Beyond the standard model: particle physics

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ELFT Particle Physics Summer School

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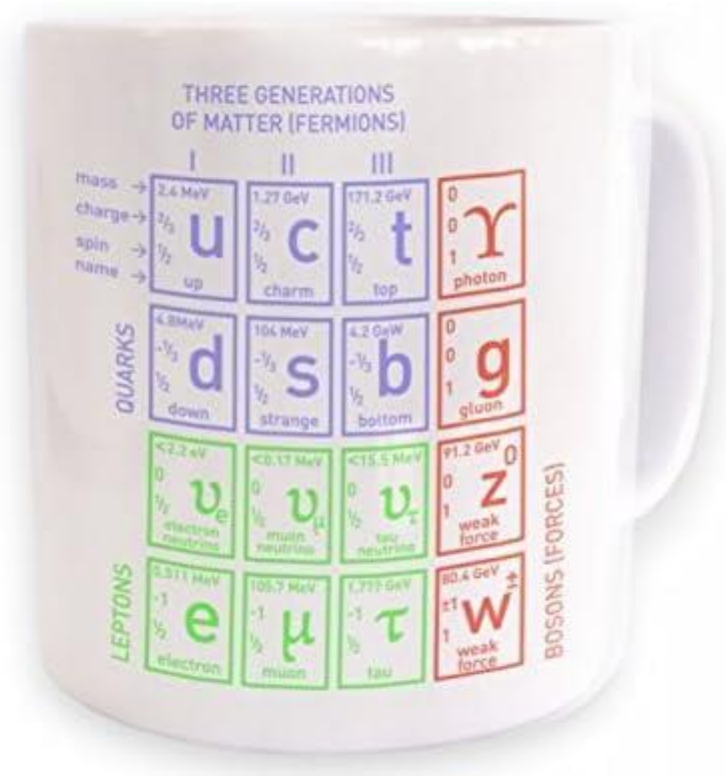
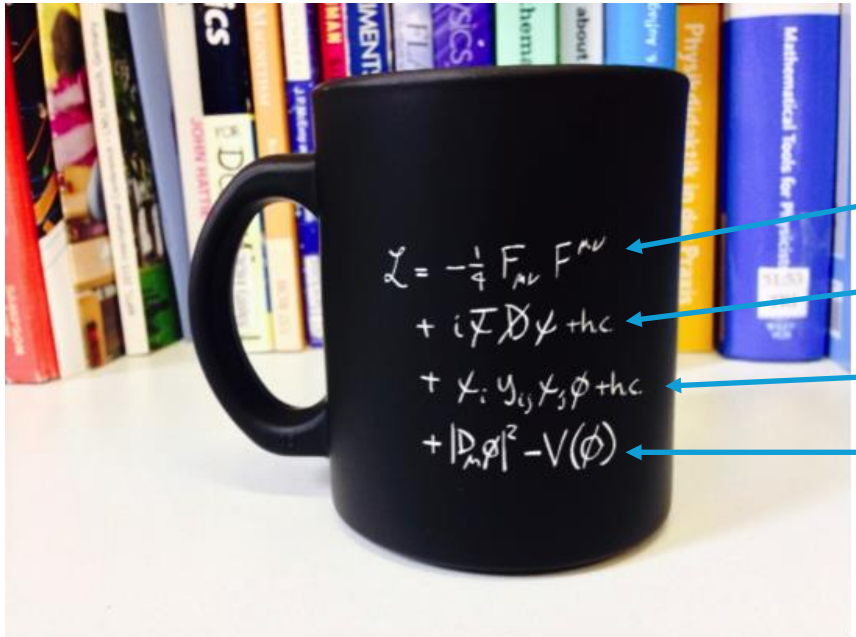
TUDOMÁNYEGYETEM

What is the standard model?

Elementary particles + interactions described precisely



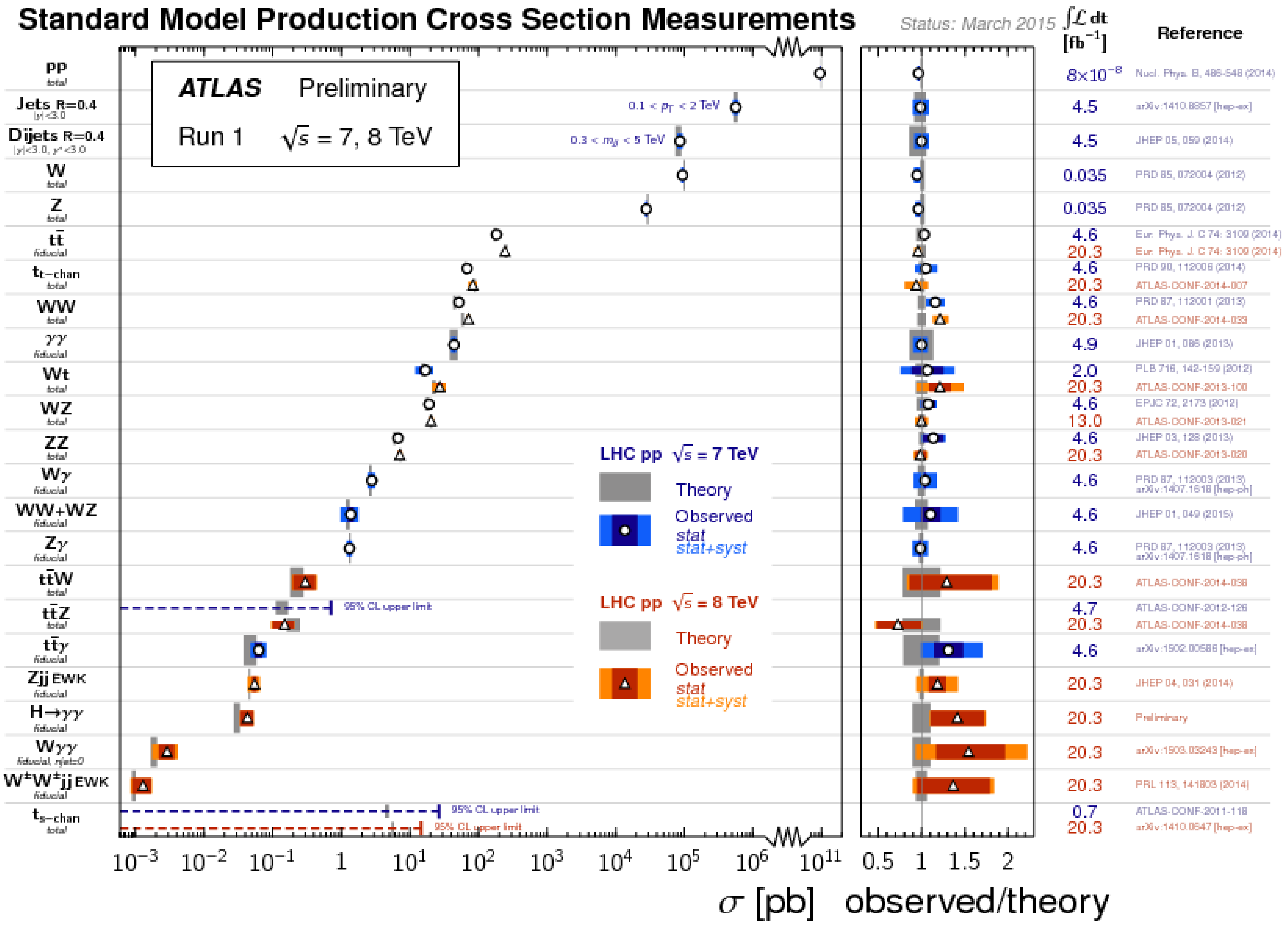


- Gauge interactions
- Matter fermions

Tested before LHC (in some cases <0.1% precision!)

- Yukawa interactions
- Higgs potential

Testing in progress


Standard Model Production Cross Section Measurements
Status: March 2015
Reference
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
95% CL upper limit
σ [pb]
observed/theory

What is beyond the standard model?

Cannot be explained in the SM:

- Neutrino masses
- Dark matter & dark energy
- Baryon asymmetry of the universe

New particles exist but hidden:

- Too heavy
- Interact too weakly

Anomalies as hint for new physics:

- 2-3 σ excesses at the LHC over SM expectation in certain processes
- Muon anomalous magnetic moment
- Promising (?) measurements to be verified independently:
  - X17 Atomki anomaly
  - CDF II measurement of the W boson mass

Puzzles (are related to the Higgs boson!):

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

- Basically every parameter in this Lagrangian
- y: Fermion masses are free parameters, SM cannot explain their origin!
- μ gives rise to the naturalness problem
- λ is too small to make the vacuum stable…
- V_0: does the Higgs field affect cosmic inflation?
- …: any new terms in the Higgs potential?

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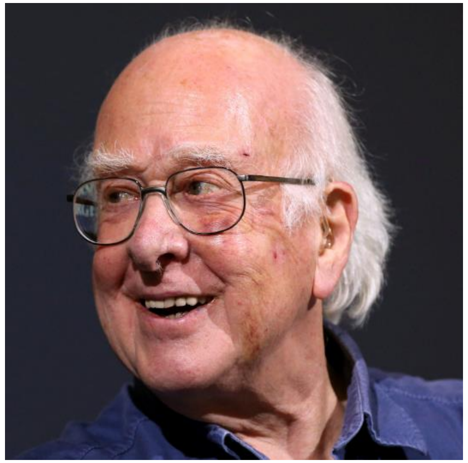
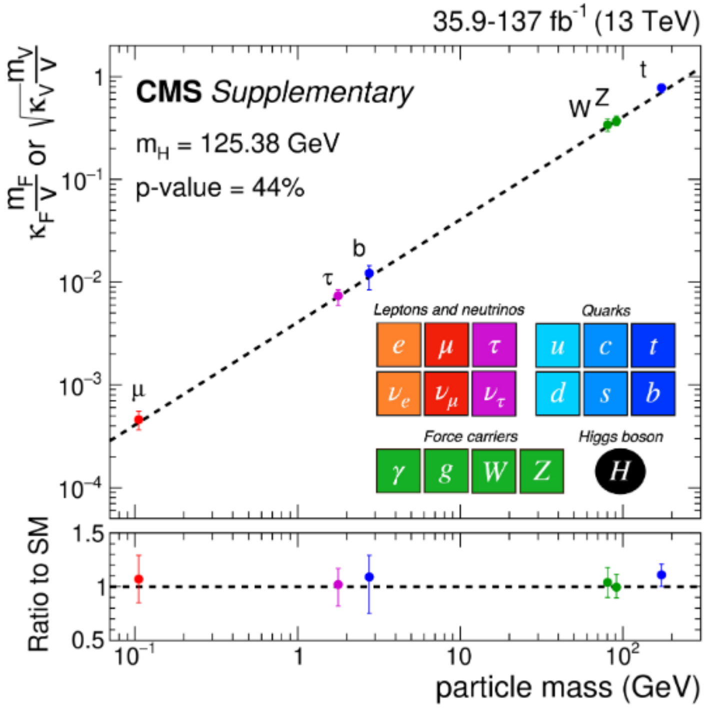
Let's start with the  sector!

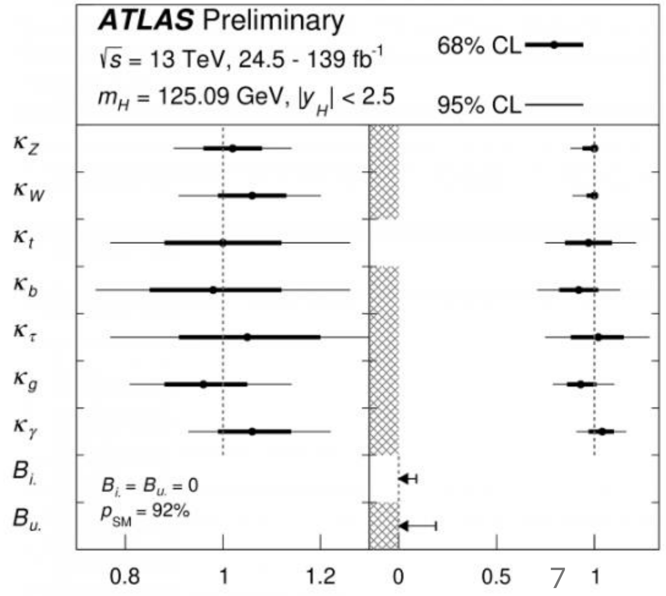
$$V(\phi) = -\frac{\mu^2}{2}\,|\phi|^2 + \frac{\lambda}{4}\,|\phi|^4$$



- Due to SSB: $\phi \;\to h + v$
- In the SM every mass is $\propto v$
- v and the masses are well measured
- Proportionality factor measured as well
- κ can signal deviation from SM

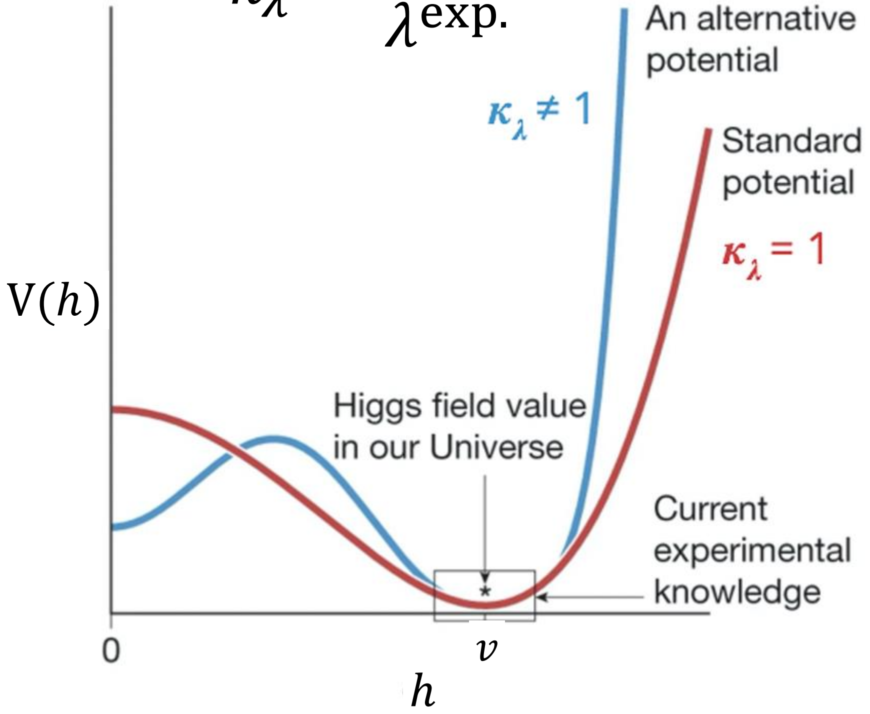
As for the Higgs boson:

- From first derivative: $0 = -\mu^2 + \lambda\, v^2$
- From second derivative: $m_h^2 = -\mu^2 + 3\lambda v^2 = 2\lambda v^2$
- λ is predicted, not measured (yet)!

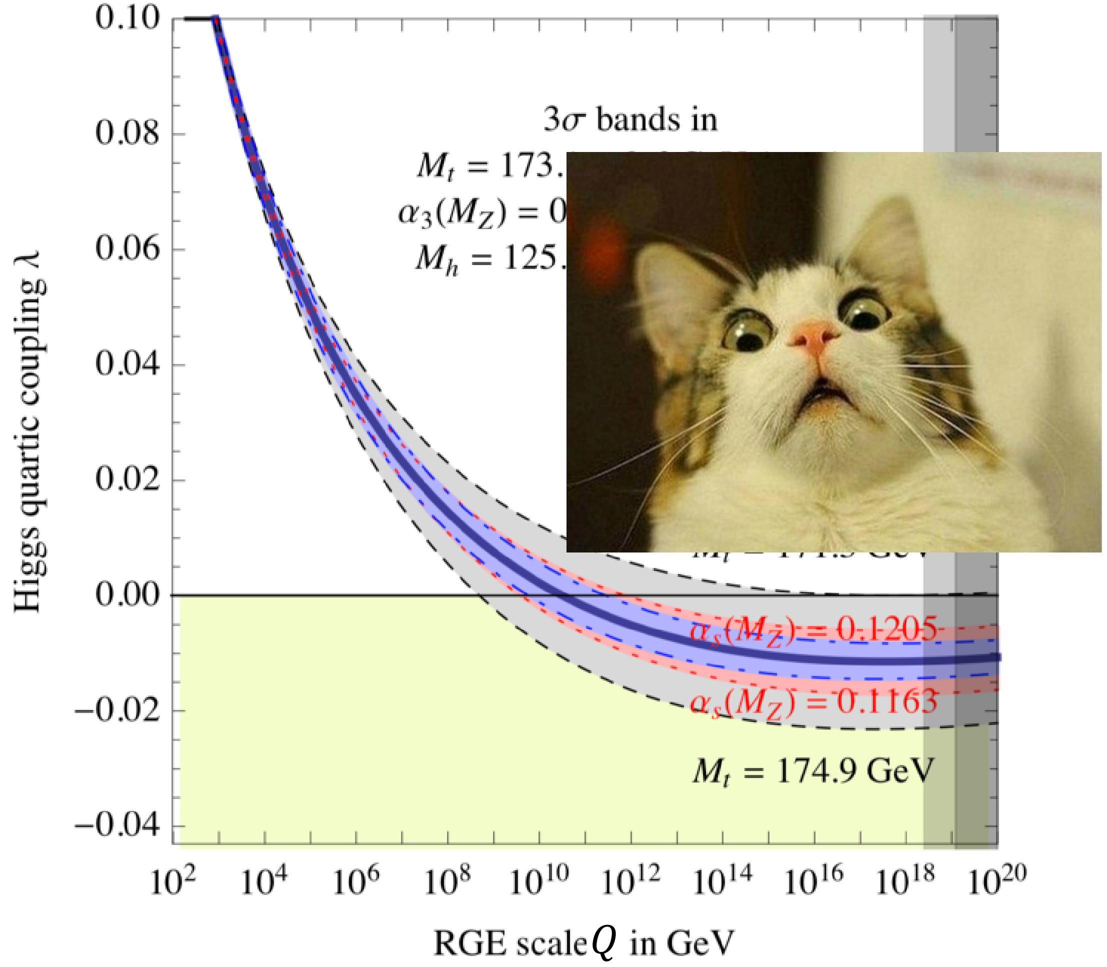


$$V(\phi) = -\frac{\mu^2}{2}\,|\phi|^2 + \frac{\lambda}{4}\,|\phi|^4$$

$$\kappa_\lambda = \frac{\lambda_{\mathrm{SM}}^{\mathrm{theo.}}}{\lambda^{\mathrm{exp.}}}$$

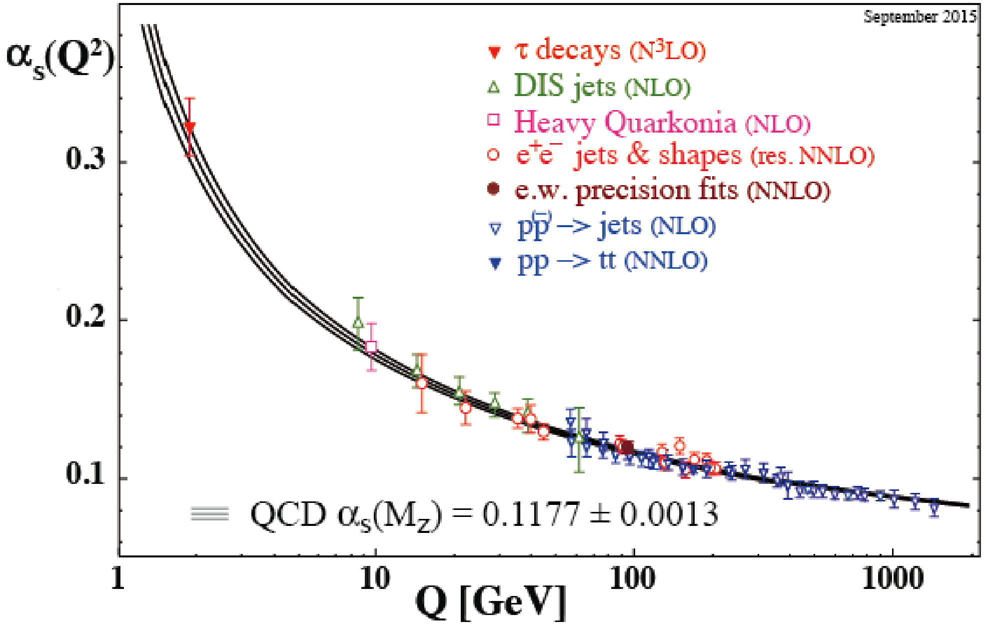


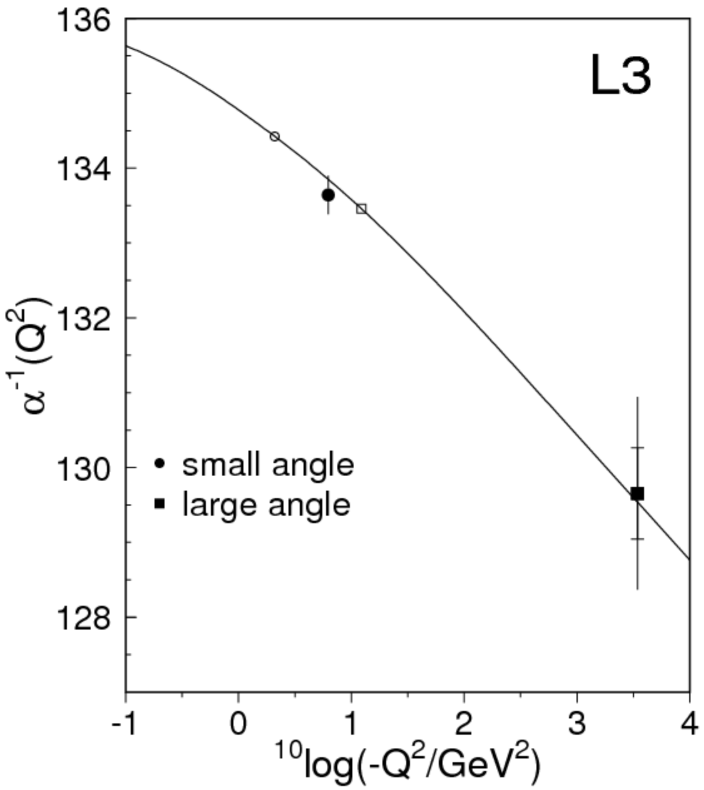
λ affects the shape of the potential…



…and depends on the energy scale

Scale dependence: $Q\frac{\partial g}{\partial Q} = \beta_g$ (RGE)

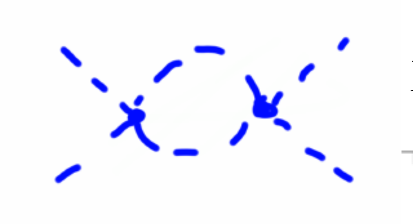




- If a collider has $\sqrt{s}$ C.M. energy → appropriate interaction strength is $g(Q=\sqrt{s})$
- Random processes due to quantum fluctuations can have much larger energies than colliders…

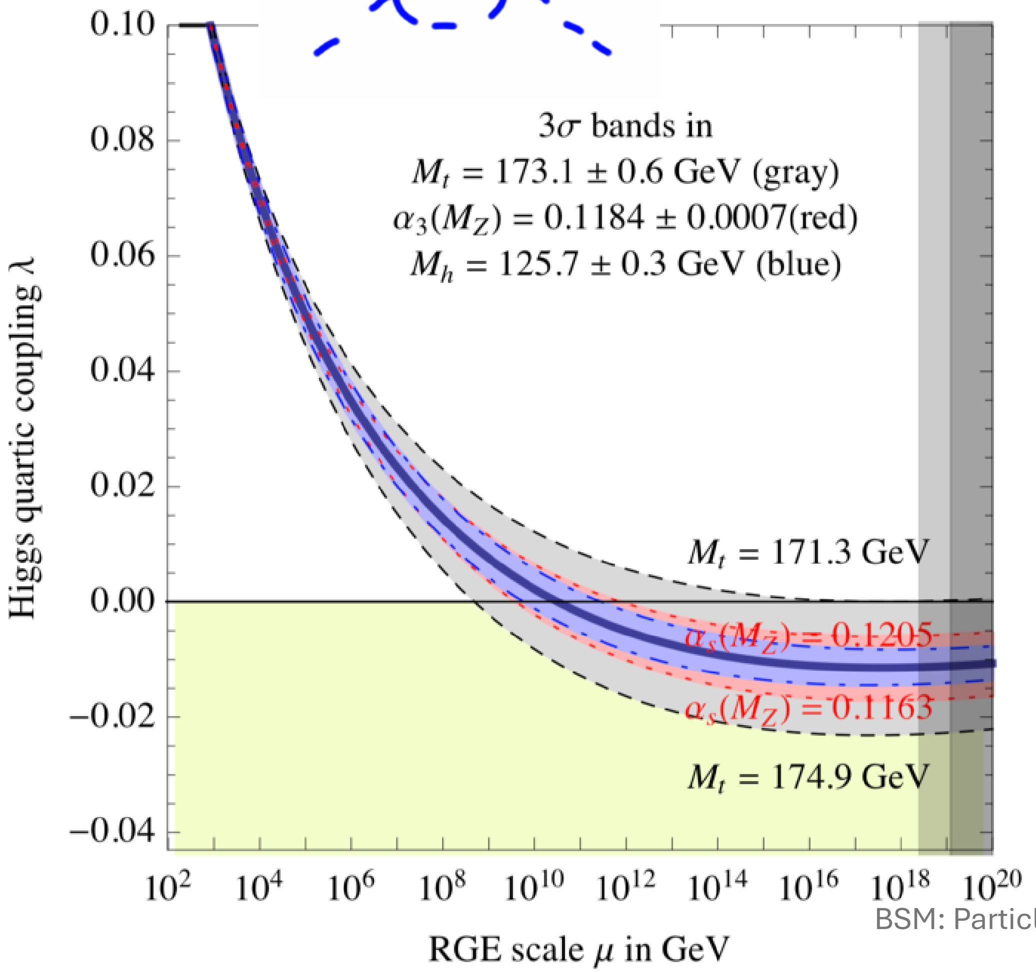
$$\beta_\lambda = \frac{1}{(4\pi)^2}\left(12\lambda^2 + \frac{3}{8}\left([g_y^2 + g_L^2]^2 + 2[g_L^2]^2\right) - 6\,y_t^4 + \cdots\right)$$

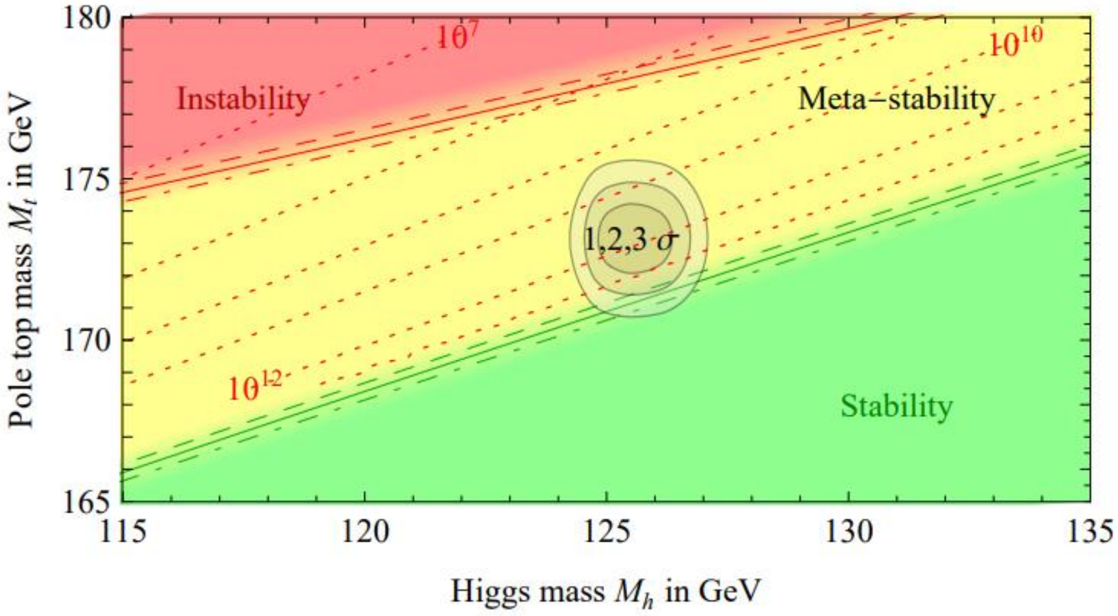
Higgs boson — Z boson — $W^\pm$ bosons — top quark



SM vacuum is metastable

Initial conditions are given at the E.W. scale





New physics should stabilize V!

$$V(\phi,\chi) = -\frac{\mu_\phi^2}{2}|\phi|^2 + \frac{\lambda_\phi}{4}|\phi|^4 - \frac{\mu_\chi^2}{2}|\chi|^2 + \frac{\lambda_\chi}{4}|\chi|^4 + \frac{\lambda}{2}|\phi|^2|\chi|^2 + \cdots$$

It is possible to extend the SM potential in many ways:

- Scalar singlet (SSM)
- Another doublet (2HDM)
- Many others, e.g.: 3HDM

Here ϕ is the BEH doublet field and χ is a complex scalar singlet

Extended potential → how to make it stable?

- $\lambda_\phi > 0$ and $\lambda_\chi > 0$ obviously
- $4\lambda_\phi\lambda_\chi - \lambda^2 > 0$ if $\lambda < 0$

Why these terms in the potential?

- An additional global symmetry constrains it (more on this later)
- No higher orders than $[\text{scalar field}]^4$: otherwise cutoff scale in the model!

What do we want?

- Scan free parameters and see if the V can be stable
- What are the free parameters? $\rightarrow \lambda_{\phi}, \lambda_{\chi}, \lambda$
- V has 5 params, but v and m_h have to be compatible with exp.
- Don't violate perturbativity $< 4\,\pi$
- The free params are initial conditions for RG equations at $Q =$ EW. Scale
- Calculation of β-functions: can be automatized up to two loop (SARAH Mathematica package)

How to represent our findings?

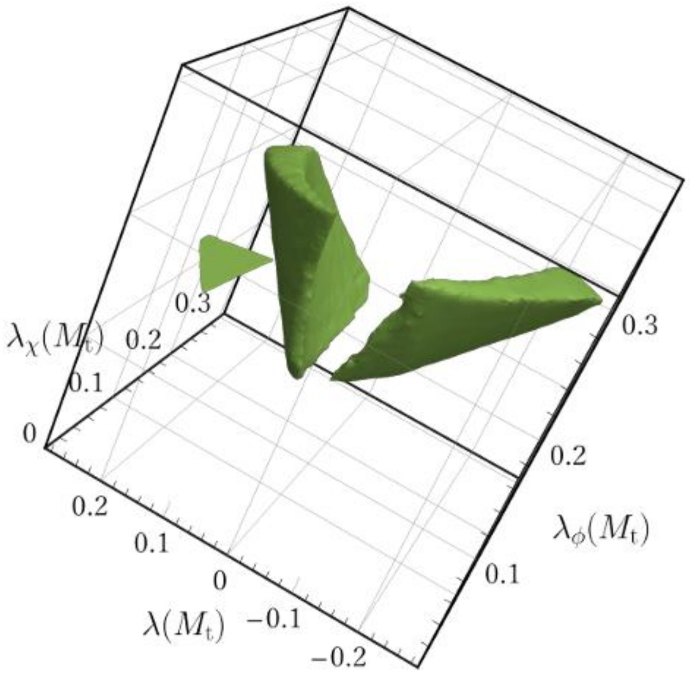
- After SSB: $\phi \to h' + v$ and $\chi \to s' + w$
- The two fields mix to form *mass eigenstates*

$$\begin{pmatrix} h' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_s & \sin\theta_s \\ -\sin\theta_s & \cos\theta_s \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- Good to have a basis where the mass matrices are diagonal:

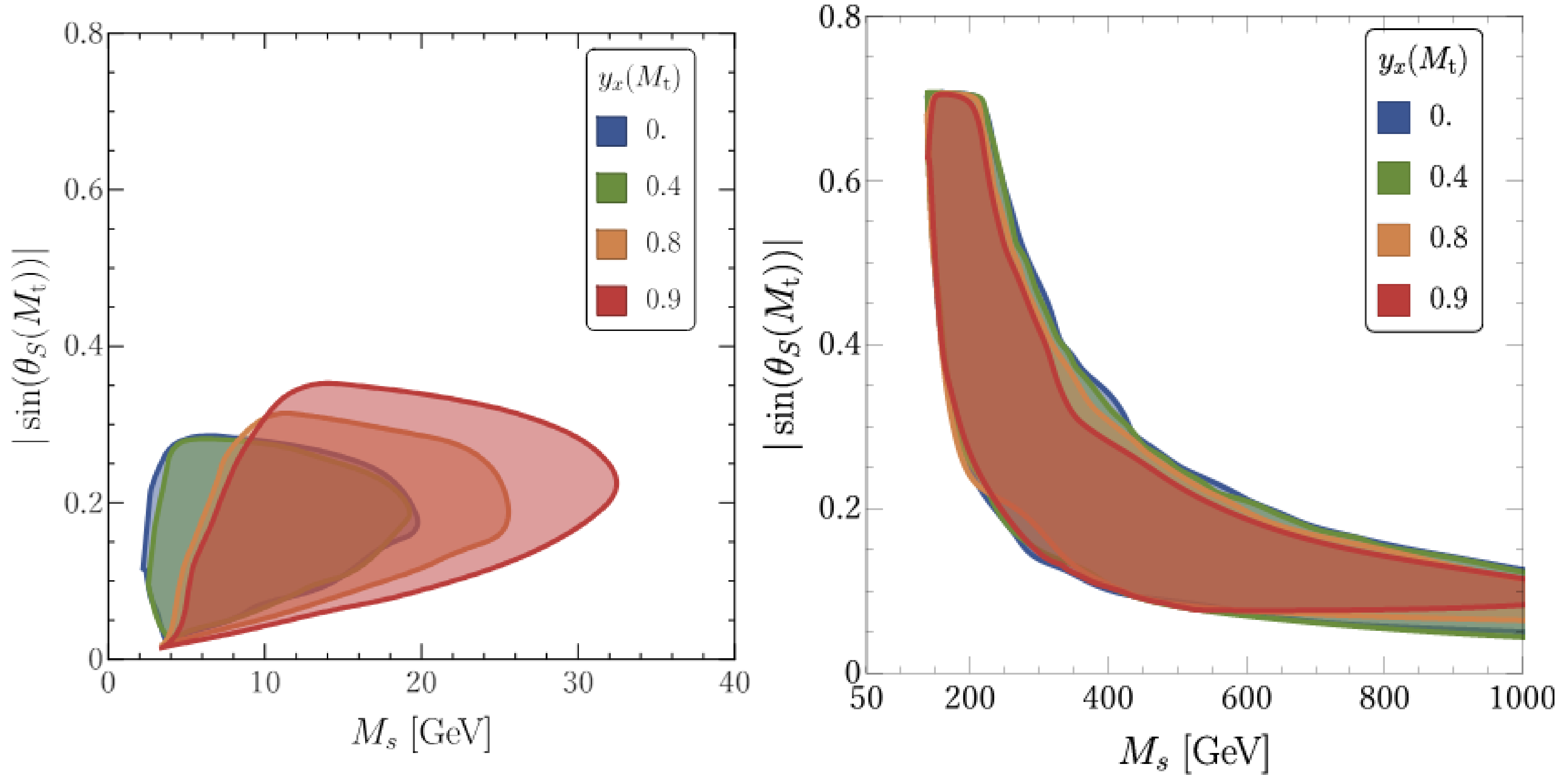
$$m_{h/s}^2 = \lambda_\phi v^2 + \lambda_\chi w^2 \mp \frac{\lambda_\chi w^2 - \lambda_\phi v^2}{\cos 2\theta_s} \text{ with } \tan 2\theta_s = \frac{\lambda\, v\, w}{\lambda_\chi w^2 - \lambda_\phi v^2}$$

- Experiments can search for a scalar with m_s and θ_s!



Lambda constraints are strong!

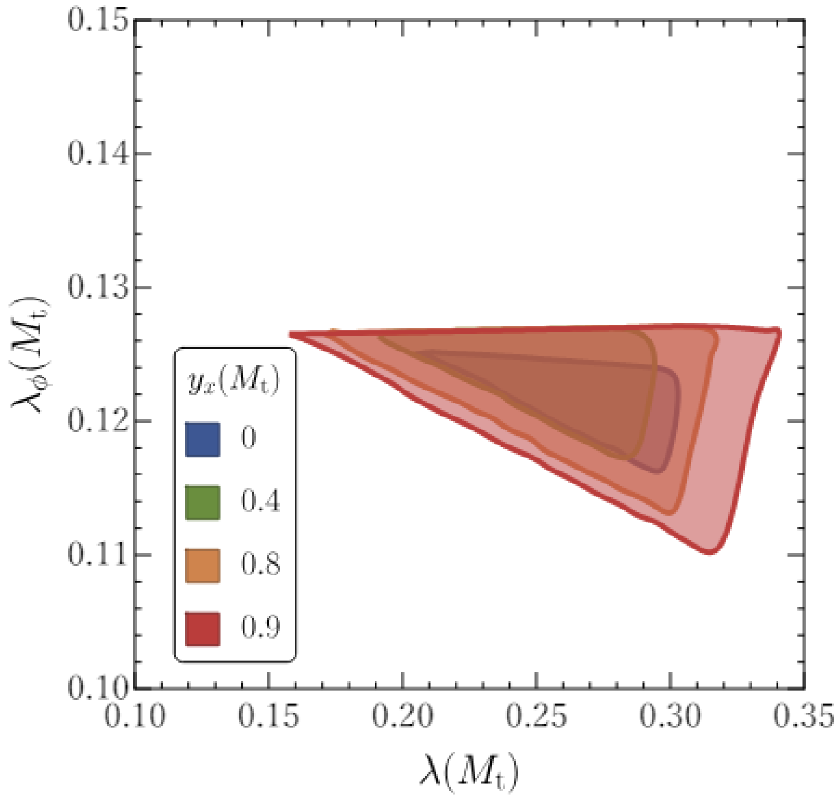
Please ignore the colors



Vacuum can be stabilized by either a lighter of a heavier scalar than the Higgs boson!

Are we consistent with everything?

- The decay width of the Higgs boson is very small: $\Gamma_h = 3.2^{+2.8}_{-2.2}$ MeV
- The SM prediction is $\Gamma_h^{\mathrm{SM}} \simeq 4$ MeV
- If the new scalar is lighter than $\frac{m_h}{2} \simeq 62.5$ GeV
- …then $h \to s\, s$ decay is allowed!
- $\Gamma(h \to ss) \simeq \lambda^2 \frac{v^2}{32\,\pi\, m_h} \simeq \lambda^2 \times (4.8\ \mathrm{GeV})$



$\lambda < 0.03$ for consistent Γ_h but $0.15 < \lambda < 0.30$ for stability

Are we consistent with everything?

- What about electroweak observables?

$$M_W^{\text{PDG22}} = 80.379 \pm 0.012 \text{ GeV or } M_W^{\text{CDF}II} = 80.433 \pm 0.009 \text{ GeV}$$

- While the SM prediction: $M_W^{\text{SM}} = 80.353 \pm 0.009$ GeV
- M_W computed from the muon decay:

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\,\alpha}{2\,M_W^2\,s_w^2}(1+\Delta\text{r})$$

- New physics affects the RHS, mostly $\Delta\text{r} \rightarrow \Delta M_W^{\text{BSM}}$

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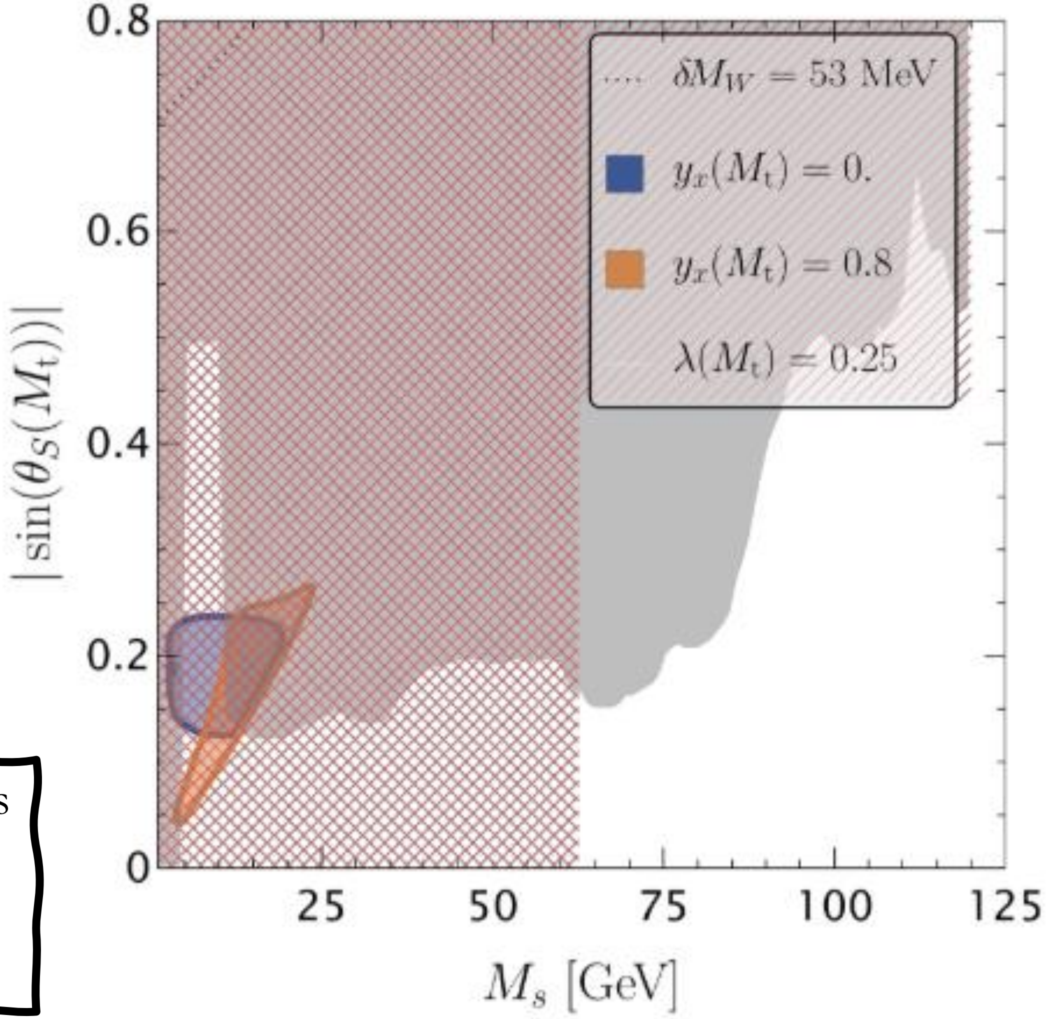
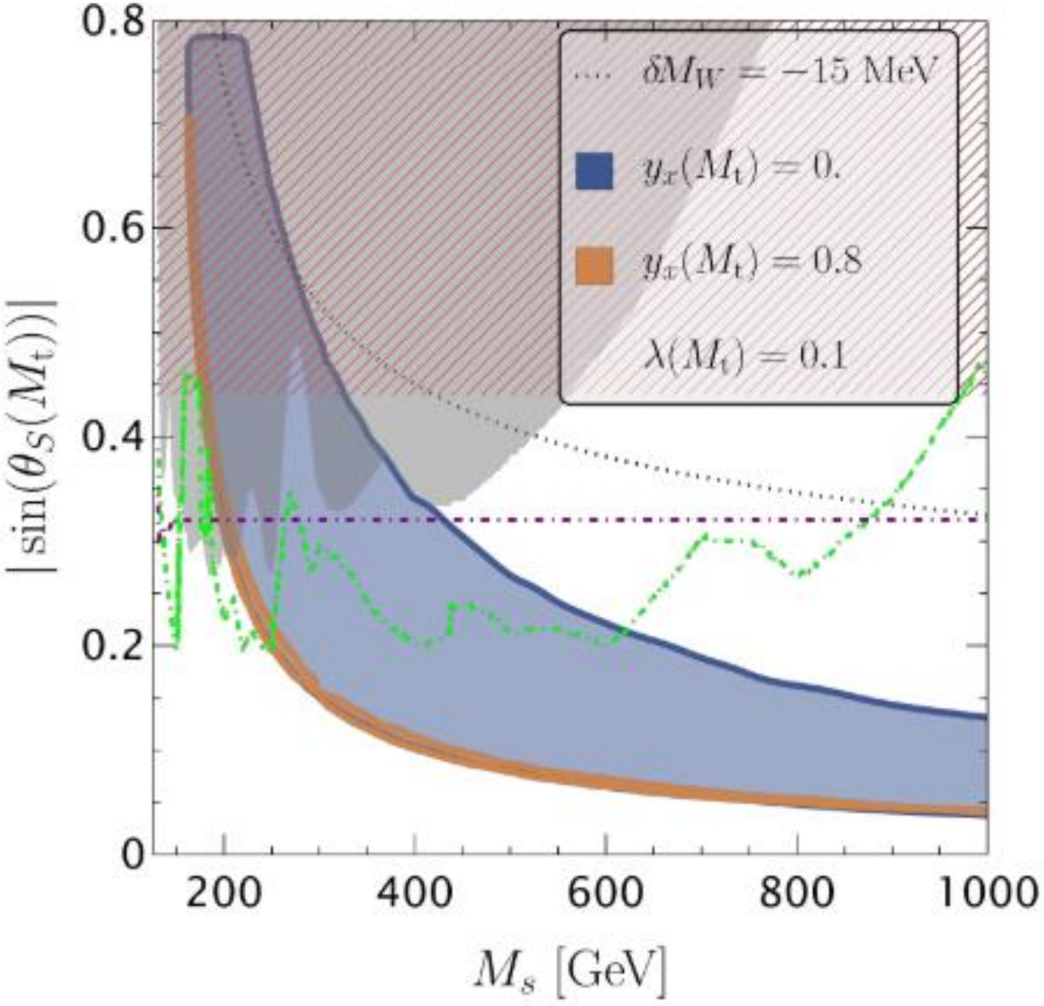
- While the SM prediction: $M_W^{\mathrm{SM}} = 80.353 \pm 0.009\ \mathrm{GeV}$
- Turns out: $\Delta M_W^{\mathrm{BSM}} > 0$ if $M_S < M_h$ (not so interesting case anymore)
- But $\Delta M_W^{\mathrm{BSM}} < 0$ if $M_S > M_h$: If the CDFII result is verified it kills the scalar singlet extensions!!

But extensive direct searches also exist!





HiggsBounds
HiggsSignals
HiggsTools
software!

What does a new scalar do?

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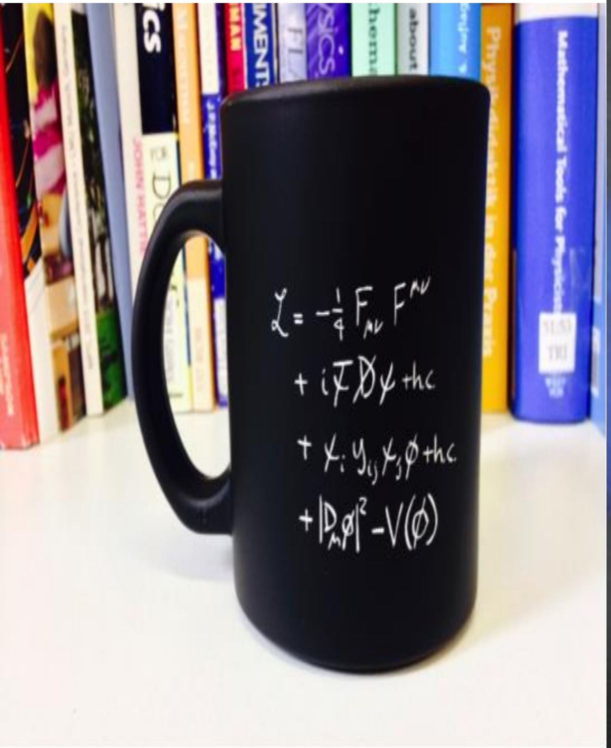
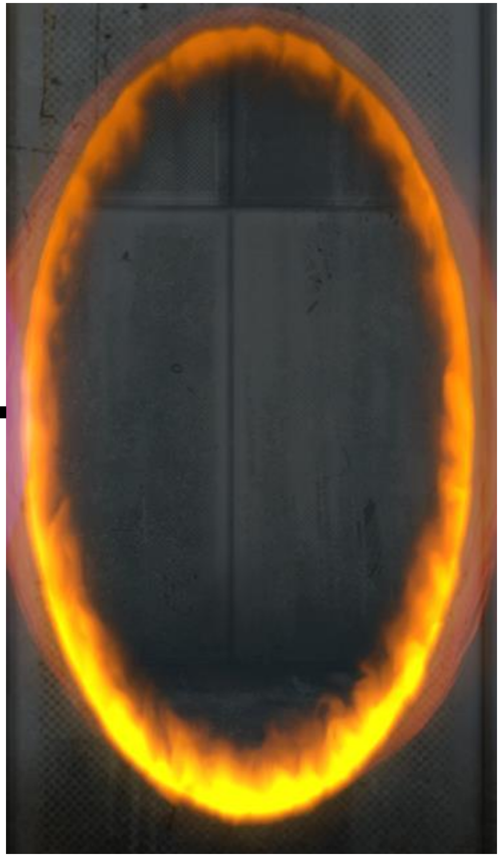
What else can we have?



Portal to new physics:

- Scalar (0)
- Vector (1)
- Tensor (2)
- Fermions (1/2)



Secluded new physics

For instance: $\lambda\, |\phi|^2 |\chi|^2$

Neutral gauge bosons: Z' (vector mediators)

Motivation for extra neutral gauge bosons (Z')

- Z' appears after breaking a $U(1)$ gauge group (or higher)
- Fifth fundamental interaction?
- Breaking a larger gauge group with a scalar VeV → the unbroken subgroup has $U(1)$-s (e.g.: GUT, SUSY, string)
- Z' can connect to a secluded sector in the SM
- A discovery would have a lot of consequences: extended scalar [χ] (make Z' massive) and extended fermion sectors [$3 \times \nu_R$] (cancel gauge anomalies)

Minimal extension of the SM

- SM gauge group + $U(1)_z$

- Covariant derivative is modified:

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

- $\eta \propto$ kinetic mixing $(F'_{\mu\nu}F^{\mu\nu})$

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

- Rotate to mass eigenstates:

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

z charge assignment

field	$SU(3)_c$	$SU(2)_L$	y	z
Q_L	3	2	$\frac{1}{6}$	$z_q = \frac{1}{3}(z_\phi - z_N)$
U_R	3	1	$\frac{2}{3}$	$z_u = \frac{1}{3}(4z_\phi - z_N)$
D_R	3	1	$-\frac{1}{3}$	$z_d = -\frac{1}{3}(2z_\phi + z_N)$
ℓ_L	1	2	$-\frac{1}{2}$	$z_\ell = z_N - z_\phi$
N_R	1	1	0	z_N
e_R	1	1	-1	$z_e = z_N - 2z_\phi$
ϕ	1	2	$\frac{1}{2}$	z_ϕ
χ	1	1	0	$z_\chi = -1$

- Cancel anomalies
  +Yukawa mass terms
  = Fix all, but two z charges

- χ : new singlet scalar
- N: right handed (sterile) neutrinos

- Choose z_N and z_ϕ to be free

z charge remarks

- 2 free z charges (due to anomaly cancellation + Yukawa masses +normalization)
- z_N ~ neutrino mass generation mechanism: tree level Majorana mass term is allowed if $z_\chi + 2z_N = 0$ ($\sim \chi\, \bar{\nu}_R \nu_R^c$)
- z_ϕ appears only in the combination: $z_\phi - \frac{\eta}{2}$ → use this one

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- 2 free z charges (due to anomaly cancellation + Yukawa masses +normalization)
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- z_ϕ appears only in the combination: $z_\phi - \frac{\eta}{2} \to$ use this one
- In the branching ratios of Z' the combination appears:

$$\mathbf{Z} = \frac{z_\phi - \eta/2}{z_N} \quad \text{e.g.: } \mathrm{Br}(Z' \to \mathrm{inv.}) = \frac{(3+n_N)}{(3+n_N)+2\left(1-2\, c_W^2\, \mathbf{Z}\right)^2} \text{ for } M_{Z'} < m_\mu$$

- B-L model: $\mathbf{Z} = \mathbf{0}$

Other free parameters:

- $M_{Z'}$ (or rather $\xi = M_{Z'}/M_Z$ to treat diff. mass scales)
- Either the mixing angle s_z or the new gauge coupling g_z:

$$-s_z c_z \frac{(1-\xi^2)}{\rho} = \frac{2}{\sqrt{g_Y^2+g_L^2}}\, g_z \left(z_\phi - \frac{\eta}{2}\right)$$

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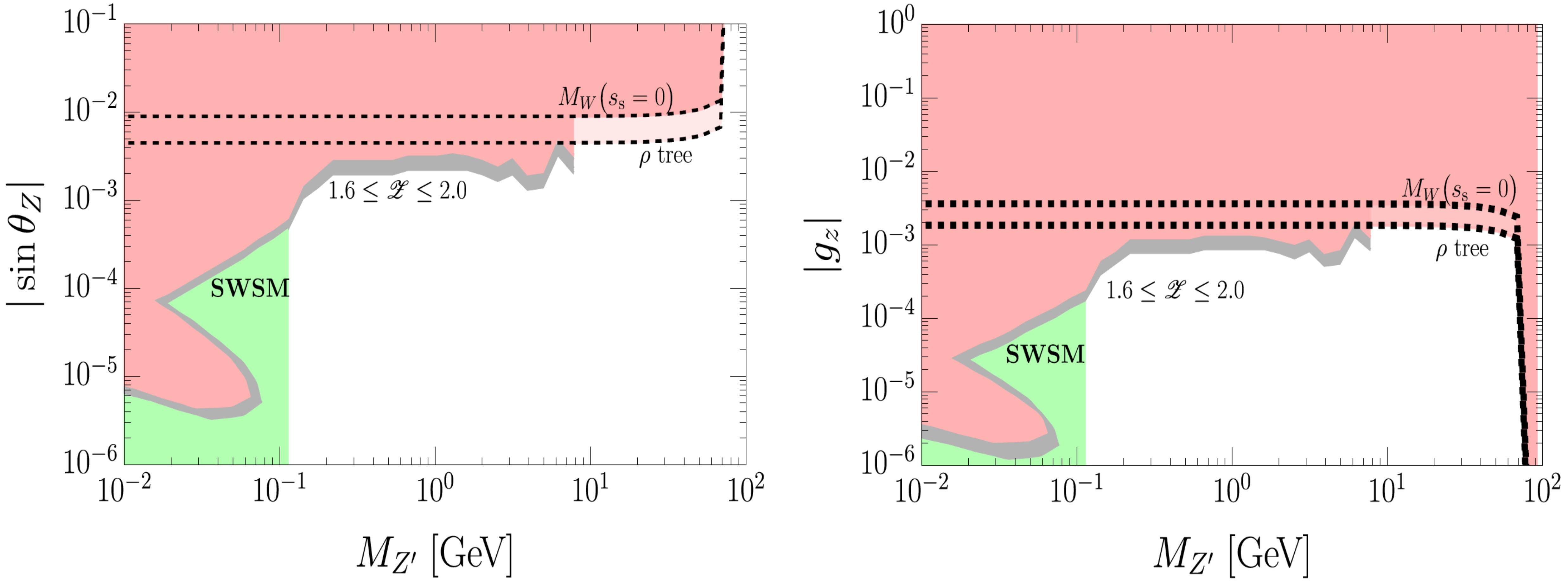
This is BSM only !

- From global fits one has: $\rho = 1.00038 \pm 0.00020$
- The tree level model prediction is:

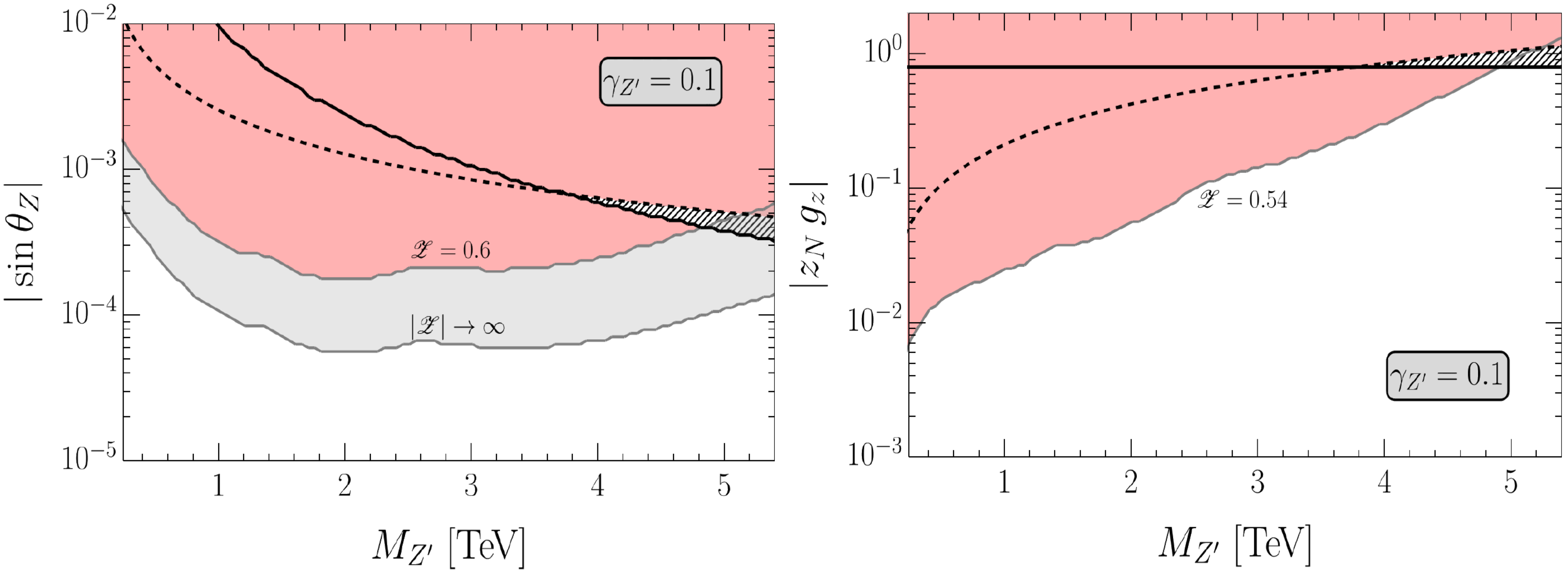
$$\rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1 + (\xi^2 - 1) s_z^2$$

Light Z': the superweak model



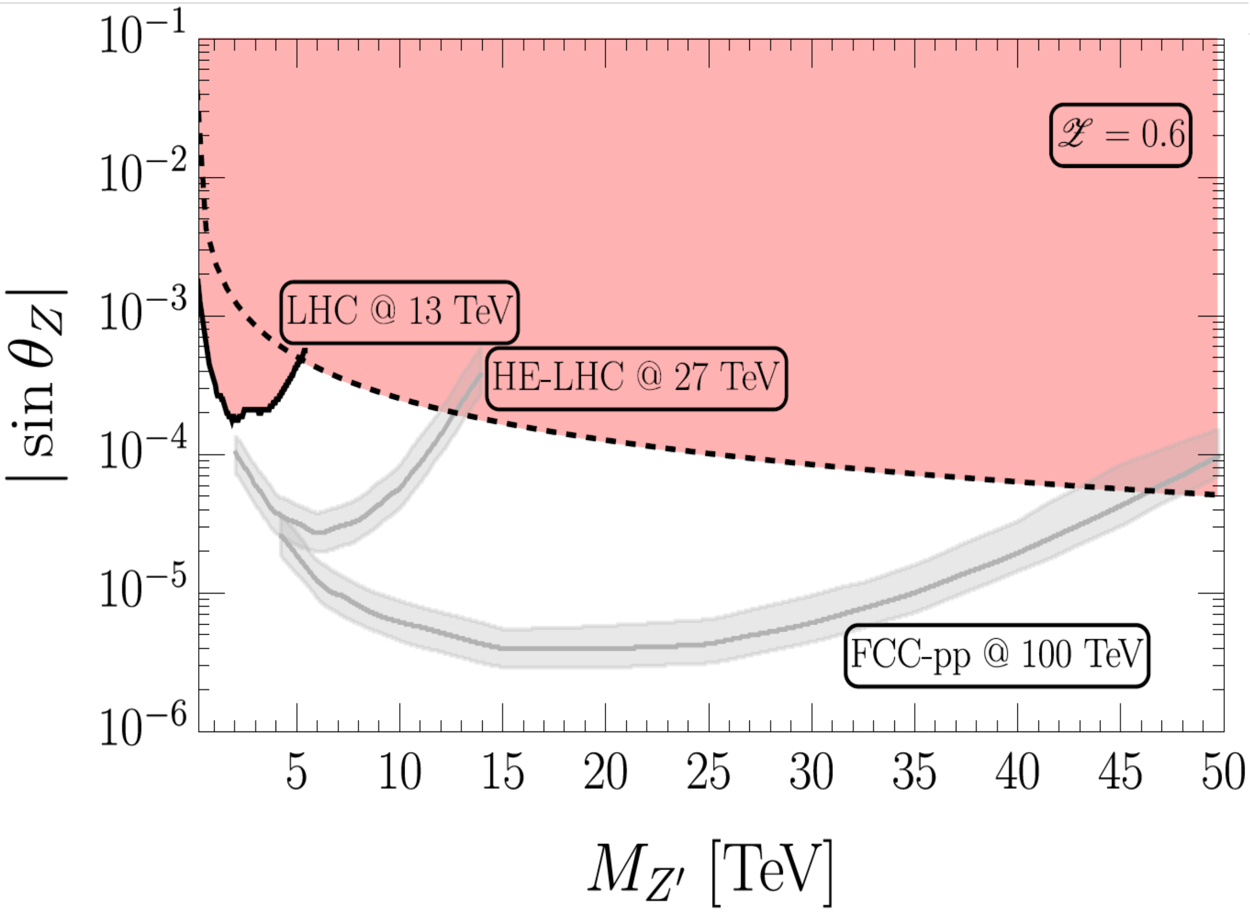
Uncertainty due to sterile neutrinos + running of η: thickness of gray line

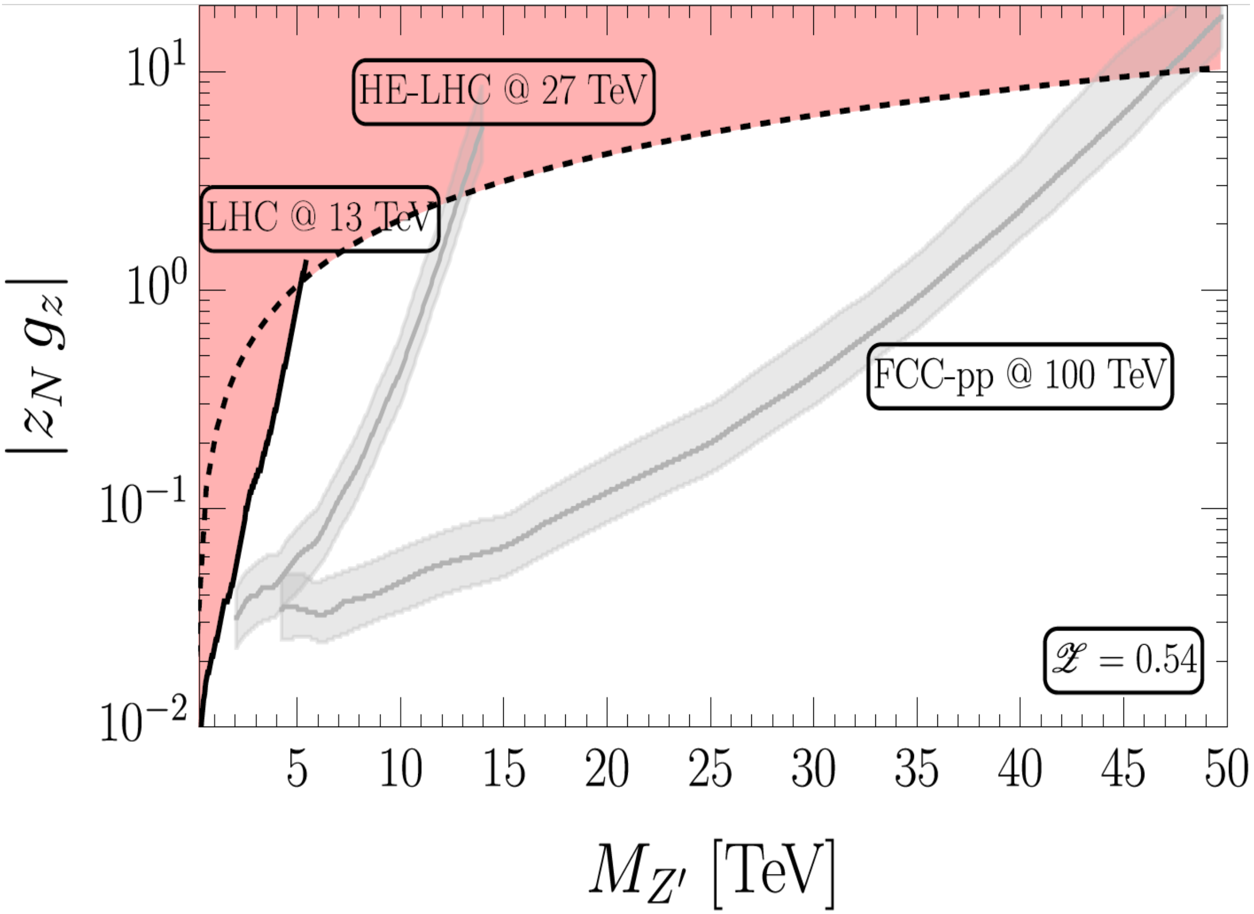
Heavy Z': almost model independet!



There is a **Z** value corresponding to a ***loosest*** bound!

Projections for future colliders





…using detector simulations for the HE-LHC and FCC-hh

Outlook

- BSM is a rich topic
- Particle physics explanation for most of the unexplained phenomena
- But the clues are hiding well
- Explore the possible new particles and their conseuqences to know what to expect