# FIMPs & Friends

## Dark matter and long-lived particles at the LHC

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mostly based on
JHEP 1701 (2017) 100 [arxiv:1611.09540]
Phys.Rev. D96 (2017) no.10, 103521 [arxiv:1705.09292]
1805.xxxxx

MAX-PLANCK-INSTITUT
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# Outline

Introduction/Motivation

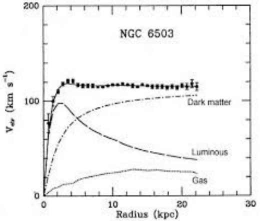
FIMP phenomenology

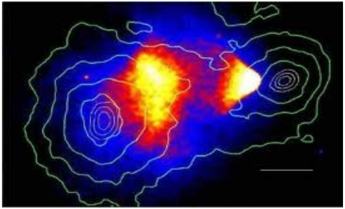
& Friends

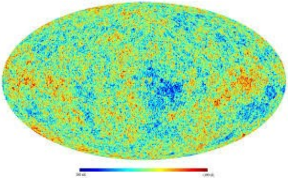
The long shot

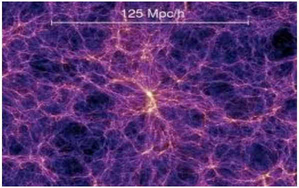
Conclusion

# What we know



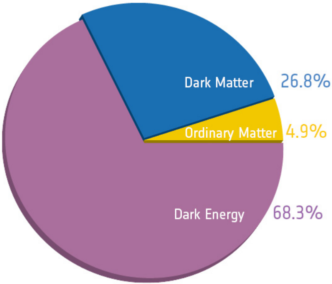





gravitational evidence for dark matter on all scales: rotation curves, clusters, large scale structure, CMB

# What we know

- abundance: $\Omega h^2 \approx 0.12$
- dark, i.e. electrically neutral
- cold (or warm)
- non-baryonic
- **physics beyond the Standard Model**



# What we don't know

- gravitational signatures do not provide any information about the nature of dark matter as a particle
- interactions with SM are highly uncertain
- will need different experiments and observations to determine properties of dark matter

Where should we look?

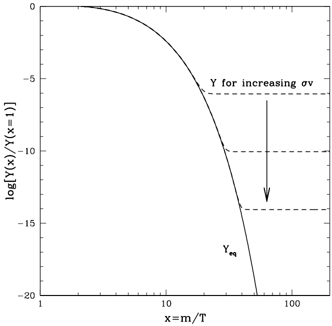
# Taking a hint from cosmology

$$\mathrm{d}n_\chi/\mathrm{d}t + 3Hn_\chi = C$$

- ingredients:
  - interactions of dark matter
  - evolution of the universe
  - initial conditions
- the production mechanism sets key aspects of DM phenomenology

# Thermal freeze-out

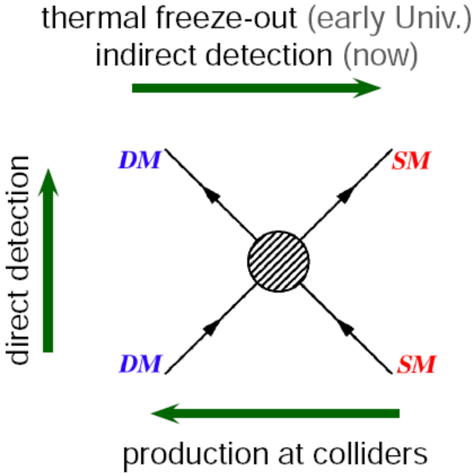
- universe starts at a high temperature
- dark matter part of plasma and in thermal equilibrium
- universe expands and cools
- once $m_{DM} \gtrsim T$ interaction rate becomes suppressed $\rightarrow$ DM drops out of thermal equilibrium
- $C = \langle \sigma v \rangle (n^2_{\chi,eq} - n^2_{\chi})$




$$\sigma v \approx 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \quad \text{weak scale cross section}$$

- weakly interacting massive particle (WIMP)

# WIMP detection



# How sure are we about the early Universe?

# Questioning assumptions

- universe starts at a high temperature?
  - dark matter mass could be significant compared to reheating temperature
  - interactions could be suppressed by large scale (gravitino etc.)
- universe expands and cools?
  - that is true but relation between expansion rate and temperature could be different (early phase of matter domination, entropy production etc.)
- ...
- ...
- dark matter part of plasma and in thermal equilibrium?

# FIMPs

# FIMP: Non-thermal production

- FIMP: feebly interacting massive particle
- interaction strength $\ll$ weak interaction strength
- FIMP not part of the high energy plasma in the early Universe
- FIMP is not in thermal equilibrium

popularized by Hall, Jedamzik, March-Russell, West 2009
earlier candidates: keV sterile neutrino

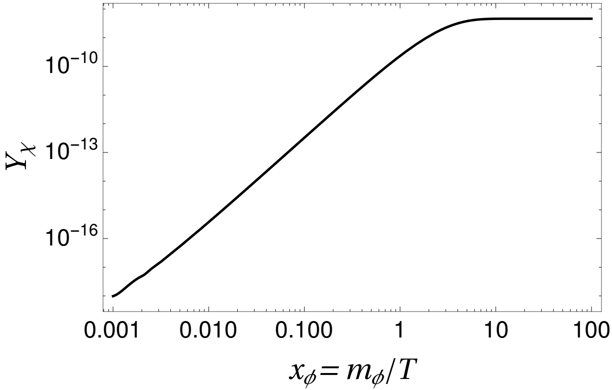
# Schematic FIMP production

- SM $+ \chi$ (FIMP) $+ \phi$ (heavy new particle)
- decay $\phi \to \chi +$ ...
- $\phi$ is in thermal equilibrium with SM plasma
- $\chi$ is not in thermal equilibrium
- production described by Boltzmann equation for $Y = \frac{n_\chi}{s}$

$$\frac{dY_\chi}{dx_\phi} = \frac{1}{3H}\frac{ds}{dx_\phi}\left[-\frac{\Gamma}{s}Y_\phi + ...\right]$$

# Schematic FIMP production

- either solve Boltzmann equation numerically




- or analytic approximation if number of degrees of freedom approximately constant

$$Y_\chi \approx \frac{135 g_\phi}{8\pi^3 (1.66) g_*^s \sqrt{g_*^\rho}} \frac{M_{Pl}\Gamma}{m_\phi^2}$$

Hall, Jedamzik, March-Russell, West 2009

# FIMP detection

small coupling

- small annihilation rate
- small direct detection rate
- small production rate at LHC

?

# Thermal equilibrium and the LHC

- in order to avoid thermalization the interaction rate has to be small compared to the Hubble rate

$$\Gamma_\phi \lesssim H$$

- if taken as decay rate of a heavy particle $\phi$

$$y \lesssim 20\sqrt{\frac{T_{max}^2}{m_\phi M_{Pl}}} \approx 10^{-9}\frac{m_\phi}{10\text{ GeV}}$$

$$c\tau \gtrsim \frac{1}{H} \approx \frac{M_{Pl}}{\sqrt{g_*}m_\phi^2} \approx 10\left(\frac{10\text{ GeV}}{m_\phi}\right)^2 \text{m}$$

- non-thermal dark matter indicates long-lived particles
- more quantitative statements are model dependent

# Scotogenic Model

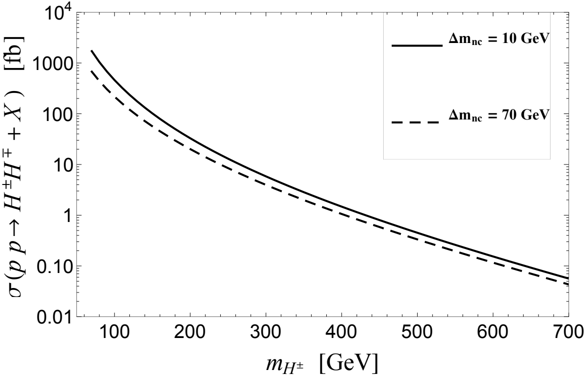
- model for radiative neutrino masses and dark matter Ma 2006
- content: 3 Majorana fermions $N_i$, one scalar doublets $H_2$, one $Z_2$ symmetry
- all new particles odd under $Z_2$
  $\rightarrow$ lightest $Z_2$ odd particle stable DM candidate

$$\mathcal{L}_{\rm int} = \lambda_3 \,(H_1^\dagger H_1)\,(H_2^\dagger H_2) + \lambda_4\,(H_1^\dagger H_2)\,(H_2^\dagger H_1) + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right]$$
$$+ \left[Y^\nu_{\alpha i}\,(\overline{\nu}_{\alpha L}\,H_2^0 - \overline{\ell}_{\alpha L}\,H^+)\,N_i + \text{h.c.}\right]$$
$$+ \text{gauge interactions}$$

- $N_1$ FIMP candidate with

$$\Omega_{N_1} h^2 \approx 0.12 \frac{M_{N_1}}{10\ \text{keV}} \frac{100\ \text{GeV}}{m_S} \left(\frac{y_1}{2\cdot 10^{-9}}\right)^2$$

# LHC production rates




- scalars produced by Drell-Yan process and through Higgs portal
- fermions have small ($N_{2/3}$) or very small couplings ($N_1$) $\to$ fermion production is negligible

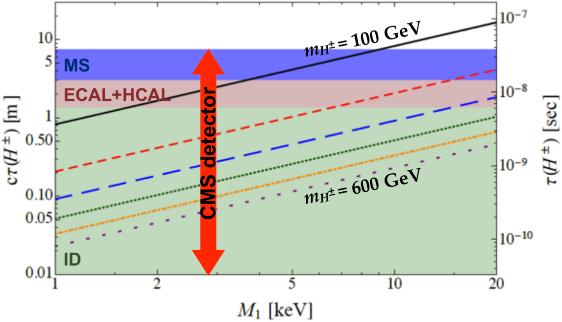
# What are the LHC signatures?

# Signatures

Signatures depend on open decays, i.e. mass spectrum

- $m_{N_1} < m_{H,A} < m_{N_{2/3}}, m_H^+$
  - $H, A$ long-lived
  - decay $H \to N_1 \nu$ invisible
- some cases do not give us detectable long-lived particles

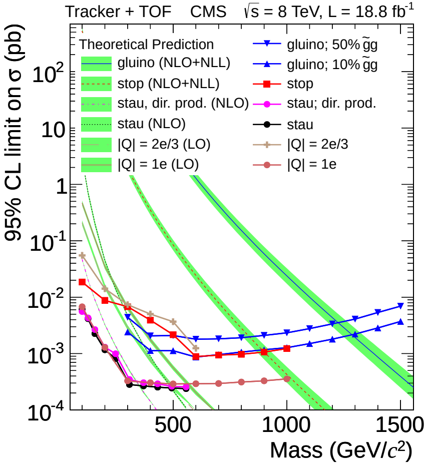
# Long-lived charged particles: $m_{N_1} < m_{H^+} < m_{N_{2/3}}, m_H, m_A$




- freeze-in fixed coupling/lifetime as function of masses
  $\rightarrow H^\pm$ long-lived

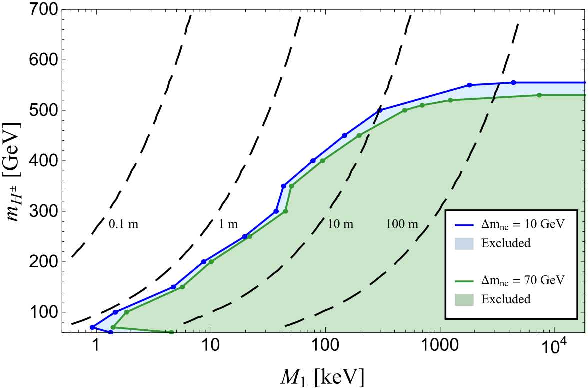
$$c\tau \approx 8.3\,\mathrm{m}\left(\frac{M_{N_1}}{10\,\mathrm{keV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{H^\pm}}\right)^2$$

# Long-lived particle search at CMS




- CMS/ATLAS can search for stable massive long-lived particles with time of flight analysis and search for anomalous energy loss in tracker figure from CMS [1305.0491]

# Recast of long-lived particle search




- search efficiency depends on production mode (angular dependence/ boost factors etc.) and decay length
- CMS provides tabulated efficiencies in $\eta, \gamma$ 1502.02522
- for sufficiently heavy $m_{N_1}$ this search excludes $m_{H^\pm} \lesssim 500$ GeV

Hessler, Ibarra, Molinaro, SV 2016

# Prompt decays: $m_{N_1} < m_{N_2} < m_{m_{H^\pm}}, m_H, m_A$

- $y_1 \ll y_2 \Rightarrow$ all scalars decay to $N_2$
- neutrino masses constrain $N_2$ Yukawa: $10^{-5} < y_2 < 10^{-2}$
- typical decay length less than mm $\rightarrow$ prompt decay
- decay $N_2 \rightarrow l \bar{l} N_1$ suppressed by very small FIMP coupling, smallish $y_2$ and three-body phase space

$$c\tau(N_2) \approx 2 \times 10^{13}\,\mathrm{m} \left(\frac{M_1}{10\ \mathrm{keV}}\right) \left(\frac{m_H}{500\ \mathrm{GeV}}\right)^3 \left(\frac{100\ \mathrm{GeV}}{M_2}\right)^5 \left(\frac{10^{-3}}{y_2}\right)^2$$

- $N_2$ stable in detector $\Rightarrow$ missing energy
- standard signature: leptons + MET

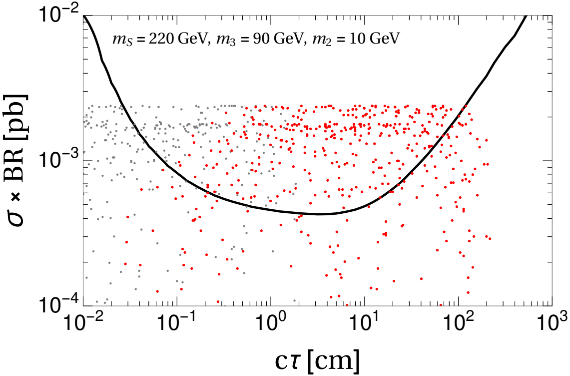
## $m_{N_1} < m_{N_2} < m_{N_3} < m_{m_{H^\pm}}, m_H, m_A$

- $N_2$ still stable on detector scales
- $N_3$ potentially long-lived
- $N_3 \to l^+ l^- \, N_2$ i.e. displace dileptons

$$c\tau(N_3) \approx 0.4\,\mathrm{m} \left(\frac{100\ \mathrm{GeV}}{M_3}\right) \left(\frac{m_H}{M_3}\right)^4 \left(\frac{10^{-3}}{y_2}\right)^2 \left(\frac{10^{-3}}{y_3}\right)^2$$

- life-time and branching ratios set by Yukawa couplings of $N_2$ and $N_3$
  $\to$ connection to radiative neutrino masses

# Testing neutrino mass generation




- recast CMS search for displaced dileptons 1411.6977
- branching ratio into testable final states depends on details of neutrino mass generation
- decay length forced into testable range by neutrino masses and $\mu \to e\gamma$ limits
- bulk of model space testable but cancellations and or hierarchical Yukawa couplings possible

# & Friends

# Conversion driven freeze-out

Let's assume a similar set-up:

- SM $+ \chi$ (FIMP) $+ \phi$ (heavy new particle)
- decay $\phi \to \chi +$ SM
- $\phi$ in equilibrium with SM bath
- **but** $\Gamma \approx H$

What happens now?

# Conversion driven freeze-out

- same starting point but back-reaction term and scattering no longer negligible

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[-\frac{\Gamma_\phi}{s}\left(Y_\phi - Y_\chi\frac{Y_\phi^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) + \frac{\Gamma_{\chi\to\phi}}{s}\left(Y_\chi - Y_\phi\frac{Y_\chi^{\mathrm{eq}}}{Y_\phi^{\mathrm{eq}}}\right)\right]$$

- evolution of $\phi$ controlled by annihilation and feedback from $\chi$

$$\frac{\mathrm{d}Y_\phi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{\phi\phi^\dagger}v\rangle\left(Y_\phi^2 - Y_\phi^{\mathrm{eq}\,2}\right) - \frac{\Gamma_{\chi\to\phi}}{s}\left(Y_\chi - Y_\phi\frac{Y_\chi^{\mathrm{eq}}}{Y_\phi^{\mathrm{eq}}}\right) + \frac{\Gamma_\phi}{s}\left(Y_\phi - Y_\chi\frac{Y_\phi^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)\right]$$

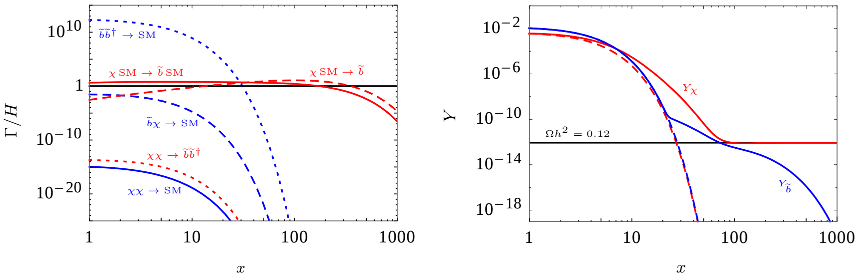
# Example

- fermionic dark matter $\chi$ + color charged scalar mediator ("squark")

$$\mathcal{L}_{\text{int}} = |D_\mu \widetilde{q}|^2 - \lambda_\chi \widetilde{q} \bar{q} \frac{1-\gamma_5}{2} \chi + \text{h.c.},$$

- decay $\tilde{q} \to q\chi$ connects DM with partner

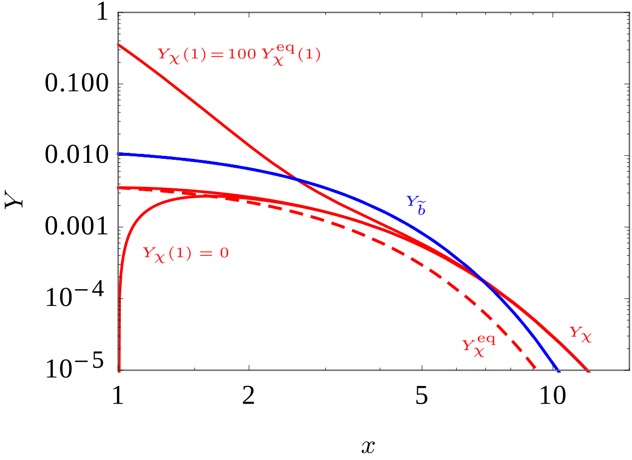
# Conversion driven freeze-out




- conversion driven freeze-out effective for $\Gamma \approx H$
- distinct from FIMP and standard freeze-out
- $\Gamma \approx H$ implies macroscopic decay length $c\tau$
  $\Rightarrow$ long-lived R-hadron

Garny, Heisig, Lülf, SV 2017

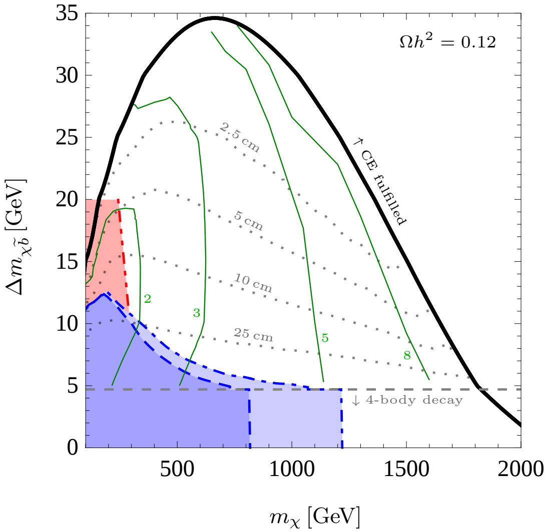
# Conversion driven equilibration




- $\Gamma \approx H$ is sufficient to allow equilibration
- no dependence on initial condition, i.e. between FIMP and freeze-out ("coannihilation without chemical equilibrium")

Garny, Heisig, Lülf, SV 2017

# Parameter space




Garny, Heisig, Lülf, SV 2017

# The long shot

# Generic decay length

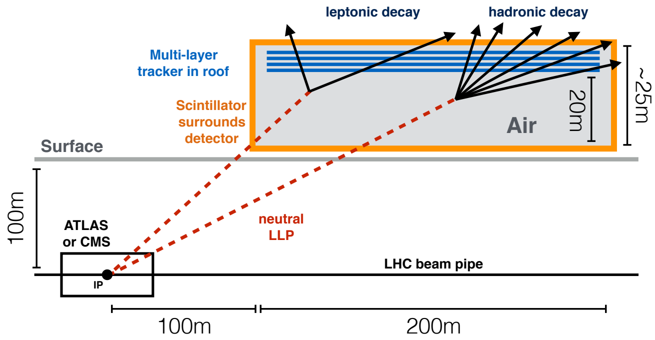
- the generic decay length of a FIMP progenitor is large

$$c\tau \approx 160\text{m}\,\frac{m_\chi}{1\,\text{MeV}}\left(\frac{100\,\text{GeV}}{m_\phi}\right)^2$$

- typical detector $\lesssim$ 10 m

$\Rightarrow$ want big far away detector

# MATHUSLA




Curtin, Peskin 2017

- recent "crazy" proposal of 200 m $\times$ 200 m $\times$ 25 m surface detector for HL-LHC
- look for pair of fermions with displaced vertex
- background "free"

Chou, Curtin, Lubatti 16

# Could we learn something about dark matter?

## Limitations!

- no energy or momentum
- only directions are measured

- Could we tell three-body from two-body decays
- Could we determine particle properties?
- Could we figure out the underlying physics?
- ....

$\rightarrow$ focus on angular observables

# Triple product

- angular observables are sensitive to underlying physics
- triple product can tell two and three-body decay apart

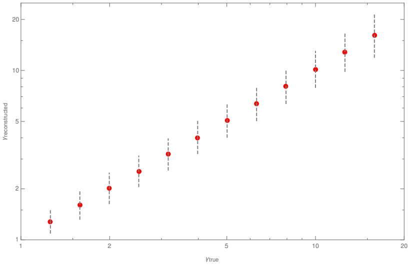
$$T = \frac{\vec{V}}{|\vec{V}|} \cdot \left( \frac{\vec{v}_1}{|\vec{v}_1|} \times \frac{\vec{v}_2}{|\vec{v}_2|} \right)$$

- measures angle between decay plane and direction of mother particle
- for two-body $T = 0$ due to momentum conservation

# Reconstruct particle properties?

- not enough information to reconstruct particle physics parameters
- try statistical inference instead
- strategy:
  - commit to new physics model
  - predict distribution of angular observables
  - try to reconstruct model parameters

# Simplistic example



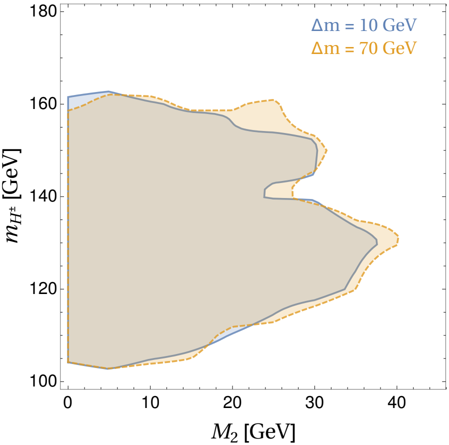

preliminary

- assume all mother particles produced with same momentum
- isotropic decay
- $\gamma$ can be reconstructed with 50 events
- more realistic physics scenarios require more statistics

# Conclusion

- feebly interacting massive particles (FIMPs) and friends (other DM candidates) are an intriguing possibility
- FIMPs generically point towards long-lived particles
- long-lived particles can be searched for very efficiently at the LHC

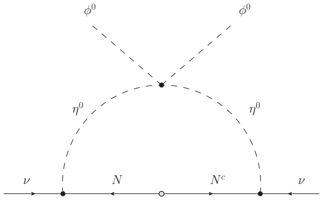
# Recast SUSY searches




- SUSY search for leptons + MET (electroweak slepton production) ATLAS 1403.5294
- standard tools available (here: CheckMATE)
- low sensitivity: $m_{H^\pm} \gtrsim 160$ GeV is fine

Hessler, Ibarra, Molinaro, SV 2016

# Radiative neutrino masses




- SM neutrino masses generated radiatively

$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_5\, v^2}{32\,\pi^2} \sum_k \frac{Y^\nu_{\alpha k}\, Y^\nu_{\beta k}}{M_{N_k}} \left[\log\left(\frac{M^2_{N_k}}{m_0^2}\right) - 1\right]$$

$$\simeq 10^{-2} \frac{\lambda_5 y^2_{2,3}}{10^{-11}} \frac{1\,\text{TeV}}{M_{2,3}}$$

- $\lambda_5 \lesssim 0.1 \Rightarrow Y_{i,j} \gtrsim 10^{-6}$
- $\Rightarrow$ opportunity to test details of radiative neutrino mass generation