Flavour Task Force Report

The Mandate

In view of the interesting results of flavour experiments involving charged fermions both in the b-quark sector (LHCb, Belle, Babar R_K and $R(D^*)$) as well as in the muon sector $(g-2)_\mu$, the mandate is to explore what opportunities there might be for DESY in the years 2026+. This should include (but not be limited to) possible Belle-II Upgrades, the opportunities at the HL-LHC by LHCb, ATLAS and CMS, and future dedicated charm, muon and tau experiments. The landscape should be explored broadly as laid out in the 2020 European Particle Physics Strategy Update and in the ongoing Snowmass process in the US.

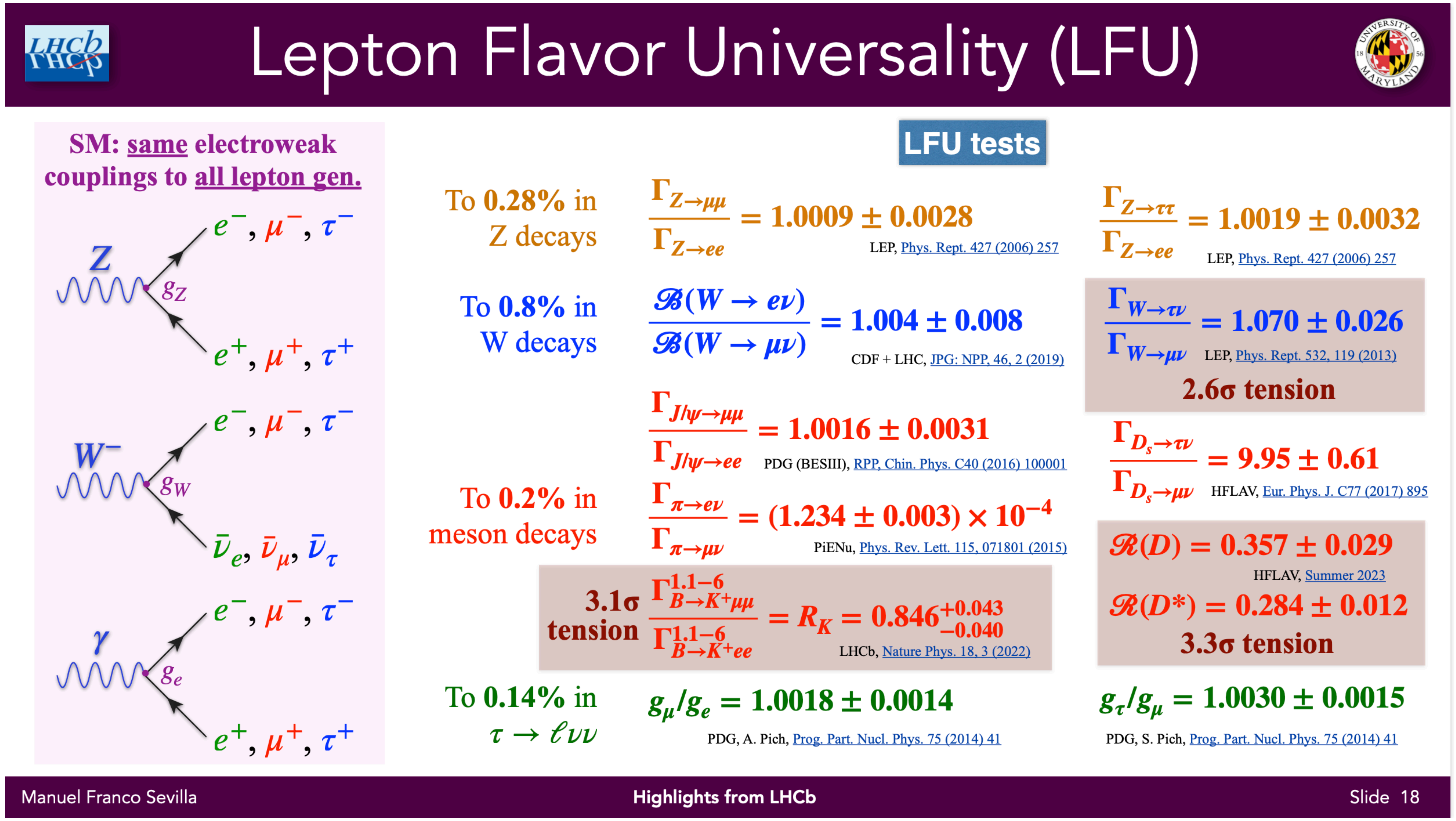
The task force should primarily consider the physics interest, but should also reflect on the technical expertise we might be able to provide and contributions we could make to a possible construction, and DESY's role as hub for the German participation in international projects. However, at present only very informal conversations can be held as it is yet unclear if we will be able to commit to any international experiment and if so to which one.

A. Ali, L. Beresford, F. Bishara, E. Gallo, A. Glazov, C. Grojean, R. Mankel, P. Pani, A. Rostomyan, M. Stanitzki

All started with anomalies…

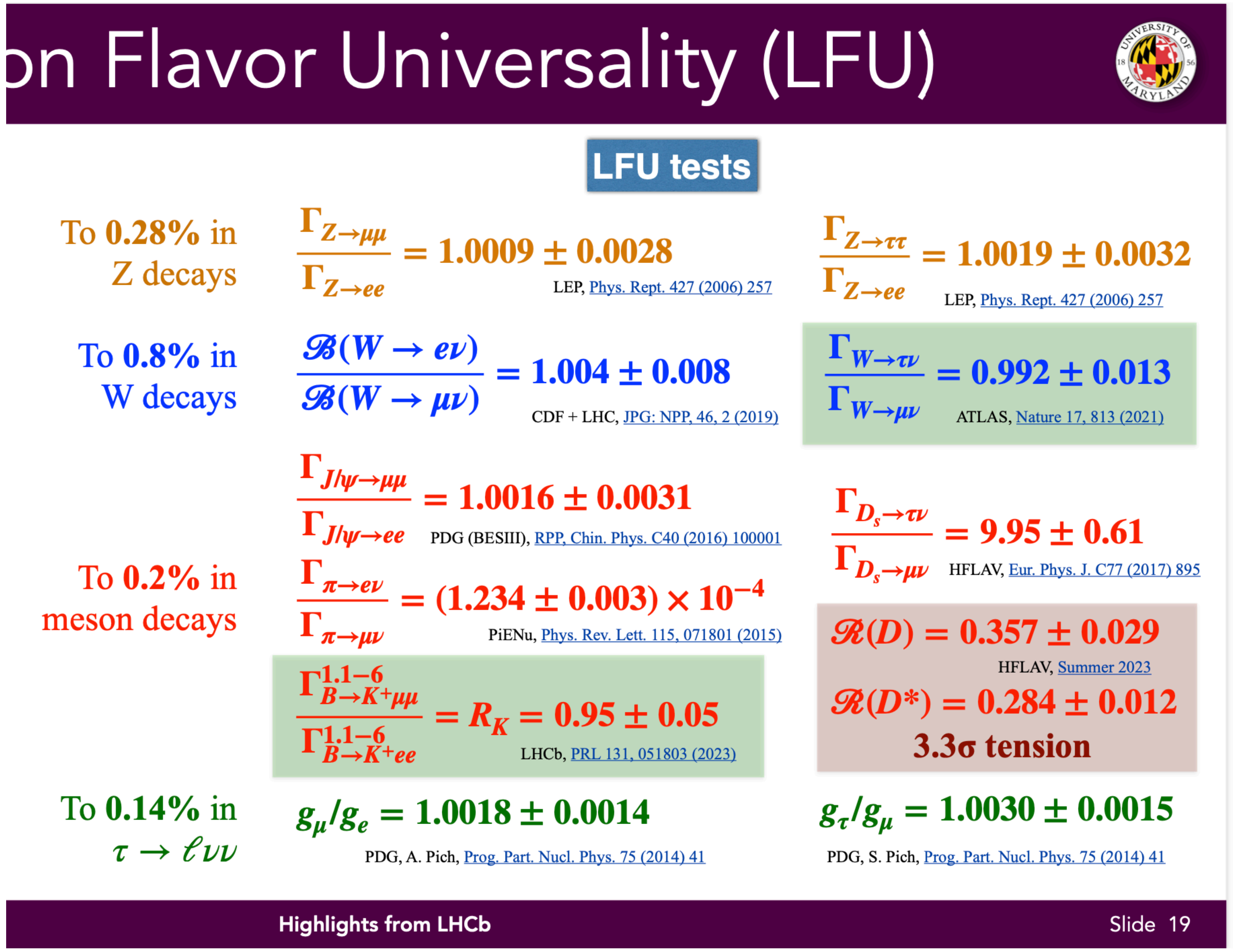
< 2023

- ➡ Several measurements deviated from the SM predictions



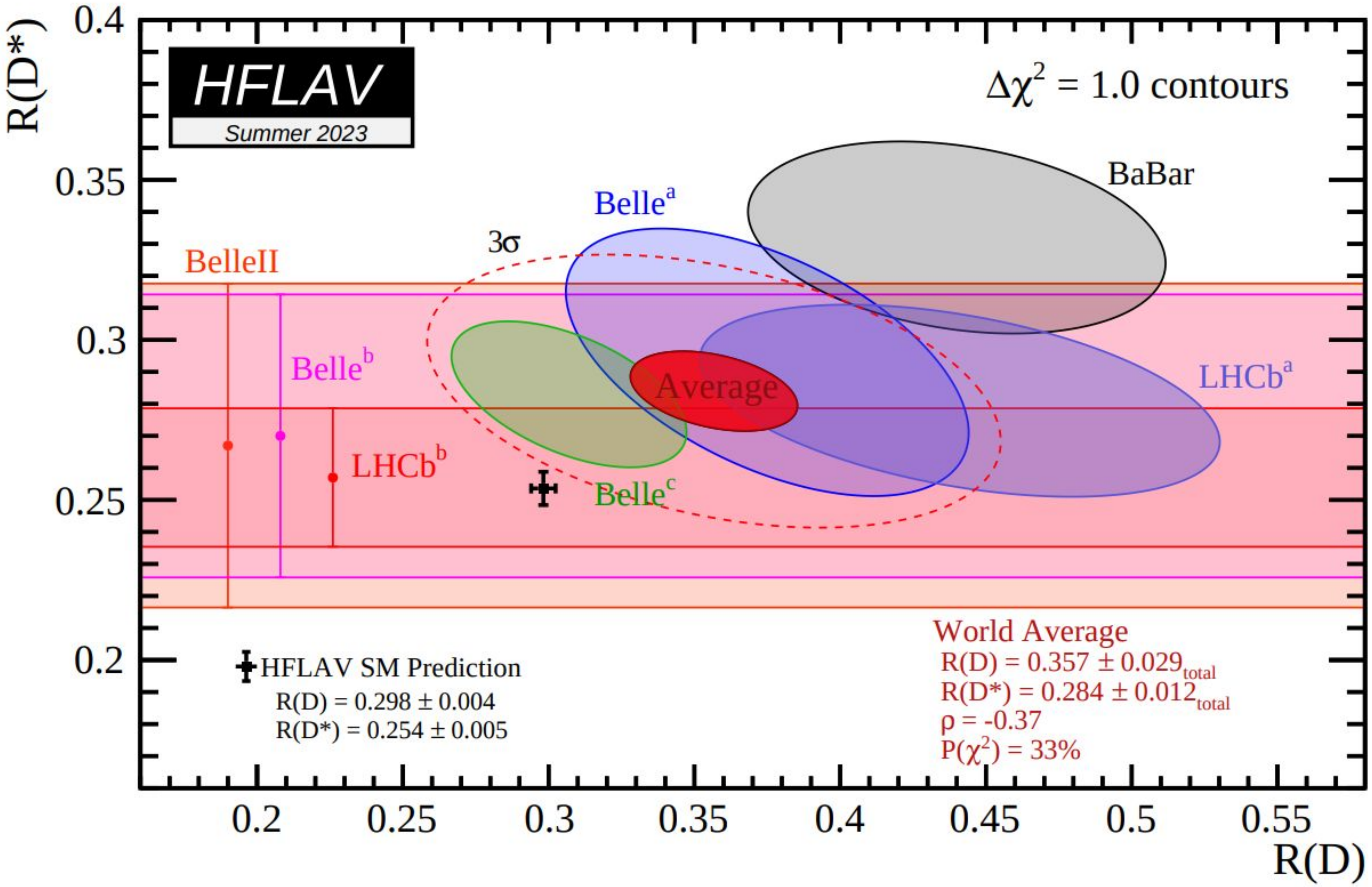
>2023

- ➡ Only one is left



- ➡ W-decay anomaly disappeared with precise measurement @ ATLAS
- ➡ R(K) anomaly disappeared with new measurement from LHCb, is confirmed by CMS
- ➡ R(D) % R(D*) still there

The only tension left



Players in the game @ DESY

ATLAS & CMS @ LHC

Belle II @ SuperKEKB

What about LHCb?

➡ no overarching physics argument to join LHCb

Scenario 1 The performance of SuperKEKB remains an order of magnitude below of its original design goal in accumulating a data sample with the luminosity of 50 ab^{-1}. In this case the Belle II experiment will only partially achieve its original physics goals. Despite this potential outcome, DESY's significant contributions to Belle II, and to ATLAS and CMS, position DESY well to keep making major contributions to the field.

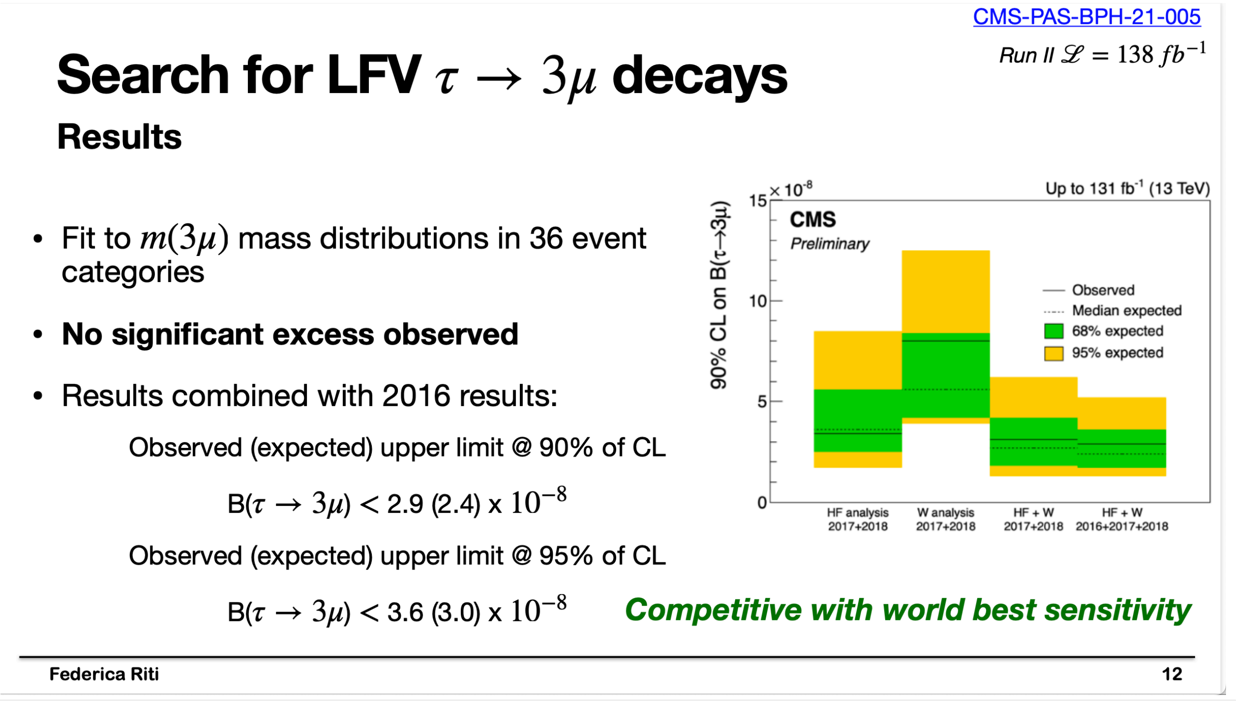
Scenario 2 The performance of SuperKEKB recuperates and Belle II accumulates a significant share of the originally envisioned 50 ab^{-1}. In this case most of the original high level physics goals of Belle II can be achieved on a reasonable timescale. Then DESY, contributing to Belle II, Atlas and CMS, can have a leading position in the flavour field.

Players in the game @ DESY

What do we do at CMS?

- A huge effort has been done in CMS in the past years to make LF(U)V measurements possible
  - **LF(U)V searches** in many sectors
    - Higgs sector → **Search for $H \to e\mu$** arXiv:2305.18106 ⟶ **G. Correia Silva's talk**
      → **Search for $H \to e\tau$ and $H \to \mu\tau$** Phys. Rev. D 104, 032013
    - Leptonic decays → **Search for LFV $\tau \to 3\mu$ decays** CMS-PAS-BPH-21-005 **In this talk**
    - Top quark decays → **Search for LFV in top quark sector** CMS-PAS-TOP-22-005 **In this talk**
    - Exotic sector → **Search for LQ coupling with τ and b** CMS-PAS-EXO-19-016
      → **Search for LFUV Z'** CMS-PAS-EXO-22-016 **In this talk**

Federica Riti


CMS-PAS-BPH-21-005
Run II $\mathscr{L} = 138\ fb^{-1}$

Search for LFV $\tau \to 3\mu$ decays

Results

- Fit to $m(3\mu)$ mass distributions in 36 event categories
- **No significant excess observed**
- Results combined with 2016 results:

Observed (expected) upper limit @ 90% of CL

B($\tau \to 3\mu$) < 2.9 (2.4) x 10^{-8}

Observed (expected) upper limit @ 95% of CL

B($\tau \to 3\mu$) < 3.6 (3.0) x 10^{-8} ***Competitive with world best sensitivity***

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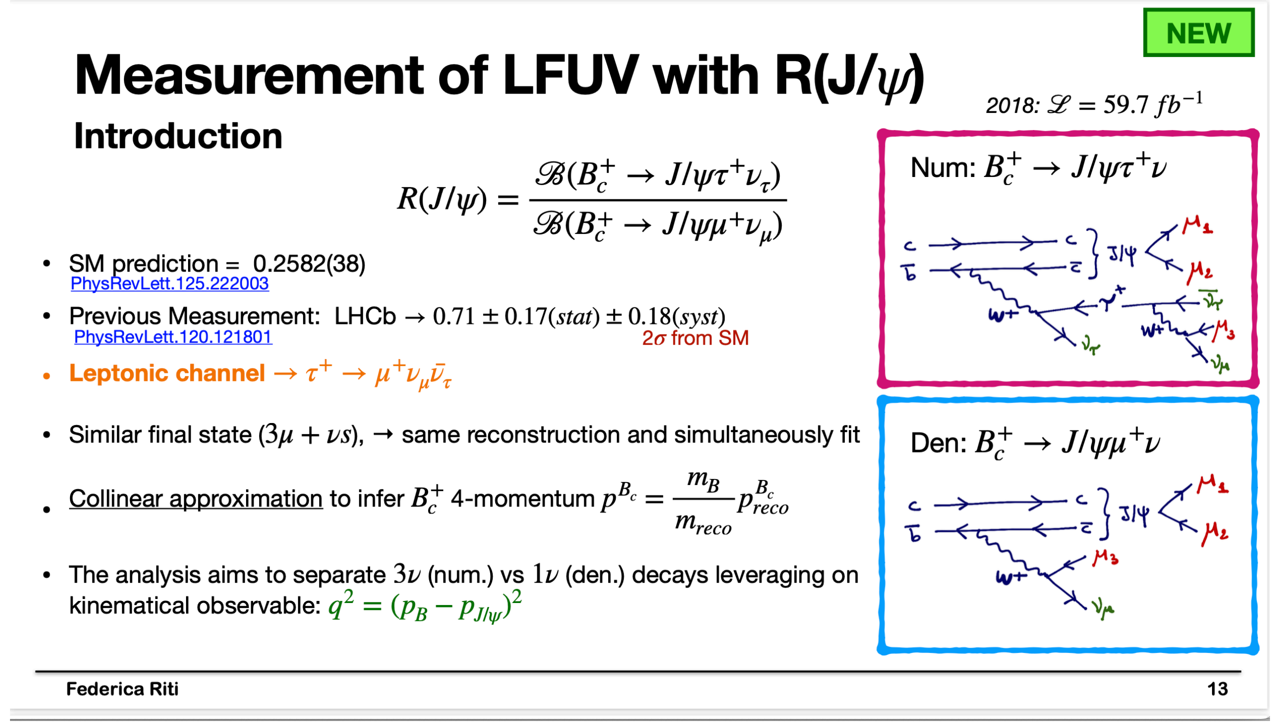
NEW

Measurement of LFUV with R(J/ψ)

2018: $\mathscr{L} = 59.7\ fb^{-1}$

Introduction

$$R(J/\psi) = \frac{\mathscr{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

- SM prediction = 0.2582(38) PhysRevLett.125.222003
- Previous Measurement: LHCb → $0.71 \pm 0.17(stat) \pm 0.18(syst)$ PhysRevLett.120.121801 2σ from SM
- **Leptonic channel → $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$**
- Similar final state ($3\mu + \nu s$), → same reconstruction and simultaneously fit
- Collinear approximation to infer B_c^+ 4-momentum $p^{B_c} = \frac{m_B}{m_{reco}} p^{B_c}_{reco}$
- The analysis aims to separate 3ν (num.) vs 1ν (den.) decays leveraging on kinematical observable: $q^2 = (p_B - p_{J/\psi})^2$

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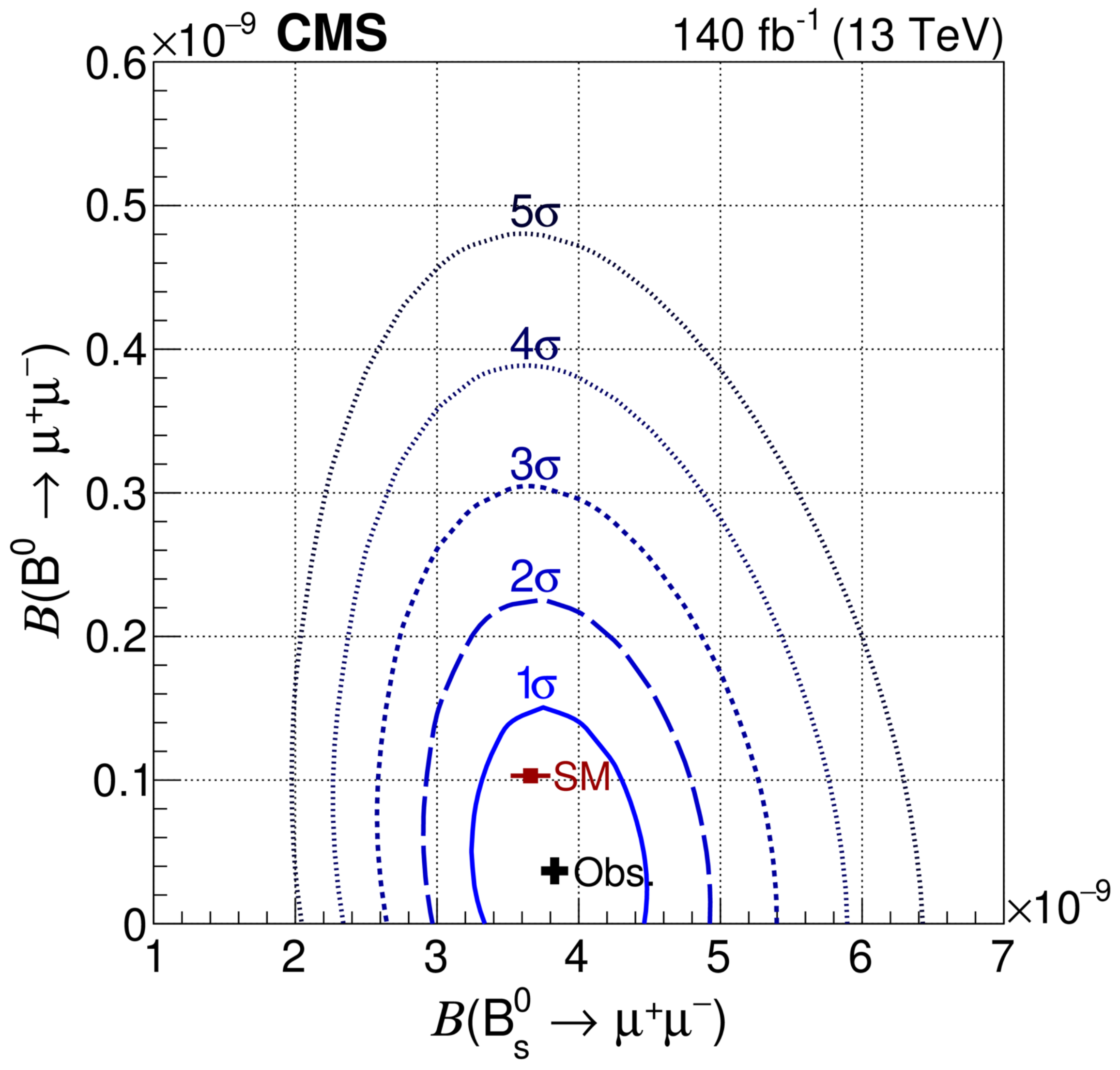
$B_s \to \mu^+\mu^-$

➡ LHC experiments combined 2.4σ from SM

➡ Most precise signle measurement from CMS, in agreement with SM



Results

$R(J/\psi) = 0.17^{+0.33}_{-0.33}$

$R(J/\psi) = 0.17^{+0.21}_{-0.22}(Syst.)^{+0.19}_{-0.18}(Theo.)^{+0.18}_{-0.17}(Stat.)$

Compatibile with SM prediction within 0.3 σ

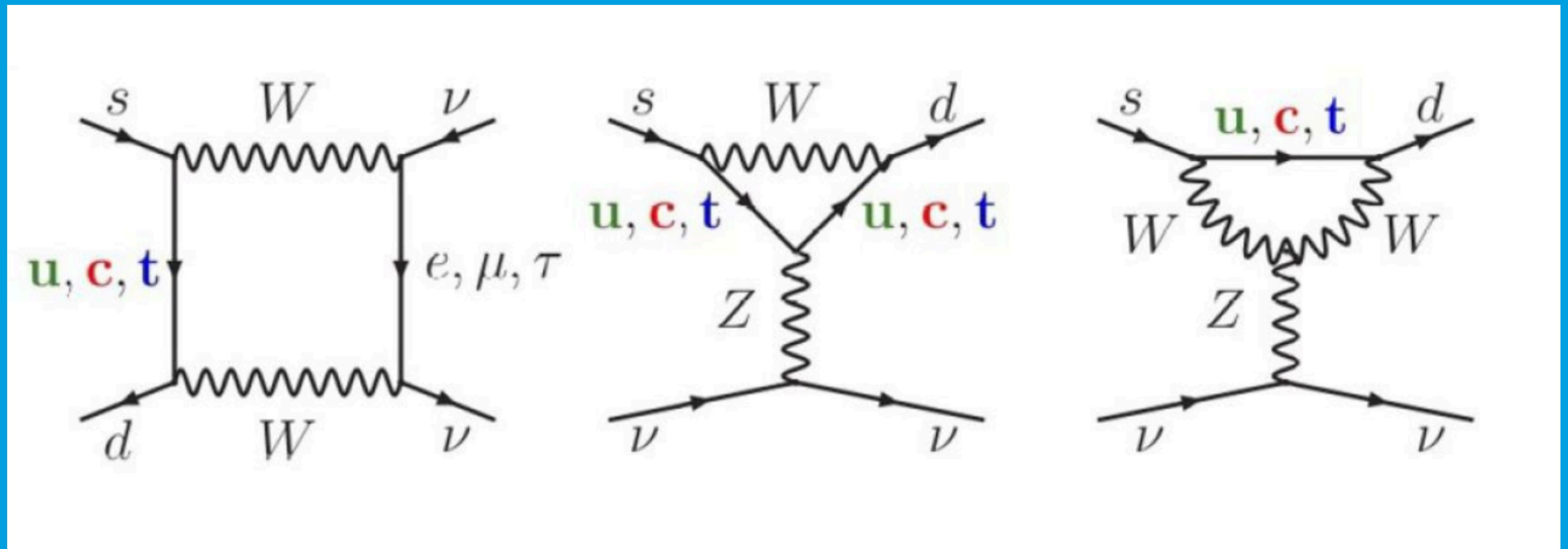
with LHCb result within 1.3 σ

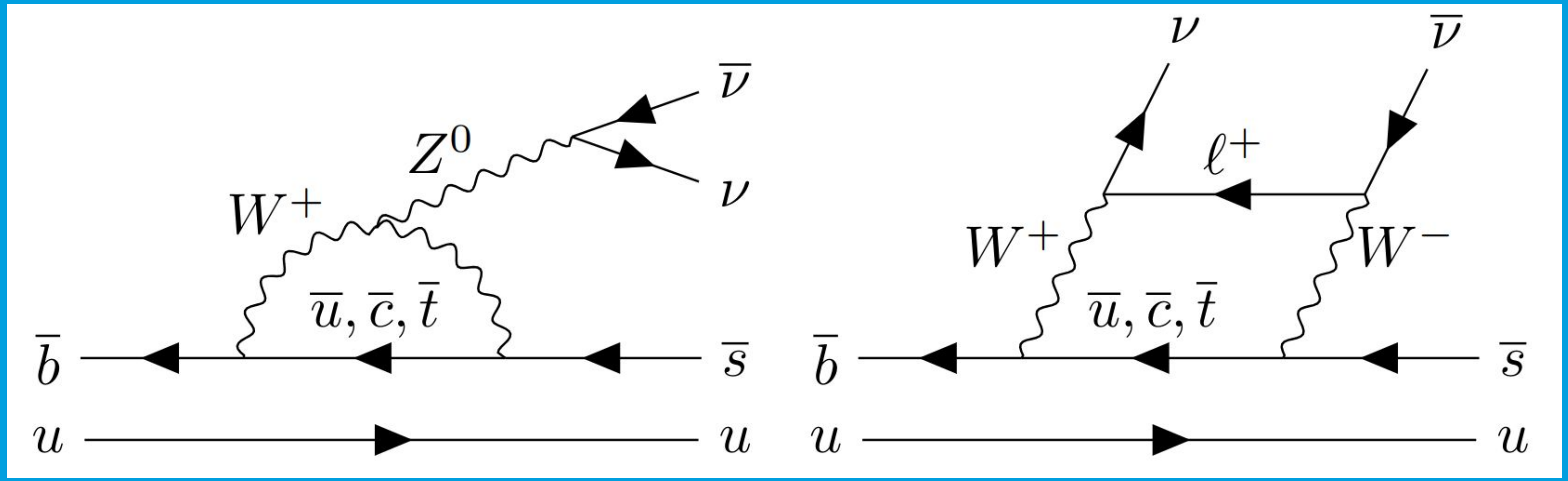
- **The first LFUV result in $b \to cl^-\bar{\nu}_l$ in CMS**, on limited part of the statistics (only 2018 data)
- Sensitivity expected to significantly improve in the next iteration

FCNCs golden channels

$s \to d\nu\bar{\nu}$

$b \to s\nu\bar{\nu}$





Golden channels of rare decays

FCNCs very clean theoretically

$s \to d\,\nu\,\bar{\nu}$

$K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 \nu \bar{\nu}$

NA62 (CERN) KOTO (JPARC)

$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu})_{SM} = (8.62 \pm 0.42) \times 10^{-11}$

Buras et al. 1503.02693, 2109.11032

$\mathrm{NA62}_{2021}$:

$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$ at 68% CL

$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu})_{SM} = (2.94 \pm 0.15) \times 10^{-11}$

Buras et al. 1503.02693, 2109.11032

KOTO_{2021}: $\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ @ 90%CL

KOTO_{2023}: $\mathrm{BR}(K_L \to \pi^0 \nu \nu) < 2.0 \times 10^{9}$

Unique for B-factories

$b \to s\,\nu\,\bar{\nu}$

$B \to K^{(*)} \nu \bar{\nu}$

BaBar, Belle, Belle II (JPARC)

$\mathrm{BR}(B^0 \to K^{*0} \nu \bar{\nu})_{SM} = (9.05 \pm 1.4) \times 10^{-5}$

Becirevic et al. 2301.06990

Belle_{2017}: $\mathrm{BR}(B^0 \to K^{*0} \nu \bar{\nu}) < 1.8 \times 10^{-5}$ @ 90%CL

$\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu})_{SM} = (5.06 \pm 0.31) \times 10^{-6}$

Becirevic et al. 2301.06990

BaBar_{2013}: $\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu}) < 1.6 \times 10^{-5}$ @ 90%CL

Belle_{2017}: $\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu}) < 1.9 \times 10^{-5}$ @ 90%CL

$\mathrm{Belle\text{-}II}_{2021}$: $\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu}) < 4.1 \times 10^{-5}$ @ 90%CL

$\mathrm{Belle\ II}_{2023}$: $\mathrm{BR}(B^+ \to K^+ \nu \nu) < (2.4 \pm 0.7) \times 10^{5}$

Prospects: HIKE/KLEVER and KOTO-II

$K^+ \longrightarrow \pi^+ \nu \bar{\nu}$, $K_L \longrightarrow \pi^0 \nu \bar{\nu}$

HIKE/KLEVER: multi-purpose high-intensity kaon decay-in-flight experiments proposed at CERN SPS

- High-intensity beams at CERN North Area after LS3 with x 4-6 current NA62 nominal
- **Phase 1** K^+ : 2.2×10^{13}decays per year ($K^+ \to \pi^+ \nu \nu$ **at ~5% precision)**
- **Phase 2:** K_L : 3.8×10^{13} decays per year ($K_L \to \pi^0 \nu \nu$ **at ~20% precision)**
- Comprehensive program of rare kaon decays, precision measurements, searches

$K_L \longrightarrow \pi^0 \nu \bar{\nu}$

KOTO II: high-beam-power experiment proposed at J-PARC

- Increase proton beam power > 100 kW
- New neutral beamline
- Increase fiducial volume from 2x2m to 3x12m → new detectors
- 60 SM events of $K_L \to \pi^0 \nu \nu$ in 3 years, ~20% precision
- Search for exotic particles in $K_L \to \pi^0 X$

CLFV in muons

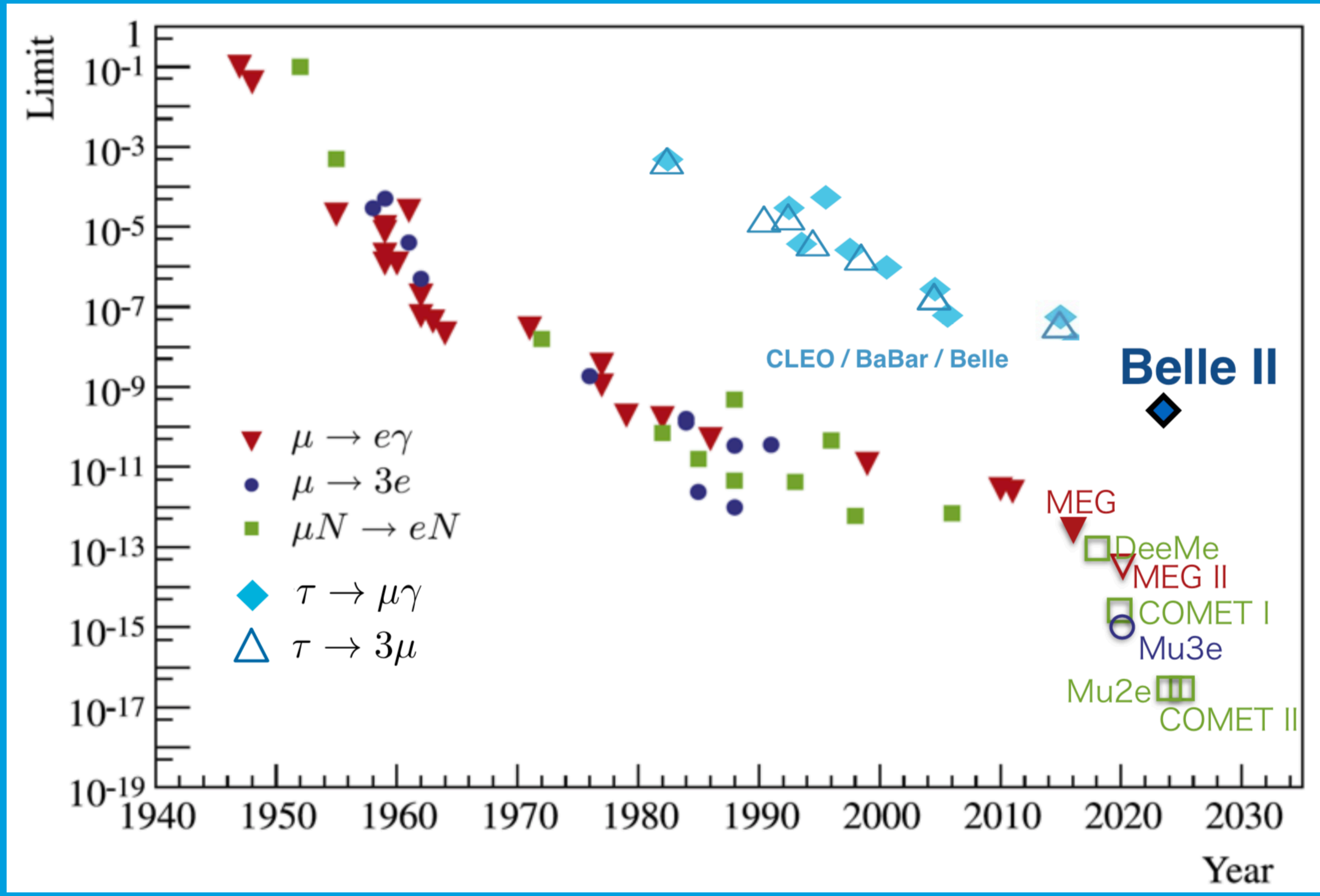
$\mu^+ \to e^+\gamma$ — MEG II

$\mu^+ \to e^+e^-e^+$ — Mu3e

$\mu^-N \to e^-N$ — COMET, DeeMee, Mu2e (II)

$\mu^-N \to e^+N$

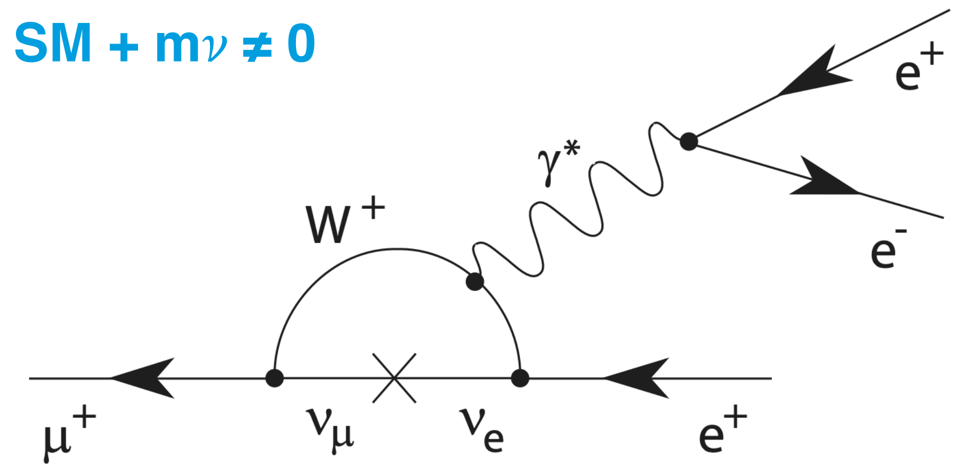
$\mu^+ \to e^+X$

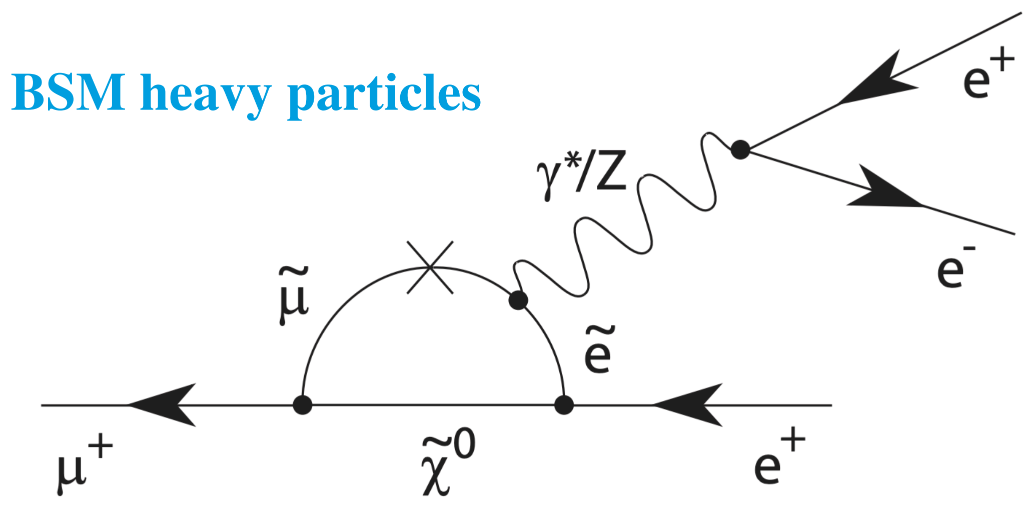


CLFV in muons

Current status and prospects

$$\mu^+ \to e^+ e^- e^+$$





Best limit from the SINDRUM experiment @ PSI:

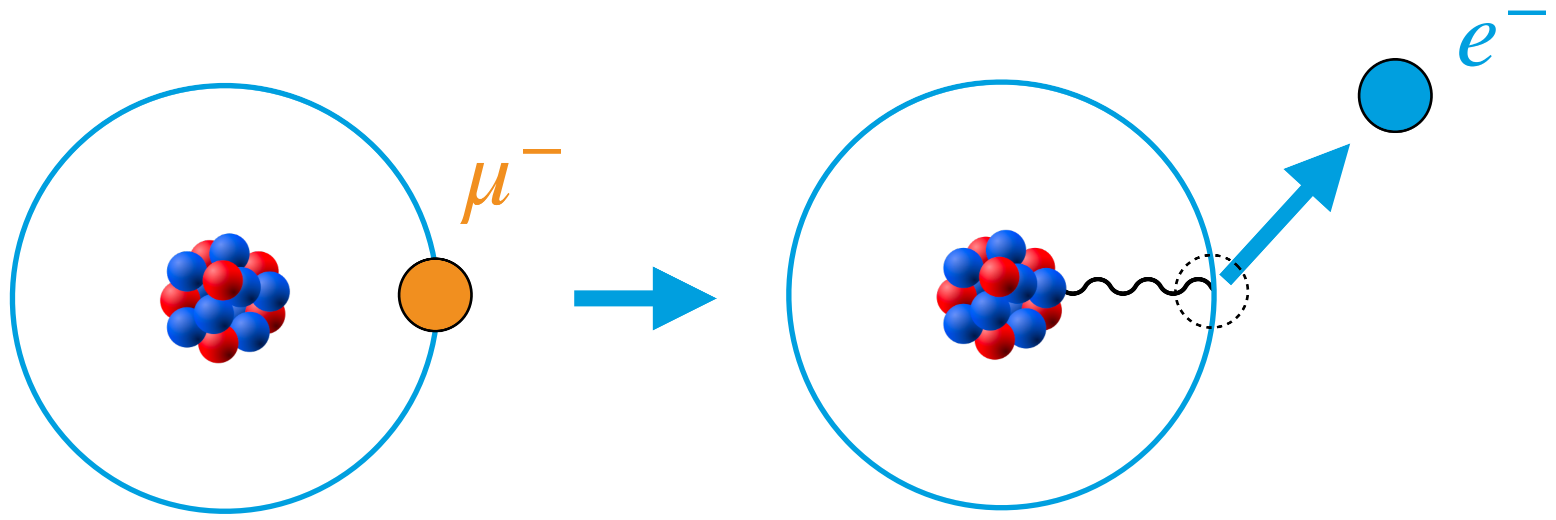
- ➡ $BR(\mu^+ \to e^+ e^- e^+) < 1.0 \times 10^{-12}$ (90% CL)

Sensitivity from Mu3e @ PSI experiment: ~10^{-16}

- ➡ data taking > 2025
- ➡ high intensity muon beam under study, available > 2028

$$\mu^- N \to e^- N$$

μ - e conversion in the field of a nucleus

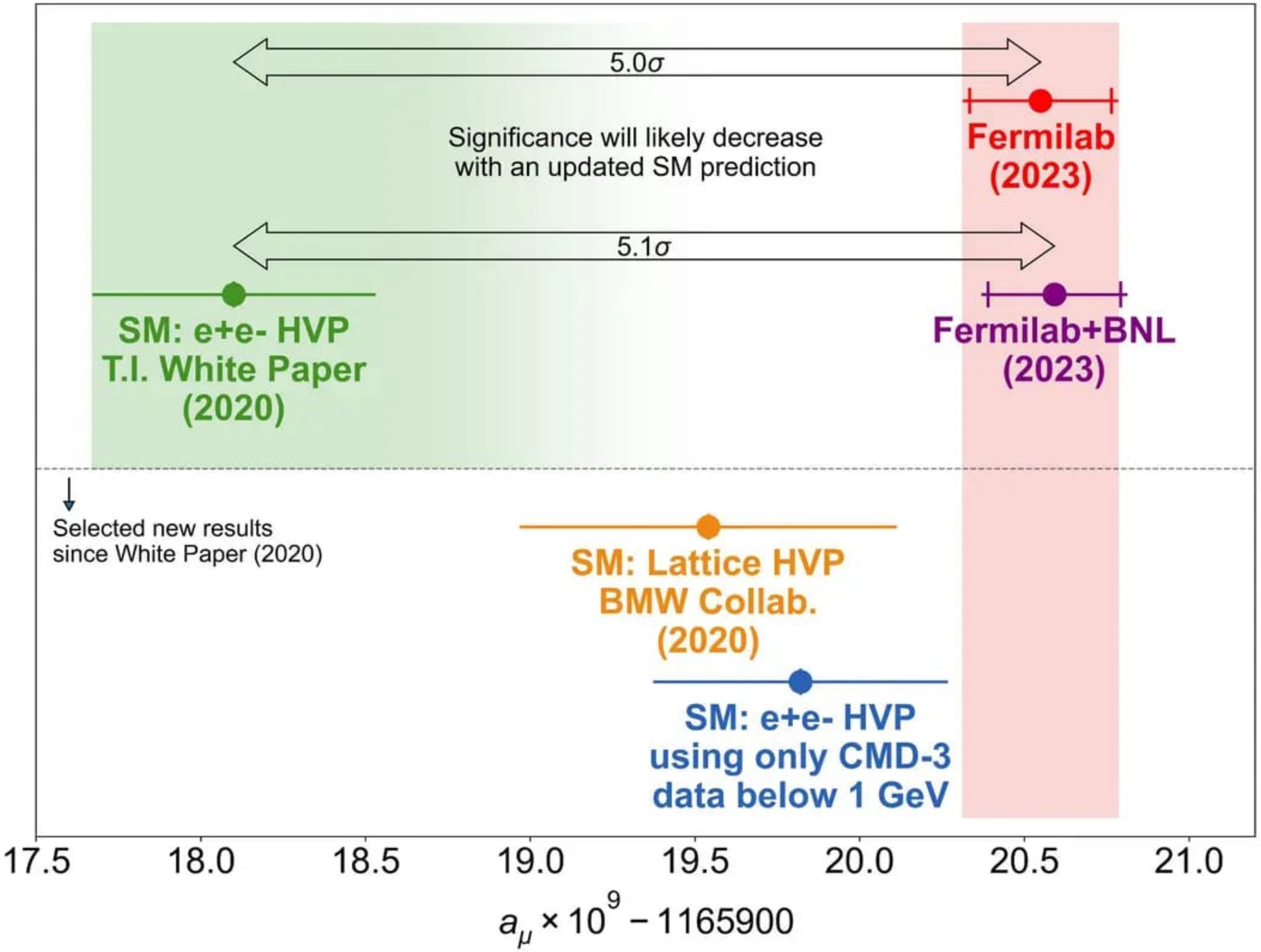


Best limit from the SINDRUM experiment @ PSI:

$$\frac{\mu^- N \to e^- N}{\text{captured } \mu - N} < 3.3 \times 10^{-13}$$

- ➡ COMET (J-PARC), Sensitivity of ~$\mathbf{10^{-17}}$ AL target
- ➡ DeeME (J-PARC), Sensitivity of ~$\mathbf{10^{-13}}$ Carbon target
- ➡ Mu2e (FNAL) - run I FY2024; run II up to FY2030. Sensitivity of ~$\mathbf{10^{-17}}$
- ➡ Mu2e II (FNAL) > FY2030 Sensitivity of ~10^{-18}

$(g-2)_\mu$



5.0σ
Significance will likely decrease with an updated SM prediction
Fermilab (2023)
5.1σ
SM: e+e- HVP T.I. White Paper (2020)
Fermilab+BNL (2023)
Selected new results since White Paper (2020)
SM: Lattice HVP BMW Collab. (2020)
SM: e+e- HVP using only CMD-3 data below 1 GeV
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
$a_\mu \times 10^9 - 1165900$

Short list

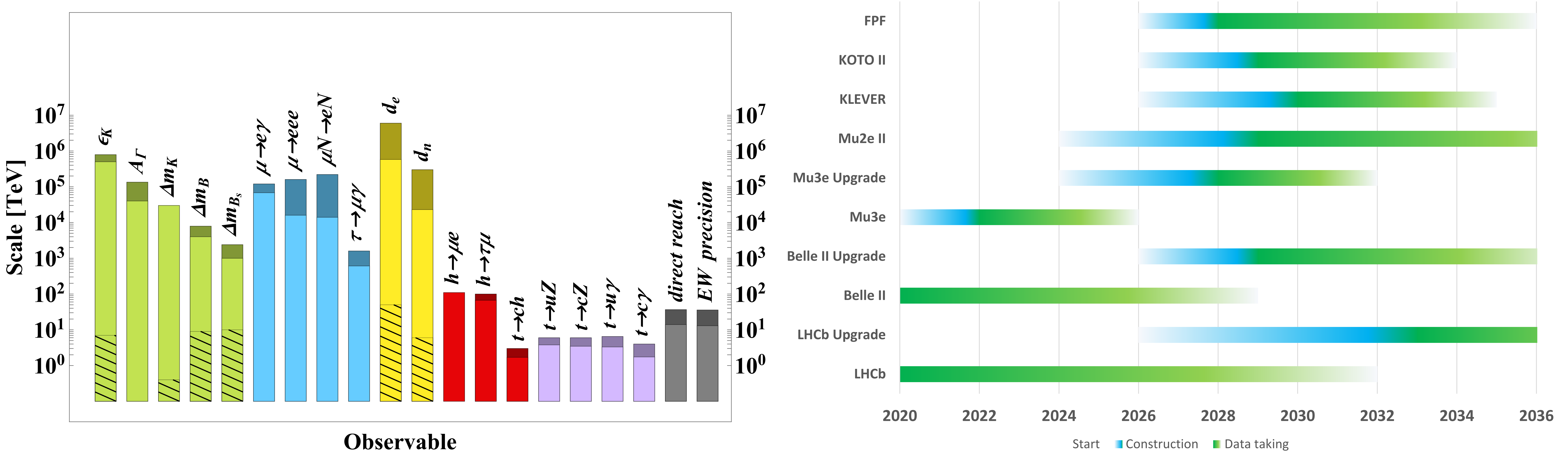


Figure 1: Left panel: *Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of the observables is as follows: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and electroweak precision measurements. The operator coefficients are taken to be either 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS). The plot is taken from [1].* ***Right panel:*** *The timeline of the experiments as extracted from publicly available information. The bars fade to the left and right as a measure of the uncertainty.*

Outcome

Experiments	Labs	Impact	Timeline	Measurement/Limit
Mu3e upgrade	PSI	✓	✓	L
Mu2e II	Fermilab	✓	✓	L
KOTO 2	KEK/J-PARC	✓	✓	M
KLEVER	CERN	✓	✓	M
J-PARC $(g-2)$	J-PARC	✓	✓	M
MUonE	CERN	✓	✓	M

- Mu3e II or Mu2e II experiments:
  - search for LFV in muon decays;
  - high sensitivity to NP.
- KOTO 2 or KLEVER experiments:
  - search for the $K_L \to \pi^0 \nu\nu$ decay which has not been observed yet;
  - the highest sensitivity to NP in the kaon sector.
- J-PARC $(g-2)$ or MUonE experiments
  - contributions to the current tension between the experimental result and the SM prediction.

Current participation from German institutions