The Dark Light Higgs scenario and semi-visible exotic Higgs decays

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JGU Mainz

Phys. Rev. Lett. 112 (2014) 22, 221803, [arXiv:1309.6633 [hep-ph]]
Phys. Rev. D90 (2014) 11, 115006, [arXiv:1407.0038 [hep-ph]]
with Jinrui Huang, Tao Liu, Lian-Tao Wang

Exotic Higgs Decays workshop, SLAC
November 8, 2016

Introduction and Motivation

- Precision Higgs physics establishes direct window to new light states via decays

  LHC Higgs Xsec WG [1610.07922]

  - Small SM partial widths (Γ_H = 4.1 MeV, m_h = 125.09 GeV) easily challenged by light NP states
    - Also provides indirect window to heavy physics via Higgs portal
- (Mostly) gauge singlets at any scale are difficult to detect
  - Exotic Higgs decays provide a production anchor, enhanced access to marginal couplings compared to direct production at colliders

Dark Light Higgs scenario

Draper, Liu, Wagner, Wang, Zhang
PRL **106** 121805 (2011) [1009.3963]

- Nearly Peccei-Quinn limit of NMSSM
  - Addresses μ fine-tuning problem of MSSM

Kim, Nilles PLB **138**, 150 (1984)

$$\mathbf{W} = \lambda \mathbf{S} \mathbf{H}_u \mathbf{H}_d + \mathcal{O}(\kappa)$$

$$V_{\rm soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 - (\lambda A_\lambda H_u H_d S + \text{h.c.}) + \mathcal{O}(\kappa)$$

  - Dynamical solution: $\mu \equiv \lambda \langle S \rangle$, take $\lambda = \dfrac{\mu}{v_S} \lesssim 0.1$
    - PQ-symmetric limit differs from $U(1)_R$-symmetric limit

Dobrescu, Landsberg, Matchev, PRD **63**, 073003 (2001)
Dermisek, Gunion, PRL **95**, 041801 (2005)

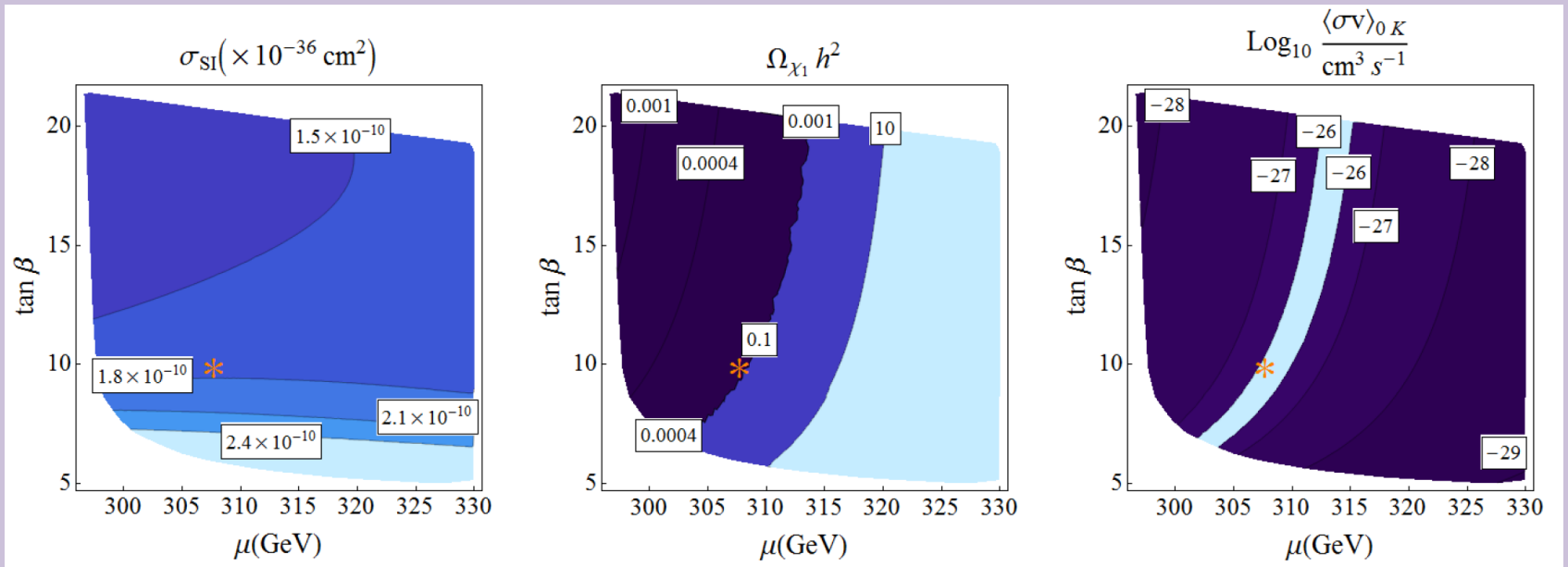
    - PQ axion supermultiplet components are all light
      - (PQ-limit realized when $\kappa/\lambda \to 0$, $A_\kappa \to 0$, explicitly broken by κ)
  - Light h_1, a_1, and χ_1 PQ supermultiplet states provide rich interplay of Higgs and DM physics

Connecting Higgs exotic decays and sub-EW DM physics

- Rich interplay of Higgs and DM physics
  - Fermi galactic center γ-ray excess motivated the original work using exotic Higgs decays as cross-check of DM explanation

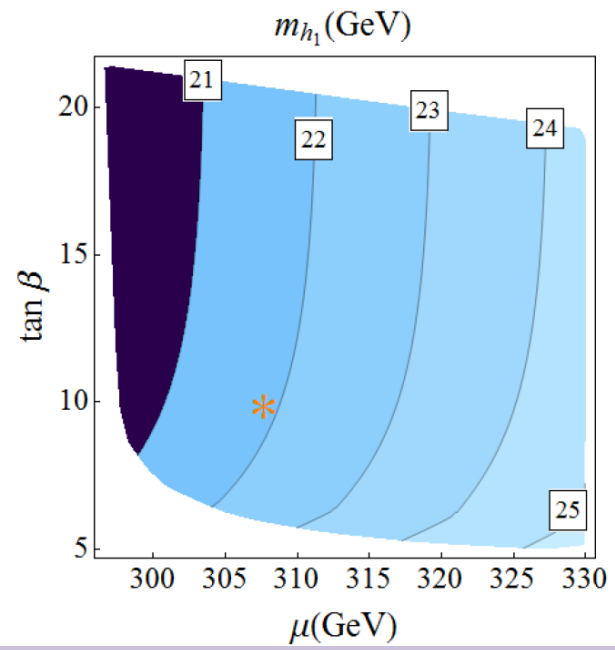
    Fermi-LAT, Astrophys. J **750**, 3 (2012) [1202.4039]
    - Current literature disagrees about DM origin of the γ-ray excess

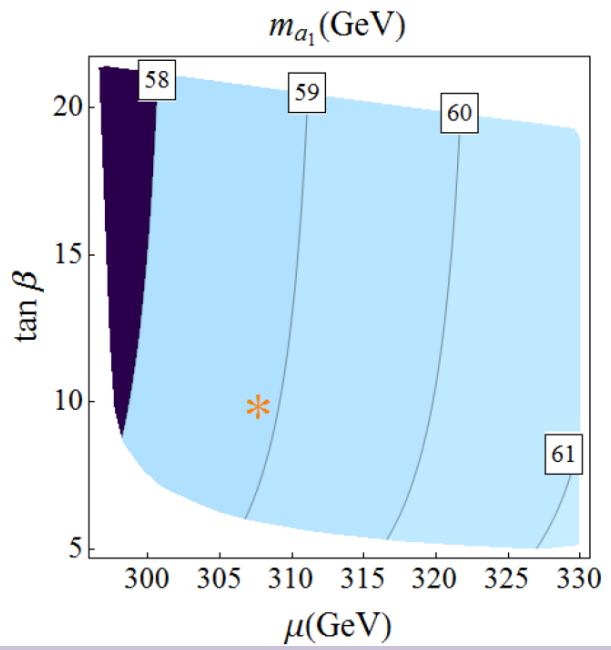
      See, e.g. Lee, Lisanti, Safdi, Slatyer, Xue, PRL **116** 5, 05113 (2016) [1506.05124]
- Consistent with Ωh^2, direct and indirect detection

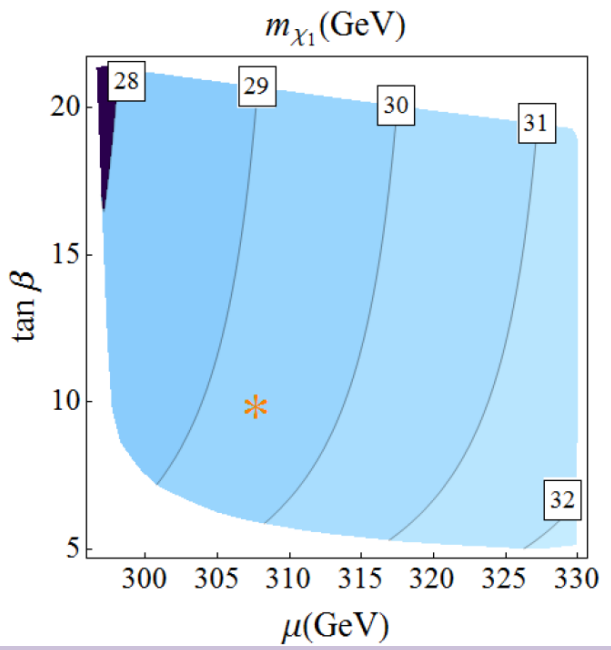


Connecting Higgs exotic decays and sub-EW DM physics

- Rich interplay of Higgs and DM physics
  - Realizes the class of **semi-visible exotic decays**
    - Contrast with fully visible (h→4b, 4g, 2b2μ, 2b2τ, etc.) and fully invisible (h→χχ) decays







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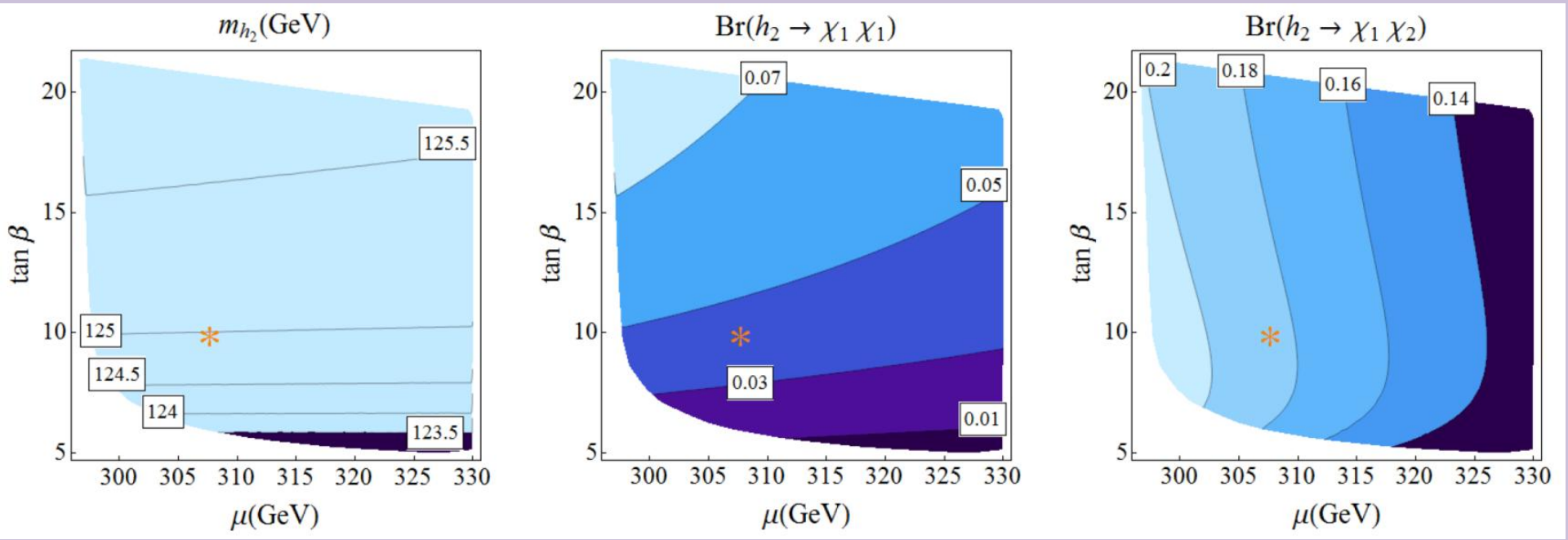
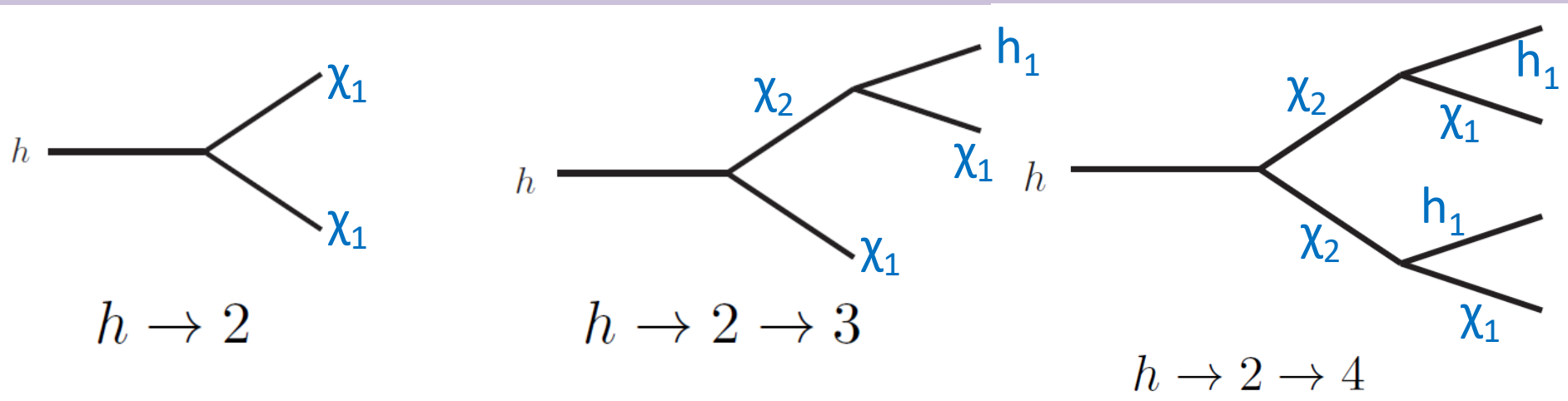


χ_1 is singlino-like, χ_2 is bino-like

Semi-visible exotic decays

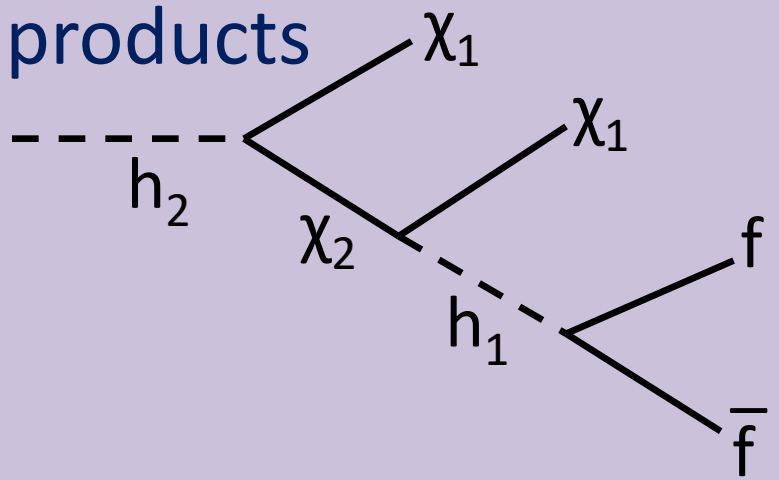
- Mixings and kinematics motivate h→2→3 topology, more than the well-known h→2 decay
  - Suppress $h \to \chi_1\chi_1$ by mixing, $h \to \chi_2\chi_2$ by kinematics
  - Leaves cascade decay $h \to \chi_1\chi_2$ dominant
    - h_1 decays to fermion pairs (μμ, bb, ττ)



Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong
PRD **90** (2014) 7, 075004 [1312.4992]

General collider phenomenology for semi-visible exotic decays

- h→2→3 topology with MET exacerbates challenges in fully visible h→2→4 studies
  - Z_2 parity requires two (even) DM decay products, Higgs not fully reconstructed
    - MET associated with Higgs decay not immediately disentangled from remainder of event
- Collider sensitivity depends on interplay between DM mass scale with visible products



General collider phenomenology for semi-visible exotic decays

- Generally need additional trigger
  - MET correlated with Higgs production mode
- Leptonic decays for associated Vh production are simplest
- Three case studies: μμ + MET, bb+MET, ττ + MET
  - For μμ+MET channel, use Wh mode, use trilepton trigger
  - For bb+MET and ττ+MET channels, use Zh mode, use dilepton trigger
  - (Interesting to study VBF and Higgs+jet as additional triggers and provide additional rate)

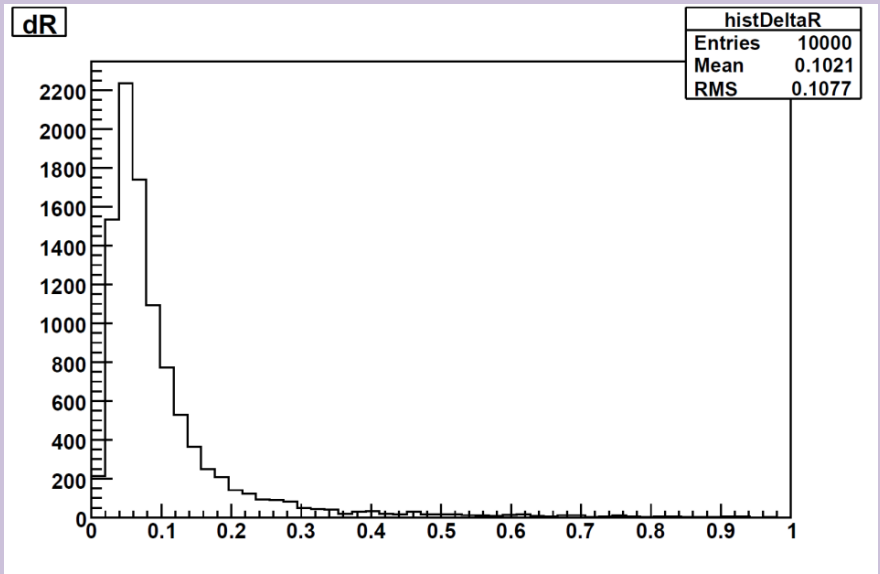
First channel: μμ+MET

- Good muon resolution to low p_T affords a clean signature

	m_{h_1} (GeV)	m_{h_2} (GeV)	m_{χ_1} (GeV)	m_{χ_2} (GeV)
$h_1 \to \mu^+\mu^-$	1	125	10	80

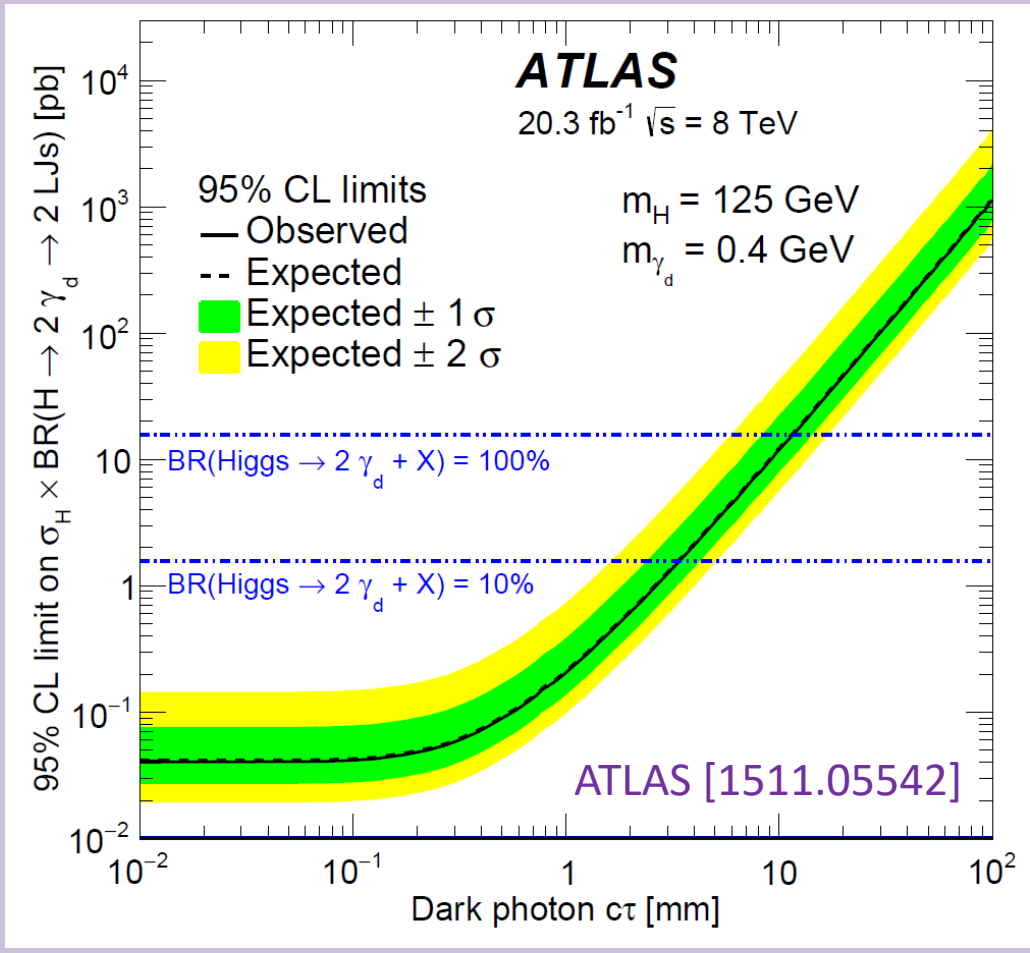
  - Wh, W→lν production mode gives appreciable MET
- Signal muons from h_1 decay are typically close, normal muon isolation requirement fails

Use $\Sigma p_T < 5$ GeV within $\Delta R < 0.4$ cone of each muon candidate, not including second muon candidate



μμ+MET – LHC constraints

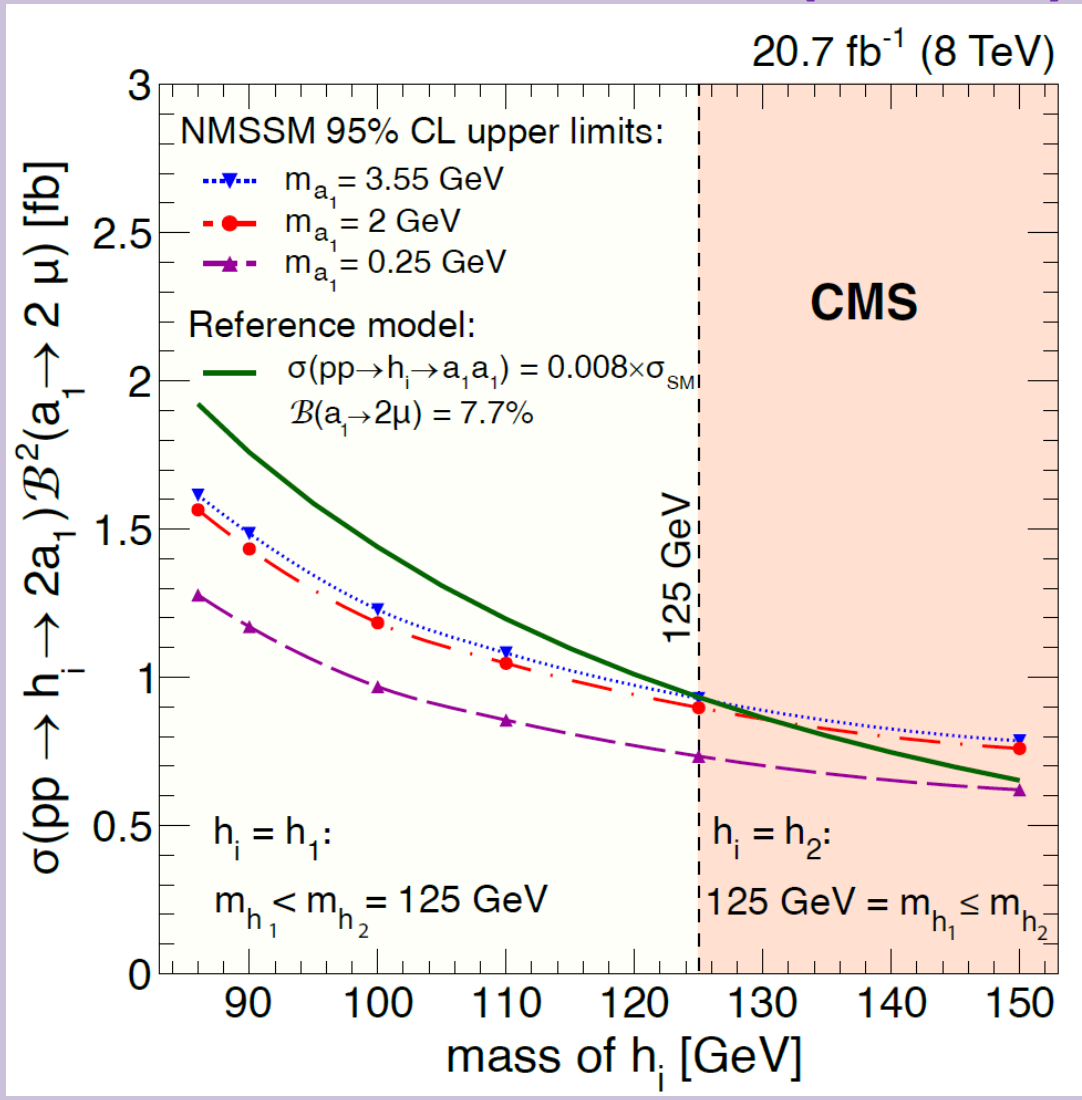
- Small ΔR separation, but current lepton jets studies insensitive
  - At least two lepton jets required



μμ+MET – LHC constraints

CMS [1506.00424]

- Resonances decaying to muon pairs
  - h_1, a_1 masses above 1 GeV open decays to strange mesons, gluon pairs
  - Can evade constraint by adjusting g_{h2h1h1} and g_{h2a1a1} couplings



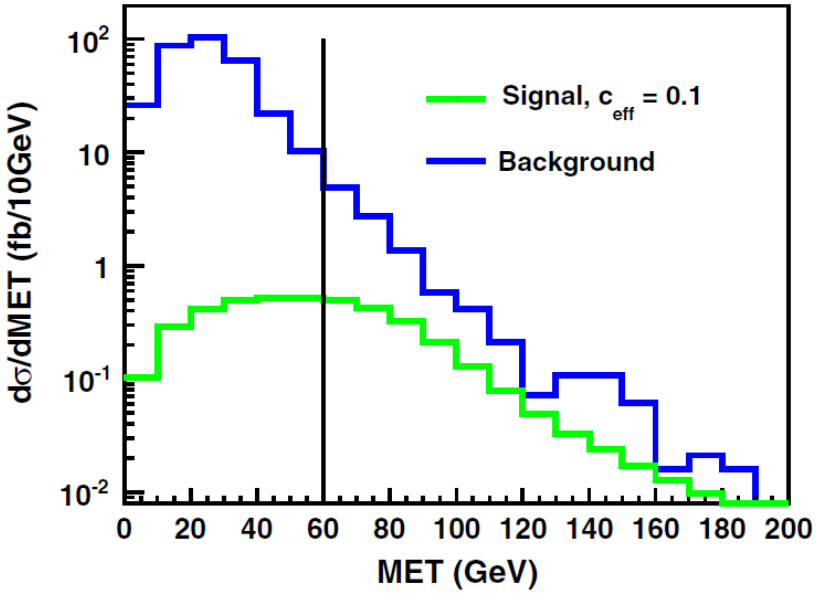
μμ+MET: LHC event selection

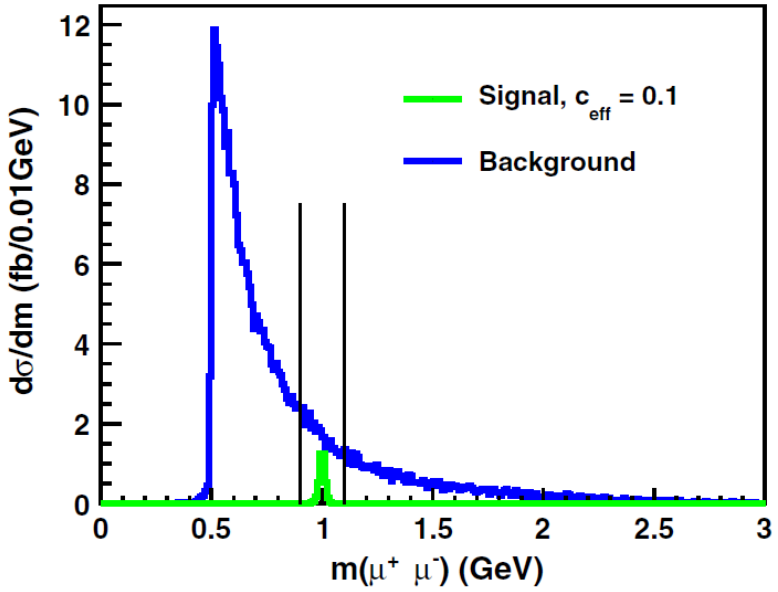
- Main cuts: $p_{T,1}^{\mu} > 20\ \mathrm{GeV}, p_{T,2,3}^{\mu} > 10\ \mathrm{GeV}, \Delta R_{\mu\mu} < 0.2, |\eta| < 2.4$

  $\not{E}_T > 60\ \mathrm{GeV}$

  - Primary background is W(γ*/Z), provides continuum dimuon mass spectrum
  - Rates rescaled using combination of Br factors:

$$c_{\mathrm{eff}} = \frac{\sigma(pp \to W^{\pm} h_2)}{\sigma(pp \to W^{\pm} h_{\mathrm{SM}})} \times \mathrm{Br}(h_2 \to \chi_1\chi_2) \times \mathrm{Br}(\chi_2 \to h_1\chi_1) \times \mathrm{Br}(h_1 \to f\bar{f})$$





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  $\not{E}_T > 60\ \text{GeV}$
  - Primary background is W(γ*/Z), provides continuum dimuon mass spectrum
  - High local significance from dimuon mass window cut
  - 8 TeV sensitivity numbers:

Cuts and efficiencies	Wh_2	$W(\gamma^*/Z \to \mu^+\mu^-)$
Cross section (pb)	$0.149 \times c_{\text{eff}}$	26.6
Lepton geometric, p_T, and isolation requirements	28.2%	1.22%
$\not{E}_T \geq 60$ GeV	12.5%	0.0403%
$0.9 \leq m_{\mu^+\mu^-} \leq 1.1$ GeV	12.3%	0.0047%
S, B, $S/\sqrt{B}$ (20 fb^{-1}, $c_{\text{eff}} = 0.1$)	37, 32, 6.5σ	

  - For 13 TeV, performing search probes smaller c_{eff}

Second channel: bb+MET

- Much more difficult than dimuon channel
  - h_1 decays to bb dominantly for $m(h_1) > 10$ GeV
  - Efficiency for tagging b-jets poor at low p_T
- Use Zh production, Z to dileptons
  - Signature is dileptonic Z, MET, b-tagged jet
  - For heavier h_1, signal becomes progressively easier
    - Can use jet substructure for semi-boosted bb resonance
- Benchmark

	m_{h_1}	m_{h_2}	m_{χ_1}	m_{χ_2}
$h_1 \to b\bar{b}$	20 GeV	125 GeV	30 GeV	80 GeV

  - Complemented by h→2a→4b, but different NP parameter space

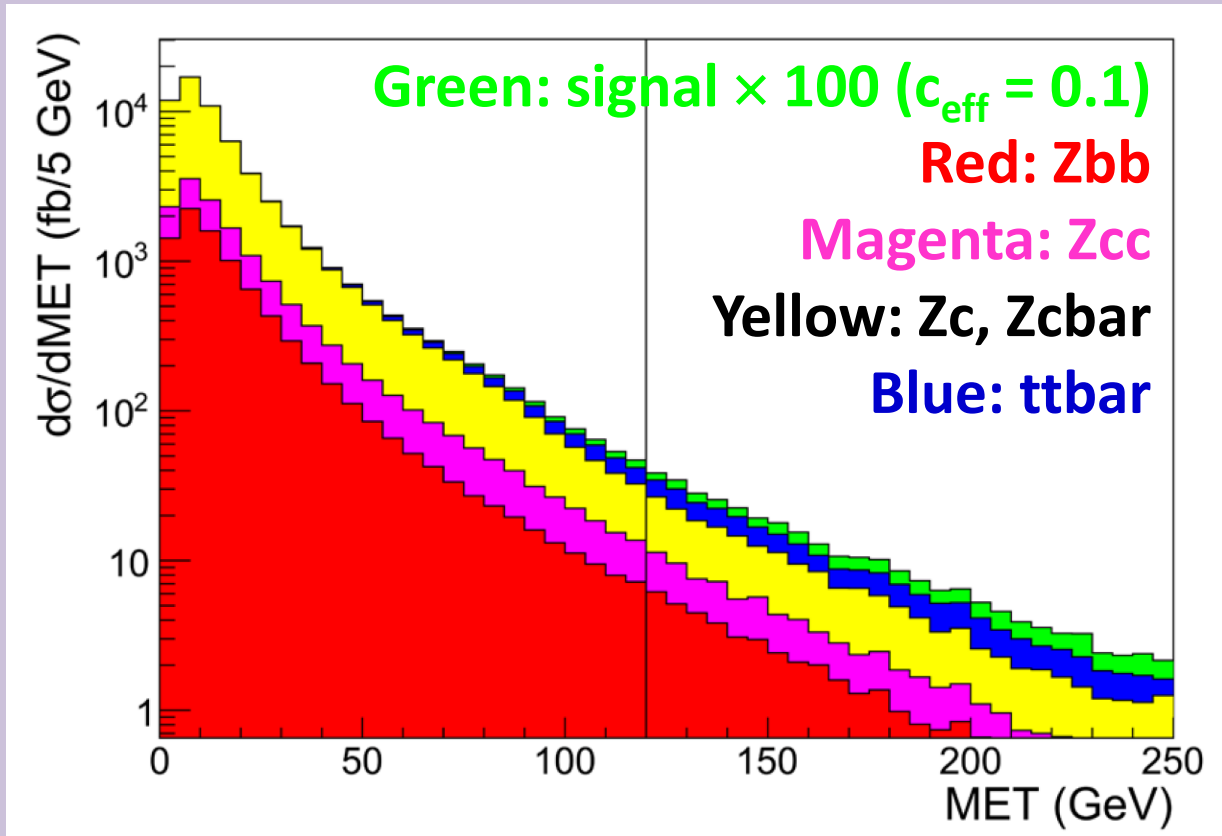
ATLAS [1606.08391]

bb+MET study

- Many backgrounds with detector simulation
  - Z+jets, broken up into
    - Zg, g→bb
    - Zg, g→cc
    - Zc + Zcbar
  - ttbar
- Use 60% b-tagging efficiency, 10% charm mistagging rate, 1% light jet mistagging rate for the fat jet
  - (Could consider prospects for b-tagging of subjets or double-tagging fat jets)

bb+MET: LHC14 event selection

- bb system is captured by C/A jet with R = 1.2
- Trigger on dileptons from Z
  - Each $p_T > 40$ GeV, $|m_{ll} - m_Z| < 10$ GeV, within acceptance
- MET > 120 GeV



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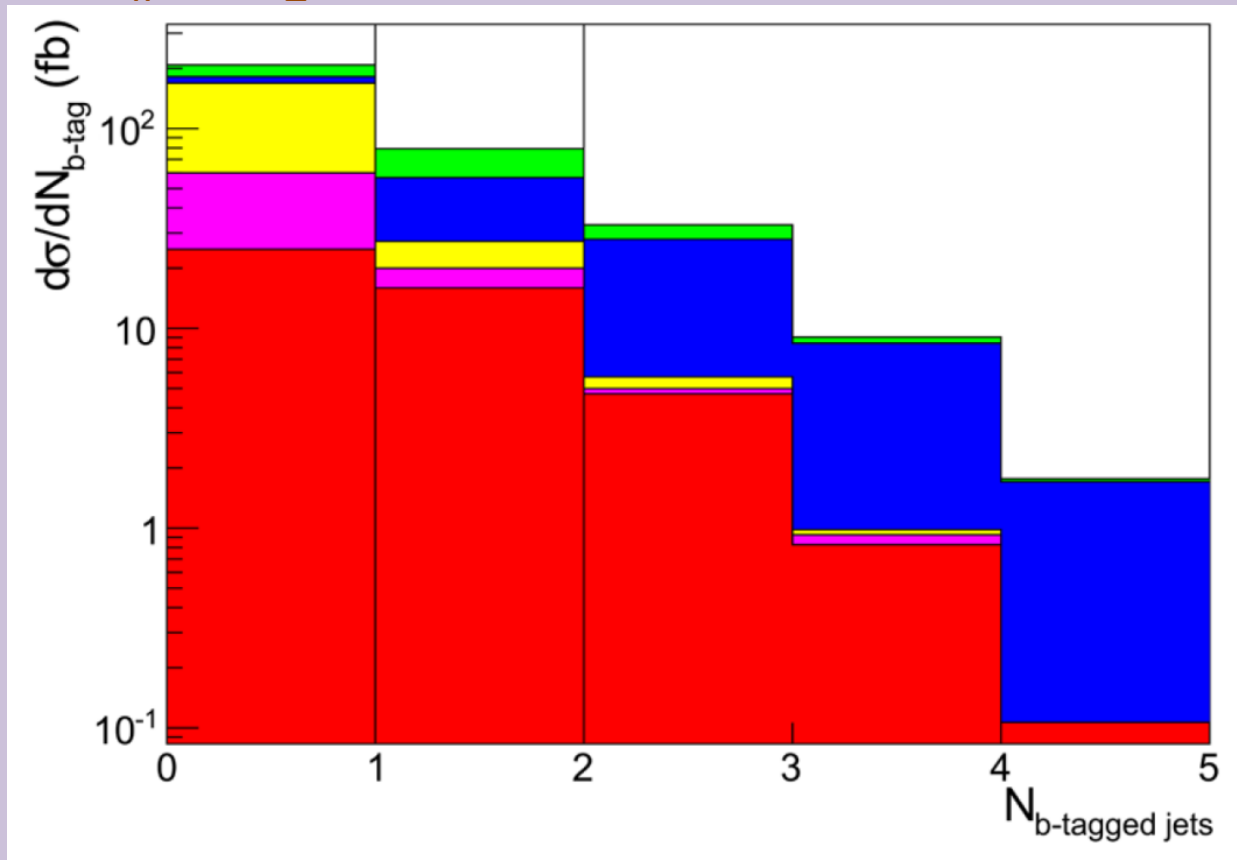
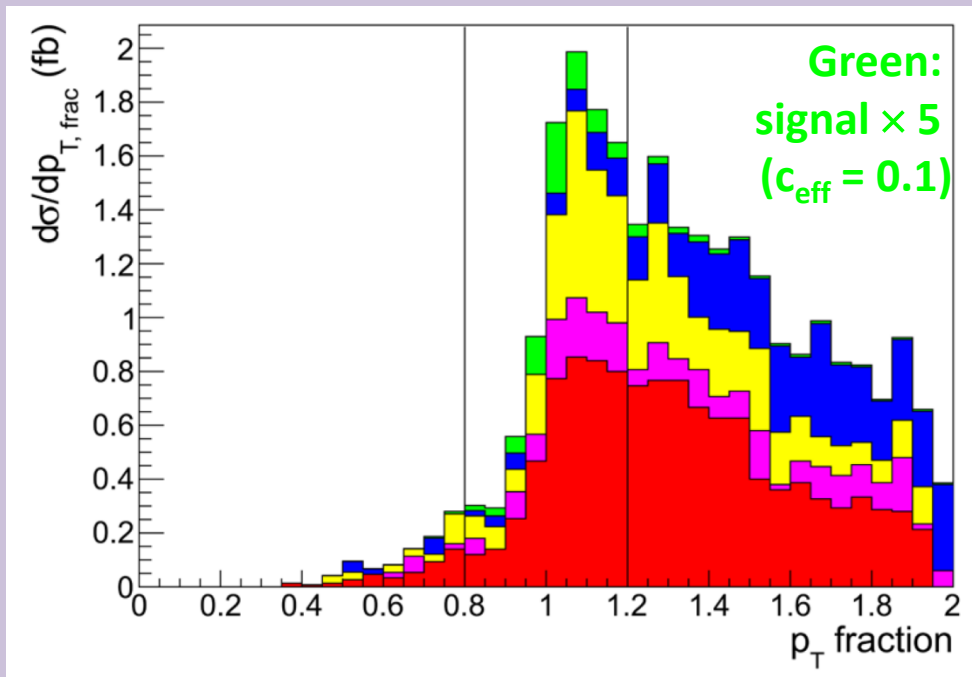
- Trigger on dileptons from Z
  - Each $p_T > 40$ GeV, $|m_{ll} - m_Z| < 10$ GeV, within acceptance
- MET > 120 GeV
- $N_{b\text{-tags}} = 1$
  - Jet $p_T > 20$ GeV



Semi-visible decays: Novel feature

- Introduce $p_{T,\,frac} = p_T(h_{2,cand})/p_T(ll_{sys})$ to keep Higgs events balanced in p_T against Z boson
  - Want MET collimated with b-tagged jet since signal MET has a single cascade
  - Discriminates from backgrounds with neutrinos in separate decay chains
- Subject to mismeasure-ment of jet p_T
- Use $0.8 < p_{T,\,frac} < 1.2$

$$p_T(h_2, \text{cand}) = p_T(b\text{-jet}) + |\not{E}_T|$$



bb+MET: LHC14 yields

	m_{h_1}	m_{h_2}	m_{χ_1}	m_{χ_2}
$h_1 \to b\bar{b}$	20 GeV	125 GeV	30 GeV	80 GeV

- Without using bb invariant mass selection, have marginal sensitivity with LHC14, 3 ab^{-1}

Cut and Efficiencies	Zh_2 0.098 $\times c_{\rm eff}$ pb	Zbb 48.4 pb	$Zc\bar{c}$ 32.8 pb	$Zc + Z\bar{c}$ 138.9 pb	$t\bar{t}$ 41.8 pb
At least two SF, OS leptons with $p_T > 40$ GeV, within Z window	0.1946	0.1774	0.1707	0.1634	0.01193
MET > 120 GeV	5.547E-2	9.597E-4	1.205E-3	4.213E-4	1.765E-3
$N_{b-\rm tags} = 1$, jet $p_T > 20$ GeV	2.303E-2	3.294E-4	1.231E-4	2.620E-5	7.058E-4
$0.8 < p_{T,\ \rm frac} < 1.2$	2.105E-2	1.935E-4	4.265E-5	1.160E-5	7.565E-4
Event Number (50 $\rm fb^{-1}$, $c_{\rm eff} = 0.5$)	40	213	53	64	26
$S/\sqrt{S+B}$(50 $\rm fb^{-1}$, $c_{\rm eff} = 0.5$)	2.0 σ				

TABLE V: Cut flow: Analysis cuts and efficiency table for the $h_1 \to b\bar{b}$ channel, $m_{h_1} = 20$, $\chi_1 = 30$, $\chi_2 = 80$ GeV. The decays $Z \to \ell^+\ell^-$ and $W \to \ell\nu$, $\ell = e, \mu, \tau$ are included in the quoted cross sections.

- Rescaling to $c_{eff} = 0.1$ requires 1.2 ab^{-1} of HL-LHC luminosity for 2.0σ sensitivity (w/o systematics)

bb+MET: LHC14 event selection

- Different benchmark (with $m(h_1) = 45$ GeV) has better prospects, but requires tricky soft subjet reconstruction

Cut, efficiencies	Zh_2	$Zb\bar{b}$	$Zc\bar{c}$	$Zc + Z\bar{c}$	$t\bar{t}$
Cross section (pb)	$0.09 \times c_{\text{eff}}$	48.4	32.8	139	41.8
Lepton cut	0.191	0.177	0.170	0.163	0.012
$\not{E}_T > 80$ GeV	8.31E-2	3.15E-3	4.41E-3	1.80E-3	4.57E-3
$N_{b\text{-tags}} = 1$, jet $p_T > 20$ GeV	3.78E-2	1.09E-3	4.88E-4	1.31E-4	1.86E-3
$0.8 < p_{T,\text{frac}} < 1.2$	2.59E-2	3.35E-4	1.06E-4	3.59E-5	7.70E-5
Two hardest subjets: $34 < m_{jj} < 46$ GeV	3.48E-3	7.17E-6	2.44E-6	5.00E-7	1.44E-6
S, B, $S/\sqrt{B}$ (600 fb^{-1}, $c_{\text{eff}} = 0.5$)	$93, 208 + 48 + 42 + 36, 5.1\sigma$				

  - Invitation for further optimization by experimental colleagues
    - Interface of jet substructure and *b*-tagging with Higgs-scale kinematics

Third channel: ττ+MET

- Even harder than bb+MET
  - Even more information lost to tau neutrinos
  - Studied hadronic tau decays, focus on identifying excess of Z (→ll) + MET + 1-/3- prong charged tracks events
- Two leptons: each $p_T > 40$ GeV, $|m_{ll} - m_Z| < 10$ GeV, within acceptance
- MET > 75 GeV
- Veto b-jets, one jet $p_T > 20$ GeV
- Benchmark

	m_{h_1}	m_{h_2}	$m_{\chi 1}$	$m_{\chi 2}$
$h_1 \to \tau^+\tau^-$	8 GeV	125 GeV	10 GeV	80 GeV

  - Again, complemented by h →4τ search

CMS [1510.06534]

ττ+MET study

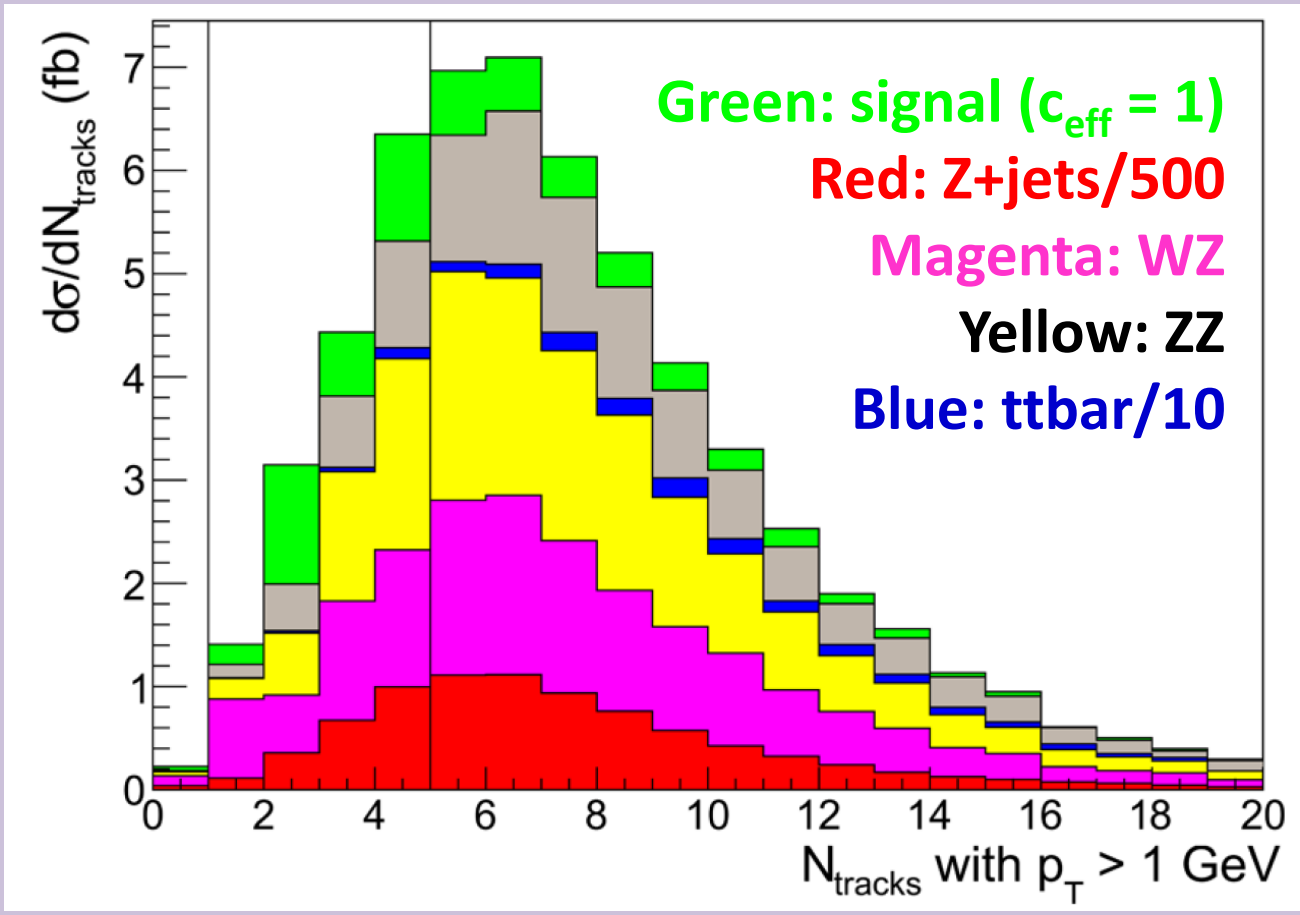
- Main backgrounds are
  - Z + jets (reduced by MET cut)
  - ttbar (reduced by Z mass window cut, b-jet veto)
  - WW + jets (reduced by Z mass window cut)
  - WZ, ZZ + jets (more or less irreducible)

Cut and Efficiencies	$Z + h_2$ 0.098 $\times c_{\text{eff}}$ pb	$Z+$ jets, $Z \to \ell\ell$ 593.4 pb	$t\bar{t} \to b\ell^+\nu b\bar{\ell}^-\nu$ 41.82 pb	$W^+W^- \to \ell^+\nu\ell^-\nu$ 2.412 pb	$W^\pm Z \to \ell^\pm\nu\ell^+\ell^-$ 0.3461 pb	$ZZ \to \ell^+\ell^-\nu\nu$ 0.1299 pb
At least two SF, OS leptons with $p_T > 20$ GeV, within Z window	0.4389	0.4950	3.161E-2	3.151E-2	0.3113	0.4977
MET > 75 GeV	0.1632	1.803E-2	1.544E-2	9.002E-3	0.1057	0.2269
Require $N_{b-\text{tags}} = 0$, only one jet $p_T > 20$ GeV	6.052E-2	7.046E-3	4.03E-4	4.729E-3	4.226E-2	0.1313
Require $1-5$ tracks with $p_T > 1$ GeV	3.710E-2	2.739E-3	6.526E-5	1.464E-3	1.575E-2	4.712E-2
Event Number (500 fb^{-1}, $c_{\text{eff}} = 1.0$)	1800	8.10E+5	1400	1800	2700	3100
$S/\sqrt{S+B}$(500 fb^{-1}, $c_{\text{eff}} = 1.0$)	2.0 σ					

TABLE III: Cut flow table for Zh_2, $Z \to \ell^+\ell^-$, $h_2 \to \chi_1\chi_1\tau^+\tau^-$. Cross sections for backgrounds include preselection cuts of at least one jet with $p_T > 20$ GeV and leptons with $p_T > 20$ GeV. Leptons from decays of gauge bosons include e, μ, and τ.

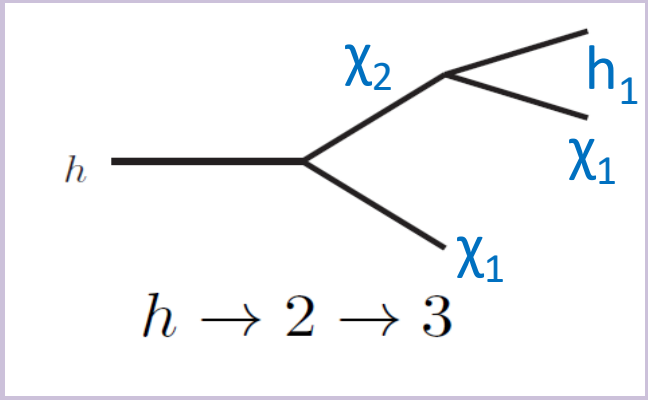
ττ+MET

- Inability to reconstruct h_1 resonance makes it very difficult to identify signal kinematics



Tackling semi-visible exotic decays

- Trigger objects from associated production collimate Higgs decay products
  - More dangerous since MET aligned with visible products
- Best prospects for hard showers with large mass splittings (light DM particles)
  - Cascade decays allow DM candidate to recoil against visible objects in Higgs frame
- Reconstructing light, semi-boosted resonances is critical for good sensitivity
  - Straddles cut and count vs. resonant reconstruction



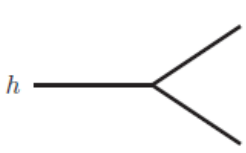
Conclusions

- New challenges for exotic Higgs decays from semi-visible class
  - h→2→3 topology readily realized in nearly-PQ NMSSM
  - Also features rich interplay between Higgs and DM physics
- VH production can be complemented by VBF, Higgs+jet production
  - Different, well-motivated final states exhibit drastic differences in sensitivity ranging from clean (μμ+MET) to hard (bb+MET) to really hard (ττ+MET)
  - Invites questions on MET calibration in semi-visible decays
  - Semi-boosted resonance reconstruction with jet substructure and multi-b-tagging of fat jets, b-tagging for subjets
    - Also relevant for fully visible h→2→4 searches

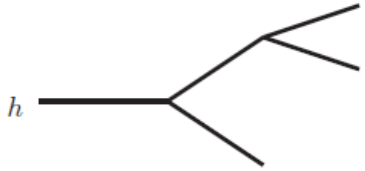
Exotic decays

Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong
PRD **90** (2014) 7, 075004 [1312.4992]

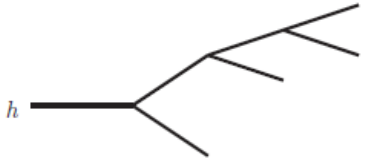
- Characterize exotic Higgs decays via
  - **topologies** from a sequence of two-body decays
  - nature of **decay products**
    - *(i)* all visible; *(ii)* all invisible; *(iii)* semi-visible



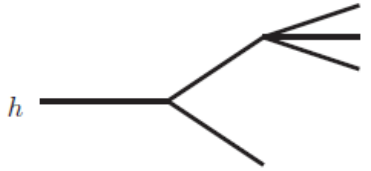
$h \to 2$



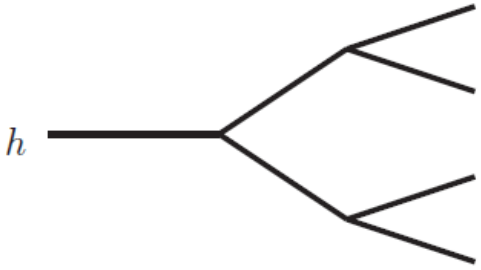
$h \to 2 \to 3$



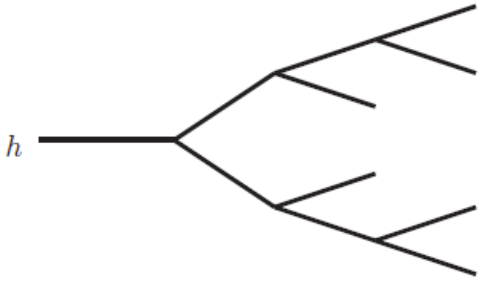
$h \to 2 \to 3 \to 4$



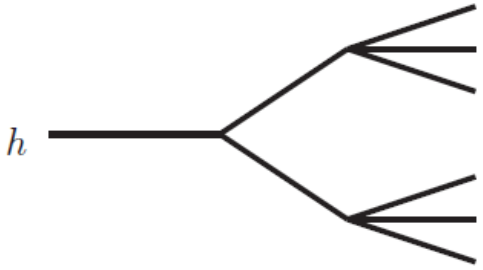
$h \to 2 \to (1+3)$



$h \to 2 \to 4$



$h \to 2 \to 4 \to 6$



$h \to 2 \to 6$

Dark Light Higgs scenario

- Higgs mass in nearly PQ limit
  - Recall $\kappa/\lambda \to 0$, $A_\kappa \to 0$

$$\left(m_{h_1}^2\right)_{\rm tree} \approx -4v^2\epsilon^2 + \frac{4v^2\lambda^2}{\tan^2\beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2\mu^2}{\lambda^2}$$

$$\epsilon \equiv \frac{\lambda\mu}{m_Z}\epsilon', \quad \epsilon' \equiv \frac{A_\lambda}{\mu\tan\beta} - 1$$

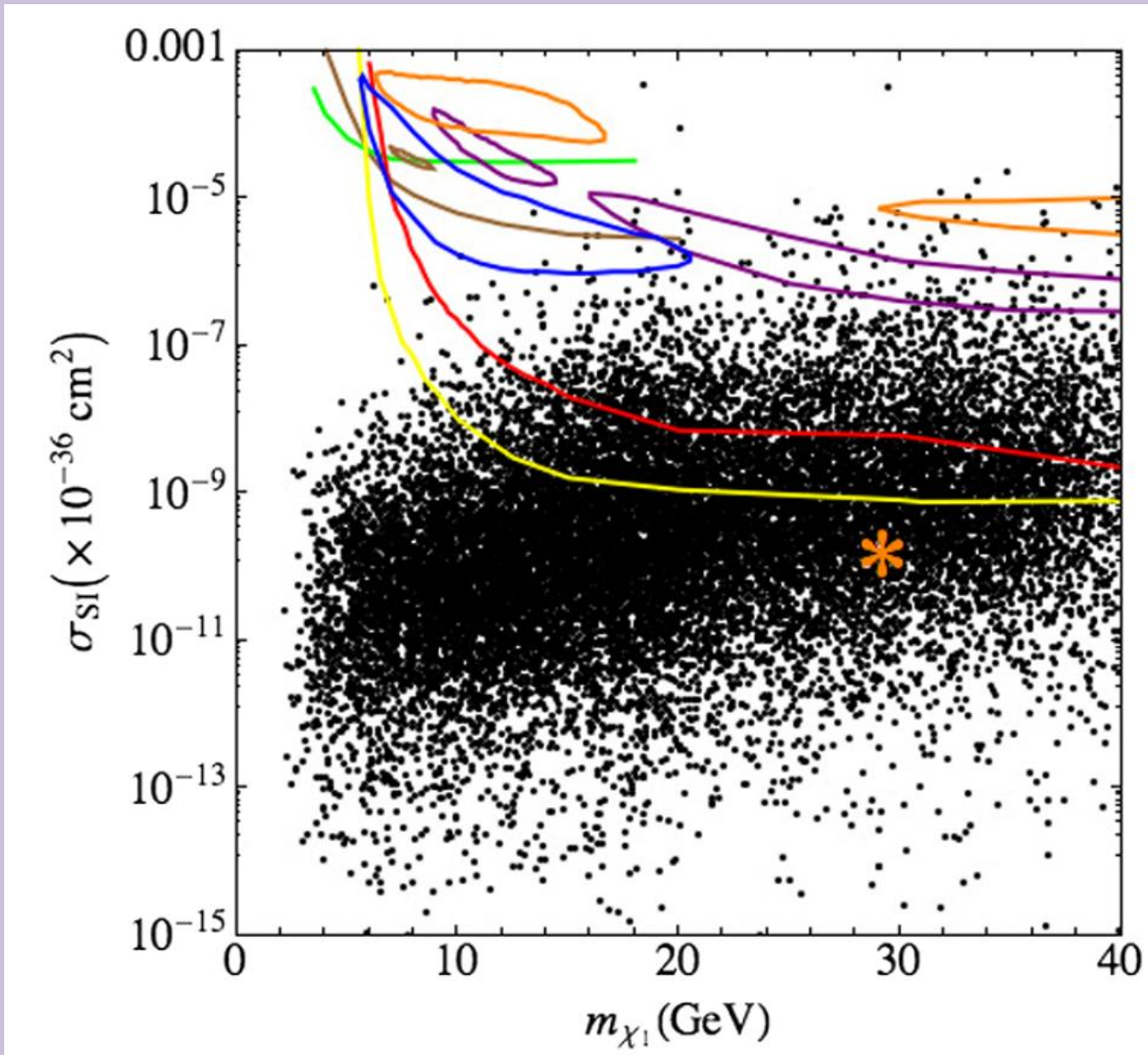
- So ε cannot be too large, and can scan over small ε values
  - Vacuum stability condition gives an upper bound on ε

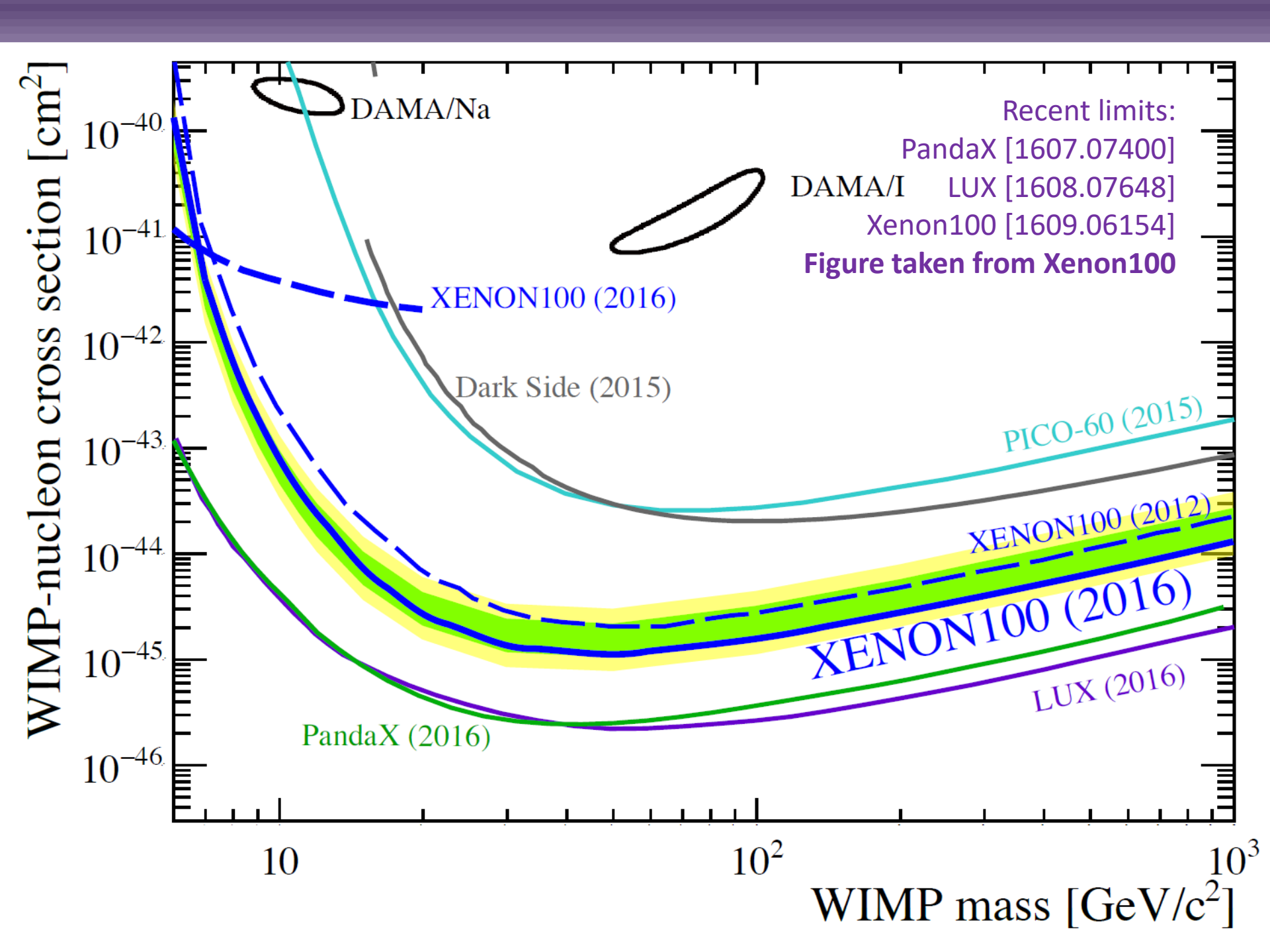
$$\Delta m_{h_1}^2 \approx \frac{\lambda^2\mu^2}{2\pi^2}\log\frac{\mu^2\tan^3\beta}{m_Z^2}$$

$$\epsilon_{\rm max}^2 \approx \frac{1}{4v^2}\left(\frac{4\lambda^2v^2}{\tan^2\beta} + \frac{\kappa A_\kappa\mu}{\lambda} + \frac{4\kappa^2\mu^2}{\lambda^2} + \Delta m_{h_1}^2\right)$$

DLH direct detection

Bulk of χ_1 range is light mass, low σ_{SI}




WIMP-nucleon cross section [cm^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10
10^2
10^3
WIMP mass [GeV/c^2]
DAMA/Na
DAMA/I
Recent limits:
PandaX [1607.07400]
LUX [1608.07648]
Xenon100 [1609.06154]
Figure taken from Xenon100
XENON100 (2016)
Dark Side (2015)
PICO-60 (2015)
XENON100 (2012)
XENON100 (2016)
LUX (2016)
PandaX (2016)