Test of global symmetries of the Standard Model in the top quark sector

With CMS at LHC

Phd Days 2024

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IP2I Lyon - CMS

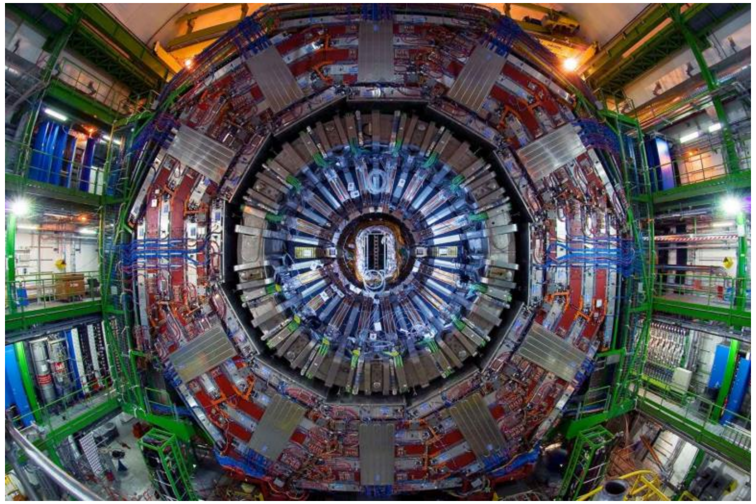
16 avril 2024

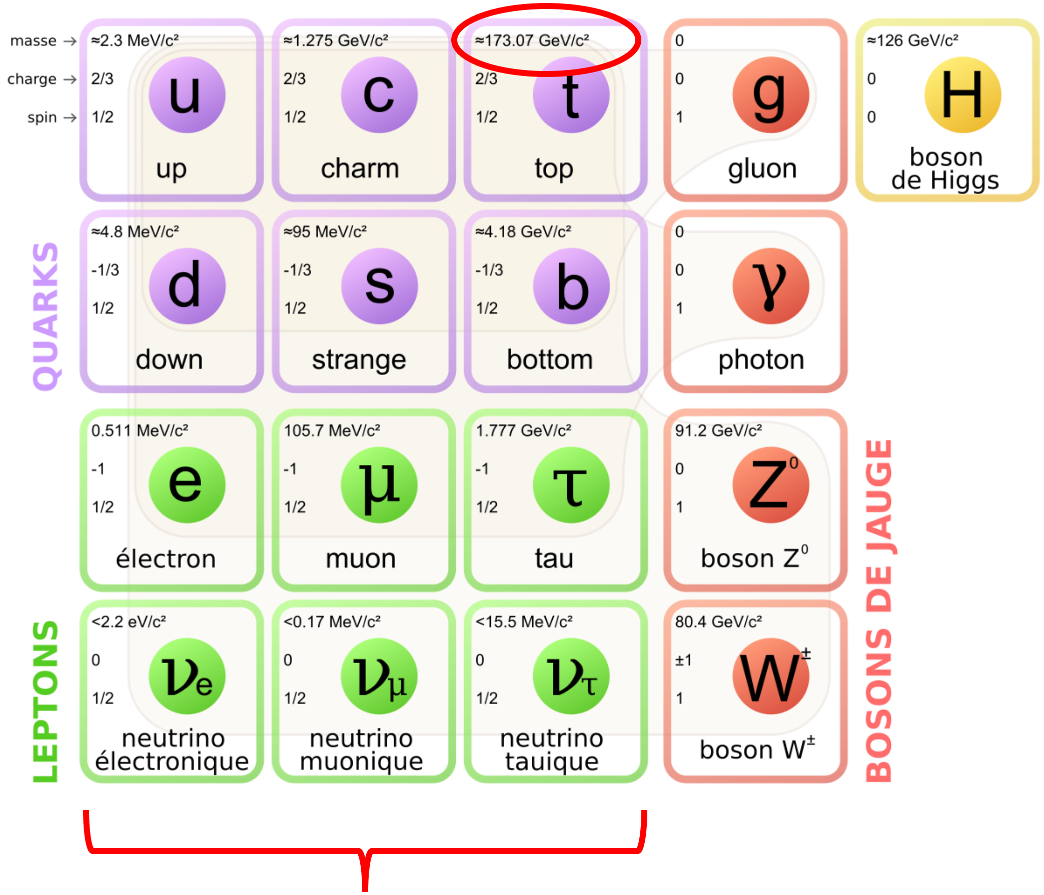
Motivations – Lepton Flavor Universality (LFU)

The top quark is the **heaviest elementary particle** in the Standard Model.

Many models beyond the SM predict a **special coupling** of the top quark with new resonances at high energy scales.

Testing **lepton flavor universality** with top quarks at CMS



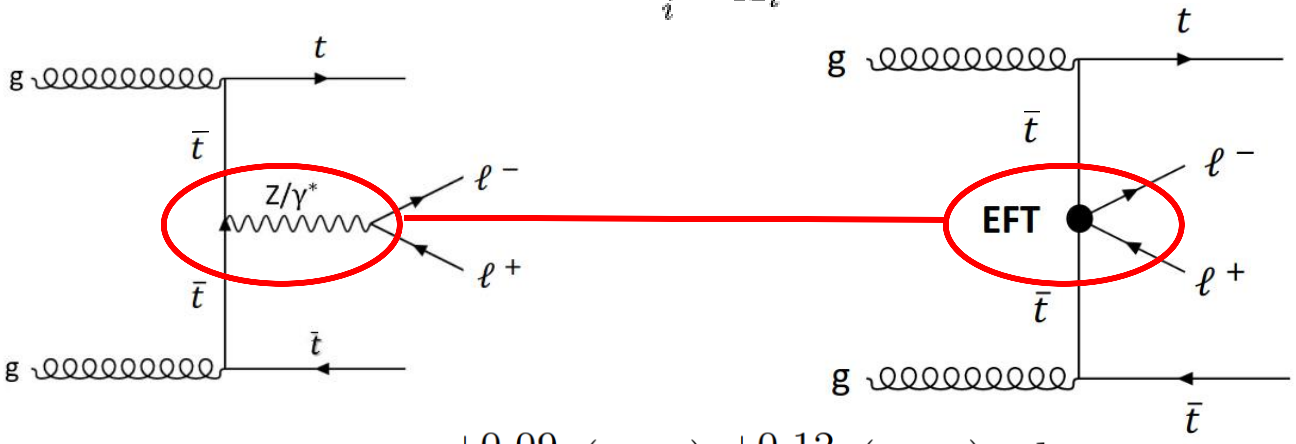


3 generations that differ only by their masses according to the Standard Model

Search for LFU violation with Run 2 CMS data

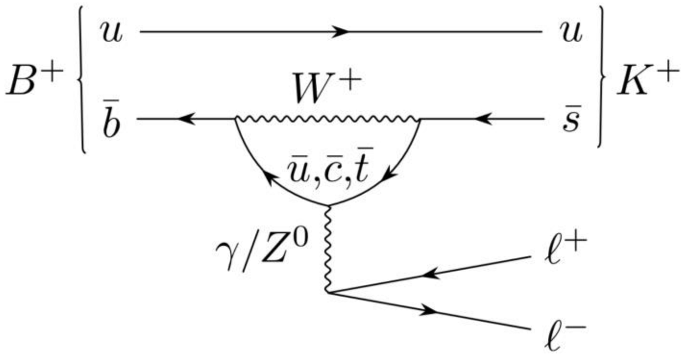
Modeling the violation of lepton flavor universality with an effective theory

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda_i} O_i + h.c.$$



$$\sigma_{t\bar{t}Z/\gamma^*} = 0.99^{+0.09}_{-0.08}\ (\mathrm{stat})\ ^{+0.12}_{-0.11}\ (\mathrm{syst})\ \mathrm{pb}$$

CMS collaboration
(1711.02547)



Connection between top quark physics and B physics

Measurement of the SM $t\bar{t}\gamma^*$ process, never measured at the LHC

Measurement of the effective coupling between the top quark and leptons using the EFT, separately for electrons and muons

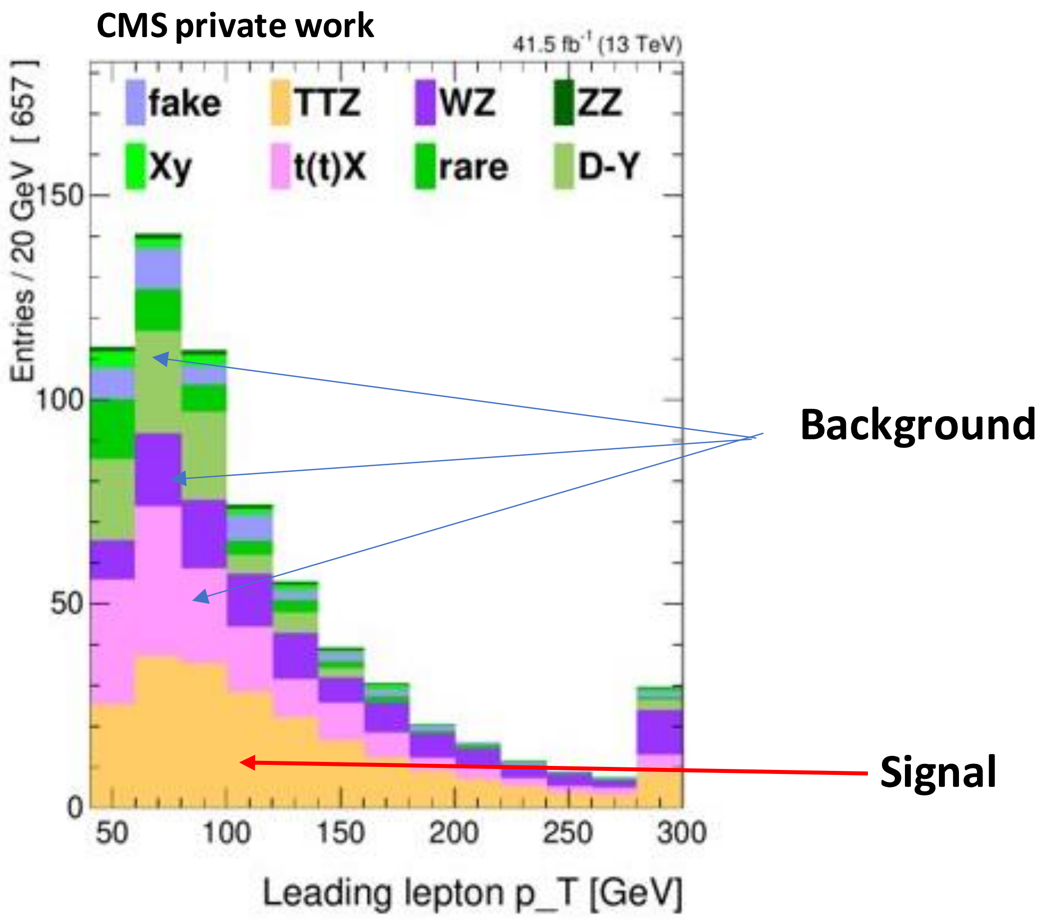
We are studying the multi-lepton channel (3 or 4 leptons in the final state)

Example of an EFT operator :

$O_{lt}^{(ij)} = (\bar{l}_i \gamma^\mu l_j)(\bar{t}\gamma^\mu t)$ et $O_{et}^{(ij)} = (\bar{e}_i \gamma^\mu e_j)(\bar{t}\gamma^\mu t)$

CMS Analysis - Signal Region

Targeting our signal $t\bar{t} + ll$



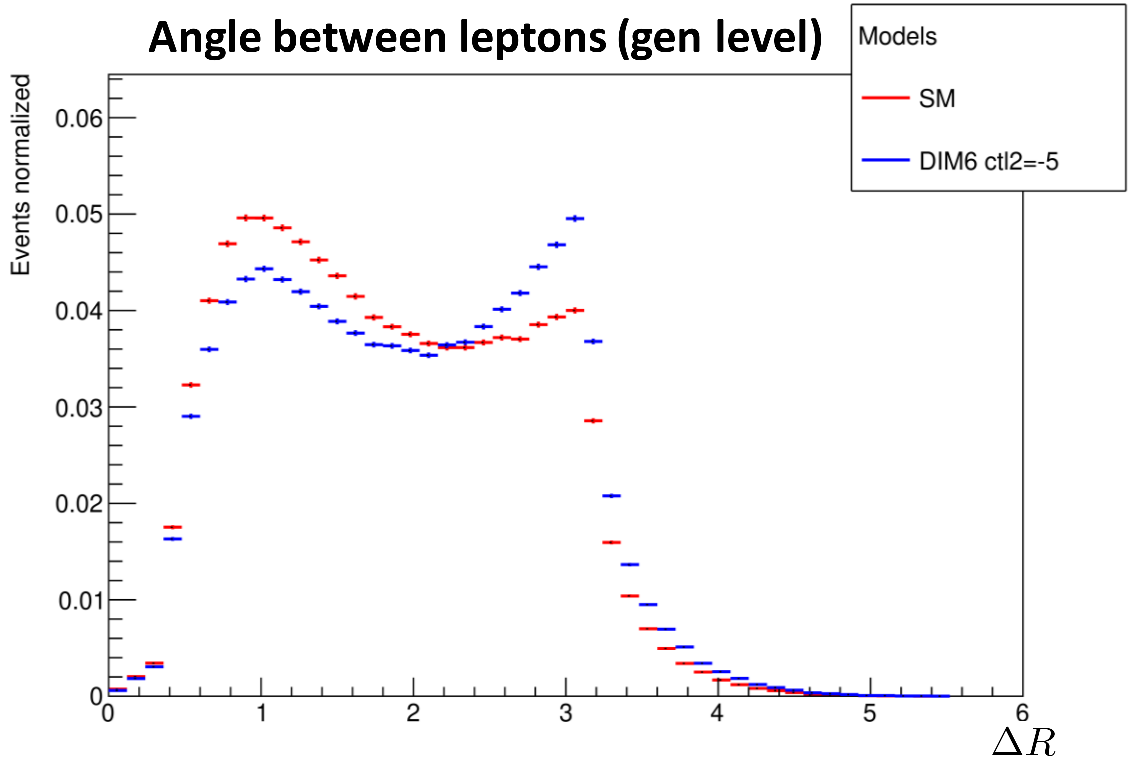
This signal region will be used to :

1) Measure the process $t\bar{t}\gamma^*$ (inside $t\bar{t}Z$ in this plot)
2) Measure the EFT coefficients for lepton flavor violation

Variable to test to extract the signal :

- The invariant mass of the leptons
- The angles between the leptons
- Advanced methods such as Matrix Element Method (MEM) or Machine Learning

CMS Analysis - Phenomenology of the Signal Region



$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

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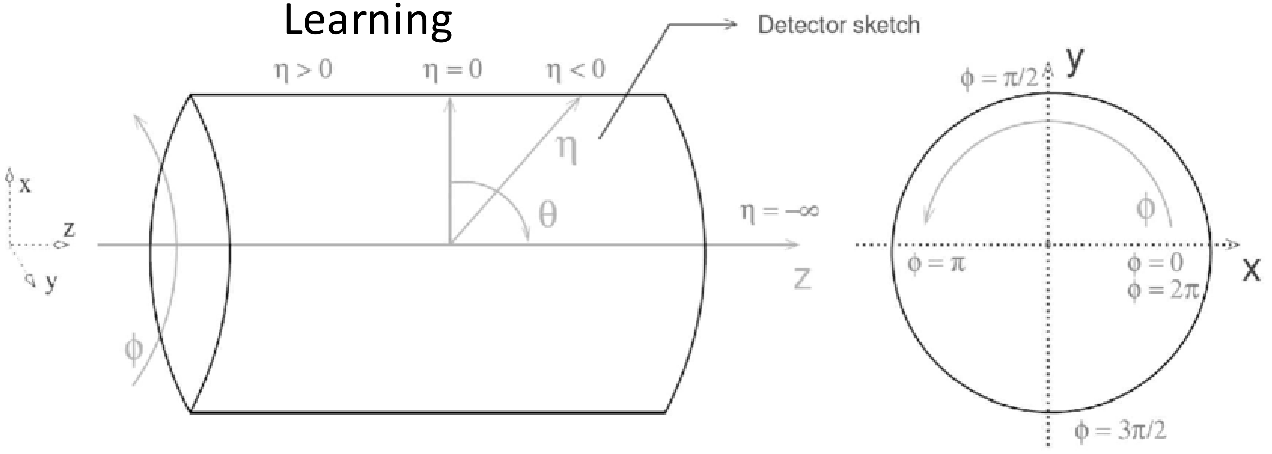
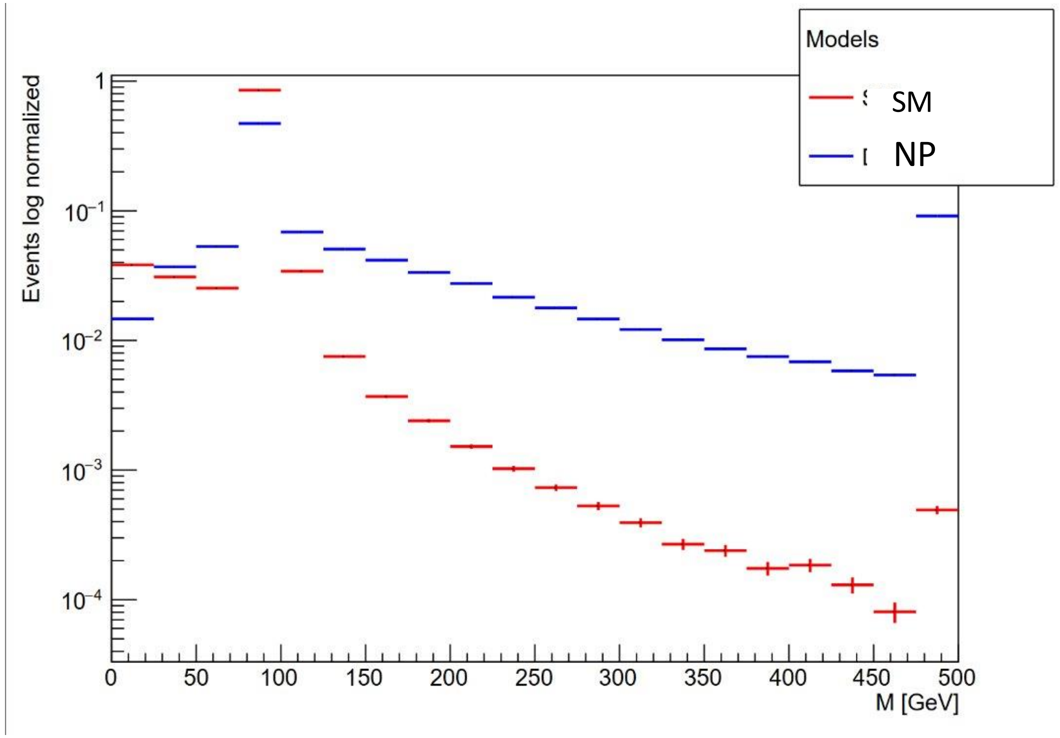


CMS Analysis - Phenomenology of the Signal Region

Leptons' invariant mass (gen level)



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Variable to test to extract the signal :

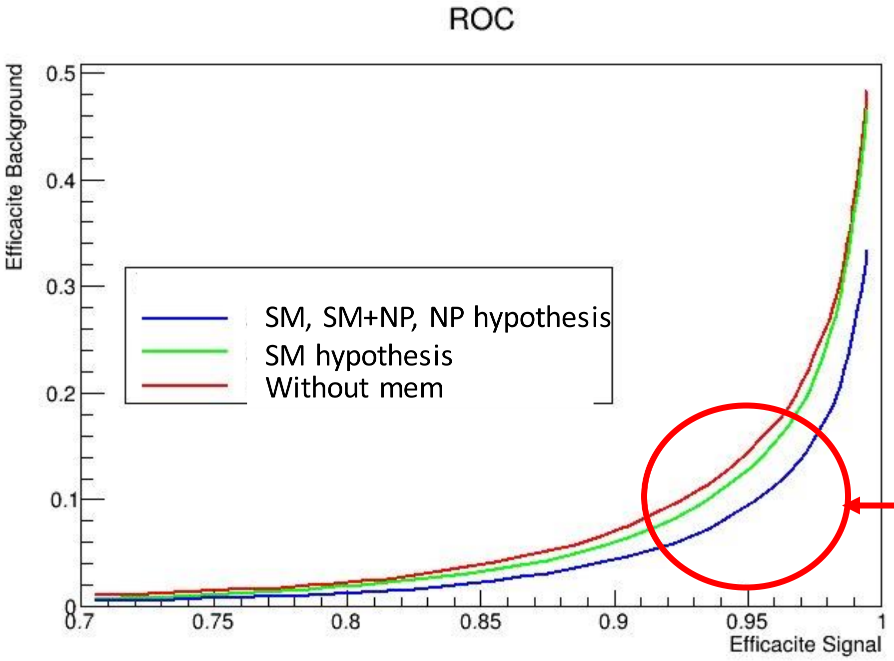
- The angles between the leptons
- **The invariant mass of the leptons**
- Advanced methods such as Matrix Element Method (MEM) or Machine Learning

CMS Analysis – Matrix Element Method

- Calculation of the partial cross-section corresponding to the phase space of the reconstructed event

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 3} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F)f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

Matrix Element
For the New Physics, the element is computed using MadGraph

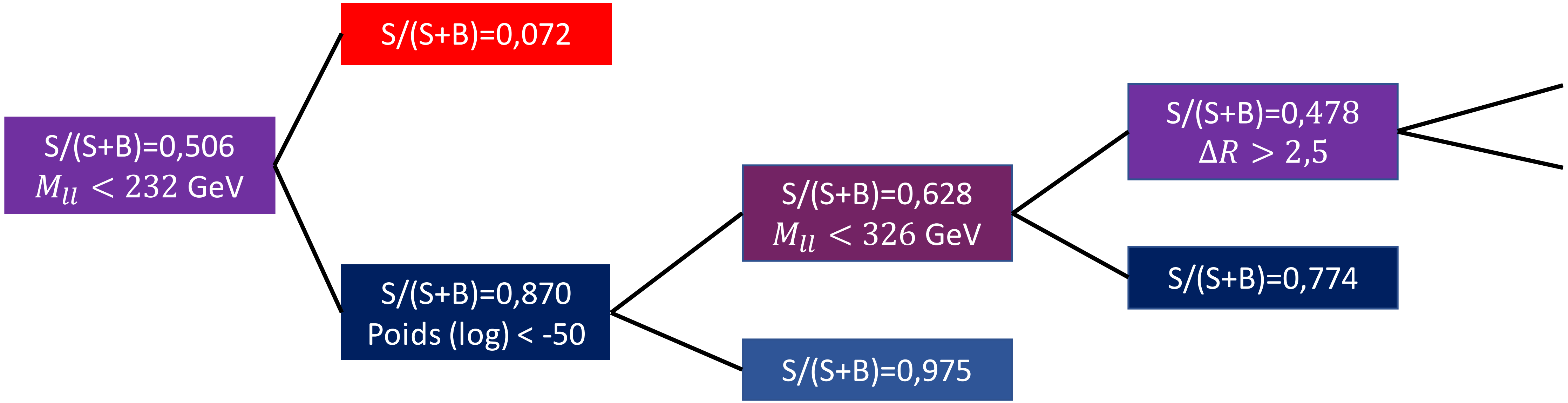


Relative reduction of background noise efficiency by 30%

CMS Analysis – Boosted Decision Tree

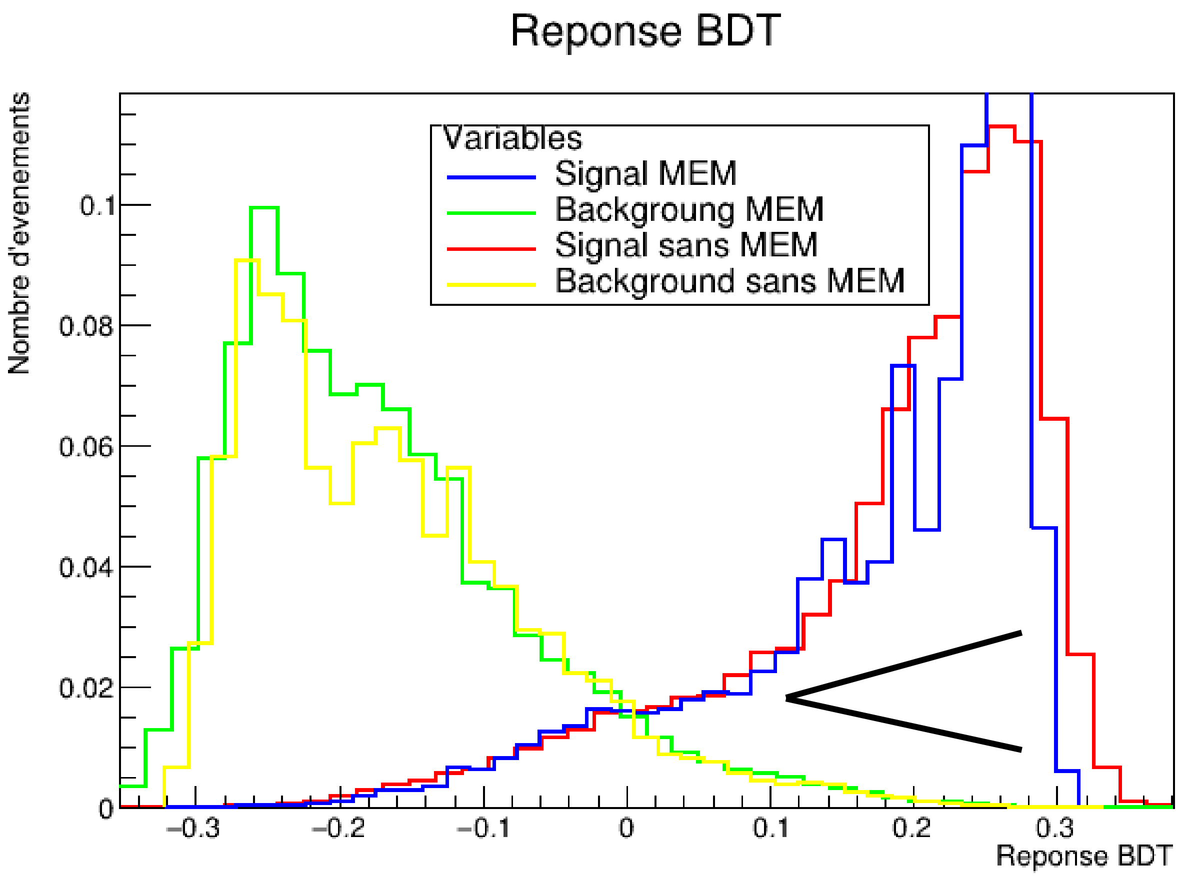
- We select input variables that should be discriminative
- We construct weak classifiers slightly better than random classification.
- Each classifier depends on the previous ones.

- We construct the strong classifier by weighted averaging of the weak classifiers
- Ranking at each step into 2 categories: here, Standard Model (background noise) and New Physics (signal)
- Decision cascade until a condition on the weights is met



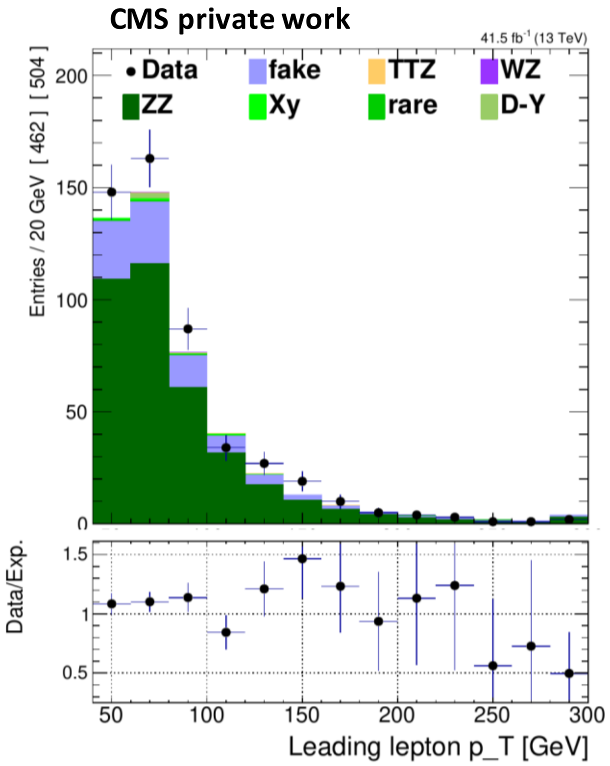
CMS Analysis – Boosted Decision Tree

- The BDT response shows the classification of events.
- A good polarization of the samples.
- The MEM allows for better classification.

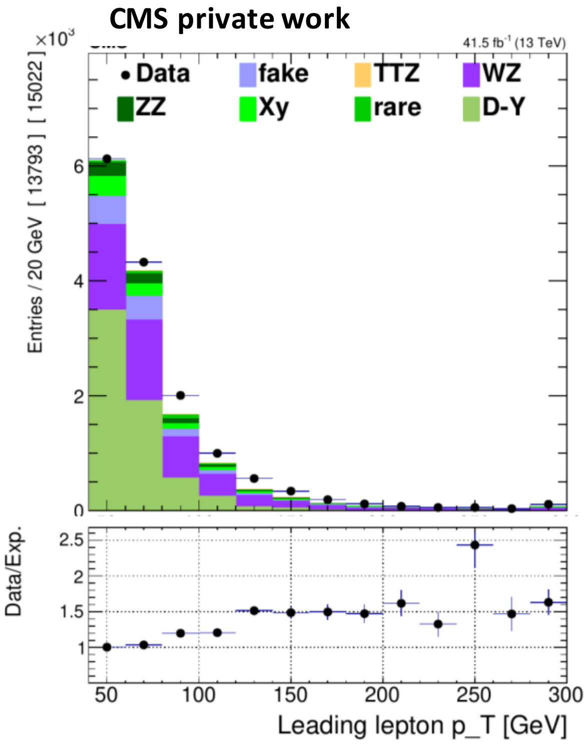


CMS Analysis - Control Regions

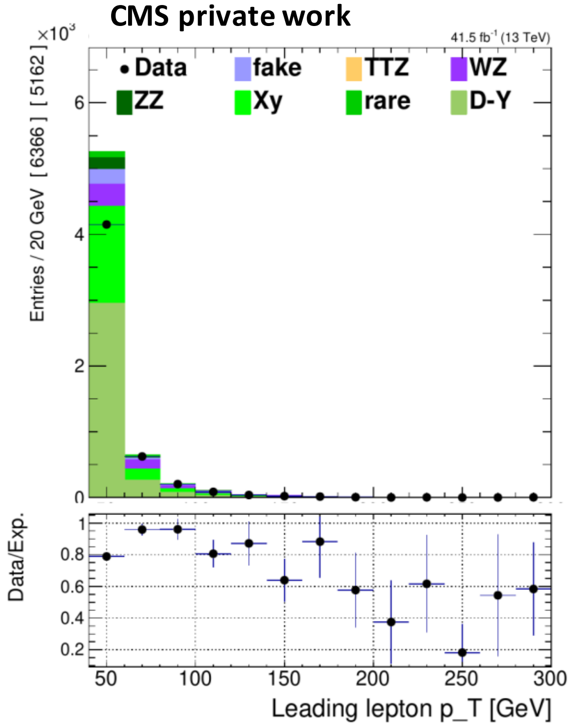
Similar topology with the signal, but **negligible signal yield**



ZZ



WZ



$\mathbf{X}\gamma$

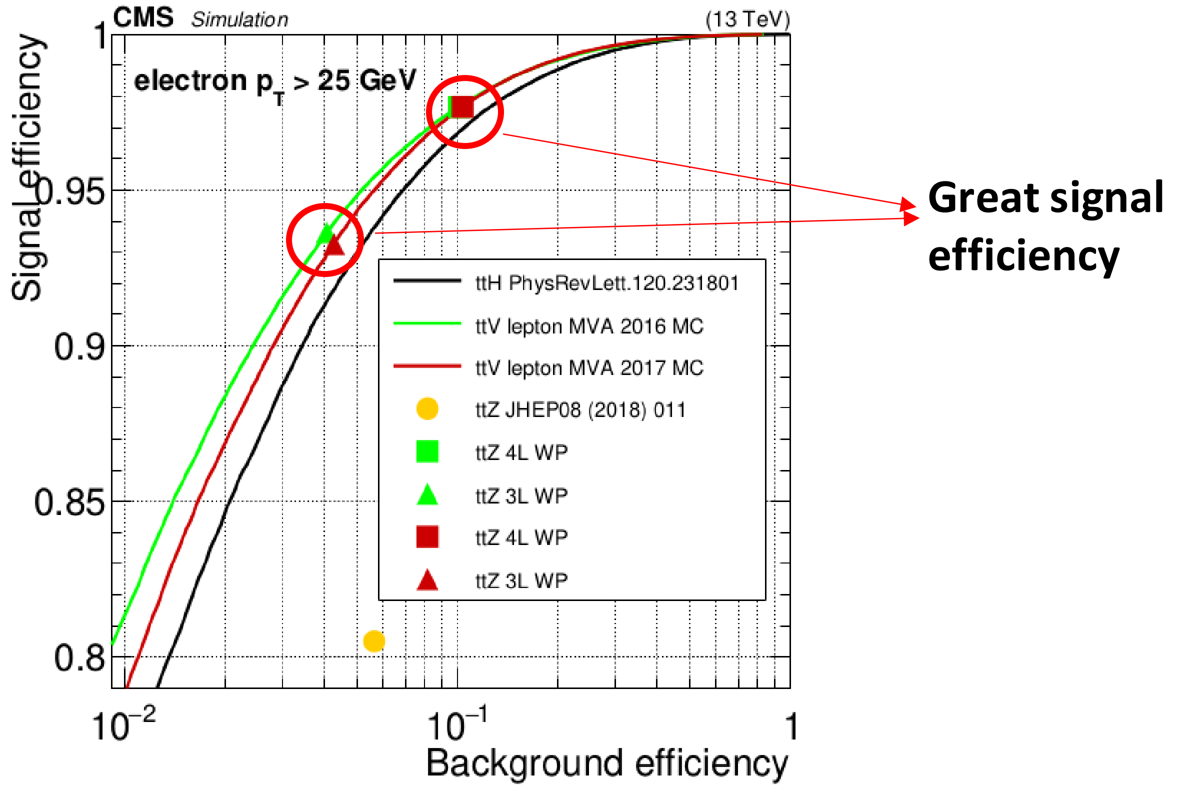
(conversion $\gamma \rightarrow l^+l^-$)

The goal is to **control the background processes**

Monte Carlo – data agreement will be improved after adding the recommended corrections

CMS Analysis – Improvement of lepton selection

Improved lepton identification using a multivariable discriminant (LeptonMVA)



CMS Collaboration (1907.11270)

The goal is to **improve background rejection**

The selection criterion in the analysis has an efficiency of approximately 70%

The LeptonMVA **effectively rejects** a substantial amount of **background**

It was developed within the CMS collaboration

Lagrangian 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

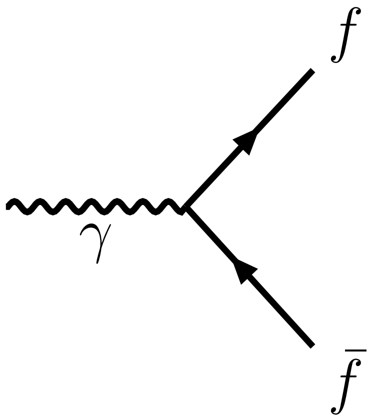
$\tilde{\kappa}_{tr} \in (-1,0) \implies v_{gr} > 1$ Photon decay in vacuum

- **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** : $\tilde{\kappa}_{tr}$

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 $\tilde{\kappa}_{tr} \rightarrow 0$ where the threshold goes to infinity since this process is forbidden when the symmetry is intact

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

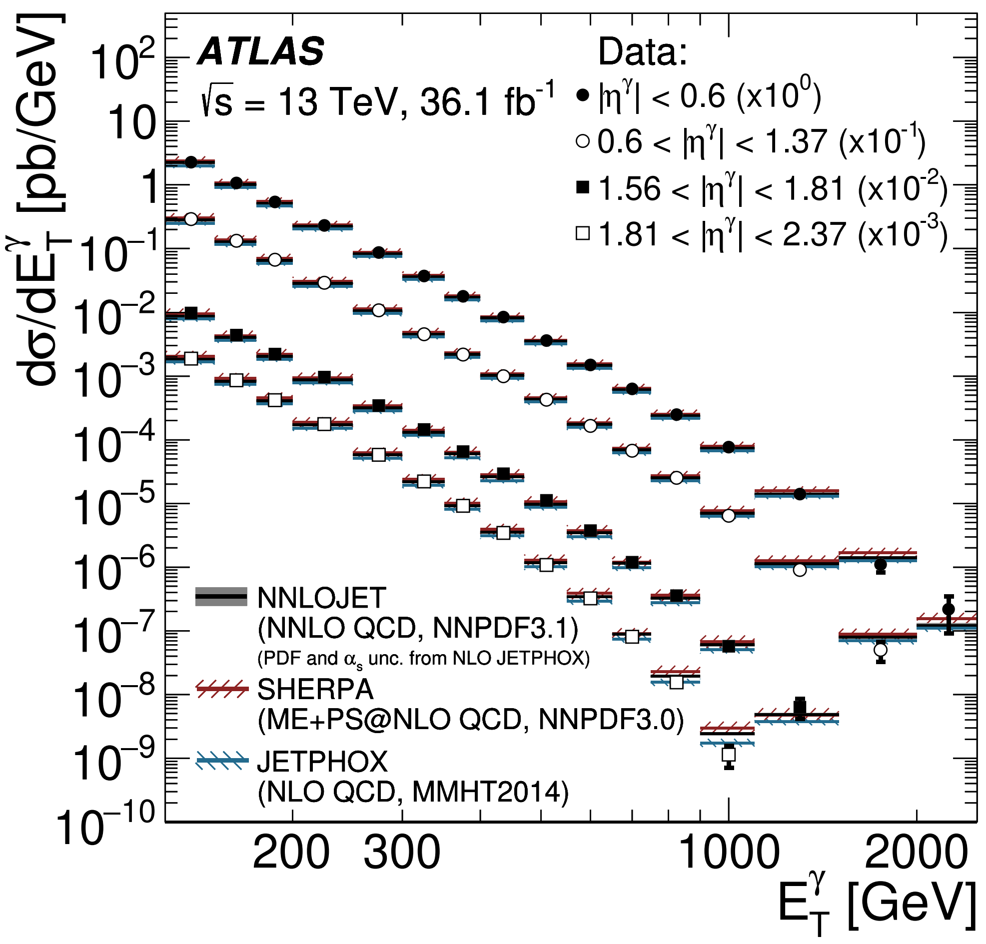
To constrain $\tilde{\kappa}_{tr}$, we need to find the **threshold energy** above which photons could decay in the vaccum.

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

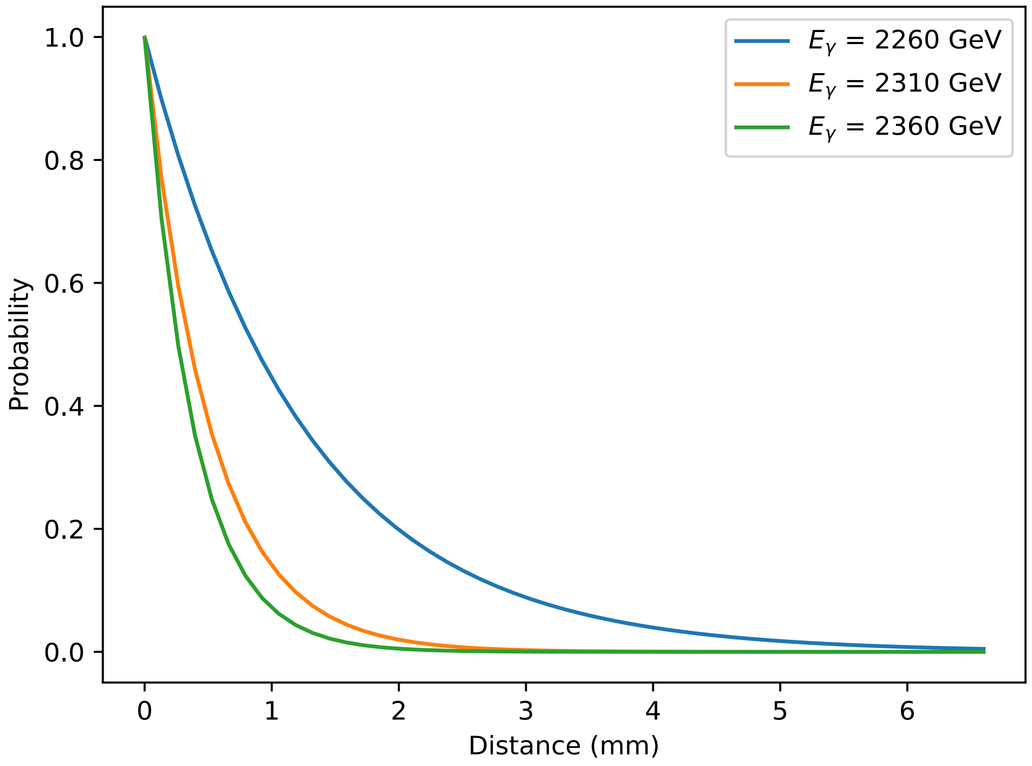
$$\frac{MC_{ATLAS,i}}{MC_{local,i}}$$

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

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



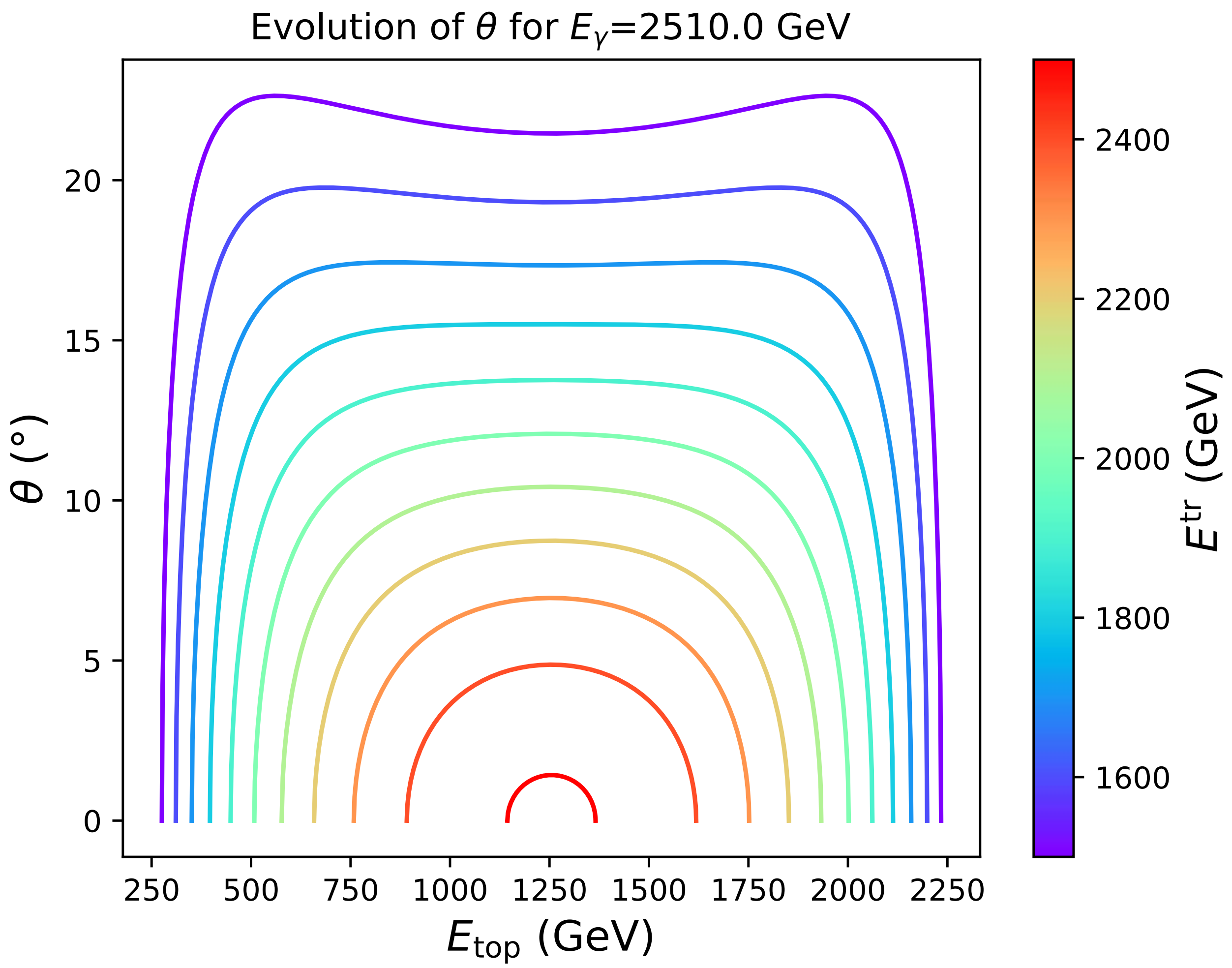
Photon decay – opening angle

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

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

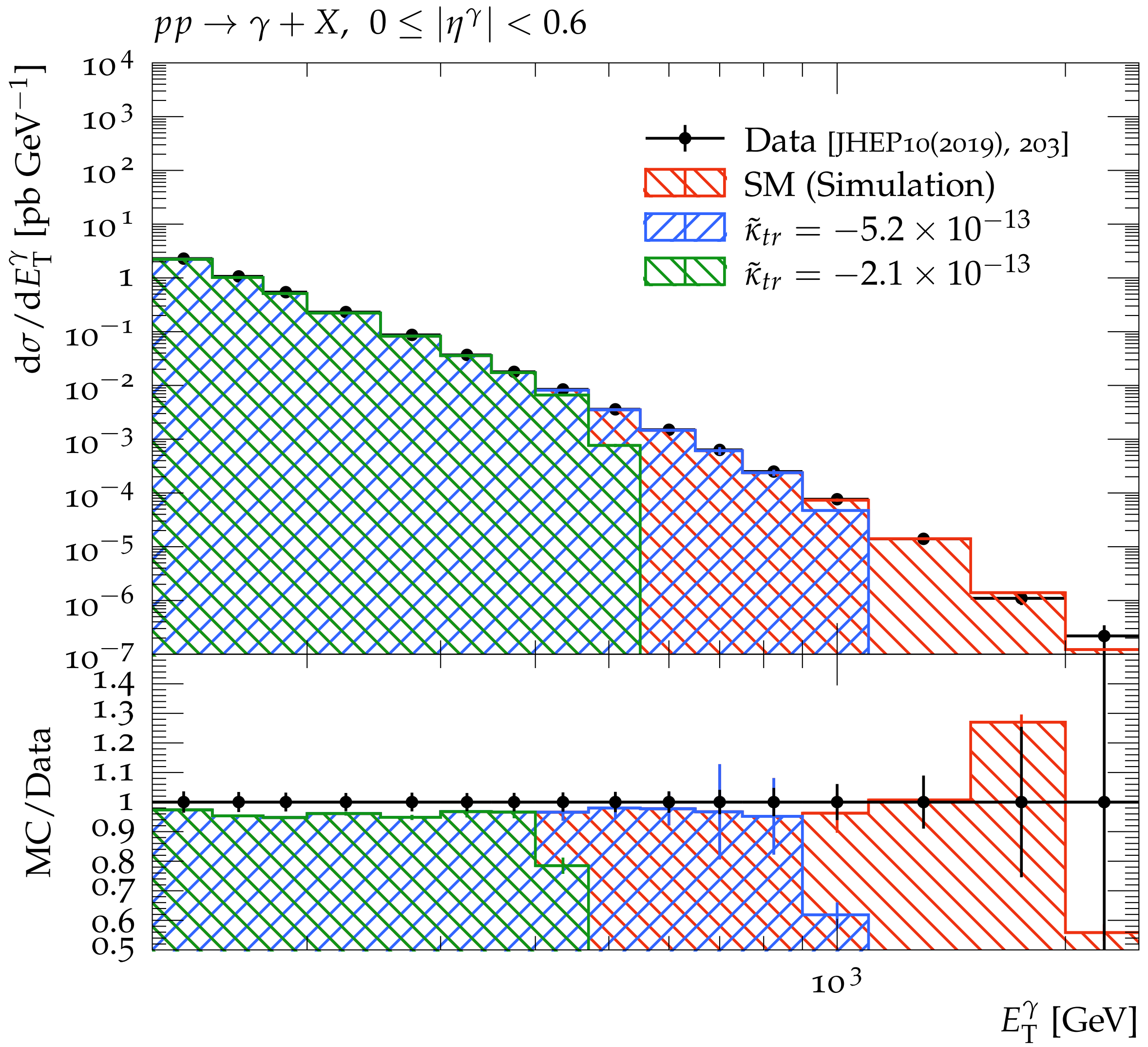
Where E_γ and E_f are the energies of the incoming photon and outgoing fermions

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



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



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 :

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

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

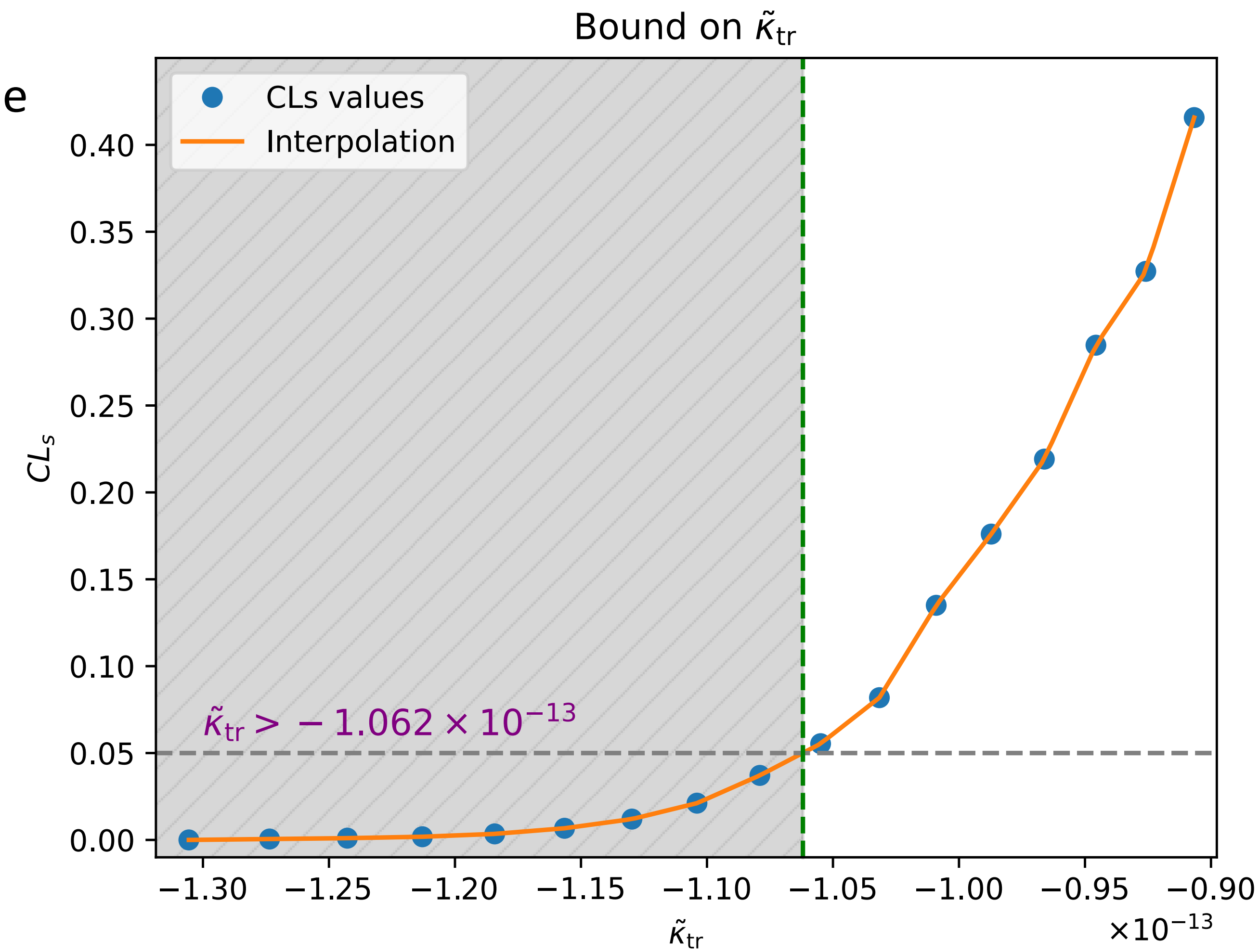
$$CL_s = \frac{CL_{s+b}}{CL_b}$$

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 :

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



Contribution to the validation of CMS reconstruction

In CMS detector, a **reconstucted hits** (RecHits) represent an **energy deposit** of a particle

We look at RecHits inside the **Hadron Calorimeter,** and only look at **neutrals particles** around electrons

Neutral isolation helps to distinguish between collision point particles and background sources particles

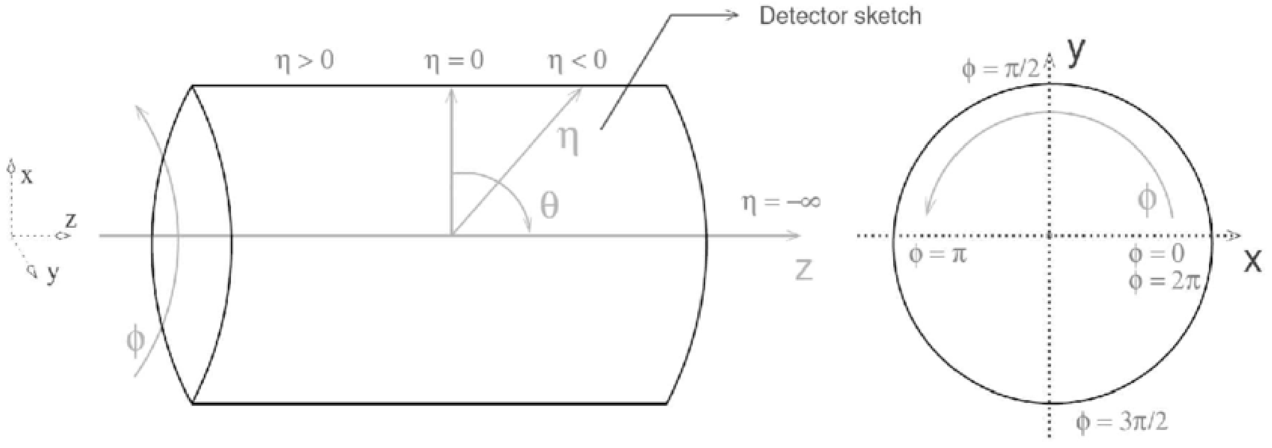
The neutral isolation is defined as :

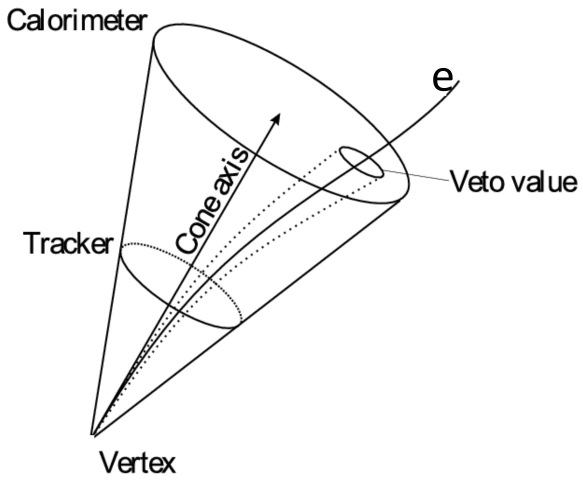
$$\sum_n E_{T_n}$$

Where n is a neutral RecHits in a ΔR cone around the electron

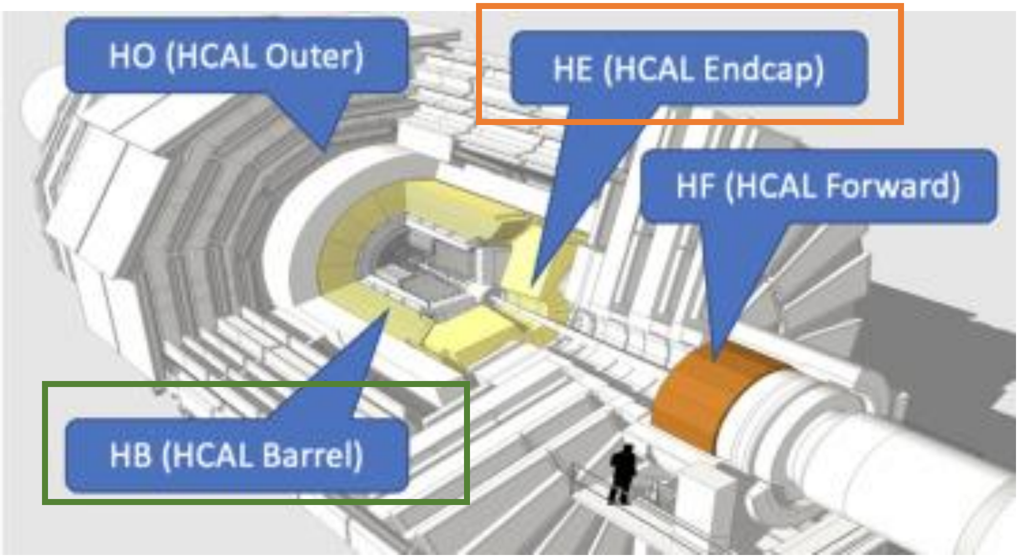
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

The RecHits are selected if 0.15 < ΔR < 0.3





EPR task – Hadron Neutral Isolation



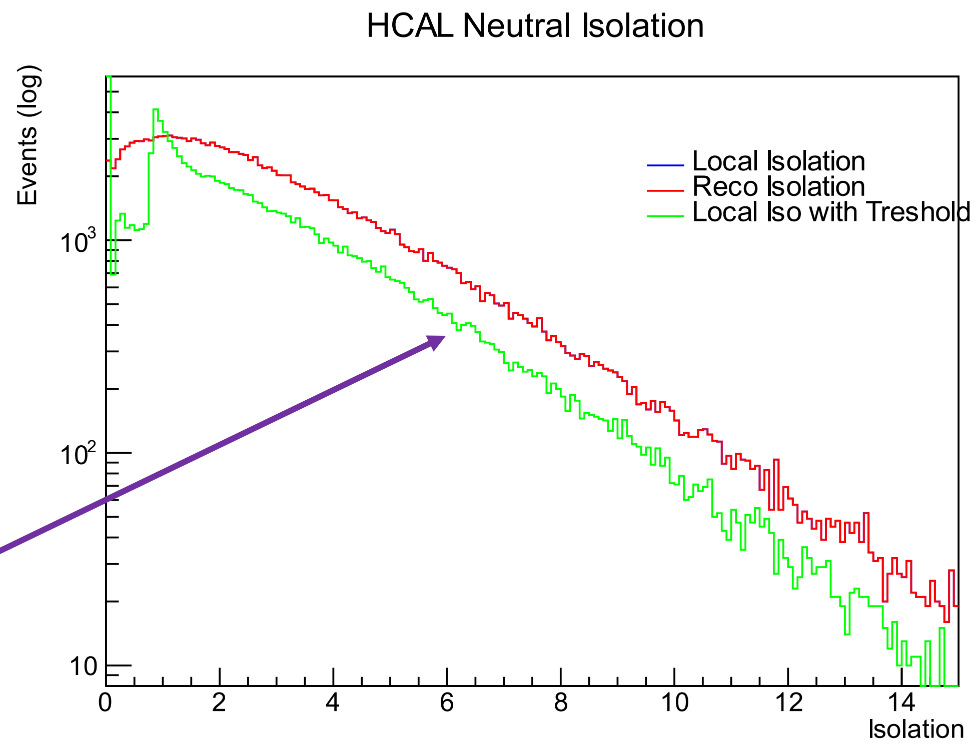
There are 2 differents zone inside the HCAL :

- The Barrel
- The Endcap

Reproduced HCAL isolation stored in CMS samples. Working on the HCAL cone size and validating HCAL isolation between data and MC.

Cuts are applied on the RecHits to compute the Isolation :

- For a RecHits in the Barrel, we need E_t > 0.8GeV
- For a RecHits in the Endcap, we need E_t > 0.2 GeV



Summary

Lepton Flavor Universality

- **Implementation of the selection** to define control and signal region
- Defined baseline **discriminating variables**
- **Measure** of $t\bar{t}\gamma^*$ process in the SM
- **Generate** signal sample
- **Extraction** of the EFT coefficients

Lorentz Invariance Violation

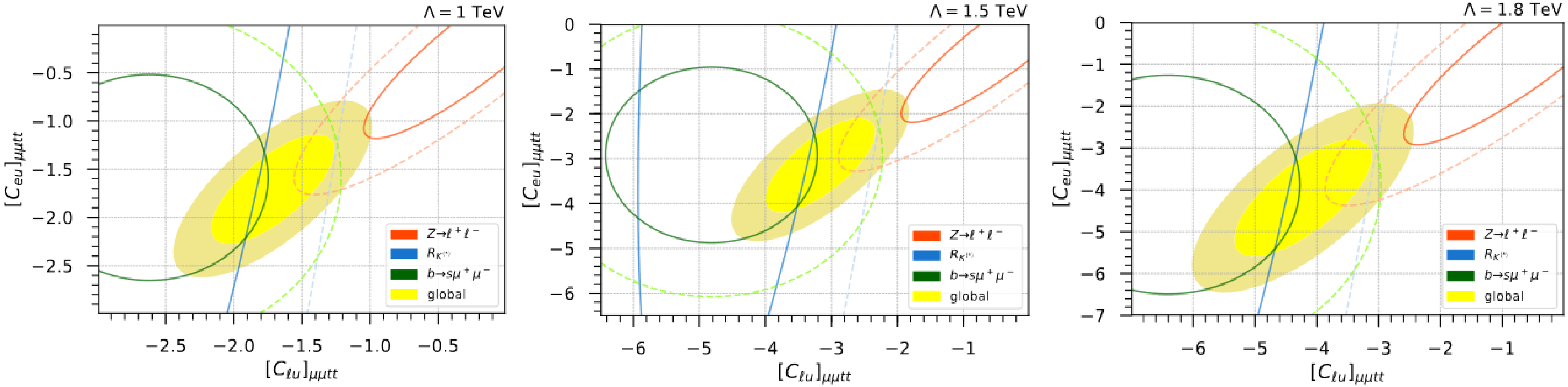
- Put a **constraint** on the LIV coefficient around **55 times better** than the previous mesurement
- Still no LIV observation
- Publication : arxiv:2312.11307. **Accepted by PRL. Presented at IRN Terrascale 2024**

Contribution to the validation of CMS reconstruction

- **Optimisation** of the HCAL isolation cone size
- Need to **compare Data/MC**

Back-up slides

Estimation of the value of the coefficient



arXiv:1805.04917v

Matrice CKM

Matrix containing the probabilities of flavor change during a weak interaction.

$$\begin{bmatrix} |V_{\mathrm{ud}}| & |V_{\mathrm{us}}| & |V_{\mathrm{ub}}| \\ |V_{\mathrm{cd}}| & |V_{\mathrm{cs}}| & |V_{\mathrm{cb}}| \\ |V_{\mathrm{td}}| & |V_{\mathrm{ts}}| & |V_{\mathrm{tb}}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix}$$

Probability of flavor change from bottom quark to top quark.

Describing the mixing between mass eigenstates and flavor eigenstate

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix} = \begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix}$$

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]*
$-\left(\tilde{\kappa}_{tr} - \frac{4}{3}c^{e}_{00}\right)$	$< 6 \times 10^{-21}$	"	[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**

Fermion momentum construction

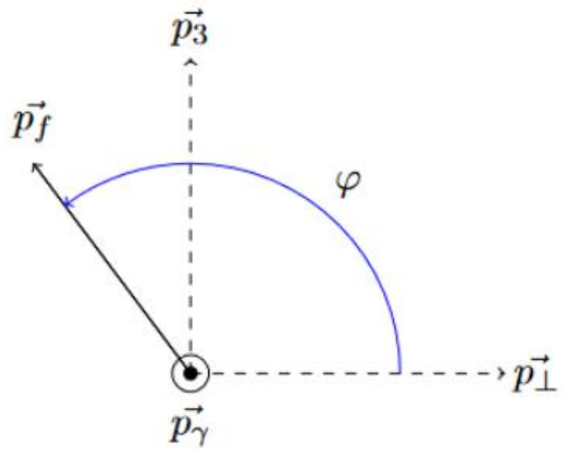
We construct the fermion momentum following :

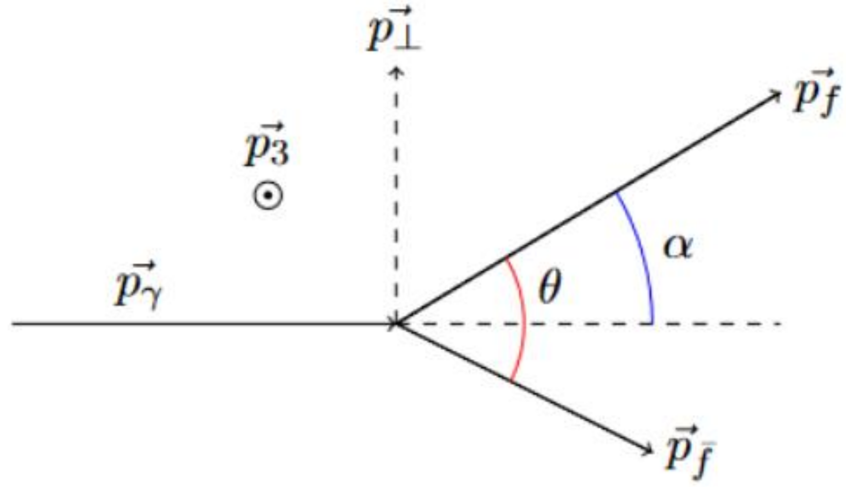
$$\cos\theta = \frac{E_e(E_\gamma - E_e) + \frac{\tilde{\kappa}tr}{1-\tilde{\kappa}tr}E_\gamma^2 + m_e^2}{\sqrt{[E_e^2 - m_e^2][(E_\gamma - E_e)^2 - m_e^2]}}$$

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

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

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

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

Measurement – CLs method

The CLs method is used to set upper or lower limit on parameters

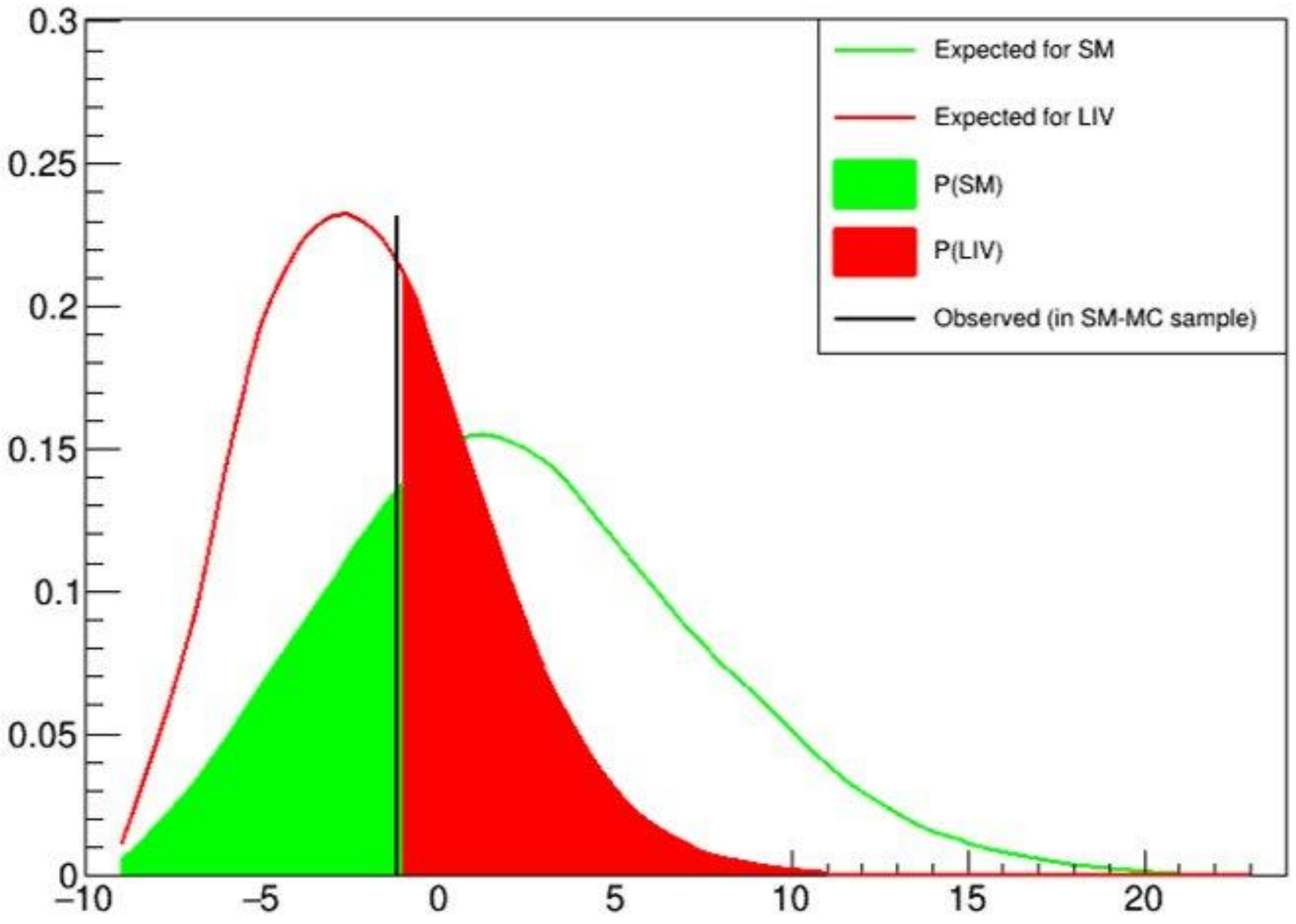
For a statistical test q, we define :

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

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

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

We use CLs < 0.05 by convention



Measurement – Statistical test

The statistical test is a log likelihood ratio. It is evaluated over the Y variable defined as :

$$Y \sim \mathcal{P}(X) \text{ with } X \sim \mathcal{N}(\mu_i, \sigma_i)$$

where μ_i is the bin value and σ_i the systematic uncertainty.

The data systematic uncertainties are already given by the ATLAS mesurement. They include:

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