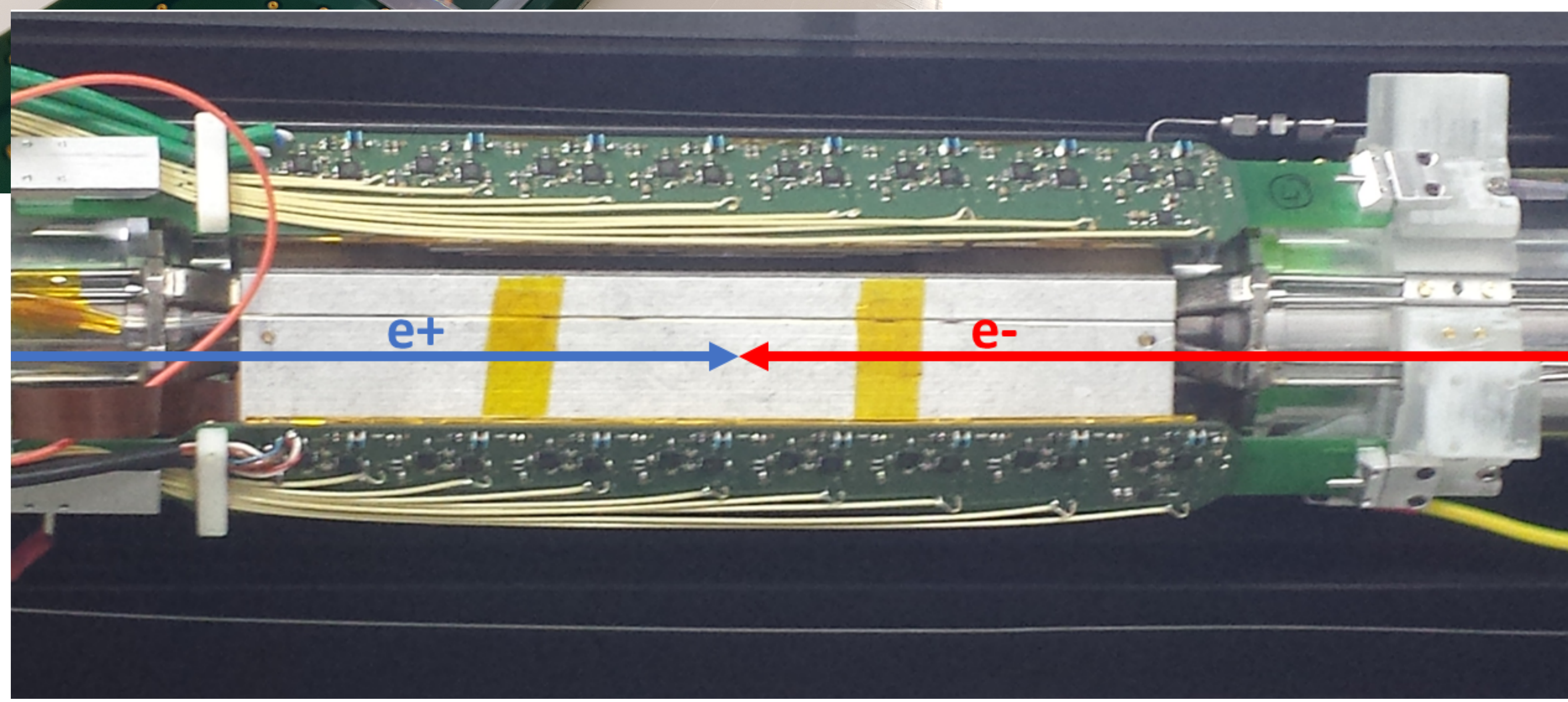
Installed at KEK in Fall

Ready for beam in 2018



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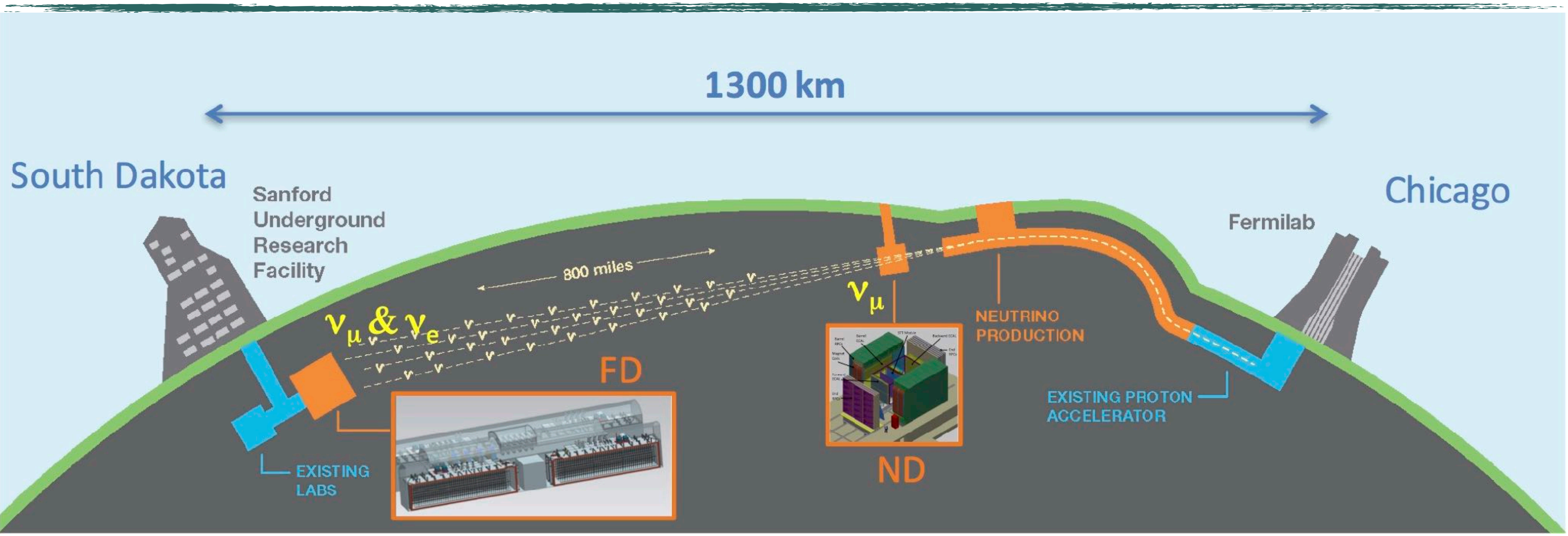
Beyond Colliders: The DUNE Near Detector



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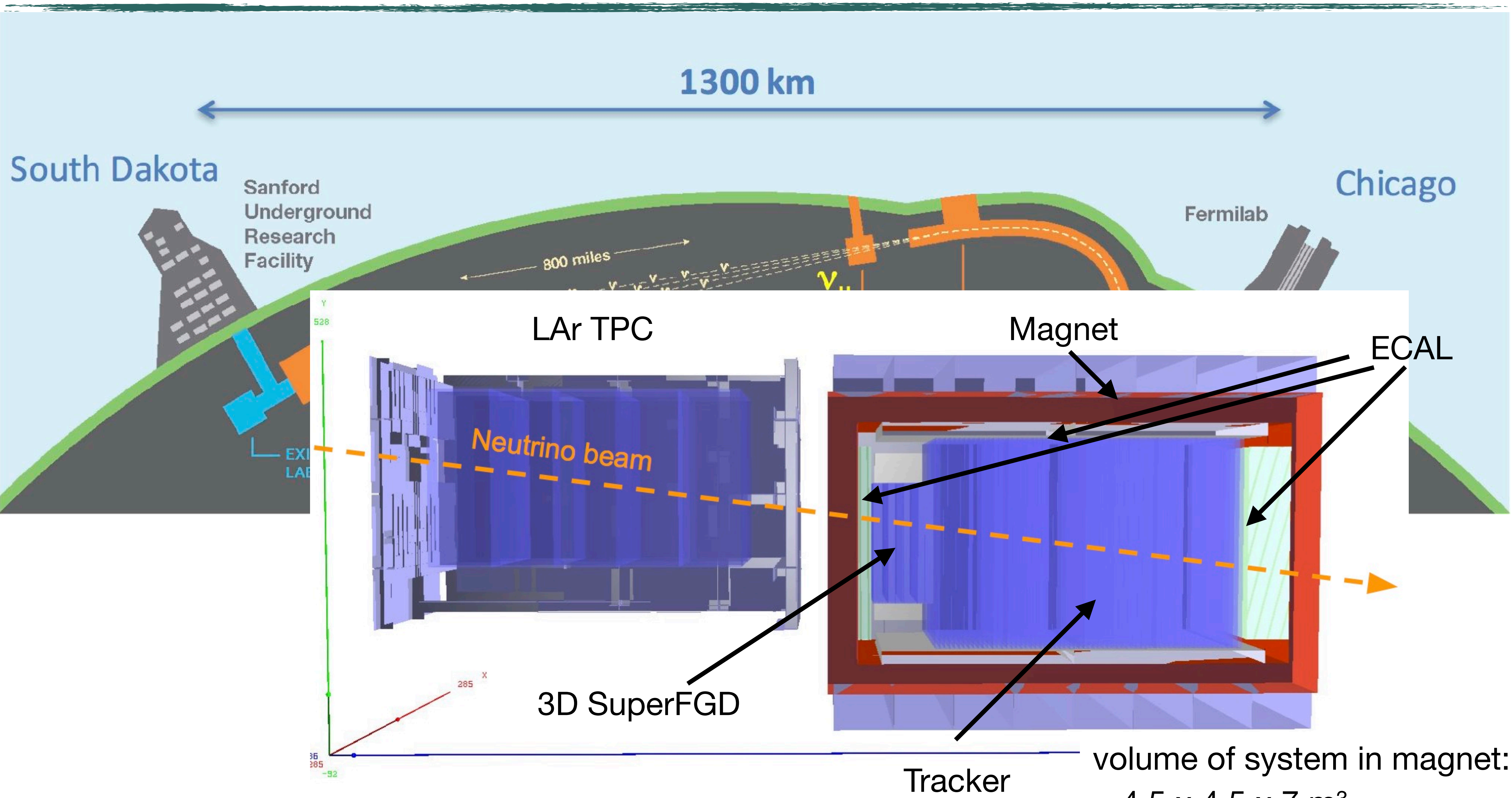

volume of system in magnet:
~ 4.5 x 4.5 x 7 m^3

- a multi-component near detector to constrain the neutrino source flux as a key part of the oscillation measurements, and to study neutrino interactions

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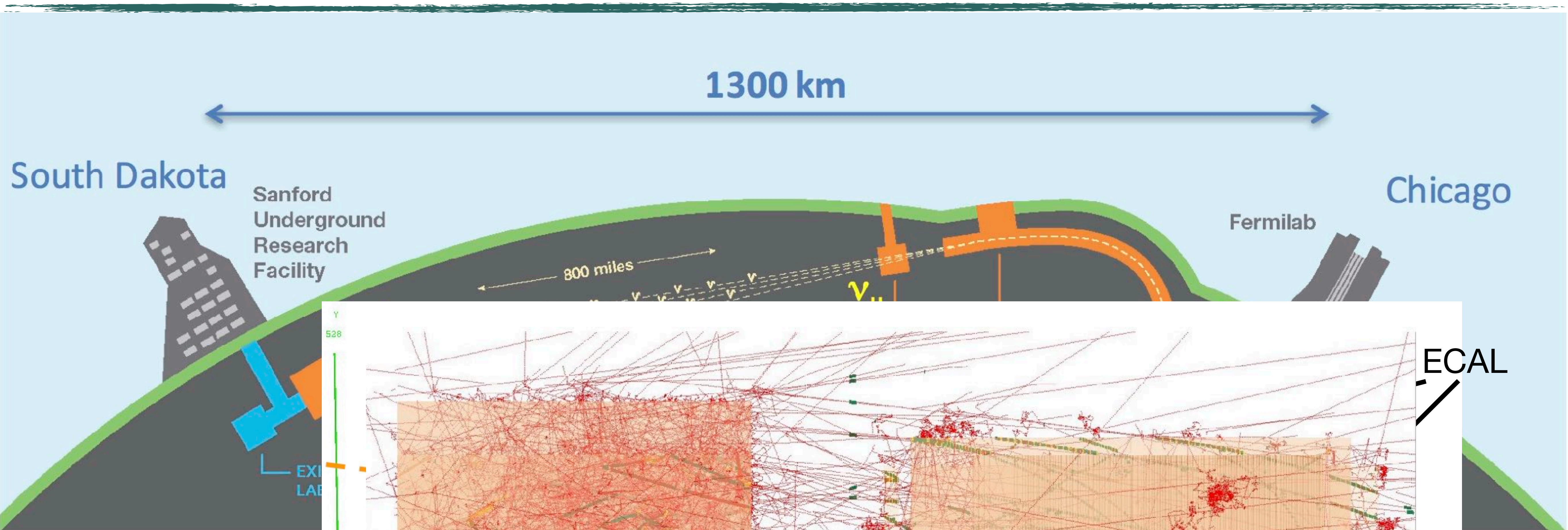

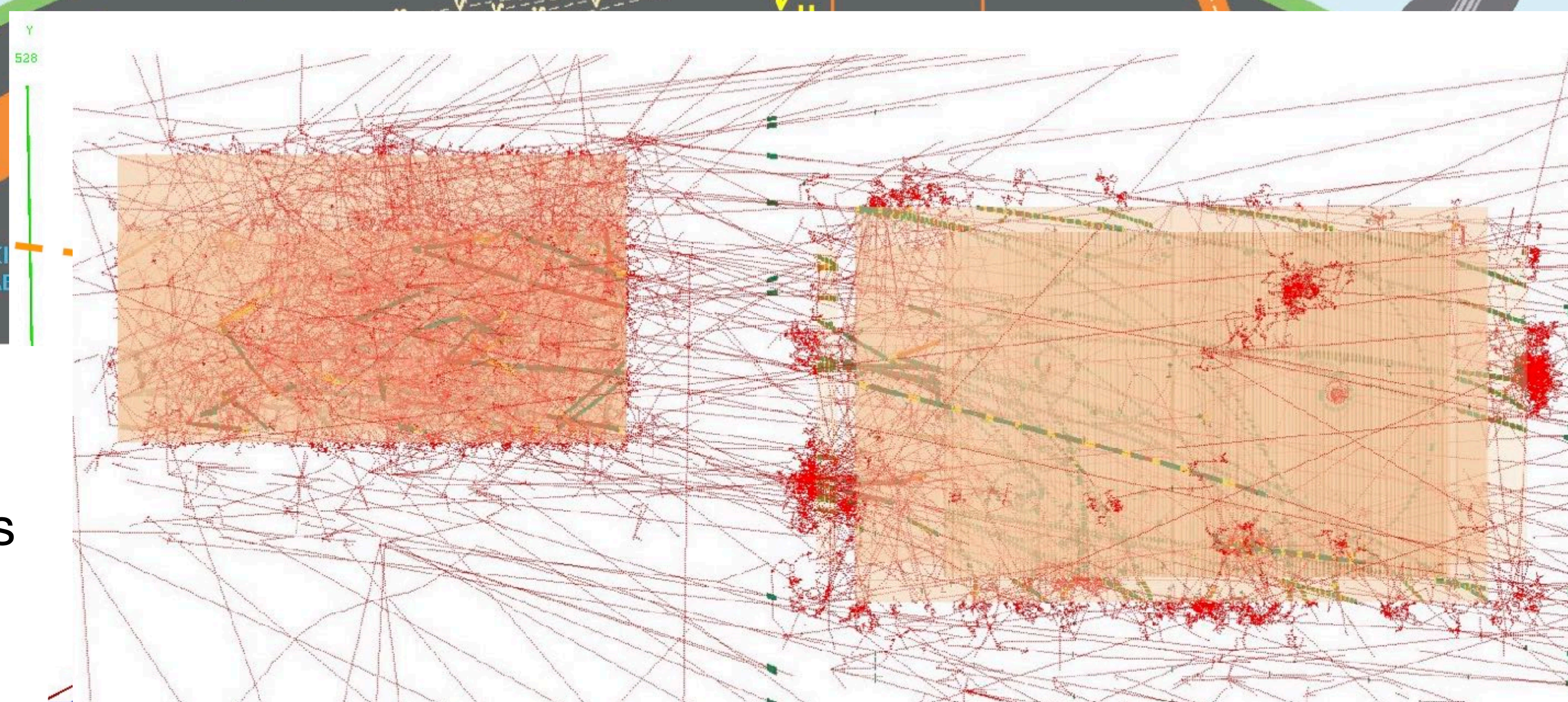

ECAL

high-intensity ν beam, showing one spill of 10 μs w/o interactions in rock/dirt, infrastructure

Tracker

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First Studies for a DUNE ND ECAL

- *Informally* exploring the potential of highly granular CALICE - like technologies for the DUNE Near Detector ECAL
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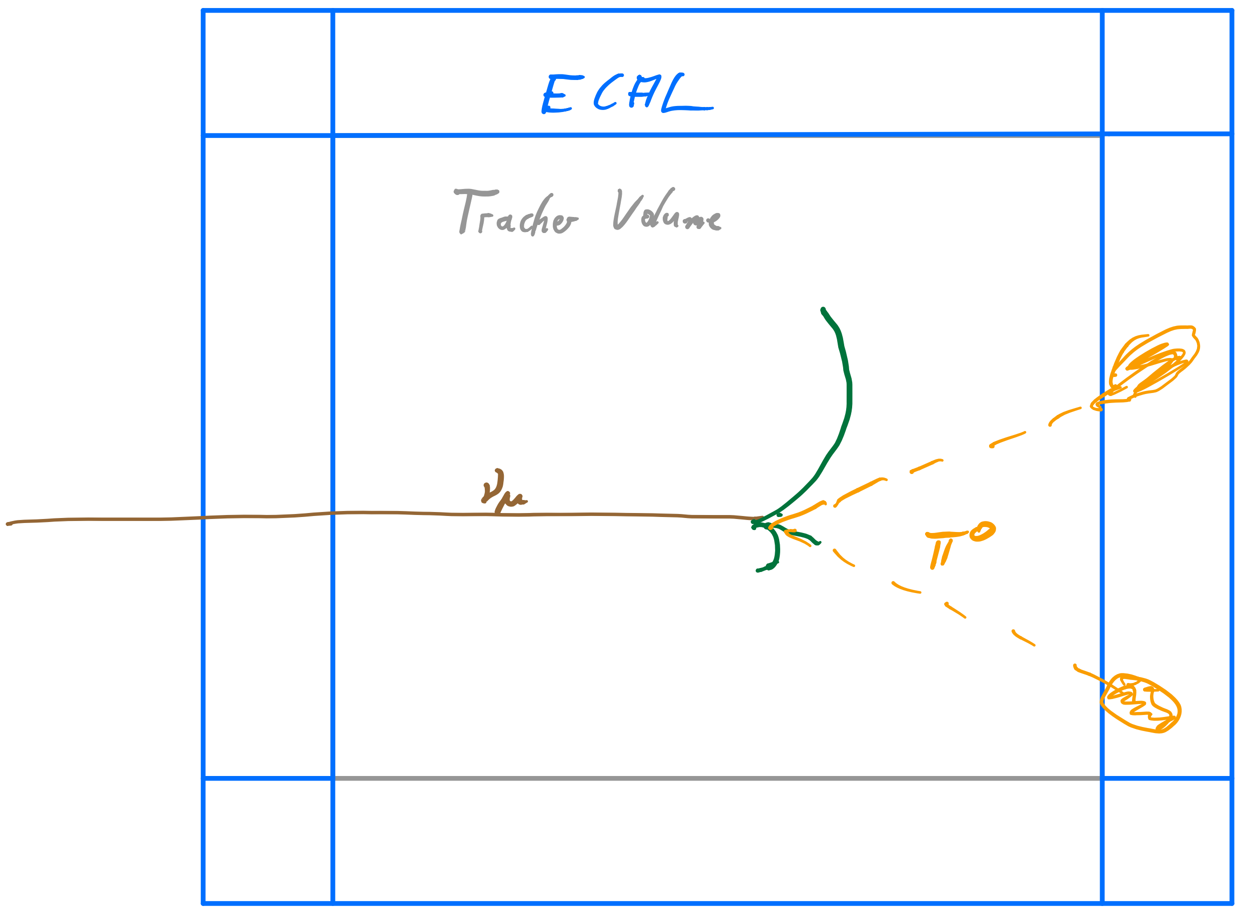

Lorenz Emberger

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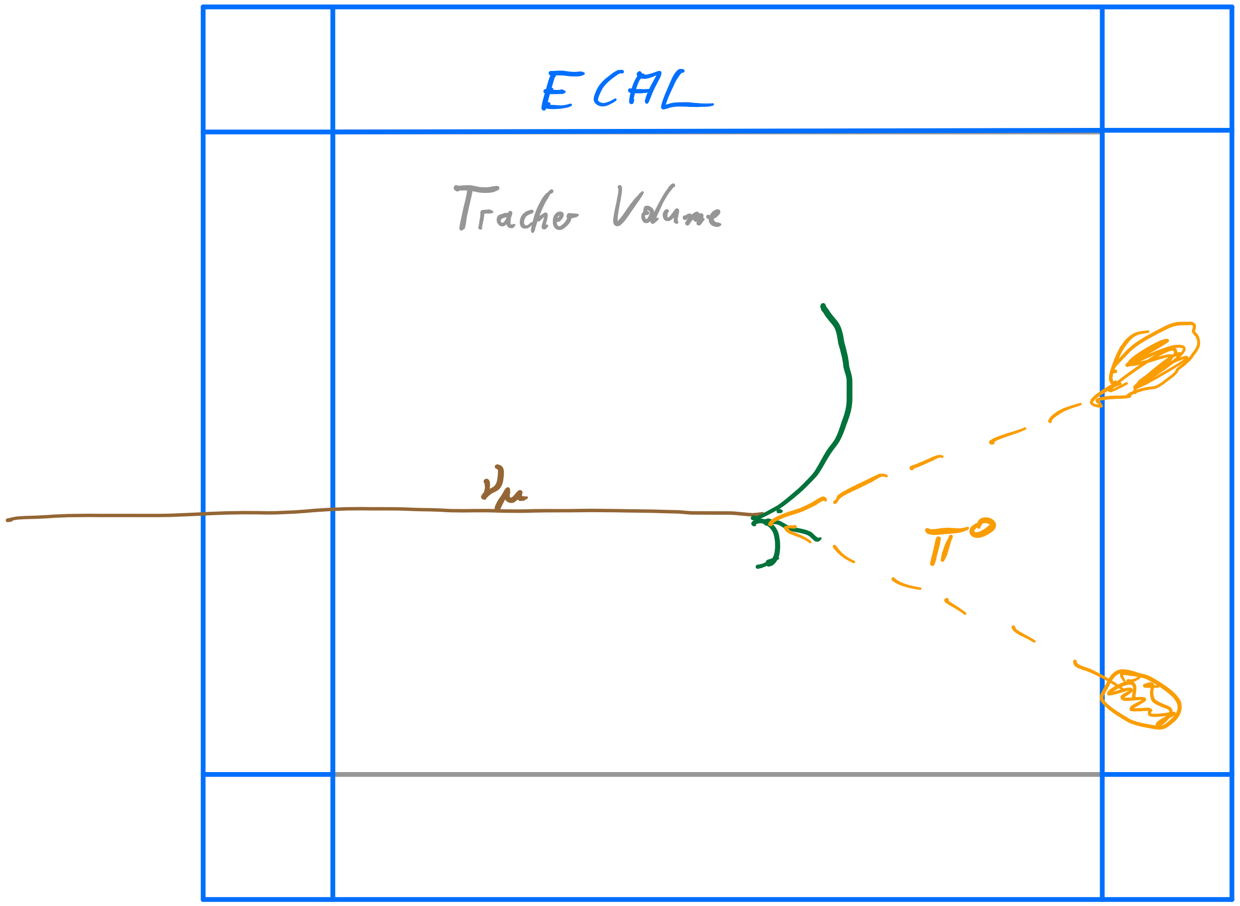
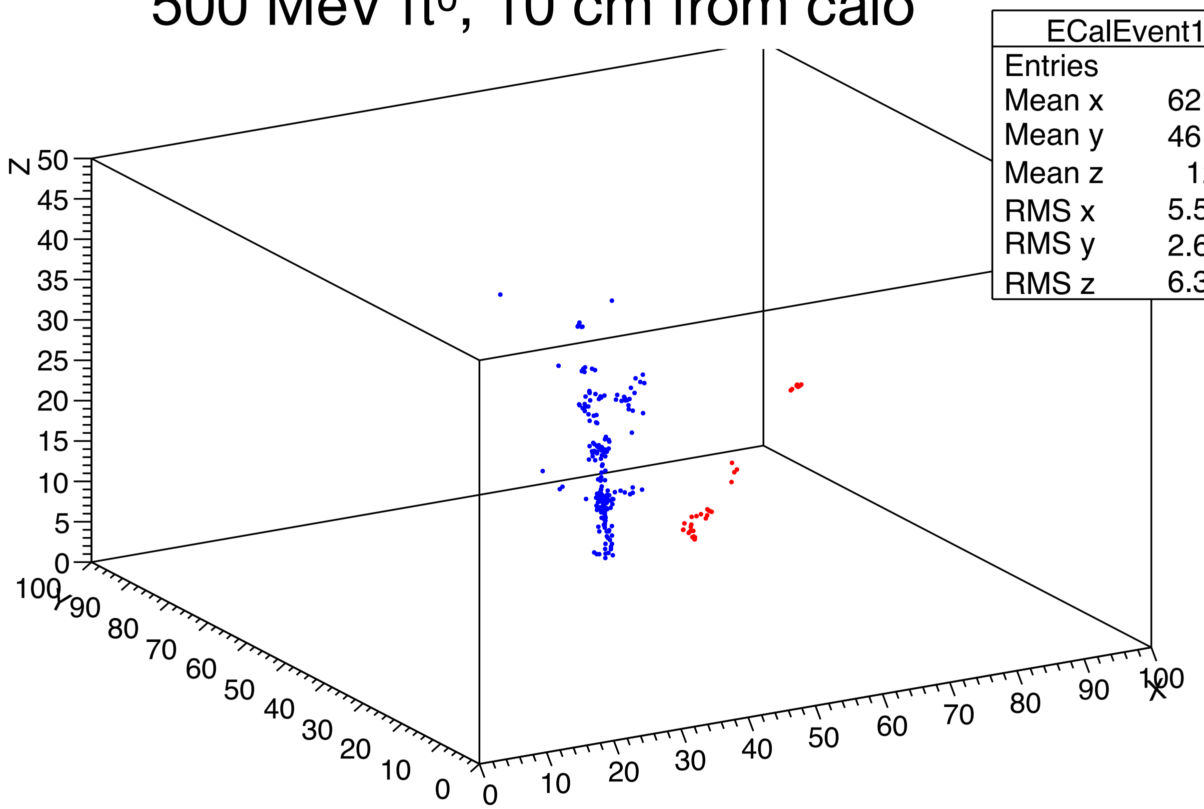


500 MeV π^0, 10 cm from calo



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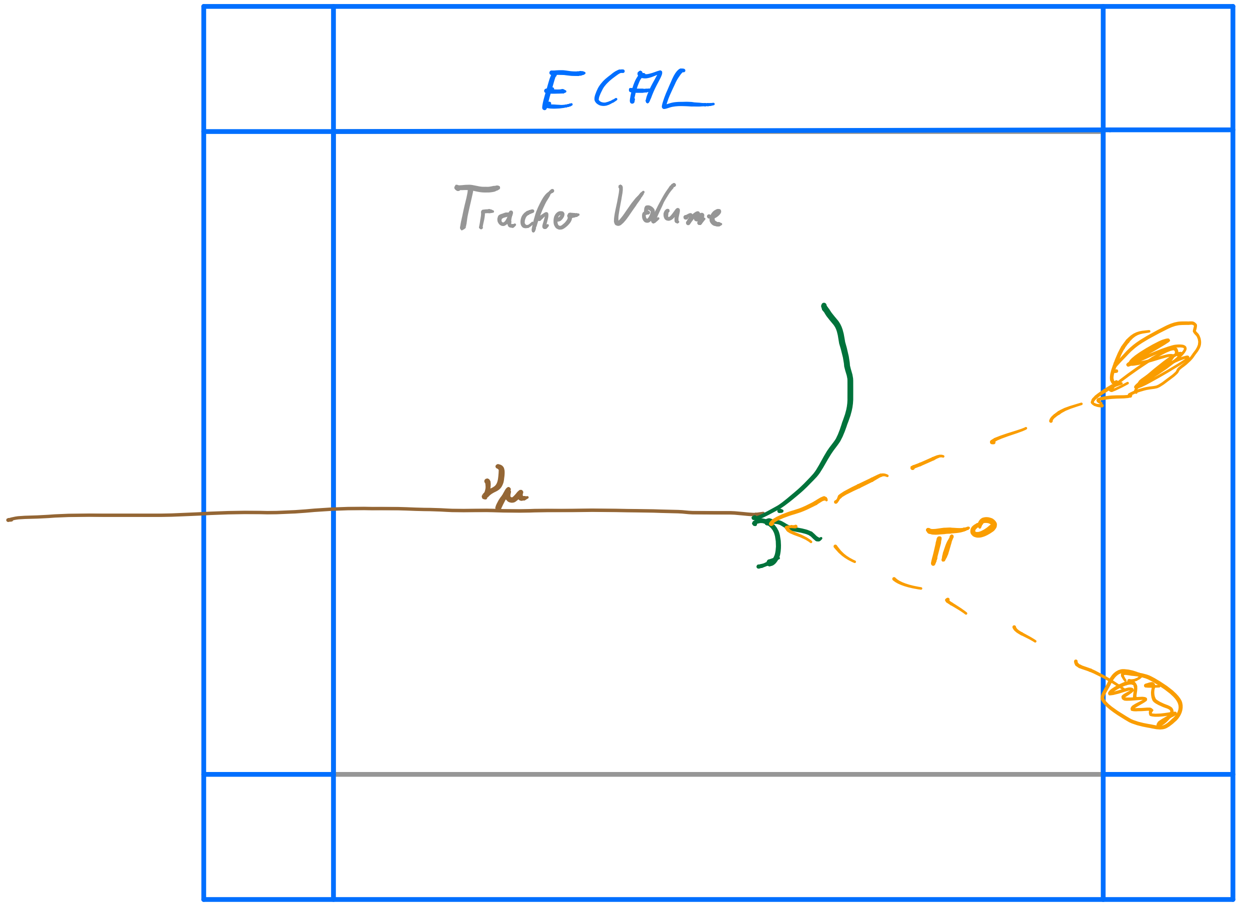

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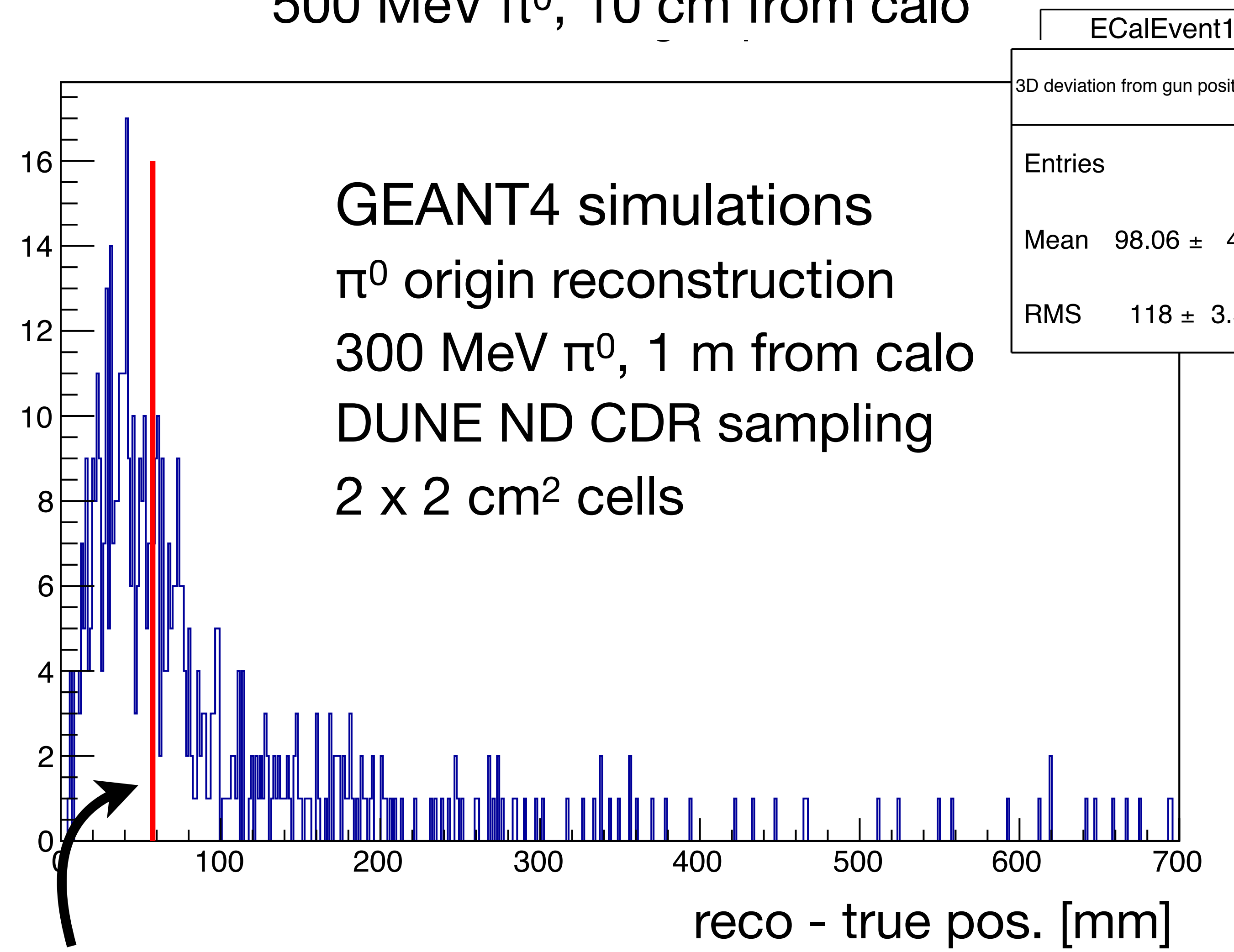

mean offset: 60 mm

Lorenz Emberger

Towards a Detector Concept

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  - Strongly builds on synergies with CALICE activities

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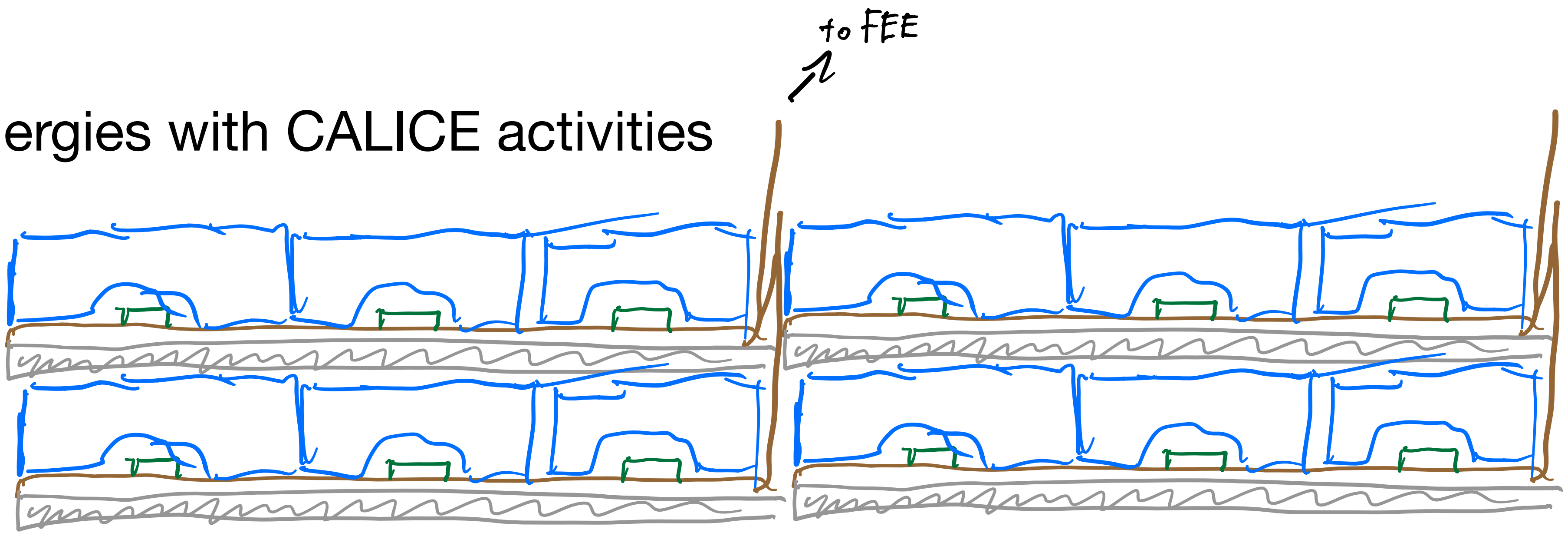

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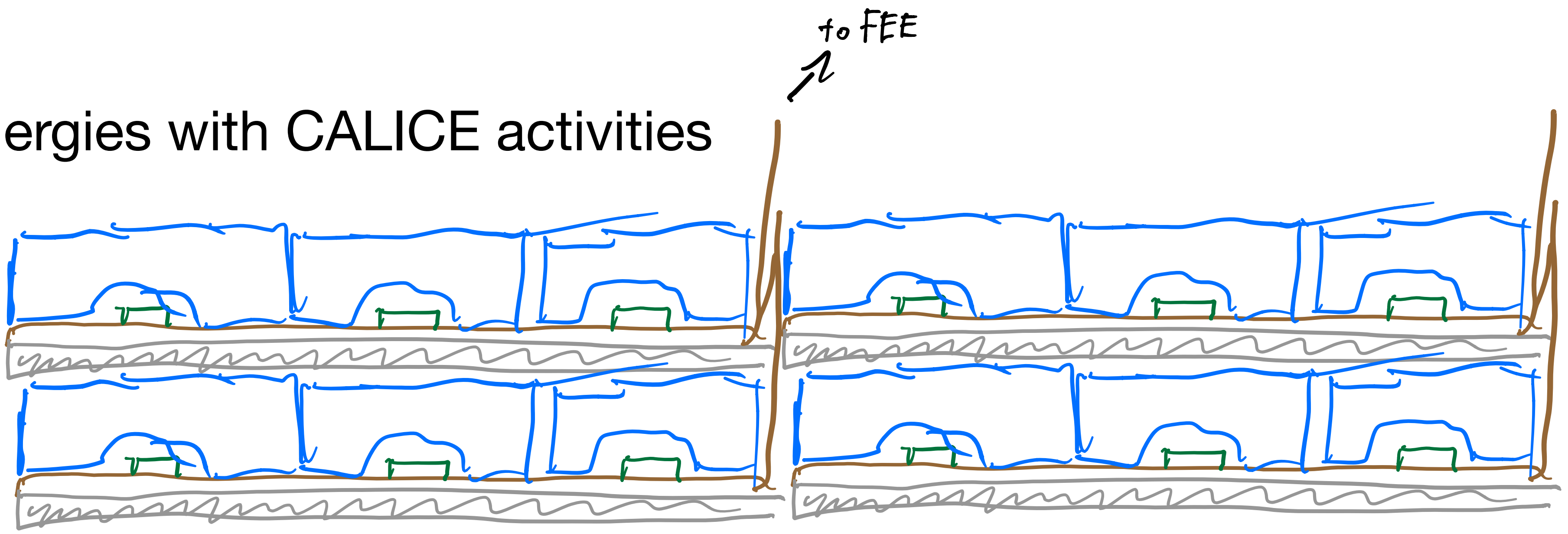
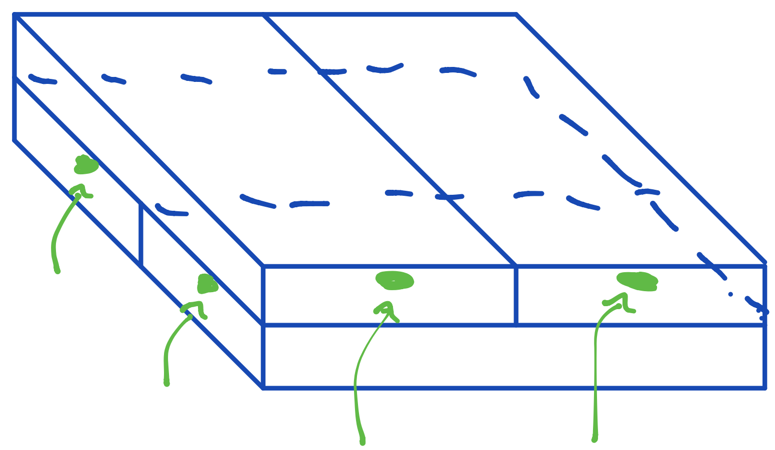


Orthogonal crossed strips, with embedded WLS for light collection, SiPM readout on both ends, strip segmentation potentially with "megatile" solution



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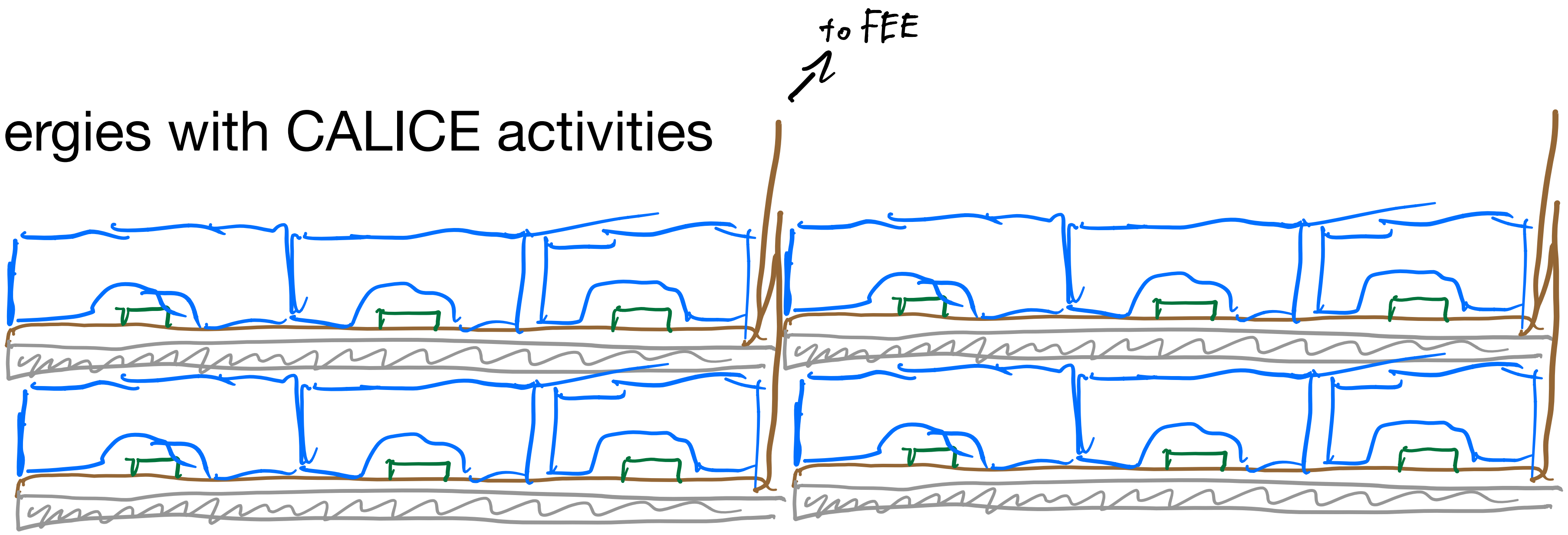

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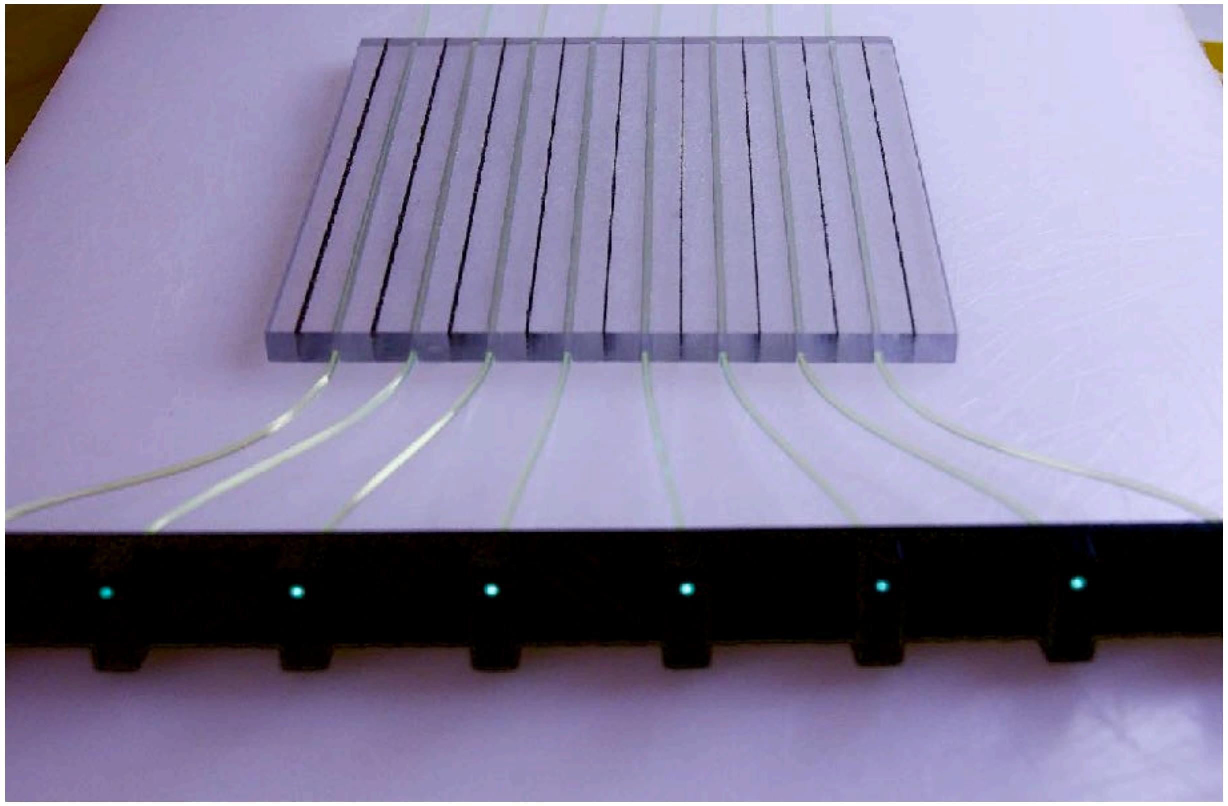

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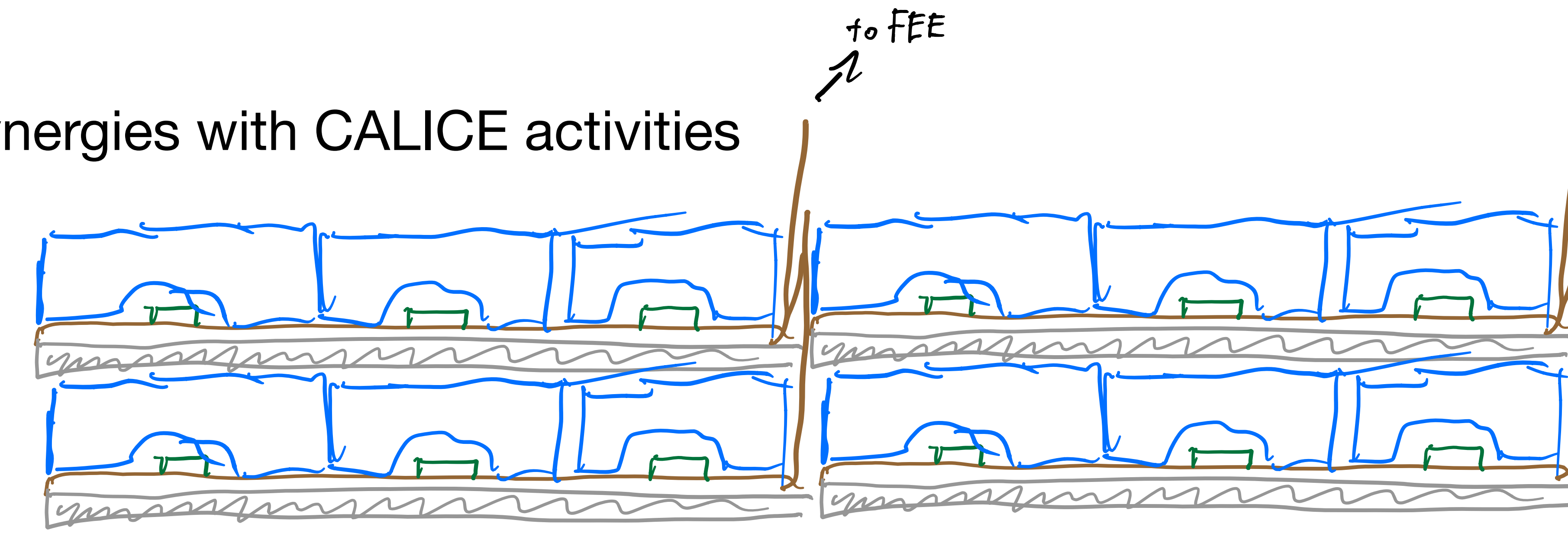

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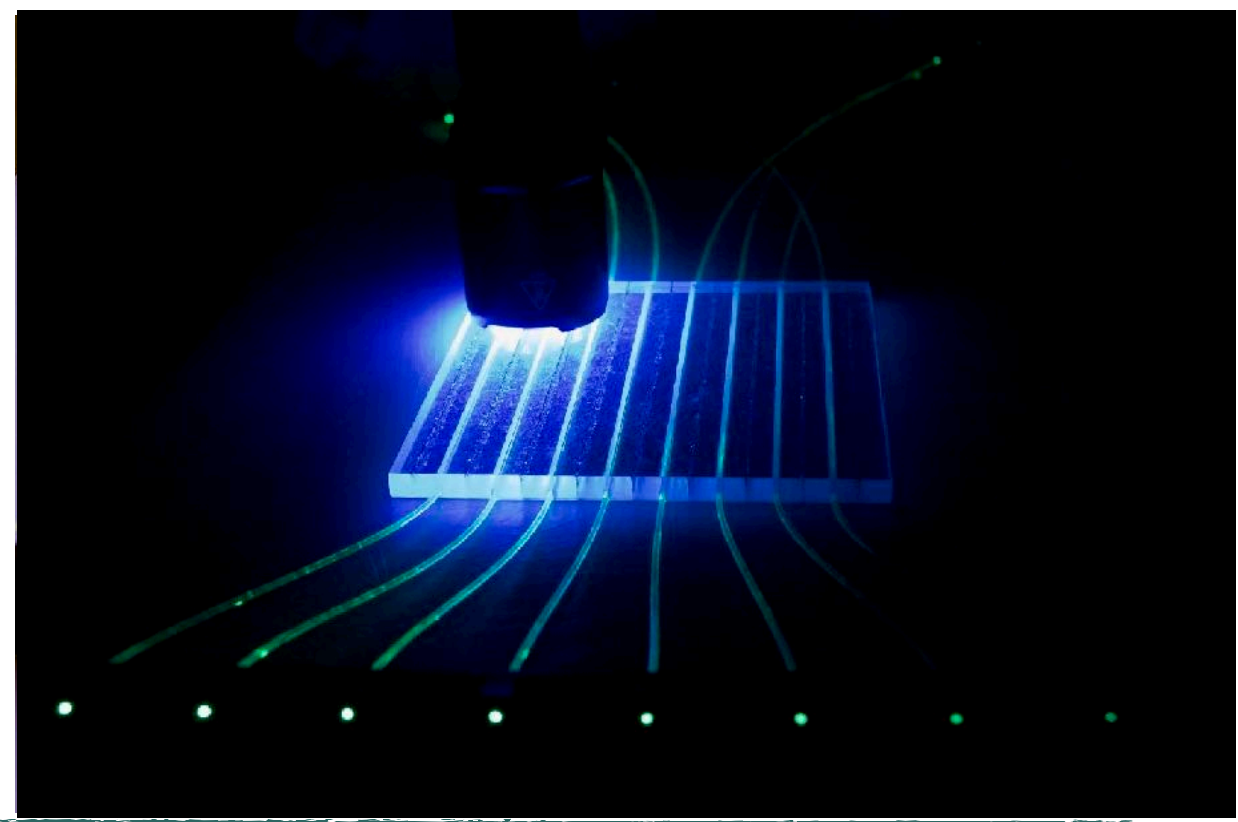

Way Forward & Summary

- The next year(s) are highly important for future large-scale projects in HEP: Decisions on future directions expected in the framework of the European Strategy Process: Input by ***end of 2018***, community meeting ***May 2019***, Conclusions ***May 2020***

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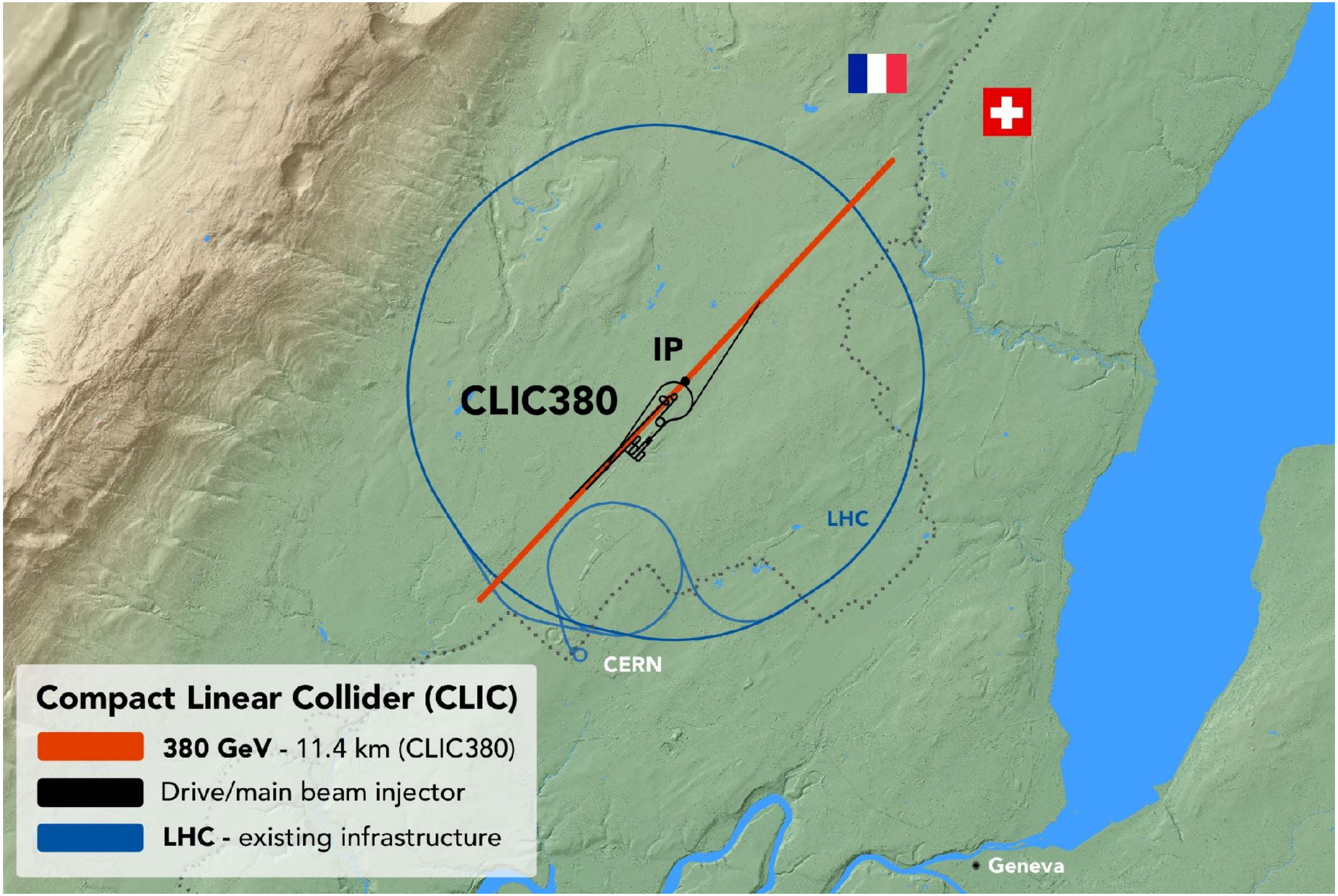
- Applications of CALICE technologies closer to the “real axis”:
  - Background measurements in SuperKEKB - key for PXD operations in Belle II
  - Exploring options for the electromagnetic calorimeter of the DUNE Near Detector
    - Key aspects of near detector concept to be defined by mid 2018

Extras

CLIC 380 GeV



IP
CLIC380
LHC
CERN
Geneva
Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
Drive/main beam injector
LHC - existing infrastructure

Dreams to Software: Particle Flow Algorithms

- Jets consist of a mix of particles
  - typically 60% charged hadrons, 30% photons, 10% neutral hadrons
  - ➯ “classical” calorimeter-only reconstruction is driven by calorimeter resolution for hadrons

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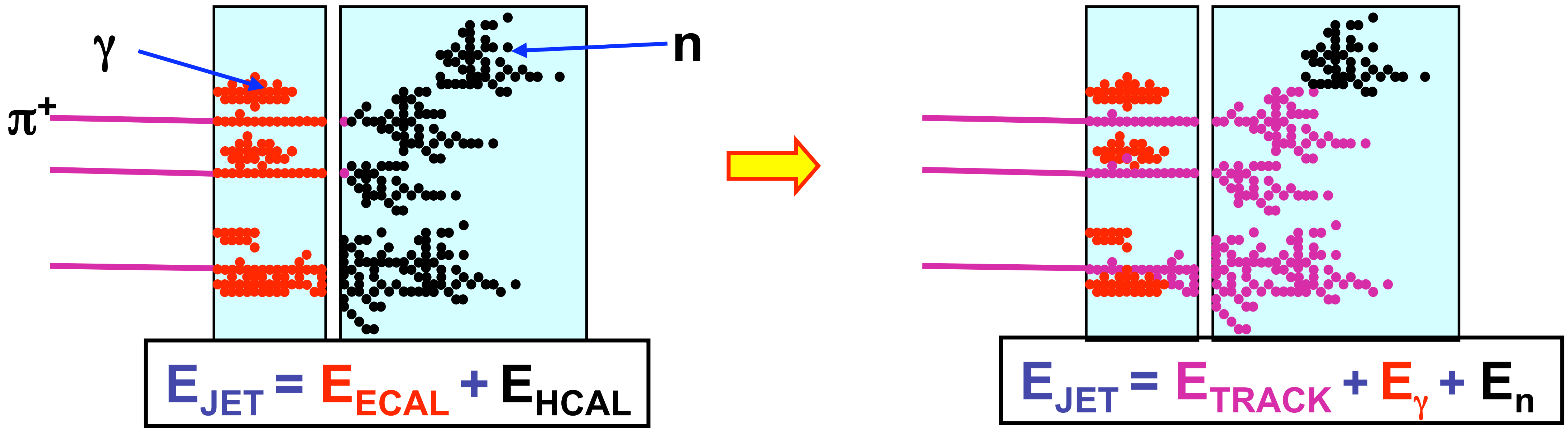

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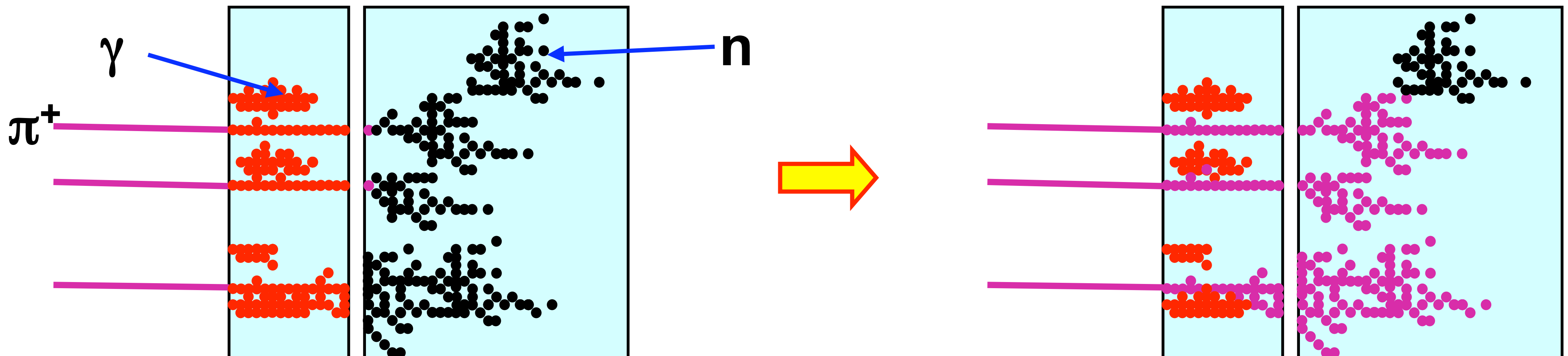


$$E_{JET} = E_{ECAL} + E_{HCAL}$$

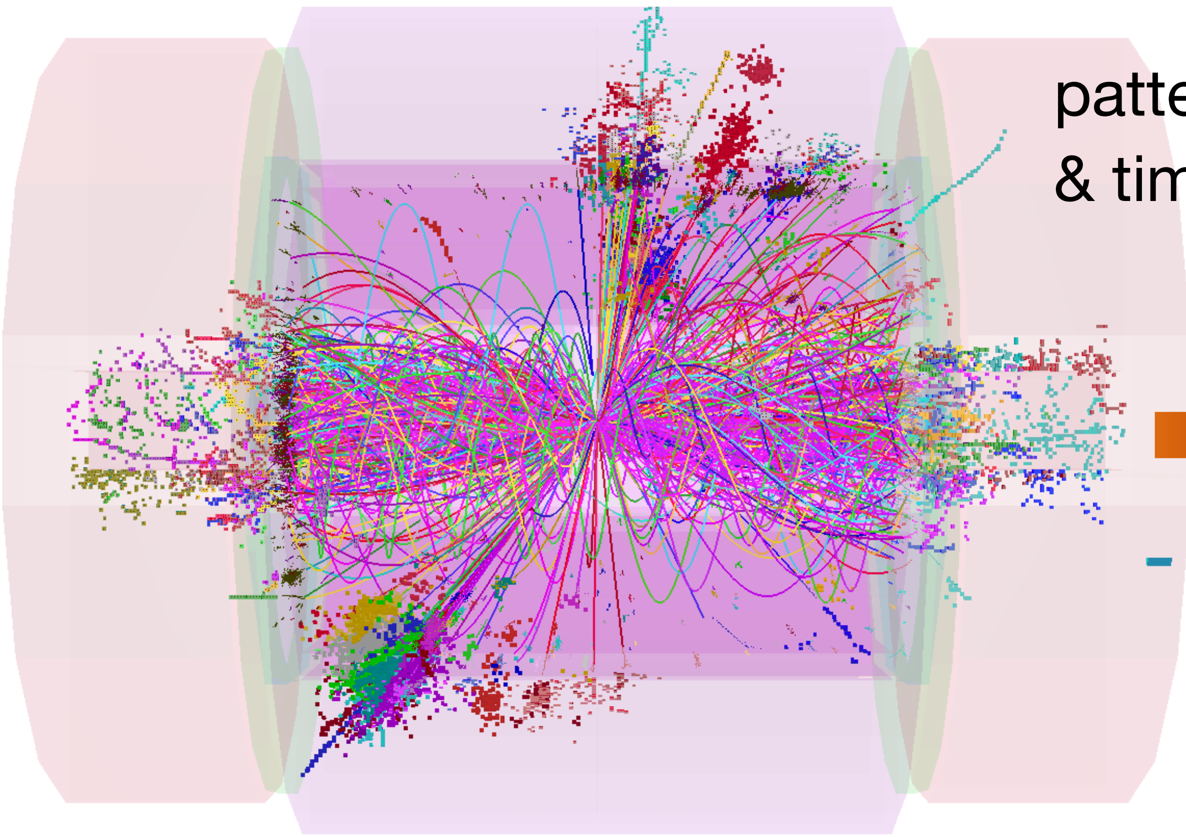
$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

For best results: high granularity in the calorimeters to correctly separate showers

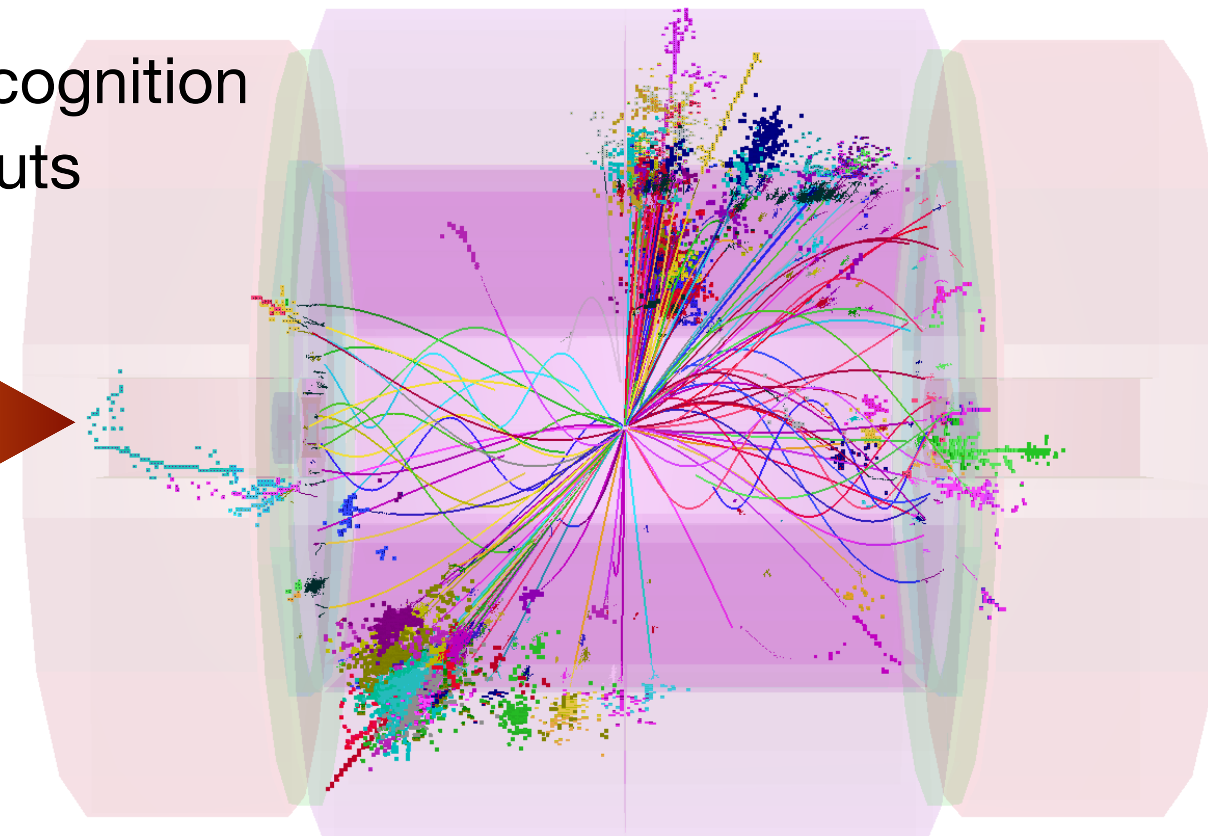
The level of mistakes, "***confusion***", determines the achievable jet energy resolution, not the intrinsic resolution of the calorimeters!

PFA: Not just Jet Energy Resolution

- Granularity is not just beneficial for resolution: Opens the door for pattern-based rejection of background - even more powerful with the addition of timing

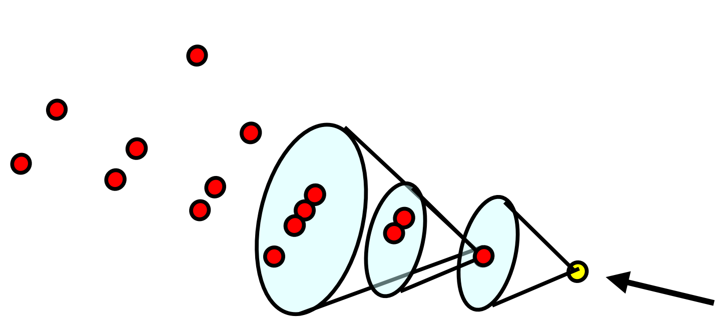


pattern recognition & timing cuts



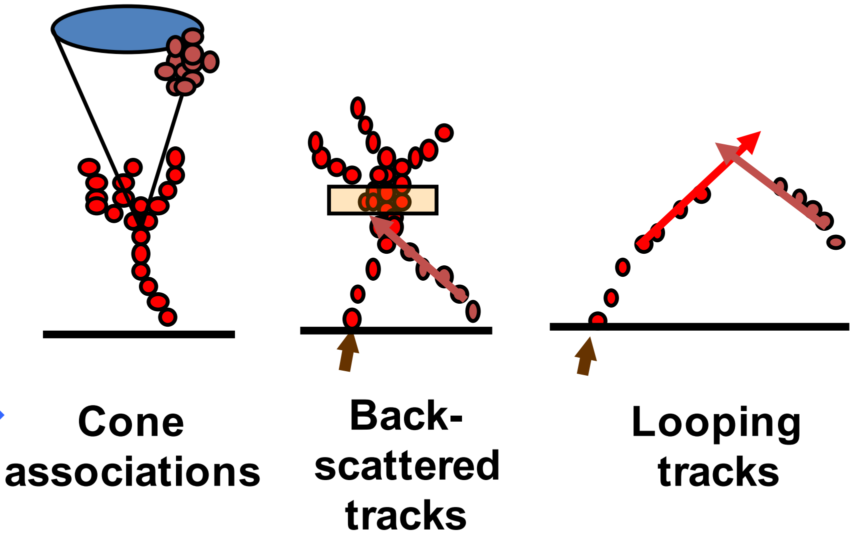
- Extensively studied at CLIC: pile-up of γγ -> hadrons background, combined with 0.5 ns bunch - to - bunch spacing
- Very relevant for hadron colliders - reflected in upgrade plans of CMS

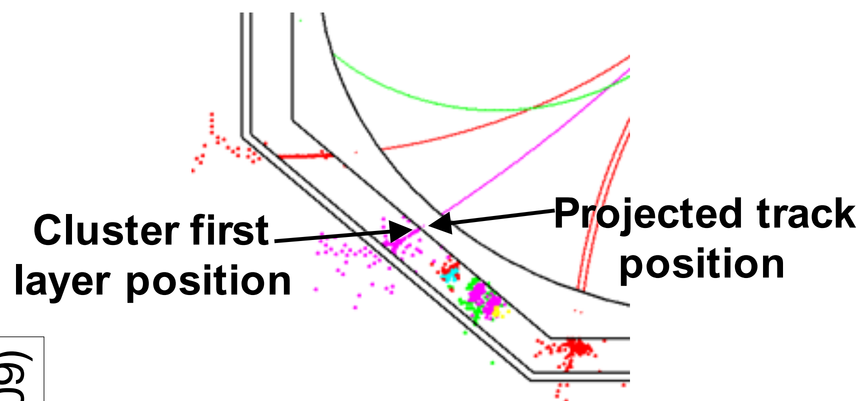
Under the Hood: Particle Flow Algorithms



ConeClustering Algorithm

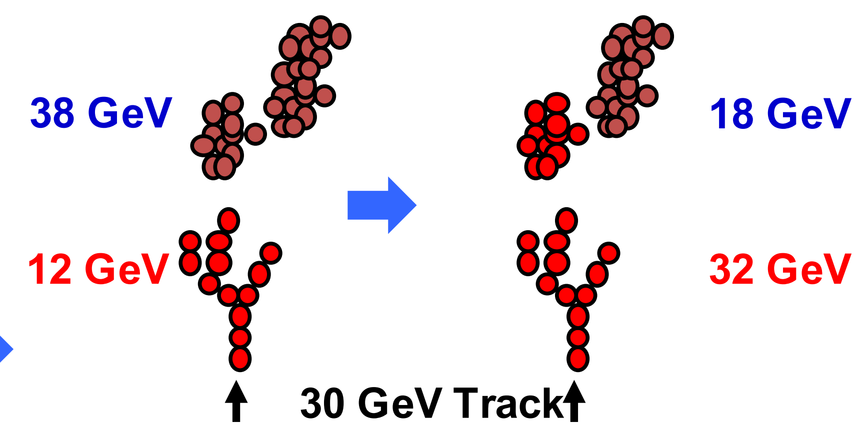
Topological Association Algorithms

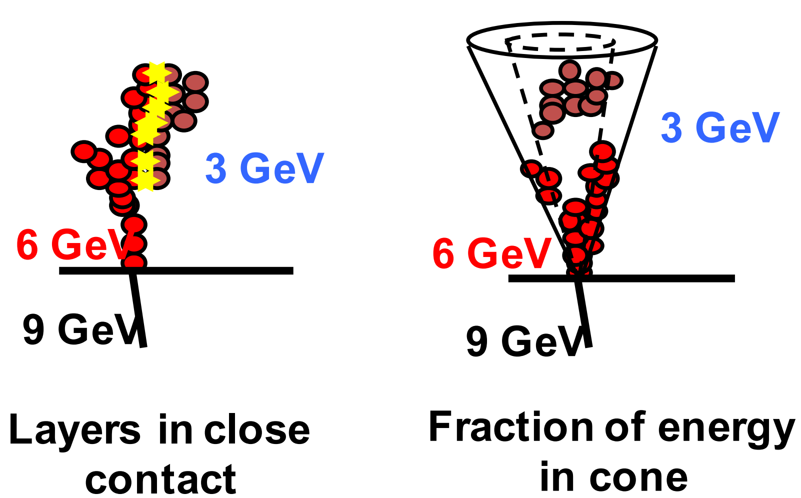




Track-Cluster Association Algorithms

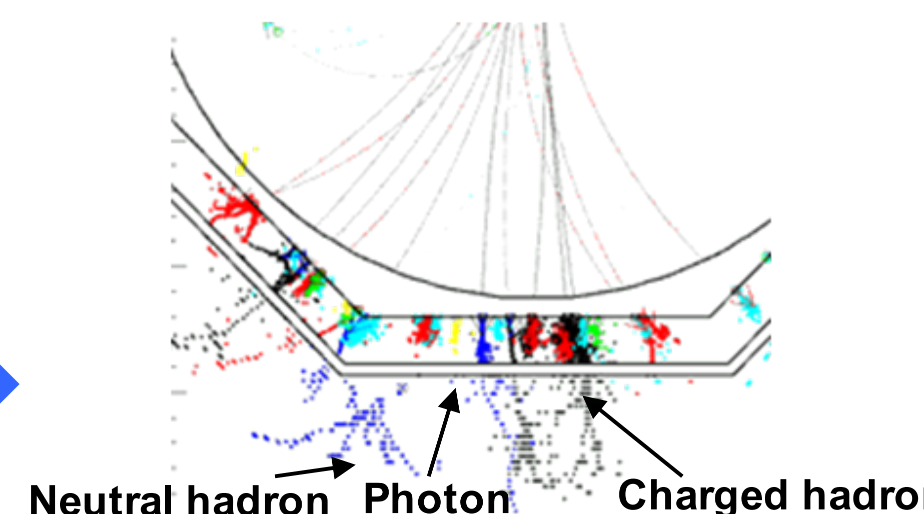
Reclustering Algorithms





Fragment Removal Algorithms

PFO Construction Algorithms



M. Thomson, NIM A61, 24 (2009)

Making PFA Happen: Granularity!

- Sophisticated pattern recognition in calorimeters to correctly assign calorimeter energy to particles seen in tracker: ***Imaging calorimeters***

➯ Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers

- ➯ X_0 / ρ_M drive ECAL and HCAL (electromagnetic subshowers)

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Depends on material:

- in W: X_0 ~ 3 mm, ρ_M ~ 9 mm
- in Fe: X_0 ~ 20 mm, ρ_M ~ 30 mm

NB: Best separation for narrow showers particularly important in ECAL
➯ Use W in ECAL!

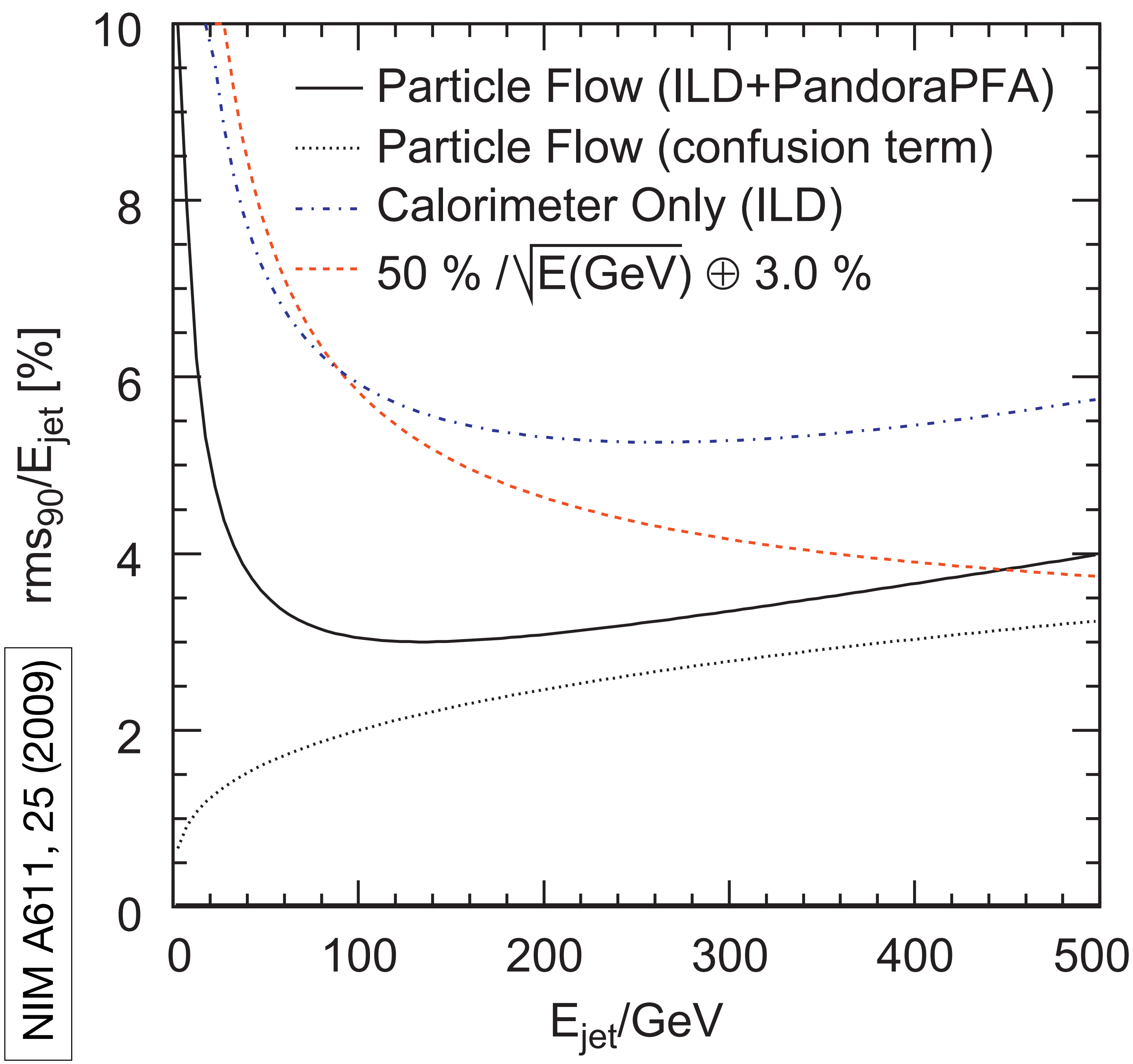
When adding active elements: ~ 0.5 cm^3 segmentation in ECAL, ~ 3 - 25 cm^3 in HCAL

➯ $\mathcal{O}$ $10^{7\text{-}8}$ cells in HCAL, 10^8 cells in ECAL for typical detector systems!

- ▸ fully integrated electronics needed
- ▸ requires active elements that support high granularity and large channel counts

Dissecting PFA Performance

- Particle Flow Performance has been extensively studied in full detector simulations in the context of Linear Colliders



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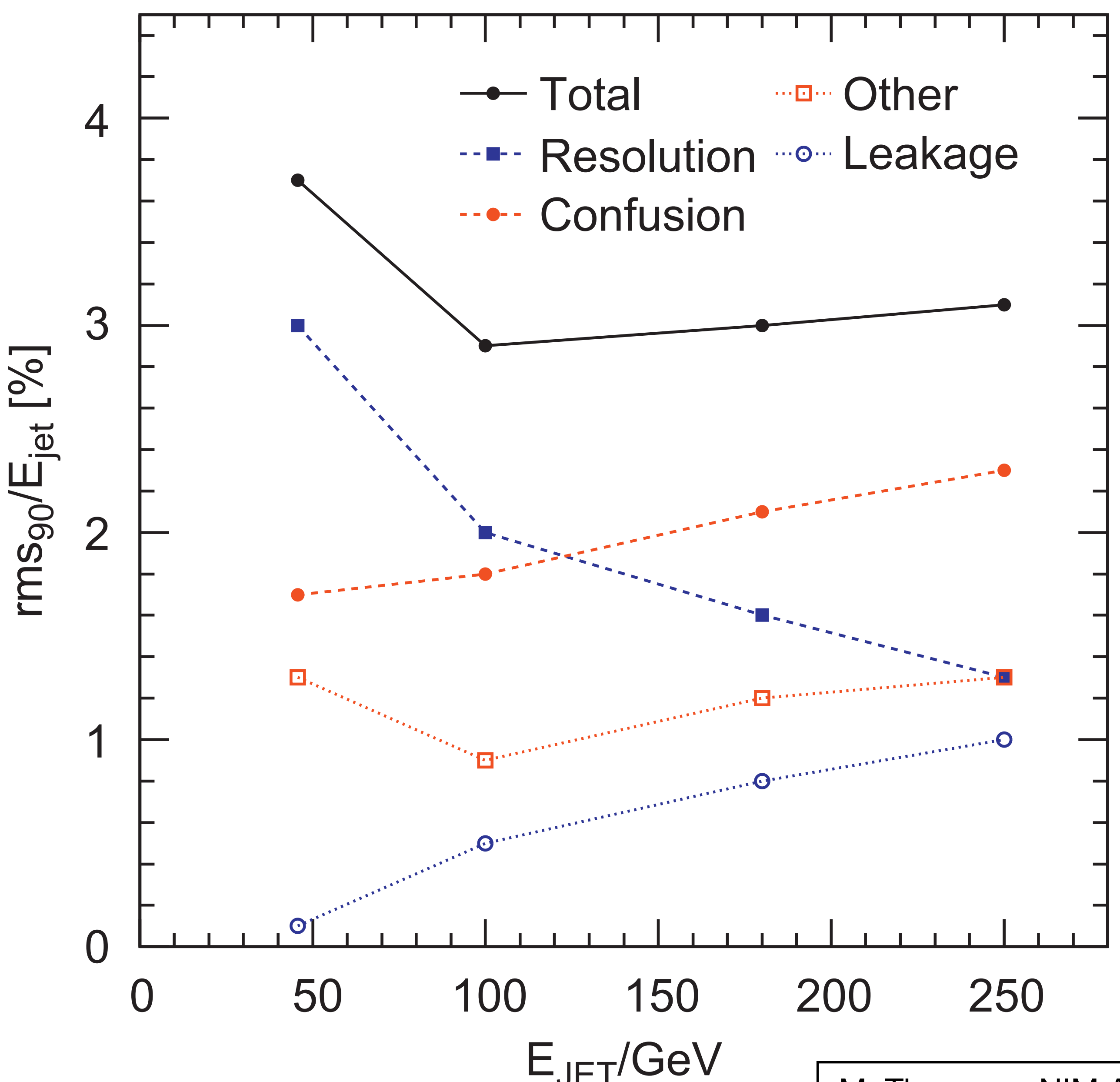


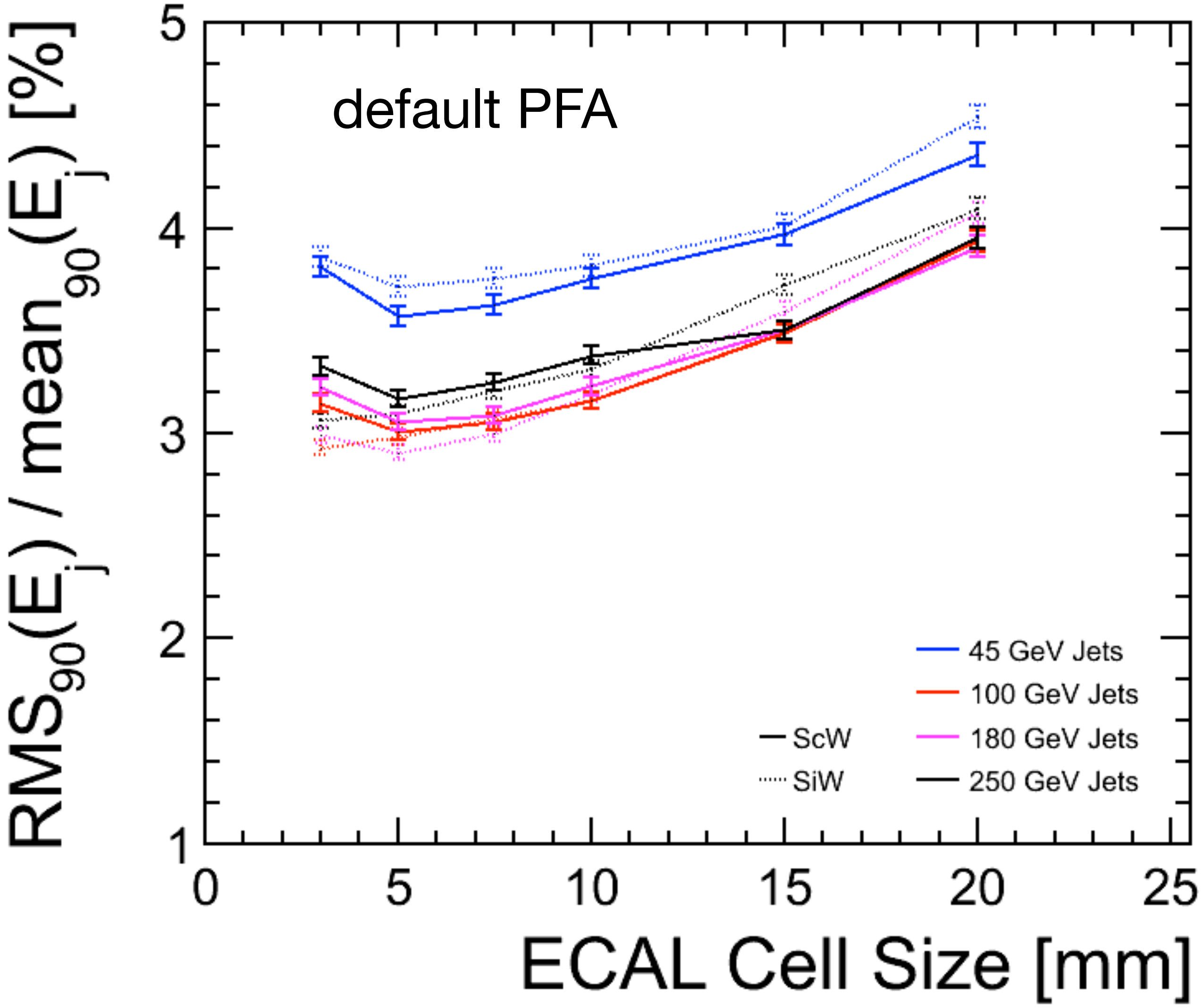
- At low energy resolution dominates - in particular the HCAL resolution
- At higher energy confusion takes over
  - depends on calorimeter granularity, capability of pattern recognition and algorithm quality

NB: The point where confusion takes over depends on the detector (granularity, radius, tracker details) and on the algorithm!

M. Thomson, NIM A611, 25 (2009)

Understanding Granularity Requirements: ECAL

- Very detailed study in the context of the CLIC detector optimisation (J. Marshall et al.) - to understand ECAL requirements



- Clear dependence on ECAL cell size - confusion for close-by em showers increases with decreasing granularity

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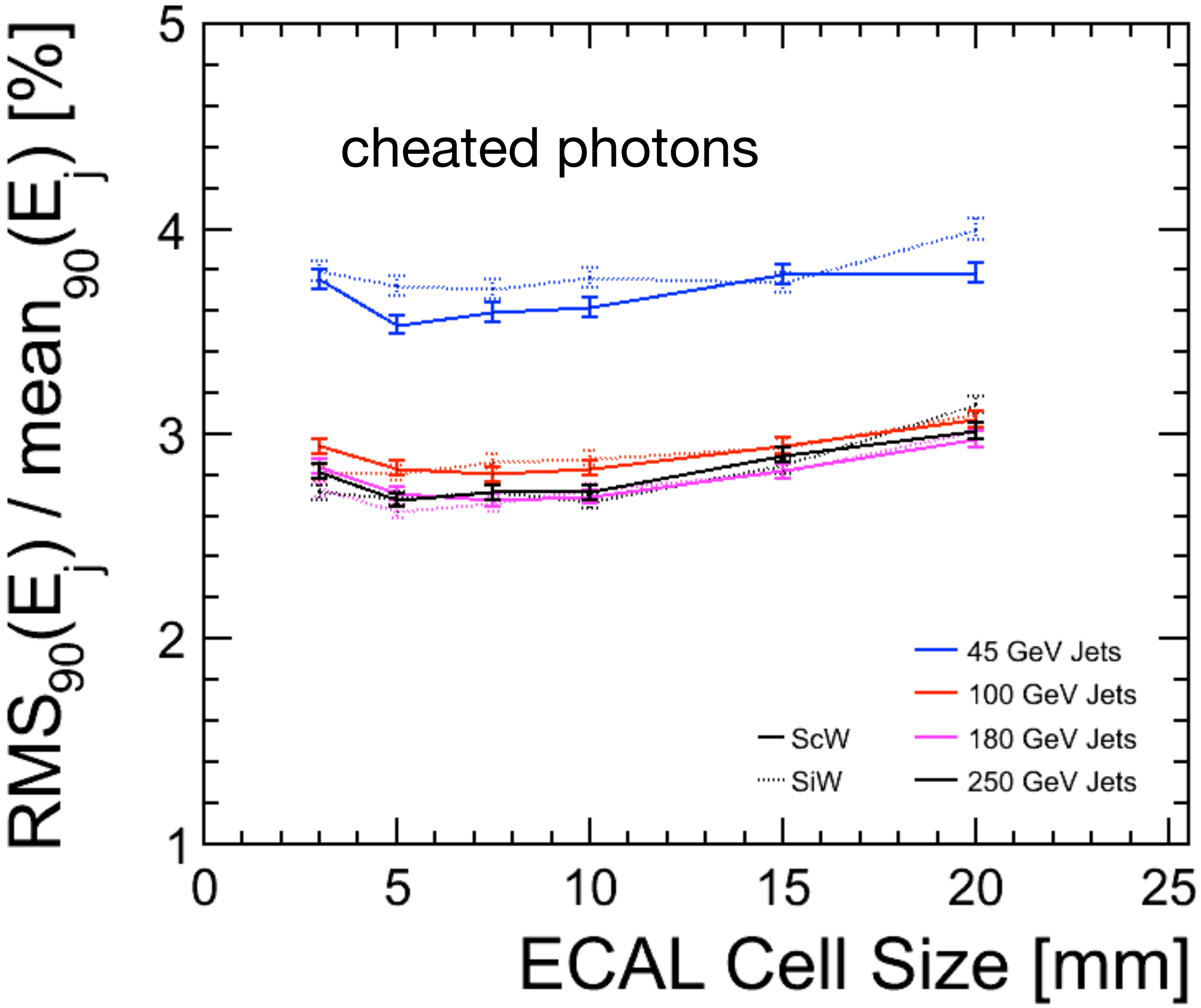

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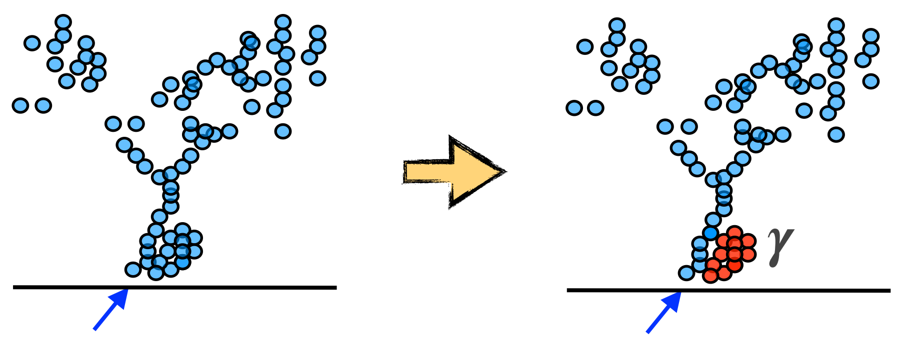

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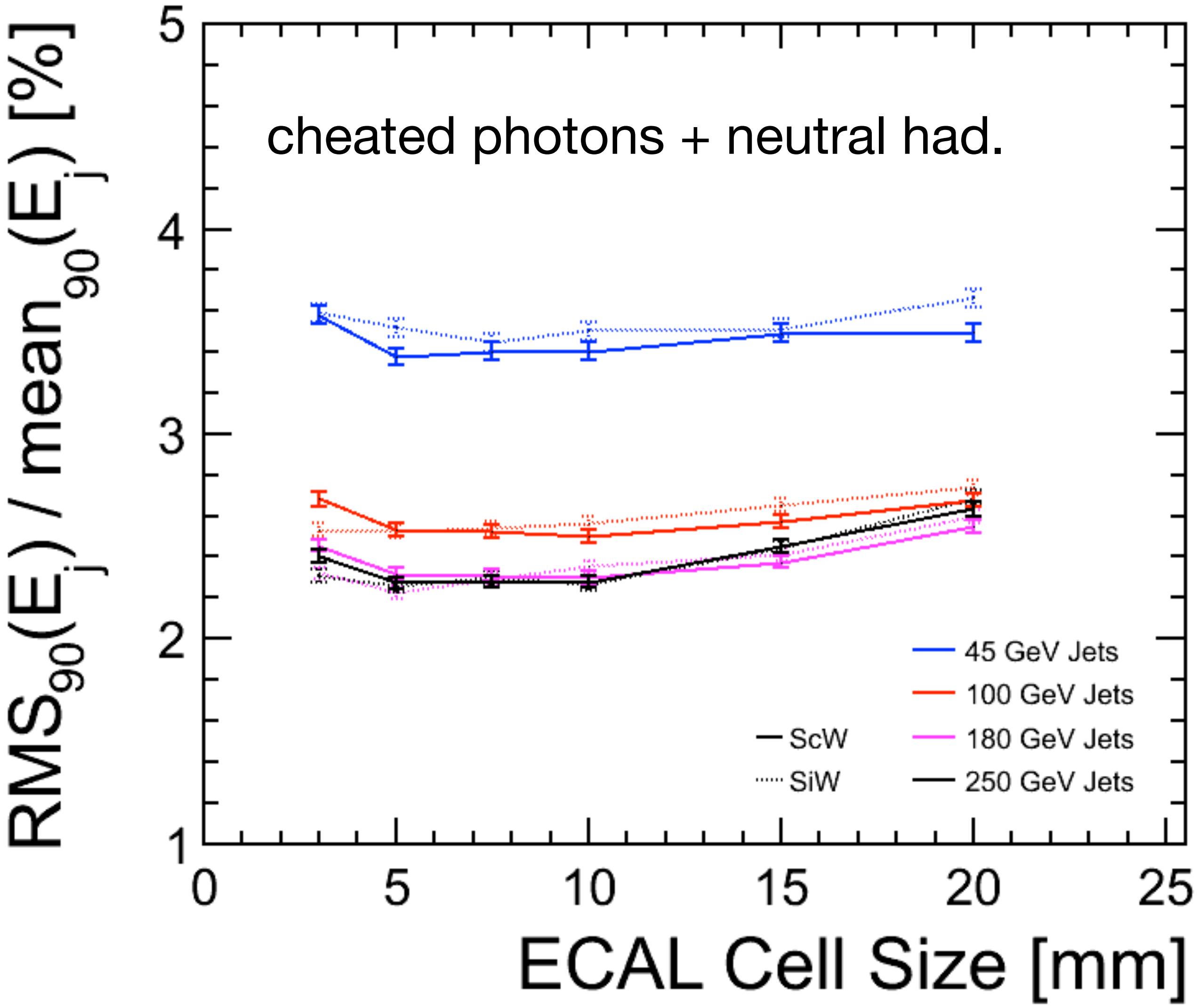

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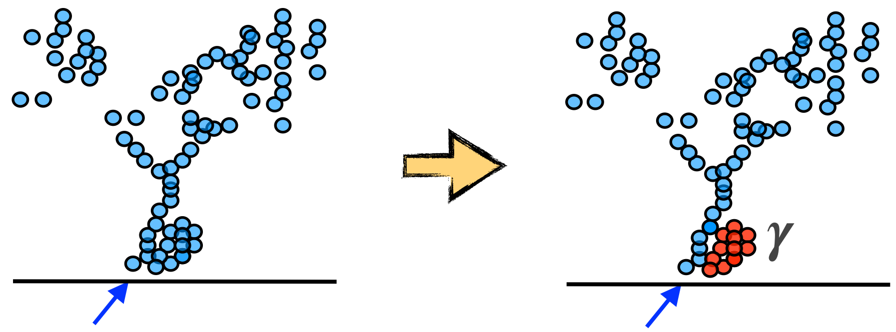

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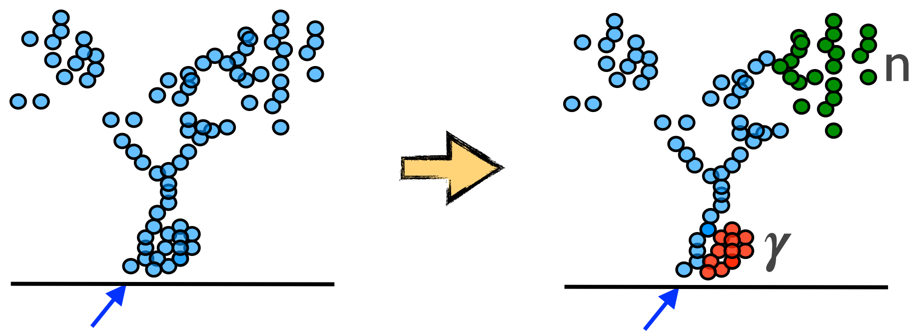

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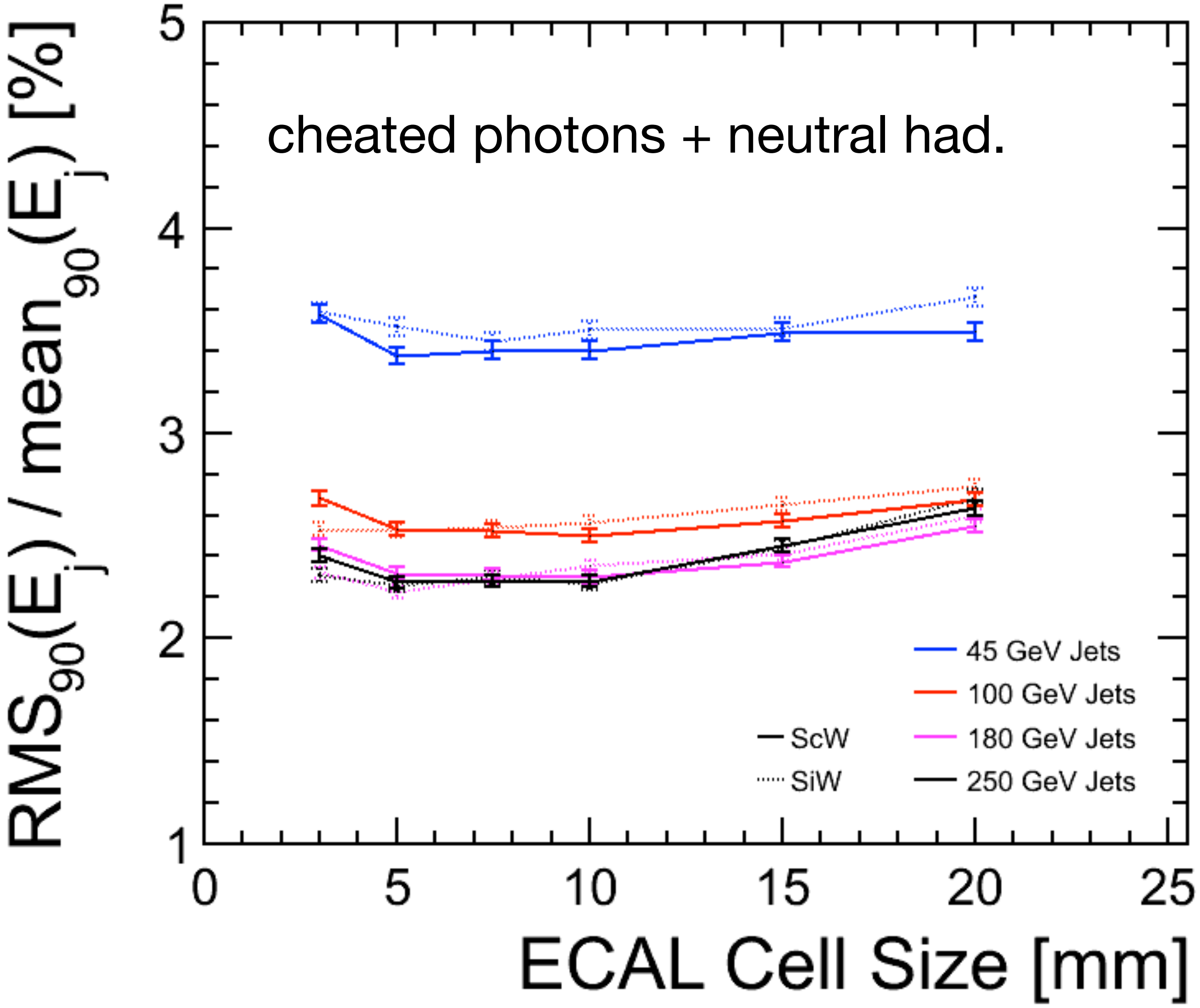

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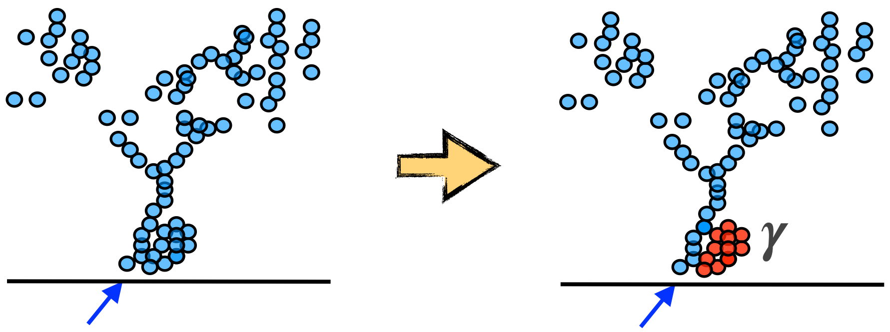

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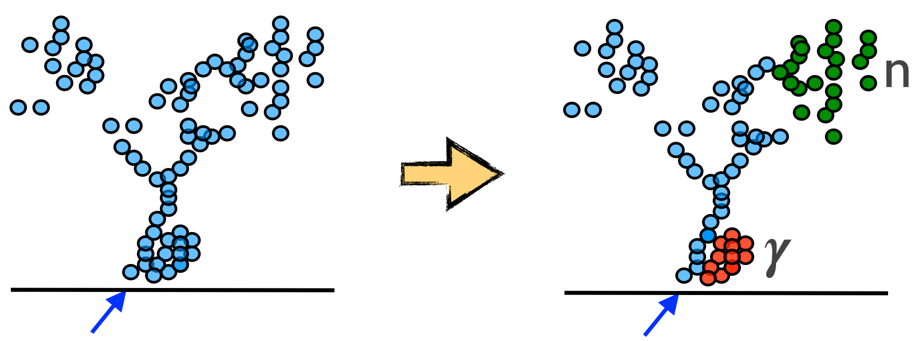
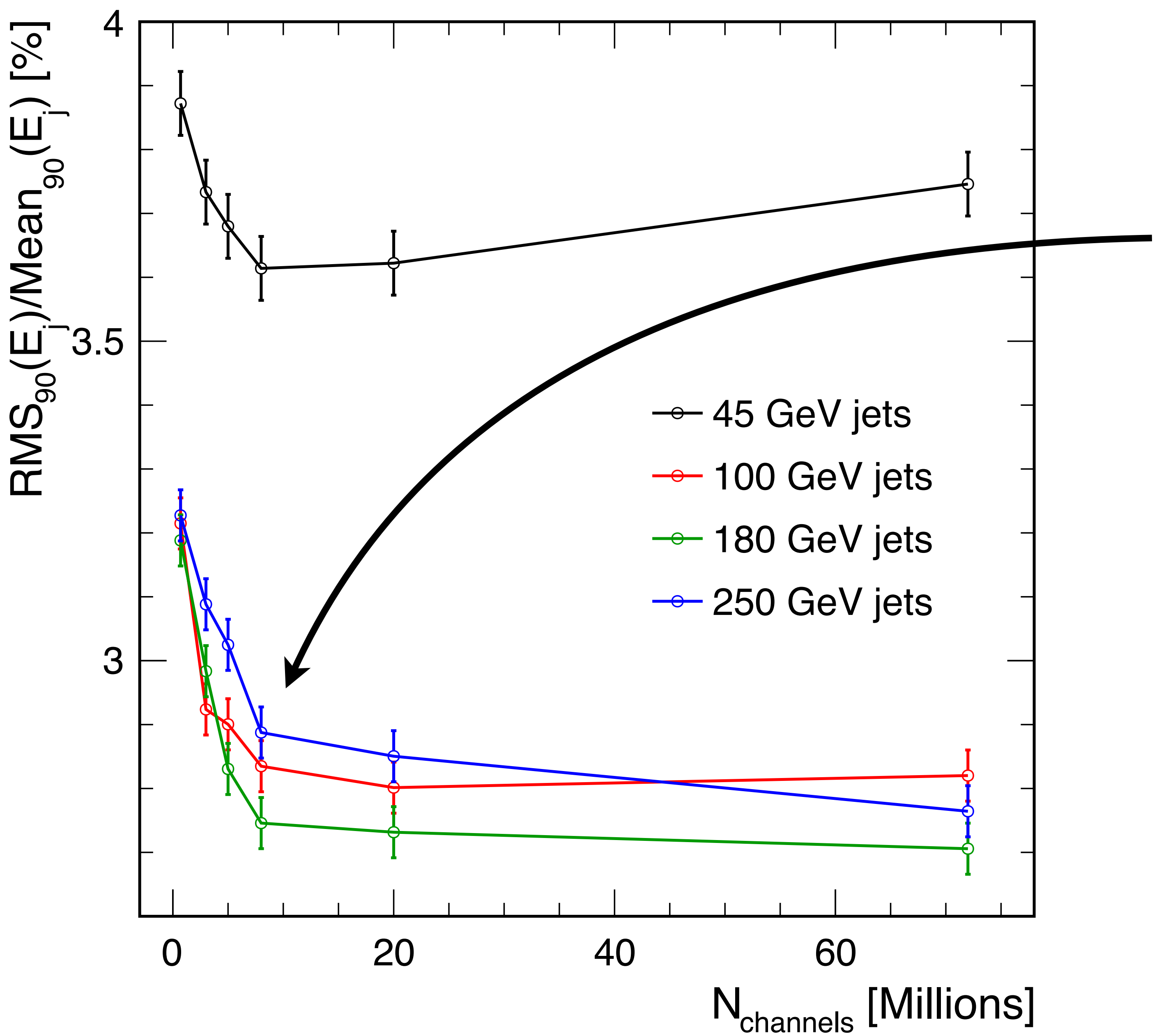


Target: ECAL cell size ≤ 10 x 10 mm^2 with full analog information in each cell

Understanding Granularity Requirements: HCAL

- Similar studies also performed in the HCAL - with less sophistication in the disentanglement of different effects, since photons do not enter the HCAL in a realistic detector geometry



plastic scintillator tiles
30 x 30 mm²

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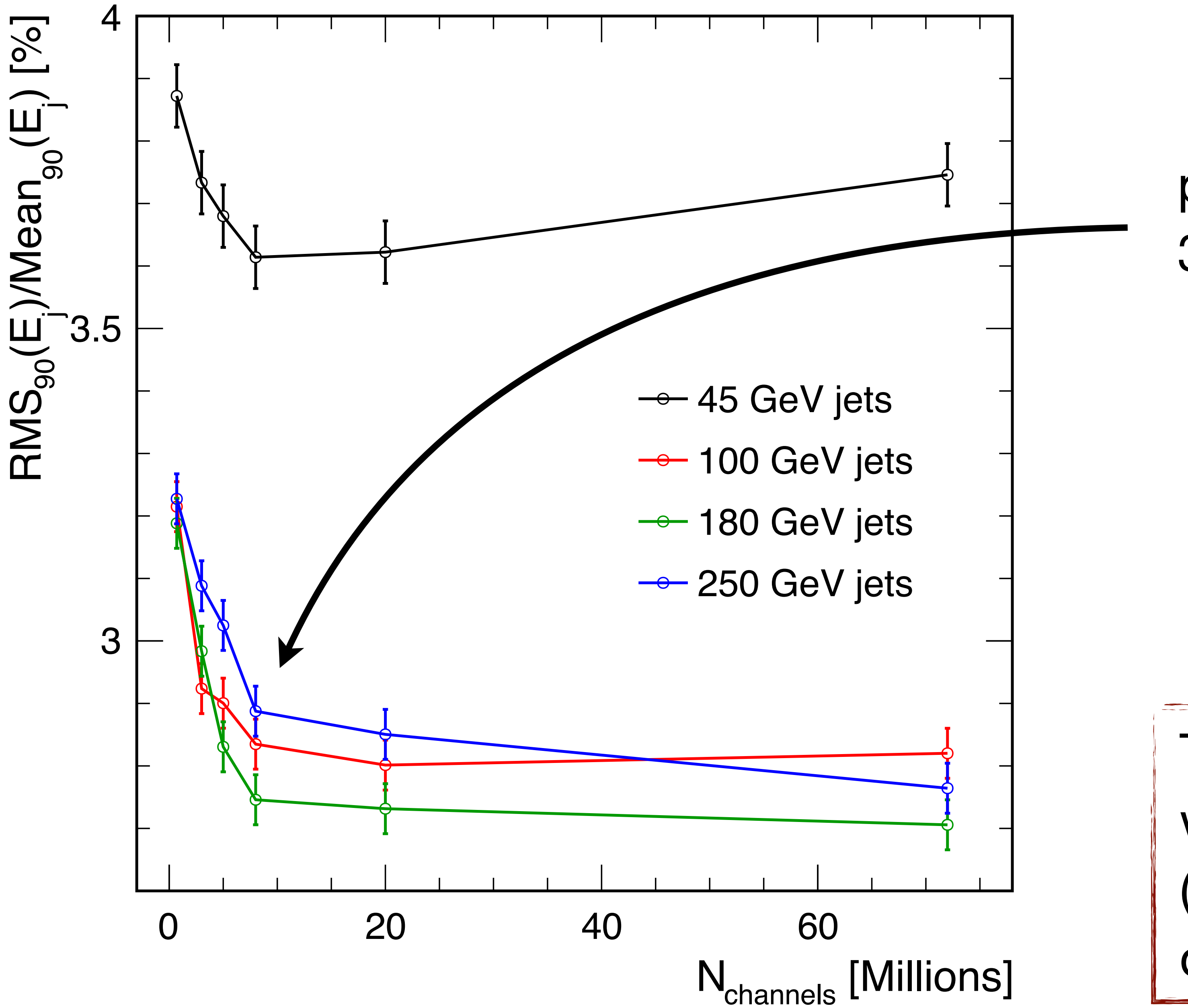
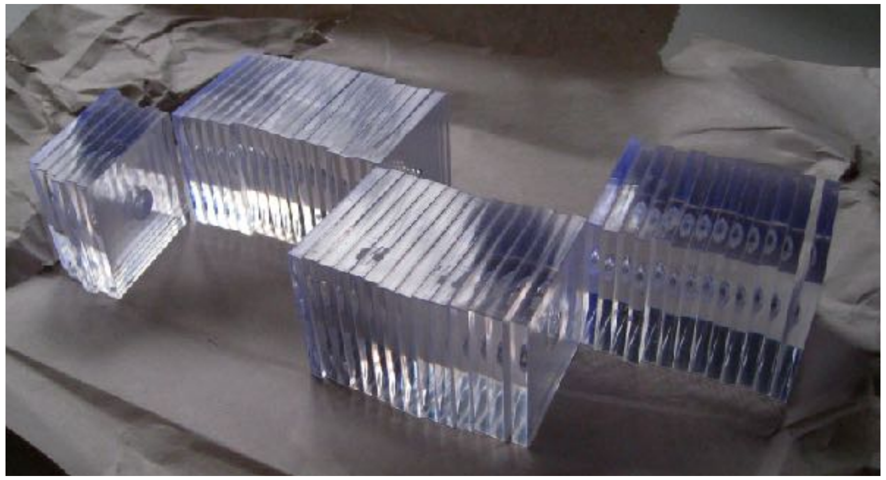


Target: HCAL cell size ≤ 30 x 30 mm² with full analog information in each cell (substantially smaller when using digital / semi-digital readout)

Proving Scalability: The Next AHCAL Prototype

- Construction of a full hadronic prototype ongoing - 24k channels - ready in 2018
  - Demonstrates technological solutions for a collider detector, addresses issues of mass production and scalability



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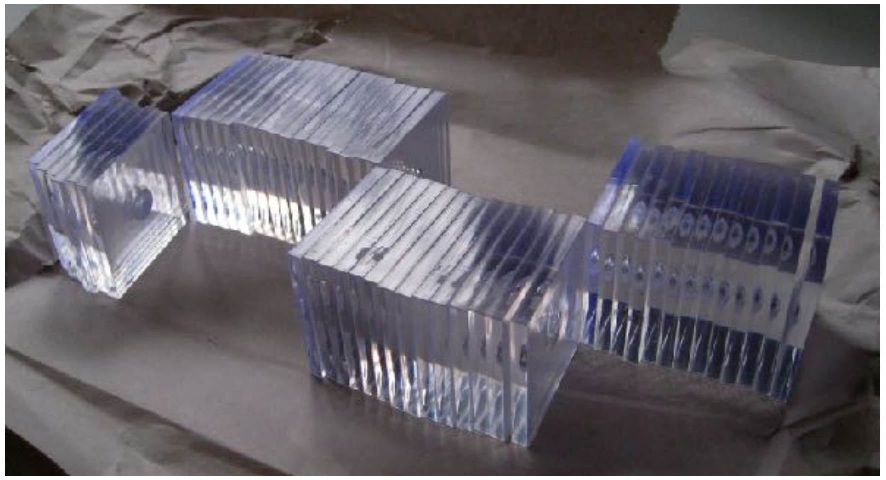
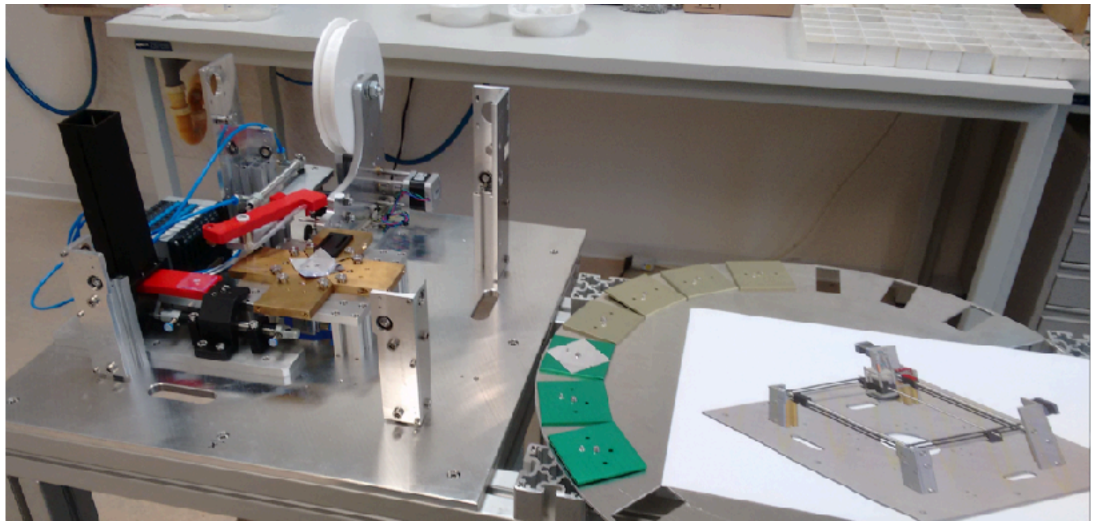


automatic wrapping of injection-molded scintillator tiles



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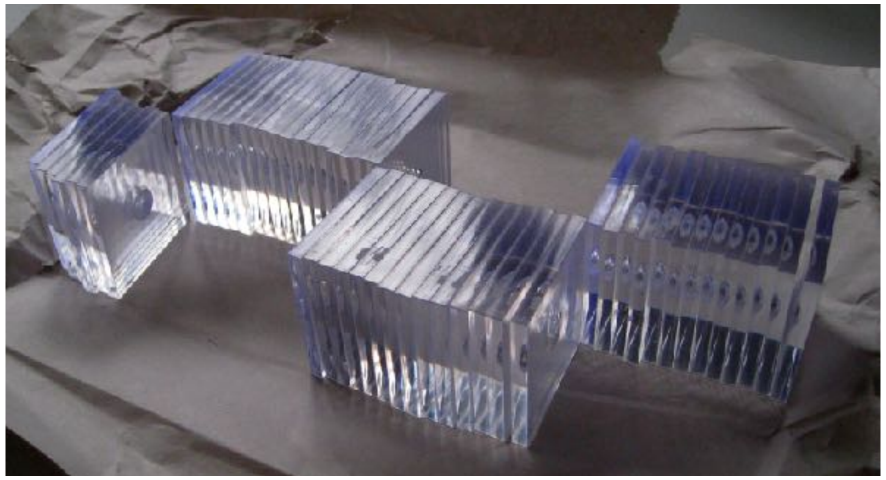

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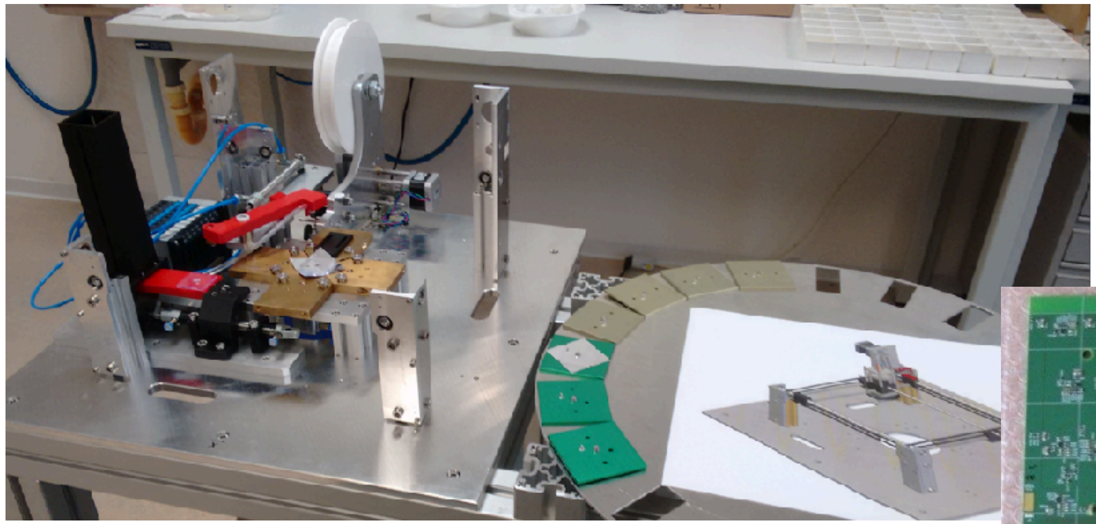
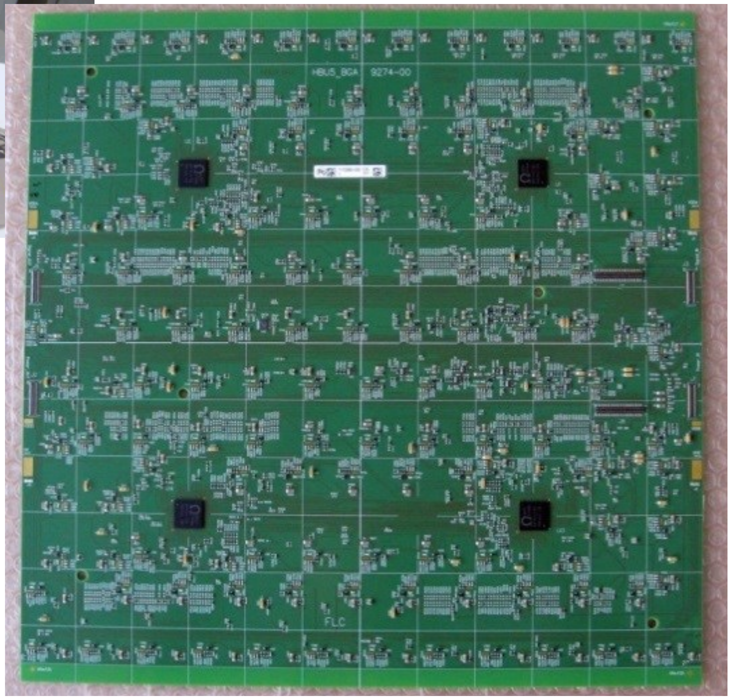


new generation of ASICs



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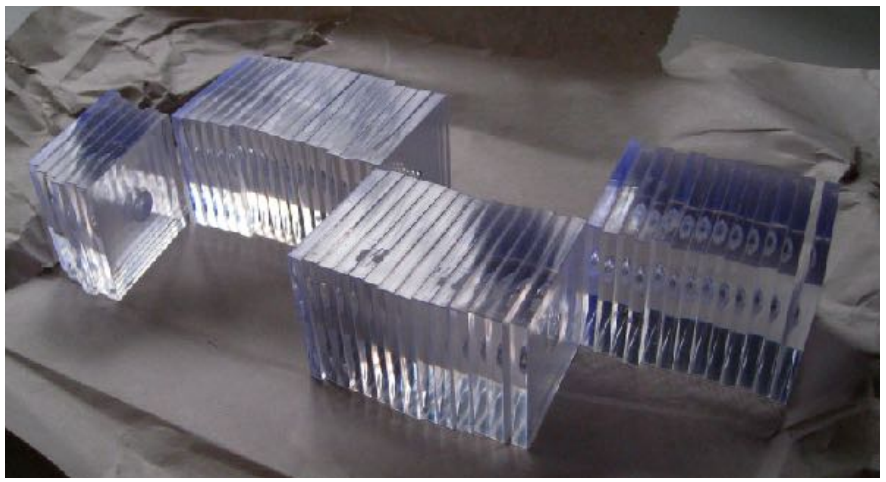

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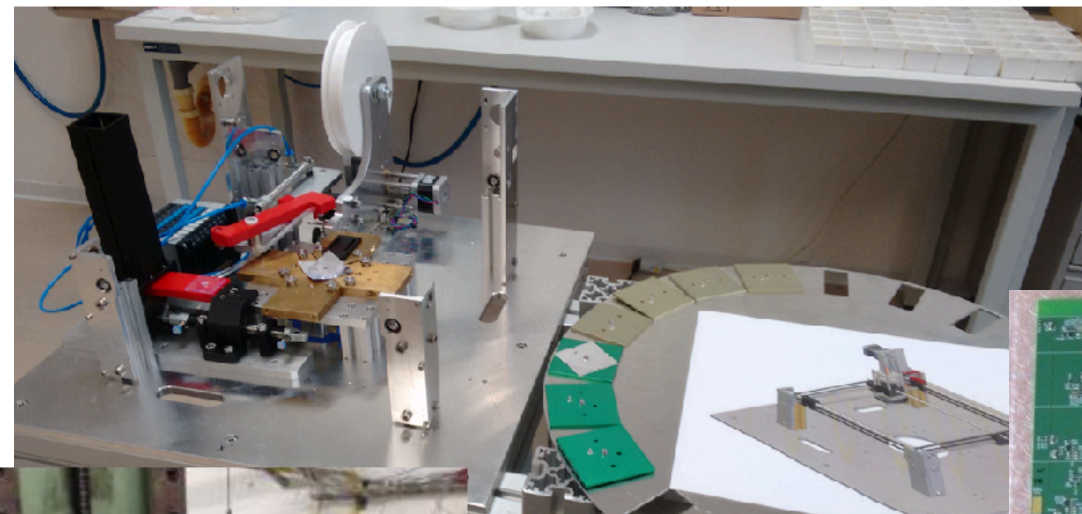

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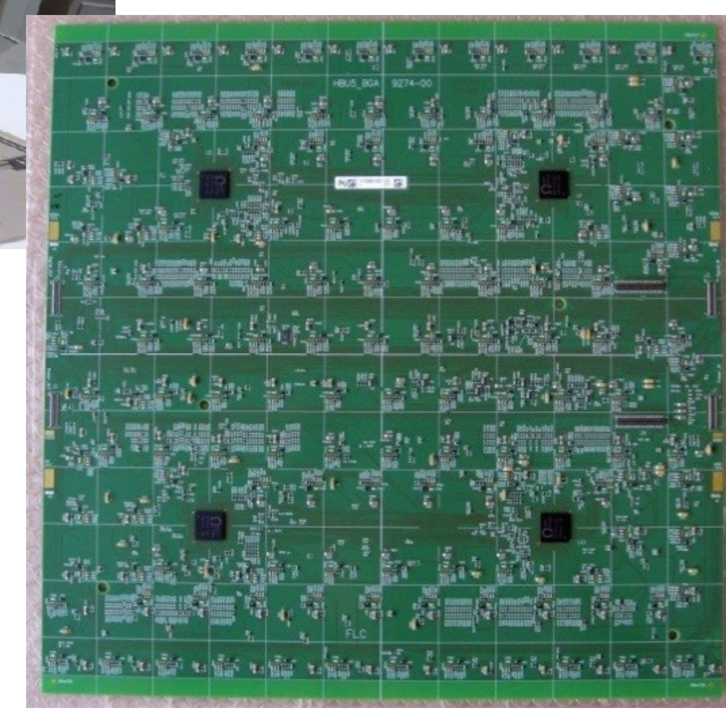
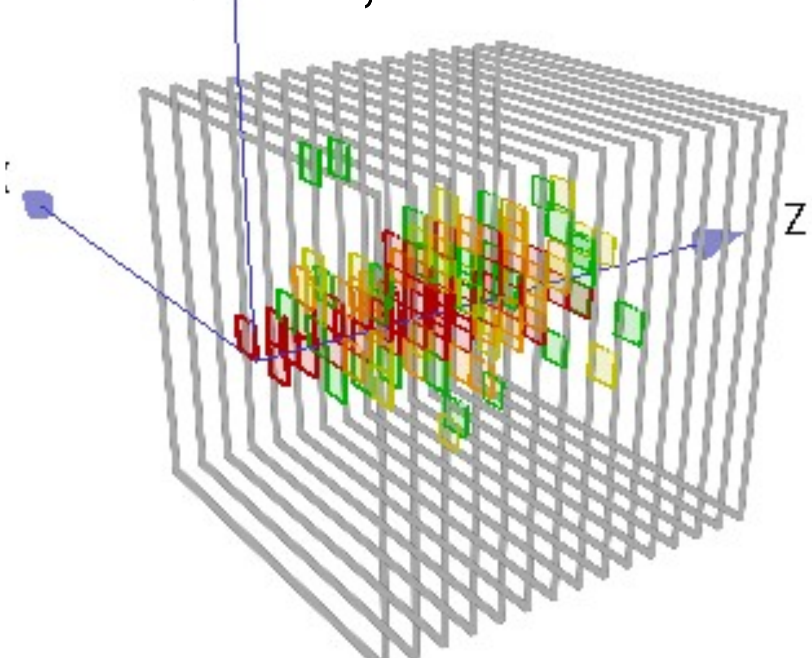


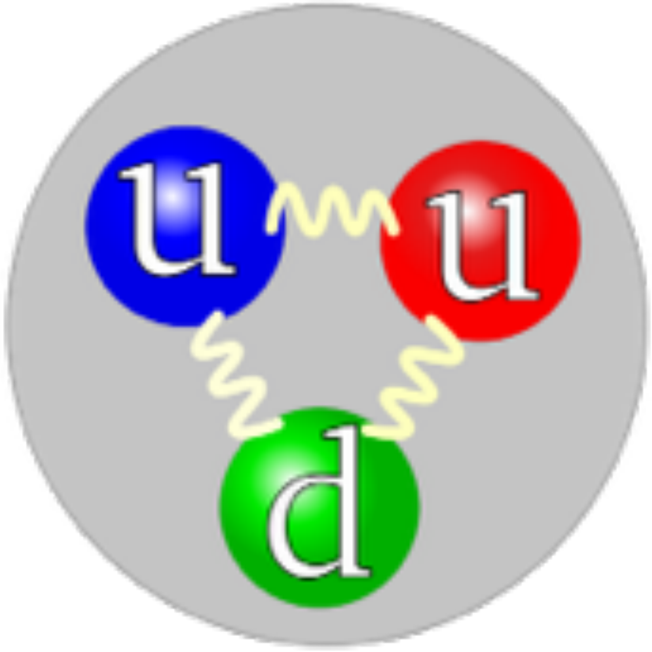
60 GeV e^-, in 1.5 T field



first test with smaller prototype successful

CALICE and Linear Colliders

- CALICE is one of the “gluons” of Linear Collider detector concepts



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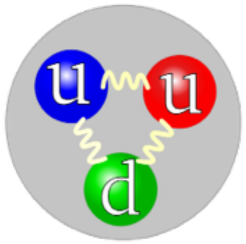

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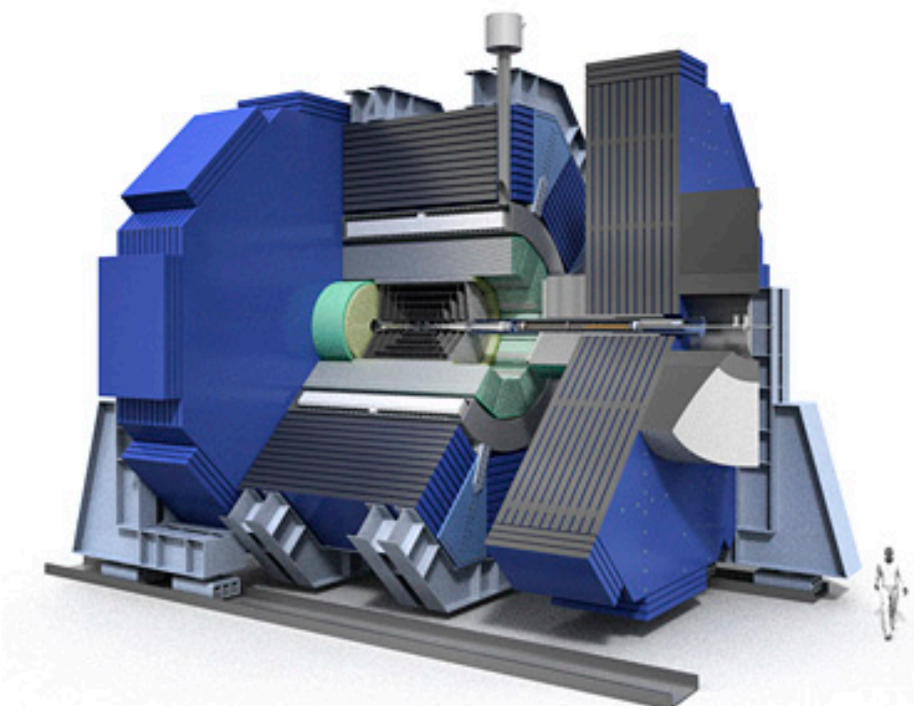

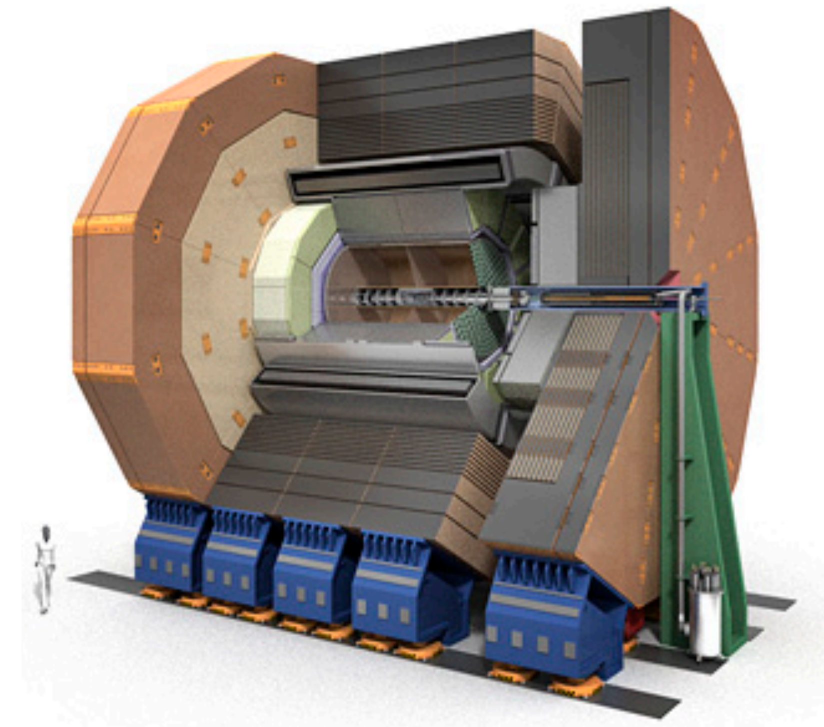

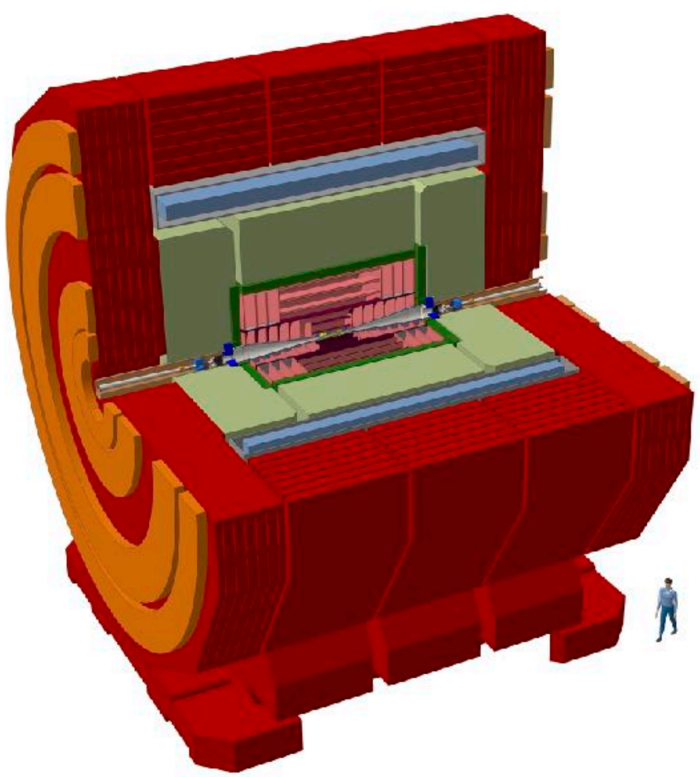

All LC detector concepts build on CALICE calorimeters:

- ILD: ECAL (Si or Sc) + HCAL (Sc or SD)
- SiD: HCAL (Sc or D)
- CLIC: ECAL (Si or Sc) + HCAL (Sc)

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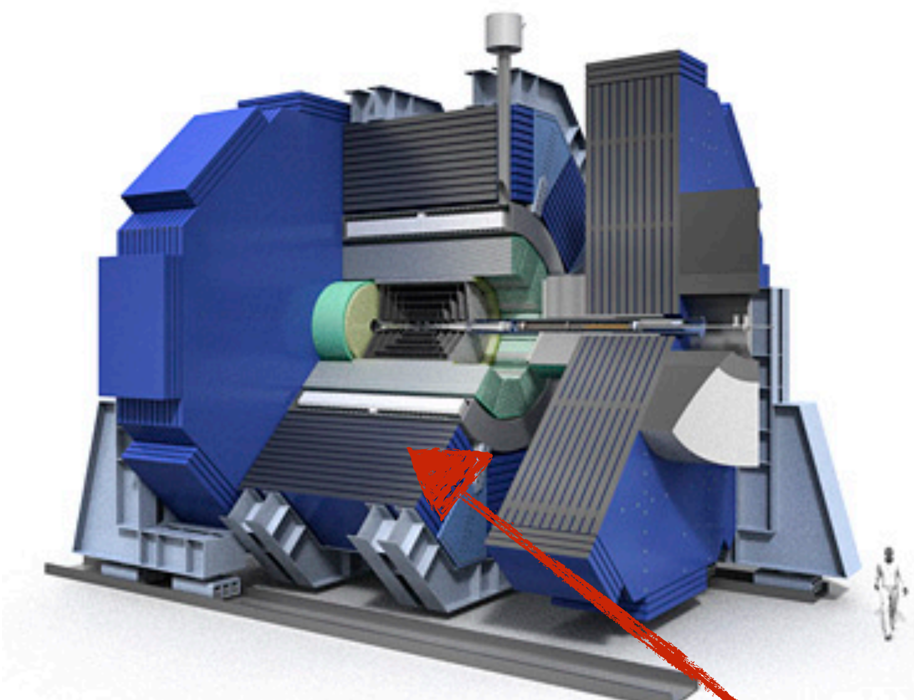

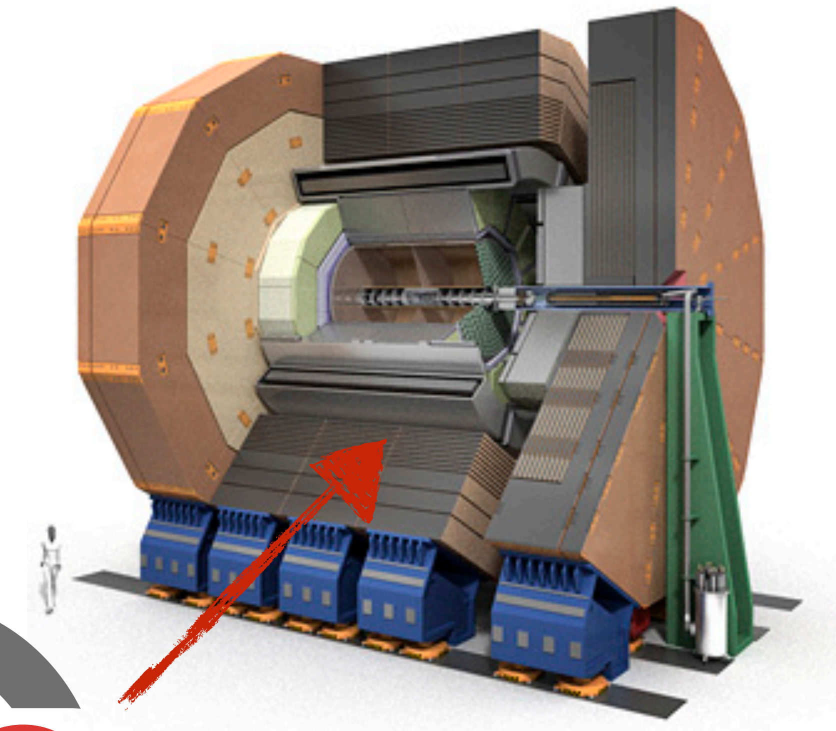

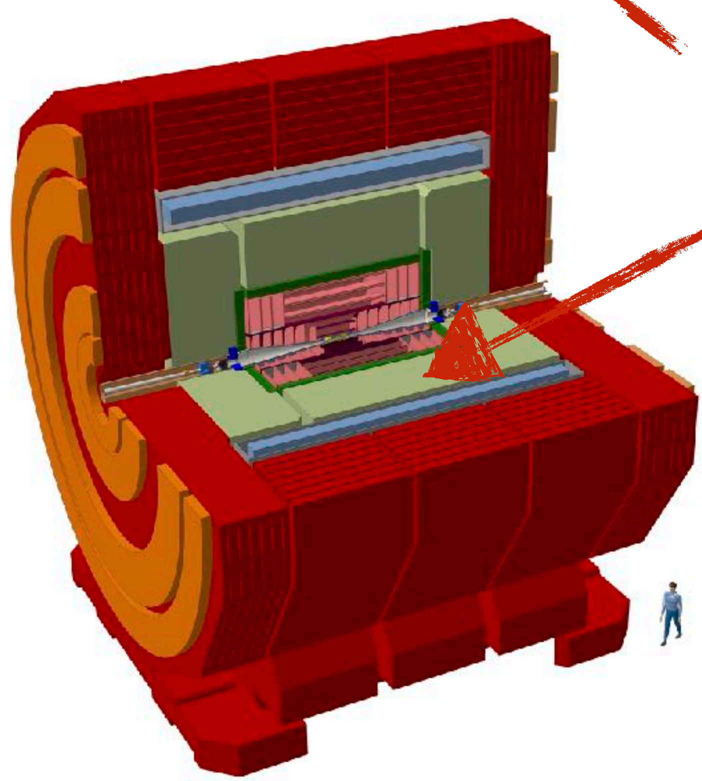

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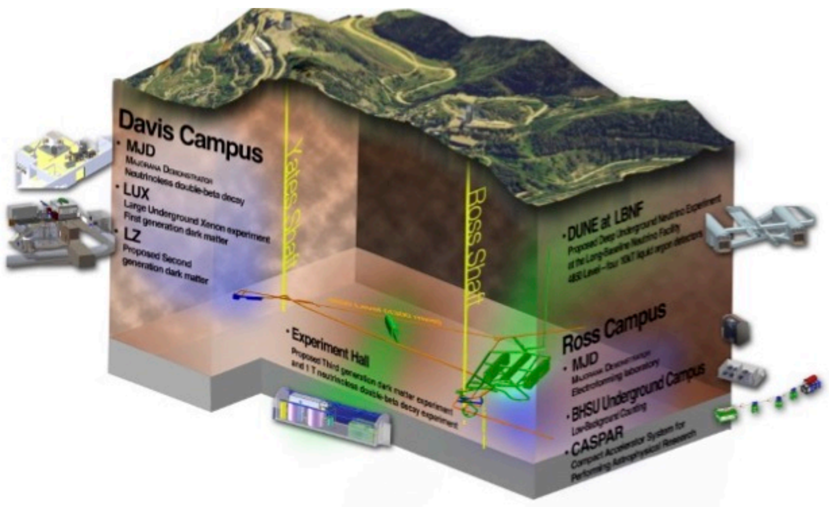
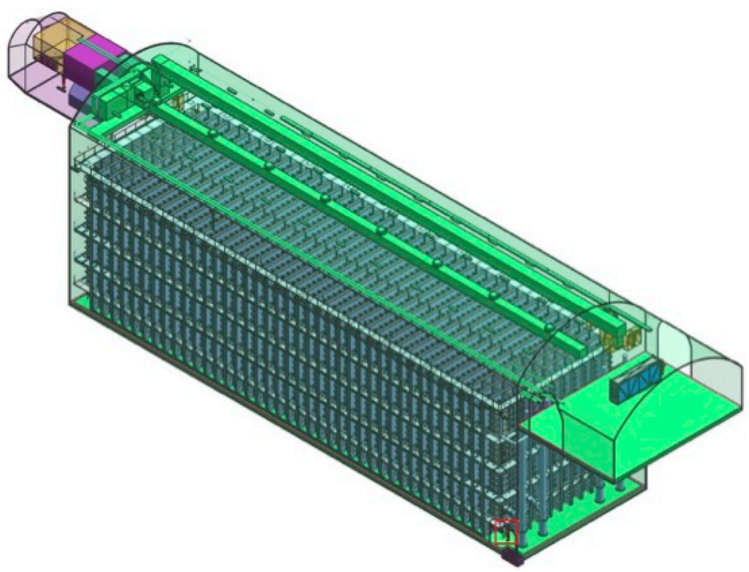
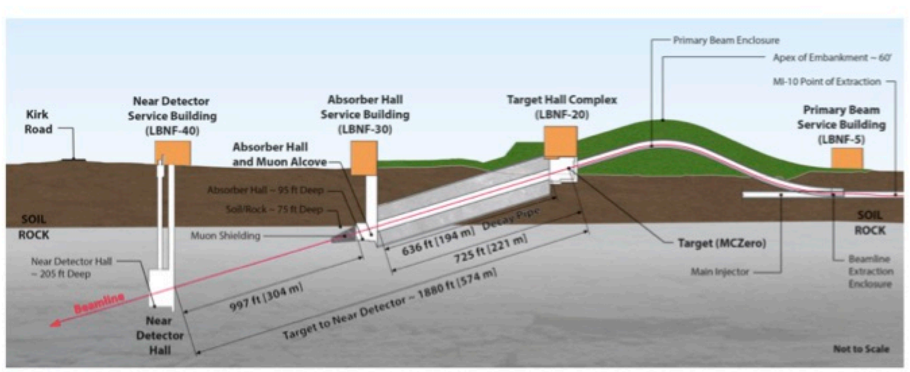
DUNE Global Timeline







2017: Far Site Construction Begins

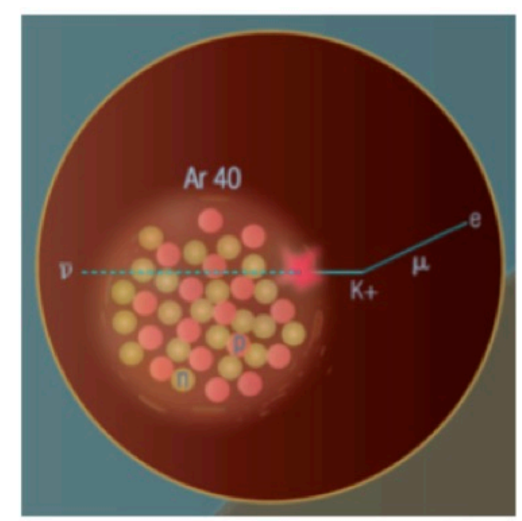
2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available

The CERN Neutrino Platform



ND Installation: 2025-2026, to be ready for first beam

DUNE Near Detector Timeline

- Decision on magnet concept (dipole or KLOE solenoid): 02/2018
- Decision on tracker concept (STT or HPTPC, also on SuperFGD): 04/2018
- Draft of Near Detector CDR: 04/2019; review 08/2019
- Draft of Near Detector TDR: 04/2020
- DOE Review of Near Site & Detector: 08/2020

➫ Global detector design being fixed in the coming months