Exotic Decays

of the

125 GeV h

(Theory)

Matt Strassler
PITT PACC
h and Beyond
12/3/15

- Much of today's talk is based on hep-ph/1312.4992

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

- Will also discuss long-lived particles briefly

Covered in Our Study

Exotic Decays of the 125 GeV Higgs Boson

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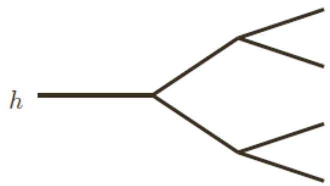
h decays

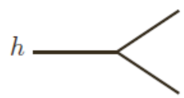
- to at most four visible SM partons
- and involving at least one non-SM particle in intermediate step

Cases With No MET

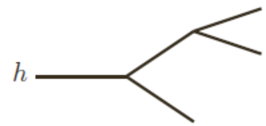


$h \to 2 \to 4$

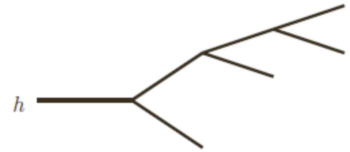
Cases With MET



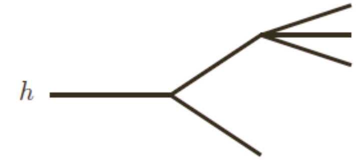
$h \to 2$



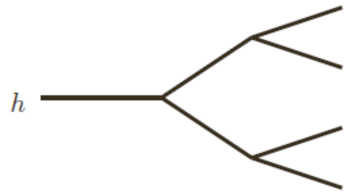
$h \to 2 \to 3$



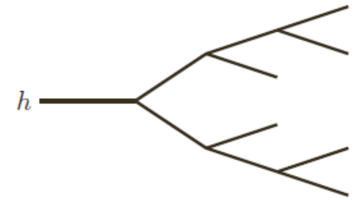
$h \to 2 \to 3 \to 4$



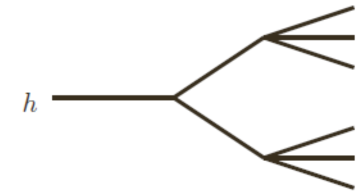
$h \to 2 \to (1+3)$



$h \to 2 \to 4$



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



$h \to 2 \to 6$

Not Covered in our Study

- Certain subtleties when particles are collimated
  - We only covered “simple lepton jets” (each jet has 2 leptons, nothing else)
- Higher parton-multiplicity final states
- New long-lived particles: require different treatment

Also:

- Simple and well-studied final states like $h \rightarrow \tau\ \mu$
- Decays involving new *off-shell* particles

Motivation

- h decays may serve as window to weakly-interacting 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%.

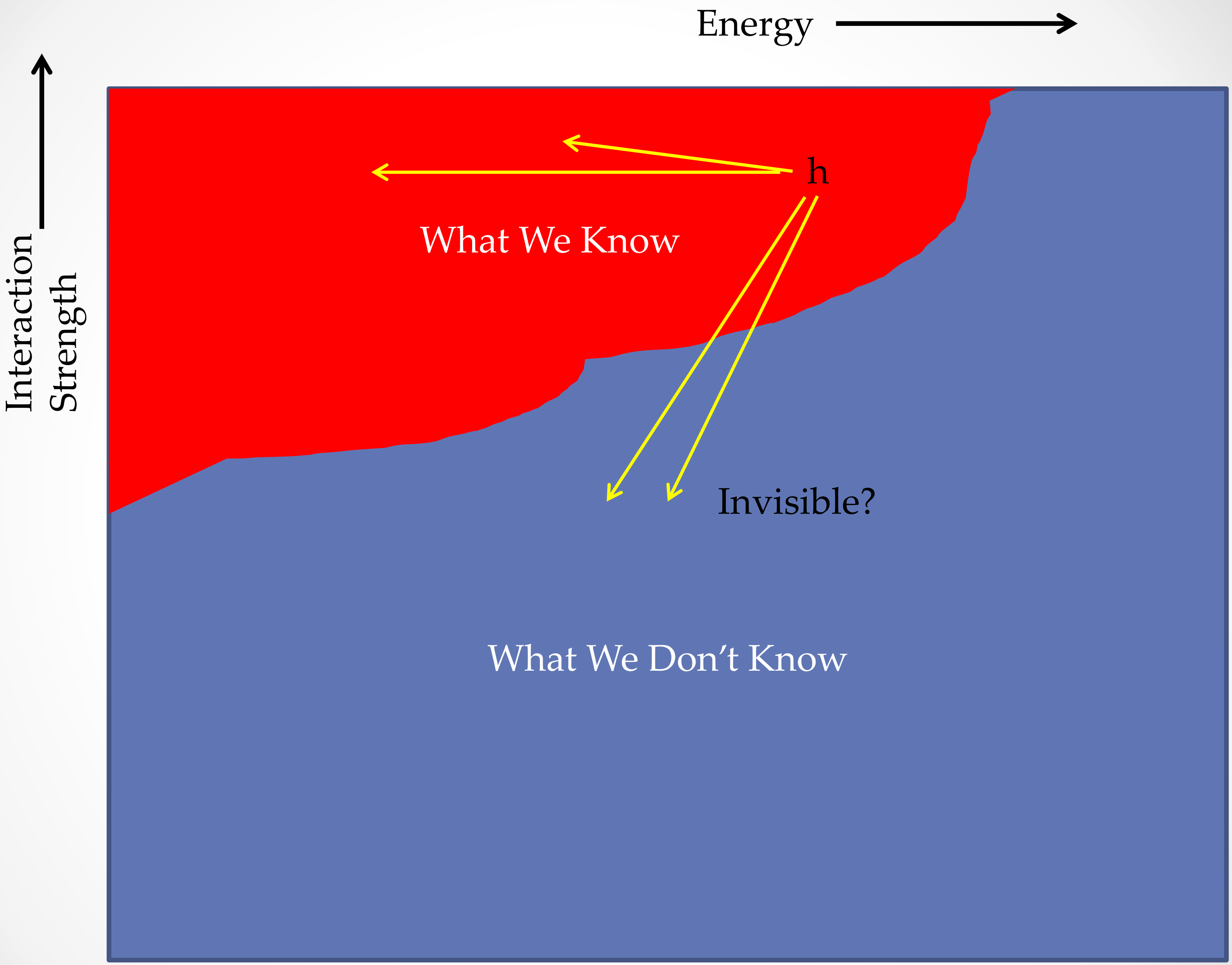
- Number of h produced is large, so potential to reach Br ~ 10^{-4} or better
  - 10^6 already produced
  - Approaching 10^8 in foreseeable future
    - But --- trigger and analysis challenges!

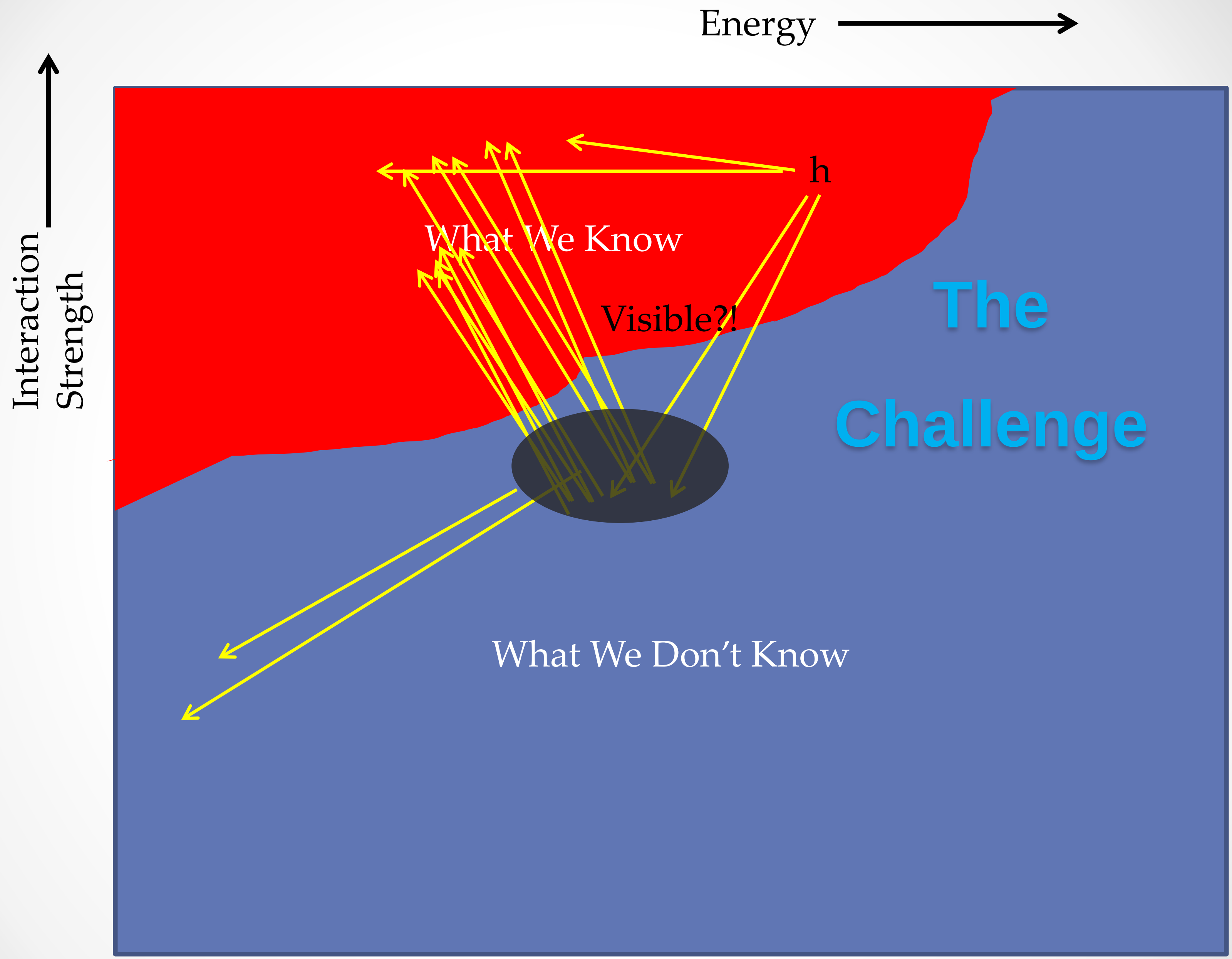
- In some theories,
  - h decays are **first** BSM physics discoverable at LHC
  - Or even the **only** BSM physics discoverable at LHC14!

- Same searches might turn up new members of scalar sector (e.g. H) if decays dominated by non-SM final states

Motivation (3)

- SUSY
  - NMSSM: Dermasek Gunion 04; Chang Fox Weiner 05 …
  - RPV: Carpenter Kaplan Rhee 06 …
- Hidden Valleys *(SM+hidden sector with mass gap/ledge)*
  - Make use of ``Higgs portal'' MJS Zurek 06 …
- Neutrino Masses at weak scale Graesser 07 de Gouvea 07 …
- Dark Matter Hooper Zurek, Pospelov Ritz, Finkbeiner et al. 09 …
- Baryogenesis Cui Shuve 15 …
- Hidden Naturalness
  - Models: [Burdman] Chacko Goh Harnik 05,06 …
  - HV Pheno: Craig, Katz, MJS, Sundrum 15; Curtin & Verhaaren 15 …
- Cosmological Relaxation *[with higher cutoff]* Graham, Kaplan, Rajendran 15


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

Urgency? Trigger!

- h → 4 or more partons ➔ typical p_T ~ 30 GeV or less
  - Very low except for muons!
- ATLAS/CMS: Trigger challenge met for SM 4-body decays
- But not necessarily for non-SM decays with few e's, μ's
- Significant progress since 2013 but maybe more to be made?

Since 2013

- Lots of models (or regions of param space) predicting non-SM h decays.
- A substantial number of new experimental results!!
  - ATLAS, CMS, LHCb
  - Next talk!
- Very few theory studies?!?!
  - Guidance needed on triggering and analysis strategies!
  - See the summary chapter of our review for open questions needing study.

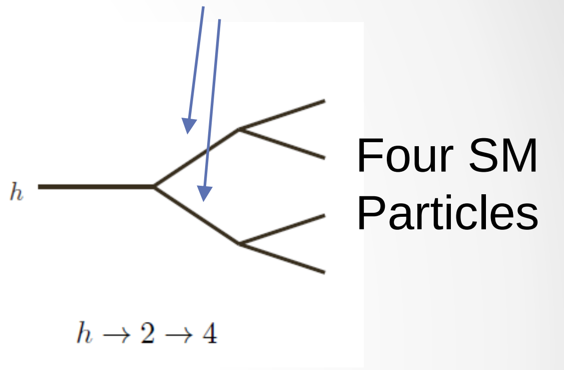
Decays Without MET

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

- With a small loophole

We consider

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



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)

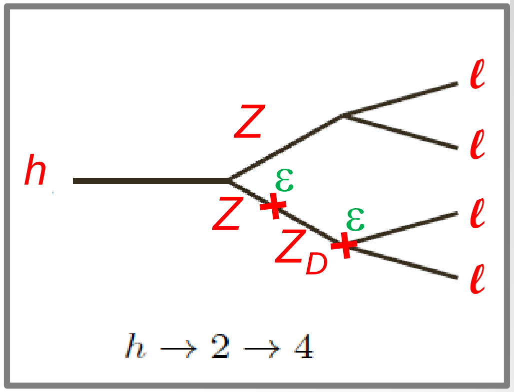
See also Davoudiasl et al, Curtin et al, Falkowski Vega-Morales, … '14

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

Four e/μ Final State

$h \rightarrow Z\, Z_D$

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



Z_D on-shell, extremely narrow width

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

Direct limit

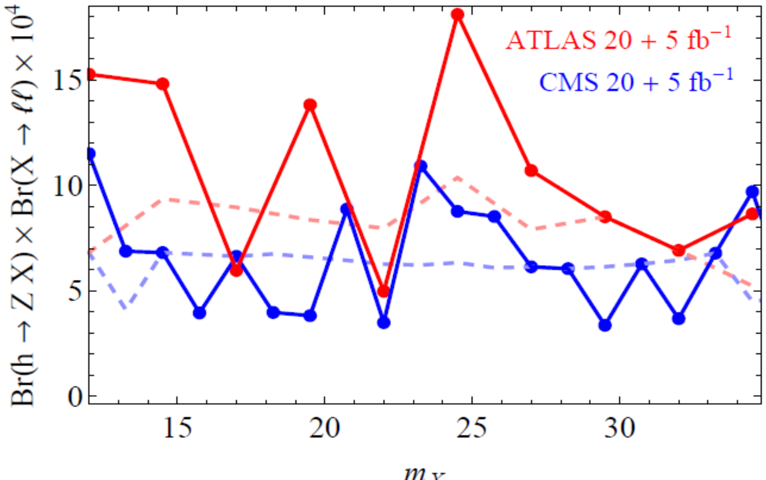
- $Br(h \rightarrow Z\,X \rightarrow 4\ell) \sim 3 \times 10^{-5}$

Including Z decay width to leptons

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

Assuming a Z_D with kinetic mixing

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

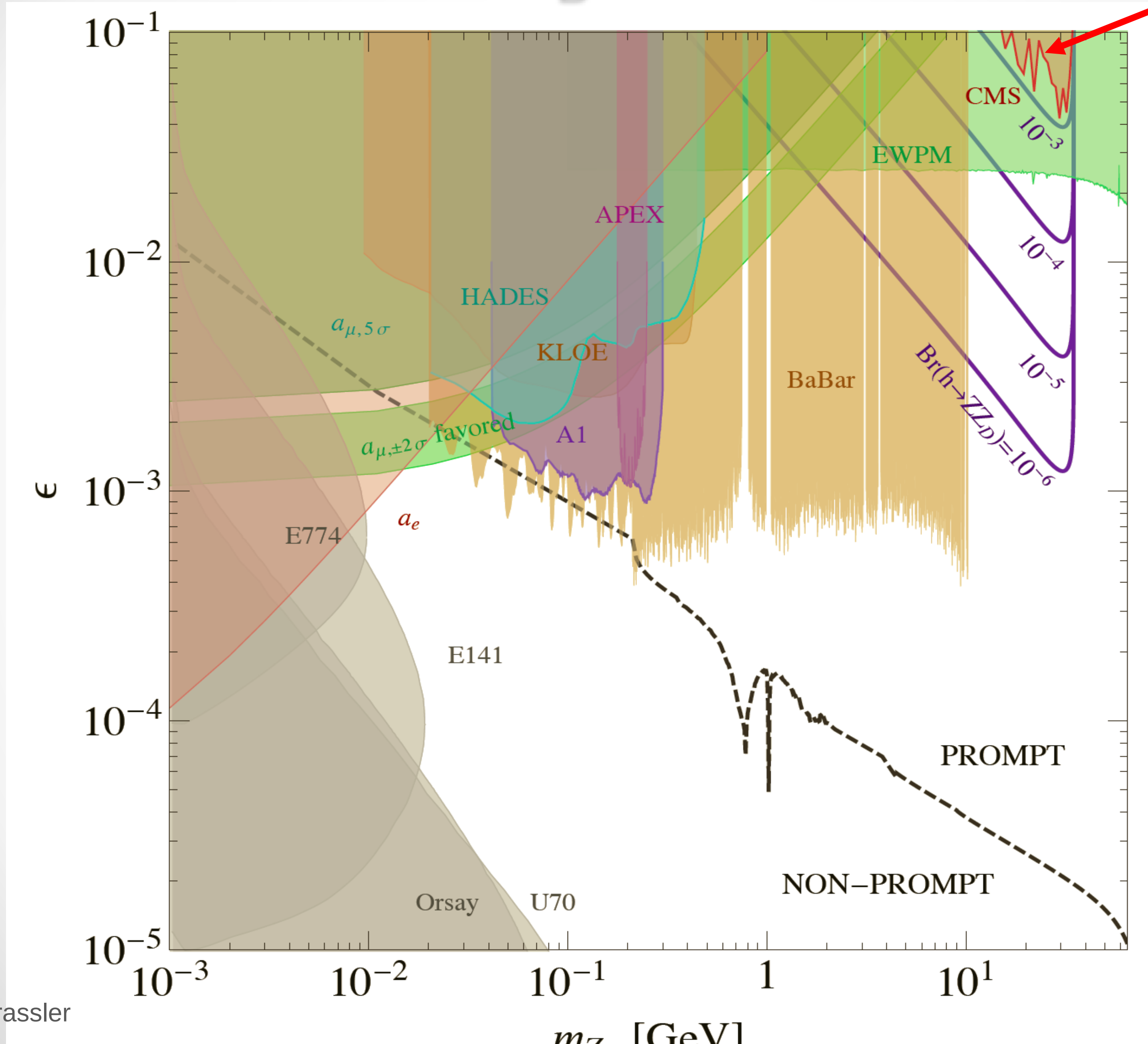


X could also be *a* with $Br(a \rightarrow \mu\mu) \sim (m_\mu/m_\tau)^2 \sim .0035$

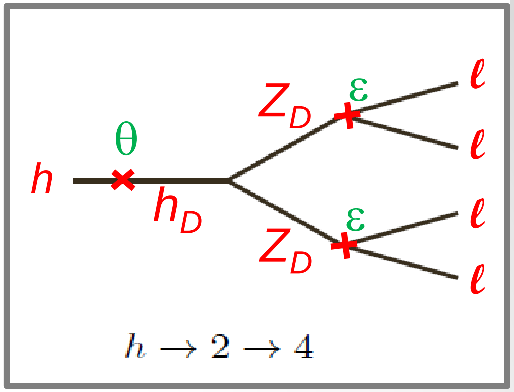
But often need $m_a < 10$ GeV

Limit ε for each Z_D mass

Our recast of CMS; Similar for ATLAS



Four e/μ Final State



h → 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 → 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

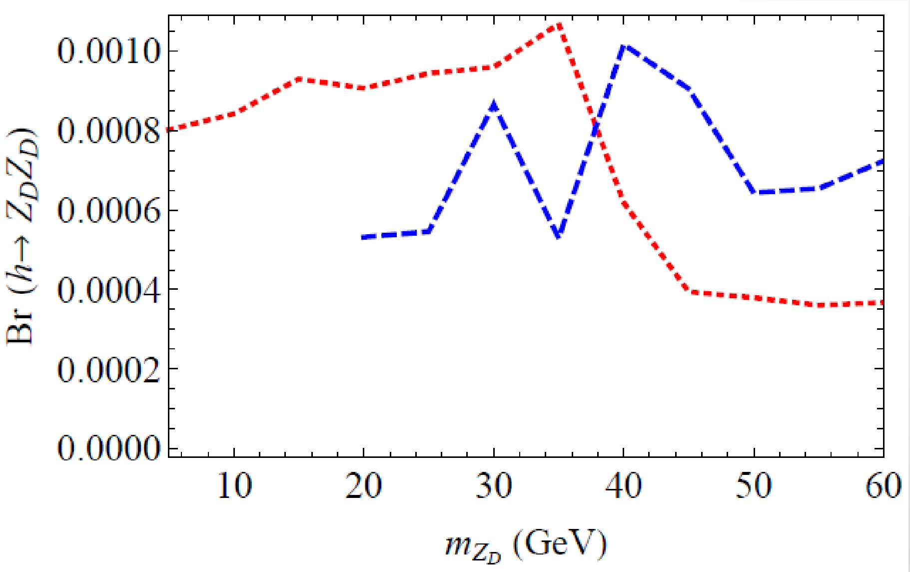
- Still we can extract limits (CMS h→ZZ*, ATLAS Z*Z*)

Direct limit

- Br(h → X X → 4ℓ) ~ 5 x 10^{-5}

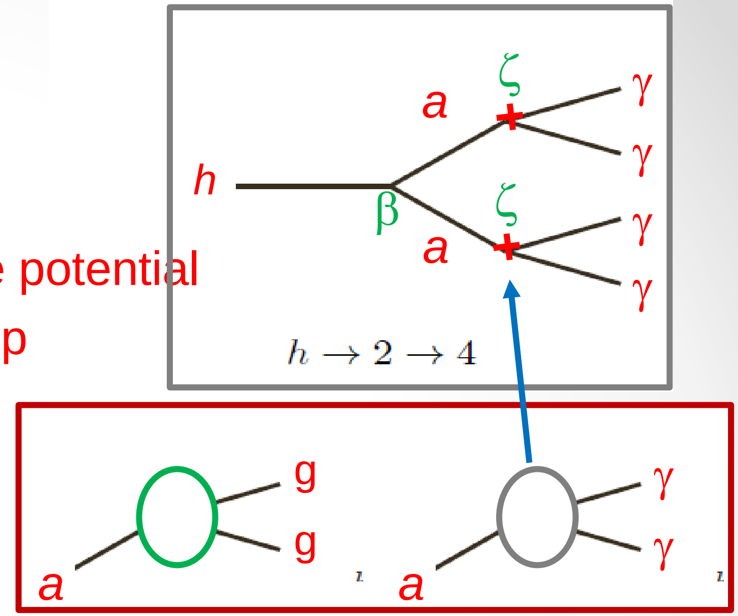
Assuming a Z_D with kinetic mixing

- Br(h → Z_D Z_D) ~ 5 x 10^{-4}



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

Four Photons



h → *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 → ff)*

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

Recommend:

- Put limits on Br(h → *a a*) [Br(*a* → γ γ)]^2 *(expect in $10^{-(4\text{-}5)}$ range now)*
  - 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

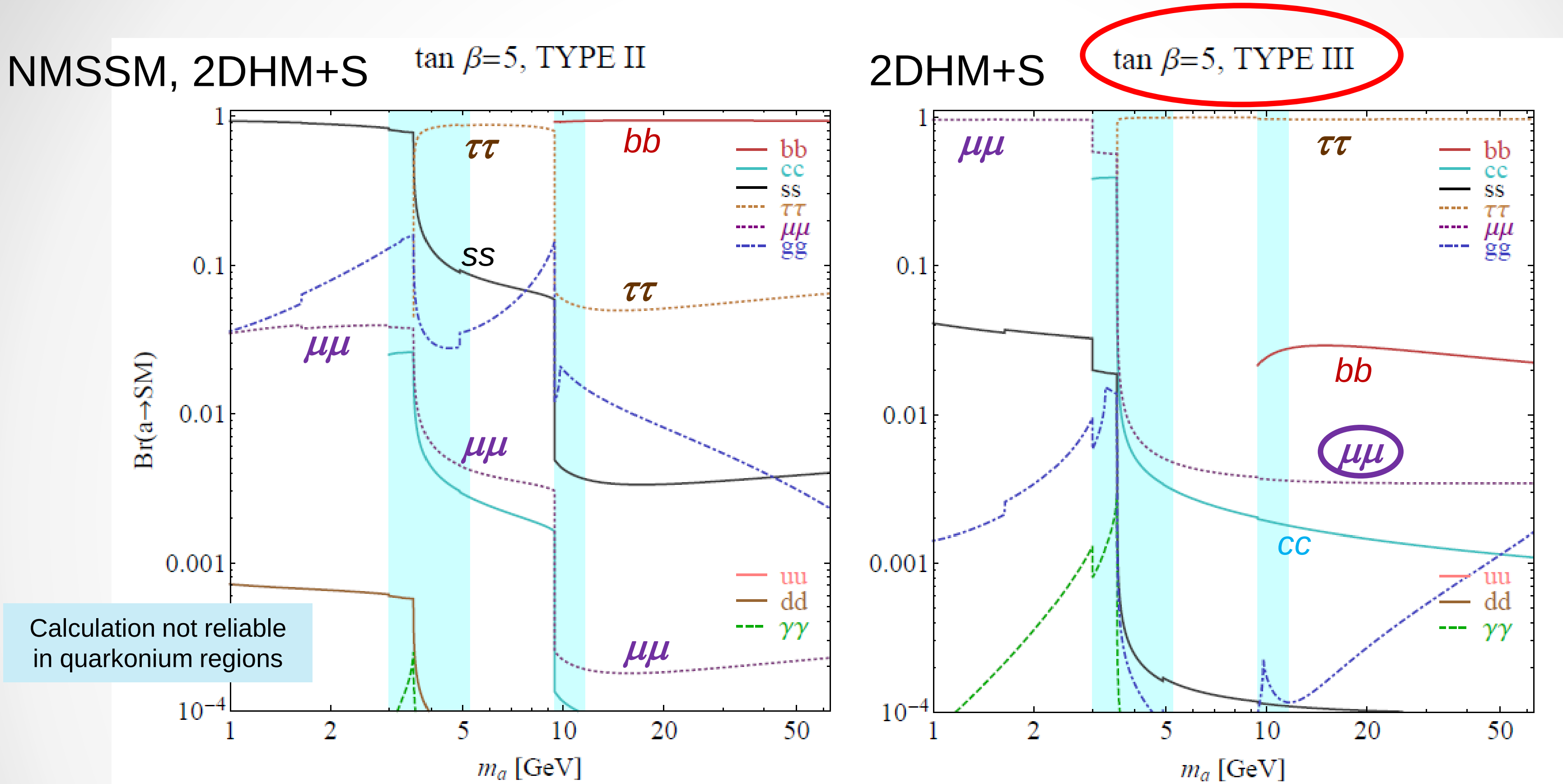
Example: NMSSM -- gets lot of attention, but **where is S**?

- *a* branching fractions similar to comparable-mass h
- $a \to \tau\tau$ small, $\mu\mu$ 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 $a \to \tau\tau$ large, $\mu\mu$ 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 $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [**14**] TeV	Production Mode	quarks allowed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [**14**] TeV	quarks suppressed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 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 [?] $m_a > 2\, m_\tau$

See Curtin et al '14

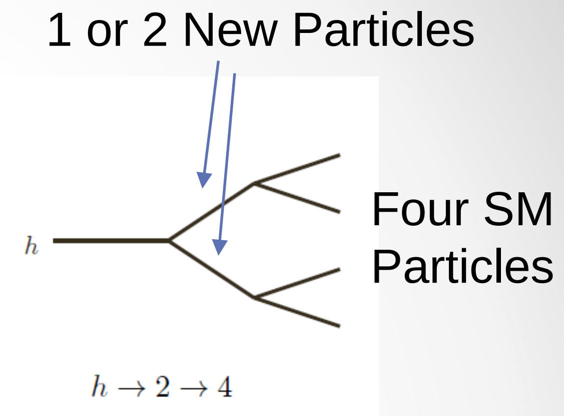
100 fb^{-1}

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

Summary: Decays Without MET

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

4 e/μ



3. $h \rightarrow a\ a \rightarrow$ 4 SM bosons
   - Br($h \rightarrow a\ a$) vs. a mass

4 photons

Mixed final states possible, e.g. $bb\gamma\gamma$

4. $h \rightarrow a\ a \rightarrow$ 4 SM fermions
   - NMSSM-like model
   - Models with leptons enhanced, quarks suppressed

bbbb, $bb\mu\mu$, $bb\tau\tau$, $\tau\tau\mu\mu$, $\mu\mu\mu\mu$

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.

Invisible Decays

Invisible Decays

- There may be light singlets
- They may not have visible decays
- Higgs may decay to them

- *But they might have visible decays!*

Partly Visible Decays

With MET, # of processes, parameters grows rapidly

- Any final state can arise from many decay chains
  - Need multiple simplified models

- Theory/Experimental studies needed!
  - Experimental issues are subtle

- 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} ?

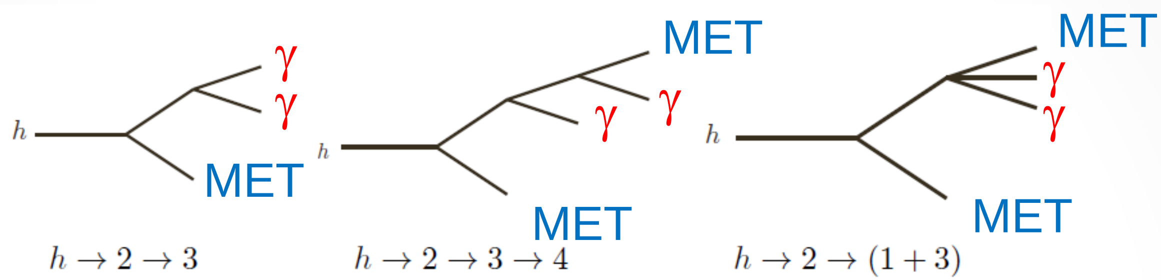
Recently: *Gabrielli et al. '14*

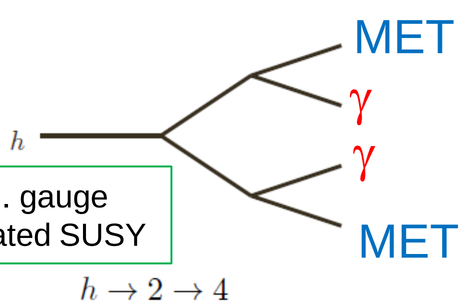
Recently: *Huang et al. '14*

Challenges (1)

- Often multiple possible decay chains with different kinematics

Incomplete List





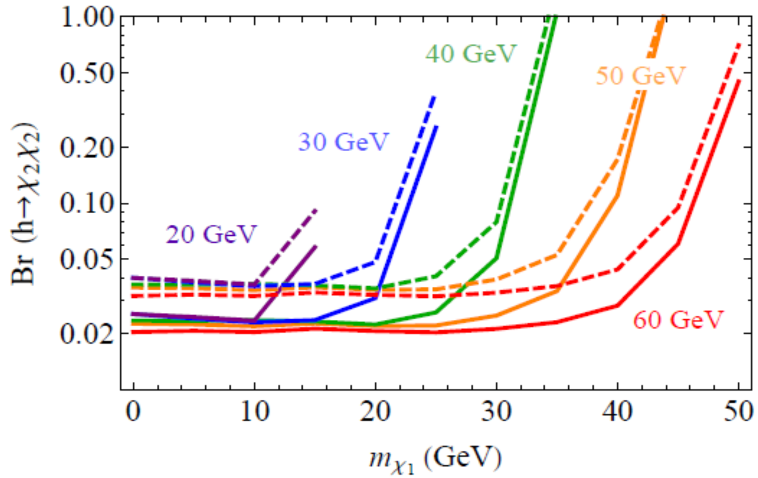
e.g. gauge mediated SUSY

- *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)

2 photons + MET

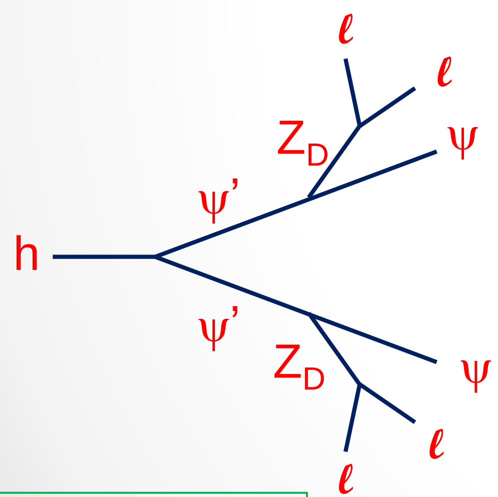
- Weak limit from CMS GMSB search



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

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

<u>Example: 4 leptons + MET</u>

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

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, might 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

Collimated Objects

- Uncollimated vs. Collimated vs. Cross-over?

- Simple lepton jets (2 particles) vs Complex lepton jets (>2 particles)
  - Preliminary searches for h decays to dielectron, dimuon exist
  - Very preliminary searches for multi-electron, multi-muon
  - Challenge of multiple mass scales

- Multi-jets (Very challenging searches)
  - Boosted h → 4 jets has been studied
  - What if h → neutralino → RPV decays to jets

Long Lifetimes

Any of previous decays can occur to objects with long lifetimes

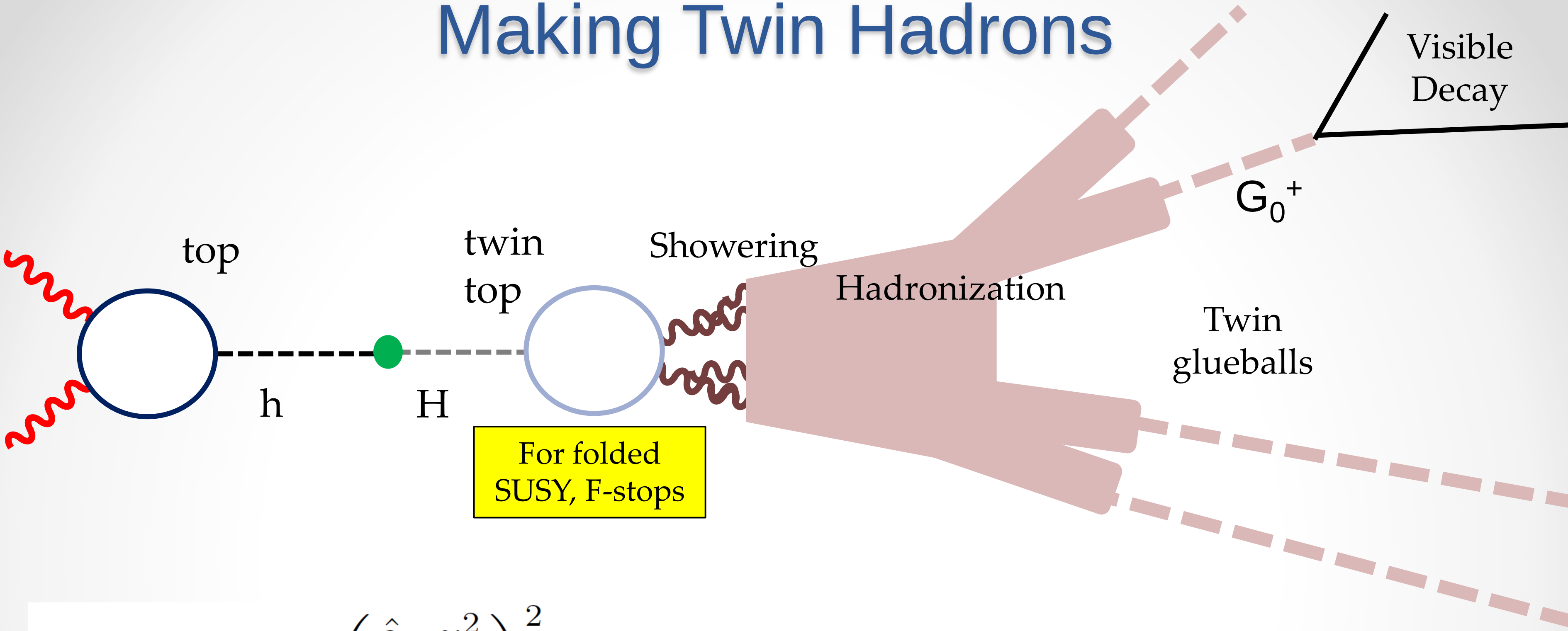
- Commonly a symmetry restored at infinite lifetime
  - So technically natural
  - And in many models it is common due to natural suppression
    - e.g. non-abelian dark vector ➔ kinetic mixing higher-dim op
    - e.g. composite dark vector ➔ mixing suppressed by compositeness

So we can use the same theories, but very different experimental situation

- No SM background unless kinematics & lifetime near B,D mesons
- Detector backgrounds
  - cannot be simulated by theorists
  - but are often very small
- Trigger and reconstruction challenges are unique

ATLAS, CMS, LHCb: exciting progress on results, new triggers

Making Twin Hadrons



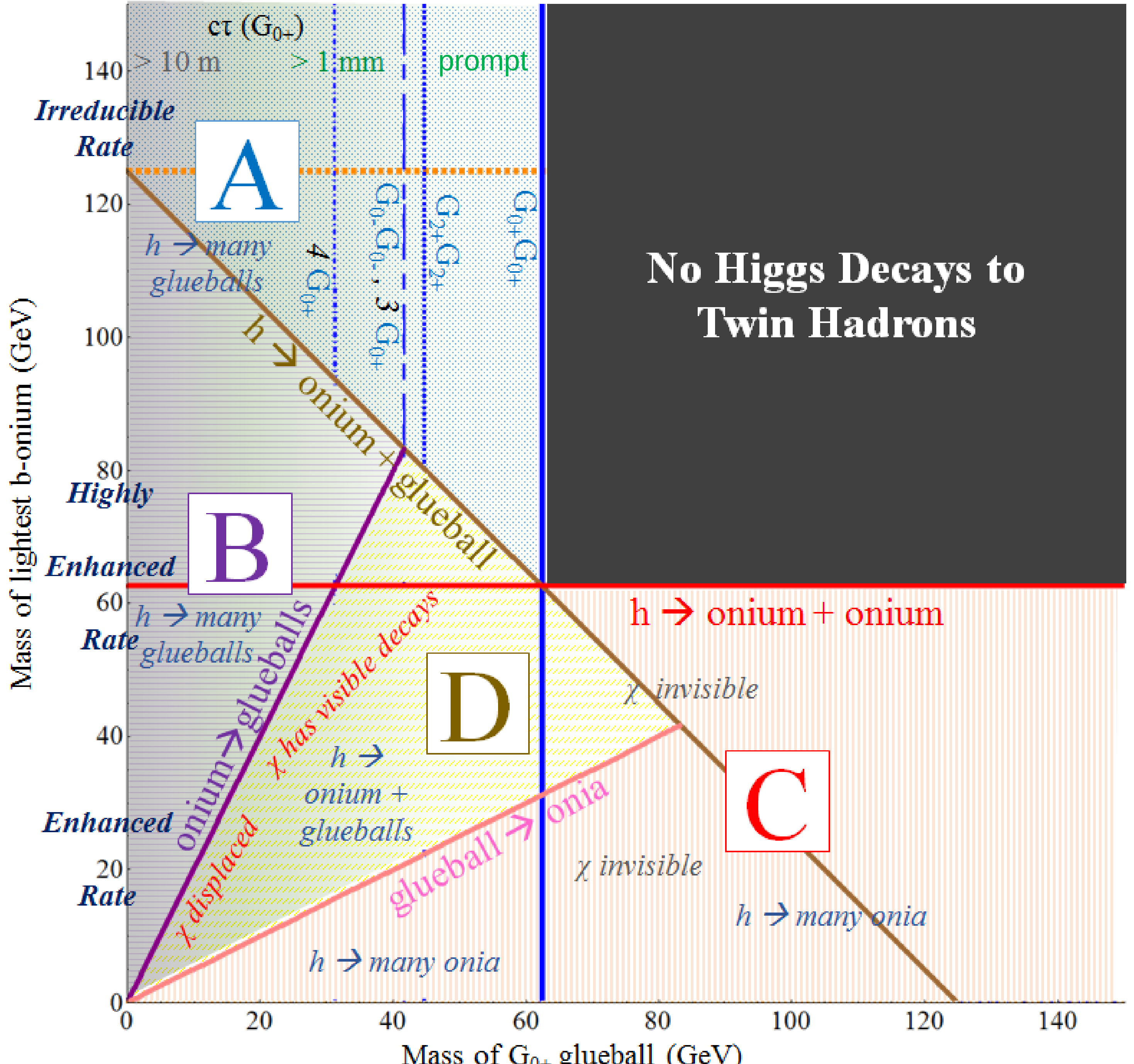
$$\Gamma(h \to \hat{g}\hat{g}) \simeq \left(\frac{\hat{\alpha}_3}{\alpha_3}\frac{v^2}{f^2}\right)^2 \Gamma(h \to gg)$$

For folded
SUSY, x ¼

- Br (h→ twin gluons) ~ 0.1% for f = 3 v
- Enhanced by 60 $(y'_b/y_b)^2$ if h → twin bb

Fraternal
Twin
Higgs

Craig et al ‘15



Long Lifetimes: Experimental Methods

Look for various non-SM “objects”

- Bottom-like jet with vertex unusually displaced/massive/high-multiplicity
- Reconstructed tracks with vertex in pixel detector
- Apparently track-less jet, with vertex visible with special track reco.
- Vertex in HCAL: narrow “tau-like” jet with no ECAL energy
- Tracks in ATLAS muon system with no jet or ordinary tracks behind it

Triggering:

- On the displaced non-SM object
- On VBF jets or a lepton (from W,Z,t) or jet+MET
- On a combination of the two

Allowing trigger strategy and analysis strategy to decouple

Long Lifetimes: Analysis

ATLAS, CMS, LHCb searches

Sometimes can focus on a single object

- Displaced lepton pair + X in the tracker
- High-p_T displaced jet pair + X in the tracker

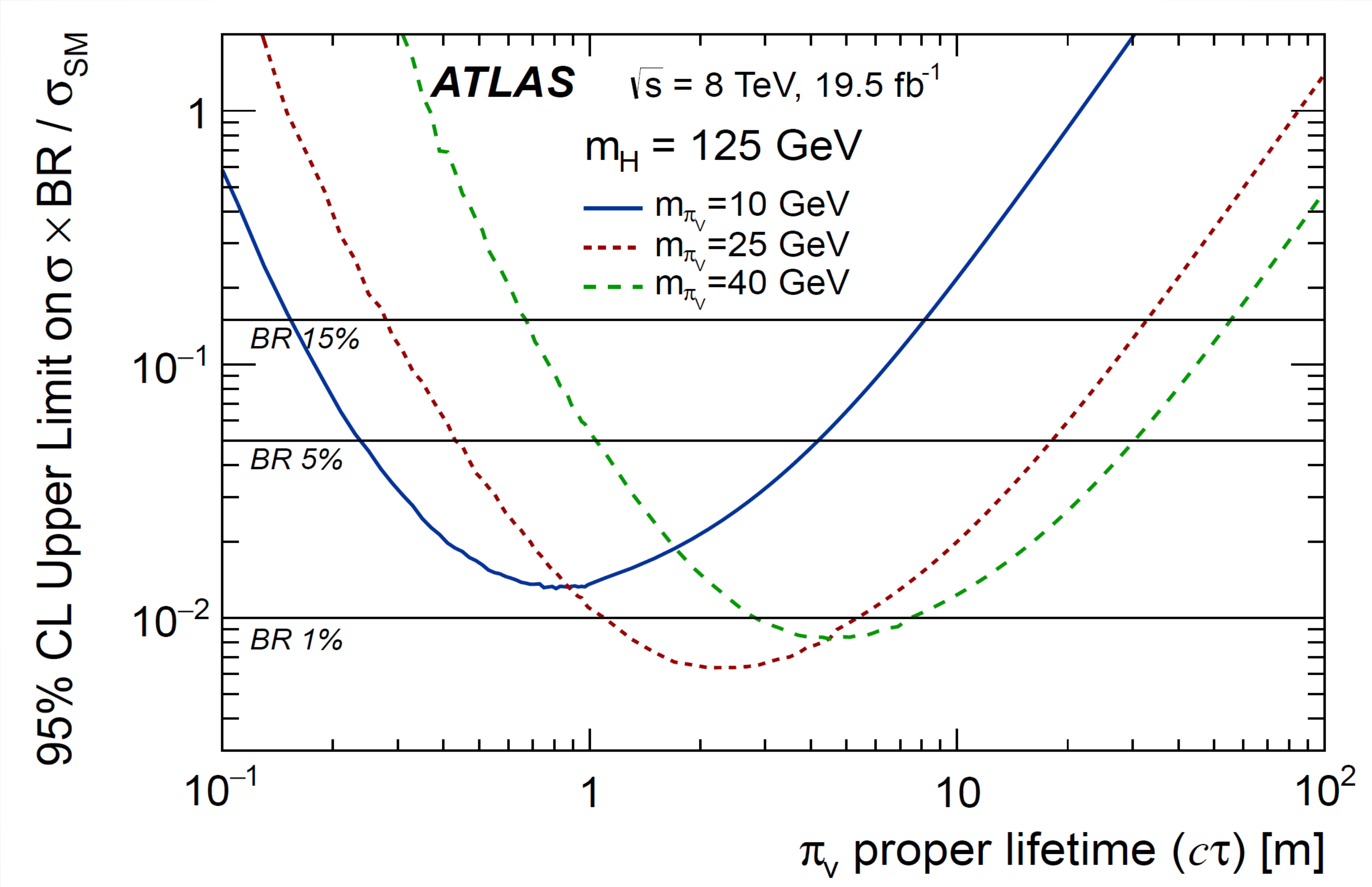
Often need two to beat backgrounds

- Two displaced jet pairs in the muon system - ATLAS
- Two displaced vertices in the HCAL – ATLAS

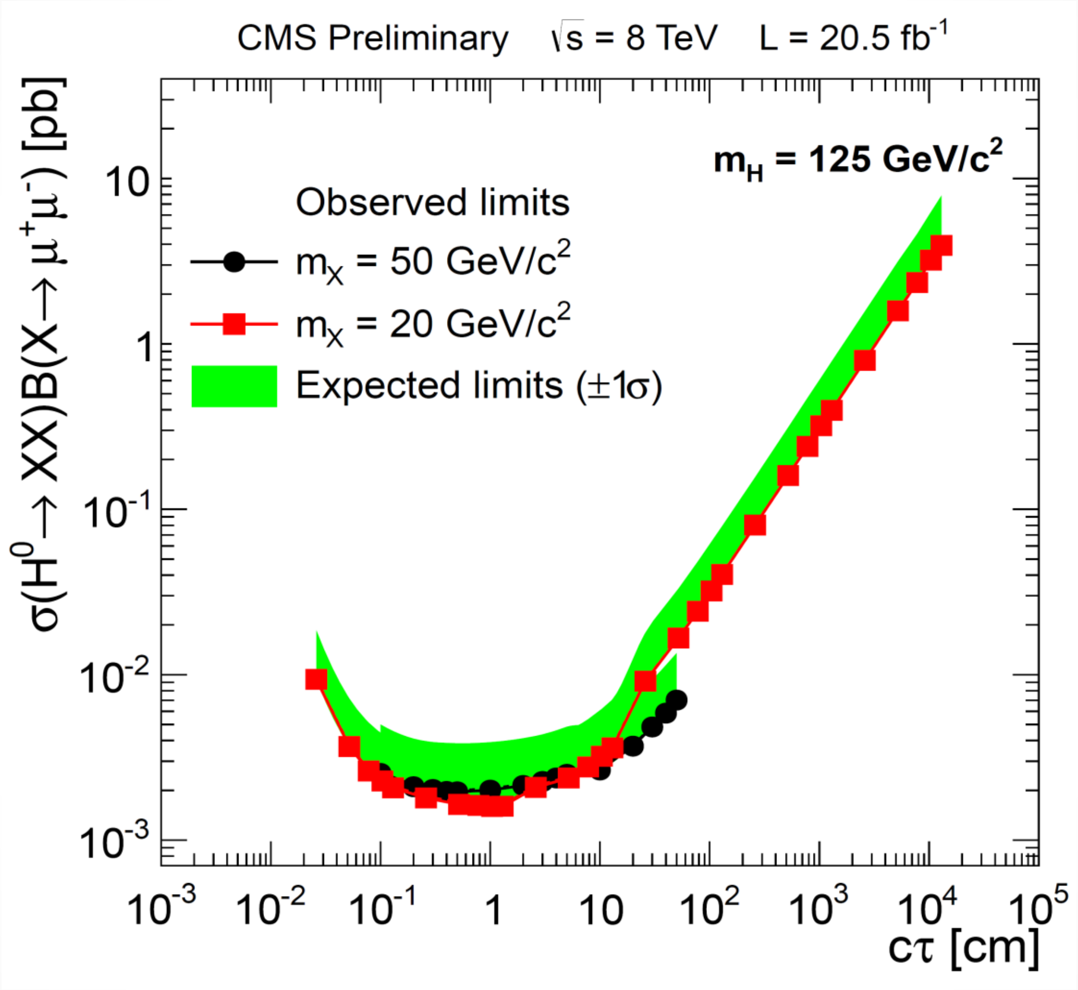
To get to good sensitivity to Higgs decays (and/or long lifetimes)

- Need searches for a single object
- Trigger and/or background reduction using VBF jets, lepton(s), jet+MET
- Push down in mass, push down in lifetime, eventually both

Two Decays Observed



Single Displaced Dilepton Pair



Summary

Need a comprehensive approach to non-SM h decays

- Could be the only new physics at the LHC
- We do not have a strong theoretical bias as to what it will look like

- Comprehensive low-multiplicity no-MET case exists now
- Comprehensive low-multiplicity MET case is harder, partially exists

- Need to exploit the analyses more thoroughly
- Need to cover uncollimated, collimated and transition region

- Long lifetimes – more powerful searches needed – role of new triggers
- Higher multiplicity poses challenges

NEED MORE THEORY/EXPT. STUDIES for high-priority channels

- Still a little time left to influence trigger choices in Run 2

Additional Slides

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.

1 photon + MET

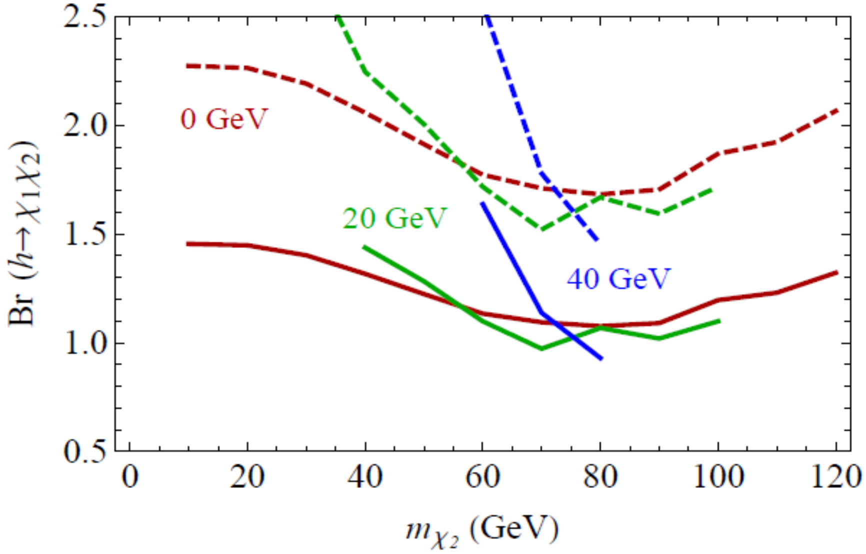
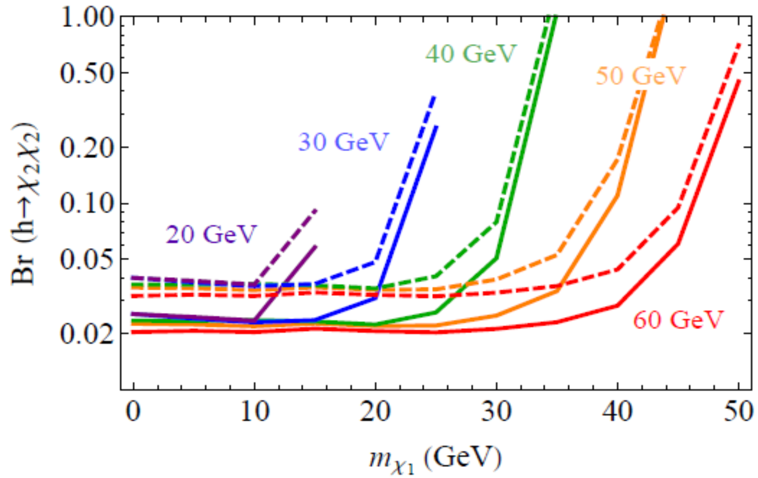


FIG. 31: Approximate 95% C.L. upper limit on $(\sigma/\sigma_{SM}) \times \mathrm{Br}\,(h \to \chi_1\chi_2 \to \gamma + \not{E}_T)$ from the results of Ref. [355], for $m_{\chi_1} = (0\ \mathrm{GeV}, 20\ \mathrm{GeV}, 40\ \mathrm{GeV}) < m_{\chi_2}$. Solid lines correspond to 100% photon efficiency,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

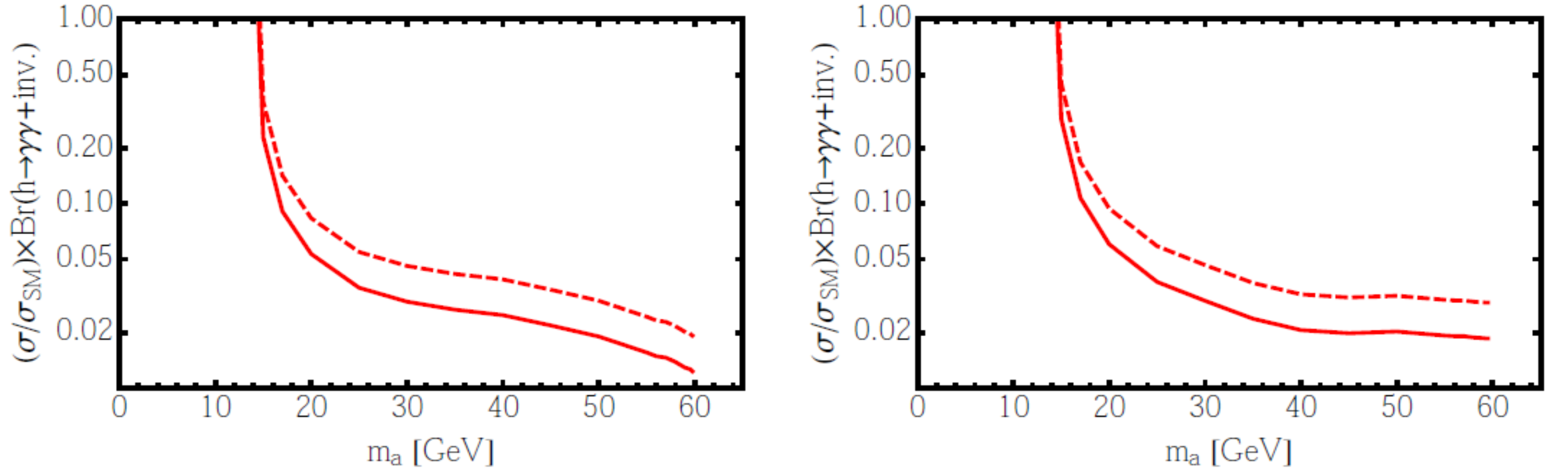


FIG. 33: Approximate 95% C.L. upper limit on $(\sigma/\sigma_{SM}) \times \text{Br}(h \to 2\gamma + \not{E}_T)$ from the $2\gamma + \not{E}_T$ search in [355]. The solid lines correspond to 100% photon efficiency, and the dashed lines to a (flat) 80% photon efficiency. **Left:** Resonant case, where $h \to aa$, 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

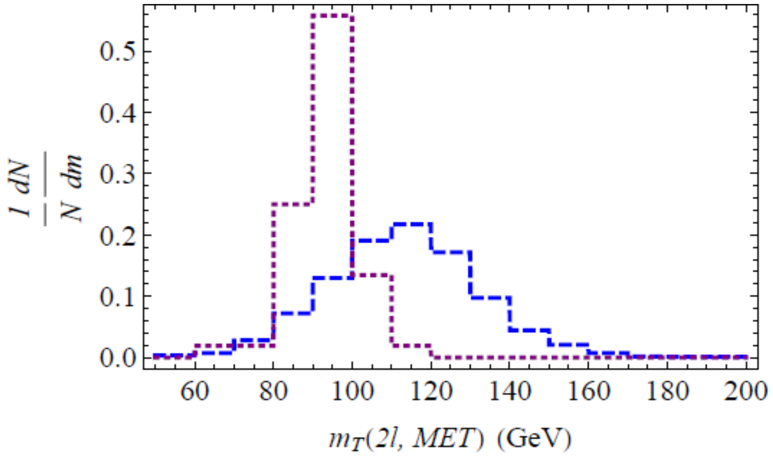


FIG. 34: Unit-normalized distributions of $m_T(2\ell, \not{E}_T)$. The blue dashed line shows the ATLAS prediction for SM $h \to WW^*$ events passing all selection criteria in both 7 and 8 TeV data sets [372]. The purple dotted line shows the distribution for the BSM $h \to 2\ell + \not{E}_T$ events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

2 {μ⁺μ⁻}-jets + MET

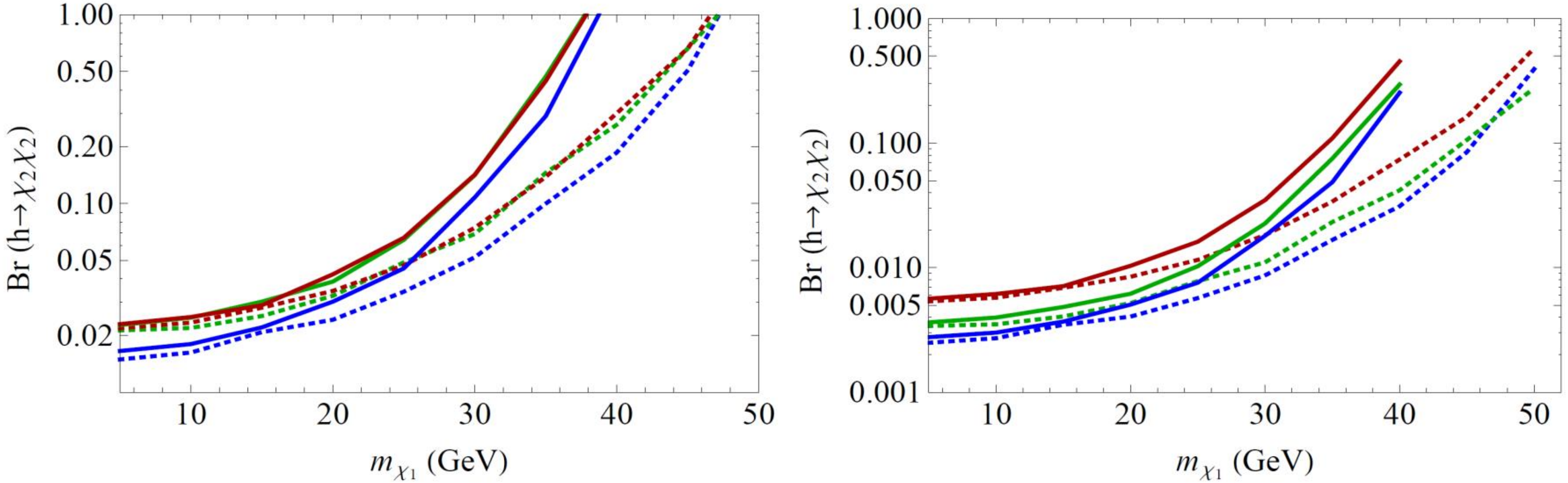


FIG. 35: Approximate bounds on the branching fraction for $h \to \chi_2\chi_2$, assuming **(left)** $\mathrm{Br}(\chi_2 \to a\chi_1) = 1$, and **(right)** $\mathrm{Br}(\chi_2 \to Z_D\chi_1) = 1$, as a function of m_{χ_1}, from [335]. Here solid lines indicate $m_{\chi_2} = 50$ GeV and dotted lines $m_{\chi_2} = 60$ 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).

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 → 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…

Other MET-less 4-body Decays

- $h \rightarrow aa$
  - bb bb
  - bb $\tau\tau$
  - bb $\mu\mu$
  - $\tau\tau$ $\tau\tau$ ← Trilepton search
  - $\tau\tau$ $\mu\mu$ ← Trilepton search + dimuon resonance
  - $\gamma\gamma$ $\gamma\gamma$
  - $\gamma\gamma$ gg
- $h \rightarrow a\, Z_D$, a a'

Benchmark Model

- SM x U(1)$_X$

$$\mathcal{L}_X = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

$$\chi \to \frac{\epsilon}{\cos\theta_W}$$

$$\begin{aligned}\mathcal{L}_\Phi \quad = \quad & |D_\mu\Phi_{SM}|^2 + |D_\mu\Phi_H|^2 + \mu^2_{\Phi_H}|\Phi_H|^2 + \mu^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ & -\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \kappa|\Phi_{SM}|^2|\Phi_H|^2,\end{aligned}$$

'dark higgs' Φ_H with $U(1)_X$ charge q_X

Summary of Review

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