Semi-visible Exotic Higgs Decays

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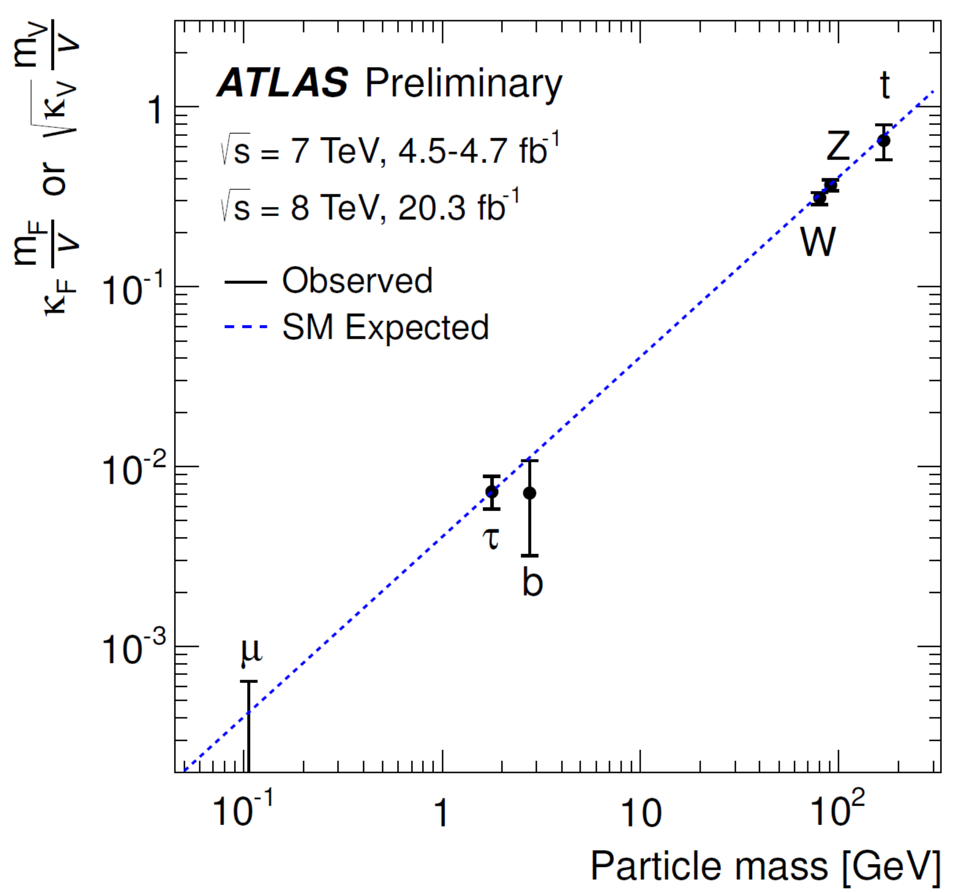
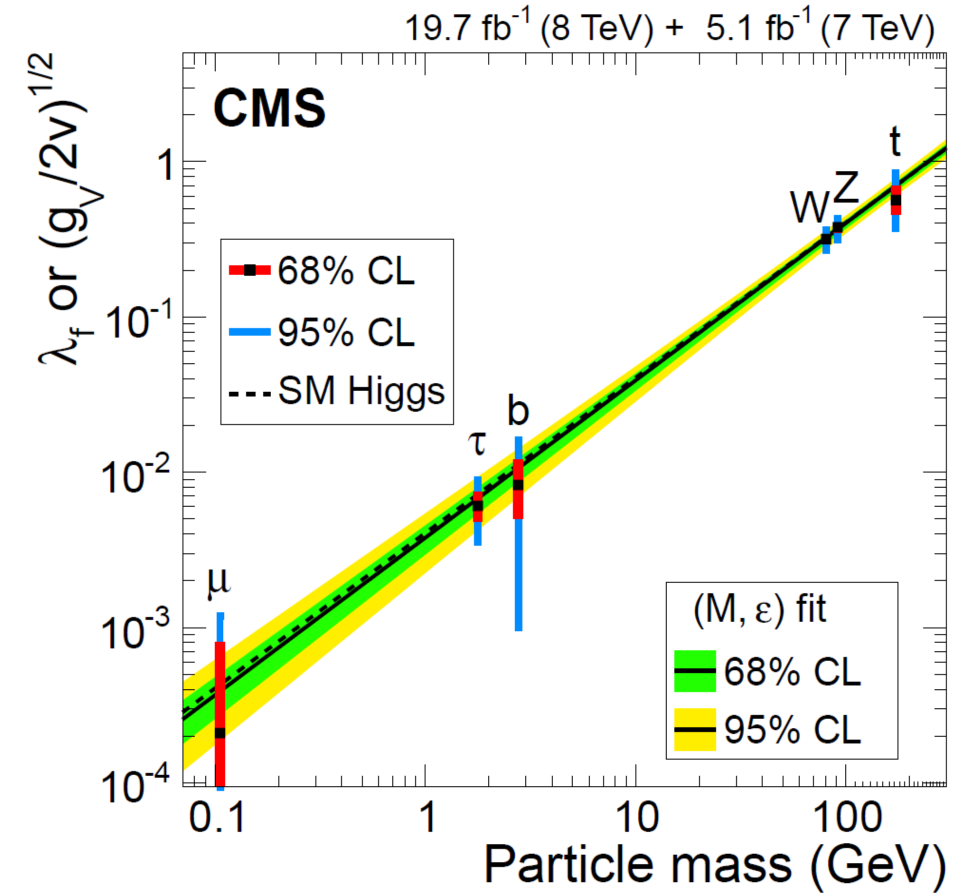
with Jinrui Huang, Tao Liu, Lian-Tao Wang

WG3: Exotic Higgs Decays, Fermilab
May 21, 2015

Motivation

- Thus far, all fits of Higgs couplings show consistency with the mass-coupling relation dictated in the SM





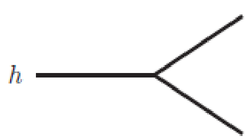
Motivation

- Thus far, all fits of Higgs couplings show consistency with the mass-coupling relation dictated in the SM
  - Cannot directly measure the Higgs total width at the LHC
    - At best, have model dependent upper-limit constraints from ATLAS and CMS
    - (Have model independent lower limits)
- Numerically, the bottom Yukawa (at m_h) ≈ 1/60
- A new light particle with even small couplings to the Higgs can induce a sizeable exotic Higgs decay

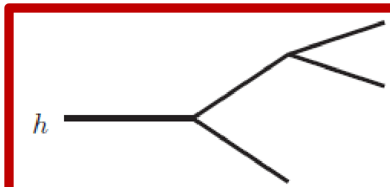
Exotic decays

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

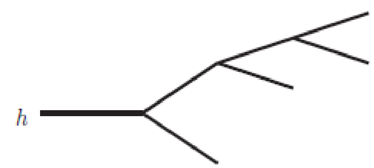
- Characterize exotic Higgs decays via
  - **topologies** from a sequence of two-body decays
  - nature of **decay products**
    - *(i)* all visible; *(ii)* all invisible; *(iii)* semi-visible



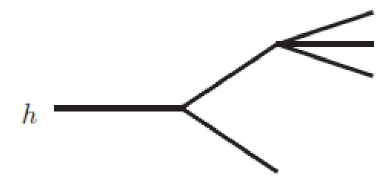
$h \to 2$



$h \to 2 \to 3$

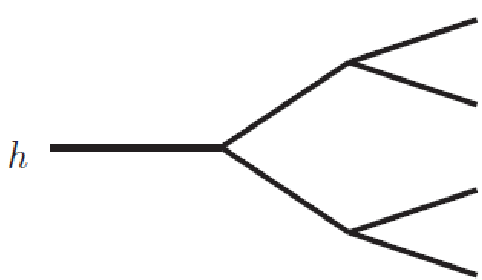


$h \to 2 \to 3 \to 4$

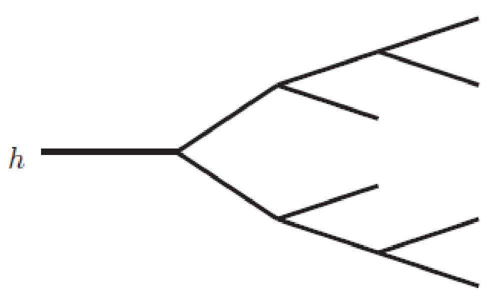


$h \to 2 \to (1+3)$

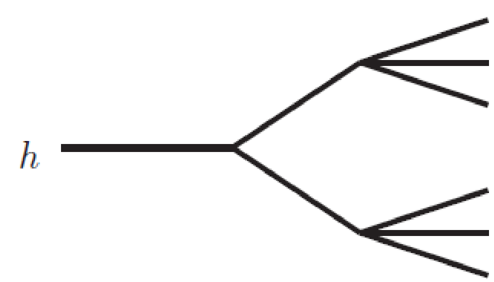
Will focus here on the cascade (shower) decay topology



$h \to 2 \to 4$



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



$h \to 2 \to 6$

Outline

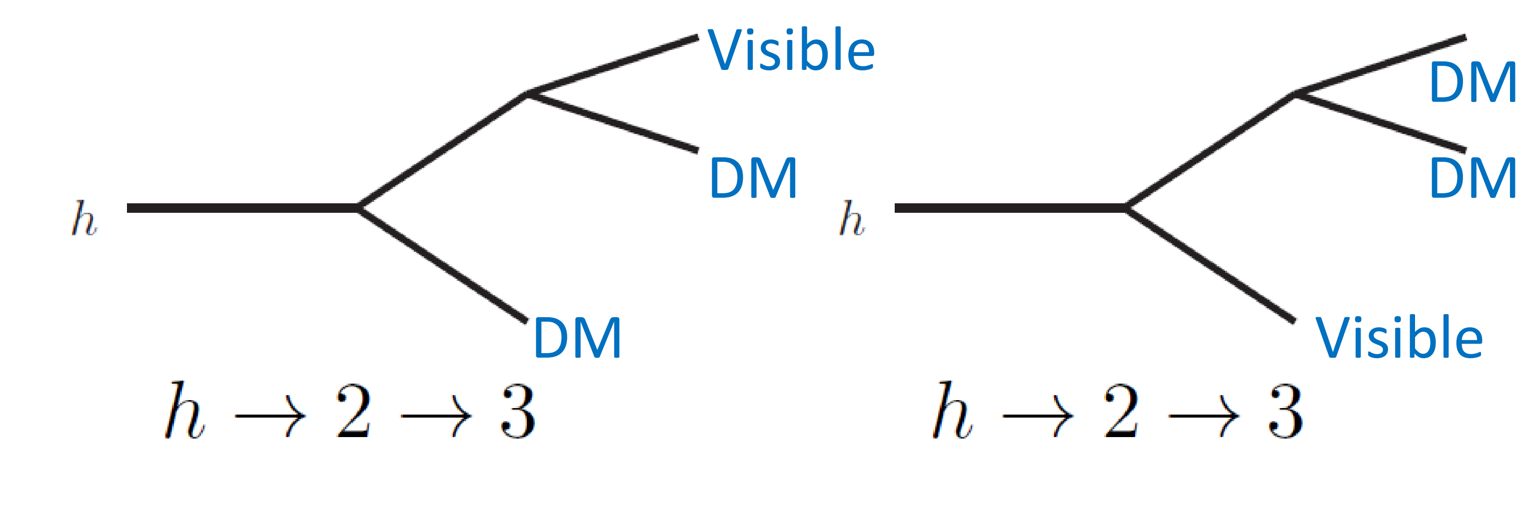
- Brief theory background for semi-visible decay channels – nearly PQ NMSSM[1]
- Semi-visible topology and phenomenology
- LHC sensitivity studies
  - $\mu\mu$+MET channel
  - bb+MET channel
  - $\tau\tau$+MET channel
- Conclusions

[1]Draper, Liu, Wagner, Wang, Zhang Phys. Rev. Lett. **106** 121805 (2011)

Semi-visible prompt decay channels

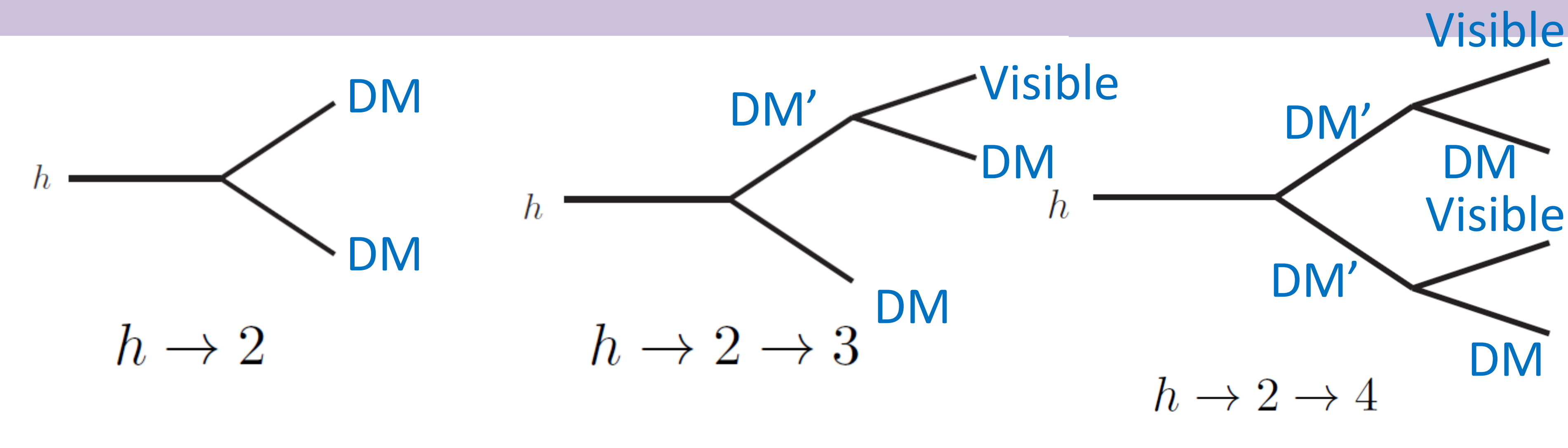
- Bottom up approach allows two different showers producing semi-visible decay in h→2→3 topology
  - DM candidate is invisible particle, assume DM parity
  - Generally related to h→2 and h→2→4 topologies
  - Intermediate particle is part of either DM sector or SM sector (assuming DM parity)

Also related to Higgs decay to Nν (see de Gouvea)



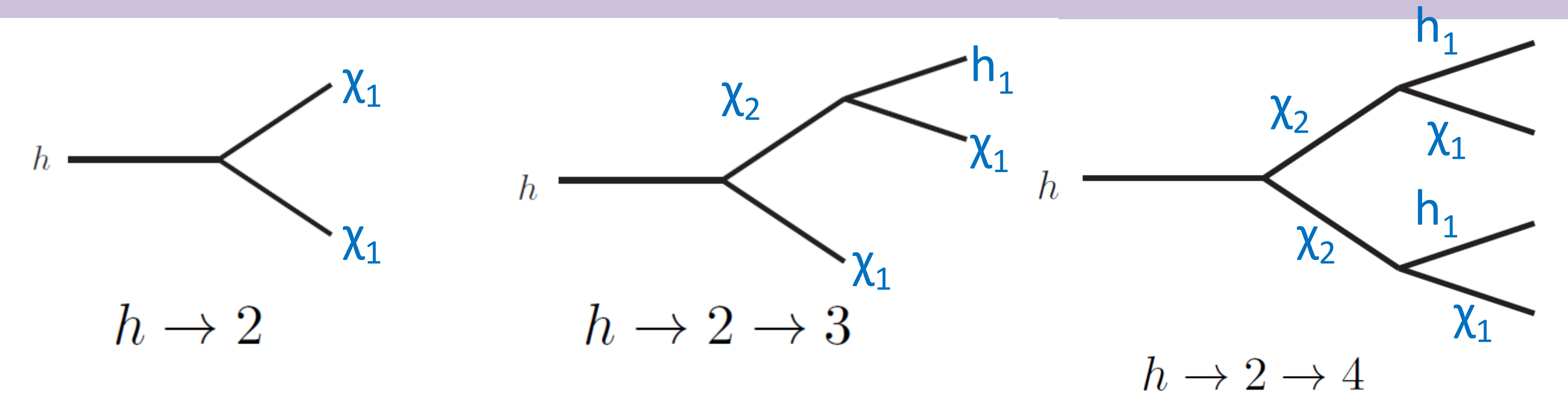
Relation to h⟶2 and h⟶2⟶4

- From top down view, Higgs decays to DM sector particles can also motivate h→2→3 topology, more than the well-known h→2 decay



Relation to h→2 and h→2→4: NMSSM

- In nearly-Peccei-Quinn NMSSM, DM is dominantly singlino, DM' is dominantly bino, and the gauge singlet scalar decays to fermion pairs

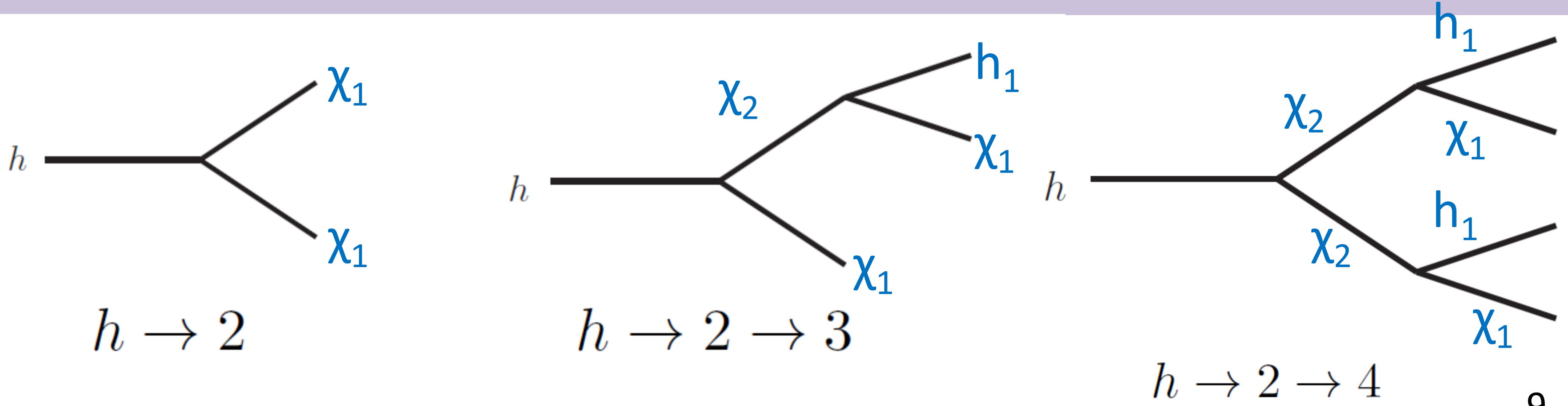


Relation to h⟶2 and h⟶2⟶4: NMSSM

- Two-body decay to singlinos (h→2 decay) suppressed by mixing angles
- Two-body decay to binos (h→2→4 decay) suppressed by kinematic threshold
- Asymmetric decay to bino-singlino (h→2→3 decay) dominant

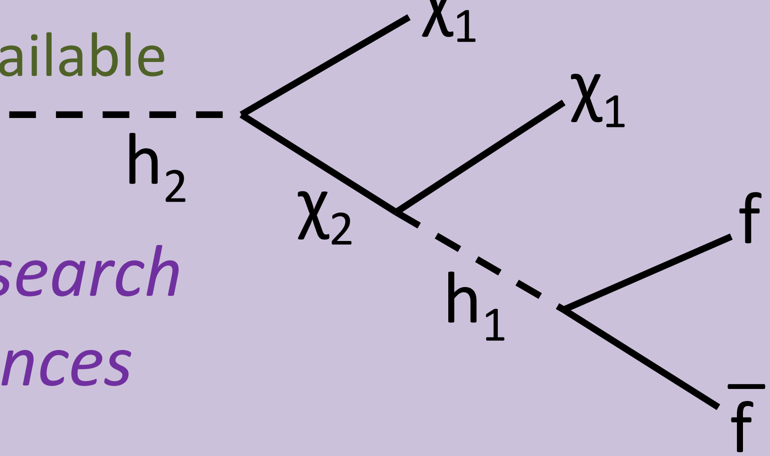
– SM-like Higgs is second heaviest CP-even scalar

- Two-body decay to $h_1 h_1$ suppressed from PQ limit



Semi-visible h decay phenomenology

- In Higgs rest frame, can partition 125 GeV of energy to decay products
- For semi-visible decay, two decay products are DM candidates
  - Heavier DM masses lead to less energy for visible products
  - In NMSSM, h_1 inherits couplings from mixing with Higgs
    - Decays to heaviest fermion pair available



Contrast to fully visible decay, where search strategy focuses on correlated resonances

Triggering semi-visible h decays

- Generally need additional trigger
  - MET correlated with Higgs production mode
- Leptonic decays for associated Vh production are simplest
  - For μμ+MET channel, use Wh mode, use trilepton trigger
  - For bb+MET and ττ+MET channels, use Zh mode, use dilepton trigger

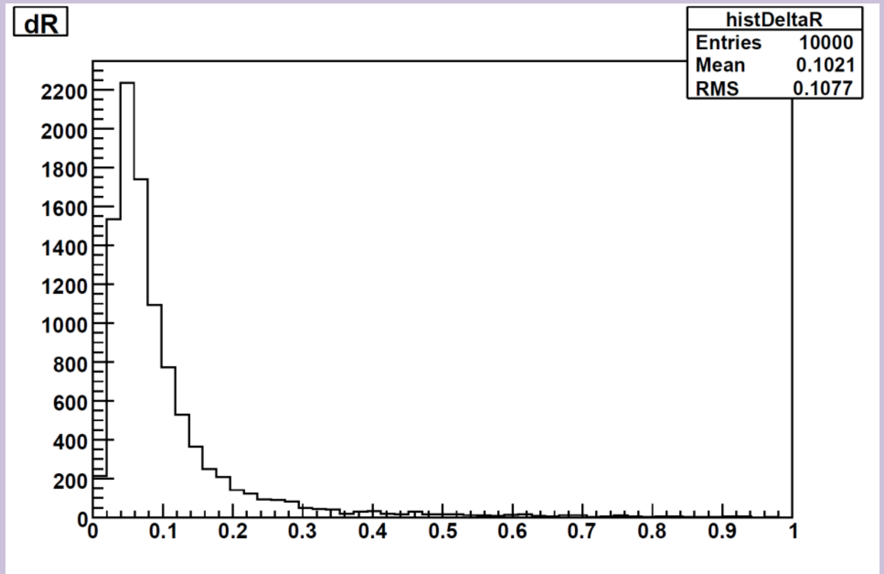
μμ+MET channel

- 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 Σp_T < 5 GeV within ΔR < 0.4 cone of each muon candidate, not including second muon candidate



$\mu\mu$+MET channel – LHC constraints

- Lepton jets studies insensitive
  - Require displaced vertex for lepton jet
  - Four muons within single lepton jet
  - At least two lepton jets

ATLAS, PLB **721**, 32 (2013)
ATLAS, PLB **719**, 299 (2013)
ATLAS, New J. Phys. **15**, 043009 (2013)

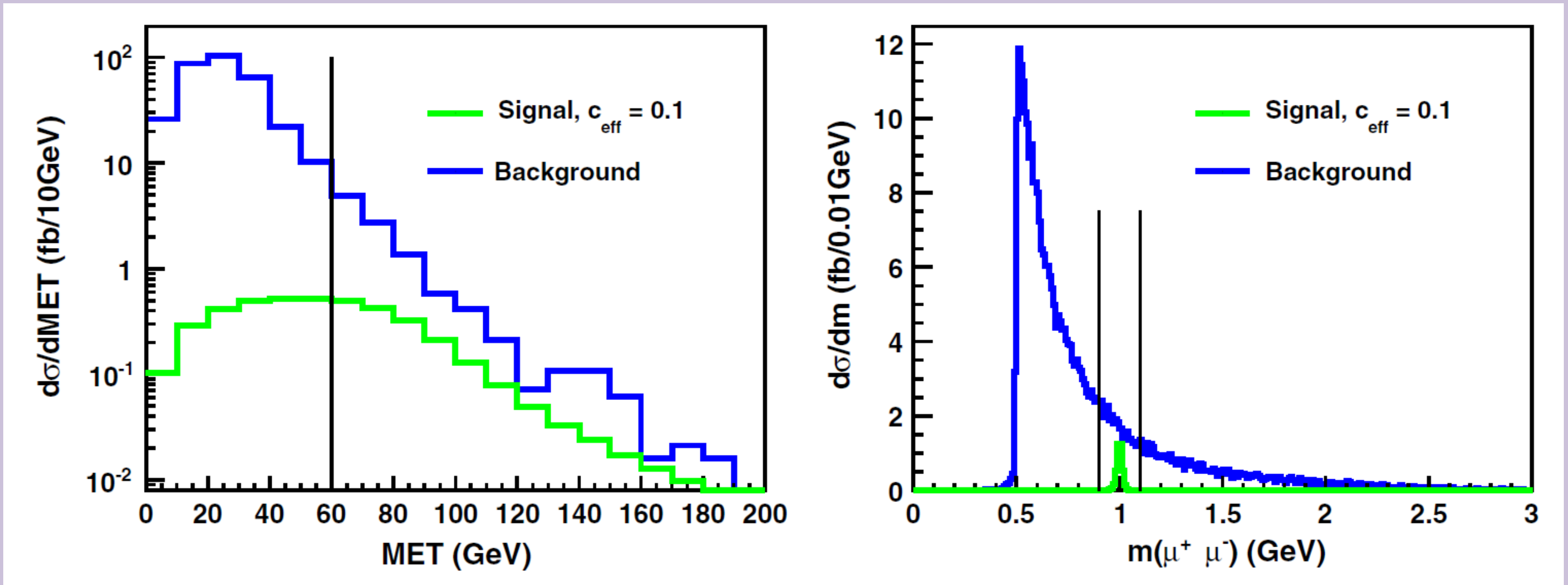
- Resonances decaying to muon pairs

CMS, JHEP **07** (2011) 098

  - Constrain 0.15-0.7 pb cross section for resonance masses below 1 GeV
  - Our signal rate is 0.1 pb × c_{eff} ≈ 0.01 pb for c_{eff} = 10%
    - (c_{eff} is the effective branching fraction for the h→2→3 decay topology and possibly enhanced Vh production scaling)

$\mu\mu$+MET: LHC8 event selection

- Use $p_{T1} > 20$ GeV, $p_{T2,3} > 10$ GeV, $\Delta R_{\mu\mu} < 0.2$, within $|\eta| < 2.4$
- MET > 60 GeV
- Primary background is $W(\gamma^*/Z)$, provides continuum dimuon mass spectrum



μμ+MET: LHC8 yields

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- MET > 60 GeV
- Primary background is $W(\gamma^*/Z)$, provides continuum dimuon mass spectrum
  - High local significance from dimuon mass window cut

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	

bb+MET channel

- 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

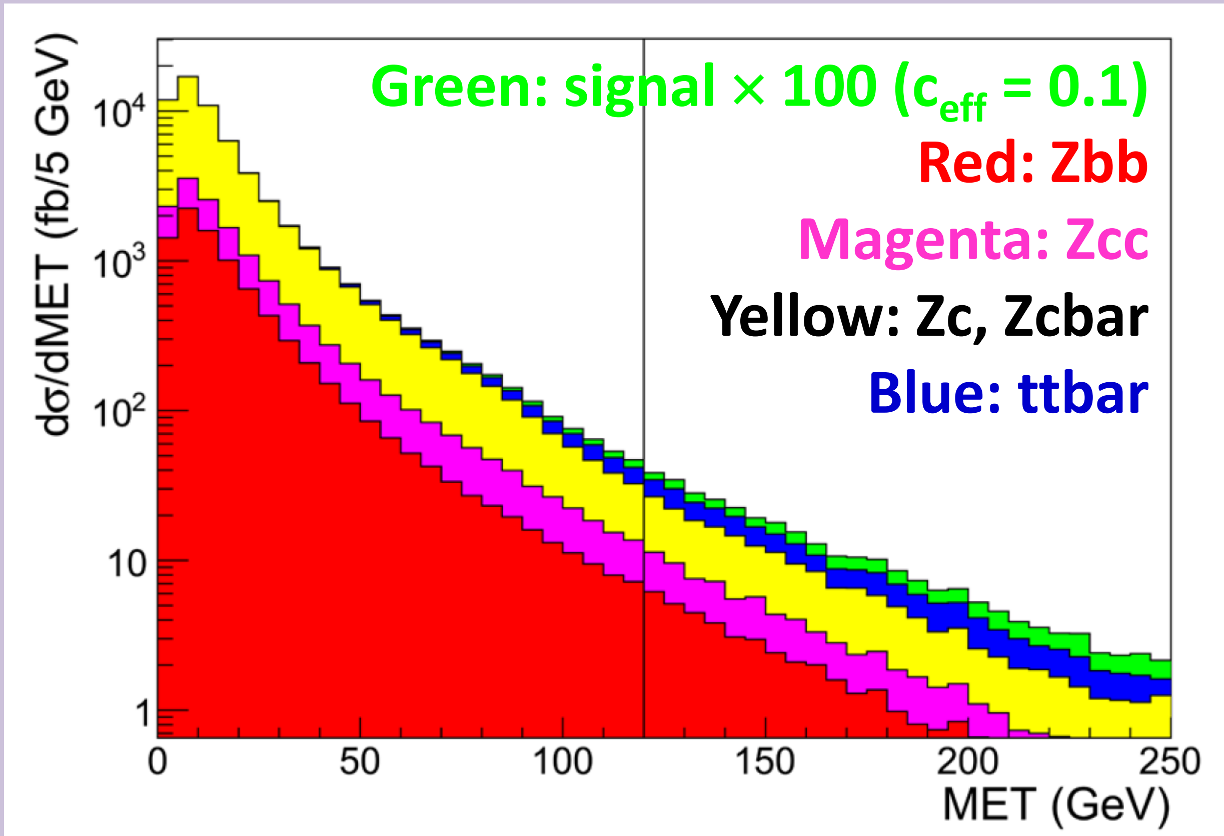
	m_{h_1}	m_{h_2}	m_{χ_1}	m_{χ_2}
$h_1 \to b\bar{b}$	20 GeV	125 GeV	30 GeV	80 GeV

bb+MET channel

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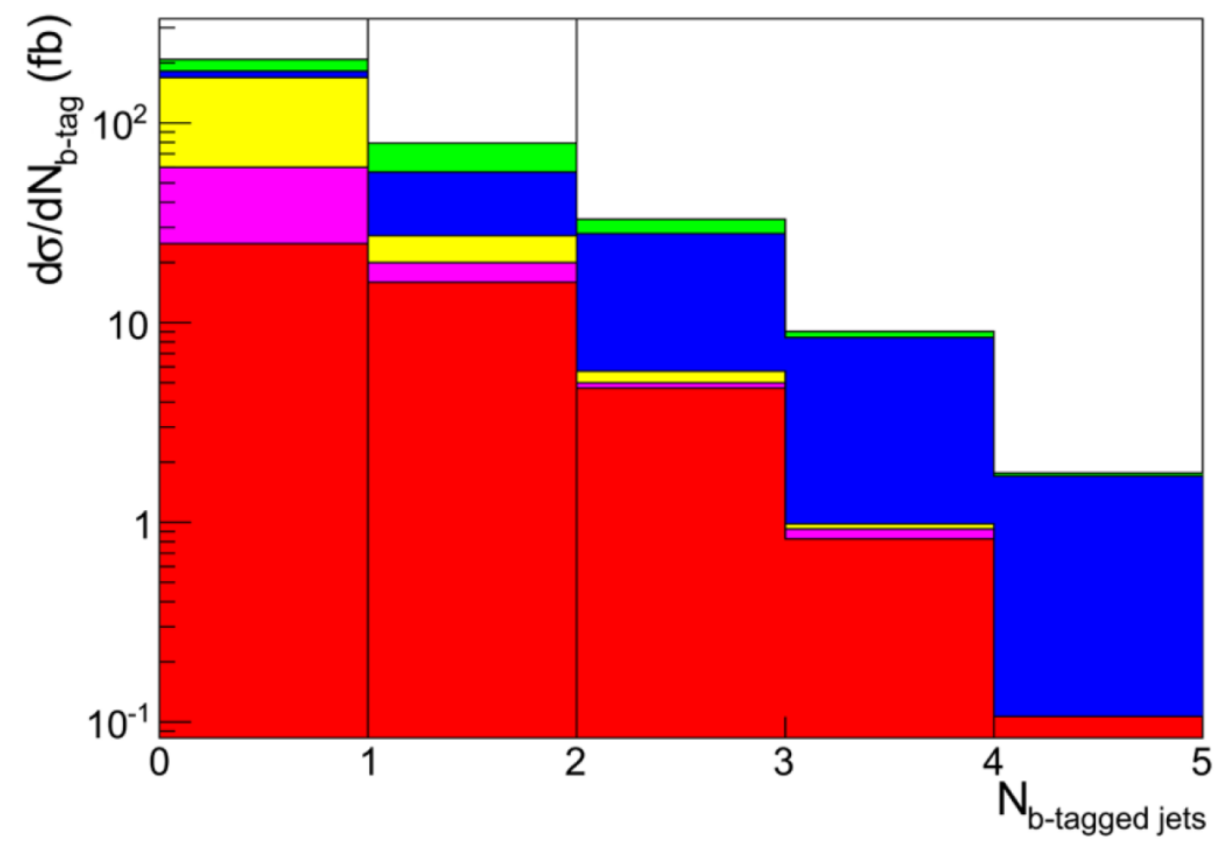
- Trigger on dileptons from Z
  - Each p_T > 40 GeV, $|m_{ll} - m_Z| < 10$ GeV, within acceptance
- MET > 120 GeV
- $N_{b\text{-}tags} = 1$
  - Jet p_T > 20 GeV

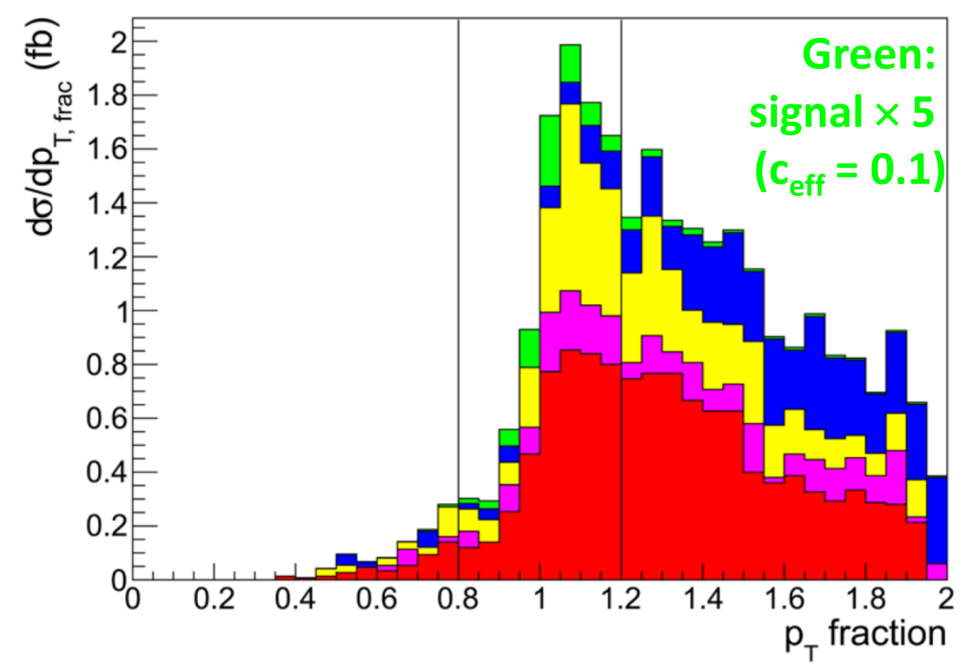


Semi-visible decays: Novel feature

- 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

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

- Subject to mismeasurement of jet p_T
- Use $0.8 < p_{T,\,frac} < 1.2$



bb+MET: LHC14 yields

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

bb+MET: LHC14 event selection

- Without using bb invariant mass selection, have marginal sensitivity with LHC14, 3 ab^{-1}
  - 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)	$0.09 \times c_{\rm eff}$	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
$0.8 < p_{T,\rm frac} < 1.2$	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}, $c_{\rm eff} = 0.5$)	93, 208 + 48 + 42 + 36, 5.1σ				

ττ+MET channel

- 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

TABLE II. Benchmark used for the collider analysis of $h_2 \to \tau^+\tau^- + \not{E}_T$.

	m_{h_1}	m_{h_2}	m_{χ_1}	m_{χ_2}
$h_1 \to \tau^+\tau^-$	8 GeV	125 GeV	10 GeV	80 GeV

ττ+MET channel

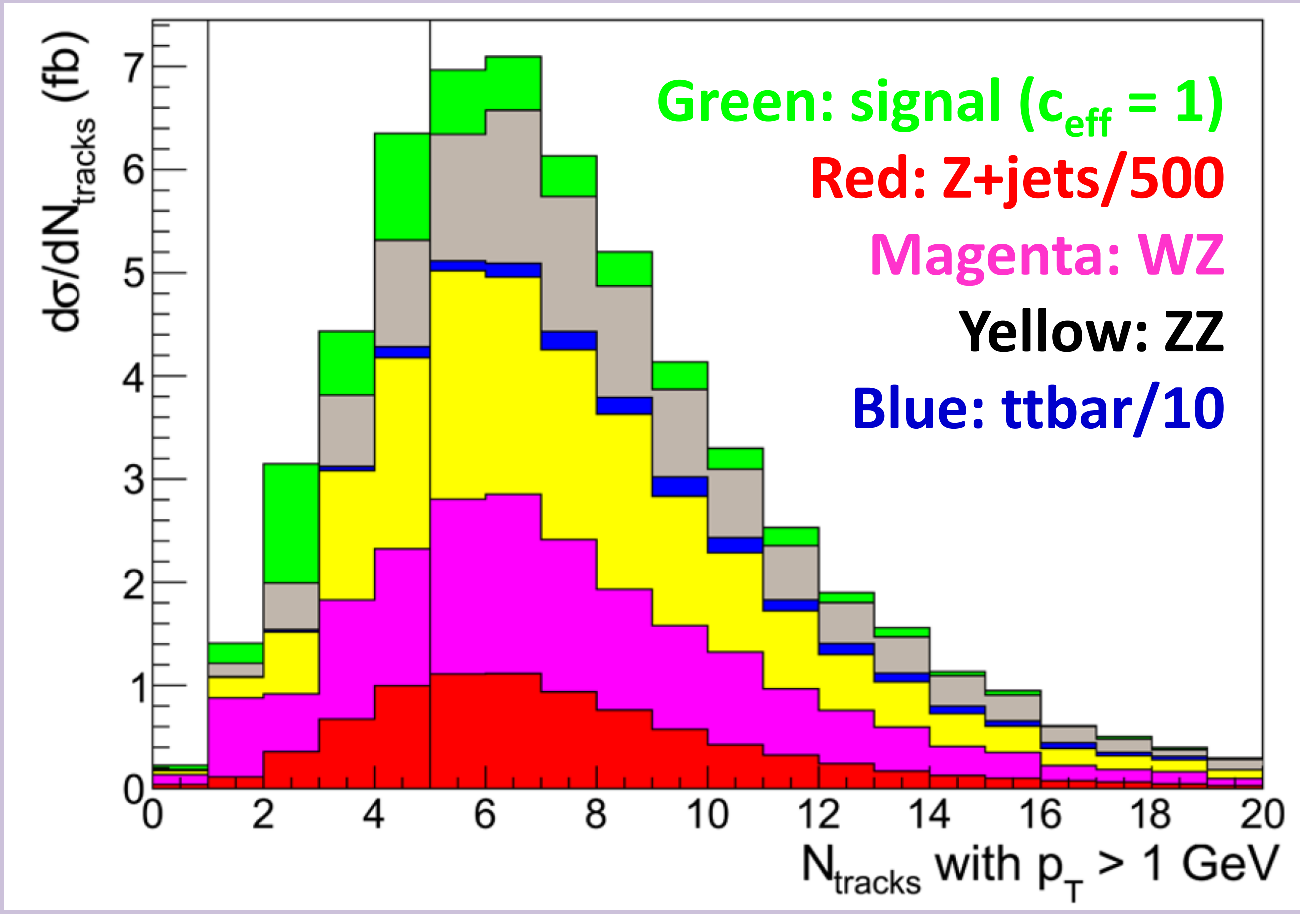
- Main backgrounds are
  - Z + jets (reduced by MET cut)
  - ttbar (reduced by Z mass window cut, b-jet veto)
  - WW + jets (reduced by Z mass window cut)
  - WZ, ZZ + jets (more or less irreducible)

Cut and Efficiencies	$Z+h_2$ 0.098 $\times c_{\rm eff}$ pb	$Z+$ jets, $Z\to\ell\ell$ 593.4 pb	$t\bar{t}\to b\ell^+\nu\bar{b}\ell^-\nu$ 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 $N_{b-\rm tags}=0$, 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}, $c_{\rm eff}=1.0$)	1800	8.10E+5	1400	1800	2700	3100
$S/\sqrt{S+B}$(500 fb^{-1}, $c_{\rm eff}=1.0$)	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.

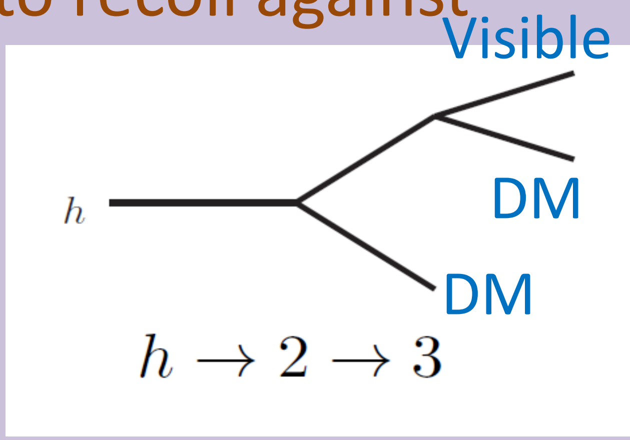
ττ+MET channel

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



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
  - Overlaps with fully visible h→2→4 topology



Conclusions

- Semi-visible exotic decays is a challenging class of exotic Higgs decays
  - May be only accessible production of the visible resonances and DM candidates
- Advances in experimental techniques could greatly push sensitivity
  - MET calibration in semi-visible Higgs decay
    - Contrast to SUSY cascade decays, ttbar
  - Semi-boosted resonance reconstruction with jet substructure
  - Multi-b-tagging of fat jets, b-tagging for subjets
    - Generic displaced vertices in cone jets

Dark Light Higgs scenario

- Nearly PQ limit of NMSSM

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

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

  - Take $\kappa/\lambda \to 0$, $A_\kappa \to 0$
    - Peccei-Quinn symmetry explicitly broken by κ
  - Moderate or small λ, $\lambda < 0.1$
  - The Higgs potential arises from the above soft breaking terms, SUSY gauge interactions and F-terms
    - Generate vevs for h_u, h_d, and N → $\mu \equiv \lambda \langle N \rangle$

Dark Light Higgs scenario

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

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

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

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

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

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

Dark Light Higgs phenomenology

- Three CP-even Higgses (h_1, h_2, h_3), two CP-odd Higgses (a_1, a_2)
  - h_1, a_1, χ_1 are all light (O(1)-O(10) GeV)
  - Heaviest state is strongly down type, with mass $m_{h3}^2 \sim m_{Hd}^2 \sim A_\lambda^2$

DLH direct detection

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