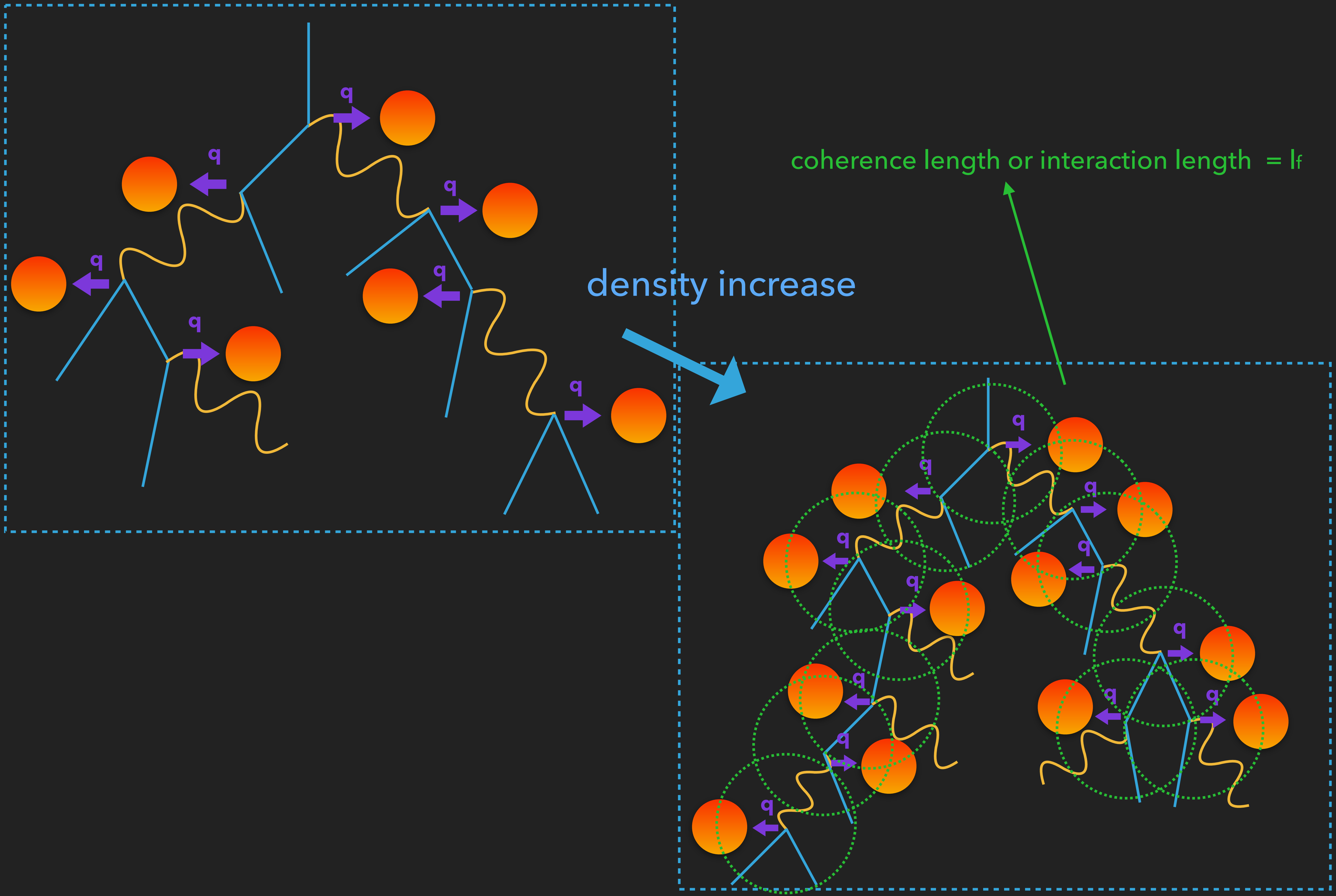
LPM EFFECT

KM3NET JUNIOR GROUP MEETING - 5/3/2020

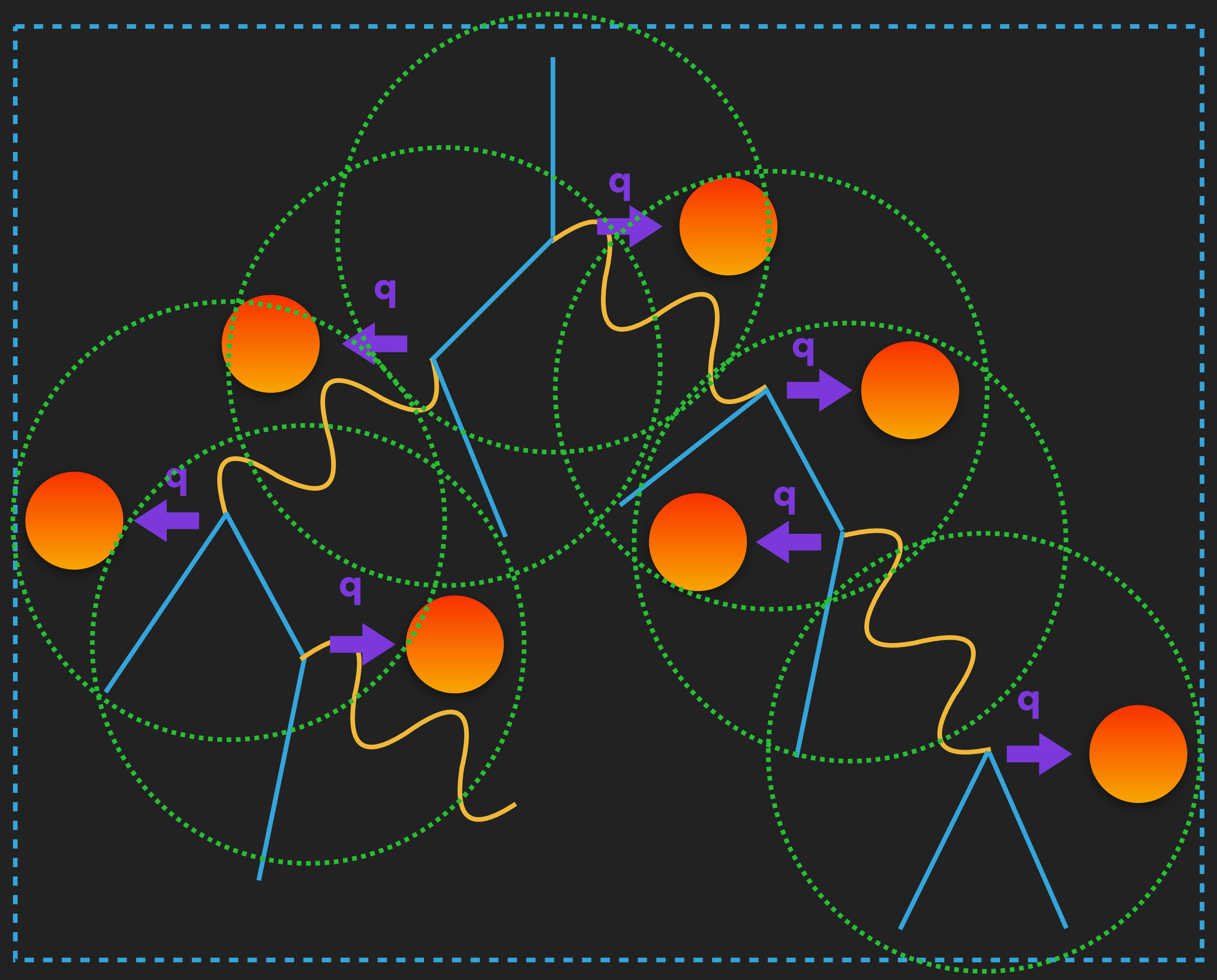
CLARA GATIUS

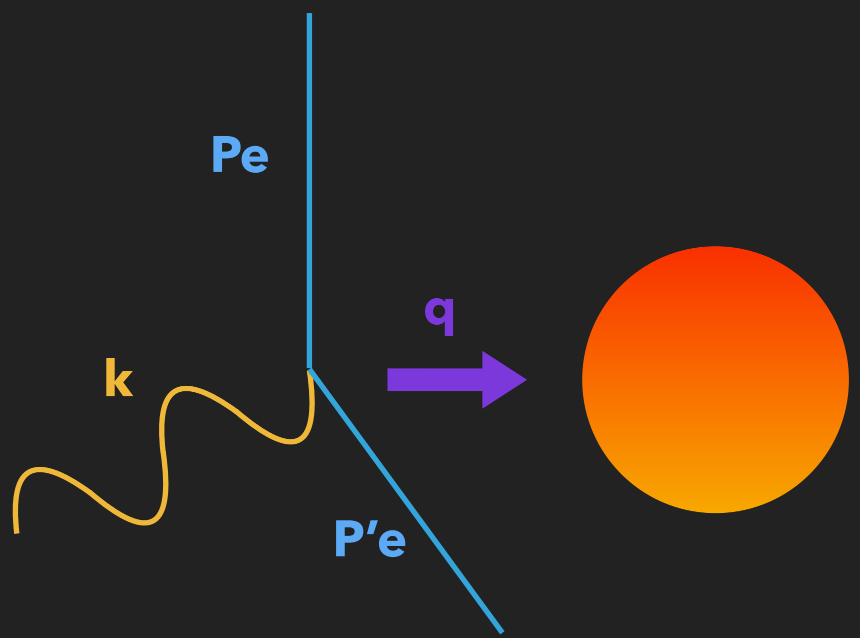
LANDAU-POMERANCHUK-MIGDAL EFFECT:

Supression of the Bremsstrahlung and Pair Production cross-section at high densitites or high energies.


q
density increase
coherence length or interaction length = l_f

increase particles energy –> increase coherence length or interaction length





Bremsstrahlung interaction

$$q_{\parallel} = p_e - p'_e - p_\gamma = \sqrt{(E/c)^2 - (mc)^2} - \sqrt{[(E-k)/c]^2 - (mc)^2} - k/c$$

$$\sqrt{1-y} \sim 1 - y/2$$

$$q_{\parallel} \sim \frac{m^2 c^3 k}{2E(E-k)}$$

as higher E –> smaller momentum transfer

as lower k –> smaller momentum transfer

Some numbers to illustrate....

E = 1 EeV , k = 100 PeV –> q = 10^-9 eV/c

Uncertainty principle becomes rellevant!!!

Uncertainty principle

$$\Delta x \, \Delta p \geq \hbar$$

$$l_{f0} = \frac{\hbar}{q_{\parallel}} = \frac{2\hbar E(E-k)}{m^2 c^3 k}.$$

coherence length or interaction length:

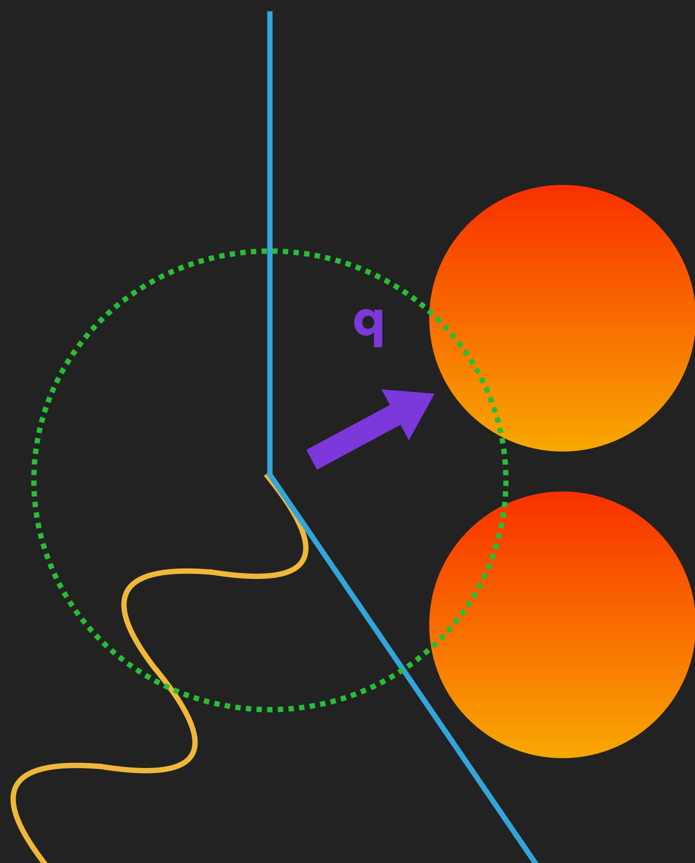
space the interactions need to take place

as higher E –> higher l_f

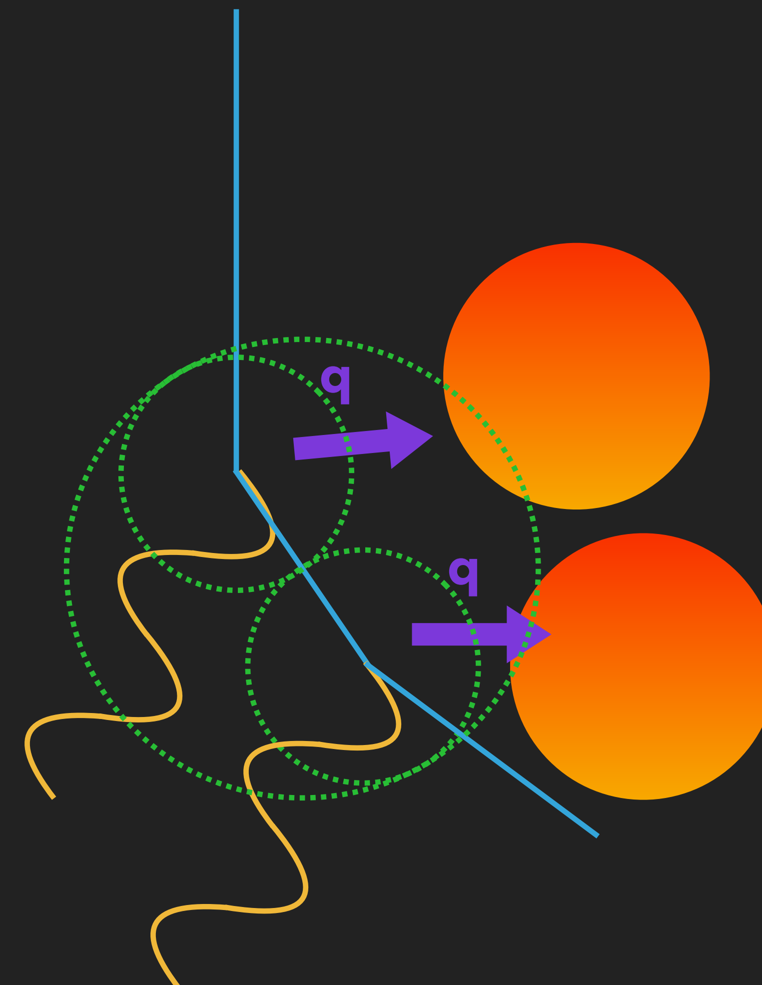
Gives room for other interactions to take place!

Continuing the "some numbers to illustrate…"

E = 1 EeV , k = 100 PeV –> l_f = 200 m



Bremsstrahlung interaction



Double Bremsstrahlung interaction

increasing the number of interactions…

Radiation intensity $\propto$ l_f

	q	–>	2q
	l_f	–>	l_f / 2
Radioation intensity:	$\sim l_f^2$	–>	$\sim 2 \cdot (l_f/2)^2$

3 sources of supression:

1. Multiple scattering of the e-
2. Interaction of the emitted photon with the medium (dielectric effect)
3. Pair creation by the emitted photon

Multiple scattering of the e-

$$q_{\parallel} = \sqrt{(E\cos\theta_{MS/2}/c)^2 - (mc)^2} - \sqrt{[(E-k)\cos\theta_{MS/2}/c]^2 - (mc)^2} - k/c,$$

$$q_{\parallel} = \frac{km^2c^3}{2E(E-k)} + \frac{k\theta_{MS/2}^2}{2c} \longrightarrow l_f = l_{f0}\sqrt{\frac{kE_{LPM}}{E(E-k)}}$$

Supression:

$$S = \frac{d\sigma/dk}{d\sigma_{BH}/dk} = \frac{l_f}{l_{f0}} = \sqrt{\frac{kE_{LPM}}{E(E-k)}}$$

as bigger its contribution –> smaller lf –> more supressed cross-section

Condition for supression:

$$\theta_{MS/2} > 1/\gamma.$$

higher E –> higher limit for photon energy

medium dependent

$$k < k_{LPM} = \frac{E(E-k)}{E_{LPM}}, \quad E_{LPM} = \frac{m^2c^3X_0\alpha}{4\pi\hbar} \approx 7.7\ \text{TeV/cm} \cdot X_0$$

Material	Z	ρ (g/cm^3)	X_0 (cm)	E_{LPM} (TeV)	y_{die}	E_p
Hydrogen (liquid at BP)	1	0.07	865	6.6 PeV	1.4×10^{-5}	4.6 PeV
Helium (liquid at BP)	2	0.125	755	5.8 PeV	1.5×10^{-5}	4.3 PeV
Carbon	6	2.2	19.6	151	5.5×10^{-5}	410 TeV
Aluminum	13	2.70	8.9	68	6.0×10^{-5}	205 TeV
Iron	26	7.87	1.76	13.6	1.0×10^{-4}	67 TeV
Lead	82	11.35	0.56	4.3	1.1×10^{-4}	24 TeV
Tungsten	74	19.3	0.35	2.7	1.5×10^{-4}	20 TeV
Uranium	92	18.95	0.35	2.7	1.4×10^{-4}	19 TeV
Gold	79	19.32	0.33	2.5	1.5×10^{-4}	19 TeV
Air (STP)	-	0.0012	30400	234 PeV	1.3×10^{-6}	15 PeV
Water	-	1.00	36.1	278	3.9×10^{-5}	540 TeV
Std. rock	11	2.65	10.0	77	6.0×10^{-5}	230 TeV

Dielectric effect

$$q_{\parallel} = \frac{k}{2c\gamma^2} + \frac{(\hbar\omega_p)^2}{2ck} \longrightarrow l_f = \frac{2\hbar c k \gamma^2}{k^2 + k_p^2}$$

Supression: $S = \frac{k^2}{k^2 + k_p^2}$

as bigger its contribution –> smaller lf –> more supressed cross-section

Condition for supression:

$$k < k_p \quad , \quad k_p = \gamma\hbar\omega_p \quad , \quad \epsilon(k) = 1 - (\hbar\omega_p)^2/k^2$$

$$y = k/E < y_{die} \quad , \quad y_{die} = \hbar\omega_p/mc^2$$

plasma frequency medium

permitivity

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Pair production

$$l_{f0} > X_0$$

Supression:

$$S = \frac{X_0}{l_{f0}} = \frac{m^2 c^3 k X_0}{2\hbar E(E-k)}$$

Condition for supression:

$$E > E_p = \frac{X_0 \omega_p E_s}{\sqrt{2} c} \quad , \quad E_s = mc^2 \sqrt{4\pi/\alpha}$$

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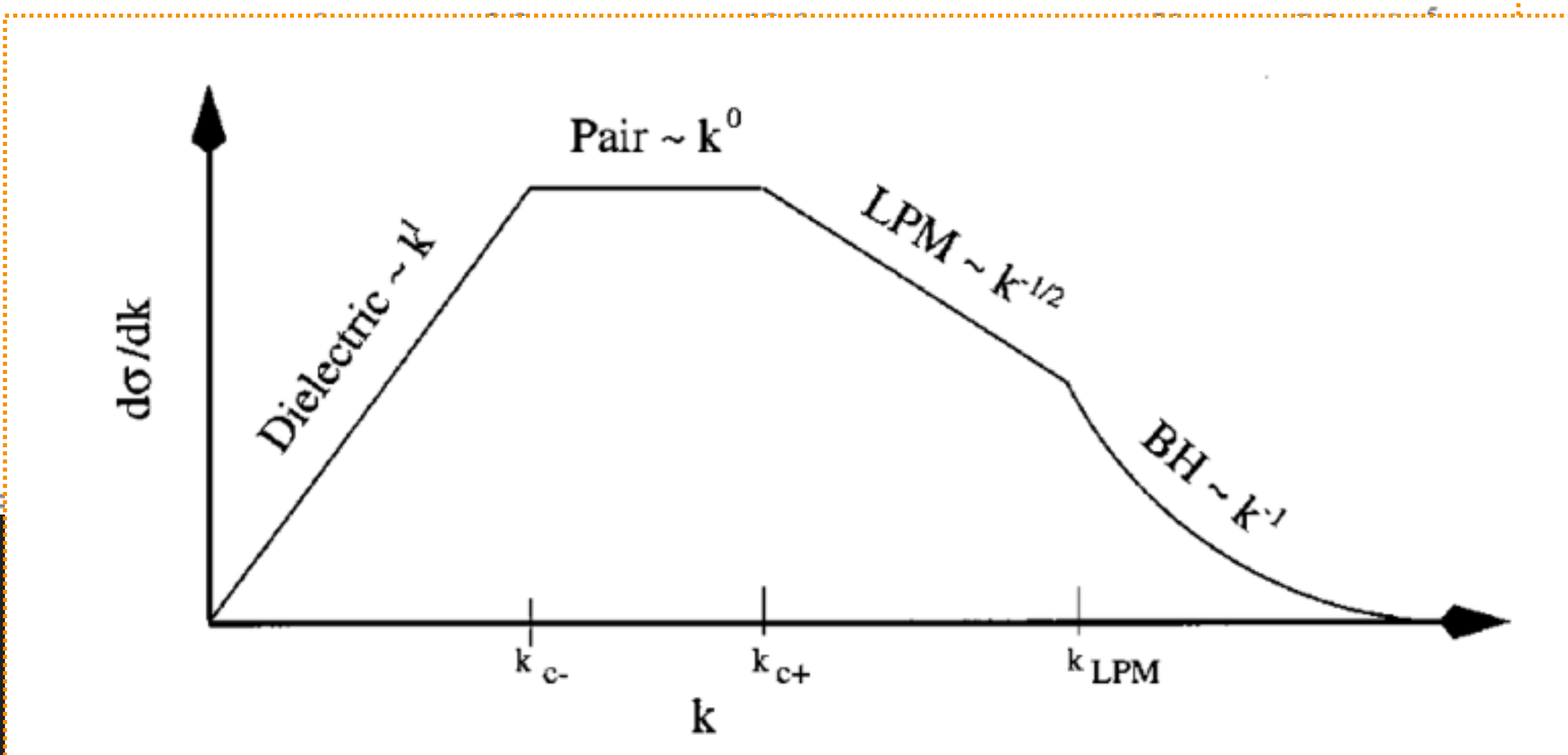
Carbon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10 TeV
Aluminum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	05 TeV
Iron	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7 TeV
Lead	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4 TeV
Tungsten	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0 TeV
Uranium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9 TeV
Gold	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9 TeV
Air (STP)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5 PeV
Water	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40 TeV
Std. rock	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	30 TeV



Total supression…

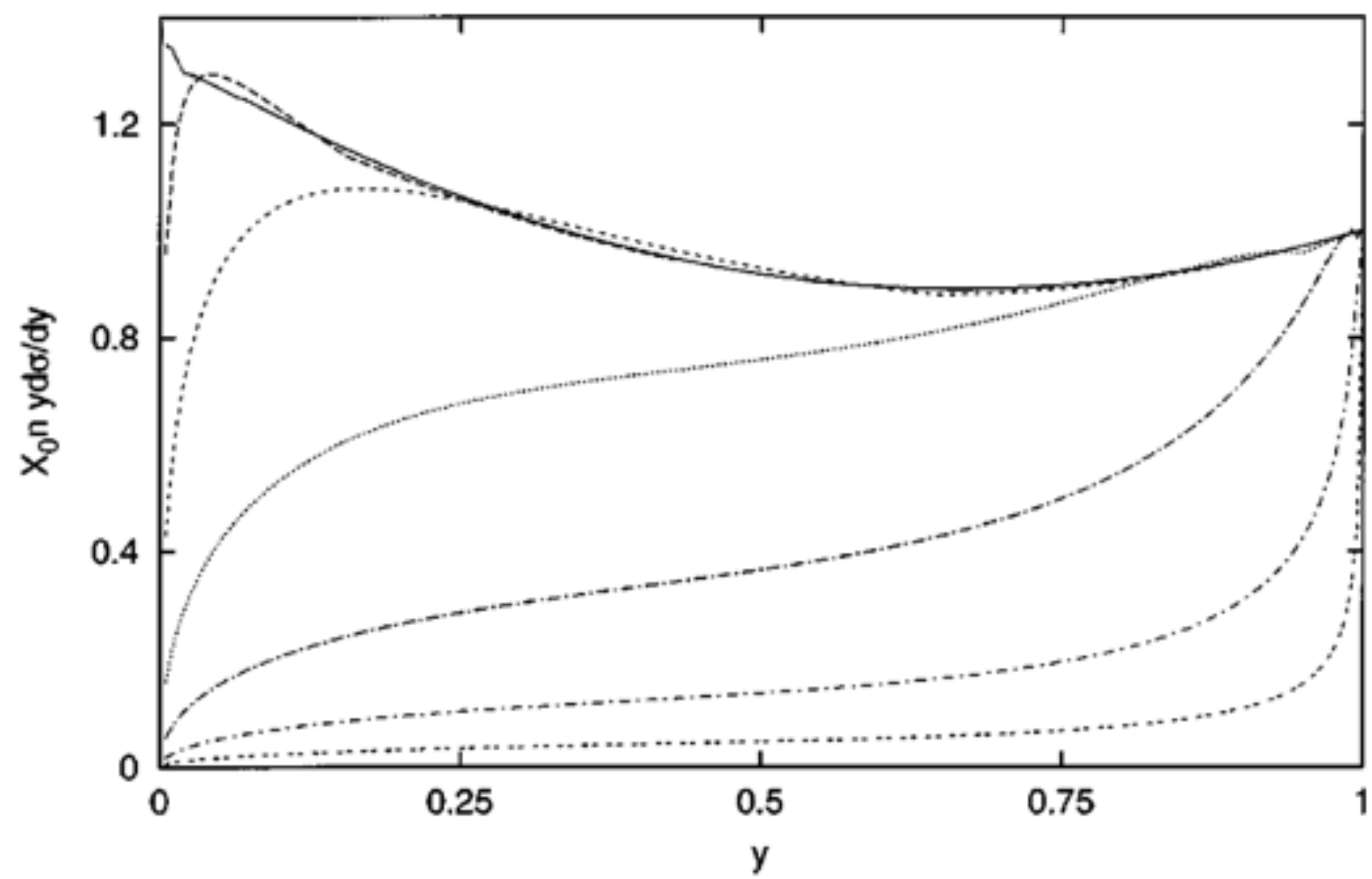


FIG. 9. Energy-weighted differential cross section for bremsstrahlung, $X_0 ny\, d\sigma_{LPM}/dy$, for various electron energies in a lead target, showing how the spectral shape changes: top curve, electrons of energies 10 GeV; remaining curves, 100 GeV, 1 TeV, 10 TeV, 100 TeV, 1 PeV, and 10 PeV (bottom curve). The units are fractional energy per radiation length.

source of supression: Bremsstrahlung.

Partically produced e- and e+ undergo Bremsstrahlung.

Identical approach as for multi-scattering, but now the contribution to the momentum transfer is given by the Bremsstrahlung of e- or e+

$$\rightarrow \quad l_f = l_{f0} \sqrt{\frac{k E_{LPM}}{E(k-E)}}$$

Supression: $S = \sqrt{\frac{E_{LPM} k}{E(k-E)}}$

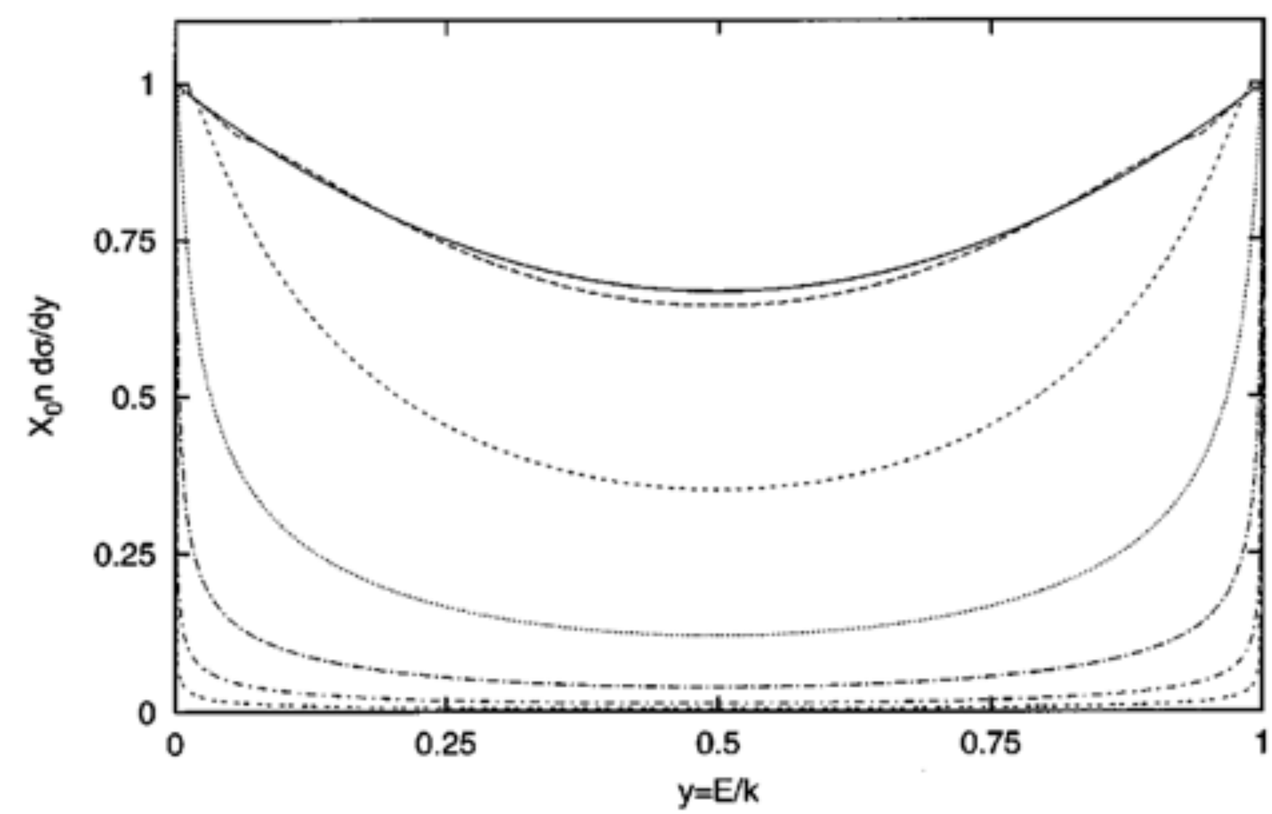


FIG. 10. Differential cross section for pair production, $X_0 n\, d\sigma_{LPM}/dy$, in lead for various photon energies, showing how the spectral shape changes. Cross sections are plotted for photons of energies 1 TeV (top curve), 10 TeV, 100 TeV, 1 PeV, 10 PeV, 100 PeV, and 1 EeV (bottom curve).

+ not only effect on particle spectrum, also effect on angular distribution !

(by all types of supressions)

$l_{f0} \propto 1/\theta$ –> less room for interference of other interactions

↓

supression small emision angles

↓

increase angular spread

Improvements by Migdal:

- No use of an average scattering angle
- Addition of quantum effects: electron spin and photon polarization

Approach: calculation of averaged radiation per interaction and the following interference between radiation from different collisions.

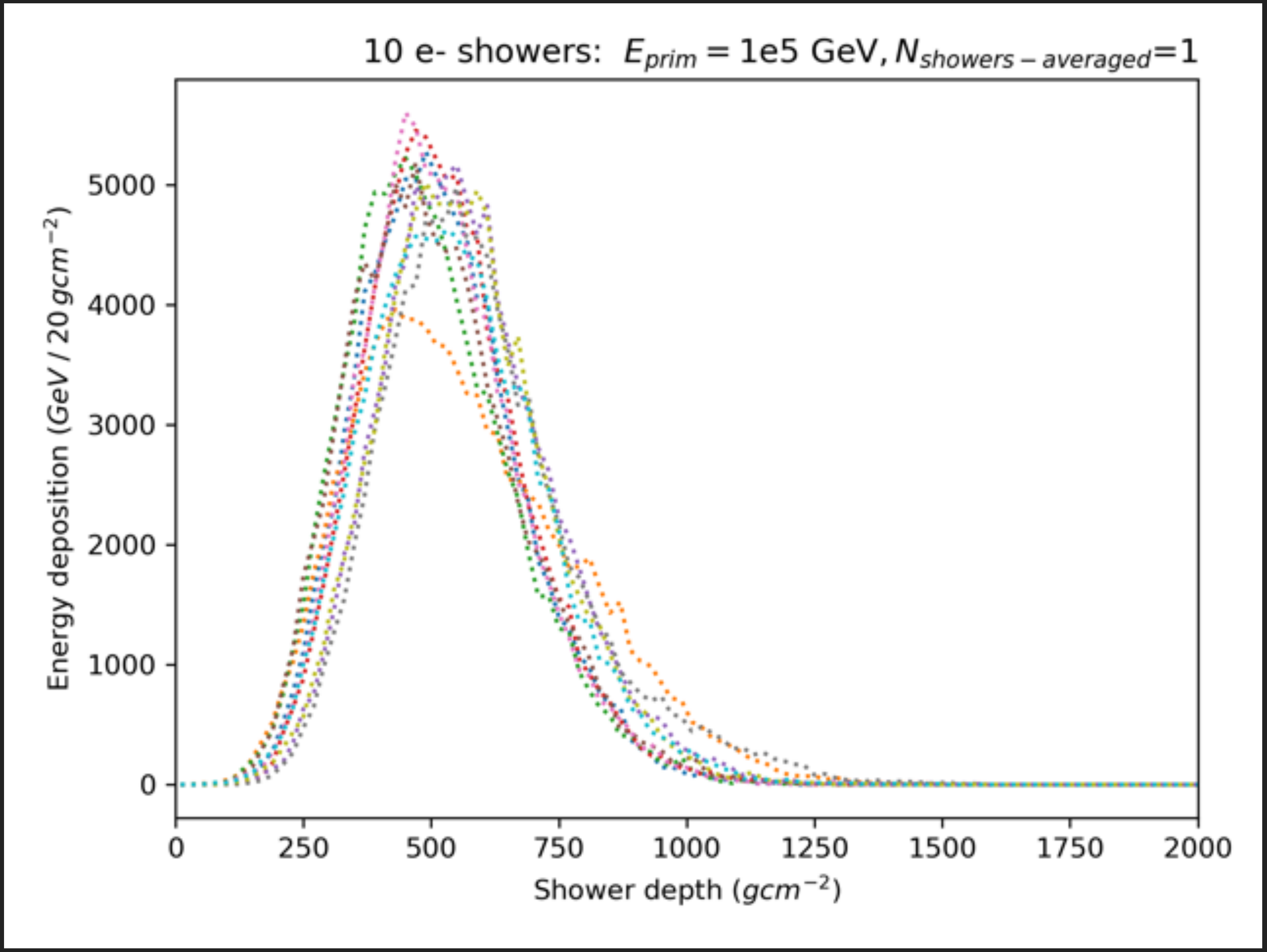
Bremsstrahlung:

$$\frac{d\sigma_{LPM}}{dk} = \frac{4\alpha r_e^2 \xi(s)}{3k}\{y^2 G(s) + 2[1+(1-y)^2]\phi(s)\}Z^2 \times \ln\left(\frac{184}{Z^{1/3}}\right),$$

Pair production:

$$\frac{d\sigma_{LPM}(\gamma\to e^+e^-)}{dE} = \frac{4\alpha r_e^2 \xi(\tilde{s})}{3k}\left\{G(\tilde{s}) + 2\left[\frac{E^2}{k^2} + \left(1-\frac{E}{k}\right)^2\right]\phi(\tilde{s})\right\}$$

LPM EFFECT ON ELECTROMAGNETIC SHOWERS IN WATER:



[Simulation CORSIKA-6600-IW]

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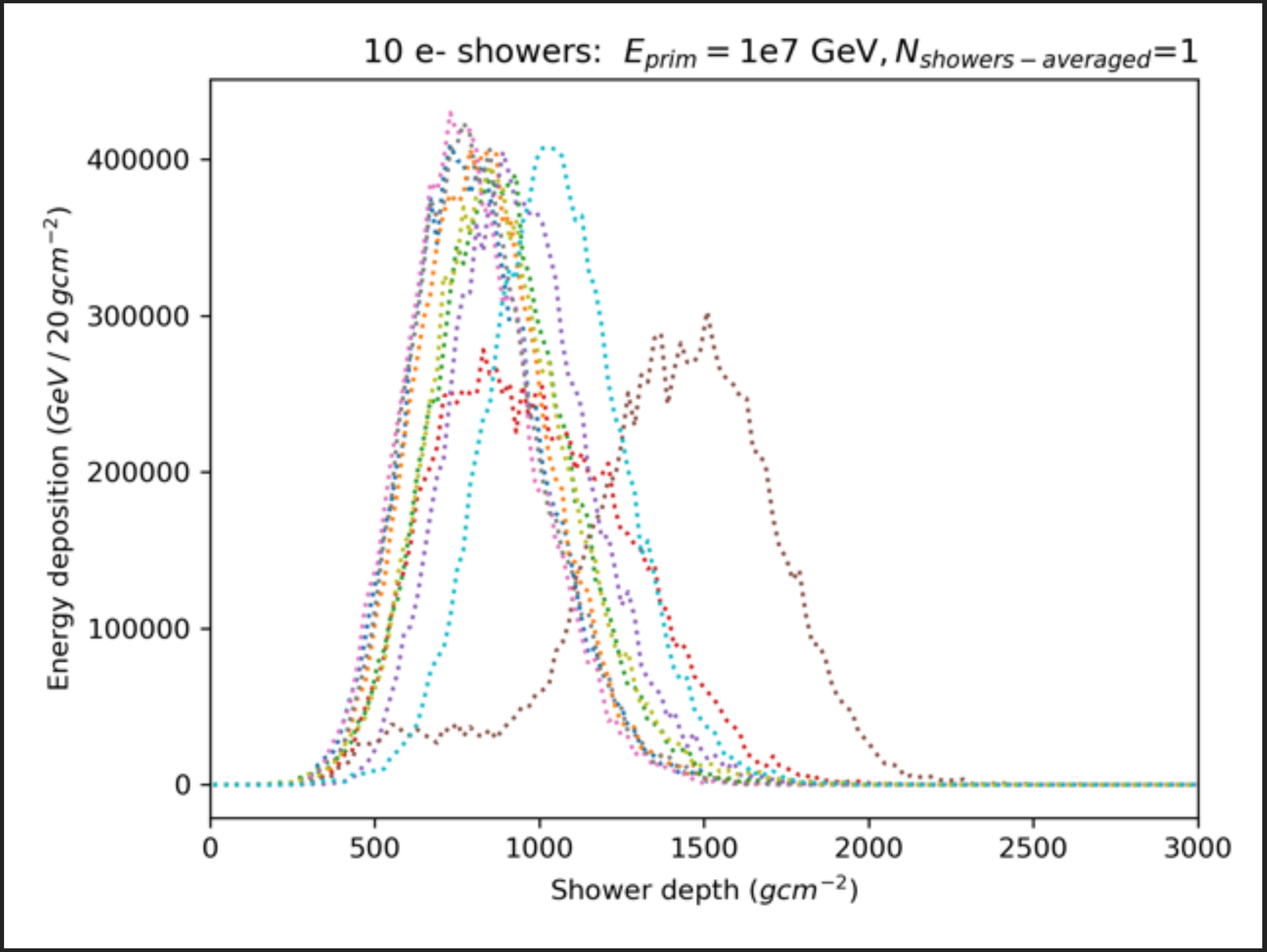

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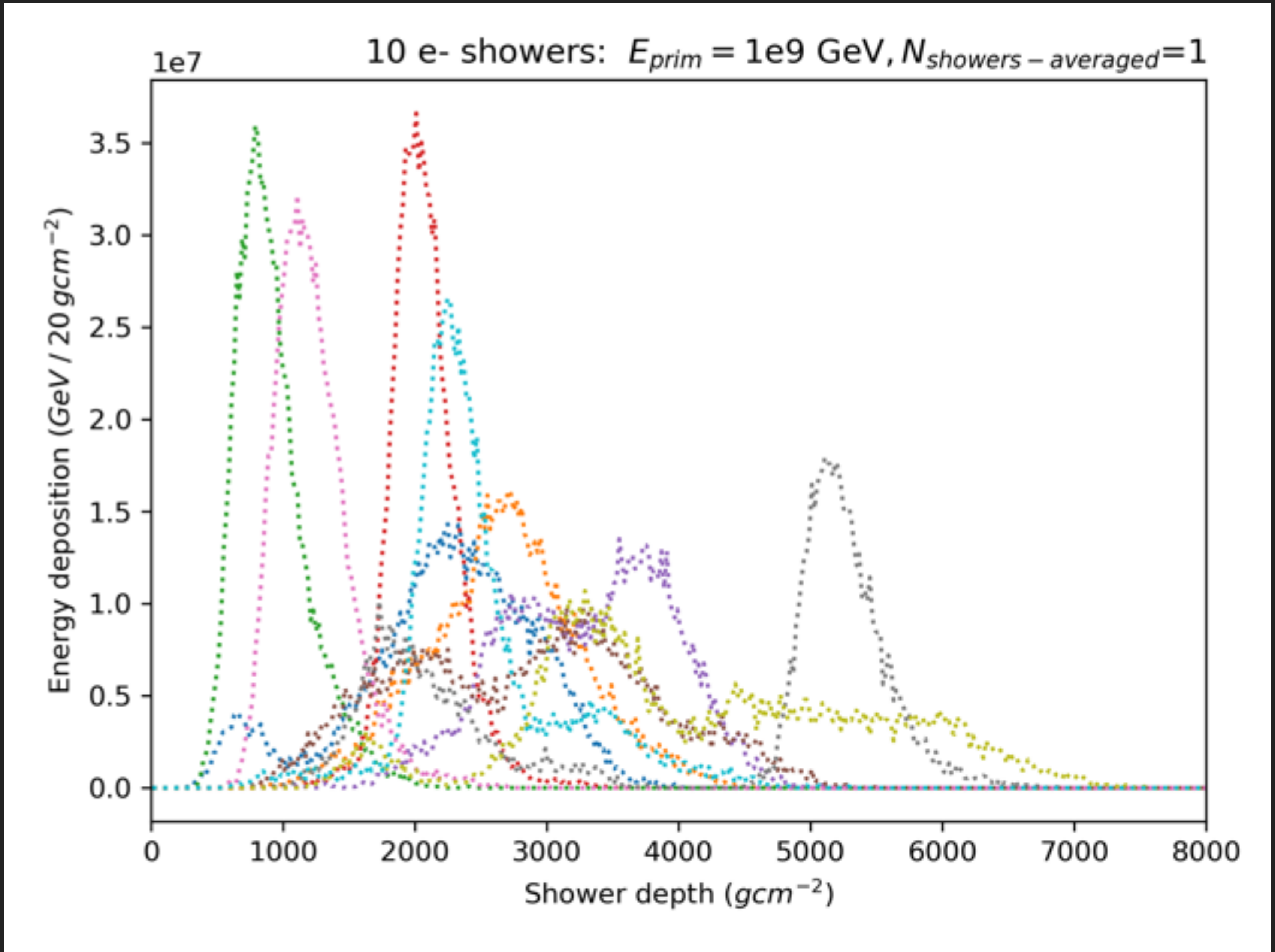

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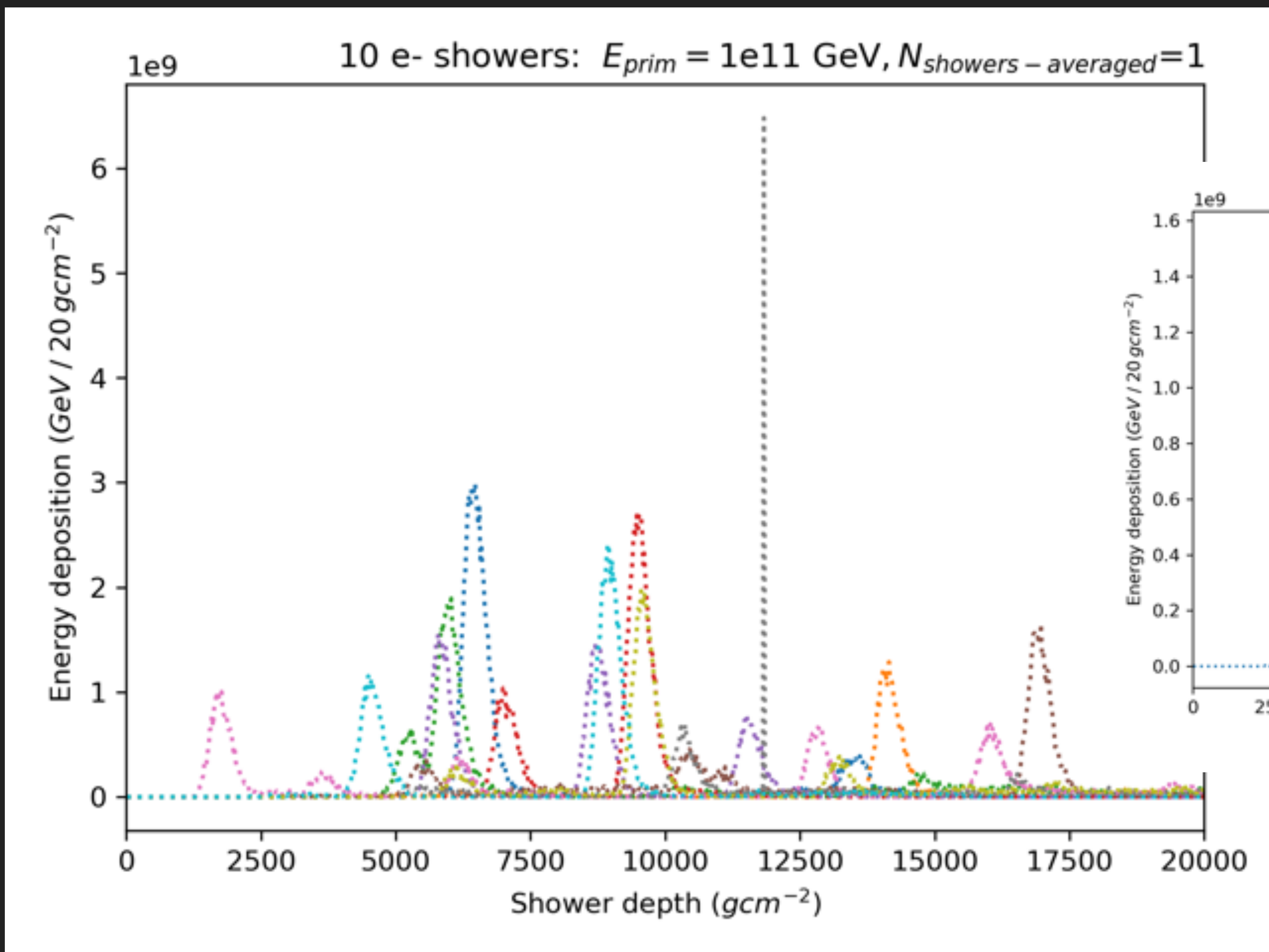

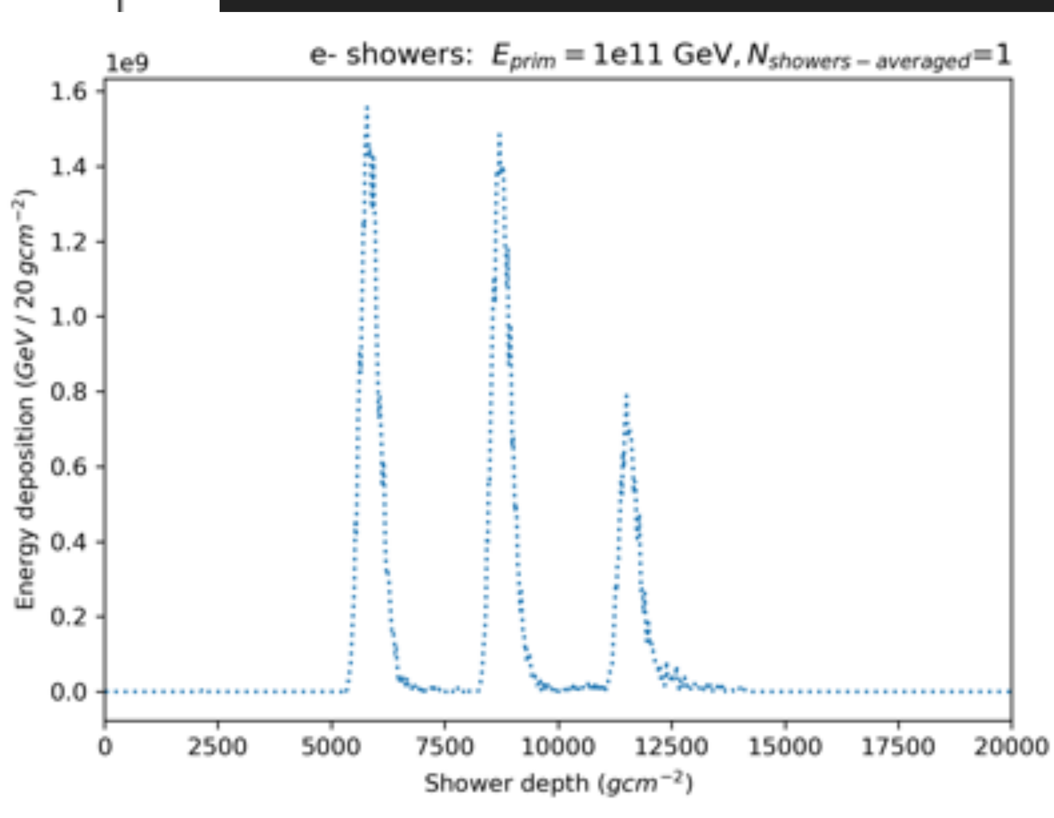

[Simulation CORSIKA-6600-IW]

1. Klein, S. Suppression of bremsstrahlung and pair production due to environmental factors. Rev. Mod. Phys. 71, 1501–1538 (1999).

2. Klein, S. R. Bremsstrahlung and Pair Creation: Suppression Mechanisms and How They Affect EHE Air Showers. (2000).

3. Migdal, A. B. Bremsstrahlung and pair production in condensed media at high energies. Phys. Rev. 103, 1811–1820 (1956).