Looking for Dark forces with multi-leptons

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High energy theory seminar

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1. Introduction:
   - The long quest for new massive gauge bosons
   - New "dark" gauge bosons for Dark Matter/Neutrino phenomenology

2. A kinetically mixed dark gauge boson
   - Interplay between EWPMs, Drell-Yan production and Higgs exotic decays

3. Gauging the $L_\mu - L_\tau$ number
   - Role of neutrino experiments to probe new $Z'$ gauge bosons
     (past: CCFR, future: LBNE)

Exotic decays of the 125 GeV Higgs boson
- D. Curtin, R. Essig, S.G., P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen,
- D. Curtin, R. Essig, S.G., J. Shelton, 14xx.xxxx

Dressing $L_\mu - L_\tau$ in color
- W. Altmannshofer, S.G., M. Pospelov, I. Yavin, 1403.1269 + 1406.2332
The long quest for new forces

<table>
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- Naturally arising in **Grand Unified Theories**, models of **compositeness** or extra dimensions, ...

- In SUSY models, they can **address the μ problem**, they can give a sizable **tree level contribution** to the Higgs mass

- Used in **neutrino model building**, **dark matter model building**, **electroweak baryogenesis**, to solve the long standing discrepancy in \((g-2)_\mu\)
Z' searches @ colliders

Multi-hundred GeV/TeV - scale Z'

CMS PAS EXO-12-061

Z' searches @ colliders

Multi-hundred GeV/TeV - scale Z'

CMS PAS EXO-12-061

ATLAS-CONF-2013-066

CMS PAS B2G-12-007

ATLAS-CONF-2012-148

Dobrescu, Yu, 1306.2629

CMS Preliminary

L = \frac{g_B}{\mathcal{L}^2} Z'_{B\mu} q \bar{q} \gamma^\mu q

M_{Z'} [GeV]

10^{-7} [GeV]

10^{-5} [GeV]

10^{-4} [GeV]

10^{-3} [GeV]

10^{-2} [GeV]

10^{-1} [GeV]

1 [GeV]

10 [GeV]

100 [GeV]

1000 [GeV]

2000 [GeV]

3000 [GeV]

4000 [GeV]

5000 [GeV]

8 TeV

ee (19.6 fb^{-1}), \mu^+\mu^- (20.6 fb^{-1})

median expected

66% expected

95% expected

Z'_{SSM}

Z'_{0}

95% CL limit

\sigma(pp\rightarrow Z') \times BR(Z'\rightarrow q\bar{q}) [pb]

Expected

Expected ± 1σ

Expected ± 2σ

Observed limit

Z'_{SSM}

Z'_{SSM} th. uncert.

ATLAS Preliminary

\int \mathcal{L} dt = 19.5 fb^{-1} \sqrt{s} = 8 TeV

\tau_{had} \tau_{had} channel

Dobrescu, Yu, 1306.2629

CMS Preliminary

95% CL upper limit on \sigma_q

19.7 fb^{-1} at \sqrt{s} = 8 TeV

CMS PAS-B2G-12-007
Well-hidden gauge bosons

1. \( g, W, Z, \gamma \)
   Known forces

Vector portal

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

"Dark sectors" forces, particles, dark matter

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Well-hidden gauge bosons

1. Known forces

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

"Dark sectors" forces, particles, dark matter

2. Gauging \( L^-_\mu - L^-_\tau \) symmetry

Neutrino mass model building, Heeck, Rodejohann, 1107.5238

Quarks

- EM: \( \checkmark \)
- Weak: \( \checkmark \)
- Strong: \( \checkmark \)
- New Force?: -

Leptons

- EM: \( \checkmark \)
- Weak: \( \checkmark \)
- Strong: -
- New Force?: -

Neutrinos

- EM: -
- Weak: \( \checkmark \)
- Strong: -
- New Force?: \( \checkmark \)

Dark Matter?

- EM: -
- Weak: -
- Strong: -
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Kinetically mixed Z'  

- Higgs phenomenology  
- Drell-Yan production  
- EWPMs
A DM-motivated framework

DM does not interact "directly" with our SM world, but only "indirectly".

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

For a recent study, see Cline et al. 1405.7691.

They ultimately decay to SM states thanks to the kinetic mixing "portal".

Pospelov et al. 0711.4866
Feldman et al. 0702123
The simplified model

\[ \mathcal{L} = -\frac{1}{4} \hat{V}_{\mu\nu} \hat{V}^{\mu\nu} - \frac{1}{4} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} + \frac{\epsilon}{2 \cos \theta} \hat{V}_{\mu\nu} \hat{B}^{\mu\nu} + \]

\[ + \frac{1}{8} \frac{w^2 g_D^2}{v^2} (\hat{V}_{\mu\nu})^2 + \frac{1}{8} v^2 (-g \hat{W}_\mu^3 + g' \hat{B}_\mu)^2 + \]

\[ + \zeta |S|^2 |H|^2 \text{ (} + \text{ Interactions with Dark Matter)} \]

Breaking of the U(1)' symmetry in the dark sector \( S \rightarrow \langle S \rangle \equiv w \)

In GUT theories, the kinetic mixing operator is generated at one loop

\[ \epsilon \sim \frac{g_1 g'}{16 \pi^2} \log \left( \frac{M_1}{M_2} \right) \sim (10^{-3} - 10^{-4}) \log \left( \frac{M_1}{M_2} \right) \]
The simplified model

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\[ + \frac{1}{8} \omega^2 g_D^2 (\hat{V}_{\mu\nu})^2 + \frac{1}{8} \nu^2 (-g \hat{W}_\mu^3 + g' \hat{B}_\mu)^2 + \]

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If \( m_s, m_{DM} > m_{ZD} \), the \( Z_D \) pheno depends only on \( \epsilon, m_{ZD} \)

„Minimal model“

- \( m_{ZD} \ll m_Z \Rightarrow Z_D f \bar{f} \sim \epsilon Q \)
- \( m_{ZD} \sim m_Z \Rightarrow Z_D f \bar{f} \sim \epsilon (T_3 - Q s_W^2) \)

\[ \Gamma_{Z_D} \propto \epsilon^2 m_{ZD} \]

\( Z_D \) decays prompt \((c\tau < 1\mu m)\) for \( \epsilon \geq \text{few} \times 10^{-5} \) and \( m_{ZD} \geq 10 \text{ GeV} \)
Overview of the existing bounds for $Z_D$

\[ \mathcal{L} \supset \frac{\epsilon}{2 \cos \theta} \hat{B}_{\mu \nu} \hat{Z}_{\mu \nu} \]

"Minimal model"

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

Hook, Izaguirre, Wacker, 1006.0973

$e^+e^- \rightarrow \gamma \mu^+\mu^-$

1406.2980

Fixed target/beam dump experiments

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992
Overview of the existing bounds for $Z_D$.

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

Hook, Izaguirre, Wacker, 1006.0973

Something we can do here?

Fixed target/beam dump experiments

$e^+e^- \rightarrow \gamma \mu^+\mu^-$

1406.2980

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992
Here it comes the Higgs...

1. In the „Minimal model“:

\[ h Z Z_D \sim 2 \epsilon \tan \theta \frac{m_{ZD}^2}{v} \]

\[ h Z_D Z_D \sim \epsilon^2 \tan^2 \theta \frac{m_{ZD}^4}{m_Z^2 v} \]
Here it comes the Higgs...

1. In the „Minimal model“:

   \[ hZDZ_D \sim 2\epsilon \tan \theta \frac{m^2_{ZD}}{v} \]

2. In the „Next to Minimal model“:

   The Higgs will generically mix with the scalar responsible of \( U(1)' \) breaking

   \[ \zeta |S|^2 |H|^2 \]

   - Higgs „SM pheno“ changes:
     all Higgs couplings to SM fermions and gauge bosons will be suppressed by \( \cos(\alpha) \)
   - Set of new possible Higgs decays
Here it comes the Higgs...

1. In the „Minimal model“:

\[ h_{\mathcal{Z} \mathcal{Z}_{\mathcal{D}}} \sim 2\epsilon \tan \theta \frac{m_{\mathcal{Z} \mathcal{D}}}{v} \]

2. In the „Next to Minimal model“:

The Higgs will generically mix with the scalar responsible of U(1)' breaking

\[ \xi |S|^2 |H|^2 \]

- Higgs „SM pheno“ changes: all Higgs couplings to SM fermions and gauge bosons will be suppressed by \( \cos(\alpha) \)
- Set of new possible Higgs decays
"Hidden" exotic decays

Exotic decays will contribute to the Higgs width

太小，不能直接测量，除了在μ子对撞机上，可以通过共振产生辉光

\[ \Gamma_{h}^{\text{SM}}(125 \text{ GeV}) \sim 4.1 \text{ MeV} \]

现在

Off-shell interference in \( H \rightarrow ZZ \)

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

CMS PAS HIG-14-002

Based on
Caola, Melnikov, 1307.4935
Campbell, Ellis, Williams
1311.3589, 1312.1628
In general the extraction of the Higgs width at hadron colliders is difficult. It has to rely on some assumption (e.g. $\kappa_Z, \kappa_W \leq 1$).

Typically ~10% at 300 fb$^{-1}$, ~5% at 3000 fb$^{-1}$ LHC.

Small branching ratios are difficult to discover in this way. Importance of looking directly for Higgs exotic decays.
Minimal model and Higgs decays

See also Falkowski, Vega-Morales, 1405.1095

120 GeV < $m_{4\ell}$ < 130 GeV
No SFOS lepton pair with $m_{ll} < 12$ GeV

1. |$M_1 - m_Z$| < 15 GeV
2. |$M_1 - m_Z$| > 15 GeV

Bump hunt in the SFOS dilepton invariant mass

$$|M_2 - m_{Z_D}| < \begin{cases} 0.02M_2 & \text{(electrons)} \\ 2.5(0.026 \text{ GeV} + 0.013M_2) & \text{(muons)} \end{cases}$$

for muons, we are using the (pessimistic) mass resolution for forward muons: $\eta_{\mu} > 0.9$

BR($h\rightarrow ZZ_{D}$)~$10^{-4}$ can be tested at the HL-LHC
Drell-Yan production

Search for a light (5.5-14 GeV) pseudoscalar Higgs in the di-muon channel:
\[ \varepsilon < 2 \times 10^{-3} \text{ at } m_{Z_D} \sim 12 \text{ GeV}, \]

Hoenig, Samach, Tucker-Smith, 1408.1075

Recast CMS analysis
1310.7291, 7 TeV data

Leading (sub-leading) muon with \( p_T > 14 \) (9) GeV

Proposed search with 8 TeV data \( p_T > 20 \) (10) GeV

Assuming the same trigger threshold as for the 8 TeV

HLM-LHC


S.Gori
Because of kinetic mixing, the $Z_D$ mixes with the SM $Z$ boson

**Effects on the $Z$ phenomenology**

- **Tree level shift in the $Z$ mass:**
  
  $$m_Z^2 \sim m_{Z_0}^2 (1 + \epsilon^2 \tan^2 \theta)$$

- **Modification of the $Z$ couplings**
  
  $$\sim (Z f \bar{f})_{SM} \left(1 + \frac{\epsilon^2 \tan^2 \theta}{2} \cdot \frac{T_3 - Q(1 + \cos^2 \theta)}{T_3 - Q \sin^2 \theta} \right)$$
Complementarity with EWPMs

Because of kinetic mixing, the $Z_D$ mixes with the SM $Z$ boson.

**Effects on the $Z$ phenomenology**

- **Tree level shift in the $Z$ mass:**
  \[ m_Z^2 \sim m_{Z_0}^2 (1 + \epsilon^2 \tan^2 \theta) \]

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

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<tr>
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<th>Now</th>
<th>Future HL-LHC</th>
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<tr>
<td>$\delta m_W$</td>
<td>15 MeV</td>
<td>5 MeV</td>
</tr>
<tr>
<td>$\delta m_h$</td>
<td>0.24 GeV</td>
<td>0.05 GeV</td>
</tr>
<tr>
<td>$\delta m_t$</td>
<td>0.76 GeV</td>
<td>0.2 GeV</td>
</tr>
<tr>
<td>$\delta \Delta \alpha^{(5)}_{\text{had}}$</td>
<td>$10 \cdot 10^{-5}$</td>
<td>$4.7 \cdot 10^{-5}$</td>
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Babar expectation

Curtin, Essig, SG, Shelton, appearing soon
An un-explored "Next-to-Minimal" model

If $\epsilon$ is small ($<10^{-3}$) all constraints are washed out.

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

Responsible for the decay of $Z_D$ back to the SM

Free parameters:

$$m_{Z_D}, m_s, \epsilon, \kappa' \equiv \zeta \frac{m_h^2}{|m_h^2 - m_s^2|}$$

$$V(H, S) \supset \zeta |S|^2 |H|^2$$
An un-explored „Next-to-Minimal“ model

If $\epsilon$ is small ($<10^{-3}$) all constraints are washed out

Free parameters:

$\begin{align*}
  m_{ZD}, m_s, \epsilon, \kappa' \equiv \frac{m_h^2}{|m_h^2 - m_s^2|}
\end{align*}$

$m_{ZD}$, $m_s$, $\epsilon$, $\kappa'$

Recast CMS-ATLAS $h \rightarrow ZZ^* \rightarrow 4l$:

Because of mispairing:

$m_{ZD} = 40 \text{ GeV}$

$m_1$ in (40-120) GeV,

$m_2$ in (12-120) GeV

$m_{ZD} = 20 \text{ GeV}$

$\text{BR}(h \rightarrow Z_D Z_D \rightarrow 4l) \leq \text{few} \times 10^{-5}$, at best
A dedicated analysis

Two di-lepton resonances at the same mass;

ΔR_{μμ} > 0.05,
ΔR_{ee} > 0.02,

This corresponds to set a bound on the Higgs mixing with another scalar at the level of

κ' \sim \text{few} \cdot 10^{-5}

Only di-muon channel at low mass (< 10 GeV)

HL is crucial since the search is almost background free/statistically limited

See also CMS PAS HIG-13-010 for h → aa → 4μ with m_a < 2m_τ
Main limitation for the search of Higgs exotic decays:
soft objects coming from the decay of a (light) Higgs

Possible problem in triggering, especially in going to higher energies!

\[ p_T^j \lesssim 30 \text{ GeV} \]
Main limitation for the search of Higgs exotic decays:

soft objects coming from the decay of a (light) Higgs

\[ p_T^j \lesssim 30 \text{ GeV} \]

Possible problem in triggering, especially in going to higher energies!

In our four lepton case, we use 8 TeV thresholds: \( p_{Tl} > 20 \) (10) GeV

Still, even raising a bit the thresholds would not affect much the reach.
What if the kinetic mixing is very small \( \epsilon \lesssim 10^{-4} - 10^{-5} \) and \( Z_D \) does not decay promptly?

Probed by \( h \to Z_D Z_D \)

Accessible?
A non-promptly decaying $Z_D$

What if the kinetic mixing is very small $\epsilon \lesssim 10^{-4} - 10^{-5}$ and $Z_D$ does not decay promptly?

Let's estimate...

Accessible?

Probed by $h \rightarrow Z_D Z_D$

The BR we measure

$$BR_{\text{eff}} = BR(h \rightarrow Z_D Z_D) \cdot P(L, \sqrt{s}, m_{Z_D}, \epsilon)$$

Probabilty for $Z_D$ to decay inside the detector
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### A anomaly free

\[ \tilde{L}_\mu - L_\tau \] \text{ gauge symmetry}

- \((g-2)_\mu\)
- LHC bounds
- EWPMs
- Trident di-muon production
A well motivated gauge symmetry

Lμ - Lτ gauge symmetry
(one of the few anomaly free)

1. It can generate a hierarchy between neutrino masses and mixing, in agreement with data

- Before breaking the gauge symmetry:
  \[ \Theta_{23} = \text{maximal}, \ \Theta_{13} = \Theta_{12} = 0, \text{ and} \]
  two neutrinos are degenerate in mass.

- In seesaw models, with the breaking of the gauge symmetry
  \[ \Theta_{13}, \ \Theta_{12} \text{ non zero and (small) splitting between} \]
  the two degenerate neutrinos

2. It can address the anomaly in the flavor violating B-meson decay: \[ B \rightarrow K^* \mu\mu: \sim 3.5\sigma \]

See e.g.
Salvioni, Strumia, Villadoro, Zwirner, 0911.1450

See e.g.
Heeck, Rodejohann,
1107.5238

Altmannshofer, SG, Pospelov, Yavin, 1403.1269
A well motivated gauge symmetry

"Benchmark theory"

$L_\mu - L_\tau$ gauge symmetry
(one of the few anomaly free)

1. It can generate a hierarchy between neutrino masses and mixing, in agreement with data
   - Before breaking the gauge symmetry: $\Theta_{23} = \text{maximal}, \Theta_{13} = \Theta_{12} = 0$, and two neutrinos are degenerate in mass.
   - In seesaw models, with the breaking of the gauge symmetry $\Theta_{13}, \Theta_{12}$ non zero and (small) splitting between the two degenerate neutrinos

2. It can address the anomaly in the flavor violating B-meson decay: $B \rightarrow K^* \mu\mu$: $\sim 3.5\sigma$
   Altmannshofer, SG, Pospelov, Yavin, 1403.1269

3. It can address the anomaly in $(g-2)_\mu$: $3.2\sigma$

See e.g. Salvioni, Strumia, Villadoro, Zwirner, 0911.1450
Measurement of the branching ratio of $Z \rightarrow 4l$

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

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

To be compared to the measured value

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

ATLAS (CONF-2013-055), see also CMS (1210.3844)
A LHC multi-lepton opportunity

Measurement of the branching ratio of $Z\rightarrow4\ell$

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

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$$BR(Z\rightarrow4\ell)_{\text{exp}}=(4.2\pm0.4)\times10^{-6}$$

ATLAS (CONF-2013-055), see also CMS (1210.3844)

Our $Z'$ contribute to the four muon bin:
78 events expected and 77 observed

See also
Harigaya et.al.
1311.0870
Early 90s experiments:

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

**Difficult measurement since small cross section:**
~5-6 orders of magnitude smaller than the inclusive neutrino-nucleus cross sec.
Early 90s experiments:

- First observed by CHARMIIE 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

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<th>SM</th>
<th>Only W</th>
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<td>37.0 ± 12.4</td>
<td>45.3 ± 2.3</td>
<td>78.1 ± 3.9</td>
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- No conclusive evidence from the NuTeV experiment at Fermilab (Phys.Rev.D 61, 092001)

Difficult measurement since small cross section:
~5-6 orders of magnitude smaller than the inclusive neutrino-nucleus cross sec.

SM prediction is ~60% W contribution

$$\frac{\sigma_{\text{CHARMIIE}}}{\sigma_{\text{SM}}} = 1.58 \pm 0.57, \quad \frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28.$$
The $Z'$ contribution interferes always **constructively** with the SM $W$ contribution.

- For $m_{Z'} \gtrsim 5$ GeV, four fermion interaction approximation

$$\frac{\sigma}{\sigma_{SM}} \approx 1 + \left(1 + 4s_W^2 + 2(g')^2v^2/m_{Z'}^2\right)^2$$

- For $m_{Z'} \lesssim 5$ GeV, computation of the full $2 \rightarrow 4(3)$ process

In particular, in the limit $m_{Z'} \ll m_\mu$

$$\sigma^{(Z')} \sim \frac{1}{m_\mu^2} \frac{7g'^4\alpha}{72\pi^2} \log \left(\frac{m_\mu^2}{m_{Z'}^2}\right)$$

Threshold for CCFR with $\sim 160$ GeV neutrinos

$$\sigma_{CCFR}/\sigma_{SM} = 0.82 \pm 0.28$$

Altmannshofer, SG, Pospelov, Yavin, 1406.2332
The Z' contribution interferes always constructively with the SM W contribution

- For \( m_{Z'} \gtrsim 5 \text{ GeV} \), four fermion interaction approximation

\[
\frac{\sigma}{\sigma_{\text{SM}}} \approx \frac{1 + (1 + 4s_W^2 + 2(g')^2v^2/m_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}
\]

- For \( m_{Z'} \lesssim 5 \text{ GeV} \), computation of the full \( 2 \rightarrow 4(3) \) process

In particular, in the limit \( m_{Z'} \ll m_\mu \)

\[
\sigma^{(Z')} \approx \frac{1}{m_\mu^2} \frac{7g'^4\alpha}{72\pi^2} \log \left( \frac{m_\mu^2}{m_{Z'}^2} \right)
\]

Threshold for CCFR with \( \sim 160 \text{ GeV} \) neutrinos

\( (37 \pm 12.4 \text{ events}) \)

Altmannshofer, SG, Pospelov, Yavin, 1406.2332
Great future prospects

Example for 5 GeV neutrinos on Argon

Great opportunity for low energy neutrino experiments!

\[
\frac{\sigma}{\sigma_{SM}} \approx \frac{1 + \left(1 + 4s_{W}^2 + 2(g')^2v^2/m_{Z'}^2\right)^2}{1 + (1 + 4s_{W}^2)^2}
\]
What are the prospects for measuring this process at the near detector of LBNE?

- Huge detector: 18ton Argon
- Huge number of protons on target: $6 \times 10^{20}$ POT/year
- Huge rate for the charge current: \(\sim 26\, M/\text{year}\)
- Neutrinos with a smaller energy: (2-5)GeV

Assumed CC events: \(\sim 236\, \text{K/ton} / 10^{20}\, \text{POT}\)

This corresponds to \(\sim 100\) signal events/year
An interesting analysis

Work in progress...
An interesting analysis

Work in progress...

Charm background

$$\nu + (d, s) \rightarrow \mu^- + c$$

should come at higher invariant masses

From CCFR, Phys.Rev.Lett. 66, 3117
Great opportunity to test new light forces using multi-lepton signatures!

- Interesting possibility of testing $Z_D$ gauge bosons using new Higgs boson decays
- We will incredibly benefit from the High-Luminosity LHC, since the signature is very clean
- We can set bounds $\text{BR}(h \rightarrow Z_D Z_D \rightarrow 4l) \sim \text{few} \times 10^{-7}$!

The new force will generically couple to the neutrinos.

Possibility of totally closing the $(g-2)_\mu$ window at the LBNE.
What we will gain on the Higgs exo. decays going to higher energy?  

**Huge productions!**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sqrt{s}=14$ TeV</th>
<th>$\sqrt{s}=33$ TeV</th>
<th>$\sqrt{s}=100$ TeV</th>
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<tbody>
<tr>
<td>ggF</td>
<td>50.4 pb</td>
<td>178 pb</td>
<td>740 pb</td>
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<tr>
<td>VBF</td>
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<td>17 pb</td>
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<tr>
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</tr>
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<td>ttH</td>
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<td>HH</td>
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Higgs cross section working group
Going to higher energy?

What we will gain on the Higgs exo. decays going to higher energy?

Huge productions!

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1. Difficult decay modes
Benefit from having „accessible“ Higgs production in association with tops, Z bosons, ...

2. Clean decay modes
At the high-lumi LHC, we cannot expect to be able to put bounds on \( \text{BR}_{\text{exo}} \leq 10^{-6} - 10^{-7} \)
because of the lack of statistics
What we will gain on the Higgs exo. decays going to higher energy?

**Huge productions!**

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Higgs cross section working group

1. **Difficult decay modes**
   Benefit from having „accessible“ Higgs production in association with tops, Z bosons, ...

![Graph showing Higgs mixing case, Br(h→ZZ→4l) limit at $\sqrt{s} = 14$ TeV and $\sqrt{s} = 100$ TeV](image)
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

\[
\begin{align*}
  h &\rightarrow 2 \\
  h &\rightarrow 2 \rightarrow 3 \\
  h &\rightarrow 2 \rightarrow 3 \rightarrow 4 \\
  h &\rightarrow 2 \rightarrow (1+3) \\
  h &\rightarrow 2 \rightarrow 4 \\
  h &\rightarrow 2 \rightarrow 4 \rightarrow 6 \\
  h &\rightarrow 2 \rightarrow 6 \\
  h \rightarrow \text{MET} &\rightarrow \gamma + \text{MET} \\
  h \rightarrow 4b &\rightarrow 2 \gamma + \text{MET} \\
  h \rightarrow 2b2\tau &\rightarrow 4 \gamma + \text{MET} \\
  h \rightarrow 2b2\mu &\rightarrow 2 \gamma + \text{MET} \\
  h \rightarrow 4J &\rightarrow \text{one lepton jet} \\
  h \rightarrow 2\gamma2j &\rightarrow \text{two lepton jets} \\
  h \rightarrow 4\gamma &\rightarrow \text{bb} + \text{MET} \\
  h \rightarrow ZZ_D \rightarrow 4l &\rightarrow \tau\tau + \text{MET}
\end{align*}
\]
Z' “indirect” searches

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

Is the ew sector of nature now complete?

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

Last ingredient to complete the SM: the Higgs mass

p-value = 0.21

My fit, following the Gfitter procedure
Higgs width: direct measurement

Very interesting new CMS measurement

In a nutshell:

\[
\sigma_{gg\to H\to ZZ}^{\text{on-peak}} = \frac{k_g^2 k_Z^2}{r} \left( \sigma \cdot \text{BR} \right)_{\text{SM}} \equiv \mu (\sigma \cdot \text{BR})_{\text{SM}} \\
\sigma_{gg\to H\to ZZ}^{\text{off-peak}} \frac{dm_{ZZ}}{d\Gamma} = k_g^2 k_Z^2 \sigma_{gg\to H\to ZZ}^{\text{off-peak, SM}} \frac{dm_{ZZ}}{d\Gamma} = \mu r \sigma_{gg\to H\to ZZ}^{\text{off-peak, SM}} \frac{dm_{ZZ}}{d\Gamma}
\]

\[\begin{align*}
k_g &= g_{ggH}/g_{ggH}^{\text{SM}} \\
k_Z &= g_{HZZ}/g_{HZZ}^{\text{SM}} \\
r &= \Gamma_H/\Gamma_H^{\text{SM}}
\end{align*}\]

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

Combining the 4l and the 2l2v channels
Present bound

\[ h \xrightarrow{Z, \ell} \text{leptons} \]


Bound from the CMS, ATLAS \( h \to ZZ^* \) analysis

\[ \text{BR}(h \to ZZ_D) \sim 10^{-3} \text{ are already probed with the present (un-dedicated) (7+8) TeV LHC searches} \]
Bounds coming from SM $h \rightarrow ZZ^* \rightarrow 4l$ searches at the LHC


Because of mispairing:

$m_{ZD} = 20\text{ GeV}$

$40\text{ GeV} < m_1 < 120\text{ GeV}$,

$12\text{ GeV} < m_2 < 120\text{ GeV}$

To compare to the experimental data:

CMS PAS HIG-13-002
Setting bounds on $Z_D Z_D$: present

Bounds coming from SM $h \rightarrow ZZ^* \rightarrow 4l$ searches at the LHC


Because of mispairing:

$m_{ZD} = 20$ GeV

$m_{ZD} = 40$ GeV

40 GeV < $m_1$ < 120 GeV,
12 GeV < $m_2$ < 120 GeV

To compare to the experimental data:

For $m_{ZD} > 40$ GeV:
$m_{ZD} \pm 5$ GeV

CMS PAS HIG-13-002
Setting bounds on $Z_D$: present

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Experimental data:

For $m_{Z_D} > 40 \text{ GeV}$:

$m_{Z_D} \pm 5 \text{ GeV}$
Importance of detector design

Reach at 100 TeV, with 3000 fb$^{-1}$

$h \to ZZ_D \to 4l$

$h \to Z_D Z_D \to 4l$

Increased lepton acceptance $|\eta|<4$

Improved mass resolution

$|M_{ll} - m_{Z_D}| < 0.015 M_{ll}$
Importance of detector design

Reach at 100 TeV, with 3000 fb$^{-1}$

$h \rightarrow Z_{ZD} \rightarrow 4l$

$h \rightarrow Z_{ZD} Z_{ZD} \rightarrow 4l$

Increased lepton acceptance $|\eta| < 4$

Improved mass resolution

$|M_{ll} - m_{ZD}| < 0.015 M_{ll}$
Importance of detector design

Reach at 100 TeV, with 3000 fb$^{-1}$

$h \rightarrow Z_{D} Z_{D} \rightarrow 4l$

Increased lepton acceptance $|\eta|<4$

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$|M_{\ell \ell} - m_{Z_D}| < 0.015 M_{\ell \ell}$
Bound from the CMS, ATLAS $h \rightarrow ZZ^*$ analysis

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

\[ h \rightarrow ZZ_D, \ h \rightarrow Z_DZ_D \]

### Exotic scorecard

<table>
<thead>
<tr>
<th></th>
<th>jj</th>
<th>bb</th>
<th>(\tau\tau)</th>
<th>ll</th>
<th>(\nu\nu)</th>
</tr>
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</table>

### Prospects?

## Initial attempt for \( h \rightarrow Z_DZ_D \) (by theorists)

<table>
<thead>
<tr>
<th>Decay Mode ( \mathcal{F}_i )</th>
<th>Projected/Current 2(\sigma) Limit on (\text{BR}(\mathcal{F}_i)) 7+8 [14] TeV</th>
<th>Production Mode</th>
<th>(\frac{\text{BR}(\mathcal{F}_i)}{\text{BR}(\text{non-SM})})</th>
<th>Limit on (\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{BR(\text{non-SM})}) 7+8 [14] TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(jjjj)</td>
<td>(\geq 1) [0.1*]</td>
<td>(W)</td>
<td>0.25</td>
<td>(\geq 1) [0.4*]</td>
</tr>
<tr>
<td>(llll)</td>
<td>(4 \cdot 10^{-5})</td>
<td>(G)</td>
<td>0.09</td>
<td>(4 \cdot 10^{-4})</td>
</tr>
<tr>
<td>(jj\mu\mu)</td>
<td>(0.002 - 0.008) [(5 - 20) (\cdot 10^{-4})]</td>
<td>(G)</td>
<td>0.15</td>
<td>(0.01 - 0.06) [(0.003 - 0.01)]</td>
</tr>
<tr>
<td>(bb\mu\mu)</td>
<td>((2 - 7) \cdot 10^{-4}) [(0.6 - 2) (\cdot 10^{-4})]</td>
<td>(G)</td>
<td>0.015</td>
<td>(0.01 - 0.05) [(0.003 - 0.01)]</td>
</tr>
</tbody>
</table>

Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, Mckeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992