Where to look for new physics?

Indications from Dark Matter and extra Higgses

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Fermilab, 3 Sept 2015

The Standard Model

?The Standard Model?

? Supersymmetry ? ??? ? Composite models ?

Any indication of a New Physics scale?

Data: no answer, but something has to be there, like Dark Matter

Theory: answer "$\equiv$" attitude towards the hierarchy problem

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

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

The Fermi scale is **natural** Fine-tuning Δ "small" $\Rightarrow$ $M_{\rm NP}$ "small"

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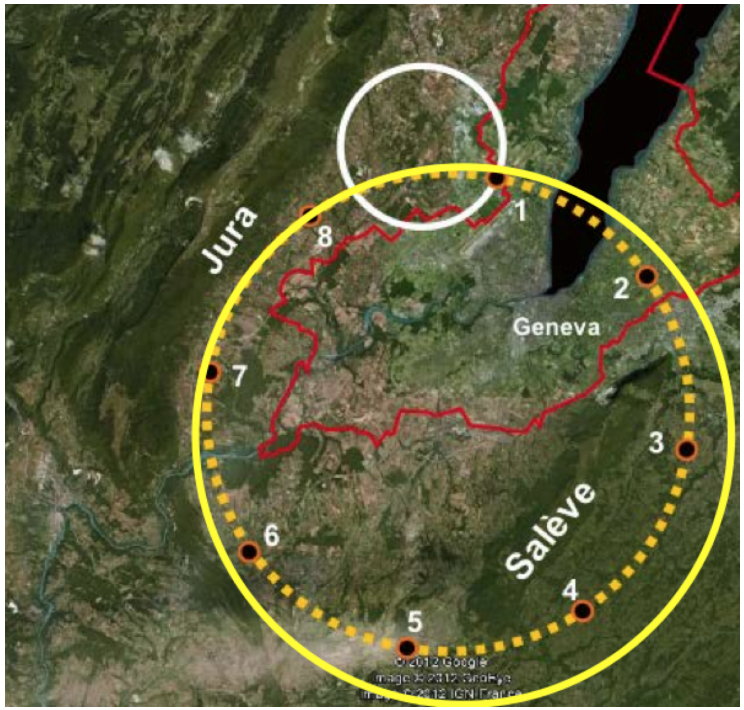
$M_{\rm NP}$ can be $\gg$ TeV

$\rightarrow$ Think different (e.g. "UV naturalness", cosmological relaxation)

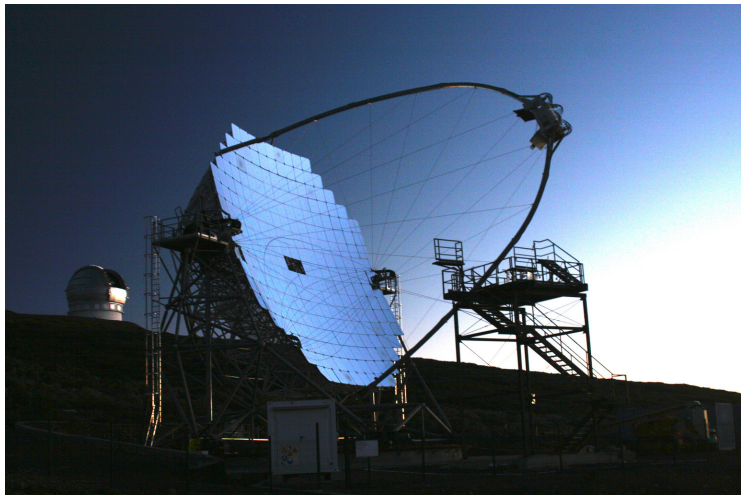
$\rightarrow$ Accept the tuning Δ (and go anthropic)

Future lampposts in this talk

Colliders



Telescopes



Where to look for New Physics?

→ Indications from "natural" New Physics

mostly based on Buttazzo S Tesi, 1505.05488

→ Indications from WIMP Dark Matter

mostly based on Cirelli Hambye Panci S Taoso, 1507.05519

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- Can new Higgses be the lightest new particles around?

- How to look for them?

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

→ Twin Higgs

→ Supersymmetry

→ Electroweak Baryogenesis (independent of naturalness)

Twin Higgs

Chacko Goh Harnik 2005, Barbieri Gregoire Hall 2005,...

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

7 are massless Goldstone bosons

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

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

Light extra Higgses in Supersymmetry

MSSM

$$\boxed{m_h^2 \leq m_Z^2 \cos^2 2\beta + \Delta_t^2} \quad \Rightarrow \quad \Delta_t \gtrsim 85 \text{ GeV} \quad \Rightarrow \quad \text{stops heavier than} \sim 1.5 \text{ TeV}$$

Fine tuning worse than 1%! $\boxed{\dfrac{dv^2}{dm_{H_u}^2} \simeq \dfrac{4}{g^2}}$ $\quad \delta m_{H_u}^2 \sim -\dfrac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log \dfrac{\Lambda}{m_{\tilde{t}}}$

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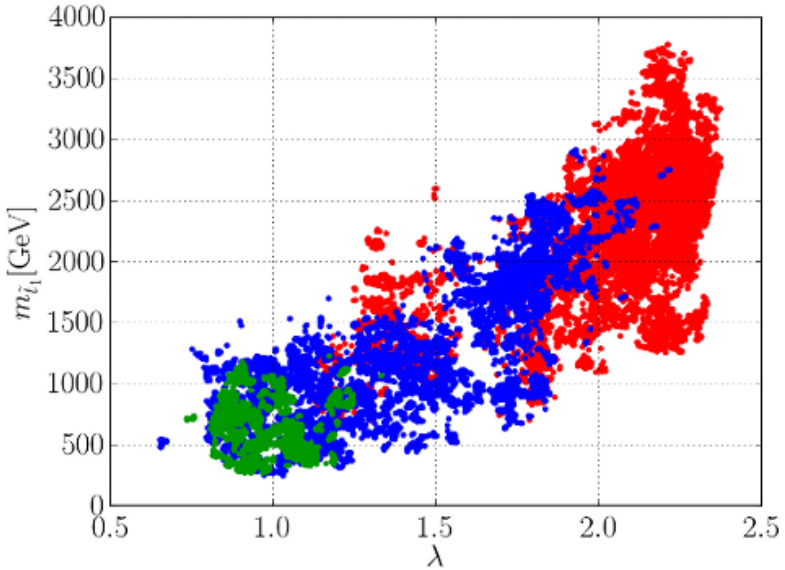
NMSSM

Add a singlet S $\qquad \Delta W = \lambda S H_u H_d + f(S)$

$$m_h^2 \leq m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2$$

Fine tuning better than 5%!
[green points, $\tan\beta \lesssim 5$]

$$\frac{dv^2}{dm_{H_u}^2} \simeq \frac{\kappa}{\lambda^3} \frac{1}{t_{2\beta}}$$

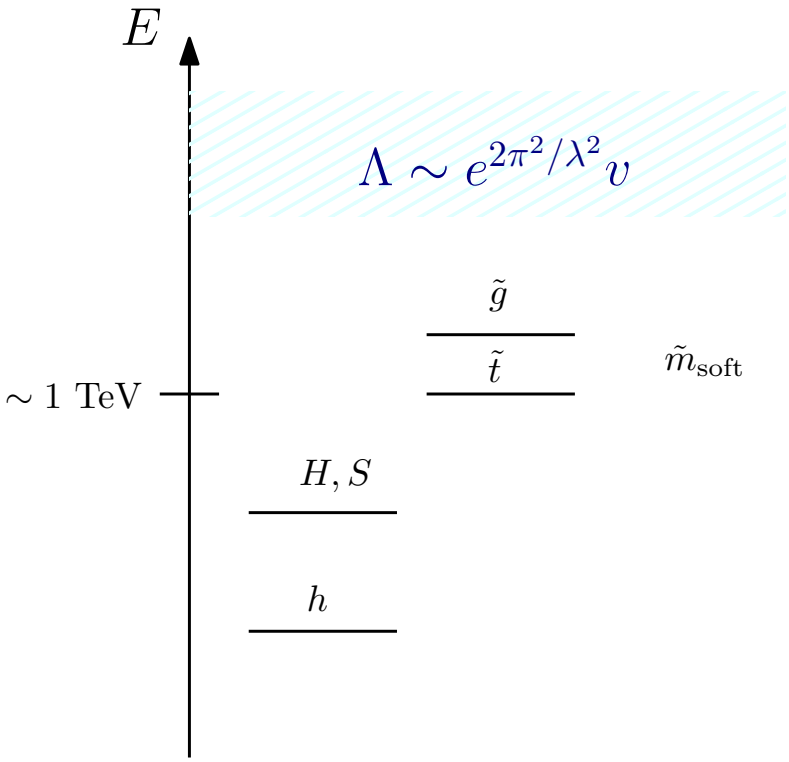


Gherghetta et al. 1212.5243 [$\Lambda = 20$ TeV]

NMSSM spectrum

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

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



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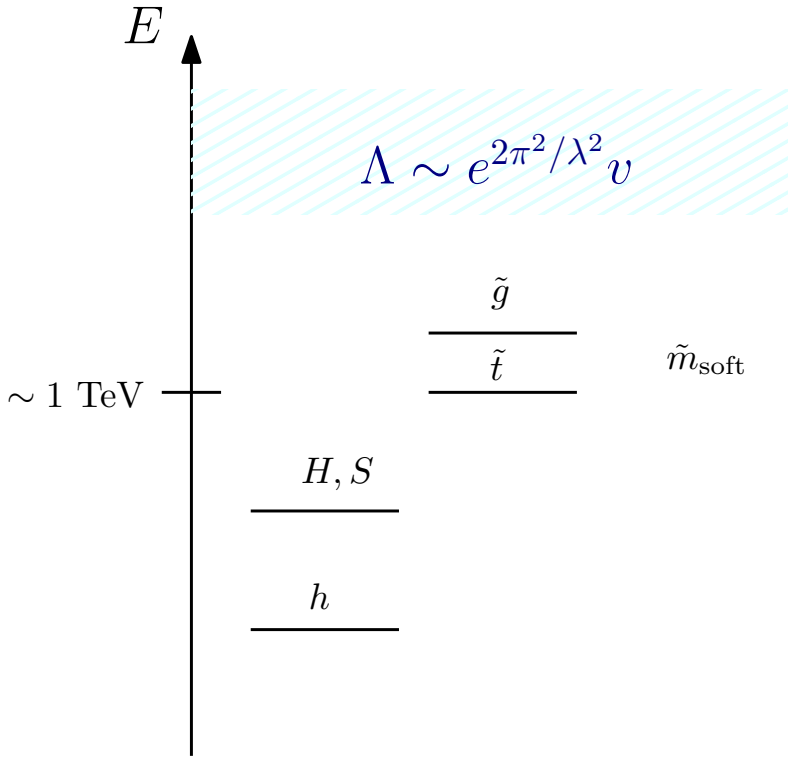
The scalars are:

CP-even h, h_3, ϕ (from h_v, H, S)

CP-odd A, A_s

$H^{\pm}$



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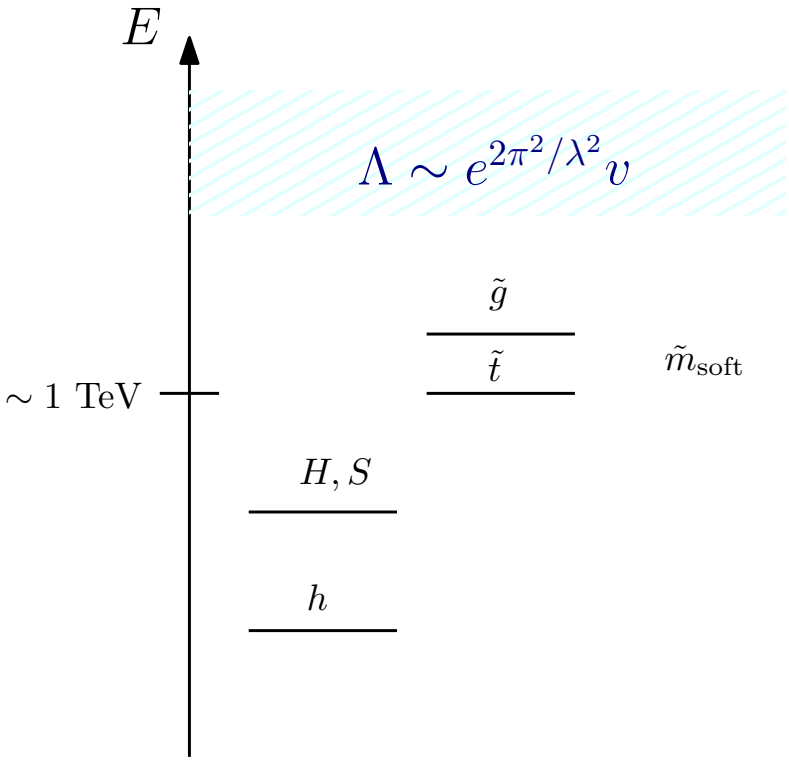

$$\mathcal{H}_{\rm ph} \equiv \begin{pmatrix} h_3 \\ h \\ \phi \end{pmatrix} = R^T \begin{pmatrix} H \\ h_v \\ S \end{pmatrix}, \quad R = R^{12}_{\delta} R^{23}_{\gamma} R^{13}_{\sigma}$$

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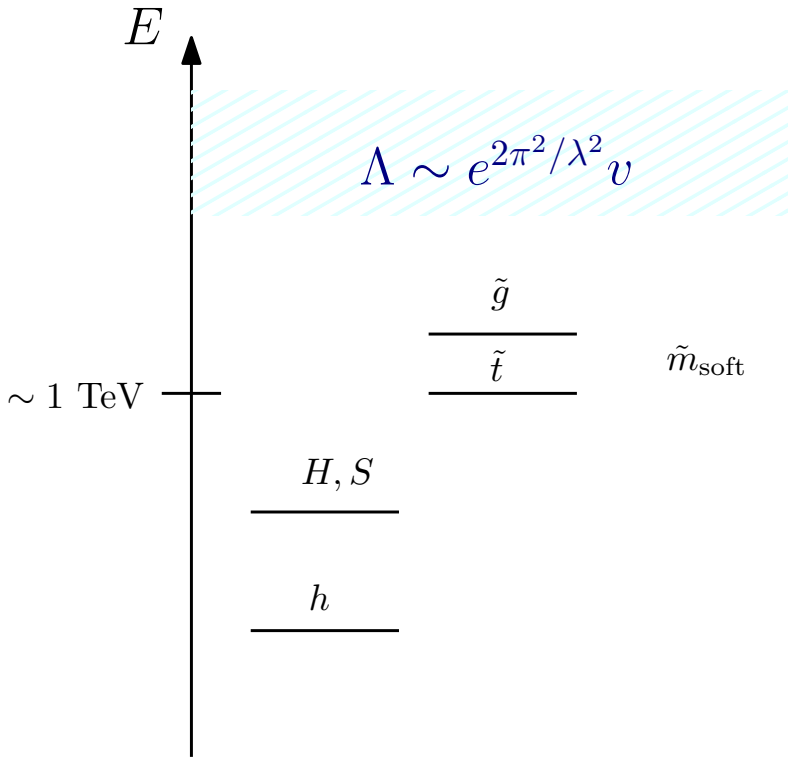

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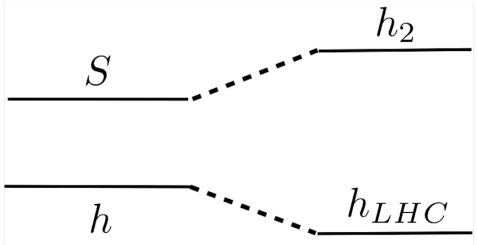

$\gamma = h_v - S$ mixing

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

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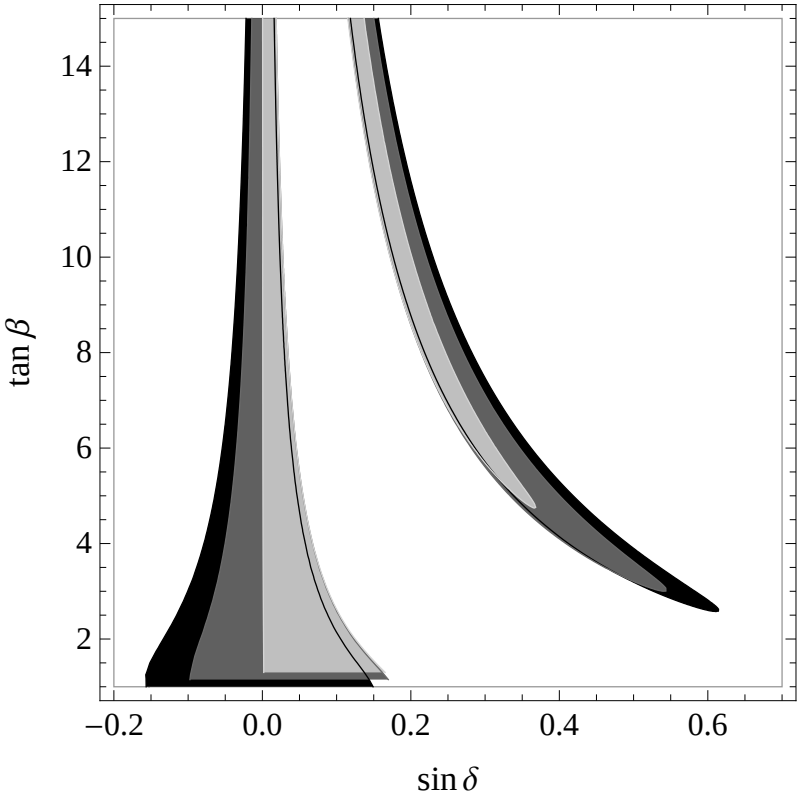
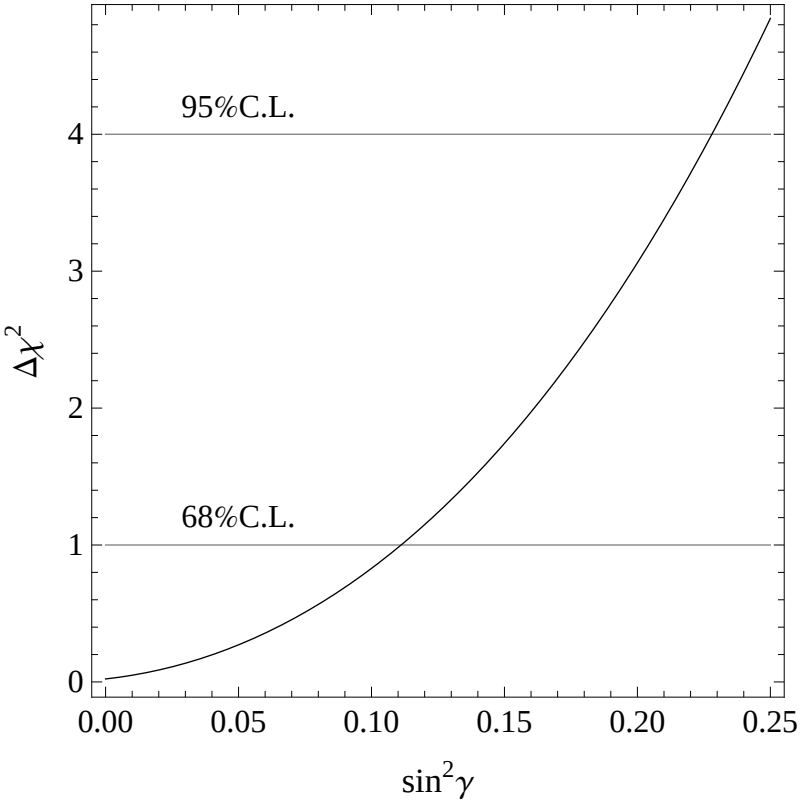
$$h_{\rm LHC} = h = c_\gamma(c_\delta h_v - s_\delta H) + s_\gamma S$$

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

LHC8 status





$s_\gamma^2 = 0,\ 0.15,\ 0.3$

Bottom-up motivation for a Singlet: Higgs couplings fit

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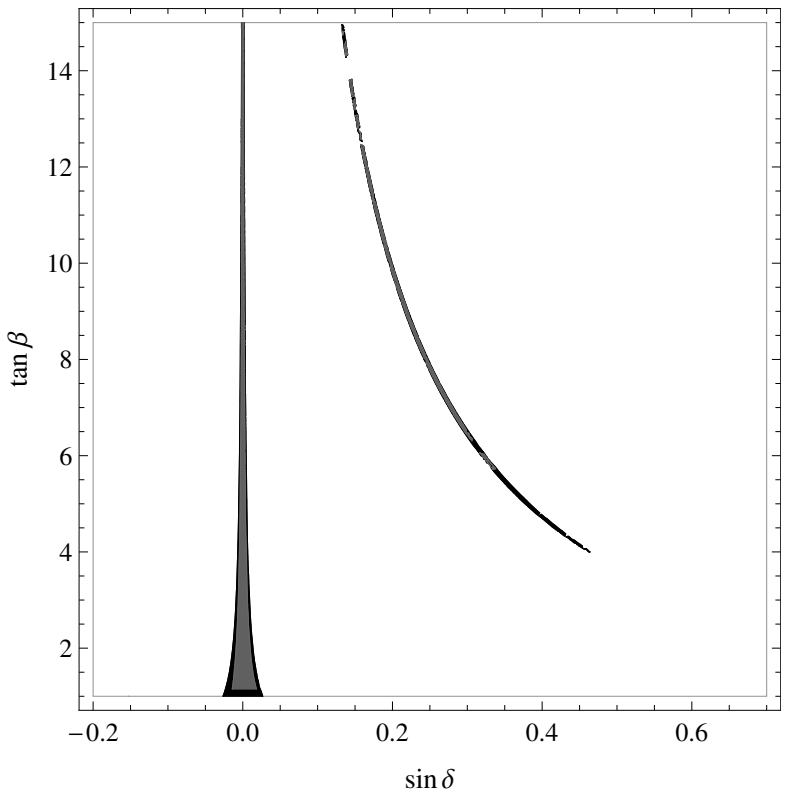
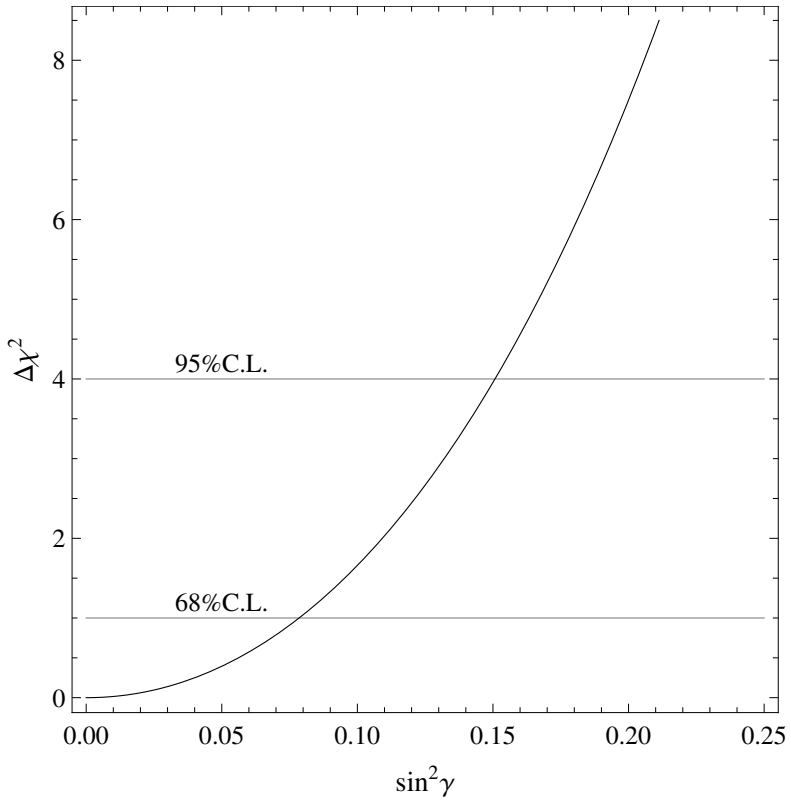
LHC14 projections (300 fb^{-1})





$s_\gamma^2 = 0$, 0.15, 0.3

✓ Can new Higgses be the lightest new particles around?

◇ How to look for them?

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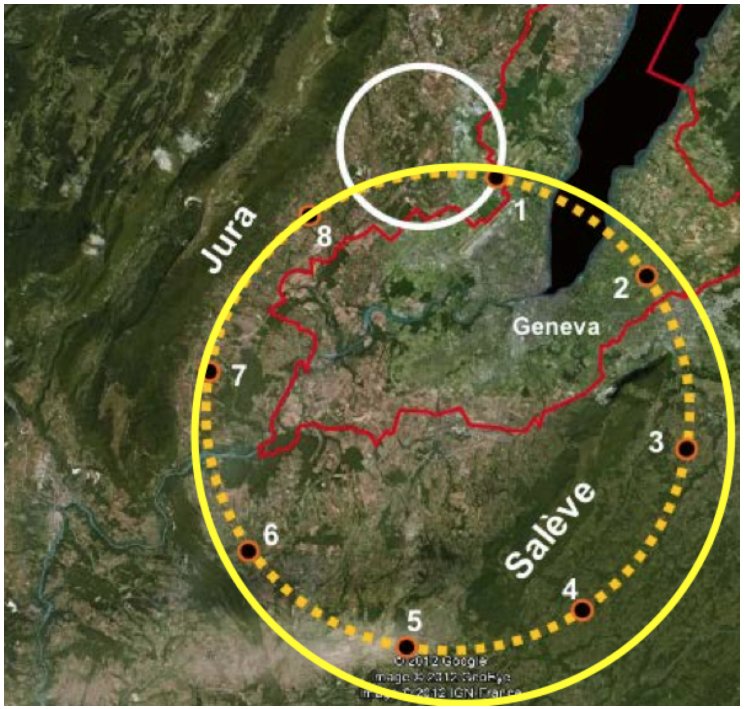
At which machines?

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

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

Master formula, valid for **any** model

2 free parameters control all pheno!

$+\ \mathrm{BR}_{\phi\to hh}$ ($= \mathrm{BR}_{\phi\to ZZ}$ at $m_\phi \gg m_W$)

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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

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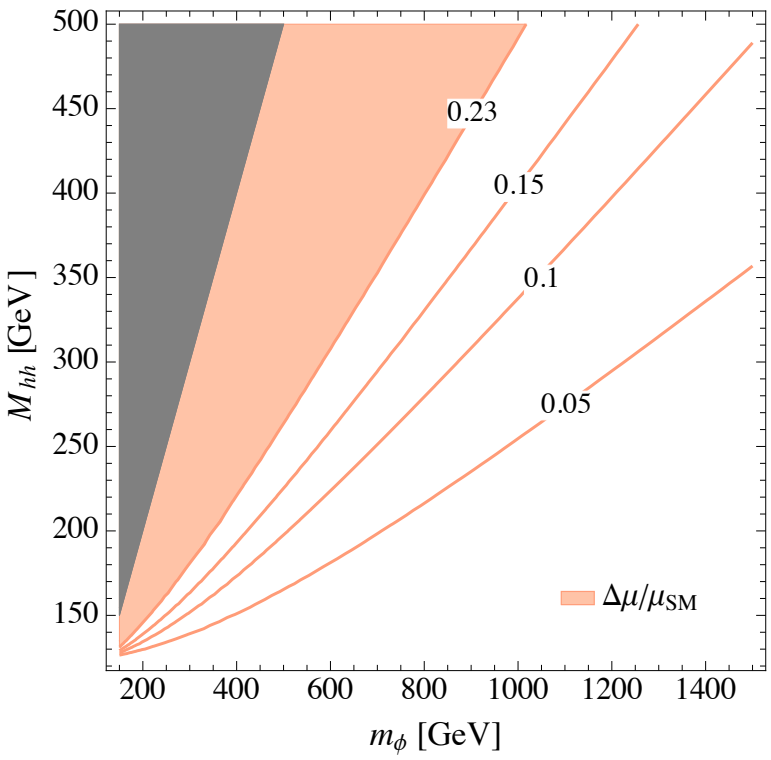

1σ reach in	s_γ^2	$\left\lvert 1 - \frac{g_{hhh}}{g_{hhh}^{\mathrm{SM}}}\right\rvert$
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LHC14	0.08-0.12	–
HL-LHC	4-8×10^{-2}	0.5
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ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
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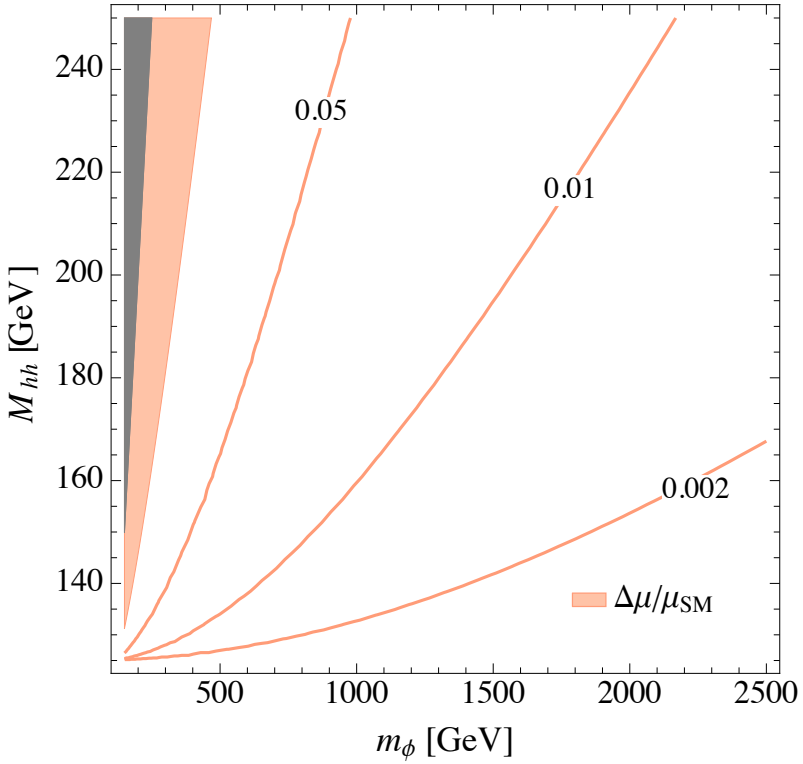
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

Snowmass 2013



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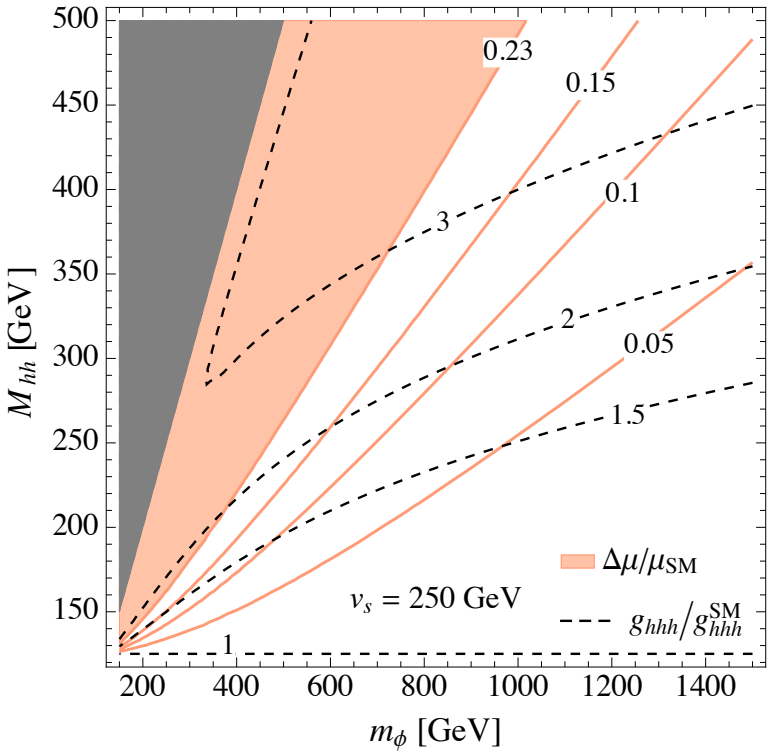
Add g_{hhh}: could be first deviation seen!



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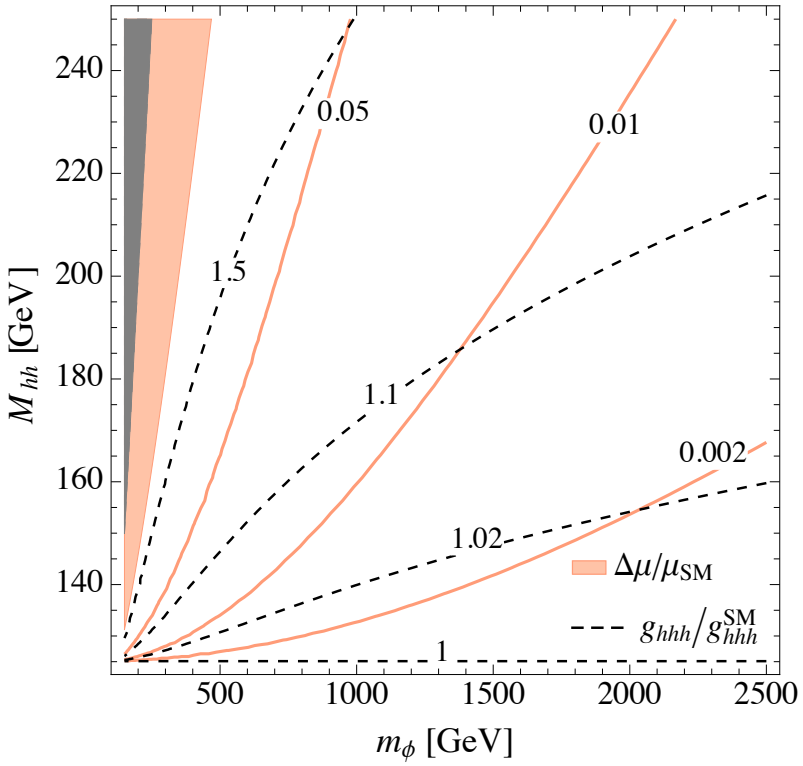

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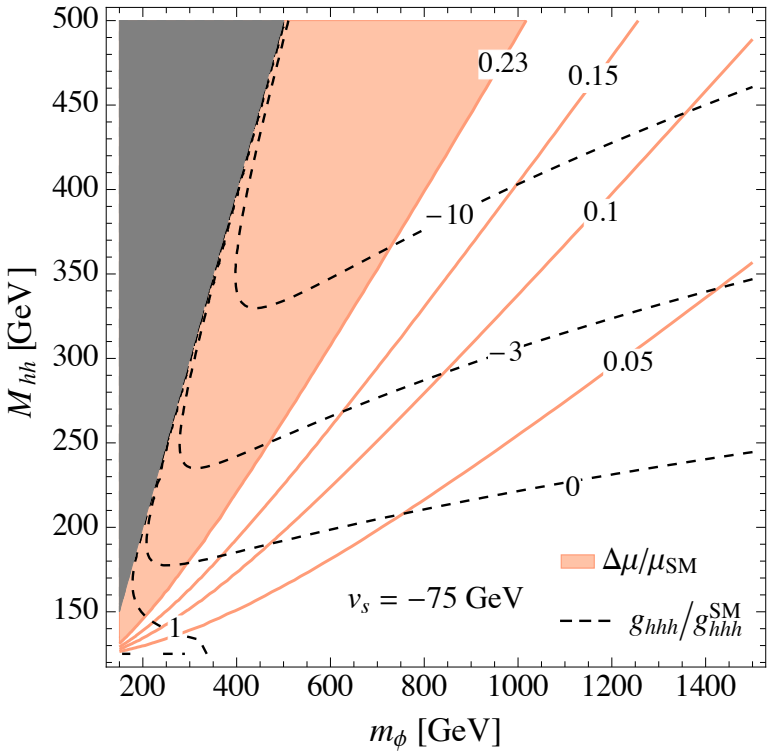

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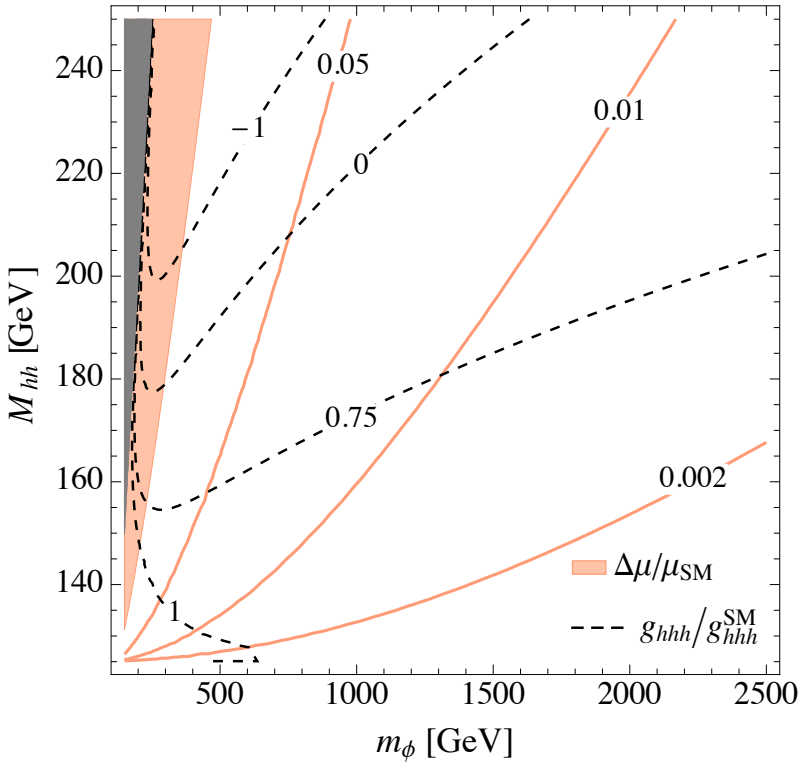

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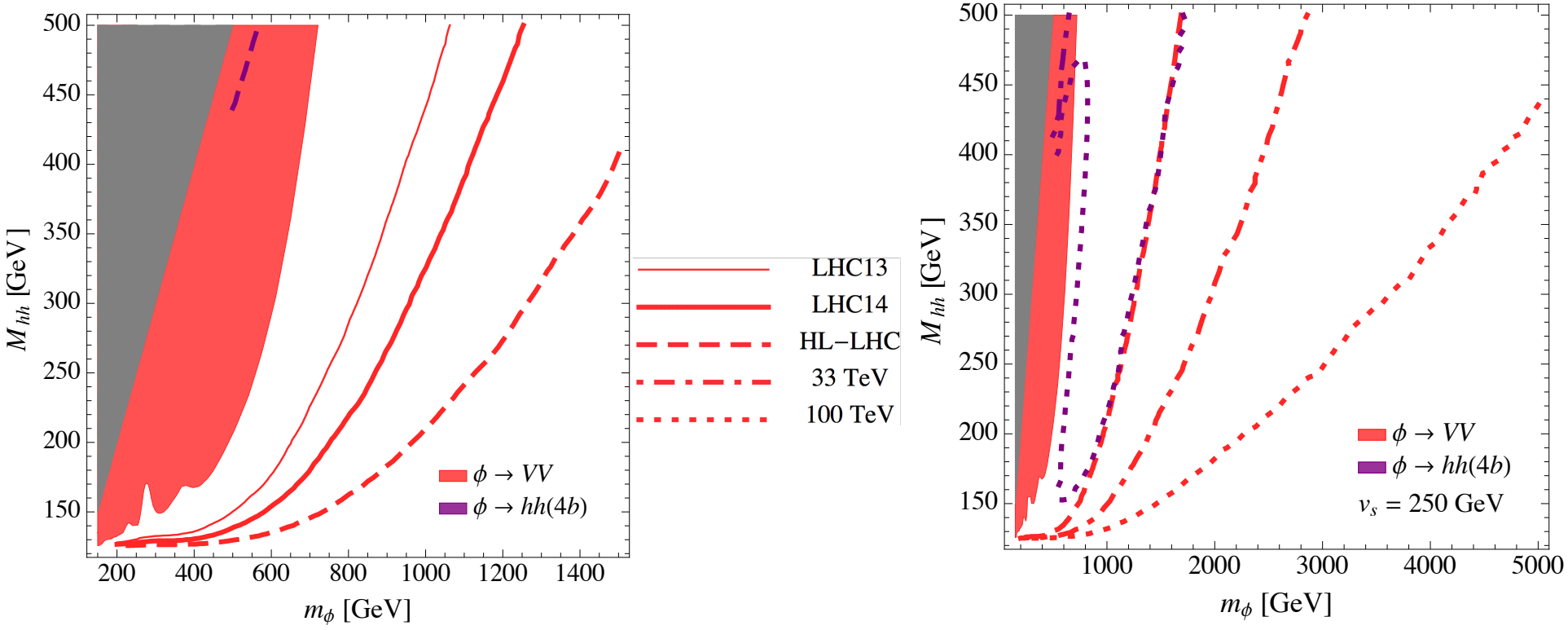

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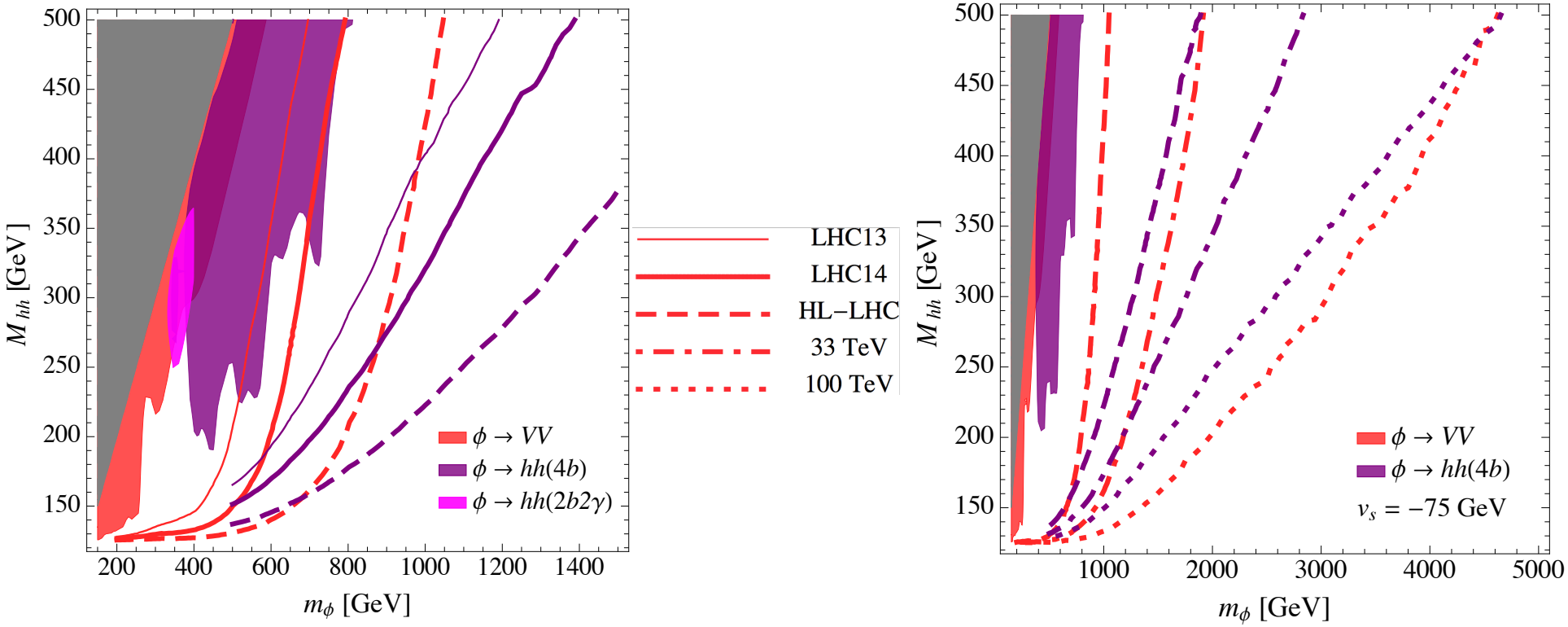

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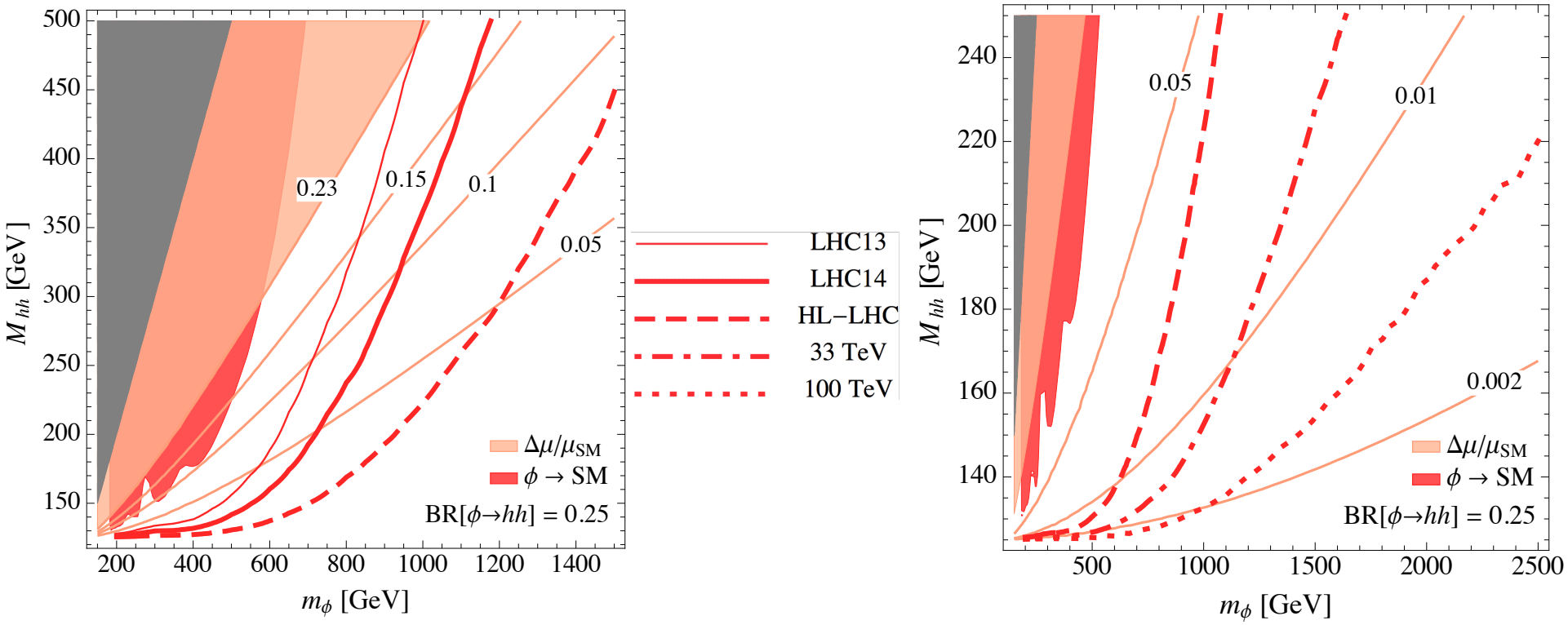

Higgs as a PNG boson: Twin Higgs

Higgs as a PNG boson: Twin Higgs

Take-home message:

$$\text{Mixing angle } \boxed{\sin\gamma \simeq \frac{v}{f}}$$

$$\Downarrow$$

Direct searches of the singlet are promising!

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 $m_\sigma > m_Z \times f/v$]

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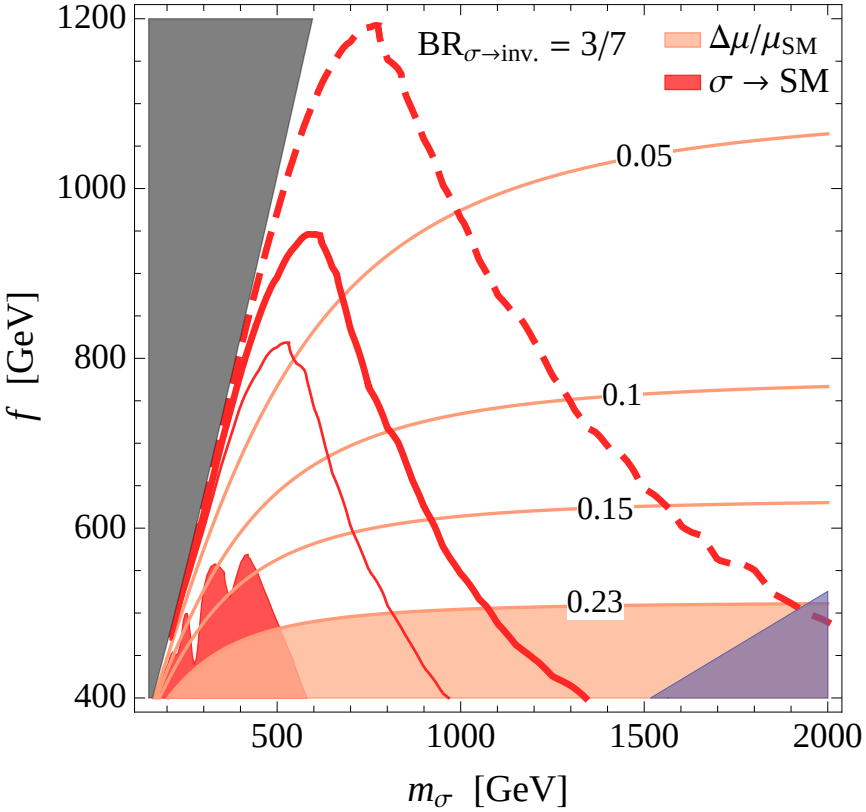

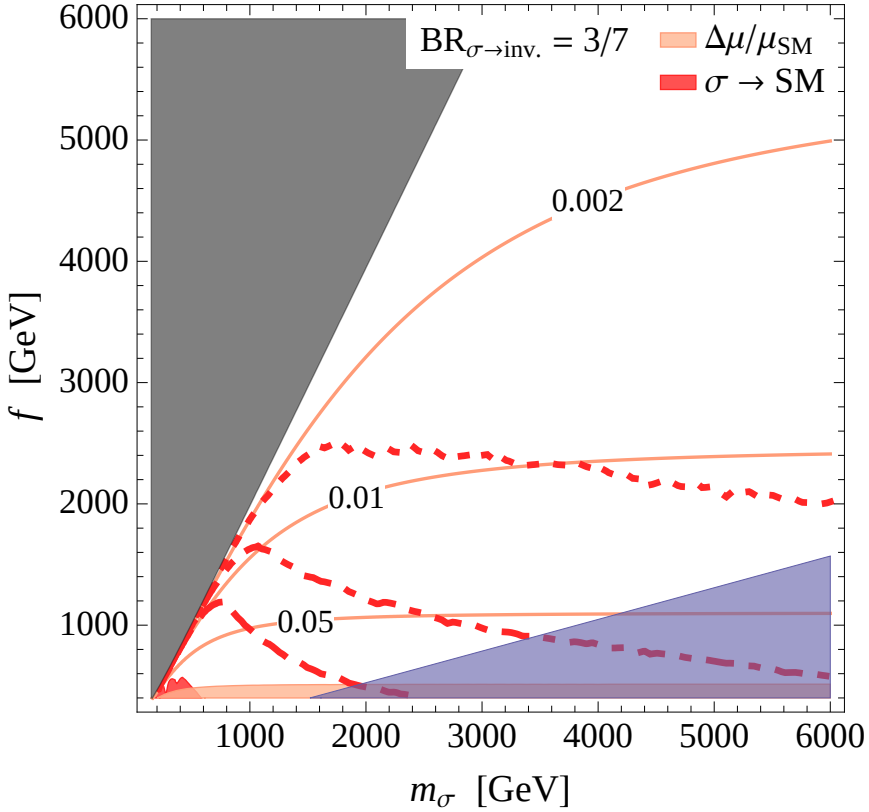

The NMSSM

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

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

Remember: naturalness $\Rightarrow \lambda \sim 1$

Δ = all loop effects, e.g. top-stop

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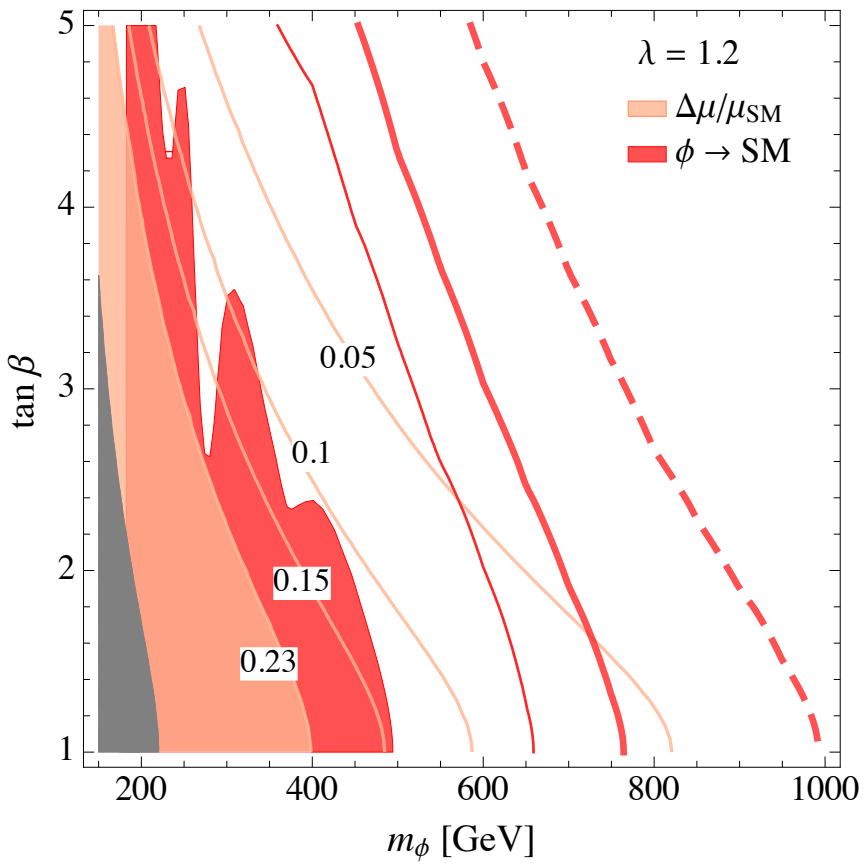
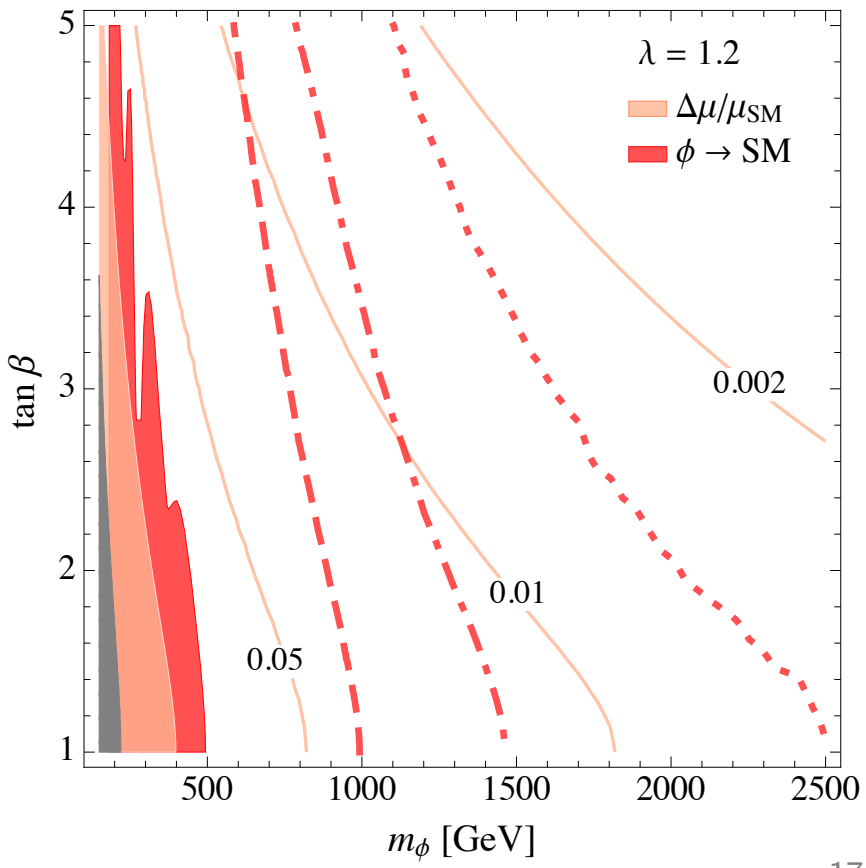
Here $\lambda = 1.2$ $\Delta = 70$ GeV

$\tan\beta$ "small" otherwise EWPT





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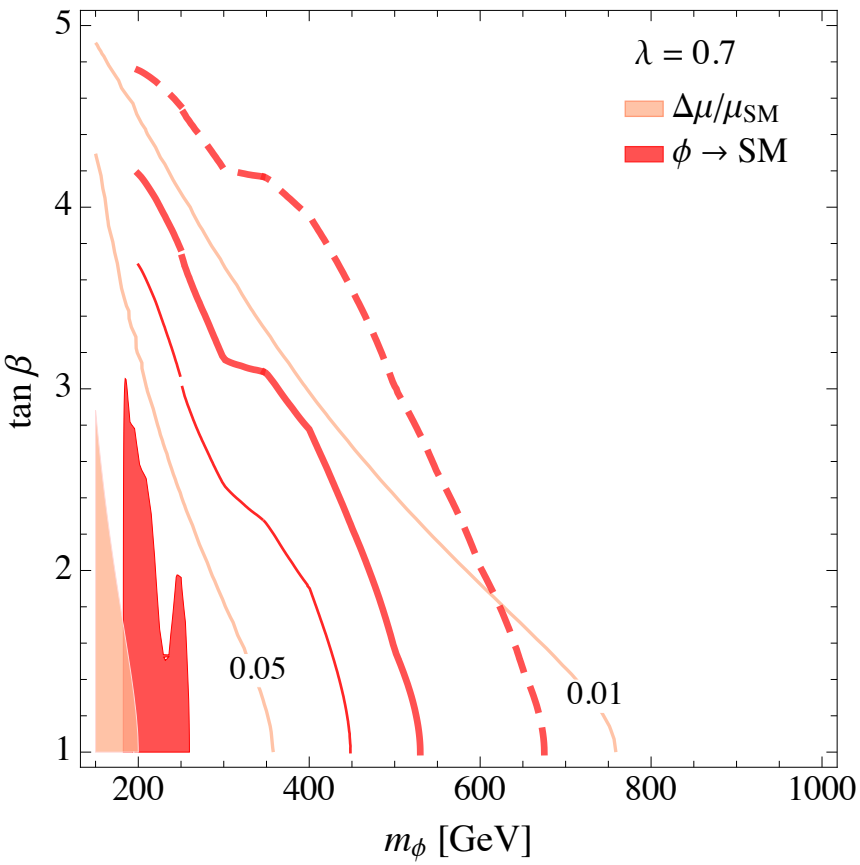
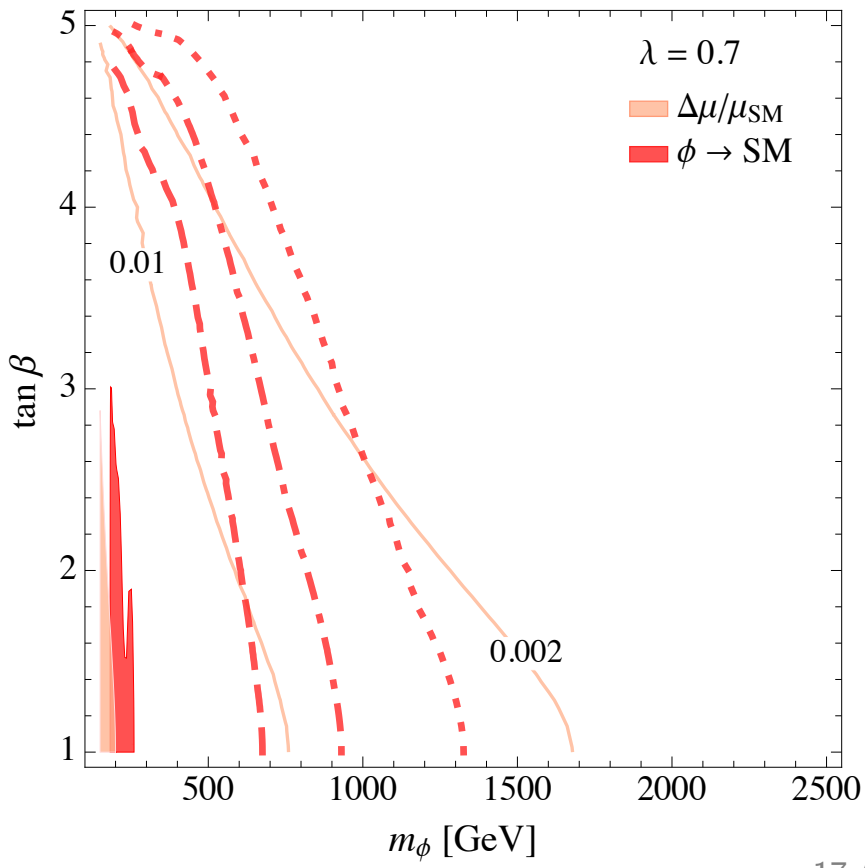
Here $\lambda = 0.7$ $\Delta = 80$ GeV

$\tan\beta$ "small" otherwise EWPT



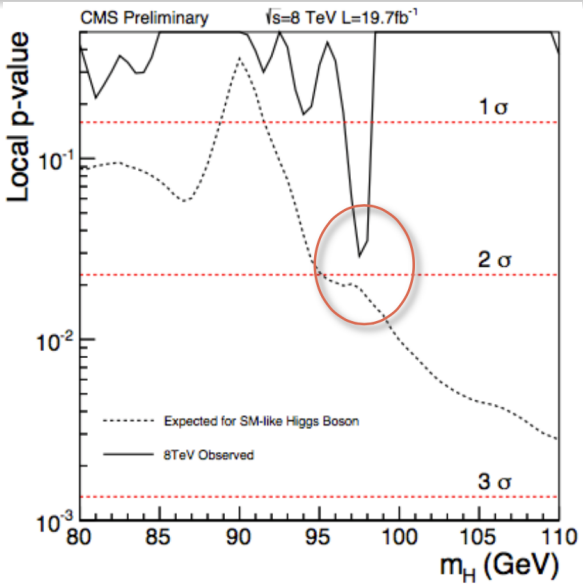


Fully mixed case and a $\gamma\gamma$ signal

Singlet-like state lighter than 125 GeV

Hard to see, but maybe already found??

SUSY 2015, Tristan du Pree



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Barbieri et al 1304.3670, 1307.4937

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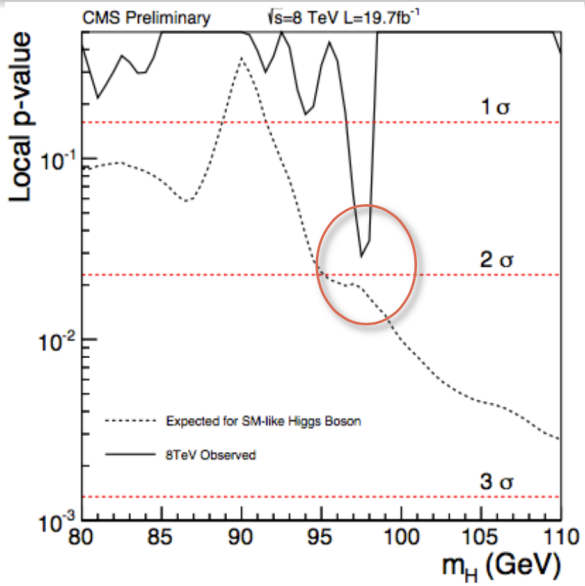
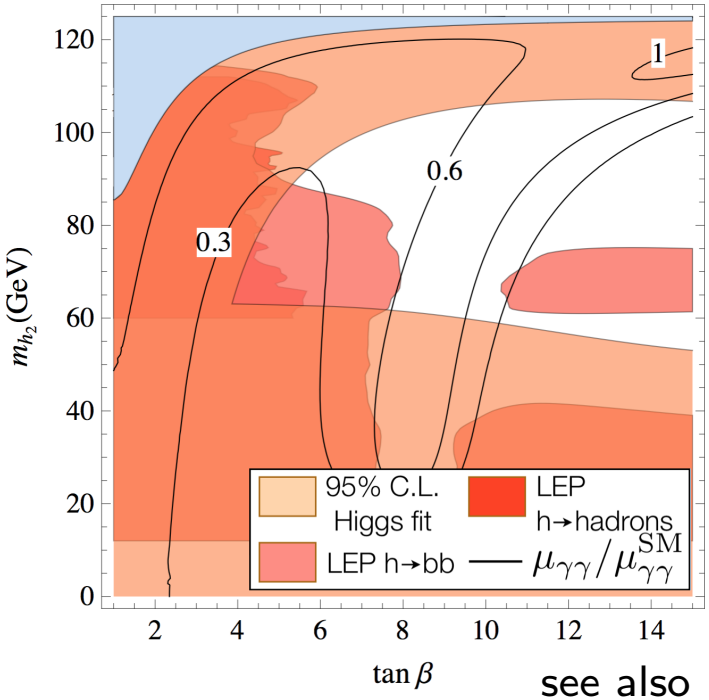
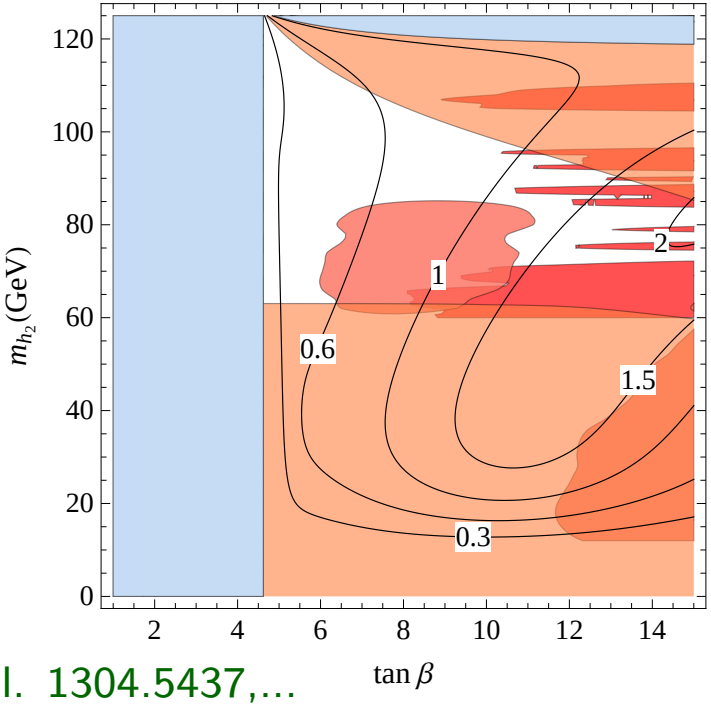


$[m_{h_3} = 500 \text{ GeV},\ s_\sigma^2 = 10^{-3},\ v_s = v]$

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



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



see also Badziak et al. 1304.5437,...

Where to look for New Physics?

✓ Indications from "natural" New Physics

mostly based on Buttazzo S Tesi, 1505.05488

→ Indications from WIMP Dark Matter

mostly based on Cirelli Hambye Panci S Taoso, 1507.05519

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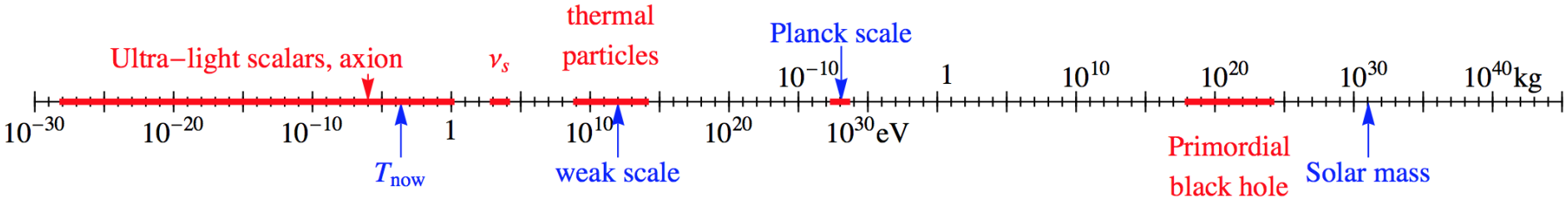
Where is Dark Matter?



[courtesy of Marco Cirelli]

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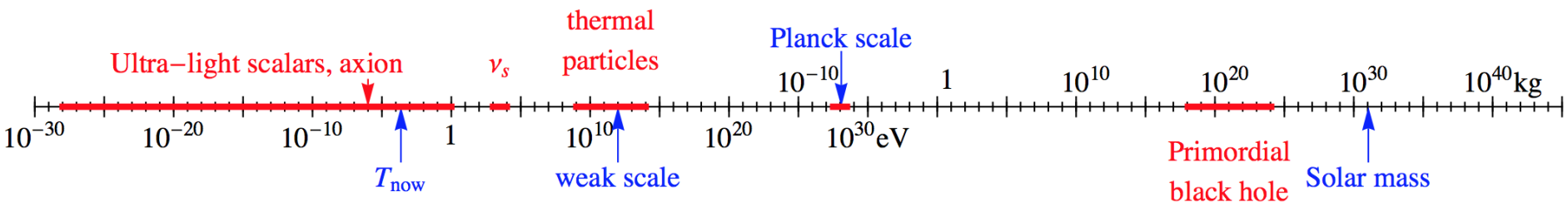

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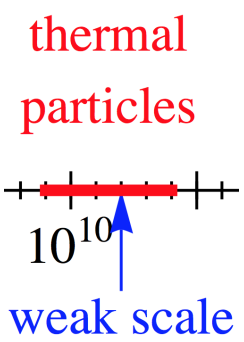


How to probe the "thermal relic WIMP" paradigm?

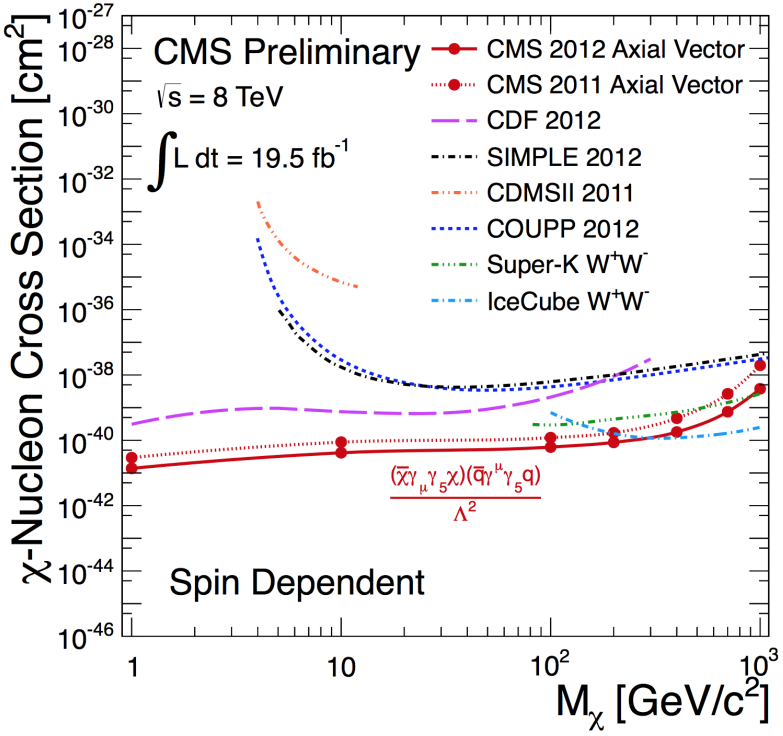
[Unitarity bound: $M_{\rm DM} < 80 \div 120$ TeV Griest Kamionkowski 1990, ... Cahill-Rowley et al. 1501.03153]

General strategy: effective field theories?

The EFT approach:

☺ Model-independent

☺ easy comparison collider - direct detection



General strategy: effective field theories?

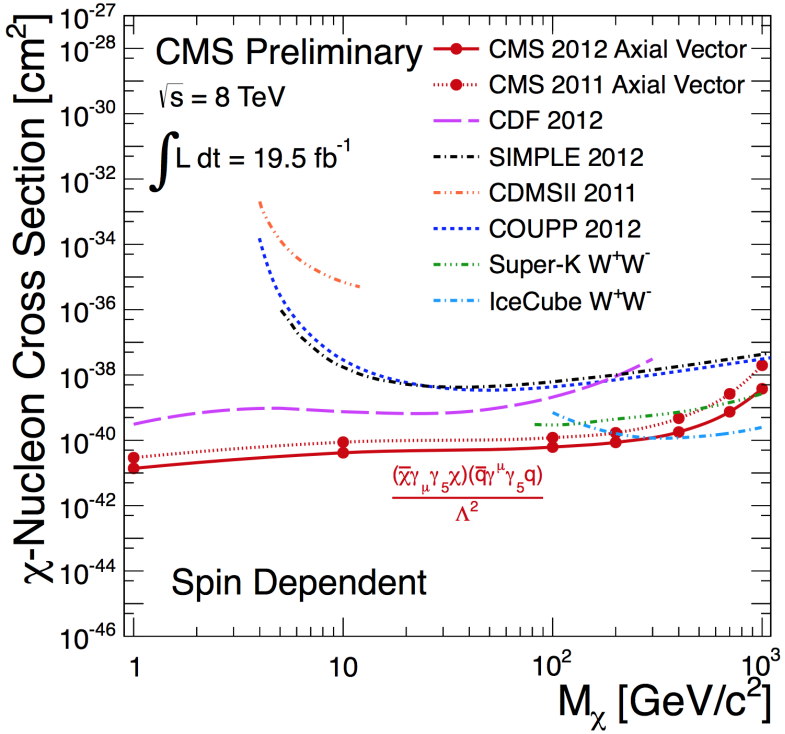
The EFT approach:

☺ Model-independent

☺ easy comparison collider - direct detection

☹ $\sim$ wrong for LHC (especially 14 TeV) !!

often $\boxed{\text{momentum transfer} > \text{suppression scale } \Lambda}$



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

Minimal Dark Matter: intro

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

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

other terms forbidden without new symmetries

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

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

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

Electroweak multiplets at colliders

5plet No hopes to reach M_{thermal}

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

Electroweak multiplets at colliders

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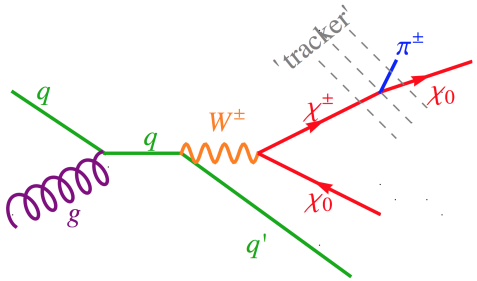
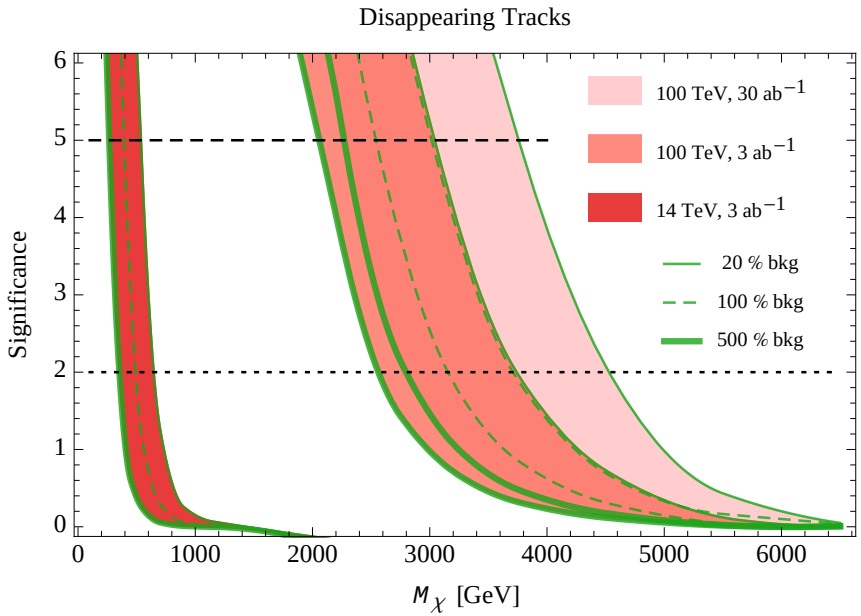
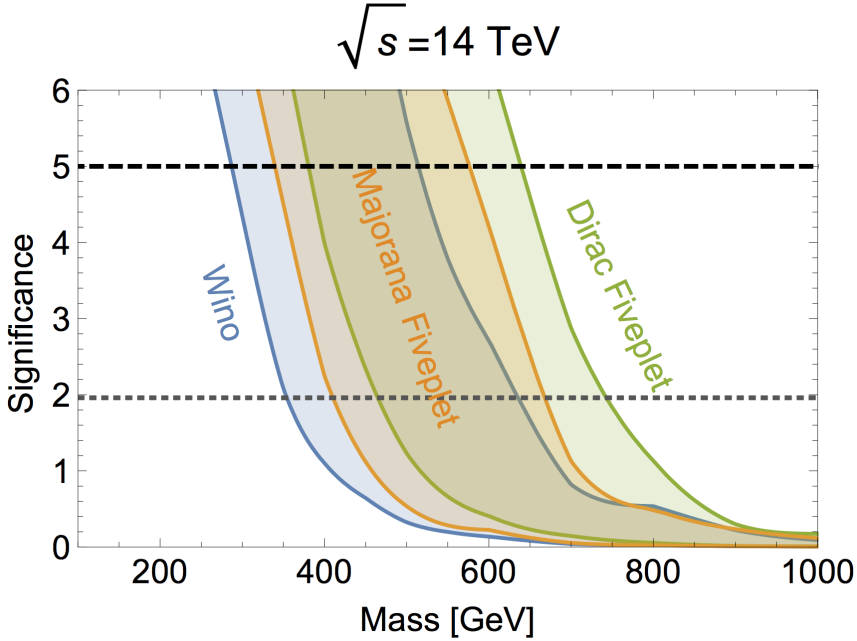
Most promising channel: disappearing tracks

current stronger probe $M_\chi \gtrsim 270$ GeV





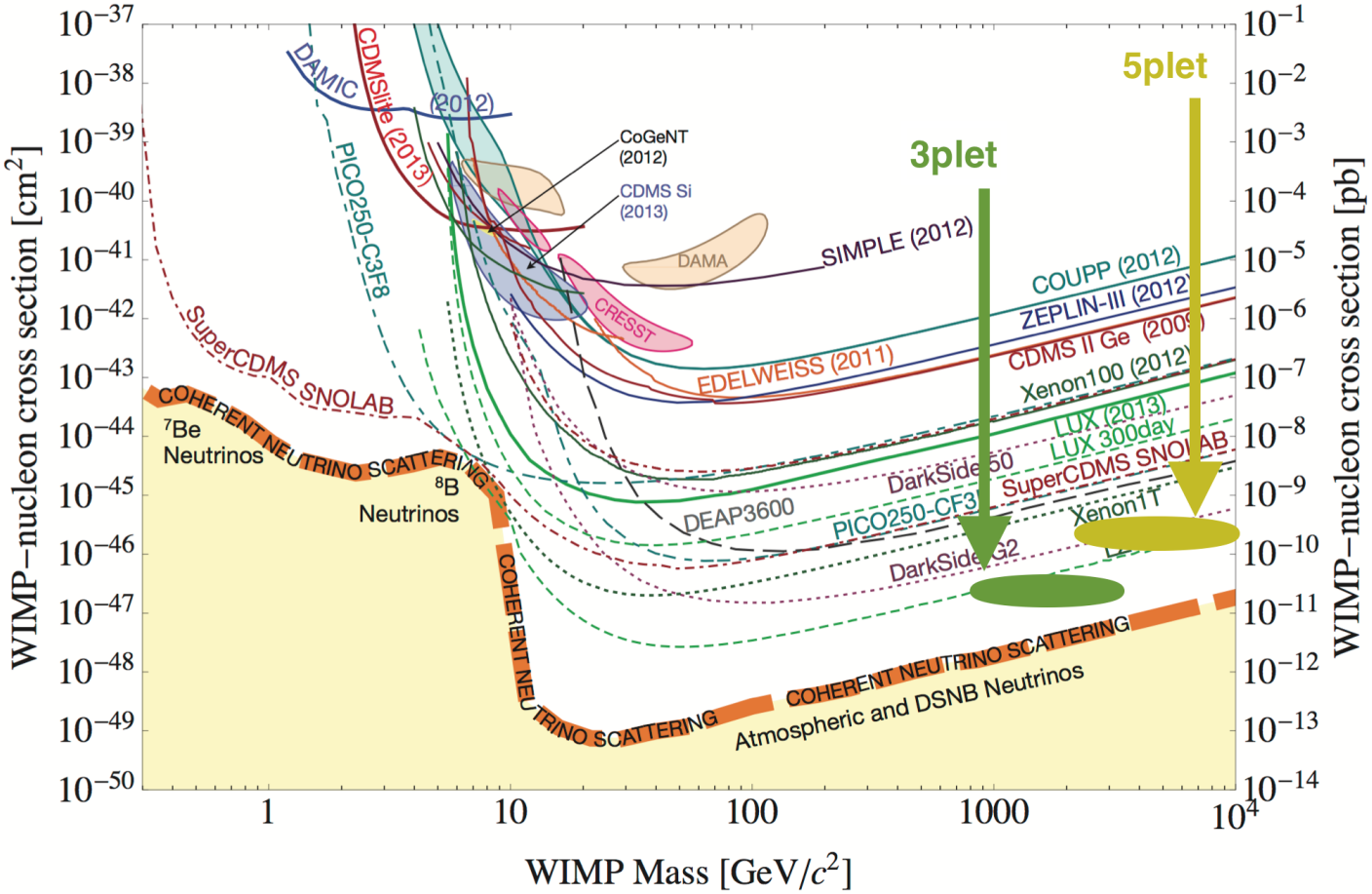
Cirelli S Taoso 1407.7058

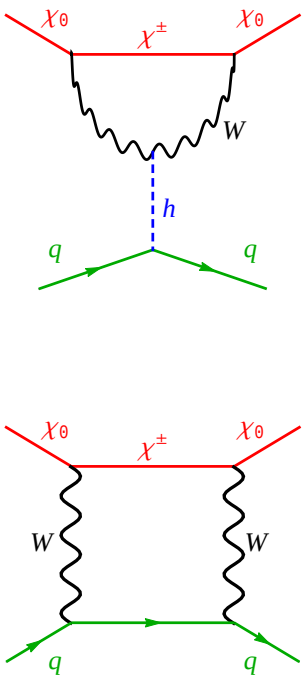


Ostdiek 1506.03445

see also Feng Strassler 1994 ... Low Wang 1404.0682

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]

Electroweak multiplets in the (γ) sky

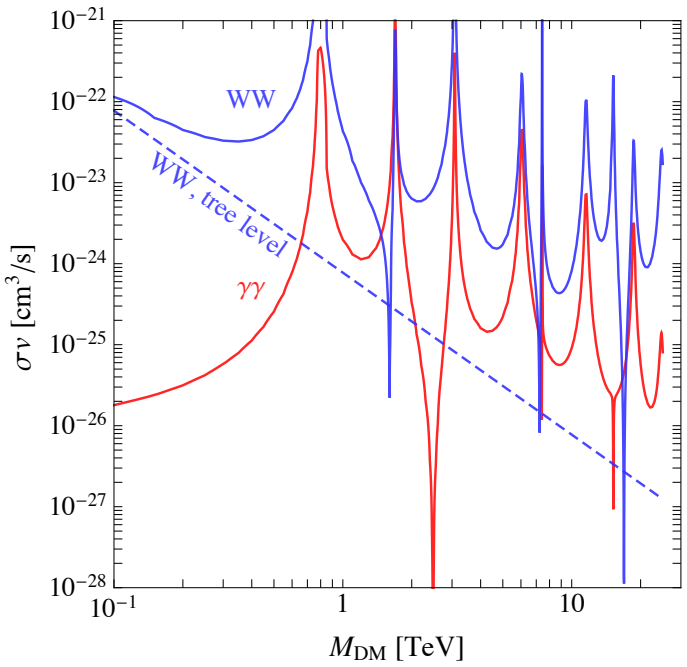
Sommerfeld enhancement

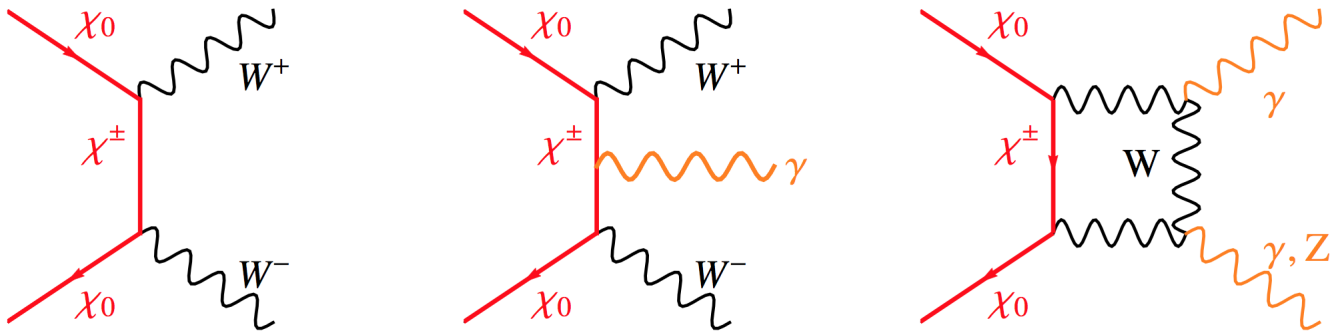
at low velocities non-rel. attractive potential

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

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

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





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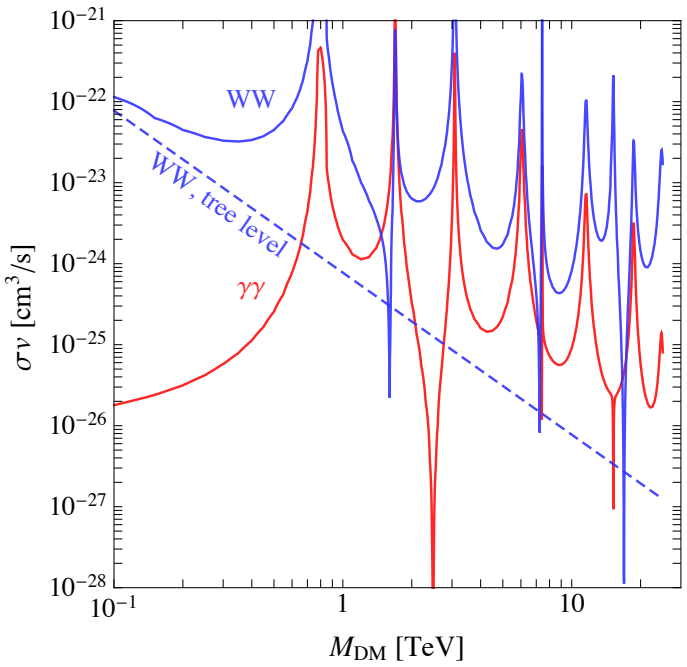

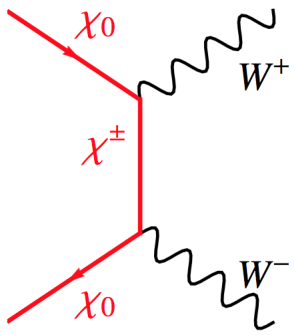

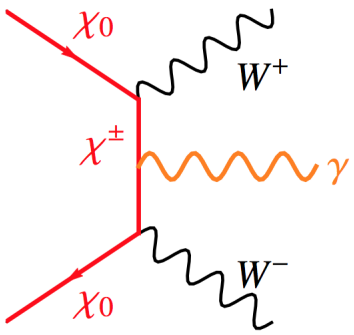

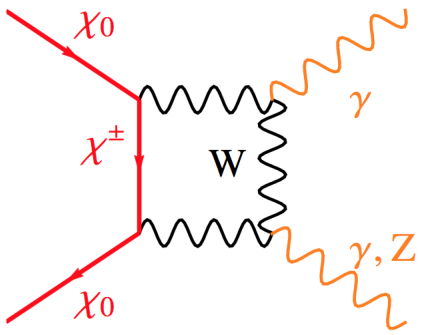

$\bar{p}$, e^+, ν, $\gamma, \ldots$

γ ray lines: smaller cross-sections

but features in γ spectrum enhance sensitivities

γ continuum with FERMI

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

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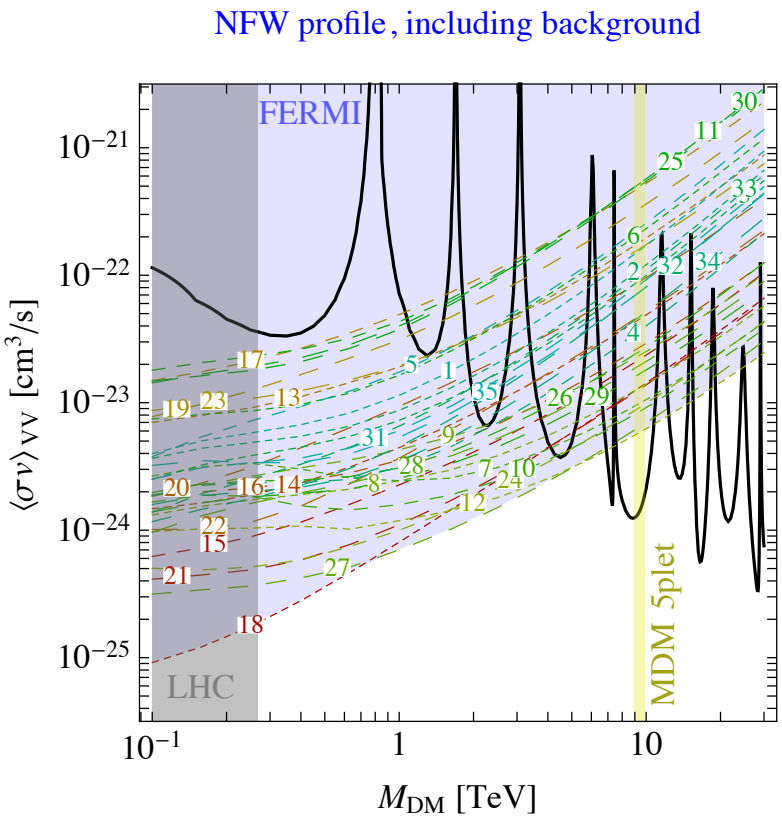

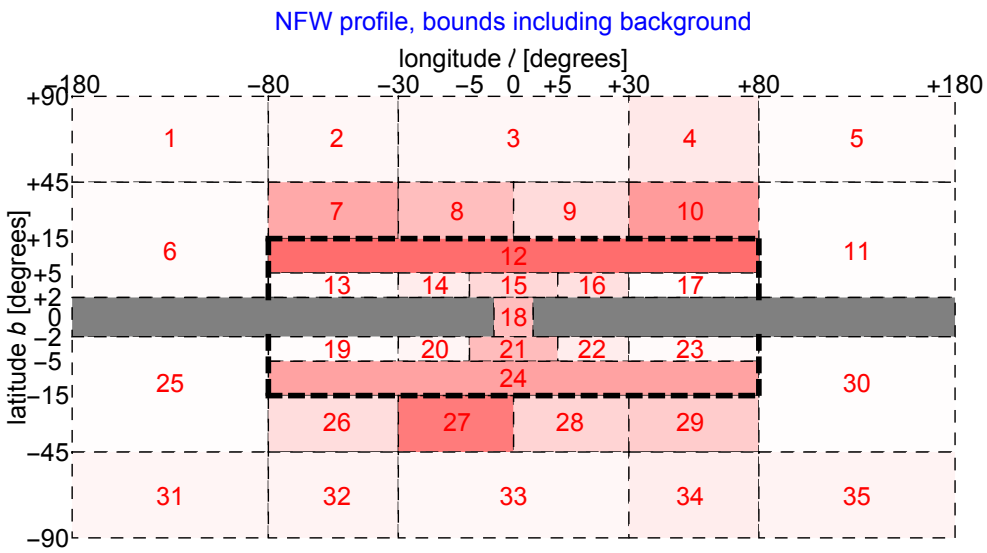

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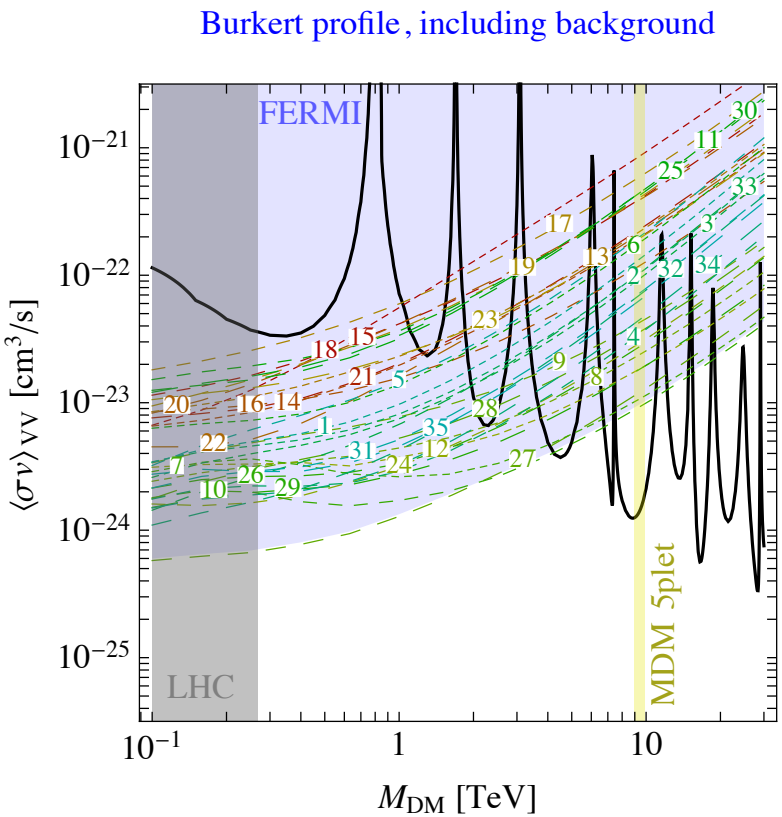

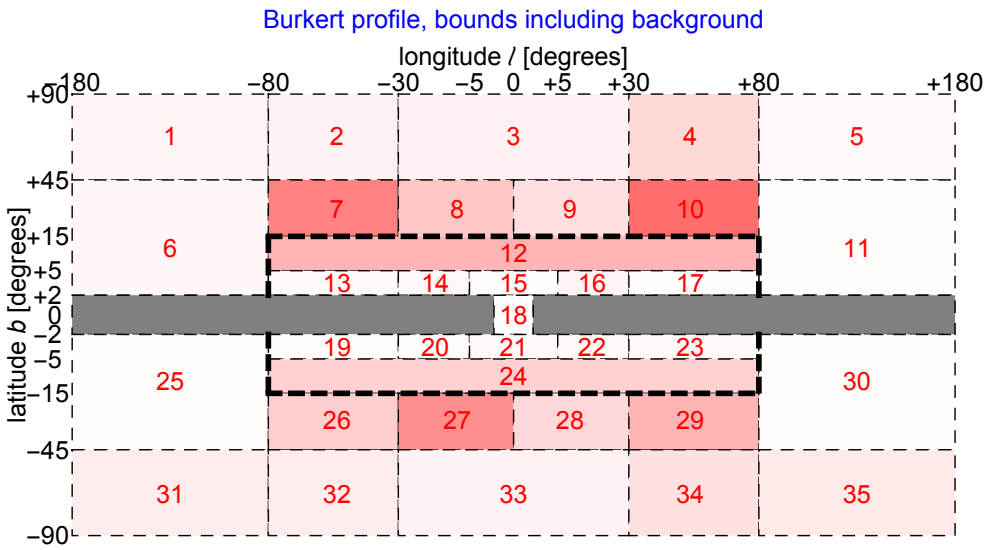

◇ Galactic bounds depend on DM profile

◇ All bounds assume 5plet = 100% of DM

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]

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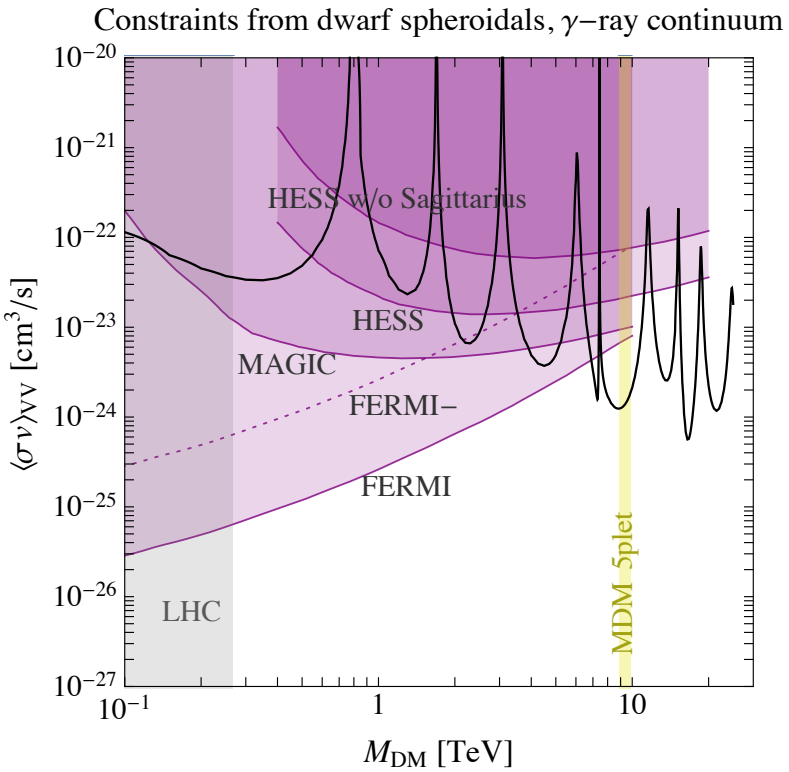

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HESS: subset of 4, plus Sagittarius

MAGIC: only Segue1 (large uncertainties!)

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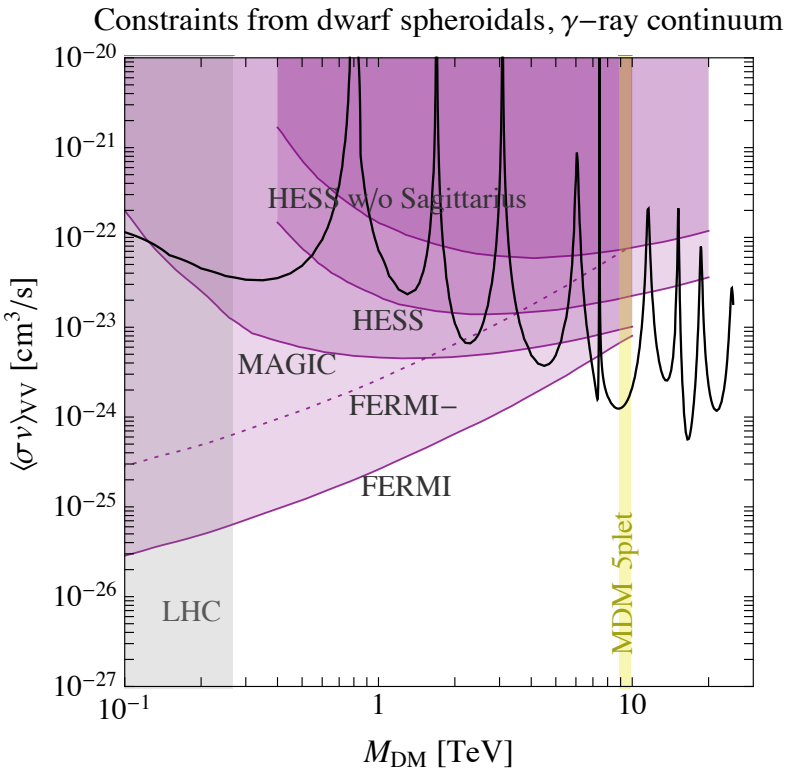

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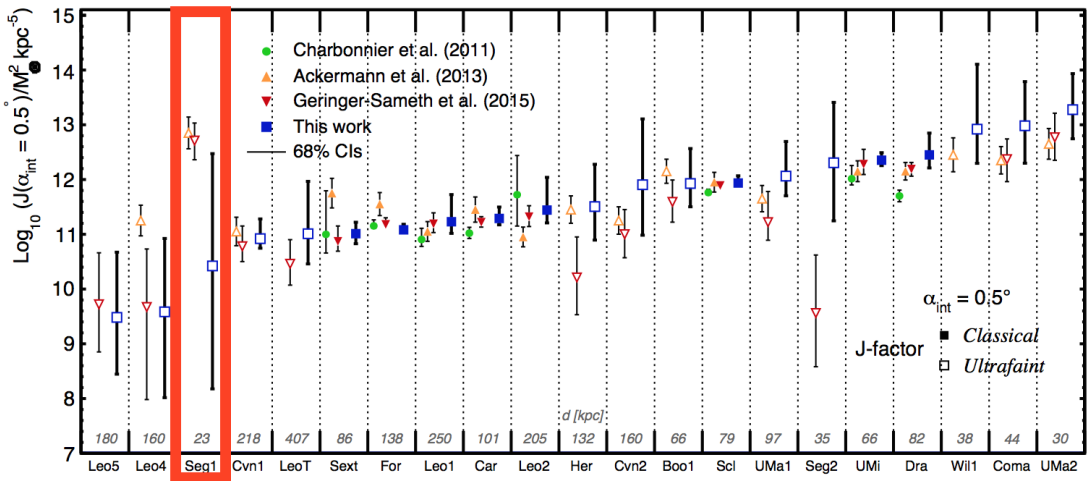
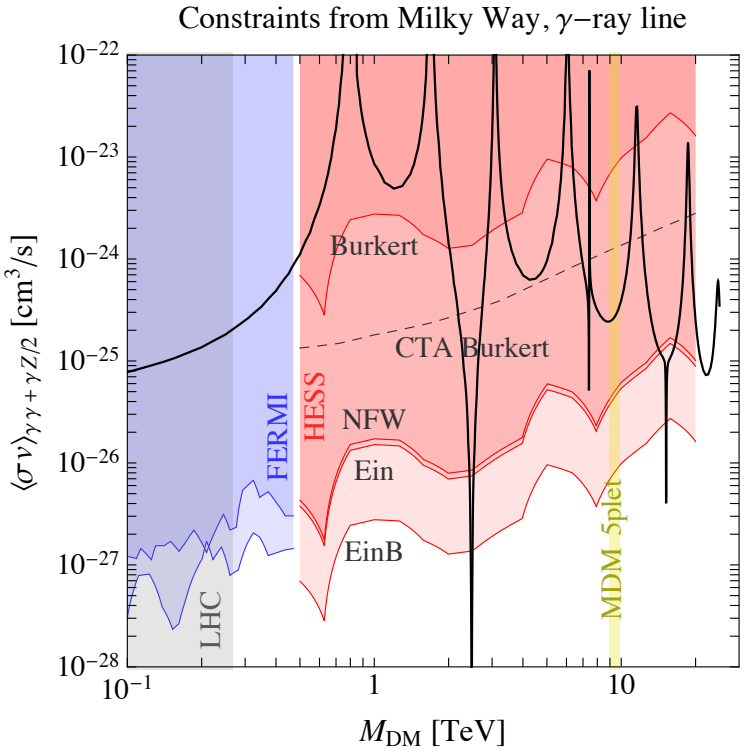
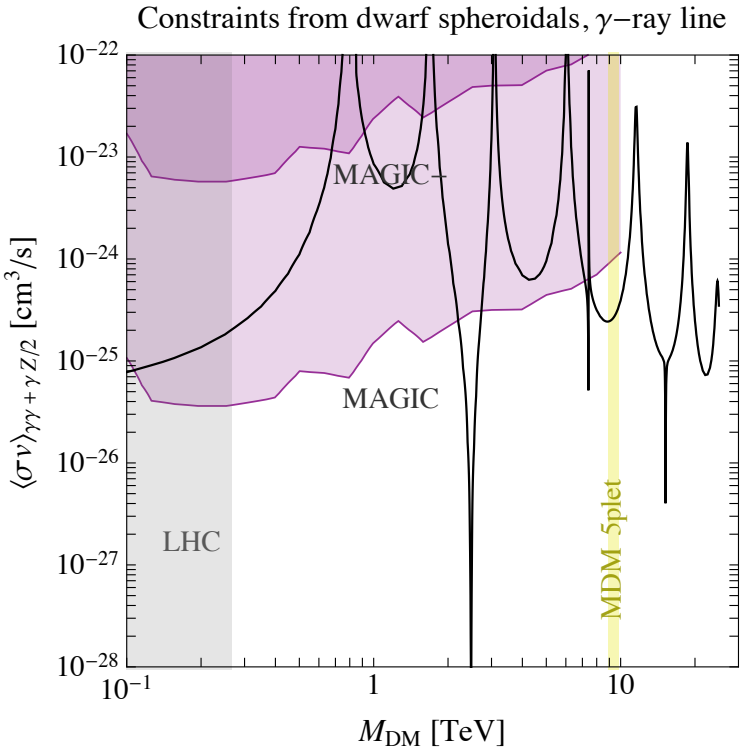


Bonnivard et al 1504.02048

γ lines: galactic center and dwarves





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

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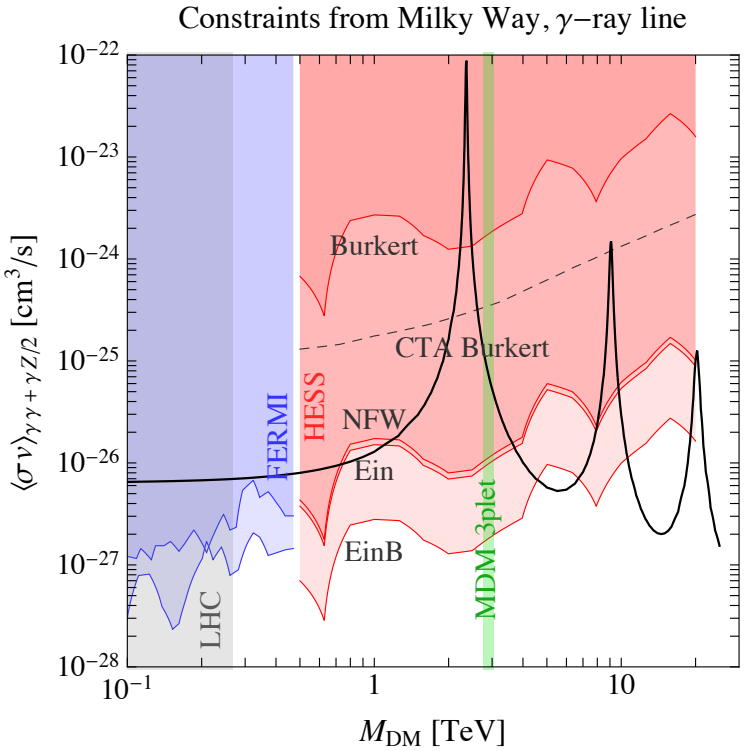
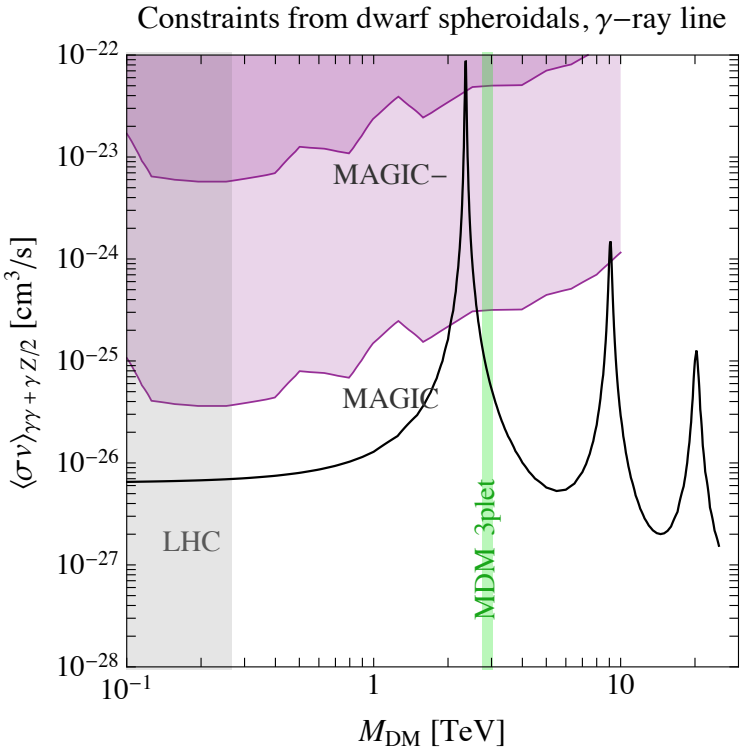
Lot of progress conceivable with dwarf spheroidals!

→ 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





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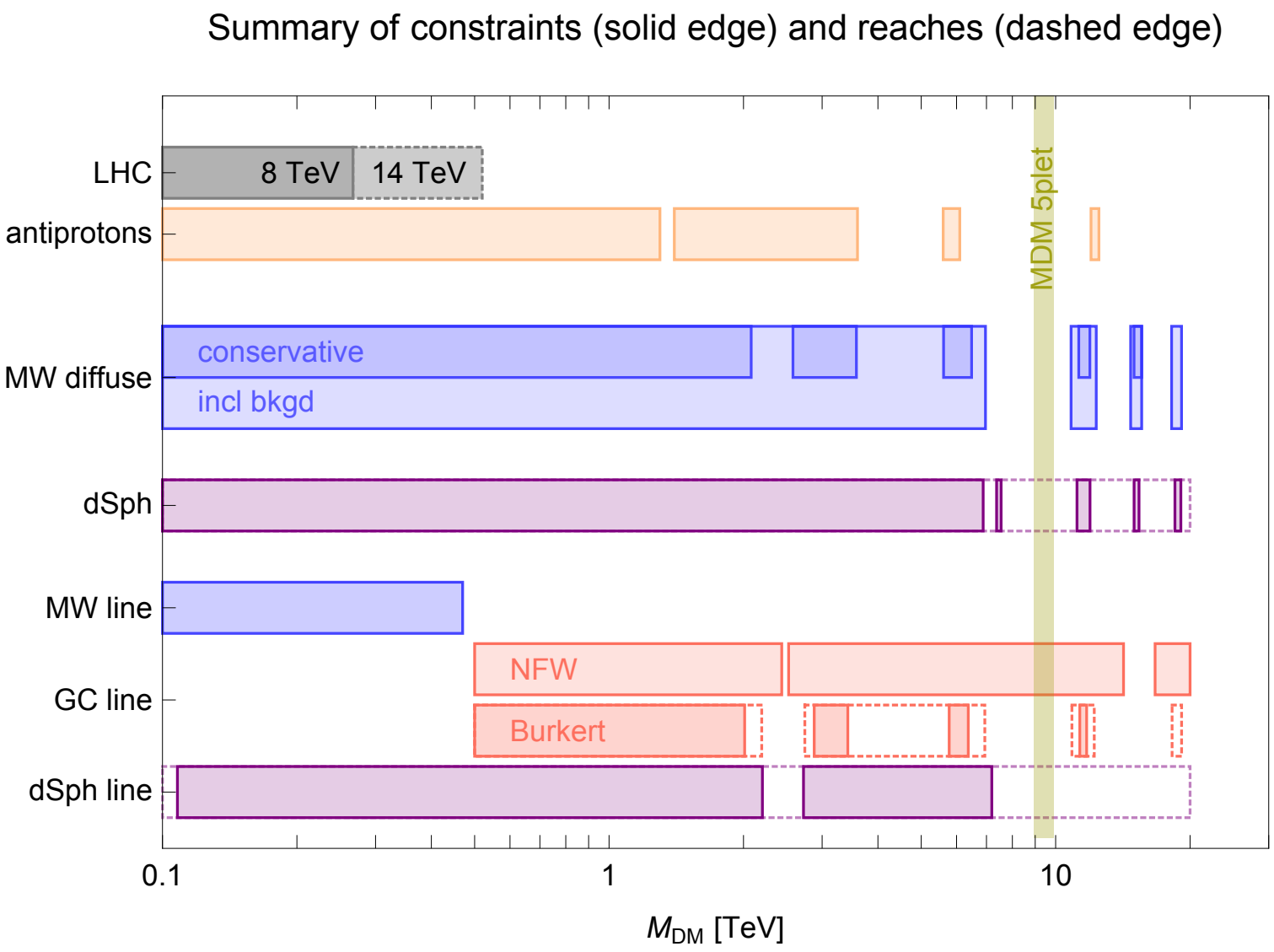
An EW fermion 5plet: pheno summary



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  Buttazzo S Tesi, 1505.05488

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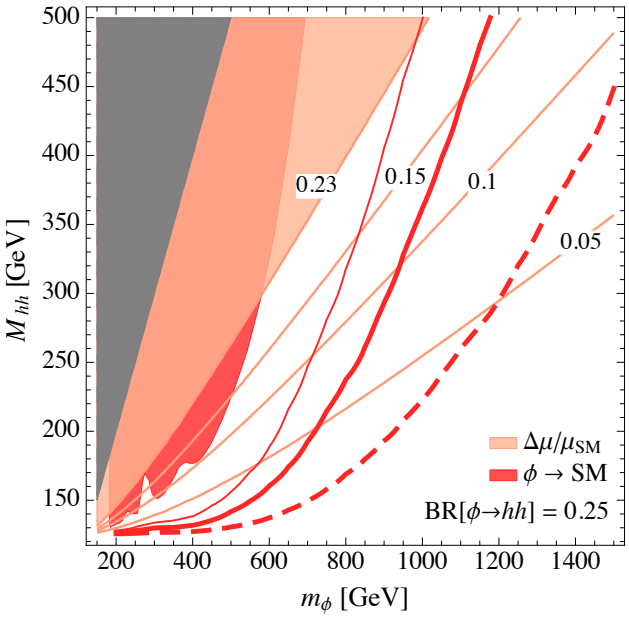
An extra Singlet-like Higgs
appears in NMSSM, Twin Higgs, ...

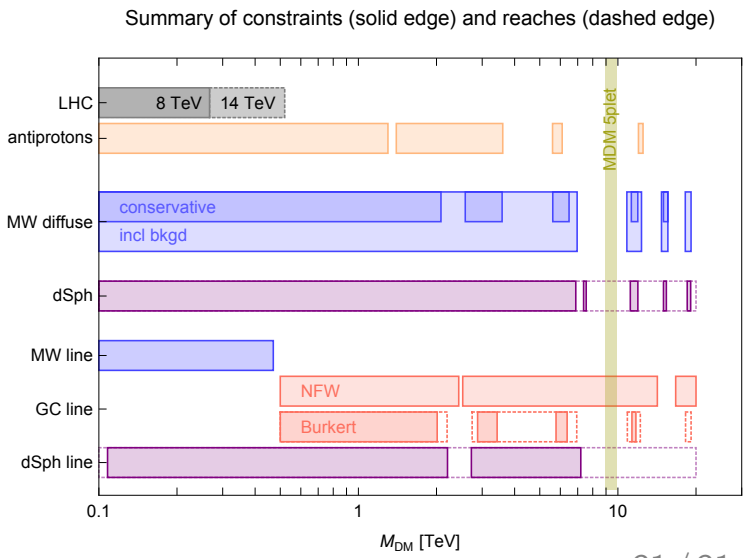
$h_2 \to VV, hh, \quad h$ couplings, $\quad g_{hhh}$



✓ Indications from WIMP Dark Matter
Cirelli Hambye Panci S Taoso, 1507.05519

An EW fermion multiplet, focus on 5plet
◇ "simplest" simplified model?
◇ Minimal Dark Matter ◇ 3plet = Wino ...

If 100% of DM, dwarves might be the future



Back up Dark Matter

Minimal Dark Matter: candidates

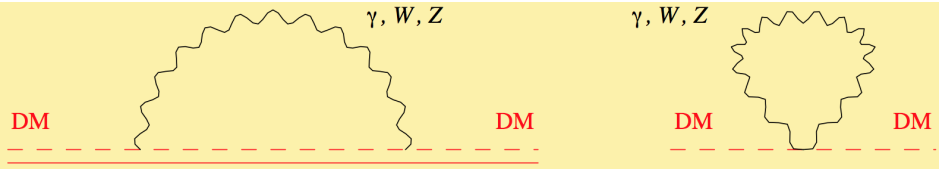
Allowed: χ neutral under g, γ, and almost under Z (direct detection)

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

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

$\Rightarrow$ first candidates are $n = 5$ fermion and $n = 7$ scalar

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

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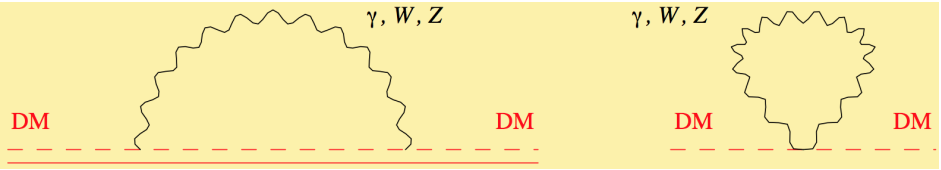

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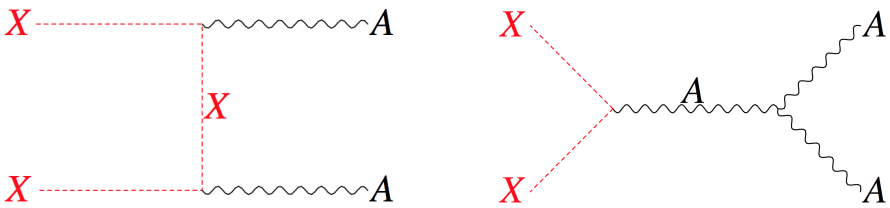
Avoid g_2 Landau pole before $M_{\rm Pl}$ $\Rightarrow$ n not too large

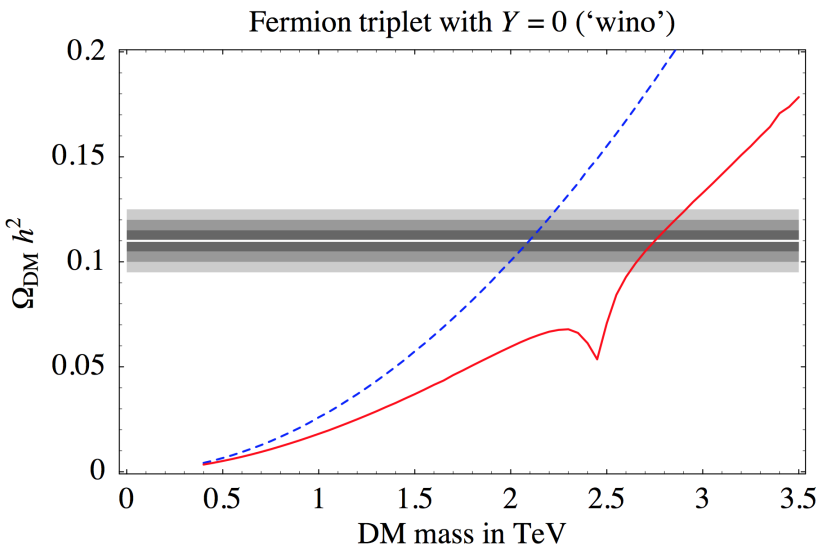
In practice: $n \leq 8$ for scalars, $n \leq 5$ for fermions

[issue from 2-loop? Nardecchia et al, work in progress]

Relic abundance

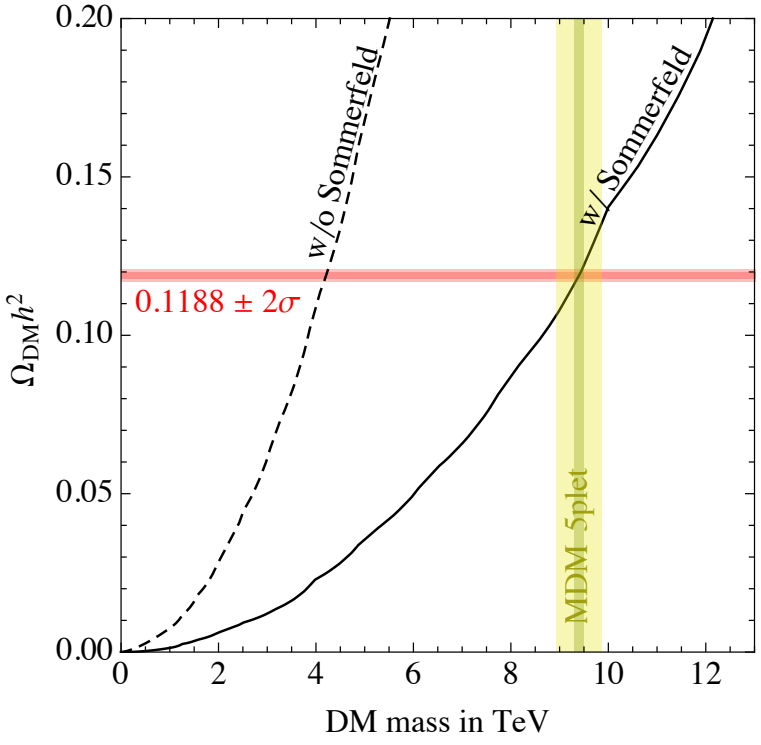
Typical WIMP candidate $\rightarrow M_{\mathrm{DM}} \sim$ TeV





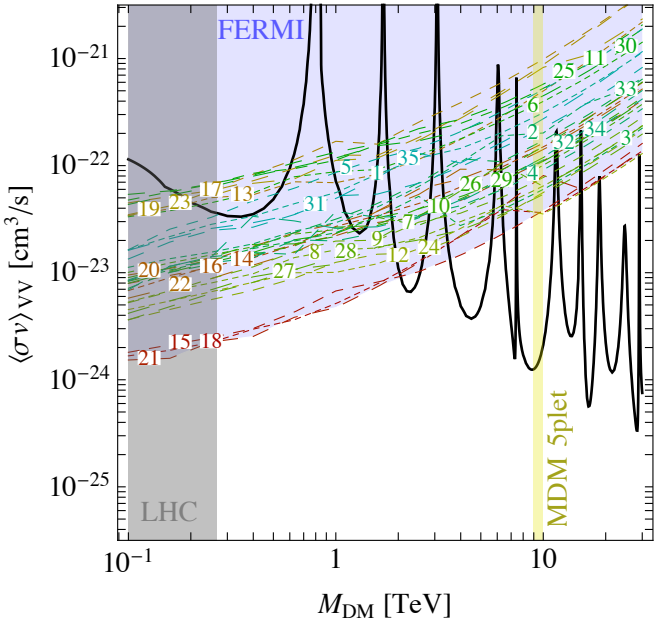
Important to include:

- ◇ Coannihilations
- ◇ Sommerfeld enhancement
- ? NLL corrections



γ continuum with FERMI - II

NFW profile, conservative bound



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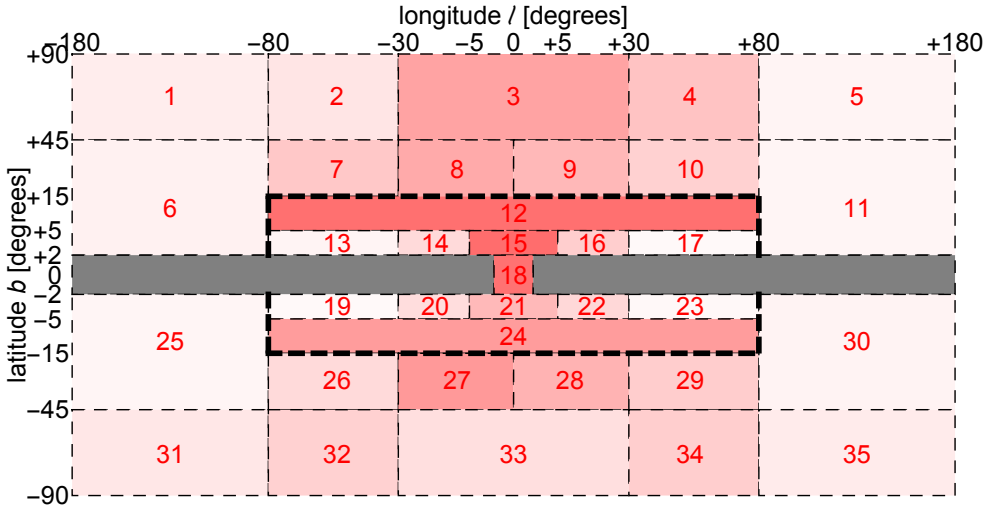
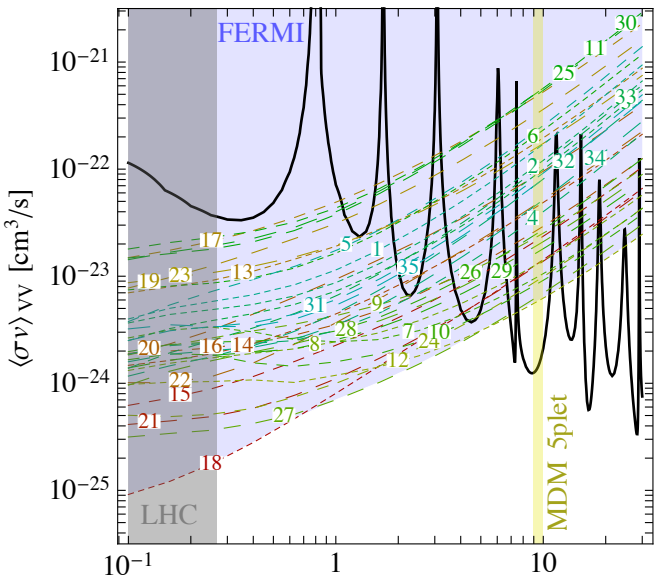
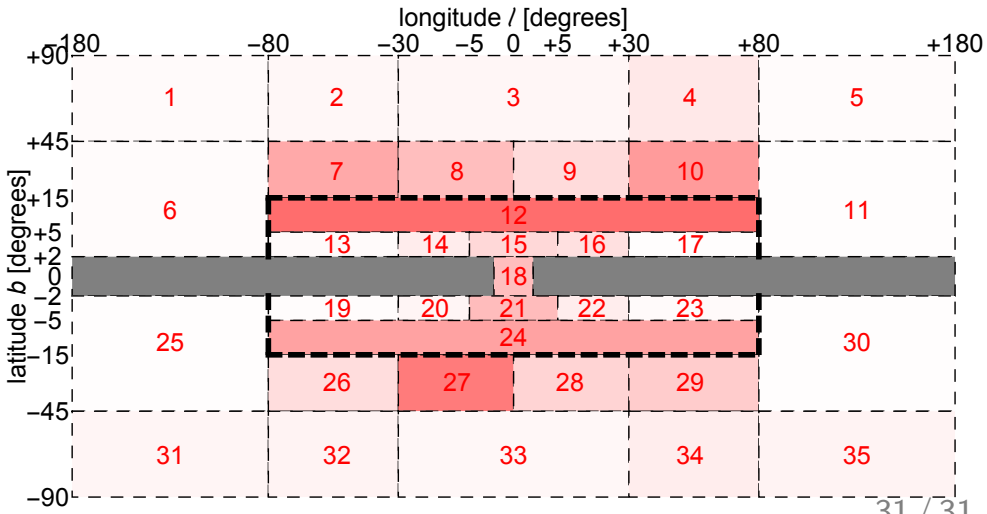


NFW profile, including background

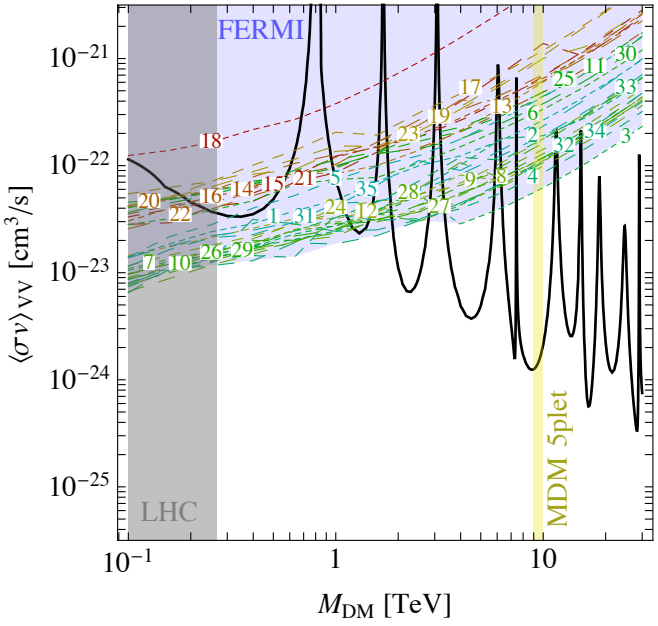


NFW profile, bounds including background

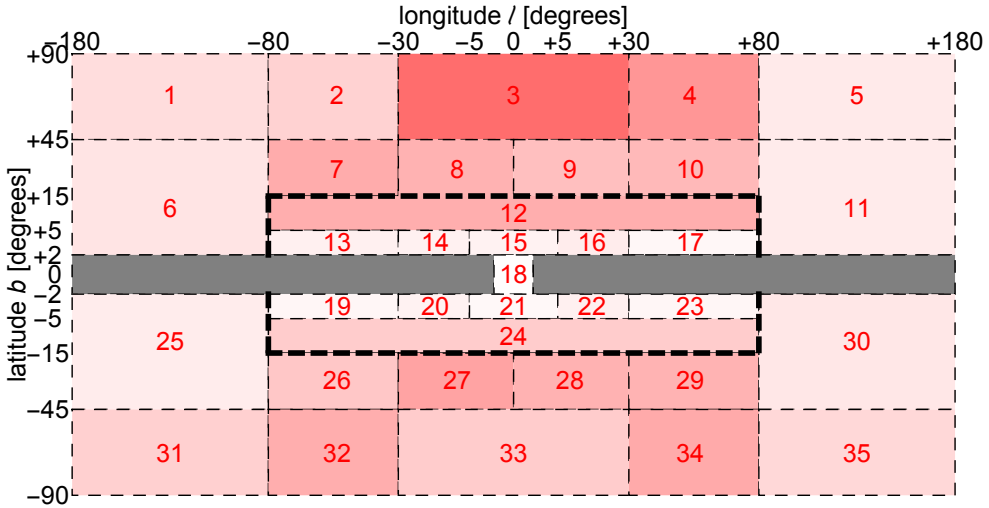


γ continuum with FERMI - II

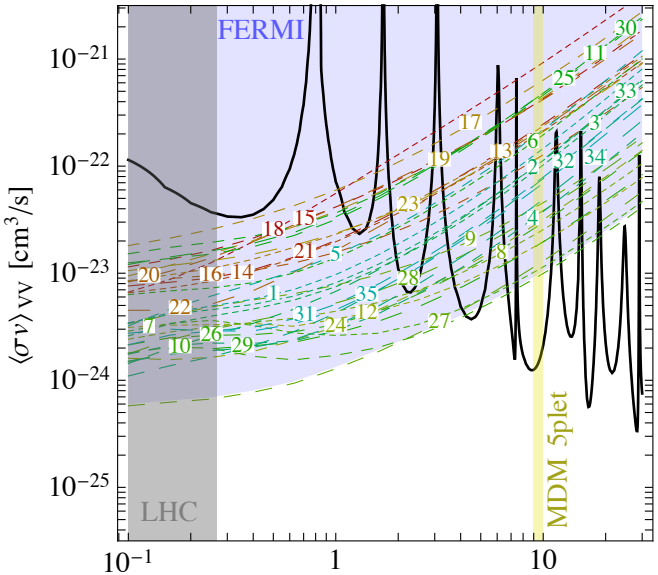
Burkert profile, conservative bound



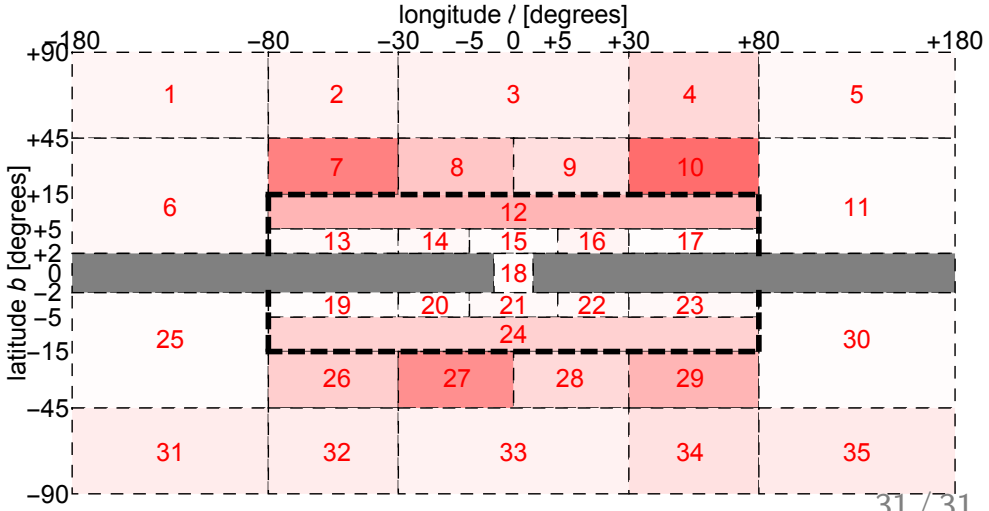
Burkert profile, conservative bounds



Burkert profile, including background



Burkert profile, bounds including background



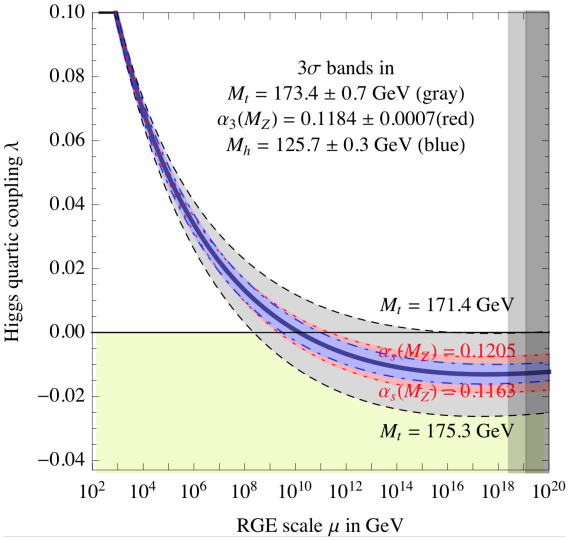
Why an EW fermion triplet?

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

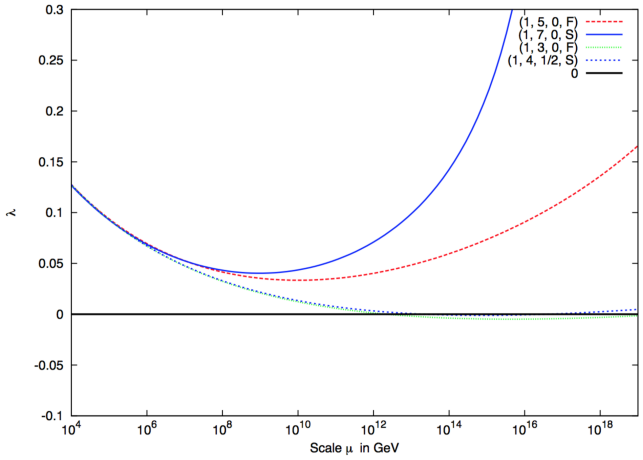
[also kills all higher-dimensional operators that could make it decay]

→ Stabilizes Standard Model vacuum

without MDM [Buttazzo et al 1307.3536]



with MDM [Chao et al 1210.0491]

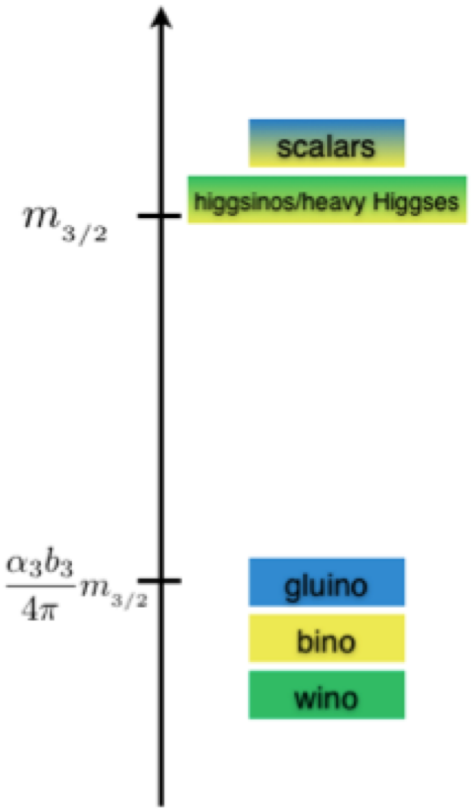


→ Not big contribution to m_h $\Rightarrow$ does not worsen fine-tuning

→ 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

Extrapolation of direct searches I

We started from (and improved)

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 $\boxed{B(s_1, L_1, m_1) = B(s_0, L_0, m_0)}$

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

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

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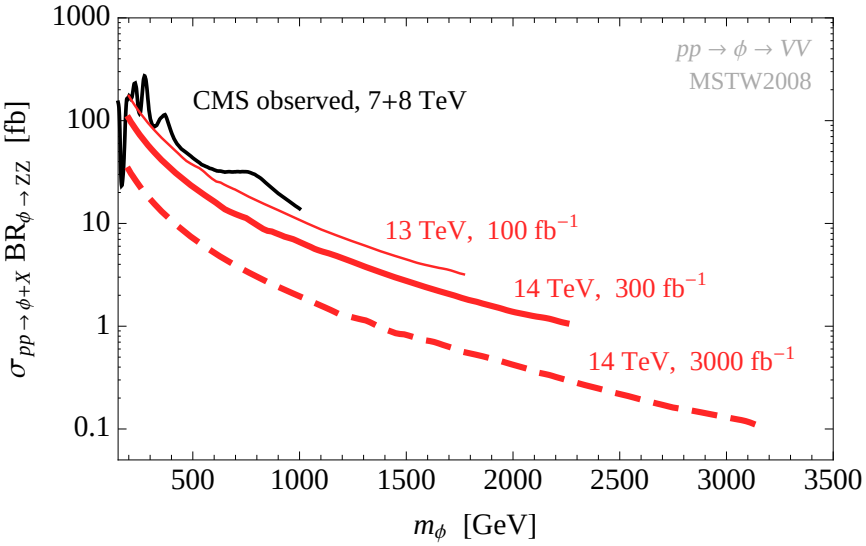

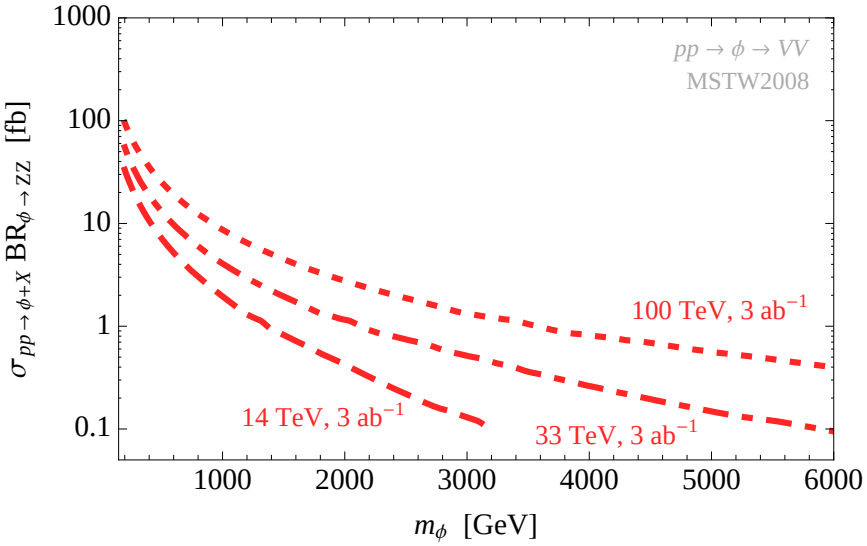

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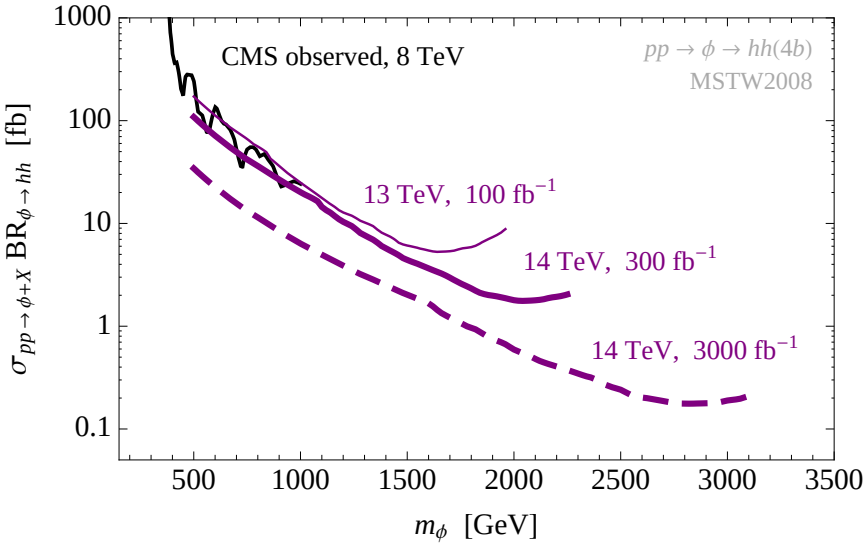
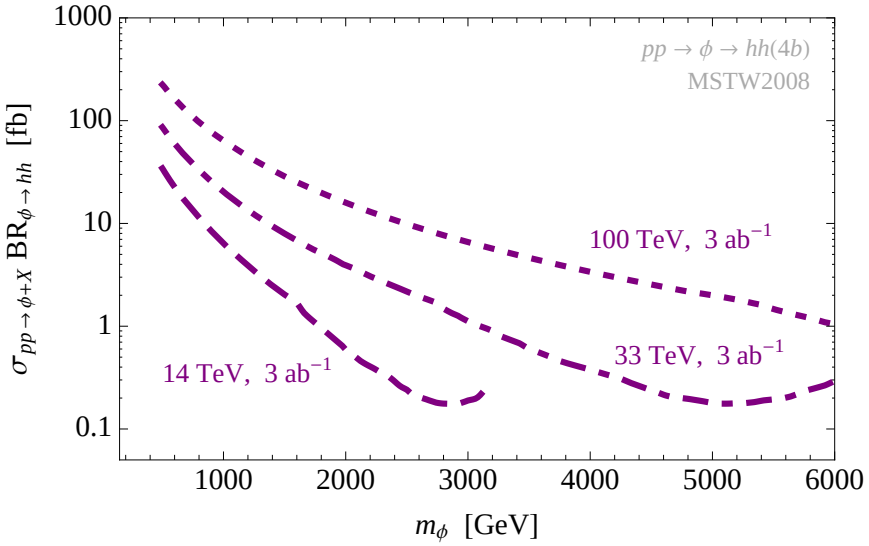
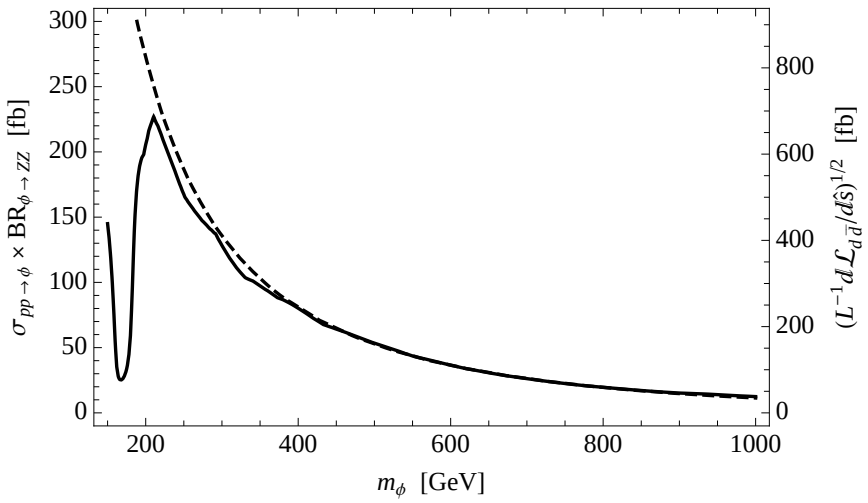
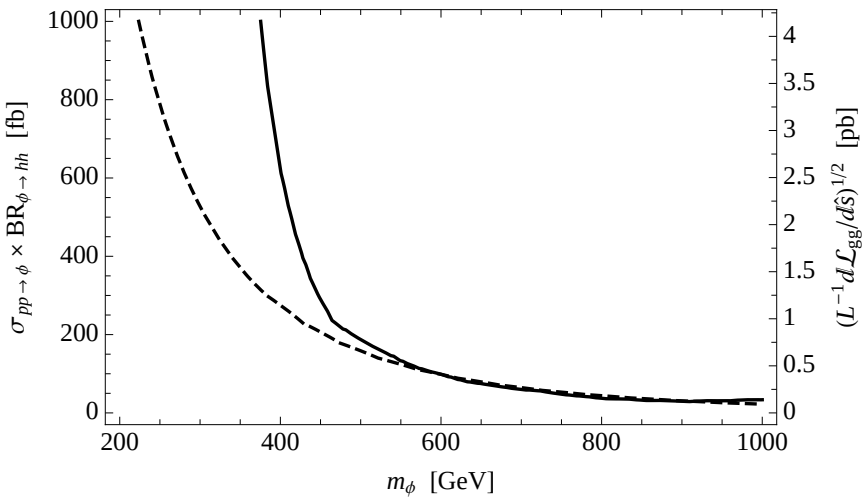




Extrapolation of direct searches II

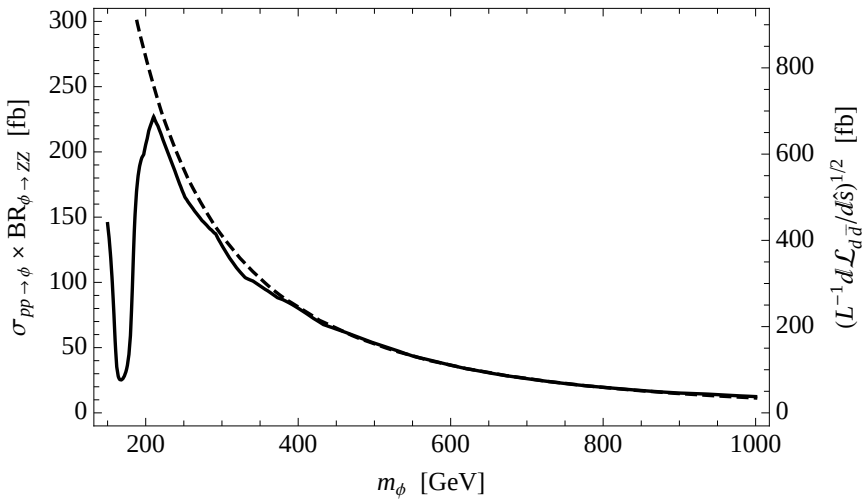


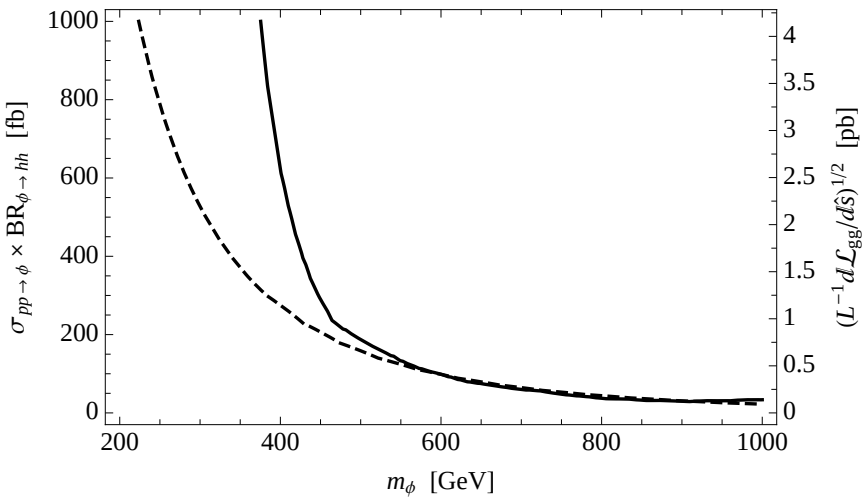


Assumptions/limitations

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

Extrapolation of direct searches II





Assumptions/limitations

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

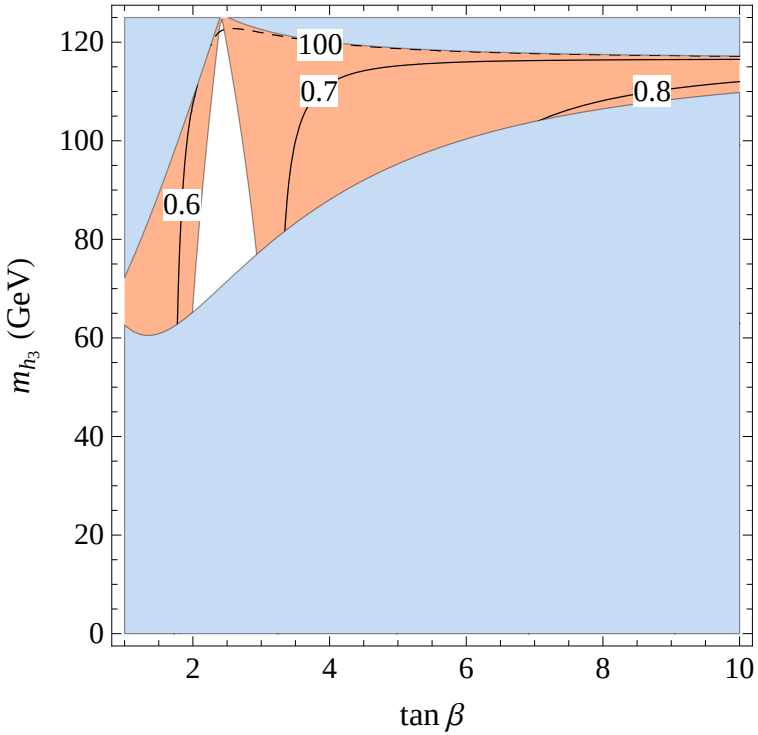
An extra doublet-like state H $[\gamma, \sigma = 0, \quad m_{h_2} \gg m_{h_1}, m_{h_3}]$

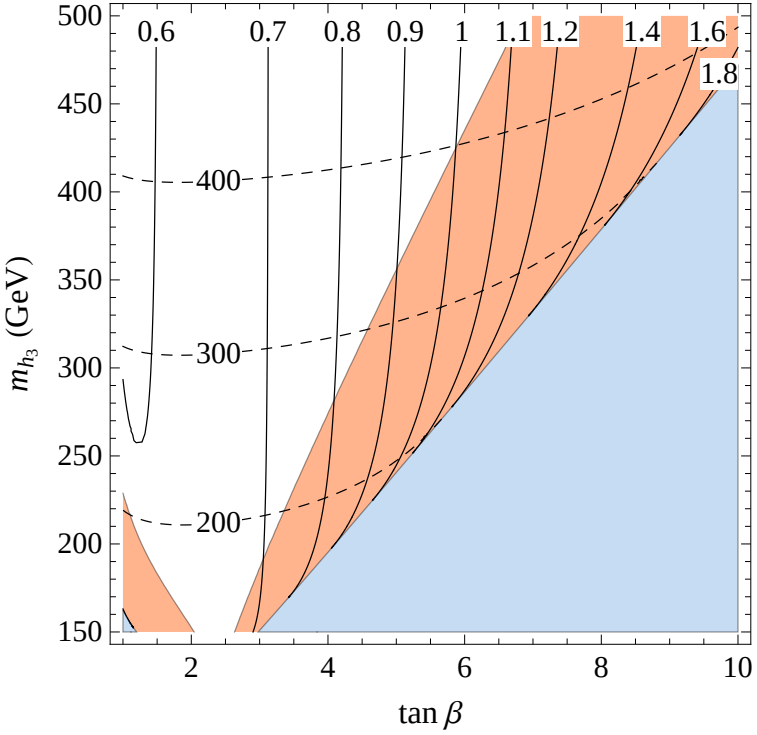
Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

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

Status fit LHC8:

dashed: $m_{H^\pm}$ cont: λ





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

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

h_3 phenomenology: more similar to MSSM

see e.g. Craig et al. 1504.04630

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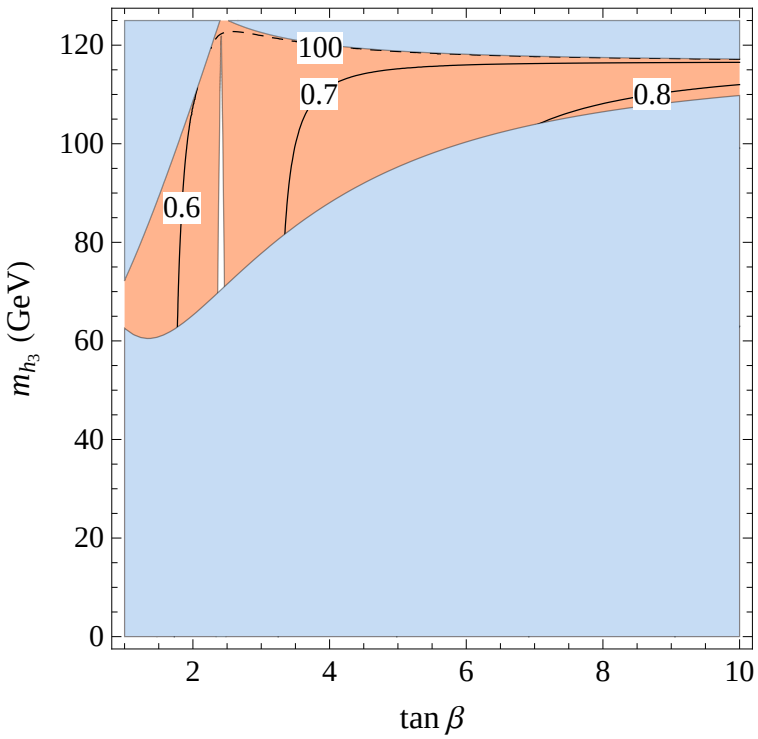
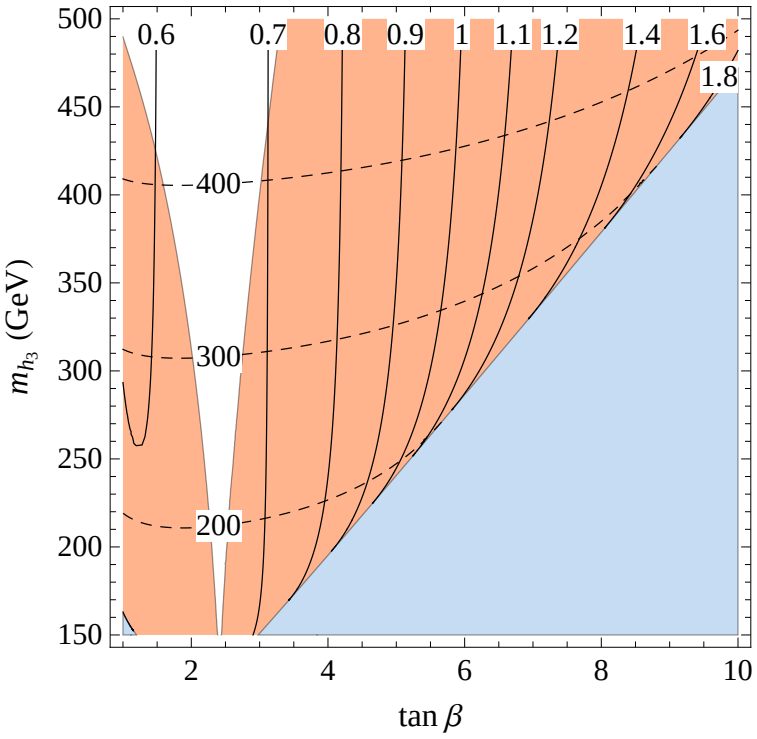
Projections fit LHC14 (300 fb^{-1}): dashed: $m_{H^\pm}$ cont: λ





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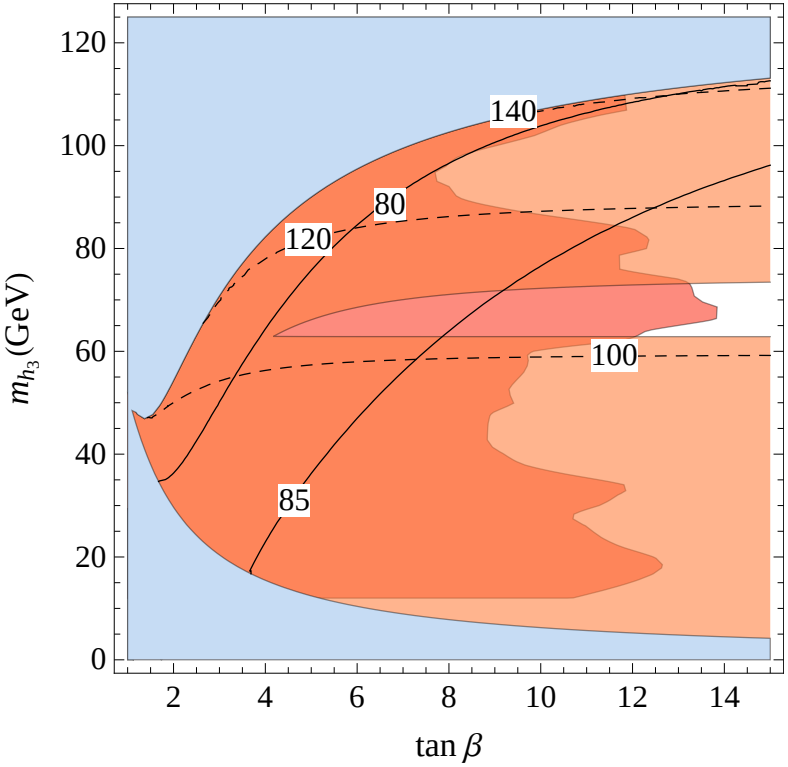
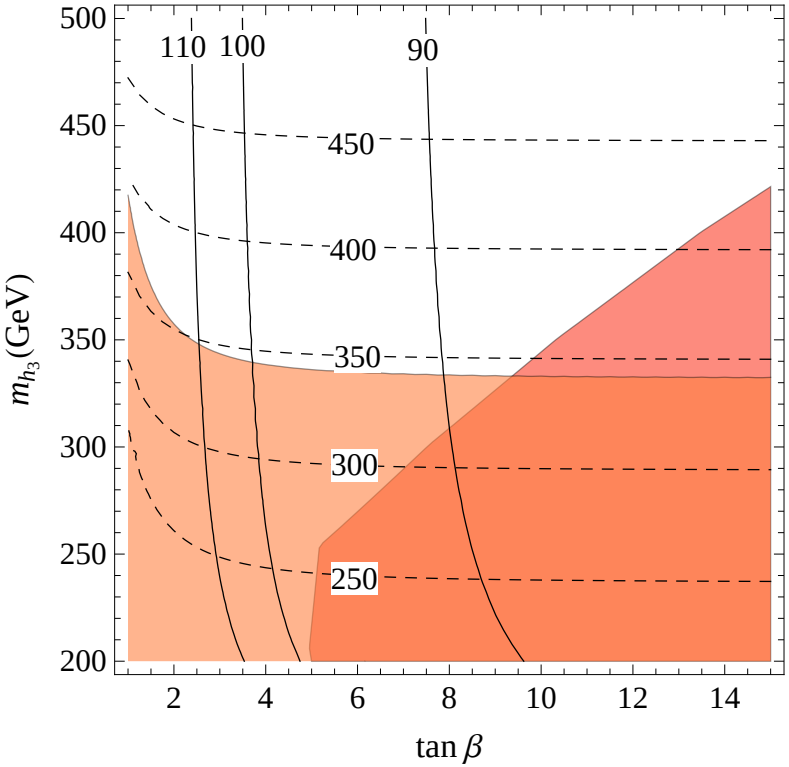
MSSM [free parameters: m_{h_3}, t_β]

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...]