ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

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DEBRECEN

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), 2402.14786 (submitted)

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

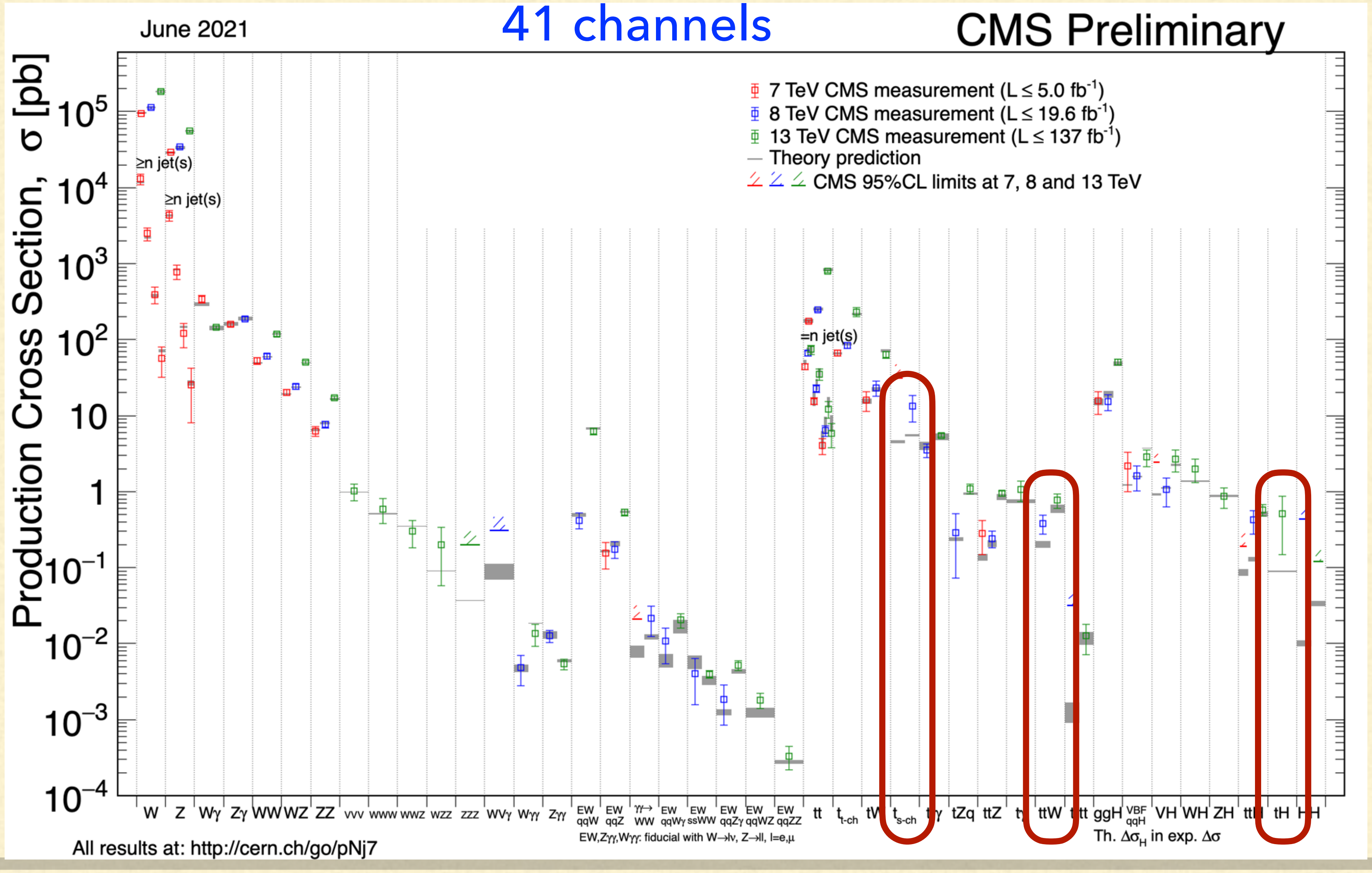
V4 workshop, 12 March, 2024

OUTLINE

1. Motivation: status of particle physics
   - Energy frontier
   - Cosmology & intensity frontiers
2. Superweak $U(1)_z$ extension of SM (SWSM)
3. Neutrino masses and dark matter candidate
4. Vacuum stability and scalar sector constraints
5. Contribution to M_W and gauge sector constraints
6. Conclusions
7. *Appendix:*
   - *Muon anomalous magnetic moment*
   - Constraints from non-standard interactions

Status of particle physics: energy frontier

- Colliders: SM describes final states of particle collisions precisely [CMS public]

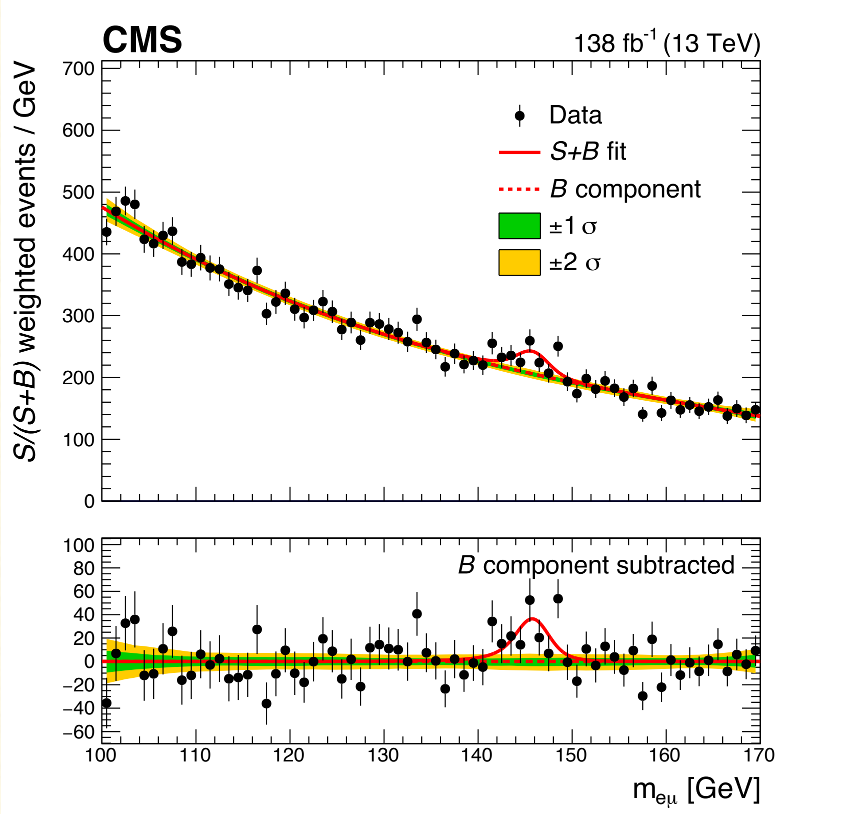


Status of particle physics: energy frontier

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

$\mathrm{pp} \to X(=\text{new Higgs boson}) \to \mathrm{e}^{\pm}\mu^{\mp}$

[CMS preprint]



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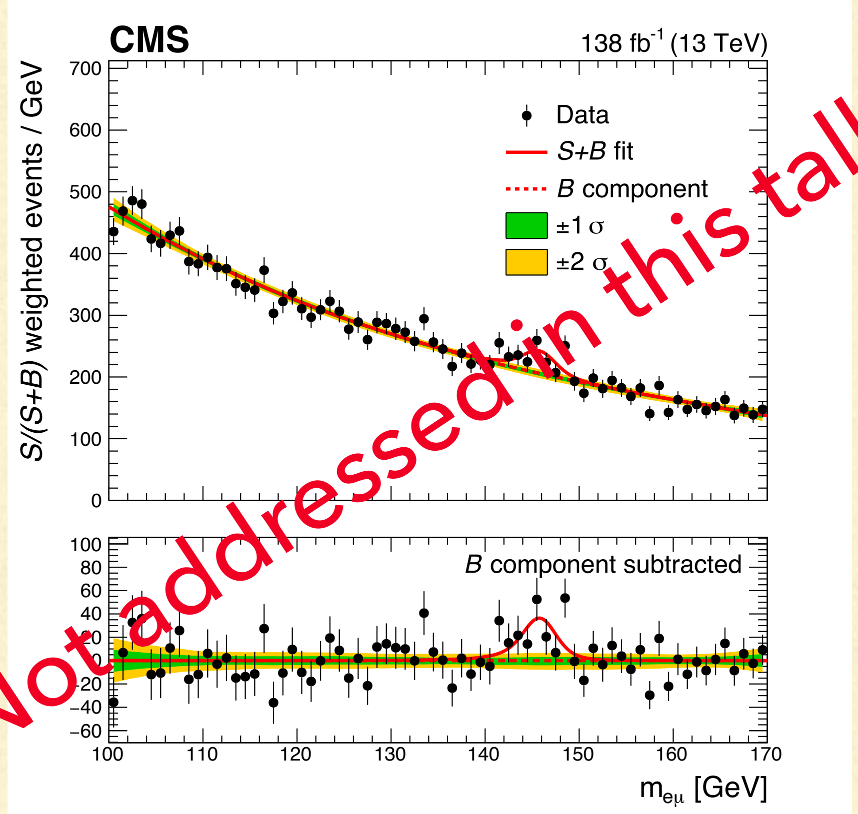

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Status of particle physics: cosmic and intensity frontiers

- 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]

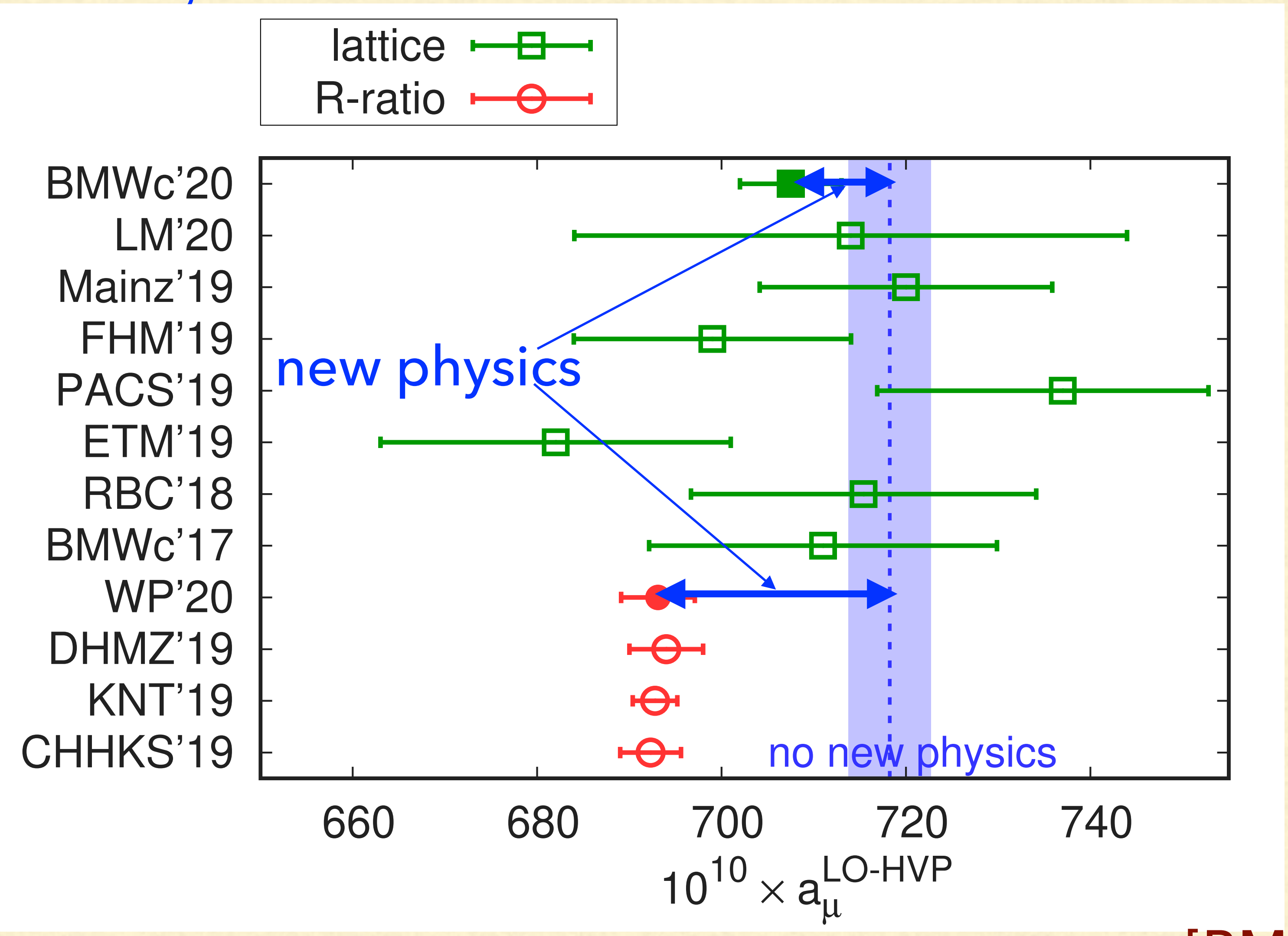
Established observations require physics beyond SM, but do not suggest rich BSM physics

Phenomenological approach to new physics

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

Before proceeding: a word on the muon anomalous magnetic moment

- We are certain that there is new physics beyond the SM
- "Final word" on a_μ will tell how BSM should affect the muon g-2



[BMW compilation]

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- The experimental result appears robust, only its uncertainty will reduce further
- Main task:

  Resolve discrepancy between theory predictions
- Until then

  everything else is speculation

Muon anomalous magnetic moment: complying with lattice result

- New physics should have a small (smaller then EW) contribution to a_μ
- May constrain the available parameter space, but unlikely to exclude a model compatible with ElectroWeak Precision Observables (EWPOs)

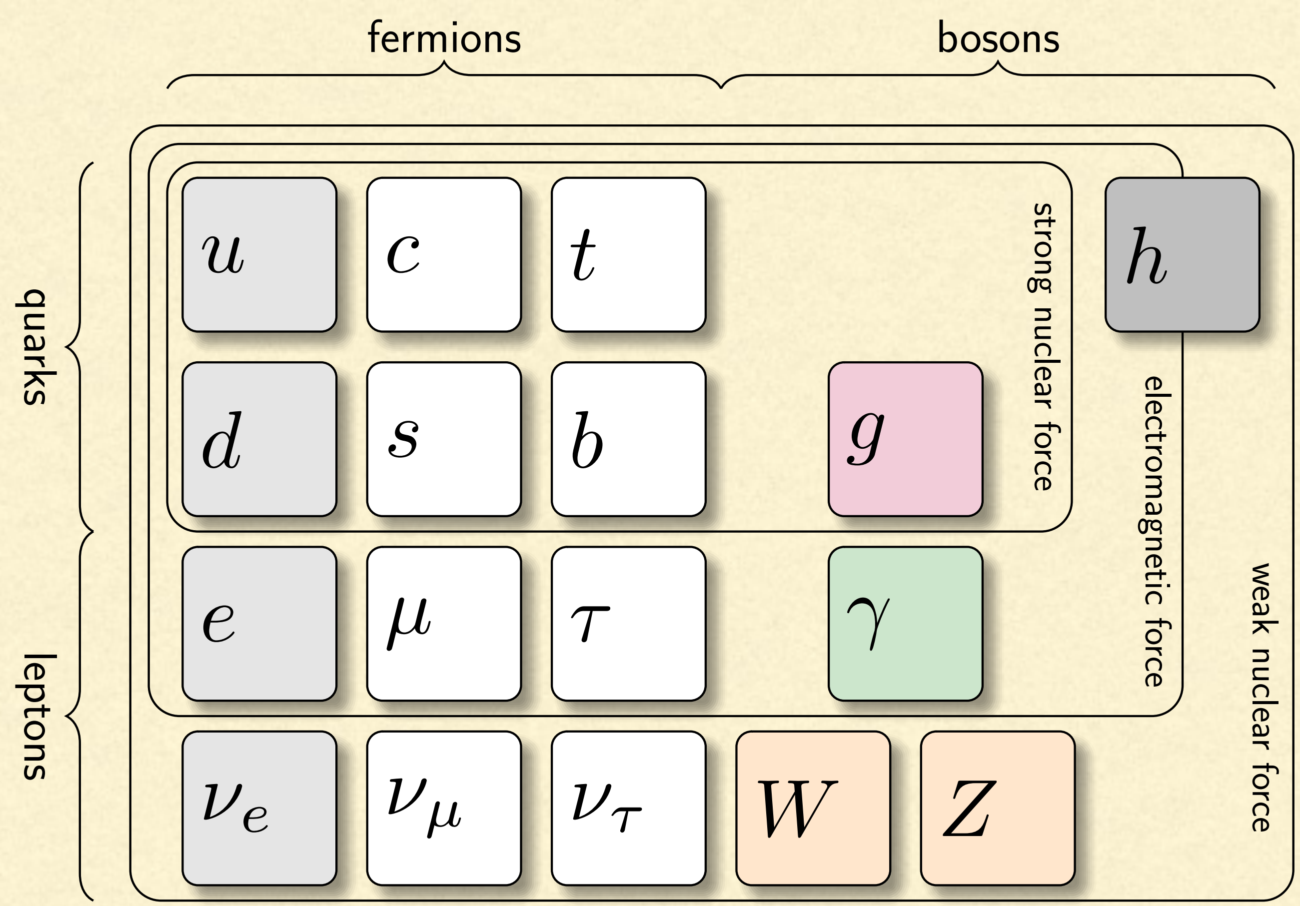
Extension of SM: three alternatives with different strength and weaknesses

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

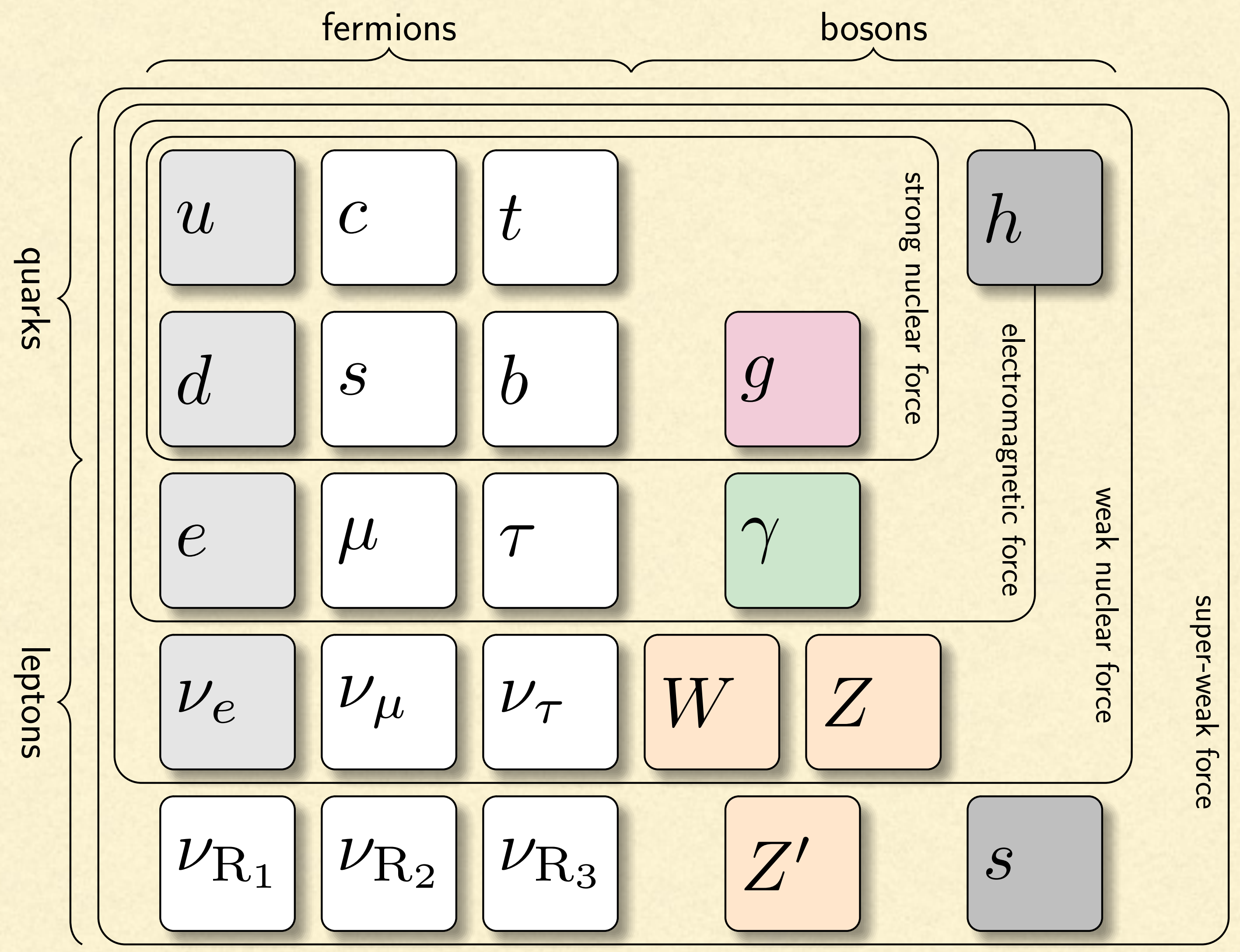
- Simplified models, such as dark photon, extended scalar sector or right-handed neutrinos: "easily accessible" phenomenology, but focus on specific aspect of new physics, so cannot explain all BSM phenomena

- 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

[ZT, 1812.11189]

Mixing in the neutral gauge sector

$$\begin{pmatrix} B_\mu \\ W^3_\mu \\ B'_\mu \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_Z & -s_Z \\ 0 & s_Z & c_Z \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

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

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

[Zoltán Péli and ZT, arXiv: 2305.11931]

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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: $\dfrac{M_W^2}{c_W^2} = c_Z^2 M_Z^2 + s_Z^2 M_{Z'}^2$ $\left(M_W = \dfrac{1}{2} g_\mathrm{L} v\right)$

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Scalars in the SWSM

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

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

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

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5 new parameters:

- in **gauge** sector: $\{g_z$ and $g_{yz}\}$ or $\{\kappa$ and $\tau\}$ or $\{\theta_Z$ and $M_{Z'}\}$
- in **scalar** sector: $\{\mu_\chi^2, \lambda_\chi$ and $\lambda\}$ or $\{w, \lambda_\chi$ and $\lambda\}$ or $\{M_S, \theta_S$ and $\lambda\}$

After SSB neutrino mass terms appear

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

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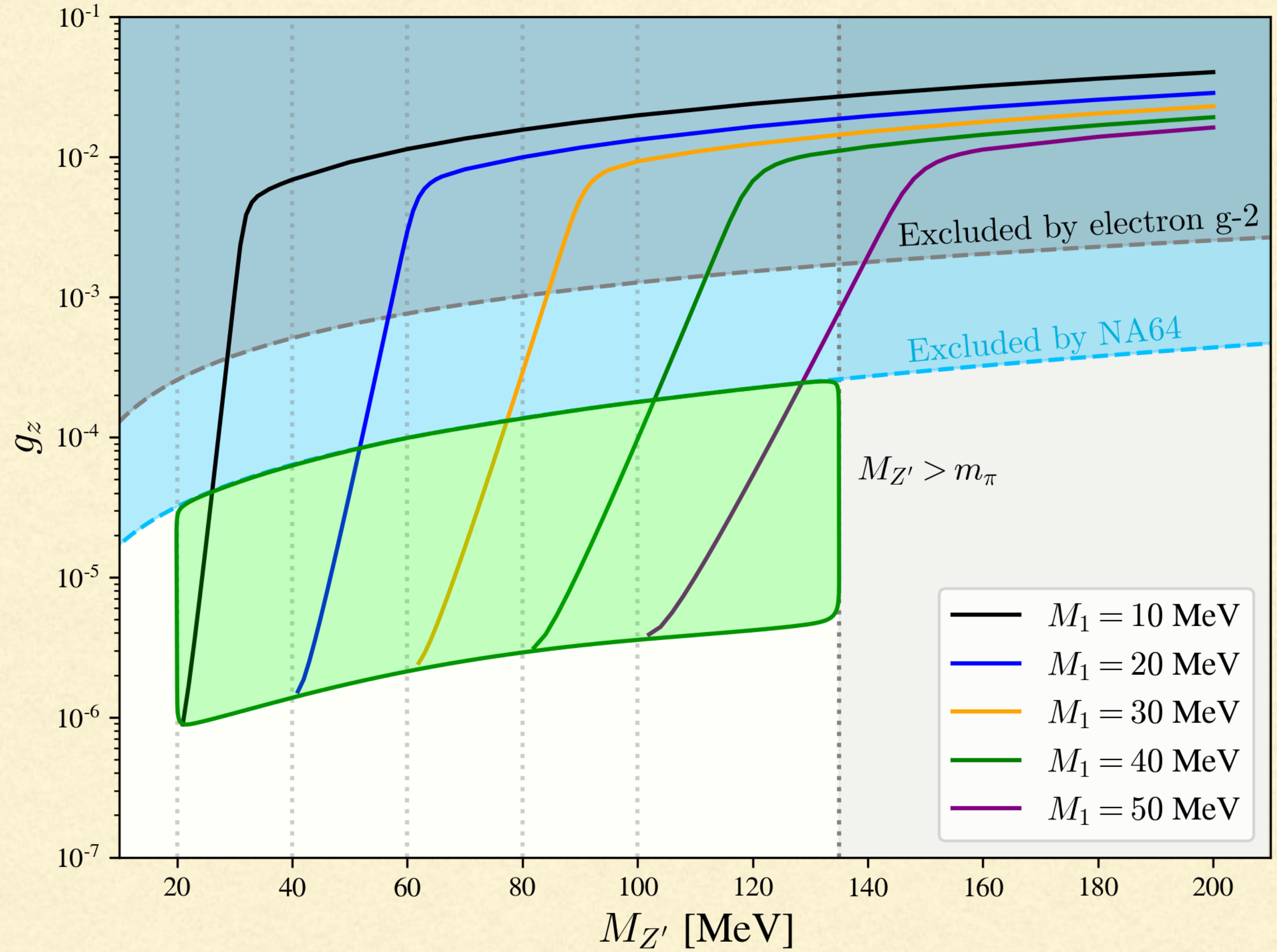
- DM exists, but known evidence is based solely on the gravitational effect of the dark matter on the luminous astronomical objects and on the Hubble-expansion of the Universe
- Assume that the DM has particle origin
- Only chance to observe such a particle if it interacts with the SM particles, which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

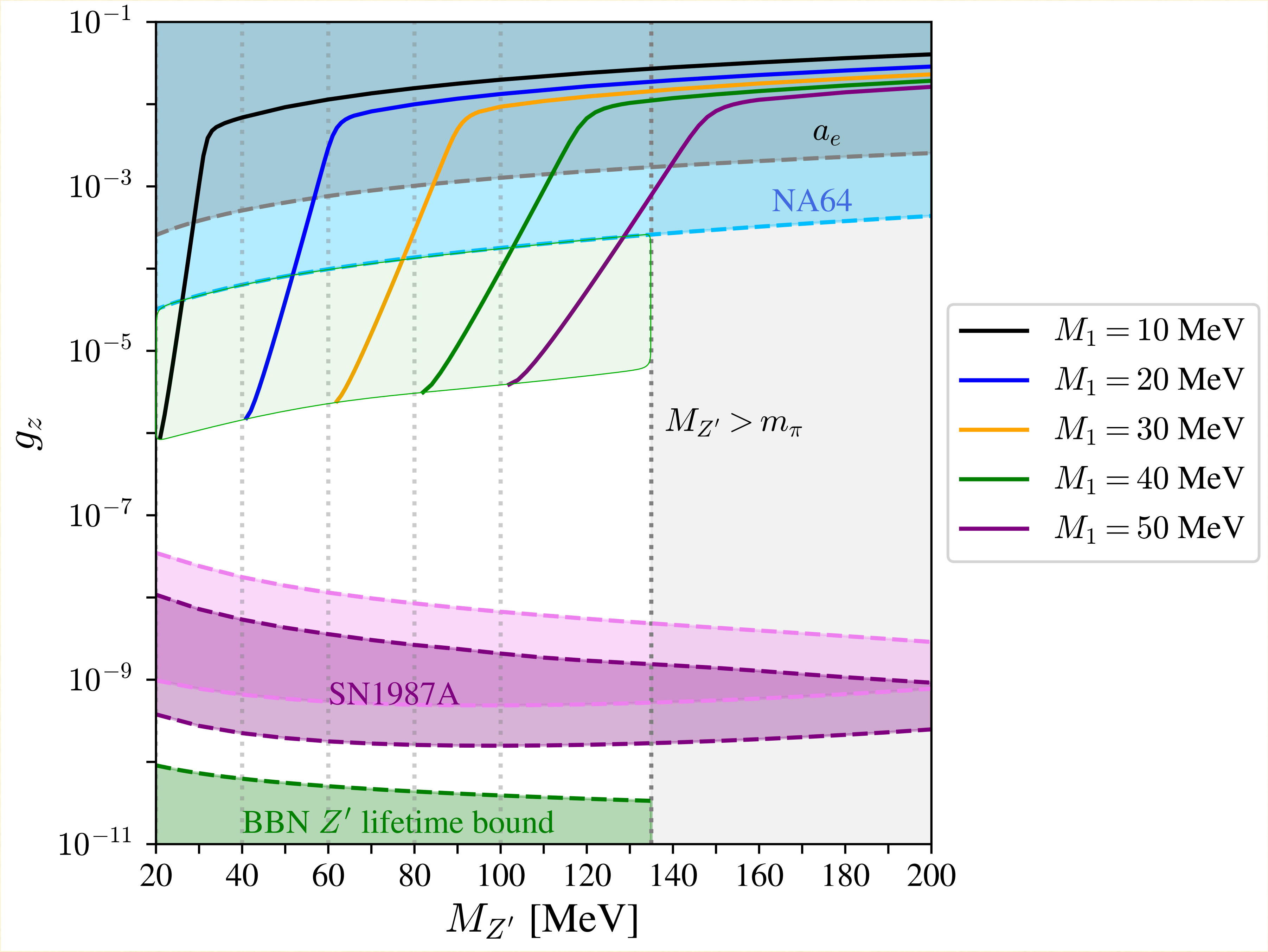


It is essential for the SWSM DM candidate that the resonance in SM+SM $\to Z' \to$ DM+DM can dominate the integral in the rate

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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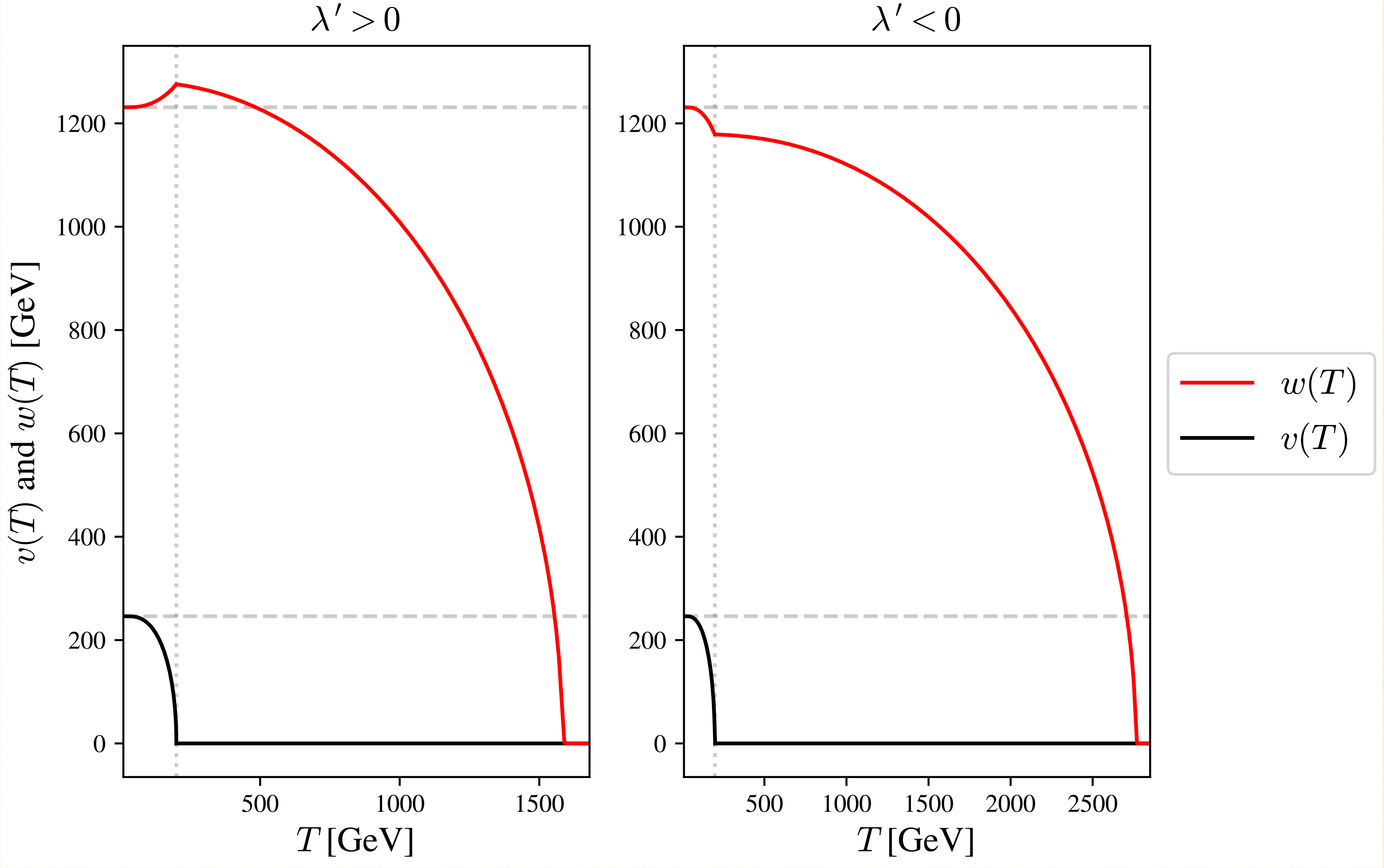
Prerequisite: Phase-transitions in the SWSM

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



$$M_S = 200\,\text{GeV},\quad M_N = 150\,\text{GeV},\quad w = 5v\,,\quad |\lambda| = 0.0394$$

[Seller, Szép, ZT, arXiv:2301.07961]

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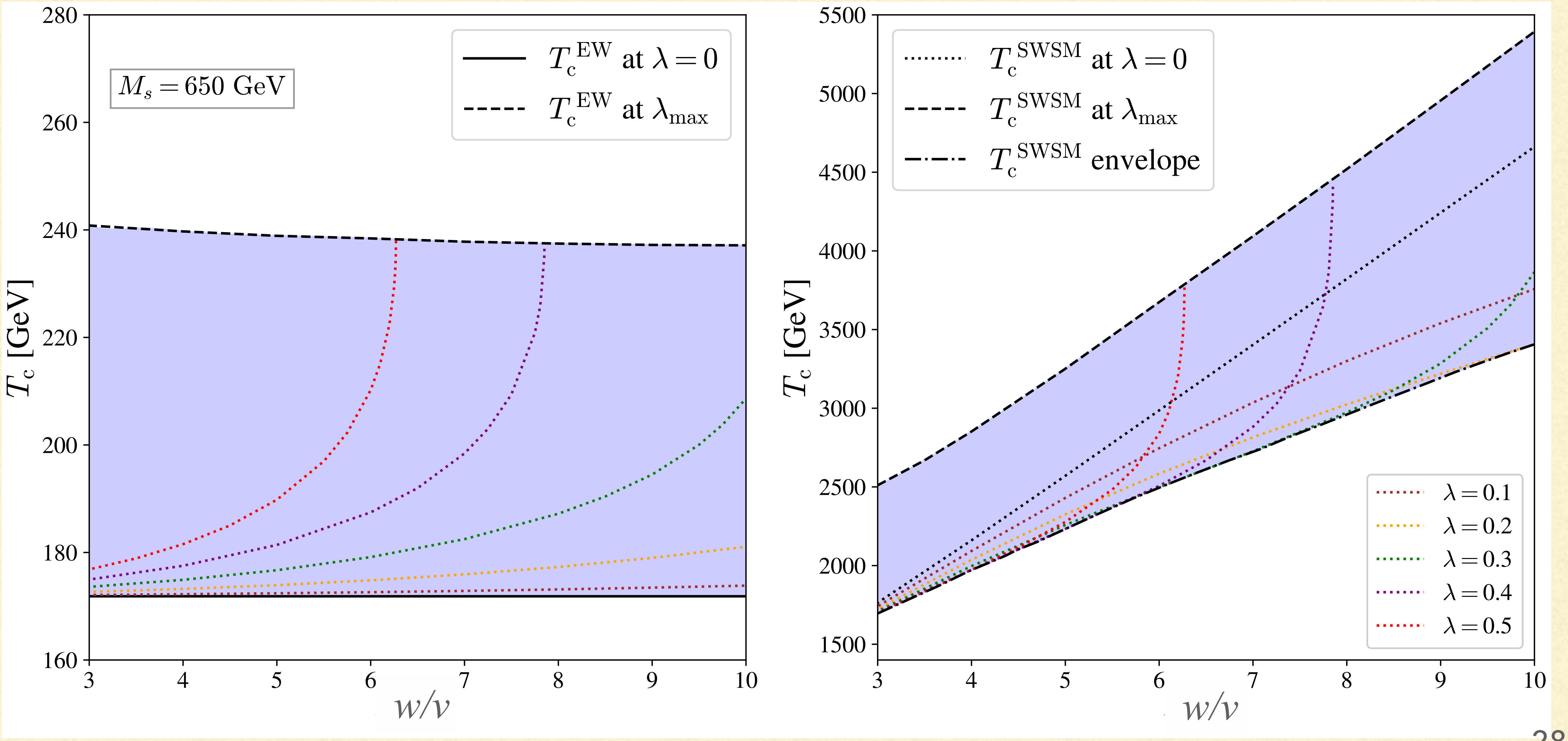

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SWSM has the potential of explaining all known results beyond the SM

Main questions

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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?

Important test

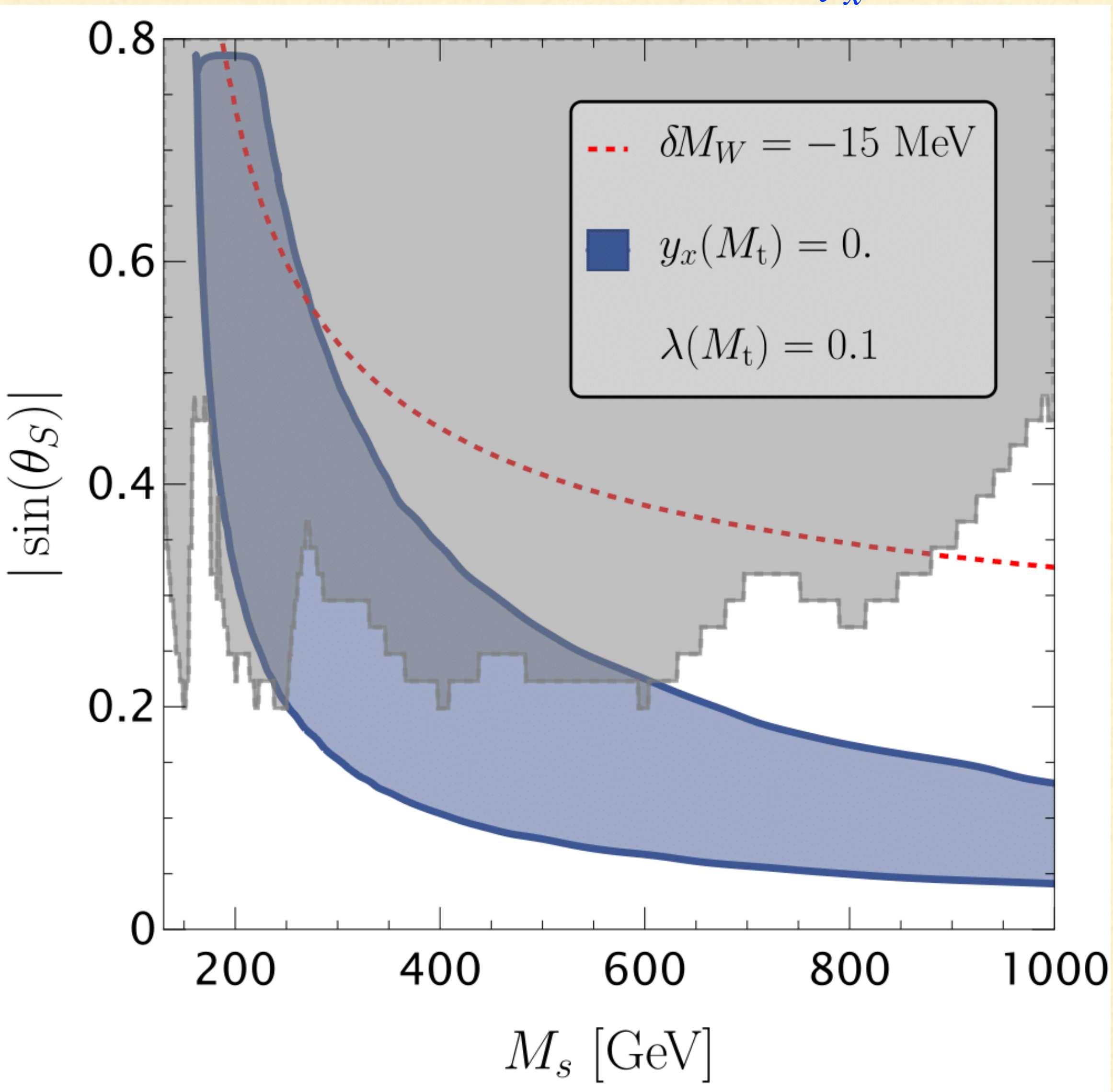
Once the allowed region of the parameter space for fulfilling the expectations is understood

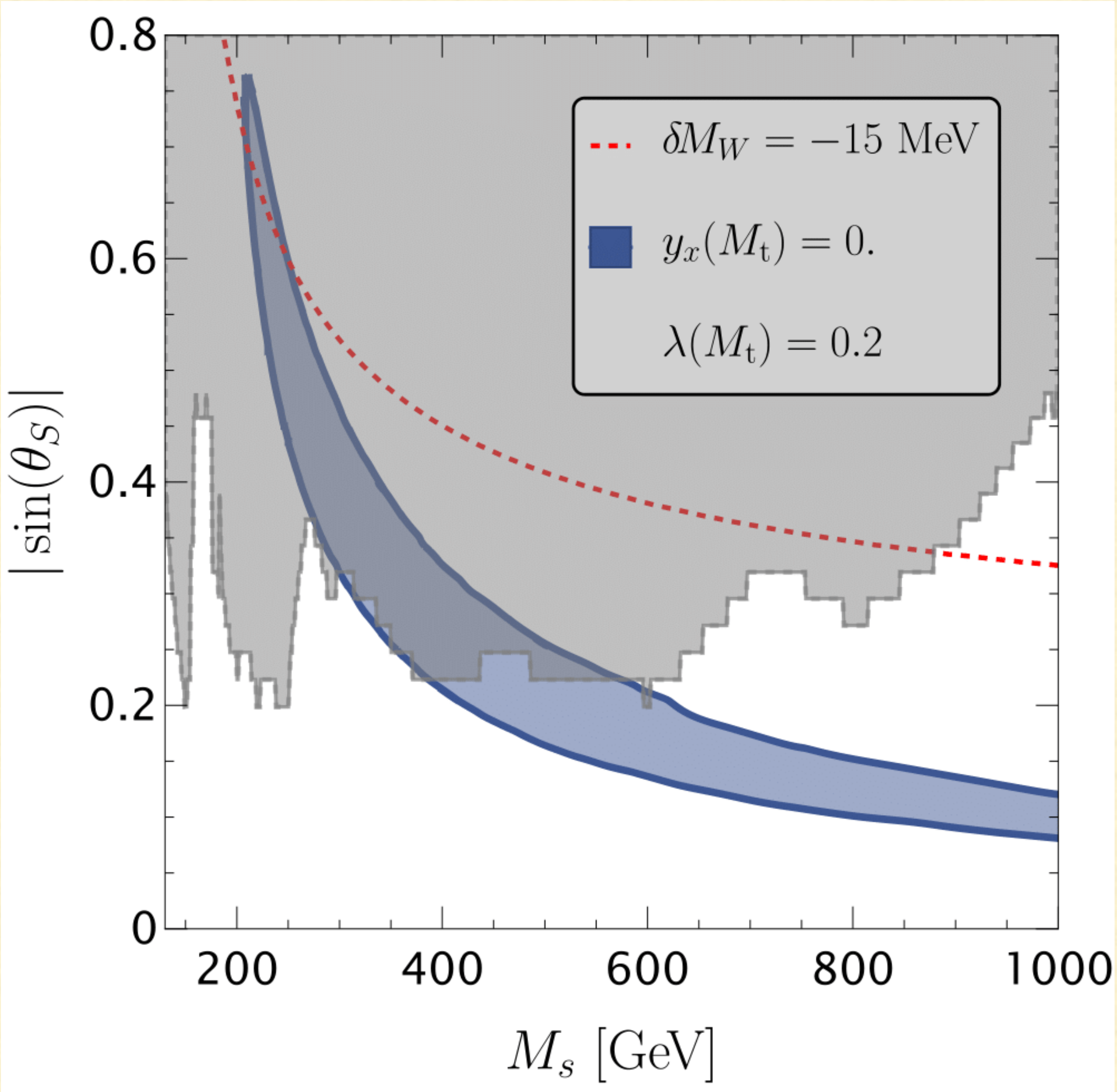
the observation of the Z' or S in the allowed region

Experimental constraints in the scalar sector from direct searches and M_W

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

$y_x = 0$: scalar sector decouples





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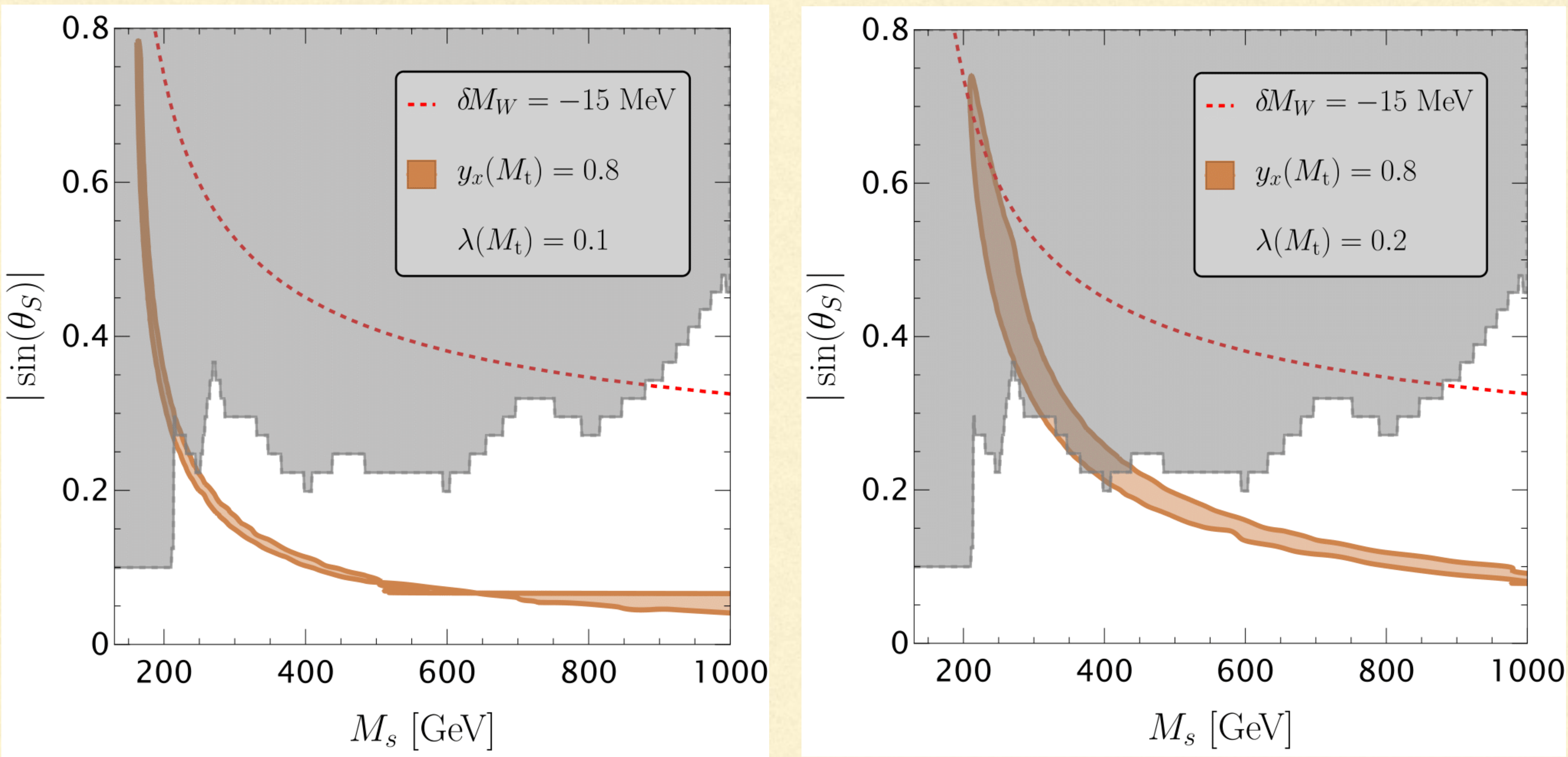
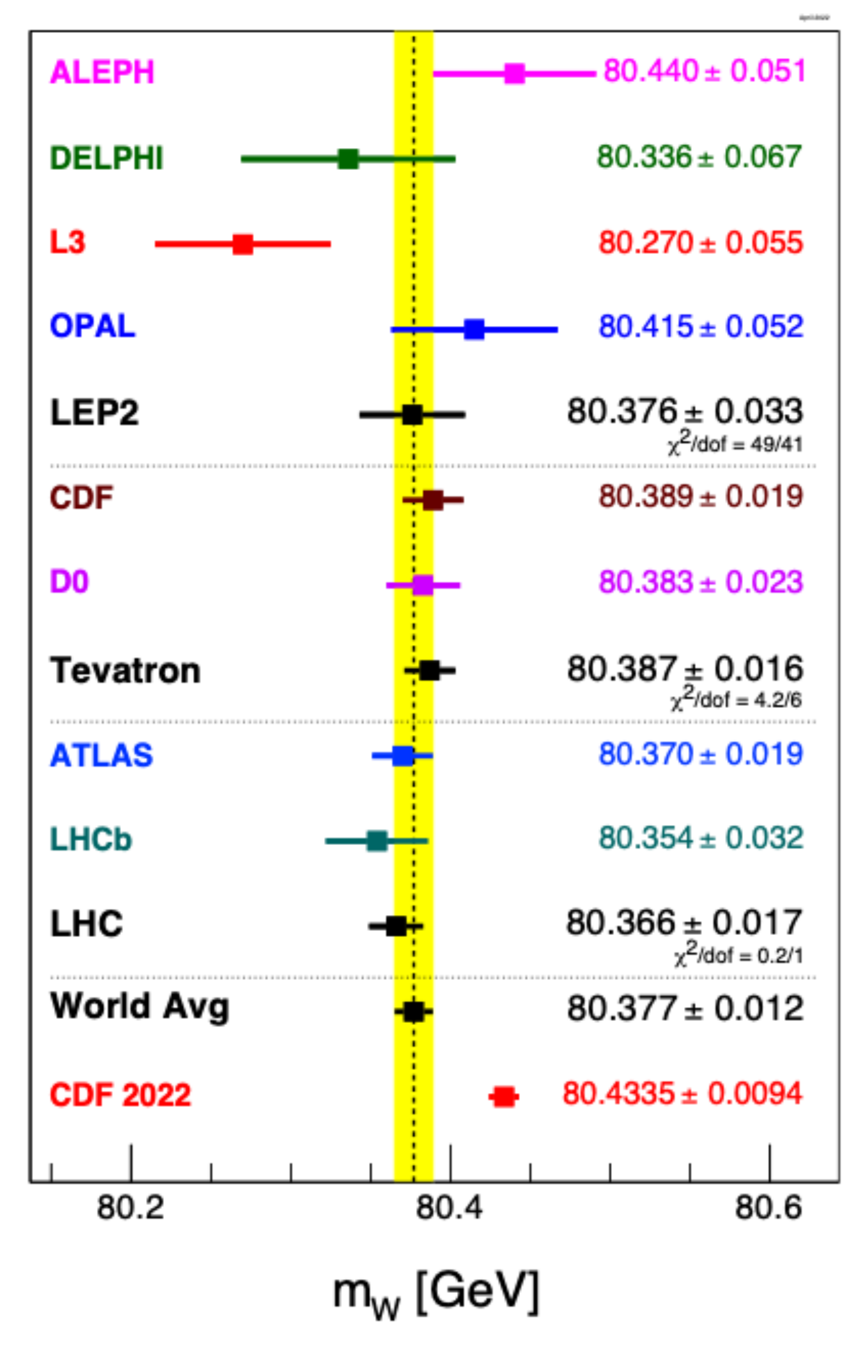


M_W is measured and computed precisely (with per myriad precision)



[https://pdg.lbl.gov]

Prediction of M_W in the SWSM

- Can be determined from the decay width of the muon:

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

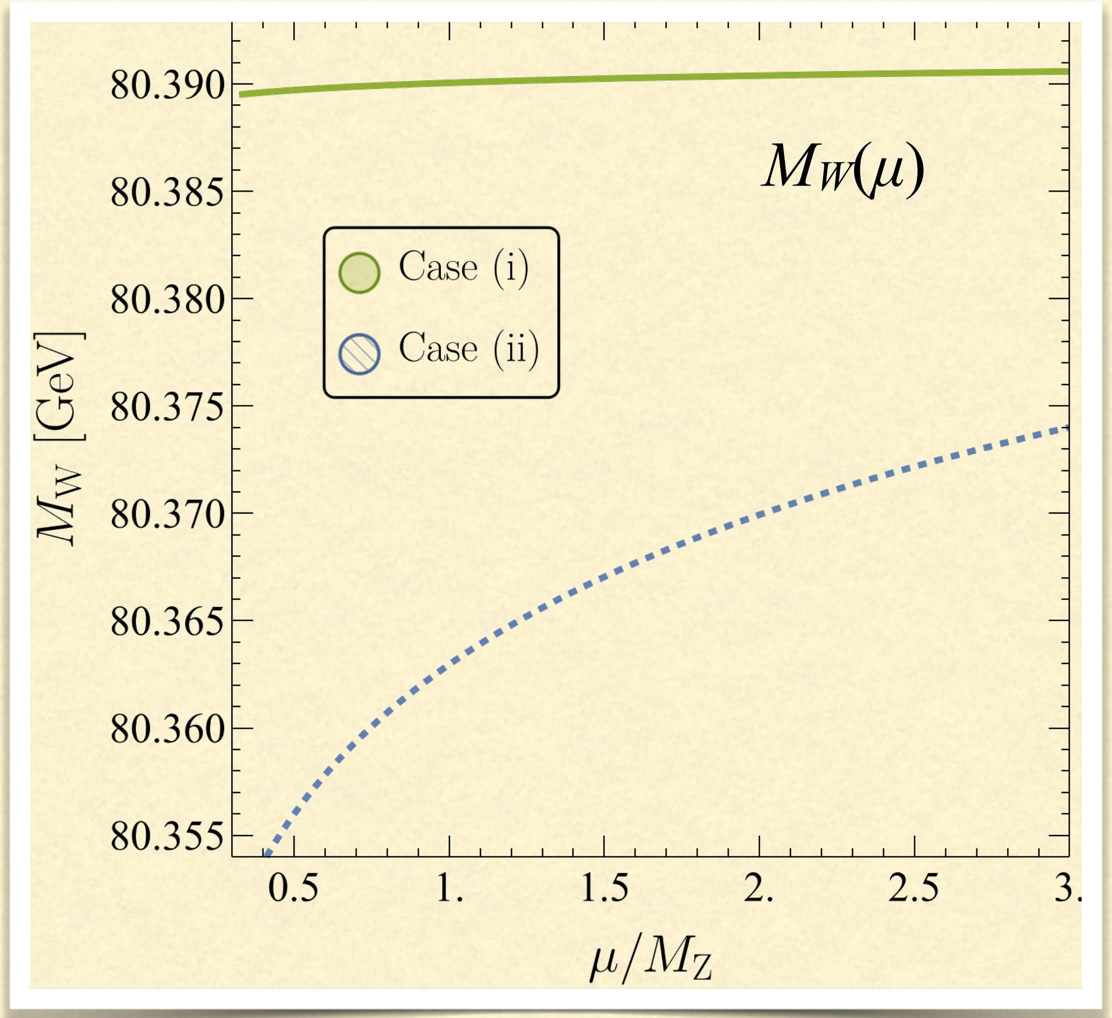
  - Valid in $\overline{\text{MS}}$
  - θ_Z is the $Z - Z'$ mixing angle
  - Δr_{SM} collects the SM quantum corrections (known completely at two loops and partially at three loops)
  - $\Delta r_{BSM}^{(1)}$ collects the formally SM quantum corrections but with BSM loops
  - $\Delta r_{BSM}^{(2)}$ collects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

[Zoltán Péli and ZT, arXiv: 2305.11931]

Prediction of M_W in the SWSM

Case (i) full one-loop corrections

Case (ii) corrections without $\Delta r^{(2)}_{BSM}$



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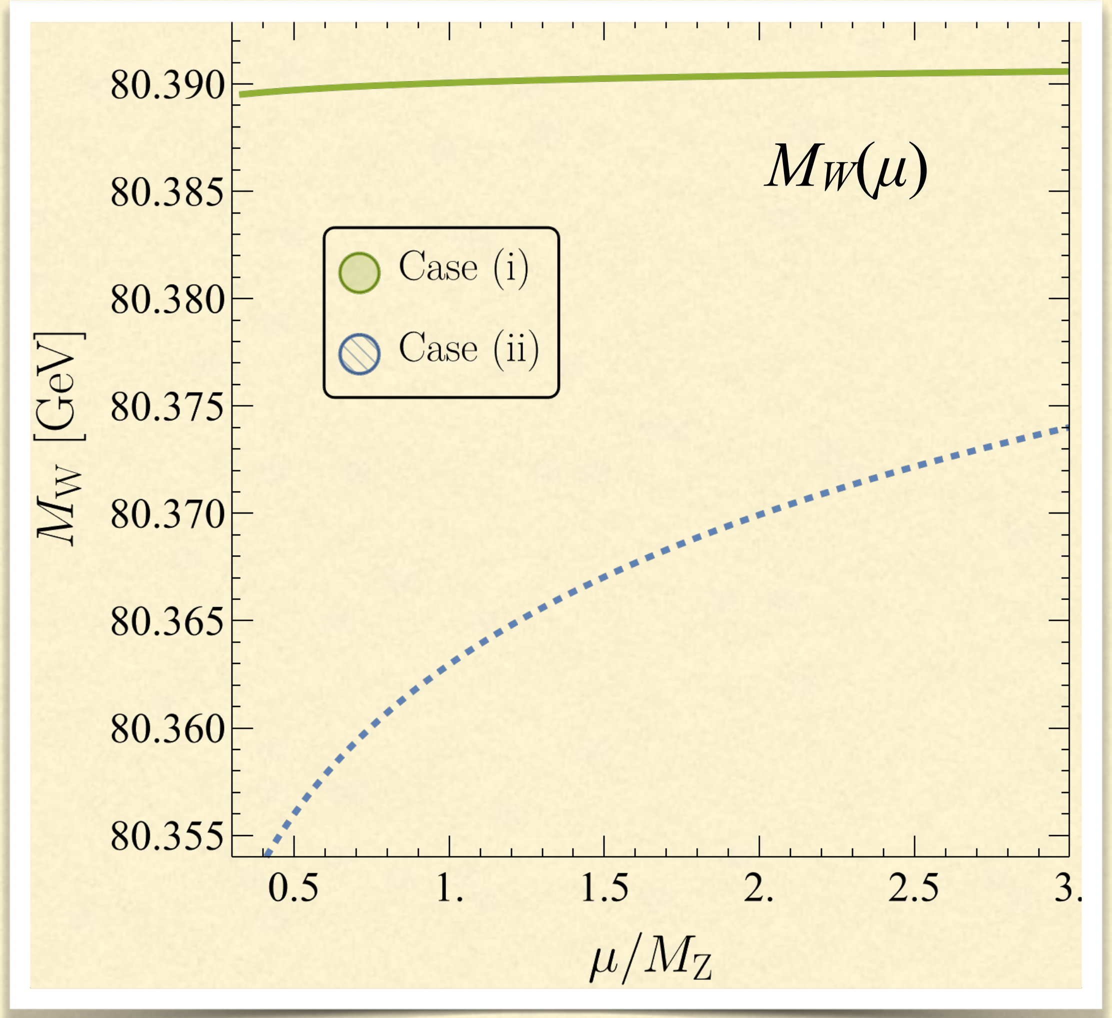

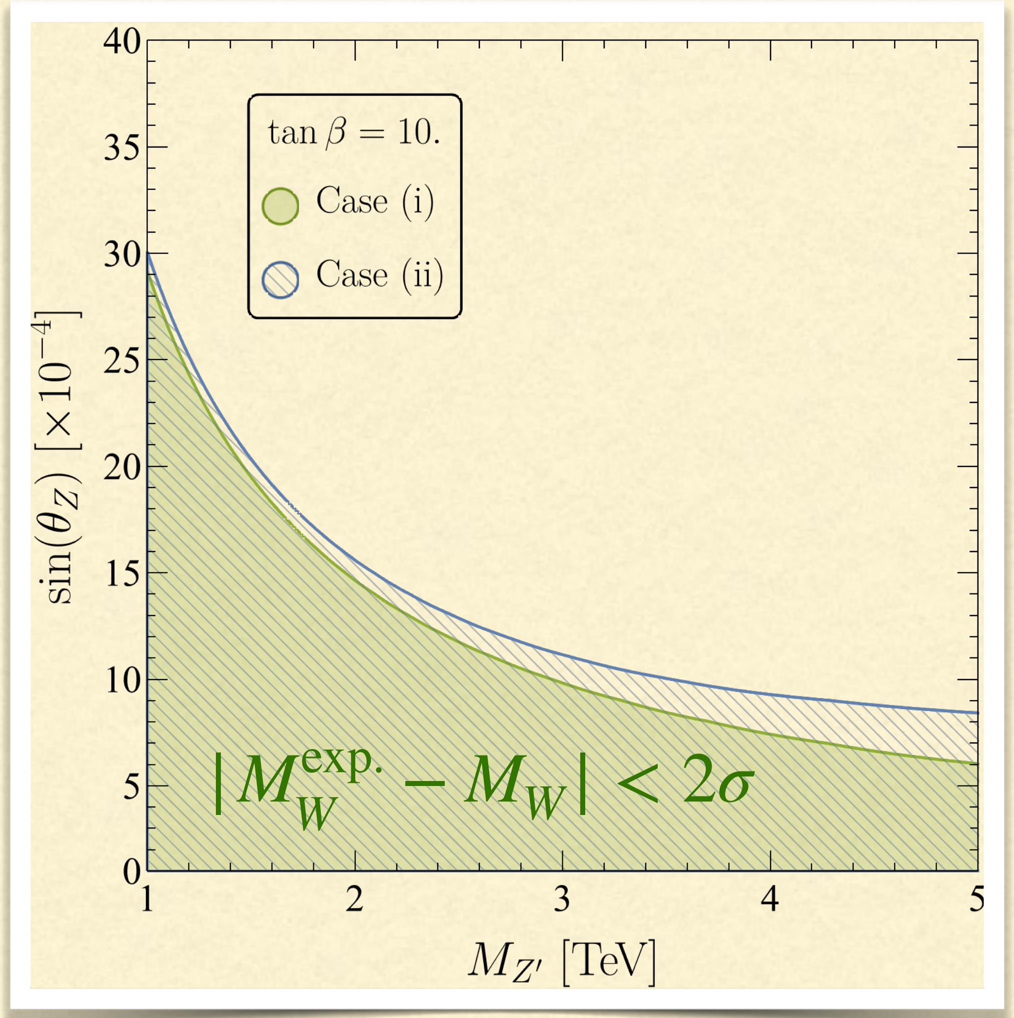

Experimental constraints in the gauge sector from direct searches and EWPOs

- Gauge sector parameters: $g_z\,,\,g_{yz}(=\epsilon g_y)\,,\ \tan\beta\,,\,z_\phi\,,\,z_N$
  - Not all independent: exclusion bounds depend on either

$$\left(\sin\theta_Z\,,M_{Z'}\,,x\right) \text{ or } \left(g_z z_N\,,M_{Z'}\,,x\right)$$

where

$$x = \frac{z_\phi - \frac{1}{2}\frac{g_{yz}}{g_z}}{z_N}$$

and z_N is the z charge of the right-handed neutrino

General U(1)$_z$ anomaly free charge assignment

field	$SU(3)_c$	$SU(2)_L$	y_j	z_j	z_j
$U_L,\ D_L$	3	2	$\frac{1}{6}$	Z_1	$\frac{1}{3}(z_\phi - z_N)$
U_R	3	1	$\frac{2}{3}$	Z_2	$\frac{1}{3}(4z_\phi - z_N)$
D_R	3	1	$-\frac{1}{3}$	$2Z_1 - Z_2$	$z_d = -\frac{1}{3}(2z_\phi + z_N)$
$\nu_L,\ \ell_L$	1	2	$-\frac{1}{2}$	$-3Z_1$	$z_\ell = z_N - z_\phi$
ν_R	1	1	0	$Z_2 - 4Z_1$	z_N
ℓ_R	1	1	-1	$-2Z_1 - Z_2$	$z_e = z_N - 2z_\phi$
ϕ	1	2	$\frac{1}{2}$	z_ϕ	z_ϕ
χ	1	1	0	z_χ	$z_\chi := -1$

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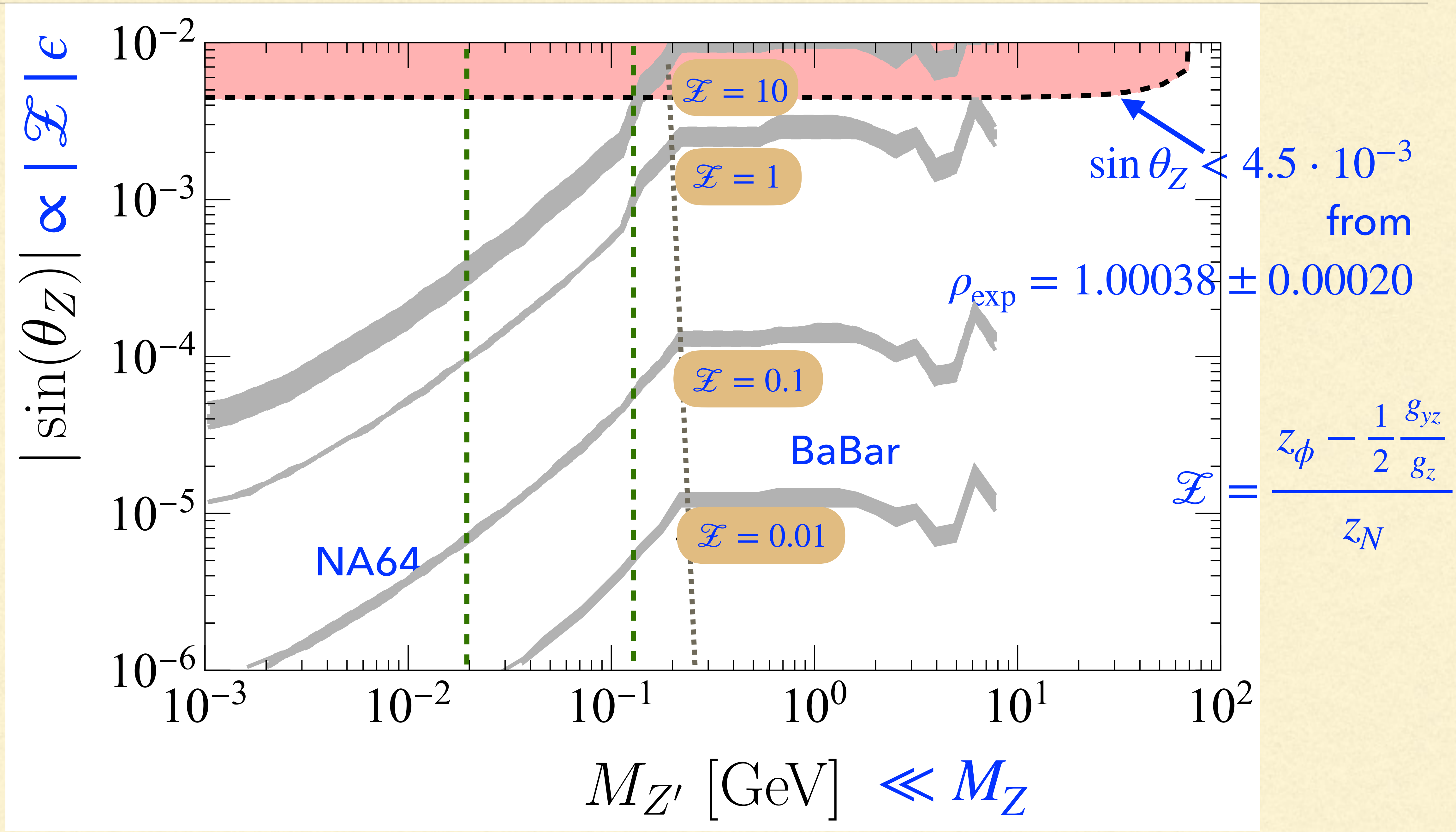
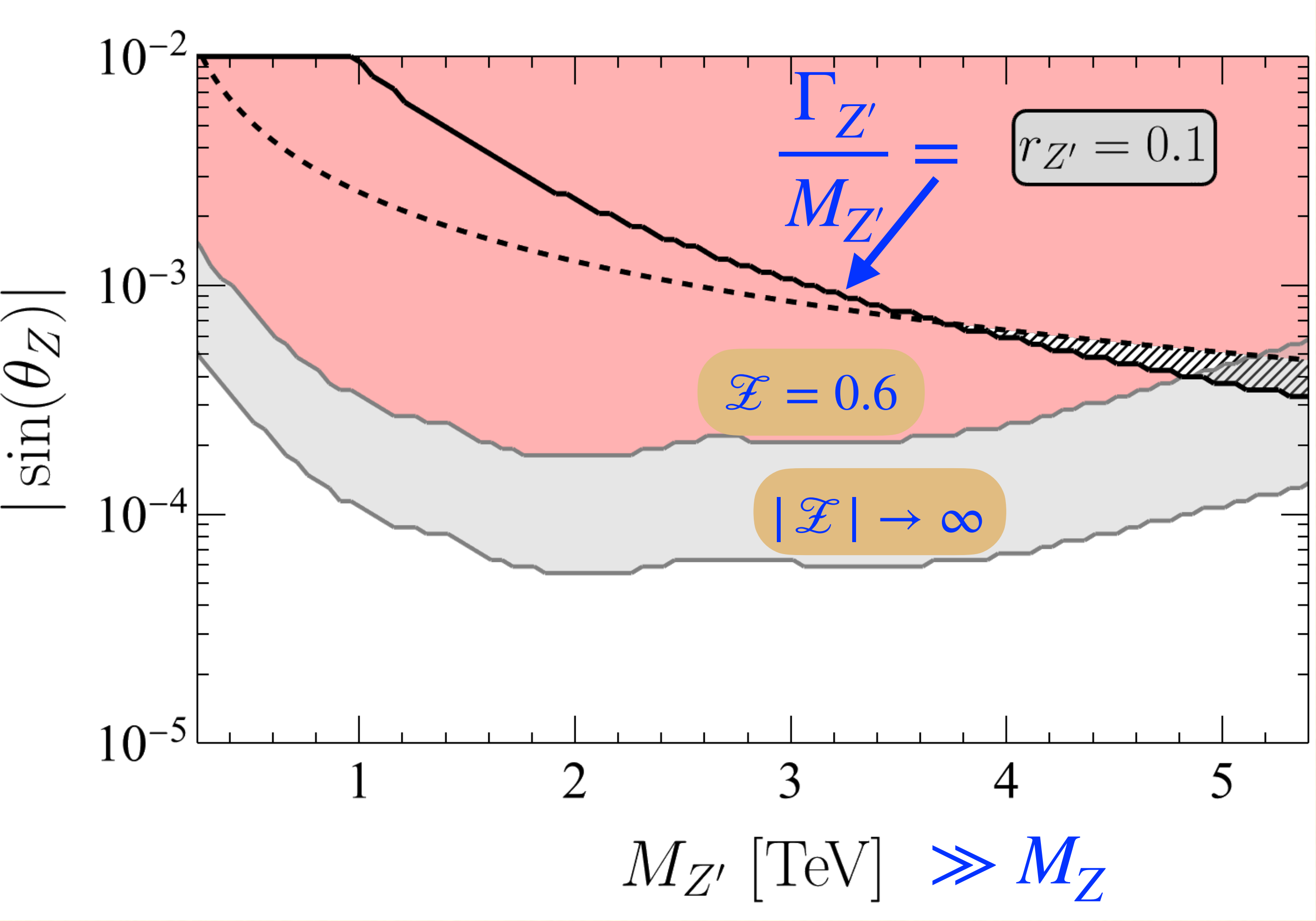
  - Not all independent: exclusion bounds depend on either $\left(\sin\theta_Z\,, M_{Z'}\,, x\right)$ or $\left(g_z z_N\,, M_{Z'}\,, x\right)$
- Most stringent limits emerge in direct searches
  - for small masses ($\xi = M_{Z'}/M_Z \ll 1$): from NA64 search for dark photon
  - for large masses ($\xi \gg 1$): from LHC search for Z'
  - difficult to distinguish from Z for intermediate masses – best limits from LEP (not discussed here)

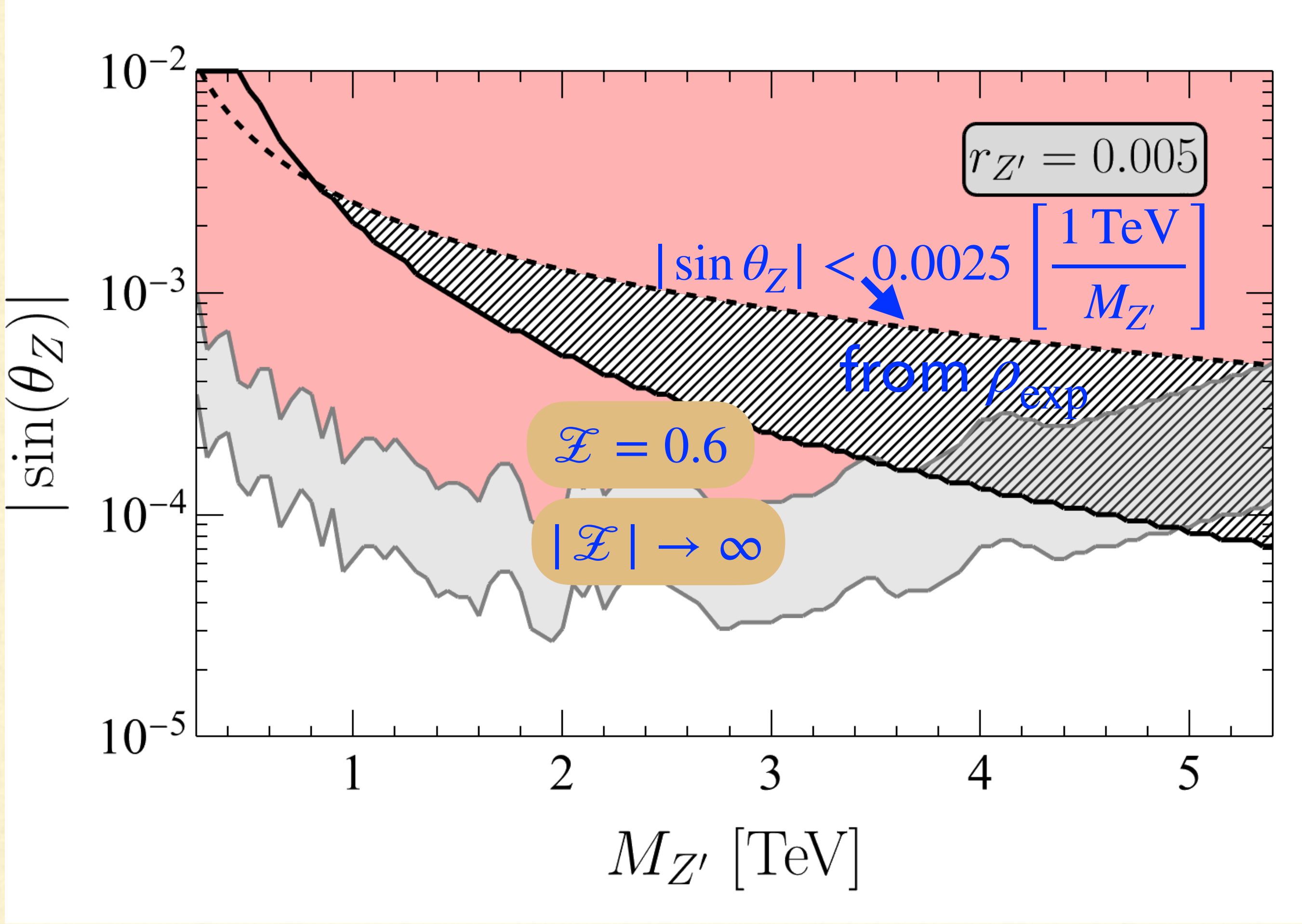
Experimental constraints in the gauge sector from direct searches and EWPOs: SWSM region



[Zoltán Péli and ZT, 2402.14786]

Experimental constraints in the gauge sector from direct searches and EWPOs





$$\mathcal{Z} = \frac{z_\phi - \frac{1}{2}\frac{g_{yz}}{g_z}}{z_N}$$

Conclusion: $\theta_Z \lesssim 10^{-4}$

[Zoltán Péli and ZT, 2402.14786]

Conclusions

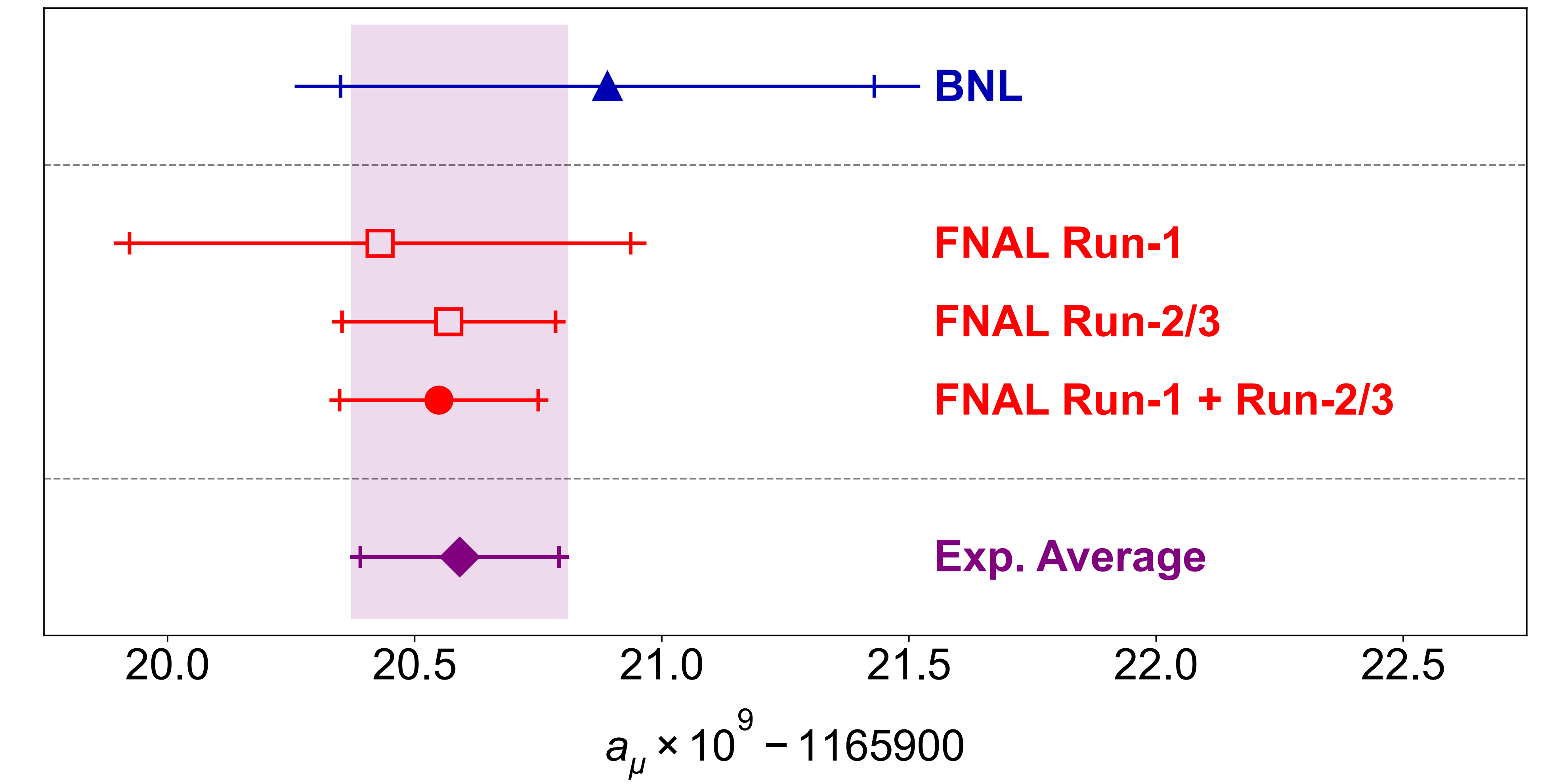
- Established observations require physics beyond SM, but do not suggest rich BSM physics
- $U(1)_z$ superweak extension has the potential of explaining all known results beyond the SM
- Neutrino masses are generated by SSB at tree level
- One-loop corrections to the tree-level neutrino mass matrix computed 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

the end

Appendix

Status of the muon anomalous magnetic moment: experiment

- The muon g-2 has been a smoking gun for new physics for many years, more recently:



[https://muon-g-2.fnal.gov/result2023.pdf]

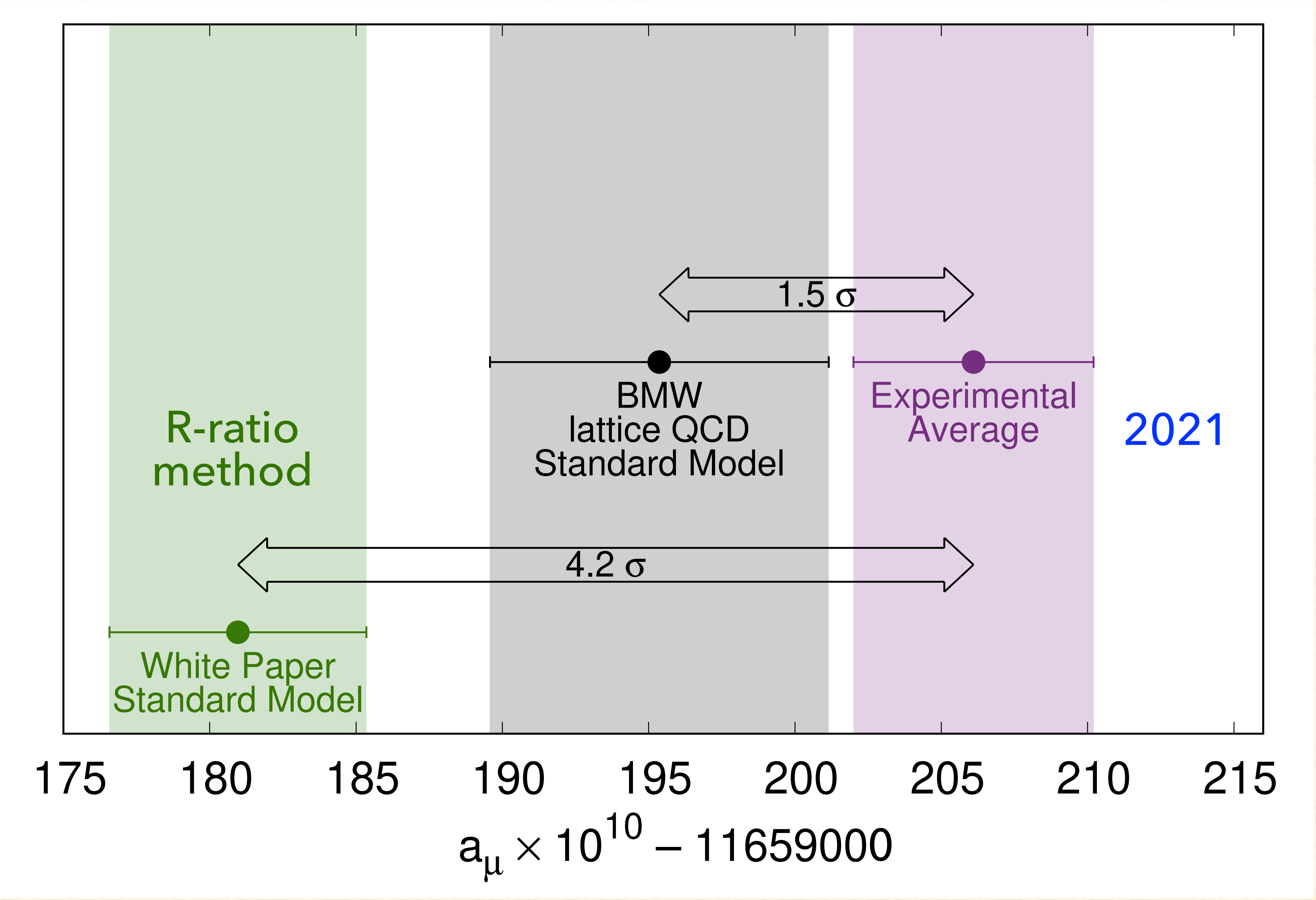
Status of the muon anomalous magnetic moment: experiment

- The muon g-2 has been a smoking gun for new physics for many years
- The most precise experimental value is from FNAL (2023) :

$$a_\mu = \frac{g-2}{2} = 116\,592\,055(24) \cdot 10^{-11} \quad (0.20\,\text{ppm})$$

- ...equivalent to a bathroom scale sensitive to a single eyelash:

Status of the muon anomalous magnetic moment: experiment vs. theory



[BMW compilation]

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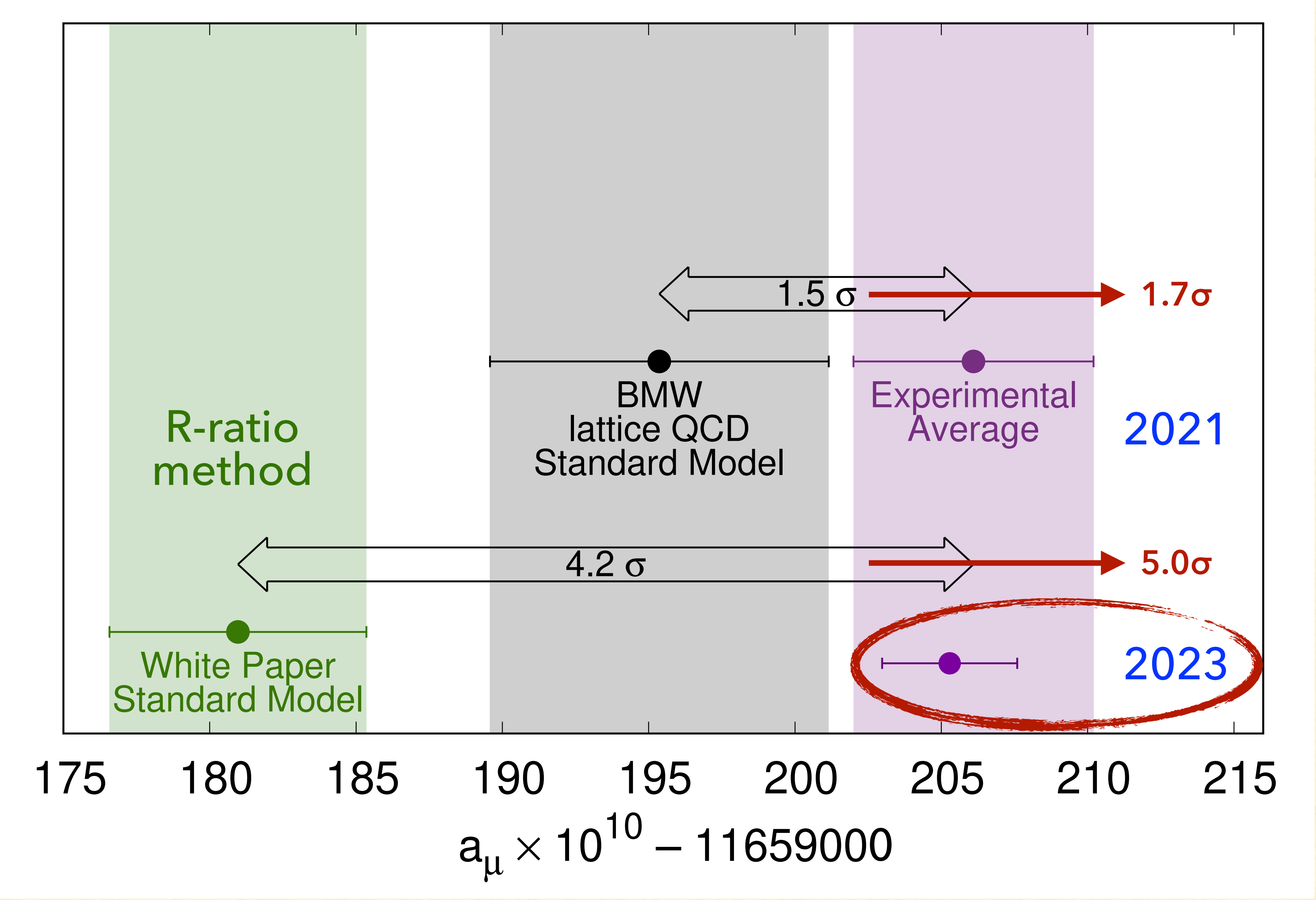
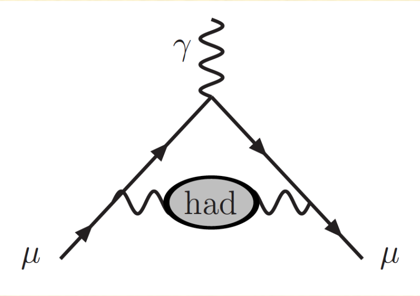


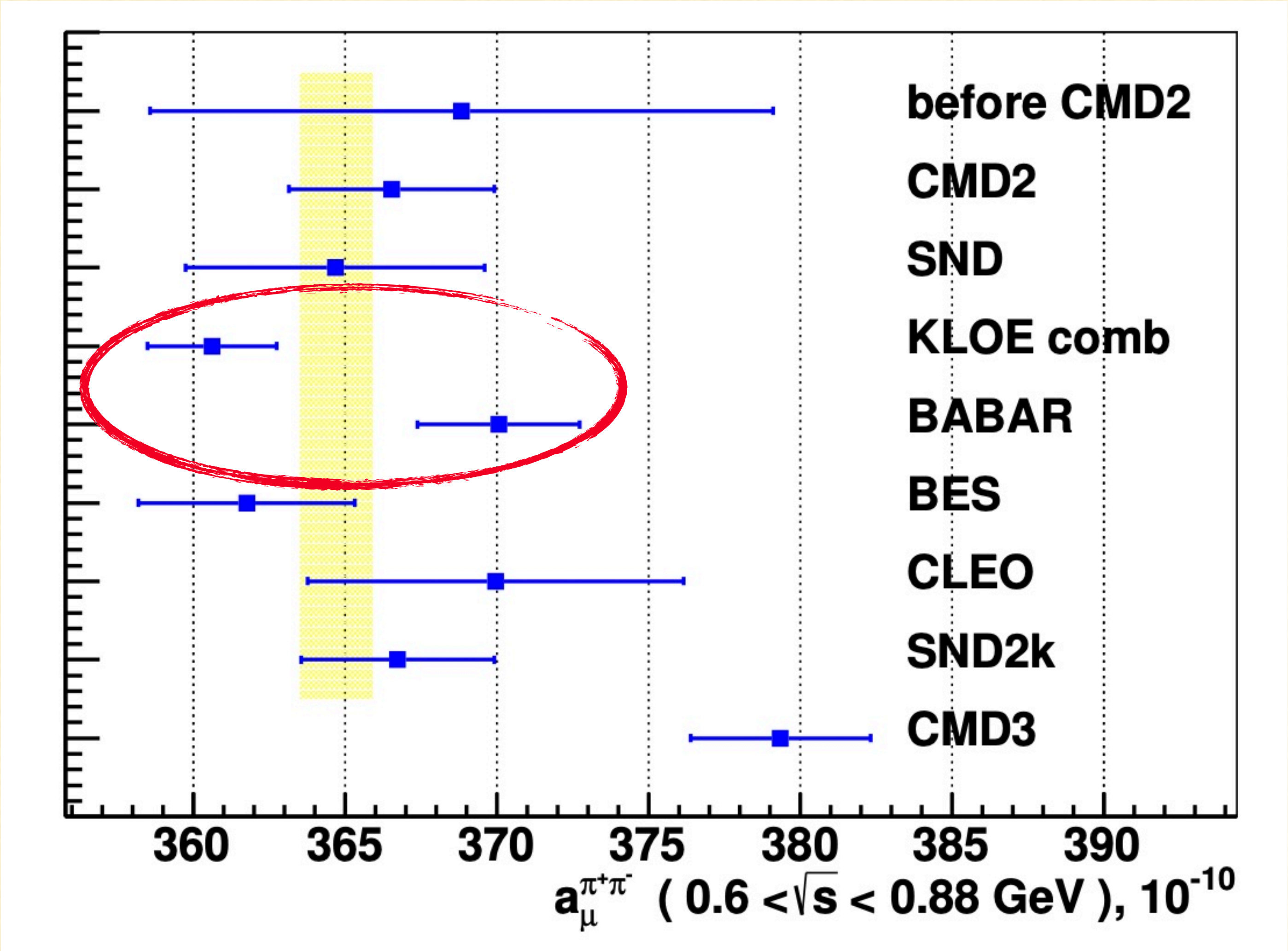
[BMW compilation]

Status of the muon anomalous magnetic moment: theory with R-ratio

- The muon g-2 has been a smoking gun for new physics for many years, but tension already in earlier data used for theory prediction:

$\sigma(e^+e^- \to \pi^+\pi^-)$ cross section in this energy range gives more than 50% to total HVP contribution to a_μ



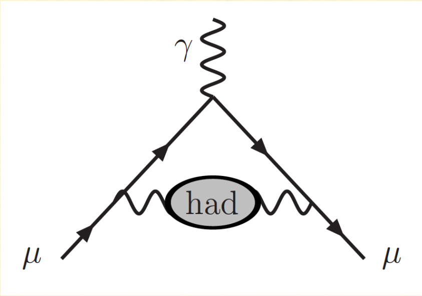


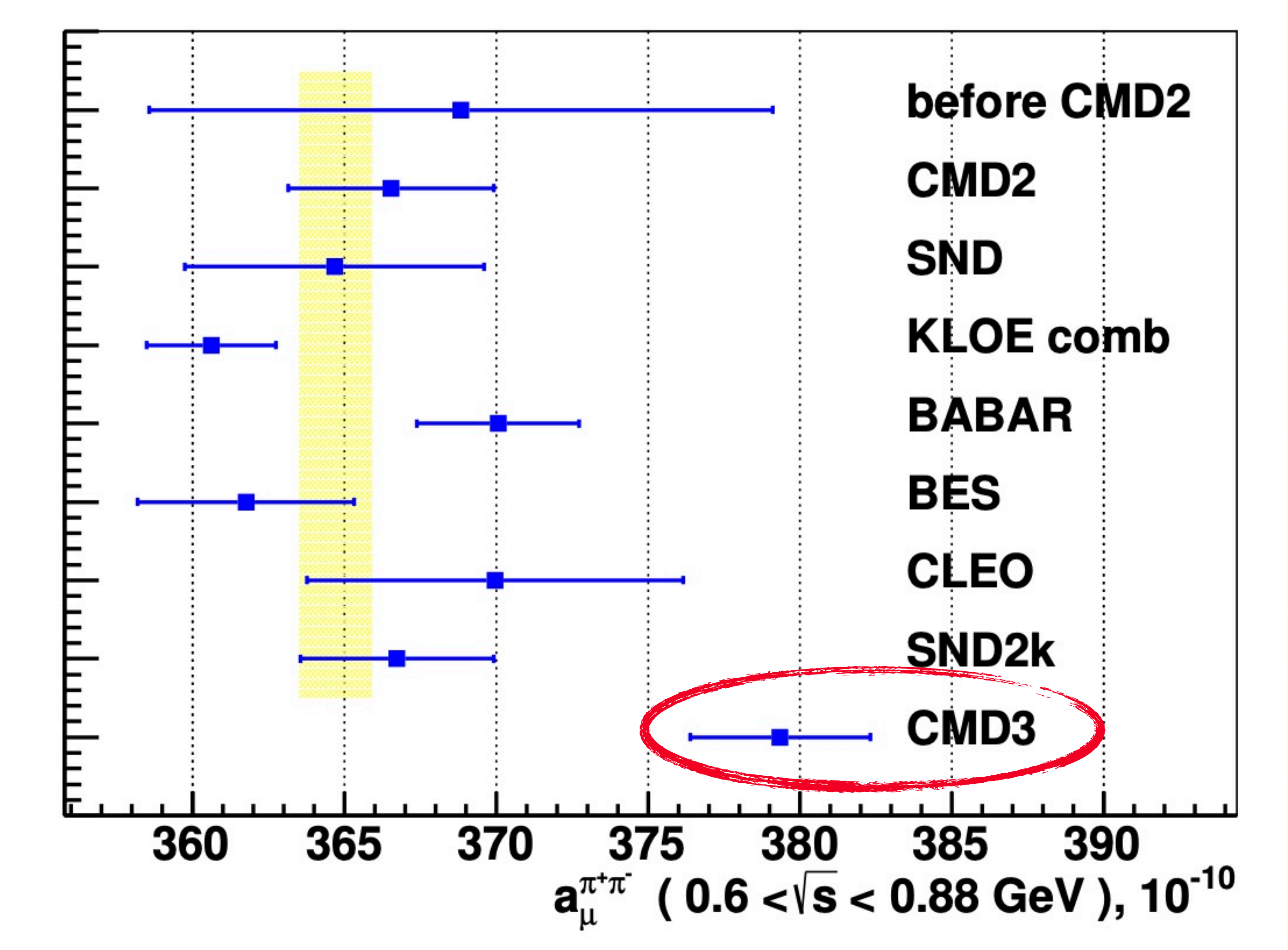
[BMW compilation]

Status of the muon anomalous magnetic moment: theory with R-ratio

- New CMD3 data show a ~15 unit increase in central value and 4.4σ tension with old average:

$\sigma(e^+e^- \to \pi^+\pi^-)$ cross section in this energy range gives more than 50% to total HVP contribution to a_μ

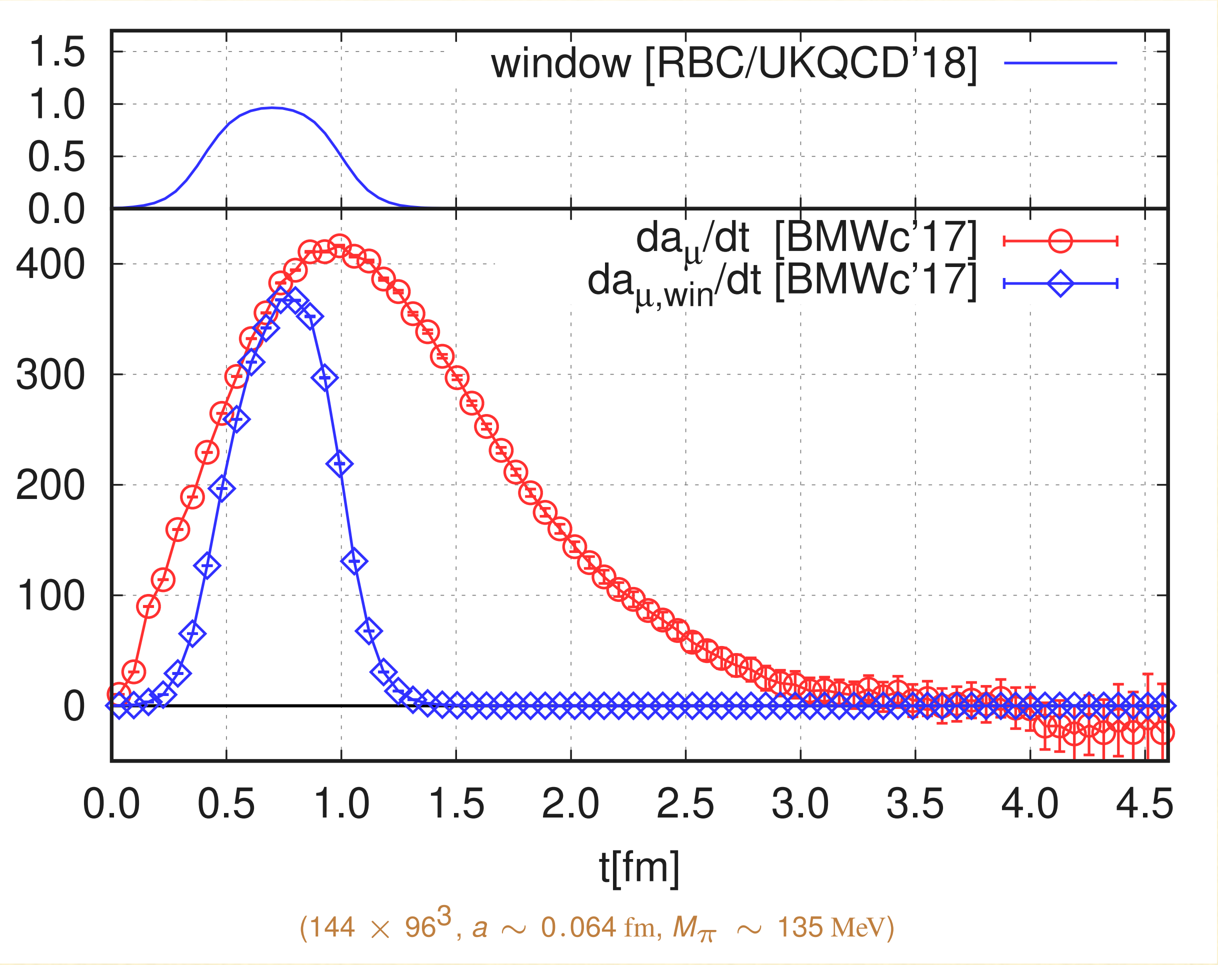


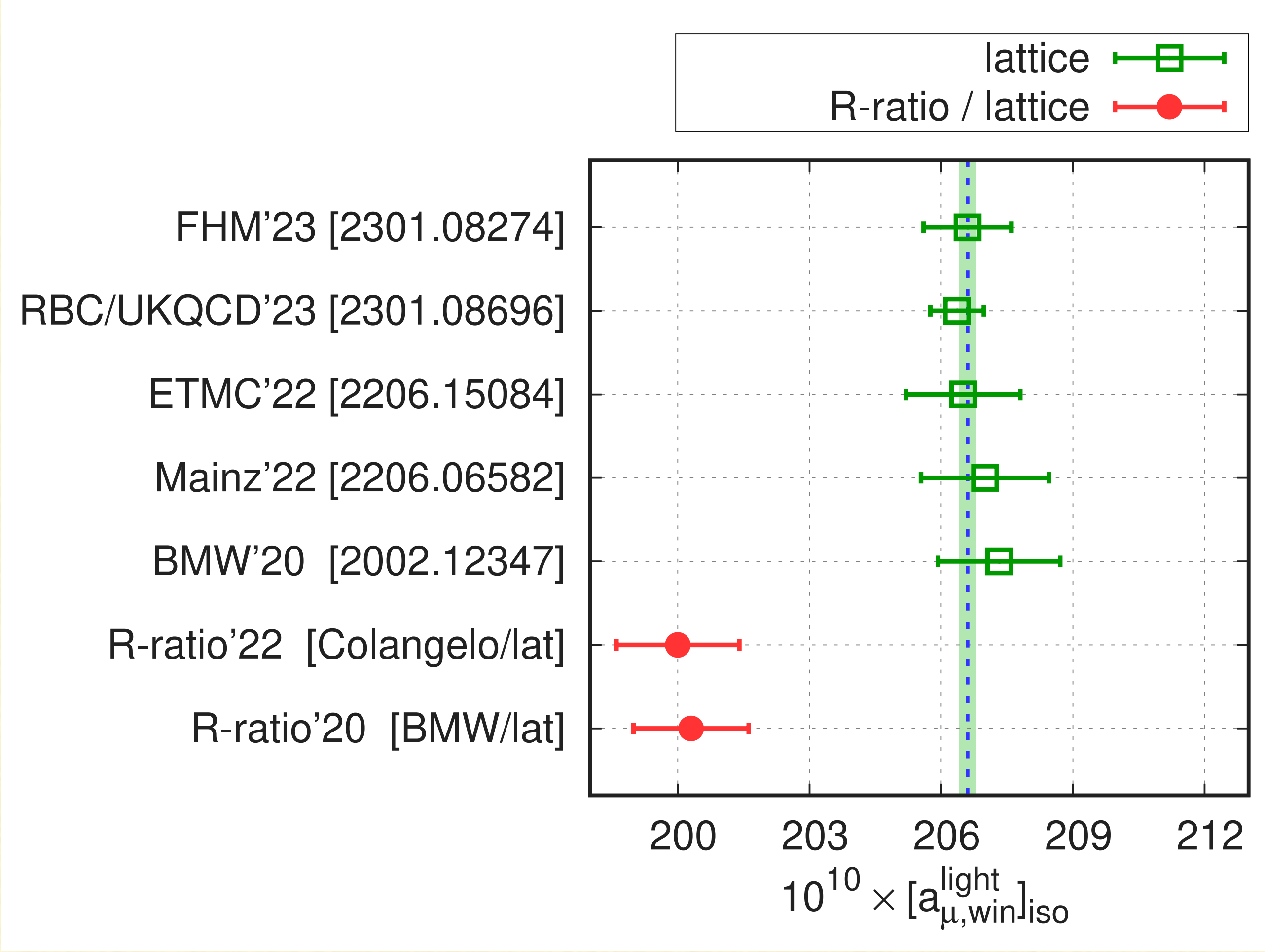


[BMW compilation]

Status of the muon anomalous magnetic moment: window observable

- restrict correlation window to [0.4,1.0] fm:
- two orders of magnitude easier (less CPU, less manpower needed) lattice vs. R-ratio: 4.9σ tension:





Non-standard interactions and the SWSM

[Timo J. Kärkäinen and ZT, arXiv: 2301.06621]

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

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:

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

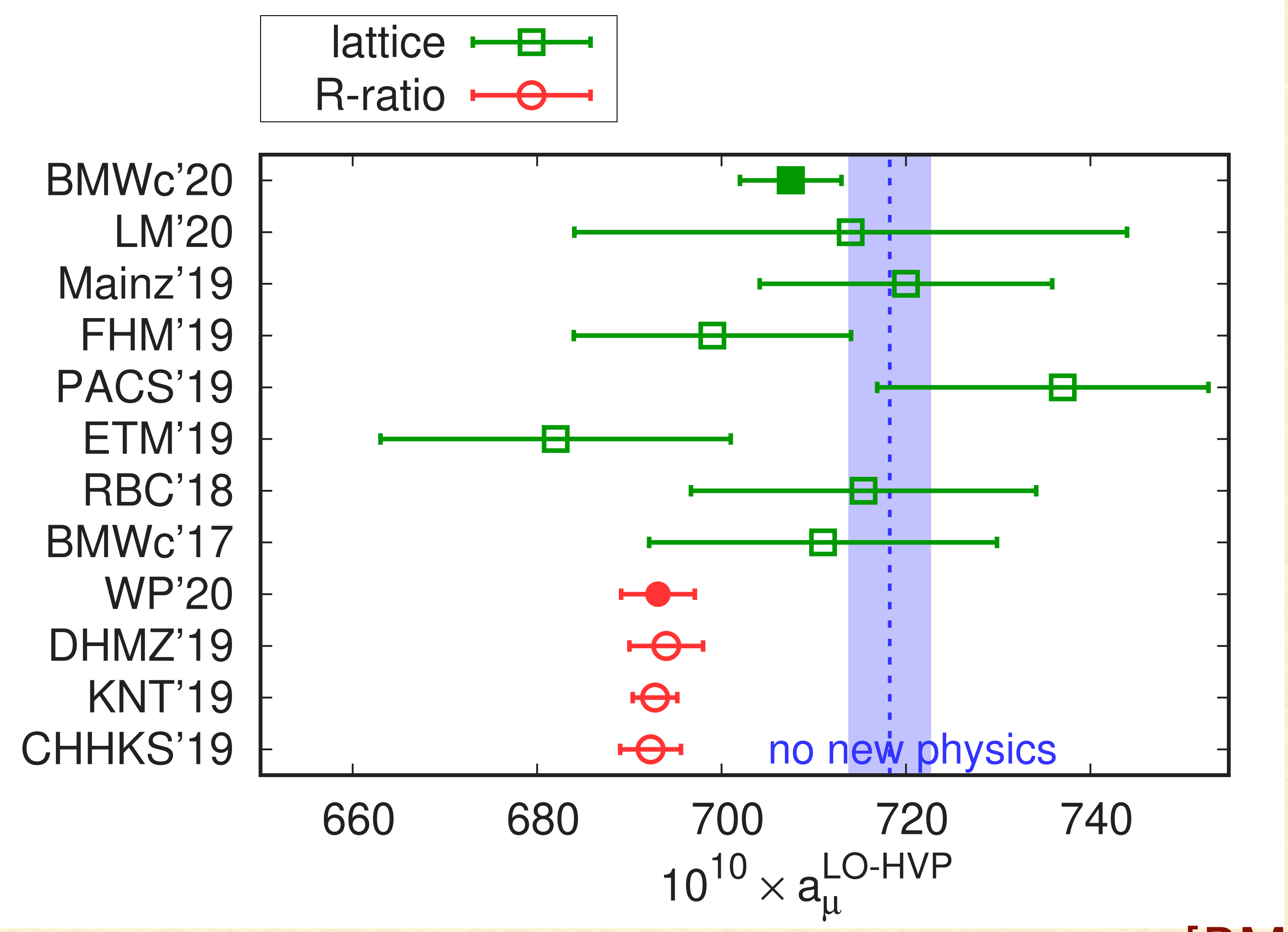
where $\varepsilon^{f,X}_{\ell,\ell'} \propto +\frac{1}{q^2}$ if $q^2 \gg M^2$, "light NSI"

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

for a mediator of mass M

Status of the muon anomalous magnetic moment: lattice vs. R-ratio

- Lattice: $a_\mu^{\mathrm{HVP@LO}} = 707.5(2.3)_{\mathrm{stat}}(5.0)_{\mathrm{sys}}[5.5]_{\mathrm{tot}}$
- ~15 units above the R-ratio white paper value (a 2.1σ tension)



[BMW compilation]

Non-standard interactions and the SWSM

assume $M = 50$ MeV, which is

- light in CHARM or NuTEV $q^2 = O((20\,\mathrm{GeV})^2)$
- 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

Non-standard interactions and the SWSM

- High-energy theory enforces texture for NSI matrix:

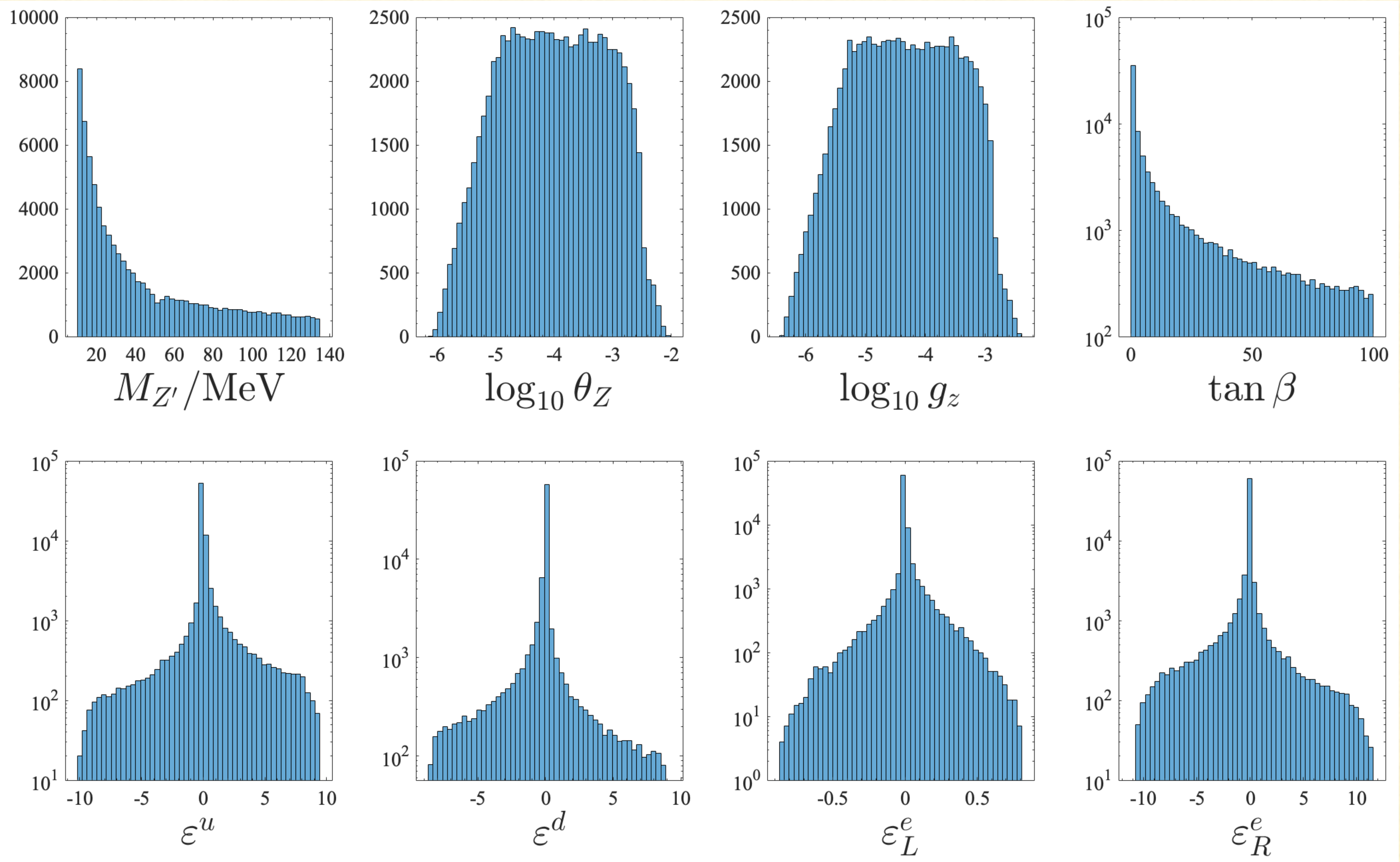
$$\varepsilon^m_{\ell\ell} = \underbrace{\varepsilon^e_{\ell\ell} + 2\varepsilon^u_{\ell\ell} + \varepsilon^d_{\ell\ell}}_{=0} + \frac{N_n}{N_e}(\varepsilon^u_{\ell\ell} + 2\varepsilon^d_{\ell\ell})$$

SWSM

	$\begin{pmatrix} \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix}$ $\mu - \tau$ symmetry	$\begin{pmatrix} \varepsilon_e & 0 & 0 \\ 0 & \varepsilon_\mu & 0 \\ 0 & 0 & \varepsilon_\tau \end{pmatrix}$ Flavour-conserving	$\begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}$ Flavour-universal
CLFV decays	✓	No	No
ν oscillation	✓	✓	No
CEνNS	✓	✓	✓
ν scattering	maybe	maybe	maybe

- Existing limits on NSI constrain the parameters of the high-energy theory

Non-standard interactions and the SWSM: preferred regions of the parameters



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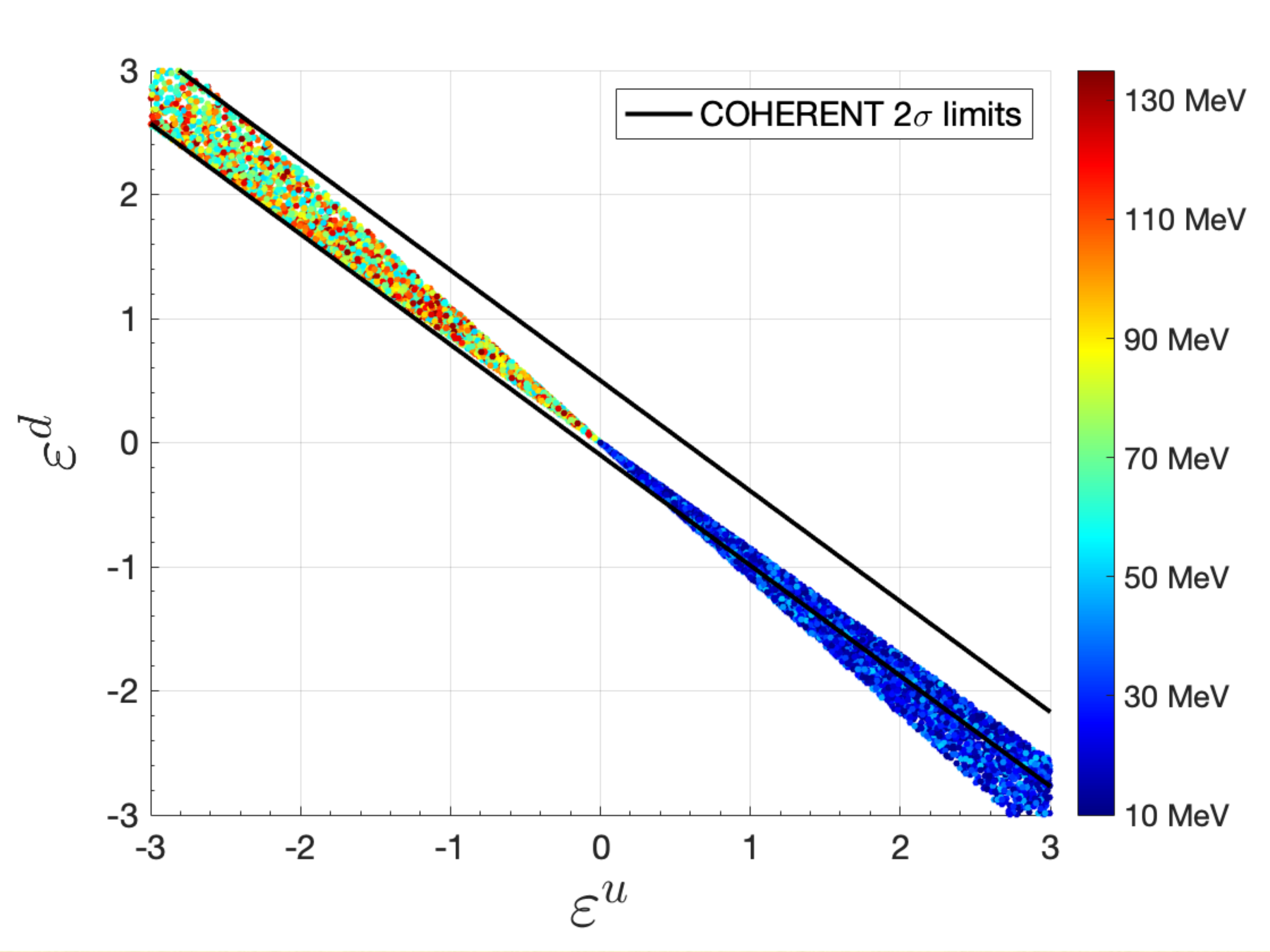

Particle model

New fields: 3 right-handed neutrinos ν_R^f, a new scalar χ, and new U(1)$_z$ gauge boson B'

- fermion fields (Weyl spinors):

$$\psi_{q,1}^f = \begin{pmatrix} U^f \\ D^f \end{pmatrix}_{\rm L} \qquad \psi_{q,2}^f = U_{\rm R}^f\,, \qquad \psi_{q,3}^f = D_{\rm R}^f$$

$$\psi_{l,1}^f = \begin{pmatrix} \nu^f \\ \ell^f \end{pmatrix}_{\rm L} \qquad \psi_{l,2}^f = \nu_{\rm R}^f\,, \qquad \psi_{l,3}^f = \ell_{\rm R}^f$$

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$$\mathcal{D}_\mu^{U(1)} = -i(y g_y B_\mu + z g_z B'_\mu)$$

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$$\mathcal{D}_\mu^{\mathrm{U}(1)} = -\mathrm{i}(y g_y B_\mu + z g_z B'_\mu)$$

- the new U(1) kinetic term includes kinetic mixing:

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

Kinetic mixing

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- or equivalently can choose basis s. t.:

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and can parametrize the coupling matrix s.t.:

$$\hat{\mathbf{g}} = \begin{pmatrix} \hat{g}_{yy} & \hat{g}_{yz} \\ \hat{g}_{zy} & \hat{g}_{zz} \end{pmatrix} = \begin{pmatrix} g_y & -\eta g'_z \\ 0 & g'_z \end{pmatrix}\begin{pmatrix} \cos\epsilon' & \sin\epsilon' \\ -\sin\epsilon' & \cos\epsilon' \end{pmatrix}$$

with

$$g'_z = g_z/\sqrt{1-\epsilon^2}$$
$$\eta = \epsilon g_y/g_z.$$

Neutral currents

- covariant derivative: $\mathscr{D}_\mu^{\text{neut.}} \supset -\mathrm{i}(\mathscr{Q}_A A_\mu + \mathscr{Q}_Z Z_\mu + \mathscr{Q}_{Z'} Z'_\mu)$

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- $Z - Z'$ mixing is small, the weak neutral current is only modified at order $\mathrm{O}(g_z^2/g_{Z^0}^2)$

Rough estimates of gauge parameters

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  in order to avoid SM precision constraints $\mathrm{O}(g_z/g_{Z^0}) \ll 1$

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- Masses of sterile neutrinos:

  assume N_1 to be light (keV-MeV scale), while $M_{2,3} = \mathrm{O}(M_{Z^0})$

Production of DM in freeze-out scenario

- We consider $M_1 = \mathrm{O}(10)\,\mathrm{MeV} \Rightarrow$ decoupling happens at $T_{\mathrm{dec}} = \mathrm{O}(1)\,\mathrm{MeV}$
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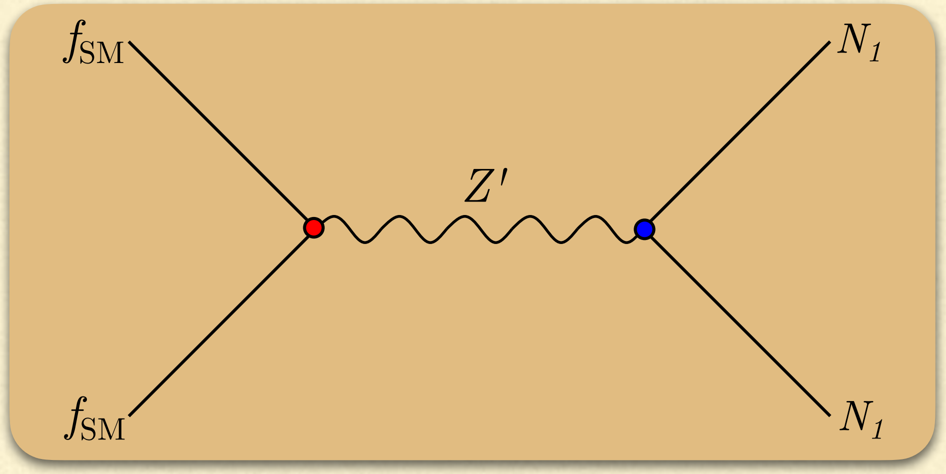
  At this temperature electrons and SM neutrinos are abundant, negligible amounts of heavier fermions
- Relevant cross section for the production process



$$N_1 N_1 \to f_{\rm SM} f_{\rm SM}: \quad \sigma_{\rm t} \propto g_z^4 \sqrt{1 - \frac{4M_1^2}{s}} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$

Resonant production of DM

Need to increase $\langle \sigma v_{\mathrm{Mol}} \rangle$ without increasing g_z (excluded experimentally): exploit resonant production ($2M_1 \lesssim M_{Z'}$)

Resonant production of DM

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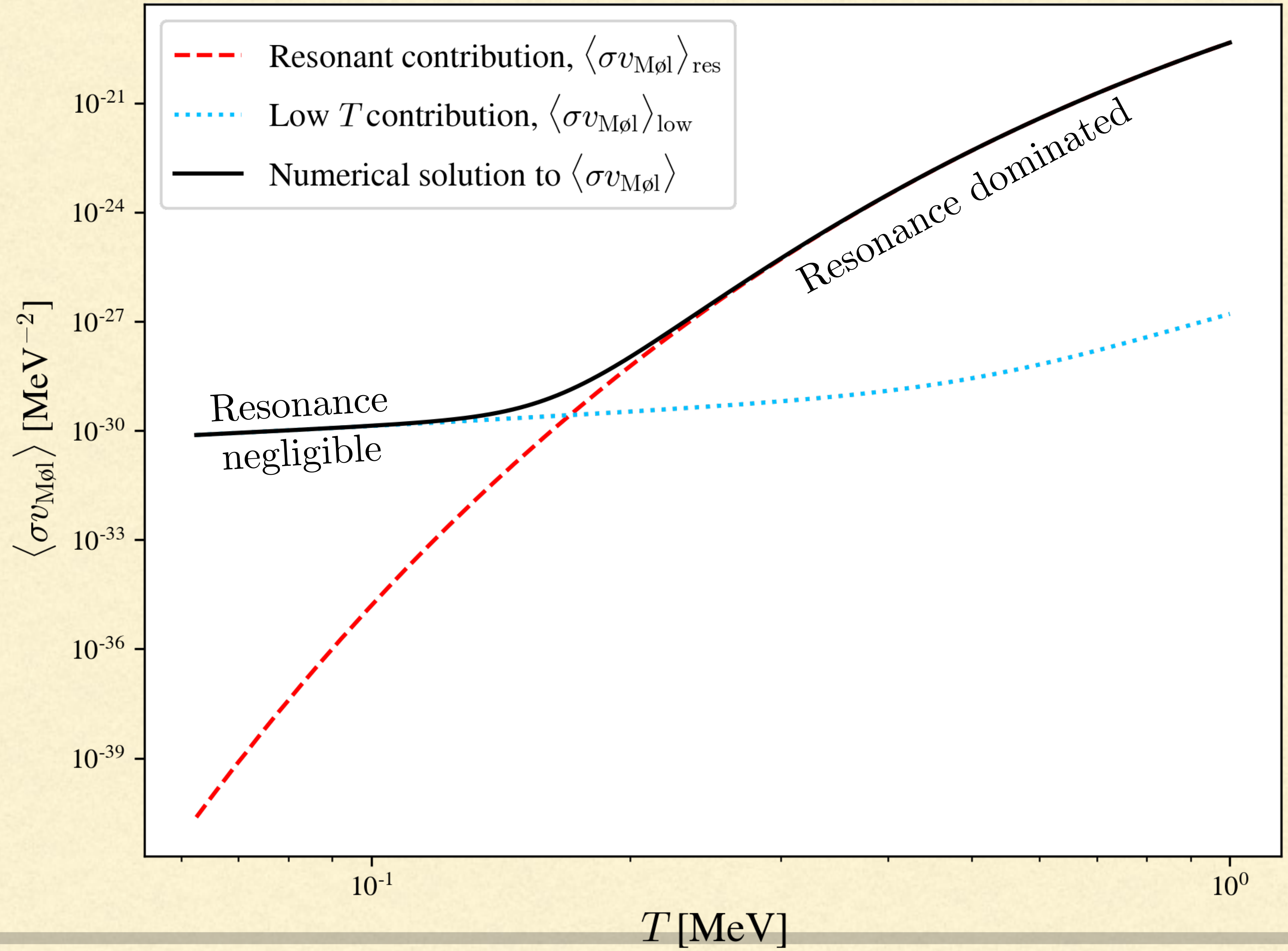
- the Bessel function K_1 vanishes exponentially at large arguments
- $T_{\rm dec} \approx 0.1 M_1$, hence $K_1(10 M_{Z'}/M_1)$ can be small at the resonance $s = M_{Z'}^2$ depending on the ratio $M_{Z'}/M_1$

Resonant amplification: example

calculated within the SWSM for $M_1 = 10\,\mathrm{MeV}$ & $M_{Z'} = 30\,\mathrm{MeV}$



Masses of the neutral gauge bosons again

can also be expressed with chiral couplings:

$$M_Z^2 = \frac{v^2 e^2}{\cos^2\theta_{\mathrm{G}}}\left(C^L_{Z\nu\nu} - C^R_{Z\nu\nu}\right)^2$$

$$M_{Z'}^2 = \frac{v^2 e^2}{\sin^2\theta_{\mathrm{G}}}\left(C^L_{Z'\nu\nu} - C^R_{Z'\nu\nu}\right)^2$$

which are crucial for checking gauge independence

Neutral current couplings on mass basis

recall: $$\Gamma^{\mu}_{V\bar{f}f} = -\mathrm{i}e\gamma^{\mu}(C^{R}_{V\bar{f}f}P_R + C^{L}_{V\bar{f}f}P_L)$$

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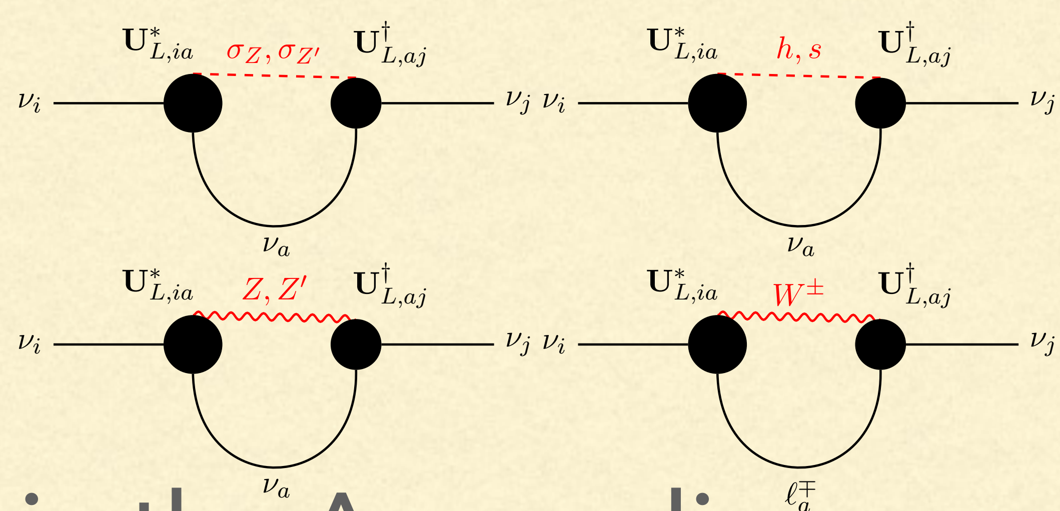

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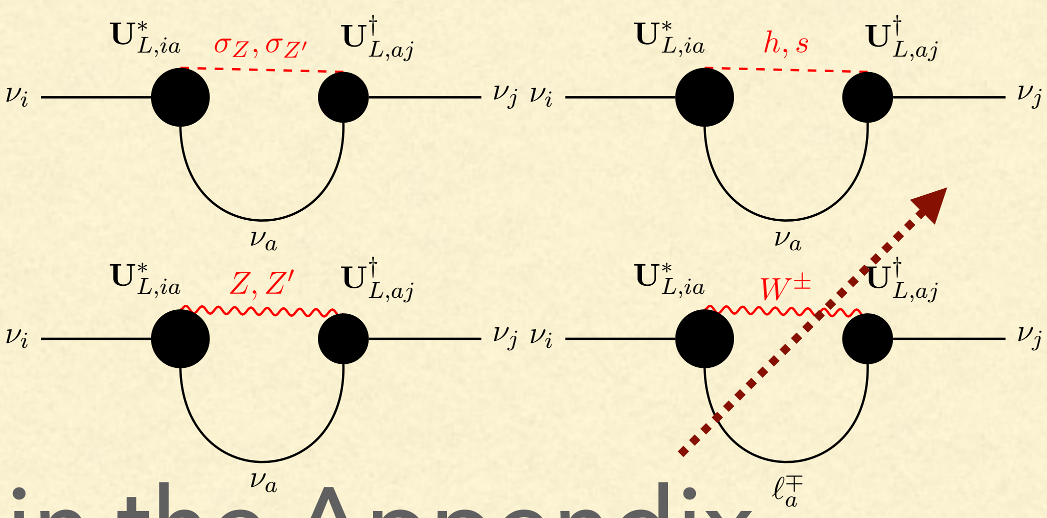

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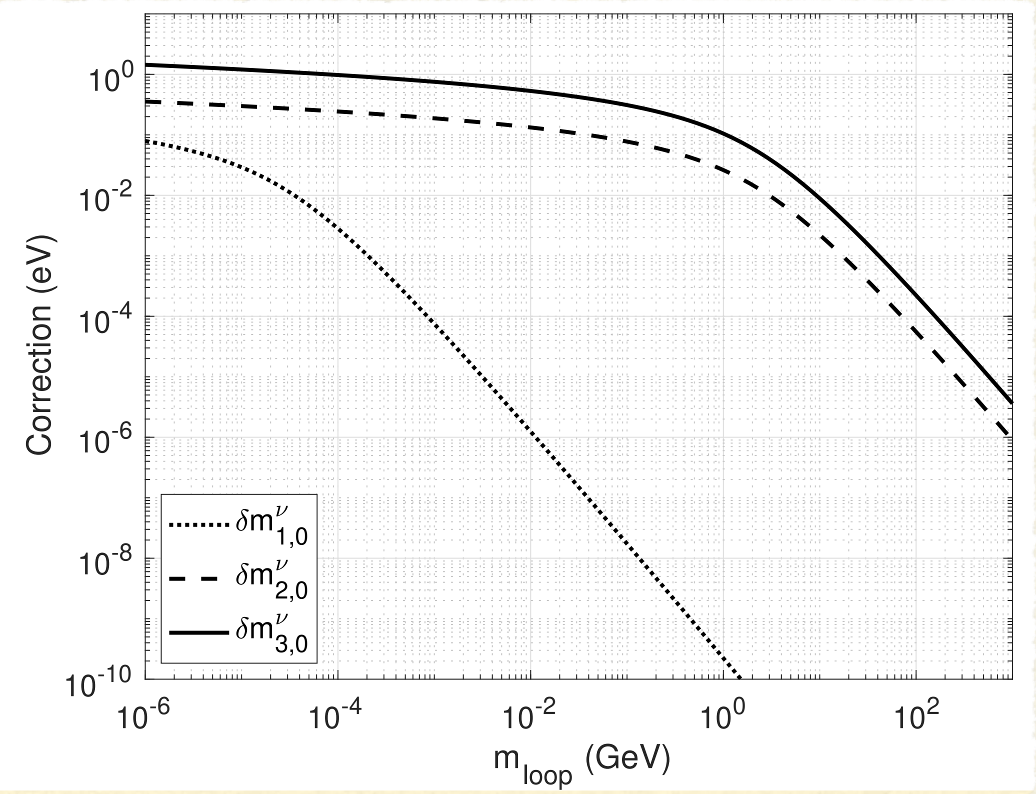
gauge terms cancel

Numerical estimates

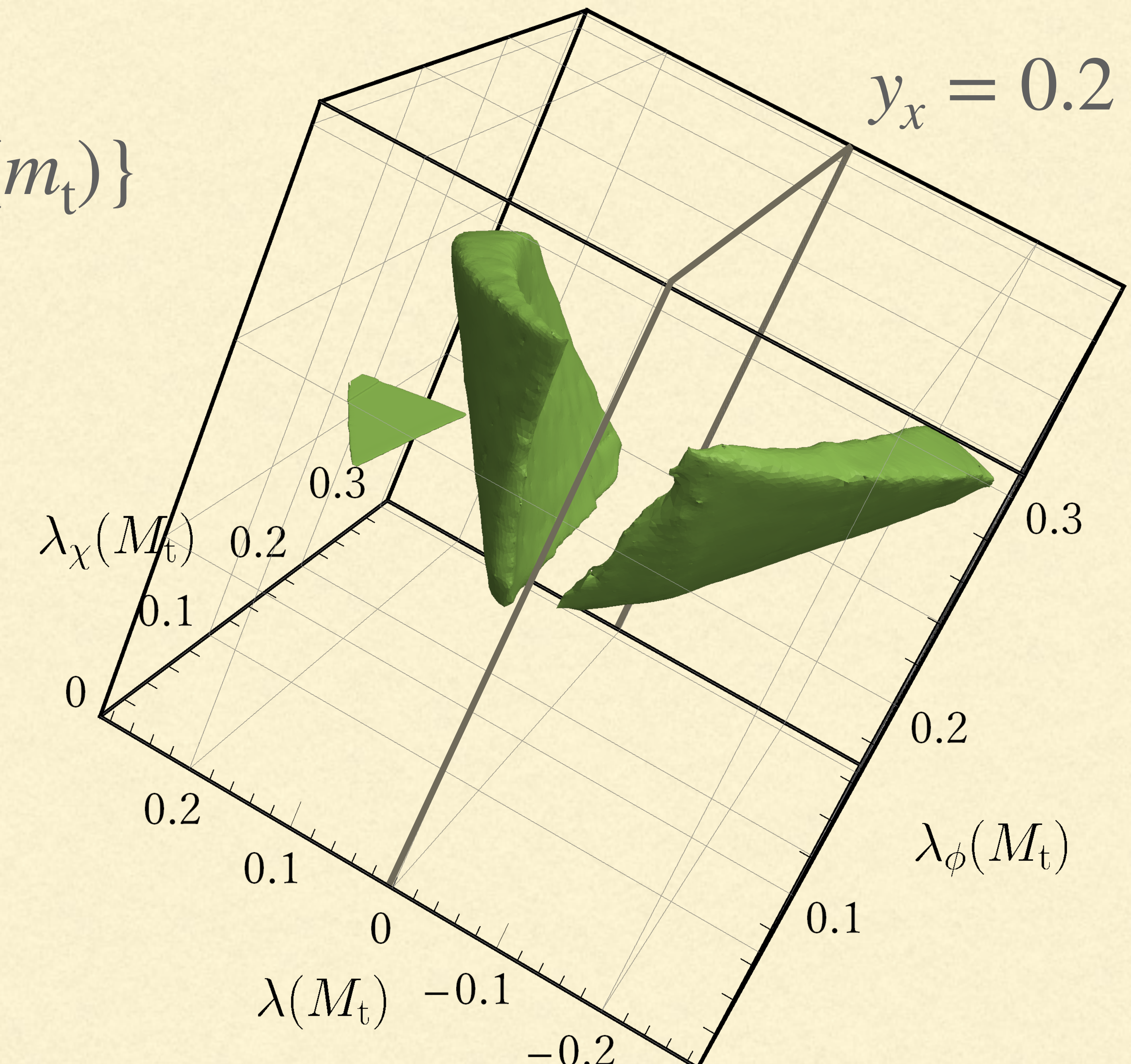


Eigenvalues of the matrix F as a function of the mass of the boson in the loop m_{loop}, assuming m_1^{tree} = 0.01 eV, m_4^{tree} = 30 keV, $m_5^{tree} \approx m_6^{tree}$ = 2.5 GeV, and normal neutrino mass hierarchy

eigenvalues can be large, but coupling suppression tames the relative correction to the tree-level mass below percent level

Scanning couplings for vacuum stability: allowed region of scalar couplings at 2 loops

- For given input
  $\{\lambda_\phi(m_t), \lambda_\chi(m_t), \lambda(m_t), y_x(m_t)\}$



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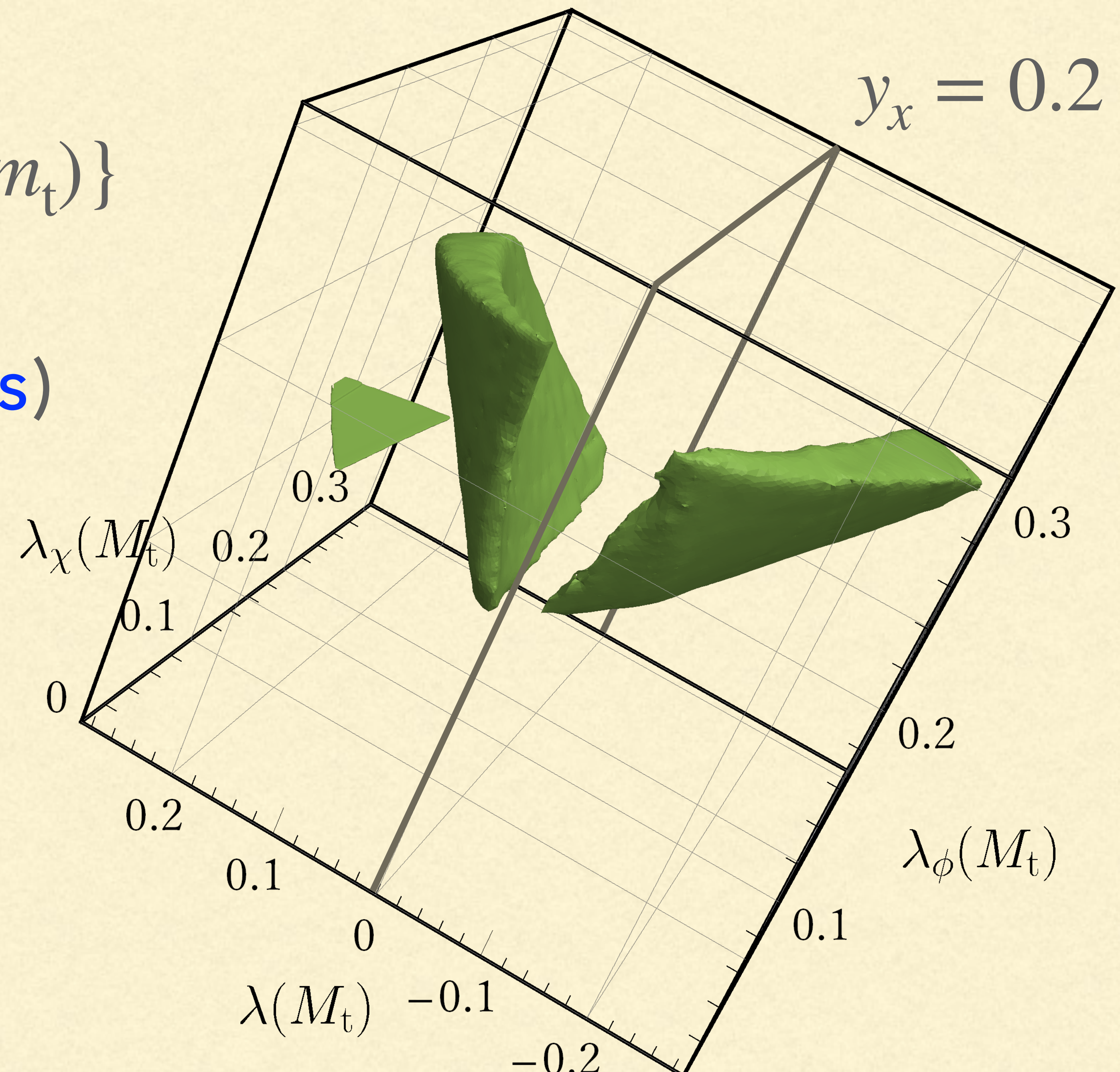

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- Run RGE and check
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  - perturbativity