A Comprehensive Approach *to* Non-SM Decays of the 125 GeV Boson:

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

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Ineffective Field Theory *[Higgs IFT]*

- If particles lighter than h to which the h can decay, effective theory with momentum expansion obviously inappropriate
- What do we really want to know?
  - Does the h have non-SM decays via lighter particles?
- Can study specific models with particular features – e.g. NMSSM
  - but risk of missing signatures common in other models
- Best (comprehensive) approach:
  - Systematically list all the options for signatures
  - Design finite # (ideally small!) of LHC searches that cover all the options
- Along the way:
  - Simple benchmark/toy models that produce the signatures
  - Simplified Models (On-Shell "Effective" Theories) for interpreting results

Motivation

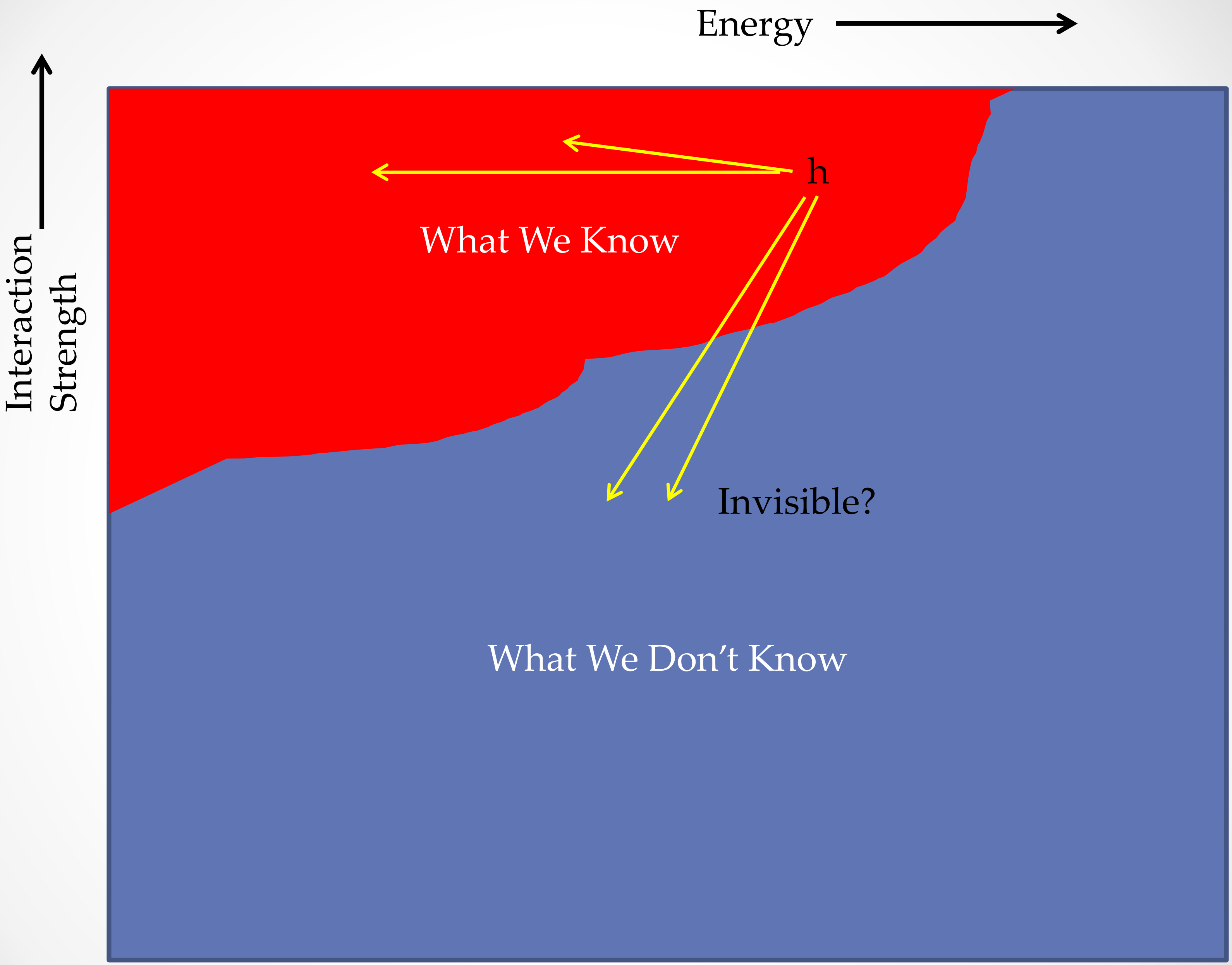
- h decays may serve as window to weakly-interacting unknown particles.
  - e.g. discovery of neutrino in beta decay, other neutrinos in muon, tau decay
  - e.g. non-discovery of 4^{th} neutrino, majorons, others in Z decay

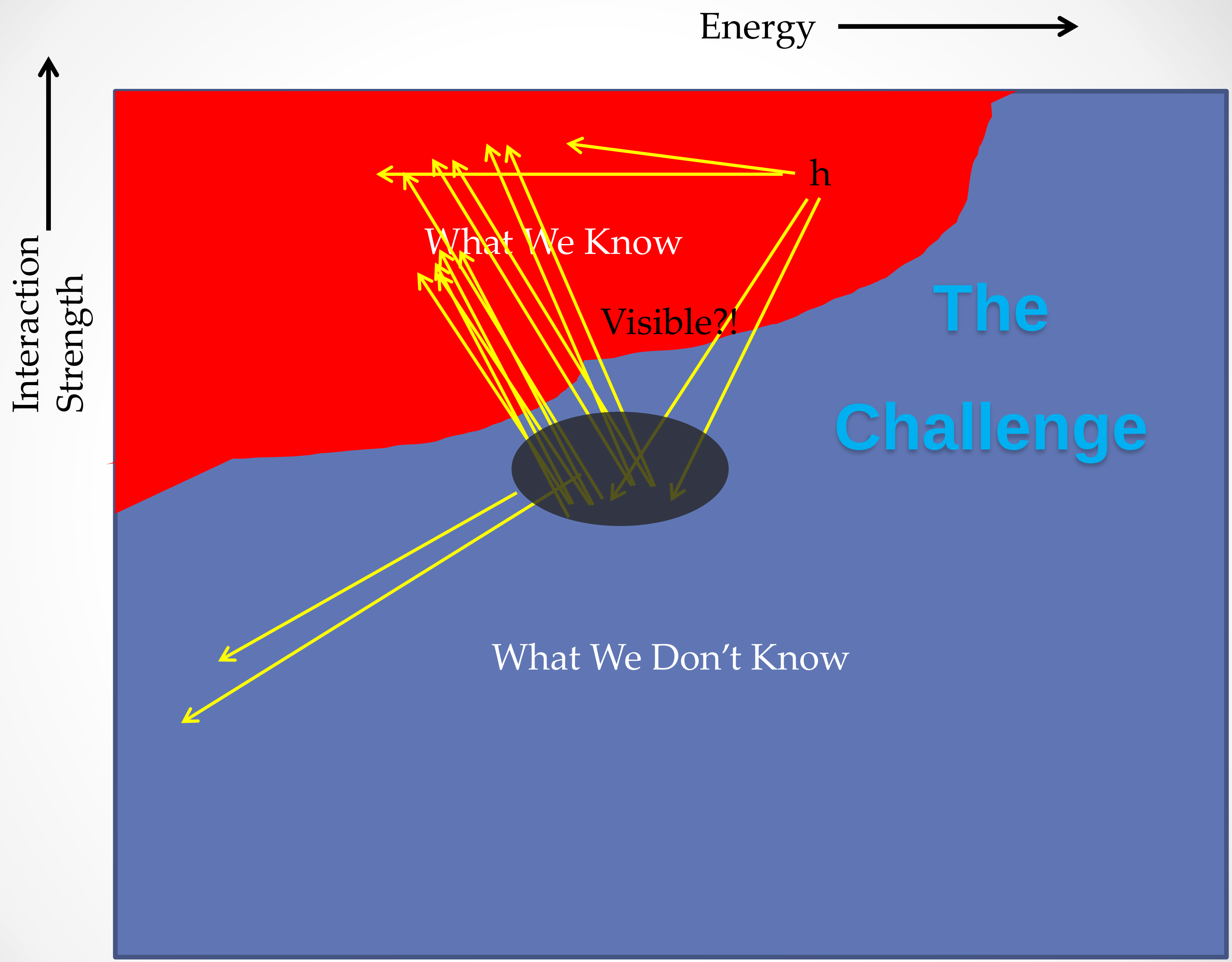
- Dark Matter exists;
  - if it is particles, these particles may not carry SU(2) quantum numbers
  - Therefore these particles may have evaded LEP & have mass < 100 GeV
  - So possible that h → DM → invisible decay
    - Difficult to observe for Br < 10%
  - If DM part of low mass dark **sector** ("*hidden 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

Urgency? Trigger!

- Higgs has m ~ 125 GeV
- 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

Covered in Our Study

Exotic Decays of the 125 GeV Higgs Boson

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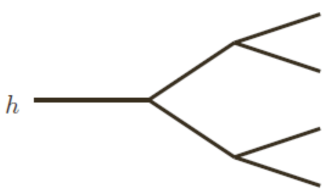
h decays

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

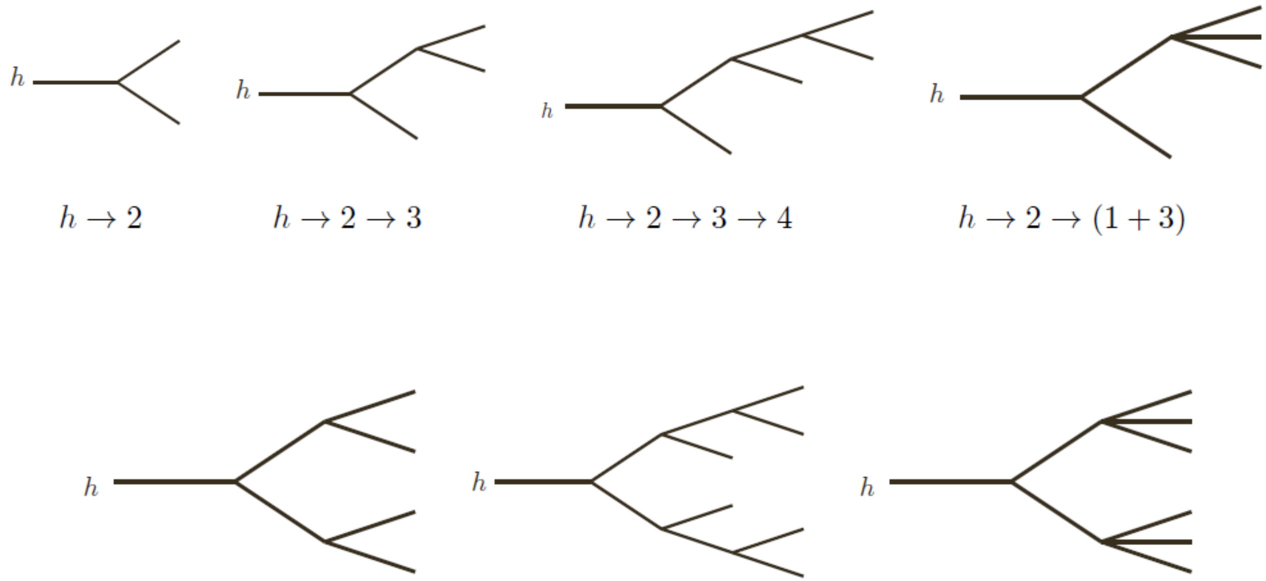
Cases With No MET



$h \to 2 \to 4$

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

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

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

Also:

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

Initial Comments

- Some of our paper is indeed literature review
  - Theory studies (some quite old)
  - Experimental results (very few)
- Some of our paper involves new results
  - New theory studies for certain decay channels
  - New interpretation of some ATLAS/CMS results
- And we provide *preliminary prioritization*:
  - Which channels are most promising in the near term?

Main take-away message:

- Need for improved theory studies for a number of channels!
- Need for dedicated experimental studies!

- And then there are many channels we did not study at all

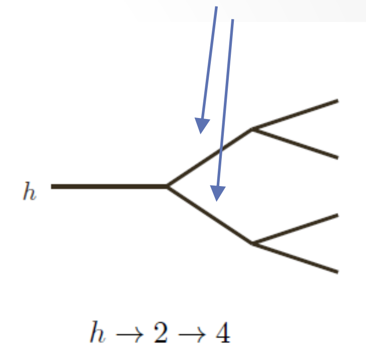
Decays Without MET

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]



- *Spin ½ ➔ h decay to 6 visible fermions or MET + 4 visible particles*
  - *e.g. h → neutralinos → 6 fermions via RPV*

1. h → Z Z_D → 4 SM fermions
2. h → Z_D Z_D → 4 SM fermions
3. h → a a → 4 SM bosons
4. h → a a → 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

Simple Models and Simplified Models

Example:

- $h \rightarrow Z Z_D$ from Vector Boson Z_D mixing through kinetic mixing only

- The Simple Model
  - SM x U(1)', H' charged under U(1) only, Z_D gets a mass m'
  - kinetic mixing ε , **V**(h') parameters, e'

- Simplify:
  - Most of these parameters do not affect the pheno of $h \rightarrow Z Z_D$
  - In search for $h \rightarrow Z Z_D \rightarrow$ 4 leptons (best channel), need m and $Br(h \rightarrow ZZ_D)$
    - Limit on Br as function of m
  - Note ε matters directly if lifetime long; then use $\Gamma(Z_D)$ as parameter.

- Thus complete or largely complete many-parameter model reduces to simplified model ➔ few-observable method for data interpretation

Benchmark Model

- SM x $U(1)_X$

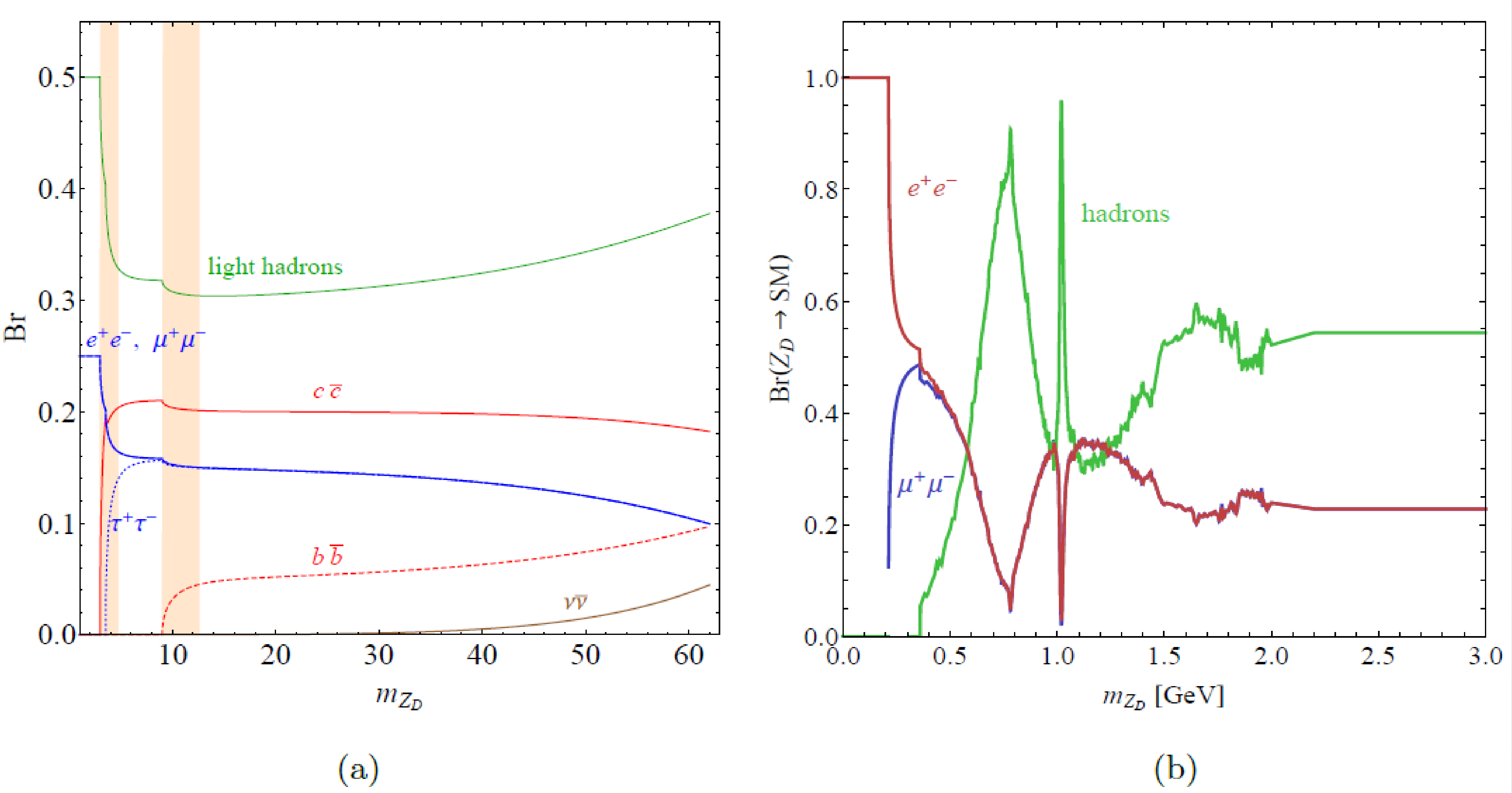
$$\mathcal{L}_X = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

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

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

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

Br's for Z_D with only kinetic mixing



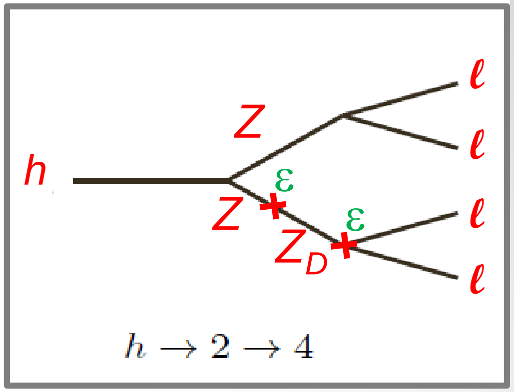
$\mathrm{Br}(Z_D \to ee) + \mathrm{Br}(Z_D \to \mu\mu) > 20\%$ (except at ρ,ω); typically 30%

Four e/μ Final State

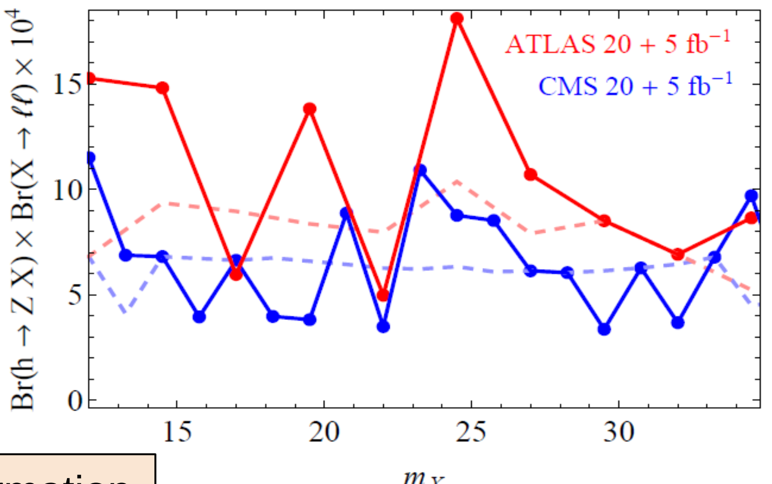
$h \rightarrow Z\, Z_D$

- 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 allow 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

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

Note: no information below 12 GeV

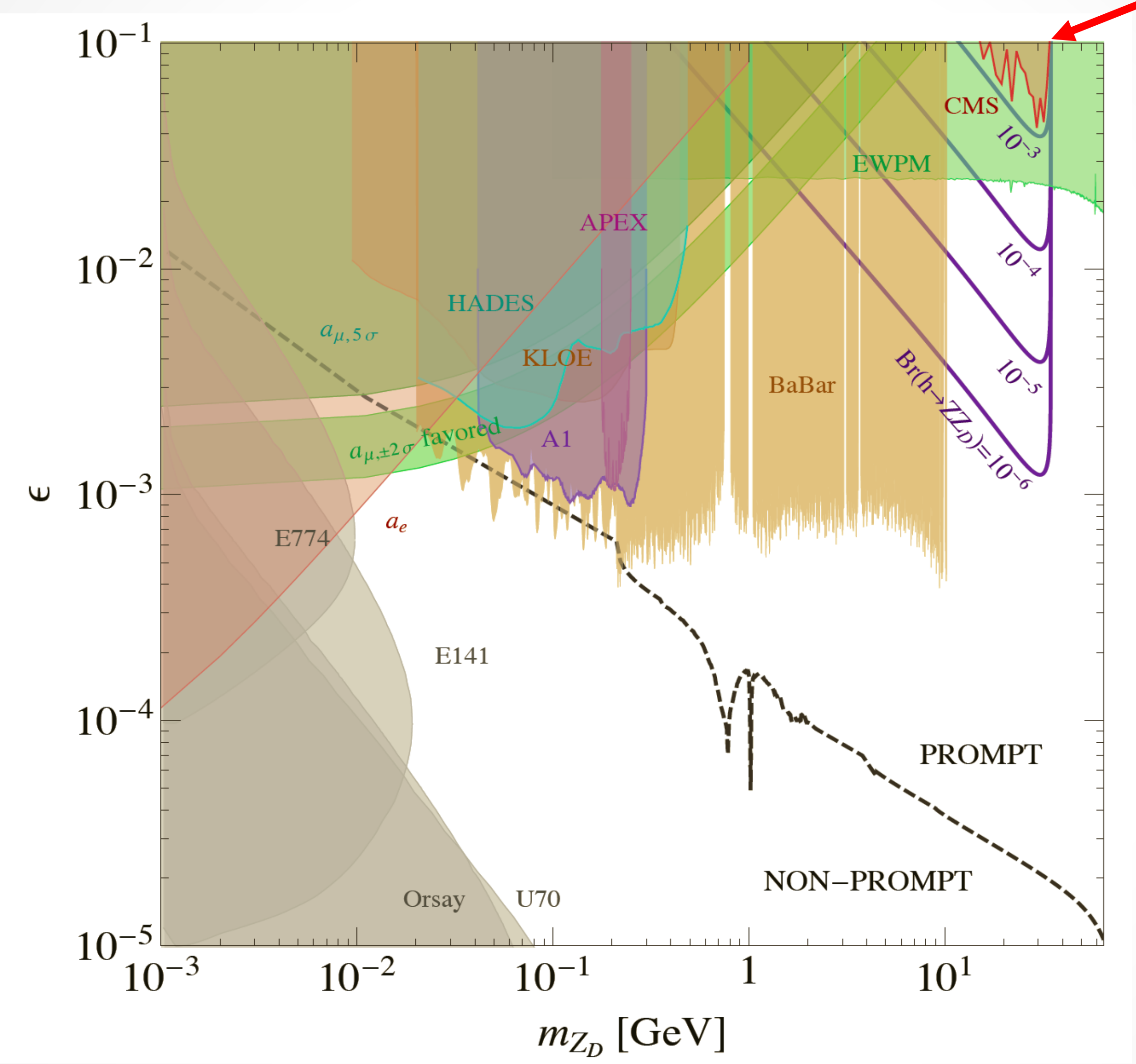
X could also be *a* with $Br(a \rightarrow \mu\mu) \sim (m_\mu/m_\tau)^2 \sim .0035$

But often need $m_a < 10$ GeV

See also Gonzalez-Alonso talk
Falkowski and Vega-Morales 2014

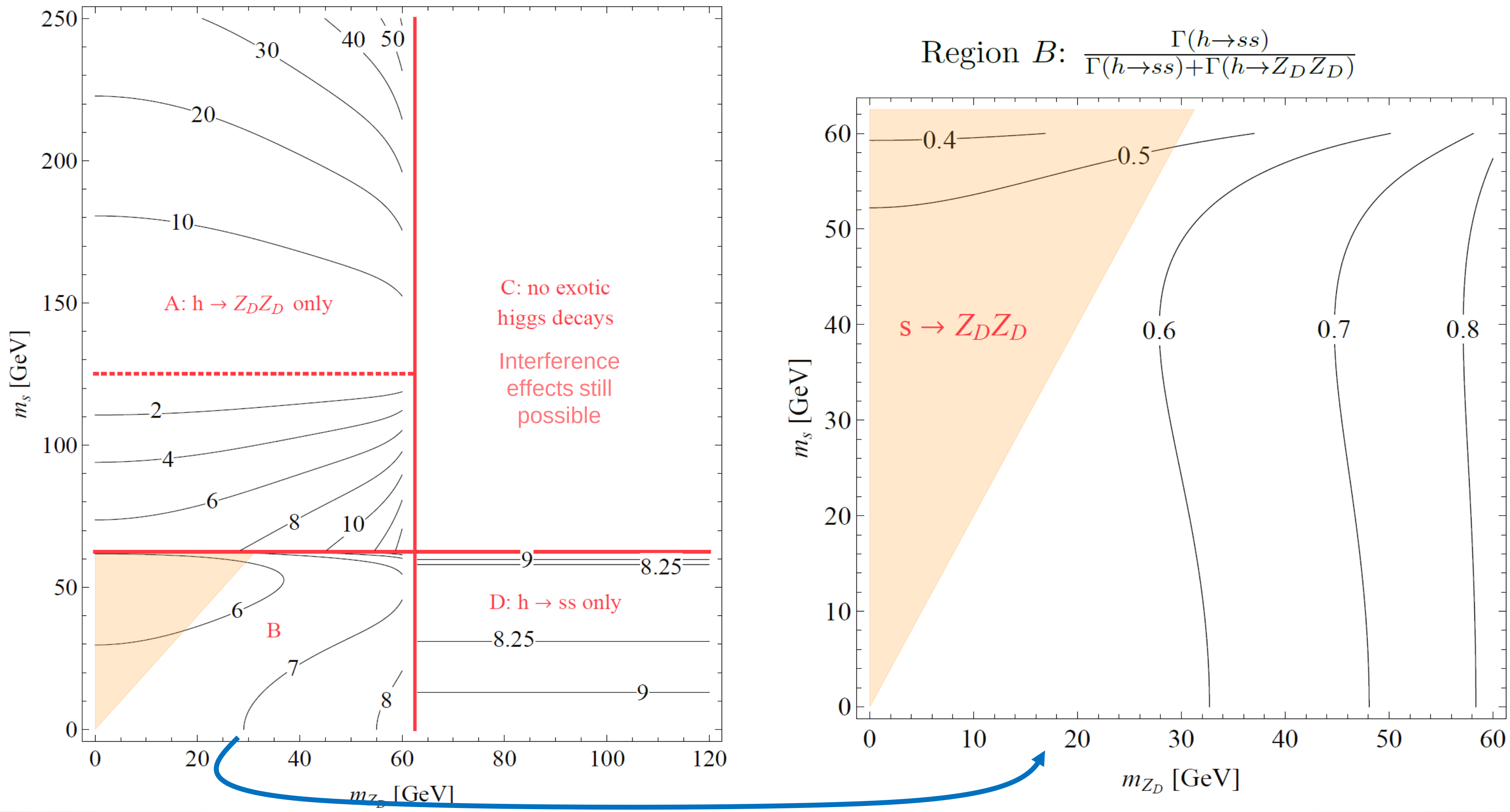
Limit ε for each Z_D mass

Our recast of CMS;
Similar for ATLAS



See also Gonzalez-Alonso t

Mass plane when h mixing >> Z kinetic mixing.



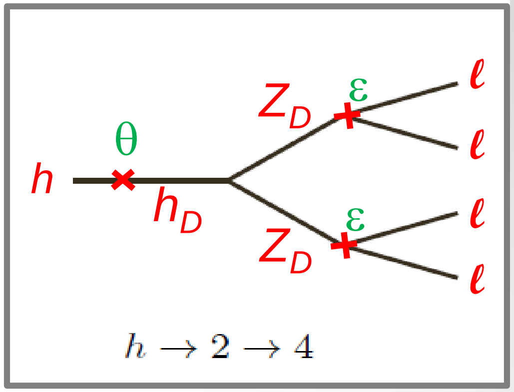
Regions:
(A) no h → ss; (D) no h → $Z_D Z_D$;(B) both (C) none;.

Black contours:
Values of κ required for Br(non-SM h decays) =10%.

Black contours:
Br(h → ss)/Br(non-SM h decays)

Pink:
8-fermion final states dominate

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 $h \to ZZ^*$, ATLAS non-resonant Z*Z*)

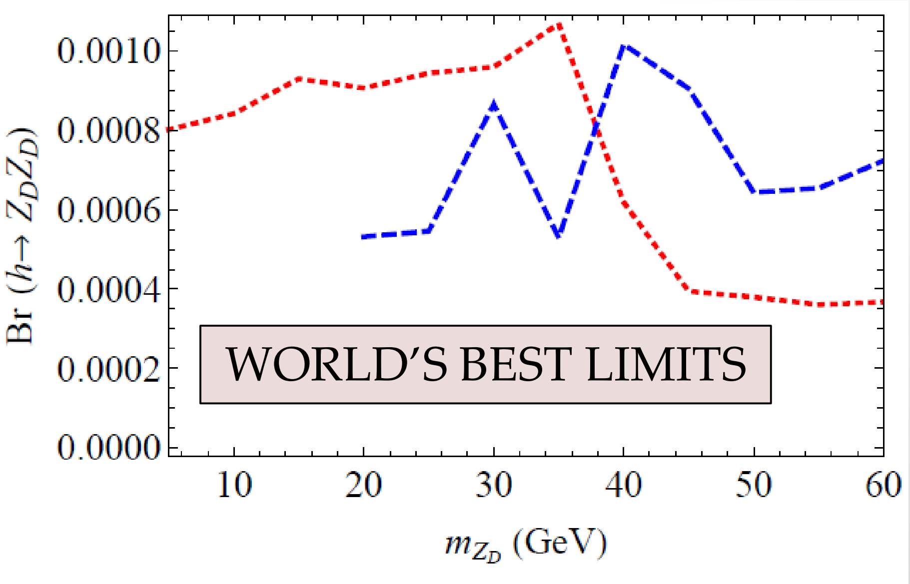
Direct limit

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

Assuming a Z_D with kinetic mixing

- $Br(h \to Z_D Z_D) \sim 5 \times 10^{-4}$

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



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'

Decays with MET

With MET, # of processes, parameters grows rapidly

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

- 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} ?

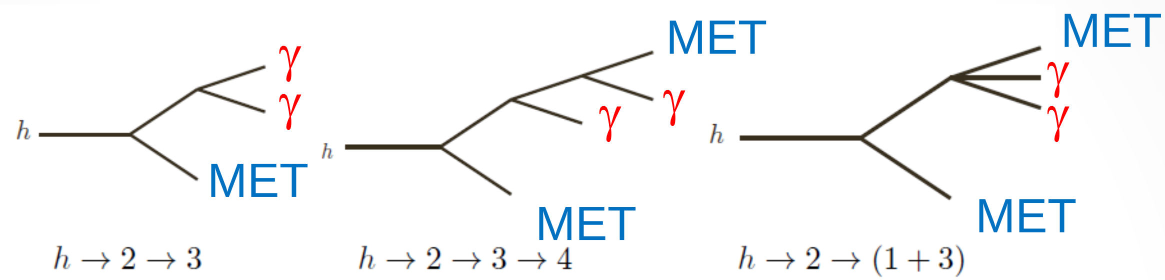
Recently: *Gabrielli et al. '14*

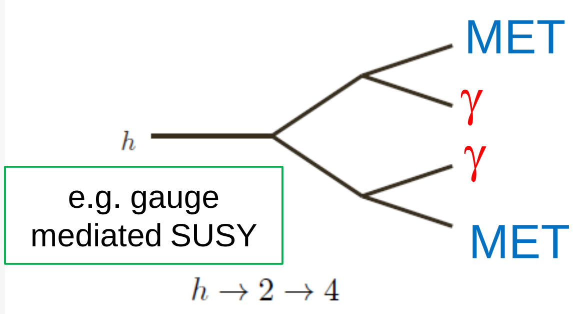
Recently: *Huang et al. '14*

Challenges (1)

- Often multiple possible decay chains with different kinematics

Incomplete List



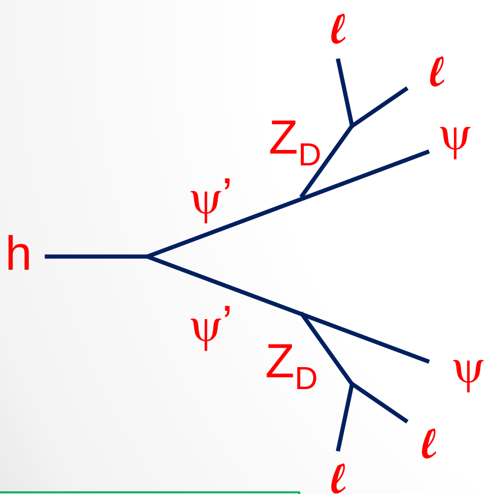


- *Hard (p_T ~ 40) vs. Soft (p_T ~ 15)*
- *Resonant vs.non-resonant*
- *Edge vs. endpoint*
- *Collimated vs. uncorrelated*

- 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

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

- *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?)

NMSSM versus Simpler Theories?

- NMSSM
  - R-sym limit of NMSSM: light R-axion to which h can decay
  - PQ-sym limit of NMSSM: light PQ-axion, scalar and singlino;
    - h→ fermions dominates, e.g. bino + singlino
    - Common: bino → singlino + a :
- In NMSSM, a → heaviest fermion

Recent Studies: Huang et al. ‘12,’13,’14

- Outside NMSSM, more general 2 doublet + 1 singlet model
  - a → leptons may dominate
  - a → up-type quarks may dominate

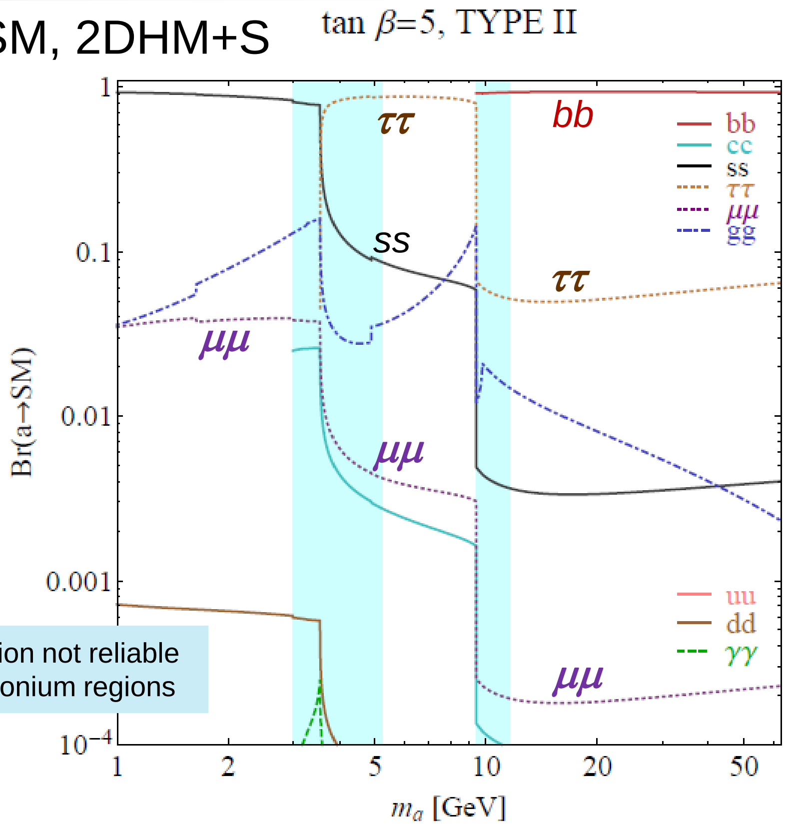
  This has dramatic effects on searches

Need general framework, motivated by but not constrained by NMSSM

- In absence of superpartners, important to remain agnostic

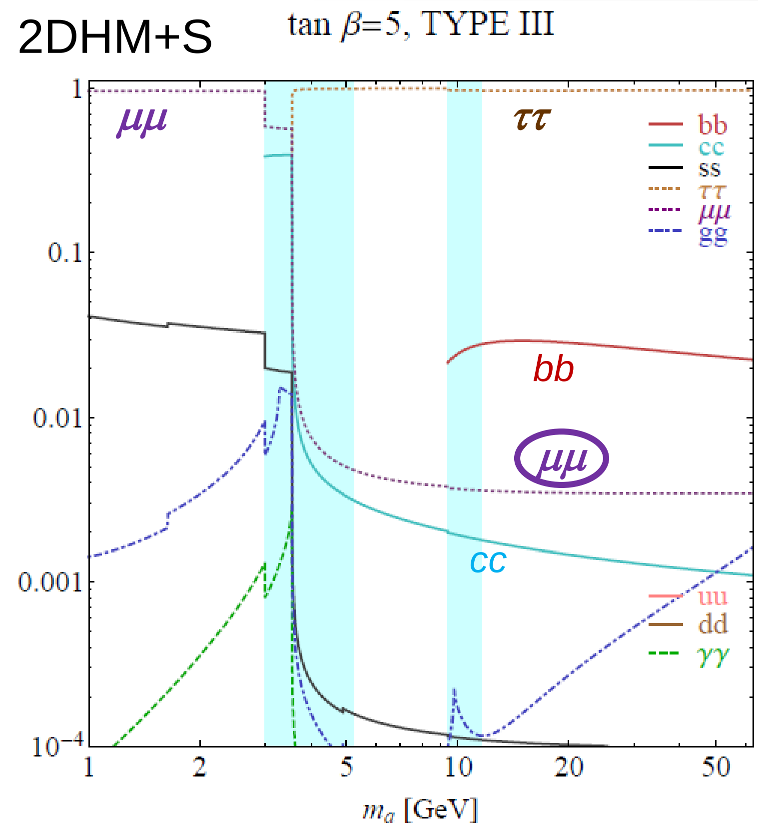
Different Branching Fractions for *a*

NMSSM, 2DHM+S



Calculation not reliable in quarkonium regions

2DHM+S



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

Collimated Objects

- 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
  - Little for both e and mu
  - Nothing for e, mu and pions,
  - Challenge of multiple mass scales

- Multi-jets
  - Boosted h → 4 jets has been studied
  - What if h → s s and s → collimated quarks or gluons?
  - What if h → neutralino → RPV decays to jets?
    - Very challenging searches

This is still a frontier for thinking: how to be comprehensive?

- Simplest models are same as before with small masses or splittings
- But higher-multiplicity models have more (relevant) parameters

Long Lifetimes

Take any of previous decays; there are models with long lifetimes

- Commonly there is a symmetry that is restored at infinite lifetime
  - So long lifetime is 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 making slow, unsteady but significant progress

Long Lifetimes: Experimental Methods

How is it done?

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

Many tricks

- Use displaced muon as special pointer.
- Displaced muon pairs are special;
  - Can be found even in calorimeter or outer tracker

Typically use specialized triggers (but overused?)

Long Lifetimes

ATLAS, CMS, LHCb searches

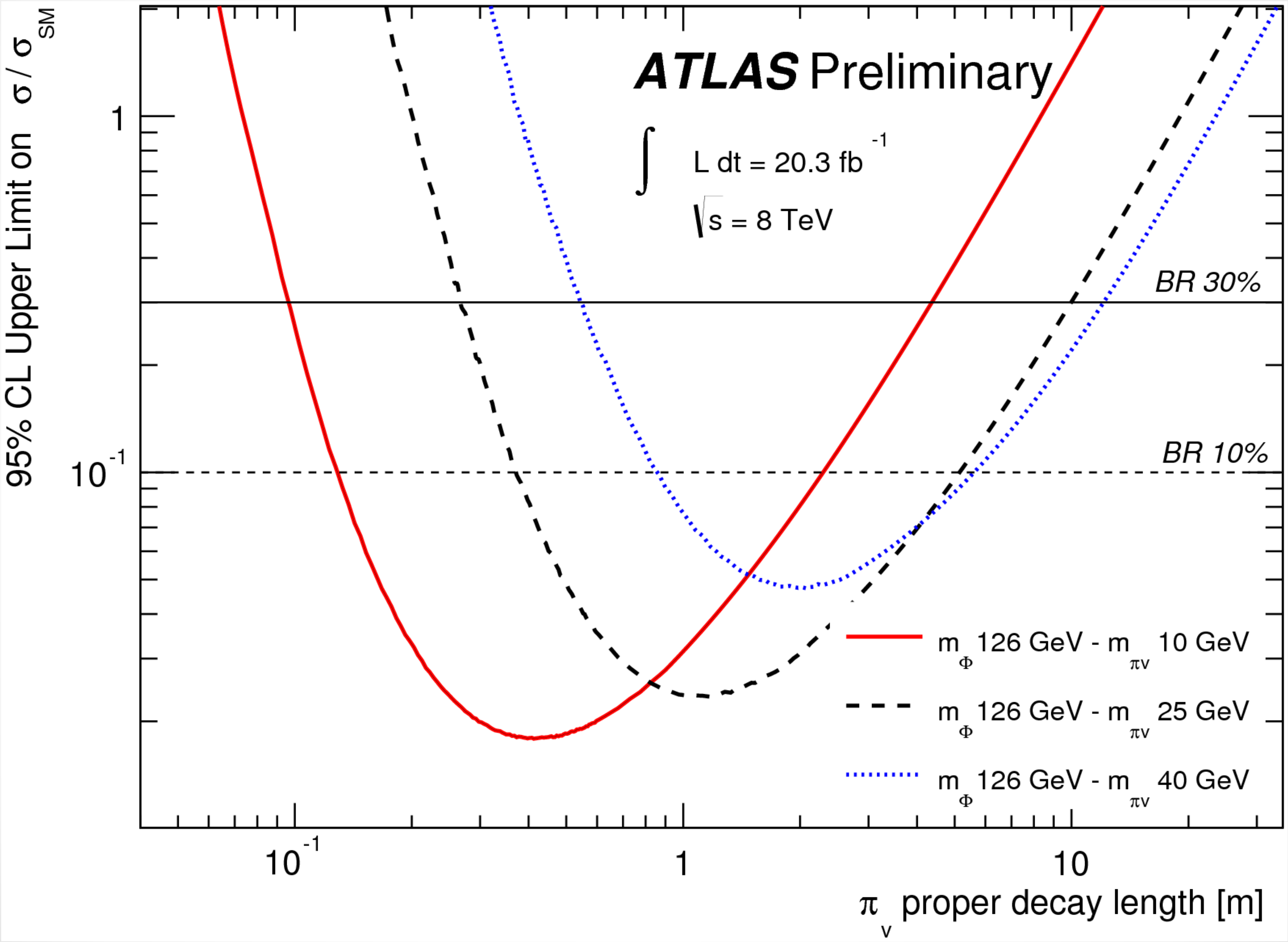
Sometimes can focus on a single object

- Displaced lepton pair + X in the tracker
- 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

Two Decays in Hadronic Calorimeter



Single-Vertex Searches

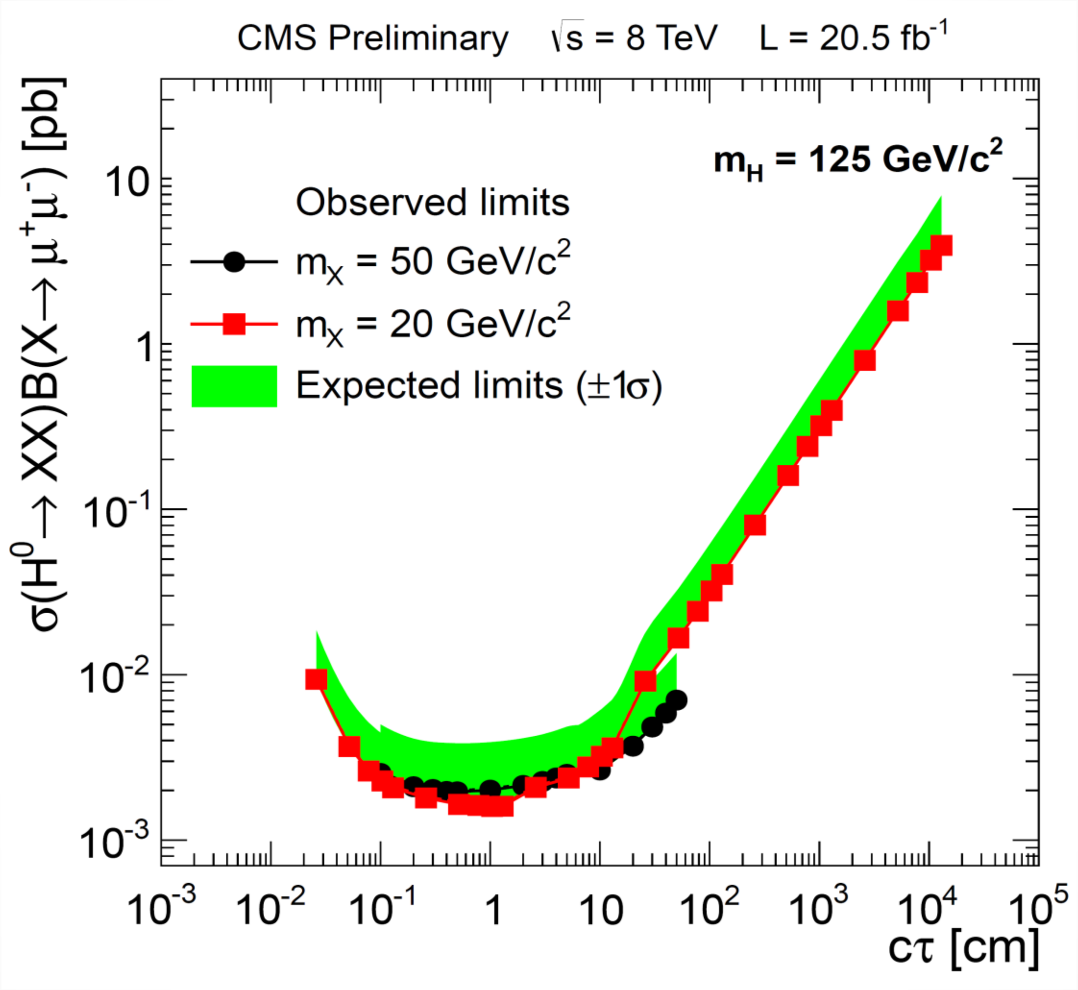
Several at CMS, not at ATLAS

- CMS searches very powerful
  - For di-lepton vertex in tracker
  - For di-jet vertex in tracker
    - Many theorists still don't realize how devastating this search was!
    - CMS needs to extend reach to 125 GeV h, to longer/shorter lifetime

Importance of single vertex detection at ATLAS!!

- Needed for access to long-lifetime limit
  - ATLAS is bigger and can use its muon system as a tracker
- But should be able to use
  - VBF jets + vertex,
  - lepton + vertex
  - MET + vertex [EXTREMELY IMPORTANT for long lifetimes!]

Displaced Dilepton Pair



Long Lifetimes and High Multiplicity

- This “Embarrassment of Riches” is unfortunately technically difficult from all perspectives
  - Many parameters (masses, lifetimes) play a role in the phenomenology
  - If multiple displaced vertices, each vertex may ruin isolation of others
    - E.g. a vertex in the tracker may have a “jet” in the HCAL
    - E.g. a vertex in the HCAL may have ECAL energy from another vertex
    - E.g. a vertex in the ECAL ruins isolation of a vertex in muon system

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 improve collimated case, especially transition to uncollimated

- Long lifetimes – more powerful searches needed
- Higher multiplicity poses many problems

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

  - e.g. $bb\mu\mu$, γ + MET, $\gamma\gamma$ + MET (for varying cascades, mass ranges)
- Still a little time left to influence trigger choices in 2015!