Particle Flow and Imaging Calorimeters:

Event Reconstruction for Next Generation Colliders

Frank Simon
MPI for Physics & Excellence Cluster 'Universe'
Munich, Germany

KEK Seminar

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

TUM
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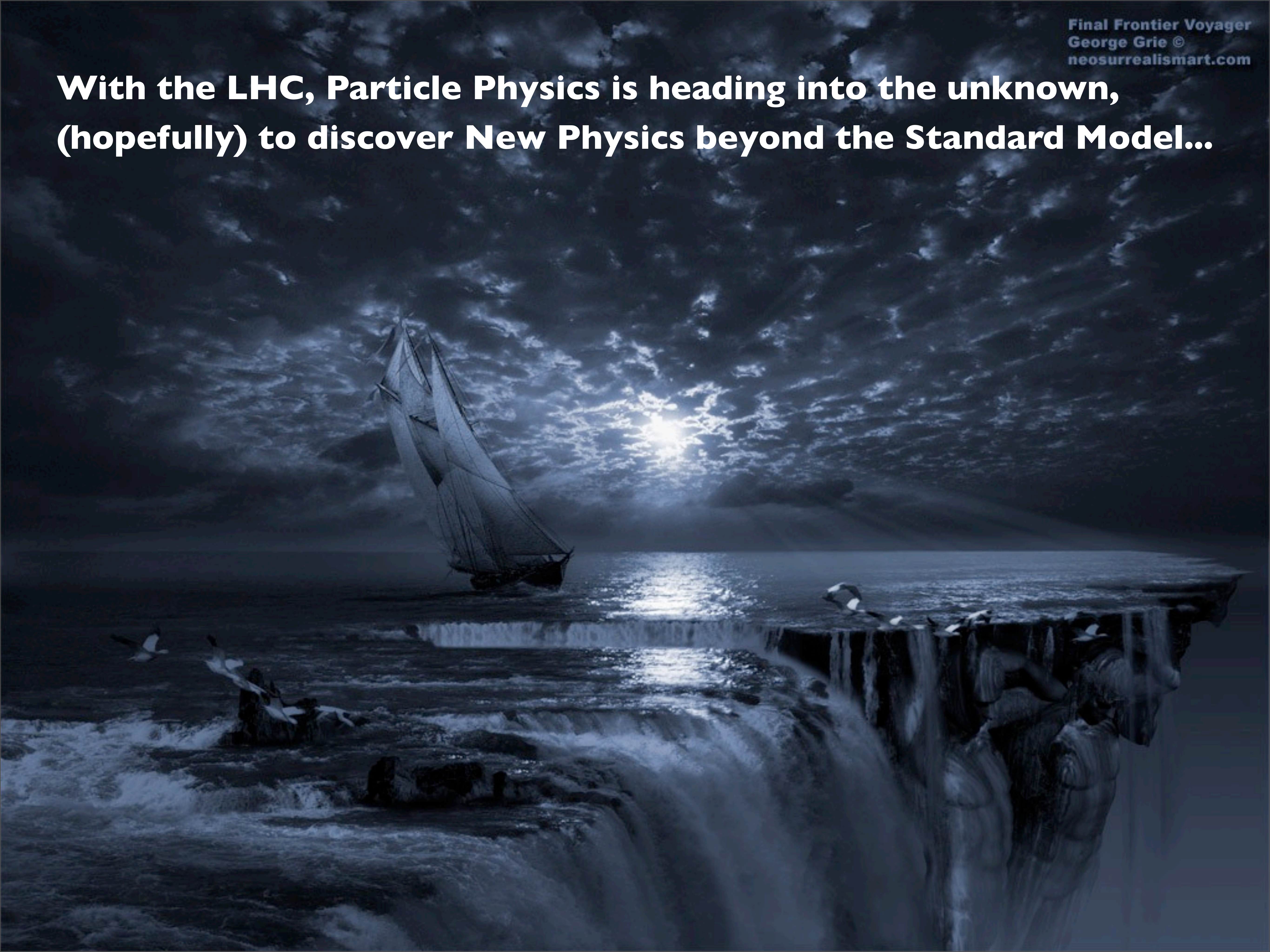
Universe

With the LHC, Particle Physics is heading into the unknown, (hopefully) to discover New Physics beyond the Standard Model...



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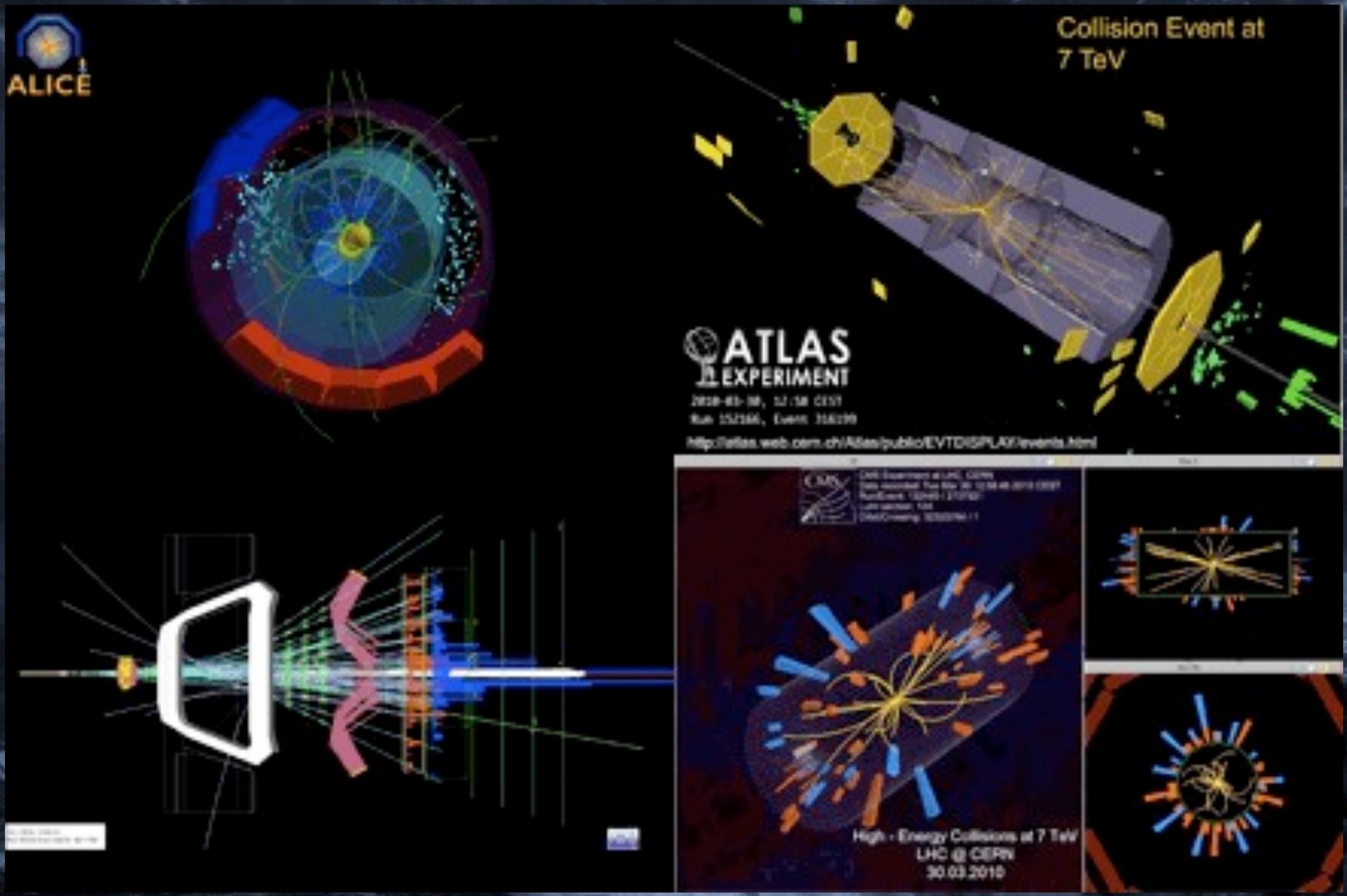

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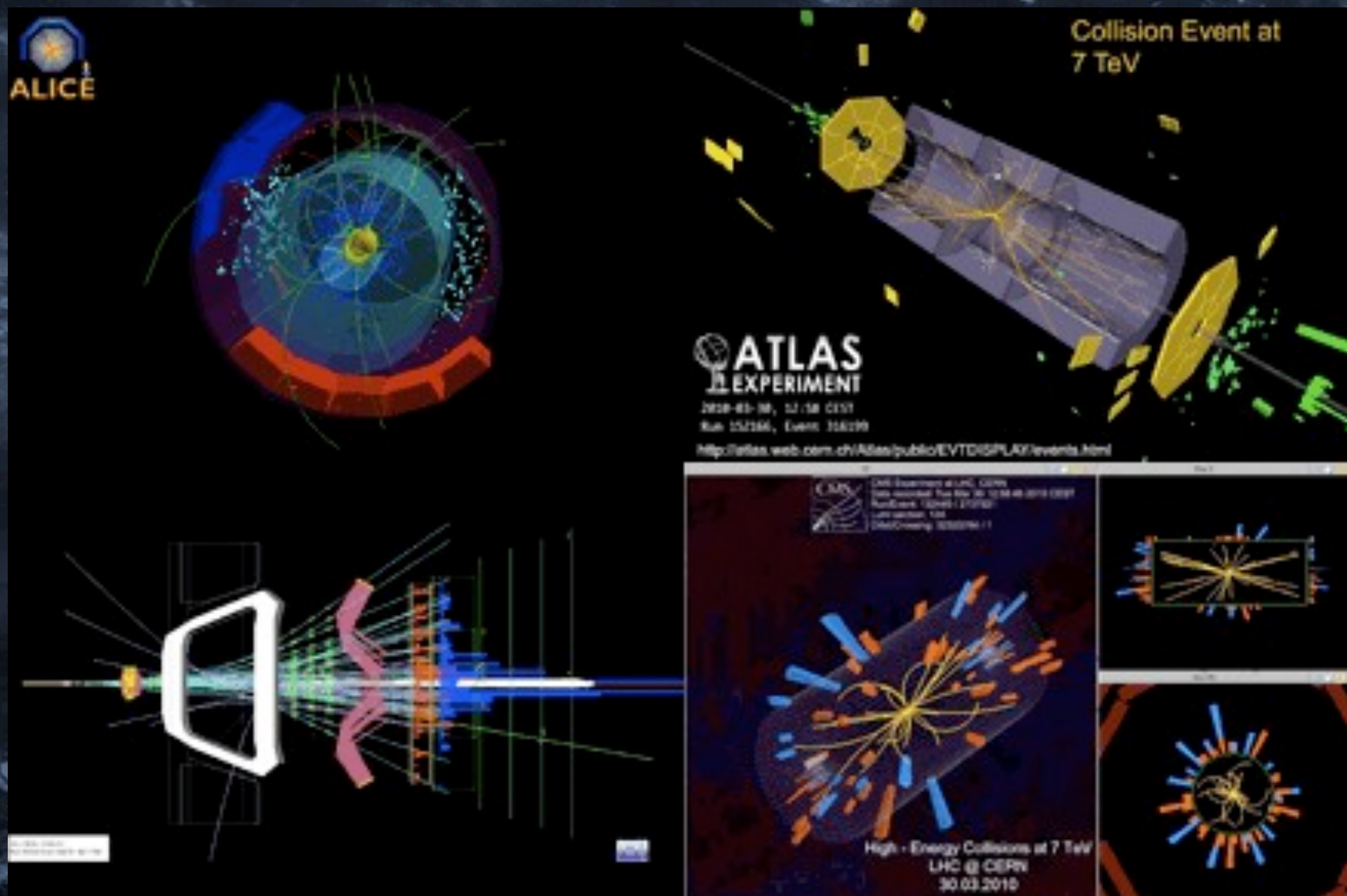
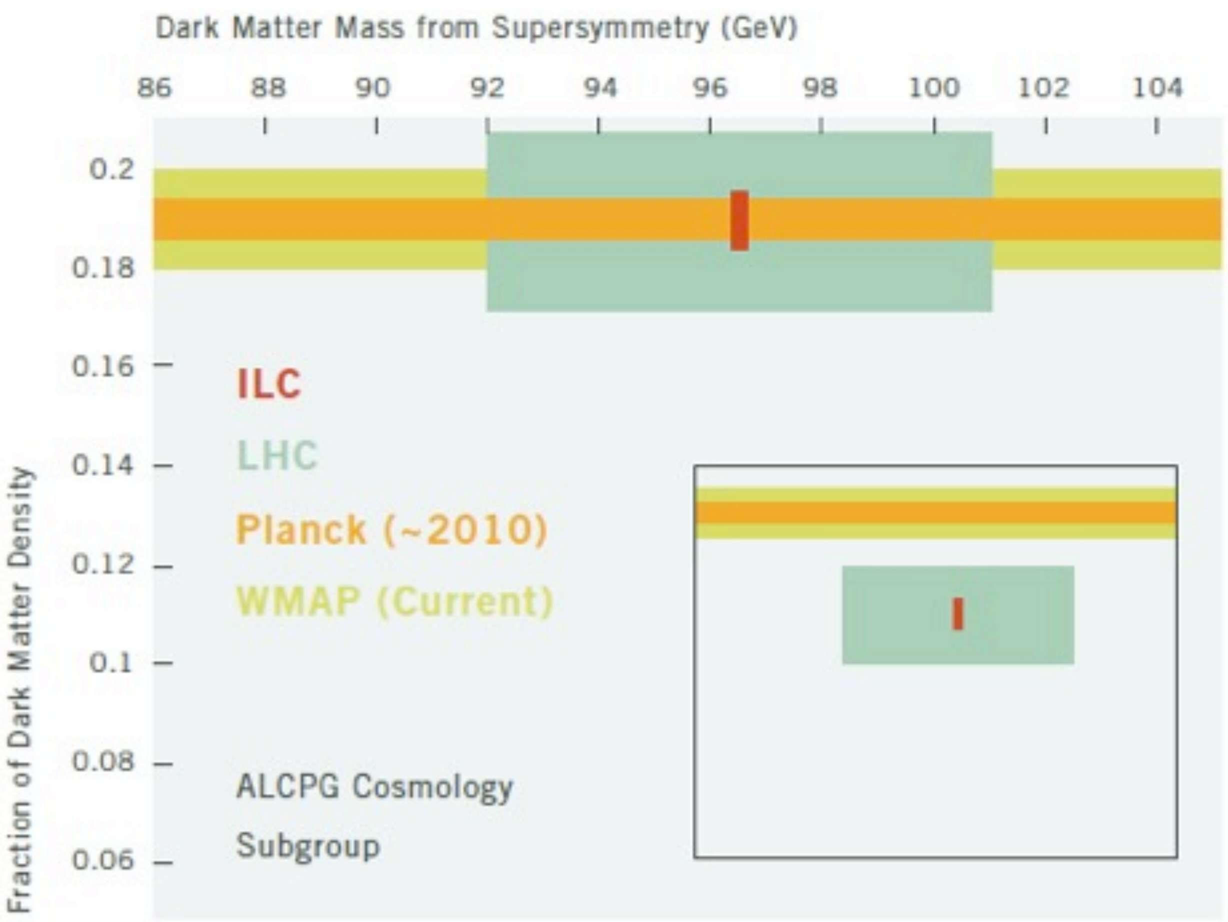


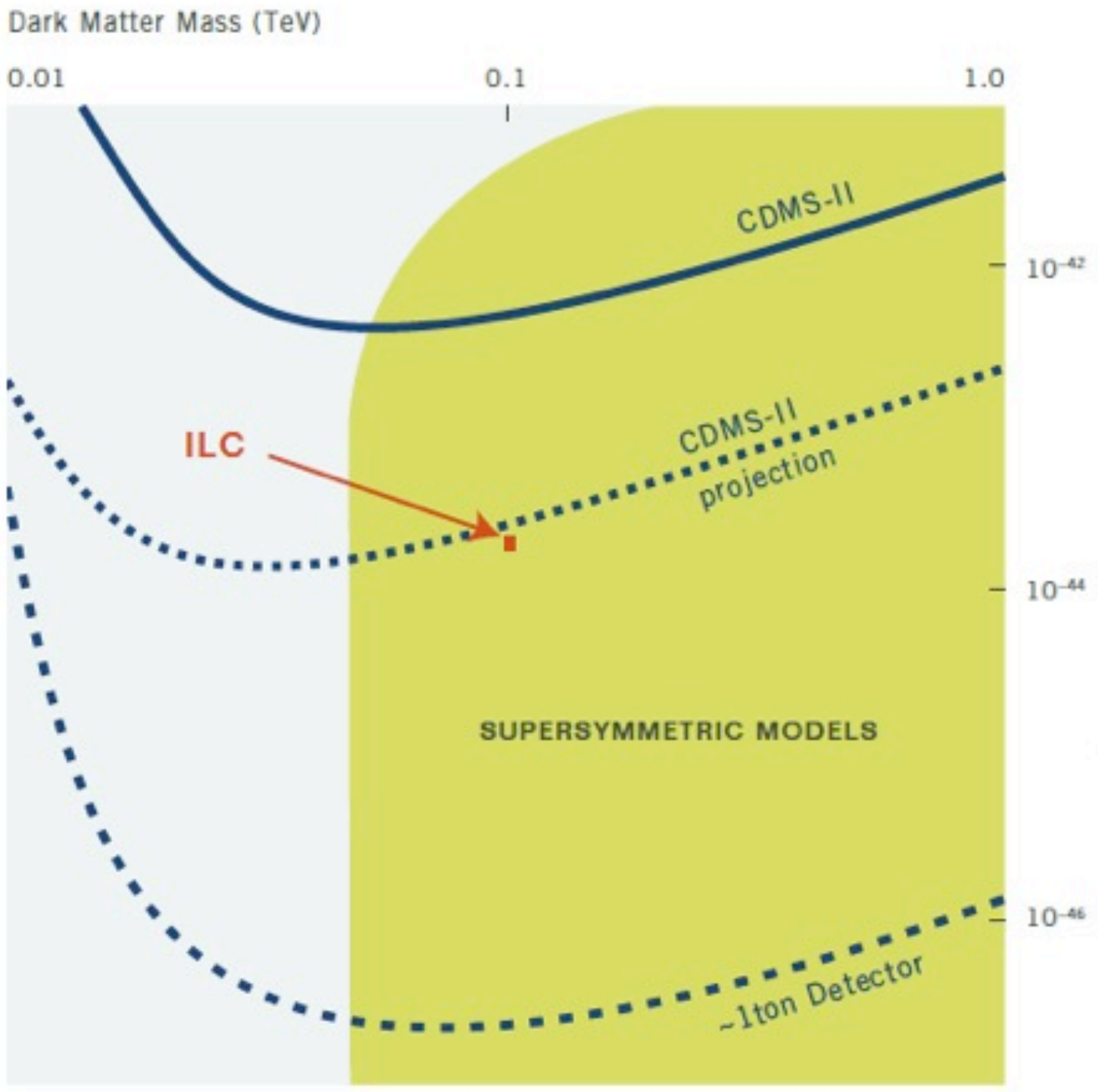
... what do we need to fully understand what we might find?

Linear Colliders: Precision at the Terascale

- LHC will show us a rough outline of New Physics, but:
  Detailed understanding needs additional precision measurements

What is the nature of Dark Matter?





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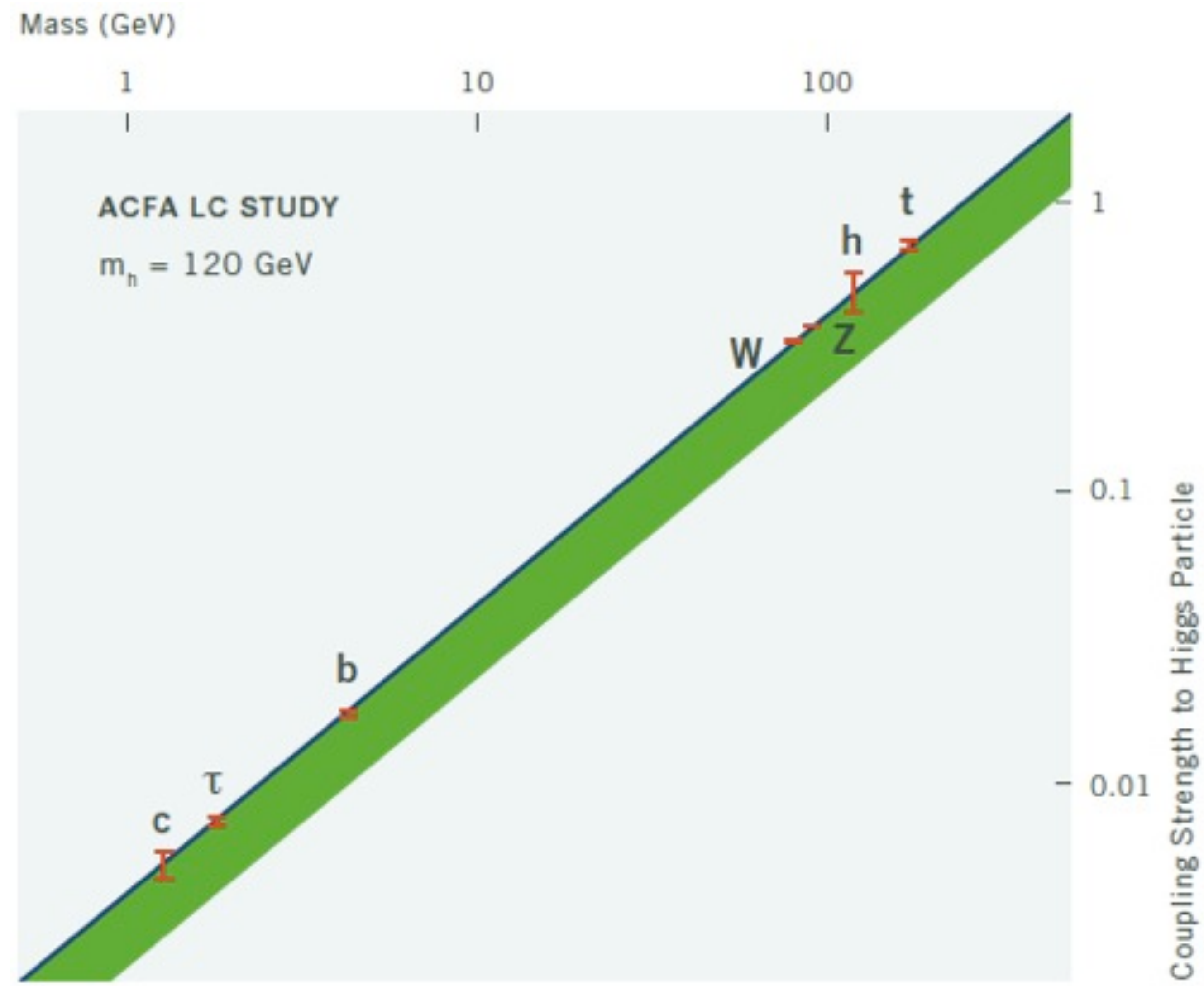
Is the Higgs really "The Mother of Mass"?



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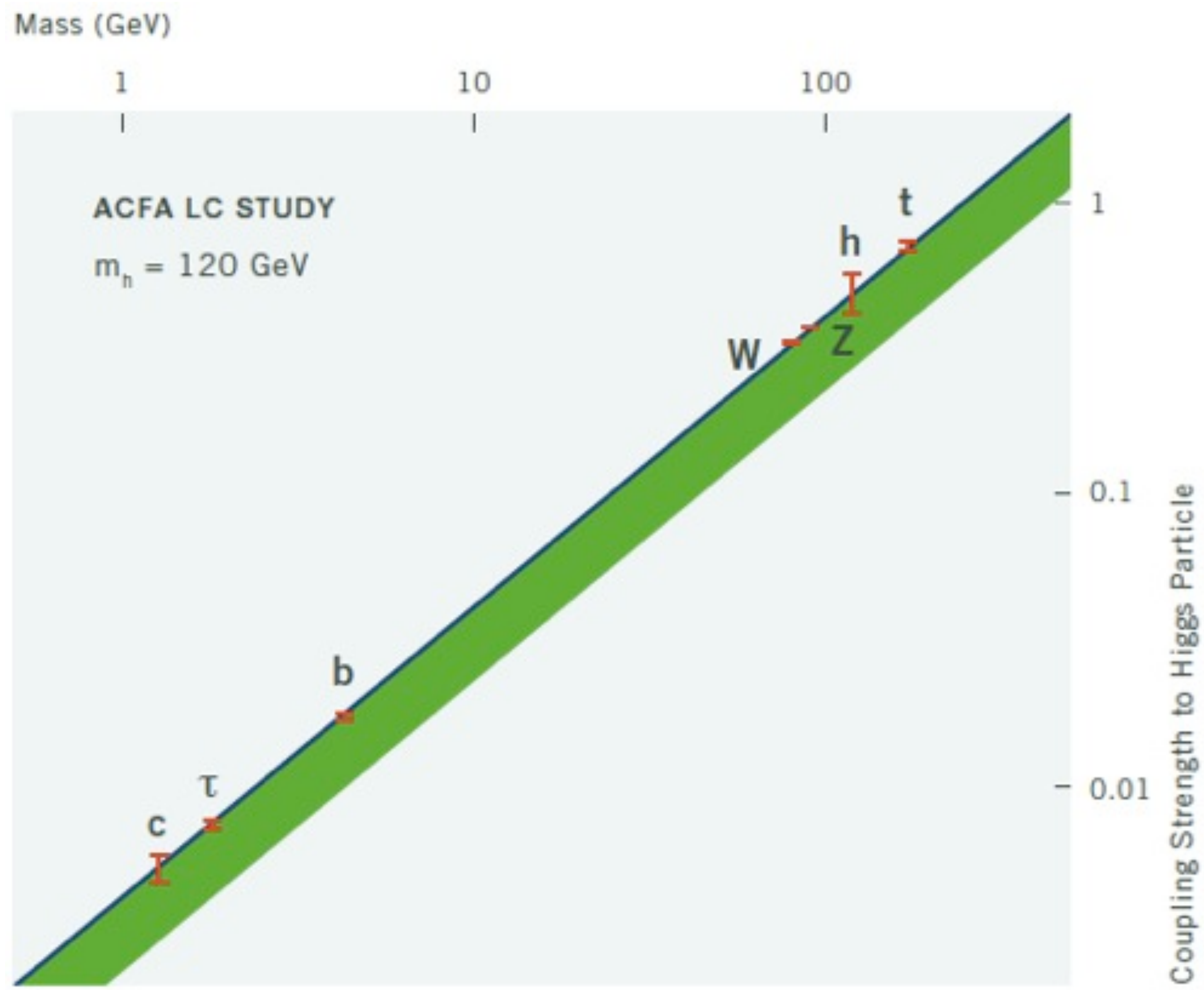
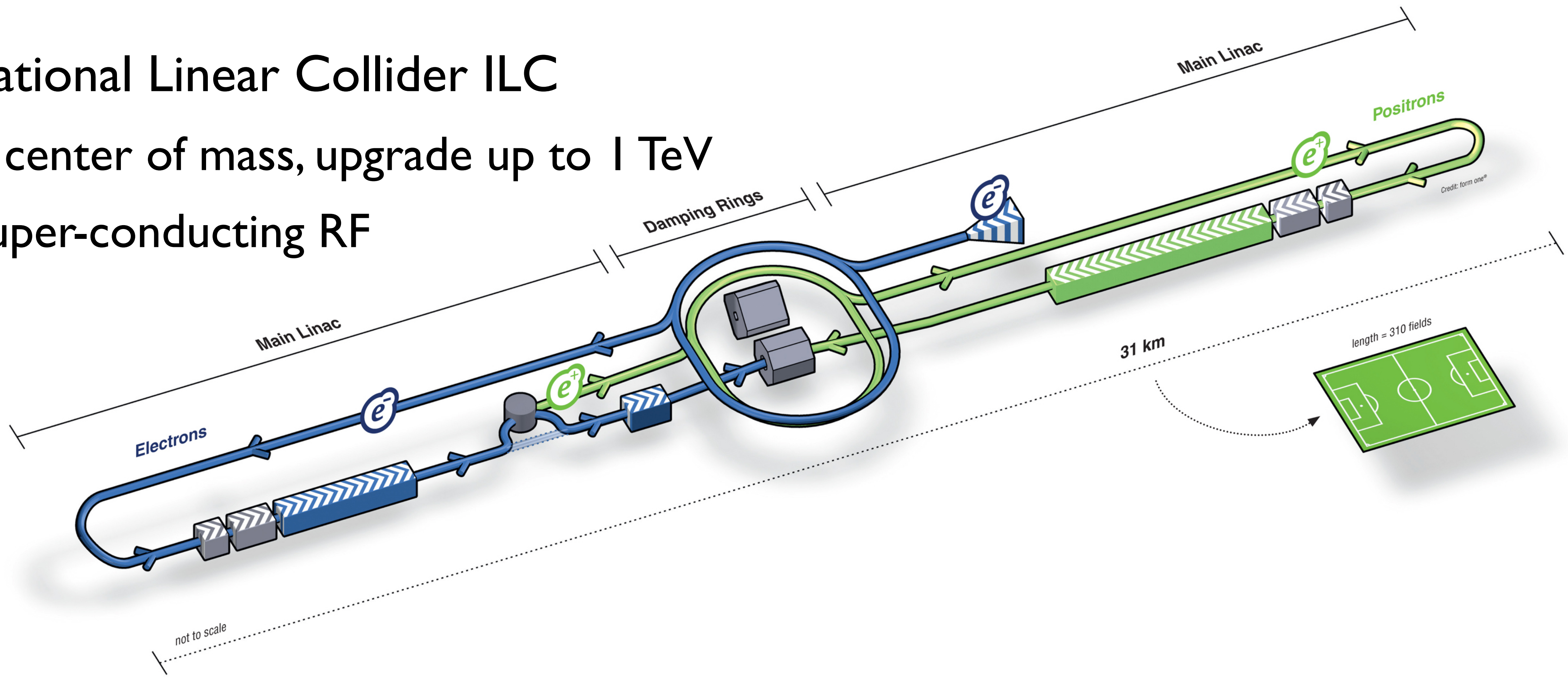


Can be answered with a future high-energy e^+e^- collider!

Concepts for the Next Big Collider

- The International Linear Collider ILC
  - 500 GeV center of mass, upgrade up to 1 TeV
  - Proven super-conducting RF



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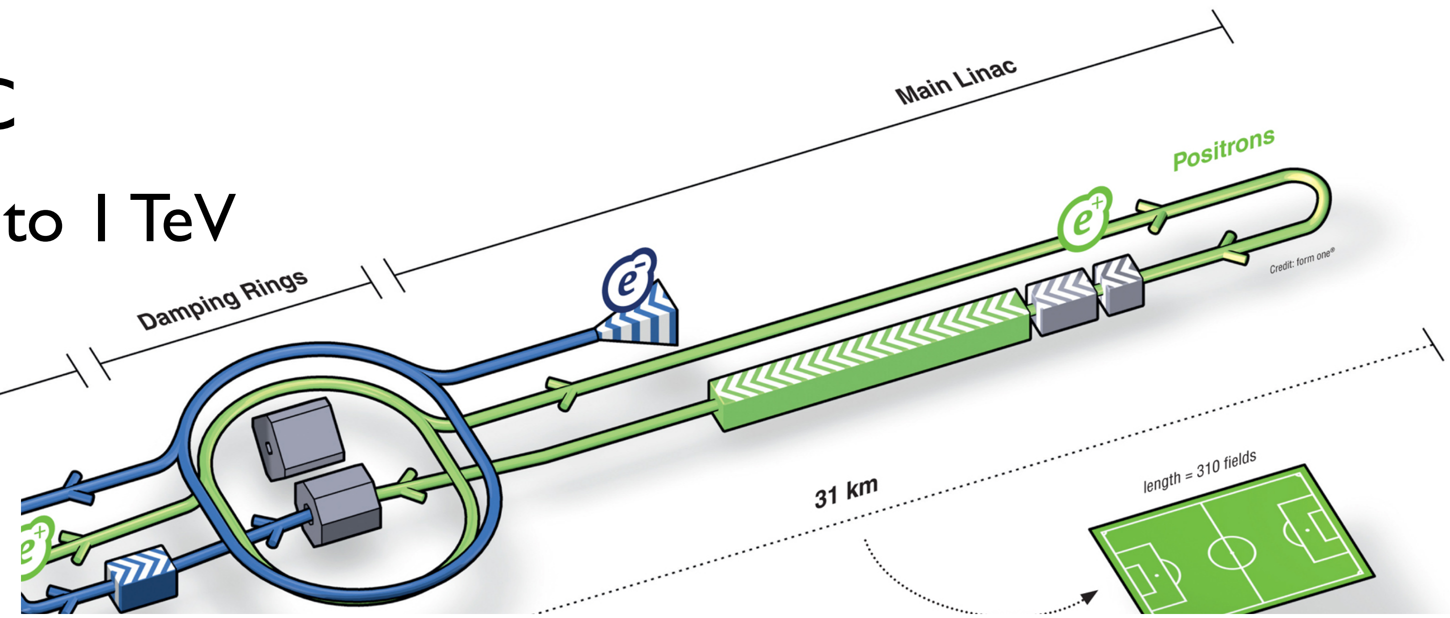
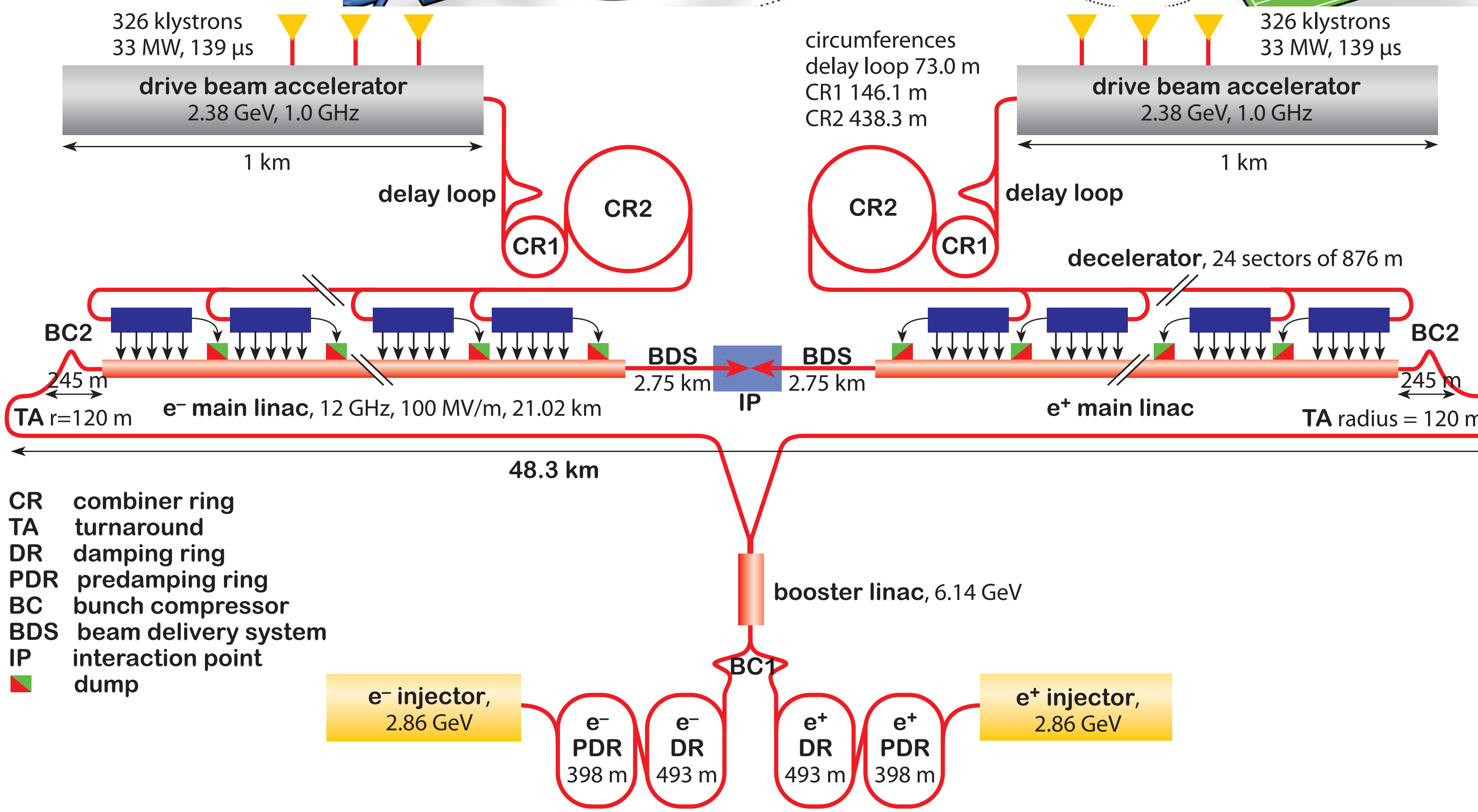


- The Compact Linear Collider CLIC
  - 3 TeV center of mass
  - 2-beam acceleration (in development)



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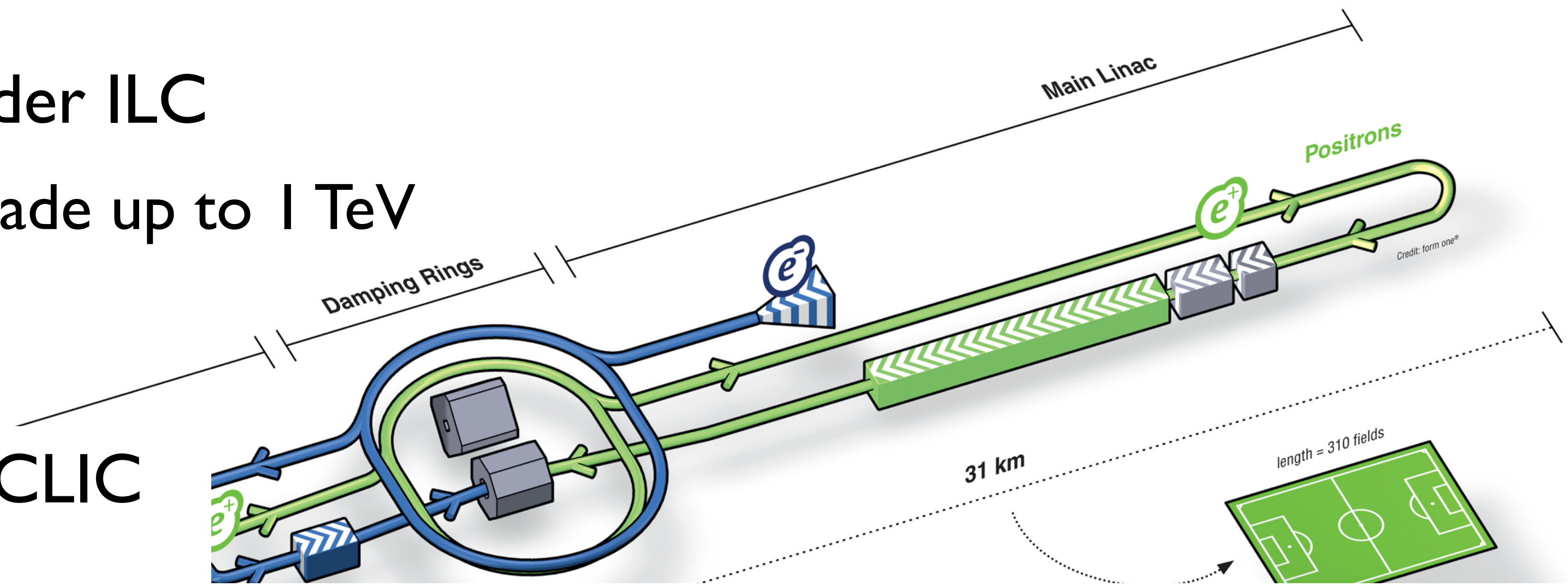

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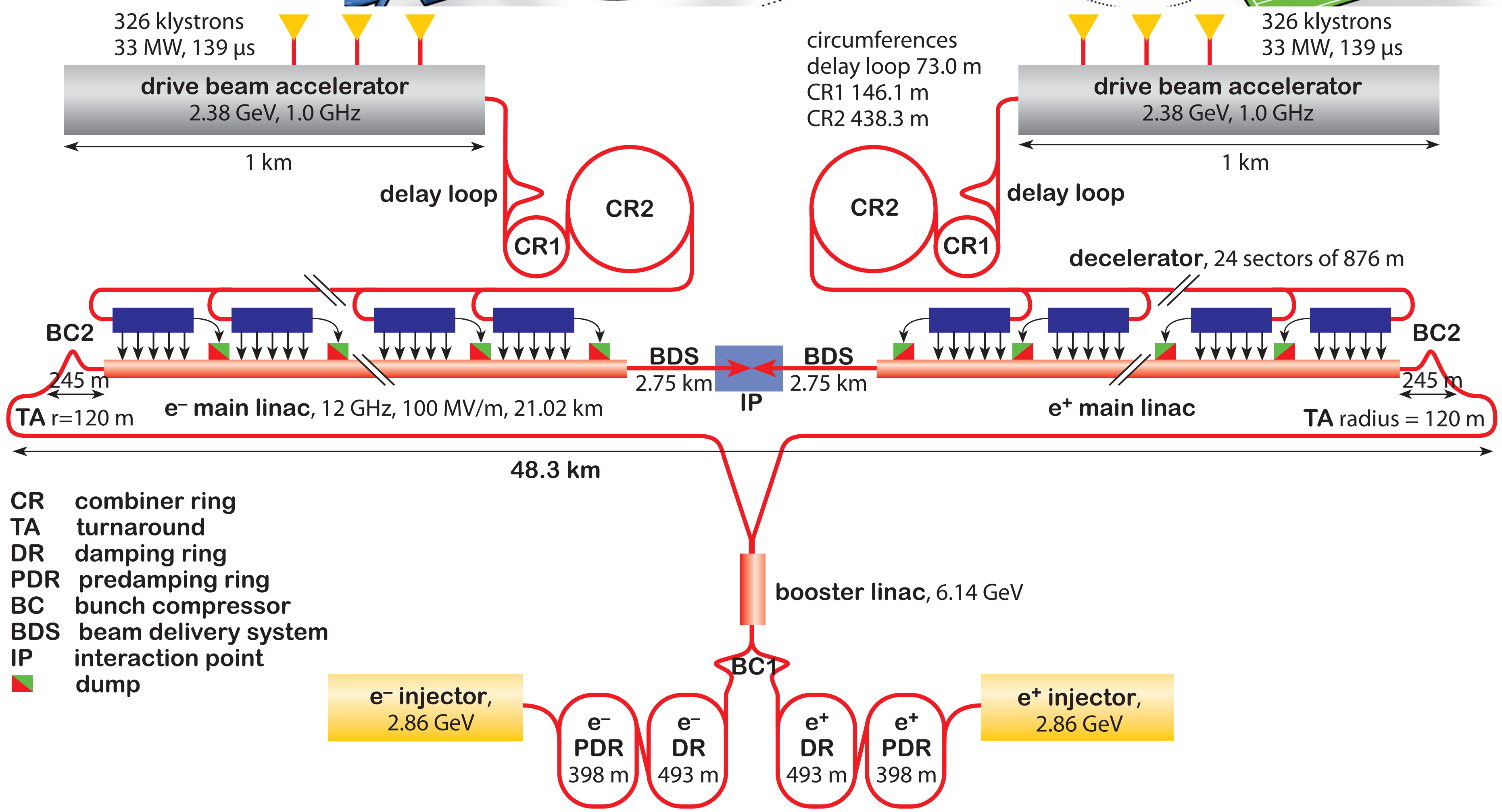


The scale of New Physics will determine which machine to build!

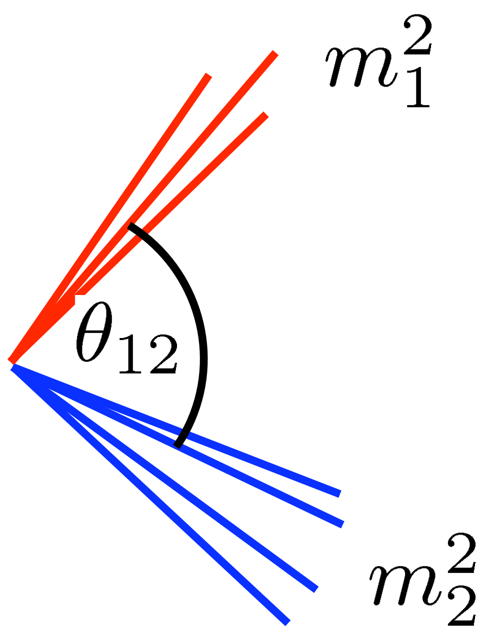
Outline

- Hadronic Final States: Requirements at a Future Lepton Collider
- Particle Flow Algorithms
  - The Concept
  - Expected Performance
- Imaging Calorimeters
  - Focus Topic: Analog Hadron Calorimeter
- Hadronic Showers in Imaging Calorimeters
  - 3D Studies of Showers
  - Energy Reconstruction
- Summary

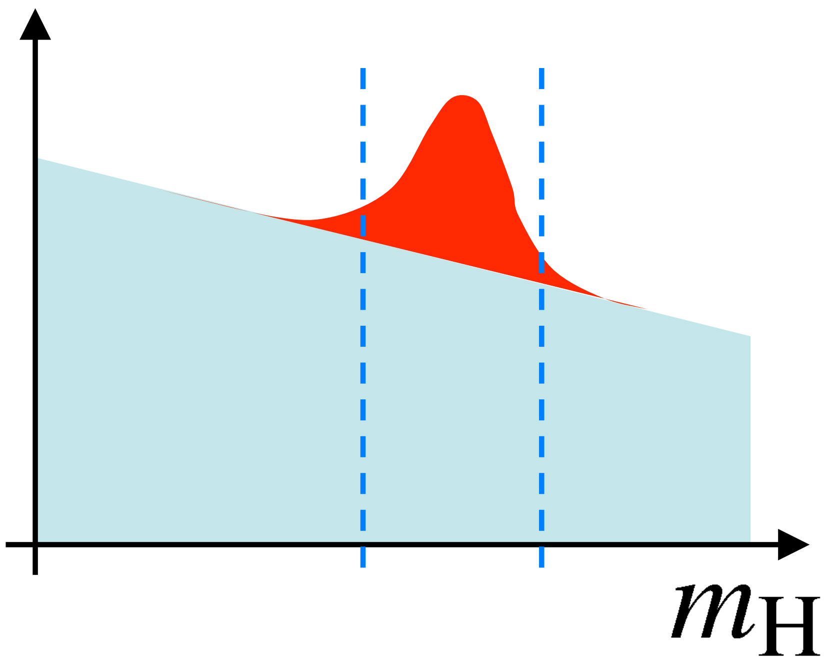
Hadronic Final States: Requirements at Future Lepton Colliders

Mass Resolution in Hadronic Final States

- The precise requirements depend on the physics!
- Very likely of big importance: di-jet mass resolution



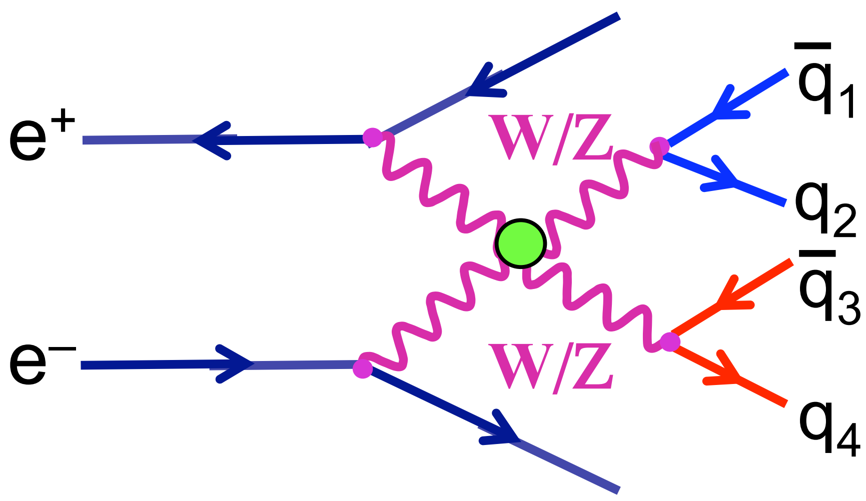
Typical case:
A narrow resonance decaying into quark pairs

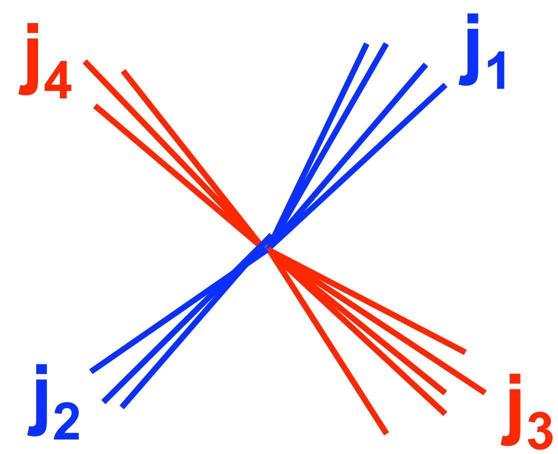


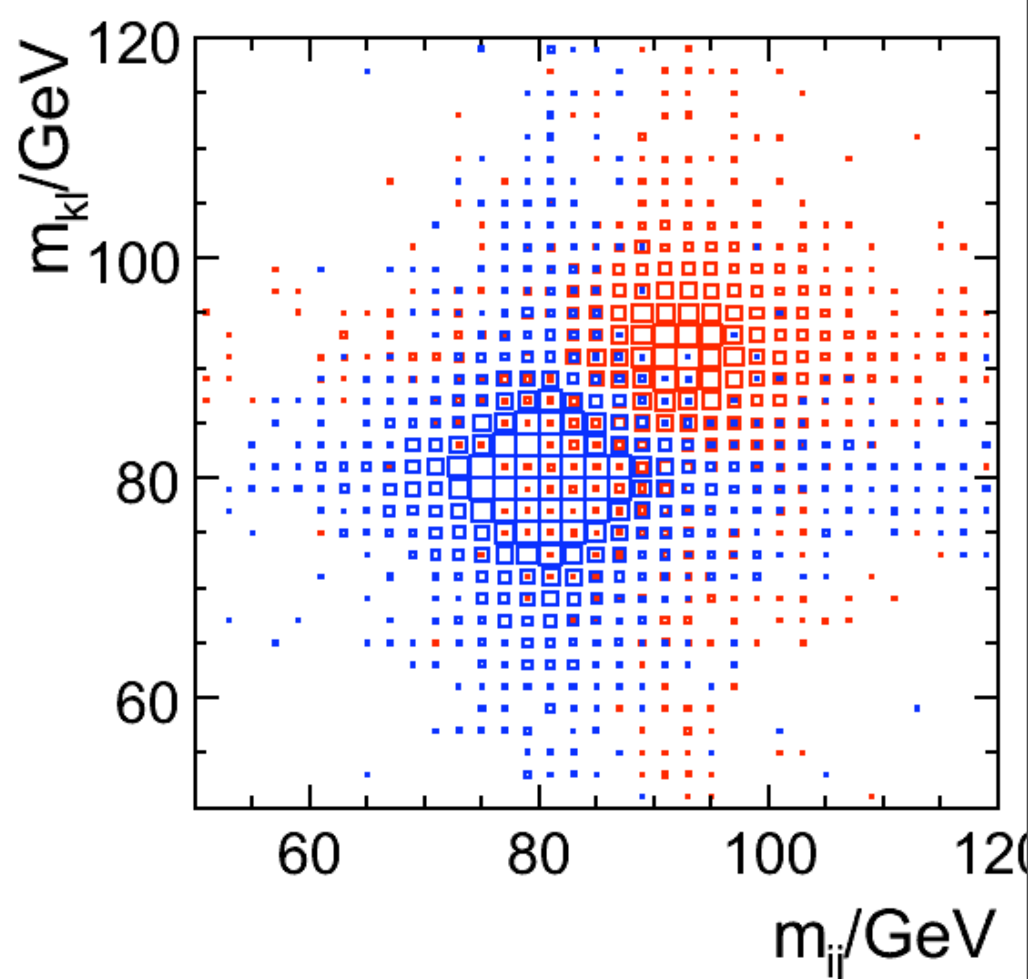
Significance: $\propto \frac{S}{\sqrt{B}} \qquad \propto \frac{1}{\sqrt{\sigma(M)}}$

Minimum Requirement: Separate Gauge Bosons

- Gauge bosons (W, Z) are important signatures:
  - Can show up in many final states of heavy particles
  - Potential strong interaction: Scenarios for electroweak symmetry breaking







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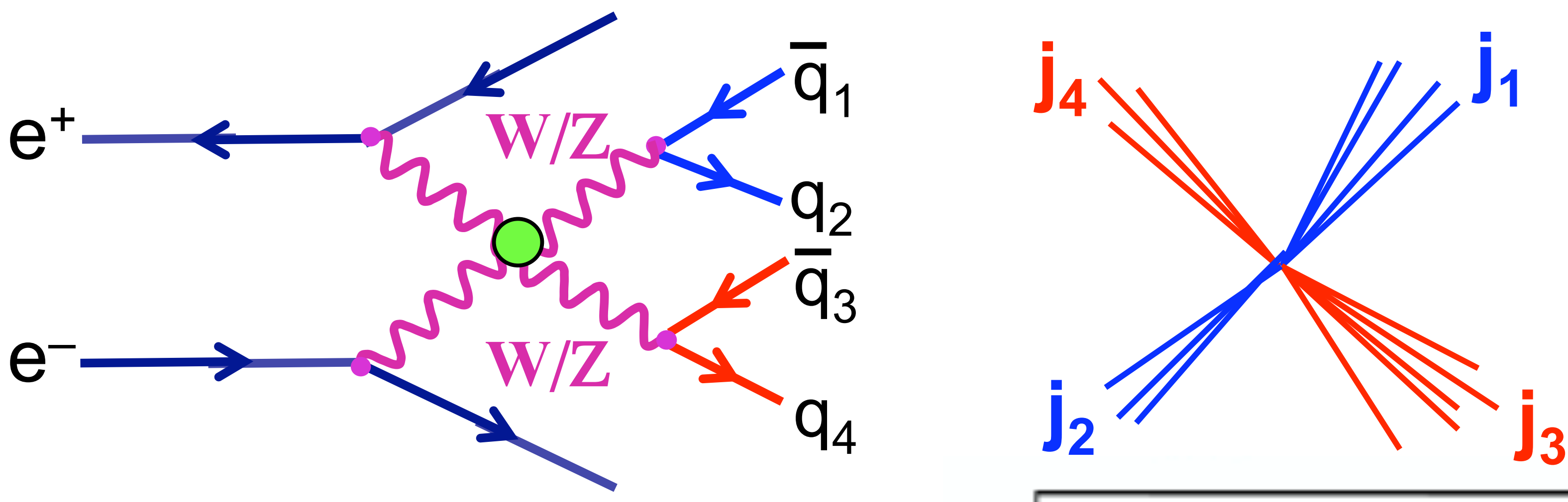
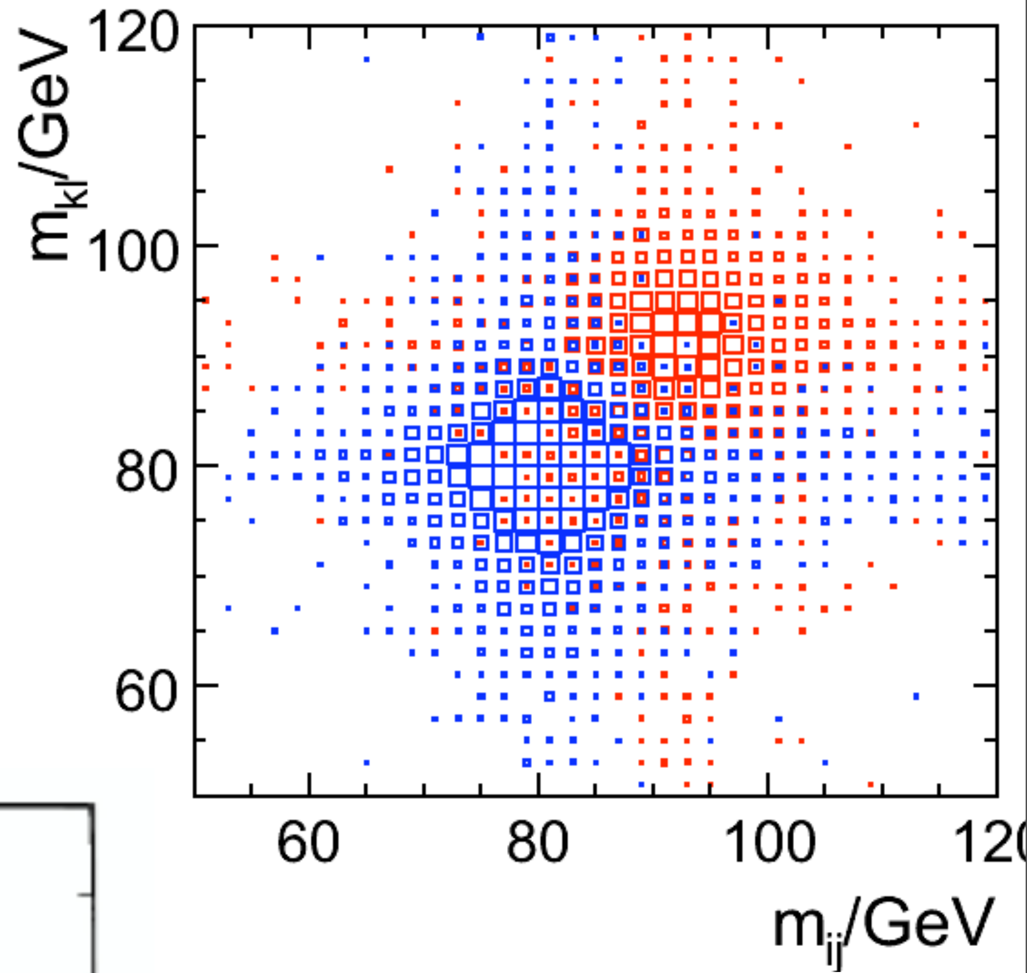
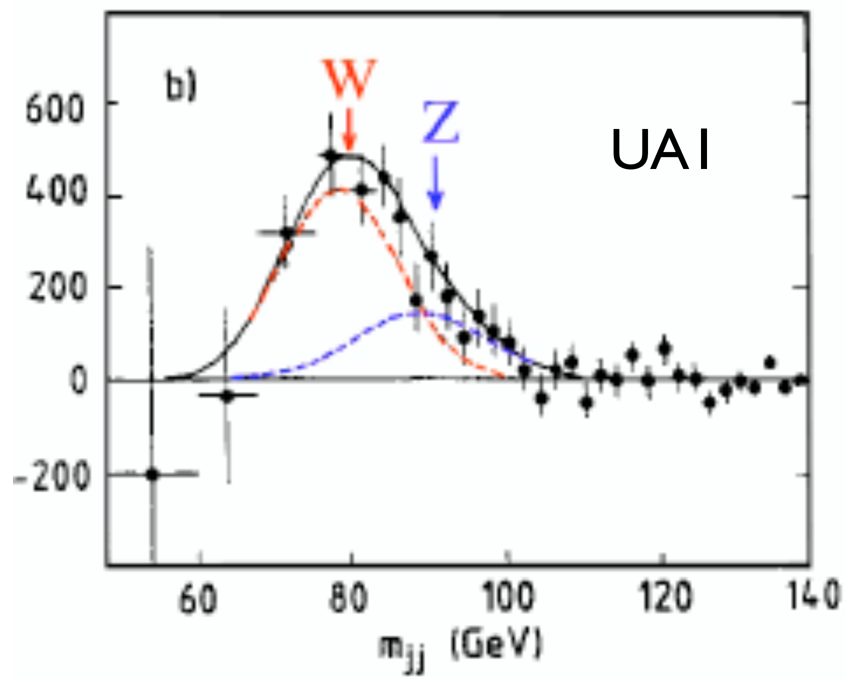


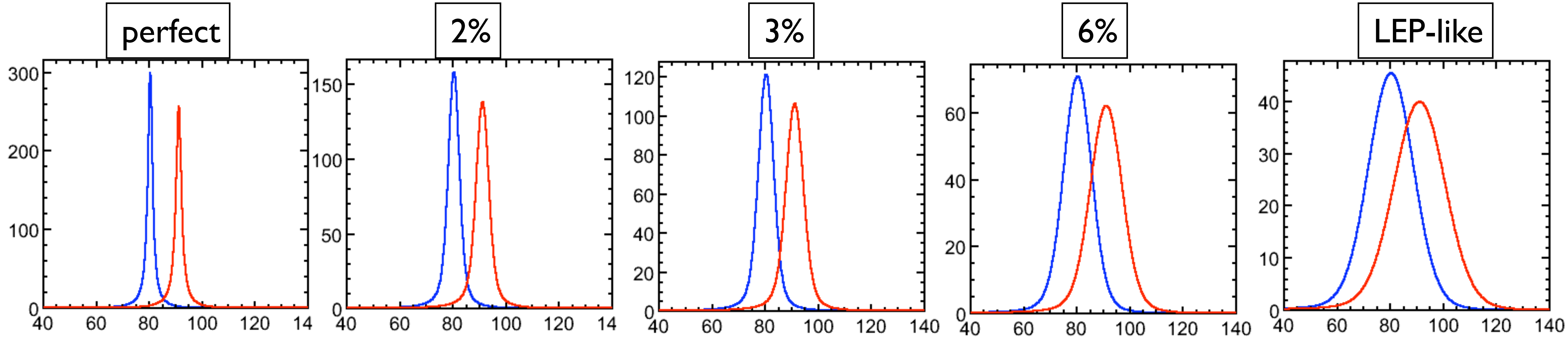


From discovery signal to sensitive tool: a long way to go!



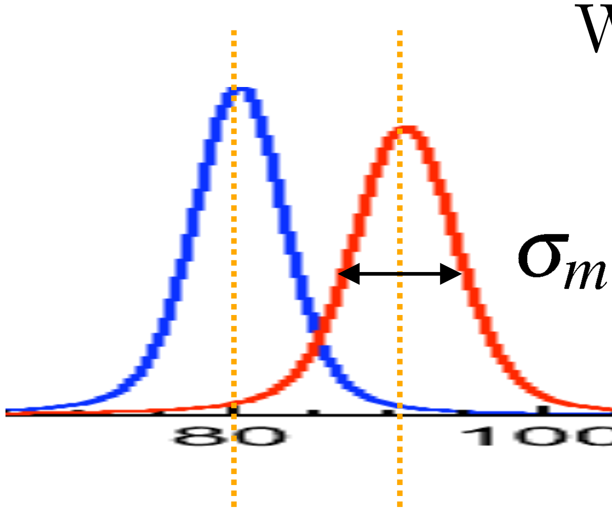
Mass Resolution: Requirements for separation

- Width of gauge bosons sets a natural scale for the required resolution



Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

$$\text{W/Z separation} = (m_Z - m_W)/\sigma_m$$



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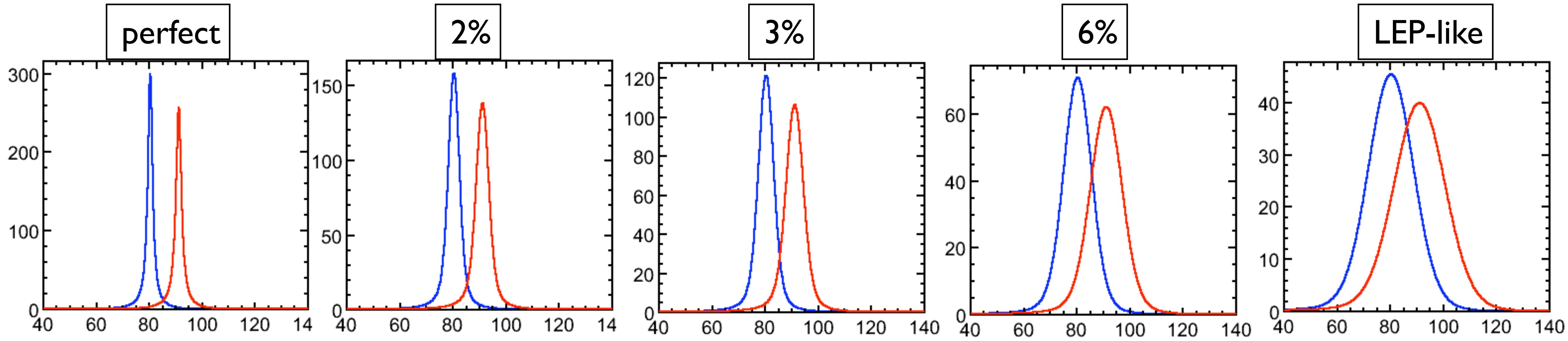

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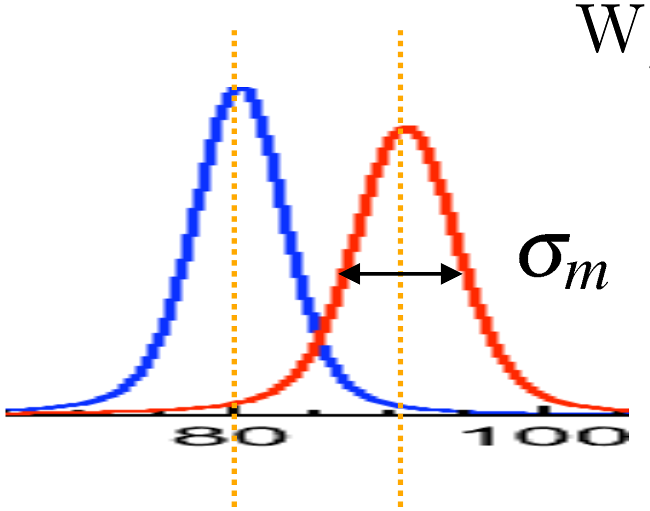

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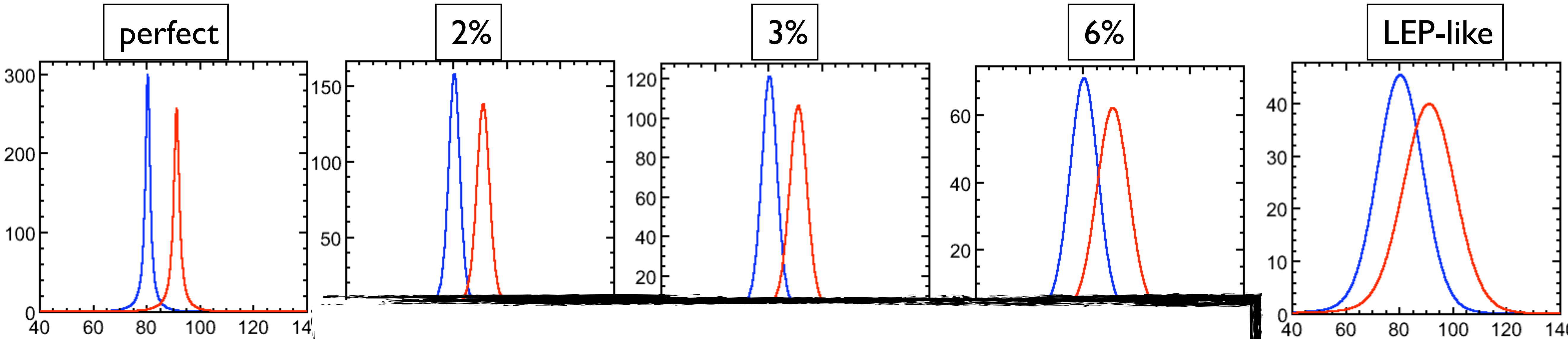

About a factor of 2 better than ATLAS
(state of the art!)

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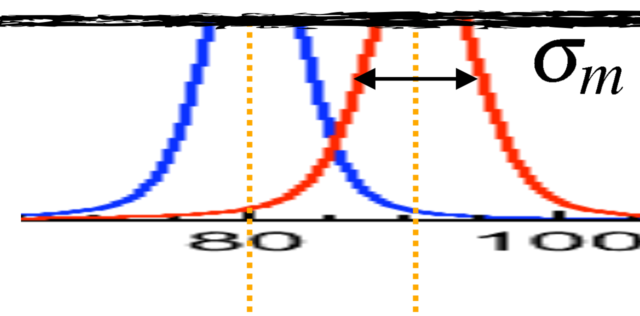

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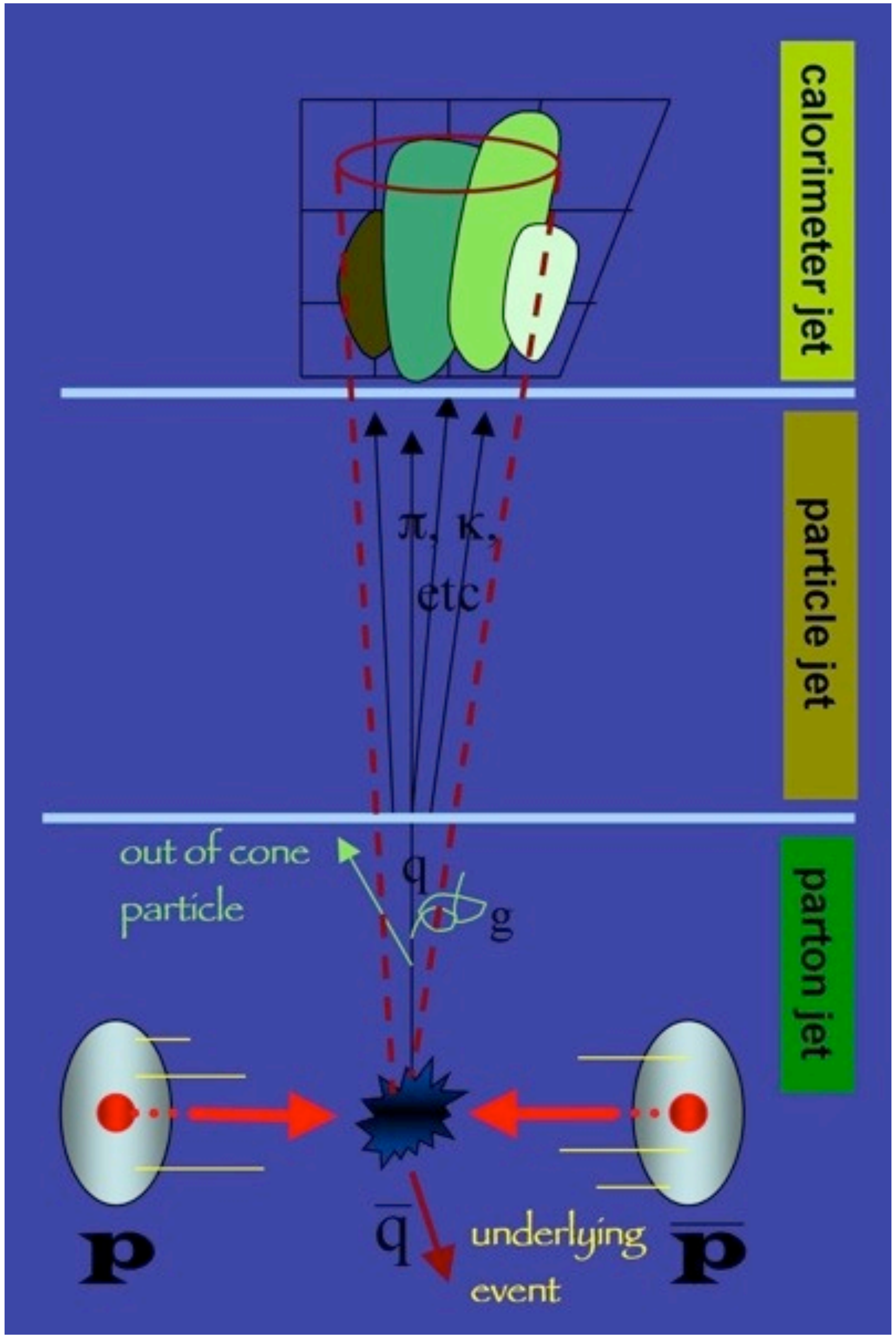
Where is the Challenge?

- Typical jet composition
  - 60% charged hadrons
  - 30% photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10% neutral hadrons (mainly n, K_L)
- Classical jet reconstruction relies exclusively on calorimetry: 70% of jet energy measured in the hadron calorimeter



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Hadron Calorimeter: Limited energy resolution

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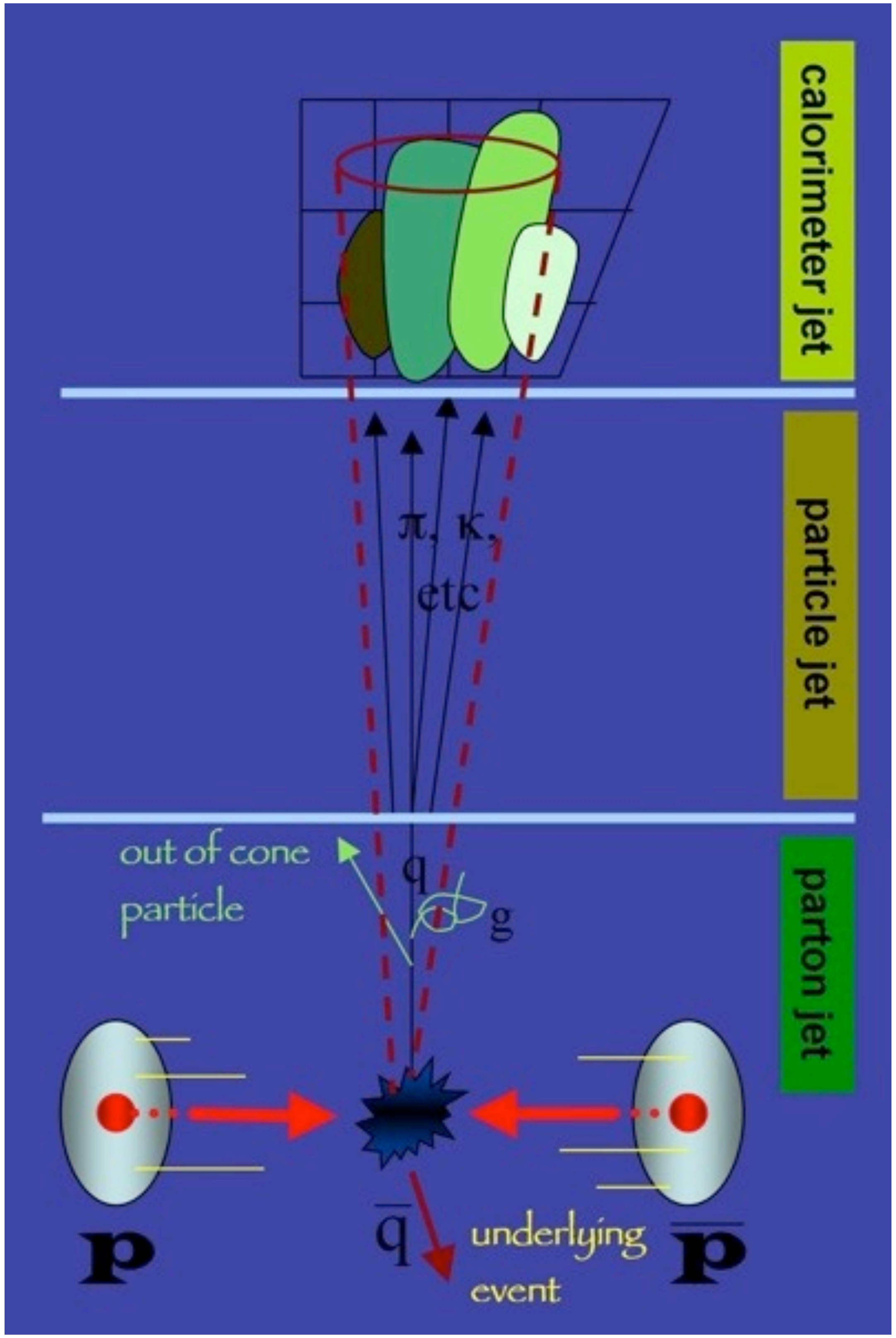
$$\sigma(E)/E \sim 60\%/\sqrt{E\,[\mathrm{GeV}]}$$

(often worse)



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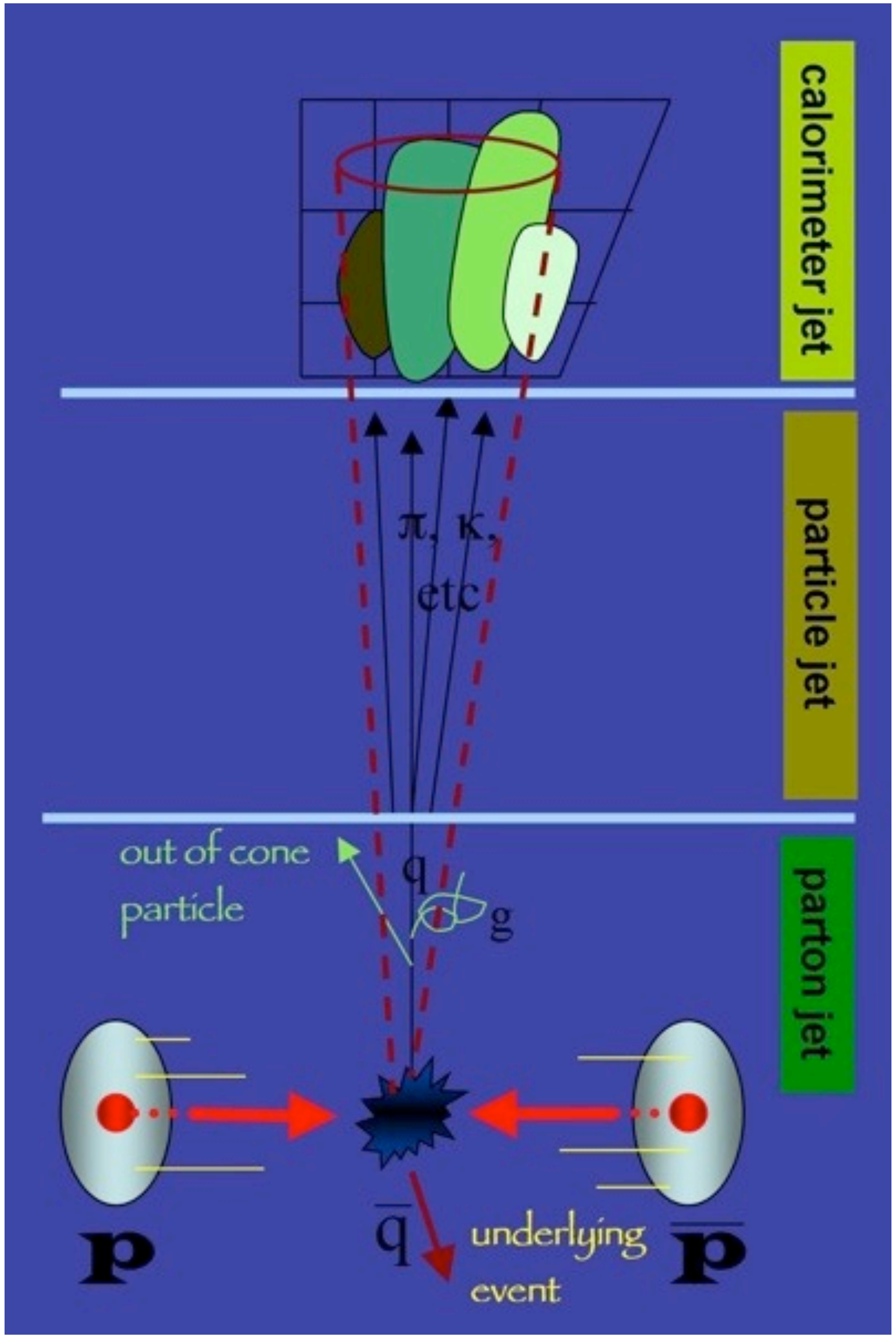
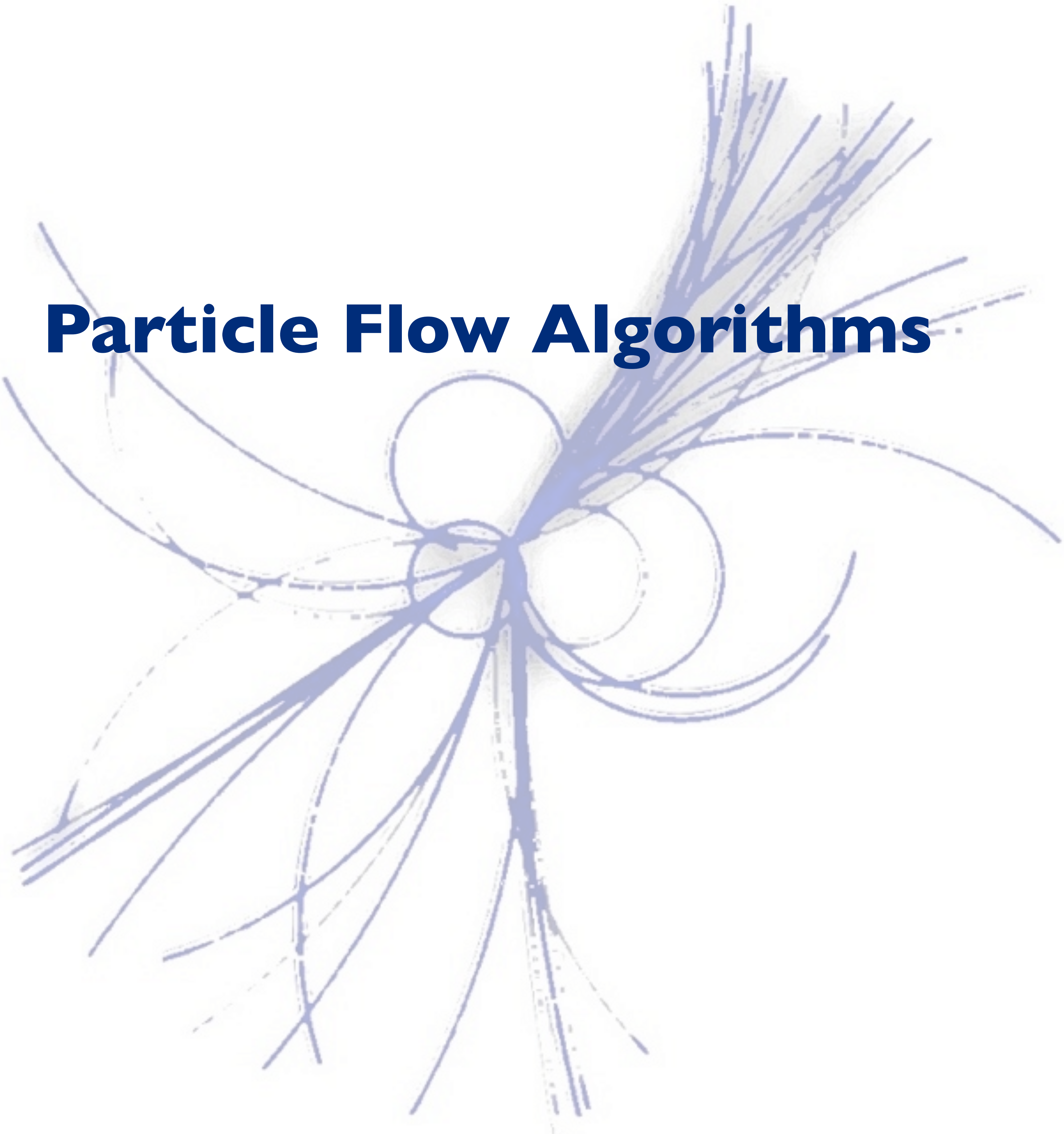
➩ Reduce the importance of the HCAL for jet reconstruction!

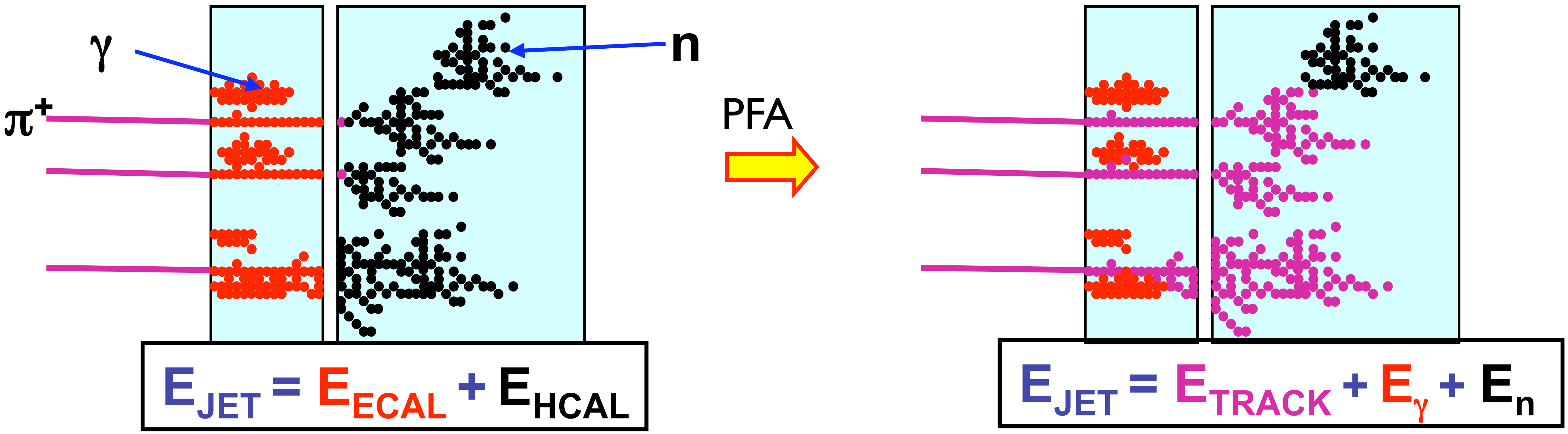


Particle Flow Algorithms



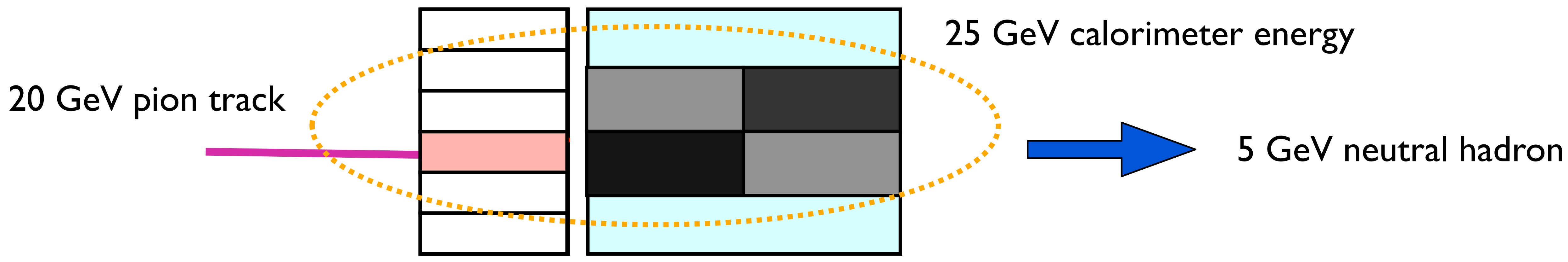
Particle Flow: A simple Idea

- Improve jet energy reconstruction by measuring each particle in the jet with best possible precision
  - Measure all charged particles in the tracker (remember, 60% charged hadrons!)
  - ▸ Significantly reduce the impact of hadron calorimeter performance: Only for neutral hadrons
  - ▸ Measure only 10% of the jet energy with the "weakest" detector: significant improvement in resolution



Energy Flow: A first Step

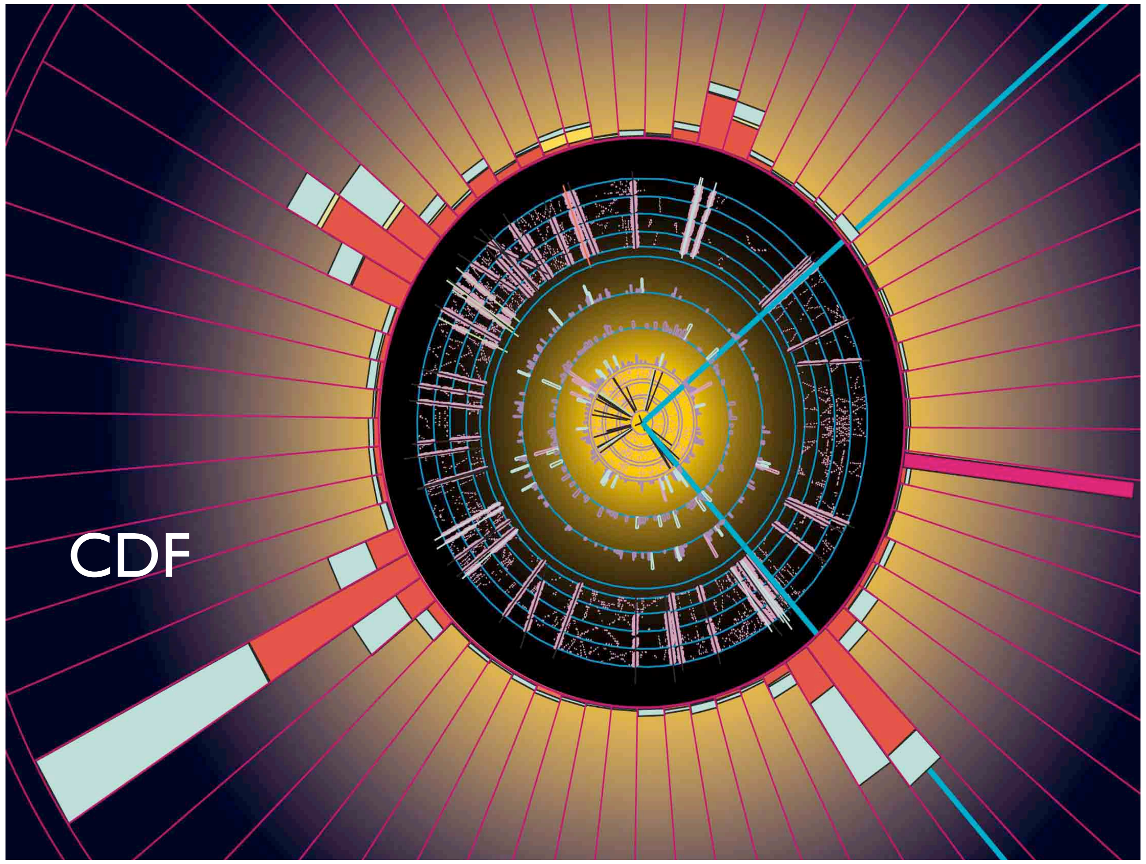
- The idea behind Particle Flow is not new:
  Energy Flow by ALEPH at LEP (NIM A360, 481 (1995))
  - Identify electrons, photons, muons - remove from calorimeter hits
  - ▸ Left with charged and neutral hadrons in the calorimeter
    - Reconstruction of neutral hadrons by subtraction



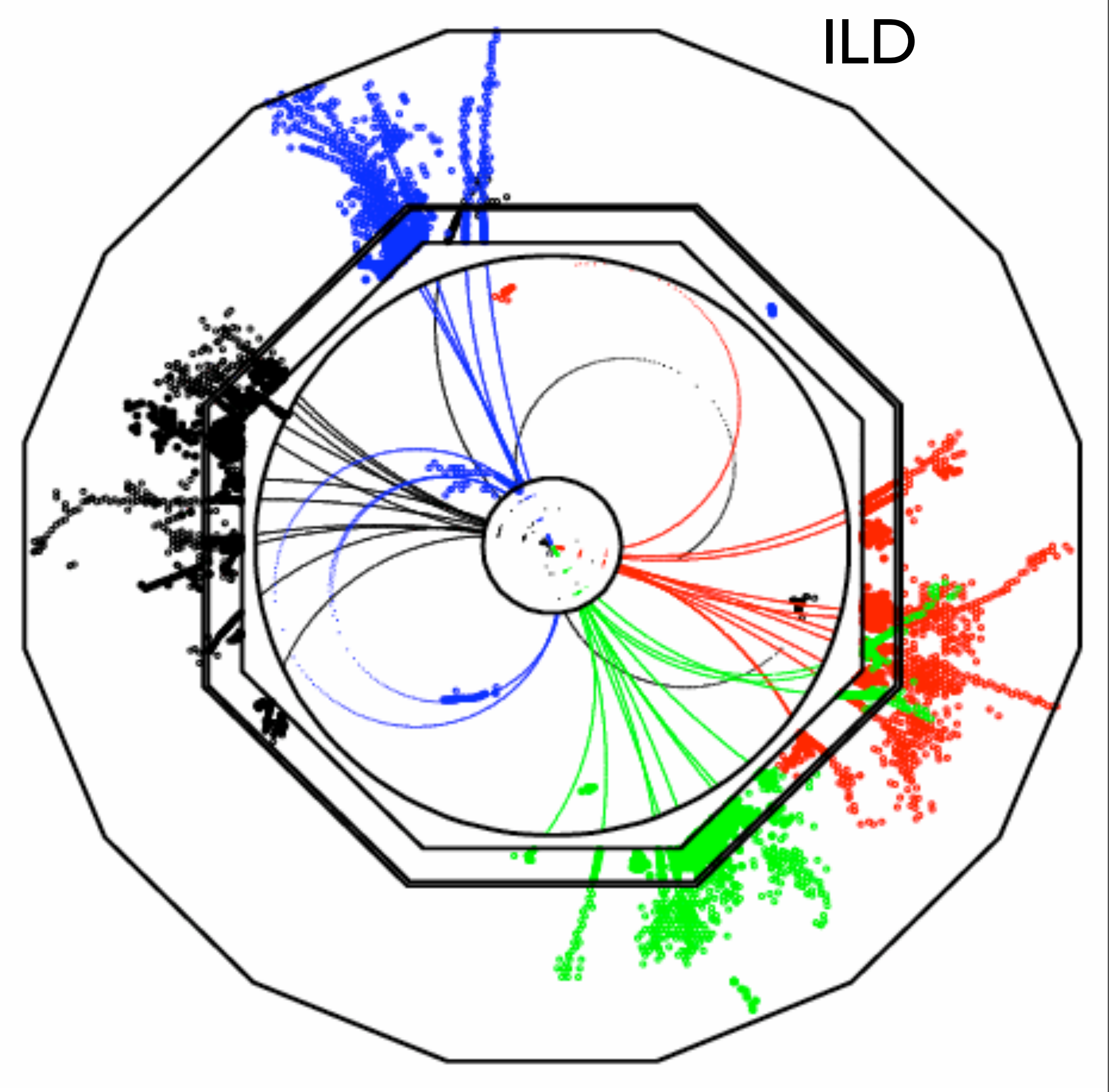
➯ Energy resolution still dominated by hadron calorimeter
(electron, photon, muon ID helps to improve jet resolution,
neutral hadron ID by subtraction does not help)

Particle Flow: Very Different Detectors

- Pushing the idea further: Identify neutral and charged hadrons in the calorimeter directly
  - Requires extremely high granularity in the calorimeters



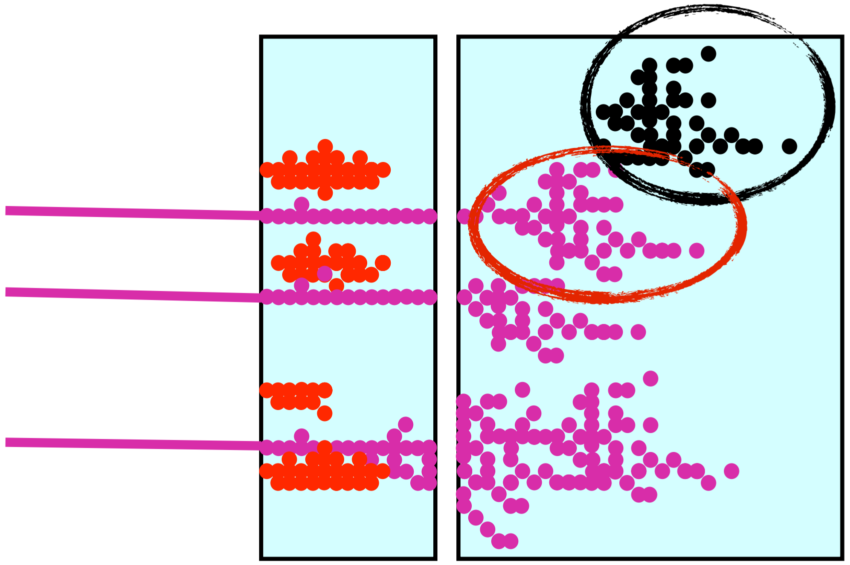
from this...



to this!

Particle Flow: A Challenging Concept

- Key issues of PFA:
  - Avoid double counting of energy
  - Separate individual particles



if **these** hits are clustered with **these**, the energy of the neutral hadron is lost: Jet energy measurement ruined

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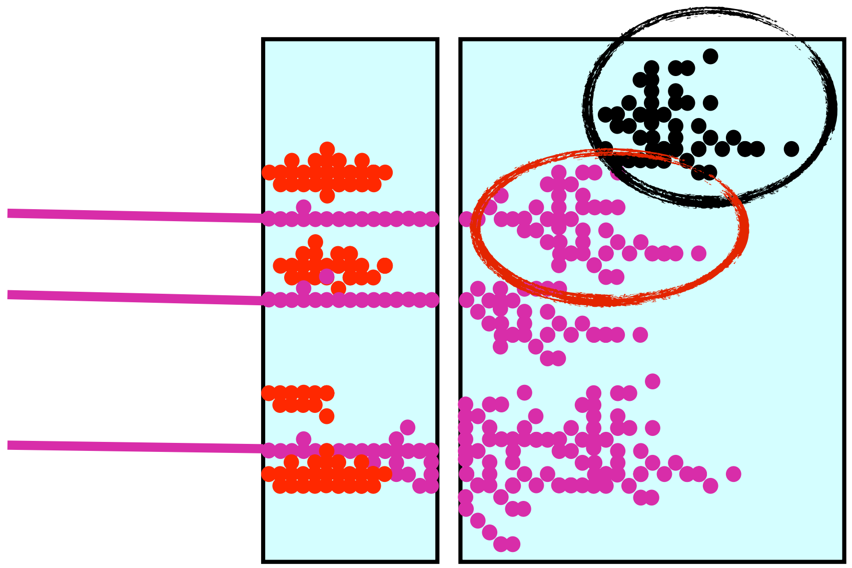

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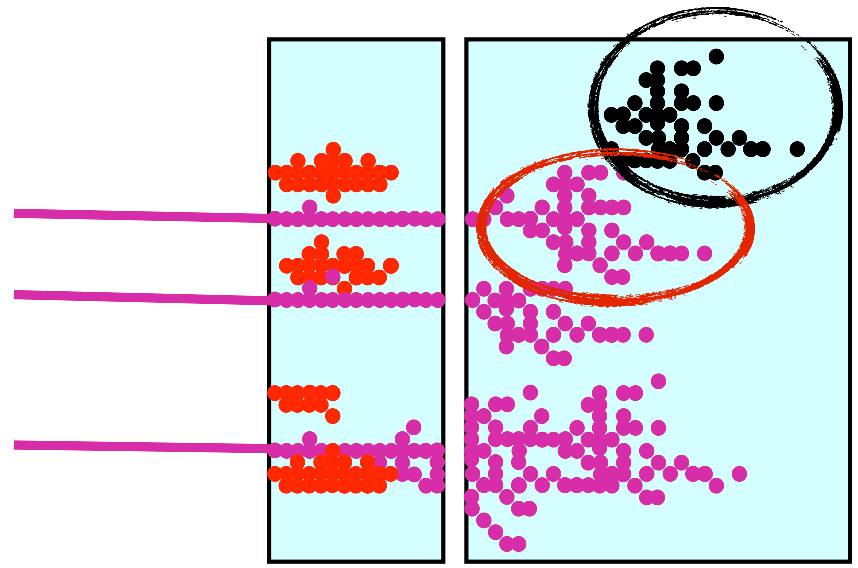

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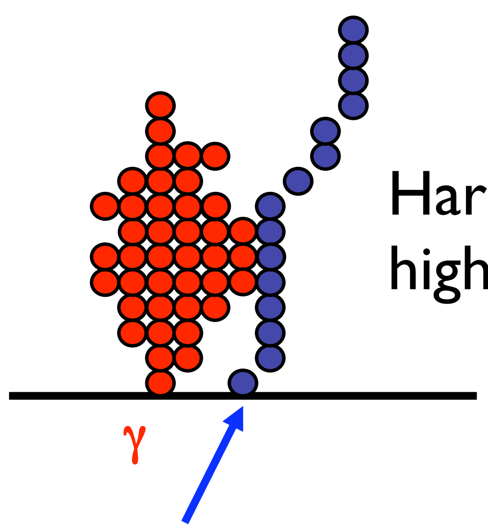
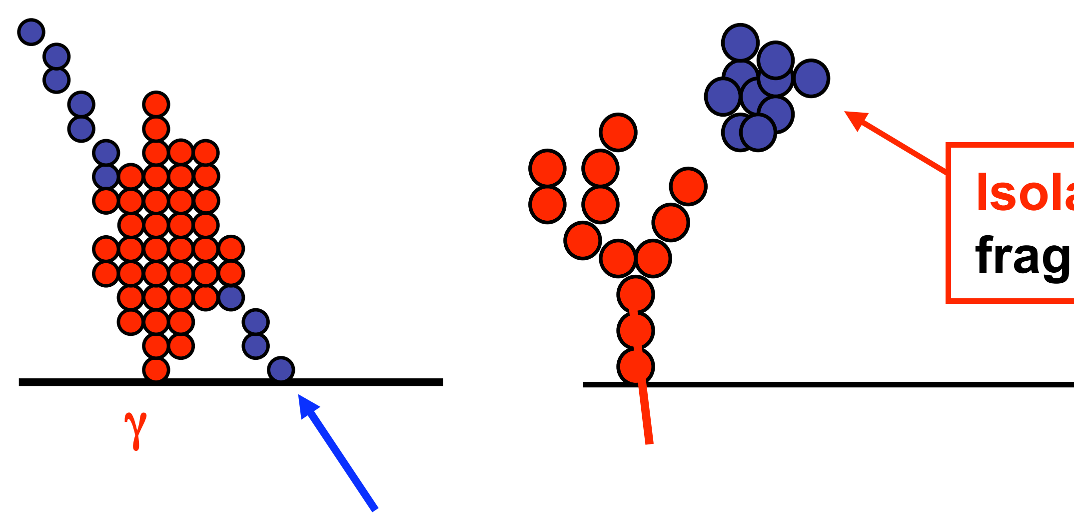
PFA Requirements:



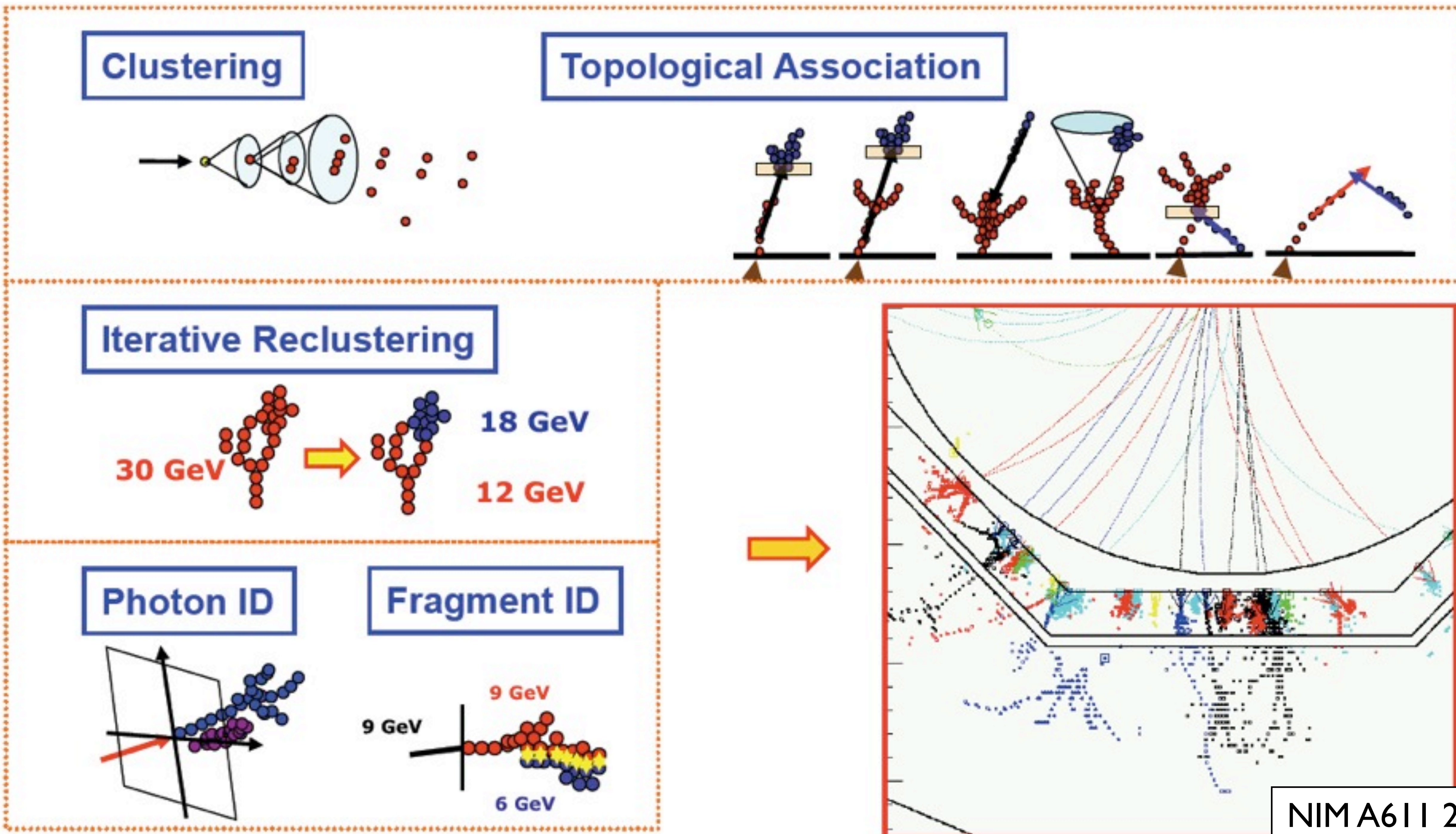
Hardware:
high granularity

Software: very sophisticated algorithms



Particle Flow Algorithms: Technology

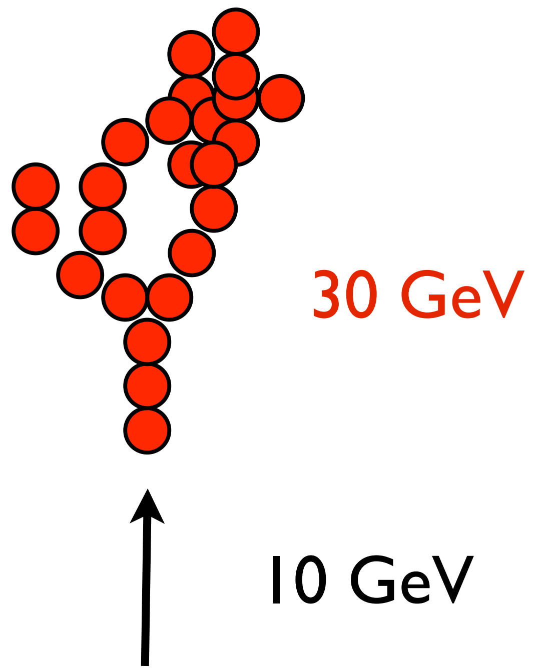
- The most performant PFA at present: PandoraPFA (Mark Thomson, Cambridge)
  - highly complex software package



NIM A611 24, 2009

PFA Technology: One Example

- Iterative reclustering: Pushing the PFA Concept further
  - In a high-density environment (e.g. high-energy jet), pure PFA hits limits: Showers can not be clearly separated
  - Use consistency of track momentum and shower energy to guide the clustering: recluster if energies are inconsistent



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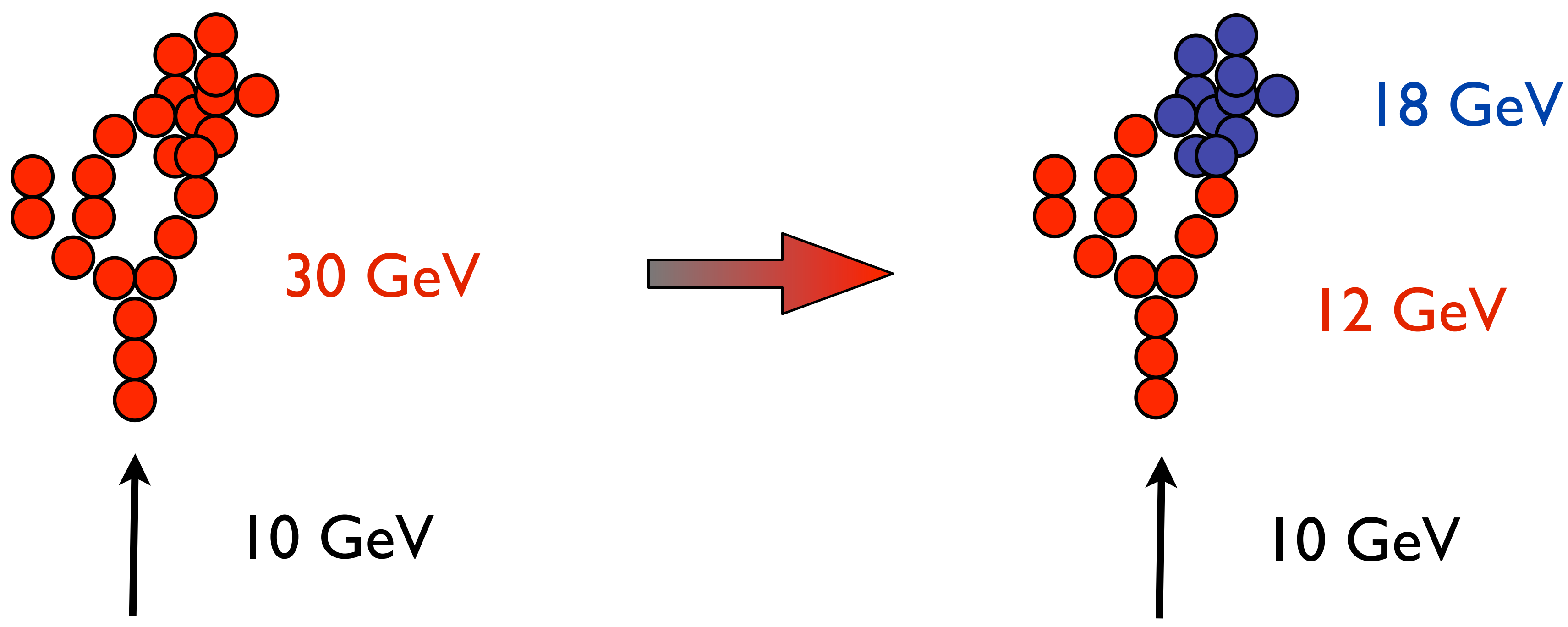
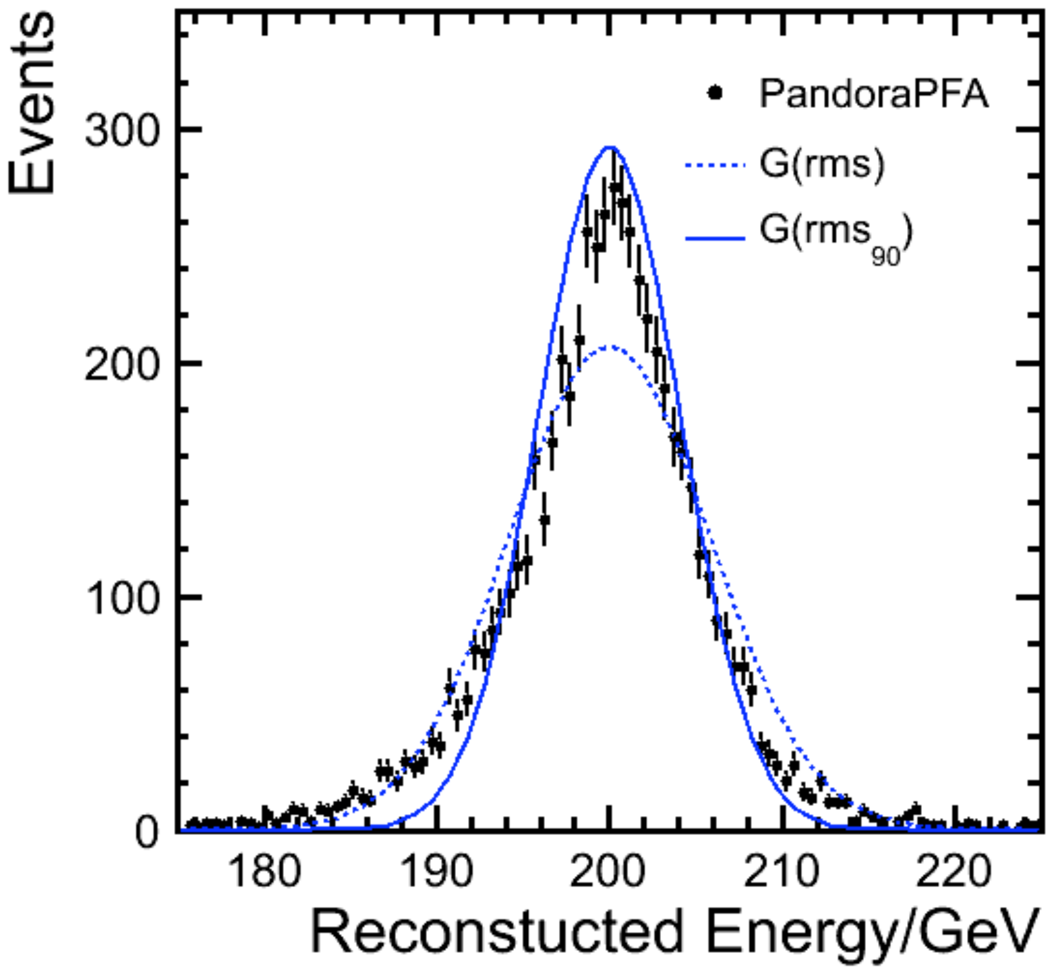


➫ much more powerful than subtraction or one-stage clustering

Particle Flow Performance

- Detailed studies with PandoraPFA have been performed for the ILD detector concept

Resolution is given as RMS_{90}, the RMS of the 90% most central events:
PFA is inherently non-gaussian (driven by confusion): narrow core, wide tails
In terms of analyzing power: $RMS_{90} \sim 0.9\ \sigma_{Gauss}$



E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
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For 45 GeV: Factor 3 better than LEP best (ALEPH)!

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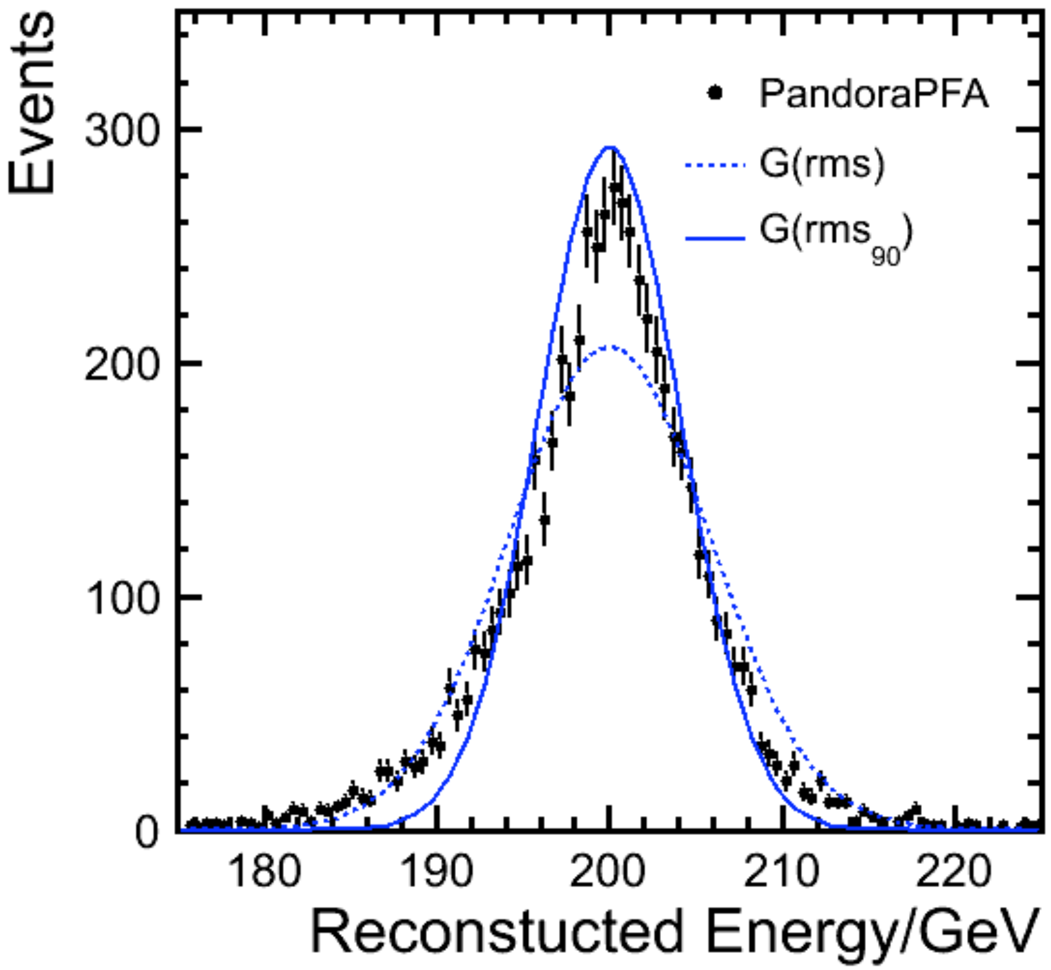

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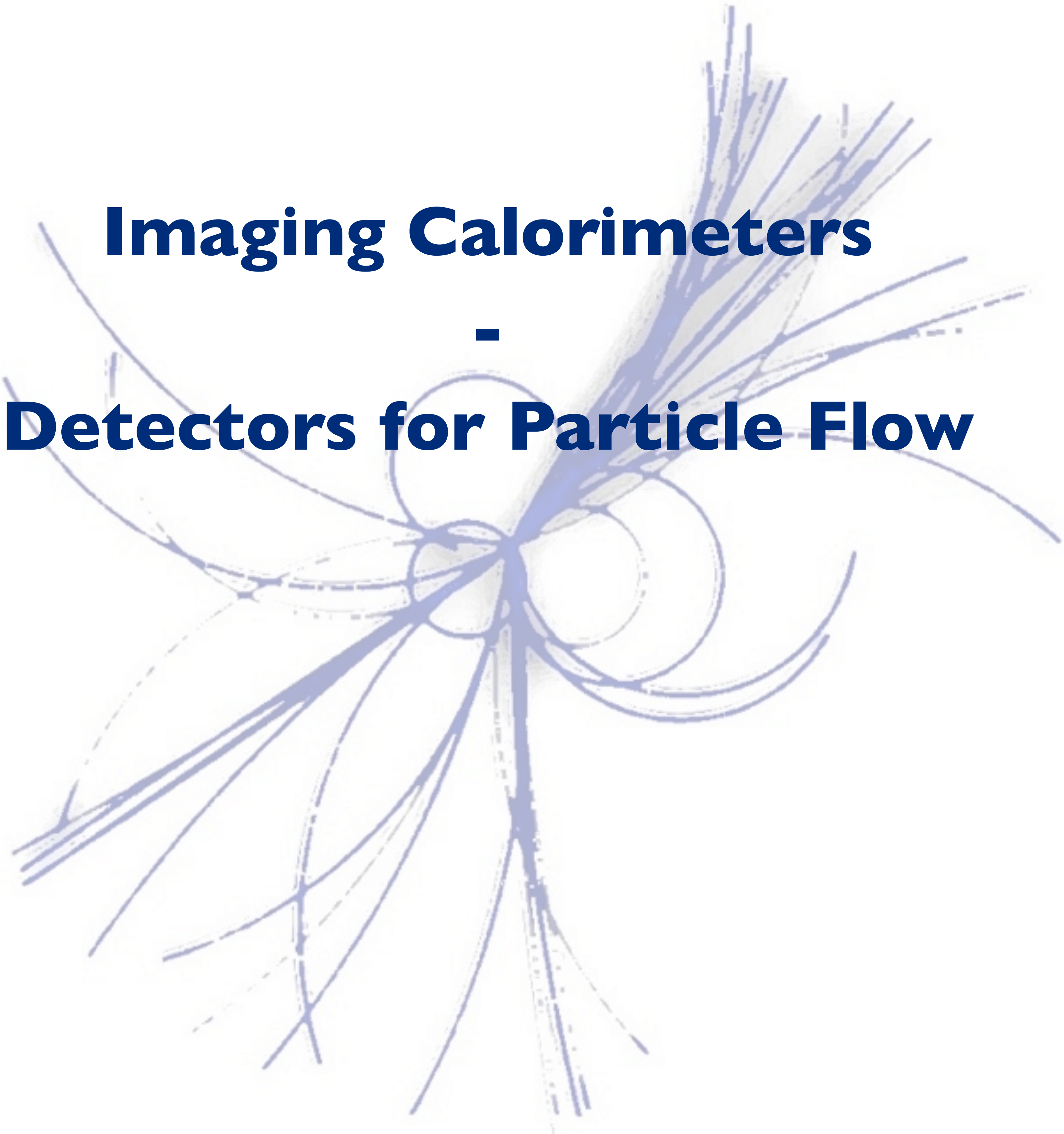
➾ PFA delivers unprecedented jet energy resolution: Requirements for a Linear Collider are met!

Imaging Calorimeters
-
Detectors for Particle Flow



Imaging Calorimeters

- Particle Flow needs extreme granularity:
  - Electromagnetic Calorimeter
    - Small Moliere radius for shower separation: Tungsten absorber
    - Imaging capabilities: Read each layer separately, pads on each layer < Moliere radius: ~ 5 x 5 mm^2
  - Hadronic Calorimeter
    - Steel or Tungsten absorber (Tungsten to limit leakage for high energy jets)
    - Imaging capabilities: Read each layer separately (sampling ~ 1 X_0 to retain resolution for em subshowers), small cells: 3 x 3 cm^2

- Explosion of the channel count!
  - ILD: ~100 M channels in ECAL, ~10 M channels in the HCAL
  - Compare to LHC: CMS ECAL: 76 k channels, ATLAS HCAL: ~10 k channels

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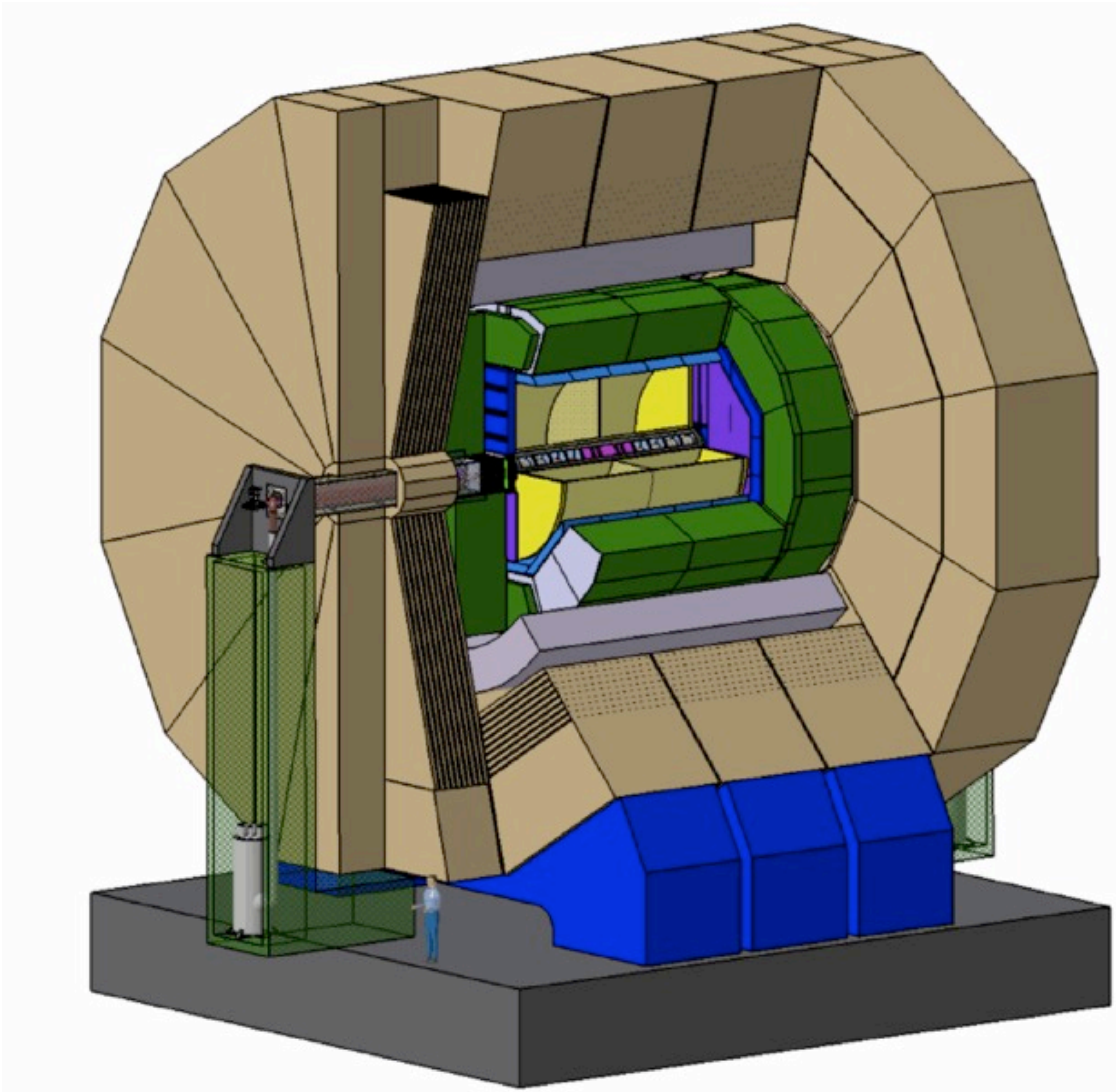
About a factor of 1000 more channels: A totally different calorimeter technology!

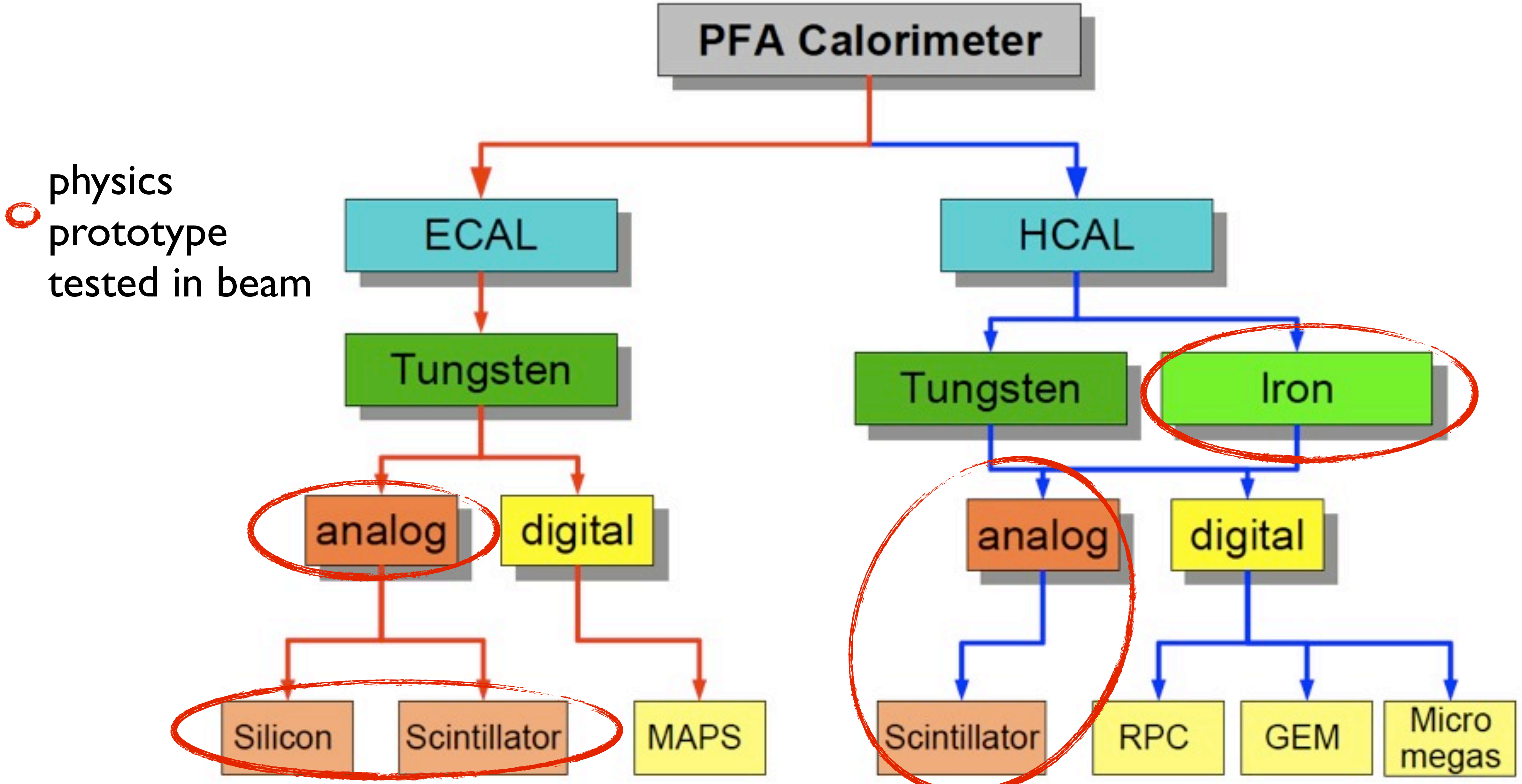
ILD: Concept of a PFA Detector for the ILC



- Typical collider detector:
  - Vertex detector
  - Large-volume tracking: TPC
  - Calorimetry (em & had)
    - Silicon-Tungsten ECAL
    - Scintillator-Iron HCAL
  - Muon tracking

CALICE: Proving the PFA Calorimetry Concept

- Global Collaboration: ~330 Scientists from 57 Institutions in 17 countries on 4 continents
- The goal: Study different technologies for PFA calorimetry



Imaging HCAL: Technological Basis

- How do you increase the granularity (e.g. the number of channels) of a scintillator sampling calorimeter by 3 orders of magnitude?

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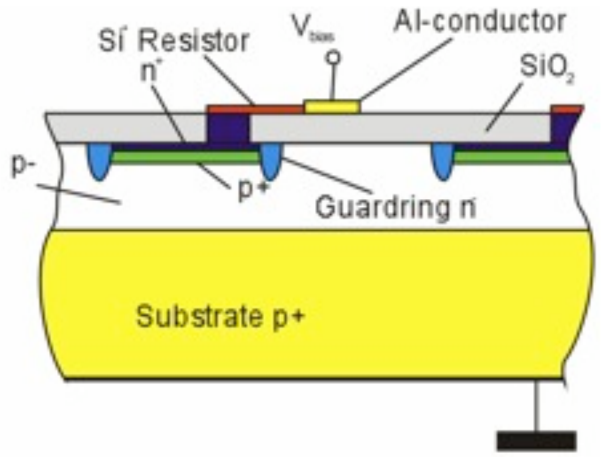
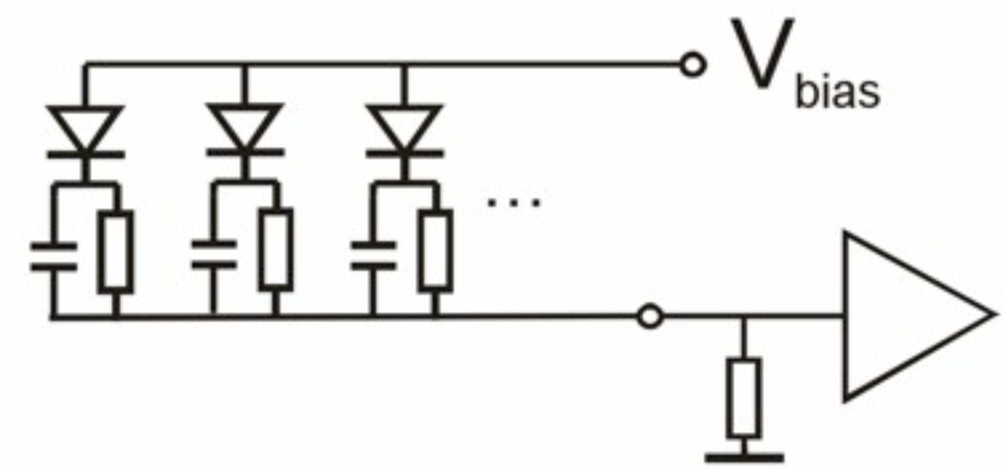
N x





Gain ~ 10^6
counting of single photons is possible

Frank Simon (frank.simon@universe-cluster.de)

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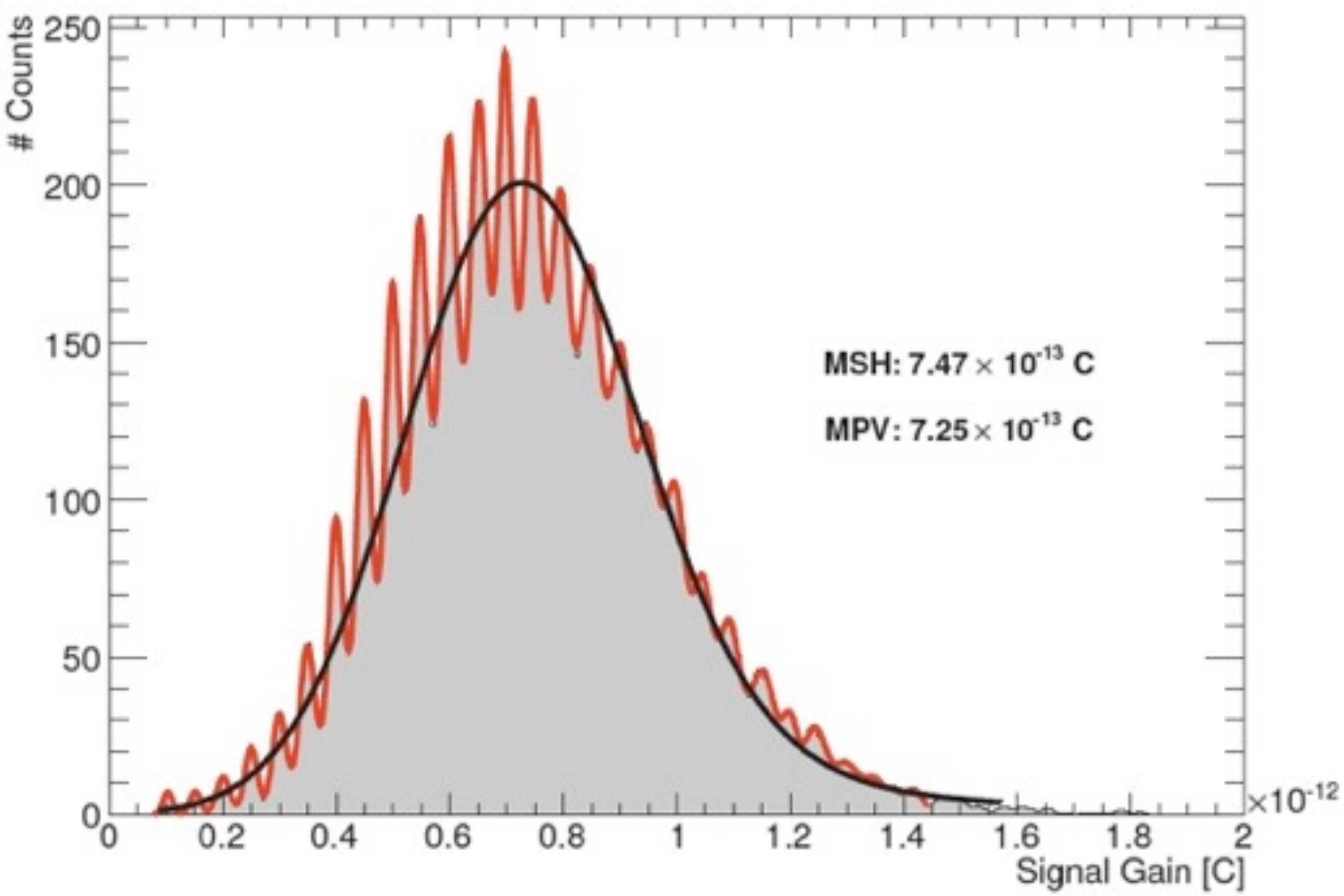
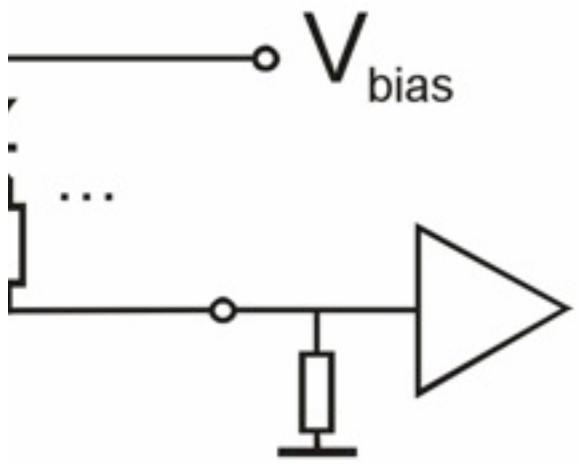


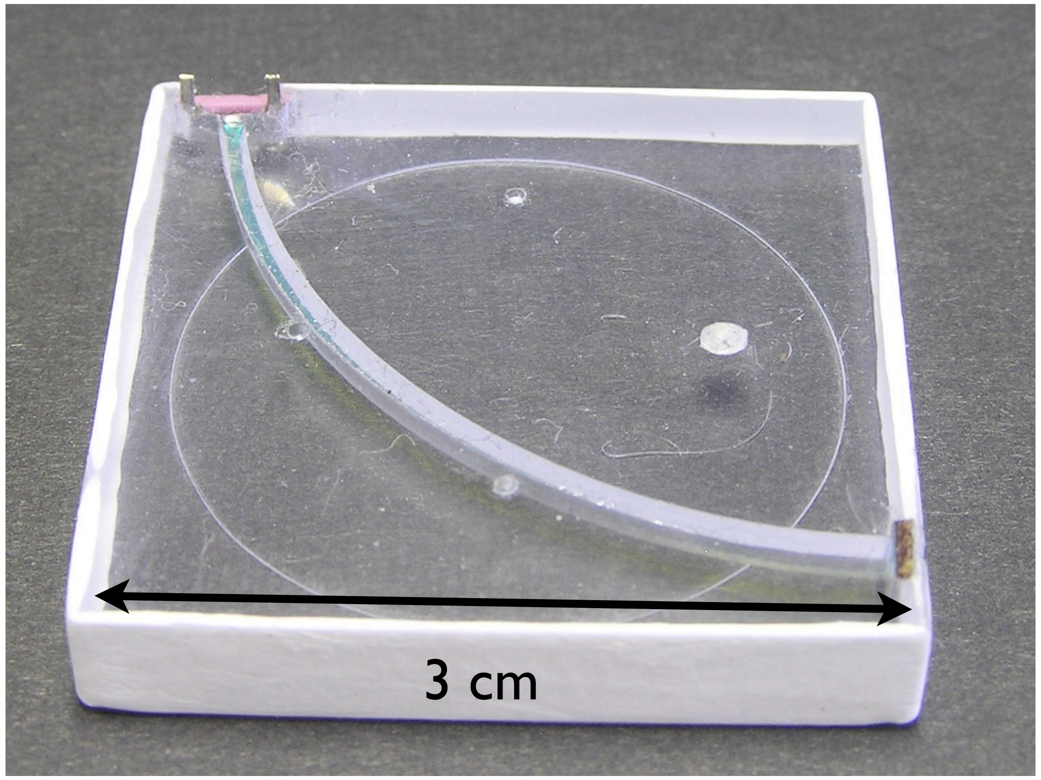


Gain ~ 10^6
counting of single photons is possible

scintillator read out with a SiPM

Analog HCAL: Active Elements

- The unit: scintillator tile with SiPM



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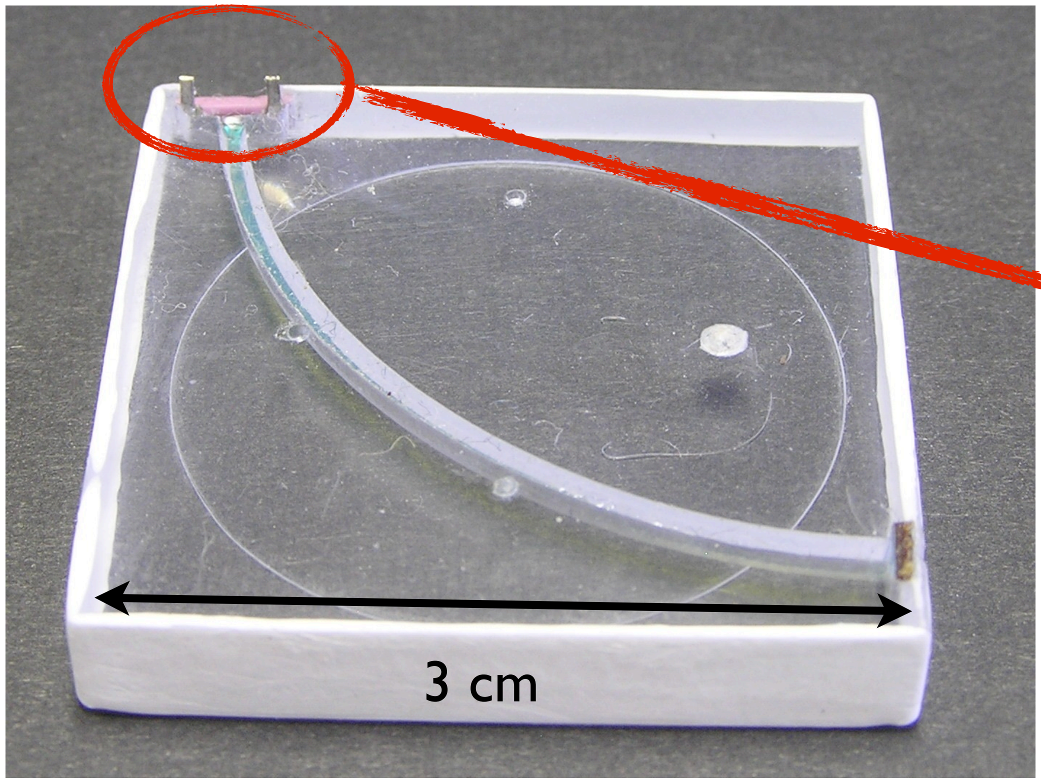
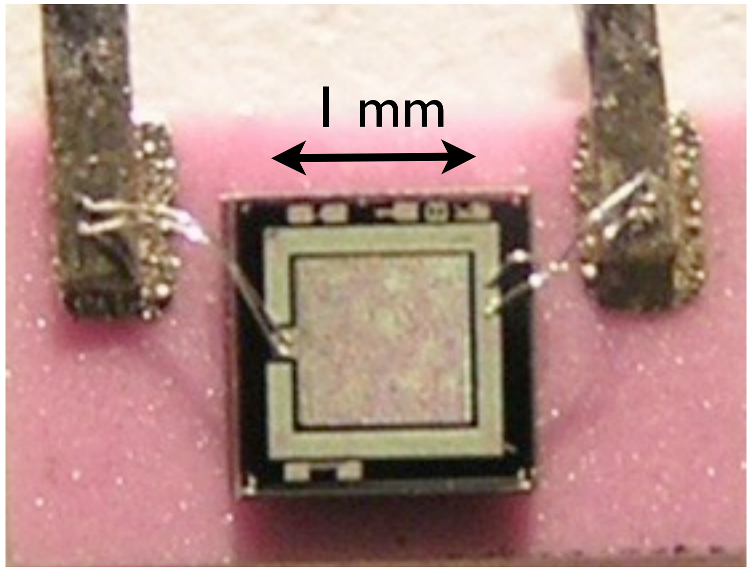


- SiPM: 1156 pixels, manufactured by MePhI/PULSAR



Maximum efficiency in green spectral range: Wavelength shifting fiber to collect and shift blue scintillation light

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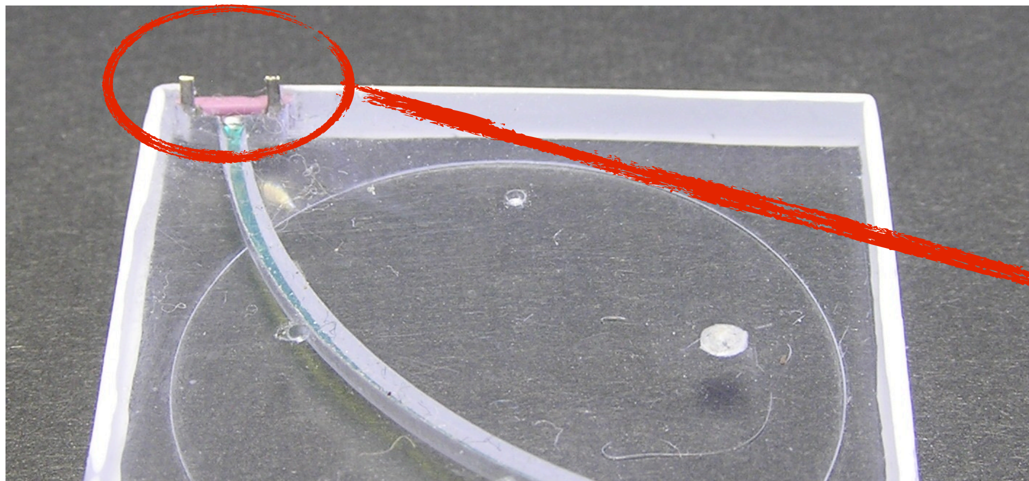

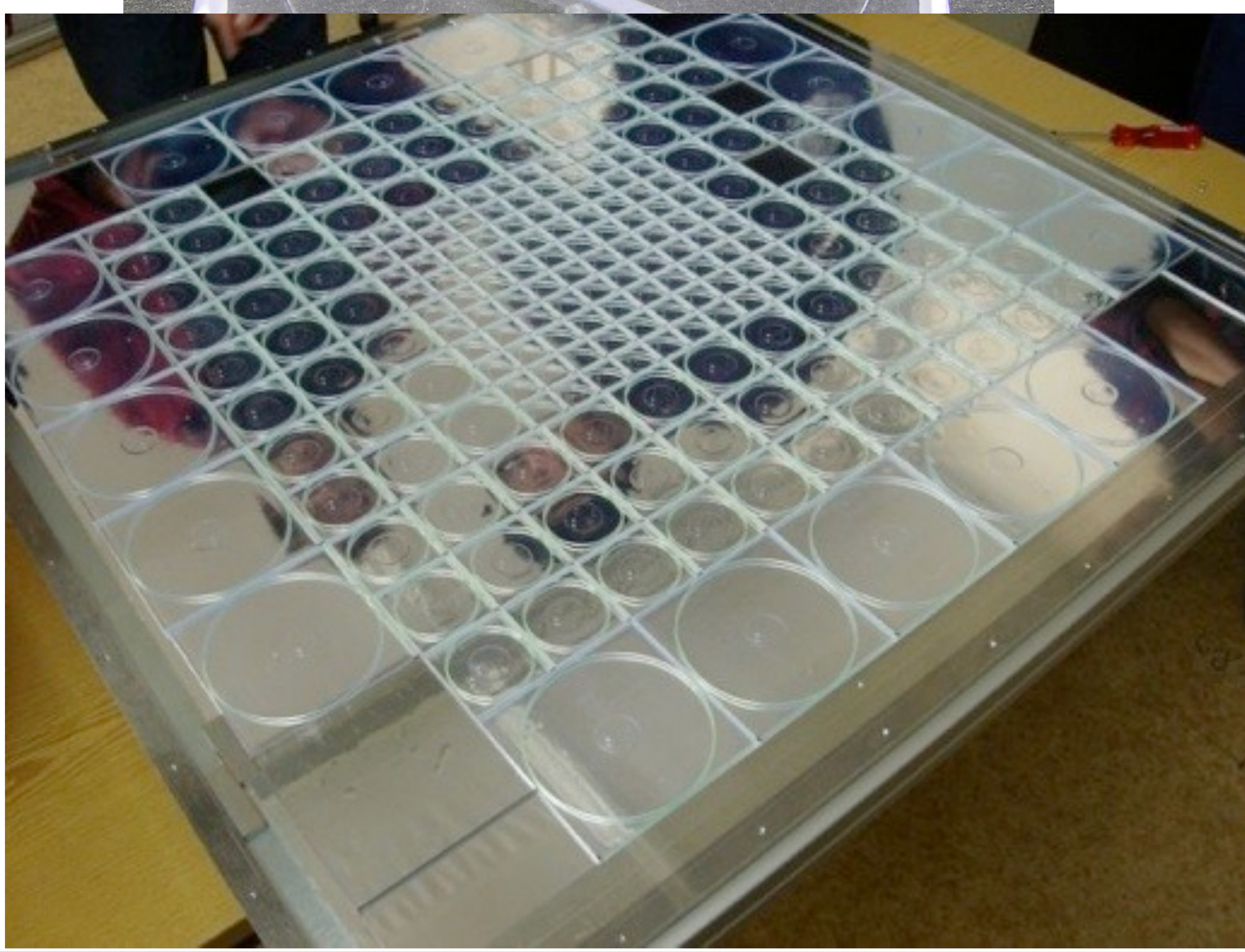

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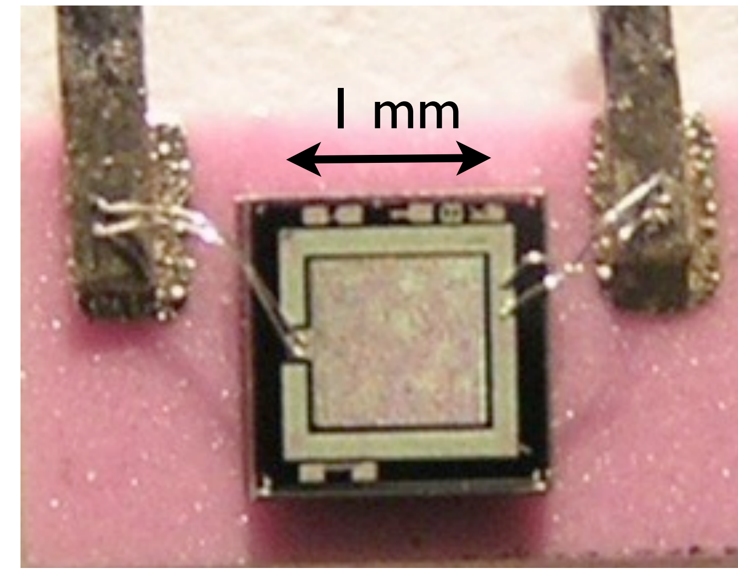
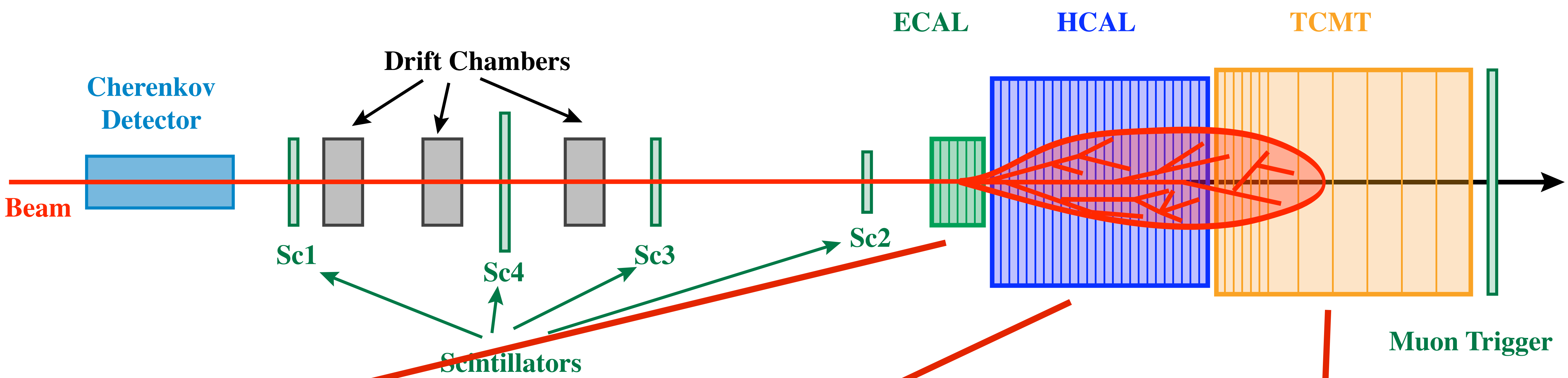
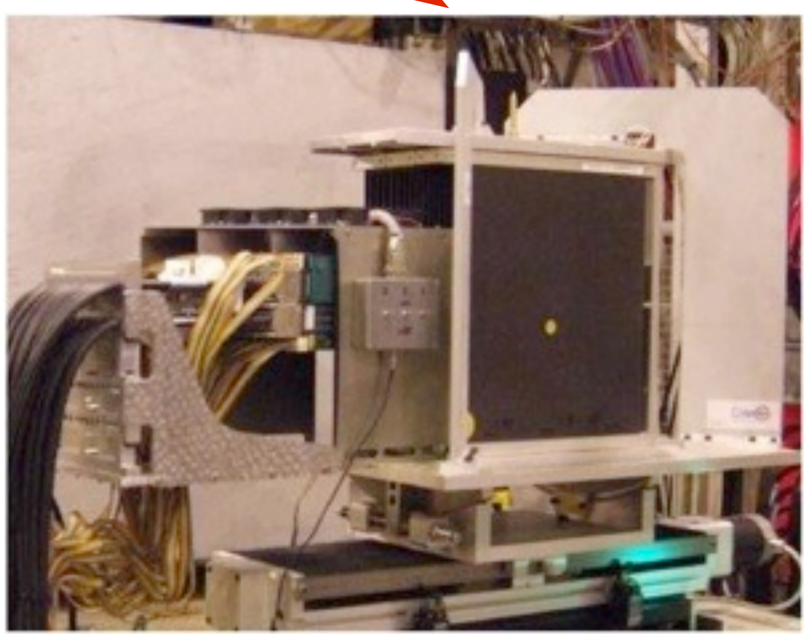


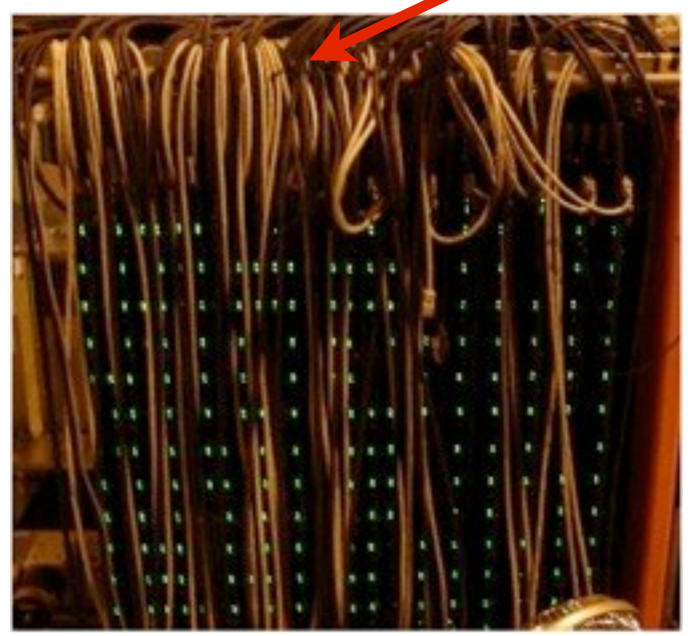
ximum efficiency in green spectral range: velength shifting fiber to collect and shift e scintillation light

- Active layers: 90 x 90 cm^2
  212 scintillator tiles (100 in high granular core)

CALICE: Putting it all together





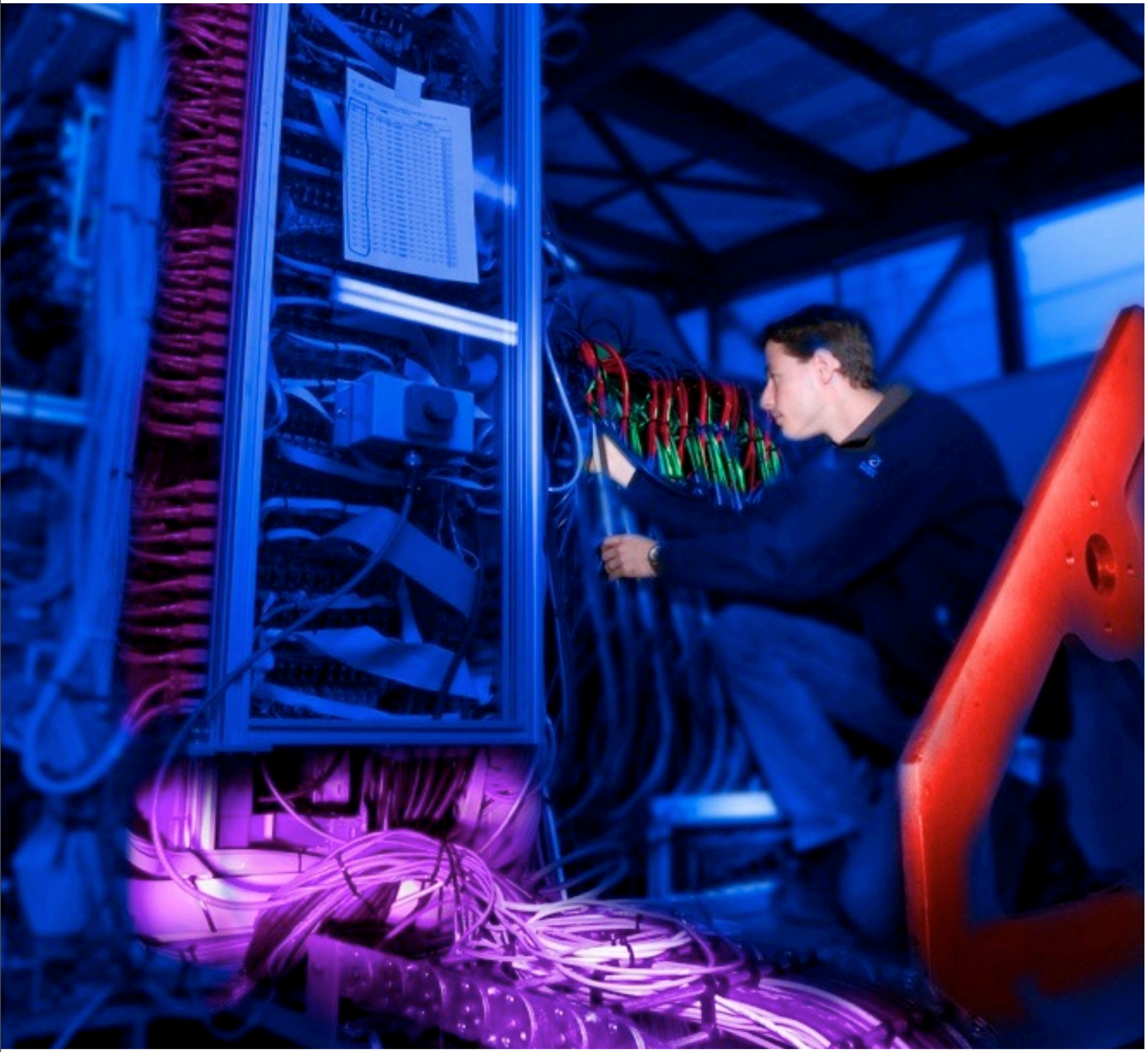


Si-W ECAL
1x1 cm^2 lateral segmentation
30 layers, ~ 0.9 λ, 30 X_0
~ 10 k channels

Analog HCAL
3x3 - 12x12 cm^2 lateral segmentation
38 layers, ~ 5.3 λ
~ 8 k channels

Tail Catcher / Muon Tracker
5 x 100 cm^2 Scintillator Strips
16 layers
~ 300 channels

Extensive Test Beam Campaign

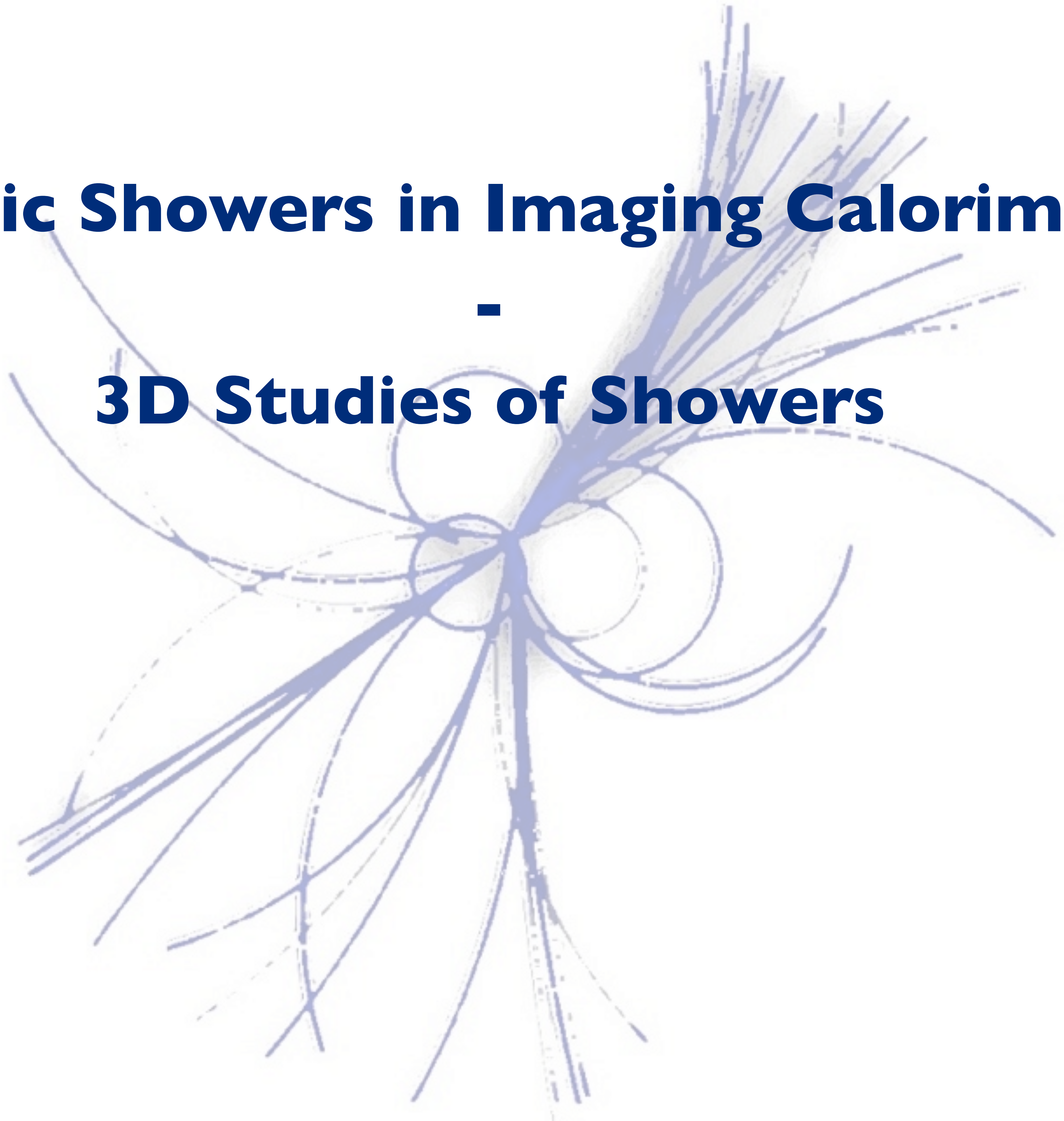


- Beam tests at
  - DESY 2006
  - CERN 2006, 2007
  - FNAL 2008, 2009
- Electrons, Muons, Hadrons in a wide energy range: 1 GeV - 80 GeV

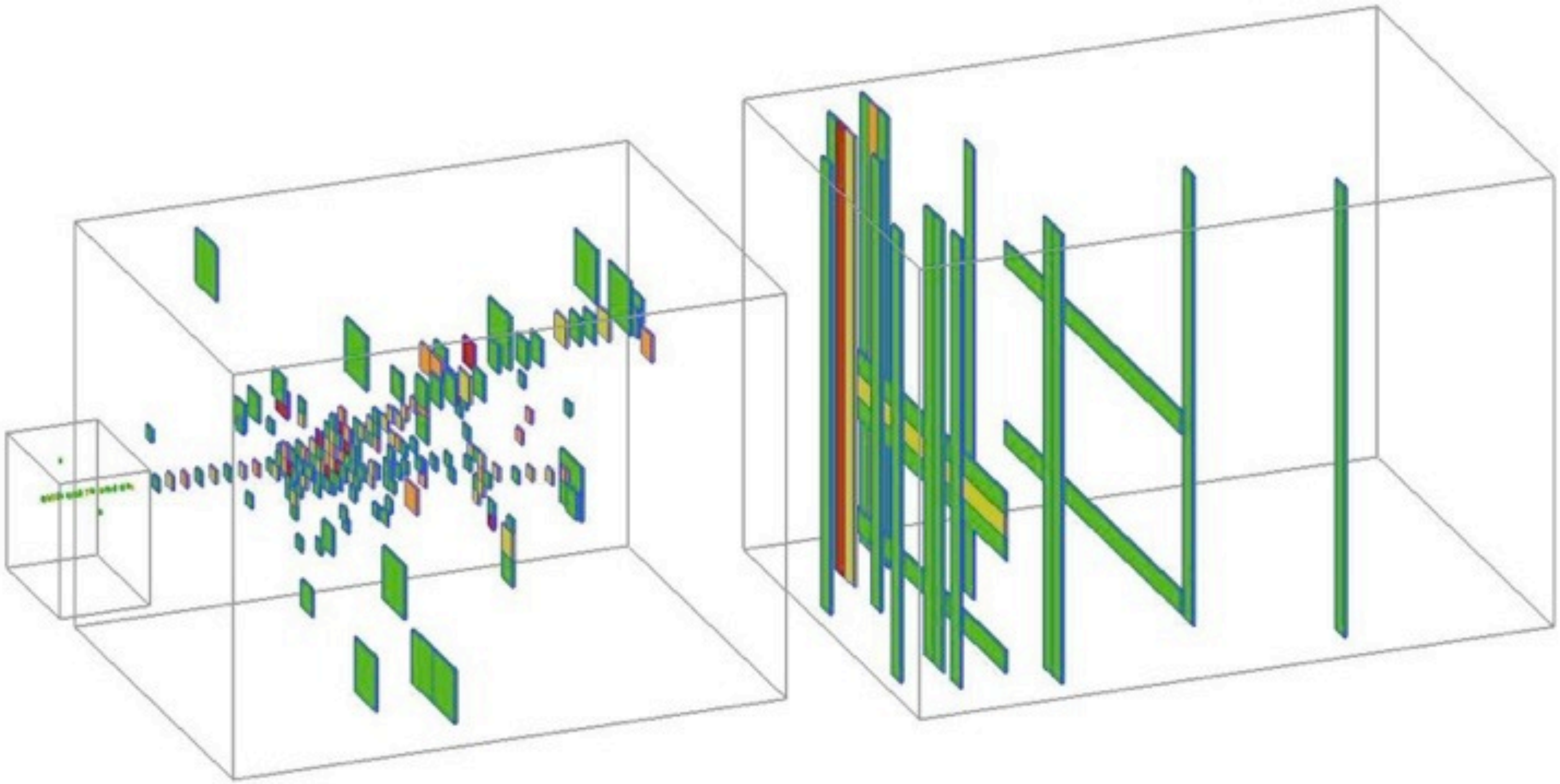
Hadronic Showers in Imaging Calorimeters

-

3D Studies of Showers



Detailed 3D Images of Particle Showers



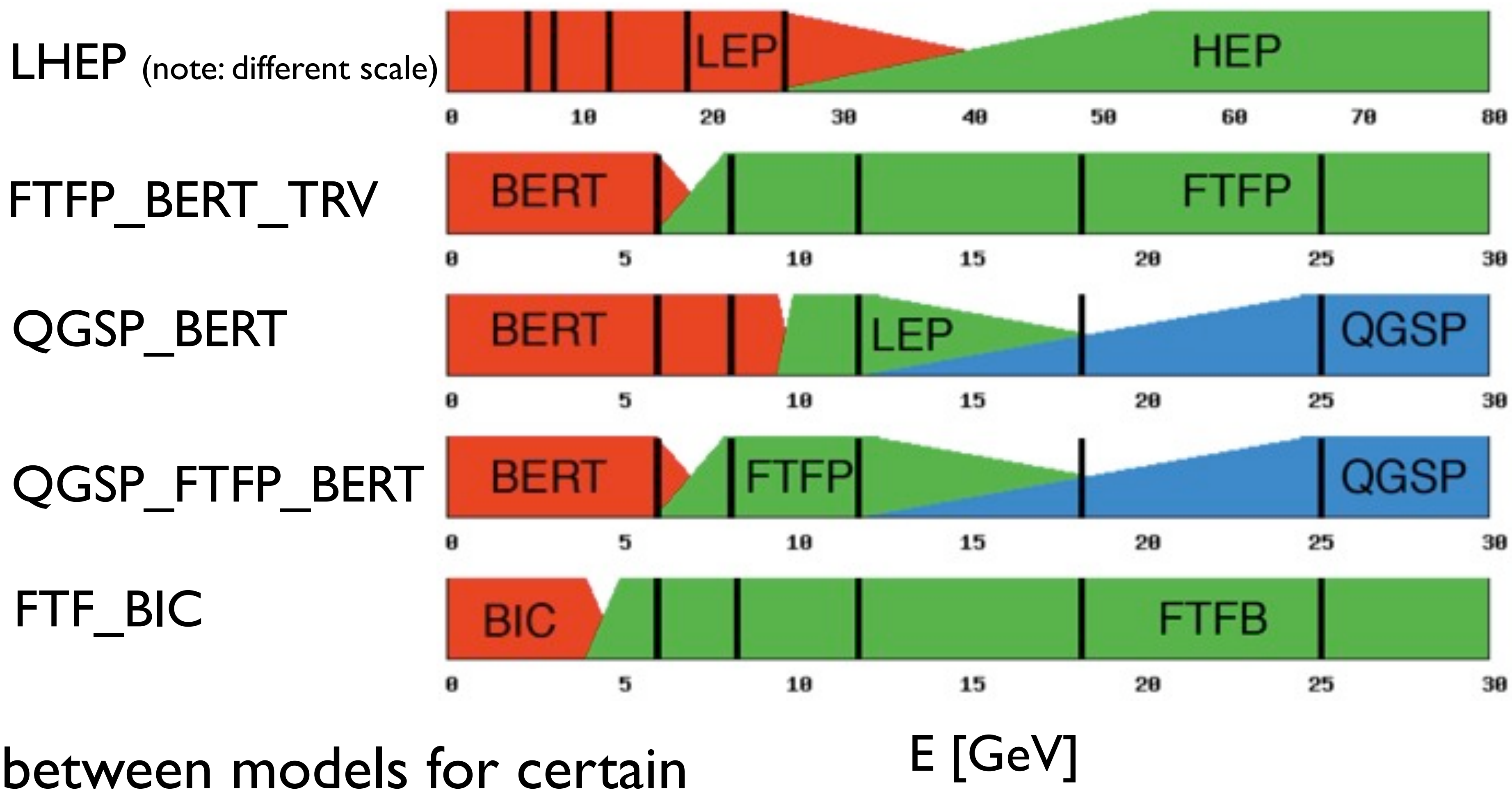
- Study hadronic showers in a realistic detector in great detail
  - Provide input for next-generation detectors
  - Validate shower simulations
    - Crucial to establish the reliability of PFA simulation studies
    - Further improve shower modeling in GEANT4

Detector Simulations: GEANT4

- A detailed model of the CALICE test beam setup is implemented in GEANT4
  - Includes absorbers, cassette material, electronics, scintillator, beam line instrumentation, ...
  - Digitization: Inclusion of noise from data, modeling of light collection, saturation behavior of SiPM, ...

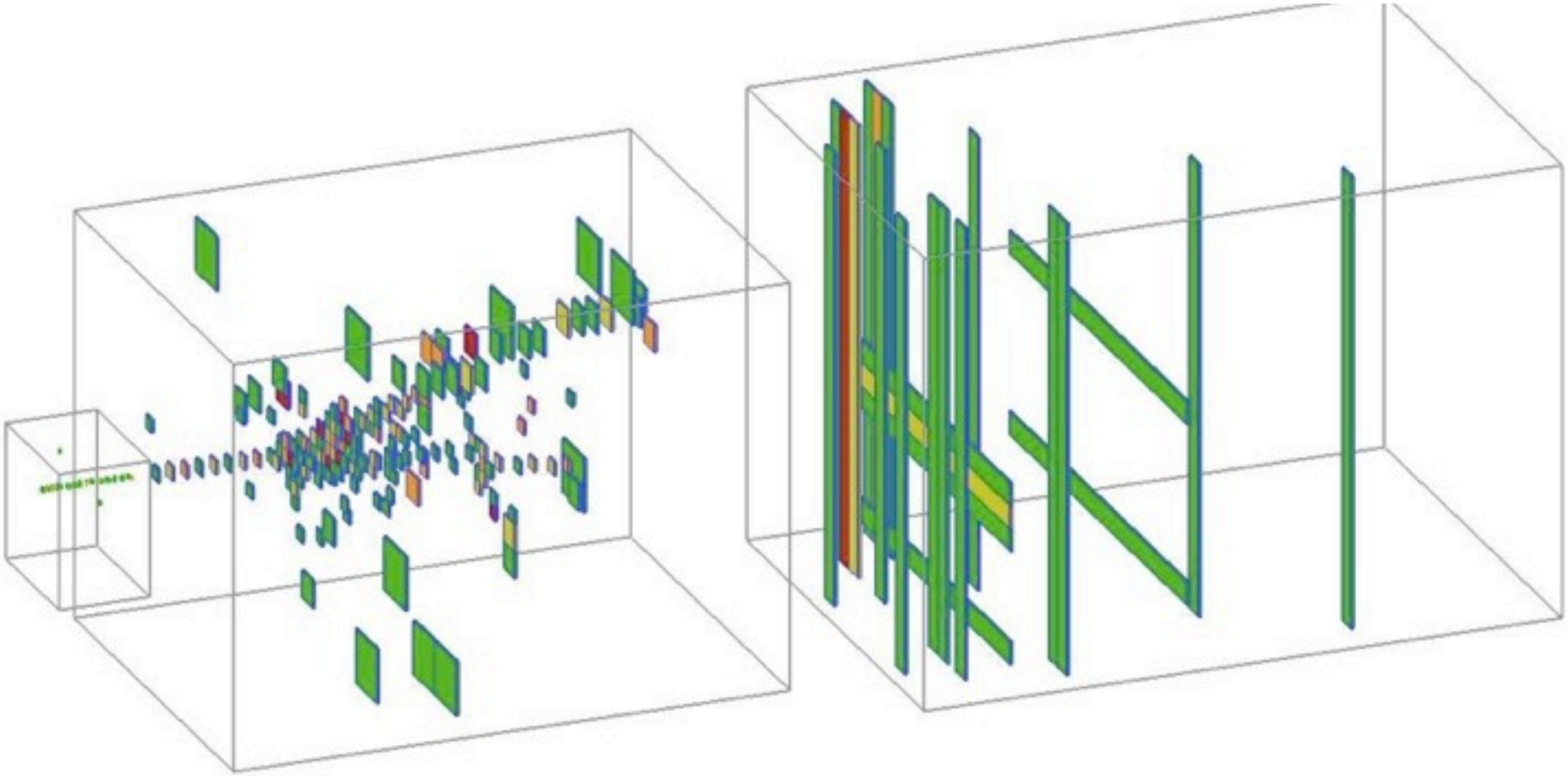
Different "Physics Lists":

Model used to describe hadronic shower depends on particle energy, combination of different models to achieve best description



➾ Significant differences between models for certain observables, data can provide answers!

Shower Studies: Things to look for



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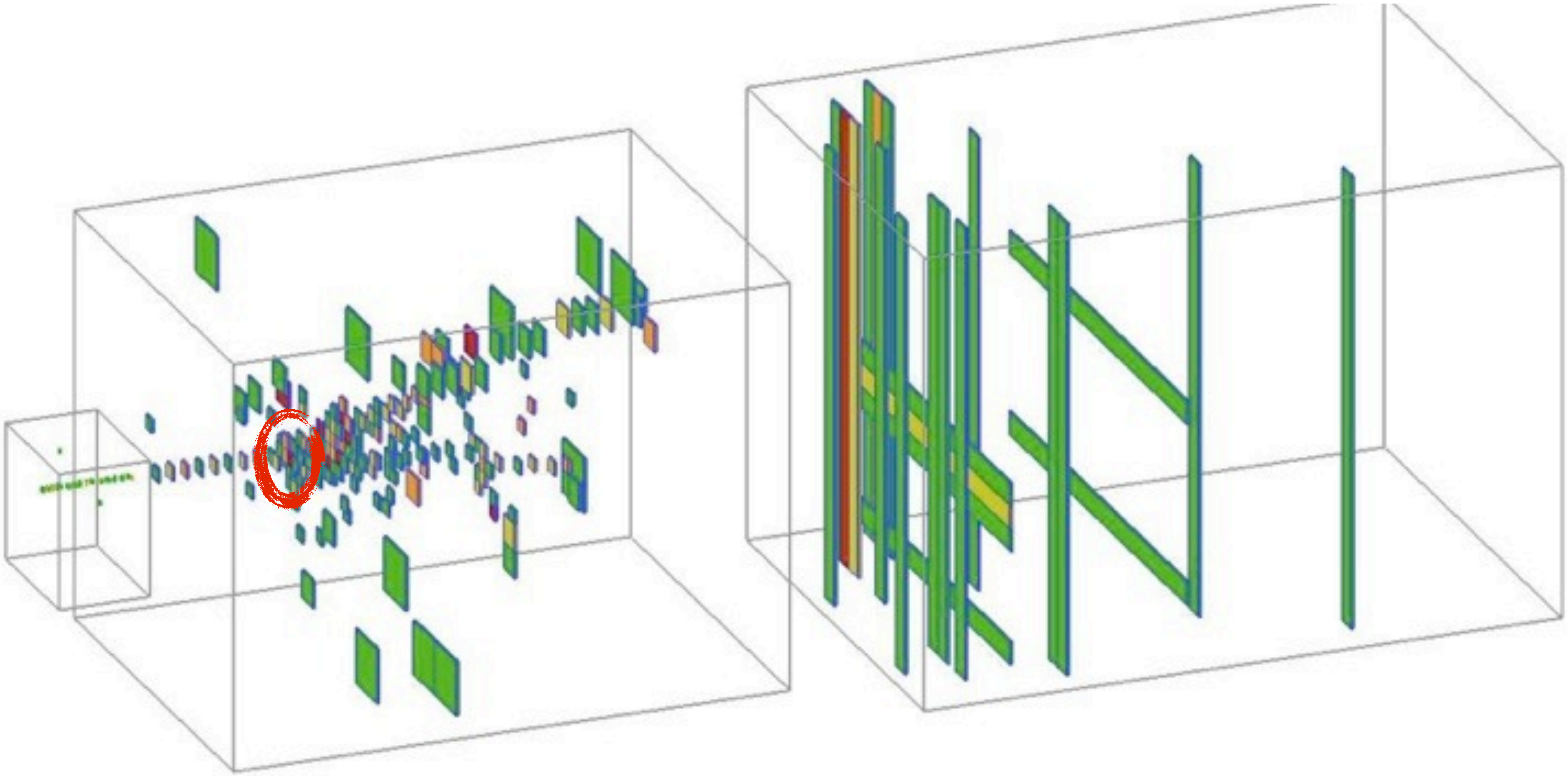
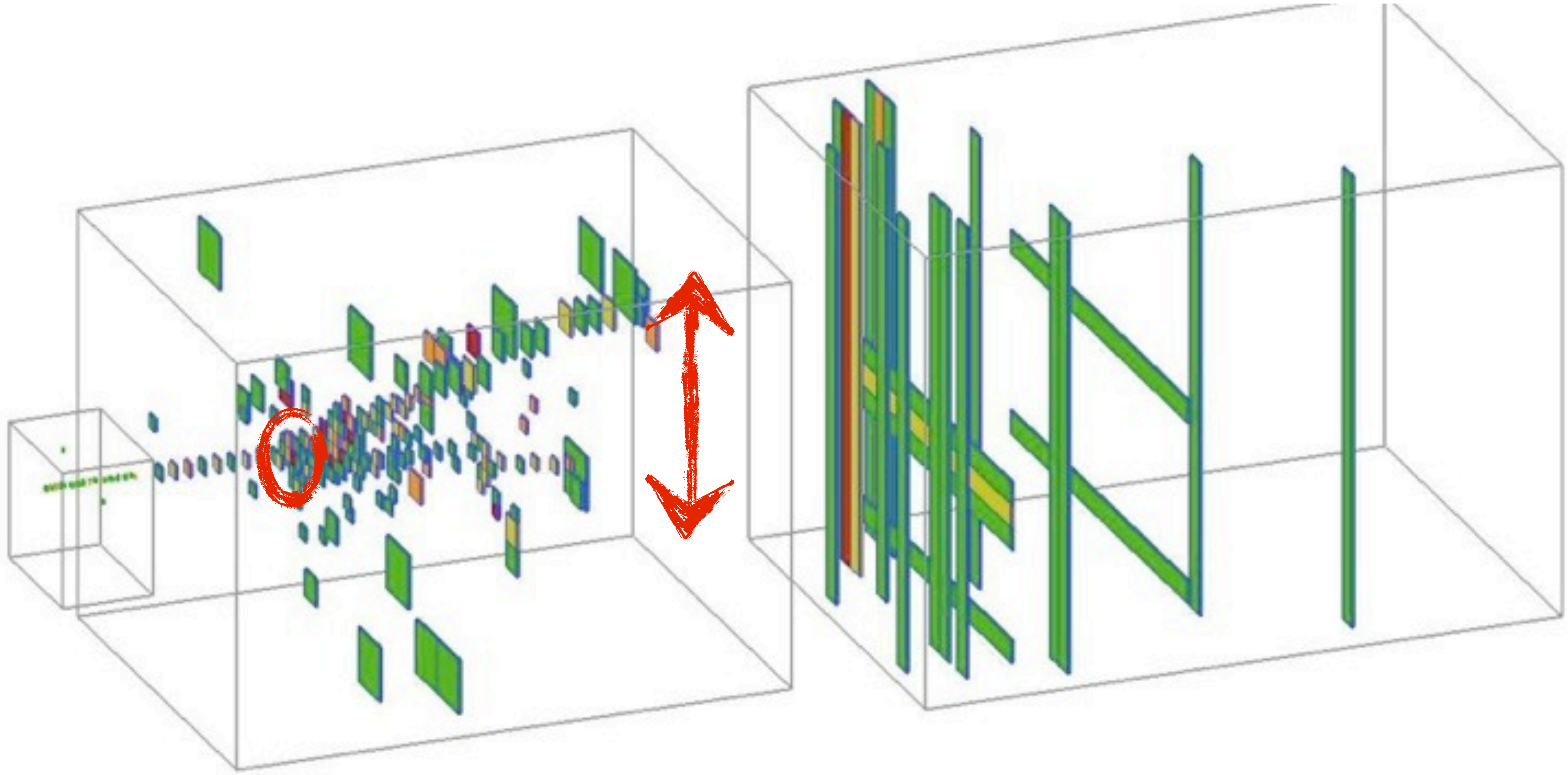


➫ Shower start point: Study shower properties without fluctuations of initial interaction

Shower Studies: Things to look for



- ➯ Shower start point: Study shower properties without fluctuations of initial interaction
- ➯ Transverse shower profile: Crucial for shower separation in PFA

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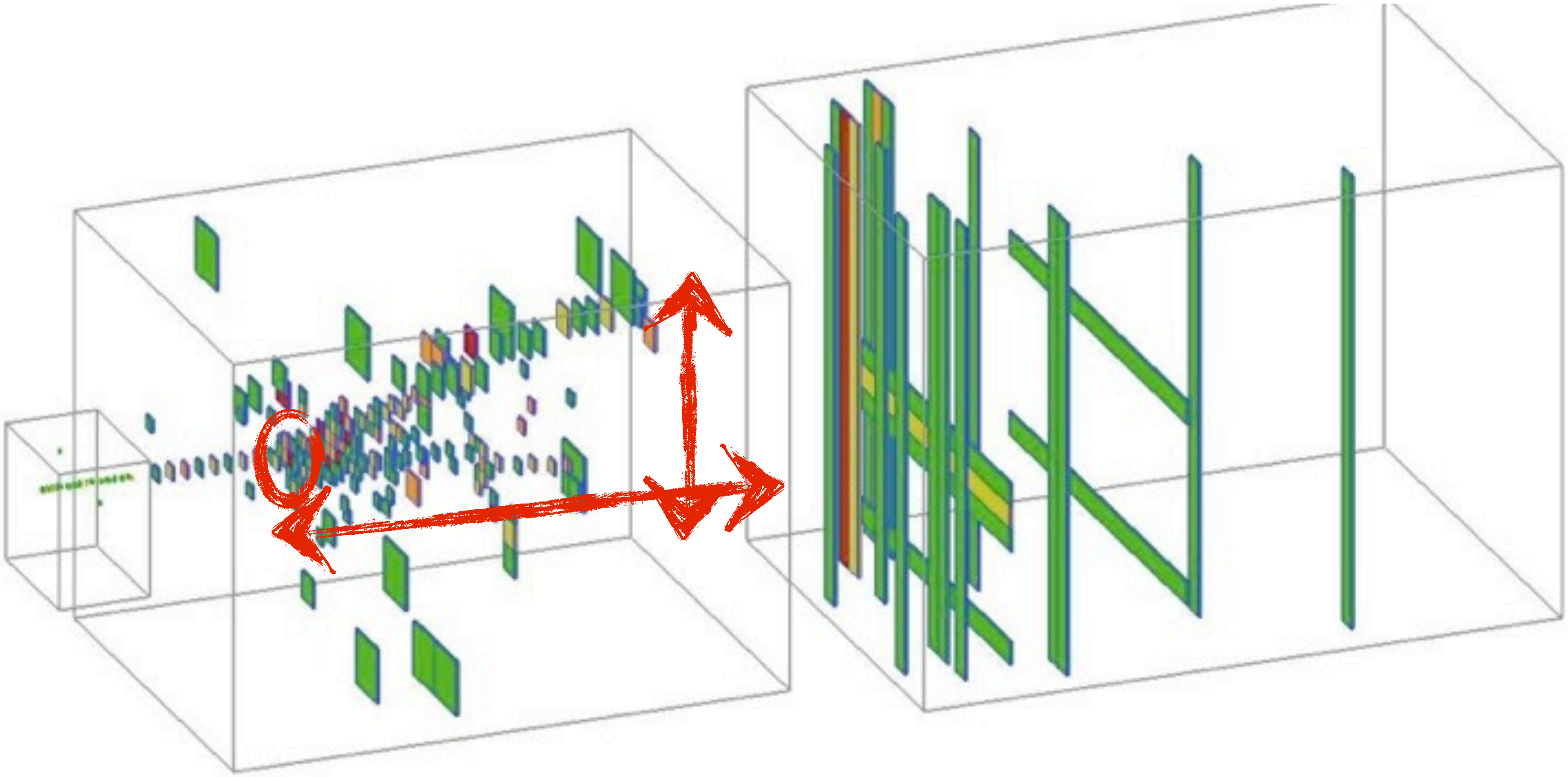

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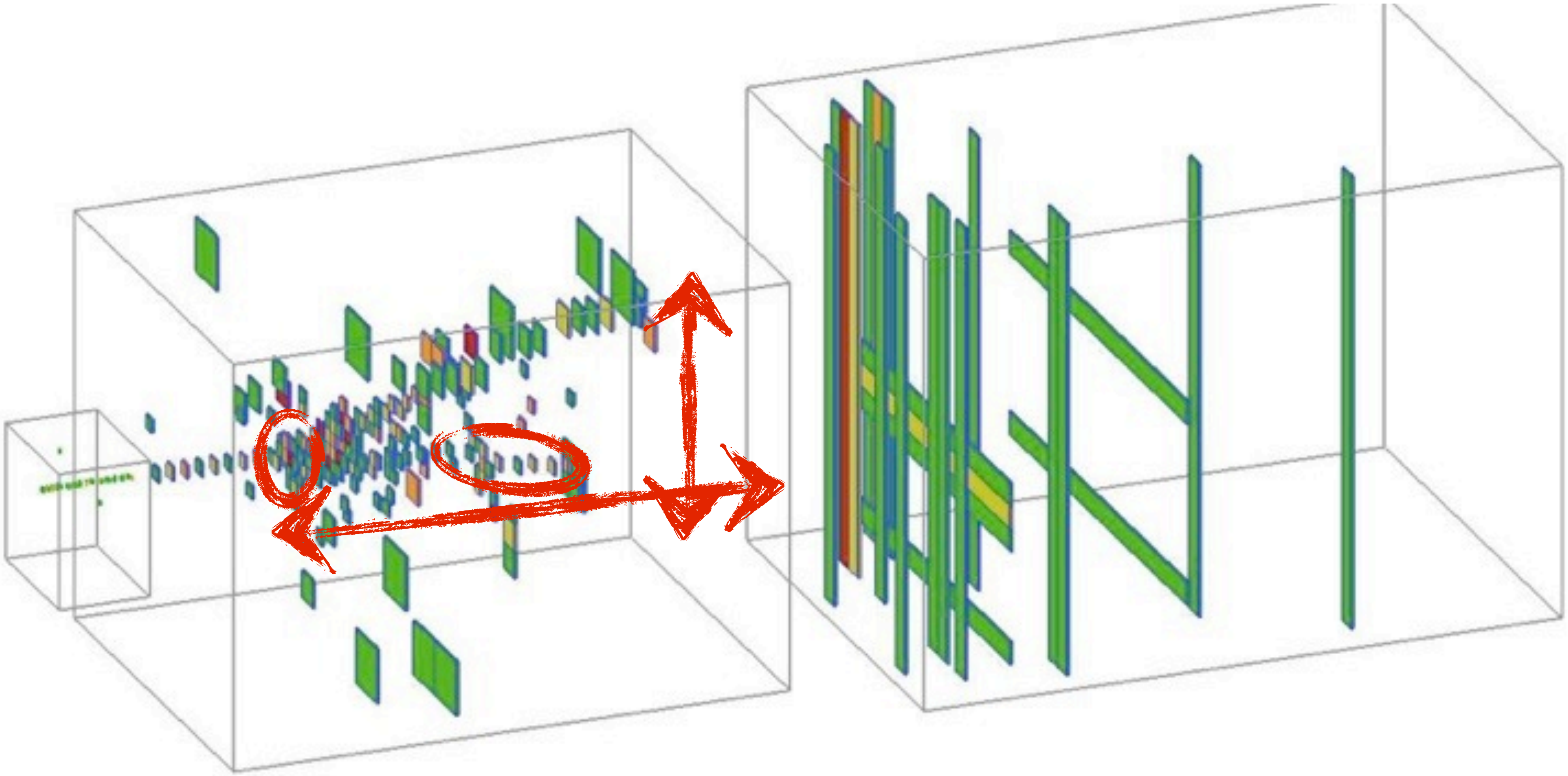

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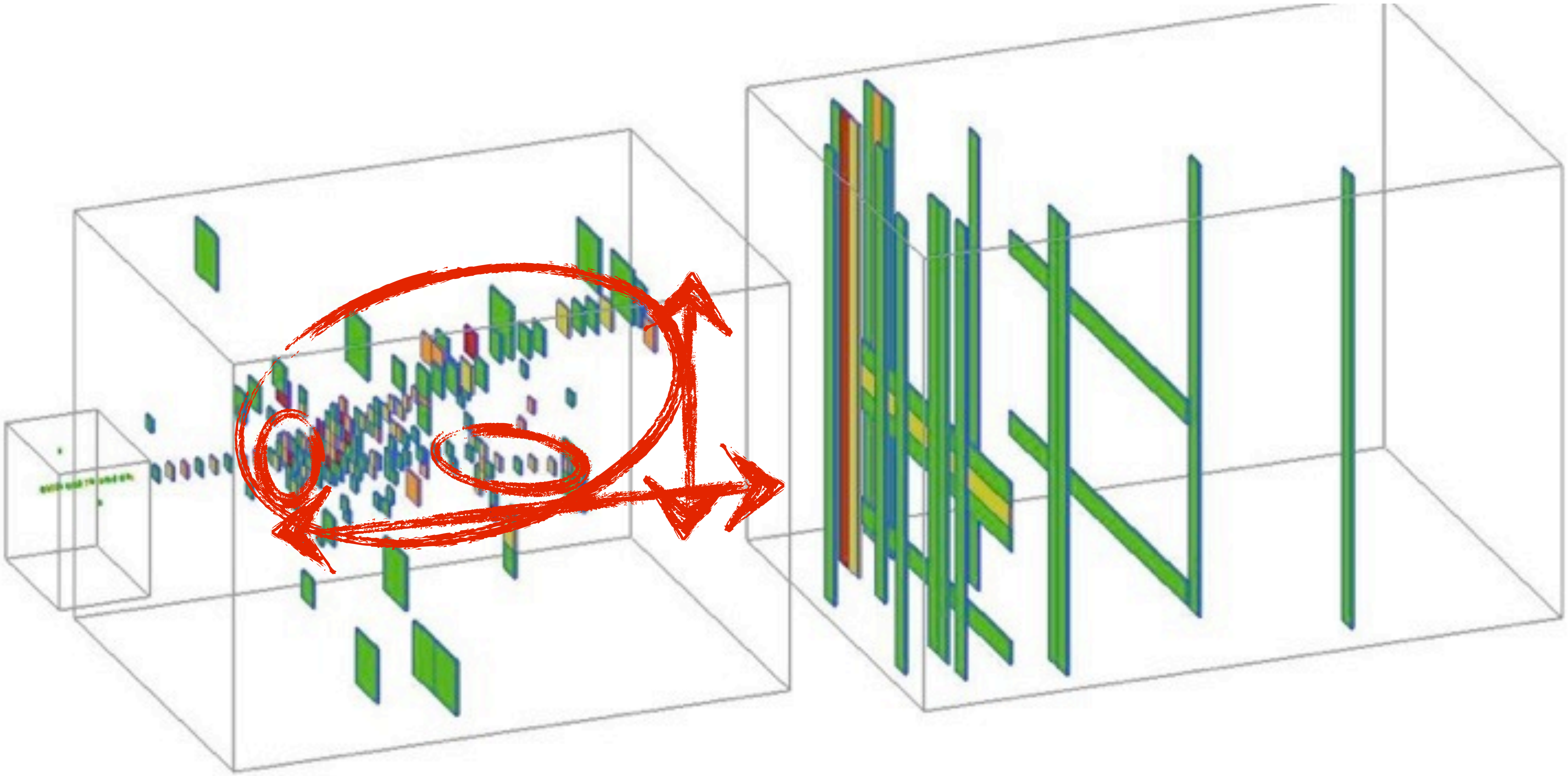

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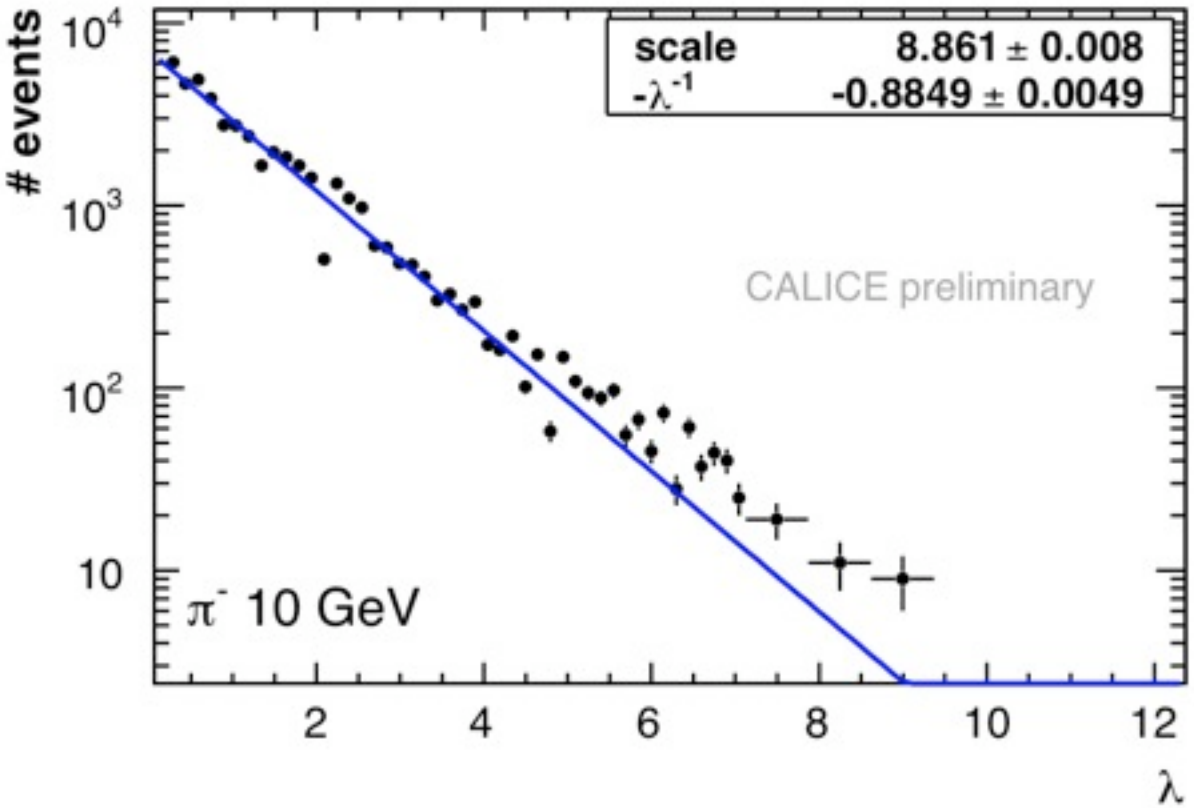
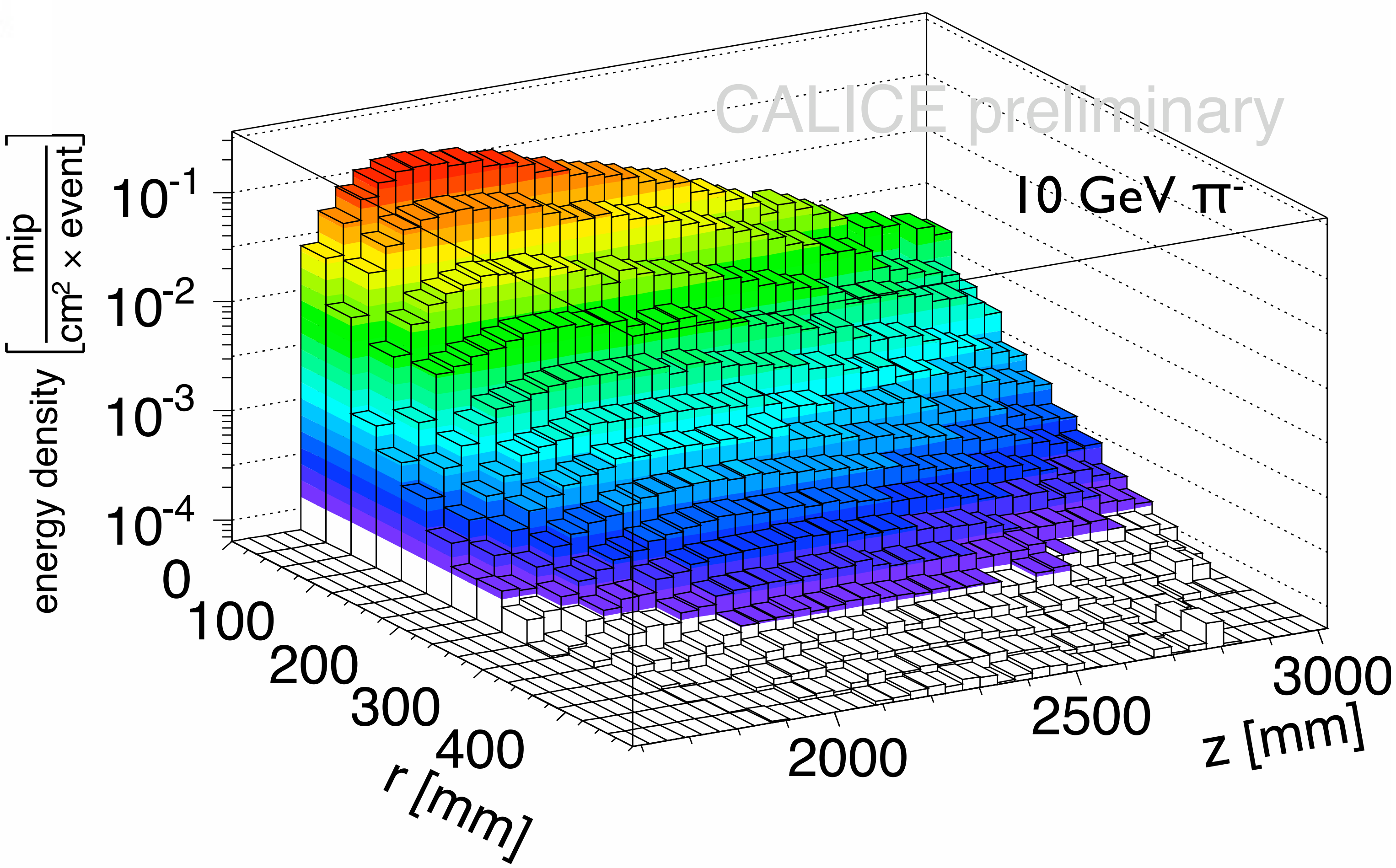
- Shower substructure: Detailed information about hadronic interactions
- Energy and energy density: Improved resolution with software compensation

Shower Start & Shower Profiles

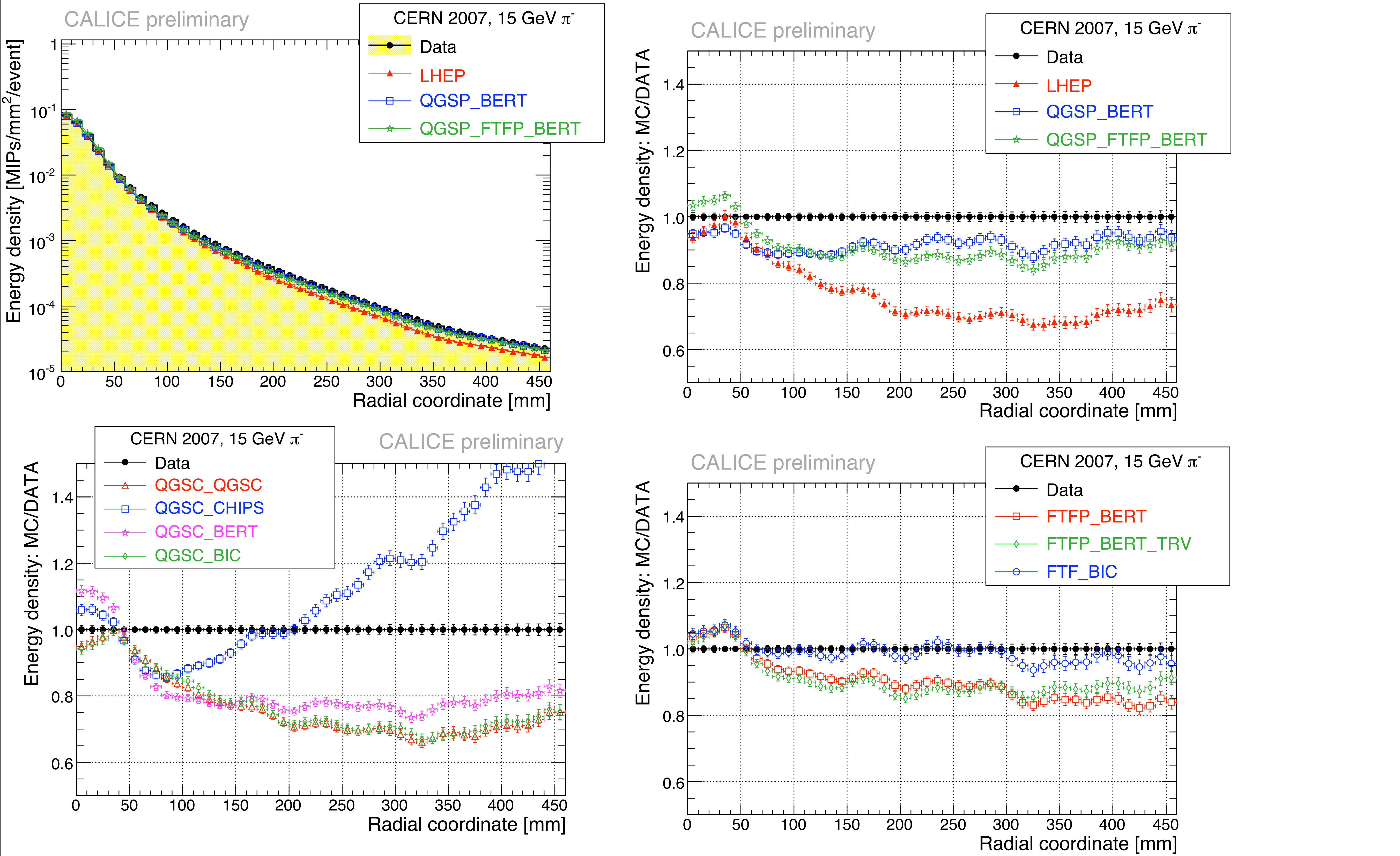


- Identification of the shower start point: Increase of activity in the detector

- Full profile of showers with high resolution:
  Perfect for detailed studies and MC comparisons



Transverse Shower Profiles: Comparison to MC



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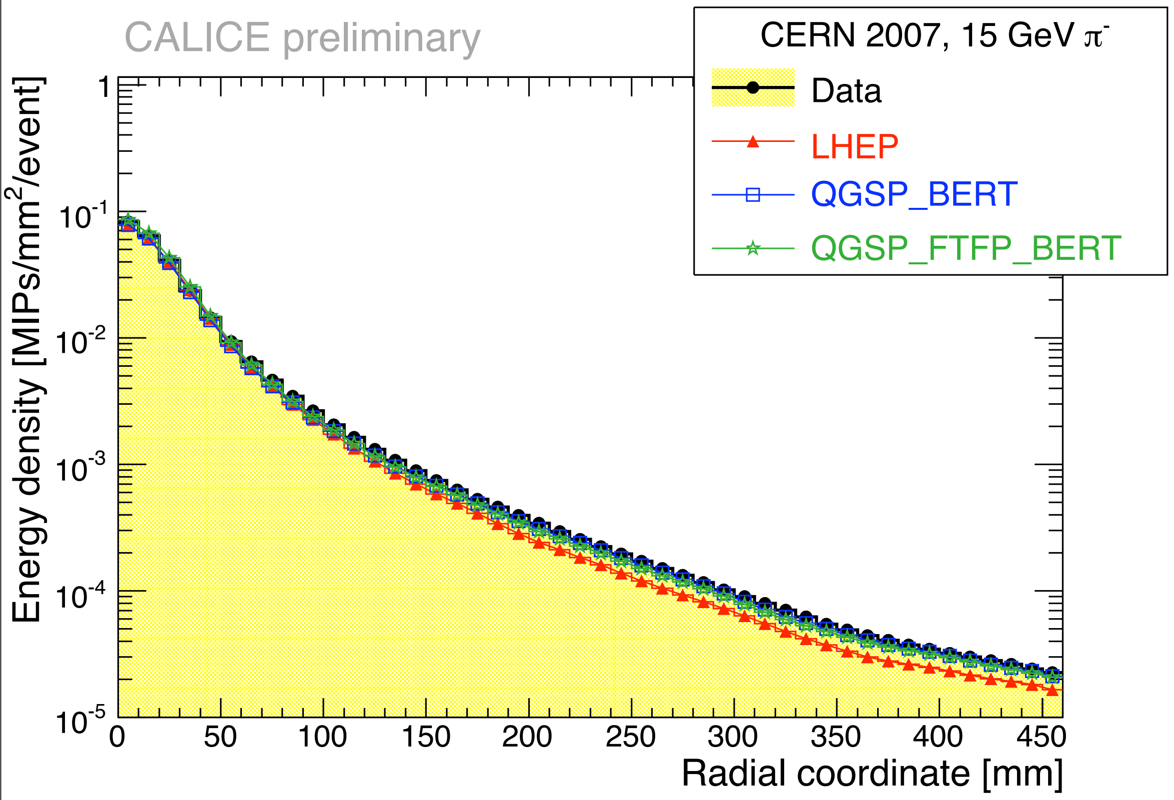
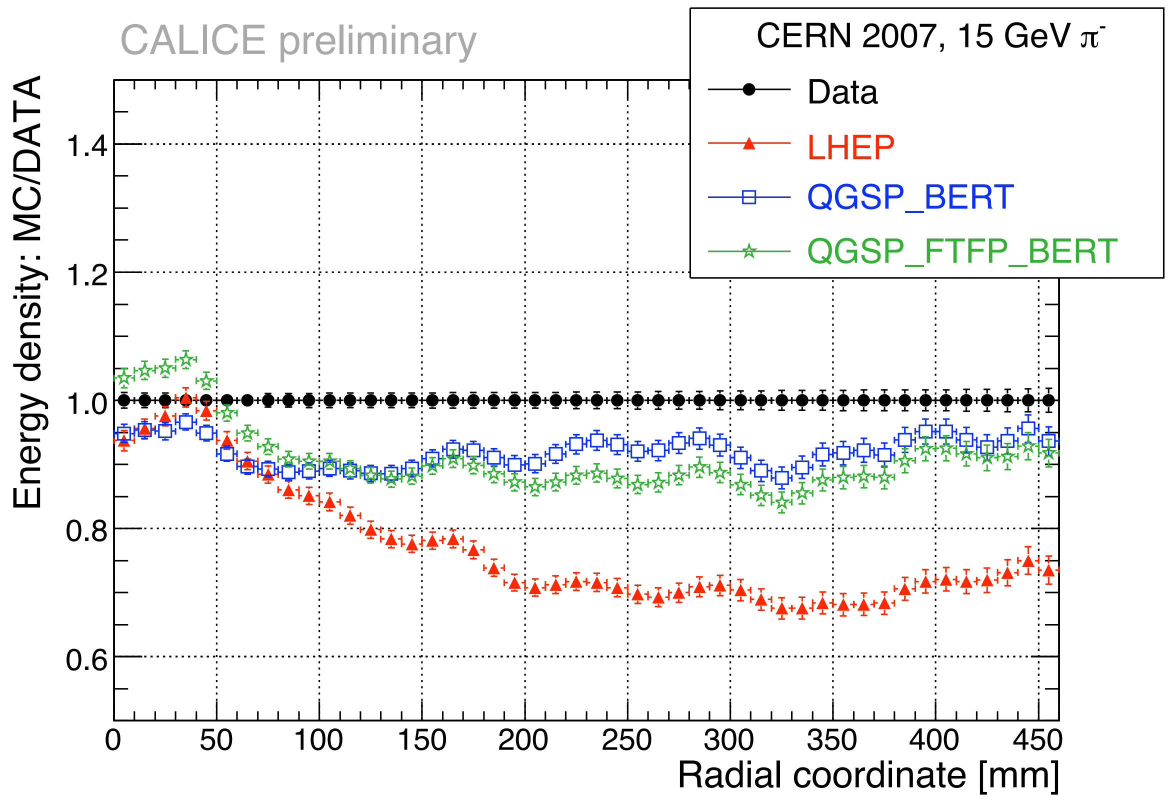
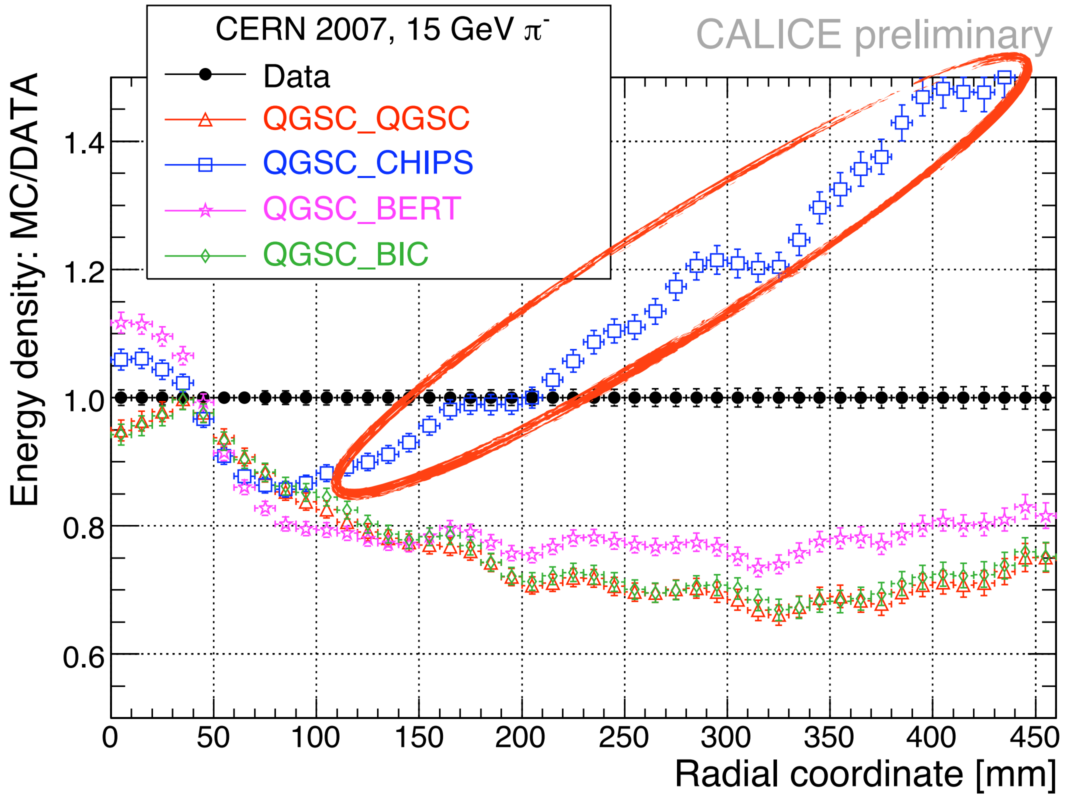
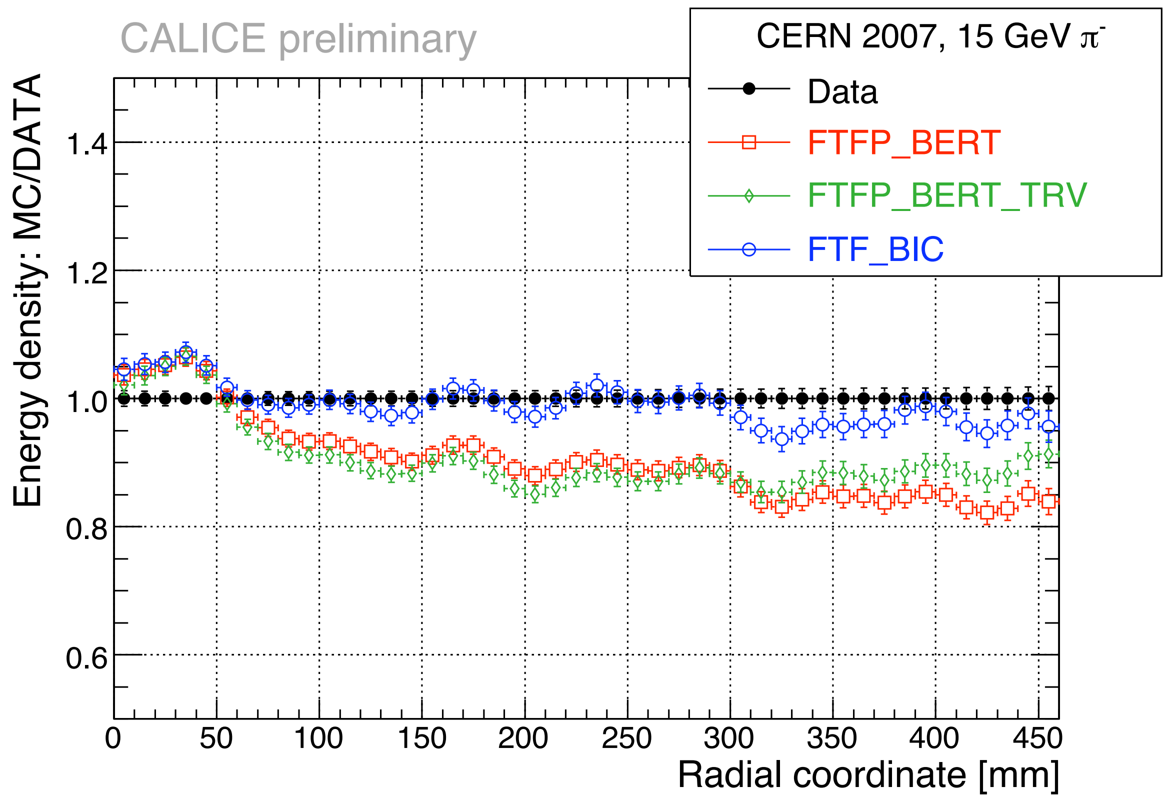
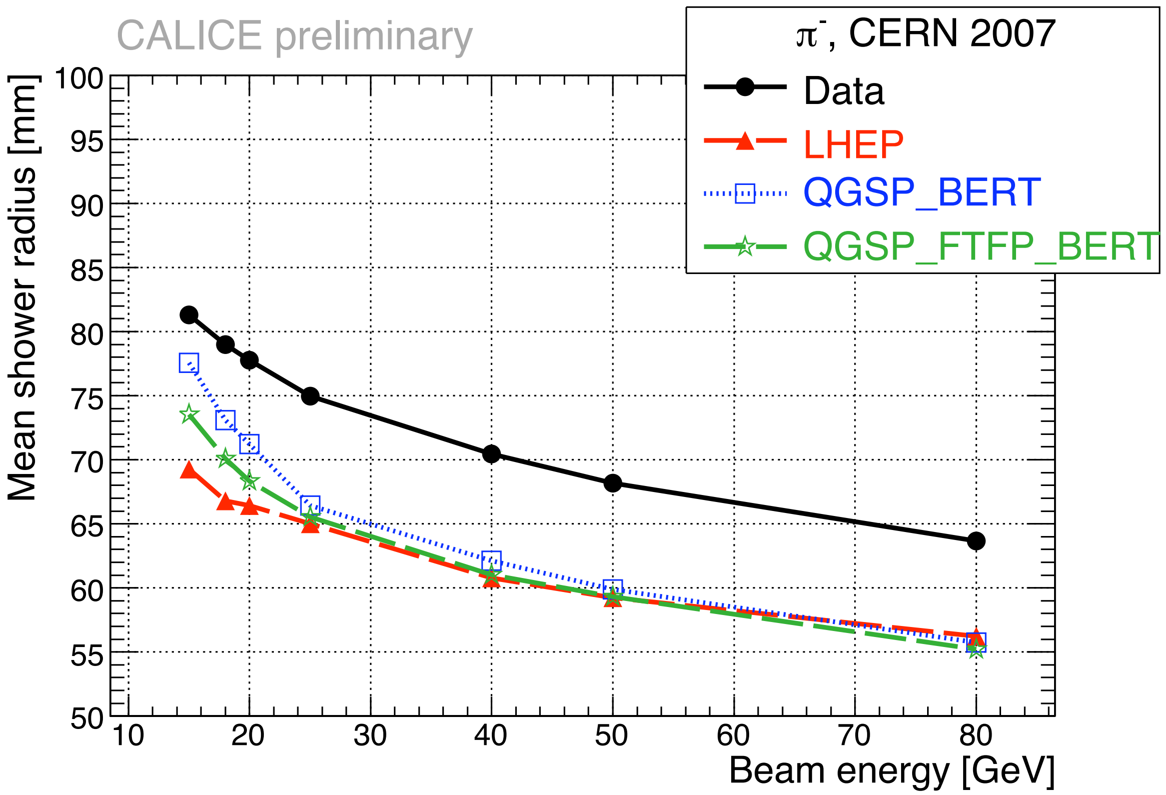




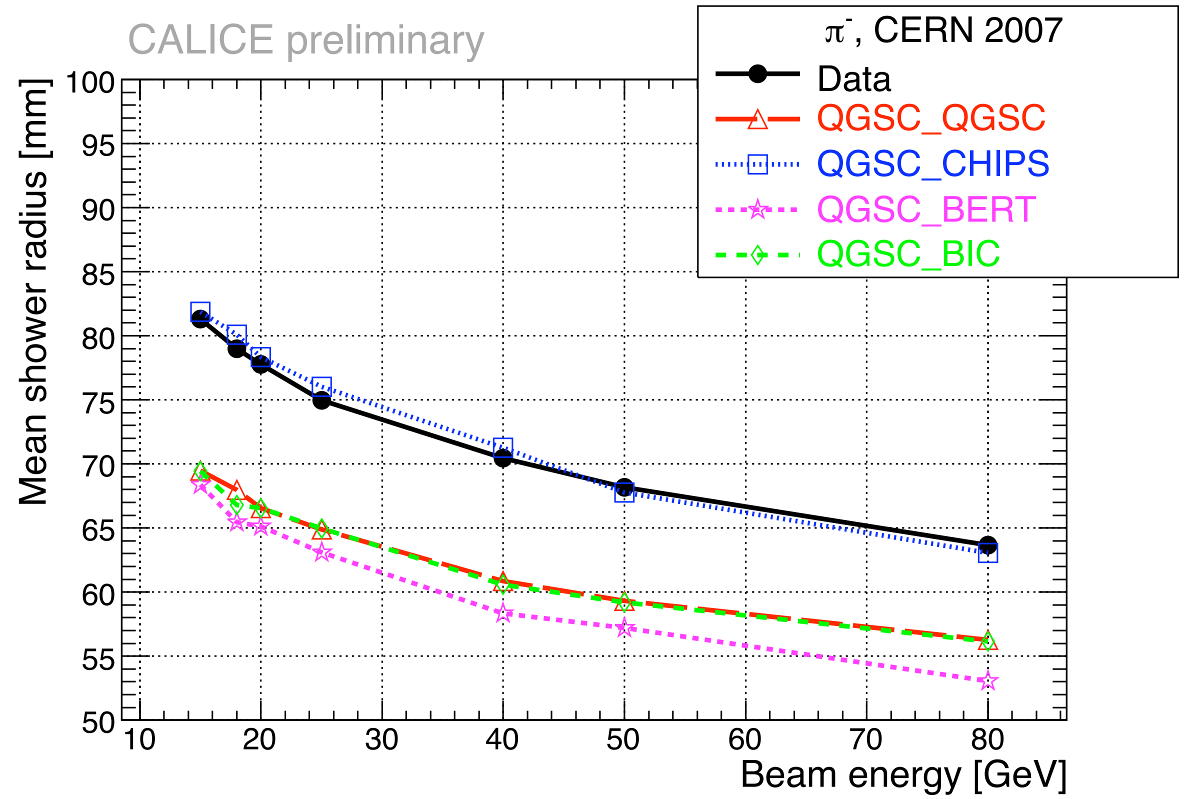


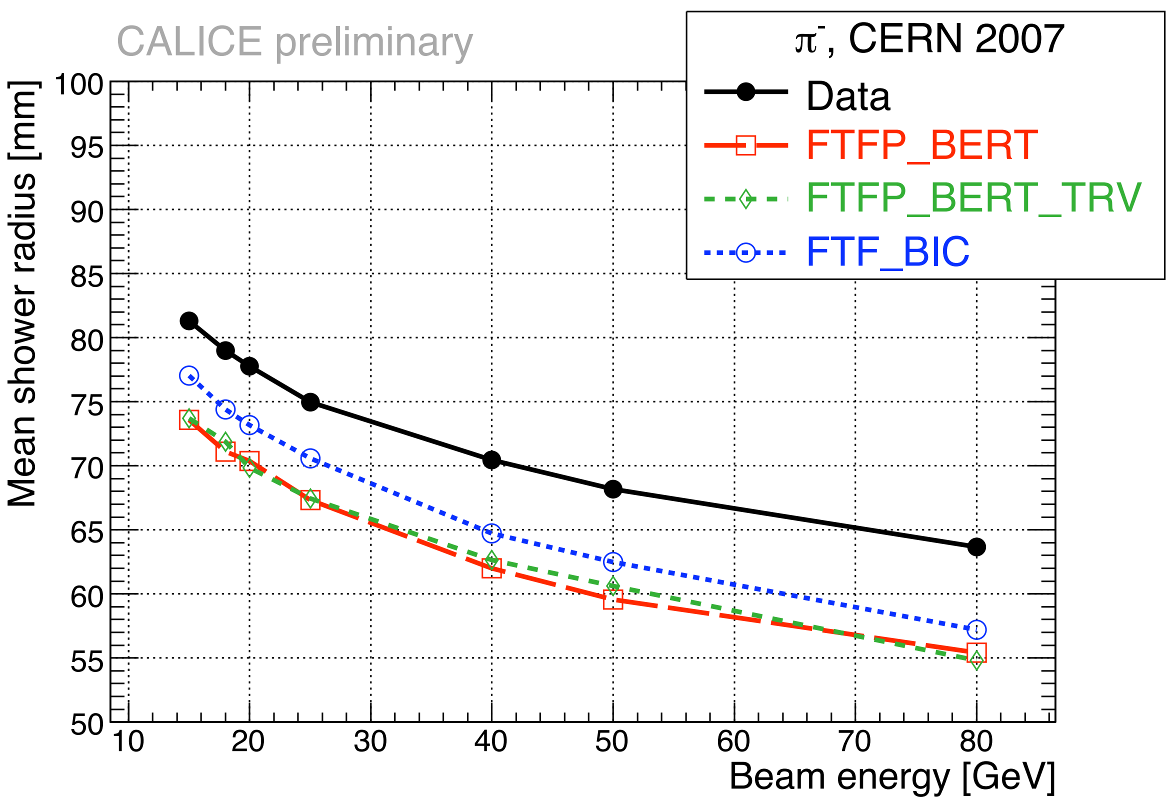


Mean Shower Radius



- Mean radius, energy weighted





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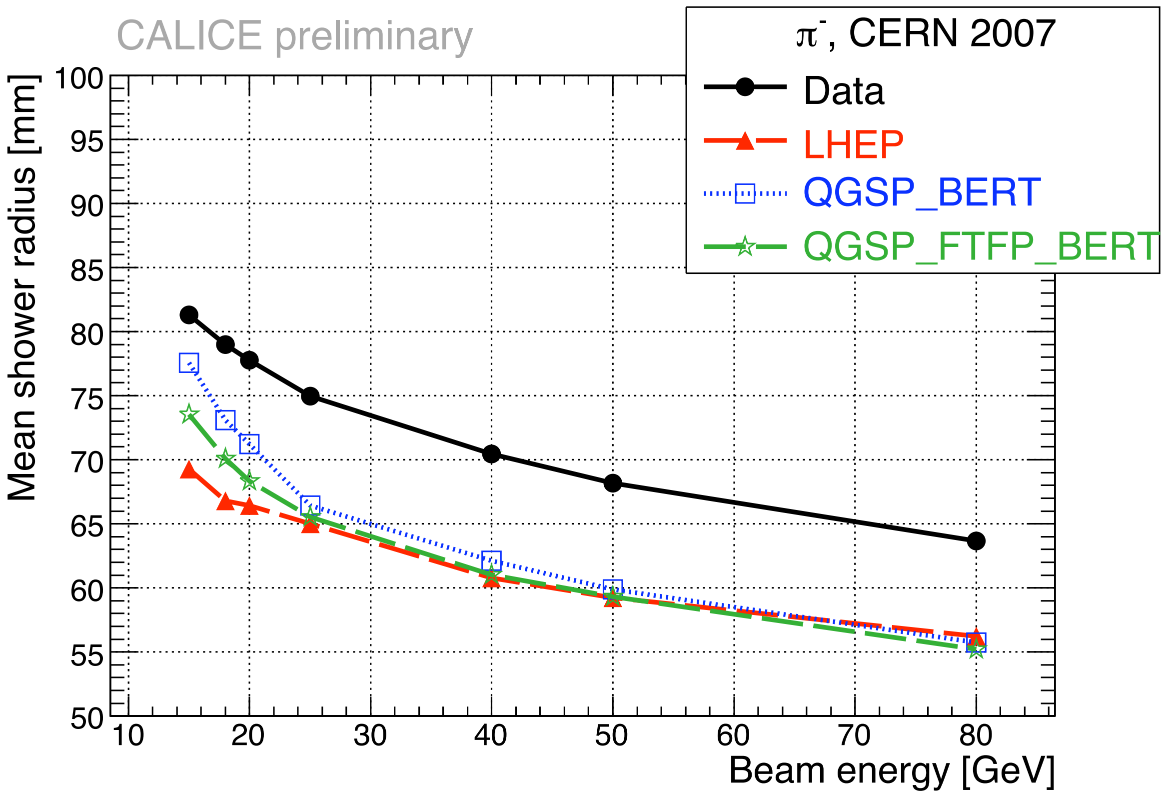

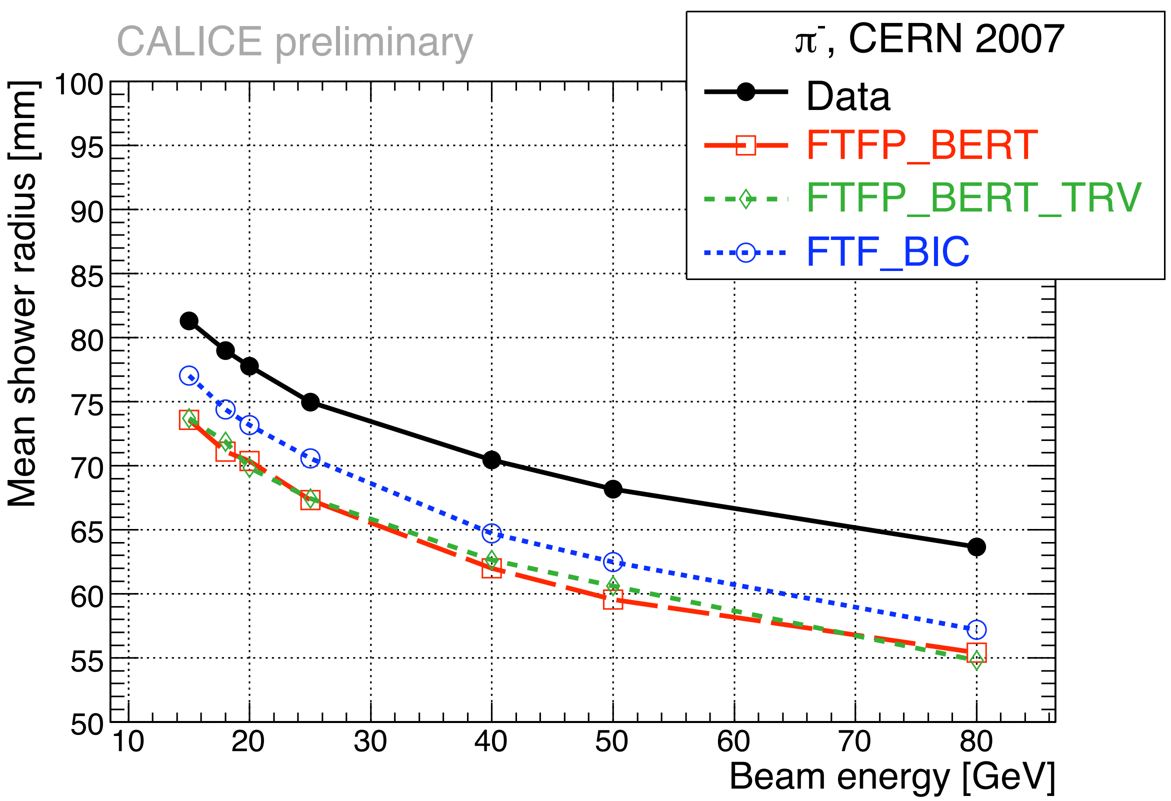

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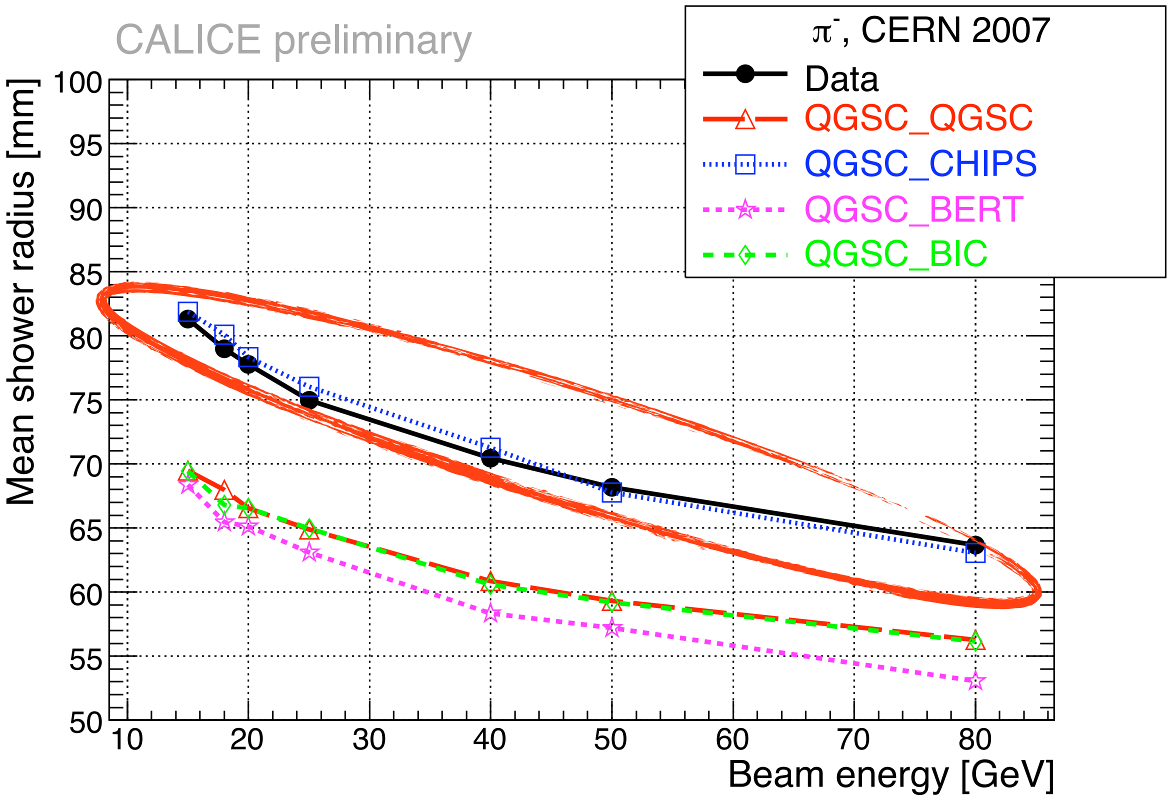
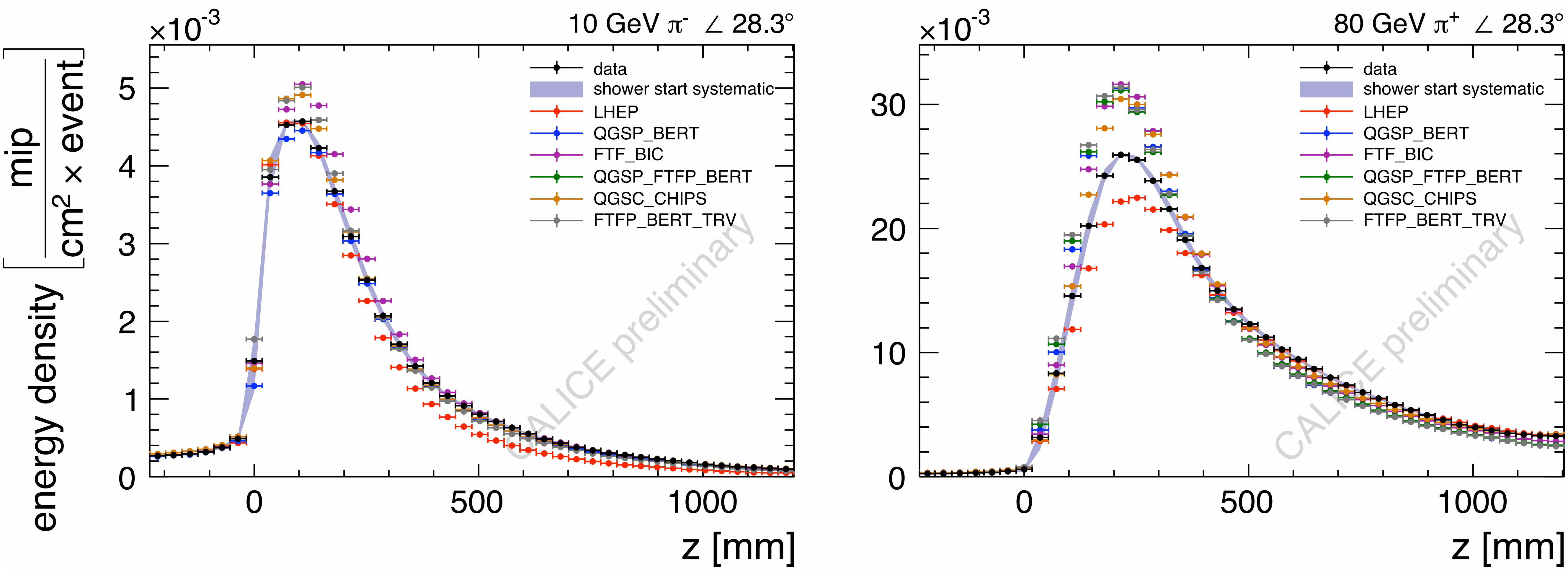


- Inclusive variables alone don't tell the whole story!
  - QGSC_CHIPS was found to be buggy, fixed in latest GEANT4 release
- Compare detailed distributions, use a large variety of observables

The Anatomy of a Hadronic Shower: Longitudinal Profile

- Use identified shower start: Factorization of distribution of first interaction and shower development



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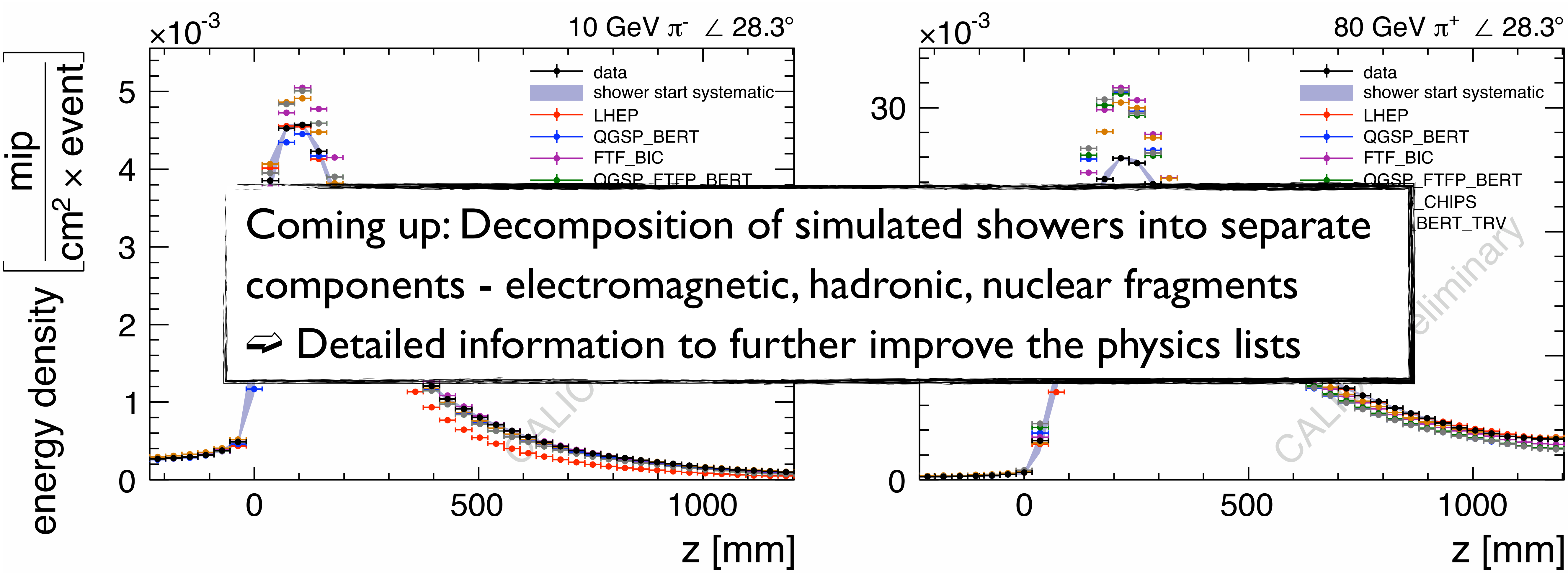


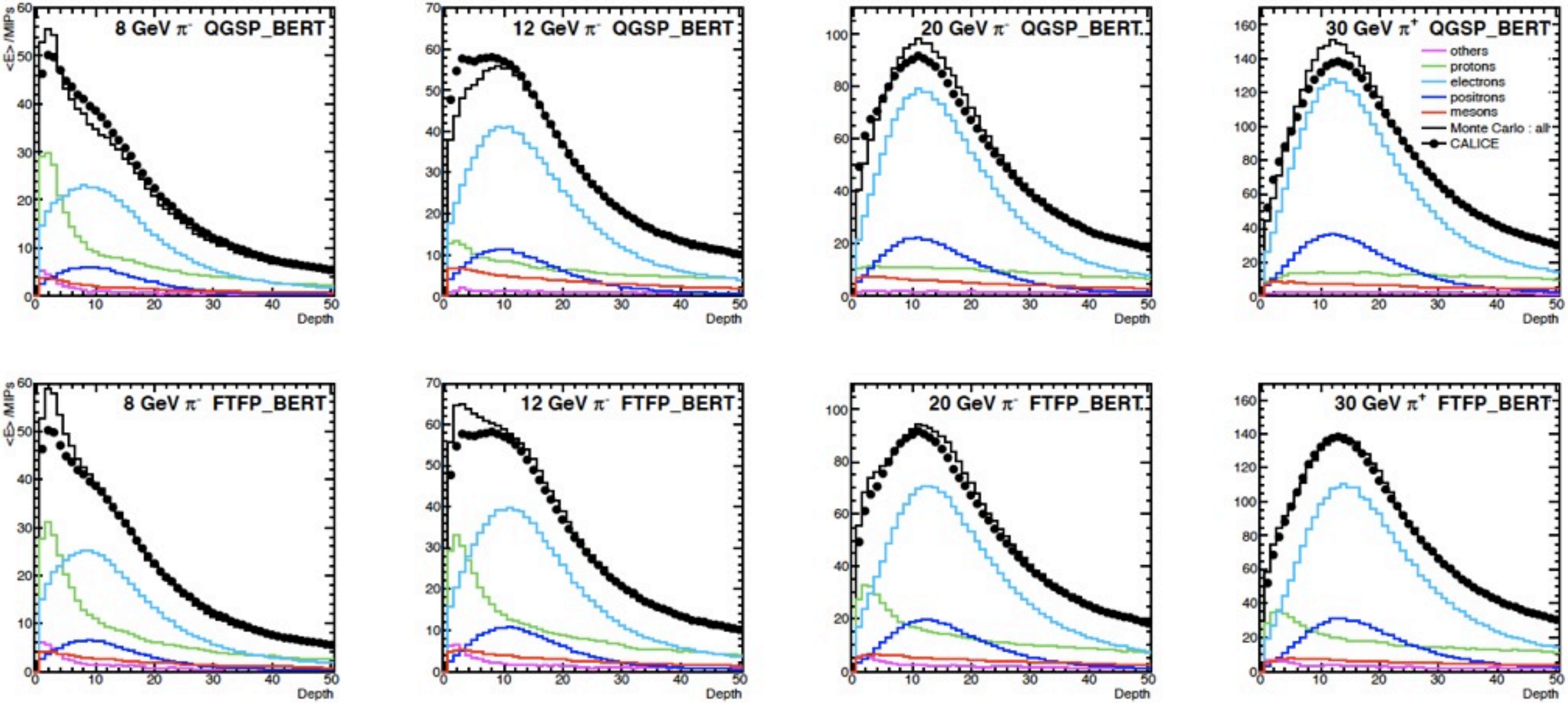
Coming up: Decomposition of simulated showers into separate components - electromagnetic, hadronic, nuclear fragments

➯ Detailed information to further improve the physics lists

- Variations from physics list to physics list, LHEP shows different behavior than other lists
- Discrepancy with data in particular at high energy near the shower maximum

The Anatomy of a Hadronic Shower: Longitudinal Profile

- Composition of showers for the ECAL (Silicon, Tungsten)
  - differences for HCAL expected: Sensitivity to neutrons due to Hydrogen in scintillator



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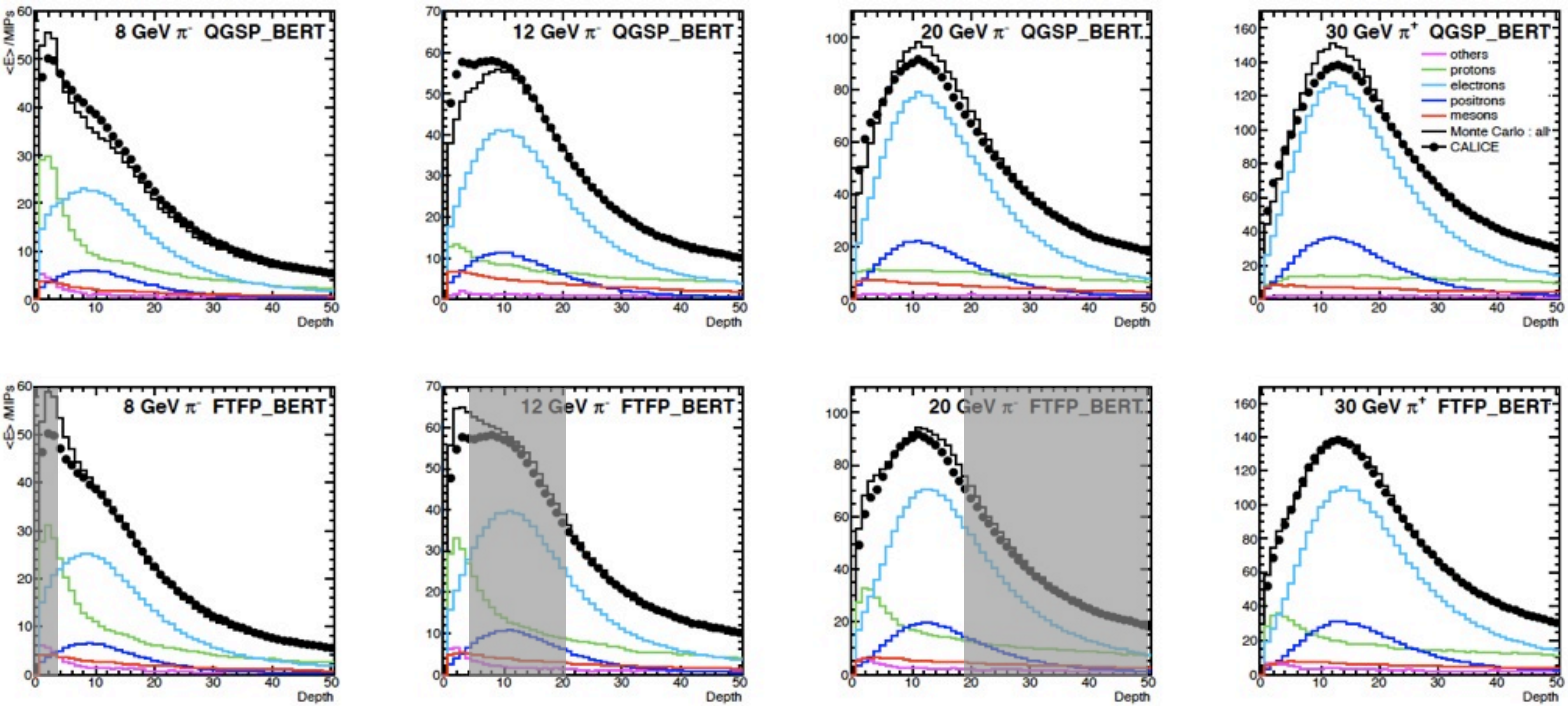
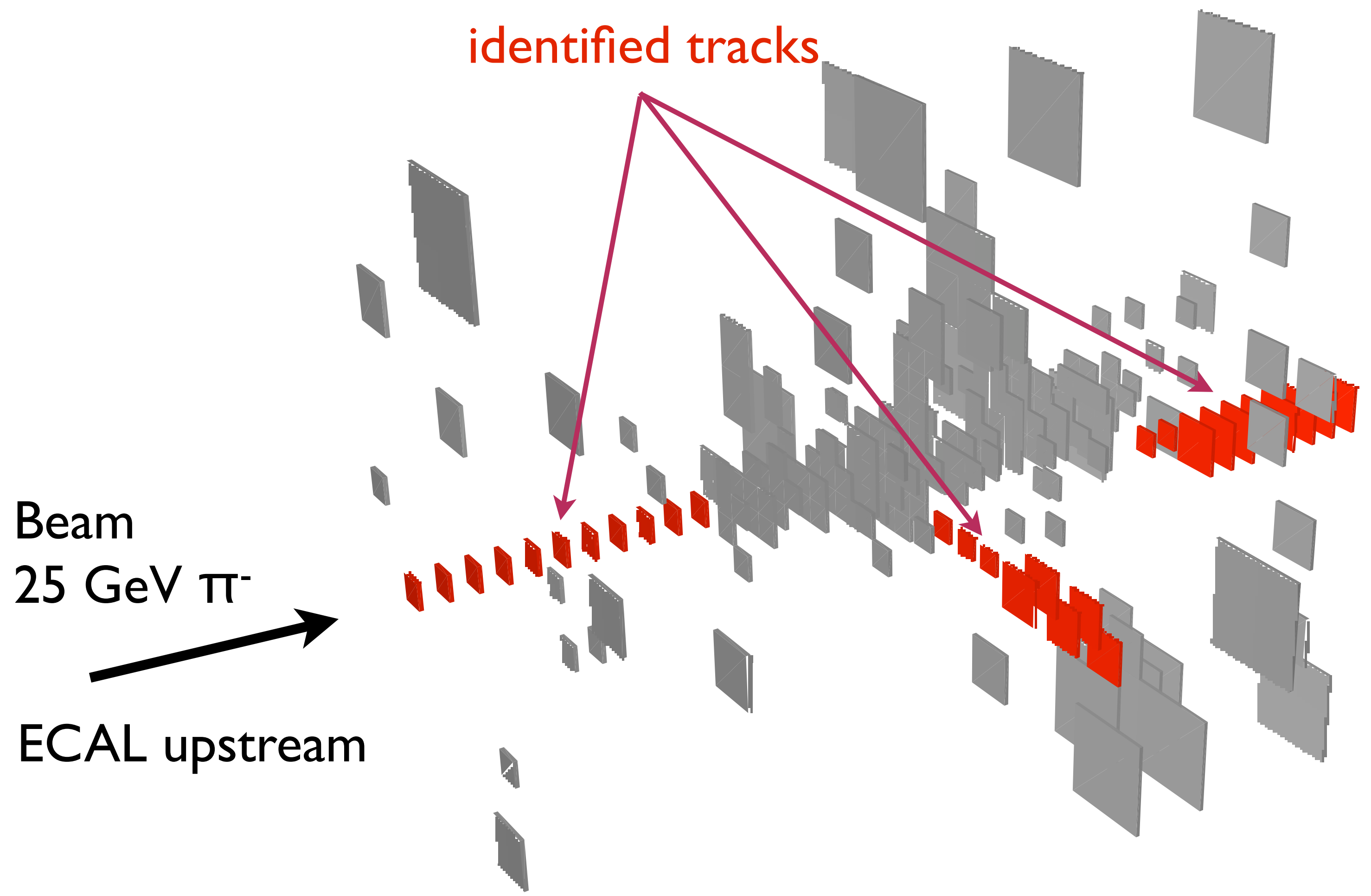


nuclear breakup   electromagnetic component   tail: hadronic & electromagnetic components

Digging Deeper: 3D Substructure - Particle Tracks



- Imaging capability of detector allows the identification of individual MIP-like tracks within hadronic showers

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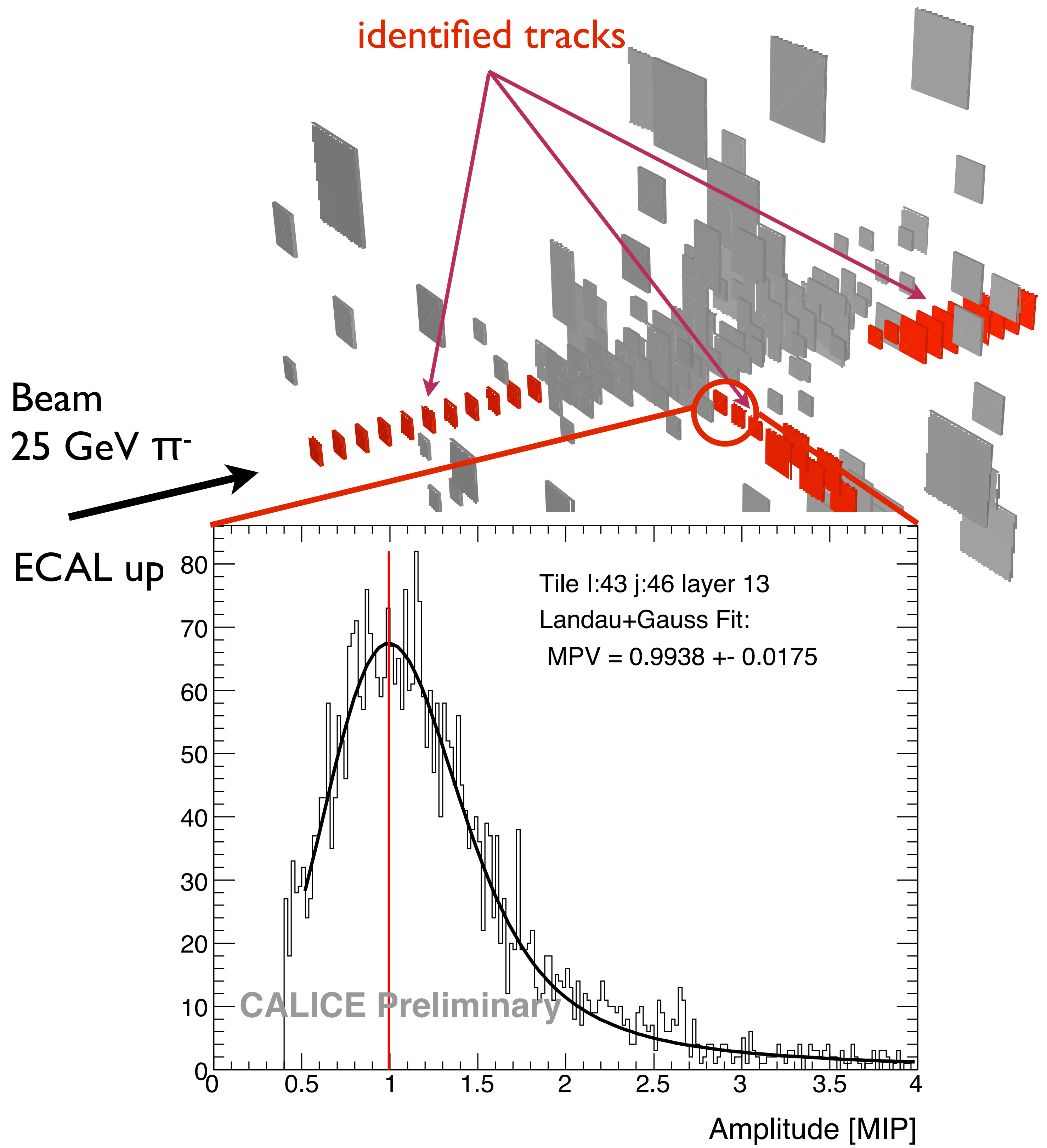
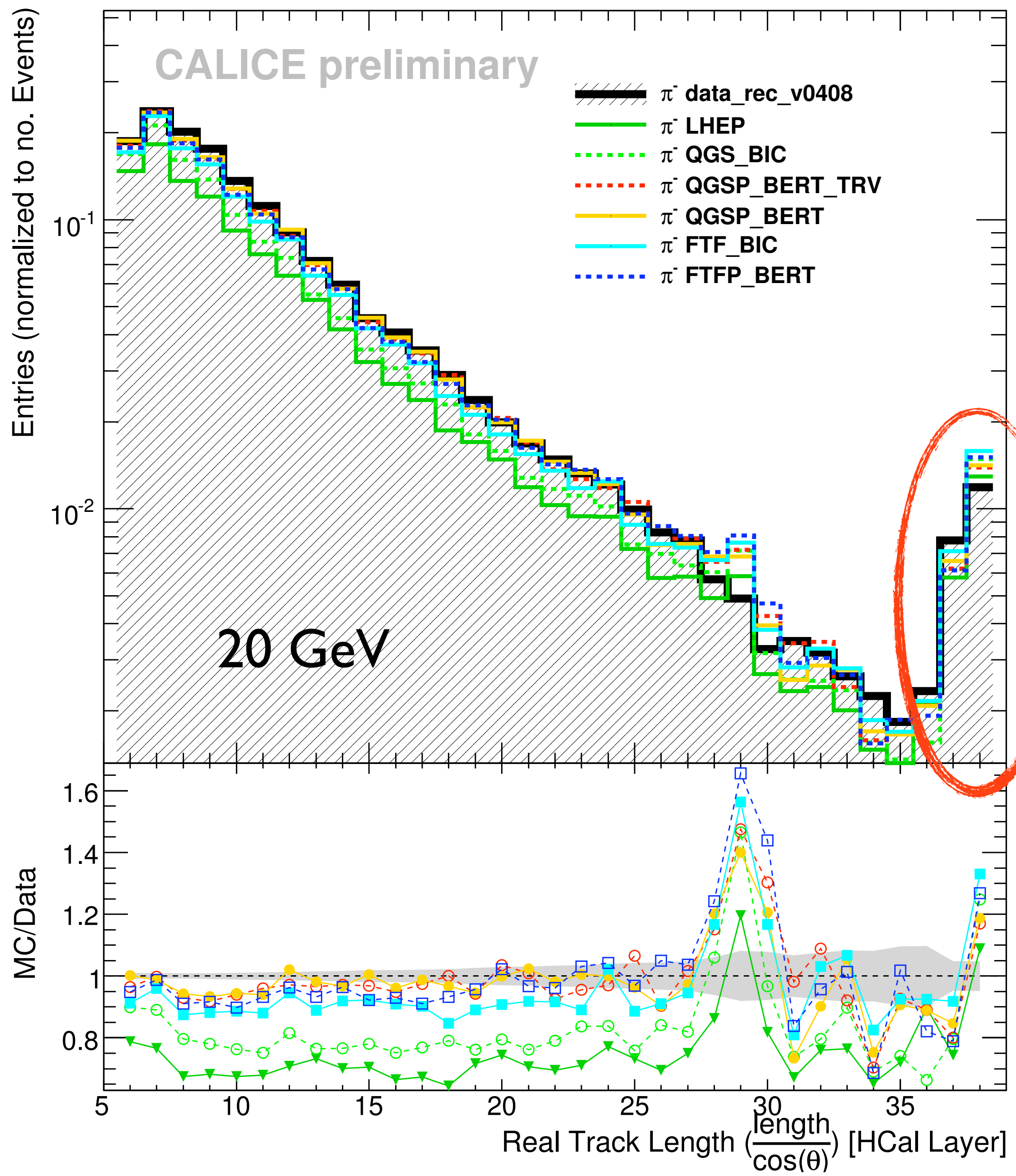


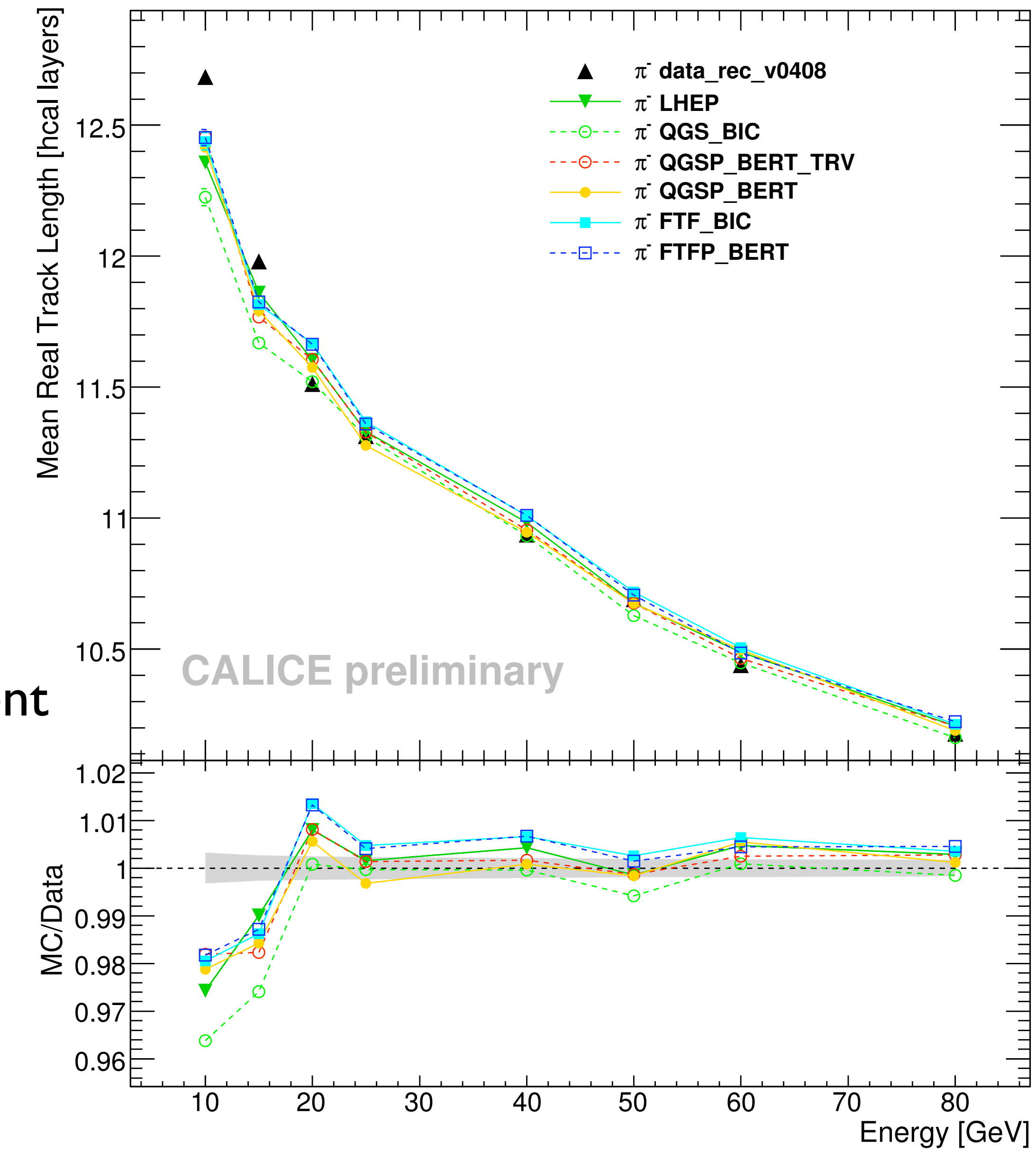
- Imaging capability of detector allows the identification of individual MIP-like tracks within hadronic showers

- Track identification provides a clean sample of minimum ionizing particles: An alternative calibration tool!

Track Segments in Hadronic Showers: Length

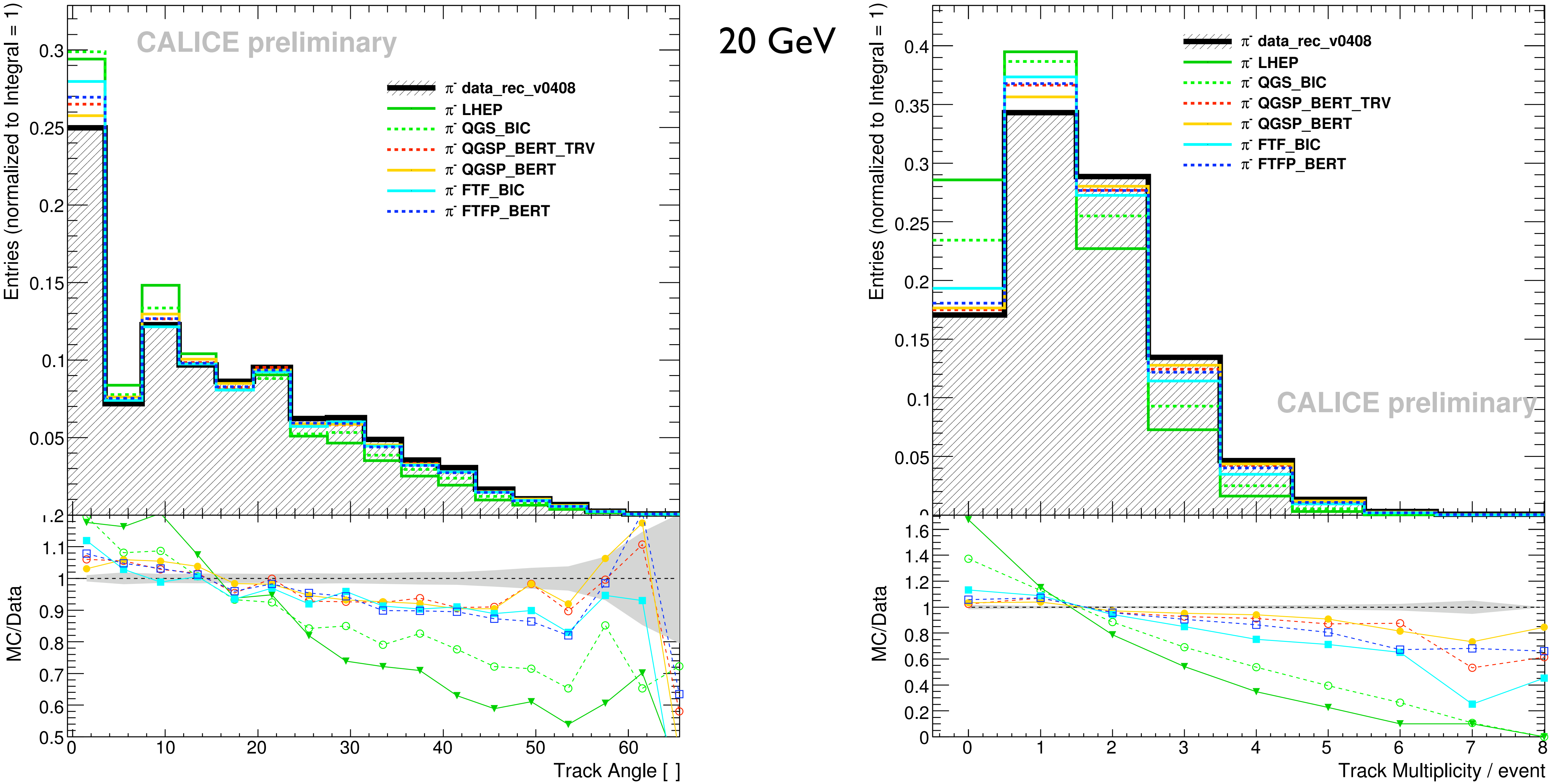


μ component in beam



- Track length and slope well described by all models:
  - Beam composition well modeled, satisfactory inclusion of detector noise
  - High energy cross sections well described

Track Distributions: Angles & Multiplicities



- Large discrepancy between different models
  - Best agreement with QGSP_BERT
  - LHEP, QGS_BIC have too small angles and too small multiplicity: Insufficient production of high-energy secondaries at large angles

Hadronic Showers in Imaging Calorimeters

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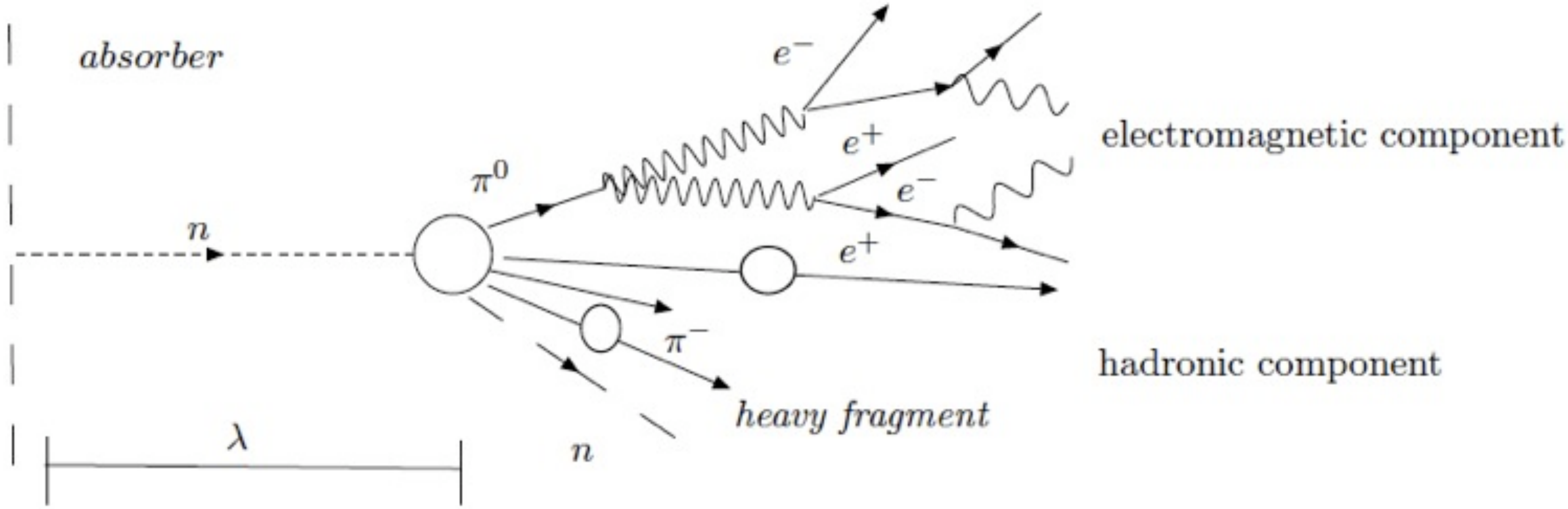
Energy Reconstruction

Hadronic Showers: A Tough Business

- The "secret" behind Particle Flow: Avoid the HCAL as much as possible
  Why?



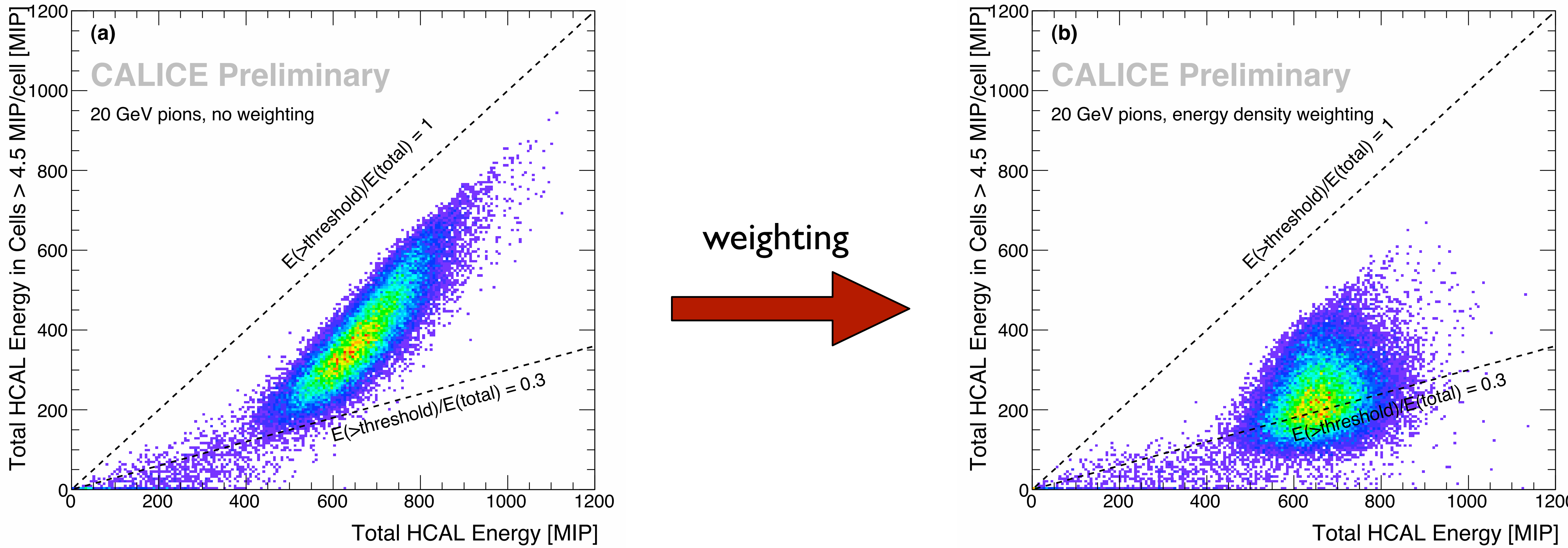
A calorimeter typically responds differently to the different components of the shower

- Usually larger response for electromagnetic part
- ‣ Fluctuations from shower to shower limit the energy resolution
- ‣ Energy dependence of average shower composition leads to non-linearities

Energy Reconstruction & Software Compensation

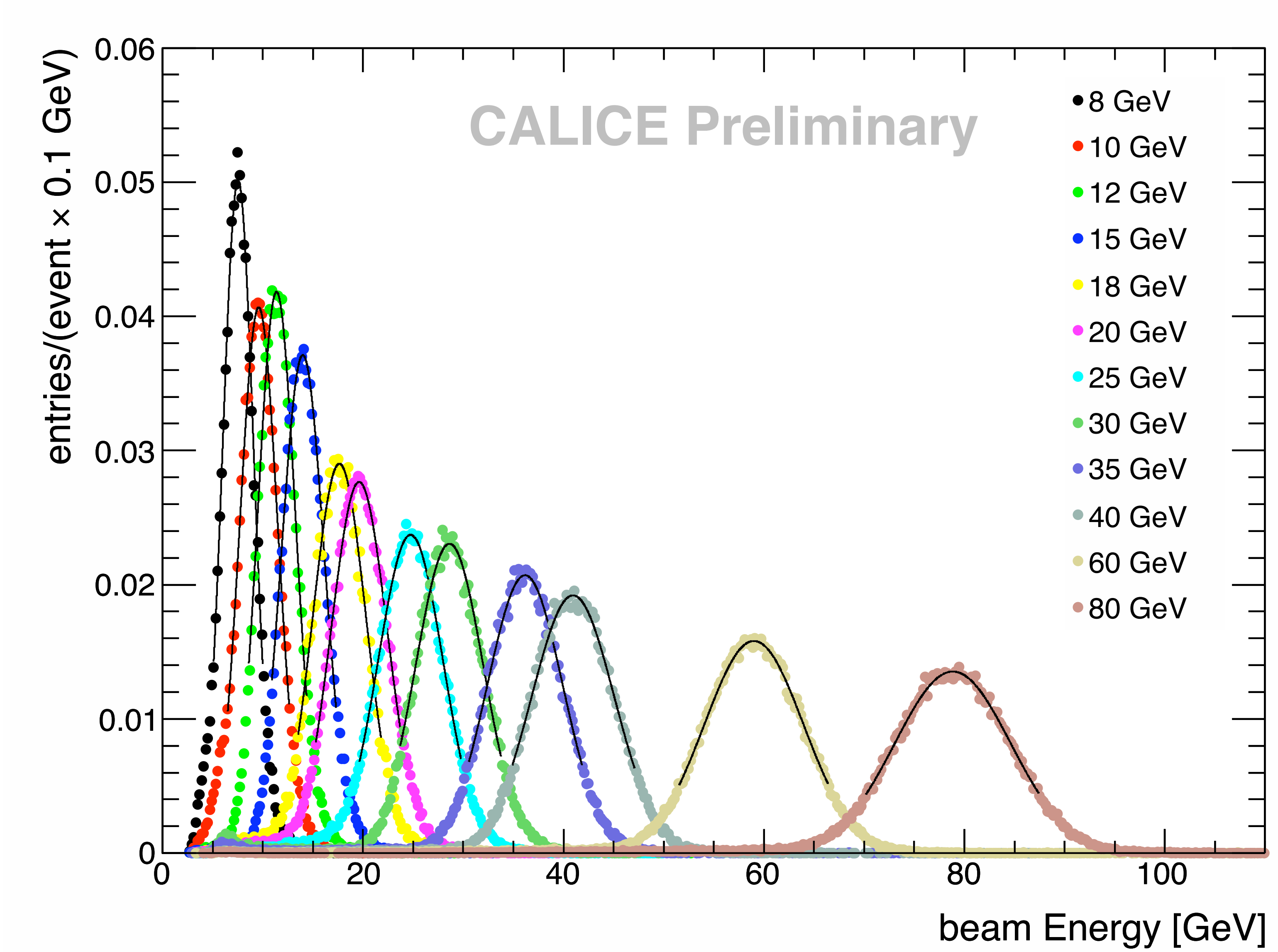
- The CALICE HCAL is non-compensating: e/π ~ 1.3 (energy dependent)
- High granularity provides detailed information for software compensation:
  - Electromagnetic energy deposits tend to be denser than hadronic ones
  - Improvement studied on the cell (local) and on the cluster (global) level

Local method: apply weight to cells according to their energy, lower weight for cells with higher energy content, weights are determined with a minimization technique



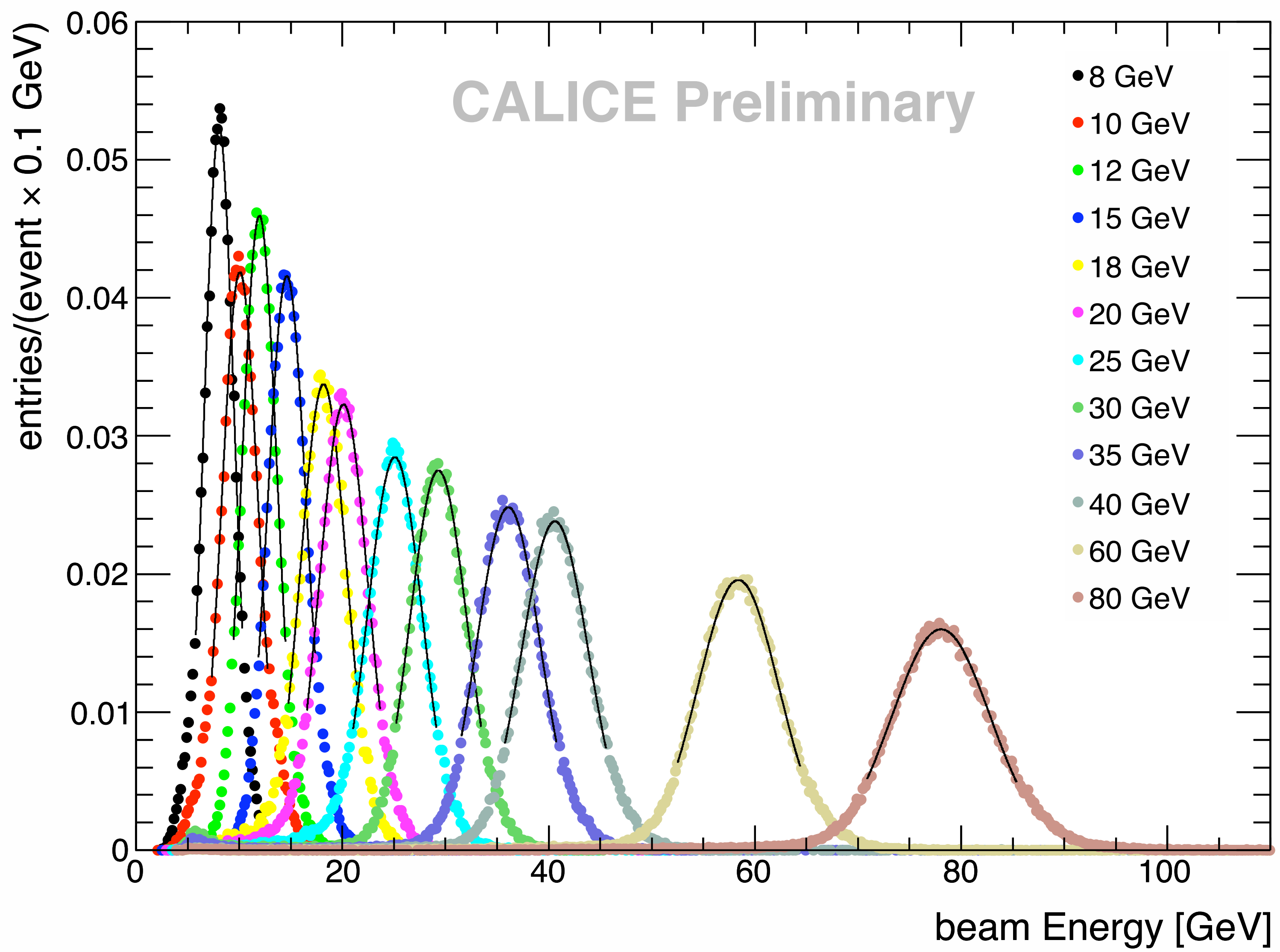
Software Compensation: Improved Energy Resolution

- Compare two reconstruction methods:
  - Simple reconstruction: Constant factor to convert calorimeter signal to energy



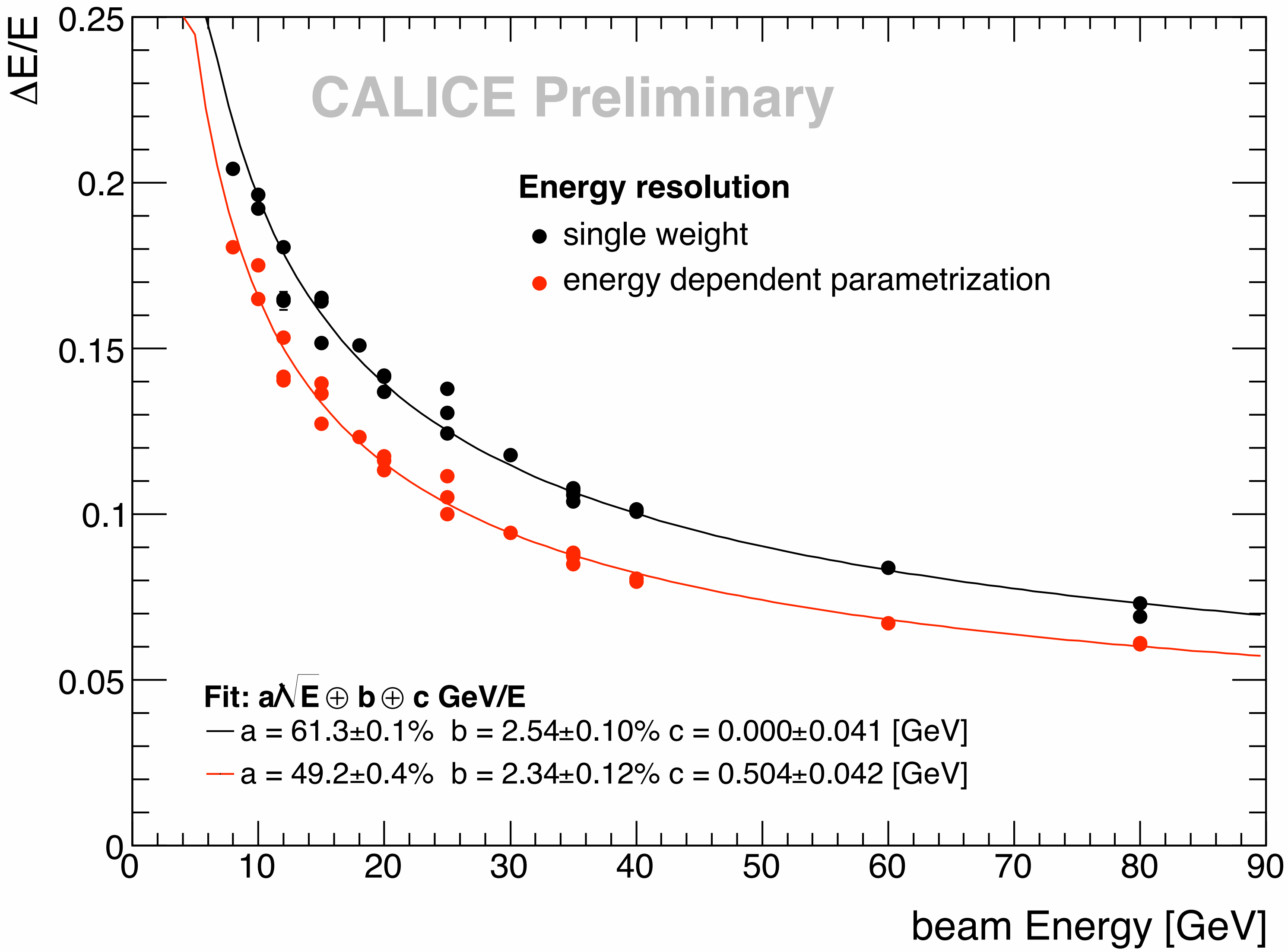
Software Compensation: Improved Energy Resolution

- Compare two reconstruction methods:
  - Simple reconstruction: Constant factor to convert calorimeter signal to energy
  - Local software compensation:
    Energy density dependent weighting, parametrized energy dependence



Software Compensation: Local Method

- Weights determined from data, parametrized energy dependence
  - No prior knowledge of beam energy necessary for application
- Improved linearity of response, within ~3% from 8 to 80 GeV
  - without temperature correction, proton rejection: Better performance expected in the near future!



Complete CALICE Setup (ECAL, HCAL, TCMT):

Resolution improved by ~ 18%

Resolution given by Gaussian sigma / mean of a fit to the distribution within 1.5σ of peak

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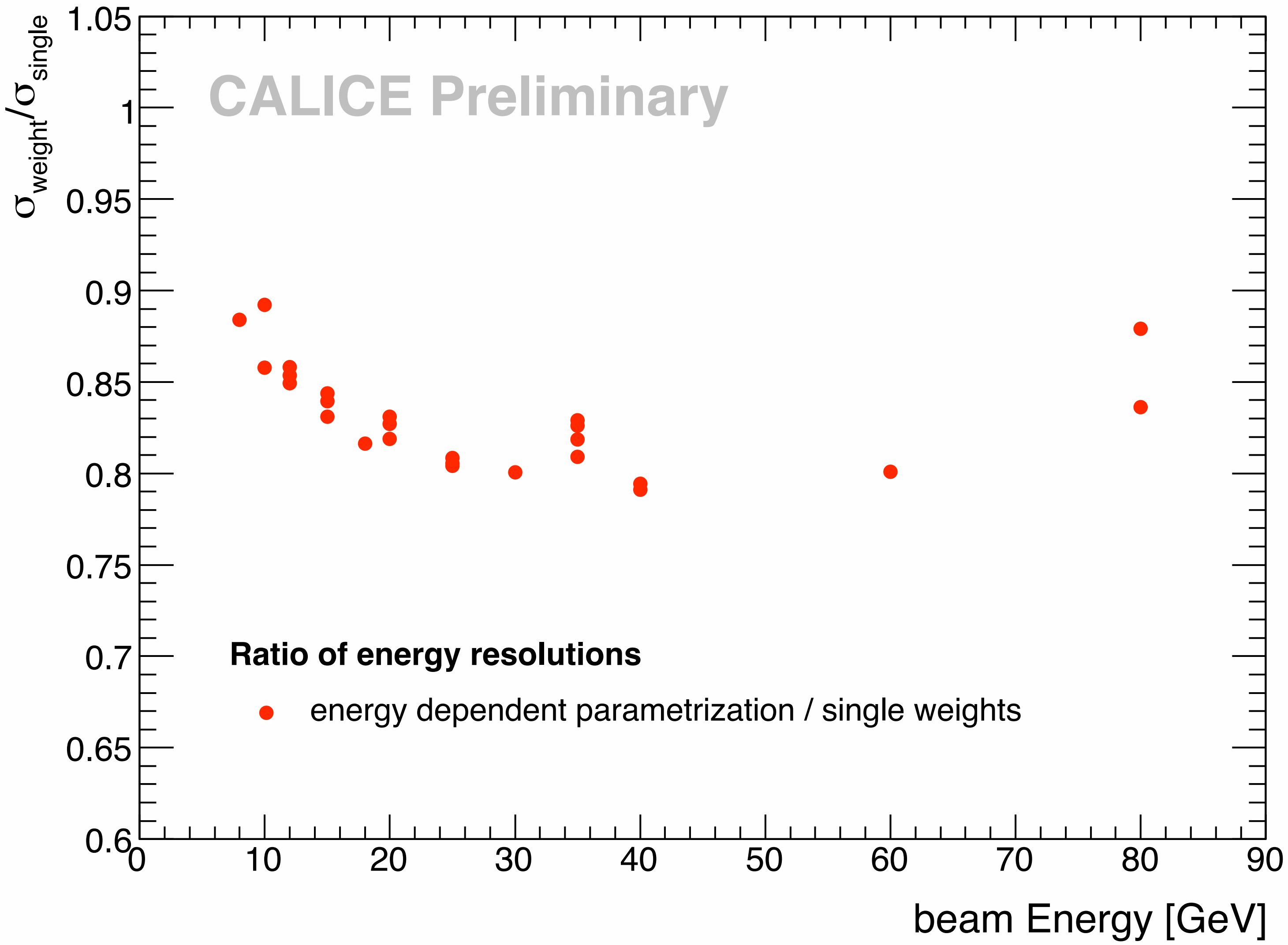

Complete CALICE Setup (ECAL, HCAL, TCMT):

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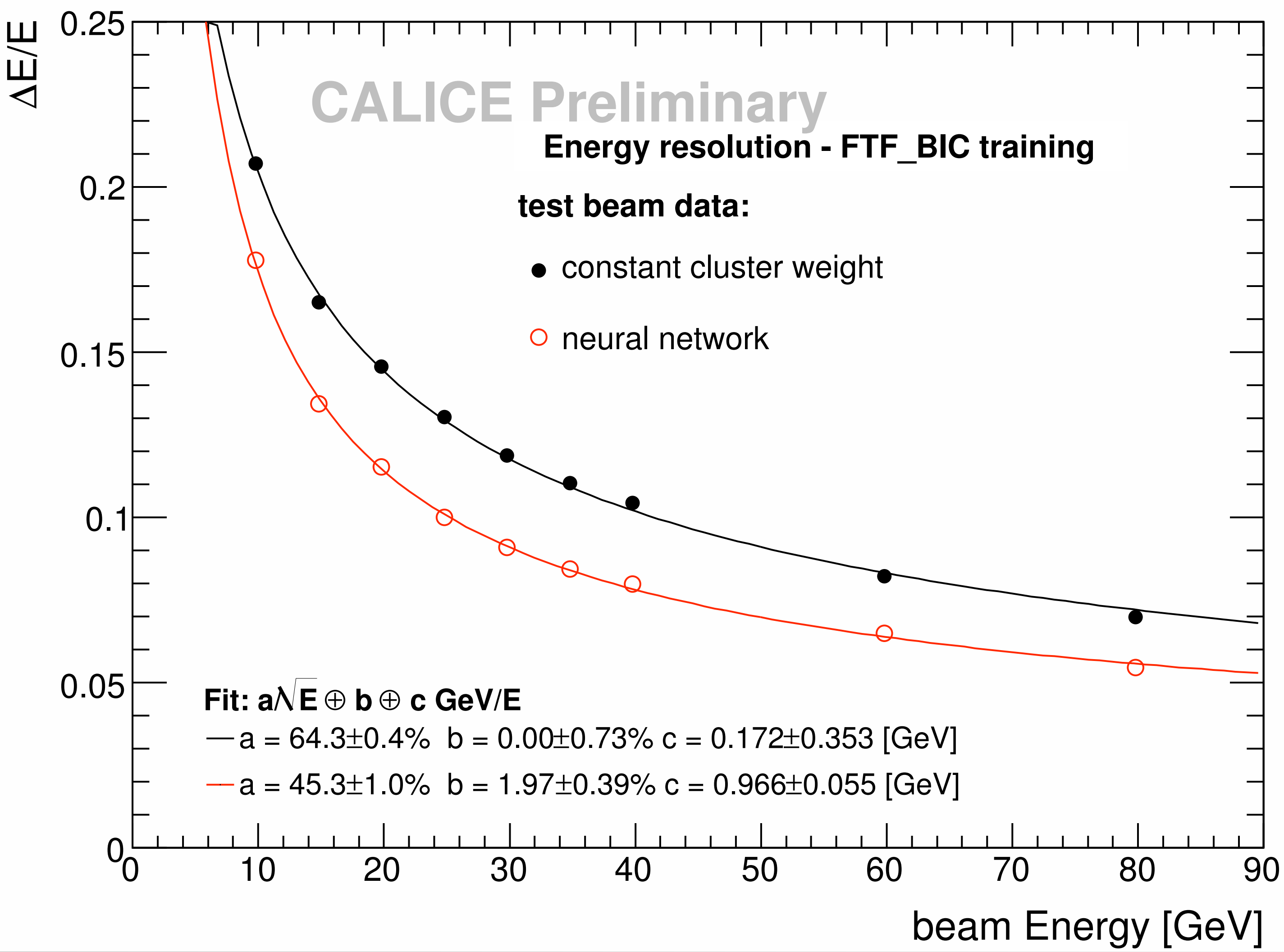
Software Compensation: Global Method

- Cluster finding in HCAL and TCMT to determine properties of the shower: total energy, volume, length, width, energy in TCMT, energy in last 5 HCAL layers
  - Used as input for a neural net, training of the NN with simulations (quasi-continuous energy)
  - No prior knowledge of the beam energy needed for application of method



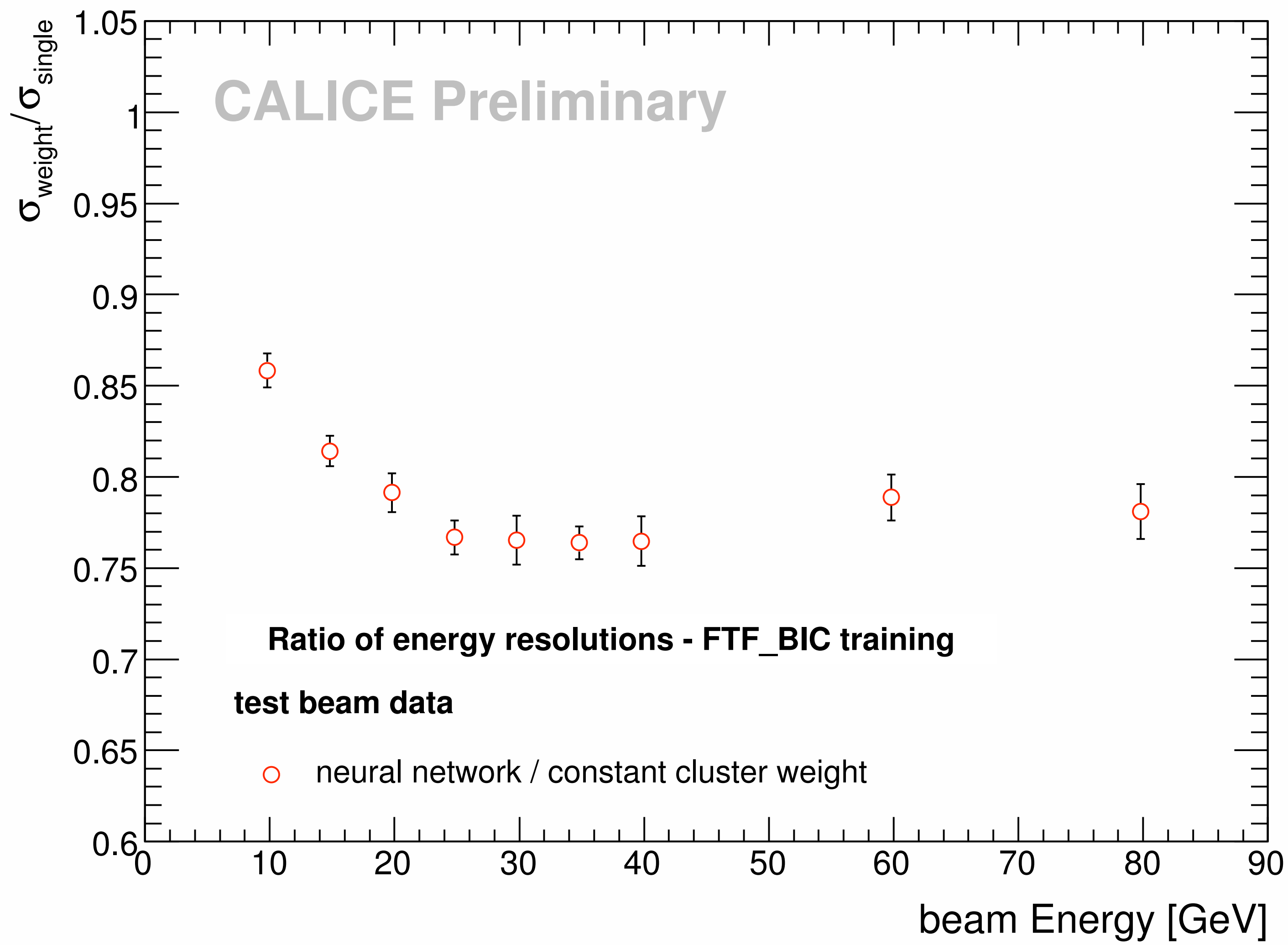
HCAL+TCMT
NN trained with FTF_BIC

Resolution improved by ~25%
(~15% at 10 GeV, ~20% at 15 GeV)

Resolution given by
Gaussian sigma / mean of a fit to
the distribution within 1.5σ of peak

Software Compensation: Global Method

- Cluster finding in HCAL and TCMT to determine properties of the shower: total energy, volume, length, width, energy in TCMT, energy in last 5 HCAL layers
  - Used as input for a neural net, training of the NN with simulations (quasi-continuous energy)
  - No prior knowledge of the beam energy needed for application of method



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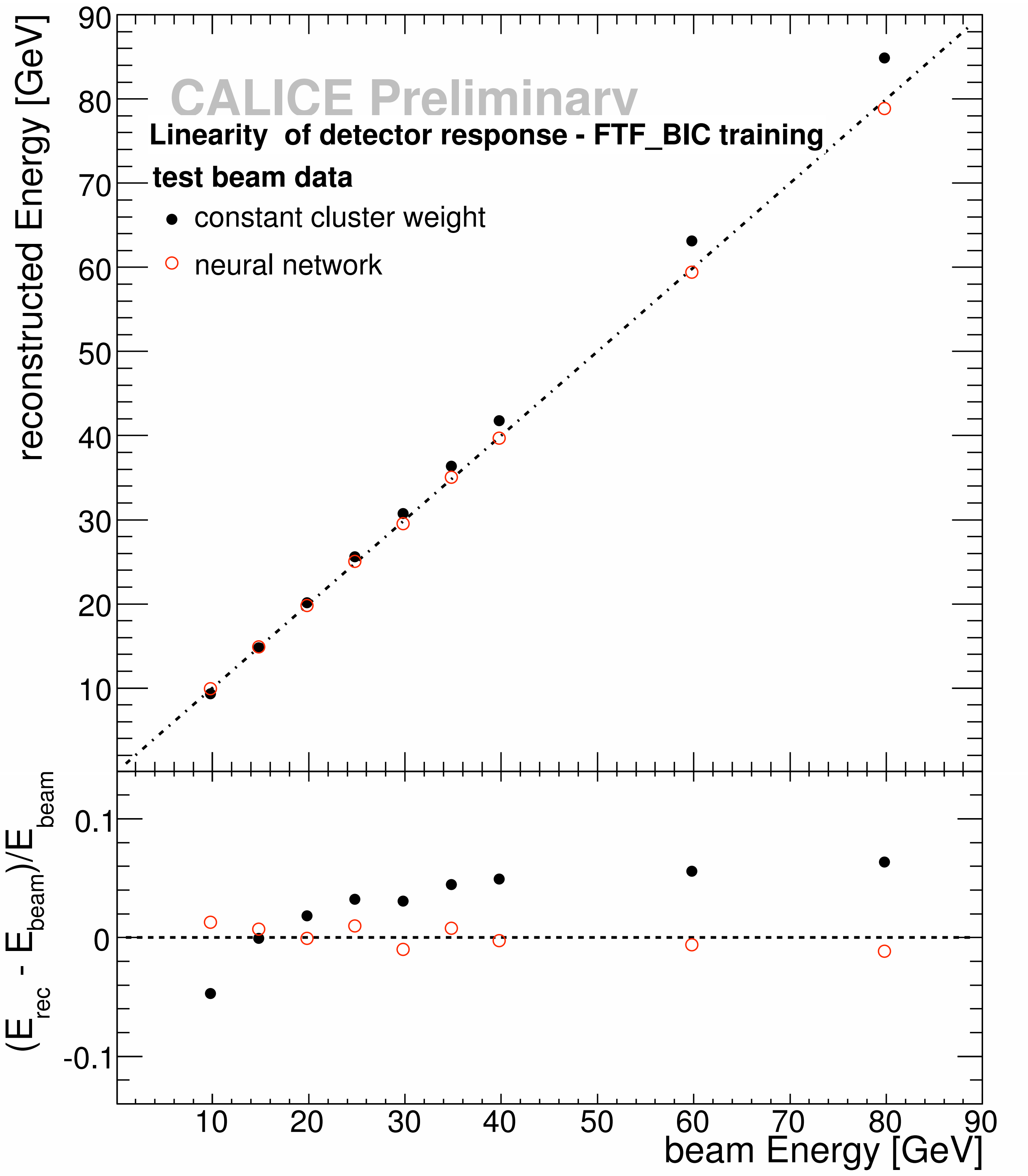
Software Compensation: Linearity of Response



- Unweighted reconstruction shows typical non-linear behavior: Increased response at high energies
- Software compensation recovers linearity within < 2% from 10 to 80 GeV

Software compensation currently being implemented in PandoraPFA: Further improvement of performance expected

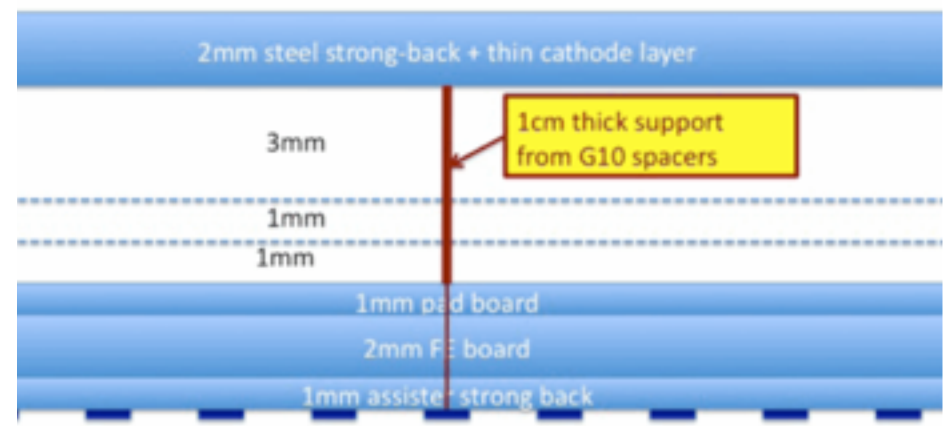
Outlook: Where Do We go from here?

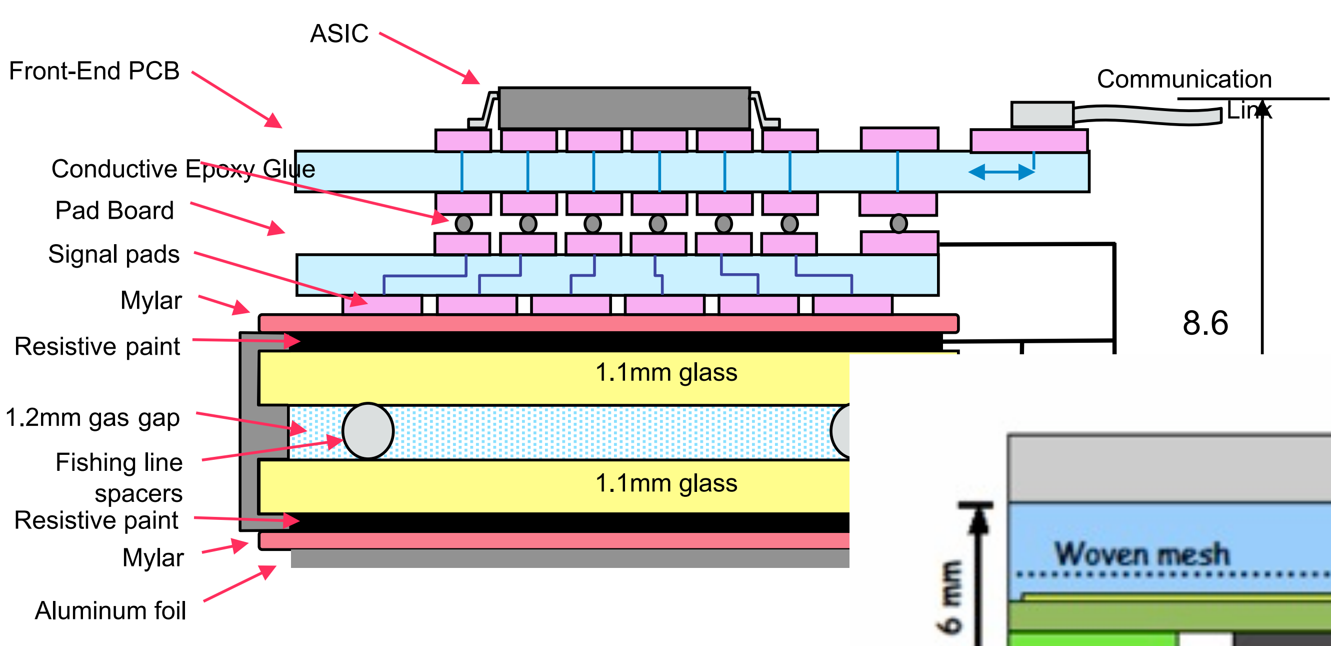
Technological Diversity

- Coming up: Alternative technologies for the HCAL: Digital / Semi-Digital calorimeters using gas detectors as readout
  - x10 more channels than the analog HCAL: pad size ~ 1 cm^2
  - 1 or 2 bits per channel
  - Insensitivity to neutrons (no hydrogen in active material!): Narrower showers, might be an advantage for PFA

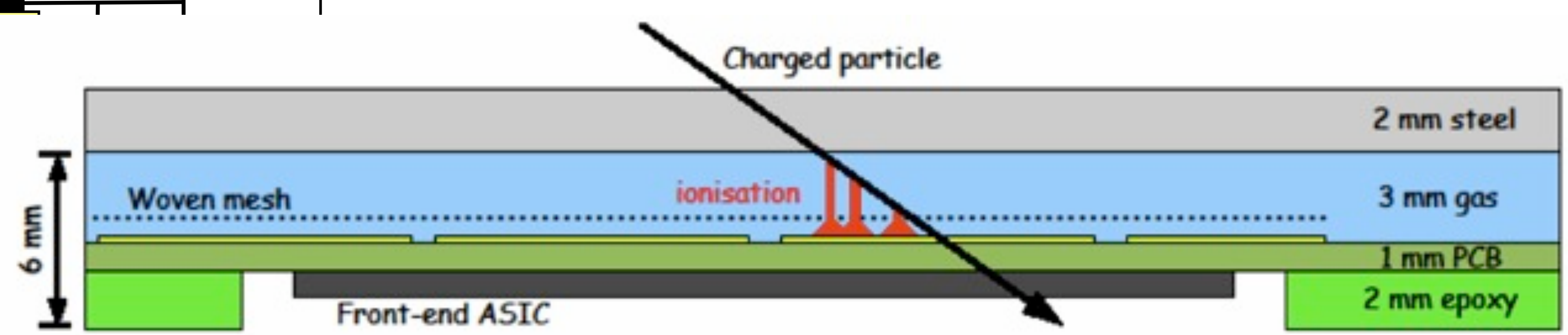
Different technologies:

Double GEM digital





RPCs digital/semi-digita



Micromegas semi-digital

Higher Energy: Tungsten as Absorber

- At a multi-TeV e^+e^- collider a very deep HCAL is required: Absorber with short interaction length mandatory to fit detector into solenoid
  - Tungsten is an obvious choice

- Tungsten is very different from Steel:
  - very different λ/X_0 ratio: em subshowers very short
  - heavier nucleus: More neutrons in the shower

Material	Fe	W
λ_I [cm]	16.77	9.95
X_0 [cm]	1.76	0.35
dE/dx [MeV/cm]	11.4	22.1
R_M [cm]	1.72	0.93

➾ How well does a Tungsten HCAL work for PFA? Need beam tests to answer!

The strategy: Use existing active layers, with a modified absorber structure, 10 mm W plates in Al frames

30 layers in production for beam test at CERN PS in November

2^{nd} Generation: Engineering Prototypes

- Realistic Calorimeter modules under development:
  - Fully integrated electronics
  - Power pulsing to reduce heat load
  - Realistic mechanical design

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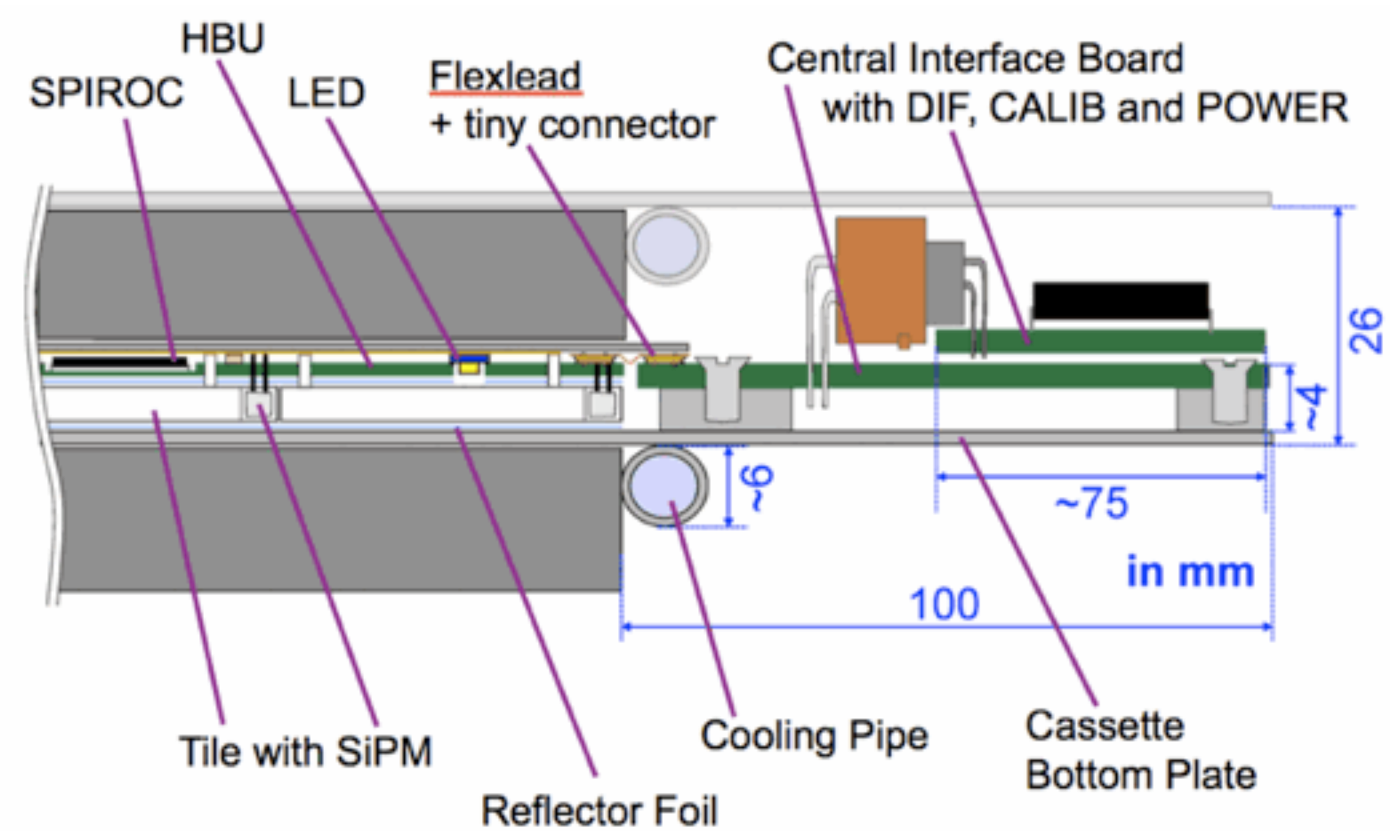
Analog HCAL

compact layers:
3 mm thick tiles + electronics in a cassette



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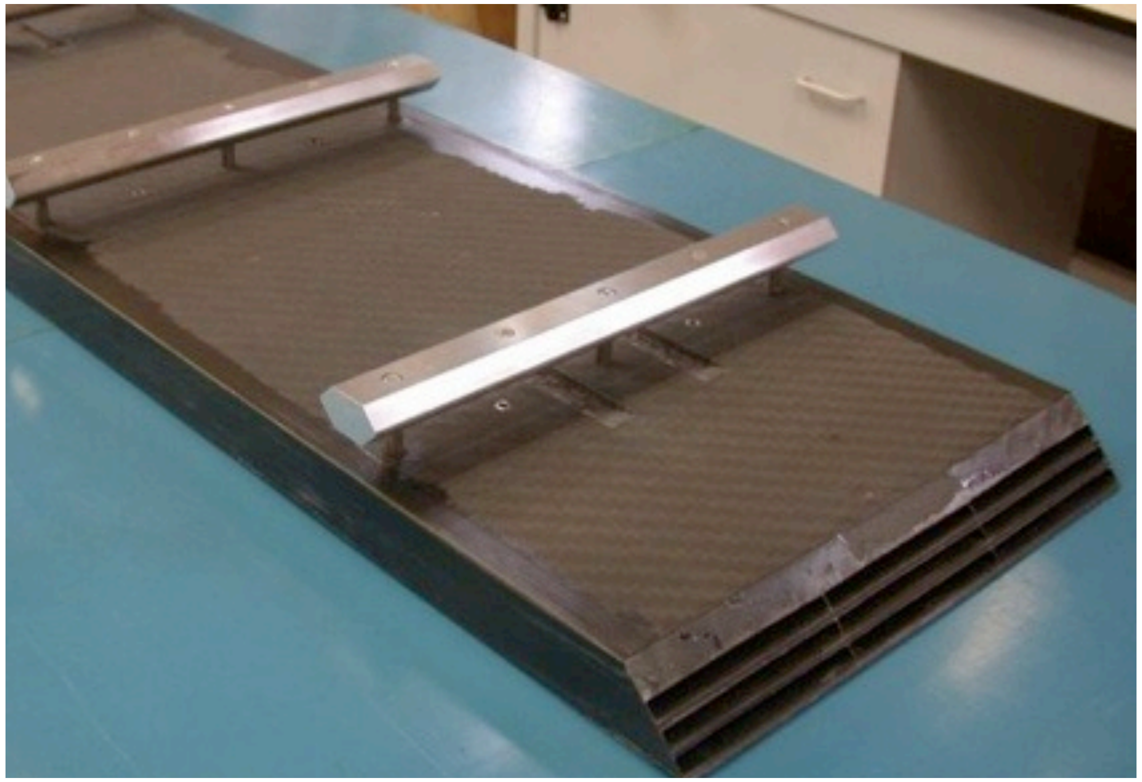

SiW ECAL: Complete mechanical structure

Analog HCAL

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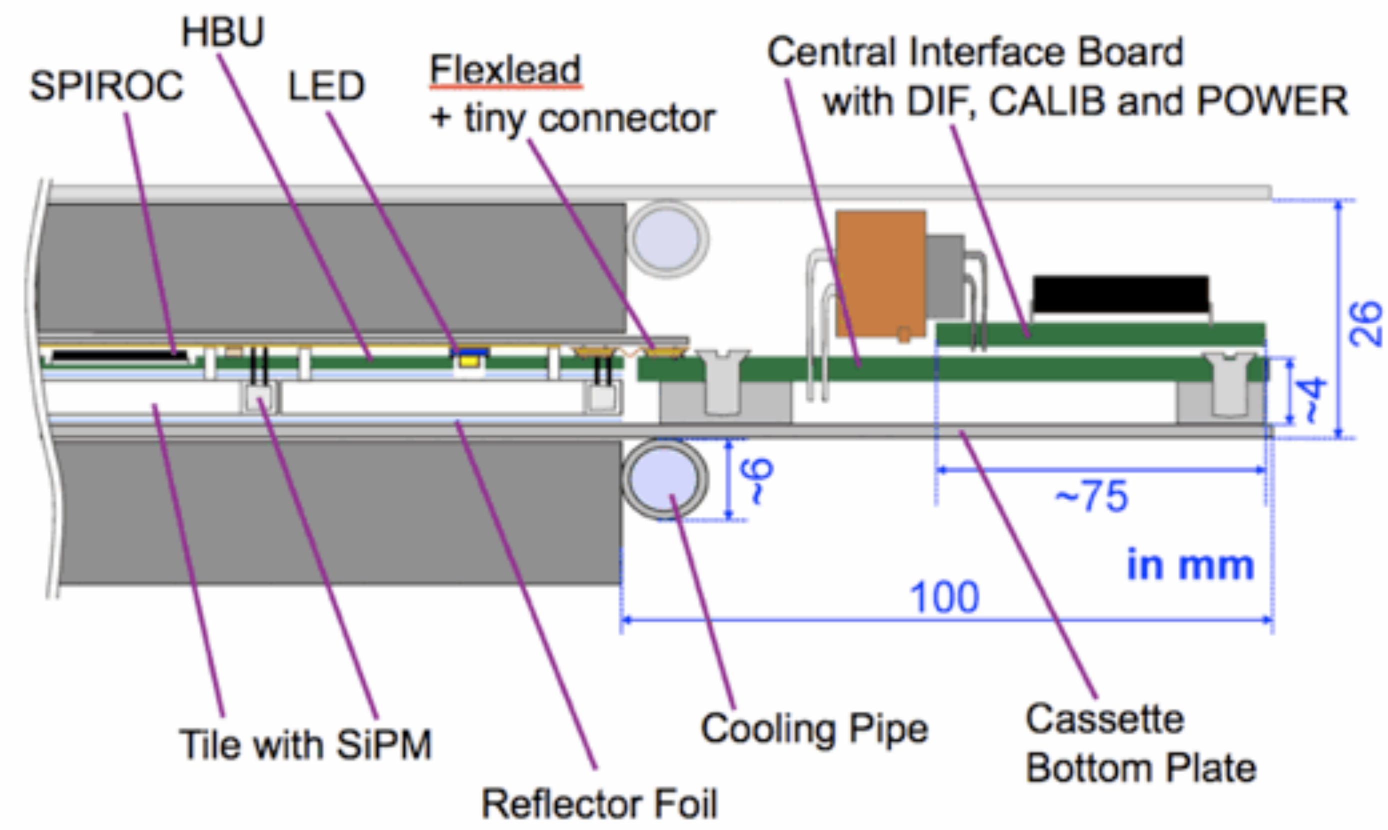
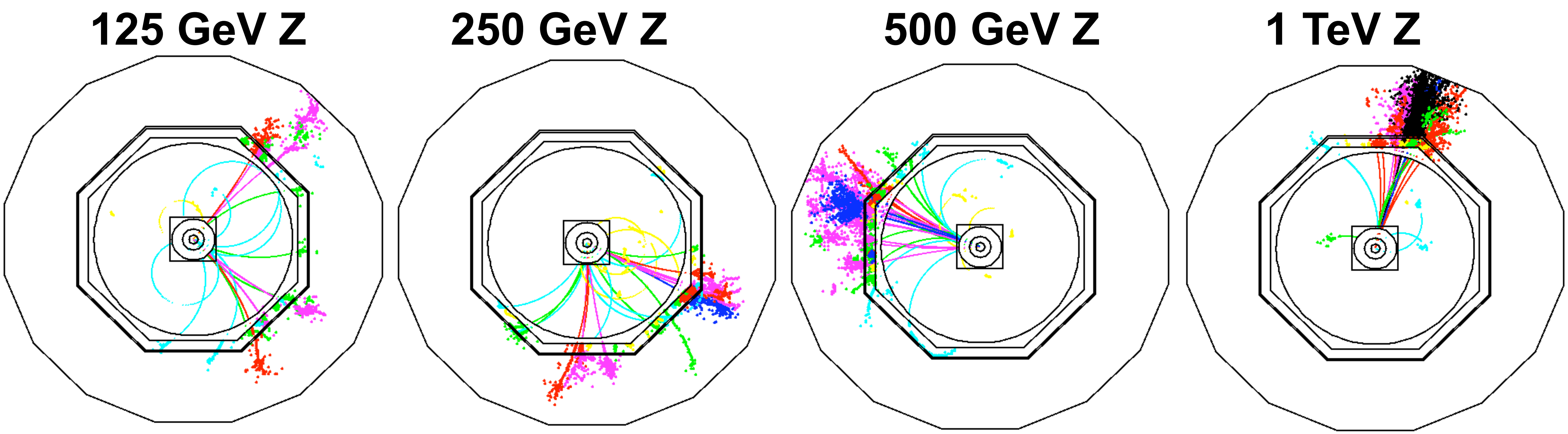


PFA at High Energy

- PFA at high (multi-TeV) energy is challenging: Very narrow jets!
  - Particle multiplicity does not change, boost increases density



These studies are just beginning:
PFA shows potential for significant improvements in mass reconstruction also at high energies, potentially by reconstructing mono-jet mass instead of di-jet mass
➪ Much progress expected during the ongoing CLIC CDR phase!

Conclusion

- We need a high-energy linear collider to pin down New Physics
- Particle Flow is a very promising technique to achieve unprecedented jet energy resolution at such a machine: better than 3% over a wide energy range
- Particle Flow Algorithm need extremely granular "imaging" calorimeters
  - Different technologies for such calorimeters are studied by the CALICE collaboration
  - Imaging calorimetry works!
    - Detailed studies of the structure of hadronic showers, important input for the further development of shower simulations
    - Advanced reconstruction algorithms for calibration and energy reconstruction
  - On the way to realistic detector prototypes