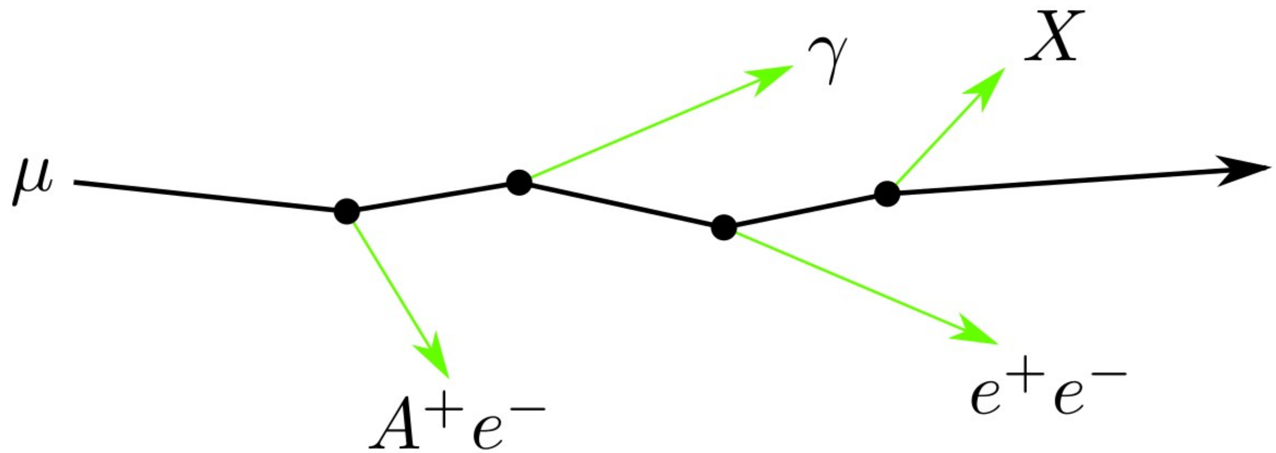

Theoretical uncertainties of muon transport calculations for very large volume neutrino telescopes

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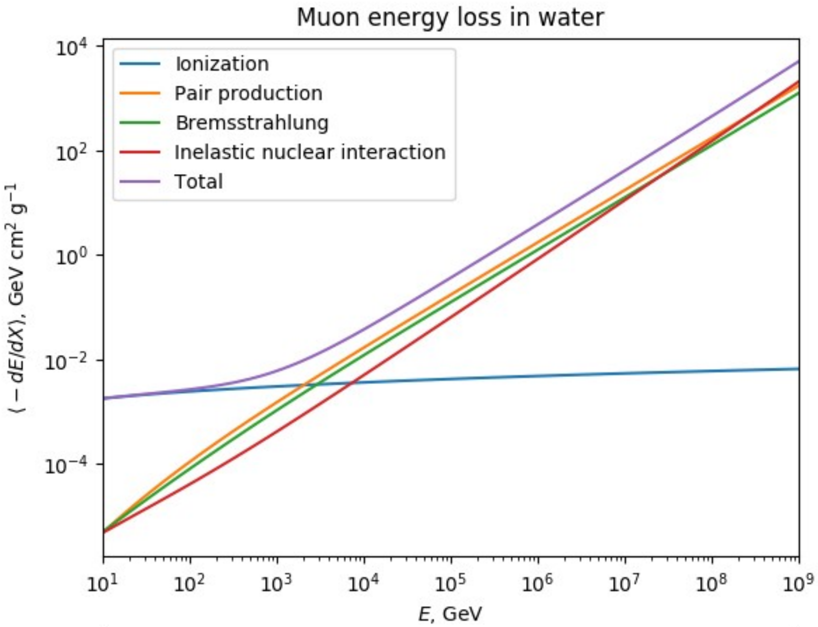
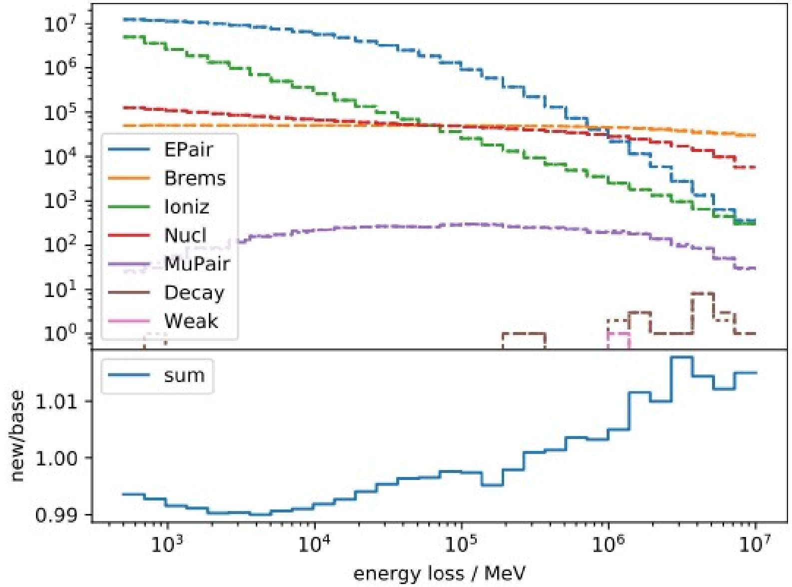
Muons in VLVνT

- Sources of muons
  - Interaction of muon neutrinos
  - Extended air shower
  - (Secondary muons due to muon pair production)
- Muons are heavy and loose their energy slowly
  - Large range
  - Muons from EAS reach experiments deep underground
- Energy loss is a stochastic process → Monte Carlo simulation

Muon energy loss processes

- Ionization
  - Small quasi-continuous energy losses
  - Dominant at low energies
- Pair production
  - Small quasi-continuous energy losses
- Bremsstrahlung
  - Large stochastic energy losses
- Inelastic nuclear interaction
  - Large stochastic energy losses
  - Share in total energy loss rises with energy





Muon propagation software used in current VLVνT

- IceCube (South Pole)
  - PROPOSAL (Koehne et al. 2013; Dunsch et al. 2019)
  - See also talk by Jean-Marco Alameddine on Thursday
- Baikal-GVD (Siberia)
  - MUM (Sokalski, Bugaev & Klimushin 2001; Bugaev et al. 2004)
- ANTARES/KM3Net (Mediterranean Sea)
  - MUSIC (Kudryavtsev 2009)
  - MUM

Cross section parametrizations used

- PROPOSAL, MUSIC and MUM offer several different parametrizations of the bremsstrahlung and inelastic nuclear interaction cross sections
- The following is based on the selection used in the IceCube collaboration for PROPOSAL, the recommended cross sections for MUSIC and the standard cross sections for MUM.

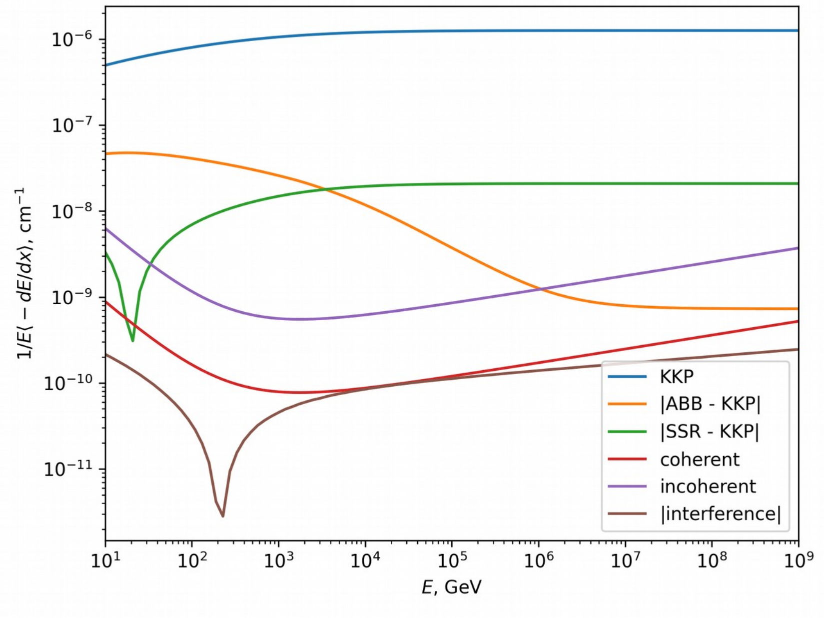
Differences in used parametrizations of radiative processes

- Ionization
  - Bethe-Bloch equation with density correction and radiative corrections
  - No density correction and radiative corrections in MUSIC
- Pair production
  - Always Kokoulin & Petrukhin (1969, 1971) with Kelner (1998) for the atomic electron contribution
- Bremsstrahlung
  - Kelner, Kokoulin & Petrukhin (1995, 1997) with atomic electrons
  - Andreev, Bezrukov & Bugaev (1995) for MUM
- Inelastic nuclear interaction
  - Bugaev & Shlepin (2003) for ANTARES/KM3Net and Baikal-GVD
  - Abramowicz & Levy (1997) with Butkevich & Mikheyev (2002) shadowing for IceCube

Recent theoretical developments
and
Differences between currently used cross sections

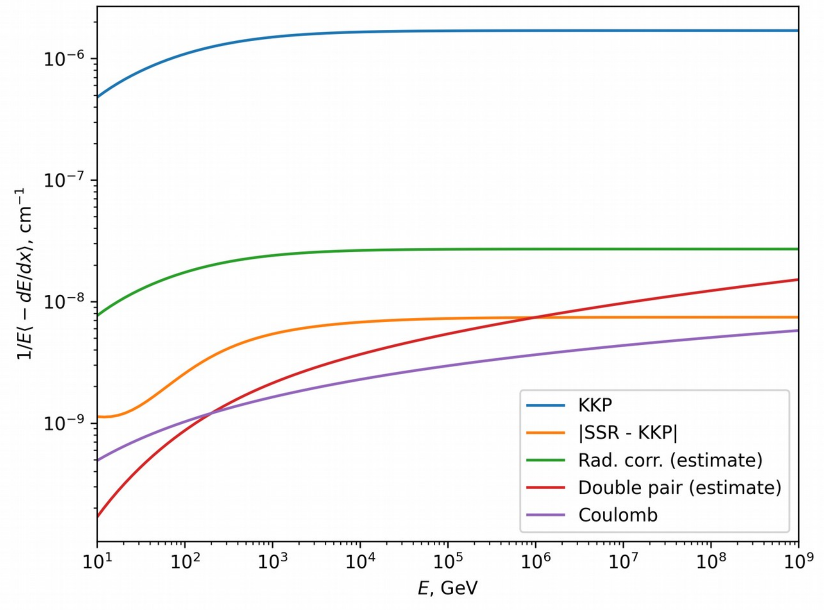
Bremsstrahlung

- Differences between ABB und KKP
  - Different atomic formfactor (dipole vs. Thomas-Fermi), different radiation logarithm
  - Different treatment of atomic electrons
  - Screening functions $\Phi_{1,2}$
- New developments
  - SSR: Radiative corrections, screening function, ~2%
  - Diffractive corrections: $\gamma^* A \rightarrow \gamma A$



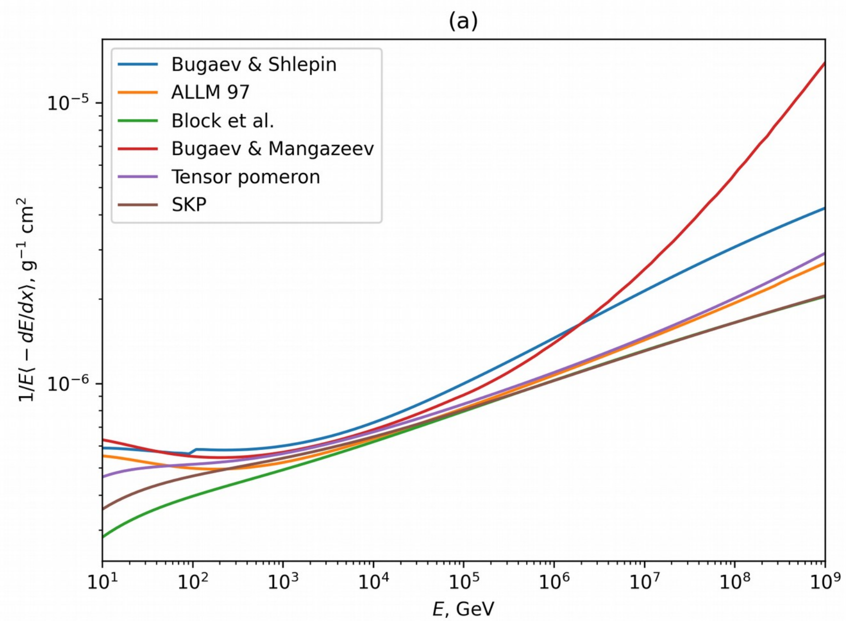
Pair production

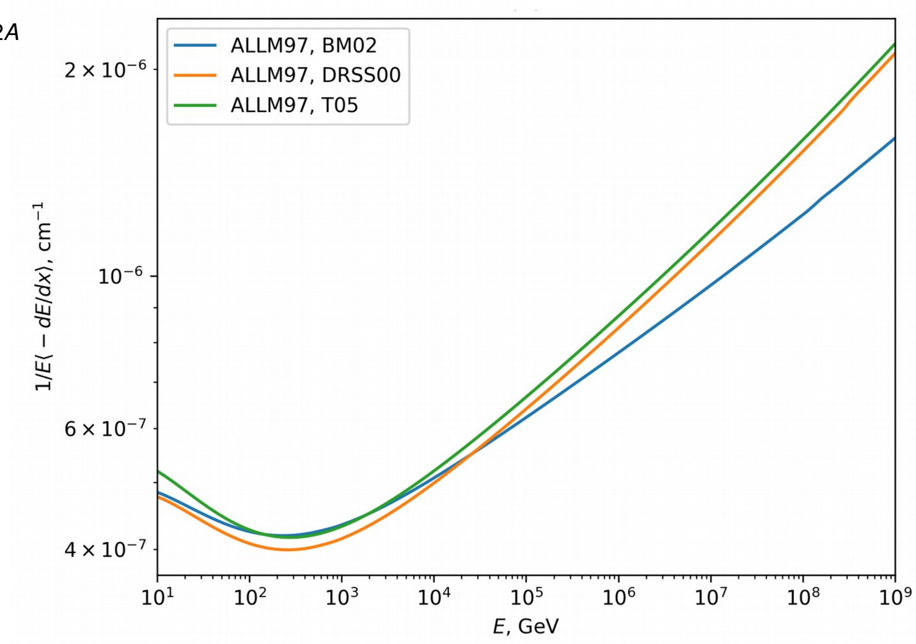
- Recent developments
  - Refined treatment of screening functions: ~−0,5%
  - Coulomb corrections
  - Estimate of radiative corrections
    - Double pair production:
      ~ $2\times10^{-5}\ \ln^2 (E/\mu)$
    - Radiative corrections to e^+e^-: ~0,9%
    - Radiative corrections to μ: ~0,5%
    - Vacuum polarization: ~0,2%



Inelastic nuclear interaction

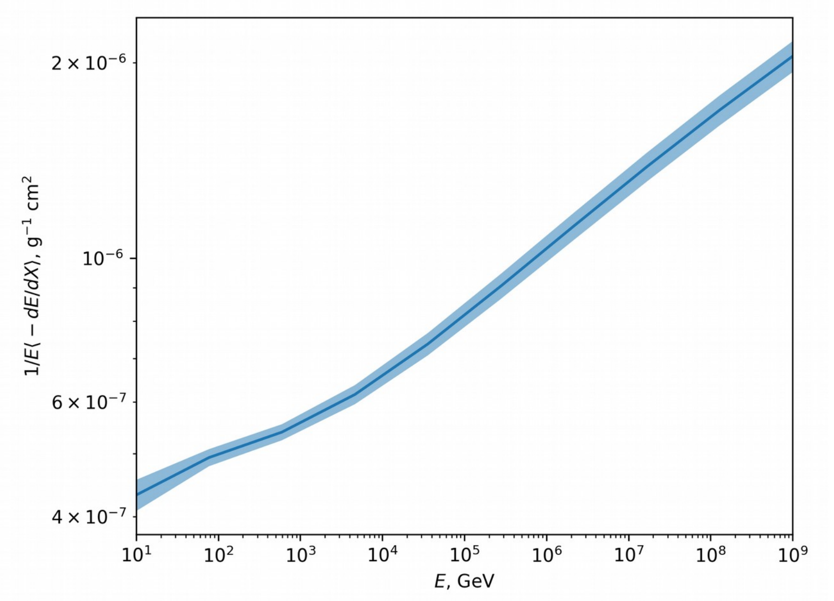
- Two problems to solve
  - No unified theory for perturbative and non-perturbative γp interactions → phenomenological fits
  - Nuclear effects such as shadowing $F_{2A} < A\,F_{2N}$
- Models currently used are based on pre-HERA or early HERA data
- Combined H1+ZEUS data have become available → new parametrizations of γp interactions





Uncertainty propagation, BDH-fit to combined HERA data

- Refit of modified Block et al. parametrization of structure functions to combined HERA data
- Using fit values and correlations between parameters, parameter values were sampled.
- Average energy loss calculated for each sample to estimate uncertainty for protons.
- 3–5%, slowly increasing with energy



Effects on muon spectra

- Muon spectra with surface spectral index γ at depth h determined approximately by product $b\gamma h$
- Estimation of the energy inside the detector
  - Small energy losses (ionization, pair production) well-correlated to energy
  - Large stochastic losses (bremsstrahlung, inelastic nuclear interaction) ill-correlated $\rightarrow$ typically discarded for the energy estimation
  - Energy reconstruction of high-energy muons dominated by pair production $\rightarrow$ only uncertainties on pair production contribute significantly
- Propagation outside the detector
  - Not observable, all energy losses contribute
  - For atmospheric muons, range is given by geometry
    - Increased energy losses translate to larger energies at the surface.

Conclusions

- Process dominating uncertainty depends on energy
  - Radiative corrections to pair production
  - Nuclear shadowing
- Effect for energy reconstruction inside detector
  - Dominated by pair production
- Effect for estimate of muon surface energy
  - All processes contribute
- Uncertainties have decreased in recent years