The E in SEWM:

Extremely high-energy bremsstrahlung in ordinary matter

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reporting on work with

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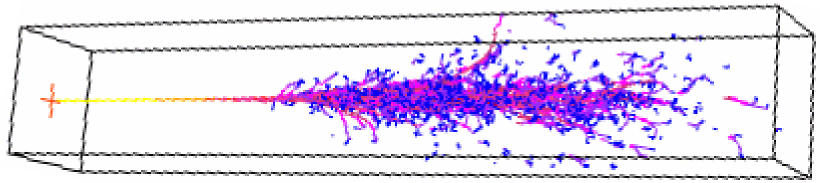
Shahin Iqbal

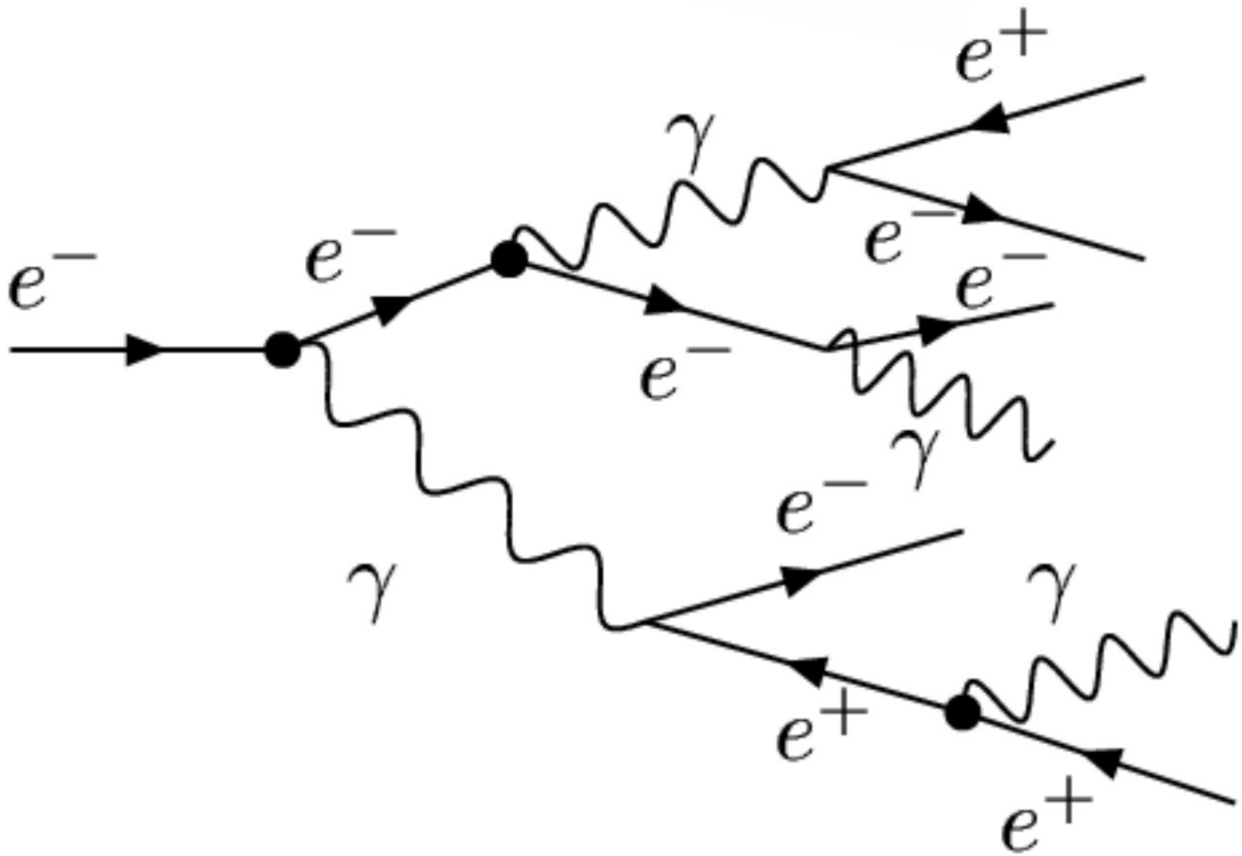
Omar Elgedawy

arXiv: 2604.18685 (letter/summary)
2408.07129 (part 1), 2605.03002 (part 2)

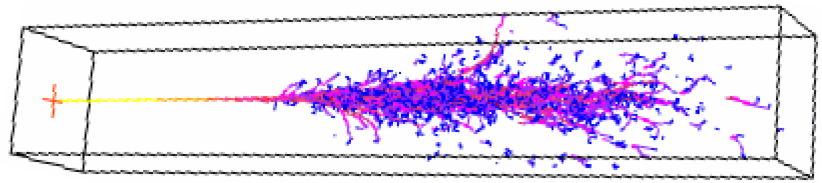
Electromagnetic showers

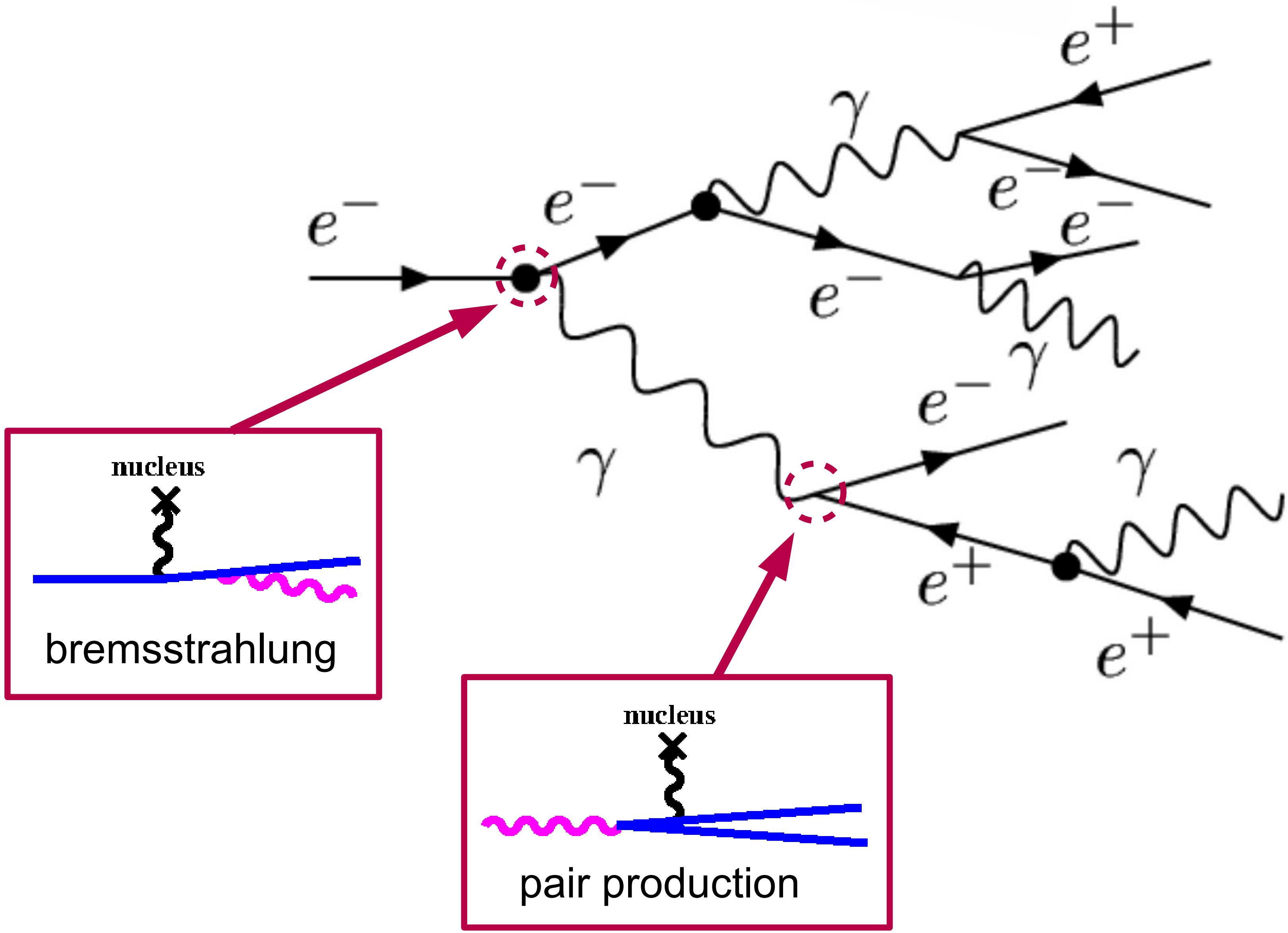


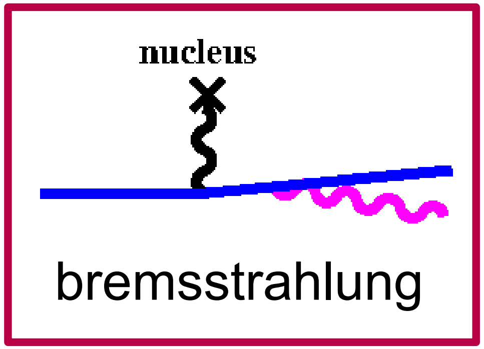
$$E \gg mc^2$$



Electromagnetic showers



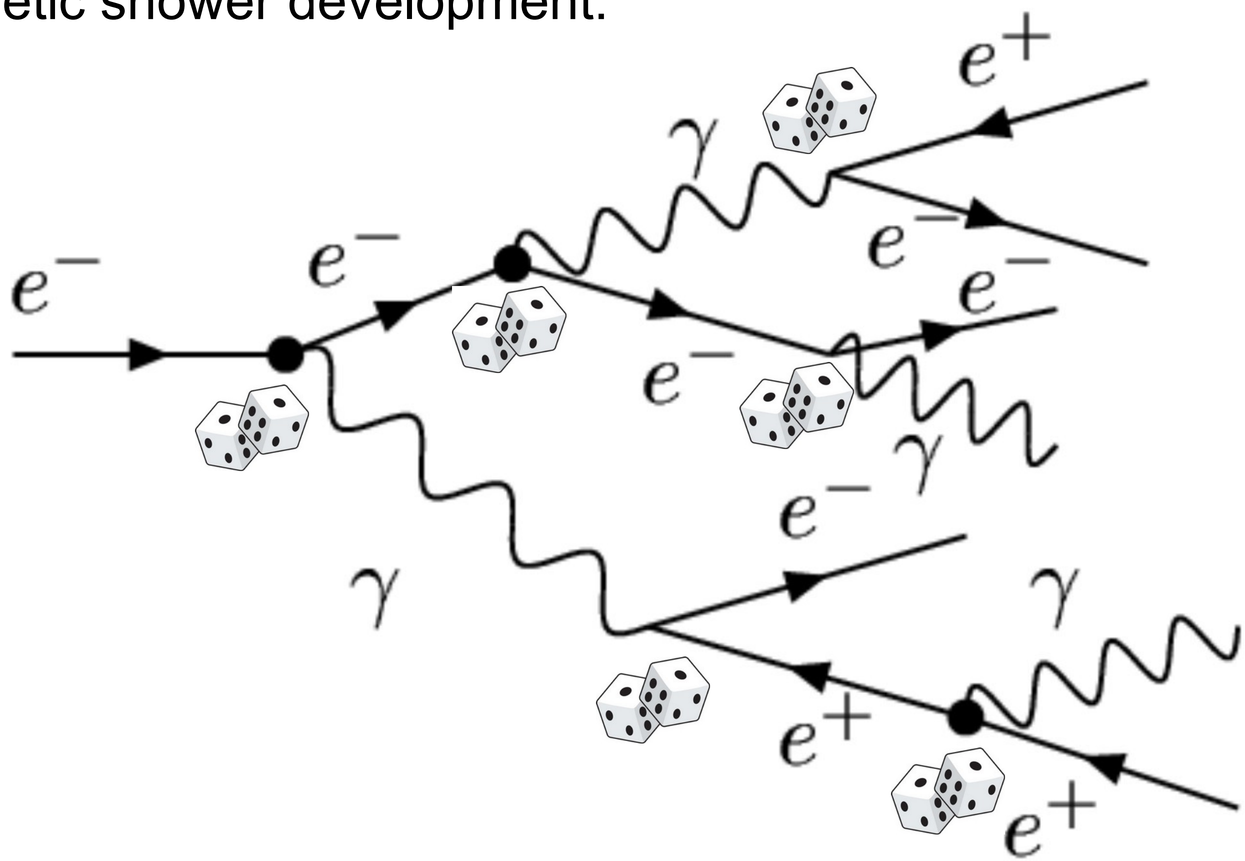


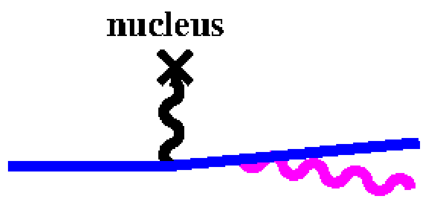


Probability computed by Bethe and Heitler in 1932.

YAY!

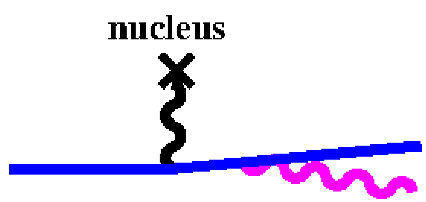
Use this and similar calculation of the pair-production rate to compute electromagnetic shower development:

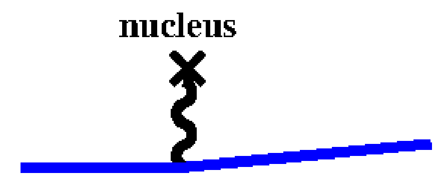




bremsstrahlung

Probability computed by Bethe and Heitler in 1932.

Prob (

) $\sim$ α Prob (

)

bremsstrahlung

scattering

[up to logarithms]

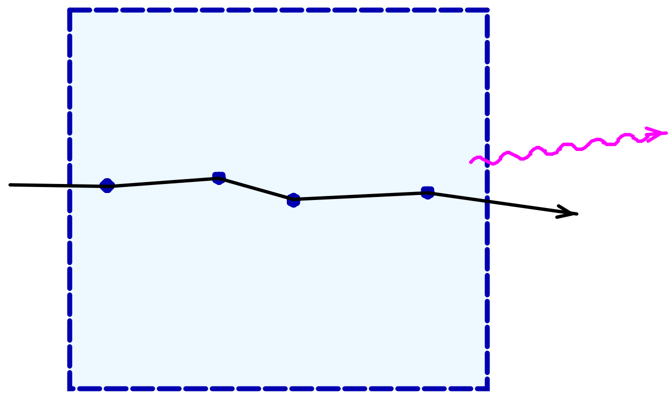
<u>The important thing for this talk</u>

Every scattering has an O(α) chance of generating bremsstrahlung

An important modification at very high energy:

the Landau-Pomeranchuk-Migal (LPM) effect
(1950s)

Consider consecutive collisions with the medium (air, ice, Gold target, whatever)



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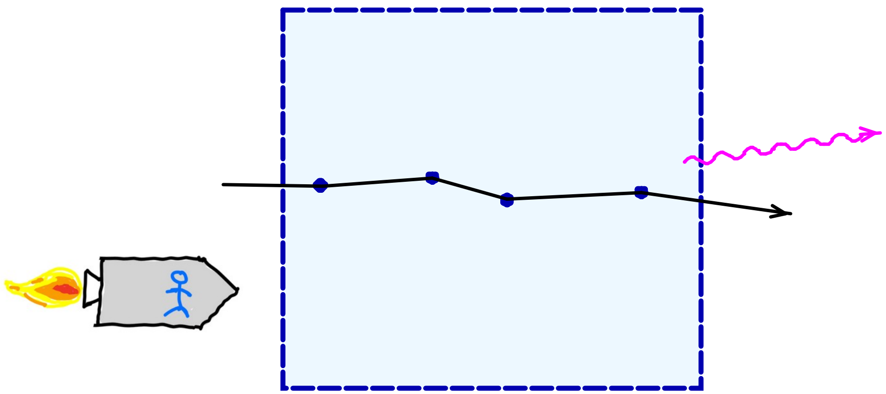
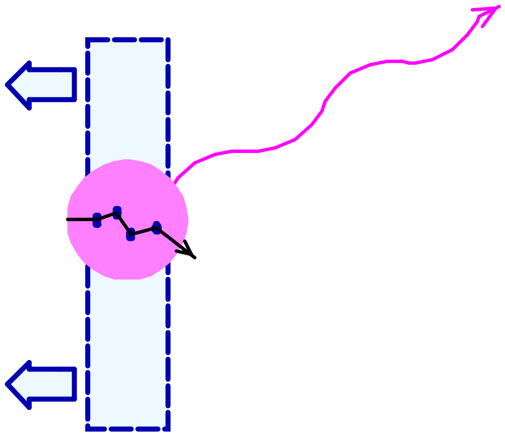
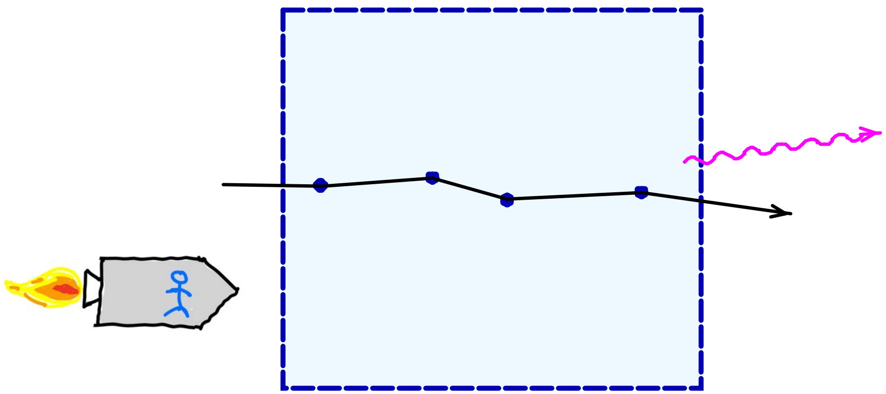


(lab frame)

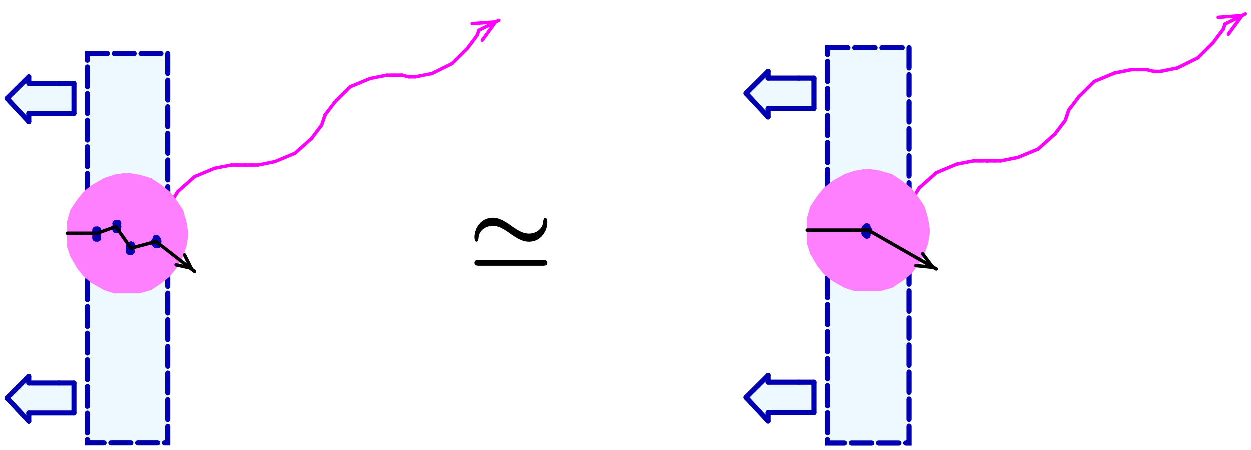


(rocket frame)

Consider consecutive collisions with the medium (air, ice, Gold target, whatever)



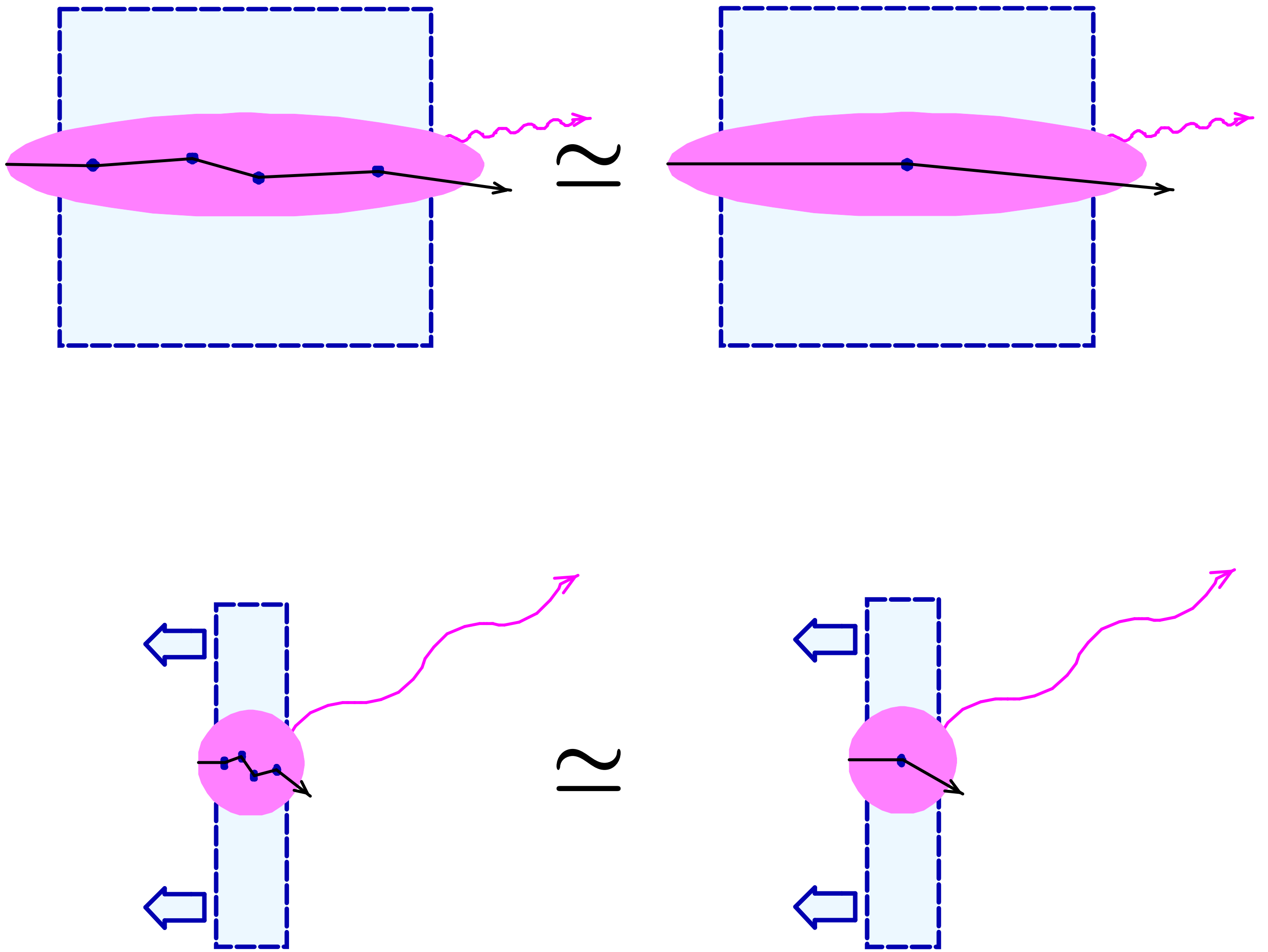
(lab frame)



(rocket frame)

Only 1 chance for bremsstahlung!

Consider consecutive collisions with the medium (air, ice, Gold target, whatever)



(lab frame)

(rocket frame)

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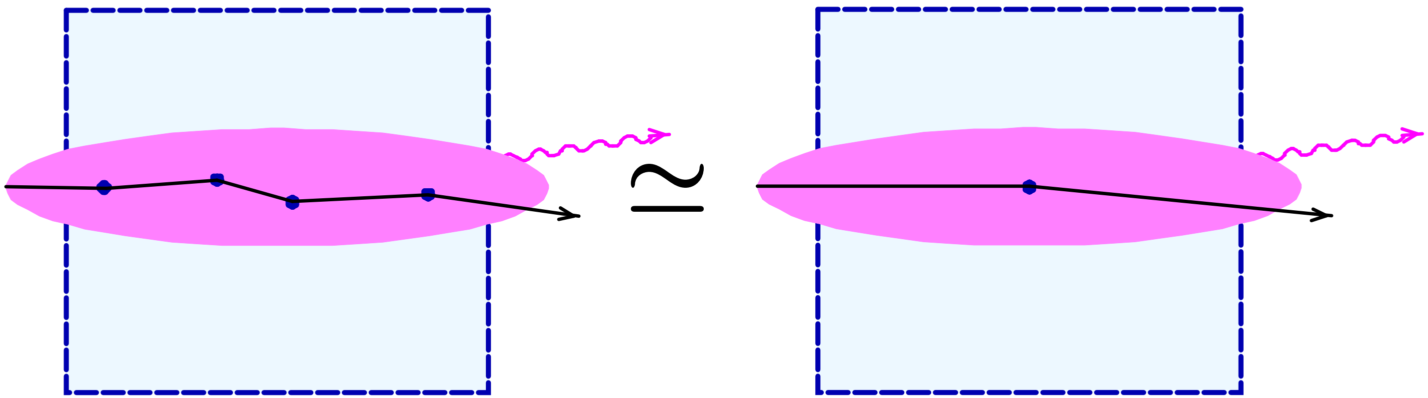


(lab frame)

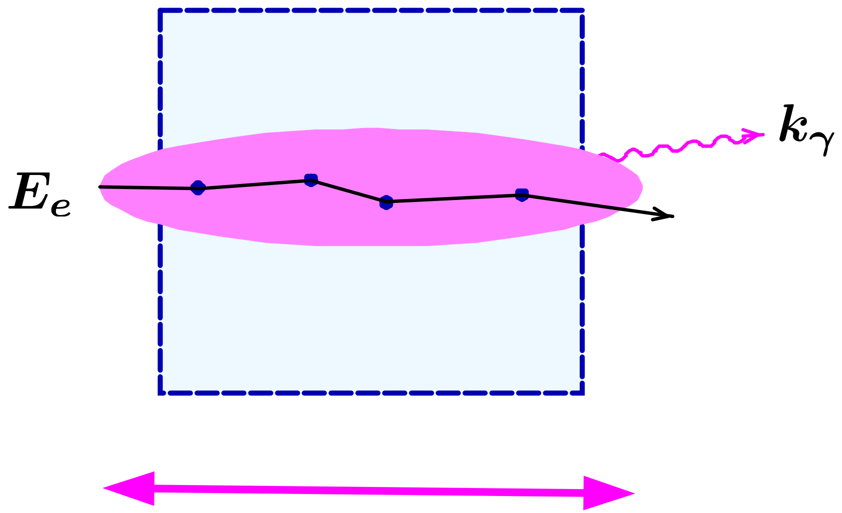
$\boxed{\text{Only 1 chance for bremsstrahlung!}}$

⇨ suppression of Bethe-Heitler (1932) bremsstrahlung rate!

Called the Landau-Pomeranchuk-Migal (LPM) effect.

1953: Landau-Pomeranchuk – classical calculation for soft bremsstrahlung $(k_\gamma \ll E_e)$

1955: Migdal – full quantum calculation (any k_γ)



(lab frame)

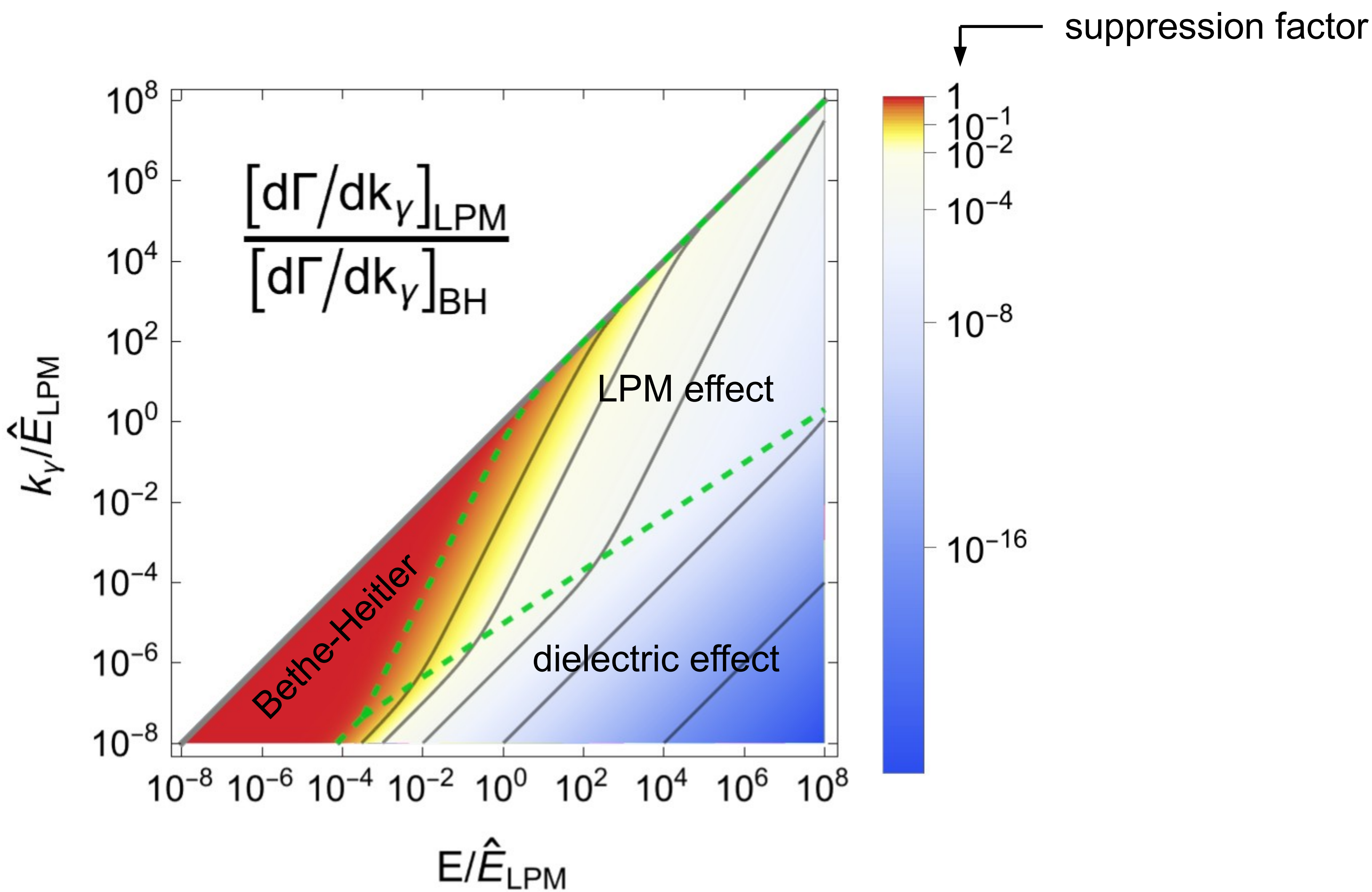
formation length
coherence length

formation (or coherence) time = (formation length) / c

= quantum duration of bremsstrahlung

formation length $\propto \dfrac{E_e}{\sqrt{k_\gamma}}$

bigger E_e
or smaller k_γ ⇒ more suppression



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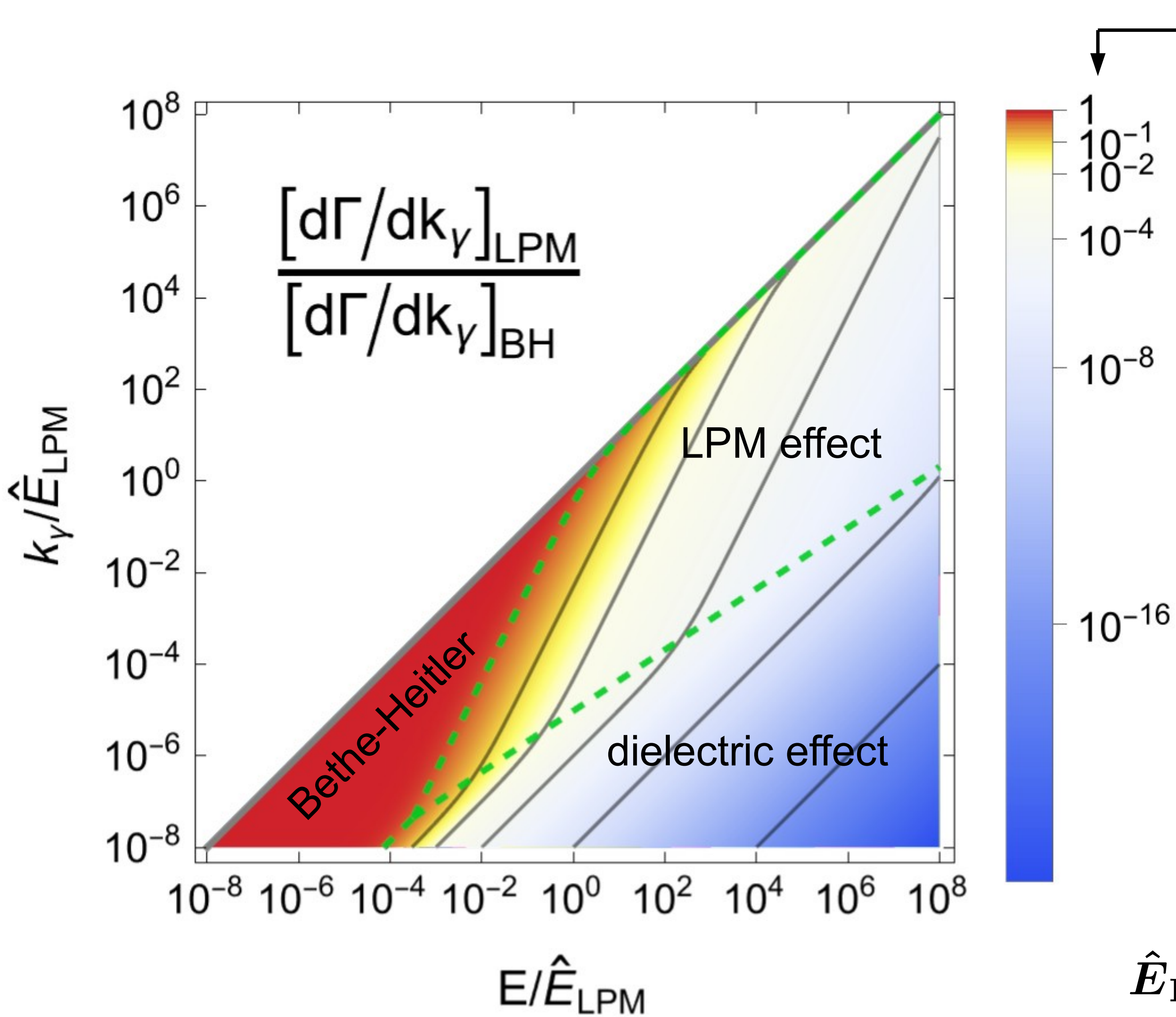
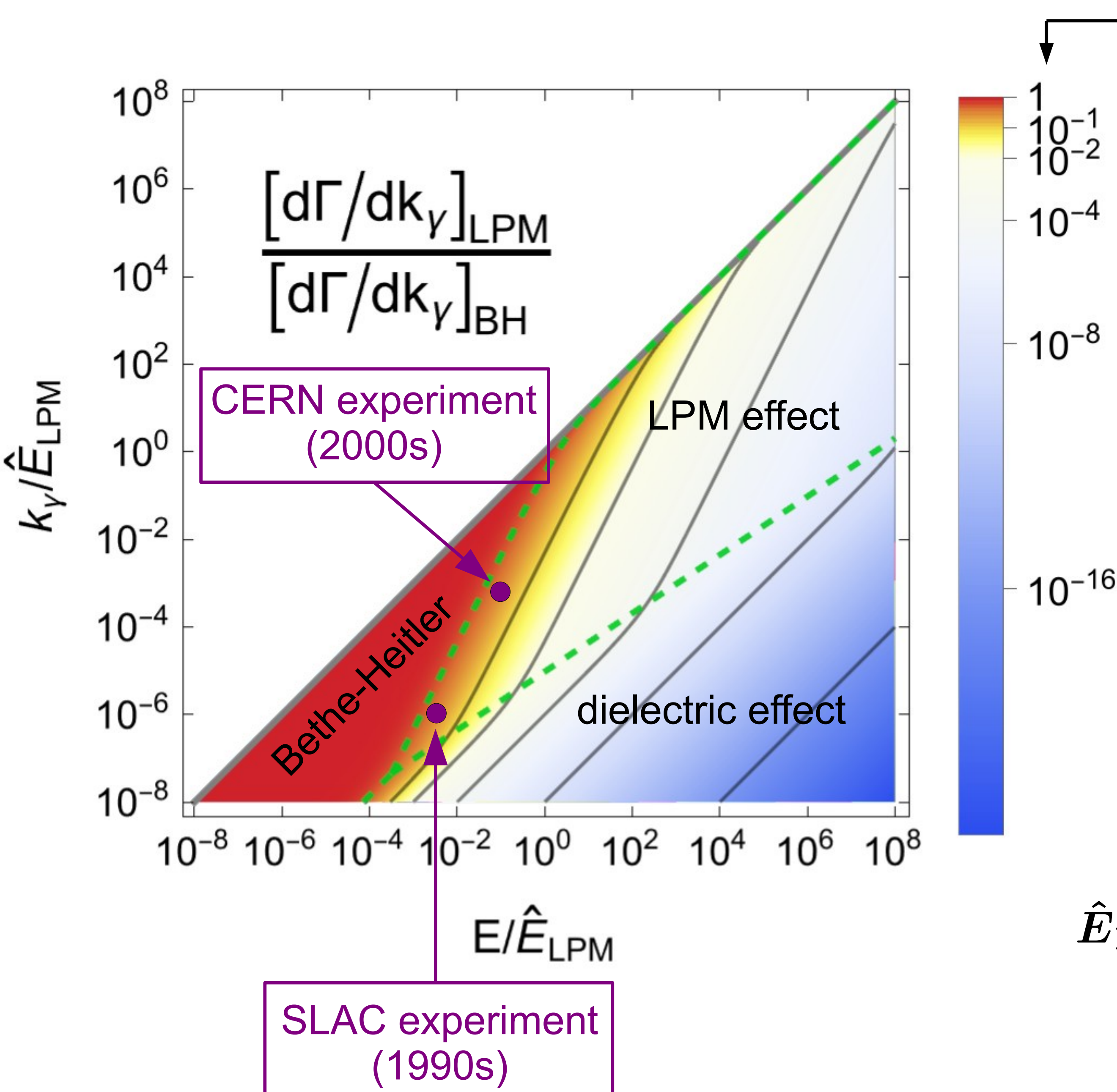


$\hat{E}_{\mathrm{LPM}} =$ 5 TeV (Gold)
154 TeV (std. rock)
568 PeV (air @ STP)

bigger E_e or smaller k_γ	→	more suppression



$$\hat{E}_{\mathrm{LPM}} = \begin{array}{l} \text{5 TeV (Gold)} \\ \text{154 TeV (std. rock)} \\ \text{568 PeV (air @ STP)} \end{array}$$

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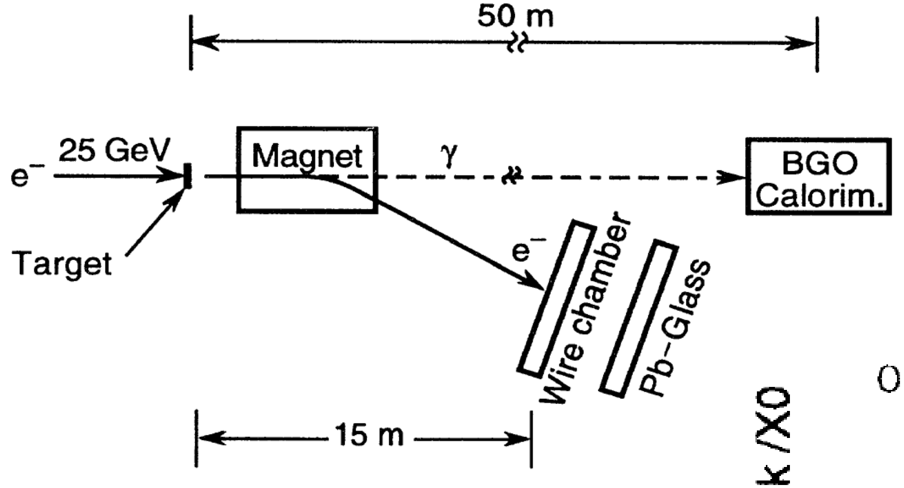
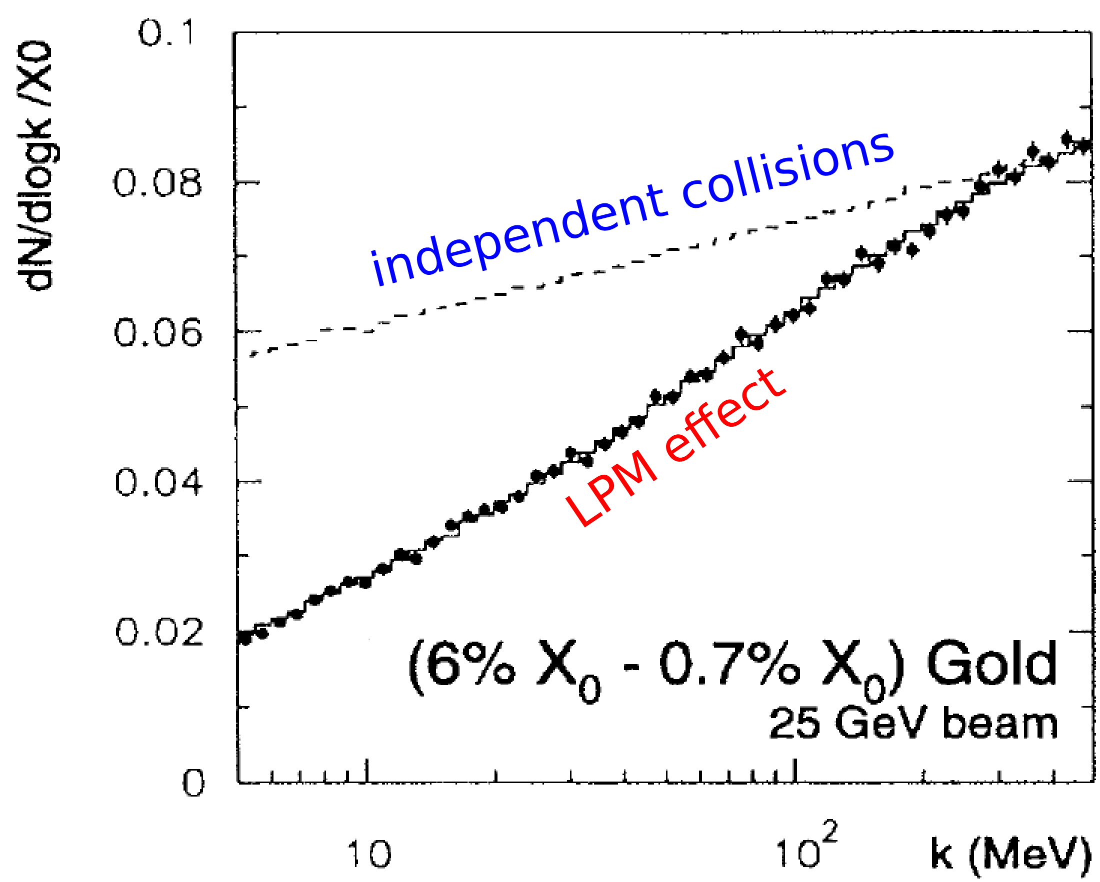
SLAC Measurement of LPM (QED)



SLAC E-146

Phys. Rev. Lett. **75** (1995) 1949.



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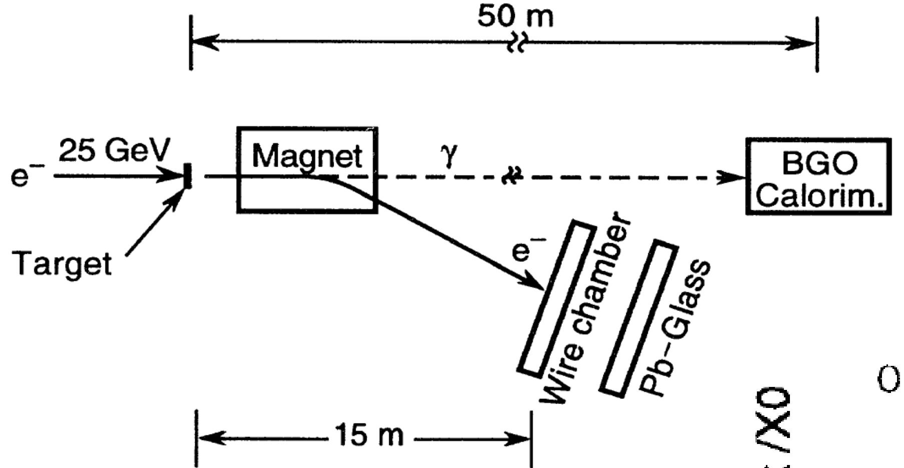

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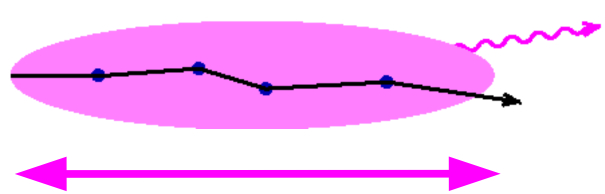
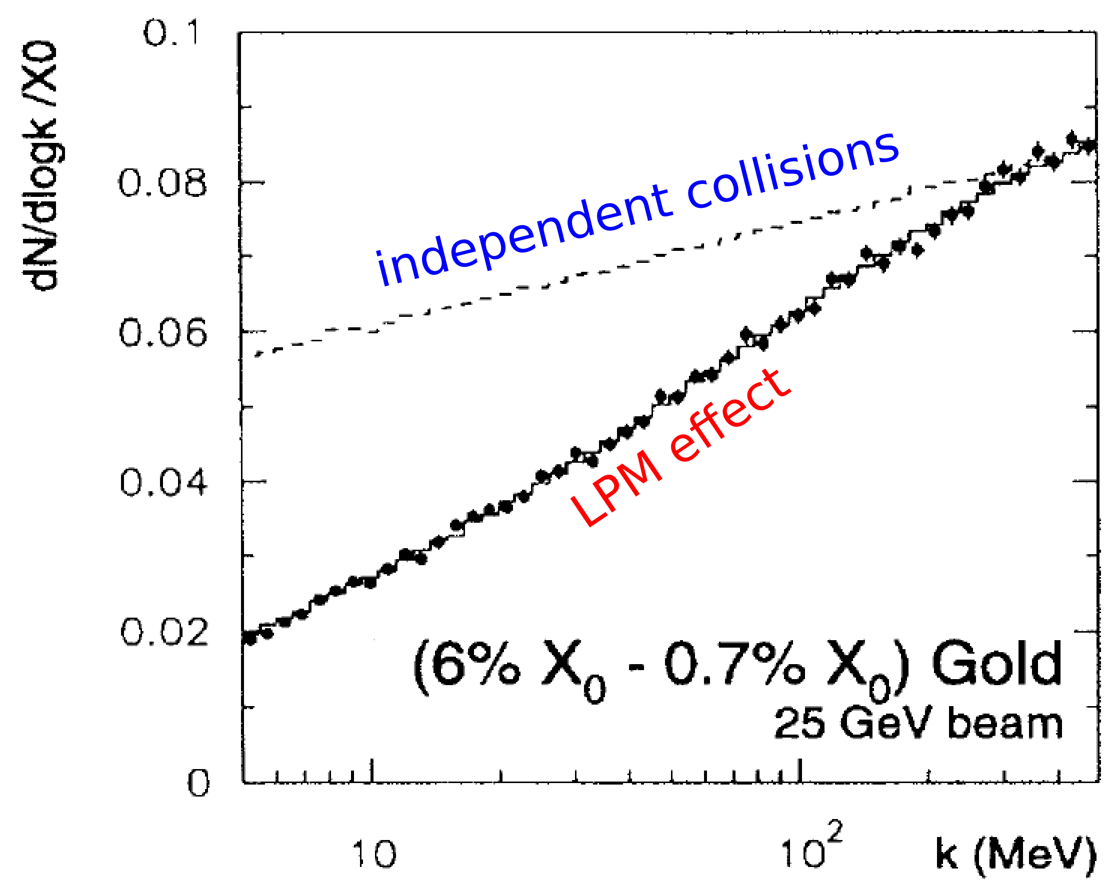
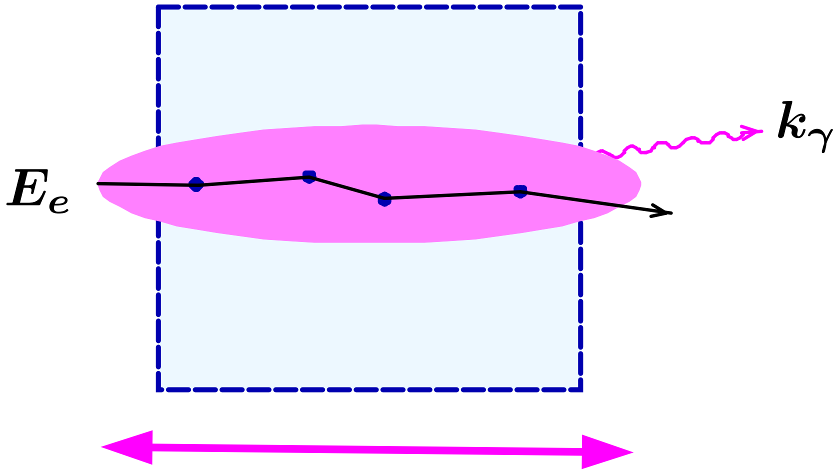


formation time ~ 0.01 mm



What's new to this story?

Earlier:

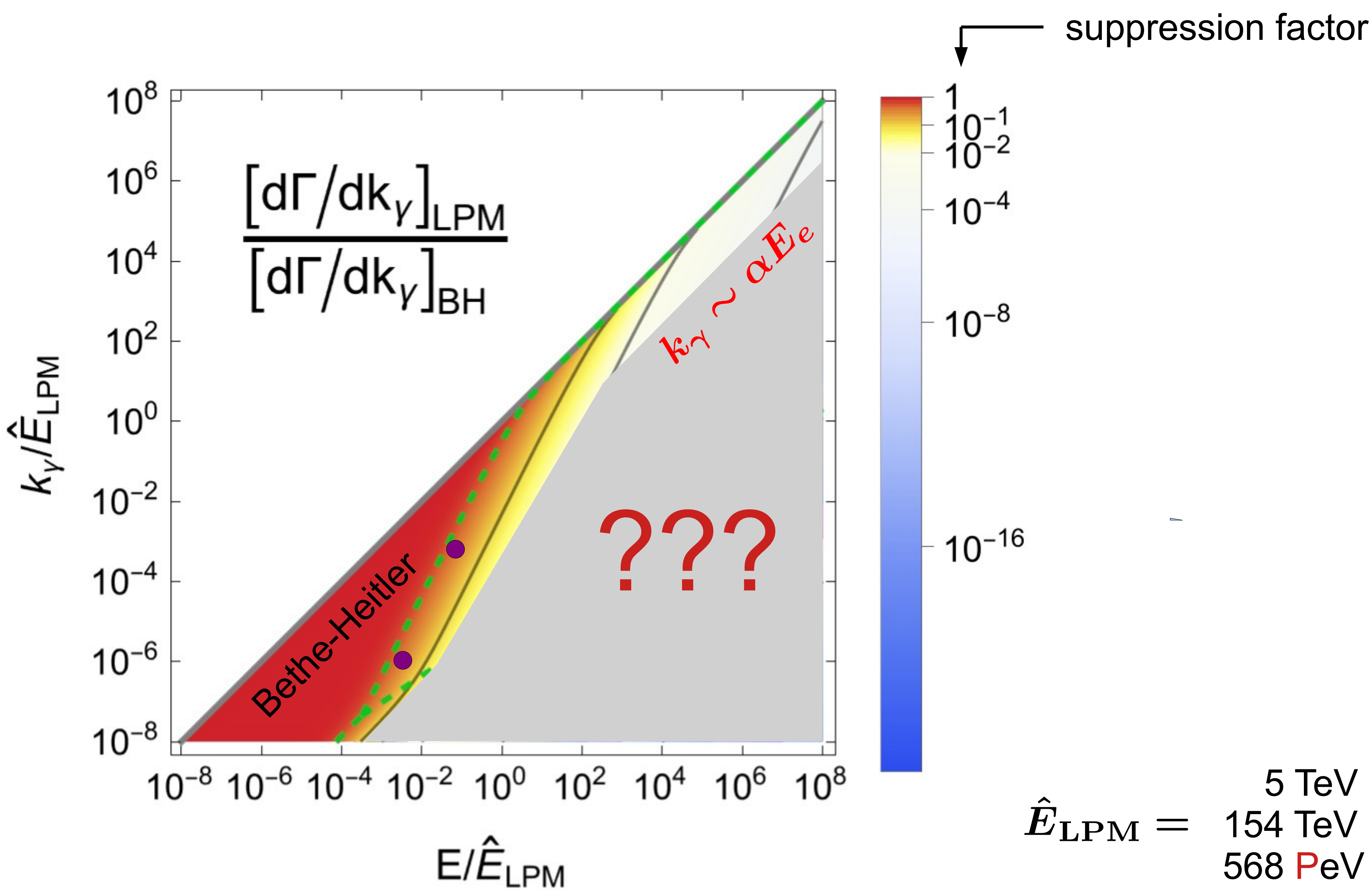


formation length

formation length $\propto \dfrac{E_e}{\sqrt{k_\gamma}}$

Q: Can bremsstrahlung formation time <u>also</u> overlap subsequent pair production?

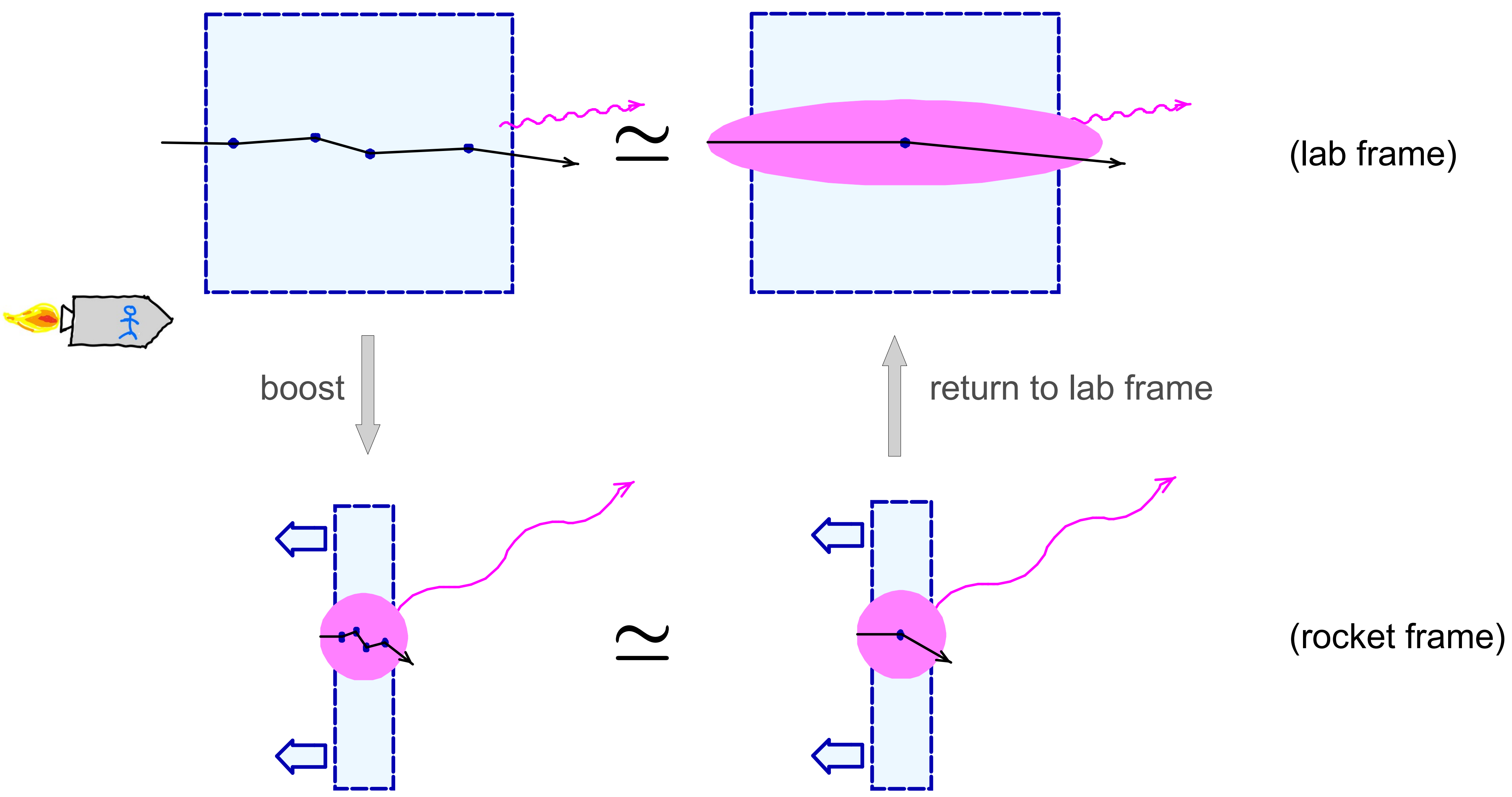
A: Yes...

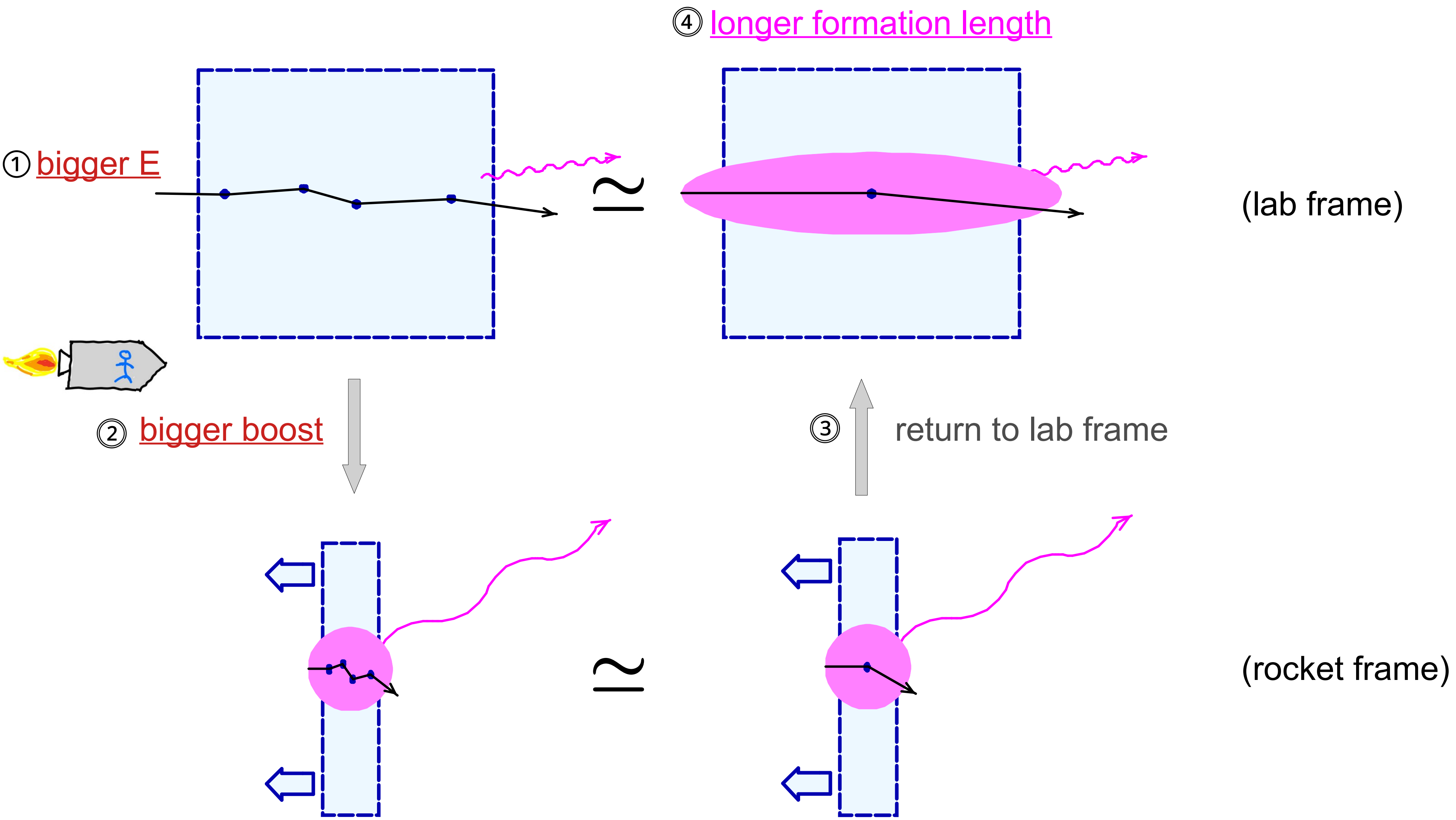


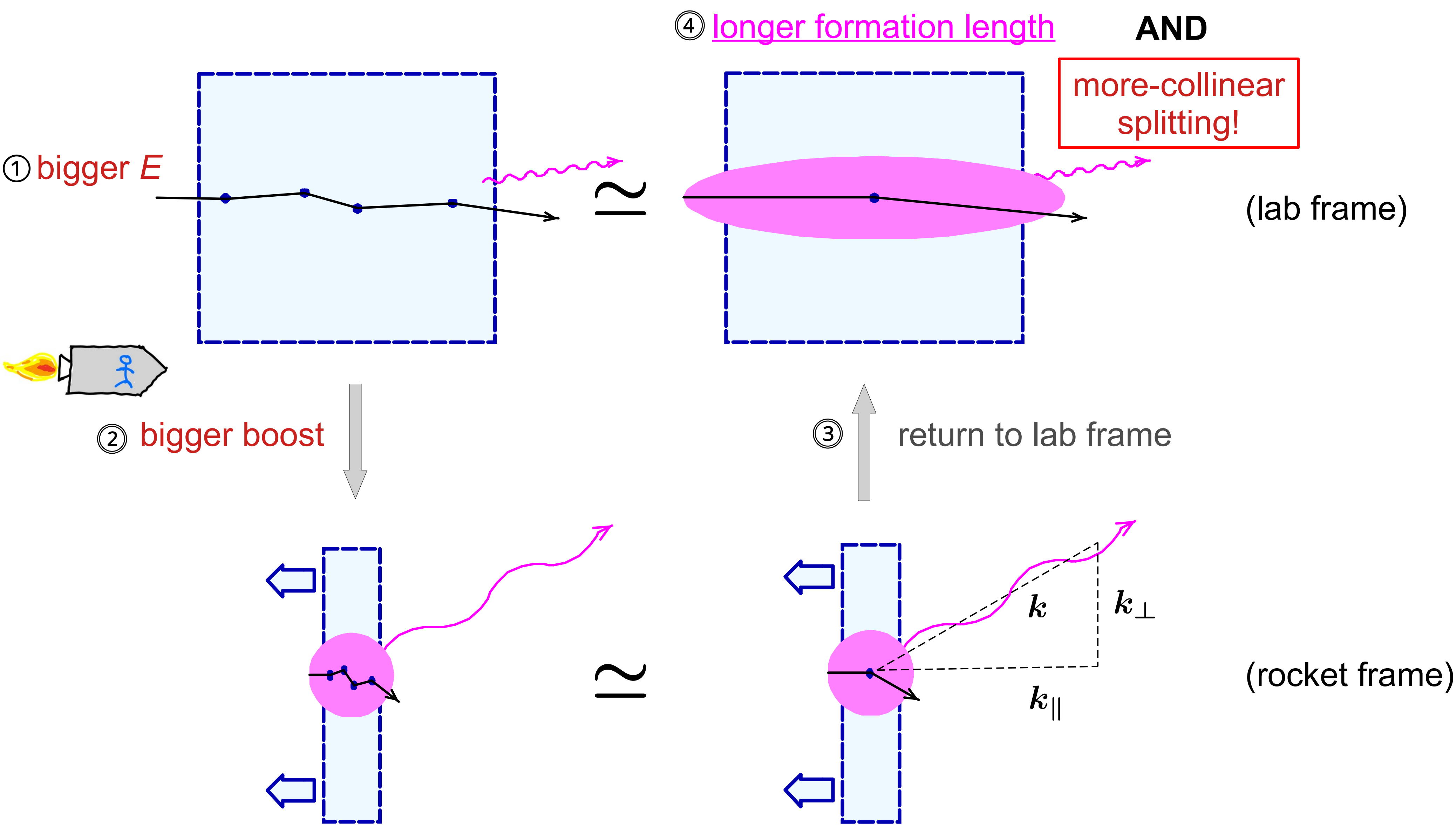
$$\hat{E}_{\mathrm{LPM}} = \begin{array}{l} \text{5 TeV (Gold)} \\ \text{154 TeV (std. rock)} \\ \text{568 PeV (air @ STP)} \end{array}$$

Note: Issue only arises for “soft” photon emission $(k_\gamma \ll E_e)$

Return to




④ longer formation length
① bigger E
$\simeq$
(lab frame)
② bigger boost
③ return to lab frame
$\simeq$
(rocket frame)



④ longer formation length
AND
more-collinear splitting!
① bigger E
≃
(lab frame)
② bigger boost
③ return to lab frame
$\boldsymbol{k}$
$\boldsymbol{k}_\perp$
$\boldsymbol{k}_\parallel$
≃
(rocket frame)

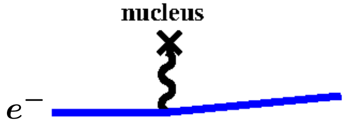
Qualitative take-away

more-collinear $e \to e\gamma$ ⟺ longer formation length

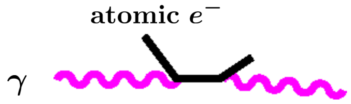
less-collinear $e \to e\gamma$ ⟺ shorter formation length

Relevant because

1. To first approximation: high-energy electrons get kicks from the medium;
   high-energy photons don't



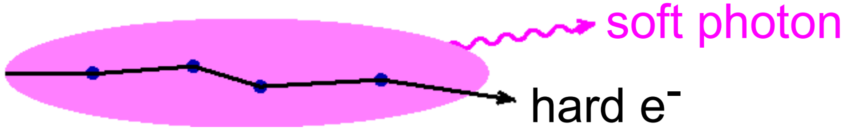
vs.



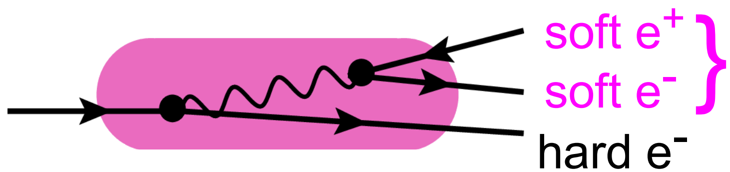
action at a distance! photons have to hit something

2. The same kick will deflect a low-energy electron more than a high-energy one.

Normal LPM in case of soft photon emission $(k_\gamma \ll E_e)$



Overlapping pair production $(k_\gamma \ll E_e)$



deflected easily! ⇒ shorter formation length

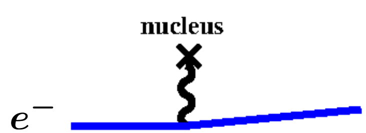
⇒ less LPM suppression

⇒ larger rate!

less-collinear $e \to e\gamma$ ⇔ shorter formation length

Relevant because

1. To first approximation: high-energy electrons get kicks from the medium; high-energy photons don't



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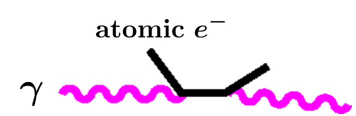
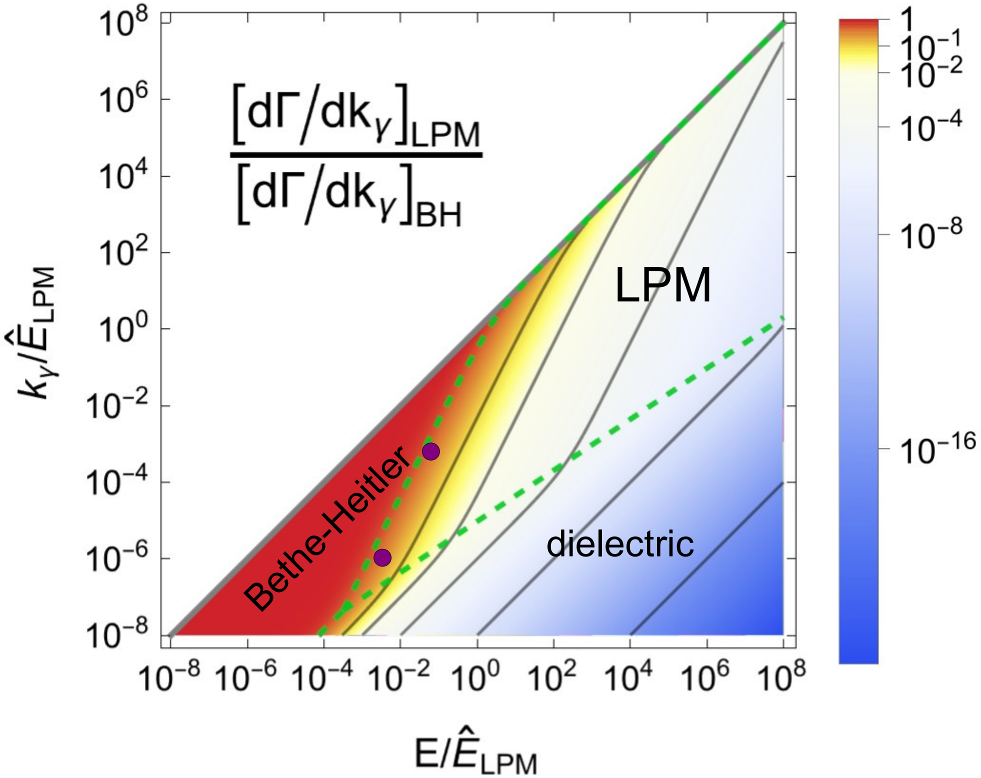


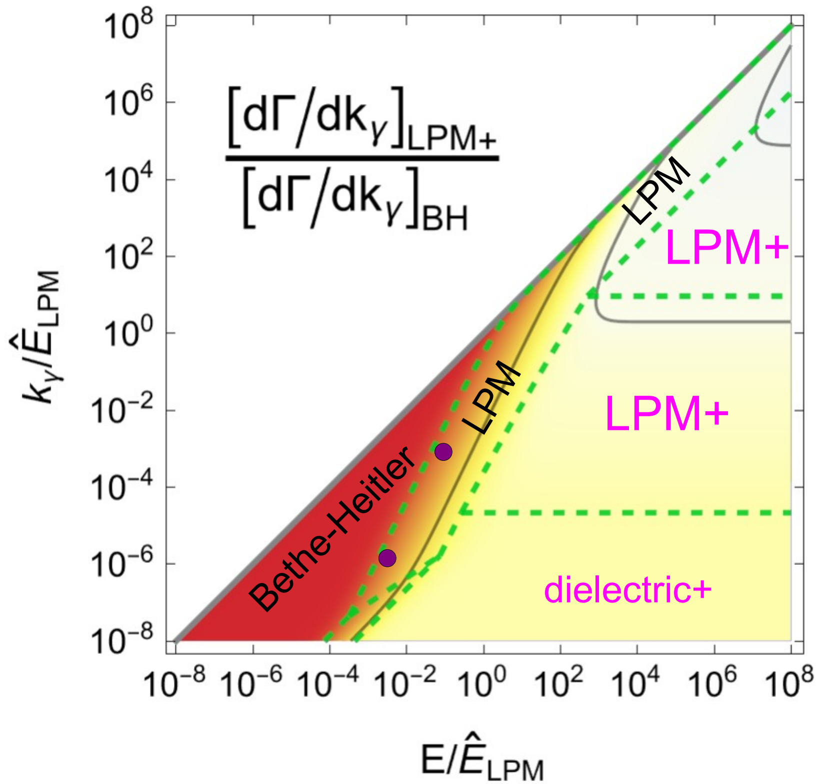
action at a distance!   photons have to hit something

2. The same kick will deflect a low-energy electron more than a high-energy one.

original LPM theory (1953)

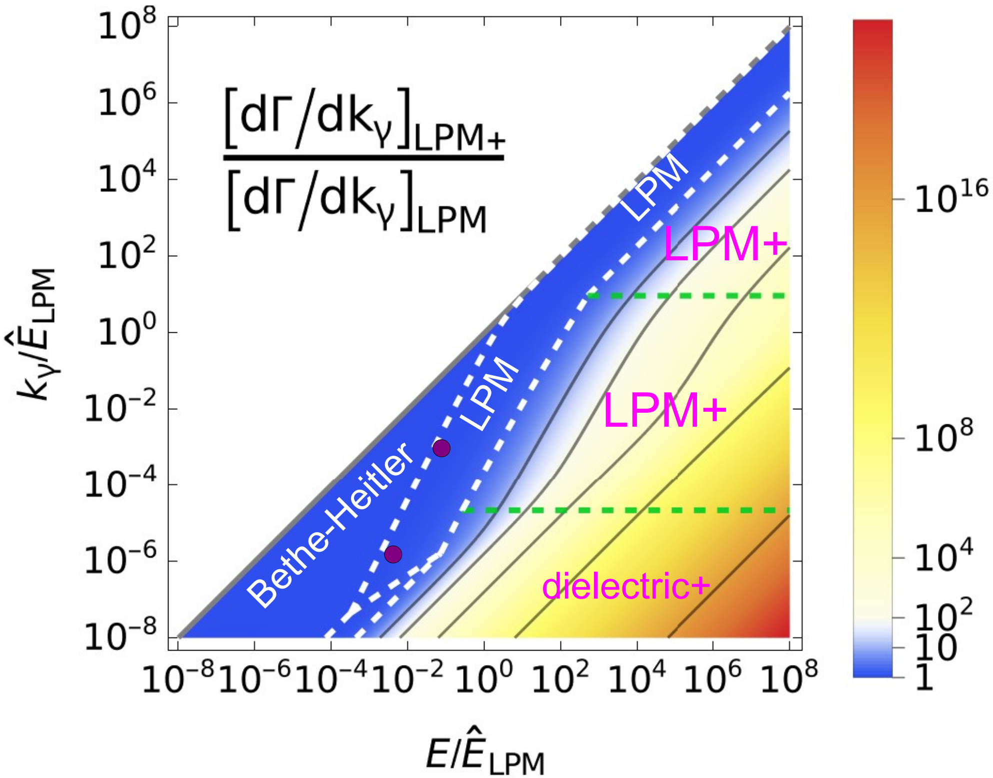


now (LPM+) w/ overlapping pair production included (2025)



Much bigger rates for soft photon emission than LPM calculation.

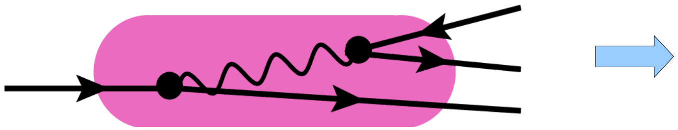
Enhacement LPM+/LPM of our rate compared to 1953 rate (LPM)



Much bigger rates for soft photon emission than LPM calculation.

But I've left some history out of this story ...

Overlapping pair production $(k_\gamma \ll E_e)$



shorter formation length

This was already pointed out by V. M. Galitsky and I. I. Gurevich in **1964** !

But...

Overlapping pair production $(k_\gamma \ll E_e)$

⇒ shorter formation length

This was already pointed out by V. M. Galitsky and I. I. Gurevich in **1964** !

But... they thought this would have the opposite effect:

soft photon emission rate $\ll$ original LPM rate (Galitsky & Gurevich)

instead of

soft photon emission rate $\gg$ original LPM rate (us)

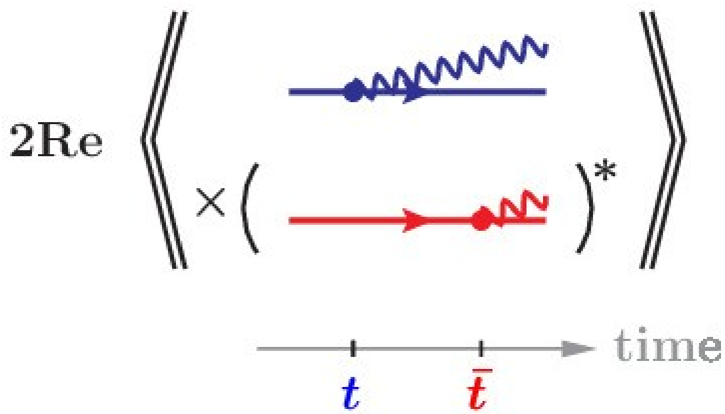
How can we know who's right? ...

Do an actual calculation.

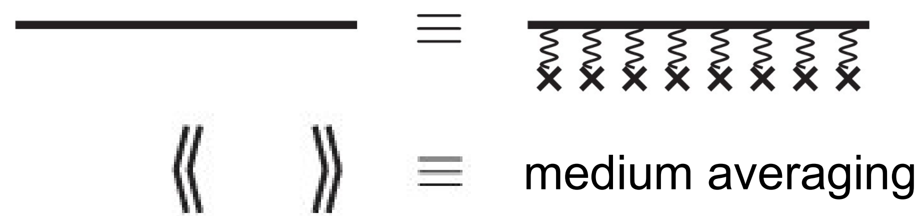
Generalize the calculation methods Migdal used to *also* include overlapping pair production.

Made possible by extending techniques originally developed for similar questions for QCD showers inside quark-gluon plasmas.

Calculating ordinary LPM bremsstrahlung

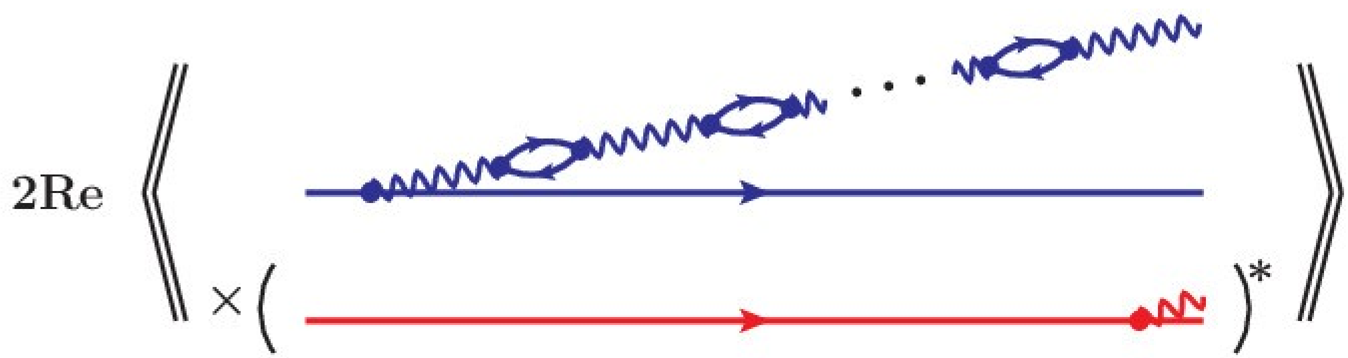


where



and old-fashioned time-ordered perturbation theory *much* (!!) easier than Feynman pert. th,

Calculating LPM+ bremsstrahlung

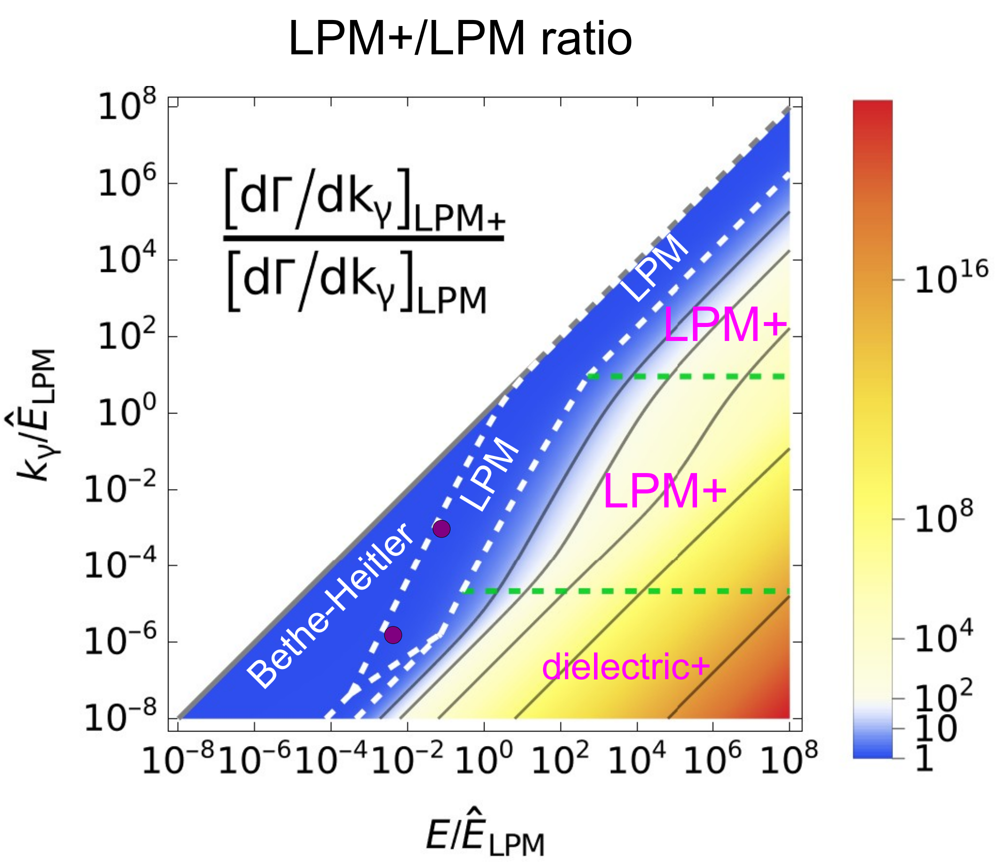


Physically, including the virtual pair production loops

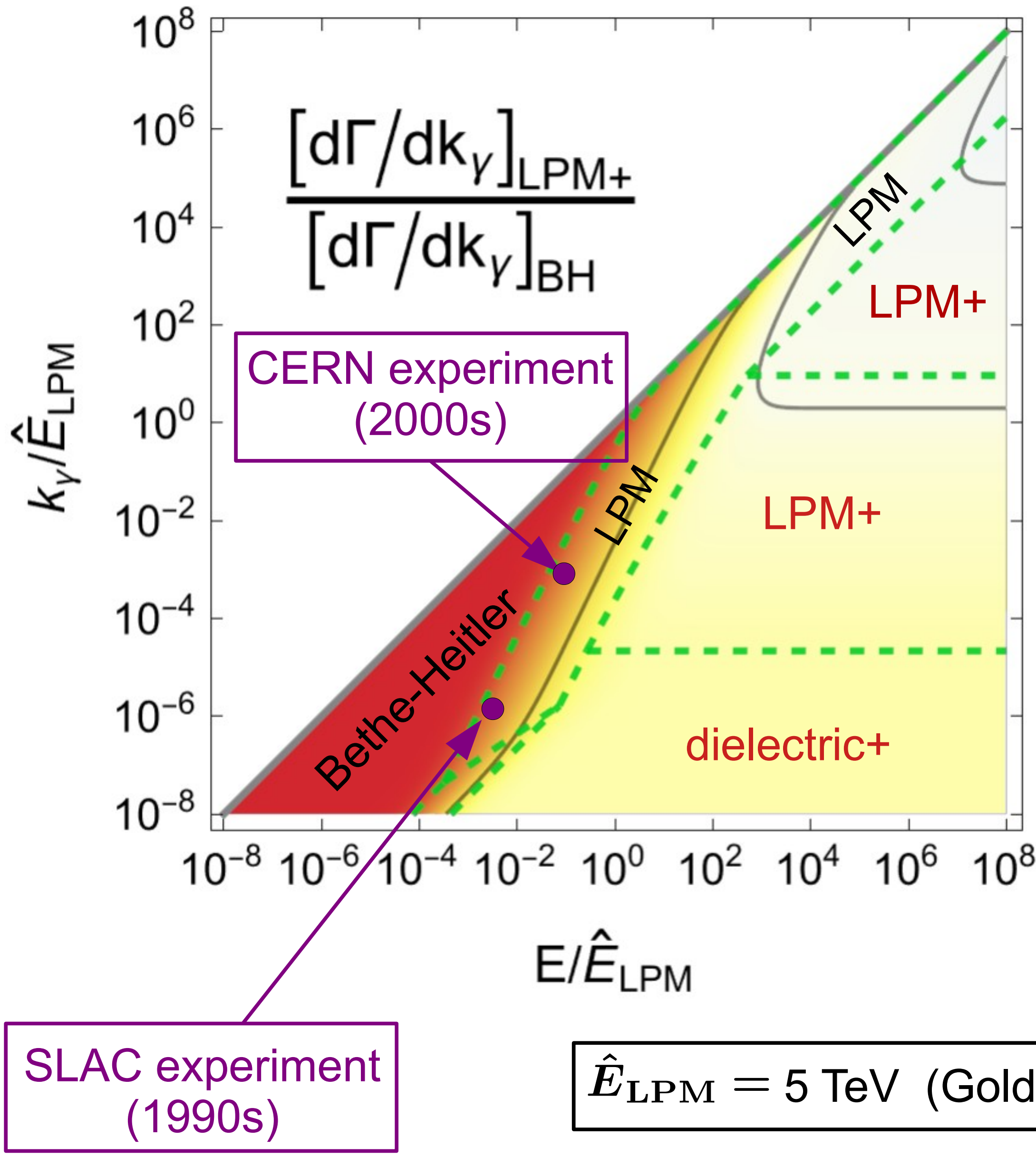
- ⇨ restricts brem duration $\lesssim$ time before real pair production
- ⇨ the LPM+ effect

A long formula I won't inflict on you

but kinda fun because involves obscure special functions related to the Riemann zeta function. ☺

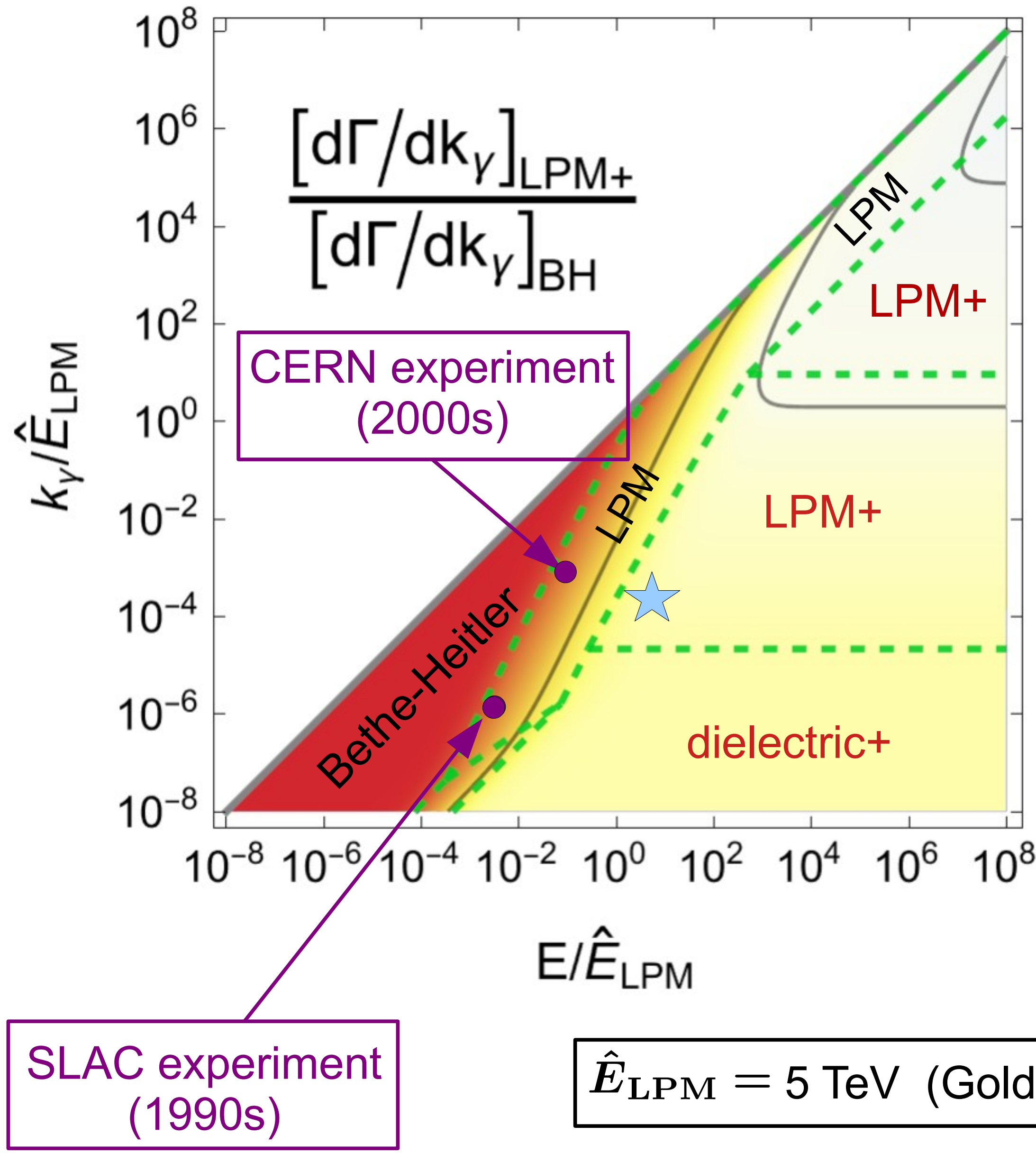


Could we ever check LPM+ with an experiment?



$\hat{E}_{\mathbf{LPM}} = 5$ TeV (Gold)

For *example*: could we up the CERN experiment energy E by a factor of 100?



$\hat{E}_{\mathrm{LPM}} = 5$ TeV (Gold)

CERN experiment (2000s) used

~300 GeV electron beam

created from a

~400 GeV proton beam

from the SPS proton accelerator (now the pre-accelerator for the LHC)

Proposals (FCC-hh) for a future proton accelerator at CERN imagine 50 TeV proton beams.