# Searches For Hidden Valleys

(Self-Interacting Dark Sectors with Mass Gap)

# at the LHC

Dark Interactions

Matt Strassler

Harvard

October 2016

in memory of Guido Ciapetti

# Plan of the Talk

- Why Hidden Valleys?
- Why is the LHC a good place to look for them?
- Three basic methods to look for HV particles
  - Quasi-inclusive
  - Unusual objects or events
  - Decays of known objects
- What do we know from LHC studies?
  - Very few direct searches for HVs
  - Very few “recasts” of existing searches as constraints on HVs

  Consequently, we don’t know very much at all.

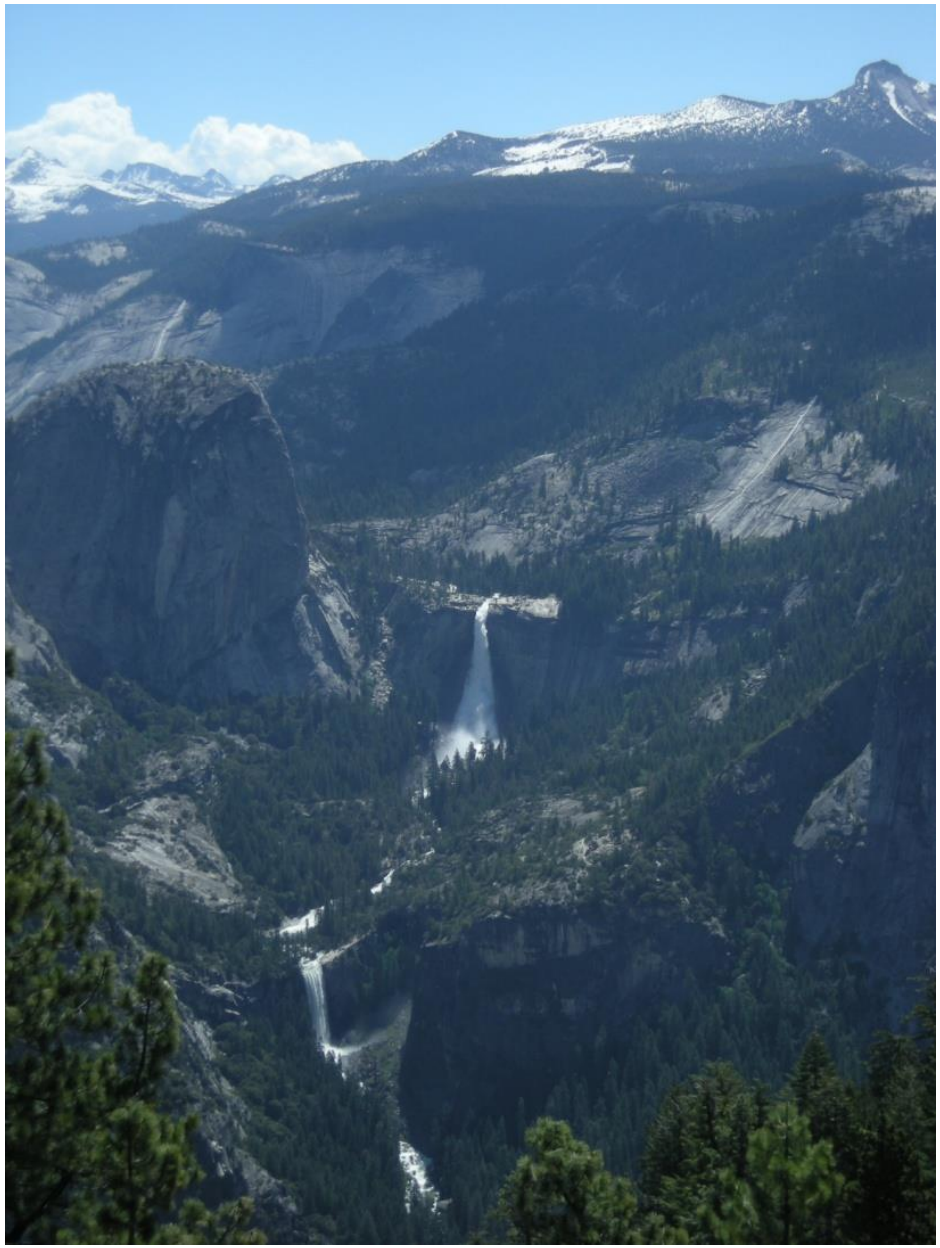
# “Hidden Valley”?

MJS + Zurek 06

A unexpected place …

… of beauty and abundance …

… discovered only
after a long climb …



# "Hidden Valley"?

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Hidden/Dark Sector

Low-Mass Particles

With Self-Interactions

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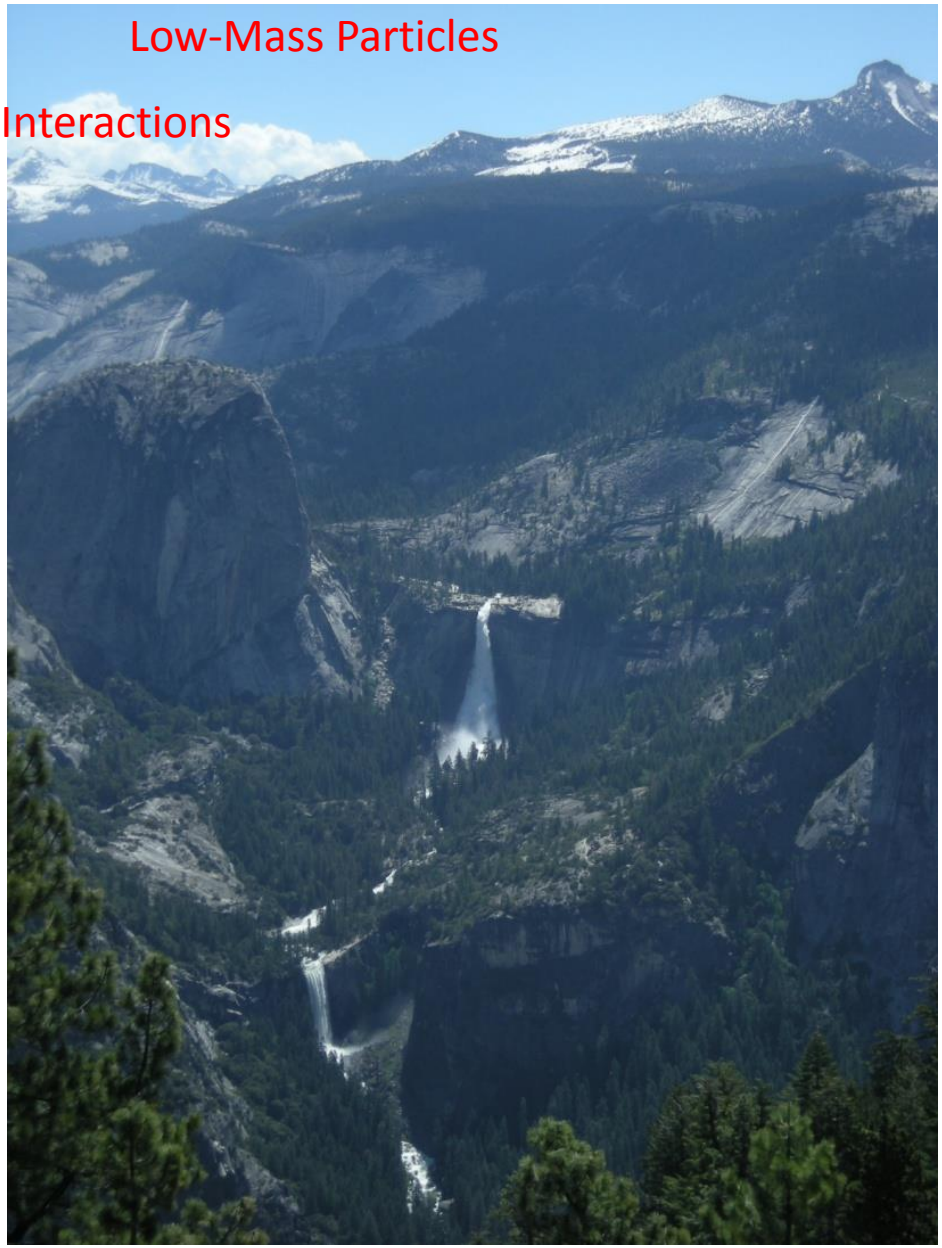
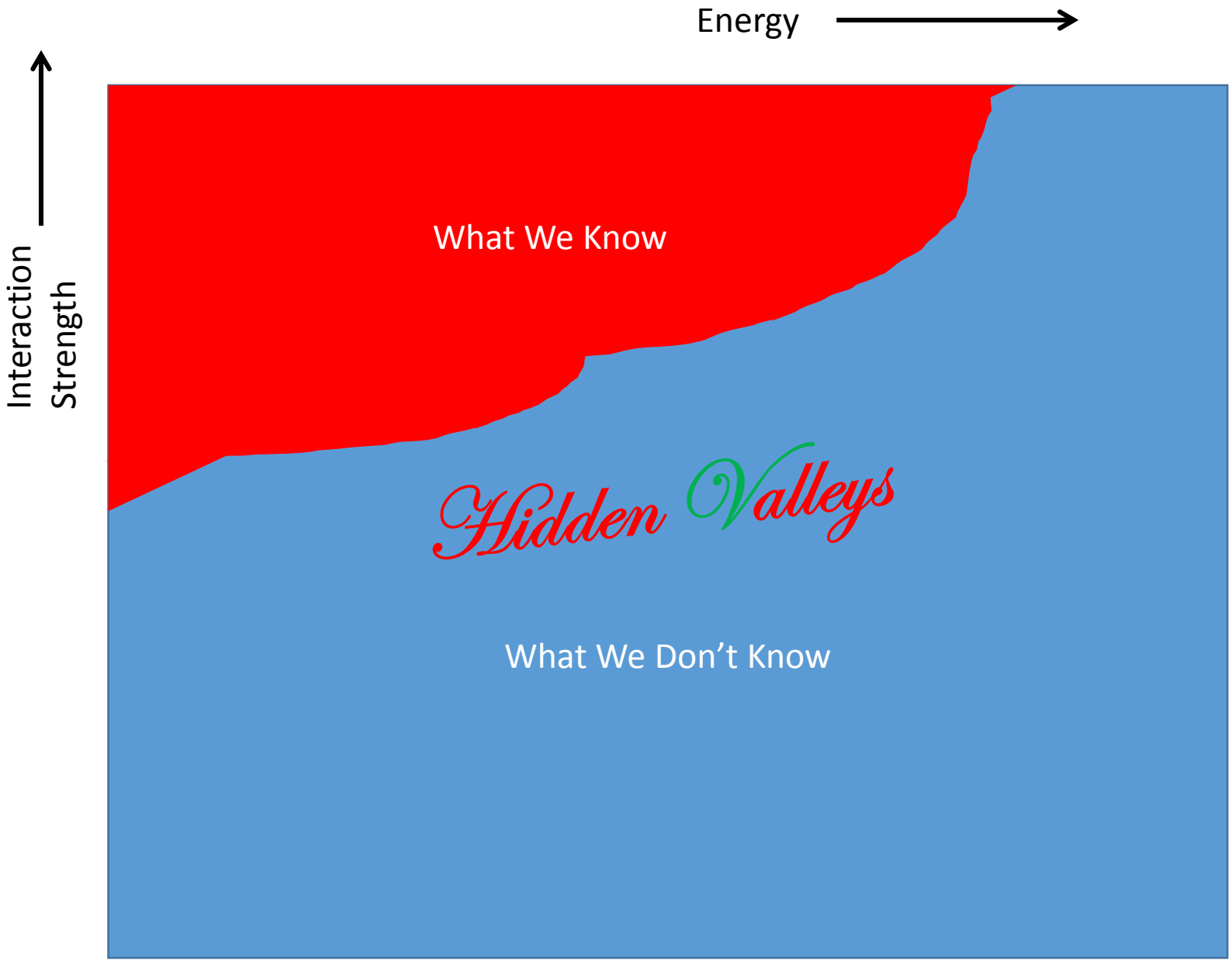



Energy
Interaction Strength
What We Know
Hidden Valleys
What We Don't Know

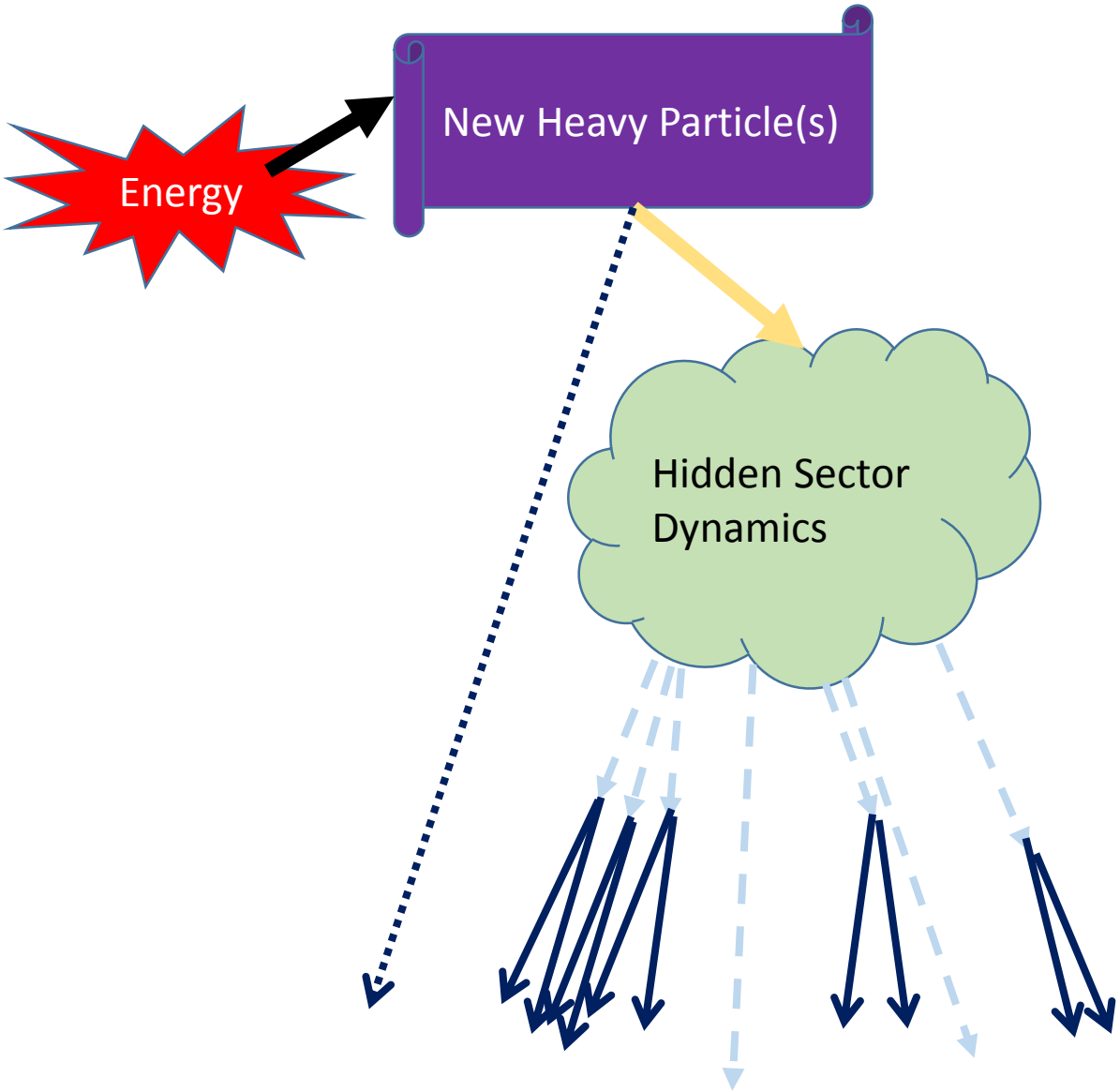
# Motivations

MJS + Zurek 06

- Top-Down Theory: String theory
  - Abundance of sectors even at TeV scale
- Cosmology: Dark Matter
  - "Dark Sectors"
    - WIMPless miracle, etc.
    - SIMPs, AsymDM
    - …
- Bottom-Up Theory: Naturalness
  - Supersymmetry Breaking
  - Neutral Naturalness
- Opportunity: Higgs Portal

# Hidden Valleys

MJS + Zurek 06



# Why LHC?

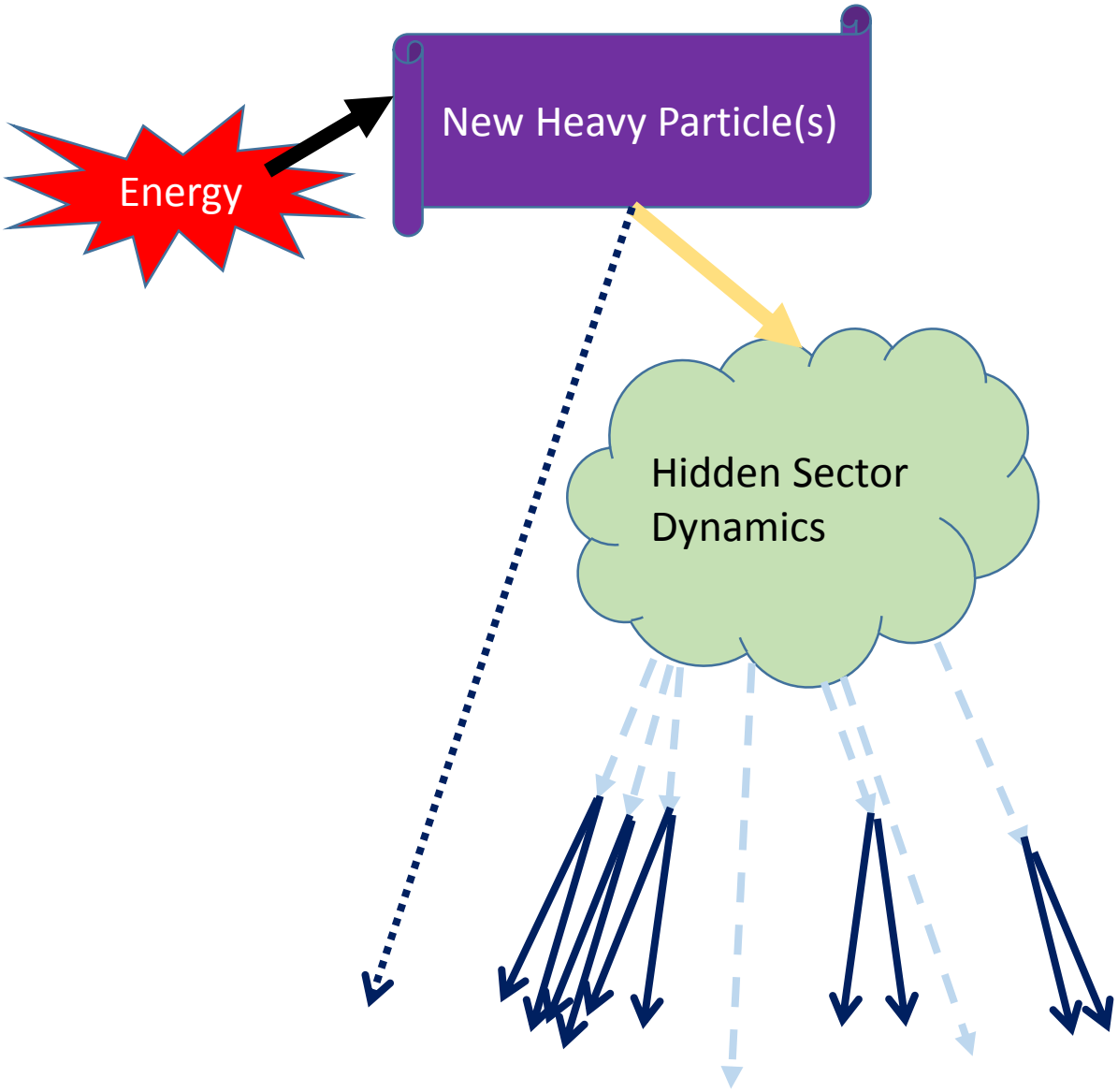
MJS + Zurek 06

HV particles – how heavy?

- In 2006, LHC imminent and urgent; we focused on > GeV
  - 2006: LHC experiments were not prepared (not even triggers)
  - Below GeV, many particles develop lifetimes > km
- Many of the same phenomena extend to 10s of MeV
  - Especially for dark vector or scalar

# Hidden Valleys

MJS + Zurek 06



# "Portals"

In an HV, must be possible to go back/forth from SM sector to hidden sector

- Z'/Z mass mixing
- Higgs
  - (including SM extensions)
- Quirks
- LSP of SUSY
  - (similar in T-parity Little Higgs, KK-parity Extra Dims)

- Photon/Z kinetic mixing
- Neutrinos
- RS Gravitons/Black Holes/Strings

- …

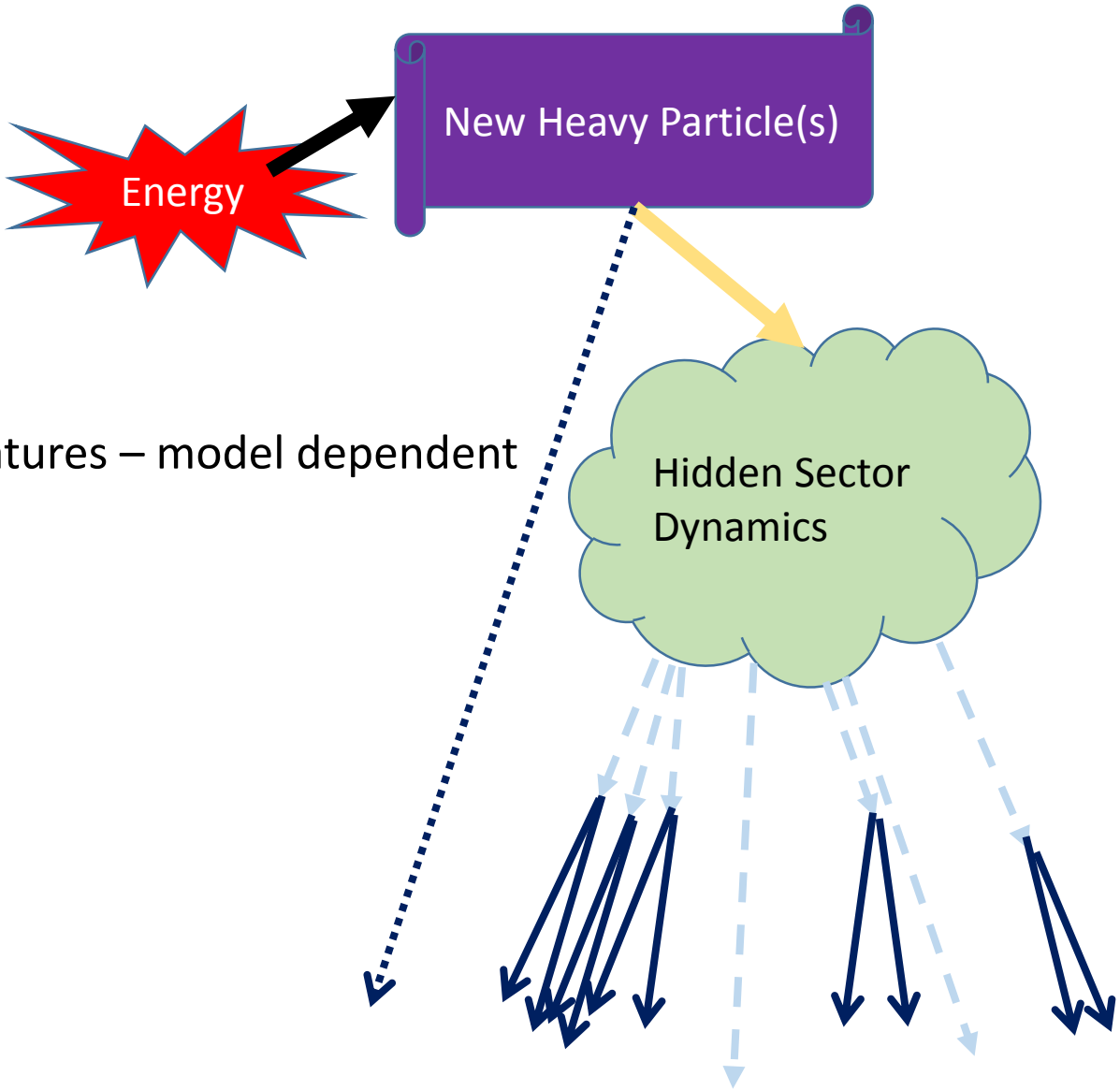
# Typical of Hidden Valleys (and not of minimal models)

MJS + Zurek 06

New neutral particles –

- Numerous
- Boosted
- Clustered
- Displaced

-- May see any/all of these signatures – model dependent



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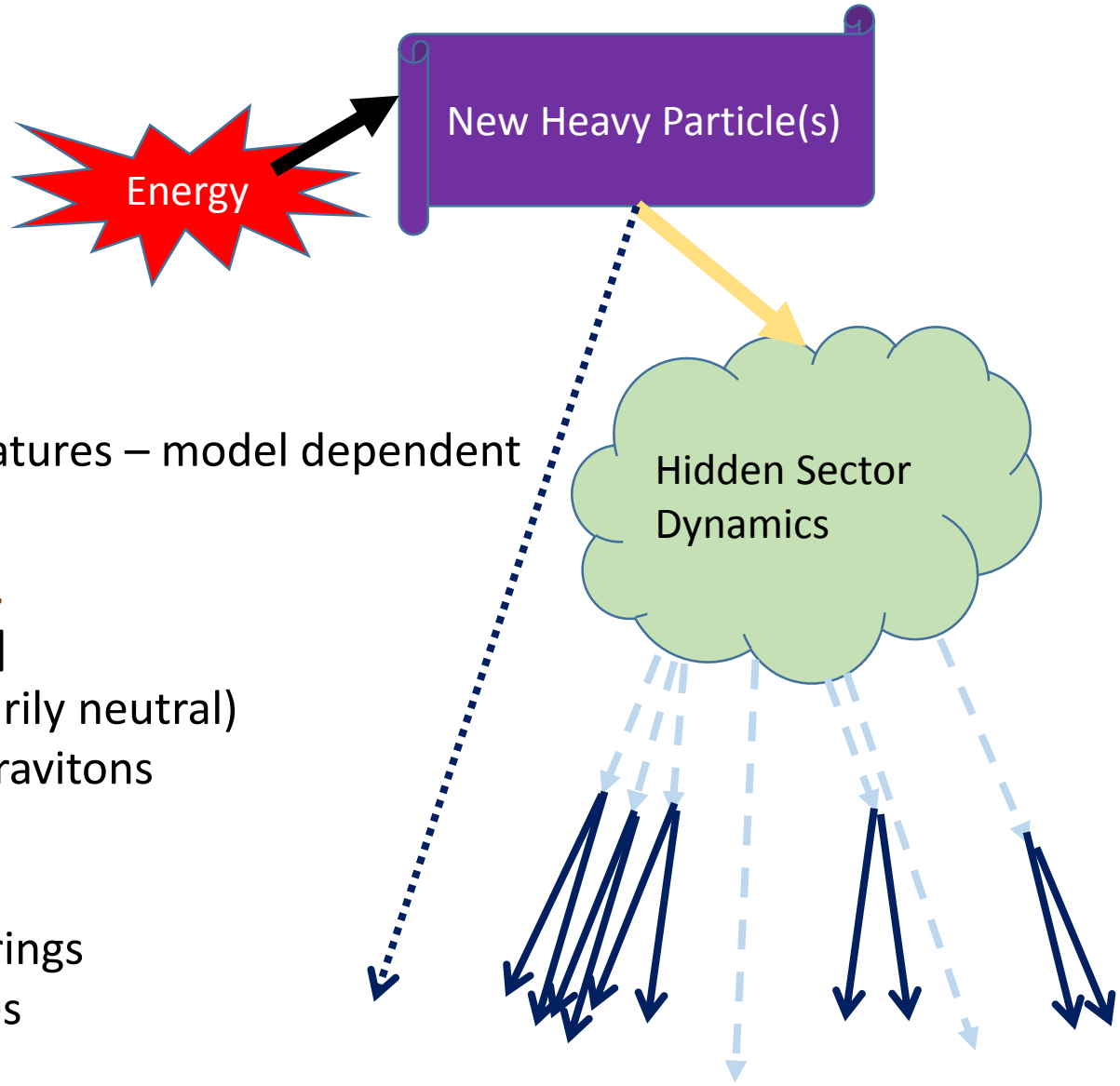


Produced in all sorts of decays…

- Higgs(es) ["Higgs 'portal']
- LSP/LKP/LTP (not necessarily neutral)
- Techni-resonances ; RS-gravitons
- Z'
- Quirk-onium
- Black Holes or Excited Strings
- Radiated off new particles

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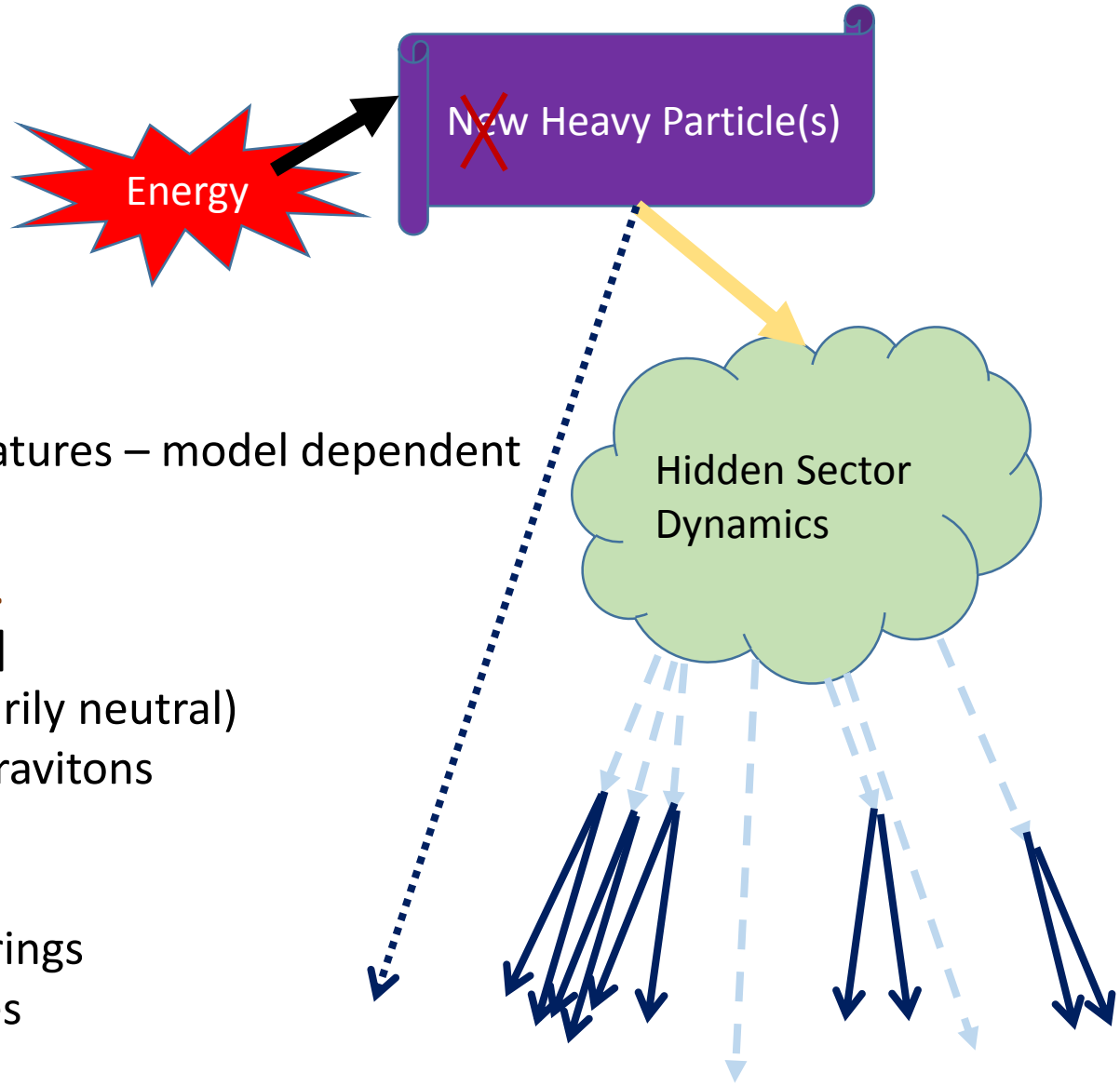


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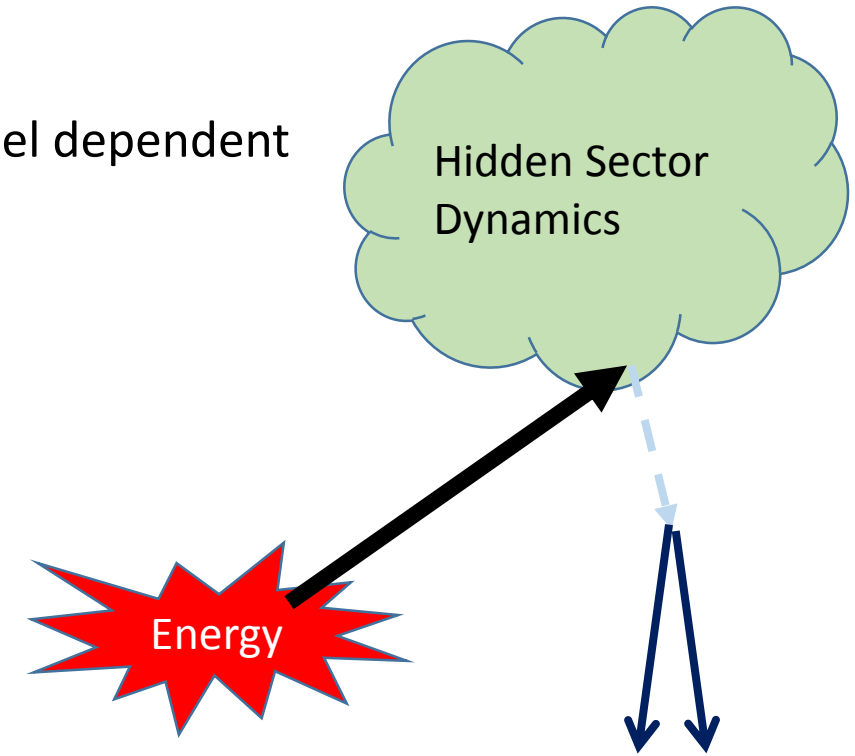
Can produce at luminosity frontier

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# Some Typical Classes of HV Particles

- Neutral Bosonic Resonances
  - Spin 0
    - Heavy flavor decays (b's, tau's, mu's)
    - Gauge boson decays (gluons, W's, Z's, photons)
  - Spin 1
    - Quasi-democratic decays (quarks, leptons, W's)
  - Spin 2
    - Gauge boson decays (jets, W's, Z's, photons)
- Neutral Fermionic Resonances
  - Spin ½
    - $W^{(*)}$+lepton, MET + bosonic resonance
- Cascades
  - Boson/fermion → boson/fermion/MET + **non-resonant** quark/lepton pair
- Invisible (stable, or stable on detector time-scales)

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The easiest ones if prompt decays

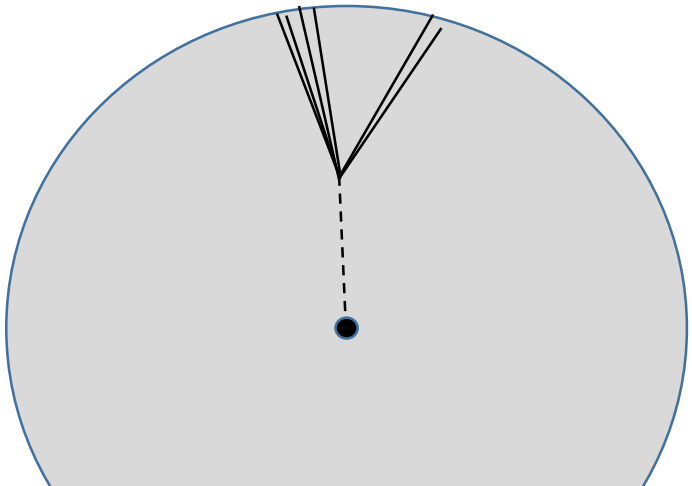
# Neutral LLPs (Long-Lived HV Particles)

Why LLPs?

- Normally, Width ~ Mass * Coupling
- As in QCD, decays for many states can be suppressed by
  - Approximate Symmetries
  - Weak couplings
  - High dimension operators
  - Natural degeneracies

With complex spectrum, many possible patterns

- Alone
- Clustered
- Seeded
- Cascades



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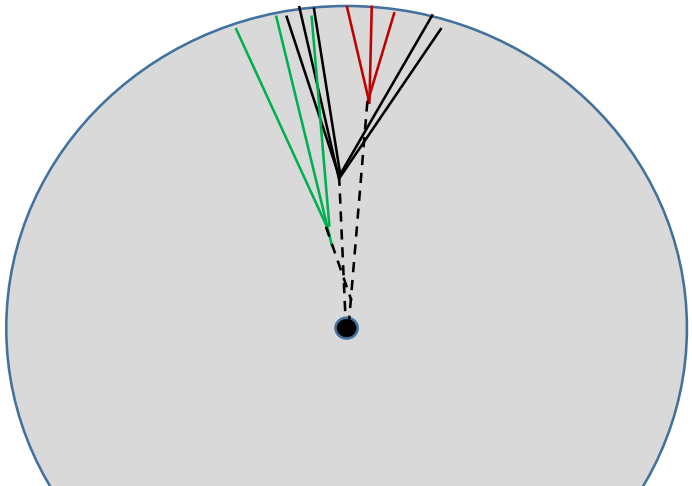

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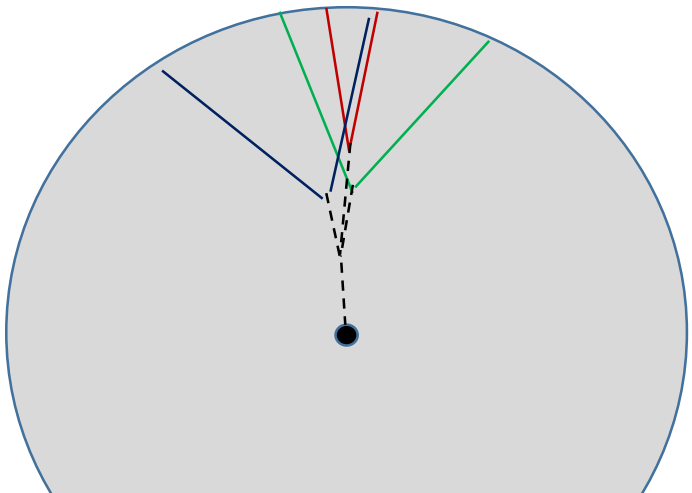

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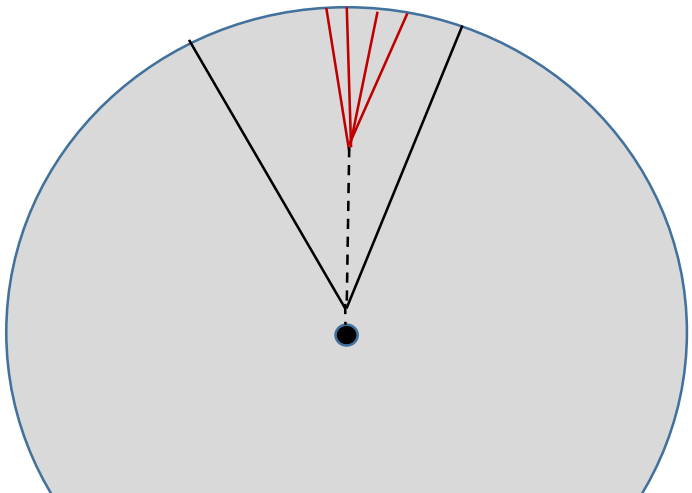
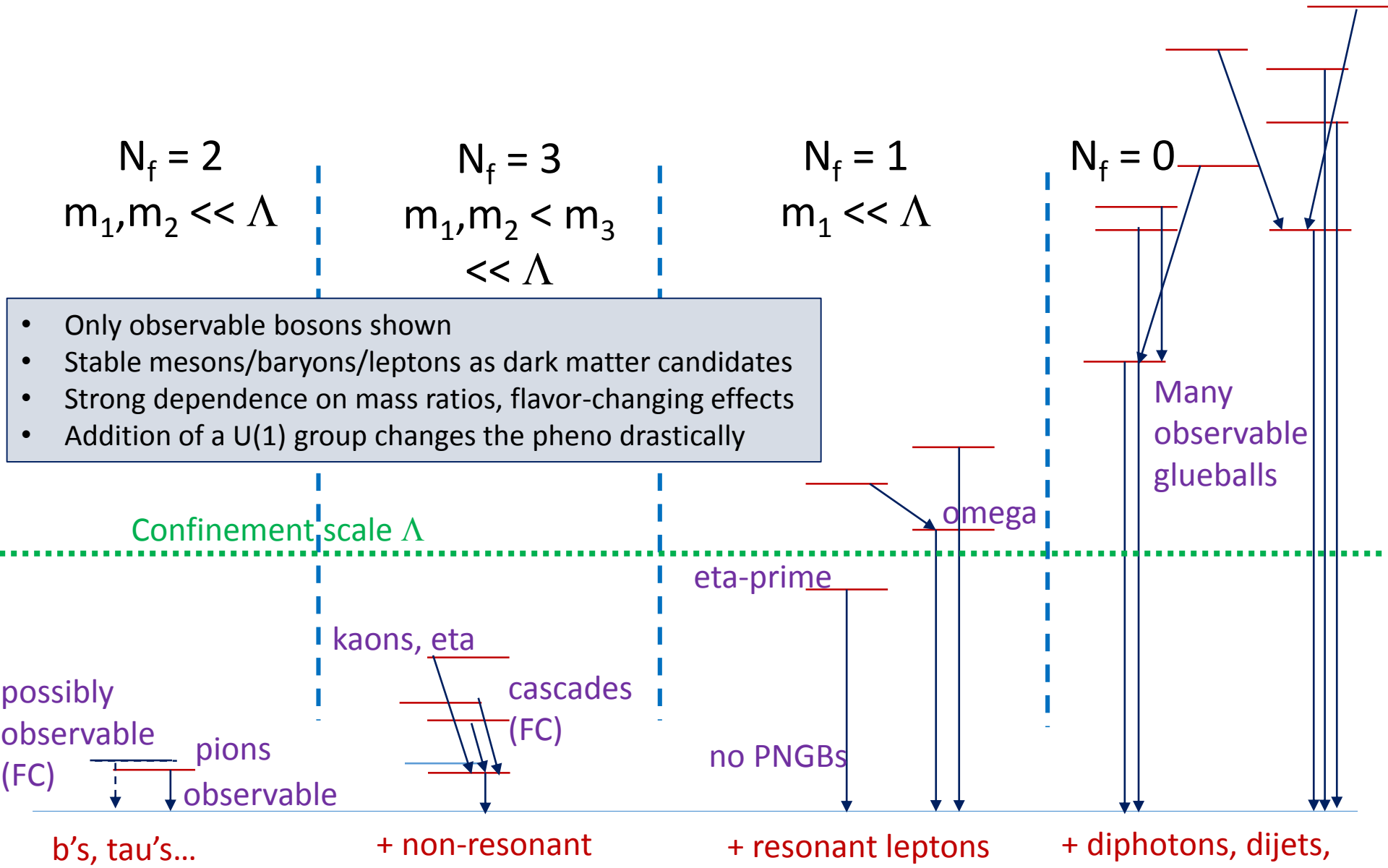


# Some Example HVs to Illustrate Diversity

- Hidden Valleys **do** require interactions and a mass gap (or ledge)
- Confinement, however, is not required
- However, confining theories are useful examples
  - because they show how complex physics can be even with simple inputs
- Complex results can and do arise in Higgsed theories too
  - via cascade decays and perturbative showering
  - but there (because of weak coupling) you mostly get out what you put in

# Diverse Spectra of SU(N) QCD-like HVs



# Strategies to Find HV Particles

- Look for class of HV particle (semi-)inclusively (production-agnostic)
  - Require only the particle and put no/few other demands on the event
- Select unusual events or objects, then look within for HV particles
- Look for HV particles in decays of known particles (h,Z,t,W)

# Example from Neutral Naturalness

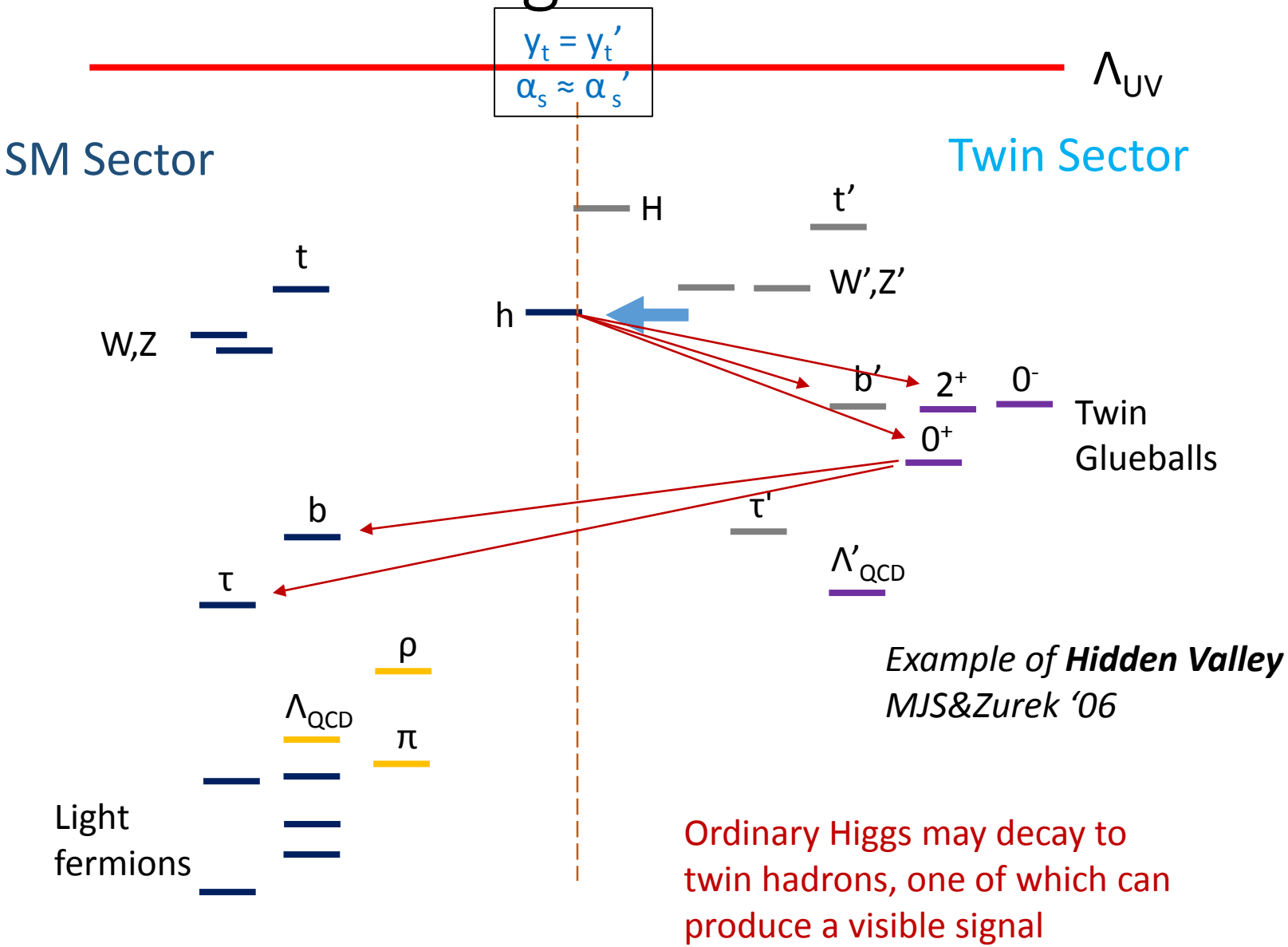
Main HV object is $0^{++}$ glueball decaying through Higgs portal to b's

- Mass $m_0$
- May be prompt if 30-60 GeV, will be long-lived if << 50 GeV

Produced in

- 125 GeV Higgs decay
  - h → 2 (or more if $m_0$ small) glueballs
  - Br at least few x $10^{-4}$ , possibly as large as 10%-20%
- Heavy Higgs (300-1500 GeV) decay
  - H → many glueballs
  - Events very rare but high energy, MET, multiplicity – spectacular
- In Folded SUSY, squirk annihilation
  - Similar to H decays, plus additional soft activity

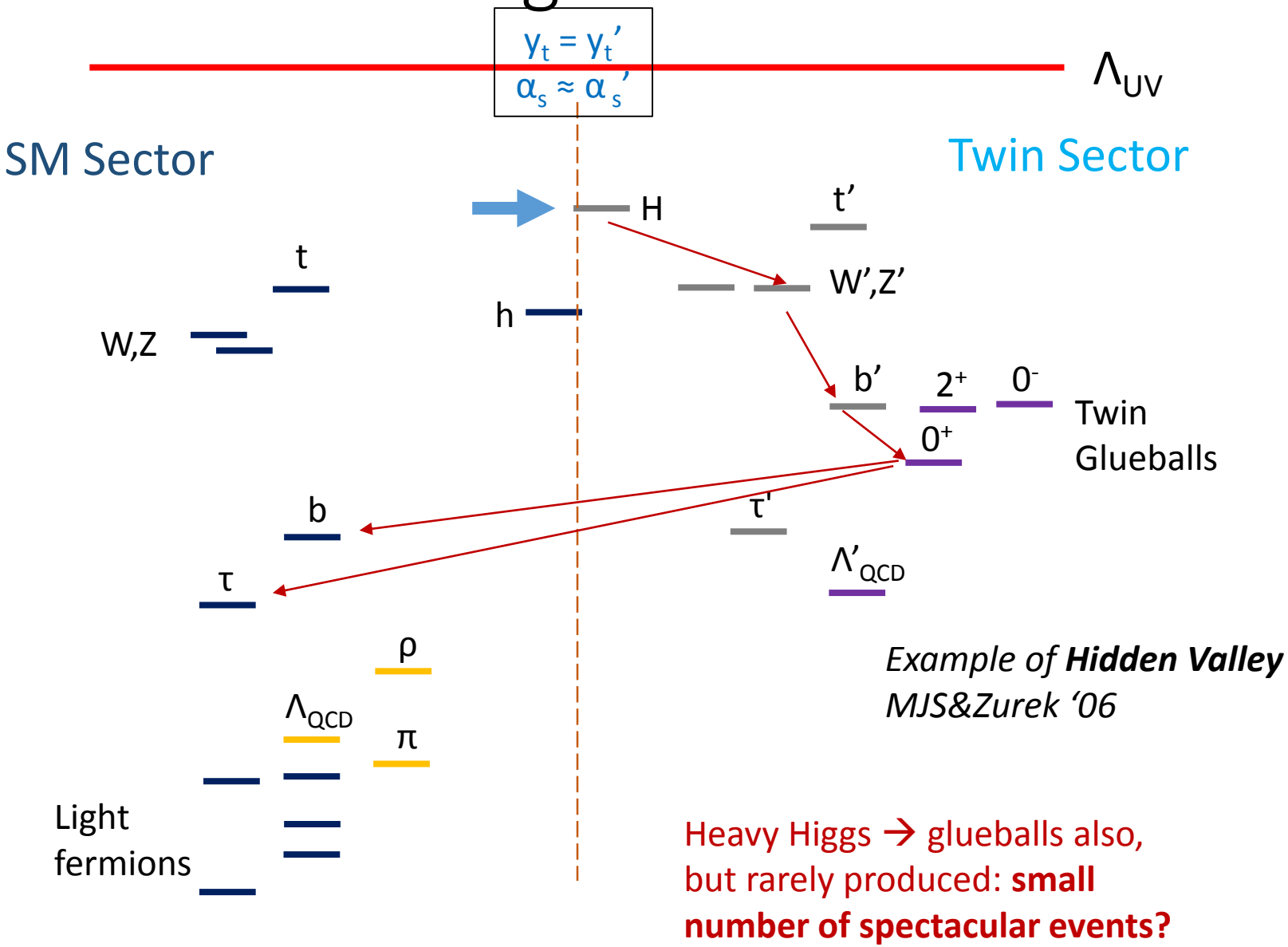
# Signals




*Example of **Hidden Valley***
*MJS&Zurek '06*

Ordinary Higgs may decay to twin hadrons, one of which can produce a visible signal

# Signals




*Example of **Hidden Valley***
*MJS&Zurek '06*

Heavy Higgs → glueballs also, but rarely produced: **small number of spectacular events?**

# Strategies for Fraternal Twin Higgs

- Look for class of HV particle (semi-)inclusively (production-agnostic)
  - Require only the particle and put no/few other demands on the event
    - Boosted b-pair resonance or boosted tau pairs
    - Displaced tau-pair or two displaced jets (or jet pairs)

h or H decays

- Select unusual events or objects, then look within for HV particles
  - High $S_T$ ($m_{eff}$) or MET
  - High jet multiplicity or displaced-track multiplicity
    - Then look for prompt b-pair resonances or displaced vertex(vertices)

H decays

- Look for HV particles in decays of known particles (h,Z,t,W)
  - h → bbbb, bb$\mu\mu$, $\tau\tau\mu\mu$ prompt
  - h → single displaced vertex
    - requiring associated VBF jets or lepton(s)/MET from W,Z

h decays

# Single Object Searches: Prompt Bosons

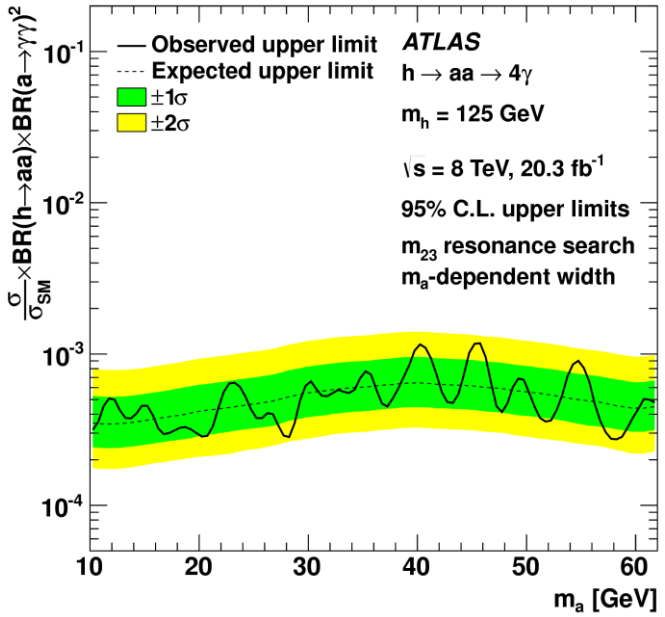
- Fully Inclusive – not effective
  - Not easy to find hidden low-mass bosons in inclusive dilepton search, etc.

- Highly Boosted (e.g. produced in decay) – very poorly covered
  - Lepton pair
    - Low-mass “simple” lepton-jet only
  - Photon pair
    - Low-mass “simple” photon-jet in Higgs decays only
  - Bottom quark pair
    - None?

# Double Object Searches: Prompt Bosons

Constraints on models where >1 resonance → leptons or photons:

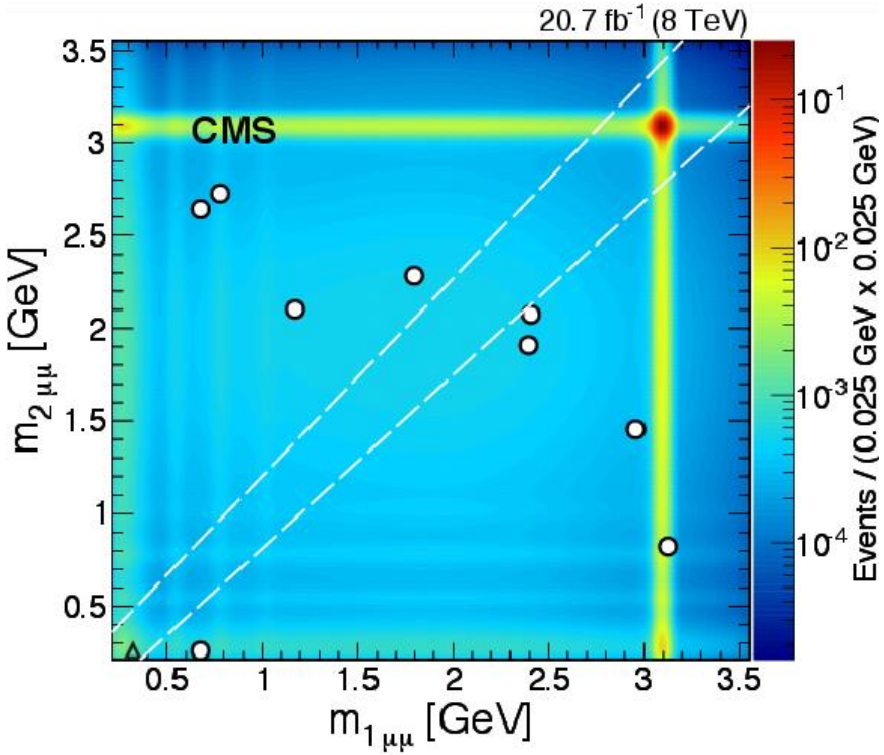
- Multi-lepton searches
- ATLAS multi-photon search
  - 3 photons: order 10 fb's




- Caution: ineffective if HV particles boosted or clustered
  - isolation cuts

# Simultaneous pairs of prompt dimuon pairs

Limits at fb level on two pairs of muons with same mass.



# Single/Double Object Searches for LLPs

We heard a lot about this yesterday *(talks by T. Kolberg, A. Coccaro)*

- Leptonic
  - CMS dilepton; e+mu;
  - ATLAS lepton-jet
- Jets
  - CMS dijet
  - ATLAS (2 vertices required, or 1 with high trigger threshold)
  - LHCb
- Semileptonic
  - ATLAS (but high trigger threshold)
- Photonic
  - ATLAS (2 required HCAL)
- Quasi-Generic
  - ATLAS (2 required HCAL)

CMS dilepton vertex

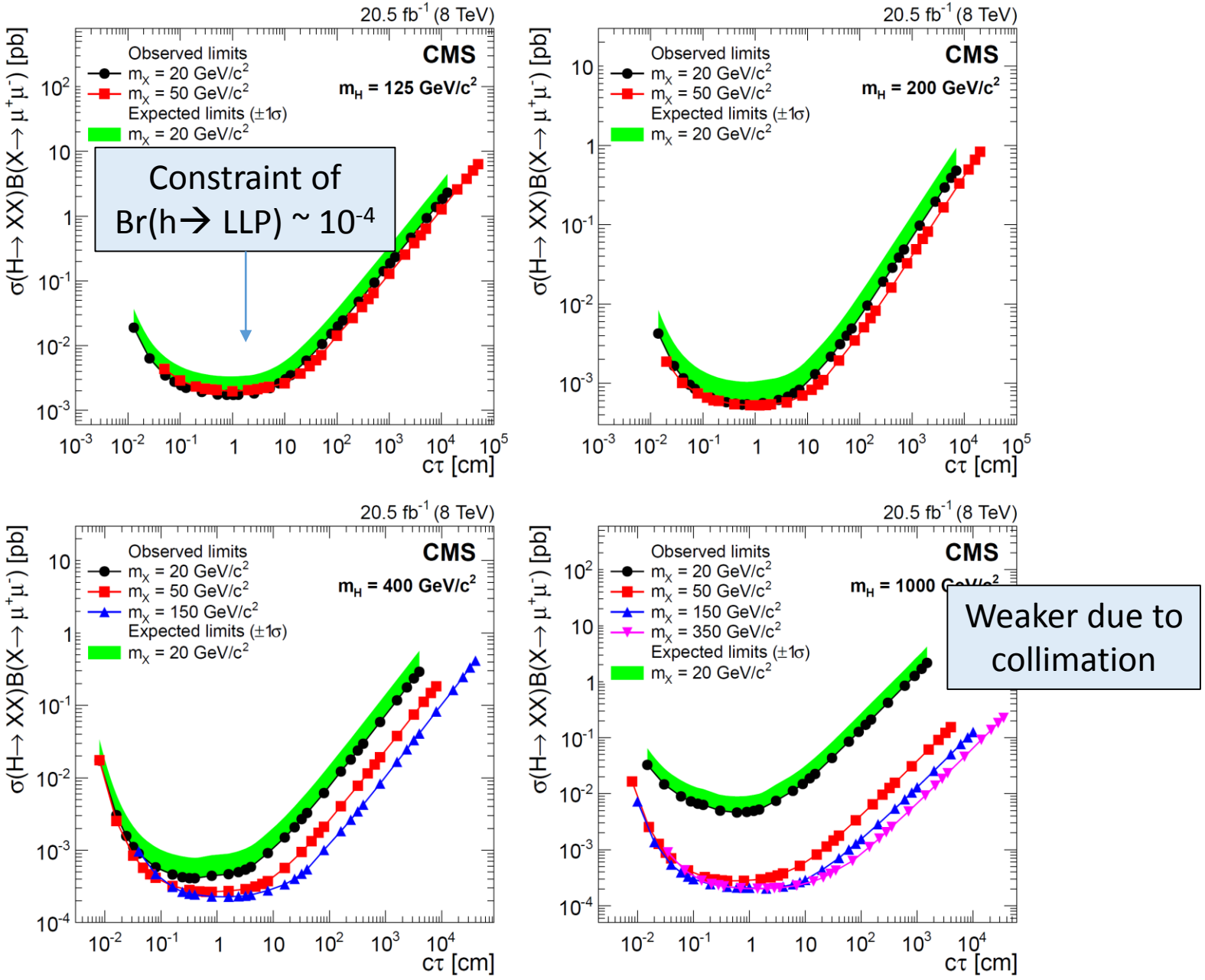


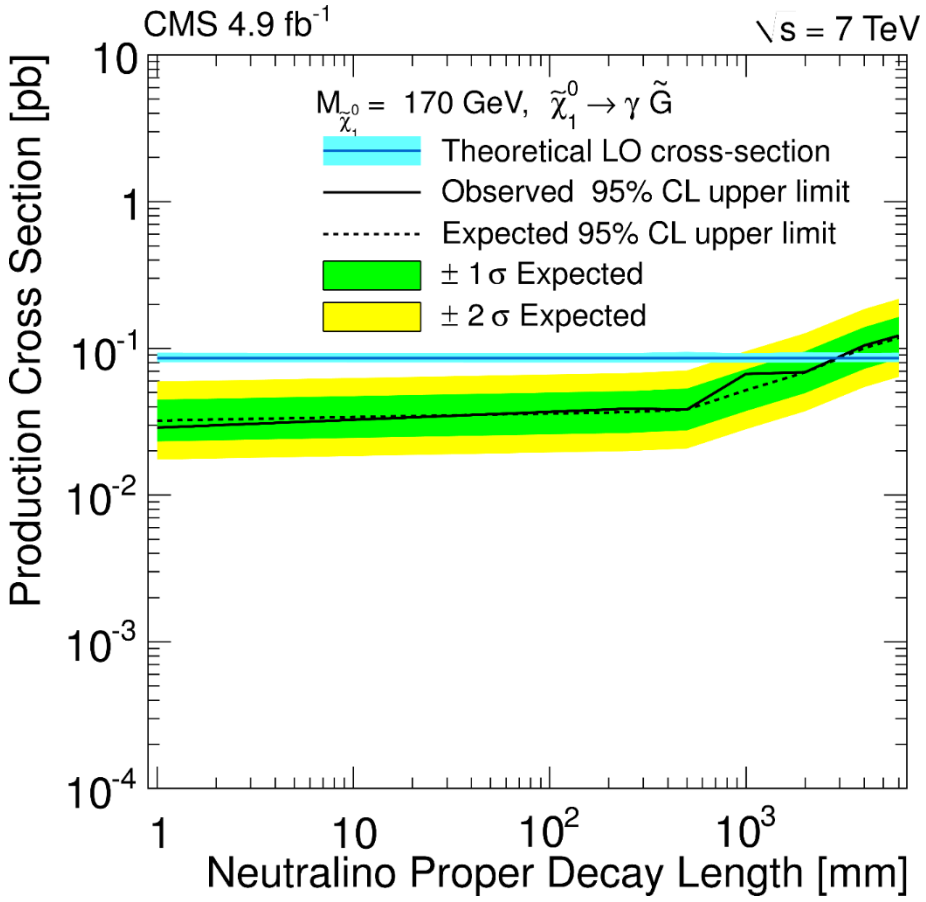

Figure 5: The 95% CL upper limits on $\sigma(\mathrm{H} \to \mathrm{XX})\mathcal{B}(\mathrm{X} \to \mu^+\mu^-)$, as a function of the mean proper decay length of the X boson, for Higgs boson masses of 125 GeV/$c^2$ (top left), 200 GeV/$c^2$ (top right), 400 GeV/$c^2$ (bottom left), and 1000 GeV/$c^2$ (bottom right). In each plot, results are

# Displaced Photons

Displaced diphotons using time of flight

But requires jets and MET…

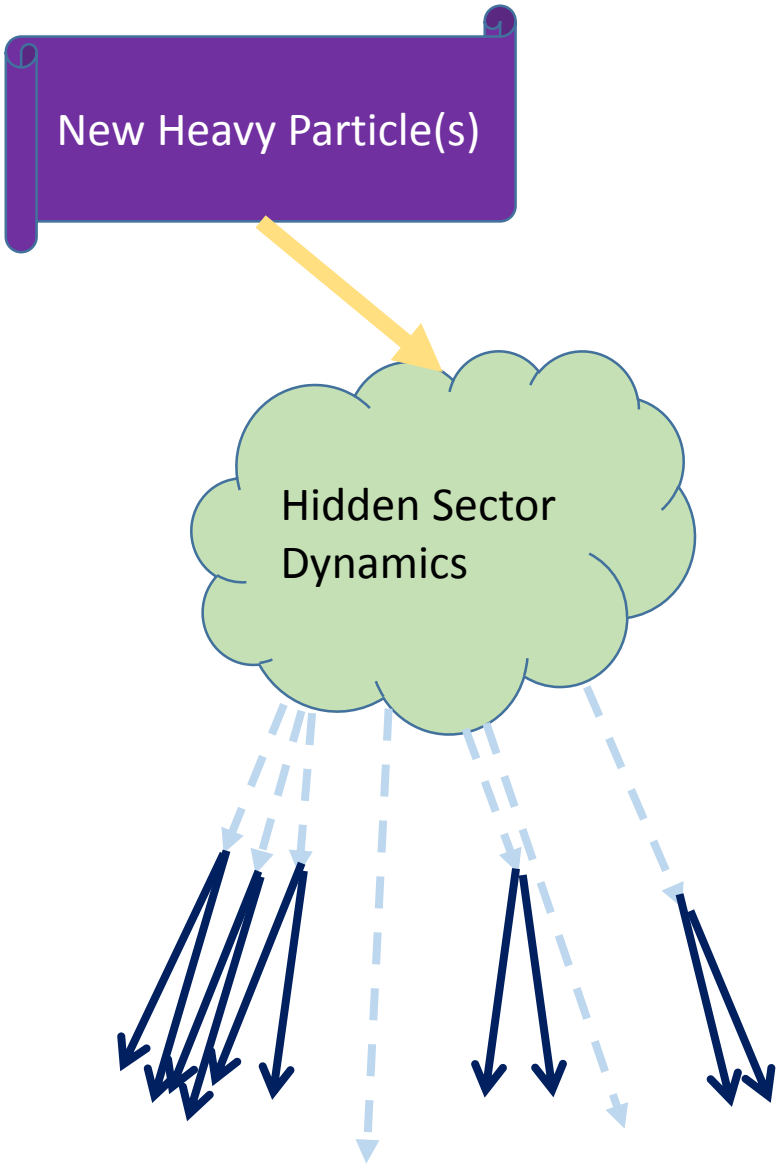
So not generally applicable…



# Searches in Unusual Conditions

Why Unusual Conditions?

- Possibly high energy or high MET
- Possibly high multiplicity
  - Possibly b-heavy
  - Possibly tau-heavy
- Possibly high boost



# Searches in Unusual Events

Prompt

- Require event with
  - High # jets (or b-jets)
  - High # non-isolated leptons
  - High S_T and/or MET
  - High [accidental] jet mass(es)
- Then search for resonance in leptons, photons, b's, etc.

- Some limits from non-resonance SUSY searches…

# Searches in Unusual Events

ATLAS-CONF-2016-052: **Search for pair production of gluinos decaying via top or bottom squarks in events with b-jets and large missing transverse momentum at** 13 **TeV with the ATLAS detector**

A search for … pair production of gluinos decaying via third-generation squarks to the lightest neutralino …The signal is searched for in events containing several energetic jets, of which at least 3 must be identified as b-jets, large MET, and, potentially, isolated electrons or muons. A topological observable formed from the mass of large-radius jets in the event is used to enhance signal discrimination. No excess is found above the predicted background. For $c_0$ masses below ~ 200 GeV, gluino masses of less than 1.89 TeV are excluded at the 95% CL in simplified models of the pair production of gluinos decaying via sbottom or stop…

- This clearly excludes some classes of HVs
  - At least 2 b pairs and MET from decay of a heavy resonance
- But why not look for a di-b resonance in these events?

# Searches in Unusual Events

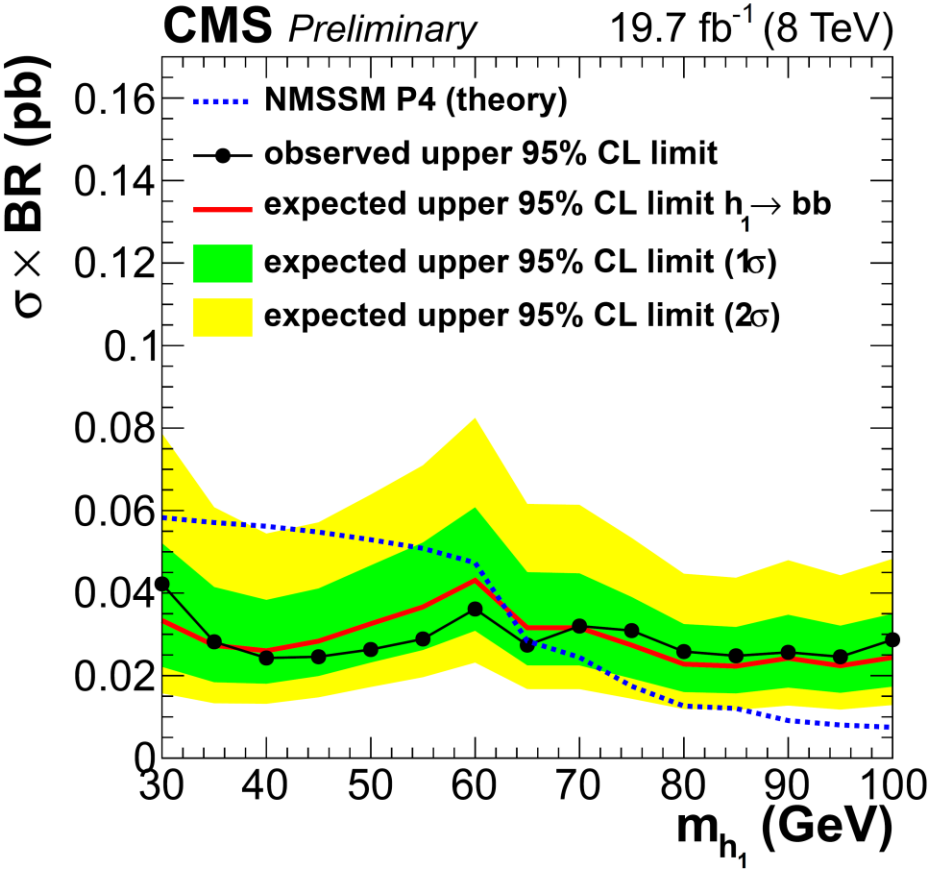
ATLAS-CONF-2016-094: **Search for new physics in a lepton plus high jet multiplicity final state with the ATLAS experiment using sqrt(s) = 13 TeV proton-proton collision data**

A search for new physics in final states characterized by high jet multiplicity, an isolated lepton (electron or muon) and either zero or at least three b-tagged jets is presented... No significant excess of events is observed … constraining supersymmetric models where the gluino is pair-produced, and decays to a pair of top quarks and jets through the R-parity violating decay of either the neutralino into three quarks or the top squark into a b- and an s- quark. In addition model-independent limits are set on the contribution of new phenomena to the signal region yields of up to 8 fb at 95% confidence level.

- This clearly excludes some classes of HVs
  - Lots of b pairs and occasional tau pairs from decay of a heavy resonance
  - With very little MET
- But why not look for a di-b resonance in these events?

# B-pair resonance in events with jets + MET

- Looking for SUSY Higgs
  - NMSSM Higgs
- Events are dramatic
  - at least two very energetic jets
  - large missing energy
- Then for 30 < m < 100 GeV, <40 fb
- But note
  - Result very model-dependent
  - No similar searches without MET
  - No searches for boosted resonance



# Easy Searches Not Yet Performed

Select events with high $S_T$/MET and/or many (b-)jets

- Search for dilepton resonance
  - Possibly non-isolated, possibly collimated
  - Possibly non-resonant with edge/endpoint
  - Challenge/Opportunity: do this systematically and optimally
- Same applies for diphoton resonance

# Searches for Unusual Composite Objects

Prompt

- complex lepton-jets (all leptons, or leptons+hadrons)
- complex photon-jets
- Accidental/nonaccidental substructure (from clustered decays)

LLPs

- Clusters of displaced lepton-jets (ATLAS LJ0)
- Clusters of displaced hadronic vertices (“Emerging jets”)
- Displaced photon jets (ATLAS LJ2)

# Exotic Decays of Known Particles

Potentially difficult due to trigger

- Higgs at Br < $10^{-(1\text{-}5)}$
- Z at Br ~ $10^{-(6\text{-}8)}$

Much easier to trigger

- W, t at Br ~ $10^{-(5\text{-}7)}$
- b (LHCb? Compete with other B factories?)

# Exotic Decays of Higgs to Prompt Final States

Our Study of Non-SM Decays of Higgs boson: 1312.4992

- Bounds relevant if Br(H → Exotic) < 0.25 or so

| | Final State Br | Total Exotic Br | Expt |
|---|---|---|---|
| h → a a → bbbb | < 1 | h → a a not constrained | ATLAS |
| h → a a → bbμμ | < 5 x $10^{-4}$ | h → a a not constrained | CMS |
| h → a a → ττμμ | < few x $10^{-4}$ | h → a a < .1 (if no a → bb) | ATLAS,CMS |
| h → a a → μμμμ | < few x $10^{-4}$ | h → a a < ~ $10^{-2}$ ($m_a$< 3 GeV) | CMS |
| h → V V → 4 leptons | < 5 x $10^{-5}$ | h → V V < 5 x $10^{-4}$ | ATLAS |
| h → a a → 4 photons | < 3 x $10^{-4}$ | Same, if a decays only to γγ | ATLAS |
| h → χχ → MET + γ | < .1 | | CMS |

Caution: Rough estimates! See the papers for detailed limits!!

- A few of these (without a mass constraint) relevant to Z decays (?)
  - No explicit searches for rare Z decays

# Exotic Decays of Higgs to LLPs

- See experimental talks from yesterday; limits still at $10^{-1}$ – $10^{-3}$ level for lifetimes in few cm to few m range,
  - but very different for jets than for leptons

- Neutral naturalness motivates aiming for $10^{-3}$ – $10^{-4}$ level across a much wider range for decays to b's and tau's

# Exotic Top/W Decays

- Trigger on lepton
- Reconstruct leptonic top
- Check decay of the other top or W
  - e.g. 5-body decays [jj][jj]c
  - e.g. [bb]c decays
  - e.g. b + [W → lepton + jets + MET]

  - Leptonic decays probably excluded by multilepton **if isolated**;
    - collimated case?
  - Photonic decays? (diphoton [collimated?] + lepton search?]

- Missing: good benchmark models

# Conclusions

- Hidden Valleys *(Interacting Dark Sectors w/ Mass Gap)* offer rich opportunities for theory, cosmo/astro and collider pheno
- LHC is sensitive to wide classes of HVs, but few dedicated searches and very few "recasts" of existing analyses, so little is known
  - Most hidden valleys are still hidden, and one may be hiding in LHC data now
- HV's predict new resonances, possibly displaced, that can be sought individually (semi-inclusively) or in pairs
- HV's predict that resonances may be produced boosted and/or clustered and/or displaced, so requiring unusual objects or events may make it much easier to find them.
- Z, W, t and especially Higgs (cf. neutral naturalness) can have non-SM decays to HVs, offering discovery opportunities
  - Warning for h, Z: **triggers!!!!!**
- More (and accurate) Monte Carlos, more benchmark models and more studies needed to motivate program of directed searches.