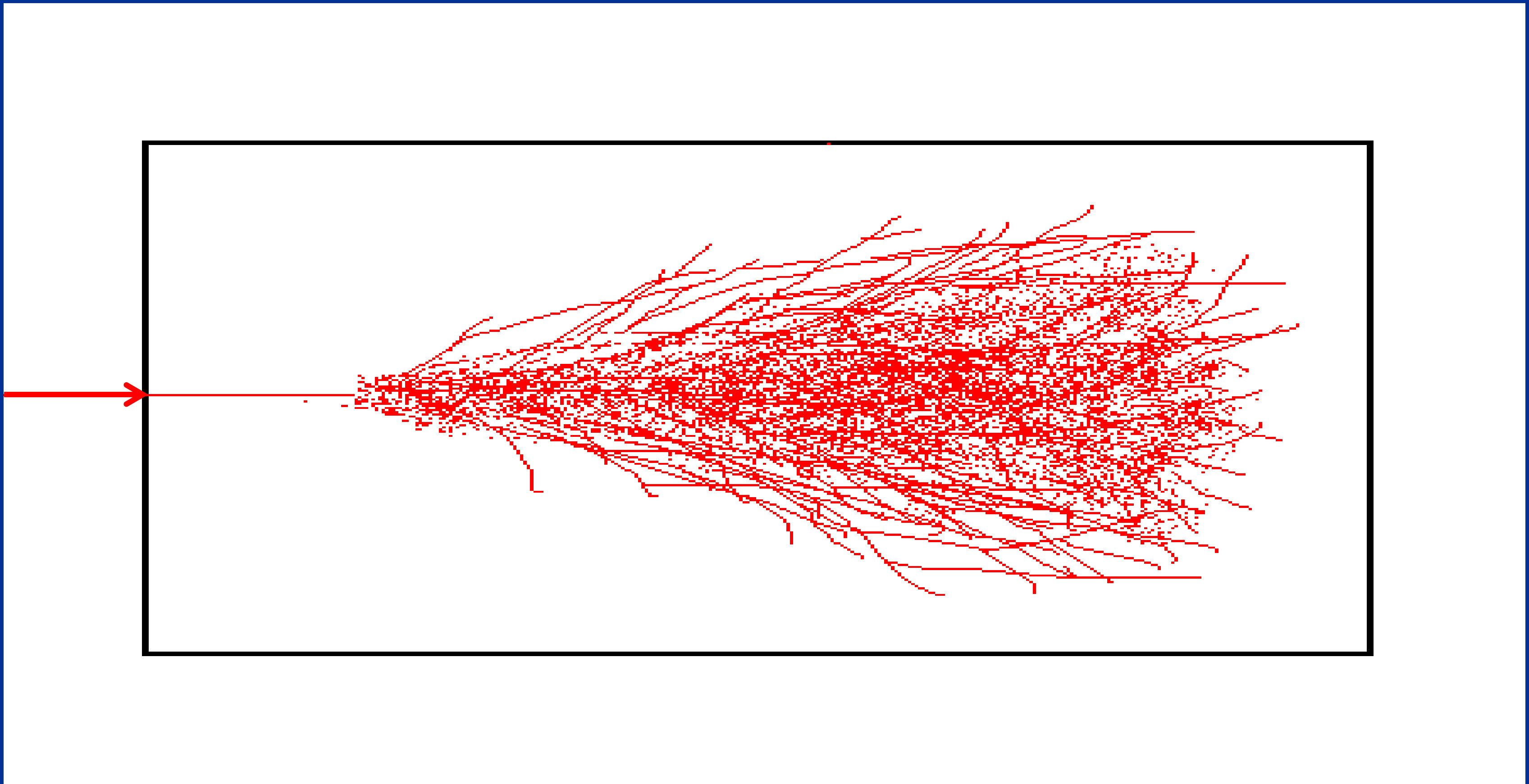
# Minimum Time Integration Calorimetry

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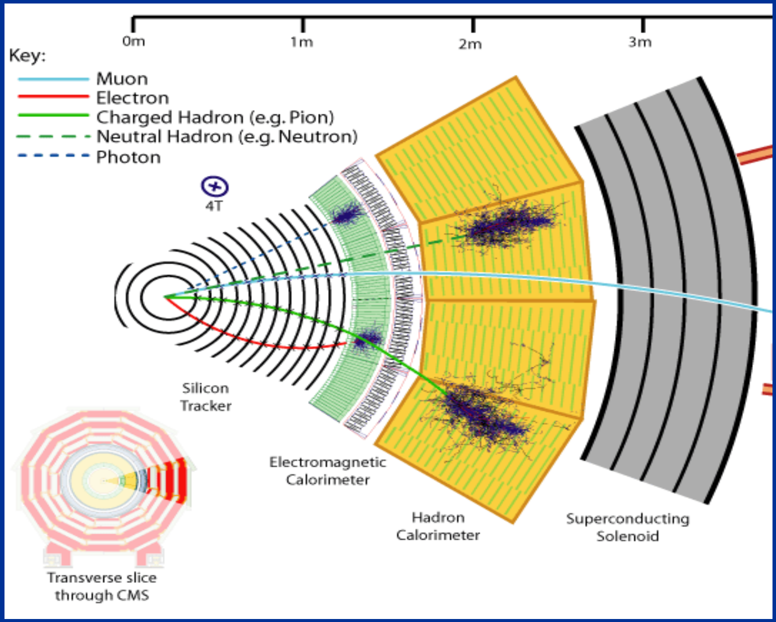
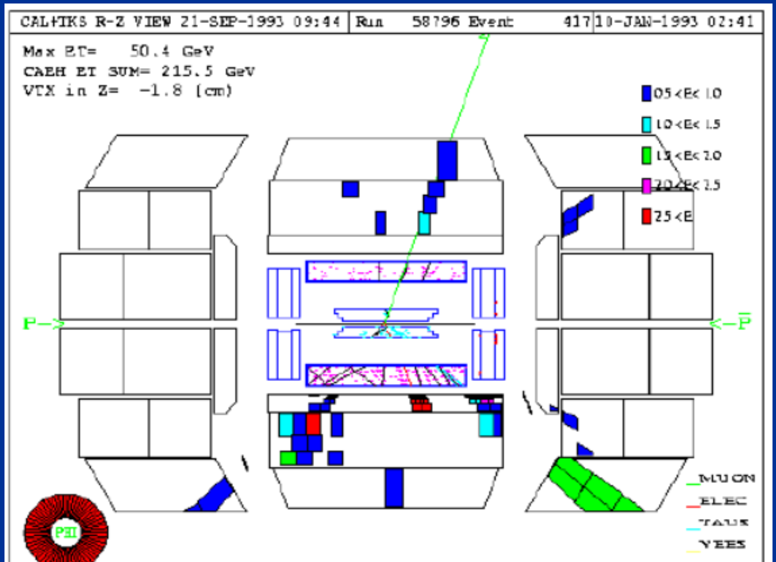
**Fermilab**


**FCC April 2016 Meeting, Rome, April 13 2016**

# Calorimetry in High Energy Physics

- To measure the energy of high energy hadrons such as pions, neutrons, protons and others in particle physics we use calorimeters
  - As well as electrons and photons
- 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 were critical for large number of discoveries and precision measurement in particle physics
  - Their developments are important for continuing progress in particle physics

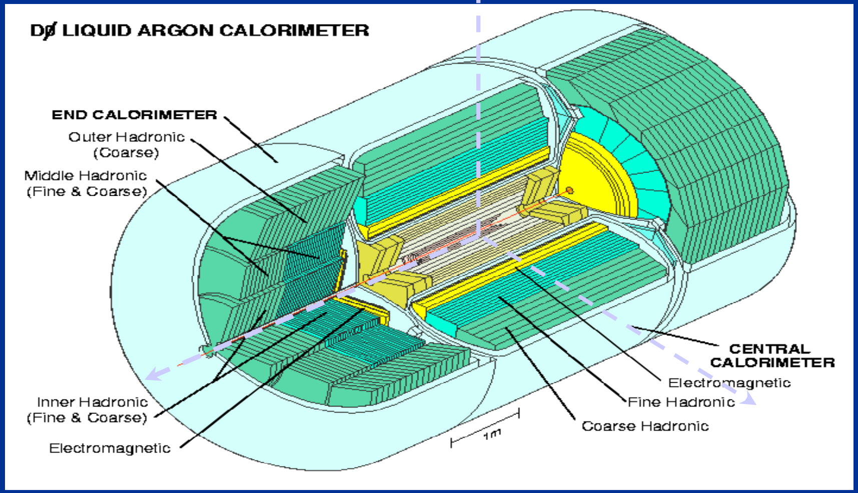



Top quark discovery 20 years ago

# Calorimetry and Future Colliders

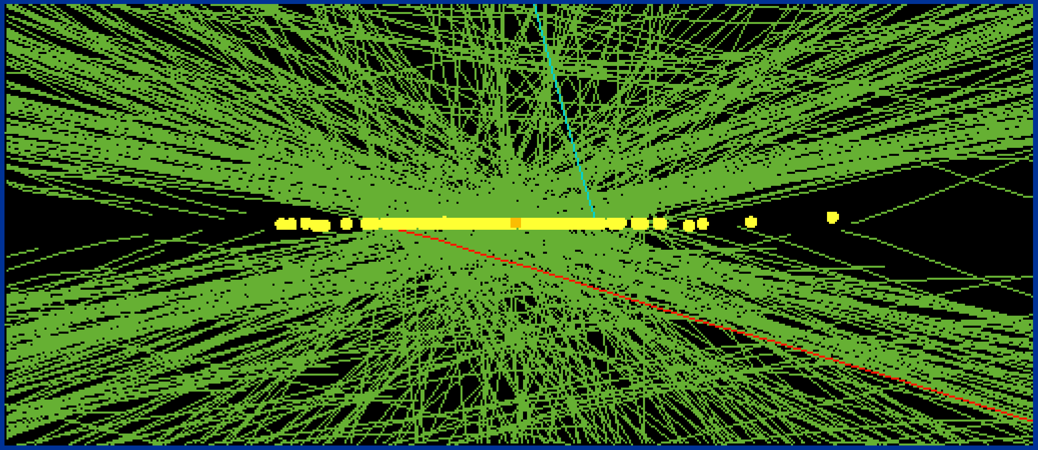
- There are extensive discussions of future high energy colliders such as FCC, ILC, CepC, CppC, muon collider, and others
  - Some of them require substantially higher energies of particles to be detected
- All of the future collider detectors have calorimetry as a critical element of a detector
  - The only way to precisely measure energy of photons, electrons and quarks/gluons
  - Shower depth is ~ln(E)
    - Minor increase in a calorimeter size in comparison with the Tevatron and LHC
  - Calorimetry 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

- **Main requirements**
  - **Small constant term in the resolution, stable, easy to calibrate**
  - **Thick for excellent energy resolution and accurate missing energy detection**
  - **Radiation hard (for hadron colliders)**
- **Challenges**
  - **Events pile up at hadron colliders**
    - **About ~50GeV/jet cone deposited from pile up at L=$10^{34}$ cm$^{-2}$sec$^{-1}$ for 100TeV 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**
- **Precise timing of the signals from "interesting interaction" should help to reject the backgrounds**

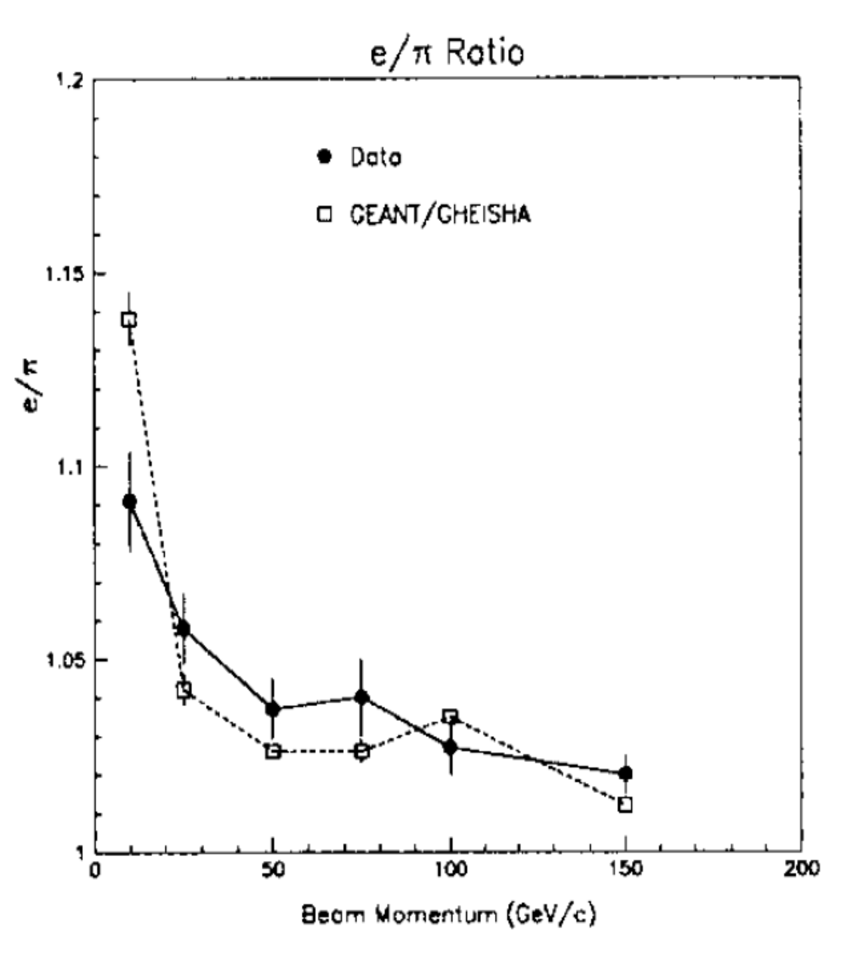
78 interactions LHC event



# Calorimeters Signal Integration Time

- **Hadron calorimeter integration time is very important parameter due to the physics of the showers developments**
- **During Tevatron Run I DZero calorimeter had very good energy resolution due to "compensation"**
  - **Uranium absorber helped to equalize detected energies of the electrons and hadrons**
- **With smaller ~0.45μs vs ~2μs charge integration window for Tevatron Run II compensation deteriorated**
  - **Decays of excited uranium nuclei happen long after shower development and corresponding charge not captured with short integration time**
  - **Resolution of the calorimeter deteriorated substantially**

**DZero Run I Calorimeter Uranium/Liquid Argon**



# Timing of Hadron Showers

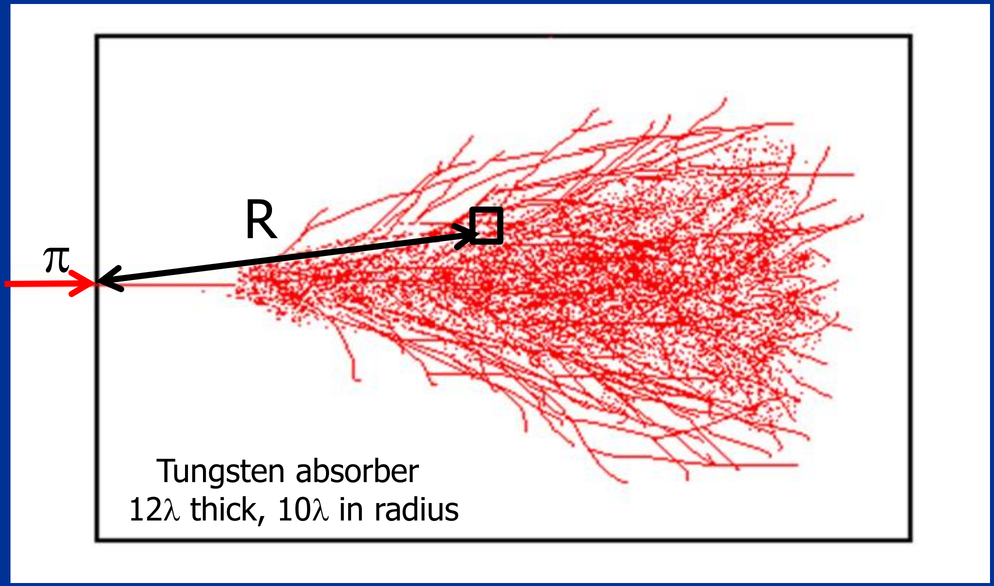
- There are two definitions of hadronic showers "timing" we have to separate
  - Measurement when a hadron interacted with the calorimeter
    - Usually achieved by measuring arrival time of the energy deposition signal from some or all elements of the calorimeter
    - Energy of the hadron is measured separately
  - Integration time for the measurement of the energy deposition from the calorimeter
    - This parameter defines fraction of the energy deposition we collect
    - If the integration window could be reduced substantially vs typical of ~10's to 100's of ns some backgrounds could be substantially reduced
      - From other beams crossings at hadron colliders
      - From out of time beam induced backgrounds at muon and electron colliders

- Question we address in this study

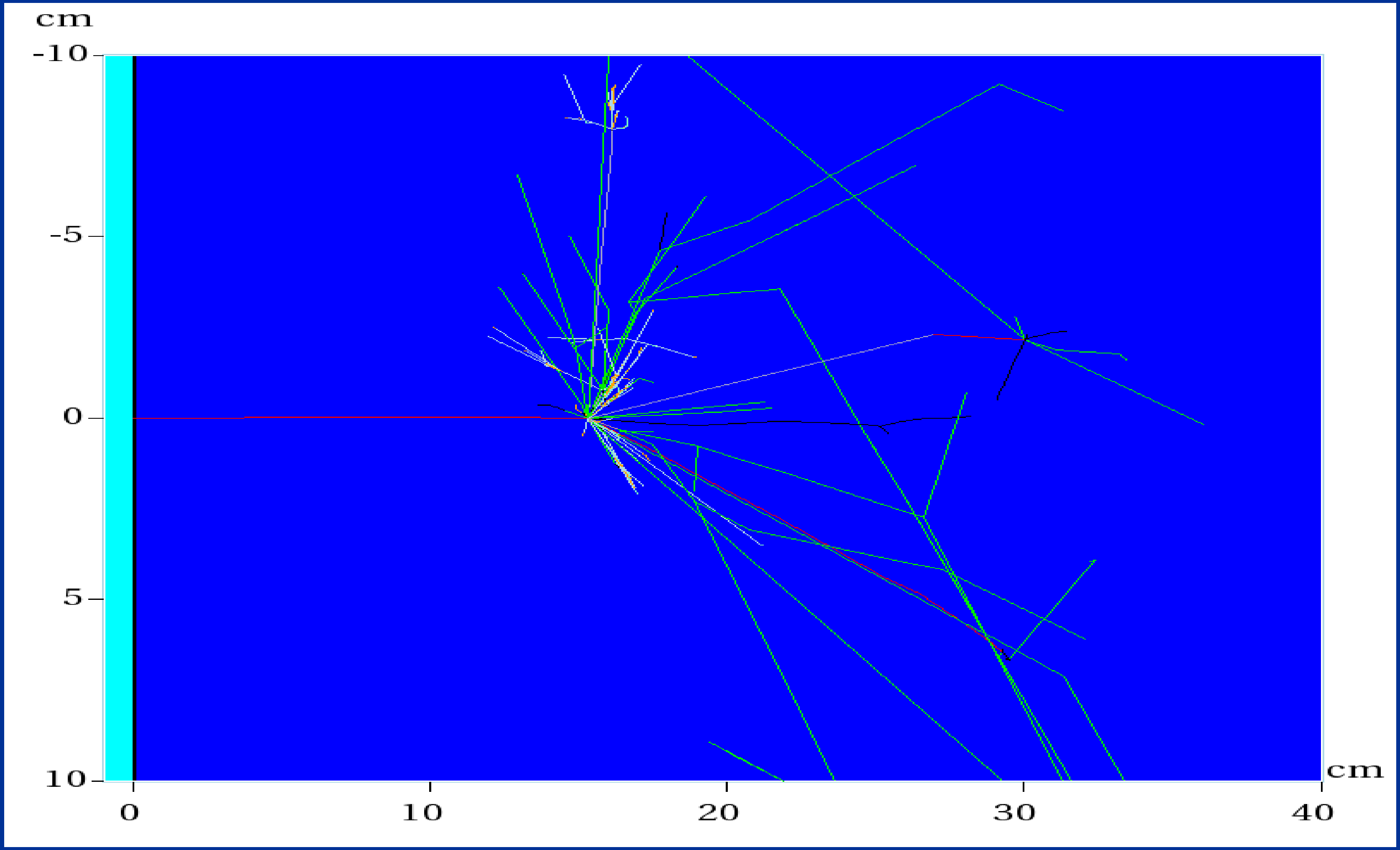
**How narrow could be the signal integration window in a hadron calorimeter in order to preserve energy resolution?**

# The Study

- We simulated development of hadronic showers in tungsten initiated by charged pions with different incident energies
- Showers were simulated using MARS version MARS15(2014)
  - N.V. Mokhov and S.I. Striganov, "MARS15 overview", AIP Conf. Proc. 896 (2007), pp.50-60. http://www-ap.fnal.gov/MARS
  - MARS15 is similar to GEANT4, but has better handling of low energy nuclear interactions/disintegrations as well as particle production processes in the energy region of a few GeV
- We studied energy deposition in hadronic showers for two cases
  - Using absolute time of the energy deposition from the moment incident particle enters the calorimeter $t_{abs}$
  - Relative time of the energy deposition defined as $t_{rel} = t_{abs} - R/c$ (see R definition below)

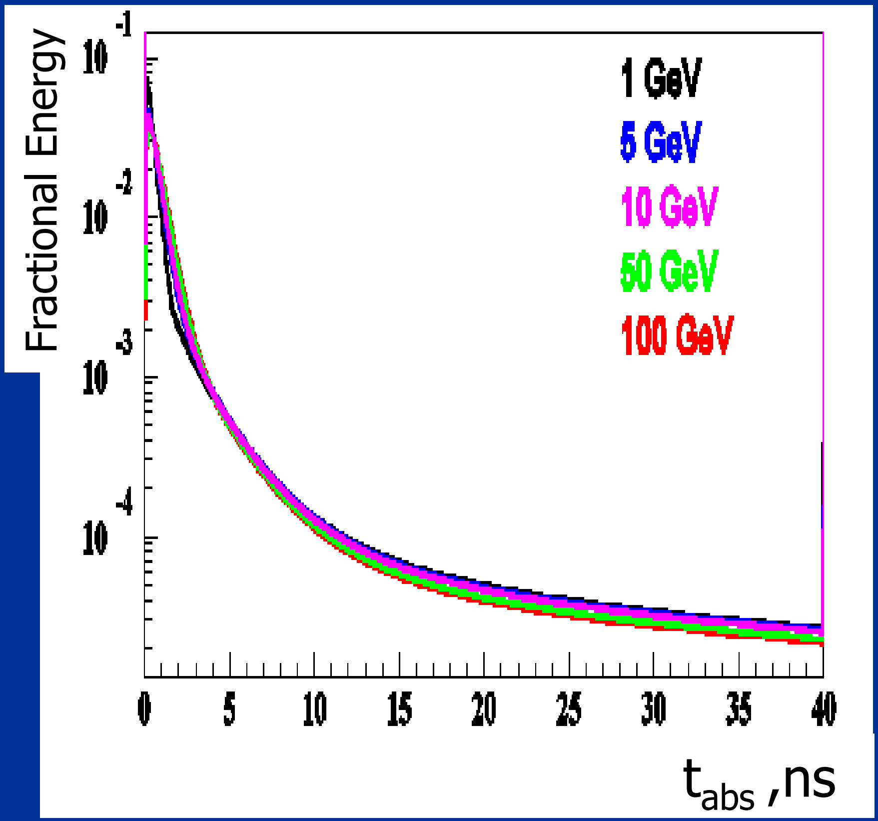


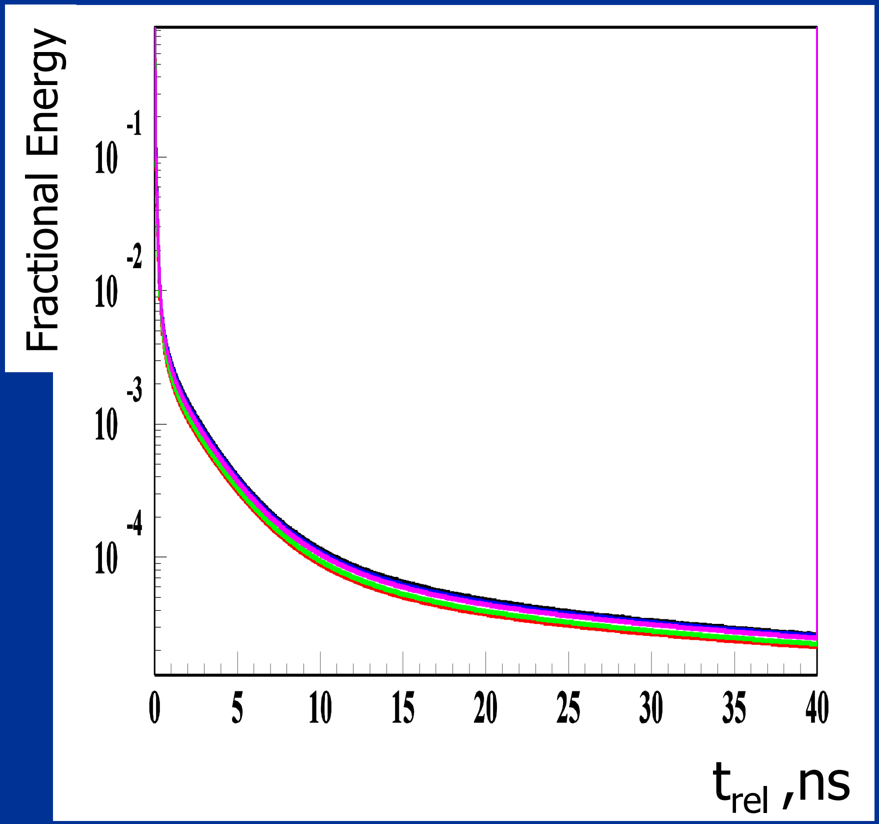
# 10 GeV $\pi$ Induced Shower in Tungsten




- **Dark blue - tungsten**
- **Red lines - pions, black - protons, green - neutrons, grey - photons…**

# Shower Energy Deposition vs Time

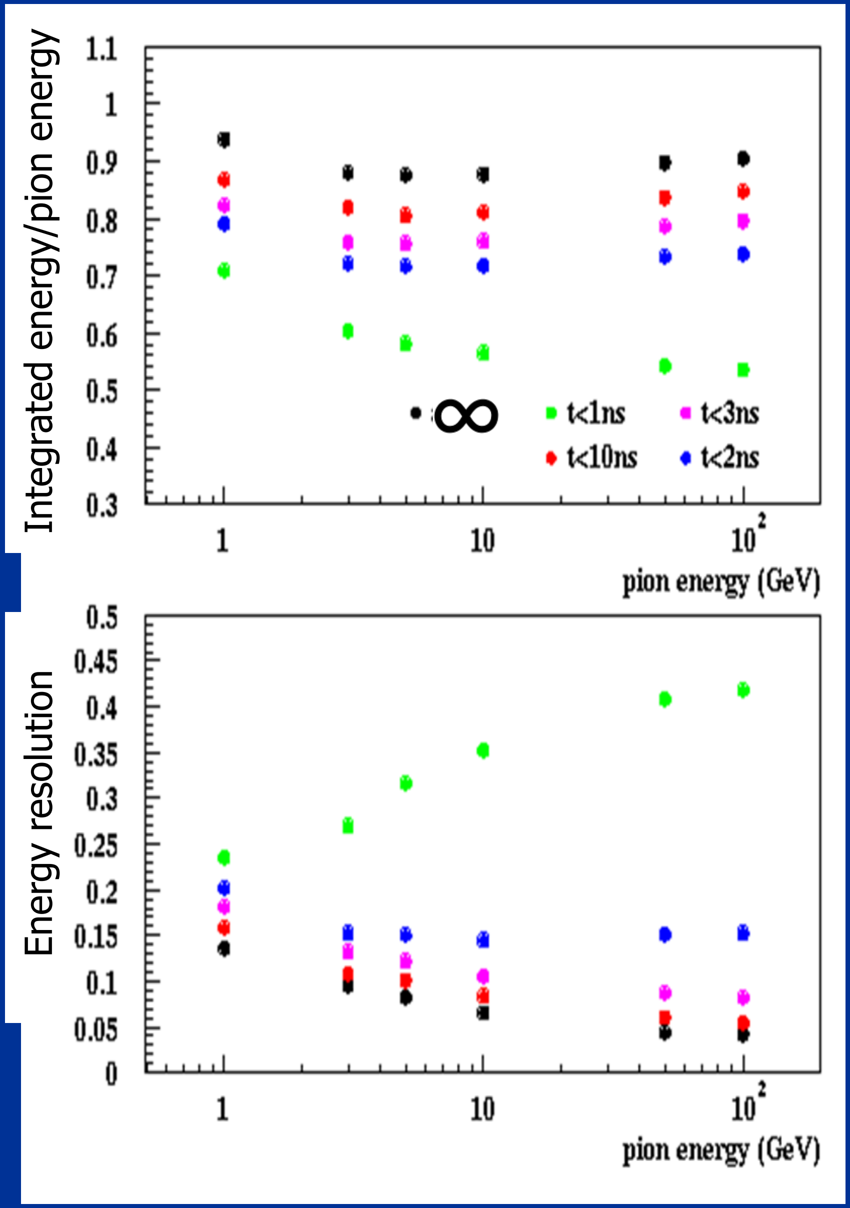



- **$t_{abs}$ distribution has a typical width of "a few" ns driven by the size of the shower (~1meter/c) with tail caused by low energy particles, mainly neutrons**
- **$t_{rel}$ distribution is much narrower with shape independent of the incident particle energy**

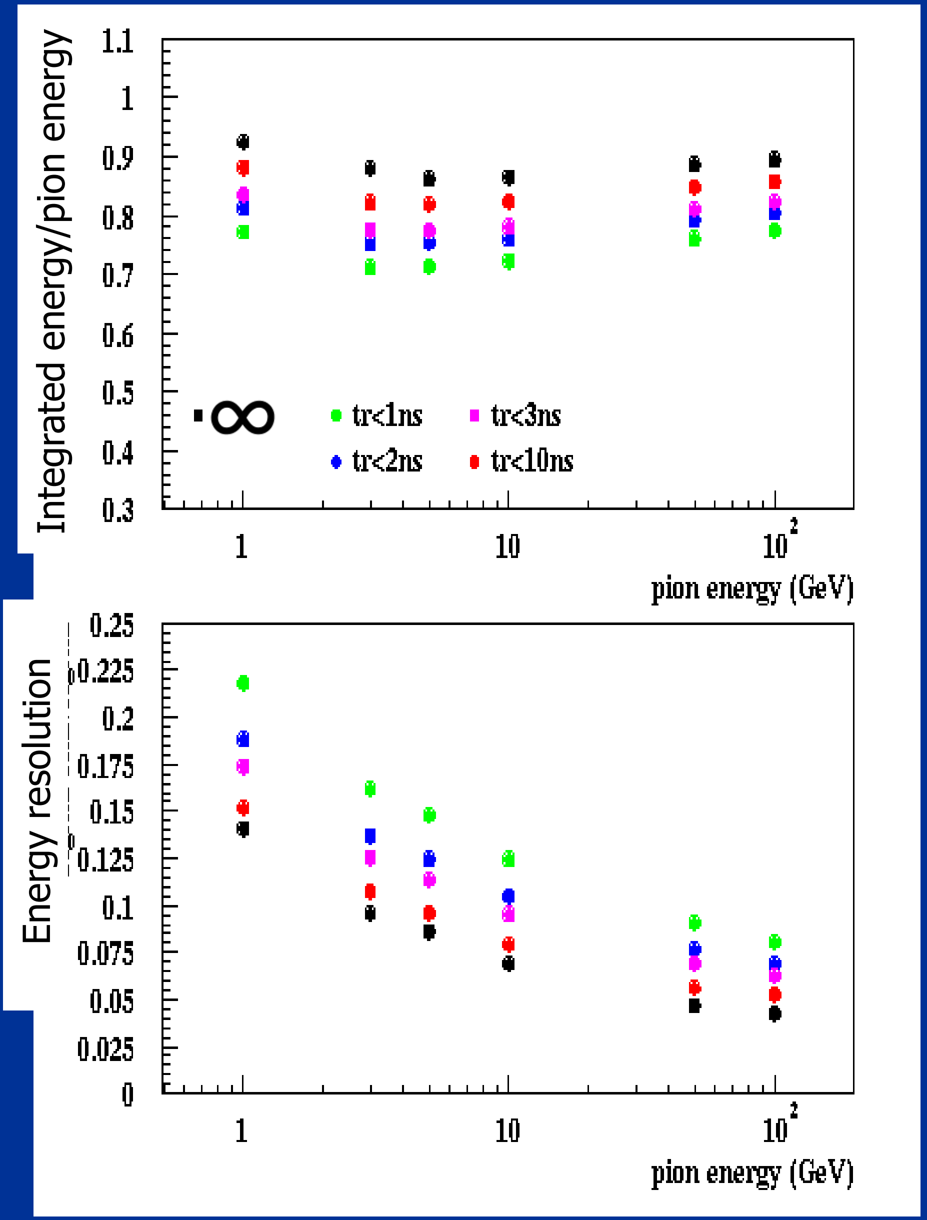
# Energy Deposition vs Integration Time for $t_{abs}$

- **Energy integration window starts when the pion hits the absorber and ends at the time specified on the plots**
- **For short integration windows only small initial part of the shower development is integrated**
  - **Even for infinite integration window there is "undetected" energy due to nuclear fragments and escaping neutrons/neutrinos**
- **For the integration times below 3 ns energy resolution defined as RMS of the integrated energy over the pion initial energy deteriorates significantly**
  - **For the integration times of ~5 ns and above the energy resolution is comparable to the ideal**

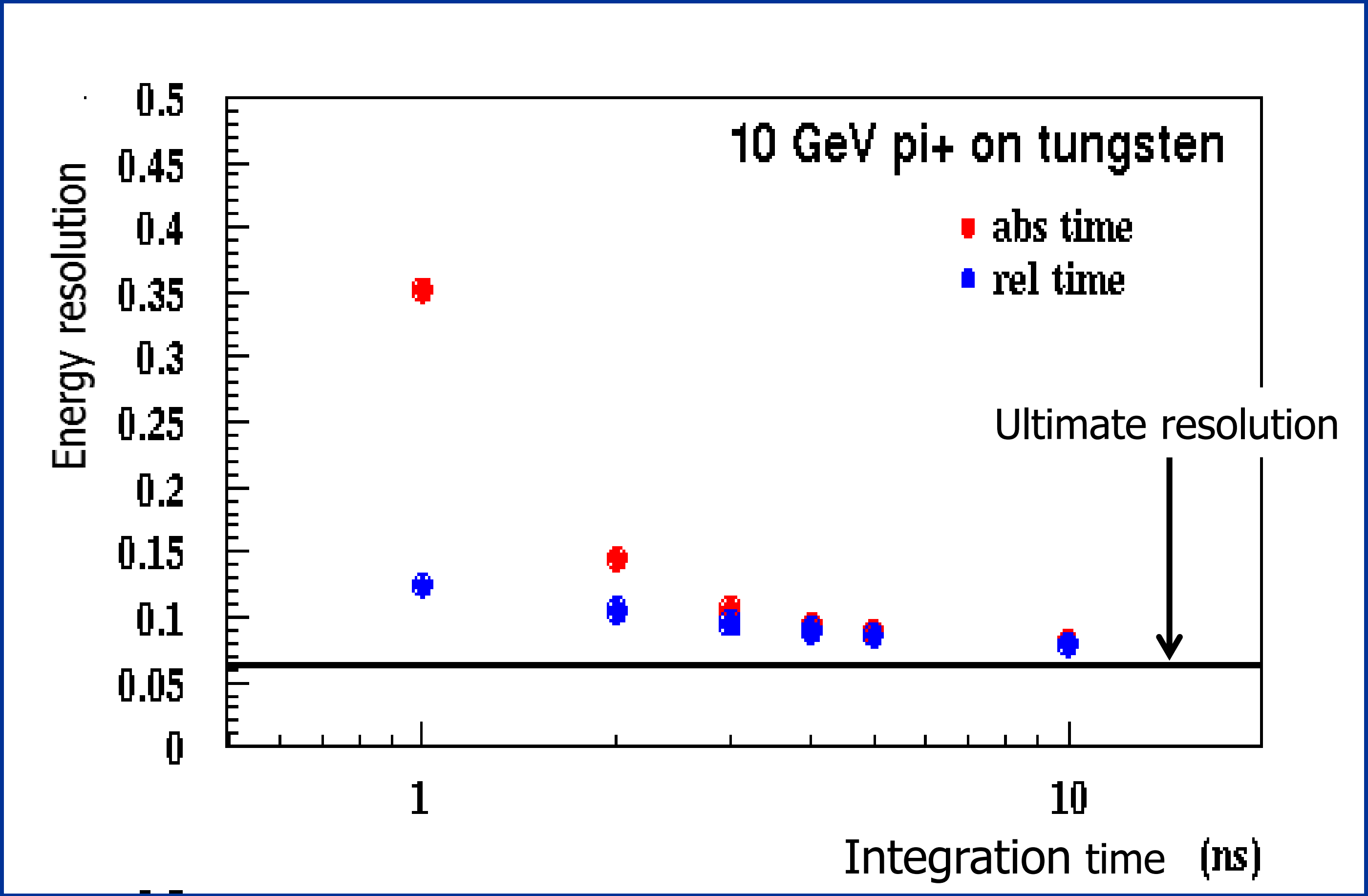


# Energy Deposition vs Integration Time for $t_{rel}$

- **Energy integration window starts at time R/c and ends at the time specified on the plots**
  - **Easy to implement in practice in the longitudinally segmented calorimeter**
- **Even for short integration time of 1 ns ~80% of the shower energy is detected!**
- **Energy resolution even for short integration times behaves similar to the infinite integration dependence**
  - **For the integration windows of ~3 ns and above the energy resolution is comparable to the ideal**



# Energy Resolution vs Integration Time




- **Even a few ns integration time (=electronics integration gate) in $t_{rel}$ 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 interesting option to reduce out of time backgrounds at high energy colliders
- Energy integration window as low as 1-3 ns provides similar information about the shower energy as much longer windows
  - Hadronic shower energy deposition is very fast!
- Replacement of tungsten with copper as an absorber does not affect main conclusions of the studies
- Perfromed simulation does not take into account energy detection process
  - Active media, such as scintillator or silicon, is required to detect the energy deposition
  - Fast active media has clear advantages in this case
- The main conclusions of this study hold for the electron/photon induced showers as well
  - Due to faster electrons speed vs hadrons and lack of neutrons in the showers

# Backup Slides

# Energy Deposition $t_{abs}$