New Physics at the LHC

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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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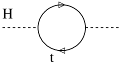
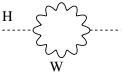
More physics at higher scales

– 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]
$\Rightarrow$ general effective–theory Lagrangian with those interactions and particles
$\Rightarrow$ cutoff scale built in, size of Λ negotiable
$\Rightarrow$ who the hell cares....???

Beyond the Standard Model





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

– top loop in Higgs self energy Σ

$$\Sigma \sim - \left(\frac{g\, m_t}{v} \right)^2 \int \frac{d^4 q}{(2\pi)^4} \, \frac{(\not{p} + m_t)\,(\not{p} + \not{q} + m_t)}{[q^2 - m_t^2]\,[(q+p)^2 - m_t^2]} \sim - \frac{1}{(4\pi)^2} \left(\frac{g\, m_t}{v} \right)^2 \Lambda^2 + \cdots$$

– sum to Higgs–mass correction

$$\begin{aligned} \frac{1}{p^2 - m_H^2} \longrightarrow & \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \ldots \\ = & \frac{1}{p^2 - m_H^2} \sum_{j=0}^{\infty} \left(\frac{\Sigma}{p^2 - m_H^2} \right)^j = \frac{1}{p^2 - m_H^2} \, \frac{1}{1 - \dfrac{\Sigma}{m^2 - m_H^2}} \\ = & \frac{1}{p^2 - m_H^2 - \Sigma} \end{aligned}$$

– and see the desaster after collecting all loop functions

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

⇒ Higgs mass including loops wants to be cutoff scale Λ

⇒ effective Standard–Model destabilized [Higgs wants to be at Λ, but does not function there]

⇒ 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

$\Rightarrow$ easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly

$\Rightarrow$ or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs (Goldstone Higgs)
Higgsless, composite Higgs, TopColor,
YourFavoriteNewPhysics...

$\Rightarrow$ typically cancellation by new particles or discussing away high scale

$\Rightarrow$ beautiful concepts, but problematic at TeV scale [data seriously in the way]

$\Rightarrow$ 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

	bottom-up EFT	simplified models	full models
agnostic	lecture 2		
data-driven		lecture 3	lecture 4
theory-driven		lecture 3	

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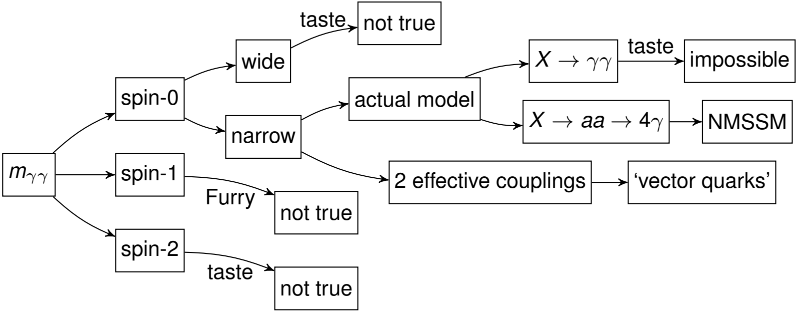
	bottom-up EFT	simplified models	full models
agnostic	lecture 2	dishonest	pre-LHC
data-driven	boring	lecture 3	lecture 4
theory-driven	pointless	lecture 3	pre-LHC

750 GeV — the finger to particle theory



My take on all those 750 GeV papers

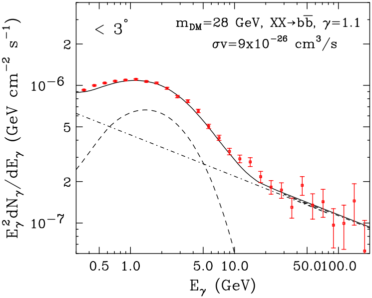
- open questions due to limited significance
- general problem: signal rate large
- largely EFT exercise
- dimension-5 operators $XG^{\mu\nu}G_{\mu\nu}$ and $XA^{\mu\nu}A_{\mu\nu}$ $\longrightarrow$ avoid di-jet constraints
- gauge invariant $XB^{\mu\nu}B_{\mu\nu}$ and $XW^{\mu\nu}W_{\mu\nu}$ $\longrightarrow$ avoid VV constraints
- no clear link to other data

$\Rightarrow$ 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
- $m_\chi \sim 25 \dots 30$ GeV from spectrum



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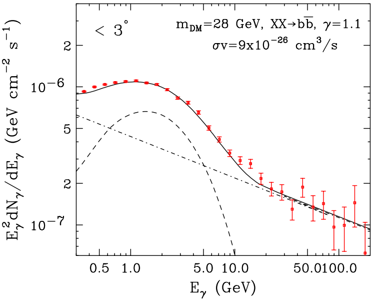

In conclusion, we have studied the angular distribution and energy spectrum of gamma rays measured by the Fermi Gamma Ray Space Telescope in the region surrounding the Galactic Center, and find that this data is well described by a scenario in which a 25-30 GeV dark matter particle, distributed with 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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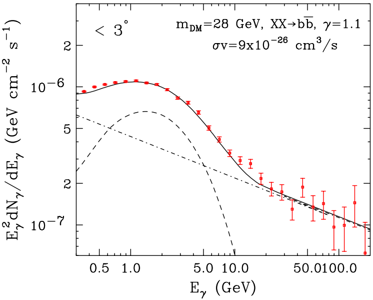

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- analysis with all uncertainties
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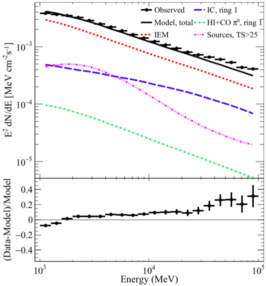

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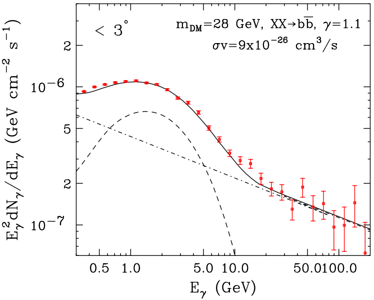

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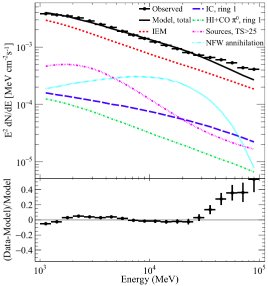

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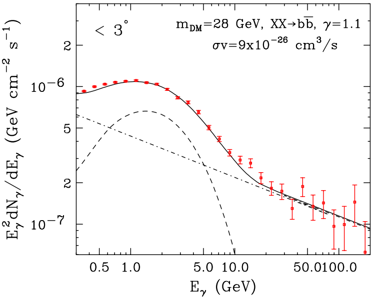

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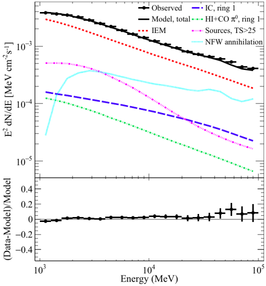
of the analysis that has previously not been employed. After subtraction of interstellar emission and point sources, an extended residual is present. It can be fit with a centrally peaked profile with a specified spectral model, but not all of the positive residual is accounted for by such a model. Because 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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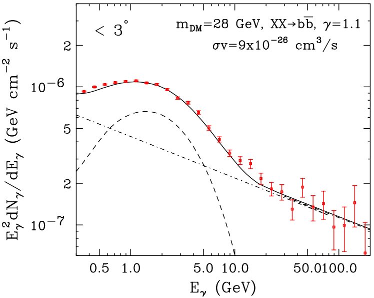

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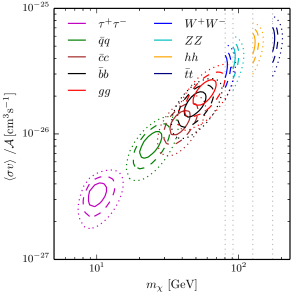
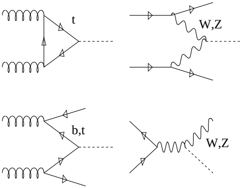
- even better with modified NFW contribution
- different DM candidates [Calore etal]

$\Rightarrow$ DM model playground



Higgs couplings



Agnostic: why super-simple SM-Higgs sector? [SFitter]

– or: all couplings proportional to masses?

– assume: narrow CP-even scalar
  Standard Model operators

– total production/decay rates only

– Lagrangian

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

– electroweak renormalizability through some UV completion

– QCD renormalizability not an issue

$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $qq' \to VH$	$\longleftrightarrow$	$g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$	$\longleftrightarrow$	$H \to ZZ$ $H \to WW$ $H \to b\bar{b}$ $H \to \tau^+\tau^-$ $H \to \gamma\gamma$

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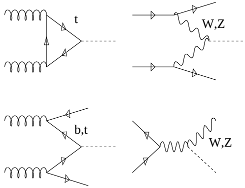

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Total width

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

$$N = \sigma \, BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}} \frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}} \sim \frac{g^4}{g^2 \sum \frac{\Gamma_i(g^2)}{g^2} + \Gamma_{\text{unobs}}} \stackrel{g^2 \to 0}{\longrightarrow} = 0$$

gives constraint from $\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \quad \to \Gamma_H|_{\text{min}}$

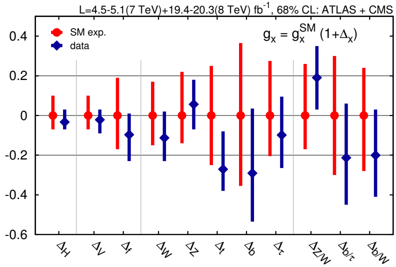
– $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \quad \to \Gamma_H|_{\text{max}}$ [HiggsSignals]
– our assumption $\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j$ [plus generation universality]

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



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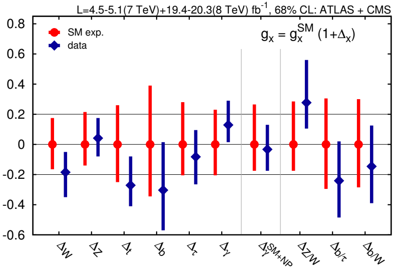

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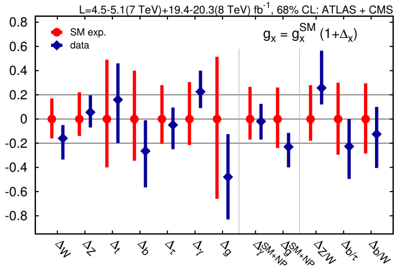

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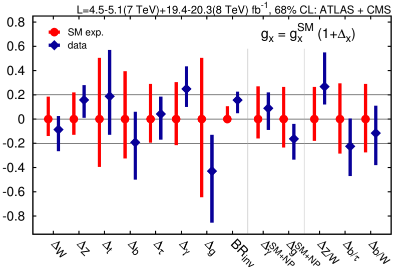
– including invisible decays

$\Rightarrow$ Standard Model within 25%



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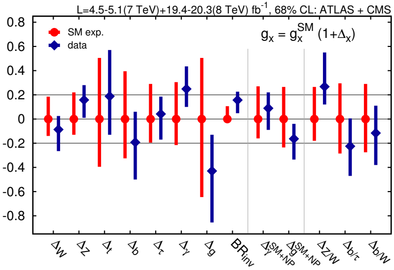
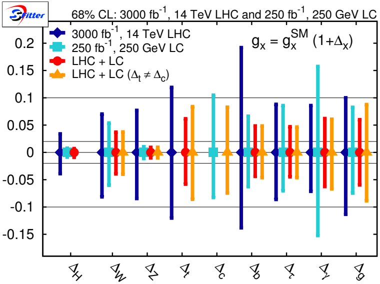


Future [SFitter; Cranmer, Kreiss, Lopez-Val, TP]

– LHC extrapolations unclear
– systematic/theory uncertainties large
– e^+e^- linear collider much better
unobserved decays avoided
width measured from σ_{ZH}
$H \to c\bar{c}$ accessible
invisible decays hugely improved
QCD theory error bars avoided



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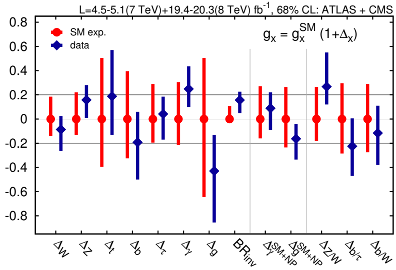

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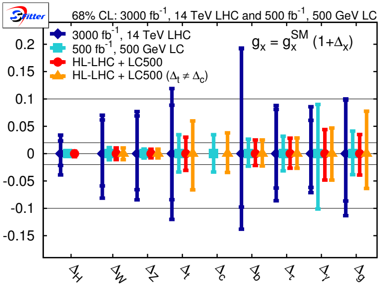

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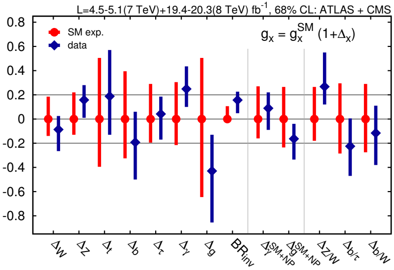

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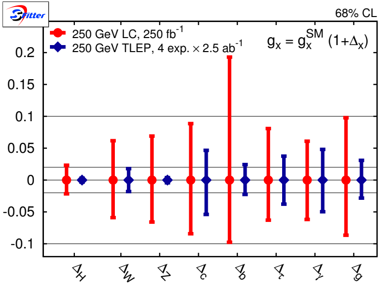
$\Rightarrow$ Higgs factory case obvious



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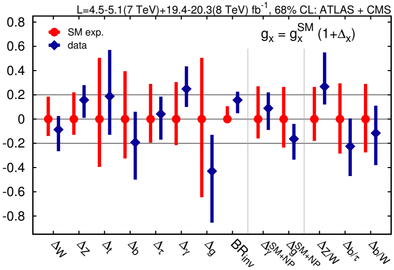
⇒ Standard Model within 25%



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]

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

$$\mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3 \qquad \mathcal{O}_{\phi,4} = (D_\mu \phi)^\dagger \, (D^\mu \phi) \left(\phi^\dagger \phi\right)$$

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– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

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$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

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$$\mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3 \qquad \mathcal{O}_{\phi,4} = (D_\mu \phi)^\dagger \, (D^\mu \phi) \left(\phi^\dagger \phi\right)$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

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

$$\begin{aligned} \mathcal{L}^{HVV} &= g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\ &+ g_Z^{(1)} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} \; H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} \; H Z_\mu Z^\mu \\ &+ g_W^{(1)} \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g_W^{(2)} \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g_W^{(3)} \; H W^+_\mu W^{-\,\mu} + \cdots \end{aligned}$$

D6 Higgs operators

Higgs sector effective field theory

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

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

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– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

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

$$\begin{aligned}
\mathcal{L}^{HVV} &= g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\
&+ g^{(1)}_Z \; Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_Z \; H Z_{\mu\nu} Z^{\mu\nu} + g^{(3)}_Z \; H Z_\mu Z^\mu \\
&+ g^{(1)}_W \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g^{(2)}_W \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g^{(3)}_W \; H W^+_\mu W^{-\,\mu} + \cdots
\end{aligned}$$

– 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]

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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– linked to Higgs couplings

$$g_g = \frac{f_{GG} v}{\Lambda^2} \equiv -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \qquad g_\gamma = -\frac{g^2 v s_w^2}{2\Lambda^2} \frac{f_{BB} + f_{WW}}{2}$$

$$g_Z^{(1)} = \frac{g^2 v}{2\Lambda^2} \frac{c_w^2 f_W + s_w^2 f_B}{2 c_w^2} \qquad g_W^{(1)} = \frac{g^2 v}{2\Lambda^2} \frac{f_W}{2}$$

$$g_Z^{(2)} = -\frac{g^2 v}{2\Lambda^2} \frac{s_w^4 f_{BB} + c_w^4 f_{WW}}{2 c_w^2} \qquad g_W^{(2)} = -\frac{g^2 v}{2\Lambda^2} f_{WW}$$

$$g_Z^{(3)} = M_Z^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right) \qquad g_W^{(3)} = M_W^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right)$$

$$g_f = -\frac{m_f}{v} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right) + \frac{v^2}{\sqrt{2}\Lambda^2} f_f$$

D6 Higgs operators

Higgs sector effective field theory

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

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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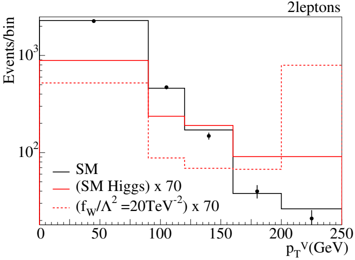
Run 1 legacy

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [remember #2]



D6 Higgs operators

Higgs sector effective field theory

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

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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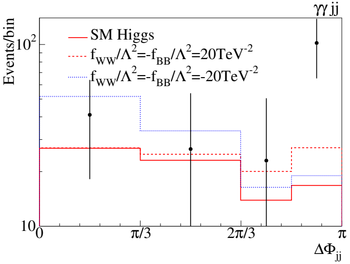

D6 Higgs operators

Higgs sector effective field theory

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

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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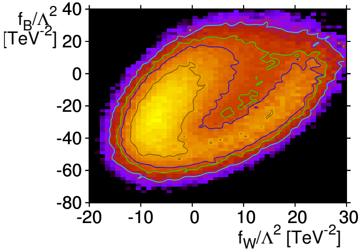
Run 1 legacy

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [remember #2]

– with impact...



D6 Higgs operators

Higgs sector effective field theory

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

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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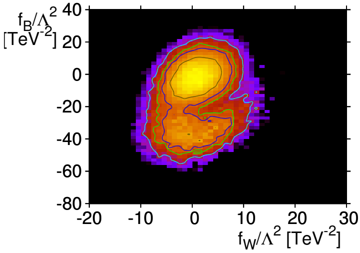
Run 1 legacy

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [remember #2]

– with impact...

...in last bin



D6 Higgs operators

Higgs sector effective field theory

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

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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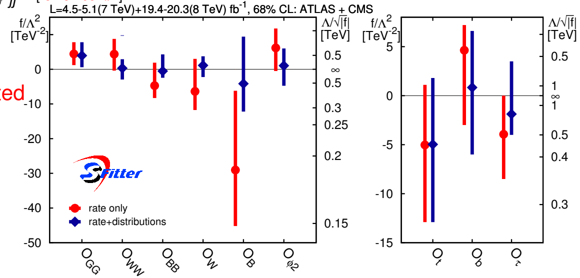
Run 1 legacy

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [remember #2]

– with impact...

...in last bin

$\Rightarrow$ Run I sensitivity limited



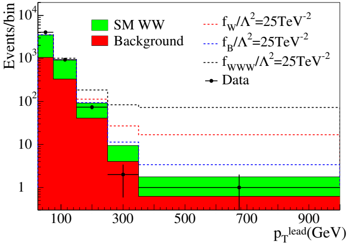
D6 Higgs-gauge operators

Triple gauge couplings

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

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

– kinematics: $p_{T,\ell}$ in VV production



D6 Higgs-gauge operators

Triple gauge couplings

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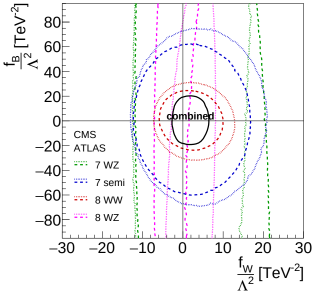
– kinematics: $p_{T,\ell}$ in VV production

– combined LHC channels



D6 Higgs-gauge operators

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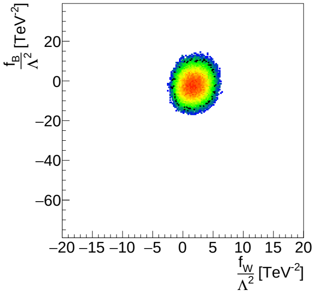
– kinematics: $p_{T,\ell}$ in VV production

– combined LHC channels

– affecting correlations



D6 Higgs-gauge operators

Triple gauge couplings

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

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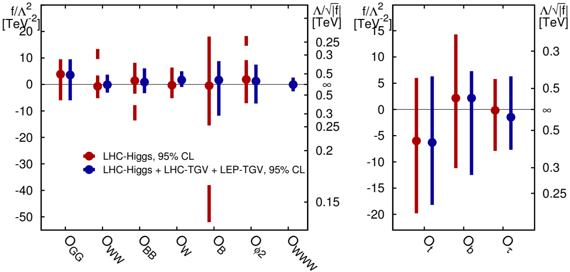
– kinematics: $p_{T,\ell}$ in VV production

– combined LHC channels

– affecting correlations

⇒ complete Higgs-gauge analysis



D6 Higgs-gauge operators

Triple gauge couplings

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

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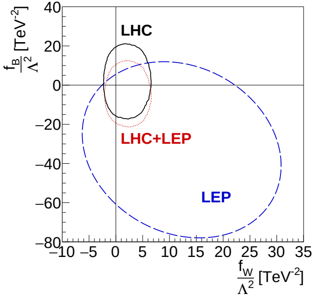
– kinematics: $p_{T,\ell}$ in VV production
– combined LHC channels
– affecting correlations
⇒ complete Higgs-gauge analysis

LHC vs LEP

– triple gauge vertices g_1, κ, λ 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

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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 [LSZ]

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H} \, \partial^\mu \tilde{H} \left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H \, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}}$$

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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

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$$\mathcal{L}_\text{kin} = \frac{1}{2} \partial_\mu \tilde{H} \, \partial^\mu \tilde{H} \left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H \, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}}$$

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

$$\mathcal{L}_\text{mass} = -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_{\phi,3}}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \stackrel{!}{=} -\frac{m_H^2}{2} H^2$$

$$\Leftrightarrow \qquad m_H^2 = 2 \lambda v^2 \left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{f_{\phi,3} v^2}{2 \Lambda^2 \lambda} \right)$$

Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

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Higgs self couplings momentum dependent

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

Exercise: higher-dimensional operators

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

Higgs self couplings momentum dependent

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

alternatively, strong multi-Higgs interactions

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

Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

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

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$\Rightarrow$ operators and distributions linked to poor UV behavior

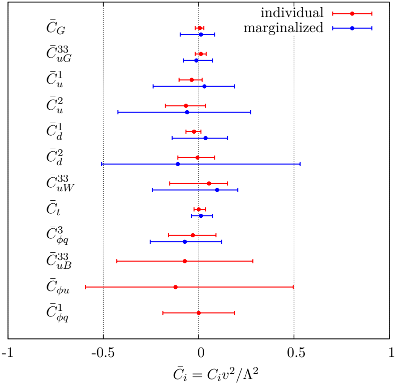
D6 top operators

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

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

– profile likelihoods and individual limits
⇒ Generic D6 reach ∼ 500 GeV [$C = 1$]



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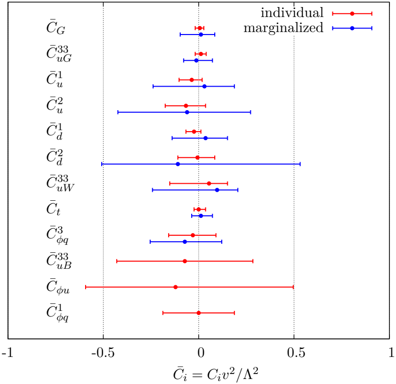

For theorists: in terms of models

– axigluon: $M_A > 1.4$ TeV [$t\bar{t}$ resonance]
– SM-like W': $M_{W'} > 1.2$ TeV [t-channel,...]
⇒ models less sensitive to correlations

D6 dark matter operators

Combining direct, indirect, collider results for WIMPs [Tait etal]

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

Label	Coefficient	Operator	σ_{SI}	$\langle \sigma_{\text{ann}} v \rangle$
		Real scalar		
R1	$\lambda_1 \sim 1/(2M^2)$	$m_q \chi^2 \bar{q} q$	✓	s-wave
R2	$\lambda_2 \sim 1/(2M^2)$	$i m_q \chi^2 \bar{q} \gamma^5 q$		s-wave
R3	$\lambda_3 \sim \alpha_s/(4M^2)$	$\chi^2 G_{\mu\nu} G^{\mu\nu}$	✓	s-wave
R4	$\lambda_4 \sim \alpha_s/(4M^2)$	$i\chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$		s-wave
		Complex scalar		
C1	$\lambda_1 \sim 1/(M^2)$	$m_q \chi^\dagger \chi \bar{q} q$	✓	s-wave
C2	$\lambda_2 \sim 1/(M^2)$	$i m_q \chi^\dagger \chi \bar{q} \gamma^5 q$		s-wave
C3	$\lambda_3 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$	✓	p-wave
C4	$\lambda_4 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu \gamma^5 q$		p-wave
C5	$\lambda_5 \sim \alpha_s/(8M^2)$	$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$	✓	s-wave
C6	$\lambda_6 \sim \alpha_s/(8M^2)$	$i\chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$		s-wave

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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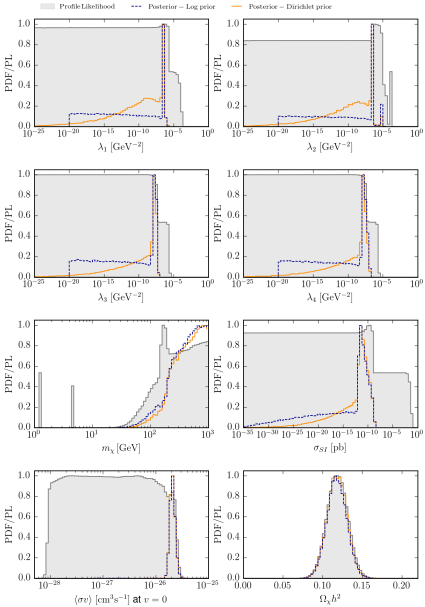
– profile likelihood

– flat prior on log λ_i [prior $1/\lambda_i$]

– Dirichlet prior prefering similar-sized Wilson coefficients



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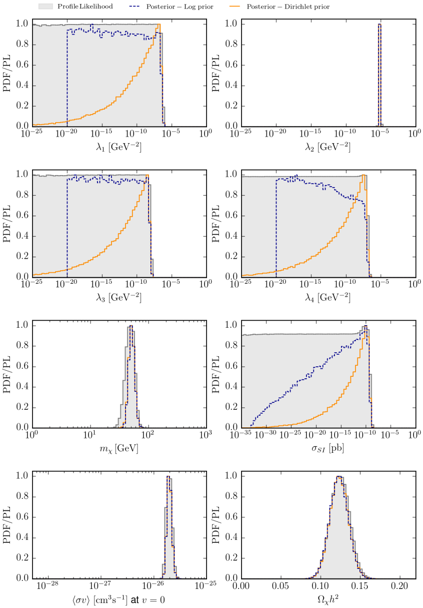
– Fermi: GCE plus dwarf galaxies

$\Rightarrow$ 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]

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

– mixing to the observed Higgs mass eigenstate

$$H_1 = \cos\chi\, H_\phi + \sin\chi\, S$$

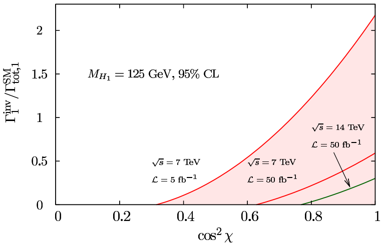
– decays to SM and hidden sectors [plus $H_2 \to H_1 H_1$ cascade decays]

$$\Gamma_1 = \cos^2\chi\,\Gamma_1^{\rm SM} + \sin^2\chi\,\Gamma_1^{\rm hid} = \cos^2\chi\,\Gamma_1^{\rm SM}\left(1 + \tan^2\chi\,\frac{\Gamma_1^{\rm hid}}{\Gamma_1^{\rm SM}}\right)$$

– constraints on event rate

$$\frac{\sigma_{H_1\to{\rm SM}}}{\sigma^{\rm SM}_{H_1\to{\rm SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi\,\frac{\Gamma_1^{\rm hid}}{\Gamma_1^{\rm SM}}} \stackrel{!}{<} \mathcal{R}$$

– collider reach



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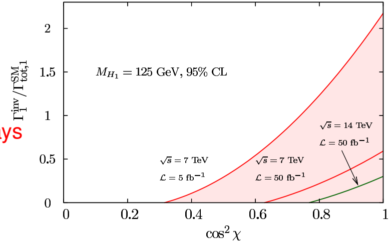
$\Rightarrow$ resonance, rates, and invisible Higgs decays



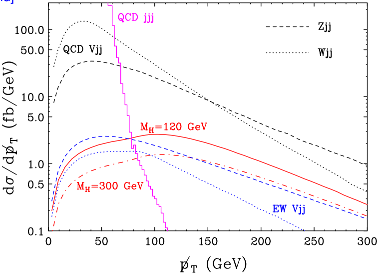
Invisible Higgs decays

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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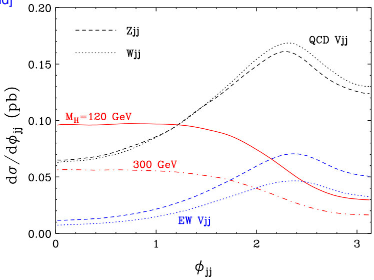

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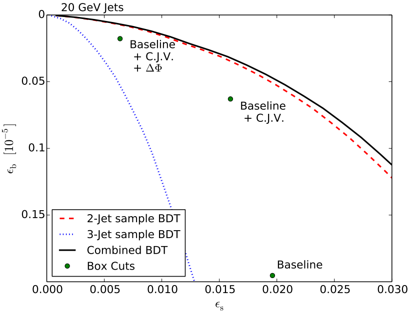
Multivariate update [Bernaciak, TP, Schichtel, Tattersall]

– baseline cuts: jet veto plus $\Delta\phi_{jj}$
multivariate: 2-jet, 3-jet sample

– reach $\text{BR}_\text{inv} \sim 4\%$ for 3000 fb^{-1}

– further improvement to 2%
from QCD jets to 10 GeV...

$\Rightarrow$ QCD the limiting factor



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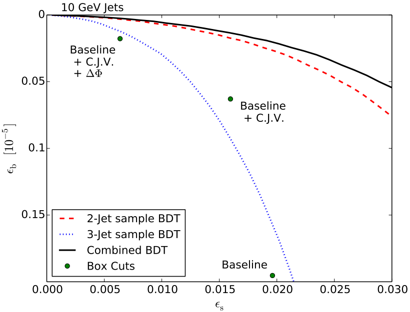

(Simplified) two Higgs doublets

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

$$V(\phi_1,\phi_2) = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - \left[m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.} \right]$$
$$+ \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 |\phi_1^\dagger \phi_2|^2$$
$$+ \left[\frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \lambda_6 (\phi_1^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \lambda_7 (\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2) + \text{h.c.} \right]$$

Two doublets [no flavor, CP, custodial troubles]

– angle $\beta = \text{atan}(v_2/v_1)$
angle α defining h and $H \rightarrow$ gauge boson coupling $g_{W,Z} = \sin(\beta - \alpha) g_{W,Z}^\text{SM}$

– type-I: all fermions with ϕ_2
type-II: up-type fermions with ϕ_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 [simplfied supersymmetry]

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

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

- contribution through loops all over Higgs-gauge sector

Triplet gauge extension [whatever that becomes in the UV]

- additional vector triplet field V_μ

$$\mathcal{L} \supset -\frac{1}{4} \tilde{V}^a_{\mu\nu} \tilde{V}^{\mu\nu a} + \frac{M^2_{\tilde{V}}}{2} \tilde{V}^a_\mu \tilde{V}^{\mu a} + i \frac{g_V}{2} c_H \tilde{V}^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \phi \right] + \frac{g_w^2}{2 g_V} \tilde{V}^a_\mu \sum_{\text{fermions}} c_F \overline{F}_L \gamma^\mu \sigma^a F_L$$
$$+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} \tilde{V}^a_\mu \tilde{V}^b_\nu D^{[\mu} \tilde{V}^{\nu]c} + g_V^2 c_{VVHH} \tilde{V}^a_\mu \tilde{V}^{\mu a} (\phi^\dagger \phi) - \frac{g_w}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu} \tilde{V}^b_\mu \tilde{V}^c_\nu$$

- 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]

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theory: how do D6 vs EFT vs full model differences appear?

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

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 10\% \qquad \Leftrightarrow \qquad \Lambda \lesssim 400 \ \text{ GeV}$$

no scale hierarchy for testable models?!

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  matching conditions with $v \lesssim \Lambda$, v-improved matching?

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– LHC simulations: D6-Lagrangian vs full model
  production: WBF, VH, HH
  decays: $H \to \gamma\gamma, 4\ell$

– check where differences appear at 13 TeV
  kinematic distributions like $p_{T,j}$ or m_{VH}?
  resonance peaks of new states?

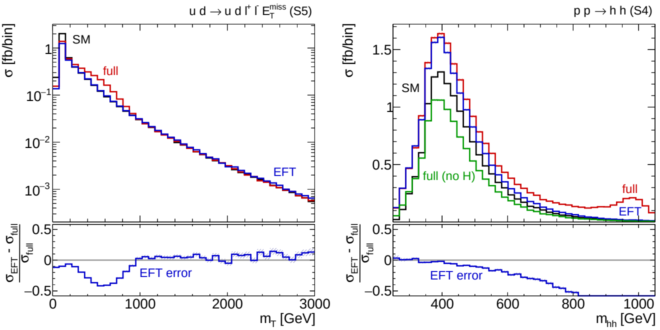
Higgs D6 breakdown

Higgs portal

– testable benchmarks for LHC

Singlet				EFT			EFT (v-improved)	
m_H	$\sin\alpha$	v_s/v	$\Delta_x^{\text{singlet}}$	Λ	$\bar{c}_H$	Δ_x^{EFT}	$\bar{c}_H$	Δ_x^{EFT}
500	0.2	10	−0.020	491	0.036	−0.018	0.040	−0.020
350	0.3	10	−0.046	336	0.073	−0.037	0.092	−0.046
200	0.4	10	−0.083	190	0.061	−0.031	0.167	−0.083
1000	0.4	10	−0.083	918	0.183	−0.092	0.167	−0.092
500	0.6	10	−0.200	407	0.461	−0.231	0.400	−0.200

– effects in WBF and hh



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Higgs portal

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2HDM

– testable benchmarks for LHC

2HDM							EFT		
Type	$\tan\beta$	α/π	m_{12}	m_{H^0}	m_{A^0}	$m_{H^\pm}$	$\lvert\Lambda\rvert$ [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

Higgs D6 breakdown

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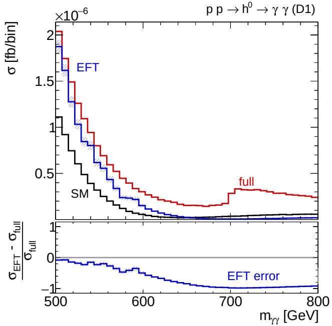
I	20	0	45	200	500	500	[illegible]	[illegible]	[illegible]

- effects in $H \to \gamma\gamma$



Higgs D6 breakdown

Higgs portal

– testable benchmarks for LHC
– effects in WBF and *hh*

2HDM

– testable benchmarks for LHC
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Top partners

– testable benchmarks for LHC

Scalar top-partner model						EFT		
M	κ_{LL}	κ_{RR}	κ_{LR}	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$\bar{c}_H$	$\bar{c}_W$	$\bar{c}_{HW}$
500	-1.16	2.85	0.147	500	580	$6.22 \cdot 10^{-3}$	$-3.11 \cdot 10^{-7}$	$3.99 \cdot 10^{-7}$
350	-3.16	-2.82	0.017	173	200	$4.30 \cdot 10^{-3}$	$-2.55 \cdot 10^{-4}$	$2.55 \cdot 10^{-4}$
500	-7.51	-7.17	0.012	173	200	$1.66 \cdot 10^{-2}$	$-2.97 \cdot 10^{-4}$	$2.97 \cdot 10^{-4}$

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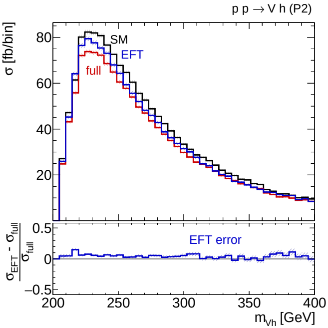

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Vector triplet [Brehmer, Biekötter, Krämer, TP]

– testable benchmarks for LHC

Triplet model						EFT			
M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ	$\bar{c}_W$	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_f$
591	3.0	−0.47	−5.0	2.0	1200	−0.044	0.000	0.000	0.000
946	3.0	−0.47	−5.0	1.0	1200	−0.017	0.000	0.000	0.000
941	3.0	−0.28	3.0	1.0	1200	0.006	0.075	0.100	0.025
1246	3.0	−0.50	3.0	−0.2	1200	0.006	0.103	0.138	0.034
846	1.0	−0.56	−1.32	0.08	849	−0.007	−0.020	−0.027	−0.007

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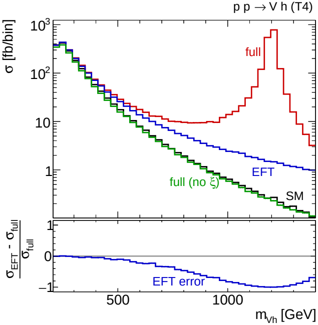

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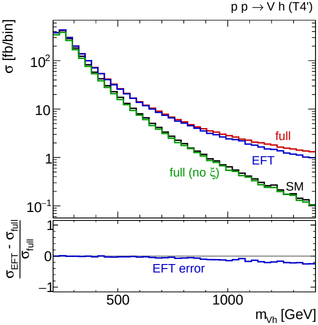

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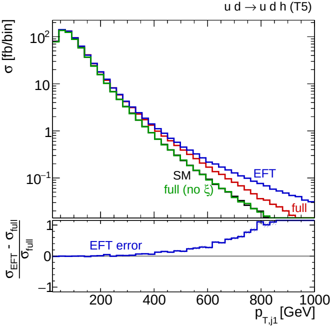

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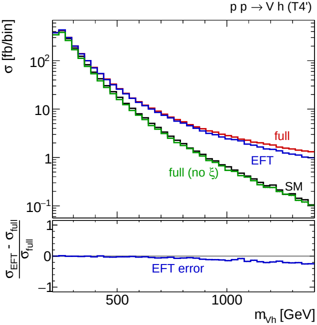

Higgs D6 breakdown

Reasons for D6-breakdown in Higgs sector at LHC

Model	Process	EFT failure		
		resonance	kinematics	matching
singlet	on-shell $h \to 4\ell$, WBF, Vh, ...			$\times$
	off-shell WBF, ...		$(\times)$	$\times$
	hh	$\times$	$\times$	$\times$
2HDM	on-shell $h \to 4\ell$, WBF, Vh, ...			$\times$
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vector triplet	WBF		$(\times)$	$\times$
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	hh	$\times$	$\times$	$\times$
top partner	WBF, *Vh*			$\times$
vector triplet	WBF		$(\times)$	$\times$
	Vh	$\times$	$(\times)$	$\times$

Lessons from Higgs sector

– start with D6 description [data-driven era of particle physics]

– EFT expansion in E/Λ 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 [data-driven question]

- scalar dark matter, $m_S = 10 \ldots 100$ 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

$$m_S = \sqrt{2\mu_S^2 - \lambda_3 v_H^2} \qquad g_{SSH} = -2\lambda_3 v_H \qquad g_{SSHH} = -2\lambda_3$$

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DM conditions

– (in-) direct detection: same as DM EFT
LHC: $m_S \leftrightarrow m_H$ open, all propagating states

– thermal relic density $\Omega h^2 \sim 0.12$ [$SS \to b\bar{b}, HH$]

$$\sigma_{\text{ann}} \propto \begin{cases} \dfrac{\lambda_3^2 m_b^2}{m_H^4} & m_S \ll \dfrac{m_H}{2} \qquad \lambda_3 \approx 0.3 \\ \dfrac{\lambda_3^2 m_b^2}{m_H^2 \Gamma_H^2} & m_S = \dfrac{m_H}{2} \qquad \lambda_3 \approx 10^{-3} \\ \dfrac{\lambda_3^2}{m_S^2} & m_S > m_Z, m_H \qquad \lambda_3 \approx 0.1 \end{cases}$$

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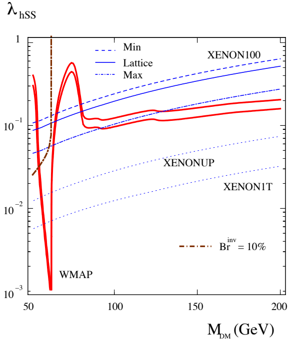

(Simplified) DM scalar

(In-) direct detection boundary conditions

– Higgs mediator coupling to proton
  same effective *ggH* interaction as for gluon fusion production

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

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

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 λ_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...

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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

$\Rightarrow$ there is no such thing as a wrong simplified model

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General structure of simplified DM models

– relatively light dark matter candidate
– mediator, often inducing $2 \to 2$ scattering process $\chi\chi \to$ SM SM
– predicting relice density, (in-) direct detection, LHC observables

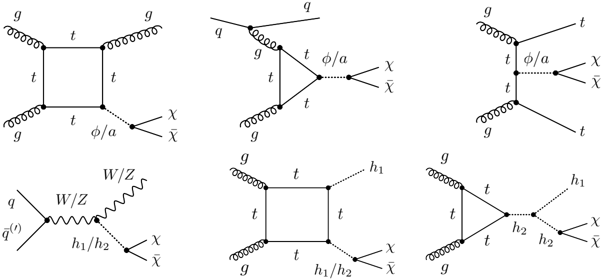
(Simplified) DM models

DM–mediator pairings [1506.03116, 1507.00966]

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

$$\mathcal{L}_{\text{fermion},\phi} \supset -g_\chi \phi \bar{\chi}\chi - \frac{\phi}{\sqrt{2}} \sum_f g_f y_i^f \bar{f}_i$$

– mono-jet(s), mono-V, mono-Higgs [not necessarily ISR]



⇒ mediators almost more relevant than DM states

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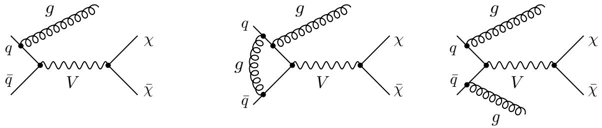
$$\mathcal{L}_{\text{fermion},V} \supset V_\mu \bar{\chi}\gamma^\mu (g_\chi^V - g_\chi^A \gamma_5)\chi + \sum_f V_\mu \bar{f}\gamma^\mu (g_f^V - g_f^A \gamma_5) f \,,$$

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

– mono-jet(s) or di-jet resonances



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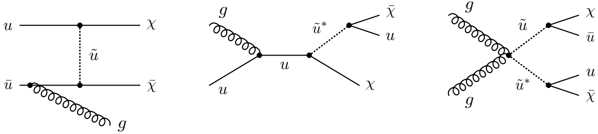
(3) t-channel mediator, fermion DM [scalar darkoquark]

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

– mono-jet(s), associated, pair production [mono-jet vs jet(s + MET]



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– 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, $Z\widetilde{H}^0\widetilde{H}^0$ and $h\widetilde{H}^0\widetilde{W}^0$ 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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– pure-state WIMP electroweakinos heavy

– chargino co-annihilation crucial

– mixed bino scenario through mixing

$\Rightarrow$ not covered by usual simplified models

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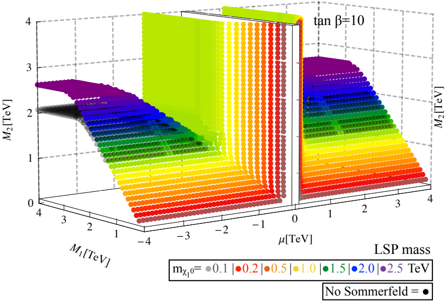
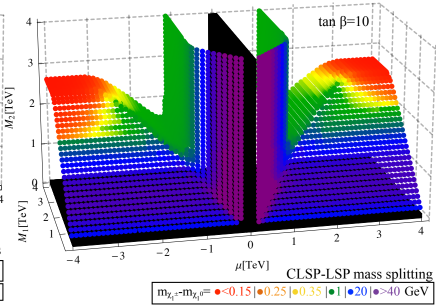
Relic neutralino surface [MSSM; Bramante,...]





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(μ) and tan β in Higgs sector

– gauge, anomaly, gaugino mediation...?

⇒ measure spectrum at LHC [pMSSM]

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
→ sfermion	$\tilde{f}_L$, $\tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^o, H^o, A^o	0	3	
→ neutralinos	$\tilde{\chi}_i^o$	1/2	$4 \cdot 2$	SM
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→ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	

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(μ) and $\tan\beta$ in Higgs sector

– gauge, anomaly, gaugino mediation...?

$\Rightarrow$ measure spectrum at LHC [pMSSM]

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
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Search strategies at the LHC [Oliver's talk]

– squarks, gluinos strongly interacting
$p\bar{p} \to \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$

decays to jets and DM state
$\tilde{g} \to \tilde{q}\bar{q}$, $\tilde{q}_L \to q\tilde{\chi}_2^0$, $\tilde{q}_R \to q\tilde{\chi}_1^0$

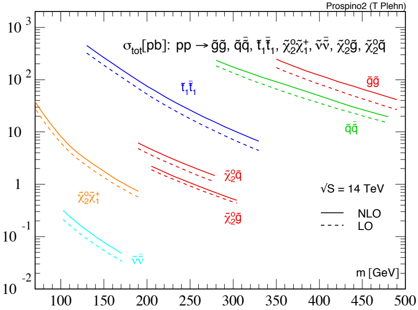
additional jets and leptons possible

$\Rightarrow$ 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 $\longleftrightarrow$ LHC [Butter etal]

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

$\Rightarrow$ linked to LHC signatures?

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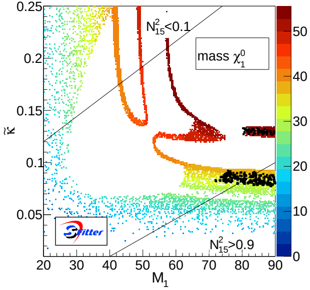
LHC signatures [Butter etal]

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

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



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LHC signatures [Butter etal]

– requiring relic density

– requiring GCE rate

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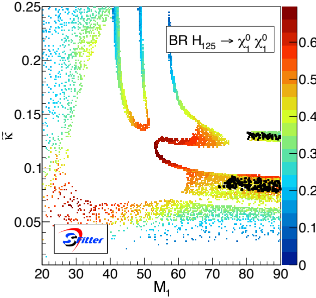
$\Rightarrow$ chargino-neutralino rate [Cao, Zurek,...]

$\Rightarrow$ 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/`

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