The Lunar A**SKA**ryan project

Neutrino interactions
&
the Landau-Pomeranchuk-Migdal (LPM) effect

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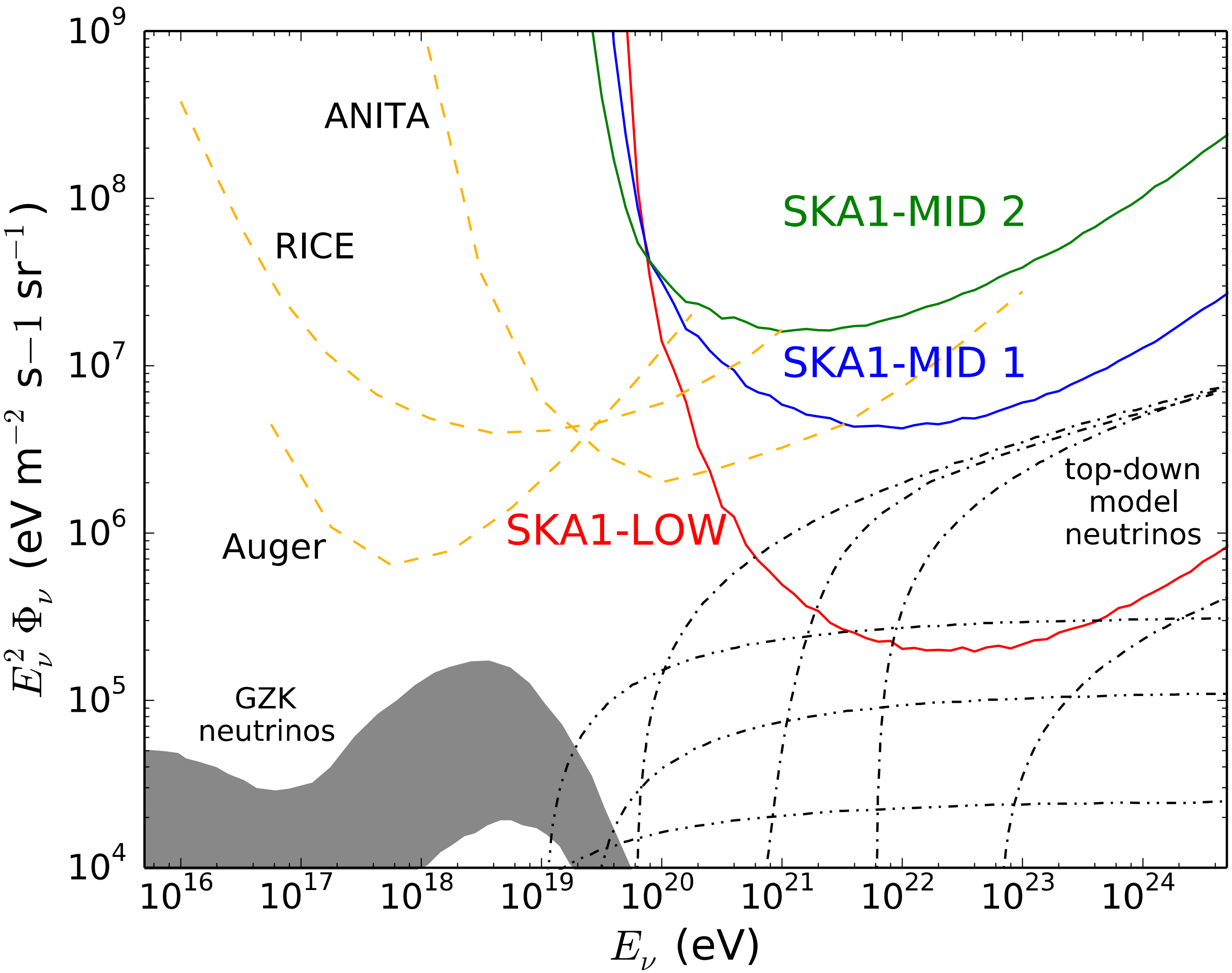
Spain

SKA sensitivity to Extremely High-Energy neutrinos



SKA-LOW 100 – 350 MHz

SKA-MID 1 350 – 1050 MHz

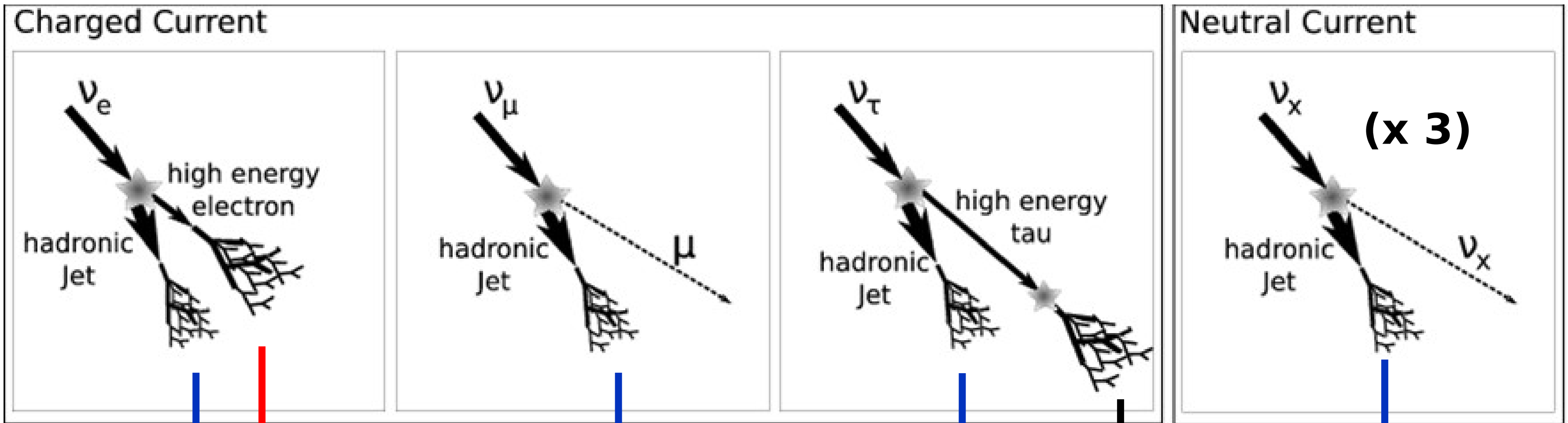
SKA-MID 2 950 – 1760 MHz

Calculations based on detailed MC simulations by C.W. James, J.D. Bray, R. Protheroe

J.D. Bray et al. SKA Lunar Science Chapter arXiv:1408.6069v2

Neutrino – induced showers

Neutrino – nucleon Deep Inelastic Scattering (DIS)



"Mixed" showers

$E_{electromagnetic} \approx 80\%\ E_\nu$ @ EeV

$E_{hadronic} \approx 20\%\ E_\nu$ @ EeV

Hadronic showers

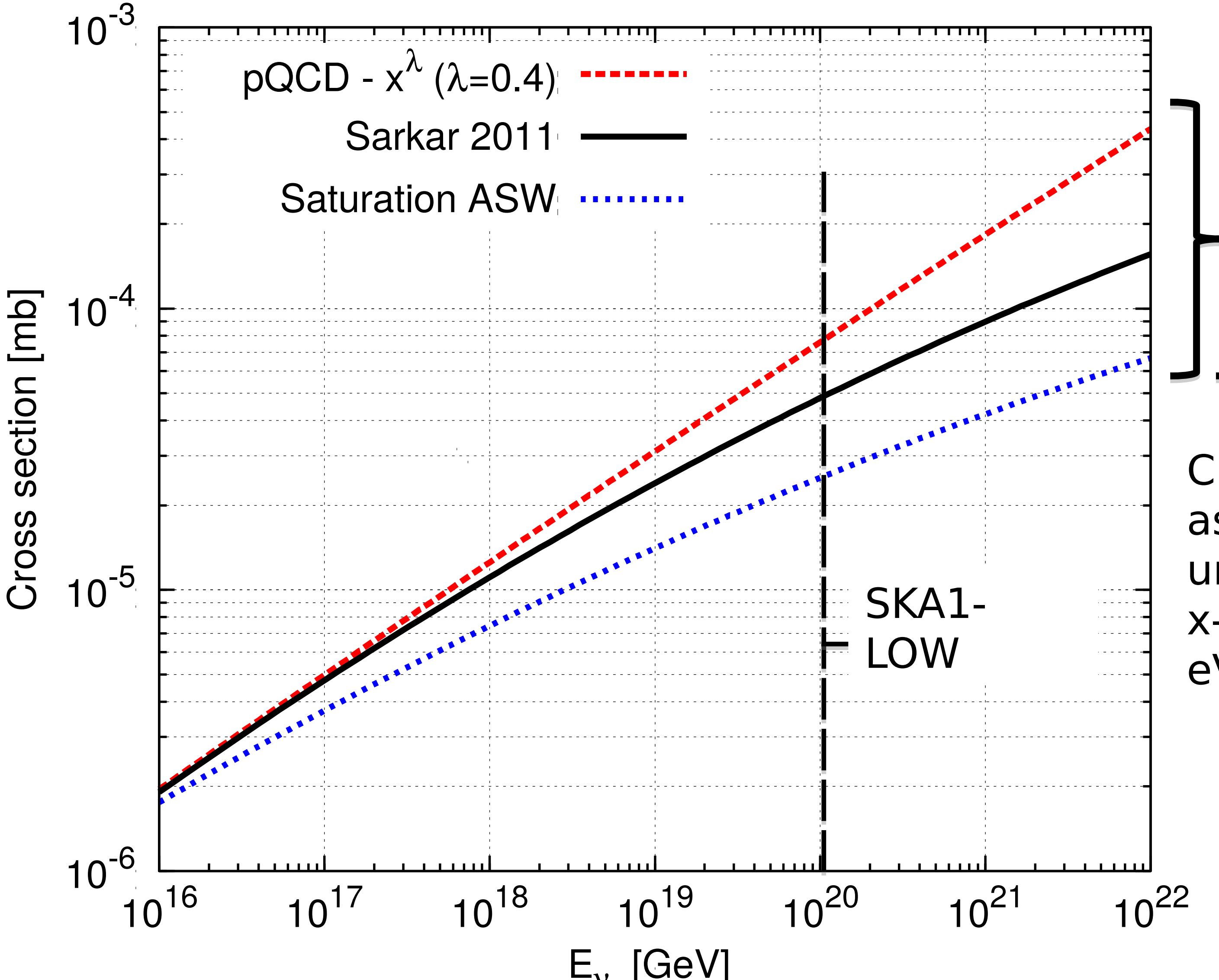
$E \approx 20\%\ E_\nu$ @ EeV

Electromagnetic

or

Hadronic

ν – nucleon CC cross-section

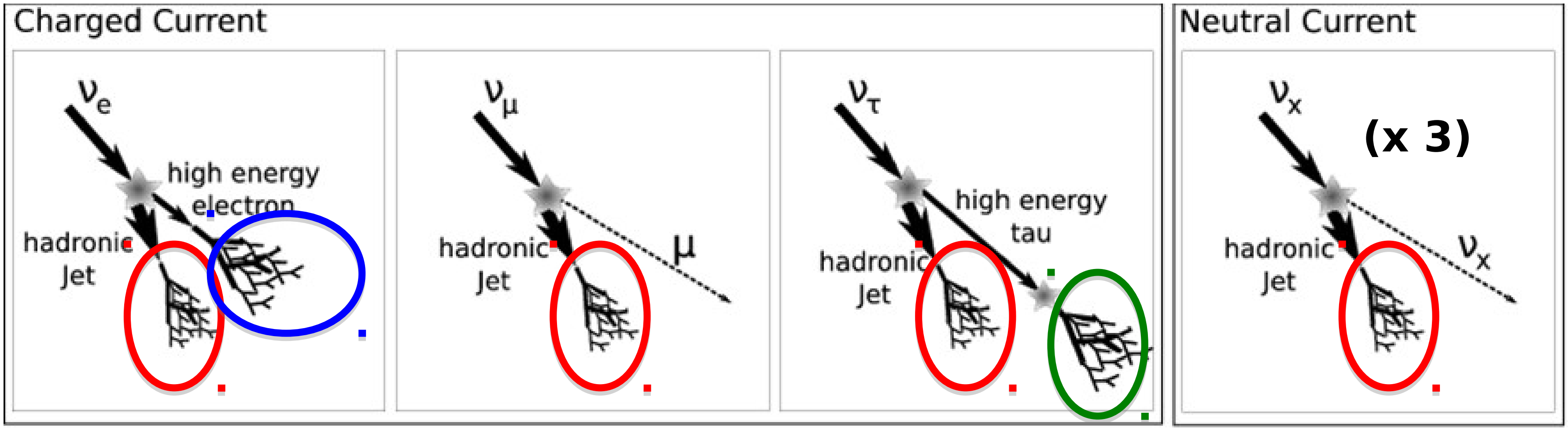


Large uncertainty even within the Standard Model

Currently assuming ~20% uncertainty in x-section at 10^{20} eV

Effective area to neutrino detection proportional to x-section

Relative contribution to aperture in SKA-LOW at $E_\nu = 10^{21}$ eV



Type of shower/interaction	Relative contribution
Primary hadronic ν_μ & ν_τ CC & all ν NC	~ 93%
Primary electromagnetic ν_e CC	~ 1%
Tau photonuclear ν_τ CC	~ 5%
Other (muon, tau bremss, etc...)	~ 1%

C.W. James, R.J. Protheroe, Astropart. Phys. 30 (2009) 318

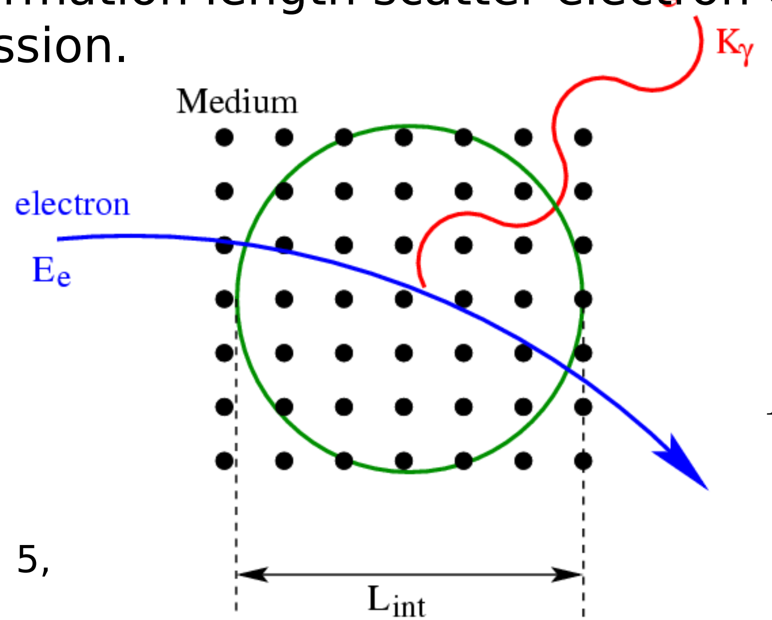
The Landau-Pomeranchuk-Migdal (LPM) effect

- Quantum mechanical effect that suppresses:
- bremsstrahlung by electrons or positrons
- pair production by photons

L. Landau and I. Pomeranchuk, Dokl. Akad. Nauk SSSR **92**, 535, 1953
A.B. Migdal, Phys. Rev. **103**, 1811, 1956

- Interactions do not occur at a point, but along a distance (formation length) $L_{int} \sim 1/q_{||}$ ($q_{||}$ = parallel momentum transfer) that increases with Energy

- Typically if $E > E_{LPM} \sim 10^{15}$ eV then L_{int} >> interatomic distance => interactions along formation length scatter electron & suppress bremsstrahlung emission.



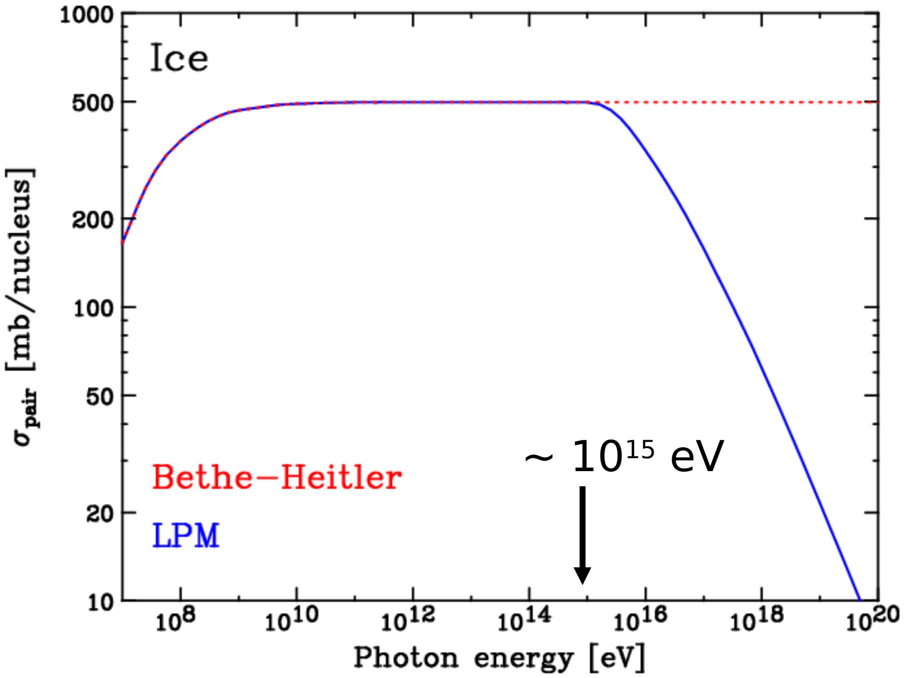
suppressed emission of bremss. photon

$$L_{\rm int} \sim \frac{1}{q_{||}} \propto \frac{E(E-k)}{k}$$

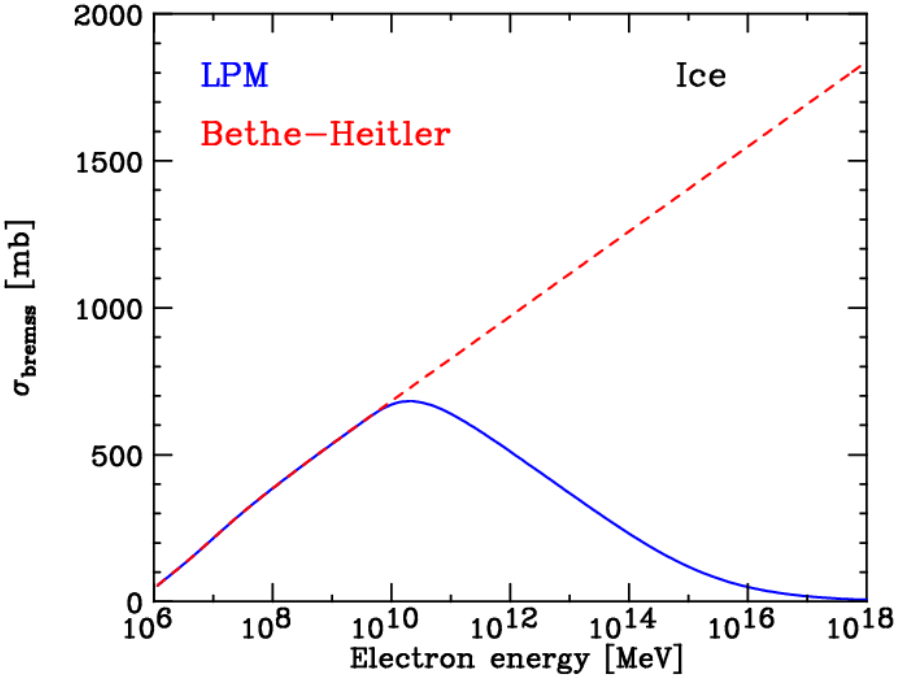
S.R. Klein, Revs. Modern Phys. **71**, No. 5, 1999

LPM effect: Cross sections

Pair production by photons



Bremsstrahlung by electrons



- Significant reduction of pair-production and bremsstrahlung cross sections with respect to Bethe-Heitler predictions

- Also suppression of “soft” bremsstrahlung

T.Stanev & H.P.Vankov, PRD **25** (1982)

LPM effect & showers

Electromagnetic showers

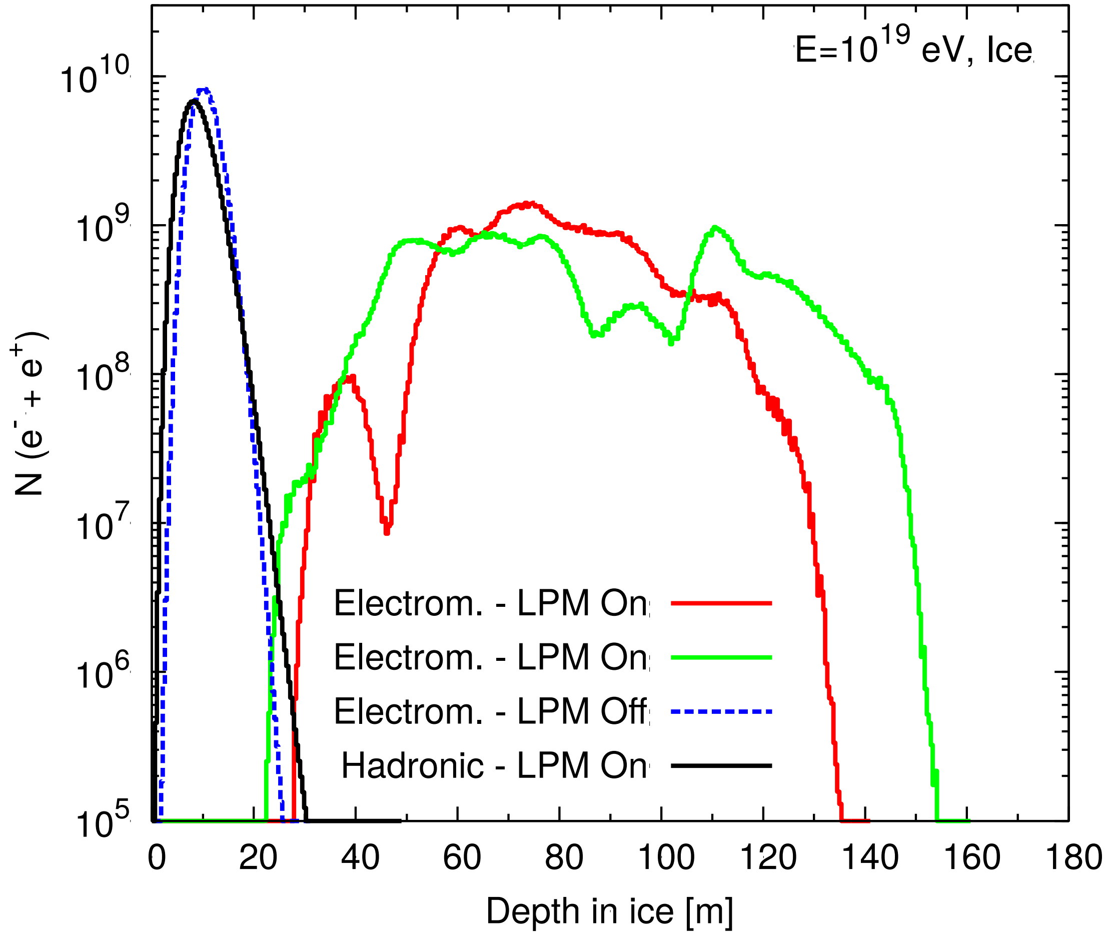
having E > E_{LPM}

(~ 10^{15} eV regolith):

- strongly affected by LPM effect
- more penetrating than those with E < E_{LPM}.
- Width of long. profile (shower length L) increases faster than ~ log E, typically as $E^{1/3}$
- Energy deposition is clumpy

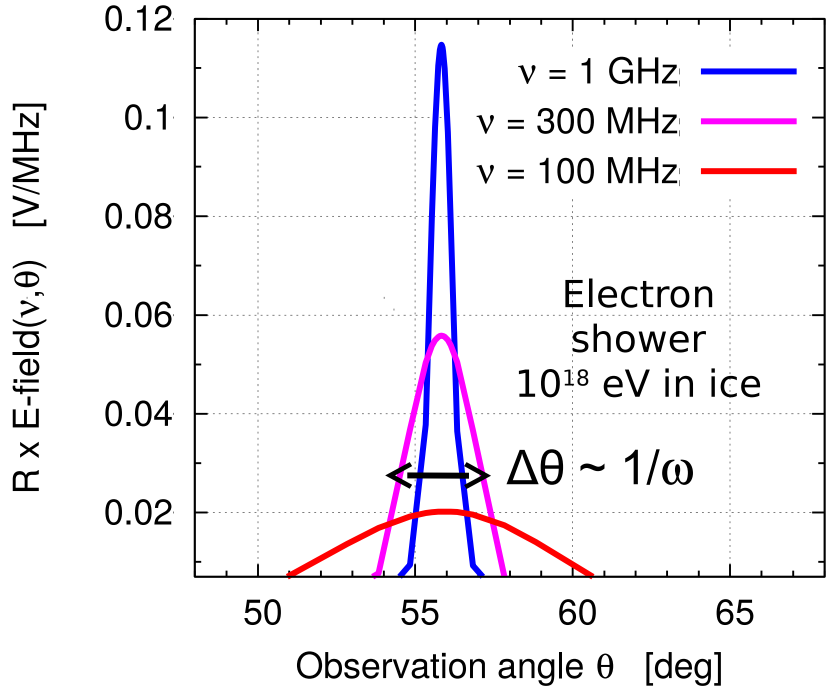
Hadronic showers

- much less affected by LPM effect



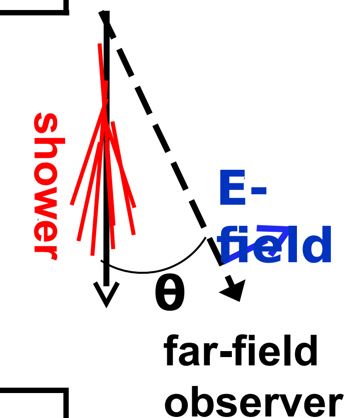
J.A-M & E.Zas, Phys. Lett. B **411** (1997) 218
J.A-M & E.Zas, Phys. Lett. B **434** (1998) 396
J.A-M, R.A. Vazquez & E.Zas, Phys. Rev. D **61** (1999) 023001

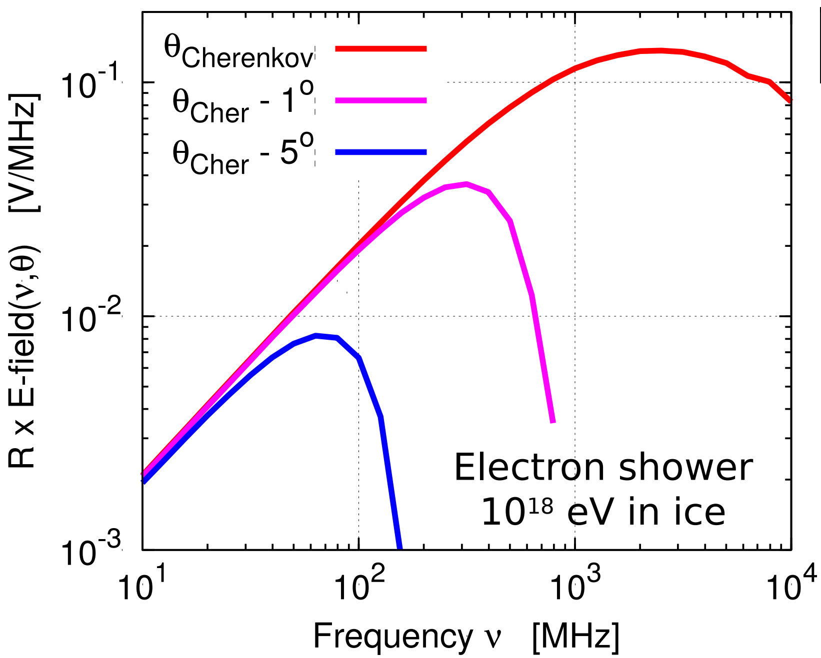
Properties of signal (freq.-domain)



Angular distribution

- Radiation emitted in a cone around Cherenkov angle.
- Width proportional to inverse of frequency.





Frequency spectrum

- Broad-band frequency spectrum.
- Field increases with frequency up to a cut-off depending on observation angle.

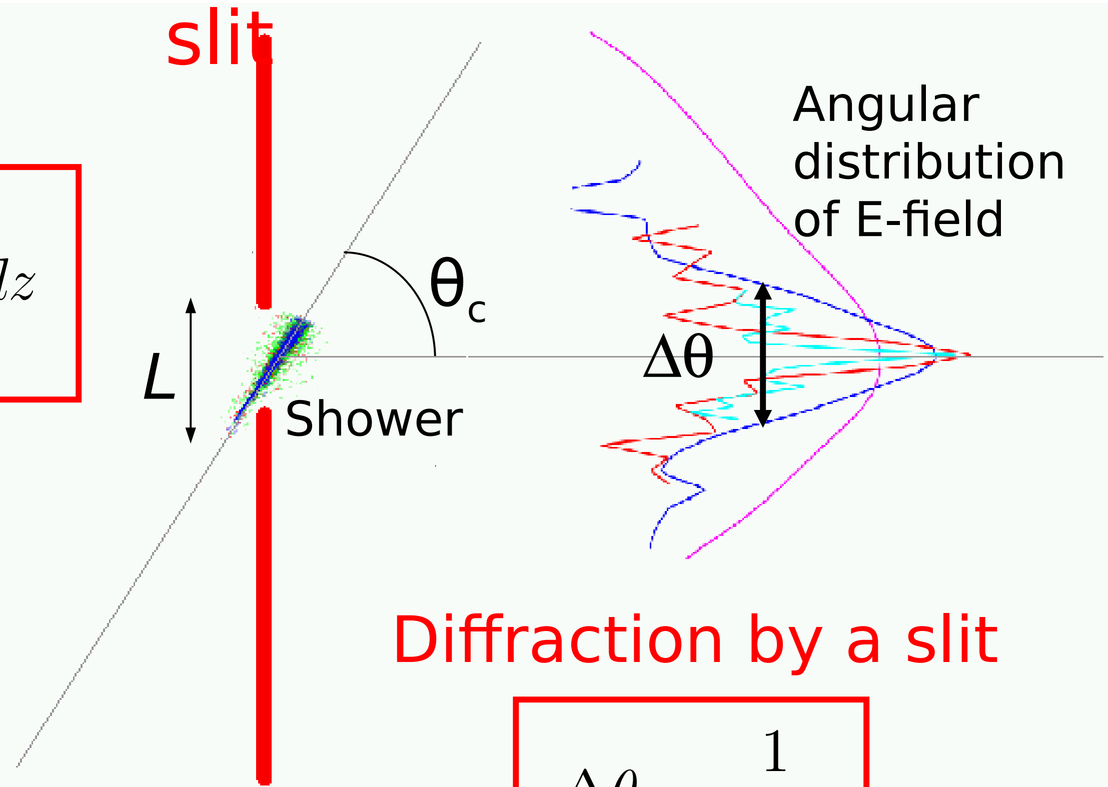
E. Zas, F. Halzen, T. Stanev, PRD 45, 162 (1992),
J. A-M & E. Zas, PLB 411, 218 (1997)
J.A-M, C.W. James, R.J. Protheroe, E. Zas, APP 32, 100 (2009)

Optics analogy to understand radio emission: diffraction by a single slit

- The shower plays the role of the slit in elementary optics.
- Electric-field can be obtained Fourier-transforming the longitudinal profile Q(z) of excess charge (Fraunhofer diffraction)

$$\boxed{E(\omega,\theta) \;\propto\; \omega \int Q(z)\, e^{ipz}\, dz}$$

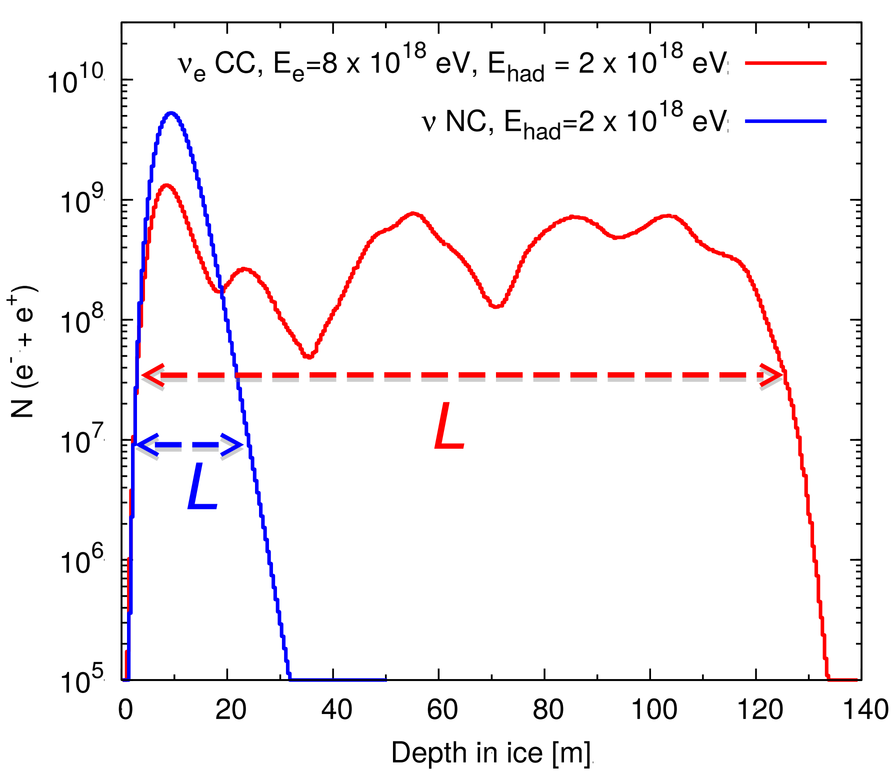
$$\boxed{p(\omega,\theta) \;=\; \omega\,(1 - n\cos\theta)/c}$$

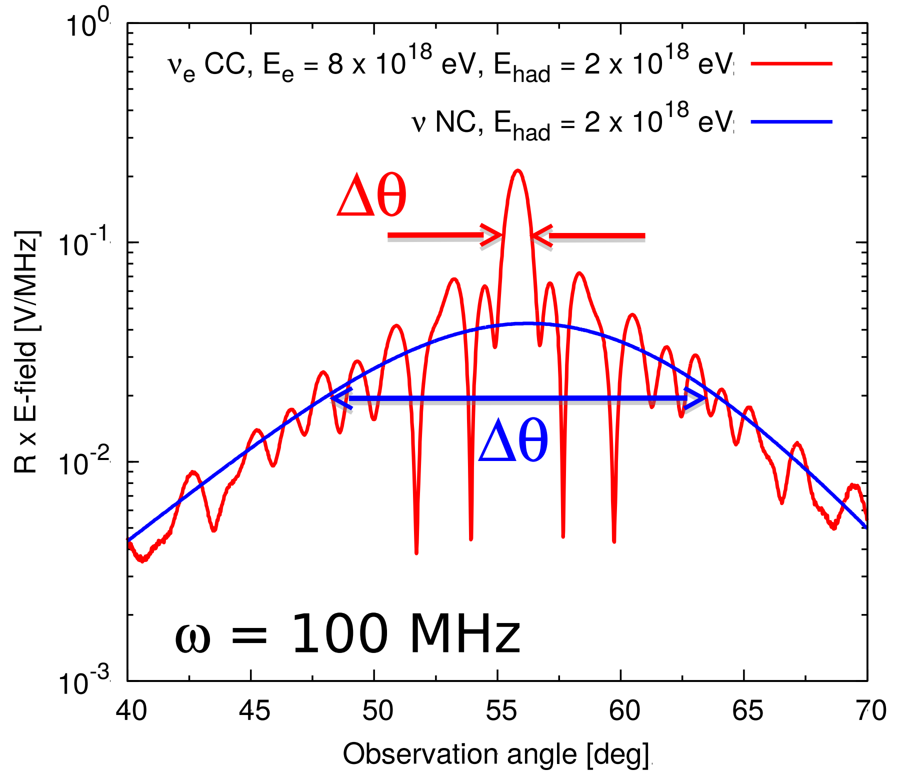


$$\boxed{\Delta\theta \sim \frac{1}{\omega\; L}}$$

J. A-M, R.A. Vazquez, E. Zas, PRD **61**, 023001 (1999).
J. A-M & E. Zas, PRD **62**, 063001 (2000)

Radioemission & LPM effect in neutrino-induced showers





- LPM effect “stretches” electron-induced showers in ne CC => Cherenkov cone “shrink

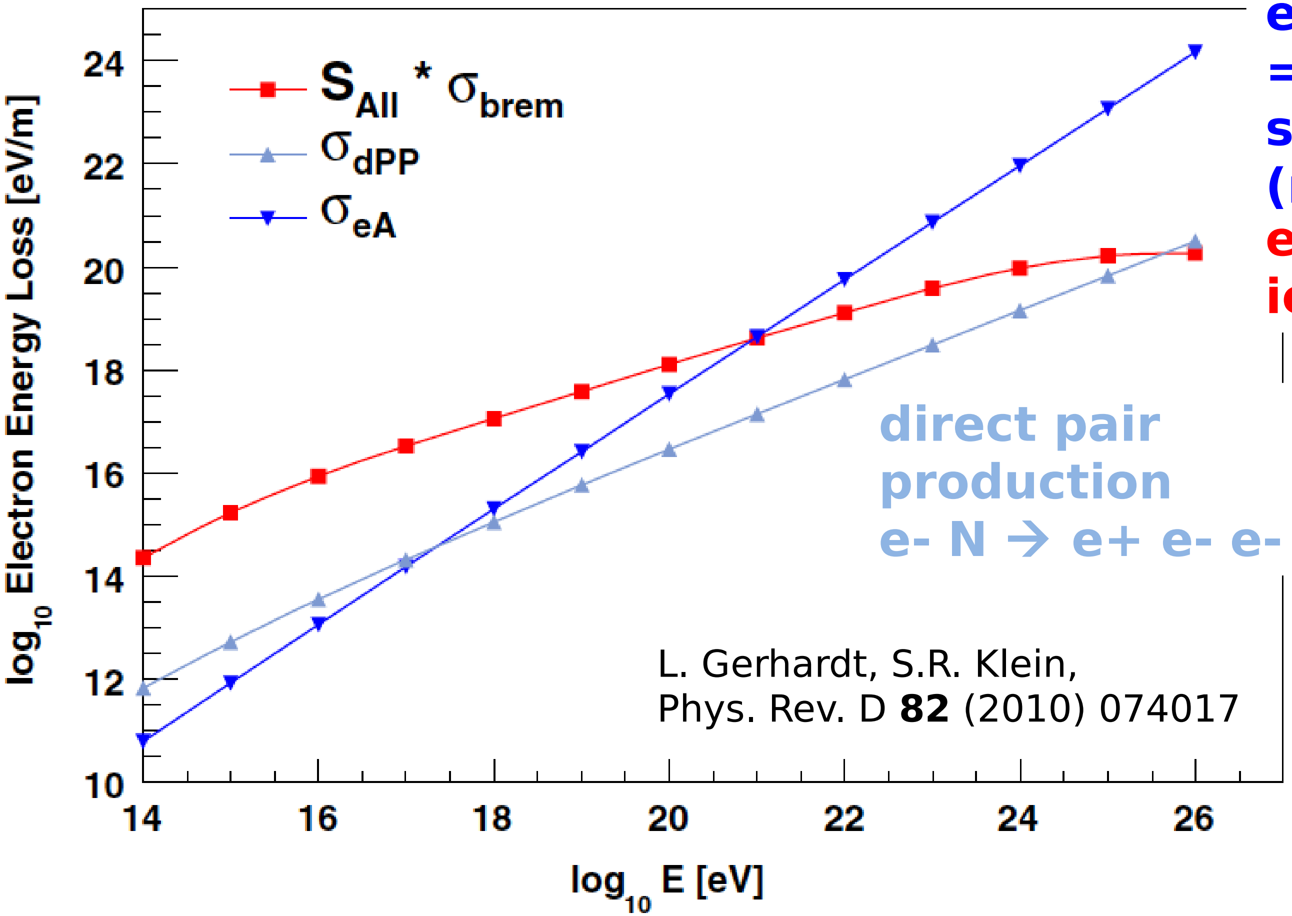
- Reduced solid angle: Δθ ~ 1º @ 10 EeV & 100 MHz

$$\Delta\theta \sim \frac{1}{\omega\ L}$$

J.A-M, R.A. Vazquez & E.Zas, Phys. Rev. D **61** (1999)

LPM effect vs electronuclear interactions

- LPM effect suppresses electron bremsstrahlung above 10^{15} eV
- Suppression of energy loss to electromagnetic showers is so large above ~ 10^{20} eV that electron starts to lose energy to hadronic showers (little affected by LPM !)

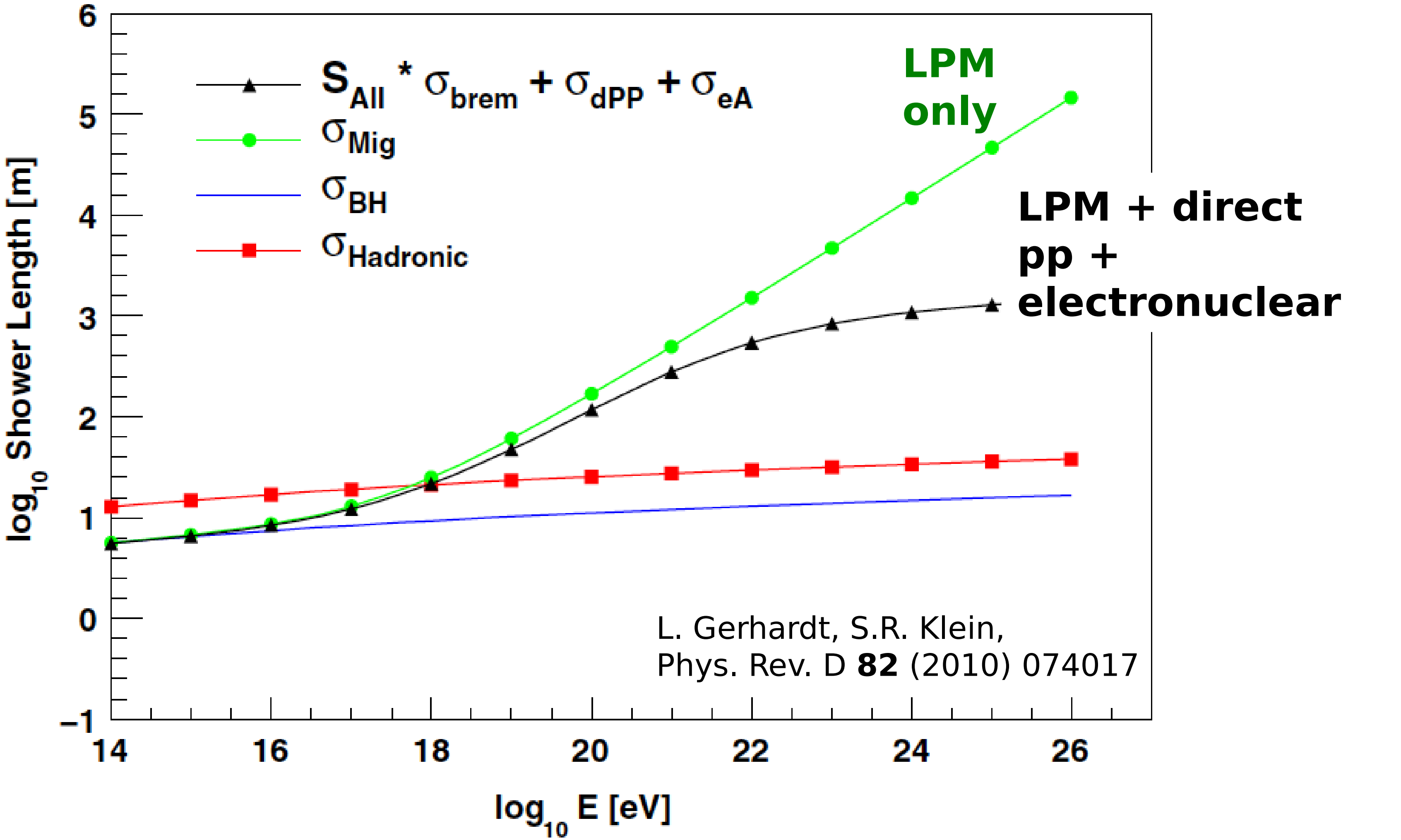


electronuclear => hadronic shower (no LPM !)

electromagnetic E-loss (LPM)

direct pair production
e- N → e+ e- e- N

Shower length L vs energy

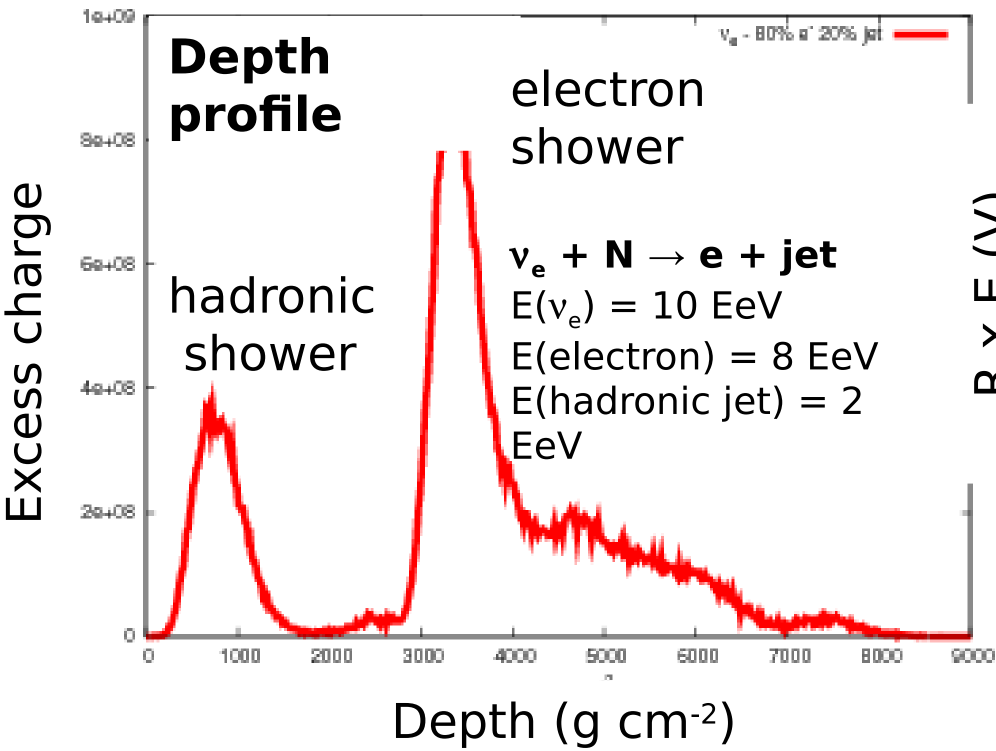


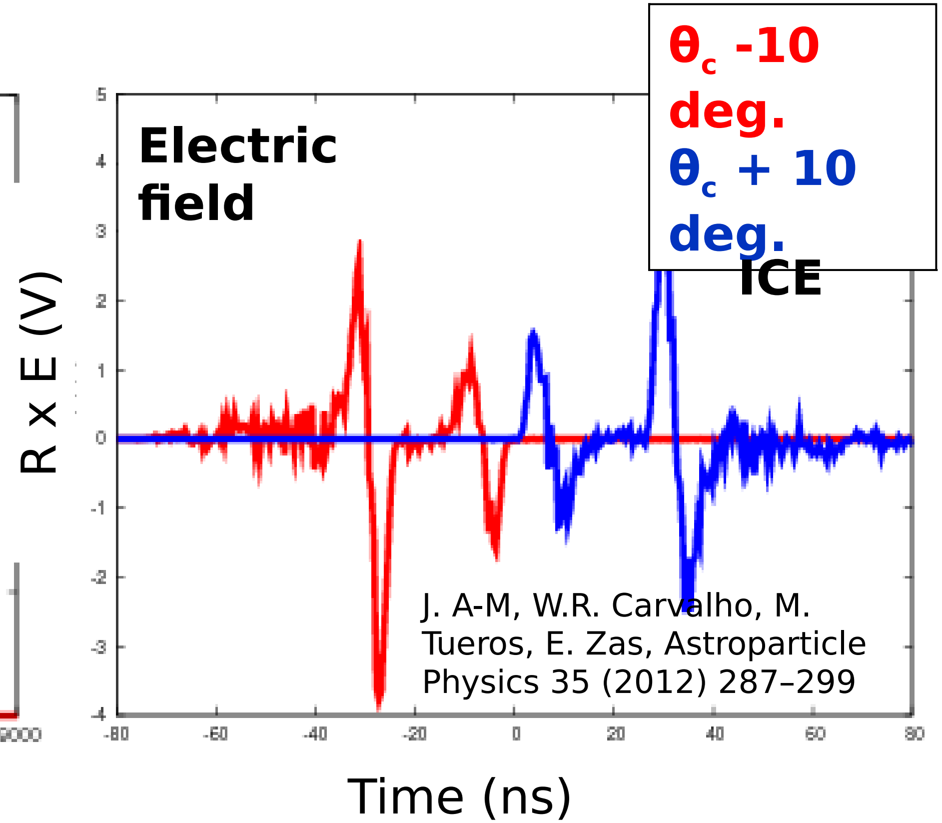
- Moderate rise in electron neutrino-induced shower length, ameliorating the dramatic shower stretching due to LPM effect.
- Should increase relative contribution to exposure from electron neutrinos.

Full simulations of ν-induced showers in regolith/megaregolith/etc...

Full simulations of ν-induced showers in (almost any) dense dielectric media now possible with ZHAireS: hadronic, mixed, tau decay-shower,...

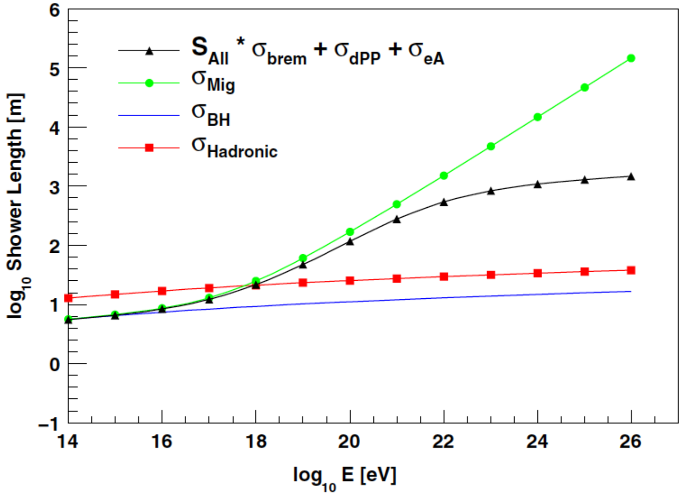
Scaling of radiopulse from ice to regolith probably accurate enough but could be improved if needed.





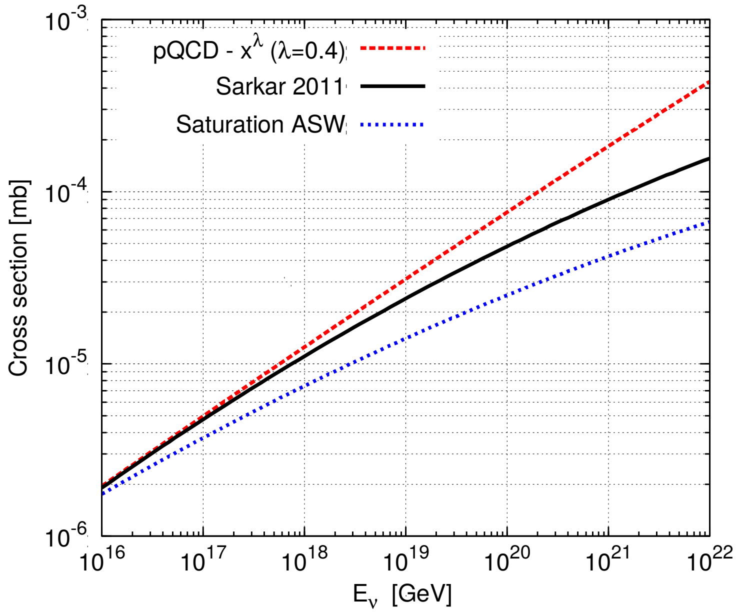
Improvements in modeling

1. Take into account, in calculations of exposure to EHE neutrinos, the hadronic behaviour of electron above 10^{20} eV => increase in exposure



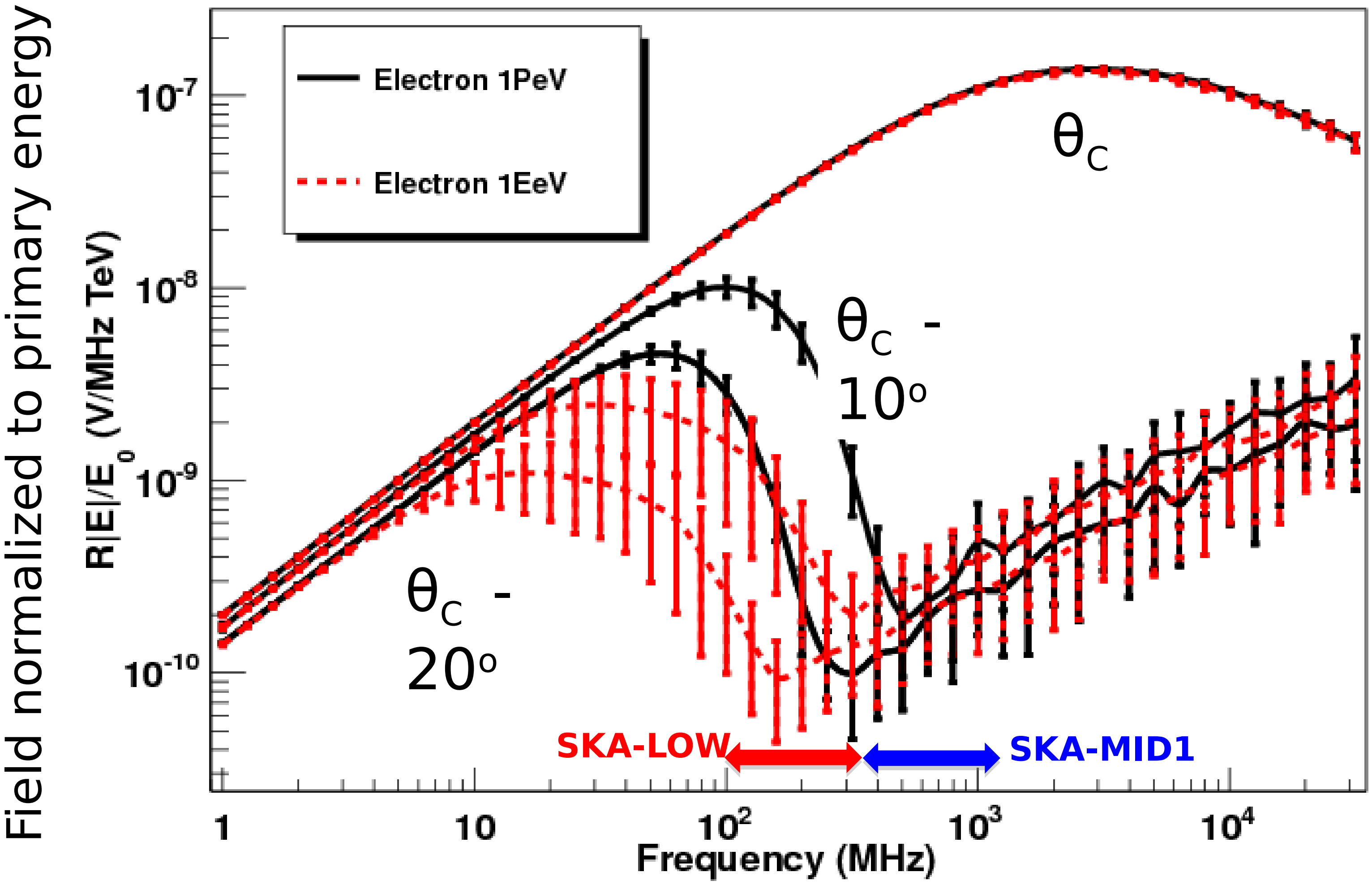
1. Include larger uncertainty in the neutrino cross-section

1. New parameterization of showers in regolith/megaregolith ?



Backup

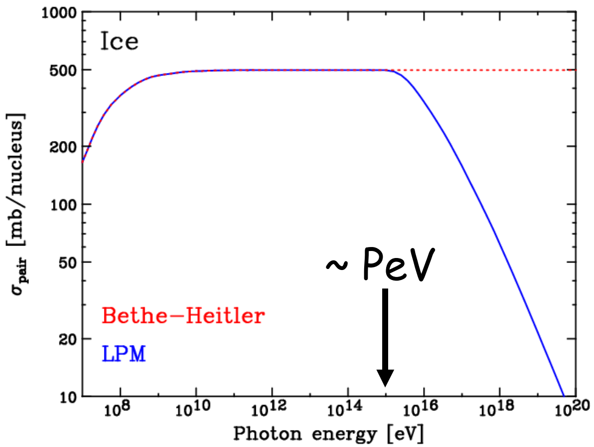
Frequency spectrum in LPM showers



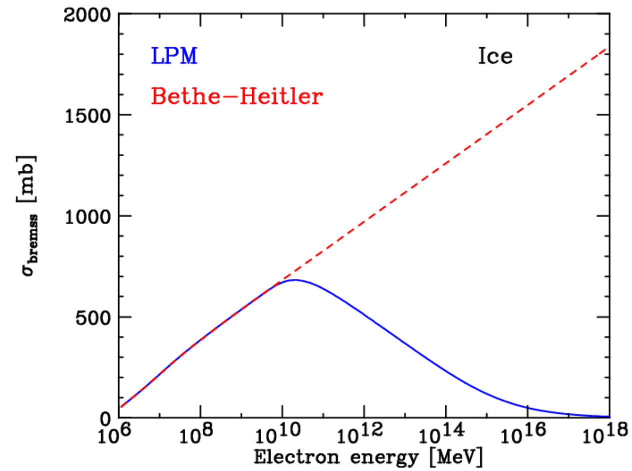
- Elongated profiles at EeV induce smaller cut-off frequencies at $\theta \neq \theta_c$
- Cut-off frequency at Cherenkov angle unaffected.

LPM effect: Cross sections

Pair production cross sections

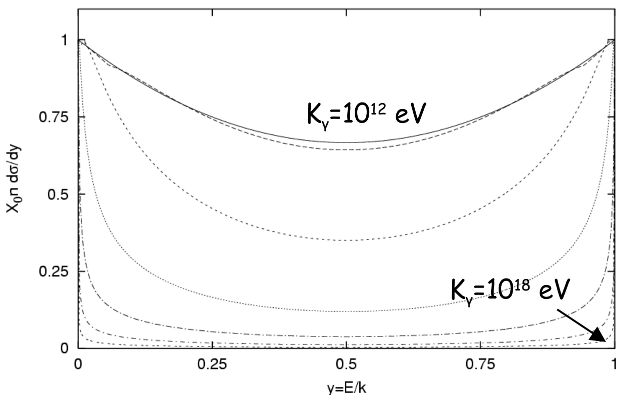


Bremsstrahlung cross sections



Total

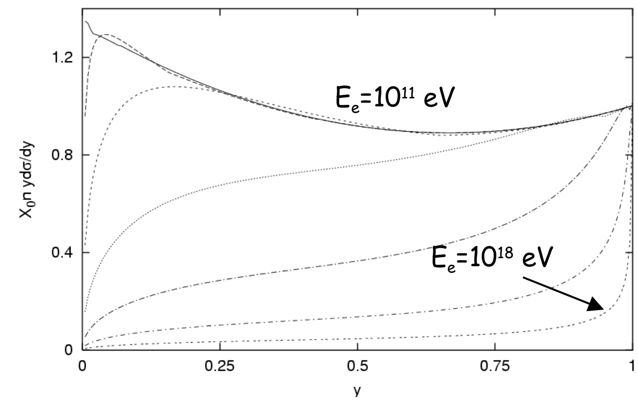
(Ice)



energy fraction carried by e^-

Differential

(Lead)



energy fraction carried by γ

e^-e^+ pair asymmetric in energy

Suppression of emission of low K_γ photons

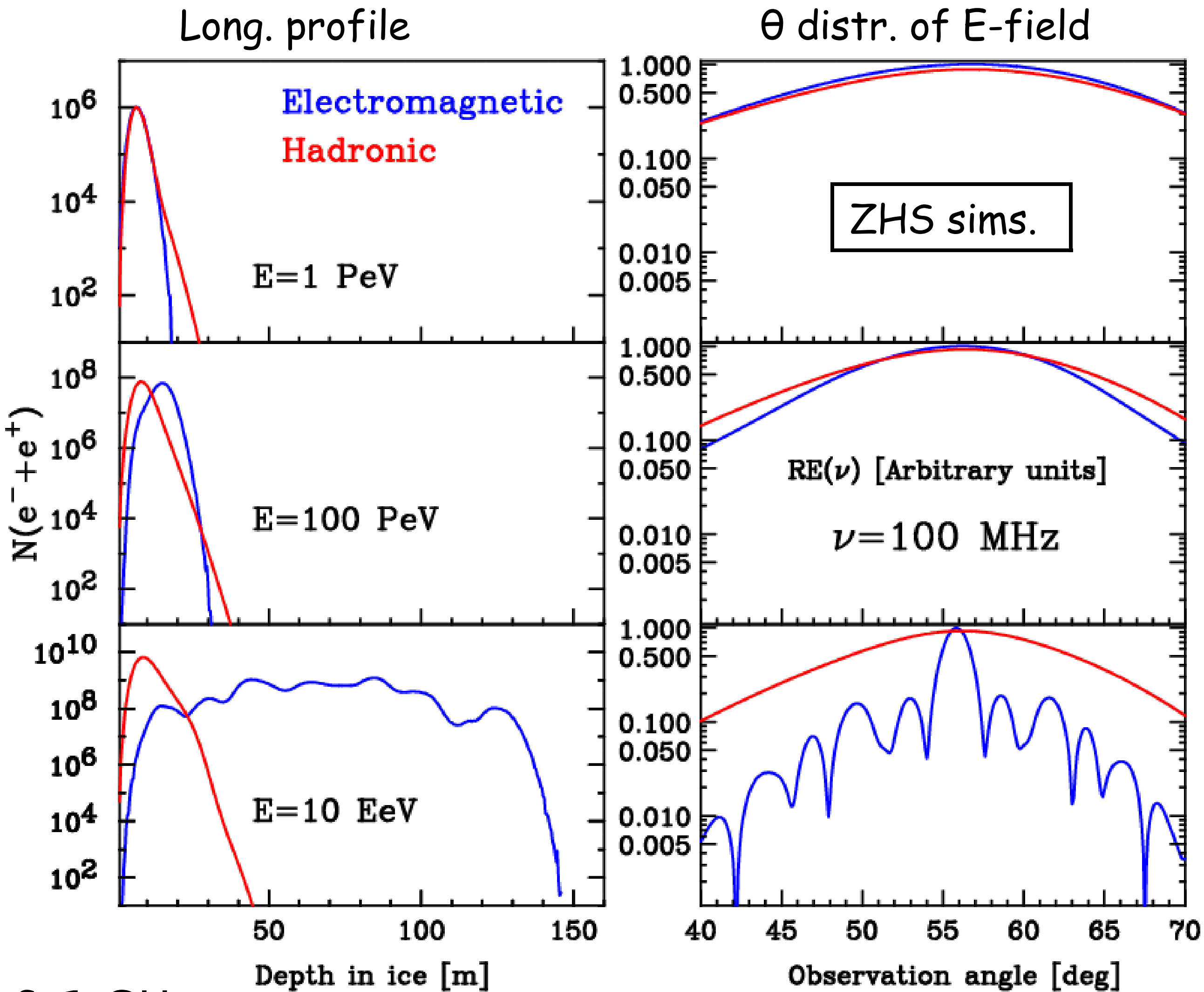
T.Stanev & H.P.Vankov, PRD 25 (1982)

Radioemission & LPM effect

$\Delta\theta \sim 1/L$ (L = width of the longitudinal shower development).
(Power @ θ_C still ~ E_{shower})

Cone shrinks

Peak field at Cherenkov angle unchanged



$\Delta\theta \sim$ 2 mrad @ 20 EeV & 1 GHz
update value using new params.

J.A-M, R.A. Vázquez & E.Zas PRD 61 (1999)