PAUL SCHERRER INSTITUT PSI

Andreas Crivellin

University of Zuich & PSI

The Flavour Anomalies and New Physics Models

Neckarzimmern, 16.03.2023

Outline

- Introduction: 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
  - ΔA_{FB}
- New Physics explanations for the anomalies
  - Z', W', Leptoquarks, MSSM, 2HDMs, extra dimensions…
- Simultaneous explanations
- Conclusions and outlook

Physics Beyond the Standard Model

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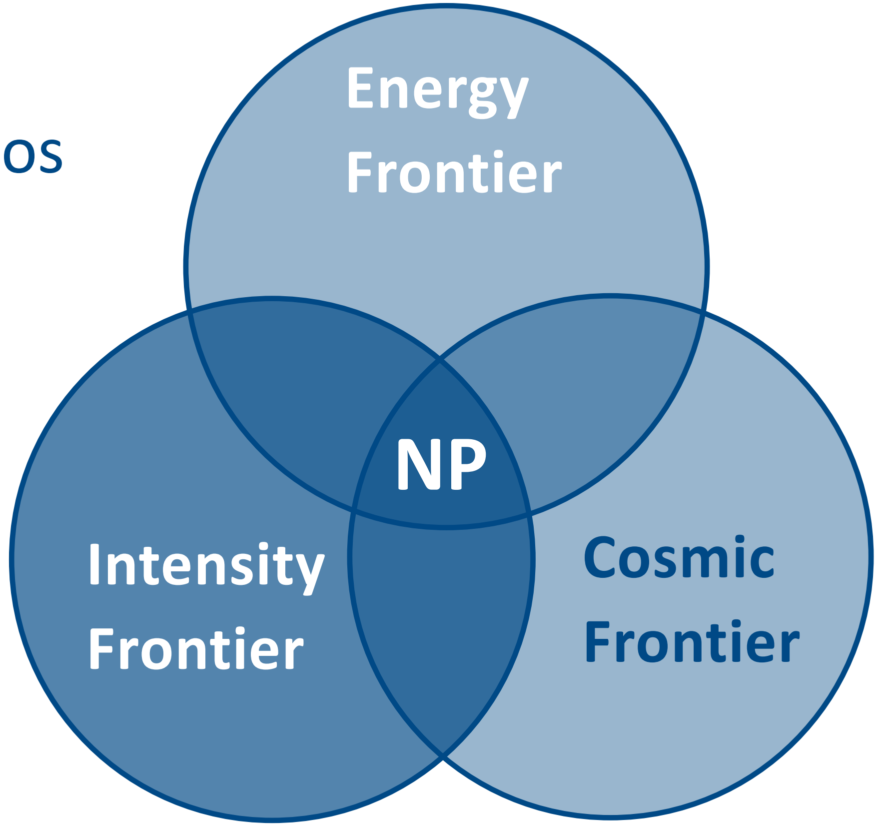
- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions
- More symmetries

New particles and interactions exist!

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

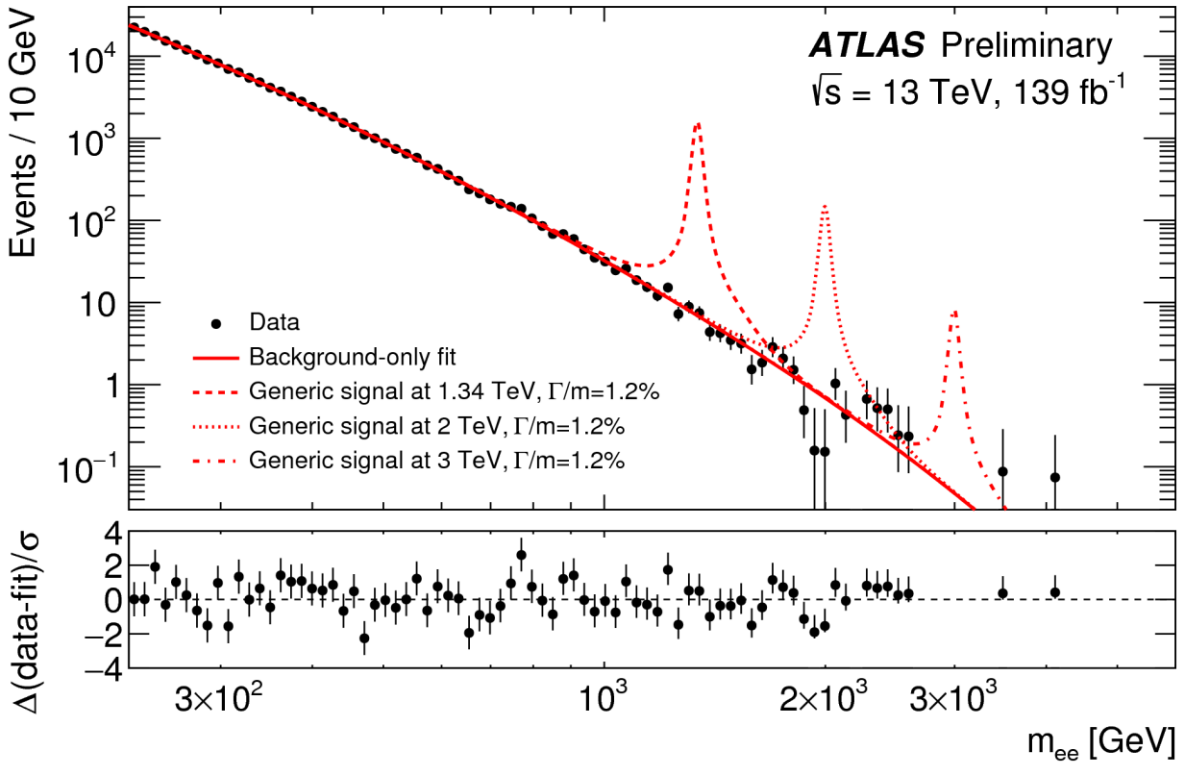
Discovering New Physics

- 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



Direct Searches for New Physics

- Searches for resonances in the spectrum
- Direct information of the mass



Limited by the available energy of the collider

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

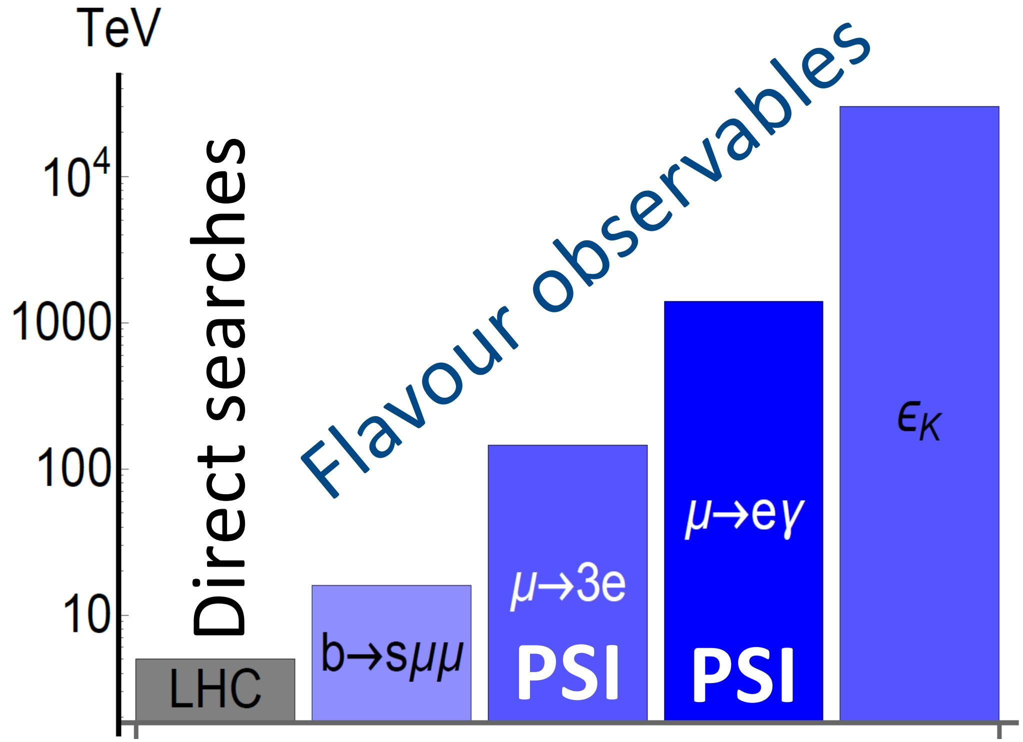
Experiment

≠

Standard Model

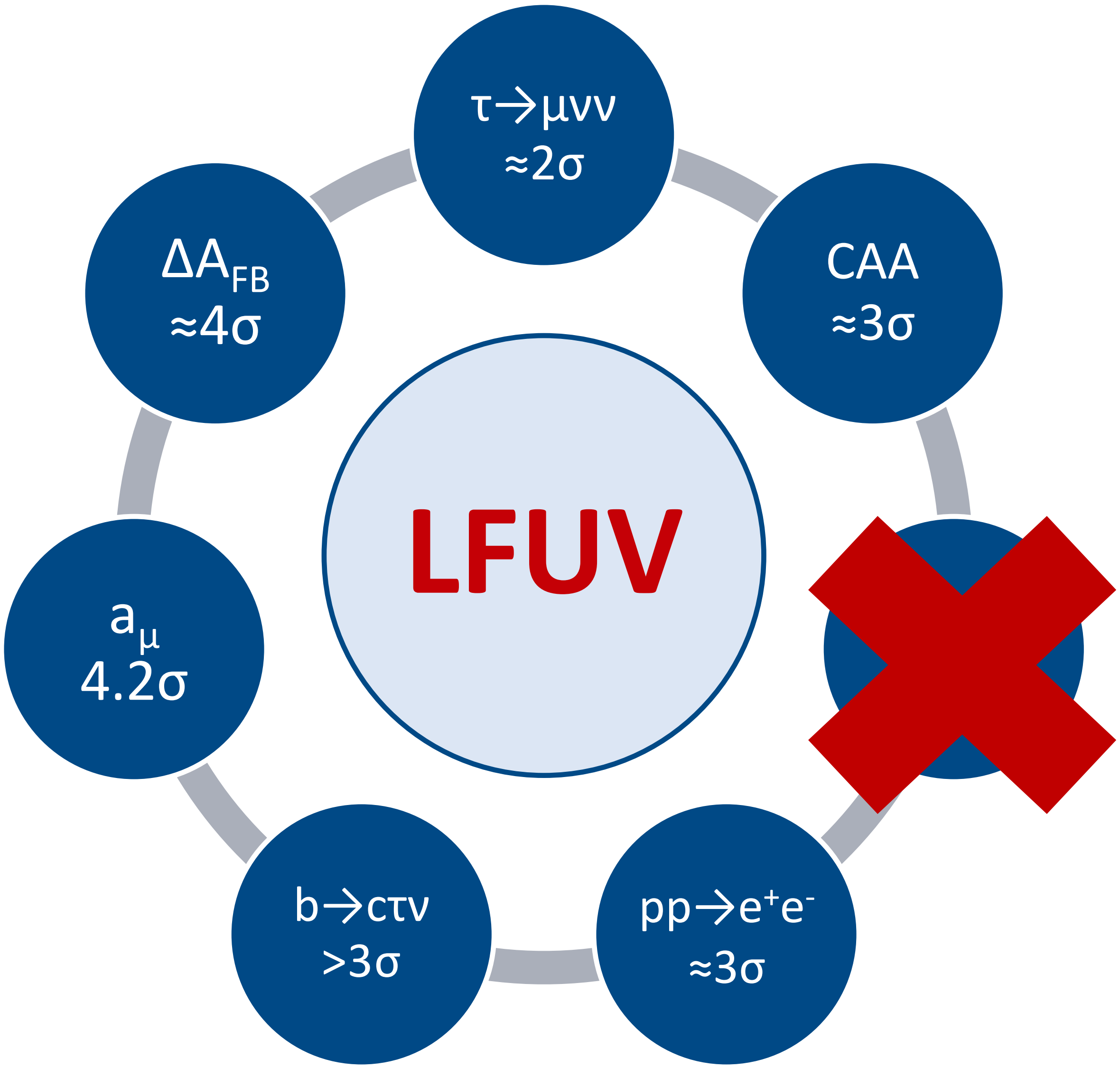
↓

New Physics



Flavour observables are sensitive to higher energy scales than collider searches

Flavour Anomalies



Lepton Flavour (Universality) Violation

In the Standard Model:

- Lepton Flavour is conserved (for vanishing neutrino masses)
  - ➢ Excellent approximation: branching ratios smaller than 10^{-45}

⇨ Any observation proves **new physics**

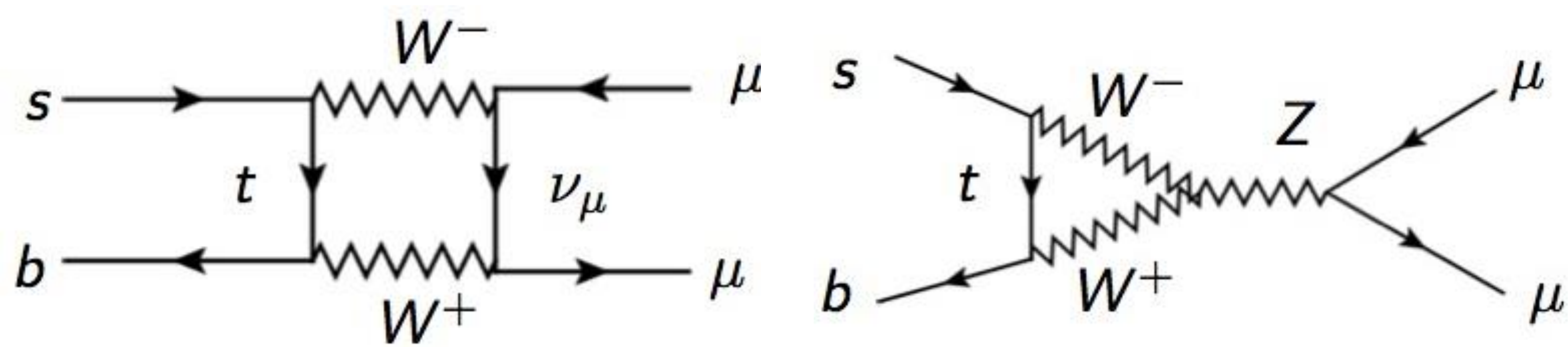
- Gauge Interactions are Lepton Flavour Universal
- Only Higgs Yukawa distinguish flavors

⇨ Very small effect (except for phase space)

LFUV is an excellent probe of the SM

$b \to s l^+ l^-$

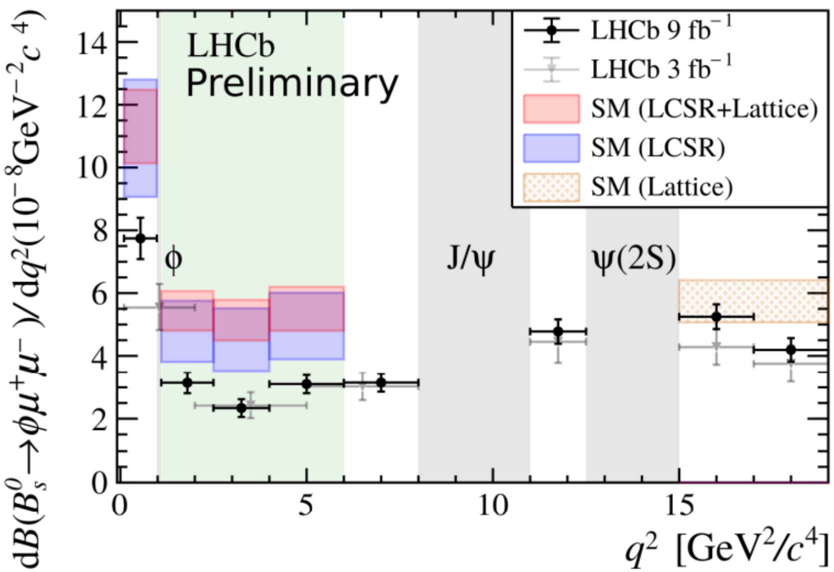
- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
  - The CKM elements $V_{cb} \approx 0.04$
  - Electroweak scale m_t^2 / m_W^4
  - Loop-factor $1/\left(16\pi^2\right)$

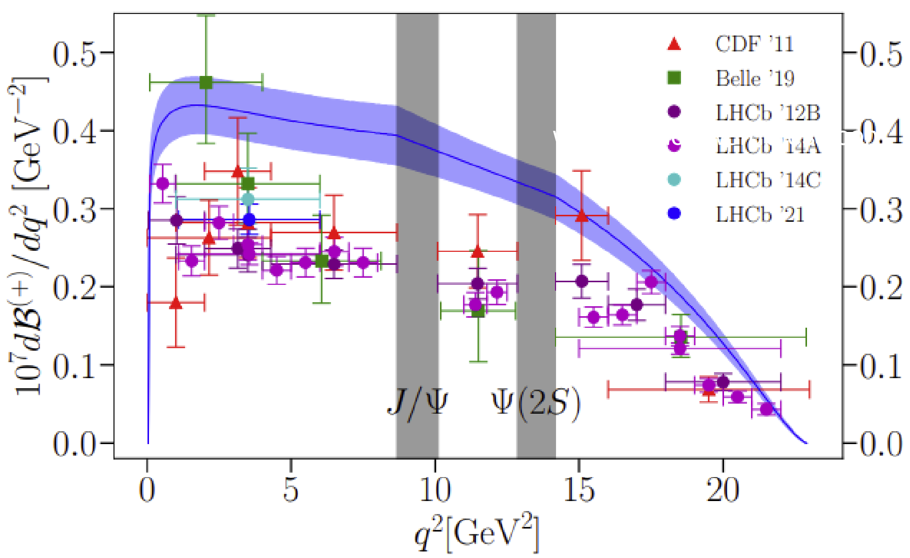


Suppressed and very sensitive to New Physics

$B \to K\mu\mu$ and $B_s \to \phi\mu\mu$

- 4σ-5σ deficit in the total branching ratios using lattice QCD and LCSR
- Signs for NP in angular $B_s \to \phi\mu\mu$ observables as well





Br's ≈ 20% below SM expectations

Reducing hadronic uncertainties

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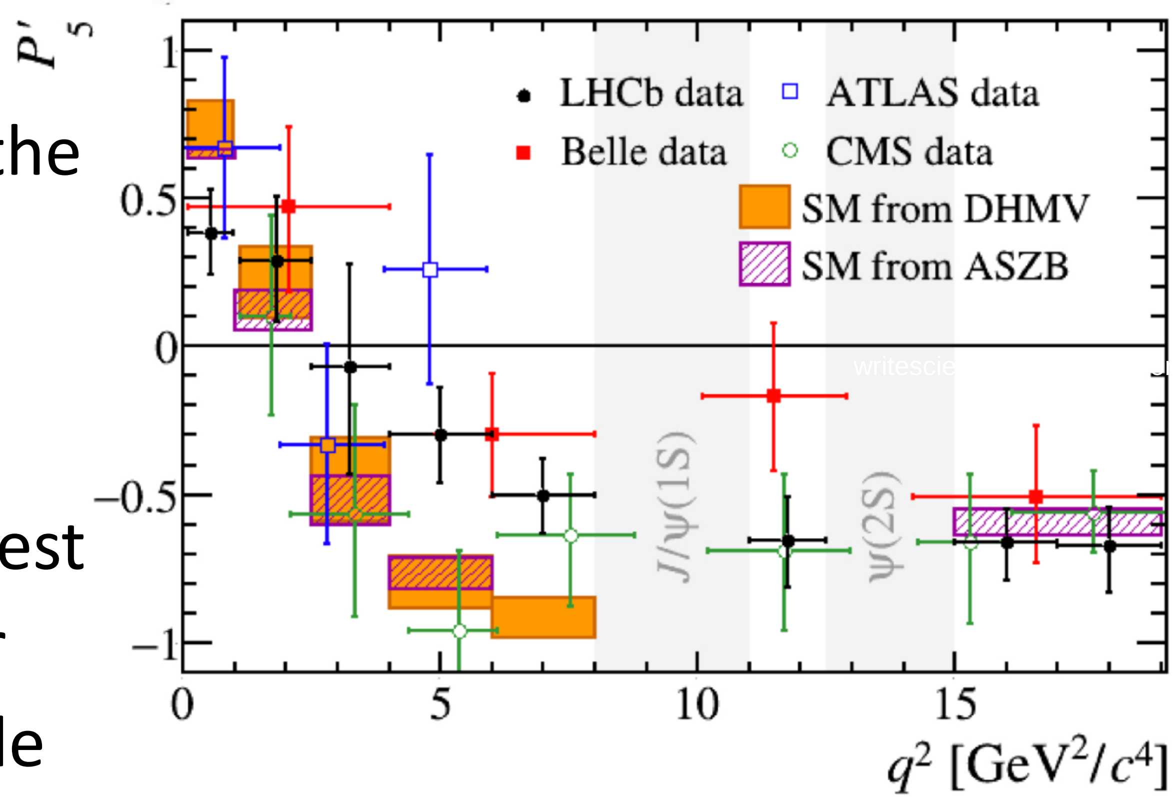
- Angular observable with minimized dependence on the form factors (P observables)
- Zero crossing of the forward-backward asymmetry
- Ratios of different lepton modes
- Lepton flavour violating decays

Clever choice of observables can reduce hadronic uncertainties

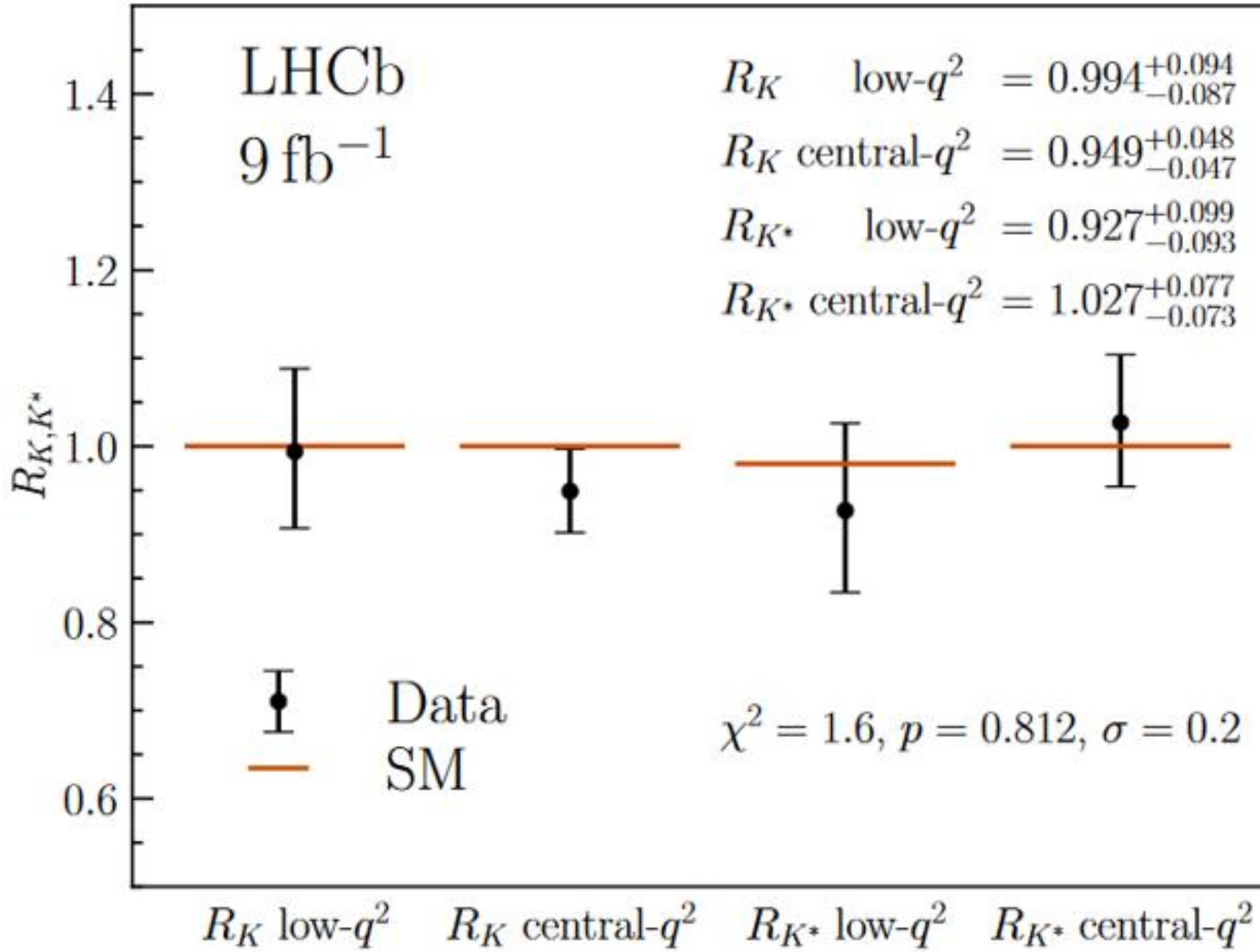
The P_5' Anomaly

- P_5´ angular observables in B→K*μμ S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 2013
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the charged mode



>3σ deviation from the SM prediction

R(K)&R(K*)



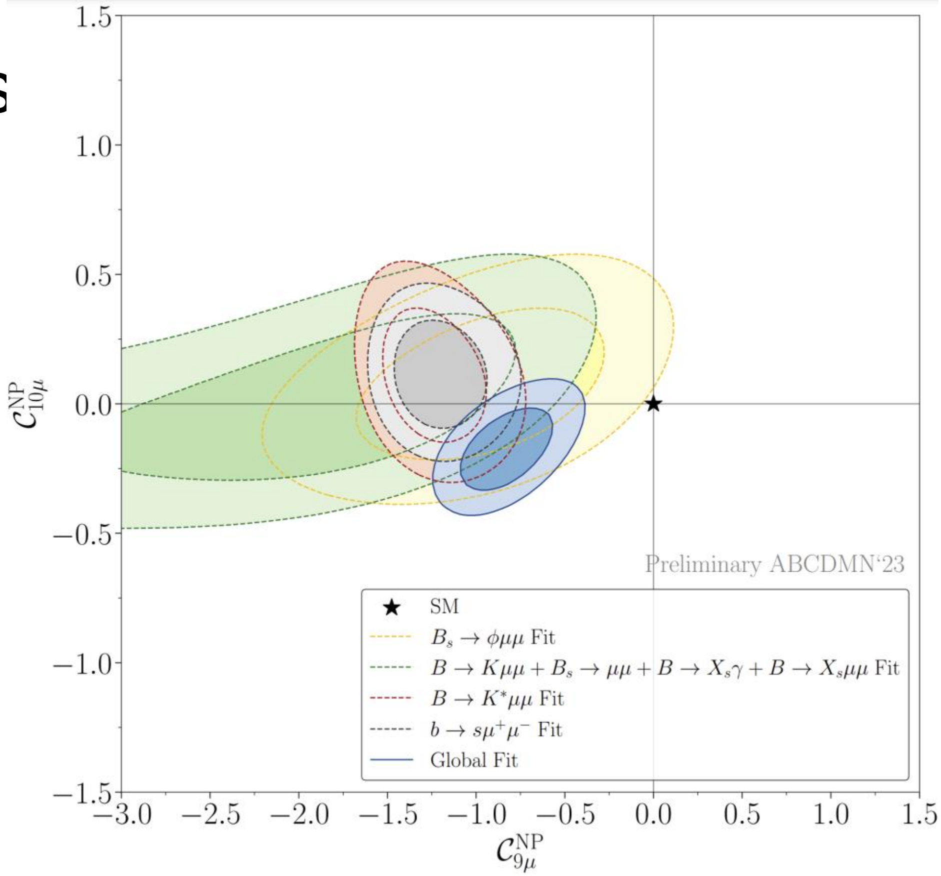
No sign of LFV anymore

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

- Perform global model independent fit to include all observables (≈150)
- Several NP hypothesis are significantly preferred over the SM hypothesis
- Study via effective interactions

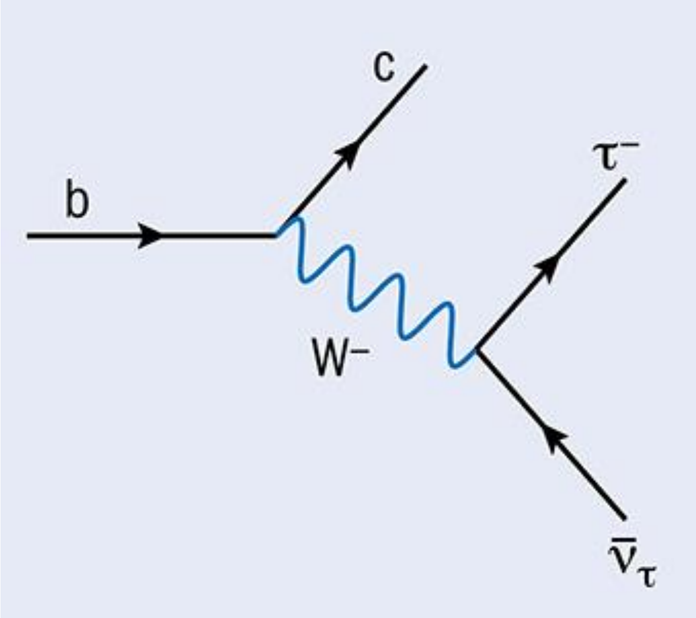
$$O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$$

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



Fit is >7 σ better than the SM

$b \to c\tau\nu$ Transitions



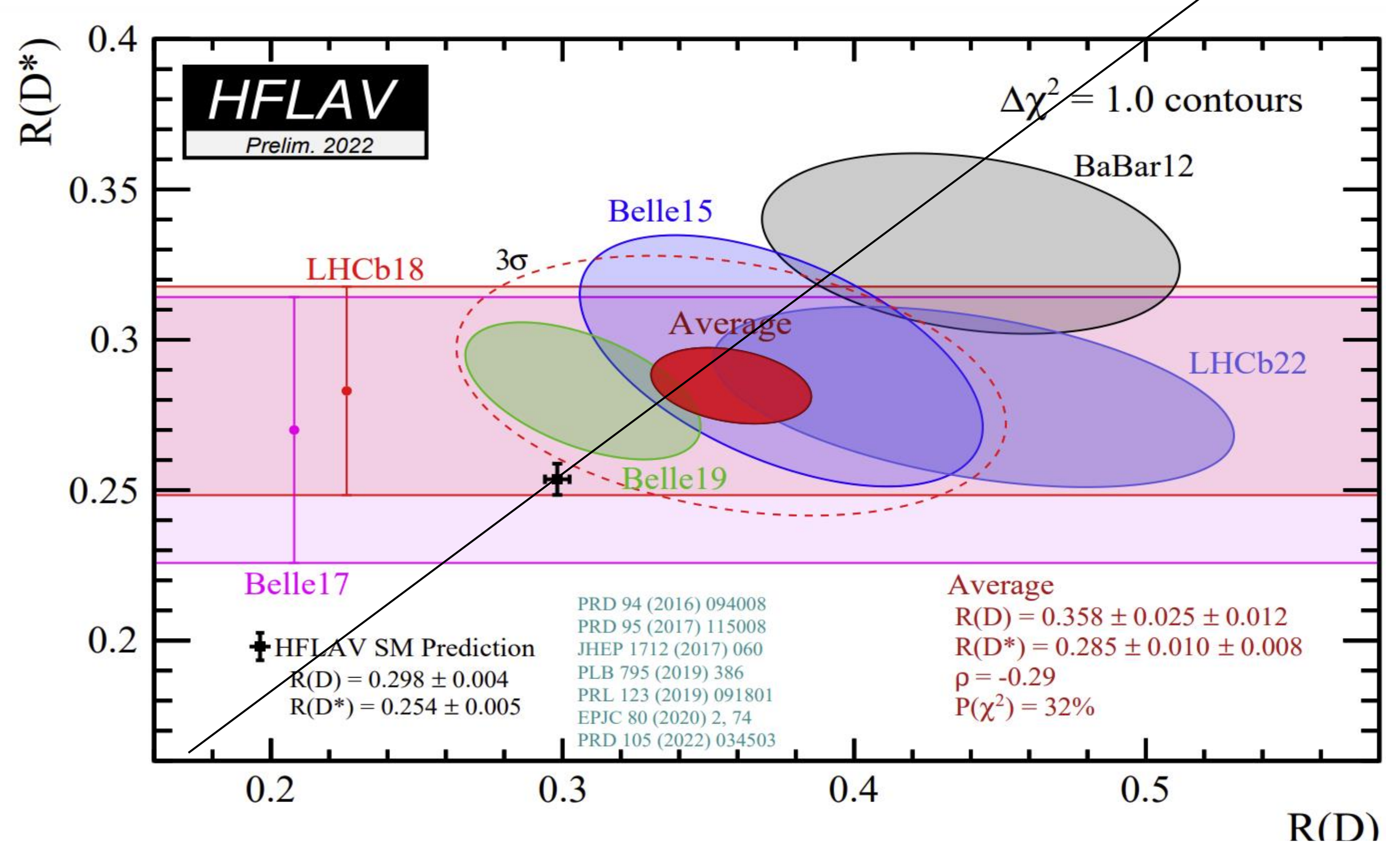
- $B \to D\tau\nu$, $B \to D^*\tau\nu$
- Tree-level decays in the SM
- Form factors needed
- With light leptons (μ, e) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with ΔF=2 processes

Largest B branching ratios, used to determine the CKM elements, usually assumed to be free of NP

b→cτν Measurements

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu / B \to D^{(*)}\ell\nu$$

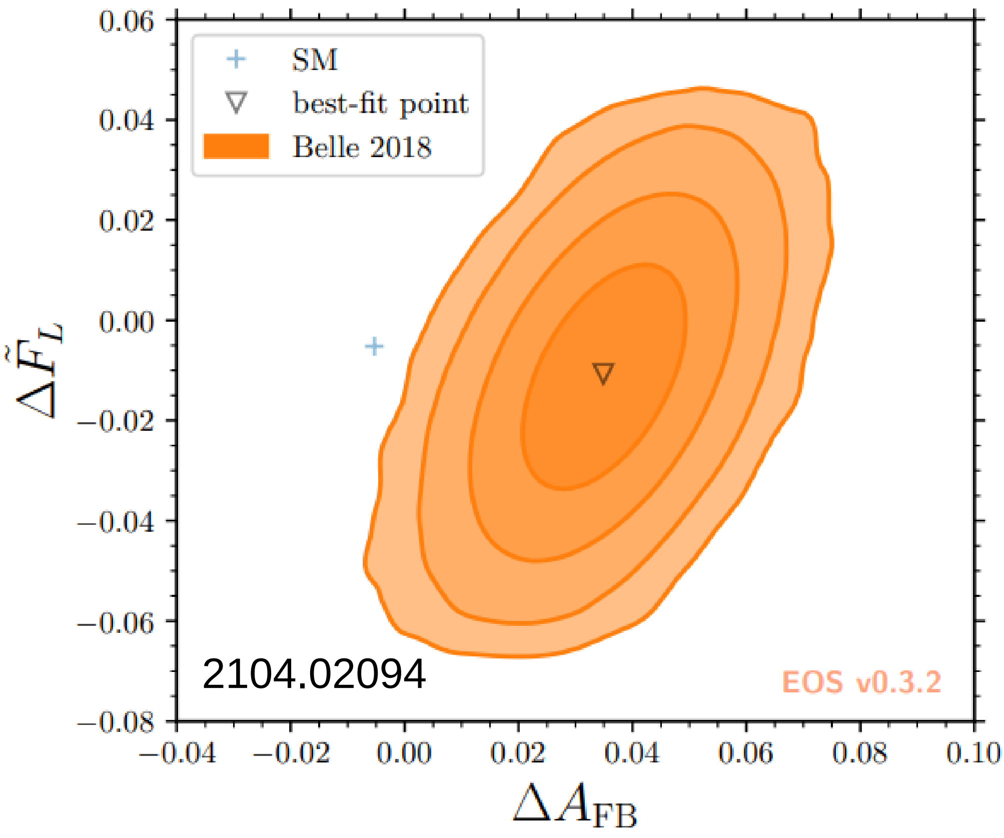
$$\frac{R(D)}{R(D)_{SM}} = \frac{R(D^*)}{R(D^*)_{SM}}$$



All measurements above the SM prediction
O(10%) constructive effect at 3σ preferred

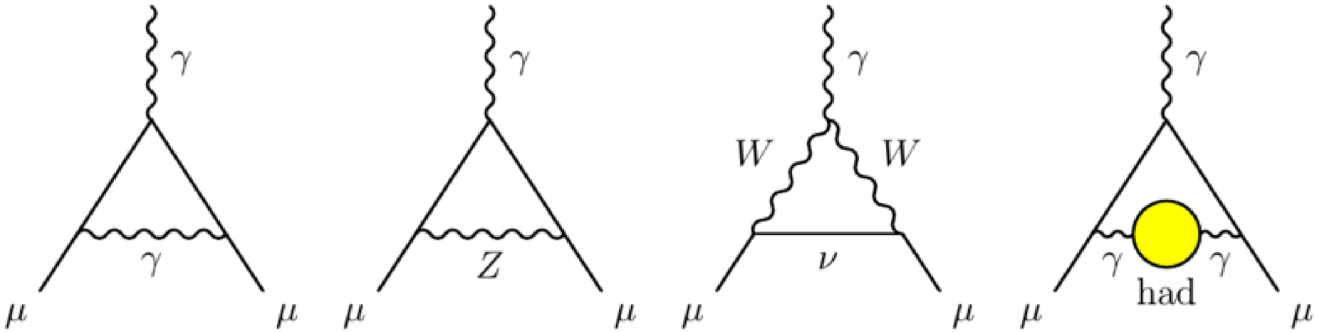
ΔA_{FB} in B→D*lν

- $\Delta A_{FB} = A_{FB}\left(b \to c\mu\nu\right) - A_{FB}\left(b \to ce\nu\right)$
- 4σ deviation found by 2104.02094 based on BELLE data 1809.03290
- Scalar and/or tensor operators required for an angular asymmetry
- g-2 and b→sμμ motivate new physics related to muons



Hint for scalar/tensor NP in b→cμν

Muon Anomalous Magnetic Moment



- Theory prediction challenging (hadronic effects)

$$\Delta a_{\mu} = \left(251 \pm 49\right) \times 10^{-11}$$ 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 $m_{\mu} \rightarrow 0$ ⇨ **measure of LFUV**

4.2σ deviation from the SM prediction

τ→μνν

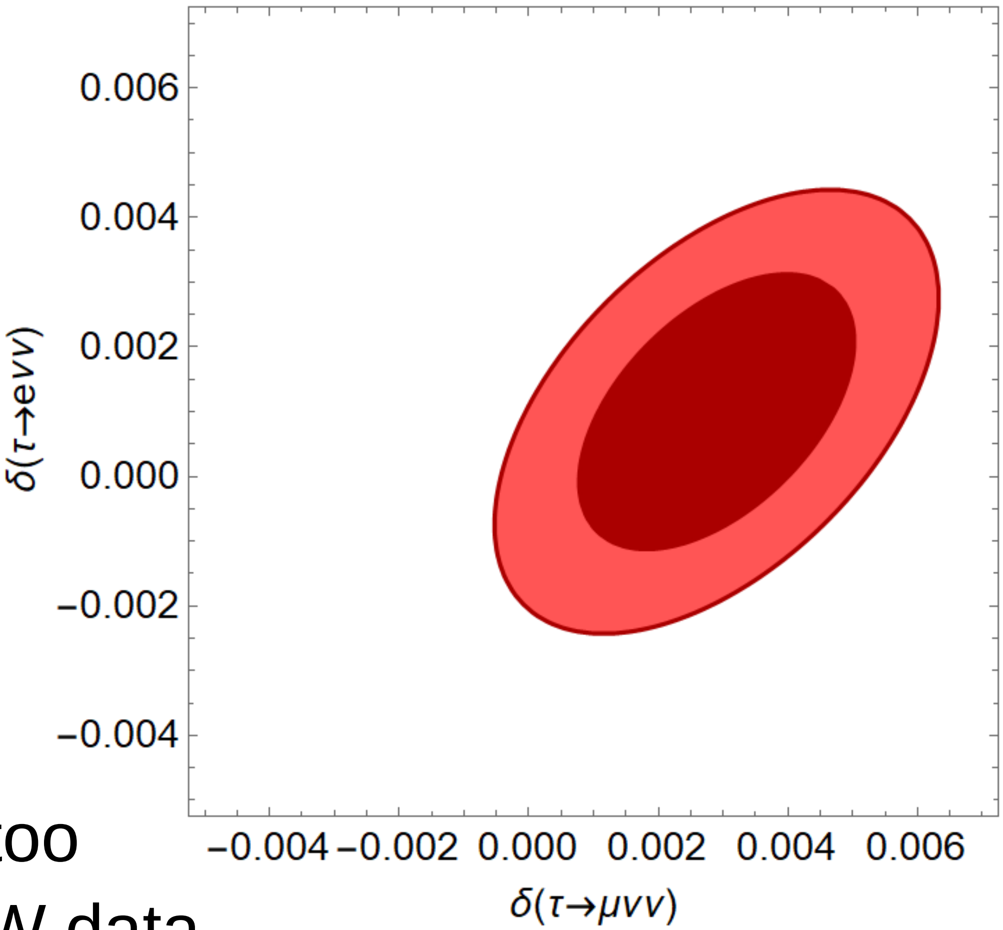
- Ratios of leptonic tau decays

$$\frac{\mathcal{A}_{\text{EXP}}(\tau\to\mu\nu\bar{\nu})}{\mathcal{A}_{\text{SM}}(\mu\to e\nu\bar{\nu})}=1.0029\pm0.0014$$

$$\frac{\mathcal{A}_{\text{EXP}}(\tau\to\mu\nu\bar{\nu})}{\mathcal{A}_{\text{SM}}(\tau\to e\nu\bar{\nu})}=1.0018\pm0.0014$$

$$\frac{\mathcal{A}_{\text{EXP}}(\tau\to e\nu\bar{\nu})}{\mathcal{A}_{\text{SM}}(\mu\to e\nu\bar{\nu})}=1.0010\pm0.0014$$

$$\rho=\begin{pmatrix}1.00 & 0.49 & 0.51\\ 0.49 & 1.00 & -0.49\\ 0.51 & -0.49 & 1.00\end{pmatrix}$$

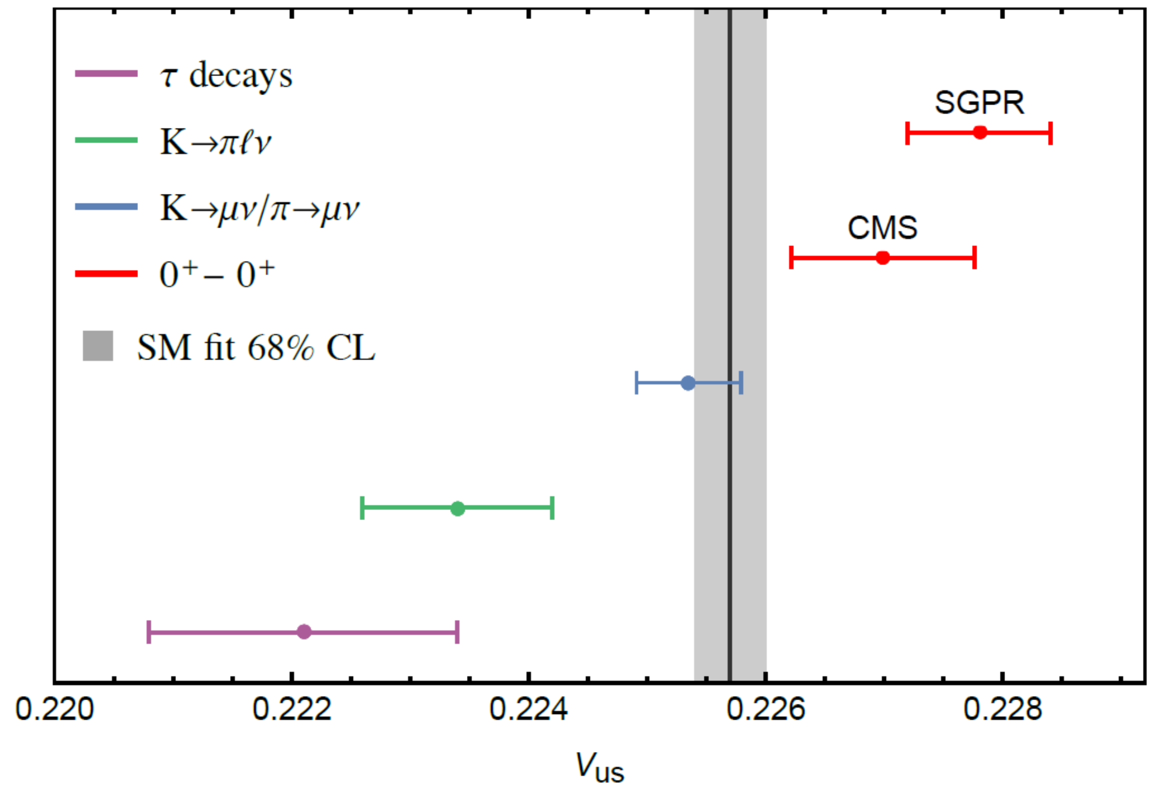


- NP in muon decay too constrained from EW data

≈2σ hint for LFUV in tau decays

Cabibbo Angle Anomaly

- V_{ud} from super-allowed beta decays
- V_{us} from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity



CMS, SGPR: radiative corrections

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005\,(\text{PDG})$$

≈3σ hint for LFUV in the charged current

CAA and LFUV

- Assume modified Wℓν couplings

$$L = i\, g_2/\sqrt{2}\, \nu_f \gamma^\mu P_L \ell_i W_\mu \left(\delta_{fi} + \varepsilon_{fi}\right)$$

- V_{ud} from beta decays depends on Fermi constant

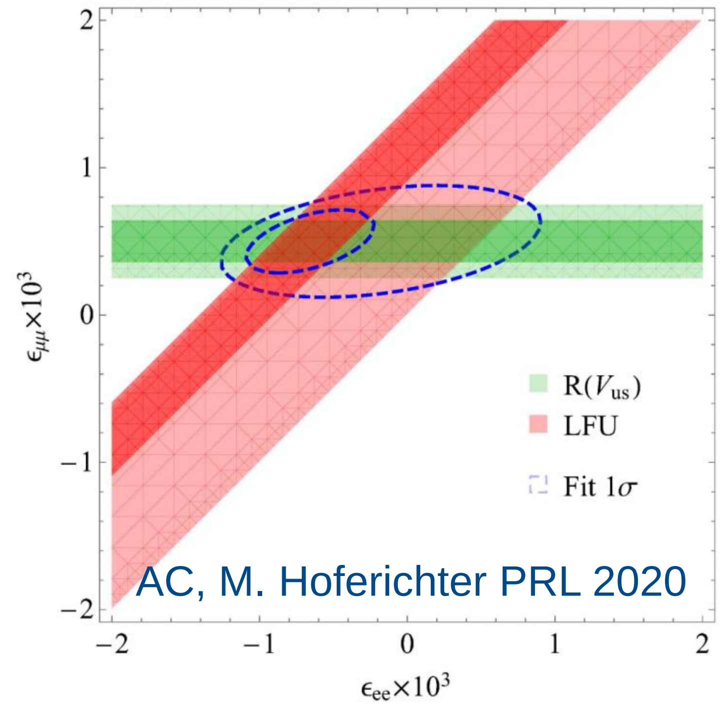
$$1/\tau_\beta \sim \left|V_{ud}\left(1+\varepsilon_{ee}\right)\right|^2 G_F^2$$

- Fermi constant determined from muon decay

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q)\left(1+\varepsilon_{ee}+\varepsilon_{\mu\mu}\right)^2$$

- Dependence on ε_{ee} cancels

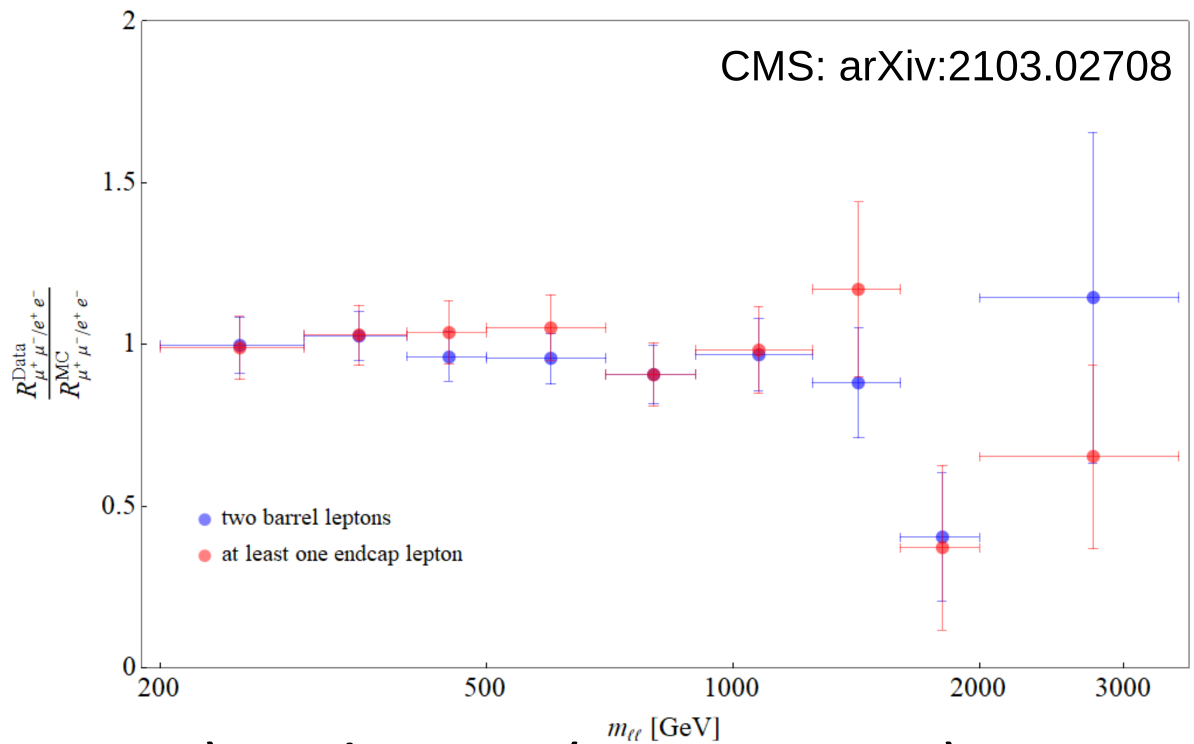
$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1-\left(V_{ud}^{\beta}\right)^2-\left|V_{ub}\right|^2}} \approx 1-\left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu}$$



The CAA can be interpreted as a sign of LFUV

Non-Resonant Di-Leptons

- Excess in di-electrons at m_{ee}>1800GeV
- Observed: 44 events
- Expected 29.2 ± 3.6 events



- Also ATLAS (2006.12946) and HERA (1902.03048) observe slightly more electrons than expected.
- No excess in muon data

≈3σ hint for LFUV

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- $\Delta A_{FB} = A_{FB}\left(B \to D^* \mu \nu\right) - A_{FB}\left(B \to D^* e \nu\right)$
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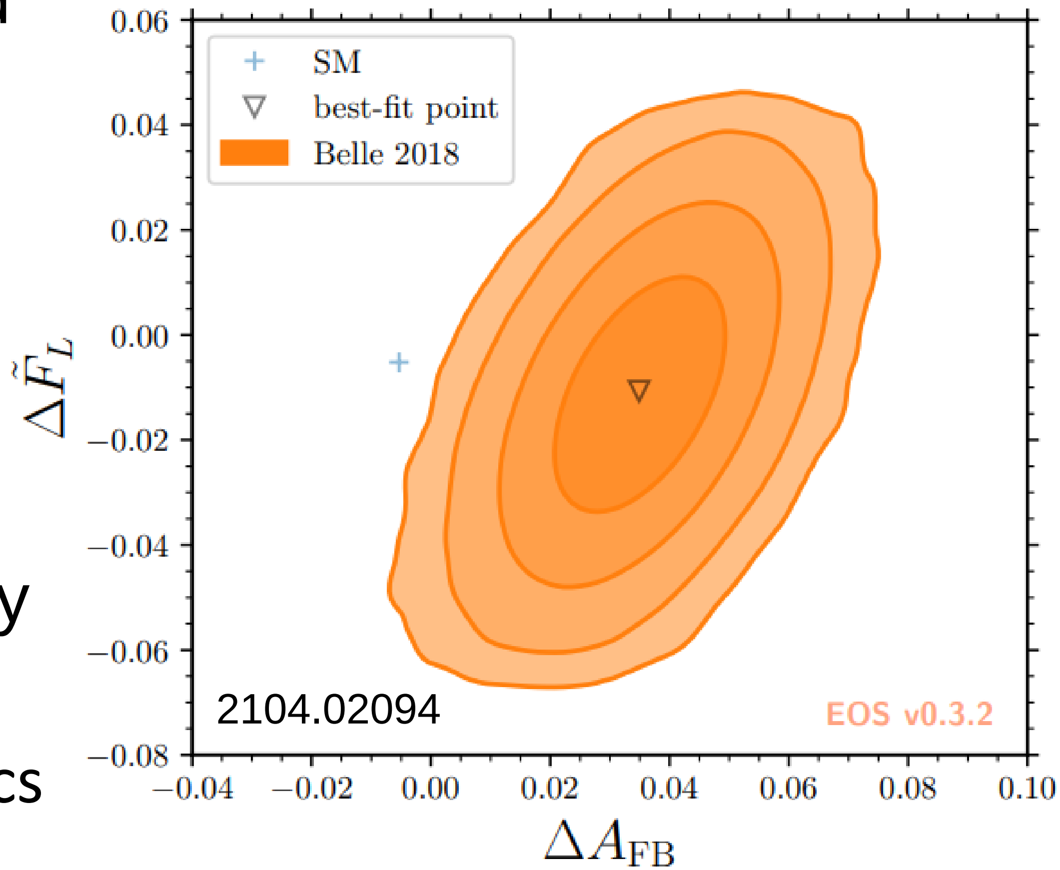
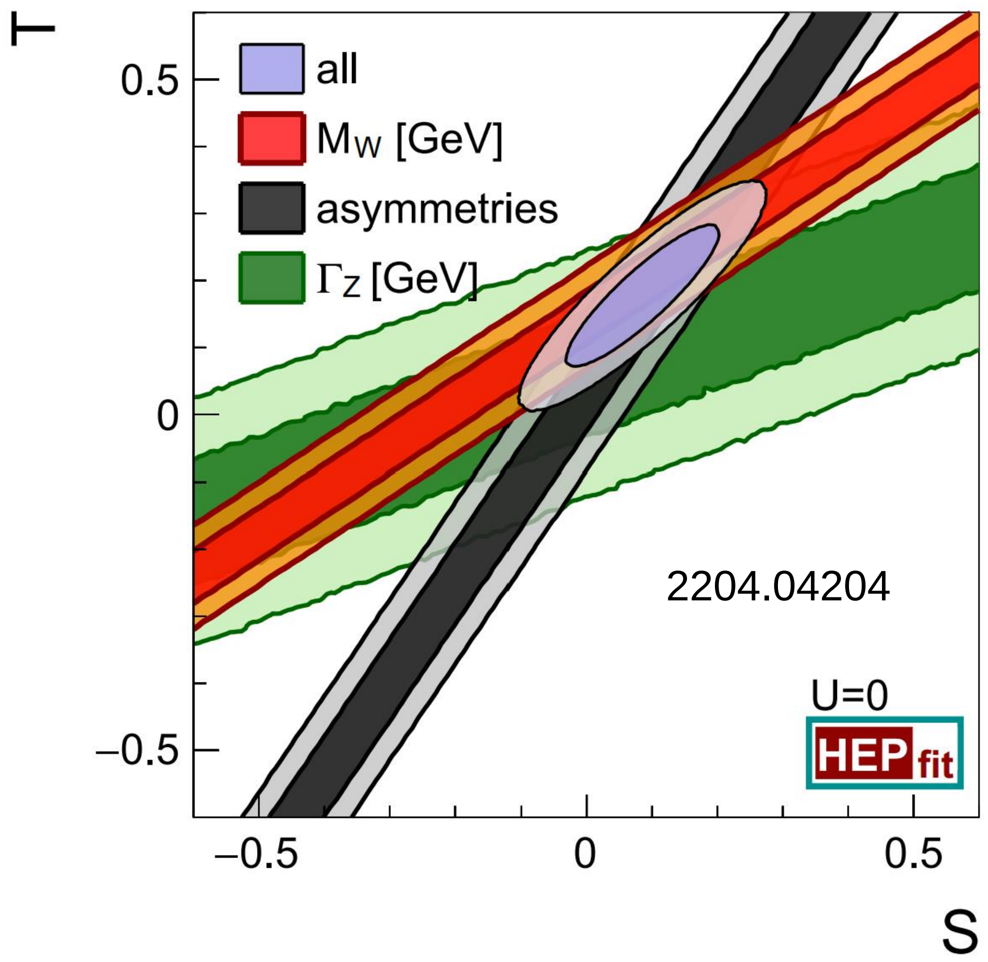


Hint for scalar/tensor NP in b→cμν

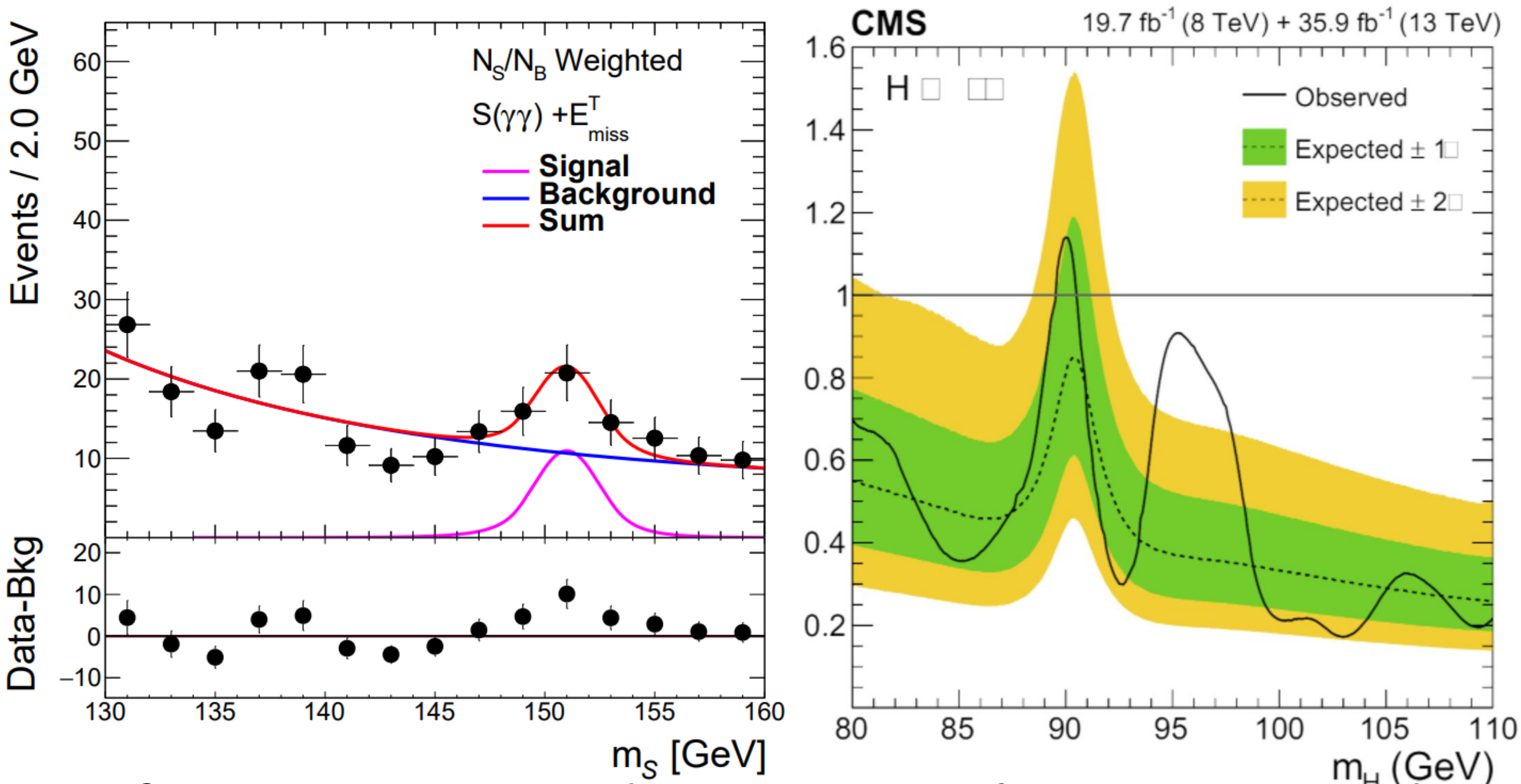
EW fit: W mass and Z→bb,

- 3.7σ tension in the W mass using a conservative error combination
- 2σ tension in Z→bb from LEP



Related to LFUV?

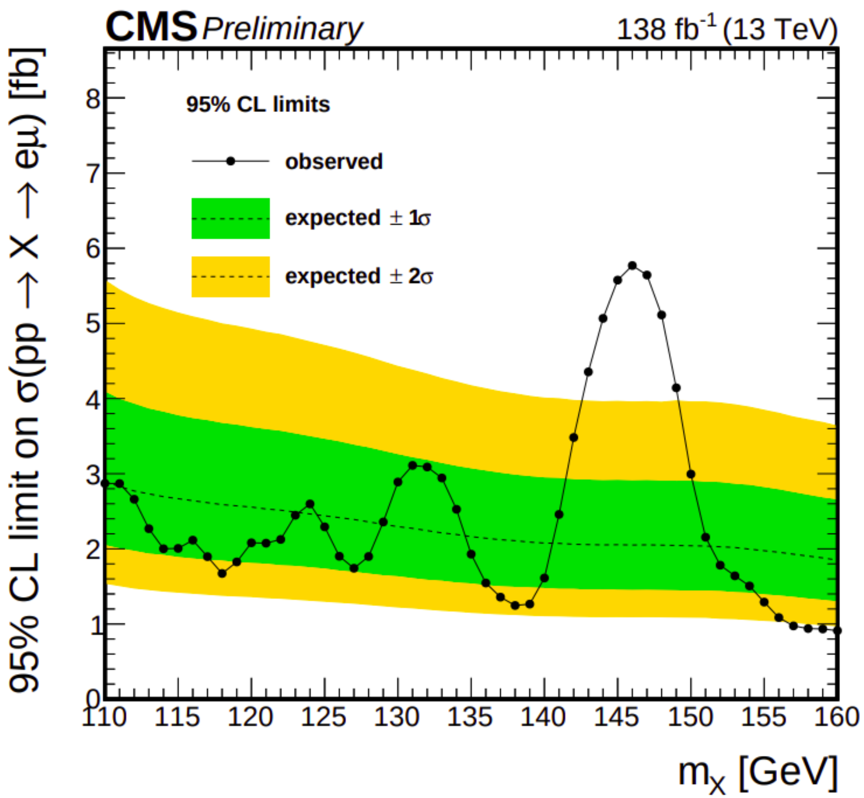
Hint for New Higgses in Di-Photons

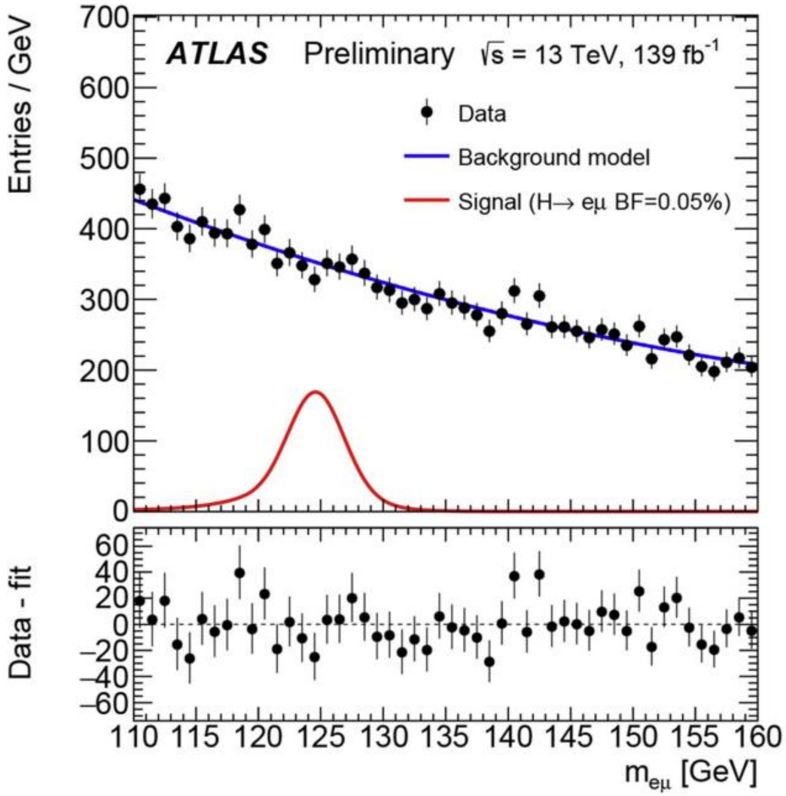


- Hints for a resonance decaying to photons around 96 GeV, 151 GeV and 680 GeV

New Scalar (Higgs) boson? Relation to DM?

h→eμ



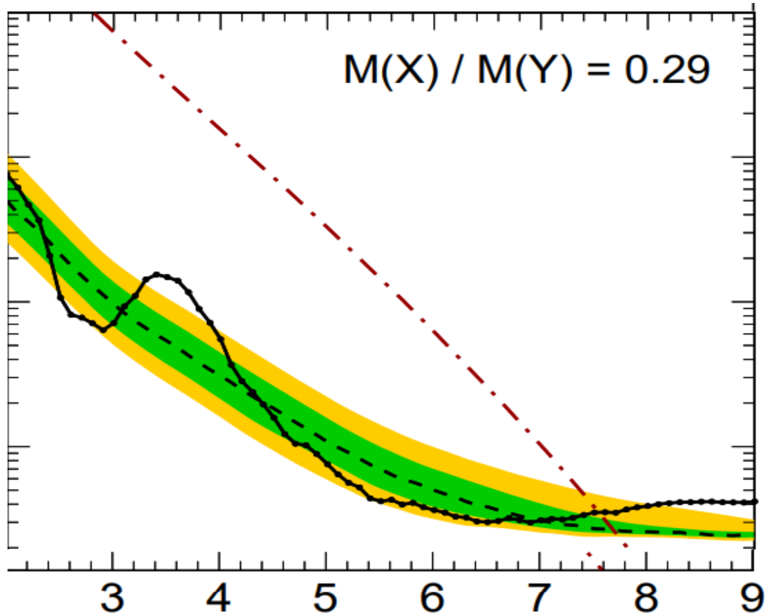


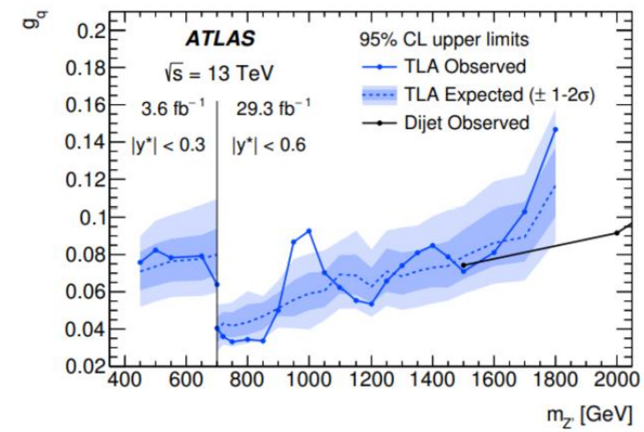
- CMS and ATLAS partially compatible
- Partially compatible with 151

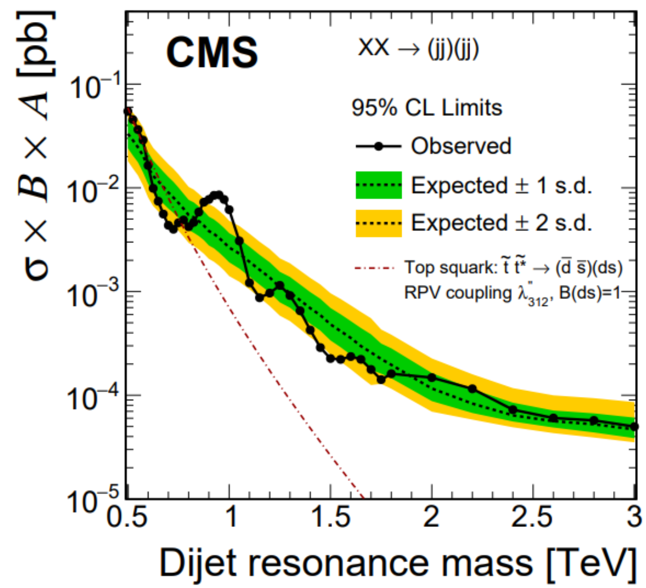
LFV resoance?

Di-(Di-)Jets

- ATLAS excess in di-jets searches
- Agrees with the di-jet mass of the CMS analysis
- Y→XX
- Global significance 3.6σ
- New 2.4TeV particle in RS setup



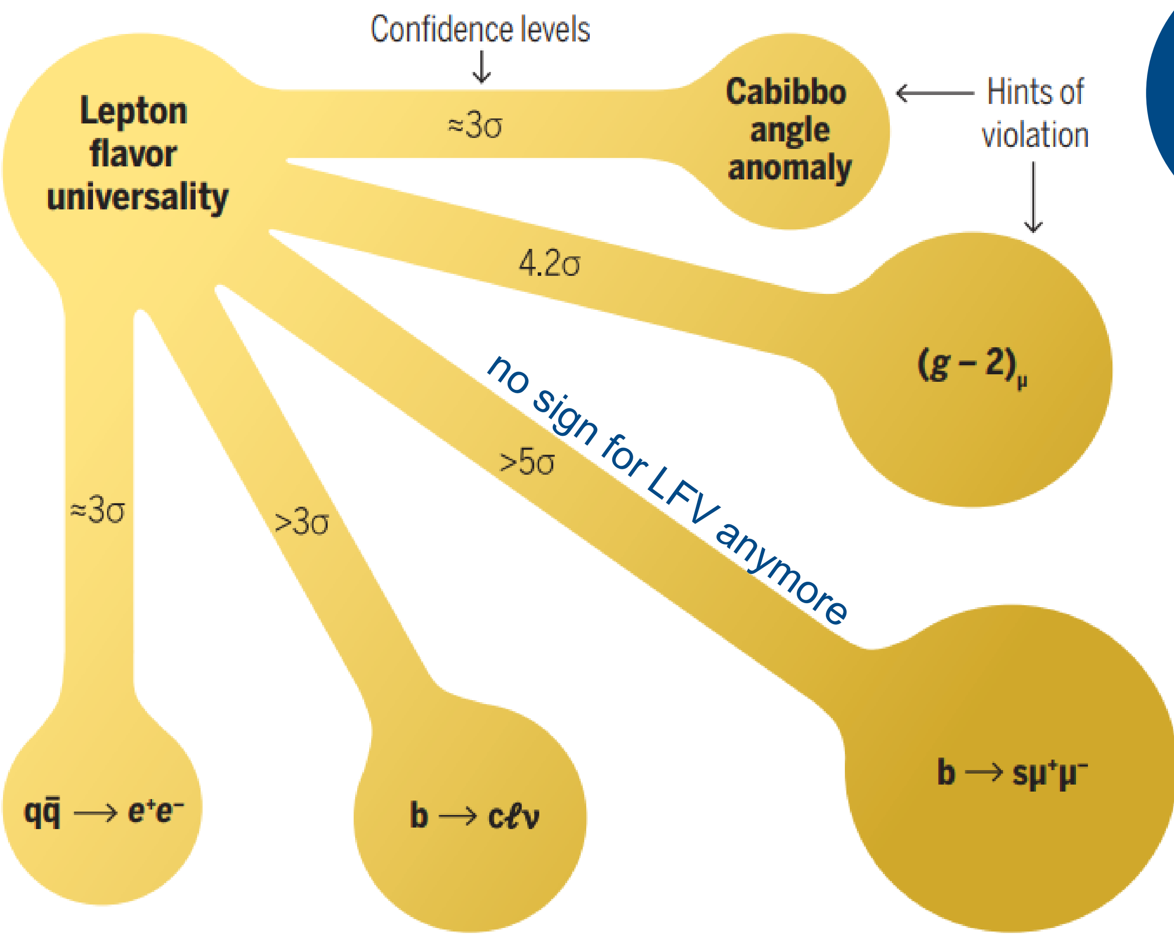




New Heavy Gluons?

Hints for New Physics

- LFUV AC, M. Hoferichter, Science 374 (2021)



- EW observables
  - m_W ≈3-4σ
  - $Z \rightarrow bb$

- Direct searches
  - γγ ττ
  - jj
  - 4b bbττ
  - $h \rightarrow \mu e$

Extensions of the Standard Model

New Particles

- On the renormalizable level on can add:
  - Scalars (spin 0, mass dimension 1)
  - Fermions (spin ½, mass dimension 3/2)
  - Vectors (spin 1, mass dimension 1)

Limited number of new interactions

Leptoquarks

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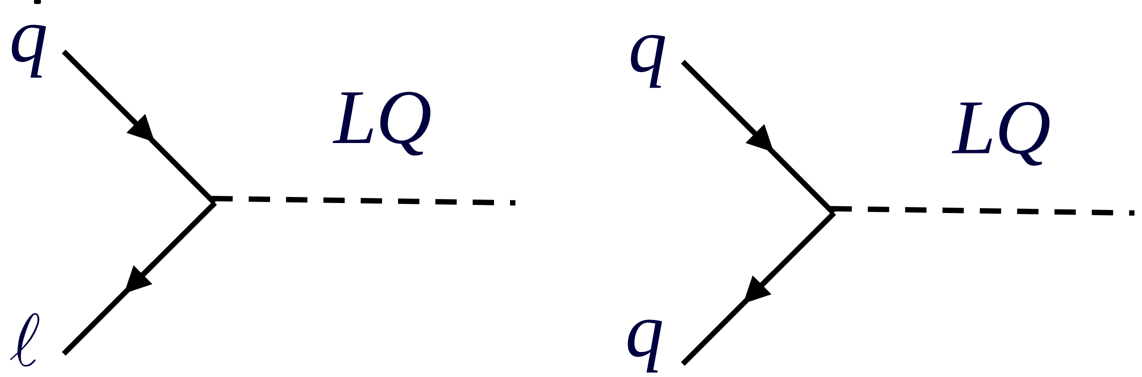
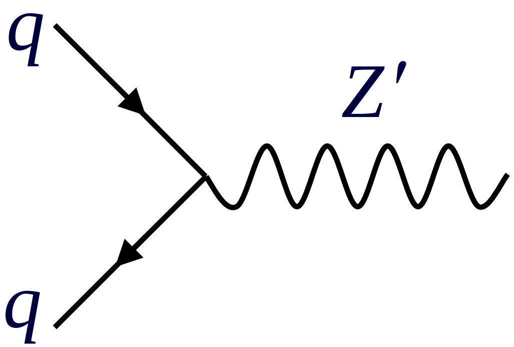
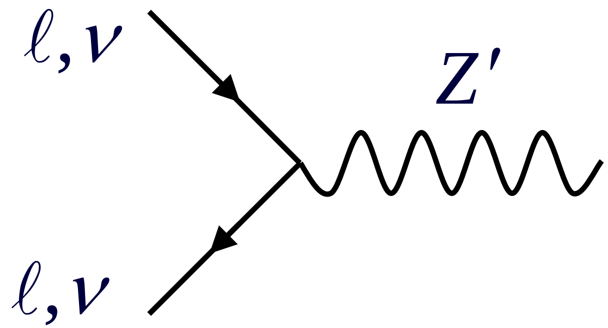
- Scalars or Vectors
- 5 gauge representations each which are invariant under the SM gauge group
- Couple quarks to leptons
- Maybe also quarks to quarks
  - Proton decay
- Are present in Grand Unified Theories



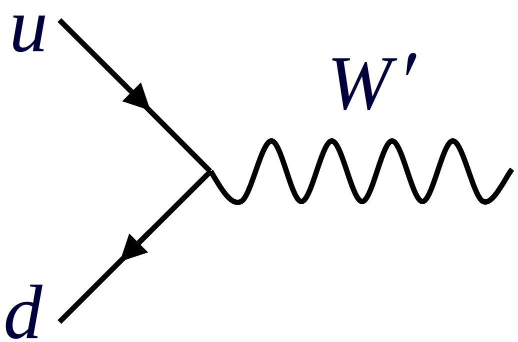
Z’ and W’

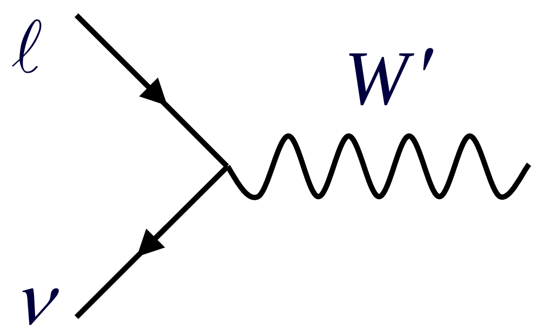
- Z’: new neutral heavy gauge boson





- W’: new charged heavy gauge boson





New heavy gauge bosons

Vector-like fermions

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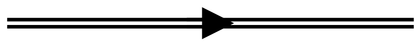
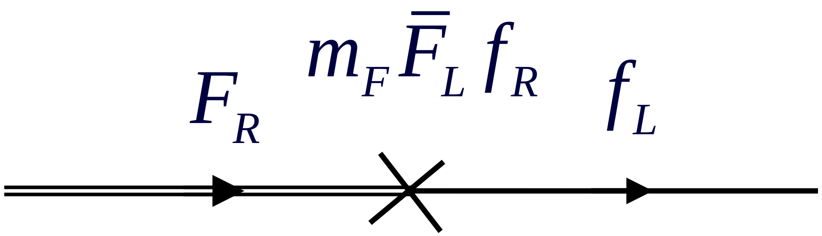
- Left-handed and handed fields have the same quantum numbers
  - Bare mass term (without symmetry breaking)

$M_F \bar{F}_L F_R$



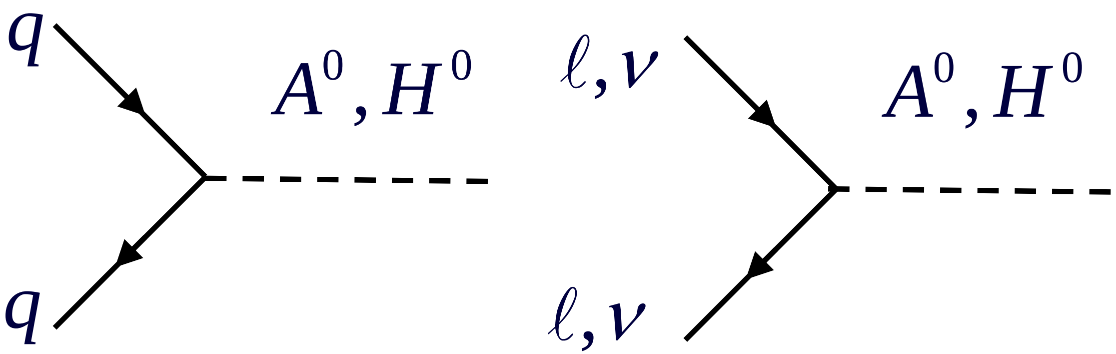
- Can mix with SM fermions



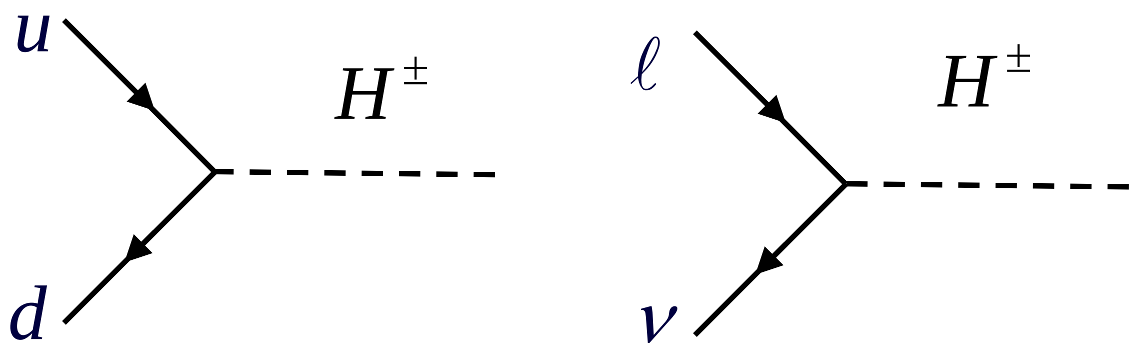
Massive new fermions

Scalars (uncharged under QCD)

- H: new neutral boson



- H⁺: new charged heavy gauge boson



New Higgses

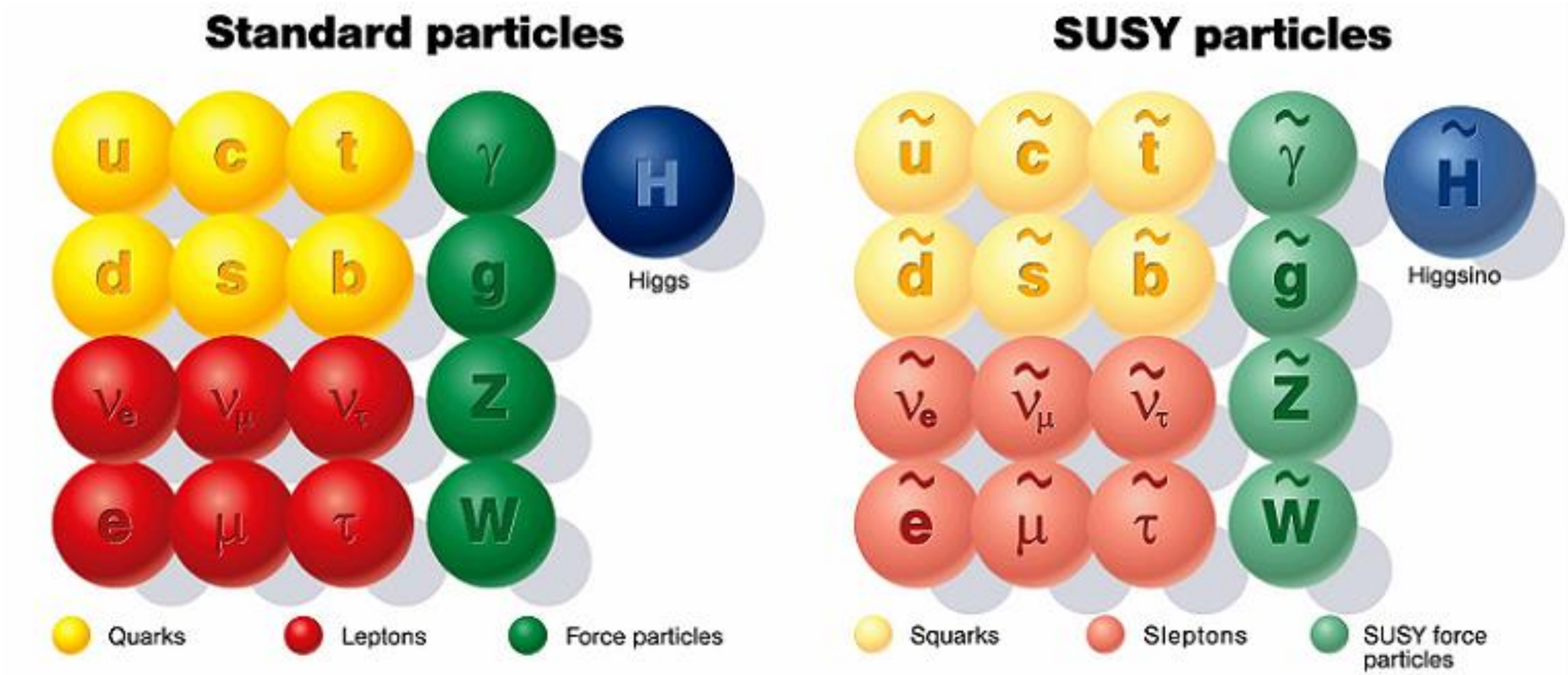
Grand Unified Theories

- Unification forces in a simply connected group
- SU(5)
  - Proton decays, 2 representationPati Salam
- Pati Salam
  - $SU(4)xSU(2)_LxSU(2)_R$
  - No Proton decay, right-handed neutrinos with See-Saw mechanism
- SO(10)
  - Single representation, right-handed neutrinos

Coupling unification and leptoquarks

MSSM

- Minimal Supersymmetric Standard Model
- All SM particles get partners with differ in spin



Particle spectrum doubled

Extra dimensions

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- Additional (compact) dimension
- Kaluza Klein excitations:
  - Massive vector bosons
  - Heavy vector like fermions
- SM particle are 0 modes
- No zero mode for gauge bosons corresponding to broken generators
- Duality with Technicolor

Tower of heavy copies of the SM particles

Explanations of the Anomalies

R(D) & R(D*)

- Charged scalars
  - Problems with q^2 distributions and B_c lifetime
- W’
  - Strong constraints from direct LHC searches
- Leptoquark (also in the RPV MSSM)
  - Strong signals in $qq \to \tau\tau$ searches

Explanation difficult but possible with Leptoquarks

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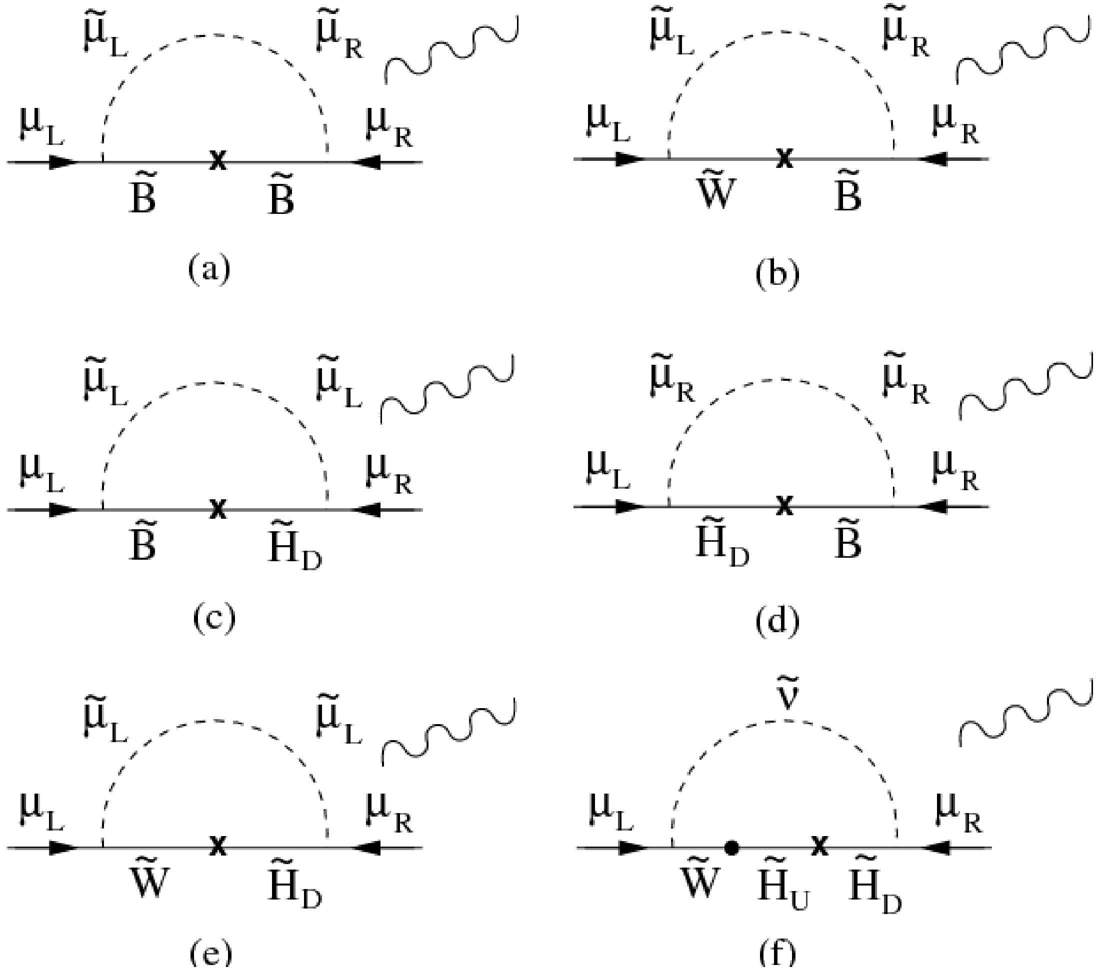
a_μ: MSSM

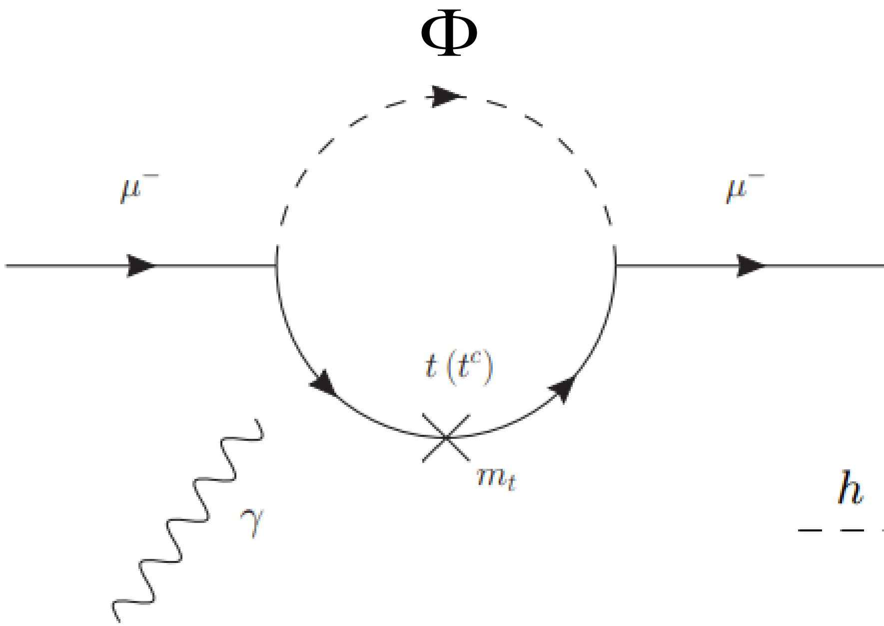


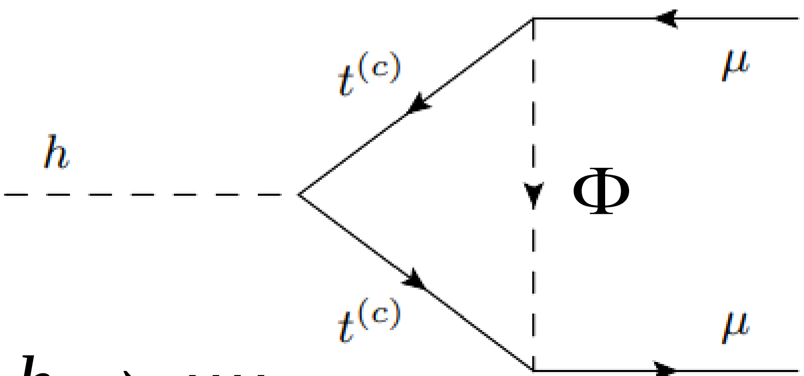
e.g. D. Stockinger, hep-ph/0609168

tan(ß) enhanced slepton and sneutrino loops

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



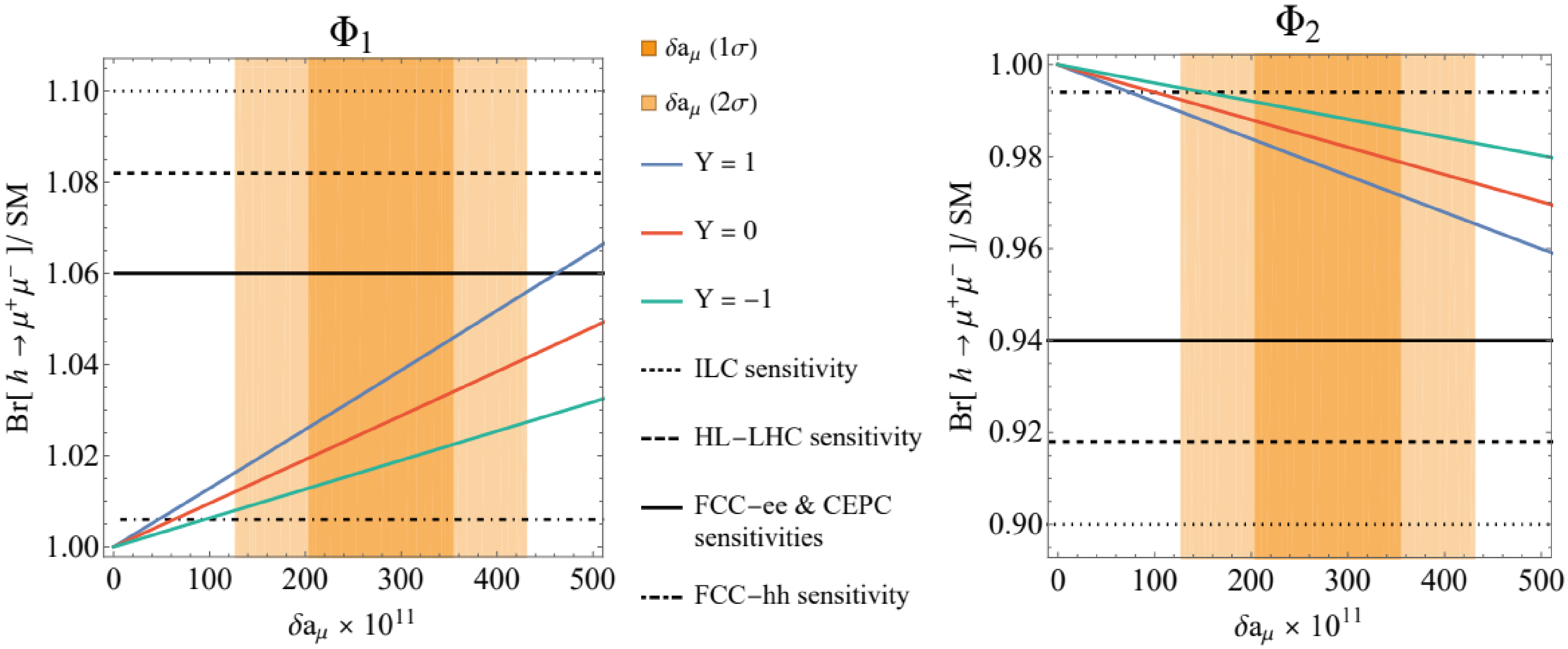


- m_t/m_μ enhanced effect $h \to \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \to \mu\mu$

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

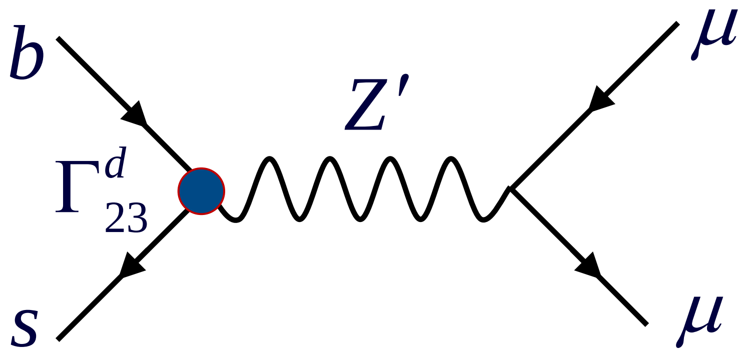


A.C., D. Mueller, F. Saturnino, PRL 2021

h→μμ at future colliders

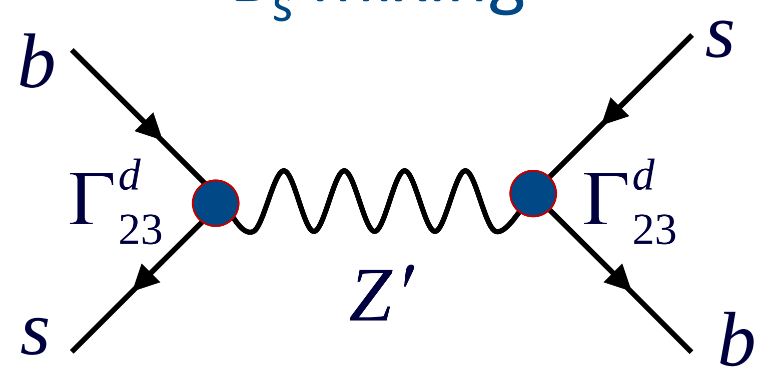
$b \to s\mu^+\mu^-$: Z’

b→sμμ



$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

B$_s$ mixing

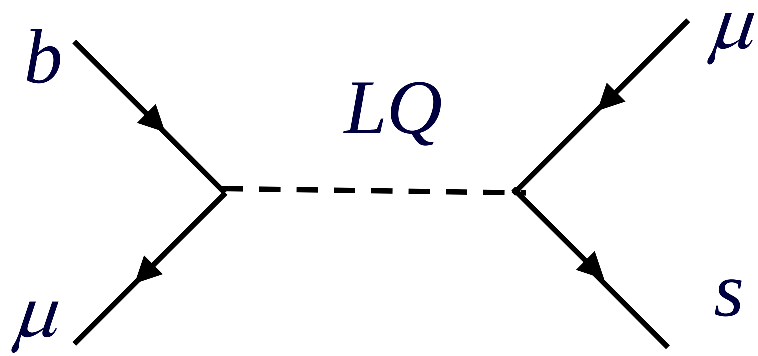


$$\frac{\Delta M_{12}}{M_{12}^{\mathrm{SM}}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$

Effect in B$_s$ mixing expected

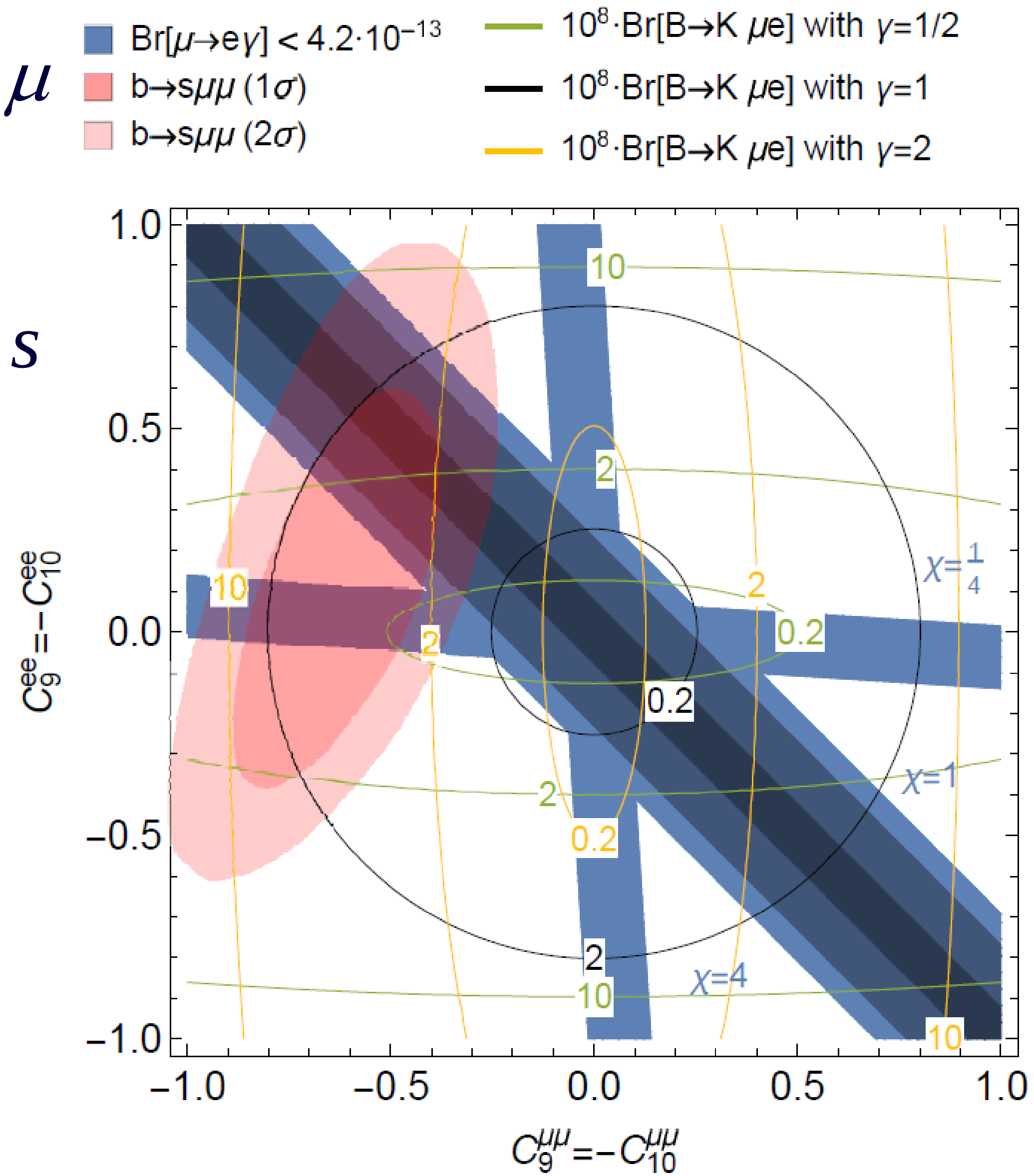
b-s coupling must be small

$b\to s\mu^+\mu^-$: LQ



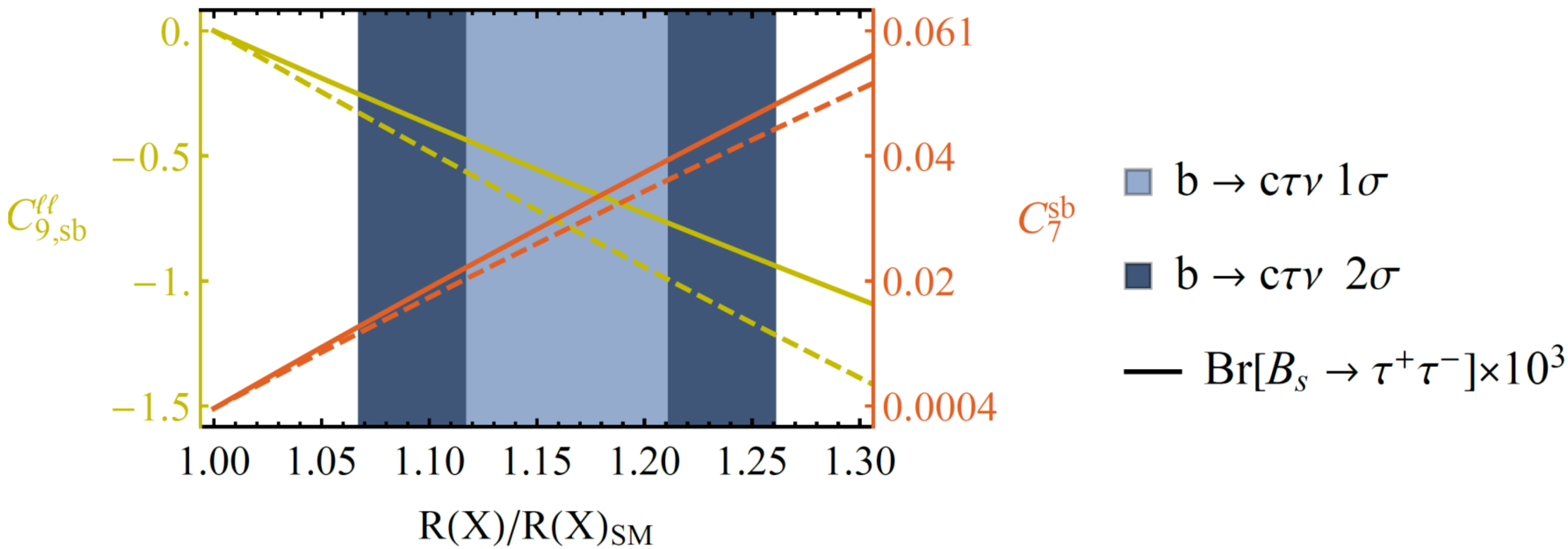
- Small effect in B_s mixing

Lepton flavour violation



Important Loop-Effects

- Explanation of b→cτν requires large bτ and sτ couplings (follows from SU(2) invariance)



AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

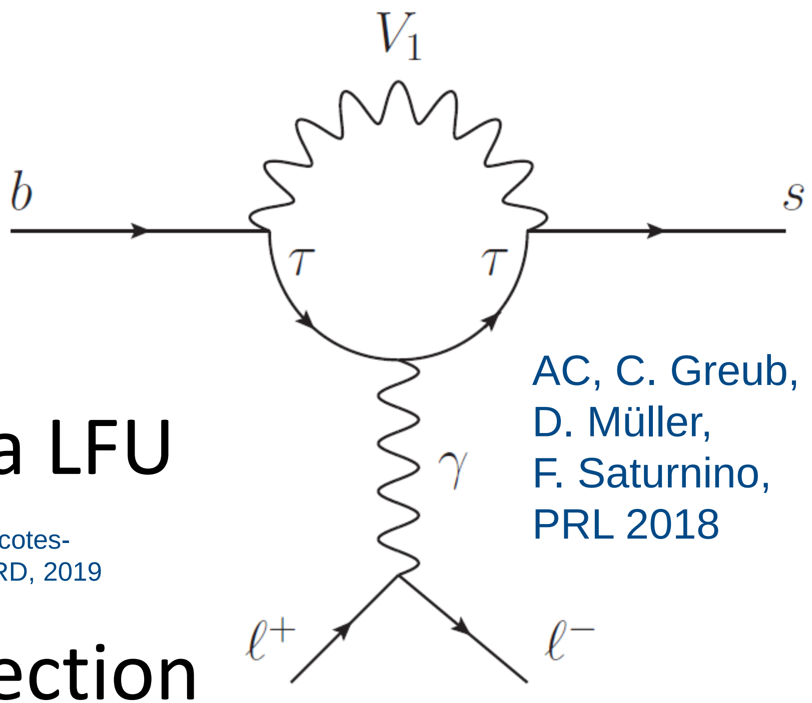
Large loop effects in b→sμμ

Important Loop-Effects

- Explanation of b→cτν requires large LQ-bτ and LQ-c-ν_τ couplings
- Via SU(2) invariance this leads to large effects in b→sττ processes
- Closing the tau-loop gives a LFU effect in b→sll

M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan, J. Matias, PRD, 2019

- Effect goes in the right direction

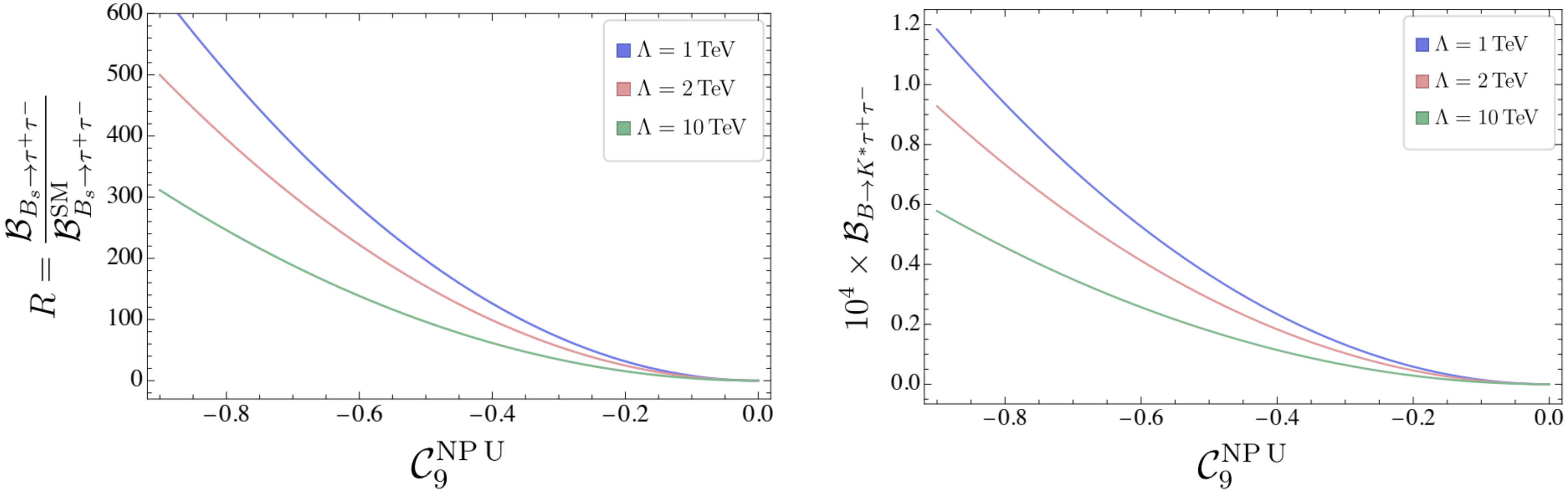


AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Explanation of b→cτν leads to loop effects in b→sμμ

$R(D^{(*)})$ and $b\to s\tau\tau$ (model-independent)

- Large couplings to the second generation
- Cancelation in $b\to s\nu\nu$ needed: $C^{(1)}=C^{(3)}$



Lepton flavour universal effect
B_s mixing constraints

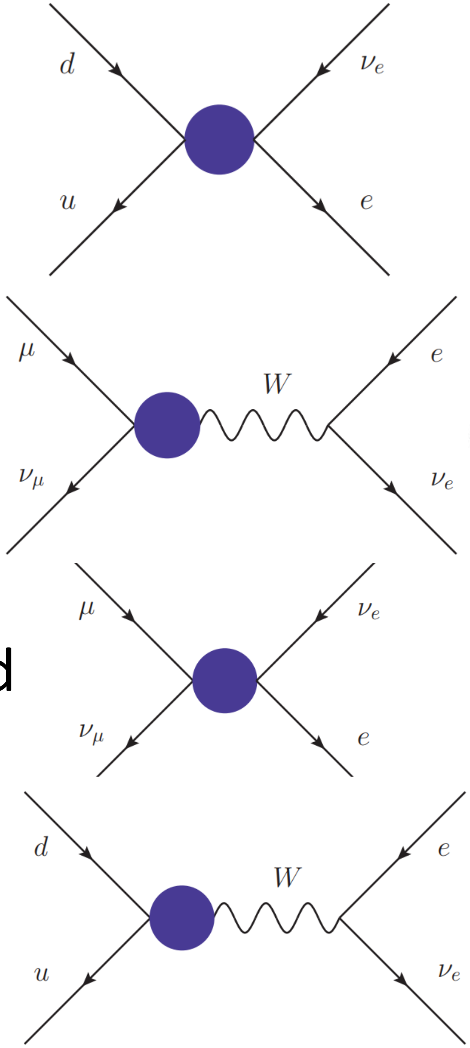
Cabibbo Angle Anomaly and EW Fit

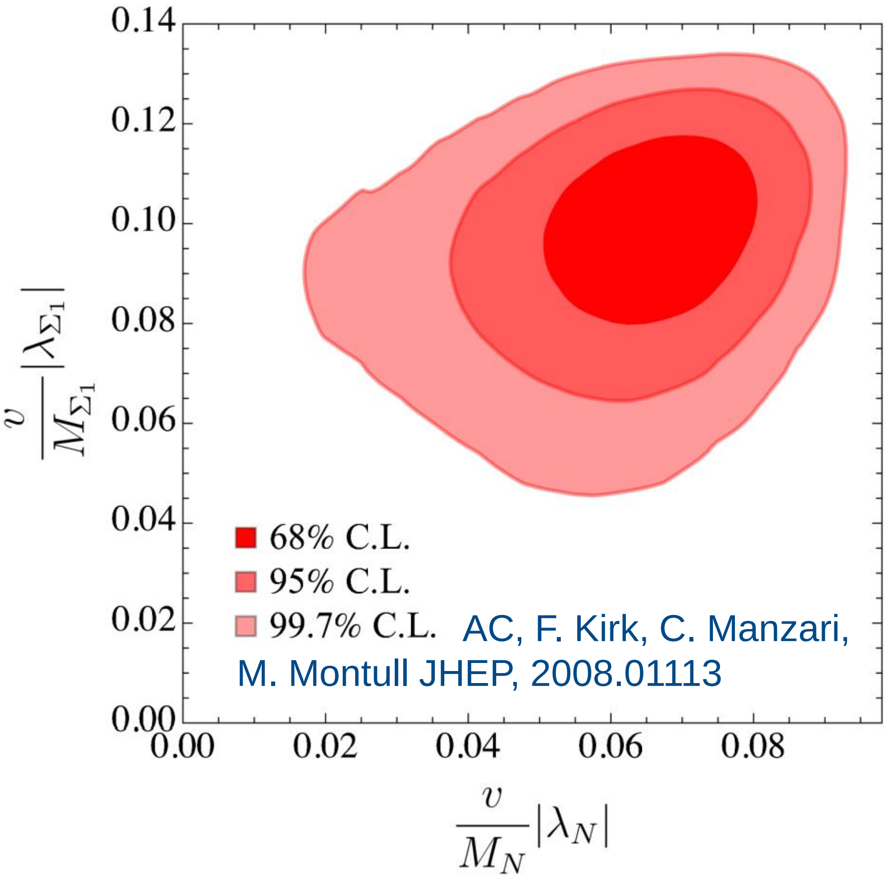
- LQs
- W‘

- W-W‘ mixing
- Vector-like leptons

- Z‘
- Singly charged scalar

- Vector-like quarks

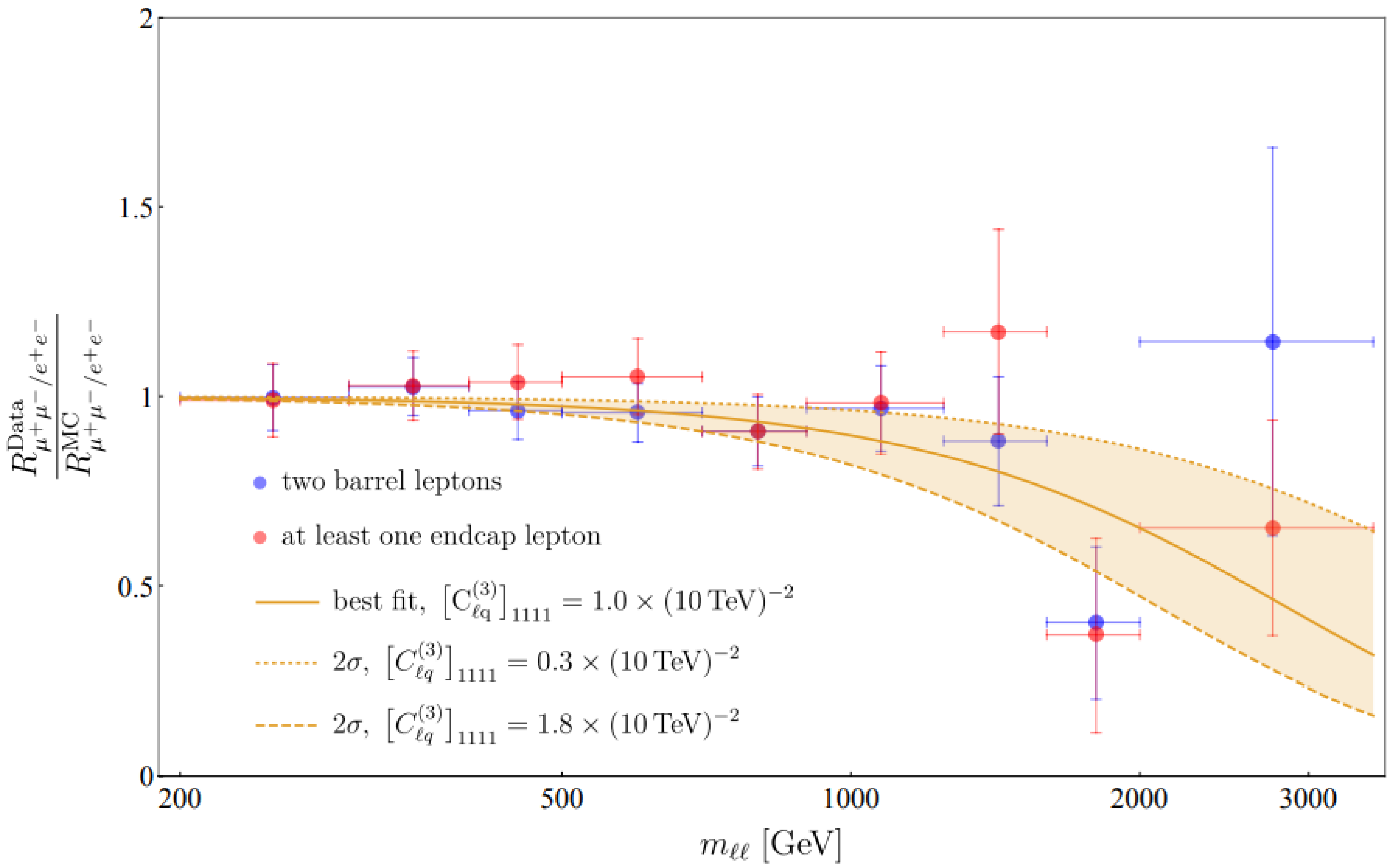




AC, F. Kirk, C. Manzari, M. Montull JHEP, 2008.01113

>5σ improvement over SM hypothesis with VLLs

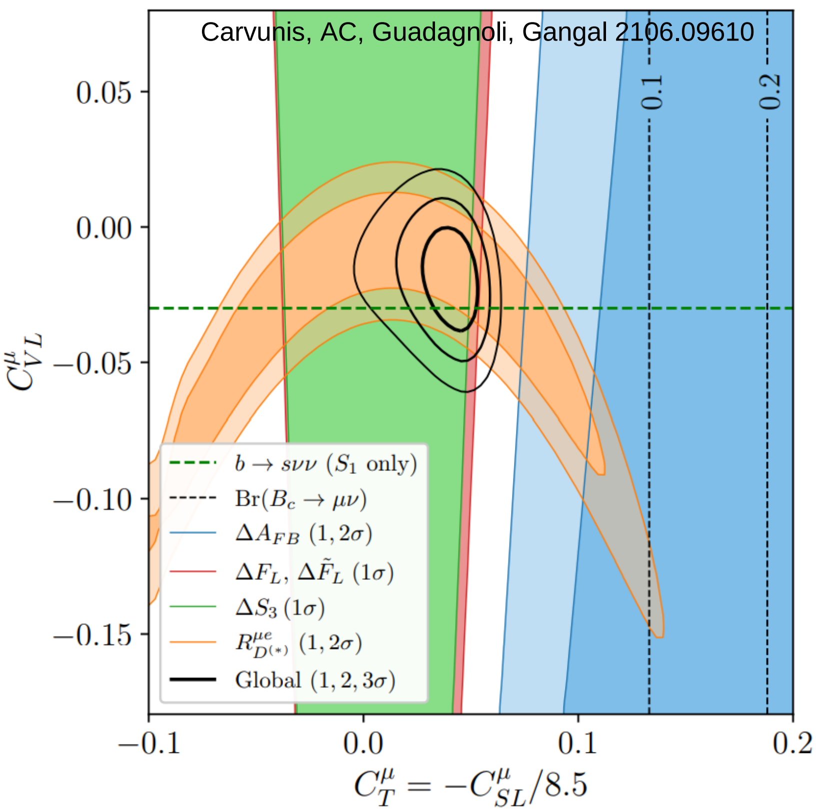
Non-Resonant Di-Leptons

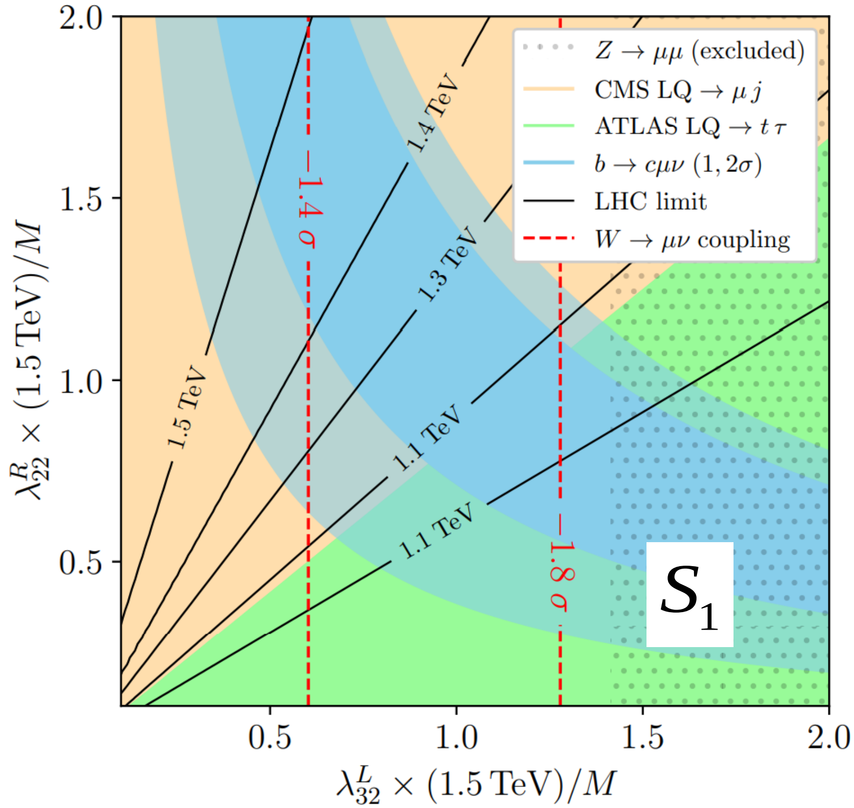


Constructive heavy NP in electrons

ΔA_{FB}

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

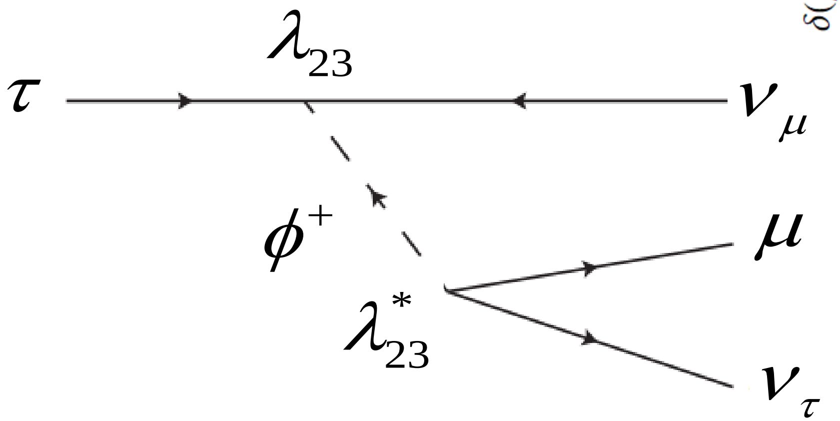




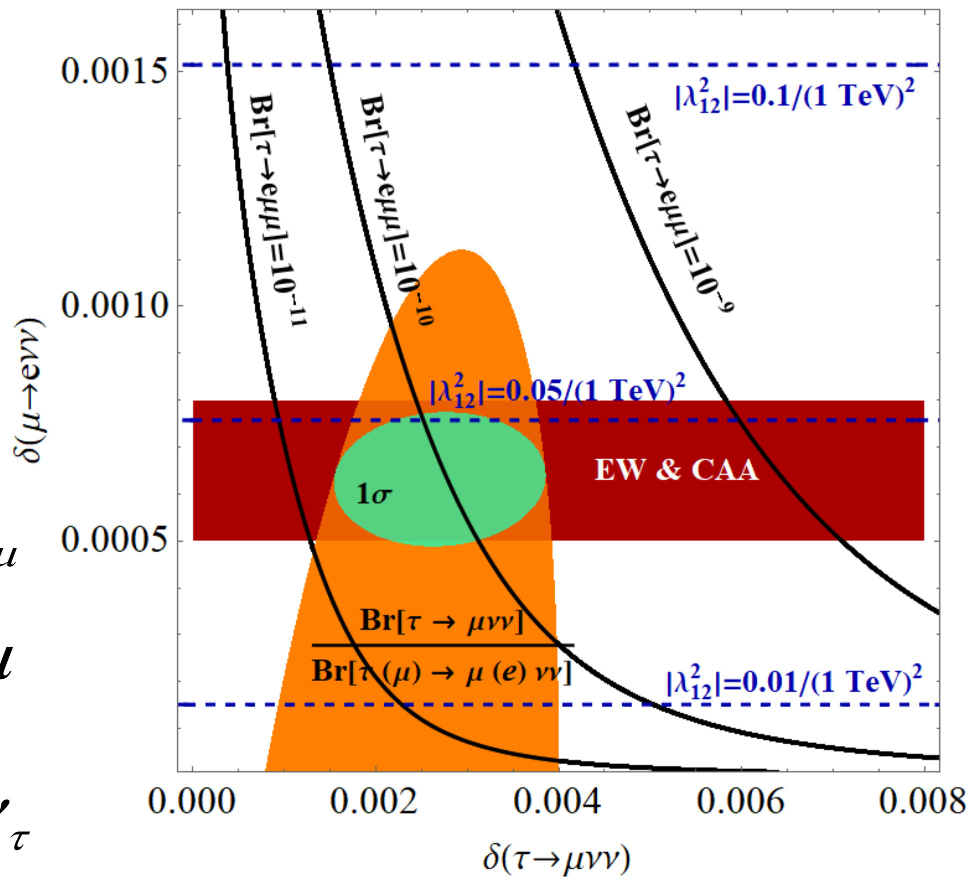
Hint for scalar leptoquarks

$\tau \to \mu\nu\nu$

- L_μ-L_τ Z' (box diagrams)
- LFV violating Z'
- Modified Wlν couplings
- W'
- Singly charged scalar



Singly charged scalar

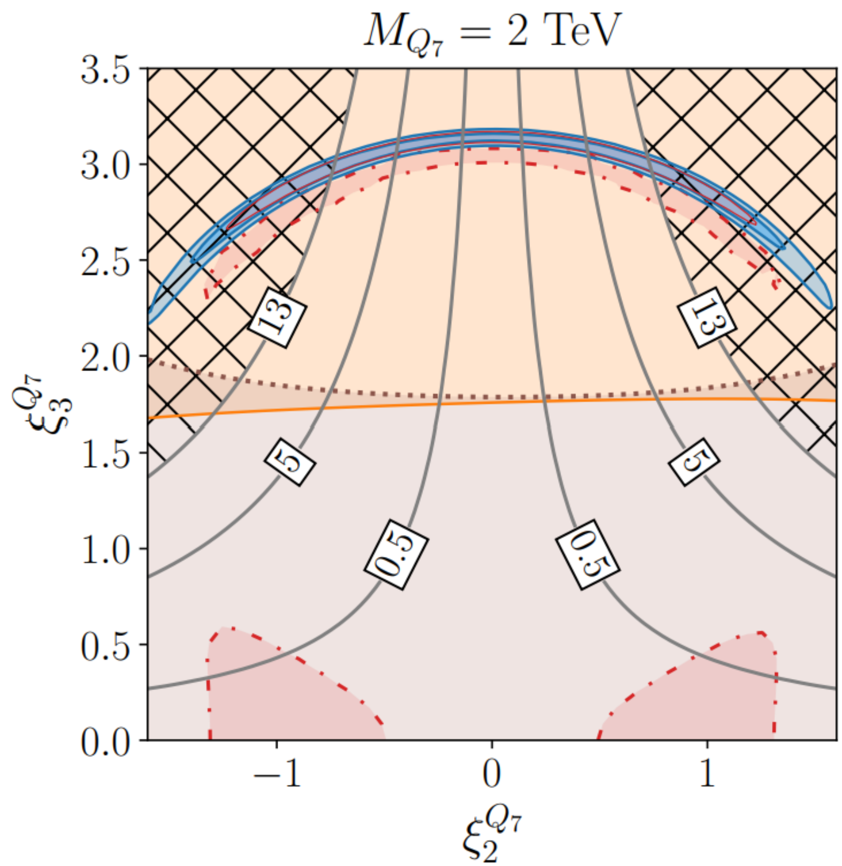


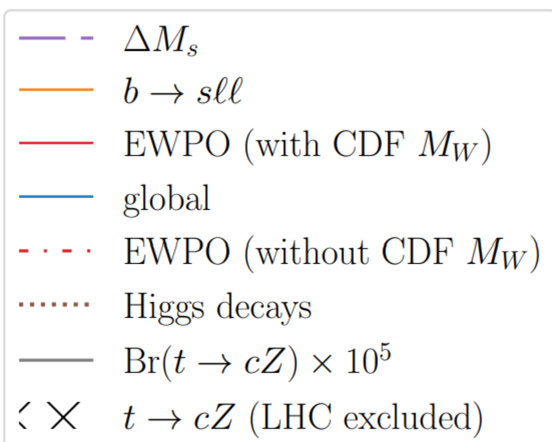
A.C., F. Kirk, C. Manzari, L. Panizzi, arXiv:2012.09845

4σ hint for modified neutrino couplings

W mass

- Loop effects of fermions or scalars with sizable Higgs couplings
- Z-Z' mixing
- SU(2) triplet scalar
- Leptoquarks





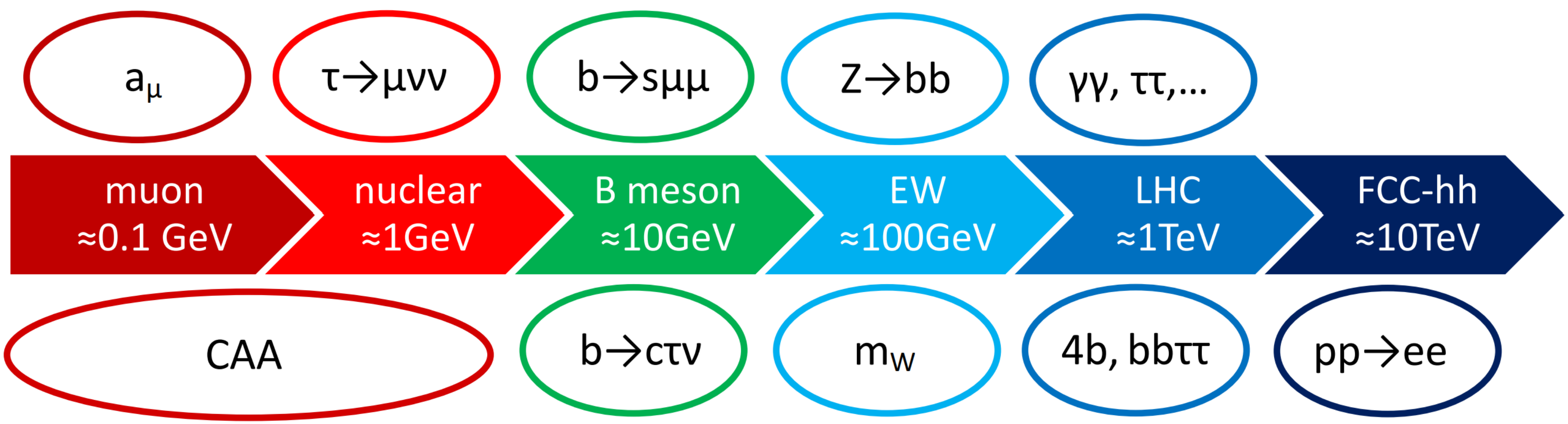
A.C., M. Kirk, T. Kitahara, F. Mescia, arXiv:2204.05962

Possible relation to t→cZ

Conclusions

- Many intriguing anomalies emerged in the last years:
  - LFUV
  - EW observables
  - Direct LHC searches

The Standard Model is crumbling



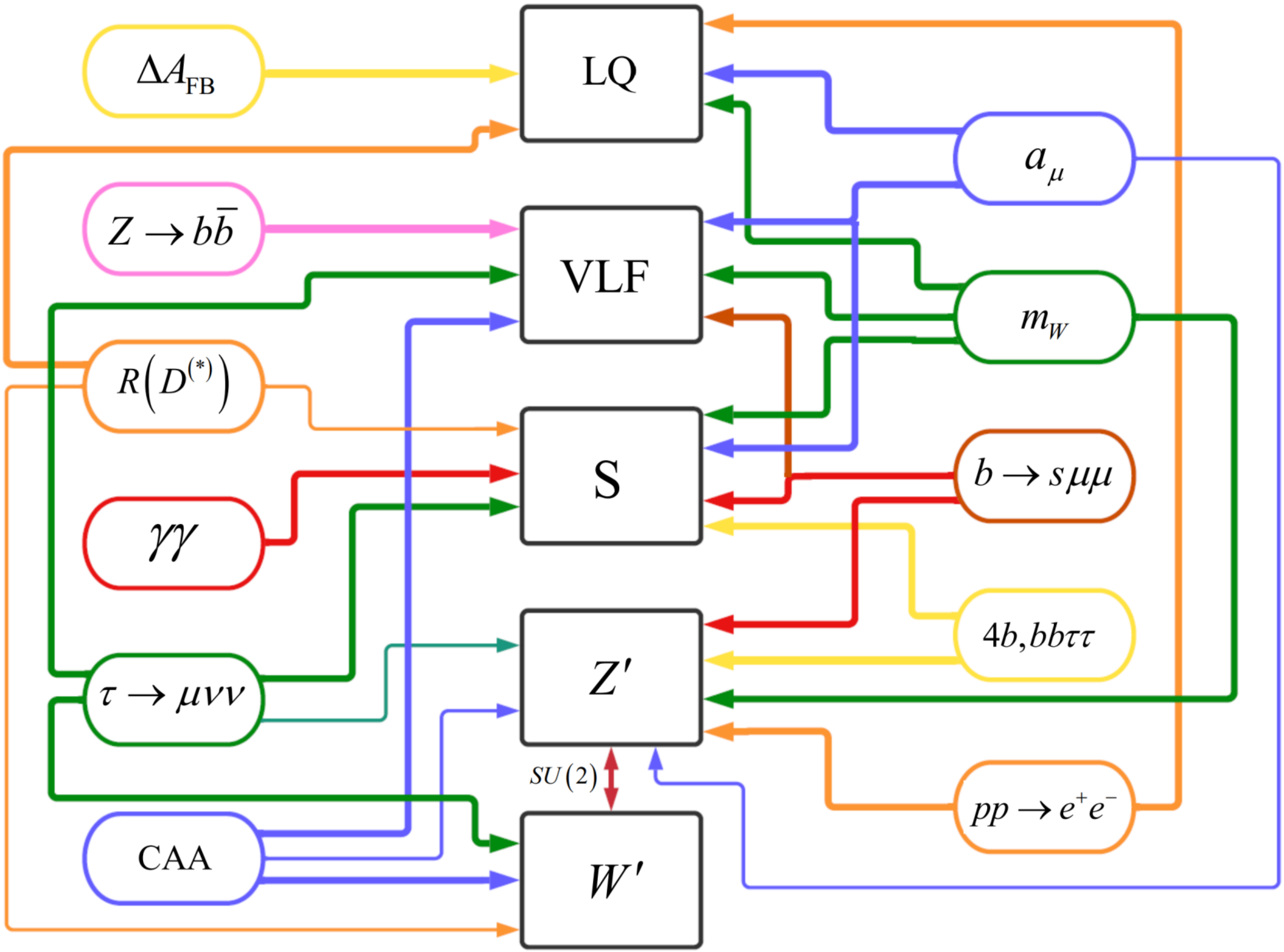
Outlook: Multi Lepton Anomalies

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	~4.5σ
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

Talk of Bruce Mellado, ICNFP 2021, Crete

Leptons + jets + missing energy

Outlook: Beyond the Standard Model



Implications for FCC-ee