Non-SM Decays of the 125 GeV Boson

Survey for the HXSWG

Matt Strassler
Harvard
6/13/14

Exotic Decays of the 125 GeV Higgs Boson

David Curtin,[1] Rouven Essig,[1] Stefania Gori,[2,3] Prerit Jaiswal,[4] Andrey Katz,[5] Tao Liu,[6] Zhen Liu,[7] David McKeen,[8,9] Jessie Shelton,[5] Matthew Strassler,[1] Ze'ev Surujon,[1] Brock Tweedie,[10] and Yi-Ming Zhong[1,*]

Contains extensive list of references

Outline

- Agenda: Which non-SM decays covered/not covered today?
  - Decays not discussed in our recent review paper
- Motivation: Why might we expect non-SM multi-body *h* decays?
- Decays with no intrinsic MET (except neutrinos)
  - Promising channels
  - Benchmarks/Simplified Models
- Decays with new sources of MET
  - Complexities
  - Promising channels
    - Low MET vs High MET
  - Benchmarks/Simplified Models

Not Covered In Our Review

$h \rightarrow Z\gamma$; $h \rightarrow \tau\mu$

- These are actively under study by the experiments
- Benchmarks not needed: parameterize as a Branching Fraction [Br]

Also I will say nothing about h → invisible today; well-studied.

h → many visible particles (with or without MET)

  - $h \rightarrow 6\tau$; $h \rightarrow 8b$; $h \rightarrow \geq 6\ \mu/e$ etc. e.g. in NMSSM
  - h → 2 triplets of fermions e.g. via RPV SUSY
  - h → many leptons (unclustered)
  - h → complex lepton jets
    - [complex → more than two tracks, possibly including hadrons]
- Needs special discussion all its own – very complicated

h → long-lived particles decaying in flight

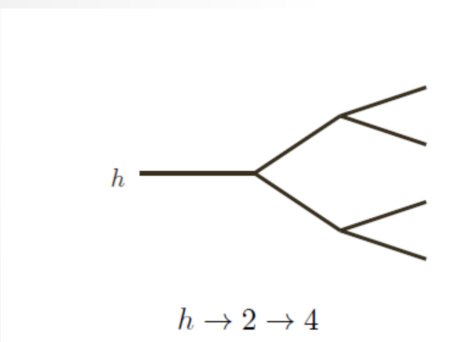
- Needs special discussion all its own – very complicated

Covered Today and in Our Review

h decays

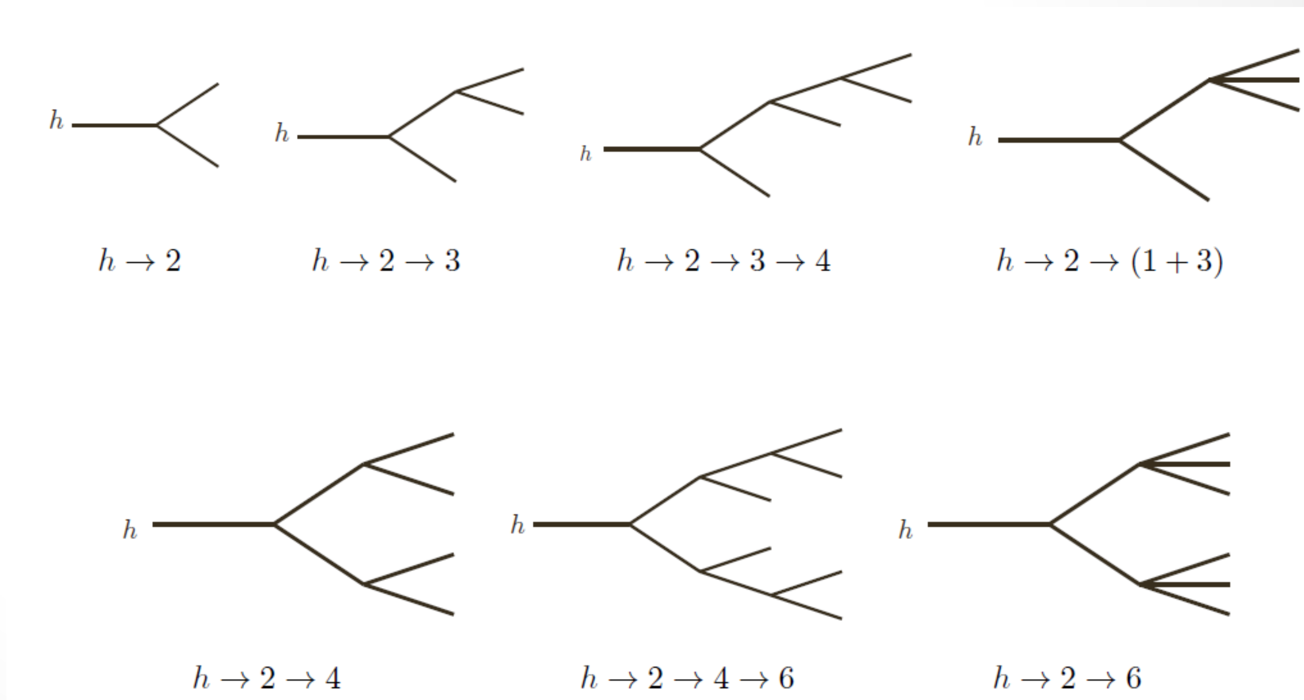
- to at most four visible SM partons
- and involving at least one non-SM particle in intermediate step

Cases With No MET



$\gamma + Z_D$?
$\gamma + a$?

Cases With MET



Motivation

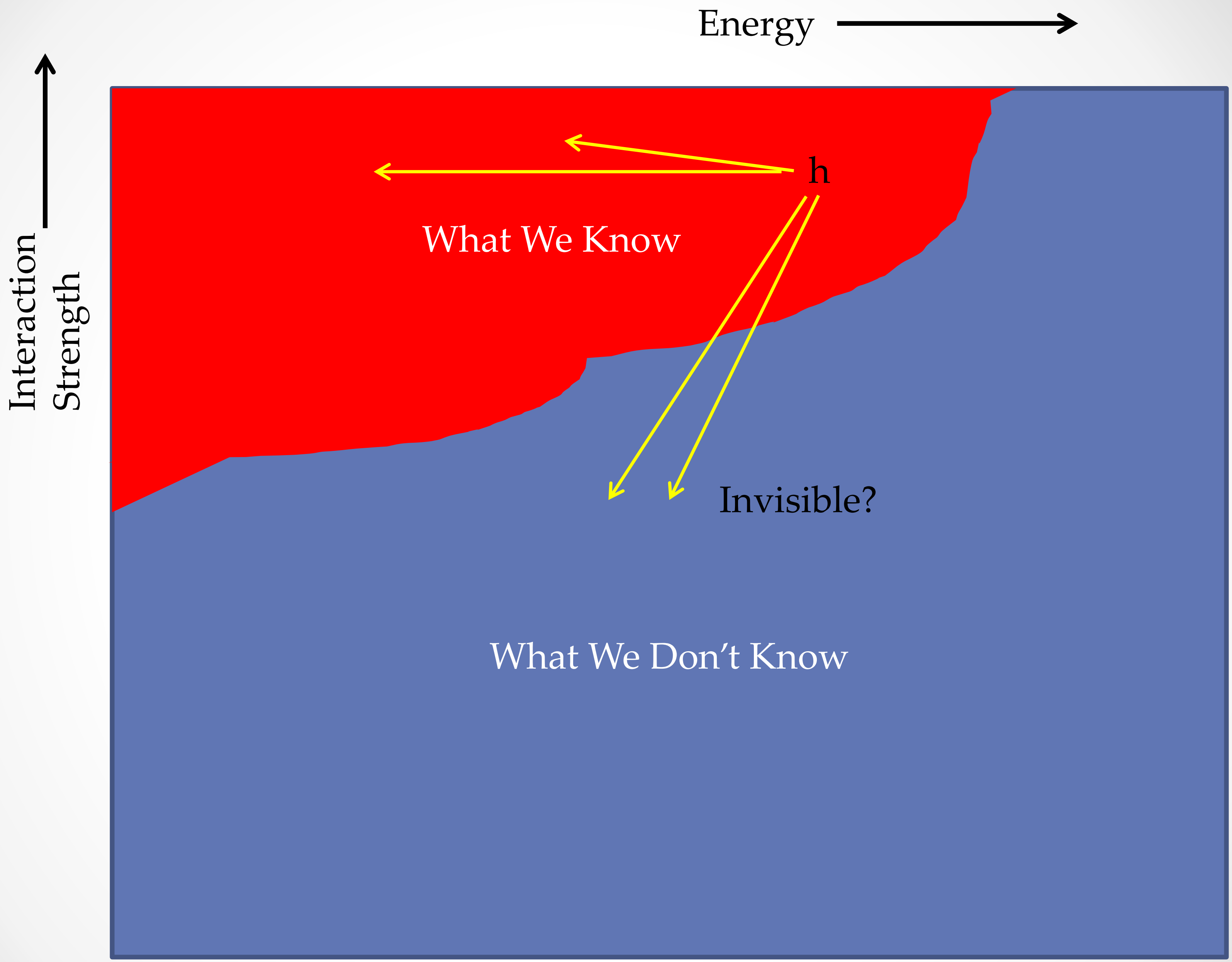
- h decays may serve as window to unknown particles.
  - e.g. discovery of neutrino in beta decay, other neutrinos in muon, tau decay
  - e.g. non-discovery of 4th neutrino, majorons, others in Z decay

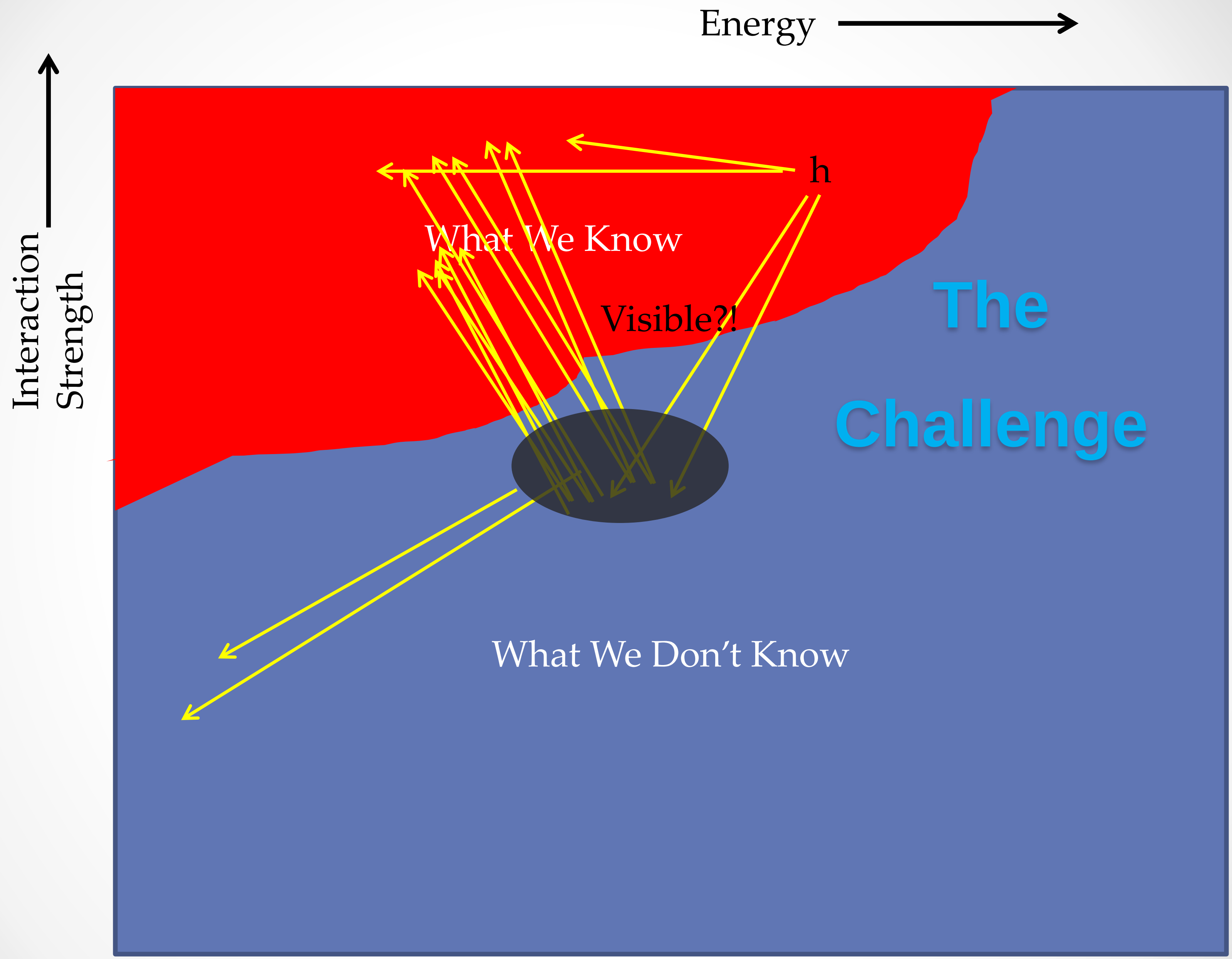
- Dark Matter exists;
  - if it is particles, these particles may not carry SU(2) quantum numbers
  - Therefore these particles may have evaded LEP & have mass < 100 GeV
  - So possible that h → DM → invisible decay
    - Difficult to observe for Br < 10%
  - If DM part of low mass dark **sector** (“*hidden valley*”), then maybe
    - h → dark sector particles → visible particles, with or without MET
      - Much easier to observe! Can sometimes reach Br <<< 10%

- H “Portal” – easy access to dark/hidden sectors/valleys
  - H operator has dimension 1, $|H|^2$ is gauge invariant, dimension 2
  - Coupling to “dark” sector involves low dimension operator

Motivation (2)

- 125 GeV h has very narrow width
  - ➔ small interactions with new sector can generate new decays
  - These decays could have had Br ~ 100%; could still have Br ~ 10%.
- Number of h produced is large, so potential to reach Br ~ 10^{-4} or better
  - 10^6 already produced
  - Approaching 10^8 in foreseeable future
    - But --- trigger and analysis challenges!
    - 2011-2012 data may still be useful!
- In some theories,
  - h decays are **first** BSM physics discoverable at LHC
  - Or even the **only** BSM physics discoverable at LHC14!
- Same searches might turn up new members of scalar sector (e.g. heavy H) whose decays are dominated by non-SM final states


Energy
Interaction
Strength
h
What We Know
Invisible?
What We Don't Know



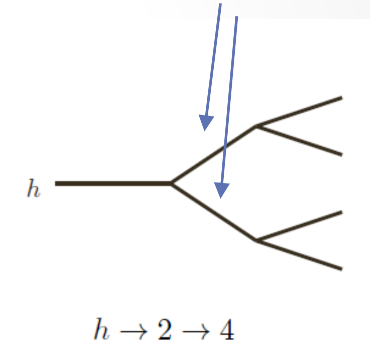
Energy
Interaction Strength
h
What We Know
Visible?!
The Challenge
What We Don't Know

Decays Without MET

New particles with $m < m_h$ must be **neutral** to avoid LEP discovery

- With a small loophole

1 or 2 New Particles



Four SM Particles

We consider

- Spin 0 “a” [scalar or pseudo-scalar]
- Spin 1 “Z_D” [vector or pseudo-vector]

  - *Spin ½ ➔ h decay to 6 visible fermions or MET*
    - *e.g. h → neutralinos → 6 fermions via RPV*

Will move from simplest to most complex.

1. $h \to Z\, Z_D \to$ 4 SM fermions
2. $h \to Z_D\, Z_D \to$ 4 SM fermions
3. $h \to a\, a \to$ 4 SM bosons
4. $h \to a\, a \to$ 4 SM fermions

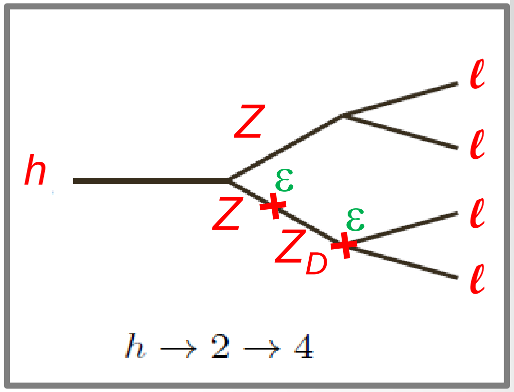
4 e/μ (1, 2)

4 photons (3)

bbbb, bb$\mu\mu$, bb$\tau\tau$, $\tau\tau\mu\mu$, $\mu\mu\mu\mu$ (4)

Mixed final states possible, e.g. bb$\gamma\gamma$, but not currently sensitive

Four e/μ Final State



$h \to Z Z_D$

- Z_D produced & decays via kinetic mixing with γ/Z
- 2 parameters: Z_D mass, $\varepsilon << 1$

Z_D has extremely narrow width

Published ATLAS/CMS ZZ* data allow us to extract limits

Direct limit

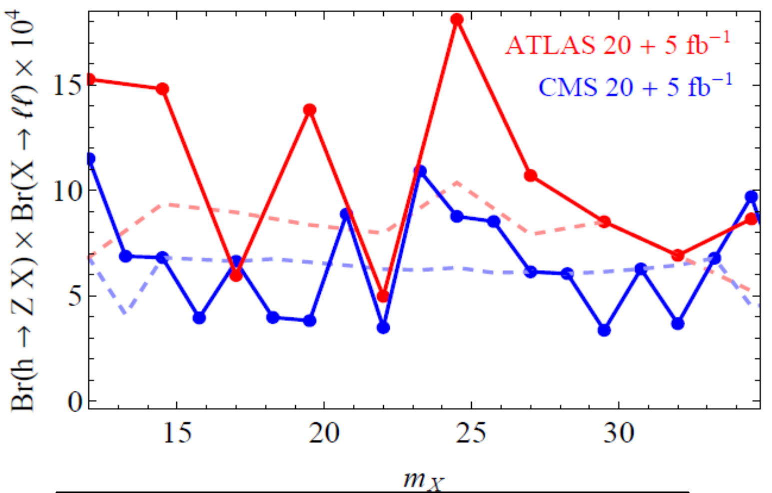
- $Br(h \to Z X \to 4\ell) \sim 3 \times 10^{-5}$

Including Z decay width to leptons

- $Br(h \to Z X)\, Br(X \to \ell\ell) \sim 5 \times 10^{-4}$

Assuming a Z_D with kinetic mixing

- $Br(Z_D \to \ell\ell) \sim 0.3$
- $Br(h \to Z Z_D) \sim 2 \times 10^{-3}$

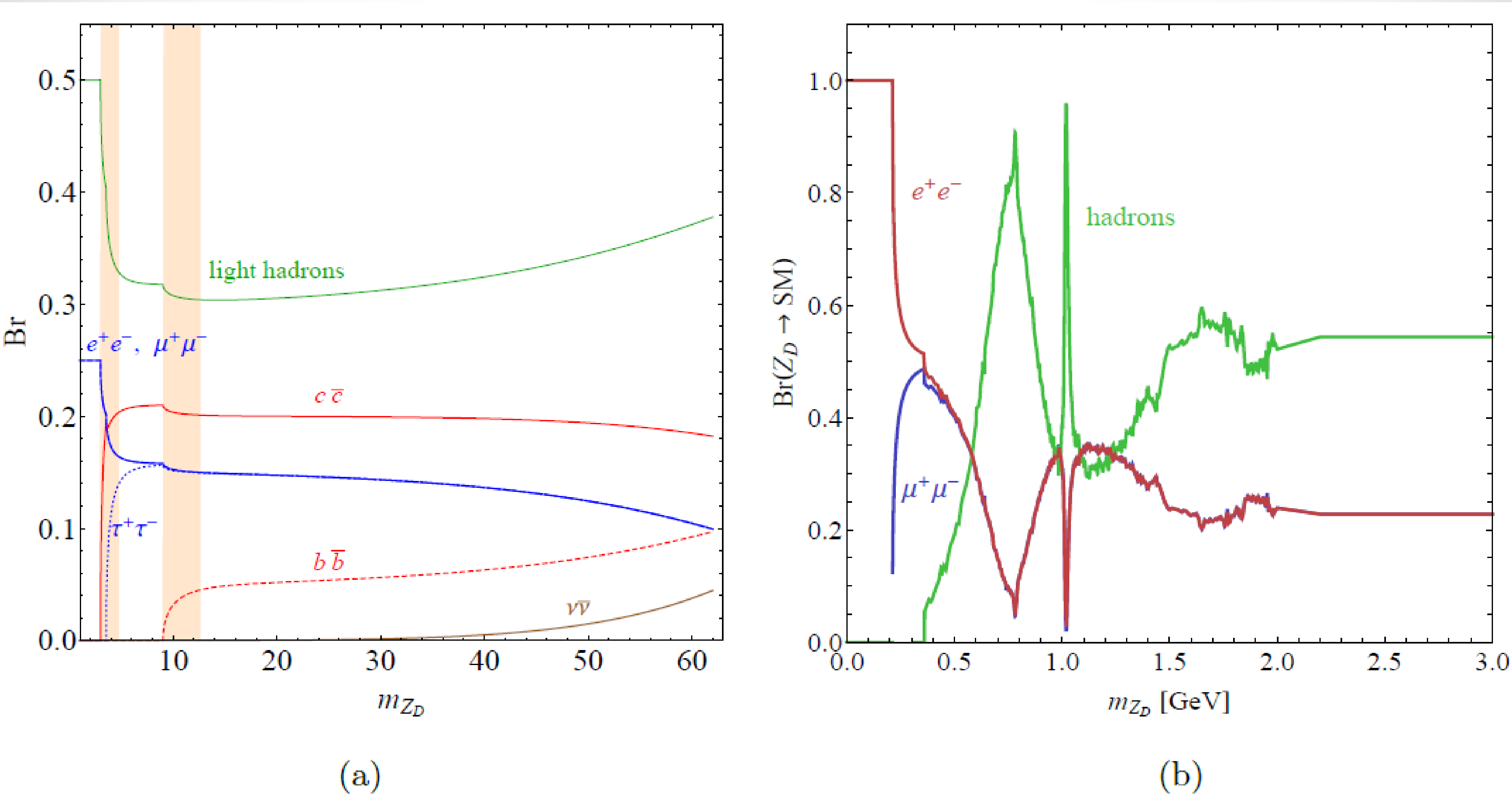


Note: no information below 12 GeV

X could also be *a* with $Br(a \to \mu\mu) \sim (m_\mu/m_\tau)^2 \sim .0035$

But often need $m_a < 10$ GeV

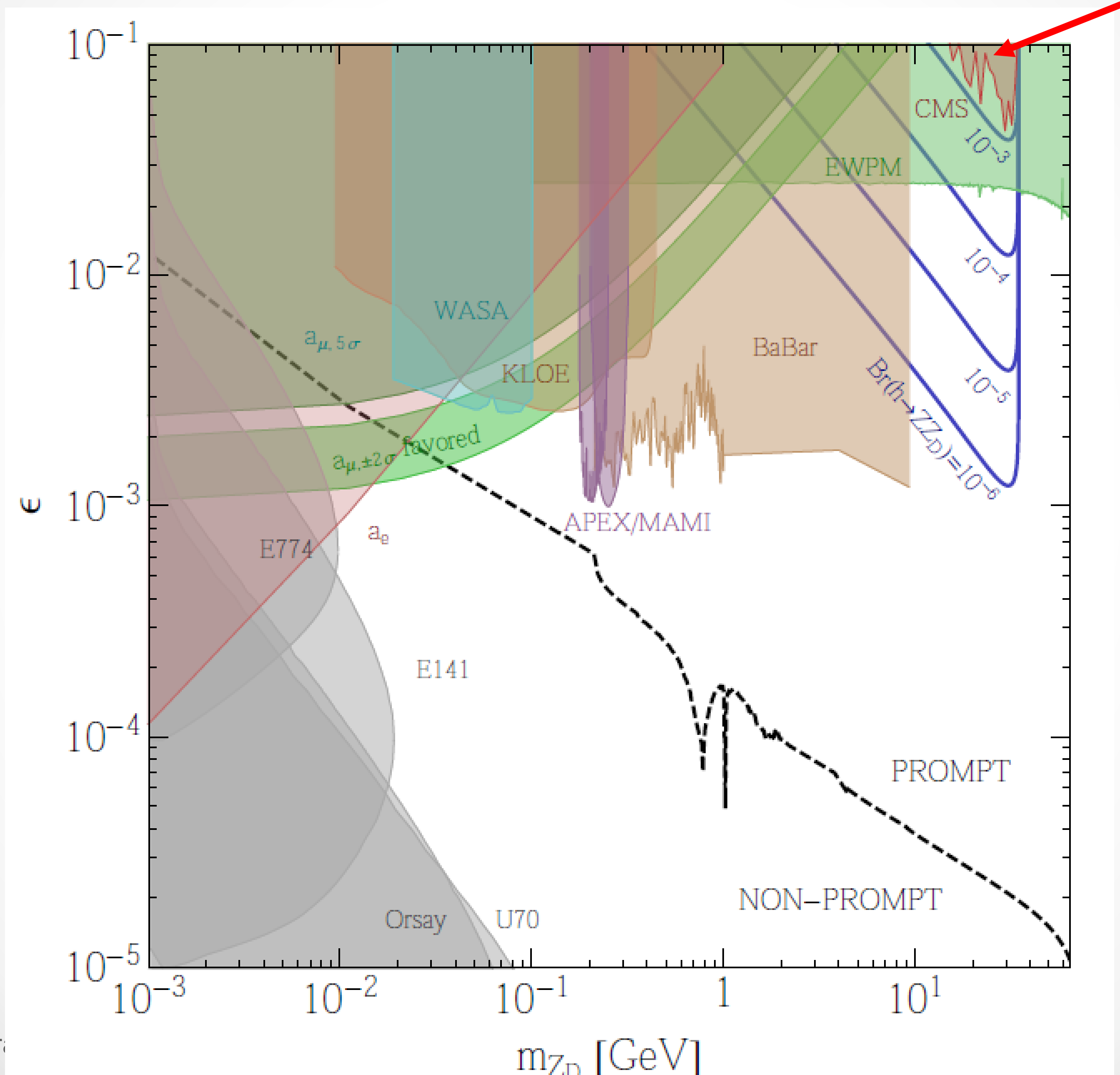
Br's for Z_D with only kinetic mixing



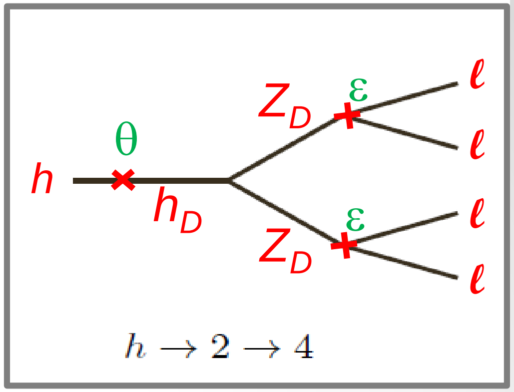
$Br(Z_D \text{ -> } ee) + Br(Z_D \rightarrow \mu\mu) > 20\%$ (except at ρ,ω); typically 30%

Limit ε for each Z_D mass

Our recast of CMS;
Similar for ATLAS



Four e/μ Final State



$h \to Z_D Z_D$

- Z_D produced via mixing of h with h_D
- Z_D decays via mixing with γ/Z

Why doesn't $h \to Z Z^*$ take care of this?

- Incorrectly pair leptons in almost all eeee, μμμμ events
- Eliminate most eeμμ events for $m_{\ell\ell}$ < 40 GeV

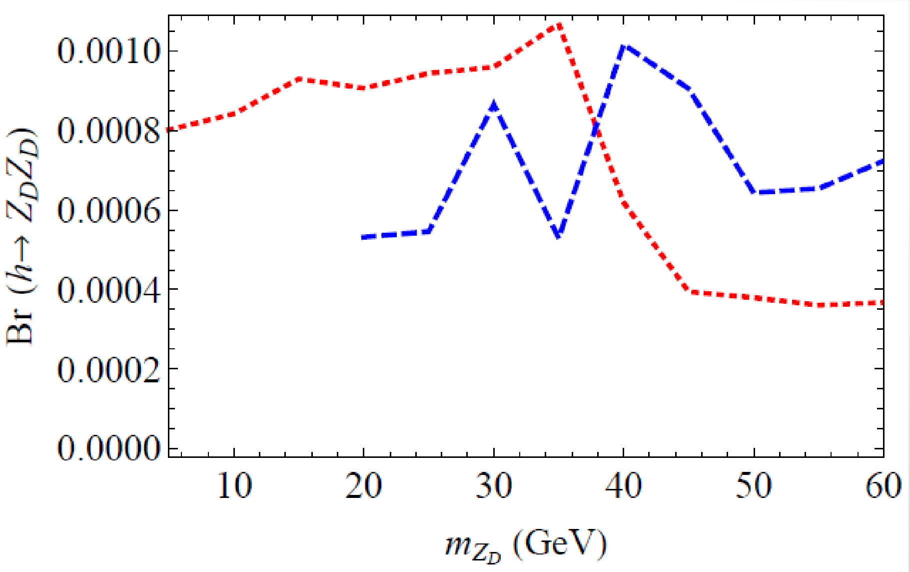
- Still we can extract limits (CMS h→ZZ*, ATLAS Z*Z*)

Direct limit

- Br(h → X X → 4ℓ) ~ 5 x 10^{-5}

Assuming a Z_D with kinetic mixing

- Br(h → Z_D Z_D) ~ 5 x 10^{-4}

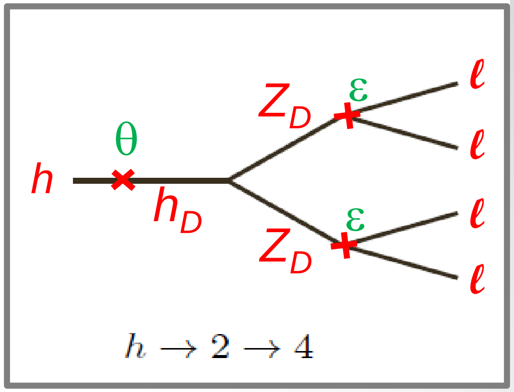


We think ATLAS/CMS could do factor of 2 - 8 better <u>now</u>, especially at low mass

Four e/μ Final State

$h \rightarrow Z_D Z_D$

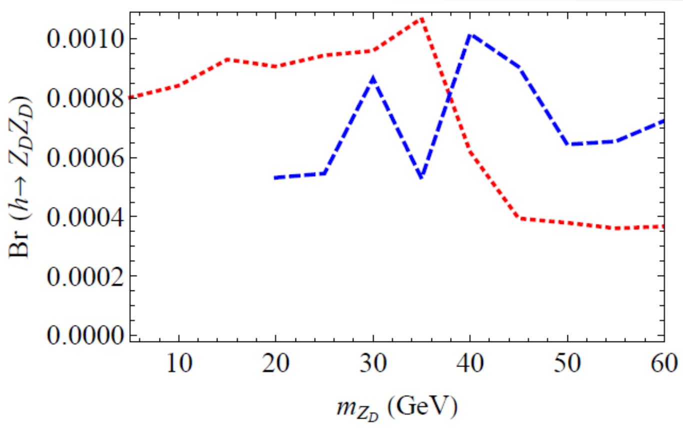
- Z_D produced via mixing of h with h_D
- Z_D decays via mixing with γ/Z



Unless Z_D is long-lived, ε does not enter phenomenology

Therefore two parameters:

1. Z_D mass
2. Replace θ with $Br(h \rightarrow Z_D Z_D)$



3rd parameter: assumed Z_D mixing pure kinetic

- This determines Z_D branching fractions

However, we think this parameter can be ignored.

Model: Limit Br(h → Z_D Z_D) vs. mass of Z_D

h → Z_D Z_D

- 4ℓ ; 2ℓ 2j ; 4j
- (rare) final states with neutrinos

2 jets → 1 jet if low Z_D mass

Sensitivity from 4 leptons far greater than for any other final states

- Quantified (subject to further study) in our paper

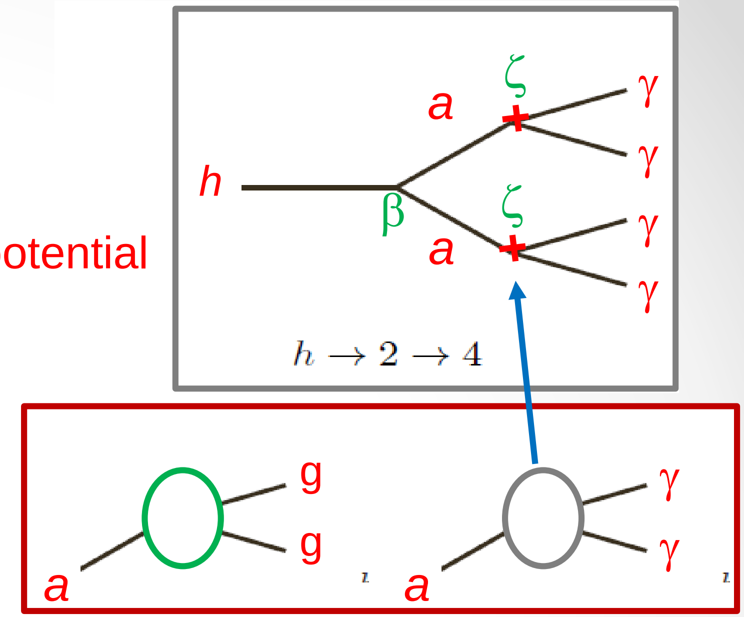
Therefore it is enough to state result from 4 leptons in one model.

- Easy to convert to any other model
  - Just multiply by $[\mathrm{Br}(Z_D \to \ell\ell)_{new} / \mathrm{Br}(Z_D \to \ell\ell)_{old}]^2$

Recommend:

- Assume pure kinetic mixing → Br(Z_D → $\ell\ell$) determined
- 2 Parameters: Br(h → Z_D Z_D), mass of Z_D

Four Photons



$h \to a\ a$

- *a* produced via coupling in scalar effective potential
- *a* decays to gluons and/or photons via loop
  - No coupling to fermions

3 parameters *(unlike $Z_D \to ff$)*

- m_a
- Br($h \to a\ a$)
- Br($a \to \gamma\ \gamma$) – depends on charge/mass of loop particles
  - Colorless particles in loop: Br($a \to \gamma\ \gamma$) = 1
  - Colored particles in loop: Br($a \to \gamma\ \gamma$) < 0.005 usually
  - General spectrum Anything between

Recommend:

- Put limits on Br($h \to a\ a$) [Br($a \to \gamma\ \gamma$)]^2 *(expect in $10^{-(4\text{-}5)}$ range now)*
- For now, ignore Br($a \to \gamma\ \gamma$) ; keep it unspecified. Why?
  - If we take Br($a \to \gamma\ \gamma$) = 1 , nothing new;
  - But if we take Br($a \to \gamma\ \gamma$) < 0.01 , no interesting limit until late LHC14 !
  - And it doesn't matter: 4j, 2j2γ searches maybe relevant only at ~300(?) fb^{-1}

An *a* that couples to fermions

h → *a a*

- *a* produced via coupling in scalar effective potential
- *a* decays mainly to fermions via Yukawa-like couplings

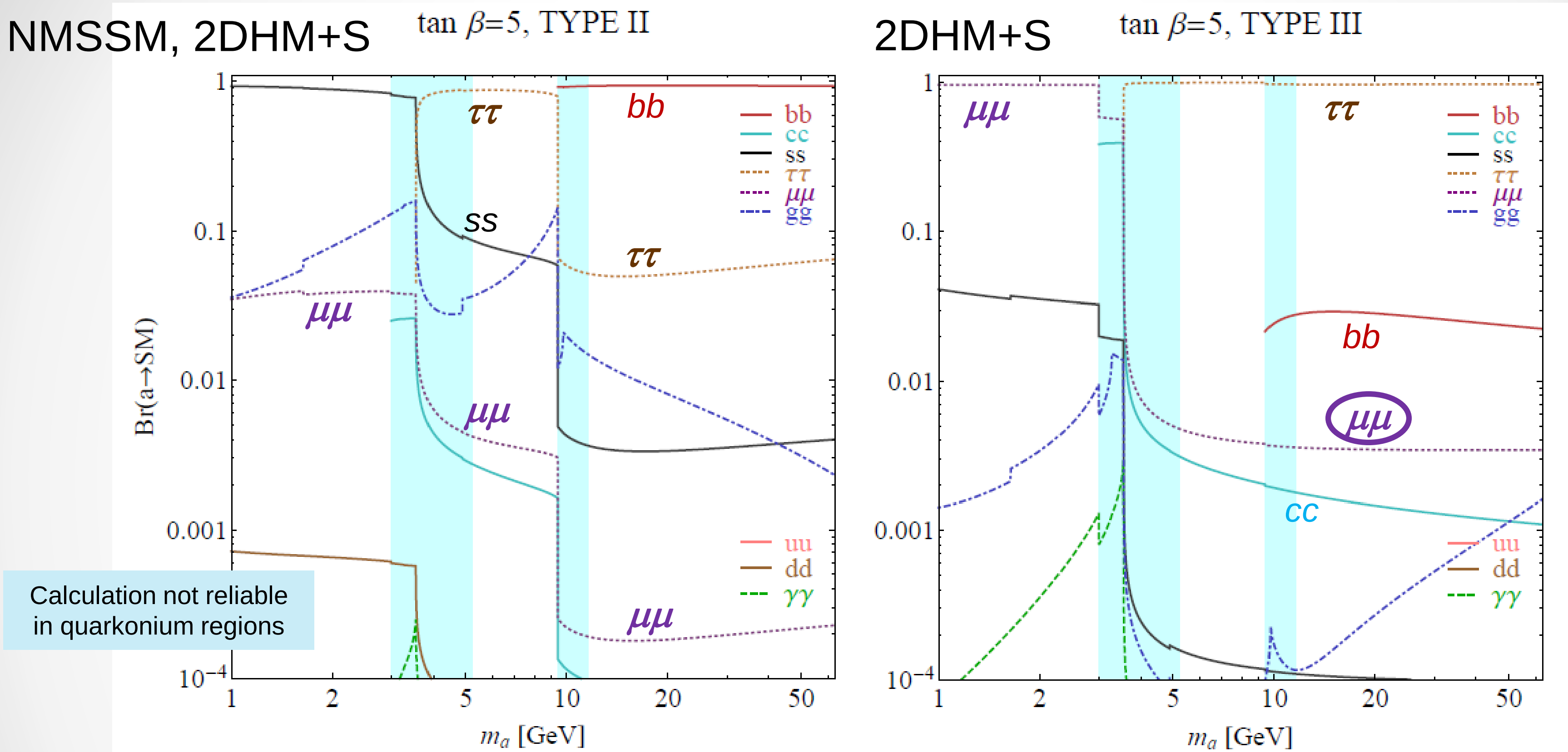
Example: NMSSM -- gets lot of attention, but **where is S**?

- *a* branching fractions similar to comparable-mass h
- *a* → ττ small, μμ negligible if $m_a > 2\ m_b$

Example: More general 2HDM + singlet scalar

- Leptonic, up-type, down-type Br's may grow/shrink relative to NMSSM
- Can have *a* → ττ large, μμ measurable **even if** $m_a > 2\ m_b$

Different Branching Fractions for *a*



Should not restrict searches to NMSSM-motivated scenario!

Recommend use of at least two benchmark models:

1. NMSSM-like model
2. Leptonic-dominated quark-suppressed 2DHM+S model

Current Estimates of Sensitivity

NMSSM-like | Leptonic 2HDM+S; NMSSM at low m_a

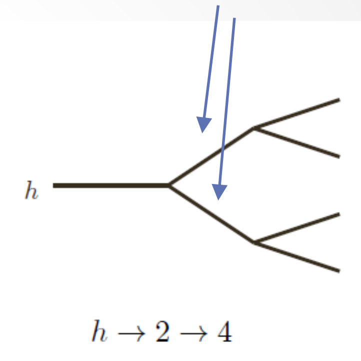
Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [**14**] TeV	Production Mode	quarks allowed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [**14**] TeV	quarks suppressed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [**14**] TeV
$b\bar{b}b\bar{b}$	0.7 [0.2]	Wh	0.8	0.9 [0.2]	0	– [–]
$b\bar{b}\tau\tau$	> 1 [0.15]	VBF	0.1	> 1 [1]	0	– [–]
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4}$ [$(0.6-2)\cdot 10^{-4}$]	gg	3×10^{-4}	$0.5-1$ [$0.2-0.8$]	0	– [–]
$\tau\tau\tau\tau$	$0.2-0.4$ [?]	gg	0.005	$40-80$ [?]	1	$0.2-0.4$ [?]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4}$ [?]	gg	3×10^{-5}	$10-20$ [?]	0.007	$0.04-0.1$ [?]
$\mu\mu\mu\mu$	$1\cdot 10^{-4}$ [?]	gg	$1\cdot 10^{-7}$	1000 [?]	$1\cdot 10^{-5}$	10 $m_a > 2\,m_\tau$ [?]

100 fb^{-1}

- $b\bar{b}b\bar{b}$: 14 TeV boosted Wh
- $b\bar{b}\tau\tau$: 14 TeV VBF
- $b\bar{b}\mu\mu$: 14 TeV gg → h
- $\tau\tau\tau\tau$: 8 TeV gg → h (from multilepton recast)
- $\tau\tau\mu\mu$: 8 TeV gg → h (our analysis proposal)
- $\mu\mu\mu\mu$: 8 TeV gg → h. Important for $m_a < 2\,m_\tau$

Summary: Decays Without MET

1 or 2 New Particles



Four SM Particles

1. h → Z Z_D → 4 SM fermions
   - Mixing ε vs. Z_D mass
2. h → Z_D Z_D → 4 SM fermions
   - Br(h → Z_D Z_D) vs. Z_D mass

4 e/μ

3. h → *a a* → 4 SM bosons
   - Br(h → *a a*) vs. *a* mass

   How best to incorporate Br(*a* → γγ)?

4 photons

Mixed final states possible, e.g. bbγγ

4. h → *a a* → 4 SM fermions
   - NMSSM-like model
   - Model with leptons enhanced, quarks suppressed

   Caution: arbitrary model choices; unwarranted bbττ pessimism

bbbb, bbμμ, bbττ, ττμμ, μμμμ

Lepton/photon collimation, jet merging at low a, Z_D mass

Spin ½ → h decay to 6 visible fermions
- *e.g. h → neutralinos → 6 fermions via RPV*

Asymmetric Decays (e.g. h → a a')

Higher multiplicity: e.g. 8b, complex lepton jets, etc.

Decays with MET

- With MET, the number of processes and parameters grows rapidly
- Any final state can arise from many decay chains
  - Need multiple simplified models

- Low MET vs High MET
  - Very different strategies needed
  - Big differences in sensitivity as masses are varied

- Studies needed!
  - Experimental issues are subtle, so especially need experimental studies!

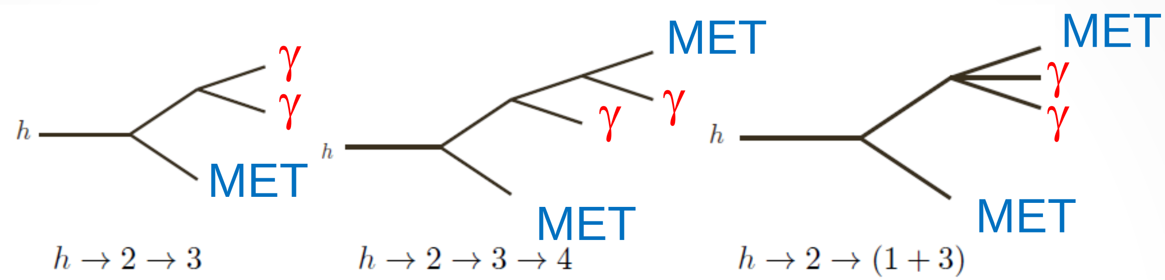
- Here: focus only on most promising final states
  - 1 or more photons + MET
  - 1 or more lepton **pairs** + MET

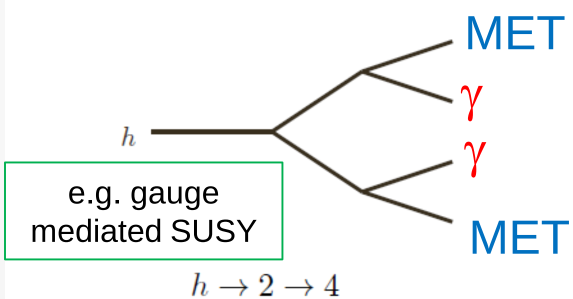
  No evidence yet that other final states are feasible at high MET
  - Maybe resonant bb + MET at 300 fb^{-1} ?

Challenges (1)

- Often multiple possible decay chains with different kinematics

Incomplete List



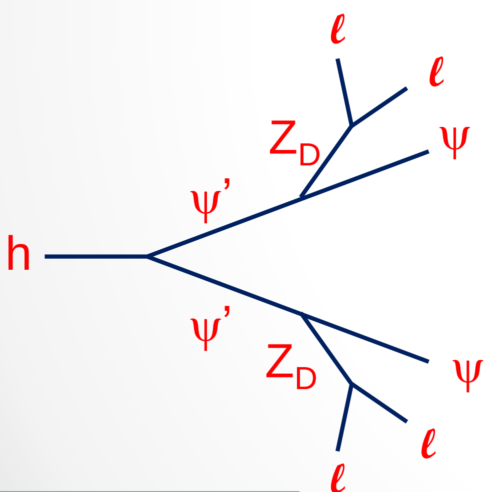


- *Hard (p_T ~ 40) vs. Soft (p_T ~ 15)*
- *Resonant vs.non-resonant*
- *Edge vs. endpoint*
- *Collimated vs. uncorrelated*

- Need several simplified models to cover kinematics
- Typically have 3 or more parameters (multiple masses, Br's)

Challenges (2)

- High MET: MET is useful in bkgd reduction, but γ/ℓ soft, inefficient
  - MET-based search, plus soft visible objects to reduce backgrounds
    - Possible kinematic features in the visible objects
- Low MET: harder γ/ℓ, but MET useless; just changes kinematics
  - Visible parton-based search, but with relaxed kinematic constraints



e.g. SUSY + hidden valley / dark sector

Example: 4 leptons + MET

- *High MET: use VBF + MET search*
  - *+ require 3 soft ℓ or + 2 SS ℓ ?*

- *Low MET: use 4-lepton search*
  - *Require all 4 ℓ detectable*
  - *Do **not** demand $m_{4\ell}$ = 125 GeV*
  - *Look for resonances or edges in $\ell^+\ell^-$ pairs*

(alternate: use trilepton search, look for Z_D resonance?)

MET Story Very Incomplete

Not enough studies (by us or by others) to justify strong recommendations

- e.g. no study of $\gamma\gamma$ + MET where $\gamma\gamma$ is **resonant**
- Best search techniques are often unclear

Only have preliminary & probably pessimistic estimates of what's possible.

Even pessimistically, kinematic regimes of nice models exist where MET +

- 2ℓ
- 4ℓ
- 2γ (and presumably 4γ)

already can be realistically tested with **current data**

Not clear for MET + γ

Nothing known for MET + 4b, etc.

Suggested Models For MET Cases

Not complete list!

- Search for $h \to \ell^+\ell^- + \not\!\!E_T$, including regimes where the leptons are collimated, and including the cases where there is a resonance in $m_{\ell\ell}$. Benchmark models include $h \to XY \to Z_D YY$ or aYY, $h \to XX \to aa^{(\prime)}YY$ for $m_a < 2m_\tau$, $h \to XX \to Z^*Z^*YY$, where Y is invisible and Z^* is an off-shell Z boson.

Occurs in NMSSM

- Search for $h \to \ell^+\ell^-\ell^+\ell^- + \not\!\!E_T$, including regimes where the leptons are collimated, and including the cases where there is a resonance in $m_{\ell\ell}$. Benchmark models include $h \to XX \to Z_D Z_D YY$, $h \to XX \to aa^{(\prime)}YY$ for $m_a < 2m_\tau$, $h \to XX \to Z^*Z^*YY$, where Y is invisible and Z^* is an off-shell Z.

Also: RPV neutralinos → $\ell\ell\nu$

- Search for $h \to \gamma\gamma + \not\!\!E_T$, including the cases where there is a resonance in $m_{\gamma\gamma}$. Benchmark models include $h \to XY \to aYY$, $h \to XX \to aa^{(\prime)}YY$, $h \to XX \to (\gamma Y)(\gamma Y)$, where Y is invisible.
- $h \to XY \to \gamma YY$ where Y is invisible, giving $\gamma + \not\!\!E_T$

Here X,Y may be scalars or fermions

Y could be dark matter

Summary

Non-SM decays of h to new particles very well motivated

- We considered low-multiplicity prompt decays of this type
  - Extensive, but by no means a complete survey of non-SM h decays!

- Decays without MET suggest simple benchmark targets
  - h → 2 spin 1 particles → 4 leptons
  - h → 2 spin 0 particles → 4 photons
  - h → 2 spin 0 particles → b/τ/μ final states
    - Need both NMSSM-like model & model with leptons enhanced

- Decays with MET ; story less complete
  - Much more complex; poorly studied; many challenges
  - Most promising: photons + MET, leptons + MET; look ahead to b's + MET
  - Each final state allows various decay chains ➔ several simplified models
    - These include NMSSM, RPV SUSY, many dark matter models

Additional Slides

Collimated Objects in h Decays

Experimental & theoretical input on h decays to collimated

- leptons
- photons
- jets

G: ggh production
W: W/Zh production
U: unknown limit

14 TeV:
assumes 100 fb^{-1} unless "*", in which case assumes 300 fb^{-1}

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on Br($\mathcal{F}_i$) 7+8 [14] TeV	Produc-tion Mode	Comments
$\{\mu\mu\}\{\mu\mu\}$	$1 \cdot 10^{-5}$ $(5 \cdot 10^{-3})$ [U]	G	CMS [335], $2m_\mu < m_a < 2m_\tau$ (CMS [375] $m_a < 5$ GeV)
$\{ee\}\{ee\}$	limit unclear [U]	W, G	reinterpretation of [223, 285] needed
$\{\mu\mu\}X$	1 [U]	G	CMS, [375], $2m_\mu < m_a < 5$ GeV
$\{\mu\mu\}$ $\not{E}_T$	0.03^L [U]	W	Theory study, [52, 53]
$\{\mu\mu\}\{\mu\mu\}$ $\not{E}_T$	$1 \cdot 10^{-5}$ $(5 \cdot 10^{-3})$ [U]	G	CMS [335], $2m_\mu < m_a < 2m_\tau$ (CMS [375] $m_a < 5$ GeV) however, see text for important details
$\{ee\}\{ee\}$ $\not{E}_T$	limit unclear [U]	W, G	reinterpretation of [223, 285] needed
$\{\tau\tau\}\{\mu\mu\}$	$(3-7) \cdot 10^{-4\ T}$ [U]	G	This work, see Sec. 6.2
$\{\gamma\gamma\}\{\gamma\gamma\}$	0.01 [U]	G	ATLAS [320], $m_a < 400$ MeV
$\{\gamma\gamma\}$ $\not{E}_T$	U[U]		no studies
$\{gg\}\{gg\}$	> 1 $[0.7^L]$	W	boosted Wh [263], $m_a < 30$ GeV
$\{b\bar{b}\}\{b\bar{b}\}$	0.7^T $[0.2^L]$	W	boosted Wh [263], $m_a \sim 15$ GeV

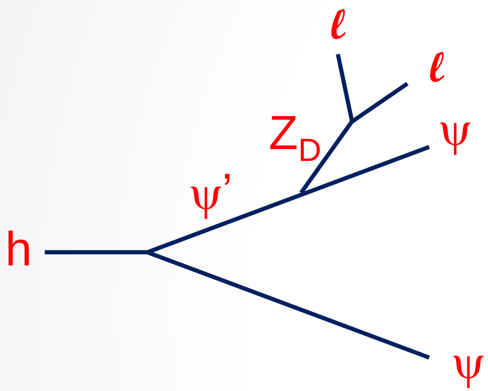
TABLE XX: Estimates for sensitivity of certain searches for collimated pairs of objects; collimation is denoted by curly brackets. See Table XII for notation and text for more details. The superscripts indicate: $* = 300$ fb^{-1}, L = estimate from theory literature, T = our theoretical study, R = our recast of experimental data.

Benchmark Models: Beyond LO

- Easy for theorists like those on our team to generate BSM benchmark models at LO for experimenters to use.
  - Some of our team are working on this.
- N(N)LO BSM corrections to production are usually unimportant
  - SM corrections are usually sufficient
  - Exception: multi-doublet models where production is not SM even at LO
- But NLO corrections to the decays are beyond us!
  - We do not have branching fractions or differential distributions at NLO
- Need expert help here.

Possible Approach to MET models

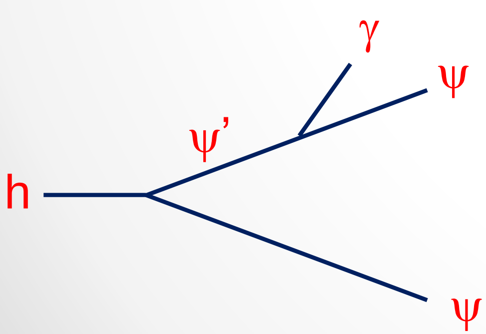
- Perhaps a "single-sided" process is most important first target model

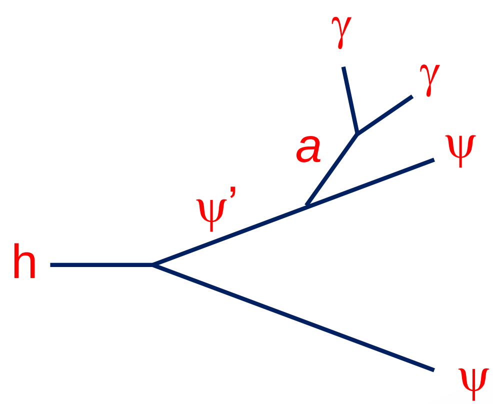


- More MET, fewer objects
  - More like invisible Higgs, less like all-visible
- Linear in Br, not quadratic
  - Fewer parameters matter

If one can search for $h \rightarrow \psi'\psi$, where ψ is invisible, then $h \rightarrow \psi'\psi'$, $\psi'\psi''$ will often be easier

(but not if MET becomes too low!)





(with *a* on- <u>or</u> off-shell)

1 photon + MET

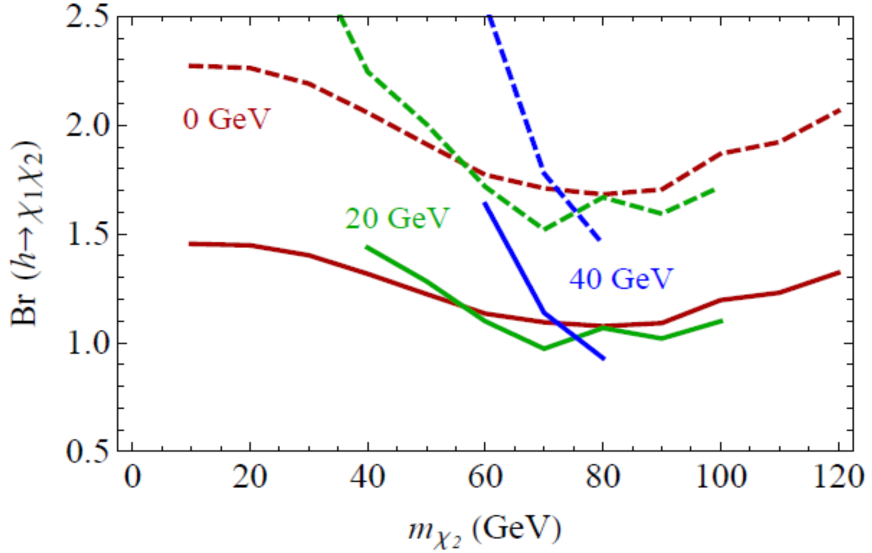
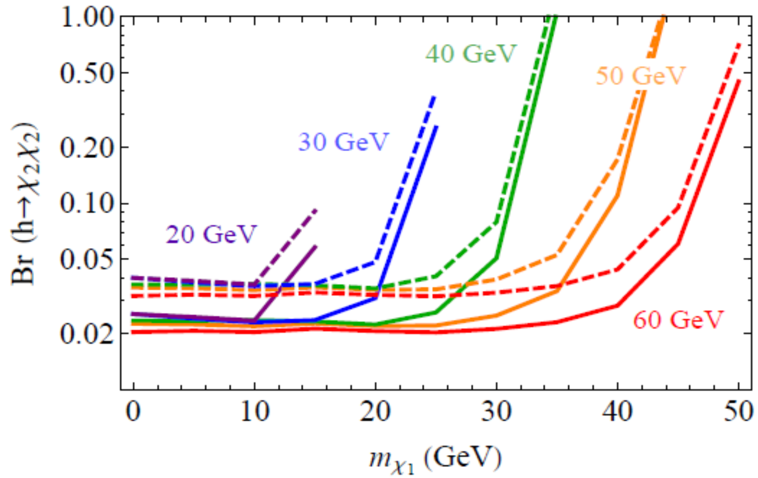


FIG. 31: Approximate 95% C.L. upper limit on $(\sigma/\sigma_{SM}) \times \text{Br}\,(h \to \chi_1\chi_2 \to \gamma + \not{E}_T)$ from the results of Ref. [355], for $m_{\chi_1} = (0\text{ GeV}, 20\text{ GeV}, 40\text{ GeV}) < m_{\chi_2}$. Solid lines correspond to 100% photon efficiency, and dashed lines to a (flat) 80% photon efficiency.

2 photons + MET

- Weak limit from GMSB search



Approximate 95% C.L. upper limit on $(\sigma/\sigma_{SM}) \times \mathrm{Br}\,(h \to \chi_2\chi_2 \to 2\gamma + \not{E}_T)$

2 photons + MET

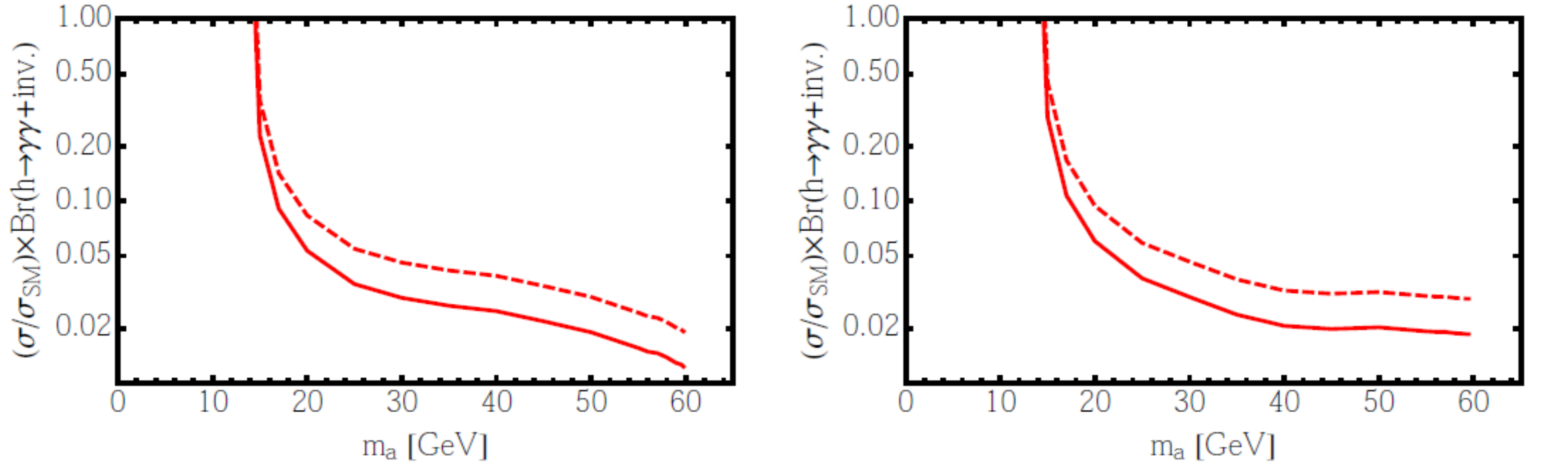


FIG. 33: Approximate 95% C.L. upper limit on $(\sigma/\sigma_{SM}) \times \text{Br}(h \to 2\gamma + \not{E}_T)$ from the $2\gamma + \not{E}_T$ search in [355]. The solid lines correspond to 100% photon efficiency, and the dashed lines to a (flat) 80% photon efficiency. **Left:** Resonant case, where $h \to aa$, one a decays to $\gamma\gamma$ and the other decays invisibly. **Right:** Cascade case, where $h \to \chi_1\chi_2$, $\chi_2 \to s\chi_1$, $s \to \gamma\gamma$. Here $m_{\chi_1} = 0$ and $m_{\chi_2} = 60$ GeV (although the limit is insensitive to the particular value of m_{χ_2} as long as it is

2 leptons + MET

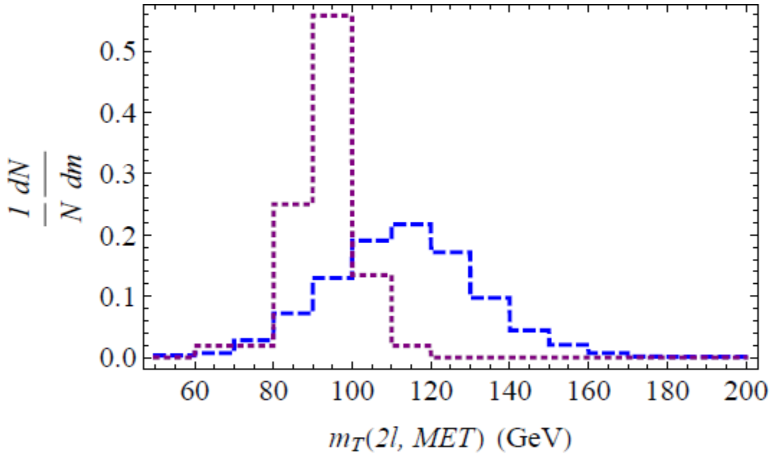


FIG. 34: Unit-normalized distributions of $m_T(2\ell, \not{E}_T)$. The blue dashed line shows the ATLAS prediction for SM $h \to WW^*$ events passing all selection criteria in both 7 and 8 TeV data sets [372]. The purple dotted line shows the distribution for the BSM $h \to 2\ell + \not{E}_T$ events arising from $h \to \chi_2\chi_1$ at the 8 TeV LHC in the benchmark model described in the text.

2 {$\mu^+\mu^-$}-jets + MET

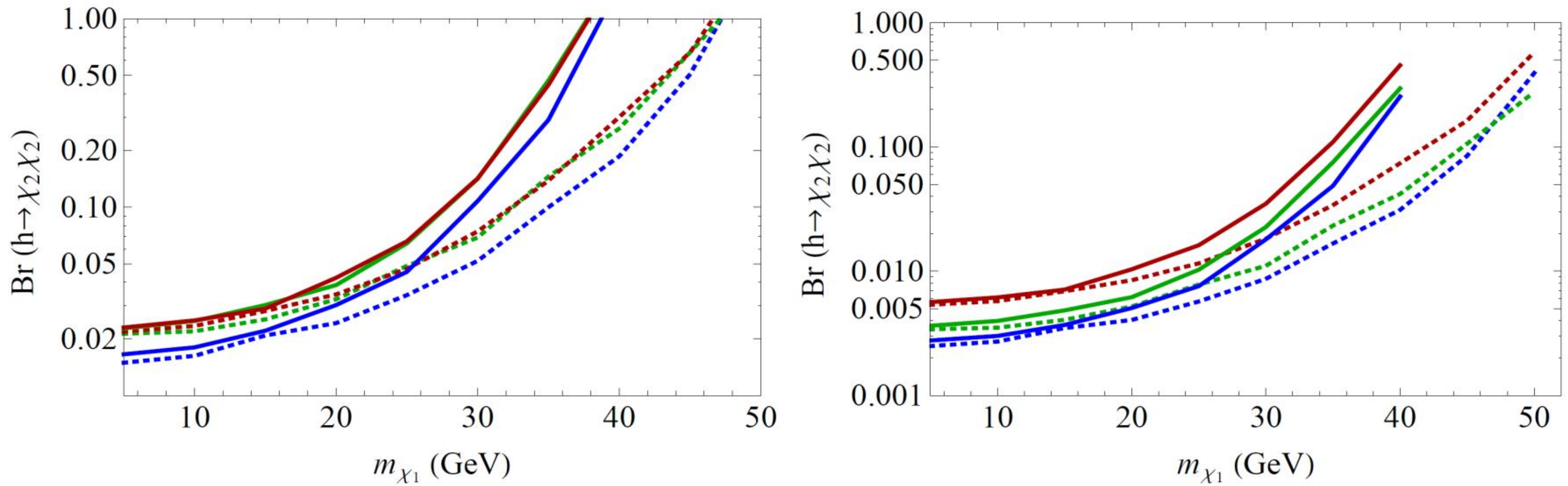


FIG. 35: Approximate bounds on the branching fraction for $h \to \chi_2\chi_2$, assuming **(left)** $\mathrm{Br}(\chi_2 \to a\chi_1) = 1$, and **(right)** $\mathrm{Br}(\chi_2 \to Z_D\chi_1) = 1$, as a function of m_{χ_1}, from [335]. Here solid lines indicate $m_{\chi_2} = 50$ GeV and dotted lines $m_{\chi_2} = 60$ GeV, while red, green, and blue correspond to $m_{a,Z_D} = 3$ GeV, 1 GeV, and 0.4 GeV respectively. We use tree-level results for $\mathrm{Br}(Z_D \to \mu\mu)$ (see Fig. 13) and a reference $\mathrm{Br}(a \to \mu\mu) = 0.1$ (which can occur in Type IV 2HDM+S models, see Fig. 9).

Prioritizing: Partially Visible Decays

Examples which are experimentally "easy" but can't be reconstructed:

- γ + MET
- $\ell^+\ell^-$ + MET *(non-resonant leptons)*
- $\ell^+\ell^-\ell^+\ell^-$ + MET *(resonant or non-resonant leptons)*
- $\gamma\gamma$ + MET, $\gamma(\gamma\gamma)$ + MET *(resonant or non-resonant photons)*
- …

- If MET is large, pick up in existing invisible searches
- If MET is smaller, pick up in previous visible searches

Quite difficult to prioritize (few theory studies, many possible final states)

- Suggest:
  - Experimentalists: complete first round of invisible & fully-visible searches
  - Theorists: do some studies in coming months
  - Then compare and evaluate the opportunities

Prioritizing: Decays to Unusual Objects

- Unusual Objects means
  - New particles with displaced decays
  - Clusters of new particles with prompt or displaced decays
  - Soft final states

- Many of these searches cannot reconstruct *h* resonance
  - In this case, can use generic search for unusual objects -- not *h*-specific
  - Or require the jets from VBF or the lepton(s) from *Wh, Zh*

- Only thoroughly studied case is “lepton-jets”
  - Hidden particles with m < few GeV decaying to lepton pairs, hadron pairs
  - Possibly produced in clusters

- Neither theorists nor experimentalists can study this alone
  - Must communicate and do joint studies
  - Need to plan workshops for later in 2014

Dark Sectors (and/or Hidden Valleys)

Sectors of SM Singlets:

- Very little constrained by previous data!
- Motivated by known BSM:
  - Sterile Neutrinos (for neutrino masses)
  - Dark Matter
- Dark Sector (>1 particle) simple if all particles invisible
  - MET signals only
  - Phenomenologically identical or similar to minimal case of one particle
- (Partially?) Visible Dark Sector *(i.e. Hidden Valley-type)*
  - With multiple particles, visible or partially visible decays often possible
  - If interactions, then rich set of phenomenological signatures available

$h \rightarrow$ invisible

Non-SM Visible h Decays

Non-SM Partly Visible h Decays

Singlets

Rich singlet sector possible, as complex as SM

(Dark Sector; Twin Higgs; NMSSM; Hidden Valley; Unparticles…)

- Minimally constrained by previous data!

- Few SM particles couple to singlets in renormalizable way
  - U(1) hidden gauge boson V coupling to U(1) hypercharge boson ($F^{\mu\nu}F'_{\mu\nu}$)
  - Scalar S coupling to doublet Higgses (SH^*H, S^*SH^*H)

- But then S or V can couple to other singlets in renormalizable way
  - E.g. $S\psi\psi$
- Or additional BSM particles can allow renormalizable couplings
  - E.g. Bino-quark-squark
- Other couplings may be induced by strong dynamics in hidden sector

- Eventually some metastable singlets may decay back to SM particles
  - This can happen promptly or well-displaced inside the LHC detectors

Singlets

Singlets (Dark Sector; Twin Higgs; NMSSM; Hidden Valley; Unparticles…)

  - Minimally constrained by previous data!

- Often produced in decay of something heavier
- May be stable ➔ MET
- May decay to SM particle pairs ➔ visible
  - Couplings may be very small ➔
    - Masses may be small
    - Lifetimes may be long
- May decay to other singlets which in turn…