SUMMARY OF SIMULATIONS OF HE SHOWERS

E. ZAS

RADHEP-2000

SIMULATIONS OF PULSES

- 1st Simulations:
  Electromagnetic showers E < 1 PeV
  Specifically designed program.
  F. Halzen, T. Stanev, E.Z. PLB 257 (91) 432
  PRD 45 (92) 362

  FEATURES OF RADIOEMISSION

- 1-D Approximation

  1-D Hybrid simulations (MC parameterizations)
  J. Alvarez-Muñiz PhD thesis, Santiago 1999

  Emag. Showers (Greisen param..) E < 10 EeV
  LPM SHOWERS → REDUCTION OF WIDTH (θ_c)
  J.A.M, E.Z PLB 411 (97) 218

  Had. Showers (Ad Hoc param...) E < 100 EeV
  J.A.M, E.Z. PLB 434 (98) 396
  HARDLY ANY LPM ELONGATION

  ν_e - Showers
  J.A.M, R. Vazquez, E.Z. PRD 61 (00) 023001
  PATTERN MERGING measure y?

  Validity of approximations
  Fraunhofer
  1-D ...
  approx. Tested
  J.A.M, R.V., E.Z, PRD 62 (00) 063001

  Moon Rock Simulations
  scaling is possible
  J.A.M RADHEP-2000

"ZHS" SIMULATOR

F. Halzen, T. Stanev, E.Z.
PRD 45 (92) 362

- PAIR PRODUCTION
- BREMSSTRAHLUNG
- ELASTIC SCATTERING (Lateral Spread)
  (multiple - Moliere)
- CONTINUOUS Energy LOSS

- COMPTON
- MØLLER
- BHABHA
- e^+e^- ANIHILATION

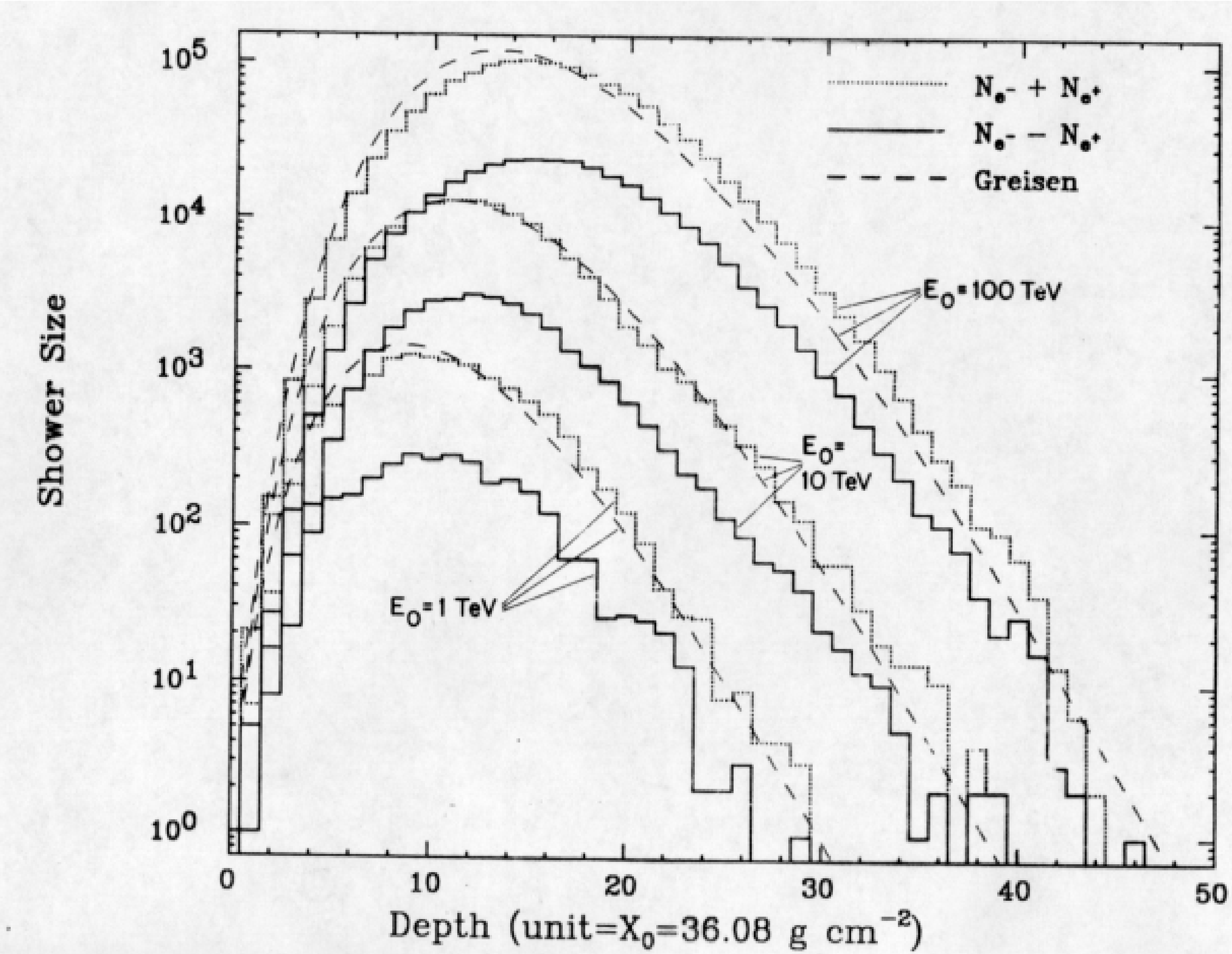
excess charge 20%

- TIMING
- LOW THRESHOLD ~ 100 keV (E_{KIN} ~)
- 3-D
- FAST
- LPM effect

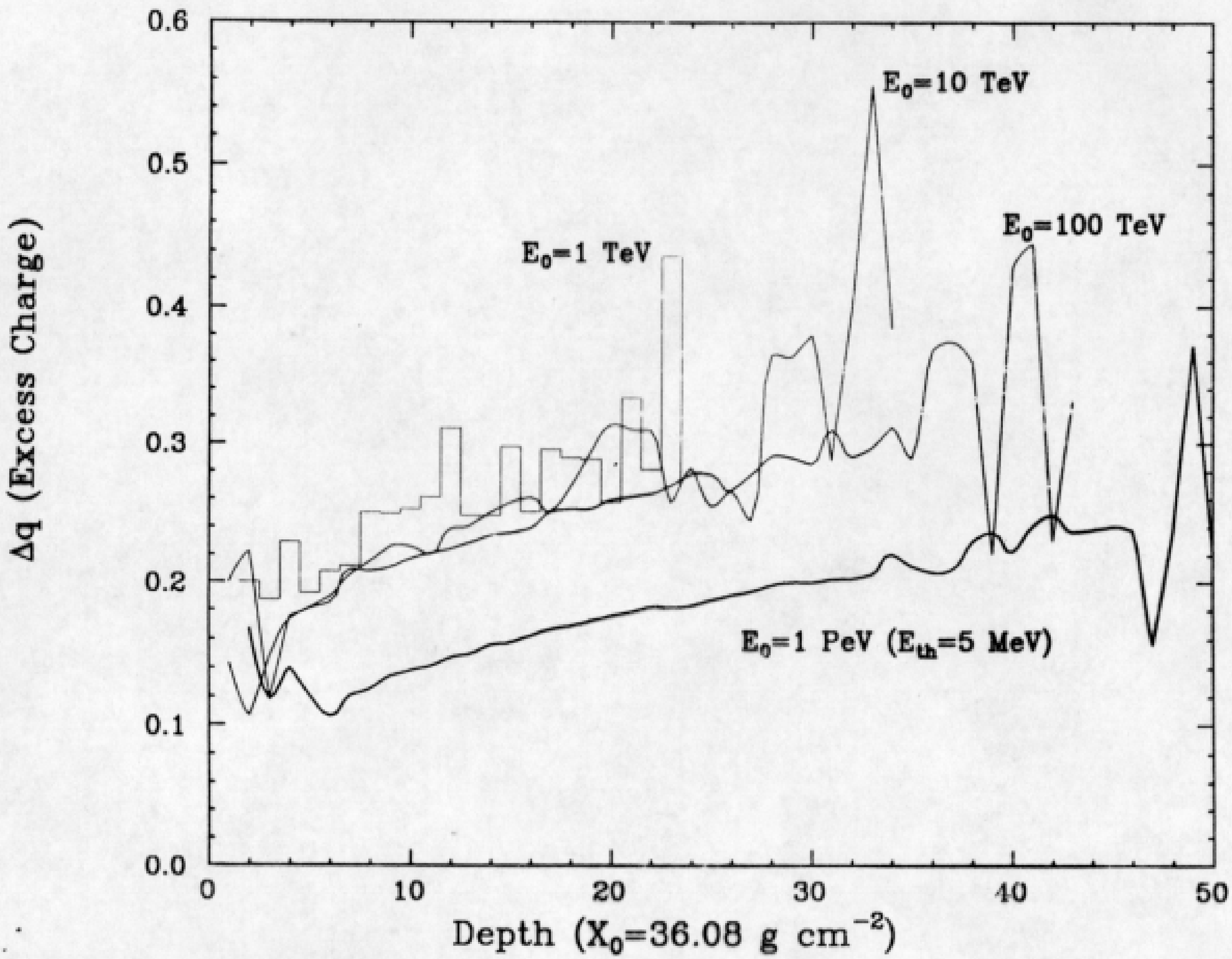
Special Features

$\frac{1}{n} = \beta \rightarrow E \sim 600$ keV

SPECIFICALLY DESIGNED FOR RADIO EMISSION IN HOMOGENEOUS ICE



Shower Size
Depth (unit=X0=36.08 g cm-2)
Ne- + Ne+
Ne- − Ne+
Greisen
E0=100 TeV
E0= 10 TeV
E0=1 TeV



Δq (Excess Charge)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
Depth (X_0=36.08 g cm^{-2})
E_0=1 TeV
E_0=10 TeV
E_0=100 TeV
E_0=1 PeV (E_{th}=5 MeV)

RADIO EMISSION

$$\vec{E}(\omega,\vec{x}) = \ldots\ldots \; i\omega \int dt'\, d^3x' \; e^{i\omega t' + ik|\vec{x}-\vec{x}'|} \; \frac{\vec{J}_\perp(t',x')}{|\vec{x}-\vec{x}'|}$$

$k = n\frac{\omega}{c}$ $\qquad$ $\vec{J}_\perp(\omega,\vec{k}) = \hat{u}\times[\hat{u}\times\vec{J}(\omega,\vec{k})]$

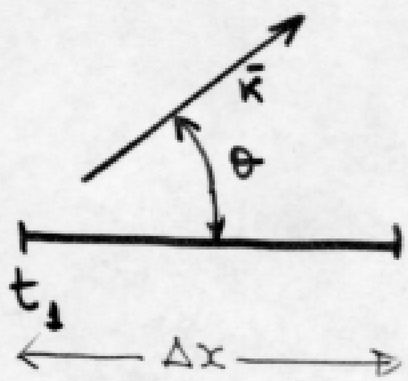
$\hat{u}$ unit vector in observation directi

FINITE TRACK

(uniformly moving) $\qquad$ FRAUNHOFER APROX. (R large)

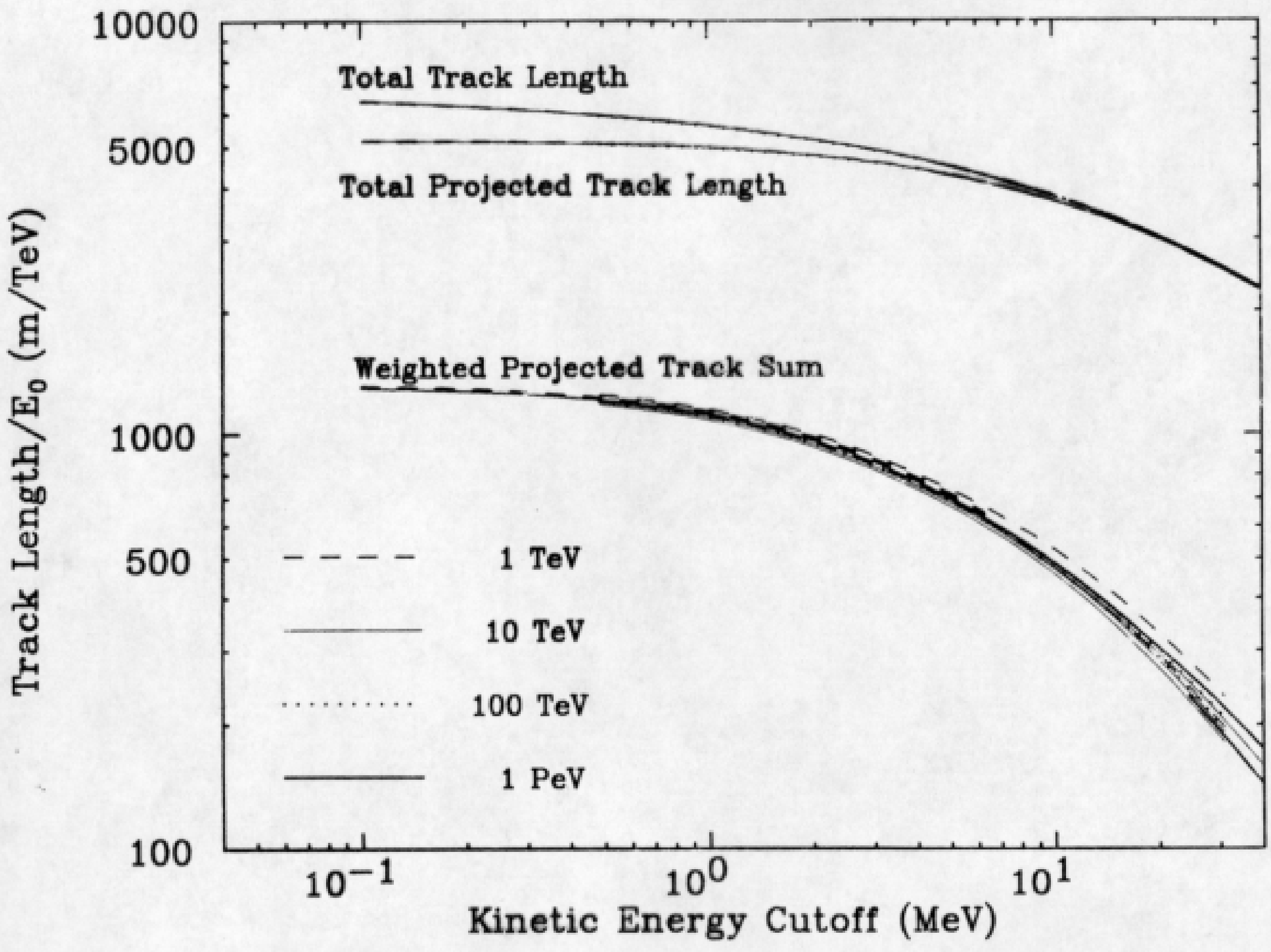
$$\vec{E}(\omega,\vec{x}) = \ldots \; i\omega \; \underbrace{\frac{e^{ikR}}{R}\, e^{i(\omega-\vec{k}\cdot\vec{v})t_1}}_{\text{overall phase}} \vec{J}_\perp \; \frac{e^{i(\omega-\vec{k}\cdot\vec{v})\delta t} - 1}{i(\omega-\vec{k}\cdot\vec{v})}$$

$$\omega - \frac{\omega n}{c} v\cos\theta = \omega(1-n\beta\cos\theta) =$$

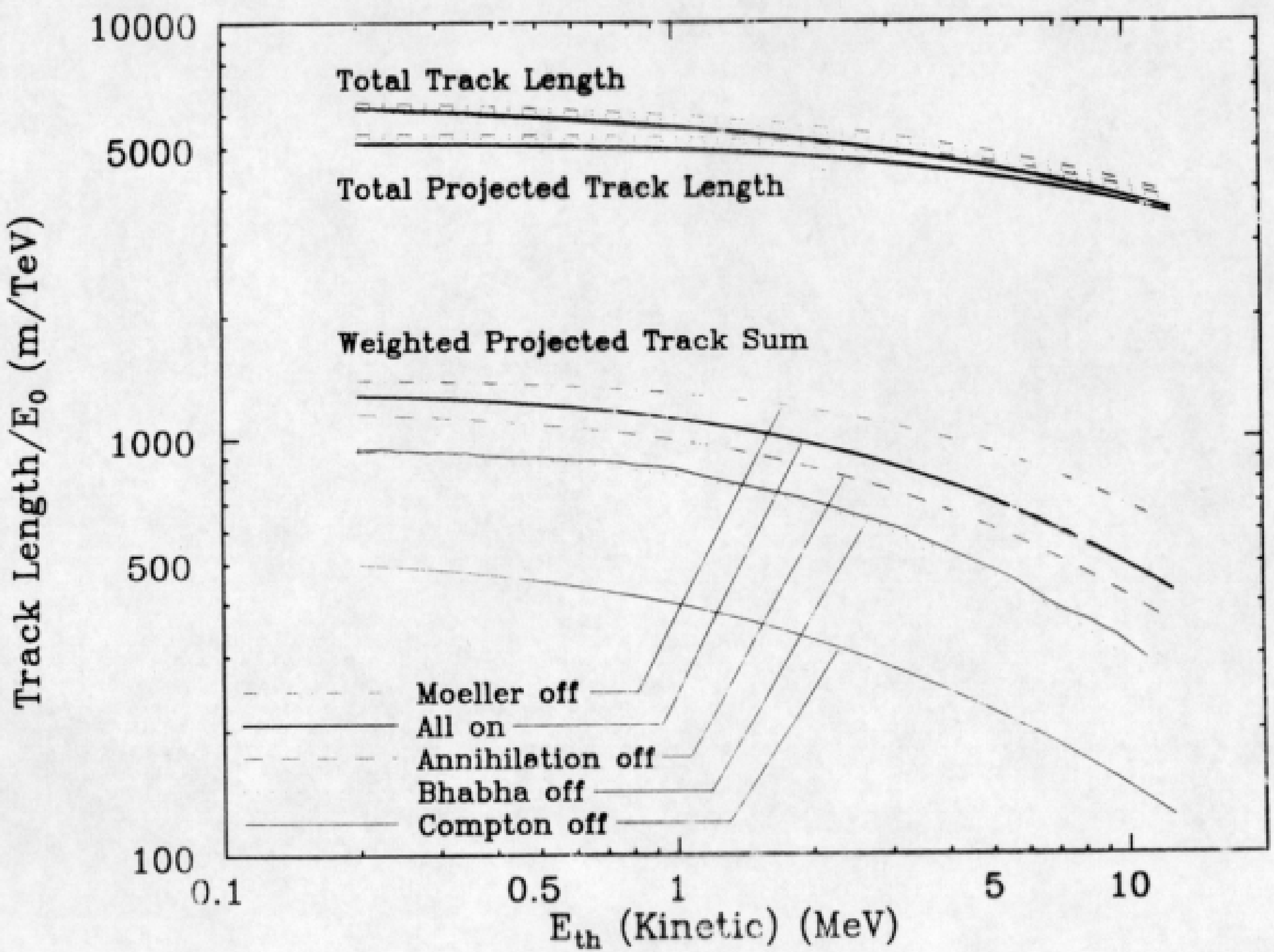


$$\frac{e^{i(\omega-\vec{k}\vec{v})\delta t} - 1}{i(\omega-\vec{k}\vec{v})} = \delta t\, \frac{\sin[(1-n\beta\cos\theta)\omega\delta t]}{(1-n\beta\cos\theta)\omega\delta t} \cdot \text{pha}$$

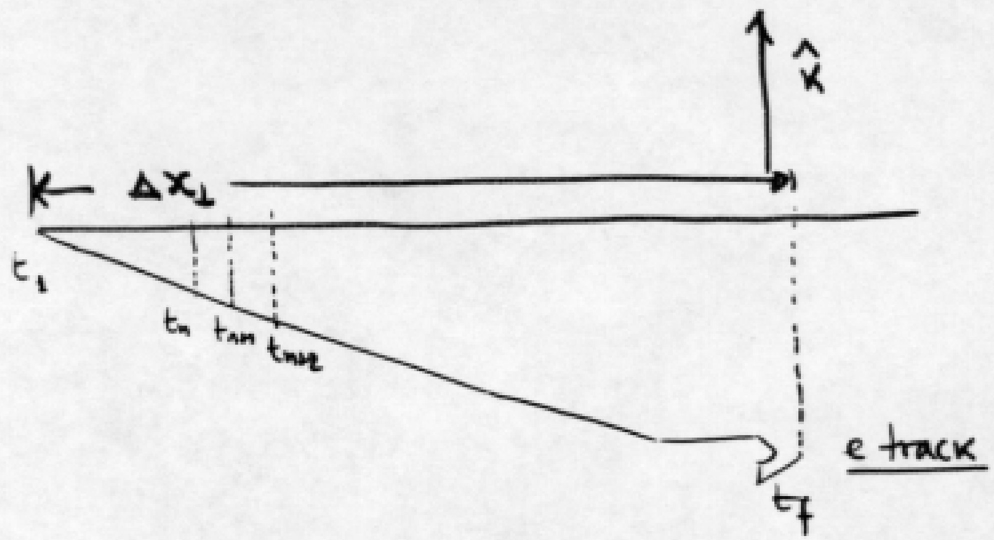
- $v_t\delta t = v\delta t\sin\theta = \Delta x \sin\theta$
  ↑ TRACKLENGTH
- $\text{sinc}\,[(1-n\beta\cos\theta)\omega\delta t] \longrightarrow 1 \begin{cases} \omega, \delta t \to 0 \\ \theta = \theta_c \to \text{F.T.} \end{cases}$



Total Track Length
Total Projected Track Length
Weighted Projected Track Sum
1 TeV
10 TeV
100 TeV
1 PeV
10000
5000
1000
500
100
Track Length/E_0 (m/TeV)
10^{-1}
10^{0}
10^{1}
Kinetic Energy Cutoff (MeV)


Total Track Length
Total Projected Track Length
Weighted Projected Track Sum
Moeller off
All on
Annihilation off
Bhabha off
Compton off
Track Length/E0 (m/TeV)
Eth (Kinetic) (MeV)
10000
5000
1000
500
100
0.1
0.5
1
5
10

BOOK KEEPING



If $|V|$ is constant : Huge number of cancellations

$\Rightarrow$ ONLY END POINTS

Use average V

$\sum V_\perp \Delta t = \Delta x_\perp$ Aprox a.

Subdivide @ interactions (discrete) Approx b

Subdivide further (cont. losses) Approx c

$\Downarrow$

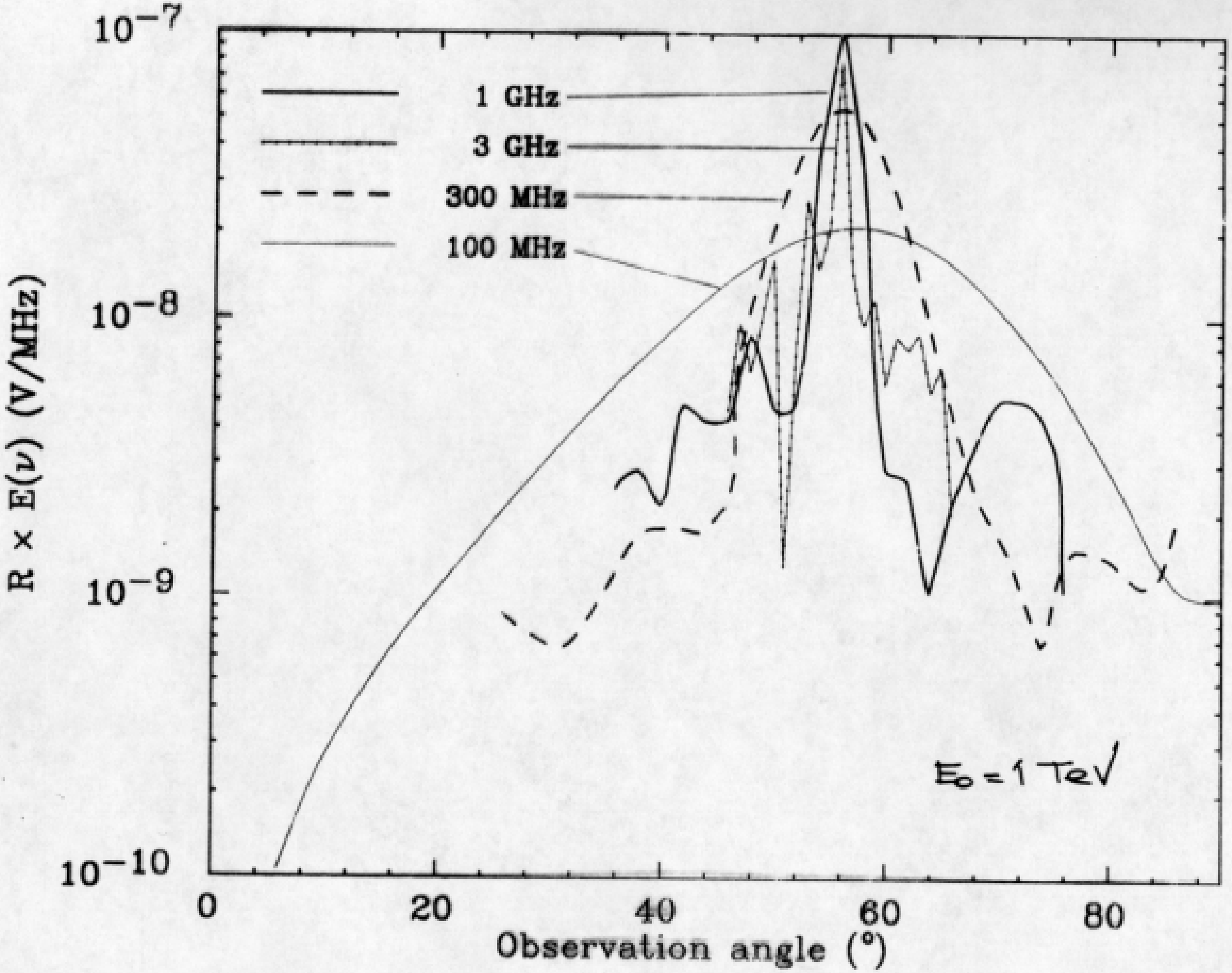
Approx a is very good (& fast!)

(Default)

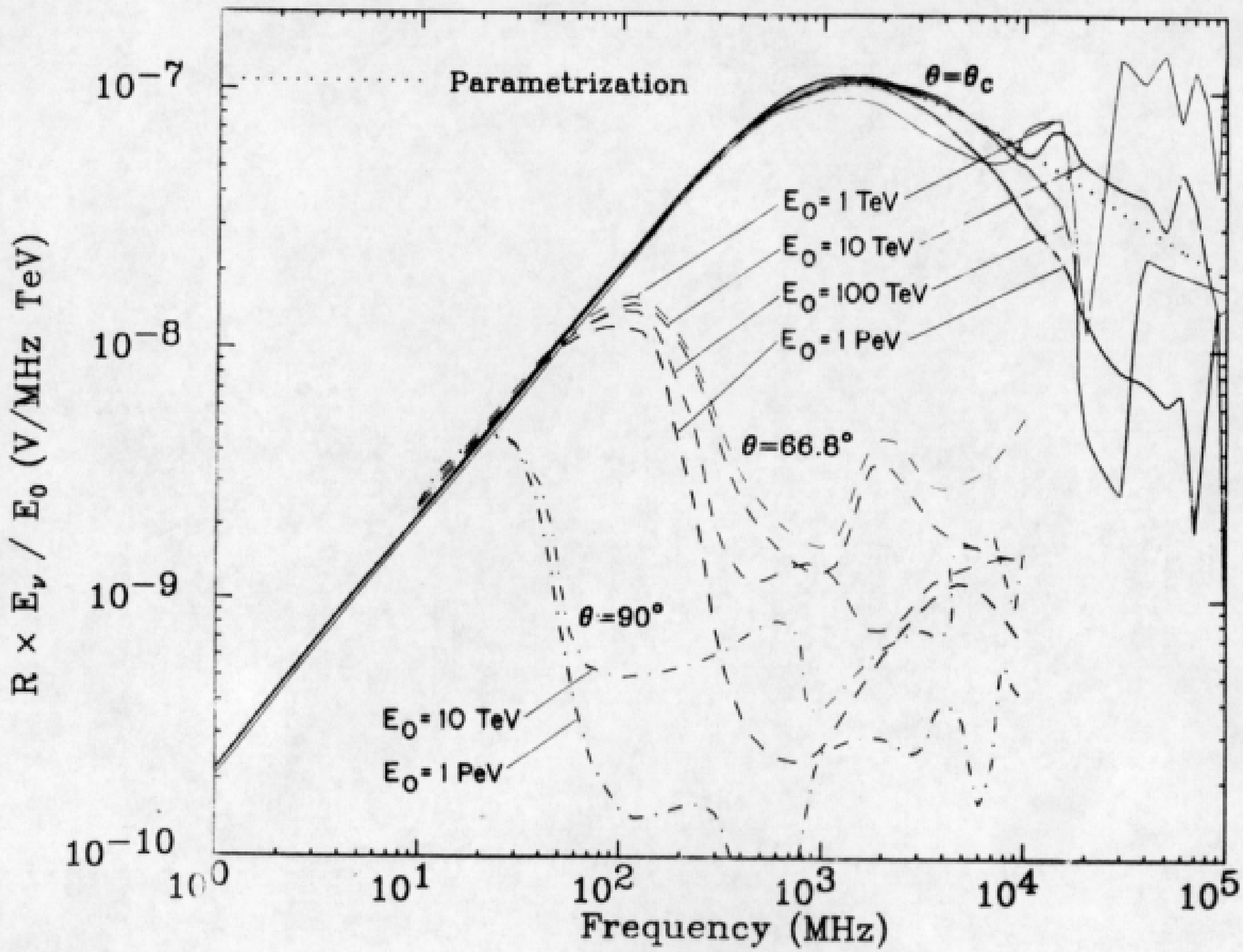
J. Alvarez-Muñiz, G. Parente, E.Z
24 ICRC (95) V. 1 p. 1023

J.A.M., R. Vazquez, E.Z. PRD 62 (2000) 63001

SEE
RADIO PATTERN AS DIFFRACTION !



R × E(ν) (V/MHz)
10−7
10−8
10−9
10−10
1 GHz
3 GHz
300 MHz
100 MHz
E0 = 1 TeV
0
20
40
60
80
Observation angle (°)



R × E_ν / E_0 (V/MHz TeV)
Frequency (MHz)
Parametrization
θ=θc
E0= 1 TeV
E0= 10 TeV
E0= 100 TeV
E0= 1 PeV
θ=66.8°
θ=90°
E0= 10 TeV
E0= 1 PeV

1-D Approximation

- MC too slow for EeV showers
- GOOD SCALING up to 10 PeV BUT
- Expect breakup of SCALING (LPM) J. Ralston & D. McKay, Ann Arbor 1990

⇓

WAY OUT: RELATE SHOWER FEATURES
TO RADIO PULSE DISTRIBUTION

- ANGULAR DISTRIBUTION ⟷ LONG. DEVELOP.

↓

STUDY EFFECT OF LONGITUDINAL DEVELOPMENT

$$\left.\begin{array}{l}\bullet\ \text{NEGLECT LATERAL DISTRIBUTION}\\ \bullet\ \text{ASSUME ALL PARTICLES HAVE "c"}\end{array}\right\}\ \text{1-D}$$

⇓

GOOD AGREEMENT @ $\nu < 300$ MHz

OVER PREDICTION @ $\nu > 300$ MHz
(growing with ν) (lateral spread ignored)
OK!

DIFFRACTION ANALOGY

Take $\vec{J}_\perp(\vec{x}';t) = Q(\vec{z}')\,\vec{c}_\perp\,\delta^3(\vec{x}'-\vec{c}t')$

to get

$$\vec{E}(\omega,\vec{x}) = \frac{e\mu_r}{2\pi\epsilon_0 c^2}\, i\omega \sin\theta\, \frac{e^{ikR}}{R}\,\hat{n}_\perp \int dz'\, Q(z')\, e^{ipz'}$$

- $\vec{E}(\omega,\vec{x})$ behaves as F.T. of charge excess $Q(z)$
- $p = (1-n\cos\theta)\frac{\omega}{c}$ relates standard "slit" diffraction to Cherenkov pattern

  $p=0 \Rightarrow \theta_C \qquad \vec{E}(\omega,\vec{x}) \propto \int dz'\, Q(z')$

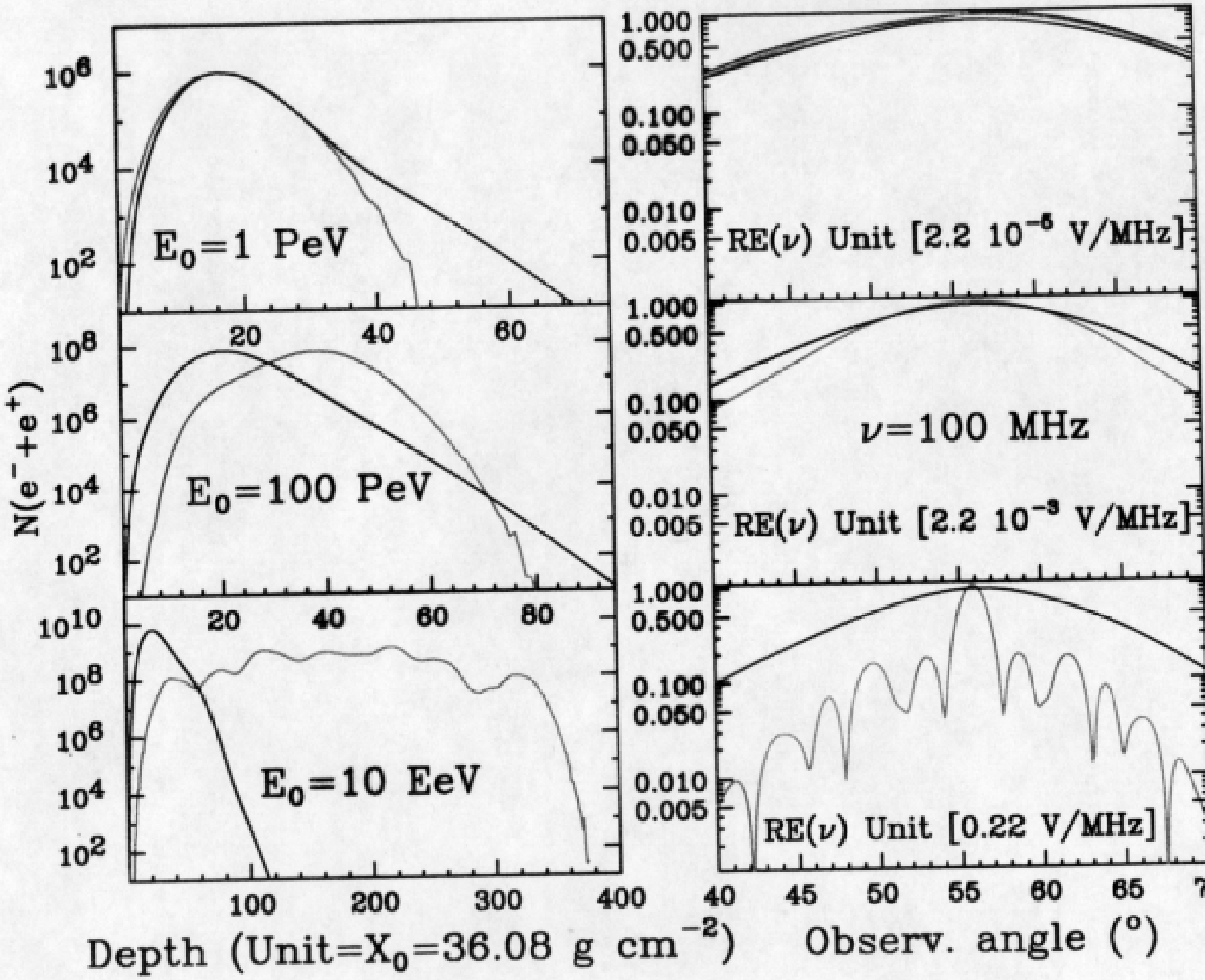
  EXCESS TRACKLENGTH
- Amplitude of $\vec{E}$ @ θ_C scales with tracklength (stable LPM too)
- Gaussian fit to $Q(z)$ $\Rightarrow$ Gaussian about θ_C $\sigma_p \simeq \frac{1}{\sigma_z}$

  Expanding $\theta = \theta_C + \Delta\theta \rightarrow p = \frac{\omega}{c}\sqrt{n^2-1}\,\Delta\theta$
- Secondary peaks in simulations $\leftrightarrow$ "oscillations" / fluctuations in $Q(z)$
- large p $\rightarrow$ large $\Delta\theta$ $\rightarrow$ short scale correlations

Lateral distribution can be corrected for by "unique" function because it is approximately the same (for LPM showers too)

Analytical approach $\rightarrow$ R.V. Buniy, J.P. Ralston astro-ph/0003408

Form factor


N(e⁻+e⁺)
E0=1 PeV
E0=100 PeV
E0=10 EeV
Depth (Unit=X0=36.08 g cm-2)
RE(ν) Unit [2.2 10-6 V/MHz]
ν=100 MHz
RE(ν) Unit [2.2 10-3 V/MHz]
RE(ν) Unit [0.22 V/MHz]
Observ. angle (°)

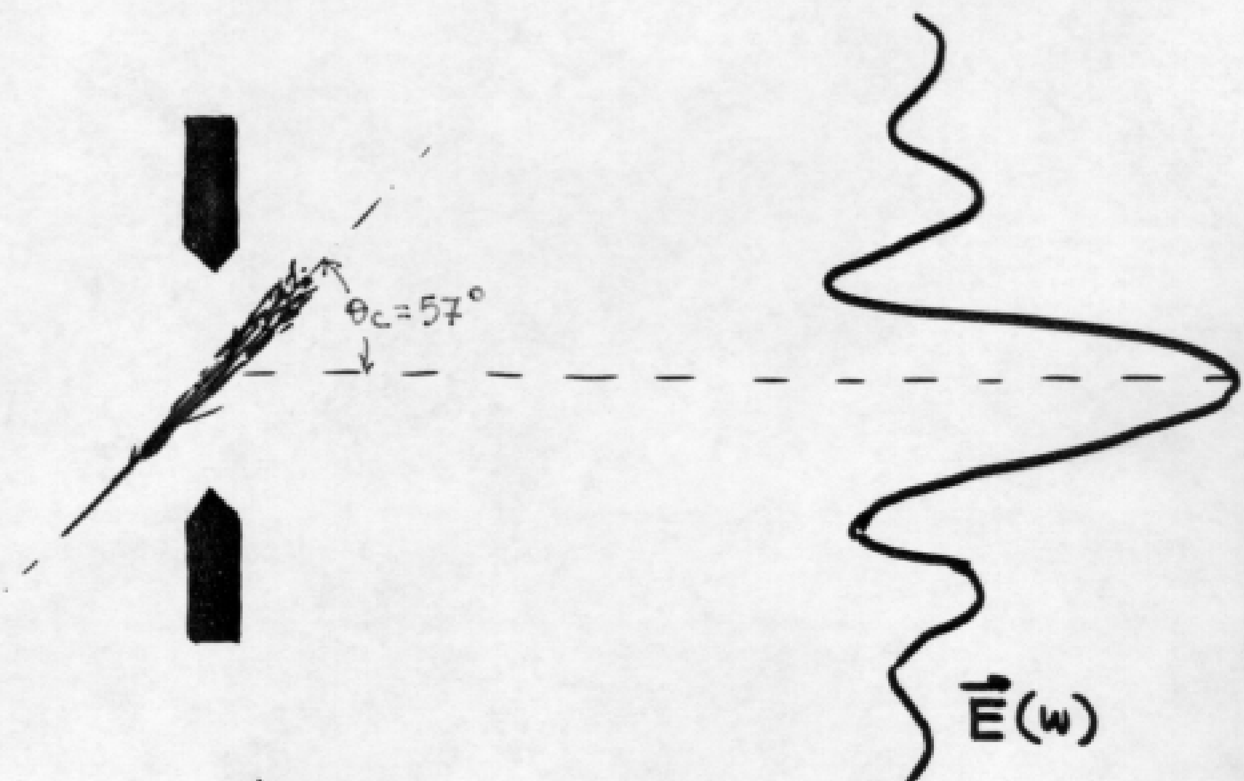
MC. Work 1990

Complex diffraction pattern ~(slit)

Halzen, Stanev, E.Z.
PLB 257 (91) 432
PRD 45 (92) 362

$E_{sh} < 10$ PeV

50% signal by e^- $E < 5$ MeV



Approx

$$R|\vec{E}(\omega)| \sim \int dz\, Q(z)\, e^{ikz}$$

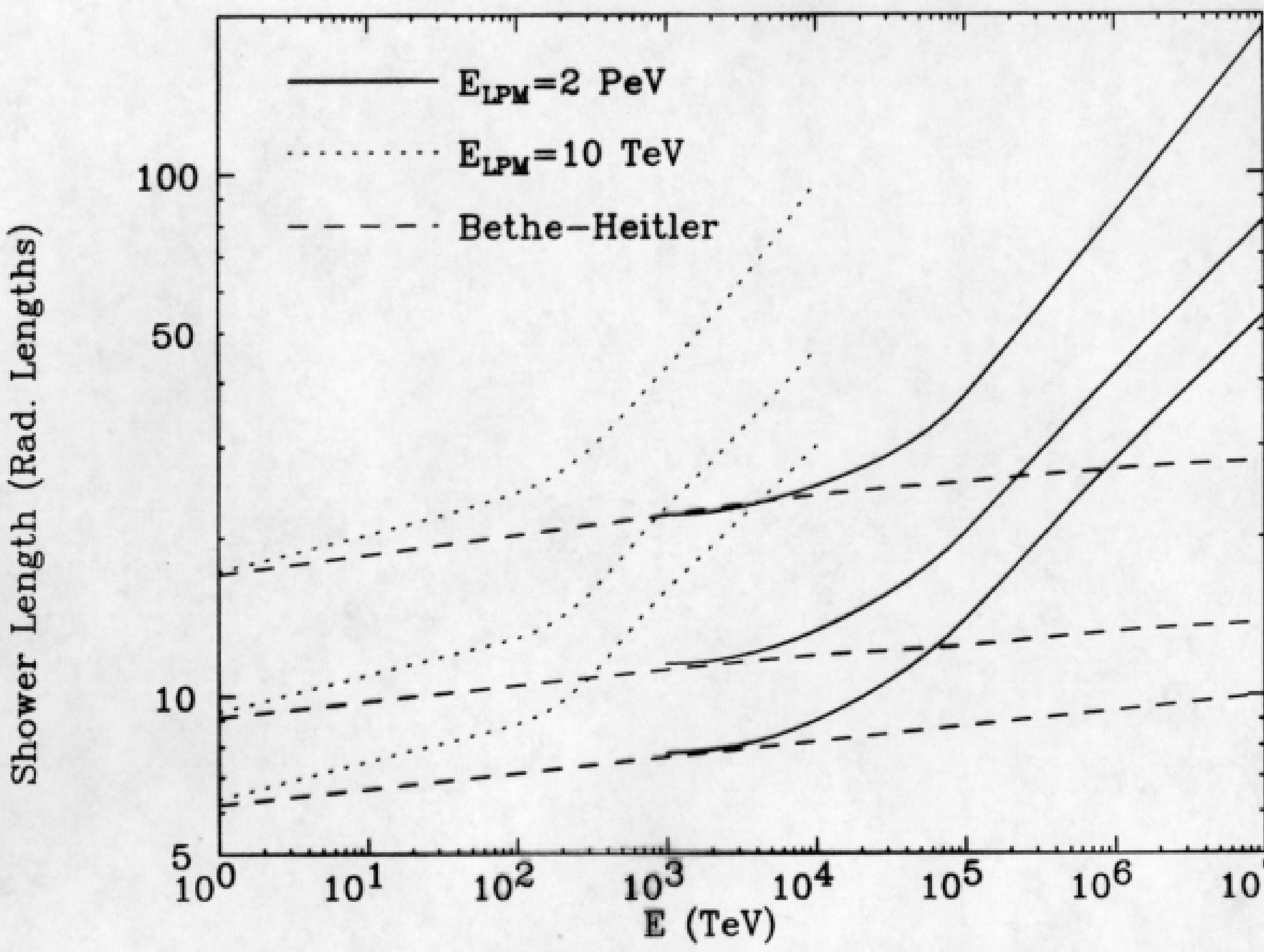
$$k = \frac{\omega}{c}(1 - n\cos\theta) \sim \omega\Delta\theta$$

$$\Delta\theta = \theta - \theta_c$$

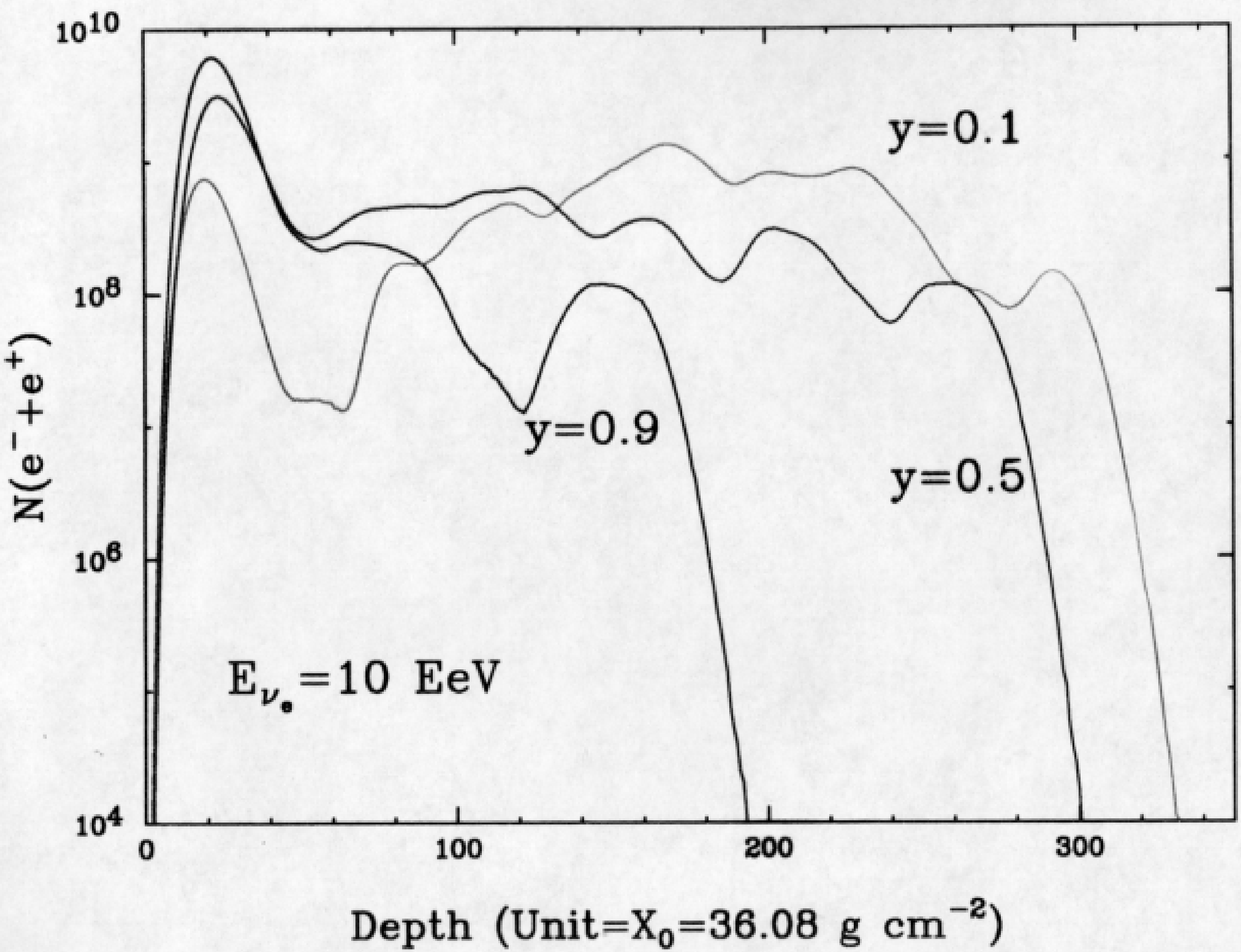
Allows E_{sh} to the EeV scale

J. Alvarez E.Z.
PLB 411 (97) 218
PLB 434 (98) 396

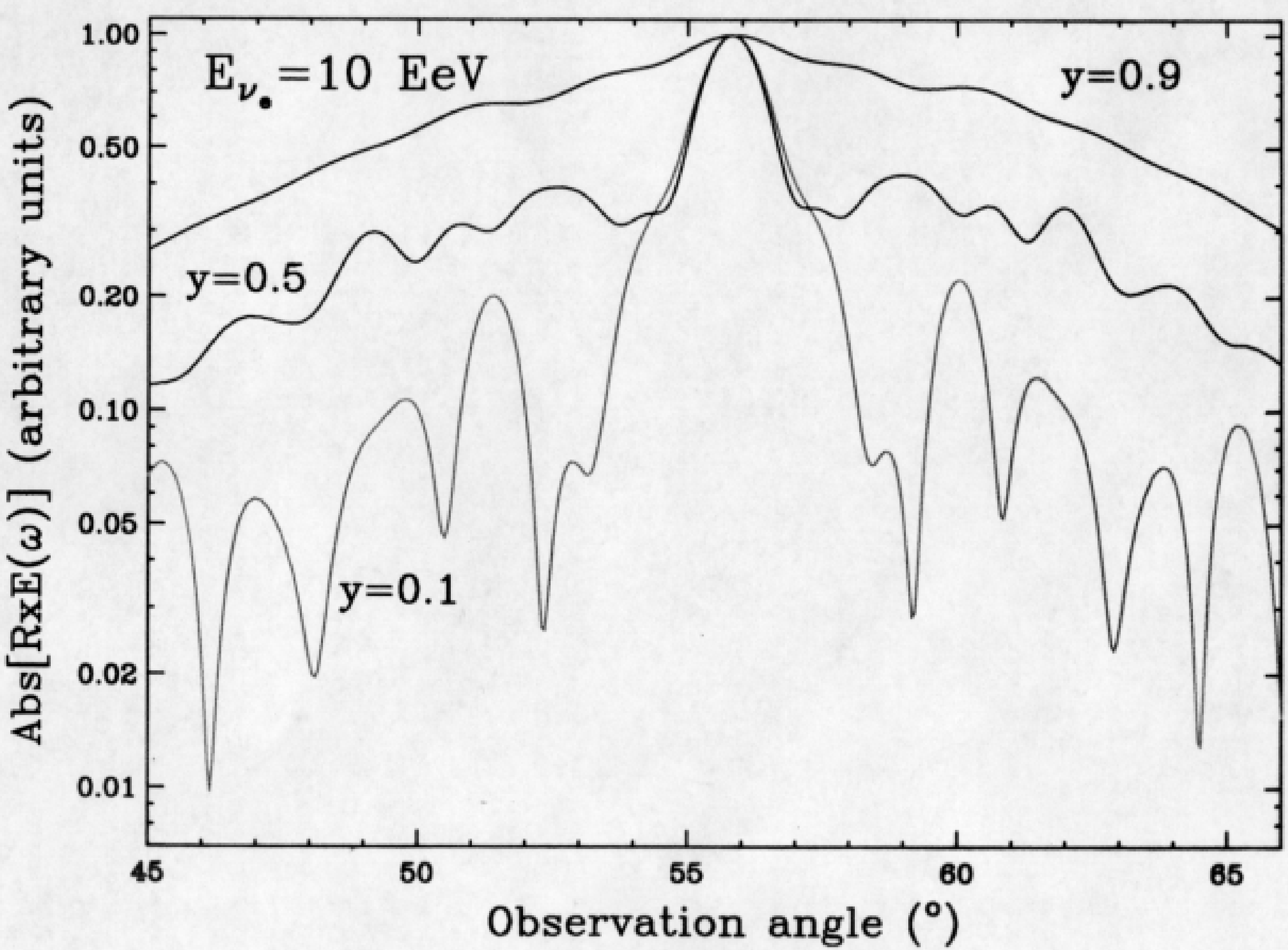
Figure 1



E_{LPM}=2 PeV
E_{LPM}=10 TeV
Bethe-Heitler
Shower Length (Rad. Lengths)
100
50
10
5
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
E (TeV)



N(e⁻+e⁺)
10^10
10^8
10^6
10^4
0
100
200
300
Depth (Unit=X_0=36.08 g cm^-2)
y=0.1
y=0.9
y=0.5
E_νe=10 EeV



E_{ν_e}=10 EeV
y=0.9
y=0.5
y=0.1
Abs[RxE(ω)] (arbitrary units)
Observation angle (°)
1.00
0.50
0.20
0.10
0.05
0.02
0.01
45
50
55
60
65

FRESNEL EFFECTS

USE 1-D approximation
without taking Fraunhofer limit

$$\Downarrow$$

$$\vec{E}(\vec{x},\omega) = \frac{e\mu_r}{2\pi\epsilon_0 c^2}\, i\omega \sin\theta\, \hat{n}_\perp \int dz'\, Q(z')\, \frac{e^{i\frac{\omega}{c}z' + ik|\vec{x} - z'\hat{u}_{z'}|}}{|\vec{x} - z'\hat{u}_{z'}|}$$

Fraunhofer limit $R > R_F = \frac{L_s^2}{\lambda} = [3\,m]\left[\frac{L_s}{1\,m}\right]^2\left[\frac{\nu}{1\,GHz}\right]$

FRESNEL EFFECTS

USE 1-D approximation
without taking Fraunhofer limit

$$\Downarrow$$

$$\vec{E}(\vec{x},\omega) = \frac{e\mu_r}{2\pi\epsilon_0 c^2}\, i\omega \sin\theta\, \hat{n}_\perp \int dz'\, Q(z')\, \frac{e^{i\frac{\omega}{c}z' + ik|\vec{x} - z'\hat{u}_{z'}|}}{|\vec{x} - z'\hat{u}_{z'}|}$$

Fraunhofer limit $R > R_F = \frac{L_s^2}{\lambda} = [3\,m]\left[\frac{L_s}{1\,m}\right]^2\left[\frac{\nu}{1\,GHz}\right]$