New constraint for Isotropic Lorentz Violation from LHC data

IRN Terascale, Frascati – 15/04/2024

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Accepted by PRL

David Amram (IP2I Lyon), Killian Bouzoud (SUBATECH), Nicolas Chanon (IP2I Lyon), Hubert Hansen (IP2I Lyon, Marcos R. Ribeiro Jr (Universidade de Sao Paulo), Marco Schreck (Universidade Federal do Maranhao)

Langrangian under Lorentz-violation

Lorentz-violating Standard Model Extension (SME) is motivated by string theory, quantum loop theory and non commmutative field theory. All operators that break Lorentz symmetry are added.

$$\mathcal{L}_{SME} = -\frac{1}{4}(\eta^{\mu\rho}\eta^{\nu\sigma} + \kappa^{\mu\nu\rho\sigma})F_{\mu\nu}F_{\rho\sigma} + \frac{1}{2}\bar{\psi}(\gamma^\mu i D_\mu - m_f)\psi + h.c$$

The dispersion relation is modified such as :

$$\omega = \sqrt{\frac{1-\tilde{\kappa}_{tr}}{1+\tilde{\kappa}_{tr}}}|\mathbf{k}|$$

2 Cases :

$\tilde{\kappa}_{tr} \in (0,1) \implies v_{gr} < 1$ Cherenkov radiation

$\tilde{\kappa}_{tr} \in (-1,0) \implies v_{gr} > 1$ Photon decay in vacuum

- **Parametrize** the Lorentz invariance violation
- Contains **19 independants coefficients**
- They are **tensors**, staying **constant** (not transforming) under a **Lorentz transformation**, thereby breaking Lorentz invariance
- Only **one degree of freedom** describes Lorentz violation effects that are **spatially isotropic** : $\tilde{\kappa}_{tr}$

Existing bounds

arXiv:0801.0287v17

Table D16. Photon sector, $d = 4$ (part 1 of 7)

Combination	Result	System	Ref.
$(\tilde{\kappa}_{e-})^{XY}$	$(-2.3 \pm 5.4) \times 10^{-17}$	Rotating optical resonators	[148]
$\lvert(\tilde{\kappa}_{e-})^{XY}\rvert$	$< 2.7 \times 10^{-22}$	Laser interferometry	[149]
$(\tilde{\kappa}_{e-})^{XY}$	$(0.8 \pm 0.4) \times 10^{-17}$	Rotating optical resonators	[150]
"	$(-0.7 \pm 1.6) \times 10^{-18}$	Sapphire cavity oscillators	[151]
"	$(0.8 \pm 0.6) \times 10^{-16}$	Rotating microwave resonators	[152]
"	$(-0.31 \pm 0.73) \times 10^{-17}$	Rotating optical resonators	[153]
"	$(0.0 \pm 1.0 \pm 0.3) \times 10^{-17}$	"	[154]
"	$(-0.1 \pm 0.6) \times 10^{-17}$	"	[155]
"	$(-7.7 \pm 4.0) \times 10^{-16}$	Optical, microwave resonators	[78]*
"	$(2.9 \pm 2.3) \times 10^{-16}$	Rotating microwave resonators	[156]
"	$(-3.1 \pm 2.5) \times 10^{-16}$	Rotating optical resonators	[157]
"	$(-0.63 \pm 0.43) \times 10^{-15}$	Rotating microwave resonators	[158]

Anistropic effects are well constrained with laboratory experiment

arXiv:0801.0287v17

Table D16. Photon sector, $d = 4$ (part 5 of 8)

Combination	Result	System	Ref.
$\tilde{\kappa}_{tr}$	$> -1.06 \times 10^{-13}$	Collider physics	[176]
"	$< 3 \times 10^{-20}$	Astrophysics	[177]*
$-(\tilde{\kappa}_{tr} - \frac{4}{3}c^{e}_{00})$	$< 6 \times 10^{-21}$	"	[178]*
$\lvert\tilde{\kappa}_{tr}\rvert$	$< 6.43 \times 10^{-18}$	"	[179]
$\tilde{\kappa}_{tr}$	$> -3 \times 10^{-19}$	"	[180]*

Our result improves previous result from D0

$$\tilde{\kappa}_{tr} > -5.8 \times 10^{-12}$$

with a factor of ~55

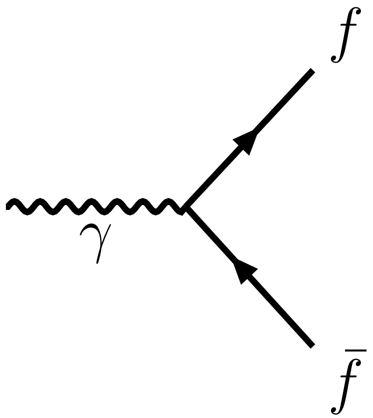
Isotropic effects are mainly constrained with astrophysics, but the photon source is not controled

Earth-based laboratory experiments are **less model dependent**

Photon decay under LIV : threshold

In the SM, photons decaying in the vacuum **is forbidden**

We look at photons decaying to **fermions-antifermions pairs**



This process is governed by a **threshold** :

$$E^{th} = 2m_e\sqrt{\frac{1-\tilde{\kappa}_{tr}}{-2\tilde{\kappa}_{tr}}}$$

This process is only allowed for $\tilde{\kappa}_{tr} < 0$, and we retrieve the SM limit for $\tilde{\kappa}_{tr} \to 0$ where the threshold goes to infinity since this process is forbidden when the symmetry is intact

Photon decay : differential decay width

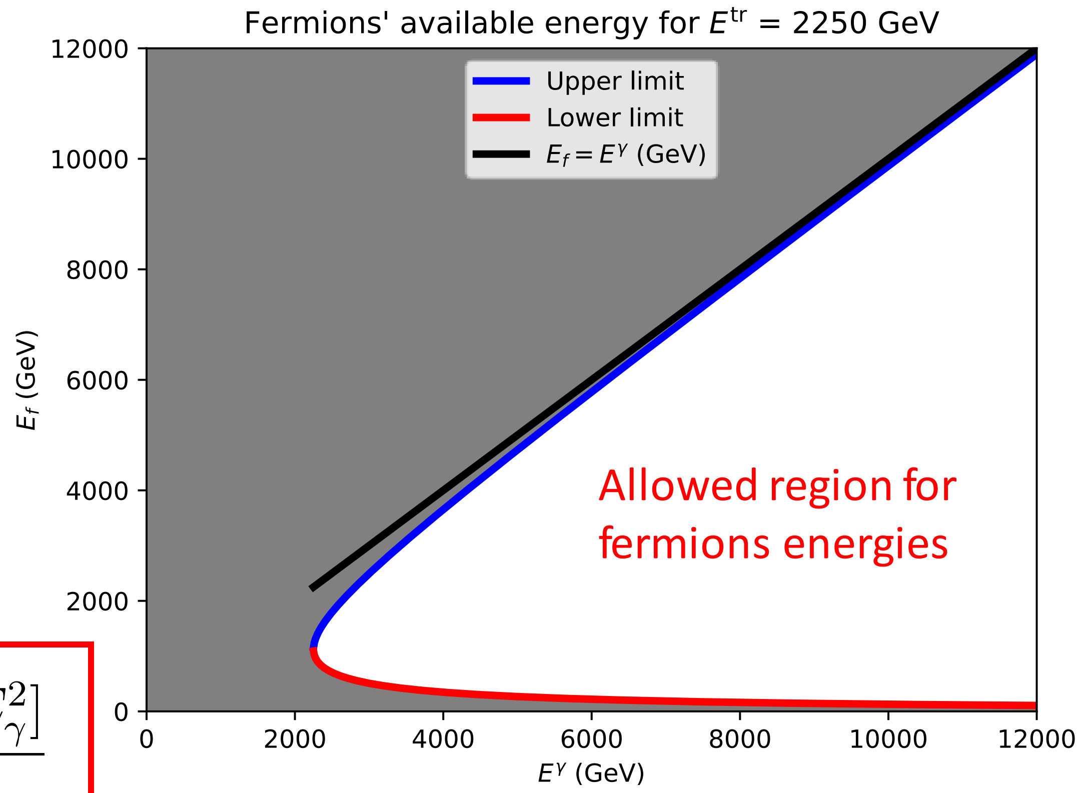
The created fermion energy lies within the interval :

$$E_f \in [\frac{1}{2}(E_\gamma - \bar{E}), \frac{1}{2}(E_\gamma + \bar{E})]$$

$$\bar{E} = \sqrt{\frac{1+\tilde{\kappa}_{tr}}{1-\tilde{\kappa}_{tr}}[E_\gamma^2 + 2(\frac{1}{\tilde{\kappa}_{tr}} - 1)m_f^2]}$$

The partial decay width as a function of the energy of the final fermion has been computed and is expressed as :

$$\frac{d\Gamma}{dE_f} = \frac{\alpha[(1-\tilde{\kappa}_{tr})[2\tilde{\kappa}_{tr}E_f(E_\gamma - E_f) + (1+\tilde{\kappa}_{tr})m_f^2] - \tilde{\kappa}_{tr}E_\gamma^2]}{(1+\tilde{\kappa}_{tr})^2\sqrt{1-\tilde{\kappa}_{tr}^2}E_\gamma^2}$$



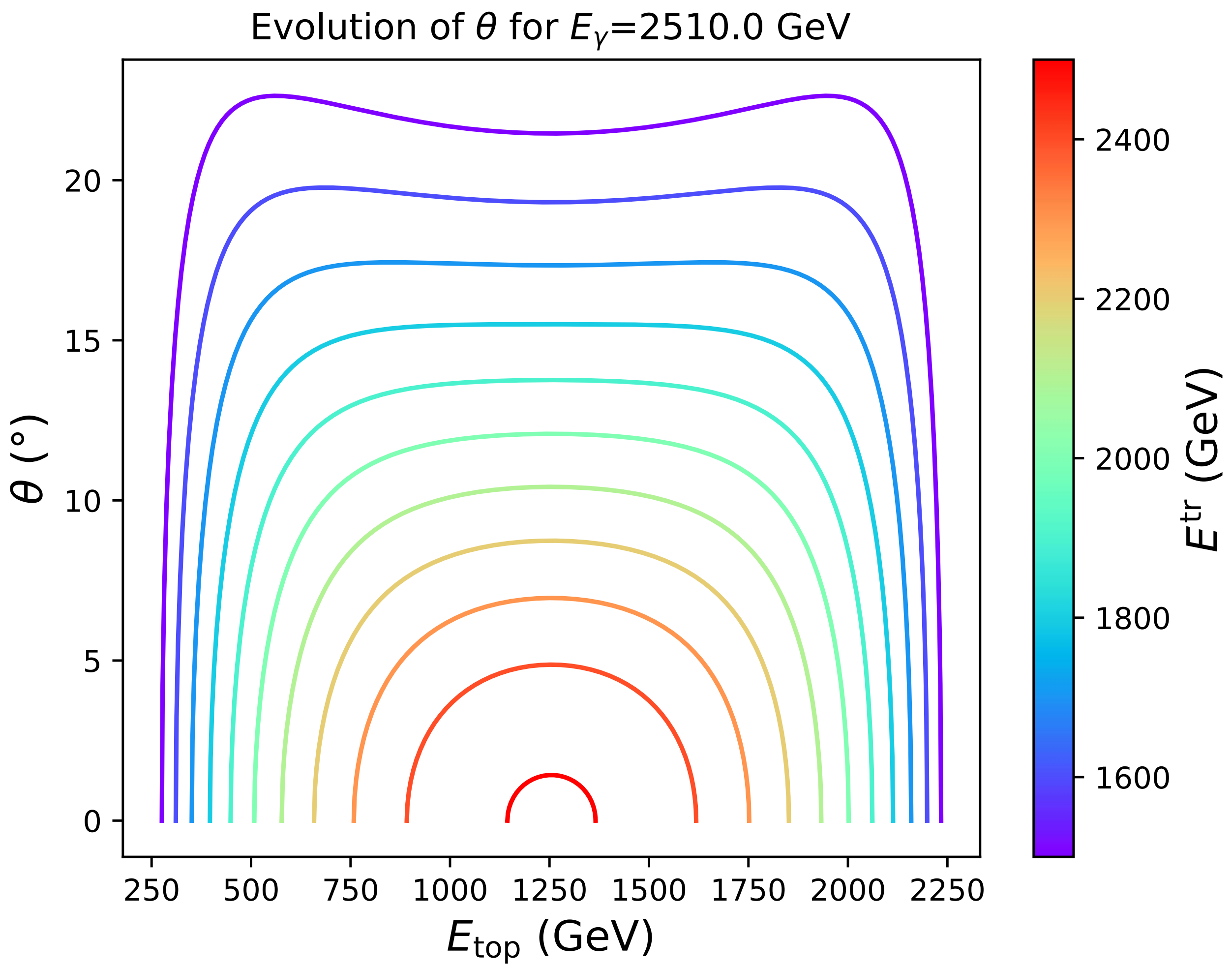
Photon decay : opening angle

If the upcoming-photon energy exceeds the threshold, the surplus is used to provide a **nonzero** θ **angle** between fermions such as

$$\cos\theta = \frac{E_f(E_\gamma - E_f) + \frac{\tilde{\kappa}_{tr}}{1-\tilde{\kappa}_{tr}}E_\gamma^2 + m_f^2}{\sqrt{[E_f^2 - m_f^2][(E_\gamma - E_f)^2 - m_f^2]}}$$

Where E_γ and E_f are the energies of the incoming photon and outgoing fermions

As an illustration, we can look at the decay of photons into top quarks pairs



Photon decay : constraint on $\tilde{\kappa}_{tr}$

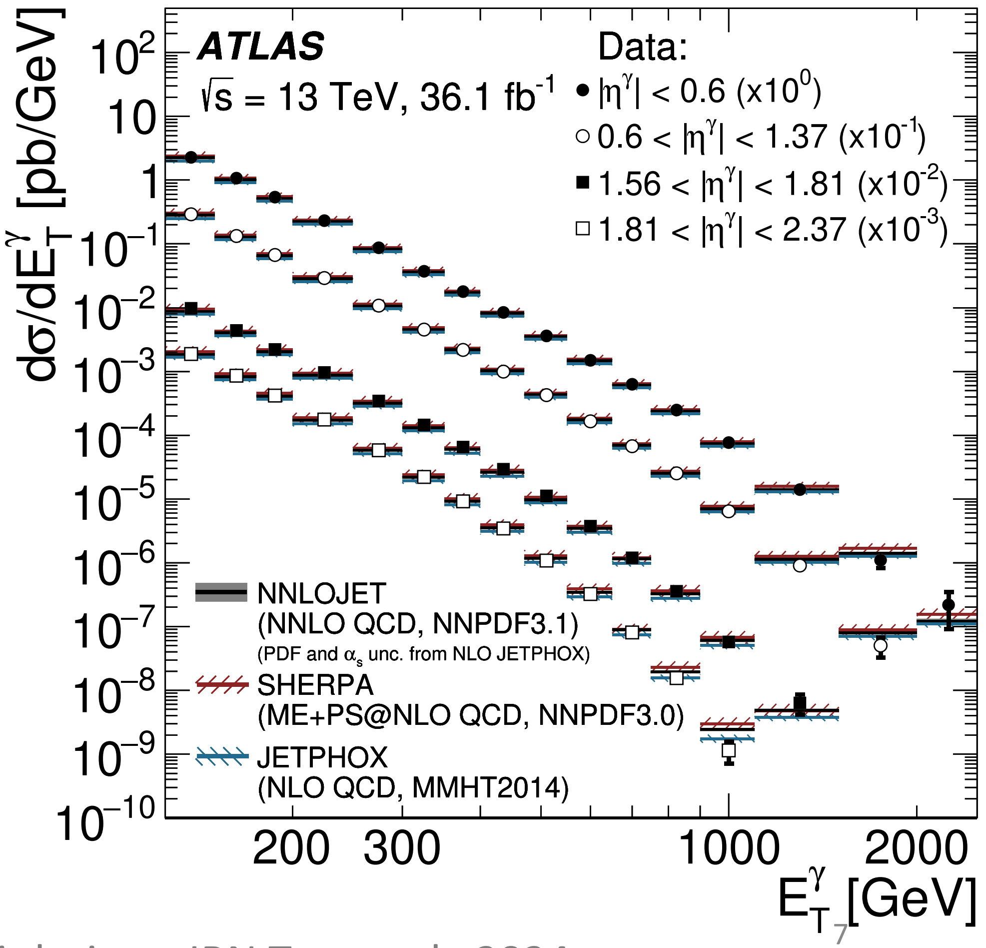
To constrain $\tilde{\kappa}_{tr}$, we need to find the **threshold energy** above which photons could decay in the vaccum.

We suppose that photons **decay to electrons**. Therefore, we analyze the number of photons as a function of E_γ

We reinterpret ATLAS results of E_γ^T for the process :

$$p\ p \rightarrow \gamma + X$$ (ATLAS inclusive photon measurement)

ATLAS collaboration, arXiv:1908.02746



Analysis strategy

Generate a sample of Sherpa $p\,p \to \gamma +$ up to 3 jets at LO
ATLAS MC sample is at NLO + up to 3 jets at LO
The event is reweighted to match ATLAS MC sample

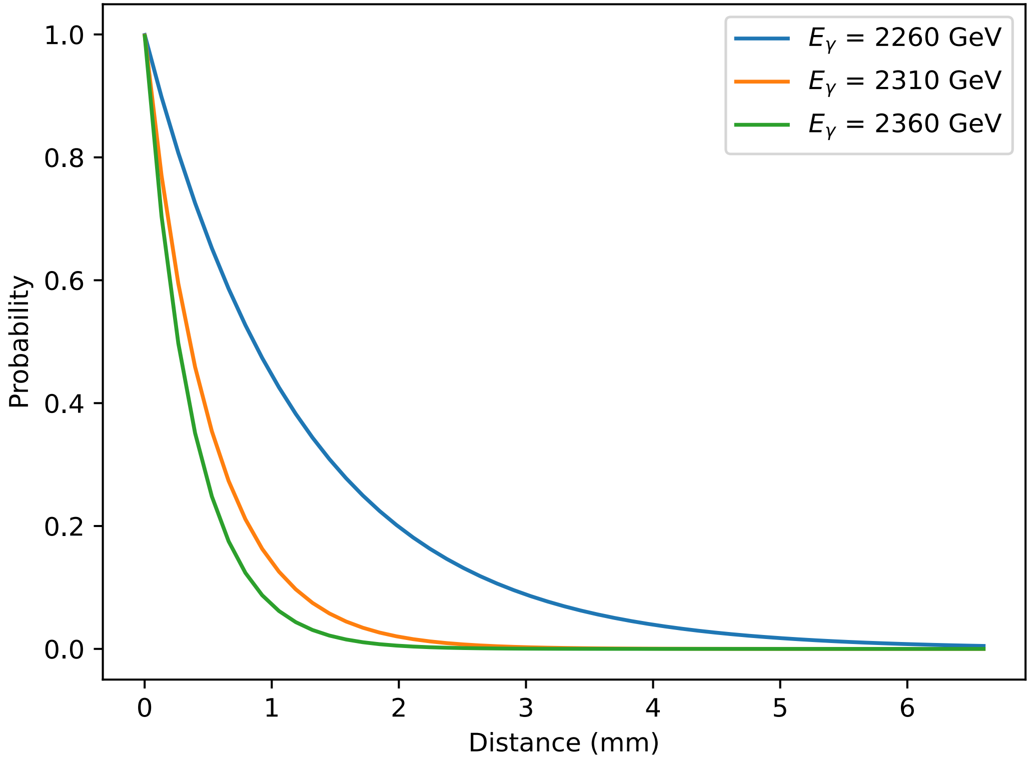
$$\frac{MC_{ATLAS,i}}{MC_{local,i}}$$

For each simulated event, if $E_\gamma > E_{tr}$ the photon decays with a probability of $1 - e^{-\Gamma x}$ with

$$\Gamma = \int_{\frac{E\gamma - \bar{E}}{2}}^{\frac{E\gamma + \bar{E}}{2}} \frac{d\Gamma}{dE_f} dE_f$$

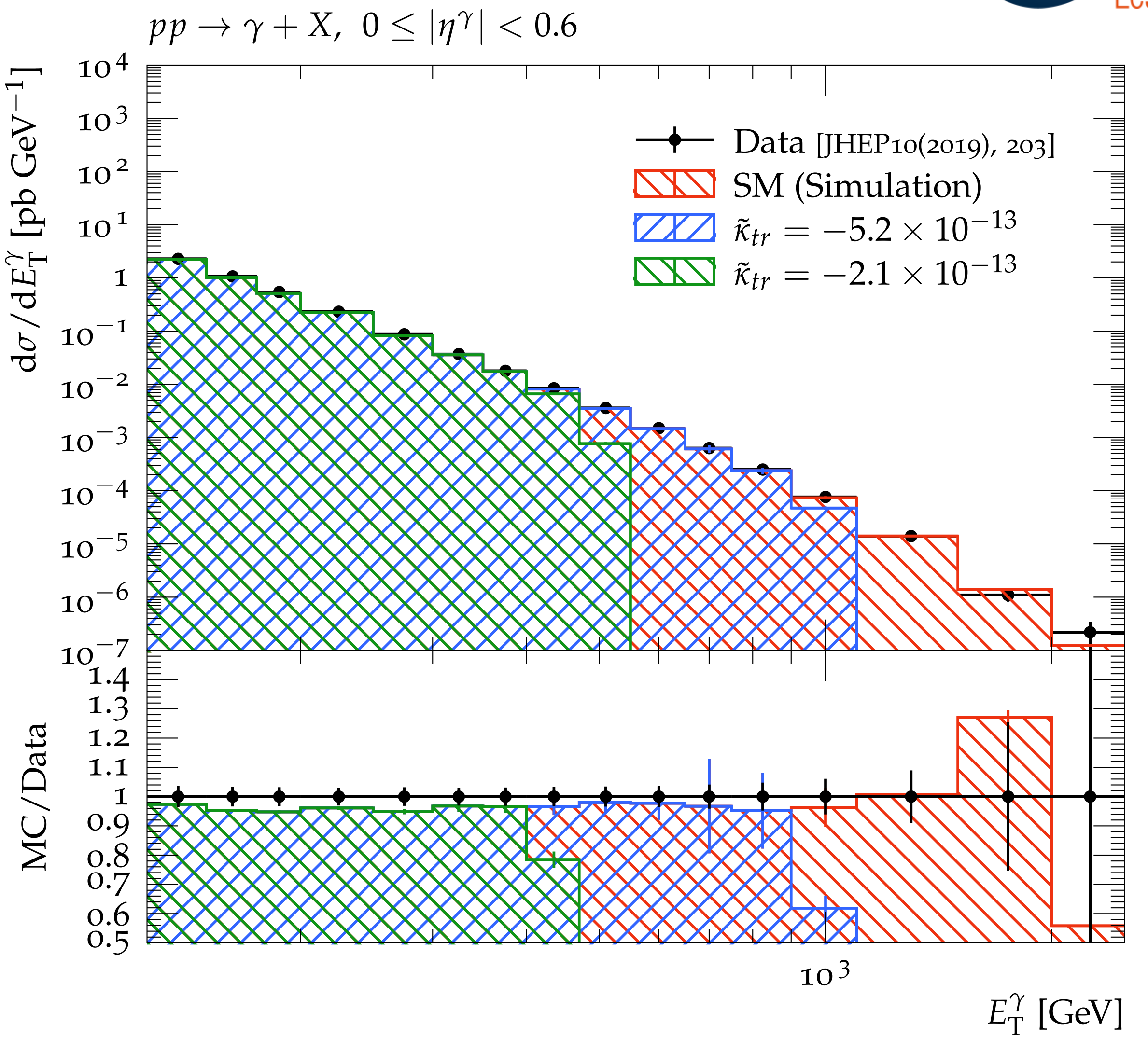
Fermion's energy is randomly chosen following $\frac{d\Gamma}{dE_f}$ with

$$E_f \in [\frac{1}{2}(E_\gamma - \bar{E}), \frac{1}{2}(E_\gamma + \bar{E})]$$



Search for disappearing photon

- If the photon does not decay, **we add it's** E_T to the histogram
- The procedure mentioned before is **apply to a range of** E_{tr}. We clearly see the effect of the threshold on the histogram
- **Signature**: **disappearing** photon in the E_T^γ spectrum

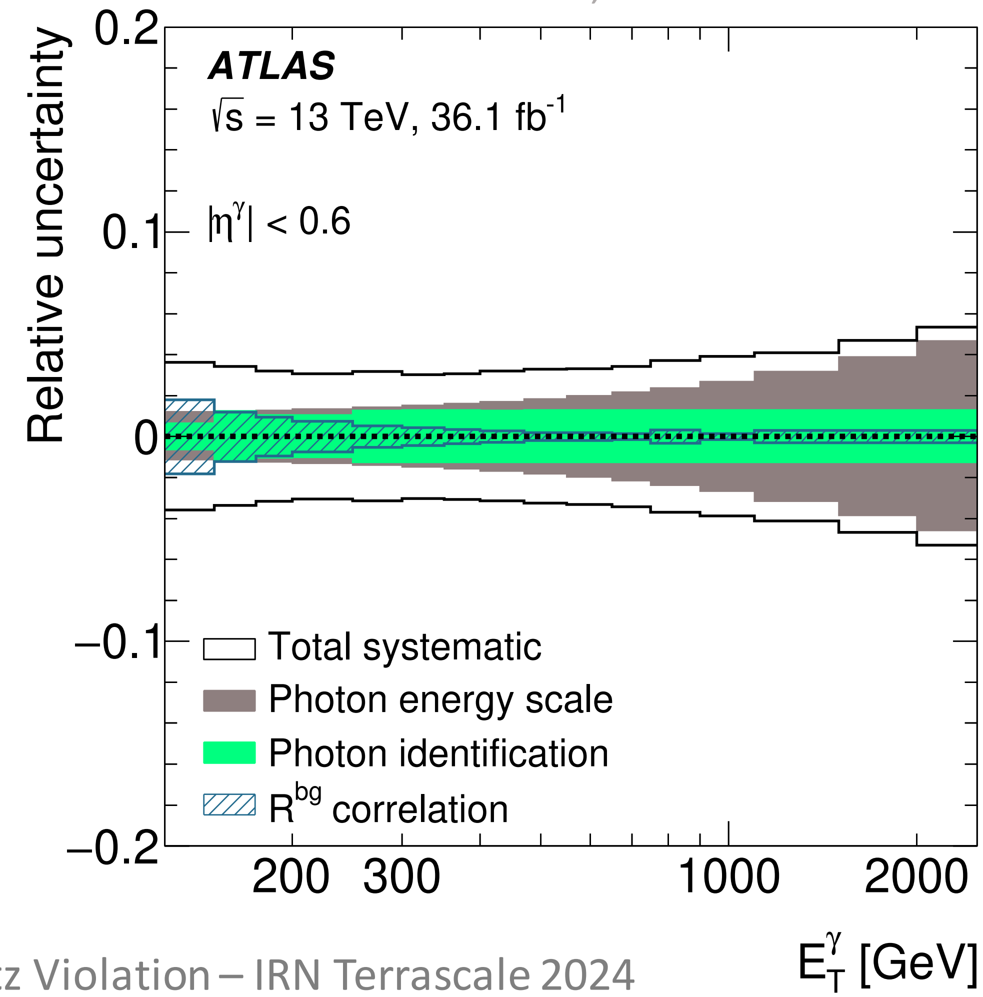


Correction for misidentification

We introduce a **photon decay uncertainty**.
In the ATLAS mesurement, the photon identification uncertainty is **less than 1.5%**.
We assign the value of the photon identification uncertainty to **the probability of an e+/e- to be reconstructed as a** photon.

- If one of them is reconstructed as a photon, **we add its Et to the histogram**
- If both of them are reconstructed as photons, we add the highest p_T electron to the E_T^γ histogram**.**

ATLAS collaboration, arXiv:1908.02746

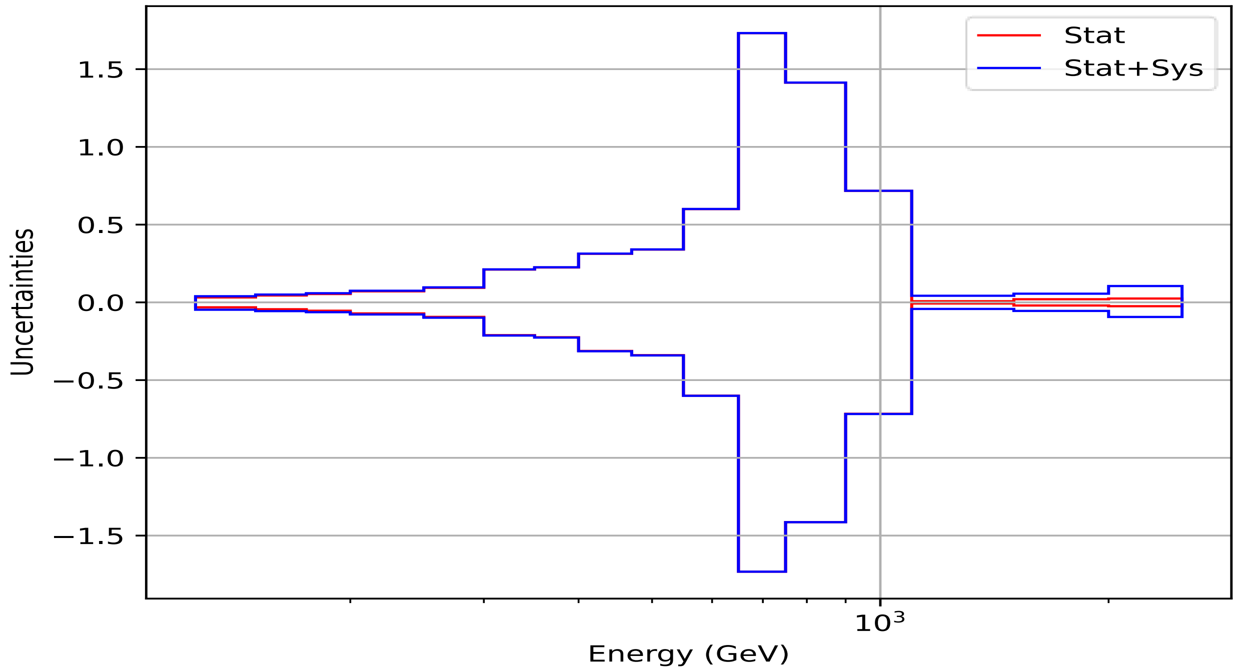


Systematic uncertainties

The data systematic uncertainties are **already given by the ATLAS mesurement**. We take them from HepData.

They include :

- the background substraction
- the unfolding
- the pile-up
- the trigger efficiency
- the luminosity measurement
- the photon energy scale and resolution



Their values **are added in quadrature** and treated conservatively as a **separate Gaussian nuisance parameter** for each bin.

Measurement : results

The **CLs method** is used to set a limit on $\tilde{\kappa}_{tr}$
With **q the likelihood ratio** of the BSM against the SM hypothesis, we define :

$$CL_{s+b} = p_{s+b} = P(q > q_{obs}|s+b) = \int_{q_{obs}}^{inf} f(q|s+b)dq$$

$$CL_b = 1 - p_b = 1 - P(q < q_{obs}|b) = 1 - \int_{inf}^{q_{obs}} f(q|b)dq$$

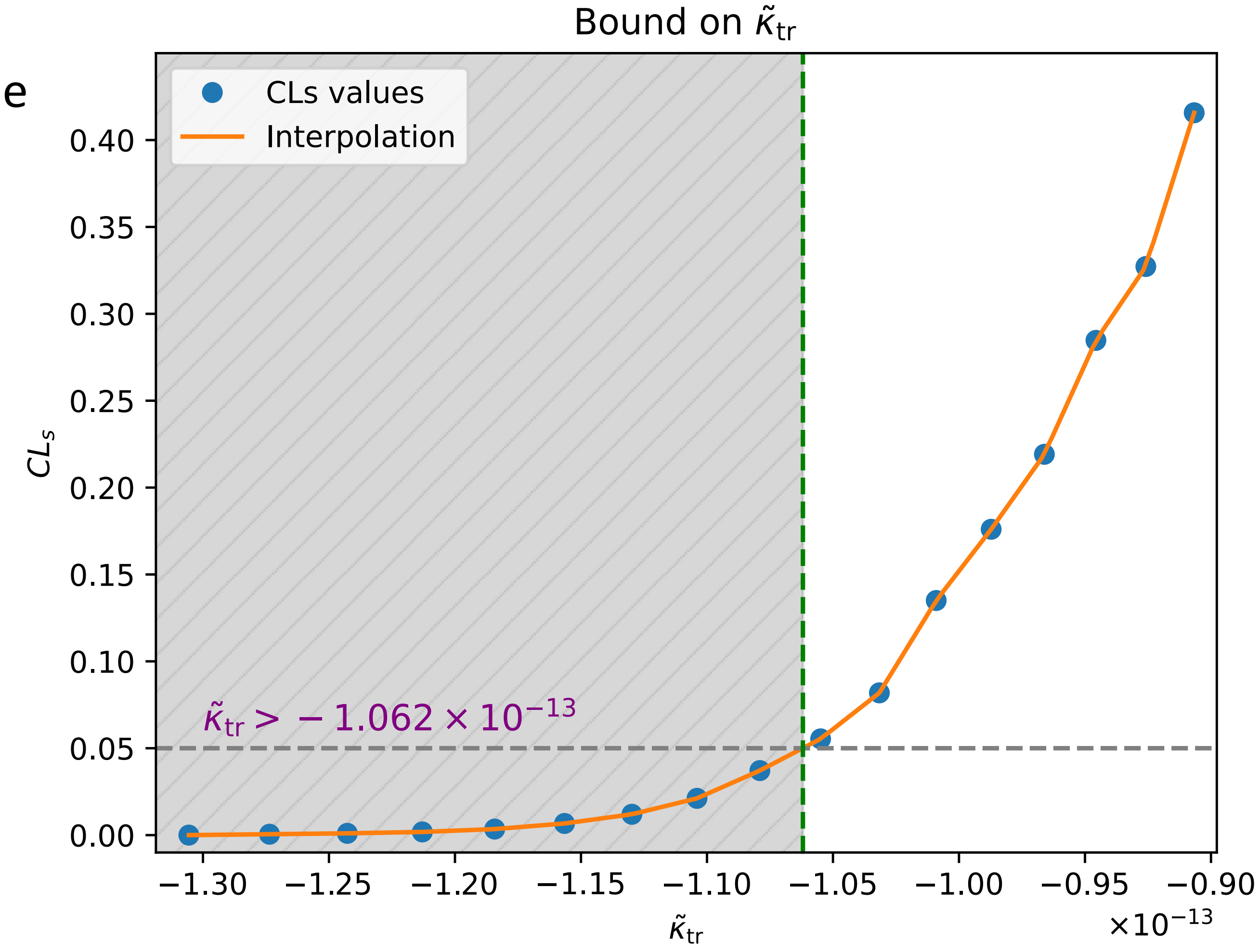
$$CL_s = \frac{CL_{s+b}}{CL_b}$$

We use the conventional criteria **CLs < 0.05** to set the limit :

$$\tilde{\kappa}_{tr} > -1.06 \times 10^{-13}$$

Without systematics uncertainties, the results would be :

$$\tilde{\kappa}_{tr} > -1.045 \times 10^{-13}$$



Conclusion and perspective

Summary :

A **new calculation** of the kinematics of photon decay into fermion in vacuum is provided

The case of photon decay to top quarks ilustrates **the change in kinematics** relative to the SM prediction

A new bound on the isotropic SME coefficient is set from LHC data as $\tilde{\kappa}_{tr} > -1.06 \times 10^{-13}$

Improvement of the previous mesurement from D0 **by a factor of 55**

This paper sets a **new standard** for re-interpreting collider data as constraints on Lorentz violation

Perspective :

The FCC-hh would collide 100 TeV protons. Assuming that prompt photons of ≈ 20 TeV would be produced, the lower bound would **improve by 2 orders of magnitude**

Back-up slides

Fermion momentum construction

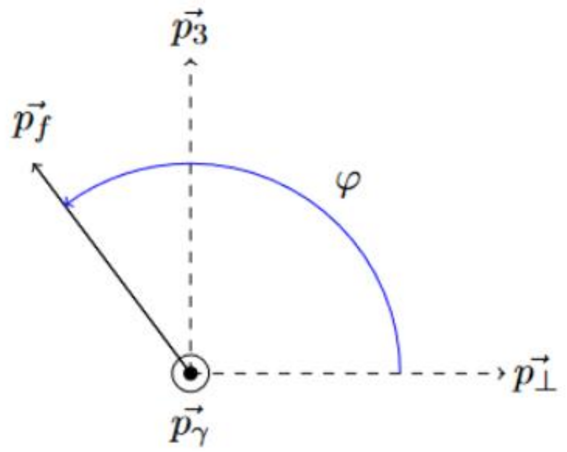
We construct the fermion momentum following :

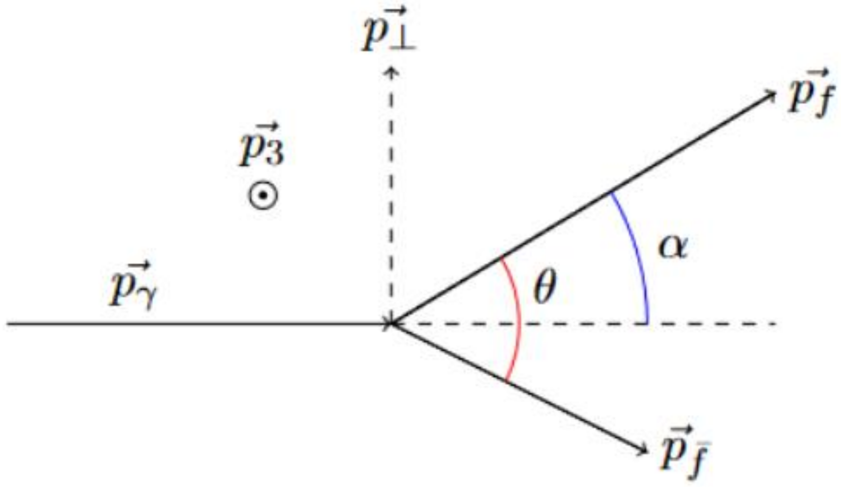
$$\cos\theta = \frac{E_e(E_\gamma - E_e) + \frac{\tilde{\kappa}tr}{1-\tilde{\kappa}tr}E_\gamma^2 + m_e^2}{\sqrt{[E_e^2 - m_e^2][(E_\gamma - E_e)^2 - m_e^2]}}$$

$$\cos\alpha = \frac{||\vec{p}_f|| + ||\vec{p}_f||\cos\theta}{||\vec{p}_f||}$$

$$\vec{p}_f = ||\vec{p}_f||(\vec{p}_\gamma \cos\alpha + \sin\alpha(\cos\varphi\ \vec{p}_\perp + \sin\varphi\ \vec{p}_3))$$

φ is randomly choosen using the uniform distribution on the interval$]-\pi,\pi]$





Details on $\tilde{\kappa}_{tr}$

Over the 19 coefficients, the 9 nonbirefringent are parameterized by

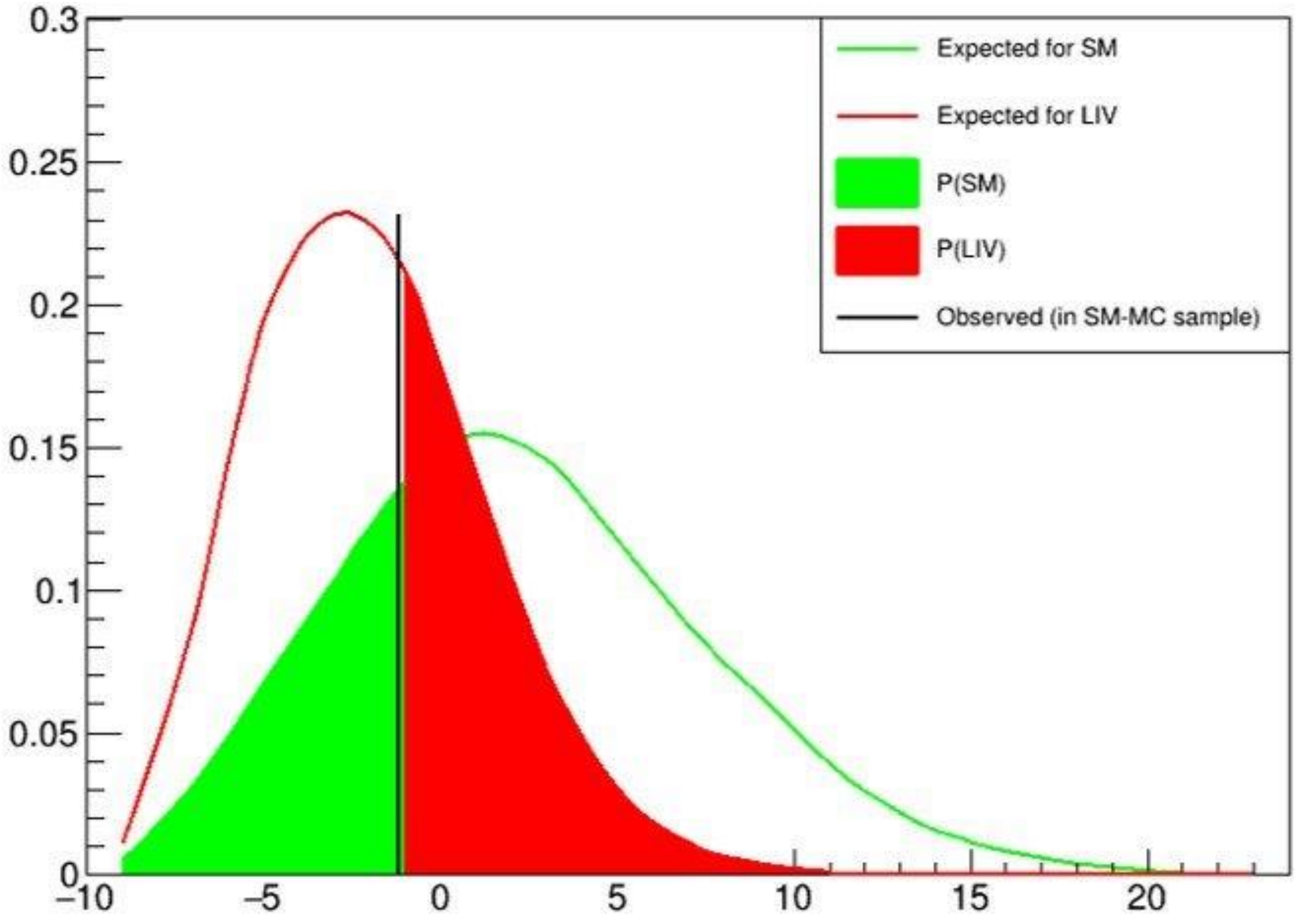
$$\kappa^{\mu\nu\rho\sigma} = \frac{1}{2}(\eta^{\mu\rho}\tilde{\kappa}^{\nu\sigma} - \eta^{\mu\sigma}\tilde{\kappa}^{\nu\rho} + \eta^{\nu\sigma}\tilde{\kappa}^{\mu\rho} - \eta^{\nu\rho}\tilde{\kappa}^{\mu\sigma})$$

$\tilde{\kappa}^{\mu\nu}$ is a symmetric and traceless 4 x 4 matrix

A single coefficient parameterizes isotropic LV. The coefficients of the matrix are then chosen as

$$\tilde{\kappa}^{\mu\nu} = \frac{3}{2}\tilde{\kappa}_{tr}\mathrm{diag}\left(1, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)^{\mu\nu}$$

CLs method



Expected for SM
Expected for LIV
P(SM)
P(LIV)
Observed (in SM-MC sample)
0.3
0.25
0.2
0.15
0.1
0.05
0
−10
−5
0
5
10
15
20