BSM THEORY

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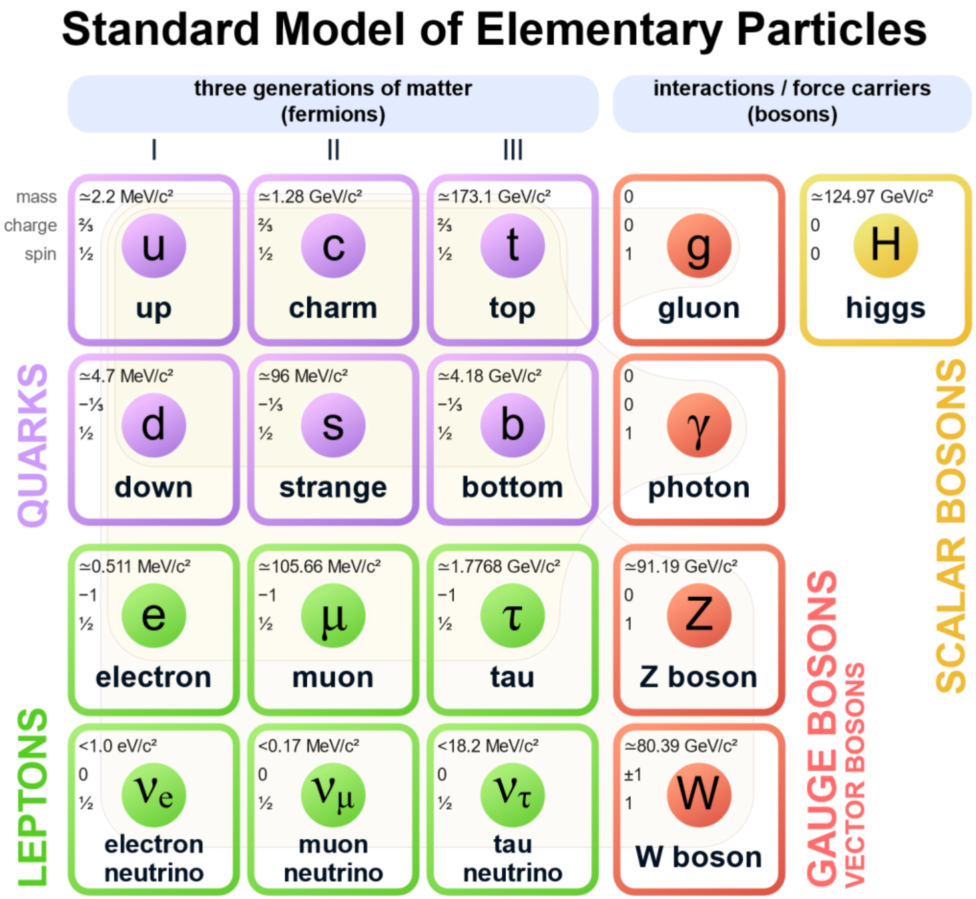
2022 LHC Days in Split, October 4, 2022

Introduction

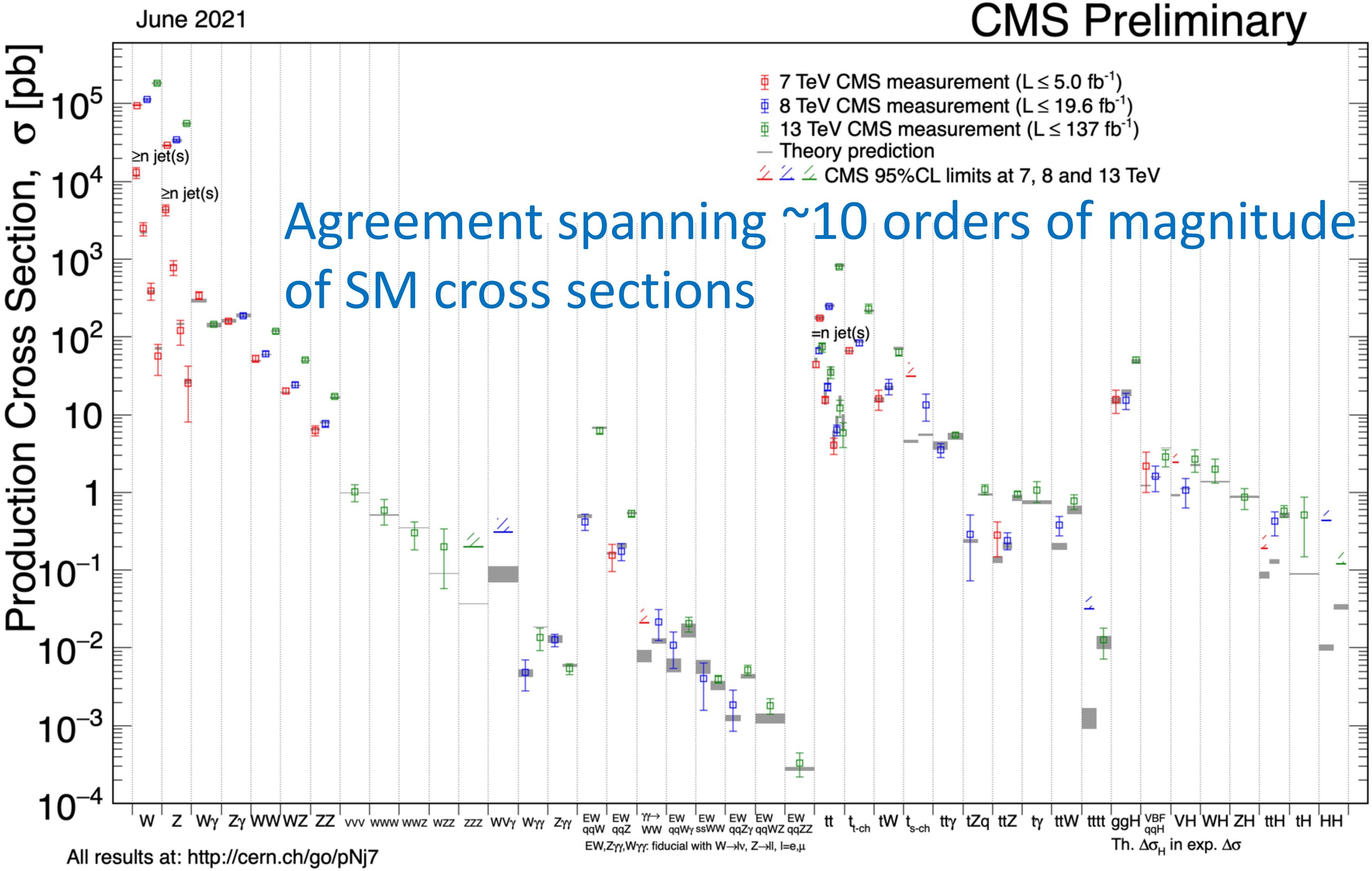
The **Standard Model** particle content is **complete**, and we can be justifiably proud of its **success** in explaining **ATLAS and CMS data**



Standard Model of Elementary Particles

	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
	<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	

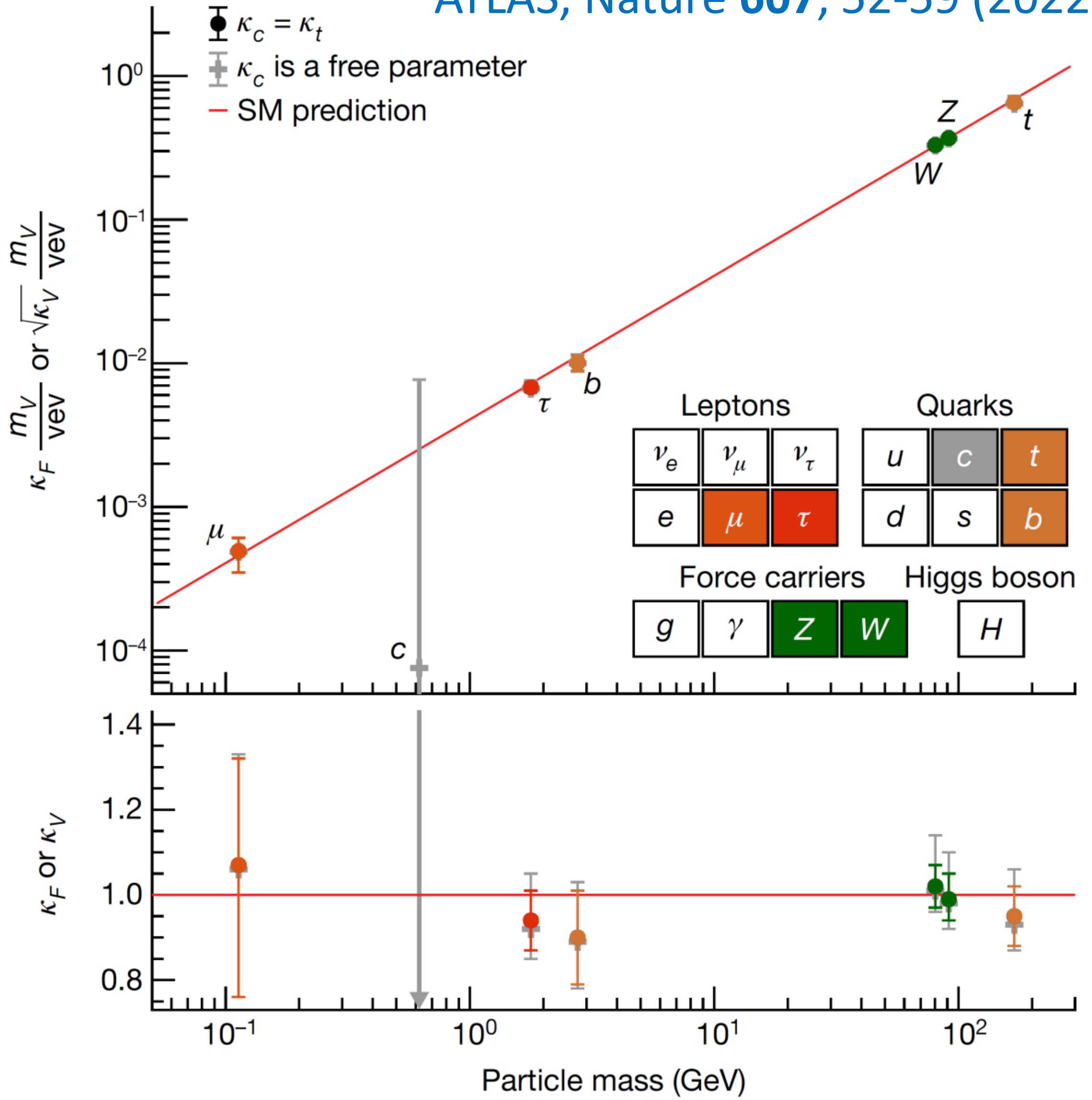
Introduction



Agreement spanning ~10 orders of magnitude of SM cross sections

Introduction

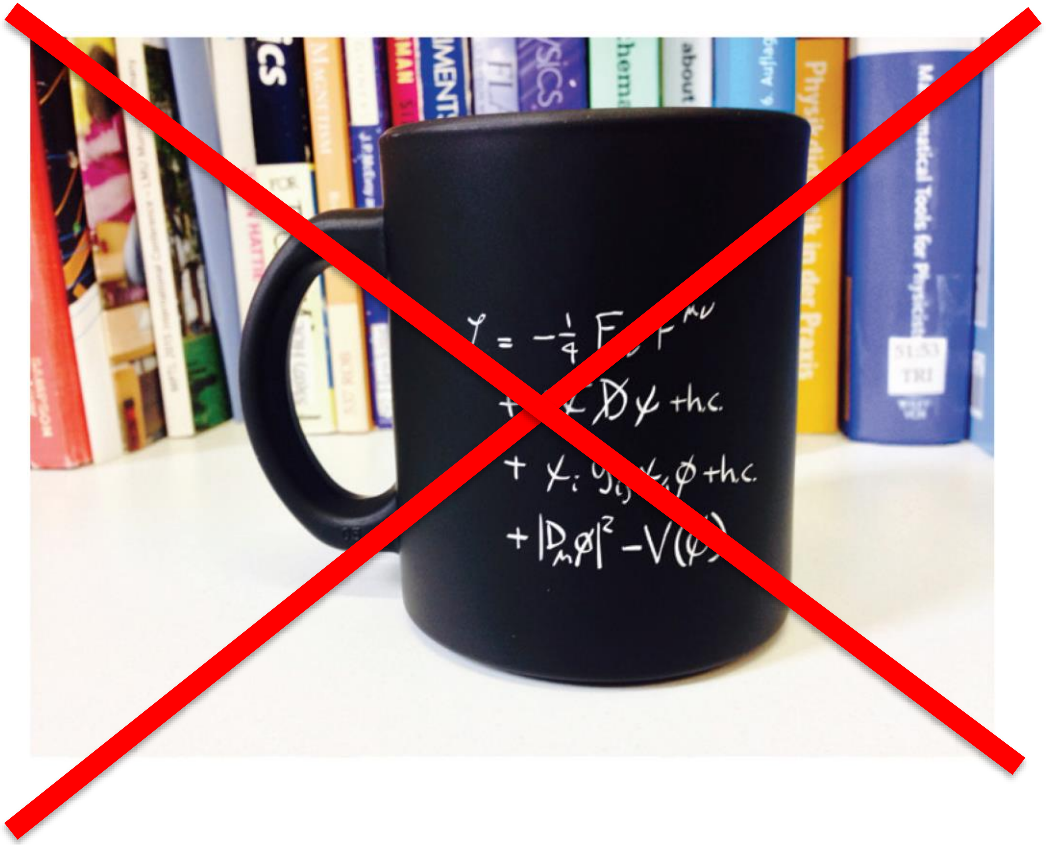
ATLAS, Nature **607**, 52-59 (2022)



And the SM expectations are also being borne out in **current Higgs measurements**

Lest ye forget…

The Standard Model **cannot** be the end of the story



EXISTENTIAL QUESTIONS

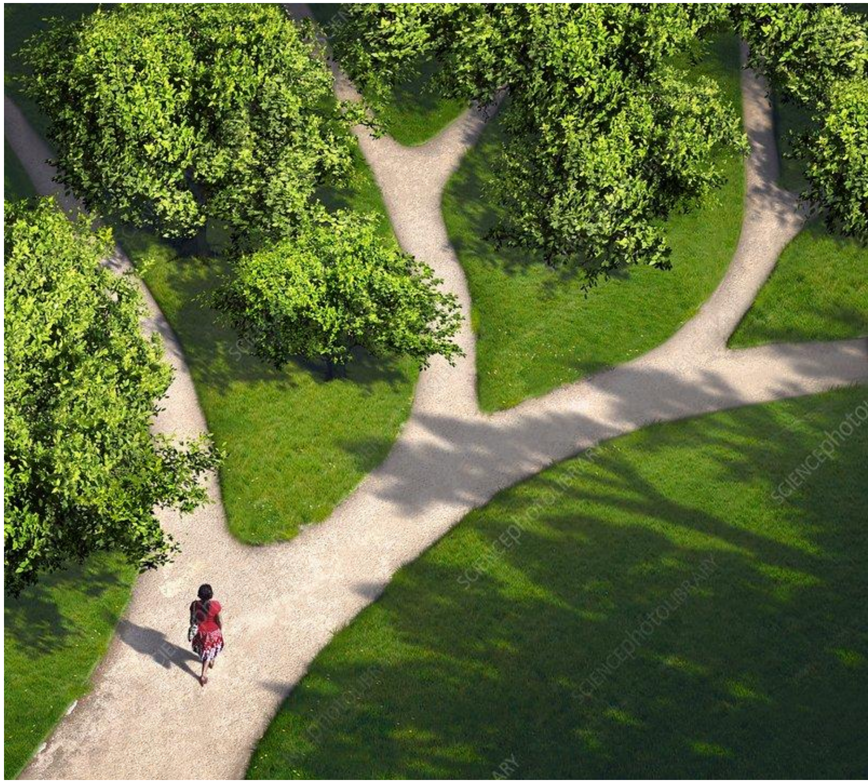
- Fundamental nature of neutrinos?
- Matter/antimatter asymmetry?
- Dark matter and dark energy?

For these existential questions, the Standard Model is a spectacular **failure**

Starting point for BSM

- The SM has a (wide) range of validity, but can only be an ***effective theory*** of NATURE
  - Goal for discovery = probe SM breakdown at the edge of its validity

Photo credit: SMETEK / Science Photo Library

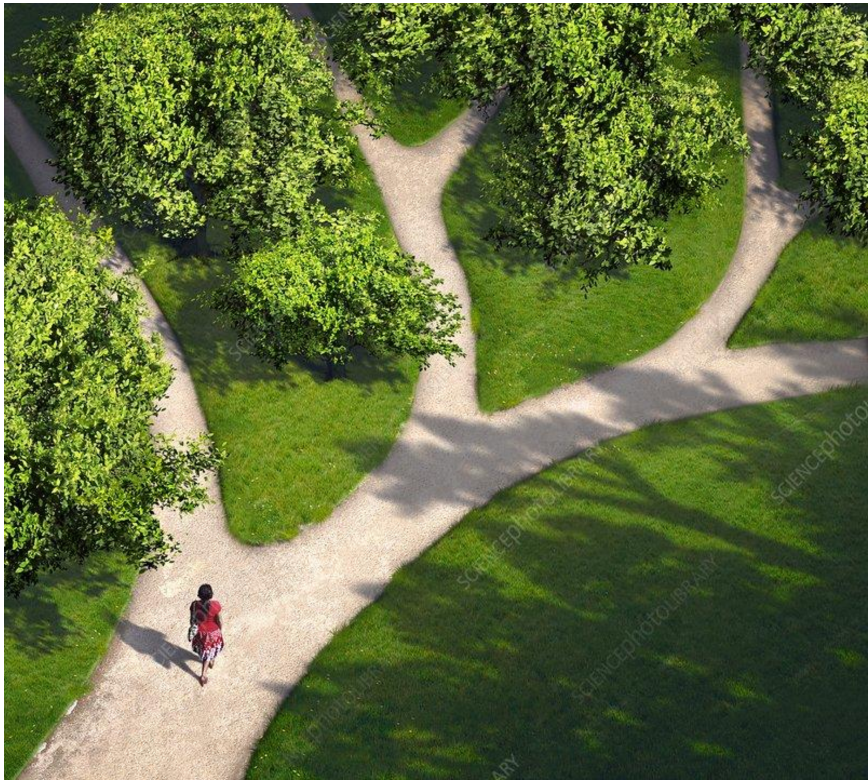


Leads to a BSM GARDEN OF BRANCHING PATHS

BSM Garden of Branching Paths

- Treat SM as SMEFT, agnostic about UV physics
  - Caveats: no light dofs, limited regime of validity, closure test on EFT applicability, New Physics Flavor Problem
- Build top-down model, usually motivated by solving particular problem
  - Neutrino models, baryogenesis/leptogenesis models, dark matter models, naturalness, strong CP, flavor…
  - Also agnostic about theory motivation and instead aim to develop novel phenomenology

Photo credit: SMETEK / Science Photo Library



Where is the new physics?

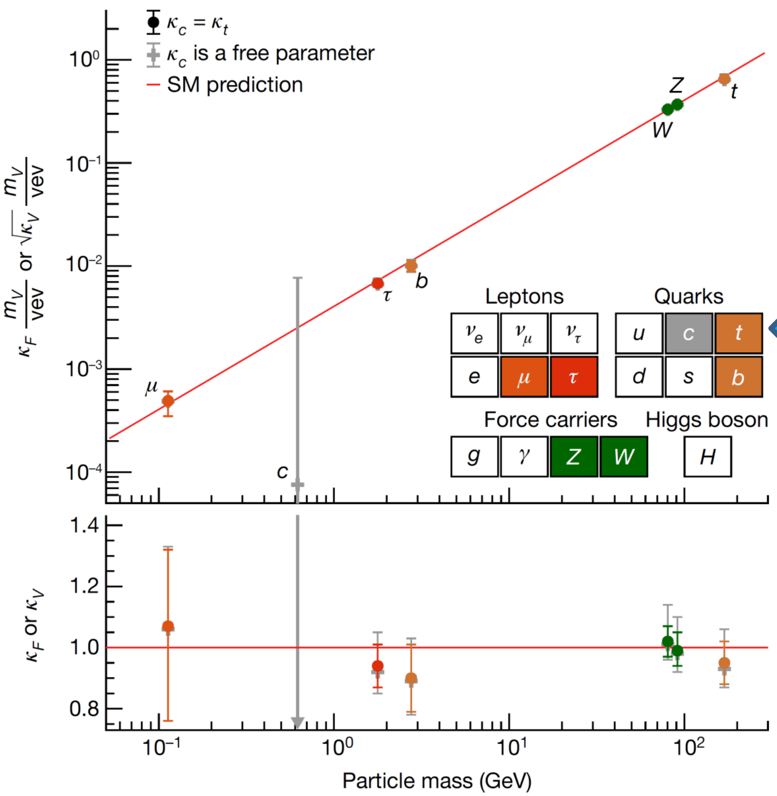
- No guarantees, only soft guiding principles
  - Naturalness
  - Minimality
  - Thus far, fundamental laws of Nature have always exhibited a reduction in dynamical complexity at higher energy scales
    - More symmetric spacetime and more minimal dofs
    - Side remark: Supersymmetry?!
- Decoupling vs. non-decoupling
  - Any new physics model amenable to SMEFT description will smoothly decouple as $\Lambda_{NP} \rightarrow \infty$
    - However, particular NP model classes can exhibit *non-decoupling*
      - E.g. chiral theories, chiral anomalies, UV-IR mixing, gravity effects
  - Viable NP models will always be "just around the corner"
    - State of the art will always be a competition between **direct** probes of Λ_{NP} vs. **indirect** tests via EFT description

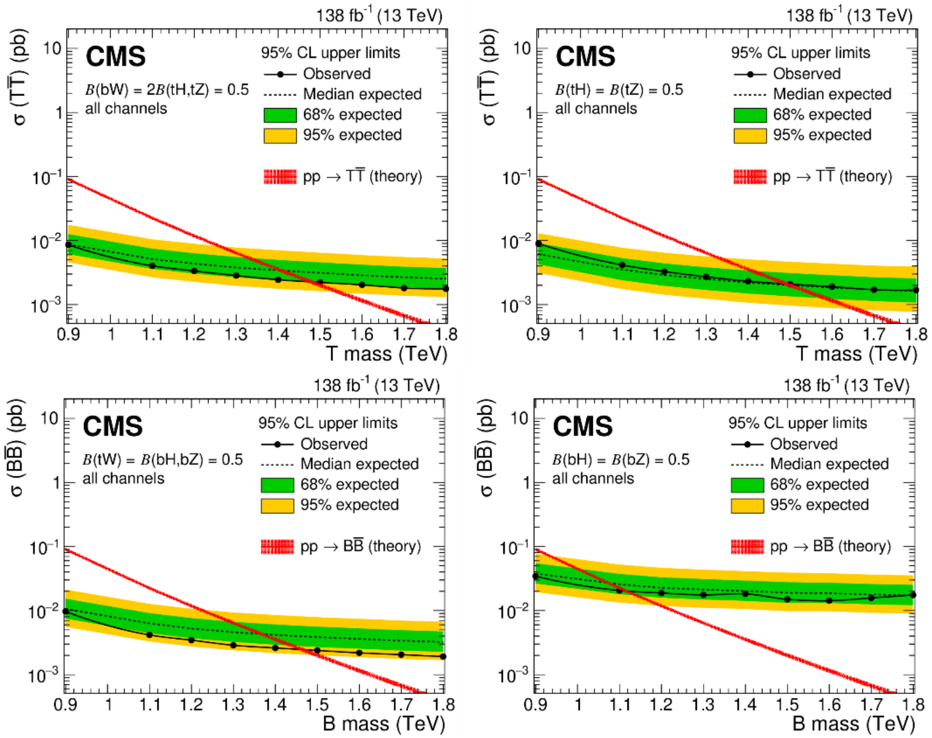
LHC = energy + precision

- Illustrate the interplay of direct and indirect tests via current state of Higgs physics

ATLAS, Nature **607**, 52-59 (2022)

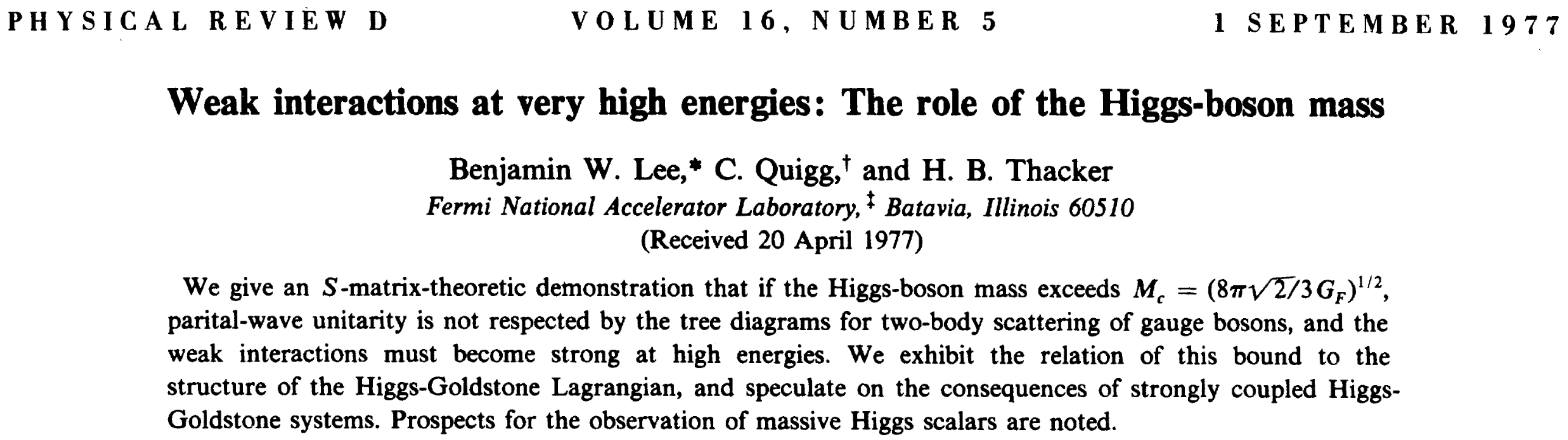
CMS [2209.07327]





Case study: SM Higgs “no-lose” theorem

- SM weak gauge boson scattering results in breakdown of perturbative unitarity if Higgs is absent or if Higgs mass is too heavy



PHYSICAL REVIEW D VOLUME 16, NUMBER 5 1 SEPTEMBER 1977

Weak interactions at very high energies: The role of the Higgs-boson mass

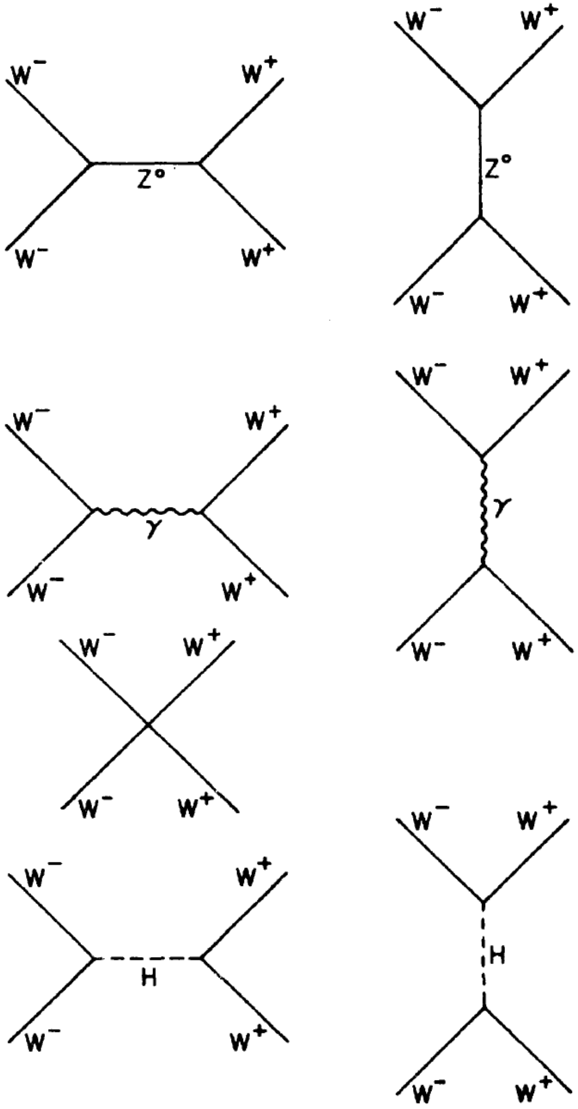
Benjamin W. Lee,* C. Quigg,† and H. B. Thacker
Fermi National Accelerator Laboratory,‡ *Batavia, Illinois 60510*

(Received 20 April 1977)

We give an S-matrix-theoretic demonstration that if the Higgs-boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, parital-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

M_H from perturbative unitarity

- SM calculation of longitudinal gauge boson scattering
- Partial wave expansion of scattering amplitude
- Unitarity on partial wave coefficients dictates M_H bound



$$M_H \leq M_c = (8\pi\sqrt{2}/3G_F)^{1/2} \simeq 1\ \text{TeV}/c^2$$

Lee, Quigg, Thacker (1977)

Reinterpret calculation for non-SM κ_V

s-channel, Z+gamma

$$i\mathcal{M}_{s,\ Z+\gamma} = \frac{ig^2}{m_W^4}\frac{u-t}{4}\left(s + 5m_W^2 + \ldots\right)$$

t-channel, Z+gamma

$$i\mathcal{M}_{t,\ Z+\gamma} = \frac{ig^2}{m_W^4}\frac{t-3m_W^2}{4}\left(-s + u + 8m_W^2 + \ldots\right)$$

quartic

$$i\mathcal{M}_4 = \frac{ig^2}{4m_W^4}\left(s^2 + 4st + t^2 - 4m_W^2(s+t) - \frac{8m_W^2}{s}ut + \ldots\right)$$

s-channel, Higgs

$$i\mathcal{M}_{s,h} = \frac{ig^2}{m_W^2}\left(1 + \frac{m_h^2}{s}\right)\left(-\frac{s}{4} + m_W^2 + \frac{3m_W^4}{s} + \ldots\right)$$

t-channel, Higgs

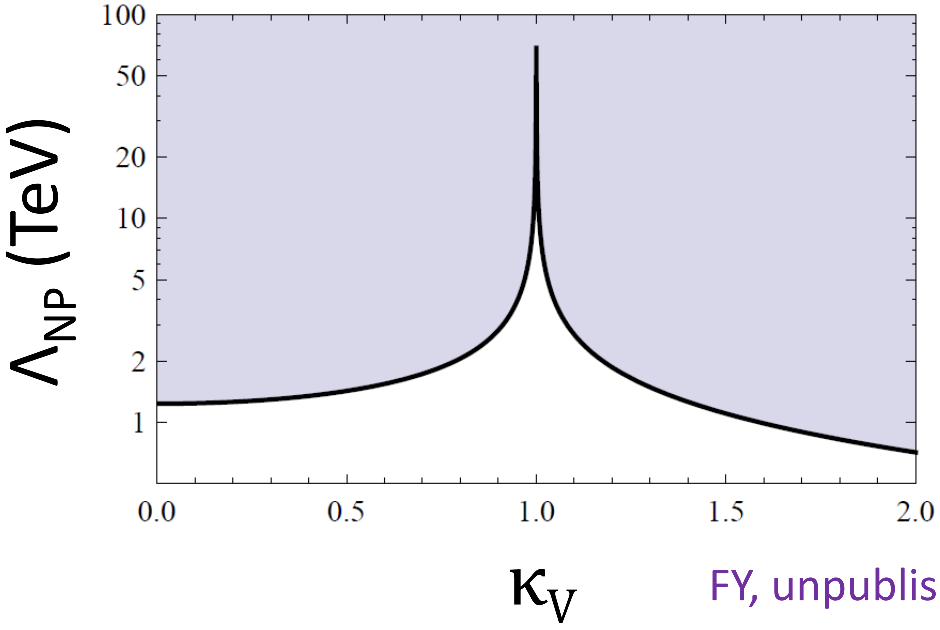
$$i\mathcal{M}_{t,h} = \frac{ig^2}{m_W^2}\left(1 + \frac{m_h^2}{t}\right)\left(-\frac{t}{4} + m_W^2 + \frac{3m_W^4}{t} + \frac{2m_W^2 u}{s} + \ldots\right)$$

New Physics scale from κ_V

- Modifying Higgs amplitudes by κ_V reintroduces unitarity violation

$$i\mathcal{M} = \frac{ig^2}{m_W^2}\left(\frac{u}{4}\left(1-\kappa_V^2\right) - m_W^2\left(3+\kappa_V^2\right) - \frac{u\,m_W^2}{s}\left(6-2\,\kappa_W^2\right)\right)$$

κ_V	Λ_{NP} (TeV)
{0.8, 1.2}	{2.1, 1.9}
{0.9, 1.1}	{2.8, 2.7}
{0.95, 1.05}	{4.0, 3.9}
{0.98, 1.02}	{6.2, 6.1}
{0.99, 1.01}	{8.8, 8.7}
{0.995, 1.005}	{12.4, 12.3}
{0.999, 1.001}	{27.6, 27.6}



FY, unpublished

New Physics scale from κ_V

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κ_V	Λ_{NP} (TeV)
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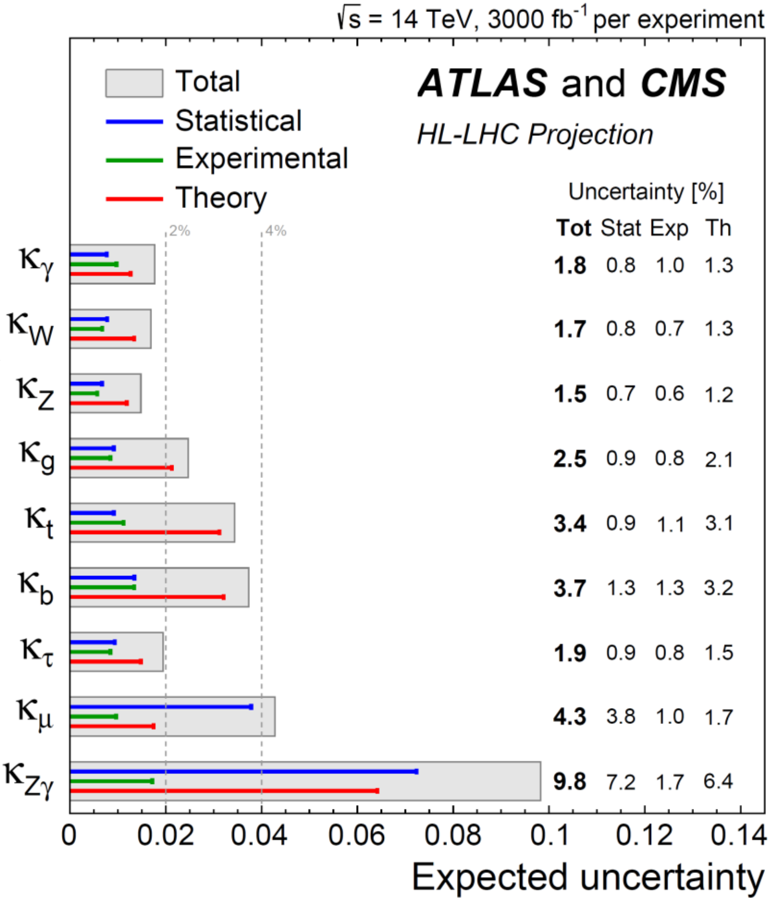
Scales connect here



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

CERN Yellow Report 4

Higgs κ-framework – modern twist

- Realization of a given non-SM κ_V has new particles below Λ_{NP}
  - Manifest in 2HDM models or VLQs/VLLs
- Same for Yukawa couplings
  - For example, $f\bar{f} \to W^+W^-$ scattering breaks unitarity at

$$E_f \simeq \frac{8\pi v^2}{\zeta|m_f - y_f v|}\,, \quad \begin{array}{ccll} \zeta & = & \sqrt{3} & \text{quarks} \\ \zeta & = & 1 & \text{leptons} \end{array}$$

Appelquist, Chanowitz, PRL **59**, 2405 (1987)

κ-matching to dim-6 SMEFT

- Scale of unitarity violation subsumed by adopting dimension-6 effective operators

$$\begin{aligned}\mathcal{L} \quad &\supset \quad y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R \\ &+ \quad y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{ h.c.}\end{aligned}$$

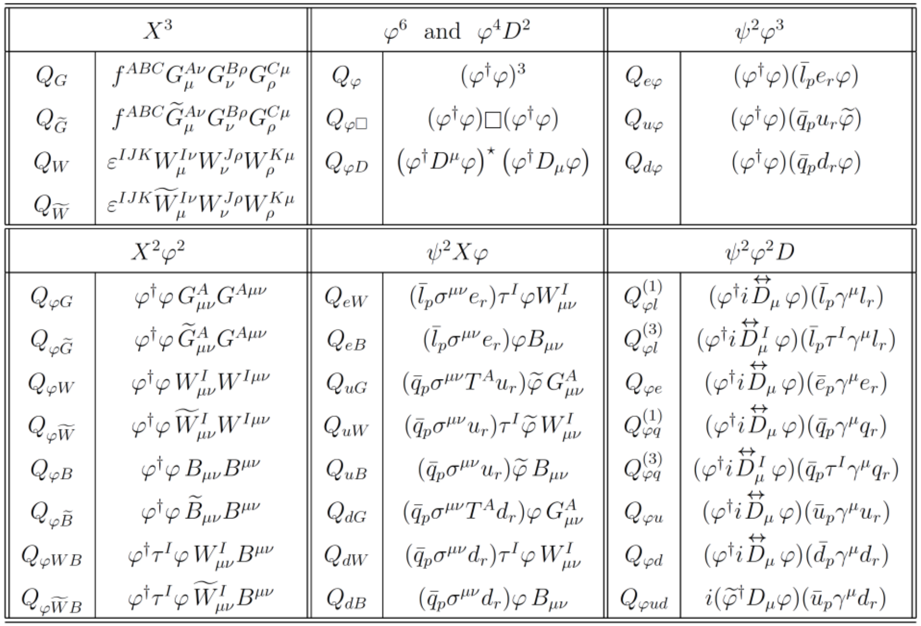
  - Diagonalize masses, obtain Yukawas

$$m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2} \qquad \frac{y_{f,\text{ eff}}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3 y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2 y'_f v^2}{2\sqrt{2}\Lambda^2}$$

  - Resulting Yukawa interactions are not necessarily diagonal or CP-conserving!
  - This is the **New Physics Flavor Problem**

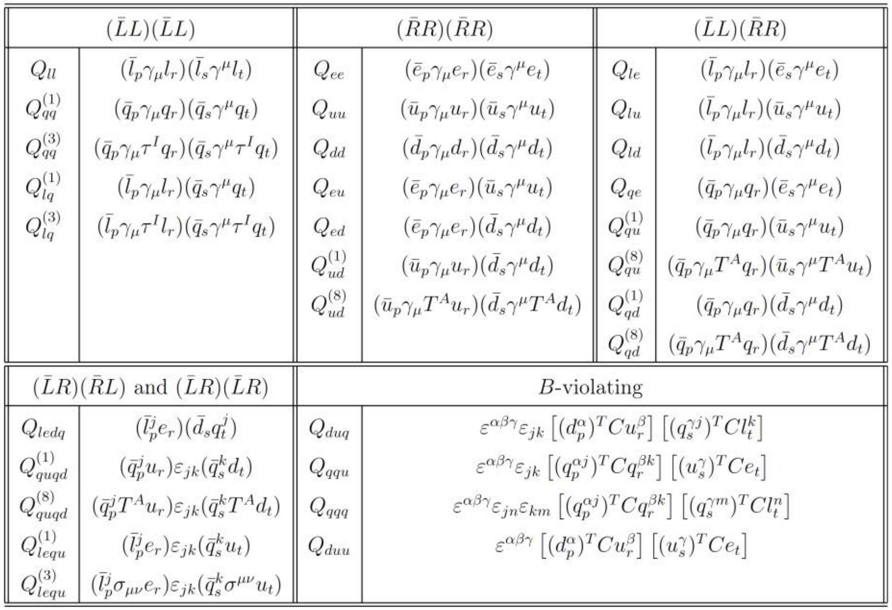
New Physics Flavor Problem and SMEFT

- Dim-6 SMEFT has 76 (one generation) vs. 2499 operators (three generations)
  - Practical requirement: reduce to “physical observables”



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$



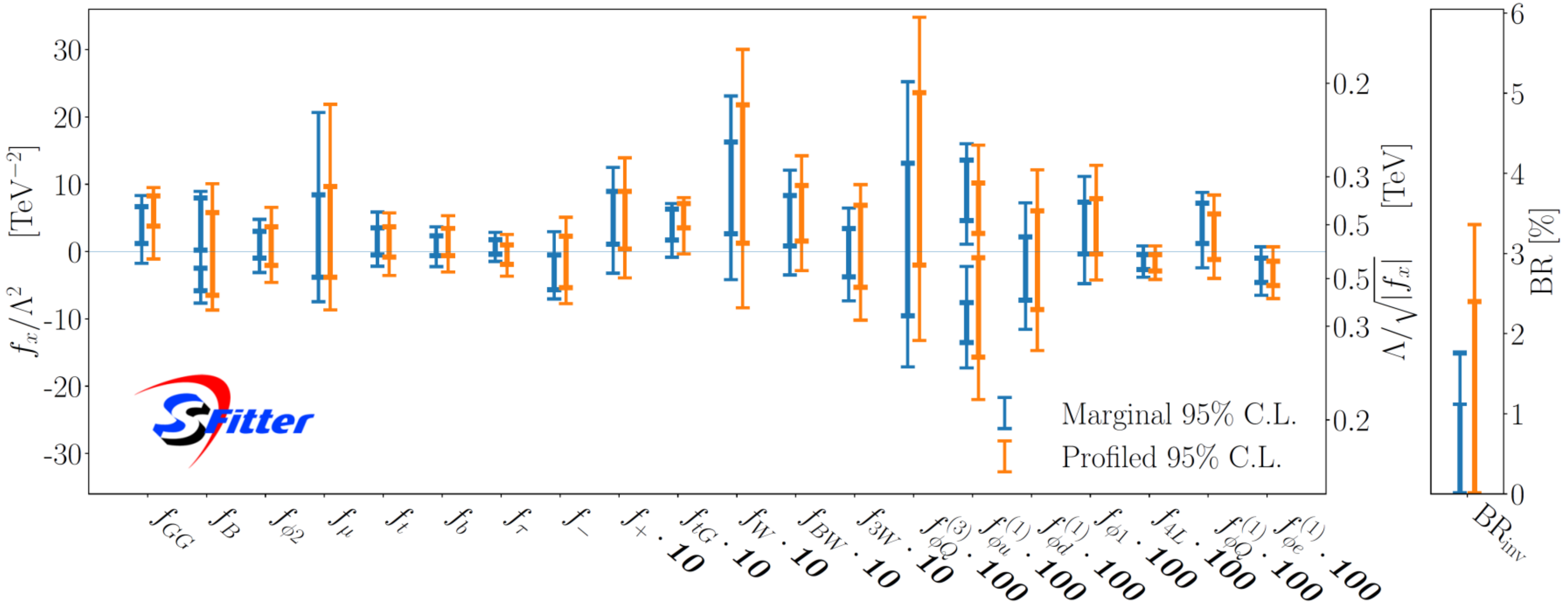
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu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

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

Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]

SMEFT global fit

- Dim-6 SMEFT has 76 (one generation) vs. 2499 operators (three generations)
  - Practical requirement: reduce to "physical observables"



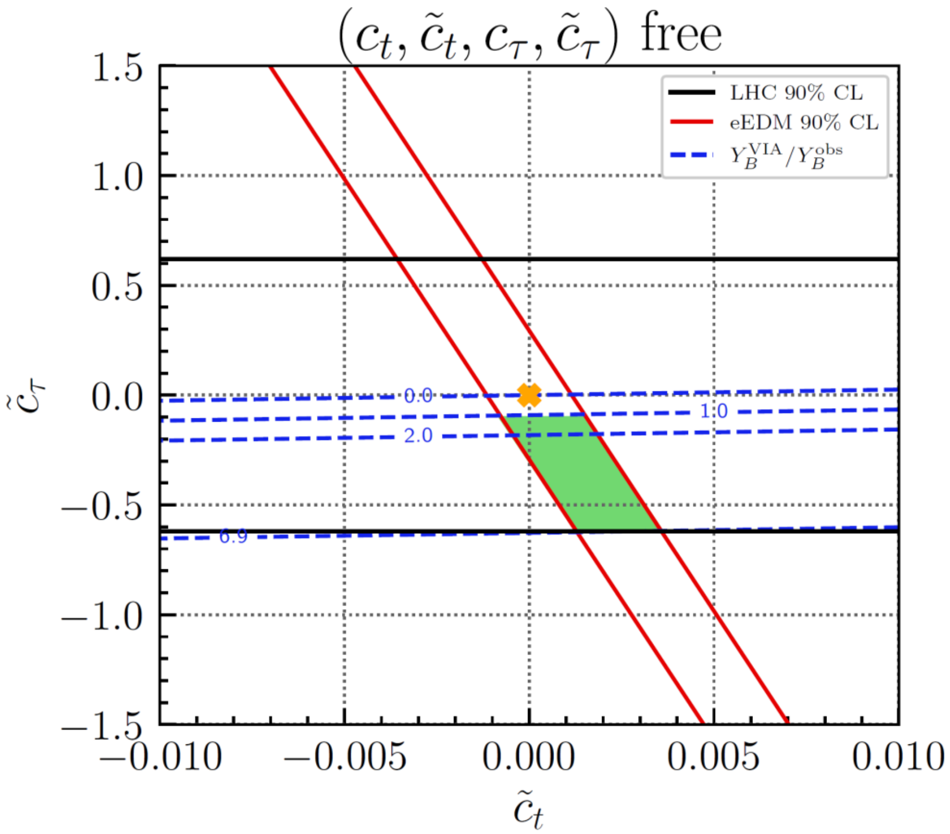
Brivio, Bruggisser, Elmer, Geoffray, Luchmann, Plehn [2208.08454]

New Physics Flavor Problem and SMEFT

- Dim-6 SMEFT has 76 (one generation) vs. 2499 operators (three generations)
  - SMEFT does not increase global flavor symmetry of SM!
  - Generic choice of couplings is excluded by precision flavor measurements, CPV
  - Typically adopt minimal flavor violation, but still motivates new flavor observables and CPV centered around Higgs
    - Connection to baryogenesis CPV

CPV and baryogenesis

- New sources of CPV are generic but highly constrained by EDMs and precision flavor probes



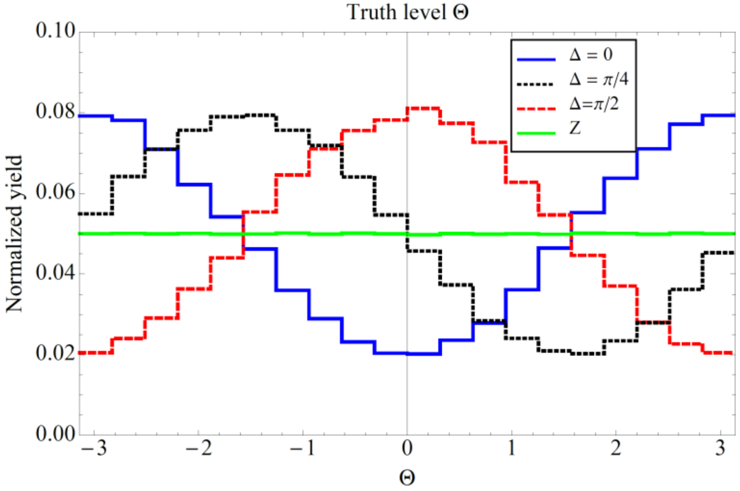
Bahl, Fuchs, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein [2202.11753]

Th-Exp Connection, going differential

- Identified h→ττ as promising decay mode for CPV test

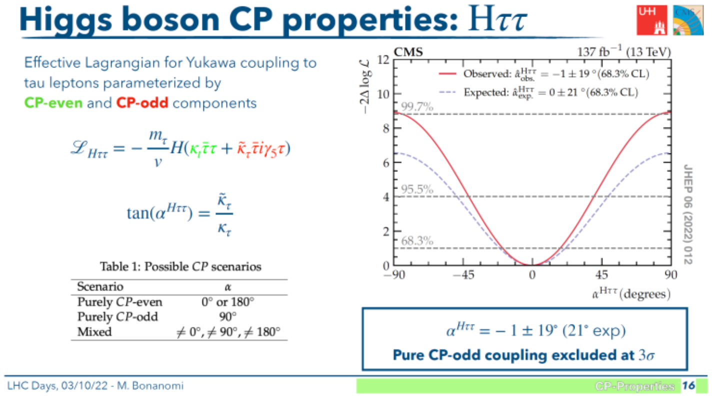
$$\mathcal{L}_{\text{pheno}} \supset -m_\tau \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} h\bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau$$

$$\Theta = \text{sgn}\left[\vec{v}_{\tau+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \text{Arccos}\left[\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+|\,|\vec{E}_-|}\right]$$



Harnik, Martin, Okui, Primulando, FY [1308.1094]

Slide from Matteo Bonanomi [CMS]



Higgs boson CP properties: $H\tau\tau$

Effective Lagrangian for Yukawa coupling to tau leptons parameterized by **CP-even** and **CP-odd** components

$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

Table 1: Possible *CP* scenarios

Scenario	α
Purely *CP*-even	0° or 180°
Purely *CP*-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$

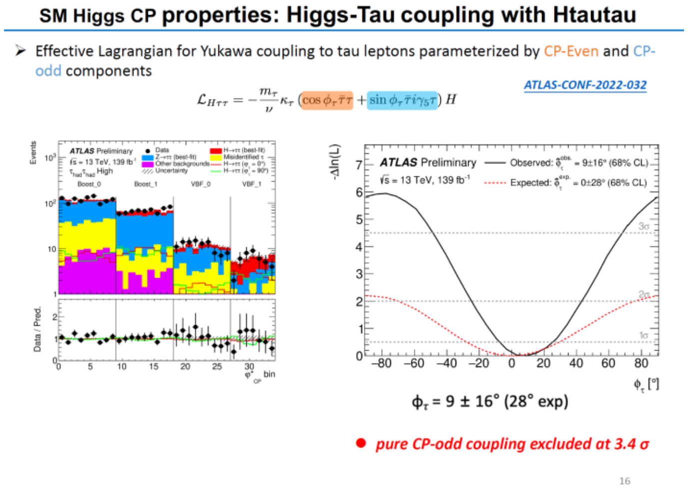
$\alpha^{H\tau\tau} = -1 \pm 19°$ (21° exp)

Pure CP-odd coupling excluded at 3σ

LHC Days, 03/10/22 - M. Bonanomi

CP-Properties 16

Slide from Yanhui Ma [ATLAS]



SM Higgs CP properties: Higgs-Tau coupling with Htautau

- Effective Lagrangian for Yukawa coupling to tau leptons parameterized by CP-Even and CP-odd components

ATLAS-CONF-2022-032

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\nu}\kappa_\tau\left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau\right) H$$

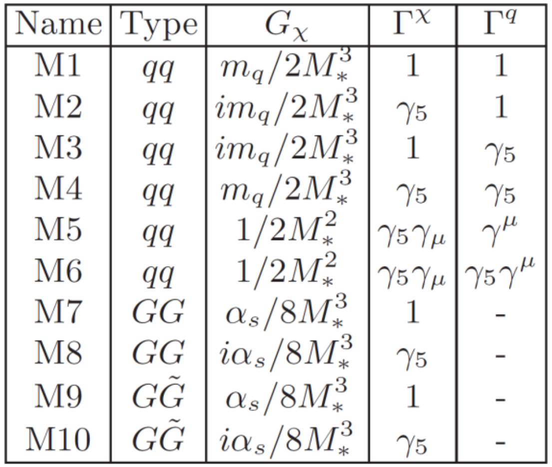
$\phi_\tau = 9 \pm 16°$ (28° exp)

- *pure CP-odd coupling excluded at 3.4 σ*

16

SMEFT caveats

- Aside from NP flavor problem, thinking of BSM = SMEFT precludes the possibility of light dofs
- Biggest reason for new light and hidden dof: DM
  - – MET signature at LHC experiments
  - – Long history for DM EFT leading to simplified models



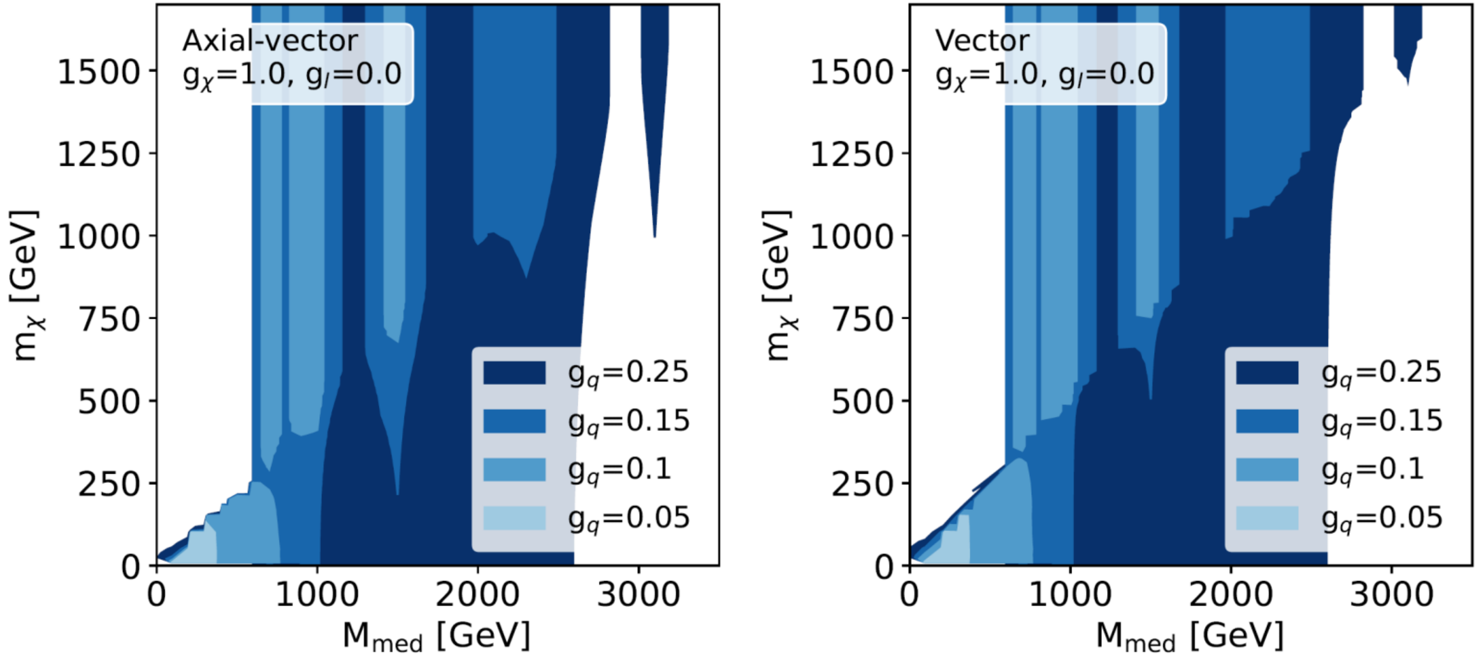
Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

$$\mathcal{L} = G_\chi \, [\bar{\chi}\Gamma^\chi \chi] \times [\bar{q}\Gamma^q q]$$

Goodman, et. al. [1005.1286, 1008.1783],
Bai, Fox, Harnik [1005.3797]

DM EFT caveats

- LHC probes of high energy tails typically invalidates MET+X EFT treatment
  - Resolved by s-channel or t-channel mediator simplified model



Snowmass whitepaper on DM collider constraints [2203.12035]

Reasons for hope: DM at LHC

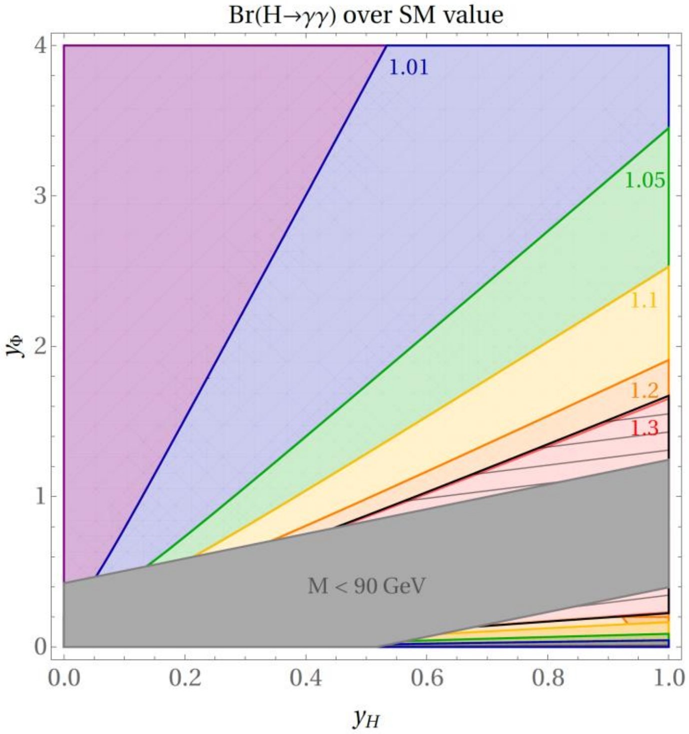
- DM is colorless, EM neutral – how does it couple to SM?
- Portal operators – leading marginal operators to new physics (mediators or DM directly)
  - Scalar Higgs portal $(\mu\phi + \lambda\phi^2)H^\dagger H$
  - Neutrino portal $y_n LHN$
  - Kinetic mixing portal $-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
  - Axion portal (dim. 5) $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$
- Soft principle from quantum theory: anything not *forbidden* (by symmetry) is **mandatory**

DM and Z′ connection

- s-channel simplified model for DM vector coupling to quarks is **leptophobic vector boson**
- Naturally realized as **gauged baryon number Z'_B**

Since baryon number is anomalous, require new chiral fermions – viable only if mainly chiral under baryon number Higgs vev

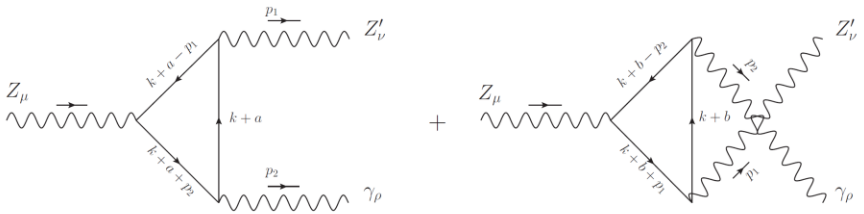
Michaels, FY [2010.00021]

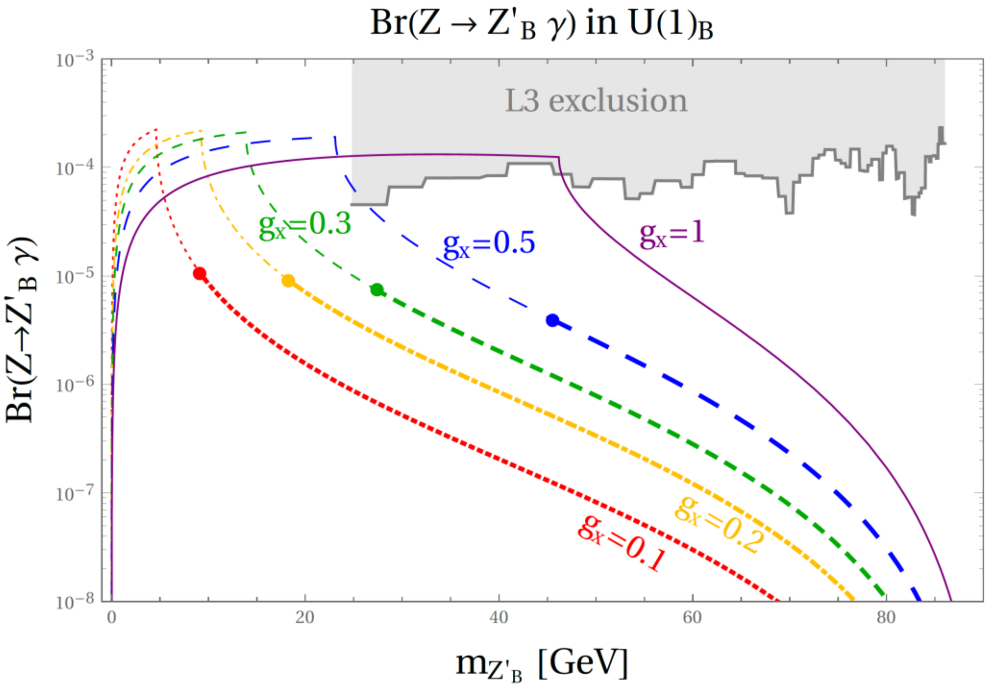


Illustrates **non-decoupling chiral new physics,** another caveat of standard SMEFT

Exotic Z→Z′ γ decay

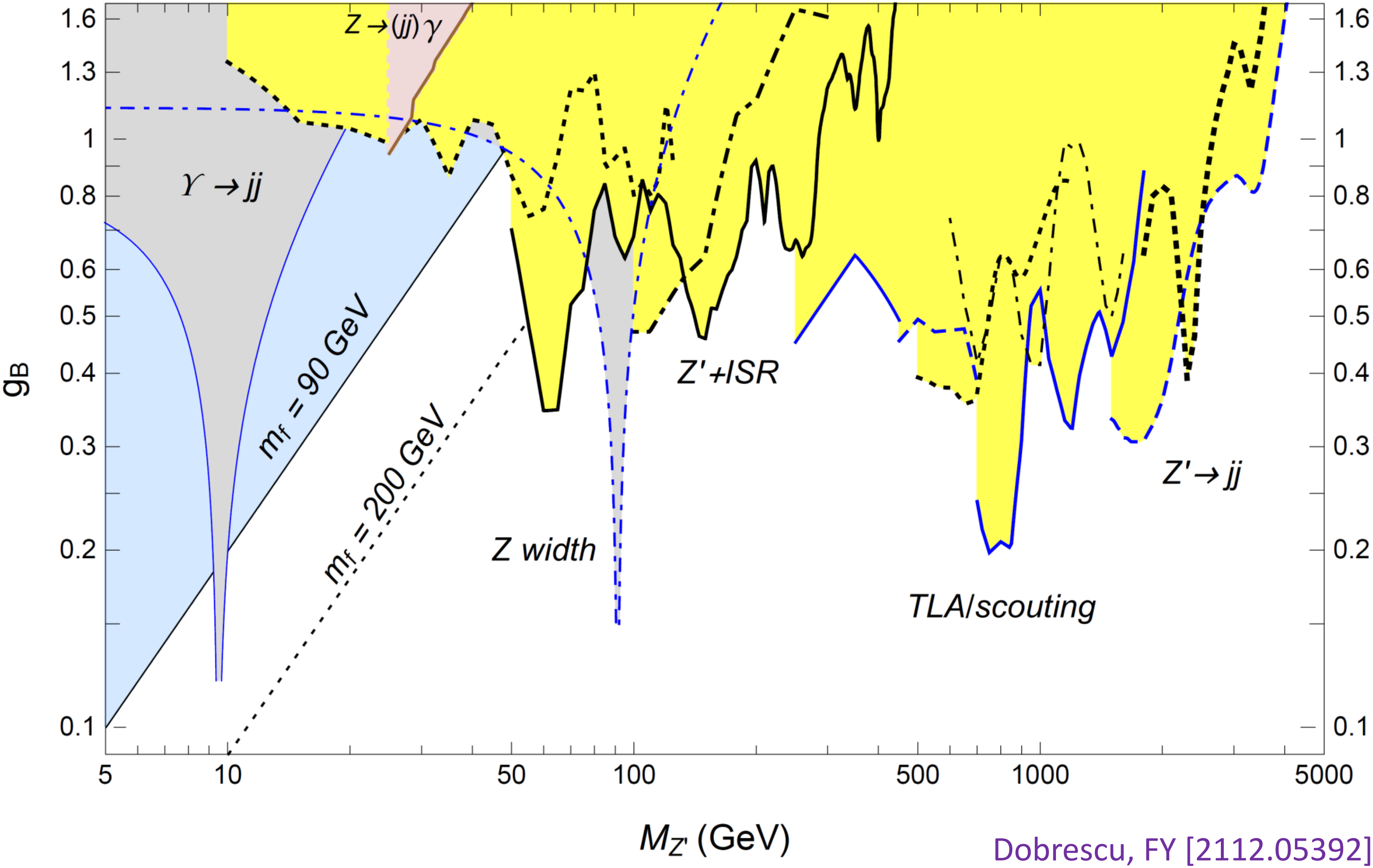
- Unique phenomenology: anomaly-induced Z-Z′-γ vertex
- Signature is exotic Z decay to $(jj)_{res}+\gamma$
- Z′ resonant decay to leptons signature also possible





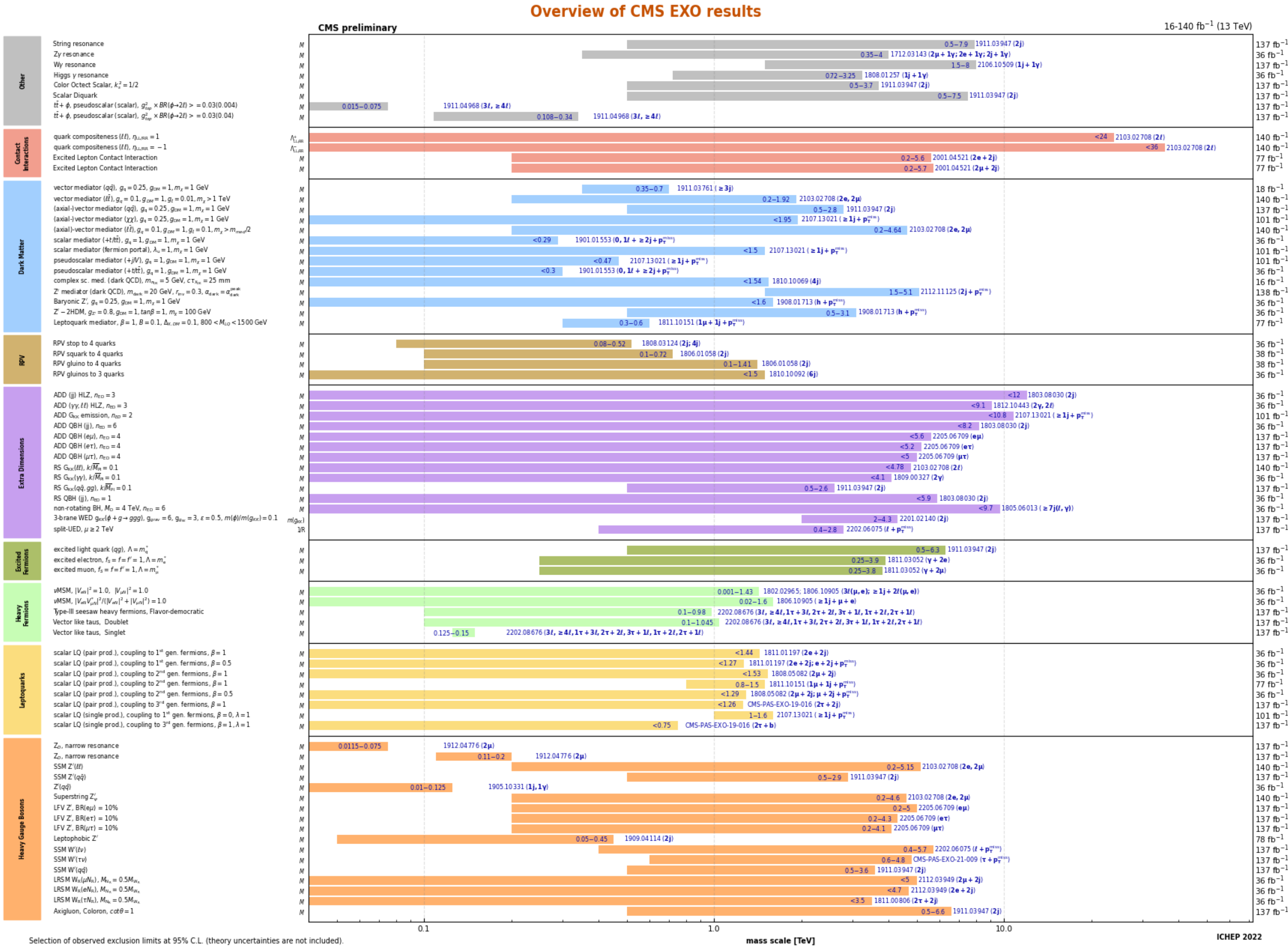
Michaels, FY [2010.00021]

Current status of direct and indirect constraints on baryon-number Z’



Dobrescu, FY [2112.05392]

Wealth of models meets multitude of constraints



Other 2-body resonances

EFT operators

DM simplified models

RPV SUSY

Extra spacetime dimensions

Compositeness

VL fermions

Leptoquarks

Z′, W′ bosons

Navigating model parameters for exotics

- Main rule of thumb: new particles charged under SM gauge symmetries guarantee pair-production cross sections: xsec only depends on mass
  - Examples: LQs, VLQs, VLLs, SUSY
  - Decays and collider signatures are model-dependent (fully visible, cascades, X+MET)
- New vectors: new gauge coupling and mass
  - Limits depend strongly on coupling
  - More informative to present limits in coupling vs. mass plane

Z′ bosons as a standard candle

- Offer one way to organize future collider BSM sensitivity
- New gauge coupling determines production rate, particle width, and lifetime

Robert Harris, FY, co-convenors of "New Bosons" subsection of Snowmass Energy Frontier BSM report [2209.13128]

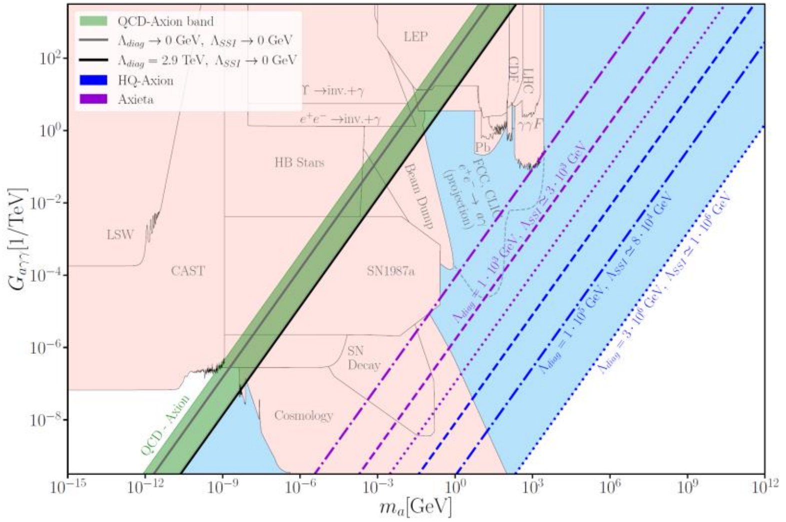
Machine	Type	$\sqrt{s}$ (TeV)	$\int L\,dt$ (ab^{-1})	Source	Z′ Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \rightarrow$ dijet	4.2	**5.2**
				ATLAS	$Z'_{SSM} \rightarrow l^+ l^-$	6.4	**6.5**
				CMS	$Z'_{SSM} \rightarrow l^+ l^-$	6.3	**6.8**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**6**
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	4.9	**7.7**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**7**
HE-LHC/ FNAL-SF	p p	27	15	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**11**
				ATLAS	$Z'_{SSM} \rightarrow e^+ e^-$	12.8	**12.8**
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	8.3	**13**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**13**
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**19**
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_Z'=0.2)$	10	**20**
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	14	**22**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**21**
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**24**
FCC-hh	p p	100	30	R.H.	$Z'_{SSM} \rightarrow$ dijet	25	**32**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**35**
				EPPSU	$Z'_{SSM} \rightarrow l^+ l^-$	43	**43**
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_Z'=0.2)$	42	**70**
VLHC	p p	300	100	R.H.	$Z'_{SSM} \rightarrow$ dijet	67	**87**
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \rightarrow$ dijet	96	**130**

Increasing Z′ Sensitivity

Topics not covered

- Anomalies in current data – **Stathes Paganis**
- Neutrino theory – **Vedran Brdar**
- LFnU – **Damir Becirevic**
- DM theory – **Marco Cirelli**
- $(g\text{-}2)_\mu$ and lattice – **Lukas Varnhorst**
- Precision QCD – **Kresimir Kumericki**
- Machine learning – **Jernej Kamenik**
- Gravity – **Gia Dvali**
- New naturalness and other models
  - Relaxion
  - Clockwork
  - Axions and ALPs
- Lifetime frontier

Highlight: new models for collider scale QCD axions – Kivel, Laux, FY [2207.08740]



Conclusions

- The SM lives on, but only as an effective description of NATURE
- Motivations for new physics remain as urgent as ever
- BSM garden of branching paths: SMEFT and explicit new models
  - Scales of new physics: interplay of direct and indirect searches
  - Decoupling vs. non-decoupling
- LHC is both precision and energy frontier machine

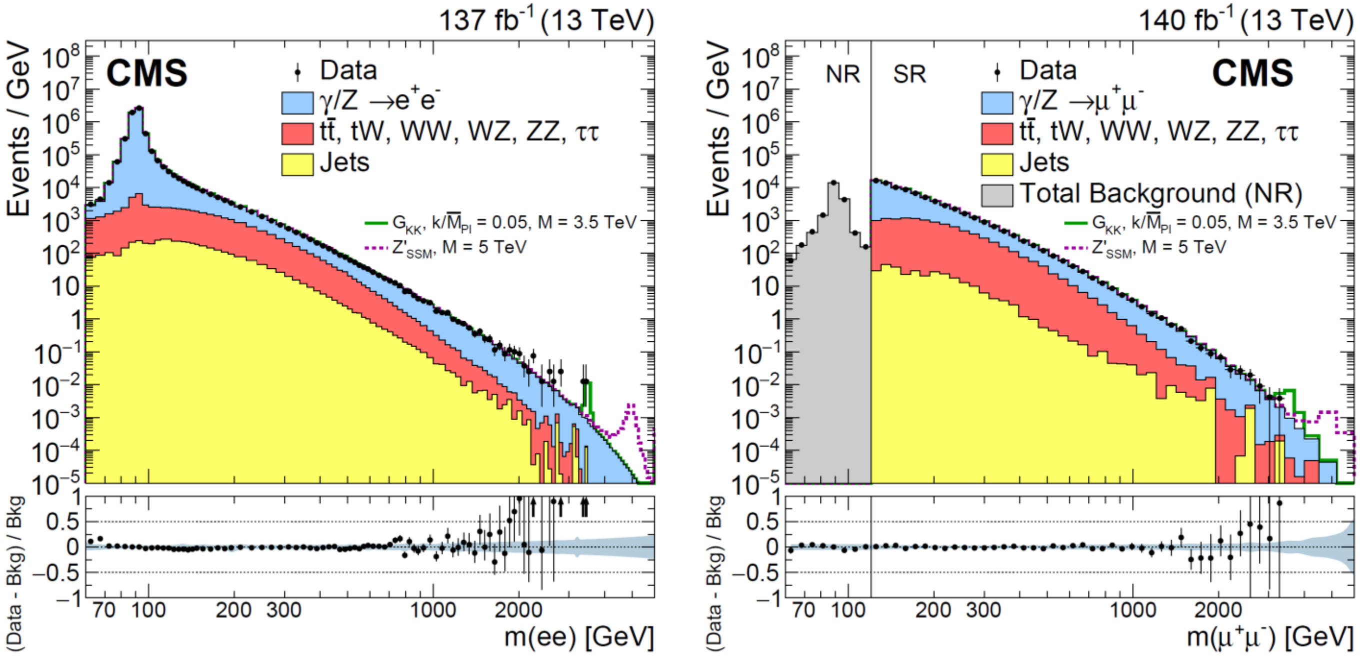
The Standard Model **cannot** be the end of the story – ultimately, precision calculations, discrepant data, and robust interpretations will spell the downfall of the SM

Discovery targets for new physics

- Dark Matter and dark energy
  - WIMPs, light and hidden
- Baryogenesis
  - Electroweak phase transition and triple Higgs coupling
- New particles, new forces
  - Z’/W’/A’ bosons, VLQs, VLLs
- How is the naturalness questions resolved?
  - SUSY, composite Higgs, extra dimensions, new models – relaxion, clockwork
- Origin of neutrinos – Majorana or Dirac
- Strong CP
- New Physics Flavor Problem
- SMEFT and precision SM measurements

Introduction and Motivation

- Z′ bosons are a standard benchmark model for experimental searches
  - SM precision calculations also critical for long tails of distributions



CMS [2103.02708]

Kinetic mixing and mass mixing

- Kinetic mixing operator induces non-unitary field transformations

See, e.g. Liu, Wang, FY [1704.00730]

  - Operator generated by charged matter content under both U(1) currents
  - In EW broken phase, have separate Z and photon kinetic mixings and possible mass mixing with SM Z boson

$$\frac{1}{2} Z_B'^{\mu\nu} \left(\kappa_Z \, Z_{\mathrm{SM}\mu\nu} - \kappa_\gamma F_{\mu\nu}\right) + \Delta M^2_{Z'Z} Z_B'^{\mu} Z_{\mathrm{SM}\mu}$$

    - Real part of 2-pt. amplitude generates kinetic and mass mixing

$$\mathrm{Re}\, \mathcal{A}^{\mu\nu}_{Z'Z} = \kappa_Z \left(g^{\mu\nu} p^2 - p^\mu p^\nu\right) + \Delta M^2_{Z'Z}\, g^{\mu\nu}$$

Kinetic mixing and mass mixing

- When calculating 2-pt. amplitude, necessarily sum over products of charges of fermions

Dobrescu, FY [2112.05392]

$$\mathcal{A}^{\mu\nu} = i\,\frac{g_B g}{c_W} \int_0^1 dx \sum_f N_f \left\{ m_f^2 \left(g_L^f z_R^f + g_R^f z_L^f \right) g^{\mu\nu} I_0^f \right.$$

$$\left. + \left(g_L^f z_L^f + g_R^f z_R^f \right) \left[g^{\mu\nu} I_1^f + x(1-x) \left(g^{\mu\nu} p^2 - 2 p^\mu p^\nu \right) I_0^f \right] \right\} \quad , \qquad (\mathrm{A}.2)$$

$$I_0^f = \frac{-i}{(4\pi)^2} \ln \left(\frac{m_f^2}{\mu^2} - x(1-x) \frac{p^2}{\mu^2} - i\epsilon_0 \right)$$

$$I_1^f = -\left(m_f^2 - x(1-x) p^2 \right) I_0^f \quad ,$$

Kinetic mixing and mass mixing

- When calculating 2-pt. amplitude, necessarily sum over products of charges of fermions

Dobrescu, FY [2112.05392]

$$\mathcal{A}^{\mu\nu} = i\,\frac{g_B g}{c_W} \int_0^1 dx \sum_f N_f \left\{ m_f^2 \left(g_L^f z_R^f + g_R^f z_L^f \right) g^{\mu\nu} I_0^f \right.$$

$$\left. + \left(g_L^f z_L^f + g_R^f z_R^f \right) \left[g^{\mu\nu} I_1^f + x(1-x) \left(g^{\mu\nu} p^2 - 2p^\mu p^\nu \right) I_0^f \right] \right\} \quad , \qquad \text{(A.2)}$$

  - Can eliminate leading log divergence and universal finite remainder via *trace orthogonality* condition
    - Distinct from anomaly cancellation condition

$$\sum_f N_f \left(g_L^f z_L^f + g_R^f z_R^f \right) = 0$$

Finite kinetic mixing

- In our canonical gauged baryon-number $U(1)_B$ model, resulting kinetic mixing is finite and log growth is fixed

$$\kappa_Z \simeq \frac{g_B g}{48\pi^2 c_W}\left[\left(\frac{1}{2}-\frac{4}{3}s_W^2\right)\mathcal{F}(m_t^2/M_Z^2)+\sum_{f=\text{anom.}} N_f\left(g_L^f B_L^f + g_R^f B_R^f\right)\mathcal{F}(m_f^2/M_Z^2)\right]$$

$$\mathcal{F}(m_f^2/M_Z^2) \simeq 2\ \ln\left(\frac{m_f}{M_Z}\right)+\frac{5}{3}-\frac{M_Z^2}{5\,m_f^2}$$

  - – Previous calculations decoupling anomalon sector and reintroduced log divergence e.g. Carone, Murayama [hep-ph/9501220]
    - Not physically realistic given chiral $U(1)_B$ anomalon masses tie together Z′ mass scale with heavy anomalons

Gauged baryon model

- Minimal set of anomalons (SU(2), U(1)$_Y$, U(1)$_B$)
  - Collider pheno like SUSY EWinos

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

- Introduce ϕ as baryon-number Higgs ($Q_B = 3$)

$$\mathcal{L} = -y_L \bar{L}_L \phi^* L_R - y_E \bar{E}_L \phi E_R - y_N \bar{N}_L \phi N_R + \text{ H.c.}$$

- In this construction, tree-level Z-Z′ mixing vanishes
  - Reintroduced logarithmically at anomalon mass scale but cannot be decoupled
  - Can also have tree or loop-generated Higgs-ϕ mixing

EW precision and Z pole constraints

- Kinetic mixing with Z boson constrained by hadronic Z decay width and change in hadronic Z-mediated cross section

PDG, PTEP 2020, 8 083C01 [2020]

$$-5.3 \times 10^{-4} < \frac{\Delta\Gamma_{\text{had}}(Z)}{\Gamma_{\text{had}}^{\text{SM}}(Z)} < 4.3 \times 10^{-3}$$

$$-3.4 \times 10^{-4} < \frac{\Delta\sigma_{\text{had}}}{\sigma_{\text{had}}^{\text{SM}}} < 3.2 \times 10^{-3}$$

  - Leads to direct constraints on g_B, baryon gauge coupling constant

$$g_B < \begin{cases} 0.90\left(1 - \frac{M_{Z'}^2}{M_Z^2}\right)^{1/2} , & \text{for } M_{Z'} \lesssim M_Z - \Gamma_Z \\ 2.6\left(\frac{M_{Z'}^2}{M_Z^2} - 1\right)^{1/2} , & \text{for } M_{Z'} \gtrsim M_Z + \Gamma_Z \end{cases}$$

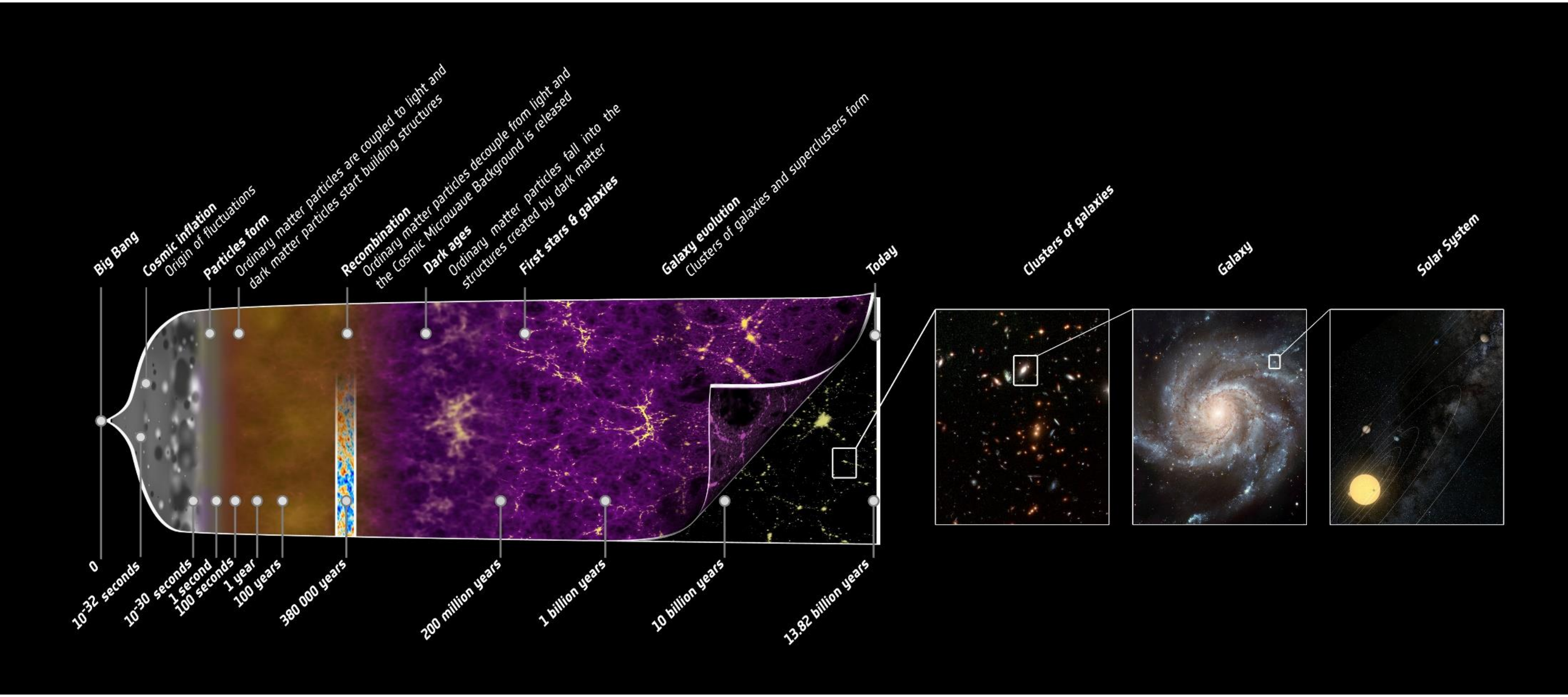
$$g_B^2 + \left[\left(\frac{1 - M_{Z'}/M_Z}{8.7 \times 10^{-3}\, g_B^2}\right)^2 + 0.40\right]^{-1} < \begin{cases} 1.0\left(1 - \frac{M_{Z'}}{M_Z}\right) , & \text{for } \kappa_Z \lesssim 1 - \frac{M_{Z'}}{M_Z} \lesssim \frac{\Gamma_Z}{M_Z} \\ 9.8\left(\frac{M_{Z'}}{M_Z} - 1\right) , & \text{for } \kappa_Z \lesssim \frac{M_{Z'}}{M_Z} - 1 \lesssim \frac{\Gamma_Z}{M_Z} \end{cases}$$

From hadronic Z width

From hadronic Z cross section

Introduction

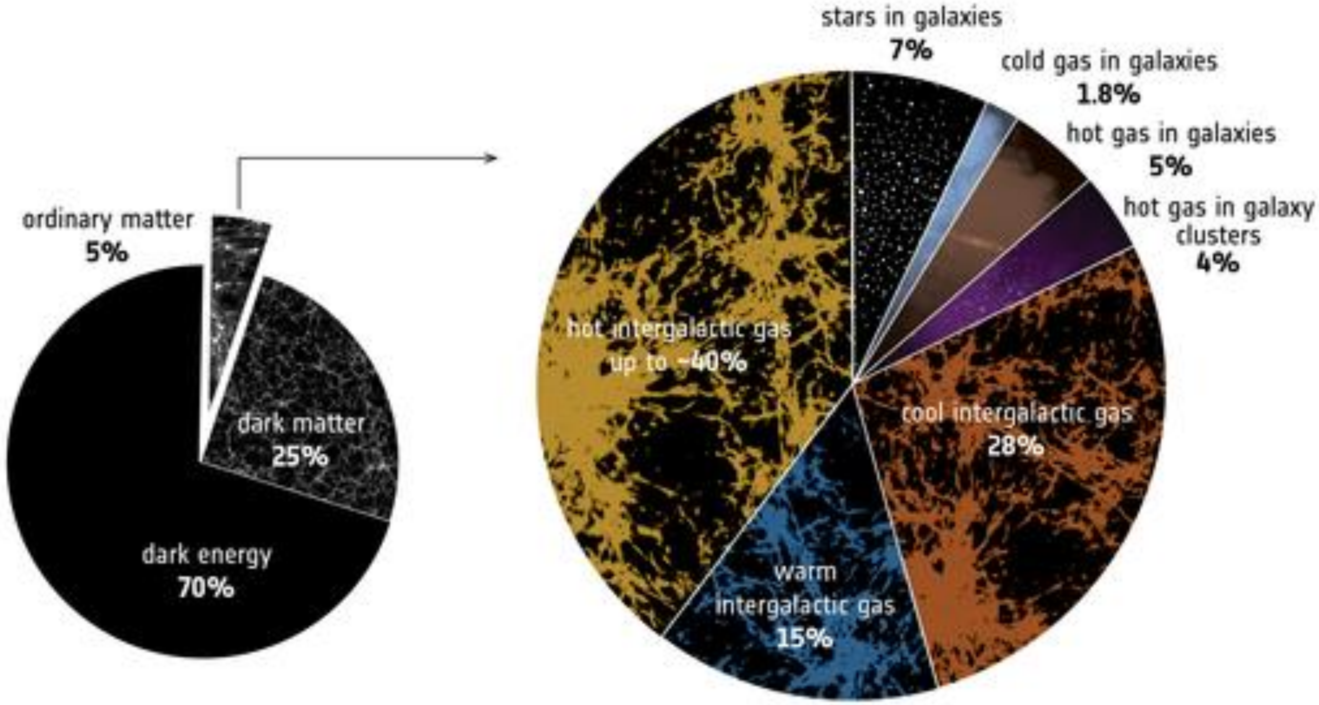
- And span cosmological history of the universe



ESA Planck

What's left to do?

- The Standard Model only accounts for 5% of the matter/energy budget of the universe



ESA

What's left to do?

- Neutrino masses are unexplained
- Origin of the matter/antimatter asymmetry is unexplained
- Dark matter and dark energy

EXISTENTIAL QUESTIONS

- Quantum theory of gravity
- Mass gap in Yang-Mills theory (Millennium problem)

FOUNDATIONAL QUESTIONS

- Are there new dimensions of spacetime?
- Are there new Higgs bosons?
- Are there new gauge symmetries?
- Does Nature realize supersymmetry?

WHAT IS NATURE?

- Strong CP, new physics flavor puzzle, hierarchy problem, cosmological constant…

CLUES TO A NEW THEORY?

Two concrete illustrative models

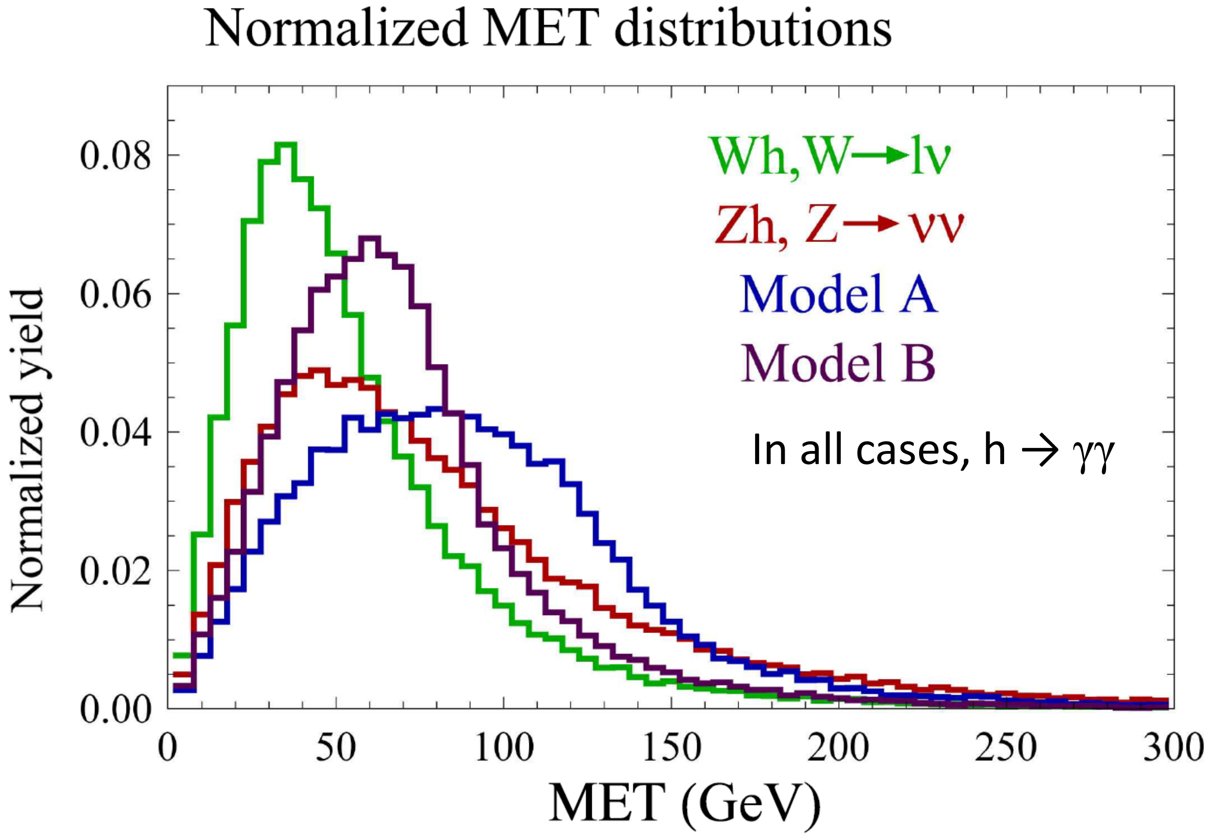
- Use Softsusy + SUSYHIT for spectrum generation and decay tables, Prospino for NLO xsec, micrOMEGAs for relic density
- All other SUSY particles are heavier

Model A	
$\chi_1^{+/-}$	213 GeV
χ_2^0	215 GeV
χ_1^0	57.8 GeV
Br(χ_2^0 to h χ_1^0)	66.2%
Br(χ_2^0 to Z χ_1^0)	33.8%
Br(χ_1^+ to W^+ χ_1^0)	100%
NLO xsec ($\chi_1^{+/-}$ χ_2^0) @ 8 TeV	0.184 pb
Ωh^2	0.0211

Model B	
$\chi_1^{+/-}$	191 GeV
χ_2^0	191 GeV
χ_1^0	61.5 GeV
Br(χ_2^0 to h χ_1^0)	79.1%
Br(χ_2^0 to Z χ_1^0)	20.9%
Br(χ_1^+ to W^+ χ_1^0)	100%
NLO xsec ($\chi_1^{+/-}$ χ_2^0) @ 8 TeV	0.917 pb
Ωh^2	0.117

Testing for exotic production

- Also should look at MET distributions
- Disentangling these shapes requires high-resolution final states (*e.g.* 4l or γγ)



In all cases, h → γγ

Exotic Z decay – complete result

- Anomalons do not decouple from partial width
  - If they only obtain mass from Z’ symmetry breaking

Michaels, FY [2010.00021]

$$\begin{aligned}\Gamma(Z \to Z'_B \gamma) = {} & \frac{\alpha_{\rm EM}\alpha\alpha_X}{96\pi^2 c_W^2}\frac{m'^2_Z}{m_Z}\left(1-\frac{m^4_{Z'}}{m^4_Z}\right) \\ & \Bigg| -\sum_{f\in\,\mathrm{SM}} T_3(f)Q^e_f\left[\frac{m_Z^2}{m_Z^2-m_{Z'}^2}\left(B_0(m_Z^2,m_f)-B_0(m_{Z'}^2,m_f)\right)+2m_f^2C_0(m_f)\right] \\ & +3\left(\frac{m_Z^2}{m_Z^2-m_{Z'}^2}\left(B_0(m_Z^2,M)-B_0(m_{Z'}^2,M)\right)+2M^2\frac{m_Z^2}{m_{Z'}^2}C_0(M)\right)\Bigg|^2 ,\end{aligned}$$

- C_0 and B_0 are usual three-pt., two-pt. scalar integrals
  - Top quark effectively acts as an anomalon

Canonical resonance: Z′ bosons

- Z′ gauge bosons are ubiquitous
  - – GUT extensions, *e.g.* B-L
  - – Simplest Z′ dijet resonance (avoiding dilepton signals) arises in gauged baryon number
    - Revisited as *s*-channel simplified model of DM production
- Lagrangian and branching fraction

$$\mathcal{L}_q = \frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3} \bar{q}_L \gamma^\mu q_L + \frac{1}{3} \bar{q}_R \gamma^\mu q_R \right)$$

$$B(Z'_B \to jj) = \left[1 + \frac{1}{5} \left(1 + \frac{2m_t^2}{M_{Z'}^2} \right) \left(1 - \frac{4m_t^2}{M_{Z'}^2} \right)^{1/2} \right]^{-1}$$

Anomaly cancellation

- Renormalizability in UV requires new chiral fermions
  - VL representations ≡ allow tree-level Dirac mass term ≡ vanishing chiral anomaly contribution
  - Chiral representations ≡ forbidden tree-level Dirac mass term ≡ nonzero chiral anomaly contribution
- Mixed anomalies force introduction of new EW-charged states

Fileviez Perez, Wise [1002.1754]

  - Anomalons do not have to carry color
- Minimal set of anomalons (SU(2), U(1)$_Y$, U(1)$_B$)

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

Chiral anomalies

- Anomalons *are* basically SM leptons, except allow chiral mass under EW symmetry and chiral mass under U(1)$_B$

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

- Field content admits SM-like Yukawas as well as ϕ-coupled Yukawas
  - With both Yukawa terms, would have triangle diagrams with FCNC fermions

$$\begin{aligned}\mathcal{L} = &- y_L \bar{L}_L \phi^* L_R - y_E \bar{E}_L \phi E_R - y_N \bar{N}_L \phi N_R + \text{ H.c.}\\ &- y_1 \bar{L}_L H E_R - y_2 \bar{L}_R \tilde{H} E_L + \text{ H.c.}\end{aligned}$$

Gauged baryon model vs. EW SM

- Same structure in both cases
  - Chiral fermions, spontaneous breaking, Zs and Higgses
- One underlying scale for each chiral symmetry
- Yet, $U(1)_B$ (and any new chiral U(1)′) can exhibit different mass hierarchy pattern than SM
- Consider all Yukawas larger than g_B, λ_B
  - Anomalons are non-decoupling a la top quark in $h \to \gamma\gamma$, $h \to gg$

Gauge anomalies and EFT

- Besides non-decoupling in Higgs physics, chiral fermions also exhibit non-decoupling in gauge interactions
  - Induce Wess-Zumino terms

$$\mathcal{L} \supset g_B g'^2 c_{BB} \epsilon^{\mu\nu\rho\sigma} Z_{B,\mu} B_\nu \partial_\rho B_\sigma$$
$$+ g_B g^2 c_{WW} \epsilon^{\mu\nu\rho\sigma} Z_{B,\mu} (W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} g \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma)$$

Harvey, Hill, Hill
Dror, Lasenby, Pospelov

Calculation details

$$\mathcal{A}^{\mu\nu} = i\,\frac{g_B g}{c_W}\mu^{4-D}\int\frac{d^Dk}{(2\pi)^D}\sum_f\frac{N_f}{\left[(p+k)^2-m_f^2\right]\left(k^2-m_f^2\right)}\left\{m_f^2\left(g_L^f z_R^f+g_R^f z_L^f\right)g^{\mu\nu}\right.$$
$$\left.+\left(g_L^f z_L^f+g_R^f z_R^f\right)\left[p^\mu k^\nu+k^\mu p^\nu+2k^\mu k^\nu-g^{\mu\nu}(p+k)\cdot k\right]\right\} \quad . \qquad \text{(A.1)}$$

$$\mathcal{A}^{\mu\nu} = i\,\frac{g_B g}{c_W}\int_0^1 dx\sum_f N_f\left\{m_f^2\left(g_L^f z_R^f+g_R^f z_L^f\right)g^{\mu\nu}I_0^f\right.$$
$$\left.+\left(g_L^f z_L^f+g_R^f z_R^f\right)\left[g^{\mu\nu}I_1^f+x(1-x)\left(g^{\mu\nu}p^2-2p^\mu p^\nu\right)I_0^f\right]\right\} \quad , \qquad \text{(A.2)}$$

$$\left\{I_0^f\,,\,I_1^f\right\}=\mu^{4-D}\int\frac{d^Dk}{(2\pi)^D}\frac{1}{\left[k^2-m_f^2+x(1-x)p^2\right]^2}\left\{1\,,\,k^2\left(\frac{2}{D}-1\right)\right\}$$

Dobrescu, FY [2112.05392]

Calculation details

$$I_0^f = \frac{-i}{(4\pi)^2} \ln\left(\frac{m_f^2}{\mu^2} - x(1-x)\frac{p^2}{\mu^2} - i\epsilon_0\right)$$

$$I_1^f = -\left(m_f^2 - x(1-x)p^2\right) I_0^f \quad ,$$

$$\kappa_Z = 2\,\frac{g_B g}{c_W} \sum_f N_f \left(g_L^f z_L^f + g_R^f z_R^f\right) \mathrm{Re}\, i \int_0^1 dx\, x(1-x) I_0^f \quad ,$$

$$\Delta M_{Z'Z}^2 = -\frac{g_B g}{c_W} \sum_f N_f\, m_f^2 \left(g_L^f - g_R^f\right)\left(z_L^f - z_R^f\right) \mathrm{Re}\, i \int_0^1 dx\, I_0^f$$

$$\int_0^1 dx\, x(1-x)\, I_0^f = \frac{-i}{6(4\pi)^2}\left[\ln\left(\frac{p^2}{\mu^2}\right) - \frac{5}{3} + \mathcal{F}(m_f^2/p^2) + i\pi\, \mathcal{G}(m_f^2/p^2)\right]$$

$$\mathcal{G}(y) = \theta(1-4y)\ (1+2y)\sqrt{1-4y}$$

$$\mathcal{F}(y) = \ln y - 4y + (1+2y)\,\left|4y-1\right|^{1/2} \times \begin{cases} \ln\left(\dfrac{1+\sqrt{1-4y}}{2y} - 1\right) & \text{for } y \le \dfrac{1}{4} \\ 2\ \arctan\left[(4y-1)^{-1/2}\right] & \text{for } y > \dfrac{1}{4} \end{cases}$$

Dobrescu, FY [2112.05392]

Comparison to GBE

- Our result

$$\Gamma(Z \to Z'\gamma) = \frac{g_B^2 g^2 e^2 m_{Z'}^2 (1 - (m_{Z'}^4/m_Z^4))}{221184\pi^5 c_W^2 m_Z} \times$$
$$\left(9 + 7\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\log(m_{Z'}^2/m_Z^2) + 4m_t^2 C_0(0, m_Z^2, m_{Z'}^2, m_t, m_t, m_t)\right.$$
$$\left. +2\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}(B_0(m_Z^2, m_t, m_t) - B_0(m_{Z'}^2, m_t, m_t))\right)^2$$

- Dror, et. al.: Replace Z' by Goldstone, only consider anomaly coupling
  - Ignores poles in finite form factors that cancel anomaly

$$\mathcal{L} = \frac{\mathcal{A}}{16\pi^2}\frac{g_X \varphi}{m_X} 2gg' Z_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Gamma(Z \to X\gamma) = 1.1 \times 10^{-5} \mathcal{A}^2 g_X^2 \left(\frac{100\ \text{GeV}}{m_X}\right)^2$$

Dror, Lasenby, Pospelov [1705.06726]

New gauge bosons and broken symmetries

- Consider augmenting SM by new U(1)′ symmetry
  - Directly charge SM fields under U(1)′
  - Flavor constraints imply U(1)′ should be subgroup of $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
    - Common examples: $U(1)_{B-L}$, $L_\mu - L_\tau$
- Since EW symmetry is chiral, most global symmetry choices are anomalous

Preskill (1991)

  - Renormalizability in UV requires new chiral fermions
  - Mixed anomalies force introduction of new EW-charged states $\mathcal{A}(SU(2)^2 \times U(1)_B) = \frac{3}{2}$ $\mathcal{A}(U(1)_Y^2 \times U(1)_B) = \frac{-3}{2}$

Gauge anomalies and EFT

- After EWSB (and $U(1)_B$) breaking, generate an effective Z-Z′-γ vertex
- Naively proportional to $U(1)_B$ anomaly
  - Calculate exotic Z decay width
  - Non-decoupling behavior is subtle
    - Anomalons must cancel their own anomaly contribution via mass-dependent non-decoupling limit
  - Inherent ambiguity in evaluation of triangle loop is entire motivation for ABJ chiral anomaly

WIP with L. Michaels