LQ-SP associated with a τ lepton, decaying into charm and neutrino at ATLAS

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26th November 2019

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

FSP 103

Physikalisches Institut

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Why leptoquarks and what are they ?

- Leptoquarks (LQ) are predicted by many GUT models as SU(5) unification and Pati-Salam model
- LQs carry simultaneously baryon and lepton number
- can by scalar or vector particles
- color triplet
- possible link to explanation of similarity in flavor structure of quarks and leptons

But:

Strong limits by low energy physics (e.g. proton lifetime).
$\rightarrow$ very small coupling to 1^{st} and 2^{nd} gen. quarks/lepton
$\rightarrow$ very high mass of LQ (O(TeV))

Searches at LEP and HERA yielded no signs for LQ's

Revived curiosity - a new 'Hot topic' ?


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WISSEN

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Leptoquark - Cern-Forscher hoffen auf ein spektakuläres Teilchen

Veröffentlicht am 19.06.2018 | Lesedauer: 4 Minuten

Von **Norbert Lossau**
Chefkorrespondent Wissenschaft

12

German newspaper: " Even more exciting as the higgs"

" The leptoquark, CERN scientists awaiting a spectacular particle"

Whats causing this optimism ?

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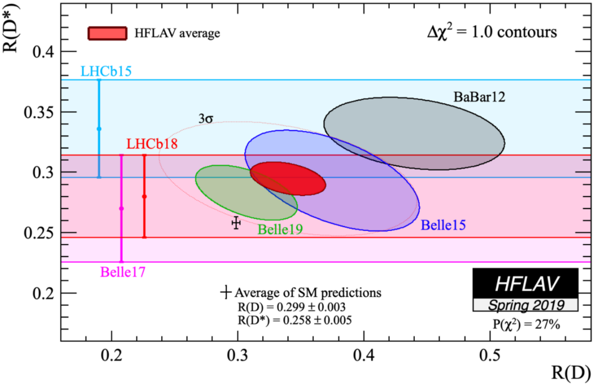
Anomalies in B-physics

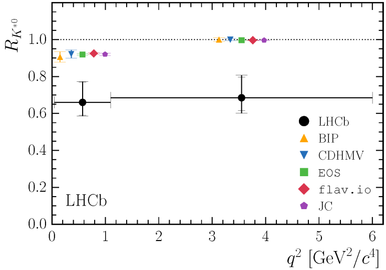
R_D vs R_{D^*} Cornella et al [1]



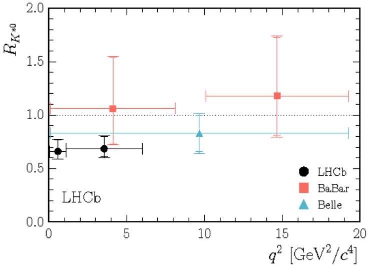
- $R_{D^{(*)}} = \frac{BR(\mathrm{B}\to\mathrm{D}^{(*)}\tau\nu_\tau)}{BR(\mathrm{B}\to\mathrm{D}^{(*)}l\bar{\nu}_l)} \to$ 3-4 σ deviation to SM
- Consistent results from multiple experiments (BaBar/Belle/LHCb)

Anomalies in B-physics

R_{K^*} vs SM pred. (small q^2) LHCb [2]



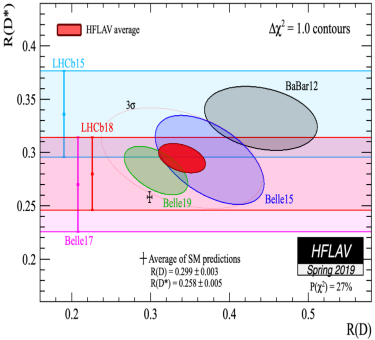
R_{K^*} vs SM pred. LHCb [2]



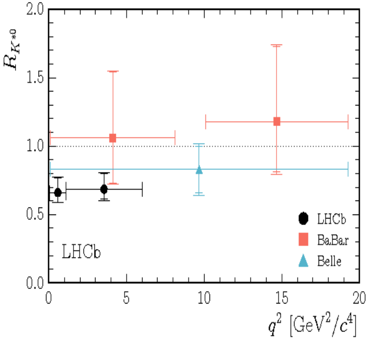
- $R_{K^{(*)}} = \frac{BR(\mathrm{B}\to\mathrm{K}^{(*)}\mu^-\mu^+)}{BR(\mathrm{B}\to\mathrm{K}^{(*)}e^-e^+)}$ → sign. deviation from SM
- LHCb result much improved precission still comp. with BaBar/Belle
- Additional Obsevables show even stronger tension

Anomalies in B-physics

R_D vs R_{D^*} Cornella et al [1]



R_{K^*} LHCb [2]



Measurements of $\mathrm{R}_{\mathrm{D}(*)}$ and $\mathrm{R}_{\mathrm{K}(*)}$ show significant deviation from SM prediction.
Contributions from LQs could explain this nicely!

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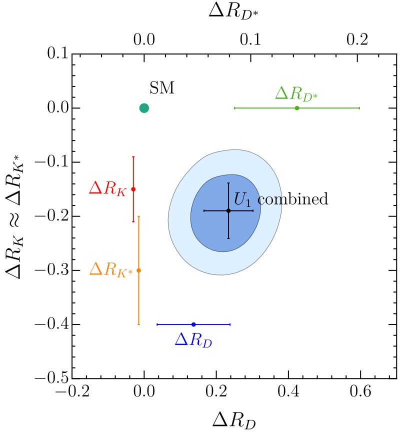
LQ models suited to explain anomalies

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

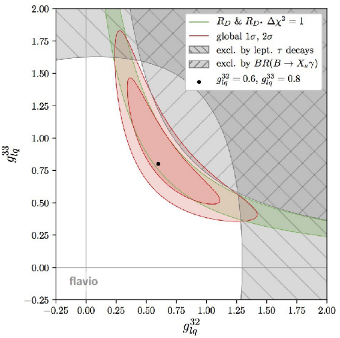
Angelescu, Becirevic, DAF, Sumensari [1808.08179]

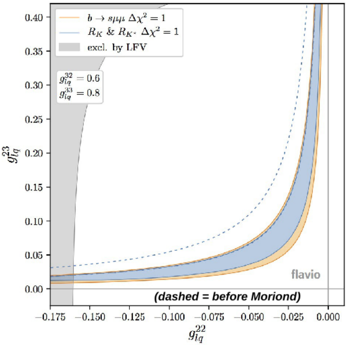
- scalar model: Require 2 new particles to cover both anomalies
- U_1 vector LQ: Only solution to explain both anomalies simutaneouly

Fit U_1 to data Cornella et. al. [1]



Additional fits





- For fixed $\lambda_{3,2} = 0.6$ and $\lambda_{3,3} = 0.8$
- Guadagnoli [3] finds fit results for $\lambda_{2,2}$ und $\lambda_{2,3}$ improved after Moriond 2019 update from Belle

Flavor structur of the U_1

Vector leptoquark model from Baker et al. [4]

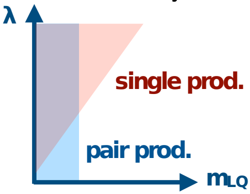
$$\mathcal{L}_{\mathrm{U}_1} \supset \frac{g_U}{\sqrt{2}} \left[U_1^{\mu} \left(\beta^{ij}{}_L \bar{q}^i_L \gamma_\mu l^j{}_L + \beta^{ij}{}_R \bar{d}^i_R \gamma_\mu e^j_R \right) + h.c. \right]$$

Flavor structure quite constrained by low energy physics (coupling to first, second generation mainly « 1)

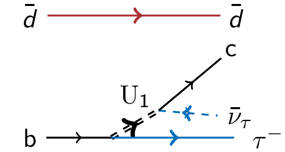
$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{13} \\ 0 & 0 & \beta_L^{23} \\ 0 & \beta_L^{32} & \beta_L^{33} \end{pmatrix} \qquad \beta_R = diag\left(0, 0, \beta_R^{33}\right)$$

Which processes are suited ?

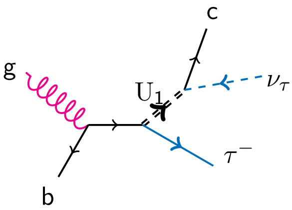
sensitivity



$B \to D^{(*)}\tau\nu_\tau$ anomaly



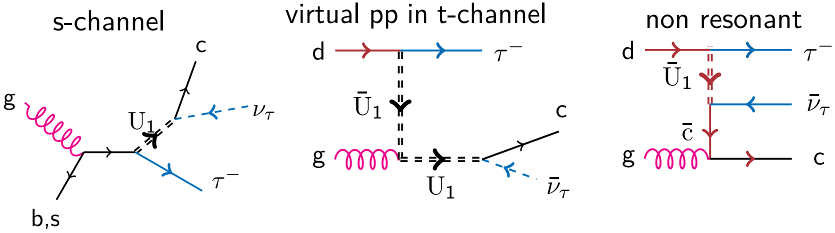
LQ Single production



- $m_{LQ} < 800\,\text{GeV}$ already excluded (PP + Reinterpretation) $\to$ look for single production (SP)
- Feynman diag. for EP in τ charm ν_τ final state completely analogue to $R(D^{(*)})$ anomaly
- Signature consists of τ, Jet (c-tagged) + MET

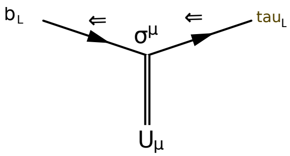
Studies with event generator (MadGraph5)

MadGraph5 find three main production diagrams for the U_1 LQ:

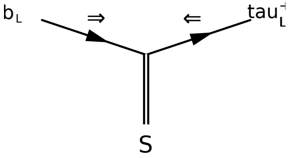


- Cross section
  - from 0.3 fb @ $M_{LQ} = 1.6$ TeV
  - to 74 fb @ $M_{LQ} = 700$ GeV
- Small cross section but a factor 100 larger than for scalar LQ

Vector cross section higher than for scalar LQ ?

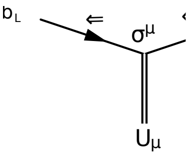


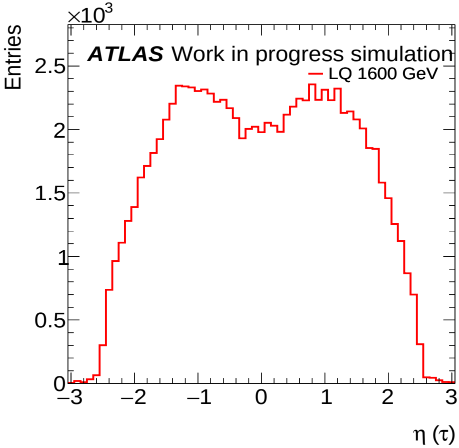
- V-LQ conserves helicty $\rightarrow\sim(1+\cos(\theta))$
- τ emitted in fw direction (rel. to incoming quark)

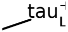


- scalar LQ requires spin flip $\rightarrow\sim(1-\cos(\theta))$
- τ emitted more central (backw. rel. to incoming quark)

Vector cross section higher than for scalar LQ ?







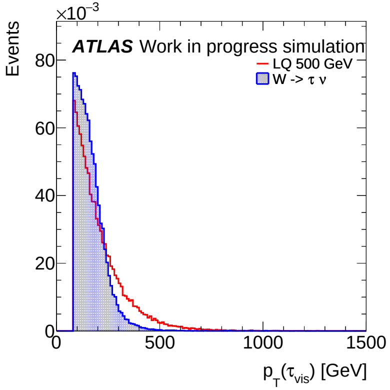
- V-LQ cons … uires spin flip
  $\rightarrow\sim (1 +$ … $(\theta))$
- τ emitted … ore central
  (rel. to inc … to incoming

Also reflects in η distribution of simulated U_1 LQ

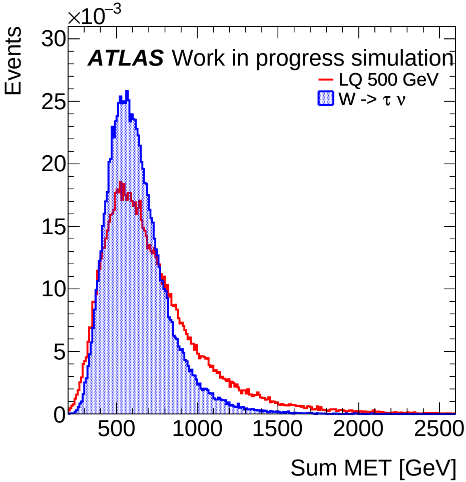
Comparisson with SM process $\mathrm{W} \rightarrow \tau\nu_\tau$

The following slides show a rough comparisson of the distributions for LQ (red curve) and $\mathrm{W} \rightarrow \tau\nu_\tau$ (blue shape) as SM process with same final state.
The plots were produced using truth information and the indivdual distributions are normalized to one.

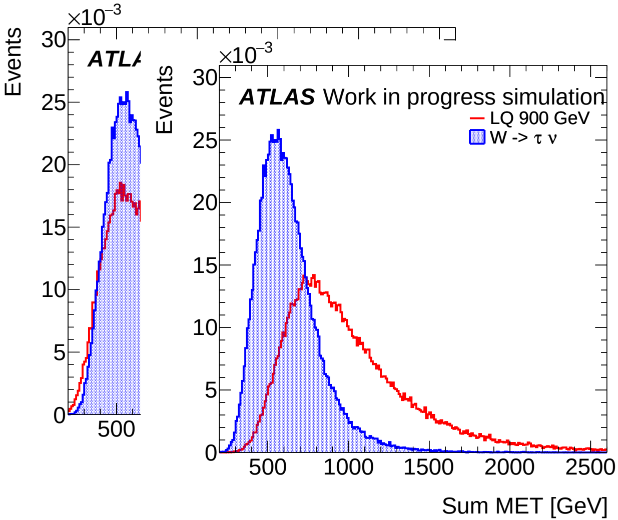
Sim. LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



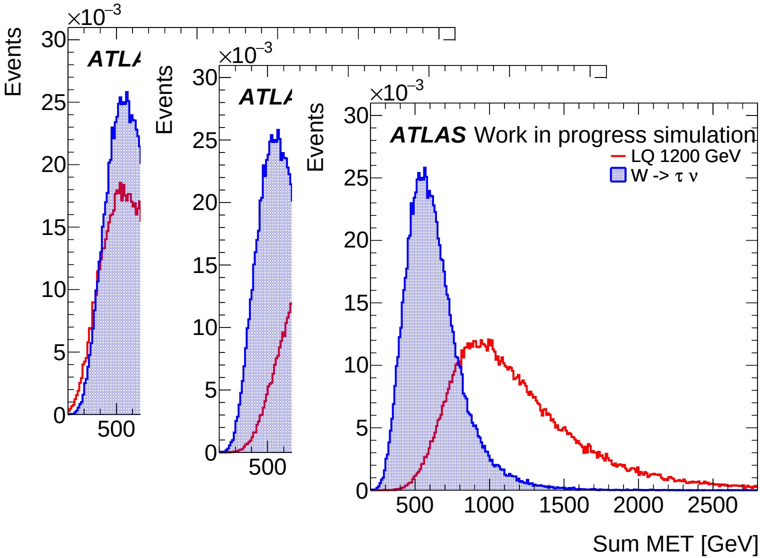
MET LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



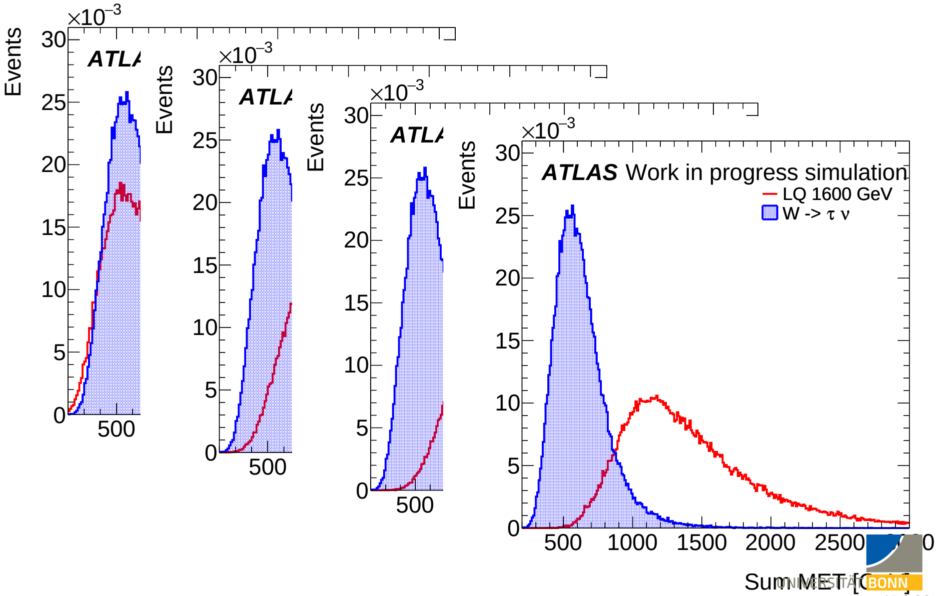
MET LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



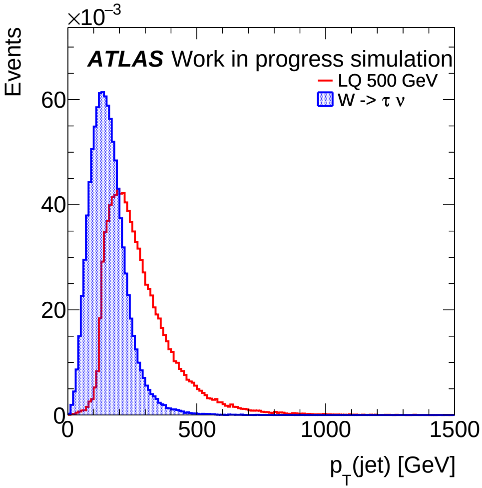
MET LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



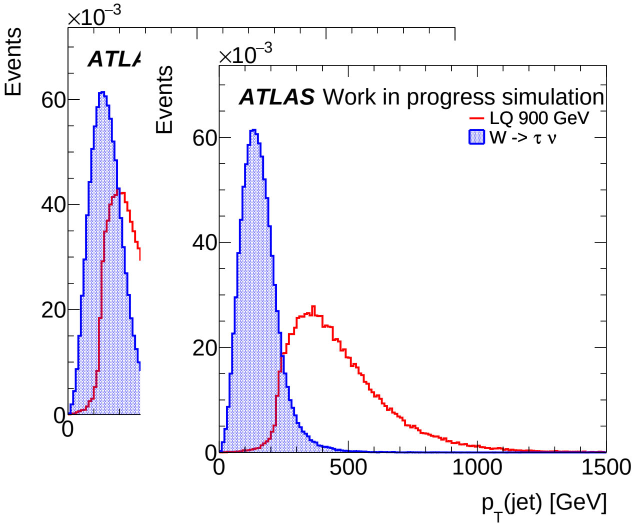
MET LQ and SM background ($b \rightarrow cW^- \rightarrow c\tau^-\bar{\nu}_\tau$)



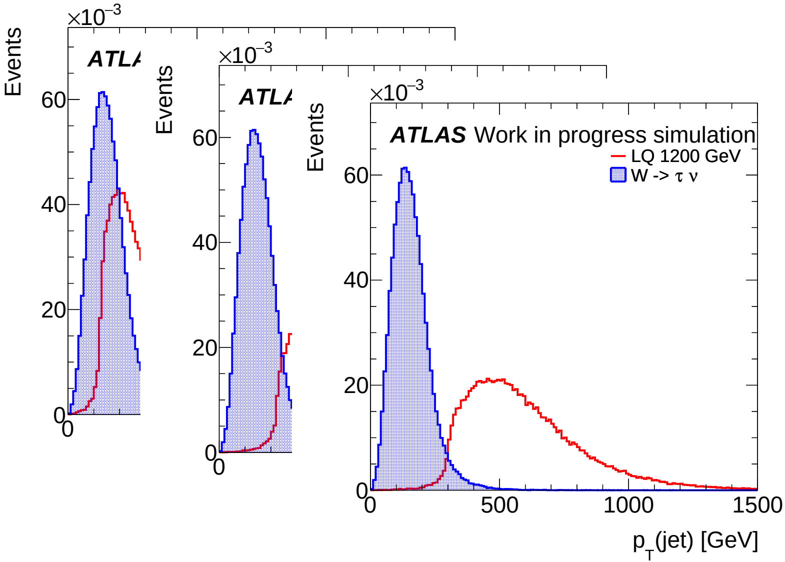
Jet pt LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



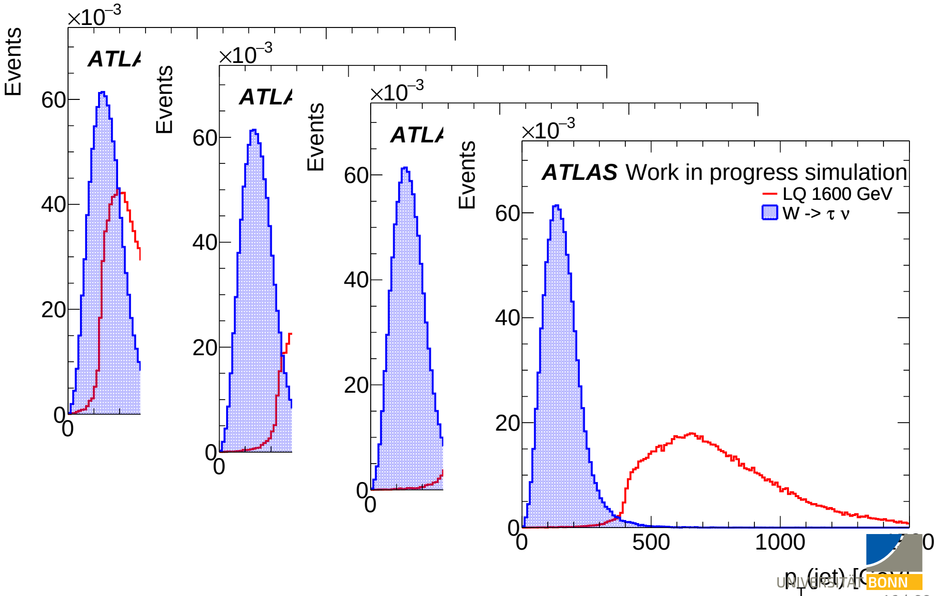
Jet pt LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



Jet pt LQ and SM background (b $\rightarrow cW^- \rightarrow c\tau^-\bar{\nu}_\tau$)



Jet pt LQ and SM background ($b \to cW^- \to c\tau^-\bar{\nu}_\tau$)



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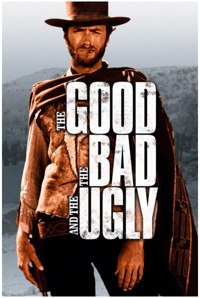
Conclusion

- Discrepancies in b physics results may be hint to new physics (BSM)
- U_1 LQ is promising candidate to resolve observed anomalies
- Tau + charm jet + neutrino well suited for U_1 LQ searches
- First analysis targeting this final state explicitly

Bonus: U_1 LQ may hint to more bsm particles

U_1 LQ model incorporates 2 additional massive vector bosons to counter UV divergencies.

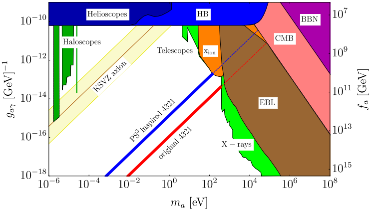


$U_1^\alpha \sim (3,1)_{\frac{2}{3}}$

$G'^\alpha \sim (8,1)_0$

$Z' \sim (1,1)_0$

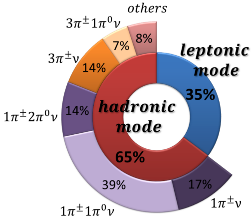
Implications on axion physics:

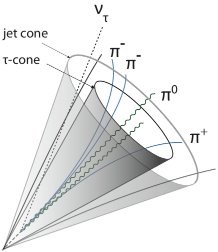


Fuentes et al. : '4321...axion!' [6]

Discovery of the U_1 LQ would point to where BSM physics is hidden.

Tau reconstruction





- Taus decay dominantly within the beampipe
- Hadronicallly decaying Taus are reconstructed as narrow jets with 1 or 3 charged tracks
- Missing transverse energy due to neutrinos

C. Cornella, J. Fuentes-Martín and G. Isidori. "Revisiting the vector leptoquark explanation of the B-physics anomalies". In: *Journal of High Energy Physics* 2019.7 (July 2019), p. 168. ISSN: 1029-8479. DOI: 10.1007/JHEP07(2019)168. URL: https://doi.org/10.1007/JHEP07(2019)168.

R. Aaij et al. "Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays". In: *JHEP* 08 (2017), p. 055. DOI: 10.1007/JHEP08(2017)055. arXiv: 1705.05802 [hep-ex].

D. Guadagnoli. "B-decays Discrepancies: How the Picture has changed After Moriond 2019". In: *Photon polarisationn in B->K $\pi\pi\gamma$ decays workshop*. IPHC-Strasbourg, 11th Apr. 2019. URL: https://indico.cern.ch/event/793995/contributions/3331512/attachments/1828235/2993092/Guadagnoli_IPHC.pdf.

M. J. Baker, G. Fuentes-Martin Javier Isidori and K. Matthias. "High-pT Signatures in Vector-Leptoquark Models". In: *Eur.Phys.J. C79 (2019) no.4, 334s.* (). URL: https://arxiv.org/abs/1901.10480v3.

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J. Fuentes-Martín, M. Reig and A. Vicente. "4321... axion!" In: (2019). arXiv: 1907.02550 [hep-ph].