Exotic Higgs Decays @ 100 TeV

"BSM Physics opportunities at 100 TeV"
Workshop
@
CERN

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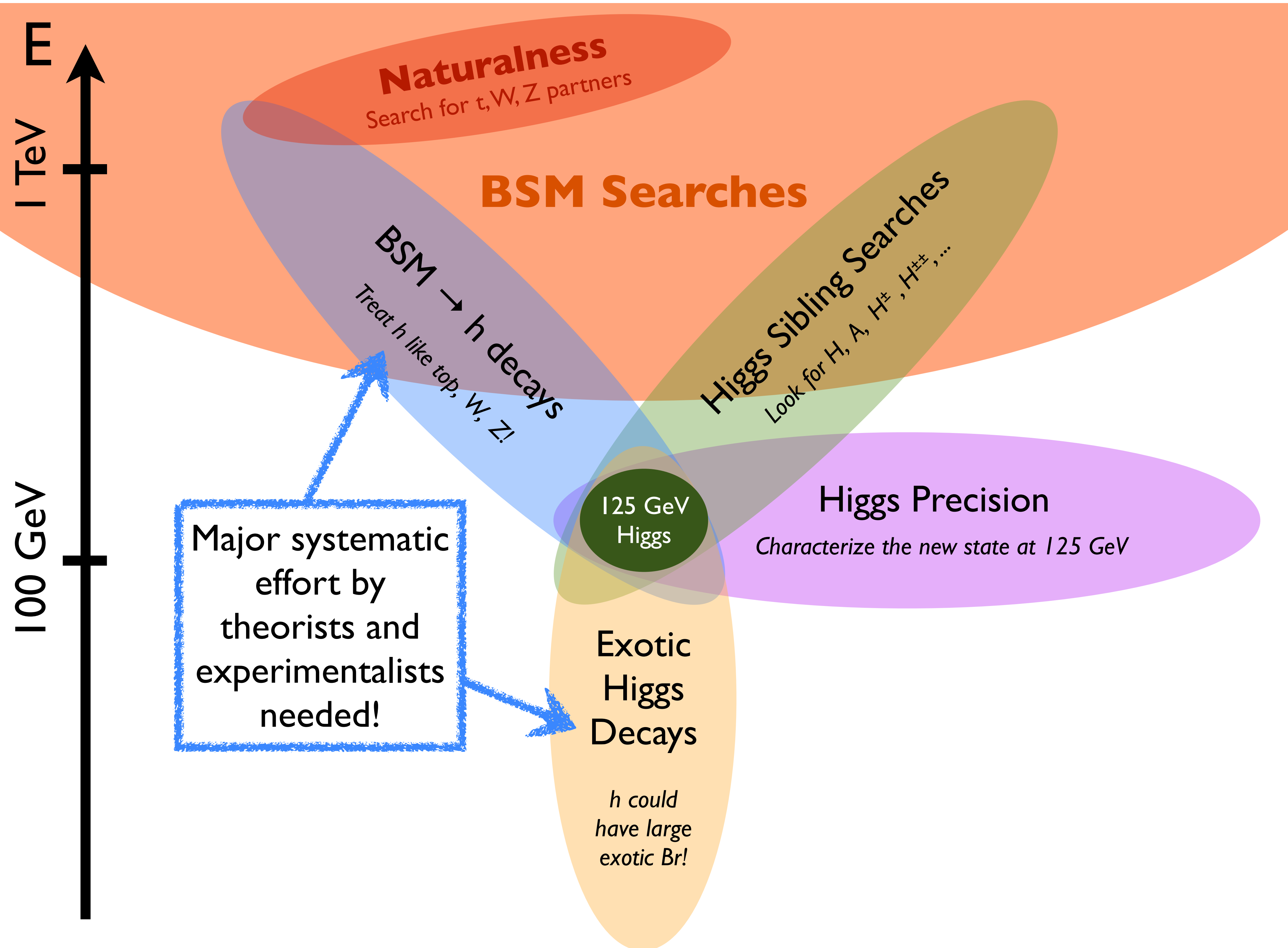
125
GeV
Higgs


E
1 TeV
100 GeV
Naturalness
Search for t, W, Z partners
BSM Searches
BSM → h decays
Treat h like top, W, Z!
Higgs Sibling Searches
Look for H, A, H±, H±±, ...
125 GeV
Higgs
Higgs Precision
Characterize the new state at 125 GeV
Major systematic effort by theorists and experimentalists needed!
Exotic Higgs Decays
h could have large exotic Br!

The Present

Exotic Higgs Decays

@

LHC

Exotic Higgs Decays

Motivation

- The couplings of the SM-like higgs will be determined by **coupling fits** with ~10% precision by the end of the LHC program.

  Br(h→invisible) can be constrained to only ~ 10% with 3000/fb

  1310.8361 Dawson et al

- Imagine an exotic higgs decay with 10% Br.

  Run 1 data could contain O(50,000) exotic higgs decays per experiment.
  Run 2: O(1 million)
  HL-LHC: O(10 million)

If we do not look, we will not find!

- Important theoretical motivations to consider exotic higgs decays:

1. The higgs width is extremely narrow (~ 4 MeV).
   Tiny couplings ~ 0.01 can give Br ~ 10%.
2. New physics can easily couple to SM via Higgs Portal $\Delta\mathcal{L} = \frac{\mu}{\Lambda^2}|H|^2\bar{\psi}\psi$ $\quad \Delta\mathcal{L} = \frac{\zeta}{2}s^2|H|^2$
3. Vast theory literature on models with light BSM sectors coupling to the Higgs.

Exotic Higgs Decays

Exotic Higgs Decays MAY be our ONLY window to new physics!

Exotic Higgs Decays

Experimental Searches

Some exotic higgs decays have been looked for by experimentalists.

ATLAS

$h \to$ di-lepton jets (2/fb)	1302.4403
$h \to$ displaced di-muon jets (2/fb)	1210.0435
$h \to$ displaced fermion pairs (2/fb)	1203.1303
$h \to 2a \to 4\gamma$ (5/fb)	ATLAS-CONF-2012-079

Good start (and more in the pipeline), but there are SO MANY possibilities.
Systematic effort needed.

Exotic Higgs Decays

Our Collaboration

Recently finished extensive survey of possible decay modes to guide experimental effort. Focus of this first document is on on Run 1 but also address Run 2.

arXiv:1312.4992

Exotic Decays of the 125 GeV Higgs Boson

David Curtin,[1] Rouven Essig,[1] Stefania Gori,[2,3,4] Prerit Jaiswal,[5] Andrey Katz,[6] Tao Liu,[7] Zhen Liu,[8] David McKeen,[9,10] Jessie Shelton,[6] Matthew Strassler,[6] Ze'ev Surujon,[1] Brock Tweedie,[8,11] and Yi-Ming Zhong[1,*]

Review literature

define simplified models

assess potential for discovery

prioritize future searches

set new constraints by recasting existing searches

exotichiggs.physics.sunysb.edu

Website contains quick summaries & will be continuously updated with new info!

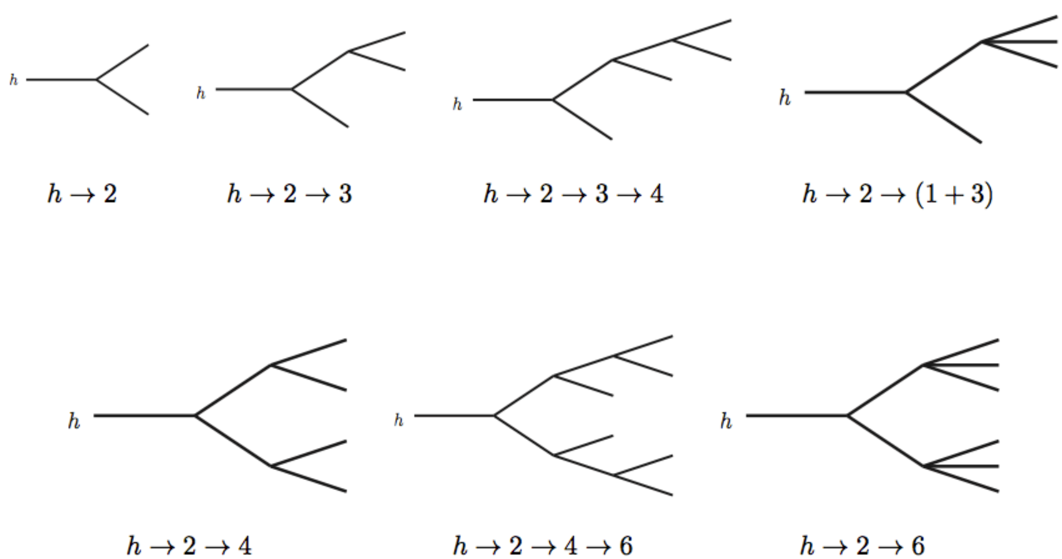
Exotic Higgs Decay Survey

What decays do we consider?

arXiv:1312.4992

To focus on those decays most likely to be discoverable at run 1 / early run 2, we made the following assumptions:

1. The 125 GeV Higgs is primarily responsible for electroweak symmetry breaking (i.e. assume we are close to alignment limit in non-minimal higgs sector models)
2. Assume the exotic decay of the 125 GeV Higgs is to **BSM particles**.
3. The initial exotic decay of the 125 GeV Higgs is **2-body.**



$h \to$ MET
$h \to 4b$
$h \to 2b2\tau$
$h \to 2b2\mu$
$h \to 4\tau, 2\tau2\mu$
$h \to 4j$
$h \to 2\gamma 2j$
$h \to 4\gamma$
$h \to Z Z_D \to 4l$
$h \to Z_D Z_D \to 4l$
$h \to \gamma$+MET
$h \to 2\gamma$+MET
$h \to 4l$+MET
$h \to 2l$+MET
$h \to$ one lepton jet
$h \to$ two lepton jets
$h \to bb$+MET
$h \to \tau\tau$+MET

Exotic Higgs Decay Survey

What models can produce exotic higgs decays?

- SM+S, 2HDM+S
  - give $h \to 2a \to 2f\ 2f'$
  - includes NMSSM (but much more varied!)

(pseudo)scalar a couplings are yukawa-ordered within each fermion family.
→ b, c, τ are the most important final states (though μ can be very helpful!)

- SM + 1 or 2 fermions
  - gives $h \to$ MET or $h \to$ 4 or 6 fermions (some can be invisible)
  - includes NMSSM in PQ-limit

very varied phenomenology and branching fractions of BSM particles.

- SM + dark vector boson
  - give $h \to Z_D Z_D$ or $Z\ Z_D \to 2f\ 2f'$
  - can get $h \to$ 8 fermions if both Z_D and dark-scalar are below $m_h/2$

(pseudo)scalar a couplings are gauge-ordered
→ spectacular lepton signals!

- Little Higgs and Hidden Valleys can give rise to many of the above

(incomplete list!)

arXiv:1312.4992

Exotic Higgs Decay Survey

Some examples of our new results

$h \to 2a \to 2b\, 2\mu$

Simple search for 2b 2μ. Full reconstruction of all 3 resonances (a, a, h)

Possible Run I limits: $Br(h \to 2b2\mu) \sim$ few x 10^{-4}
Run II: could be $< 10^{-4}$

best NMSSM $Br(h \to aa)$ limits!
~ 0.5
~ 0.2

$h \to Z_D Z_D \to 4$ leptons

Recast data from $h \to ZZ^*$ search to obtain actual limit of
$Br(Z_D Z_D \to 4$ leptons$) < 4 \times 10^{-5}$ from run I
$\Rrightarrow Br(h \to Z_D Z_D) <$ about 4×10^{-4}

Could be greatly improved with optimized analysis.

arXiv:1312.4992

Exotic Higgs Decays

Recommendations

- Several exotic higgs decays are particularly suitable for Run 1 searches, **e.g.**
  $h \to 2, 4$, more leptons, with or without MET (dark vectors, extra fermions)
  $h \to 2\mu + (2b \text{ or } 2\tau)$ for 2HDM+S type theories, including NMSSM.

- Many of these decays are **hard to trigger on**, especially at LHC14.
  Search may rely on Wh, Zh production.
  Can semi-leptonic WW trigger replace single-lepton trigger?
  May also end up using VBF triggers, parked data with lower thresholds, tth.

- Many exciting opportunities for Run 2, e.g. $h \to 2a \to 4b$, possibly $h \to 2\gamma + X$, **etc**

- Many cases we did not study in detail: decays to > 4 visible leptons, certain RPV scenarios leading to $h \to 2 \to 6$, complex lepton jets, photon jets, 3 body decays, flavor-violating decays, high multiplicity of soft particles, displaced decays, full HEFT treatment & connection to low-energy observables.

See 1312.4992 for more details!

Lots to do for Experimentalists & Theorists!

The (near?) Future

Exotic Higgs Decays

@

ILC

Higgs Precision Measurements

Future Prospects

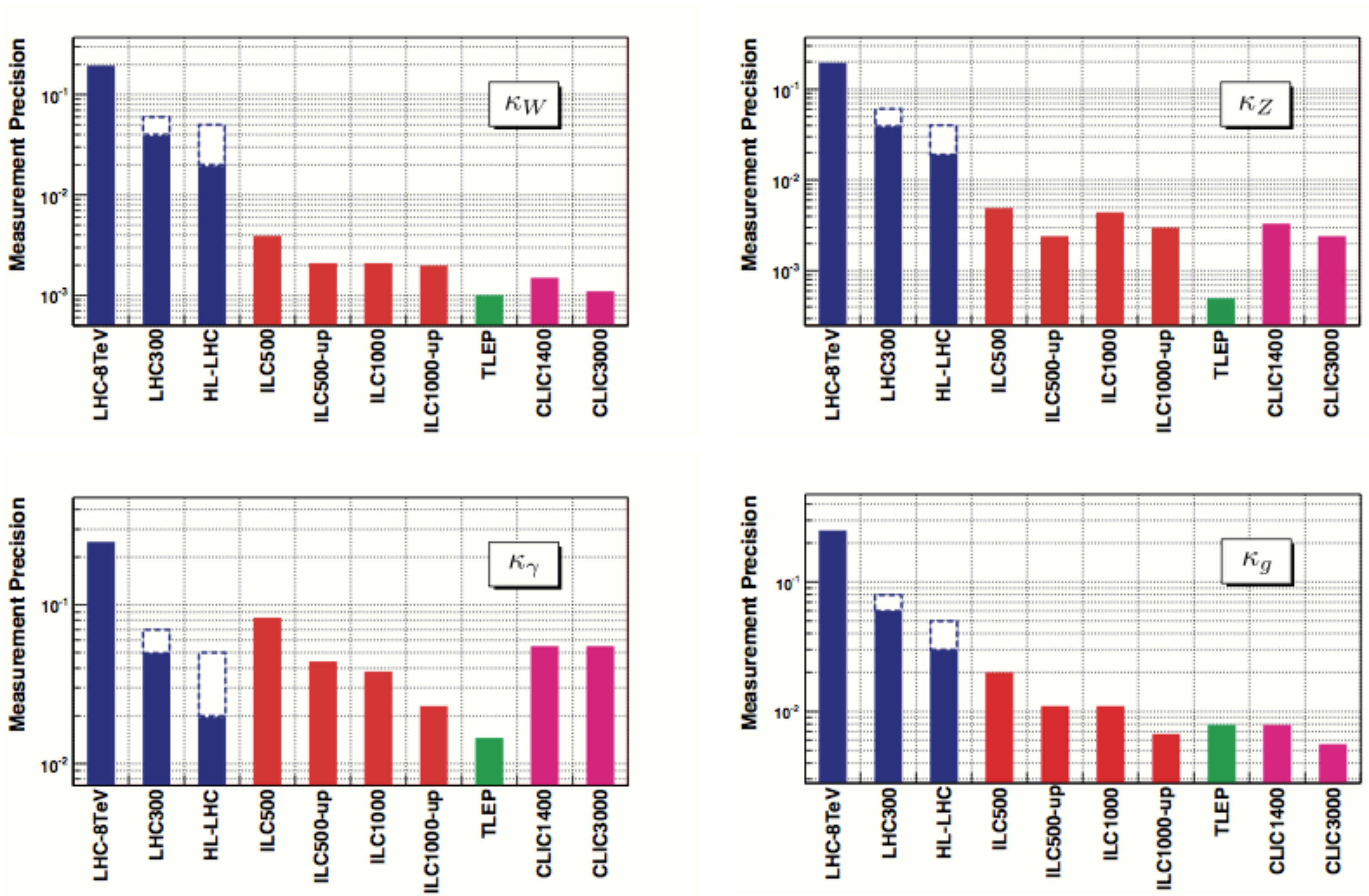


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

1310.8361 Dawson et al (Snowmass)

Constraining Exotic Decays

- The ILC is pretty much just statistics limited.

Program Name	250	500	250up	500up	1000	1000up
Energy (gev)	250	500	250	500	1000	1000
Luminosity (fb^{-1})	250	500	1150	1600	1000	2500
Nhiggs	60k	75k	300k	250k	250k	600k
Nhiggs (Zh)	60k	30k	300k	100k	15k	40

TLEP =10 x ILC(250up)

- The ILC will make O(100k) Zh events throughout its entire lifetime. This gives O(10k) 'super clean' Zh events (where $Z \to ee, \mu\mu$).

Constraining Exotic Decays

ILC gives us O(10k) ‘super clean’ Zh events (where Z $\rightarrow$ ee,μμ).

- **For purely statistics limited measurement**, an ‘invisible’ (or hard to reconstruct) exotic higgs decay can be **inferred** if

$$\mathrm{Br} \sim \frac{1}{\sqrt{N_{\mathrm{higgs}}^{(\mathrm{clean})}}}$$

$\rightarrow$ 10^{-2} sensitivity for ILC.

- A very conspicuous exotic higgs decay, on the other hand, will be **seen** if

$$\mathrm{Br} \sim \frac{\mathrm{few}}{\epsilon_{\mathrm{eff}} N_{\mathrm{higgs}}^{(\mathrm{all})}}$$

$\rightarrow$ 10^{-4} - 10^{-5} sensitivity for ILC.

benchmark
$\epsilon_{\mathrm{eff}} \sim 0.1$

Pre-100 TeV

Benchmarks

Pre-100 TeV Benchmarks

e.g.
$h \to Z_D Z_D \to 4l$

e.g.
$h \to 2a \to 4b$
or even $h \to$ jets

	E (Tev)	lumi (/fb)	N_{higgs} (all)	N_{higgs} (clean)	Br sensitivity for very **conspicuous** decays	Br sensitivity for very **difficult** decays
LHC run 1	7,8	25	500k	0	10^{-4}	O(1) or worse
LHC run 2	14	300	10 million	0	10^{-5}	O(0.1) - O(1)
HL-LHC	14	3000	100 million	0	10^{-6}	?
ILC	0.25 - 1	7000	1 million	40k	10^{-4} - 10^{-5}	10^{-2}
TLEP	0.25ish	10000	3 million	300k	10^{-5}	10^{-3}

Note that TLEP is likely 'correlated' with 100 TeV collider in its construction.

The (farther?) Future

Exotic Higgs Decays

@

100 TeV

PRELIMINARY!

What do you gain at 100 TeV?

Since higgs production is not kinematically limited even at the LHC, to 0th order you “only” gain two things when studying exotic higgs decays:

1. Ginormous Rates

2. Sci-Fi Detectors

This can of course produce qualitatively new physics results.

Which Exotic Higgs Decay?

The reach of a hadron collider depends very sensitively on the kind of exotic higgs decay mode.

$h \rightarrow ?$

easy

difficult

impossible?

4+ leptons

b-jets?

τ's?

γ's?

light jets

light jets + MET, no resonance

What helps?

leptons
resonance
photons
b-jets
taus

m_h-scale MET is not helpful at 100 TeV (in fact, it's bad)

Statistics

3000/fb of 100 TeV data gives us ~10^9 higgs particles

N(ggf)	2.3×10^9
N(VBF)	2.5×10^8
N(tth)	1.1×10^8
N(Wh)	4.7×10^7
N(Zh)	3.4×10^7
N(HH)	4.2×10^6

→ About a factor of (few x 10) more statistics than HL-LHC

→ Naively, gives us ~ 5 - 10x better Br reach, depending on BG.

For very conspicuous exotic higgs decays, could reach sensitivities

Br ~ 10^{-7} - 10^{-8}

However, this depends on choices we make for detectors etc..

Conspicuous Decays

$h \to \mu\,\tau$ is of high interest.

$h \to$ 4, 6, 8 leptons (no MET) can happen in many models.

In most models, decay to electrons is either disfavored (yukawa couplings) or on equal footing with muons (gauge couplings).

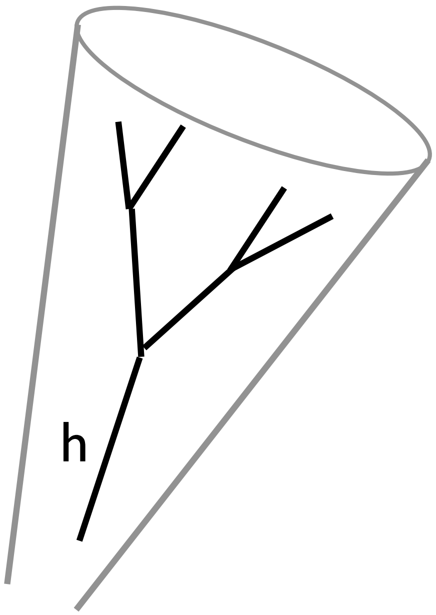
Can get away with using (almost) **only muons, but electrons would help a lot** especially for high multiplicity....

Need the detector resolution to accurately reconstruct ~30 GeV muons, even ~10 GeV for some decays.

Would also like to see softish photons...

Avoiding Systematics

Given the huge QCD background we need to make sure we avoid systematic precision limitations



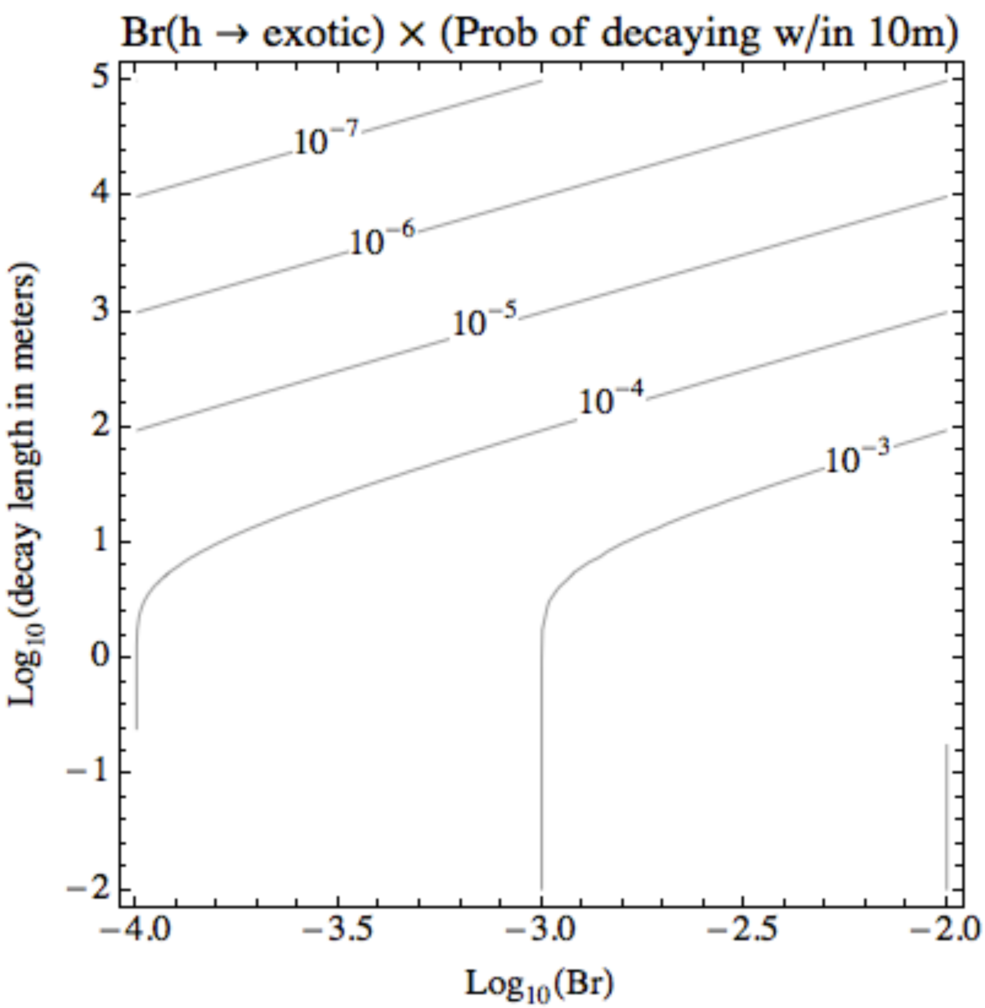
For combinatorics may have to rely on boosted higgs production

High reliance on EM objects will require BIG IMPROVEMENTS in our understanding of "**fake leptons/photons**"

May need new MC approaches...
e.g. 1306.5695 [DC, Galloway, Wacker]

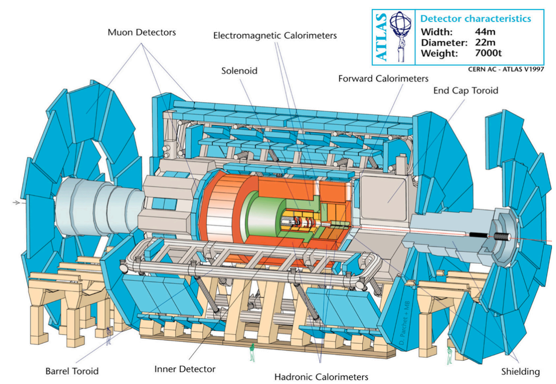
"Long" displaced decays

If tracking & triggering is precise enough, can use high rate to find relatively rare decays with naively much too long displaced vertices.



0.1% "invisible" exotic higgs decay *inferred* at TLEP could be discovered as being a decay to long-lived particles with lifetime ~ kilometers

Central vs Forward



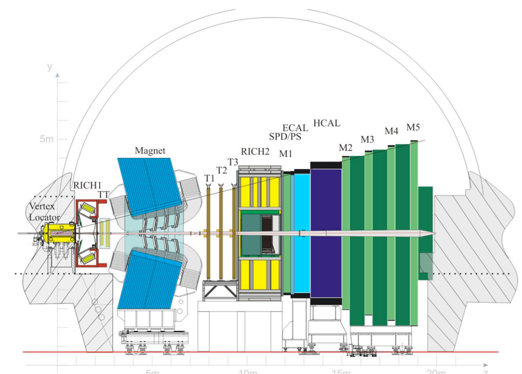
The uselessness of 'small' MET means detailed reconstruction of isolated objects becomes more important.

A forward detector covers more rapidity units per solid angle

→ can afford more instrumentation (TRACKER!)

→ better for taking advantage of huge rate

→ less focus on high-pT physics may allow better higgs reconstruction ??



Forward Detector may be the instrument of choice for exotic higgs decays!

⇛ **Think of the Higgs like a B-hadron or Tau**

- "Want to find it in isolation"
- "look for its rare decays"

100 TeV Reach

$h \rightarrow ?$

easy

difficult

4+ leptons

b-jets?

τ's?

light jets

$\boxed{\mathrm{Br} \sim 10^{-7} - 10^{-8}}$

What can we do here?

More Difficult Decays

Say the exotic higgs decay doesn't stick out like a sore thumb.

$h \rightarrow$ light jets
$h \rightarrow$ 2b+MET
...

Can high rate beat ILC?
Br ~ 1%

We need to isolate this little patch of interesting hadrons from all the other QCD activity at 100 TeV collisions.

Let's think about the **most difficult** exotic higgs decay we might realistically search for:

$h \rightarrow$ light jets (no MET)

Isolating the Higgs from QCD

With no other handles, you have to tie the hadronic exotic higgs decay to a super-taggable, non-QCD object.

Use associated production h(Z→ll), but concentrate on case where Z and h are collinear.

Higgs Signal

BG for hadronic higgs decay

collinearity does not reduce BG

Isolating the Higgs from QCD

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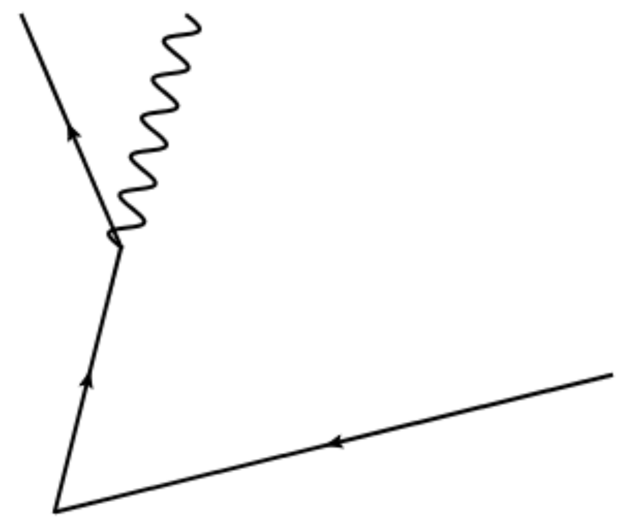

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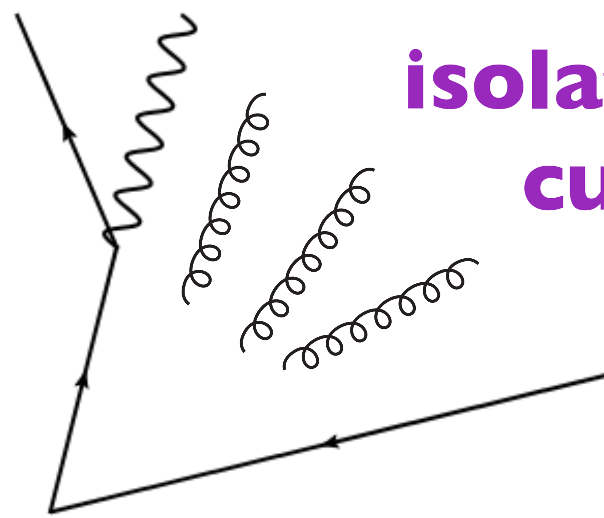
Higgs Signal

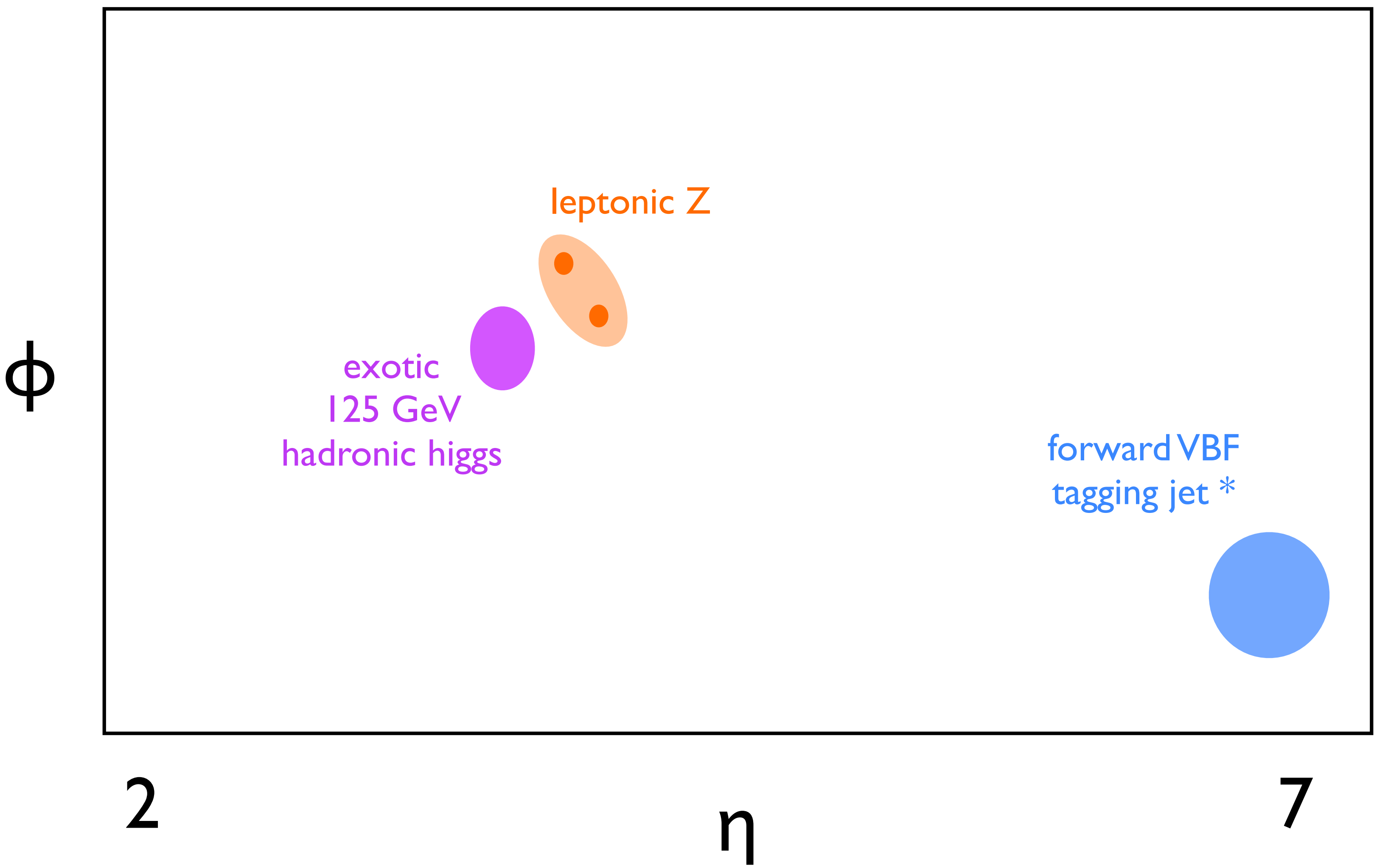
BG for hadronic higgs decay



isolation cut

Isolating the Higgs from QCD

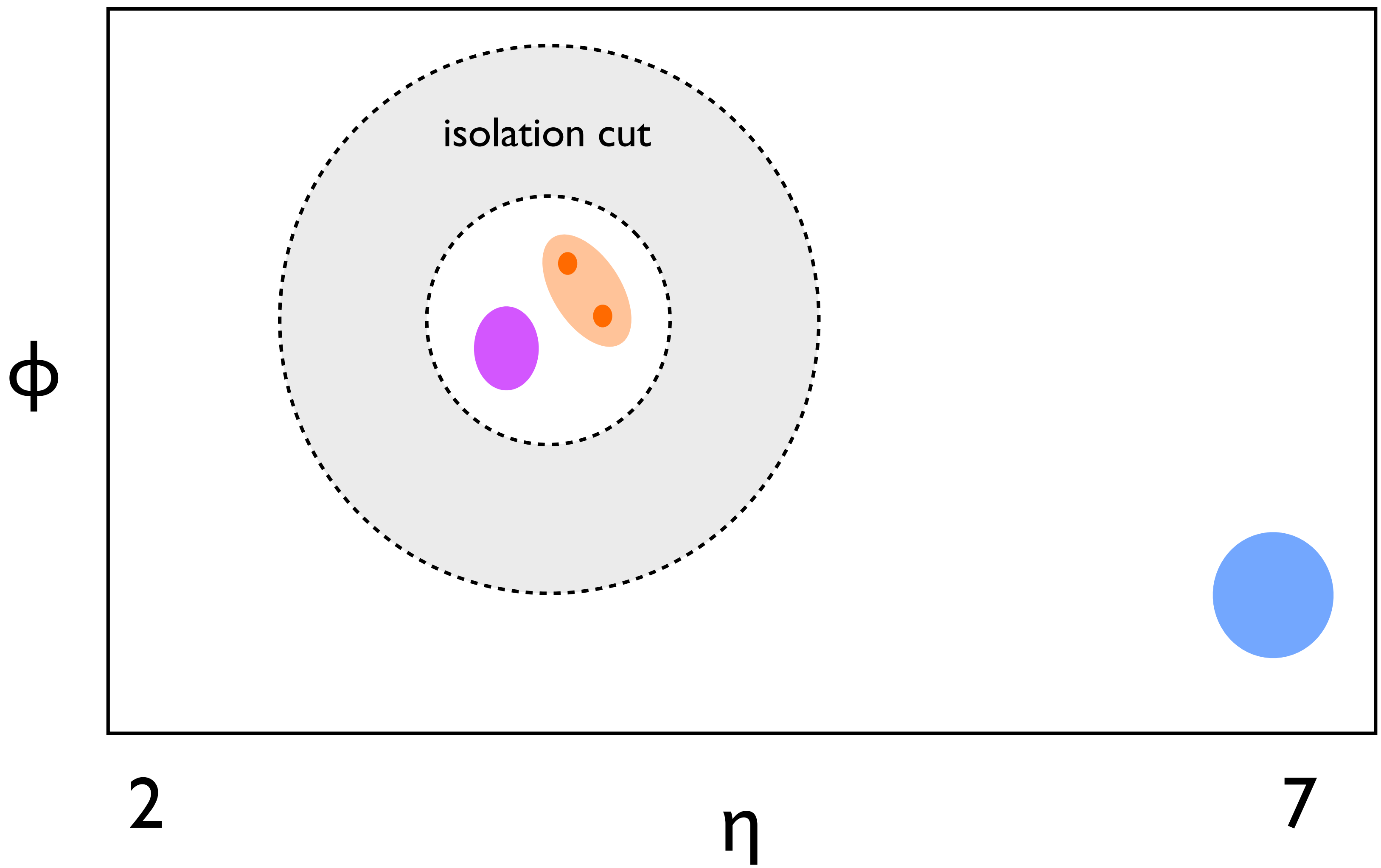
Signal Event (VBF production of $Z^* \to Zh$)



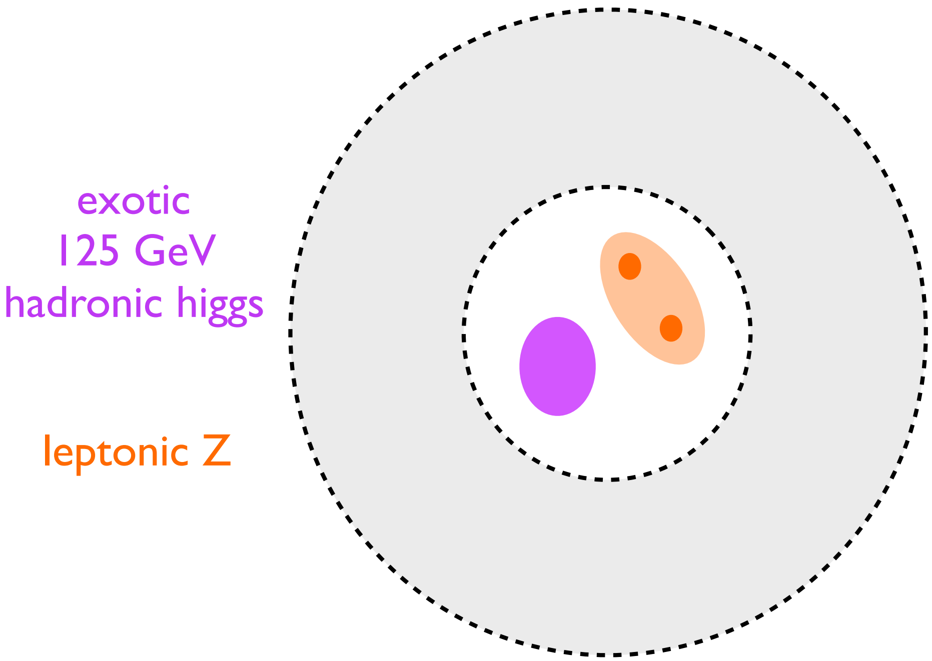
* softer than Zh system

Isolating the Higgs from QCD

Signal Event (VBF production of Z*→Zh)



Isolating the Higgs from QCD



This may be the
best object to look
(and even trigger?)
on for the 'least conspicuous'
exotic higgs decays.

Primitive MC Study

To get a feeling for kinematics perform a *very* simple parton-level MC study in MadGraph.

Does not capture isolation cut, jet mass cut, or anything else we might do to identify the hadronic-higgs candidate.

It does allow us to estimate available statistics to study such difficult decays

(more complete study in progress)

Primitive MC Study

Simulate VBF (jj) + Zh Signal vs jjj + Z background

$\sigma \sim$ pb $\sigma \sim$ O(100) pb (some generator level cuts)

Look for leptonic Z (pT > 50 GeV), h (pT > 200 GeV)
Z, h collinear ($\Delta R < 0.5$) and (Zh) isolated ($\Delta R < 1.5$)

Forward study ($2 < \eta < 7$):
single VBF tagging jet that is softer than Z, h

Central study ($|\eta| < 2.5$):
look for two VBF tagging jets

Forward study somewhat better. For leptonic Z and **1% exotic higgs Br**, get O(10k) signal events to play with. **Similar to ILC**.

Could get $S/\sqrt{B} \sim 1$ IF
- get factor of 10 BG rejection from higgs-candidate jet mass cut
- get factor of 10-100 BG rejection from Zh-ISOLATION CUT

MIGHT work. Needs dedicated studies.

Can a hadron collider beat ILC?

For the WORST kind of exotic higgs decay that's remotely possible (light jets, no MET), 100 TeV MAY be in the same ballpark as ILC.

If the decay has **any** additional features (photons, b-jets) we can use other, higher-rate processes or looser cuts to increase statistics → **beat ILC**

If the decay is very conspicuous, 100 TeV blows ILC out of the water.

Reach

$h \to ?$

easy → difficult

impossible?

light jets + MET, no resonance

4+ leptons

b-jets?

γ's?

τ's?

light jets

Br ~ 10^{-2}

(?)

Br ~ 10^{-2}

Br ~ 10^{-3}

Br ~ 10^{-4} ILC

Br ~ 10^{-5} TLEP

Br ~ 10^{-7} - 10^{-8} 100 TeV

Implications for Exotic Higgs Models

Fermionic Higgs Portal

$$\Delta\mathcal{L} = \frac{\mu}{\Lambda^2}|H|^2\bar{\psi}\psi$$

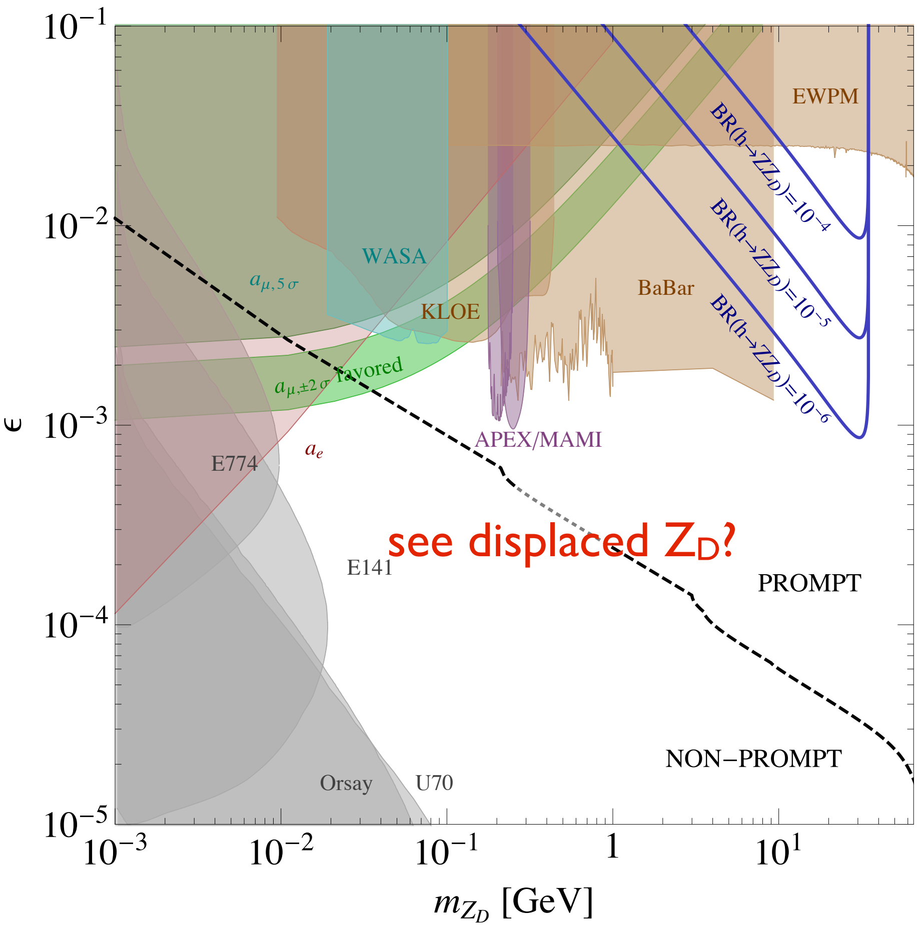
Br ~ 10^{-7} for $\mu \sim m_\psi$ would suggest $\Lambda \sim 20$ TeV

Correlate exotic higgs decay discovery with new EW-strength physics with masses that might be produced at 100 TeV collider?

Dark Vectors

Light dark vectors give decays like $h \to Z_d Z_d$, $Z Z_d \to 4$ leptons

If the decay is through gauge kinetic mixing, we could beat indirect constraints in a kinematic region that is difficult to explore in low-energy colliders.



If the decay is through dark higgs mixing, we could probe higgs mixings of ~ 10^{-5}

Light Scalars

2HDM+S or SM+S theories: often get e.g. $h \to 2a \to 4b$ decays

should be able to do significantly better than the worst case scenario.

if we can detect $Br(h \to 4b) \sim 10^{-4}$, this gives us access to couplings of $g_{haa}/v \sim 10^{-4}$.

NMSSM R-sym limit: $g_{haa} \sim \mathcal{O}\left(m_h^2/v_S^2\right) \times v$

Would point to $v_s \sim 10$ TeV.

Again an interesting scale for direct production at a 100 TeV collider?

Conclusions

Conclusions

e.g.
$h \to Z_D Z_D \to 4l$

e.g.
$h \to 2a \to 4b$
or even $h \to$ jets

	E (Tev)	lumi (/fb)	N_{higgs} (all)	N_{higgs} (clean)	Br sensitivity for very **conspicuous** decays	Br sensitivity for very **difficult** decays
LHC run 1	7,8	25	500k	0	10^{-4}	O(1) or worse
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ILC	0.25 - 1	7000	1 million	40k	10^{-4} - 10^{-5}	10^{-2}
TLEP	0.25ish	10000	3 million	300k	10^{-5}	10^{-3}
100 TeV	100	3000	few billion	0	10^{-7} - 10^{-8}	10^{-2} ????

Likely extremely dependent on details of decay!

Conclusions

A 100 TeV 3000/fb program could find conspicuous rare higgs decays with Br as low as 10^{-7} or maybe even 10^{-8}.

This may correlate with other **high-mass** measurements/discoveries possible at 100 TeV.

For very difficult decays, the ILC is hard to beat. But as long as there's any interesting feature in the higgs decay (apart from MET), 100 TeV could beat ILC. (*This may even apply to purely hadronic final states if sophisticated substructure techniques are applied.*)

but... TLEP > ILC, and TLEP construction is likely correlated with 100 TeV construction!

Experimental Challenges:
- high-resolution low-energy reconstruction!
- arbitrary displaced vertices?

Treating the higgs like a B-hadron and studying it somehow in isolation may yield other analysis approaches.

Needs further studies!