ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

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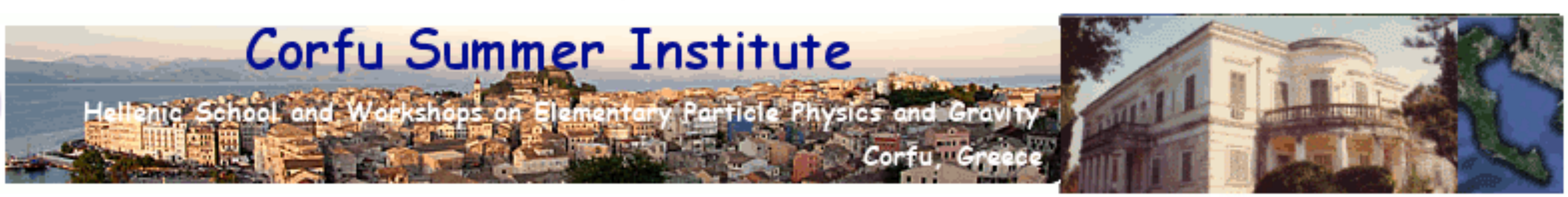
STATUS OF THE SUPERWEAK EXTENSION OF THE STANDARD MODEL

based on

arXiv:1812.11189 (*Symmetry*), 1911.07082 (*PRD*), 2104.11248 (*JCAP*), 2104.14571 (*PRD*), 2105.13360 (*J.Phys.G*), 2204.07100 (*PRD*), 2301.07961 (*JHEP*), 2301.06621 (PRD), 2305.11931 (PRDL)

with S. Iwamoto, T.J. Kärkkäinen, I. Nándori, Z. Péli, K. Seller, Zs. Szép

Corfu, 5 September, 2023



OUTLINE

1. Motivation: status of particle physics (see many talks of last week)
2. Superweak $U(1)_z$ extension of SM (SWSM)
3. Neutrino masses (see my talk at Corfu 2021)
4. Dark matter candidate (see my talk at Corfu 2021)
5. Vacuum stability and scalar sector constraints
6. Contribution to M_W (see talk by Zoltán Péli Sunday evening)
7. Constraints from non-standard interactions (will not have time)
8. Conclusions

MOTTO

Rough estimates of BSM effects
can easily be deceptive

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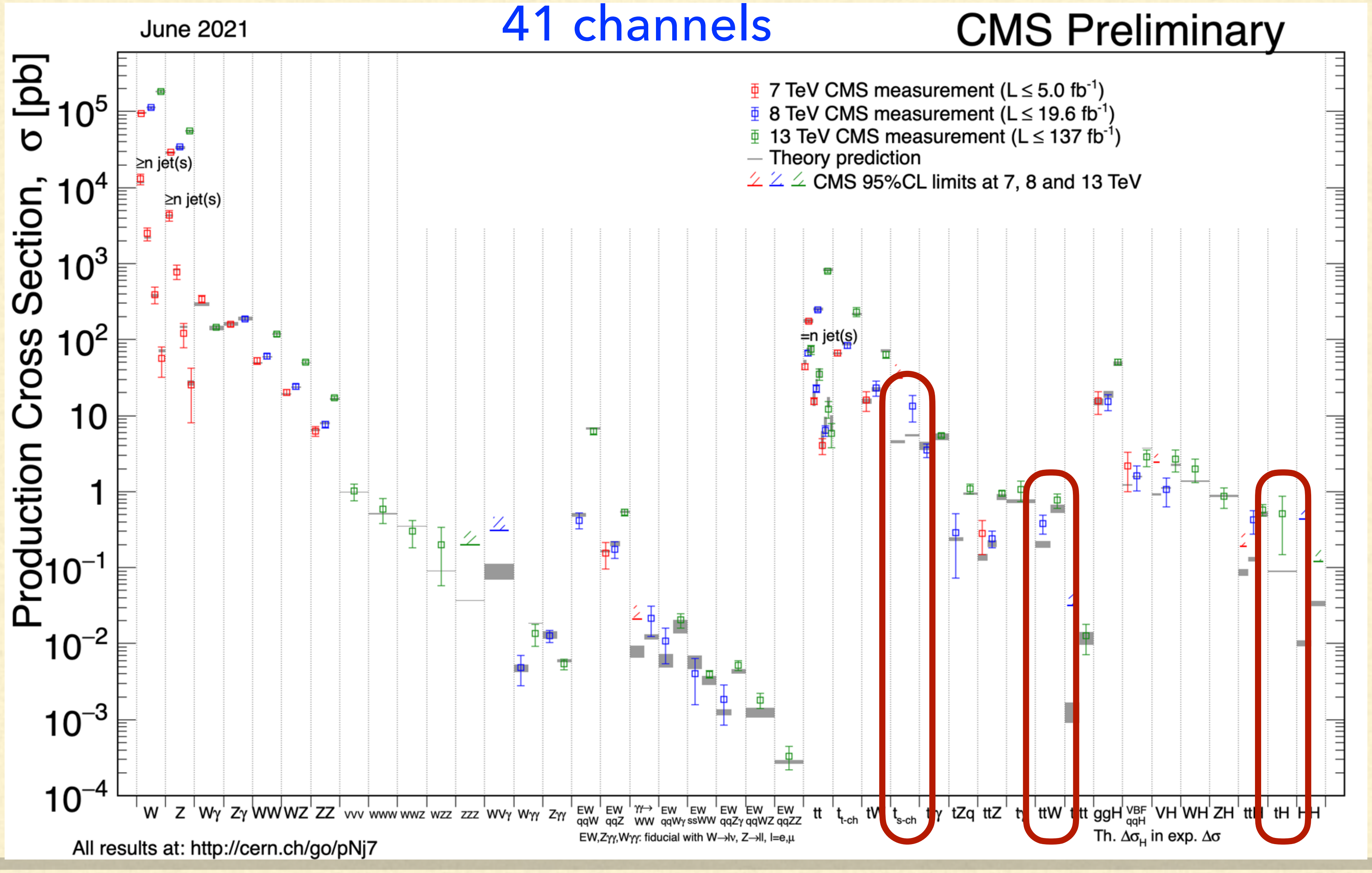
example: discovery of the Higgs particle came much faster than expected at the time of construction of the LHC because the

- detector performance was
- theoretical prediction for Higgs production was significantly

underestimated

Status of particle physics: energy frontier

- Colliders: SM describes final states of particle collisions precisely [talk by E. Rossi]



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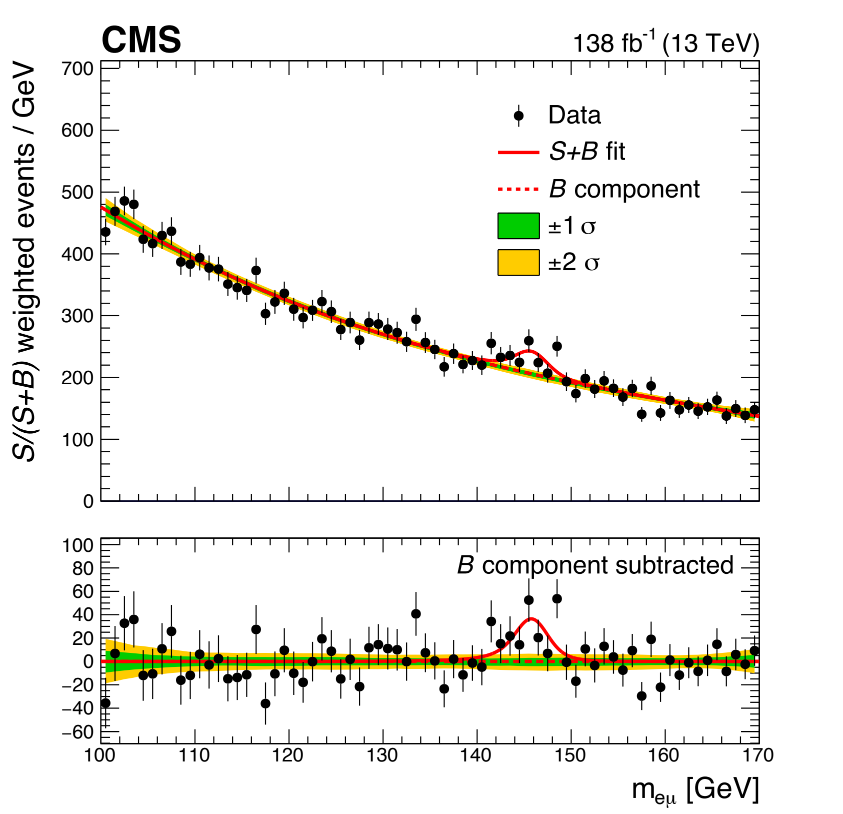

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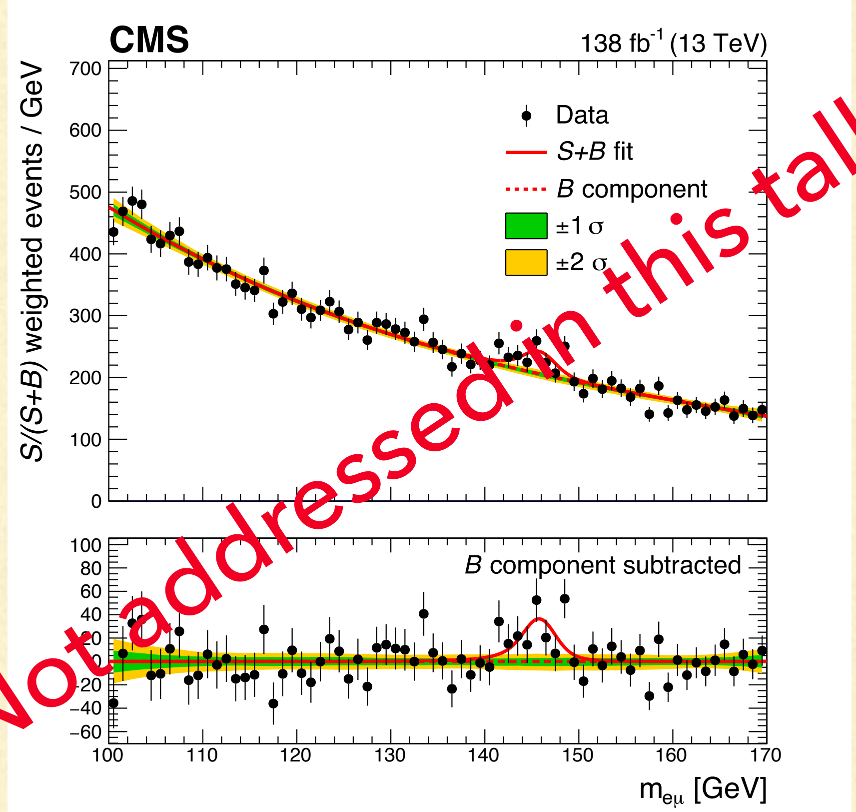

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Status of particle physics: energy frontier

- Colliders: SM describes final states of particle collisions precisely
- No proven sign of new physics beyond SM at colliders
- SM vacuum is metastable

[Bezrukov et al, arXiv:1205.2893; Degrassi et al, arXiv:1205.6497]

Status of particle physics: cosmic and intensity frontiers

- Universe at large scale described precisely by cosmological SM: ΛCDM ($\Omega_m = 0.3$)
- Neutrino flavours oscillate
- Existing baryon asymmetry cannot be explained by CP asymmetry in SM
- Inflation of the early, accelerated expansion of the present Universe

[https://pdg.lbl.gov]

Established observations require physics beyond SM, but do not suggest rich BSM physics

Phenomenological approach to new physics

Can we explain these observations,
but not more,
by the same model?

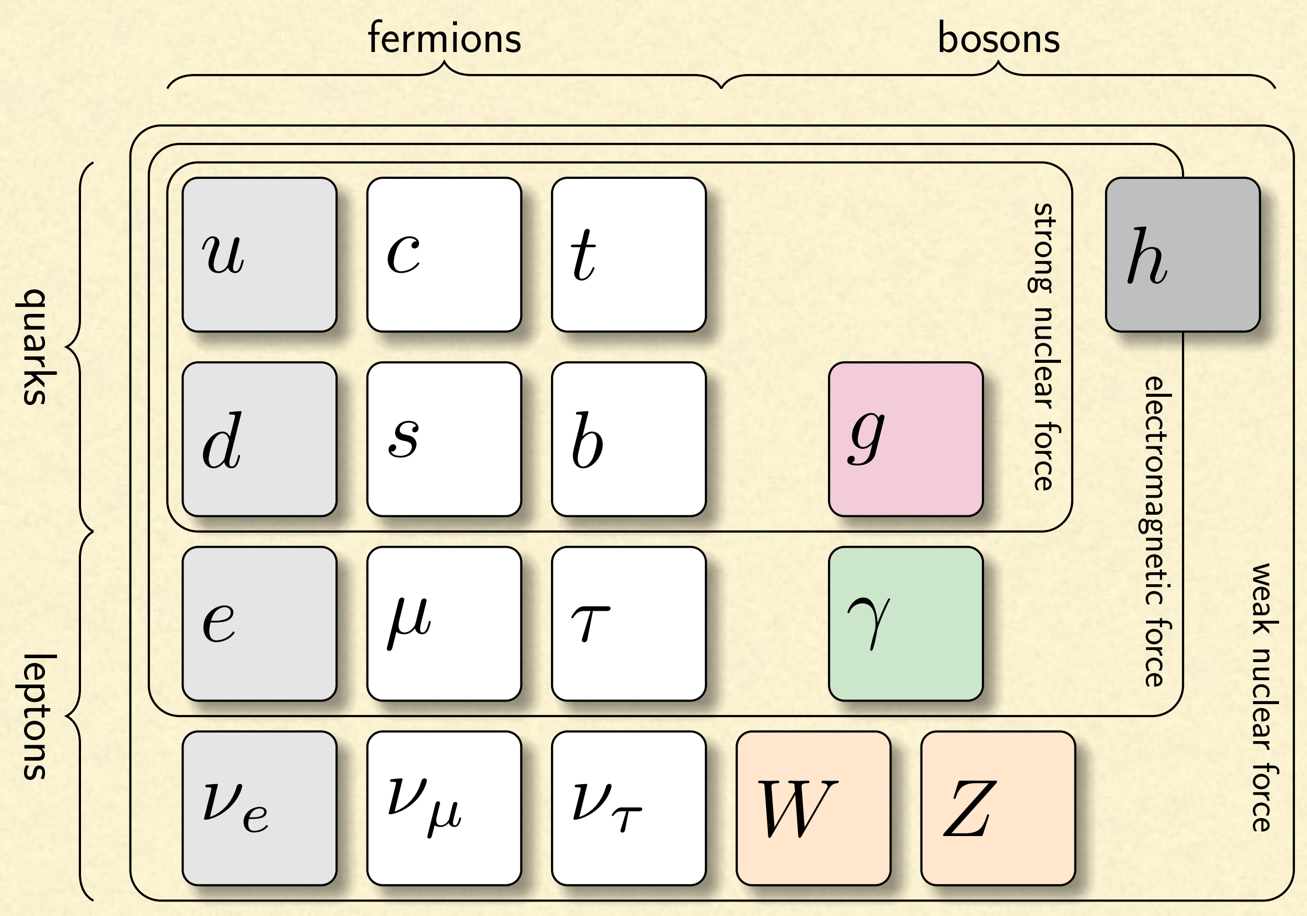
Extension of SM: three alternatives with different strength and weaknesses

- Effective field theory, such as SMEFT: general but highly complex (2499 dim 6 operators), focuses on new physics at high scales

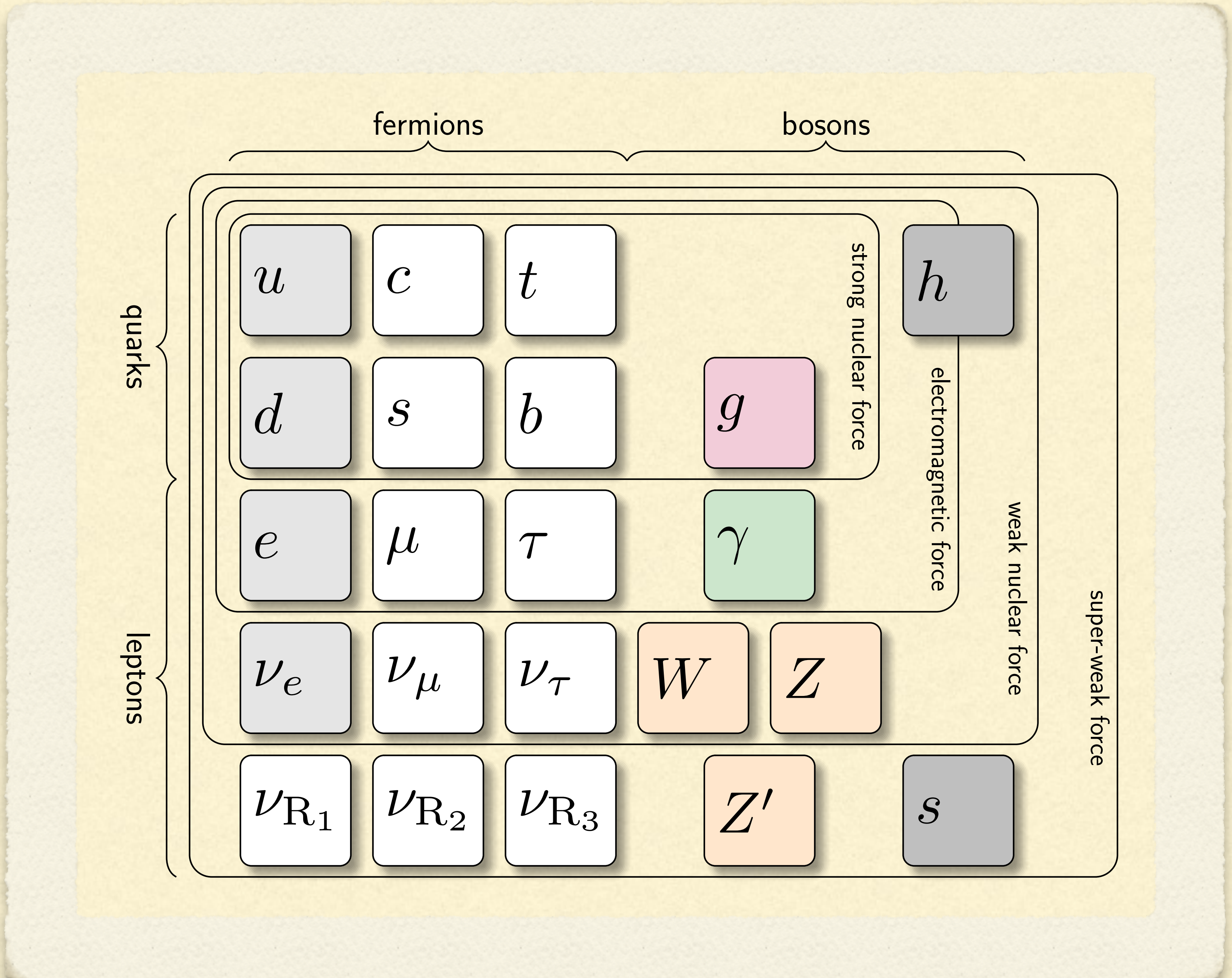
- Simplified models, such as dark photon, extended scalar sector or right-handed neutrinos: "easily accessible" phenomenology, but focus on specific aspect of new physics, so cannot explain all BSM phenomena

- UV complete extension with potential of explaining BSM phenomena within a single model such as SuperWeak extension of the Standard Model: SWSM

Particle content of SM



Particle content of SWSM
(take-home picture)



Superweak extension of SM (SWSM)

- Symmetry of the Lagrangian: local $G = G_{SM} \times U(1)_z$ with $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

renormalizable gauge theory, including all dim 4 operators allowed by G

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renormalizable gauge theory, including all dim 4 operators allowed by G

- *z*-charges fixed by requirement of
  - gauge and gravity anomaly cancellation and
  - gauge invariant Yukawa terms for neutrino mass generation

Mixing in the neutral gauge sector

$$\begin{pmatrix} B_\mu \\ W^3_\mu \\ B'_\mu \end{pmatrix} = \begin{pmatrix} \mathrm{c}_W & -\mathrm{s}_W & 0 \\ \mathrm{s}_W & \mathrm{c}_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{c}_Z & -\mathrm{s}_Z \\ 0 & \mathrm{s}_Z & \mathrm{c}_Z \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

$$c_X = \cos\theta_X$$
$$s_X = \sin\theta_X$$

where θ_W is the weak mixing angle & θ_Z is the $Z - Z'$ mixing, implicitly: $\boxed{\tan(2\theta_Z) = -2\kappa / \left(1 - \kappa^2 - \tau^2\right)}$, with κ and τ effective couplings, functions of the Lagrangian couplings

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The expressions for the neutral gauge boson masses are somewhat cumbersome, but exists a nice, compact generalization of the SM mass-relation formula: $\dfrac{M_W^2}{c_W^2} = c_Z^2 M_Z^2 + s_Z^2 M_{Z'}^2$

Scalars in the SWSM

- Standard Φ complex $SU(2)_L$ doublet and new χ complex singlet:

$$\mathcal{L}_{\phi,\chi} = [D_\mu^{(\phi)}\phi]^* D^{(\phi)\,\mu}\phi + [D_\mu^{(\chi)}\chi]^* D^{(\chi)\,\mu}\chi - V(\phi,\chi)$$

- with scalar potential

$$V(\phi,\chi) = V_0 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 + \left(|\phi|^2, |\chi|^2\right)\begin{pmatrix}\lambda_\phi & \frac{\lambda}{2}\\ \frac{\lambda}{2} & \lambda_\chi\end{pmatrix}\begin{pmatrix}|\phi|^2\\ |\chi|^2\end{pmatrix}$$

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- After SSB, G → SU(3)$_c$×U(1)$_{QED}$ in R_ξ gauge

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} -\mathrm{i}\sqrt{2}\sigma^+ \\ v + h' + \mathrm{i}\sigma_\phi \end{pmatrix} \quad \& \quad \chi = \frac{1}{\sqrt{2}}(w + s' + \mathrm{i}\sigma_\chi)$$

Mixing in the scalar sector

$$\begin{pmatrix} h' \\ s' \end{pmatrix} = \begin{pmatrix} c_S & s_S \\ -s_S & c_S \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

where θ_S is the scalar mixing angle implicitly:

$\tan(2\theta_S) = \lambda v w / \left(\lambda_\chi w^2 - \lambda_\phi v^2\right)$, with v and w VEVs

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5 (+1 less important) new parameters:

- in gauge sector: {κ and τ} or {θ_Z and $M_{Z'}$} (+a mixing coupling)
- in scalar sector: {w, λ_χ and λ} or {M_S, θ_S and λ}

After SSB neutrino mass terms appear

$$-\mathcal{L}_Y^\ell = \frac{w + s' + \mathrm{i}\sigma_\chi}{2\sqrt{2}} \overline{\nu_R^c}\, \mathbf{Y}_N\, \nu_R + \frac{v + h' - \mathrm{i}\sigma_\phi}{\sqrt{2}} \overline{\nu_L}\, \mathbf{Y}_\nu\, \nu_R + \mathrm{h.c.}$$

$$\boxed{\mathbf{M}_N = \frac{w}{\sqrt{2}} \mathbf{Y}_N} \qquad \boxed{\mathbf{M}_D = \frac{v}{\sqrt{2}} \mathbf{Y}_\nu}$$

- In flavour basis the full 6×6 mass matrix reads $\mathbf{M}' = \begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N \end{pmatrix}$

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- In flavour basis the full 6×6 mass matrix reads $\mathbf{M}' = \begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N \end{pmatrix}$
- ν_L and ν_R have the same q-numbers, can mix, leading to type-I see-saw
- Dirac and Majorana mass terms appear already at tree level by SSB (not generated radiatively)
- Quantum corrections to active neutrinos are not dangerous [Iwamoto et al, arXiv:2104.14571]

Expected consequences (take-home messages)

- Dirac and Majorana neutrino mass terms are generated by the SSB of the scalar fields, providing the origin of neutrino masses and oscillations
[Iwamoto, Kärkäinnen, Péli, ZT, arXiv:2104.14571; Kärkkäinen and ZT, arXiv:2105.13360]
- The lightest new particle is a natural and viable candidate for WIMP dark matter if it is sufficiently stable [Seller, Iwamoto and ZT, arXiv:2104.11248]
- Diagonalization of neutrino mass terms leads to the PMNS matrix, which in turn can be the source of lepto-baryogenesis
[Seller, Szép, ZT, arXiv:2301.07961 talk by Károly Seller on Sunday and under investigation]
- The second scalar together with the established BEH field can stabilize the vacuum and be related to the accelerated expansion now and inflation in the early universe
[Péli, Nándori and ZT, arXiv:1911.07082; Péli and ZT, arXiv:2204.07100]

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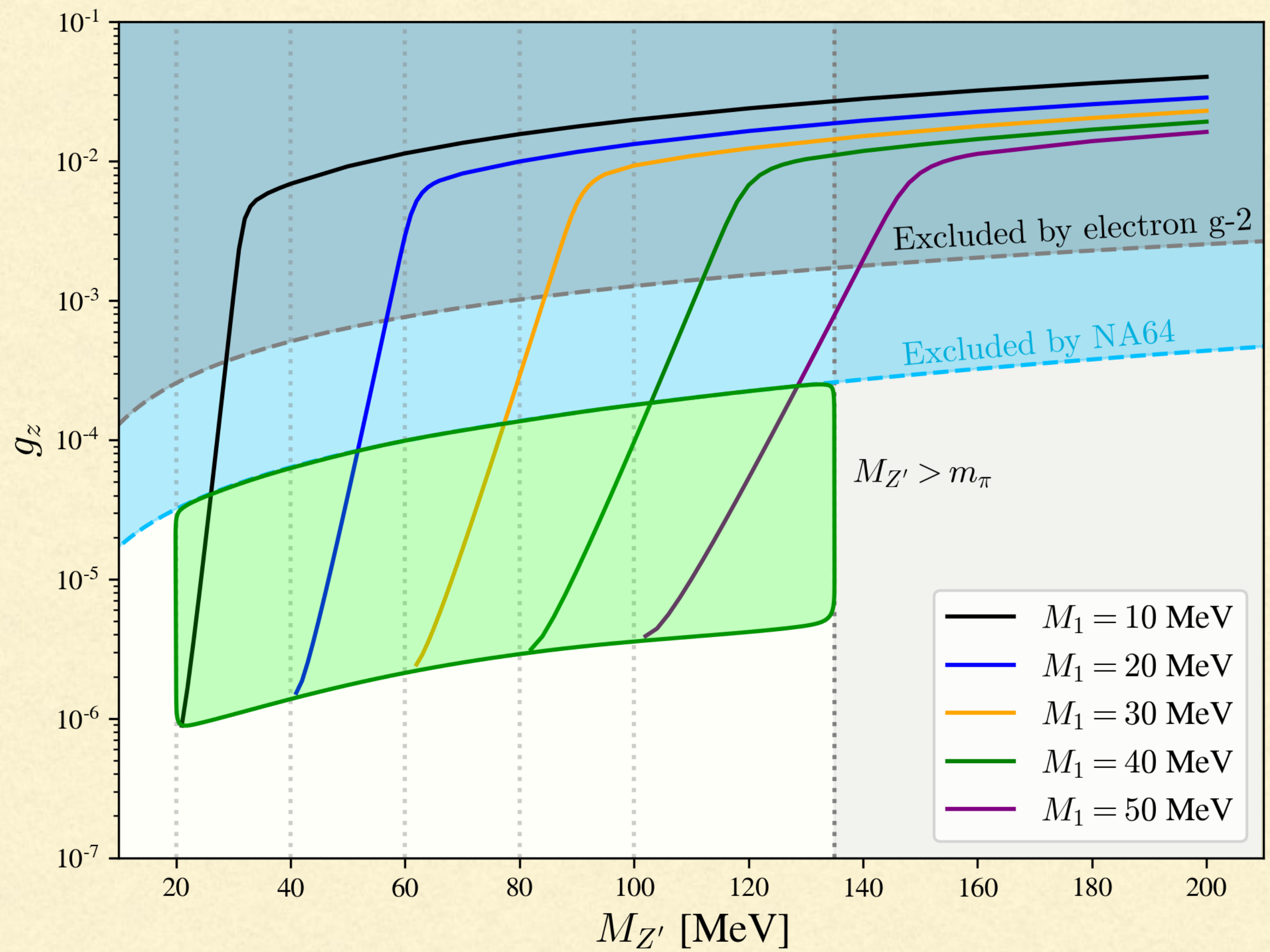
Dark matter candidate

- DM exists, but known evidence is based solely on the gravitational effect of the dark matter on the luminous astronomical objects and on the Hubble-expansion of the Universe
- Assume that the DM has particle origin
- Only chance to observe such a particle if it interacts with the SM particles, which needs a portal

In the superweak model the vector boson portal Z' with the lightest sterile neutrino ν_4 as dark matter candidate is a natural scenario (Higgs portal exists, but negligible)

Parameter space for the freeze-out scenario of dark matter production in the SWSM

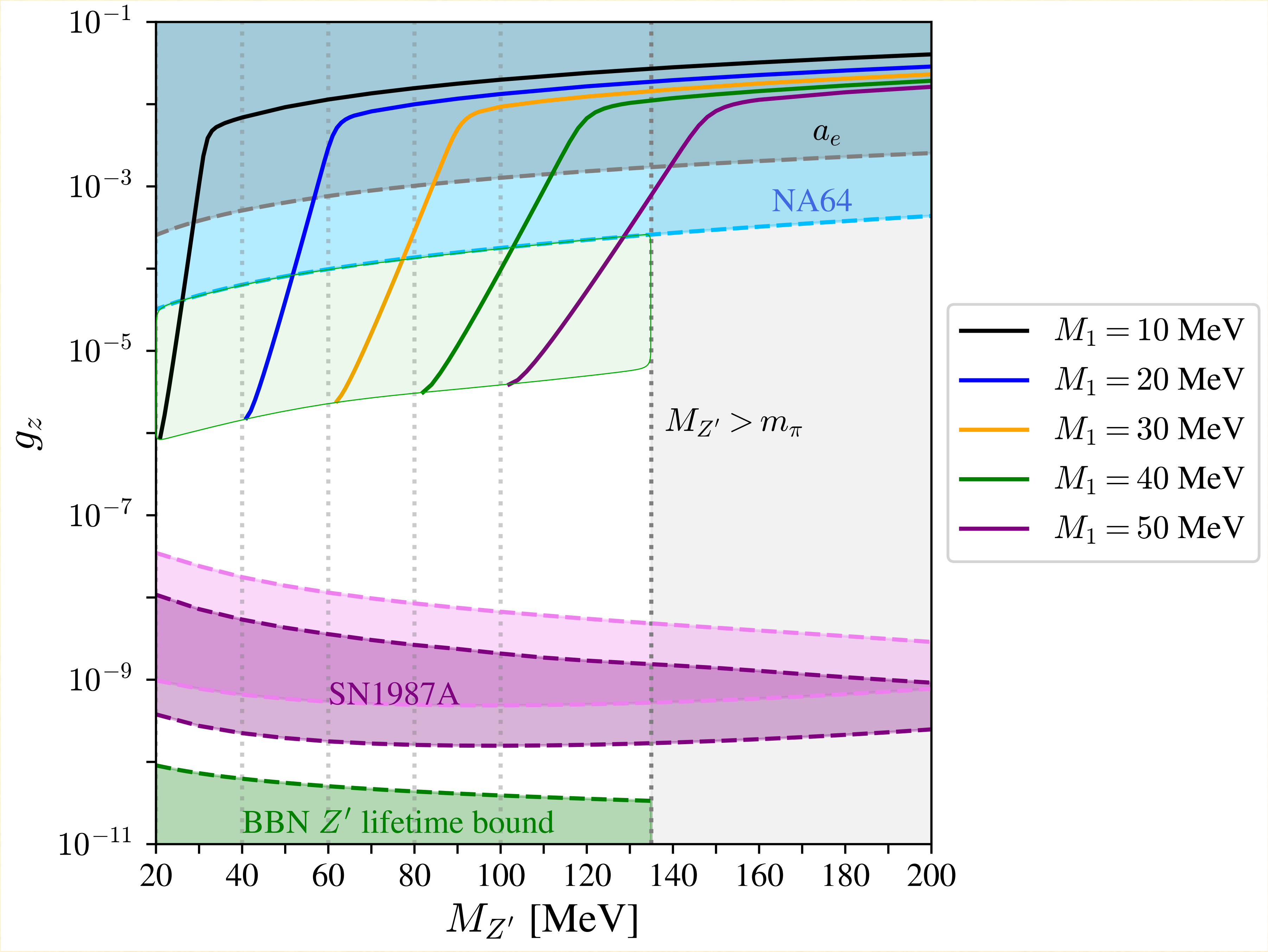


It is essential for the SWSM DM candidate that the resonance in SM+SM $\rightarrow Z' \rightarrow$ DM+DM can dominate the integral in the rate

Experimental constraints

- Anomalous magnetic moment of electron and muon
  - Z' couples to leptons modifying the magnetic moment
  - Constraints on $(g-2)$ translate to upper bounds on the coupling $g_z(M_{Z'})$
- NA64 search for missing energy events
  - Strict upper bounds on $g_z(M_{Z'})$ for any U(1) extension (dark photons)
- Supernova constraints based on SN1987A
  - Constraints are based on comparing observed and calculated neutrino fluxes
- Big Bang Nucleosynthesis provides constraints on new particles
  - New particles should have negligible effects during BBN
  - Meson production can be dangerous close to BBN
- Further constraints are due to CMB, solar cooling, beam dump experiments etc.

Cosmological constraints on the freeze-out scenario of dark matter production in the SWSM



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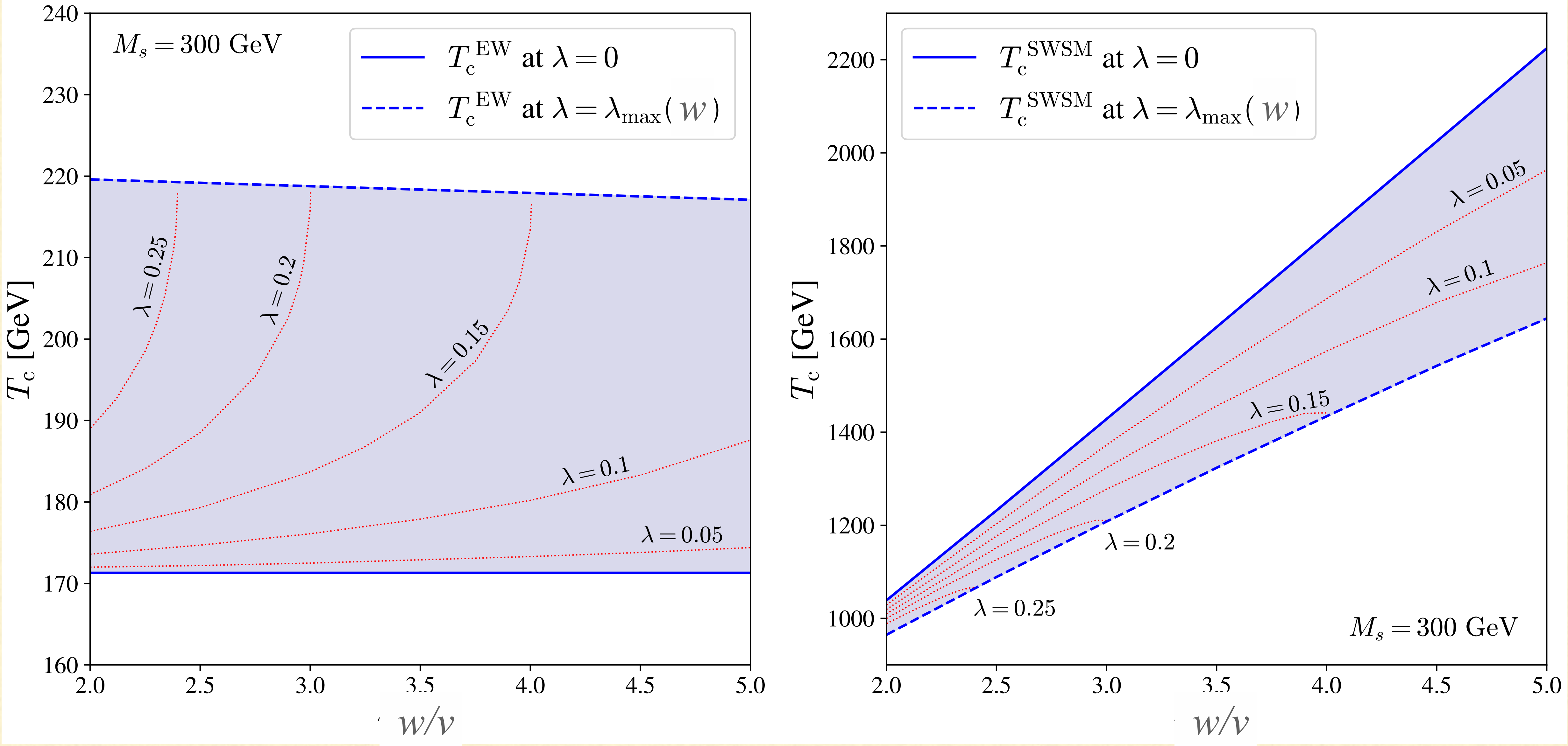
Prerequisite: phase-transition temperatures in the SWSM (see Károly Seller's talk on Sunday)

$U(1)_z$ is broken earlier than $SU(2)_L \times U(1)_Y$



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SWSM has the potential of explaining all known results beyond the SM

Main questions

Is there a non-empty region of the parameter space where all these promises are fulfilled?

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Present focus:

Is there a non-empty region of the parameter space where all these promises are fulfilled?

Can we predict any new phenomenon observable by present or future experiments?

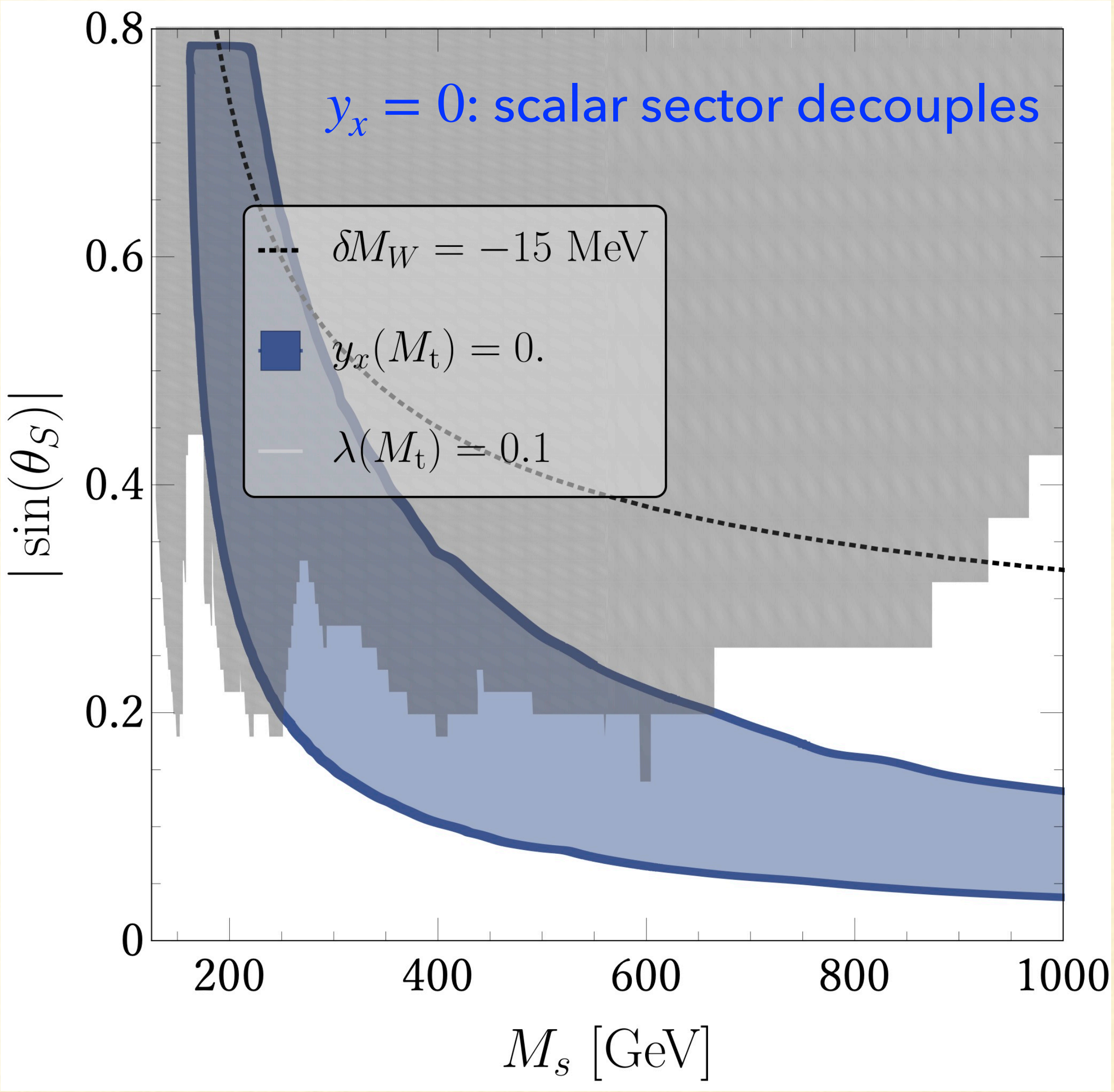
Ultimate test

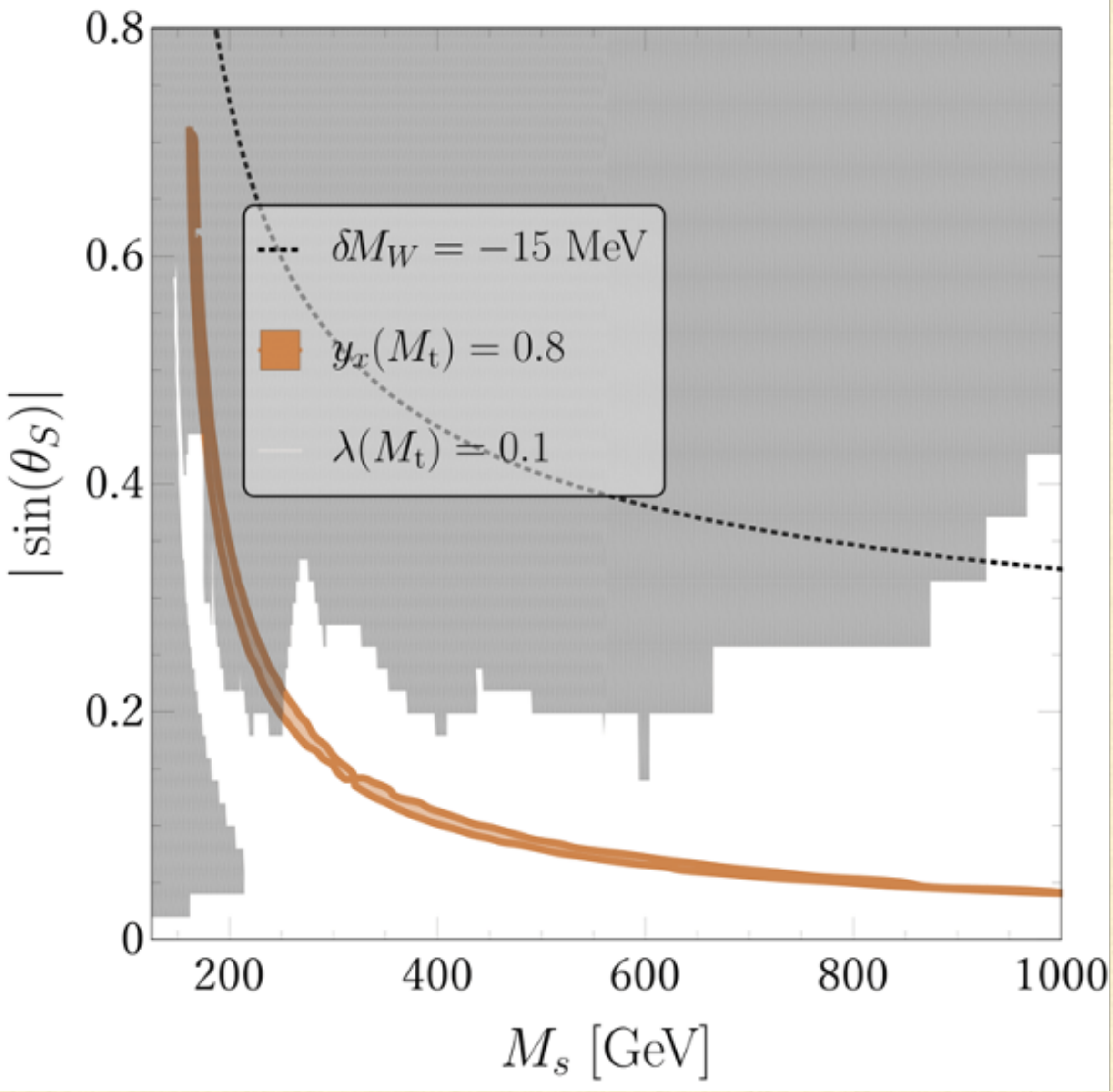
Once the allowed region of the parameter space for fulfilling the expectations is understood

the observation of the Z' or S in the allowed region

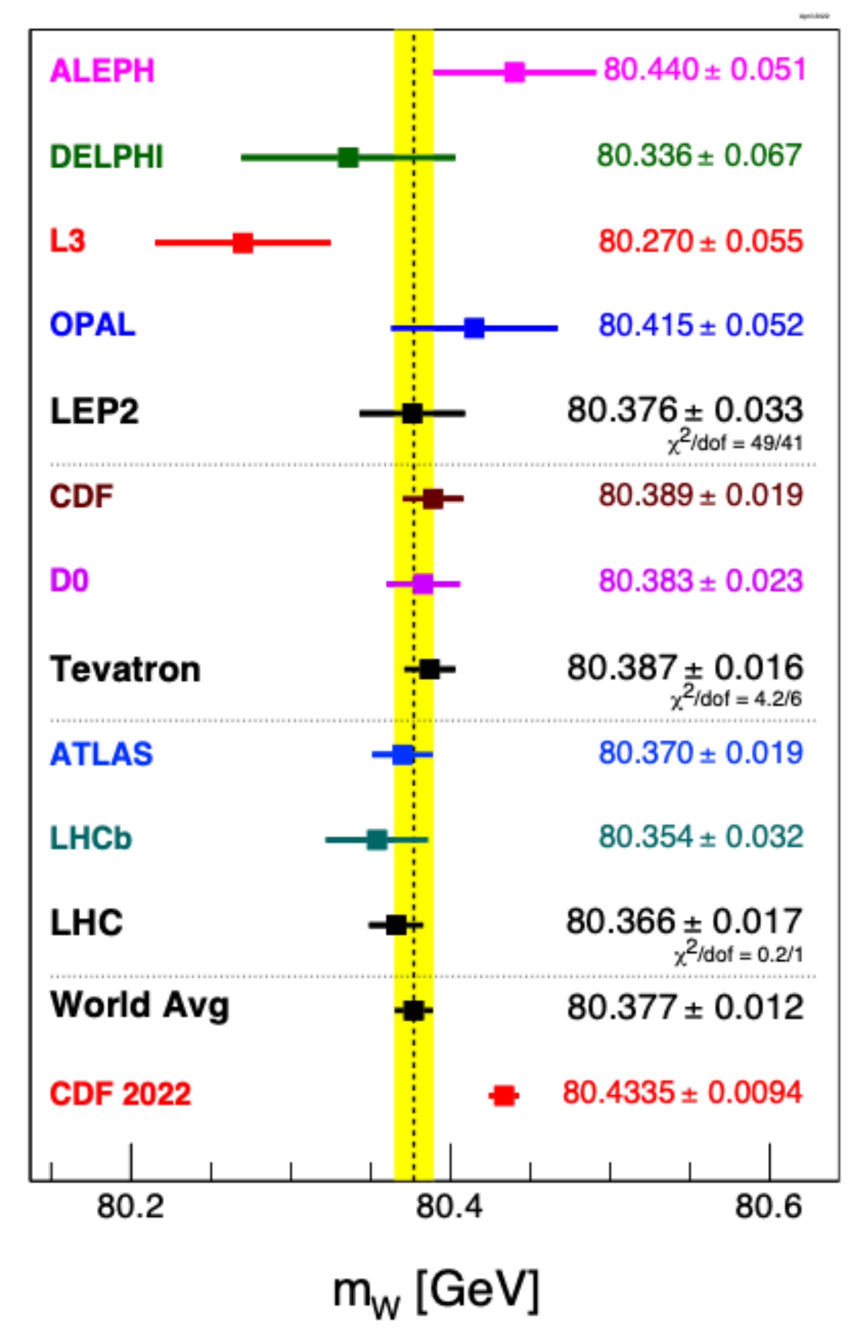
Experimental constraints in the scalar sector from direct searches and M_W

- $M_s > M_h$: [Zoltán Péli and ZT, arXiv: 2204.07100]





M_W is measured and computed precisely (with per myriad precision)



[PDG 2023]

Prediction of M_W in the SWSM

(see Zoltán Péli's talk)

Can be determined from the decay width of the muon:

$$M_W^2 = \frac{\cos^2\theta_Z M_Z^2 + \sin^2\theta_Z M_{Z'}^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha\Big/\left(\sqrt{2}G_F\right)}{\cos^2\theta_Z M_Z^2 + \sin^2\theta_Z M_{Z'}^2}\frac{1}{1 - \Delta r_{SM} - \left(\Delta r_{BSM}^{(1)} + \Delta r_{BSM}^{(2)}\right)}}\right)$$

- Valid in $\overline{\text{MS}}$
- θ_Z is the $Z - Z'$ mixing angle
- Δr_{SM} collects the SM quantum corrections (known completely at two loops and partially at three loops)
- $\Delta r_{BSM}^{(1)}$ collects the formally SM quantum corrections but with BSM loops
- $\Delta r_{BSM}^{(2)}$ collects the BSM corrections to $M_{Z'}$ and θ_Z

[Zoltán Péli and ZT, arXiv: 2305.11931]

Non-standard interactions and the SWSM

$$\mathcal{O}_{6a} = \frac{C_{6a}}{\Lambda^2}(\bar{L}\gamma^\mu P_\mathrm{L} L)(\bar{f}\gamma_\mu P_X f)$$

where Λ is the scale of new physics, can be as low as few MeV, which can be probed in Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

Standard parametrization of NSI:

$$\mathcal{L}_\mathrm{NSI} = -2\sqrt{2}G_\mathrm{F} \sum_{f,X=\pm,\ell,\ell'} \varepsilon^{f,X}_{\ell,\ell'}(\bar{\nu}_\ell\gamma^\mu P_\mathrm{L}\nu_{\ell'})(\bar{f}\gamma_\mu P_X f)$$

where $\varepsilon^{f,X}_{\ell,\ell'} \propto +\dfrac{1}{q^2}$ if $q^2 \gg M^2$, "light NSI"

$\varepsilon^{f,X}_{\ell,\ell'} \propto -\dfrac{1}{M^2}$ if $q^2 \ll M^2$, "heavy NSI",

for a mediator of mass M

Non-standard interactions and the SWSM

assume $M = 50\,\text{MeV}$, which is

- light in CHARM or NuTEV $q^2 = O((20\,\text{GeV})^2)$
- heavy in neutrino oscillation experiments $q^2 \approx 0$
- but $q^2 \approx M^2$ in CEνNS

We can still apply the NSI formalism using the full propagator with q^2 being the characteristic momentum transfer squared

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- Can be used to [Timo J. Kärkäinen and ZT, arXiv: 2301.06621]
  - Constrain the parameter space of SWSM
  - Predict relations between NSI couplings assuming SWSM

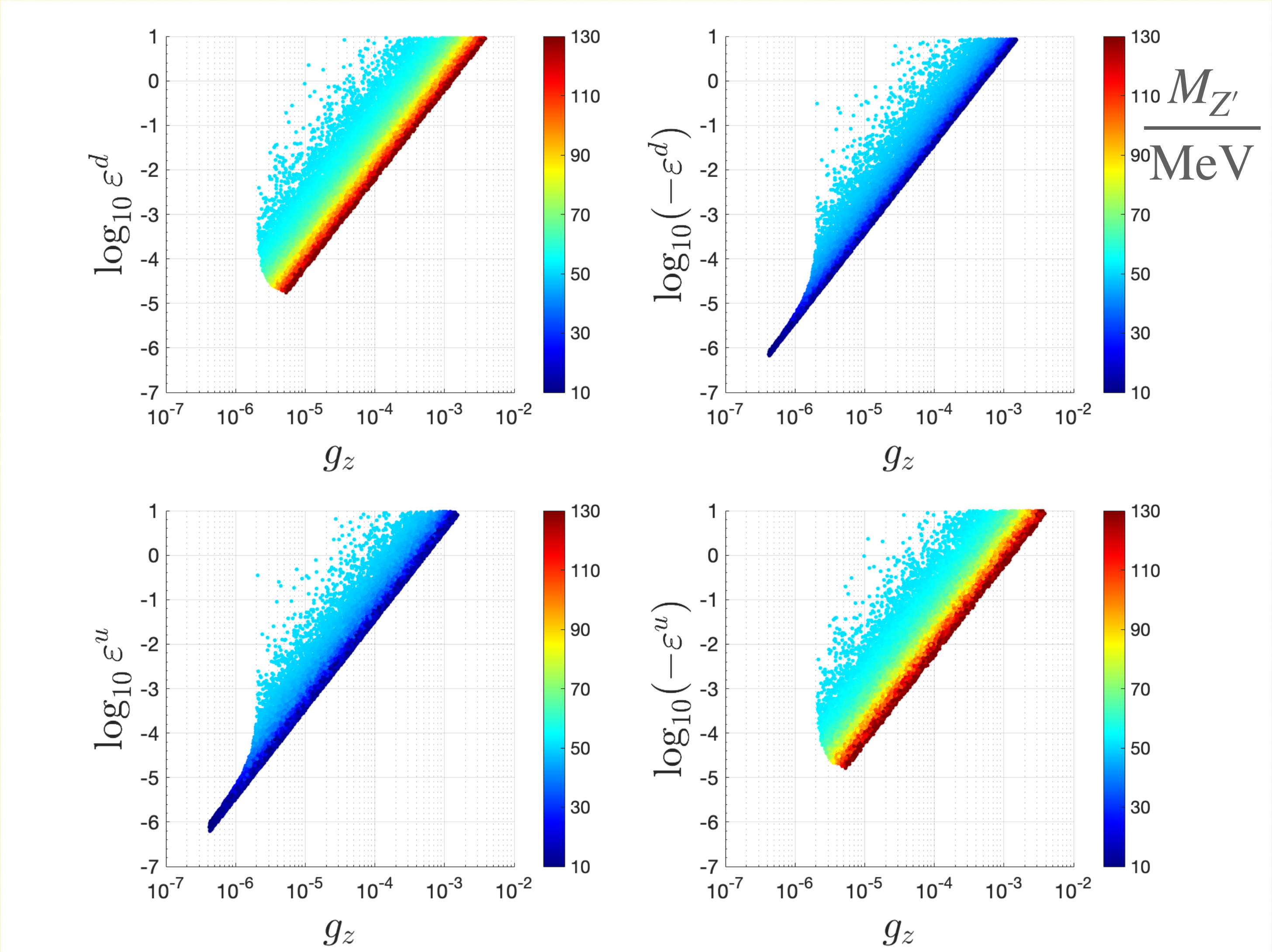
Conclusions

- Established observations require physics beyond SM, but do not suggest rich BSM physics
- $U(1)_z$ superweak extension has the potential of explaining all known results beyond the SM
- Neutrino masses are generated by SSB at tree level
- One-loop corrections to the tree-level neutrino mass matrix computed and found to be small (below 1‰) in the parameter space relevant in the SWSM
- Lightest sterile neutrino is a candidate DM particle in the [10,50] MeV mass range for freeze-out mechanism with resonant enhancement → predicts an approximate mass relation between vector boson and lightest sterile neutrino
- In the scalar sector we find non-empty parameter space for $M_s > M_h$
- Contributions to EWPOs (e.g. M_W, lepton g-2) are negligible in the superweak region and a systematic exploration of the parameter space is ongoing
- Interplay between NSI and SWSM

the end

Appendix

Non-standard interactions constrain the parameter space of the SWSM



With current COHERENT limits [Timo J. Kärkäinen and ZT, arXiv: 2301.06621]