High and low energy probes of light Z' bosons

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Question(s) I want to ask:

SU(2) × U(1) gauge symmetry is the only gauge symmetry at the low scale? Room for light (≤100GeV) gauge bosons?

If so, how to probe them?
And in particular what is the role of the Higgs boson?

What are the virtues of these new gauge bosons?
1. Introduction:
- Present searches for neutral gauge bosons

2. Kinetically mixed Z dark gauge boson
- Present bounds
- Role of the Higgs boson in probing the model: exotic Higgs decays

3. $L_\mu - L_\tau$ model
- Interesting effects in flavor physics
- Diversity of low and high energy probes of the model:
  EWPTs, $(g-2)_\mu$, $Z \rightarrow 4\mu$, neutrino trident production
1. Introduction:
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3. $L_\mu$ - $L_\tau$ model
- Interesting effects in flavor physics
- Diversity of low and high energy probes of the model: EWPTs, $(g-2)_\mu$, $Z \rightarrow 4\mu$, neutrino trident production

- Exotic decays of the 125 GeV Higgs boson
  D. Curtin, R. Essig, S.G., P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen, J. Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y-M. Zhong, 1312.4992
  D. Curtin, R. Essig, S.G., J. Shelton, in preparation

- Dressing $L_\mu$ - $L_\tau$ in color
  W. Altmannshofer, S.G., M. Pospelov, I. Yavin, 1403.1269 + in preparation


**Z' models**

- Naturally arising in **Grand Unified Theories** (e.g. $E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$)

- Models of **compositeness or extra dimensions** give raise to excited $Z$ bosons: „sequential $Z'$ bosons“

- A new $U(1)'$ symmetry can address the $\mu$ problem of the MSSM, since it can forbid the appearance of a $\mu$ term

- In Susy models, a new $U(1)'$ symmetry can give a sizable **tree level contributions to the Higgs mass**, through new non-decoupling D-terms

**From where**

**Naturalness**
Z' models

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- Models of compositeness or extra dimensions give raise to excited Z bosons: „sequential Z' bosons“

- A new U(1)' symmetry can address the $\mu$ problem of the MSSM, since it can forbid the appearance of a $\mu$ term

- In Susy models, a new U(1)' symmetry can give a sizable tree level contributions to the Higgs mass, through new non-decoupling D-terms

- Used in neutrino model building

- „Dark“ gauge bosons can arise in models for thermal dark matter

- A U(1)' Susy model can provide a sufficiently large first order phase transition for Electroweak baryogenesis

- Easy to get sizable effects in $(g-2)_\mu$ if the Z' is quite light
Plenty of LHC searches for TeV-scale $Z'$

Di-lepton resonances:

Below 100 GeV, limits from LEPII: $e^+e^- \rightarrow ff$ (for couplings of at least $10^{-2}$)
Plenty of LHC searches for TeV-scale Z'

Di-jet/top resonances:

Dobrescu, Yu, 1306.2629
Starting from the 90s, LEP, SLD, Tevatron lead a very successful program of measurement of electroweak precision observables (EWPO).

\[ p\text{-value} = 0.21 \]

See also Batell, S.G., L.T.Wang 1209.6382
Starting from the 90s, LEP, SLD, Tevatron lead a very successful program of measurement of electroweak precision observables (EWPO).

Last ingredient to complete the SM: the Higgs mass

Is the ew sector of nature now complete?

Room for another ingredient an electro-weakly coupled neutral gauge boson?

\[ p\text{-value} = 0.21 \]

See also Batell, S.G., L.T.Wang 1209.6382
Kinetically mixed $Z'$
Suppression of DM direct detection signals, but still possible to have a thermal DM candidate

The only link between the SM and the dark sector:

$$\mathcal{L} \supset \frac{\epsilon}{2 \cos \theta} \hat{B}_{\mu\nu} \hat{Z}_D^{\mu\nu}$$

+ mass term for $Z_D$

coming from Stueckelberg mechanism / dark Higgs that breaks the U(1)' symmetry
Secluded models for dark matter

**Mechanism:**

\[ m_{\text{med}} < m_{\text{DM}} \]

Suppression of DM direct detection signals, but still possible to have a thermal DM candidate

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\[ \mathcal{L} \supset \frac{\epsilon}{2 \cos \theta} \hat{B}_{\mu \nu} \hat{Z}^{\mu \nu} + \text{mass term for } Z_D \]

coming from Stueckelberg mechanism / dark Higgs that breaks the U(1)' symmetry

NP effects on the Z boson:

- **Tree level shift in the Z mass:** \( m_Z^2 \sim m_{Z0}^2 (1 + \epsilon^2 \tan^2 \theta_W) \)

- **Modification of the Z couplings:** \( (Zf\bar{f})_{\text{SM}} \left( 1 + \frac{\epsilon^2 \tan^2 \theta}{2} \cdot \frac{T_3 - Q(1 + \cos^2 \theta)}{T_3 - Q \sin^2 \theta} \right) \)
How to probe the model

A plethora of probes of the model

Mainly driven by the tree level shift in the Z boson mass

Hook, Izaguirre, Wacker, 1006.0973

e^+e^- \rightarrow \gamma Z_D

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992
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What is the role of the Higgs in probing the available parameter space? Can this $Z_D^-$ be discovered at the LHC?
A four lepton Higgs signature

\[ hZZ_D \sim 2\epsilon \tan \theta \frac{m_{ZD}^2}{v} \]

\[ hZ_DZ_D \sim \epsilon^2 \tan^2 \theta \frac{m_{ZD}^4}{m_Z^2 v} \]
A four lepton Higgs signature

Sizable branching ratio into two leptons

For $m_{Z_D} > \theta(100\text{MeV})$, $
\varepsilon > \theta(10^{-4})$ gives rise to promptly decaying dark Z bosons ($c\tau < 1\mu m$)

Sizable branching ratio into two leptons

Higgs four lepton signature!

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992
Higgs width: direct measurement

CMS PAS HIG-14-002

Very interesting new CMS measurement

In a nutshell:

\[
\begin{align*}
\sigma_{\text{on-peak}}^{gg\rightarrow H\rightarrow ZZ} &= \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \text{BR})_{\text{SM}} \equiv \mu (\sigma \cdot \text{BR})_{\text{SM}} \\
\sigma_{\text{off-peak}}^{gg\rightarrow H\rightarrow ZZ} &= \kappa_g^2 \kappa_Z^2 \frac{\sigma_{\text{off-peak, SM}}^{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}} = \mu r \frac{\sigma_{\text{off-peak, SM}}^{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}}
\end{align*}
\]

\[
\begin{align*}
\kappa_g &= \frac{g_{ggH}}{g_{ggH}^{\text{SM}}} \\
\kappa_Z &= \frac{g_{HZZ}}{g_{HZZ}^{\text{SM}}} \\
r &= \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}
\end{align*}
\]

\[\Gamma_H < 4.2(8.5) \Gamma_{H,\text{SM}}\]

Combining the 4l and the 2l2\nu channels
Constraint from the fit of the SM Higgs couplings

Assumptions going into this fit:
1. the coupling of the Higgs to photons ($k_γ$)
2. the coupling of the Higgs to gluons ($k_g$)
3. the total width of the Higgs

$\text{BR}(h \rightarrow \text{inv, undet}) \lesssim 60\%$ @ 95\% C.L.

The exact value depends on the fit. Still typically values below (20-30)\% are uncostrained.
Higgs width: indirect measurement

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With 300fb$^{-1}$ LHC data, the expected bound on the "extra width" is at the level of ~10%

See e.g. Peskin, 1207.2516
Higgs width: indirect measurement

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ASSUMPTIONS GOING INTO THIS FIT:
1. The coupling of the Higgs to photons ($k_\gamma$)
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NOW

The exact value depends on the fit. Still typically values below (20-30)% are unconstrained

FOR FUTURE

With 300 fb$^{-1}$ LHC data, the expected bound on the "extra width" is at the level of ~10%

See e.g. Peskin, 1207.2516
Importance of the ZZ channel

**ATLAS Prelim.**

- $m_H = 125.5$ GeV
- $H \rightarrow \gamma\gamma$
  - $\mu = 1.57^{+0.33}_{-0.28}$
- $H \rightarrow ZZ^* \rightarrow 4l$
  - $\mu = 1.44^{+0.40}_{-0.35}$
- $H \rightarrow WW^* \rightarrow l\nu l\nu$
  - $\mu = 1.00^{+0.32}_{-0.29}$

**Combined**

- $H \rightarrow \gamma\gamma, ZZ^*, WW^*$
  - $\mu = 1.35^{+0.21}_{-0.20}$

- $W, Z H \rightarrow b\bar{b}$
  - $\mu = 0.2^{+0.7}_{-0.6}$

- $H \rightarrow \tau\tau$ (8 TeV data only)
  - $\mu = 1.4^{+0.5}_{-0.4}$

**Combined**

- $H \rightarrow b\bar{b}, \tau\tau$
  - $\mu = 1.09^{+0.36}_{-0.32}$

**Combined**

- $\mu = 1.30^{+0.18}_{-0.17}$

**CMS Preliminary**

- $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
  - $V H \rightarrow bb$ arXiv:1310.3687
    - $\mu(m_H = 125.0$ GeV$) = 1.0 \pm 0.5$

- $H \rightarrow \tau\tau$ arXiv:1401.5041
  - $\mu(m_H = 125.0$ GeV$) = 0.78 \pm 0.27$

- HIG-13-001
  - $H \rightarrow \gamma\gamma$
    - $\mu(m_H = 125.0$ GeV$) = 0.78 \pm 0.27$

- $H \rightarrow WW$ arXiv:1312.1129
  - $\mu(m_H = 125.6$ GeV$) = 0.72 \pm 0.19$

- $H \rightarrow ZZ$ arXiv:1312.5353
  - $\mu(m_H = 125.6$ GeV$) = 0.93 \pm 0.27$

**Results**

- $6.6 \sigma$ significance @ ATLAS
- $6.8 \sigma$ significance @ CMS
LHC measurement of Higgs to four leptons

Latest results with the full (7+8) TeV LHC dataset:
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

The four leptons are divided in 2 SFOS pairs:
the leading pair „Z1“ and the subleading pair „Z2“

\[ h \rightarrow ZZ^* \]
LHC measurement of Higgs to four leptons

Latest results with the full (7+8) TeV LHC dataset:
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

The four leptons are divided in 2 SFOS pairs:
the leading pair „Z1“ and the subleading pair „Z2“

NP effects:
- Resonant $h \rightarrow ZZ_D^*$ production
- Interference with the SM amplitude $h \rightarrow ZZ^*$
Bound on the resonant $ZZ_D$ production (1)

Assuming the same efficiency as for events genuinely coming from $h \rightarrow ZZ^*$

Counting experiment:

$BR(h \rightarrow ZZ_D) \sim 10^{-3}$ are already probed with the present (un-dedicated) 7+8 TeV LHC searches

Given the $\leq 3\%$ dilepton mass resolution and the CMS binning of 1.25 GeV
The Higgs bound is already approaching the bound coming from ~20 years of EWPTs!
Future: EWPTs vs Higgs to four leptons

EW precision measurements will improve:

| $\Delta M_W$ (MeV) | Present | Tevatron full dataset | LHC14, 300 fb$^{-1}$ | LHC14, 3000 fb$^{-1}$ |
|-------------------|---------|-----------------------|----------------------|----------------------|
|                   | 15      | 9                     | 8                    | 5                    |

| $\Delta M_H$ (GeV) | Present | LHC14, 300 fb$^{-1}$ |
|-------------------|---------|----------------------|
|                   | 0.4     | 0.1                  |

We do not expect a significantly stronger bound from EWPTs

What about LHC $h \rightarrow ZZ_D$ dedicated searches?

And in particular what about the shape of the two invariant mass distributions in the case of off-shell $Z_D$? (interference effects with $h \rightarrow ZZ^*$)

Dedicated searches at LHC14 can improve the bound on the branching ratio by more than 1 order of magnitude

Davoudiasl et al.1304.4935
A anomaly free $L_\mu - L_\tau$ gauge symmetry
A gauge symmetry for neutrino physics

$L_\mu - L_\tau$ is one of the few anomaly free gauge groups.
Arbitrary linear combinations of $Y$ and $B-L$, with $L = L_e + L_\mu + L_\tau$
(not necessarily family independent)

- The associated $Z'$ couples directly with muons $\rightarrow (g-2)_\mu$

Neutrino model building:
- Before breaking the gauge symmetry:
  \[
  \begin{align*}
  \Theta_{23} &= \text{maximal}, \quad \Theta_{13} = \Theta_{12} = 0 \\
  \text{Two neutrinos are degenerate in mass. The third one is split in mass}
  \end{align*}
  \]

- In seesaw models, breaking the gauge symmetry with
  a additional scalar induces corrections

\[
\begin{align*}
\sin \theta_{13} &= \mathcal{O} \left( \frac{\langle S \rangle}{M_N} \right) \\
\sin \theta_{23} &= \frac{1}{\sqrt{2}} + \mathcal{O} \left( \frac{\langle S \rangle^2}{M_N^2} \right)
\end{align*}
\]

See e.g. Heeck, Rodejohann, 1107.5238

The two degenerate neutrinos acquire a split proportional to $\frac{\langle S \rangle^2}{M_N^2}$
Latest $B \rightarrow K^{*}\mu\mu$ results from LHCb (with 1fb$^{-1}$) 1308.1707

3.7 $\sigma$ discrepancy in the 4.3 GeV$^2 < q^2 < 8.68$ GeV$^2$ bin, with respect to the SM

- Statistical fluctuation? (full data set probably this summer)
- Underestimated SM uncertainties? (see Jager et al. 1212.2263)
- New Physics?
Considering constraints from $B_s \rightarrow \mu\mu$, $b \rightarrow s\gamma$, $B \rightarrow K\mu\mu$ and from the other observables in $B \rightarrow K^*\mu\mu$, the best fit arises for

$$O_9^{(l)} = (\bar{s}\gamma^\alpha P_L(R)b)(\bar{\mu}\gamma_\alpha \mu), \quad \text{Re}(C_9^{(l)}) \sim \mp (35 \text{ TeV})^{-2}$$

Vector coupling with muons

Axial-vector coupling with quarks

Altmannshofer, Straub, 1308.1501
Considering constraints from $B_s \rightarrow \mu\mu$, $b \rightarrow s\gamma$, $B \rightarrow K\mu\mu$ and from the other observables in $B \rightarrow K^*\mu\mu$, the best fit arises for

$$O^{(t)}_9 = (\bar{s}\gamma^\alpha P_L(R)b)(\bar{\mu}\gamma^\alpha\mu), \quad \text{Re}(C^{(t)}_9) \sim \mp (35 \text{ TeV})^{-2}$$

Couple the $Z'$ to quarks only indirectly, by mixing with heavy vector-like fermions charged under $U(1)'$ e.g. Fox, Liu, Tucker-Smith, Weiner 1104.4127

NP effect independent of the $Z'$ mass and gauge coupling

$$C_9 \sim \frac{Y_Q b Y_Q^*}{2m_Q^2}, \quad C'_9 \sim \frac{-Y_{D b} Y_{D s}^*}{2m_D^2}$$

Altmannshofer, S.G., Pospelov, Yavin, 1403.1269

Altmannshofer, Straub, 1308.1501
The $Z'$ leads also to contributions to $B_s$ meson mixing

$$M_{12}^s \propto (Y_{Qb}Y_{Qs}^*)(Y_{Db}Y_{Ds}^*) \frac{v_{\phi}^2}{m_Q^2 m_D^2}$$
The $Z'$ leads also to contributions to $B_s$ meson mixing

\[ M_{12}^8 \propto (Y_{Qb}Y_{Qs}^*)(Y_{Db}Y_{Ds}^*) \frac{v^2_\phi}{m_Q^2 m_D^2} \]

Same parameter dependence as in $B \to K^*\mu\mu$

To fit the central value of $B \to K^*\mu\mu$, one needs $v_\phi \lesssim 1.8$ TeV

Light $Z'$, $m_{Z'} = g'v_\phi$
The $Z'$ leads also to contributions to $B_s$ meson mixing. 

\[ M_{12}^s \propto \begin{pmatrix} Y_{Qb} & Y_{Qs}^* \end{pmatrix} \begin{pmatrix} Y_{Dd} & Y_{Ds}^* \end{pmatrix} \frac{v_\phi^2}{m_Q m_D^2} \]

Same parameter dependence as in $B \rightarrow K^* \mu\mu$

To fit the central value of $B \rightarrow K^* \mu\mu$, one needs $v_\phi \lesssim 1.8 \text{ TeV}$

Light $Z'$, $m_{Z'} = g' v_\phi$

**Note:**

Kaon mixing strongly constrains the couplings to first generation quarks! Tiny $Z'$ production at the LHC!
1. Anomalous magnetic moment of the muon

\[ \Delta a_\mu \simeq \frac{1}{12\pi^2} \frac{m_\mu^2}{v_\phi^2} \]

To reach the central value of the measurement:

\[ \Delta a_\mu = (2.9 \pm 0.9) \times 10^{-9} \]

\[ v_\phi \simeq 180 \text{ GeV} \]
2. Tau decays

\[
\frac{\text{BR}(\tau \to \mu \nu_\tau \bar{\nu}_\mu)}{\text{BR}(\tau \to \mu \nu_\tau \bar{\nu}_\mu)_\text{SM}} \approx 1 + \Delta
\]

\[
\Delta = \frac{3(g')^2}{4\pi^2} \frac{\log(m^2_W/m^2_{Z'})}{1 - m^2_{Z'}/m^2_W}
\]

Combining the SM prediction (Pich 1310.7922) with exp. measurement (PDG + Belle 1310.8503)

\[
\Delta = (7.0 \pm 3.0) \times 10^{-3}
\]

New more precise measurement of the τ life time
3. EW precision measurements

Modifications of the Z couplings to muons, taus and neutrinos

Axial vector couplings with muons and taus are measured at the 0.1% level at LEPII!
4. Measurement of the $Z$ decaying into four leptons

In the SM:

The branching ratio in the phase space $M_{ll} > 4\text{GeV}$ and $76\text{GeV} < M_{4l} < 106\text{GeV}$ is given by

$$\text{BR}(Z \to 4l)^{\text{SM}}_{\text{SM}} = (4.37 \pm 0.03) \times 10^{-6}$$

To be compared to the measured value

$$\text{BR}(Z \to 4l)^{\text{exp}}_{\text{exp}} = (4.2 \pm 0.4) \times 10^{-6}$$

ATLAS (CONF-2013-055), see also CMS (1210.3844)
4. Measurement of the Z decaying into four leptons

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Our Z' contribute to the four muon bin:
78 events expected and 77 observed
First observed by CHARMII experiment at CERN (55±16 events) (CERN-EP/90-75)
~20 GeV of neutrino/antineutrino mean energy
Neutrino trident muon pair production

- First observed by **CHARMII** experiment at CERN (55±16 events) (CERN-EP/90-75)
  - ~20 GeV of neutrino/antineutrino mean energy

- Later confirmed by the **CCFR** (Columbia, Chicago, Fermilab, Rochester) experiment at Fermilab (Phys.Rev.Lett. 66, 3117)
  - ~160 GeV of neutrino/antineutrino mean energy
  - First demonstration of the W-Z destructive interference

| Data          | SM          | Only $W$   |
|---------------|-------------|------------|
| 37.0 ± 12.4   | 45.3 ± 2.3  | 78.1 ± 3.9 |
Z' @ neutrino experiments

Neutrino trident muon pair production

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- Finally confirmed by **NuTeV** at Fermilab (hep-ex/9811012)
  - SM prediction is ~60% W contribution
Neutrino trident muon pair production

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  - First demonstration of the W-Z destructive interference

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Difficult measurement since small cross section:
- ~5 orders of magnitude smaller than the inclusive neutrino-nucleus cross section

Main discriminant with respect to the charm background

\[ \nu + (d, s) \rightarrow \mu^- + c \]
A powerful probe of $Z'$ interactions (1)

- The $Z'$ contribution interferes constructively with the SM $W$ contribution.

- For $m_{Z'} \gtrsim 5 \text{ GeV}$, the four fermion interaction approximation is good:

$$\frac{\sigma}{\sigma_{SM}} \approx \frac{1 + (1 + 4s_W^2 + 2v^2/v_\phi^2)^2}{1 + (1 + 4s_W^2)^2}$$

- To be compared to:

$$\frac{\sigma_{\text{CHARM-II}}}{\sigma_{SM}} = 1.58 \pm 0.57 ,$$
$$\frac{\sigma_{\text{CCFR}}}{\sigma_{SM}} = 0.82 \pm 0.28 ,$$
$$\frac{\sigma_{\text{NuTeV}}}{\sigma_{SM}} = 0.67 \pm 0.27^* .$$

(*) Later NuTeV publication does not confirm the original measurement hep-ex/9909041
At low mass $m_{Z'} < 5$ GeV, one should compute the full $2 \rightarrow 4$ process (including the $Z'$ full propagator).

The Weizsaecker-Williams method of equivalent photons can be used: Effectively it is a $2 \rightarrow 3$ process initiated by a photon-neutrino scattering, with very small photon momentum.

Cuts applied:

$E_{\mu_1} > 9$ GeV, $E_{\mu_1} > 4.5$ GeV

$M_{\mu\mu} < 2.3$ GeV
A powerful probe of $Z'$ interactions (2)

- At low mass $m_{Z'} < 5$ GeV, one should compute the full $2 \rightarrow 4$ process (including the $Z'$ full propagator)

- The Weizsaecker-Williams method of equivalent photons can be used: Effectively it is a $2 \rightarrow 3$ process initiated by a photon-neutrino scattering, with very small photon momentum

$Z'$ coupled to muons (and to the corresponding neutrino) cannot explain $(g-2)_\mu$ if they are relatively massive ($m_{Z'} \gtrsim 300$ MeV)

Future neutrino experiments to further probe the $Z'$ couplings to leptons and neutrinos? LBNE?

Cuts applied:

- $E_{\mu^1} > 9$ GeV, $E_{\mu^1} > 4.5$ GeV
- $M_{\mu\mu} < 2.3$ GeV

Altmannshofer, S.G., Pospelov, Yavin, in preparation
Conclusions

- Light ($\leq 100\text{GeV}$) new neutral gauge bosons $Z'$ are an available possibility for NP theories.
- Interesting complementarity of low (flavor/neutrino experiments) and high (Higgs and $Z$ physics) energy experiments in testing the models.

**Kinetically mixed gauge bosons**

[Diagram showing kinetically mixed gauge bosons with $L\_\mu - L\_\tau$ gauge boson highlighted.]
Our assumptions

1. The observed 125 GeV is SM-like
   • In particular its production cross section in the several channels is the one of the SM Higgs

2. The Higgs decays promptly to new BSM particles that are either stable or promptly decaying
   • we do not consider rare or nonstandard decays to SM particles

3. The Higgs decay is a 2-body decay
   • 3-body decays are possible, but require new light states with substantial coupling to h to overcome phase space suppression
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Higgs decays to two $Z_D$ gauge bosons

**A more difficult recast:**

\[ h \rightarrow Z_D Z_D \rightarrow 4\ell \]

1. For very light $Z_D$ ($2m_\mu - 2m_\tau$), it is easy:

Limits coming from the $h \rightarrow 4\mu$ search

\[ \text{BR}(h \rightarrow Z_D Z_D \rightarrow 4\mu) < 4.7 \times 10^{-5} \]

*CMS PAS HIG-13-010* (full 8 TeV data set)
Higgs decays to two $Z_D$ gauge bosons

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   Limits coming from the $h \rightarrow 4\mu$ search
   \[
   \text{BR}(h \rightarrow Z_D Z_D \rightarrow 4\mu) < 4.7 \times 10^{-5}
   \]

2. For heavier $Z_D$, limits from SM Higgs ZZ* channel
   CMS-PAS-HIG-13-002
   ATLAS-CONF-2013-013
   ATLAS-CONF-2013-020
   $40 \text{ GeV} < m_1 < 120 \text{ GeV}, 12 \text{ GeV} < m_2 < 120 \text{ GeV}$

Because of mispairing:

- \[ m_{Z_D} = 20 \text{ GeV} \]
  \[ \sigma_{\text{max}} = 7.3 \text{ fb} \]

- \[ m_{Z_D} = 40 \text{ GeV} \]
  \[ \sigma_{\text{max}} = 3.4 \text{ fb} \]
**Higgs decays to two \( Z_D \) gauge bosons**

A more difficult recast:

\[ h \rightarrow Z_D Z_D \rightarrow 4\ell \]

1. For very light \( Z_D \) (\( 2m_\mu - 2m_\tau \)), it easy:
   - Limits coming from the \( h \rightarrow 4\mu \) search
   - \[ \text{BR}(h \rightarrow Z_D Z_D \rightarrow 4\mu) < 4.7 \times 10^{-5} \]
   - **CMS PAS HIG-13-010**
   - (full 8 TeV data set)

2. For heavier \( Z_D \), limits from SM Higgs ZZ* channel
   - **CMS-PAS-HIG-13-002**
   - **ATLAS-CONF-2013-013**
   - **ATLAS-CONF-2013-020**
   - \( 40 \text{ GeV} < m_1 < 120 \text{ GeV}, 12 \text{ GeV} < m_2 < 120 \text{ GeV} \)

Because of mispairing:

- \( m_{Z_D} = 20 \text{ GeV} \)
- \( \sigma_{\text{max}} = 7.3 \text{ fb} \)
Higgs decays to two $Z_D$ gauge bosons

**A more difficult recast:**

$$h \rightarrow Z_D Z_D \rightarrow 4\ell$$

1. For very light $Z_D$ (2$m_\mu$ - 2$m_\tau$), it easy:
   - Limits coming from the $h \rightarrow 4\mu$ search
     
   $$\text{BR}(h \rightarrow Z_D Z_D \rightarrow 4\mu) < 4.7 \times 10^{-5}$$

   - **CMS PAS HIG-13-010**
     - (full 8 TeV data set)

2. For heavier $Z_D$, limits from SM Higgs ZZ* channel
   - **CMS-PAS-HIG-13-002**
   - **ATLAS-CONF-2013-013**
   - **ATLAS-CONF-2013-020**

(having already unfolded the branching ratio of $Z_D$ into leptons)
Exotic decays of the SM-like Higgs boson

A light Higgs, a lot to say:

- $\gamma\gamma$
- $g\gamma$
- $\tau\tau$
- $c\bar{c}$
- $W^+W^-$
- $Z^*Z^*$
- $b\bar{b}$

But not only

A lot of events!

| Production | $N_{\text{ev}}^{10\%}$, Now (14 TeV) |
|------------|---------------------------------------|
| ggF        | 46.000 (1500.000)                     |
| VBF        | 3.800 (125.000)                       |
| $hW^\pm$   | 1.700 (45.000)                        |
| $hZ$       | 1.000 (27.000)                        |
| $tth$      | 70 (18.000)                           |

Even a small coupling to a light NP particle can lead to a sizable Higgs branching ratio for $h \rightarrow \text{NP NP}$

$\Gamma_h^{\text{SM}} (125 \text{ GeV}) \sim 4.1 \text{ MeV}$

$\tau \rightarrow \mu \nu\nu \rightarrow \mu \nu\nu$
Higgs: here you are!

Discovery of a weakly coupled Higgs boson

**ATLAS** Preliminary

- $W,Z,H \rightarrow bb$
- $H \rightarrow \tau\tau$
- $H \rightarrow WW^{(*)} \rightarrow lvlv$
- $H \rightarrow gg$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$

**Combined**

$\mu = 1.30 \pm 0.20$

| Channel | $\sigma_{95\%}$ |
|---------|----------------|
| ZZ      | 6.6$\sigma$    |
| WW      | 3.8$\sigma$    |
| $\gamma\gamma$ | 6.1$\sigma$ |
| $bb$    | --             |
| $\tau\tau$ | 4.1$\sigma$ |

$\sqrt{s} = 7$ TeV, $L = 4.7$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $L = 13$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $L = 5.1$ fb$^{-1}$

CMS Preliminary

$\mu = 1.30 \pm 0.20$

| Channel | $\sigma_{95\%}$ |
|---------|----------------|
| ZZ      | 6.7$\sigma$    |
| WW      | 4.0$\sigma$    |
| $\gamma\gamma$ | 3.2$\sigma$ |
| $bb$    | 2.1$\sigma$    |
| $\tau\tau$ | 3.0$\sigma$ |

$\sqrt{s} = 8$ TeV, $L \leq 19.6$ fb$^{-1}$

$\mu = 1.15 \pm 0.62$

$\mu = 1.10 \pm 0.41$

$\mu = 0.77 \pm 0.27$

$\mu = 0.68 \pm 0.20$

$\mu = 0.92 \pm 0.28$

**Now:** evidence ($\geq 3\sigma$) in all channels but $bb$, at both ATLAS and CMS