What do UHE Showers really look like?

Two open issues

Spencer Klein, LBNL

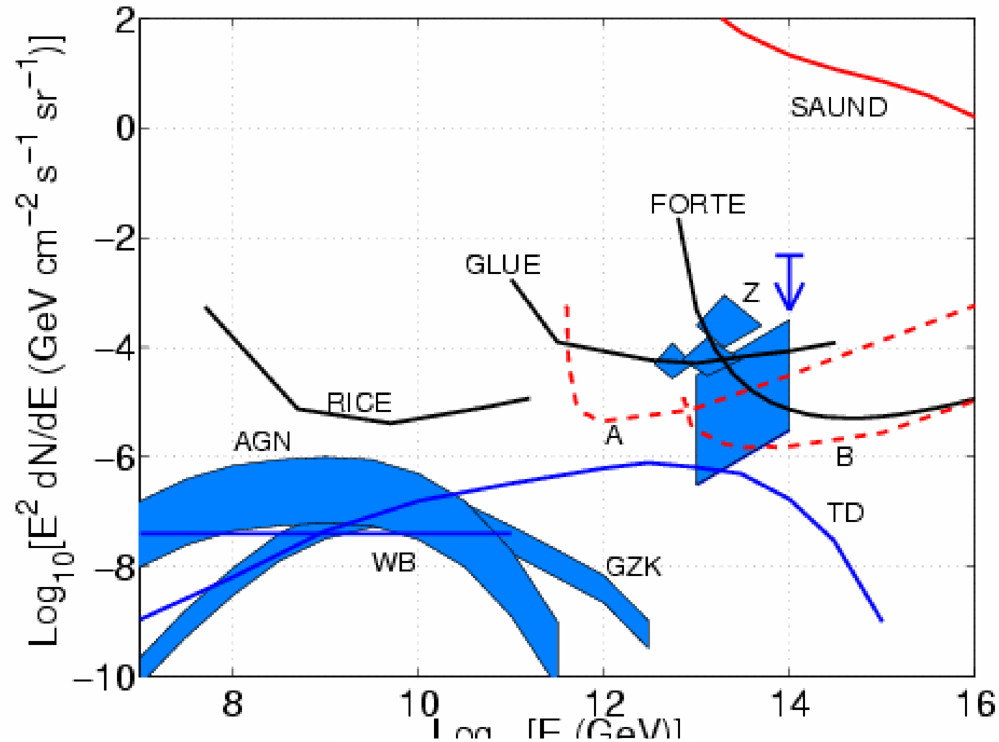
- Electromagnetic vs. hadronic showers?
  - Bremsstrahlung, pair production and the LPM effect
  - Photonuclear Interactions
  - What are the relative cross sections?
  - Shower development & Radio Cherenkov profiles
- Cherenkov Radiation from e^+e^- pairs (w/ Sourav Mandal)

Why?

- IceCube & AUGER will collect 10-1000 times as much data as existing experiments
- Some newer experiments study radio and acoustic emission from ν induced showers and set limit on neutrinos with energies up to 10^{25} eV
- Interpreting this data requires a better understanding of what ultra-high energy showers look like.

High Energy (above 10^{20} eV) searches

- Coherent electromagnetic/ acoustic radiation from showers
  - Sensitive to shower profile
- Mot analyses assume purely electromagnetic showers
  - ZHS parameterization for radio



Log_{10} E(GeV)

Vandenbroucke, Gratta and Lehtinen (Saund)

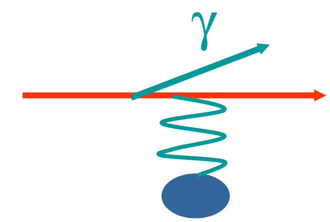
Electromagnetic vs. Hadronic Showers

- Conventional Wisdom
  - Photons produce e^+e^- pairs
  - Photonuclear interactions are rare, and can be neglected
- Reality
  - The LPM effect reduces the electromagnetic cross sections
  - $\sigma_{\gamma N}$ rises with energy
  - Photonuclear interactions are important

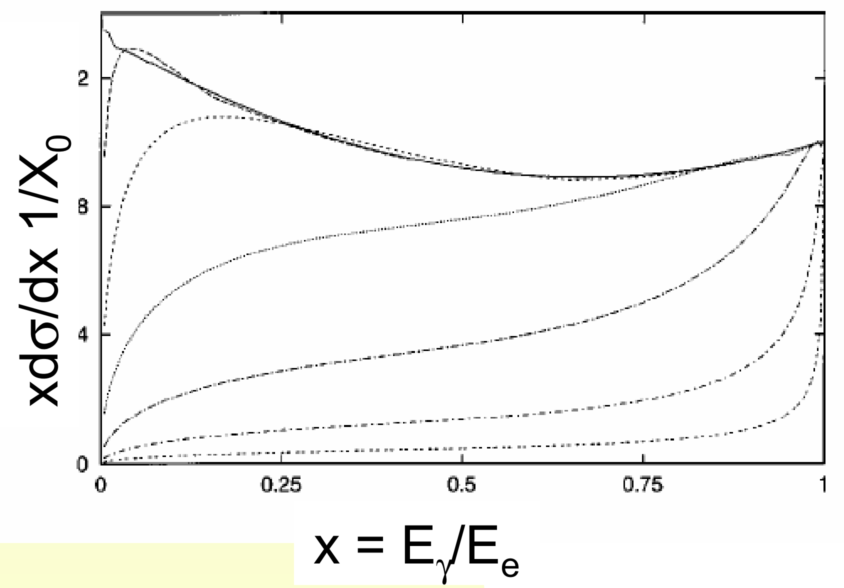
LPM Effect in brief

- At high energies, electromagnetic cross sections decrease
  - bremsstrahlung: eN-->eNγ
  - Pair production: γN -->e^+e^-N
- The longitudinal momentum transfer from the nuclear target is small
  - For pairs $p_{||} \sim M_{ee}^2/2k$
    - For $M_{ee}=2m_e$, and $k=10^{18}$ eV $p_{||} = 10^{-6}$ eV
  - The reaction is not well localized
    - $l_f = h/p_{||}$. For $k=10^{18}$ eV, $l_f= 20$ cm
- In dense media, the e/γ interacts with many nuclear targets.
- These interactions are indistinguishable and interfere destructively, reducing the cross section.

Bremsstrahlung

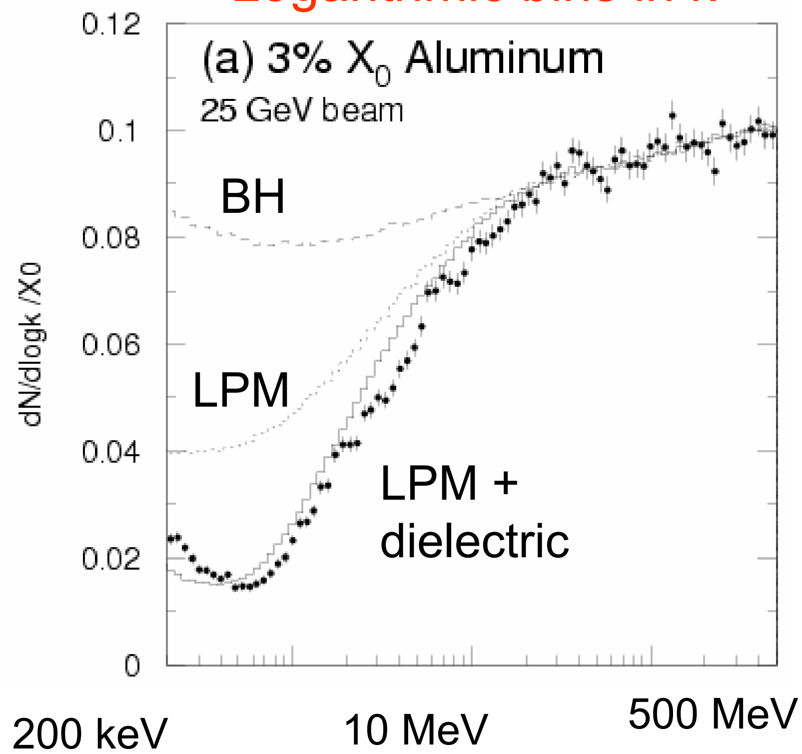


- Cross section is reduced when
  - $k < E(E-k)/E_{LPM}$
  - $E_{LPM} \sim 61.5$ TeV X_0 (cm)
- $dN/dk \sim 1/\sqrt{k}$
  - vs. Bethe-Heitler $dN/dk \sim 1/k$



for 10 GeV … 10 PeV in Lead
.0023 ….2300 E_{LPM}

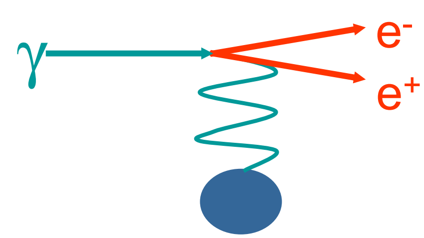
SLAC E-146
Photon energy spectrum
Logarithmic bins in k



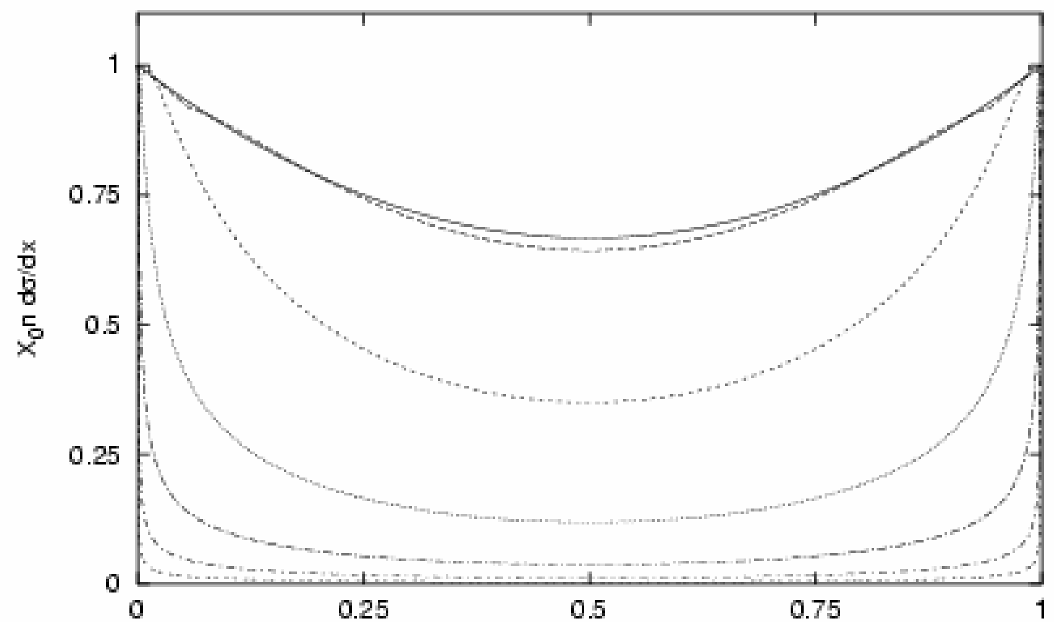
For Aluminum E_{LPM} = 68 TeV
Suppression for k< 9.2 MeV

Pair Production

- Cross section is reduced
  - Symmetric pairs most suppressed
- Scales with X_0 (in cm)
- Less affected than bremsstrahlung
  - Due to kinematics



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



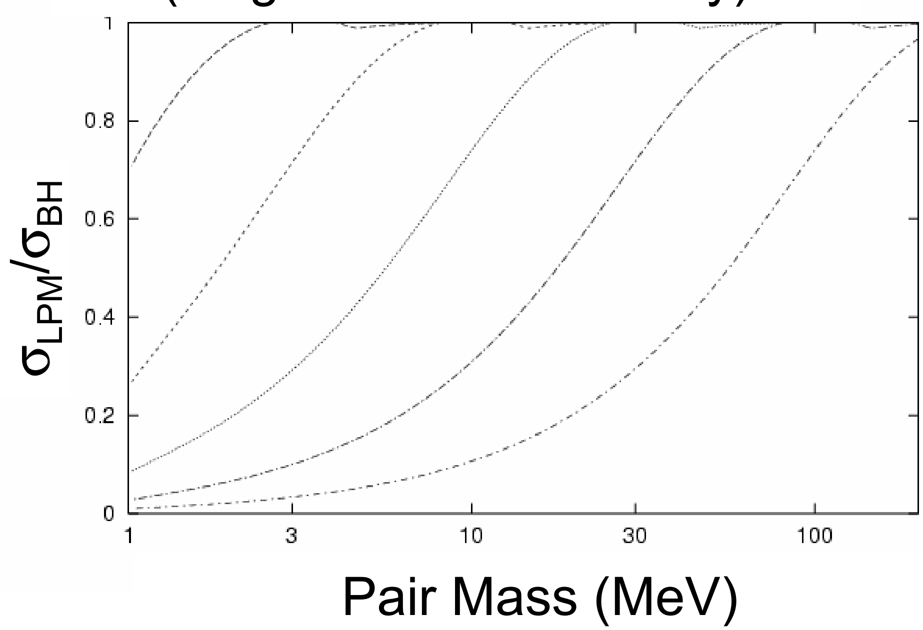
$x = e^{+}/e^{-}$ energy fraction

1 TeV (top) to 10^{18}eV (bottom) in lead
Also 70 TeV to 7 10^{19} eV in water

Pair Suppression

- High-mass pairs are less suppressed
  - $M_{ee} >> 1$ MeV
- Wide angle pairs are less suppressed
  - $\theta_{open} >> 1/\gamma$

Suppression vs. Pair mass (longitudinal effects only)



σ for 44 TeV … 440 PeV in Lead
10….105 E_{LPM}

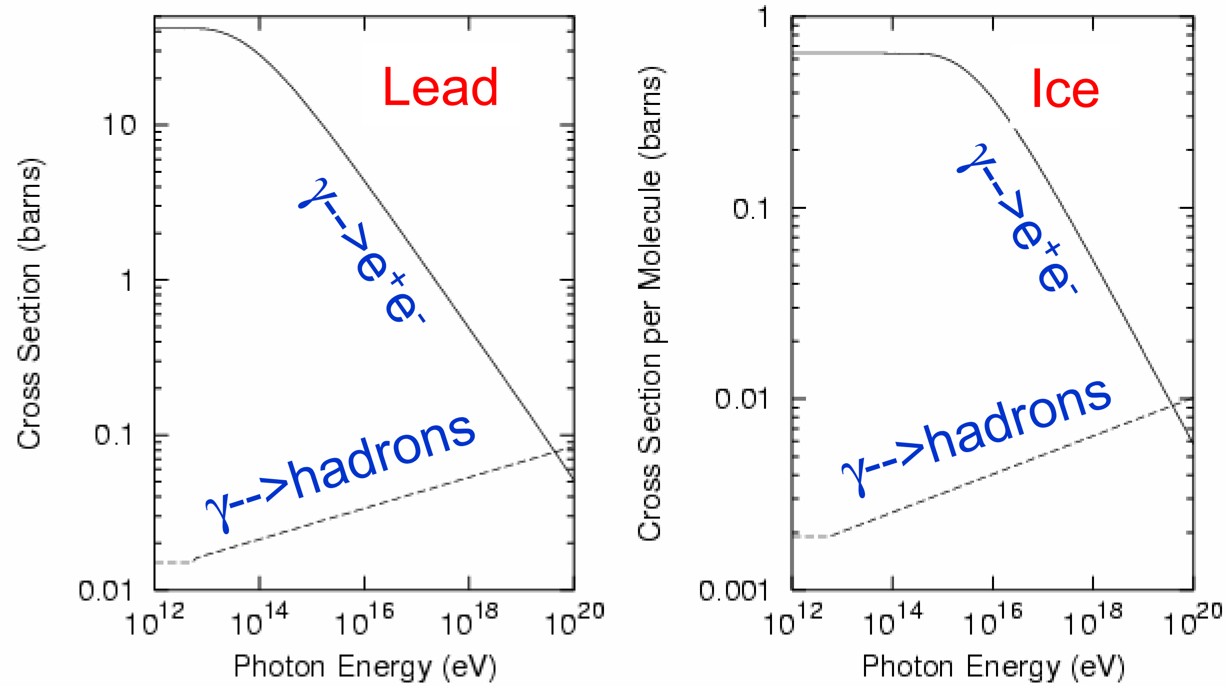
Photonuclear interactions

- Vector meson dominance
  - Photon fluctuates to a $q\bar{q}$ pair
    - $q\bar{q}$ pair interacts strongly, as a virtual ρ^0
  - Cross section rises slowly with energy
- At high energies, direct photon interactions become significant
  - $\gamma q \dashrightarrow \gamma q$
  - Faster rise in cross section
    - Not yet experimentally accessible

R. Engel, J. Ranft and S. Roessler, PRD 57, 6597 ('97)

Electromagnetic vs. Hadronic Showers

- Reality:
- LPM effect suppresses pair production
- Photonuclear cross sections increase with energy



Above ~ $10^{19.5}$ eV, in lead/ice photonuclear interactions dominate
There are no electromagnetic showers
Similar effect in air, above 10^{22} eV (at sea level)

Now … some concerns

SK: hep-ex/0402028

Some possible caveats

- How good are LPM calculations?
  - Gaussian scattering, other approximations
  - Normalization to X_0
- Suppression of bremsstrahlung due to pair conversion and vice-versa
- Higher order reactions and corrections
  - All LPM calculations are lowest order
- Radiation from electrons
- Extrapolating the photonuclear cross section

LPM - Migdal (1956)

- Most shower studies follow Migdal's (1956)
  - 1st quantum mechanical result
  - Stanev,Gaisser et al. (1982) simplified numerics
- Some simplifications
  - Gaussian scattering
    - Underestimates large angle scatters --> too much suppression?
  - No electron-electron interactions
  - No-suppression limit, → Bethe-Heitler cross section
    - Normalization of σ to modern X_0

Zakharov

- Light-cone path integral approach
  - 2-d Green's function for an imaginary potential representing e^+e^- pair scattering from a target
- Coulomb (non-Gaussian) scattering
- Separate elastic (eN) & (ee) inelastic potentials
  - Separate form factors
  - Significant for low-Z materials
- For soft photons from 1 TeV electrons, ~ 20% variation with k/E compared to Migdal
- Lower (?) cross sections than Migdal

B. G. Zakharov (1996-1998)

Baier & Katkov

- Start with electron propagator for a screened Coulomb potential in Born approximation
  - Expand perturbatively
    - Coulomb potential and inelastic
    - Coulomb corrections to potential
      - No-suppression limit reproduces Bethe-Maximon result
  - For pair production in strong suppression limit:

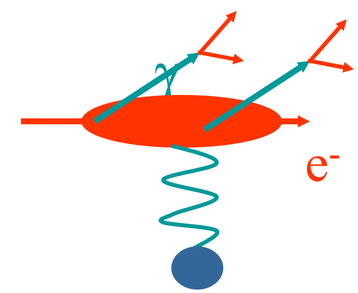
$$\frac{\sigma}{\sigma_{BM}} \approx 4.28\sqrt{\frac{E_{LPM}}{k}}\left[1-1.672\sqrt{\frac{E_{LPM}}{k}}-2.192\frac{E_{LPM}}{k}+\frac{1}{4L_1}\left(\ln\frac{k}{4E_{LPM}}+0.274\right)\right]$$

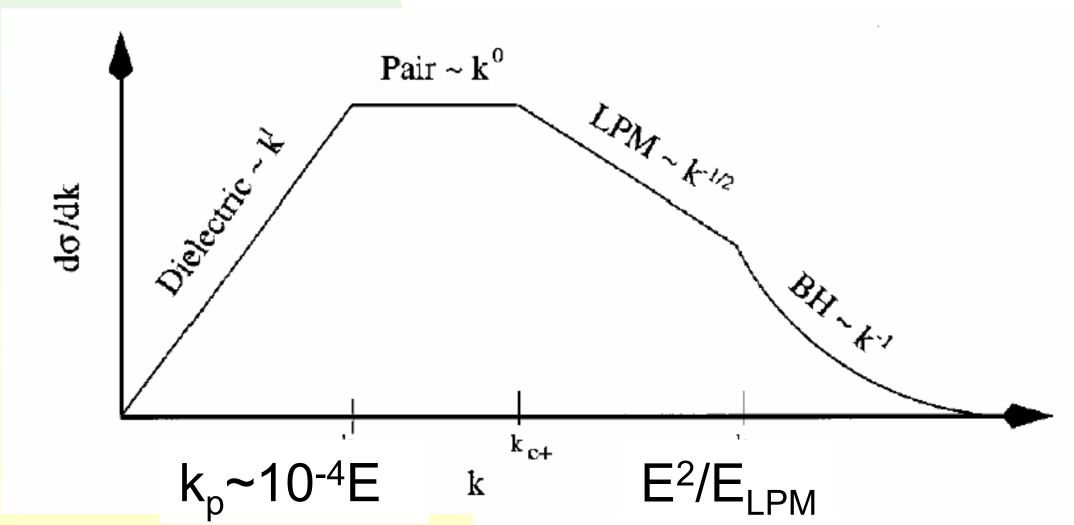
  - 4.28 instead of 4
  - Last term increases σ ~ 2-10% at very large σ
    - $L_1 = 183\, Z^{-1/3} \exp(-f)$

V. N. Baier and V. M. Katkov (1997)

Formation Length Suppression

- Additional suppression when $l_f > X_0$
  - A bremsstrahlung photon pair converts before it is fully formed.
    - Reduces effective coherence length
- A super-simple ansatz – limit l_f to X_0
  - Suppression for $k/E \sim 10^{-4}$ when
    - $E > E_p$=15 PeV (sea level air)
    - $E > E_p$ = 540 TeV (water)
  - Suppression for $k/E \sim 0.1$ for $E>5\ 10^{20}$ eV in water

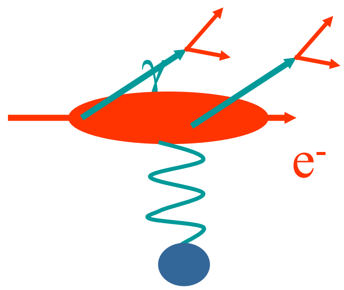




Landau & Pomeranchuk, 1953
Galitsky & Gurevitch, 1964
Klein, 1999

Formation Length Suppression

- Couples pair production and bremsstrahlung.
  - When l_f encompasses both reactions, they are no longer independent
    - Need to find cross section for complete interaction
      - eNN --> eNγN --> eNeeN
      - 2-step process – not just direct pair production
  - As the bremsstrahlung and pair production cross sections drop, the effective radiation length rises, slowly self-quenching the interaction

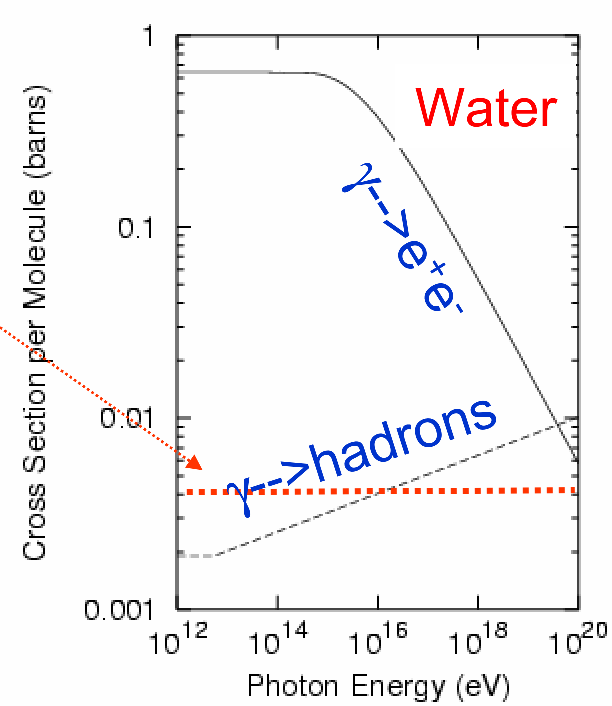


Ralston, Razzaque & Jain, 2002

- Photonuclear interactions also limit coherence
  - When $l_f > 1/\rho\sigma_{\gamma n}$
  - $\sigma_{\gamma n}$ rises with energy, unlike pair production
  - Dominates when $\sigma_{\gamma n} >> \sigma_{ee}$
    - When photonuclear interactions dominate

Higher-order corrections

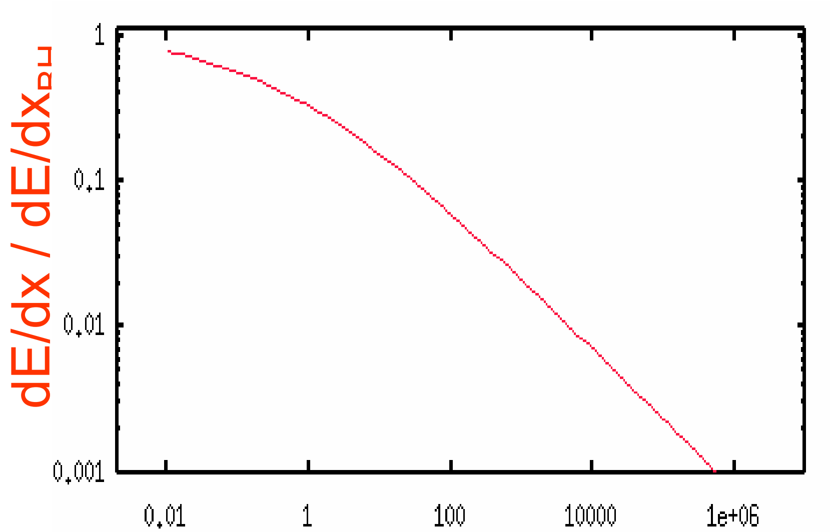
- LPM calculations are lowest order
  - May fail for $\sigma/\sigma_0 \sim \alpha_{EM} \sim 1/137$
- When suppression is large, higher order processes become more important
  - $eN \to e^+e^-eN$
    - Momentum transfer equivalent to bremsstrahlung of a massive (1 MeV) photon
  - l_f is much shorter
    - No LPM suppression up to at least 10^{20} eV



Radiation from Electrons

- Electron range increases with energy as σ_{LPM} drops
- At E=5 10^9 E_{LPM}
  - 7 10^{23} eV for water
  - dE/dx = 10^{-4} dE/dx_{BH}
    - Range ~ 10^4 X_0 ~ 3000 m
    - Ice thickness @ South pole
- Other reactions become more important.
  - Photonuclear interactions of virtual photons
  - Direct pair production
- Above ~ 10^{24} eV, electrons may begin to look like muons.

Electron dE/dx by bremsstrahlung



E/E_{LPM}

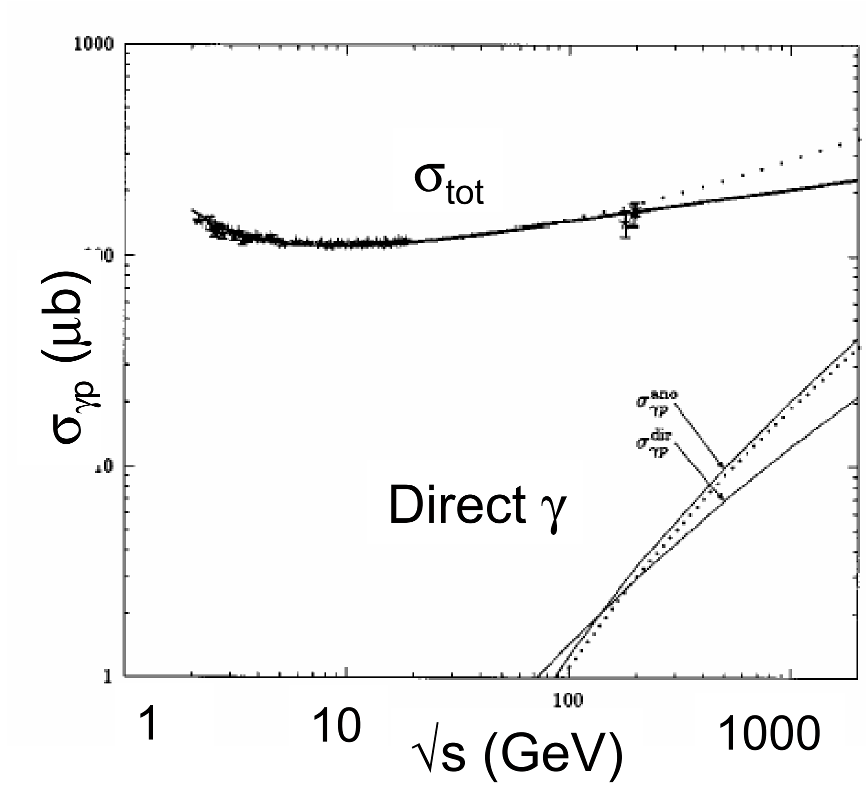
1.5 TeV – 1.5 10^{22} eV for water

Photonuclear uncertainties

- Photonuclear cross sections are extrapolated from much lower energies
  - ◆ Pomeron model
    - $\sigma \sim W^{1.16}$
    - Matches lower-energy data
  - ◆ At higher energies, direct photon interactions become important
    - Sensitive to nucleon and photon structure functions

      $\gamma q \to gq$

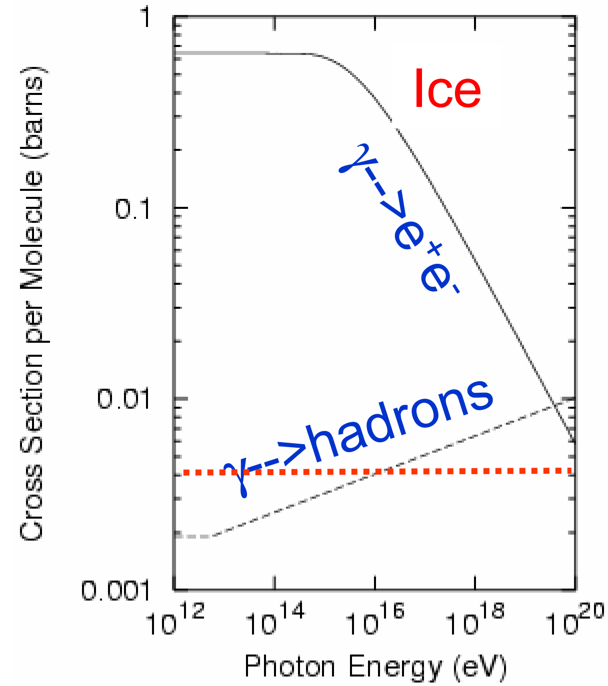
      $\gamma \to q\bar{q}$; $q\bar{q}$ interacts
- Uncertain to a factor of ~2 at 10^{20} eV ($W = 5 \times 10^5$ GeV)



R. Engel, J. Ranft and S. Roessler, PRD 57, 6597 ('97)

Uncertainties

- LPM Calculation
  - 10-20% ?
- Formation Length Limits
  - Combined & photonuclear interactions
  - Important above 10^{20} eV in water
  - Reduces electromagnetic cross sections
- Higher Order Corrections
  - May be important when $\sigma_{LPM} < \alpha_{EM}\, \sigma_{BH}$
    - above 10^{20} eV in water
- Photonuclear Cross Section
  - Factor of 2 at 10^{20} eV

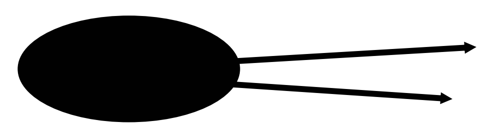


Photonuclear Interactions Predominate Above 10^{20} eV in water

What do these photonuclear interactions look like?

Effects on Showers in Ice

- ν_e and γ induced showers develop hadronically when the individual particle energy > $10^{19.5}$ eV
- Hadroproduced particles have larger p_T than those from electromagnetic interactions
  - Showers have larger transverse dimensions
    - Problematic for radio coherence
- Because of the LPM effect, hadronic showers are shorter than electromagnetic
  - More point-source-like
    - May help radio, acoustic, etc. studies,
- Muon content of showers is enhanced
  - charm/bottom
  - Electromagnetic cascades grow tails
  - Help with directional measurement?



Cherenkov Radiation from $\gamma \rightarrow e^+e^-$

(Work by Sourav Mandal, UC Berkeley)

- Cherenkov radiation occurs when the electromagnetic fields of a fast particle excites a medium (~ through dE/dx)
- e^+e^- pairs form dipoles. The fields are smaller than for 2 independent particles
- The fields largely cancel at distance d >> D (D is the pair separation)
- Radiation from the e^+/e^- from $\gamma \rightarrow e^+e^-$ may be less than from independent particles

Radiation from a Pair

- Comparison with monopole radiation:

$$\left.\frac{d^2E}{dx\,d\omega}\right|_m = \frac{(ze)^2}{c^2}\omega\left(1 - \frac{1}{\beta^2\epsilon(\omega)}\right)$$

$$\left.\frac{d^2E}{dx\,d\omega}\right|_d = \left.\frac{d^2E}{dx\,d\omega}\right|_m \times 2\left[1 - J_0\left(\frac{\omega d}{c}\sqrt{\beta^2\epsilon(\omega) - 1}\right)\right]^2$$

so

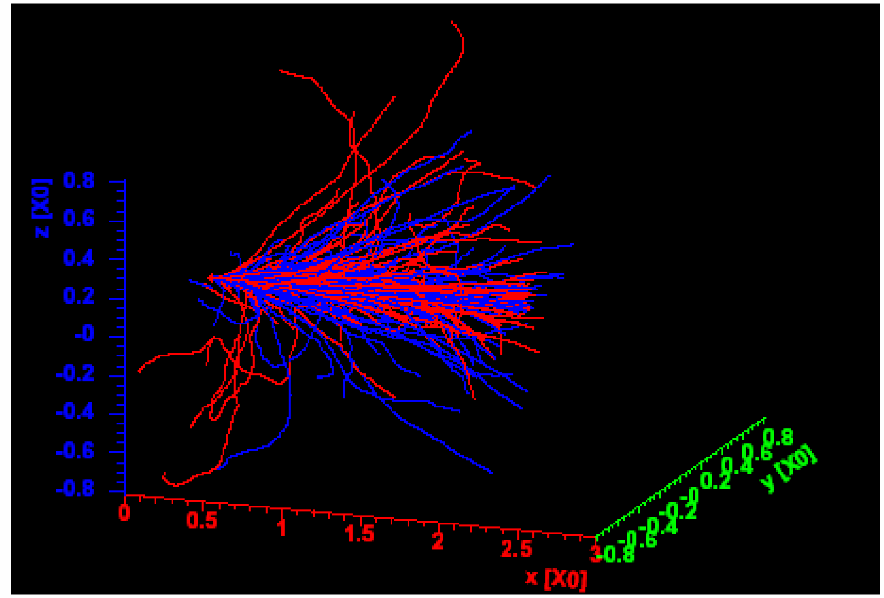
$$\left.\frac{d^2E}{dx\,d\omega}\right|_d \sim \left.\frac{d^2E}{dx\,d\omega}\right|_m$$

- Radiation is suppressed when $\frac{\omega d}{c}\sqrt{\beta^2\epsilon(\omega) - 1} < 1$

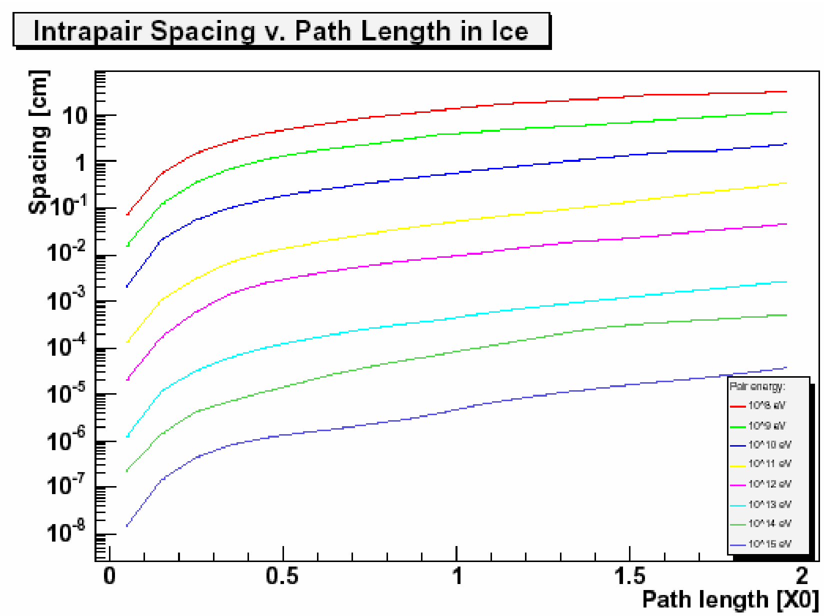
J. D. Jackson, private communication, 2004

Simulating Pairs

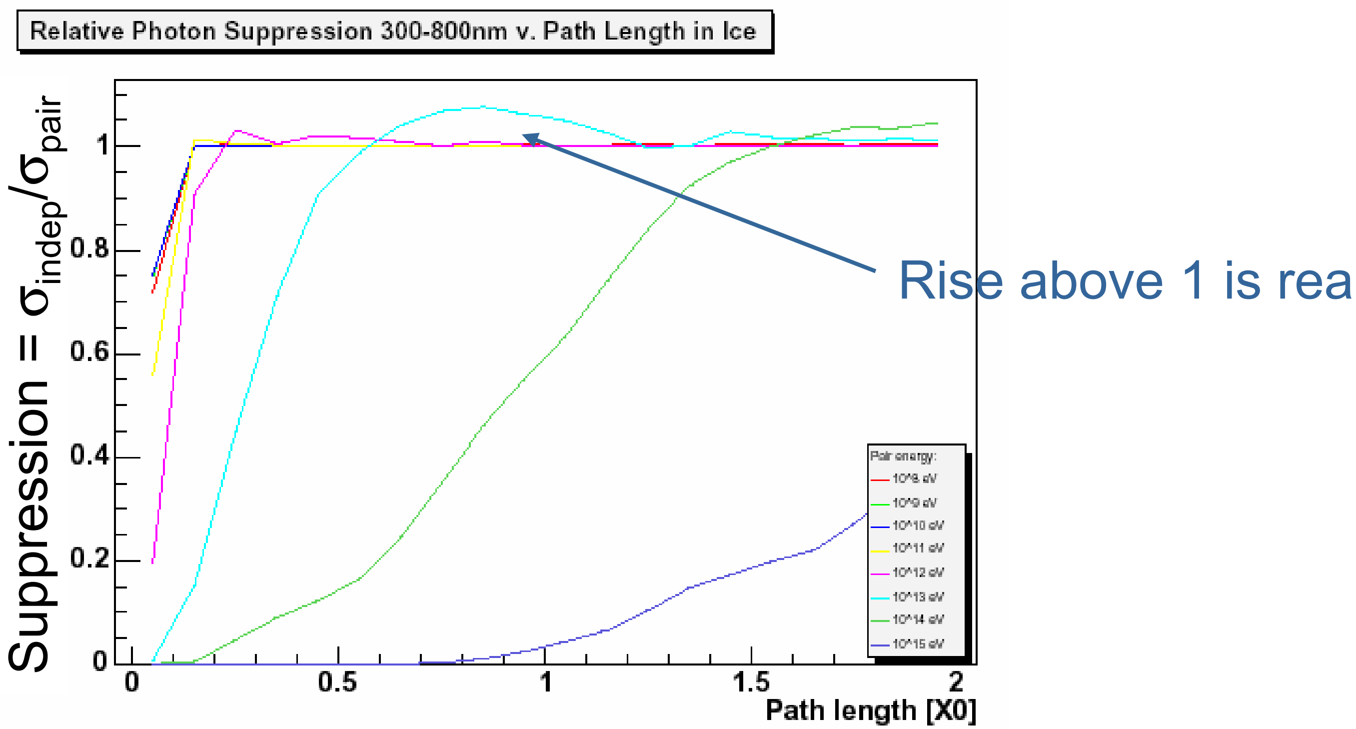
- Pair opening angle $1/\gamma$
- Gaussian multiple scattering
- Stochastic bremsstrahlung energy loss
  - 1st approximation
- Track particles over 2 X_0 or until they drop below Cerenkov threshold



Combined tracks of all particles, γ energies from 10^8 to 10^{15} eV



Radiation from Pairs



- k = 10^8 … 10^{15} eV
- Radiation suppressed for k> 10^{12} eV
  - Total radiation unaffected
  - Less radiation from front part of showers
    - Effect on observed location?

Particles in Air

- Dielectric Constant ε~1 in air
  - ε-1 decreases with increasing altitude
  - X_0 is much longer
- Overall, less affect on Cherenkov radiation

Conclusions

- Above 10^{20} eV in ice, photonuclear interactions predominate over electromagnetic interactions.
  - This changes the shower development and shape of radiating area.
  - Considerable theoretical work is required to understand this transition
    - Higher-order LPM calculations
    - LPM calculations with bremsstrahlung & photonuclear interactions
- Transition in sea level air is at 500X higher energy.
- Cherenkov radiation from e^+e^- pairs is less than for independent particles
  - May affect observation of the early development of water showers.