5D γ conversion model: high energy tests

(80 GeV - 100 TeV)

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`html`

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Context

$\gamma X \to e^+ e^- X$

- The Bethe-Heitler differential cross section (DCS) is five-differential
- G4BetheHeitler5DModel implemented in Geant4 release 10.5 in 2018
- Provides SampleSecondaries only

  (total cross section inherited from G4BetheHeitlerModel)

  $\Rightarrow$ available through G4EmLowEPPhysics physics list ($E < 80\,\mathrm{GeV}$)
- Algorithm verified at much higher energies though

  (fortran demonstration model, Nucl. Instrum. Meth., A **899** (2018) 85)
- Mihaly Novak (Sept. 2019) solved the energy limit issue
- In this talk, preparatory high-energy tests that we have performed, end of 2018.

Way out

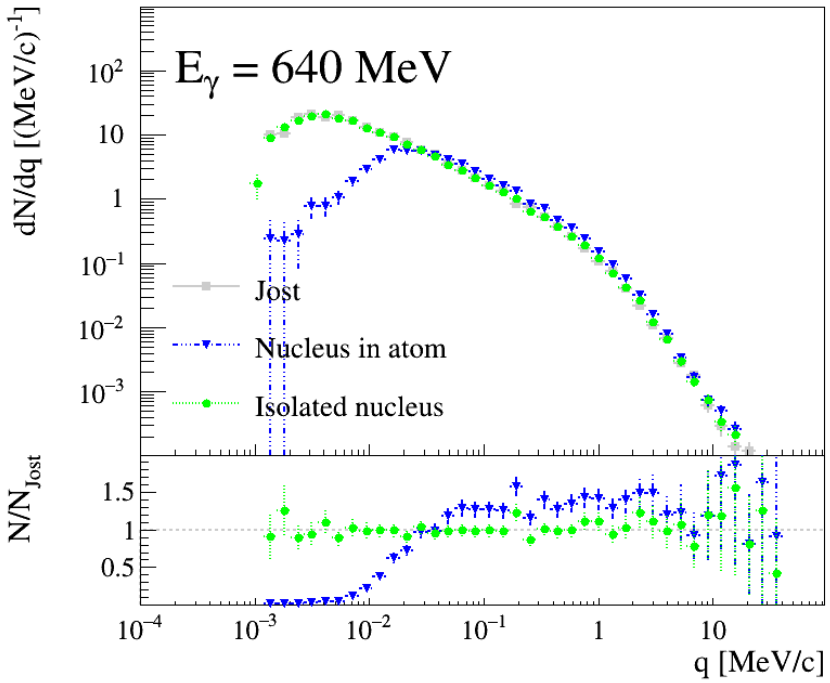
On 04 Sept. 2019 Mihaly Novak wrote:

1. Extending the high energy (G4PairProductionRelModel) pair production model down to the 2 e- mass threshold such that:
   (a) it gives good (identical to the low energy G4BetheHeitlerModel model) atomic cross sections and final states at lower energies (<80GeV)
   (b) while the modification do not alter the previous high energy (>80GeV) behaviour

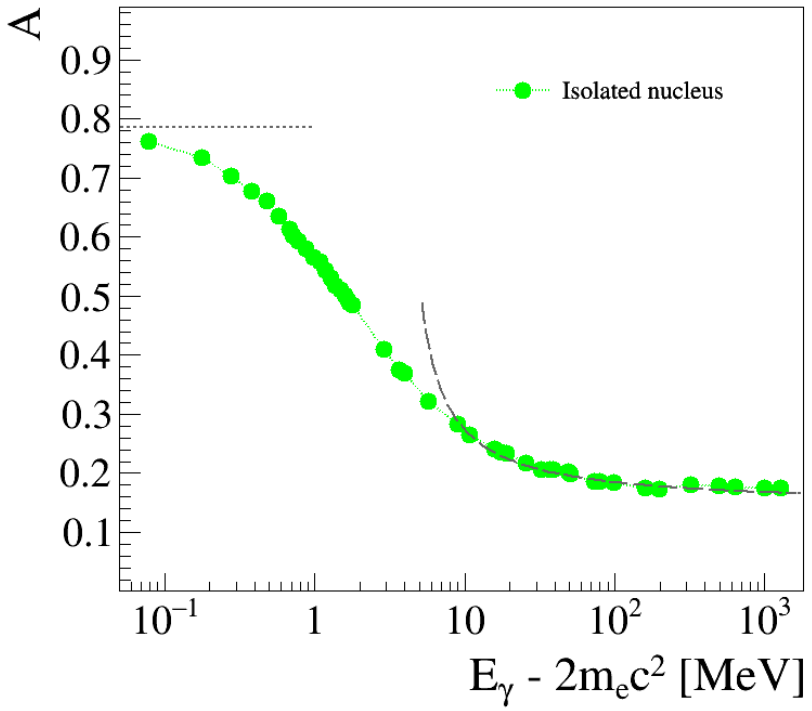
2. The base class of G4BetheHeitler5DModel is changed from the earlier G4BetheHeitlerModel to the new, extended G4PairProductionRelModel:
   (a) the new G4PairProductionRelModel can describe the interaction (both atomic cross section and final state) from the 2 e- mass threshold up to very high energies
   (b) since it has now accurate cross sections at lower energies
   (c) while the LPM suppression is included at high energies

JIRA, MR

G4BetheHeitler5DModel: past low-energy tests: 1



Recoil momentum distribution compared to the analytical high-energy expression from
Jost *et al.*, Phys. Rev. **80** (1950) 189.
The ratio plot is relative to Jost.

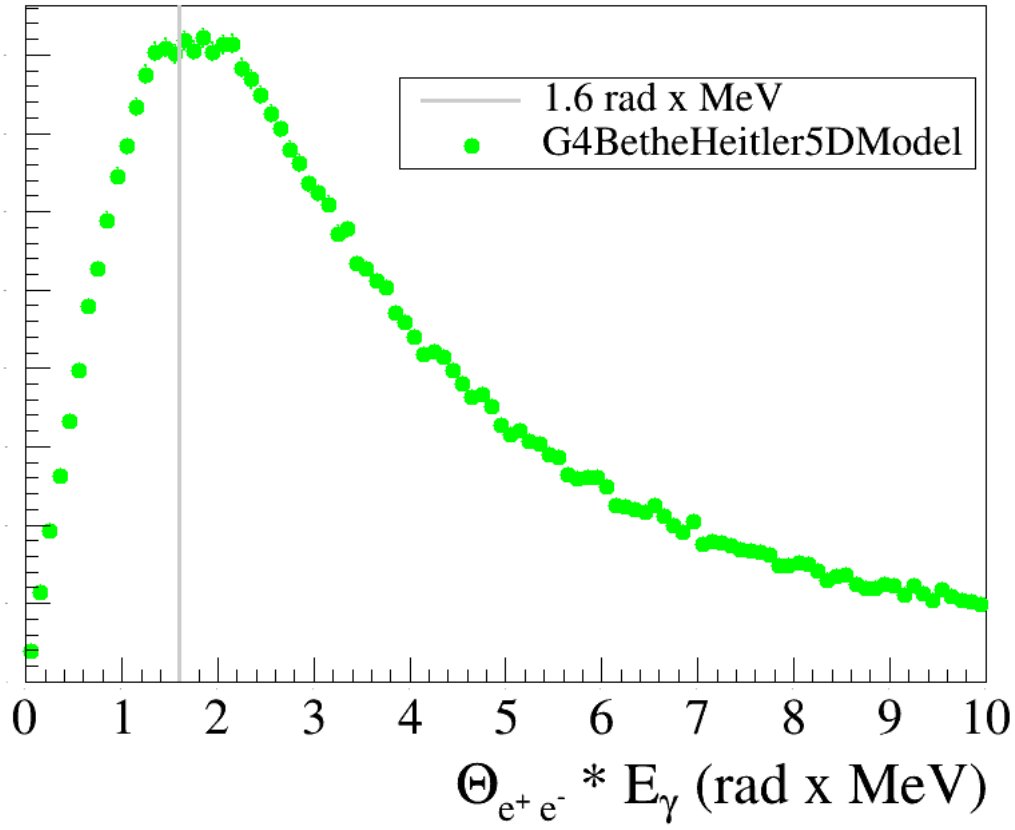


Polarisation asymmetry as a function of available energy, compared to published asymptotic expressions

I. Semeniouk & D. Bernard, Nucl.Instrum.Meth. A936 (2019) 290

G4BetheHeitler5DModel: past low-energy tests: 2

- Pair opening angle distribution, normalized to $1/E$ (1 GeV, argon)



See TestEm15/README.gamma

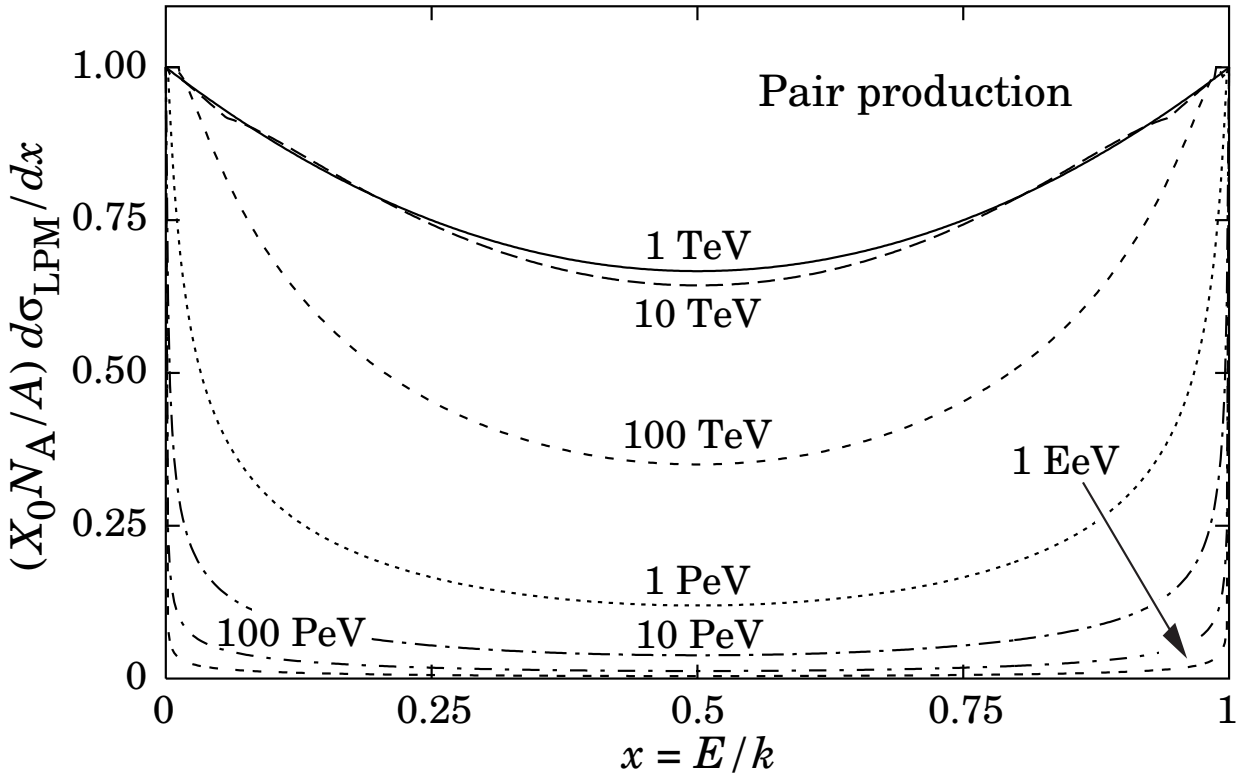
- Expected to peak at $1.6\,\mathrm{rad}\cdot\mathrm{MeV}$ H. Olsen, Phys. Rev. **131** (1963) 406

Bethe-Heitler DCS: validity energy range

- Quantum mechanical interference between amplitudes from different scattering centers (Landau-Pomeranchuk-Migdal LPM effect)

L.D. Landau and I.J. Pomeranchuk, Dokl. Akad. Nauk. SSSR **92** (1953) 535; **92** (1953) 735.

A.B. Migdal, Phys. Rev. Lett. **103** (1956) 1811



The normalized pair production cross section $d\sigma_{LPM}/dy$, versus fractional electron energy $x = E/k$. PDG

- LPM effect sizeable for $E >$ TeVs

Talk lay-out

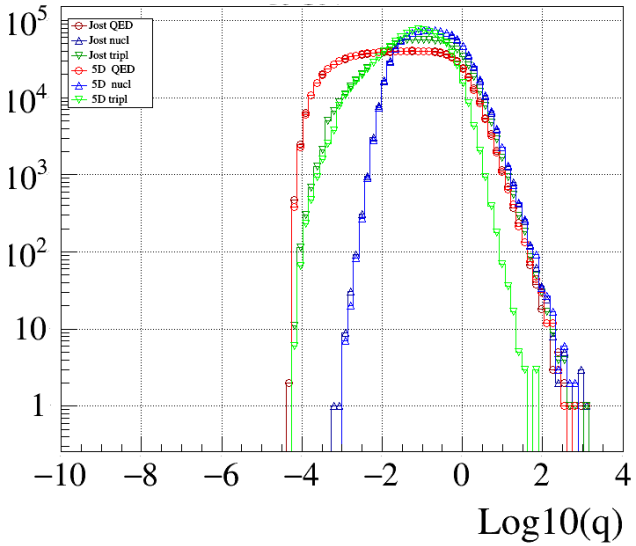
- Test of G4BetheHeitler5DModel in the energy range 80 GeV – 100 TeV
- Examination of the behaviour of the test module TestEm15

Performed with Geant4 10.5beta release

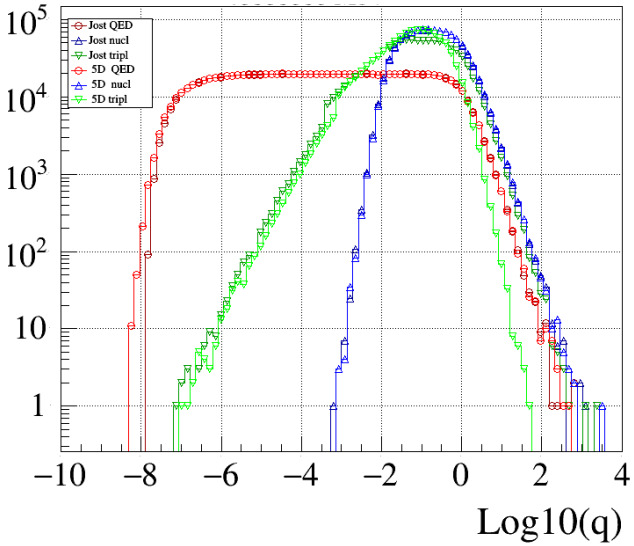
Recoil momentum

- The main limitation of the model is sampling very low recoil momentum q
- q plotted here is `PRec`, used in computing the DCS in G4BetheHeitler5DModel

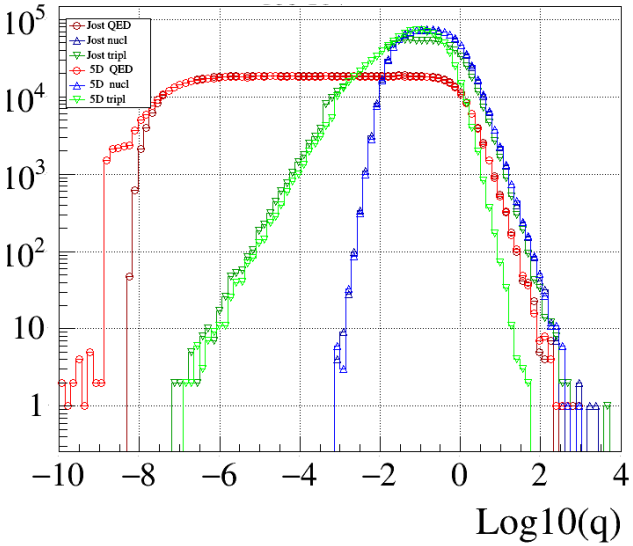
10 GeV



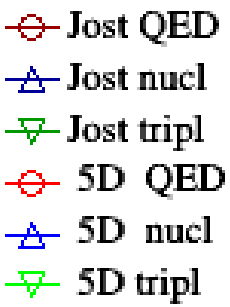
40 TeV



100 TeV



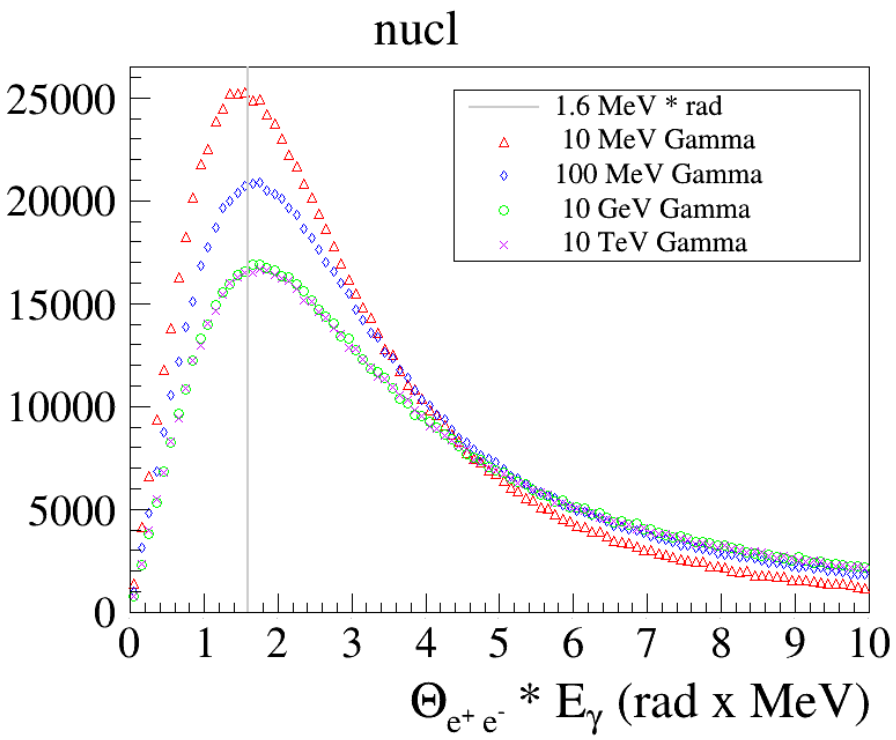
$\log_{10}(q/(\mathrm{MeV}/c))$ distributions for γ-ray conversions on Argon

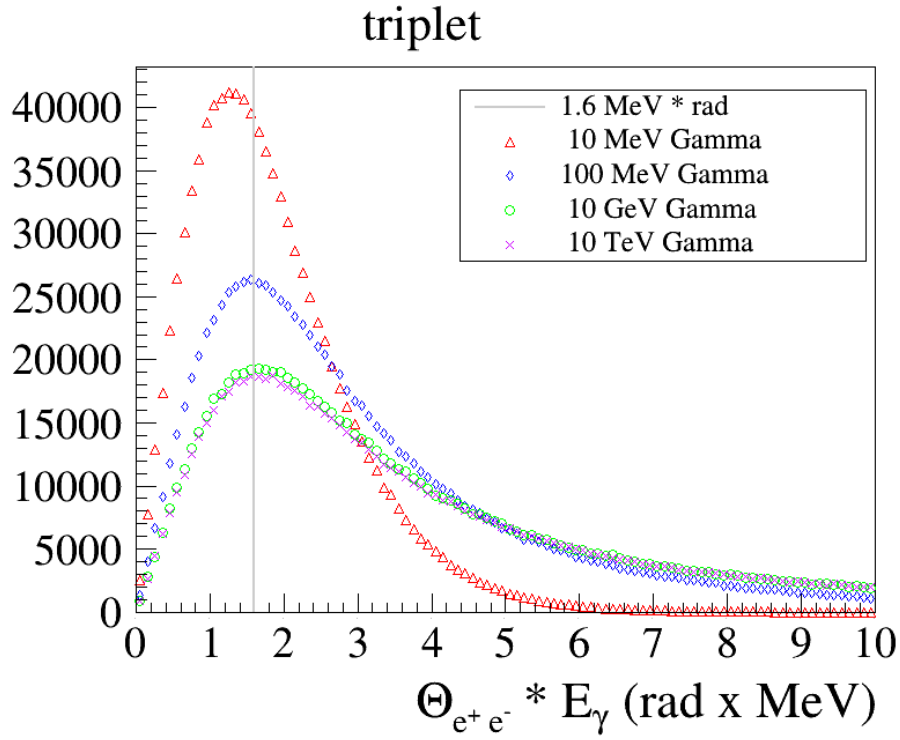


- QED (isolated targets)
- Nuclear (same form-factor for G4BetheHeitler5DModel and Jost)
- Triplet (same form-factor for G4BetheHeitler5DModel and Jost)

Problems below $q < 10^{-8}\mathrm{MeV}/c$

Opening Angle

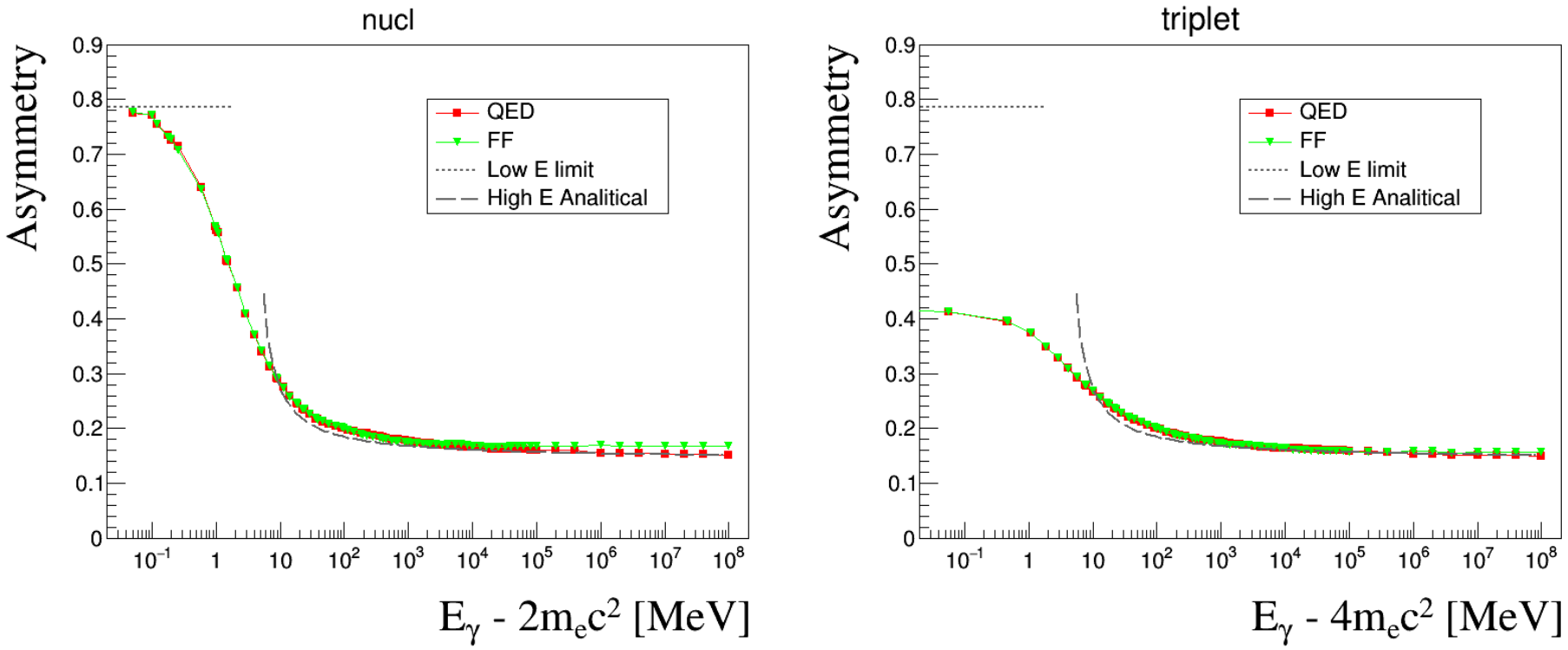




- Distribution of pair opening angle θ_{+-}, normalized to inverse of incoming photon energy
- Vertical line shows the high-energy asymoptotic prediction of the most probable value $\hat{\theta}_{+-}$ of θ_{+-} by Olsen Phys. Rev. 131 (1963) 406

$$\hat{\theta}_{+-} \approx \frac{1.6\,\mathrm{MeV}}{E}$$

Polarisation Asymmetry



Polarisation asymmetry as a function of available energy, compared to asymptotic expressions

- Nice agreement at high energy and for nuclear low energy
- Disagreement for triplet low energy
  - was already seen in fortran Nucl. Instrum. Meth., A **899** (2018) 85)
    - approximations done for calculation low-energy asymptote illegitimate for triplet ?

Bethe-Heitler approximate for low-energy triplet conversion anyway (2 diagrams missing)

TestEm15

2 issues:

- for low recoils, energy deposited at vertex: no recoil particle available
- particles recoil momentum computed in `G4DynamicParticle` class:

```
G4double energy = theKineticEnergy;
G4double momentum = std::sqrt(energy*energy+2.0*mass*energy);
```

fails when `energy` $\ll$ `mass`

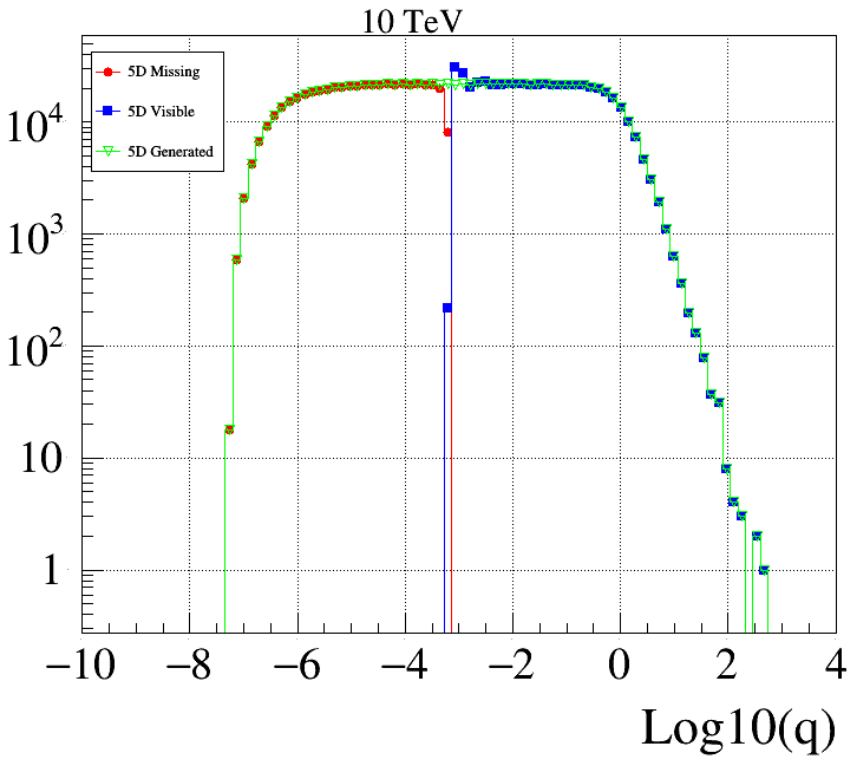
Formal issues only, mainly for QED conversion tests (isolated targets)

no user would consider tracking sub-keV/c particles in a detector (?)

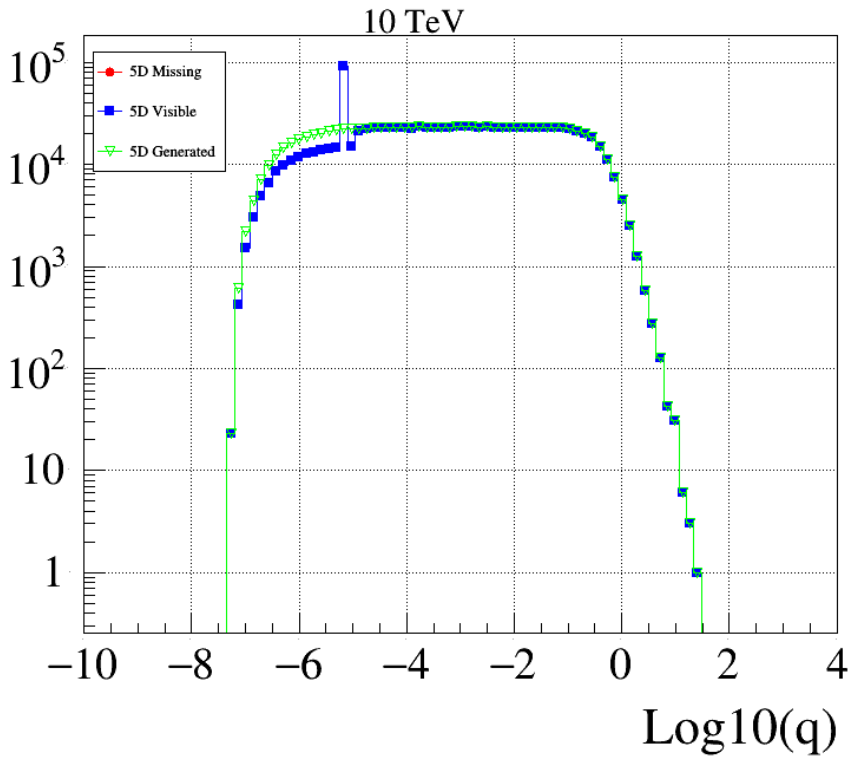
TestEm15: 10 TeV

Isolated target

nucl



triplet

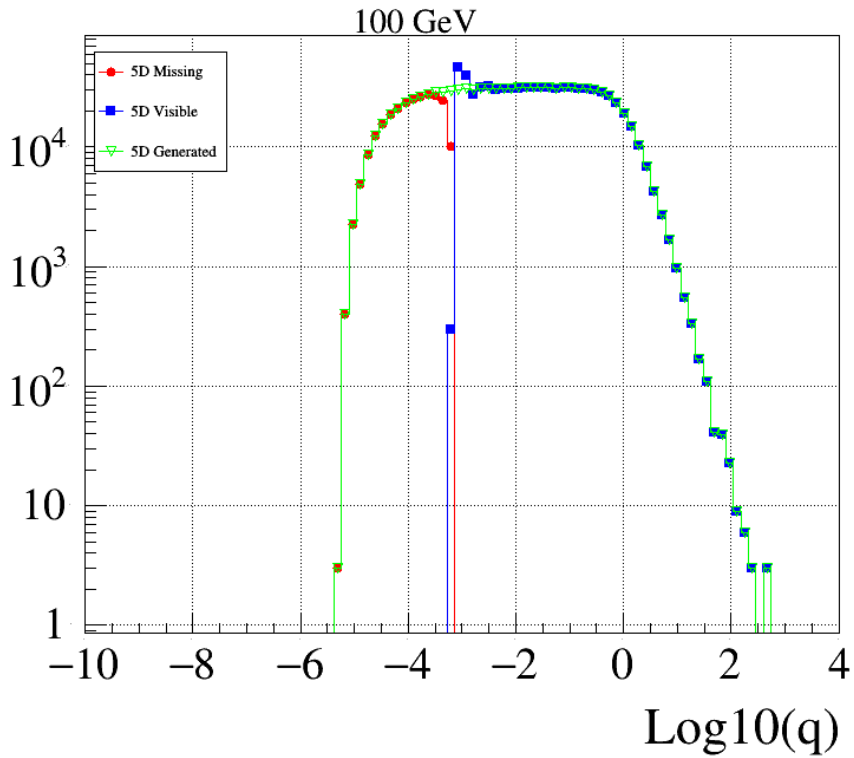


- Squares: "visible": TestEm15 out-of-the-box; (recoil momentum of present recoiling particle)
- Triangles: "Generated": recoil value as was calculated and used in G4BetheHeitler5DModel (`PRec`); all sample
- Bullets: "missing": recoil value as was calculated and used in G4BetheHeitler5DModel (`PRec`); events without a recoil particle in G4

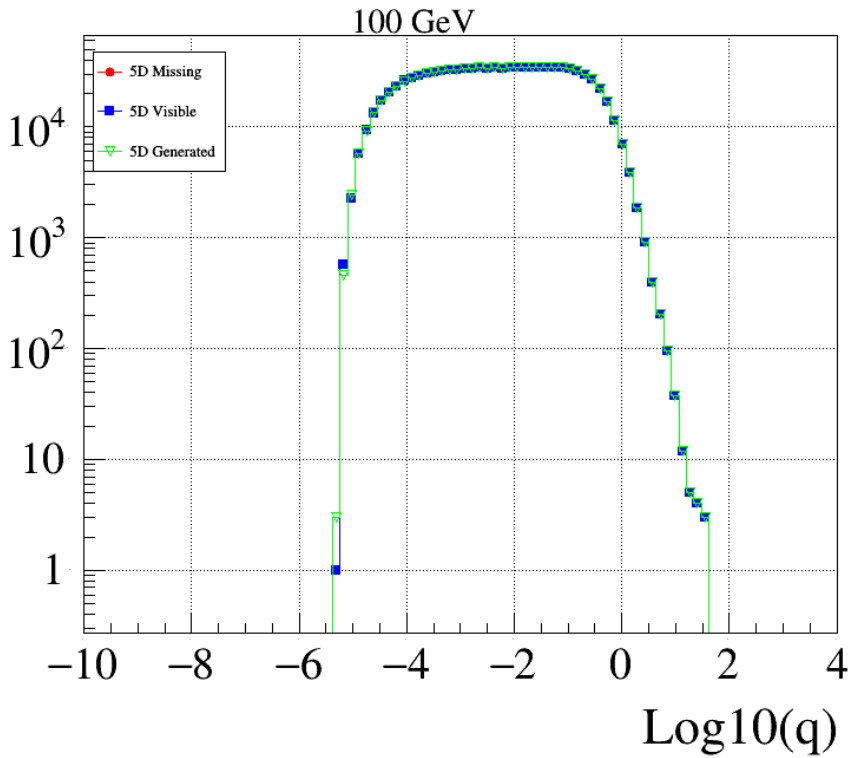
TestEm15: 100 GeV

Isolated target

nucl



triplet



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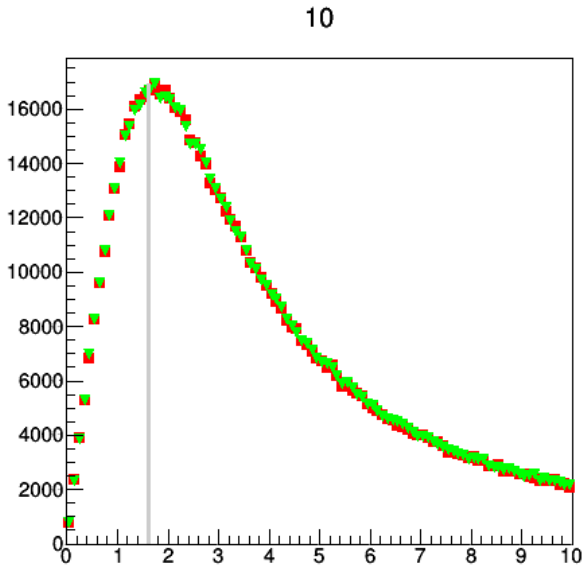
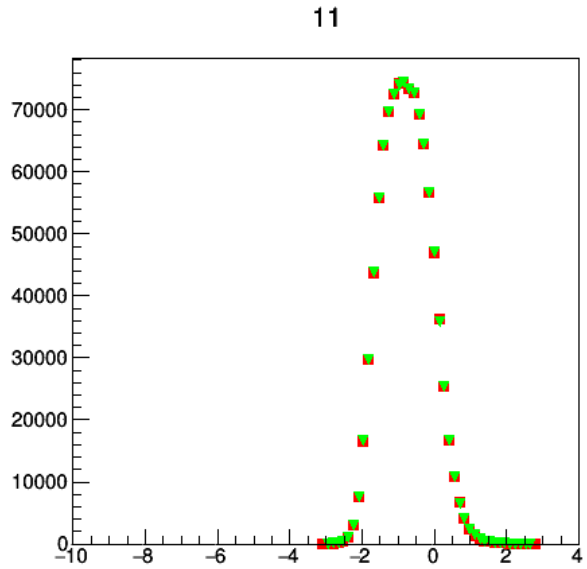
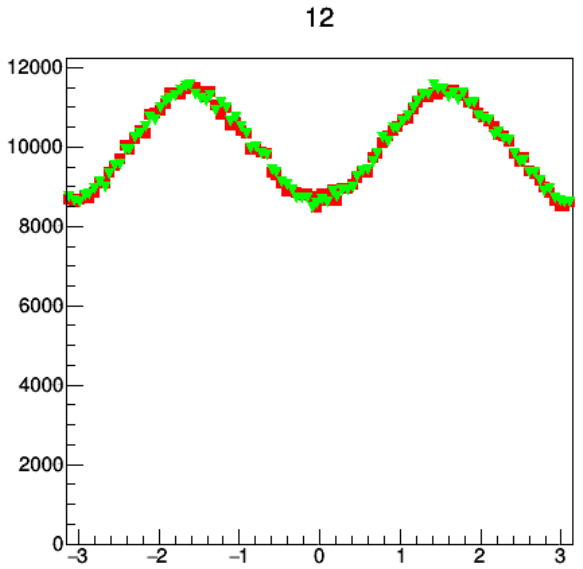
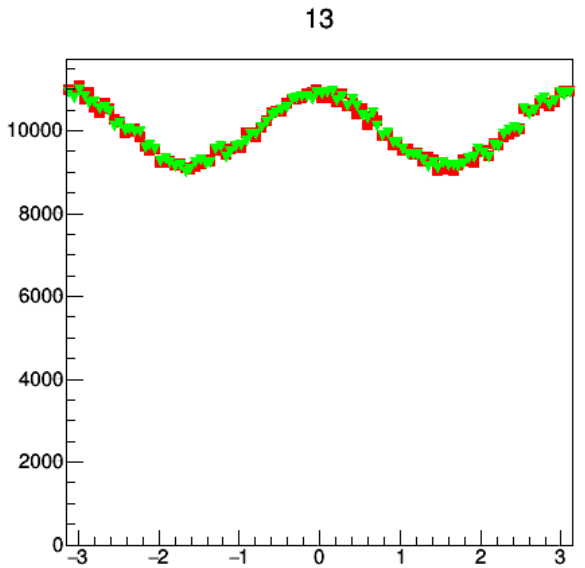
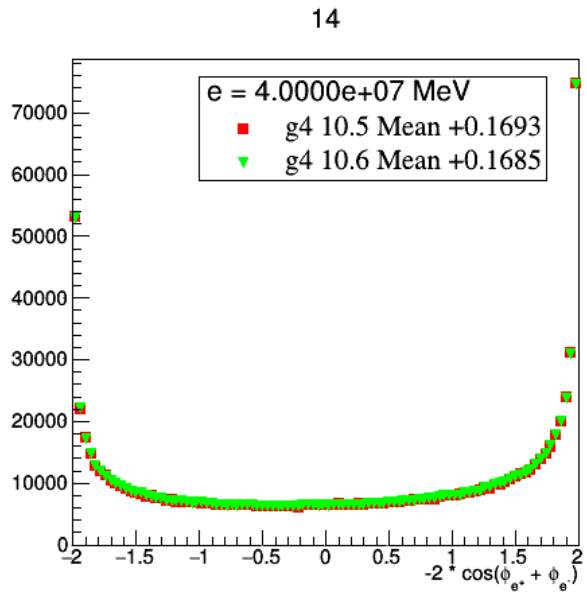
Direct check, nuclear, 40 TeV on atomic Argon

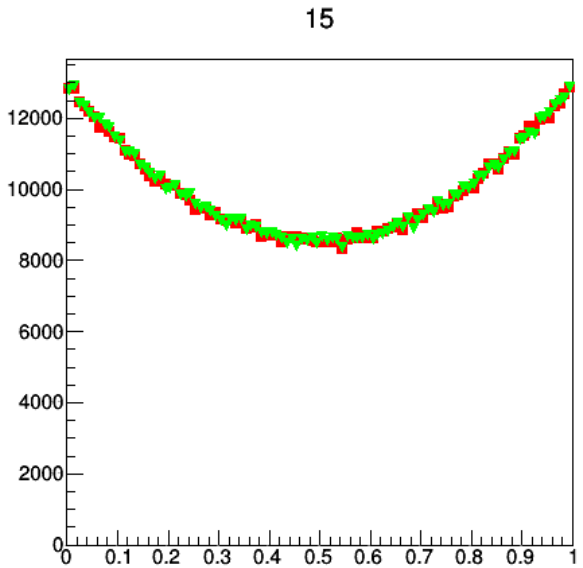












TestEm15

Thanks to Mihaly Novak

Conclusion

- G4BetheHeitler5DModel verified up to 100 TeV

  Means only that it does sample Bethe-Heitler differential cross section.

- We had to modify the code to obtain these results:
  - Exfiltrate `PRec` out of G4BetheHeitler5DModel
  - For small angles:
    obtain θ_{+-} from arcsin(cross product) instead of arcos(dot product)

- Model can't sample events with $q < 10^{-8}\mathrm{MeV}/c$ correctly, something which would happen
  - for conversions on isolated targets and $E > 40\,\mathrm{TeV}$

  (same was seen in `double precision` fortran Nucl. Instrum. Meth., A **899** (2018) 85)

- Users who would run TestEm15 out-of-the-box on high-energy conversions on isolated targets will have surprises.

Note added in proof

- On 02/09/2019 Gabriele COSMO wrote: geant4-10-05-ref-08:

  Major development/fixes included since the last development tag are:

  - physics_lists/constructors/electromagnetic:
    - [...]
    - G4EmStandardPhysics_option4: use 5D model for gamma conversion.
    - [...]

- See also EM group recommendations at this Collaboration meeting:

  - EM infrastructure and Physics Lists update (p9), Aleksandr Bagulia & Vladimir Ivantchenko, talk on 23 Sep 2019
  - Status of Electromagnetic Physics (p33), Vladimir Ivantchenko, talk 24 Sep 2019

- Our programme on G4BetheHeitler5DModel completed.

Back-up slides

Links to past presentations

Aug. 2018	Lund	Geant4 Collaboration meeting
Jan. 2018	CERN	Geant4 EM meeting
Sept. 2017	Wollongong	Geant4 User Workshop
April 2017	Guildford	Geant4 Space Users' Workshop