Dark Matter and the Higgs

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(LAPTh Annecy)

The Higgs portal to dark matter
Invisible Higgs at the LHC
Invisible Higgs in the future
Comparison with astroparticle physics
Heavy DM states
Conclusion

with Giorgio Arcadi and Martti Raidal, arXiv:1903.03616 (to appear in Phys. Rept.)

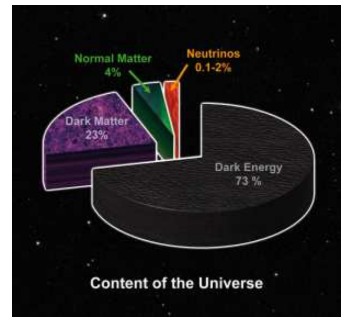
The Higgs portal to dark matter

DM indeed exists:
- Rotation curve of (clusters of) galaxies;
- CMB and large scale structure formation.

It is a new/unknown particle: no SM particle (eg ν) can do the job.

A crucial hint for physics beyond the SM of particle physics!

Makes:
25% of energy budget of Universe
80% of total matter of Universe



PLANCK: $\Omega_{\rm DM} h^2 = 0.119 \pm 0.001$

- Neutral particle and hence dark (a charged particle will shine...).
- Cold or not too warn and hence non-relativistic (ν do not work...).
- Very weakly interacting (reason why we did not observe it yet...).
- Stable or at least very long lived particle: $\tau_{\rm DM} \gg 10^{17}$ s.
- Possibly a relic from the early Universe: a window to the origin.

In short, a WIMP. It worths the effort searching for it!

The Higgs portal to dark matter

WIMPS appear in models for naturalness/hierarchy problems:

examples:
- **LSP: lightest neutralino of SUSY with Rp conserved;**
- **LKP: lightest Kaluza-Klein state in extra-dimensions;**
- **LTP: lightest T-odd state in Little Higgs/composite.**

All particles not been observed (also their companions) at the LHC.

We choose a different way, simply Agnosticism and Occam razor,
postulate the existence of a weakly interacting massive particle:
- **a singlet particle but of any spin i.e. a scalar, vector or fermion;**
- **QED neutral + isosinglet, no SU(2)xU(1) charge: no Z couplings;**
- **Z_2 parity for stability: no couplings or mixing with fermions.**

Hence, only couplings with the Higgs bosons ⇒ Higgs portal DM:
- **annihilates into SM particles through s-channel Higgs exchange;**
- **interacts with fermionic matter only through Higgs exchange;**
- **can be produced in pairs via Higgs boson exchange or decays.**

Again Occam razor: assume only the SM-like Higgs boson.

The Higgs portal to dark matter

Effective Lagrangians:

Mc Donald
Kanemura, ...
Lebedev, AD, ..

$$\Delta\mathcal{L}_s = -\frac{1}{2}M_s^2 s^2 - \frac{1}{4}\lambda_s s^4 - \frac{1}{4}\lambda_{Hss}\Phi^\dagger\Phi s^2$$

$$\Delta\mathcal{L}_v = \frac{1}{2}M_v^2 v_\mu v^\mu + \frac{1}{4}\lambda_v (v_\mu v^\mu)^2 + \frac{1}{4}\lambda_{Hvv}\Phi^\dagger\Phi v_\mu v^\mu$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi$$

EWSB: $\Phi \to \frac{1}{\sqrt{2}}(v+H)$ **with v=246 GeV and** $m_x^2 = M_x^2 + \frac{1}{4}\lambda_{Hxx}v^2$ ...

Two free parameters: DM mass m_x **and DM-Higgs coupling** λ_{Hxx}

Of course effective and even non-renormalisable models. EFT for:

- **scalars: inert Higgs doublet models (comes with others states);**
- **vectors: may be related to a spontaneously broken U(1) symmetry;**
- **fermions: fourth family, singlet-doublet or vector-like leptons..**

All these are renormalisable, unitary, perturbative (up to cut-off) ...

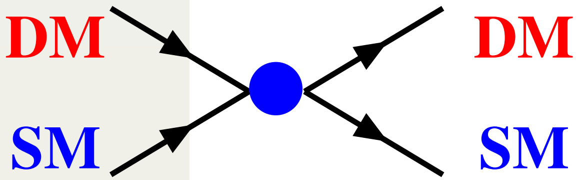
but where are all the new states gone? should have been seen?

- **Z_2 symmetry: all new particles decay at end into the DM state;**
- **eventually some mass degeneracy with the invisible DM particle.**

⇒ missing energy and soft SM particle signature: very difficult!

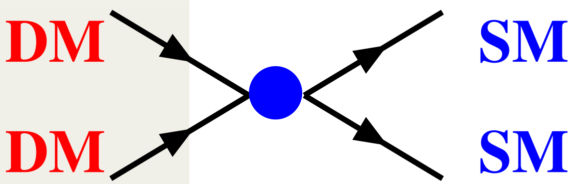
The Higgs portal to dark matter

Direct Detection:



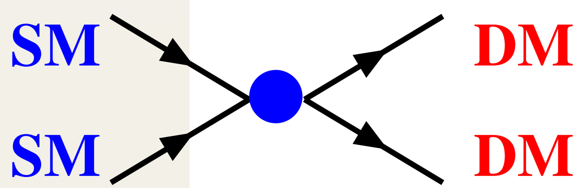
scattering on nucl. target:
XENON ⇒ LZ,DARWIN

Indirect Detection:

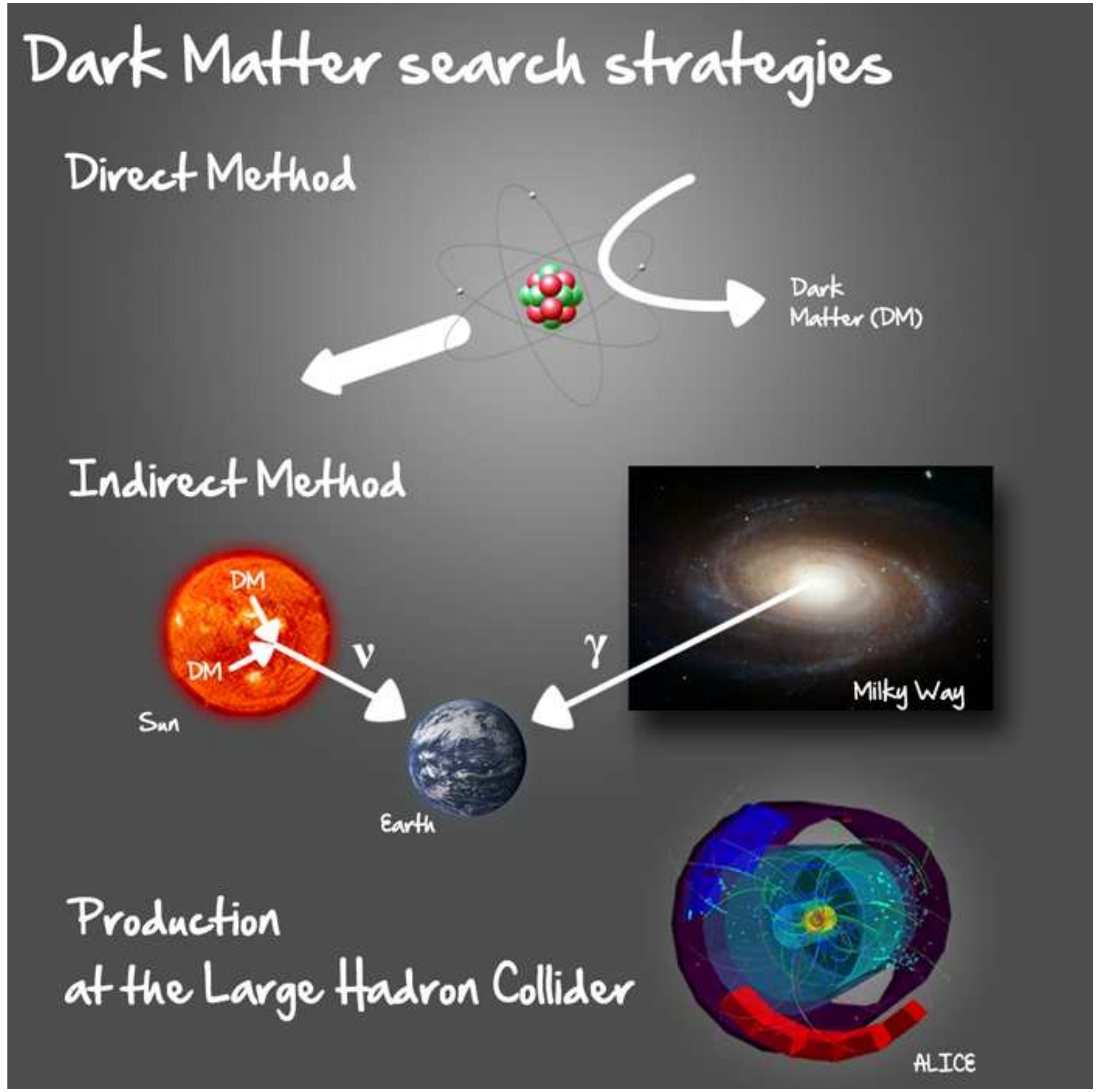


annihilation products: γ, ν
HESS,Fermi⇒ CTA, ...

Detection at colliders:



missing energy signature
LHC ⇒ HL-LHC,e^+e^-,pp



Invisible Higgs at the LHC

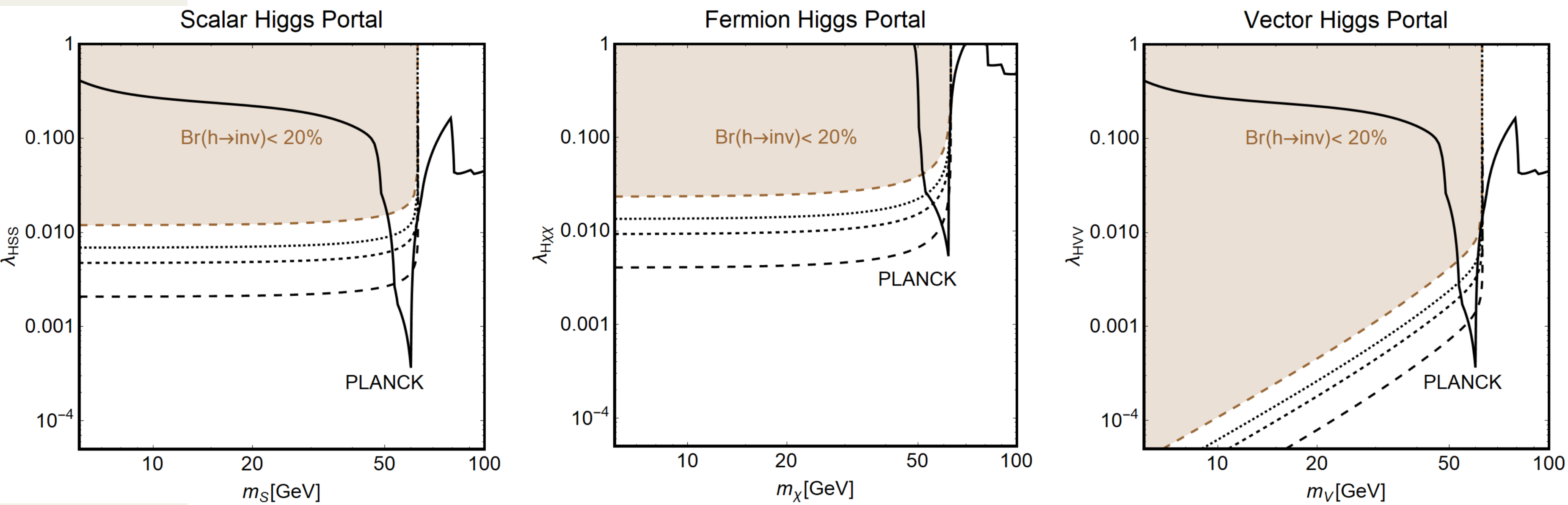
For light DM states, only possible handle at colliders is Higgs decays:

$$\Gamma_{\rm inv}(H \to ss) = \frac{\lambda^2_{Hss} v^2 \beta_s}{64\pi M_H}$$

$$\Gamma_{\rm inv}(H \to vv) = \frac{\lambda^2_{Hvv} v^2 M_H^3 \beta_v}{256\pi M_v^4}\left(1 - 4\frac{M_v^2}{M_H^2} + 12\frac{M_v^4}{M_H^4}\right)$$

$$\Gamma_{\rm inv}(H \to ff) = \frac{\lambda^2_{Hff} v^2 M_H \beta_f^3}{32\pi\Lambda^2}$$

Possible only for $m_X < \frac{1}{2}M_H \approx 62$ GeV; depends on m_X, λ_{HXX}:



One has to check also the relic density/Planck: only one input?

maybe no, X not all DM and/or Ωh^2 obtained via other means...

Invisible Higgs at the LHC

A) Direct: measurement of total Higgs decay width via interference:

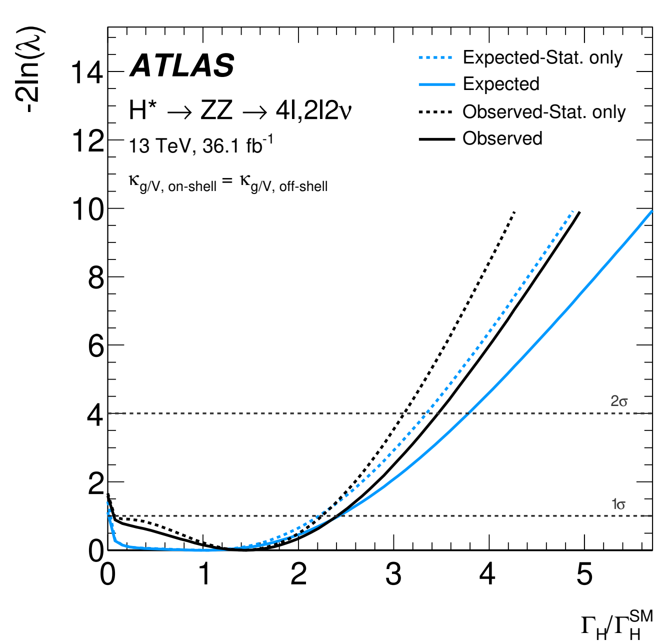
$\Gamma_H^{SM} = 4.07$ MeV $\Rightarrow$ too small to be resolved experimentally.

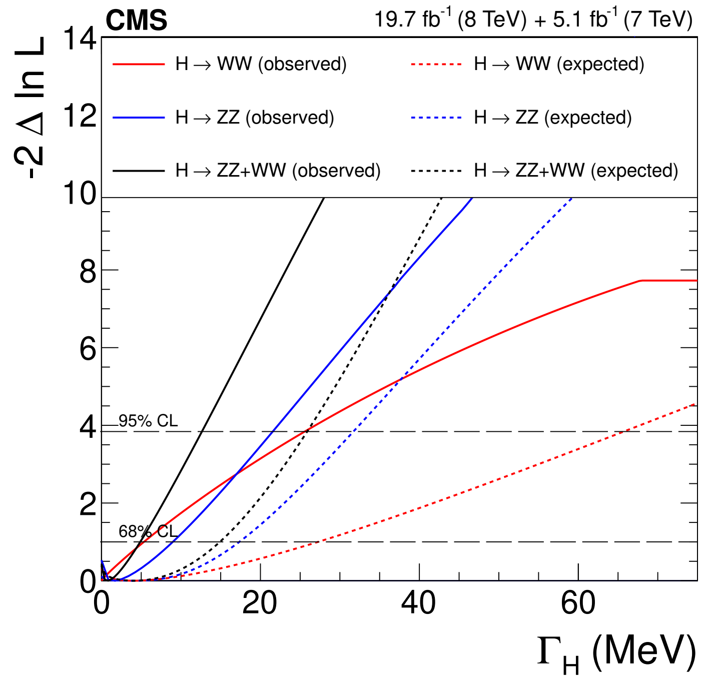
If $M_H \gtrsim 200$ GeV, $\Gamma_H > 1$GeV $\Rightarrow$ possible in $H \to ZZ \to 4\ell$.

But in $pp \to H \to ZZ \to 4\ell$, about 20% are for $M_{4\ell} \gtrsim 2M_Z$.

In fact: $\sigma^{\rm on-shell}_{gg\to H\to 4\ell} \propto g^2_{ggH}$, $\sigma^{\rm off-shell}_{gg\to H\to 4\ell} \propto g^2_{ggH}\Gamma_H \Rightarrow$ interf $\propto g_{ggH}\sqrt{\Gamma_H}$

direct measurement of Γ_H via interference with $pp \to ZZ$ continuum:





The constraints are starting to be serious: $\Delta\Gamma_H/\Gamma_H^{SM} \lesssim 1.25$@95%CL!

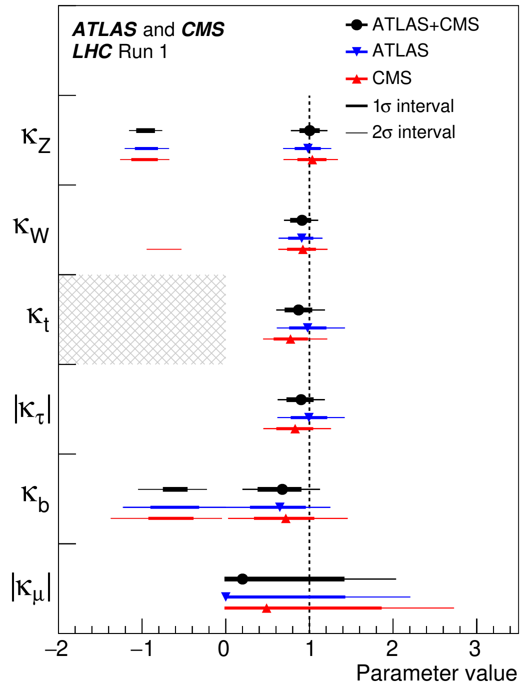
Invisible Higgs at the LHC

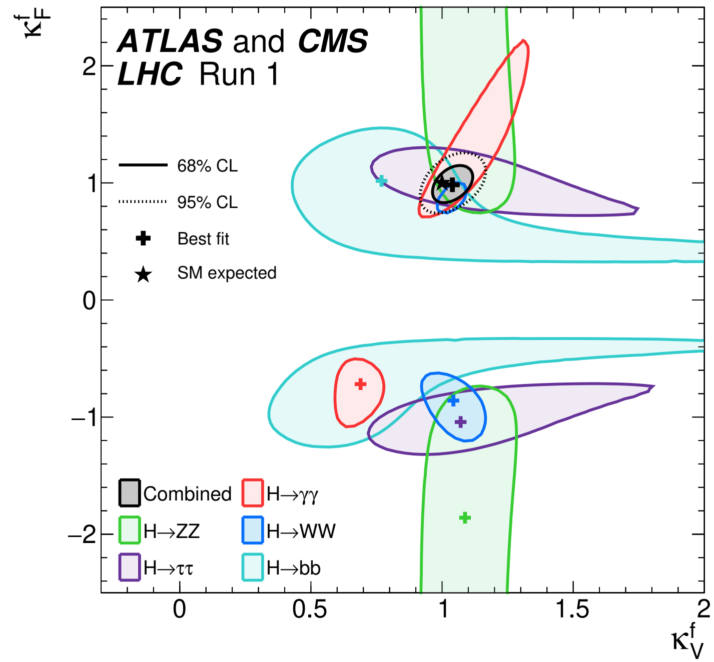
B) Indirectly: measurements of the Higgs decay branching ratios:

$$\kappa_{\mathbf{x}}^{2}=\sigma(\mathbf{x})/\sigma(\mathbf{x})|_{\mathbf{SM}}=\Gamma(\mathbf{xx})/\Gamma(\mathbf{xx})|_{\mathbf{SM}}=\mathbf{g}_{\mathbf{Hxx}}^{2}/\mathbf{g}_{\mathbf{Hxx}}^{2}|_{\mathbf{SM}}$$

$$\Gamma(\mathbf{vv})\to\kappa_{\mathbf{v}}^{2},\ \Gamma(\mathbf{ff})\to\kappa_{\mathbf{f}}^{2},\ \sigma(\mathbf{vH})\to\kappa_{\mathbf{v}}^{2},\ \sigma(\mathbf{VBF})\to\mathbf{0.74}\kappa_{\mathbf{w}}^{2}+\mathbf{0.26}\kappa_{\mathbf{z}}^{2}$$

$$\gamma\gamma)\to\kappa_{\gamma}^{2}=\mathbf{1.5}\kappa_{\mathbf{w}}^{2}+\mathbf{0.1}\kappa_{\mathbf{t}}^{2}-\mathbf{0.7}\kappa_{\mathbf{t}}\kappa_{\mathbf{w}},\ \sigma(\mathbf{ggH})\to\kappa_{\mathbf{g}}^{2}=\mathbf{1.06}\kappa_{\mathbf{t}}^{2}-\mathbf{0.07}\kappa_{\mathbf{t}}\kappa_{\mathbf{b}}$$



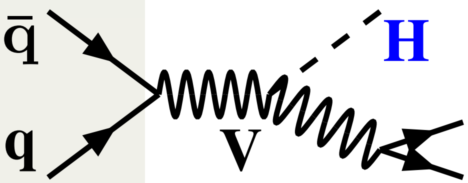


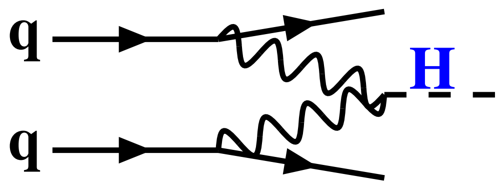
$$\kappa_{\mathbf{H}}^{2}=\mathbf{0.57}\kappa_{\mathbf{b}}^{2}+\mathbf{0.22}\kappa_{\mathbf{w}}^{2}+\mathbf{0.06}\kappa_{\tau}^{2}+\mathbf{0.03}\kappa_{\mathbf{z}}^{2}+\mathbf{0.03}\kappa_{\mathbf{c}}^{2}+\mathbf{0.0023}(\kappa_{\gamma}^{2}+\kappa_{\mathbf{z}\gamma}^{2})$$

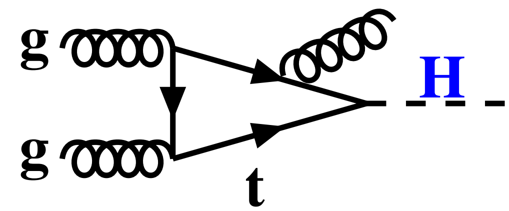
global ATLAS+CMS fit gives BR(H$\to$ invisible) $\lesssim$ 20%@95%CL

Invisible Higgs at the LHC

C) Even more direct: search for Higgs decaying invisibly and $E\!\!\!/_T$:



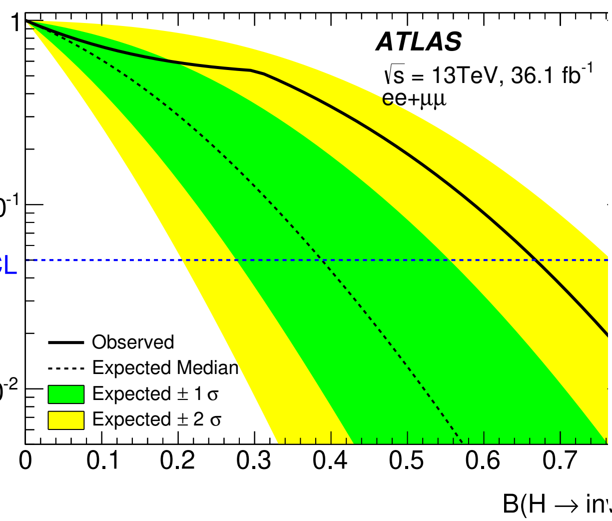


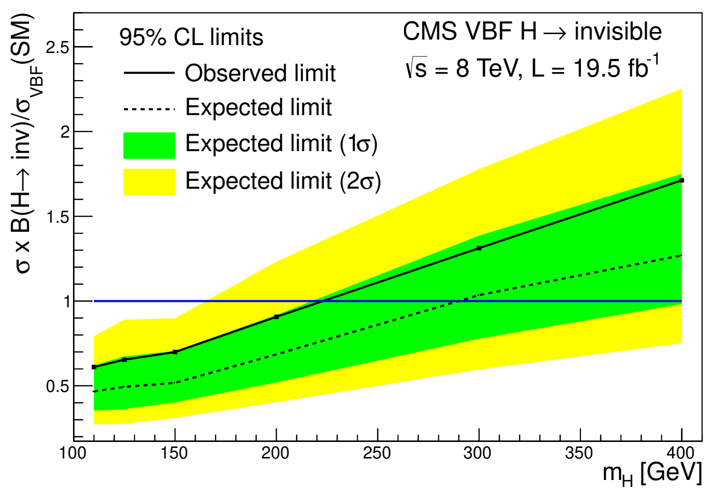


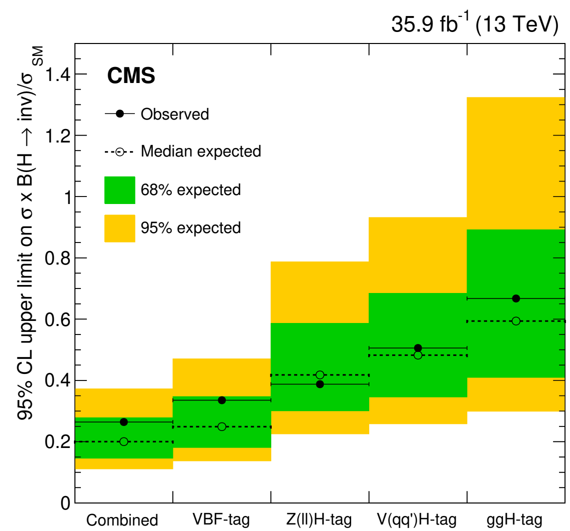
$\bar{q} \to WH \to \ell\nu + E\!\!\!/_T$ | $qq \to qqH \to jj + E\!\!\!/_T$ | $gg \to Hg \to j + E\!\!\!/_T$

$\bar{q} \to ZH \to \ell\ell + E\!\!\!/_T$ | **high-mass, p_T, η jets** | **also 2j, high rate.**

Choudhury+Roy, ..., | **Eboli+Zeppenfeld** | **AD,Falkowski,Mambrini...**



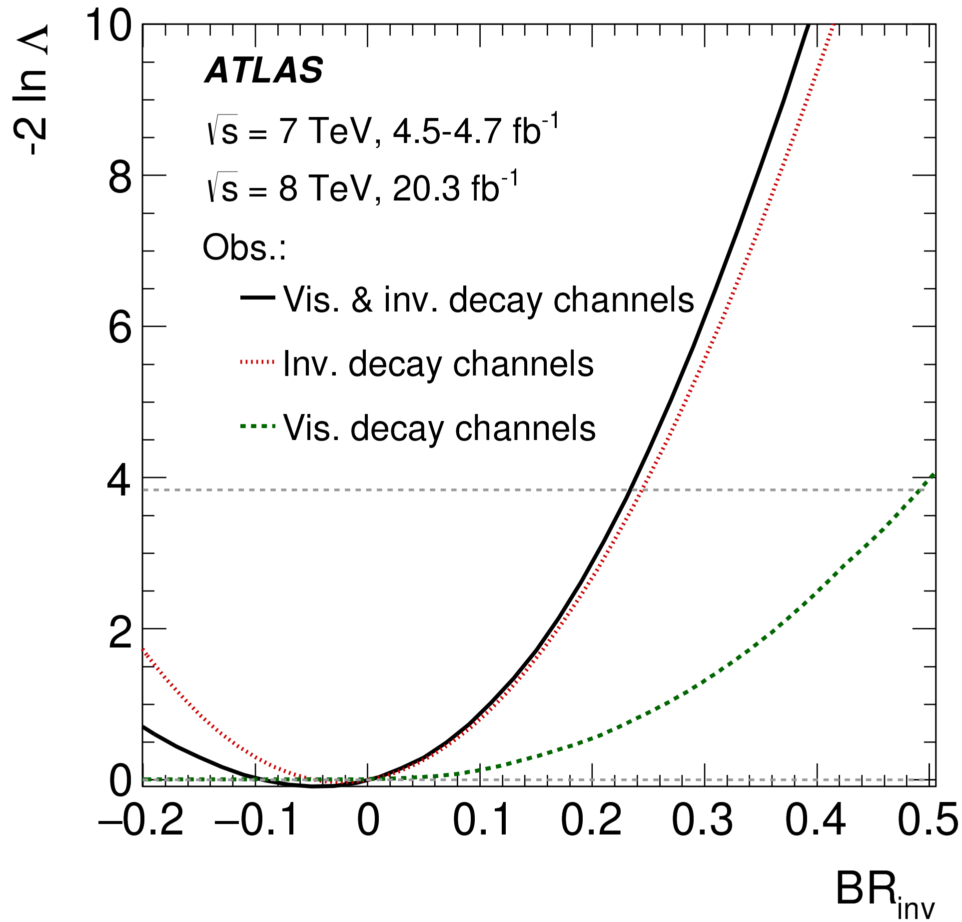




re also ATLAS+CMS combo gives BR(H→invisible) $\lesssim 20\%$@95%CL

Invisible Higgs at the LHC

D) A combination of all these channels/possibilities:

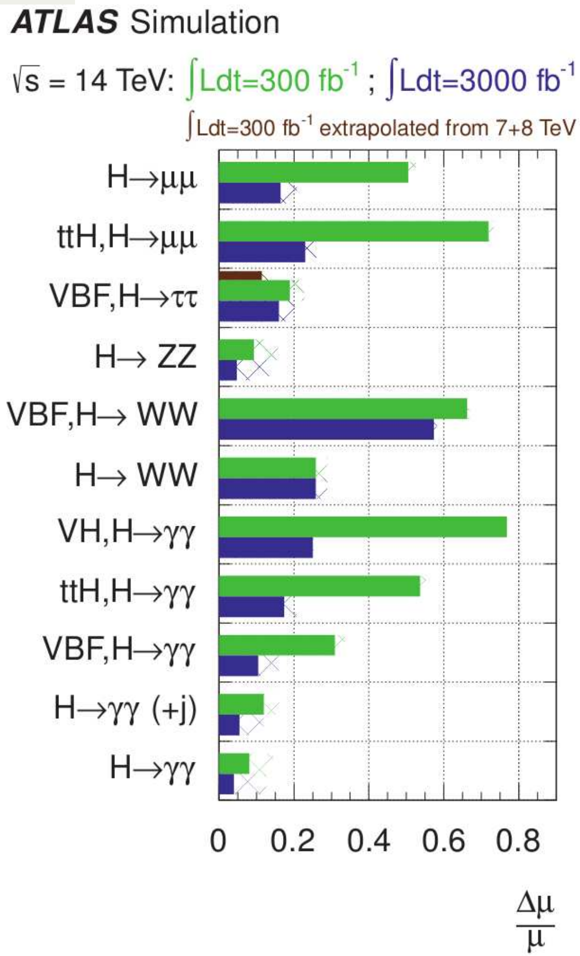


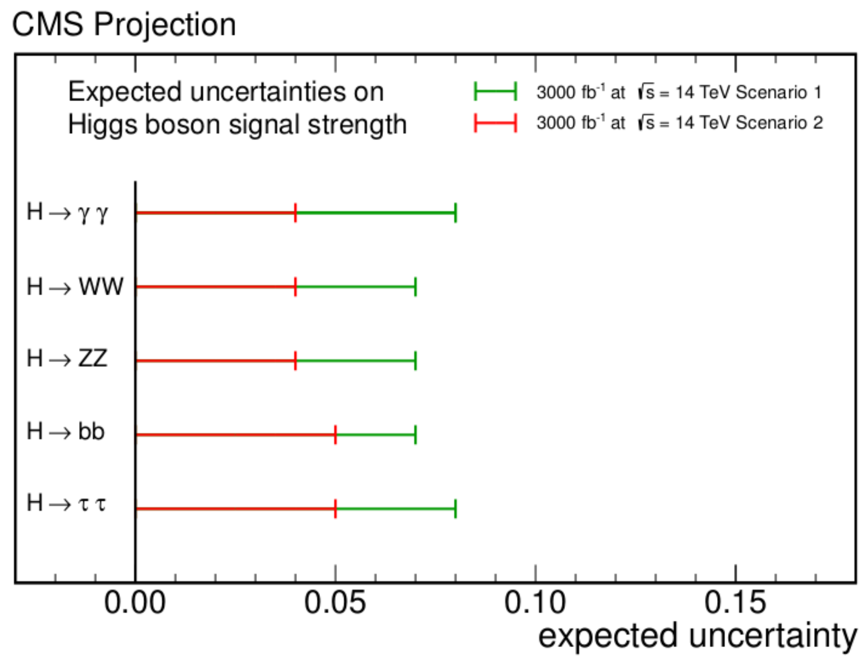
All in all at RunI+RunII LHC: BR($H \to$ inv) $<$ 20%

This not very constraining after all. Can all this can be improved?

Invisible Higgs in the future

High–Luminosity LHC: $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3\,\mathrm{ab}^{-1}$.

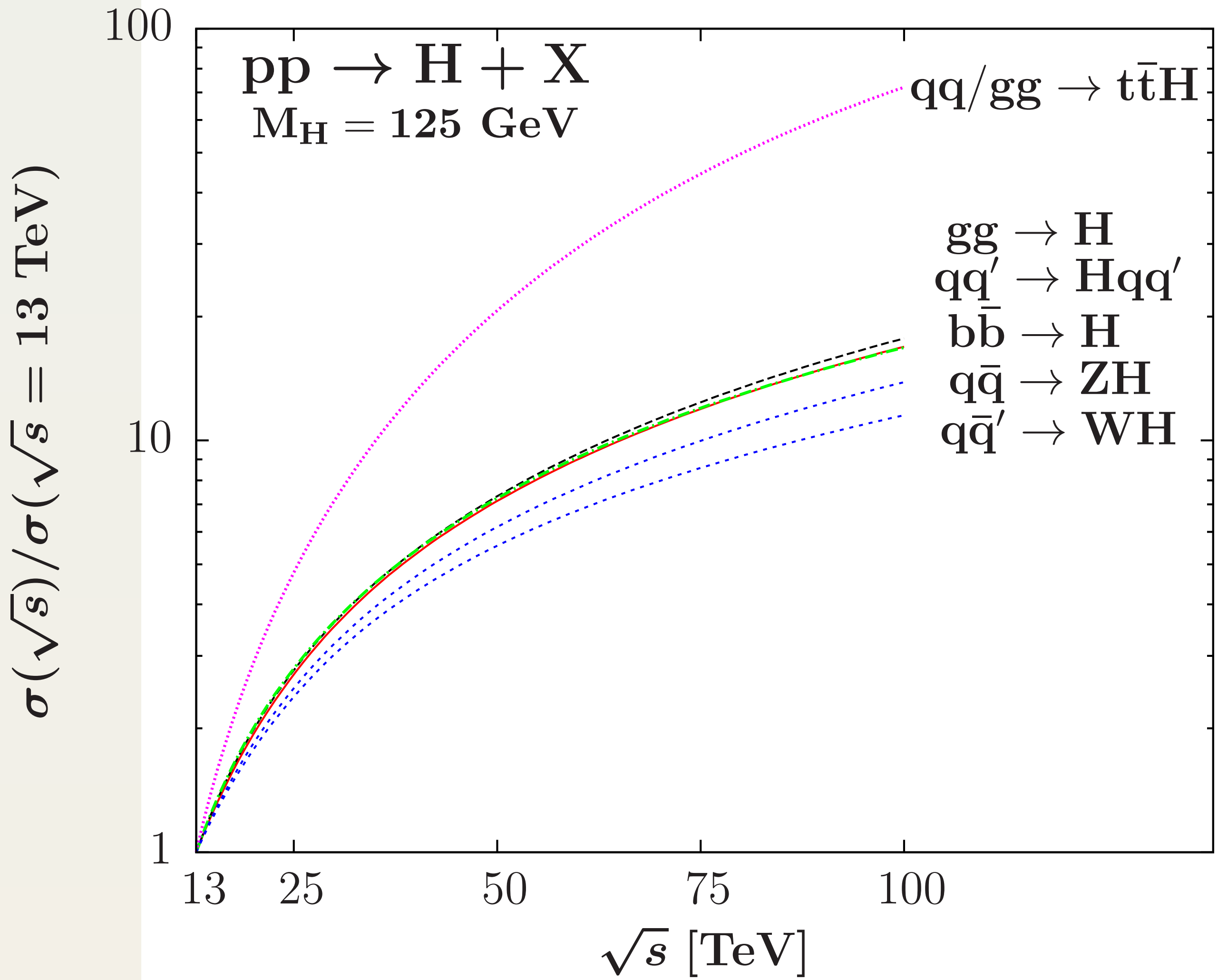




mprove sensitivity by factor two from BRs: BR(H→invisible) $\lesssim 10\%$
rge improvement in direct searches not expected; thougher conditions?)

Invisible Higgs in the future

Higher energy pp colliders ⇒ $\sqrt{s} = 28-100$ TeV and $\mathcal{L}=$few ab^{-1}

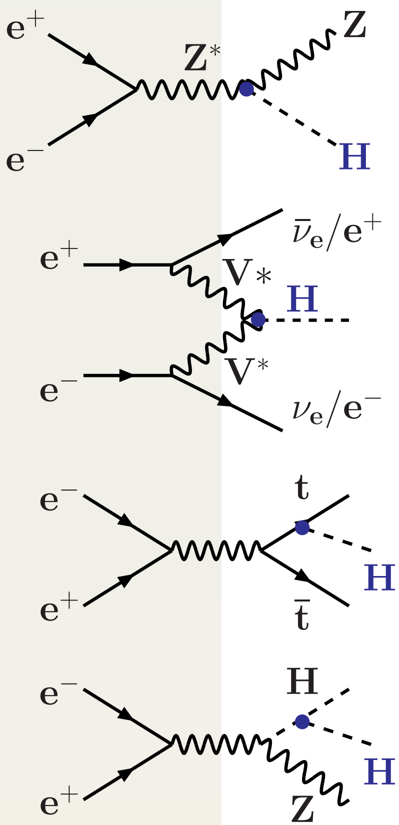


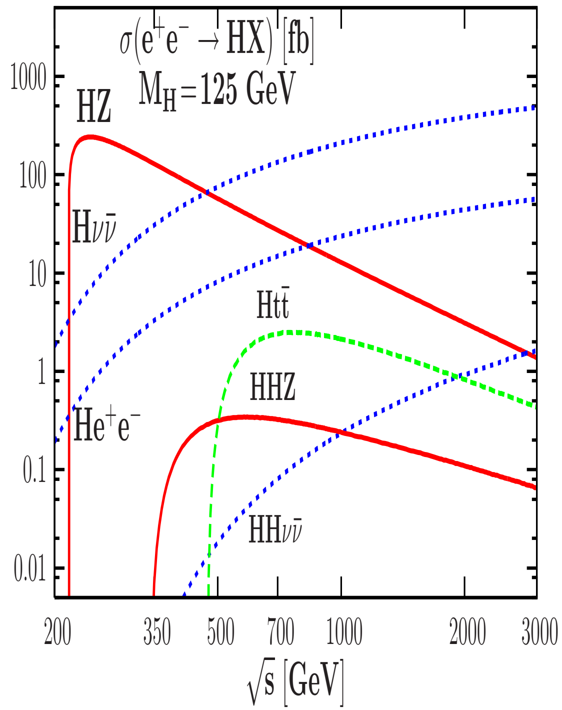
Baglio, ...

Improve the sensitivity by another factor of two: BR(H→invisible) $\lesssim 5\%$

Invisible Higgs in the future

est deal: an e^+e^- (non ILC?) machine: $\sqrt{s}=240$GeV and $\mathcal{L}=1\text{ab}^{-1}$





Very precise measurements mostly at $\sqrt{s}\approx 250$ GeV and mainly in $e^+e^- \to ZH$

g_{HZZ}	±0.01
g_{HWW}	±0.01
g_{Hbb}	±0.01
g_{Hcc}	±0.03
$g_{H\tau\tau}$	±0.03
g_{Htt}	±0.05
λ_{HHH}	±0.2
M_H	±0.0004
CP	±0.03
Γ_H	±0.05

Improve the sensitivity very seriously: BR(H→invisible) $\lesssim 1\%$

In fact: a BR(H $\to$ inv) of 1% can be observed at the 5σ level, and a BR(H $\to$ inv) of 5% can be measured with a 10% accuracy...

Comparison with astroparticle experiments

- **Relic density** $\propto 1/\langle\sigma(\mathrm{xx}\to H\to f\bar{f})v_r\rangle$ **annihilation rate.**

$$\langle\sigma^{x}_{\rm ferm}v_r\rangle=\frac{\lambda^2_{Hxx}m^2_{\rm ferm}}{16\pi}\frac{1}{(4m_x^2-M_H^2)^2}\delta_x,\quad \delta_s=1,\delta_v=\frac{1}{3},\delta_f=\frac{1}{2}\frac{v_r^2}{\Lambda^2}$$

In principle needs to fit the Planck value: $\Omega_{DM}h^2=0.119\pm0.001$

- **Spin–independent direct detection, simple for s, v, f DM states:**

$$\sigma^{SI}_{x\text{–}N}=\frac{\lambda^2_{Hxx}}{16\pi M_H^4}\frac{m_N^4f_N^2}{(m_x+m_N)^2}\delta'_x,\delta_s=\delta_v=1,\delta_f=\frac{4}{\Lambda^2}$$

$$BR_x^{inv}\equiv BR(H\to inv)=\frac{\Gamma(H\to xx)}{\Gamma_H^{SM}+\Gamma(H\to xx)}=\frac{\sigma^{SI}_{xp}}{\Gamma_H^{tot}/r_x+\sigma^{SI}_{xp}}$$

Direct detection:

$$BR_x^{inv}\simeq(\sigma^{SI}_{xp}/10^{-9}pb)[\delta_x+(\sigma^{SI}_{xp}/10^{-9}pb)]^{-1}$$

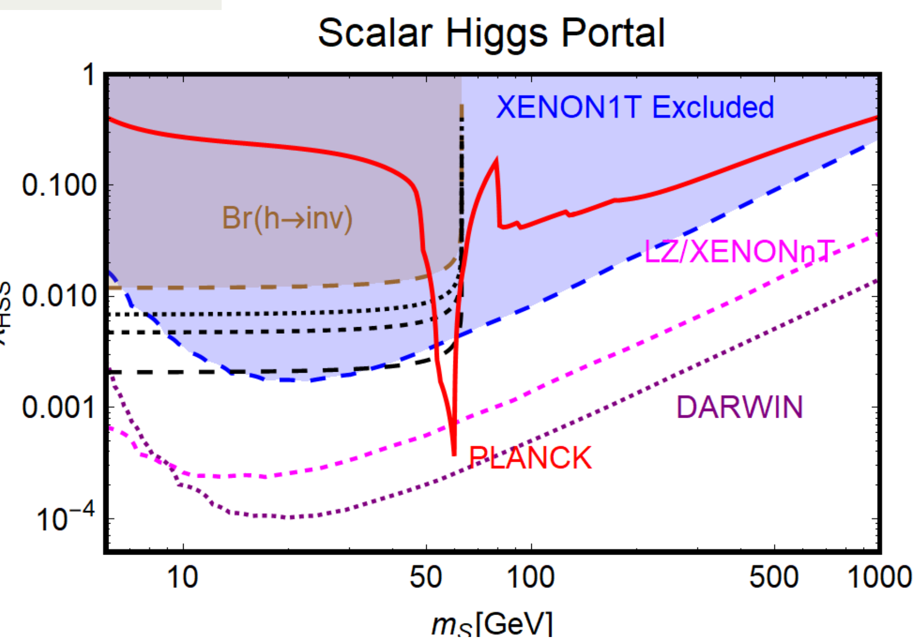
$$\delta_s=400\,(10\ GeV/m_s)^2,\ \delta_v=4\times10^{-2}\,(m_v/10\ GeV)^2,\ \delta_f=3.5$$

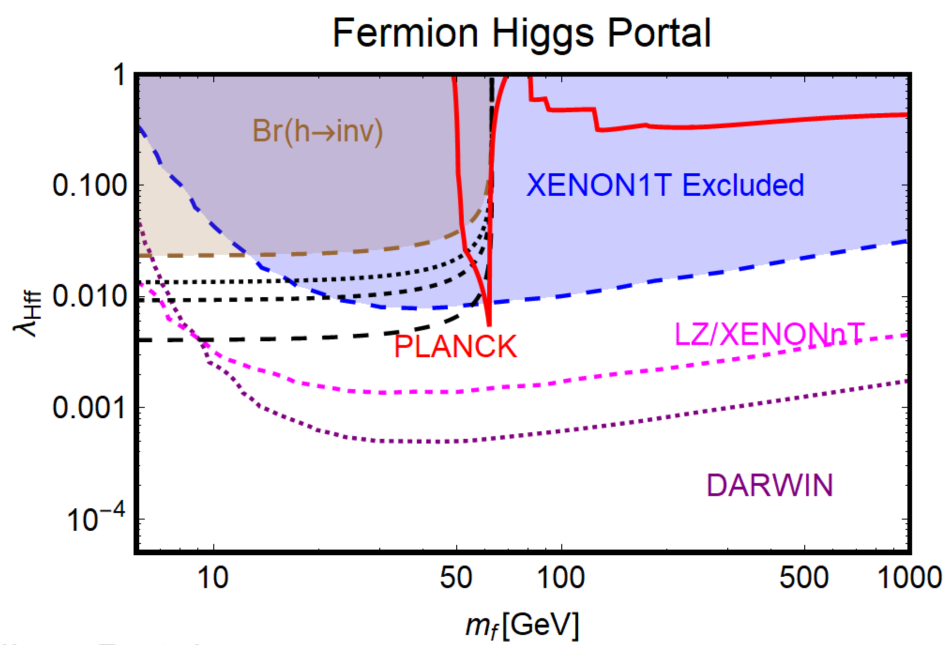
Indirect detection:

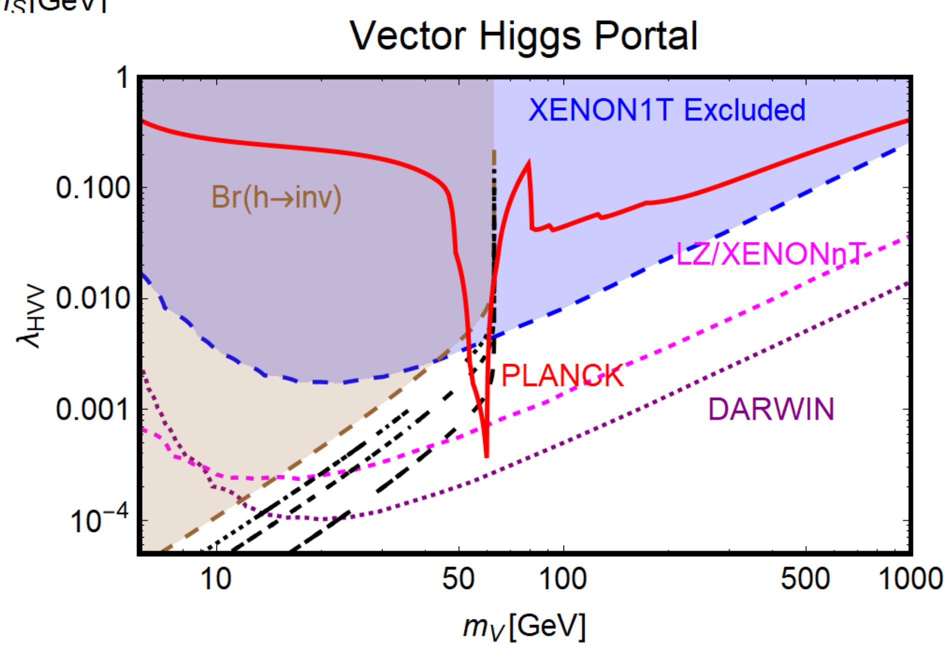
$$BR_x^{inv}\simeq(\langle\sigma v_r\rangle/10^{-10}GeV^{-1})[\delta_x+(\langle\sigma v_r\rangle/10^{-10}GeV^{-1})]^{-1}$$

$$\delta_s=2.4\times10^{-2},\delta_v=1.3\times10^{-10}\,(m_v/GeV)^4,\delta_f=3.9\times10^{-13}\,(m_f/GeV)^2$$

Comparison with astroparticle experiments







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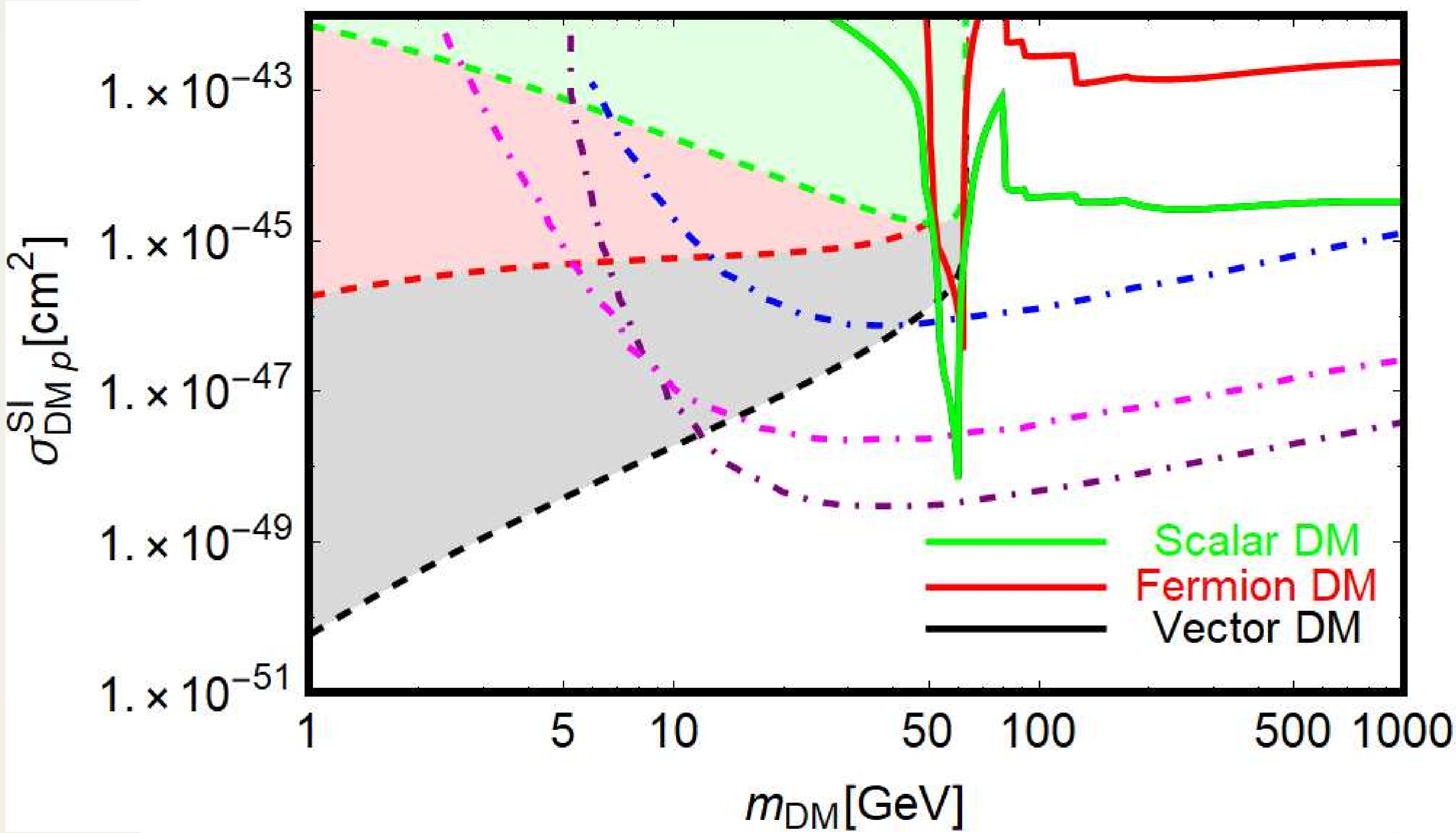
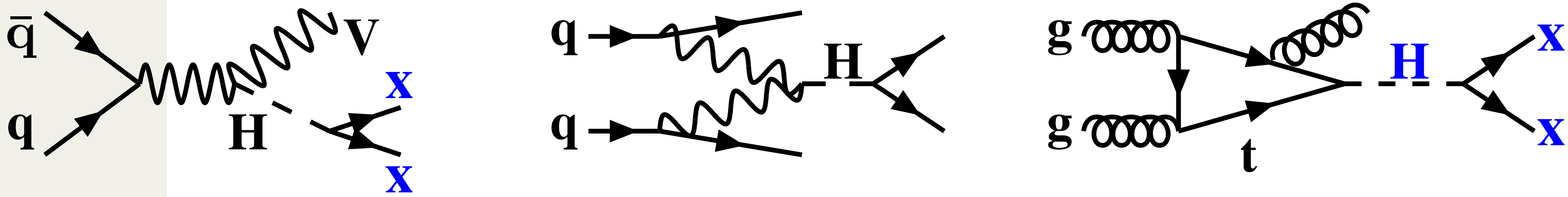


Arcadi,AD Raidal

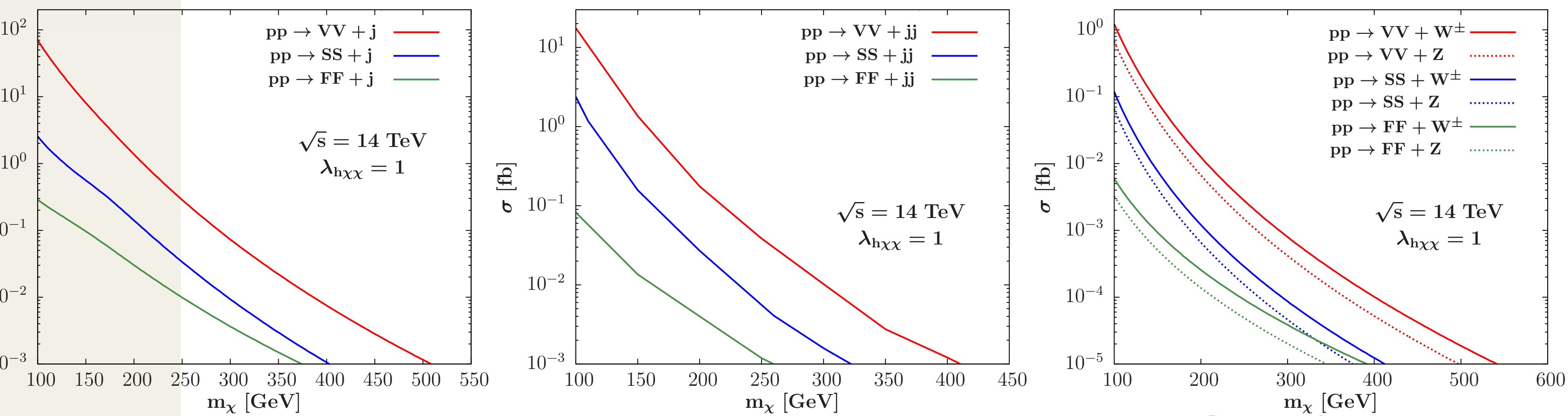
Heavy DM states

Invisible decays work only for light DM; what if $m_{DM} \gtrsim \frac{1}{2} M_H$?

Only way: produce them in pairs in continuum. At pp colliders:



- **Exactly same channels as before but with an off-shell Higgs boson.**
- **Suppressed by the Higgs virtuality and the small couplings to DM.**
- **Needs high energies, very high luminosities and some real efforts...**



Quevillon, ...

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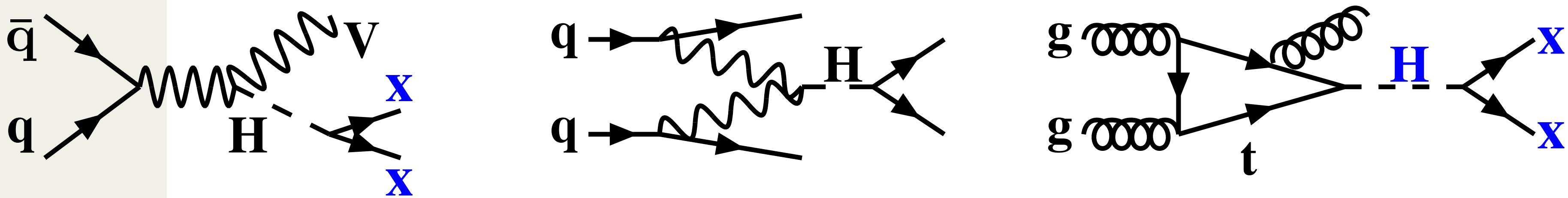

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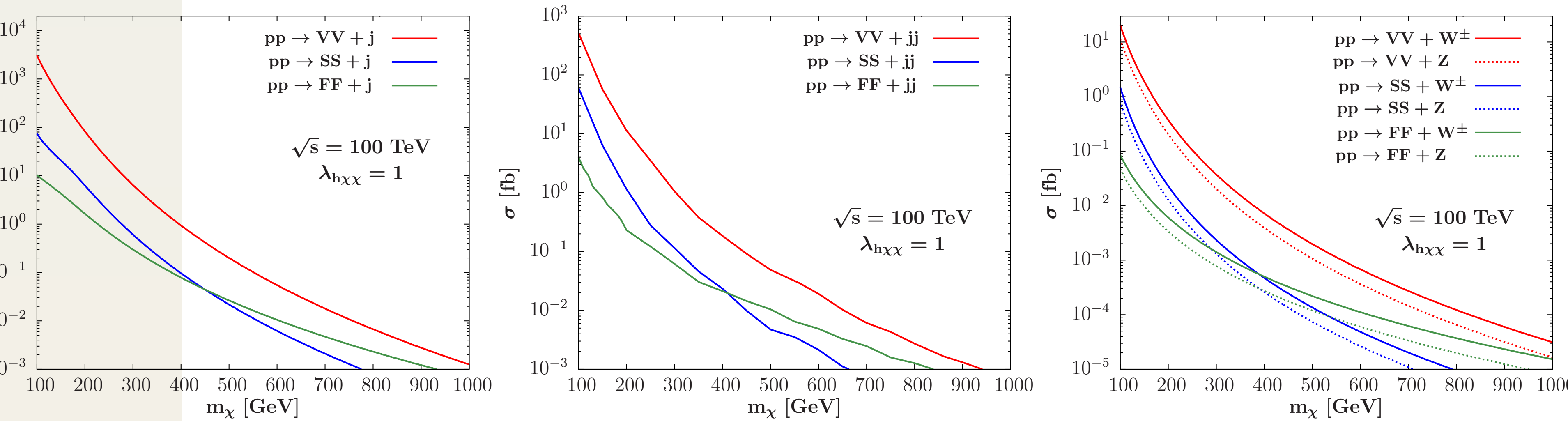

Heavy DM states

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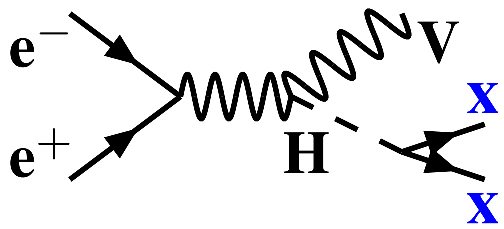

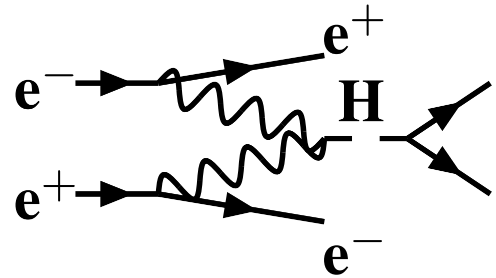

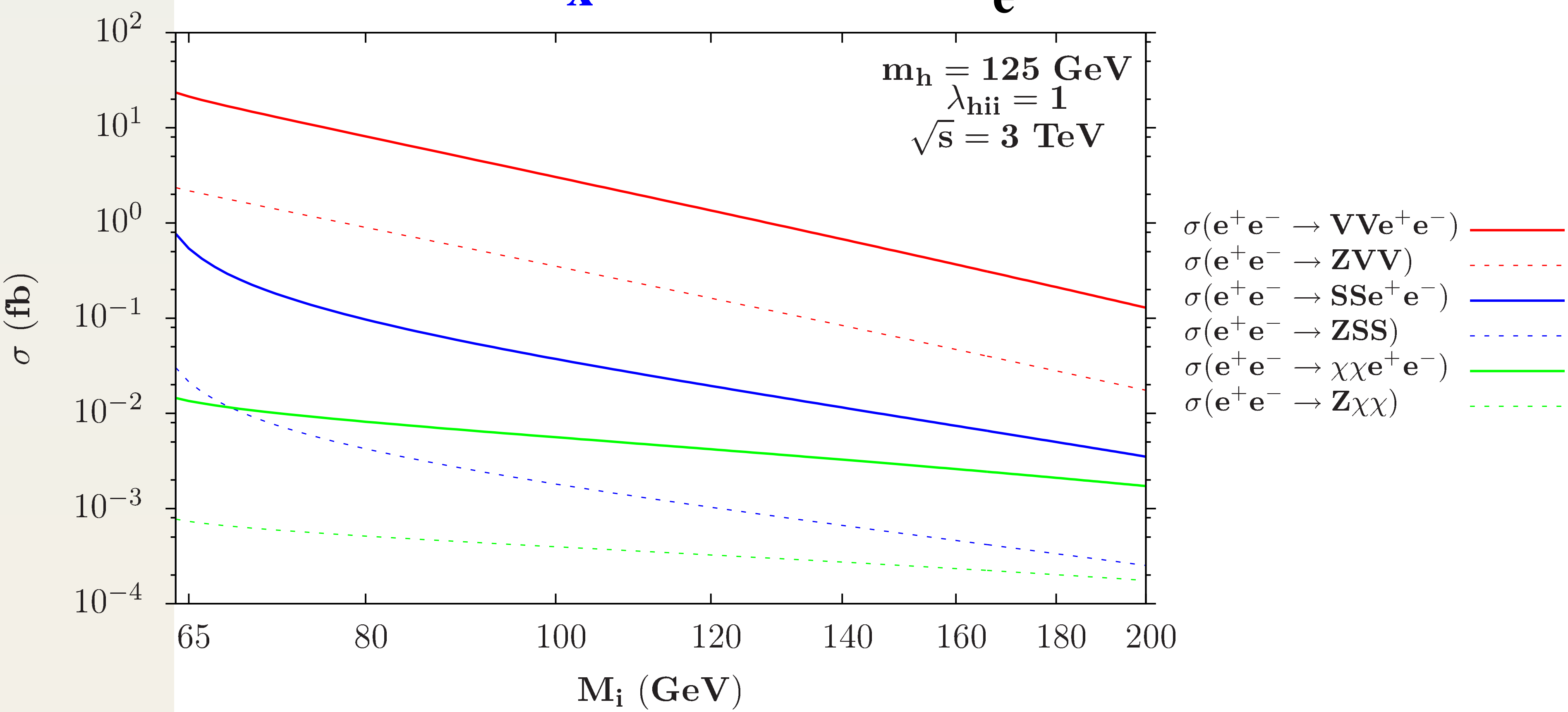

Conclusions

- Dark matter exists, maybe only reachable sign of new physics?
- The Higgs portal to DM is one of the most minimal realizations.
- Even more minimal if only the SM-like Higgs state is considered.
- Scenario being tested at LHC in Higgs searches/measurements:

– measurements of total Higgs width and various visible BRs;
– direct searches for missing energy signature in VH, VBF, ggF;
– possibility of going off-shell for $m_{DM} \gg \frac{1}{2} M_H$ not that promising.

- Limits from LHC challenged by future astrophysics sensitivity but only with some assumptions on the DM relic density, profile, etc...
- But I didn't tell you the really interesting part of the story:

– concrete realizations of Higgs-DM and search for DM companions;
– extending the Higgs sector makes it even more interesting...

$\Rightarrow$ arXiv:1903.03616.

Needs further investigations at LHC and also future e^+e^- and pp colliders besides all experiments in astroparticle physics.