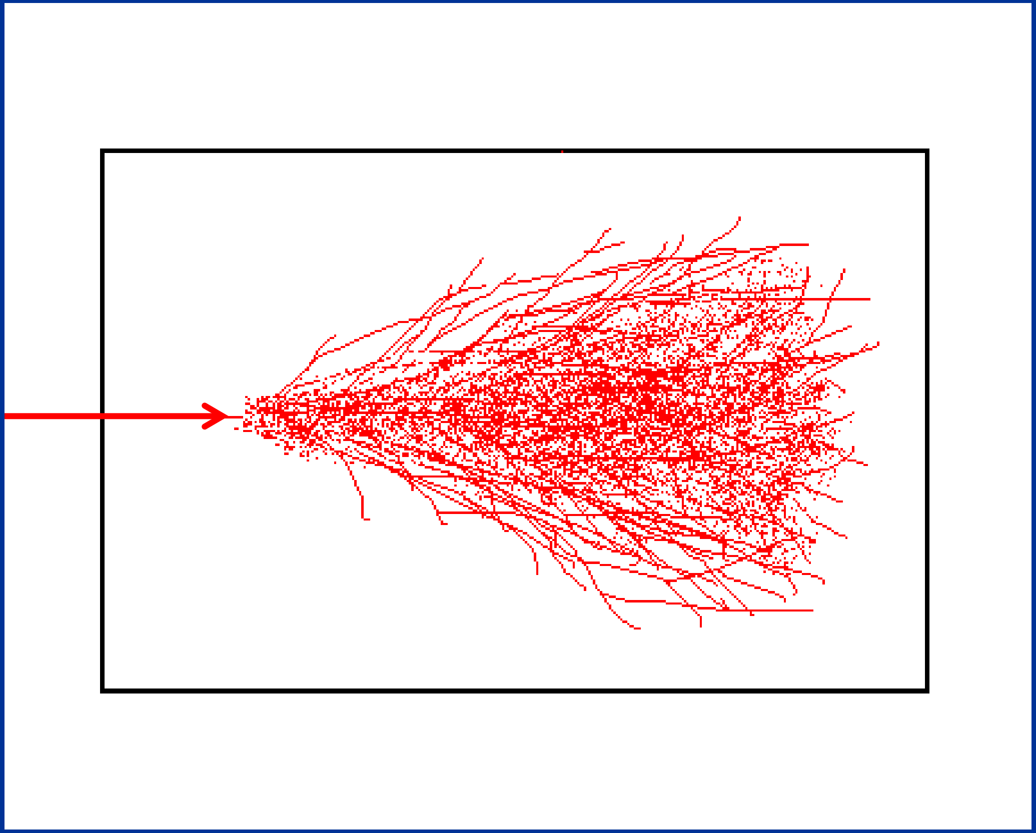
Ultra-Fast Hadronic Calorimetry



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Nucl. Instrum. Meth. A898 (2018) 125-132

CPAD 2018, Rhode Island Convention Center, December 9 2018

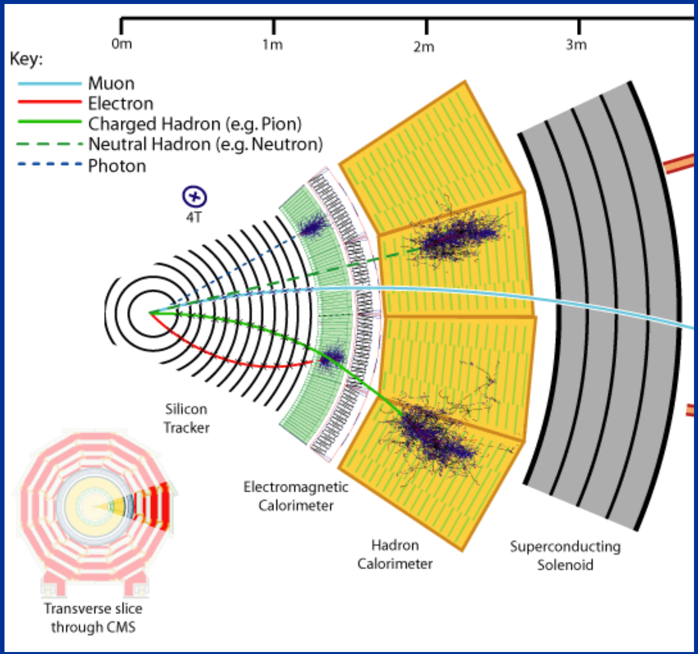
Calorimetry in High Energy Physics

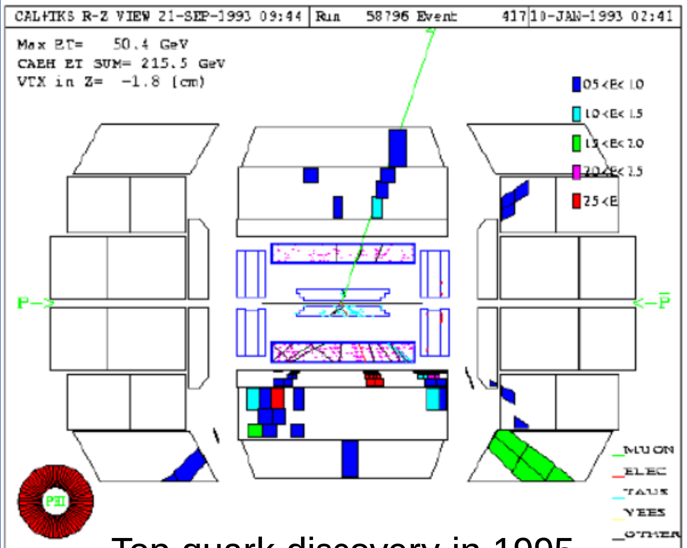
- To measure the energy of high energy hadrons such as pions, neutrons, protons, and others particles we use calorimeters

- Hadron in interaction with matter creates “showers” with 100’s and 1000’s of particles
  - Charged component of the showers deposit energy in the active medium
  - This energy is proportional to the energy of the original incident particle

- Quarks and gluons create “jets” which are large number of hadrons in a narrow cone
  - Jets detection is similar to the detection of hadrons

- Calorimeters helped with large number of discoveries and precision measurements in particle physics
  - Their developments are important for continuing progress

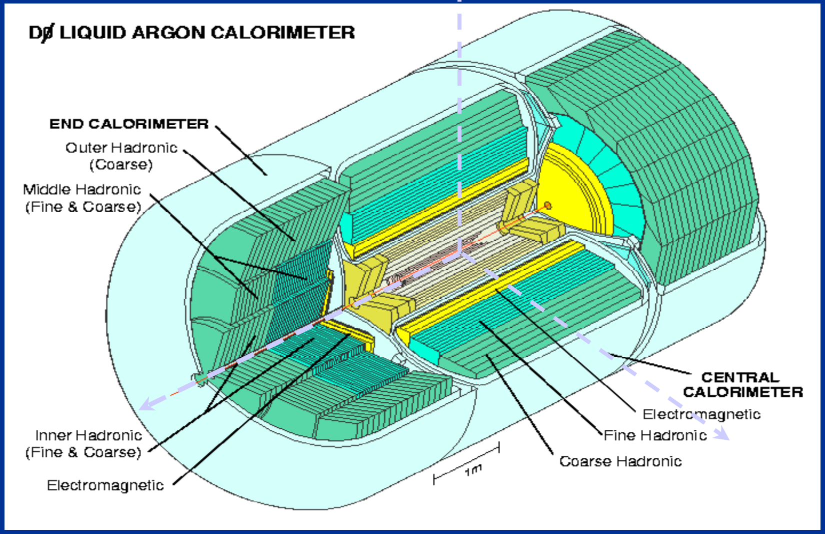




Top quark discovery in 1995

Calorimetry and Future Colliders

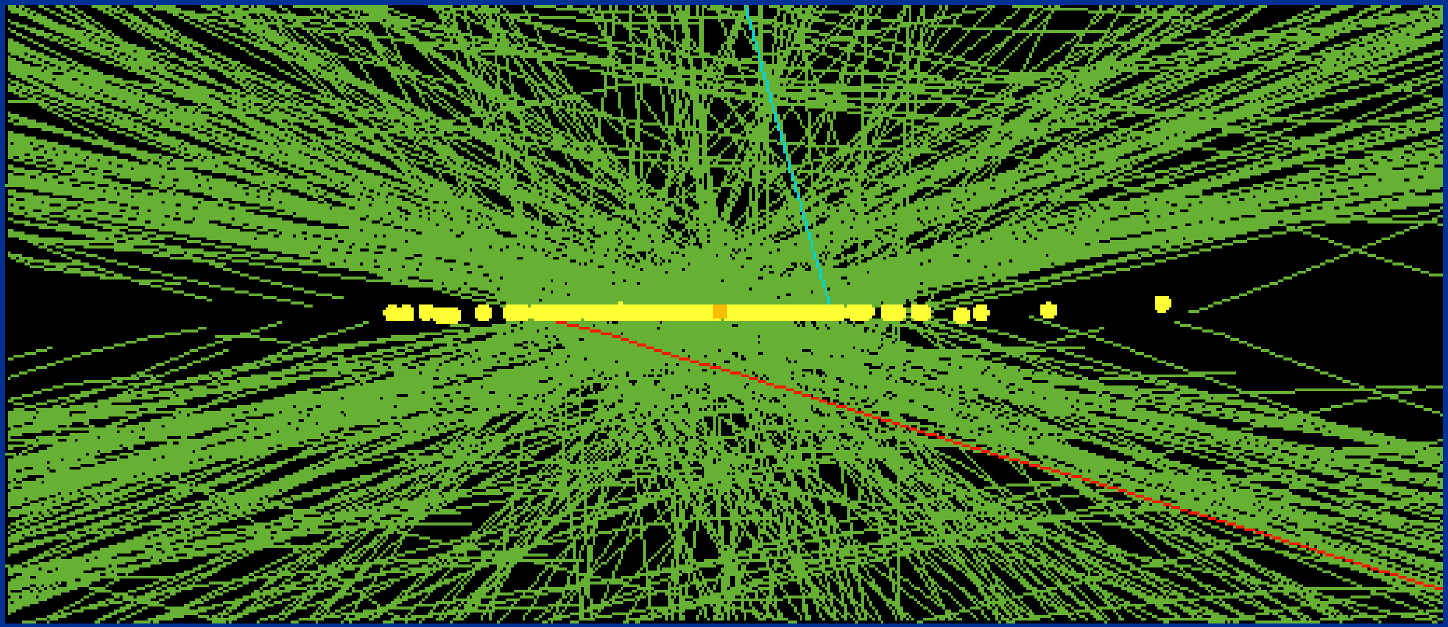
- There are discussions of future high energy colliders including ILC, CepC, FCC, SppC, muon collider, and others
  - They require high energies of particles to be detected accurately
- All of the future collider detectors have calorimetry as a critical element of a detector
  - The only way to precisely measure energy of photons, electrons and quarks/gluons
  - Shower depth is ~ln(E)
    - Minor size increase in comparison with Tevatron and LHC
  - Energy resolution:
    - Electromagnetic: ~15%/√E, ~0.5% at 1 TeV energy
    - Hadron ~50%/√E, ~2% at 1 TeV energy
- Calorimetry gets very precise at high energy!



Challenges for Calorimetry at Future Colliders

- Events pile up at hadron colliders
  - ~50 GeV/jet cone pileup at $L=10^{34}\ cm^{-2}sec^{-1}$ for 100 TeV pp collider
  - The background energy fluctuates and luminosity dependent
- Backgrounds from the beams in electron and muon colliders
  - In the case of muon collider "steady flux" of secondary particles from decays of beam muons
- Precision timing of the calorimeter signals from "interesting interaction" will help to reject the backgrounds

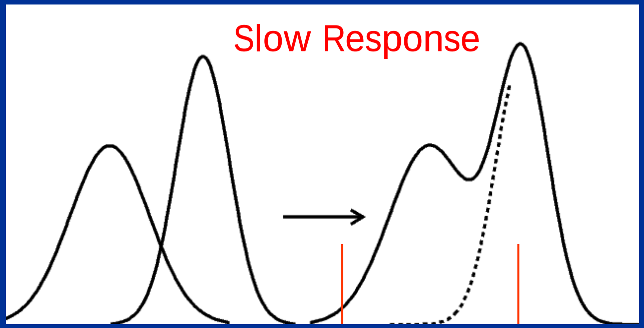
78 interactions LHC event

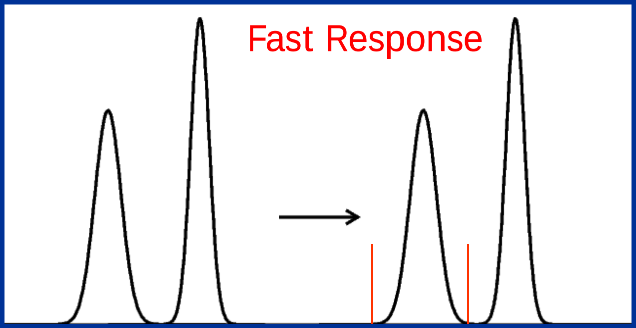


Timing of Hadron Showers

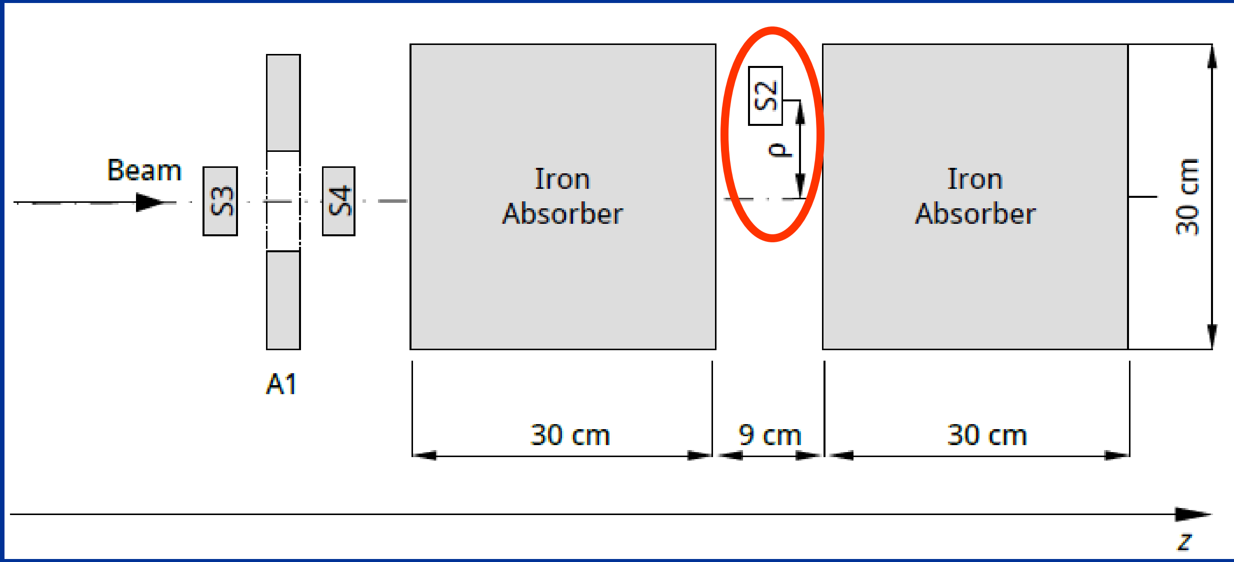
- There are two definitions of the hadronic showers "timing" we have to separate
  - Measurement when a hadron interacted with the calorimeter
    - Usually achieved by measuring arrival time of the energy deposition signals from the elements of the calorimeter
    - Even if the time measured correctly later coming particles can affect energy measurement
  - Integration time for the measurement of the energy deposition in the calorimeter
    - This parameter defines fraction of the energy deposition collected
    - If the integration window could be reduced substantially vs typical of 10's to 100's ns, backgrounds will be substantially reduced
      - From other crossings at hadron colliders
      - From beam induced backgrounds at muon and electron colliders
- Question we aimed to clarify in this study

How narrow could be the signal integration window in a hadron calorimeter in order to preserve energy resolution?





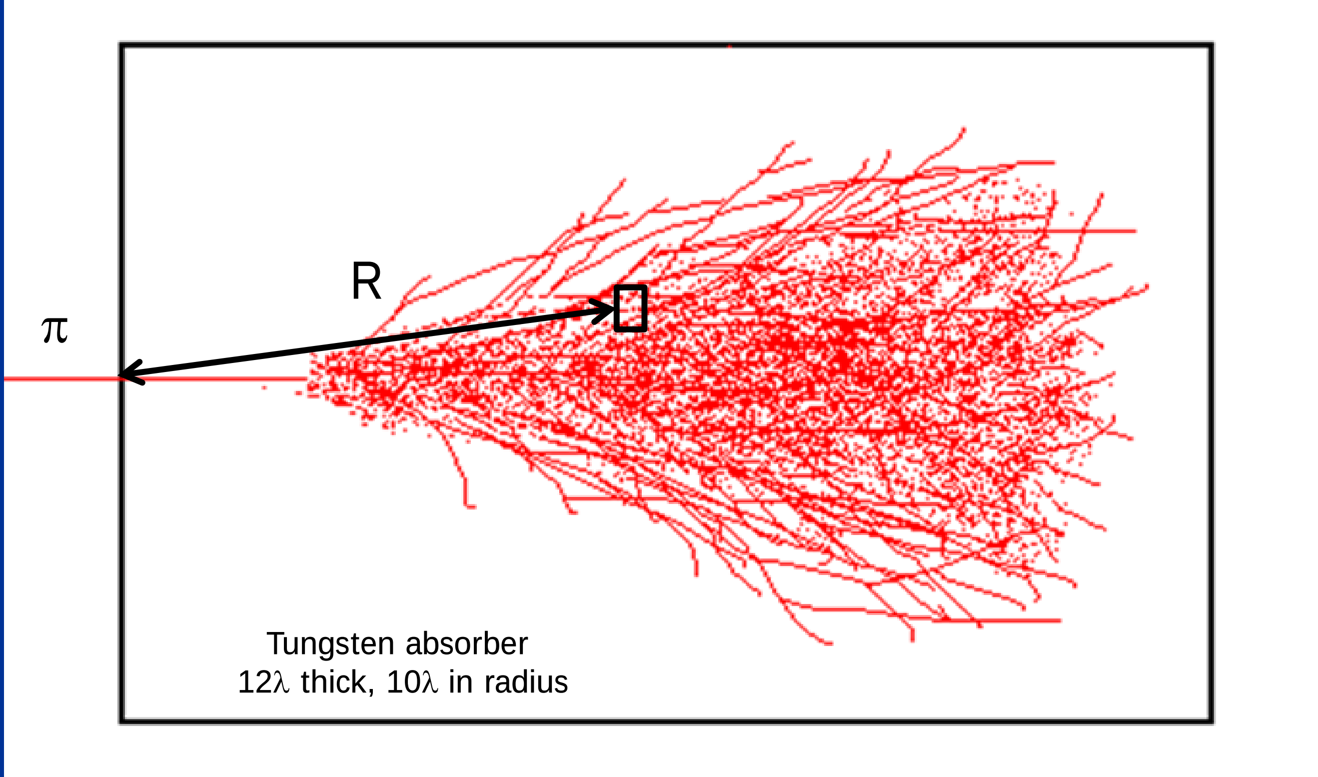
Test Beam Data and Simulation



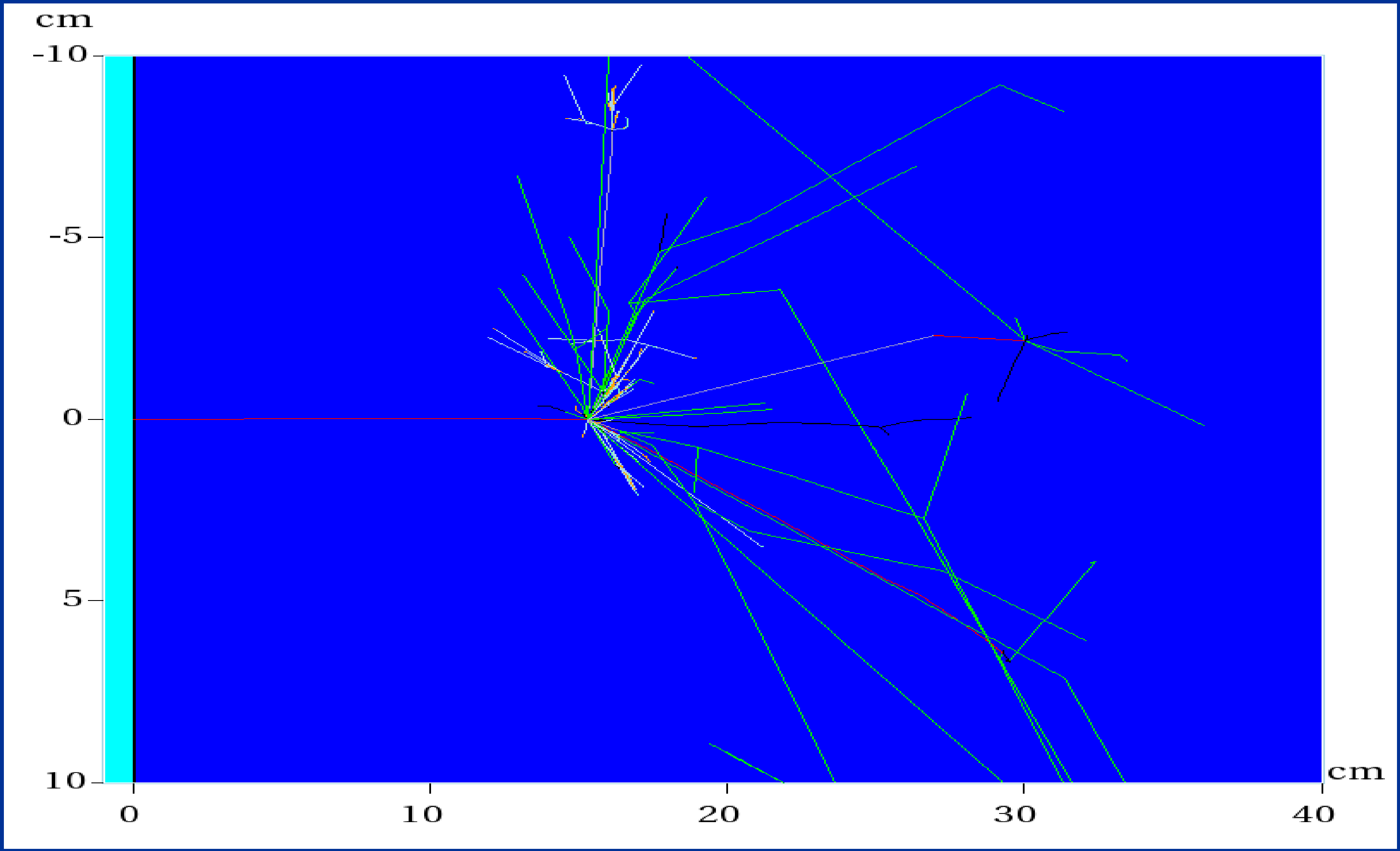
- Test beam with pion/proton energies in the range 30-120 GeV
- Small scintillation counter S_2 with fast phototube is placed at various distances from the beam and various depths (from 1.8 λ to 3.0 λ)
  - Used to measure energy deposition vs time
- Compare test beam results with MARS code simulation (code similar to GEANT4)
  - N.V. Mokhov and S.I. Striganov, "MARS15 overview", AIP Conf. Proc. 896 (2007), pp.50-60 http://www-ap.fnal.gov/MARS
  - MARS includes nuclear effects, such as decays and emissions
- Verify that MARS reproduces timing of hadronic showers well
- Use MARS to simulate performance of calorimeters vs integration time

"Relative Time" Definition

- We study energy deposition of hadronic showers for "relative time" t_{rel}
  - Absolute time of the energy deposition from the moment the incident particle enters the calorimeter is t_{abs}
  - Relative time of the energy deposition defined as $t_{rel} = t_{abs} - R/c$ (see R definition below)

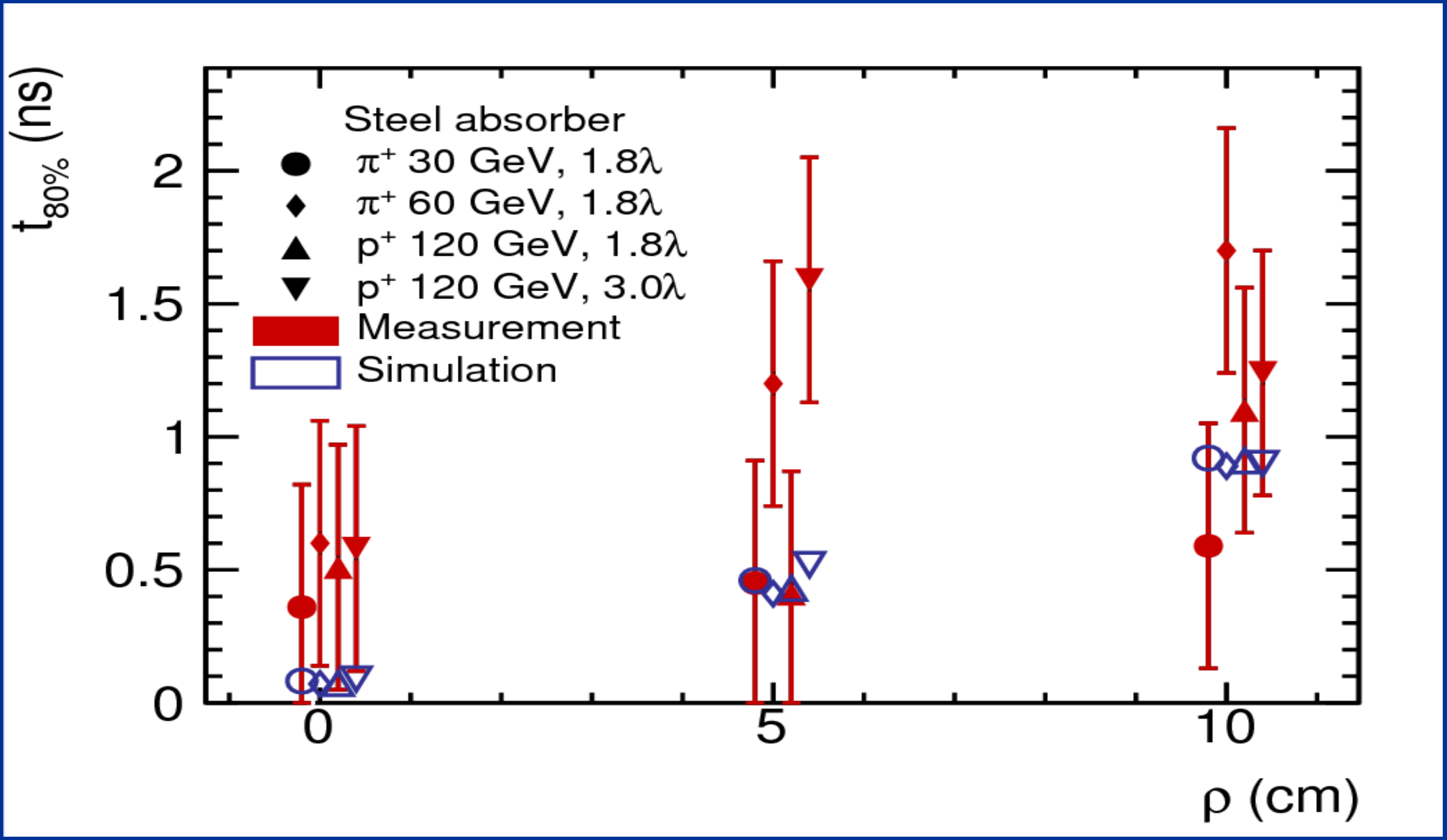


10 GeV π Induced Shower in Tungsten



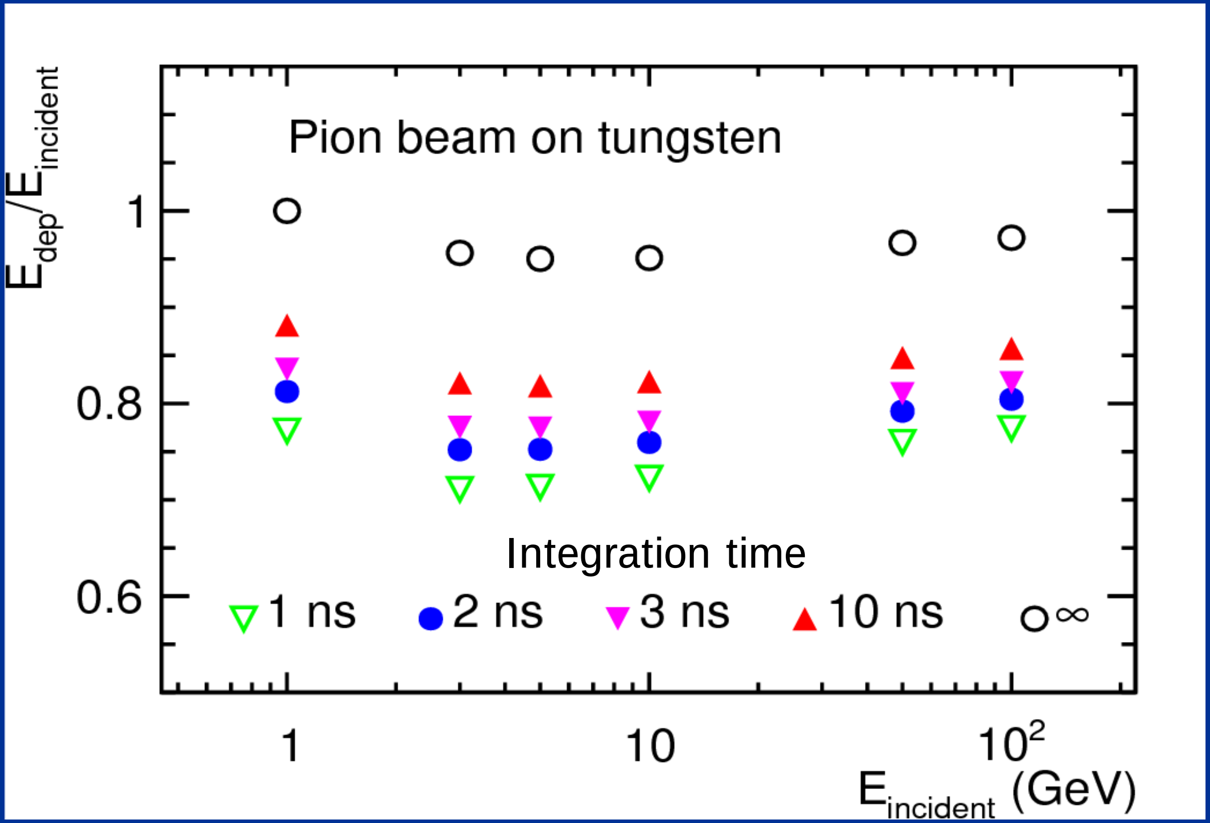
- Dark blue - tungsten
- Red lines - pions, black - protons, green - neutrons, grey – photons
- Pretty complex picture with particles moving in various directions

Data and Simulation Comparison



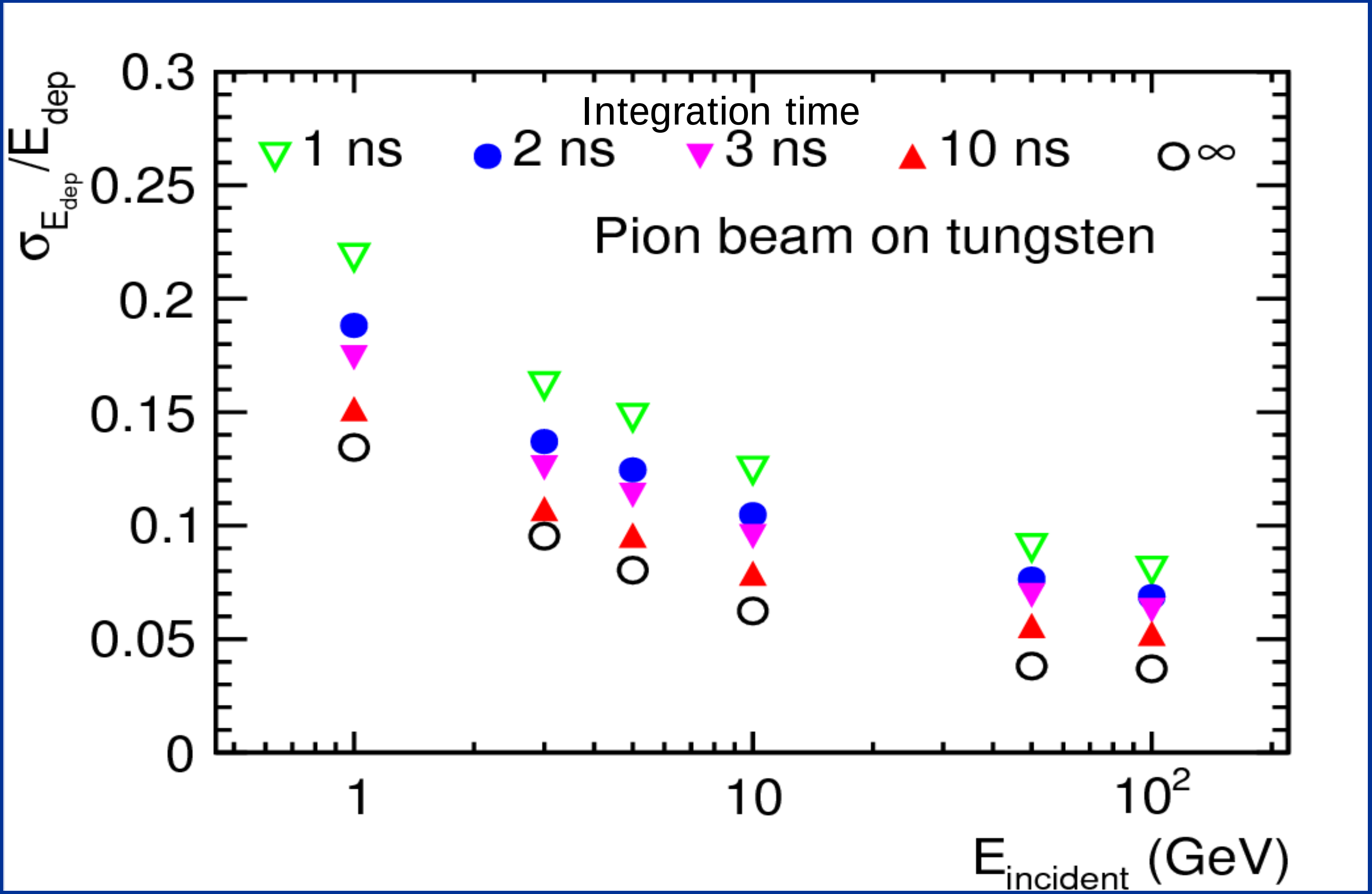
- $t_{80\%}$ is the time when 80% of the energy deposition for a given S_2 counter position is integrated
  - ρ is the distance from the beam axis
- Good agreement between data and simulation
  - $t_{80\%}$ are very small ~1 ns !

Shower Energy Deposition vs Integration Time



- After verification of MARS simulation we use MARS for prediction of a calorimeter timing performance
- Solid block of tungsten with large sizes is used as "ideal" calorimeter
- For integration times of 1-2 ns 70-80% of the incident particle energy is detected
  - What about energy resolution or fluctuations of the deposited energy?

Energy Resolution vs Integration Time



- **A few ns energy deposition integration time provides close to the ultimate energy resolution**
- **Some of the sources of the energy fluctuations, like sampling, are not taken into account in this simulation**

Summary

- **Reduction in the integration time for the hadronic calorimetry is an excellent option to reduce out of time backgrounds at high energy colliders**
- **Energy integration time as low as 2-3 ns provides similar information about the shower energy as much longer integration times**
  - **Hadronic showers energy deposition is very fast!**
  - **Matches well 5 ns beam bunches spacing option for HE-LHC / FCC-hh**
- **Replacement of tungsten with copper as an absorber does not affect main conclusions of the studies**
- **Performed simulation does not take into account energy detection process**
  - **Active media, such as scintillator, is required to detect the energy deposition**
  - **Fast (a few ns response) active media is required in this case**
- **Fast photodetectors are critical to utilize potential of very fast hadronic showers development**