Chasing the dark with high luminosity.

Dark matter searches at the HL-LHC

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DESY LHC discussion
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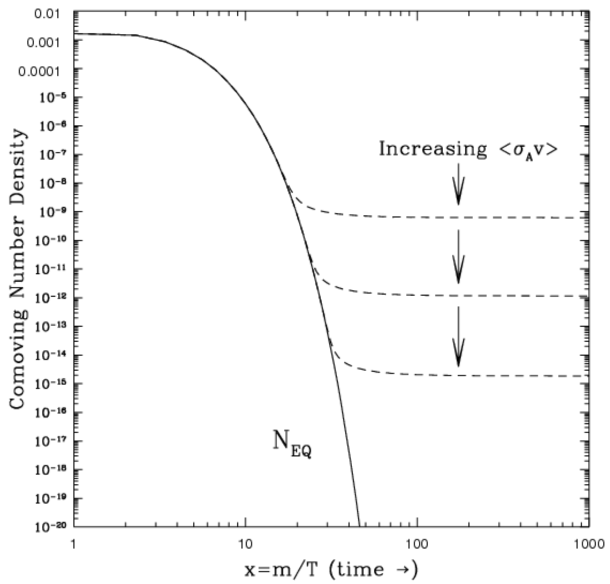
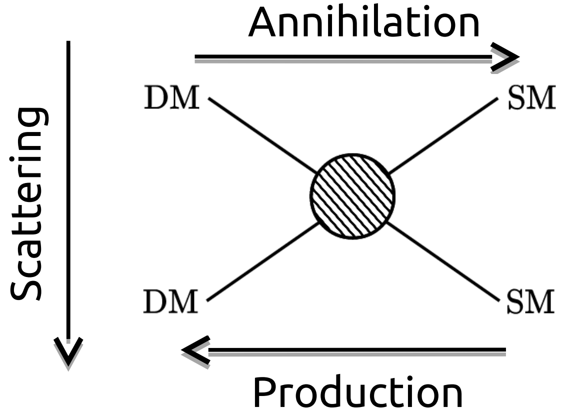
Outline

- Introduction
- Dark matter produced in association with top quarks
  - Based on arXiv:1611.09841 by Ulrich Haisch, Priscilla Pani & Giacomo Polesello
- Dark matter produced in association with Higgs bosons
  - Based on arXiv:1701.07427 in collaboration with Martin Bauer & Ulrich Haisch
- Conclusions

Why do we search for dark matter at colliders?

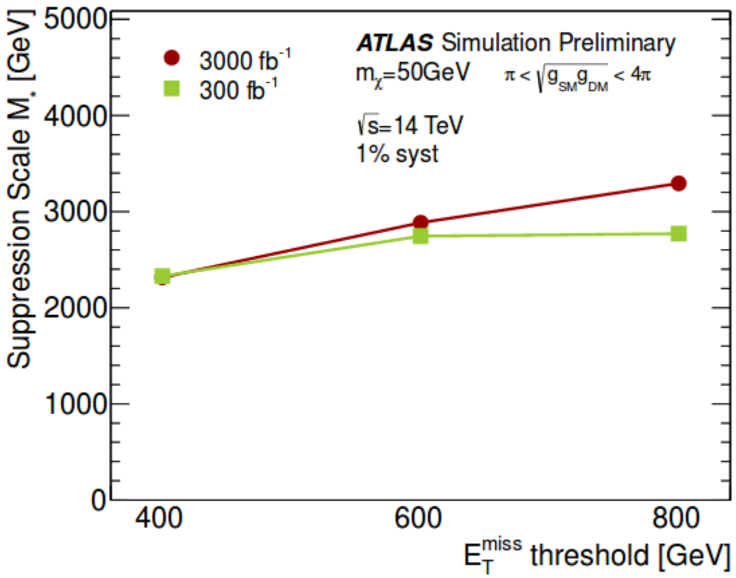
- Fundamental motivation: the paradigm of thermal freeze-out
  - DM was in thermal equilibrium with SM states at high temperatures
  - At lower temperatures the interactions freeze out
  - A particle with weak interactions and a weak-scale mass would obtain roughly the observed DM abundance





- In this framework, DM cannot be arbitrarily heavy (typically < 100 TeV) and must have sizeable interactions with SM particles
- Colliders may allow us to “invert” the annihilation processes that occurred in the early Universe

- Searches for missing energy (MET) are not exactly precision measurements
- Example: mono-jet searches
  - Largest sensitivity for a dark matter signal in the tail of the MET distribution
  - Theory uncertainties in background prediction >5% due to effects from NLO electroweak corrections
  - Experimental uncertainties (resolution, reconstruction efficiencies, …) >3%
  - Not enough to benefit from high-luminosity upgrade!
  - Need to reduce systematic uncertainties to 1% even in the tails



Dark matter precision physics

- If anything, measuring MET at the HL-LHC will only become harder!

- No! High luminosity does matter for dark matter searches where we are interested in processes with very small background rates

- Today I will focus on two examples:
  - $t\bar{t}$ + dark matter in the fully leptonic final state
  - Higgs + dark matter in the γγ final state

Theory motivation

- One of the most natural ways in which dark matter can couple to Standard Model (SM) states is via the exchange of a new scalar particle (e.g. an additional Higgs boson in the dark sector)

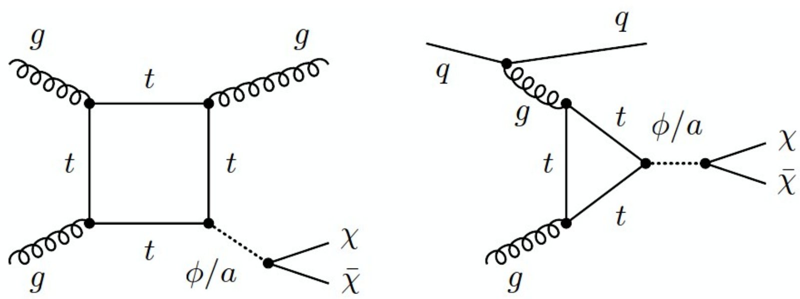
- Hypothesis of minimal flavour violation: The new scalar should couple to SM fermions proportional to their masses

- Such a set-up is for example realized naturally if the new mediator obtains its couplings to fermions from mixing with the SM Higgs boson

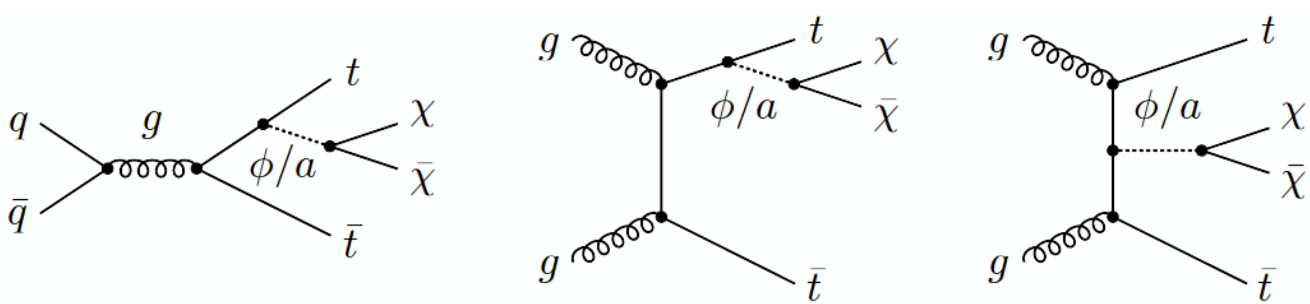
- Generic consequence: Dark matter couples most strongly to top quarks!

Dark matter interactions with top quarks

- Two experimental opportunities:
  - Dark matter + jets from top-quark loops



  - Dark matter in association with a pair of top quarks



If the W bosons from the decays of the two tops both decay leptonically, one obtains a very clean final state

Measuring CP properties

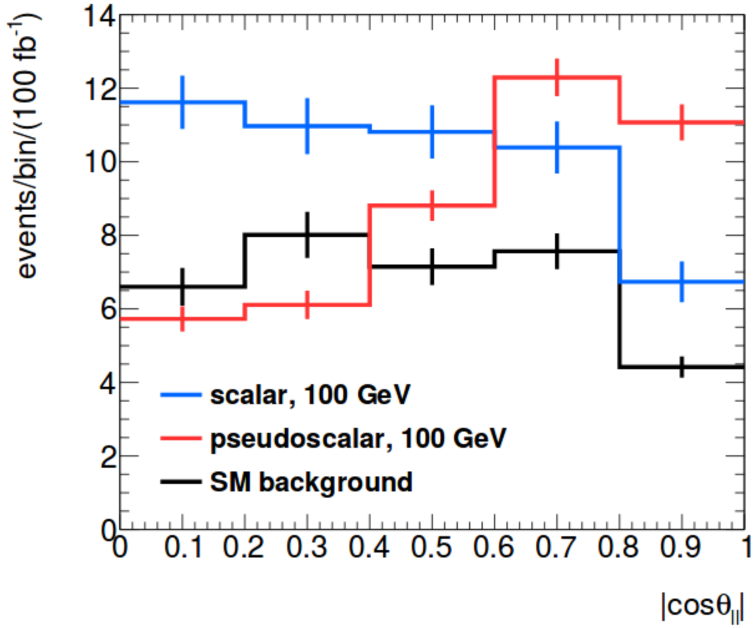
- The fully leptonic final state does not usually have the highest sensitivity for a dark matter signal, but it can be used as a CP analyser of the underlying process

- For example, the typical distance of the two leptons in the azimuthal plane depends on whether the mediator of the dark matter interactions is a scalar or a pseudoscalar

- An even more promising variable is

$$\cos\theta_{\ell\ell} \equiv \tanh\left(\Delta\eta_{\ell\ell}/2\right)$$

where $\Delta\eta_{\ell\ell}$ is the difference in pseudorapidity of the two charged leptons

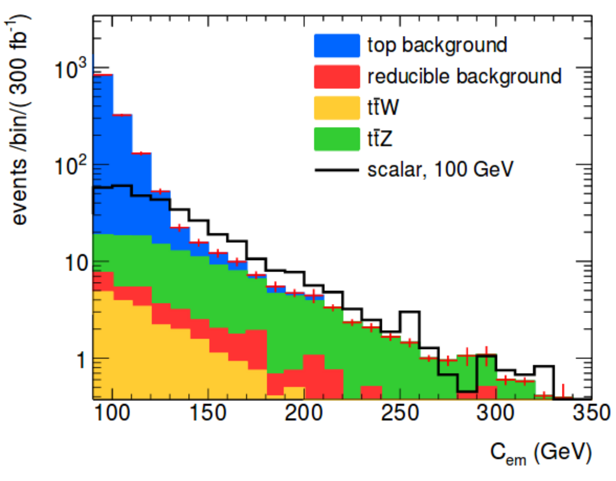


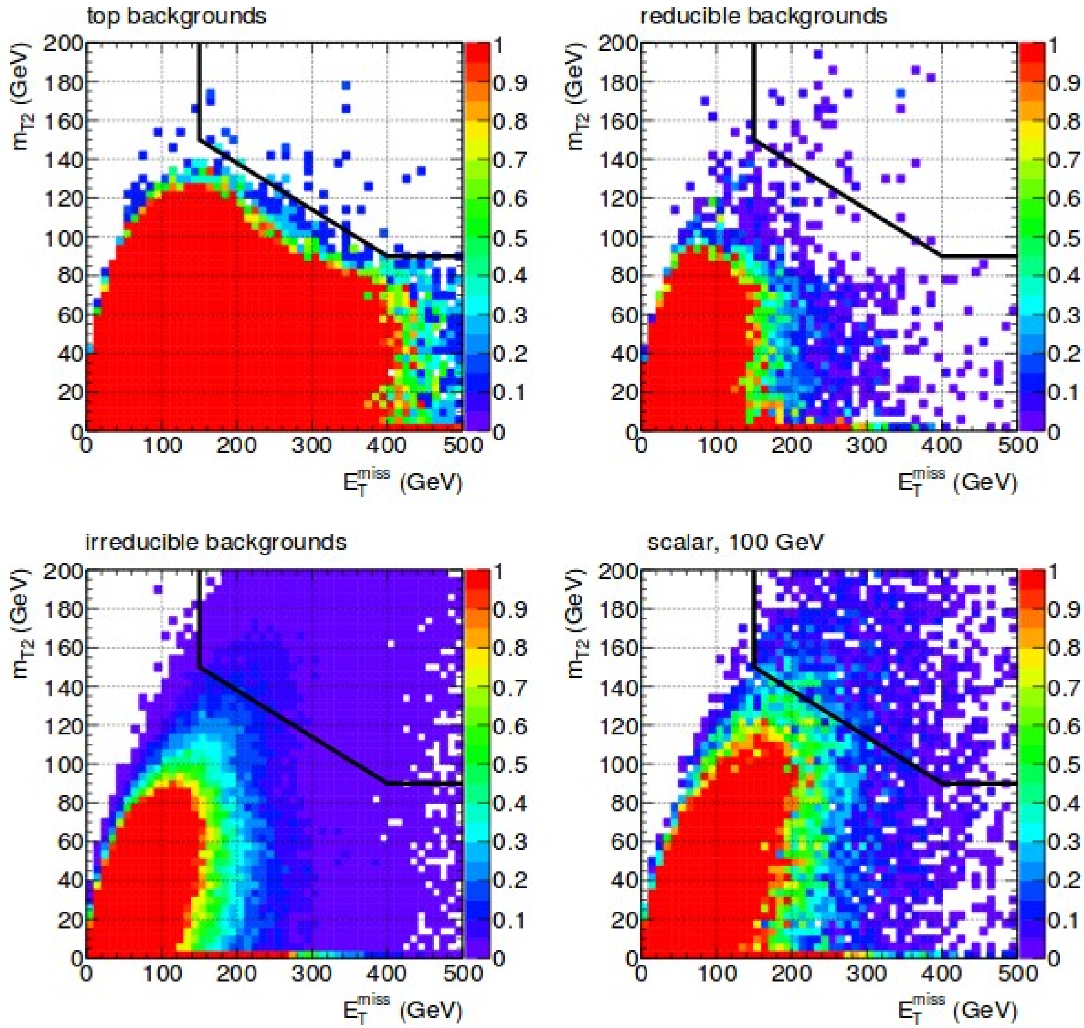
A realistic analysis

- Crucial strategy: Combination of cut on MET and m_{T2}
- Require C_{em} > 130 GeV, where

$$C_{\rm em} \equiv m_{\rm T2} + 0.2 \cdot (200\,{\rm GeV} - E_{\rm T}^{\rm miss})$$

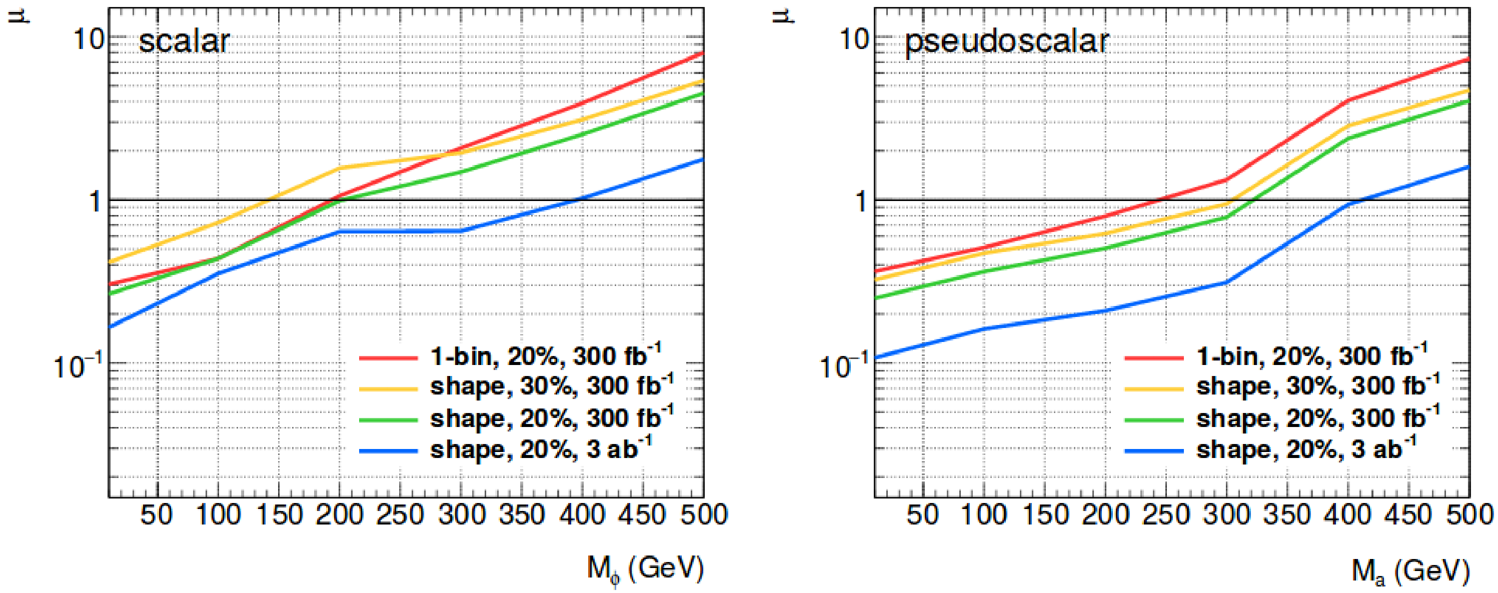
- Dominant (irreducible) background: $t\bar{t}$ + Z





Expected sensitivity

- After basic event selection, one can make use of the distribution of $|\cos\,\theta_{ll}|$ to achieve the best sensitivity
- Expected experimental sensitivity depends crucially on systematic uncertainties, i.e. detector performance and background modelling
- Assumption: 20% background uncertainty (fully correlated)



Expected discrimination power

- One can use these results to determine the signal strength required to discriminate scalar and pseudoscalar interactions
- With HL-LHC this discrimination is possible up to significantly higher mediator masses and down to significantly smaller signal strengths (i.e. couplings)
- Note: MET parametrisation tuned to reproduce Run 1 results; no pileup mitigation in MET algorithm

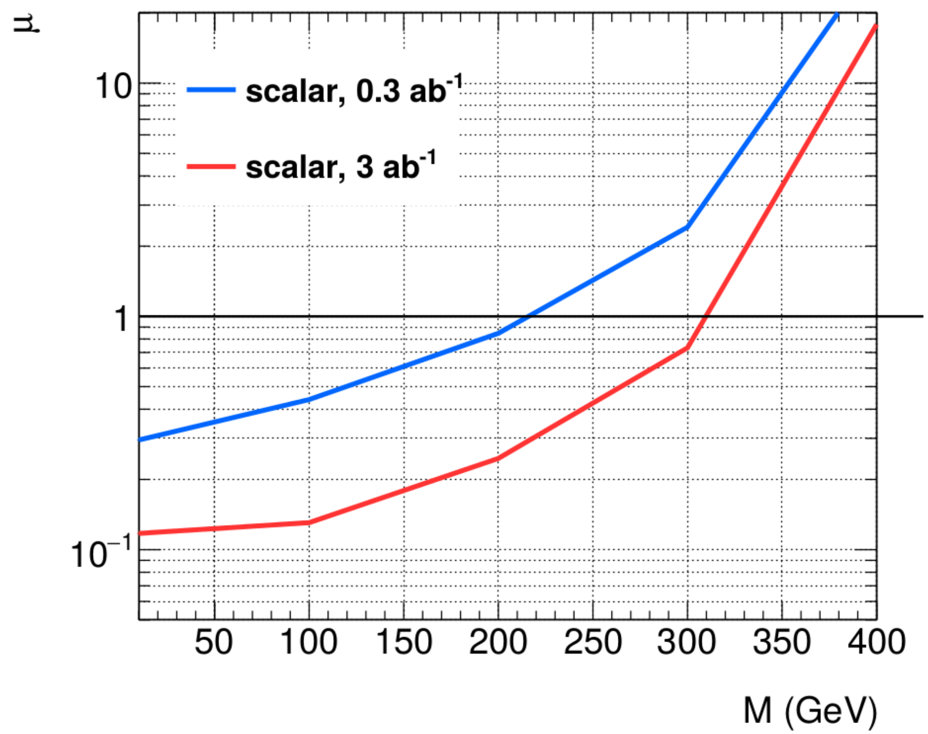
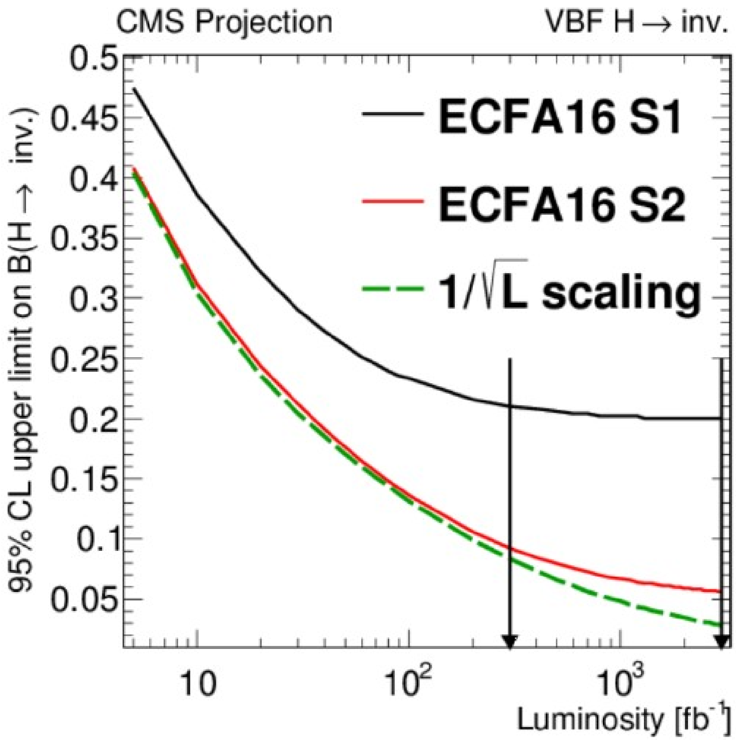


Figure kindly provided by Giacomo Polesello

Back to the theory motivation

- How exactly does the mediator obtain its couplings to SM fermions?
- If these couplings result from mixing with the SM Higgs, shouldn't this affect the properties of the SM Higgs boson?
- A mixing angle θ reduces the SM Higgs signal strength by $\theta^2/2$
- Moreover, the SM Higgs obtains couplings to the DM particle, leading potentially to a large invisible branching fraction:
  - Currently: BR(inv) < 25%
  - HL-LHC: BR(inv) < 5%
- Very little room for a dark matter signal!



Introducing a second Higgs doublet

- The situation changes significantly if we consider dark matter extensions of two Higgs doublet models (THDM)
- Rather than mixing with the SM Higgs, the spin-0 mediator can now mix dominantly with its scalar or pseudoscalar partners

$$V_P = \frac{1}{2} m_P^2 P^2 + P \left(i b_P H_1^\dagger H_2 + \text{h.c.} \right) + P^2 \left(\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2 \right)$$

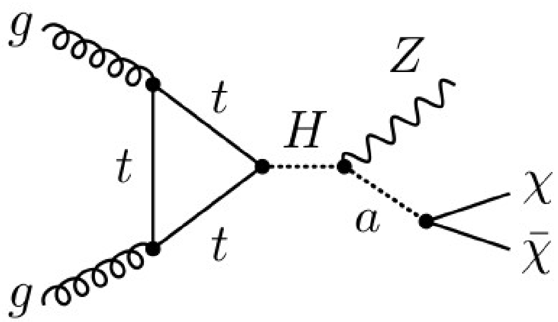
- The branching ratios of the SM Higgs remain unchanged – but the heavier states may obtain a significant invisible branching fraction (this may even explain why we haven't observed them yet)
- Note that this is in fact the minimal set-up to couple a pseudoscalar singlet to SM fermions in a gauge invariant and renormalisable way
- After mixing one obtains two pseudoscalar mass eigenstates: *A* and *a*

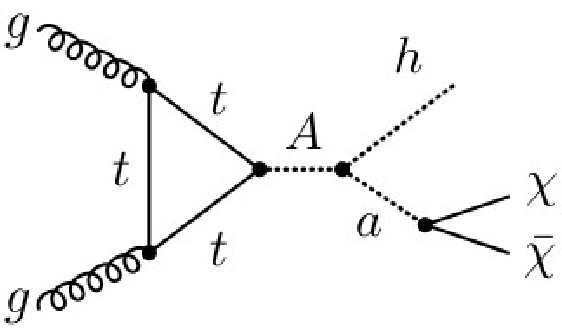
The relevant parameter space

- For simplicity I will focus on the alignment/decoupling limit, sin(β-α) = 0. The scalar h then has SM-like couplings to electroweak gauge bosons
- Flavour constraints (e.g. $B \to X_s\,\gamma$) require that the charged Higgs bosons are relatively heavy: $M_{H+} \sim 750$ GeV
- Electroweak precision constraints require $M_H = M_{H+}$ so that the tree-level scalar potential is custodially invariant
- Relevant parameters: The masses of the two pseudoscalars, their mixing angle θ and the effective top-quark coupling $1/\tan\beta$
- The dark matter mass and its Yukawa coupling is less relevant, as the lighter pseudoscalar almost always has 100% invisible branching fraction

Novel signatures: mono-Higgs and mono-Z

- The THDM set-up predicts two important new signatures not relevant in simpler dark matter models:





- These processes can be resonantly enhanced for $M_H > M_a + M_Z$ and $M_A > M_a + M_H$, respectively

- Since *a* decays invisibly, one obtains sizeable MET even if *H*/*A* is produced almost at rest

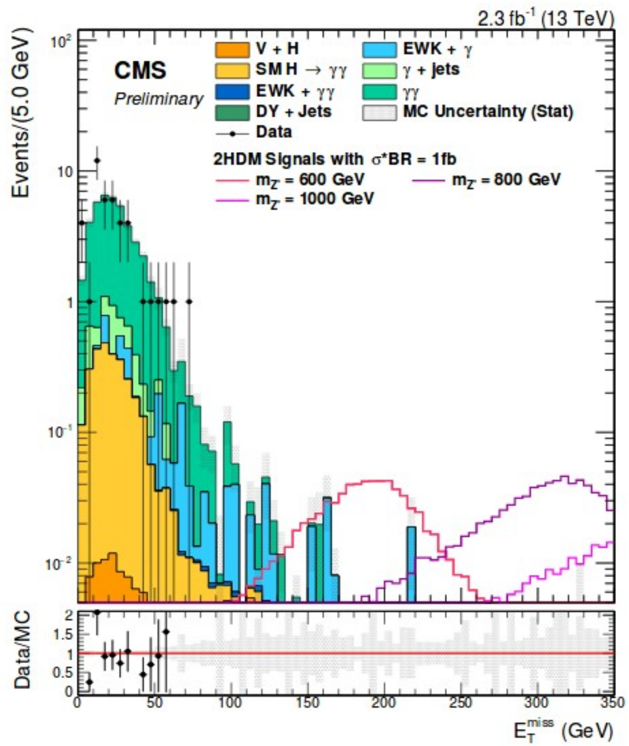
Mono-Higgs searches

- The amount of MET produced in A → a h is only moderate (typically of order 100 GeV). But this is sufficient to search for h + MET in the $\gamma\gamma$ final state

- Event selection:
  - 120 GeV < $m_{\gamma\gamma}$ < 130 GeV
  - $p_T(\gamma\gamma)$ > 90 GeV
  - $p_T(\gamma_1) > m_h / 2$
  - $p_T(\gamma_2) > m_h / 4$
  - MET > 105 GeV

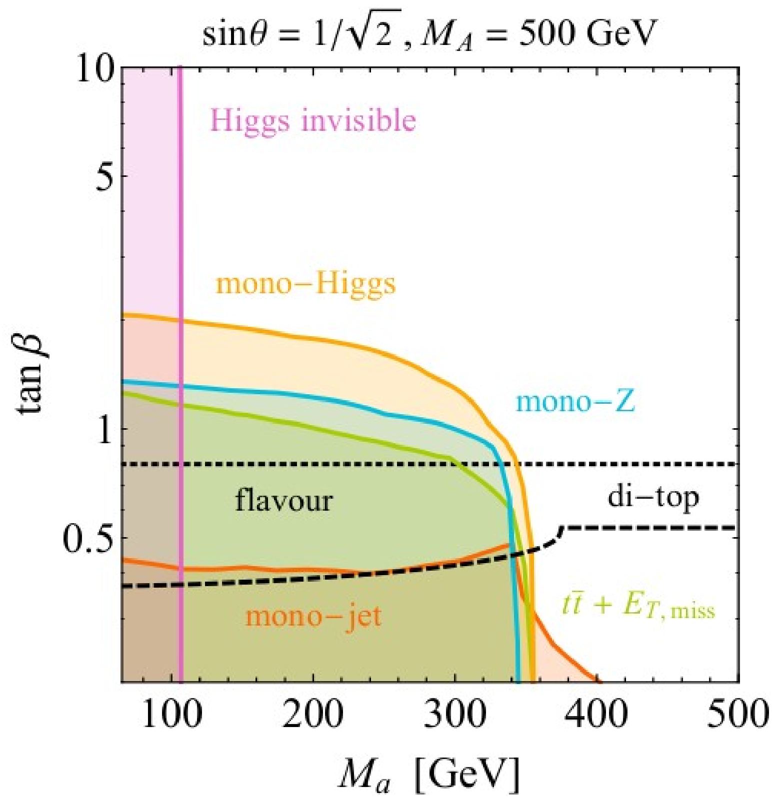
- At 2.3 fb^{-1} the total background is 0.44 events

- Mono-Higgs searches are entirely statistics dominated for the foreseeable future!



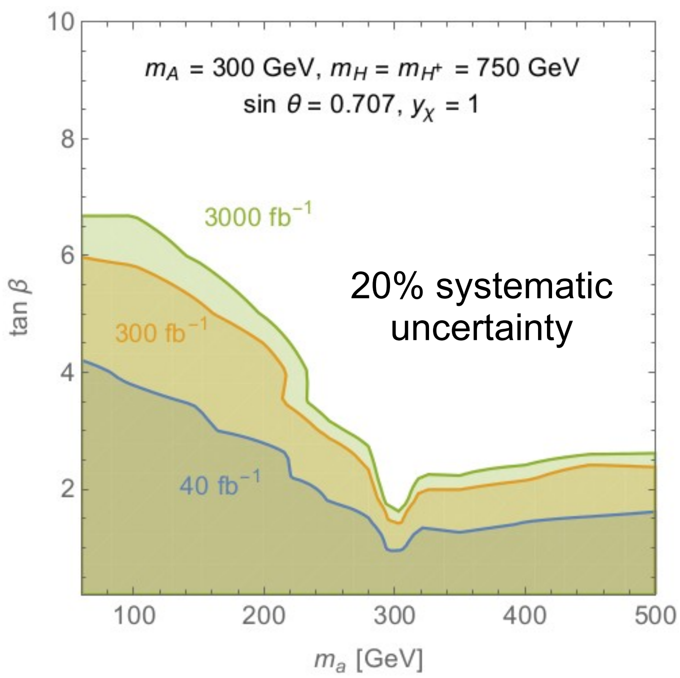
Results

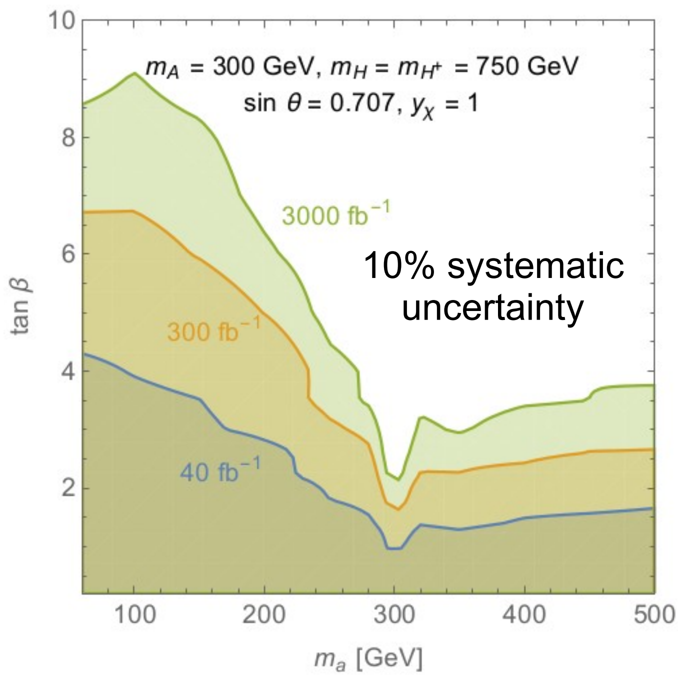
- Projected sensitivity for 40 fb^{-1} (300 fb^{-1} for tt+MET).
- Analysis chain: MadGraph5_aMC@NLO + PYTHIA + Delphes 3 + MadAnalysis 5
- Extrapolations assume that
  - relative systematic uncertainties remain the same
  - relative statistical errors scale as 1/√L with luminosity L
- Mono-Higgs and mono-Z give the strongest constraints on the parameter space



Projections for HL-LHC

- Limiting factor: Systematic uncertainty of the non-resonant background (i.e. shape of the $m_{\gamma\gamma}$ distribution
  - Current estimate of uncertainty: 20%
  - More statistics in control regions will help a lot – let's optimistically assume that it will be possible to reduce this to 10%





Additional contribution from b-quarks in the initial state not included (depends on Yukawa sector)

Light mediators

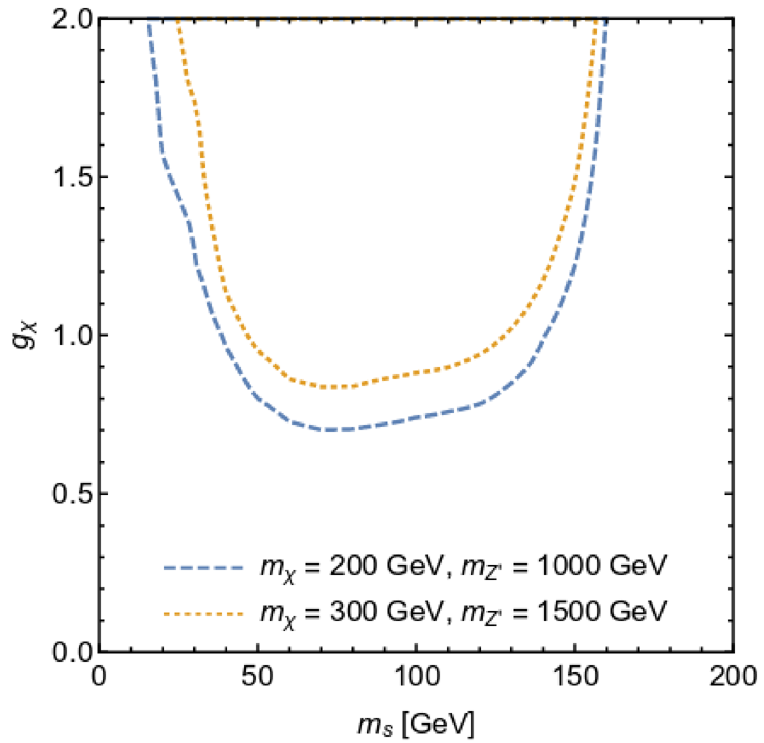
- What if the scalar mediator is lighter than the dark matter particle?
  - Invisible decays are kinematically forbidden
  - The light mediator must decay into SM fermions

- Similar to NMSSM, but the light mediator is often produced in association with dark matter (e.g. via dark-Higgs-Strahlung)

- Look for visibly decaying light Higgs boson produced with sizeable MET!

- Recent sensitivity study for bb final state (Duerr, FK et al., arXiv:1701.08780)

- Sensitivity study for $\gamma\gamma$ final state ongoing …



Conclusions

Missing energy searches are messy, but there are some channels that are sufficiently clean to benefit from a high-luminosity upgrade

- Example 1: If dark matter couples dominantly to top-quarks, we can study the fully leptonic final state to infer the CP structure of the interaction
- Dark matter extensions of THDM predict interesting novel signatures and provide a robust theoretical motivation for mono-Z and mono-Higgs searches
- Example 2: Mono-Higgs searches in the $\gamma\gamma$ final state are still entirely limited by statistics and can probe wide regions of the m_a-tanβ parameter space
- If you would like to find out more let us know: we are happy to distribute the UFO model file (detailed studies ongoing within the LHC DM working group)