Geant4 Current Status and Muon Pair Production Simulation

V. Ivanchenko CERN & Tomsk State University, Russia
For Geant4 Electromagnetic Physics Group

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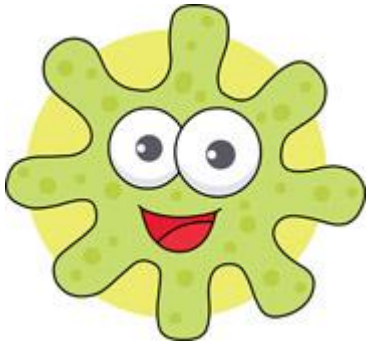
Outline



- Introduction
- Geant4 physics configuration
- Geant4 electromagnetic (EM) physics
  - Muon transport simulation
  - Muon transport benchmarks
- Gamma conversion to muon pair
  - Relativistic model
  - Recent extension to low energy
- Conclusions

The Geant4 toolkit

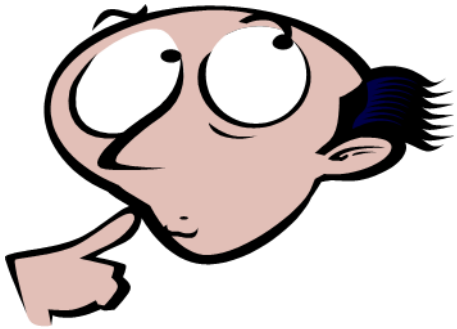
- Was initially designed for simulation of HEP experiments
  - However, have many other application domains
    - Space science, medical, nuclear physics…
    - Main publication: «Geant4 - a simulation toolkit» NIM A 506 (2003) 250 http://www.sciencedirect.com/science/article/pii/S0168900203013688 has now more than 10000 citations
- The Geant4 Collaboration Is always focus efforts on LHC experiments simulation
  - Version 9.X is used mainly for Run-1
  - Version 10.X is used for Run-2
    - Details of version 10 are described in J. Allison *et al*., "Recent Developments in Geant4", NIM A 835 (2016) 186-225 http://www.sciencedirect.com/science/article/pii/S0168900216306957
  - Version 10.4 – newest production version
    - 10.4p03 is available since February
    - CMS produces already few billion events
  - Latest Geant4 10.5 is available since December 2018

Geant4 physics configuration

- Physics List class is responsible for configuration of physics
- Geant4 provides several reference Physics Lists
  - Since version 9.6 Geant4 default is FTFP_BERT
  - Components of a reference Physics List:
    - Electromagnetic physics (EM)
    - Photo- electro-, muon- nuclear interactions
    - Hadron elastic
    - Hadron inelastic
    - Stopping processes
    - Ion processes
    - Neutron tracking cut
    - others
- User may customize any reference Physics List
  - For example, add radioactive decay
  - May choose one of alternative EM configurations
  - May use UI macro command or C++ interface to tune EM parameters
    - For example, cuts per detector region
- User may use custom physics list
  - May be combined from components

Geant4 electromagnetic physics

Geant4 EM libraries



- Low-energy
  - Livermore library γ, e- from 10 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE code rewrite , γ, e- , e+ from 100 eV up to 1 GeV (2008 version)
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (fluorescence + Auger)
- Geant4-DNA
  - microdosimetry models for radiobiology (Geant4-DNA project) from 0.025 eV to 10 MeV
- Adjoint
  - Reverse Monte Carlo processes and models to track from the volume of interest back to source of radiation
- Utils
  - general EM interfaces
- Standard
  - γ, e± up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- Muons
  - up to 1 PeV
  - energy loss propagator
- X-rays
  - X-ray and optical photon production processes
- High-energy
  - processes at high energy (E>10GeV)
  - physics for exotic particles
- Polarisation
  - simulation of circular polarized beam transport
- Optical
  - optical photon interactions

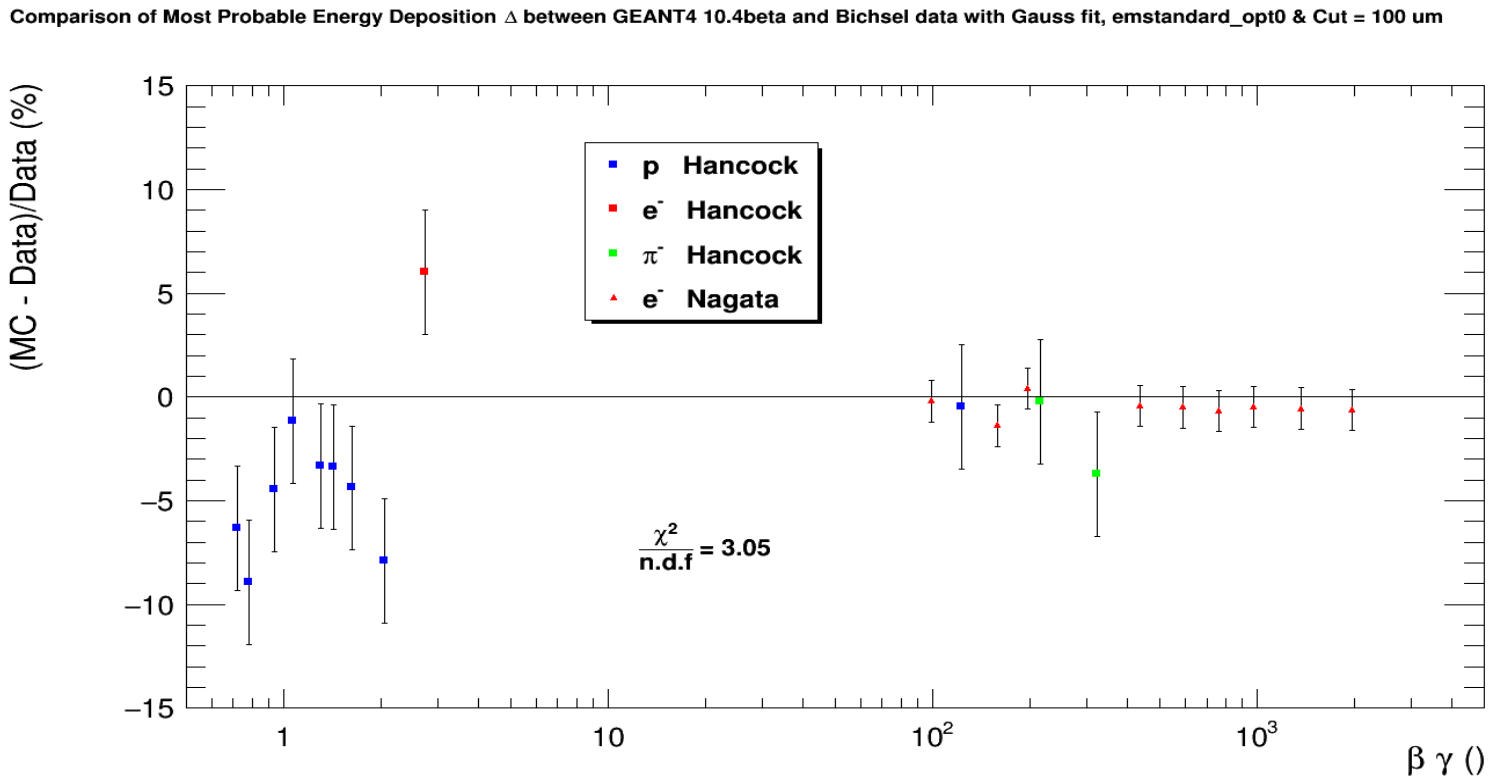
Located in $G4INSTALL/sources/processes/electromagnetic

Geant4 models of ionization for muons

- By default, classical models are used for simulation of ionisation
  - Moller-Bhabha for electrons and positrons
  - Bethe-Bloch for muons, hadrons, and ions above 2 MeV/u
  - NIST parameterization of dEdx below 2 MeV/u (PSTAR, ASTAR)
  - Parameterized model of fluctuation of energy loss (L.Urban)
    - Recommended do not reduce step size below 5 μm
- Alternative models:
  - PAI model applicable for relativistic particles
    - More accurate absolute energy deposition in thin layers
- Since Geant4 10.4 it is possible on top of any EM physics to enable models for G4Region:
  - PAI model per particle type or for all particles
  - Atomic de-excitation for ionization (PIXE) and for photo-effect and Compton with emission of gammas and electrons

Energy depositions in Silicon detectors

H. Bichsel data collection: Rev. Mod. Phys. **60**, 663, 1988



- Geant4 results for 0.3 and 1.4 mm thick Silicon detectors
  - Both Urban and PAI models reproduce well data for relativistic beams
  - Less accurate for e- and proton data for $\beta\gamma \sim 1$
    - There are questions to experiments

MSC and Single Scattering Models

Model	Particle type	Energy limit	Specifics and applicability
Urban (L. Urban 2006)	Any	-	Default model for $e^{\pm}$ below 100 MeV and for ions, tuned to data, used for LHC production.
WentzelVI & Coulomb Scattering (V.Ivanchenko 2009) LowEnergyWentzelVI (2014)	Any	-	MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons but applied also for e± above 100 MeV; low-energy variant of the model is applicable for low-energy e-
Goudsmit-Saunderson (O.Kadri 2009), revised by M.Novak since (2015)	e^+, e^-	< 10 GeV	Theory based cross sections (Goudsmit and Saunderson 1950); ELSEPA code computations, EGSnrc aproach. precise electron transport
Ion Coulomb scattering (2010) Electron Coulomb scattering (2012)	Ions e^+, e^-	-	Model based on Wentzel formula + relativistic effects + screening effects for projectile & target. From the work of P. G. Rancoita, C. Consolandi and V. Ivantchenko.
Screened Nuclear Recoil (Mendenhall and Weller 2005) TestEm5	p, ions	< 100 MeV/A	Theory based process, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space applications

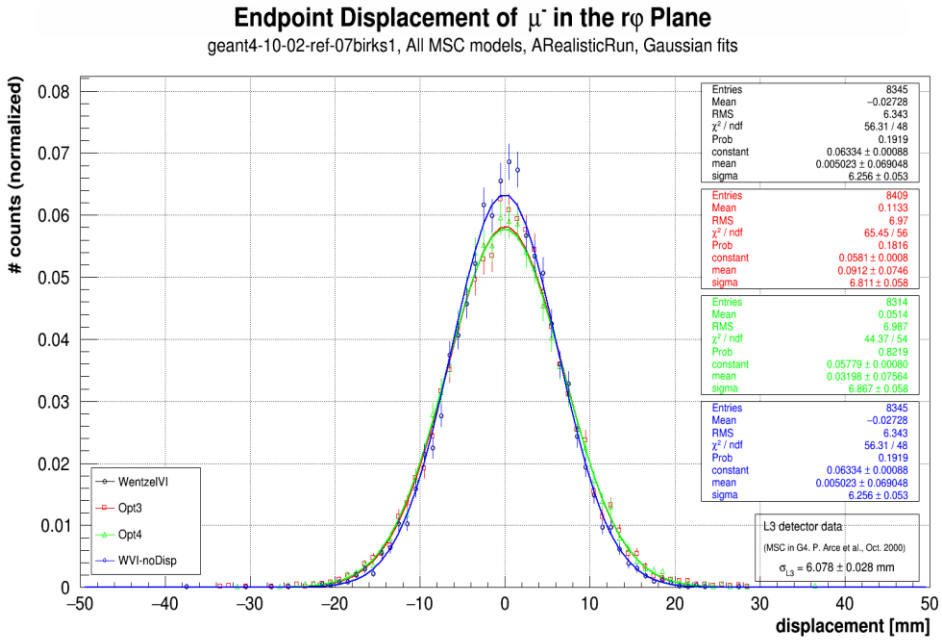
Current default for HEP applications is a combined multiple and single scattering model:

- G4WentzelVIModel + G4eCoulombScatteringModel
- Applied for high energy e+-, muons, hadrons
- Recoil nucleaus is simulated if E_{kin} is above energy threashold

For accurate e+e- tracking the Goudsmith-Sounderson model below 100 MeV

Effect of modification of EM form-factor parameterisation on L3 data (P. Arce et all)

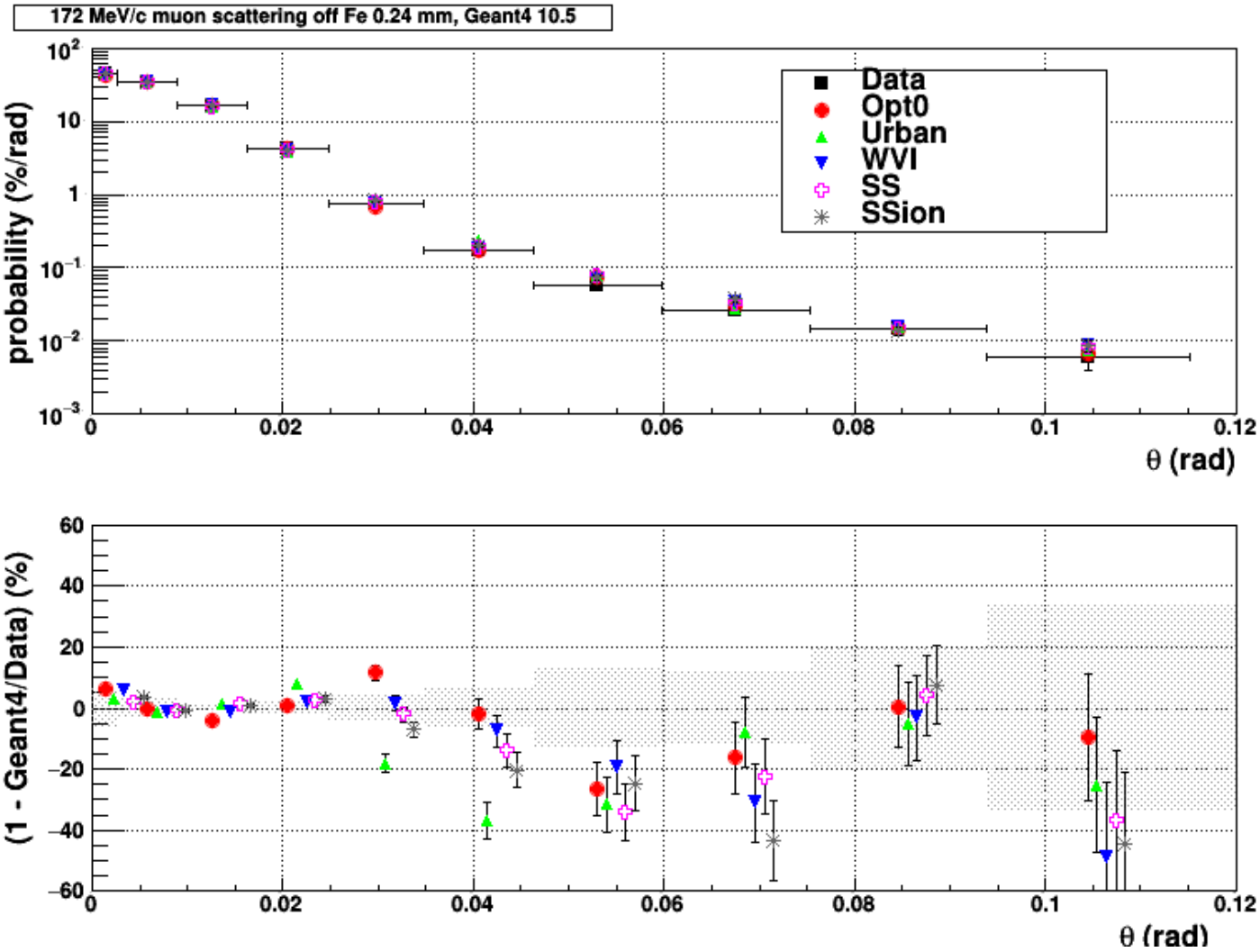
Introduction of the Gaussian form-factor parameterisation improving agreement data/MC



Model	RMS (mm) of displacement
L3 data	6.078 ± 0.028
Urban (Opt3)	6.649 ± 0.079
WentzelVI Exponential	6.254 ± 0.075
WentzelVI Gaussian	6.147 ± 0.073

MuScat benchmark

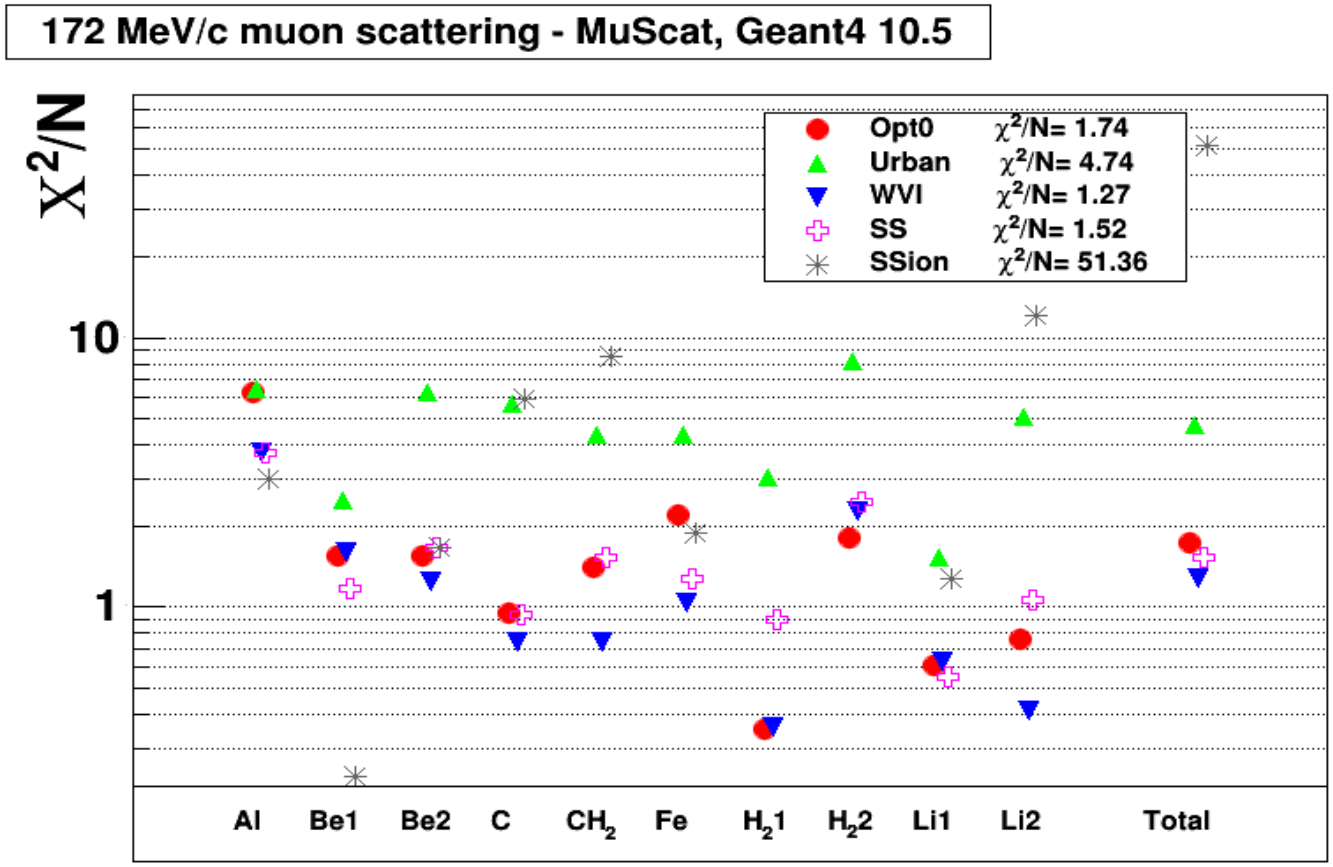
Nucl. Instr. Meth. B 251 (2006) 41



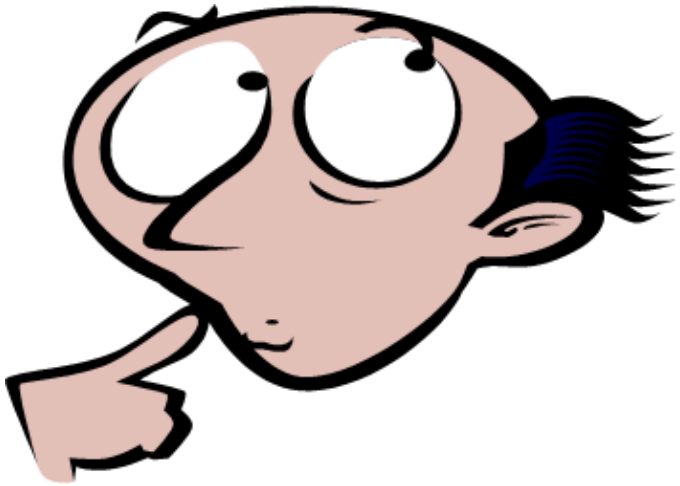
MuScat experiment was designed a test-beam for muon collider.

MuScat benchmark

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



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



Gamma conversion to muon pair

Theory of lepton pair production

- Geant4 implementation of muon pair production is based on the following works:
  - H Burkhardt, S R Kelner, and R P Kokoulin. Monte carlo generator for muon pair production. Technical Report CERN-SL-2002-016-AP. CLIC-Note-511, CERN, Geneva, May 2002. URL: https://cds.cern.ch/record/558831.
  - S.R. Kelner, R.P. Kokoulin, and A.A. Petrukhin. About cross section for high-energy muon bremsstrahlung. Technical Report, MEphI, 1995. Preprint MEPhI 024-95, Moscow, 1995, CERN SCAN-9510048.
- Which are based on classical electrodynamic formulas:
  - H. Bethe and W. Heitler, Proceeding of the Society of London A: Mathematical Physical Enjineering Science 146(856): 83-112, 1934
  - K.J. Kim and Y.-S- Tsai. Phys Rev. D8: 3109, 1973
  - Y.-S. Tsai. Rev. Mod. Phys. 46: 815, 1974; 49: 521, 1977
  - G. Baur and A. Leuscherner. Eur. Phys. J C8: 631-635, 1999

Geant4 gamma conversion to muon pair process

- G4GammaConversionToMuonPair was implemented by H.Burkhardt in collaboration with R.Kokoulin and S.Kelner
- This class is a part of G4EmExtraPhysics constructor
  - Included in all reference Physics List
  - By default is disabled
  - May be enabled by UI command /
- The primary goal of the implementation of this process was to provide simulation of muon background in the interaction region of future linear collider
  - This is an ultra relativistic use case
  - The implementation is based on parameterization of asymptotic expressions

Approximation of the differential cross section

For the approximately elastic scattering considered here, momentum, but no energy, is transferred to the nucleon. The photon energy is fully shared by the two muons according to

$$E_\gamma = E_\mu^+ + E_\mu^-$$

or in terms of energy fractions

$$x_+ = \frac{E_\mu^+}{E_\gamma}, \qquad x_- = \frac{E_\mu^-}{E_\gamma}, \qquad x_+ + x_- = 1\,.$$

The differential cross section for electromagnetic pair creation of muons in terms of the energy fractions of the muons is

$$\frac{d\sigma}{dx_+} = 4\,\alpha\,Z^2\,r_c^2\left(1 - \frac{4}{3}\,x_+x_-\right)\log(W)\,,$$

where Z is the charge of the nucleus, r_c is the classical radius of the particles which are pair produced (here muons) and

$$W = W_\infty\,\frac{1 + (D_n\sqrt{e} - 2)\,\delta\,/m_\mu}{1 + B\,Z^{-1/3}\,\sqrt{e}\,\delta\,/m_e}$$

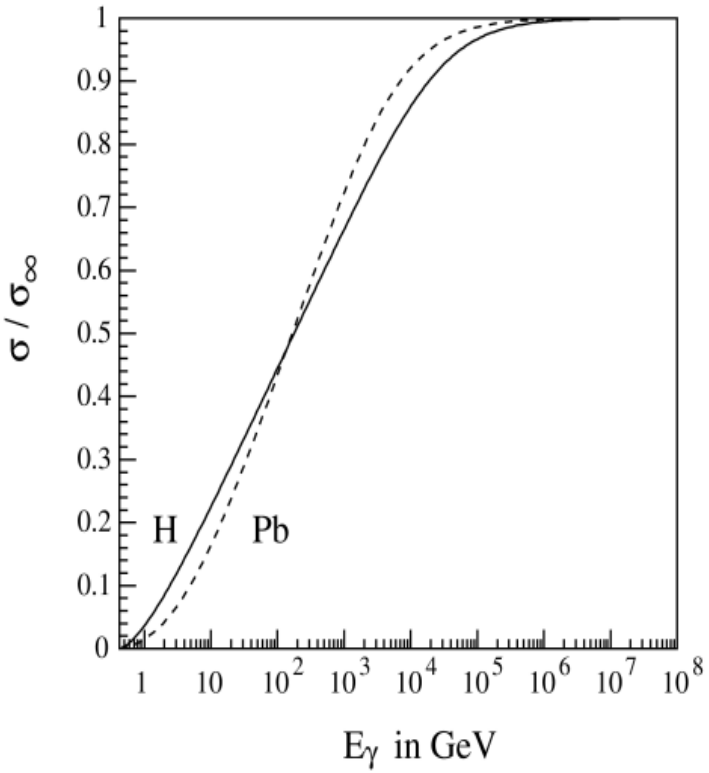
where

$$W_\infty = \frac{B\,Z^{-1/3}}{D_n}\,\frac{m_\mu}{m_e} \qquad \delta = \frac{m_\mu^2}{2\,E_\gamma\,x_+x_-} \qquad \sqrt{e} = 1.6487\ldots.$$

Total cross section

$$\sigma_{\rm tot}(E_\gamma) = \int_{x_{\rm min}}^{x_{\rm max}} \frac{d\sigma}{dx_+}\, dx_+ = 4\,\alpha\, Z^2\, r_c^2 \int_{x_{\rm min}}^{x_{\rm max}} \left(1 - \frac{4}{3}\, x_+ x_-\right) \log(W)\, dx_+ \,.$$

- At ultra relativistic energies the classical cross section is const
- LPM suppression is not taken into account
  - Not important for available energies
- At low energies formulas are approximate
  - Authors estimated 10 GeV as a low-energy validity limit
  - Software limit was 4*m_μ



Requirements for EM physics by new dark matter search experiments

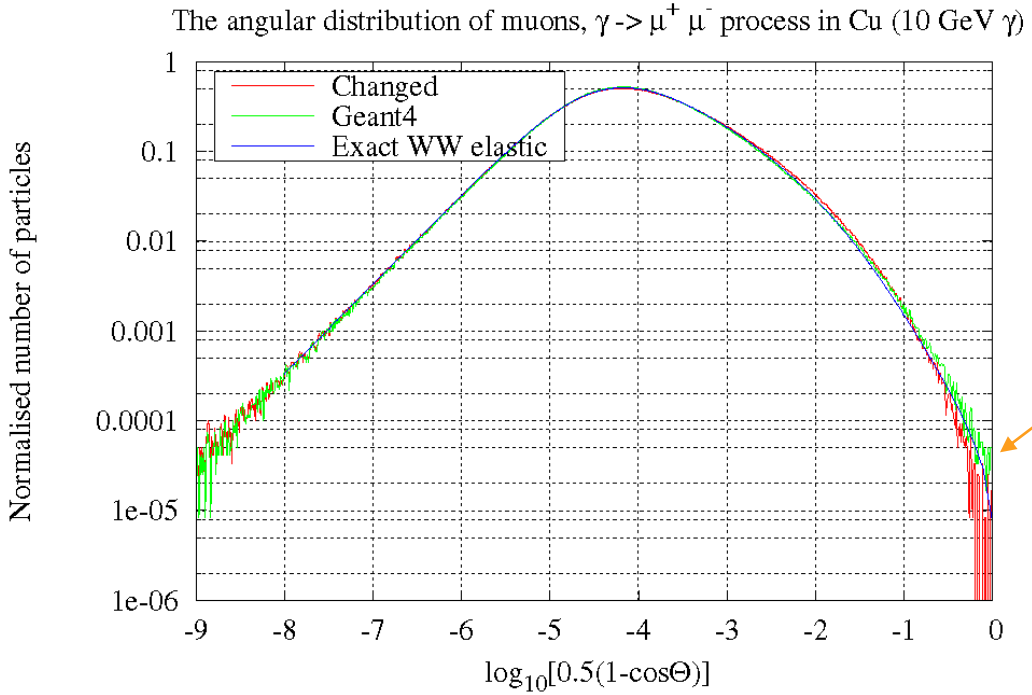
- After Higgs discovery there are intensive discussion on possible experiments for dark matter search
- Currently, several fix target experiments are under consideration or are already started
  - The most advanced is the new experiment at CERN SPS SHIP
- EM physics is an important component
  - Diagrams for production and interaction of light dark matter particles are similar to normal EM diagrams
  - EM processes are responsible for background in these searches
- We started review of EM models
  - Addition necessary next to leading order corrections to existing processes
  - Addition of rare processes
  - Extension of validity areas

Low-energy extension of muon pair production

- We started from detailed review of existing process G4GammaConversionToMuonPair
- In order to understand inaccuracy of approximations used process authors our summer student A.Sokolov performed special study
  - He integrated the Williams-Weizsacker differential cross section numerically in Wolphram Mathematica 11.0 for three different target materials: hydrogen, copper and lead
  - Studied effects of screening and nuclear form-factors

Validation of process γ→μ+μ-

CERN summer student project (A.Sokolov)



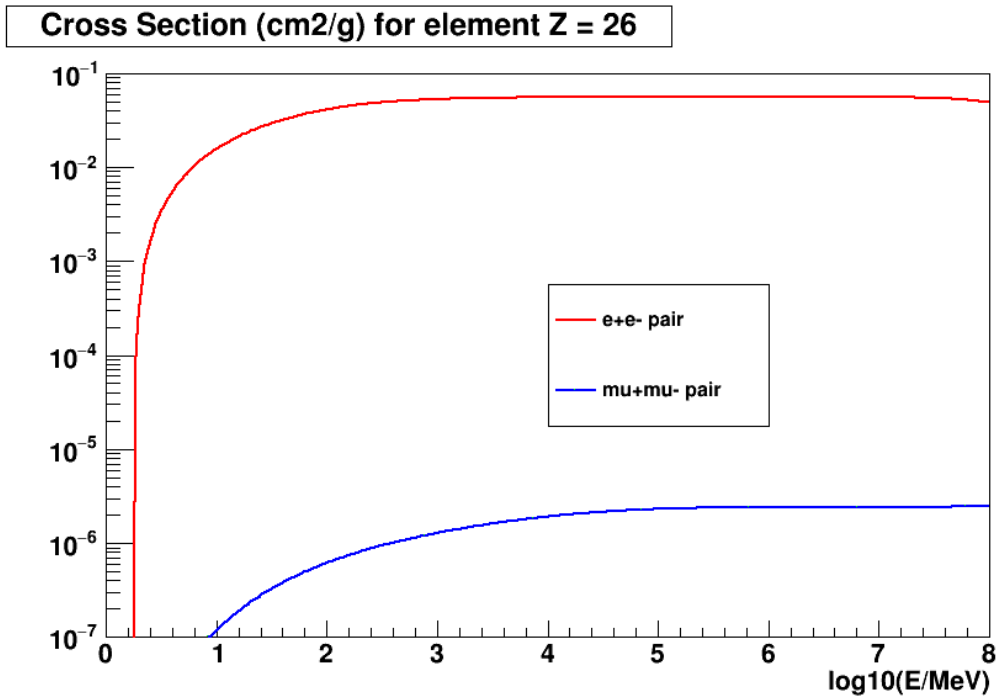
Large angle muons may be a background matter particles

important for Ship experiment design

- Total cross section were verified using numerical integration and accuracy was confirmed within 3%
- Improved expression for the elastic form-factor was introduced
  - There are no differences at high energies ~100 GeV
  - Some differences at ~10 GeV

Muon part production near the threshold

- In order to extend current model down to the threshold just recently an update of the G4GammaConversionToMuonPair was done
- Approximation used in Geant4 Bethe-Heiltler model for e+e- pair production is applied to the muon pair production



Conclusions

- The accuracy of the standard Geant4 transport of muons is adequate for design of muon collider
- Model for gamma conversion into muon pair is available
  - It may be enabled on top of any reference Physics List of Geant4
- In the coming patch to the recent version Geant4 10.5 muons cross section is non-zo down to the threshold
  - Before there was a limit $4*m_{\mu}$
- The accuracy of muon pair production by gamma depends on energy
  - For E > 10 GeV can be estimated on level of few percent
  - Accuracy of cross section near the threshold is not known
  - Extra efforts to study and evaluate the theory are required
    - Geant4 EM group has this subject in 2019 work plan
    - We will introduce newer method to bias cross section
    - We will look into possibility to have more accurate total cross section