Production of Inert Scalars at the LHC and the high energy e^+e^- colliders

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Acknowledgements

This presentation is based on the results presented at the conference "Scalars 2015" (December 03-07,2015) by

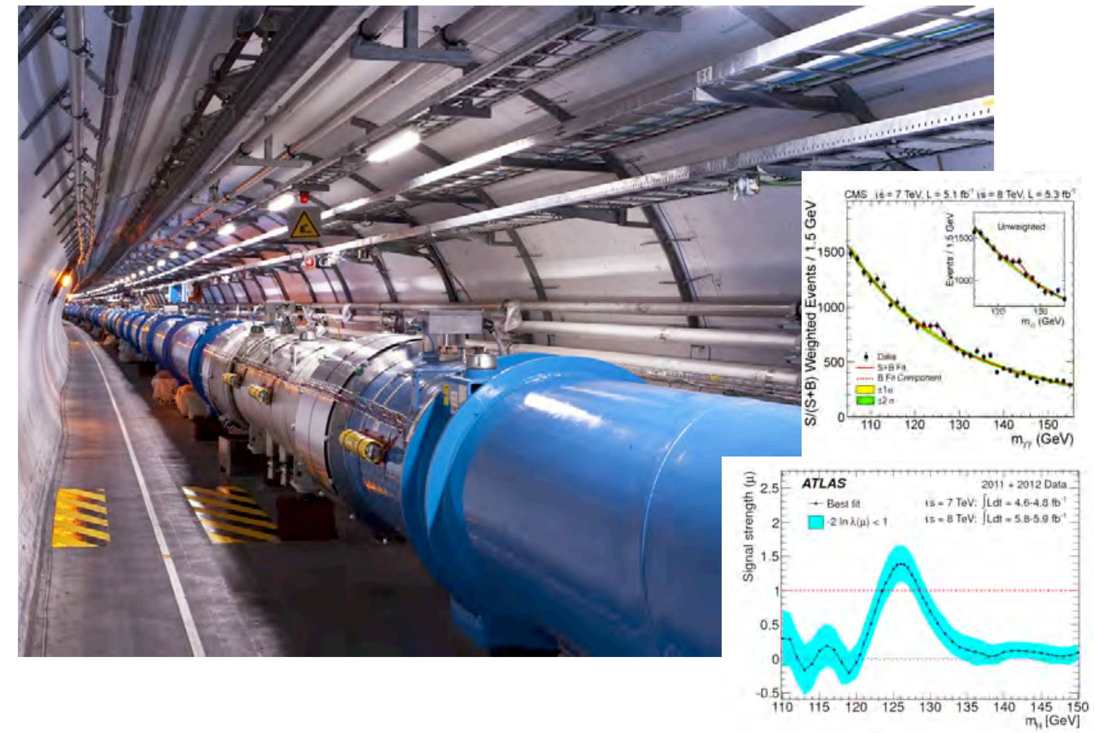
- Sabine Kraml(LPSC Grenoble)
  Recasting LHC searches: the case of the Inert Doublet Model and other examples
  based on work with/of D. Barducci, G. Belanger, S. Bein, G. Chalons, E. Conte, C. Delauney, B. Dumont, B. Fuks, B. Herrmann, A. Goudelis, S. Kulkarni, S. Pandey, S. Sharma, D. Sengupta, C. Wymant
- Tania Robens (IKTP, TU Dresden)
  The Inert Doublet Model in the light of LHC and astrophysical data
  based on work with A. Ilnicka and M. Krawczyk
  arXiv:1505.04734, arXiv:1508.01671, arXiv:1510.04159
- Saereh Najjari (University of Warsaw)
  Production of Inert Scalars at the e^+e^- Linear Colliders
  based on work with Majid Hashemi, Maria Krawczyk and AFŻ
  arXiv:1512.01175

Outline

Introduction

The LHC endeavor

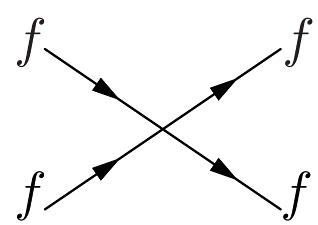
- The LHC was built as a **discovery machine** to explore new physics at the **TeV energy scale**.
- The discovery of a Standard Model (SM)-like **Higgs boson** was a tremendous first success for the LHC physics program.
- However, while the Higgs discovery completes our picture of the SM, it still leaves **many fundamental questions open** (naturalness, hierarchy problem, ...)
- **Run 2** of the LHC just started; the search for new phenomena **beyond the SM (BSM)** is one of its top priorities.
- The BSM theory might also provide the **dark matter** (DM) and generally enhance our understanding of the early Universe.



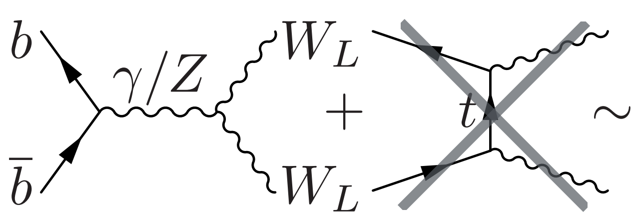
A. Wulzer, EPS-HEP 2015
arXiv:1510.05159

No more no-loose theorem

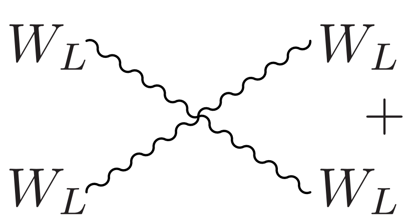
Guaranteed discoveries in the history of HEP (unitarity of scattering amplitudes):



$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \;\Rightarrow\; m_W < 4\pi v$

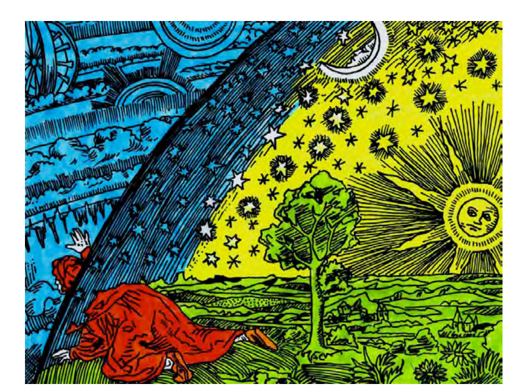


$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \;\Rightarrow\; m_t < 4\pi v$



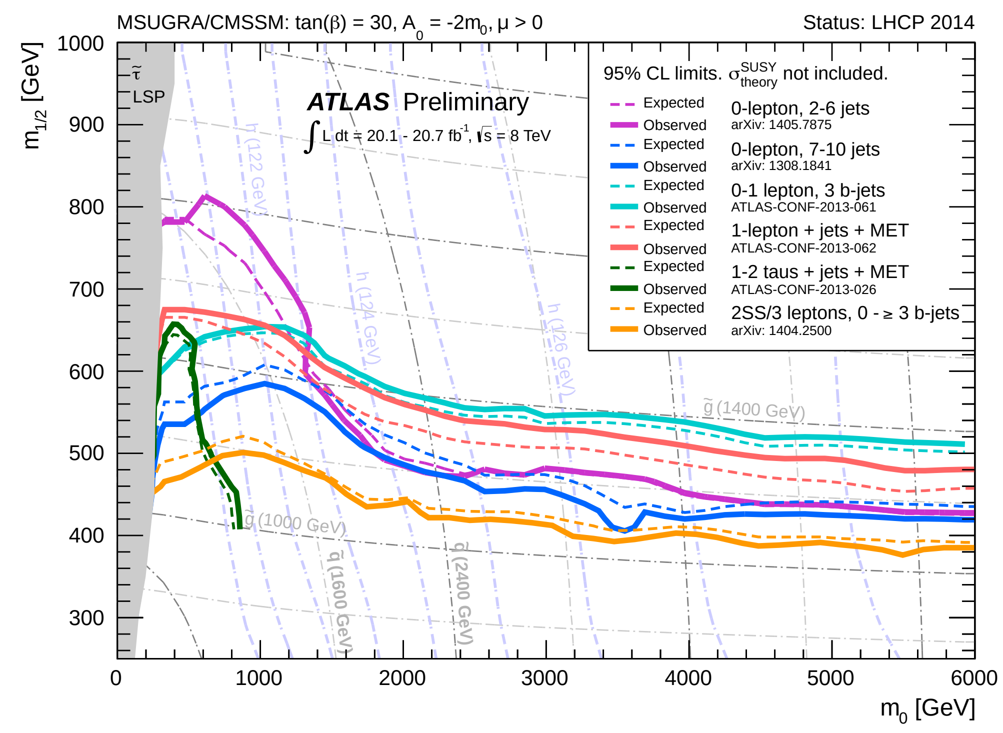
$+\ldots \sim g_W^2 E^2/m_W^2 < 16\pi^2 \;\Rightarrow\; m_H < 4\pi v$ ~3 TeV

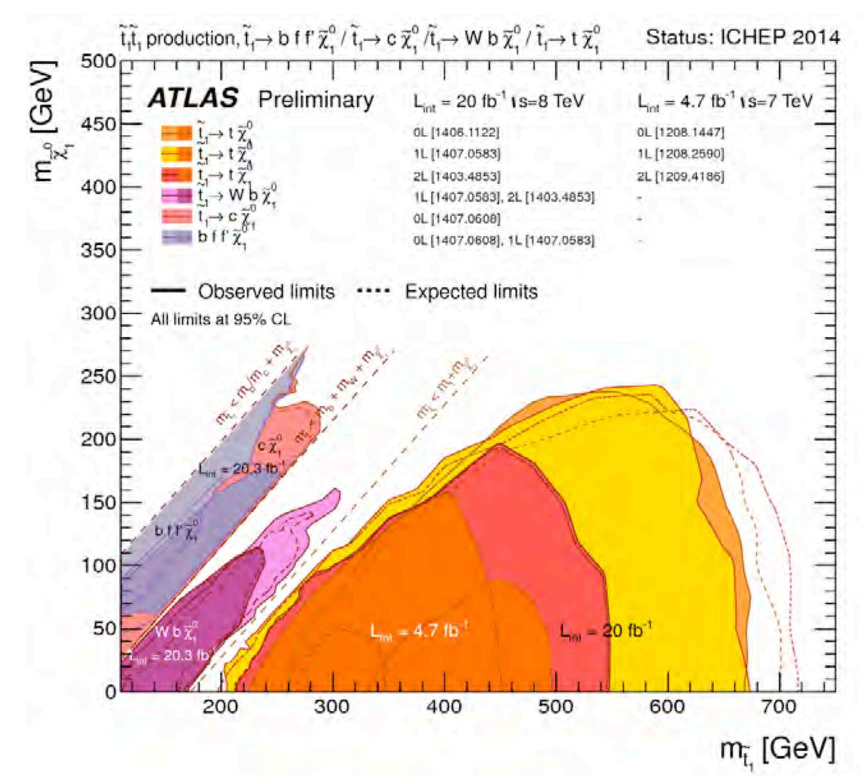
The Higgs discovery completes the SM — and leaves us without any no-loose theorem to exploit for future discoveries.



New physics searches

- ATLAS and CMS perform **searches for new physics in many different channels**.
- In the experimental publications, the **results are** typically **interpreted within popular models** as well as within topology-based “Simplified Model Spectra” (SMS).
- SUSY, VLQ, extra gauge bosons, DM models, other exotics, extra Higgses, etc.
- However, there **exists a plethora of models** and scenarios ....





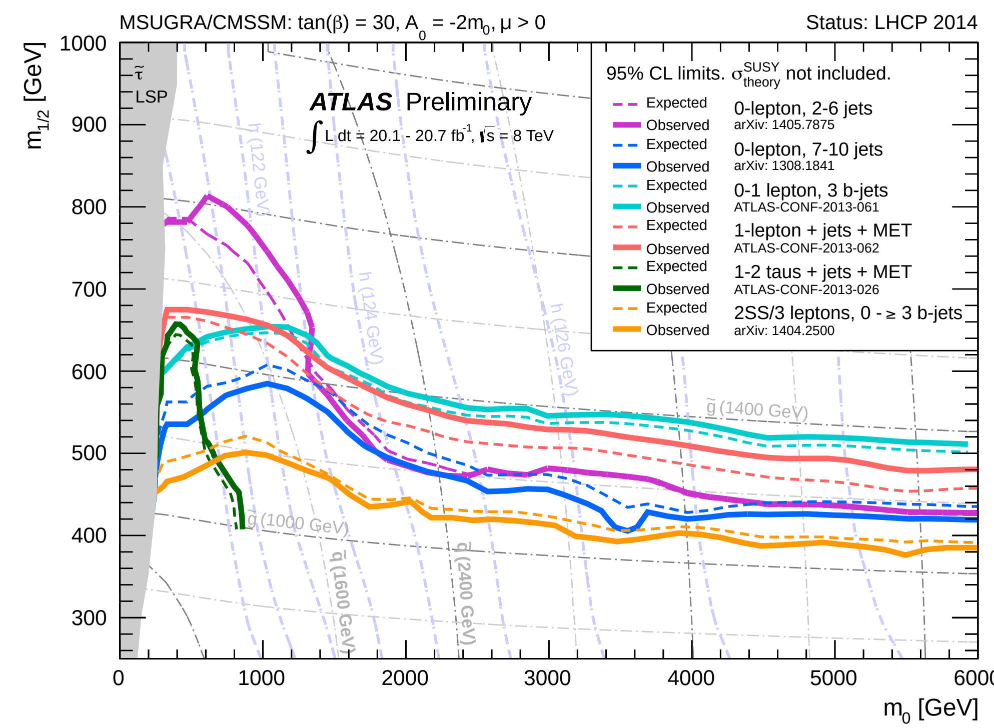
A plethora of searches

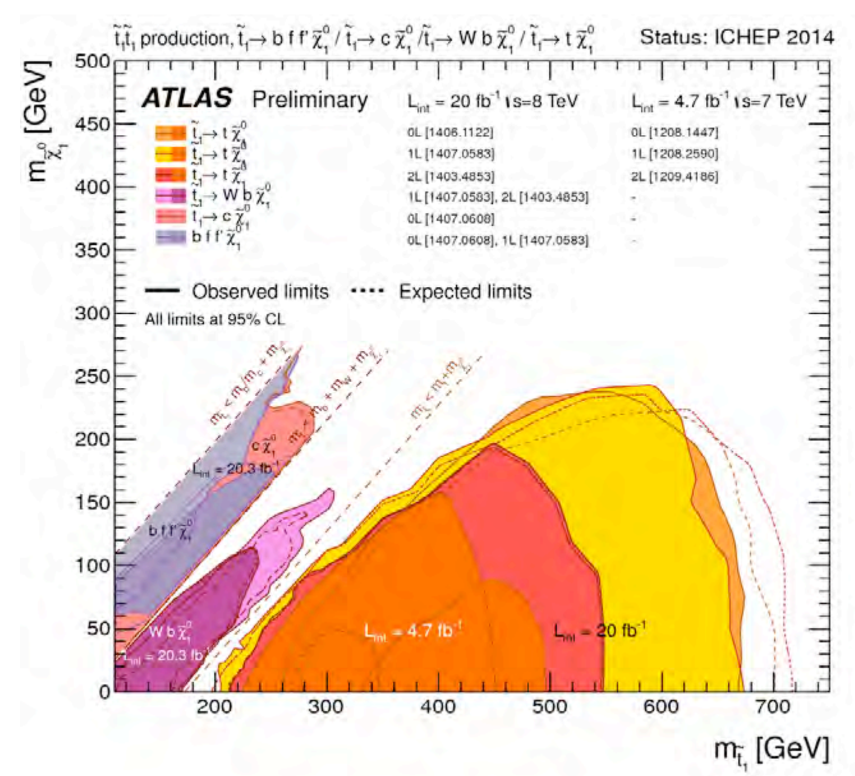
Examples of SUSY and exotics searches from ATLAS and CMS

Displaced vertex [RPV, GMSB, split-SUSY] NEW	Search for third-generation scalar leptoquarks in the top+tau channel NEW
Heavy resonance to eμ, eτ, μτ [RPV-LFV, Z'-LFV] NEW	Search for high mass resonances decaying to Z and Higgs bosons NEW
2 leptons (on/off-Z) + jets + Etmiss [incl. squarks & gluinos, GGM] NEW	Search for physics beyond the standard model in the Dilepton Mass Distribution NEW
Multijets [RPV] NEW	Reinterpretation of HSCP Analysis in the pMSSM and other scenarios NEW
Monojet + Etmiss (gravitino-squark, gravitino-gluino) NEW	Search for Stopped Long-Lived Particles NEW
Chargino neutralino decaying via Higgs NEW	Search for Heavy Majorana Neutrinos with same sign dimuons NEW
1/2 leptons + jets + Etmiss [incl. squarks & gluinos, mUED] NEW	Search for Resonances using the Dijet Mass Spectrum NEW
Search for scalar charm NEW	Search for pair-produced resonances decaying to jet pairs NEW
Top spin correlations (stealth stop)	Search for displaced dilepton pairs NEW
Long-lived particles (sleptons, charginos, R-hadrons)	Search for contact interactions and extra dimensions in dijet angular distributions NEW
Mono-photon + Etmiss [Degenerate squark/neutralino]	Search for new physics with monophotons NEW
Non-pointing, delayed photons [LLP, GMSB]	Search for new physics with monojets NEW
0 leptons + mono-jet/c-jets + Etmiss [Stop in charm+LSP]	Search for Dark Matter, extra-dimensions, W' and contact interactions in lepton+MET final states NEW
1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop]	Search for long-lived neutral particles decaying to dijets
1-2 taus + 0-1 leptons + jets + Etmiss [GMSB]	Search for disappearing tracks
0-1 leptons + >=3 b-jets + Etmiss [3rd gen. squarks]	
2 taus + Etmiss [EW production]	
Stop constraints from precise ttbar cross-section [Light stop]	
0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop]	
0 leptons + 2-6 jets + Etmiss [Incl. squarks & gluinos]	
4 leptons + Etmiss [EW production, RPV]	
2 same-sign / 3 -leptons + 0-3 b-jets + Etmiss [Incl. squarks & gluinos]	

A plethora of searches
Need for interpretation studies

- ATLAS and CMS perform **searches** for new physics **in many different channels.**
- They also provide **interpretations** of their results within **constrained models**, like the CMSSM, or within topology-based **"Simplified Model Spectra"** (SMSs).
- However, there **exists a plethora of** different **BSM models and scenarios**
- Need to interpret LHC results in the contexts of all kinds of models of new physics
  - important for deriving the current limits on them, and for finding existing loopholes;
  - crucial once there is a discovery, if we are to unravel the correct theory and determine its parameters.





Inert Doublet Model

Michael Tytgat, Bogumila Swiezewska,
Tania Robens, Saereh Najjari

The Inert Doublet Model

- In the IDM, the SM is extended by the addition of a **second scalar, Φ,** transforming as a doublet under $SU(2)_L$. This Φ is **odd under a new discrete Z_2 symmetry**.

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

- **Scalar potential**

$$V_0 = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \text{h.c.}\right].$$

$$m_h^2 = \mu_1^2 + 3\lambda_1 v^2$$
$$m_{H^0}^2 = \mu_2^2 + \lambda_L v^2$$
$$m_{A^0}^2 = \mu_2^2 + \lambda_S v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$$\lambda_{L,S} = \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)$$

The Z_2 symmetry forbids mixing among the components of H and Φ and renders the lightest Z_2-odd particle stable.
→ H^0 or A^0 can play the role of a **DM candidate**.

NB: all fermions couple to H, i.e. **2HDM Type-I** Yukawa couplings

Number of free parameters

$\Rightarrow$ then, **go through standard procedure...**

$\Rightarrow$ minimize potential

$\Rightarrow$ determine number of free parameters

Number of free parameters here: 7

- e.g.

$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{\mathbf{345}}\ [=\ \lambda_3 + \lambda_4 + \lambda_5]$$

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**

Very brief: parameters determining couplings (production and decay)

dominant production modes: through Z; Z, γ, h for AH; H^+H^-

important couplings:

- $Z\,H\,A$: $\sim\ \frac{e}{s_W\,c_w}$
- $Z\,H^+\,H^-$: $\sim\ e\ \coth\left(2\,\theta_w\right)$
- $\gamma\,H^+\,H^-$: $\sim\ e$
- $h\,H^+\,H^-$: $\lambda_3\,v$
- $H^+\,W^+\,H$: $\sim\ \frac{e}{s_w}$
- $H^+\,W^+\,A$: $\sim\ \frac{e}{s_w}$

!! mainly determined by electroweak SM parameters !!

Benchmark planes

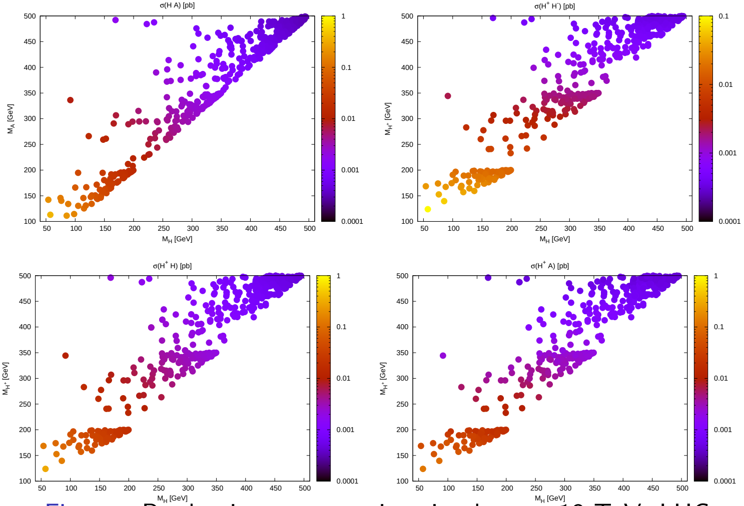
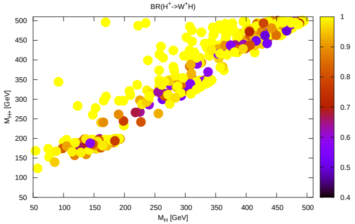


Figure : Production cross sections in pb at a 13 TeV LHC

Aside: typical BRs

- decay $A \rightarrow H\,Z$ always 100 %
- decay $H^{\pm} \rightarrow H\,W^{\pm}$



second channel $H^{\pm} \rightarrow A\,W^{\pm}$

$\Longrightarrow$ **collider signature: SM particles and MET** $\Longleftarrow$

Constraints: Theory

$\Longrightarrow$ **consider all current constraints on the model** $\Longleftarrow$

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
  $\Rightarrow$ **limits on (relations of) couplings**, e.g.

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0,\ \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0$$

- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter:

$$M_H \leq M_A,\ M_{H^\pm}$$

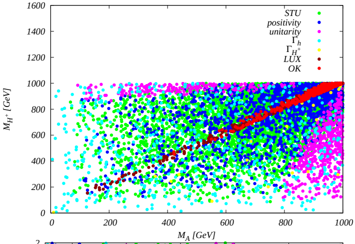
Constraints: Experiment

$$M_h = 125.1\,\mathrm{GeV},\ v = 246\,\mathrm{GeV}$$

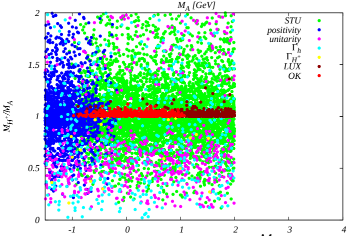
- total width of M_h
- total width of W, Z
- collider constraints from signal strength/ direct searches
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (LUX)

$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

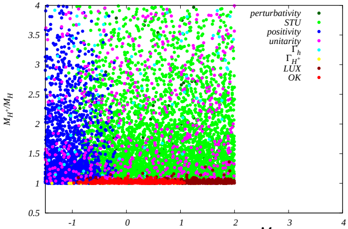
Other constraints less obvious (interplay); result ⇒ mass degeneracies



M_A vs $M_{H\pm}$ after all constraints



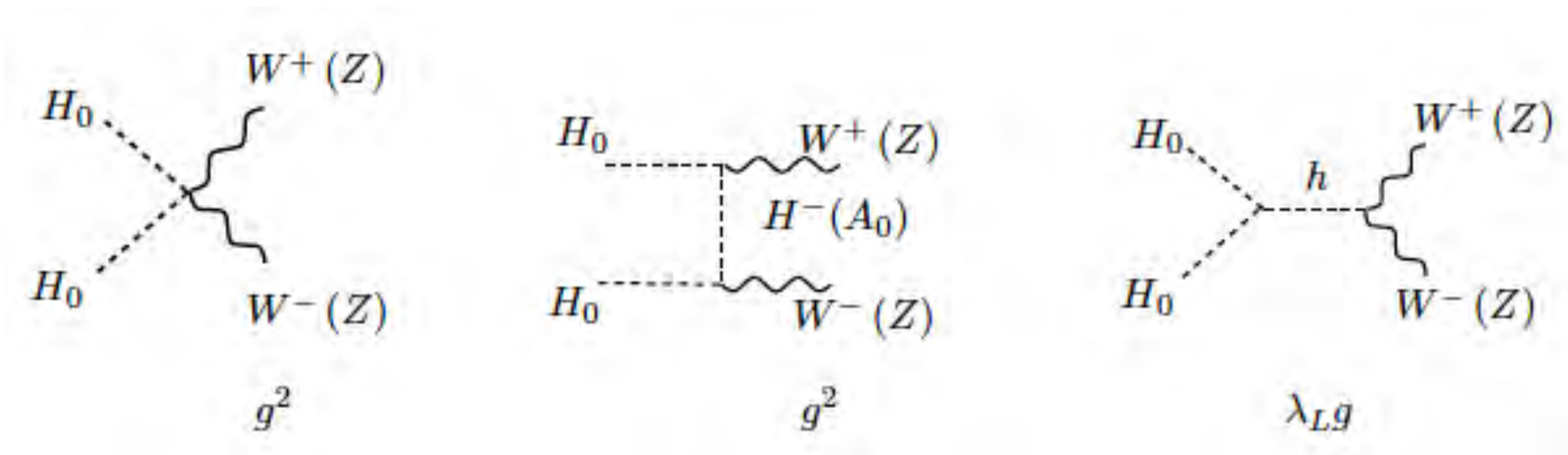
λ_{345} vs $\frac{M_{H\pm}}{M_A}$



λ_{345} vs $\frac{M_{H\pm}}{M_H}$

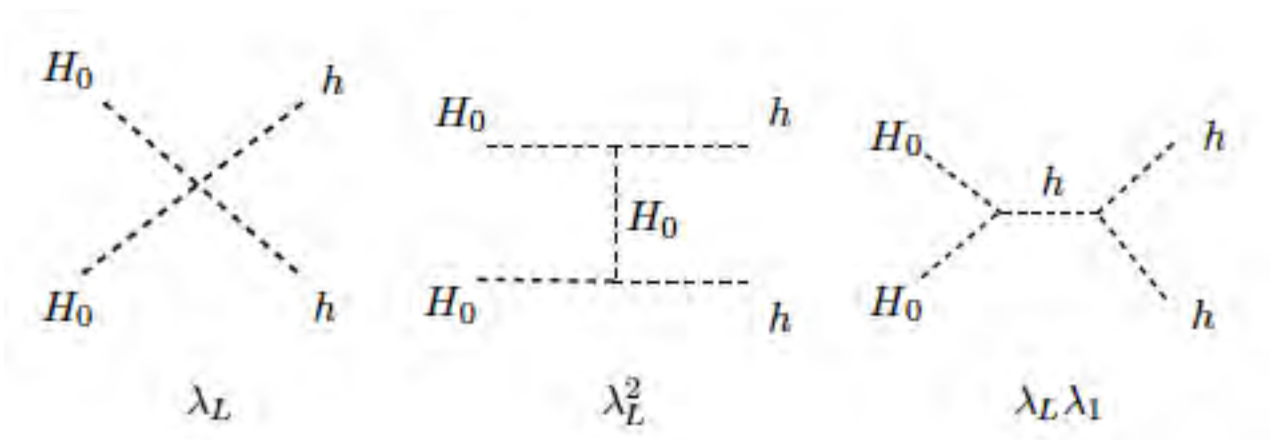
DM annihilation channels

(taking H^0 as the DM candidate)

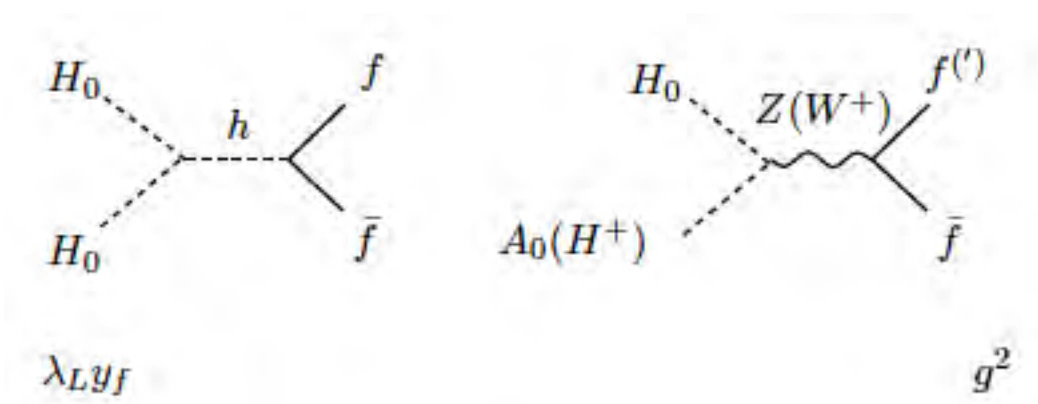


annihilation into gauge bosons

$$\lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$



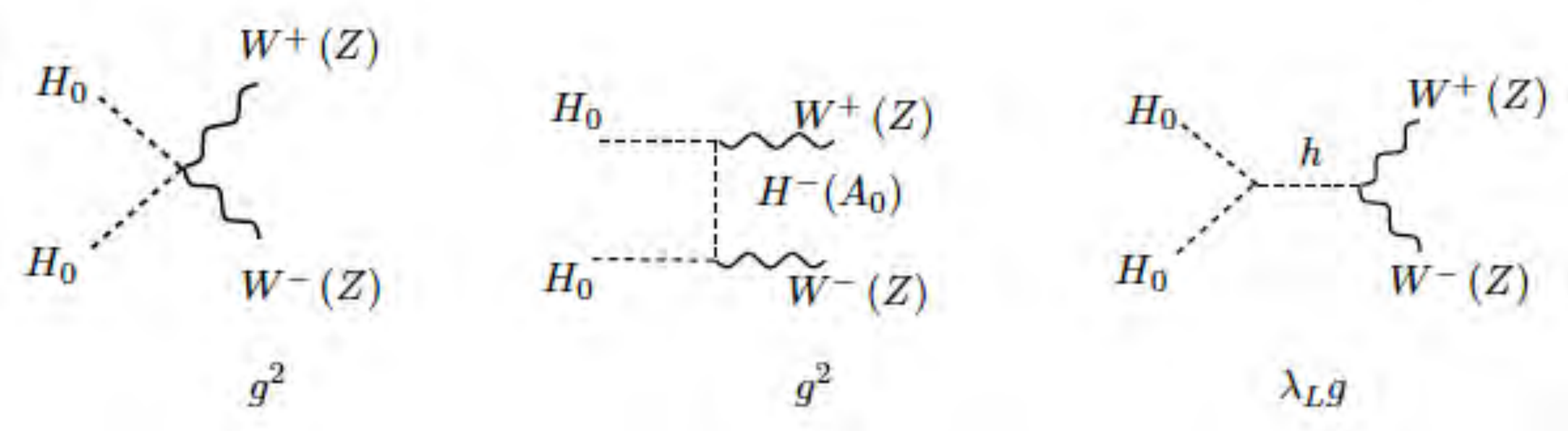
annihilation into Higgs



annihilation into fermions

DM annihilation channels

(taking H^0 as the DM candidate)



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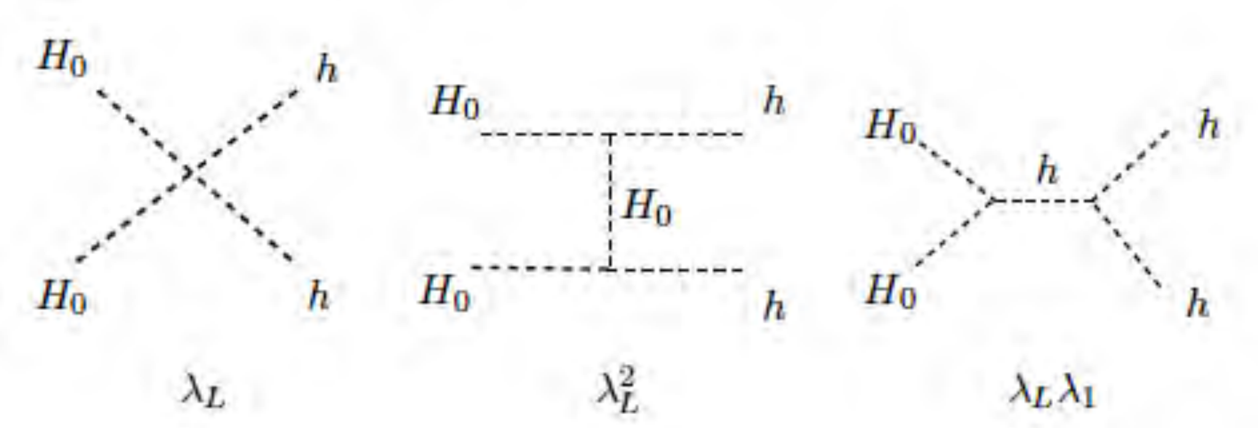
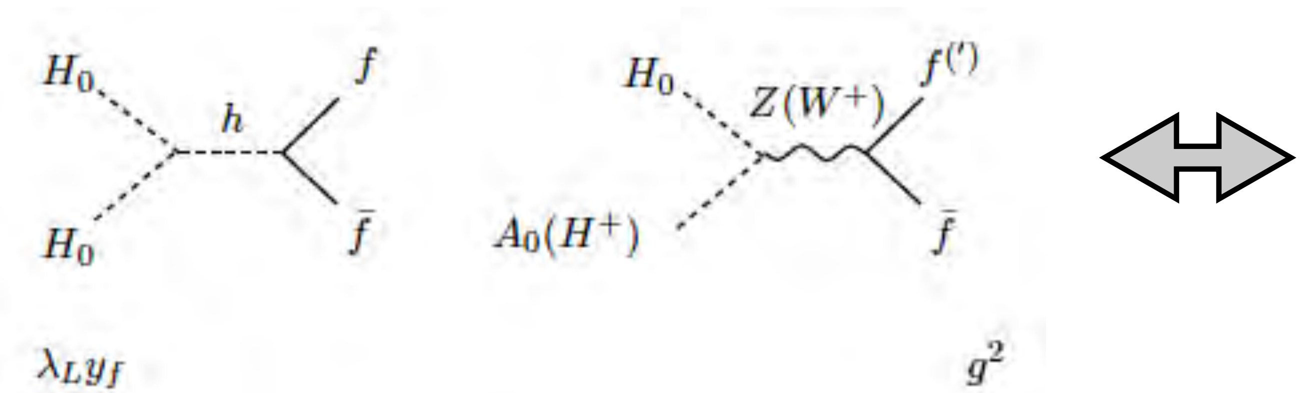
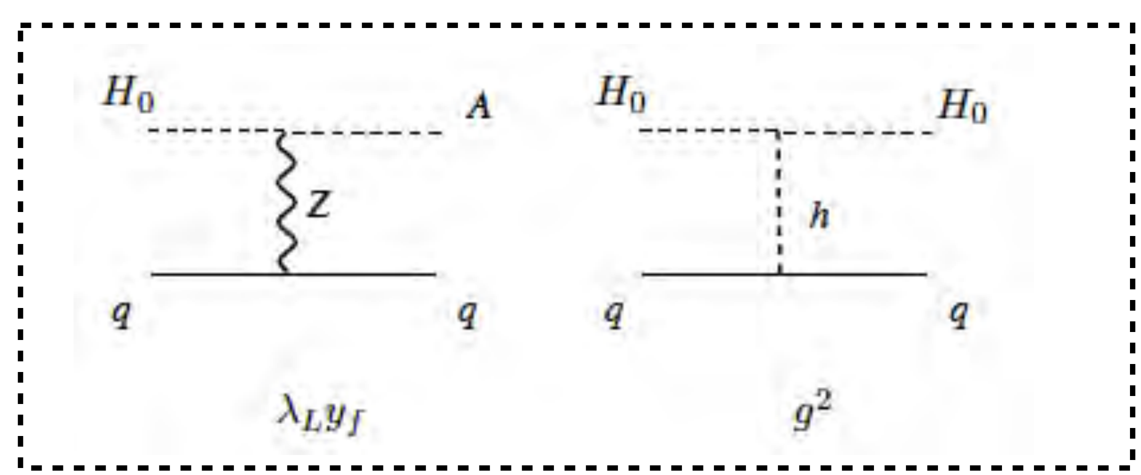


annihilation into Higgs



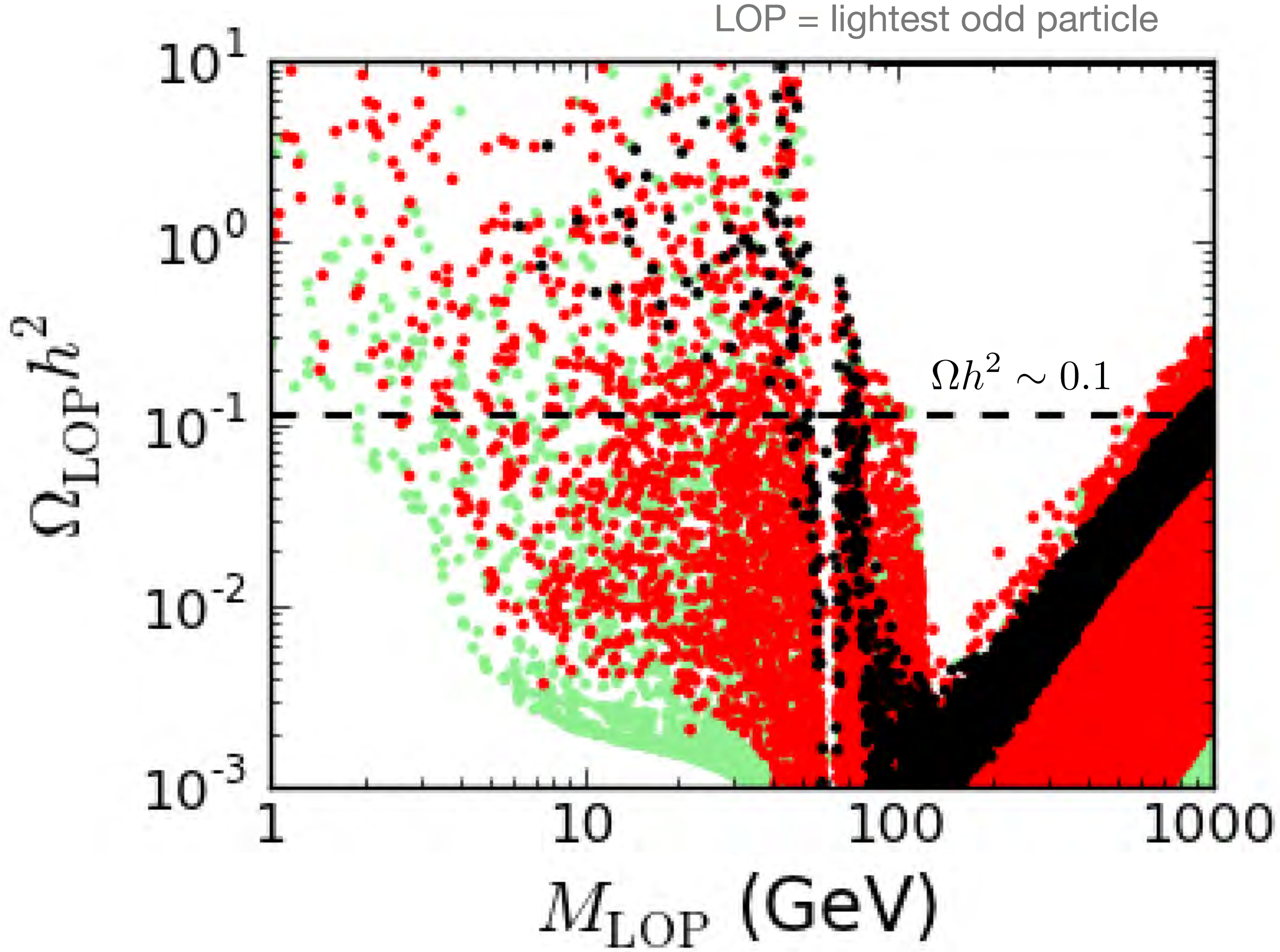
Direct DM detection



Constraints on the model

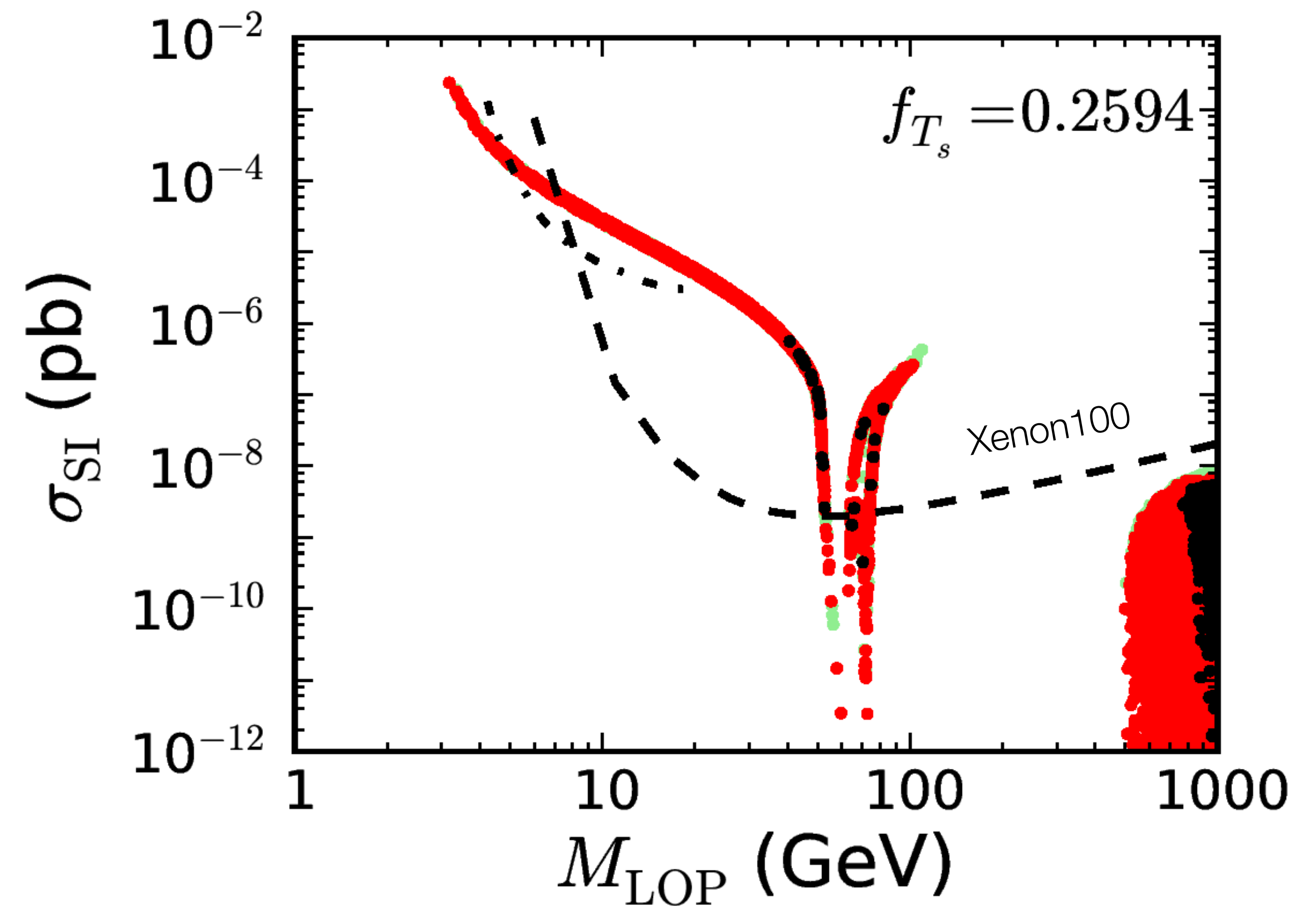
- **Relic density** (vanilla picture of thermal DM)

LOP = lightest odd particle



green: points valid at the input scale Λ = MZ,
red: points which remain valid up to Λ = 10 TeV,
black: points valid up to the GUT scale of 10^{16} GeV

- **Direct DM** searches eliminate $m_{H0} < 115$ GeV
DM region apart from $m_{H0} \sim m_h/2$



[Goudelis, Herrmann, Stal, 1303.3010]

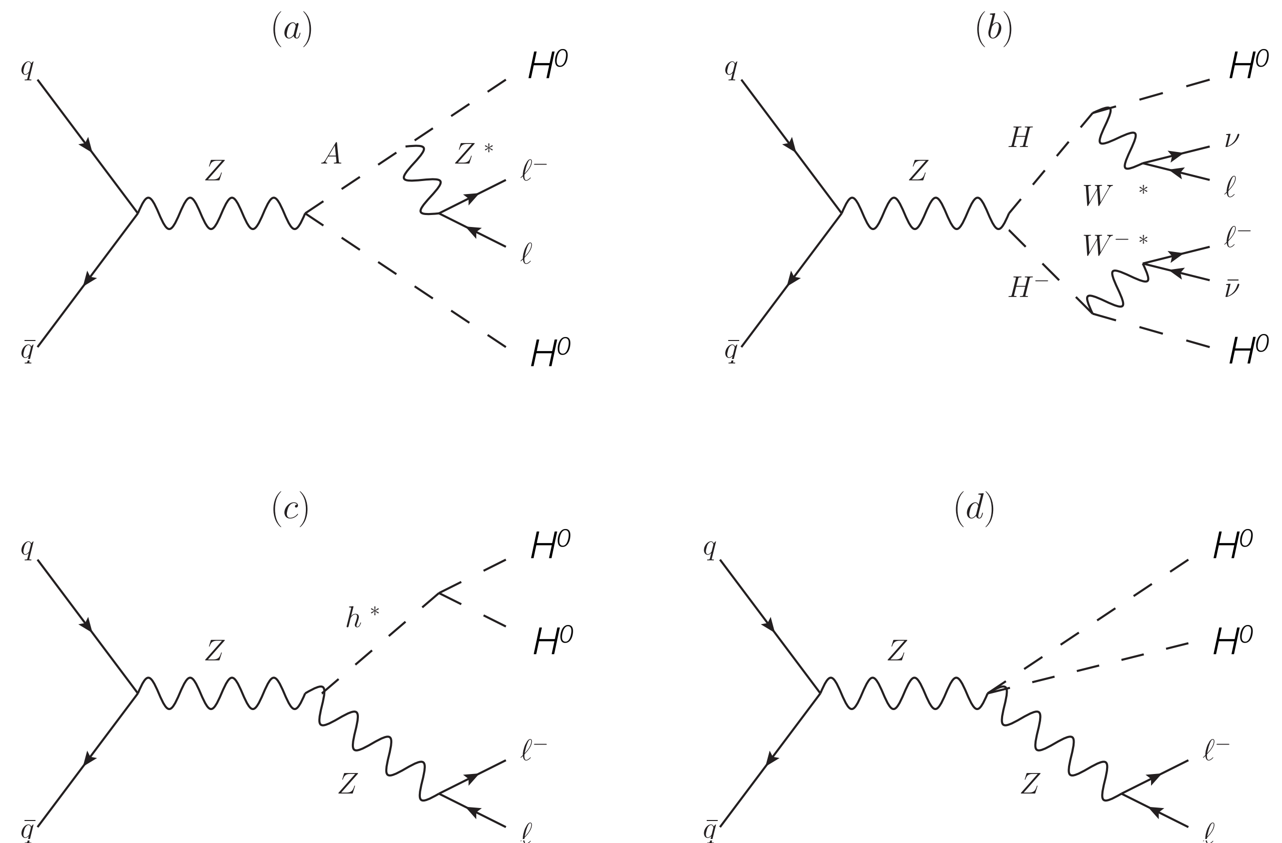
Most recent update: **A. Ilnicka, M. Krawczyk, T. Robens, 1508.01671**

IDM @ LHC

LHC signatures (assuming $m_{H^0} < m_{A^0}$)

- At the LHC, inert scalars can be pair-produced via virtual Z or W exchange (H^+H^- also via γ)
- The unstable A^0 or $H^\pm$ then decay into the H^0 plus a Z or W
- Most promising signatures: SF or DF dileptons l^+l^- + E_T^{miss} (same flavor or different flavor)

E. Dolle et al., arXiv:0909.0394



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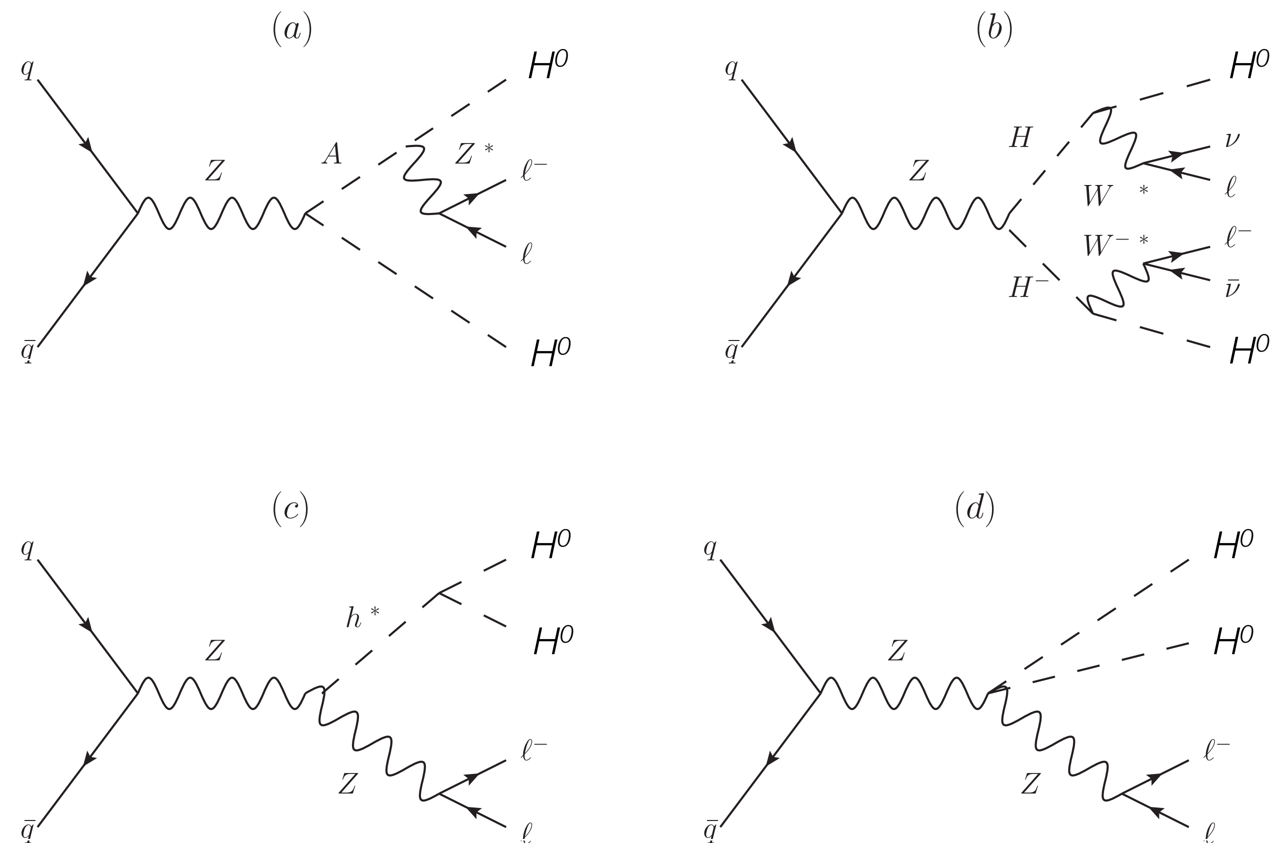

- Both ATLAS + CMS have searched for opposite-sign dileptons + E_T^{miss} at Run 1.
  While no interpretation was given for the IDM, note that
  - the **SUSY equivalent of process *(a)*** is $q\bar{q} \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ with $\tilde{\chi}_2^0 \to Z^{(*)}\tilde{\chi}_1^0$
  - **process *(b)*** resembles the signature of chargino-pair production $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$
  - **process *(c)*** is Zh production with h→inv.; (also *(a)* can look like Zh, h→inv.)
  - processes *(c)* and *(d)* are negligible, contribution from *(b)* is small.

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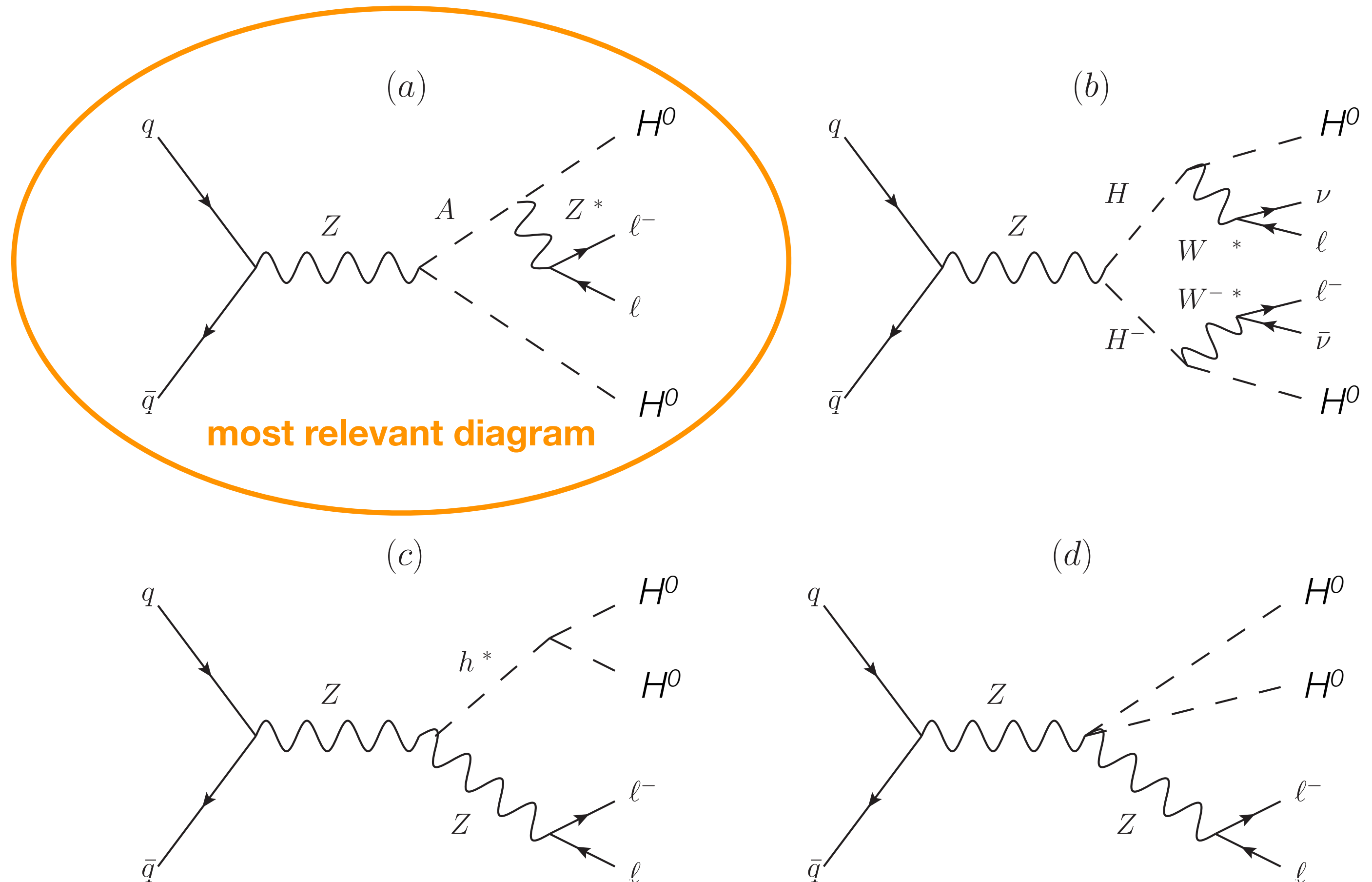

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arXiv:1503.07367

Recasting l^+l^- + E_T^{miss} analyses for the IDM

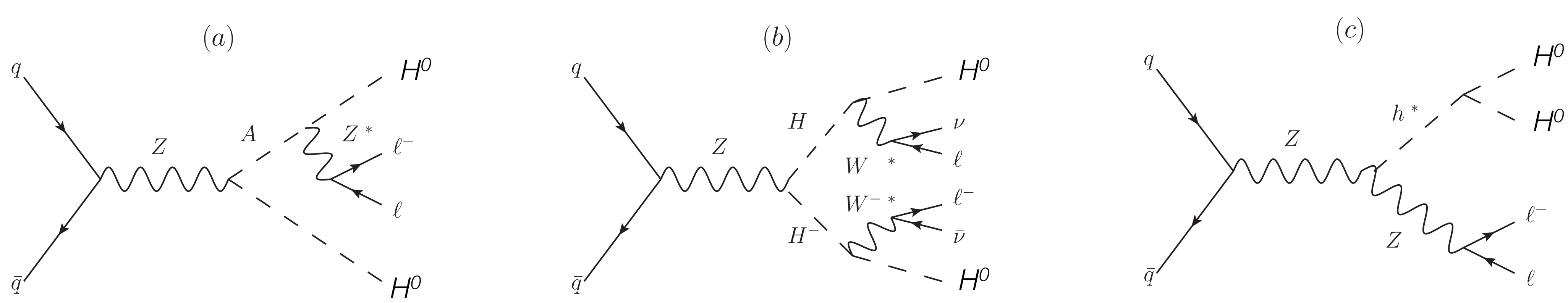
- **Implemented 2 ATLAS dilepton analyses** in the MA5 PAD
  (PAD = Public Analysis Database)

  - **SUSY-2013-11: Chargino, neutralino and slepton search** **[arXiv:1403.5294]**

    Various signal regions optimized for chargino, neutralino, slepton signals or mass regions; all leptonic signal regions regions require $|m_{ll} - m_Z| > 10$ GeV, i.e. on-shell Z bosons are vetoed; mostly relevant for $m_A < m_H + m_Z$

  - **HIGG-2013-03: ZH → l^+l^- + inv. search** **[arXiv:1402.3244]**

    Requires $|m_{ll} - m_Z| < 15$ GeV ; can be matched onto processes (c) and (d), and for $m_{A0} - m_{H0} > m_Z$ also onto (a); relevant for $m_A > m_H + m_Z$



ATLAS-HIGG-2013-03

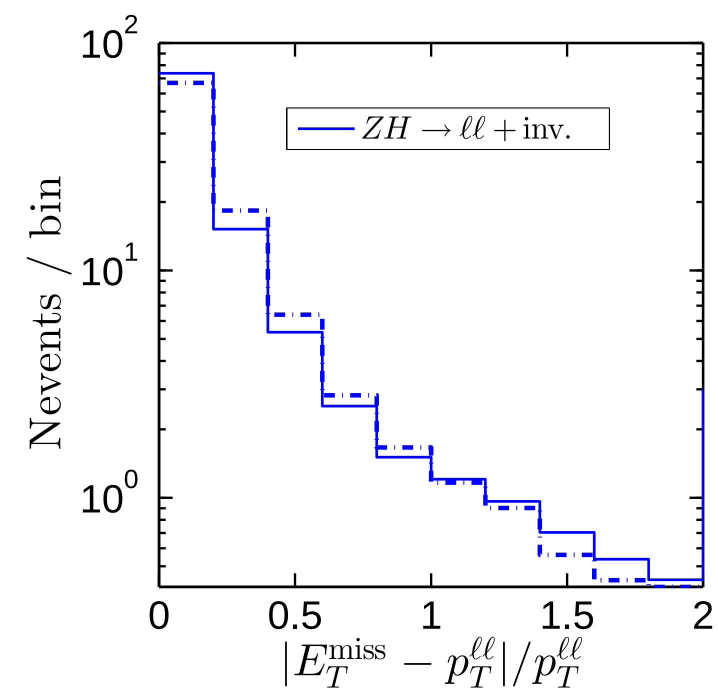
[arXiv:1402.3244]

- ATLAS search for invisible decays of the Higgs boson in the 2 lepton + MET final state

- only one SR, where it is required:
  - $|m_{\ell\ell} - m_{Z^0}| < 15$ GeV
  - $E_T^{\text{miss}} > 90$ GeV
  - $\Delta\phi(p_T^{\ell\ell}, E_T^{\text{miss}}) > 2.6$
  - $\Delta\phi(\ell, \ell) < 1.7$
  - $|E_T^{\text{miss}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$
  - no jet
  - $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 0.2$ (avoid fake MET from misreconstructed energy in the calorimeter)

- validation results include:

cut	ATLAS result	MA5 result
Initial number of events		838.9
2 OS leptons		256.2
$\|m_{\ell\ell} - m_{Z^0}\| < 15$ GeV	243	244.1
$E_T^{\text{miss}} > 90$ GeV	103	105.1
$\Delta\phi(p_T^{\ell\ell}, E_T^{\text{miss}}) > 2.6$		91.7
$\Delta\phi(\ell, \ell) < 1.7$		82.9
$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 0.2$		76.5
$\|E_T^{\text{miss}} - p_T^{\ell\ell}\|/p_T^{\ell\ell} < 0.2$		63.2
jet veto	$44 \pm 1 \pm 3$	54.8



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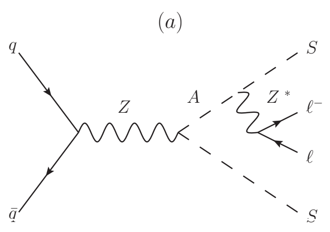


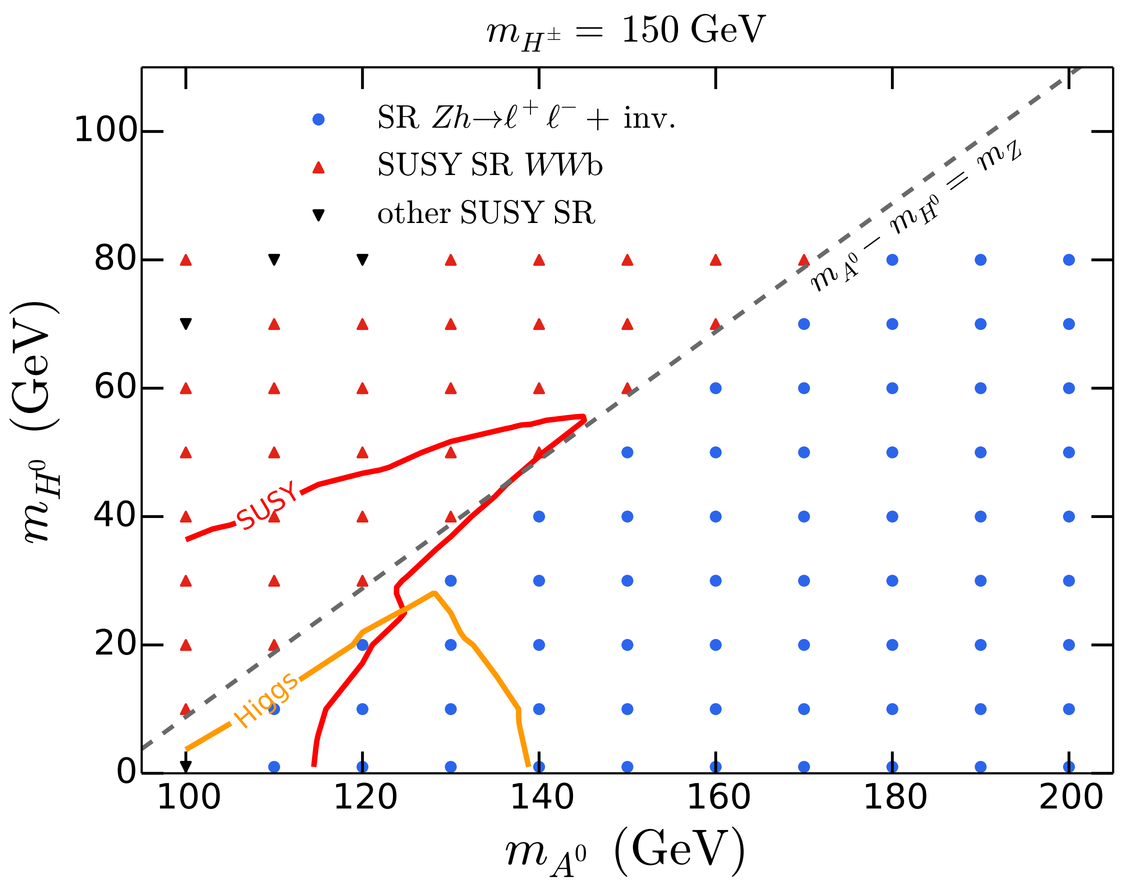
- The MadAnalysis 5 codes and detailed validation notes are **publicly available**

  10.7484/INSPIREHEP.DATA.HLMR.T56W.2
  10.7484/INSPIREHEP.DATA.RT3V.9PJK

- **Simulated signal in (m_{H0}, m_{A0}) plane** for fixed $m_{H\pm}$ and $\lambda_L = 0$

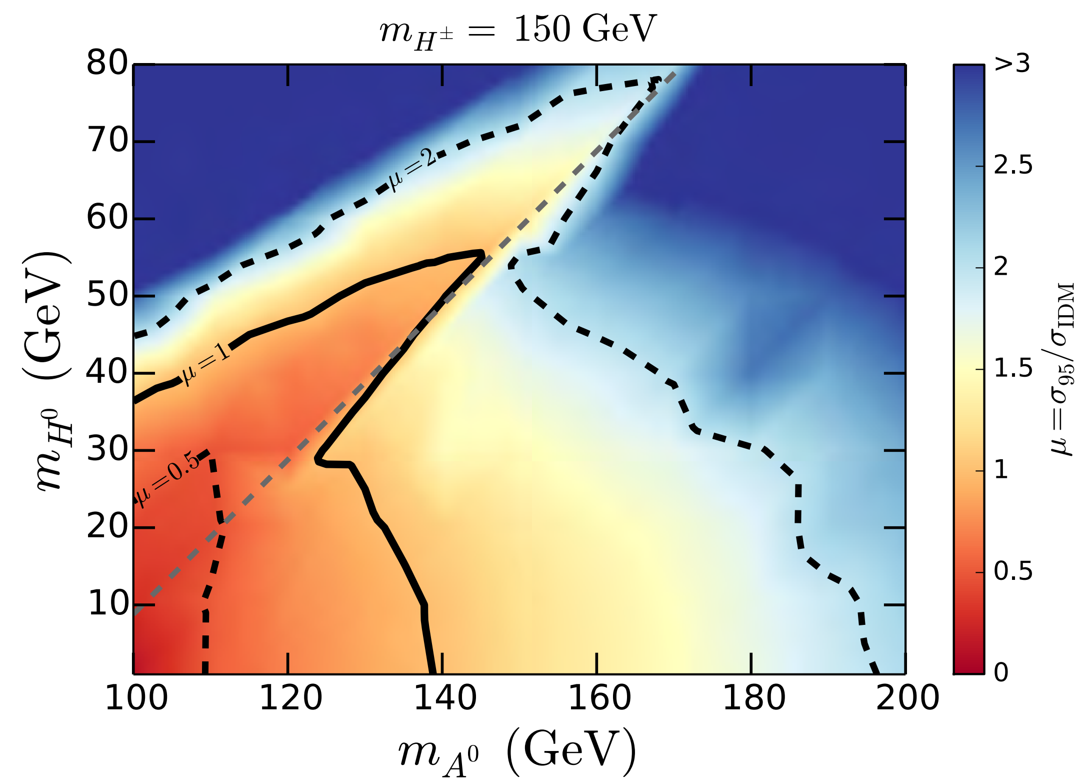
  MadGraph5 + Feynrules + CalcHEP + Delphes3 + MadAnalysis5

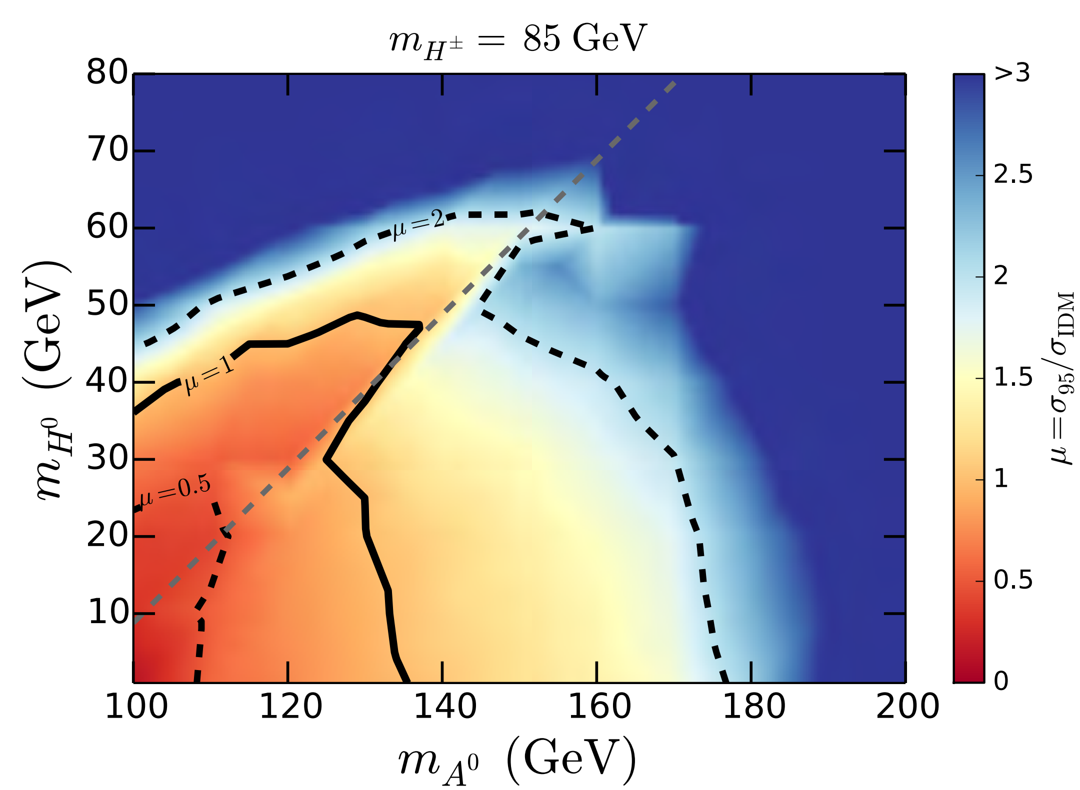
- Background numbers taken from the experimental papers to compute CLs



Comments

- The Run 1 ATLAS searches exclude, at 95% CL, $m_{H0} < 35$ GeV for $m_{A0} \approx 100$ GeV.
- The limit becomes stronger for heavier A^0, up to $m_{H0} \approx$ 45-55 GeV for $m_{A0} \approx$ 140-145 GeV (depending on $m_{H\pm}$)
- The m_{A0} dependence comes from the fact that the leptons from $A^0 \to ZH^0$, $Z \to l^+l^-$ are harder for heavier A^0.
  (and softer for lighter A^0 / smaller mass differences)
- $m_{H\pm}$ dependence: Xsection is larger for lighter $H^\pm$, but decay leptons are very soft and don't pass the signal selection cuts. Also, $A^0 \to WH^\pm$ competes with $A^0 \to ZH^0$, when kinematically allowed, reducing the signal.

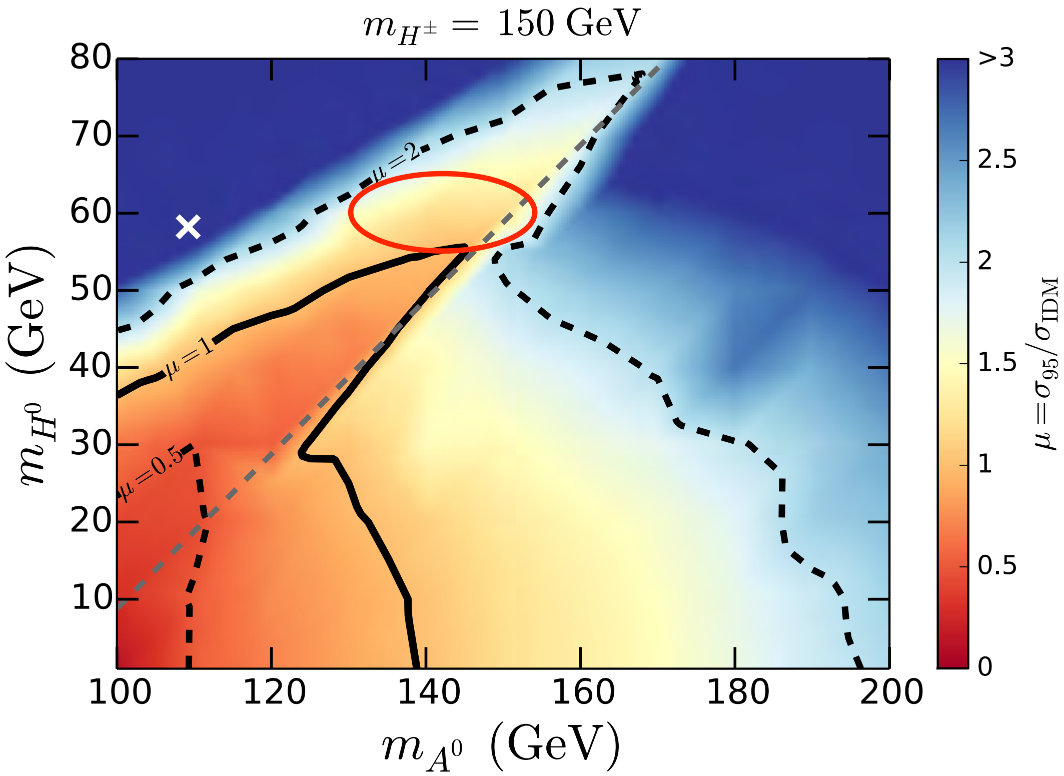




Outlook for Run 2

- Naive rescaling of signal and BG numbers: at 13 TeV and L=100 fb^{-1} the 95% CL reach should go up to **$\mu \approx$ 1.2 (1.6)** above (below) the line of $m_A = m_H + m_Z$

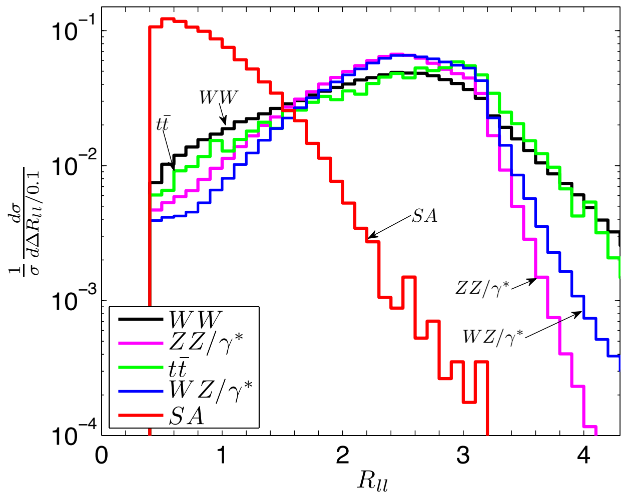
  → starts testing the funnel region $m_H \sim m_h/2$



- Exploration of benchmark points in 1508:0167 seems difficult → high luminosity option?

  Take point I with m_H = 57.5 GeV and m_A = 113 GeV: σ(pp→HA) = 371 fb but incl. BR(Z→ll)~7% and a cut acceptance of ~1% this reduces to ~0.25 fb visible XS

- The experimental analyses we recasted are not optimized for the IDM signal



Could improve sensitivity by exploiting angular separation of signal and backgrounds (cf. Dolle et al., 0909.0394)

Perhaps exploit m_{ll} inv. mass distribution?

→ Dedicated analysis at Run 2 would be highly interesting

Benchmarks submitted to Higgs Cross Section Working Group

all benchmarks: $A \to Z\,H = 100\,\%$

- **Benchmark I: low scalar mass**

$$M_H = 57.5\,\text{GeV},\; M_A = 113.0\,\text{GeV},\, M_{H^\pm} = 123\,\text{GeV}$$

$HA : 0.371(4)\text{pb},\; H^+\,H^- : 0.097(1)\text{pb}$

- **Benchmark II: low scalar mass**

$$M_H = 85.5\,\text{GeV},\; M_A = 111.0\,\text{GeV},\, M_{H^\pm} = 140,\;\text{GeV}$$

$HA : 0.226(2)\text{pb},\, H^+ H^- : 0.0605(9)\text{pb}$

- **Benchmark III: intermediate scalar mass**

$$M_H = 128.0\,\text{GeV},\; M_A = 134.0\,\text{GeV},\, M_{H^\pm} = 176.0,\;\text{GeV}$$

$H\,A : 0.0765(7)\text{pb},\; H^+\,H^- : 0.0259(3)\text{pb};$

Benchmark: high masses

- **Benchmark IV: high scalar mass, mass degeneracy**

$$M_H = 363.0\,\mathrm{GeV},\, M_A = 374.0\,\mathrm{GeV},\, M_{H^\pm} = 374.0\,\mathrm{GeV}$$

$$H, A : 0.00122(1)\mathrm{pb},\;\; H^+H^- : 0.00124(1)\mathrm{pb}$$

- **Benchmark V: high scalar mass, no mass degeneracy**

$$M_H = 311.0\,\mathrm{GeV},\, M_A = 415.0\,\mathrm{GeV},\, M_{H^\pm} = 447.0\,\mathrm{GeV}$$

$$H, A : 0.00129(1)\mathrm{pb},\;\; H^+H^- : 0.000553(7)\mathrm{pb}$$

Parameters tested at LHC: masses

- **LHC@13 TeV** **does not depend on λ_2, only marginally on λ_{345}**
- all **relevant couplings follow from ew parameters (+ derivative couplings)** $\Rightarrow$ in the end a kinematic test
- only in expectional cases λ_{345} important; did not find such points

$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

(holds for $M_H \geq \frac{M_h}{2}$)

IDM @ high energy e^+e^- colliders

Benchmark Points

BP	m_H	m_A	$m_{H^\pm}$
$BP1$	57.5	113.0	123
$BP2$	85.5	111.0	140
$BP3$	128.0	134.0	176.0

Benchmark Points: Ilnicka, Krawczyk and Robens 2015

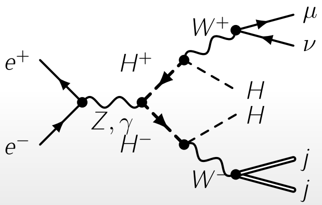
We analyse the following decay processes:

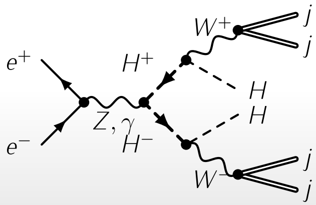
- $e^+e^- \rightarrow H^+H^- \rightarrow W^+W^-HH \rightarrow \mu\nu jjHH, jjjjHH$
- $e^+e^- \rightarrow HA \rightarrow HHZ \rightarrow HH\mu\mu, HHjj$

$e^+e^- \to H^+H^-$

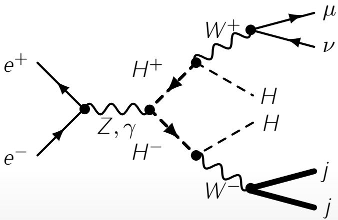
Signal and background cross sections

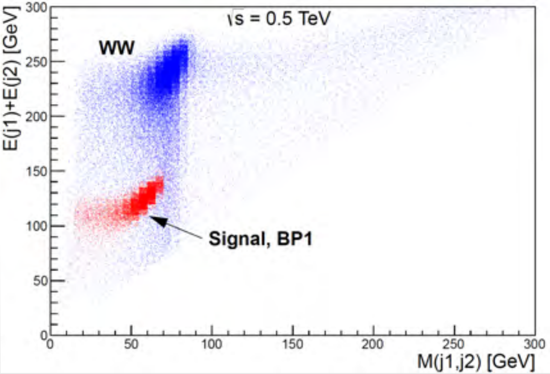
Process	Signal			Background			
	BP1	BP2	BP3	WW	ZZ	Z+jets	$t\bar{t}$
σ [fb] @ 500 GeV	164.4	141.8	89.2	7807	583	16790	595
σ [fb] @ 1 TeV	56.2	54.6	50.6	3180	233	4304	212





Correlation between the sum of energies of two jets and their invariant mass





Decay kinematics

Consider pair production of charged scalars

$$e^+e^- \to H^+H^-$$

- the energies of the charged scalars are given by the beam energy
- their Lorentz boost factor is uniquely defined by their mass

$$\gamma = E_{beam}/M_{H^\pm}$$

Charged scalars decay to dark matter scalar and virtual $W^\pm$

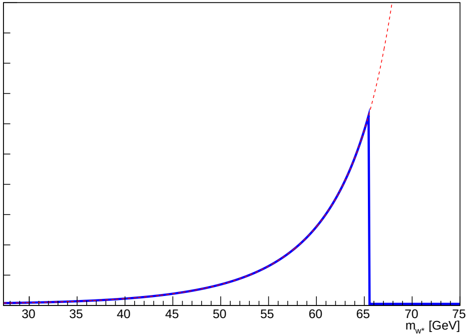
$$H^\pm \to H\ W^\pm$$

For all considered benchmark scenarios, the scalar mass difference

$$m_{H^\pm} - m_H \ll m_W$$

$\Rightarrow$ produced $W^\pm$ are always virtual ($W^\star$)

Truncated Breit-Wigner distribution for $m_{W^\star}$



Most likely is the $W^\star$ production with the maximum virtuality

$$m_{W^\star} \approx m_{H^\pm} - m_H$$

$\Rightarrow$ expect a peak in the two jet invariant mass distribution

The Lorentz boost of $W^\star$ is unknown, but if it is produced with the highest possible virtuality, it is almost at rest in the $H^\pm$ frame
$\Rightarrow$ we can use $H^\pm$ Lorentz boost factor to transform jet energies

In the $W^\star/H^\pm$ rest frame:

$$E^\star_{j_1} = E^\star_{j_2} = \frac{1}{2}\, m_{W^\star} \approx \frac{1}{2}\,(m_{H^\pm} - m_H)$$

In the laboratory frame:

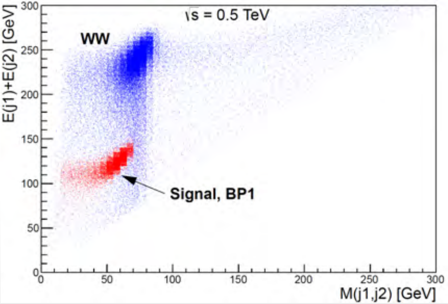
$$E_{j_{1,2}} = \gamma\ \left(E^\star_j \pm \beta p^\star_j \cos\theta^\star\right)$$

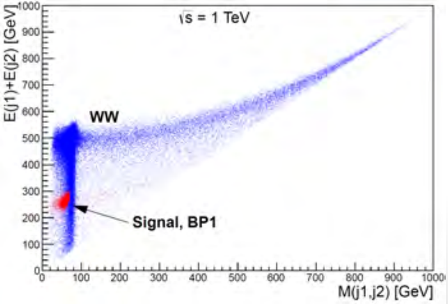
Single jet energy strongly depends on the decay angle $\theta^\star$.

But for the sum of two energies we have

$$E_{j_1} + E_{j_2} = 2\,\gamma\ E^\star_j = \gamma\,(m_{H^\pm} - m_H) = E_{beam}\ \left(1 - \frac{m_H}{m_{H^\pm}}\right) = \text{const}$$

Correlation between the sum of energies of two jets and their invariant mass

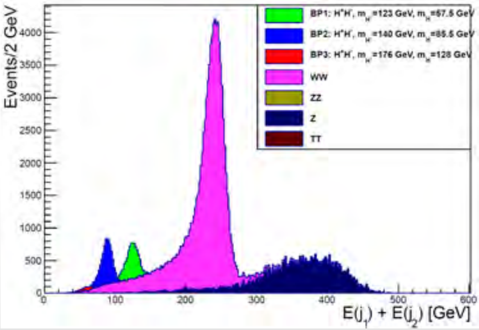


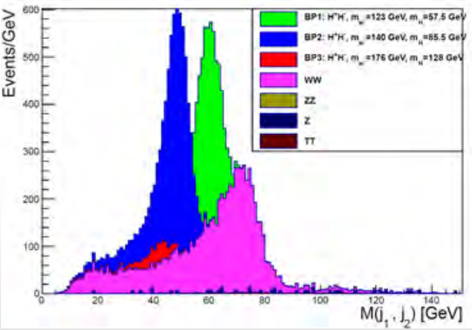


Selection cuts for semi-leptonic final state

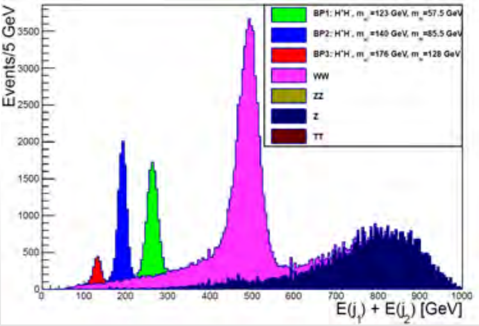
H^+H^- analysis, semi-leptonic final state selection		
Selection cut	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 1$ TeV
One lepton	$E_T > 10$ GeV	$E_T > 10$ GeV
Two jets	$E_T > 10$ GeV	$E_T > 10$ GeV
E_T^{miss}	$E_T^{\text{miss}} > 20$ GeV	$E_T^{\text{miss}} > 20$ GeV
$E(j_1) + E(j_2)$	$E(j_1) + E(j_2) < 150$ GeV	$E(j_1) + E(j_2) < 350$ GeV

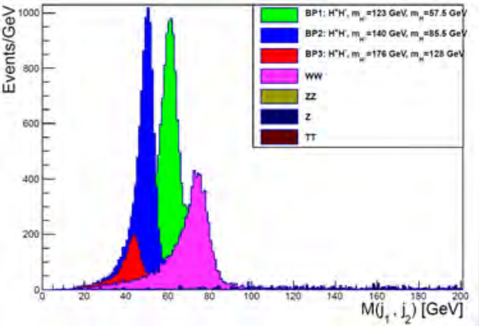
Sum of the energies and invariant mass of two jets in semileptonic final state at $\sqrt{s} = 0.5$ TeV





Sum of the energies and invariant mass of two jets in semileptonic final state at $\sqrt{s} = 1$ TeV





Signal significance

If inert charged scalars with masses $\sim M_Z$ do exist,
we should clearly see them at ILC/CLIC:

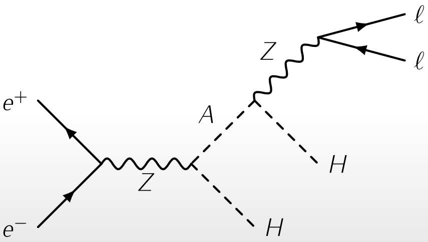
- Production cross section is model-independent
  depends only on the mass, charge and spin of the produced particle
  $\Rightarrow$ we can test, if it is a scalar...
- Well defined kinematics $\Rightarrow$ high signal selection efficiency
  - 20 – 64% for $\sqrt{s}$=0.5 TeV
  - 59 – 86% for $\sqrt{s}$=1 TeV

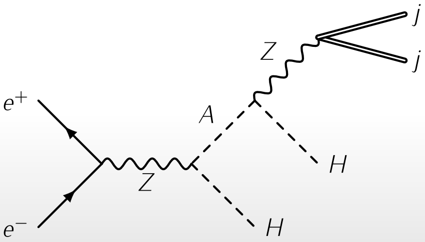
  and good background supression
- Signal to background ratio S/B after mass window cut
  - 0.35 – 4 for $\sqrt{s}$=0.5 TeV
  - 2.5 – 11 for $\sqrt{s}$=1 TeV
- Final statistical significance $S/\sqrt{S+B}$
  - 11 – 66 for $\sqrt{s}$=0.5 TeV
  - 33 – 87 for $\sqrt{s}$=1 TeV

$e^+e^- \to AH$

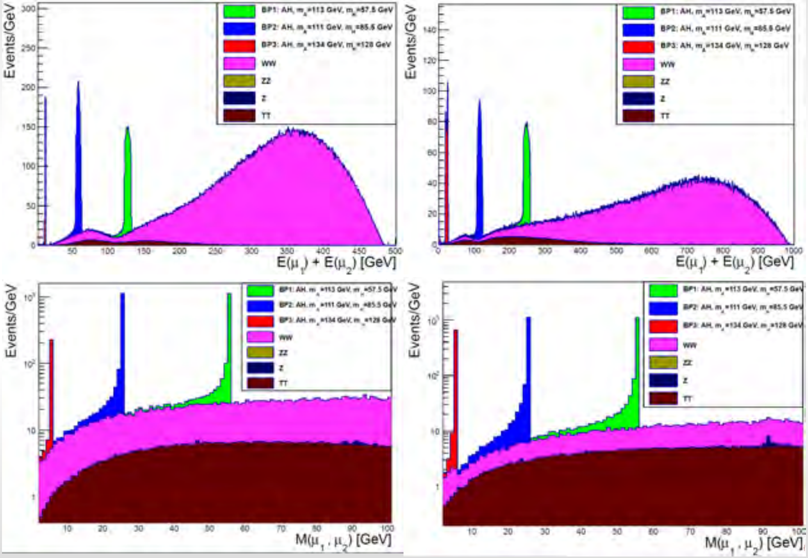
Signal and background cross sections

	$\sqrt{s} = 0.5$ TeV			$\sqrt{s} = 1$ TeV		
Process	$e^+e^- \to AH$			$e^+e^- \to AH$		
Benchmark point	BP1	BP2	BP3	BP1	BP2	BP3
Cross section [fb]	90	85.8	68.4	25	24.8	23.6





Sum of the energies (up) and invariant mass (down) of two lepton in leptonic final state at $\sqrt{s} = 0.5$ TeV (left) and 1 TeV (right).



Scalar mass reconstruction

For the charged scalar production $e^+e^- \to H^+H^-$

- Semi-leptonic channel $e^+e^- \to l\nu jjHH$
  - two jet invariant mass: $m_{jj} = m_{W^\star} \approx m_{H^\pm} - m_H$
  - sum of two jet energies: $E_{jj} = E_{beam}\,(1 - R)$, where $R = m_H / m_{H^\pm}$
- Fully hadronic channel $e^+e^- \to jjjjHH$

  As both $W^\star$ have the same Lorentz boost, jet with the highest energy (lab) comes from the same $W^\star$ as the jet with the lowest energy

  $\Rightarrow$ we can reconstruct both $W^\star$ easily
  - two jet invariant masses: $m_{14} = m_{23} = m_{W^\star} \approx m_{H^\pm} - m_H$
  - sum of four jet energies: $E_{4j} = 2\,E_{beam}\,(1 - R)$

For the neutral scalar production $e^+e^- \to HA$

- For leptonic channel $e^+e^- \to llHH$

  two lepton invariant mass: $m_{ll} = m_{Z^\star} \approx m_A - m_H$
- For hadronic channel $e^+e^- \to jjHH$

  two jet invariant mass: $m_{jj} = m_{Z^\star} \approx m_A - m_H$

Scalar mass reconstruction

Expected statistical precision of scalar mass determination with 500 fb^{-1}

Scalar	$\sqrt{s}$ [TeV]	BP1	BP2	BP3
$m_{H^\pm}$	theo.	123	140	176
	0.5	117.1±3.6	136.8±3.5	167.4±3.5
	1	112.7±2.4	131.4±1.9	172.2±2.1
m_H	theo.	57.5	85.5	128
	0.5	58.5±1.8	88.9±2.3	127.2±2.7
	1	53.0±1.1	81.5±1.2	129.1±1.6
m_A	theo.	113	111	134
	0.5	113.9±1.8	114.3±2.3	133.1±2.7
	1	104.6±1.1	105.0±1.2	134.8±1.6

The systematic shifts observed between the assumed (theo.) scalar masses and the fit results are due to the simplified approach used.
Can be corrected for based on the simulation results.

Conclusions

- Inert Doublet Model is one of the simplest extensions of the Standard Model providing a candidate for dark matter.
  - Second scalar doublet is not involved in mass generation and does not couple to fermions
  - IDM with inert scalar masses of the order of M_Z still in agreement with all existing data

Conclusions

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- LHC signatures similar to some SUSY scenarios, but cross sections small
    - Run 1 limits on m_H extend to $\sim$50 GeV only
    - Dedicated benchmark points prepared for LHC Run 2

Conclusions

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  - Second scalar doublet is not involved in mass generation and does not couple to fermions
  - IDM with inert scalar masses of the order of M_Z still in agreement with all existing data
- LHC signatures similar to some SUSY scenarios, but cross sections small
  - Run 1 limits on m_H extend to $\sim$50 GeV only
  - Dedicated benchmark points prepared for LHC Run 2
- IDM should be clearly visible at high energy e^+e^- collider for low and intermediate mass scenarios
  - Well constrained kinematics allows for efficient selection
  - Scalar masses can be reconstructed with 1 – 4 % precision

Number of events in signal and background processes after all selection cuts at integrated luminosity of 500 fb^{-1}.

H^+H^-, semi-leptonic final state at $\mathcal{L} = 500\ fb^{-1}$								
	$\sqrt{s}$ =0.5 TeV				$\sqrt{s}$ =1 TeV			
	S	B	S/B	$S/\sqrt{S+B}$	S	B	S/B	$S/\sqrt{S+B}$
BP 1	4887	3307	1.5	54	8709	2736	3.2	81
BP 2	5402	1342	4	66	8166	720	11	87
BP 3	478	1380	0.35	11	1534	602	2.5	33

Selection cuts and cut efficiencies for fully leptonic final state

HA analysis, leptonic final state selection		
Selection cut	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 1$ TeV
2 leptons	$E_T > 1$ GeV	$E_T > 5$ GeV
E_T^{miss}	$10 < E_T^{\text{miss}} < 120$ GeV	$10 < E_T^{\text{miss}} < 250$ GeV
$m_{\ell 1,\ell 2}$	$\lvert m_{\ell 1,\ell 2} - m_Z \rvert > 20$ GeV	$\lvert m_{\ell 1,\ell 2} - m_Z \rvert > 20$ GeV

HA analysis, leptonic final state selection							
Cut eff.	BP1	BP2	BP3	WW	ZZ	Z	TT
Total eff.@ 0.5 TeV	0.99	1	0.22	0.67	0	1.5e–05	0.26
Total eff.@ 1 TeV	0.98	0.98	0.65	0.45	2e–06	4.2e–05	0.42

Number of events in signal and background processes after all selection cuts at integrated luminosity of 500 fb^{-1}

HA, leptonic final state at $\mathcal{L} = 500\ fb^{-1}$								
	$\sqrt{s}$ =0.5 TeV				$\sqrt{s}$ =1 TeV			
	S	B	S/B	$S/\sqrt{S+B}$	S	B	S/B	$S/\sqrt{S+B}$
BP 1	1214	105	11.6	33	1220	55	22	34
BP 2	1223	71	17.2	34	1211	31	38.7	34
BP 3	225	34	6.6	14	666	13	50	26