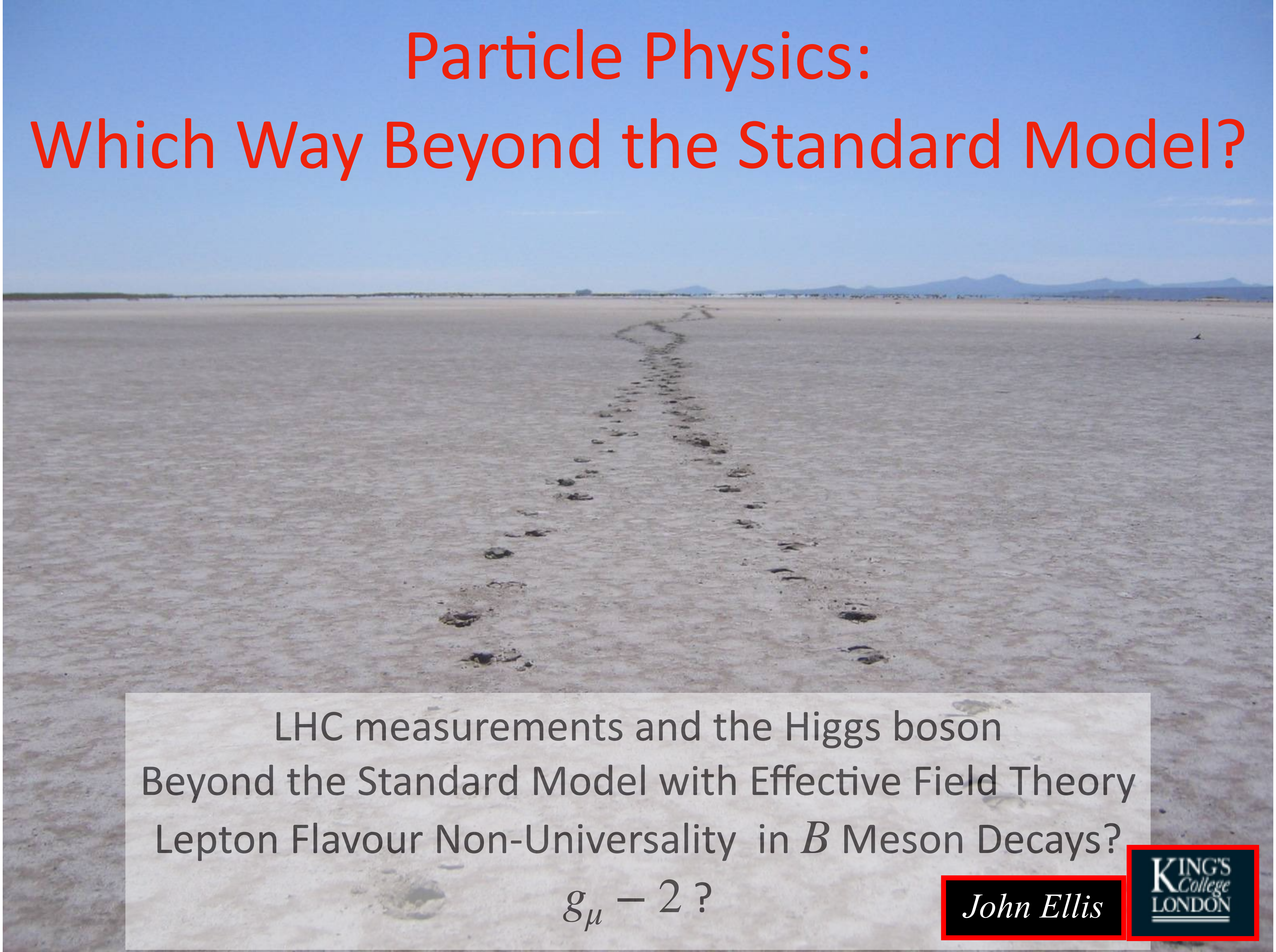
Particle Physics:
Which Way Beyond the Standard Model?



LHC measurements and the Higgs boson

Beyond the Standard Model with Effective Field Theory

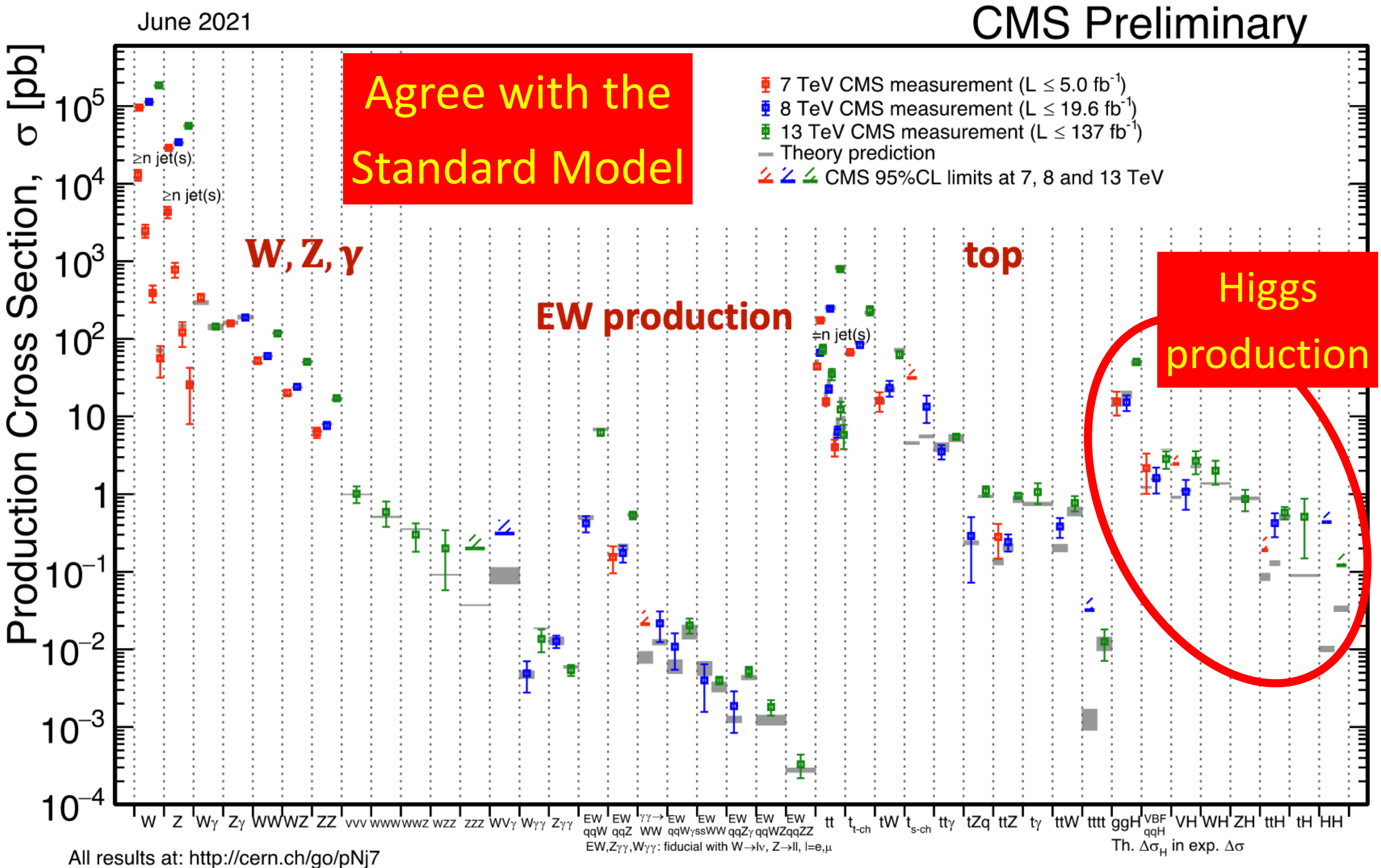
Lepton Flavour Non-Universality in B Meson Decays?

$g_\mu - 2$?

John Ellis

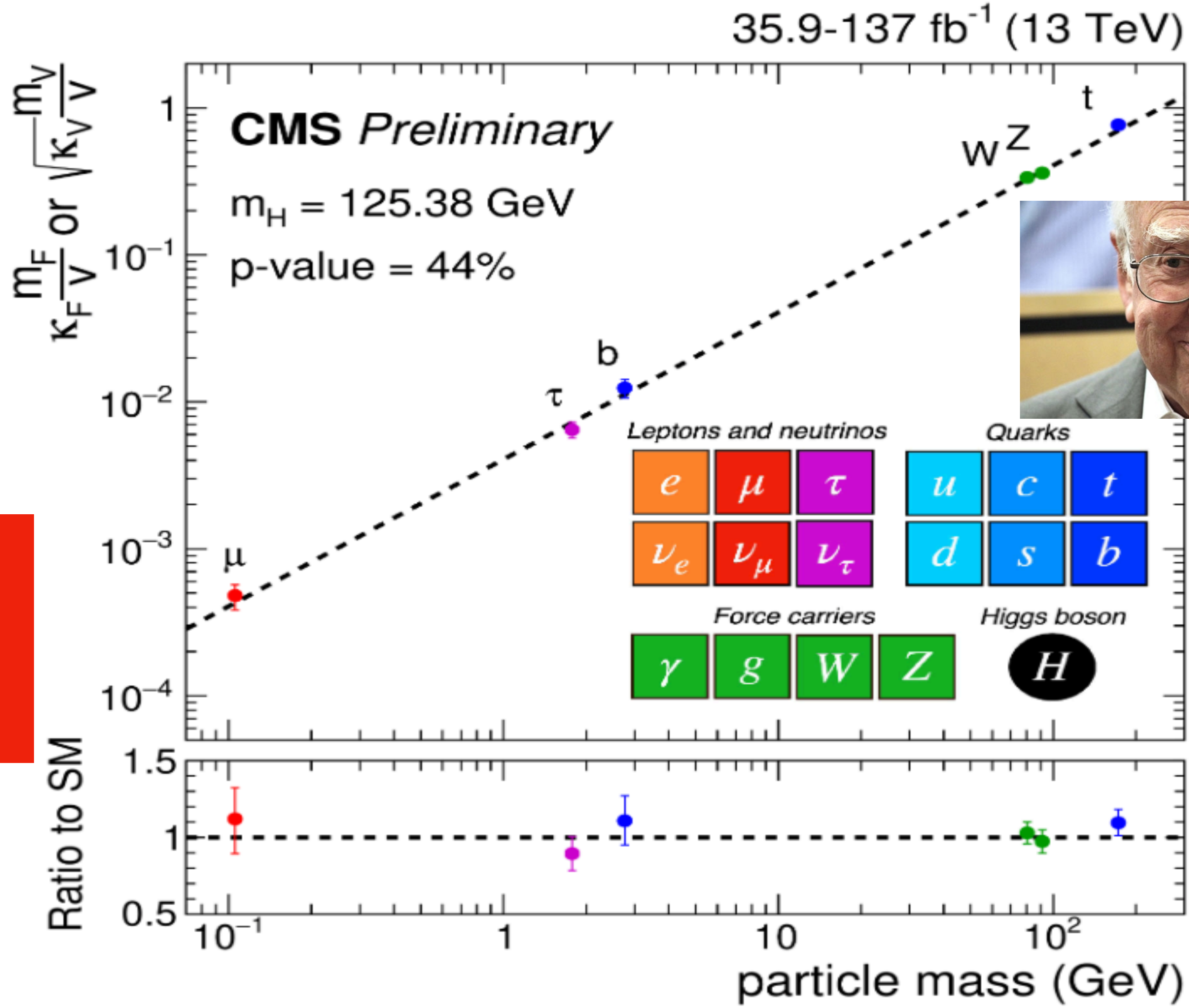
King's College London

LHC Measurements

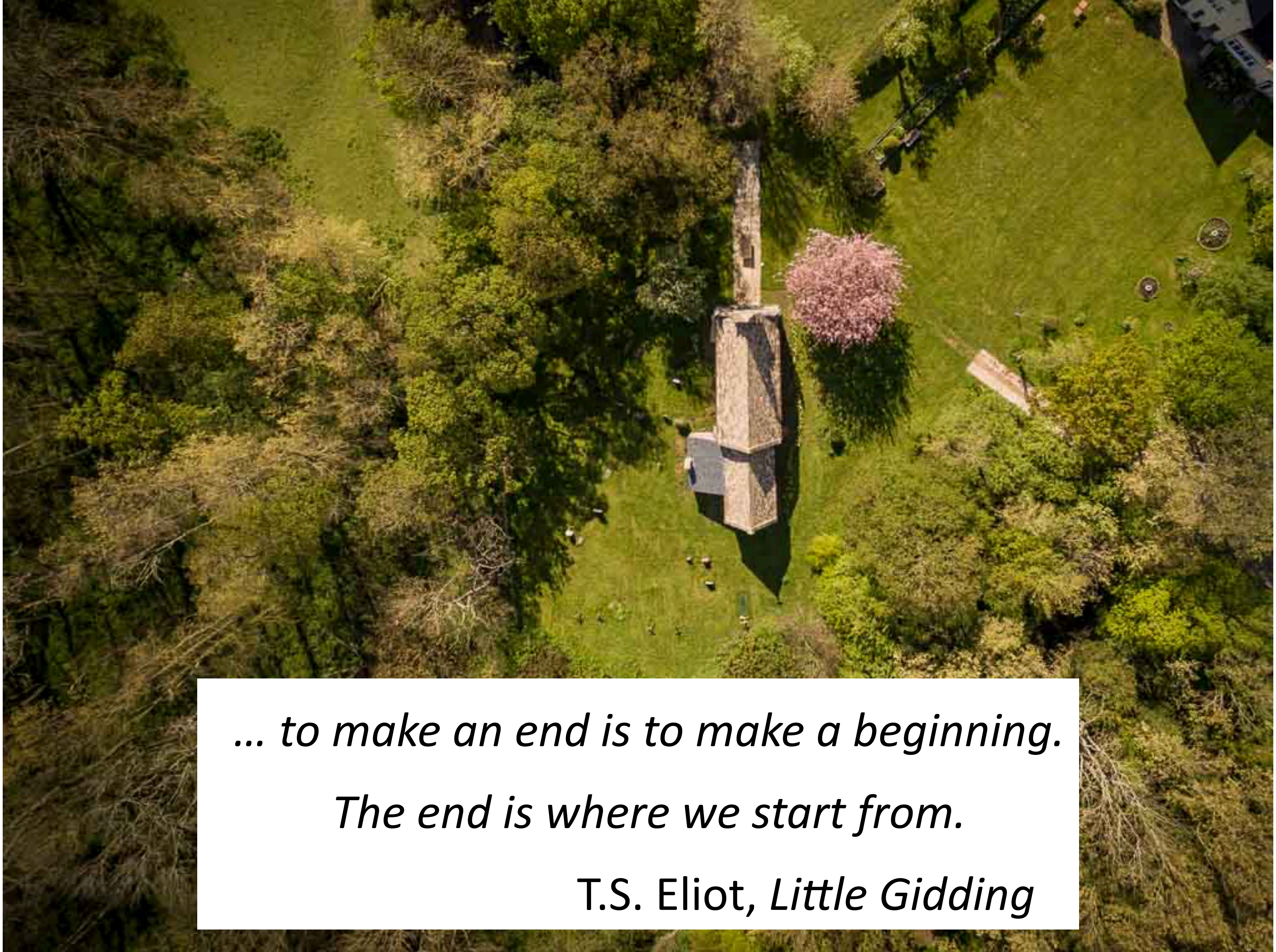


It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?



Global fit



… to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*

Everything about Higgs is Puzzling

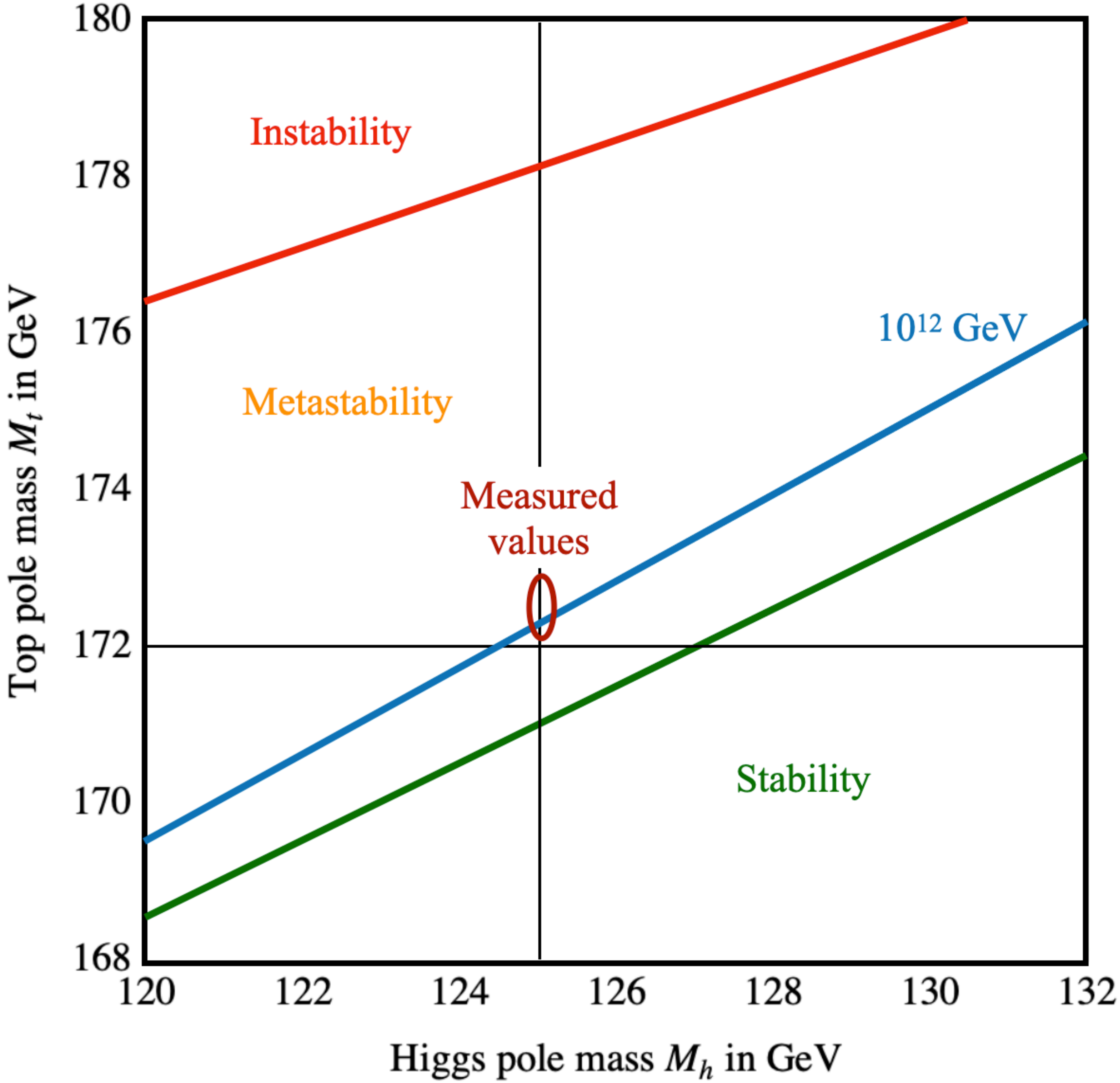
$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 \quad + \ldots$$

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

Higher-dimensional interactions?

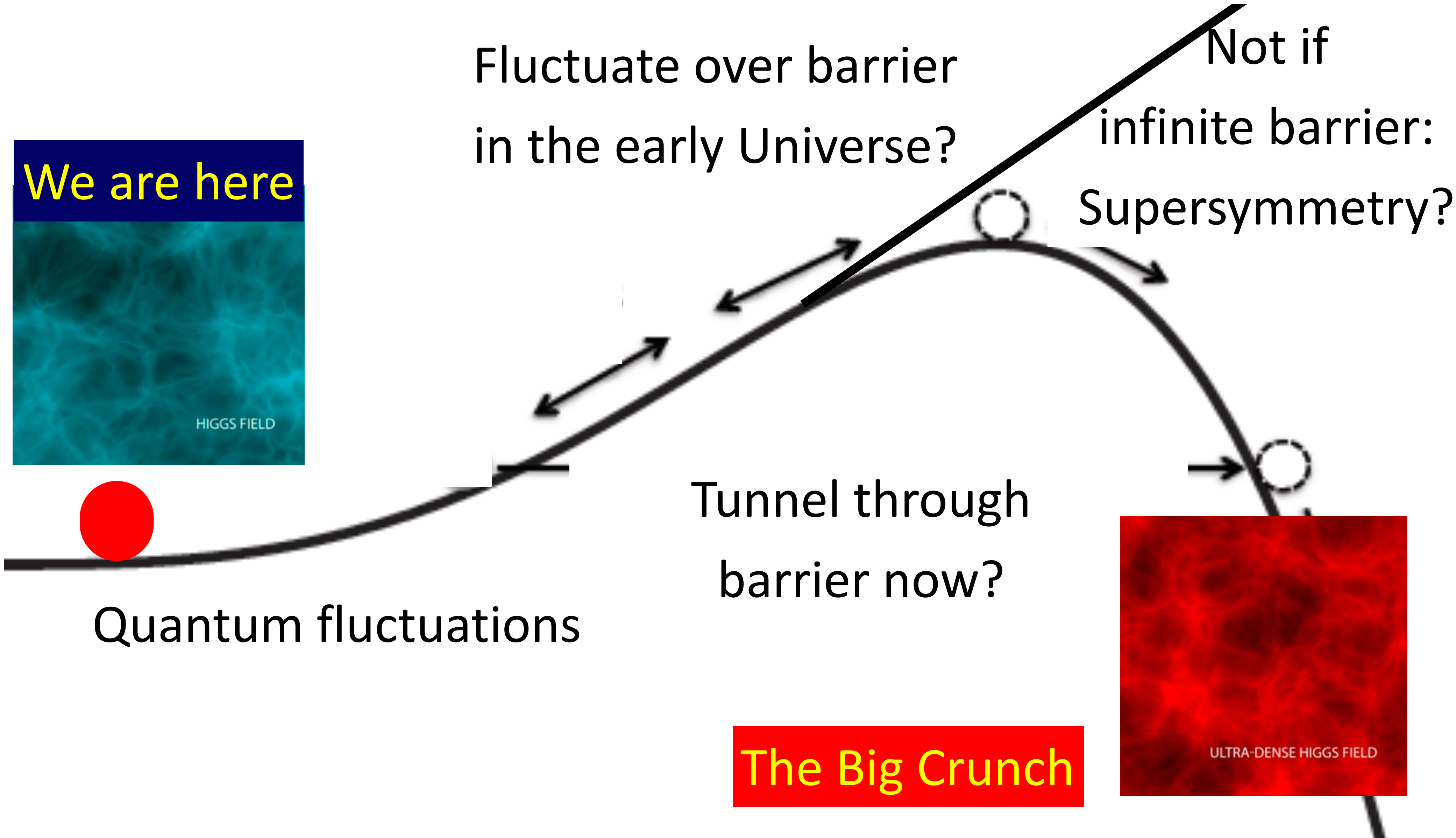
Is “Empty Space” Unstable?

Depends on masses of Higgs boson and top quark



Will the Universe Collapse?

Should it have Collapsed already?



Is “Empty Space” Unstable?

- Dependence of instability scale on masses of Higgs boson and top quark, and strong coupling:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.5 - 1.3\left(\frac{m_t}{\mathrm{GeV}} - 172.6\right) + 1.1\left(\frac{m_H}{\mathrm{GeV}} - 125.1)\right) + 0.6\left(\frac{\alpha_s(m_Z) - 0.1179}{0.0009}\right)$$

Buttazzo et al, arXiv:1307.3536; Franceschini et al, 2203.17197

- New CMS value of m_t : CMS Collaboration, April 2022

$$m_t = 171.77 \pm 0.38\,\mathrm{GeV}$$

- Particle Data Group values:

$$m_H = 125.25 \pm 0.17\,\mathrm{GeV}, \quad \alpha_s(m_Z) = 0.1179 \pm 0.0009$$

- Instability scale:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

Looking Beyond the Standard Model with the SMEFT

"...the direct method may be used...but indirect methods will be needed in order to secure victory...."

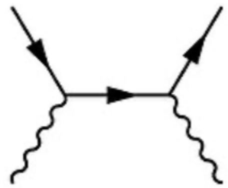
"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."

Who can exhaust the possibilities of their combination?"

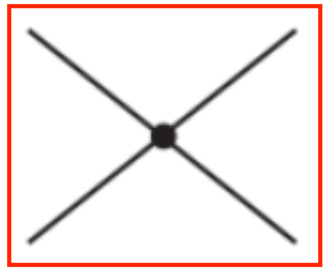
Sun Tzu

Effective Field Theories (EFTs)
a long glorious History

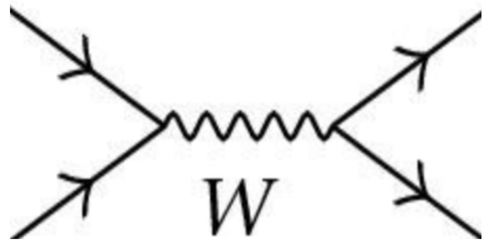
- 1930's: "Standard Model" of QED had d=4



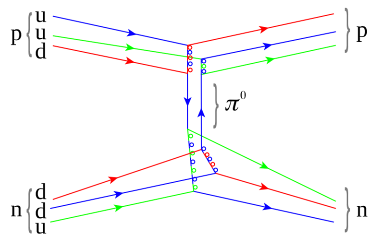
- **Fermi's four-fermion theory of the weak force**



- 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: (∂π∂π)ππ clue ➔ QCD

Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

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

Summary of Analysis Framework

- Include all leading dimension-6 operators?

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate $SU(3)^5$ symmetry
- Important when including top observables

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Anomalous magnetic moments

Flavour anomalies

Baryon decay

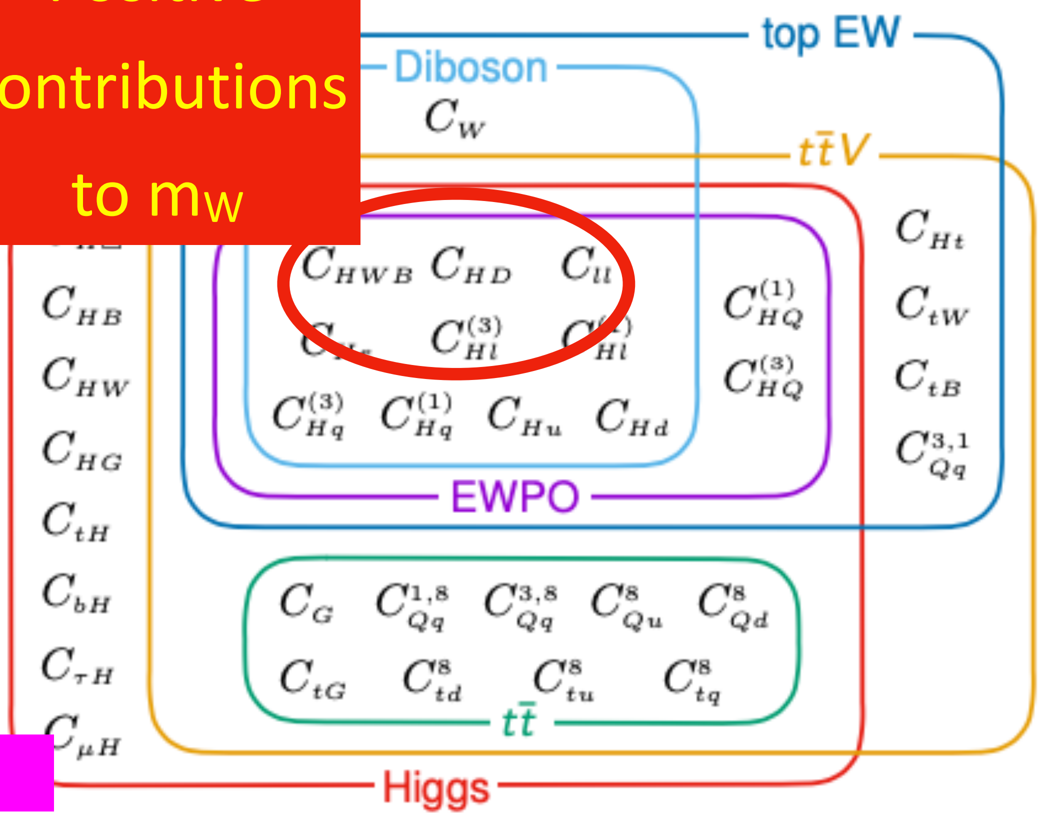
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

Positive contributions to m_W



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

Operators included in Global Fit

- 20 operators in flavour-universal $SU(3)^5$ fit

$$\text{EWPO:}\quad \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$$
$$\text{Bosonic:}\quad \mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}$$
$$\text{Yukawa:}\quad \mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.$$

Positive contributions to m_W

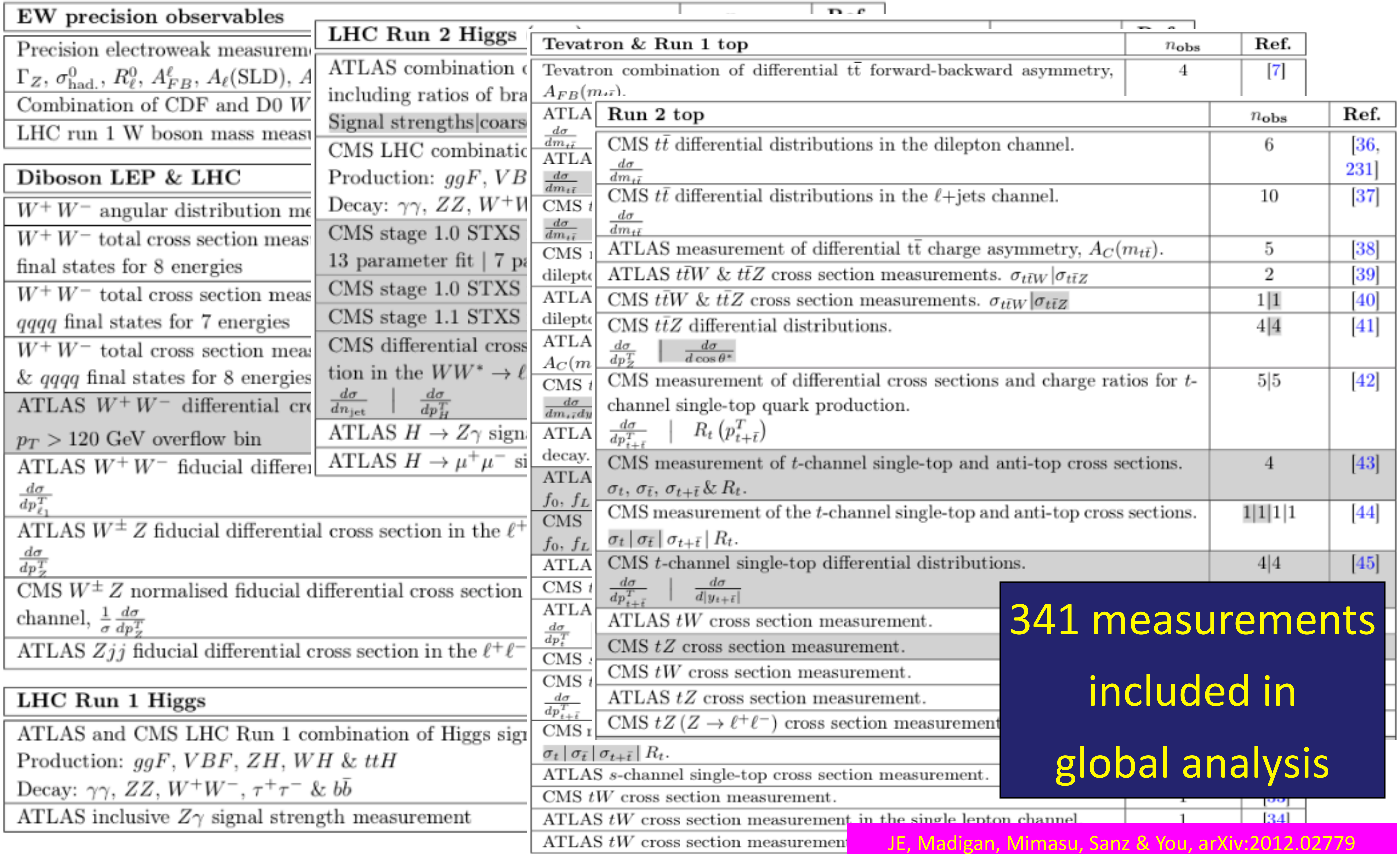
Indicating which sectors constrain which operators

- 34 operators in top-specific $SU(2)^2 \times SU(3)$ fit

$$\text{EWPO:}\quad \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$$
$$\text{Bosonic:}\quad \mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$$
$$\text{Yukawa:}\quad \mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,$$
$$\text{Top 2F:}\quad \mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$$
$$\text{Top 4F:}\quad \mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,. \qquad (2.12)$$

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

Data included in Global Fit



Run 2 top	n_{obs}	Ref.
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 231]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \| \sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \| \sigma_{t\bar{t}Z}$	1|1	[40]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp_Z^T}$ | $\frac{d\sigma}{d\cos\theta^*}$	4|4	[41]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $R_t\,(p^T_{t+\bar{t}})$	5|5	[42]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & R_t.	4	[43]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \| \sigma_{\bar{t}} \| \sigma_{t+\bar{t}} \| R_t$.	1|1|1|1	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $\frac{d\sigma}{d\|y_{t+\bar{t}}\|}$	4|4	[45]
ATLAS tW cross section measurement.		
CMS tZ cross section measurement.		
CMS tW cross section measurement.		
ATLAS tZ cross section measurement.		
CMS $tZ\,(Z \to \ell^+\ell^-)$ cross section measurement		

Tevatron & Run 1 top	n_{obs}	Ref.
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]
ATLAS s-channel single-top cross section measurement.		
CMS tW cross section measurement.		
ATLAS tW cross section measurement in the single lepton channel	1	[34]
ATLAS tW cross section measurement		

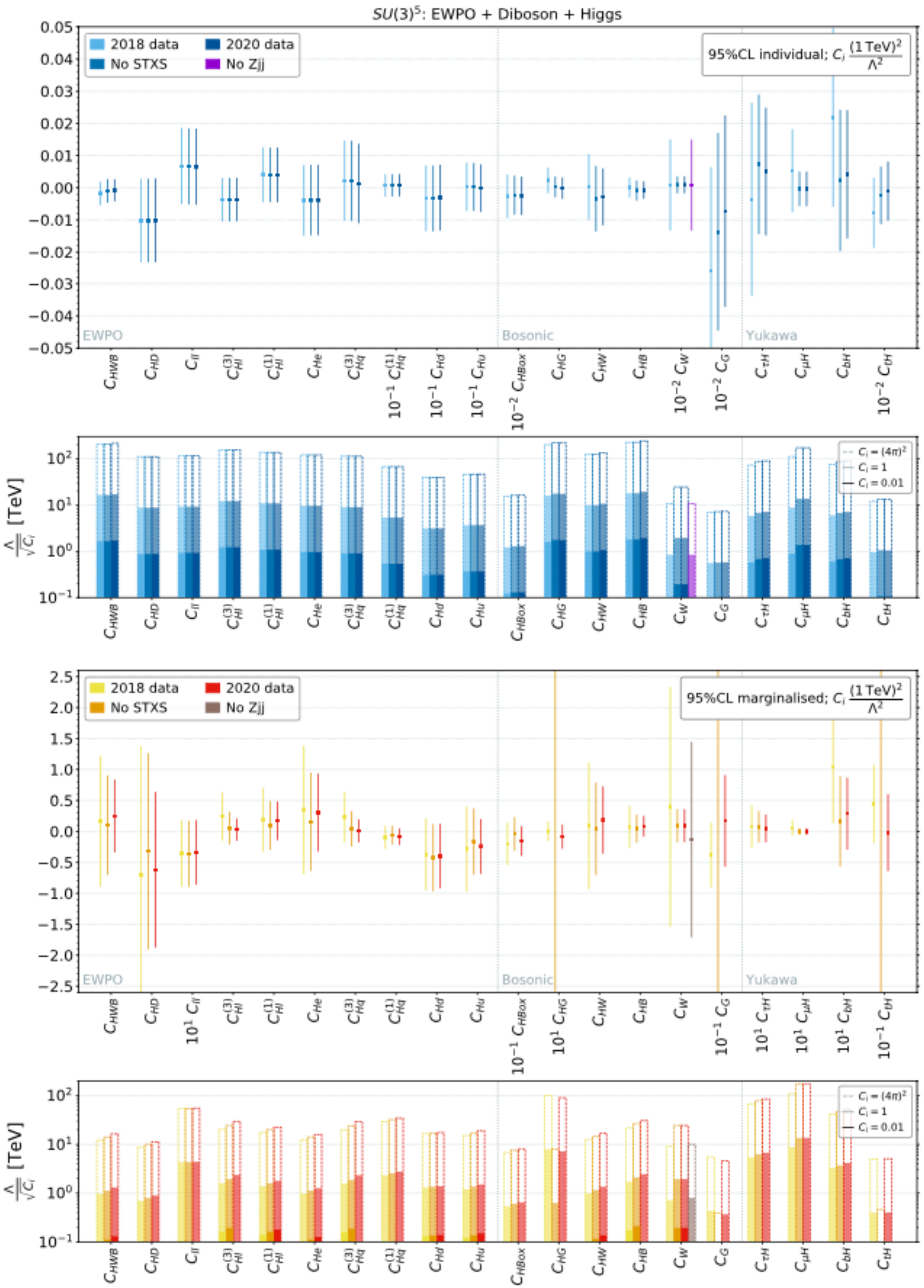
LHC Run 1 Higgs
ATLAS and CMS LHC Run 1 combination of Higgs sig… Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$
ATLAS inclusive $Z\gamma$ signal strength measurement

341 measurements included in global analysis

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

Dimension-6 Constraints with Flavour-Universal $SU(3)^5$ Symmetry

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



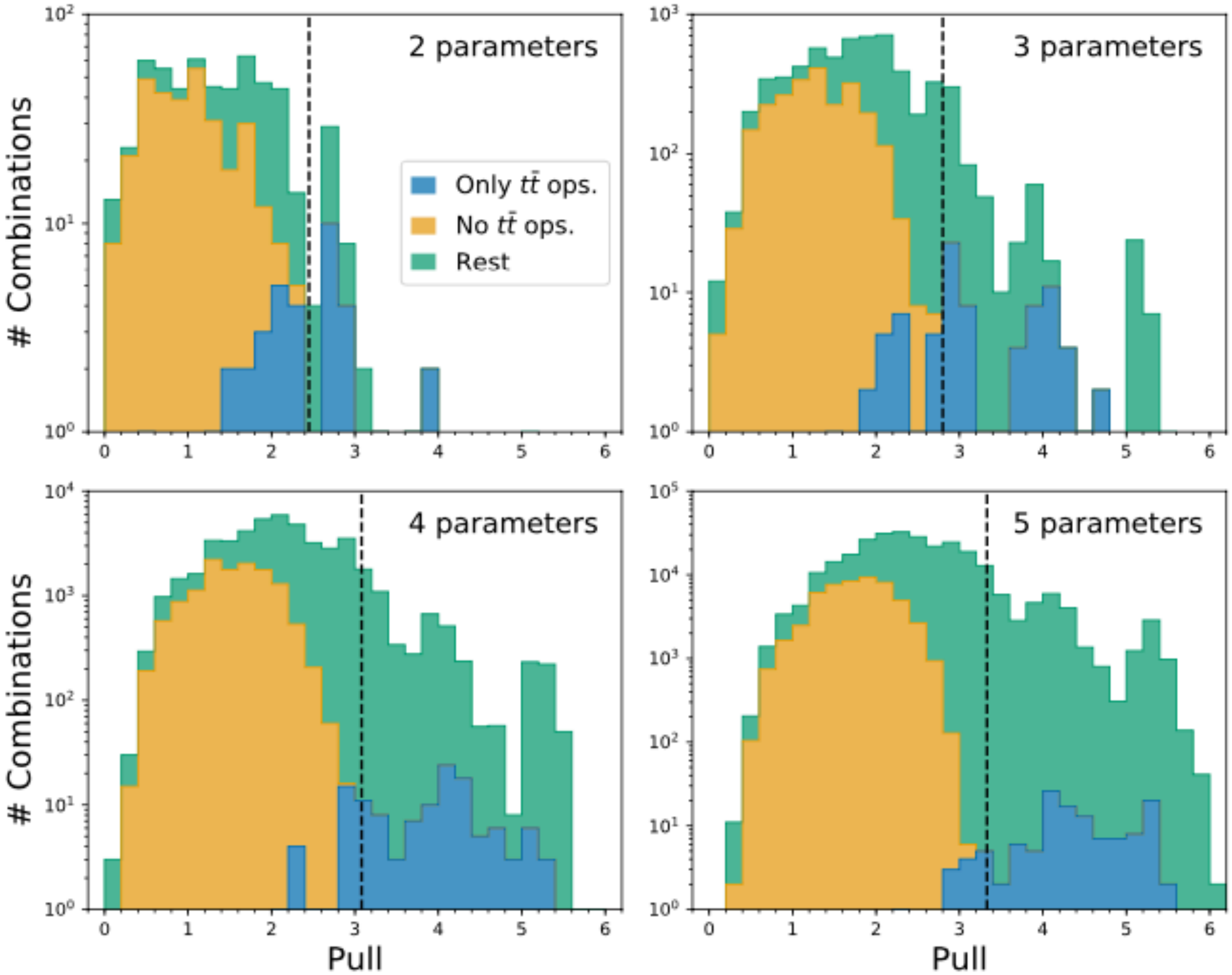
No significant deviations from SM

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

Model-Independent BSM Survey

Switch on random subsets of 2, 3, 4 or 5 operators

- Top-less sector fits SM very well
- Top sector does not fit so well
- Mixed set intermediate
- Overall, pulls not excessive
- No hint of BSM



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

CDF Collaboration, Science 376 (2022) p170

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6], A. Annovi[7], J. Antos[8,9], G. Apollinari[6], J. A. Appel[6], T. Arisawa[10], A. Artikov[11], J. Asaadi[12], W. Ashmanskas[6], B. Auerbach[13], A. Aurisano[12], F. Azfar[14], W. Badgett[6], T. Bae[15,16,17,18,19,20,21], A. Barbaro-Galtieri[22], V. E. Barnes[23], B. A. Barnett[24], P. Barria[25,26], P. Bartos[8,9], M. Bauce[3,4], F. Bedeschi[25], S. Behari[6], G. Bellettini[25,27], J. Bellinger[28], D. Benjamin[29], A. Beretvas[6], A. Bhatti[30], K. R. Bland[31], B. Blumenfeld[24], A. Bocci[29], A. Bodek[32], D. Bortoletto[23], J. Boudreau[33], A. Boveia[34], L. Brigliadori[35,36], C. Bromberg[37], E. Brucken[1,2], J. Budagov[11]§, H. S. Budd[32], K. Burkett[6], G. Busetto[3,4], P. Bussey[38], P. Butti[25,27], A. Buzatu[38], A. Calamba[39], S. Camarda[40], M. Campanelli[41], B. Carls[42], D. Carlsmith[28], R. Carosi[25], S. Carrillo[43]§, B. Casal[44], M. Casarsa[45], A. Castro[35,36], P. Catastini[46], D. Cauz[45,47,48], V. Cavaliere[42], A. Cerri[22], L. Cerrito[41], Y. C. Chen[49], M. Chertok[50], G. Chiarelli[25], G. Chlachidze[6], K. Cho[15,16,17,18,19,20,21], D. Chokheli[11], A. Clark[51], C. Clarke[52], M. E. Convery[6], J. Conway[50], M. Corbo[6], M. Cordelli[7], C. A. Cox[50], D. J. Cox[50], M. Cremonesi[25], D. Cruz[12], J. Cuevas[44], R. Culbertson[6], N. d'Ascenzo[6], M. Datta[6], P. de Barbaro[32], L. Demortier[30], M. Deninno[35]§, M. D'Errico[3,4], F. Devoto[1,2], A. Di Canto[25,27], B. Di Ruzza[6], J. R. Dittmann[31], S. Donati[25,27], M. D'Onofrio[53], M. Dorigo[45,54], A. Driutti[45,47,48], K. Ebina[10], R. Edgar[5], A. Elagin[34], R. Erbacher[50], S. Errede[42], B. Esham[42], S. Farrington[14], J. P. Fernández Ramos[55], R. Field[43], G. Flanagan[6], R. Forrest[50], M. Franklin[46], J. C. Freeman[6], H. Frisch[34], Y. Funakoshi[10], C. Galloni[25,27], A. F. Garfinkel[23], P. Garosi[25,26], H. Gerberich[42], E. Gerchtein[6], S. Giagu[56], V. 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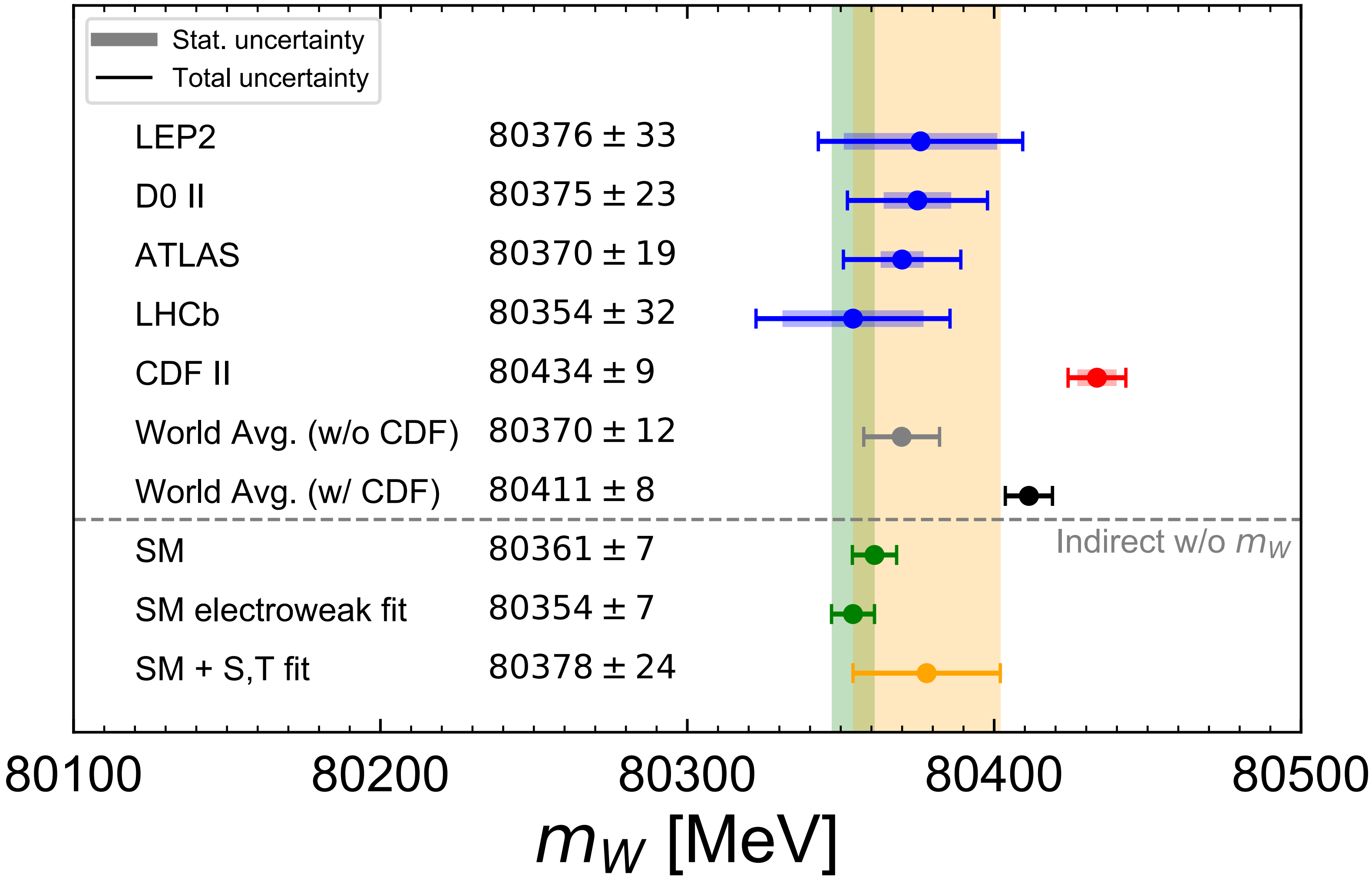
CDF Measurement of m_W

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!

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

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

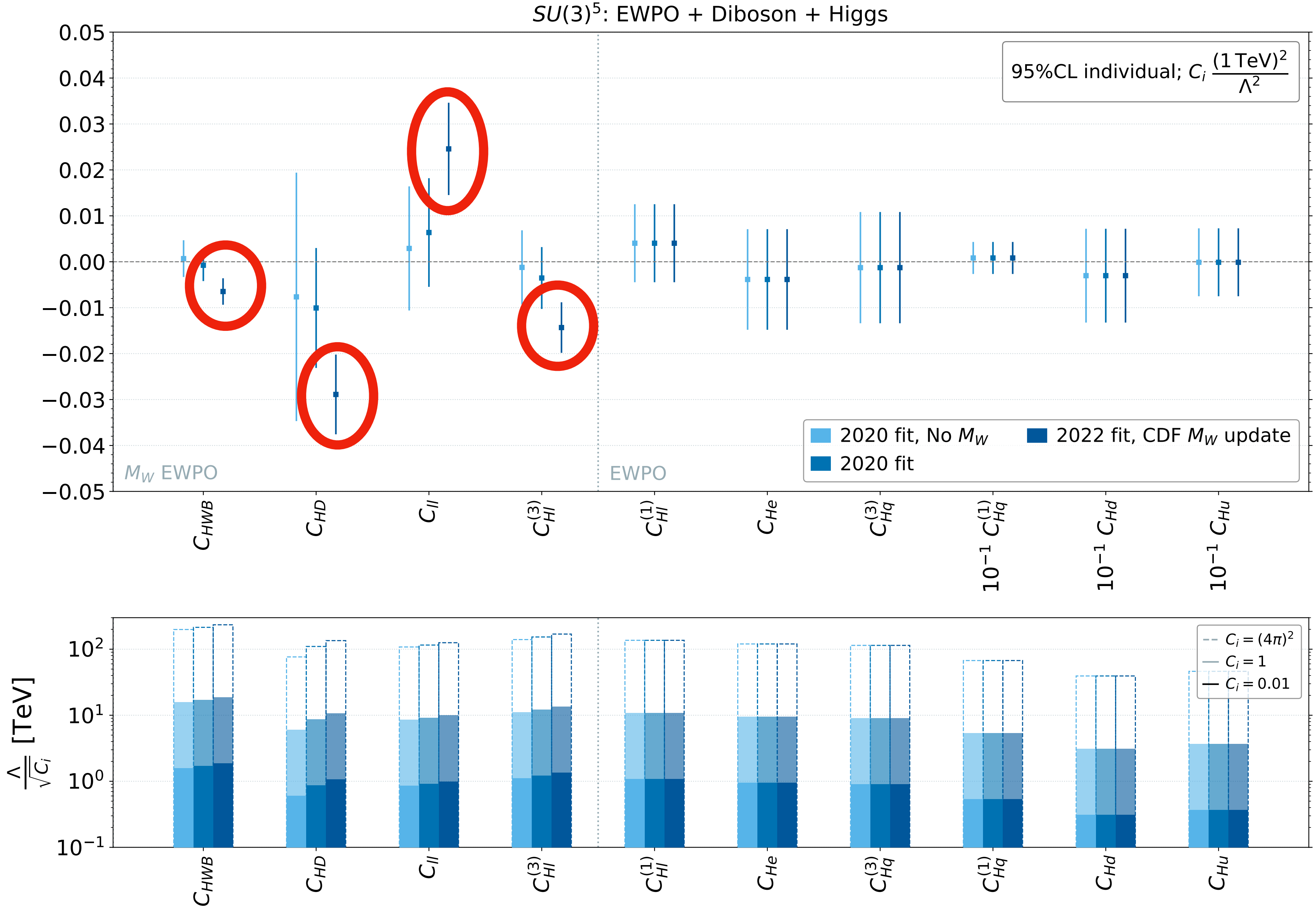
- Contributions to W mass

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w} C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C^{(3)}_{Hl} - 2C_{ll}\right) + 4C_{HWB}\right)$$

- Contributions to *S* and *T* oblique parameters

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S \quad , \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

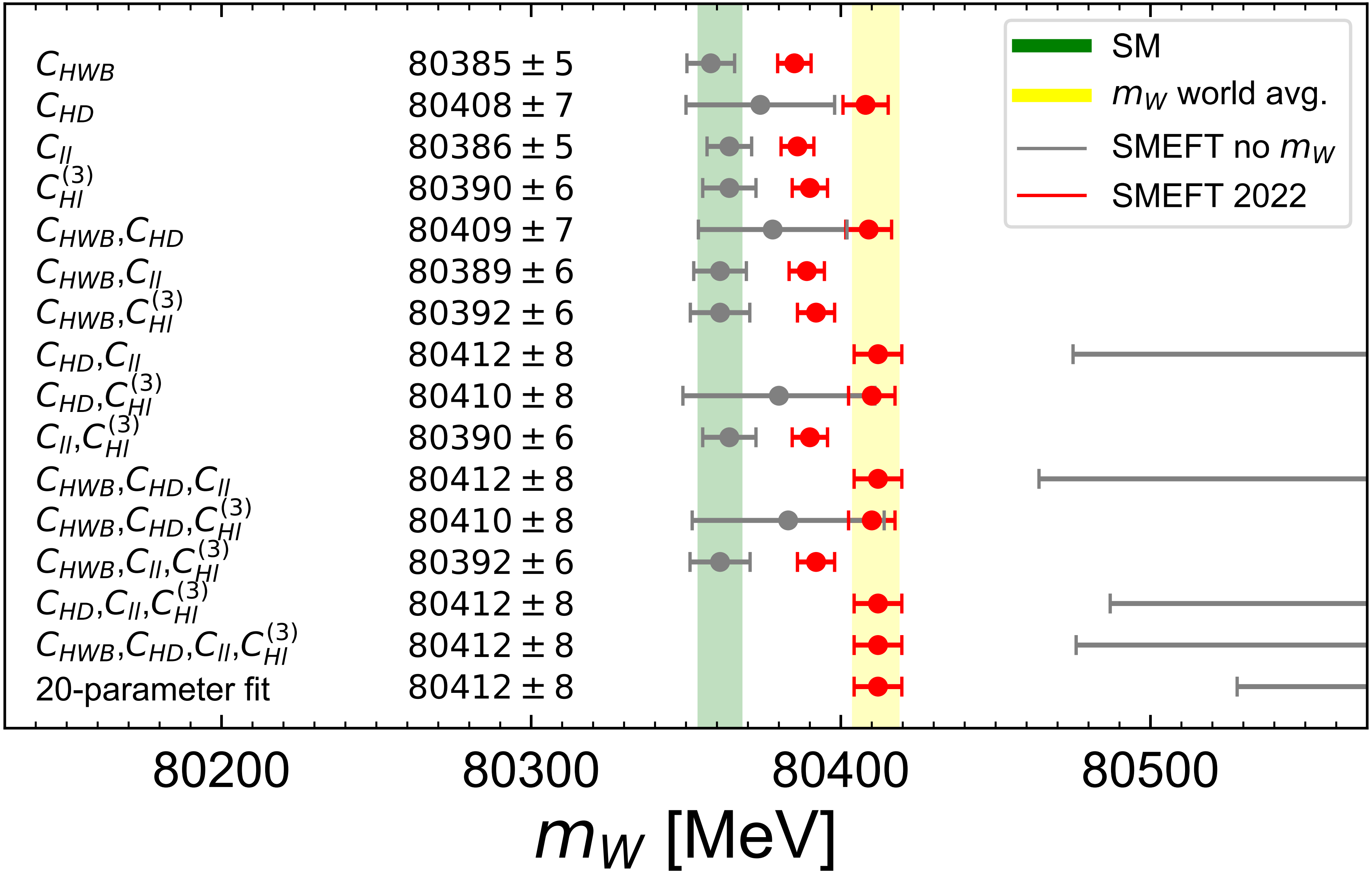
SMEFT Fit with the Mass of the W Boson



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

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

SMEFT Fits with the Mass of the W Boson



Subsets 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}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		1							
Σ			X $\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X $\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X 1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
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 $\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

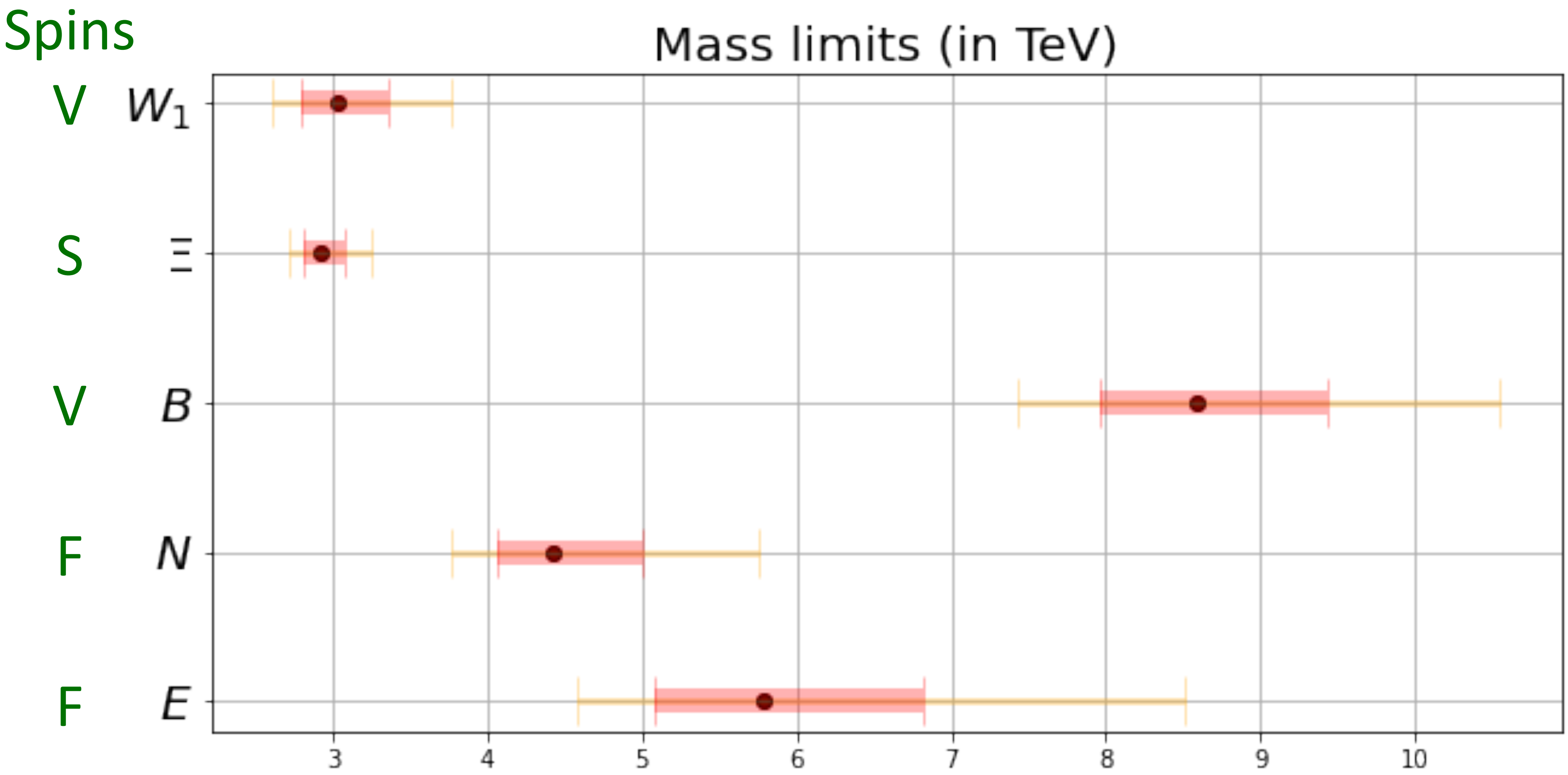
Wrong sign

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

Searching for Models Fitting the Mass of the W Boson

- W: Isotriplet vector boson, mass ~ 3 TeV x coupling, electroweak production, accessible at LHC?
- B: Singlet vector boson, mass ~ 8 TeV x coupling, phenomenology depends on fermion couplings, too heavy for LHC?
- Ξ: Isotriplet scalar boson, mass ~ 3 TeV x coupling, detectable in LHC searches for heavy Higgs bosons?
- N: Isosinglet neutral fermion, mass ~ 4 TeV x coupling, similar to (right-handed) singlet neutrino
- E: Isosinglet charged fermion, mass ~ 6 TeV x coupling, similar to (right-handed) singlet electron

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

Quo Vadis m_W?

- The jury is still out concerning the experimental measurement
    - Tension with SM, previous measurements

        "Extraordinary claims require extraordinary evidence"

- Nevertheless, much theoretical speculation (90 papers!)
- 4 SMEFT operators can increase m_W
- 3 SMEFT operators generated by single field extensions of the SM at tree level
    - Vector bosons W or B, scalar boson Ξ, fermions N, E
- Prospects for the LHC?
- Could also be important loop effects (supersymmetry?)

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

Known knowns (= SM)

Known unknowns (e.g., DM)

Unknown unknowns

Lepton flavour universality violation in B decays?

$g_\mu - 2$?

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

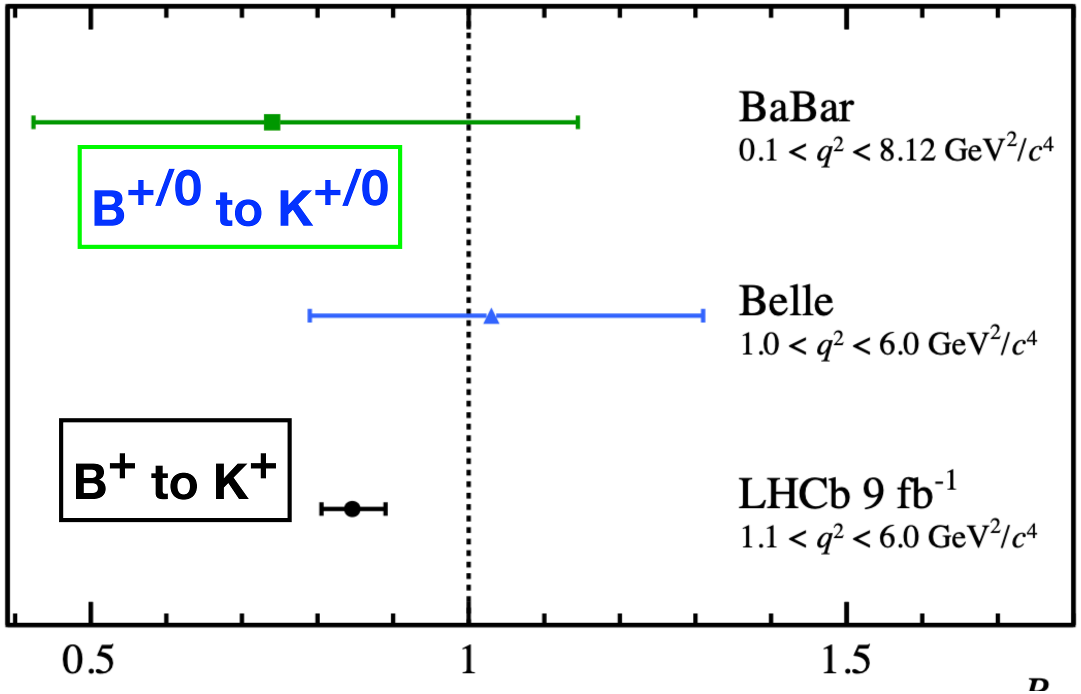
B decays to $e^+e^- > \mu^+\mu^-$

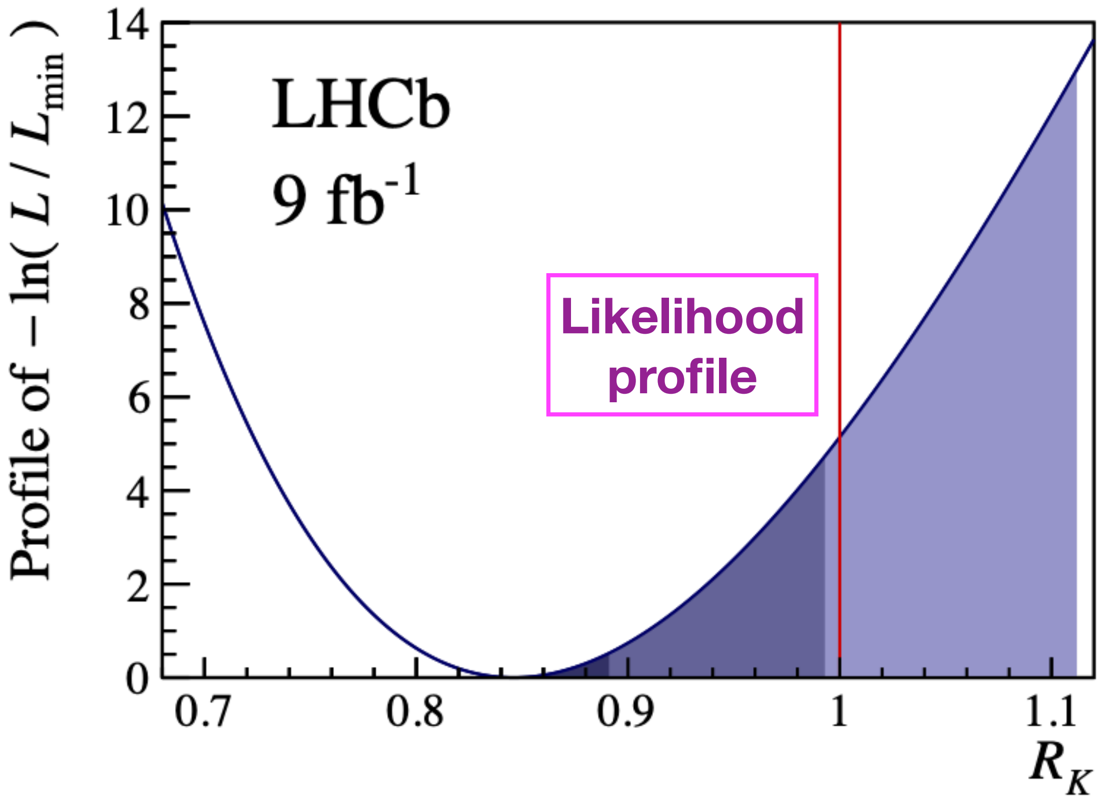
Prima facie violation of lepton universality

SM interactions flavour-universal

Except for Higgs couplings ∝ masses

LHCb Collaboration, arXiv:2103.11769



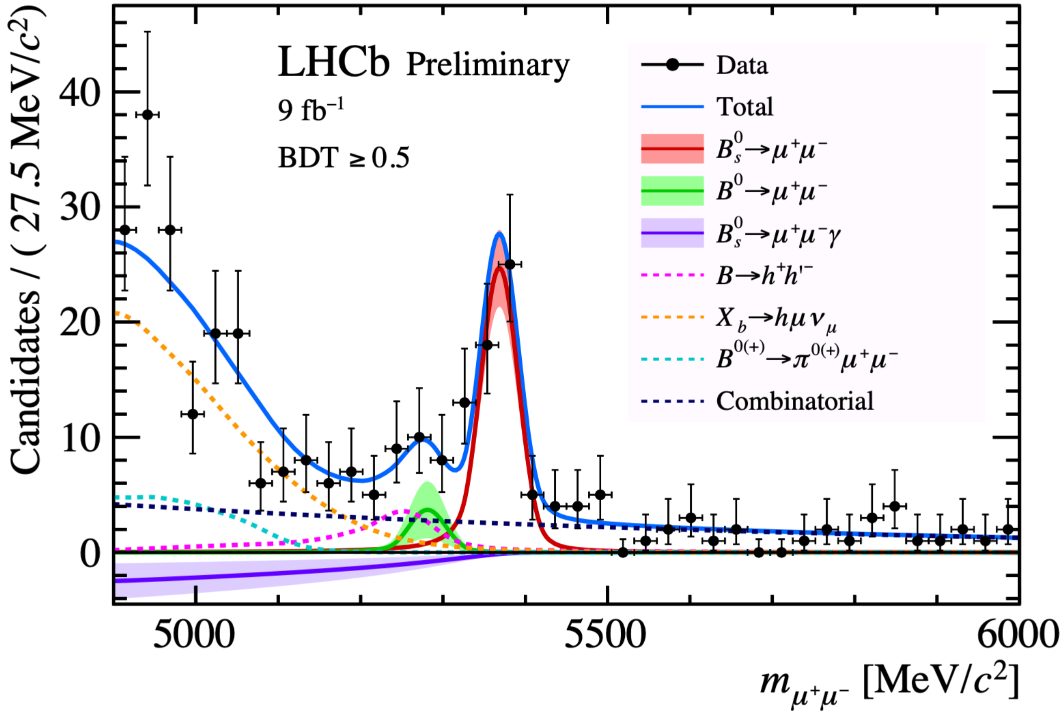


New LHCb $BR(B_s \to \mu^+\mu^-)$ Measurement

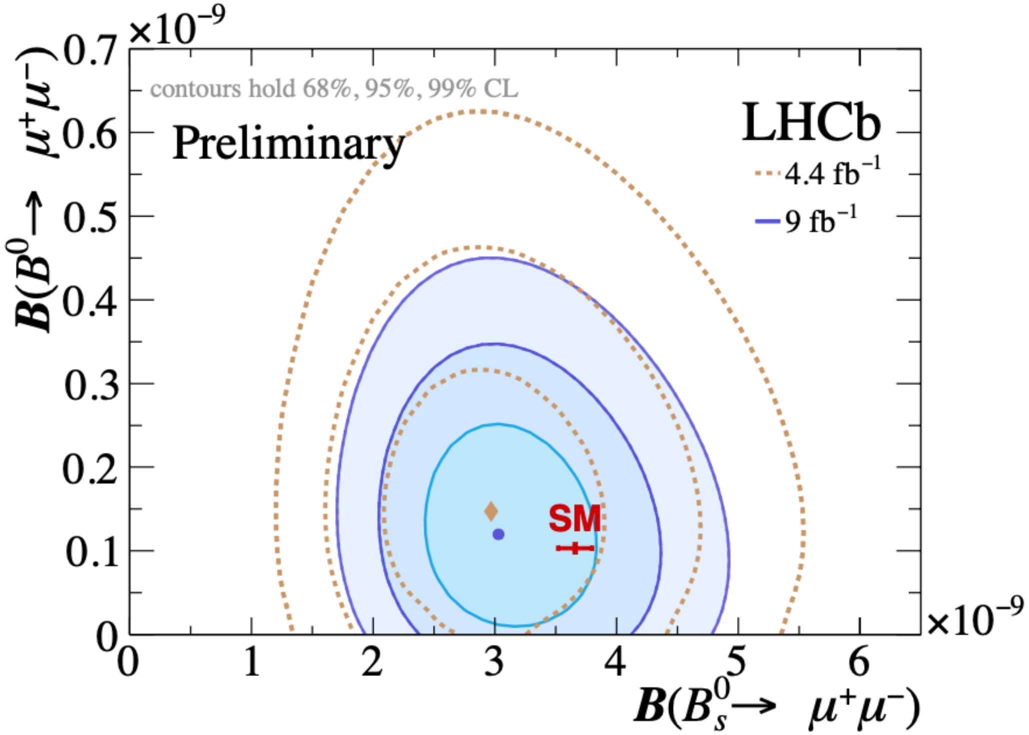
Rare decay induced by loop diagrams in SM

Measured value < SM prediction

Further evidence for new physics associated with the muon?



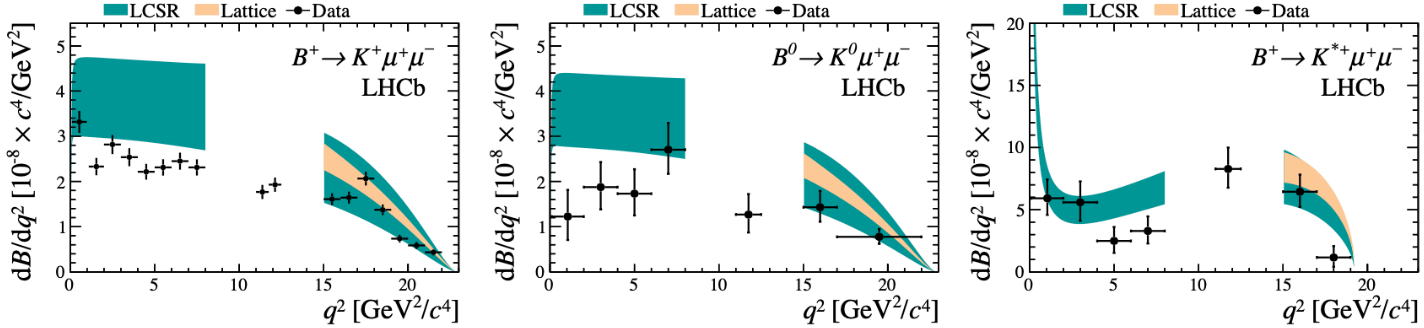
● $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (10.8σ)



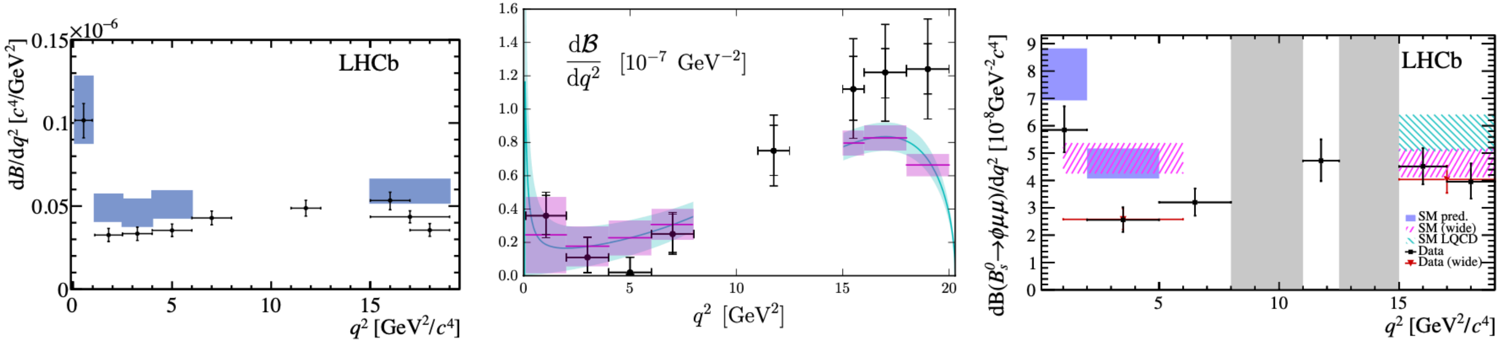
Other Previous Measurements

Rates

[JHEP06(2014)133]



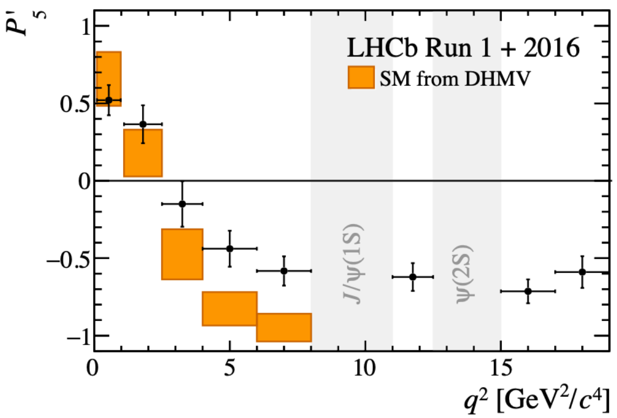
$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]

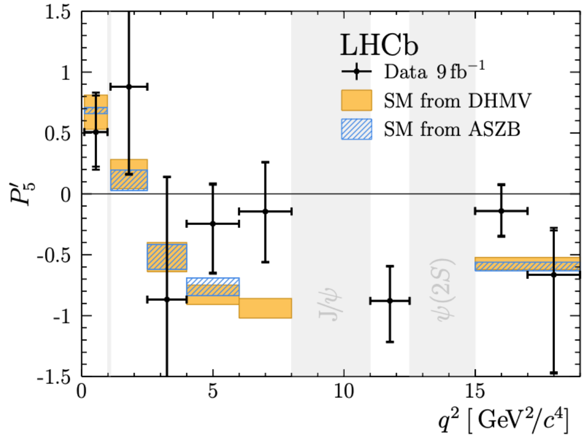


► SM predictions suffer from large hadronic uncertainties

Angular distributions

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





Flavour Anomalies in b→s Decays

- Parametrize using effective dimension-6 operators:

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

- Operators appearing in analysis:

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

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

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

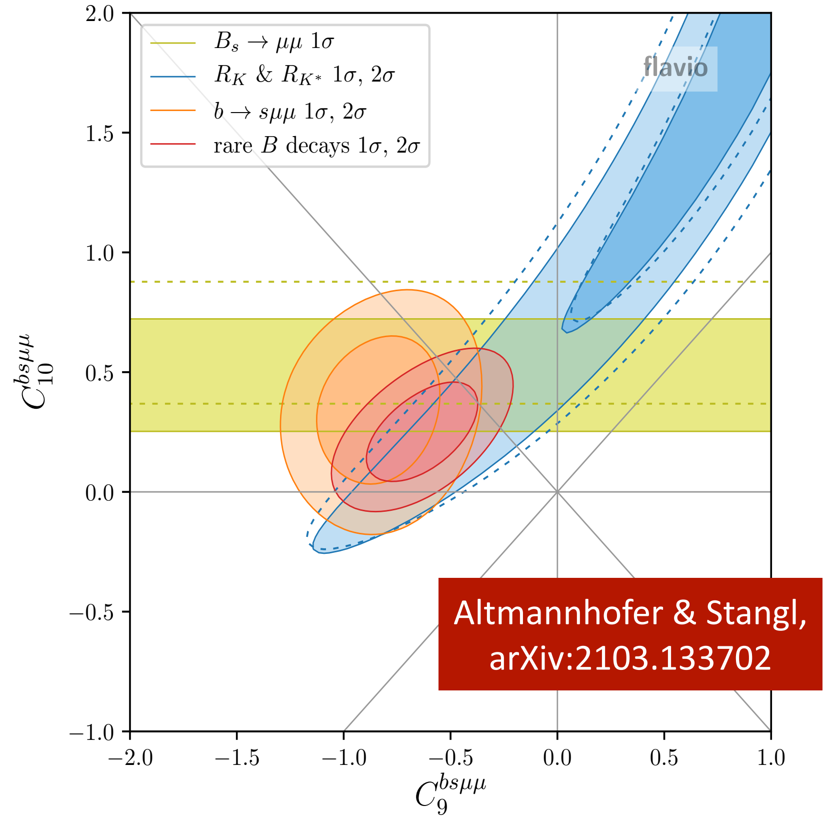
- $$O_P^{bs\ell\ell} = m_b(\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P'^{bs\ell\ell} = m_b(\bar{s} P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$

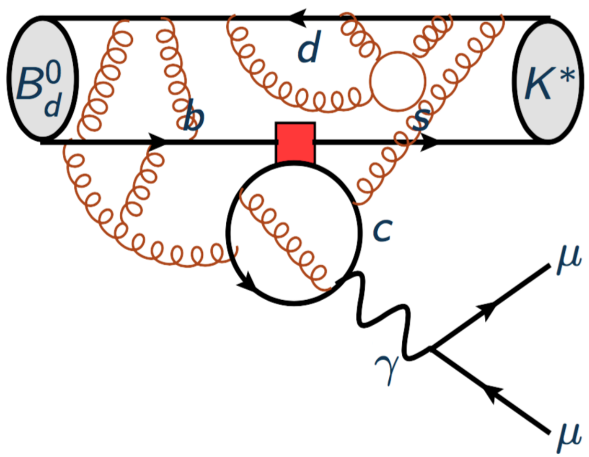
- Evidence for non-zero coefficient of $O_9^\mu \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$
- Maybe also non-zero coefficient of $O_{10}^\mu \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
- No evidence of operators with electrons

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

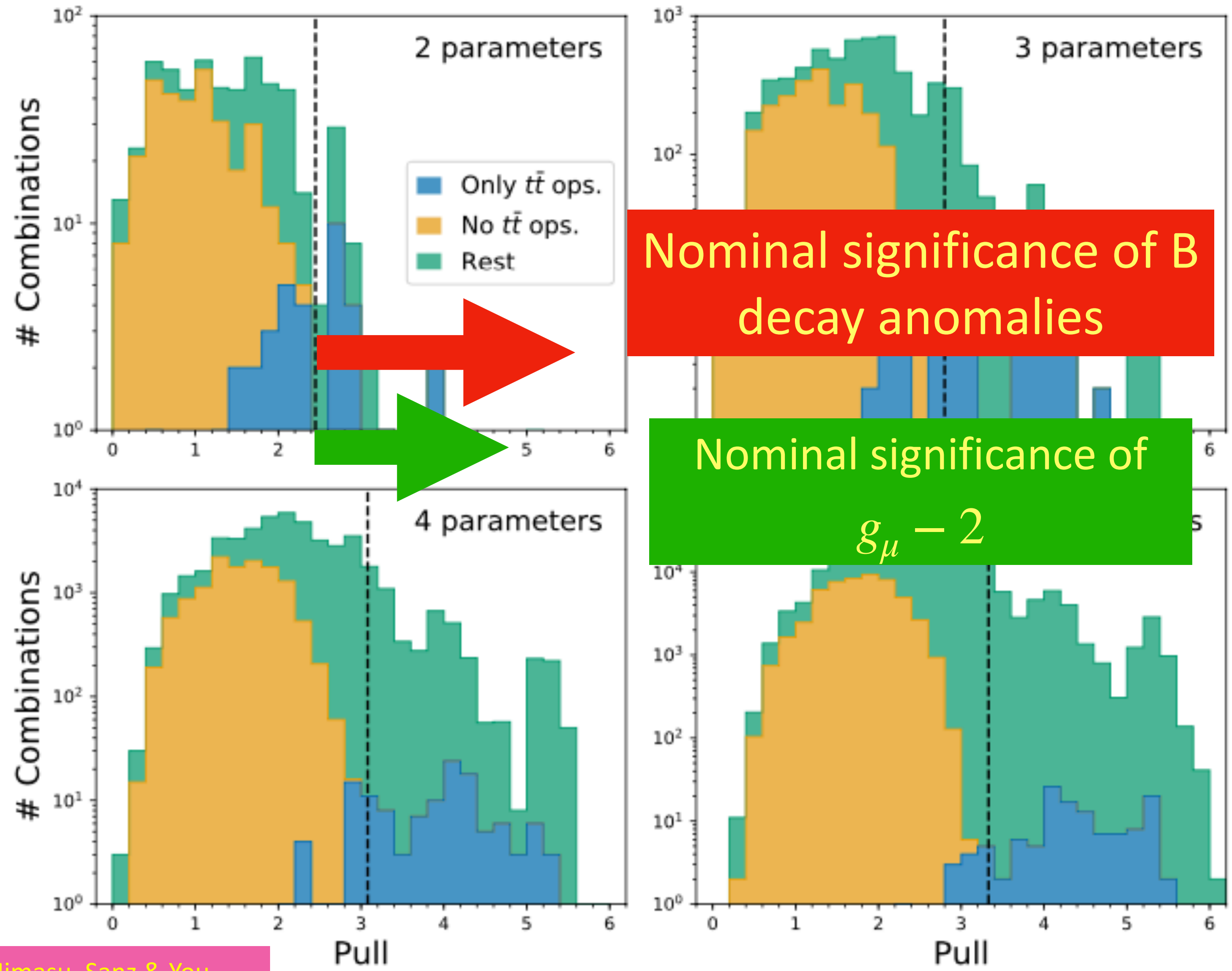
  $\to B_s \to \mu^+\mu^-$ and LFU observables have very clean theory predictions.
  - $\sim 4.5\sigma$ from SM
- Measurements point to new vector coupling (C_9^μ)





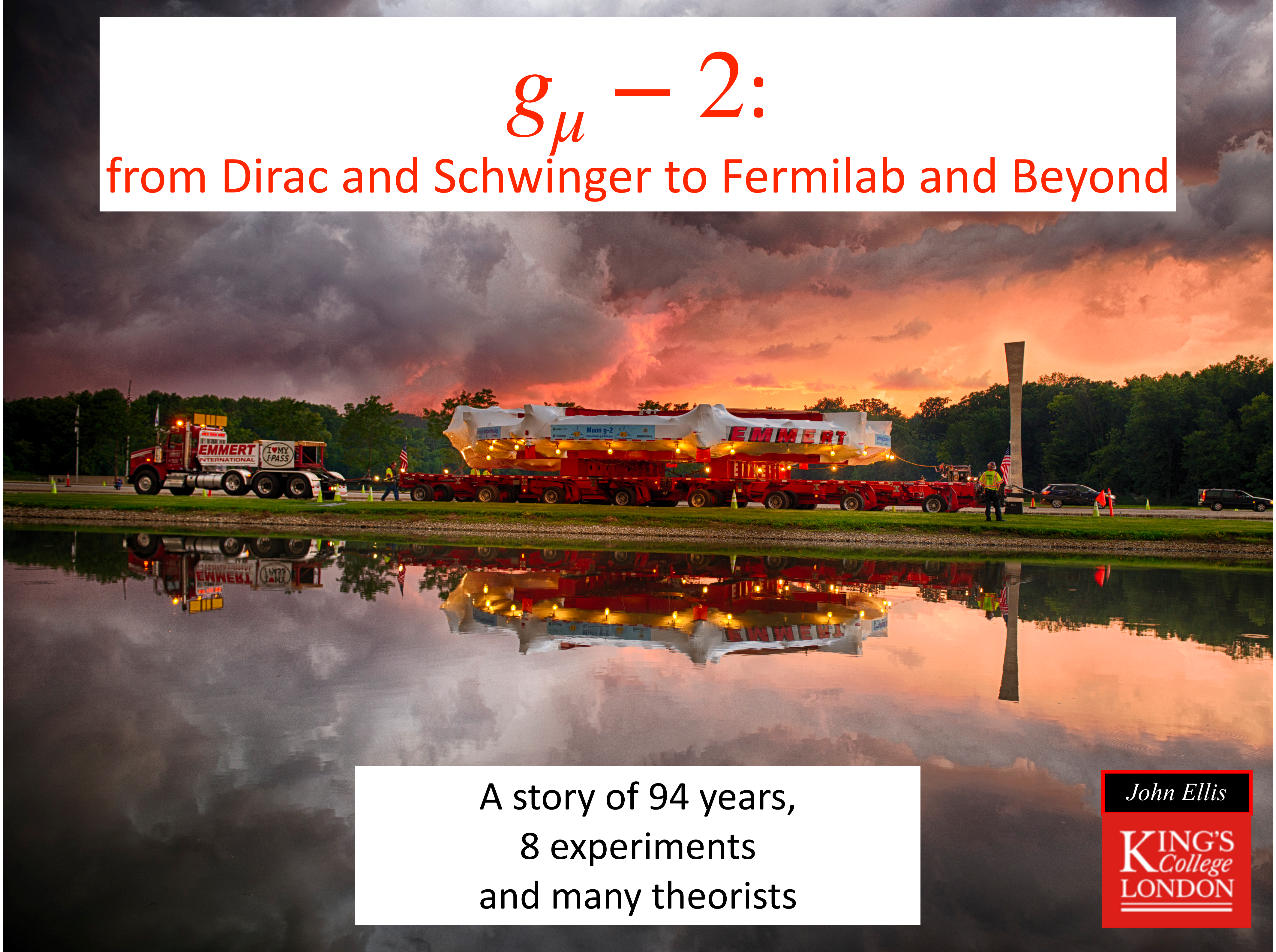
Model-Independent BSM Survey

Switch on random subsets of 2, 3, 4 or 5 operators



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

$g_\mu - 2$:
from Dirac and Schwinger to Fermilab and Beyond



A story of 94 years,
8 experiments
and many theorists

John Ellis
KING'S College LONDON

$g_\mu - 2$ in Supersymmetry

- One-loop contribution from smuon/neutralino loop

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

- where $\eta_i \equiv (m^2_{s\mu_i}/m^2_{\widetilde{G}})$
- and $\mathcal{L} = a\sqrt{2}\, s_\mu \bar{\mu}_L \widetilde{G} + b\sqrt{2}\, t_\mu \bar{\mu}_R \widetilde{G}$

Volume 116B, number 4 PHYSICS LETTERS (1982)

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

John ELLIS, John HAGELIN and D.V. NANOPOULOS
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.

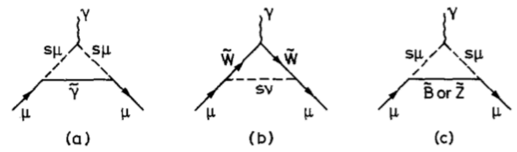


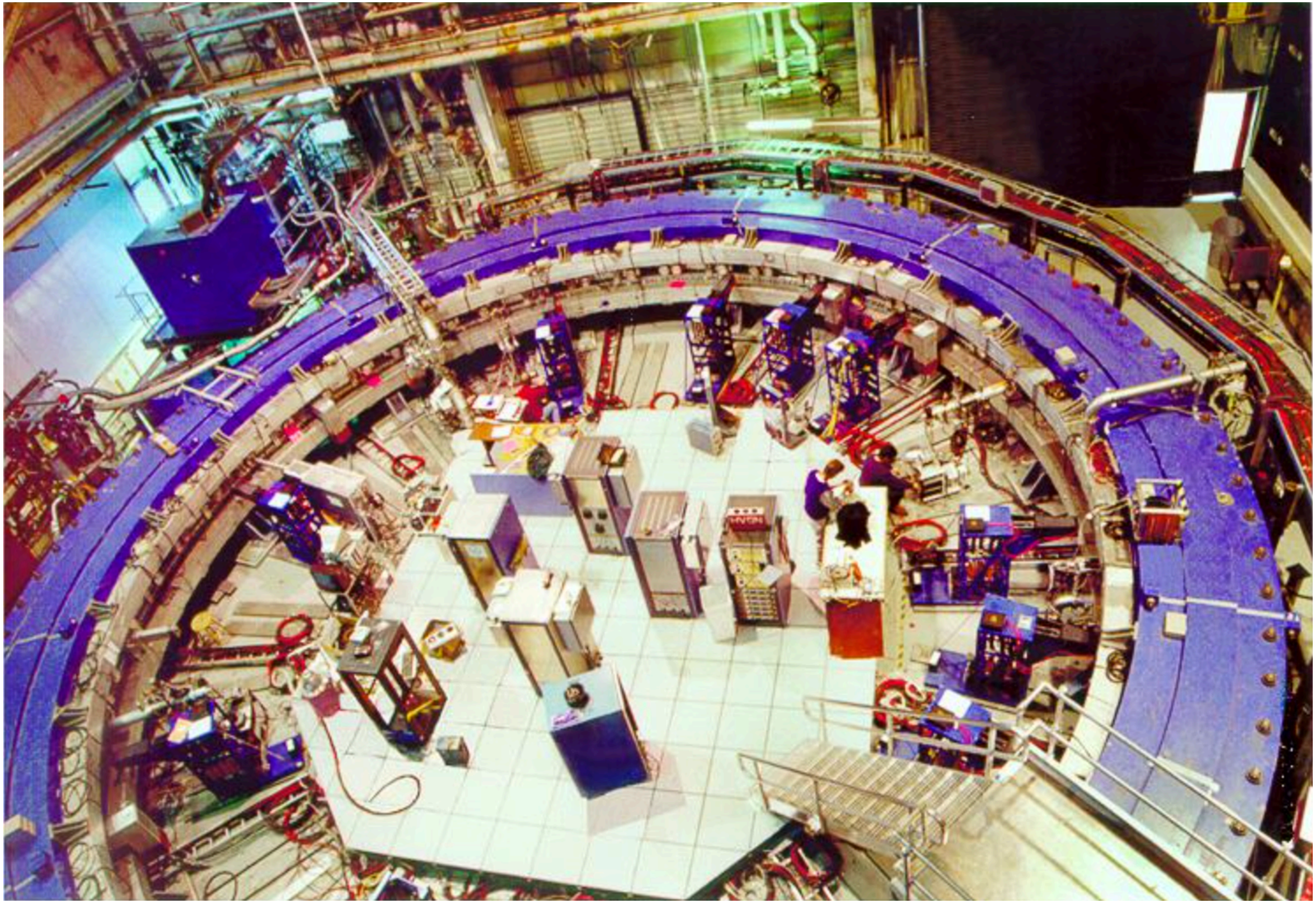
Fig. 1. One-loop diagrams contributing to $(g-2)_\mu$: (a) essentially massless photino ($\tilde{\gamma}$) exchange, (b) $\widetilde{W}$ and sneutrino ($s\nu$) exchange, and (c) $\widetilde{B}$ or $\widetilde{Z}$ exchange.

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.

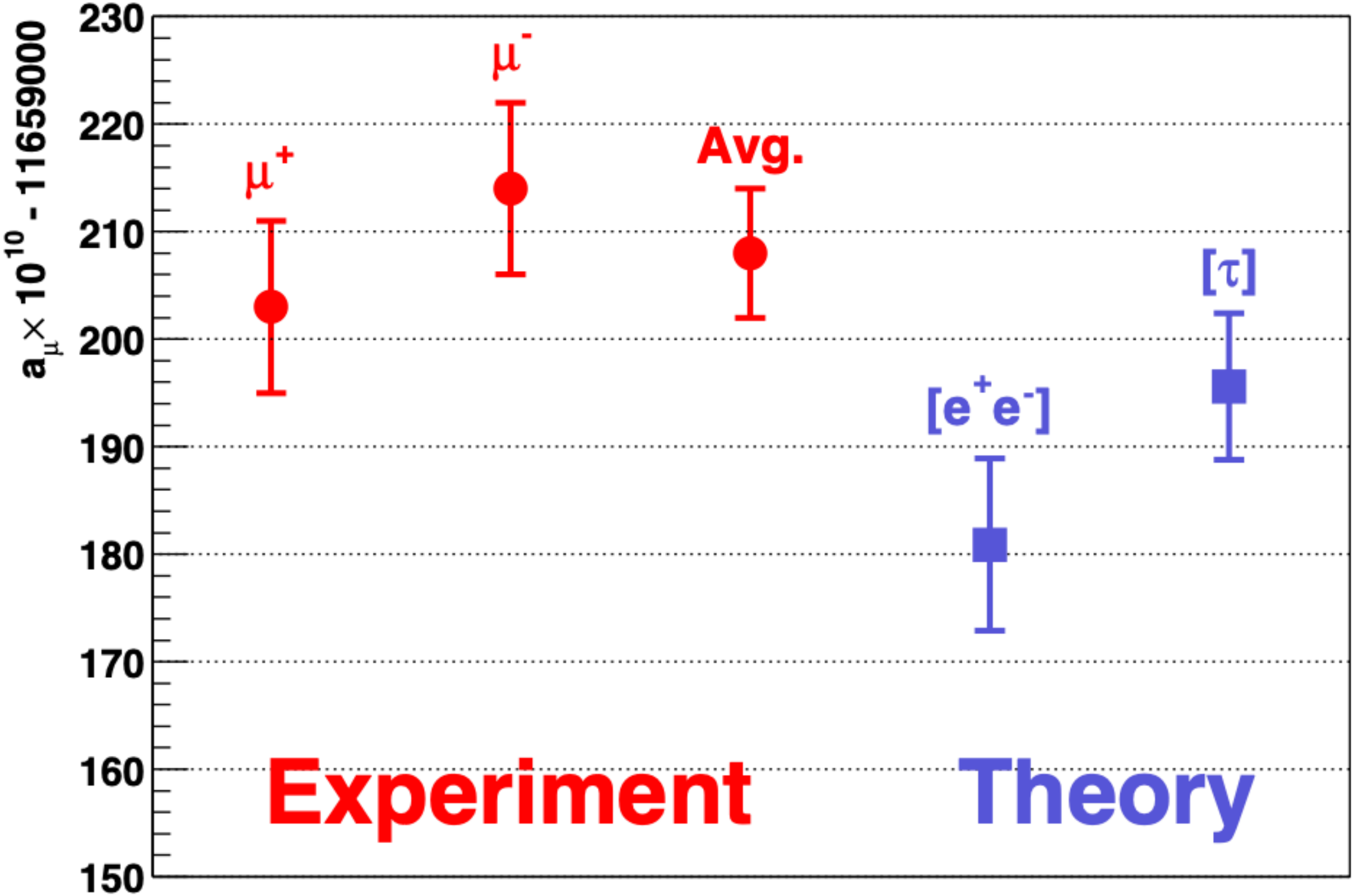
When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\tilde{\gamma}$ diagram of fig. 1a and the $\widetilde{W}$ diagram of fig. 1b as compared to the massive $\widetilde{B}$ or $\widetilde{Z}$ diagram of fig.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

BNL Experiment

(1984 - 2003)



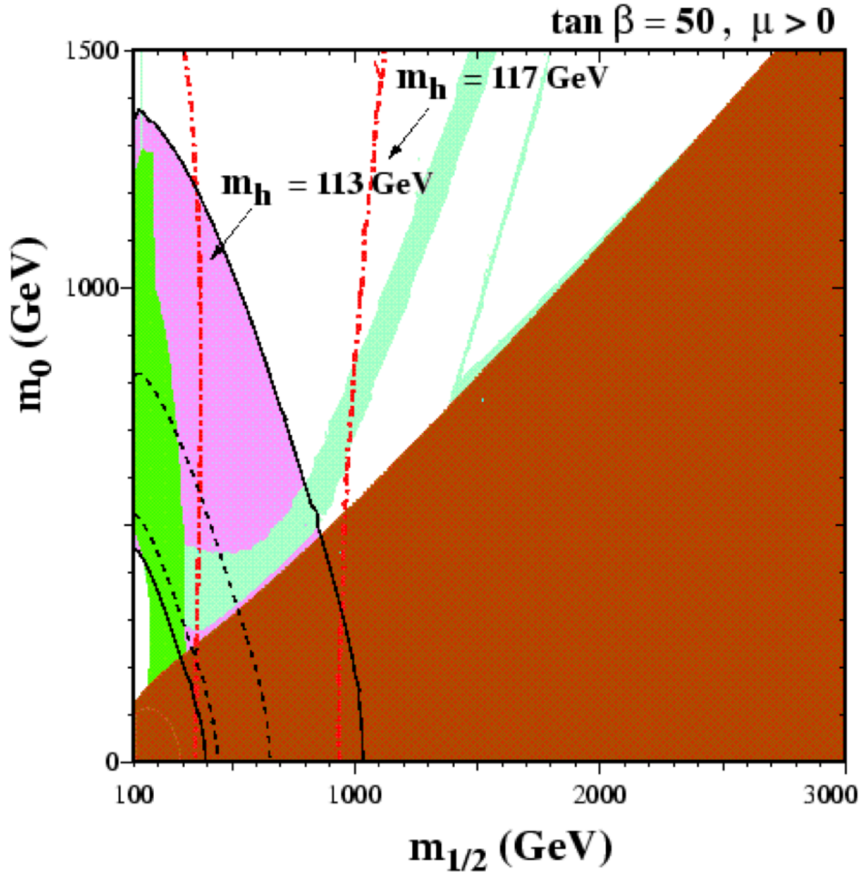
Possible Discrepancy with Theory?



$$\delta a = \pm\, 0.47\ \mathrm{ppm}$$

BNL E821 experiment, 2001 - 2006

$g_\mu - 2$ in Supersymmetry v2: the CMSSM



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24 May 2001
Physics Letters B 508 (2001) 65–73
PHYSICS LETTERS B
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Combining the muon anomalous magnetic moment with other constraints on the CMSSM

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[b] *Department of Physics, Texas A&M University, College Station, TX 77843, USA*
[c] *Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, TX 77381, USA*
[d] *Chair of Theoretical Physics, Academy of Athens, Division of Natural Sciences, 28 Panepistimiou Avenue, Athens 10679, Greece*
[e] *Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

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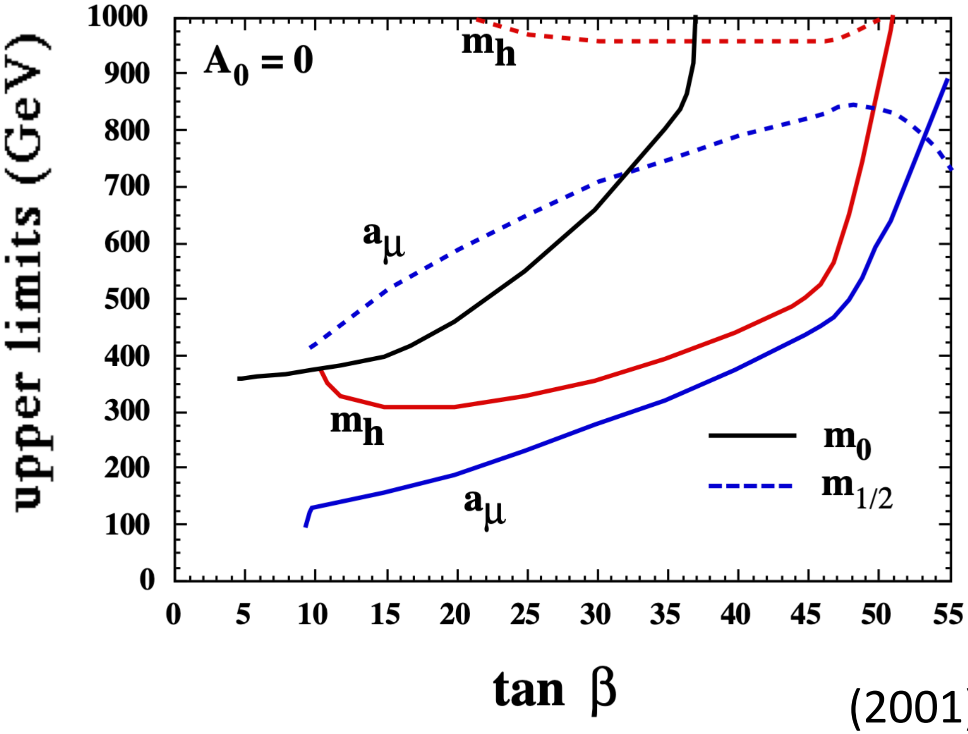
Editor: R. Gatto

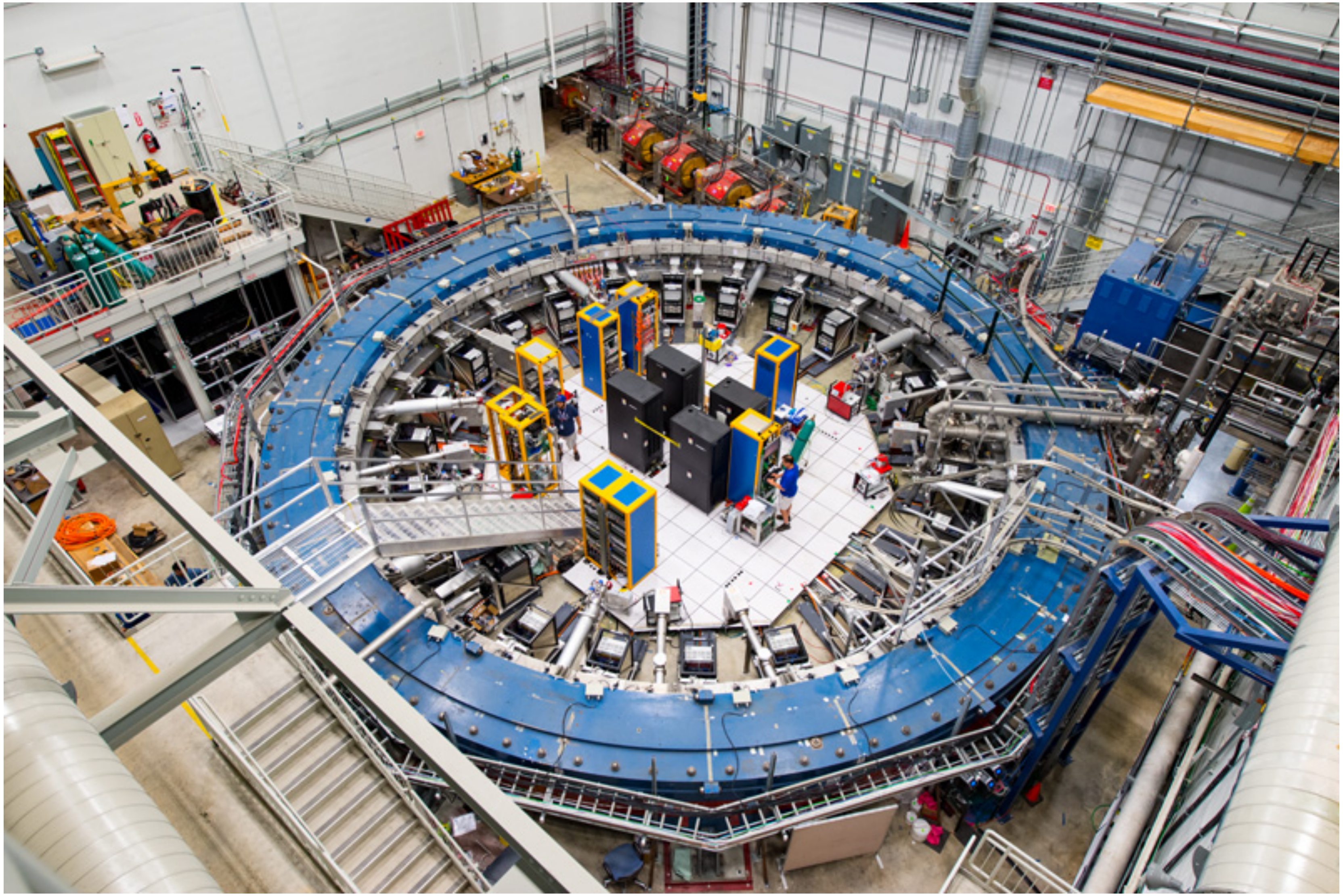
Abstract

We combine the constraint suggested by the recent BNL E821 measurement of the anomalous magnetic moment of the muon on the parameter space of the constrained MSSM (CMSSM) with those provided previously by LEP, the measured rate of $b \to s\gamma$ decay and the cosmological relic density $\Omega_\chi h^2$. Our treatment of $\Omega_\chi h^2$ includes carefully the direct-channel Higgs poles in annihilation of pairs of neutralinos χ and a complete analysis of $\chi - \tilde{\ell}$ coannihilation. We find excellent consistency between all the constraints for $\tan\beta \gtrsim 10$ and $\mu > 0$, for restricted ranges of the CMSSM parameters m_0 and $m_{1/2}$. All the preferred CMSSM parameter space is within reach of the LHC, but may not be accessible to the Tevatron collider, or to a first-generation e^+e^- linear collider with centre-of-mass energy below 1.2 TeV. © 2001 Published by Elsevier Science B.V.



(2001)

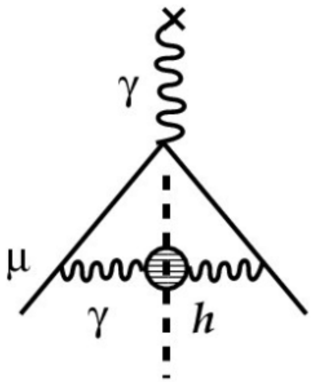
Fermilab Experiment

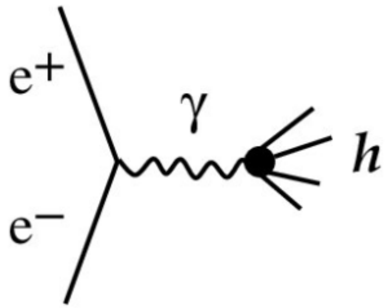


Does the magnet look familiar?

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

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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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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

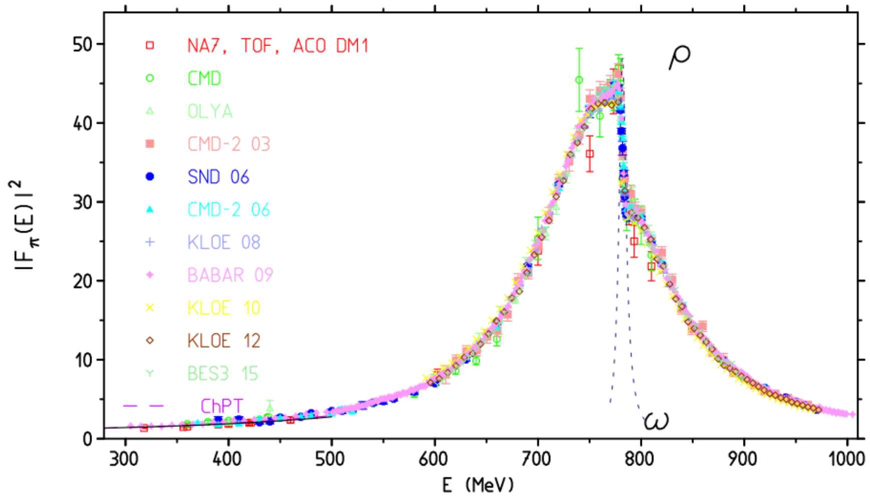
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects

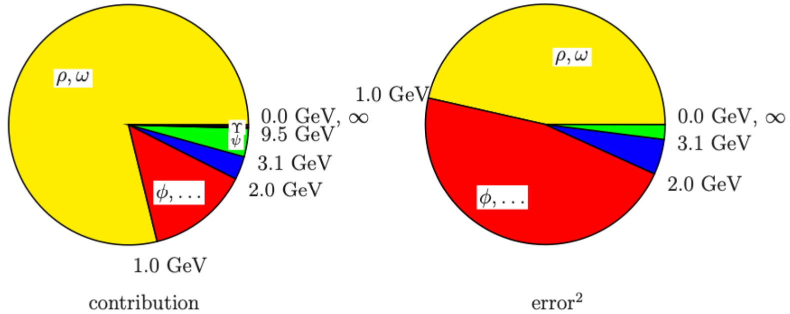
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)

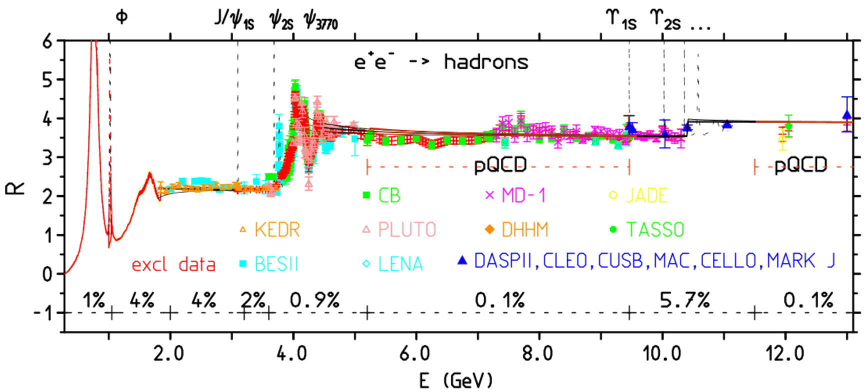
- High energies under good control from perturbative QCD

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

Aoyama et al, arXiv:2006.04822





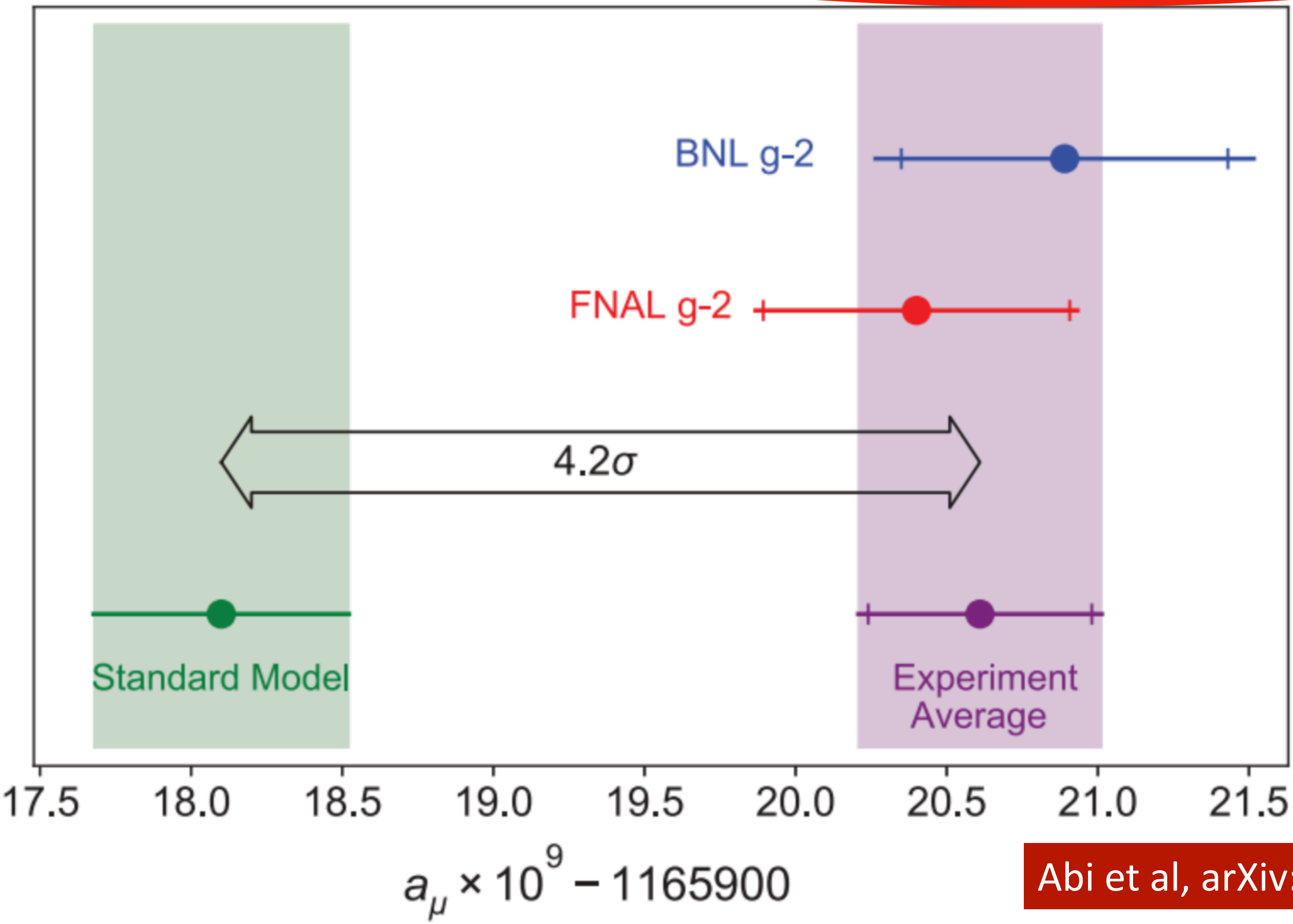


Fermilab Measurement

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

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

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



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

What lies beyond the Standard Model?

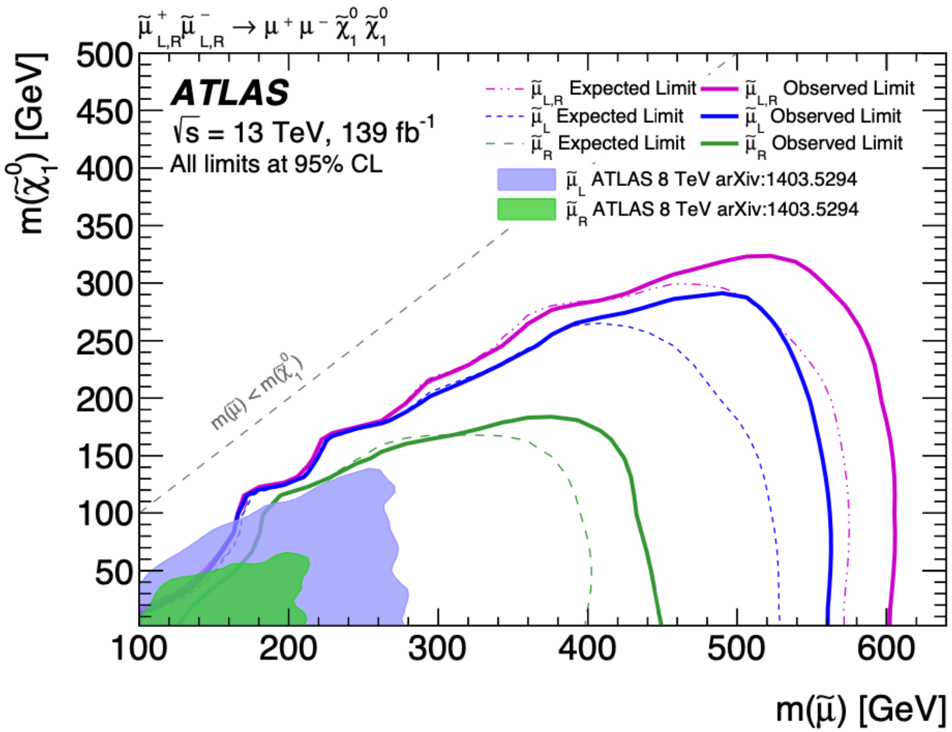
Supersymmetry

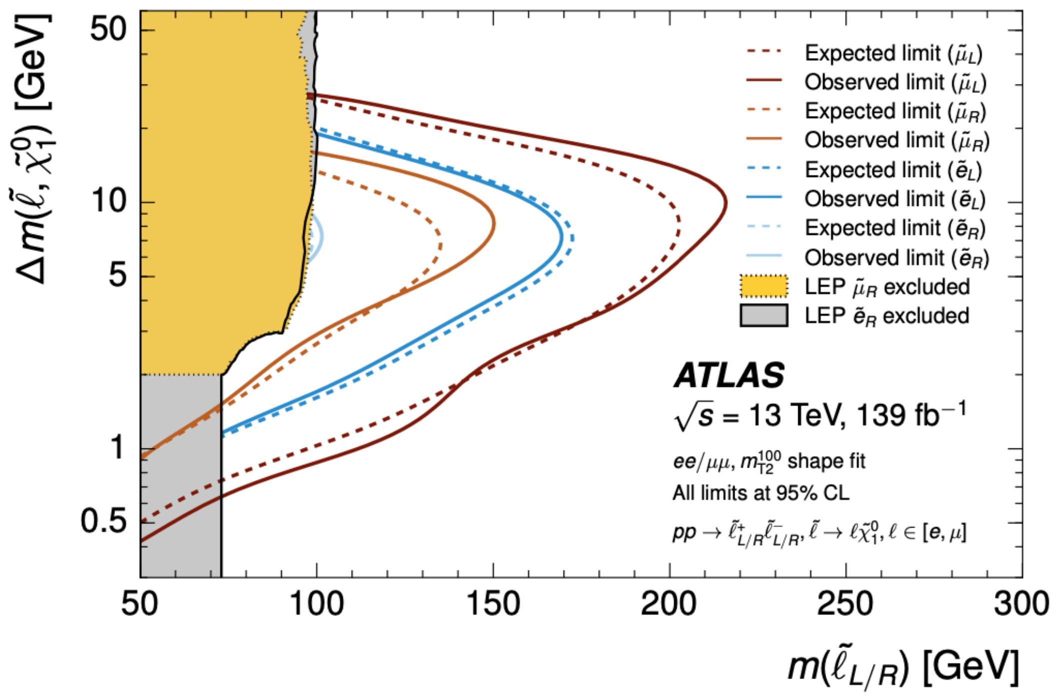
New motivations from LHC

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, dark matter, $g_\mu - 2$, …

LHC vs Supersymmetry

- LHC does not exclude (relatively) light electroweakly-interacting particles, e.g., sleptons

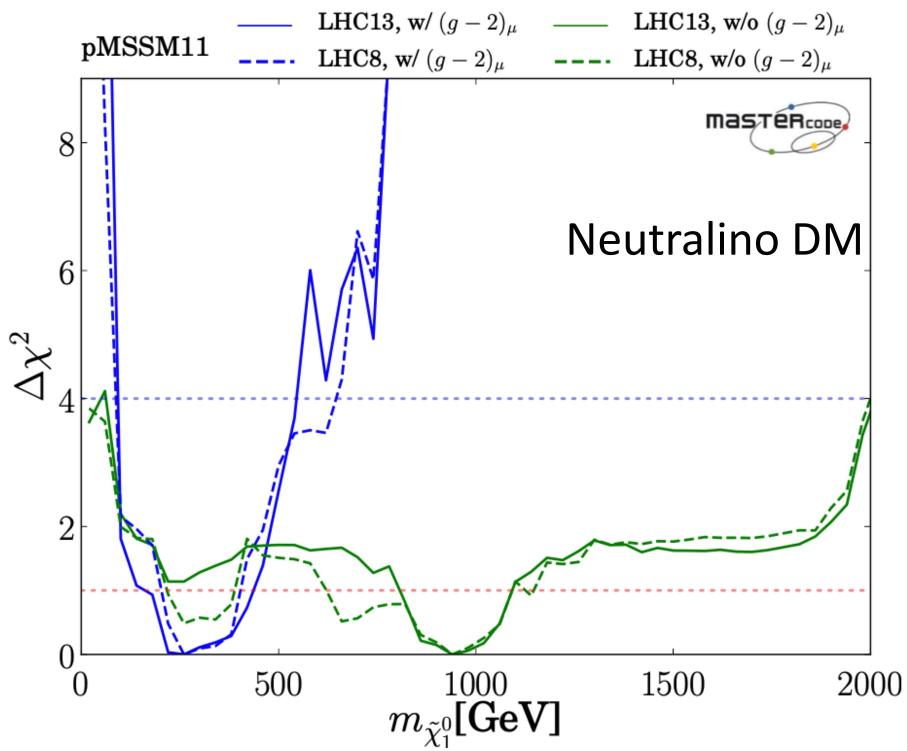


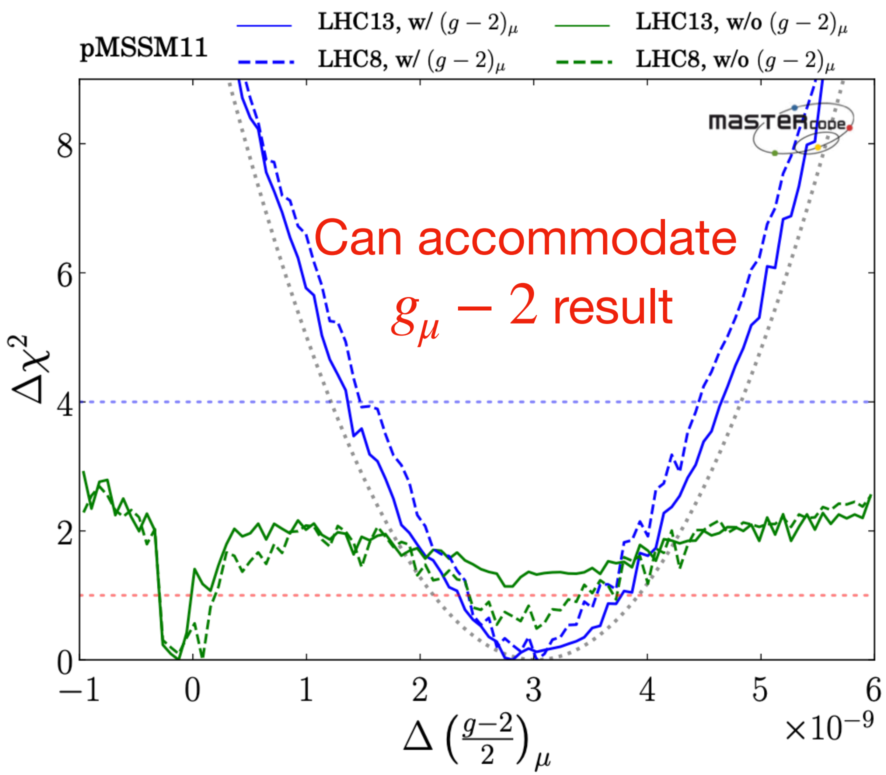


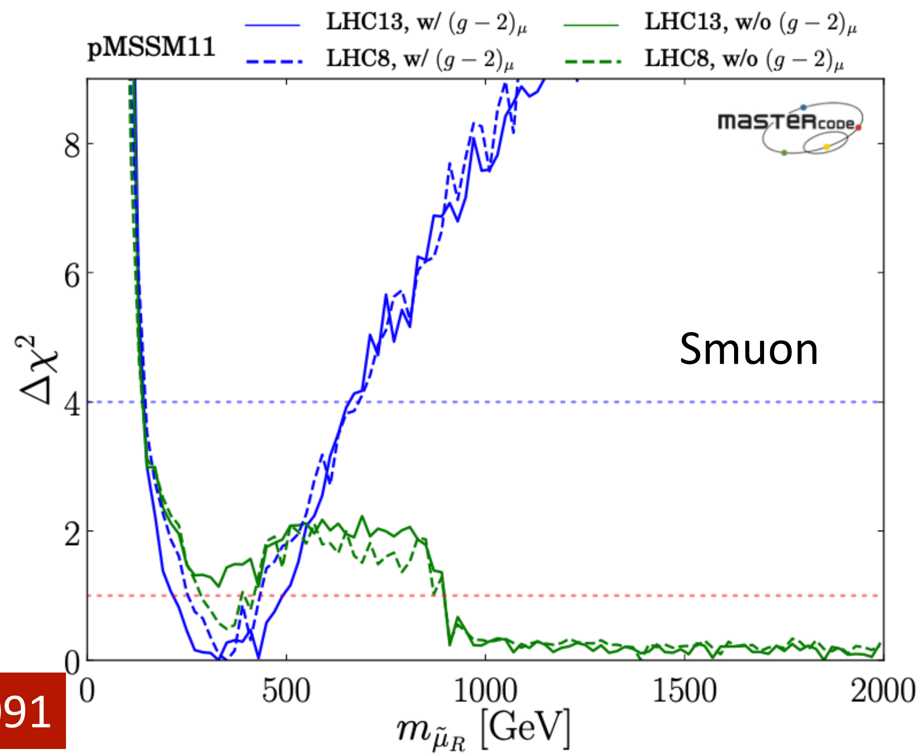
- LHC favours squarks & gluinos > 2 TeV (but loopholes)

$g_\mu - 2$ in Phenomenological Supersymmetry
(pMSSM11)

No relation between squark/gluino masses and slepton/neutralino masses





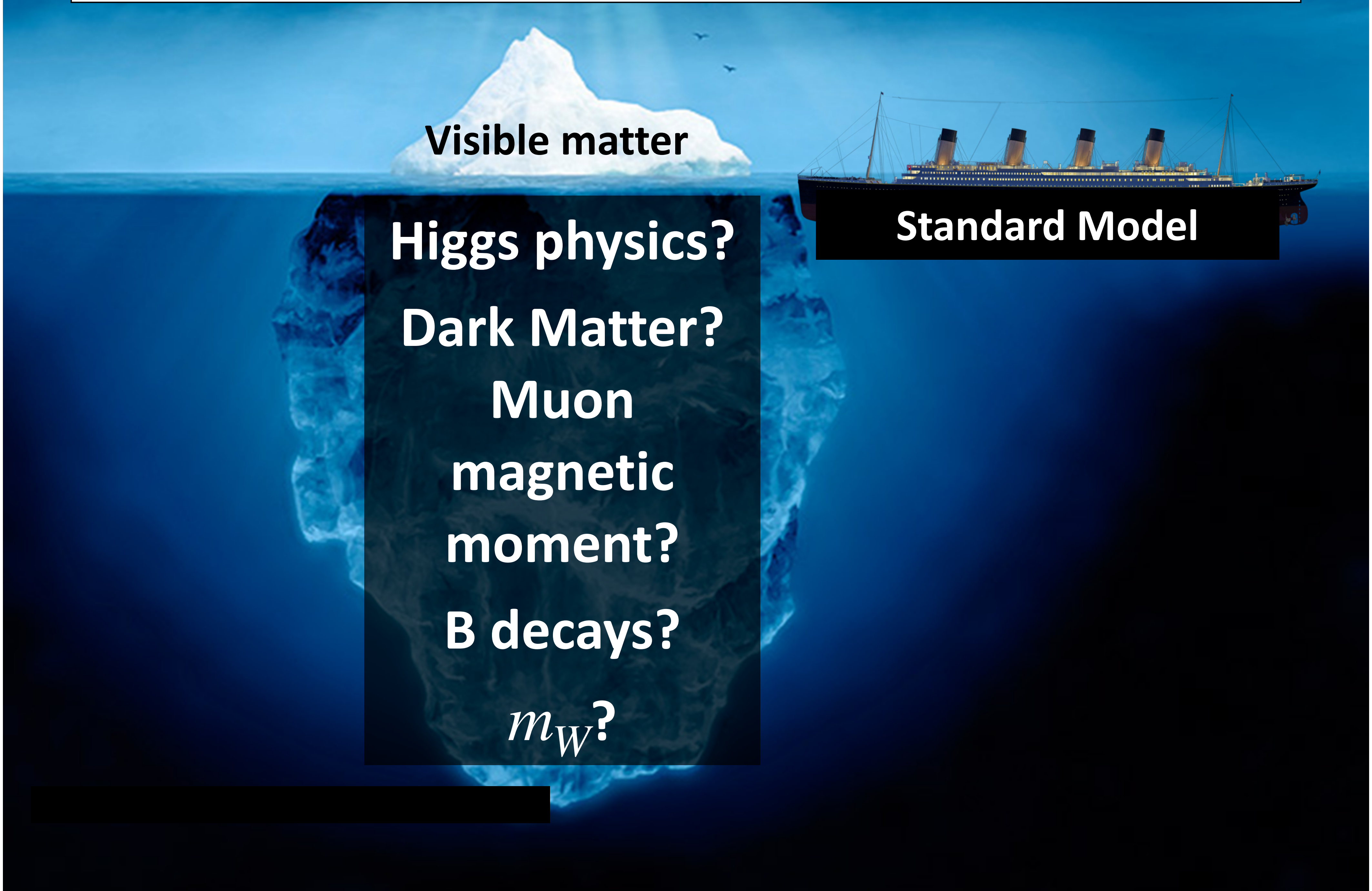


No problem accommodating BNL/FNAL result

Neutralino DM, smuon masses $\sim 300/400$ GeV

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Summary


Visible matter
Standard Model
Higgs physics?
Dark Matter?
Muon magnetic moment?
B decays?
m_W?
[redacted]