Status of flavor anomaly

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Workshop for Tera-Scale Physics and Beyond, Kyushu, 2023.6.23

Signs of physics beyond SM

Inconsistencies among experimental data and SM predictions

Large (>3σ) tension in precision frontier

Muon g-2 FNAL vs SM or R-ratio vs lattice

Lepton-flavor universality $BR(B \to D^{(*)}\tau\nu)/BR(B \to D^{(*)}l\nu)$

* anomaly also exists in BR and angular distribution of $b \to sll$

First-row CKM unitarity $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1$?

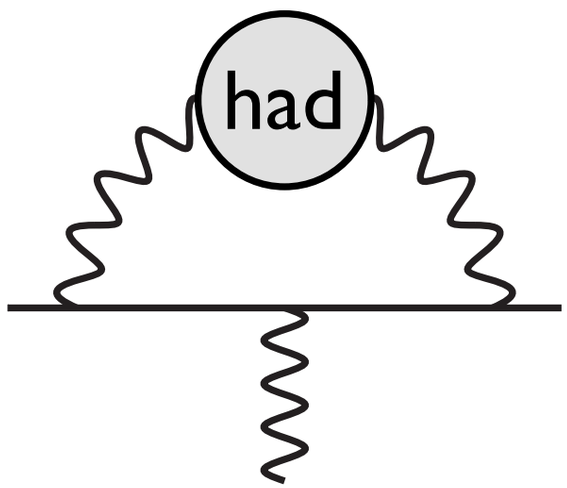
W-boson mass (not discussed today)

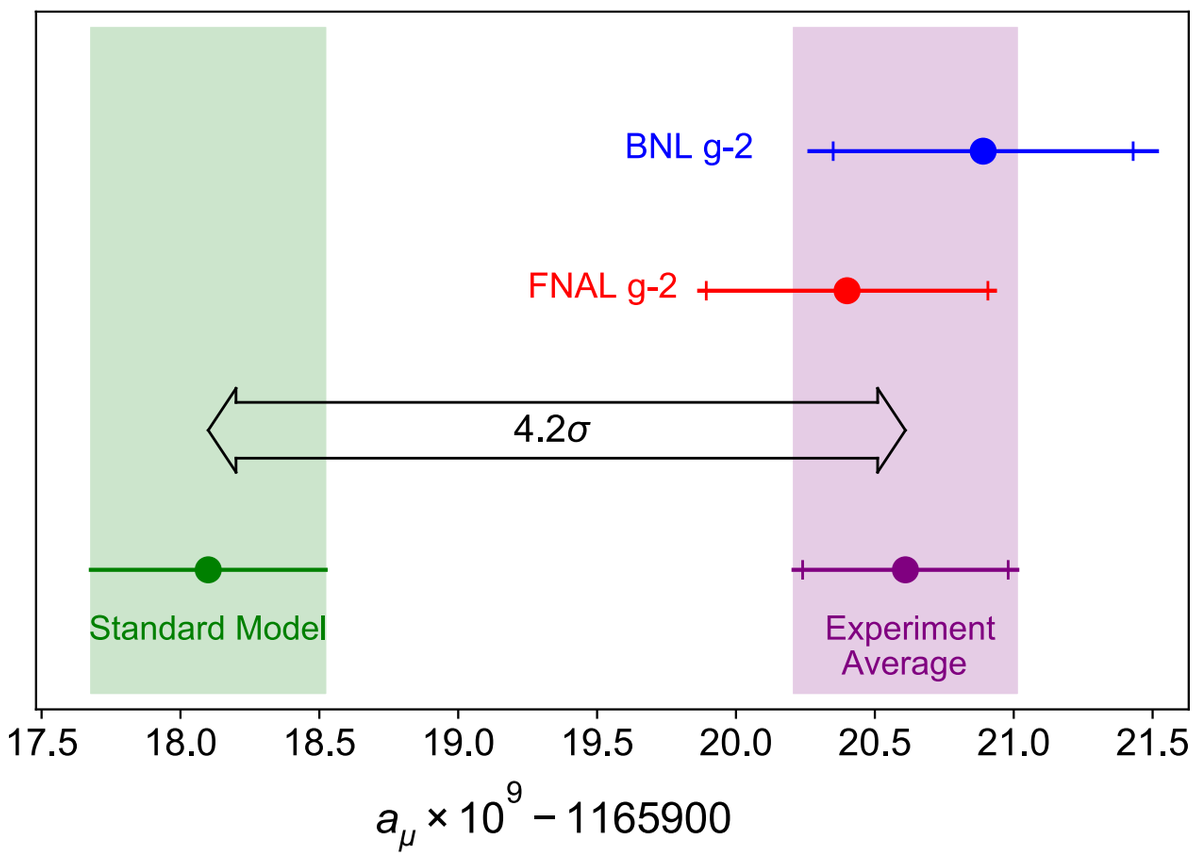
Muon anomalous magnetic moment: g-2

Tension btw FNAL (+BNL) vs SM (white paper) $\quad a_\ell = \dfrac{g_\ell - 2}{2}$

$$a_\mu^{\mathrm{BNL+FNAL}} - a_\mu^{\mathrm{SM}} = (25.1 \pm 5.9) \times 10^{-10} \qquad 4.2\sigma$$

Issues on hadronic contribution





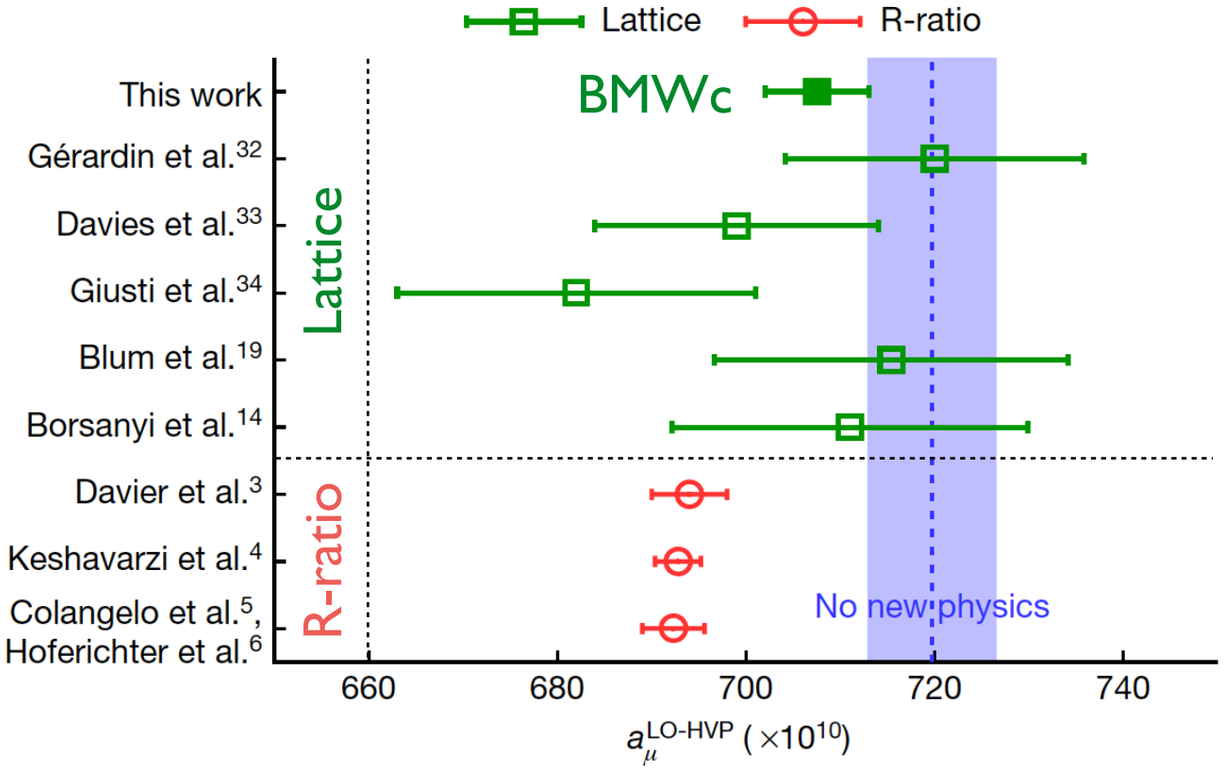
* FNAL Run2+3 planned in Aug/Sep 2023

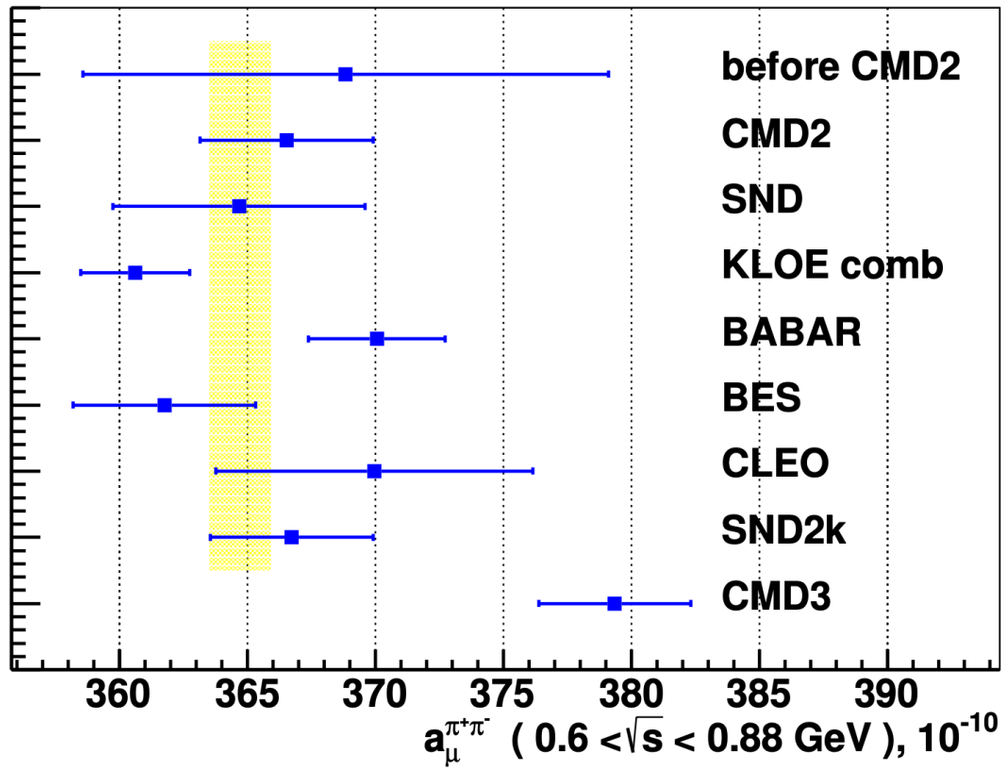
Hadronic contribution to photon vac polarization

Traditionally determined by R-ratio (dispersive approach).

BMWc (lattice) reported 2.1σ tension w/ traditional value.

CMD-3 supports BMWc, conflicting w/ other R-ratio data.



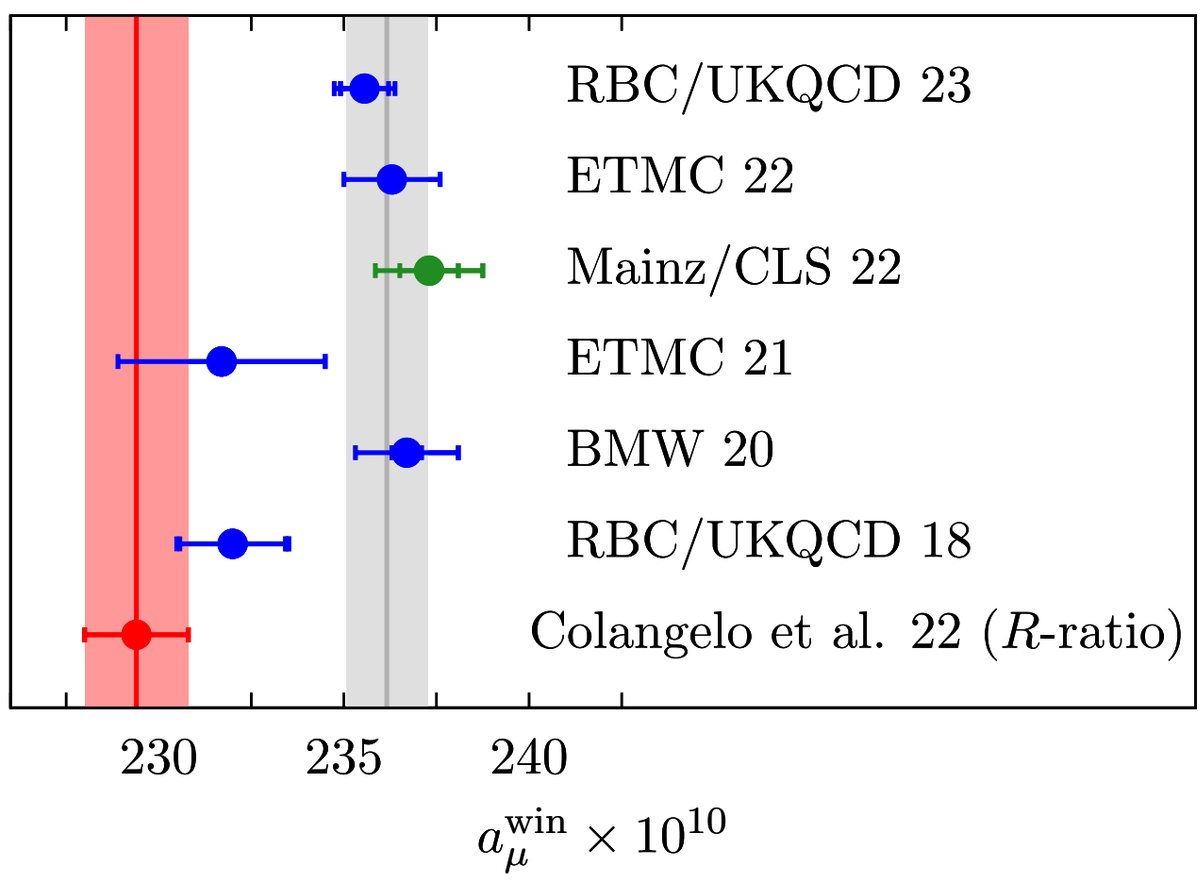


Contribution from specific energy "window"

a_μ(had) = a_μ(LD) + a_μ(win) + a_μ(SD) by weighting function.

Lattice has better control in intermediate "window" region.

~4σ tension btw lattice and R-ratio for a_μ(win).



Contribution from specific energy "window"

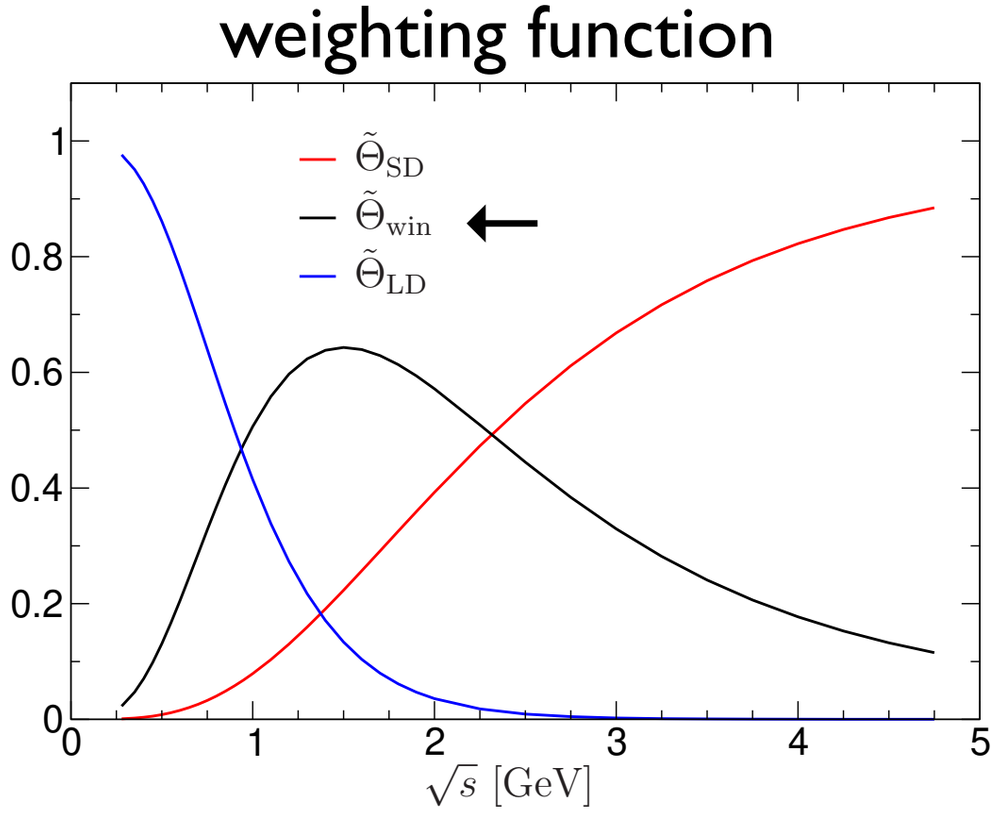
"Window" receive sizable contribution from $\sqrt{s}$ >~1GeV.

Not large enough to explain FNAL vs SM (4.2σ→3.1σ).

$$a_\mu^{\rm exp} - (a_\mu^{\rm WP} - a_\mu^{\rm win,R\text{-}ratio} + a_\mu^{\rm win,lattice}) = (18.3 \pm 5.9) \times 10^{-10}$$

⇒ Large part of a_μ(had) difference should come from <1GeV.

Further exp (Belle II, MUonE, …), and lattice are important.



There are no perfect BSM scenarios

FNAL vs R-ratio* [w/o lattice]

SUSY ~100GeV-1TeV

Leptoquark, vectrolike lepton ~1-10TeV

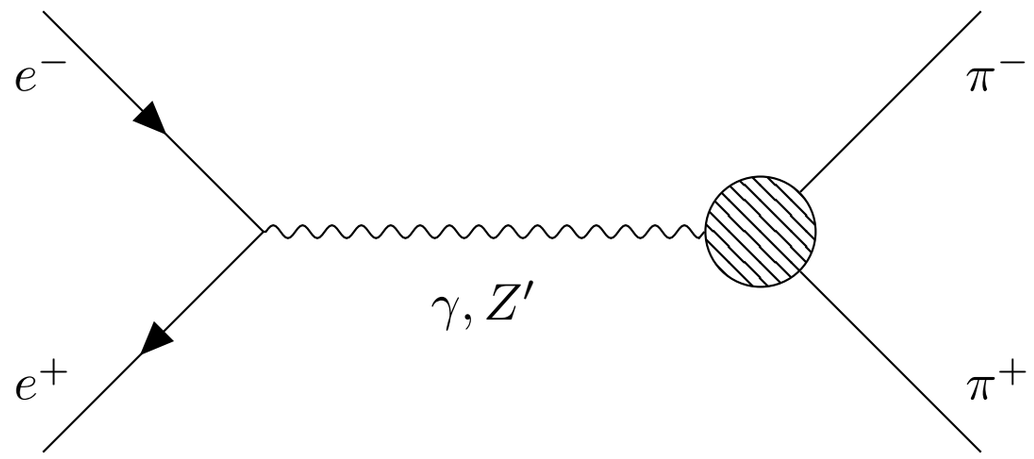
⇒ Target of LHC

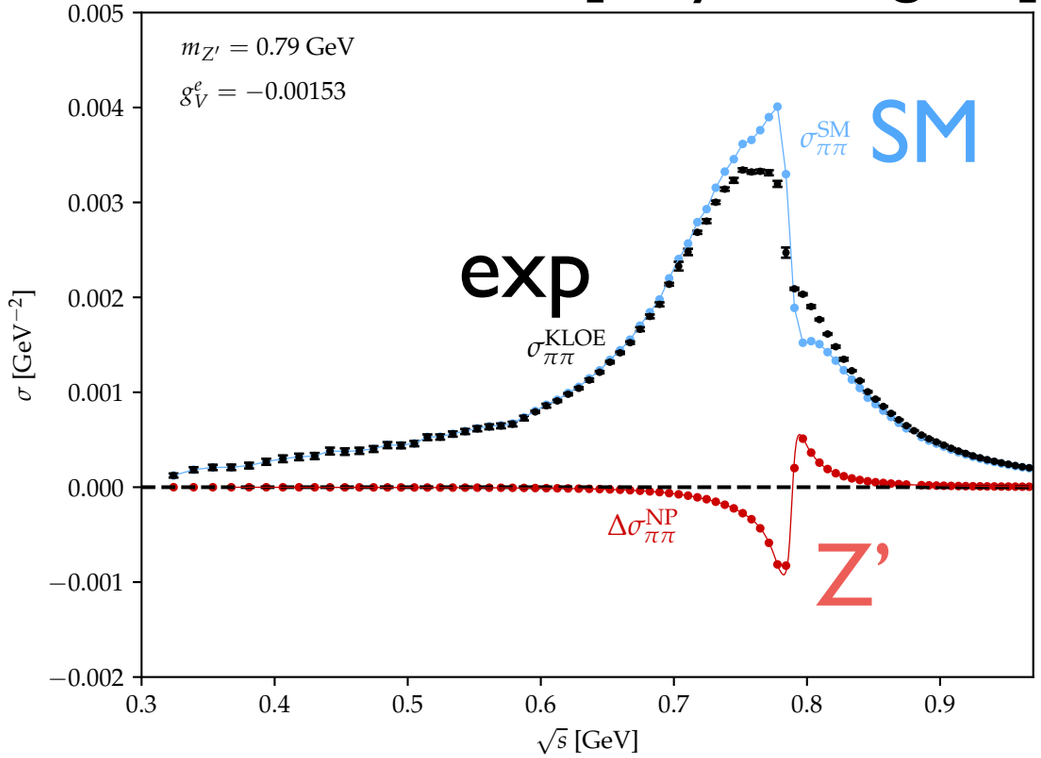
New light particle scenarios

[Coyle, Wagner]

R-ratio* vs lattice**

Z' w/ mass around ρ resonance





*CMD-3 is ignored, **window region is not discussed

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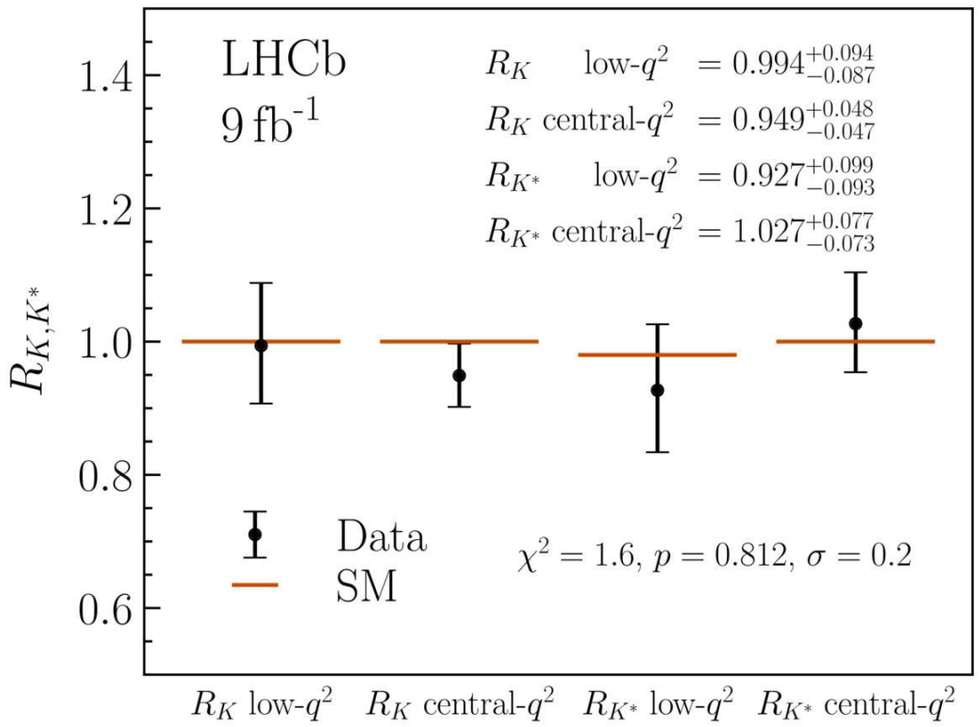
Test of lepton-flavor universality in B meson decays

Neutral current

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

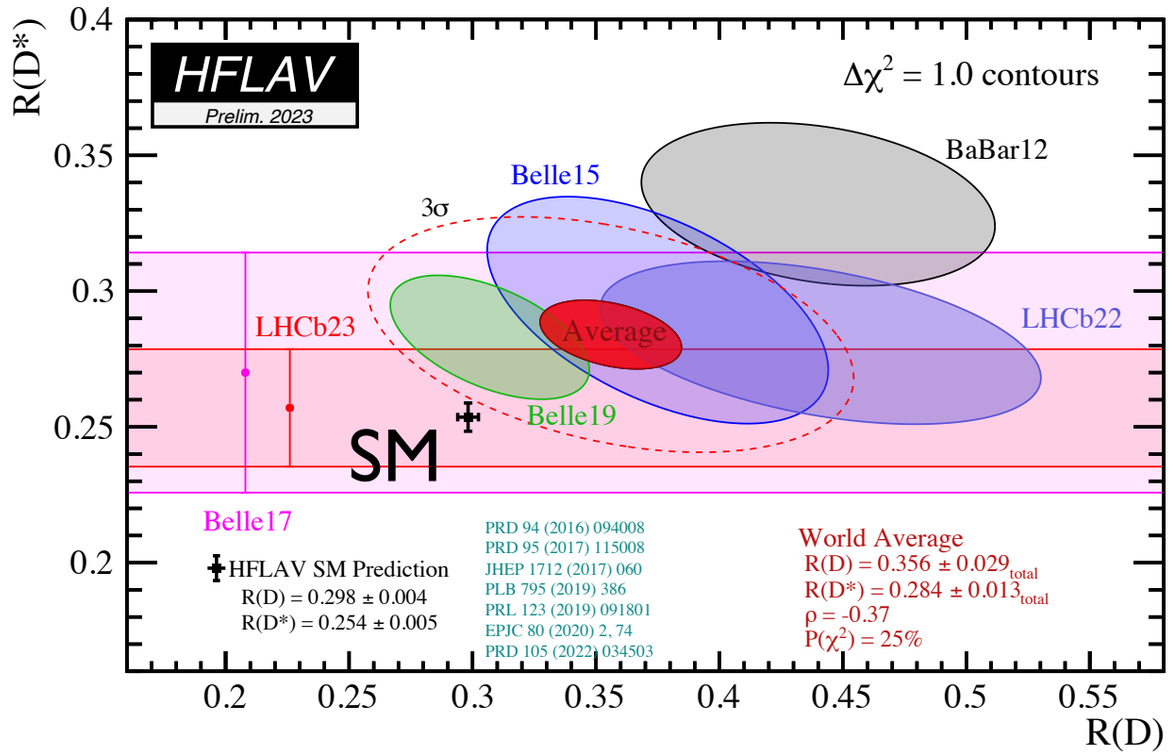


Tension has disappeared

* BR and angular distribution of b→sll still have tensions

Charged current

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$



3.2σ tension b/w exp and SM

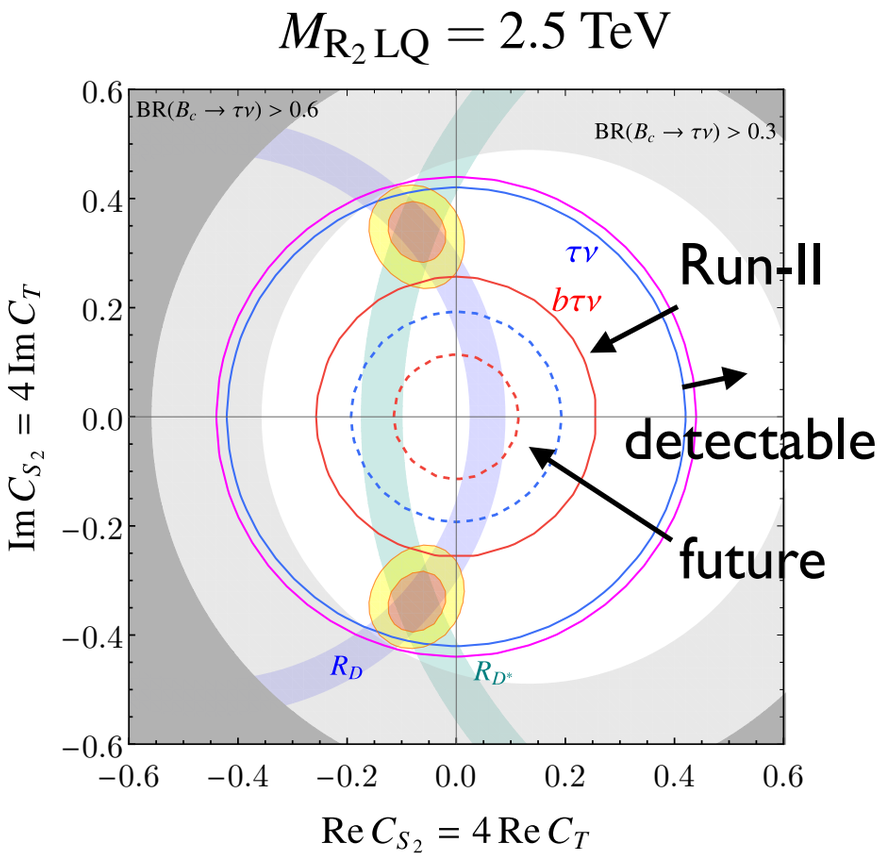
Need further experiments

BSM interpretation

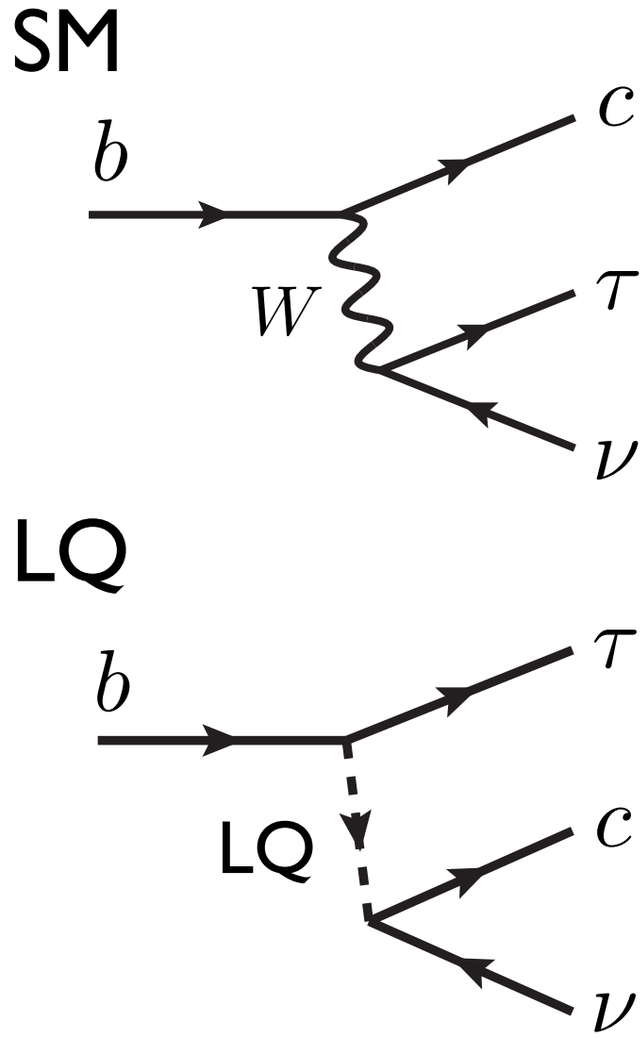
Leptoquark, charged Higgs, etc in TeV scale

Collider test at LHC, e.g., via $pp \to b\tau\nu, \tau\tau$

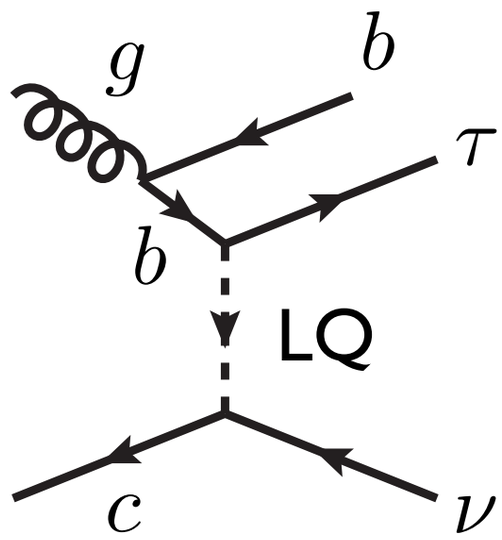
cf. Slide by T. Kitahara at "Physics in LHC and beyond"



[ME, Iguro, Kitahara, Takeuchi, Watanabe]



LQ@LHC



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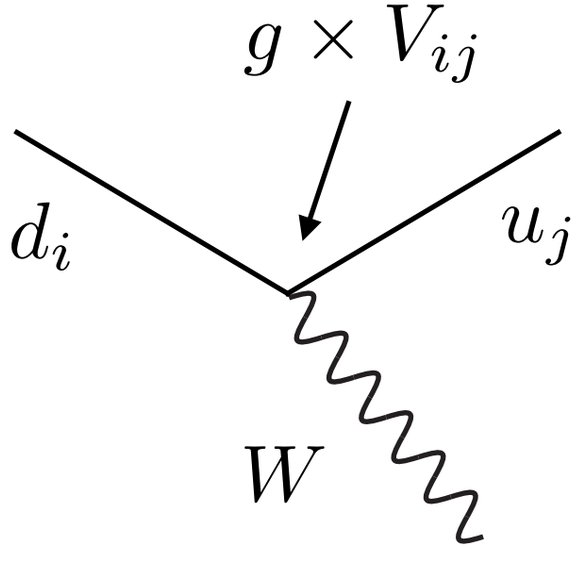
W-boson mass (not discussed today)

Test of CKM unitarity

Quark-W coupling is prop. to CKM matrix.

3x3 unitary matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

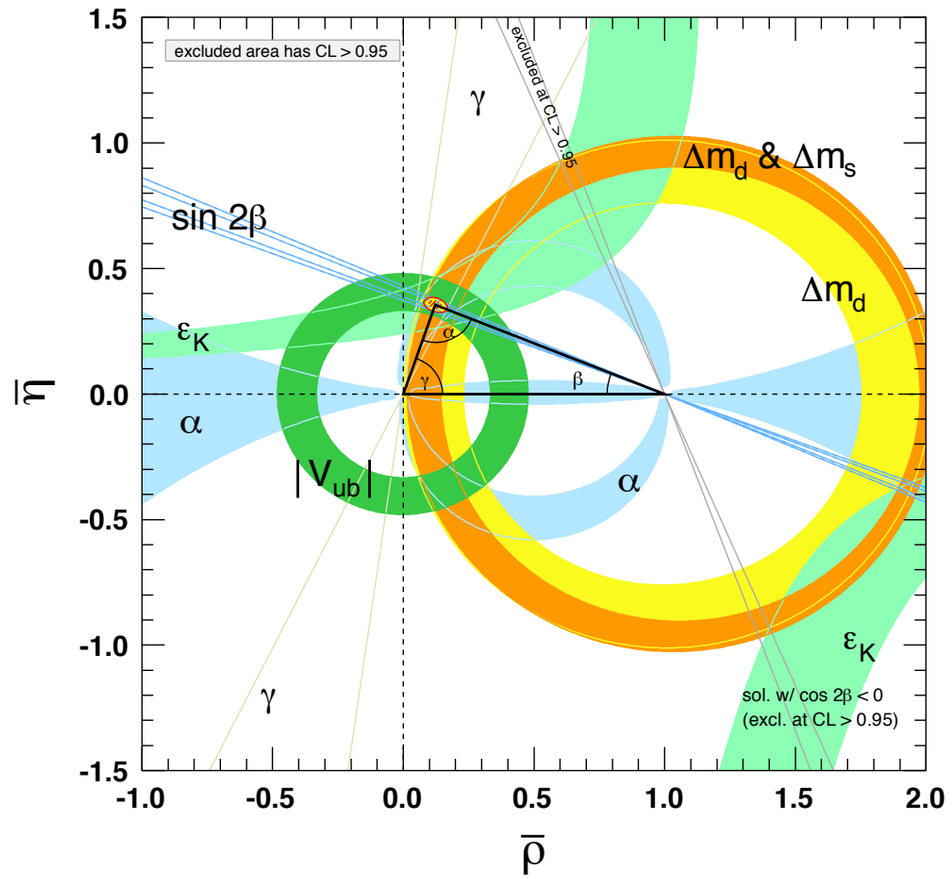


$$\sum V_{ik} V_{jk}^* = \delta_{ij}, \qquad \sum V_{ik}^* V_{jk} = \delta_{ij}$$

Test of unitarity 1: unitarity triangle

— triangle on complex plane for i≠j

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

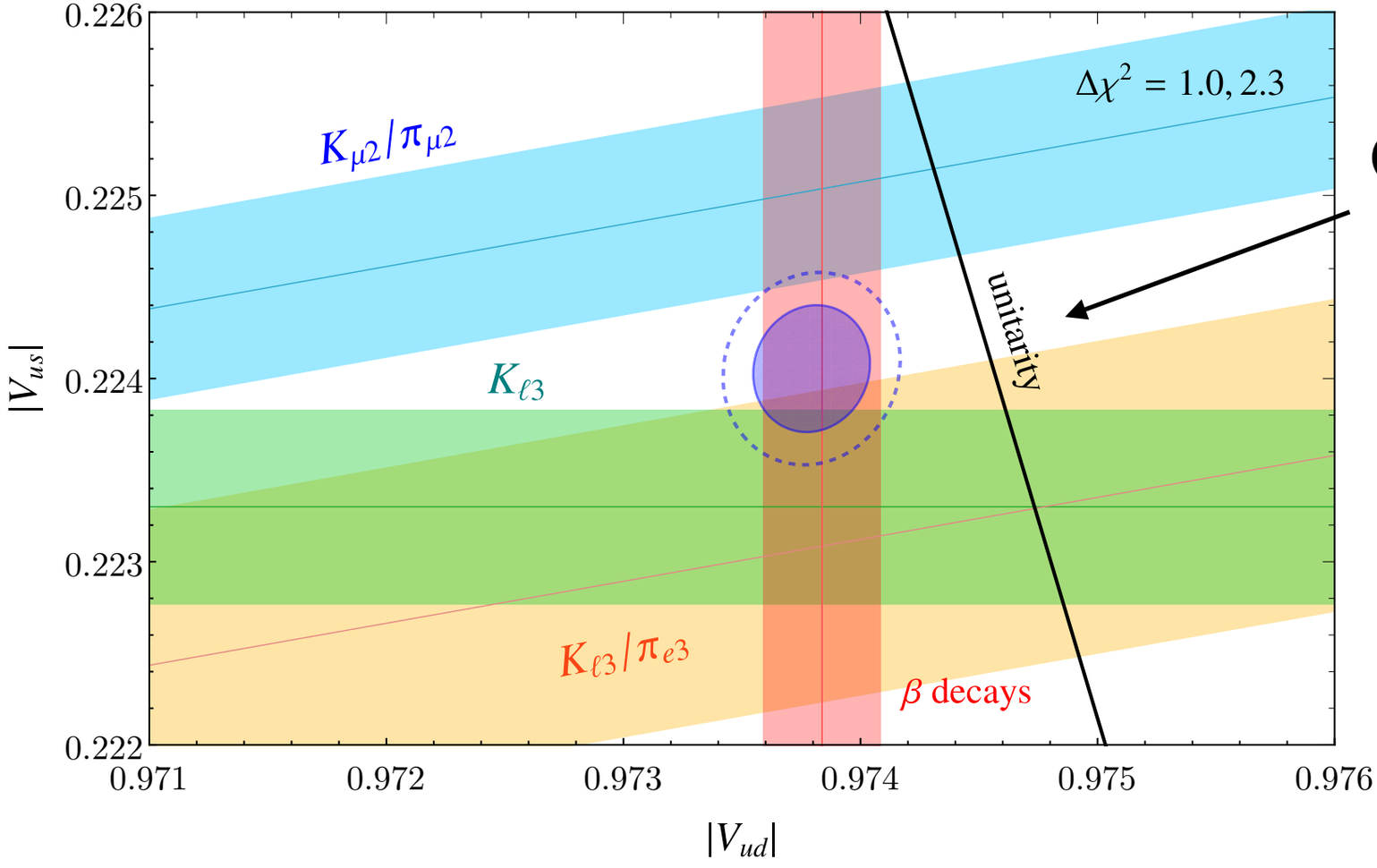


First-raw (Cabibbo angle) anomaly

Test of unitarity 2: first-row relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad (\,|V_{ub}|^2 \ll 1\,)$$

Experimental data seem to be inconsistent with SM by >3σ.



CKM unitarity (SM)

BSM interpretation

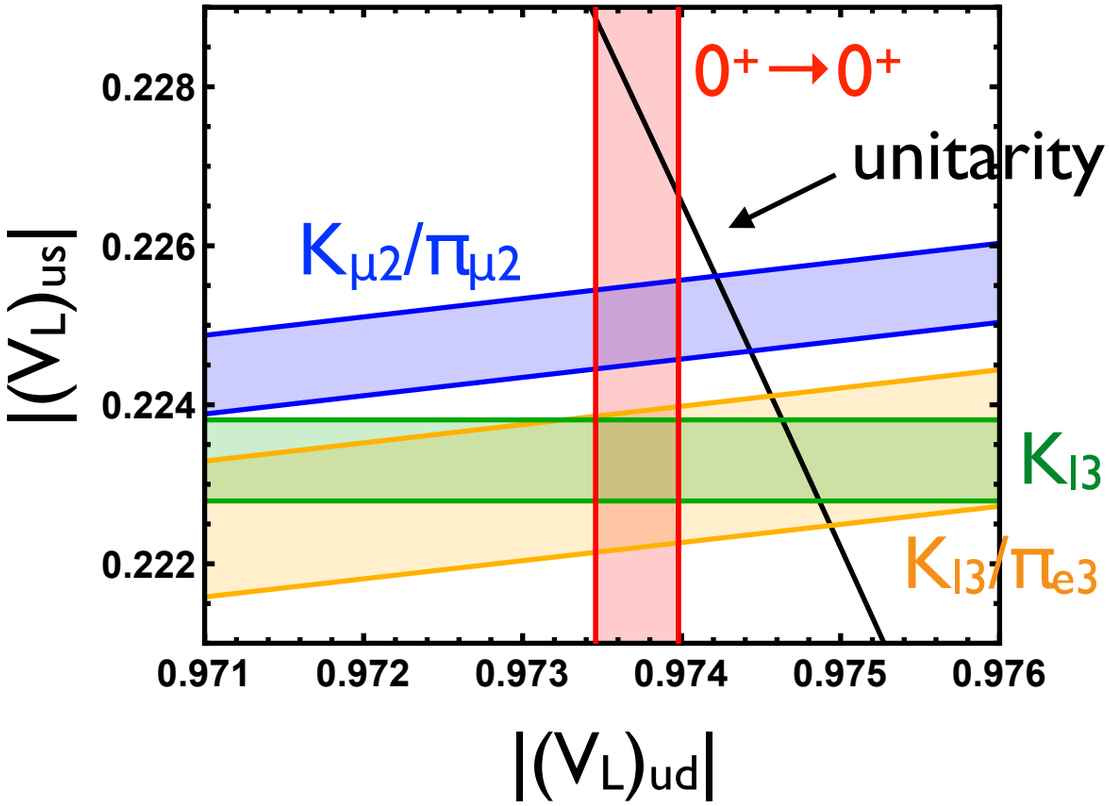
Right-handed current

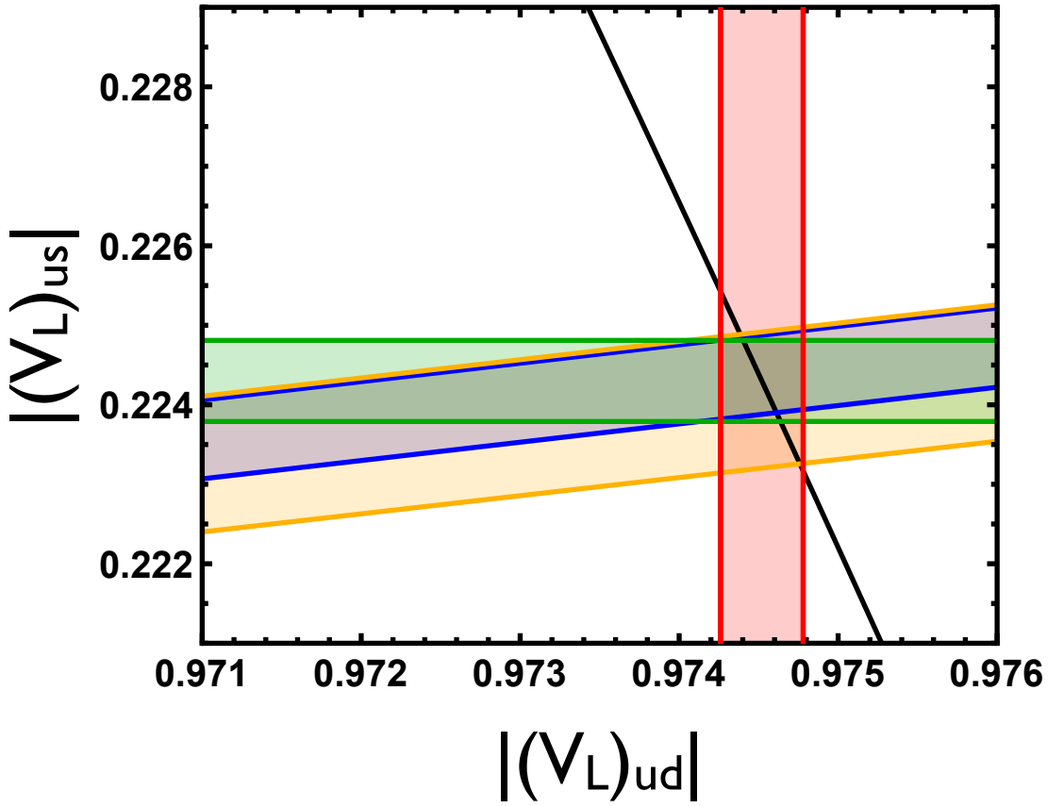
"CKM" matrix in RH current

$$\mathcal{L} = -\frac{g}{\sqrt{2}}(V_R)_{ij} W_\mu^+ \bar{u}_i \gamma^\mu P_R d_j$$

SM (V_R=0)

$$(V_R)_{ud} = -0.8 \cdot 10^{-3}$$
$$(V_R)_{us} = -1.0 \cdot 10^{-3}$$



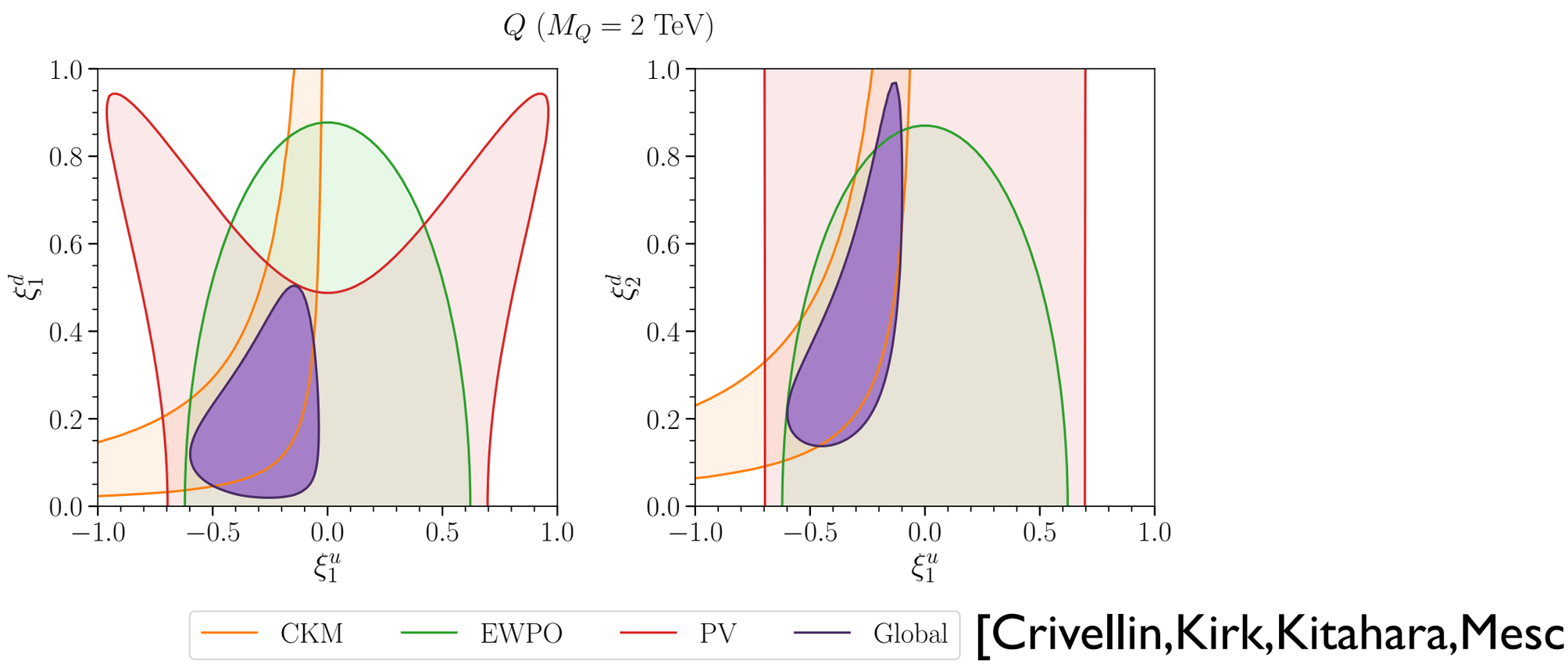


Vectorlike quark doublet: $(SU(3), SU(2))_{U(1)}=(3,2)_{1/6}$

$$\mathcal{L} = \xi^u_{fi}\bar{\mathcal{Q}}_{Lf}\tilde{H}u_{Ri} + \xi^d_{fi}\bar{\mathcal{Q}}_{Lf}Hd_{Ri} + M_{Q_f}\bar{\mathcal{Q}}_{Lf}\mathcal{Q}_{Rf} \longrightarrow \mathcal{L} = -\frac{g}{\sqrt{2}}W^+_\mu \left(\bar{u},\bar{c},\bar{t},\bar{\mathcal{T}}_R\right)\gamma^\mu V_R \begin{pmatrix} d \\ s \\ b \\ \mathcal{B}_R \end{pmatrix}$$

Single VLQ that couples to both u-d and u-s is excluded by ε_K

⇒ Predict multiple (at least two) VLQs in TeV scale



[Crivellin,Kirk,Kitahara,Mescia]

Summary

We have overviewed current flavor anomalies (>3σ):

Muon g-2 … heavy (SUSY, LQ, VLL, etc) or light (Z', ALP, etc)

R(D), R(D*) … LQ, charged Higgs, etc

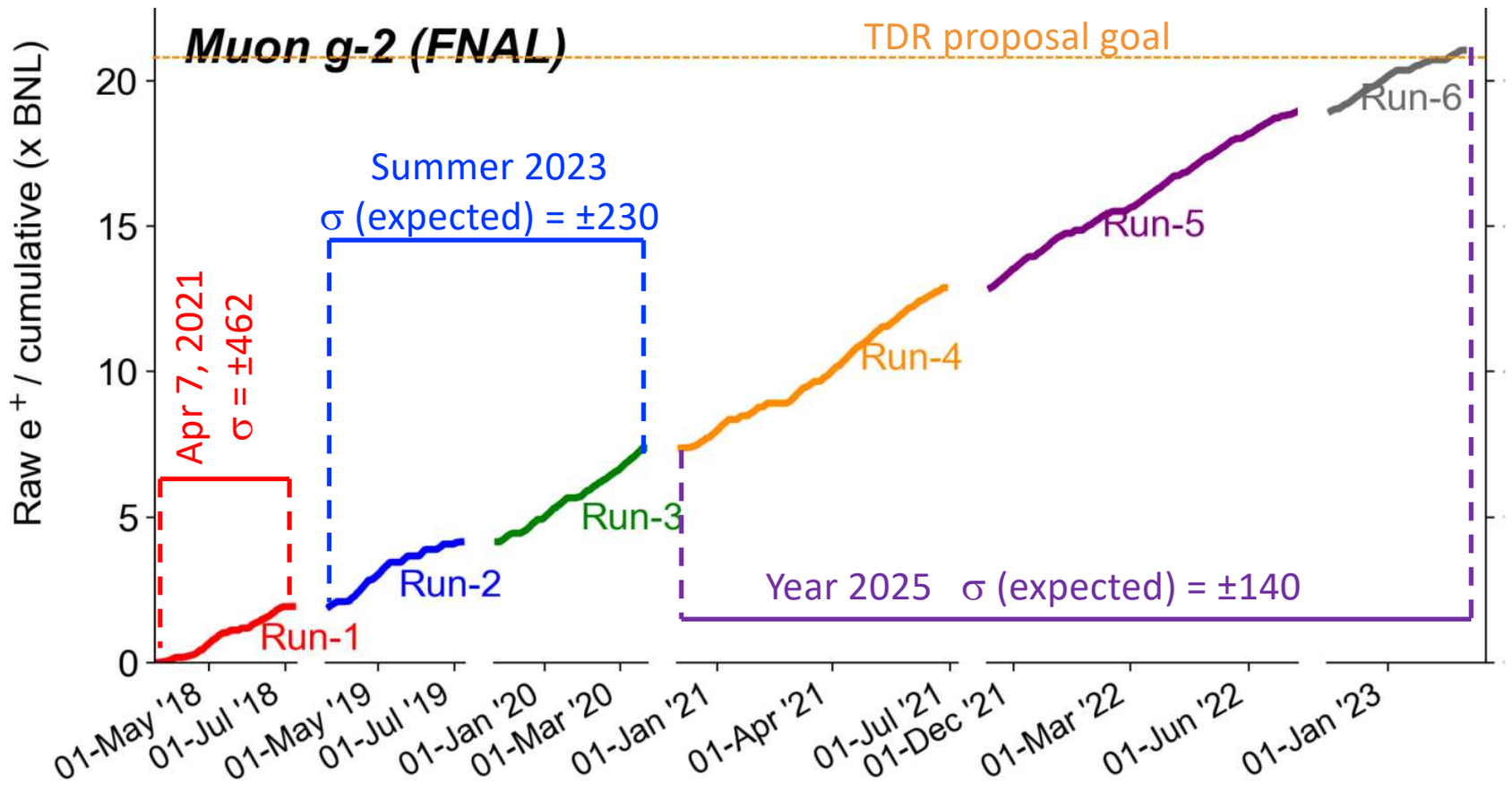
First-row CKM unitarity … VLQ, etc

All anomalies imply new particles in TeV scale, which are attractive targets in the near future.

Backup slides

Status of muon g-2 experiment at FNAL

Data collected met proposal goals … "21 BNLs"

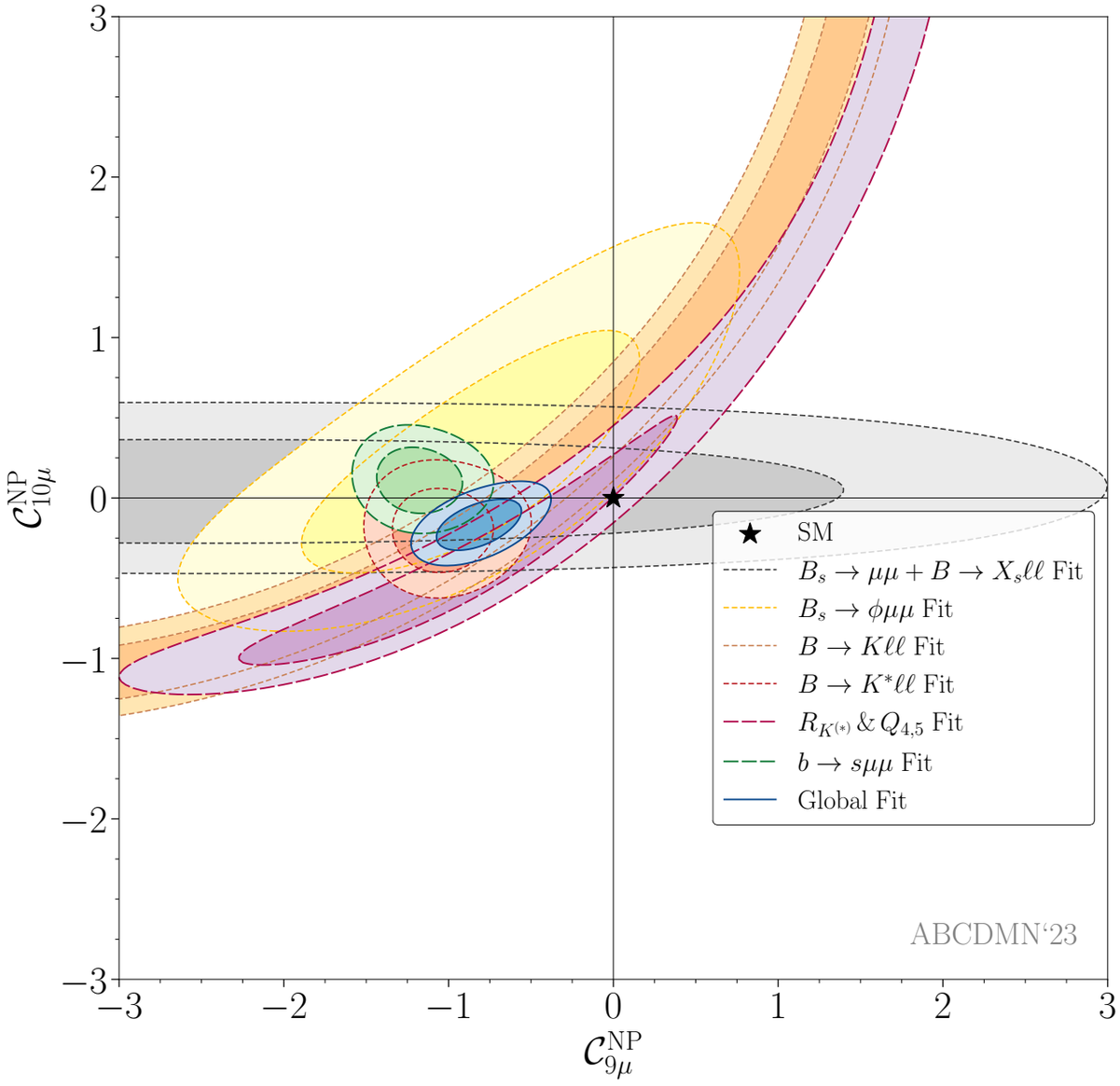


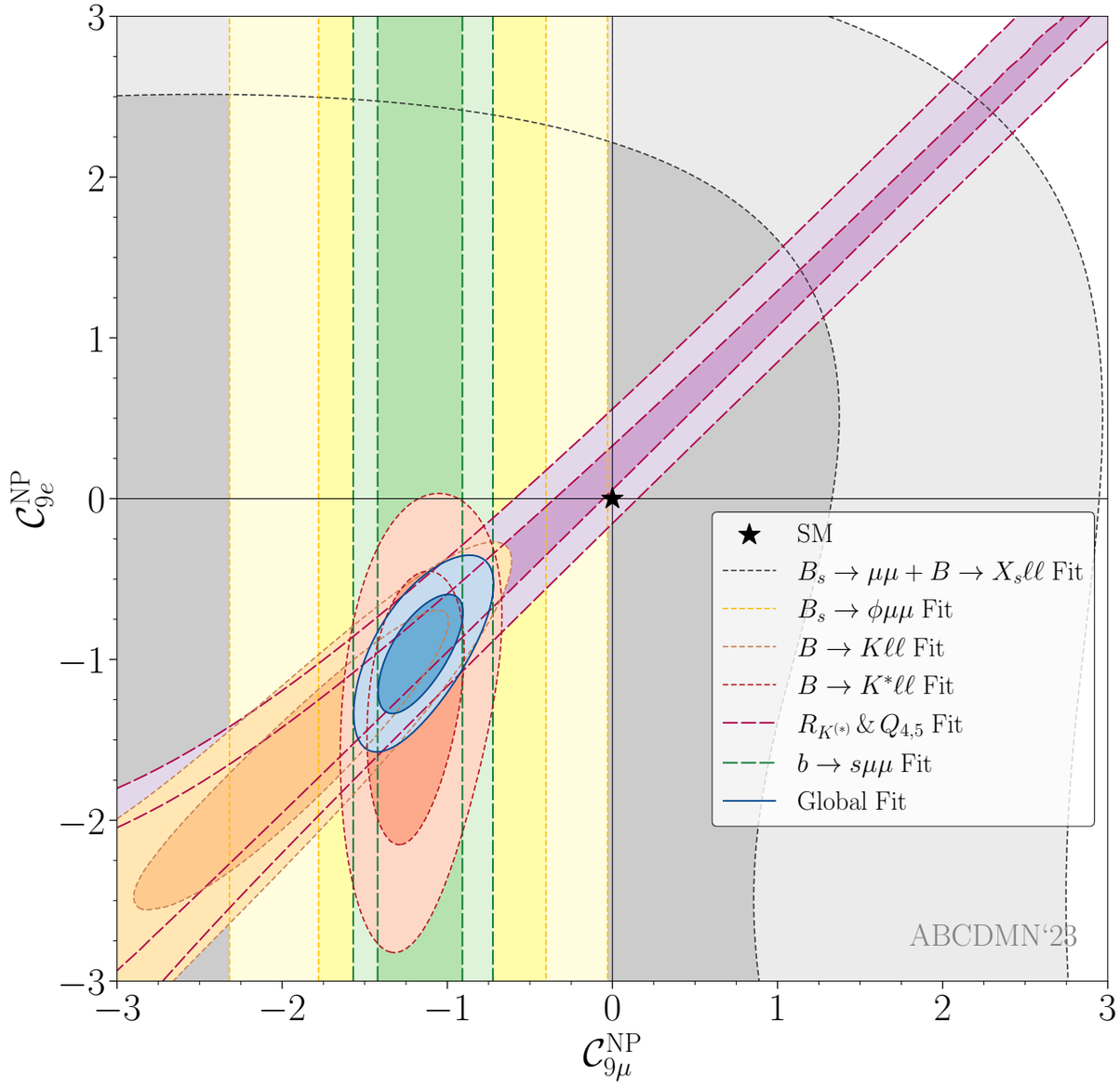
(each publication will include the average with previous runs)

Slide by M. Incagli at FPCP 2023

* FNAL Run2+3 planned in Aug/Sep 2023

Global fit of b→sll [2023]





Imply BSM contribution to C_{9U} (Pull_{SM}~5.5σ)

cf. $O_{9\ell} = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$, $C_9^{\rm SM} \simeq 4$, U: e=μ

[Alguero, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet]

Recent W-boson mass result at CDF

PDG: W-boson mass w/o new CDF

$M_W = 80.377 \pm 0.012$ GeV

Recent CDF result

$M_W = 80.4335 \pm 0.0094$ GeV

tension

SM prediction

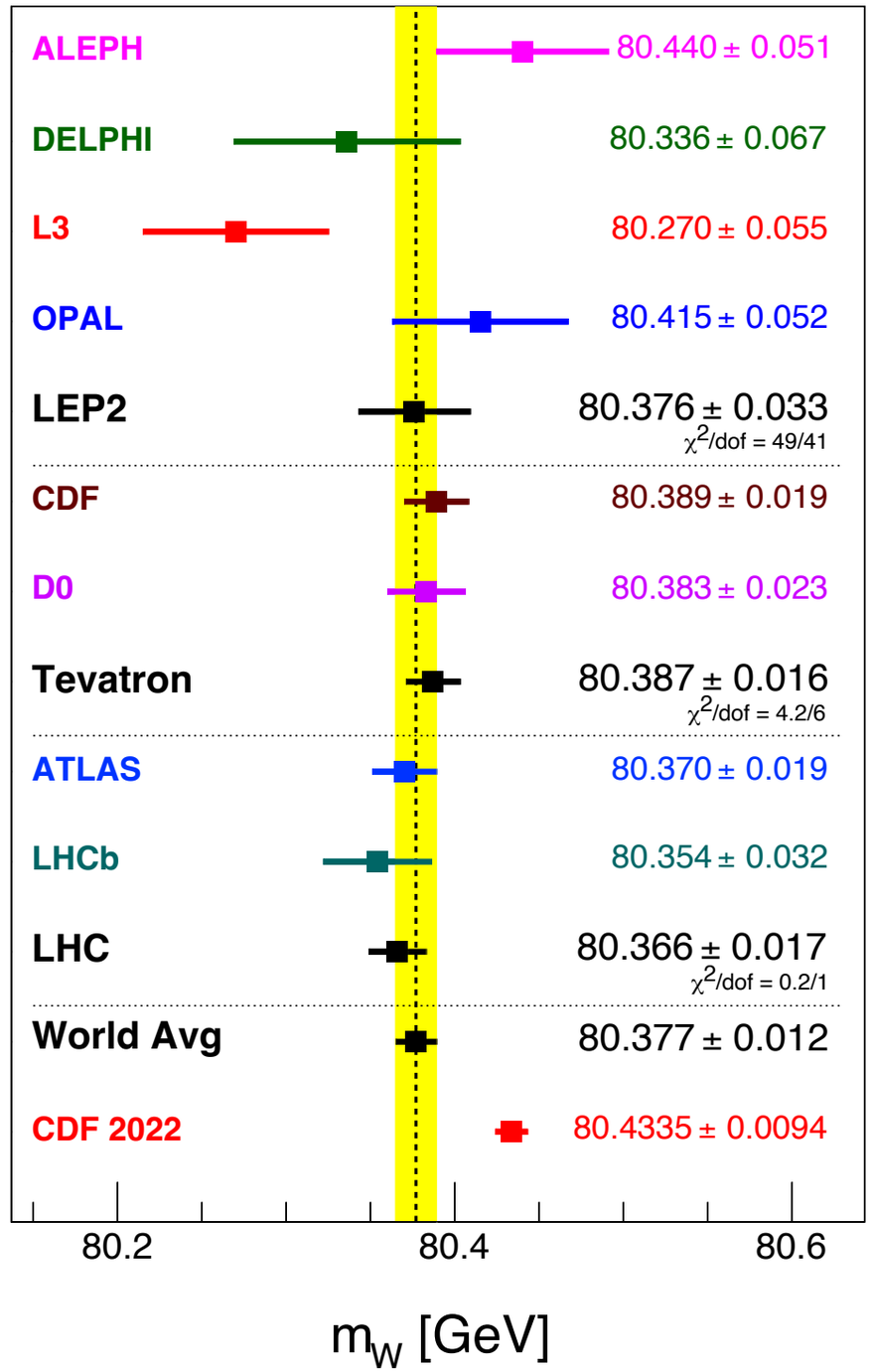
$M_W = 80.3552 \pm 0.0055$ GeV

tension

SM vs PDG → <2σ (consistent)

SM vs CDF → ~7σ

[PDG 2022]

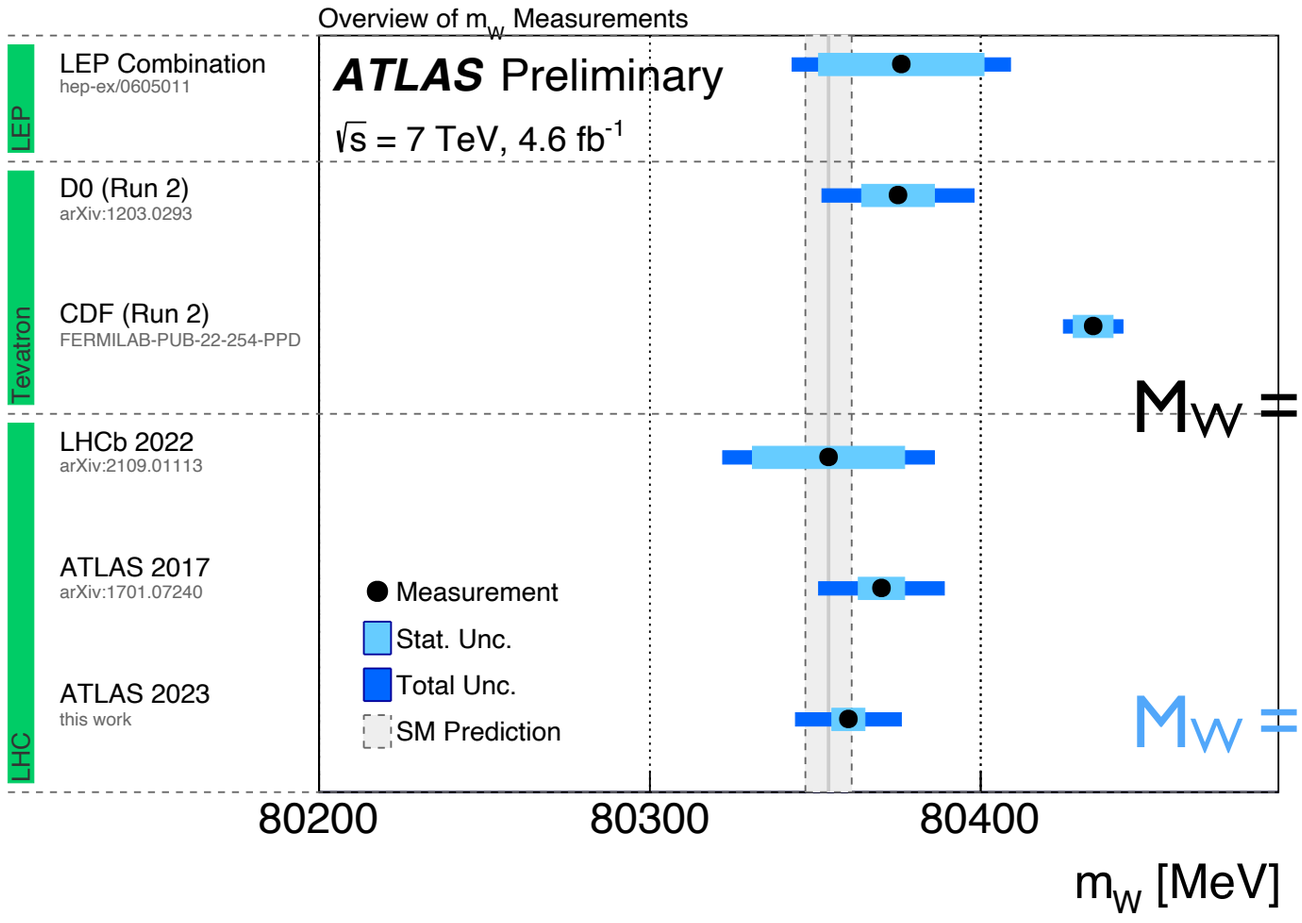


ATLAS revised 7TeV data

New ATLAS result is consistent with previous exp value.

Tension with CDF → additional measurements are needed.

If CDF is confirmed, the deviation from SM is a sing of new theory.



$M_W = 80.4335 \pm 0.0094$ GeV

~4σ

$M_W = 80.360 \pm 0.016$ GeV

Axion-like particle (ALP) [Aiko, ME]

Pseudo NG bosons associated to (approximate) global symmetry

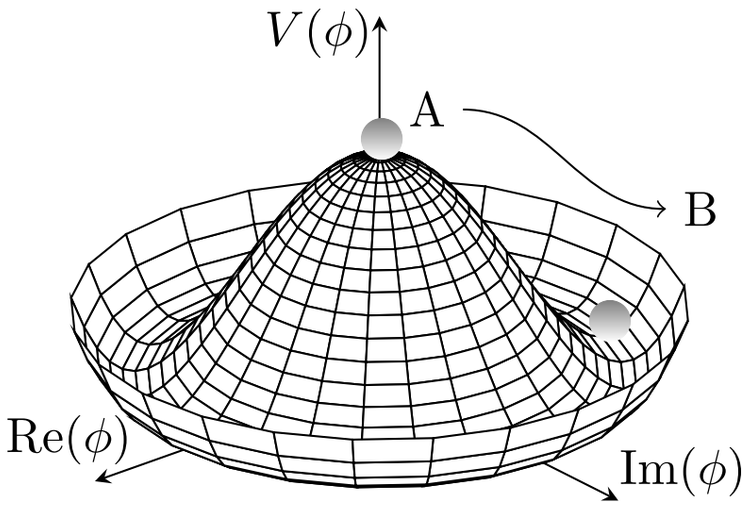
dynamical dof in flat direction → ALP mass

Interactions are invariant under shifts $a \to a + c$

Consider interactions with SM SU(2) and U(1) gauge bosons

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - c_{WW}\frac{a}{f_a} W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - c_{BB}\frac{a}{f_a} B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

spontaneous breaking of global symmetry



ALP contribution

Four interactions (after EWSB) from two ALP couplings

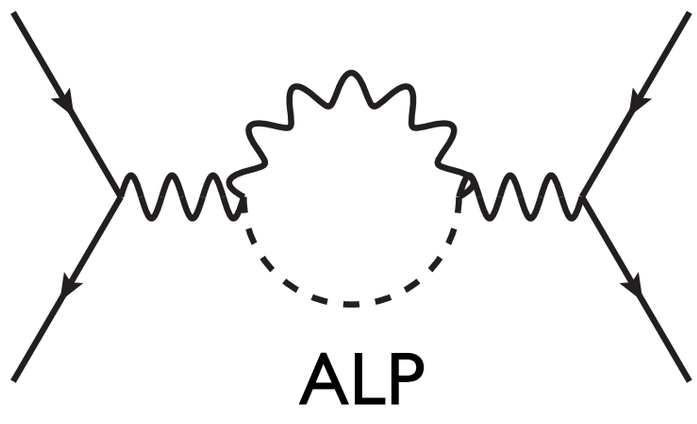
$$\mathcal{L}_{\rm ALP} = -c_{WW}\frac{a}{f_a}W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

EWSB ↓

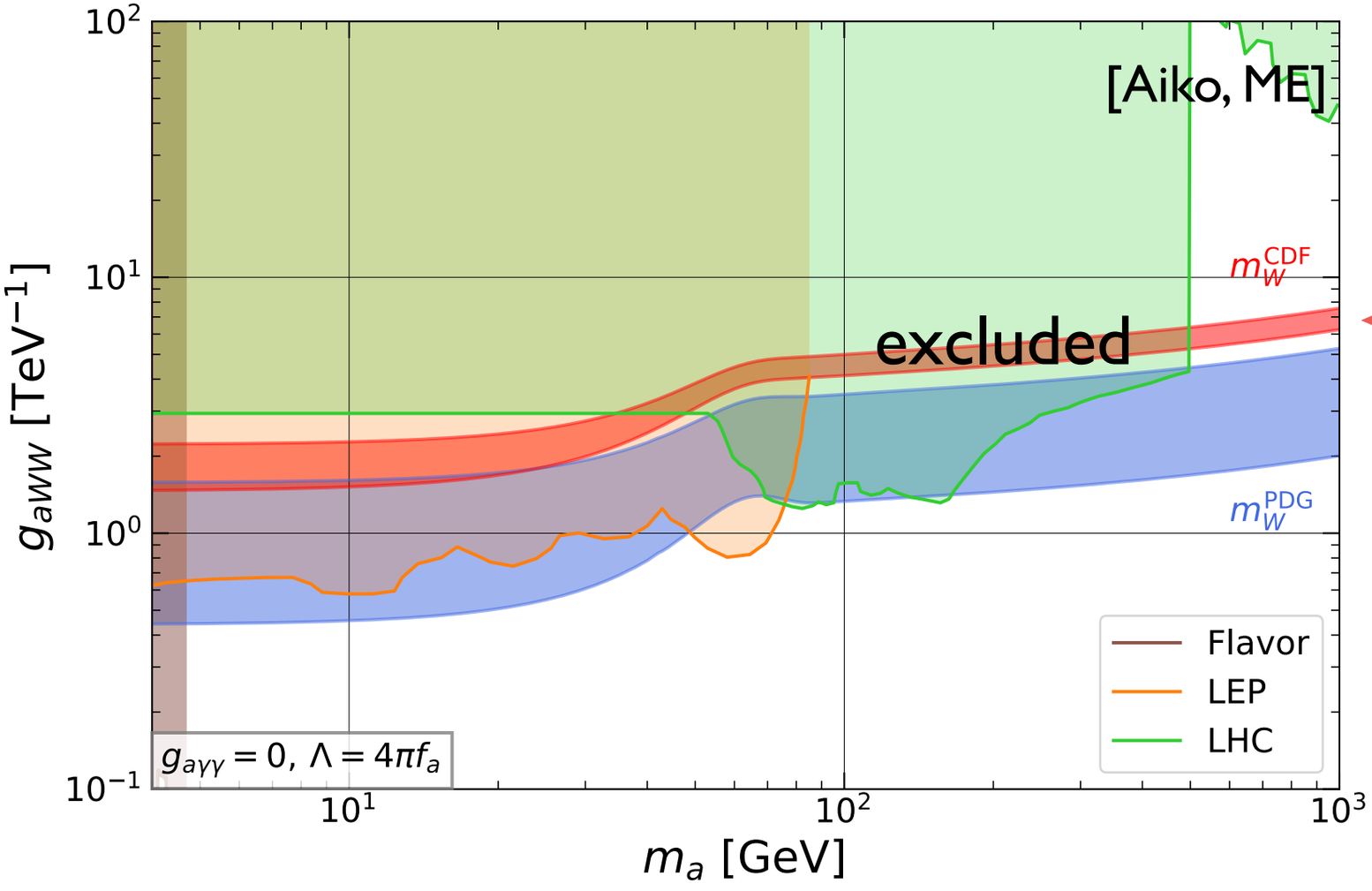
$$= -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{2}g_{a\gamma Z}aZ_{\mu\nu}\widetilde{F}^{\mu\nu}$$
$$- \frac{1}{4}g_{aZZ}aZ_{\mu\nu}\widetilde{Z}^{\mu\nu} - \frac{1}{2}g_{aWW}aW^+_{\mu\nu}\widetilde{W}^{-\mu\nu}$$

$$g_{a\gamma\gamma} = \frac{4}{f_a}(s_W^2 c_{WW} + c_W^2 c_{BB})$$
$$g_{aZ\gamma} = \frac{2}{f_a}(c_{WW} - c_{BB})s_{2W}$$
$$g_{aZZ} = \frac{4}{f_a}(c_W^2 c_{WW} + s_W^2 c_{BB})$$
$$g_{aWW} = \frac{4}{f_a}c_{WW}$$

Contribution via vacuum polarizations



Result of global fit analysis



CDF tension is solved

← triboson @LHC

ALP coupling to di-photon is disfavored by constraints.

→ focus on g_{aWW} w/ fixing $g_{a\gamma\gamma}$=0

W-boson mass is explained by ALP heavier than 500GeV.

LHC bound on EW ALP

[Craig, Hook, Kasko]