High energy muon scattering in GEANT4

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Outline

- Geant4 electromagnetic (EM) physics for CLIC and FCC
  - List of processes
  - High energy EM effects
- Muon processes in Geant4
  - List of processes
  - Validation
  - High energy muon scattering
- Summary

Standard EM proceeses in Geant4

- Gamma
  - Photoeffect
  - Gamma conversion – dominates at high energy
  - Compton scattering
  - Rayleigh scattering – not used for high energy
  - Photo-nuclear
- Electron/positron
  - Ionisation
  - Bremsstrahlung
  - Elastic scattering
  - Electro-nuclear
  - Synkrotron radiation

Effects at high energies

- LPM (landau-Pomeranchuk-Migdal) effect
  - Saturation of EM cross sections
  - Due to scattering of projectile charged particle on length below gamma formation length
  - Affect bremssrahlung and gamma conversion
- Nuclear formfactors
  - Cross section supression
  - Affect ionisation and elastic scattering
- Positron annihilation with electrons of the media
  - Of concern for interaction region design

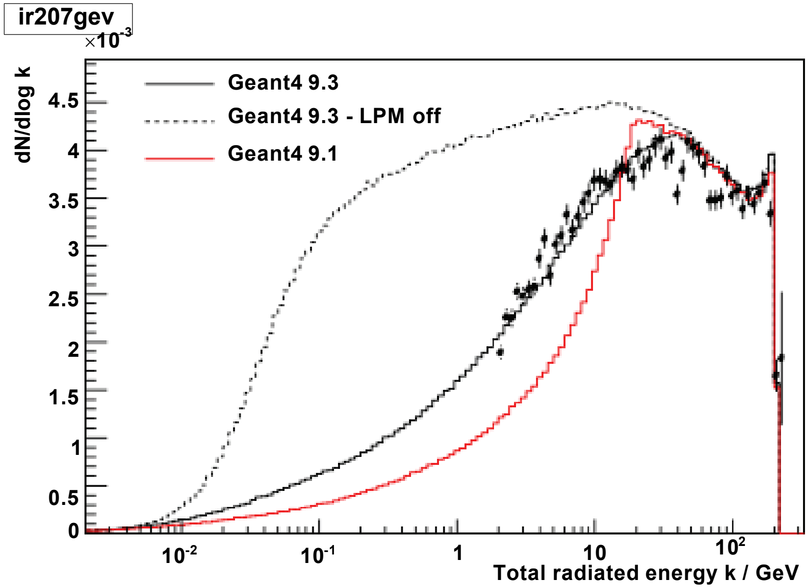
Physics validation - Bremsstrahlung & Pair production

CHEP'2010, A. Schealicke (DESY, Zeuthen)

New relativistic bremsstrahlung model

- Bethe-Heitler formula with corrections
- complete screening (valid $E > 1$ GeV)
- includes density and LPM effect

  and consistent combination
  a'la Ter-Mikaelian
- available since Geant4 version 9.2

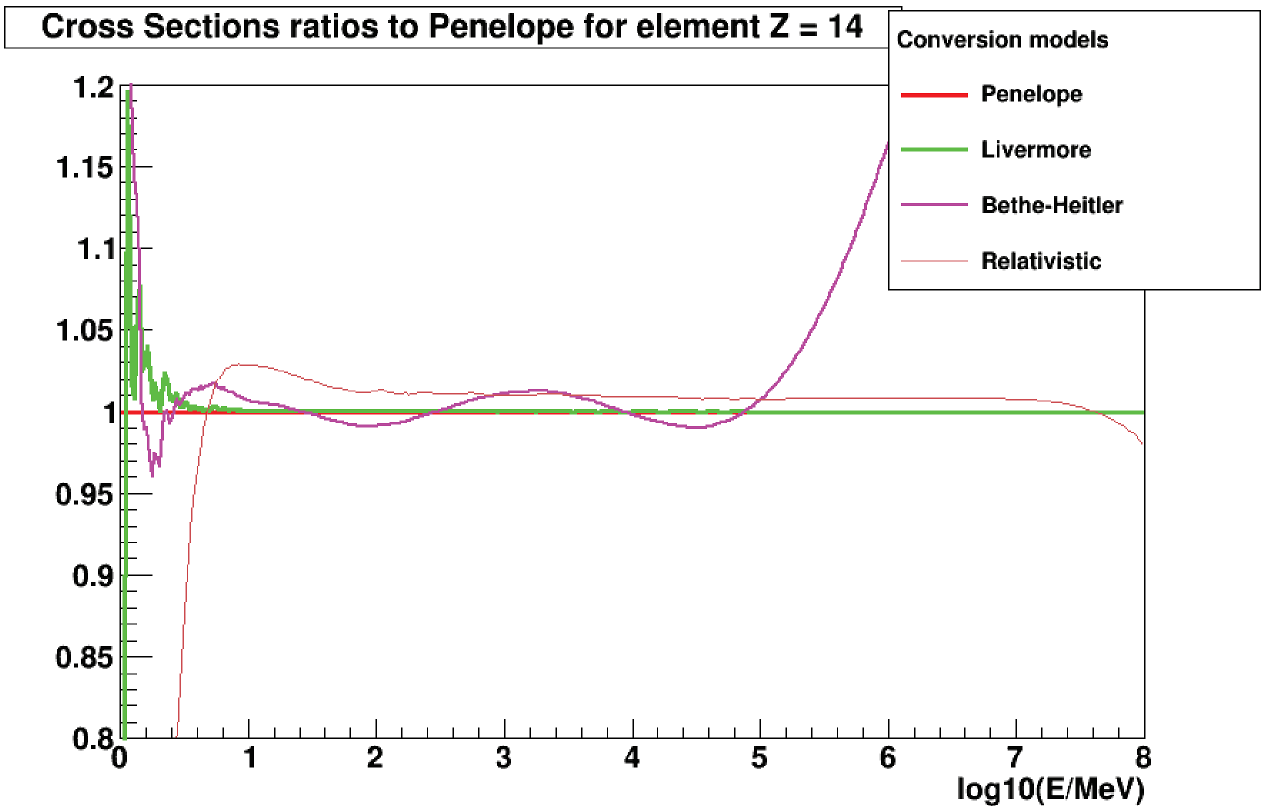


New relativistic pair production model

- includes LPM effect
- important only for $E > 1 - 10$ TeV
- available since Geant4 version 9.3

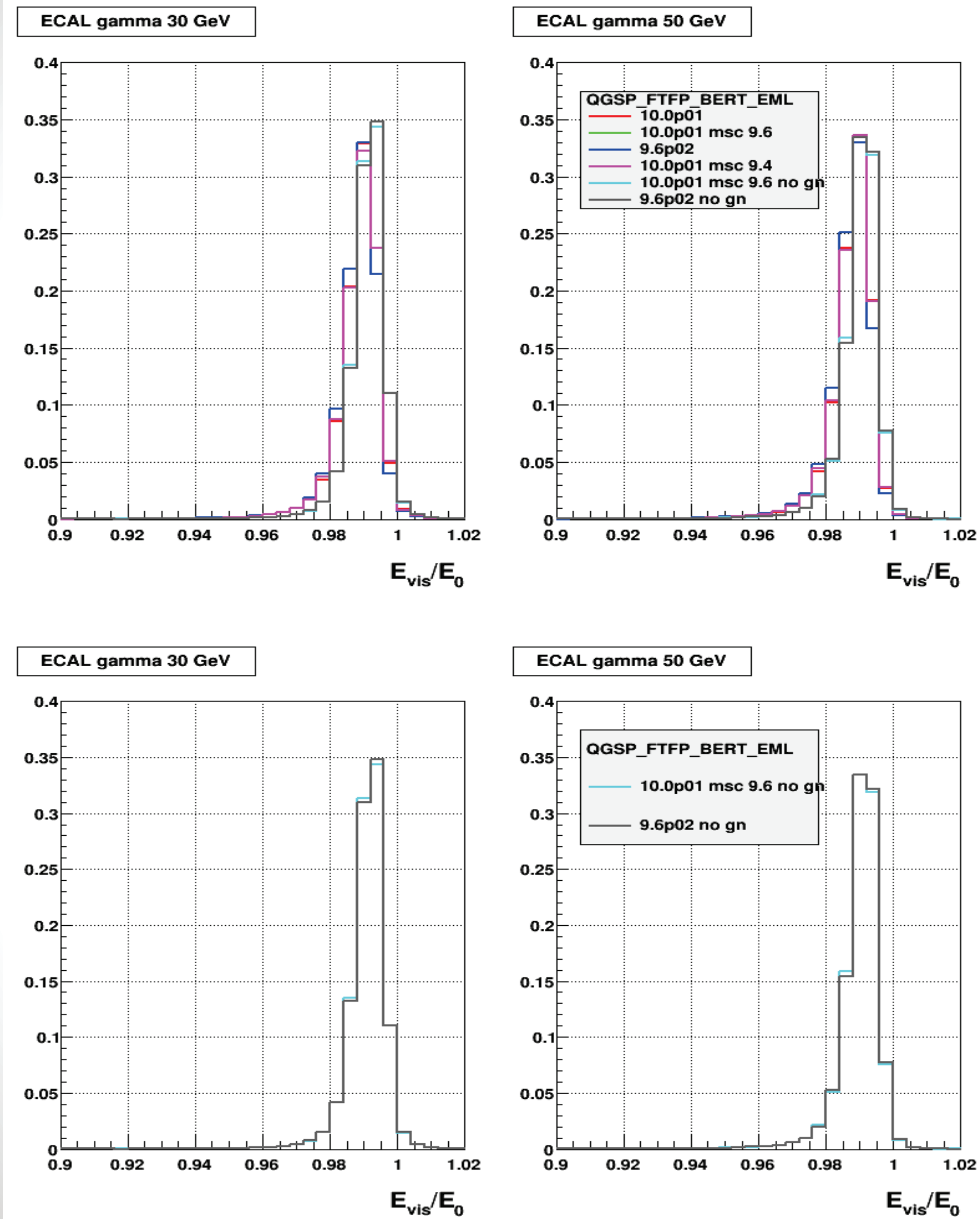
Data: H.D. Hansen et al., Phys.Rev.D 69, 032001 (2004)

Gamma conversion cross section ratios between different EM models



- Standard Bethe–Heitler model fail for E > 80 GeV
- LPM effect is seen in Si target for E > 20 TeV
- LPM effect significantly depend on Z of the target
- ATLAS confirms that updated Geant4 cross section at high energy better fit the data

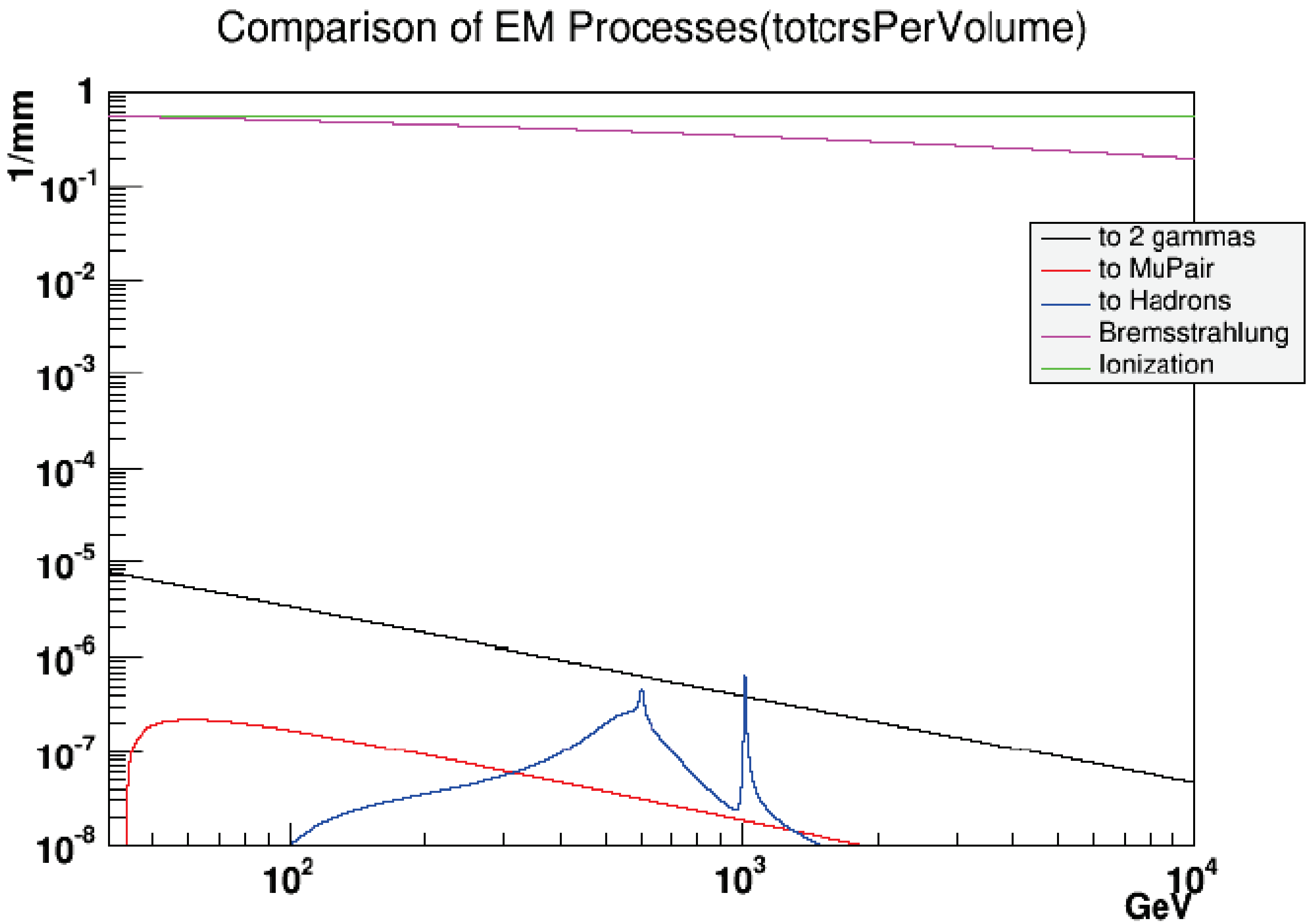
Simplified CMS calorimeter results



- Shift of visible energy in Geant4 10.0p01/9.6p02 is about 0.2%
- Shift of visible energy if γ/e-nuclear processes are off 0.5%

- This confirm effect
- Of gamma-nuclear
- on EM calorimeter
- Results for crystal
- calorimeters

Positron annihilation cross sections in Silicon



(Naruhiro Chikuma, University Tokyo, CERN summer student)

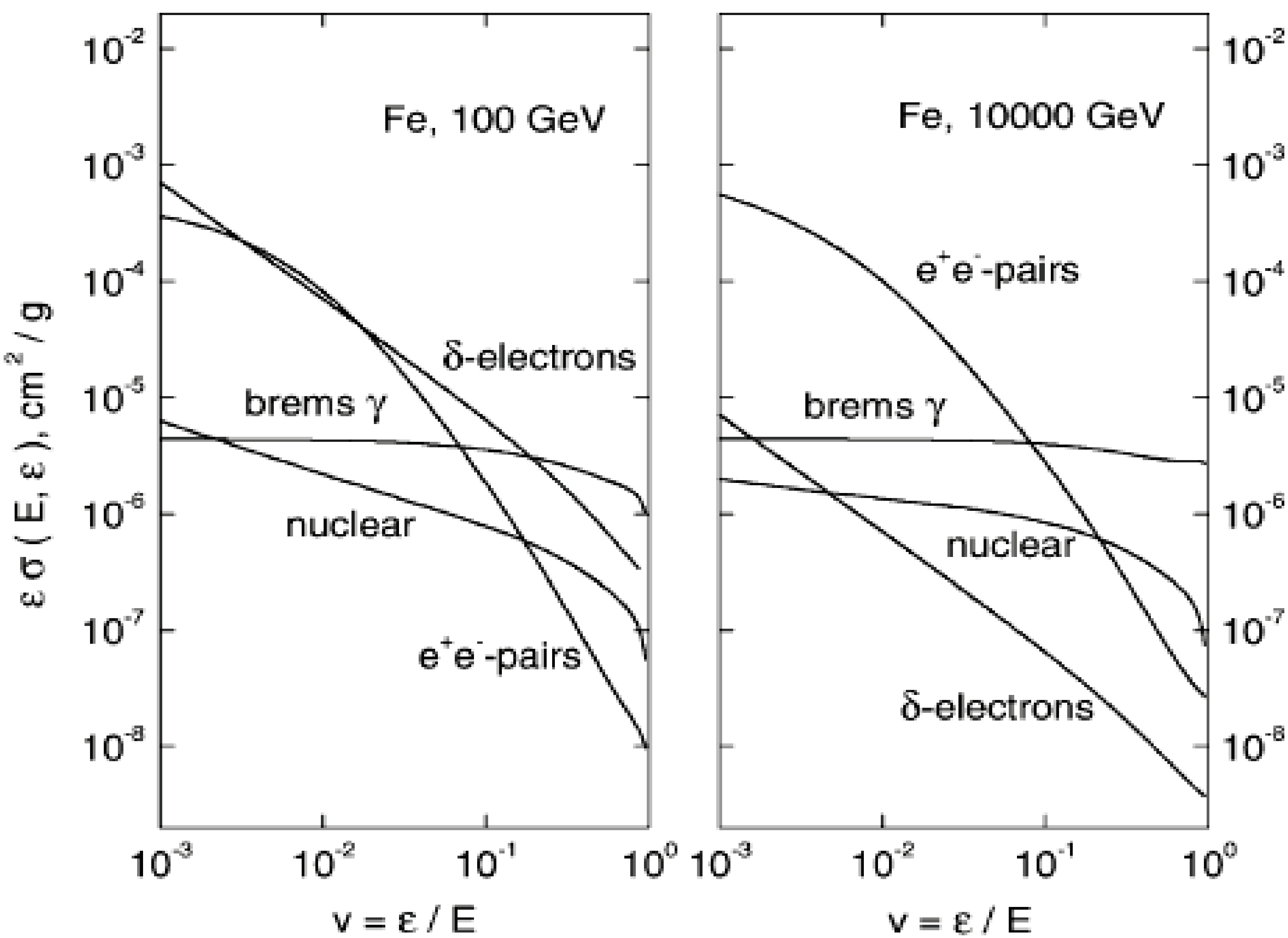
Muon processes in Geant4

- Muon ionisation
  - Modified Bethe-Bloch model
  - Radiative corrections above 1 GeV
  - Nuclear formfactor is taken into account
- Muon bremsstrahlung
  - Angular distribution by dipole approximation
  - Nuclear recoil neglected
- Electron/positron pair production by muons
  - Angular distribution by dipole approximation
  - Nuclear recoil neglected
- Muon nuclear interactions
  - Model of equivavlent photon emission and gamma-nuclear interaction
- Muon elastic scattering
  - Combined model of multiple scattering for low energles (G4WentzelVIModel) and single scattering (G4CoulombScattering)
  - Angular limit single/multiple scattering is momentum dependent on projectile momentum

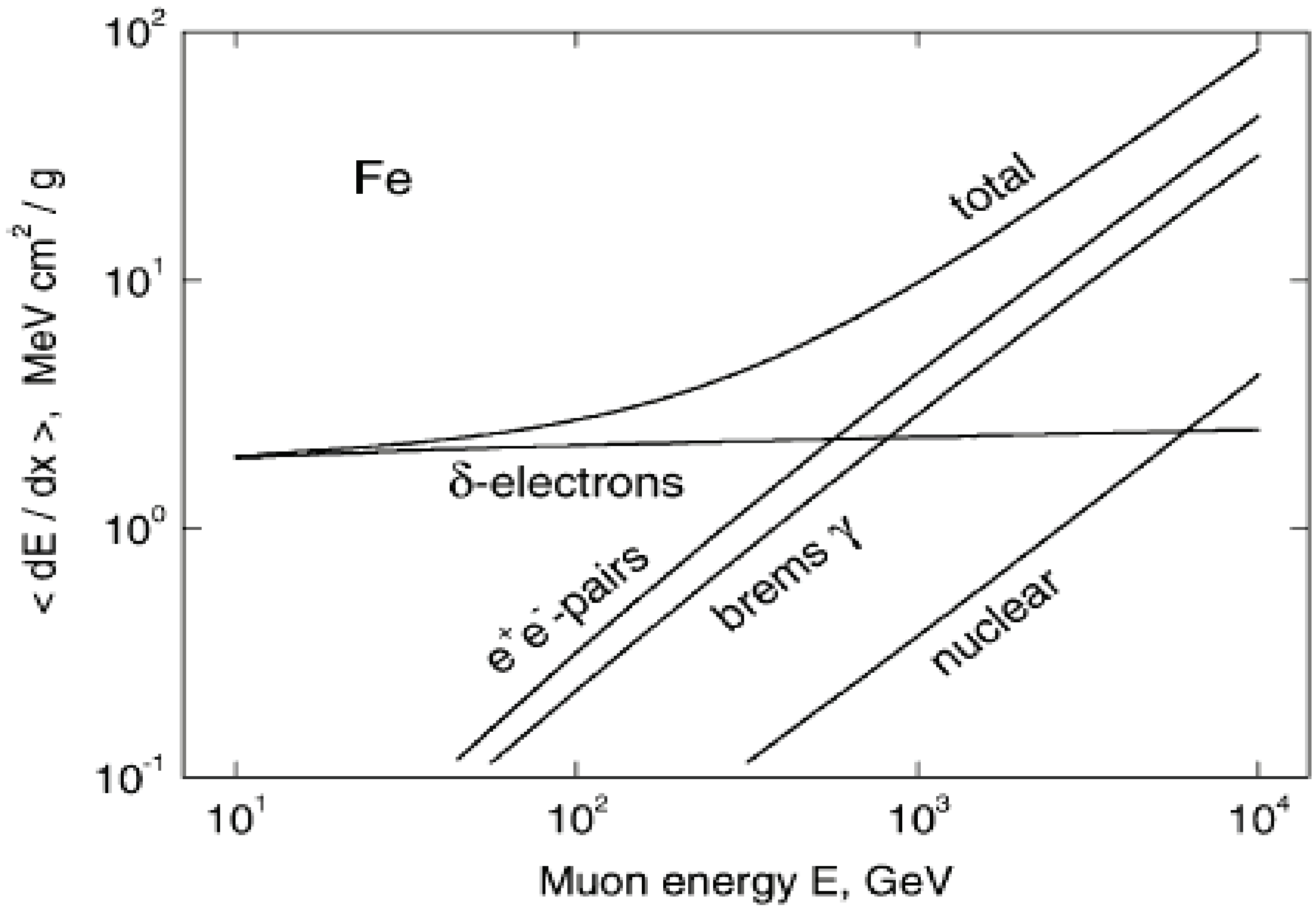
How muon processes are validated?

- There are limited number of experiments which can be used for validation of muon transport
- Validation of the code versus theory is very important , because of luck of data and well established quantum electrodynamics
  - A.G. Bogdanov et al., IEEE Trans. Nucl. Sci. 53 (2): 513-519, 2006.
- Geant4 cross sections at high energy are valid within 5%
  - Radiative corrections are not taken into account in all cases
  - LPM effect for muons is important at higher energies than for electrons
- For high energy muons above 100 GeV main energy loss is due to e+e- pair production
  - Brensstrahlung is responsible for «catastrofic energy loss»
  - Nuclear reactions is a small effect

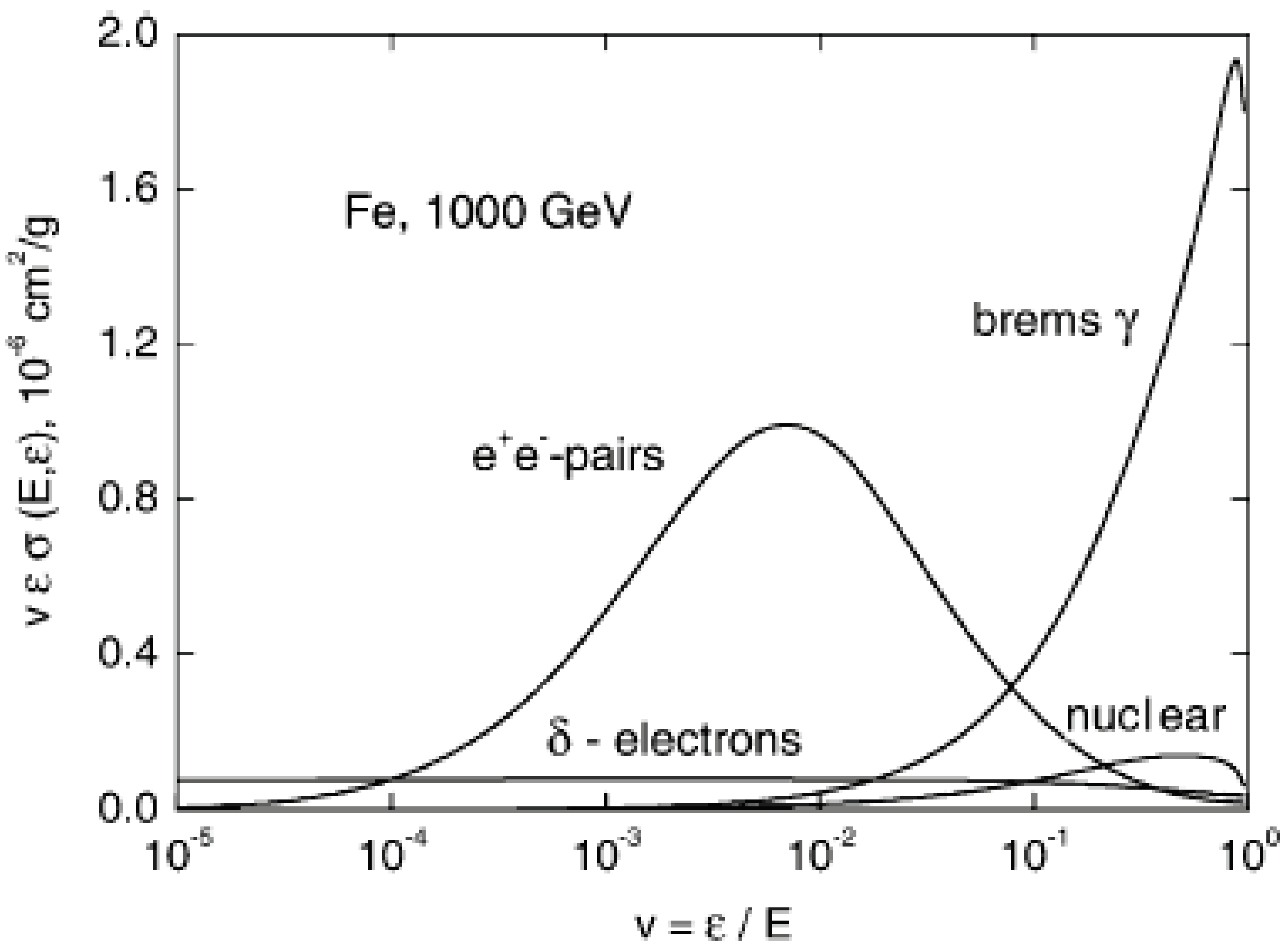
Differential cross sections for different muon processes



Stopping powers of muon in Iron



Contribution of muon stopping to the total energy loss



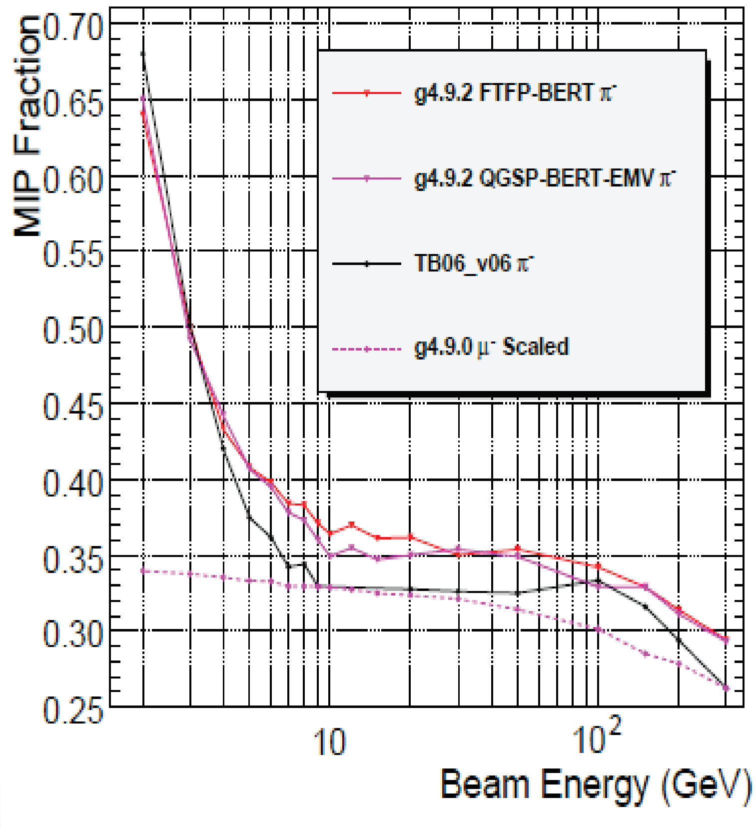
Single and multiple scattering models for muons/hadrons

- MultipleScattering models:
  - G4UrbanMscModel
    - Since 10.0 we have only one version of the Urban model
    - For 10.1 the model was updated to increase CPU performance
    - For 10.2 a new correction factor for positrons was added and improved mechanism of lateral displacement may be introduced
  - G4WentzelVIModel
    - Uses Wentzel cross section
    - Nuclear formfactor is taken into account
    - dynamically select single or multiple scattering at each step
    - Is combined with single scattering model
- Single scattering models:
  - G4eCoulombScatteringModel
    - neglect correction to cross section due to nuclear recoil
  - G4hCoulombScatteringModel
    - Available since Geant4 10.2
    - take into account cross section corrections due to nuclear recoil

High energy muon transport

- Muon trajectory in HEP detector depends on several factors
- Scattering angle due to muon processes is small
  - Interactions are rare and recoil angle is about $1/\gamma$
- Main effect on muon trajectory is due to elastic scattering
  - Cross section is much larger than inelastic processes
  - Inelastic processes affect scattering mainly because they reduce muon energy
- Effect of energy loss processes become visible at high energy
  - Testbeam data exist for pions (CMS combine calorimeter)
  - Geant4 pion models for pair production and bremsstrahlung derived from muon models
- There are also some data for muons scattering

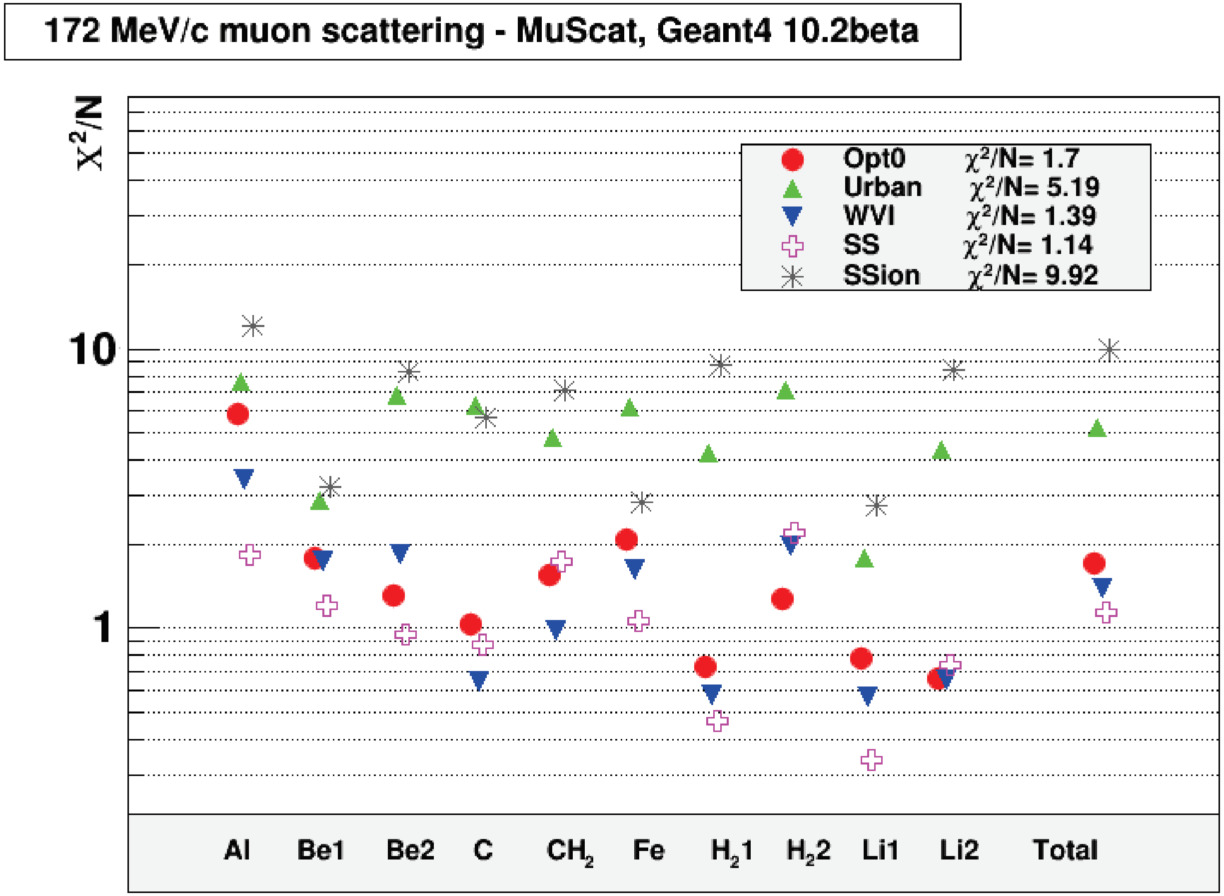
MIP fraction in pion energy deposition within ECAL part of CMS combined calorimeter testbeam (CMS-NOTE-2010-007)



- MIP fraction means that pion do not have nuclear interaction within ECAL
- Above 100 GeV number of such pions decreased and the effect can be reproduced in simulation only if pion bremsstrahlung and pair production are taken into account

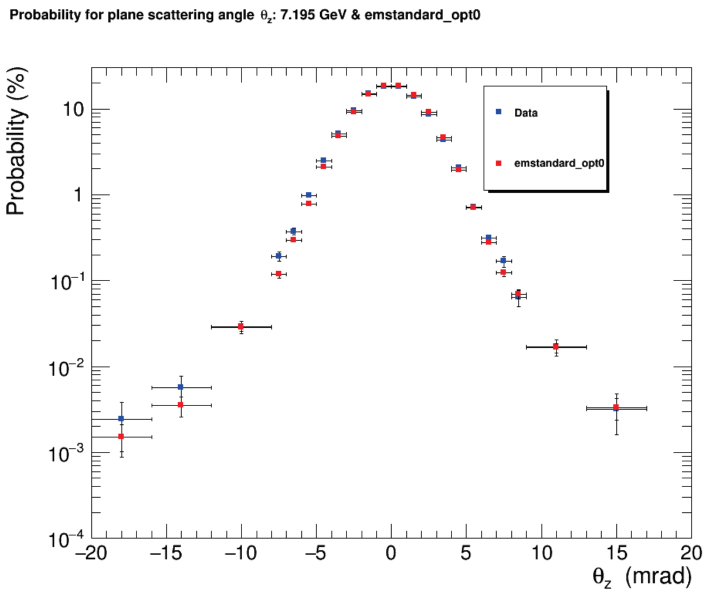
MuScat benchmark

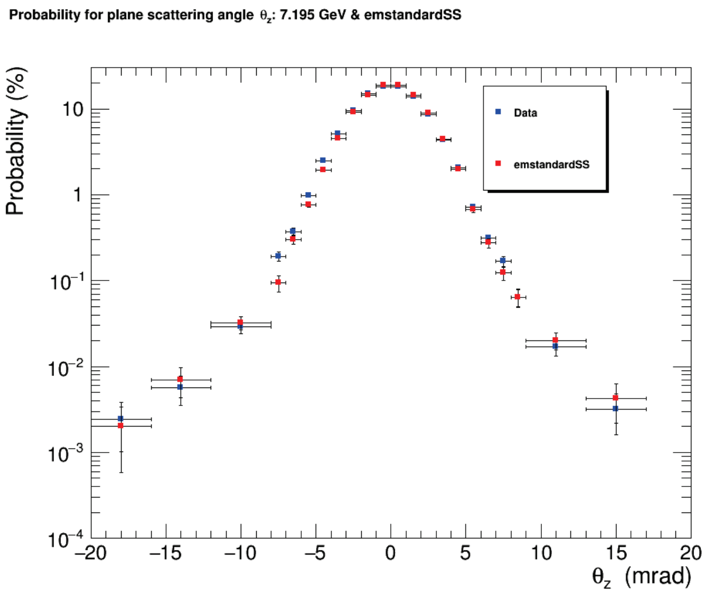
Nucl. Instr. Meth. B 251 (2006) 41



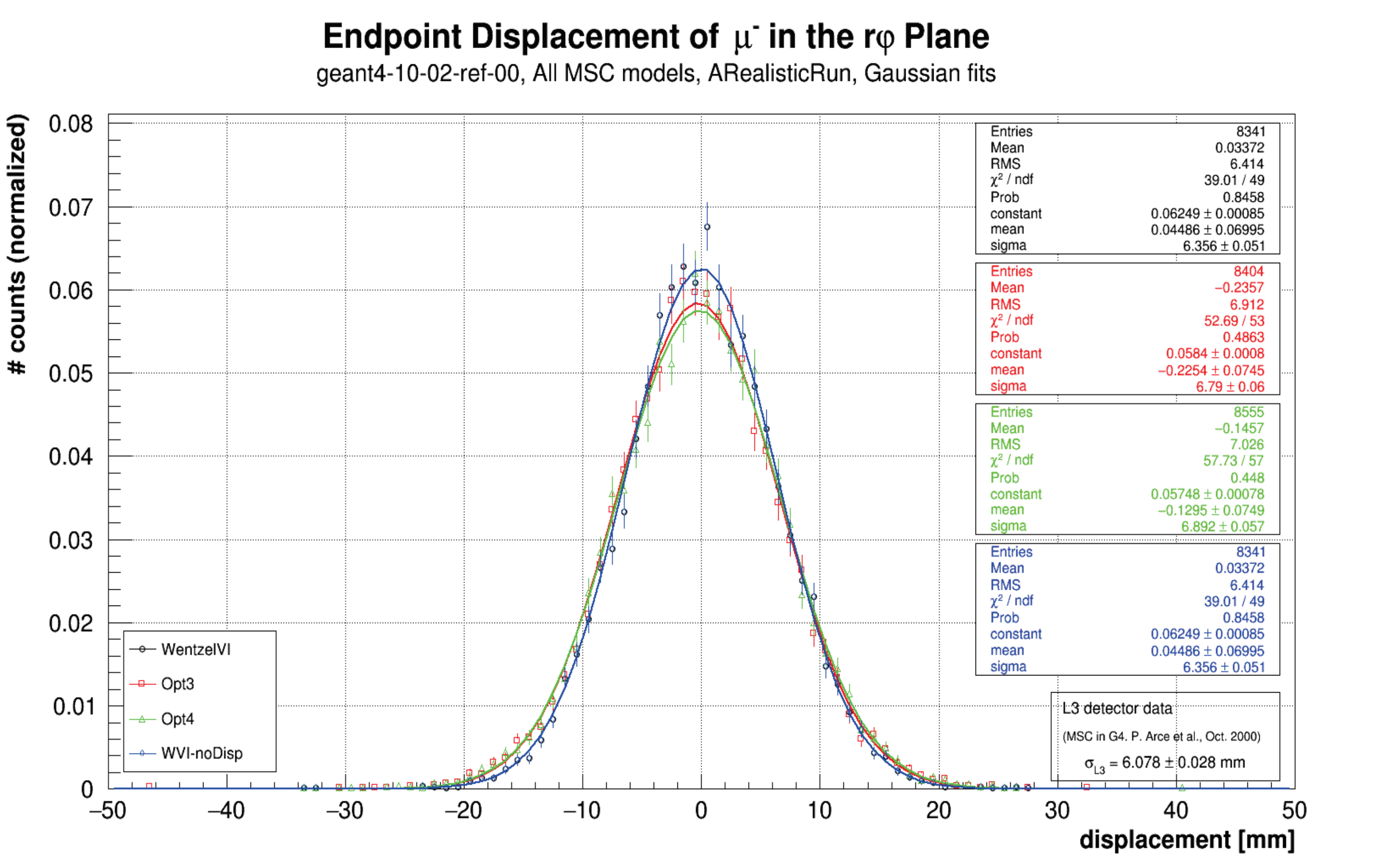
Single scattering and WentzelVI models are closer to the data than Urban models

Muon scattering in Cu target at 7.195 GeV





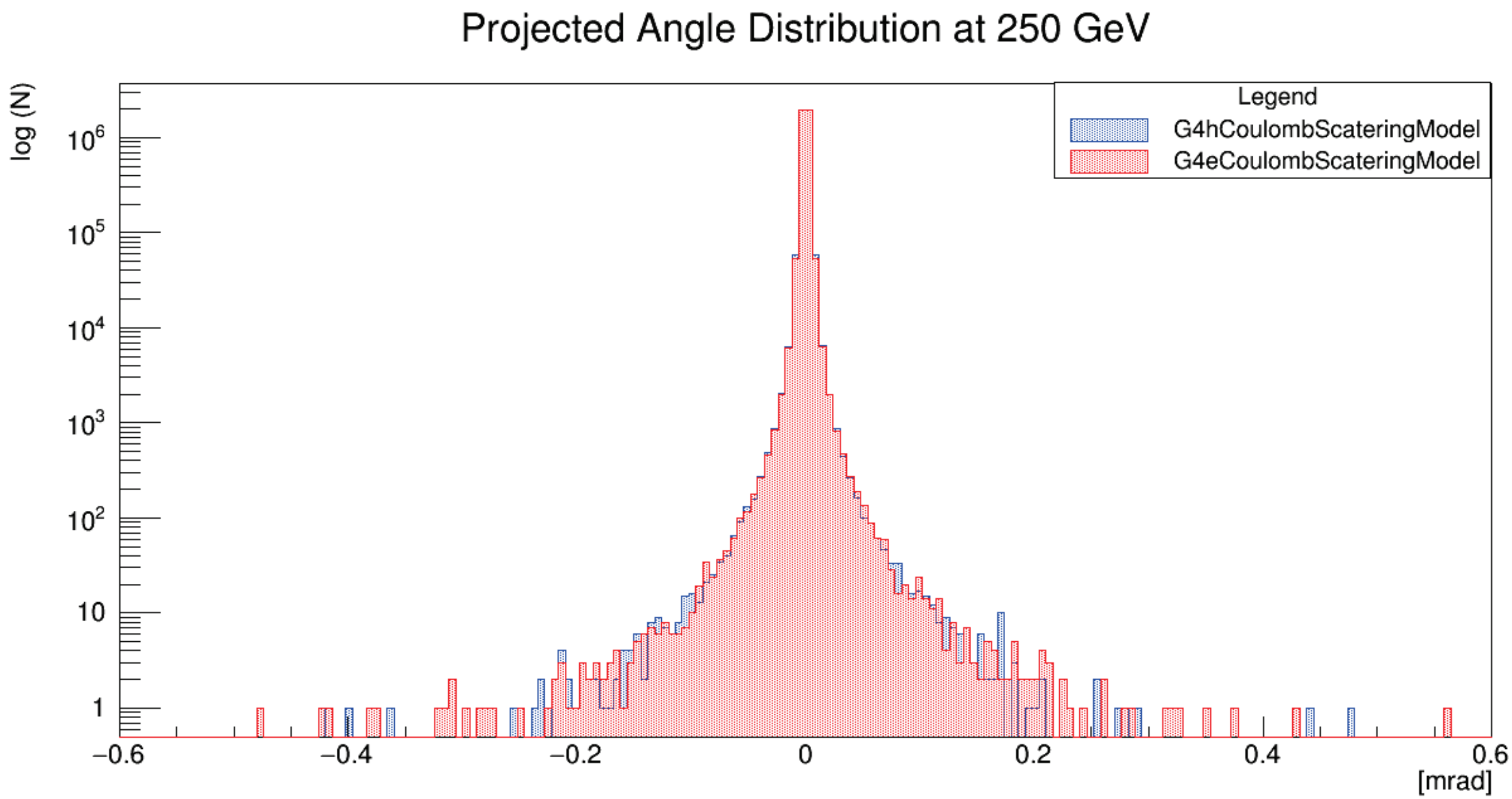
Muon dismplacement in muon system of the L3 exteriment



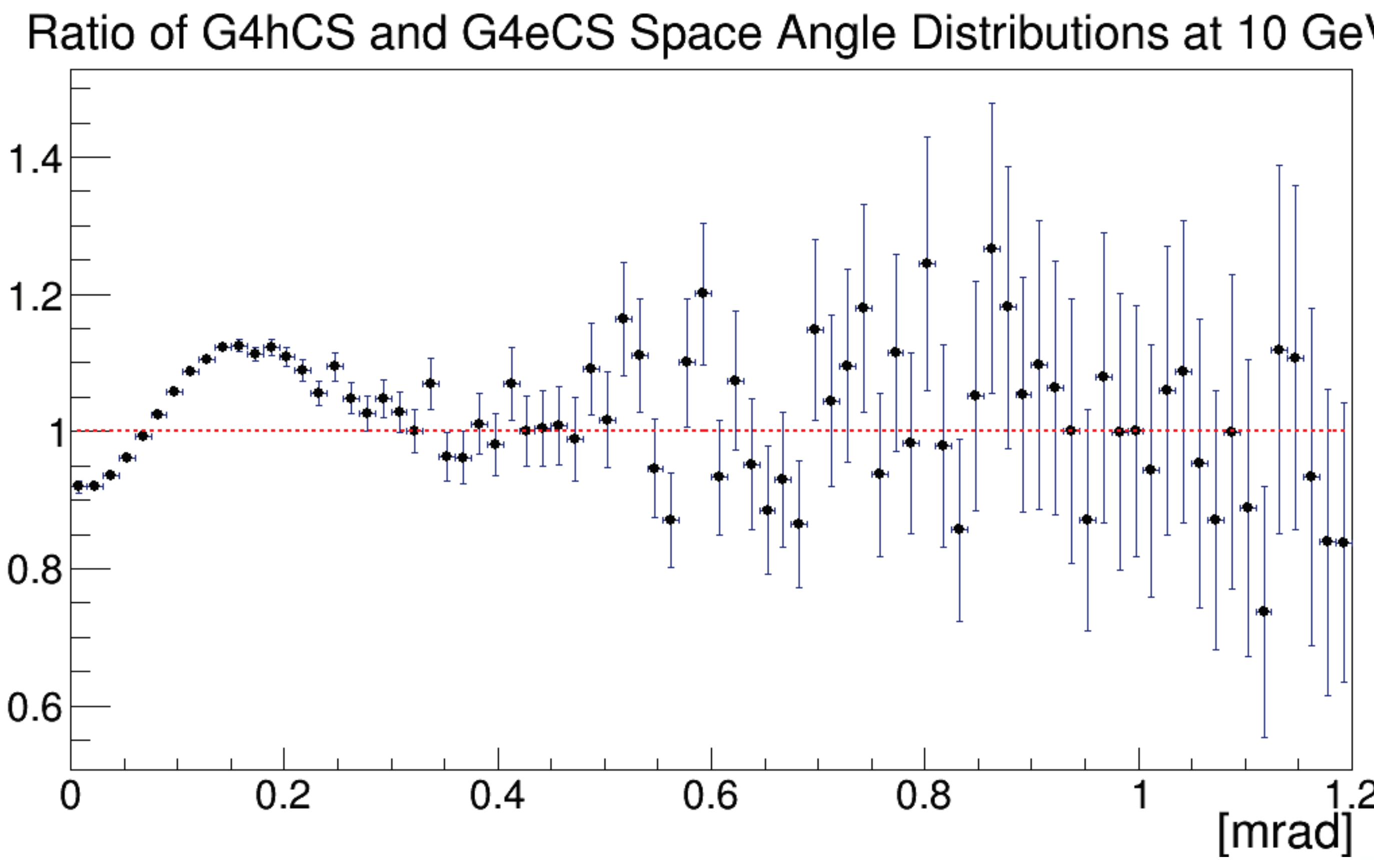
Muons are produced in Z->μ+μ– reaction

In Geant4 testing suite we reproduce absorbers of L3

Effect of nuclear recoil on angular scattering of high energy muons is small



Effect of nuclear recoil on angular scattering of high energy muons is seen at central part



Summary

- In current Geant4 main processes relevant to high energy muon transport are taken into account by default
  - Ionisation
  - Bremsstrahlung
  - Pair production
  - Nuclear interactions
  - Elastic scattering
- Accuracy of cross sections are of order of first approximation of QED
  - In some cases first order corrections are taken into account
  - Futher corrections may be included in newer Geant4
- There is a reasonable agreement versus available data
  - Data for validation is limited