ELTE
EÖTVÖS LORÁND TUDOMÁNYEGYETEM

Zoltán Trócsányi

UNIVERSITY of DEBRECEN

PRECISION PREDICTIONS IN THE GAUGE AND SCALAR SECTORS 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), 2402.14786 (PRD)

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

HP2 workshop, Torino, 12 September, 2024

To the memory of Stefano

…I was a fortunate participant of his seminal contribution to the theory of QCD quantum corrections

A General Algorithm for Calculating Jet Cross Sections in NLO QCD[*]

S. Catani

I.N.F.N., Sezione di Firenze
and Dipartimento di Fisica, Università di Firenze
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M.H. Seymour

Theory Division, CERN
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The Dipole Formalism for Next-to-Leading Order QCD Calculations with Massive Partons

Stefano Catani[1*], **Stefan Dittmaier**[2†], **Michael H. Seymour**[3] and **Zoltán Trócsányi**[4‡]

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Institute of Nuclear Research of the Hungarian Academy of Sciences
H-4001 Debrecen, PO Box 51, Hungary

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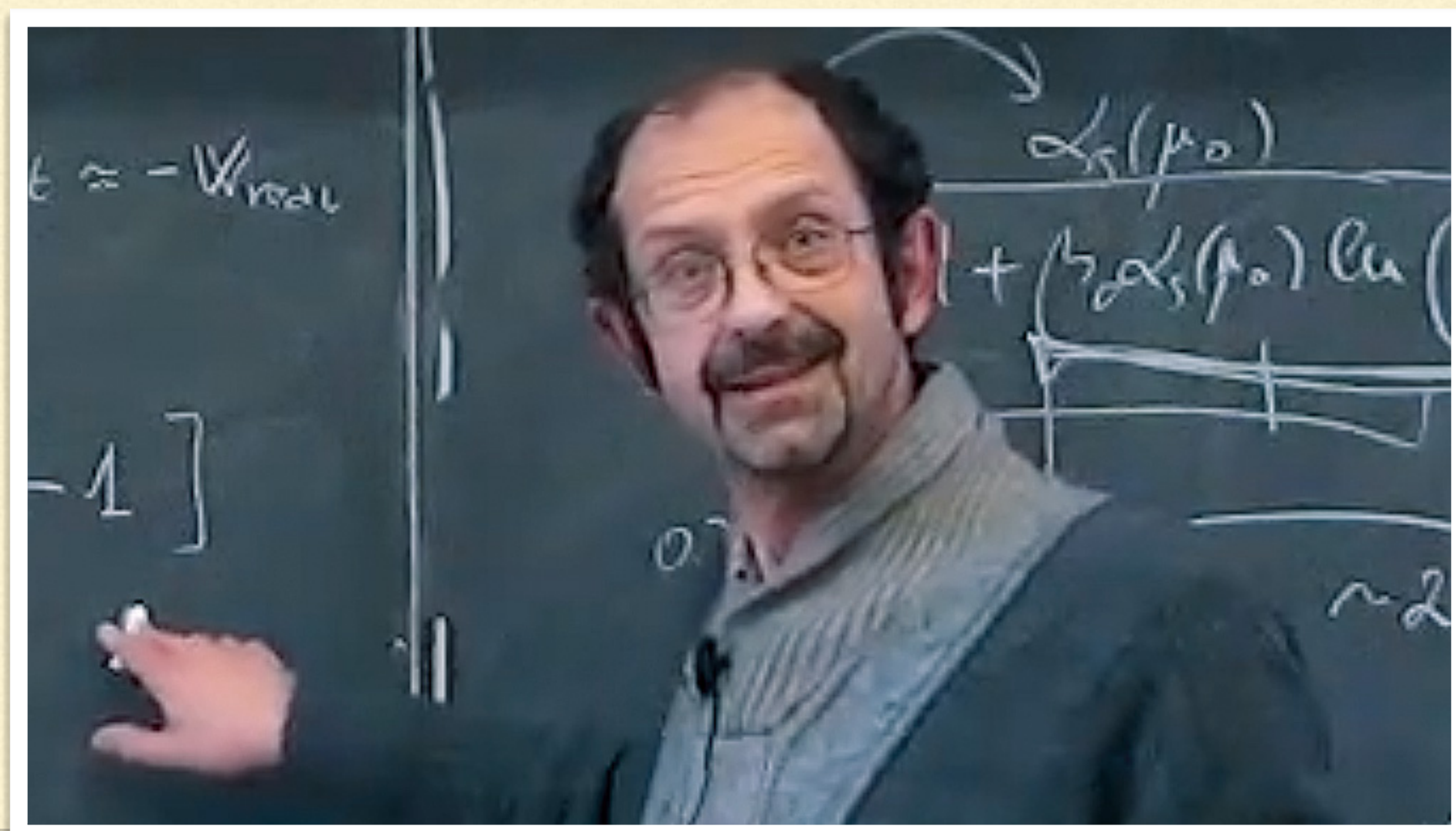
- had exceptional insight of QFT



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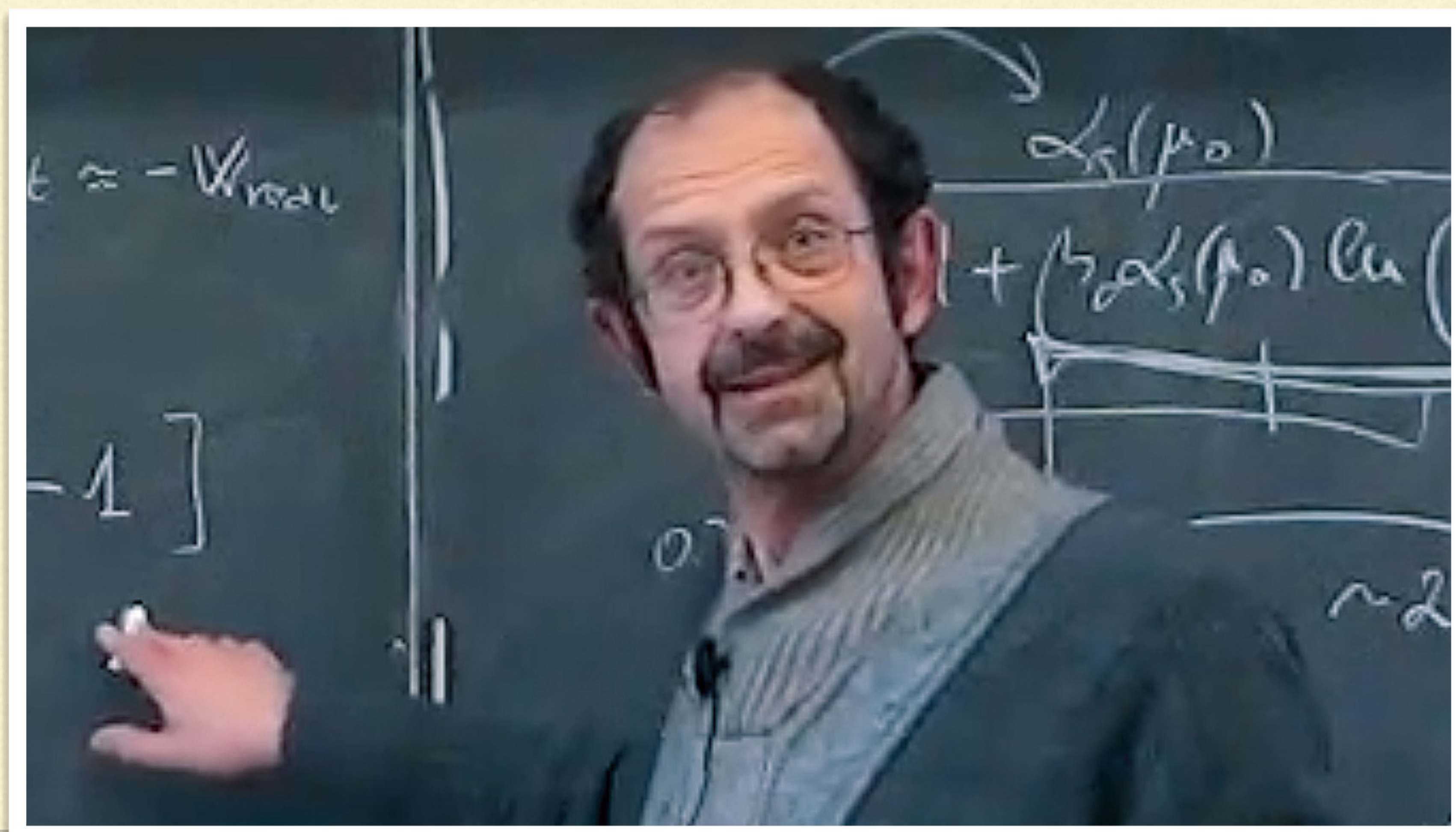

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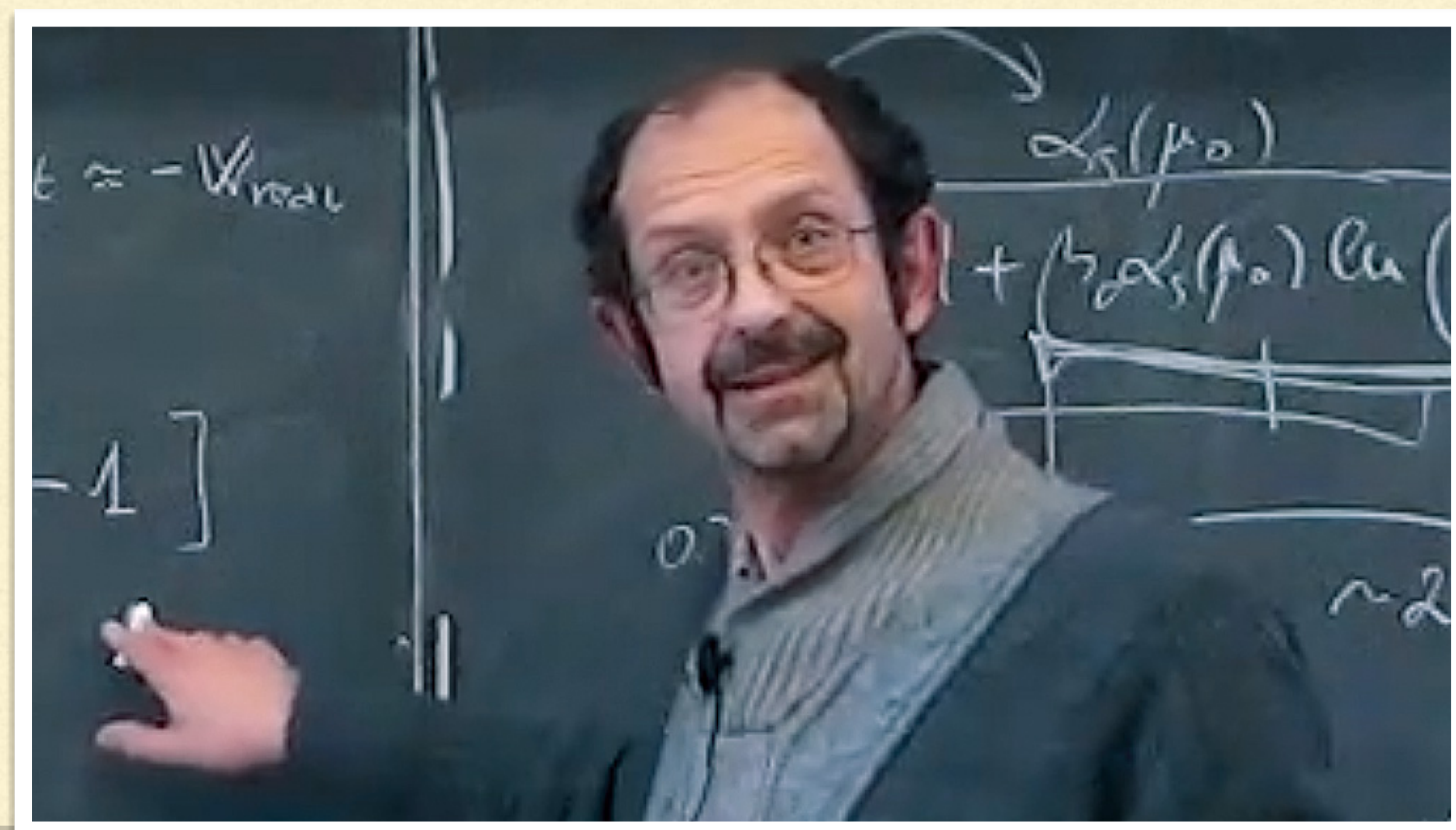
- was “a true gentleman”

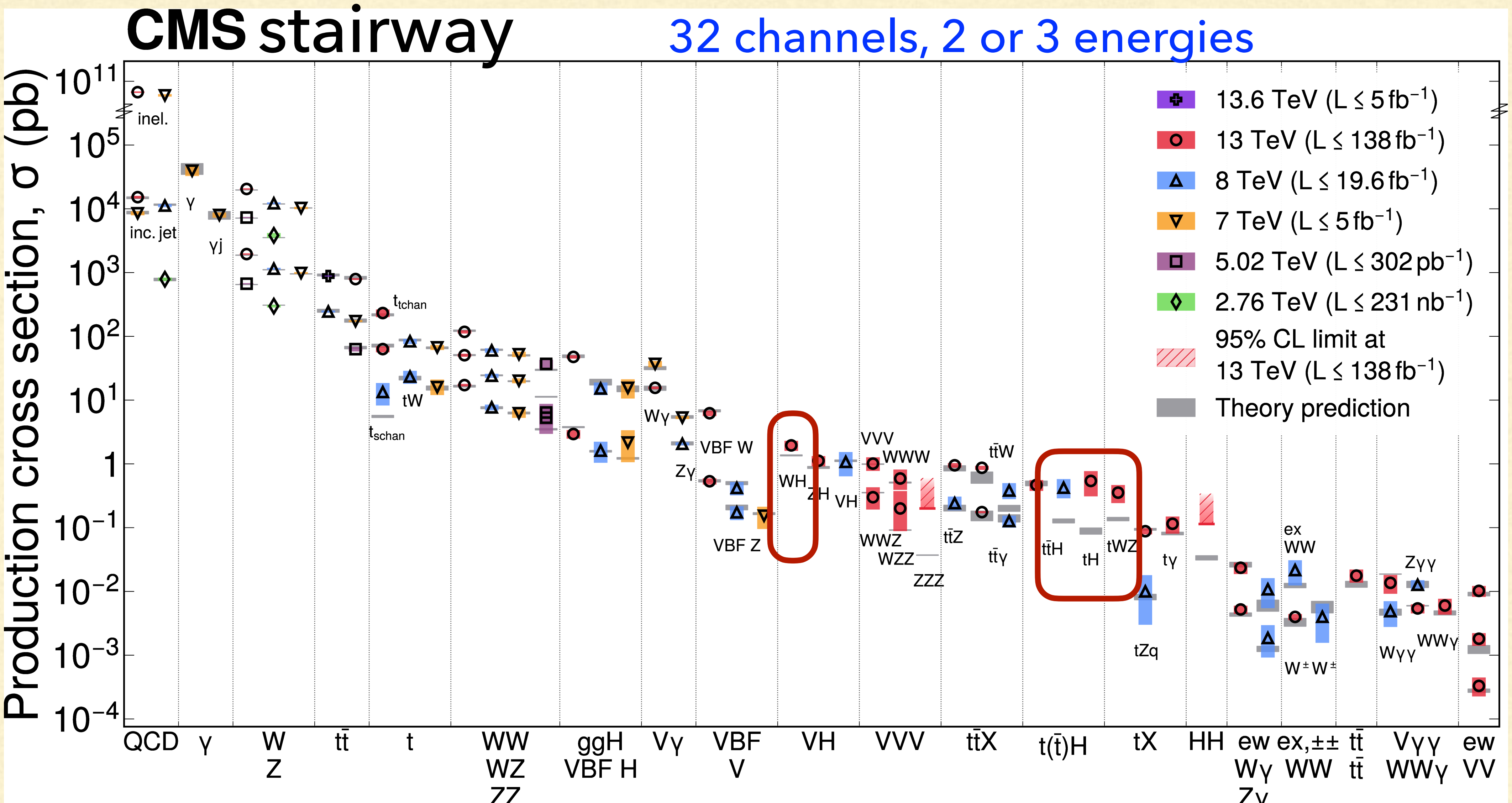


OUTLINE

1. Motivation: status of particle physics
2. Superweak $U(1)_z$ extension of SM (SWSM)
3. Vacuum stability and scalar sector constraints
4. Gauge sector constraints

Status of particle physics: energy frontier

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



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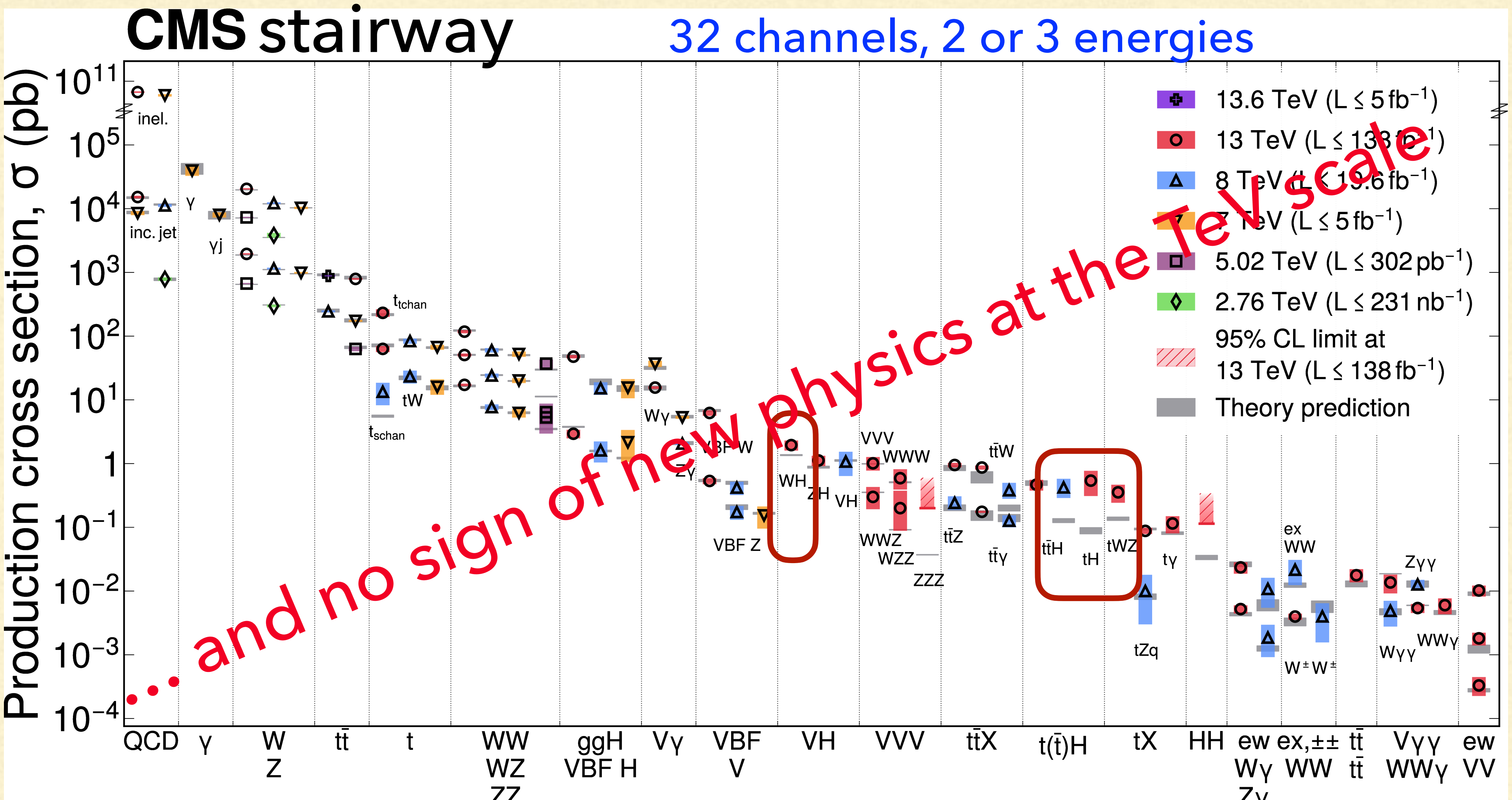

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- Neutrino masses
- Dark matter and energy
- Baryon asymmetry

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- Lagrangian and its parameters
- Yukawa couplings
- Connection to inflation
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Anomalies:
- Muon anomalous magnetic moment
- 2-3σ excesses at LHC experiments
- X17 and X38 anomalies
- CDF II result for M_W

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- X1
- CD

Not addressed in this talk, but I can share my views during discussion

Phenomenological approach to new physics

Established observations require physics beyond SM,
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Can we explain established observations,
but not more,
by the same (simple) 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

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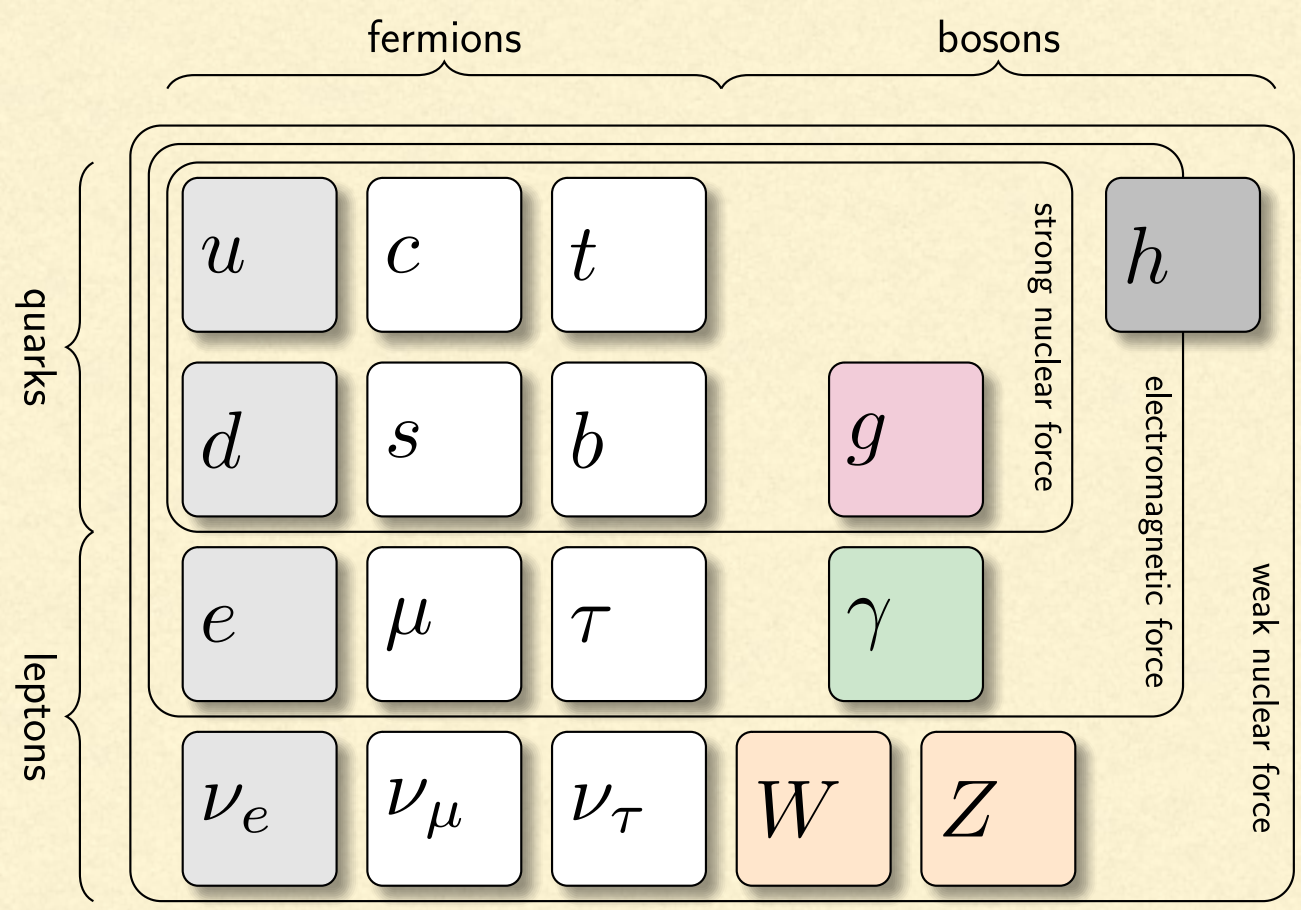
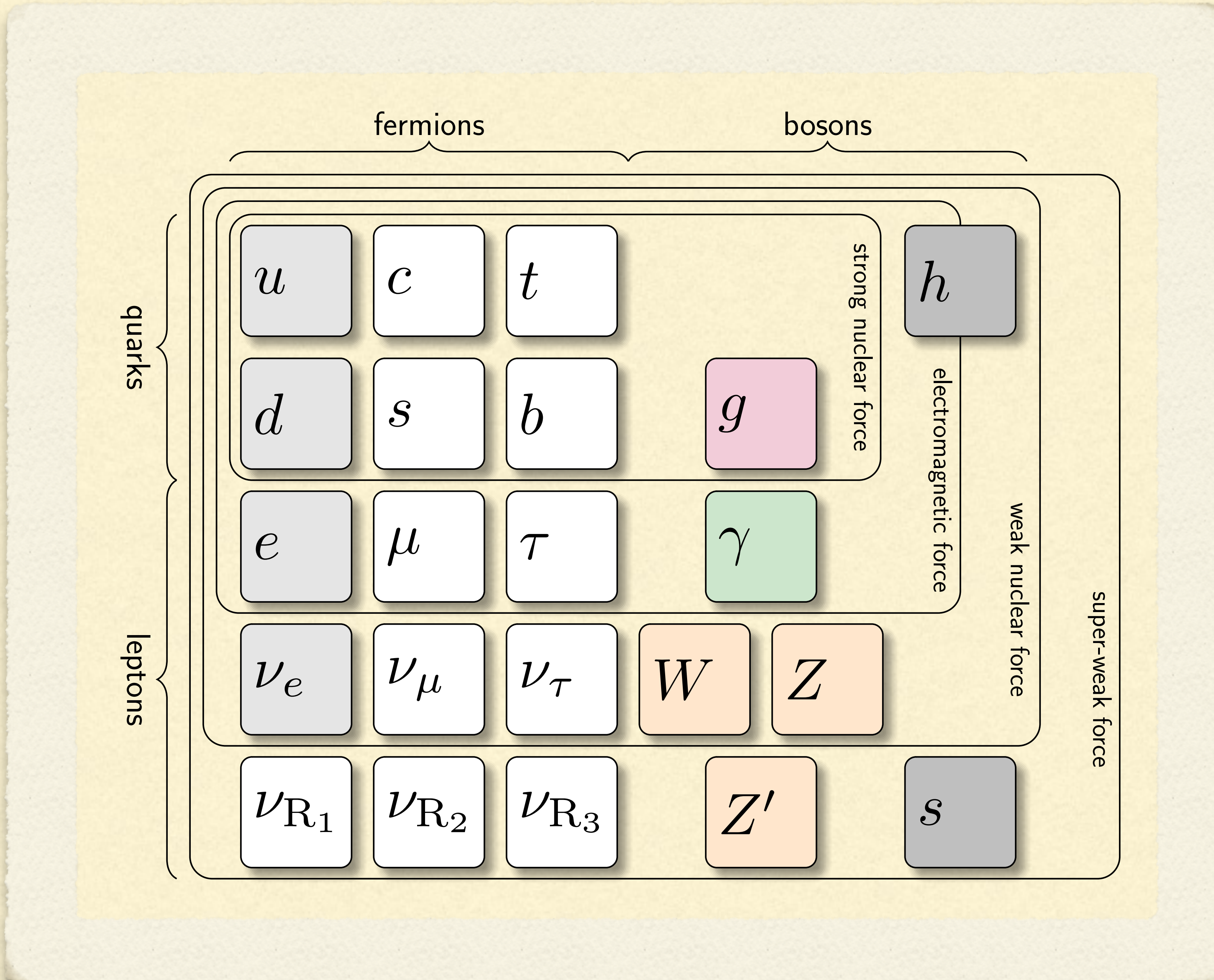
Particle content of SM



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

[ZT, 1812.11189]

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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]

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

field	$SU(3)_c$	$SU(2)_L$	y_j	z_j
$U_L,\ D_L$	3	2	$\frac{1}{6}$	Z_1
U_R	3	1	$\frac{2}{3}$	Z_2
D_R	3	1	$-\frac{1}{3}$	$2Z_1 - Z_2$
$\nu_L,\ \ell_L$	1	2	$-\frac{1}{2}$	$-3Z_1$
ν_R	1	1	0	$Z_2 - 4Z_1$
ℓ_R	1	1	-1	$-2Z_1 - Z_2$
ϕ	1	2	$\frac{1}{2}$	z_ϕ
χ	1	1	0	z_χ

traditional

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

field	$SU(3)_c$	$SU(2)_L$	y_j	z_j	z
$U_L,\ D_L$	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	$z_\chi := -1$
				traditional	new

in the SWSM $z_N = 1/2$ from Majorana mass term

U(1) covariant derivative is modified

$$\mathrm{D}_\mu^{U(1)} = -\mathrm{i}\,(y\ z)\begin{pmatrix} g_y & -g_z\,\eta \\ 0 & g_z \end{pmatrix}\begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}$$

z charges are defined at $\eta(\mu_0) = 0$

η is proportional to the kinetic mixing parameter in $\epsilon F'_{\mu\nu} F^{\mu\nu}$ but depends on the renormalization scale

Scalars in the SWSM

- Standard Φ complex SU(2)$_L$ doublet and new χ complex singlet to make Z' massive

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

- 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 h and s are mass eigenstates:

$$M^2_{h/s} = \lambda_\phi v^2 + \lambda_\chi w^2 \pm \frac{\lambda_\phi v^2 - \lambda_\chi w^2}{\cos 2\theta_S}$$

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with v and w VEVs and θ_S scalar mixing angle, implicitly:

$$\tan(2\theta_S) = \frac{\lambda v w}{\lambda_\chi w^2 - \lambda_\phi v^2}$$

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:

$\tan(2\theta_Z) = -2\kappa \Big/ \left(1 - \kappa^2 - \tau^2\right)$, 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: $\dfrac{M_W^2}{c_W^2} = c_Z^2 M_Z^2 + s_Z^2 M_{Z'}^2$ $\left(M_W = \dfrac{1}{2} g_L v \right)$

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Free parameters

- 2 in the gauge sector:

$\{g_z$ and $\eta\}$ or $\{\kappa$ and $\tau\}$ or $\{s_Z = \sin\theta_Z$ and $\xi = M_{Z'}/M_Z\}$

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where $\rho = \frac{M_W^2}{c_W^2 M_Z^2} = 1 + (\xi^2 - 1) s_Z^2$ is the rho parameter,

$\rho_{\rm exp} = 1.00038 \pm 0.00020$ (only BSM physics)

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- 3 in the scalar sector:

  $\{\mu_\chi^2, \lambda_\chi$ and $\lambda\}$ or $\{w, \lambda_\chi$ and $\lambda\}$ or $\{M_S, \theta_S$ and $\lambda\}$

Expected consequences (not discussed here)

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

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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

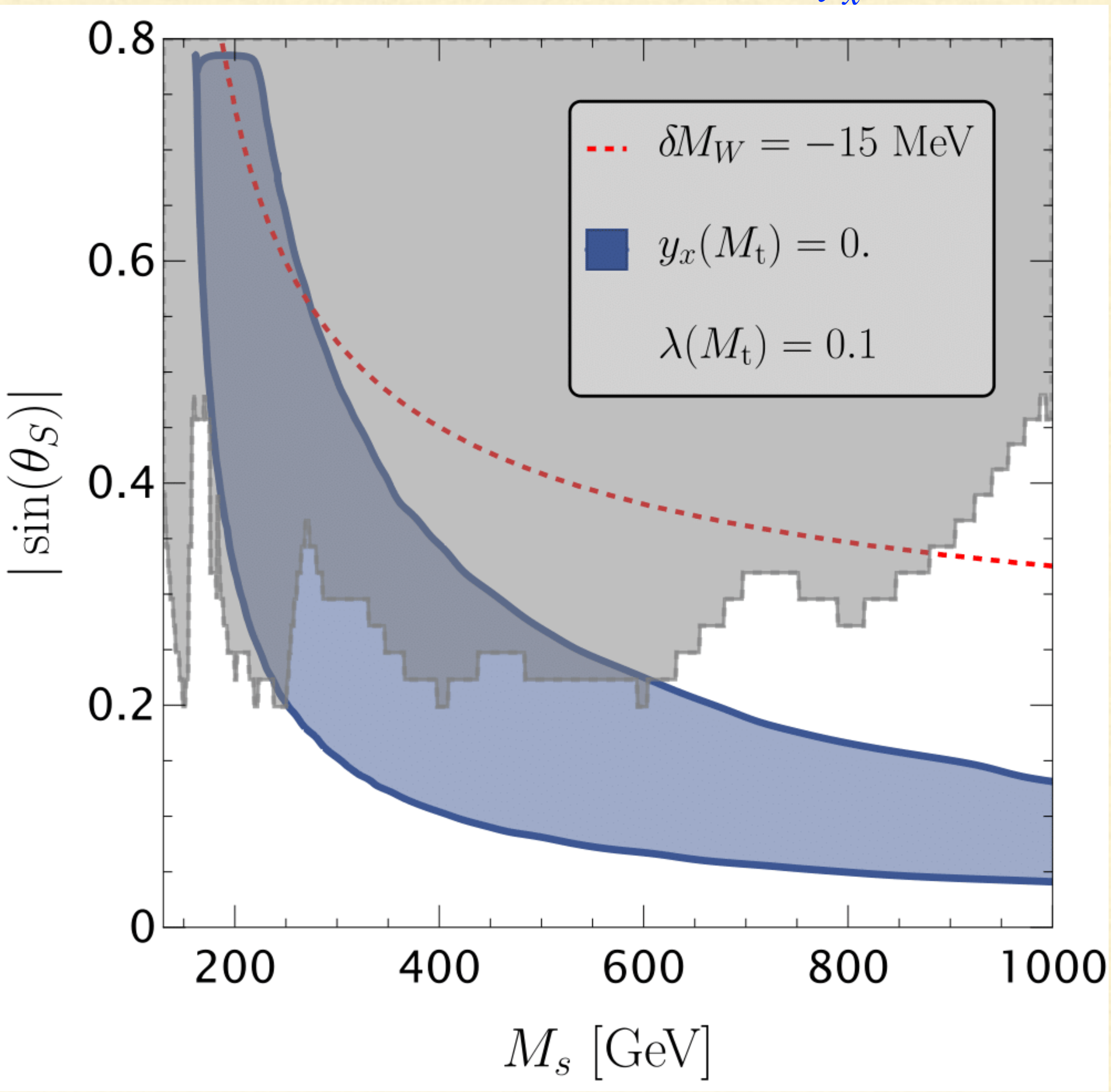
Once the allowed region of the parameter space for fulfilling the expectations is understood

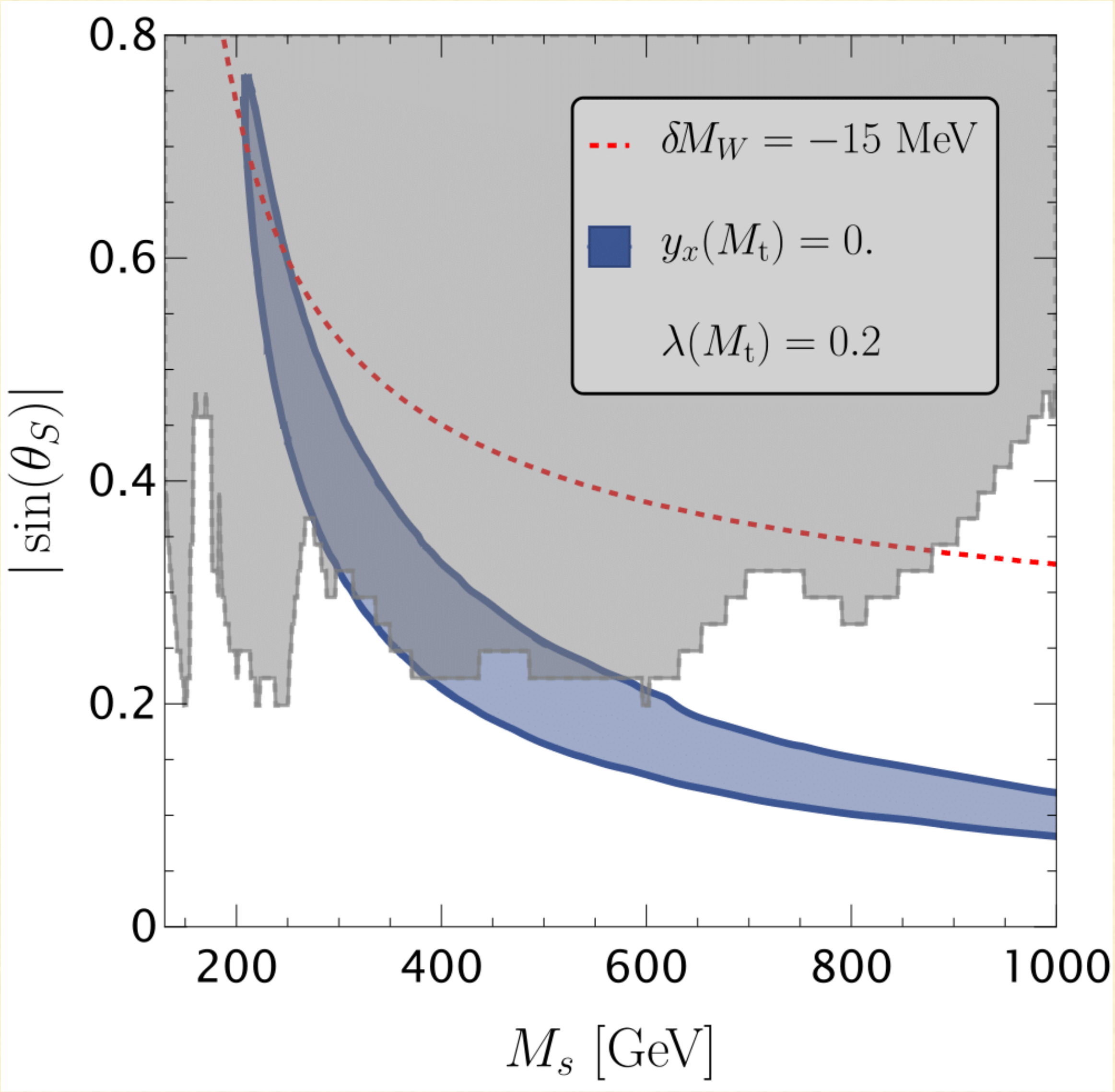
the observation of the Z' or S in the allowed region

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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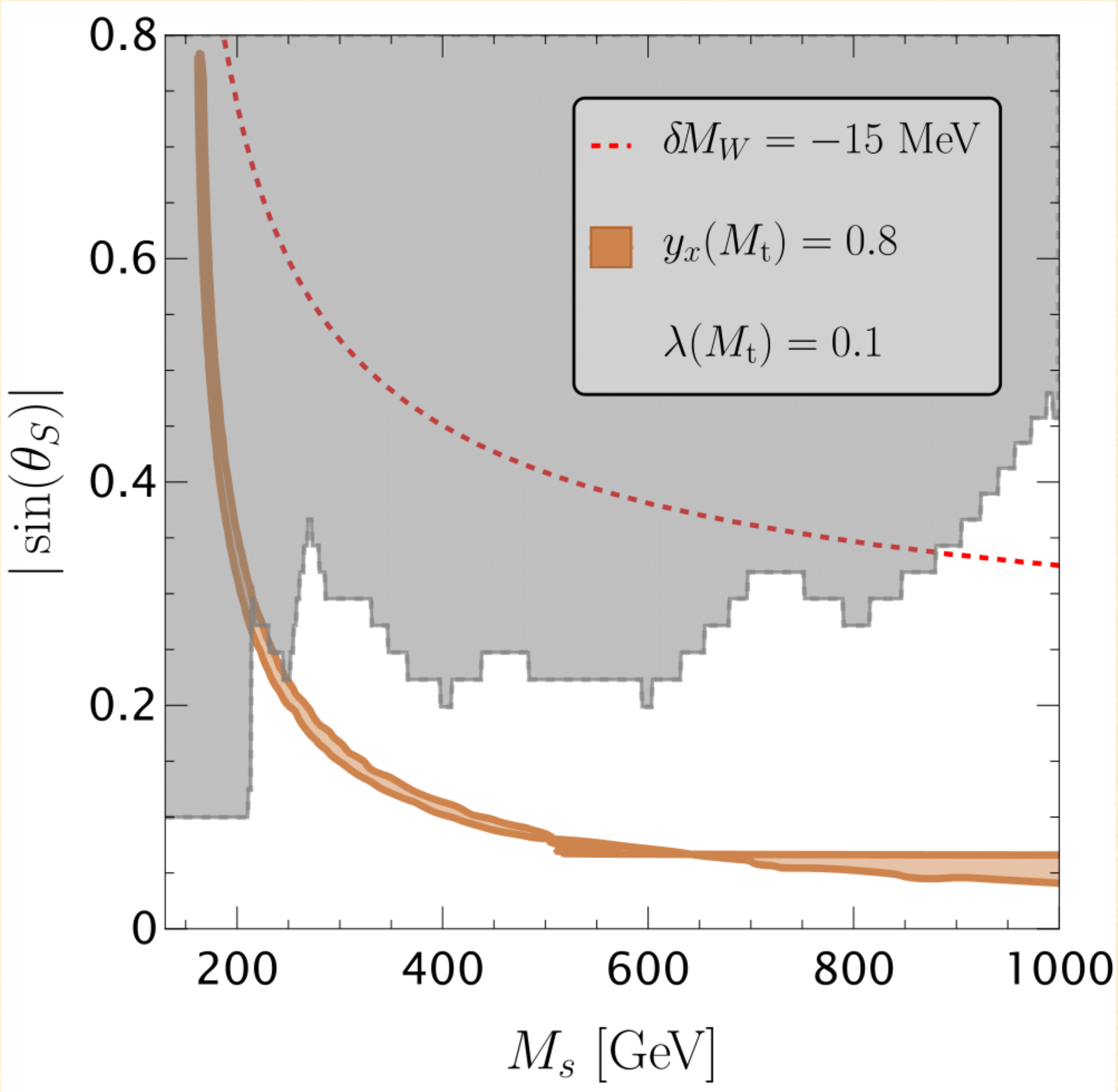

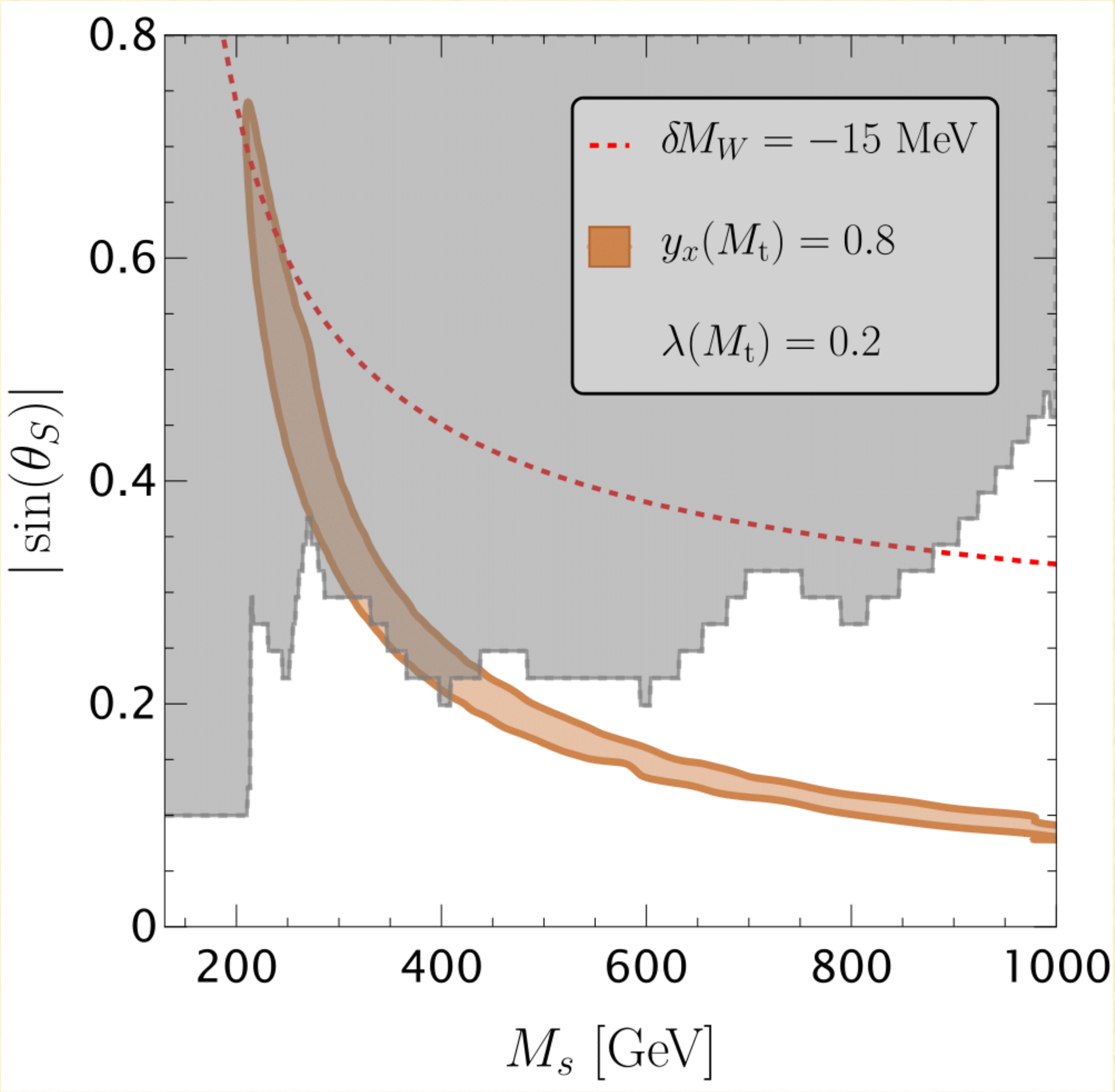

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Experimental constraints in the gauge sector from direct searches and EWPOs

- Gauge sector parameters: $g_z\,, g_{yz}(=\eta g_z = \epsilon g_y)\,,\ \tan\beta\,, z_\phi\,, z_N$
  - Not all independent: z_ϕ appears only in the combination $z_\phi - \frac{\eta}{2}$, so we define $\mathscr{Z} = \dfrac{z_\phi - \eta/2}{z_N}$
    (in B-L model $\mathscr{Z} = 0$)
  - exclusion bounds depend on either
    $\left(\sin\theta_Z\,, M_{Z'}\,, \mathscr{Z}\right)$ or $\left(g_z z_N\,, M_{Z'}\,, \mathscr{Z}\right)$

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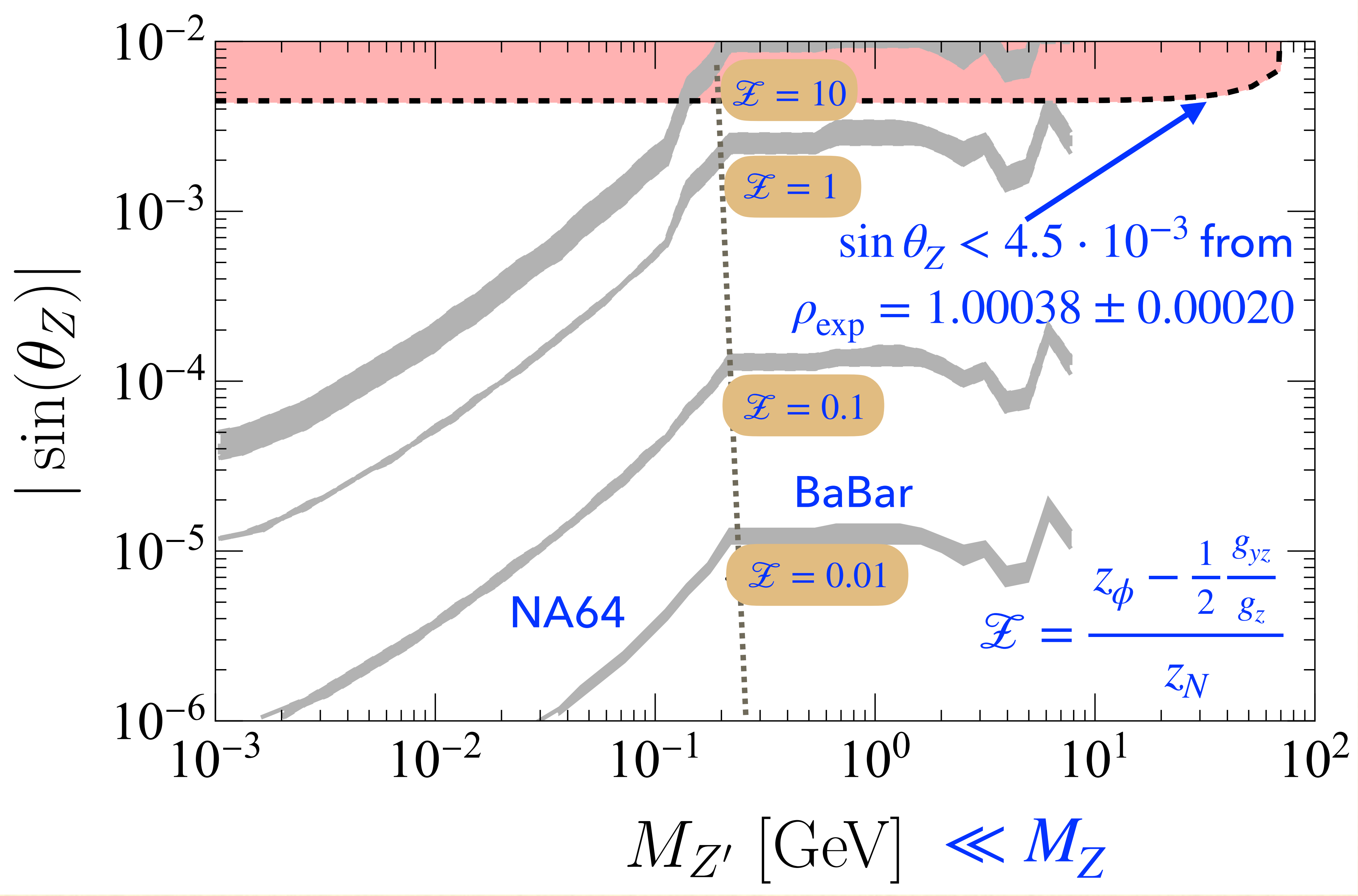
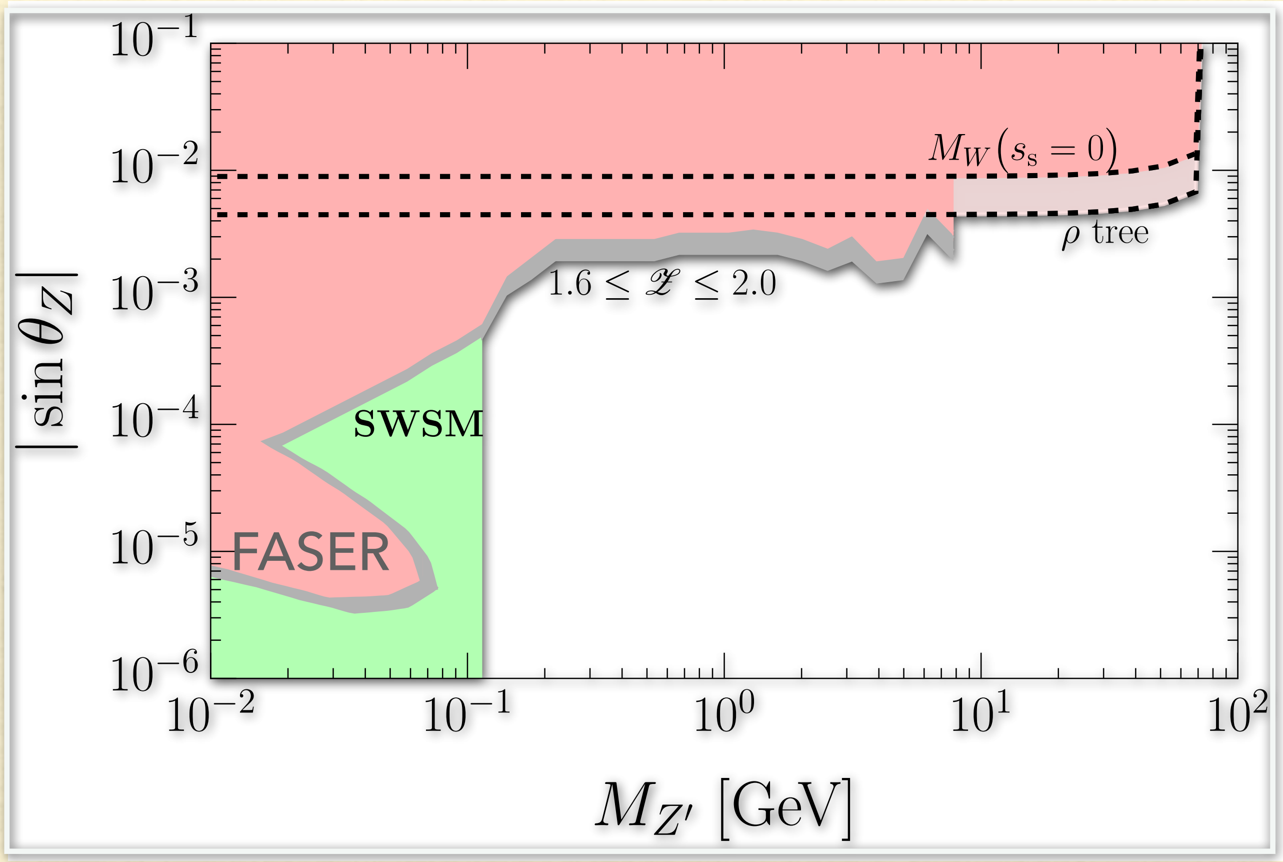
  - Not all independent: exclusion bounds depend on either $\left(\sin\theta_Z\,,\,M_{Z'}\,,\,\mathcal{Z}\right)$ or $\left(g_z z_N\,,\,M_{Z'}\,,\,\mathcal{Z}\right)$
- Most stringent limits emerge in direct searches
  - for small masses ($\xi = M_{Z'}/M_Z \ll 1$): from NA64 search for dark photon
  - 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)

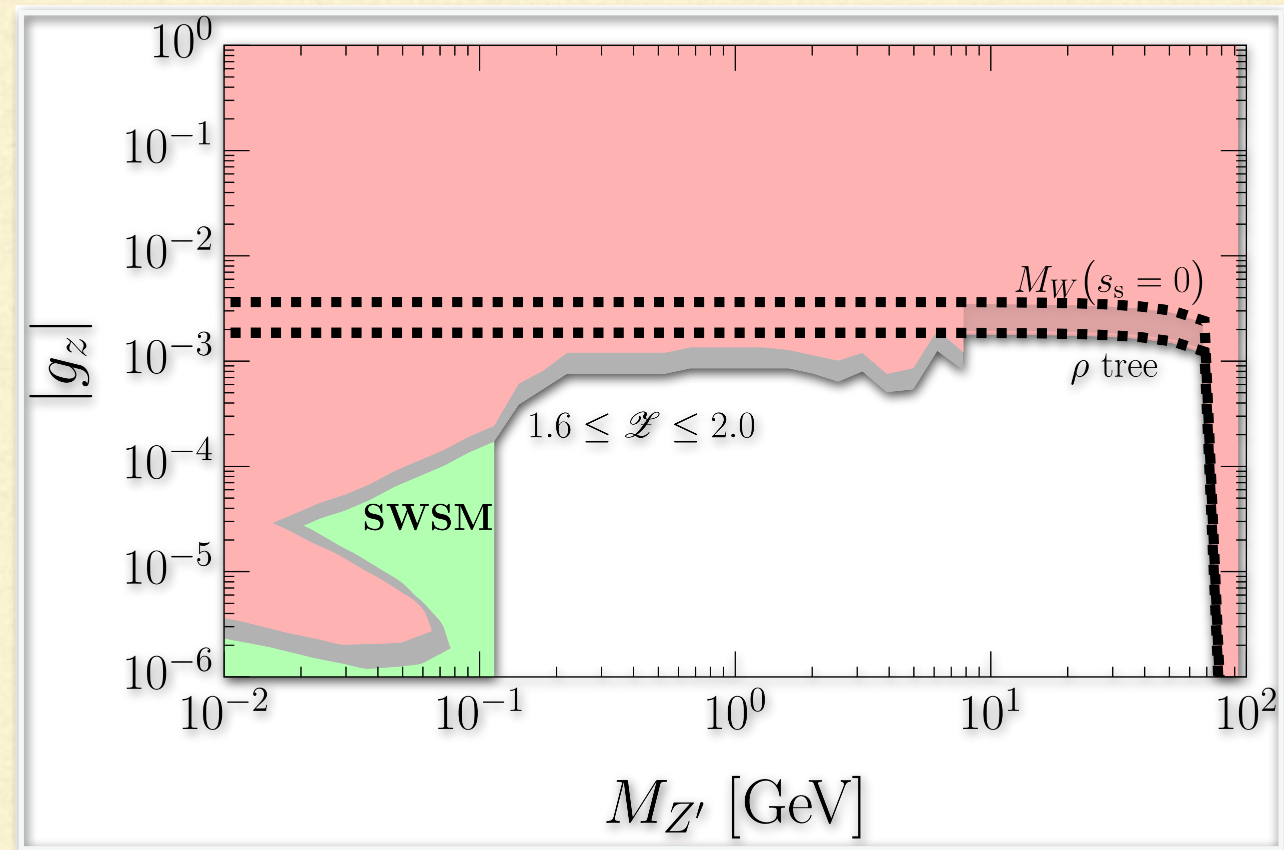
Experimental constraints in the gauge sector from direct searches and EWPOs: $M_{Z'} < M_Z$ region



[Zoltán Péli and ZT, 2402.14786]

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





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Conclusions:
see the expected consequences

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- CDF II result for M_W

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and

- in the scalar sector we find non-empty parameter space for $M_s > M_h$

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see the expected consequences

and

- 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

Coming soon:

Leptogenesis in the SWSM

arXiv:2409.07180

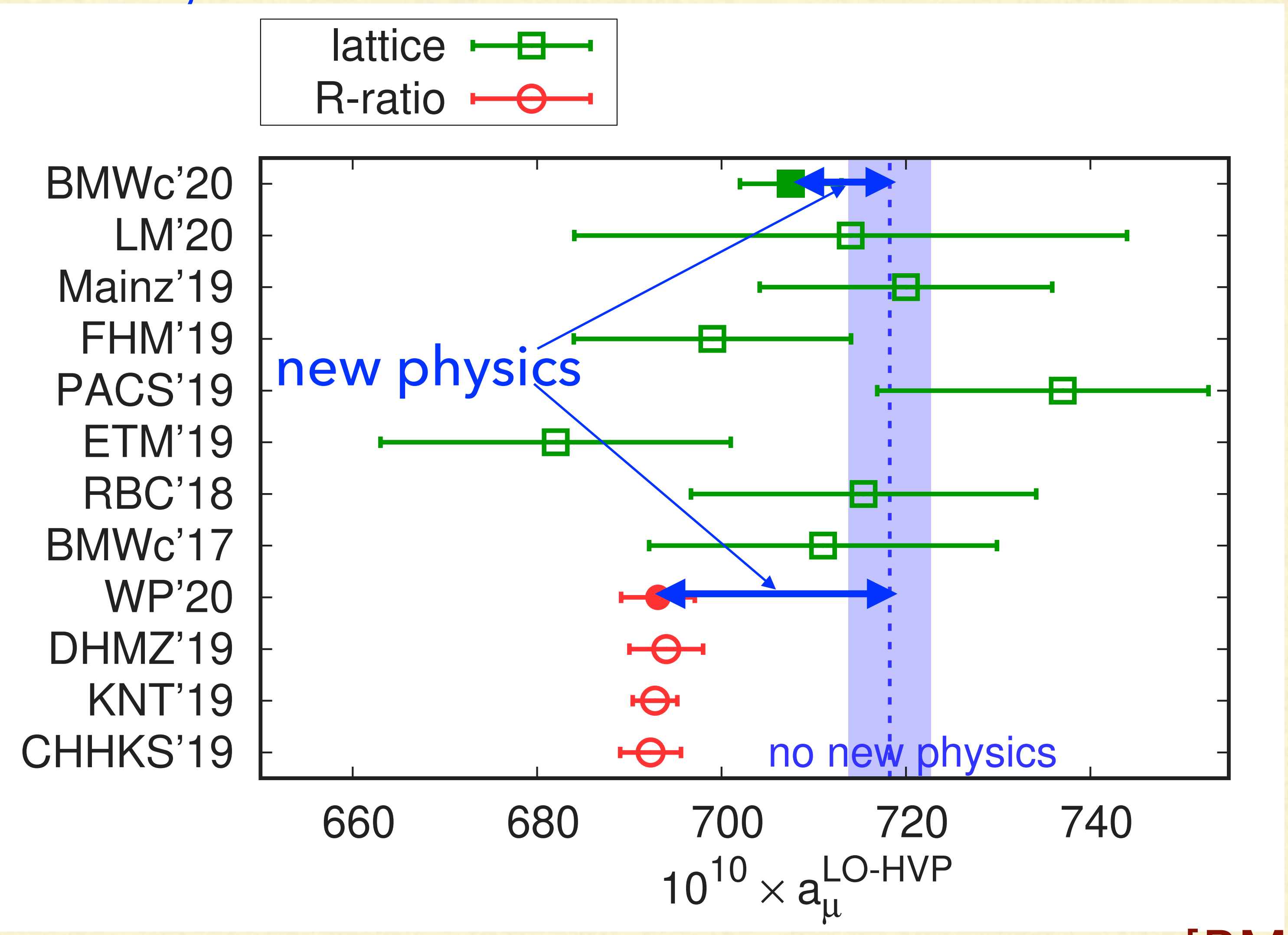
I am willing to give a seminar at your institute if you would like to learn more

the end

Appendix

Status of 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]

After SSB neutrino mass terms appear

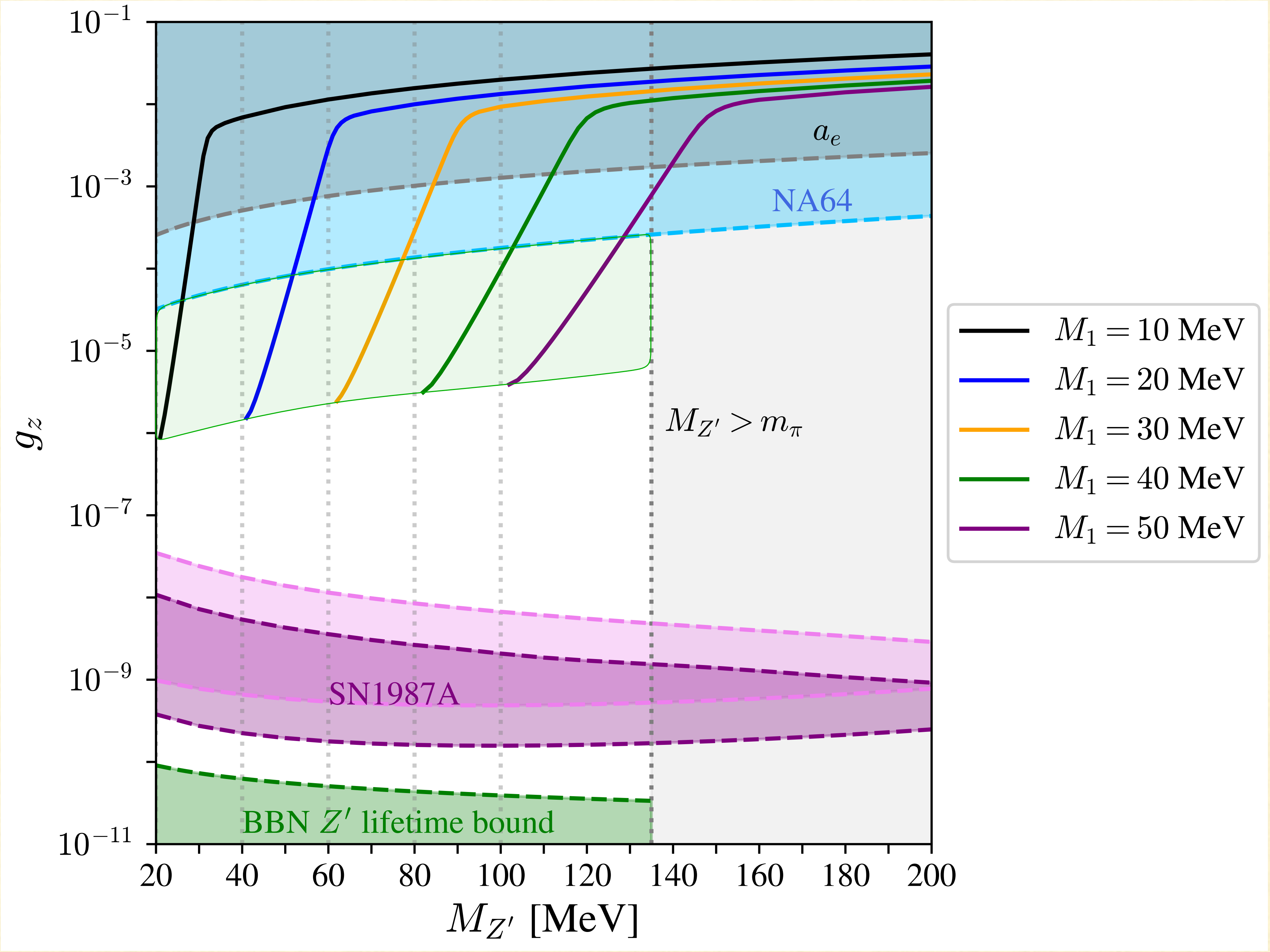
$$-\mathcal{L}_Y^\ell = \frac{w + s' + \mathrm{i}\sigma_\chi}{2\sqrt{2}} \overline{\nu_R^c}\, \mathbf{Y}_N\, \nu_R + \frac{v + h' - \mathrm{i}\sigma_\phi}{\sqrt{2}} \overline{\nu_L}\, \mathbf{Y}_\nu\, \nu_R + \mathrm{h.c.}$$

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

- In flavour basis the full $6{\times}6$ 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]

Dark matter candidate

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

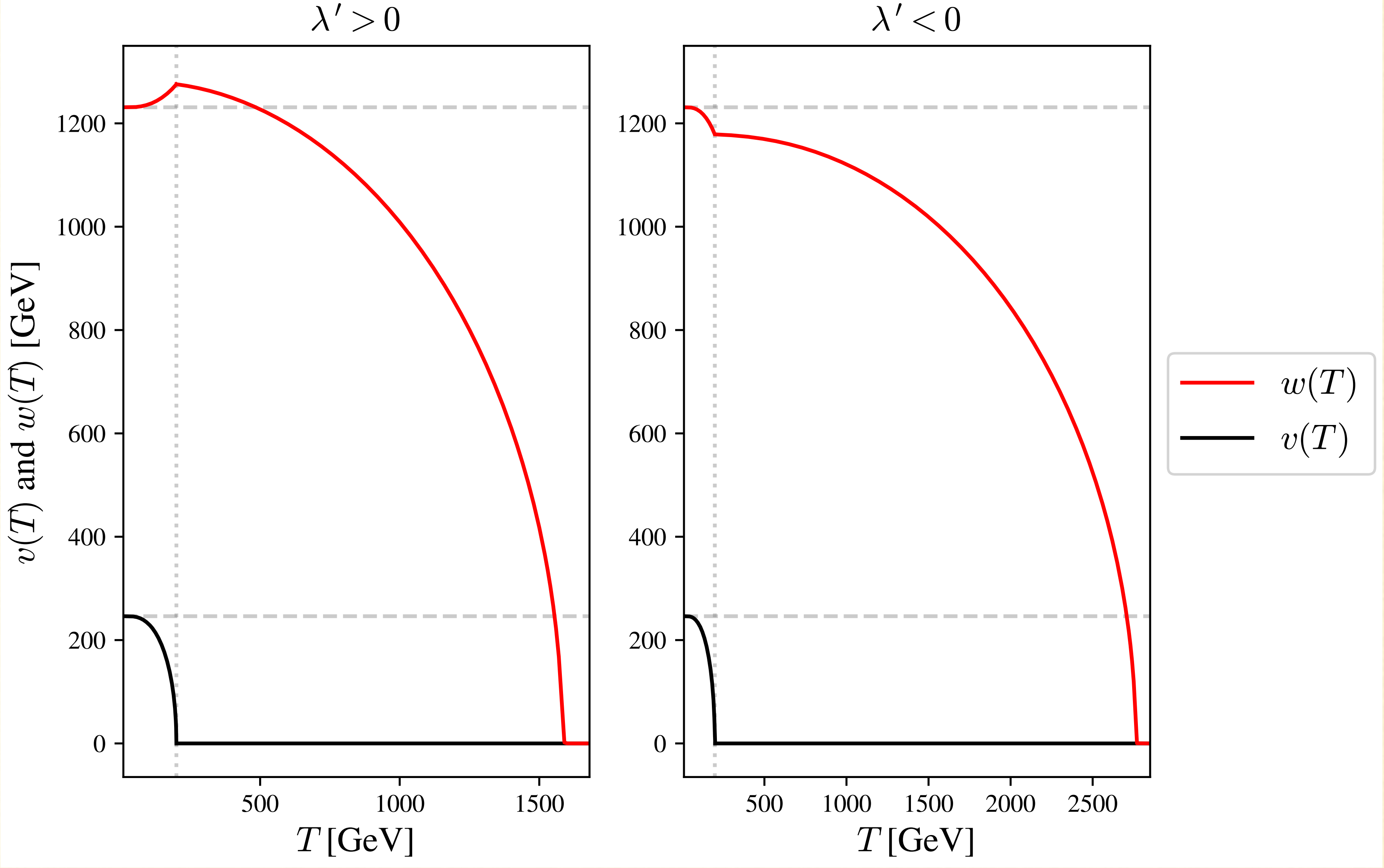


Experimental constraints

- 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.

Prerequisite: Phase-transitions in the SWSM

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

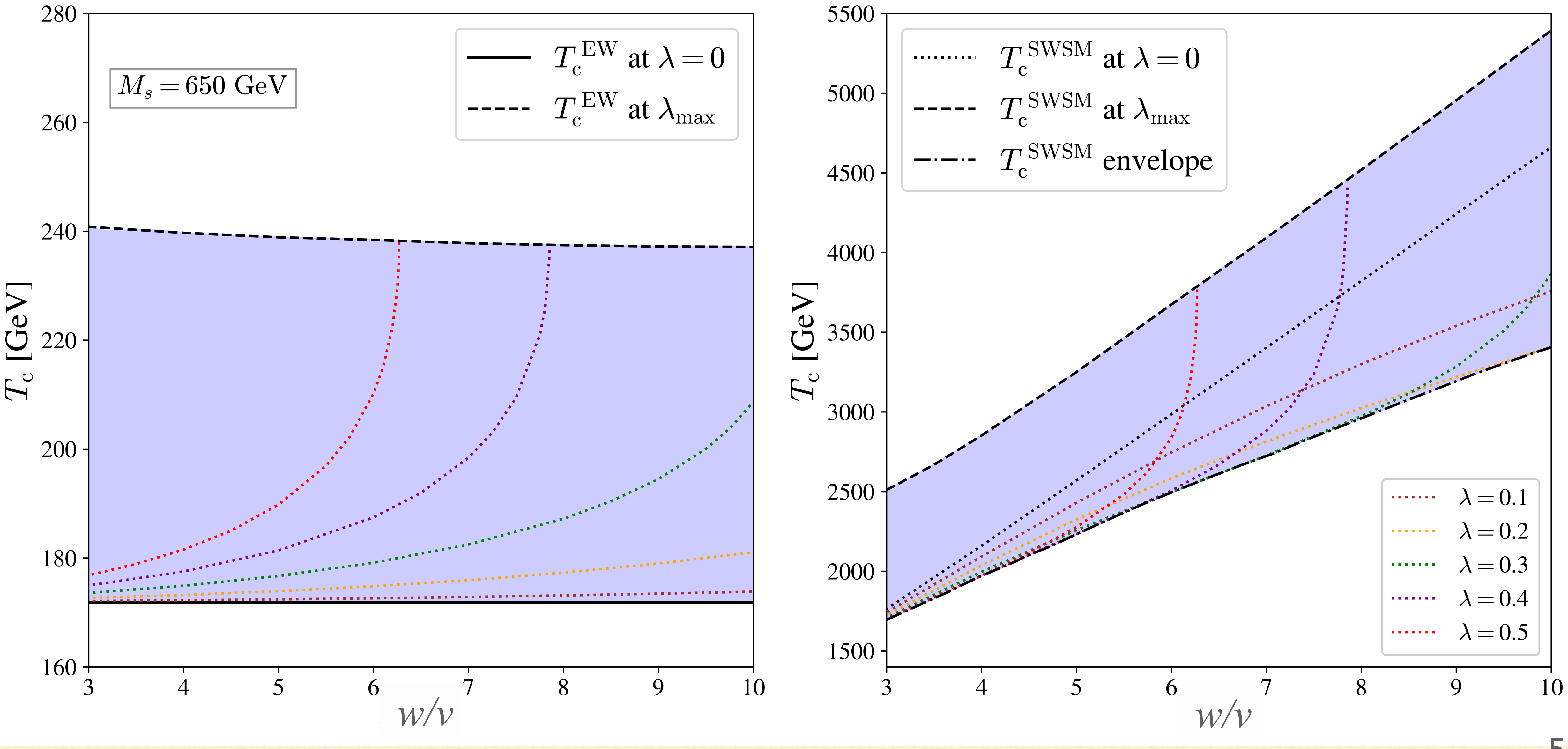


$$M_S = 200\,\mathrm{GeV}, \quad M_N = 150\,\mathrm{GeV}, \quad w = 5v\,, \quad |\lambda| = 0.0394$$

[Seller, Szép, ZT, arXiv:2301.07961]

Prerequisite: phase-transition temperatures in the SWSM

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



[Seller, Szép, ZT, arXiv:2301.07961]

Prediction of M_W in the SWSM

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

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

  - 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]

Prediction of M_W in the SWSM

Case (i) full one-loop corrections

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