Universität Heidelberg

Carl Zeiss Stiftung

INTRODUCTION TO DARK MATTER

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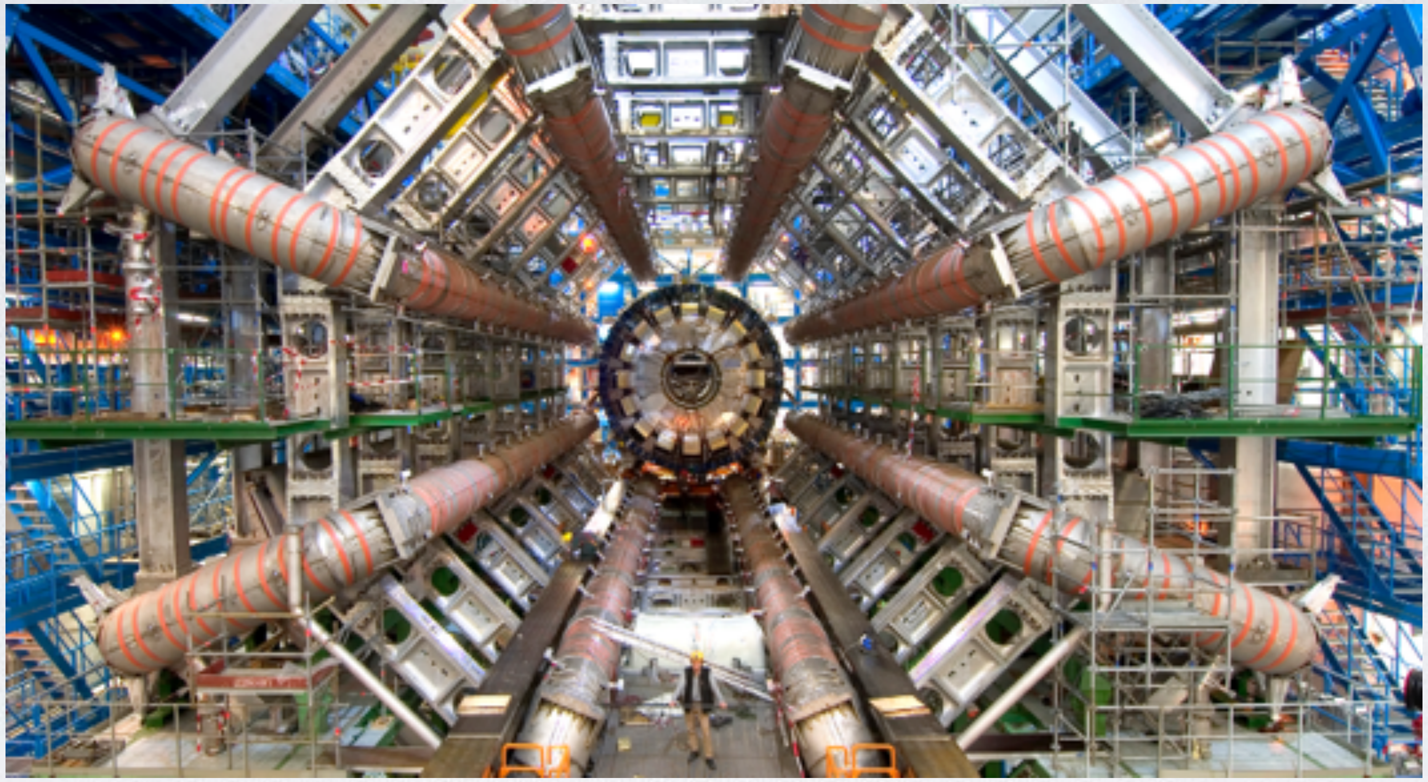
PART III COLLIDER SEARCHES



Remember DM annihilation in the early universe:

$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \approx 1\,\mathrm{pb}$$

Expect sizable WIMP production rates at the LHC:

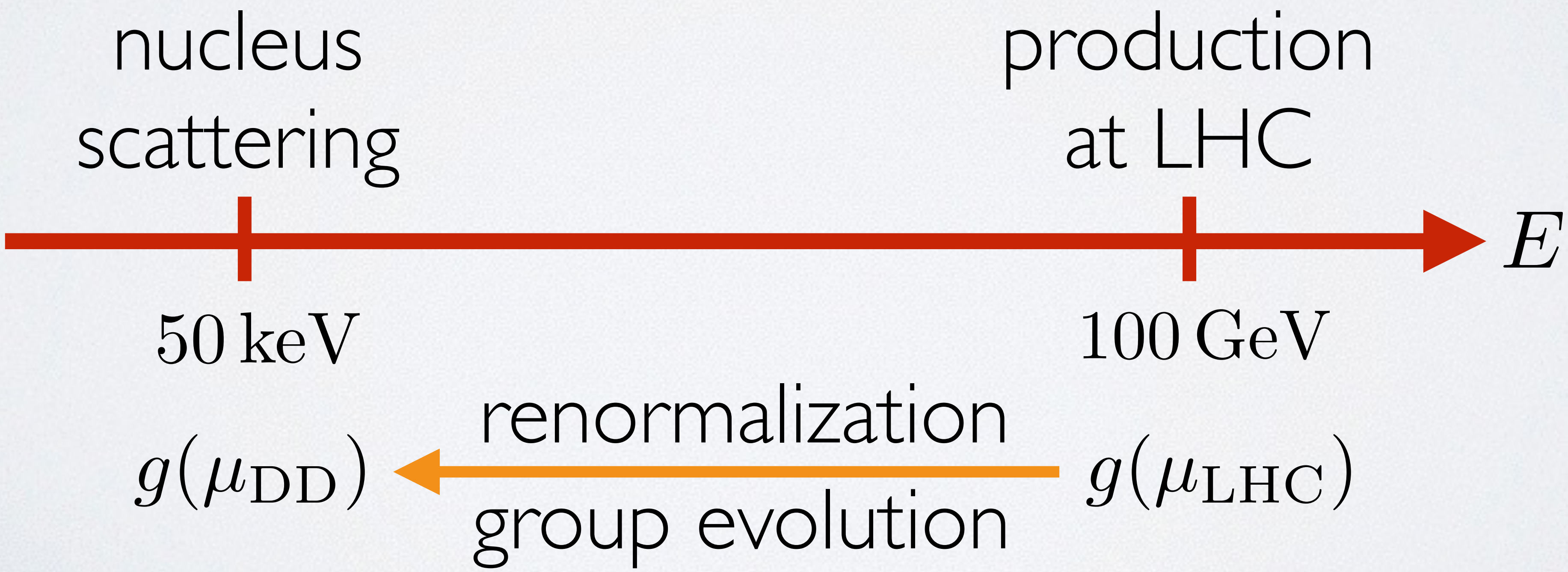
$$\sigma(pp \to X + E_T^{\mathrm{miss}}) = \int ds\, \mathcal{L}_{ij}(s) \hat{\sigma}_{ij}(s)$$

COLLIDERS AND DIRECT DETECTION

Collider searches help where direct detection is not sensitive:

- light dark matter
- pseudo-scalar or axial-vector interactions
- mostly lepton interactions

Caution when relating results obtained at different energies:



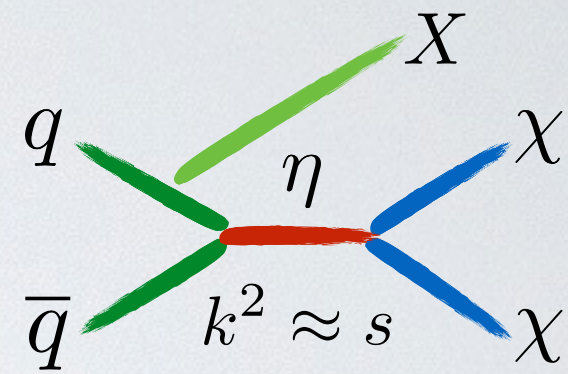
TYPICAL LHC SIGNALS

[e.g., Kahlhoefer, 1702.02430]

In high-energy collisions, **mediators** are produced **resonantly**:

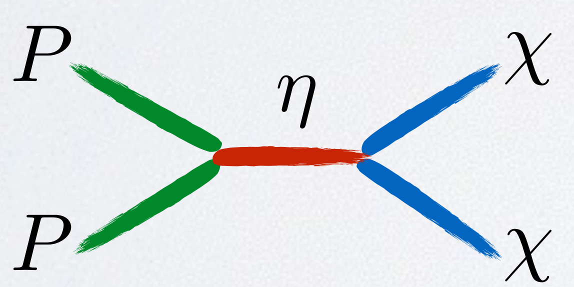
$$\sqrt{s} \sim 100 - 1000\,\mathrm{GeV}:$$

$$\frac{1}{m_\eta^2}(\overline{q}q)(\overline{\chi}\chi) \to (\overline{q}q)\frac{1}{s - m_\eta^2 + i m_\eta \Gamma_\eta}(\overline{\chi}\chi)$$

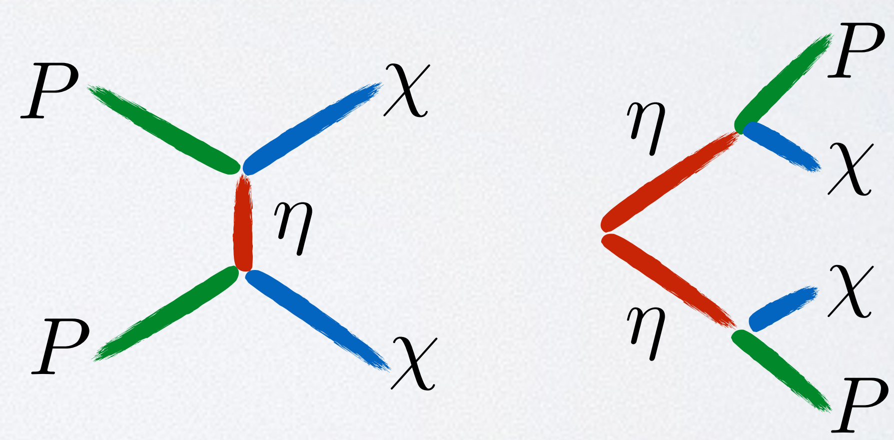


Simple models and their collider signatures:

s-channel mediation

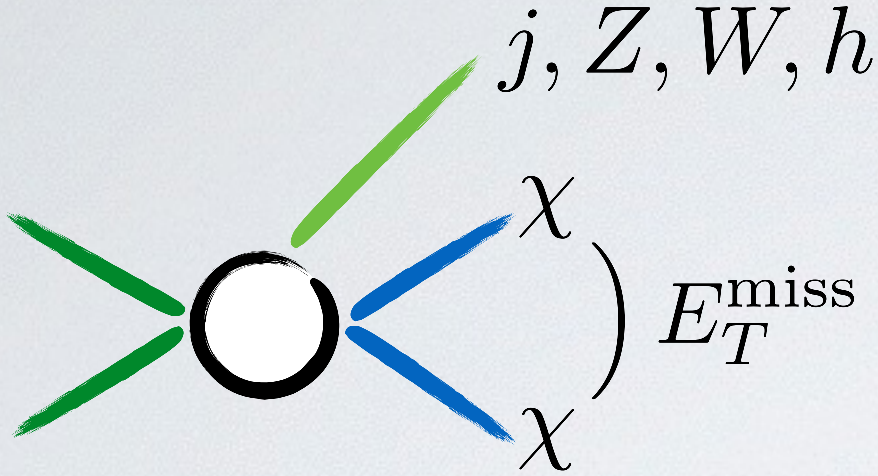


t-channel mediation



- should be gauge-invariant, unitarity-conserving, anomaly-free.
- discrete Z_2 symmetry in dark sector makes DM stable.

MISSING ENERGY SEARCHES



mono-jet:
mostly model-independent

mono-Z,W: [Carpenter et al., 1212.3352]
probe isospin-violating scenarios

mono-Higgs: [Carpenter et al., 1312.2592]
probe extended scalar sectors

$$\sigma(pp \to X + E_T^{\text{miss}}) \approx \sigma(pp \to X + \eta) \times \Gamma(\eta \to \chi\chi)/\Gamma_\eta$$

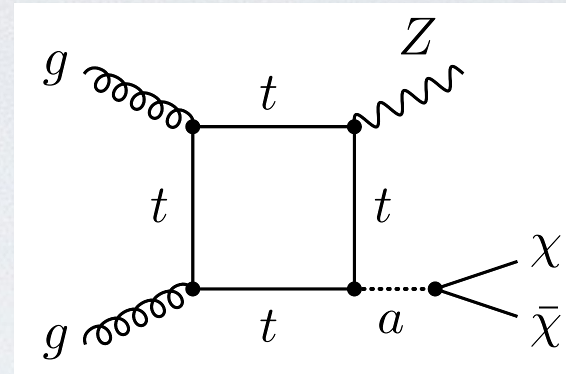
Largest branching ratio for light dark matter: $m_\chi \ll m_\eta$

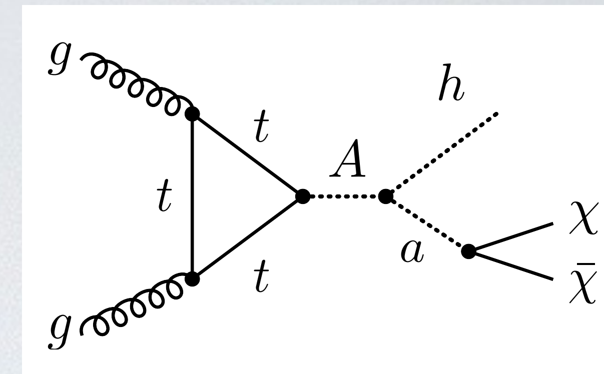
Standard-model sources of missing energy:

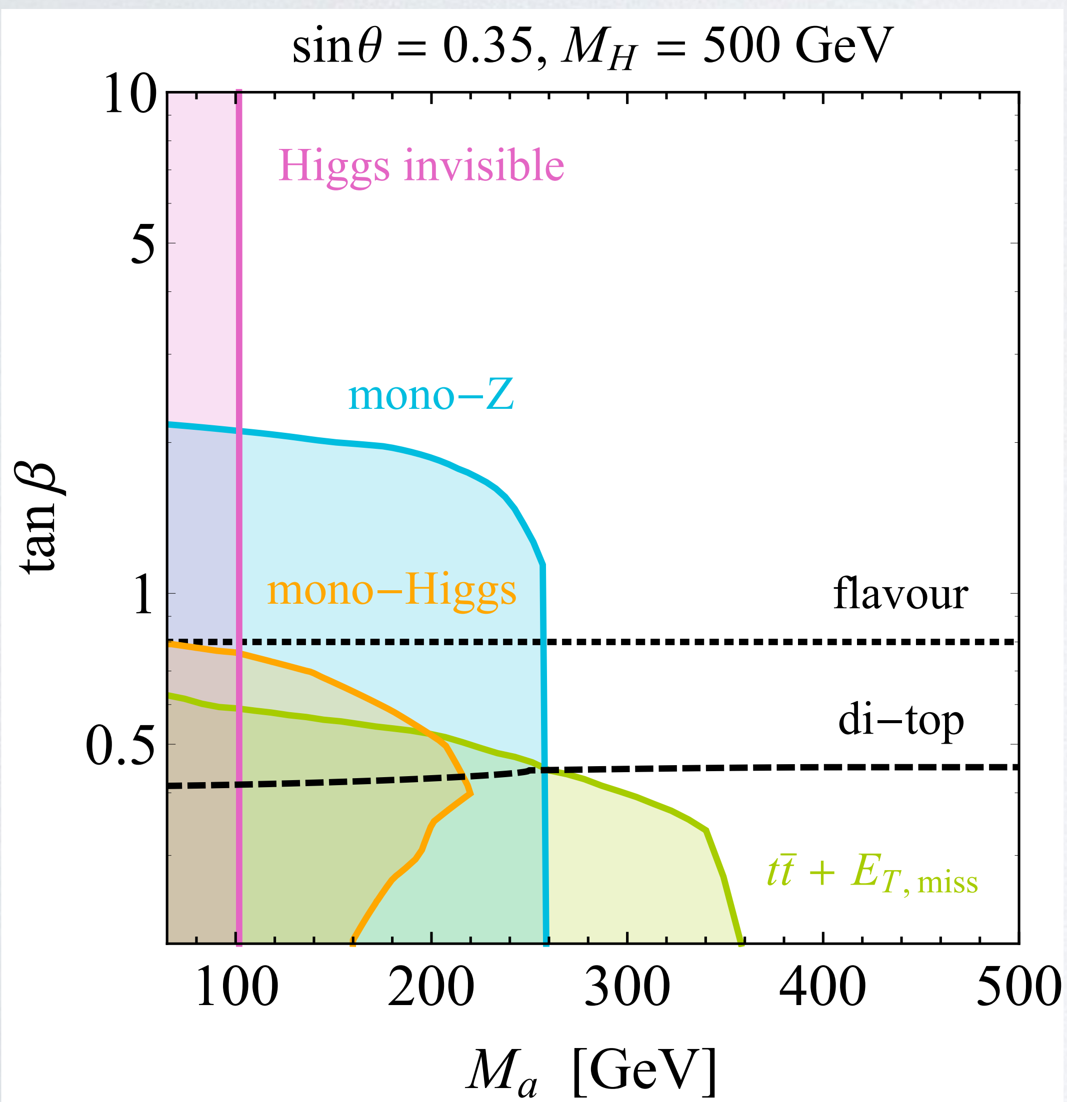
- from neutrinos, as in $Z \to \nu\bar{\nu}$, $W^\pm \to \ell^\pm\nu$, $t \to b\ell\nu$
- from missed decay products or detector deficiencies

MONO-X FROM EXTRA SCALARS

Two-Higgs-doublet model with pseudo-scalar portal:

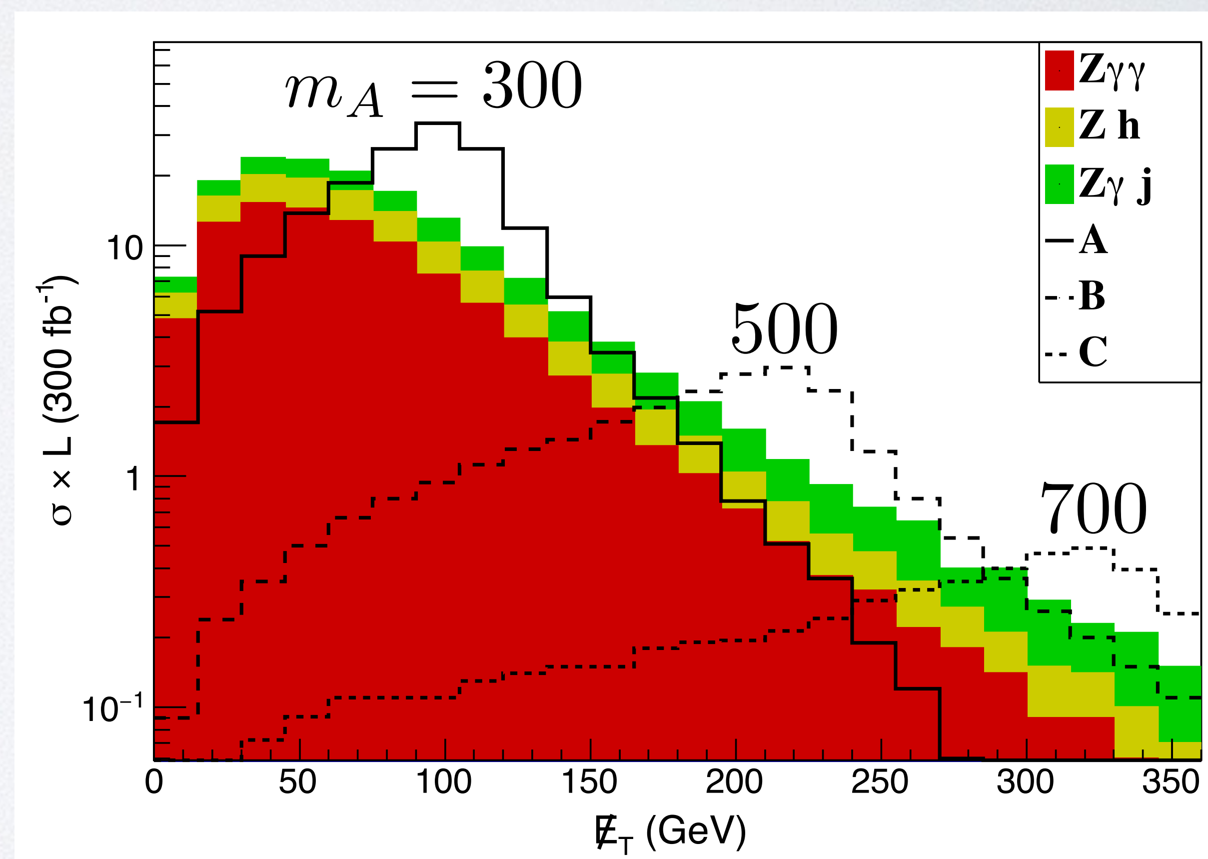






[Bauer et al., 1701.07427]

mono-Higgs:
Jacobian peak from resonant A

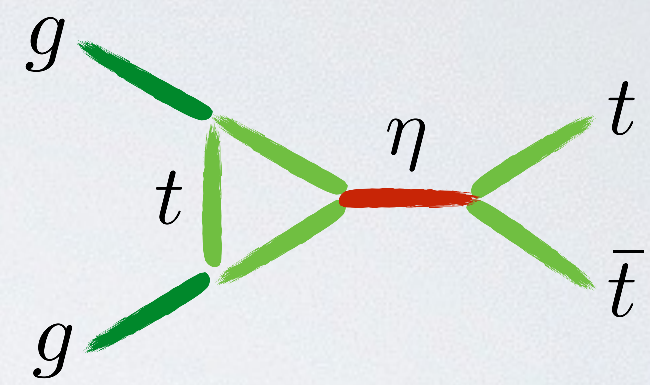


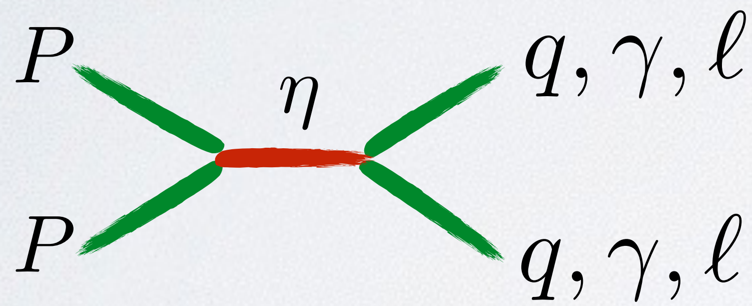
[No, 1509.01110]

MEDIATOR SEARCHES

Probe mediator-SM interaction in precise observables:

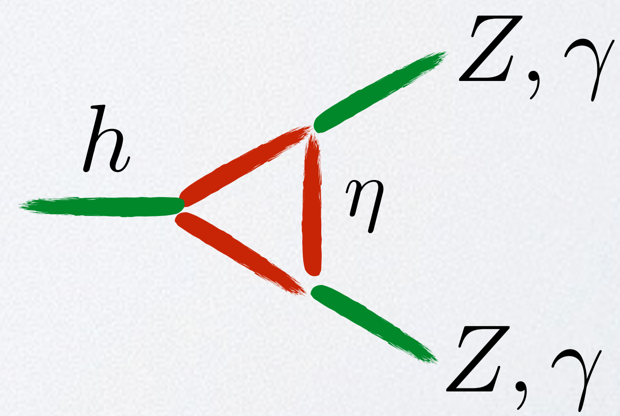
top pair production





di-jet, di-photon,
di-lepton production

virtual effects
in Higgs couplings

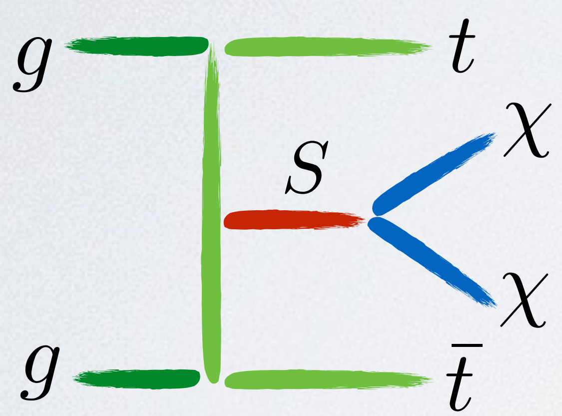


TOP-ASSOCIATED PRODUCTION

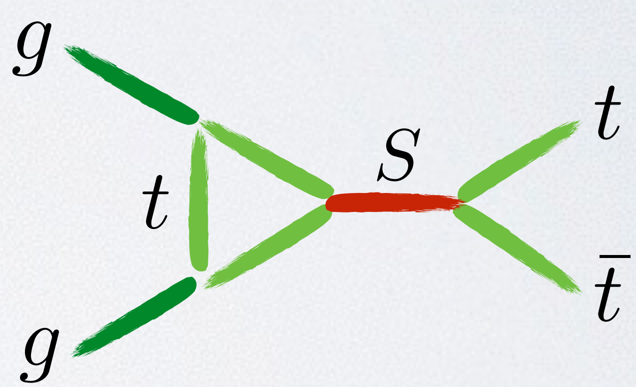
Flavor-hierarchical scalar interactions

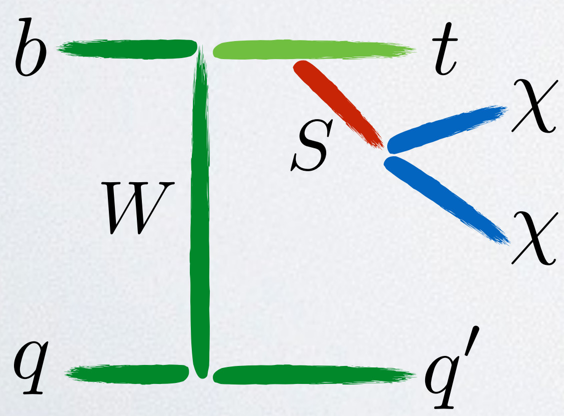
$$\mathcal{L} = g_S^\chi \, \overline{\chi}\chi \, S + g_S^q \frac{m_q}{v} \, \overline{q}q \, S$$

naturally lead to dominant effects in top-quark observables:



top-pair production



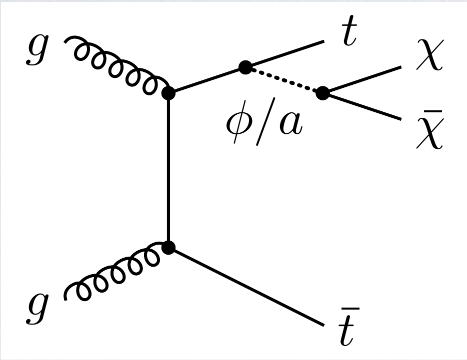


single-top production

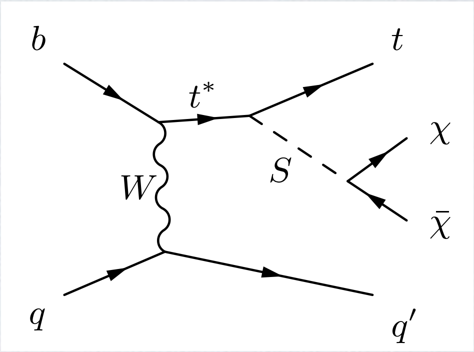
mediator production via top loop

ONE OR TWO TOPS?

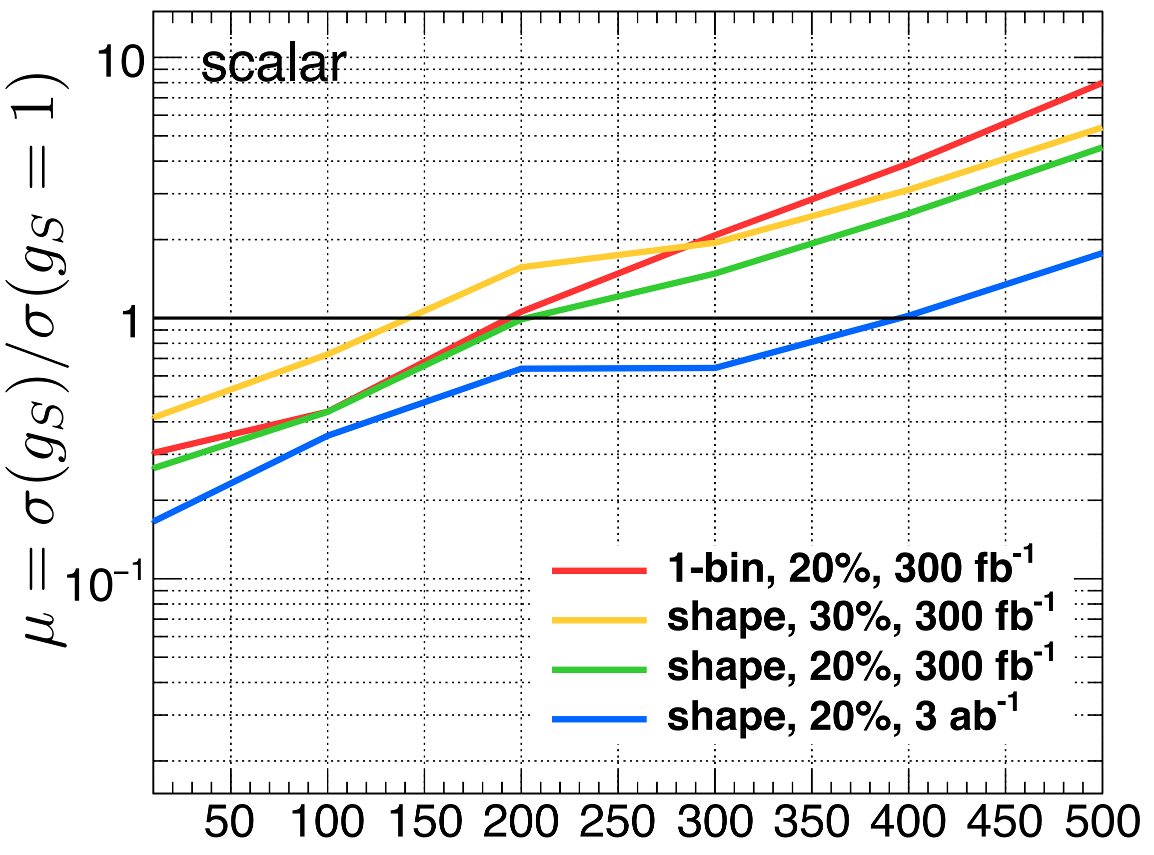
top-pair associated



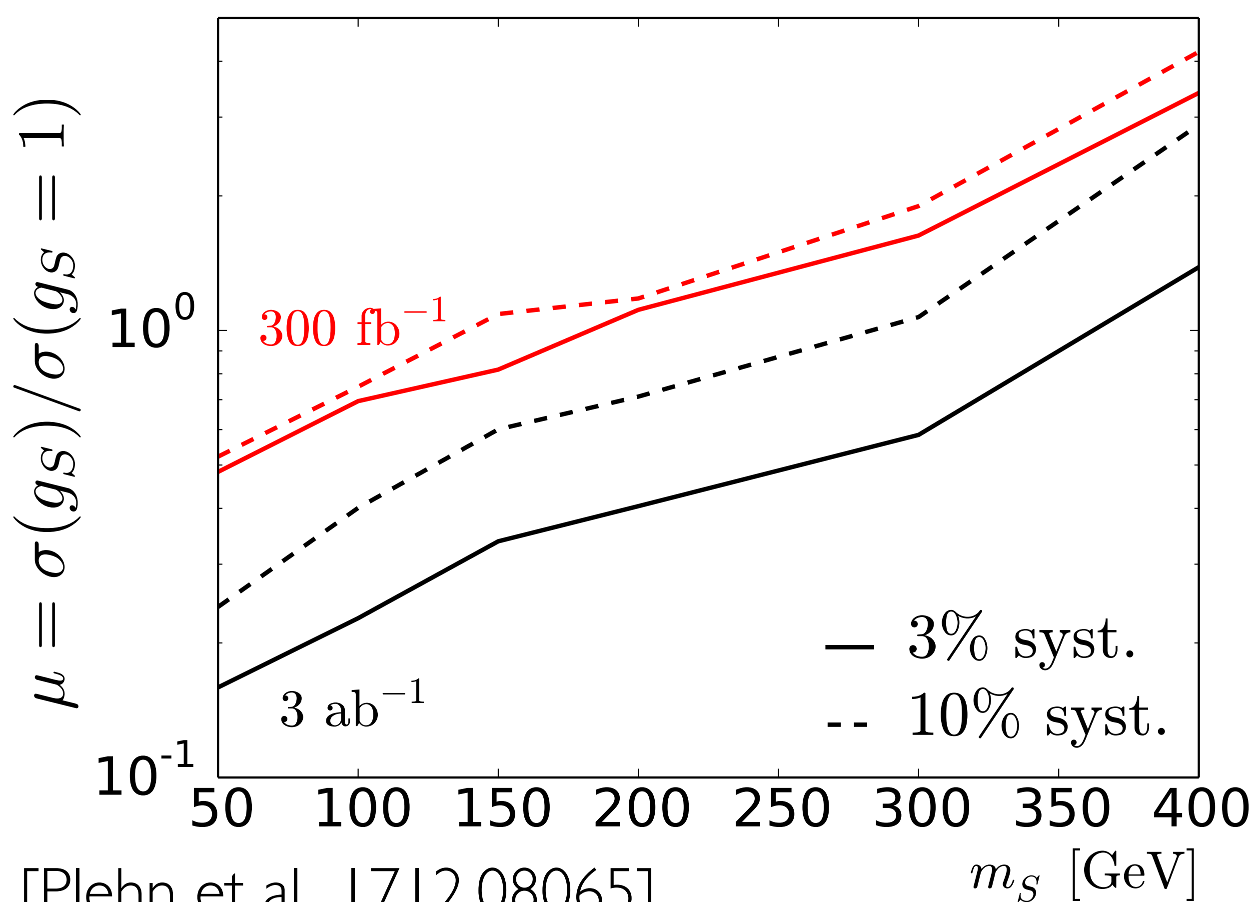
single-top associated



Signal strength that can be excluded at 95% CL:

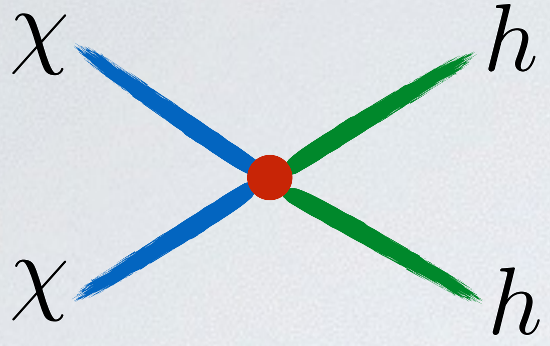


[Haisch et al., 1611.09841]



[Plehn et al., 1712.08065]

HIGGS PORTAL DARK MATTER



$(H^\dagger H)$ is a standard-model singlet.

χ is part of a dark sector.

Z_2 symmetry $\longrightarrow \chi$ stable.

Renormalizable portal interactions: [Patt, Wilczek, hep-ph/0605188]

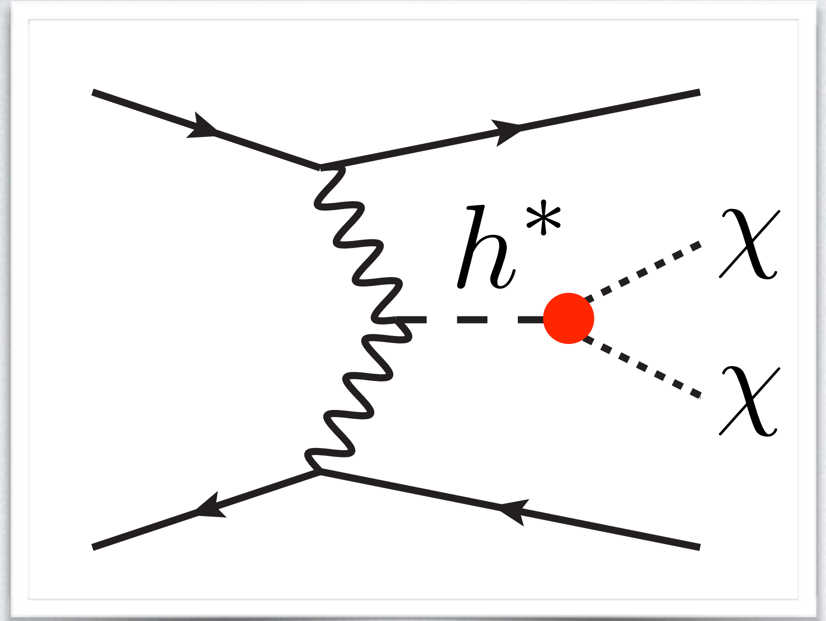
Scalar $\chi = S$: $\mathcal{L} = (S^\dagger S)(H^\dagger H)$ [e.g. O'Connell et al., hep-ph/0611014]

Vector $\chi = V_\mu$: $\mathcal{L} = (V_\mu V^\mu)(H^\dagger H)$ [e.g. Hambye, 0811.0172]

Effective portal interaction through mediator(s):

Fermion: $\mathcal{L}_{\text{eff}} = \frac{g_S}{\Lambda}(\bar{\chi}\chi)(H^\dagger H) + i\frac{g_P}{\Lambda}(\bar{\chi}\gamma_5\chi)(H^\dagger H)$

DIRECT COLLIDER PROBES



$$(\chi\chi)(H^\dagger H) \supset v\,(\chi\chi)h$$

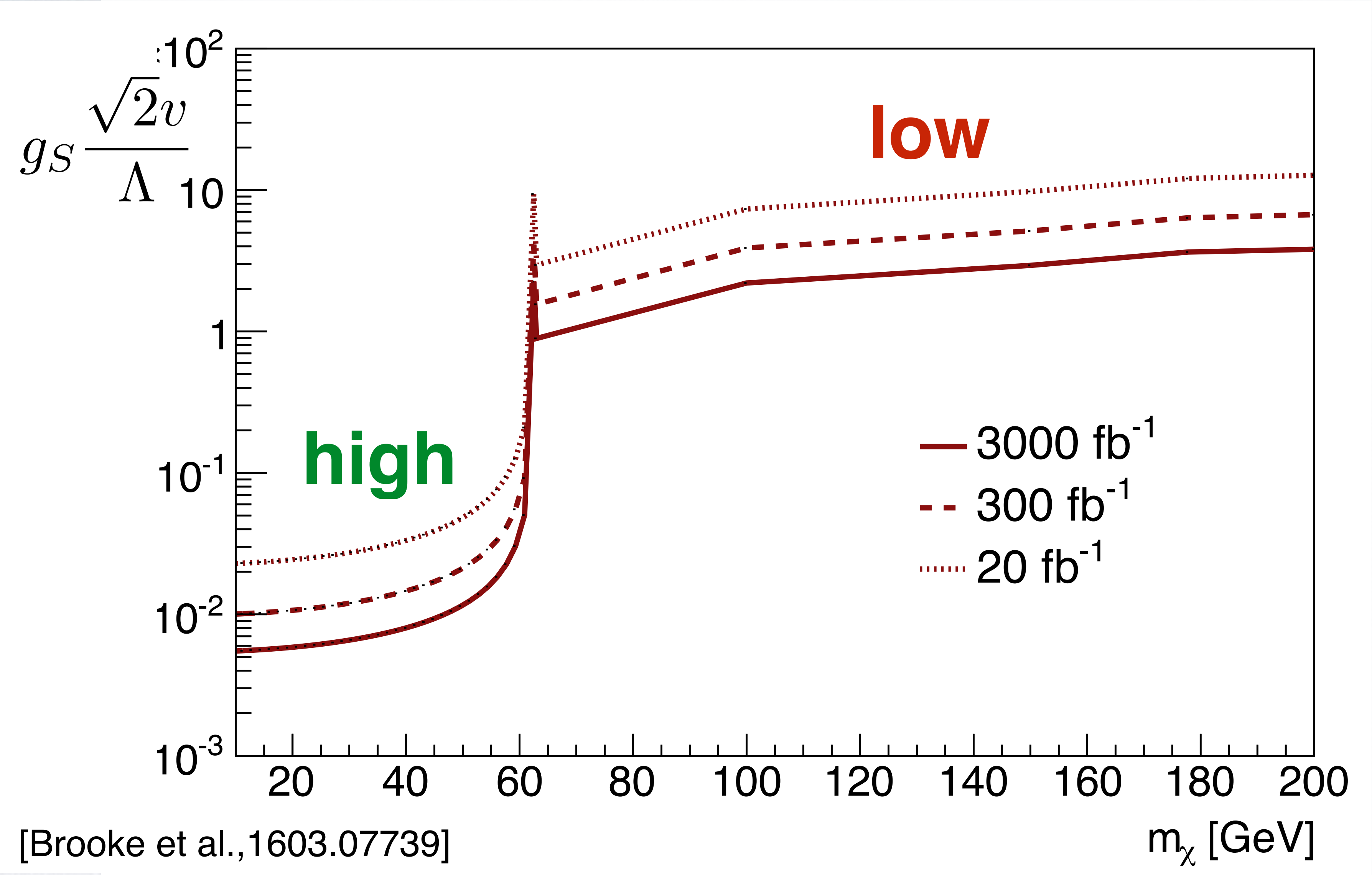
$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\,G^+ \\ v + h + iG^0 \end{pmatrix}$$

Distinguish signals by (non-)resonant Higgs production:

$2m_\chi < M_h$: invisible Higgs decays

$2m_\chi > M_h$: off-shell Higgs processes

LHC SENSITIVITY TO FERMION PORTAL



From global analysis of Higgs observables:

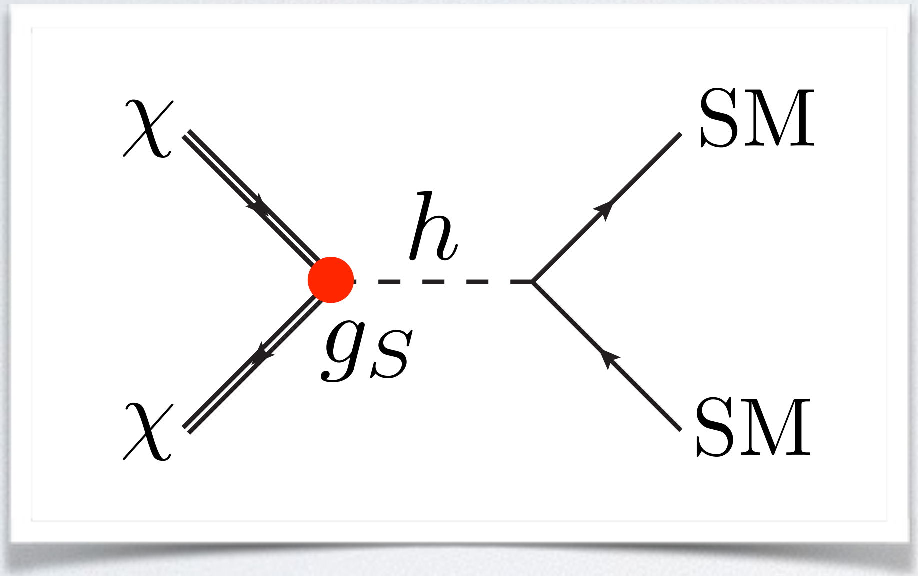
$\mathcal{B}(h \to \text{invisible}) \lesssim 30\%$ [ATLAS & CMS]

sets strong bound on DM-Higgs coupling for $2m_\chi < M_h$

THERMALLY PRODUCED DARK MATTER

Thermally averaged annihilation cross section:

$$\langle \sigma_A v \rangle_{th} = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \approx 1 \, \mathrm{pb}$$



Collider bounds ($2m_\chi < M_h$):

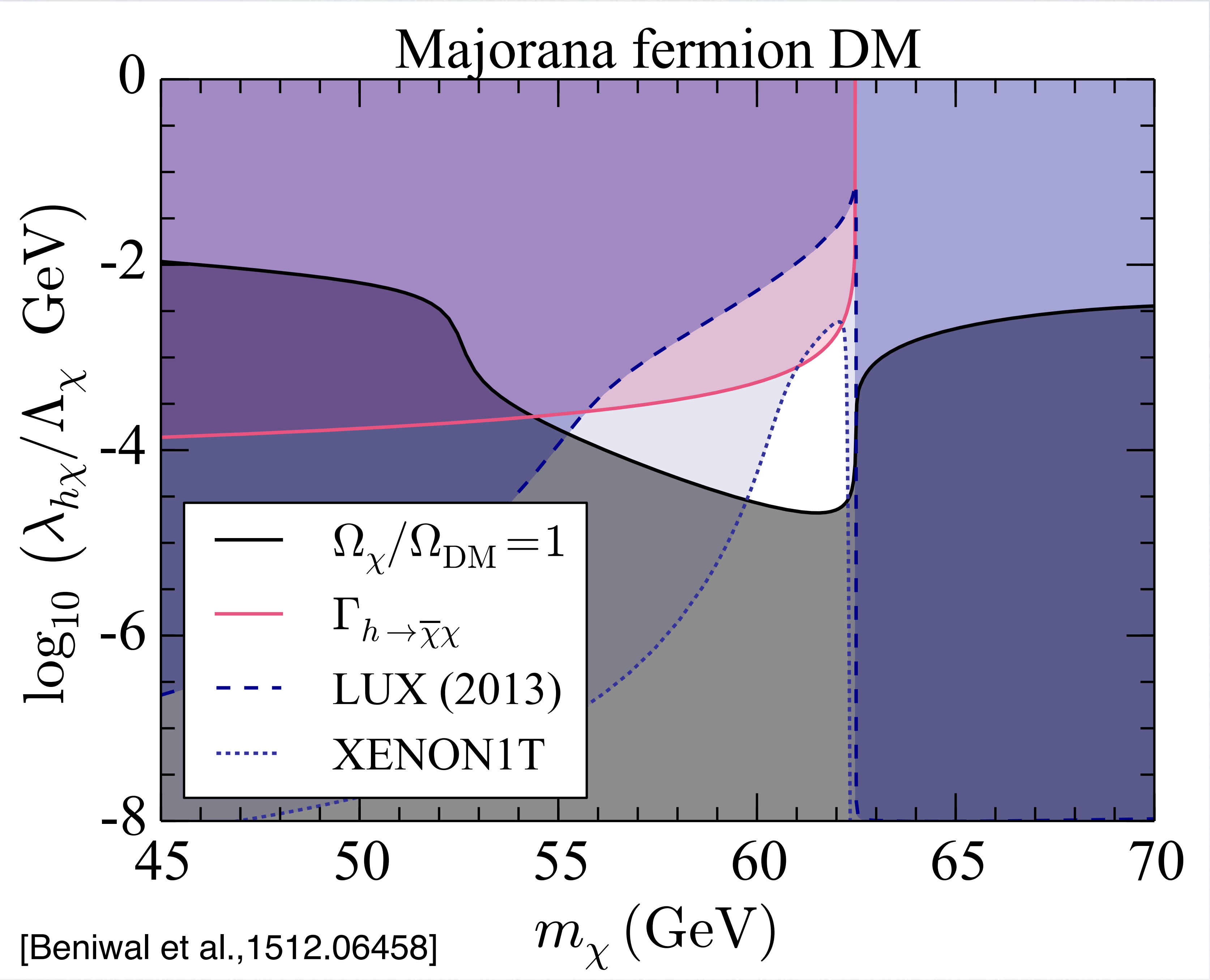
$g_S \ll g_{ew}$: $\langle \sigma_A v \rangle \ll \langle \sigma_A v \rangle_{th}$

Observed relic abundance only at resonance: $2m_\chi \approx M_h$

Annihilation and nucleon scattering through same process:

strong bound from direct detection $g_S <<< g_{ew}$

THE END?

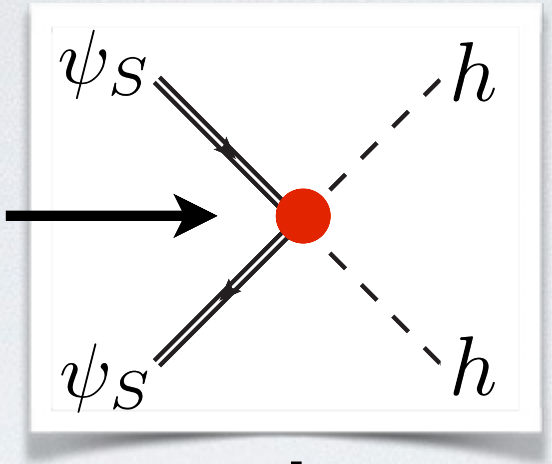


Need light mediators for thermally produced Higgs-portal dark matter.

UV-COMPLETE PORTALS

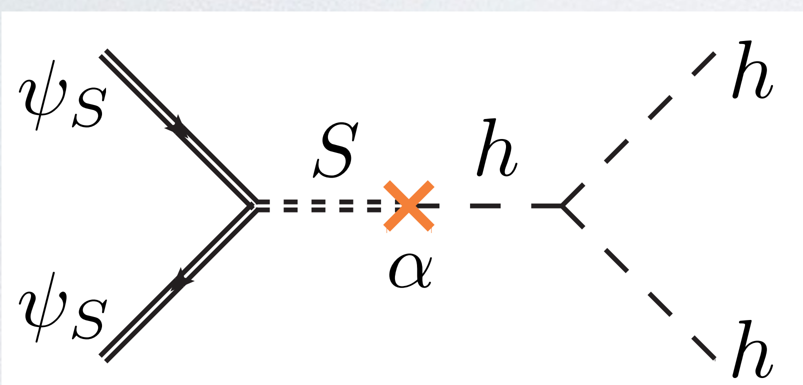
[Freitas, SW, Zupan, 1506.04149]

$$g_S = \frac{y^2}{2m_D}$$



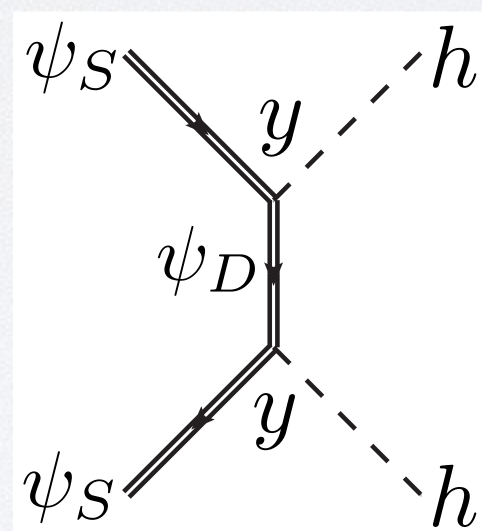
$m_D \lesssim \text{few}\,100\,\text{GeV}$

singlet-singlet



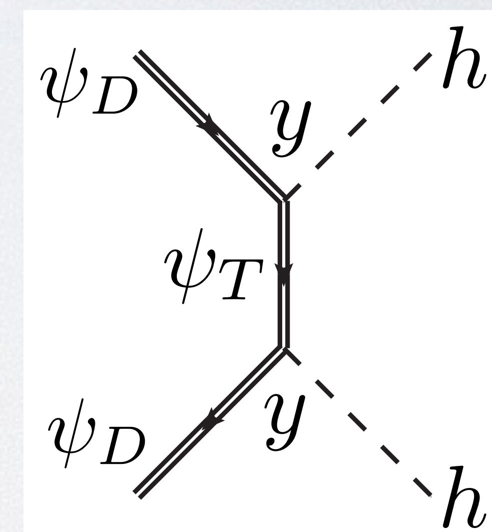
[Lee et al., 2008, …]

singlet-doublet



[Mahbubani, Senatore, 2005, …]

doublet-triplet



[Dedes, Karamitros, 2014]
[triplet-quadruplet: Tait, Yu, 2016]

similar to SUSY: bino-higgsino higgsino-wino

[Arkani-Hamed, Delgado, Giudice, hep-ph/0601041]

MAJORANA SINGLET-DOUBLET MODEL

Weyl fermions $\chi_D \sim (2, 1/2),\ \chi_D^c \sim (2, -1/2),\ \chi_S \sim (1, 0)$:

$$\mathcal{L}_m \supset m_D \chi_D^c \epsilon \chi_D - \frac{1}{2} m_S \chi_S \chi_S - y(H^\dagger \chi_D \chi_S - \chi_S \chi_D^c \epsilon H) + \text{ h.c.}$$

Mixing through electroweak symmetry breaking:

$$\chi_l^0 = \sin\theta \chi_D^0 + \cos\theta \chi_S, \quad \chi_h^0 = \cos\theta \chi_D^0 - \sin\theta \chi_S$$

Singlet dark matter

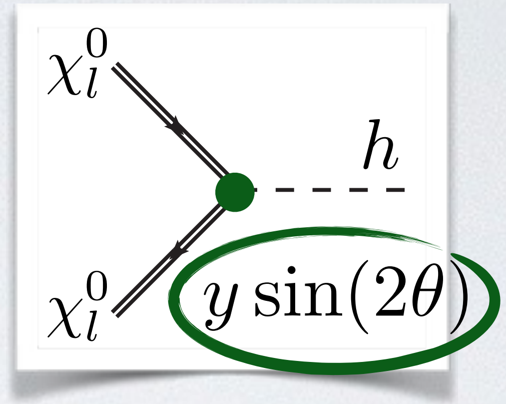
Doublet dark matter

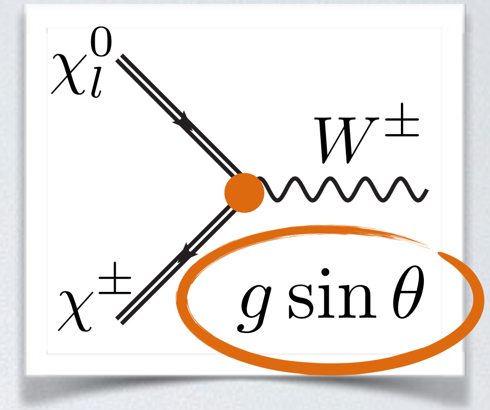
χ_l^0 SINGLET DARK MATTER

small mixing with doublet

$$\theta \sim \frac{yv}{m_D - m_S}$$

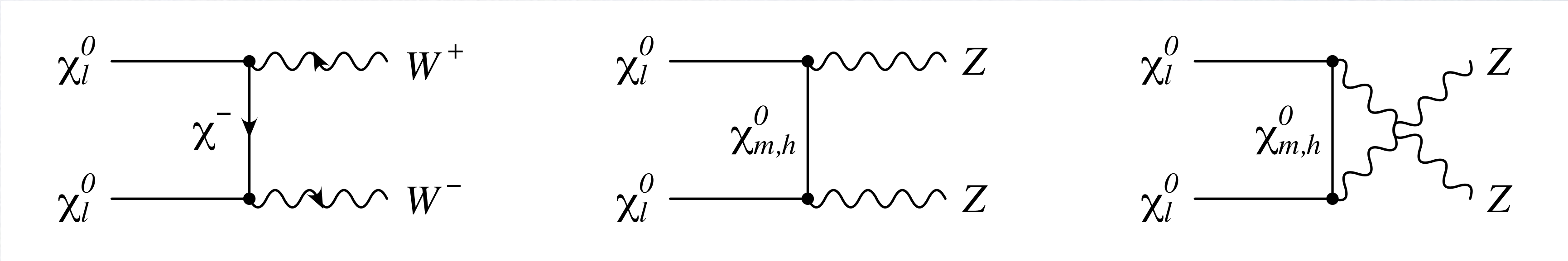
Higgs and gauge couplings





Nucleon scattering:
Higgs mediation suppressed for $\chi_l^0 \approx \chi_S$. Z mediation absent.

Relic abundance:



Pair annihilation suppressed, need co-annihilation.

$$m_l^0 \gtrsim 100\,\mathrm{GeV}, \quad m_D - m_l^0 \lesssim 30\,\mathrm{GeV}, \quad 0.01 \lesssim y \lesssim 0.1$$

χ_m^0

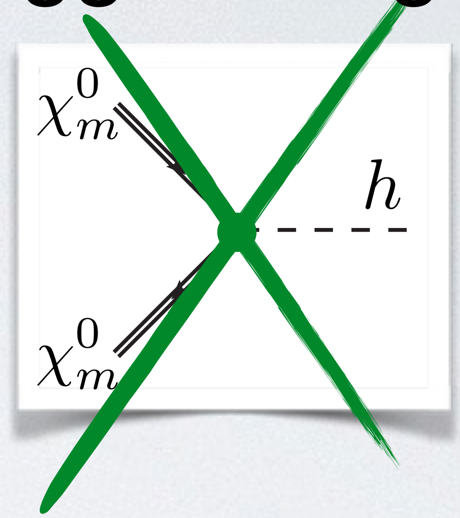
DOUBLET DARK MATTER

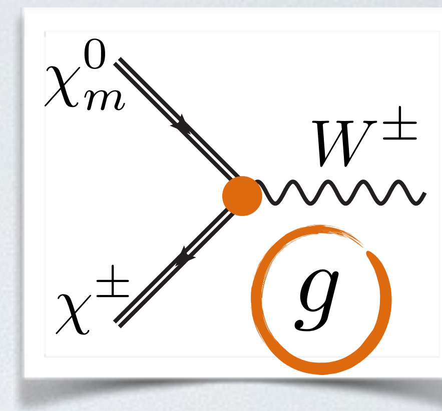
lightest state is pure doublet

loop-induced splitting

$$m^{\pm} - m_m^0$$

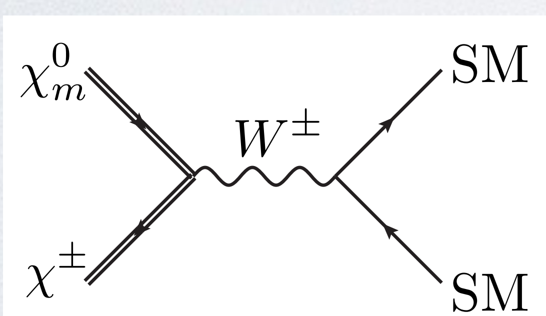
Higgs and gauge couplings





Nucleon scattering:
No spin-independent interaction at tree level.

Relic abundance:

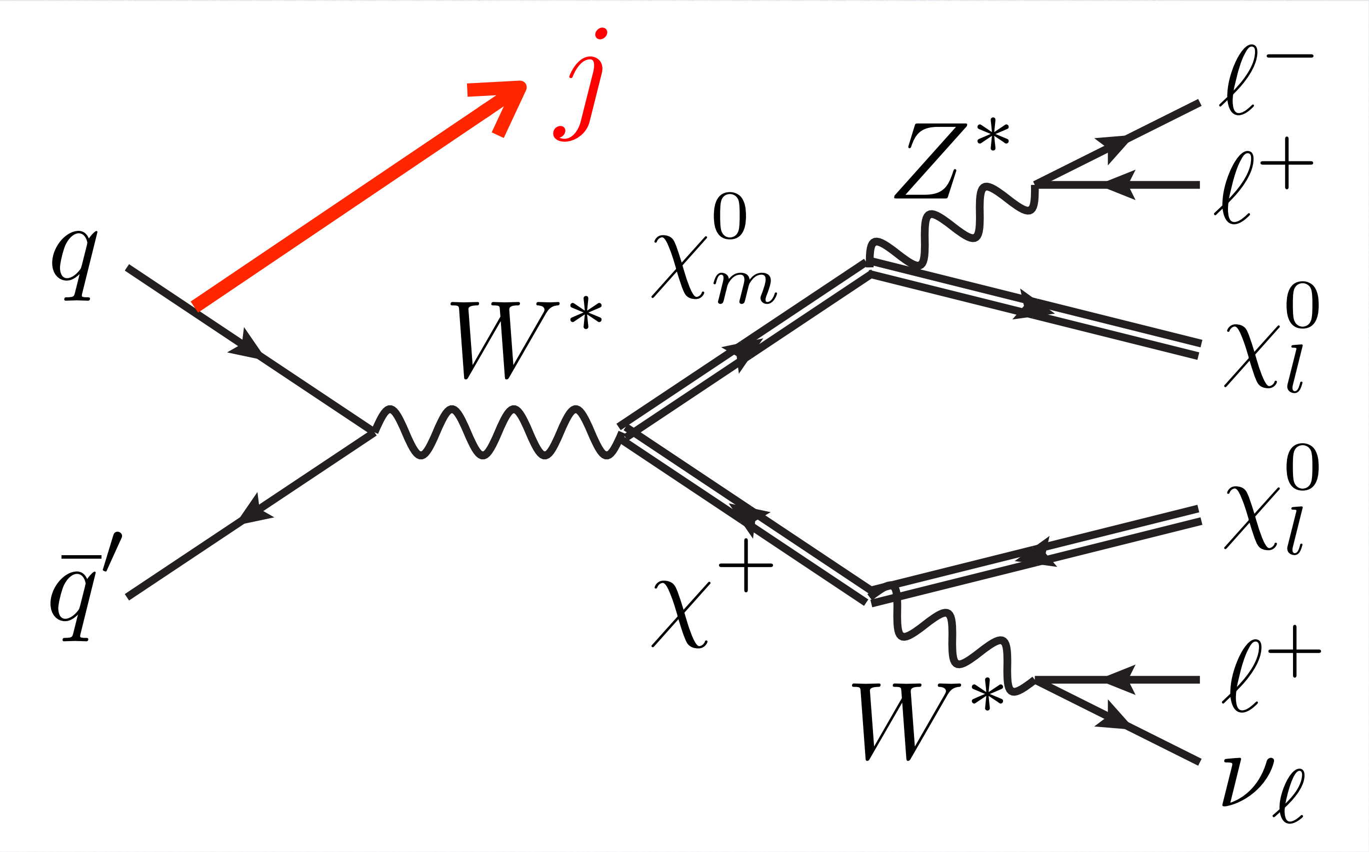


Strong co-annihilation with charged state.

$$m_m^0 \gtrsim \text{few TeV}; \quad m_l^0, y \text{ variable}$$

MEDIATOR SIGNALS AT THE LHC

$m_D - m_l^0 \lesssim 30\,\mathrm{GeV}$: soft leptons and missing energy



Similar to SUSY electroweakino and slepton signals.

[Giudice et al., 1004.4902] [Gori, Jung, Wang, 1307.5952] [Schwaller, Zurita,1312.7350] [Porod et al., 1705.06583]

Vector boson fusion might be complementary.

[Dutta et al., 1411.6043] [Berlin et al., 1502.05044]

LITERATURE

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