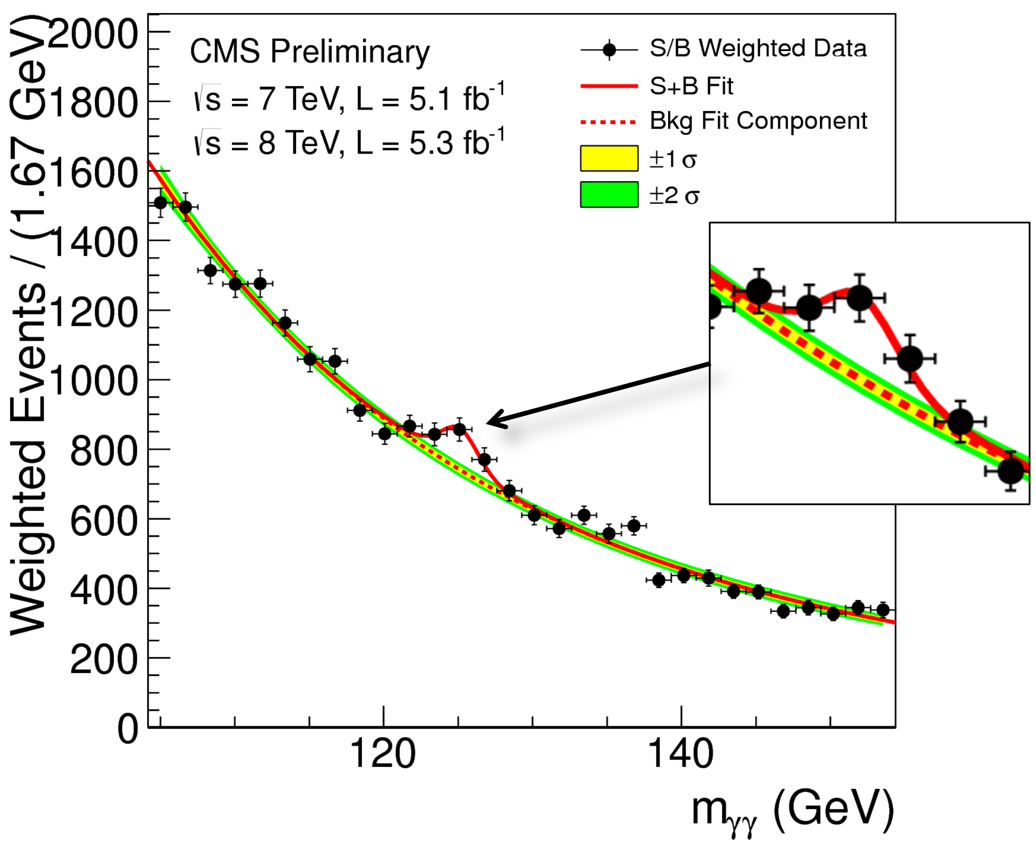
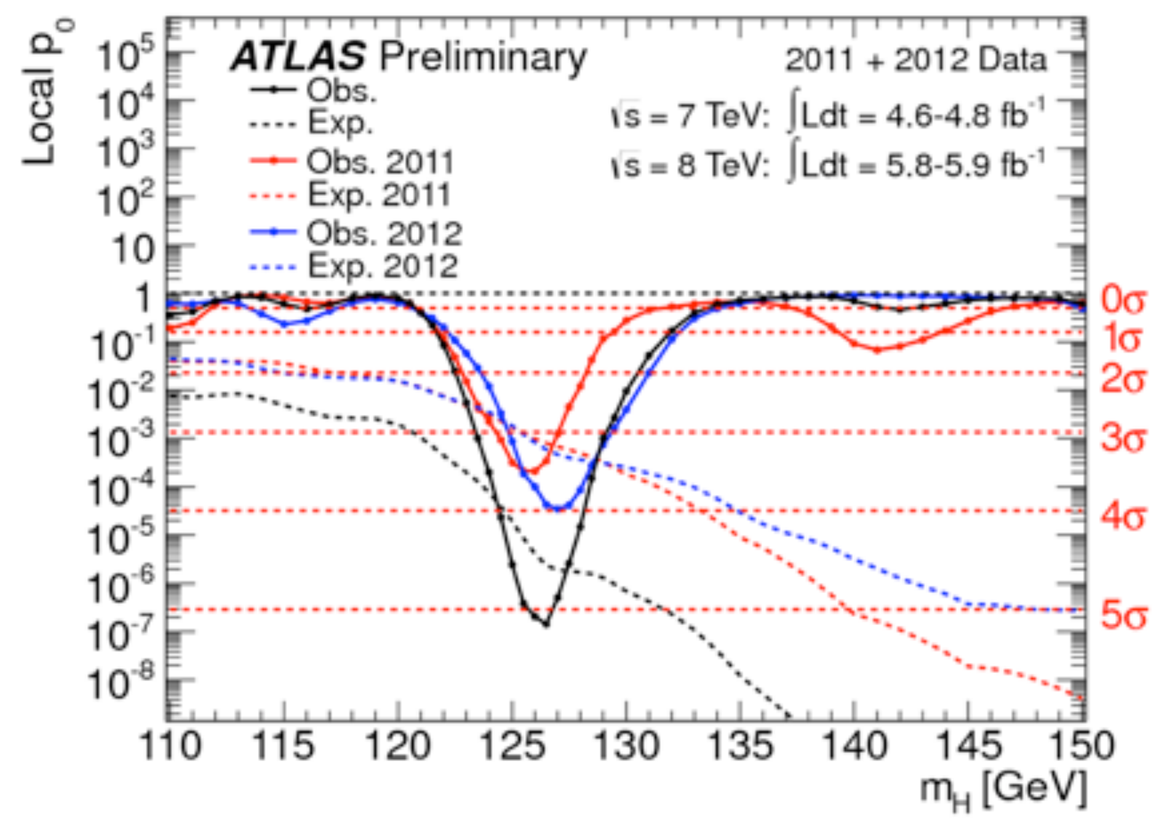
The inert doublet model in light of LHC and XENON

Sara Rydbeck

24 July 2012
Identification of Dark Matter, IDM 2012, Chicago

The CERN Large Hadron Collider





- Only discovery so far.
- If no new strongly interacting physics is found, how can we further test for new electroweak physics at the LHC?
- At 14 TeV and design luminosity, each experiment should accumulate 100/fb/ year.

The case for the inert doublet model

Based on arXiv:1206.6316 in collaboration with Michael Gustafsson, Laura Lopez-Honorez and Erik Lundström.

- IDM is a simple extension of the SM that can incorporate
  - dark matter (still needed)
  - a large range of Higgs masses (most probably not needed anymore).
- With or without a Higgs at ~125 GeV, what is the status of the IDM in light of LHC Higgs-searches and XENON direct searches?
- What are the prospects for the IDM to show up in the 14 TeV LHC data?

The Inert Doublet Model (IDM) Deshpande, Ma (1978)

- An extension of the Standard Model Higgs sector to include a second H_2 doublet, odd under a discrete unbroken $\mathbb{Z}_2$-symmetry (H_1 and all SM fields even)

$$\begin{aligned} V &= \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 \\ &+ \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \lambda_5 Re[(H_1^\dagger H_2)^2] \end{aligned}$$

- Only the SM-like Higgs doublet breaks the electroweak symmetry:

$$H_1 = \begin{pmatrix} 0 \\ v + h/\sqrt(2) \end{pmatrix}$$

- The inert doublet develops no vev and does not couple to fermions:

$$H_2 = \begin{pmatrix} H^+ \\ (H^0 + A^0)/\sqrt(2) \end{pmatrix}$$

The Inert Doublet Model (IDM)

- Simple model but rich phenomenology:
  - Can allow for a heavy SM-like Higgs (160-600 GeV) without violating EWPT (improved naturalness?)
    Barbieri, Hall, Rychkov (2006)
  - Gives a viable WIMP dark matter candidate!
    Lopez Honorez, Nezri, Oliver, Tytgat (2007)
    Gustafsson, Lundström, Bergström, Edsjö (2007)

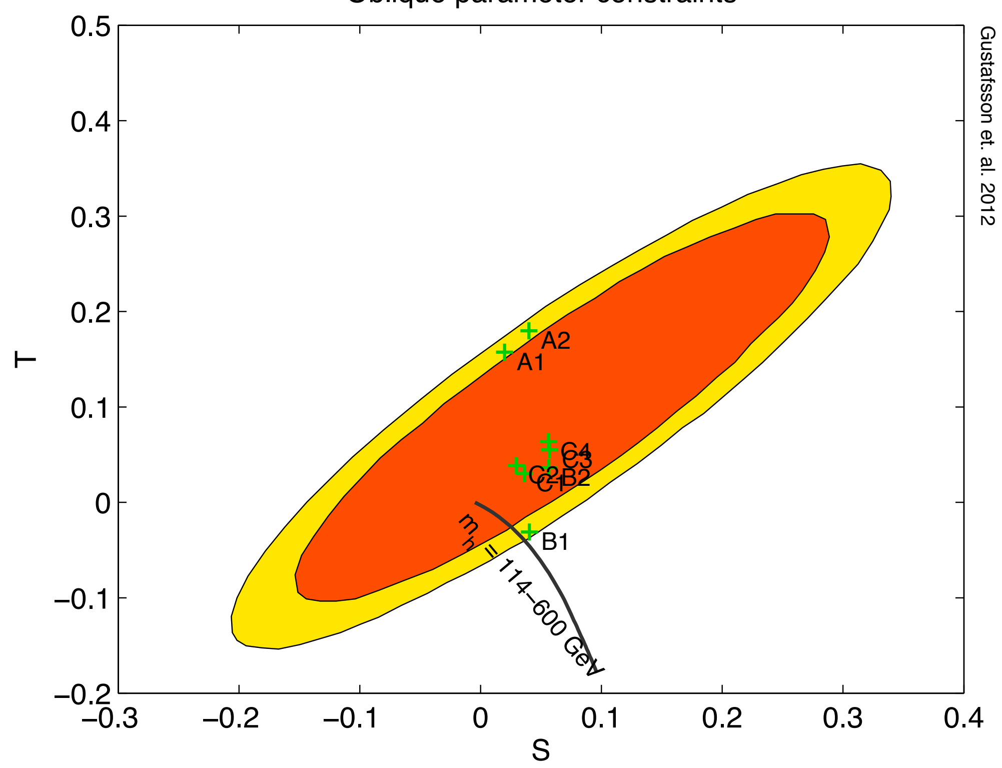
$$
\begin{aligned}
m_h^2 &= -2\mu_1 = 4\lambda_1 v^2 \\
m_{H^0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2 = \mu_2^2 + \lambda_{H^0} v^2 \\
m_{A^0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2 = \mu_2^2 + \lambda_{A^0} v^2 \\
m_{H^0}^2 &= \mu_2^2 + \lambda_3 v^2
\end{aligned}
$$

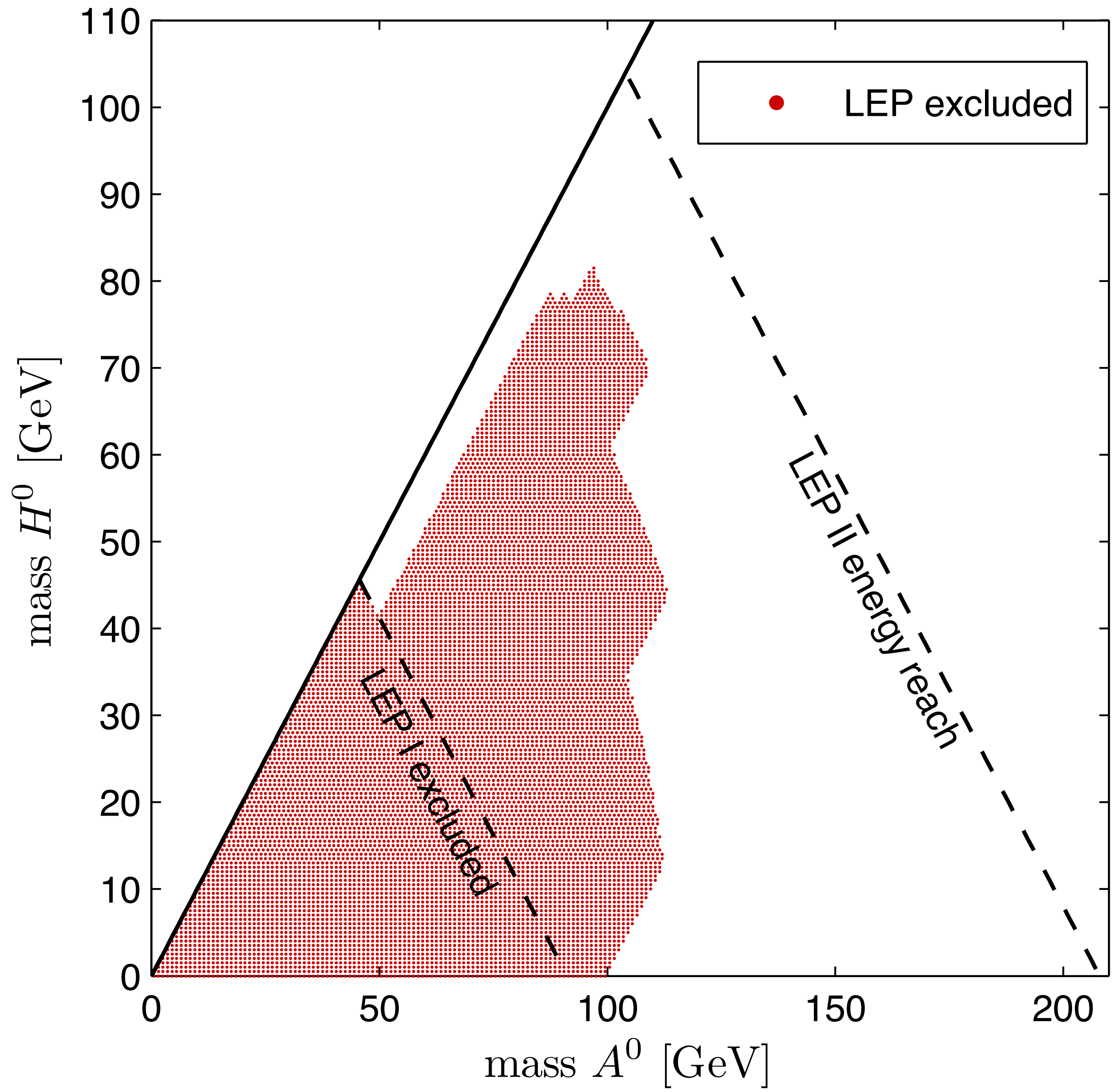
  - We take the (CP-even) H^0 to be the WIMP dark matter candidate.
  - We impose conditions on the couplings to ensure vacuum stability, perturbativity and unitarity.

Constraints on IDM

- **Particle data (pre-LHC):**
  - Electroweak precision tests (EWPT)

$$\Delta T \propto (m_{H^+} - m_{A^0})(m_{H^+} - m_{H^0})$$





Gustafsson, Lundström, Bergström, Edsjö (2009)

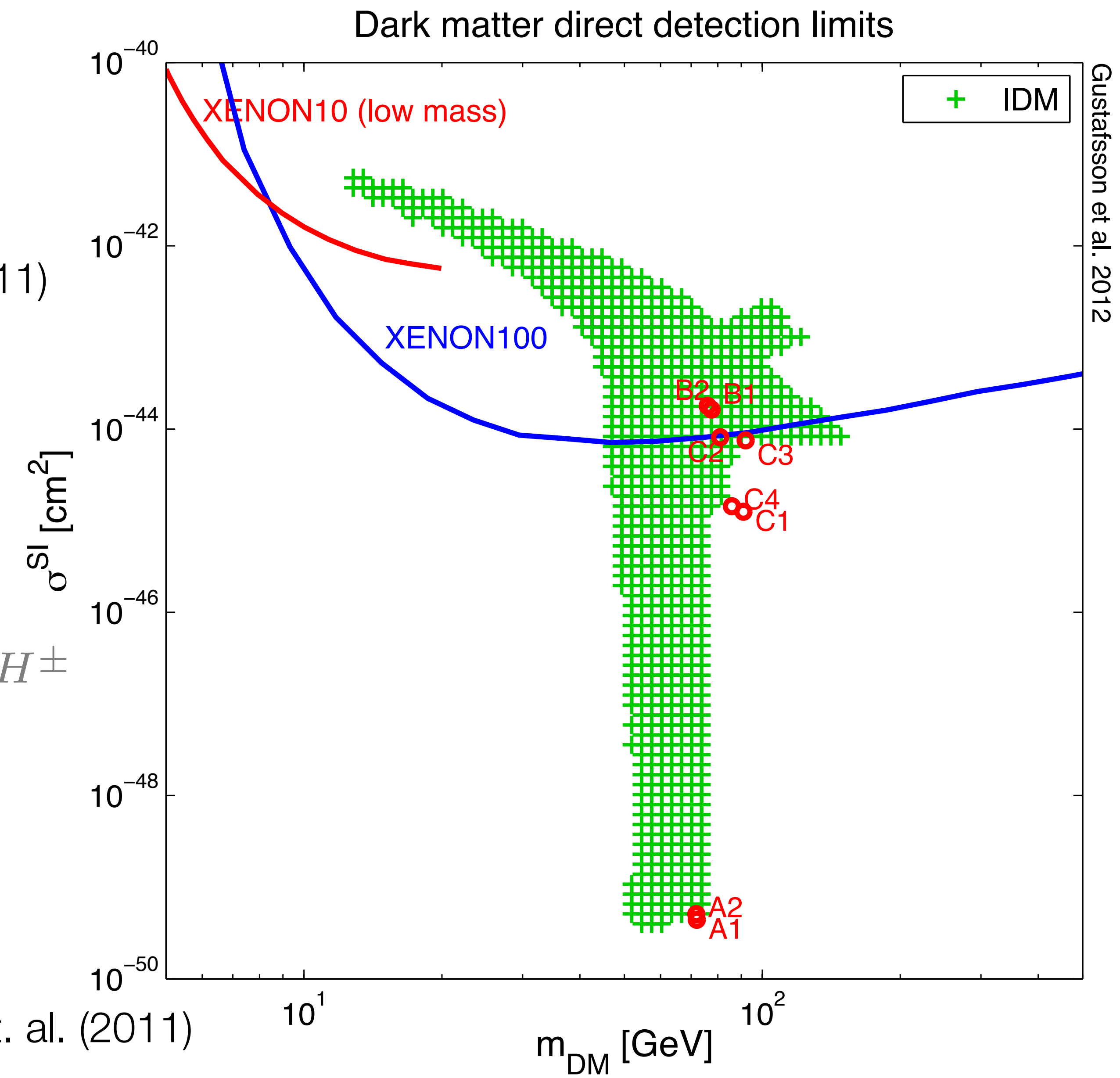
- Collider data from LEP $m_{H^\pm} \gtrsim 70\text{–}90\ \mathrm{GeV}$ Pierce, Thaler (2007)

Constraints on IDM

- **Dark matter:**
  - Relic density (WMAP-7) Larson et. al. (2011)

    $$\Omega_m h^2 = 0.1109 \pm 0.0056 (1\sigma)$$

    - Annihilation via Higgs
    - Coanniliations $m_{H^0} \sim m_{A^0}$ or $m_{H^\pm}$
    - Annihilation to $WW, ZZ, t\bar{t}$



  - Direct detection with XENON

    Angle et. al. (2011), Aprile et. al. (2011)

  - Indirect detection (gamma-ray constraints with Fermi-LAT)

    Abdo et. al. (2010), Ackerman et. al. (2011,2012)

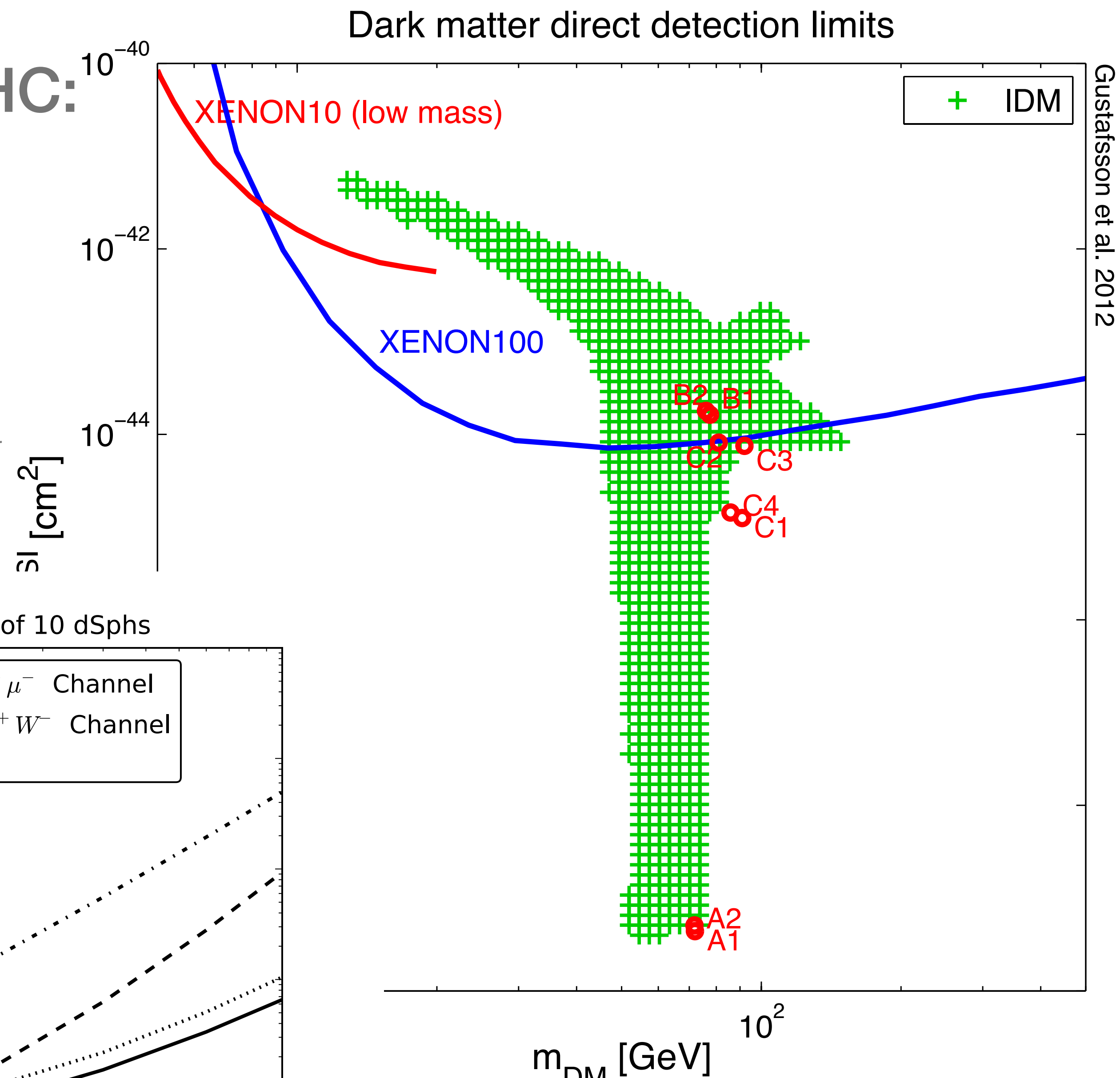
Constraints on IDM

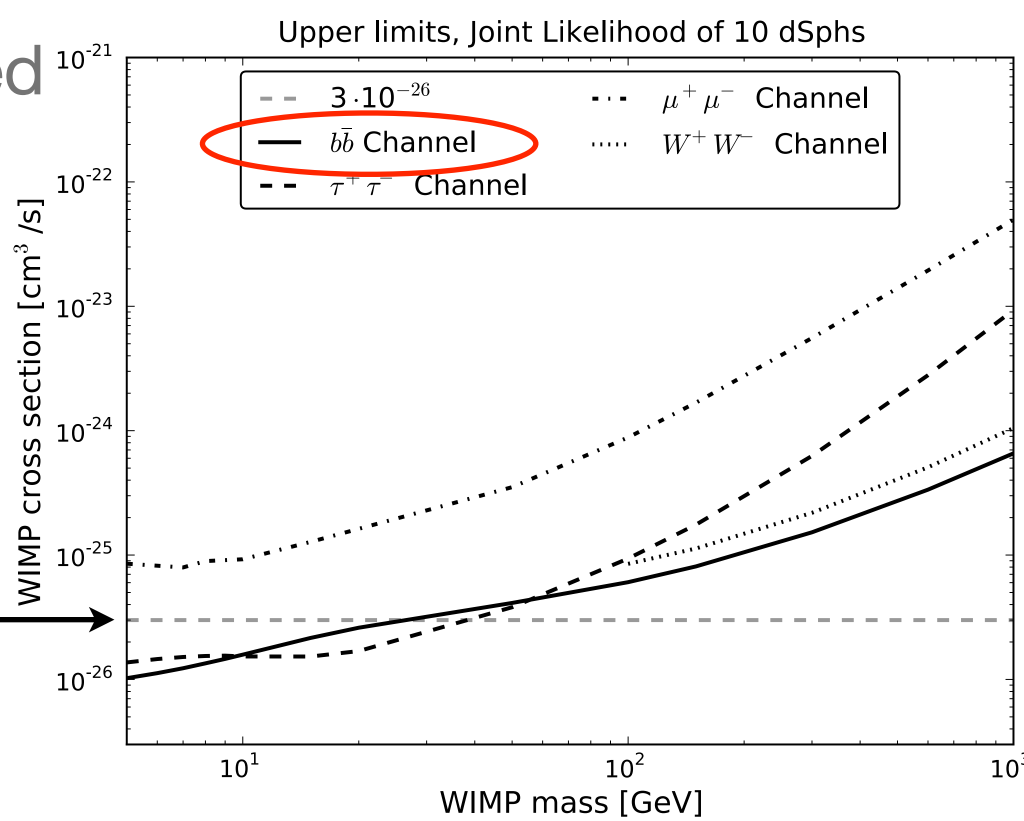
Allowed dark matter masses before LHC:

- $m_{H^0} \sim 50\text{–}80\ \mathrm{GeV}$
- 'new viable region' $m_{H^0} \sim 80\text{–}150\ \mathrm{GeV}$

Lopez-Honorez, Yaguna (2011)

- ~~~10 GeV~~ excluded





Fermi-LAT collaboration (2011)

- very high mass region ~500 GeV, not accessible at LHC

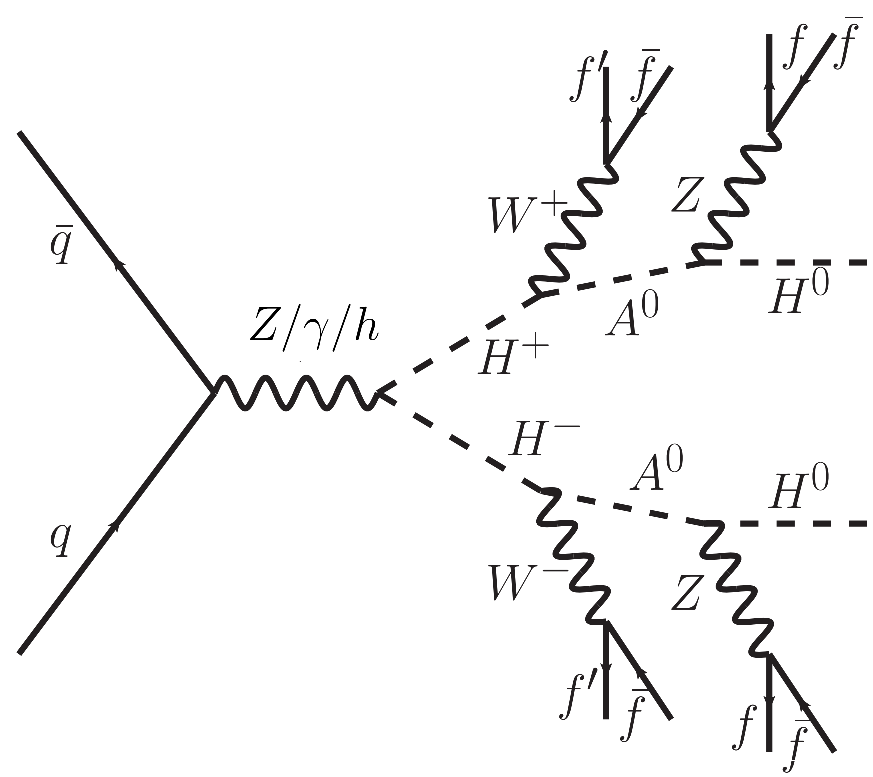
The role of multiple leptons at LHC

The IDM has been shown before to predict signals in 14 TeV data:

- in the dilepton plus missing transverse energy channel Dolle, Miao, Su, Thomas (2010)
    - dominating process $pp \to H^0 A^0, \;\; m_{H^0} < m_{A^0} < m_{H^\pm}$
- in the trilepton plus missing energy channel Miao, Su, Thomas (2010)
    - dominating process $pp \to A^0 H^\pm, H^\pm \to H^0$
- predict signal at 100-300/fb for $40 \text{ GeV} < (m_{A^0} - m_{H^0}) < 80 \text{ GeV}$ needed for a detectable signal.
- These signals have no direct dependence on the Higgs mass.

The role of multiple leptons at LHC

IDM could give rise to even higher lepton multiplicities in the final state:



The tetralepton plus missing energy channel has very low SM background.

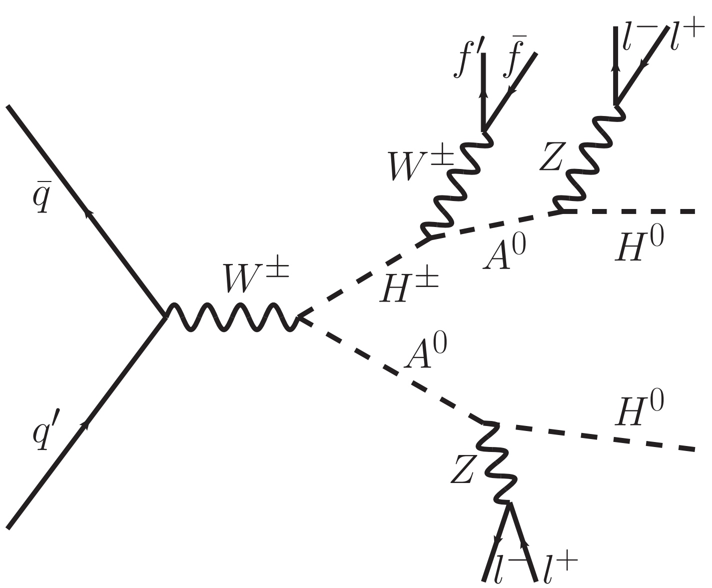
- $t\bar{t}Z, ZWW, ZZ$ reduced with b-jet veto, *Z* veto, missing energy,
- fakes may be important, for example $t\bar{t}$

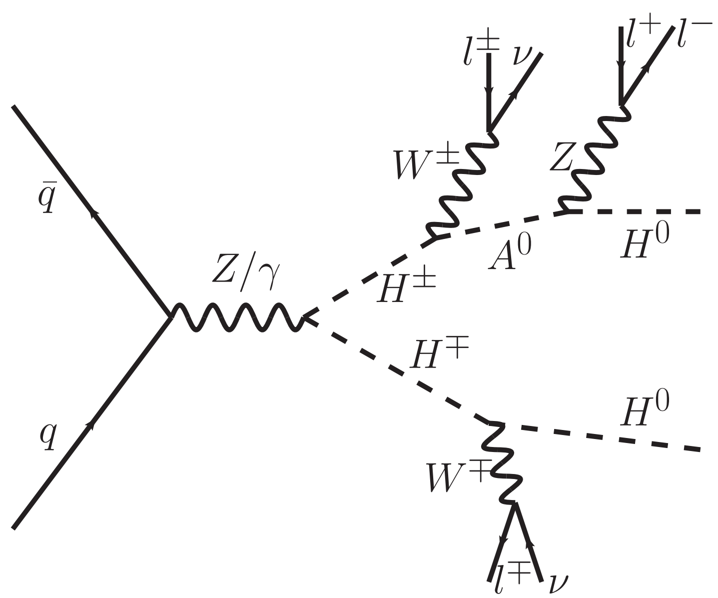
Production of four leptons via gauge bosons

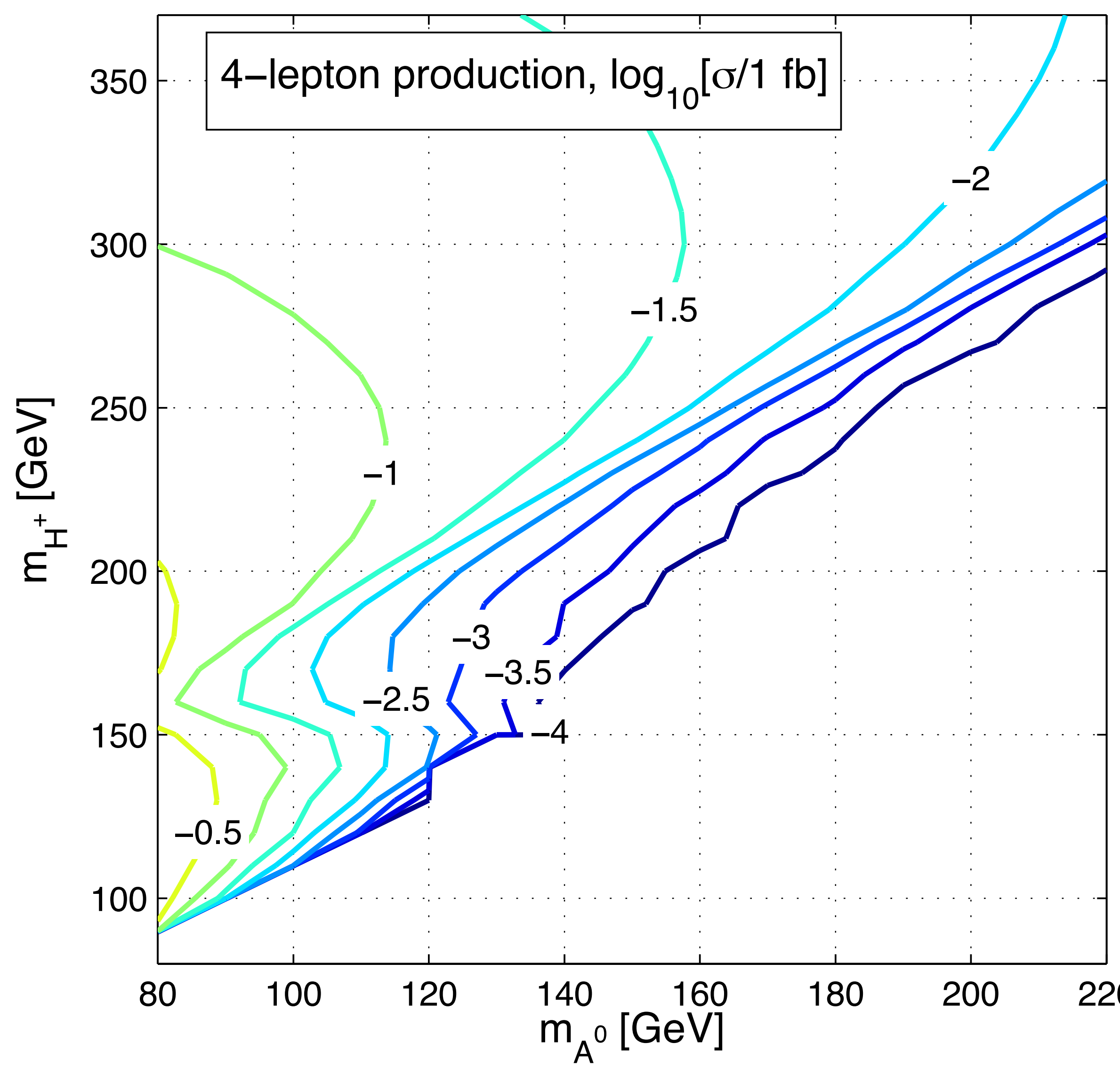
- $pp \to H^{\pm} A^0,\ H^+ H^-$

- Depends only on the masses of the inert scalars.

$m_{H^0} = 70\ \mathrm{GeV}$





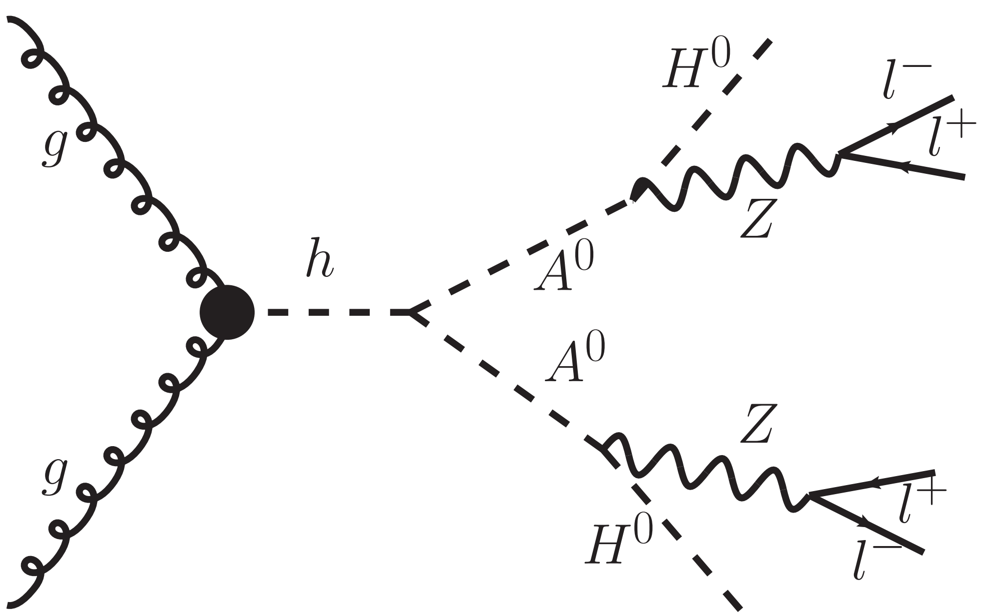


- But the signal is weak.

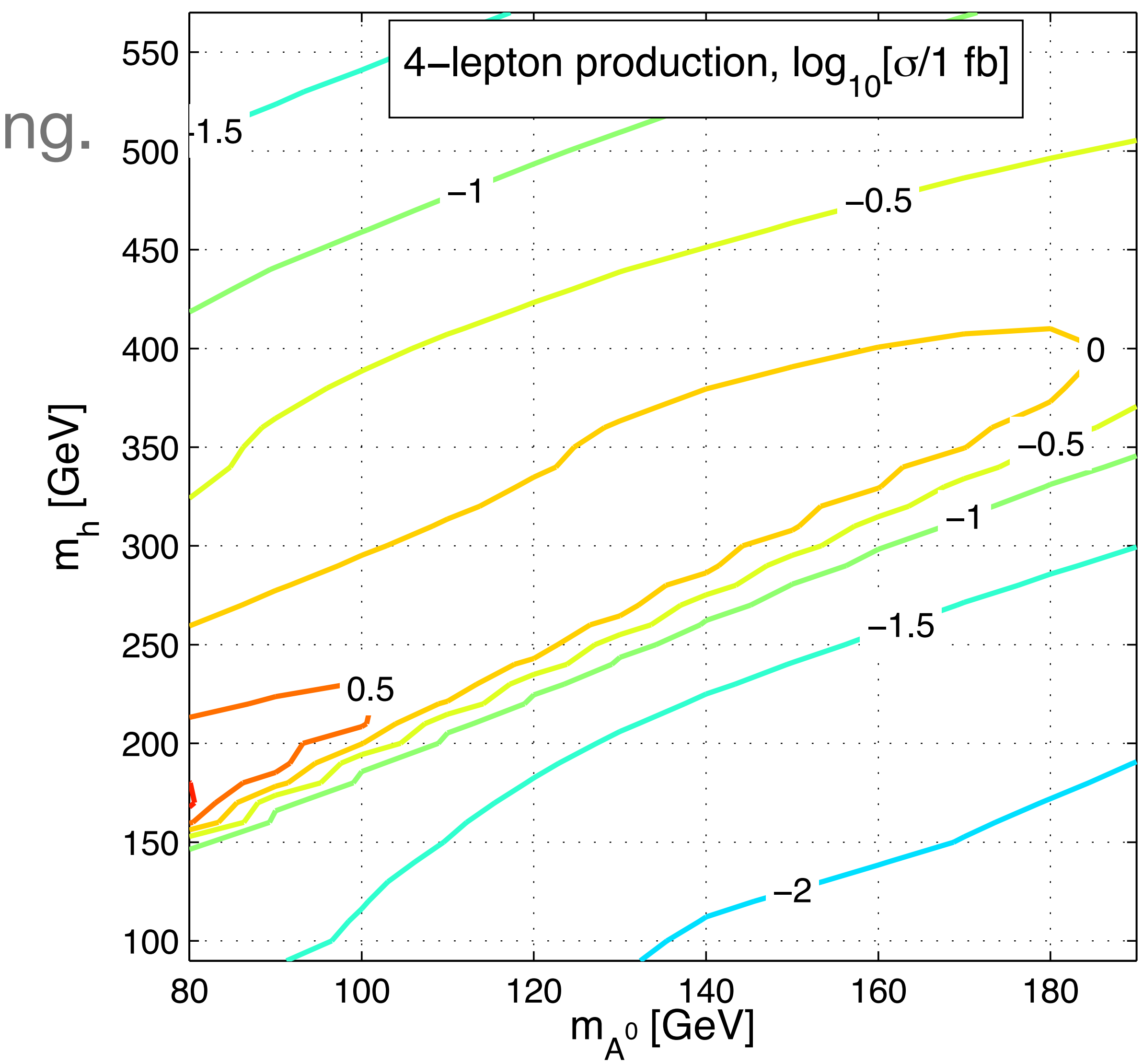
Production of four leptons via SM-like Higgs

- $pp \to A^0 A^0,\ H^+ H^-$

- Depends also on Higgs mass and coupling.



$m_{H^0} = 70$ GeV, $\mu_2^2 = 0, m_{H^\pm} = 220$ GeV



- Connection to Higgs searches and dark matter direct detection...

Complementarity of LHC Higgs searches and dark-matter direct detection

- **Higgs portal dark matter:** Higgs-DM coupling constrained by direct detection experiments -> restricts the invisibility of Higgs to collider searches

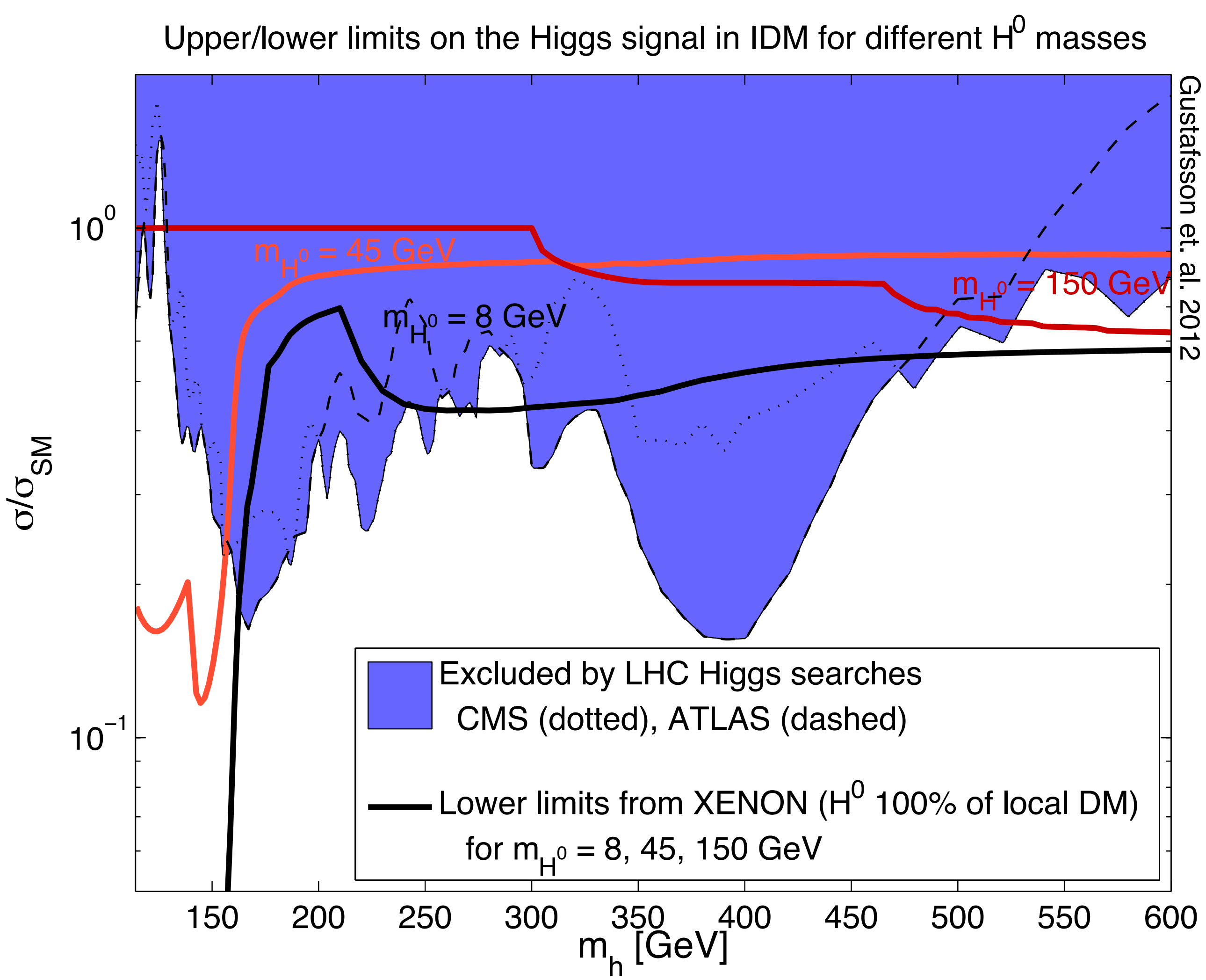
Farina et. al. (2011), Mambrini (2011), Raidal, Strumia (2011), Baek et. al. (2012), Djouadi et. al. (2011), He et. al. (2011), Lebedev et. al. (2011), Lopez-Honorez et. al. (2012), Djouadi et. al. (2012)

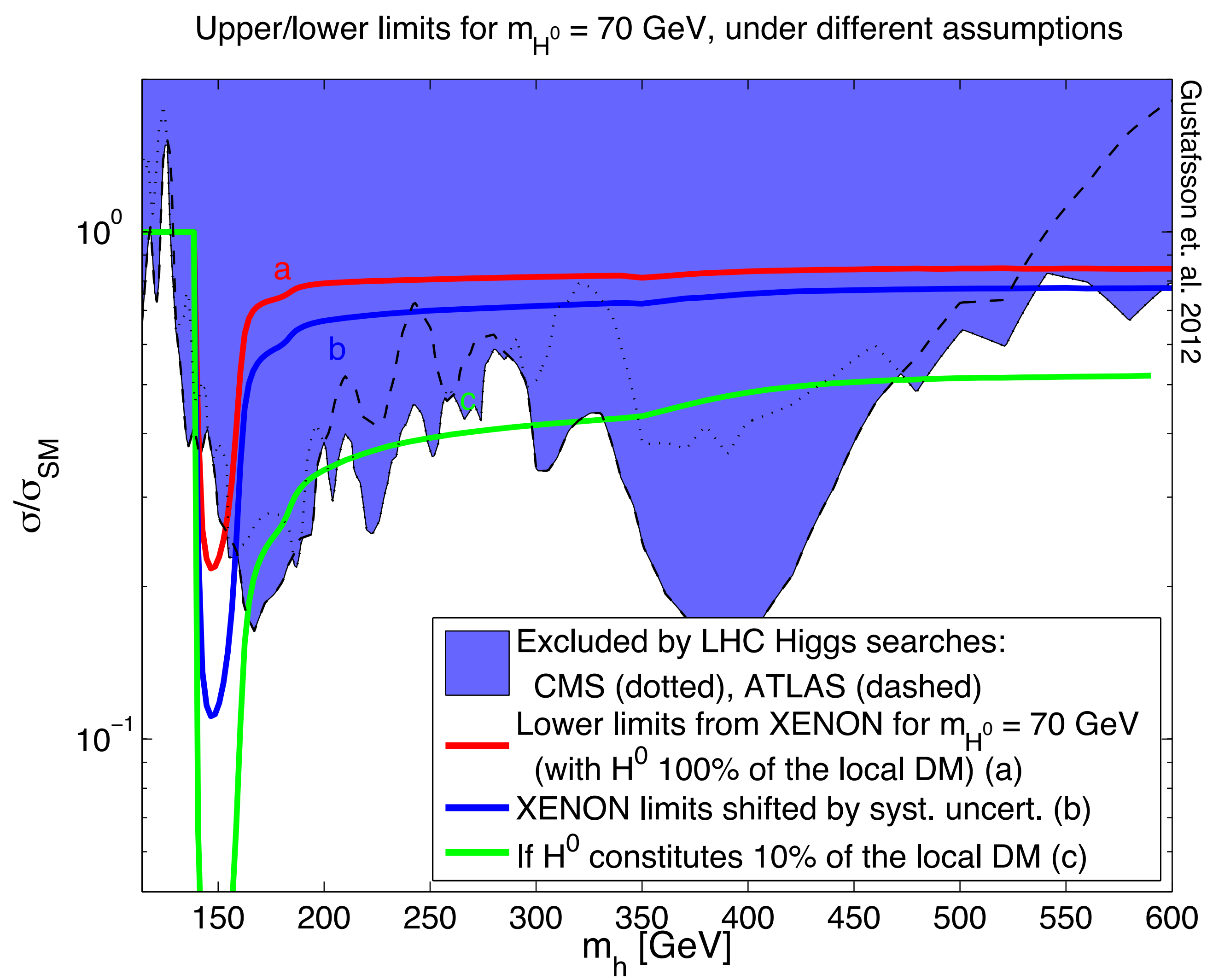
In the IDM:

- Direct detection constrains the coupling: $\lambda_{H^0} = \frac{m_{H^0}^2 - \mu_2^2}{v^2}$
- We have the relation: $\lambda_{A^0} = \lambda_{H^0} + \frac{m_{A^0}^2 - m_{H^0}^2}{v^2}$
- The larger these couplings are allowed to be, the larger is
  - the IDM contribution to the Higgs width
  - the production cross section into $A^0 A^0$ at LHC (for heavy Higgs)

Complementarity of LHC Higgs searches and dark-matter direct detection

- With 7 TeV LHC data (~5/fb March 2012) and maximum invisible width:



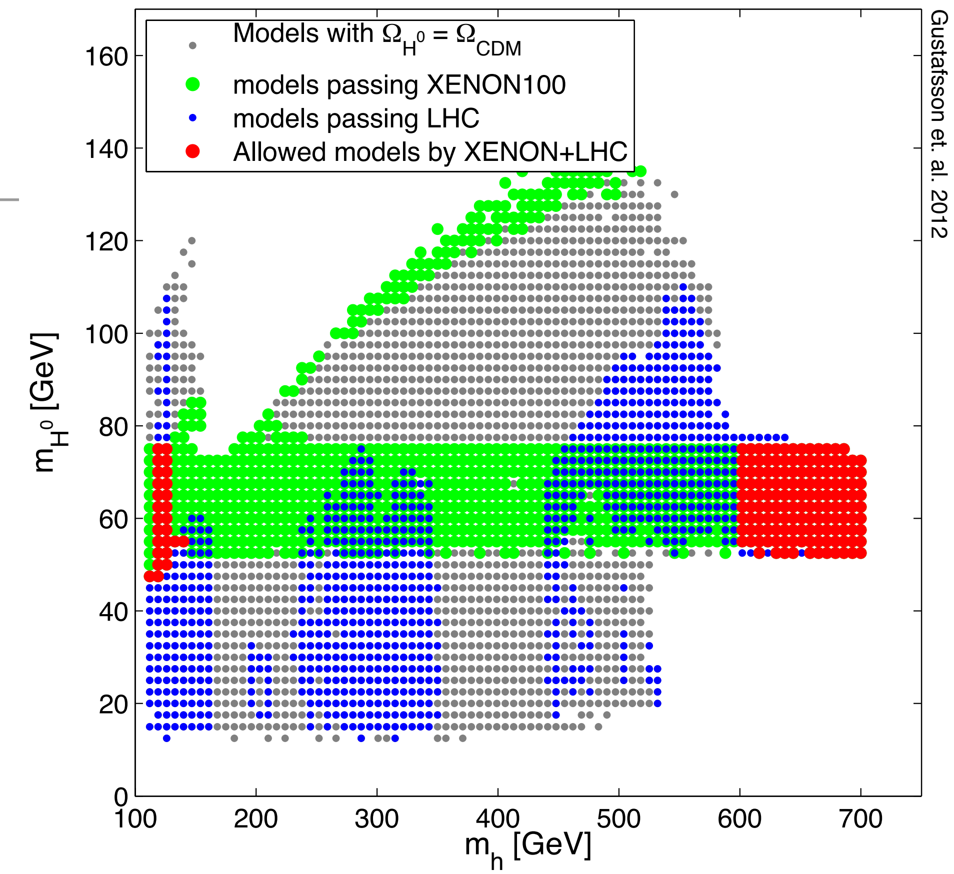


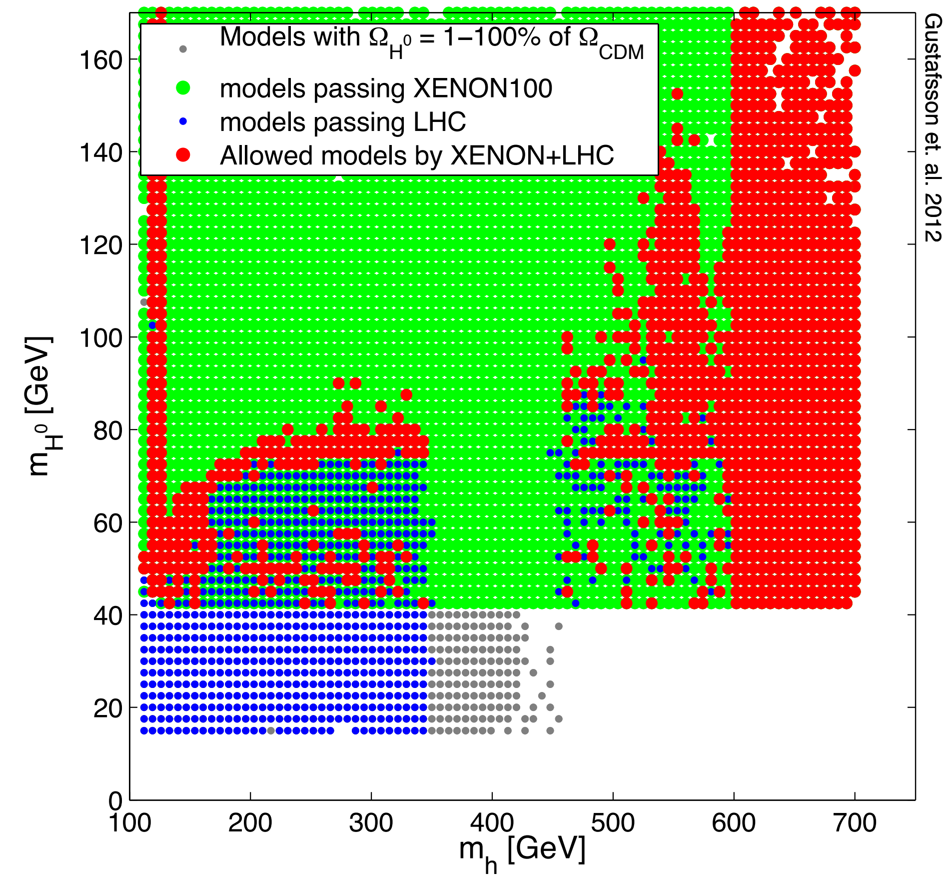
- This is before checking the relic density.

Complementarity of LHC Higgs searches and dark-matter direct detection

Taking into account also the relic density:

- “new viable region” m_{H^0}=80-150 GeV can now be ruled out
- only m_{H^0} =50-80 GeV for Higgs masses ~125 GeV, > 600 GeV (?)
- Intermediate Higgs masses could have been allowed if
  - we take into account systematic uncert.
  - IDM explains only a fraction of the DM
  - With $m_h \sim$ 300-600 GeV, IDM could have been discovered at ~10-200/fb@14TeV.

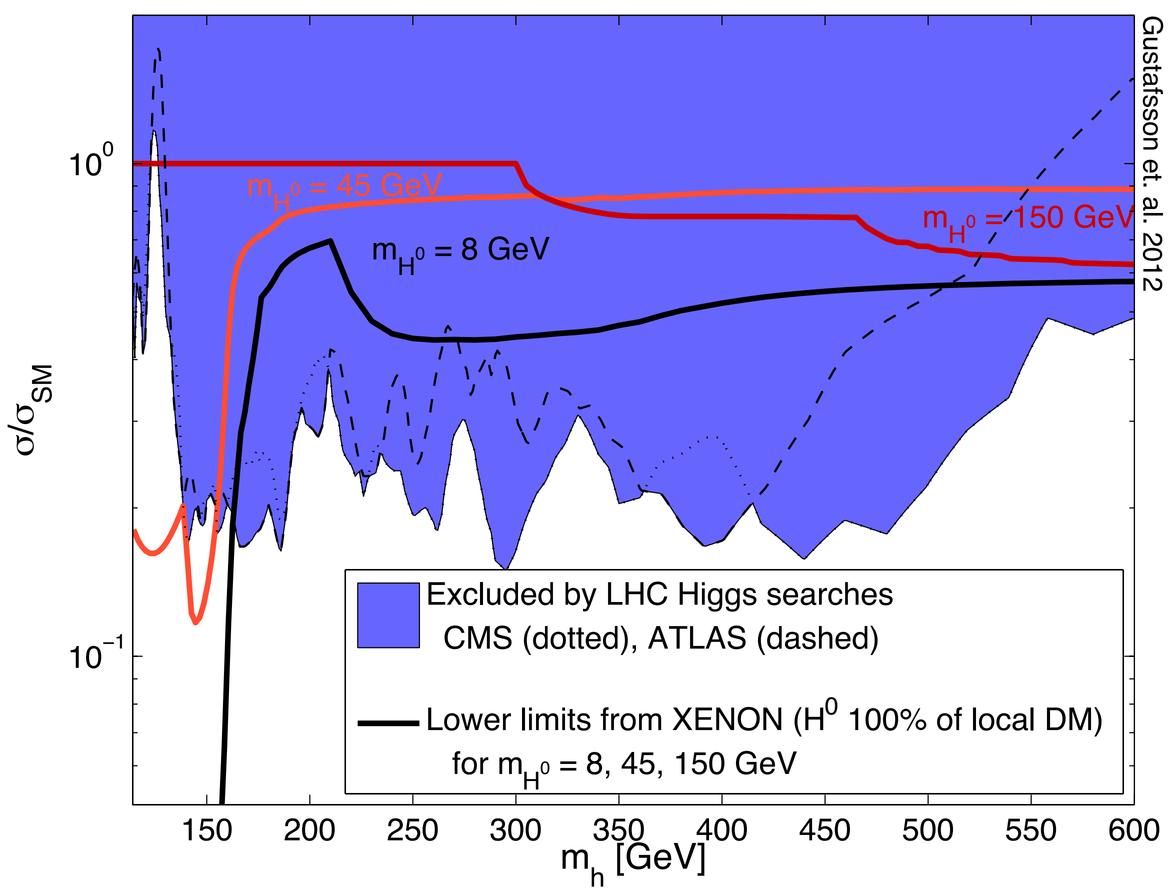




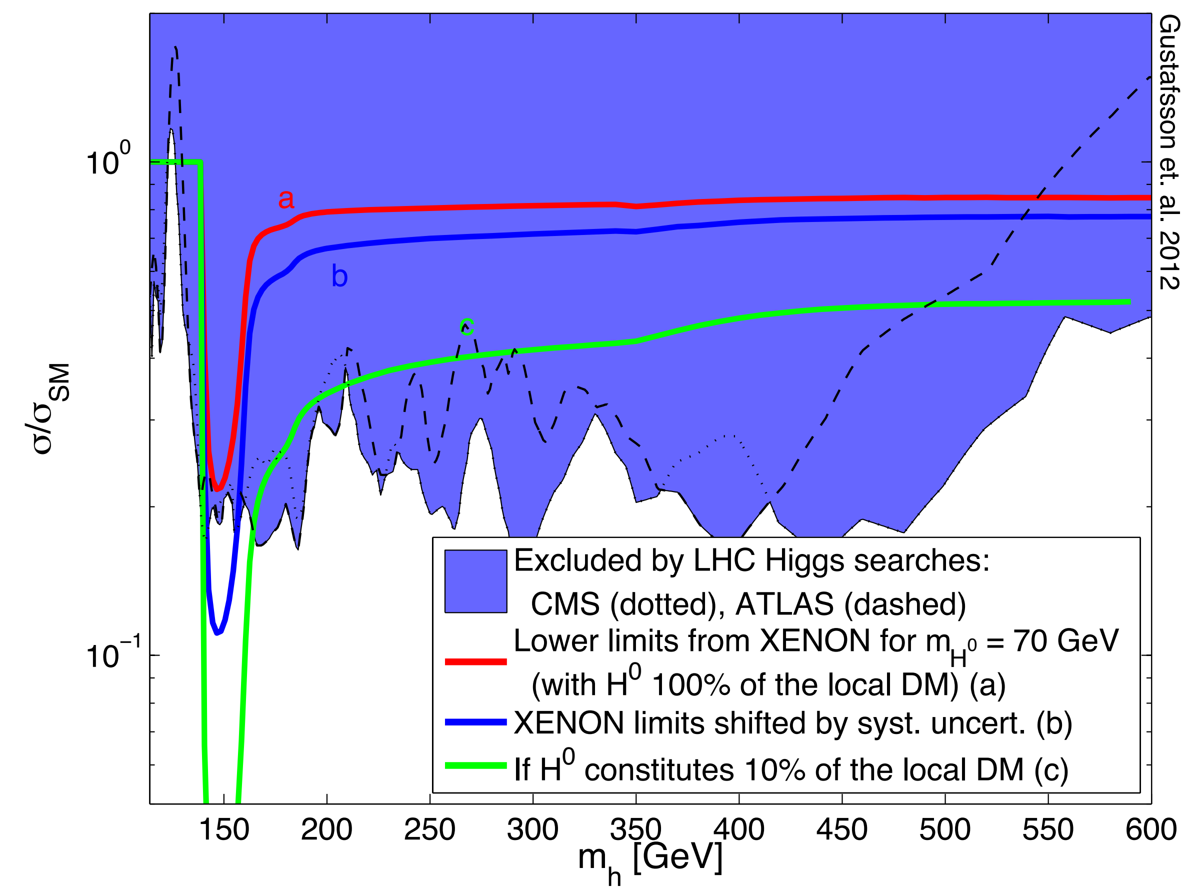
Complementarity of LHC Higgs searches and dark-matter direct detection

- Updated ATLAS- and CMS-limits with 8 TeV data:

Upper/lower limits on the Higgs signal in IDM for different H^0 masses



Upper/lower limits for m_{H^0} = 70 GeV, under different assumptions



- On top of there being a really good Higgs candidate at 125 GeV now:
- Even if DM-density could be lowered even further, couplings are becoming dangerously large (problems with unitarity and perturbativity/triviality) if we are to evade these limits for large Higgs masses.

Conclusion and outlook

- **IDM before LHC 8 TeV data:**
  - Could accommodate a heavy Higgs even though the SM could not.
  - IDM with 100% dark matter and a heavy Higgs (160-600 GeV) could be ruled out by LHC Higgs searches + XENON100 direct-detection searches once all complementary constraints were combined.
  - IDM with 10% dark matter and with Higgs masses 300-600 GeV predicted strong signals in the four-leptons+missing energy channel at LHC 14 TeV.
- **IDM after LHC 8 TeV update and with an SM-like Higgs of ~125 GeV:**
  - The prediction for the dark-matter mass in IDM is 50-80 GeV (and LHC unreachable range ~500 GeV).
  - Higgs branching ratios can be altered also at loop level ($\gamma\gamma$). Arhrib, Benbrik, Gaur (2012) Should be searched for in the LHC 14 TeV data in channels with missing energy and two or three leptons. Dolle, Miao, Su, Thomas (2010)
  - See also Andreas Goudelis' talk.