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# Scalar Leptoquark from Beyond Standard Model

*2983535D@student.gla.ac.uk*
*Supriyo Dutta*

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# Why ***NEED*** Beyond Standard Model ?

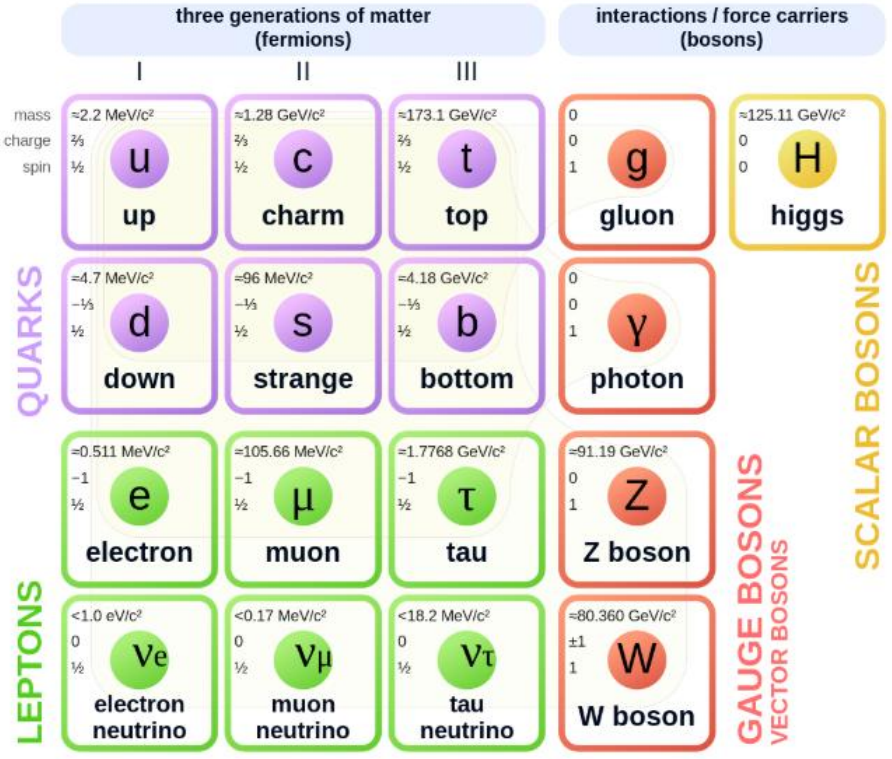


*Fig. 1: Particles of the Standard Model.*

**Gauge Symmetry**

$SU(3)_C \times SU(2)_L \times U(1)_Y$

From Discovery of Higgs in 2012 → ***SM is Complete!***

**Explained Mostly Accurate** ✓

***EXCEPT few***

***Source :***

- *Figure 1:* [*The Standard Model of Particle Physics and Beyond | ATLAS Open Data*]
- [David Tong: The Standard Model]

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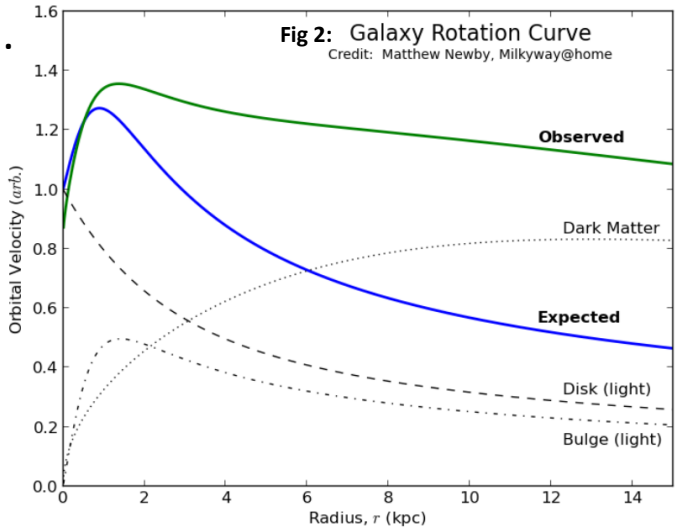
# SM Anomalies

## 1. Absence of Gravity from SM


4 fundamental forces

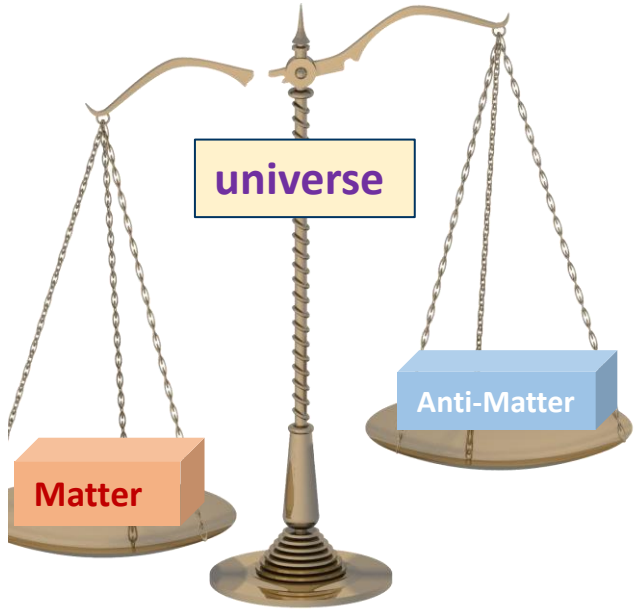
## 2. Absence of Dark Matter Particle

- .




- *Bullet Cluster*

## 3. Matter-Antimatter Asymmetry




## & Many More

**SM** → **BSM**

**Source :**

- *Figure 2: Galaxy Rotation Curve – Professor Newby's Educational Quanta*
- *Electroweak baryogenesis arXiv:1206.2942v1 [hep-ph]*
- *DOI : [2309.03870] Anomalies in Particle Physics*

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## Main Focus

$$\prod_7 \sim (aka\ R_2)$$

**Scalar Leptoquark** : *Couples to both Leptons and Quarks Together*

*Emerges from* ***Extended Higgs Sector of SU(5)***

$45_H$ *Dimensional*

*part of* ***GRAND UNIFIED THEORY***

$SU(3)_C \times SU(2)_L \times U(1)_Y$

SM Gauge Group

***Single and bigger group e.g. SU(5)***

*But why are leptoquarks* **Important** ?

**Source :**

- *Scalar leptoquarks from grand unified theories to accommodate the B-physics anomalies* DOI: https://doi.org/10.1103/PhysRevD.98.055003
- Dimension-six terms in the Standard Model Lagrangian https://doi.org/10.48550/arXiv.1008.4884

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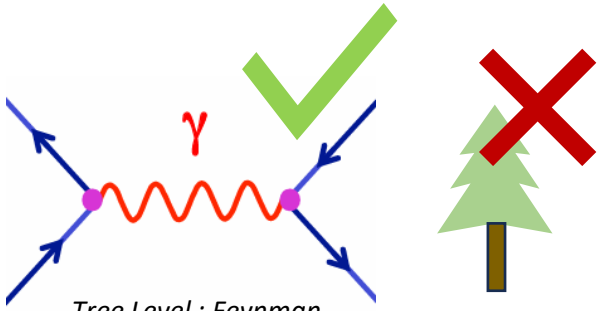
# Lepton Flavor Universality (LFU) @SM

***In gauge interaction ($W^{\pm}, Z$ : Electroweak Interaction) all of the leptons should be interacting in the same manner, regardless of their mass.***




*Tree Level : Feynman Diagram with No loop*



Actual Tree

***Lepton Family***

***doublet***

***1st GEN*** ***2nd GEN*** ***3rd GEN***

$$\begin{bmatrix} e^- \\ \nu_e \end{bmatrix} \quad \begin{bmatrix} \mu^- \\ \nu_\mu \end{bmatrix} \quad \begin{bmatrix} \tau^- \\ \nu_\tau \end{bmatrix}$$

****Bigger the yellow ball, higher the Mass***

***According to LFU,***

*in,* ***IDEAL TREE-LEVEL ELECTROWEAK PROCESS***

*When,* **W → different generation of leptons**

$$R_{\mu\tau}^{(W)} = \frac{\Gamma(W \to \mu\nu_\mu)}{\Gamma(W \to \tau\nu_\tau)} \approx 1$$

**Branching Ratio** ***Decay Width***

**However,**

**SOME** *EXPERIMENTS ARE SAYING SOMETHING*

**ELSE.**

***Source :***

- *Test of the universality of τ and μ lepton couplings in W-boson decays with the ATLAS detector https://doi.org/10.1038/s41567-021-01236-w*

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On **Beauty meson decay** *@LHCb RUN 2.*

*Contains Bottom (b) quark*

$$R_k = \frac{BR(B \to K \mu^+ \mu^-)}{BR(B \to K e^+ e^-)} < 1 \ (\sim 3.1\,\sigma)^*$$

*(Experiments)*

*Ratio of Branching Ratio*

***Loop Level Electroweak Process***

***LFU should hold here***

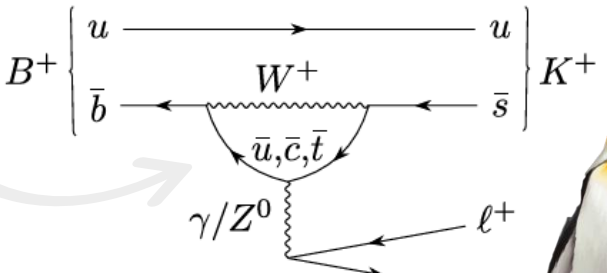


Fig : 3

***BUT it DOESN'T***

*Scientist are expecting a* ***LEPTOQUARK*** *from BSM*

***MISSING LINK***


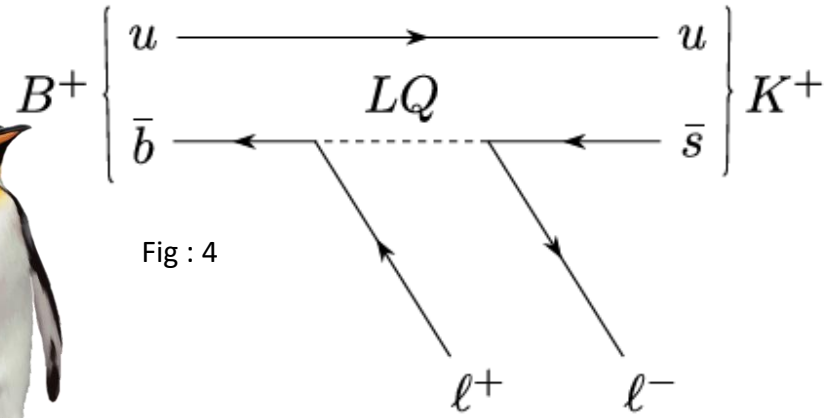


Fig : 4

**BUT, *how to* DETECT *it*** ?

**Source :**
- *Fig 3, Fig 4 : Test of lepton universality in beauty-quark decays arXiv:2103.11769*
- *Penguin : Image Link*

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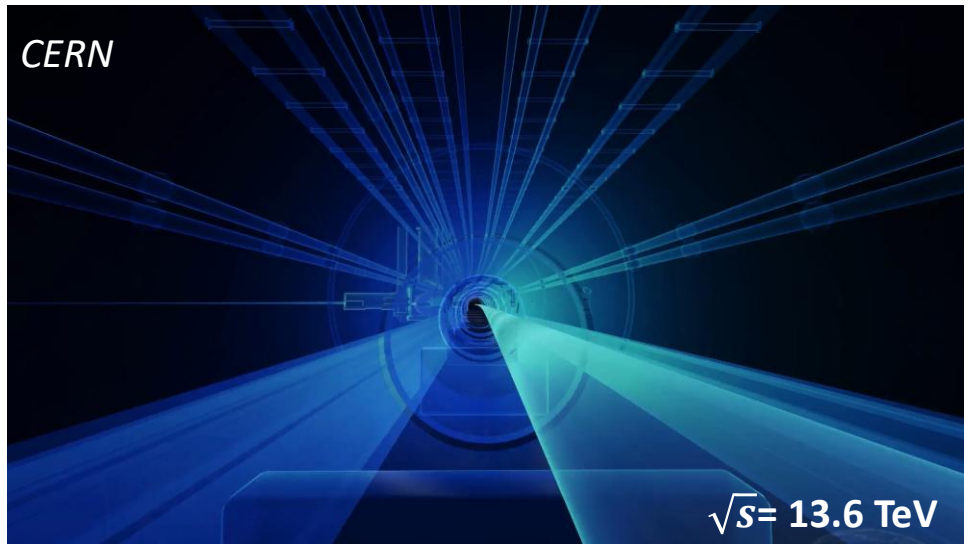
To **Detect** any Particle @Colliders

Head-On collision




No, NEW PARTICLE !!

→ MASSIVE particle → decays FASTER

Effective Field Theory

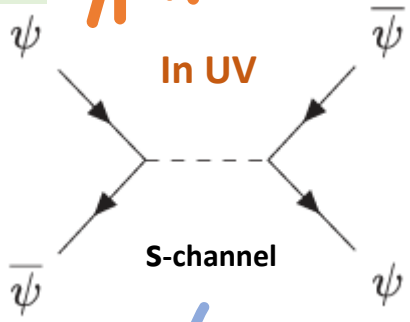
Produce ✗

Observer the Effects in SM process ✓

If it exists

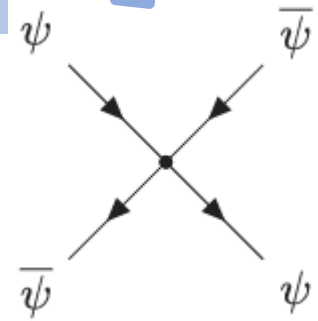
e.g.

Fig : 5




assuming $p^2 \ll m^2$

Fig : 6



This is SMEFT

HIGH Energy

Relative LOW Energy

**Source :**

- Heavy Ion Collision Event Animation | CERN
- Fig 5, Fig 6 : The standard model effective field theory at work DOI:10.1103/RevModPhys.96.015006

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$\prod_7 \sim R_2$

$(3,2)_{7/6}$

***Color Triplet*** *in SU(3)*

***Hypercharge*** *U(1)*

***Weak Doublet*** *in SU(2)*

***Gluon-gluon interaction (QCD) dominates***

$\prod_7^{2/3}$ $(r2p23hat)$

$\prod_7^{5/3}$ $(r2p53hat)$

$: p = +$

Fig : 7

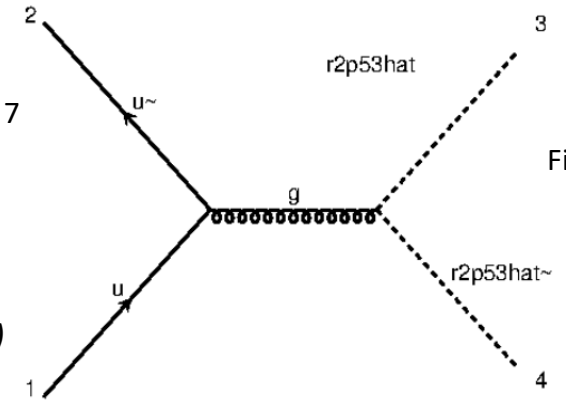



Fig : 8

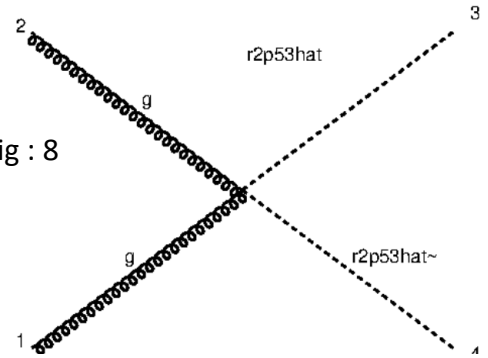
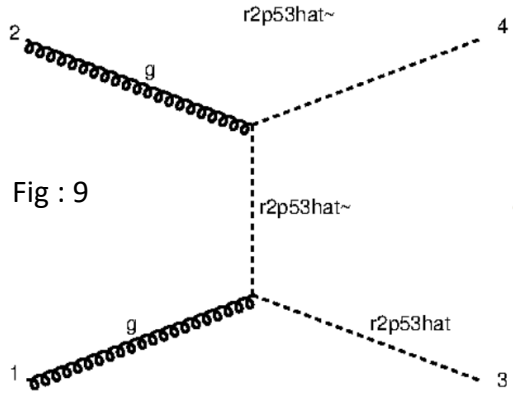



Fig : 9




*& many more*

*Diagrams are generated using* ***MadGraph,*** *Custom* ***UFO model*** *and* ***FeynRules***

*Let's know the*

**MASS** *of* $\prod_7$


***Source :***

- *Pair production of scalar leptoquarks at the LHC* https://doi.org/10.1103/PhysRevD.71.057503
- The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations https://doi.org/10.48550/arXiv.1405.0301
- UFO- The Universal FeynRules Output https://doi.org/10.48550/arXiv.1108.2040

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***Simulated using MadGraph:*** *captured cross section varying mass of our particle (fig 10)*

**MG5_aMC>generate p p > r2p53hat r2p53hat~**

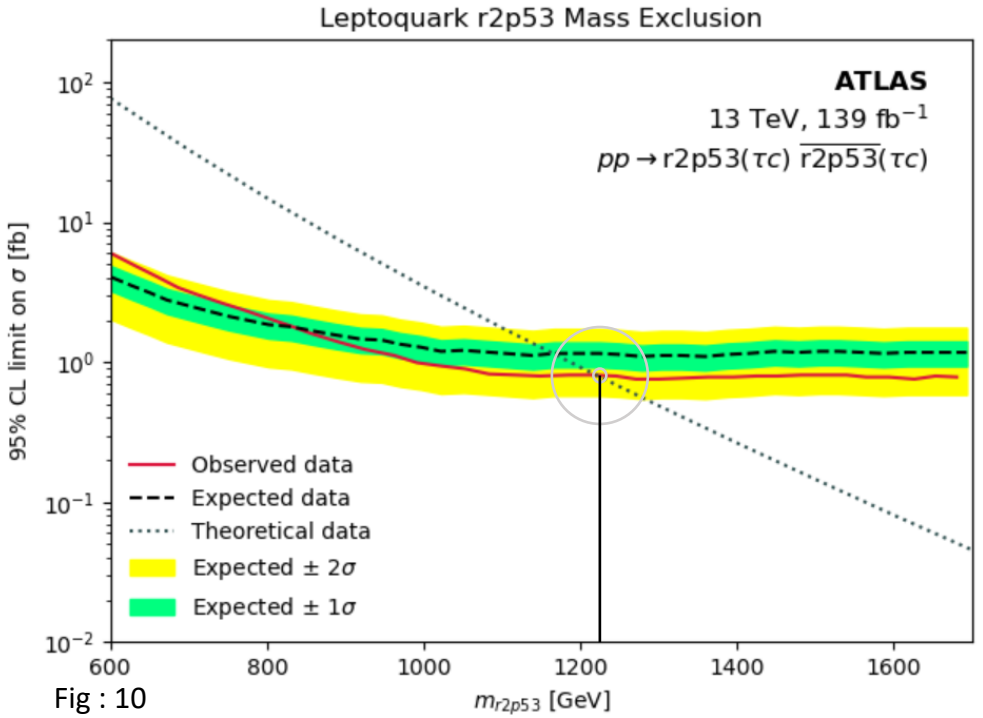


Fig : 10

***From ATLAS paper***

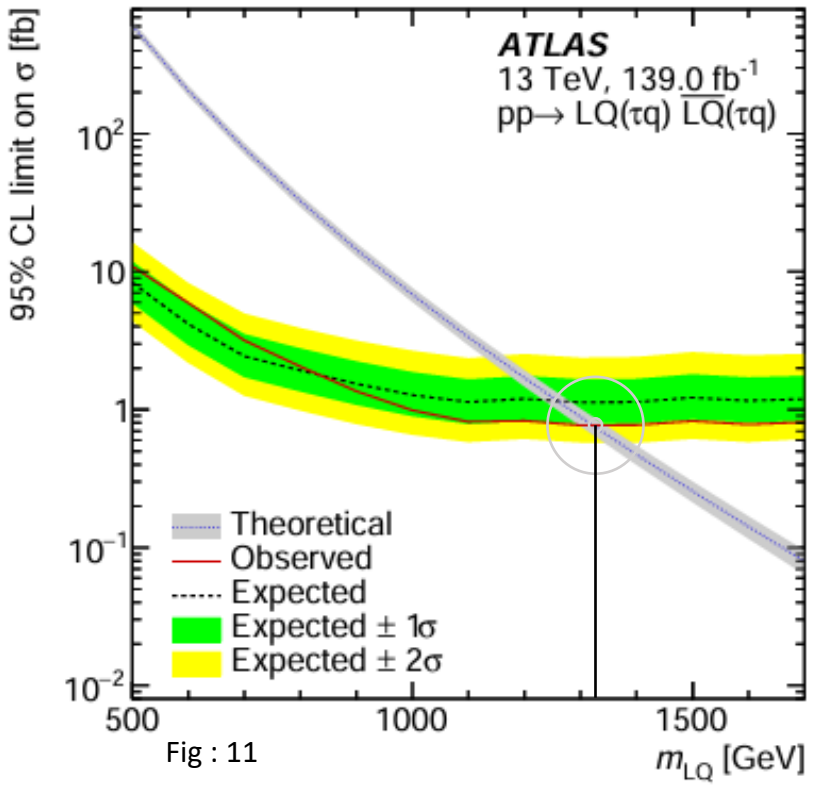


Fig : 11

***TOOS USED:***

- *MadGraph & UFO Modified Param Card*
- *Web plot digitalizer*
- *Python*

## MASS RANGE

- ***Simulated one : just above 1.2 TeV***
- ***ATLAS one : just above the 1.3 TeV***

***Source :***

- Fig 11: Search for excited $\tau$-leptons and leptoquarks in the final state with $\tau$-leptons and jets in pp collisions at $\sqrt{s}$ =13TeVwith the ATLAS detector https://doi.org/10.48550/arXiv.2303.09444
- PlotDigitizer Online App
- Source Code and Data Used for verification : HERE

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# Future Outlook

- *More intense **Data Analysis** with new **RUNs @LHC***
- *Advancing new **Software** and **Pipelines.***
- *Waiting for Higher Energy collider like **Future Circular Collider (FCC) ~ 100 TeV***


***Source :*** • The FCC integrated programme : a physics manifesto https://doi.org/10.48550/arXiv.2504.02634

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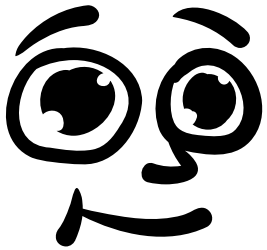
## Thank You



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# Additional Details

- *Decay Width* $(\Gamma) = \frac{\hbar}{t}$ *where, t = time*
- *Interaction Lagrangian of* $\prod_7$ *:*

$$-\mathcal{L}_S^{(\leq 4)} = (y^{lu}_{\Pi_7})_{rij}\Pi^{\dagger}_{7r} i\sigma_2 \bar{l}^T_{Li} u_{Rj} + (y^{eq}_{\Pi_7})_{rij}\Pi^{\dagger}_{7r}\bar{e}^T_{Ri} q_{Lj} + h.c$$

$(\bar{3},2)_{-7/6} \otimes (1,2)_{1/2} \otimes (3,1)_{2/3}$ : **Group Theory in Action**

- *Protons = ∑ partons*
- $\sqrt{s}$ *= Centre of Mass Energy (for 13TeV, 6.5 TeV in each beam)*
- *C = Color charge, L= left-handed & Y = Hypercharge*
- *Gell-Mann–Nishijima formula : Q= I + Y*