New constraint for Isotropic Lorentz Violation from LHC data

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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.

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

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 8)

Combination	Result	System	Ref.
$(\tilde{\kappa}_{e-})^{XY}$	$(-2.3 \pm 5.4) \times 10^{-17}$	Rotating optical resonators	[154]
$\lvert(\tilde{\kappa}_{e-})^{XY}\rvert$	$< 2.7 \times 10^{-22}$	Laser interferometry	[155]
$(\tilde{\kappa}_{e-})^{XY}$	$(0.8 \pm 0.4) \times 10^{-17}$	Rotating optical resonators	[156]
"	$(-0.7 \pm 1.6) \times 10^{-18}$	Sapphire cavity oscillators	[157]
"	$(0.8 \pm 0.6) \times 10^{-16}$	Rotating microwave resonators	[158]
"	$(-0.31 \pm 0.73) \times 10^{-17}$	Rotating optical resonators	[159]
"	$(0.0 \pm 1.0 \pm 0.3) \times 10^{-17}$	"	[160]
"	$(-0.1 \pm 0.6) \times 10^{-17}$	"	[161]
"	$(-7.7 \pm 4.0) \times 10^{-16}$	Optical, microwave resonators	[80]*
"	$(2.9 \pm 2.3) \times 10^{-16}$	Rotating microwave resonators	[162]
"	$(-3.1 \pm 2.5) \times 10^{-16}$	Rotating optical resonators	[163]

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

Anistropic effects are well constrained with laboratory experiment

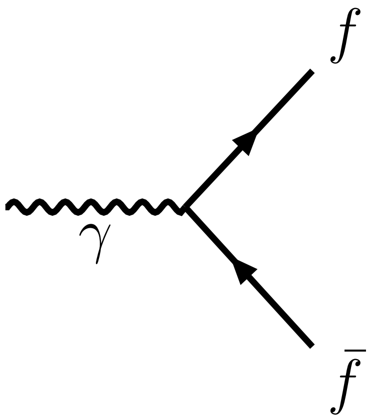
Isotropic effects are mainly constrained with astrophysics, but the photon source is not controled

Astrophysics results are much better, but 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** :

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

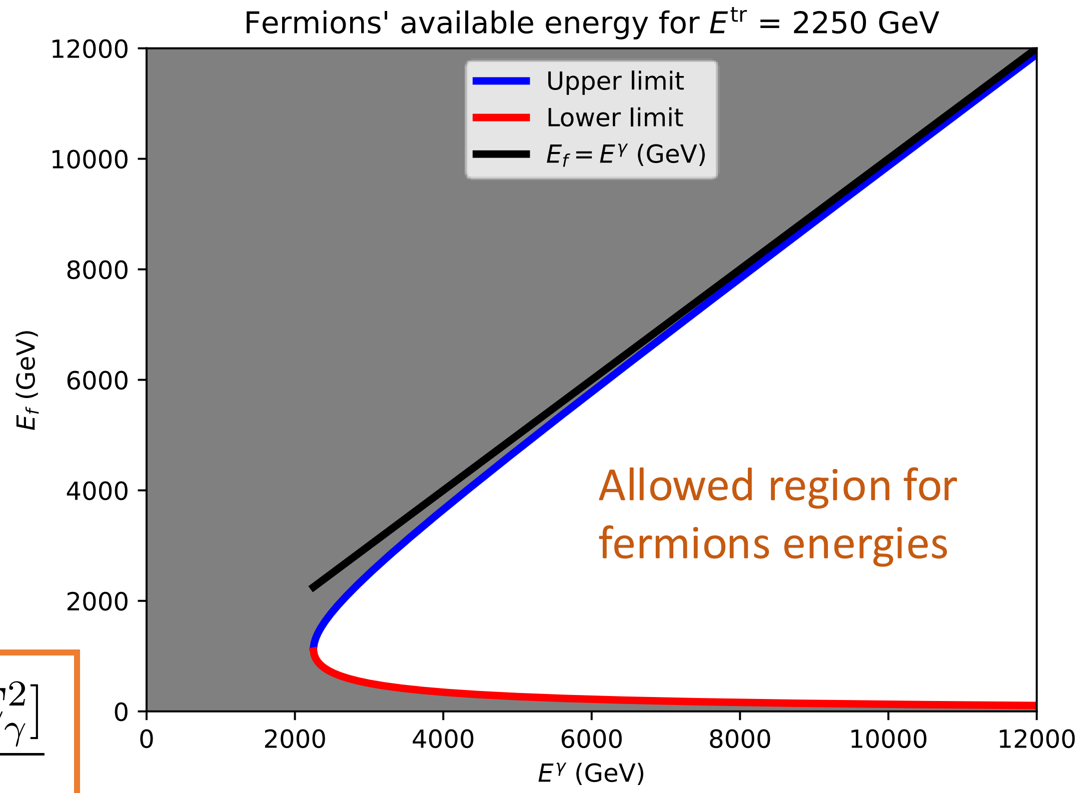
This process is only allowed for $\tilde{\kappa}_{tr} < 0$.
We retrieve the SM limit for $\tilde{\kappa}_{tr} \to 0$ where the threshold goes to infinity since this process is forbidden when the symmetry is intact

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 :

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

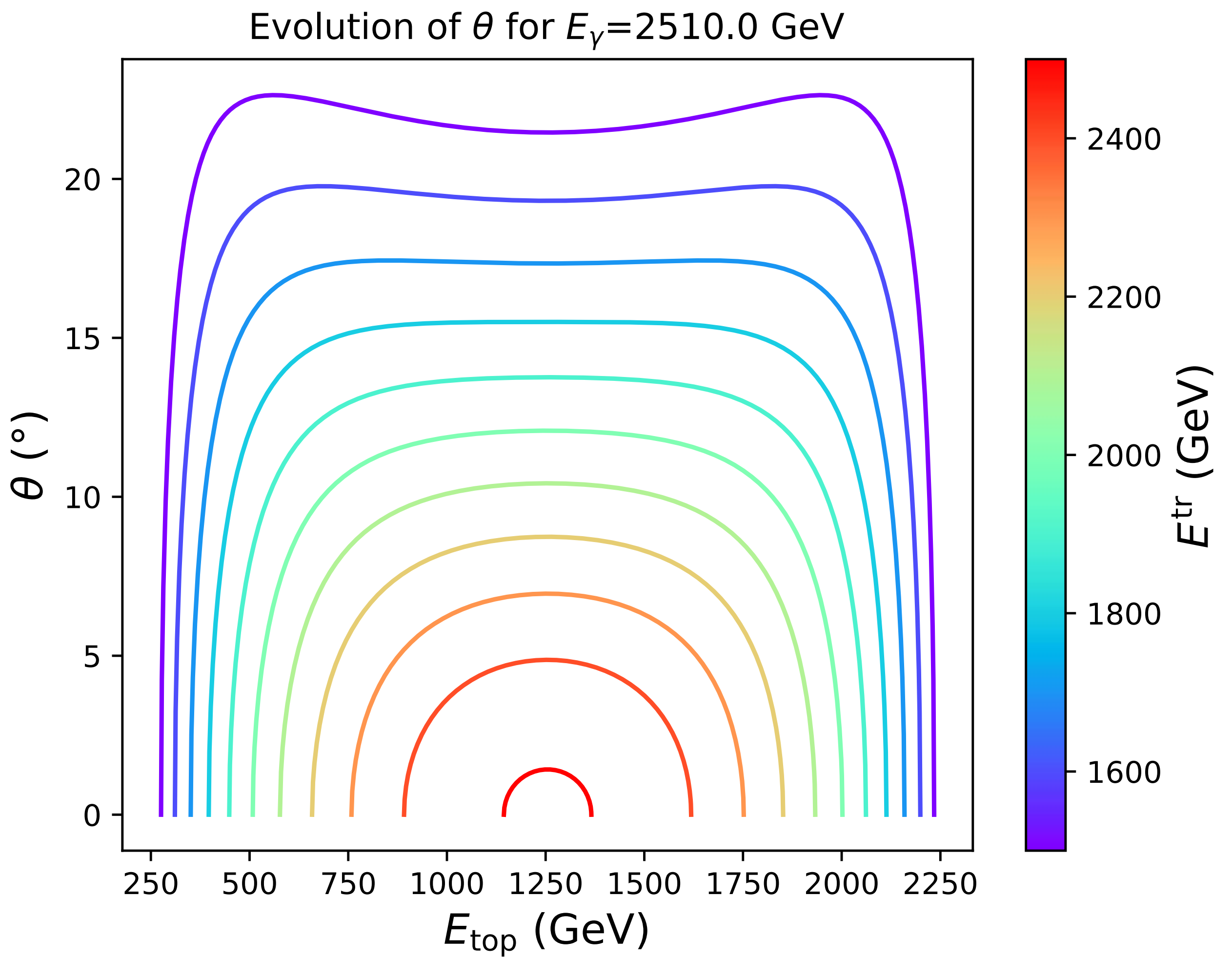
Photon decay : opening angle

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



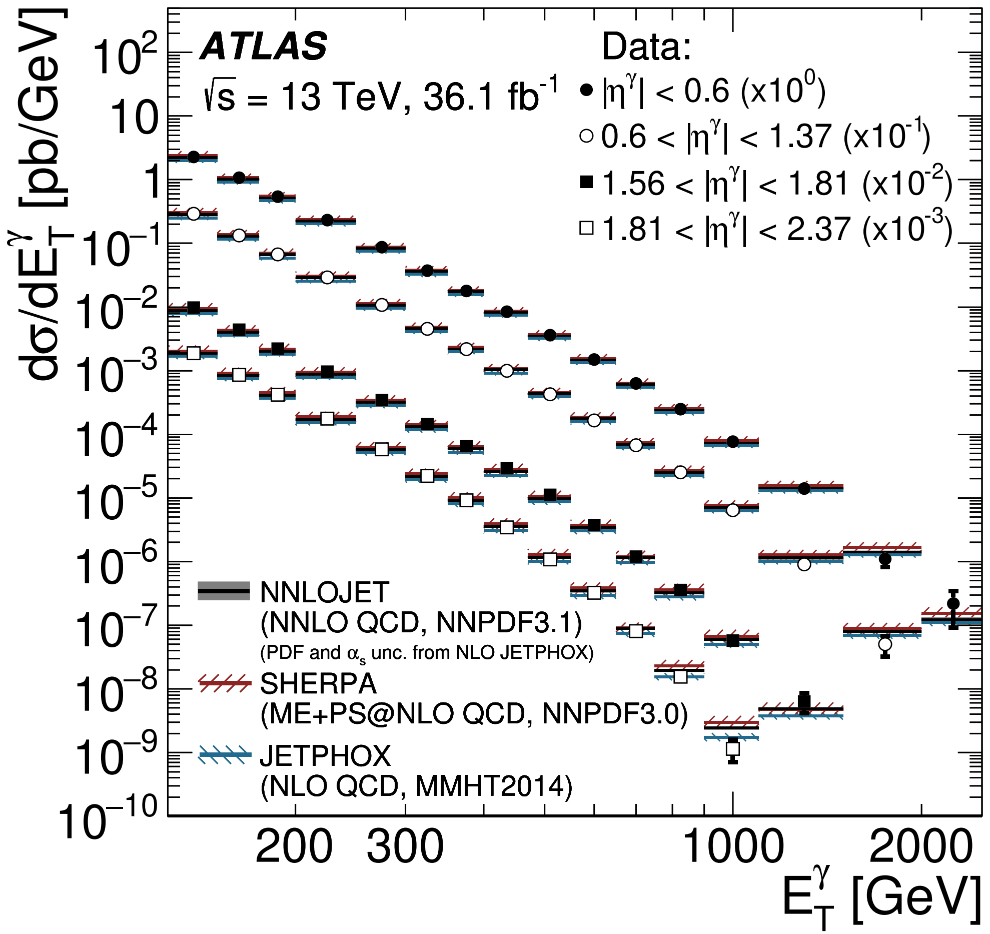
Photon decay : constraint on $\tilde{\kappa}_{tr}$

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

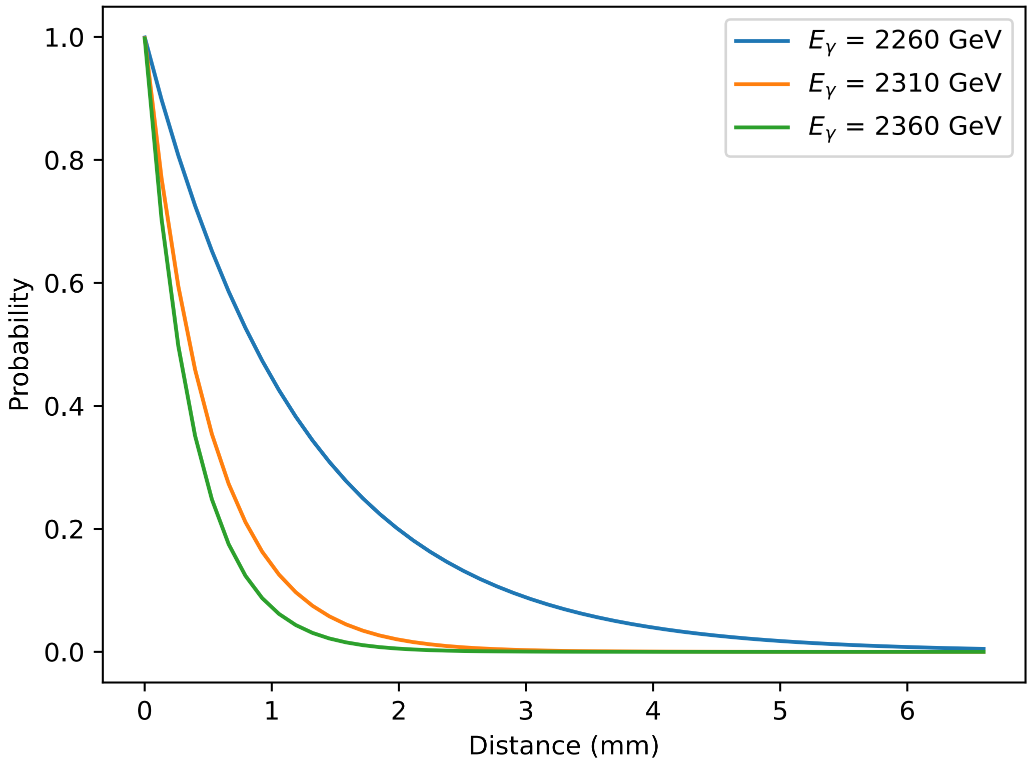
$$\frac{MC_{ATLAS,i}}{MC_{local,i}}$$

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

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

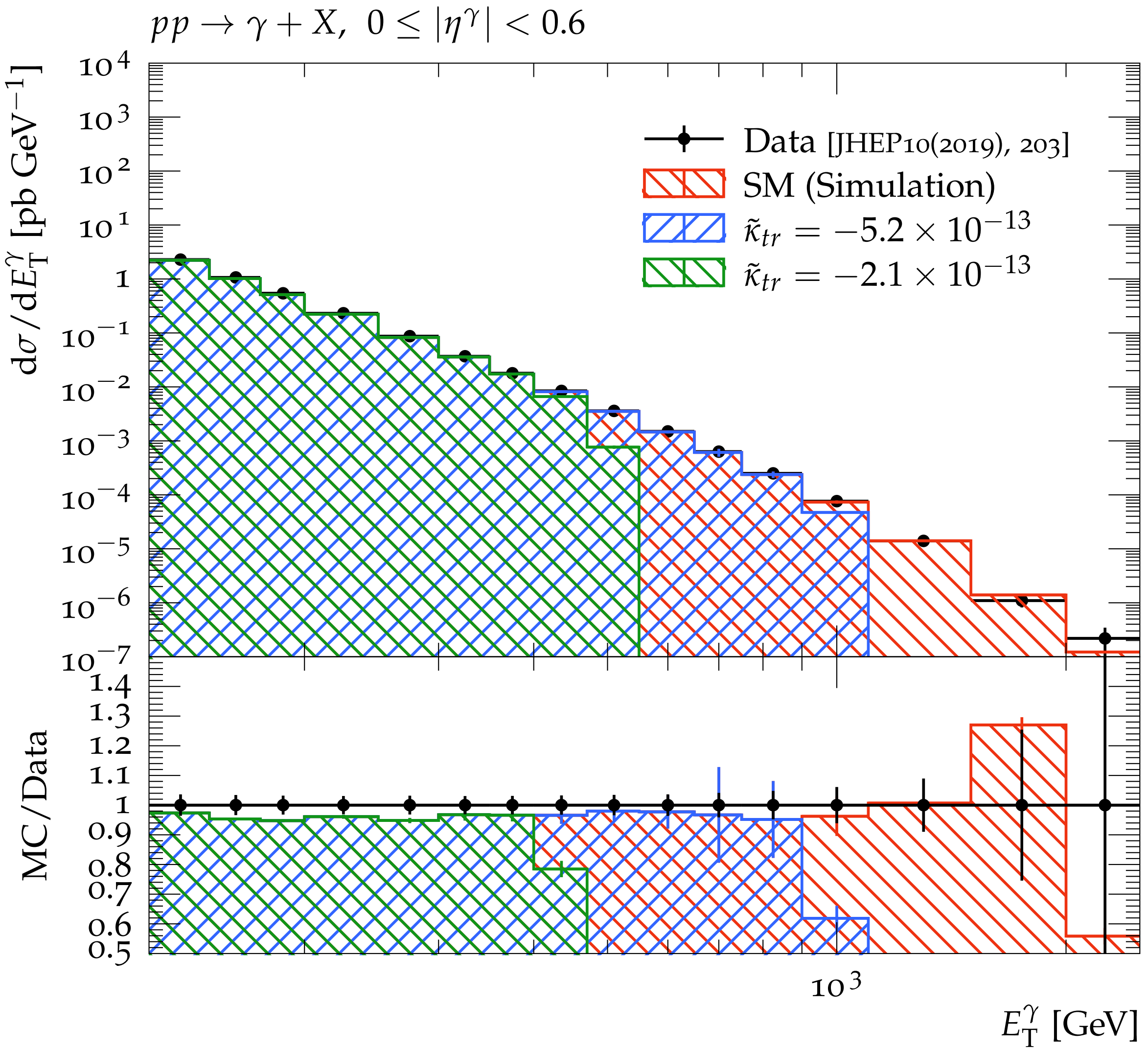
Fermion's energy is randomly chosen following $\frac{d\Gamma}{dE_f}$ with

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



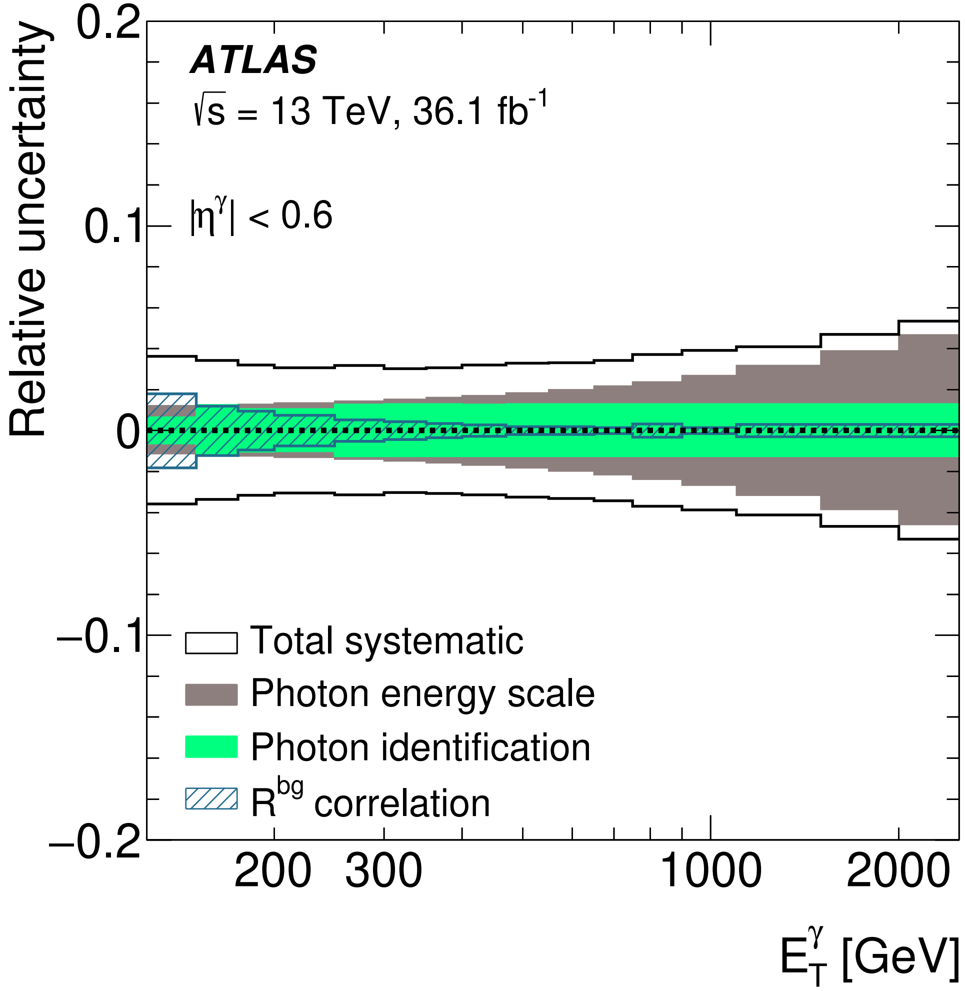
Search for disappearing photon

- 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

ATLAS collaboration, arXiv:1908.02746



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 $e^{+/-}$ to be reconstructed as a** photon:

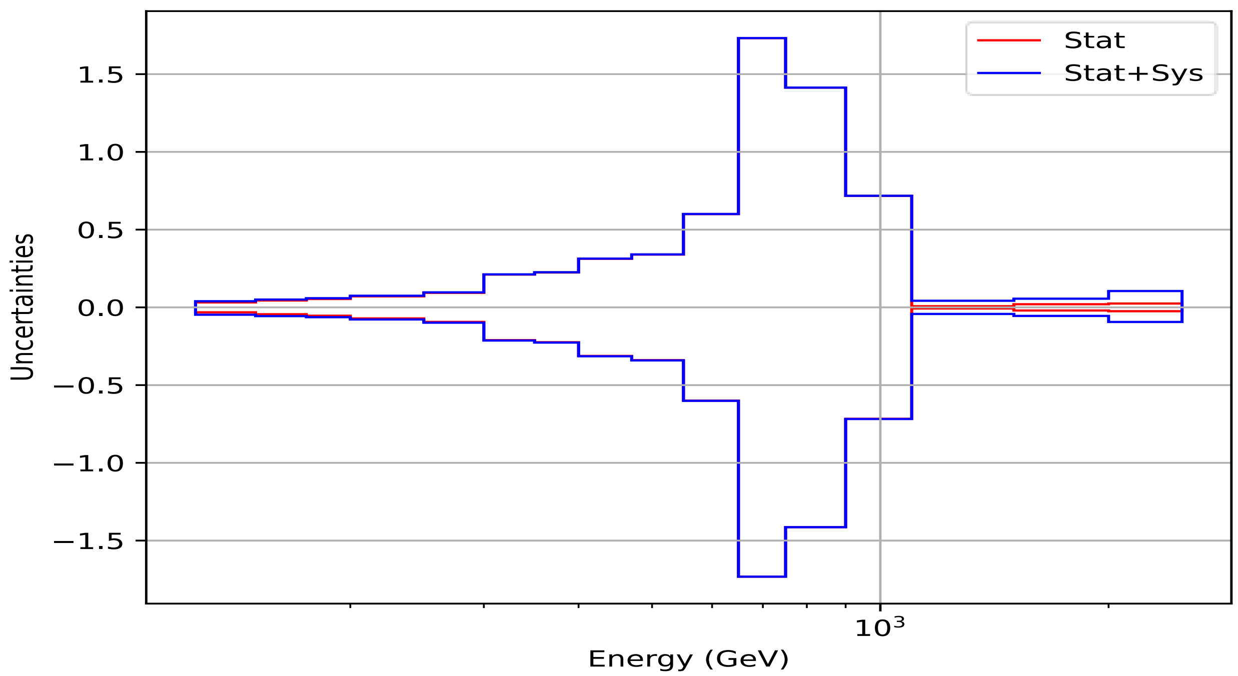
- If one of them is reconstructed as a photon, **we add its E_T to the histogram**
- If both of them are reconstructed as photons, we add the highest p_T electron to the E_T^{γ} histogram.

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 :

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

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

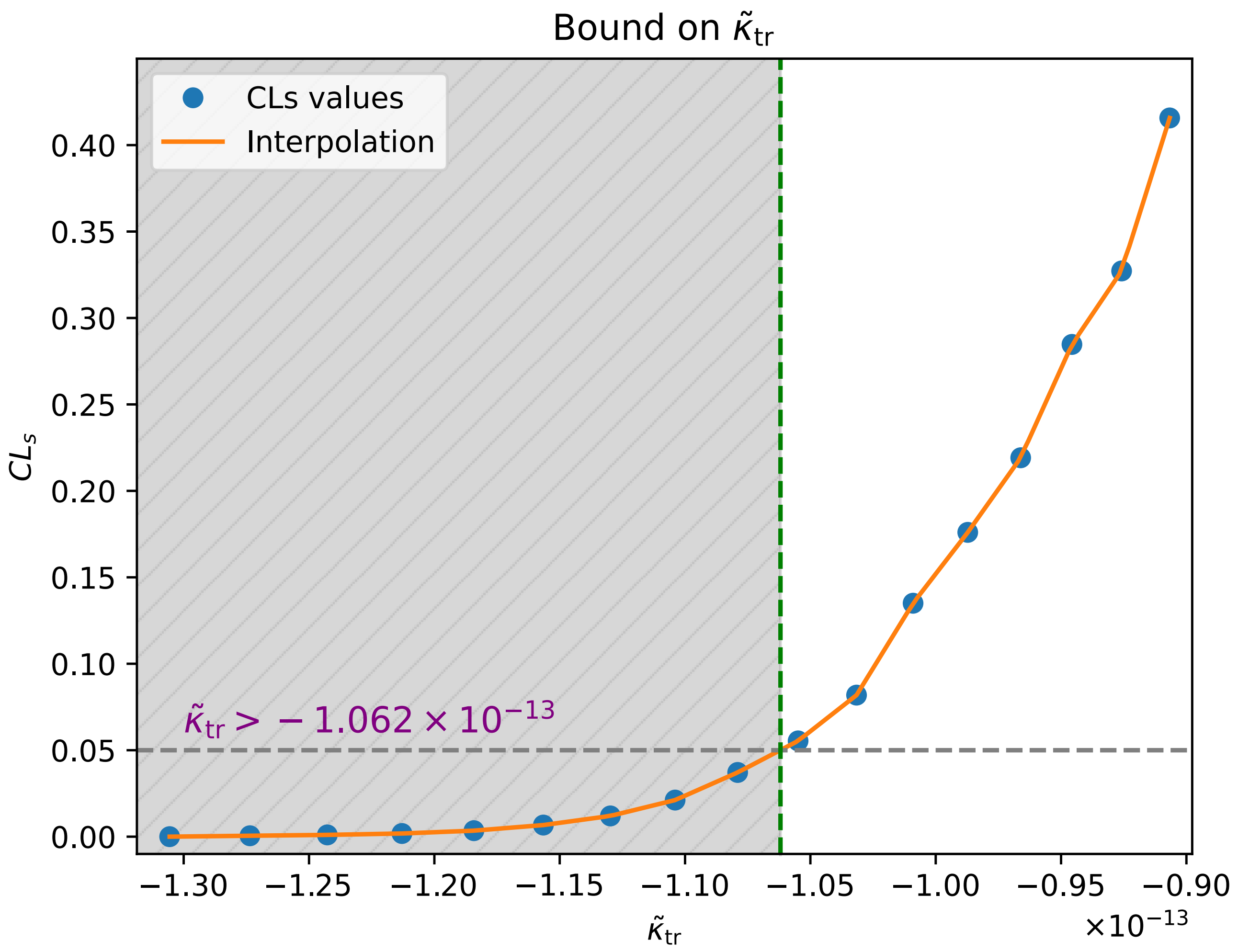
$$CL_s = \frac{CL_{s+b}}{CL_b}$$

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

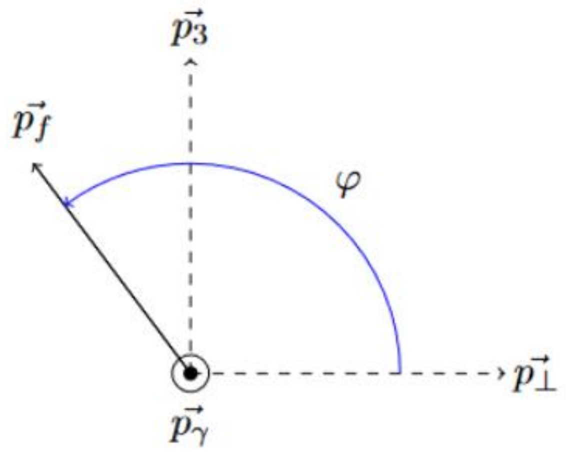
We construct the fermion momentum following :

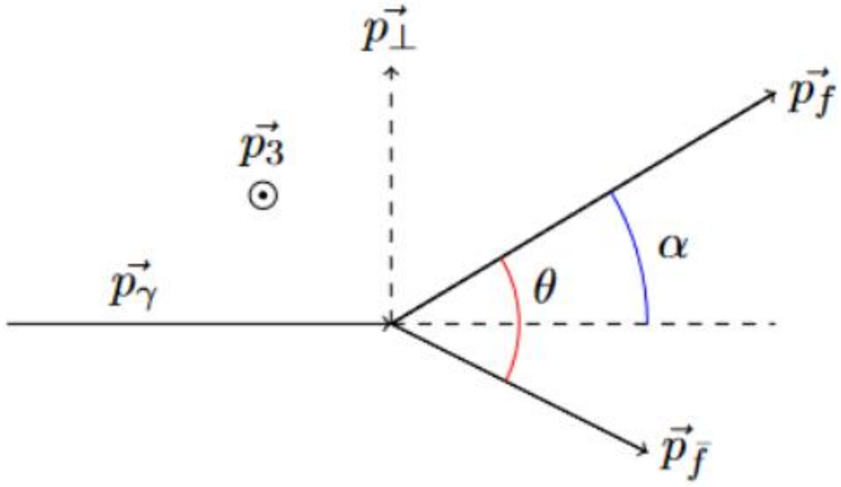
$$\cos\theta = \frac{E_e(E_\gamma - E_e) + \frac{\tilde{\kappa}tr}{1-\tilde{\kappa}tr}E_\gamma^2 + m_e^2}{\sqrt{[E_e^2 - m_e^2][(E_\gamma - E_e)^2 - m_e^2]}}$$

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

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

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

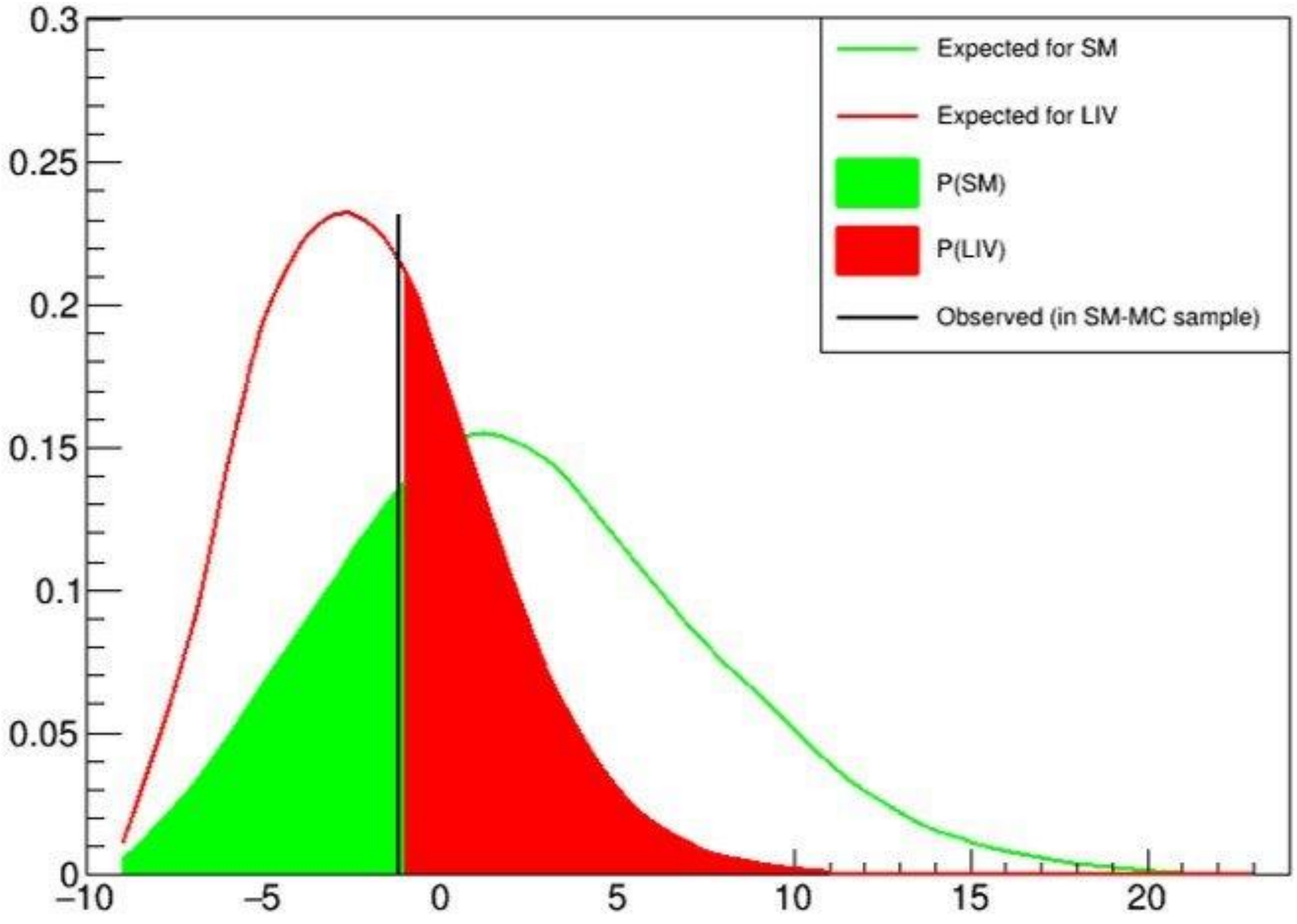
$$\kappa^{\mu\nu\rho\sigma} = \frac{1}{2}(\eta^{\mu\rho}\tilde{\kappa}^{\nu\sigma} - \eta^{\mu\sigma}\tilde{\kappa}^{\nu\rho} + \eta^{\nu\sigma}\tilde{\kappa}^{\mu\rho} - \eta^{\nu\rho}\tilde{\kappa}^{\mu\sigma})$$

$\tilde{\kappa}^{\mu\nu}$ 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