Search for new scalars with *Z'* bosons

Zoltán Péli

with Z. Trócsányi

ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

Extended Higgs Sector Subgroup Meeting
November 12, 2024

Motivation

- Many models predict a Z'
  …and it needs mass from somewhere

- E.g.: $\mathcal{L} \supset \frac{1}{2} M_{Z'}^2 Z'^2 + (e\epsilon) Z'_\mu \sum_f Q_f \bar{f} \gamma^\mu f$
  not renormalizable

- Need an extended scalar sector to get $M_{Z'}$
  (similar [1412.0018], focuses on Z')

Extra neutral gauge bosons (Z')

- Appears after breaking a $U(1)$ or larger
- Fifth fundamental interaction?
- Breaking a larger gauge group with a scalar VeV → the unbroken subgroup has $U(1)$-s (e.g.: GUT, SUSY, string)
- A discovery would have a lot of consequences: extended scalar (make Z' massive) and extended fermion sectors (cancel gauge anomalies)

Minimal extension of the SM with Z'

- SM gauge group + $U(1)_z$: new gauge field B'_μ

- 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 parameter of $F'_{\mu\nu}F^{\mu\nu}$

- Rotate to mass eigenstates (3 neutral gauge bosons):

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

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:

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

This is BSM only !

- From global fits one has: $\rho = 1.00038 \pm 0.00020$ [PDG 2022]
- The tree level prediction is:

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

[2305.1193]
[2306.01836]

The scalars h and s

- Simplest case to make Z' massive: new complex scalar field χ on top of the BEH field ϕ
- The portal interaction is allowed: $\propto \lambda|\phi|^2|\chi|^2$
- SSB: $\phi \to h' + v,\ \chi \to s' + w$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} c_s & -s_s \\ s_s & c_s \end{pmatrix} \begin{pmatrix} h' \\ s' \end{pmatrix}$$

- Scalar sector parameters: M_s, s_s and λ or $\tan\beta = w/v$:

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- If $M_{Z'} \ll M_Z$: $\rho = 1 - \left(\frac{\xi}{\tan\beta}\right)^2 \left(z_\phi - \frac{\eta}{2}\right)^2$

- If $M_{Z'} \gg M_Z$: $\rho = 1 - \left(\frac{z_\phi - \eta/2}{\tan\beta}\right)^2$

Scalars and Z'

Scalar couplings

- Scalar sector parameters: M_s, s_s and λ or $\tan\beta = w/v$
- Coupling to vectors ($\mathrm{i}\Gamma_{SVV}g^{\mu\nu}$):

$$\Gamma_{hWW} = c_s\Gamma_{hWW}^{\mathrm{SM}} \qquad \Gamma_{sWW} = s_s\Gamma_{hWW}^{\mathrm{SM}}$$

$$\Gamma_{hZZ} = 2\,M_Z^2\left(c_s c_z^2 - \frac{s_s}{\tan\beta}\, s_z^2\right) \qquad \Gamma_{sZZ} = 2\,M_Z^2\left(s_s c_z^2 + \frac{c_s}{\tan\beta}\, s_z^2\right)$$

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Decay channels for $\boldsymbol{h}$

- Most decays scale with the mixing: $\Gamma(h \to XY) = c_s^2\, \Gamma^{\mathrm{SM}}(h \to XY)$

- Other new particles too heavy or too light to contribute to Γ_h

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- Z' decays with $|s_z| \ll 1$:

$$\Gamma(h \to Z'Z') = \frac{G_f\, M_h^3}{16\sqrt{2}\pi}\left(\frac{s_s}{\tan\beta}\right)^2 + O\left(\frac{M_{Z'}^2}{M_Z^2}\right)$$

$$\Gamma(h \to Z\, Z') = \frac{G_f\, M_h^3}{8\sqrt{2}\pi}\left(1 - \frac{M_Z^2}{M_h^2}\right)^3 s_Z^2 \left(c_s + \frac{s_s}{\tan\beta}\right)^2 + O\left(\frac{M_{Z'}^2}{M_Z^2}\right)$$

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- $\frac{G_f\, M_h^3}{16\sqrt{2}\pi} \simeq 320\ \text{MeV}$ and $\Gamma_h^{\text{ATLAS}} = 3.2^{+2.4}_{-1.7}\ \text{MeV}$ / $\Gamma_h^{\text{CMS}} = 4.5^{+3.3}_{-2.5}\ \text{MeV}$

$$\Gamma_h = c_s^2\Gamma_h^{\text{SM}} + \Gamma(h \to Z'Z')$$

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$$\Gamma_h = (4.04\text{ MeV})c_S^2 + (320\text{ MeV})\left(\frac{s_S^2}{\tan\beta}\right)$$

Signal strengths

$$\mu = \frac{(\sigma \cdot \mathrm{Br})_{\mathrm{obs.}}}{(\sigma \cdot \mathrm{Br})_{\mathrm{SM}}}$$

- Production cross sections: $\sigma(pp \to h) = c_s^2\, \sigma^{\mathrm{SM}}(pp \to h)$ [changes in VBF, VH are suppressed]

- Prediction for total $\mu_{\mathrm{tot.}} = c_s^2$ (all Br-s summed over)

- The channel $h \to ZZ^* \to 4\ell$ is precisely measured (discovery channel)

Signal strengths

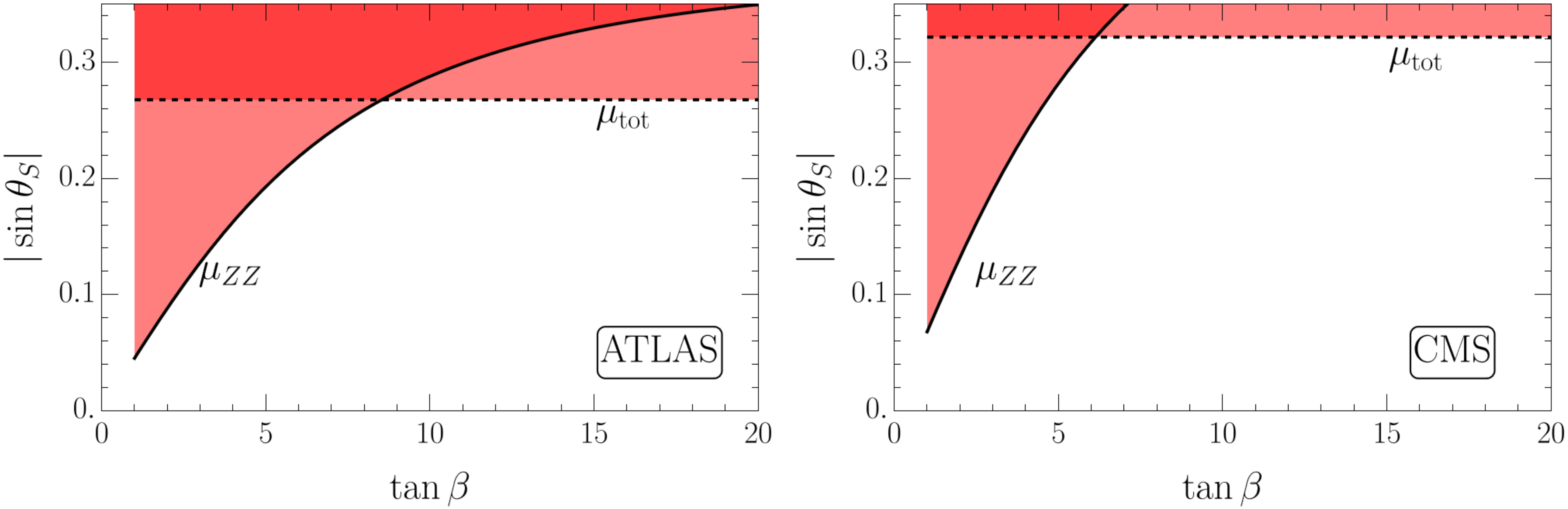
- Model: $\mu_{\text{tot.}} = c_s^2$

- Measurement: $\mu_{\text{tot.}}^{\text{ATLAS/CMS}} = 1.05 \pm 0.06/1.02 \pm 0.06$

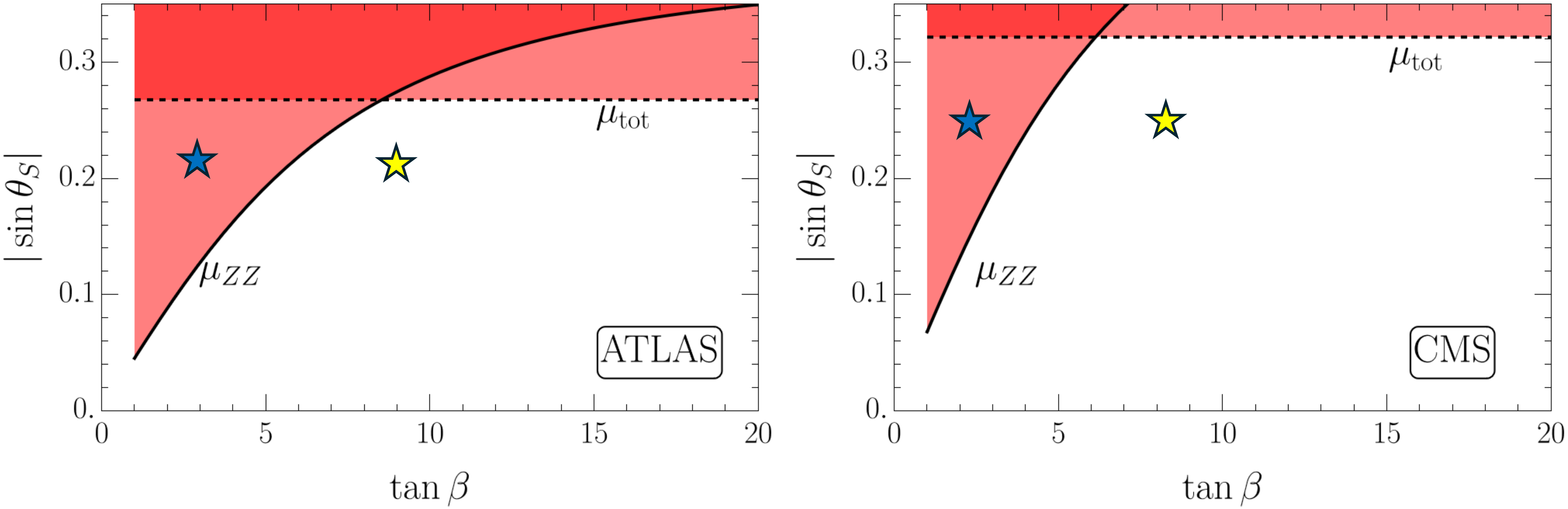
- Model: $\mu_{\text{ZZ}} = \frac{c_s^4}{c_s^2 + 78.7(s_s/\tan\beta)^2}$

- Measurement: $\mu_{\text{ZZ}}^{\text{ATLAS/CMS}} = 1.04 \pm 0.09/0.97 \pm 0.12$

Signal strengths



Benchmarks to tell models apart?



Different benchmarks, different Br-s: could exclude light Z' bosons

Summary

- Useful parametrization: different $U(1)$ extensions can be investigated on the same footing

- ρ can be used to quickly assess the constraints from EWPO

- Light Z' affects Higgs boson properties

Thank you for your attention!