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Anomalies in Particle Physics

22.03.2022

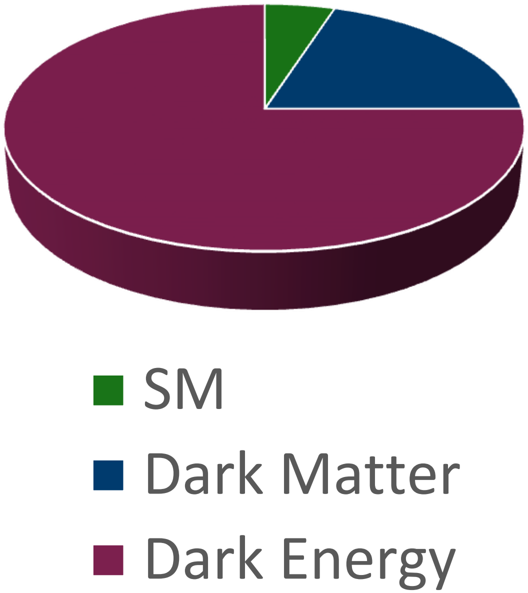
Work supported by FNSNF

Outline

- Introduction
- Status of the Flavour anomalies
  - $b \to s\mu\mu$
  - $b \to c\tau\nu$
  - a_μ
  - $\tau \to \mu\nu\nu$
  - Cabibbo Angle Anomaly
  - Non-resonant di-leptons
- Explanations of the Flavour anomalies
- Collider Anomalies
- Conclusions

Physics Beyond the Standard Model

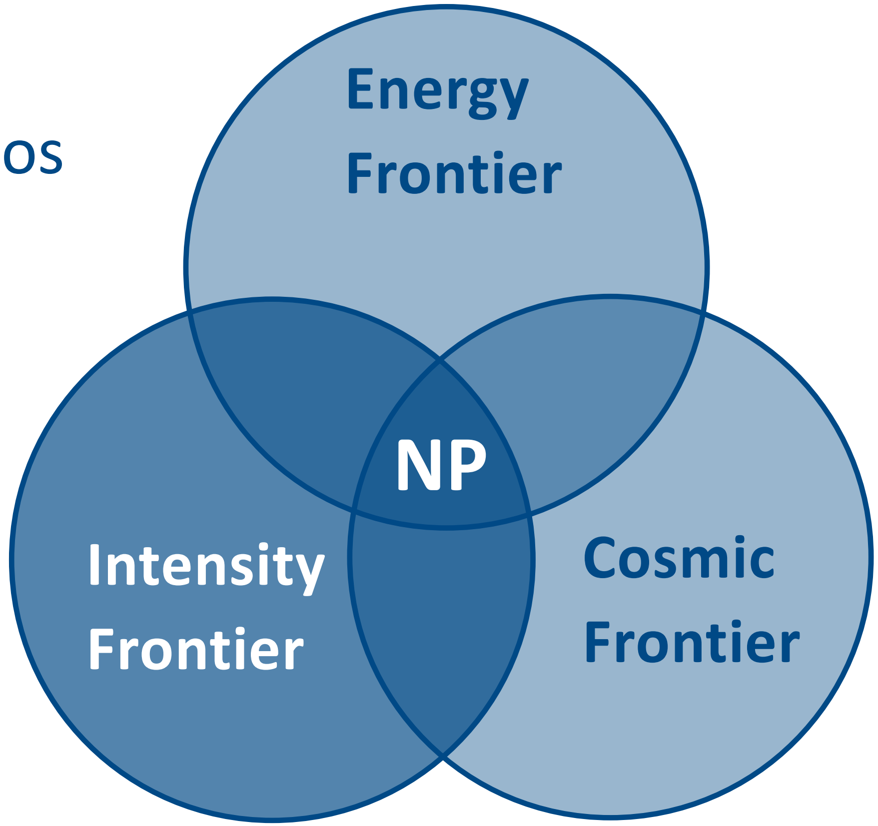
- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions



The SM must be extended!
What is the underlying fundamental theory?

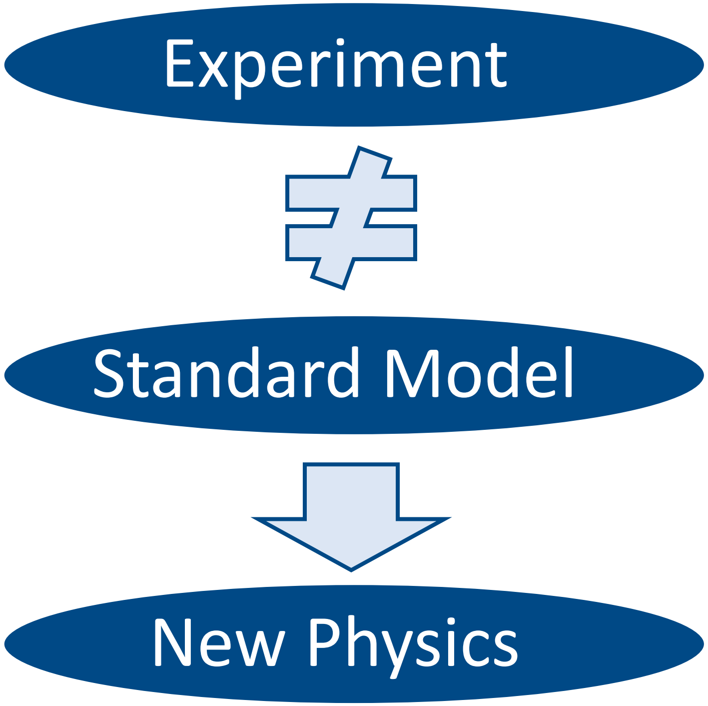
Discovering New Physics

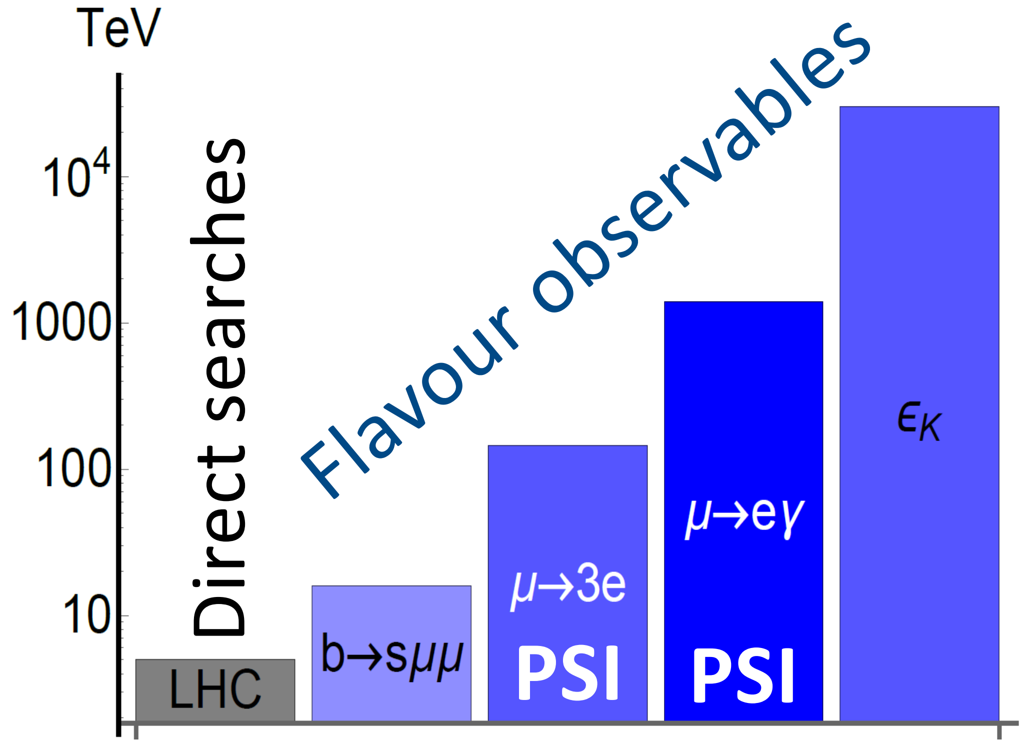
- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - Test of fundamental symmetries
  - Proton decay



Finding New Physics with Flavour

- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours





Flavour observables can be sensitive to higher energy scales than collider searches

Overview on the Flavour anomalies

LFUV in b→sℓ⁺ ℓ⁻

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-}$$

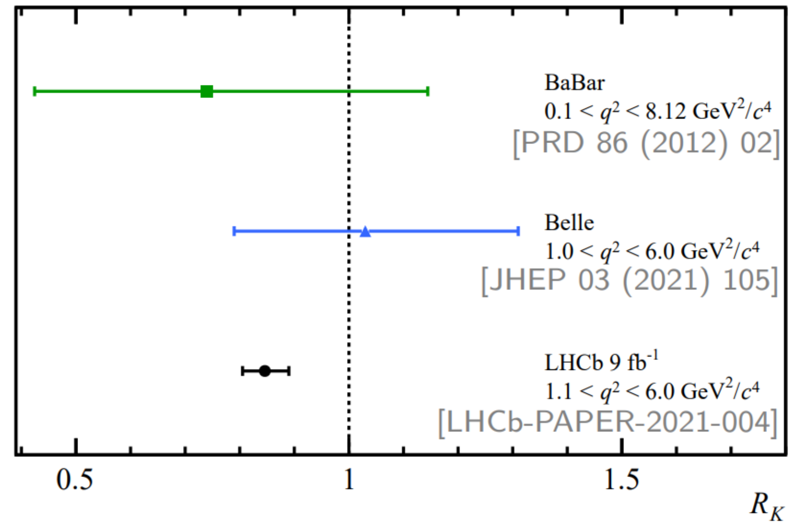
$$R(K^*) = \frac{B \to K^*\mu^+\mu^-}{B \to K^*e^+e^-}$$

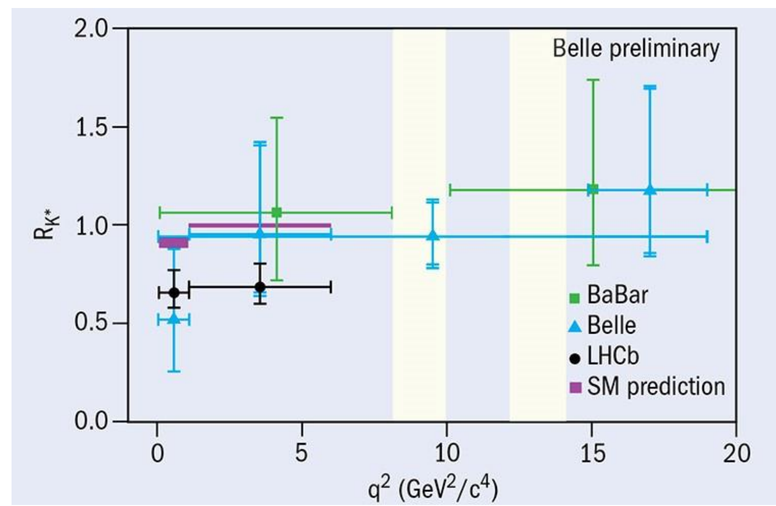
- Muon and electron masses can be neglected

⇨ **Clean prediction**

- Supported by

$$\frac{\Lambda_b \to Kp\mu^+\mu^-}{\Lambda_b \to Kpe^+e^-} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

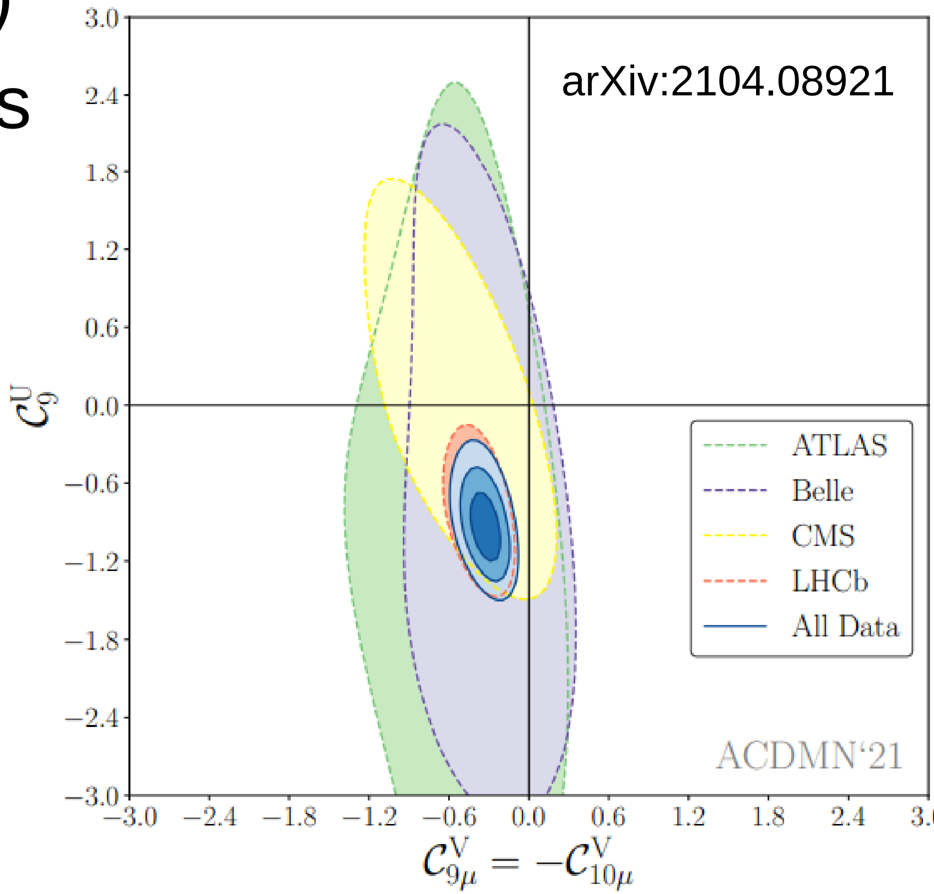




LFUV in B decays >4σ

Global Fit to $b \to s\mu^+\mu^-$ Data

- Perform global model independent fit to include all observables (≈180)
- Several NP hypothesis give a good fit to data significantly preferred over the SM hypothesis



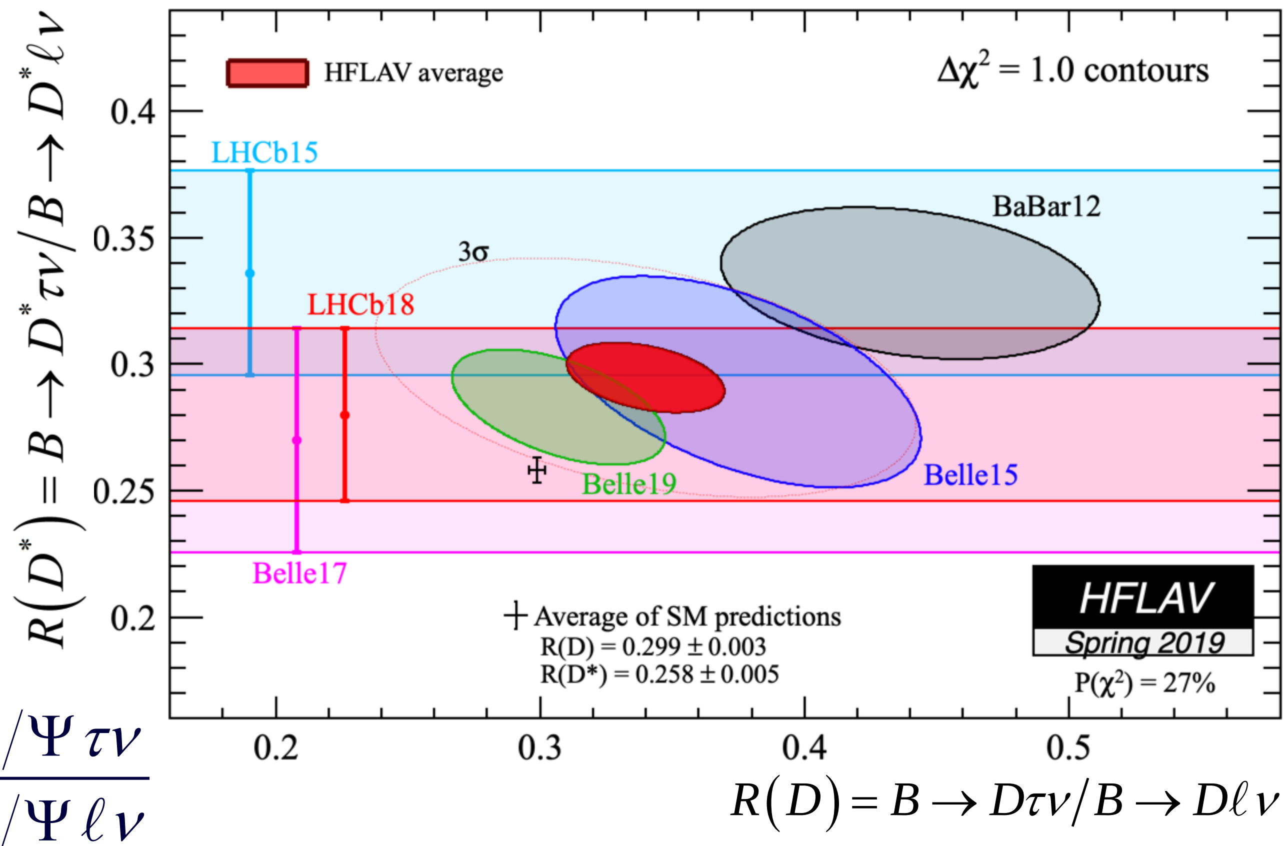
$$O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$$

$$O_{10} = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \gamma^5 \ell$$

Fit is >7 σ better than the SM

b→cτν Transitions

- LFU test of the charged current
- Tau mode consistently enhanced
- Supported by

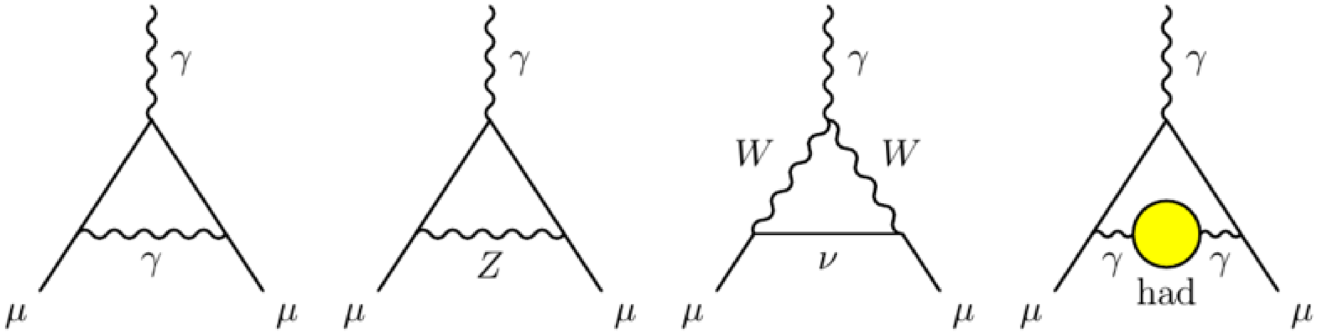


$$R(J/\Psi) = \frac{B_c \to J/\Psi\, \tau\nu}{B_c \to J/\Psi\, \ell\nu}$$

- Tree-level ⇨ **need larger NP effect**

O(10%) constructive preferred effect at 3σ

Muon Anomalous Magnetic Moment



- Theory prediction intricate (hadronic effects)

$\Delta a_\mu = (251 \pm 49) \times 10^{-11}$ T. Aoyama et al., arXiv:2006.04822

- Need NP of the order of the SM EW contribution
- Chiral enhancement necessary for heavy NP
- Soon more experimental results from Fermilab
- Vanishes for $m_\mu \to 0$ ⇨ **measure of LFUV**

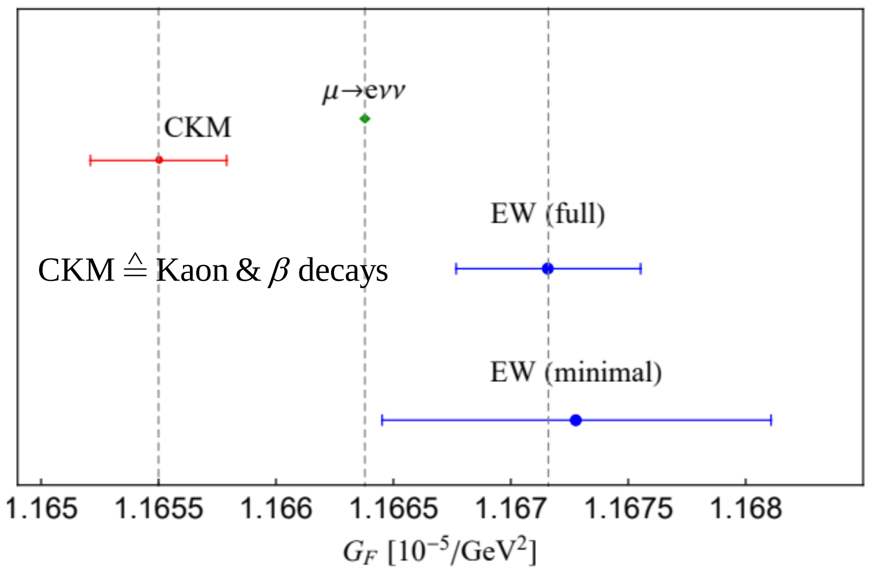
4.2σ deviation from the SM prediction

Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$
$$\left|V_{ud}^2\right| + \left|V_{cd}^2\right| + \left|V_{td}^2\right| = 0.9970 \pm 0.0018$$
(PDG)

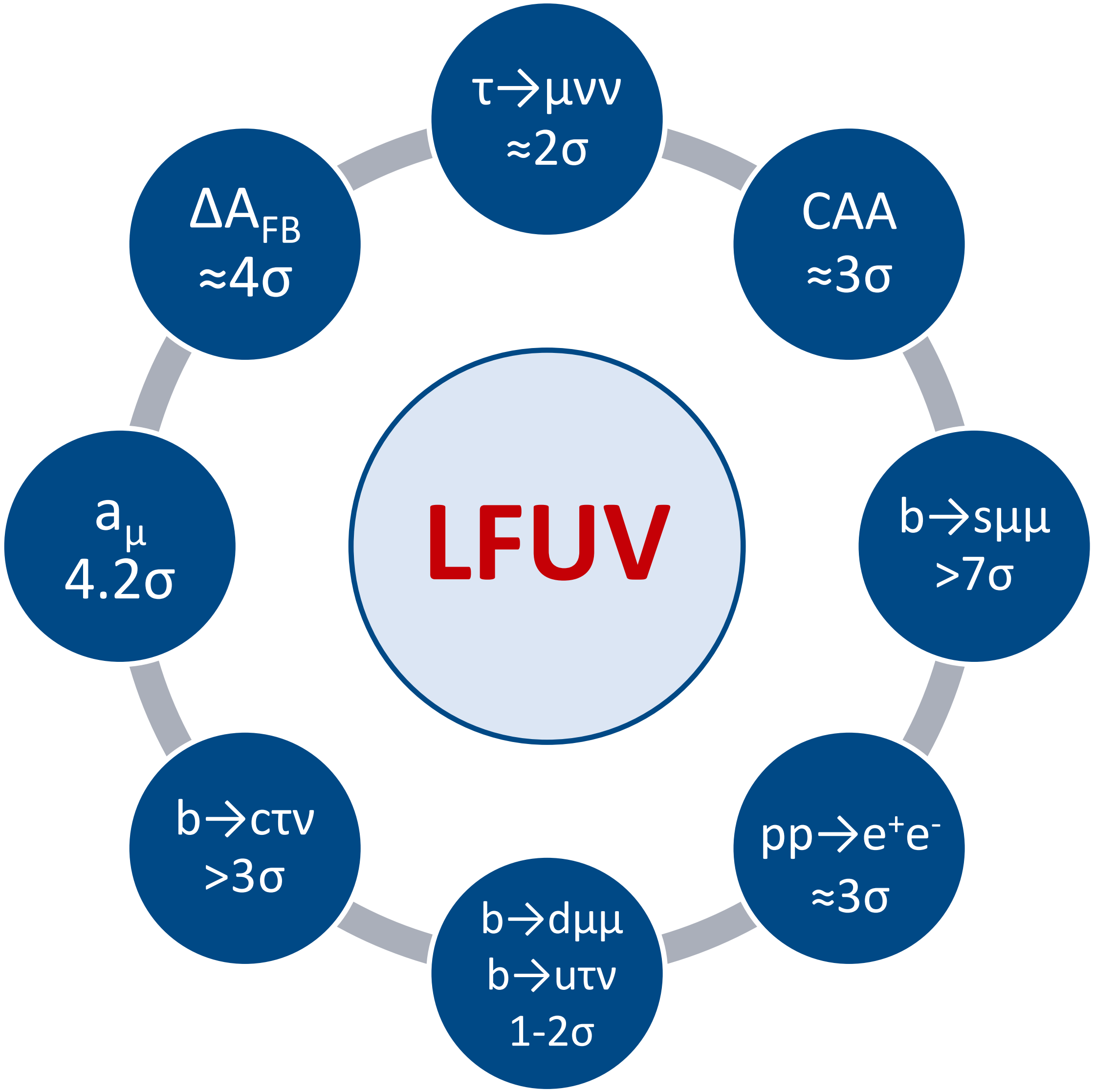
AC, Hoferichter, Manzari, 2102.02825



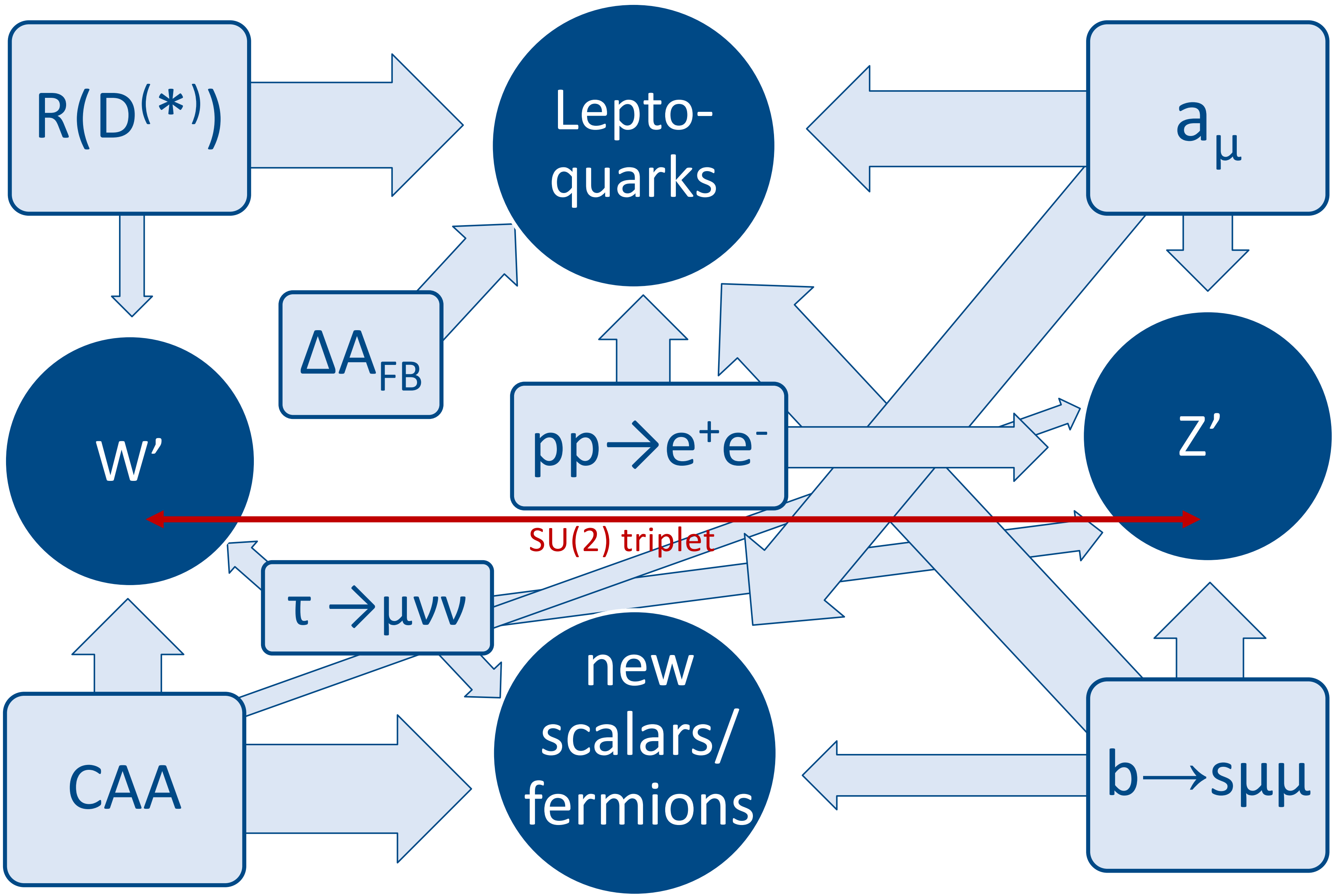
- NP in the determination of V_{ud} from beta decays needed
- Can be interpreted as
  - NP in beta decays
  - NP in the Fermi constant
  - LFUV (modified Wμν coupling)

3σ tension

Flavour Anomalies



Explanations



Outlook: Physics at Future Colliders

- Flavour Anomalies require NP at the TeV scale

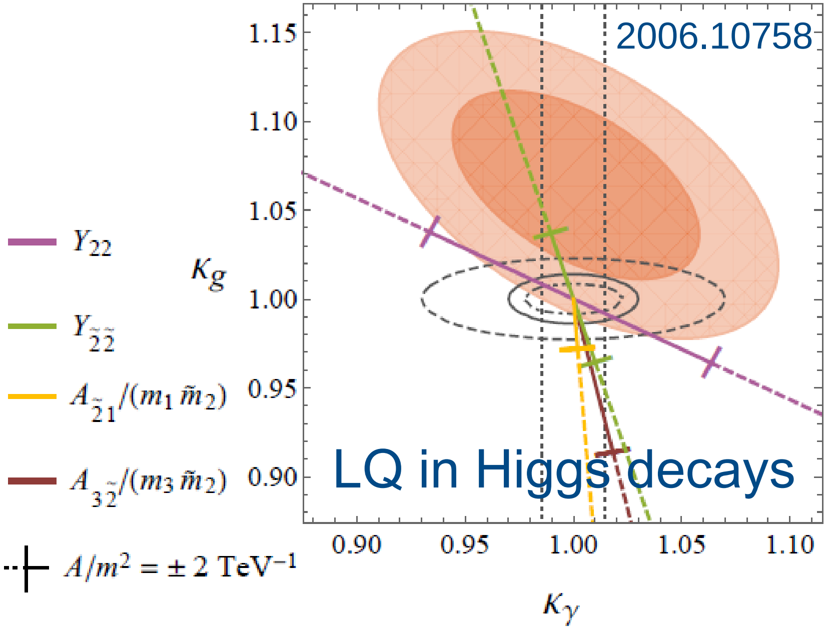
  ⇨ Direct Searches at HL-LHC, HE-LHC, FCC-pp

- This new particles in general also affect EW precision observables

  ⇨ Z decays at CLIC and FCC-ee

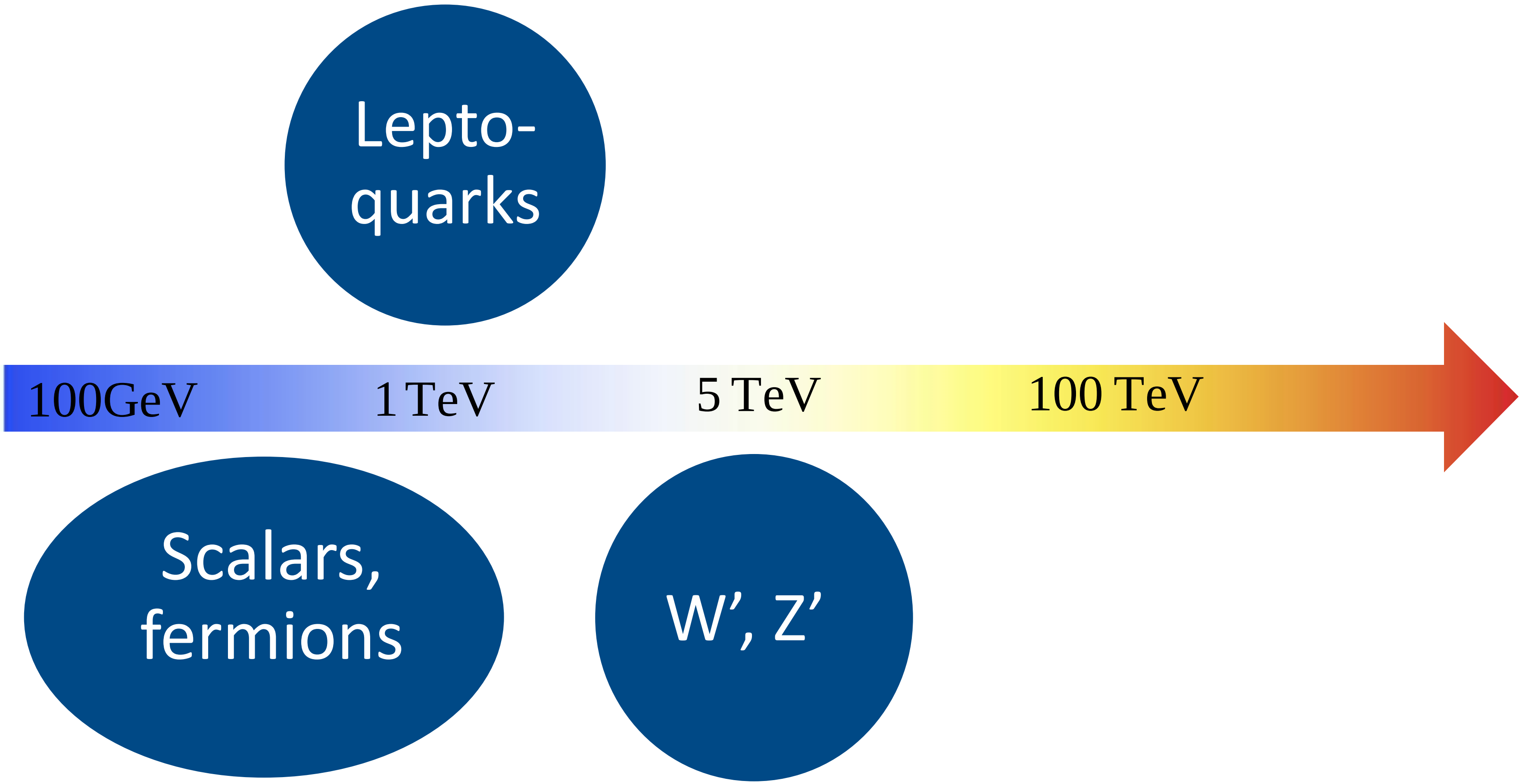
- Flavour is directly linked to the Higgs boson

  ⇨ CLIC, FCC



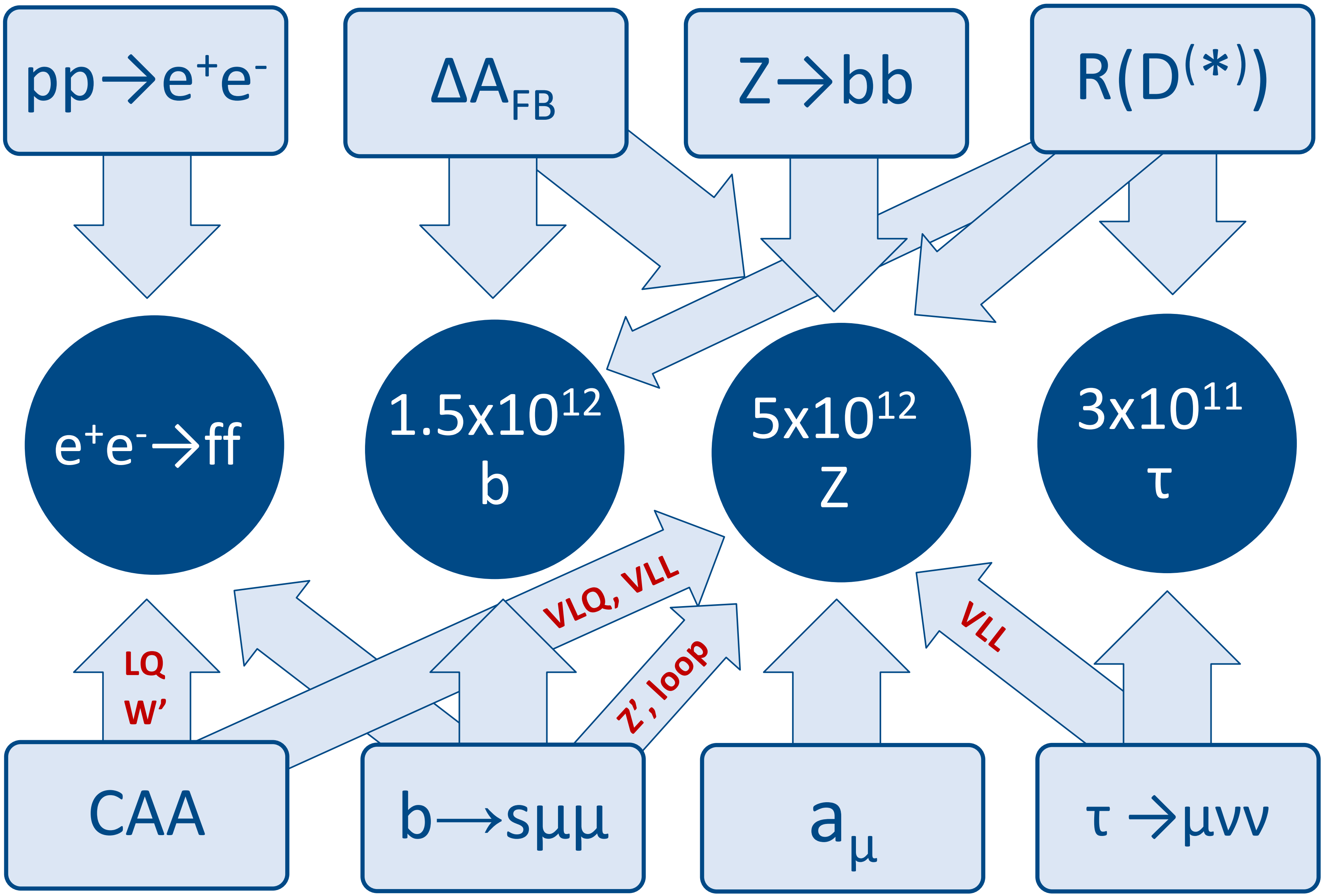
Flavour Anomalies (if confirmed) strengthen the physics case for future colliders significantly

LHC bounds and future prospects



FCC-hh reach six times higher

Implications for FCC-ee and CEPC



Collider Anomalies

Multi-leptons

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Anatomy of the multi-lepton anomalies

Final state	Characteristic	Dominant SM process	Significance
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt	>5σ
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW	~3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t	>3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh, (WWW)	4.2σ
$Z(\to l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

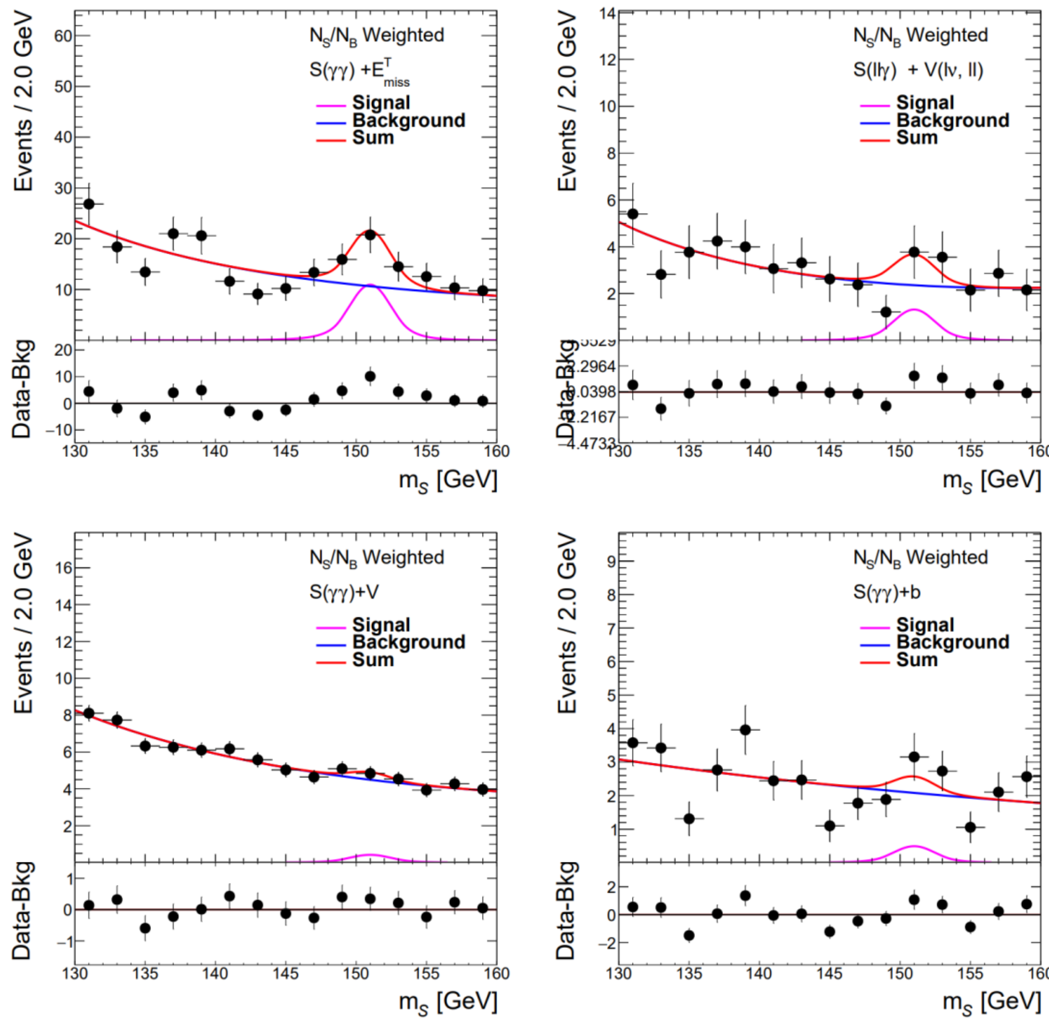
Talk of Bruce Mellado at PSI

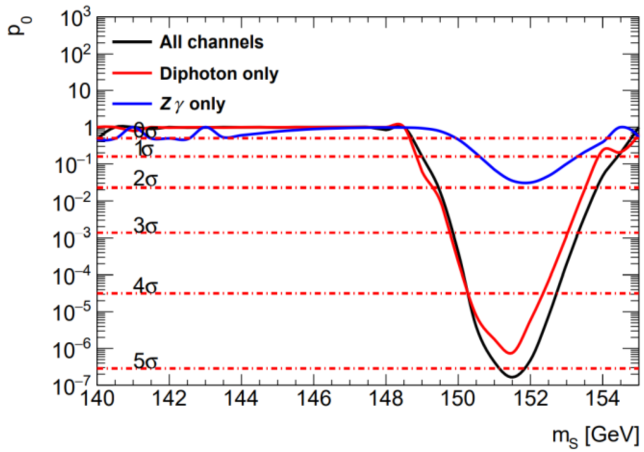
Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.

Very significant hints in low energetic di-leptons

151 GeV

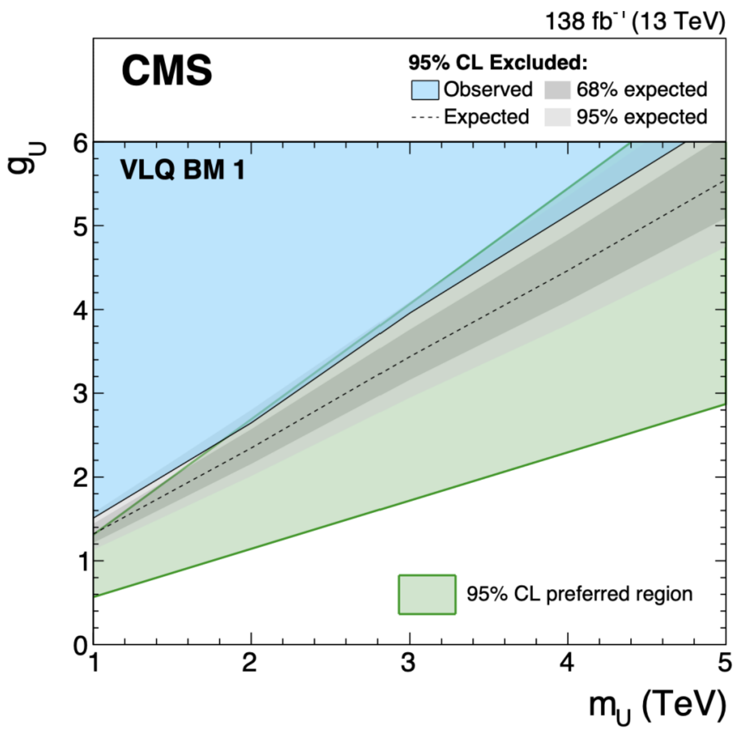
- Several channels
- Motivated by the multi-leptons



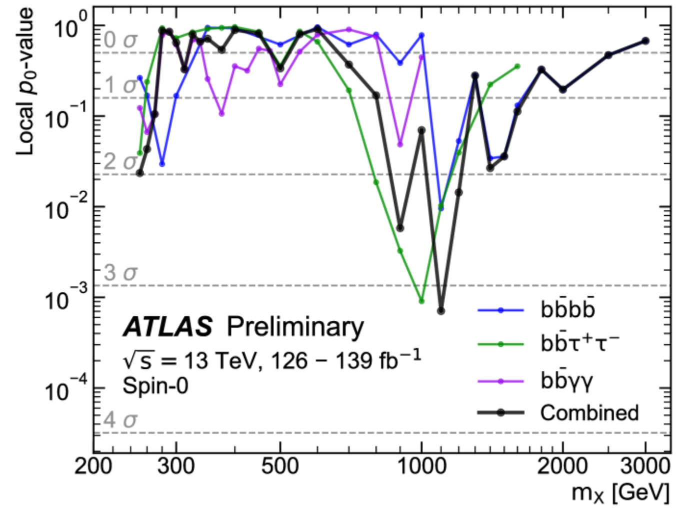


Combined significance of ≈5σ (locally)

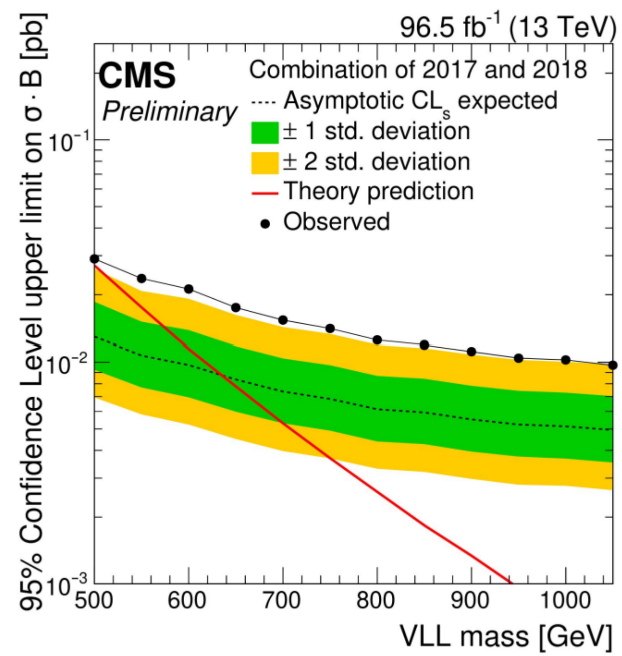
Vector-like quark, LQs, Higgs PP



CMS-PAS-HIG-21-001



ATLAS-CONF-2021-052



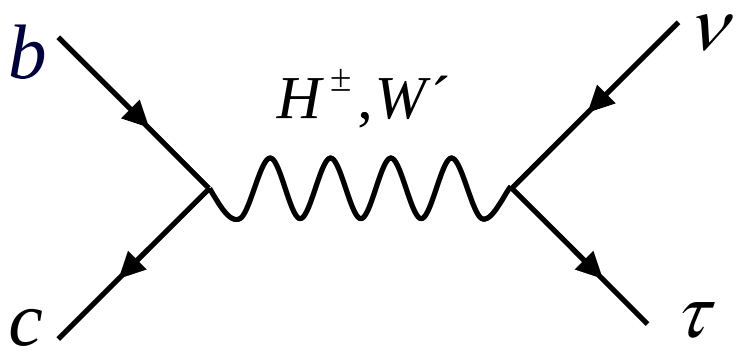
CMS-PAS-B2G-21-004

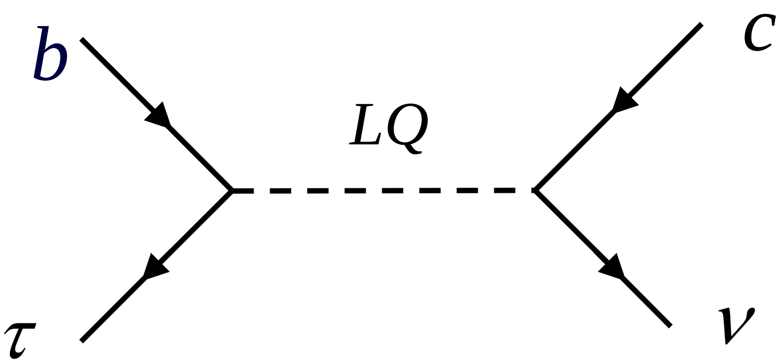
- And more…..

Interesting signals for future investigation

Backup

R(D) & R(D*)



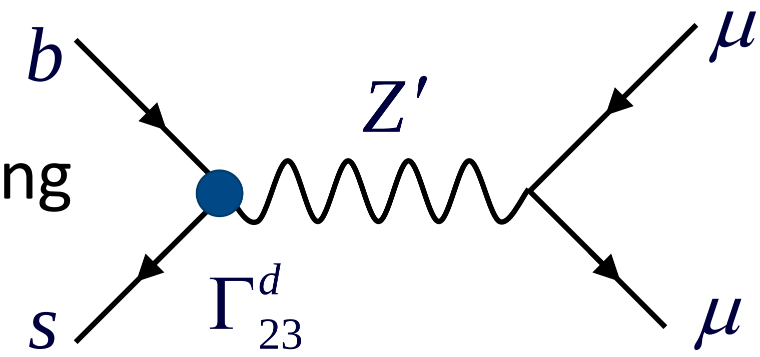


- Charged scalars: Problems with distributions and B_c lifetime
  A. Celis, M. Jung, X. Q. Li, A. Pich, PLB 2017
  R. Alonso, B. Grinstein, J. Martin Camalich, PRL 2017
- W': Strong constraints from direct LHC searches
  D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, JHEP 2017
- Leptoquark: Strong signals in $qq \to \tau\tau$ searches
  CMS, 1809.05558; ATLAS, 1902.08103

Explanation difficult but possible with Leptoquarks

$b \rightarrow s\mu^+\mu^-$ explanations

- Z' W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin 1403.1269, ….
  - Necessary effects in B_s mixing
  - Collider constraints



- Loop contributions
  - Scalars and vector-like fermions B. Gripaios, M. Nardecchia, S. A. Renner, JHEP 2016
  - 2HDM A.C., D. Müller and C. Wiegand, 1903.10440
  - R_2 Leptoquark D. Bečirević and O. Sumensari, 1704.05835
  - Z' coupling to tops J. Kamenik, Y. Soreq and J. Zupan, 1704.06005
- Leptoquarks G. Hiller and M. Schmaltz, 1408.1627
  D. Bečirević, S. Fajfer and N. Košnik,1503.09024, ….

Small effect needed; many possibilities

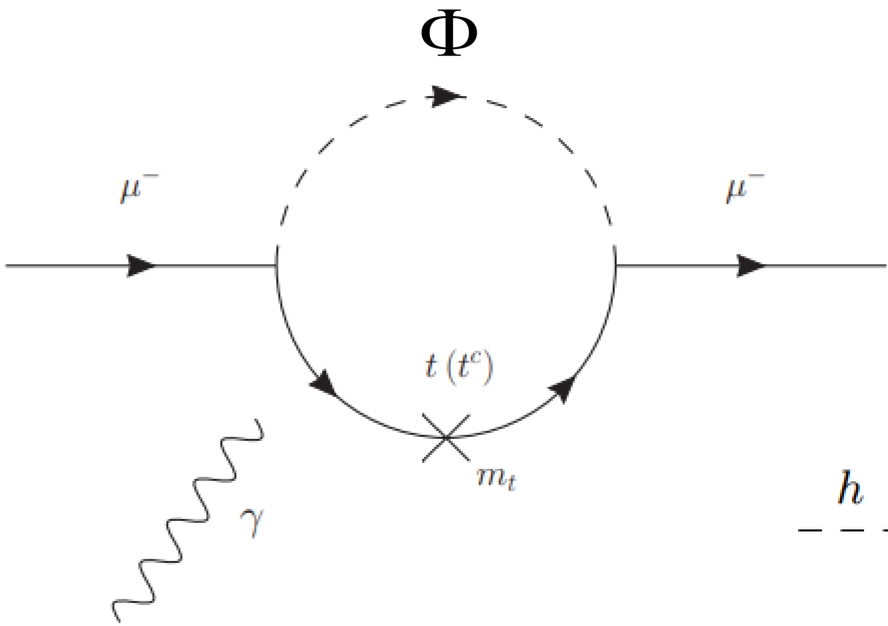
a_μ explanations

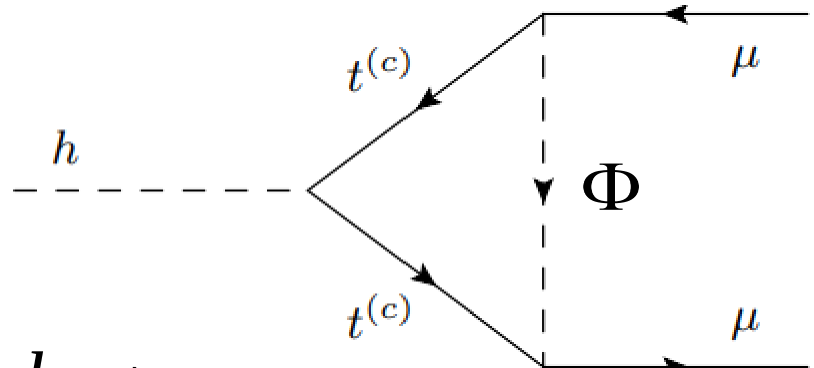
- MSSM
  - tan(ß) enhanced slepton loops
- Scalars
  - Light scalars with enhanced muon couplings
- Z’
  - Very light with τμ couplings (m_τ enhancement)
- New scalars and fermions
  - κ/Y_μ
- Leptoquarks
  - m_t enhanced effects

Chiral enhancement or very light particles

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



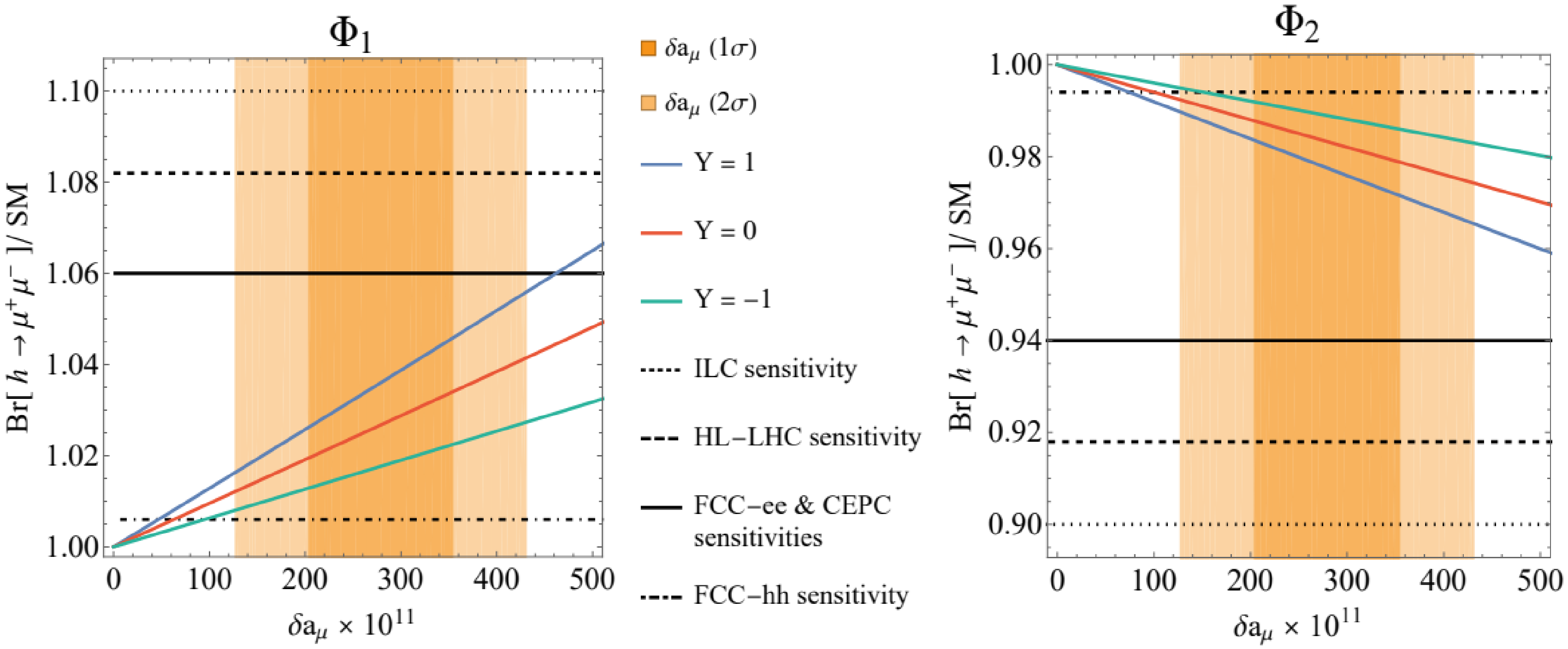


- m_t / m_μ enhanced effect $h \to \mu\mu$
- m_t^2 / m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs $h \to \mu\mu$

- Chirally enhanced effects via top-loops
- Same coupling structure → direct correlation

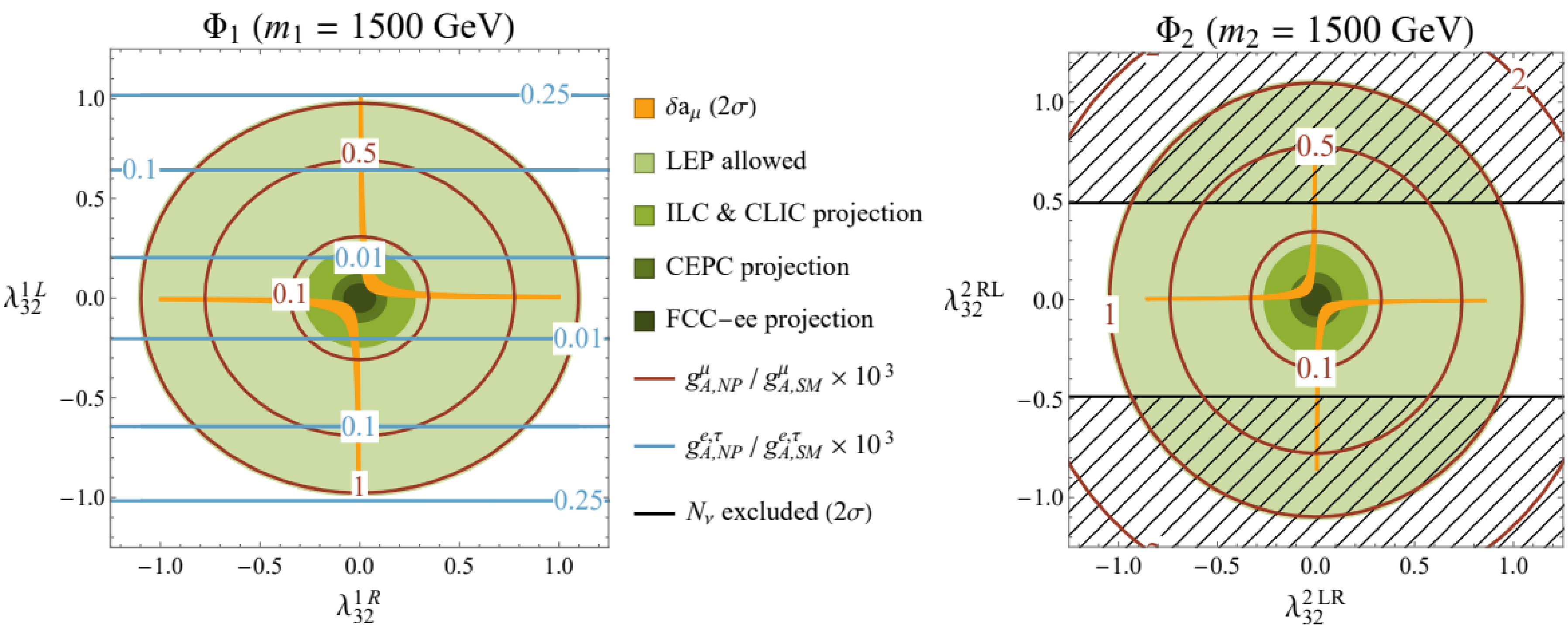


A.C., D. Mueller, F. Saturnino, 2008.02643

h→μμ at future colliders

a_μ vs $Z \rightarrow \mu\mu$

- Chirally enhanced effects via top-loops



$\lambda_\mu^{L,R}$ Left-, right-handed muon-top coupling

E. Leskow, A.C., G. D'Ambrosio, D. Müller 1612.06858
A.C, C. Greub, D. Müller, F.Saturnino, 2010.06593

$Z \rightarrow \mu\mu$ at future colliders

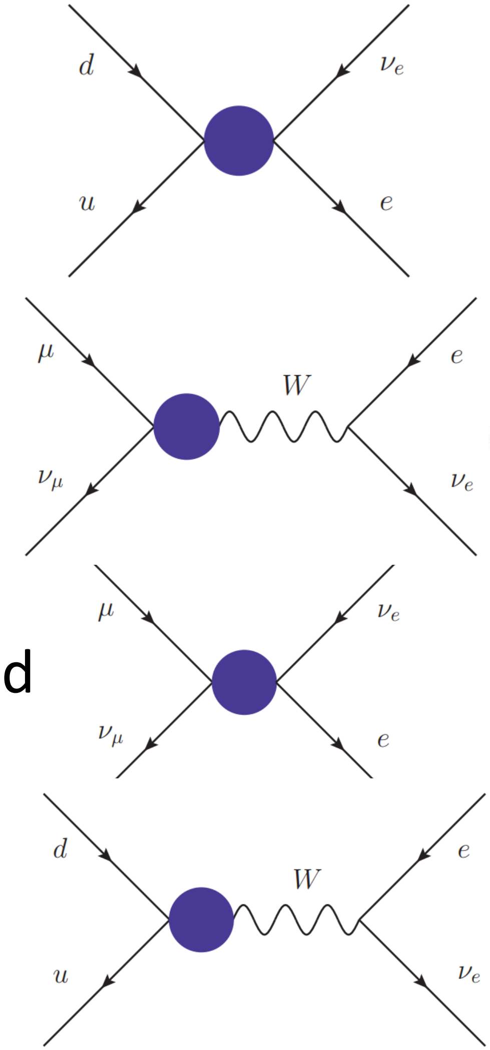
Cabibbo Angle Anomaly and EW Fit

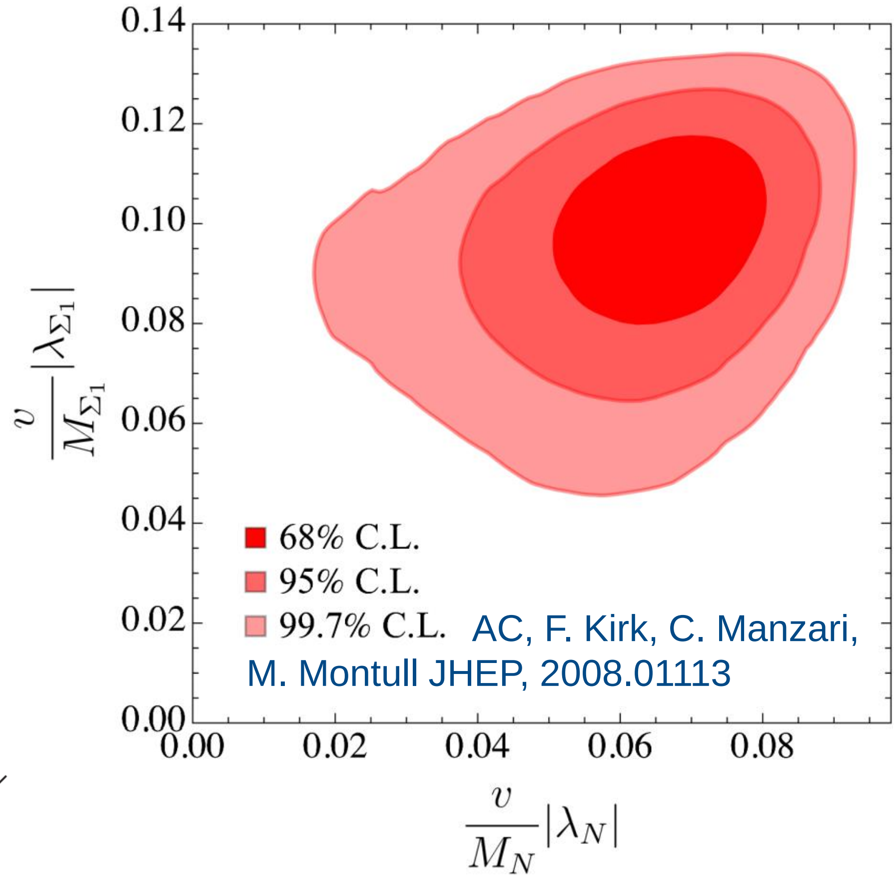
- LQs
- W‘

- W-W‘ mixing
- Vector-like leptons

- Z‘
- Singly charged scalar

- Vector-like quarks



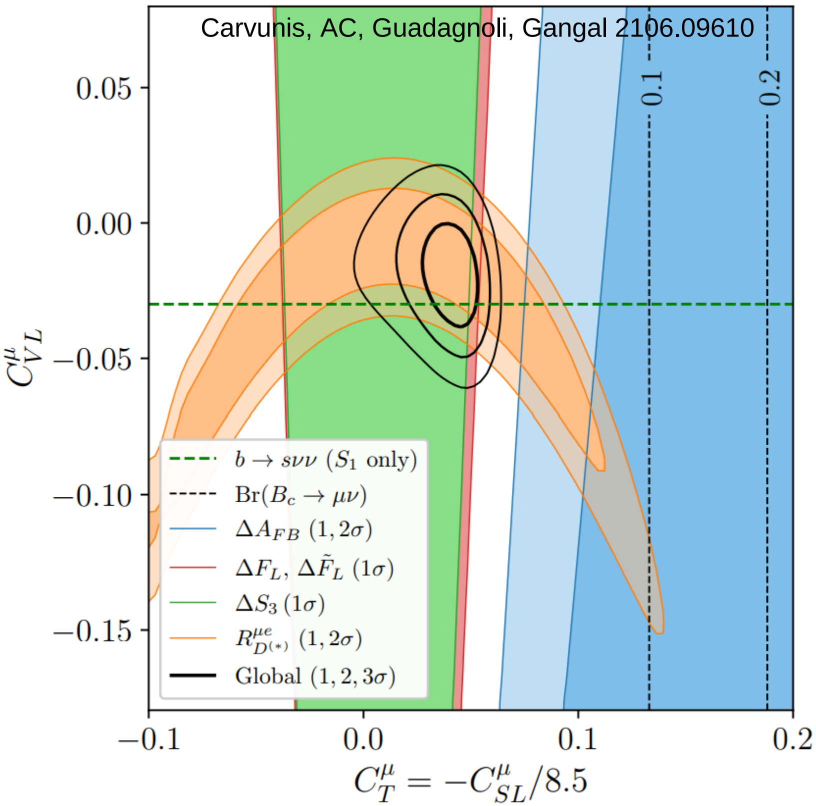


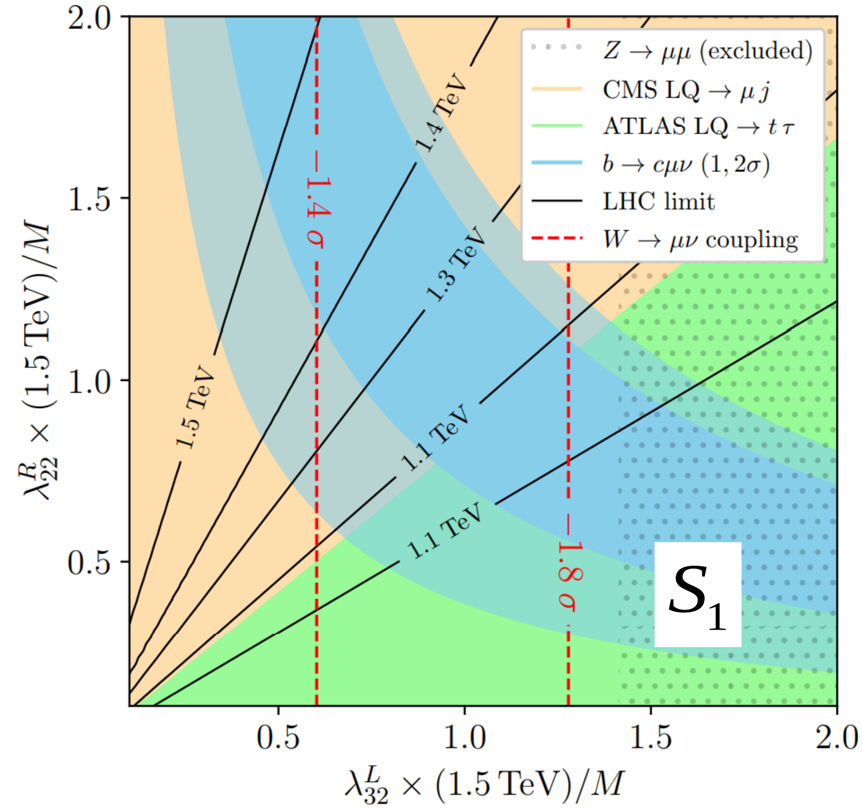
AC, F. Kirk, C. Manzari, M. Montull JHEP, 2008.01113

>5σ improvement over SM hypothesis with VLLs

ΔA_{FB}

- Right-handed vector operators LFU
- Good fit requires the tensor operator ⇨ **scalar LQ**





Hint for scalar leptoquarks