CALICE

Introduction: Highly Granular Calorimeters

Frank Simon
Max-Planck-Institute for Physics

CEPC Workshop
Shanghai / Virtual, October 2020

MAX-PLANCK-INSTITUT FÜR PHYSIK

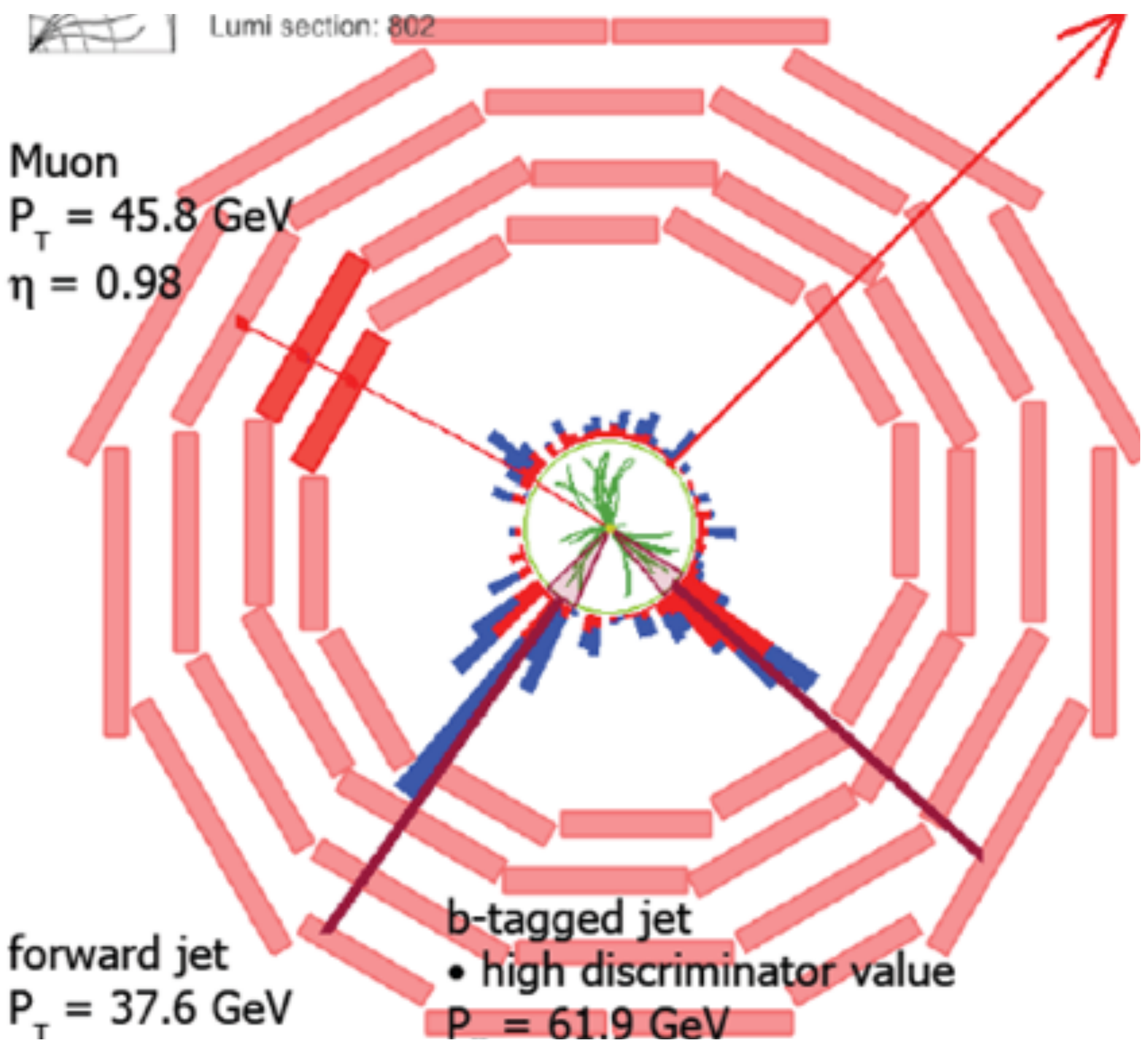
The CALICE part of the session today

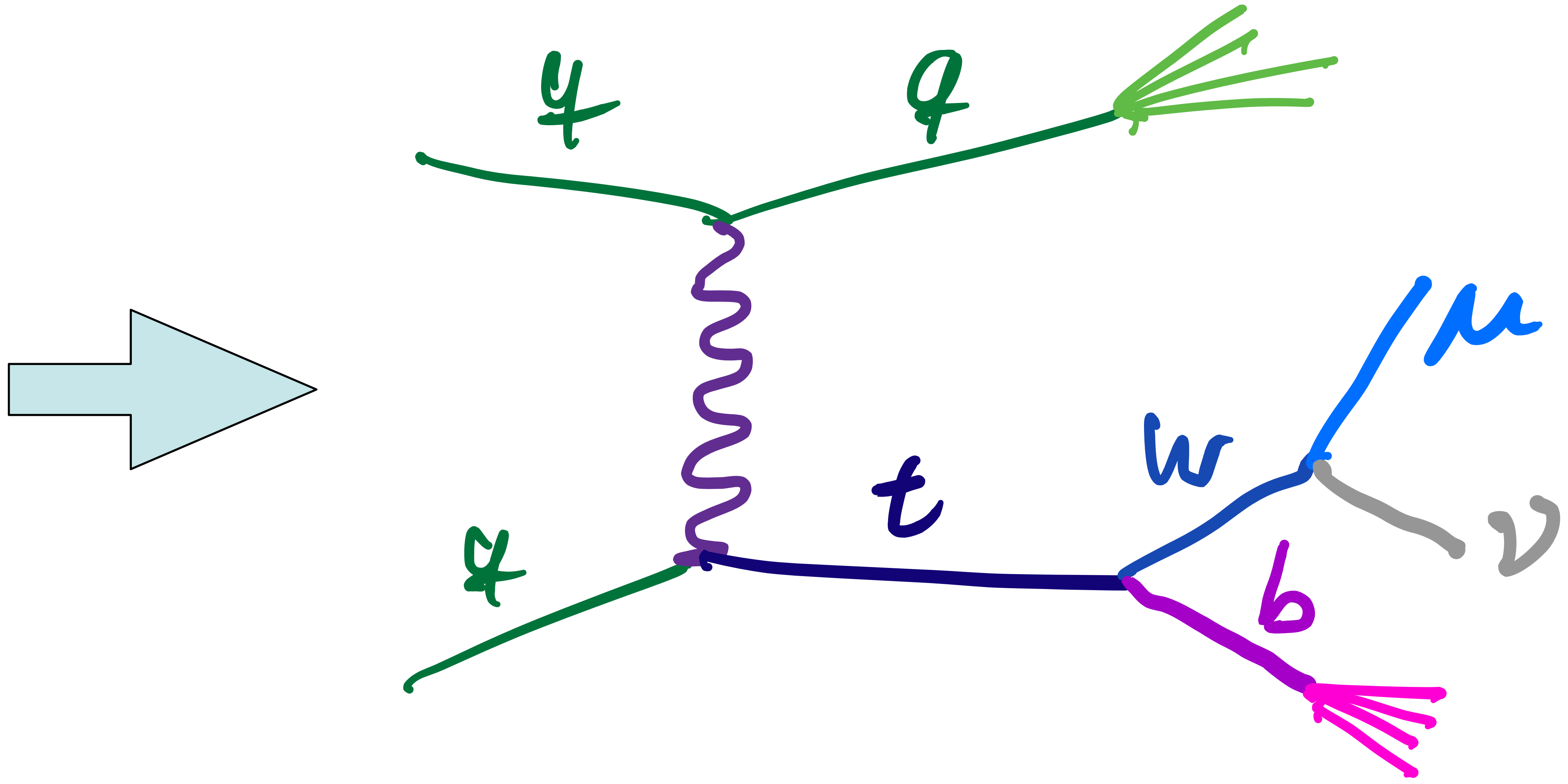
- Introduction: Motivation for Granularity, the CALICE Program
- Technological developments [Taikan Suehara]
- Results [Bing Liu]

Event Reconstruction at Future Colliders

Dreams…

- For *hadronic* (and all other) final states, we want to solve this problem:

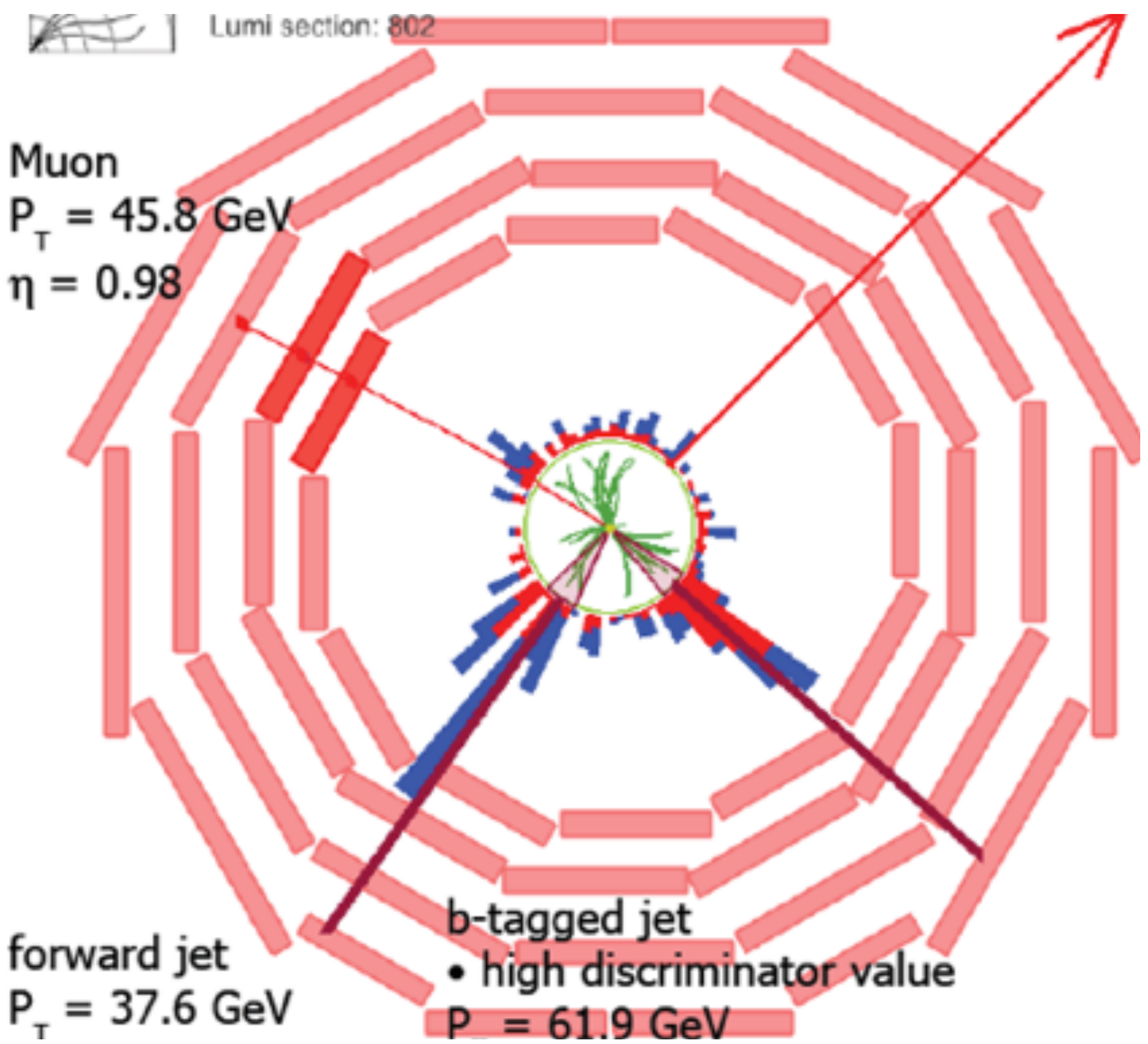


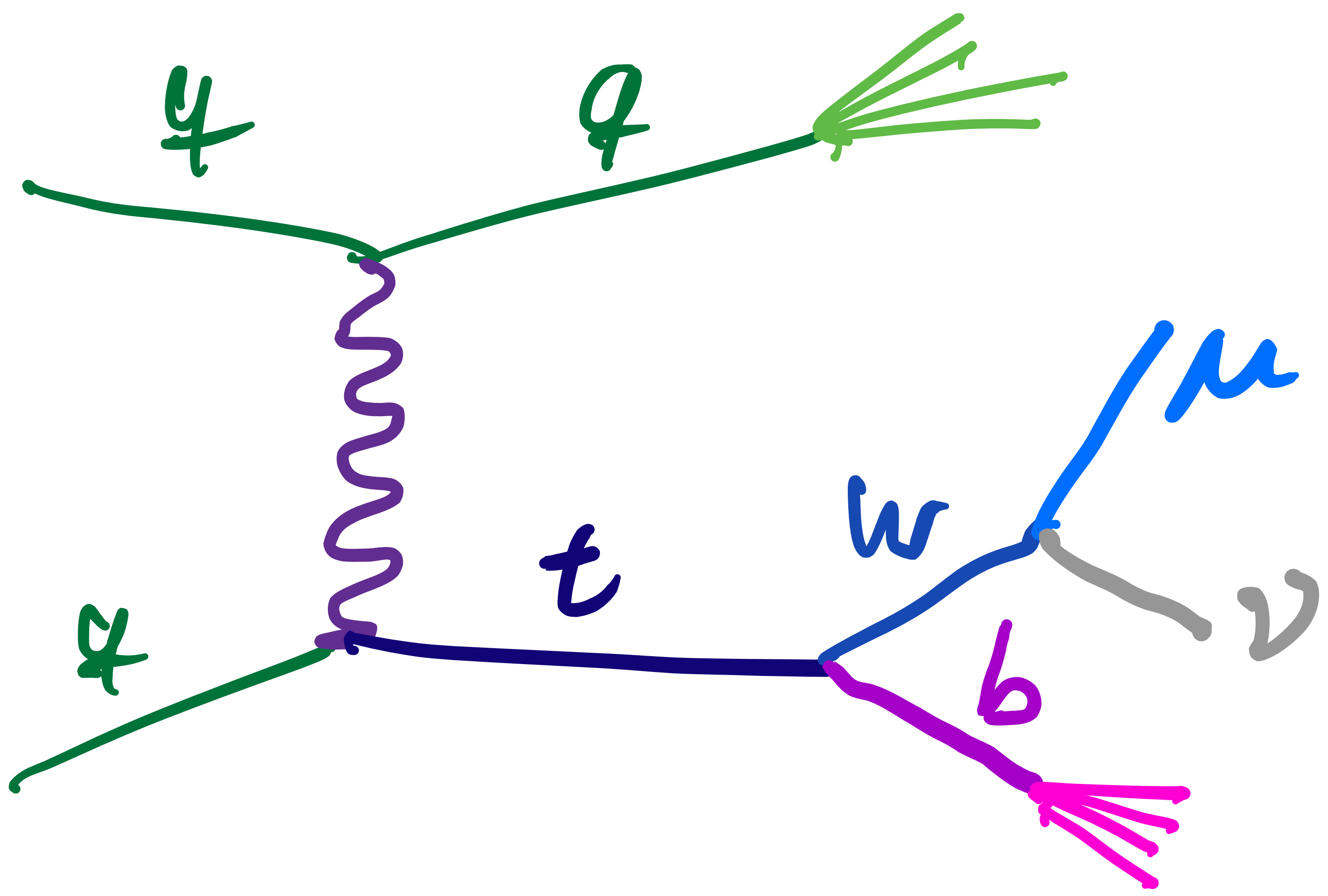


Event Reconstruction at Future Colliders

Dreams…

- For *hadronic* (and all other) final states, we want to solve this problem:





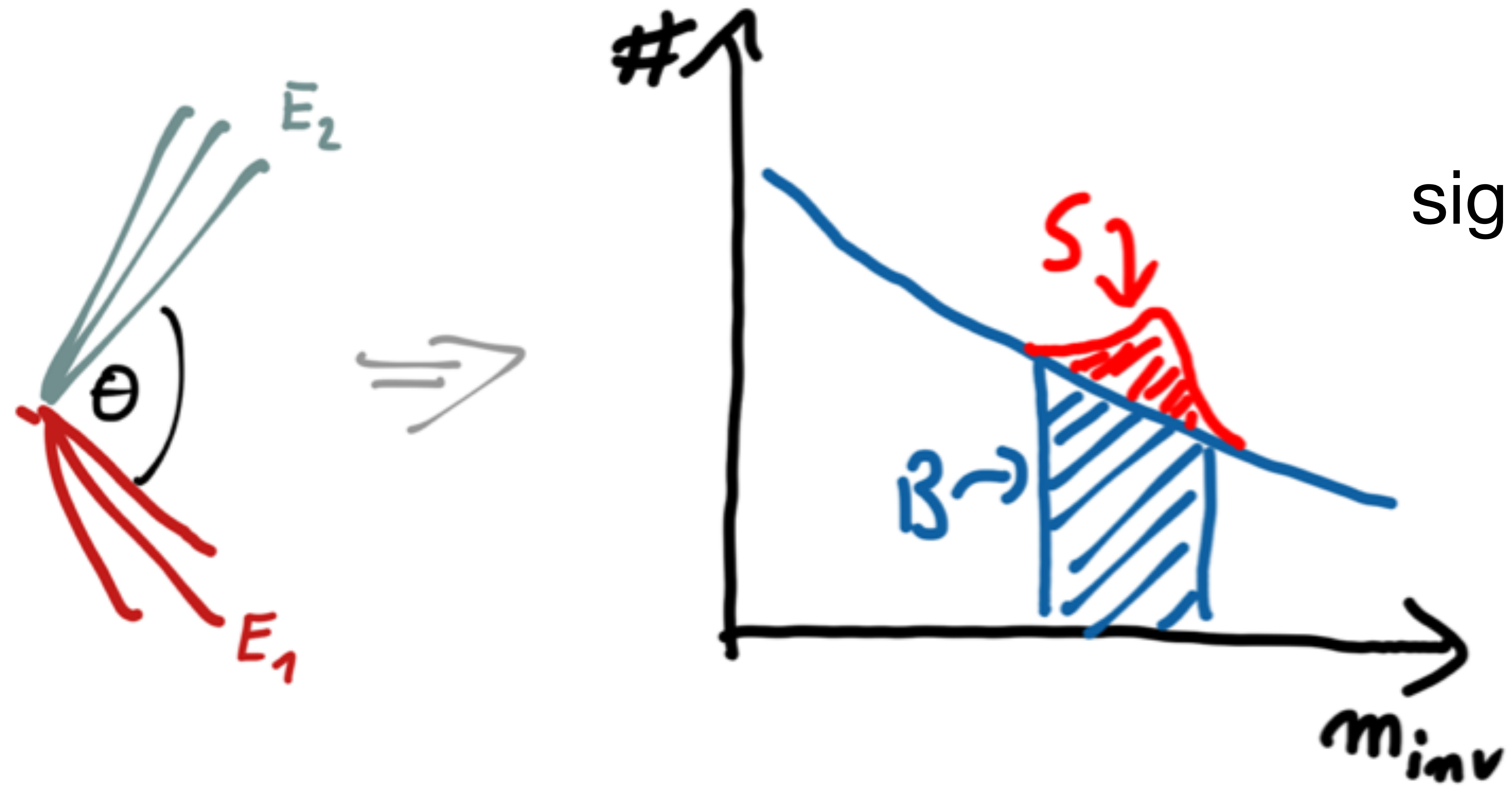
Ideally: reconstruct every single particle in the event -

not just leptons + “cones of energy”

Event Reconstruction at Future Colliders

… Goals …

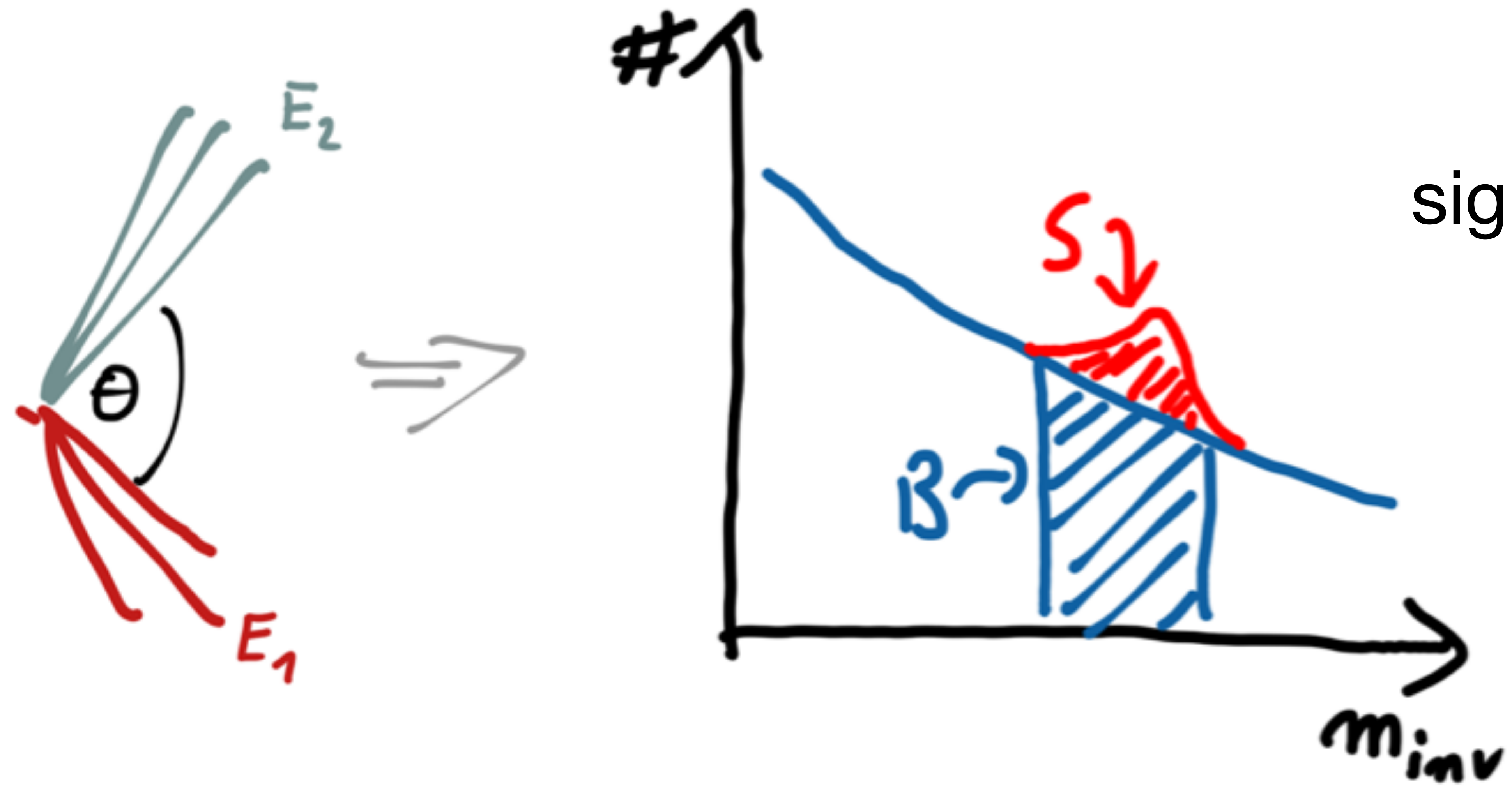
- More practically:



significance: $$\frac{S}{\sqrt{S+B}}$$

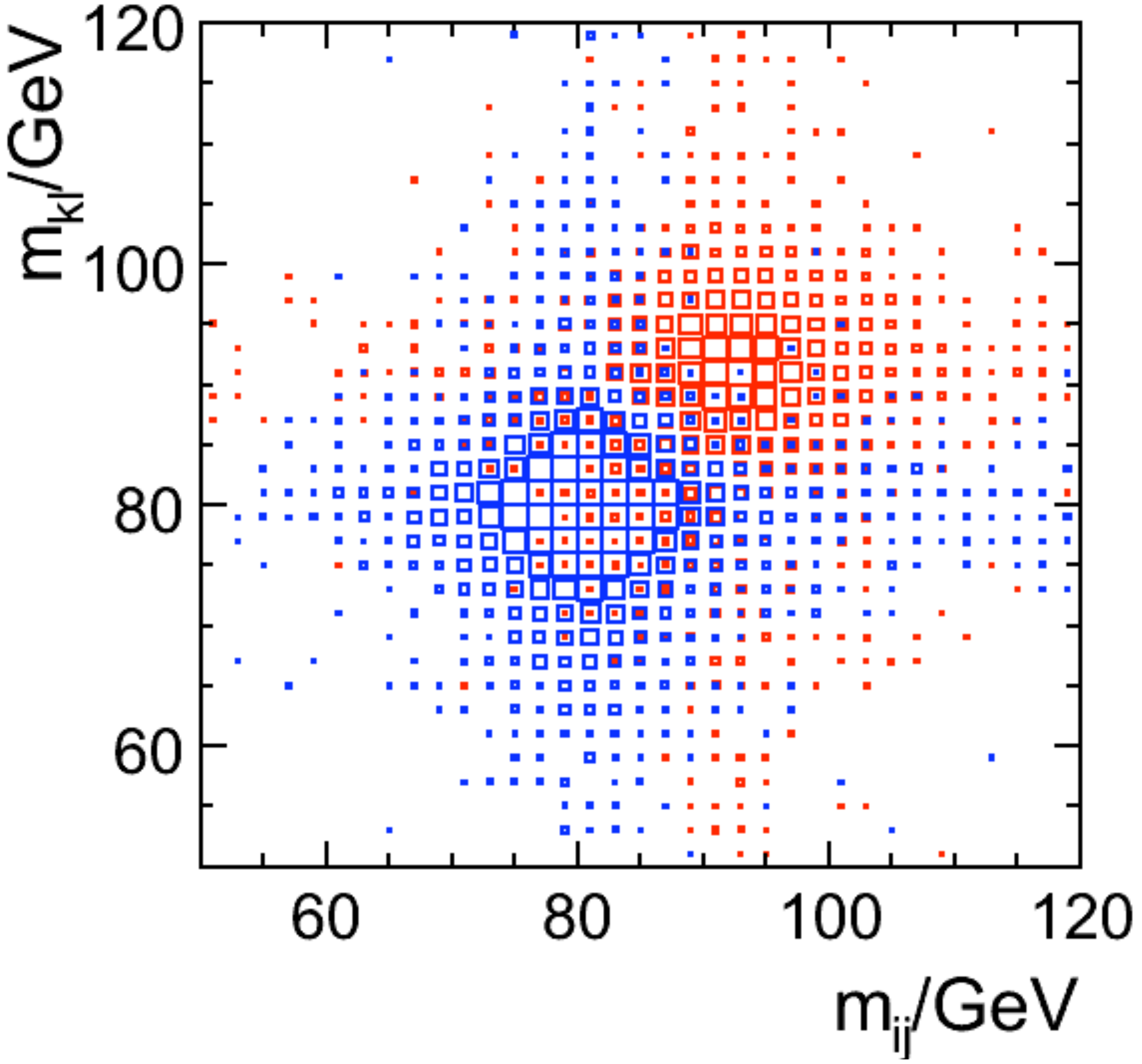
directly depends on mass resolution

- More practically:



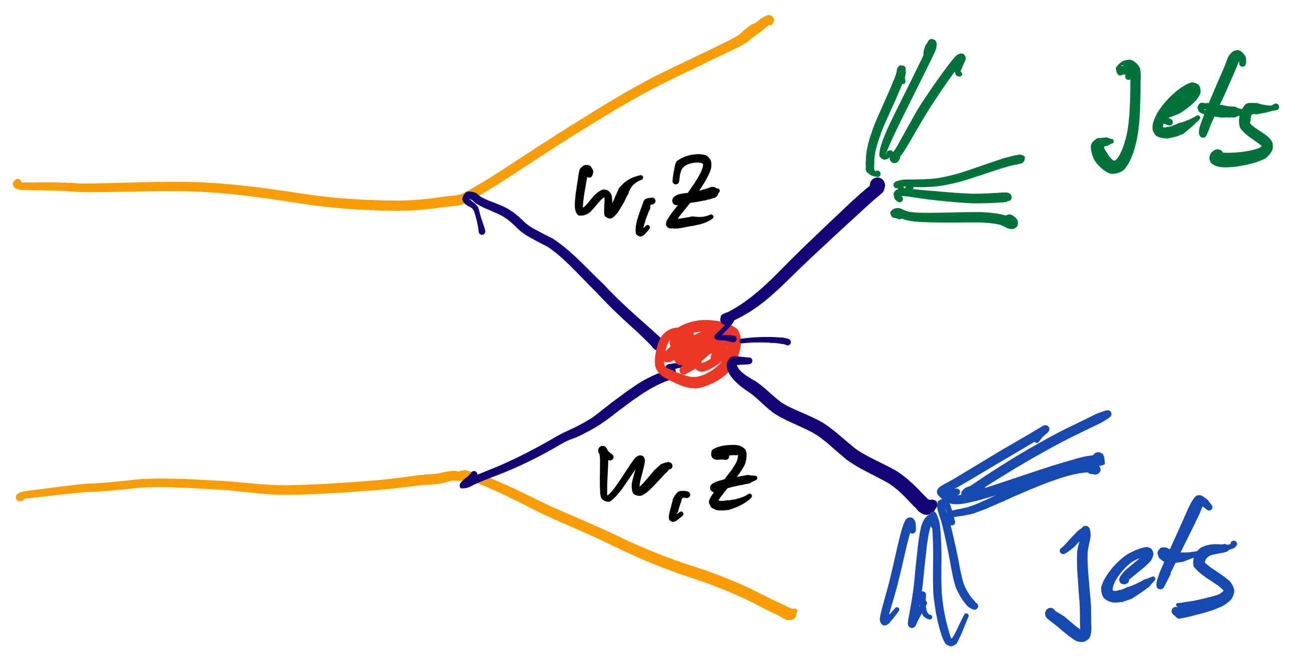
significance: $\frac{S}{\sqrt{S+B}}$

directly depends on mass resolution



The typical "PR" example:

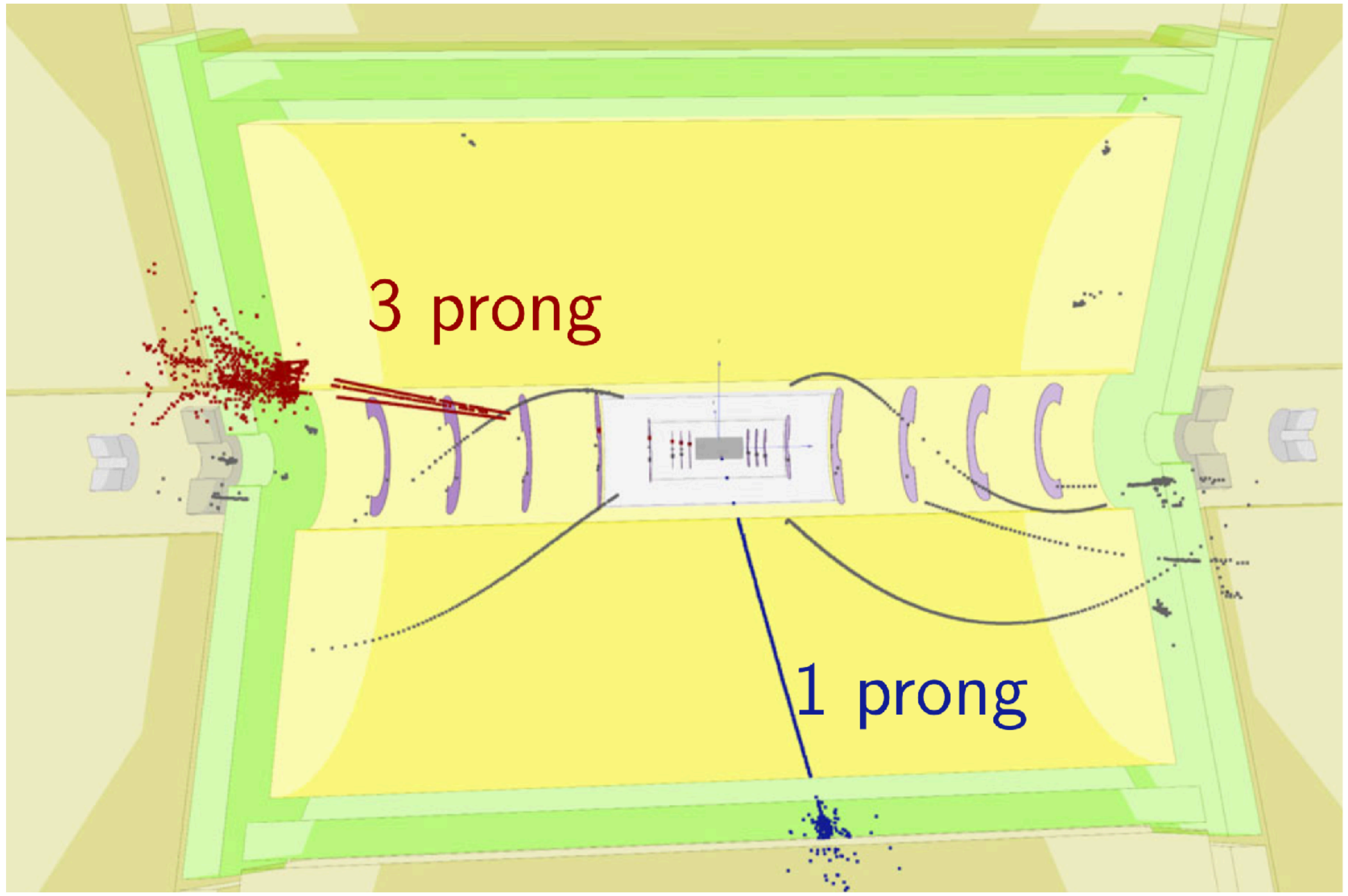
Separation of hadronic final states of heavy bosons: Requires jet energy resolution of ~ 3.5% over a wide energy range



Event Reconstruction at Future Colliders

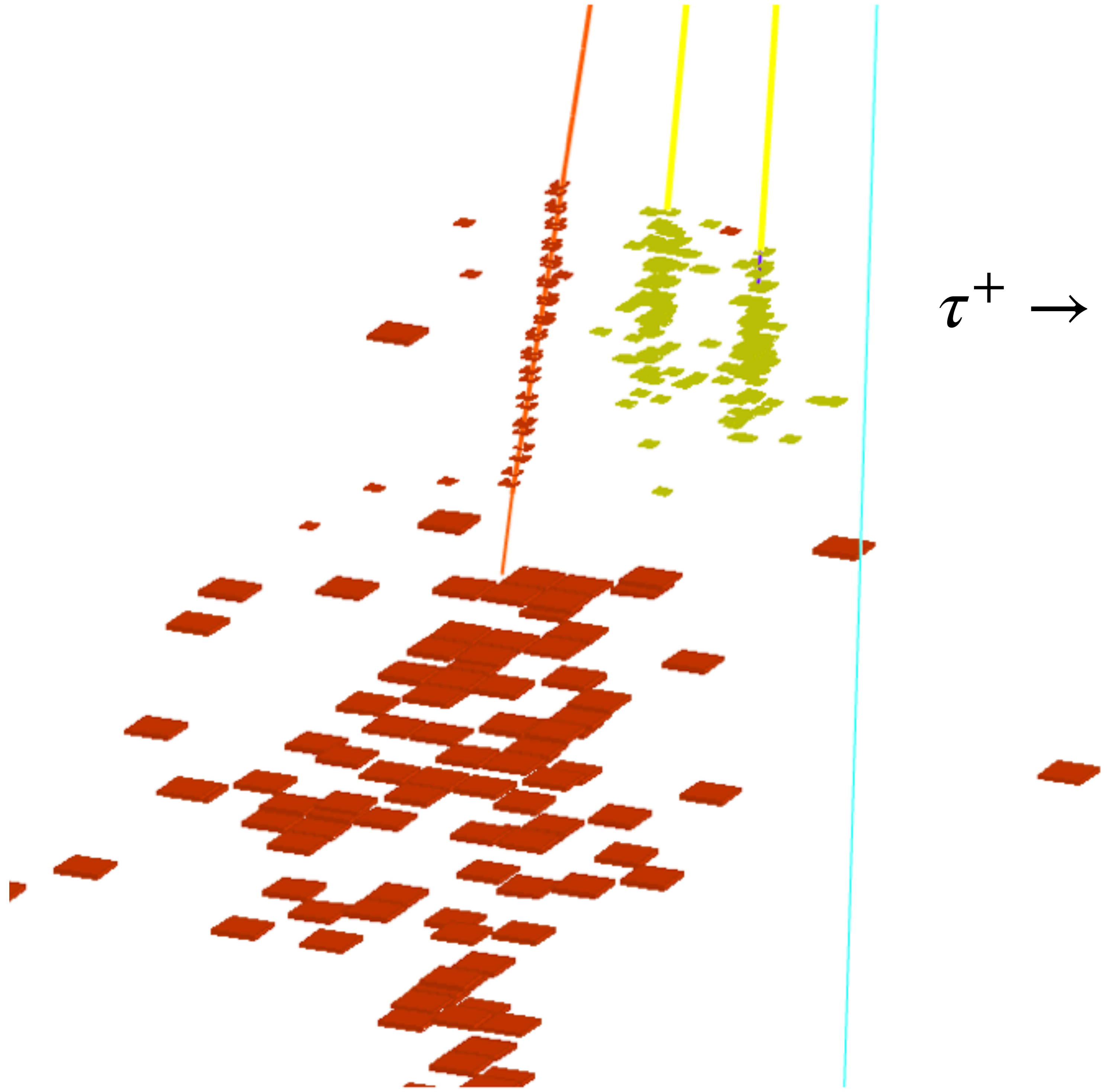
... Goals ...

- But also: Identification of particles
  A classic example: Tau reconstruction



$$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow \tau^+\tau^-\nu\bar{\nu}$$

@ 1.4 TeV at CLIC

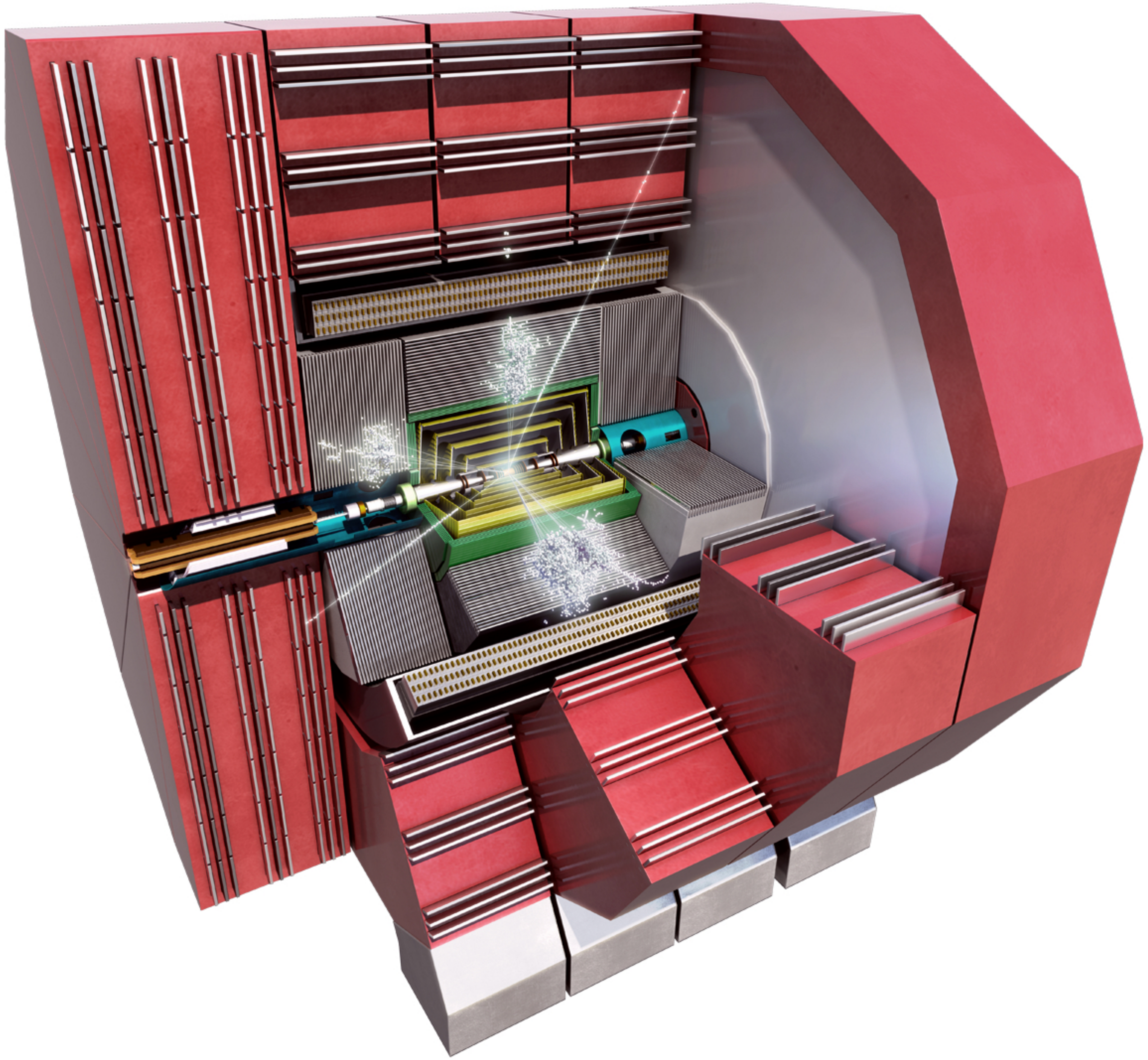


$$\tau^+ \rightarrow 2\gamma(\pi^0) + \pi^+ + \bar{\nu}_\tau$$

- Results in close-by / overlapping electromagnetic and hadronic showers

Event Reconstruction at Future Colliders

… Tools …



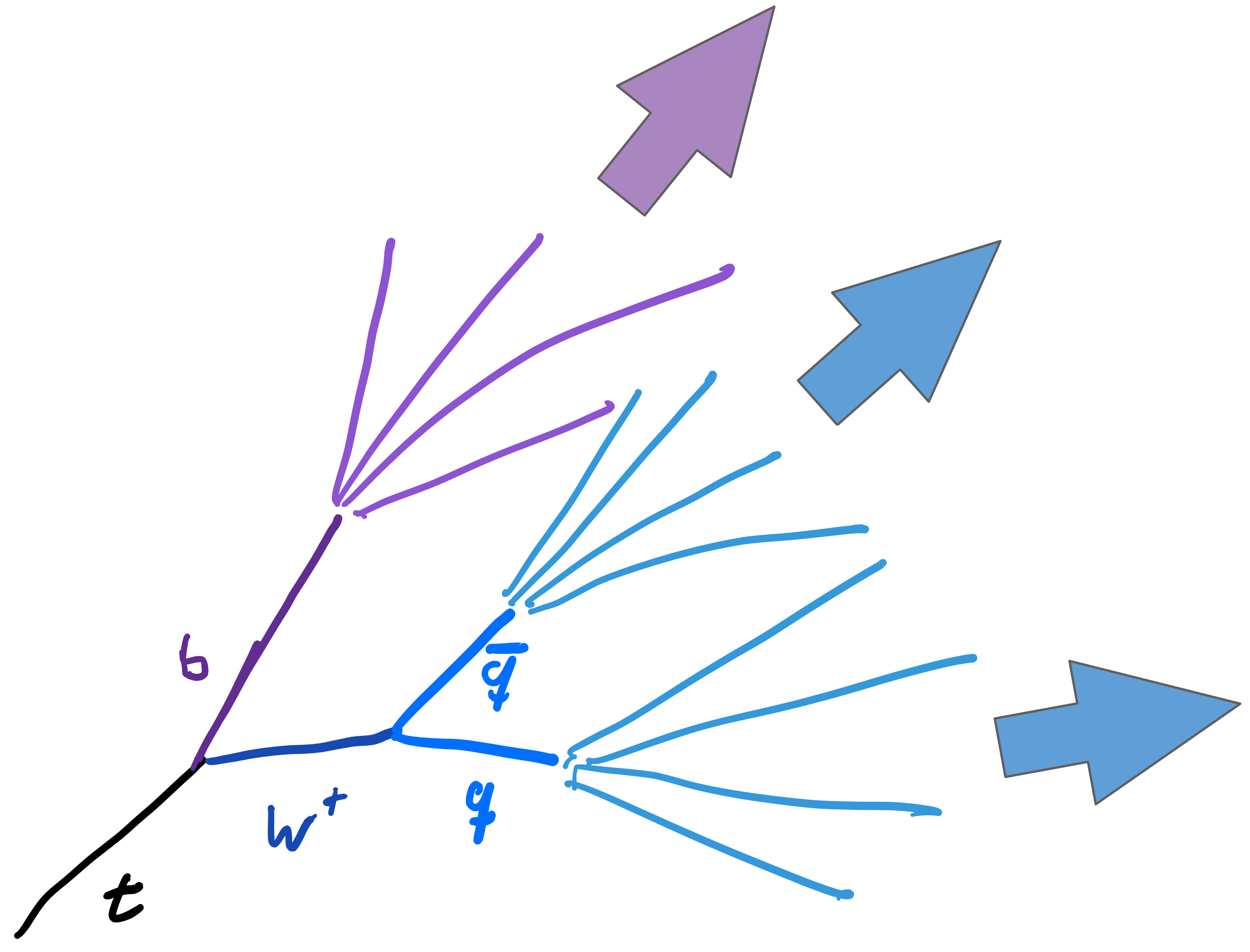
- The hardware to work with: A *Collider Detector*
  - ***Vertex detectors*** to identify heavy quarks and leptons
  - ***Tracking system*** to measure the momentum of charged particles via curvature in magnetic field
  - ***Calorimeter systems*** to measure energy of neutral and charged particles via total absorption
  - ***Muon system*** to identify muons, improve momentum measurement

Event Reconstruction at Future Colliders

… and Algorithms

- Particles decaying into quarks lead to jets: Multiple hadrons originating from final-state quarks

➯ Parton four-vector only accessible via reconstruction of final hadrons

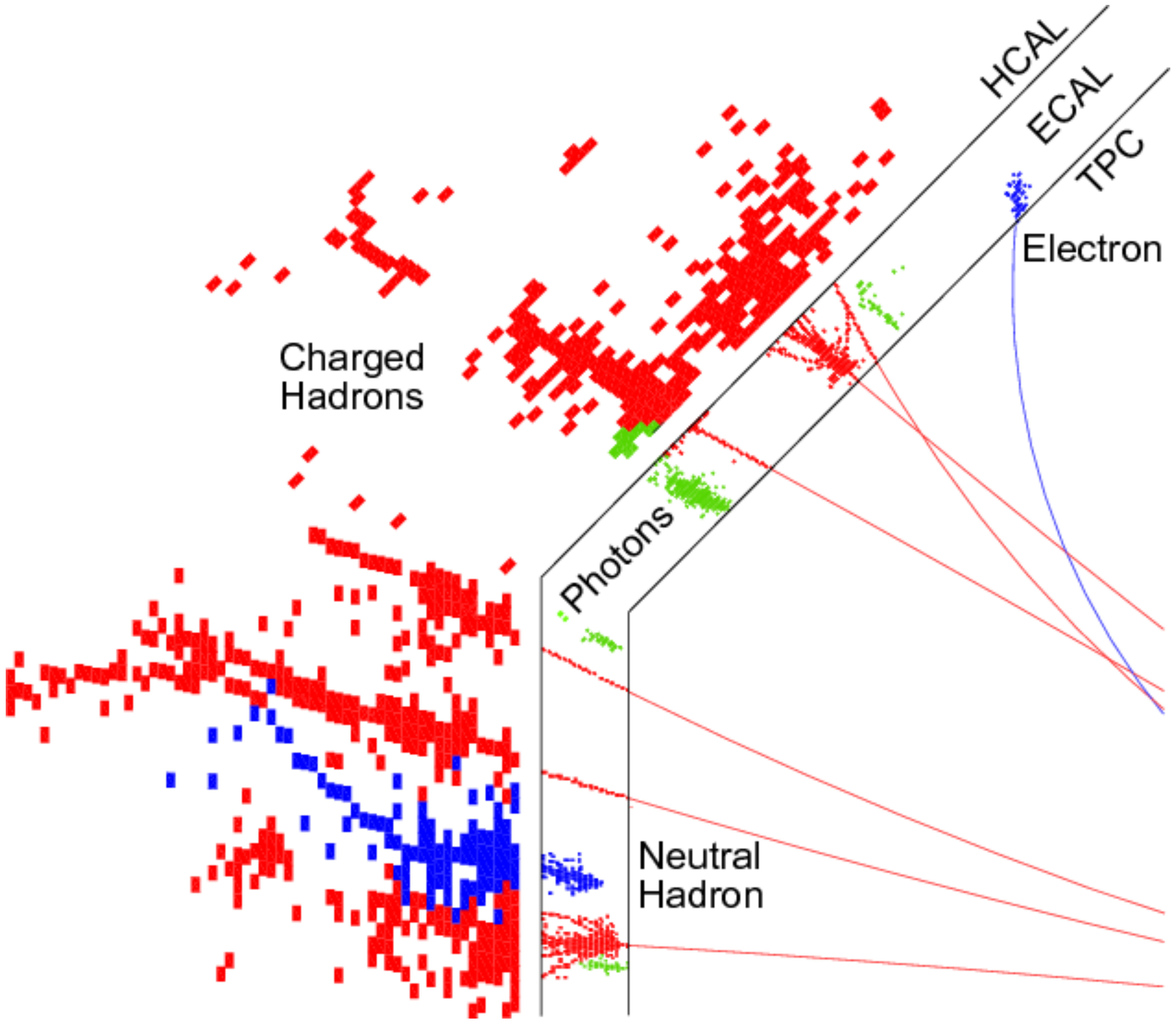


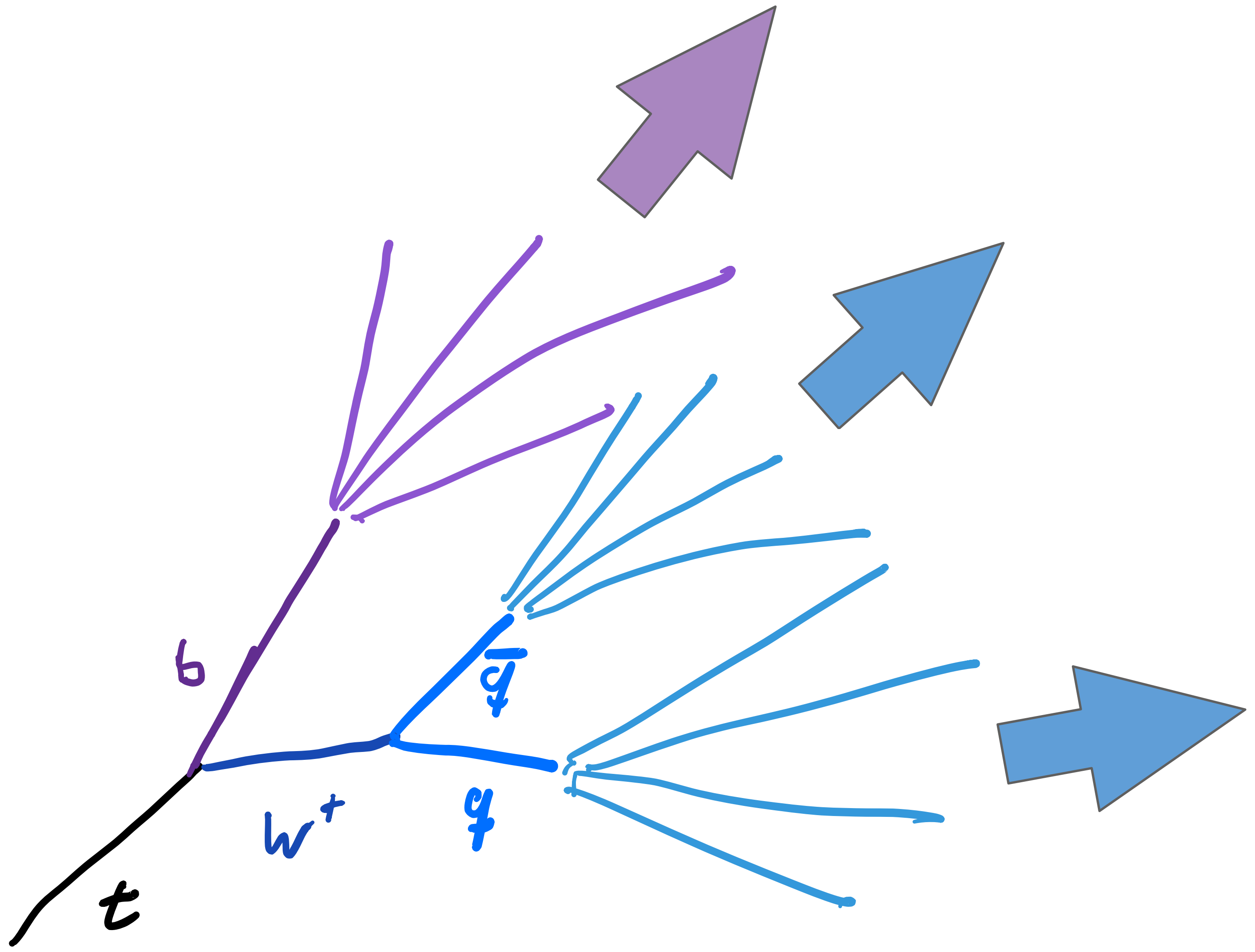
Event Reconstruction at Future Colliders

… and Algorithms

- Particles decaying into quarks lead to jets: Multiple hadrons originating from final-state quarks

➡ Parton four-vector only accessible via reconstruction of final hadrons





- Requires measuring the energies of different particle types
  - Charged hadrons ($\pi^{+/-}$, …)
  - Electromagnetic particles (γ, $e^{+/-}$)
  - Neutral hadrons (K_L, n, …)

➡ Best performance when optimally combining the information of all subsystems of the experiment: calorimetry & tracking => ***"Particle Flow"*** and ***"Imaging Calorimeters"***

Granularity Requirements

Physics drivers

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers in all 3 dimensions

➩ X_0 / ρ_M drive ECAL and HCAL (electromagnetic subshowers)

Granularity Requirements

Physics drivers

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers in all 3 dimensions

➩ X_0 / ρ_M drive ECAL and HCAL (electromagnetic subshowers)

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

Granularity Requirements

Physics drivers

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers in all 3 dimensions

➫ X_0 / ρ_M drive ECAL and HCAL (electromagnetic subshowers)

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

In addition: type of readout highly relevant: Need “analog” information for energy measurements - can be achieved also with “particle counting”, requiring correspondingly higher granularity to avoid saturation effects

N.B.: In particular in the ECAL, a granularity significantly below the typical shower width can be highly beneficial

Granularity Requirements

Physics drivers

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers in all 3 dimensions

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

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

In addition: type of readout highly relevant: Need “analog” information for energy measurements - can be achieved also with “particle counting”, requiring correspondingly higher granularity to avoid saturation effects

N.B.: In particular in the ECAL, a granularity significantly below the typical shower width can be highly beneficial

➯ *10s to 100s of millions of detector cells (or even more!) for full systems*

Motivations for Granularity

From a technological Perspective

Because we can.

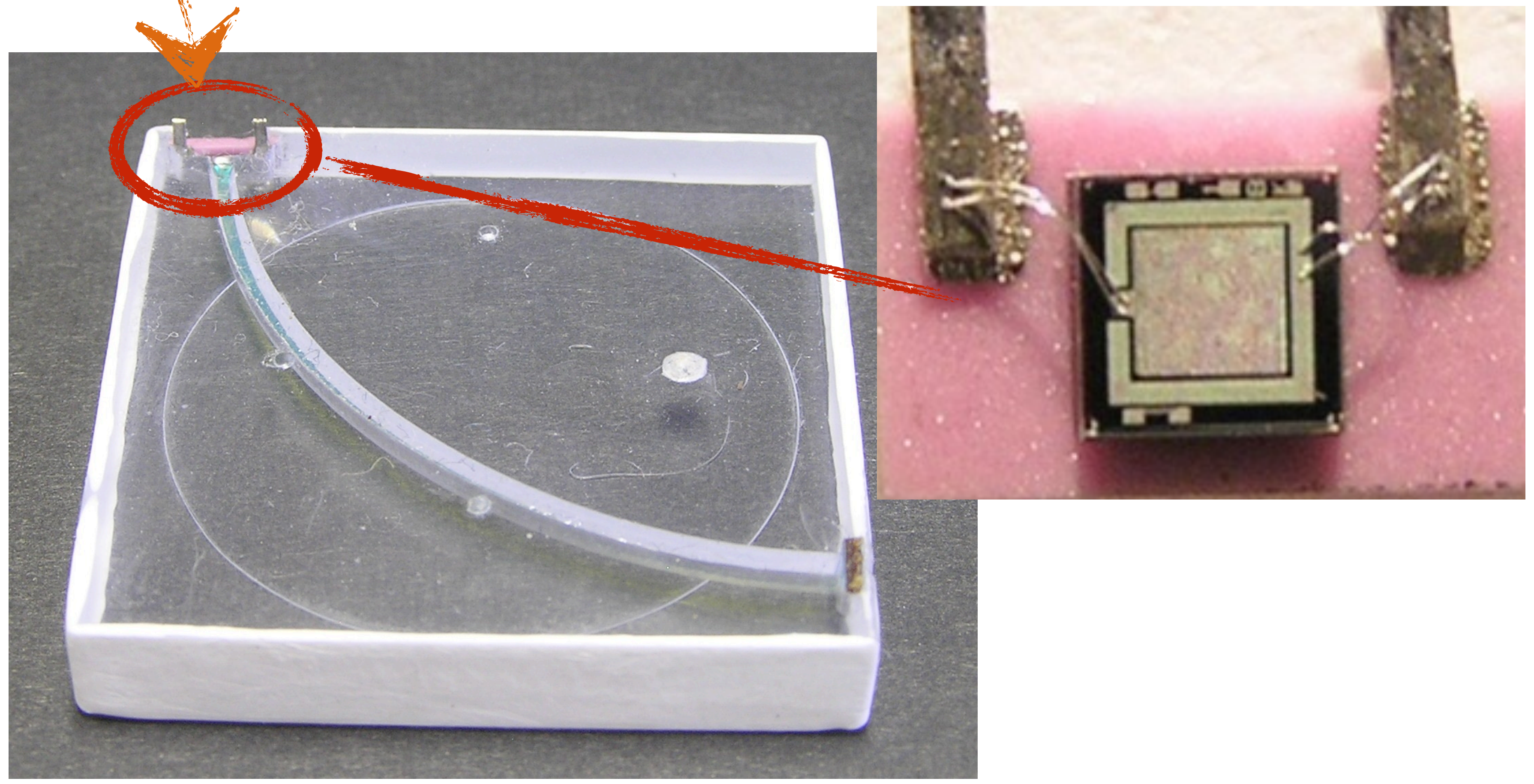
- The invention of SiPMs made scintillator-based calorimeters with very large channel counts possible

Motivations for Granularity

From a technological Perspective

Because we can.

- The invention of SiPMs made scintillator-based calorimeters with very large channel counts possible

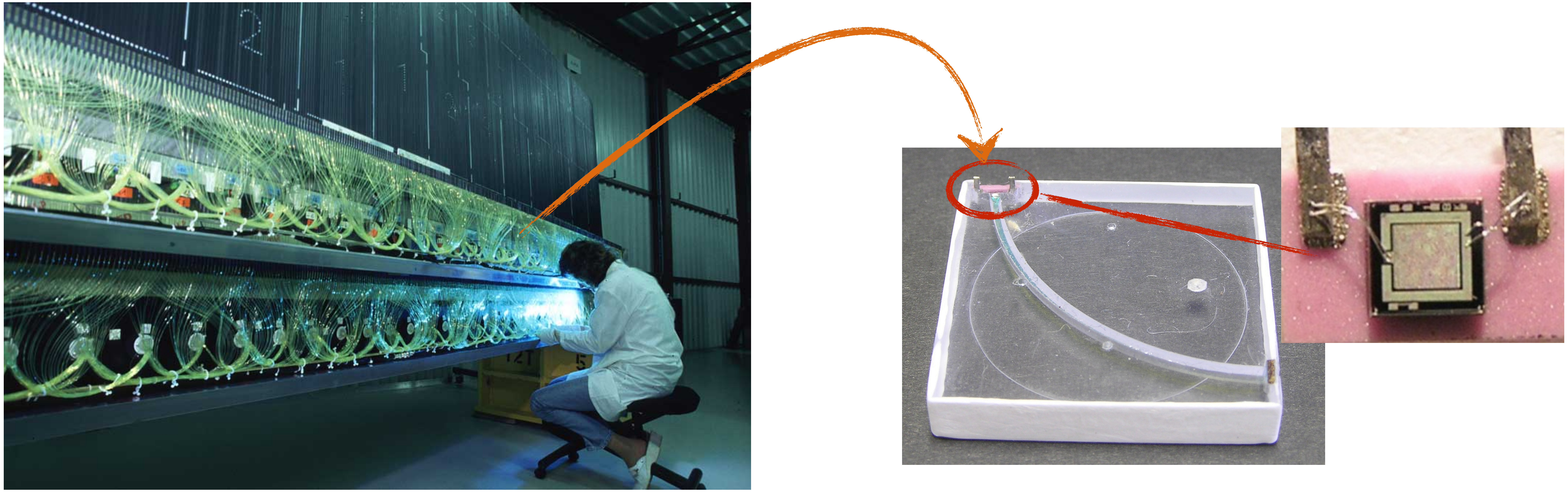


Motivations for Granularity

From a technological Perspective

Because we can.

- The invention of SiPMs made scintillator-based calorimeters with very large channel counts possible



Equally important "enabling technologies":

Advances in microelectronics, including increasing miniaturisation of analog and digital electronics and reduced power consumption

large area silicon systems for Si-based calorimetry

The CALICE Program

Phases of CALICE Development

- ***Validation*** of the concept of highly granular calorimetry:
  Physics prototypes with different ECAL and HCAL technologies in beam

The CALICE Program

Phases of CALICE Development

- ***Validation*** of the concept of highly granular calorimetry:
  Physics prototypes with different ECAL and HCAL technologies in beam

- ***Exploitation*** of the unprecedented data set on hadronic showers:
  - Development of reconstruction techniques for granular calorimeters
  - Comparison to and validation of GEANT4 simulations - providing input to development of physics lists

The CALICE Program

Phases of CALICE Development

- ***Validation*** of the concept of highly granular calorimetry:
  Physics prototypes with different ECAL and HCAL technologies in beam

- ***Exploitation*** of the unprecedented data set on hadronic showers:
  - Development of reconstruction techniques for granular calorimeters
  - Comparison to and validation of GEANT4 simulations - providing input to development of physics lists

- ***Technical Realisation*** of detector systems satisfying collider constraints:
  Technological prototypes, with fully embedded electronics, power pulsing,… tested in particle beams, partially with magnetic field

The CALICE Program

Phases of CALICE Development

- ***Validation*** of the concept of highly granular calorimetry:
  Physics prototypes with different ECAL and HCAL technologies in beam

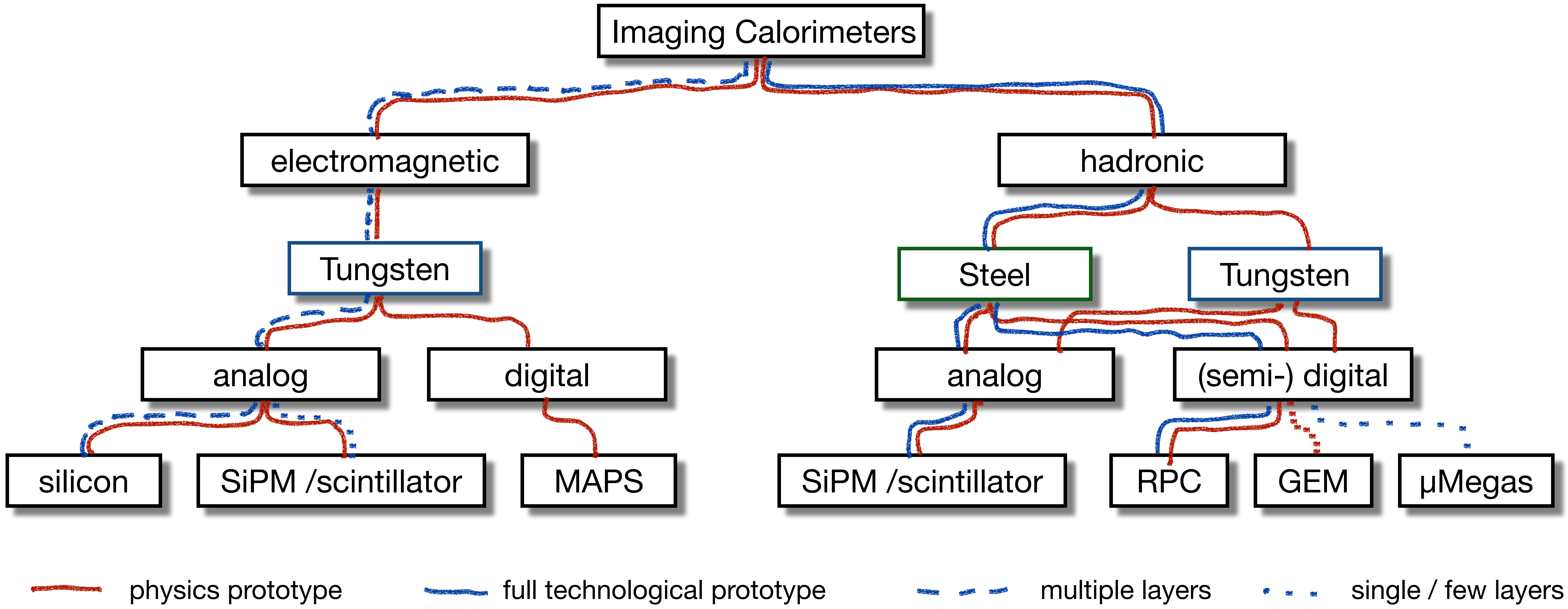
- ***Exploitation*** of the unprecedented data set on hadronic showers:
  - Development of reconstruction techniques for granular calorimeters
  - Comparison to and validation of GEANT4 simulations - providing input to development of physics lists

- ***Technical Realisation*** of detector systems satisfying collider constraints:
  Technological prototypes, with fully embedded electronics, power pulsing,… tested in particle beams, partially with magnetic field

- ***Application*** of CALICE technology in running experiments:
  - Use of CALICE detector elements
  - Full detector systems based on CALICE technology

Validation: Technologies studied by CALICE

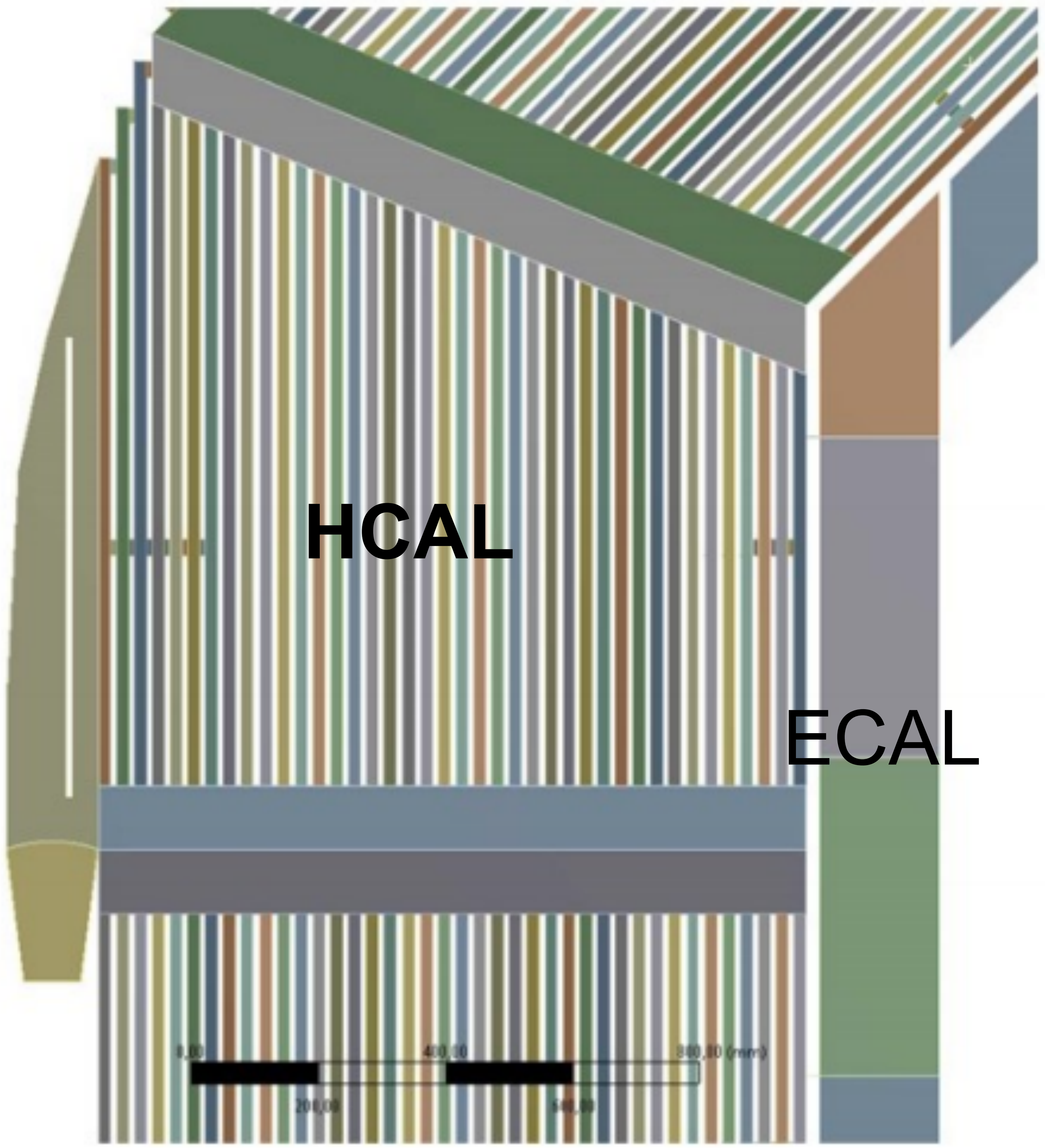
A rich test beam program since 2006, with a variety of different prototypes



- Since 2014 focus has shifted to technological prototypes: SDHCAL (since 2011), AHCAL, almost complete SiW ECAL technological prototype

The Focus Now: Technical Realisation

Key Challenges of Highly Granular Calorimeters

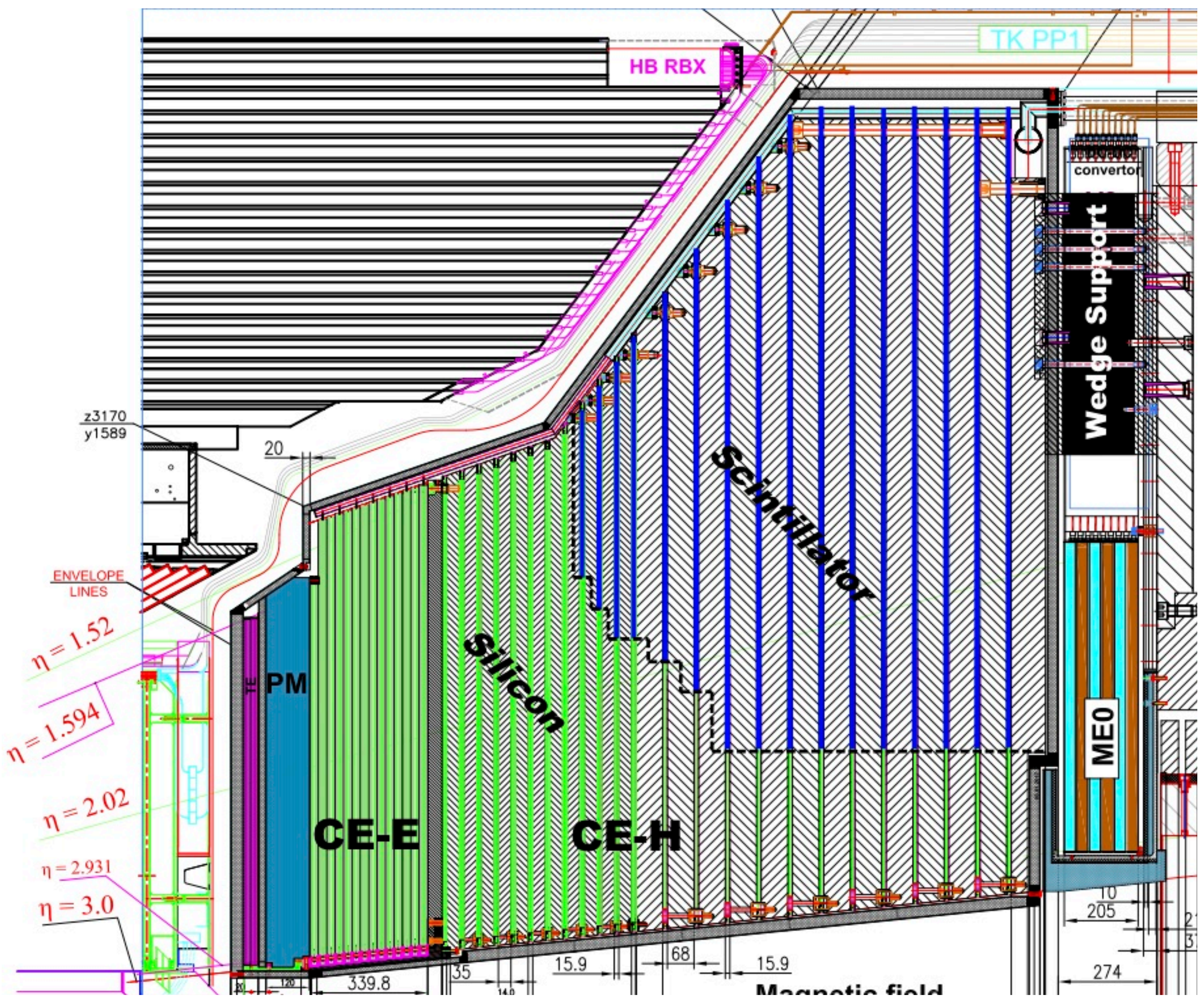


- To fully exploit the potential of highly granular calorimeter systems:
  - Extreme compactness, in particular in ECAL
  - Minimal “dead space” between ECAL and HCAL
  - No non-instrumented cracks
- For the full calorimeter systems, this imposes a number of requirements:
  - Both ECAL and HCAL inside solenoid: Further premium on compactness
  - Fully integrated electronics to support high granularity, minimal dead space outside of active area
  - Ultra low power to reduce or eliminate cooling needs, complex power distribution to support high currents during power pulsing; solutions for constant powering for circular colliders
  - Very compact interfaces: data concentration, calibration, services
  - Precise mechanics: High number of sampling layers, minimal space
  - Suitability for industrialization and automatization in QA and assembly for all detector elements

Successful "Spin-offs": Applications

CMS HGCAL Phase 2 Upgrade, Ideas for DUNE

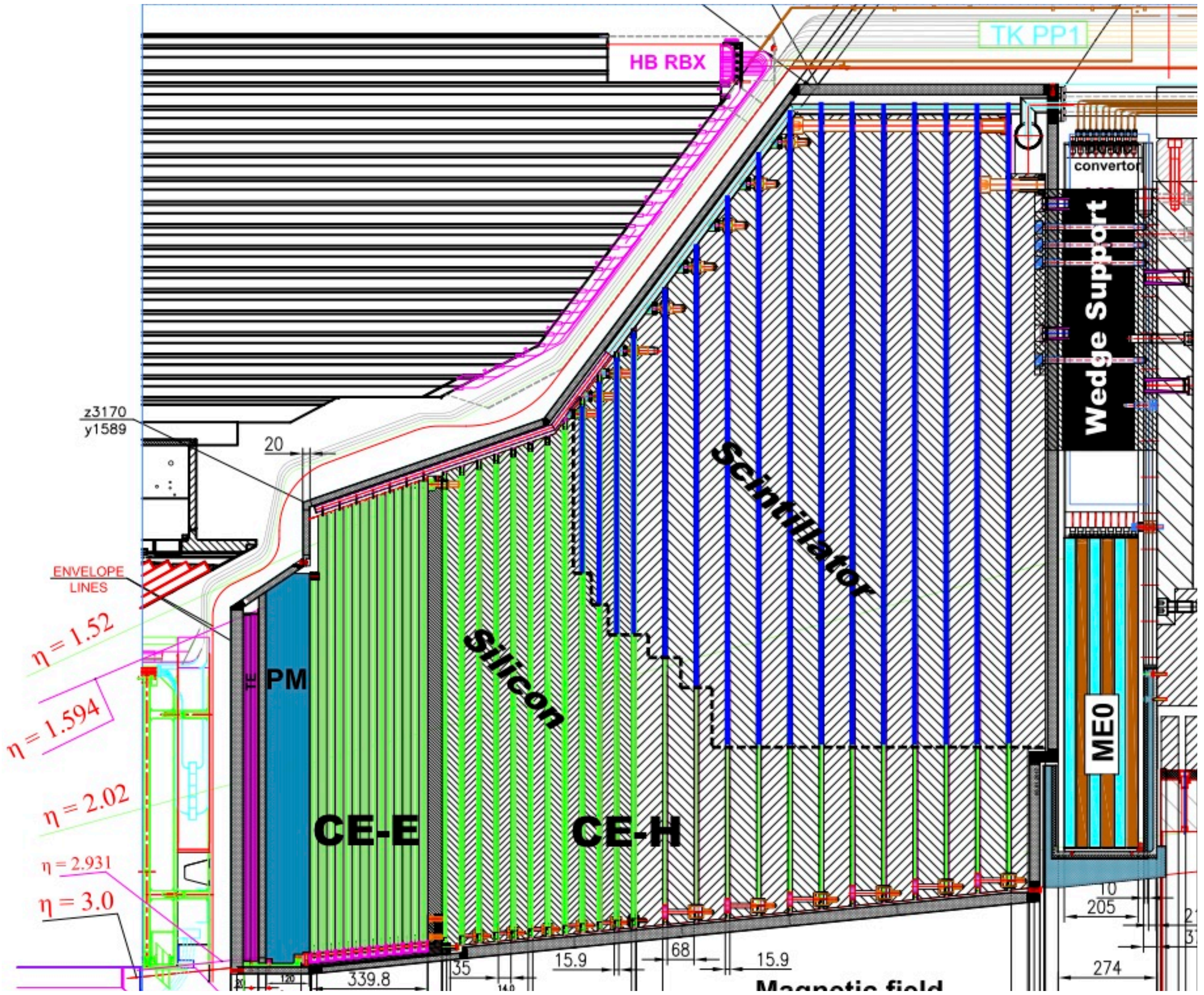
- Adopting two key technologies of CALICE for CMS HGCAL highly granular endcap calorimeters: Silicon, SiPM-on-tile
  - Requires adjustments to cope with radiation environment, data rates and timing requirements

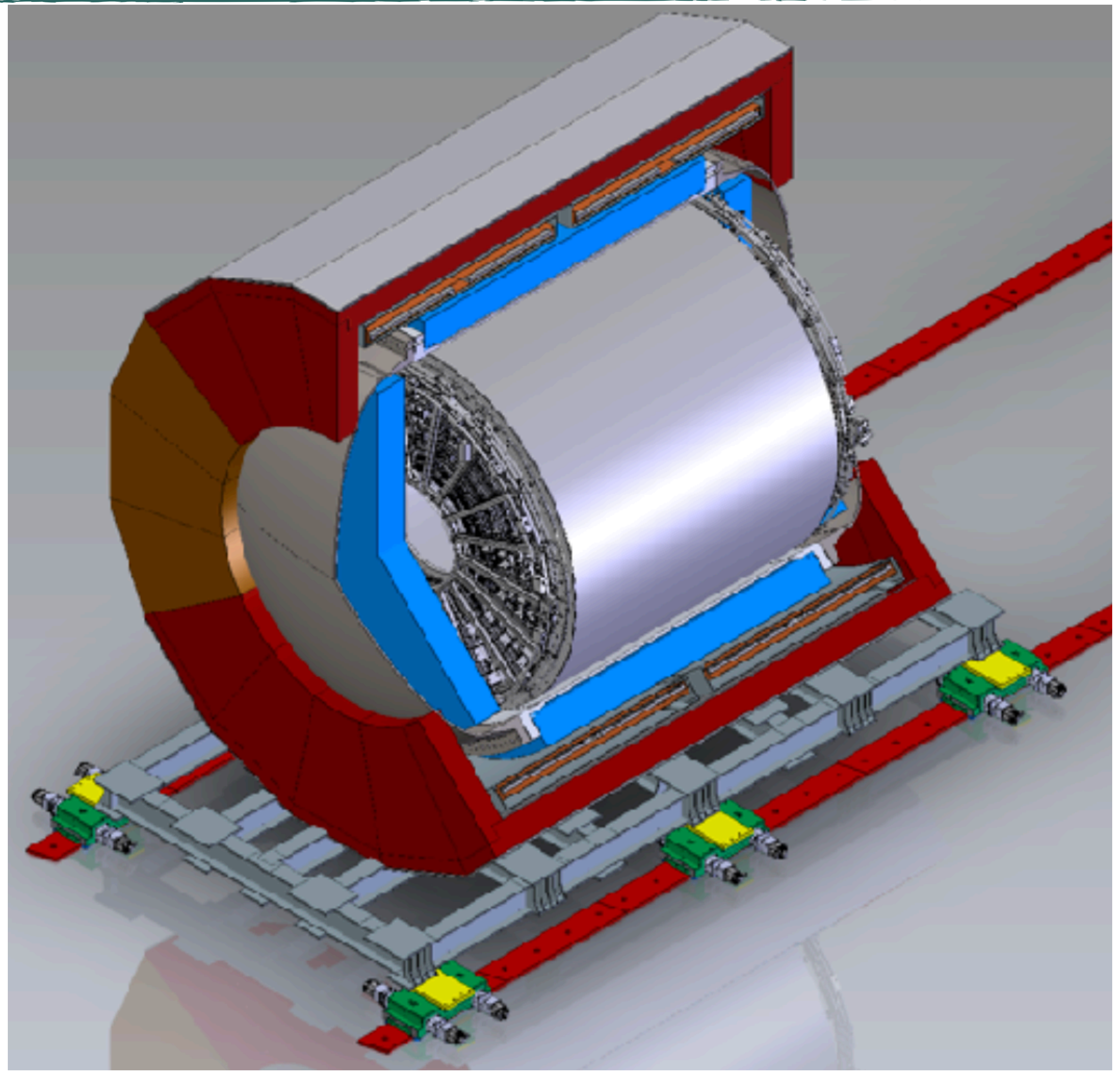


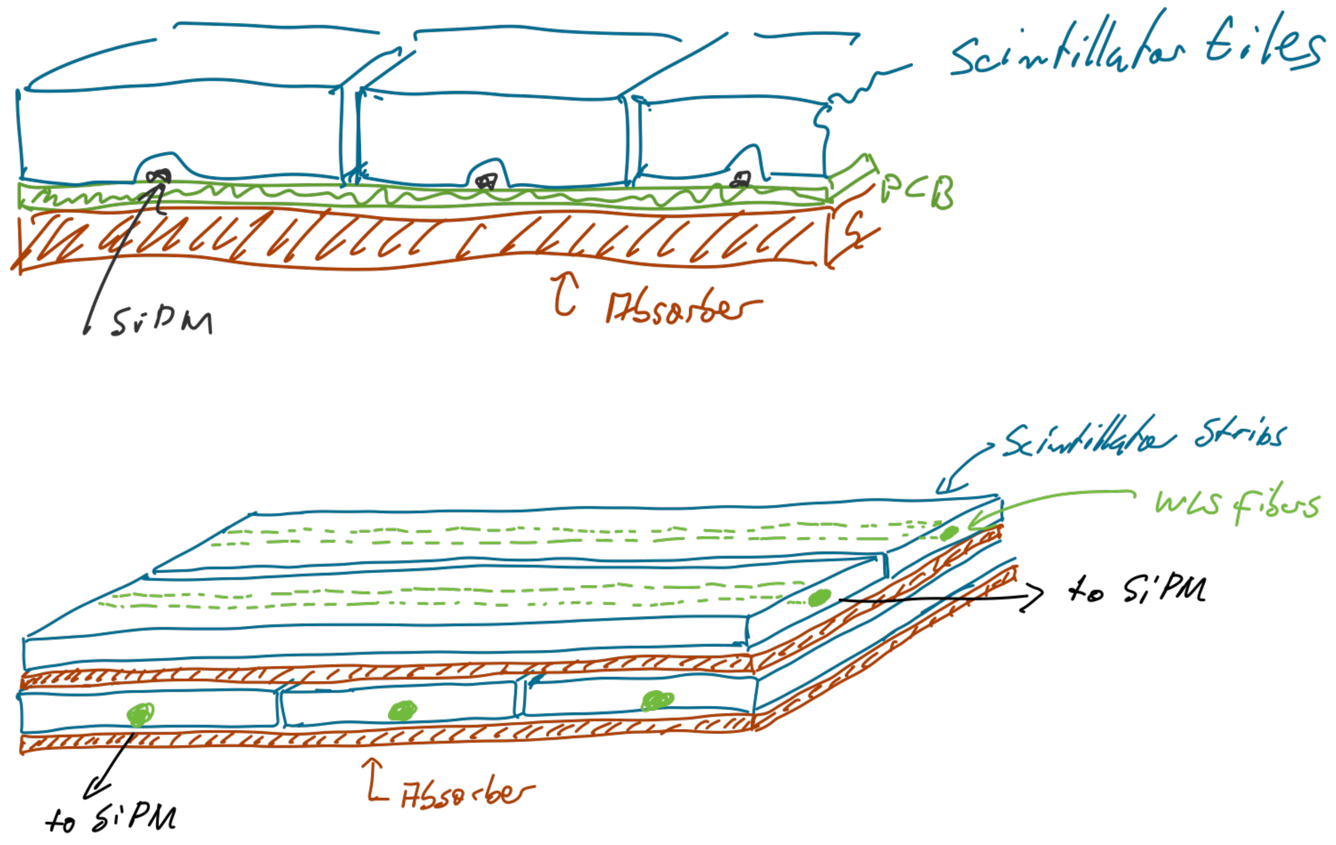
Successful "Spin-offs": Applications

CMS HGCAL Phase 2 Upgrade, Ideas for DUNE

- Adopting two key technologies of CALICE for CMS HGCAL highly granular endcap calorimeters: Silicon, SiPM-on-tile
  - Requires adjustments to cope with radiation environment, data rates and timing requirements





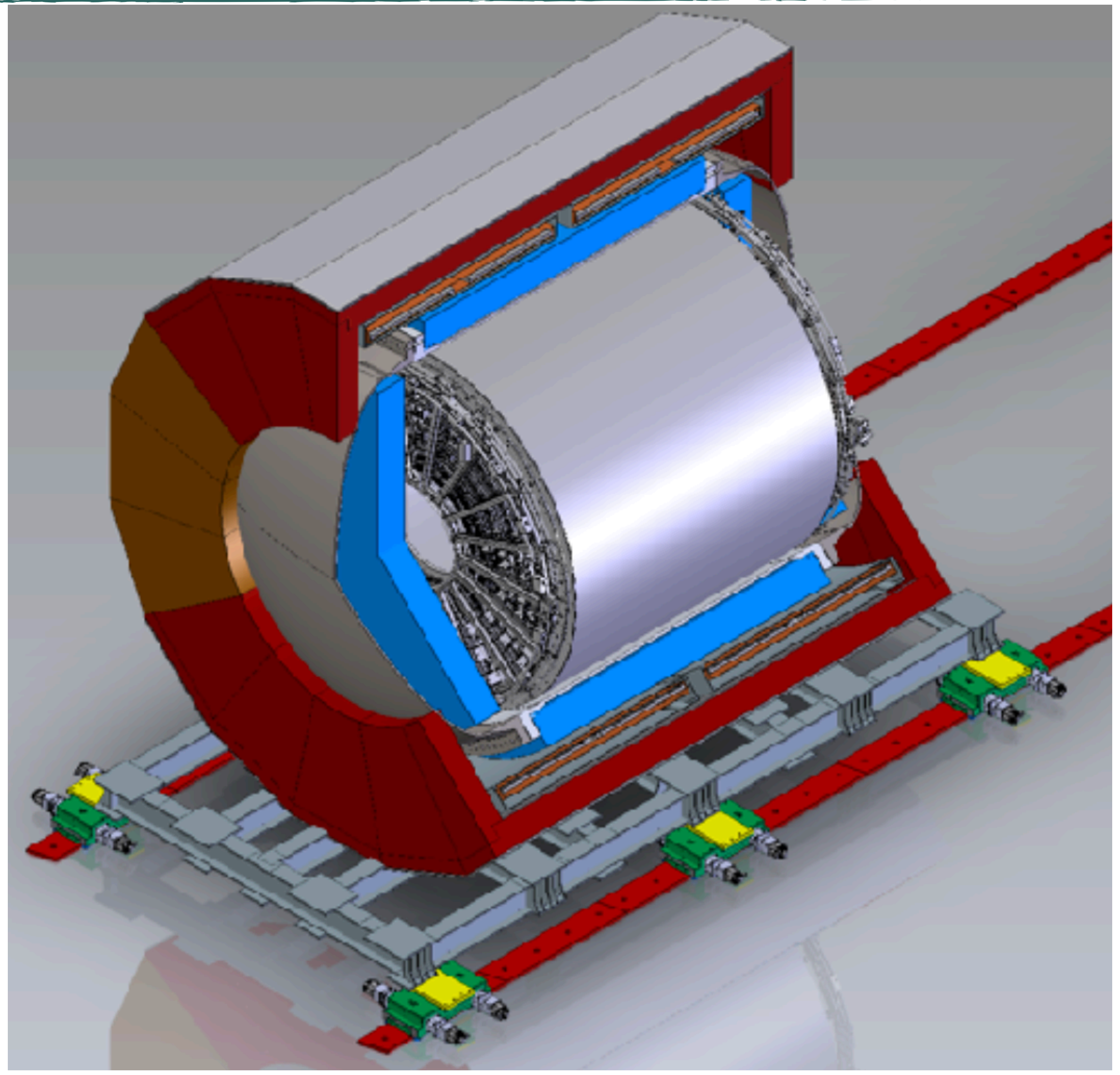


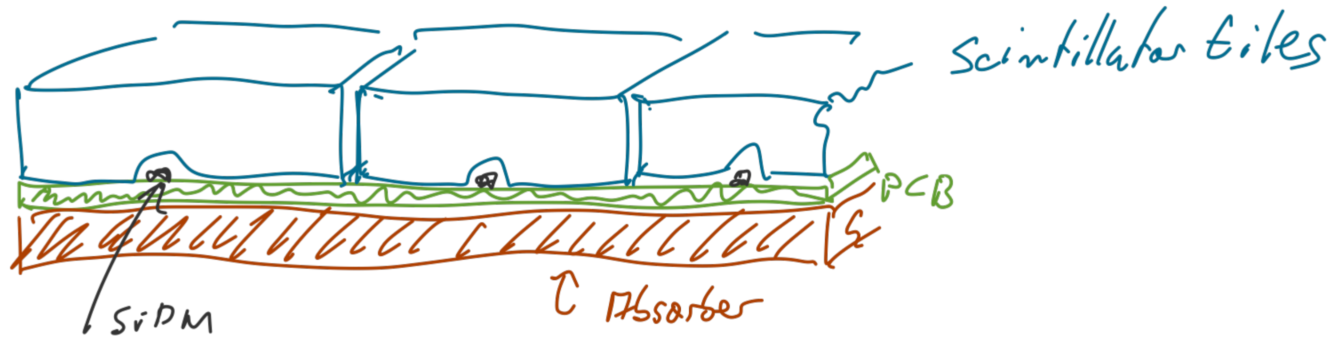
- SiPM-on-tile, combined with scintillator strips using the same electronics, under study for ECAL in the DUNE Near Detector
  - Partially orthogonal challenges relative to CMS

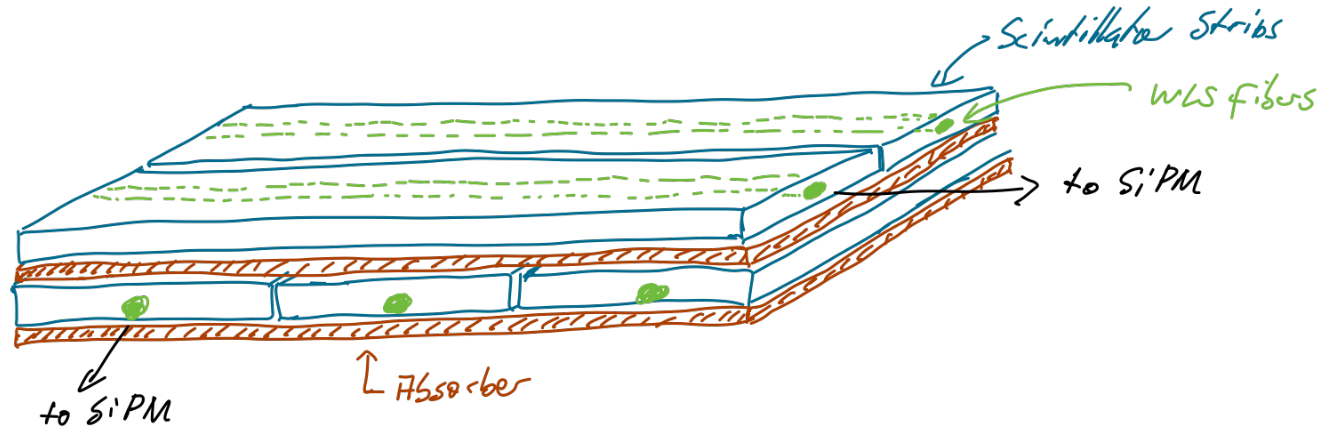
Successful "Spin-offs": Applications

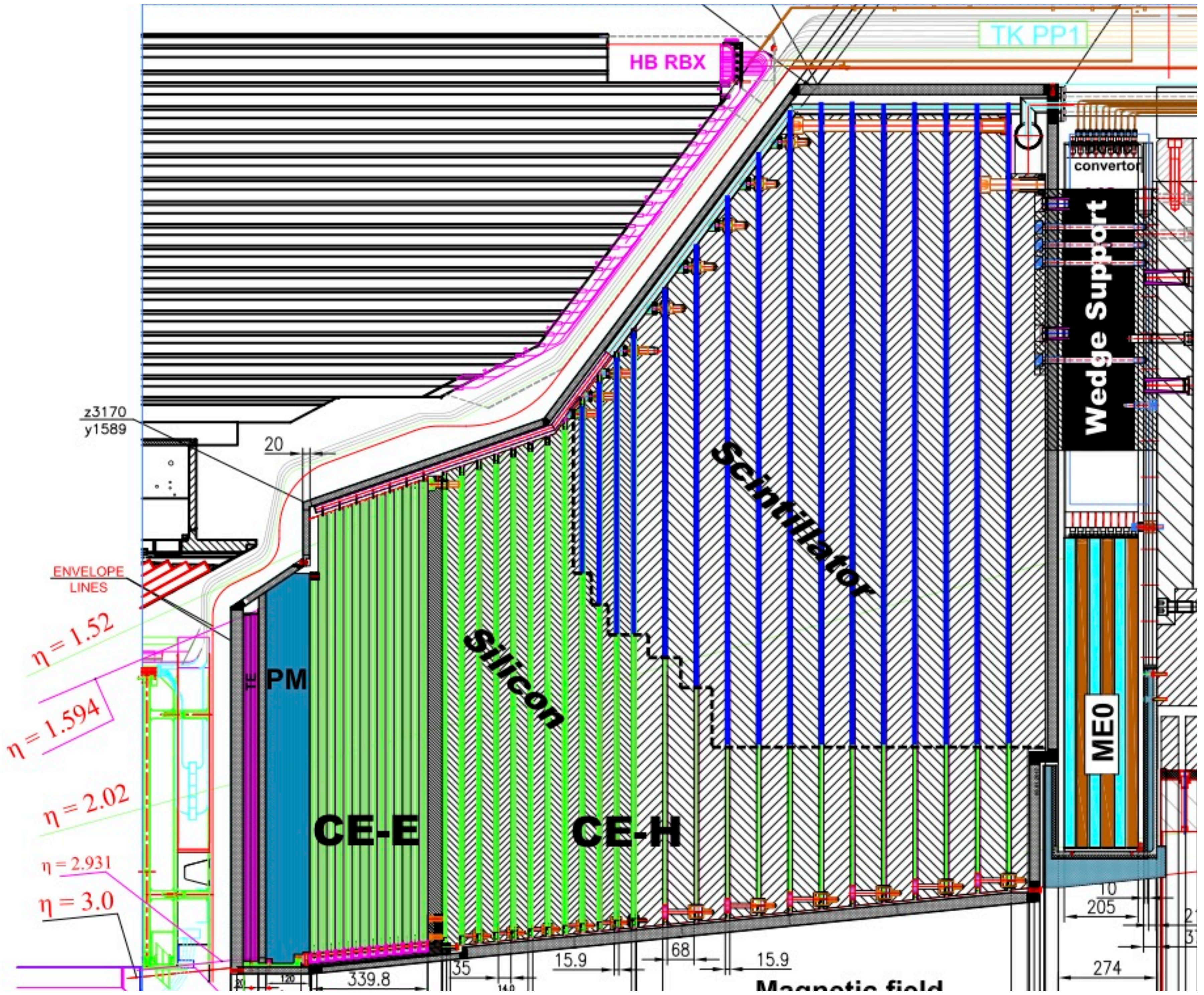
CMS HGCAL Phase 2 Upgrade, Ideas for DUNE

- Adopting two key technologies of CALICE for CMS HGCAL highly granular endcap calorimeters: Silicon, SiPM-on-tile
  - Requires adjustments to cope with radiation environment, data rates and timing requirements









- SiPM-on-tile, combined with scintillator strips using the same electronics, under study for ECAL in the DUNE Near Detector
  - Partially orthogonal challenges relative to CMS

➡ A further boost to the development of the technology, and the establishment of solutions for system integration.

Summary

- Highly granular calorimeters are motivated by PFA - based event reconstruction - to allow optimal combination of calorimetry and tracking
  - In terms of possibilities, we have most likely only looked at the tip of the iceberg: Enormous potential for advanced reconstruction techniques making full use of the 4D or 5D information provided by such detectors

- CALICE has developed imaging calorimetry from an idea to a well-proven concept with established technological solutions suited for full experiments, also addressing integration and production challenges
  - The CMS HGCAL will take this one step further - in the extreme environment of the HL-LHC, and additional non-lepton collider applications are being planned

- The technology is ready for adoption in “Higgs Factory” detectors - but interesting further R&D topics remain in many areas