High Energy Gamma Conversion Models

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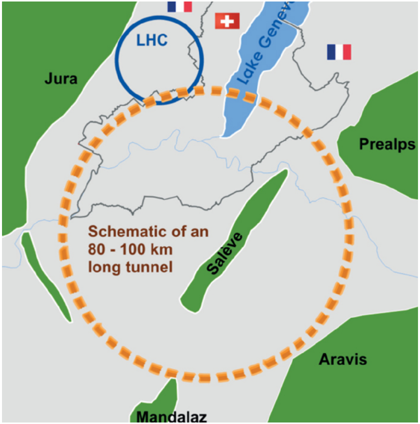
Contents

Future Circular Collider (FCC)

- Long-term goal: push the energy frontier beyond LHC
- **100 km** tunnel in the Geneva area - design driven by pp-collider (FCC-hh) requirements with possibility of a lepton (FCC-ee) and a lepton-hadron (FCC-he)
- 16 T $\rightarrow$ **100TeV** in 100 km



Future Circular Collider (FCC)

- Conceptual Design Report - CDR
  (to be concluded by 2018)
- Technical Design Report - TDR (starting $\sim$ 2020)

FCC software framework:

➠ Mainly parametrized fast simulation using **Delphes** for CDR

➠ **Geant4** needed for TDR!

Challenge:

➠ Extend Physics Models to High Energies

- Reviewing all high-energy physics processes -in view of the increased LHC energy and even more importantly for the FCC design- is crucial ($\geq \mathcal{O}(10\text{TeV})$)
- Reviewing the pair-production model in particular, including the LPM suppression mechanism at high energies
- Also of interest to other fields

  In astroparticle physics, new generation telescopes based on pair-production with minimized scattering will need accurate models describing angular resolution. Better description of pair-production detailed kinematics is therefore needed at low-energy ($\leq \mathcal{O}(100\text{MeV})$).

Contents

Different ways photons interact with matter:

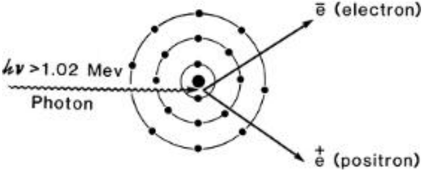
Photoelectric effect,

Compton scattering, Rayleigh scattering, Raman scattering, and

Pair-production:

coherent: e^-/e^+ pair is created in the field of the nucleus

incoherent: pair is created in the field of an orbital electron



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Starting point:

Bethe and Heitler (1934) [1]: **Unscreened Point Nucleus**

For photons of energy $E_\gamma > 50$ MeV, and an electron (positron) of energy $E_-(E_+)$, the differential cross-section (DCS) (in the *positron* variable) for pair-production is obtained as:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_+} = \frac{4r_e^2\alpha Z^2}{E_\gamma^3}\left(E_+^2 + E_-^2 + \frac{2}{3}E_+E_-\right)\left[ln\left(\frac{2E_+E_-}{mc^2E_\gamma}\right) - \frac{1}{2}\right]$$

where α is the fine structure constant,
r_e the electron radius,

Z the atomic number

[1] H. Bethe and W. Heitler, *Proc. Roy. Soc. (London), 1934*

Starting point:

Bethe and Heitler (1934) [1]: **Unscreened Point Nucleus**

For photons of energy $E_\gamma > 50$ MeV, and an electron (positron) of energy $E_-(E_+)$, the differential cross-section (DCS) (in the *positron* variable) for pair-production is obtained as:

Corrected and extended for various effects:

- the screening of the field of the nucleus
- correction to the Born approximation
- pair-creation in the field of atomic electrons
- the LPM suppression mechanism
- Nuclear recoil

[1] H. Bethe and W. Heitler, *Proc. Roy. Soc. (London), 1934*

Tsai (1974) [2]:

Screened + Coulomb Correction + Atomic Excitation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_+} = \frac{r_e^2\alpha}{E_\gamma}\Bigg\{\left(\frac{4}{3}\frac{E_+^2}{E_\gamma^2} - \frac{4}{3}\frac{E_+}{E_\gamma} + 1\right) \times \left[Z^2(\phi_1(\gamma) - \frac{4}{3}lnZ - 4f_c) + Z\left(\psi_1(\omega) - \frac{8}{3}lnZ\right)\right] - \frac{2}{3}\frac{E_+}{E_\gamma}\left(1 - \frac{E_+}{E_\gamma}\right)\left[Z^2(\phi_1(\gamma) - \phi_2(\gamma)) + Z(\psi_1(\omega) - \psi_2(\omega))\right]\Bigg\}$$

where $\phi_1(\gamma)$, $\phi_2(\gamma)$, $\psi_1(\omega)$ and $\psi_2(\omega)$ are Z-dependent functions when the Thomas Fermi model of the atom is used.

[2] Y.-S. Tsai, *Rev. of Modern Physics*, Vol. 46, **4** (1974)

Contents

For simplicity, let us consider the bremsstrahlung process:

- Ultrarelativistic electron emits a low-energy photon $\Longrightarrow q_{//}$ can be very small
- Uncertainty principle $\rightarrow$ interaction takes place over a long distance, called *formation length*
- If anything happens to the electron or photon along this distance that disturbs their coherence, the emission of the photon will be suppressed
- The *Landau-Pomeranchuk-Migdal (LPM)* effect first discussed in [3] and slightly later in [4] is the suppression due to *multiple scattering*

[3] Lev Davidovich Landau and II Pomeranchuk, *Dokl. Akad. Nauk SSSR*, volume 92, page 735, 1953.

[4] Arkady B Migdal, *Physical Review*, 103(6):1811, 1956.

- **Pair-production** differential cross-section including LPM:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon} &= 4\alpha r_e^2 Z(Z+\eta(Z))\,\xi(s) \\ &\times \left\{ \left[\frac{1}{3}G(s)+\frac{2}{3}\phi(s)\right]\left[\epsilon^2+(1-\epsilon)^2\right]\left[\frac{1}{4}\phi_1-\frac{1}{3}lnZ-f_c\right] \right. \\ &+ \left. \frac{2}{3}G(s)\,\epsilon(1-\epsilon)\left[\frac{1}{4}\phi_2-\frac{1}{3}lnZ-f_c\right]\right\}\end{aligned}$$

with $\epsilon \equiv E_+/E_\gamma$

θ_{ms}: the mean deflection angle due to multiple scattering along the formation length and θ_r: the mean emission angle

$$s \sim \frac{\theta_r}{\theta_{ms}} \textbf{ LPM is effective } \text{when } \; s \lesssim 1$$

suppression is important when:

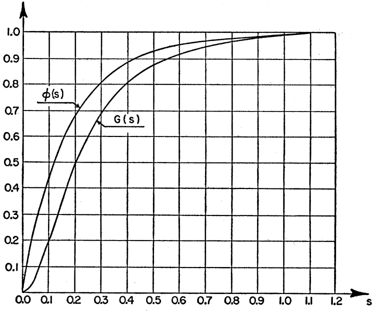
$\theta_{ms} > \theta_r \; \rightarrow \; s < 1$

$\Longrightarrow \; G(s) \rightarrow 0$ and $\phi(s) \rightarrow 0$

absence of suppression when:

$\theta_{ms} < \theta_r \; \rightarrow \; s > 1$

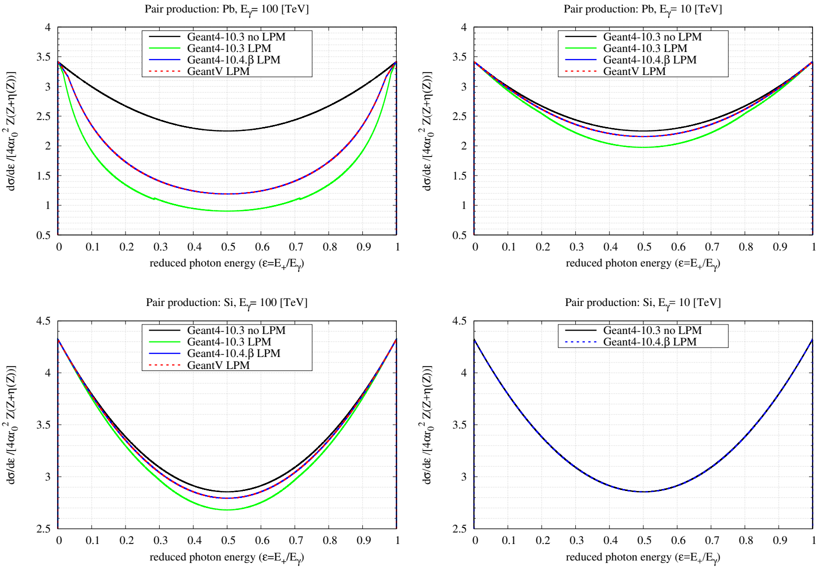
$\Longrightarrow \; G(s) \rightarrow 1$ and $\phi(s) \rightarrow 1$

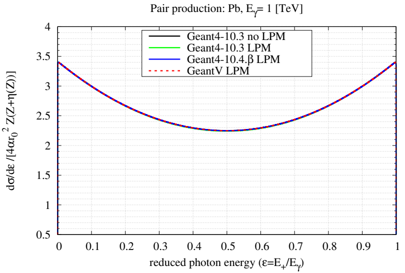


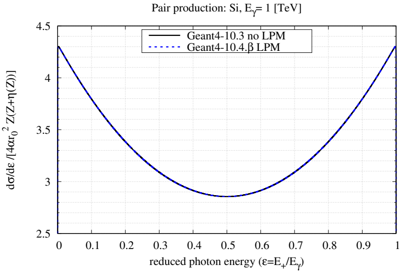
First results:

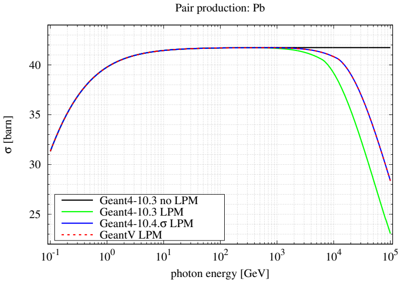
- Reviewing the pair production model including LPM suppression showed an inconsistent calculation of the LPM suppression variable and the material dependent LPM energy in the model used by *Geant4* $\leq$ *10.3*
- **An improved LPM description**, in accordance with the quantum mechanical calculations of Migdal [5] has been first implemented in a standalone code showing an improvement that would mostly affect heavy materials at FCC energies. This will be referred to as *GeantV LPM*.
- It is now integrated in Geant4. The improved Geant4 LPM will be referred to as *Geant4-10.4.*β *LPM*

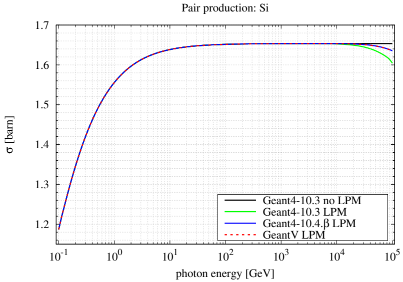
[5] Arkady B Migdal, *Physical Review*, 103(6):1811, 1956.


Pair production: Pb, Eγ= 100 [TeV]
Pair production: Pb, Eγ= 10 [TeV]
Pair production: Si, Eγ= 100 [TeV]
Pair production: Si, Eγ= 10 [TeV]
Geant4-10.3 no LPM
Geant4-10.3 LPM
Geant4-10.4.β LPM
GeantV LPM
dσ/dε /[4αr0 2 Z(Z+η(Z))]
reduced photon energy (ε=E+/Eγ)


Pair production: Pb, Eγ= 1 [TeV]
Geant4-10.3 no LPM
Geant4-10.3 LPM
Geant4-10.4.β LPM
GeantV LPM
dσ/dε /[4αr0^2 Z(Z+η(Z))]
reduced photon energy (ε=E+/Eγ)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0.5 1 1.5 2 2.5 3 3.5 4


Pair production: Si, Eγ= 1 [TeV]
Geant4-10.3 no LPM
Geant4-10.4.β LPM
dσ/dε /[4αr0^2 Z(Z+η(Z))]
reduced photon energy (ε=E+/Eγ)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
2.5 3 3.5 4 4.5


Pair production: Pb
σ [barn]
40
35
30
25
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
photon energy [GeV]
Geant4-10.3 no LPM
Geant4-10.3 LPM
Geant4-10.4.σ LPM
GeantV LPM


Pair production: Si
σ [barn]
1.7
1.6
1.5
1.4
1.3
1.2
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
photon energy [GeV]
Geant4-10.3 no LPM
Geant4-10.3 LPM
Geant4-10.4.β LPM
GeantV LPM

Summary:

- The LPM suppression is more important for heavier materials and more energetic gammas
- The *old* LPM in Geant4 overestimates the suppression
- For heavy materials, the *improved* LPM differs from the old one starting from few TeV gamma energy, which could be relevant for LHC
- For light materials, the improvement appears only above few tens of TeV gamma energy, relevant for FCC
- Improvement of LPM is already included in Geant4.10.04.β