The inert doublet model and multilepton signatures at the LHC

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DESY theory seminar, November 21, 2011

Question

- What are the prospects for discovery of the Inert Doublet Model in the four-lepton plus missing energy channel at the Large Hadron Collider, provided that the lightest inert scalar constitutes the dark matter in the universe?

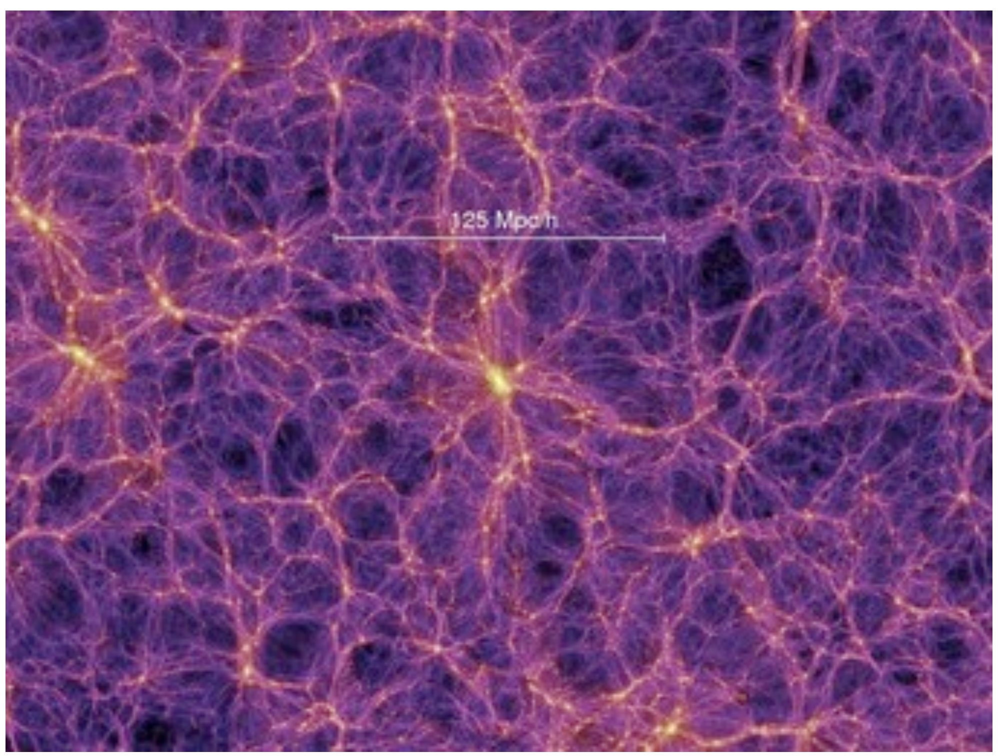
- We also investigate how these prospects relate to direct dark matter searches and to the Standard Model Higgs search.

In collaboration with Michael Gustafsson and Erik Lundström.

How to test particle nature of dark matter?

- Indirect and direct detection - astrophysical uncertainties potentially large.

- High-energy colliders - stability of particle after leaving detector?



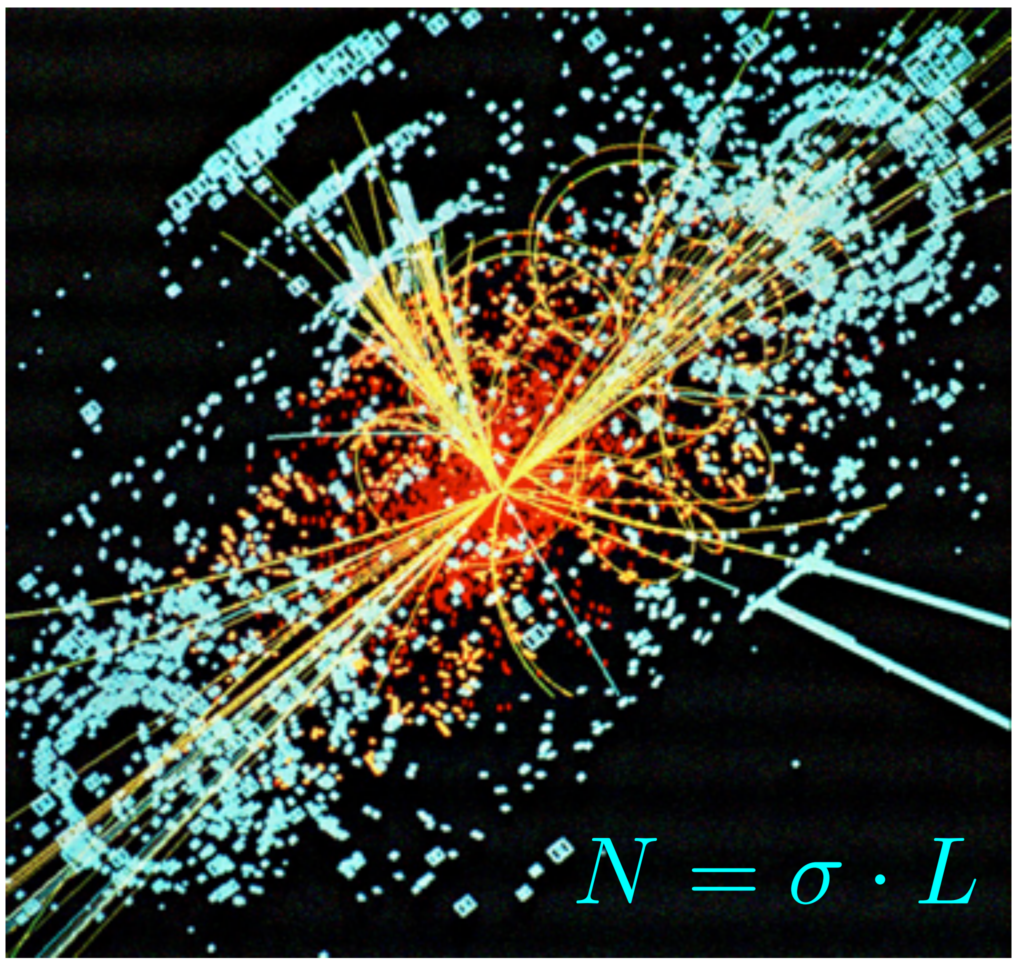
Millennium Simulation


CERN

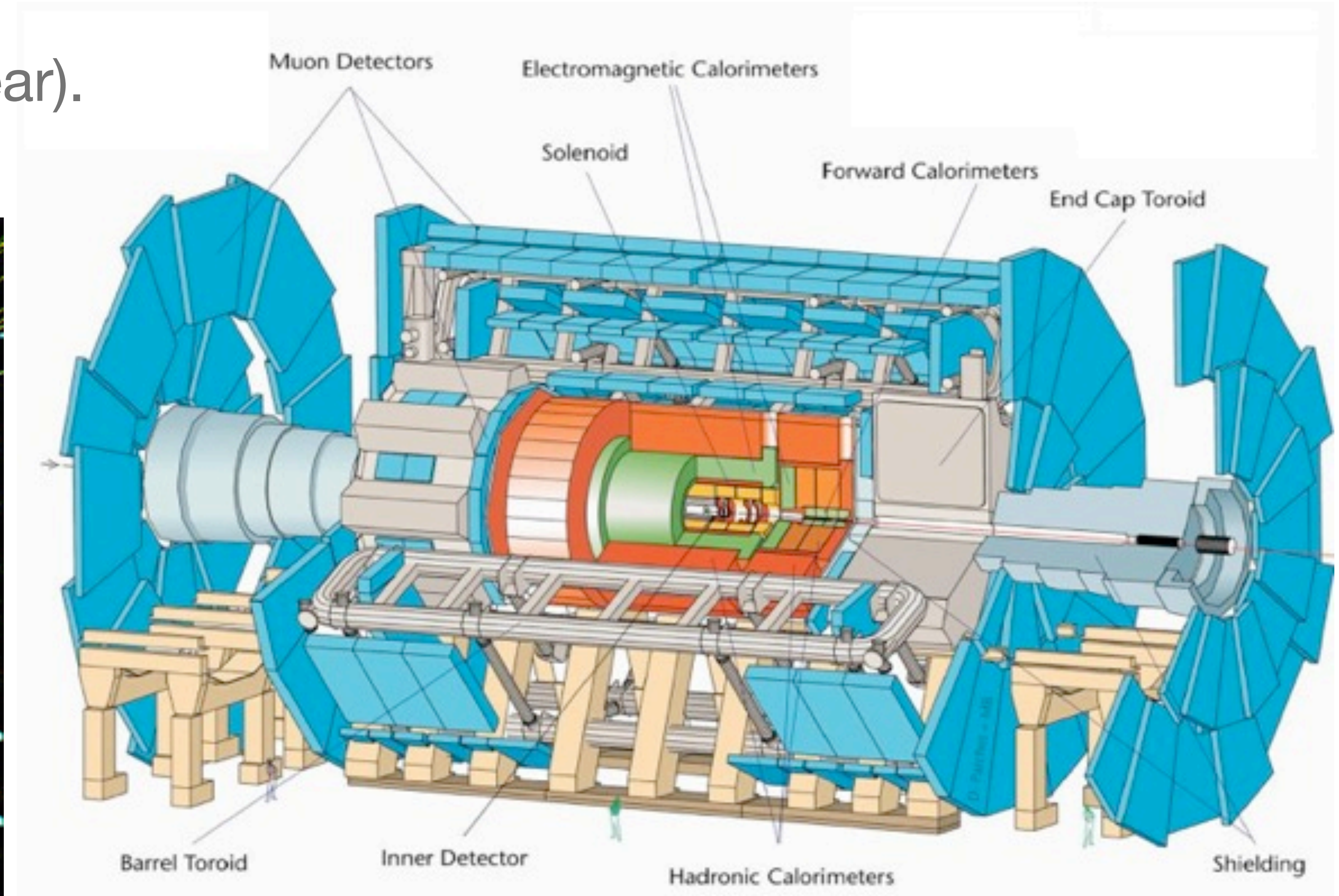
- Important complementary approaches!

The CERN Large Hadron Collider (LHC)

- Designed for proton-proton collisions at 14 TeV center-of-mass energy.
- At design luminosity 100/fb/year).

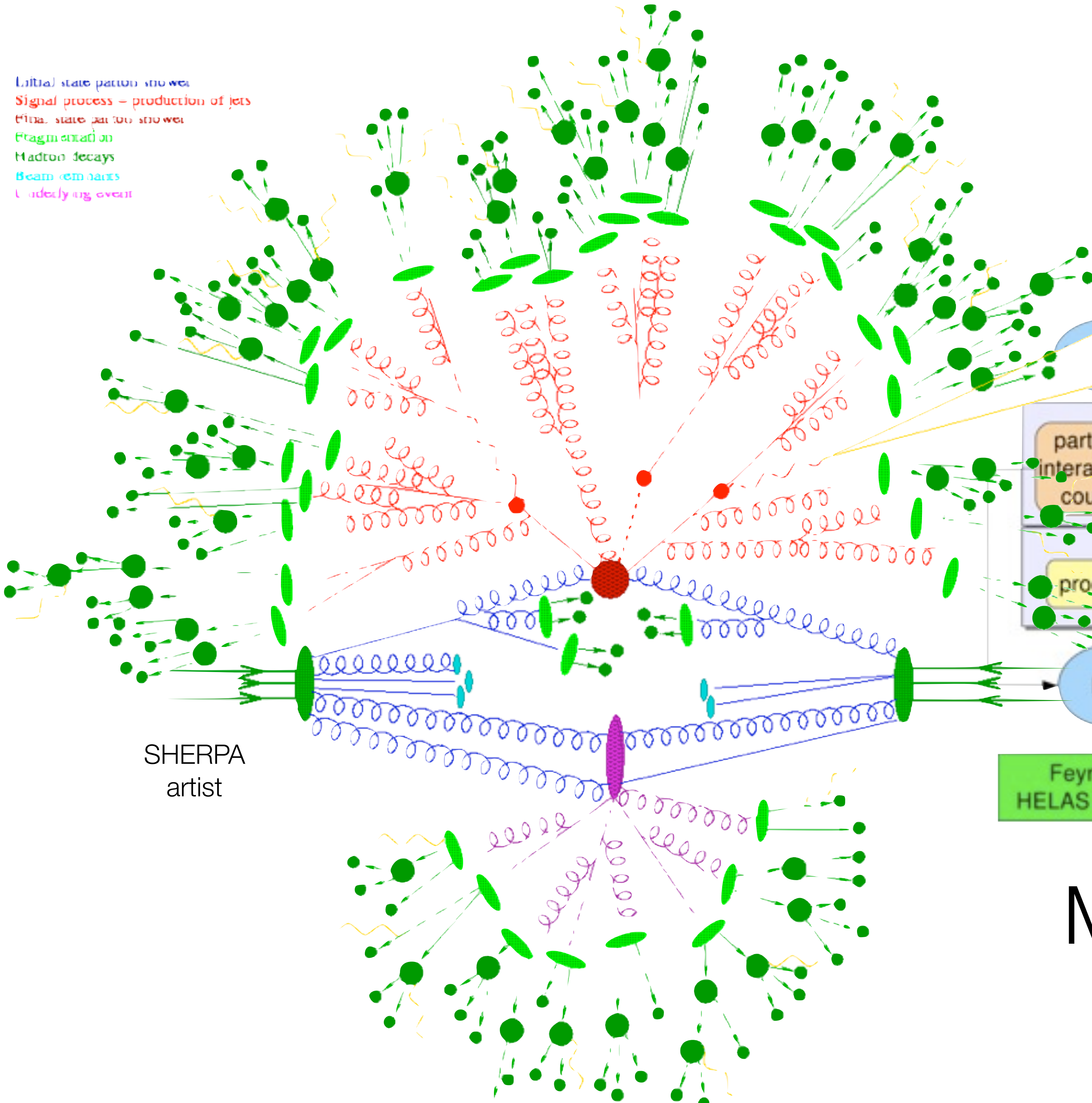


$$N = \sigma \cdot L$$

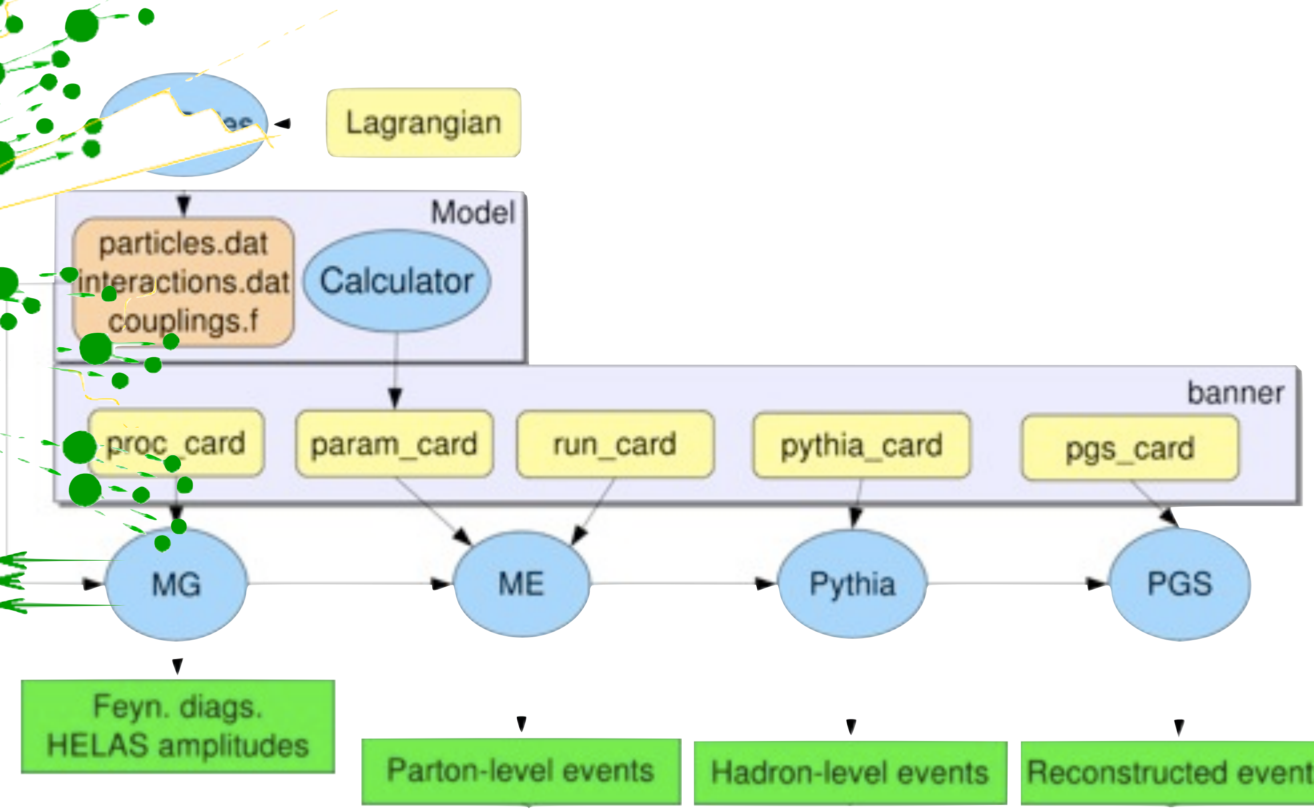


The ATLAS detector

Tools



SHERPA
artist



Madgraph/MadEvent

The Inert Doublet Model (IDM)

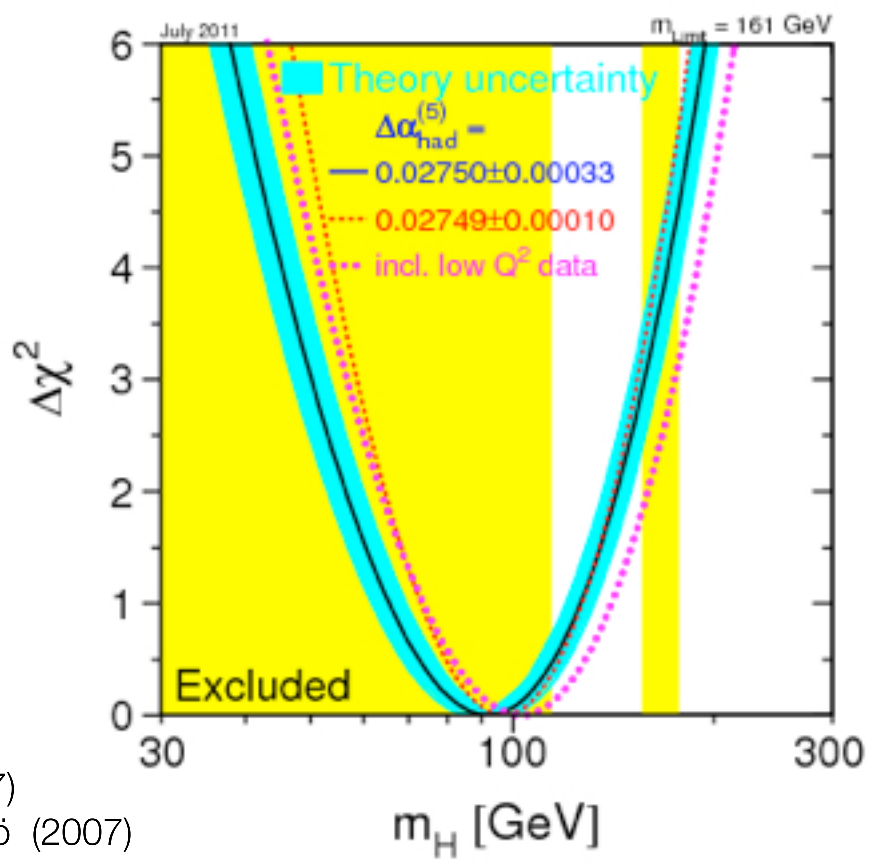
- An extension of the Standard Model Higgs sector to include an extra "inert" doublet, H_2, odd under unbroken $\mathbb{Z}_2$-symmetry, while SM fields even.

Deshpande, Ma (1978)

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

$$H_1 = \begin{pmatrix} 0 \\ v + h/\sqrt{(2)} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H^+ \\ (H^0 + A^0)/\sqrt{(2)} \end{pmatrix}$$

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



http://lepewwg.web.cern.ch/LEPEWWG/

- Phenomenologically motivated. Barbieri, Hall, Rychkov (2006)

Lopez Honorez, Nezri, Oliver, Tytgat (2007)
Gustafsson, Lundström, Bergström, Edsjö (2007)

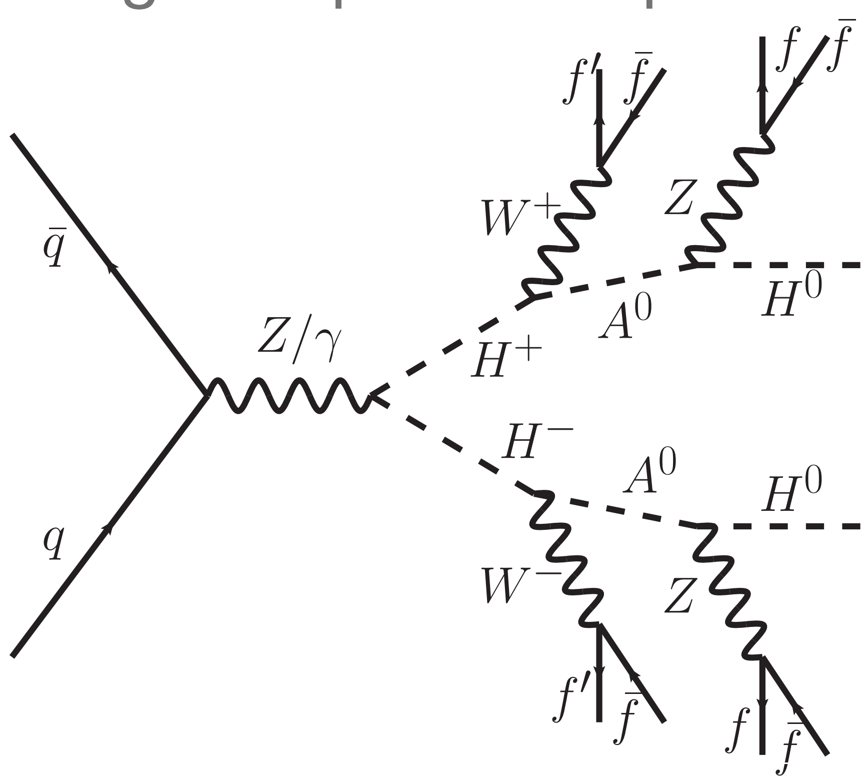
- Here we take H^0 to be the dark matter candidate (WIMP).

The role of multiple leptons at LHC

- The IDM has been shown to predict signals in di- and trilepton (plus missing transverse energy, $\not{E}_T$) channels at 100-300/fb of running at 14 TeV.

Dolle, Miao, Su, Thomas (2010), Miao, Su, Thomas (2010)

- Could give rise to even higher lepton multiplicities in the final state:

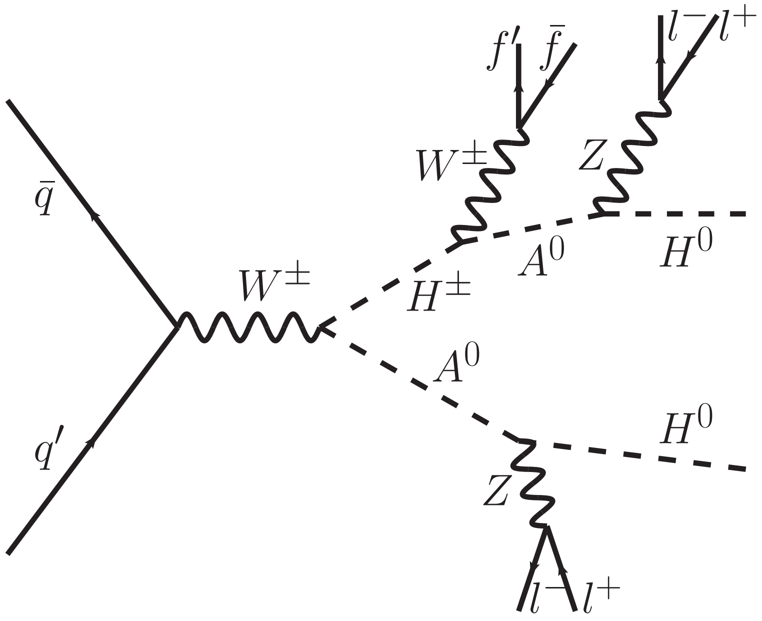


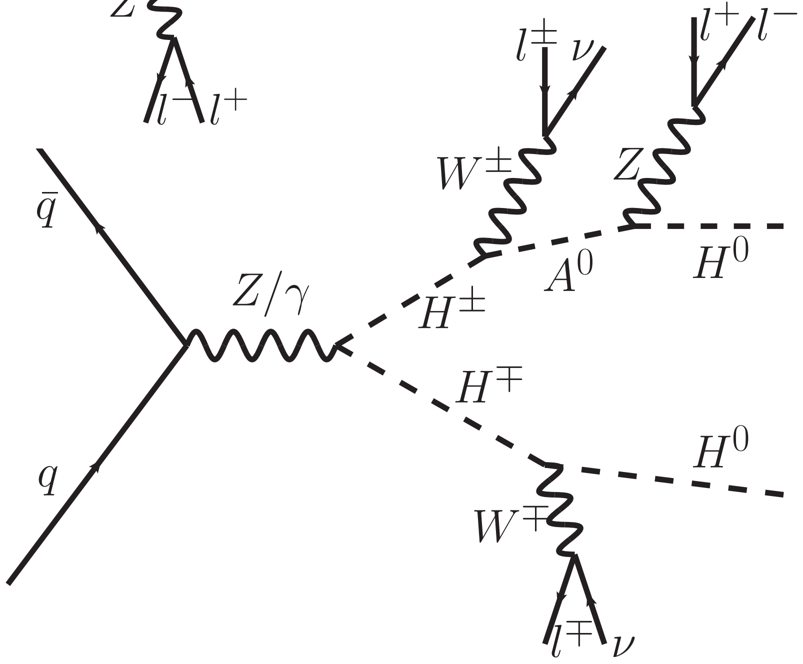
- What are the prospects for the complementary tetralepton + $\not{E}_T$ channel?

Production via gauge bosons

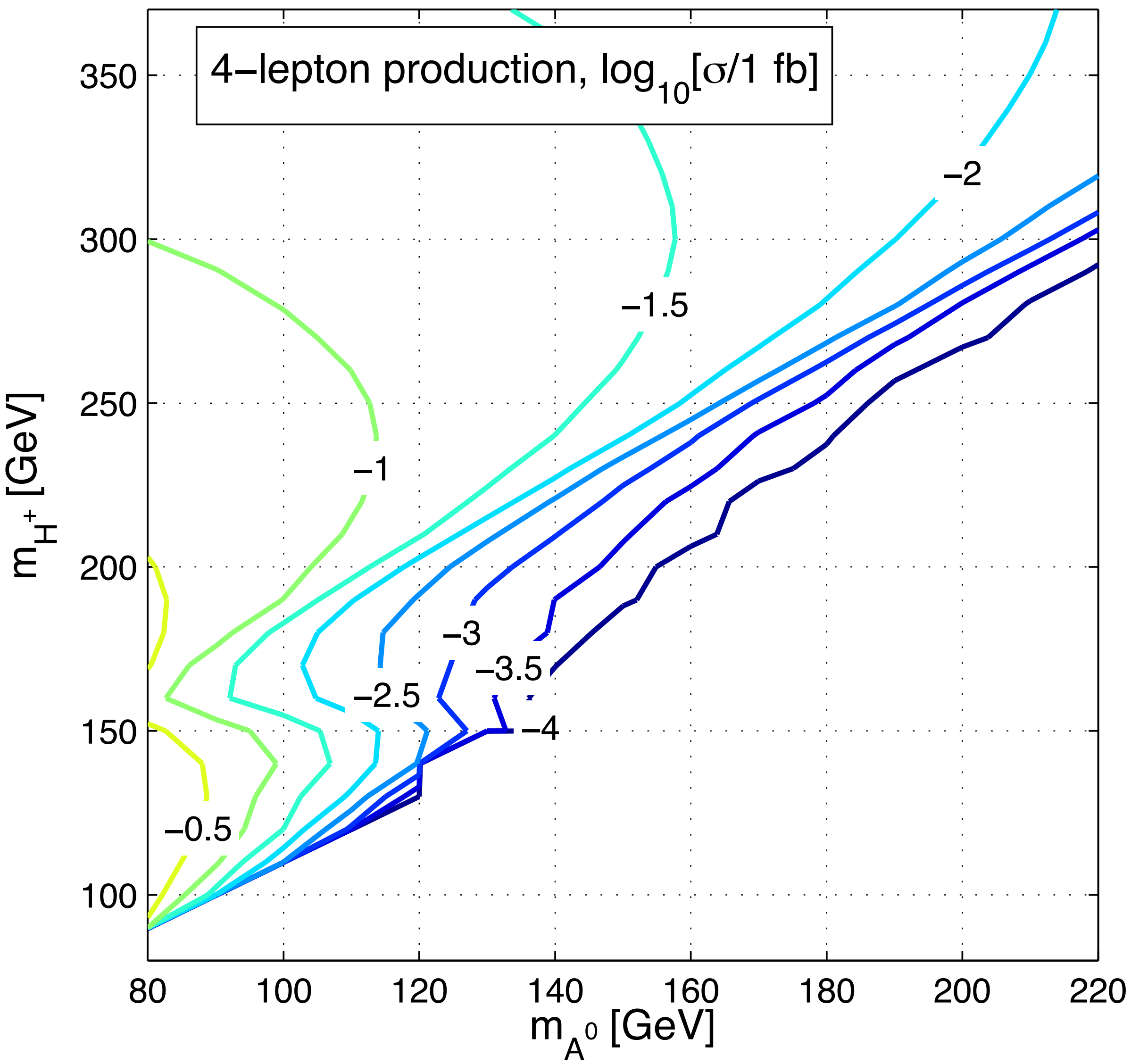
- $pp \to H^{\pm} A^0,\ H^+ H^-$

- Depends only on the masses of the inert scalars.





$m_{H^0} = 70$ GeV

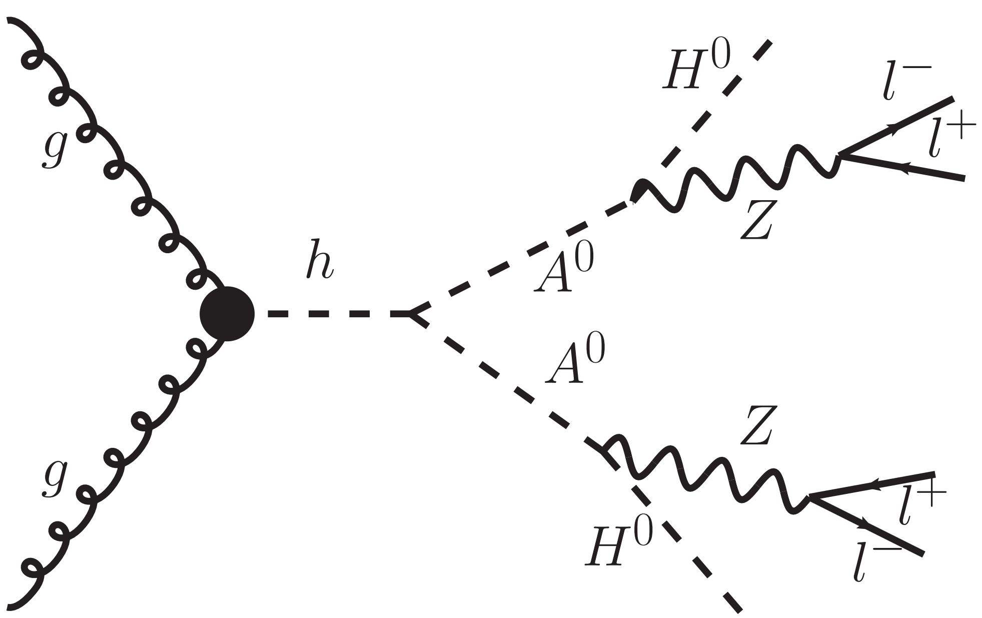


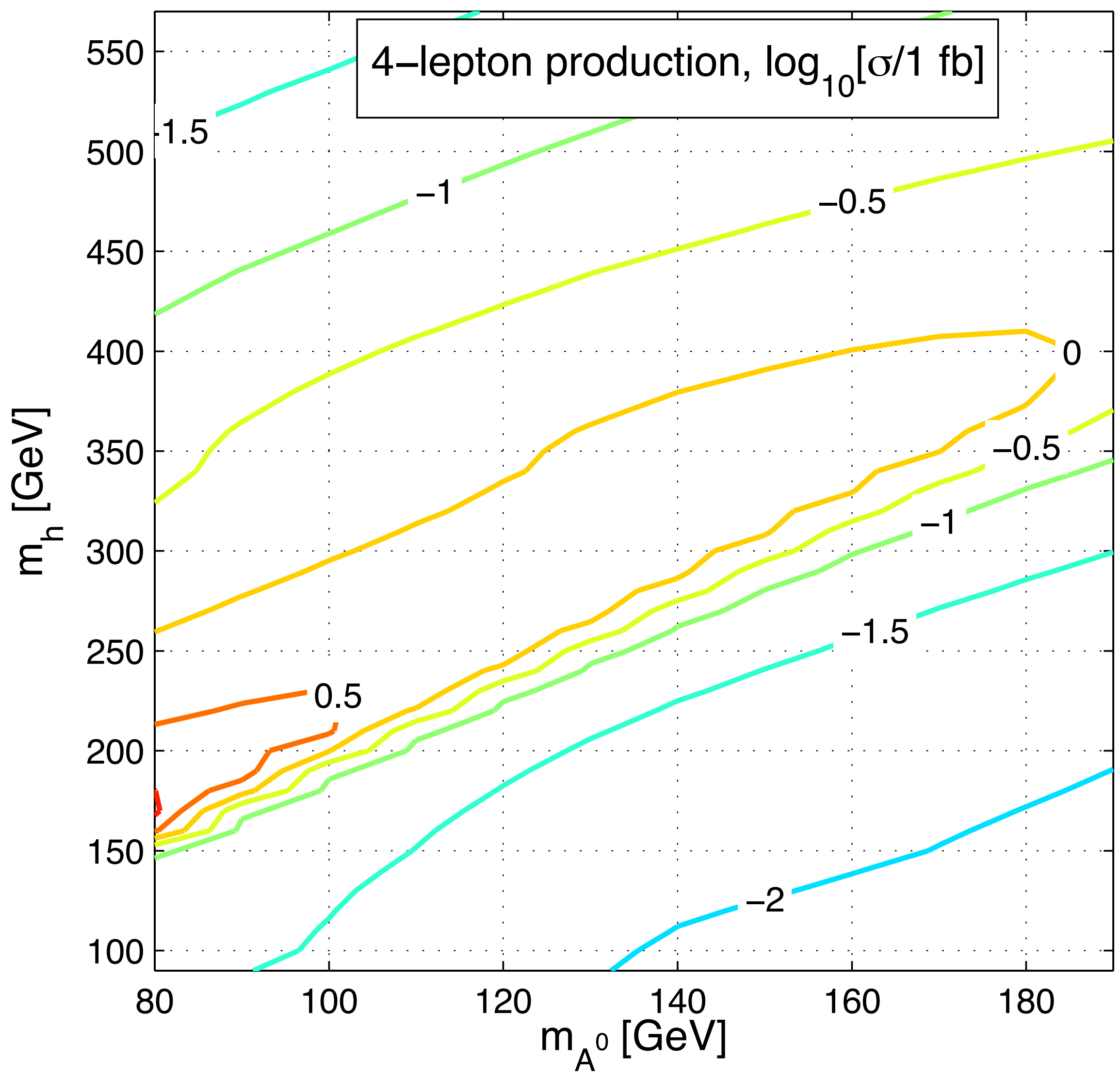
Production via SM-like Higgs

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

- Depends also on Higgs mass and coupling.

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





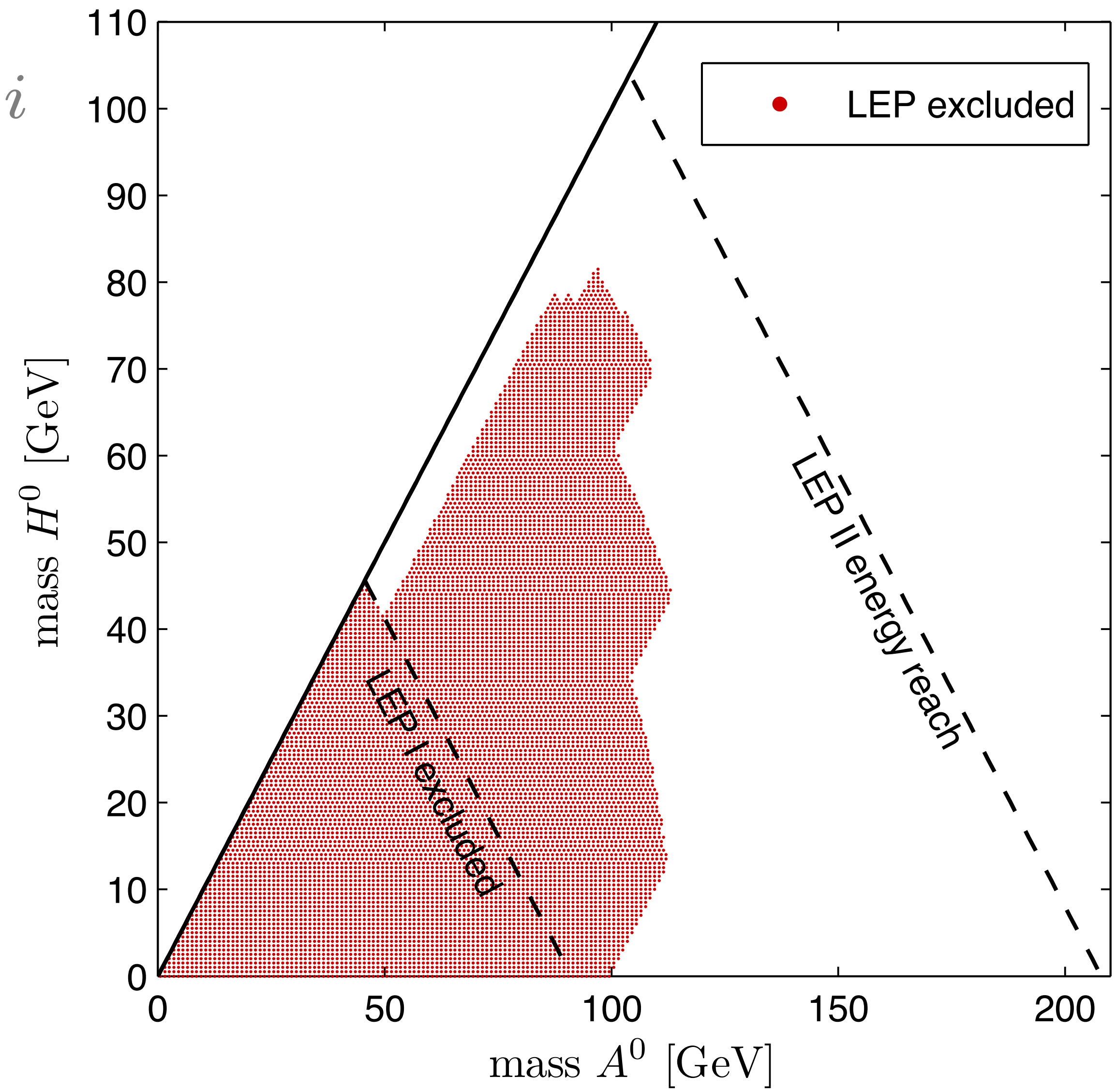
Constraints on IDM

- Vacuum stability -> “lower” bounds on λ_i
- Perturbativity -> upper bounds on λ_i
- Collider searches (Z- and W-widths)
- Electroweak precision tests (EWPT)

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

- Relic density (WMAP-7)

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



Gustafsson, Lundström, Bergström, Edsjö (2007)

Direct detection

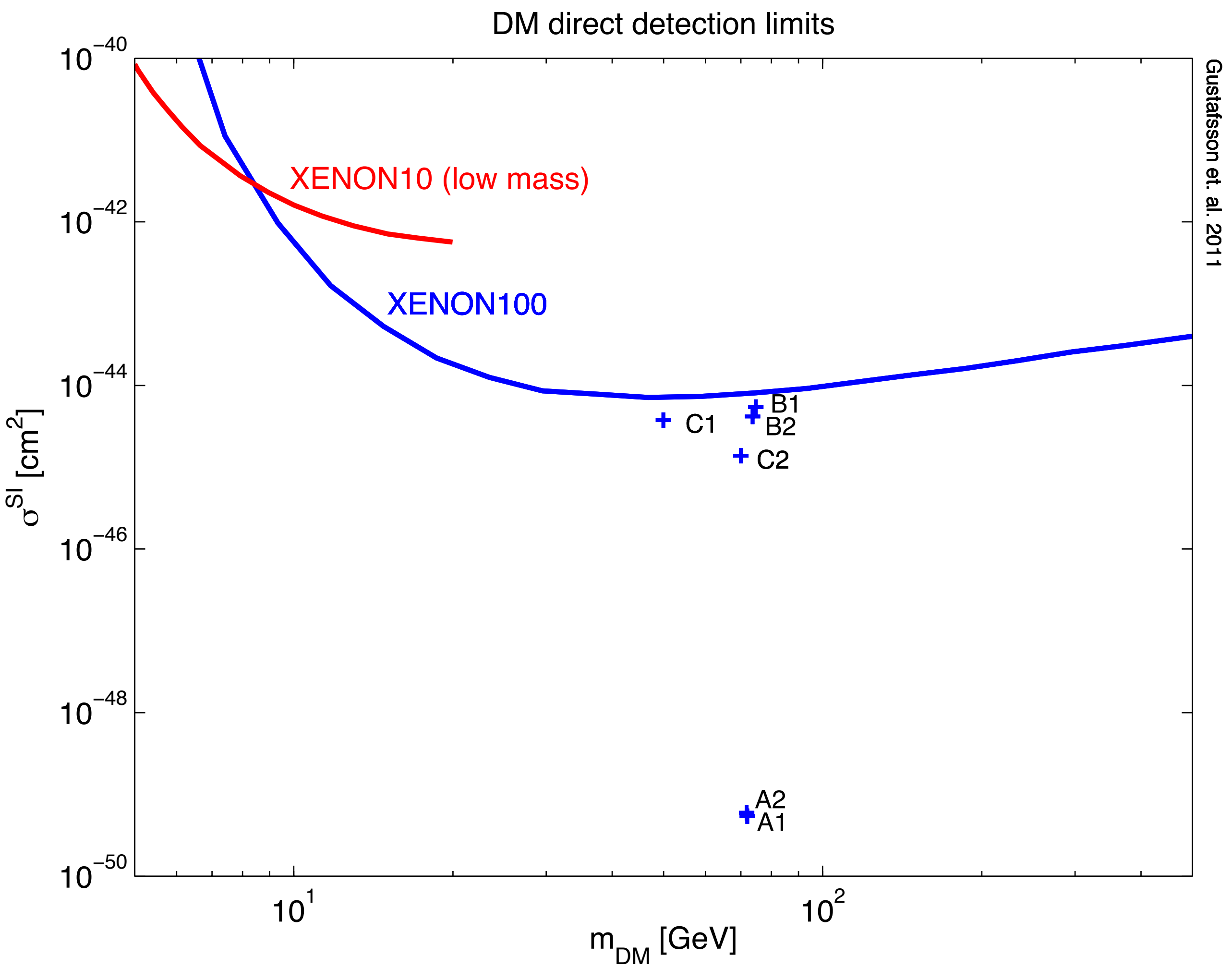
Given the dark matter mass, direct detection constrains the coupling:

$$\lambda_L = \frac{m_{H^0}^2 - \mu_2^2}{v^2}$$

which is related to the coupling

$$\lambda_A = \frac{m_{A^0}^2 - \mu_2^2}{v^2}$$

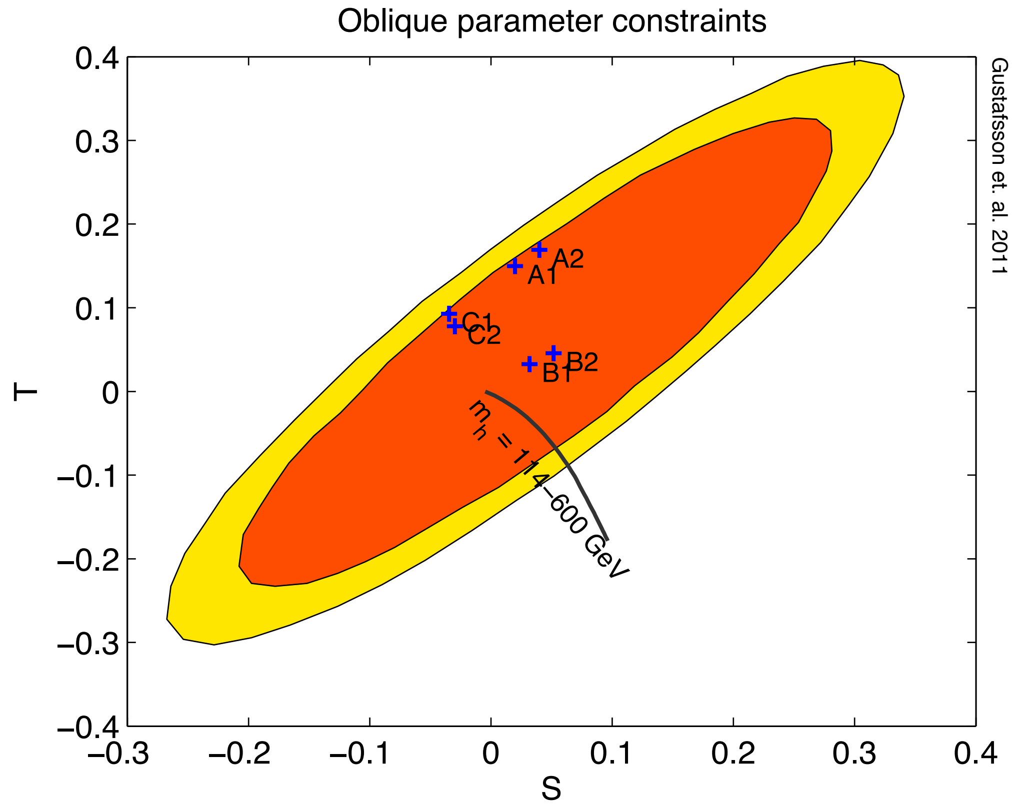
relevant for production of $A^0 A^0$ via the SM-like Higgs.



Benchmark models

- Representative of different SM-like Higgs masses.
- A-models optimized for “via gauge”-channel.
- B-models optimized for “via *h*”-channel.

Benchmark	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	λ_L	$\Omega_m h^2$
IDM-A1	300	72	110	210	0.0	0.107
IDM-A2	500	71.8	110	230	0.0	0.110
IDM-B1	300	74.7	130	190	0.34	0.113
IDM-B2	500	73.7	140	220	0.86	0.111
IDM-C1	120	50	110	160	0.04	0.110
IDM-C2	120	70	110	160	0.03	0.109



Benchmark models

- Production cross-sections in fb.

Benchmark	$\sigma_{pp\to H^+H^-}$	$\sigma_{pp\to H^+A^0}$	$\sigma_{pp\to H^-A^0}$	$\mathrm{Br}_{H^\pm\to A^0}$	σ_{4l}
IDM-A1	18.56	54.00	29.19	0.191	0.11
IDM-A2	13.36	42.65	22.68	0.293	0.12
IDM-B1	27.05	56.27	30.42	0.002	0.08
IDM-B2	16.15	36.38	19.10	0.007	0.01
IDM-C1	50.94	103.6	58.34	0.001	0.002
IDM-C2	50.92	103.7	58.38	0.005	0.005

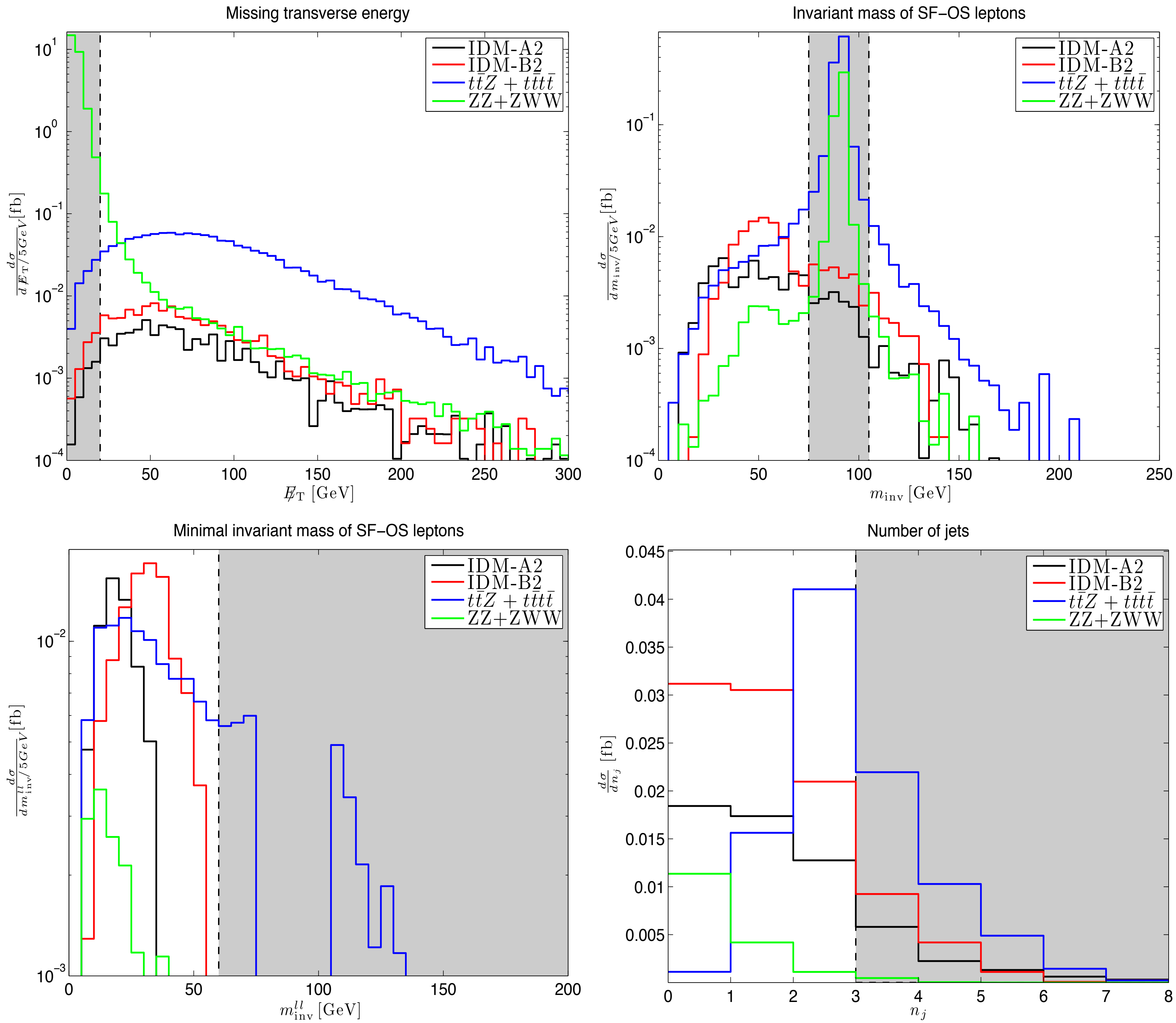
via *Z,W*

Benchmark	$\sigma_{gg\to A^0A^0}$	$\sigma_{gg\to H^+H^-}$	σ_{4l}	$\mathrm{Br}(h \to H^0H^0, A^0A^0, H^+H^-)$ (%)
IDM-A1	88.25	7.46	0.40	0.84
IDM-A2	4.66	138.0	0.32	3.7
IDM-B1	582.5	18.12	2.64	8.0
IDM-B2	121.0	323.2	0.56	12
IDM-C1	2.40	3.47	0.01	37
IDM-C2	1.38	2.77	0.006	0

via *h*

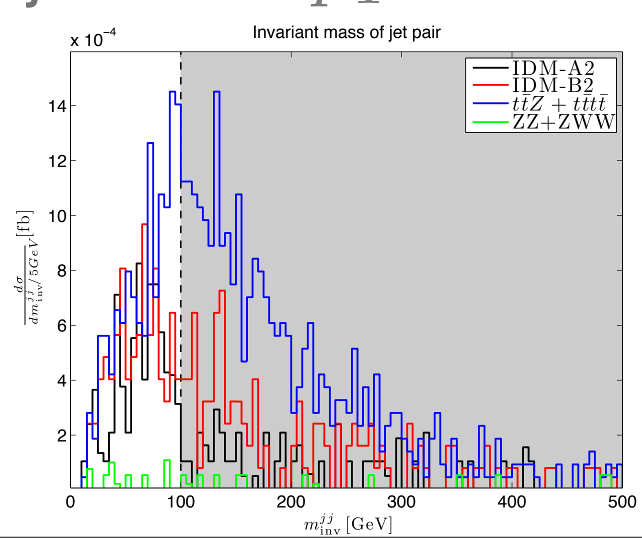
Standard Model background

- ZWW
- ZZ
- $t\bar{t}Z$
- $t\bar{t}t\bar{t}$



Cuts

- 4 (or more) isolated leptons, $p_T^1 > 20$ GeV, $p_T^{2,3,4} > 10$ GeV,
- Missing transverse energy $\not{E}_T > 20$ GeV,
- *Z* veto: no SF-OS lepton pair with invariant mass in the range 75-105 GeV,
- The minimal invariant mass of SF-OS lepton pairs per event < 60 GeV (can be optimized depending on model),
- No more than 2 jets with $p_T > 20$ GeV, and for jet pairs invariant mass <100 GeV.



Results

- Cross-sections in 0.01 fb (number of events after 100/fb).

Proc./Model	$n_l \geq 4$	$\not{E}_T$ cut	Z veto	m_{min}^{l+l-} cut	$n_j \leq 2$	m_{inv}^{jj} cut
ZWW	15	14	1.0	0.5	0.5	0.5
ZZ	2700	33	1.4	1.2	1.2	1.1
$t\bar{t}Z$	130	130	13	9.5	5.8	3.0
$t\bar{t}t\bar{t}$	0.6	0.6	0.5	0.2	0 ($<$ 0.03)	0
Total bkg	2800	180	16	11	7.5	4.6
IDM-A1	4.6	3.9	3.6	3.6	3.3	2.9
IDM-A2	7.8	7.4	6.0	5.9	4.9	4.3
IDM-B1	47	42	40	40	36	33
IDM-B2	13	12	9.8	9.8	8.3	7.0
IDM-C1	0.2	0.1	0.1	0.1	0.1	0.1
IDM-C2	0.2	0.1	0.1	0.1	0.1	0.09

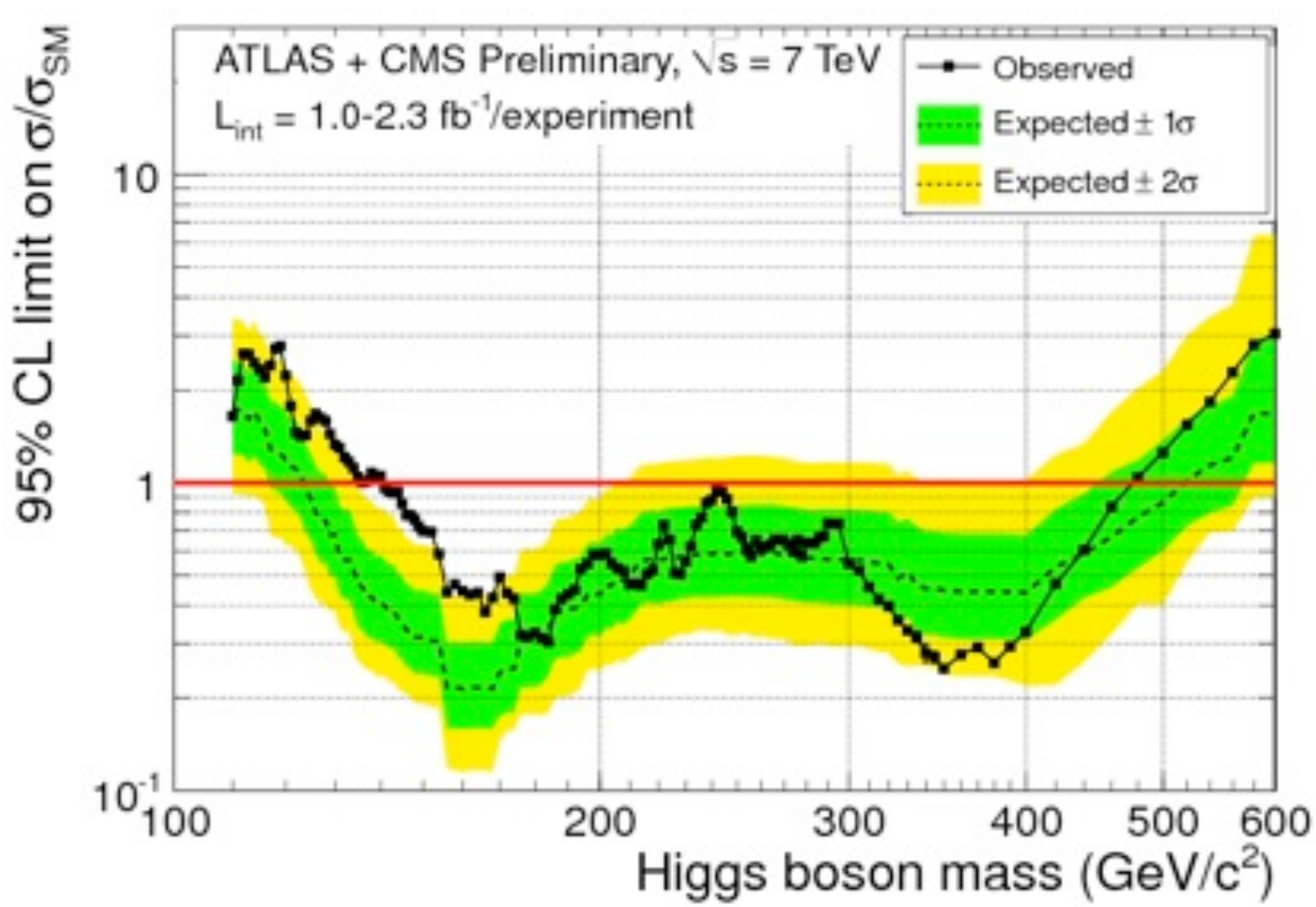
3σ @ 300/fb

15σ @ 100/fb

3σ @ 100/fb
5σ @ 300/fb

Conclusion

- We investigated the prospects for IDM dark matter to show up in the tetralepton + missing energy channel at LHC.
- Discovery channel for IDM with SM-like Higgs mass 250-300 GeV?
- Detection at 300/fb (100/fb) with 500 GeV Higgs possible.



G. Rolandi's talk at HPC 2011, Paris