New Physics at the LHC

Tilman Plehn

Universität Heidelberg

Frascati, May 2016
Beyond the Standard Model

What is the Standard Model?

– a gauge theory with the group structure $SU(3) \otimes SU(2) \otimes U(1)$
– massless $SU(3)$ and $U(1)$ gauge bosons
– massive electroweak gauge bosons
– single light Higgs scalar
– Dirac fermions in doublets and with masses equal to Yukawas
– generation mixing in quark and neutrino sector

$\Rightarrow$ QFT defined by particle content and (gauge) interactions
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⇒ QFT defined by particle content and (gauge) interactions

More physics at higher scales

– renormalizable Lagrangian [all operators to D4]
– neutrino masses? [see-saw at $10^{11}$ GeV?]
– flavor physics? [new operators above $10^4$ GeV?]
– dark matter? [only solid evidence for new physics]
– gravity? [mostly negligible, and unrenormalizable in usual sense]
⇒ general effective–theory Lagrangian with those interactions and particles
⇒ cutoff scale built in, size of $\Lambda$ negotiable
⇒ who the hell cares....???
Beyond the Standard Model

...theorists care more than even [Higgs discovery]

- top loop in Higgs self energy $\Sigma$

$$\Sigma \sim - \left( \frac{g m_t}{v} \right)^2 \int \frac{d^4 q}{(2\pi)^4} \frac{(p + m_t)(q + m_t)}{[q^2 - m_t^2][(q + p)^2 - m_t^2]} \sim - \frac{1}{(4\pi)^2} \left( \frac{g m_t}{v} \right)^2 \Lambda^2 + \cdots$$

- sum to Higgs–mass correction

$$\frac{1}{p^2 - m_H^2} \rightarrow \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \sum_j \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \sum_j \frac{1}{p^2 - m_H^2} + \cdots$$

$$= \frac{1}{p^2 - m_H^2} \sum_{j=0}^{\infty} \left( \frac{\Sigma}{p^2 - m_H^2} \right)^j = \frac{1}{p^2 - m_H^2} \left( 1 - \sum \frac{\Sigma}{m^2 - m_H^2} \right)$$

= \frac{1}{p^2 - m_H^2 - \Sigma}

- and see the desaster after collecting all loop functions

$$m_H^2 \rightarrow m_H^2 - \frac{3g^2}{32\pi^2} \frac{\Lambda^2}{m_W^2} \left[ m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 \right] + \cdots$$

$\Rightarrow$ Higgs mass including loops wants to be cutoff scale $\Lambda$

$\Rightarrow$ effective Standard–Model destabilized [Higgs wants to be at $\Lambda$, but does not function there]

$\Rightarrow$ hierarchy problem
Beyond the Standard Model

Starting from data...

...after the Higgs discovery
...and requiring high–scale physics

– Higgs mass driven to cutoff of effective Standard Model

⇒ easy solution: counter term to cancel loops ⇒ artificial, unmotivated, ugly
⇒ or new physics at TeV scale: supersymmetry
   extra dimensions
   little Higgs (Goldstone Higgs)
   Higgsless, composite Higgs, TopColor,
   YourFavoriteNewPhysics...

⇒ typically cancellation by new particles or discussing away high scale

⇒ beautiful concepts, but problematic at TeV scale [data seriously in the way]

⇒ new physics models in baroque state
Strategies

**Theory tool box**

- Lagrangian language established by Higgs discovery
- full new physics model  [built to solve problems]
- simplified models  [capturing experimental features, theoretically poor]
- effective field theory  [symmetries and particles fixed, non-renormalizable operators]
- matter of convenience and taste

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## Strategies

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My take on all those 750 GeV papers

- open questions due to limited significance
- general problem: signal rate large
- largely EFT exercise
- dimension-5 operators $X G^{\mu\nu} G_{\mu\nu}$ and $X A^{\mu\nu} A_{\mu\nu}$ → avoid di-jet constraints
- gauge invariant $X B^{\mu\nu} B_{\mu\nu}$ and $X W^{\mu\nu} W_{\mu\nu}$ → avoid $VV$ constraints
- no clear link to other data

⇒ great to play with, but only for fun, please
Hooperon — the best dark matter has to offer

Galactic center excess in FERMI data, by theorists [Goodenough & Hooper (unpublished? 2009)]

- look at gamma ray spectrum in galaxy
- remove all foregrounds
- check radial distributions
- explain by annihilating DM into photons
- $m_\chi \sim 25 \ldots 30$ GeV from spectrum

![Graph showing gamma ray spectrum](image-url)
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In conclusion, we have studied the angular distribution and energy spectrum of gamma rays measured by the Fermi Gamma Ray Space Telescope in the region surrounding the Galactic Center, and find that this data is well described by a scenario in which a 25-30 GeV dark matter particle, distributed with a halo profile slightly steeper than NFW ($\gamma = 1.1$), is annihilating with a cross section within a factor of a few of the value predicted for a thermal relic.
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- analysis with all uncertainties
- fit without dark matter not good
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- even better with modified NFW contribution

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of the analysis that has previously not been employed. After subtraction of interstellar emission and point sources, an extended residual is present. It can be fit with a centrally peaked profile with a specified spectral model, but not all of the positive residual is accounted for by such a model. Because of the uncertain nature of the properties of the positive residual due to the IEM and point source determination, a precise physical interpretation of its origin is premature.
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Kind of confirmed by FERMI

- analysis with all uncertainties
- fit without dark matter not good
- improved with NFW contribution
- even better with modified NFW contribution
- different DM candidates

⇒ DM model playground
Higgs couplings


- or: all couplings proportional to masses?
- assume: narrow CP-even scalar
  
  Standard Model operators

- total production/decay rates only
- Lagrangian

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W g_m W H \, W^\mu W_\mu + \Delta_Z \frac{g}{2 c_w} m_Z H Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \frac{m_f}{v} H (\bar{f}_R f_L + \text{h.c.}) 
+ \Delta_g F_G \frac{H}{v} G_{\mu\nu} G^{\mu\nu} + \Delta_A F_A \frac{H}{v} A_{\mu\nu} A^{\mu\nu} + \text{invisible + unobservable}
\]

- electroweak renormalizability through some UV completion
- QCD renormalizability not an issue

\[
\begin{align*}
  &gg \rightarrow H \\
  &qq \rightarrow qqH \\
  &gg \rightarrow ttH \\
  &qq' \rightarrow VH \\
  &g_{HXX} = g_{HXX}^{\text{SM}} (1 + \Delta_X)
\end{align*}
\]

\[
\begin{align*}
  &H \rightarrow ZZ \\
  &H \rightarrow WW \\
  &H \rightarrow b\bar{b} \\
  &H \rightarrow \tau^+ \tau^- \\
  &H \rightarrow \gamma\gamma
\end{align*}
\]
Higgs couplings

**Agnostic: why super-simple SM-Higgs sector?**

- or: all couplings proportional to masses?
- assume: narrow CP-even scalar
  Standard Model operators
- total production/decay rates only
- Lagrangian

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\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \, g m_W H \, W^\mu W_\mu + \Delta_Z \, \frac{g}{2 c_w} m_Z H \, Z^\mu Z_\mu - \sum_{\tau, b, t} \Delta_f \, \frac{m_f}{v} H (\bar{f}_R f_L + \text{h.c.}) \\
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\]

**Total width**

- coupling extraction impossible without width assumption
- observed partial widths:

\[
N = \sigma \, BR \propto \left( \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}^\text{obs}} \right) \left( \frac{g^2}{\sqrt{\Gamma_{\text{tot}}}} \right) \sim \frac{g^4}{g^2 \sum \Gamma_i(g^2)} + \Gamma_{\text{unobs}}
\]

\[
ge^{2 \rightarrow 0} = 0
\]

gives constraint from \[\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \rightarrow \Gamma_H |_{\text{min}}\]
- \(WW \rightarrow WW\) unitarity: \[g_{WWH} \lesssim g_{WWH}^{\text{SM}} \rightarrow \Gamma_H |_{\text{max}} \quad [\text{HiggsSignals}]\]
- our assumption \[\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j\] [plus generation universality]
Higgs couplings now and in the future

**Run I legacy**  [Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

- assume SM-like  [secondary solutions possible]
- SFitter: correct theory uncertainties

\[ L = 4.5-5.1(7 \text{ TeV}) + 19.4-20.3(8 \text{ TeV}) \text{ fb}^{-1}, 68\% \text{ CL: ATLAS + CMS} \]

\[ g_x = g_{x_{\text{SM}}} (1 + \Delta x) \]
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![Graph showing Higgs couplings]

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⇒ Standard Model within 25%
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**Future**  [SFitter; Cranmer, Kreiss, Lopez-Val, TP]

- LHC extrapolations unclear
- systematic/theory uncertainties large
- $e^{+} e^{-}$ linear collider much better
  unobserved decays avoided
  width measured from $\sigma_{ZH}$
  $H \to c\bar{c}$ accessible
  invisible decays hugely improved
  QCD theory error bars avoided
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  $\Rightarrow$ Higgs factory case obvious
Higgs couplings now and in the future

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$\Rightarrow$ Standard Model within 25%

Three major problems with approach

1– theory: no electroweak renormalizability
2– experiment: no kinematic distributions
3– phenomenology: no link to other sectors
D6 Higgs operators

Higgs sector effective field theory

- set of Higgs operators  [renormalizable, #1 solved]

\[ O_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \]

\[ O_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]

\[ O_{\phi,1} = (D_\mu \phi)^\dagger \phi^\dagger (D^\mu \phi) \]

\[ O_{\phi,3} = \frac{1}{3} \left( \phi^\dagger \phi \right)^3 \]

\[ O_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]

\[ O_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \]

\[ O_{\phi,2} = \frac{1}{2} \partial^\mu \left( \phi^\dagger \phi \right) \partial_\mu \left( \phi^\dagger \phi \right) \]

\[ O_{\phi,4} = (D_\mu \phi)^\dagger \left( D^\mu \phi \right) \left( \phi^\dagger \phi \right) \]
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\[ O_{\text{GG}} = \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \quad O_{\text{WW}} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \quad O_{\text{BB}} = \cdots \]

\[ O_{\text{BW}} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \quad O_{\text{W}} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \quad O_{\text{B}} = \cdots \]

\[ O_{\phi,1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) \quad O_{\phi,2} = \frac{1}{2} \partial^\mu \left( \phi^\dagger \phi \right) \partial_\mu \left( \phi^\dagger \phi \right) \]

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- relevant part after equation of motion, etc

\[ \mathcal{L}^{\text{HVW}} = - \frac{\alpha_s V}{8\pi} \frac{f_g}{\Lambda^2} O_{\text{GG}} + \frac{f_{\text{BB}}}{\Lambda^2} O_{\text{BB}} + \frac{f_{\text{WW}}}{\Lambda^2} O_{\text{WW}} + \frac{f_B}{\Lambda^2} O_{\text{B}} + \frac{f_W}{\Lambda^2} O_{\text{W}} + \frac{f_{\phi,2}}{\Lambda^2} O_{\phi,2} \]
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O_{BW} &= \phi^\dagger \hat{B}_{\mu \nu} \hat{W}^{\mu \nu} \phi & O_{W} &= (D_\mu \phi)^\dagger \hat{W}^{\mu \nu} (D_\nu \phi) & O_{B} &= \cdots \\
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\]

- Higgs couplings to SM particles [derivatives = momentum, #2 solved]

\[
L^{HVV} = g_g H G^a_{\mu \nu} G^a_{\mu \nu} + g_\gamma H A_{\mu \nu} A^{\mu \nu} \\
+ g_{Z}^{(1)} Z_{\mu \nu} Z^\mu \partial^\nu H + g_{Z}^{(2)} H Z_{\mu \nu} Z^{\mu \nu} + g_{Z}^{(3)} H Z_{\mu} Z^\mu \\
+ g_{W}^{(1)} \left( W_\mu^+ W^-_\mu \partial^\nu H + \text{h.c.} \right) + g_{W}^{(2)} H W^+_{\mu \nu} W^-_{\mu \nu} + g_{W}^{(3)} H W^+_{\mu} W^-_{\mu} + \cdots
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\[ + g_Z^{(1)} Z_{\mu,\nu} Z^{,\mu,\nu} H + g_Z^{(2)} H Z_{\mu,\nu} Z^{,\mu,\nu} + g_Z^{(3)} H Z_{\mu} Z^{,\mu} \]
\[ + g_W^{(1)} \left( W^{+}_{\mu,\nu} W^{-\mu,\nu} H + \text{h.c.} \right) + g_W^{(2)} H W^{+}_{\mu,\nu} W^{-\mu,\nu} + g_W^{(3)} H W^{+}_{\mu} W^{-\mu} + \cdots \]

- plus Yukawa structure \( f_{\tau,b,t} \)
- 9 operators for Run I data
D6 Higgs operators

Higgs sector effective field theory

- set of Higgs operators  [renormalizable, #1 solved]

\[
\begin{align*}
\mathcal{O}_{GG} &= \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \\
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\mathcal{O}_{\phi,4} &= (D_\mu \phi)^\dagger (D^\mu \phi) (\phi^\dagger \phi)
\end{align*}
\]

- linked to Higgs couplings

\[
\begin{align*}
g_g &= \frac{f_{GG} v}{\Lambda^2} \equiv - \frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \\
g_g^{(1)} &= \frac{g^2 v}{2\Lambda^2} \frac{c_w^2 f_W + s_w^2 f_B}{2c_w^2} \\
g_g^{(2)} &= - \frac{g^2 v}{2\Lambda^2} \frac{s_w^4 f_{BB} + c_w^4 f_{WW}}{2c_w^2} \\
g_g^{(3)} &= M_Z^2 (\sqrt{2} G_F)^{1/2} \left( 1 - \frac{v^2}{2\Lambda^2} f_{\phi,2} \right) \\
g_g^{(3)} &= M_W^2 (\sqrt{2} G_F)^{1/2} \left( 1 - \frac{v^2}{2\Lambda^2} f_{\phi,2} \right) \\
g_f &= - \frac{m_f}{v} \left( 1 - \frac{v^2}{2\Lambda^2} f_{\phi,2} \right) + \frac{v^2}{\sqrt{2\Lambda^2}} f_f 
\end{align*}
\]
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- set of Higgs operators [renormalizable, #1 solved]

\[ O_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \]
\[ O_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{\phi,1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) \]
\[ O_{\phi,3} = \frac{1}{3} (\phi^\dagger \phi)^3 \]
\[ O_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{BB} = \cdots \]
\[ O_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \]
\[ O_{B} = \cdots \]
\[ O_{\phi,2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]
\[ O_{\phi,4} = (D_\mu \phi)^\dagger (D^\mu \phi) (\phi^\dagger \phi) \]

Run 1 legacy

- kinematics: \( p_T, \nu, \Delta \phi_{jj} \) [remember #2]
D6 Higgs operators

**Higgs sector effective field theory**

- set of Higgs operators  [renormalizable, #1 solved]

\[ O_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \]
\[ O_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{\phi,1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) \]
\[ O_{\phi,3} = \frac{1}{3} \left( \phi^\dagger \phi \right)^3 \]
\[ O_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{BB} = \cdots \]
\[ O_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \]
\[ O_{B} = \cdots \]
\[ O_{\phi,2} = \frac{1}{2} \partial^\mu \left( \phi^\dagger \phi \right) \partial_\mu \left( \phi^\dagger \phi \right) \]
\[ O_{\phi,4} = (D_\mu \phi)^\dagger \left( D^\mu \phi \right) \left( \phi^\dagger \phi \right) \]

**Run 1 legacy**

- kinematics: \( p_T, \nu, \Delta \phi_{jj} \)  [remember #2]
**D6 Higgs operators**

### Higgs sector effective field theory

- set of Higgs operators [renormalizable, #1 solved]

$$
\begin{align*}
\mathcal{O}_{GG} & = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \\
\mathcal{O}_{BW} & = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \\
\mathcal{O}_{\phi,1} & = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) \\
\mathcal{O}_{\phi,3} & = \frac{1}{3} (\phi^\dagger \phi)^3 \\
\mathcal{O}_{WW} & = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \\
\mathcal{O}_{\phi,2} & = \frac{1}{2} \partial^\mu \left( \phi^\dagger \phi \right) \partial_\mu \left( \phi^\dagger \phi \right) \\
\mathcal{O}_{\phi,4} & = (D_\mu \phi)^\dagger (D^\mu \phi) \left( \phi^\dagger \phi \right)
\end{align*}
$$

### Run 1 legacy

- kinematics: $p_T, \nu, \Delta \phi_{jj}$ [remember #2]
- with impact...

![Graph showing the relationship between $f_B/\Lambda^2$ and $f_W/\Lambda^2$.](image)
D6 Higgs operators

Higgs sector effective field theory

- set of Higgs operators [renormalizable, #1 solved]

\[ \mathcal{O}_{GG} = \phi^\dagger \phi G^{a}_{\mu\nu} G^{a\mu\nu} \]
\[ \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ \mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) \]
\[ \mathcal{O}_{\phi,3} = \frac{1}{3} (\phi^\dagger \phi)^3 \]

\[ \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ \mathcal{O}_{BB} = \cdots \]
\[ \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D^\nu \phi) \]
\[ \mathcal{O}_{B} = \cdots \]
\[ \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]
\[ \mathcal{O}_{\phi,4} = (D_\mu \phi)^\dagger (D^\mu \phi) (\phi^\dagger \phi) \]

Run 1 legacy

- kinematics: \( p_{T,V}, \Delta \phi_{jj} \) [remember #2]
- with impact...
  ...in last bin

![Image of a scatter plot with f_W/\Lambda^2 and f_B/\Lambda^2 in the x and y axes respectively, with contour lines indicating data points.](image-url)
D6 Higgs operators

Higgs sector effective field theory

- set of Higgs operators [renormalizable, #1 solved]

\[ O_{GG} = \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \]
\[ O_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{\mathcal{W}}^{\mu\nu} \phi \]
\[ O_{\phi,1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) \]
\[ O_{\phi,3} = \frac{1}{3} (\phi^\dagger \phi)^3 \]
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\[ O_{B} = \cdots \]
\[ O_{\phi,2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]
\[ O_{\phi,4} = (D_\mu \phi)^\dagger (D^\mu \phi) (\phi^\dagger \phi) \]

Run 1 legacy

- kinematics: \( p_T, V, \Delta \phi_{jj} \) [remember #2]

- with impact...

...in last bin

⇒ Run I sensitivity limited

\[ \Lambda / \sqrt{|f|} \text{ [TeV]} \]
\[ L = 4.5-5.1(7 \text{ TeV}) + 19.4-20.3(8 \text{ TeV}) \text{ fb}^{-1}, \text{ 68\% CL: ATLAS + CMS} \]
D6 Higgs-gauge operators

Triple gauge couplings

- one more Higgs-gauge operator \([#3 \text{ solved}]\)

\[
O_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu}(D_\nu \phi)
\]

\[
O_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu}(D_\nu \phi)
\]

\[
O_{WW} = \text{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho\right)
\]

- kinematics: \(p_T, \ell\) in \(VV\) production

![Graph showing events/bin vs. \(p_{T\text{lead}}\) (GeV) with SM WW, data, and background lines, and legends for SM WW, Background, \(f_W/\Lambda^2 = 25\text{TeV}^{-2}\), \(f_B/\Lambda^2 = 25\text{TeV}^{-2}\), \(f_{WWW}/\Lambda^2 = 25\text{TeV}^{-2}\), and Data.]
D6 Higgs-gauge operators

**Triple gauge couplings**

- one more Higgs-gauge operator \([#3 \text{solved}]\)

\[
\begin{align*}
O_W &= (D_\mu \phi) \dagger \hat{W}^{\mu \nu} (D_\nu \phi) \\
O_B &= (D_\mu \phi) \dagger \hat{B}^{\mu \nu} (D_\nu \phi) \\
O_{WW} &= \text{Tr} \left( \hat{W}_{\mu \nu} \hat{W}^{\nu \rho} \hat{W}_{\mu}^{\rho} \right)
\end{align*}
\]

- kinematics: \(p_T, \ell\) in \(VV\) production
- combined LHC channels
D6 Higgs-gauge operators

Triple gauge couplings

- one more Higgs-gauge operator \(#3\) solved

\[
O_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu}(D_\nu \phi) \quad O_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu}(D_\nu \phi) \quad O_{WW} = \text{Tr} \left( \hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right)
\]

- kinematics: \(p_T, \ell\) in \(VV\) production
- combined LHC channels
- affecting correlations
D6 Higgs-gauge operators

**Triple gauge couplings**

- one more Higgs-gauge operator [\#3 solved]

\[ \mathcal{O}_W = (D_\mu \phi)\dagger \hat{W}^{\mu \nu} (D_\nu \phi) \quad \mathcal{O}_B = (D_\mu \phi)\dagger \hat{B}^{\mu \nu} (D_\nu \phi) \quad \mathcal{O}_{WW} = \text{Tr} \left( \hat{W}_{\mu \nu} \hat{W}^{\nu \rho} \hat{W}_\rho^\mu \right) \]

- kinematics: \( p_T, \ell \) in \( VV \) production
- combined LHC channels
- affecting correlations

⇒ complete Higgs-gauge analysis
D6 Higgs-gauge operators

**Triple gauge couplings**

- one more Higgs-gauge operator \([#3\text{ solved}]\)

\[
\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu}(D_\nu \phi) \quad \mathcal{O}_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu}(D_\nu \phi) \quad \mathcal{O}_{WW} = \text{Tr} \left( \hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^{\mu} \right)
\]

- kinematics: \(p_T, \ell\) in \(VV\) production
- combined LHC channels
- affecting correlations
⇒ complete Higgs-gauge analysis

**LHC vs LEP**

- triple gauge vertices \(g_1, \kappa, \lambda\) vs operators
- semileptonic analyses missing for 8 TeV
⇒ Run I LHC beating LEP
Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

\[ \mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi), \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3 \]
Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

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first operator, wave function renormalization

\[ \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_{\mu} (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) = \frac{1}{2} (\tilde{H} + v)^2 \partial_\mu \tilde{H} \partial^\mu \tilde{H} \]

proper normalization of combined kinetic term \[\text{[LSZ]}\]

\[ \mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H} \partial^\mu \tilde{H} \left( 1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) = \frac{1}{2} \partial_\mu H \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}} \]
Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

\[ \mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} O_i \quad \text{with} \quad O_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \partial^\mu \phi), \quad O_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3 \]

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\[ O_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \partial^\mu \phi) = \frac{1}{2} (\tilde{H} + v)^2 \partial_\mu \tilde{H} \partial^\mu \tilde{H} \]

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second operator, minimum condition giving \(v\)

\[ v^2 = -\frac{\mu^2}{\lambda} - \frac{f_{\phi,3} \mu^4}{4 \lambda^3 \Lambda^2} \]
Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

\[ \mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) , \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3 \]

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second operator, minimum condition giving \( v \)

\[ v^2 = -\frac{\mu^2}{\lambda} - \frac{f_{\phi,3} \mu^4}{4 \lambda^3 \Lambda^2} \]

both operators contributing to Higgs mass

\[ \mathcal{L}_{\text{mass}} = -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_{\phi,3}}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \quad \Leftrightarrow \quad m_H^2 \]

\[ m_H^2 = 2 \lambda v^2 \left( 1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{f_{\phi,3} v^2}{2 \Lambda^2 \lambda} \right) \]
Exercise: higher-dimensional operators

**Higgs sector including dimension-6 operators**

\[
\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi), \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3
\]

**Higgs self couplings momentum dependent**

\[
\mathcal{L}_{\text{self}} = -\frac{m_H^2}{2v} \left[ \left( 1 - \frac{f_{\phi,2} v^2}{2\Lambda^2} + \frac{2f_{\phi,3} v^4}{3\Lambda^2 m_H^2} \right) H^3 - \frac{2f_{\phi,2} v^2}{\Lambda^2 m_H^2} H \partial_\mu H \partial^\mu H \right] \\
- \frac{m_H^2}{8v^2} \left[ \left( 1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4f_{\phi,2} v^2}{\Lambda^2 m_H^2} H^2 \partial_\mu H \partial^\mu H \right]
\]
Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

\[ \mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) , \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3 \]

Higgs self couplings momentum dependent

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\[- \frac{m_H^2}{8v^2} \left[ \left( 1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4f_{\phi,2} v^2}{\Lambda^2 m_H^2} H \partial_\mu H \partial^\mu H \right] \]

alternatively, strong multi-Higgs interactions

\[ H = \left( 1 + \frac{f_{\phi,2} v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_{\phi,2} v^2}{2\Lambda^2} \tilde{H}^2 + \frac{f_{\phi,2} v^4}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4) \]
Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

\[ \mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi), \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3 \]

Higgs self couplings momentum dependent

\[ \mathcal{L}_{\text{self}} = -\frac{m_H^2}{2v} \left[ \left( 1 - \frac{f_{\phi,2} v^2}{2\Lambda^2} + \frac{2f_{\phi,3} v^4}{3\Lambda^2 m_H^2} \right) H^3 - \frac{2f_{\phi,2} v^2}{\Lambda^2 m_H^2} H \partial_\mu H \partial^\mu H \right] \]
\[ -\frac{m_H^2}{8v^2} \left[ \left( 1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4f_{\phi,2} v^2}{\Lambda^2 m_H^2} H^2 \partial_\mu H \partial^\mu H \right] \]

alternatively, strong multi-Higgs interactions

\[ H = \left( 1 + \frac{f_{\phi,2} v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_{\phi,2} v}{2\Lambda^2} \tilde{H}^2 + \frac{f_{\phi,2} v}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4) \]

⇒ operators and distributions linked to poor UV behavior
D6 top operators

Same for tops  [TopFitter: Buckley, Englert, Ferrando, Miller, Moore, Russell, White]

- single, pair-wise, and associated top production  [plus decays]
- including anomalous $A_{FB}$ from Tevatron
- 4-quark, Yang-Mills, electroweak operators

$$\mathcal{O}_{qq} = \bar{q}_\gamma q \bar{t}_\gamma t \quad \mathcal{O}_G = f_{ABC} G_{\mu\nu}^{A} G_{\nu\lambda}^{B} G_{\lambda\gamma}^{C} \quad \mathcal{O}_{\phi G} = \phi^\dagger \phi G_{\mu\nu}^{a} G_{\mu\nu}^{a} \ldots$$

- profile likelihoods and individual limits

$\Rightarrow$ Generic D6 reach $\sim 500$ GeV  [$C = 1$]
D6 top operators

**Same for tops**  
[TopFitter: Buckley, Englert, Ferrando, Miller, Moore, Russell, White]

- single, pair-wise, and associated top production  
- including anomalous $A_{FB}$ from Tevatron  
- 4-quark, Yang-Mills, electroweak operators

\[
\mathcal{O}_{qq} = \bar{q} \gamma_\mu q \, \bar{t} \gamma^\mu t \quad \mathcal{O}_G = f_{ABC} G_{\mu \nu}^A G_{\nu \lambda}^B G_{\lambda \mu}^C \\
\mathcal{O}_{\phi G} = \phi^\dagger \phi G_{\mu \nu}^a G^{a \mu \nu} \ldots
\]

- profile likelihoods and individual limits

$\Rightarrow$  
**Generic D6 reach $\sim 500$ GeV**  
$[c = 1]$

**For theorists: in terms of models**

- axigluon:  $M_A > 1.4$ TeV  
- SM-like $W'$:  $M_{W'} > 1.2$ TeV

$\Rightarrow$  
**models less sensitive to correlations**
D6 dark matter operators

Combining direct, indirect, collider results for WIMPs \[\text{[Tait et al]}\]

- choose dark matter candidate \[\text{[Majorana/Dirac fermion, scalar, dark photon]}\]
- consider D6 scattering process \[\chi\chi \rightarrow \text{SM SM}\]
- relic density from annihilation \[m_\chi / T \sim 30\]
- indirect detection even later
- direct detection non-relativistic \[E \sim 10 \text{ MeV}\]
- LHC tricky: single scale \[m_\chi \ll m_{\text{mediator}}\]
- example: scalar dark matter

<table>
<thead>
<tr>
<th>Label</th>
<th>Coefficient</th>
<th>Operator</th>
<th>(\sigma_{SI}(\sigma_{ann}v))</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{Real scalar}</td>
<td></td>
<td></td>
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<tr>
<td>R1</td>
<td>(\lambda_1 \sim 1/(2M^2))</td>
<td>(m_q \chi^2 \bar{q}q)</td>
<td>✓ s-wave</td>
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<td>R2</td>
<td>(\lambda_2 \sim 1/(2M^2))</td>
<td>(im_q \chi^2 \bar{q}\gamma^5 q)</td>
<td>s-wave</td>
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<tr>
<td>R3</td>
<td>(\lambda_3 \sim \alpha_s/(4M^2))</td>
<td>(\chi^2 G_{\mu\nu} G^{\mu\nu})</td>
<td>✓ s-wave</td>
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<tr>
<td>R4</td>
<td>(\lambda_4 \sim \alpha_s/(4M^2))</td>
<td>(i\chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu})</td>
<td>s-wave</td>
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<td>\text{Complex scalar}</td>
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<td></td>
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<tr>
<td>C1</td>
<td>(\lambda_1 \sim 1/(M^2))</td>
<td>(m_q \chi^\dagger \chi \bar{q}q)</td>
<td>✓ s-wave</td>
</tr>
<tr>
<td>C2</td>
<td>(\lambda_2 \sim 1/(M^2))</td>
<td>(im_q \chi^\dagger \chi \bar{q}\gamma^5 q)</td>
<td>s-wave</td>
</tr>
<tr>
<td>C3</td>
<td>(\lambda_3 \sim 1/(M^2))</td>
<td>(\chi^\dagger \partial_{\mu} \chi \bar{q}\gamma^\mu q)</td>
<td>✓ p-wave</td>
</tr>
<tr>
<td>C4</td>
<td>(\lambda_4 \sim 1/(M^2))</td>
<td>(\chi^\dagger \partial_{\mu} \chi \bar{q}\gamma^\mu \gamma^5 q)</td>
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</tr>
<tr>
<td>C5</td>
<td>(\lambda_5 \sim \alpha_s/(8M^2))</td>
<td>(\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu})</td>
<td>✓ s-wave</td>
</tr>
<tr>
<td>C6</td>
<td>(\lambda_6 \sim \alpha_s/(8M^2))</td>
<td>(i\chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu})</td>
<td>s-wave</td>
</tr>
</tbody>
</table>
D6 dark matter operators

Relic density plus Hooperon [Liem, Bertone, Calore, Ruiz de Austri, Tait, Trotta, Weniger]

- default input: relic density
- scalar dark matter

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<td>$\lambda_1 \sim 1/(2M^2)$</td>
<td>$m_q \chi^2 \bar{q} q$</td>
<td>s-wave</td>
</tr>
<tr>
<td>R2</td>
<td>$\lambda_2 \sim 1/(2M^2)$</td>
<td>$i m_q \chi^2 \bar{q} \gamma^5 q$</td>
<td>s-wave</td>
</tr>
<tr>
<td>R3</td>
<td>$\lambda_3 \sim \alpha_s/(4M^2) \chi^2 G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\nu_{\chi}$</td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>$\lambda_4 \sim \alpha_s/(4M^2) i \chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>s-wave</td>
<td></td>
</tr>
</tbody>
</table>

- profile likelihood
- flat prior on log $\lambda_i$ [prior $1/\lambda_i$]
- Dirichlet prior prefering similar-sized Wilson coefficients
D6 dark matter operators

Relic density plus Hooperon [Liem, Bertone, Calore, Ruiz de Austri, Tait, Trotta, Weniger]

- default input: relic density
- scalar dark matter

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<td>R1</td>
<td>$\lambda_1 \sim 1/(2M^2)$</td>
<td>$mq \chi^2 \bar{q}q$</td>
<td>✓ s-wave</td>
</tr>
<tr>
<td>R2</td>
<td>$\lambda_2 \sim 1/(2M^2)$</td>
<td>$imq \chi^2 \bar{q}\gamma^5 q$</td>
<td>s-wave</td>
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<tr>
<td>R3</td>
<td>$\lambda_3 \sim \alpha_s/(4M^2) \chi^2 G_{\mu\nu} G^{\mu\nu}$</td>
<td>✓ s-wave</td>
<td></td>
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<tr>
<td>R4</td>
<td>$\lambda_4 \sim \alpha_s/(4M^2)i\chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>s-wave</td>
<td></td>
</tr>
</tbody>
</table>

- profile likelihood
- flat prior on log $\lambda_i$ [prior $1/\lambda_i$]
- Dirichlet prior prefering similar-sized Wilson coefficients
- Fermi: GCE plus dwarf galaxies

⇒ with data, the method hardly matters...
(Simplified) Higgs portal

Higgs sector minimal? [theory-driven question]

- secondary question: D6 Higgs approach applicable?
- renormalizable extended potential [with or without VEV]

\[ V(\phi, S) = -\mu_1^2(\phi^\dagger \phi) + \lambda_1 |\phi^\dagger \phi|^2 - \mu_2^2 S^2 + \kappa S^3 + \lambda_2 S^4 + \lambda_3 |\phi^\dagger \phi| S^2 \]

\[ \rightarrow -\mu_1^2(\phi^\dagger \phi) + \lambda_1 |\phi^\dagger \phi|^2 - \mu_2^2 S^2 + \lambda_2 S^4 + \lambda_3 |\phi^\dagger \phi| S^2 \]

- mixing to the observed Higgs mass eigenstate

\[ H_1 = \cos \chi H_\phi + \sin \chi S \]

- decays to SM and hidden sectors [plus \( H_2 \rightarrow H_1 H_1 \) cascade decays]

\[ \Gamma_1 = \cos^2 \chi \Gamma_{1}^{SM} + \sin^2 \chi \Gamma_{1}^{hid} = \cos^2 \chi \Gamma_{1}^{SM} \left( 1 + \tan^2 \chi \frac{\Gamma_{1}^{hid}}{\Gamma_{1}^{SM}} \right) \]

- constraints on event rate

\[ \frac{\sigma_{H_1 \rightarrow SM}}{\sigma_{H_1 \rightarrow SM}} = \frac{\cos^2 \chi}{1 + \tan^2 \chi \frac{\Gamma_{1}^{hid}}{\Gamma_{1}^{SM}}} \leq \mathcal{R} \]

- collider reach

![Graph showing collider reach](image-url)
(Simplified) Higgs portal

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\]

\[
\Rightarrow \text{resonance, rates, and invisible Higgs decays}
\]
Invisible Higgs decays

LHC challenges: invisible decays [Eboli & Zeppenfeld]

- WBF best choice to boost Higgs
- backgrounds: $Z_{\nu\nu}jj$ in QCD $[\sigma \propto \alpha \alpha_s^2]$  
  $Z_{\nu\nu}jj$ WBF-like $[\sigma \propto \alpha^3]$  
- cut on missing energy and $\Delta \phi_{jj}$
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- central jet veto to suppress QCD background

$\Rightarrow$ trigger the problem
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**Multivariate update**  [Bernaciak, TP, Schichtel, Tattersall]

- baseline cuts: jet veto plus $\Delta \phi_{jj}$
  multivariate: 2-jet, 3-jet sample
- reach $BR_{\text{inv}} \sim 4\%$ for 3000 fb$^{-1}$
- further improvement to 2%
  from QCD jets to 10 GeV...

$\Rightarrow$ QCD the limiting factor
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⇒ QCD the limiting factor
(Simplified) two Higgs doublets

**Doublet extension**

- two complex doublets, 8 degrees of freedom
  - three Goldstones $W^\pm, Z^0$
  - five Higgs fields $h^0, H^0, A^0, H^\pm$
- renormalizable extended potential
  \[
  V(\phi_1, \phi_2) = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - \left[ m_{12}^2 \phi_1^\dagger \phi_2 + h.c. \right]
  \]
  \[
  + \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 |\phi_1^\dagger \phi_2|^2
  \]
  \[
  + \left[ \frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \lambda_6 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_7 (\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2) + h.c. \right]
  \]

**Two doublets** [no flavor, CP, custodial troubles]

- angle $\beta = \text{atan}(v_2/v_1)$
  angle $\alpha$ defining $h$ and $H \rightarrow$ gauge boson coupling $g_{W,Z} = \sin(\beta - \alpha)g_{W,Z}^{\text{SM}}$
- type-I: all fermions with $\phi_2$
  type-II: up-type fermions with $\phi_2$
  lepton-specific: type-I quarks and type-II leptons
  flipped: type-II quarks and type-I leptons
- single hierarchy $m_h \ll m_{H,A,H^\pm}$ with $\sin^2 \alpha \sim 1/(1 + \tan^2 \beta)$ [custodial symmetry]
(Simplified) scalar/gauge extensions

**Scalar top partners**  [simplified supersymmetry]

- toy model for non-Higgs scalar
- Lagrangian with scalar top partner, singlet plus doublet

\[
\mathcal{L} \supset (D_\mu \tilde{\phi})^\dagger (D^\mu \tilde{\phi}) + (D_\mu \tilde{t}_R)^* (D^\mu \tilde{t}_R) - \tilde{Q}^\dagger M^2 \tilde{Q} - M^2 \tilde{t}_R^* \tilde{t}_R - \kappa_{LL} (\phi \cdot \tilde{Q})^\dagger (\phi \cdot \tilde{Q}) - \kappa_{RR} (\tilde{t}_R^* \tilde{t}_R) (\phi^\dagger \phi) - \left[ \kappa_{LR} M \tilde{t}_R^* (\phi \cdot \tilde{Q}) + \text{h.c.} \right]
\]

- contribution through loops all over Higgs-gauge sector

**Triplet gauge extension**  [whatever that becomes in the UV]

- additional vector triplet field \( V_\mu \)

\[
\mathcal{L} \supset - \frac{1}{4} \tilde{V}^a_{\mu \nu} \tilde{V}^{\mu \nu a} + \frac{M_v^2}{2} \tilde{V}^a_{\mu} \tilde{V}^{\mu a} + \frac{g_\nu}{2} c_H \tilde{V}^a_{\mu} \left[ \phi^\dagger \sigma^a D^\mu \phi \right] + \frac{g_w^2}{2 g_v} \tilde{V}^a_{\mu} \sum_{\text{fermions}} c_F \bar{F}_\mu \gamma^\mu \sigma^a F_L \\
+ \frac{g_v}{2} c_{VVV} \epsilon_{abc} \tilde{V}^a_{\mu} \tilde{V}^b_{\nu} D^{[\mu} \tilde{V}^{\nu]c} + g_v^2 c_{VHH} \tilde{V}^a_{\mu} \tilde{V}^{\mu a} (\phi^\dagger \phi) - \frac{g_w}{2} c_{VVW} \epsilon_{abc} W^{\mu \nu} \tilde{V}^a_{\mu} \tilde{V}^b_{\nu} \tilde{V}^c_{\nu}
\]

- new states, mixing with \( W^\pm \) and \( Z \)
  - weak gauge coupling to \( W, Z \) mass eigenstates
  - strongly interacting towards UV
Higgs D6 breakdown

D6-Lagrangian breakdown  [Brehmer, Freitas, Lopez-Val, TP]

– phenomenology: does D6 capture all model features at LHC?
  theory: how do D6 vs EFT vs full model differences appear?
Higgs D6 breakdown

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- push (simplified) models to visible deviations at 13 TeV

Higgs portal, 2HDM, stops, vector triplet [weakly interacting, Eq.(2)]

\[
\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 10\% \quad \Leftrightarrow \quad \Lambda \lesssim 400 \text{ GeV}
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no scale hierarchy for testable models?!
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- construct and match D6-Lagrangian to model
  - coupling modifications $v^2/\Lambda^2$ vs new kinematics $\partial/\Lambda$?
  - matching conditions with $v \lesssim \Lambda$, $v$-improved matching?
- LHC simulations: D6-Lagrangian vs full model
  - production: WBF, $VH$, $HH$
  - decays: $H \rightarrow \gamma\gamma, 4\ell$
- check where differences appear at 13 TeV
  - kinematic distributions like $p_T, j$ or $m_{VH}$?
  - resonance peaks of new states?
Higgs D6 breakdown

Higgs portal

- testable benchmarks for LHC

<table>
<thead>
<tr>
<th></th>
<th>Singlet</th>
<th>EFT</th>
<th>EFT (v-improved)</th>
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<td>$\nu_s / \nu$</td>
<td>$\Delta x^{\text{singlet}}$</td>
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<tr>
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<tr>
<td>500</td>
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</tr>
</tbody>
</table>

- effects in WBF and $hh$

\[
u_s = \frac{m_H}{\nu} \sin \alpha \Delta x^{\text{singlet}}\]

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- effects in WBF and $hh$

2HDM

- testable benchmarks for LHC

| Type | $\tan \beta$ | $\alpha / \pi$ | $m_{12}$ | $m_{H^0}$ | $m_{A^0}$ | $m_{H^\pm}$ | $|\Lambda|$ [GeV] | $\bar{c}_u$ | $\bar{c}_{d,\ell}$ |
|------|--------------|--------------|-----------|-----------|-----------|-----------|----------------|-----------|----------------|
| I    | 1.5          | $-0.086$     | 45        | 230       | 300       | 350       | 100            | $-0.744$  | $-0.744$       |
| II   | 15           | $-0.023$     | 116       | 449       | 450       | 457       | 448            | $0.000$   | 0.065          |
| II   | 10           | 0.032        | 157       | 500       | 500       | 500       | 99             | 0.465     | $-46.5$        |
| I    | 20           | 0            | 45        | 200       | 500       | 500       | 142            | 0.003     | 0.003          |
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- effects in $H \rightarrow \gamma \gamma$

![Graph showing the cross-section for $pp \rightarrow h^0 \rightarrow \gamma \gamma$ (D1)]
Higgs D6 breakdown

**Higgs portal**

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- effects in WBF and \( hh \)

**2HDM**

- testable benchmarks for LHC
- effects in \( H \rightarrow \gamma\gamma \)

**Top partners**

- testable benchmarks for LHC

<table>
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<tr>
<th>( M )</th>
<th>( \kappa_{LL} )</th>
<th>( \kappa_{RR} )</th>
<th>( \kappa_{LR} )</th>
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Higgs D6 breakdown

Higgs portal

– testable benchmarks for LHC
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2HDM

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Top partners

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Higgs D6 breakdown

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Vector triplet [Brehmer, Biekötter, Krämer, TP]
- testable benchmarks for LHC

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Higgs D6 breakdown

**Higgs portal**
- testable benchmarks for LHC
- effects in WBF and $hh$

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**Top partners**
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**Vector triplet**  
[Brehmer, Biekötter, Krämer, TP]
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- effects in $Vh$ and WBF
Higgs D6 breakdown

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- effects in $Vh$ and WBF
# Higgs D6 breakdown

<table>
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<tr>
<th>Model</th>
<th>Process</th>
<th>EFT failure</th>
</tr>
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<td>on-shell $h \rightarrow 4\ell$, WBF, $Vh$, ...</td>
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<td></td>
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Higgs D6 breakdown

Reasons for D6-breakdown in Higgs sector at LHC

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Lessons from Higgs sector

- start with D6 description [data-driven era of particle physics]
- EFT expansion in \( E/\Lambda \) known to be dodgy
- simplified models theory-driven
- test of D6 in comparison with (simplified) models
- all relevant effect at tree level
- resonance peaks the key feature
(Simplified) DM scalar

DM scalar from Higgs sector  

- scalar dark matter, $m_S = 10 \ldots 100$ GeV
- coupling to Standard Model through renormalizable portal  
- extended potential  
  
  \[ V(\phi, S) = -\mu^2 (\phi^\dagger \phi) + \lambda_4 |\phi^\dagger \phi|^2 - \mu_S^2 S^2 + \lambda_3 (\phi^\dagger \phi) S^2 \]

- physical masses and parameters  

  \[ m_S = \sqrt{2\mu_S^2 - \lambda_3 v_H^2} \]

  \[ g_{SSH} = -2\lambda_3 v_H \]

  \[ g_{SSHH} = -2\lambda_3 \]
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DM conditions

- (in-) direct detection: same as DM EFT
- thermal relic density $\Omega h^2 \sim 0.12$  

$$\sigma_{\text{ann}} \propto \begin{cases} 
\frac{\lambda_3 m_b^2}{m_H^4} & m_S \ll \frac{m_H}{2} \quad \lambda_3 \approx 0.3 \\
\frac{\lambda_3 m_b^2}{m_H^2 \Gamma_H^2} & m_S = \frac{m_H}{2} \quad \lambda_3 \approx 10^{-3} \\
\frac{\lambda_3^2}{m_S^2} & m_S > m_Z, m_H \quad \lambda_3 \approx 0.1
\end{cases}$$
(Simplified) DM scalar

DM scalar from Higgs sector [data-driven question]

- scalar dark matter, \( m_S = 10 \ldots 100 \text{ GeV} \)
- coupling to Standard Model through renormalizable portal [Higgs as mediator]
- extended potential [\( Z_2 \) symmetry, no VEV]

\[
V(\phi, S) = - \mu^2 (\phi^\dagger \phi) + \lambda_4 |\phi^\dagger \phi|^2 - \mu_S^2 S^2 + \lambda_3 (\phi^\dagger \phi) S^2
\]

- physical masses and parameters

\[
m_S = \sqrt{2 \mu^2 S - \lambda_3 v_H^2} \quad g_{SSH} = -2 \lambda_3 v_H \quad g_{SSHH} = -2 \lambda_3
\]

DM conditions

- (in-) direct detection: same as DM EFT
  LHC: \( m_S \leftrightarrow m_H \) open, all propagating states
- thermal relic density \( \Omega h^2 \sim 0.12 \) [\( SS \rightarrow b\bar{b}, HH \)]

\[
\sigma_{\text{ann}} \propto \begin{cases} 
\frac{\lambda_3^2 m_b^2}{m_H^4} & m_S \ll \frac{m_H}{2} \quad \lambda_3 \approx 0.3 \\
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\frac{\lambda_3^2}{m_S^2} & m_S > m_Z, m_H \quad \lambda_3 \approx 0.1 
\end{cases}
\]
(Simplified) DM scalar

**In- direct detection boundary conditions**

- Higgs mediator coupling to proton
  same effective $ggH$ interaction as for gluon fusion production

$$\sigma_{S_A \rightarrow S_A} \approx 3 \cdot 10^{-7} \frac{\lambda_3^2}{m_S^2}$$

- Fermi GCE explained on the pole: $\langle \nu \sigma_{\text{ann}} \rangle \approx \langle \nu \sigma_{\text{GCE}} \rangle$

**LHC searches**

- important: for this (simplified) model we have discovered the mediator
- $m_S \ll m_H/2$ invisible Higgs decays  $[m_{\text{DM}} \ll m_{\text{mediator}}]$
  LHC searches really for mediator
- $m_S \gtrsim m_H$ off-shell invisible Higgs decays?  $[m_{\text{DM}} \gtrsim m_{\text{mediator}}]$
  LHC searches for DM particles

$\Rightarrow$ depressing in particular for small $\lambda_3$
(Simplified) DM models

Requirements for a valid simplified model [1506.03116]

(I) Besides the SM, the model should contain a DM candidate that is either absolutely stable or lives long enough to escape the LHC detectors, as well as a mediator that couples the two sectors. The dark sector can be richer, but the additional states should be somewhat decoupled...

(II) The Lagrangian should contain (in principle) all terms that are renormalizable and consistent with Lorentz invariance, the SM gauge symmetries, and DM stability. However, it may be permissible to neglect interactions or to study cases where couplings are set equal to one another...

(III) The additional interactions should not violate the exact and approximate accidental global symmetries of the SM...
(Simplified) DM models

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Things not required: simplified models...

...need a good motivation, theoretical or experimental
...need a UV completion
...need to be agreed on by everyone in the field
...should be really hard/easy to experimentally test

⇒ there is no such thing as a wrong simplified model
(Simplified) DM models

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(III) The additional interactions should not violate the exact and approximate accidental global symmetries of the SM...

General structure of simplified DM models

– relatively light dark matter candidate
– mediator, often inducing $2 \to 2$ scattering process $\chi\chi \to \text{SM SM}$
– predicting reliche density, (in-) direct detection, LHC observables
(Simplified) DM models

DM–mediator pairings  \([1506.03116, 1507.00966]\)

(1) scalar or pseudo-scalar mediator, fermion DM

\[ \mathcal{L}_{\text{fermion, } \phi} \supset -g_X \phi \bar{\chi} \chi - \frac{\phi}{\sqrt{2}} \sum_f g_f y_i^f \bar{t}_i \]

– mono-jet(s), mono-\(V\), mono-Higgs \([\text{not necessarily ISR}]\)

⇒ mediators almost more relevant than DM states
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(2) vector mediator, fermion/scalar DM

\[ \mathcal{L}_{\text{fermion}, V} \supset V_{\mu} \bar{x} \gamma^\mu (g_{\chi}^V - g_{\chi}^A \gamma_5) \chi + \sum_f V_{\mu} \bar{f} \gamma^\mu (g_f^V - g_f^A \gamma_5) f \]

\[ \mathcal{L}_{\text{scalar}, V} \supset i g_{\phi} V_{\mu} (\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*) + \sum_f V_{\mu} \bar{f} \gamma^\mu (g_f^V - g_f^A \gamma_5) f \]

- mono-jet(s) or di-jet resonances

⇒ mediators almost more relevant than DM states
**DM–mediator pairings**  \([1506.03116, 1507.00966]\]

1. **scalar or pseudo-scalar mediator, fermion DM**

\[ \mathcal{L}_{\text{fermion, } \phi} \supset -g_{\chi} \phi \bar{\chi} \chi - \frac{\phi}{\sqrt{2}} \sum_f g_f y_i f^T_l f_i \]

   - mono-jet(s), mono-\( V \), mono-Higgs  \[\text{[not necessarily ISR]}\]

2. **vector mediator, fermion/scalar Higgs**

\[ \mathcal{L}_{\text{fermion, } V} \supset V_\mu \bar{\chi} \gamma^\mu (g_{\chi}^V - g_{\chi}^A \gamma_5) \chi + \sum_f V_\mu \bar{f} \gamma^\mu (g_f^V - g_f^A \gamma_5) f \]

\[ \mathcal{L}_{\text{scalar, } V} \supset ig_\varphi V_\mu (\varphi^* \partial^\mu \varphi - \varphi \partial^\mu \varphi^*) + \sum_f V_\mu \bar{f} \gamma^\mu (g_f^V - g_f^A \gamma_5) f \]

   - mono-jet(s) or di-jet resonances

3. **t-channel mediator, fermion DM**  \[\text{[scalar darkoquark]}\]

\[ \mathcal{L}_{\text{fermion, } \tilde{u}} \supset \sum_f g \tilde{f}^* \bar{\chi} P_R f + \text{h.c.} \]

   - mono-jet(s), associated, pair production  \[\text{[mono-jet vs jet(s + MET]}\]
(Simplified) DM models

**DM–mediator pairings**  
[1506.03116, 1507.00966]

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\[ \mathcal{L}_{\text{fermion, } V} \supset V_\mu \bar{\chi} \gamma^\mu (g^V_\chi - g^A_\chi \gamma_5) \chi + \sum_f V_\mu \bar{f} \gamma^\mu (g^V_f - g^A_f \gamma_5) f, \]

\[ \mathcal{L}_{\text{scalar, } V} \supset ig_\varphi V_\mu (\varphi^* \partial^\mu \varphi - \varphi \partial^\mu \varphi^*) + \sum_f V_\mu \bar{f} \gamma^\mu (g^V_f - g^A_f \gamma_5) f \]

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- mono-jet(s), associated, pair production  
[mono-jet vs jet(s + MET]  
- scalar DM, spin-2 mediators, flavored DM, spin-17/2 DM,....

⇒ mediators almost more relevant than DM states
(Simplified) weakly interacting DM

WIMPs dark matter, classified by $SU(2)_L$ representation

- $Z, H$ mediators known  [extended Higgs sector possible]
- singlet (Majorana) fermion DM  ['bino']
  coupling only through mixing
- doublet fermion DM  [1/2 'higgsino']
  charged partner, $Z \tilde{H}^0 \tilde{H}^0$ and $h \tilde{H}^0 \tilde{W}^0$ couplings
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Relic density of (simplified) electroweakinos

- DM relic density: light, mixed bino DM
  efficient annihilation to weak bosons
  co-annihilation with charged states
- pure states typically heavy [Sommerfeld enhancement]

$$\Omega_{\tilde{W}h^2} \approx 0.12 \left( \frac{m_{\tilde{\chi}_1^0}}{2.1 \text{ TeV}} \right)^2 \xrightarrow{\text{Sommerfeld}} 0.12 \left( \frac{m_{\tilde{\chi}_1^0}}{2.6 \text{ TeV}} \right)^2$$

$$\Omega_{\tilde{H}h^2} \approx 0.12 \left( \frac{m_{\tilde{\chi}_1^0}}{1.13 \text{ TeV}} \right)^2 \xrightarrow{\text{Sommerfeld}} 0.12 \left( \frac{m_{\tilde{\chi}_1^0}}{1.14 \text{ TeV}} \right)^2$$
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**Relic density of (simplified) electroweakinos**

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  efficient annihilation to weak bosons
  co-annihilation with charged states
- pure states typically heavy [Sommerfeld enhancement]
- pure-state WIMP electroweakinos heavy
- chargino co-annihilation crucial
- mixed bino scenario through mixing
$\Rightarrow$ **not covered by usual simplified models**
(Simplified) weakly interacting DM

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Relic neutralino surface [MSSM; Bramante,...]

![Graph showing relic neutralino surface](image)

- LSP mass
- CLSP-LSP mass splitting
- No Sommerfeld

![Graph showing LSP mass](image)

![Graph showing CLSP-LSP mass splitting](image)
Minimal supersymmetric extension: MSSM

**MSSM spectrum**
- mechanism for SUSY masses unknown
- blind mediation: MSUGRA/CMSSM
  - scalars: $m_0$, fermions: $m_1/2$, tri-scalar: $A_0$
  - plus sign$(\mu)$ and tan $\beta$ in Higgs sector
- gauge, anomaly, gaugino mediation...?

$\Rightarrow$ measure spectrum at LHC  [pMSSM]
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- plus sign($\mu$) and $\tan \beta$ in Higgs sector

- gauge, anomaly, gaugino mediation...?

$\Rightarrow$ measure spectrum at LHC  [pMSSM]

Search strategies at the LHC  [Oliver’s talk]

- squarks, gluinos strongly interacting
  $p\bar{p} \rightarrow \tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$
  decays to jets and DM state
  $\tilde{g} \rightarrow \tilde{q}\bar{q}$, $\tilde{q}_L \rightarrow q\tilde{\chi}^0_2$, $\tilde{q}_R \rightarrow q\tilde{\chi}^0_1$
  additional jets and leptons possible

$\Rightarrow$ jets plus missing energy

- strongly interacting Majorana gluinos
  final–state leptons with both charges

$\Rightarrow$ like–sign dileptons
Supersymmetric Hooperon

Spirit of ambulance chasing: Hooperon $\leftrightarrow$ LHC [Butter et al]

- MSSM pushing error bars $[\chi\chi \rightarrow WW]$ linked to $\chi^0\chi^\pm$ production
- NMSSM dark matter
- simplified model: pseudo-scalar mediator Majorana fermion DM
- MSSM-like DM composition $[\tilde{B} \rightarrow \tilde{H}]$ mixed singlino DM

$\Rightarrow$ linked to LHC signatures?

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⇒ linked to LHC signatures?
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⇒ linked to LHC signatures?

LHC signatures

- requiring relic density
- requiring GCE rate
- passing Xenon limits

⇒ chargino-neutralino rate $[\text{Cao, Zurek,...}]$
Supersymmetric Hoopperon

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LHC signatures

- requiring relic density
- requiring GCE rate
- passing Xenon limits

$\Rightarrow$ chargino-neutralino rate [Cao, Zurek,...]

$\Rightarrow$ $BR_{inv}$ up to 40%
Questions

Questions waiting

- is it really the Standard Model Higgs?
- is there WIMP dark matter?
- is there TeV-scale physics beyond the Standard Model?
- should I become a particle physicist? — yes!
- is our experimental/theoretical program exciting? — yes!

Lectures on LHC Physics and dark matter updated under www.thphys.uni-heidelberg.de/~plehn/

Much of this work was funded by the BMBF Theorie-Verbund which is ideal for relevant LHC work