Experimental Anomalies

Flavour non-universality in B meson decays?
Anomalous magnetic moment of the muon?
Mass of the W boson?

All have generated theoretical enthusiasm,
but they may (well) all go away

John Ellis

KING'S College LONDON

Lepton Flavour Universality Violation in $B \to K\ell^+\ell^-$ Decays?

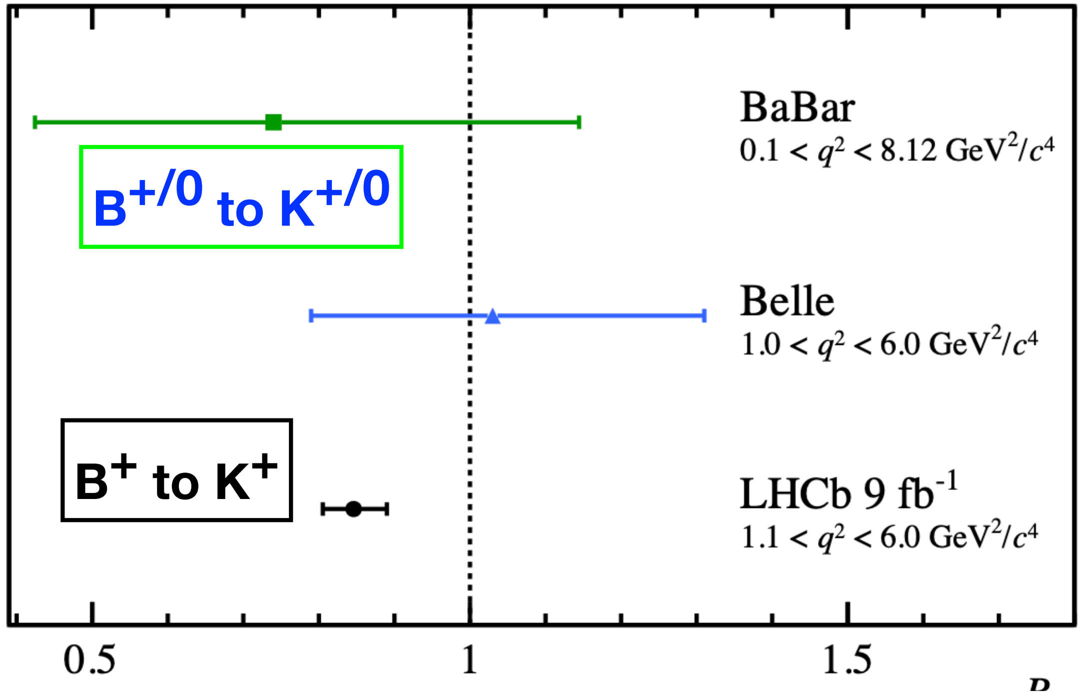
B decays to $e^+e^- > \mu^+\mu^-$

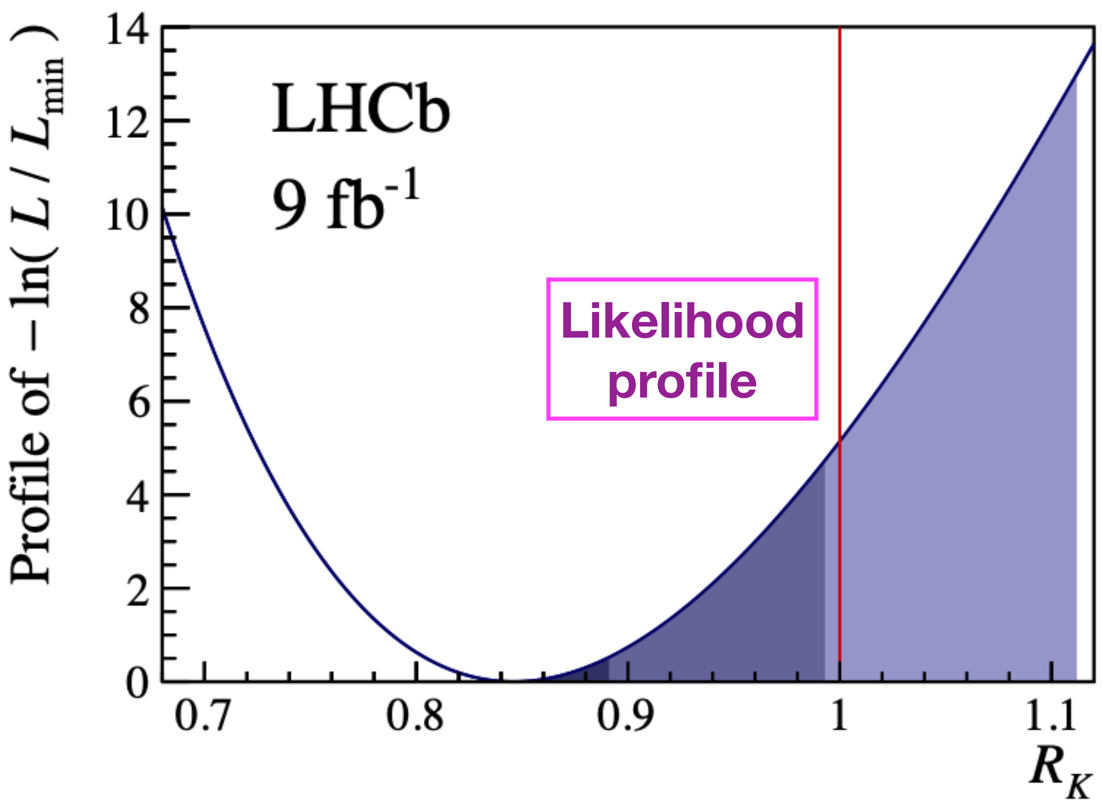
Prima facie violation of lepton universality

SM interactions flavour-universal

Except for Higgs couplings ∝ masses

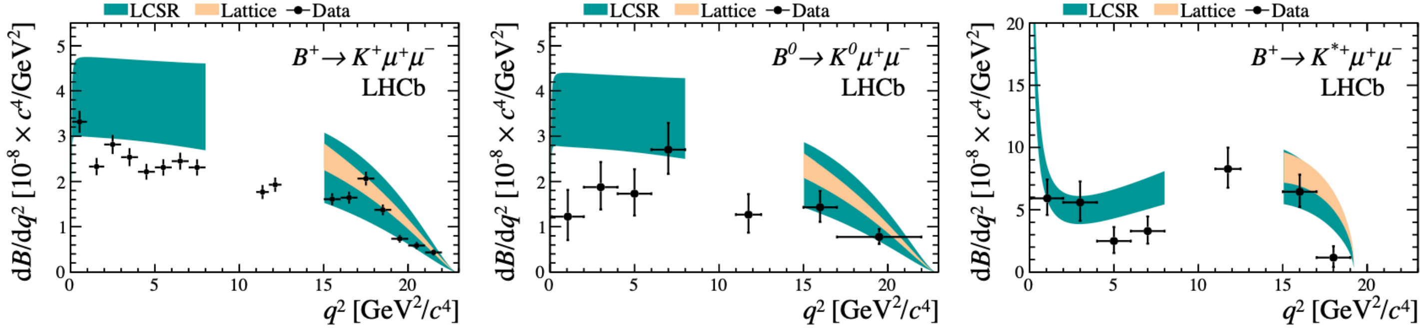
LHCb Collaboration, arXiv:2103.11769





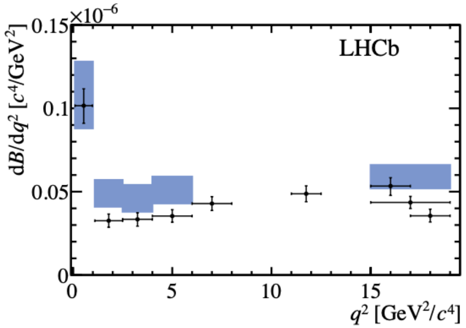
Other Previous Measurements

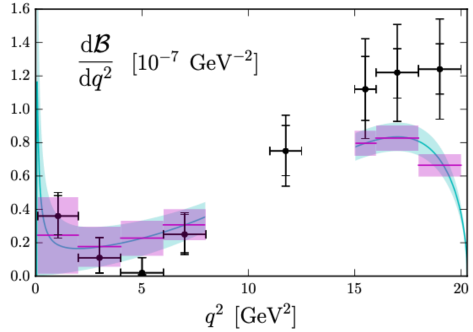
[JHEP06(2014)133]

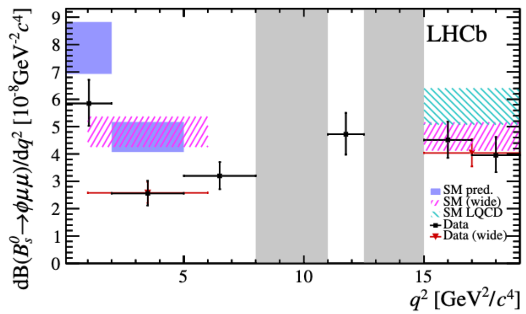


Rates

$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



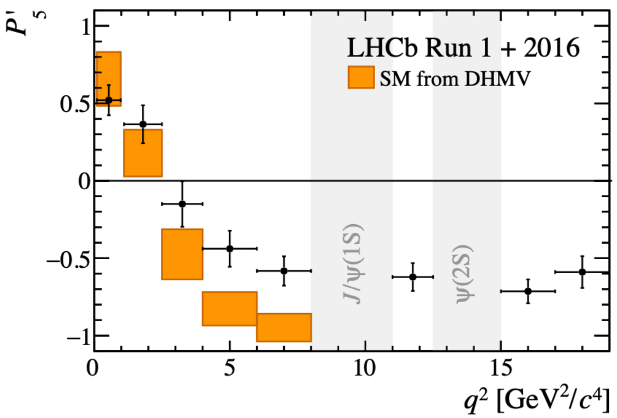


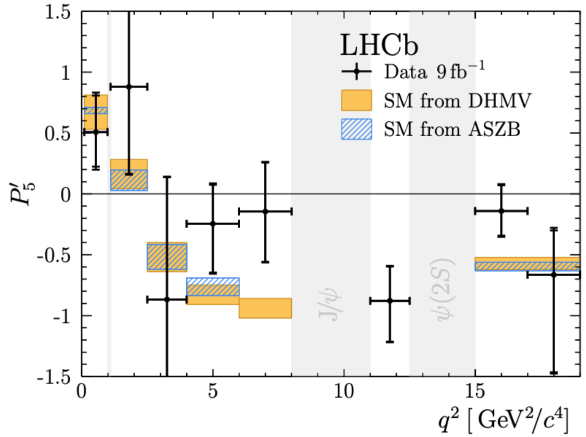


- SM predictions suffer from large hadronic uncertainties

Left: $B^0 \to K^{*0}\mu^+\mu^-$ [PRL125011802(2020)], Right: $B^+ \to K^{*+}\mu^+\mu^-$ [arXiv:2012.13241]

Angular distributions





Flavour Anomalies in b→s Decays

- Parametrize using effective dimension-6 operators:

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} (C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i^{\prime bs\ell\ell} O_i^{\prime bs\ell\ell}) + \text{h.c.}$$

- Operators appearing in analysis:

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$O_S^{bs\ell\ell} = m_b(\bar{s} P_R b)(\bar{\ell}\ell)\,, \qquad O_S^{\prime bs\ell\ell} = m_b(\bar{s} P_L b)(\bar{\ell}\ell)\,,$$

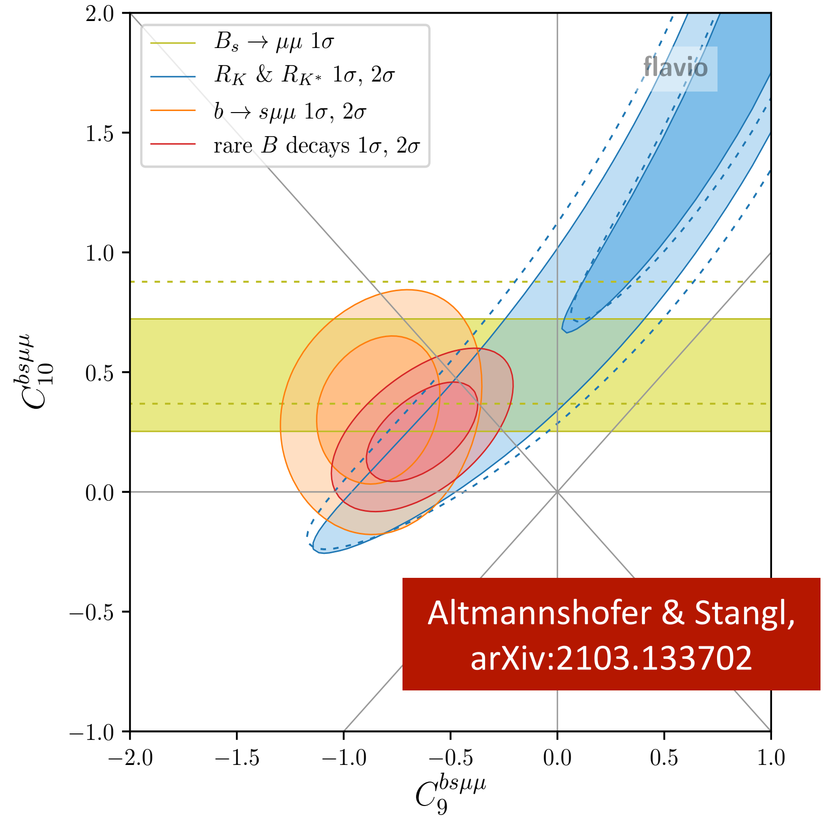
- $$O_P^{bs\ell\ell} = m_b(\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P^{\prime bs\ell\ell} = m_b(\bar{s} P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$

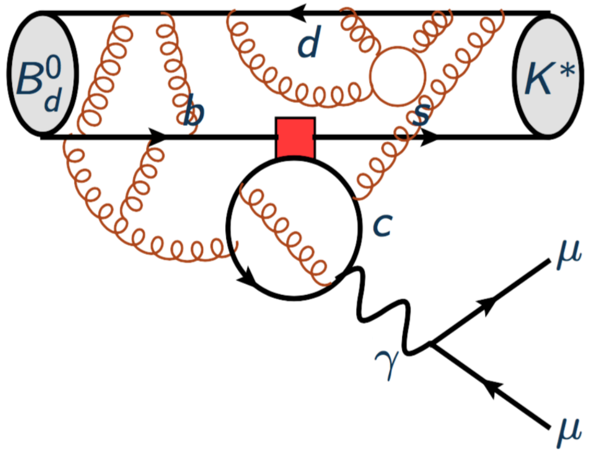
- Evidence for non-zero coefficient of $O_9^\mu \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$
- Maybe also non-zero coefficient of $O_{10}^\mu \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$.
- No evidence of operators with electrons

Putting Measurements Together

- Combination all $b \to s\ell^+\ell^-$ measurements
  - Consistent set of measurements
  - $> 6\sigma$ from SM
- But $B \to K^{(*)}\mu^+\mu^-$ BF and angular observables potentially suffer from underestimated hadronic uncertainties related to $c\bar{c}$ loop contributions

  $\to B_s \to \mu^+\mu^-$ and LFU observables have very clean theory predictions.
  - $\sim 4.5\sigma$ from SM
- Measurements point to new vector coupling (C_9^μ)



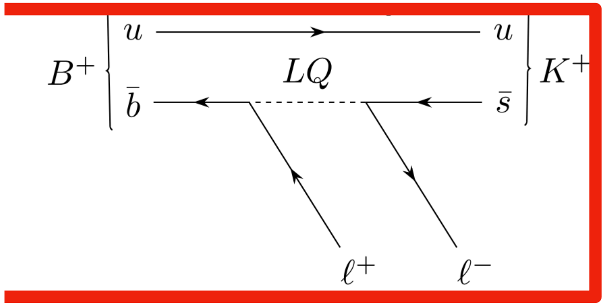


Flavour Anomalies in b→s Decays

- Results for operator coefficients

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Altmannshofer & Stangl, arXiv:2103.133702



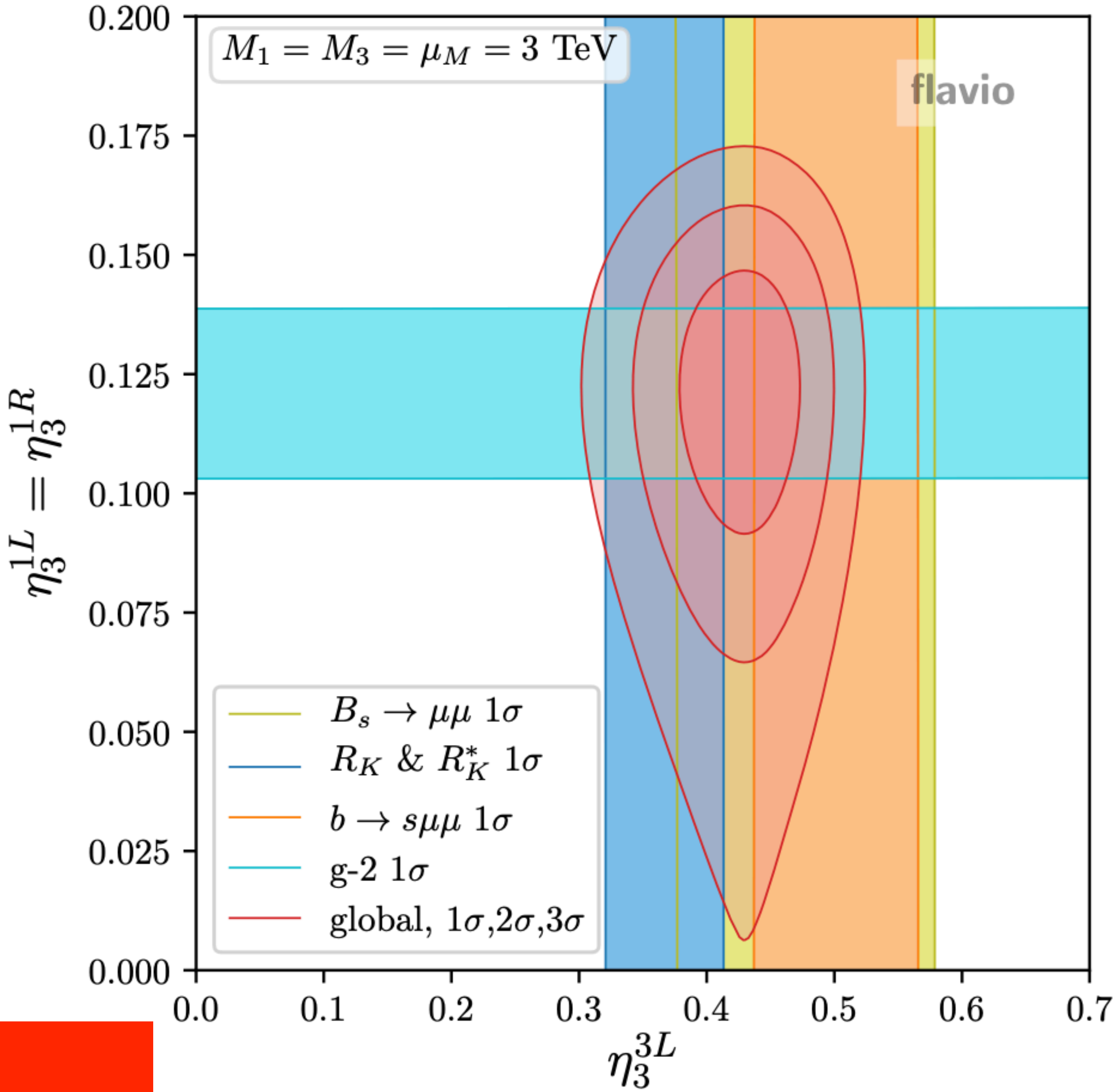
Leptoquarks?

General Lagrangian for scalar leptoquarks:

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\mathrm{SM}-V_H} &+ |D_\mu \Phi|^2 + |D_\mu S_1|^2 + |D_\mu S_3|^2 - \tfrac{1}{4} X_{\mu\nu}^2 \\ &- \Big(\boxed{\eta_i^{3\mathrm{L}}\, \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2\, S_3 - \eta_i^{1\mathrm{L}} \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2 S_1 - \eta_i^{1\mathrm{R}} \overline{u}_{\mathrm{R}}^{c\,i} \mu_{\mathrm{R}} S_1} \\ &- \tilde{\eta}_i^{1\mathrm{R}} \overline{d}_{\mathrm{R}}^{c\,i} \nu_{\mu,\mathrm{R}} S_1 + \mathrm{h.c.} \Big) + \tfrac{1}{2} \varepsilon_{BX} B_{\mu\nu} X^{\mu\nu} \\ &- V_{H\Phi}(H, \Phi) - V_{13}(H, \Phi, S_1, S_3) + \bar{\nu}_{\mathrm{R}}^i i \not{D} \nu_{\mathrm{R}}^i \\ &- \Big(y_\nu^{ij}\, \bar{\ell}_{\mathrm{L}}^i \tilde{H} \nu_{\mathrm{R}}^j + M_{\mathrm{R}}^{ij} \bar{\nu}_{\mathrm{R}}^{ci} \nu_{\mathrm{R}}^j + y_\Phi^{ij} \Phi\, \bar{\nu}_{\mathrm{R}}^{ci} \nu_{\mathrm{R}}^j + \mathrm{h.c.} \Big) \,, \end{aligned} \qquad (2)$$

Greljo, Stangl & Thomsen, arXiv:2103.13991

Leptoquark Model of b→s Anomalies



Wait and see:
LHCb is reanalysing its data …

Greljo, Stangl & Thomsen, arXiv:2103.13991

$g_\mu - 2$:

dawn of new physics or its sunset?

$g_\mu - 2$ in Supersymmetry

- One-loop contribution from smuon/neutralino loop

$$\Delta(g-2)_\mu = -ab(\cos\alpha\sin\alpha/4\pi^2)(m_\mu/m_{\tilde{G}})$$
$$\times\ \{1/(1-\eta_1) + 2\eta_1/(1-\eta_1)^2$$
$$+ [2\eta_1/(1-\eta_1)^3]\log\eta_1 - (\eta_1 \leftrightarrow \eta_2)\},$$

- where $\eta_i \equiv (m^2_{s\mu_i}/m^2_{\tilde{G}})$

- and $\mathcal{L} = a\sqrt{2}\,s_\mu \bar{\mu}_L \tilde{G} + b\sqrt{2}\,t_\mu \bar{\mu}_R \tilde{G}$

(1982)

Volume 116B, number 4 PHYSICS LETTERS

SPIN-ZERO LEPTONS AND THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

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CERN, Geneva, Switzerland

Received 14 June 1982

The anomalous magnetic moment of the muon $(g-2)_\mu$ imposes constraints on the masses and mixing of spin-zero leptons (sleptons). We develop the predictions of models of spontaneous supersymmetry breaking for the slepton mass matrix, and show that they are comfortably consistent with the $(g-2)_\mu$ constraints.

During the present resurgence of interest in supersymmetry broken at low energies [1] new significance is attached to the classical phenomenological playgrounds of gauge theories such as the anomalous magnetic moments of the electron and muon [2], flavour-changing neutral interactions [3–5] parity [6] and *CP* violation [7,8] in the strong interactions. The three latter phenomena make life rather difficult [3,7] for the most general form of soft supersymmetry breaking, whereas simple models [9–11] of spontaneously broken supersymmetry naturally [3,4 7] respect the $\Delta F \neq 0$, *P* and *CP* violation constraints. As for the anomalous magnetic moments of the leptons, it has long been known that they vanish in an exactly supersymmetric theory [12], and Fayet [2] showed that in his model of supersymmetry breaking $(g-2)_\mu$ would be compatible with experiment if the spin-zero muon (smuon) masses were heavier than 15 GeV. Direct experimental searches [13] now exclude the existence of lighter smuons. Fayet's analysis [2] was in the context of a model with a very light photino $\tilde{\gamma}$ (see fig. 1a), and Grifols and Méndez [14] have recently made the interesting observation that his analysis is significantly altered for massive gauginos (see figs. 1b, 1c). They show that there are potentially nontrivial constraints on the smuon masses in models of broken supersymmetry.

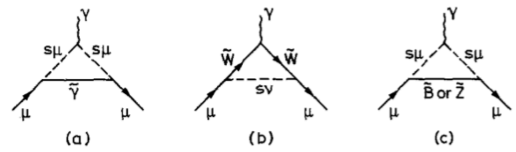


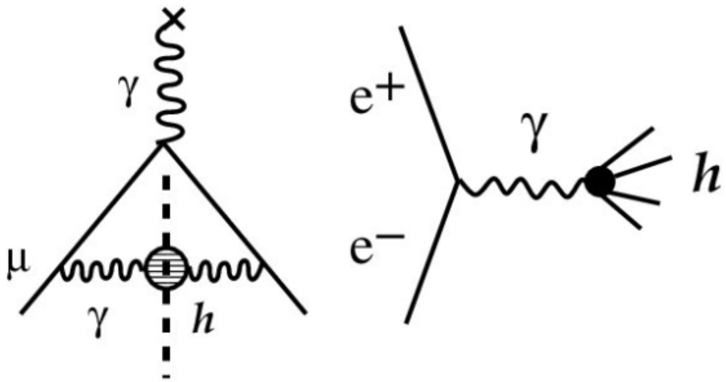
Fig. 1. One-loop diagrams contributing to $(g-2)_\mu$: (a) essentially massless photino ($\tilde{\gamma}$) exchange, (b) $\tilde{W}$ and sneutrino ($s\nu$) exchange, and (c) $\tilde{B}$ or $\tilde{Z}$ exchange.

right transition operator there is a GIM [15]-like cancellation between the smuon mass eigenstates in fig. 1c which provides a potential suppression mechanism. We analyze recent models [10,11] of spontaneous supersymmetry breaking originating in the *D* and *F* sectors, respectively. We show that in the former case $(g-2)_\mu$ is suppressed by near degeneracy between the smuon mass eigenstates, while in the latter case $(g-2)_\mu$ is suppressed by small mixing angles between the left- and right-handed smuons. We close with some remarks about $(g-2)_e$ and about parity violation in the strong interactions.

When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\tilde{\gamma}$ diagram of fig. 1a and the $\tilde{W}$ diagram of fig. 1b as compared to the massive $\tilde{B}$ or $\tilde{Z}$ diagram of fig. 1c. The

Theory Initiative

- Comprehensive review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation



Aoyama et al, arXiv:2006.04822

Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/physrep

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

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[5] LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France

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E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).

https://doi.org/10.1016/j.physrep.2020.07.006

Hadronic Vacuum Polarization

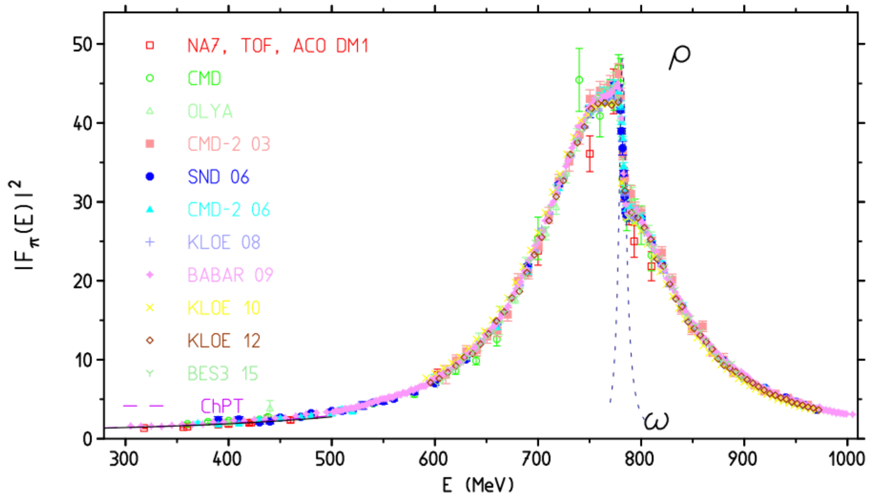
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects

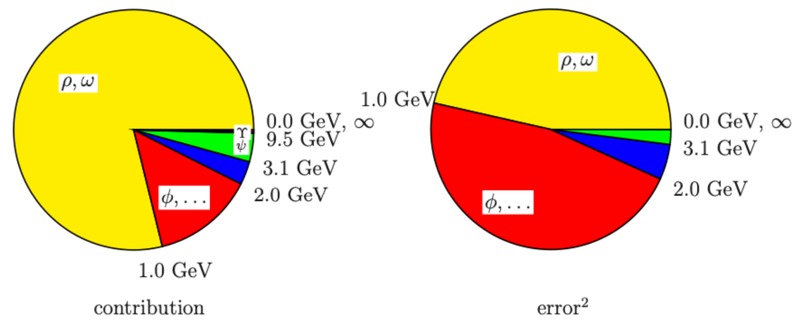
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)

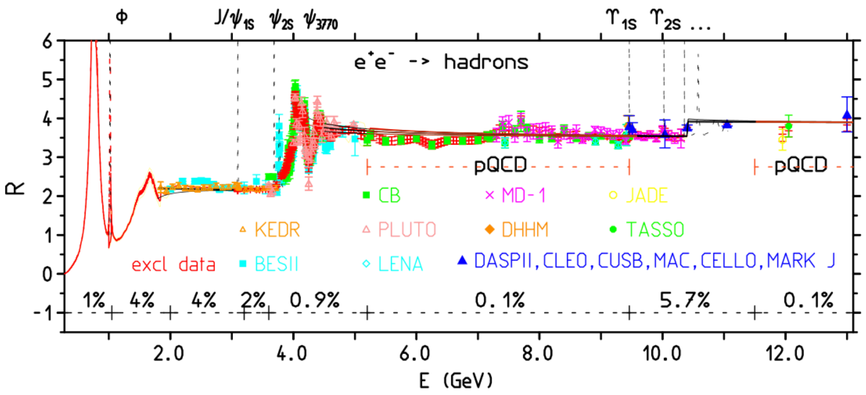
- High energies under good control from perturbative QCD

$$a_\mu^{\text{HVP, LO}} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{sys}}(0.7)_{\text{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10} \,.$$

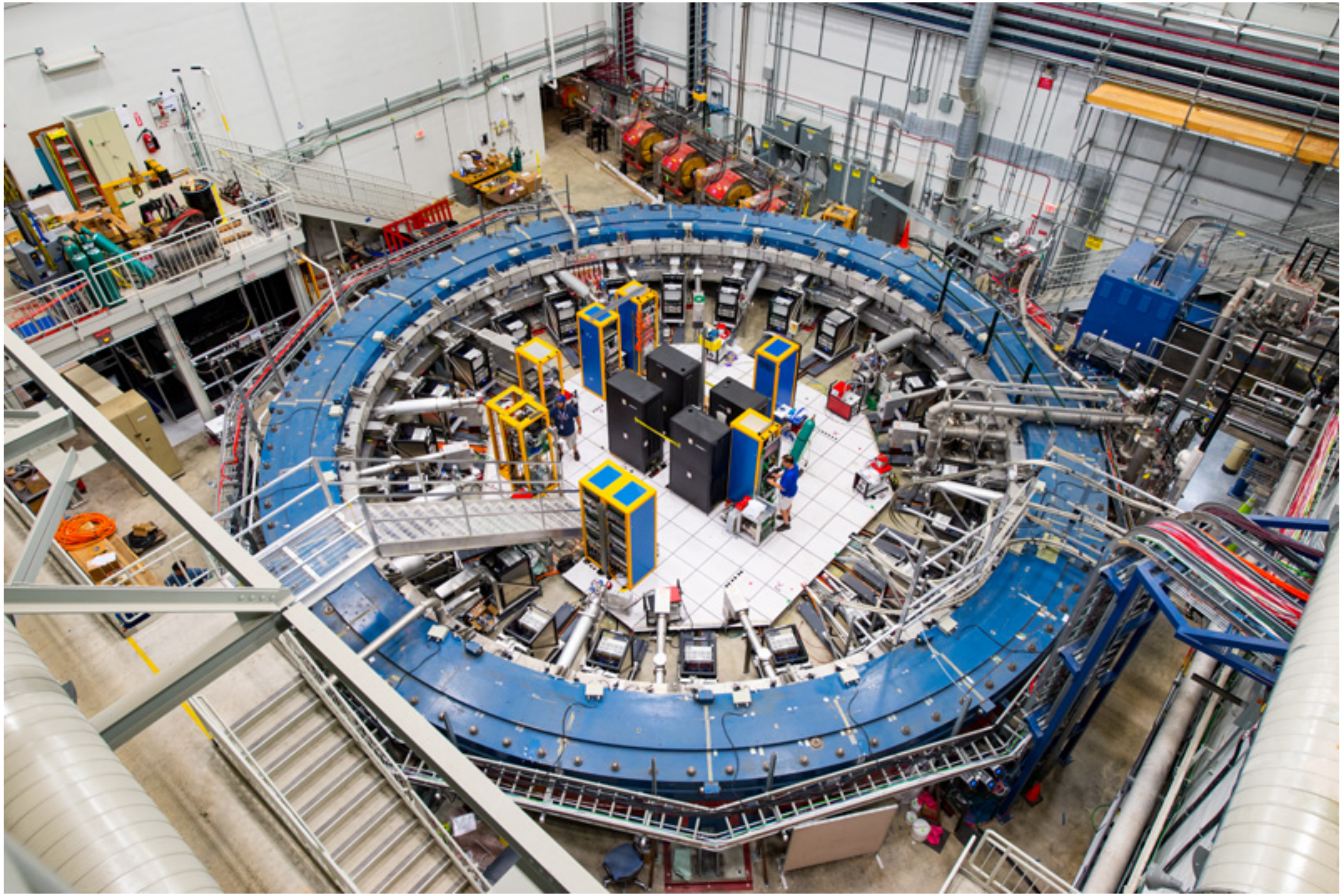
Aoyama et al, arXiv:2006.04822







Fermilab Experiment



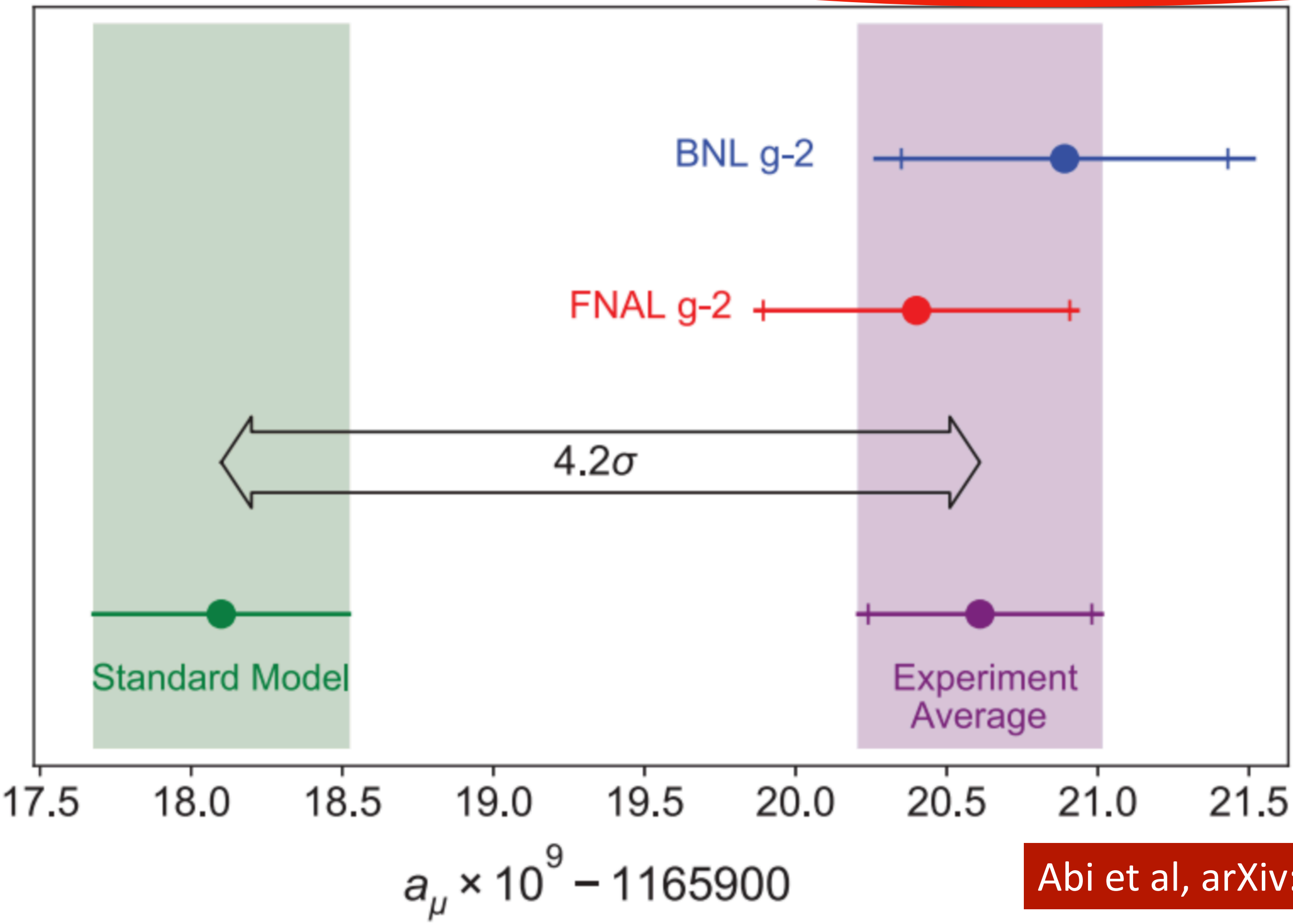
Does the magnet look familiar?

Fermilab Measurement

FNAL result: $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$

Combined result: $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$

Difference from Standard Model: $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$



Abi et al, arXiv:2104.03281

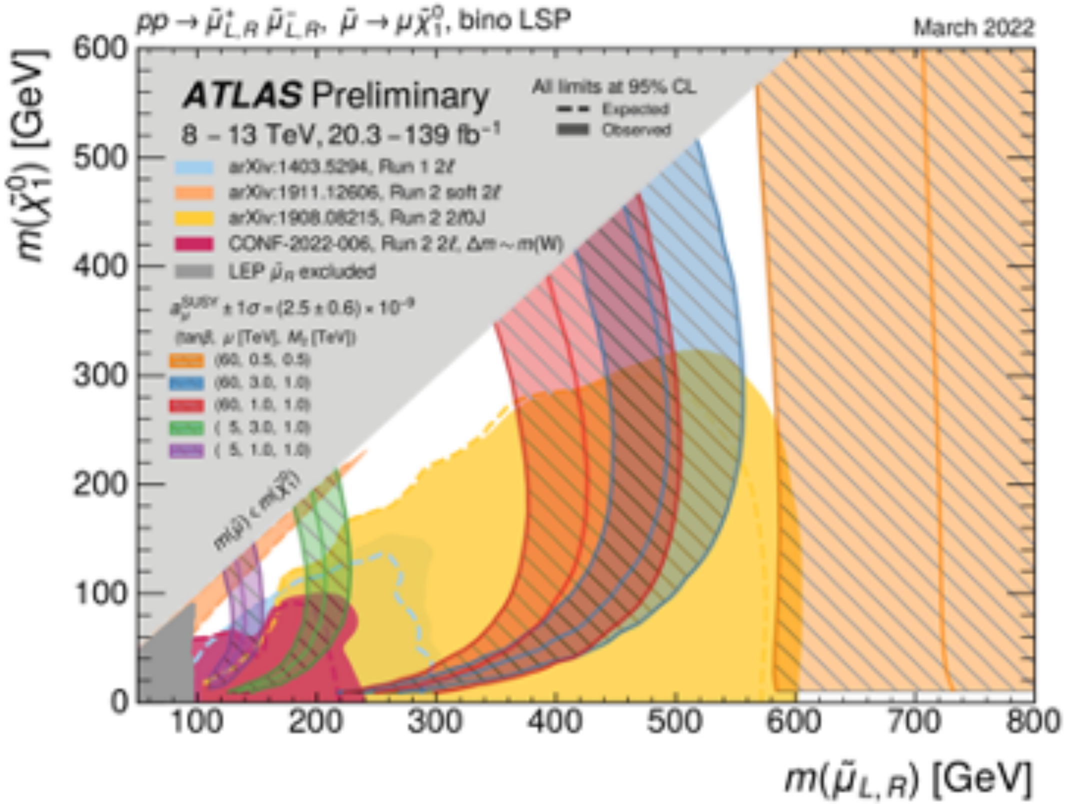
Interpretation Papers

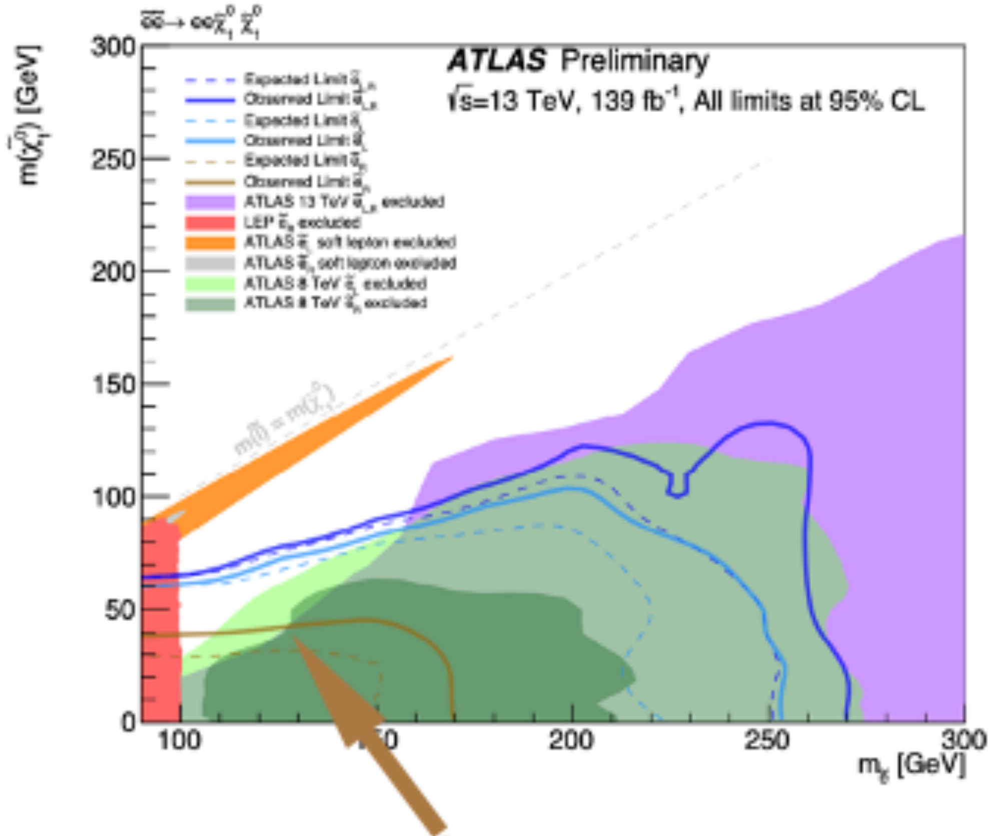
2104.05685	Vector LQ	B	Du	
5656	L_\mu - L_\tau	DM	Borah	
5006	B_q - L_\mu	B	Cen	Leptoquarks
4494	LFV	LFV	Li	
4503	Pseudoscalar	DM, H decays	Lu	Extra U(1)
4456	2HDM	DM	Arcadi	
3542	B-LSSM	H decays	Yang	Extra Higgs
3701	Leptophilic spin 0	H factory	Chun	
3839	SUSY	HL-LHC	Aboubrahim	Supersymmetry
3691	Survey	DM, LHC	Athron	
3705	Seesaw	g_e	Escribano	Axion
3699	Gauged 2HDM	B	Chen	
3239	SUSY	Gravitino DM	Gu	
3284	NMSSM	DM	Cao	
3262	GUT-constrained SUSY	DM, LHC	Wang	
3292	MSSM	CPV	Han	
3296	lepton mass matrix	Flavour	Calibbi	
3280	Z_d	Cs weak charge	Cadeddu	
3334	E_6 3-3-1	H stability	Li	
3242	\mu-\tau-philic H	\tau decays, LHC	Wang	
3259	Anomaly mediation	DM	Yin	
3245	pMSSM	DM, fine-tuning	Van Beekveld	
3274	NMSSM	DM, AMS-02 pbar	Abdughani	
3290	MSSM	DM	Cox	
3367	2HDM	V-like leptons	Ferreira	
3267	Axion	Low-scale	Buen-Abad	
3340	L_\mu - L_tau	AMS-02 positrons	Zu	
3282	ALP	V-like fermions	Brdar	
3301	Lepton portal	DM	Bai	
3276	Dark axion portal	Dark photon	Ge	
3491	GmSUGRA	LHC	Ahmed	
3227	2HDM	LHC	Han	
3302	SUSY	small \mu	Baum	
3238	Scalar	DM, p radius	Zhu	
3489	\mu \nu SSM	B, H decays	Zhang	
3287	pMSSM	ILC	Chakraborti	
3228	DM	B, H decays	Arcadi	

890	Radiative seesaw		Chiang
2103.13991	Scalar LQ	B, H decays	Greljo
2012.11766	DM		D'Agnolo
2012.07894	Axions		Darmé
1812.06851	Charmphilic LQ		Kowalska
2104.04458	GUT-constrained SUSY	DM	Chakraborti
5730	LQ + charged singlet	B, Cabibbo	Marzocca
6320	L-R symmetry		Boyarkin
6858	L_\mu - L_\tau	\nu masses	Zhou
6854	D-brane	U(1), Regge	Anchordoqui
6656	vector LQ	B	Ban
7597	SUSY	LHC, landscape	Baer
7047	3HDM	Fermion masses	Carcamo
7680	Leptophilic Z'	Global analysis	Buras
8289	Custodial symmetry	Light scalar + pseudoscalar	Balkin
9205	U(1)D	Neutrino mass	Dasgupta
8819	Lepton non-universality	Naturalness	Cacciapaglia
8640	2x2x1	Higgses, heavy nus	Boyarkina
8293	Multi-TeV sleptons in FSSM	Extended H, tau decays	Altmannshofer
10114	SO(10)	Yukawa unification	Aboubrahim
7681	U(1)B-L	DUNE	Dev
10324	Gauged lepton number	Dark matter	Ma
10175	2HDM	Lighter Higgs?	Jueid
11229	LQ	Matter unification	Fileviez
15136	U(1)	HE neutrinos, H tension	Alonso
2105.00903	Anomalous 3-boson vertex	W mass	Arbuzov
7655	U(1)T3R	RK(*)	Dutta
8670	Leptoquark	nu mass, LFV	Zhang

LHC vs Supersymmetry

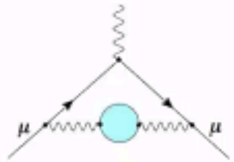
- LHC favours squarks & gluinos > 2 TeV (but loopholes)
- Does not exclude lighter electroweakly-interacting particles, e.g., sleptons



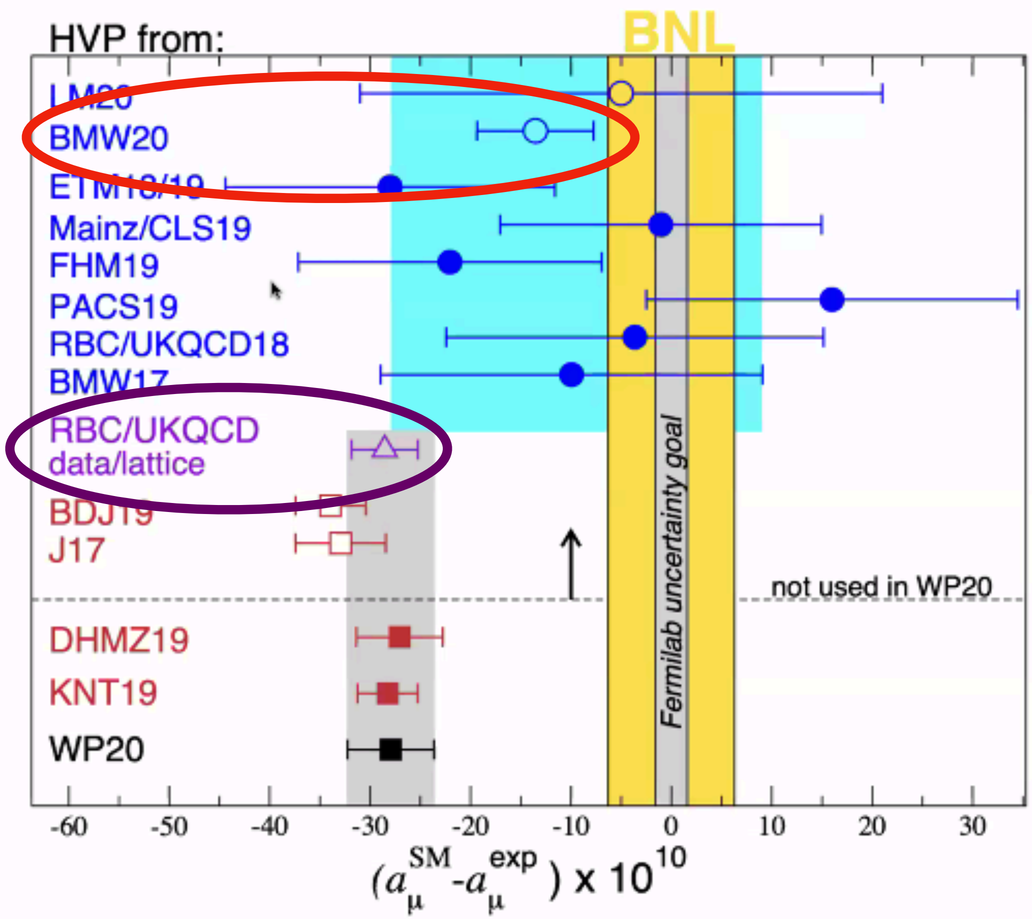


- Most models have $m_{\tilde{\mu}_L} > m_{\tilde{\mu}_R}$ but $m_{\tilde{\mu}_R} \simeq m_{\tilde{e}_R}$: **relevant constraint**

Comparison of Calculations of Hadronic Vacuum Polarization



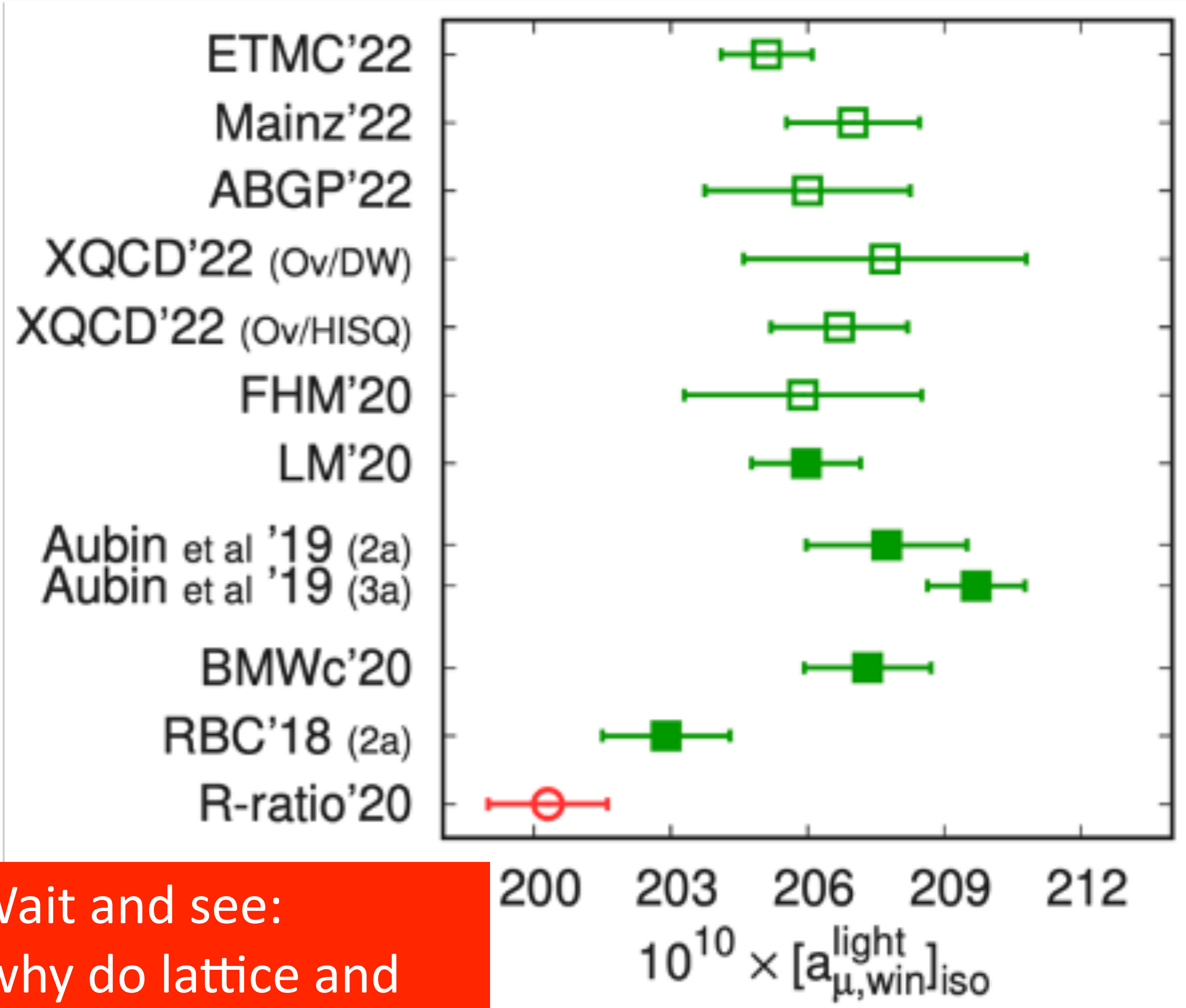
$$\boxed{a_\mu^{\rm HVP} + [a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm HLbL}]} \;\; a_\mu^{\rm SM}$$



Not such a big problem according to (some) lattice calculations

Aoyama et al, arXiv:2006.04822

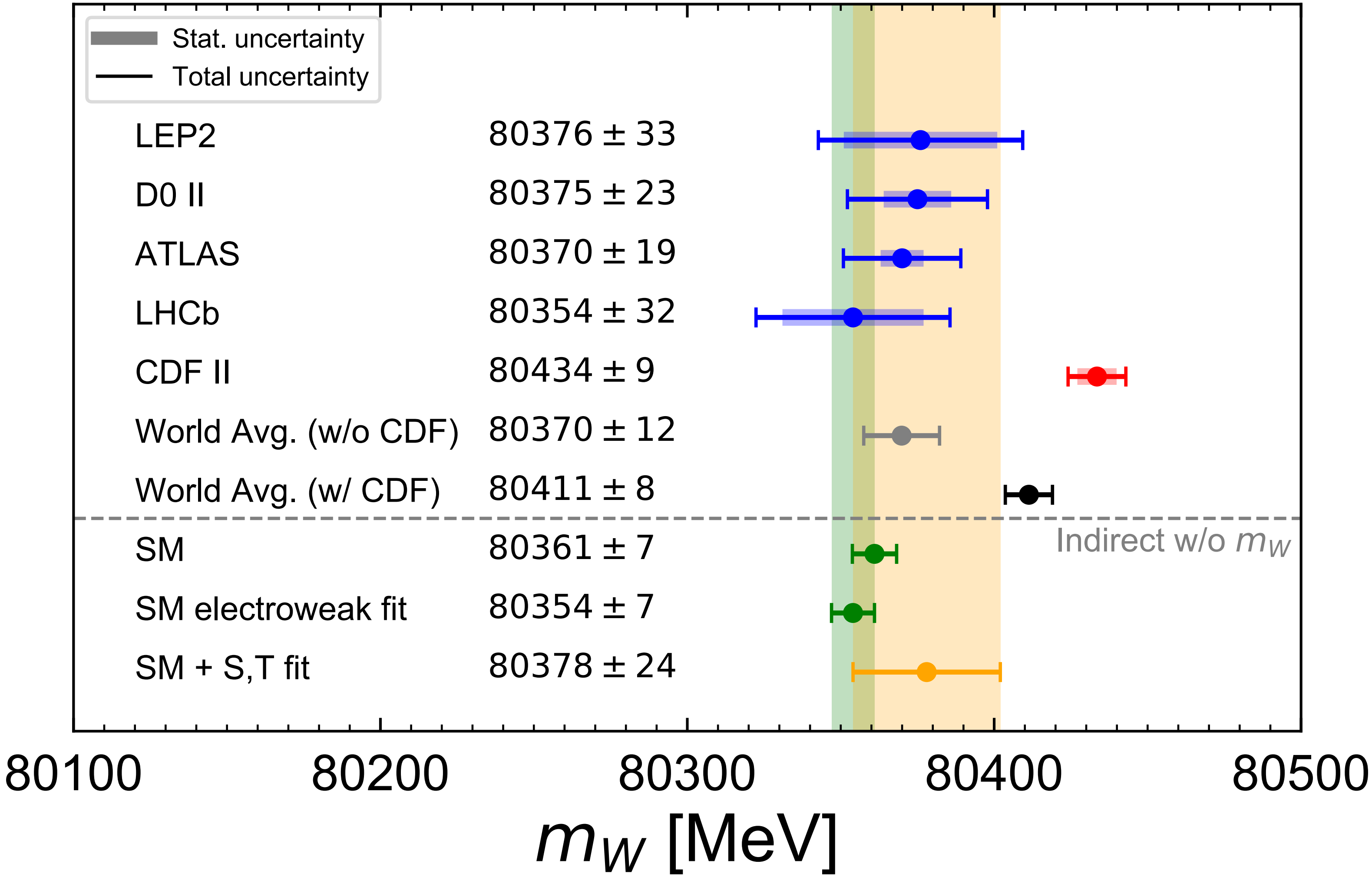
Update on Lattice Calculations



Wait and see:
How/why do lattice and
data-driven calculations differ?

CDF Measurement of m_W

compared with previous measurements



Tension: 7-σ discrepancy with Standard Model?

Theoretical Interpretations of W Mass

taking CDF measurement at face value

90 papers and counting!

Supersymmetry?

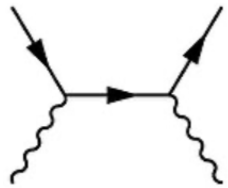
3667	DM	Zhu
3693	Inert H	Fan
3797	EWPO	Lu
3996	Relation to g-2	Athron
4183	Axion, chameleon	Yuan
4191	EWPO	Strumia
4202	SUSY	Yang
4204	EWPO	de Blas
4286	SUSY GMSB	Du
4356	SUSY NMSSM	Tang
4514	non-standard H	Cacciapaglia
4559	RH neutrinos	Blennow
4710	SUSY NMSSM	Cao
5031	Seesaw triplet	Cheng
5085	2HDM	Song
5260	SMEFT	Bagnaschi
5267	Custodial symm	Paul
5269	2HDM	Bahl
5283	S&T	Asadi
5284	Higgs physics	Di Luzio
5285	FlexibleSUSY	Athron
5296	S&T, SMEFT	Gu
5302	D3-Brane	Heckman
5303	2HDM	Babu
5728	2HDM	Heo
5760	Georgi-Machacek	Du
5942	Leptoquark	Cheung
5962	VL quarks	Crivellin
5965	Single-field	Endo
5975	2HDM + singlet	Biekötter
5992	SMEFT	Balkin
6327	Non-local SM	Krasnikov
6485	2HDM	Ahn
6505	2HDM	Han
6541	RPV MSSM	Zheng
7022	Lepton portal DM	kawamura
7144	Triplet H	Fileviez

7970	GUT, finite group	Wilson
8067	Extra U(1)	Zhang
8266	Seesaw	Borah
8390	Zee model	Chowdhury
8406	2HDM	Arcadi
8440	Beta decay	Cirigliano
8546	Oblique	Carpenter
8568	Seesaw	Popov
9001	2HDM	Ghorbani
9029	Stueckelberg	Du
9031	Leptoquarks	Bhaskar
9376	Triplet	Batra
9477	VLQ	Cao
9487	Extra U(1)	Zeng
9585	Extra U(1)	Baek
9671	DM fermions	Borah
10130	SMEFT	da Silva
10156	Dark photon	Cheng
10274	Triplet seesaw	Heeck
10375	FOPT triplet	Addazi
10338	2HDM	Lee
11570	Extra U(1)	Cai
11755	2HDM	Benbrik
11871	nu-lepton collider	Yang
11945	Scotogenic DM	Batra
11991	Atomic PV	Tran Tan
12018	2HDM	Abouabid
12453	Colour-octet	Gisbert
12898	Georgi-Machacek	Chen
13027	Extra U(1)	Zhou
13690	RG running	Gupta
5.00758	Flipped SU(5)	Basiouris
783	DM	Wang

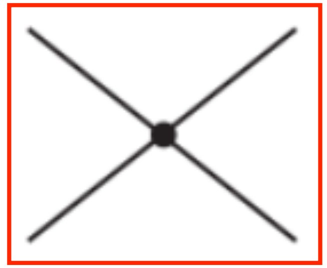
1115	2HDM	Botella
1437	2HDM	Kim
1699	Braneworld	Barman
1701	2HDM	Kim
1911	Dark photon	Thomas
2088	Leptoquark+VLQ	He
2205	bs anomalies	Li
2217	DM + g-2	Dcruz
2788	ResBos2	Isaacson
3877	GUT triplet	Evans
3917	VLQ	Chowdhury
3942	PDFs	Gao
4016	Lepton portal	Kim
4473	LLP	Giudice
4824	SO(10) axion	Lazarides
5022	SU(5)	Senjanovic
5041	Triplet	Ghosh
5610	Coloured scalars	Miralles
8215	SESM	Li
9109	SUSY 331	Rodriguez

Effective Field Theories (EFTs)
a long and glorious History

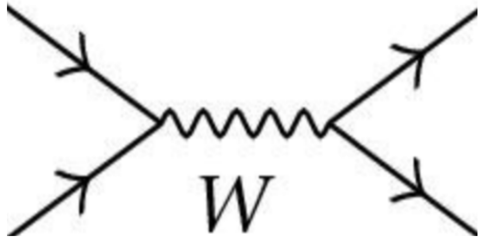
- 1930's: "Standard Model" of QED had d=4



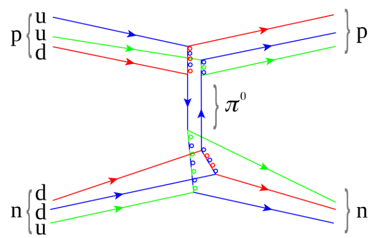
- **Fermi's four-fermion theory of the weak force**



- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?

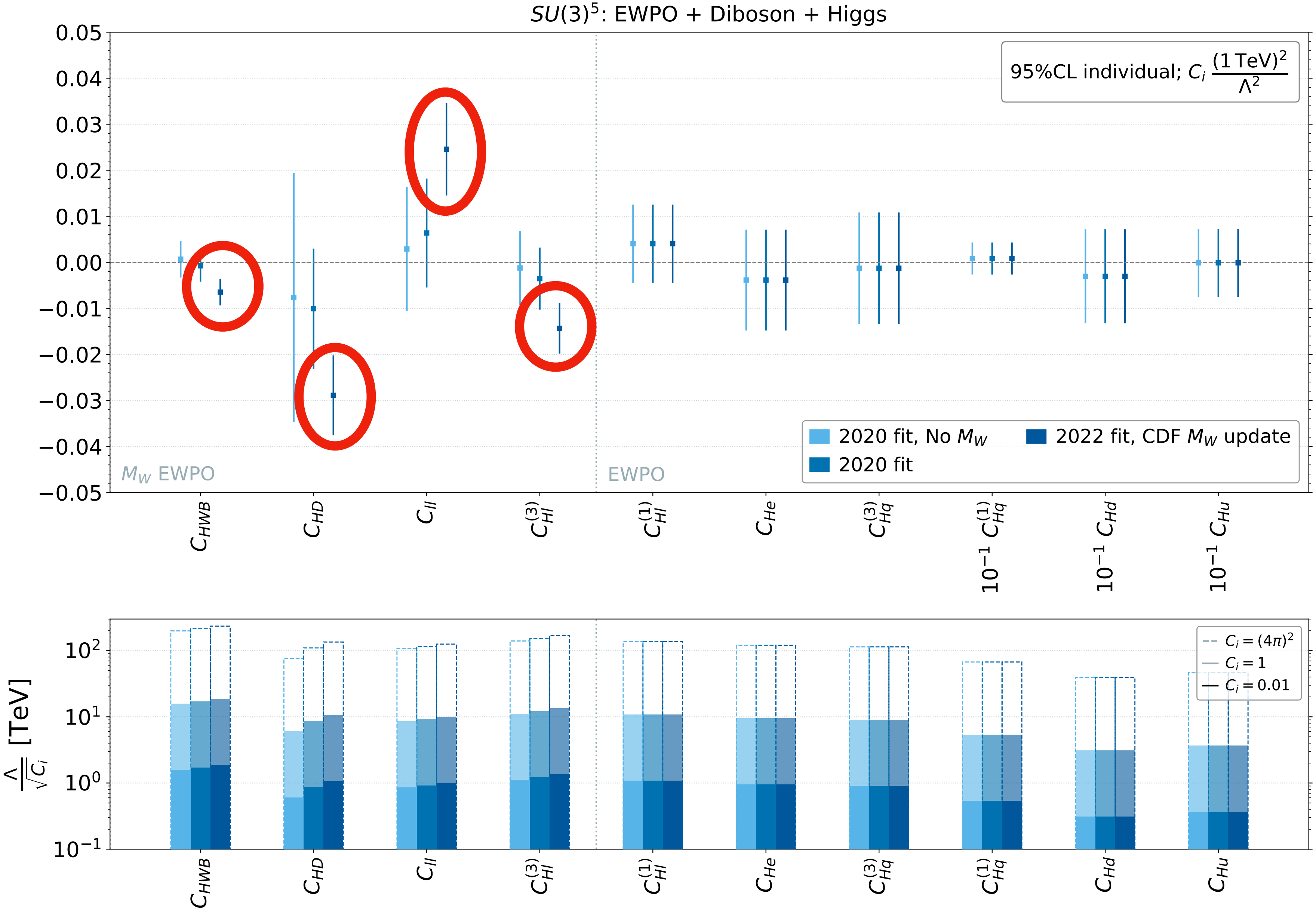


- V-A ➔ massive vector bosons ➔ gauge theory
- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? ➔ pions



- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue ➔ QCD

SMEFT Fits with the Mass of the W Boson



Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Extensions of the Standard Model

Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Single-Field Models that can Contribute to W Mass

Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\square}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		X							
Σ			X	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	X					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

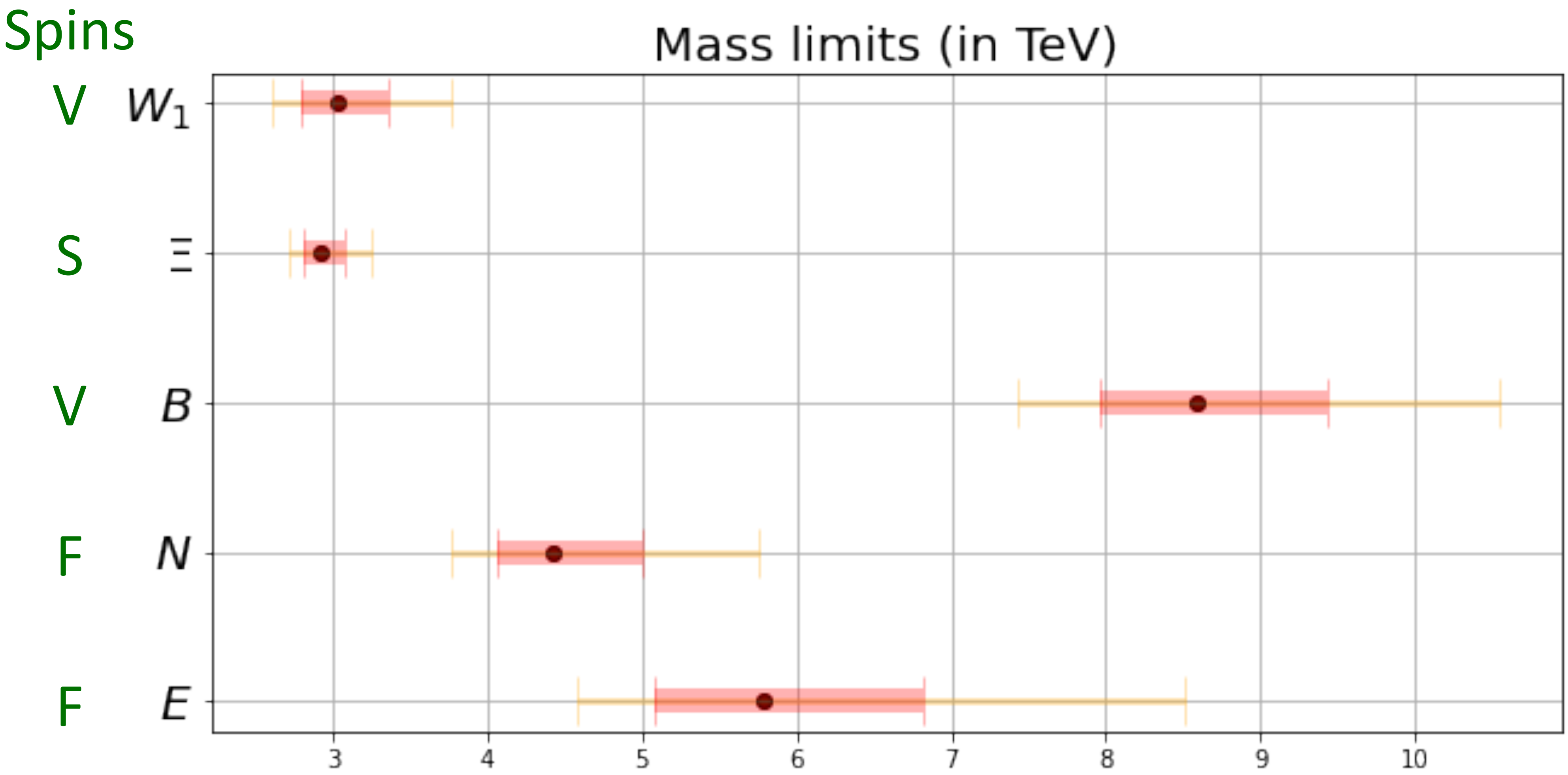
Wrong sign

Right sign

Operators contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

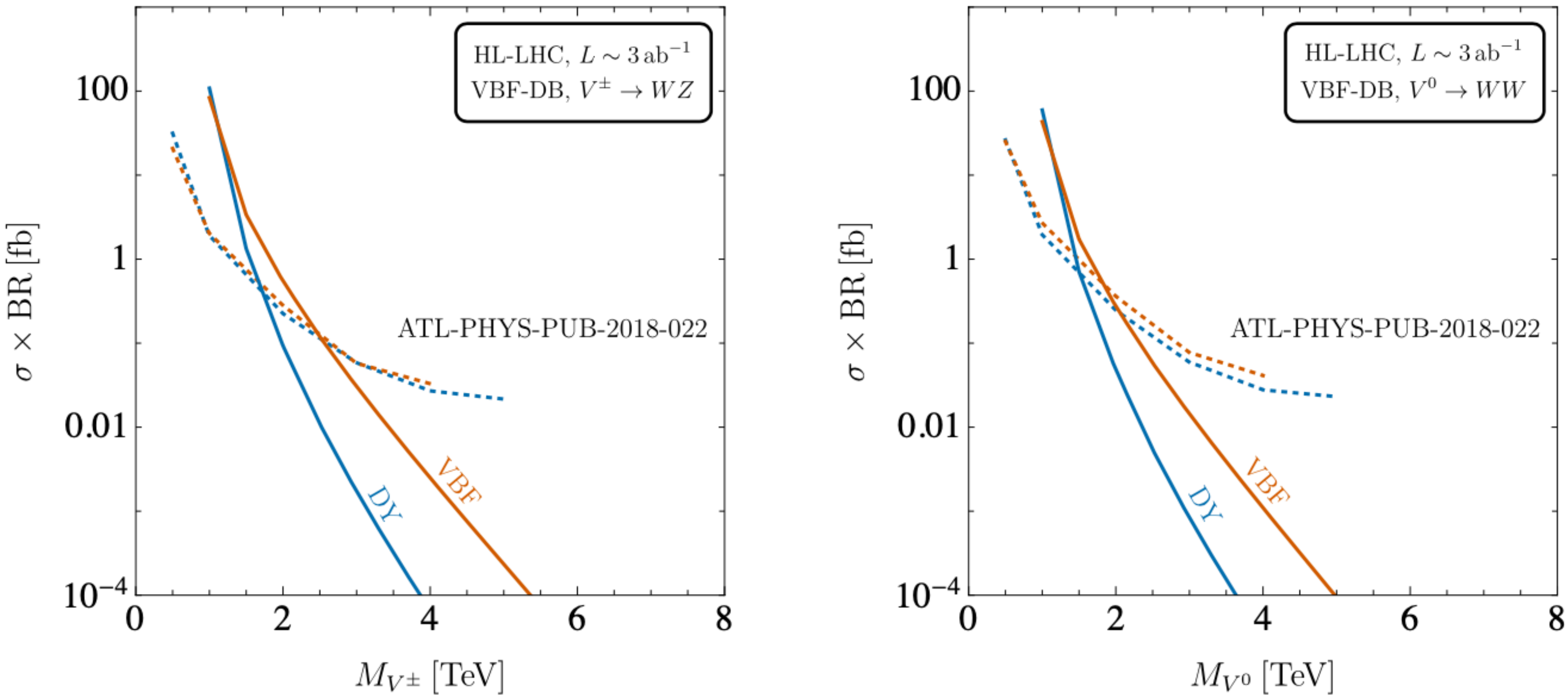
Models Fitting the Mass of the W Boson



68 and 95% CL ranges of masses assuming unit couplings

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

HL-LHC Search for Triplet Vector Boson

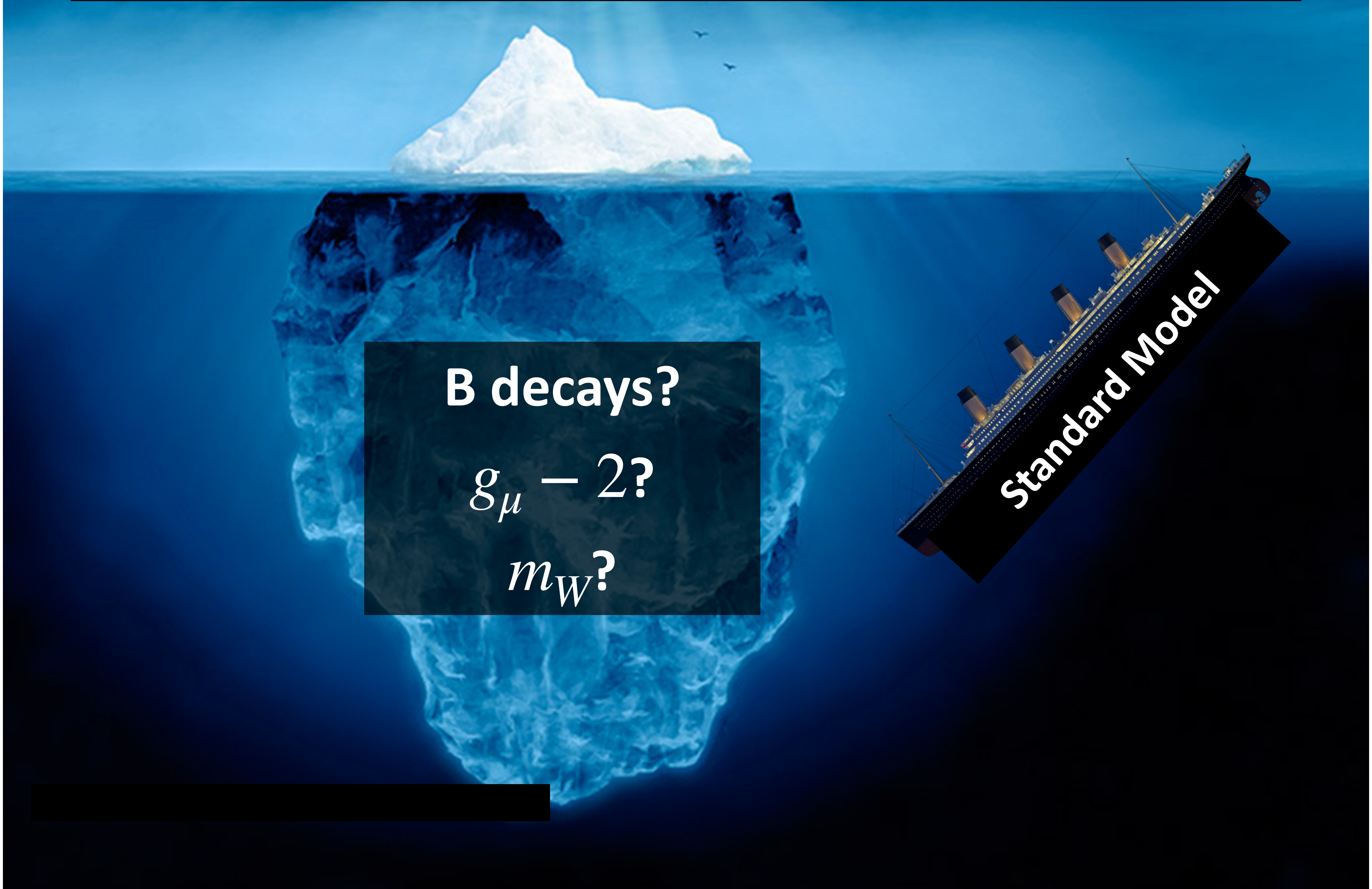


Wait and see:
Will LHC experiments confirm CDF?

Could be discovered with future LHC data

Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

Summary



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