The LPM effect: A Summary

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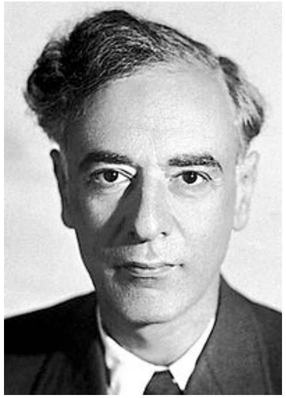
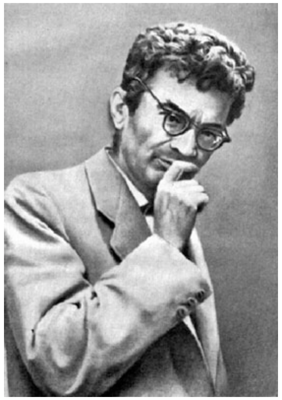
Connolly Group Meeting

Landau-Pomeranchuk-Migdal (LPM) Effect

- Qualitatively - At high energies or high matter densities, the cross-sections for bremsstrahlung and pair-production decrease
- 1953 – Lev Landau and Isaak Pomeranchuk showed that the cross-sections at high energies do not follow the Bethe-Heitler formula (otherwise the correct relation)
- 1956 – Arkady Migdal showed what the proper quantum mechanic treatment for the cross sections would be
- L(andau) P(omeranchuk) M(igdal)

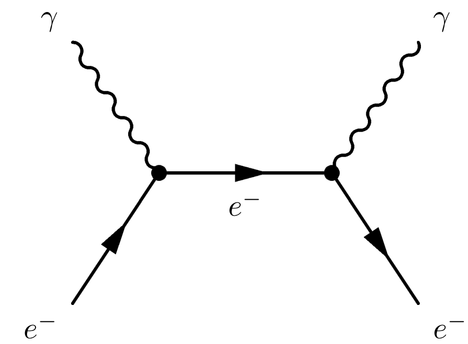


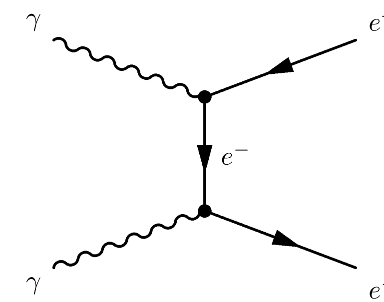


Why does this happen?

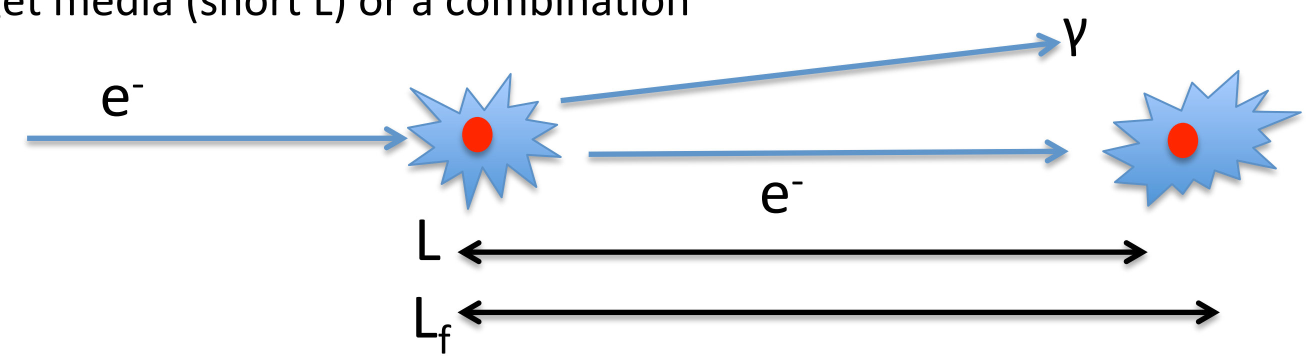
- Only for bremsstrahlung and pair production
  - Same interaction, rotated Feynman diagrams
- Requires low momentum transfer between the nucleus and the electron (q)

$$q = \sqrt{E^2 - m^2} - \sqrt{(E-k)^2 - m^2} - k \sim \frac{m^2}{2E(E-K)} \sim \frac{k}{2\gamma^2}$$





- Since γ is high and the emitted photon energy (k) is low, q is very low
- Since q is low, the interaction must occur over a large distance or formation length, L_f – uncertainty principle
- If L (mean free path) ~ L_f, the emissions cannot be seen as independent, i.e. the first emission interferes with the second
  - Bremsstrahlung and pair production are suppressed
- Happens at high energy (low momentum transfer, long L_f) or high density target media (short L) or a combination



Energy Threshold

- LPM effect becomes important for particles (electrons and photons) above

$$E_{LPM} = \left(\frac{4mc^2}{E_s}\right)^2 \left(\frac{mc}{2\hbar}\right) Lmc^2 = 61.5\ L_{cm}\ TeV$$

$$L_{LPM} \approx \left(\frac{E_0}{E_{LPM}}\right)^{1/2} L$$

- Where L is the standard Bethe-Heitler radiation length and L_{cm} is the L_{LPM} value in cm
- L_{LPM} is the radiation length for bremsstrahlung and 4/3 the mean free path for pair production

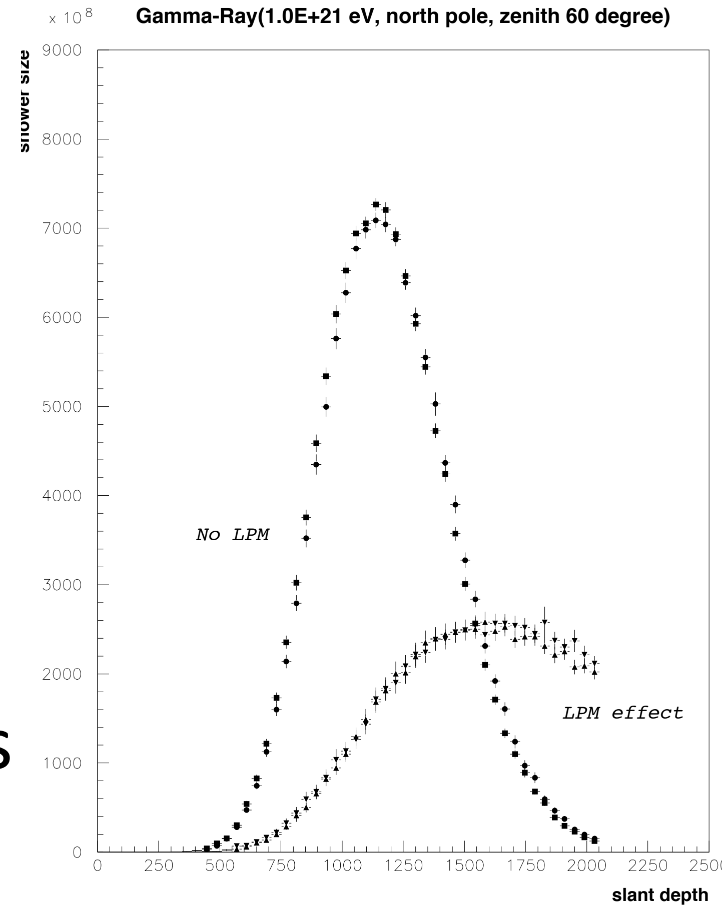
Different Materials

- Radiation lengths dramatically change above E_{LPM}

Material	Density (g/cm^3)	Radiation Length (g/cm^2)	Radiation Length (cm)	E_LPM (TeV)	L_LPM for 1EeV (cm)	L_LPM/L
Water	1	36.4	36.4	2240	769.1	21.1
Lead	11.35	6.4	0.56	35	94.7	169.0
Ice	0.918	36.08	39.31	2418	799.4	20.3
Air (estimate at STP)	1.28E-03	36.66	2.87E+04	148707	74538.4	2.6

What about particle showers?

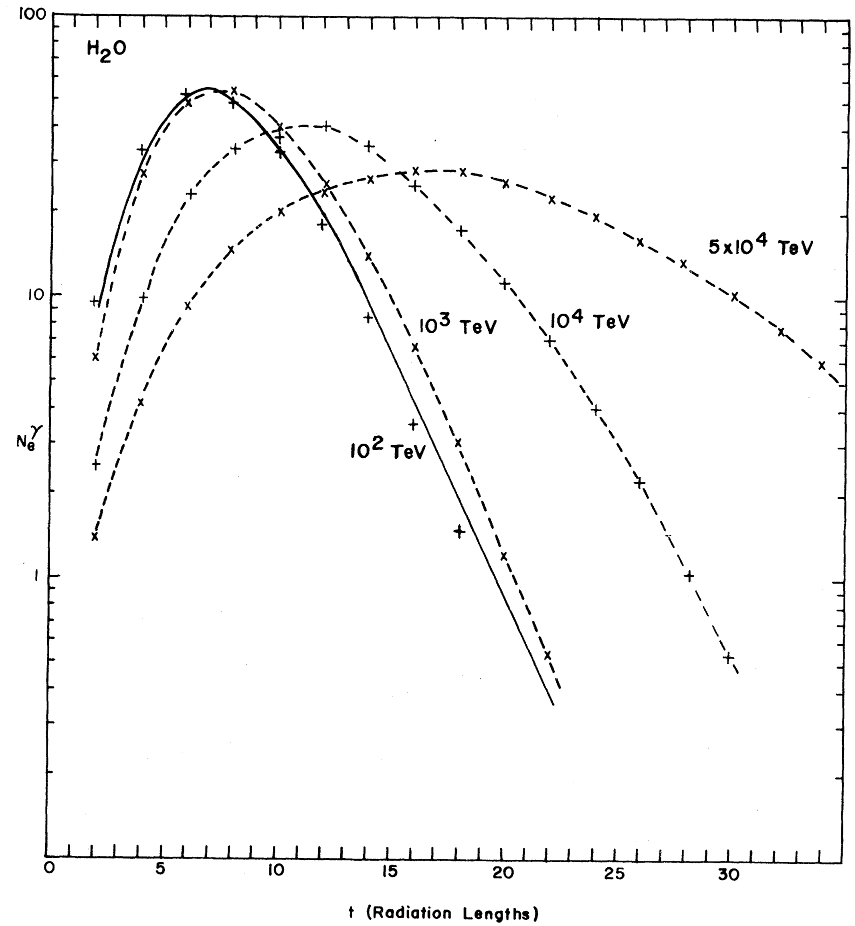
- LPM effect decreases cross section, thus increases interaction length
- If E_0 is high enough, drastic lengthening
  - The primary and "enough" secondary particles must be above the energy required
- Longitudinal shower development (shower profile) is important for the shape of the radio pulse observed emitted



K.Kim, et al. ICRC 1999, OG 4.5.12

E-M cascades and Energy

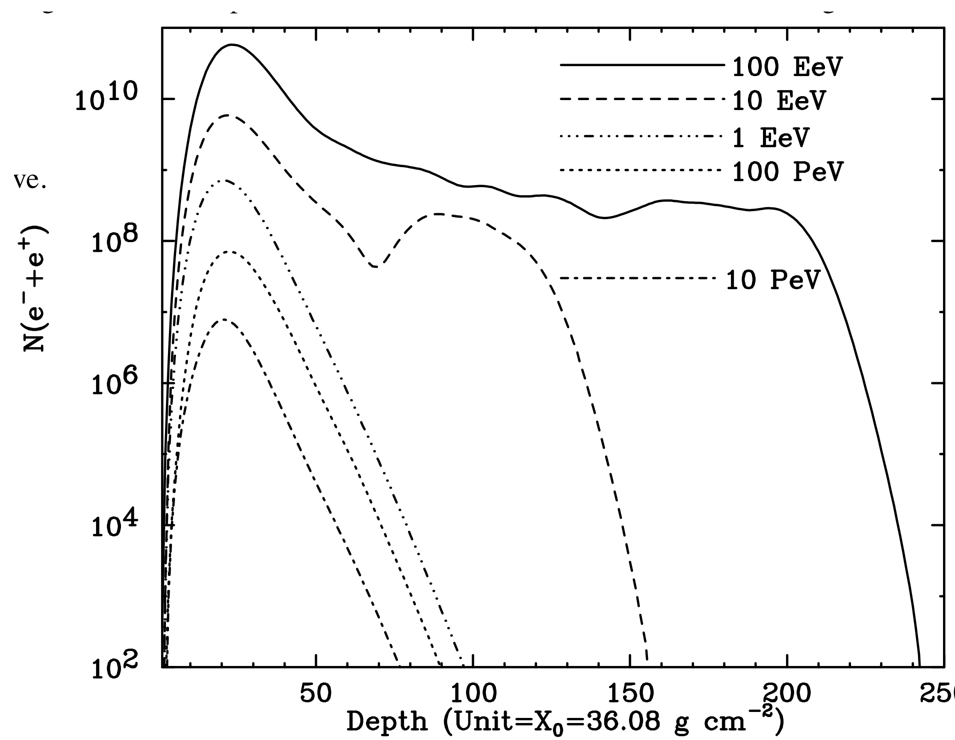
- Averages of simulated photon-initiated cascades in water
- As energy increases, shower lengthens



T. Stanev et al., PRD, 25, 5, p. 1299

Hadronic Shower Development

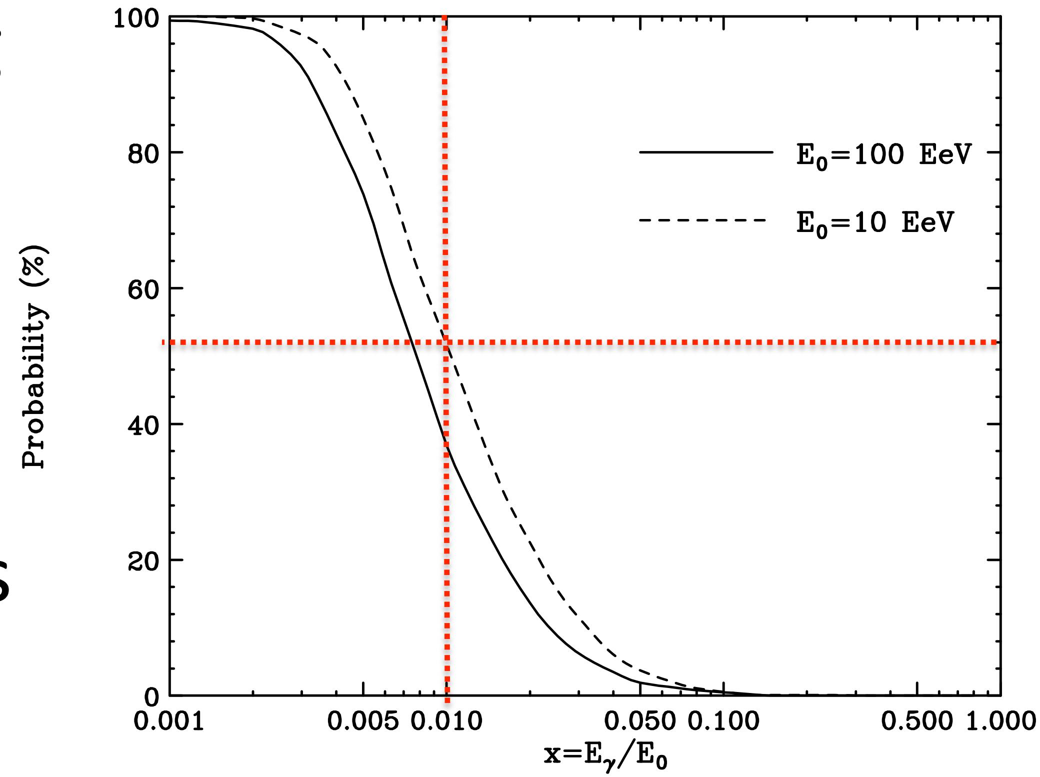
- Average longitudinal development of hadronic showers initiated by neutrinos interacting in ice
- Okay up to 1 EeV
  - Fits standard shower profile
  - Average photon energy produced by pion core is ~35PeV
- At higher E, tails produced by E-M decays of resonances with short lifetimes from early in the shower



J. Alvarez-Muniz and E. Zas, ICRC 1999, arXiv:astro-ph/9906347

E-M component of Hadronic Shower

- Probability of creating a photon with $E_\gamma > xE_0$ from a neutrino induced shower in ice
- Photons with E > 100 PeV produce LPM tails



J. Alvarez-Muniz and E. Zas, ICRC 1999, arXiv:astro-ph/9906347

Further Reading

- **Original QM treatment:**
  – A. B. Migdal, Phys. Rev., V. 103 (1956) 6, pp. 1811-1820.
- **UHE EM cascades and their characteristics**
  – T. Stanev et al., Phys. Rev. D, V. 25 (1982) 5, pp. 1291-1304. - **H_2O and Pb**
  – A. Misaki, Phys. Rev. D, V. 40 (1989) 9, pp. 3086-3096. – **Pb**
  – E. Konishi et al., J. Phys. G: Nucl. Part. Phys. 17 (1991) pp. 719-732. – **Pb**