New physics at the TeV scale: extra Higgses and WIMP Dark Matter

Filippo Sala

LPTHE Univ. Paris 6 and CNRS

IFAC, Université de Montpellier, 8 Dec 2015

The Standard Model

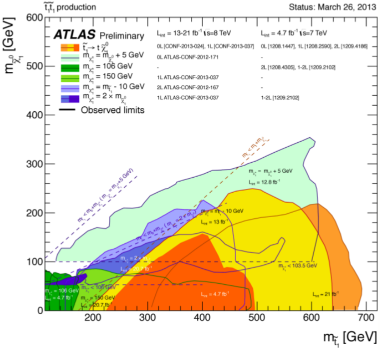
?The Standard Model?

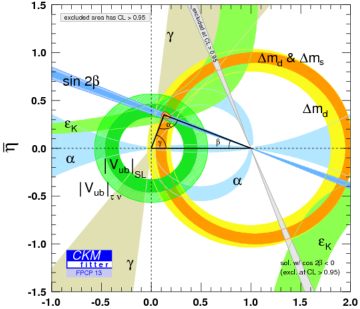
? Supersymmetry ?   ???   ? Composite models ?

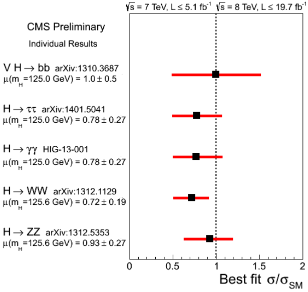
Where is New Physics? Experiments

Neat indications of NP:

Gravity, Dark Matter, ν, ... but:







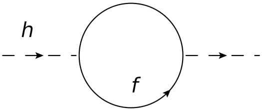
The Hierarchy Problem of the Fermi scale [Wilson 1971,...]

$m_h \approx \Lambda$ [$\Lambda =$ highest scale h couples to, e.g. $M_{\rm Planck,GUT}$]

The Hierarchy Problem of the Fermi scale [Wilson 1971,...]

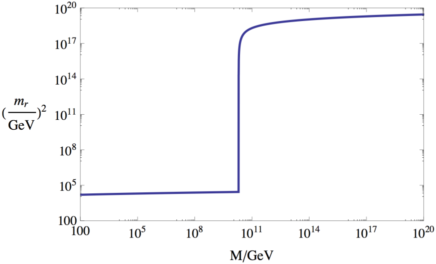
$m_h \approx \Lambda$ [$\Lambda =$ highest scale h couples to, e.g. $M_{\rm Planck,GUT}$]

$\Lambda =$ "cutoff"? Misleading: SM is renormalizable and divergences do not appear.



$$\mathcal{L} \supset y\, h \bar{f} f \quad \Rightarrow \quad \frac{dm_h^2}{d\log\mu} = -\frac{3y^2}{4\pi^2} M_f^2$$

$$m_h^2(m_h^2) \simeq m_h^2(M_{NP}) - aM_{NP}^2 \log \frac{M_{NP}^2}{m_h^2}$$



Fine tuning $\Delta \simeq aM_{NP}^2/m_h^2$

[e.g. $a \propto y^2$]

Hierarchy Problem: initial condition $m_h^2(M_{NP})$ to be chosen with precision $\sim 1/\Delta$

Physics at the Fermi scale depends on details of way shorter distances!

Where is New Physics? Theory

Answer "$\equiv$" attitude towards the hierarchy problem

Where is New Physics? Theory

Answer "$\equiv$" attitude towards the hierarchy problem

$M_{\rm NP} = 0.1 \div 10$ TeV   The Fermi scale is **natural**

Protect the mass of the scalars from any NP   ['t Hooft 1979, ...]

Examples   1. Supersymmetry   2. Compositeness

1. Symmetry wants $m_h = 0$, like chiral symmetry wants $m_e = 0$
   SUSY broken at scale $\sim M_{\rm NP}$

2. Higgs is a condensate of new strongly-interacting theory at $M_{\rm NP}$

☺ "Big" hierarchy m_h vs $M_{\rm Planck,GUT}$ solved

Where is New Physics? Theory

Answer "≡" attitude towards the hierarchy problem

$M_{\rm NP} = 0.1 \div 10$ TeV

The Fermi scale is **natural**

Protect the mass of the scalars from any NP ['t Hooft 1979, ...]

Examples 1.Supersymmetry 2.Compositeness

1. Symmetry wants $m_h = 0$, like chiral symmetry wants $m_e = 0$
   SUSY broken at scale $\sim M_{\rm NP}$

2. Higgs is a condensate of new strongly-interacting theory at $M_{\rm NP}$

☺ "Big" hierarchy m_h vs $M_{\rm Planck,GUT}$ solved

☹ "Little" hierarchy problem: Fine-tuning Δ "small" $\Rightarrow M_{\rm NP}$ "small"
but experiments $\Rightarrow M_{\rm NP}$ "largish"...

Where is New Physics? Theory

Answer "≡" attitude towards the hierarchy problem

$M_{\rm NP} = 0.1 \div 10$ TeV

The Fermi scale is **natural**

Protect the mass of the scalars from any NP ['t Hooft 1979, ...]

Examples 1.Supersymmetry 2.Compositeness

1. Symmetry wants $m_h = 0$, like chiral symmetry wants $m_e = 0$
SUSY broken at scale $\sim M_{\rm NP}$

2. Higgs is a condensate of new strongly-interacting theory at $M_{\rm NP}$

☺ "Big" hierarchy m_h vs $M_{\rm Planck,GUT}$ solved

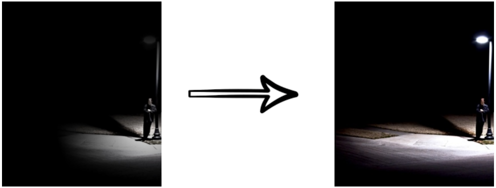
☹ "Little" hierarchy problem : Fine-tuning Δ "small" $\Rightarrow M_{\rm NP}$ "small"
but experiments $\Rightarrow M_{\rm NP}$ "largish"...

$M_{\rm NP}$ can be $\gg$ TeV

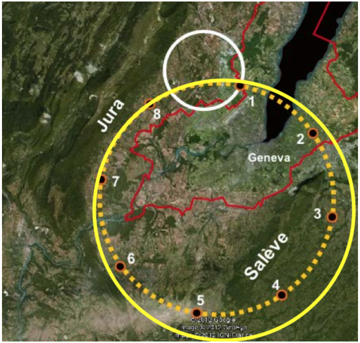
→ Think different (e.g. "UV naturalness", cosmological relaxation)

→ Accept the tuning Δ (and go anthropic)

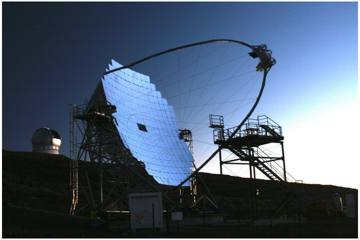
Future lampposts in this talk



Colliders



Telescopes



Where to look for New Physics?

→ Extra Higgses and "natural" New Physics

mostly based on Buttazzo S Tesi, 1505.05488

→ Heavy WIMP Dark Matter

Cirelli Hambye Panci S Taoso, 1507.05519 and in progress

Where to look for New Physics?

→ Extra Higgses and "natural" New Physics

mostly based on Buttazzo S Tesi, 1505.05488

- ◇ Can new Higgses be the lightest new particles around?

- ◇ How to look for them?

◇ Can new Higgses be the lightest new particles around?

Another light scalar looks hard to be justified with anthropic arguments

◇ Can new Higgses be the lightest new particles around?

Another light scalar looks hard to be justified with anthropic arguments

Extra **Singlet**-like Higgses are ubiquitous, for example in

→ Twin Higgs

→ Supersymmetry

→ Electroweak Baryogenesis (independent of naturalness)

Could the radial mode be the first new particle seen?

Could the radial mode be the first new particle seen?

Why TH interesting? Solves little hierarchy, without coloured top partners

If nothing new at the LHC14, TH models still quite natural!

→ Add a Z_2-symmetric copy of the SM

[only copy of top strictly necessary see e.g. J Serra @ MIAPP 2015]

→ 8 “Higgs” degrees of freedom - vs 4 in the SM

7 are massless Goldstone bosons

one, σ = radial mode of $\mathcal{G} \to \mathcal{H}$

$\langle\sigma\rangle = f$, $m_\sigma \sim f$ conceivable if UV completion is weakly coupled

Could the radial mode be the first new particle seen?

Why TH interesting? Solves little hierarchy, without coloured top partners

If nothing new at the LHC14, TH models still quite natural!

→ Add a Z_2-symmetric copy of the SM

[only copy of top strictly necessary see e.g. J Serra @ MIAPP 2015]

→ 8 "Higgs" degrees of freedom - vs 4 in the SM

7 are massless Goldstone bosons

one, σ = radial mode of $\mathcal{G} \to \mathcal{H}$

$\langle\sigma\rangle = f$, $m_\sigma \sim f$ conceivable if UV completion is weakly coupled

Other particles? Either $M \gtrsim 4\pi f$ or very weakly coupled

Extra Higgses in Supersymmetry

Could the singlet-like scalar be the first new particle seen?

Extra Higgses in Supersymmetry

Could the singlet-like scalar be the first new particle seen?

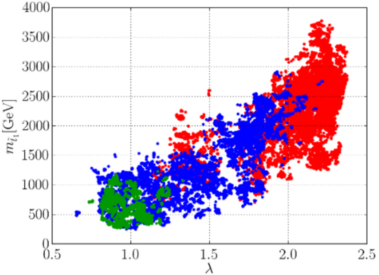
MSSM Fine tuning worse than 1%! [v sensitivity to $m_{\tilde{t}}$ fixed by $SU(2)_L$]

NMSSM Given a fixed tuning, $\tilde{t}$ and $\tilde{g}$ heavier by $\sim \lambda/g$ than in MSSM

$$\text{NMSSM} \quad = \quad \text{MSSM} + \text{singlet } S$$

$$W = W_{\text{MSSM}} + \lambda S H_u H_d + f(S)$$

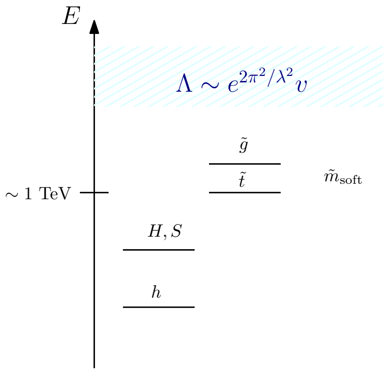
Fine tuning better than 5% $\longrightarrow$
[green points, $\tan\beta \lesssim 5$, $\Lambda = 20$ TeV]



Gherghetta et al. 1212.5243
see also Gherghetta et al. 1401.8291
Cao et al. 1409.8431

NMSSM with $\lambda \sim 1$ and heavy stops & gluinos

[$\lambda \gtrsim 0.7$ needs a completion before GUT scale!]



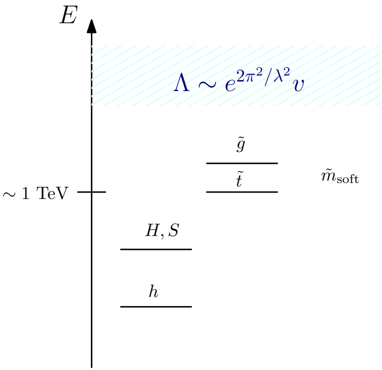
NMSSM spectrum

NMSSM with $\lambda \sim 1$ and heavy stops & gluinos

[$\lambda \gtrsim 0.7$ needs a completion before GUT scale!]

The scalars are:

- CP-even h, h_3, ϕ (from h_v, H, S)
- CP-odd A, A_s
- $H^{\pm}$



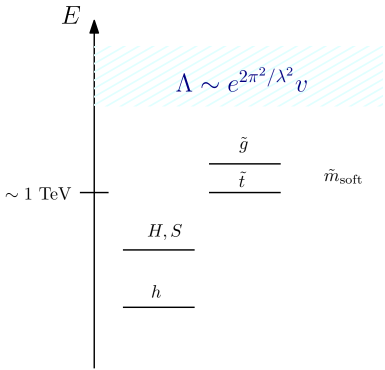
NMSSM spectrum

NMSSM with $\lambda \sim 1$ and heavy stops & gluinos

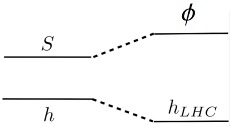
[$\lambda \gtrsim 0.7$ needs a completion before GUT scale!]

The scalars are:

CP-even h, h_3, ϕ (from h_v, H, S)



$$\mathcal{H}_{\text{ph}} \equiv \begin{pmatrix} h_3 \\ h \\ \phi \end{pmatrix} = R^T \begin{pmatrix} H \\ h_v \\ S \end{pmatrix}, \quad R = R^{12}_{\delta} R^{23}_{\gamma} R^{13}_{\sigma}$$



$\gamma = h_v - S$ mixing

A motivated limiting case

$m_{h_3} \gg m_{h,\phi}$ and $\sigma, \delta \to 0$

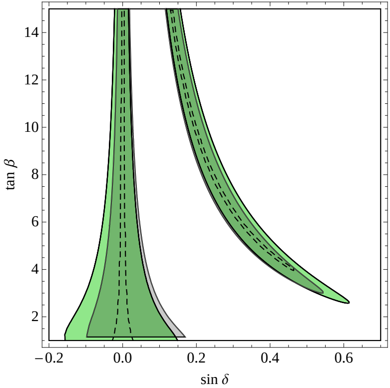
Bottom-up motivation for a Singlet: Higgs couplings fit

Bottom-up motivation for a Singlet: Higgs couplings fit

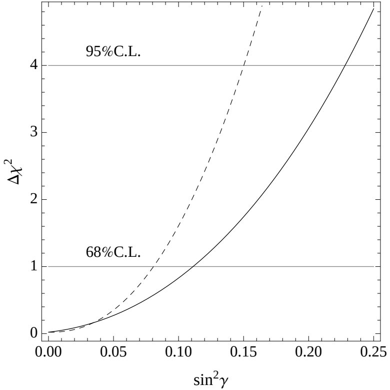
$$h_{\rm LHC} = h = c_\gamma(c_\delta h_v - s_\delta H) + s_\gamma S$$

$$\left[\frac{g_{htt}}{g_{htt}^{\rm SM}} = c_\gamma\left(c_\delta + \frac{s_\delta}{\tan\beta}\right), \qquad \frac{g_{hbb}}{g_{hbb}^{\rm SM}} = c_\gamma(c_\delta - s_\delta \tan\beta), \qquad \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = c_\gamma c_\delta\right]$$

cont: LHC8 status   dashed: LHC14 projections (300 fb^{-1})



$s_\gamma^2 = 0, 0.15$

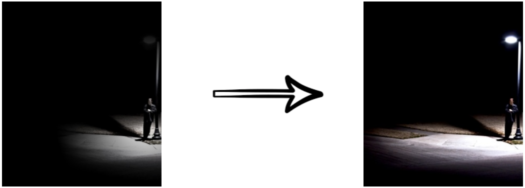


✓ Can new Higgses be the lightest new particles around?

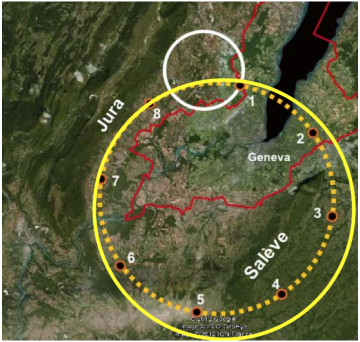
◇ How to look for them?

◇ How to look for them?

At which machines?



Currently unclear where particle physicists will put (EU? China? ???) money:



HL-LHC $\sqrt{s} = 14$ TeV, 3000 fb^{-1}, $\sim$ 2025-2035

HE-LHC $\sqrt{s} = 33$ TeV, needs new technology

FCC-hh $\sqrt{s} \sim 100$ TeV, start $\sim$ 2040(?),
needs $\sim$ 100 km tunnel

ILC $\sqrt{s} = 0.5 - 1$ TeV, maybe Japan soon

CLIC $\sqrt{s}$ up to 3 TeV, needs new technology

FCC-ee $\sqrt{s}$ up to 500 GeV, higher luminosity,
needs $\sim$ 100 km tunnel

Generic singlet

$$\boxed{\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}}$$

Master formula, valid for **any** model

2 free parameters control all pheno! $+ \text{BR}_{\phi\to hh}$ ($= \text{BR}_{\phi\to ZZ}$ at $m_\phi \gg m_W$)

Generic singlet

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

Master formula, valid for **any** model

2 free parameters control all pheno! $+ \mathrm{BR}_{\phi\to hh}$ $(= \mathrm{BR}_{\phi\to ZZ}$ at $m_\phi \gg m_W)$

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\mathrm{SM}}$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\mathrm{SM}}(m_\phi)$ [barring $\phi \to hh$]

Generic singlet

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

Master formula, valid for **any** model

2 free parameters control all pheno! $+ \ \mathrm{BR}_{\phi\to hh}$ $(= \mathrm{BR}_{\phi\to ZZ}$ at $m_\phi \gg m_W)$

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\mathrm{SM}}$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\mathrm{SM}}(m_\phi)$ [barring $\phi \to hh$]

What does one learn from the potential $f(S)$?

$$\mathrm{BR}_{\phi\to hh} = \frac{1}{4} - \frac{3}{4}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi} + O\left(\frac{v^2}{m_\phi^2}\right)$$

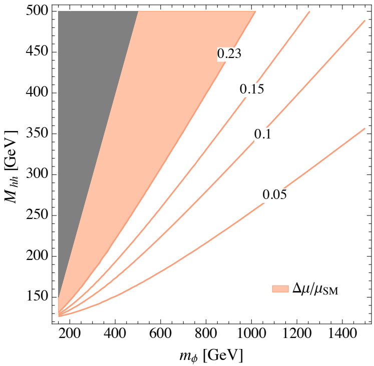
$$\frac{g_{h^3}}{g_{h^3}^{\mathrm{SM}}} = 1 + \frac{2}{3}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi}\left(\frac{M_{hh}^2}{m_h^2} - 1\right) + O\left(\frac{v^2}{m_\phi^2}\right)$$

Valid for **any** potential!! v_s leading new parameter

Generic singlet: Higgs couplings

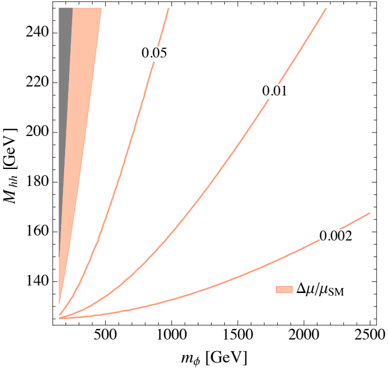
$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$



1σ reach in	s_γ^2	$\left\lvert 1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}} \right\rvert$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	4-8×10^{-2}	0.5
HE-LHC	–	0.2
FCC-hh	–	0.08
ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
CLIC	2-3×10^{-3}	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

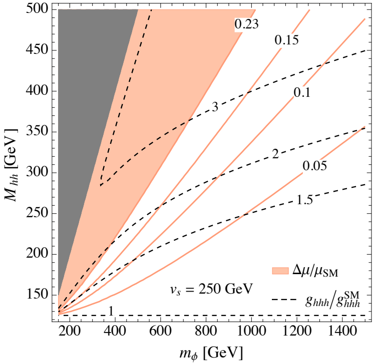
Snowmass 2013



Generic singlet: Higgs couplings

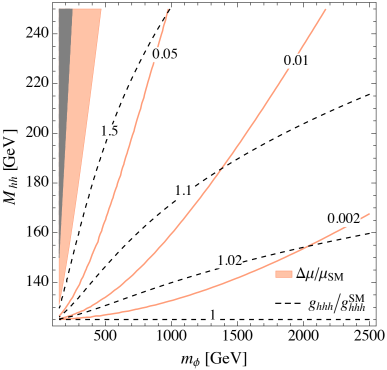
$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$ Add g_{hhh}: could be first deviation seen!



1σ reach in	s_γ^2	$\left\|1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}}\right\|$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	4-8×10^{-2}	0.5
HE-LHC	–	0.2
FCC-hh	–	0.08
ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
CLIC	2-3×10^{-3}	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

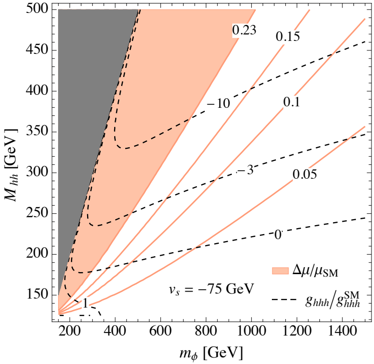
Snowmass 2013



Generic singlet: Higgs couplings

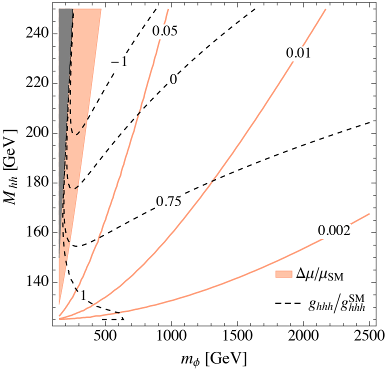
$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$ Add g_{hhh}: could be first deviation seen!



1σ reach in	s_γ^2	$\left\|1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}}\right\|$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	4-8×10^{-2}	0.5
HE-LHC	–	0.2
FCC-hh	–	0.08
ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
CLIC	2-3×10^{-3}	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

Snowmass 2013



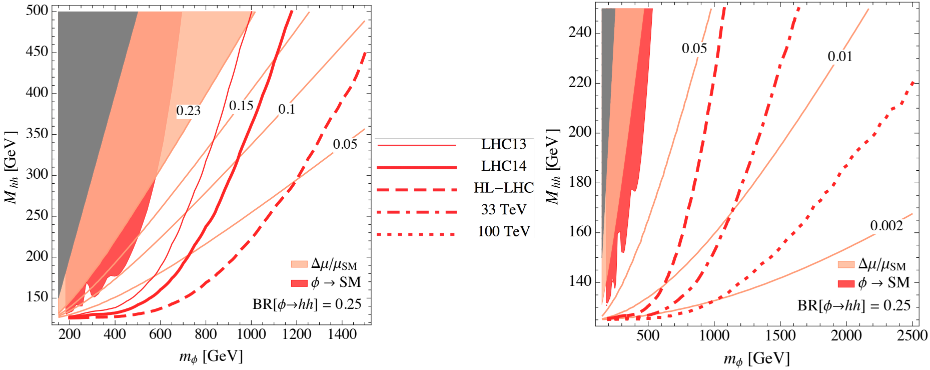
Generic singlet: Higgs couplings vs direct searches

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

LHC bounds scaled with parton luminosities

[$\phi \to VV$ dominates over $\phi \to hh$, unless $v_s < 0$ and small]

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\rm SM}(m_\phi)$ [barring $\phi \to hh$]



Twin Higgs and the NMSSM

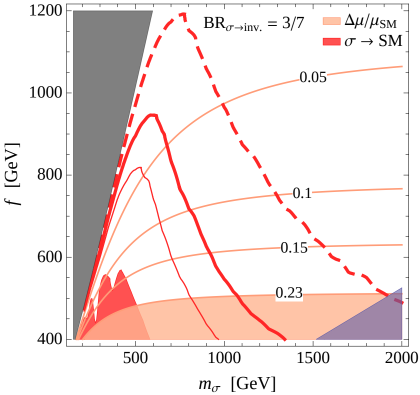
$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

Twin Higgs: $M_{hh}^2 = (m_h^2 + m_\phi^2)\, v^2/f^2$

Take-home messages

Twin Higgs:

- → Signal strengths μ_h more effective than direct ϕ searches, unless $m_\phi \sim f$
- → no significant deviations in g_{hhh}



...more in back up slides

Twin Higgs and the NMSSM

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

Twin Higgs: $M_{hh}^2 = (m_h^2 + m_\phi^2)\, v^2/f^2$

NMSSM: $M_{hh}^2 = m_Z^2\, c_{2\beta}^2 + \lambda^2 v^2\, s_{2\beta}^2 + \Delta^2$

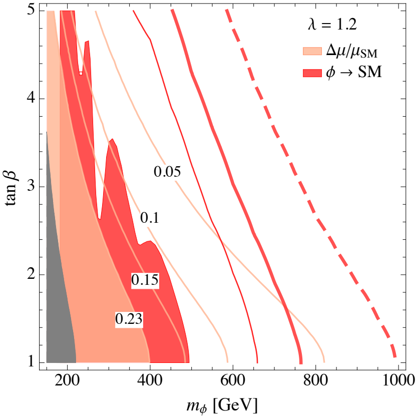
Take-home messages

Twin Higgs:

- → Signal strengths μ_h more effective than direct ϕ searches, unless $m_\phi \sim f$
- → no significant deviations in g_{hhh}

NMSSM:

- → For μ_h to do better than direct ϕ searches, per-mille precision needed
- → g_{hhh} could show significant deviations

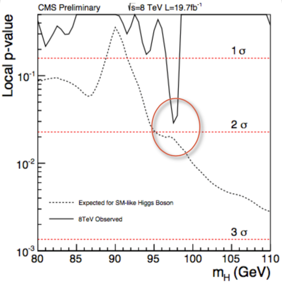


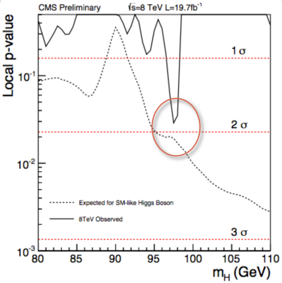
...more in back up slides

Fully mixed case and a $\gamma\gamma$ signal

Singlet-like state lighter than 125 GeV

Hard to see, could it explain this hint?





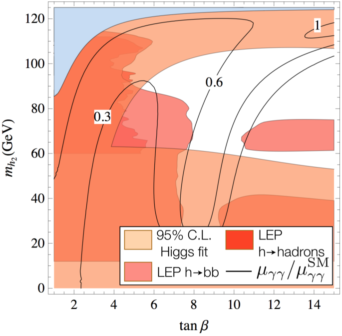
Singlet-like state lighter than 125 GeV

Hard to see, could it explain this hint?

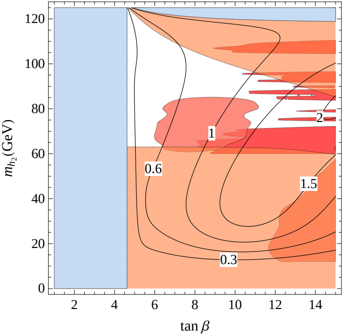
[see also Badziak et al. 1304.5437,...]

$[m_{h_3} = 500 \text{ GeV},\ s^2_\sigma = 10^{-3},\ v_s = v]$

$\lambda = 0.1, \Delta_t = 85$ GeV



$\lambda = 0.8, \Delta_t = 75$GeV



Where to look for New Physics?

✓ Extra Higgses and "natural" New Physics

mostly based on Buttazzo S Tesi, 1505.05488

→ Heavy WIMP Dark Matter

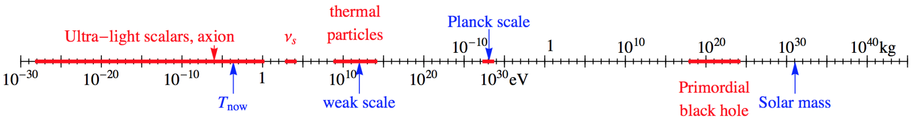
Cirelli Hambye Panci S Taoso, 1507.05519 and in progress

Where to look for New Physics?

$\rightarrow$ Heavy WIMP Dark Matter

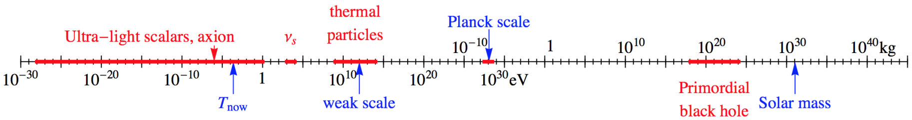
Cirelli Hambye Panci S Taoso, 1507.05519 and in progress

Where is Dark Matter?

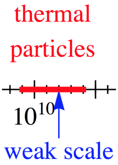


[courtesy of Marco Cirelli]

Where is Dark Matter?



[courtesy of Marco Cirelli]



How to probe the "thermal relic WIMP" paradigm?

[Unitarity bound: $M_{\rm DM} < 80 \div 120$ TeV Griest Kamionkowski 1990,

...

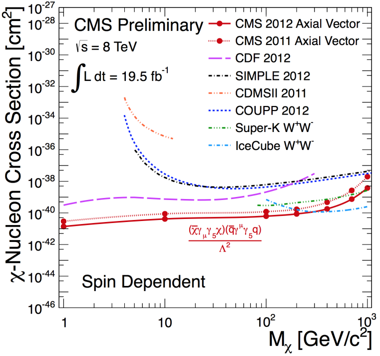
Cahill-Rowley et al. 1501.03153]

General strategy: effective field theories?

The EFT approach:

☺ Model-independent

☺ easy comparison collider - direct detection



General strategy: effective field theories?

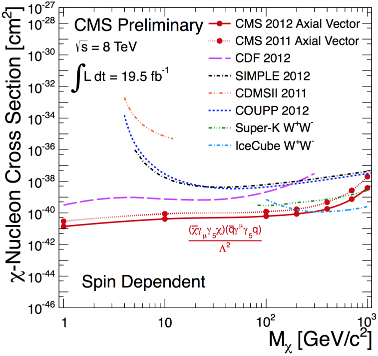
The EFT approach:

☺ Model-independent

☺ easy comparison collider - direct detection

☹ ∼ wrong for LHC (especially 14 TeV) !!

often momentum transfer > suppression scale Λ



Lot of recent activity Busoni et al 1307.2253 and 1402.1275,
Buchmuller et al 1308.6799,...
Abdallah et al 1409.2893,
Racco Wulzer Zwirner 1502.04701

Need to go to benchmark/simplified models!

Quantum numbers		
$SU(2)_L$	$U(1)_Y$	Spin
3	0	F
5	0	F

An EW fermion multiplet

Possibly the "simplest" simplified model

Despite a simple benchmark, why an EW multiplet χ?

- ☺ **Minimal Dark Matter** Cirelli Fornengo Strumia hep-ph/0512090

  Philosophy: Focus on DM, and try to preserve SM successes (flavour & CP, ..)
  + DM stability, adding the least possible ingredients to the theory

  Approach: add to the SM extra particle χ
  and determine its "good" quantum numbers

  "good" = i) stable ii) lightest component neutral iii) allowed

  Result: 5plet, 3plet [but add symmetry, like $B - L$ or L or subgroup...]

- ☺ **Supersymmetry**: EW triplet $\equiv$ pure Wino LSP! (Split SUSY, ...)

Despite a simple benchmark, why an EW multiplet χ?

☺ **Minimal Dark Matter** Cirelli Fornengo Strumia hep-ph/0512090

Philosophy: Focus on DM, and try to preserve SM successes (flavour & CP, ..)
+ DM stability, adding the least possible ingredients to the theory

Approach: add to the SM extra particle χ
and determine its "good" quantum numbers

"good" = i) stable ii) lightest component neutral iii) allowed

Result: 5plet, 3plet [but add symmetry, like $B-L$ or L or subgroup...]

☺ **Supersymmetry**: EW triplet ≡ pure Wino LSP! (Split SUSY, ...)

Phenomenology:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\,\bar{\chi}(i\hat{D} - M_\chi)\chi$$

M_χ is the only one free parameter, fixed if we impose thermal relic abundance!

$$M^{\rm 3plet}_{\rm thermal} \simeq 3 \text{ TeV} \qquad M^{\rm 5plet}_{\rm thermal} \simeq 9.4 \text{ TeV}$$

EW multiplets at colliders: disappearing tracks

5plet No hopes to reach $M_{\rm thermal}$

3plet No hopes to reach $M_{\rm thermal}$ before a 100 TeV collider (i.e. before 2040)

EW multiplets at colliders: disappearing tracks

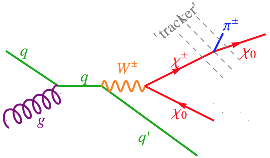
5plet No hopes to reach $M_{\rm thermal}$

3plet No hopes to reach $M_{\rm thermal}$ before a 100 TeV collider (i.e. before 2040)

$$M_{\chi^\pm} - M_{\chi_0} = 165 \text{ MeV} > m_\pi \quad \Rightarrow \quad \text{lifetime } \tau \simeq 6\,\text{cm} \simeq 0.2\,\text{ns}$$

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors

Feng et al 1999, ...



ATLAS performed this analysis!

Current strongest limit on pure Wino

$$M_{\chi_0} > 270 \text{ GeV}$$

Monojet etc: way less reach

EW multiplets at colliders: disappearing tracks

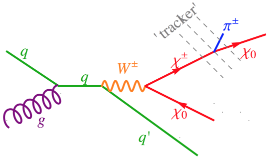
5plet No hopes to reach $M_{\rm thermal}$

3plet No hopes to reach $M_{\rm thermal}$ before a 100 TeV collider (i.e. before 2040)

$$M_{\chi^\pm} - M_{\chi_0} = 165 \text{ MeV} > m_\pi \quad \Rightarrow \quad \text{lifetime } \tau \simeq 6\,\text{cm} \simeq 0.2\,\text{ns}$$

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors

Feng et al 1999, ...Cirelli S Taoso 1407.7058 [Madgraph + Pythia + Delphes]:

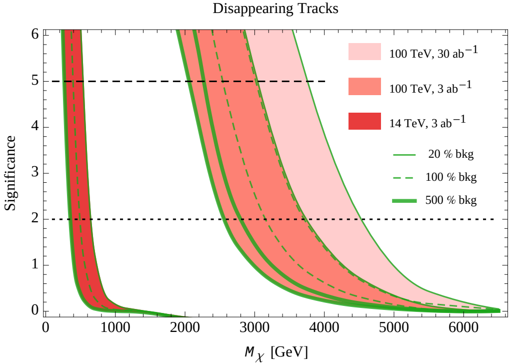


ATLAS performed this analysis!

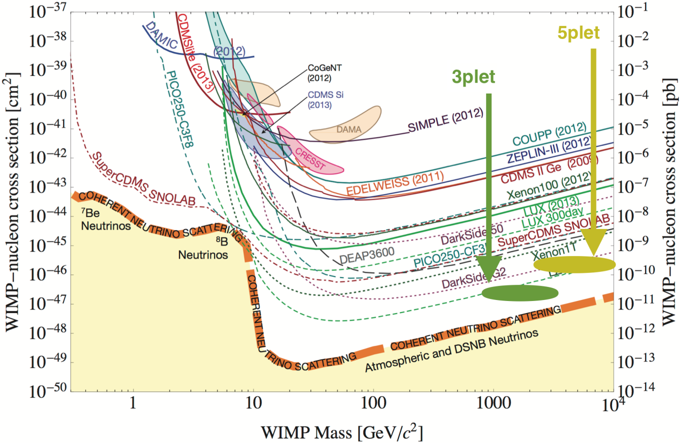
Current strongest limit on pure Wino

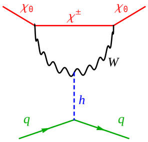
$M_{\chi_0} > 270$ GeV

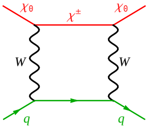
Monojet etc: way less reach



Direct Detection







Hisano et al. 1504.00915: $\sigma_{\rm SI}^{\rm 5plet} = 1.9 \times 10^{-46}{\rm cm}^2$ $\sigma_{\rm SI}^{\rm 3plet} = 2.3 \times 10^{-47}{\rm cm}^2$

full NLO in α_S, $O(50\%)$ uncertainties   [largest error from charm content of nucleon]

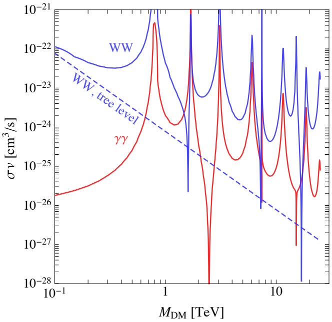
Sommerfeld enhancement

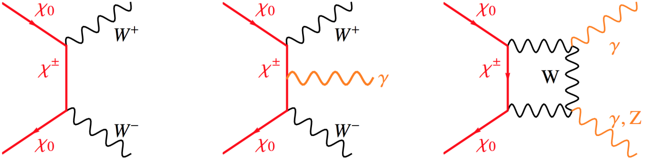
at low velocities non-rel. attractive potential

Milky Way $v \sim 10^{-3}c$

Dwarf spheroidals $v \sim 1 - 5 \times 10^{-5}c$

$\chi_0\chi_0 \to WW, \gamma\gamma$ $\quad\sigma v$ saturates at $v \lesssim 10^{-2}$ $\to$





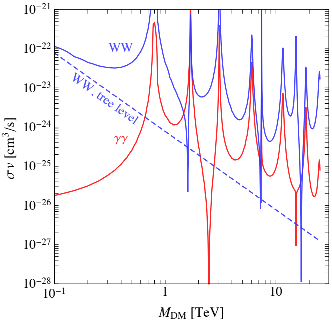
Sommerfeld enhancement

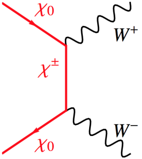
at low velocities non-rel. attractive potential

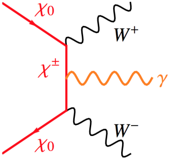
Milky Way $v \sim 10^{-3}c$

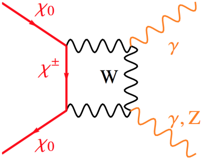
Dwarf spheroidals $v \sim 1 - 5 \times 10^{-5}c$

$\chi_0\chi_0 \to WW, \gamma\gamma$ σv saturates at $v \lesssim 10^{-2}$ $\to$









$\bar{p},\ e^+,\ \nu,\ \gamma, \ldots$

γ ray lines: smaller cross-sections

but features in γ spectrum enhance sensitivities

γ continuum from dwarf spheroidal galaxies

A primer on dwarf spheroidal galaxies

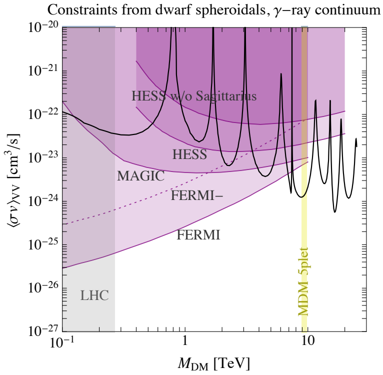
- gravitationally linked to our galaxy
- DM dominated objects $\rightarrow$ this is why they are good targets!
- often "trackers" are just a few $\rightarrow$ big uncertainties on DM properties

[with respect to Milky Way: almost no bkg, large uncertainties in J factors]

A primer on dwarf spheroidal galaxies

- gravitationally linked to our galaxy
- DM dominated objects → this is why they are good targets!
- often "trackers" are just a few → big uncertainties on DM properties

[with respect to Milky Way: almost no bkg, large uncertainties in J factors]



FERMI: 15 dwarves, assumes $\Delta J < 40\%$

HESS: subset of 4, plus Sagittarius

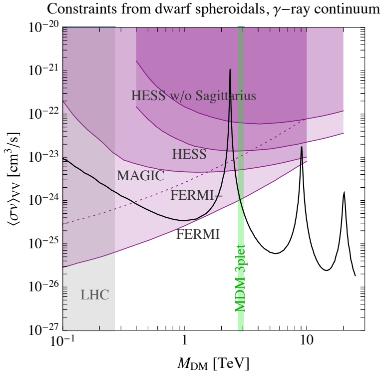
MAGIC: only Segue1 (large uncertainties!)

γ continuum from dwarf spheroidal galaxies

A primer on dwarf spheroidal galaxies

- ◇ gravitationally linked to our galaxy
- ◇ DM dominated objects → this is why they are good targets!
- ◇ often "trackers" are just a few → big uncertainties on DM properties

[with respect to Milky Way: almost no bkg, large uncertainties in J factors]



FERMI: 15 dwarves, assumes $\Delta J < 40\%$

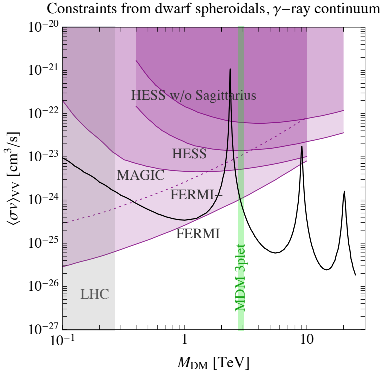
HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)

A primer on dwarf spheroidal galaxies

- gravitationally linked to our galaxy
- DM dominated objects → this is why they are good targets!
- often "trackers" are just a few → big uncertainties on DM properties

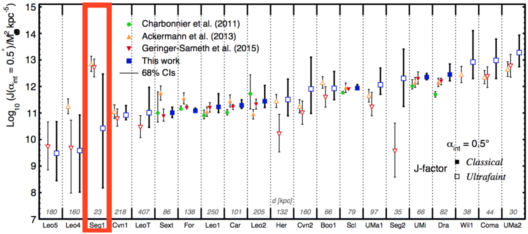
[with respect to Milky Way: almost no bkg, large uncertainties in J factors]



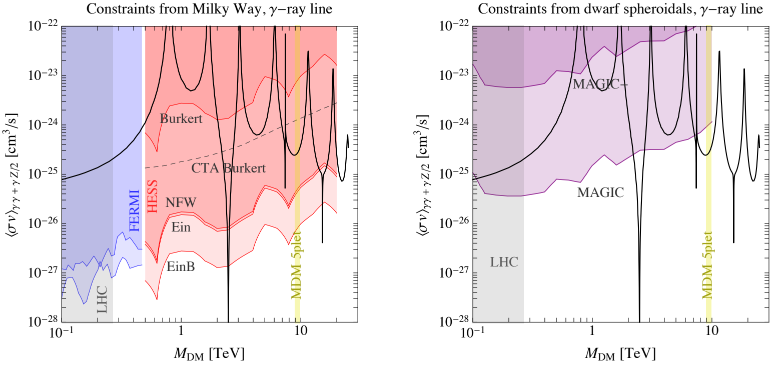
FERMI: 15 dwarves, assumes $\Delta J < 40\%$

HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)



Bonnivard et al 1504.02048



[CTA prospects from Ovanesyan et al 1409.8294 and Bergstrom et al 1207.6773]

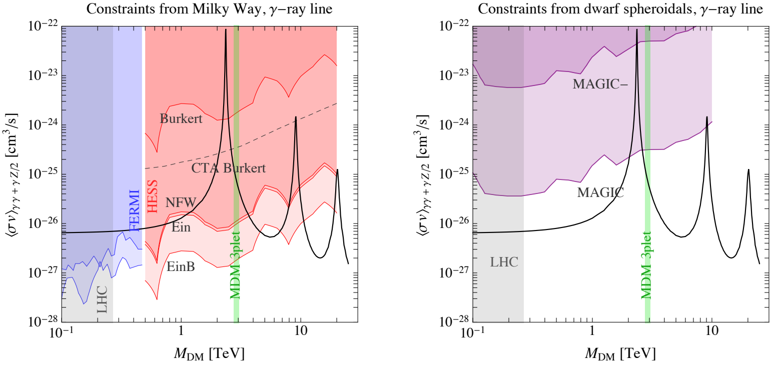
MAGIC = only one that looked for lines from dwarves - but just Segue1

Lot of progress conceivable with dwarf spheroidals!

→ Look at the same (other) dwarves with other (the same) experiments

→ measure better DM properties to reduce uncertainties

γ lines: galactic center and dwarves - 3plet



[CTA prospects from Ovanesyan et al 1409.8294 and Bergstrom et al 1207.6773]

MAGIC = only one that looked for lines from dwarves - but just Segue1

Lot of progress conceivable with dwarf spheroidals!

→ Look at the same (other) dwarves with other (the same) experiments

→ measure better DM properties to reduce uncertainties

Astrophysical uncertainties and the galactic center

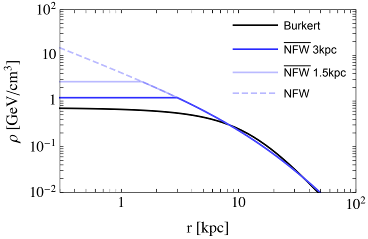
DM density ρ in the Milky Way:

N-body simulations "resolve" $\sim$1 kpc

Di Cintio et al 1306.0898,...

Observations do not probe DM below $\sim$ 5 kpc

Pato Iocco 1511.05571,...



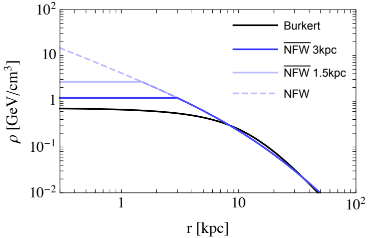
DM density ρ in the Milky Way:

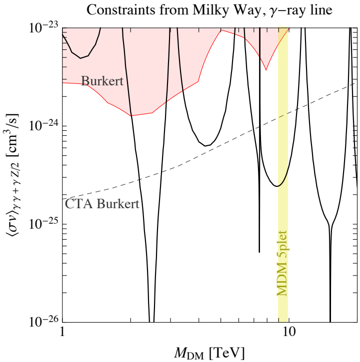
N-body simulations "resolve" $\sim$1 kpc

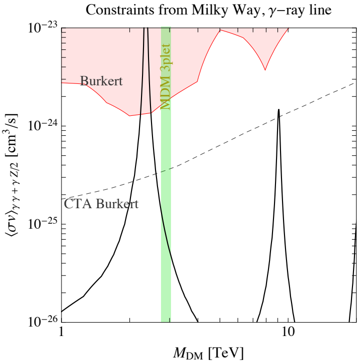
Di Cintio et al 1306.0898,...

Observations do not probe DM below $\sim$ 5 kpc

Pato Iocco 1511.05571,...







Astrophysical uncertainties and the galactic center

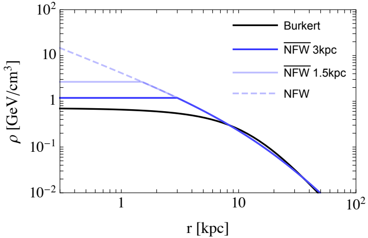
DM density ρ in the Milky Way:

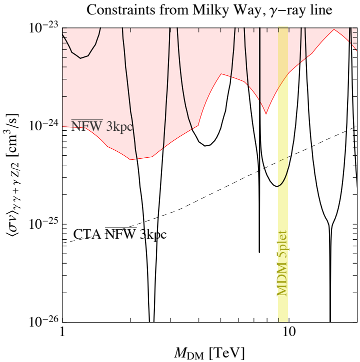
N-body simulations "resolve" $\sim$1 kpc

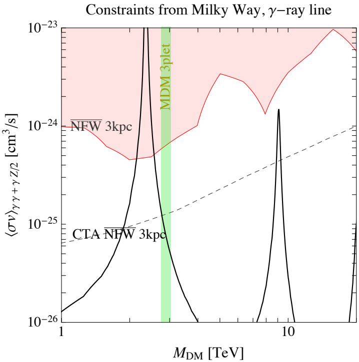
Di Cintio et al 1306.0898,...

Observations do not probe DM below $\sim$ 5 kpc

Pato Iocco 1511.05571,...







Astrophysical uncertainties and the galactic center

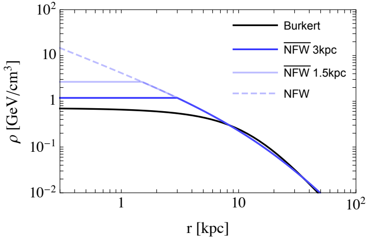
DM density ρ in the Milky Way:

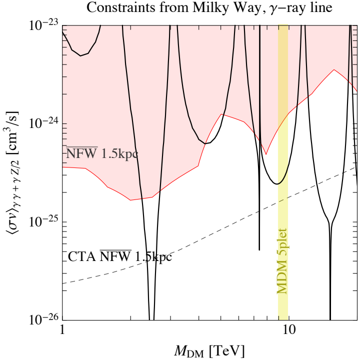
N-body simulations "resolve" $\sim$1 kpc

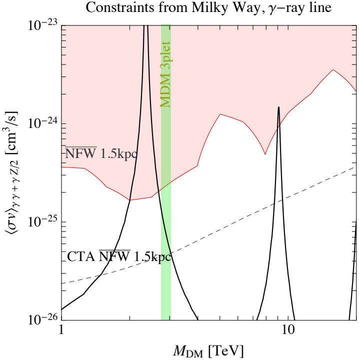
Di Cintio et al 1306.0898,...

Observations do not probe DM below $\sim$ 5 kpc

Pato Iocco 1511.05571,...







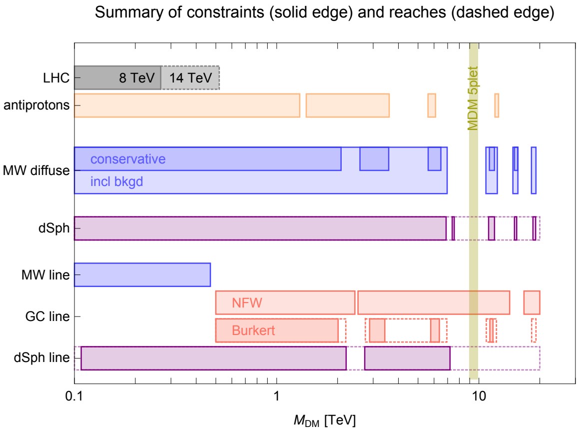
An EW fermion 5plet: summary

Why interesting?

Simple benchmark of a WIMP, and moreover

Minimal Dark Matter

Phenomenology:



An EW fermion 3plet: summary

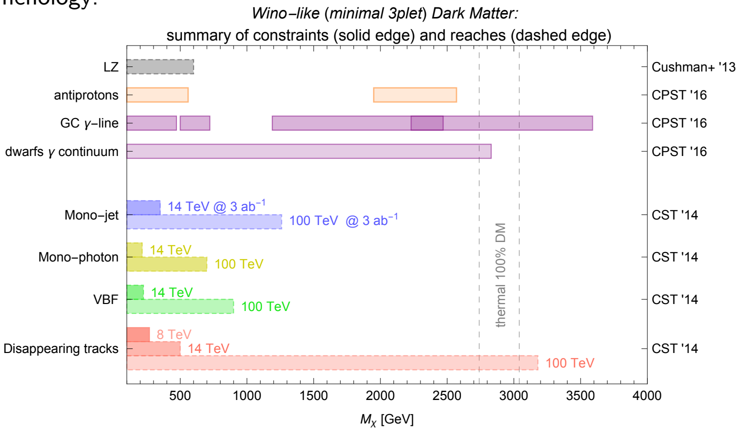
Why interesting?

Simple benchmark of a WIMP, and moreover

Minimal Dark Matter $+ (B - L)$

Supersymmetry pure Wino LSP, typical of Split SUSY,...

Phenomenology:



New Physics at the TeV scale?

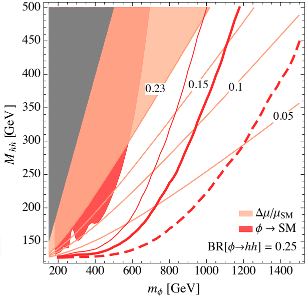
Both necessary inputs to plan future of HEP [both included in FCC-hh CERN reports]

✓ Extra Higgses and "natural" New Physics
Buttazzo S Tesi, 1505.05488

✓ Heavy WIMP Dark Matter
Cirelli Hambye Panci S Taoso, 1507.05519

Both necessary inputs to plan future of HEP [both included in FCC-hh CERN reports]

✓ Extra Higgses and "natural" New Physics
Buttazzo S Tesi, 1505.05488

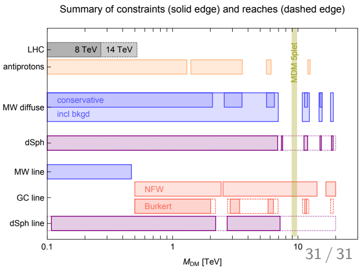


An extra Singlet-like Higgs
appears in NMSSM, Twin Higgs, ...
search it in $\phi \to VV, hh$, h couplings, g_{hhh}

What next?: extra doublets, CP-odd,...

✓ Heavy WIMP Dark Matter
Cirelli Hambye Panci S Taoso, 1507.05519

Indirect detection is almost there!



Exciting road ahead
astro: effect of DM clumps?
astro: simulations of inner 1-3 kpc?
astro: dwarf spheroidals?
particle: bound states?

Back up Dark Matter

Minimal Dark Matter: candidates

Allowed: χ neutral under g, γ, and almost under Z (direct detection)

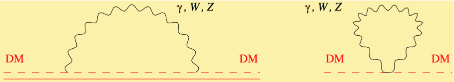
$$\Rightarrow \boxed{\chi = n\text{-tuplet of } SU(2)_L \qquad Y = 0}$$

Stable: No renormalizable nor dim-5 operators that lead to decay

$\Rightarrow$ first candidate is a $n = 5$ fermion

($n = 7$ scalar killed recently Di Luzio et al. 1504.00359)

Lightest component neutral: $M_Q - M_{Q=0} \simeq Q(Q + \frac{2Y}{c_{\theta_W}})\Delta M$



$\Delta M^{2-\text{loop}} = 164.5 \pm .5$ MeV

Ibe Matsumoto Sato 1212.5989

Minimal Dark Matter: candidates

Allowed: χ neutral under g, γ, and almost under Z (direct detection)

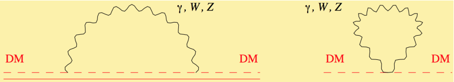
$$\Rightarrow \boxed{\chi = n\text{-tuplet of } SU(2)_L \qquad Y = 0}$$

Stable: No renormalizable nor dim-5 operators that lead to decay

$\Rightarrow$ first candidate is a $n = 5$ fermion

($n = 7$ scalar killed recently Di Luzio et al. 1504.00359)

Lightest component neutral: $M_Q - M_{Q=0} \simeq Q(Q + \frac{2Y}{c_{\theta_W}})\Delta M$



$\Delta M^{2-\text{loop}} = 164.5 \pm .5$ MeV

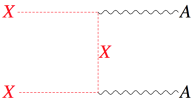
Ibe Matsumoto Sato 1212.5989

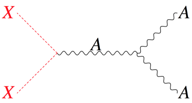
Avoid g_2 Landau pole before $M_{\rm Pl}$ $\Rightarrow$ n not too large

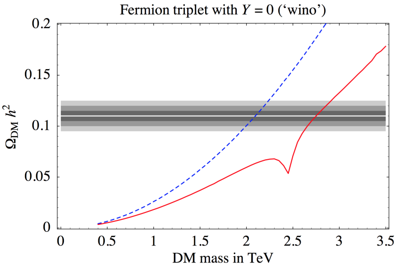
In practice: $n \leq 8$ for scalars, $n \leq 5$ for fermions

Relic abundances

Typical WIMP candidate $\rightarrow M_{\rm DM} \sim$ TeV



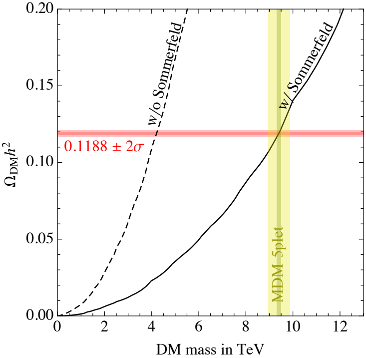




Important to include:

- ◇ Coannihilations
- ◇ Sommerfeld enhancement
- ? Higher orders/non perturbative effects

5plet from Cirelli et al 1507.05519 →



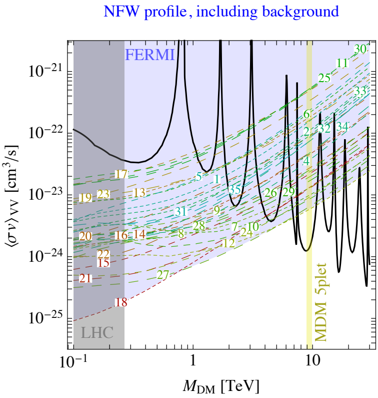
γ continuum with FERMI - I

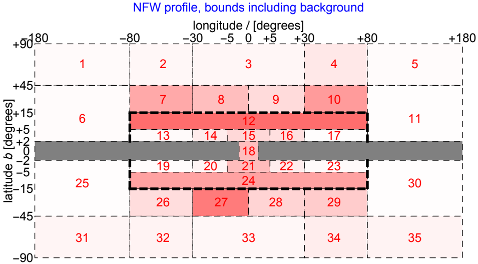
- $\rightarrow$ FERMI measures γ flux from all sky
- $\rightarrow$ We "conservatively" model astrophysical backgrounds
- $\rightarrow$ We divide the sky into regions, and extract bounds from each one

→ FERMI measures γ flux from all sky

→ We "conservatively" model astrophysical backgrounds

→ We divide the sky into regions, and extract bounds from each one





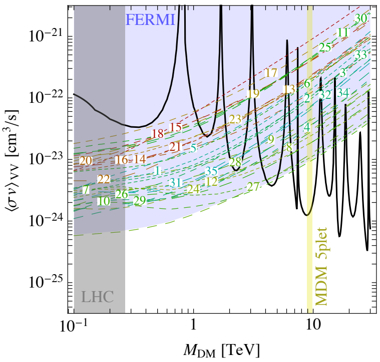
γ continuum with FERMI - I

→ FERMI measures γ flux from all sky

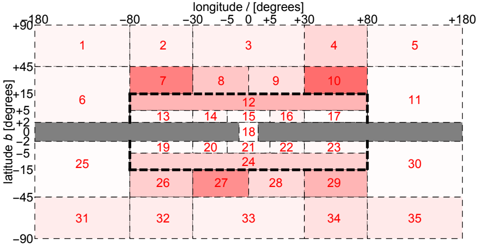
→ We "conservatively" model astrophysical backgrounds

→ We divide the sky into regions, and extract bounds from each one

Burkert profile, including background



Burkert profile, bounds including background

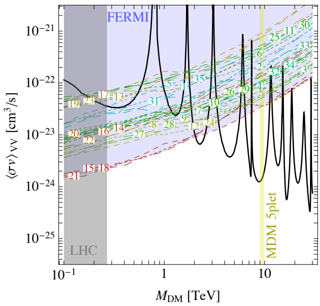


◇ Galactic bounds depend on DM profile

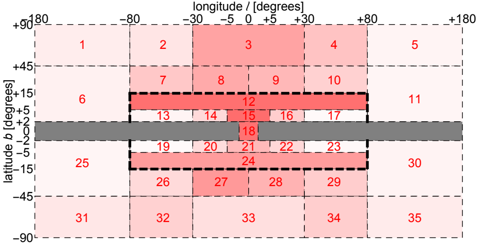
◇ All bounds assume 5plet = 100% of DM

γ continuum with FERMI - II

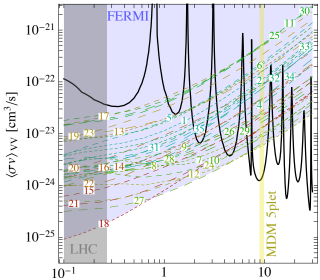
NFW profile, conservative bound



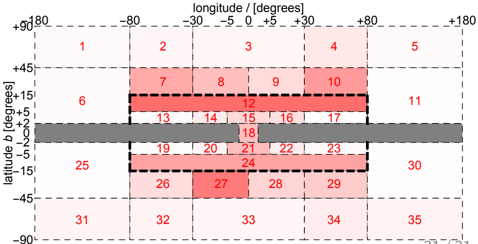
NFW profile, conservative bounds



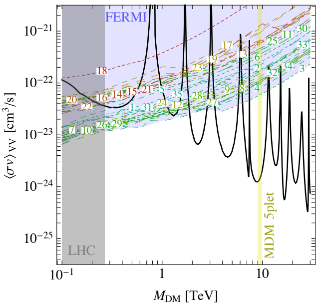
NFW profile, including background



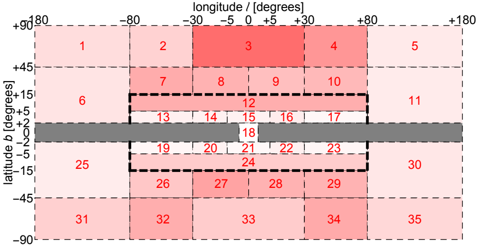
NFW profile, bounds including background



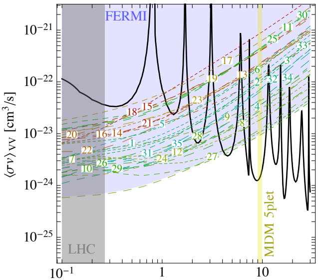
Burkert profile, conservative bound



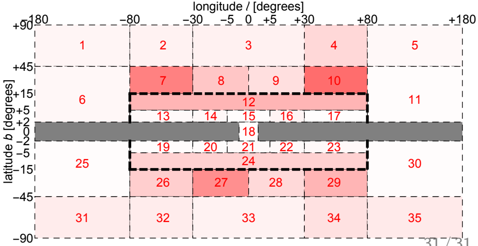
Burkert profile, conservative bounds



Burkert profile, including background



Burkert profile, bounds including background



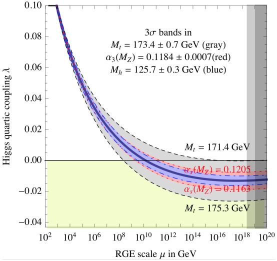
Why an EW fermion triplet?

→ Stable if one imposes L or $B-L$ or discrete subgroup (already in the SM!)

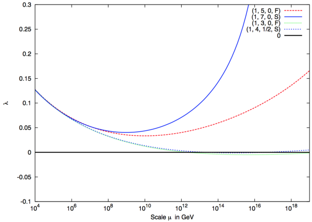
[also kills all higher-dimensional operators that could make it decay]

→ Stabilizes Standard Model vacuum

without MDM [Buttazzo et al 1307.3536]



with MDM [Chao et al 1210.0491]

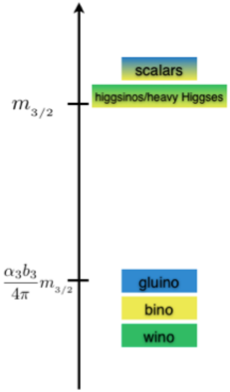


→ Not big contribution to m_h ⇒ does not worsen fine-tuning

→ Helps with unification of gauge couplings

Why an EW fermion triplet?

→ Connection with SUSY with heavy scalars   James Wells hep-ph/0306127



Keep all good features of Supersymmetry
DM, unification of gauge couplings,...

And accept a tuned m_h (e.g. anthropic)

→ All other scalars are heavier

→ Higgsinos also heavier if $\mu \sim m_{3/2}$

→ Wino LSP candidate for Dark Matter!

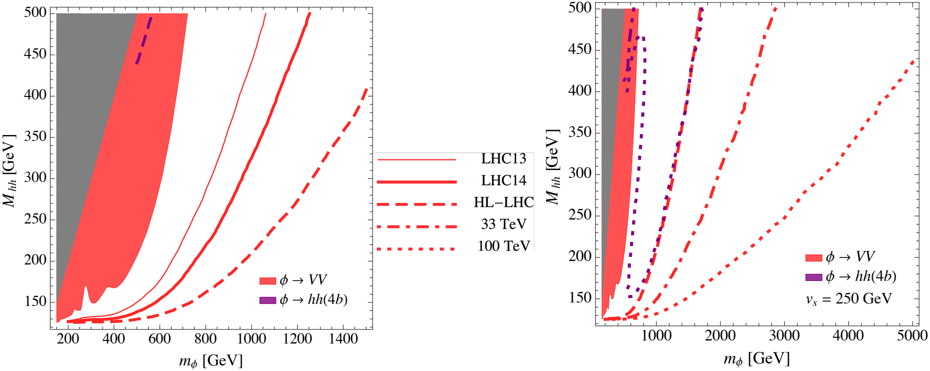
See also:
Arkani-Hamed Dimopoulos hep-th/0405159
Giudice Romanino hep-ph/0406088
...
Arvanitaki Craig Dimopoulos Villadoro 1210.0555
...
D'Eramo Hall Pappadopulo 1409.5123

Back up Extra Higgses

Generic singlet: direct searches

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

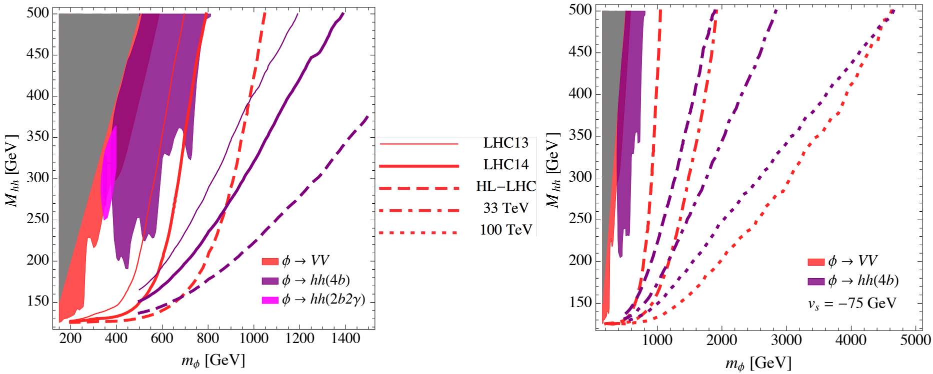
ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\rm SM}(m_\phi)$ [barring $\phi \to hh$]



Generic singlet: direct searches

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

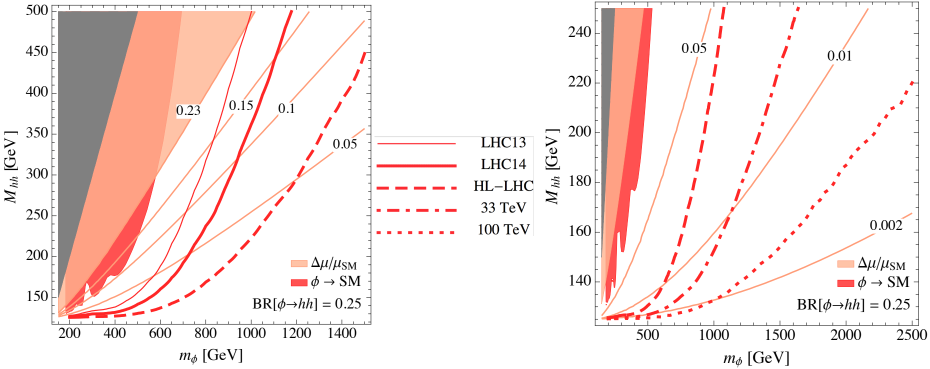
Large $\mathrm{BR}_{\phi\to hh}$ easier for $v_s < 0$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\rm SM}(m_\phi)$ [barring $\phi \to hh$]



Generic singlet: direct searches

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\rm SM}(m_\phi)$ [barring $\phi \to hh$]

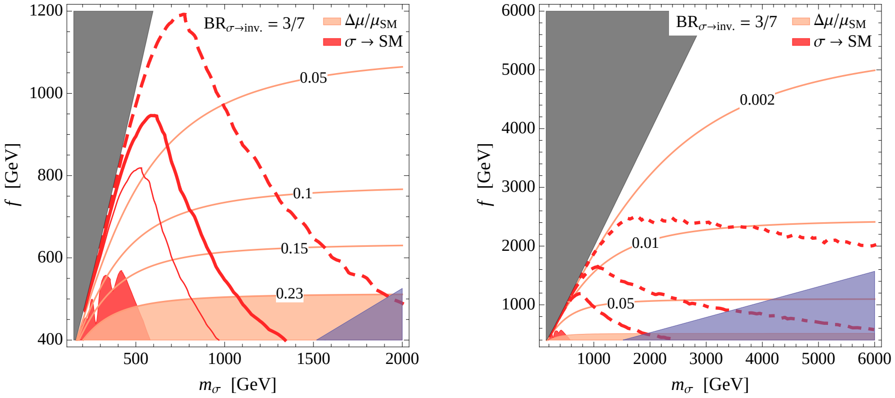


Higgs as a PNG boson: Twin Higgs

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\sigma^2 - m_h^2} \qquad M_{hh}^2 = (m_h^2 + m_\sigma^2)\, v^2/f^2$$

Only two free parameters f and m_σ $\Rightarrow$ $\mathrm{BR}_{\sigma\to hh}$ fixed everywhere

Twin SM $\Rightarrow$ $\mathrm{BR}_{\sigma\to inv.} \neq 0$ [equivalence theorem: $\mathrm{BR}_{\sigma\to inv.} \to 3/7$ for $m_\sigma > m_Z \times f/v$]

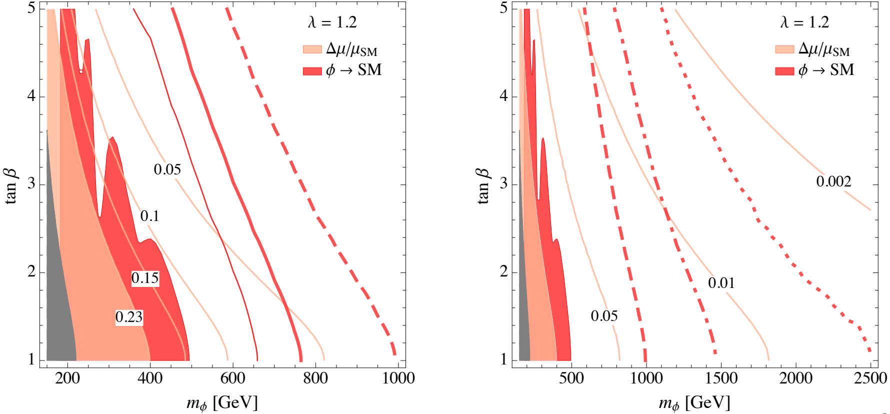


The NMSSM

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2} \qquad M_{hh}^2 = m_Z^2\, c_{2\beta}^2 + \lambda^2 v^2\, s_{2\beta}^2 + \Delta^2$$

Δ = all loop effects, e.g. top-stop

Here $\lambda = 1.2$ $\quad \Delta = 70$ GeV $\qquad \tan\beta$ "small" otherwise EWPT

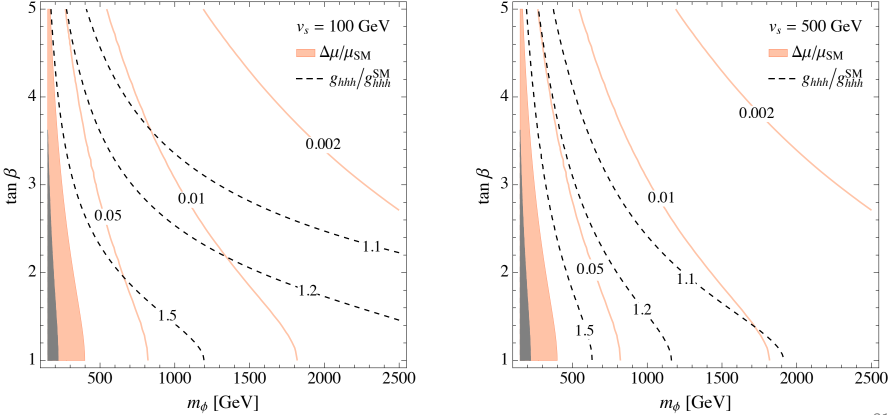


$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

$$M_{hh}^2 = m_Z^2\, c_{2\beta}^2 + \lambda^2 v^2\, s_{2\beta}^2 + \Delta^2$$

Δ = all loop effects, e.g. top-stop

Here $\lambda = 1.2$ $\quad \Delta = 70$ GeV $\qquad \tan\beta$ "small" otherwise EWPT



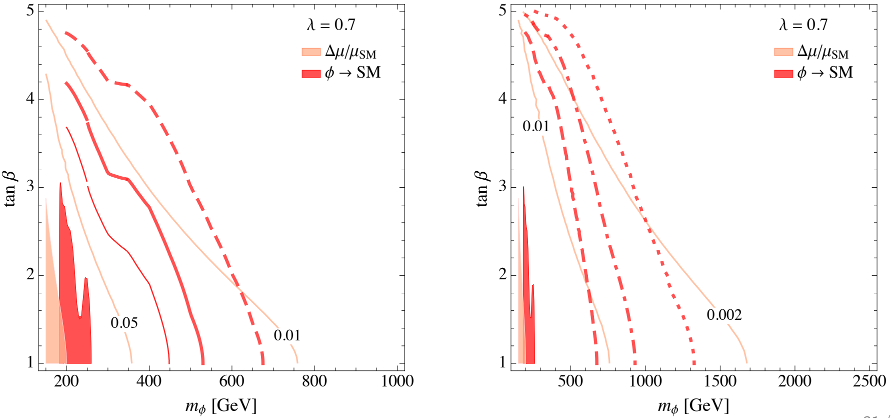
The NMSSM

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

$$M_{hh}^2 = m_Z^2\, c_{2\beta}^2 + \lambda^2 v^2\, s_{2\beta}^2 + \Delta^2$$

Δ = all loop effects, e.g. top-stop

Here $\lambda = 0.7$ $\quad\Delta = 80$ GeV $\qquad\tan\beta$ "small" otherwise EWPT



Extrapolation of direct searches I

We started from

i) Collider Reach (β) Salam Weiler 2014 ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$

$$B(s, L, m) \propto L \times \int d\hat{s}\, \frac{1}{\hat{s}}\, \hat{s}\hat{\sigma}(\hat{s})\, \frac{d\mathcal{L}}{d\hat{s}}(s)$$

Extrapolation of direct searches I

We started from

i) Collider Reach (β) Salam Weiler 2014   ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$

$$B(s, L, m) \propto L \times \frac{\Delta \hat{s}}{m^2} \hat{s}\hat{\sigma}(\hat{s}) \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2}$$

Extrapolation of direct searches I

We started from

i) Collider Reach (β) Salam Weiler 2014 ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $\boxed{B(s_1, L_1, m_1) = B(s_0, L_0, m_0)}$

$$B(s, L, m) \propto L\times \quad \frac{\Delta \hat{s}}{m^2}\, c\, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \;\Rightarrow\; \frac{d\mathcal{L}}{d\hat{s}} \text{ drives the reach}$$

Extrapolation of direct searches I

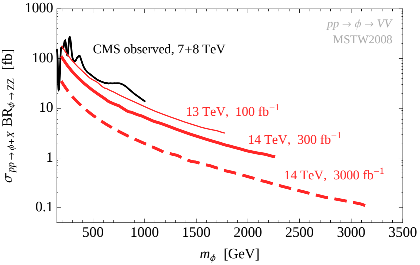
We started from

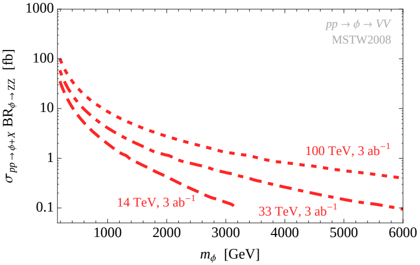
i) Collider Reach (β) Salam Weiler 2014   ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$

$$B(s, L, m) \propto L \times \frac{\Delta \hat{s}}{m^2} \, c \, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \Rightarrow \frac{d\mathcal{L}}{d\hat{s}} \text{ drives the reach}$$

$$L_1 \, c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_1)\Big|_{\hat{s}=m_1^2} = L_0 \, c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_0)\Big|_{\hat{s}=m_0^2}$$





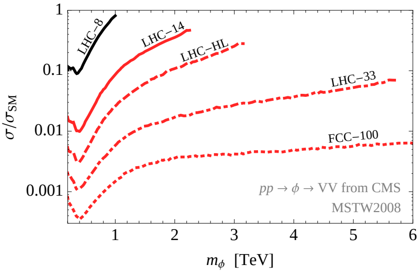
We started from

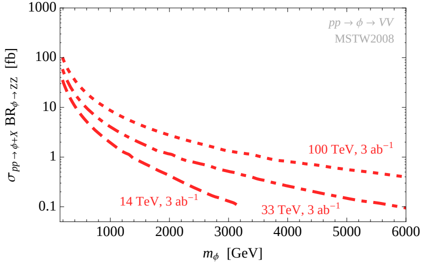
i) Collider Reach (β) Salam Weiler 2014 ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$

$$B(s, L, m) \propto L \times \quad \frac{\Delta\hat{s}}{m^2}\, c\, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \;\Rightarrow\; \frac{d\mathcal{L}}{d\hat{s}} \text{ drives the reach}$$

$$L_1\, c_{ij}\, \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_1)\Big|_{\hat{s}=m_1^2} = L_0\, c_{ij}\, \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_0)\Big|_{\hat{s}=m_0^2}$$





Extrapolation of direct searches I

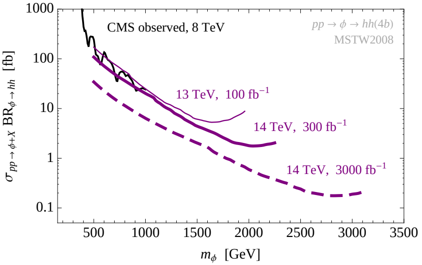
We started from

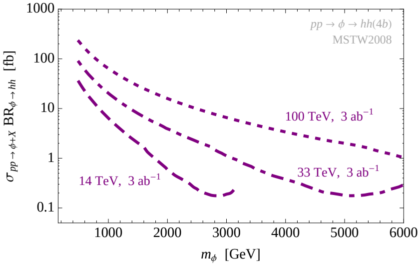
i) Collider Reach (β) Salam Weiler 2014   ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$

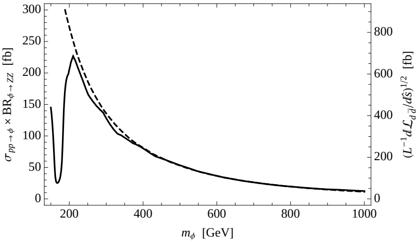
$$B(s, L, m) \propto L \times \quad \frac{\Delta\hat{s}}{m^2}\, c\, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \;\Rightarrow\; \frac{d\mathcal{L}}{d\hat{s}} \text{ drives the reach}$$

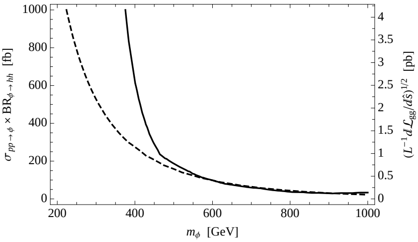
$$L_1\, c_{ij}\, \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_1)\Big|_{\hat{s}=m_1^2} = L_0\, c_{ij}\, \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_0)\Big|_{\hat{s}=m_0^2}$$





Extrapolation of direct searches II

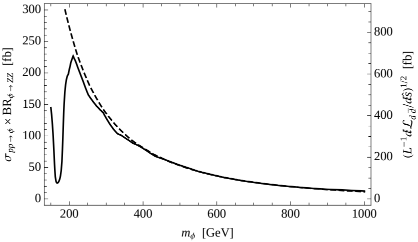


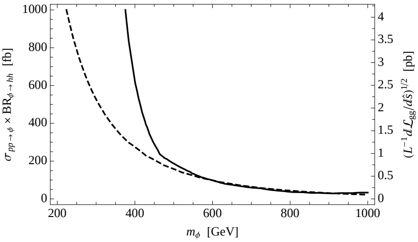


Assumptions/limitations

→ Not valid if systematics dominate and change significantly from s_0 to s_1

Extrapolation of direct searches II





Assumptions/limitations

- $\rightarrow$ Not valid if systematics dominate and change significantly from s_0 to s_1
- $\rightarrow$ $\hat{s} \gg m_{\mathrm{bkg}}$ [i.e. not valid at $\hat{s} \sim 2m_t$ for $\phi \to hh(4b)$]
- $\rightarrow$ $\dfrac{\Delta\hat{s}}{m^2} \ll 1$ i.e. not valid if analysis depends a lot on shape far from peak

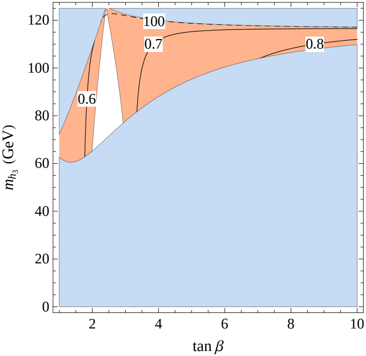
An extra doublet-like state H $[\gamma, \sigma = 0, \quad m_{h_2} \gg m_{h_1}, m_{h_3}]$

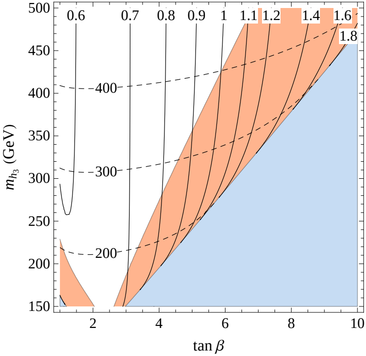
Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

$$\frac{g_{h_3 tt}}{g_{htt}^{SM}} = s_\delta - \frac{c_\delta}{t_\beta} \qquad \frac{g_{h_3 bb}}{g_{hbb}^{SM}} = s_\delta + t_\beta c_\delta \qquad \frac{g_{h_3 VV}}{g_{hVV}^{SM}} = s_\delta \qquad [\Delta_t = 75 \text{ GeV}]$$

Status fit LHC8:

dashed: $m_{H\pm}$ cont: λ





$m_{H^\pm} > 480$ GeV from $B \to X_s \gamma$!

$[\widetilde{\mathcal{M}}^2_{12}(t_\beta, \ldots) = 0 \to \delta = 0]$

h_3 phenomenology: more similar to MSSM

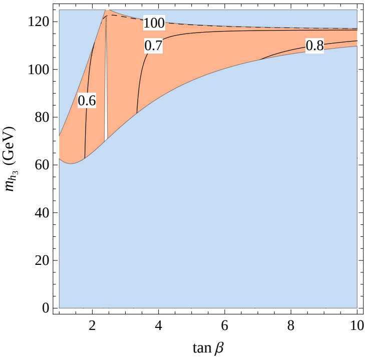
see e.g. Craig et al. 1504.04630

An extra doublet-like state H $[\gamma, \sigma = 0, \quad m_{h_2} \gg m_{h_1}, m_{h_3}]$

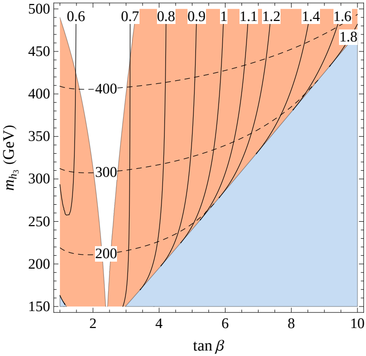
Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

$$\frac{g_{h_3 tt}}{g^{SM}_{htt}} = s_\delta - \frac{c_\delta}{t_\beta} \qquad \frac{g_{h_3 bb}}{g^{SM}_{hbb}} = s_\delta + t_\beta c_\delta \qquad \frac{g_{h_3 VV}}{g^{SM}_{hVV}} = s_\delta \qquad [\Delta_t = 75 \text{ GeV}]$$

Projections fit LHC14 (300 fb^{-1}): dashed: $m_{H^\pm}$ cont: λ



$m_{H^\pm} > 480$ GeV from $B \to X_s \gamma$!



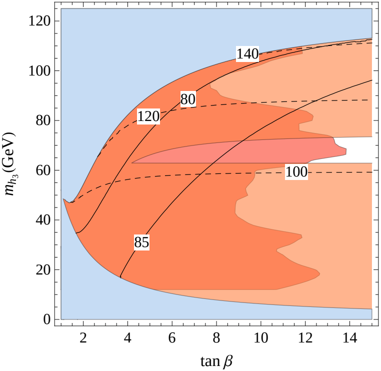
$[\widetilde{\mathcal{M}}^2_{12}(t_\beta, \ldots) = 0 \to \delta = 0]$

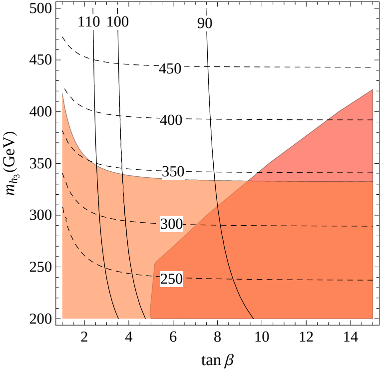
h_3 phenomenology: more similar to MSSM

see e.g. Craig et al. 1504.04630

Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

Status fit LHC8: [dashed: $m_{H^\pm}$ cont: Δ_t]





Red regions excluded by direct searches at LEP and CMS

Projections fit LHC14: above regions completely excluded

[if $\frac{\mu A_t}{m_{\tilde{t}}^2}$ very large, conclusions could change...]