Restrictive scenarios from Lorentz Invariance Violation to cosmic-γ rays propagation

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Standar Model

The SM is a **quantum field theory** with the following characteristics

- Particle Content (bosons, fermions;Q,L, …, scalars)
- Gauge Group: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- *Re-normalizable* ($d=4$, $\hbar = c = 1$)
- **Lorentz Invariant** (space-time). A physical system is said to have Lorentz Symmetry if the relevant laws of physics are unaffected by Lorentz transformations. $\longrightarrow$ Lorentz scalar
- **CPT invariant.** A system is said to have CPT Symmetry if the physics is unaffected by the combined transformations CPT.

what if…?

$\longrightarrow$ VHE…

Lorentz Symmetry SO (3,1)

Lorentz Group → SO(3)

Lorentz Group → Boost

Lorentz Violation

- **Generic:**
  Relatively easy to use, quick results; not fundamental, conservation laws?

- **Spontaneous symmetry breaking:**
  Preserve all the properties that we like from the SM.
  Bjorken'63. Nambu'68.

Generic LIV

1. Add a non Lorentz invariant term to a generic free particle Lagrangian

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - \mu^2 \phi^* \phi + \epsilon \partial_i \phi \partial^i \phi \quad (+\epsilon \partial_0 \phi \partial^0 \phi)$$

2. Check the dispersion equation. (For p or E)

$$\Longrightarrow \quad E^2 - (1+\epsilon)p^2 - m^2 = 0,$$

3. Since the LIV contributions are small, expand in Taylor form

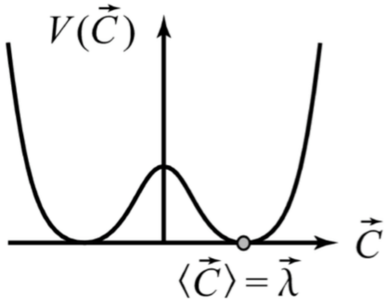
$$E^2 - p^2 - m^2 = p^2 \left(\epsilon'(0) \cdot \frac{p}{M} + \epsilon'(0) \cdot \left(\frac{p}{M}\right)^2 + \dots \right)$$

4. Use very high energy limit. Then $A := \{E, p\}$. Keep only one term at time $n = 1, 2, \ldots$

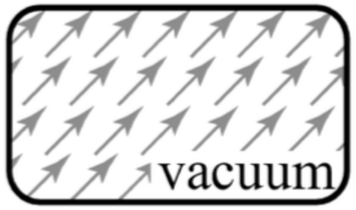
General LIV dispersion equation:

$$E^2 - p^2 = m^2 - \alpha_n A^{n+2}, \quad \alpha_n := \epsilon^{(n)}/M^n \approx 1/M^n$$

LIV Spontaneous Symmetry Breaking



1. Select an SM $\mathcal{L}$ sector:

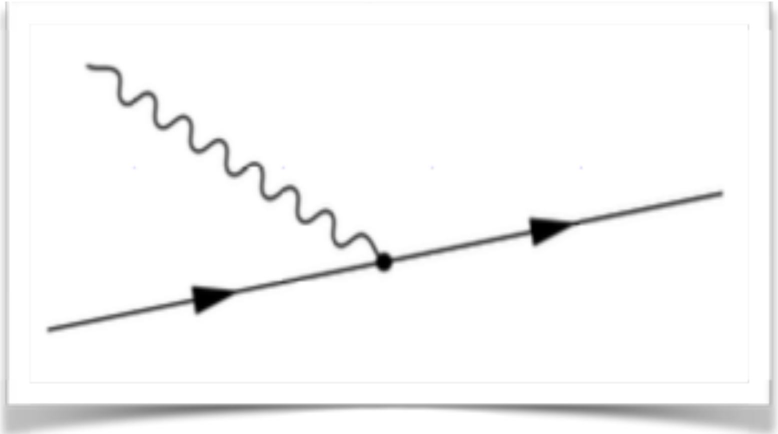


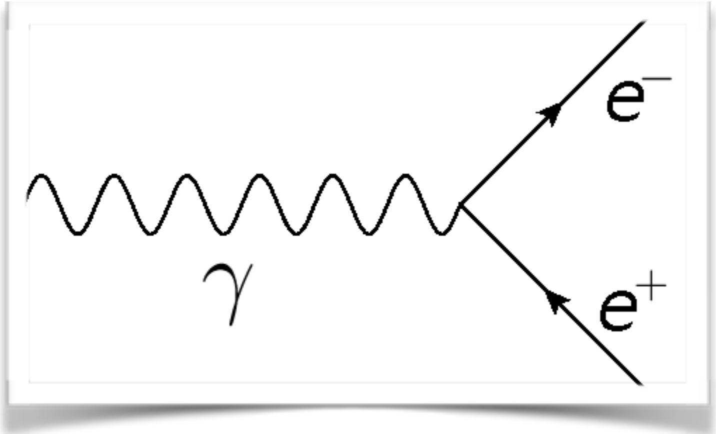
$$\mathcal{L}^{SM}_{photon} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (+\mathcal{L}_{Dirac})$$

2. Add SME terms

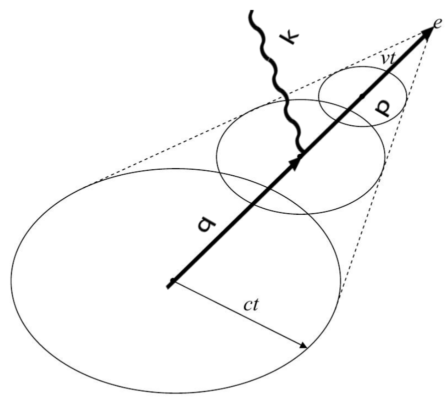
$$\mathcal{L}^{CPT-even}_{photon} = -\frac{1}{4}(k_F)_{\rho\lambda\mu\nu}F^{\rho\lambda}F^{\mu\nu} \qquad \mathcal{L}^{CPT-odd}_{photon} = \frac{1}{2}(k_{AF})^{\rho}\epsilon_{\rho\lambda\mu\nu}A^{\lambda}F^{\mu\nu}$$

3. Phenomenology





Vacuum Cherenkov Radiation

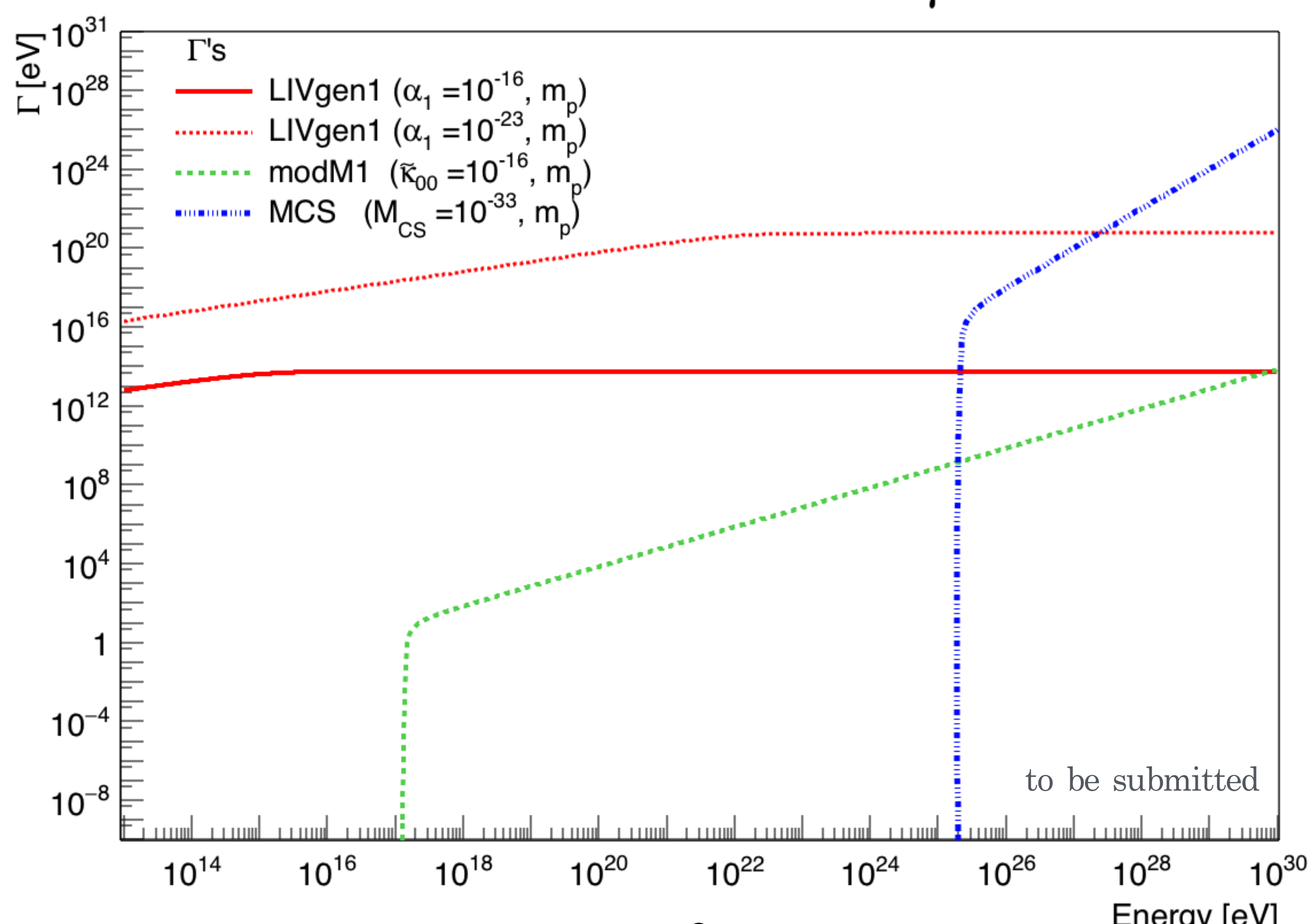


SSB $\mathcal{L}^{CPT-even}_{photon}$ $\mathcal{L}^{CPT-odd}_{photon}$

Generic $\omega^2 = k^2(1+\alpha_n k^n)$

$$d\Gamma = \frac{S}{2}\frac{1}{E(q)}\,|\,\mathbf{M}\,|^2\,\frac{d^3p}{(2\pi)^3 2E_p(p)}\,\frac{d^3k}{(2\pi)^3 2\omega(k)}(2\pi)^4\delta^{(4)}(q-p-k)$$

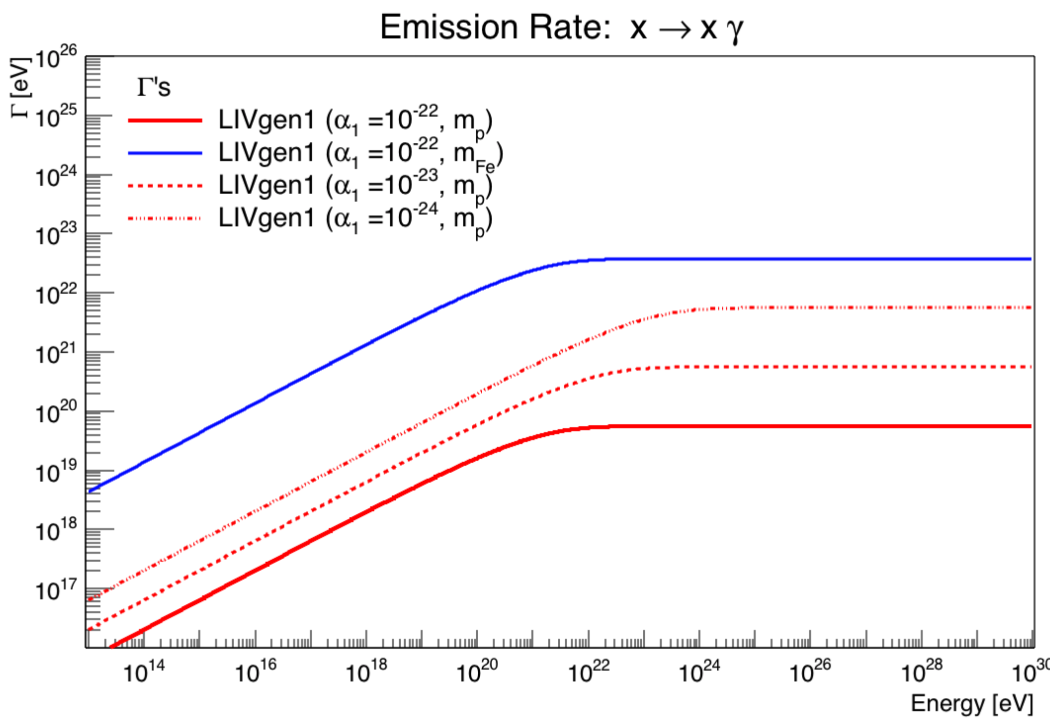
Emission Rate: x → x γ

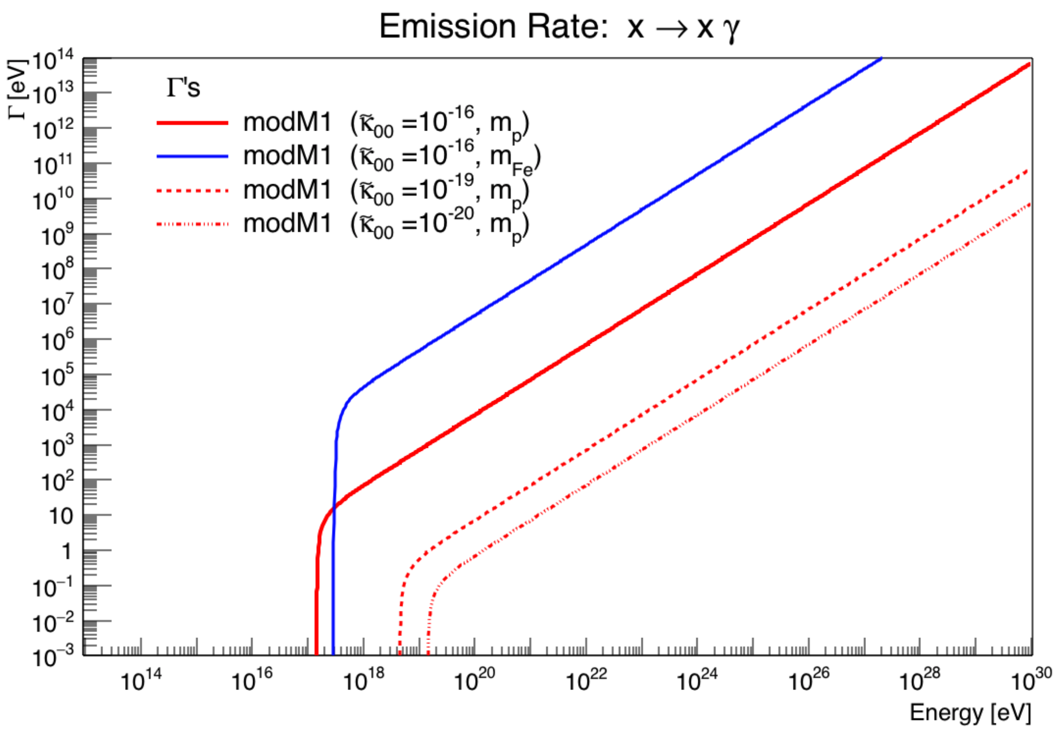


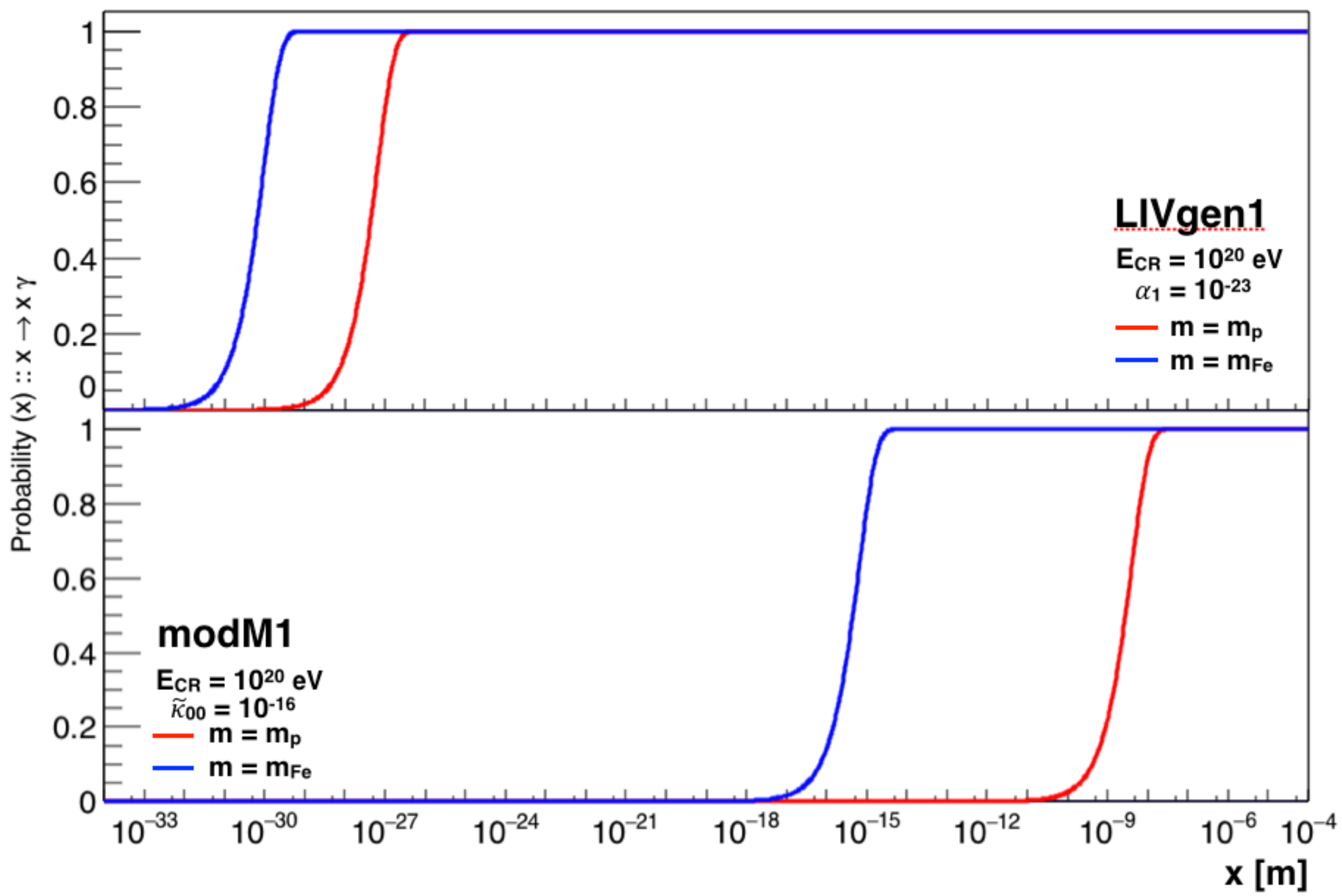
F.R. Klinkhamer and M. Schreck. Phys. Rev. D **78**, 085026 (2008)

C. Kaufhold and F.R. Klinkhamer Phys. Rev. D **76, 025024 (2007)**

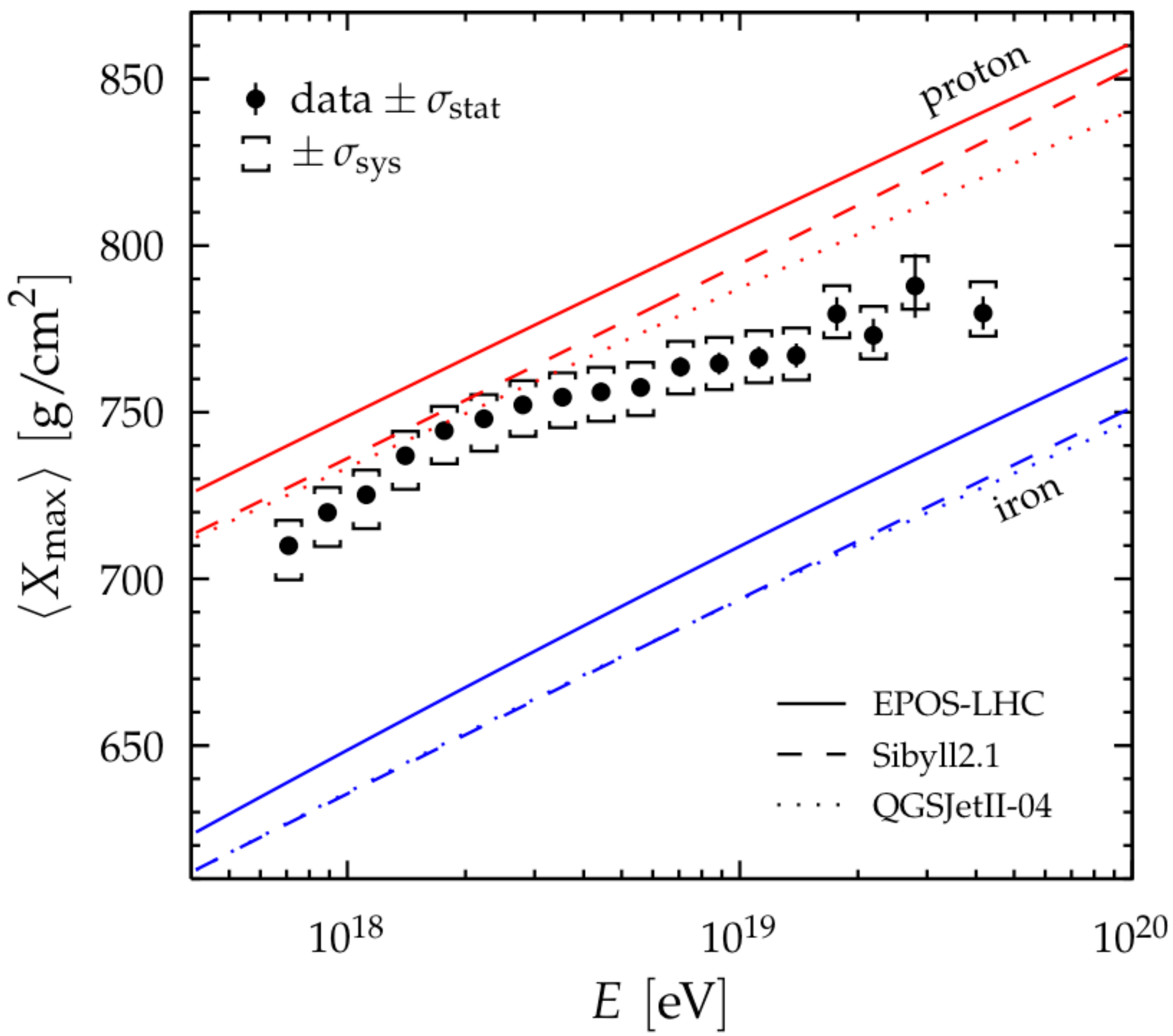
Vacuum Cherenkov Radiation

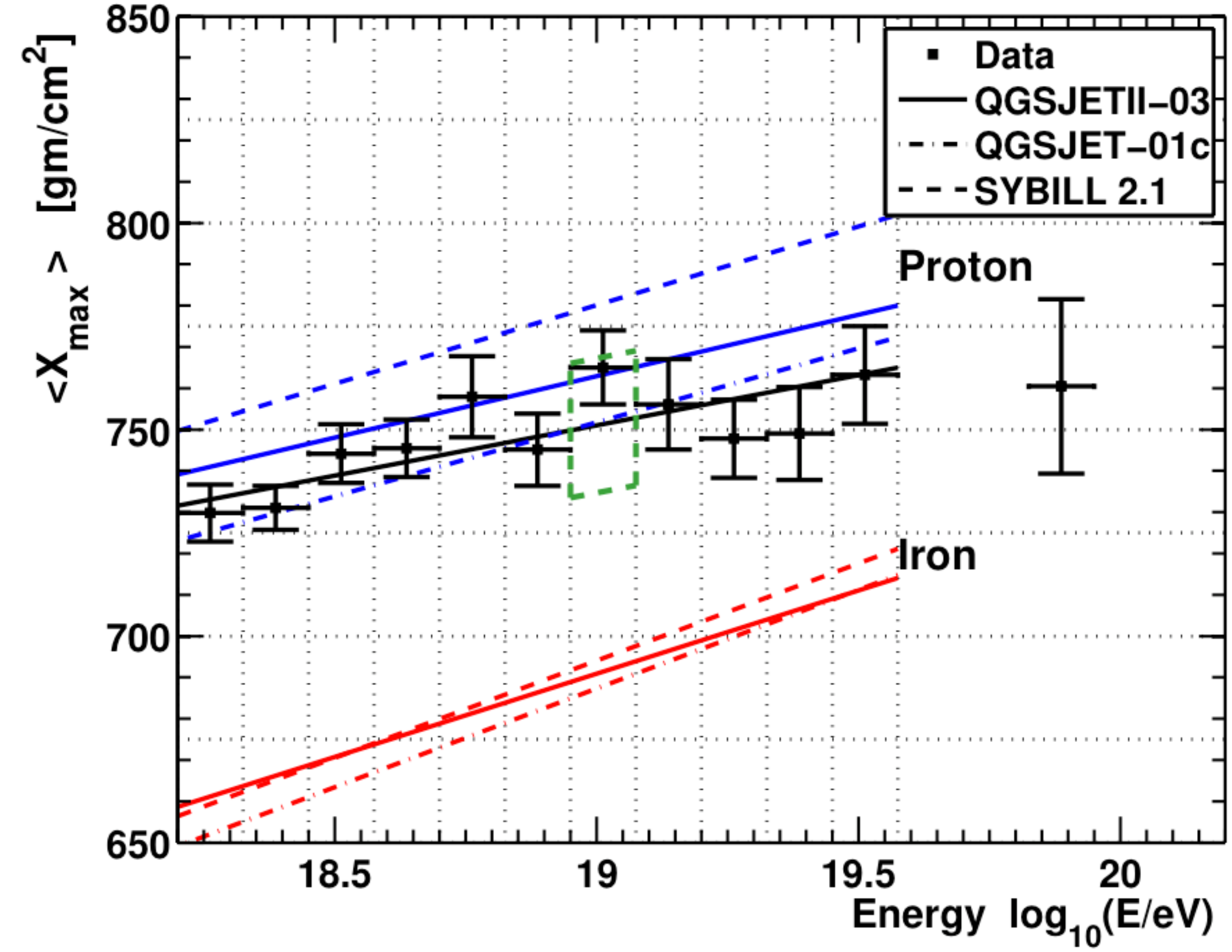






Cosmic Rays





PIERRE AUGER OBSERVATORIO

X_{max} as measured by the Pierre Auger (left) and Telescope Array (right) Collaboration. The colored lines denote predictions of air shower simulation (note that different models are shown in the left andright panel, only Sibyll2.1 is the same). The black line on the right panel is a straight-line fit to the TA data.

TELESCOPE ARRAY PROJECT

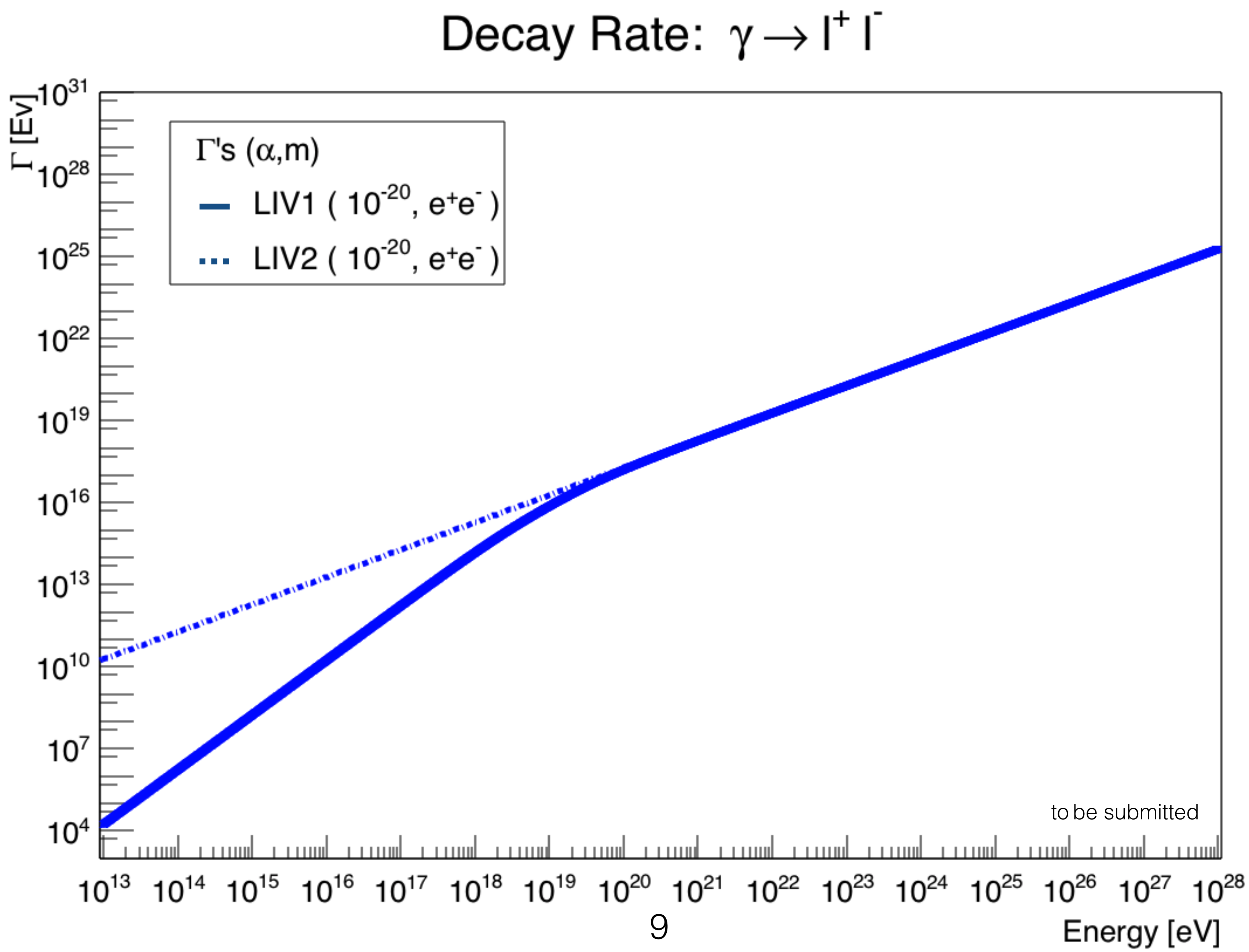
Proc. 34th ICRC'2015

Photon Decay

$$\omega^2 = k^2(1+\alpha_n k^n) \qquad \longrightarrow \qquad \gamma \to l^+ l^-$$
$$= k^2 + m_\gamma^2(k,n,\alpha)$$

$\Gamma(k, m, \alpha, n)$

$$d\Gamma = \frac{S}{2}\frac{1}{\omega(k)}\,|\,\mathbf{M}\,|^2\,\frac{d^3p^+}{(2\pi)^3 2E_p^+(p^+)}\,\frac{d^3p^-}{(2\pi)^3 2E_p^-(p^-)}(2\pi)^4\delta^{(4)}(k-p^+-p^-)$$



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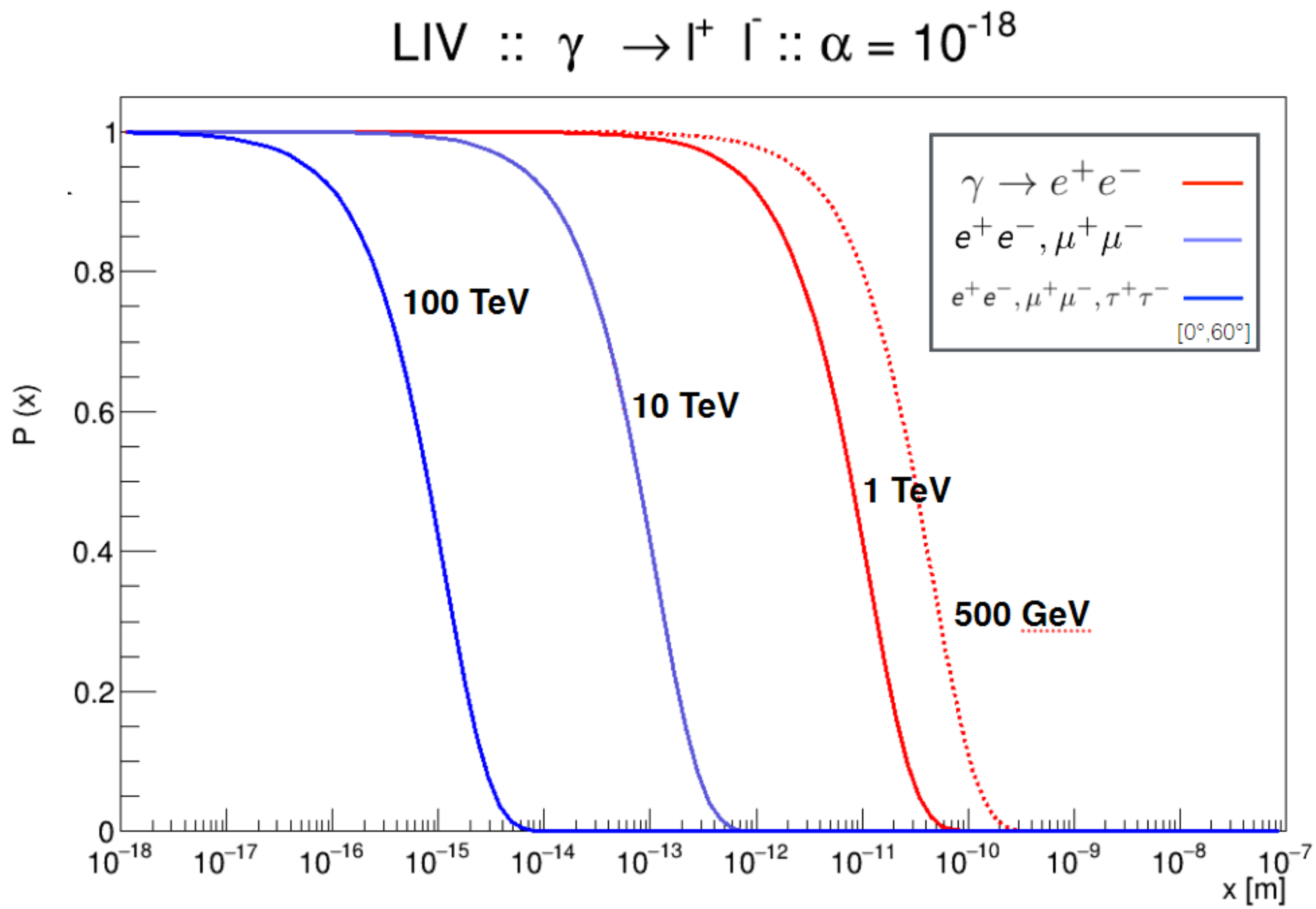
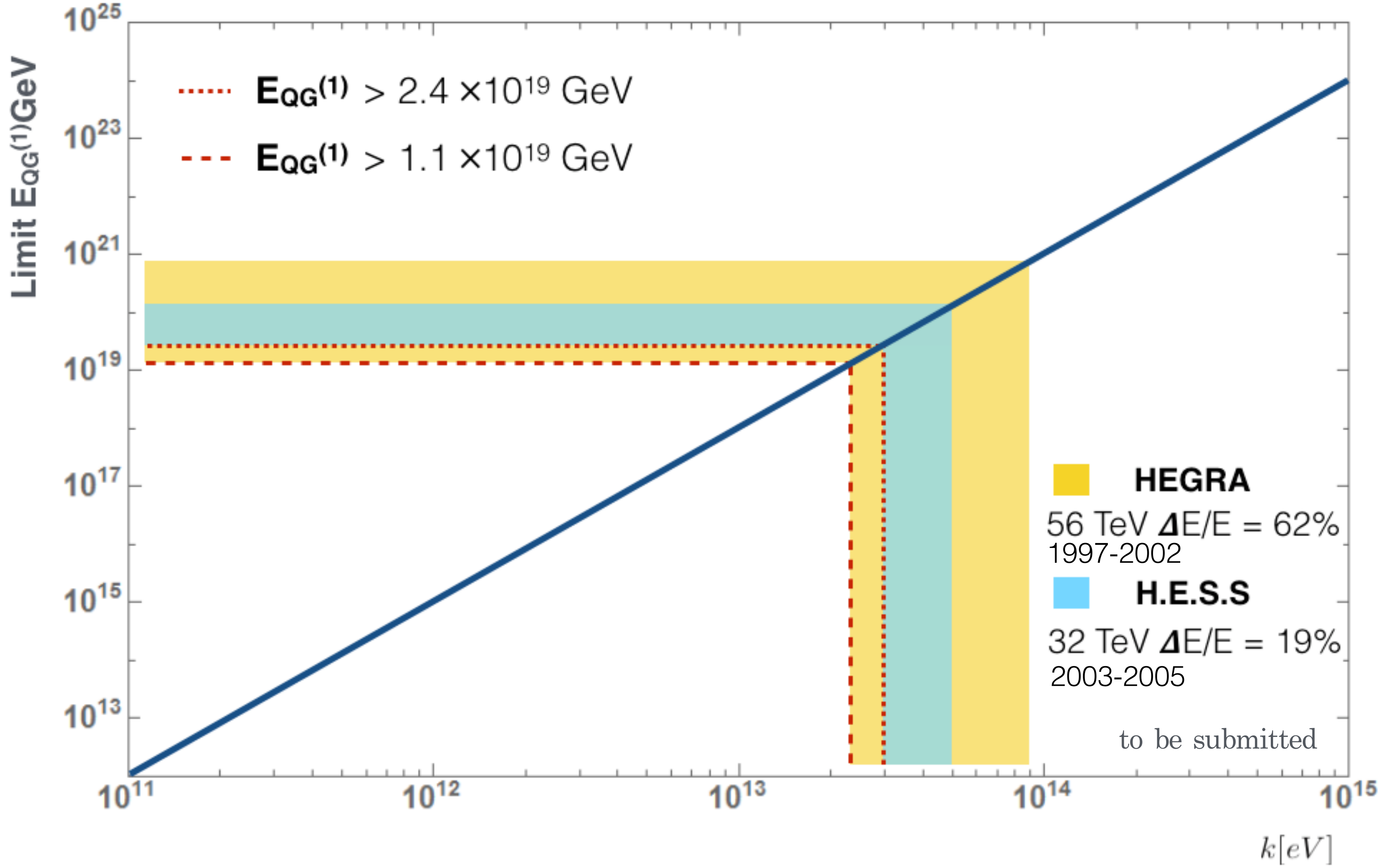
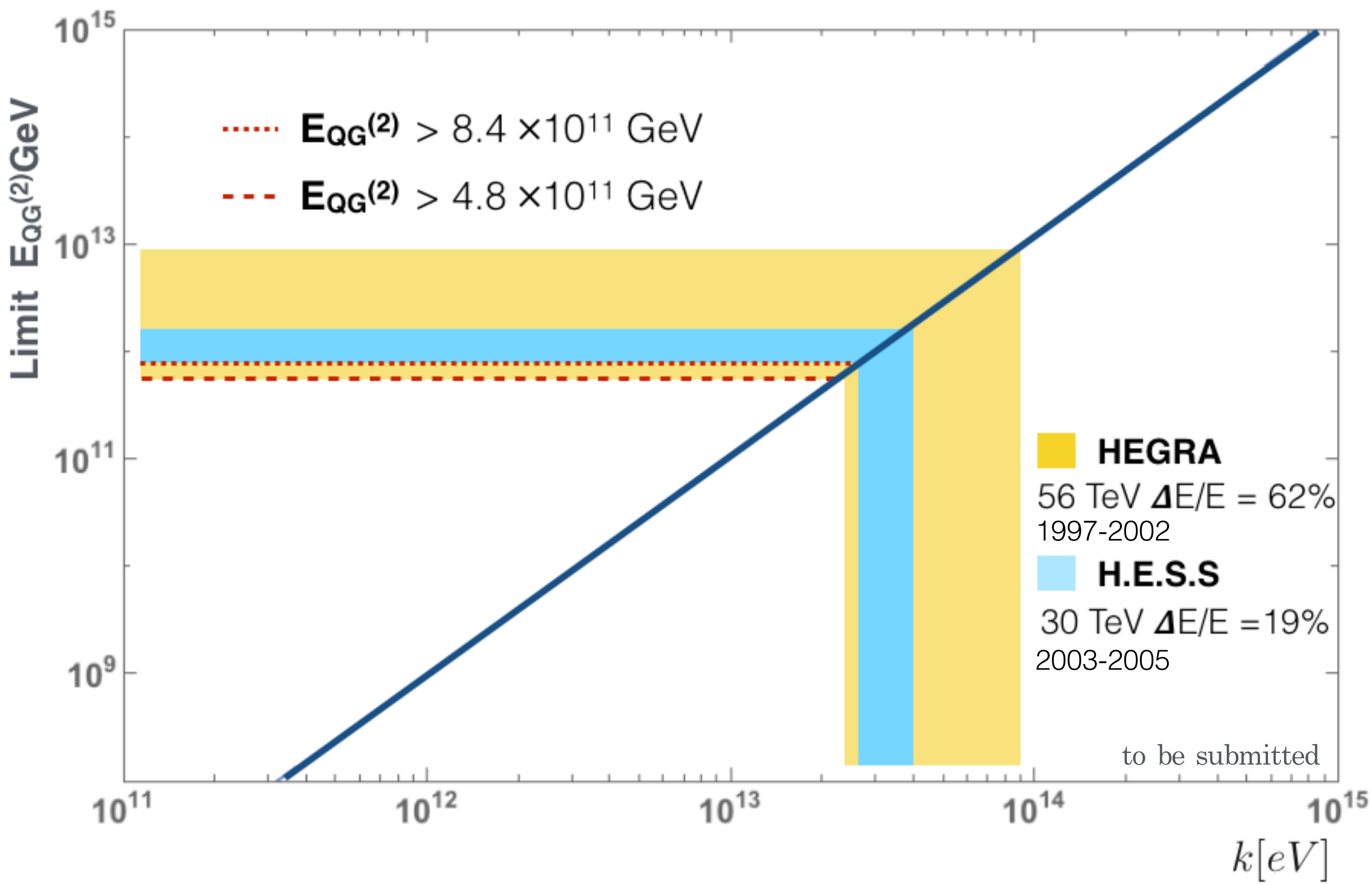
$$\boxed{d\Gamma = \frac{S}{2}\frac{1}{\omega(k)} \mid \mathbf{M} \mid^2 \frac{d^3p^+}{(2\pi)^3 2E_p^+(p^+)} \frac{d^3p^-}{(2\pi)^3 2E_p^-(p^-)} (2\pi)^4 \delta^{(4)}(k - p^+ - p^-)}$$





Source	Experiment	Limit on $E_{QG}^{(1)}$	Limit on $E_{QG}^{(2)}$	Distance	Δt	E_{max}
Crab	VERITAS	$1.7 \cdot 10^{17}$ GeV	$7 \cdot 10^{9}$ GeV	2.2 kpc	100 μs	120 GeV
GRB090510	Fermi/LAT	$9.1 \cdot 10^{19}$ GeV	$1.3 \cdot 10^{11}$ GeV	$z = 0.903$	combined methods	
PKS 2155-304	H.E.S.S.	$2.1 \cdot 10^{18}$ GeV	$6.4 \cdot 10^{10}$ GeV	$z = 0.116$	likelihood fit	
PG 1553+113	H.E.S.S., Fermi/LAT	$4.3 \cdot 10^{17}$ GeV	$2.1 \cdot 10^{10}$ GeV	$z = 0.49 \pm 0.04$	combined analysis	
HAWC Pulsar ref.	HAWC	10^{17} GeV	$9 \cdot 10^{9}$ GeV	2 kpc	1 ms	500 GeV
HAWC GRB ref.	HAWC	$4.9 \cdot 10^{19}$ GeV	$1.1 \cdot 10^{11}$ GeV	$z = 1$	1 s	100 GeV

Lukas Nellen, ICRC'2015



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Thanks!