The Post Discovery Era

What do we do now?

Higgs Quo Vadis
Matt Strassler
3/11/13

Prioritization

- Huge data sets at ATLAS, CMS, LHCb
- Vast array of possible signals of new phenomena
- Disturbingly finite human resources

Crucial to set priorities wisely:

- Choose searches with good balance of
  - Experimental motivation:
    - Ease of analysis
      - Straightforward event selection, small backgrounds, resonances
    - Opportunity and ingenuity
      - It's never been done so it might allow an immediate discovery
  - Theoretical motivation:
    - Many theories (or well-loved theory) predict this signal
    - Some other experiment suggests this signal
- Be efficient in use of resources by
  - Combining multiple searches in one analysis

Post-Discovery & Post-Easy-Signals

What do we learn from 2011-2012?

- Higgs boson?
  - Yes! (and SM-like)
- TeV-scale colored particles with colorless particles in their decays?
  - No! (roughly speaking; at least, they are not common)

These two facts interplay; both are relevant for naturalness

- Data shows no conflicts with the Standard Model
- But the Standard Model is not Natural

What's going on? And how do we prioritize our efforts?

  - (Will assume in this talk that no discovery shows up by summer!)

Naturalness is Profound

We often say "Naturalness problem has to do with the small *h* mass".

- But this assumes v = 246 GeV; in that case the problem is with m_h

Really the problem is with the minimization of $V(H)$

- $V_{tot} = V_{cl} + V_{qu}$ where V_{qu} = Zero-Point Energy of vacuum

  - Zero Point Energy depends on particle masses, which depend on $\langle H \rangle = v$

  CC λ

  - So $V_{tot} = V_{tot}(H) = \#\Lambda^4 + \#\, \Lambda^2 H^2 + \#\, H^4 + \ldots$

  $-\mu^2$

Here Λ is UV cutoff on SM as effective theory

- Natural solutions: $m_h^2 \sim \Lambda^2$ *and (i)* $v = 0$ *or (ii)* $v \sim \Lambda$

Zero-Point Energy + H-Field-Dependent Masses + Dimensional Analysis

Nothing More Required

Is Our World "Natural"?

Natural theories must remove UV sensitive top contribution to m_h^2

- Top quark must have large coupling to this Higgs
- *hgg* coupling appears to be SM-like; induced by top loops

To cancel top loops typically expect top partner

- Top prime (colored)
  - Partial solution – typically only to one loop, UV completion at 10 TeV
- Top squark (colored)
  - But top squark is a scalar and has its own naturalness problem
  - Requires a gluino to cancel off its own UV-sensitive loops

So typically expect TeV-scale colored particles at LHC

- But no sign of gluinos or top-primes or indeed anything new and colored
  - So what is up?

Naturalness Quo Vadis?

- Is Naturalness *Delayed*?
  - Colored partner particles heavier than expected; too much for 8 TeV LHC?

- Is Naturalness Obscured?
  - Gluino, top partner decaying without MET and/or leptons/photons
    - Pure QCD final states with many jets and no simple resonances
    - Energy going into soft or hyper-soft objects signals (e.g. quirk effects)

Hidden

- Is Naturalness Hidden?
  - Maybe top partners are in hidden sector? (Twin Higgs as existence proof)

- Is Naturalness **WRONG**? (Need New Guideposts!)
    - Dark Matter
      - Neutral member of electroweak multiplet
      - Part of an entire Hidden Sector
    - Others?

Delayed Naturalness

If colored partners out of reach, target color-neutral particles

- Especially Higgs partners!
  - SU(2) doublets
  - Possibly spin-0, ½
  - Often near-degenerate (if SU(2) multiplet structure little broken)
- Also W partners
  - SU(2) triplets; spin?
- Singlets too, but often very low cross sections

Challenging

  - Small production rates, many possible decay modes
  - Often difficult to extract from large top & electroweak backgrounds
  - Need dedicated searches for each model and mode

- Question: are we covering all the cases (not just SUSY)?

Obscured Naturalness

Possible (any good models?) that new physics hiding in QCD backgrounds?

- Few searches attempted with all-jet backgrounds
  - 3-jet resonances, pairs of 2-jet resonances
  - Black holes (rising multi-jet cross-sections at high ST)
- QCD measurements could be turned into opportunities

Possible that signals hide due to presence of exotic objects?

- Long-lived particles?
  - Particles decaying in flight can cause mis-reconstruction
  - Quality cuts may remove events with non-prompt jets/leptons
- Clustered particles?
  - Non-QCD jet-like objects may be treated as boring QCD jets –
    - substructure, lepton-jets
  - May also include long-lived objects
- Soft or hyper-soft signals?
  - Suppose 1.5 TeV goes into a few hard objects and many soft ones
  - Would we identify such signals?
    - `Quirks' [particles with SM charge and infracolor/hidden valley charge]
    - Strong-coupling hidden-valley quarkonium?

Wait! Were We Thorough?

Not yet! (at least, not quite)

Signals with very low MET, high jet multiplicity, high but not ultra-high S_T

- Natural RPV SUSY, HV SUSY (inclu. Stealth)
  - i.e. gluino, stop, higgsino not out of natural range
- Top prime with unusual decays to top + jets.

are far less constrained than people think

- natural models below TeV still possible!

Missing from the search menu (***still***!) (Lisanti, Schuster, Strassler & Toro 2011)

- Lepton + 6 or more jets (look at n_{jet}, n_b, S_T distributions)
  - CMS, ATLAS finally have searches but not optimized for this purpose!
- Curiously ATLAS many-jets+small MET is sensitive (but how sensitive?)
  - Tau + many jets
  - Lost lepton + many jets

Hidden Naturalness

- Colorless top partners
  - A role for hidden sector?
- Cancellation of top loop by hidden partner (twin Higgs, folded SUSY)
- As with little Higgs, only one-loop delay of hierarchy problem
- Experimental signatures may be quite limited
  - Hidden-valley-type signals?
- We need more examples of how this can work from the theory side!
  - If there are any…

Natur~~alness~~e

In this case we do not know where to go on basic theoretical grounds.

But we do know the SM isn't complete

- Strong CP problem
  - Axions?
- Neutrino masses
  - ➔ sterile neutrinos (But at what mass scale? Composite?)
- Dark Matter
  - But how coupled to SM? And what mass scale?
  - Axions? WIMPs? Dark-Sector [inclu. hidden valley] Massive Particles?

- LHC WIMP searches motivated
- LHC dark-sector (inclu. hidden-valley) searches also motivated
    - Needs more theoretical work to improve theoretical prioritization
    - Prioritization from e.g. Pamela signals too time-dependent

What About the Higgs Sector?

The 125 GeV *h* boson has a role to play in all of these possibilities

- May appear in decays of colorless or heavy colored BSM particles
  - Or even in rare top decays
- May decay to colorless BSM particles

Other members of Higgs sector may be waiting for us…

- Narrow heavy states decaying mainly to *bb, tt,* rarely to *WW,ZZ*, $\gamma\gamma$
  - Possible decaying to *h* itself
- Charged states decaying to *tb*, more complex final states
- Lightweight mostly-singlet states decaying to
  - Light SM particles
  - Yet more singlets which in turn…

Non-SM h Production

A particle with m > 125 GeV might decay to *h*:

- Top quark ($t \to h\, q$)
  - Use *t* pairs where one $t \to \ell \nu\, b$ *and other* $t \to q\, h$,
    - *h* → *bb resonance [gives lepton + 3 b's, reconstruct it]*
    - *h* → *WW* → *one or two leptons [gives SS- or tri-leptons]*

- Something unknown
  - *Higgsino, Wino* → *h* + invisible (perhaps + soft-ish jets or lepton)
  - *t'* → *h* + *t, b'* → *h* + b
  - $H^0 \to h^0\, h^0$ in 2-Higgs doublet (e.g. SUSY) or doublet+singlet models
  - *W'* → *Wh, Z'* → *Zh*

Question for theorists:

- When a priority even without **other** signal for the heavy particle?
  - i.e. when is this likely to be discovery channel of the new particle?

Non-SM h Production

Displaced *h* possible:

- Example: *Higgsino* → *h* + *gravitino* or *singlino*
- Often 2 per event
- Or displaced *h* + displaced Z or γ

<u>Searches at ATLAS, CMS, **LHCb**:</u>

- Possible 2nd vertex in event, or MET if lifetime long
- Typically without a mass constraint, so general purpose method

- Displaced $\mu\mu$, *ee*, μ*e* vertices from *WW*, $\tau\tau$ (both leptonic)
- Jet(s) from common displaced vertex **with muon track**
  - From *bb*, *cc*
  - From *WW*, $\tau\tau$ (one leptonic)
- Or jet(s) from displaced vertex with **prompt** lepton from elsewhere
  - From any hadronic decay

Non-SM h Decays: General Motivation

- 2011-2012: ~500,000 Higgs(-like) particles within ATLAS and CMS
    - Fewer in LHCb but still potentially interesting
  - How many were triggered we don't know
    - But at least 1% on the lepton(s) from *Wh* (*Zh*), perhaps 1%-2% on parked VBF production

- SM decays have small rates
    - bb, $\tau\tau$ from small couplings
    - WW*,ZZ* are off-shell
    - gg, $\gamma\gamma$, Zγ through loops

➔ Small new interactions can give *(as many theorists have pointed out)*
    - Unexpected enhancements of rare SM decays
    - Unexpected non-SM decays (**as common as allowed: 10-20%**!)

- Most have not been looked for yet, so **discoveries at 5σ still possible before 2015**, unlike SM Higgs measurements

Non-SM h Decays

- Yes, measure all SM decay modes with the highest possible precision
  - But let's not waste resources!!
  - We have many places to look for possible discoveries!

- Rare modes: *h* (or another Higgs) may decay with much-enhanced rate
  - Zg, $\mu\mu$, $\tau\mu$

- Decays to non-SM particles
  - WIMPs (mostly singlet)
  - Singlets with no weak interactions [dark sectors/hidden valleys]

Invisible h Decays

Non-SM Visible h Decays

Non-SM Partly Visible h Decays

Singlets

Rich singlet sector possible, as complex as SM

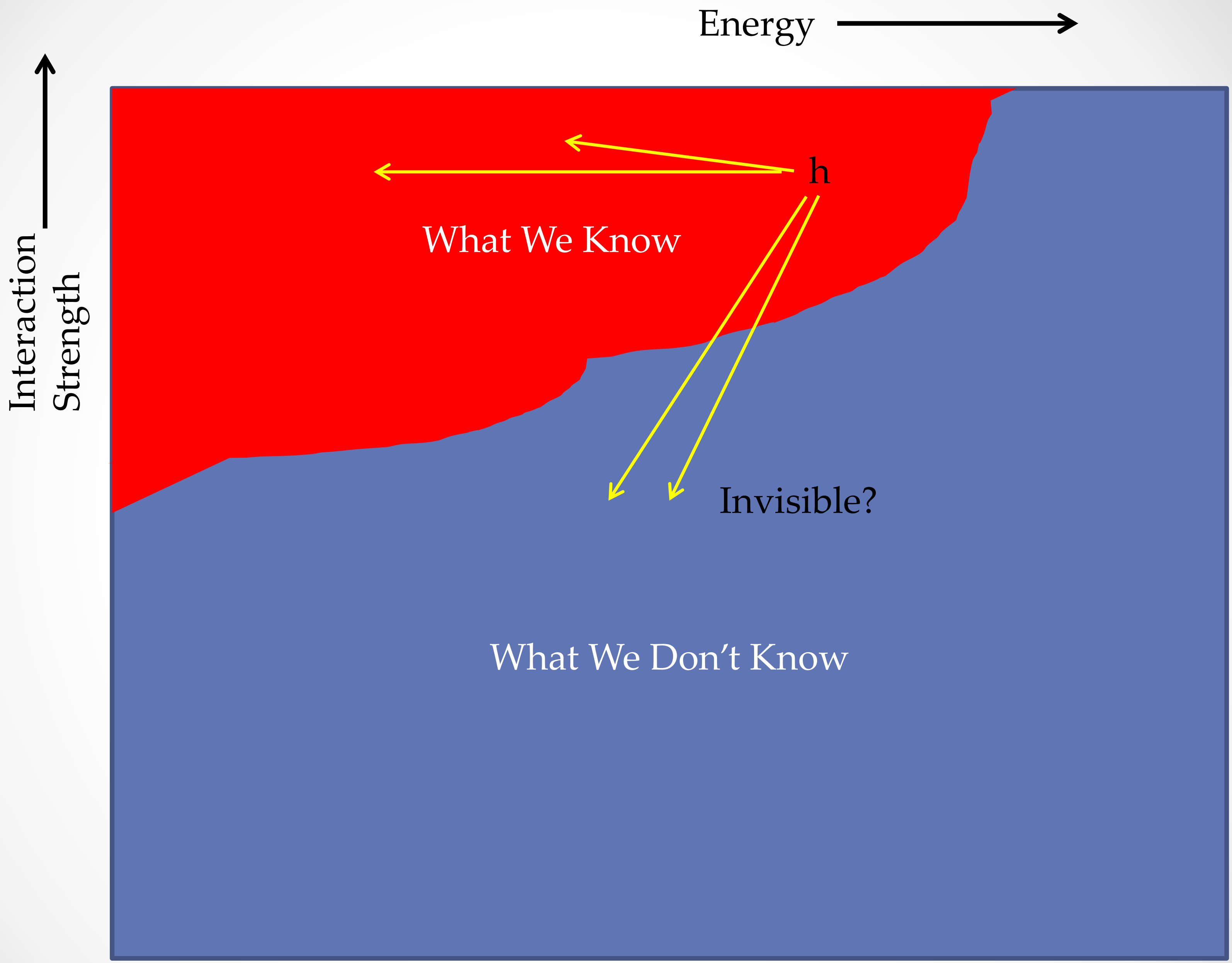
(Dark Sector; Twin Higgs; NMSSM; Hidden Valley; Unparticles…)

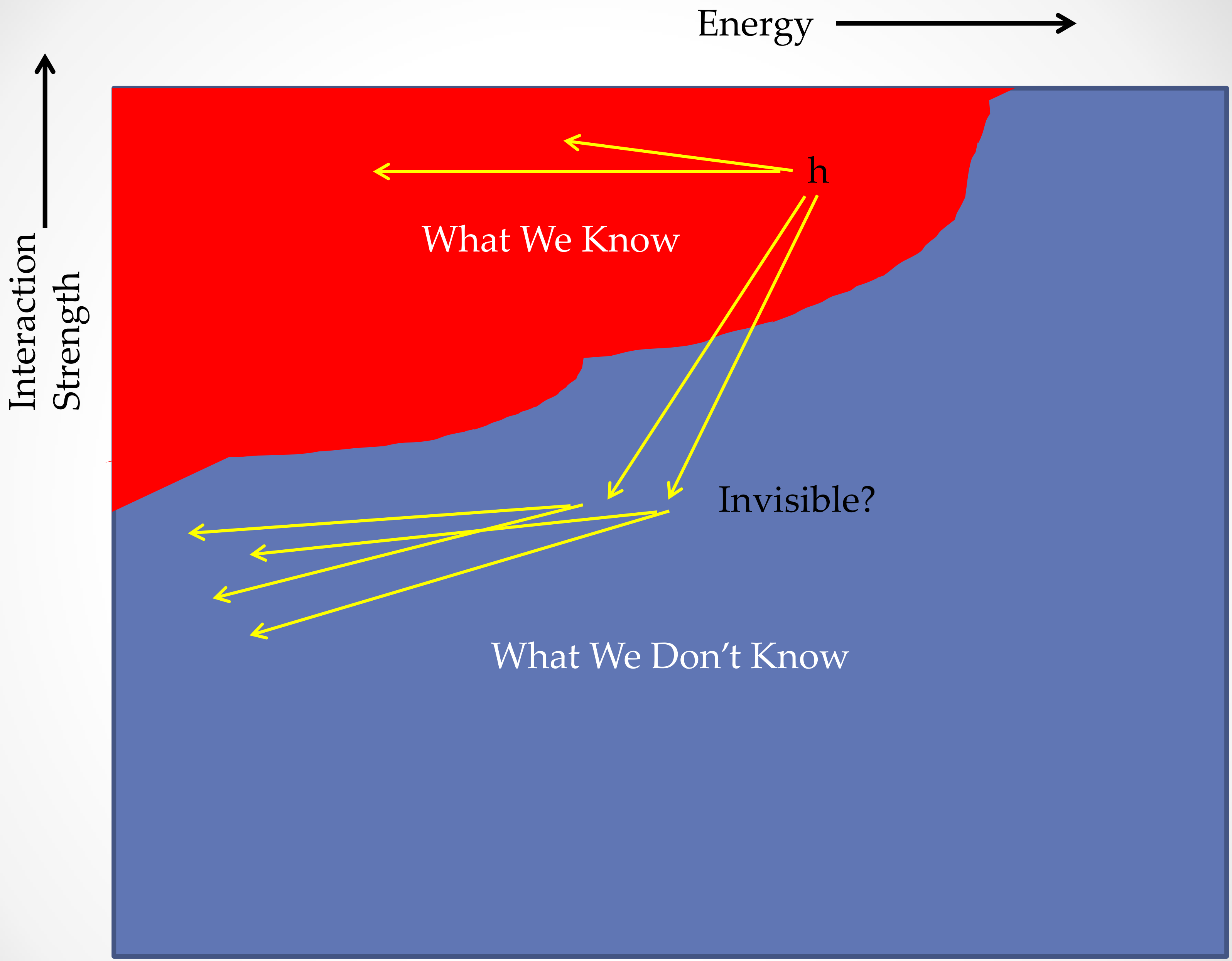
- Minimally constrained by previous data!

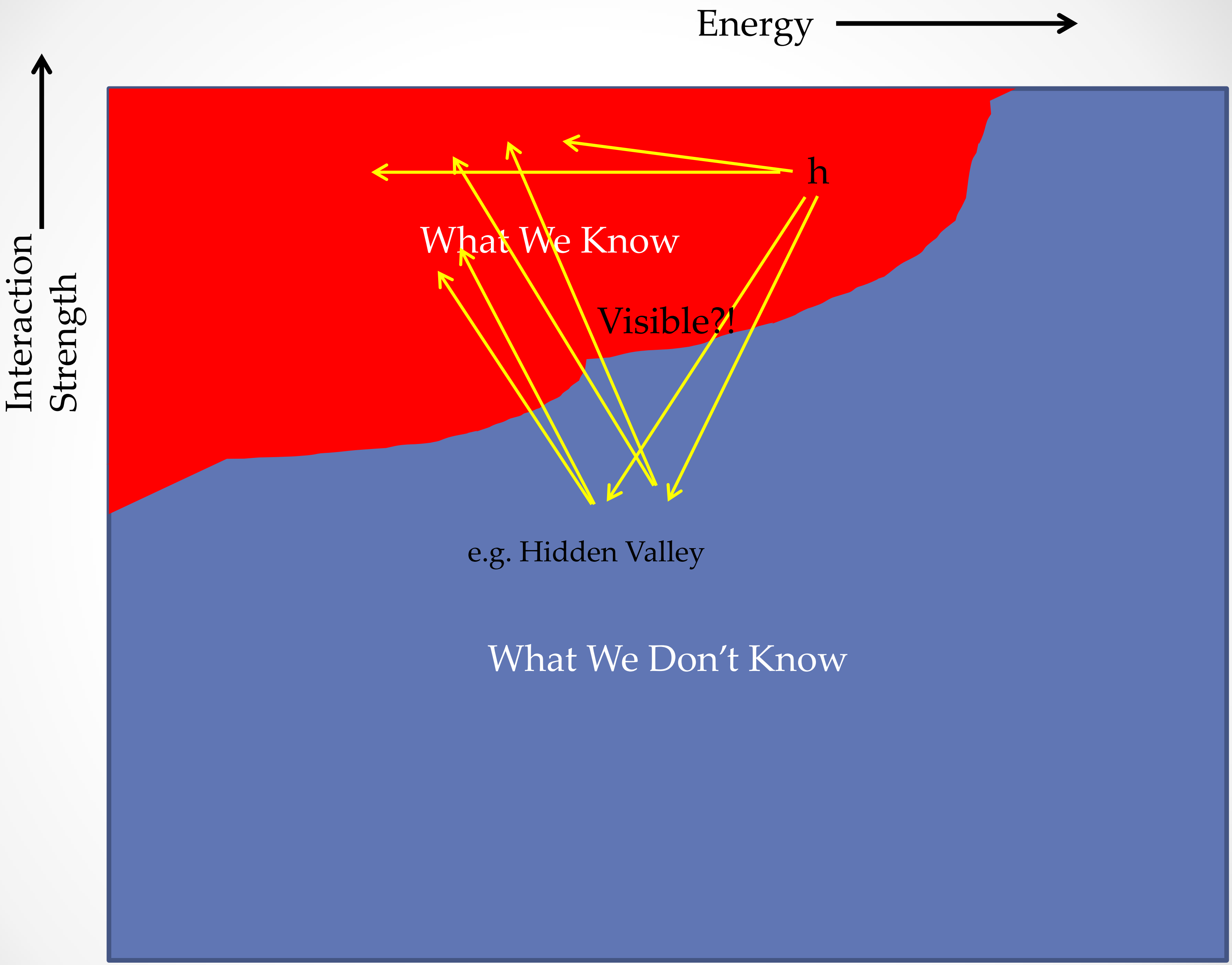
- Few SM particles couple to singlets in renormalizable way
  - U(1) hidden gauge boson V coupling to U(1) hypercharge boson ($F^{\mu\nu}F'_{\mu\nu}$)
  - Scalar S coupling to doublet Higgses (SH^*H, S^*SH^*H)

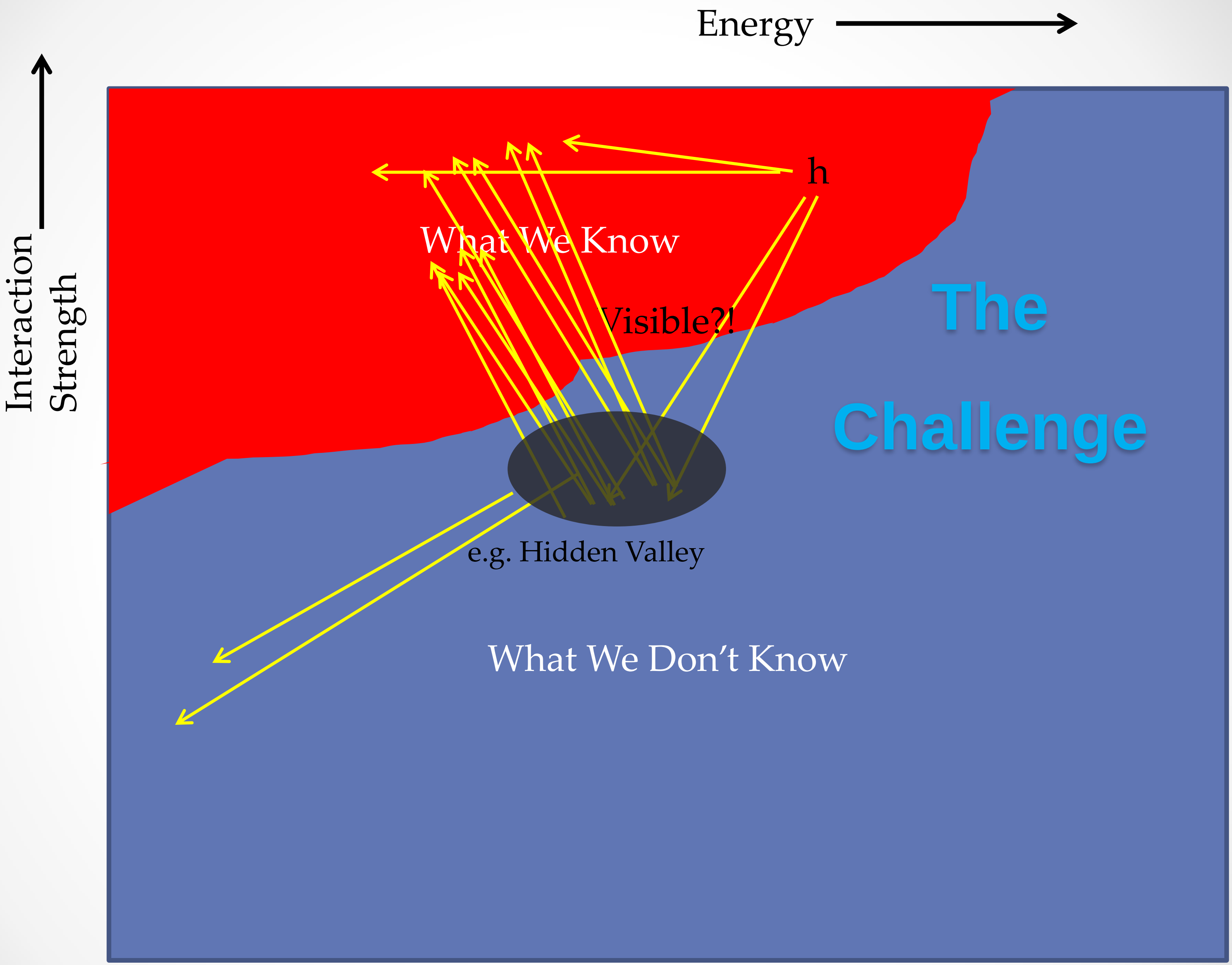
- But then S or V can couple to other singlets in renormalizable way
  - E.g. $S\psi\psi$
- Or additional BSM particles can allow renormalizable couplings
  - E.g. Bino-quark-squark
- Other couplings may be induced by strong dynamics in hidden sector

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


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


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


Energy
Interaction Strength
h
What We Know
Visible?!
e.g. Hidden Valley
What We Don't Know


Energy
Interaction Strength
h
What We Know
Visible?!
The Challenge
e.g. Hidden Valley
What We Don't Know

Priority Searches: non-SM Decays

Invisible – very high priority

Dark sector with dark photon
HV with U(1) factor or ρ-like meson
…

Entirely visible – very high to high priority include

- $(\ell^+\ell^-)(\ell^+\ell^-)$, $(\gamma\gamma)(\gamma\gamma)$, $(bb)(\tau\tau)$
- $(\ell^+\ell^-)(qq)$, $(\gamma\gamma)(gg)$, $(\gamma\gamma)(bb)$, $(bb)(bb)$
- $(\ell^+\ell^-)\gamma$, $(bb)(\mu\mu)$, $(\tau\tau)(\mu\mu)$, $(\tau\tau)(\tau\tau)$

NMSSM
Confining HV
…

Partly visible (i.e. not entirely invisible) – harder to prioritize

- 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)*

Dark Matter in split multiplets
HV with stable fermions
…

To exotic objects

- Long-lived low-mass neutral particles decaying in flight
- Clusters of low-mass neutral particles decaying promptly or in flight
- Soft final states (e.g. *h → 8 b's)*

Prioritizing: Visible Non-SM h Decays

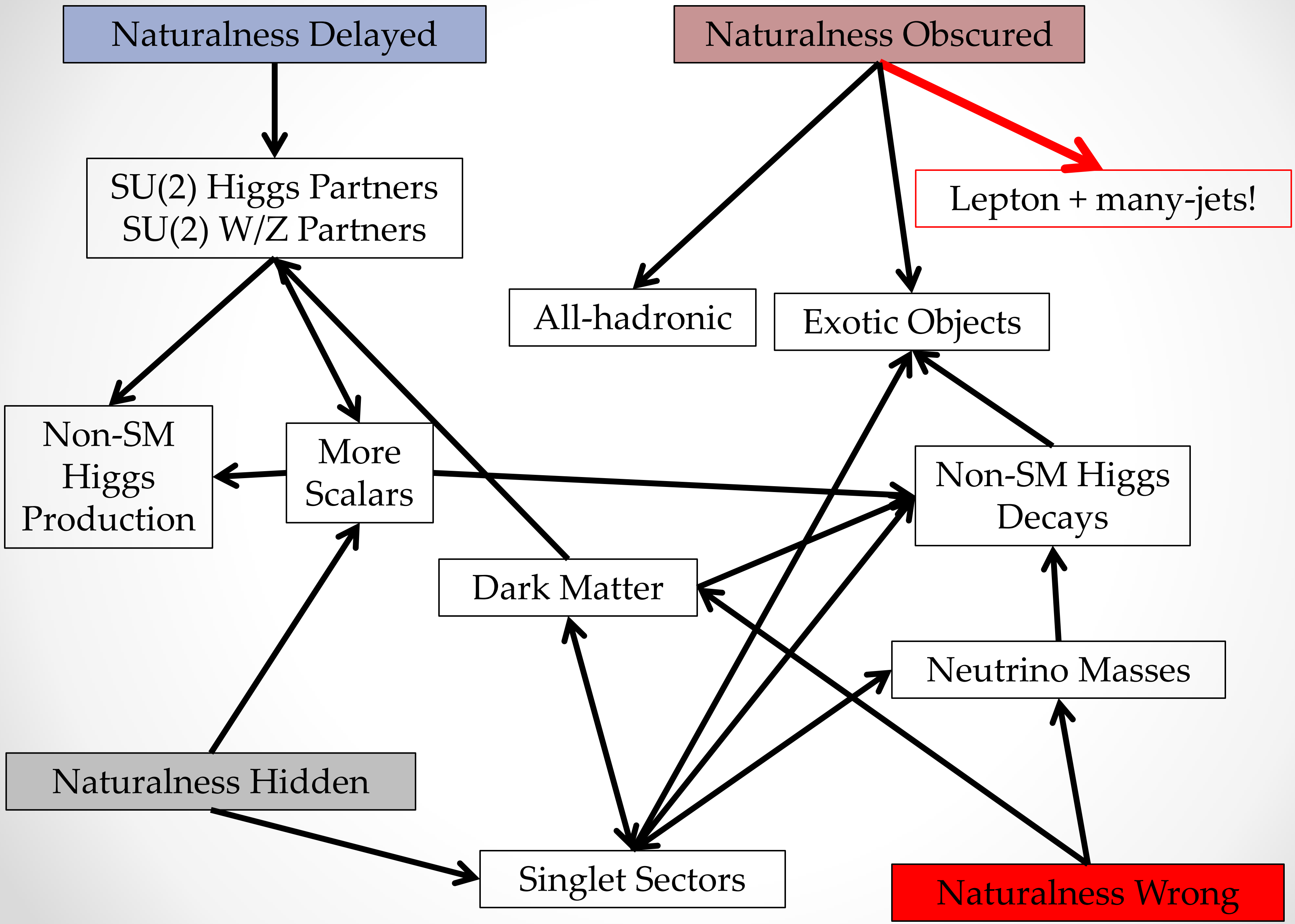
Tentative prioritization list (review in preparation):

Final State	Theoretical Motivation	Experimental Motivation
$(\ell^+\ell^-)(\ell'^+\ell'^-)$	High Dark Matter models with dark photon or "gluon" Hidden composite vector Light Scalar (m < 1GeV, $\ell = \mu$)	**Very High** Ready data sample from h → 4 ℓ 3 resonances (assume 2 w/ same mass?) Small Backgrounds so high sensitivity High trigger & selection efficiency *(may need to relax isolation)*
$(\gamma\gamma)(\gamma\gamma)$	Medium Hidden composite scalar Pseudoscalar in extended H sector	**Very High** 3 resonances (assume 2 w/ same mass?) Very small backgrounds ➔ high sensitivity Good trigger & selection efficiency (should be!) *(may need to relax isolation)*
$(bb)(\tau\tau)$	**Very High** NMSSM and others with h → aa Doublet+singlet h sectors Many DS/HV models	Low 3 Resonances but very challenging Events hard to reconstruct (requires MET) Low trigger and selection efficiency Big *tt* backgrounds Reduced branching fraction vs. 4 *b*'s

Summary of Post-Discovery Era

- Is Naturalness Delayed, Obscured, Hidden or Wrong?
  - Theoretical and phenomenological work needed!
  - Electroweak and singlet production means tough slogging ahead
  - Need to close big search gap using lepton + many-jets search

- Is it SM or not?
  - Precision measurements of easily measured SM h production/decays
    - BUT DIMINISHING RETURNS WILL SHORTLY SET IN!
  - Search for other scalars as in MSSM, NMSSM, Little Higgs, HV
  - Search for non-SM production modes
    - New particles decaying to h
    - Rare t decays
      - *Note: theorists need to look into rare t, W decays!*
  - Search for non-SM decay modes (role for parked/delayed data)
    - Systematic prioritization needed
      - Prompt visible, prompt partly visible
      - Exotic: long-lived,clustered, or both; or soft


Naturalness Delayed
Naturalness Obscured
SU(2) Higgs Partners
SU(2) W/Z Partners
Lepton + many-jets!
All-hadronic
Exotic Objects
Non-SM Higgs Production
More Scalars
Non-SM Higgs Decays
Dark Matter
Neutrino Masses
Naturalness Hidden
Singlet Sectors
Naturalness Wrong

Additional Slides

Prioritizing: Visible Non-SM h Decays

Tentative prioritization list (review in preparation):

Final State	Theoretical Motivation	Experimental Motivation
$(\ell^+\ell^-)(\ell'^+\ell'^-)$	High Dark Matter models with dark photon or "gluon" Hidden composite vector Light Scalar (m < 1GeV, $\ell = \mu$)	**Very High** Ready data sample from h → 4 ℓ 3 resonances (assume 2 w/ same mass?) Small Backgrounds so high sensitivity High trigger & selection efficiency *(may need to relax isolation)*
$(\gamma\gamma)(\gamma\gamma)$	Medium Hidden composite scalar Pseudoscalar in extended H sector	**Very High** 3 resonances (assume 2 w/ same mass?) Very small backgrounds ➔ high sensitivity Good trigger & selection efficiency (should be!) *(may need to relax isolation)*
$(bb)(\tau\tau)$	**Very High** NMSSM and others with h → aa Doublet+singlet h sectors Many DS/HV models	Low 3 Resonances but very challenging Events hard to reconstruct (requires MET) Low trigger and selection efficiency Big *tt* backgrounds Reduced branching fraction vs. 4 *b*'s

Prioritizing: Visible Non-SM h Decays

Tentative prioritization list (review in preparation):

Final State	Theoretical Motivation	Experimental Motivation
$(\ell^+\ell^-)(qq)$	High Dark Matter models with dark photon or "gluon" Hidden composite vector Light Scalar (m < 1GeV, $\ell = \mu$)	**High** Often higher branching fraction than $h \rightarrow 4\ell$ Much bigger backgrounds than $h \rightarrow 4\ell$ 3 resonances but not as high resolution Lower trigger efficiency *(may need to relax isolation)*
$(\gamma\gamma)(bb)$ $(\gamma\gamma)(gg)$	Medium Hidden composite scalar Pseudoscalar in extended H sector	**High** Often higher branching fraction than $h \rightarrow 4\gamma$ Much bigger backgrounds than $h \rightarrow 4\gamma$ 3 resonances but not as high resolution Lower trigger efficiency *(may need to relax isolation)*
(bb)(bb)	**Very High** NMSSM Other extended H sectors Scalar mixing with known h Many DS/HVs	**Very Low?** 3 Resonances but poor resolution Low trigger and very low selection efficiency Requires boosted-*h* methods & *Wh* events *(probably not enough events in 2011-2012)* Higher branching fraction than 4 *b*'s

Prioritizing: Visible Non-SM h Decays

Tentative prioritization list (review in preparation):

Final State	Theoretical Motivation	Experimental Motivation
$(\ell^+\ell^-)\gamma$	Medium Dark Matter models with dark photon or "gluon" Hidden composite vector Light Scalar (m < 1GeV, $\ell = \mu$) Often rare	**Very High** Ready data sample from $h \rightarrow Z\gamma$ 2 resonances, one known Small Backgrounds so high sensitivity High trigger & selection efficiency *(may need to relax isolation)*
$(\tau\tau)(\mu\mu)$	**High** NMSSM and others with h → aa **Relevant if $m_a < 2m_b$** Doublet+singlet h sectors Many DS/HV models	High? *(better or worse than 4τ?)* Good dimuon resonance Hard to fully reconstruct (requires MET) Moderate (?) backgrounds *(must relax isolation)*
$(bb)(\mu\mu)$	**High** NMSSM and others with h → aa Doublet+singlet h sectors Many DS/HV models But signal is often too low	Medium 3 Resonances, poor resolution on 2 Very few events! Big *tt* backgrounds

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 2013

Obscured Naturalness

Can long-lived particles hide a signal?

- Long-lived particles pose detector challenges
  - Particles decaying in flight can cause mis-reconstruction
  - Quality cuts may discard events with non-prompt jets/leptons
- So maybe signals could lie mostly in discarded or misinterpreted events

- Some searches for long-lived particles have been done
  - Displaced muon pairs
  - Displaced vertices with several reconstructed tracks
  - Displaced vertices in ATLAS muon system

- Quite difficult to infer what might have slipped through
  - Need to have more systematic program covering more ground

- Extensive workshop on this subject in summer/fall 2013??

Obscured Naturalness

Can soft or hyper-soft signals hide new phenomena?

- Suppose 1.5 TeV of energy goes into
  - 2 hard back-to-back jets and ~ 20 gluons with pT = 5-50 GeV?
  - 2 hard back-to-back jets and ~ 200 photons with pT = 0.1 - 5 GeV?
  - 4 hard jets and 250 well-spread tracks with pT = 0.3 – 10 GeV?
  - 2 leptons surrounded by 40 quarks/antiquarks with pT=3-30 GeV?
    - How does isolation work here?
- Would we identify such signals?
  - What models can generate them?
    - `Quirks' [particles with SM charge and infracolor/hidden valley charge]
    - Strong-coupling hidden-valley quarkonium?
  - Can we calculate them? [often no; a lot of guesswork involved]
  - Many search strategies not yet developed –
    - Needs to be done in 2013 so searches can be performed in 2014
    - One trick: W + photon or dijet or dilepton resonance + soft activity

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

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…