Exotic Physics at the LHC

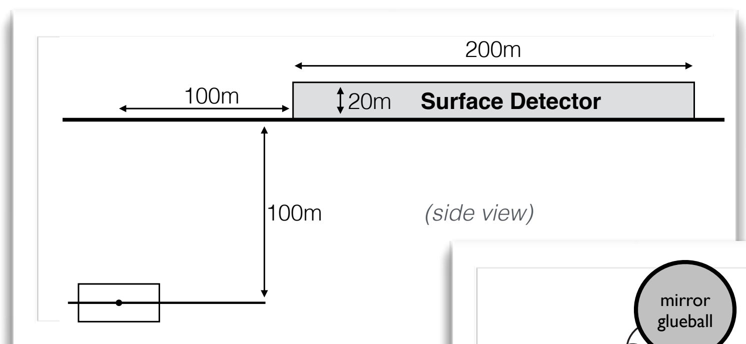
(and connections to Multi-Boson Physics)

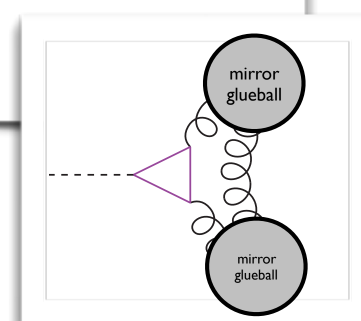
Multi-Boson Interaction Workshop

University of Wisconsin - Madison

26. August 2016

David Curtin
University of Maryland





Exotics & MBI Physics

New Physics is either ‘around the corner’ or not obvious.

Finding its traces could require very precise SM precision measurements.

Electroweak measurements have a rich history of setting New Physics constraints.

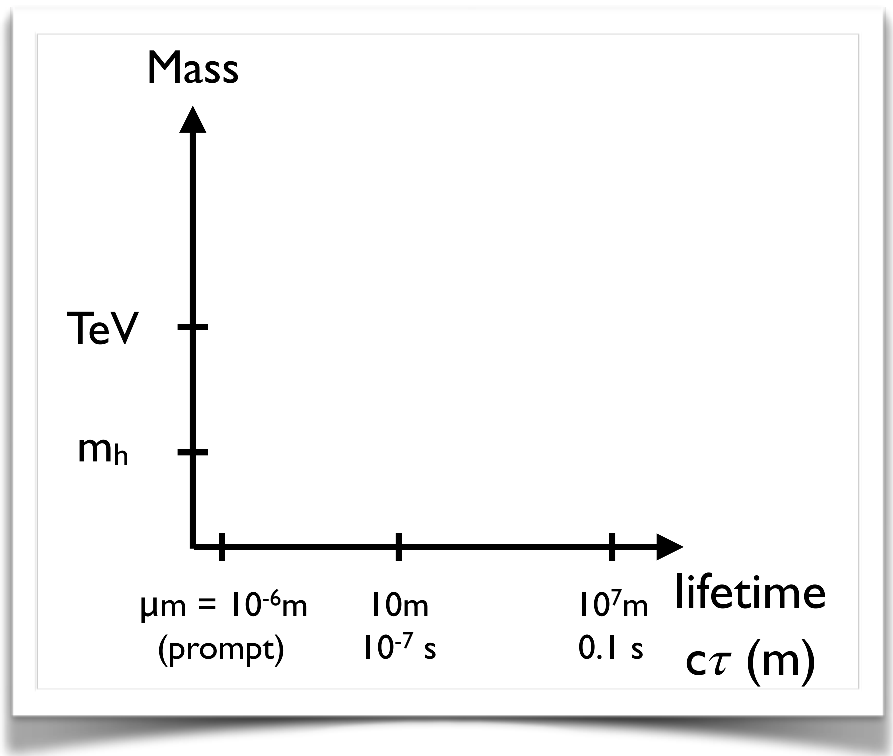
As we go up in energy, MBI measurements provide BSM sensitivity in new ways.

Exotics & MBI Physics

New Physics is either 'around the corner' or not obvious.

Need to expand "Reach" in every direction, including searches for long-lived particles.

In some cases, triggers on (multi-)boson production are the only inclusive way of capturing these signals.



Outline

— Exotics Medley —

1. Electroweak Baryogenesis *(Higgs self coupling!)*

2. Neutral Naturalness *(Long-Lived Particles!)*

3. Long-Lived Particle Searches at the LHC

4. The MATHUSLA Experiment *(Really Long-Lived Particles!)*

Electroweak Baryogenesis

DC, Meade, Yu 1409.0005

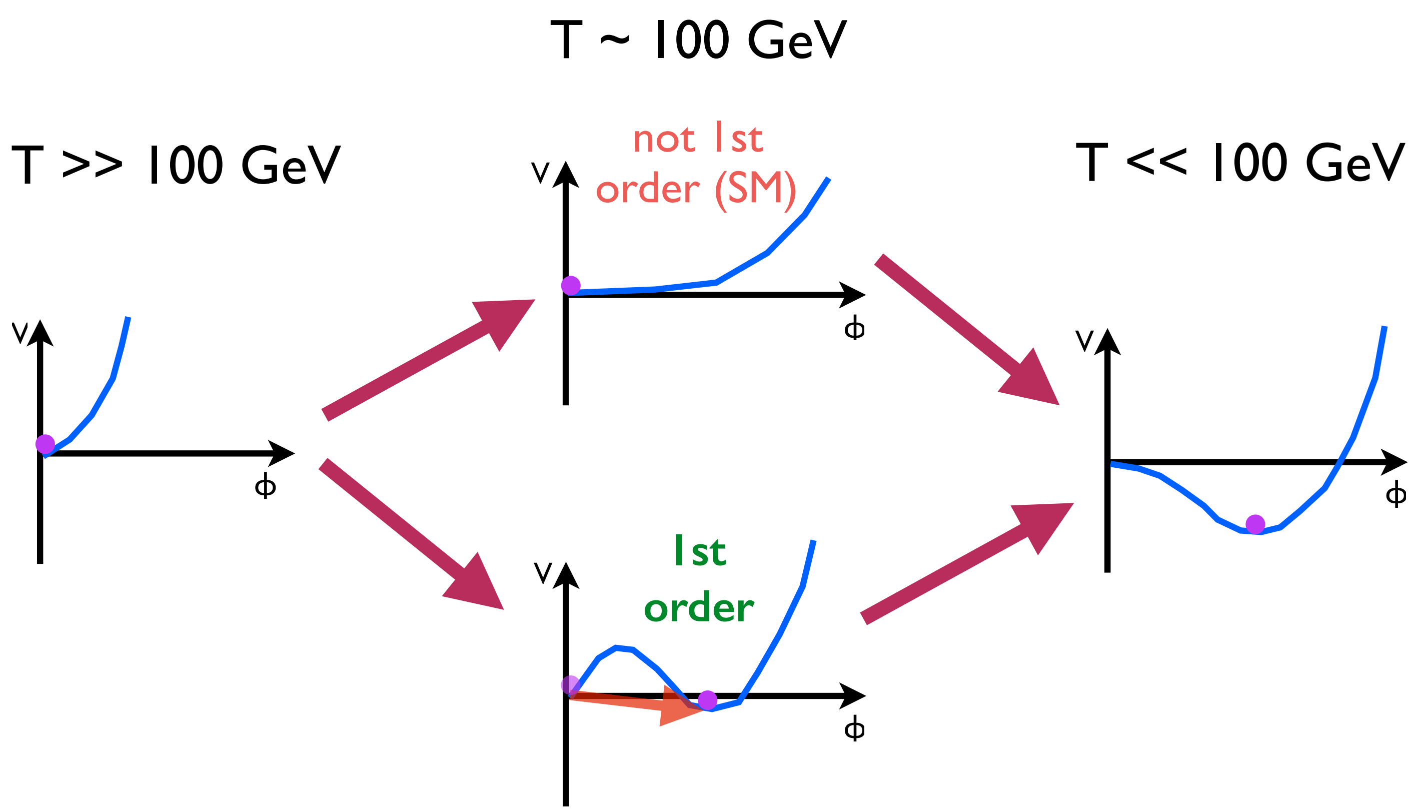
DC, Jaiswal, Meade 1203.2932

DC, Meade, Ramani, 1610.XXXXX

Electroweak Baryogenesis

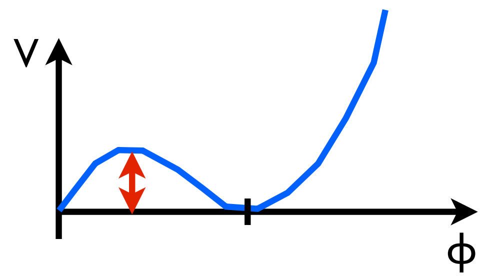
Dynamical creation of baryon number in early universe requires departure from thermal equilibrium.

BSM effects on Higgs Potential can make the electroweak phase transition at T ~ 100 GeV strongly first order.



Achieving a strong PT

How to modify SM to generate energy barrier?



1. New O(100 GeV) <u>bosonic</u> BSM states

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T)$$

tree-level potential

loop correction

finite temperature corrections

2. Zero-Temperature tree- or loop-effects (generate barrier or reduce depth of potential well)

Detecting EWBG

Crucial measurement to determine shape of Higgs potential:
Higgs self coupling!

Likely requires **100 TeV collider** for precise measurement.

Will also require greater theoretical understanding of hh production at pp colliders!

e.g.
Dawson, Ismail, Low 1504.05596; Dawson, Lewis 1508.05397;
Kanemura, Kikuchi, Yagyu 1608.01582, 1511.06211;
Degrassi, Giardino, Gröber, 1603.00385;
….

Achieving a strong PT

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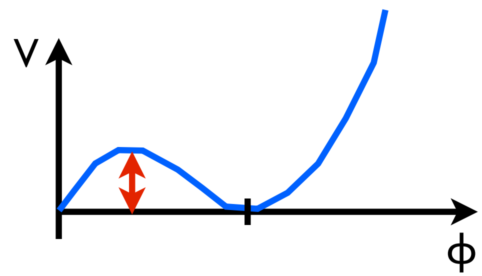

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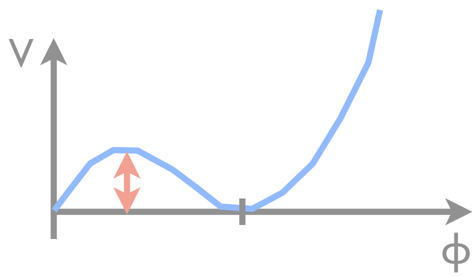

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$$V_{\text{eff}}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T)$$

tree-level potential | loop correction | finite temperature corrections

2. Zero-Temperature tree- or loop-effects (generate barrier or reduce depth of potential well)

1. How to realize these possibilities?
Probe mechanisms, not individual models!

2. Can we (always?) discover each mechanism at colliders?

A continuum of theories

real scalar with
unbroken Z_2 symmetry

$$\delta V_0 = \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{HS} |H|^2 S^2$$

More scalars, doublets, etc…

General single real scalar

hardest!

Difficulty of experimental verification

more signatures..

Higgs-Singlet mixing leads to variety of signatures

absence of mixing removes most signatures

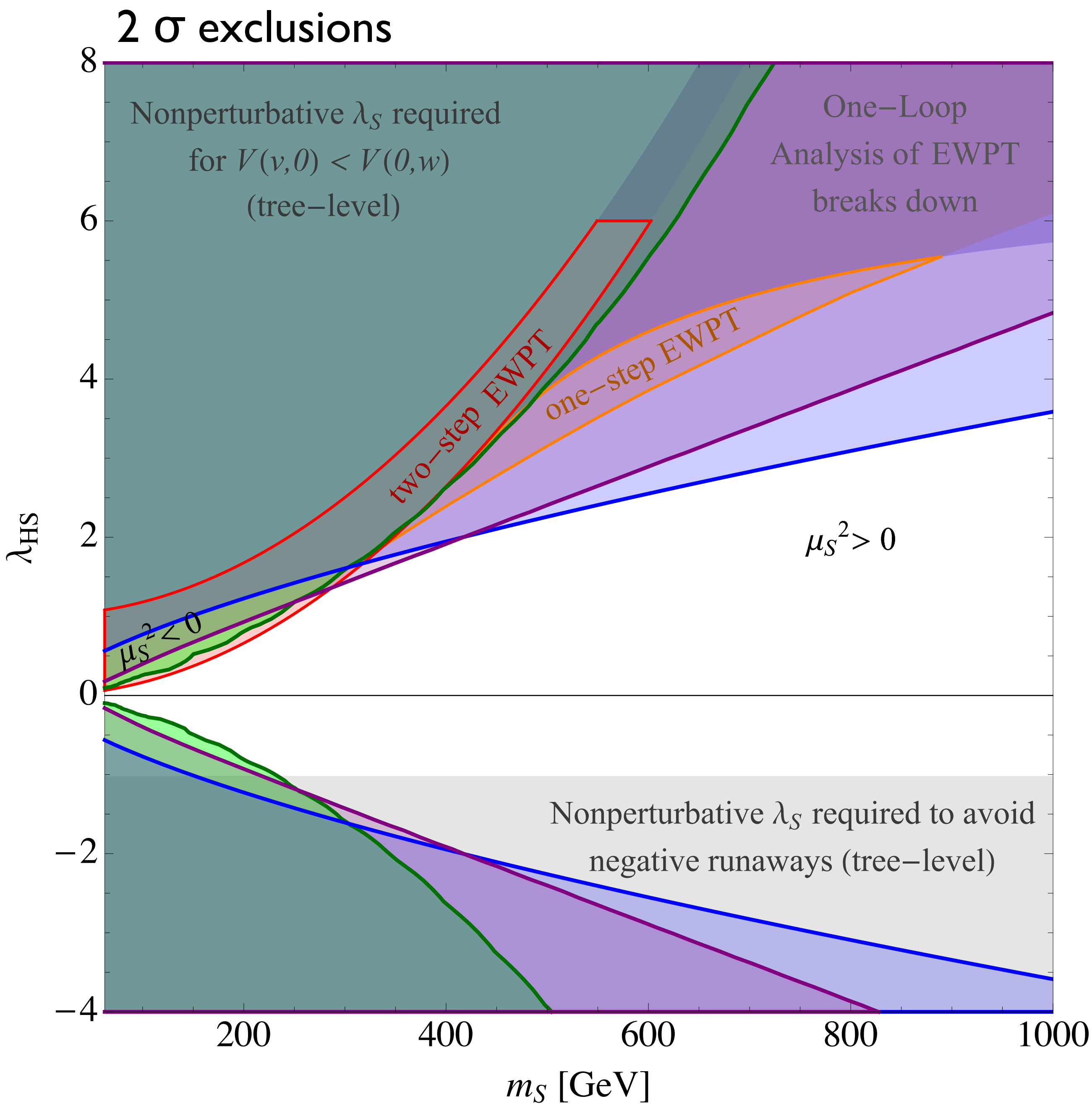
Will **probably** be discovered at LHC or future colliders *(more work needed)*

Parameter space much simpler.
Can you construct a no-lose theorem?

Phenomenological No-Lose Theorem for EWBG in Z_2 singlet extension

DC, Meade, Yu 1409.0005

EWPT in SM+S



100 TeV Collider, 30/ab

triple-Higgs coupling measurement (> 10%)

Direct detection of VBF h* → SS
($S/\sqrt{B}$ > 2)

TLEP

$\delta\sigma_{Zh}$ measurement (> 0.3%)

100 TeV collider could cover *entire* parameter space.

TLEP can cover *almost all* of parameter space.

Potential complimentarily!

Theoretical Challenges

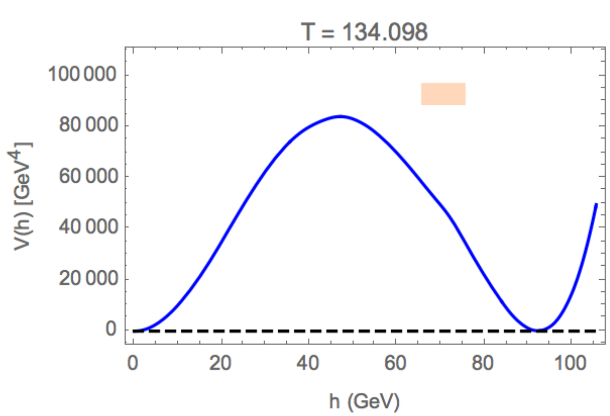
Another challenge:

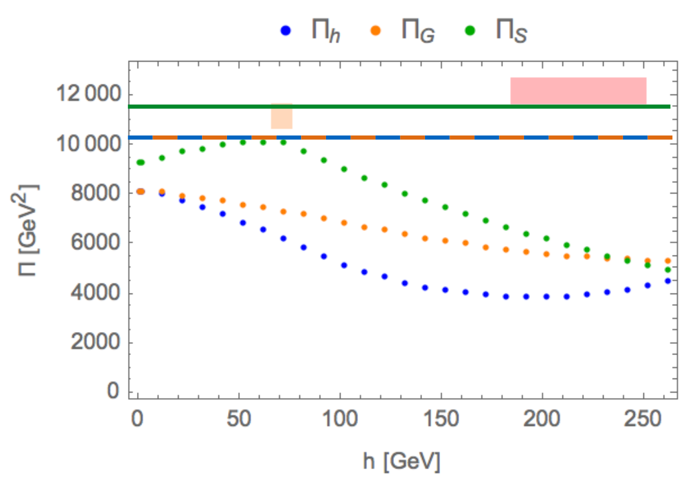
Theoretical control of the finite-temperature calculation.
Matching to Effective Theories at zero temperature.

Solved: consistent finite-T resummation of thermal mass effects!

DC, Meade, Ramani, 1610.XXXXX

Will affect correlation of PT to collider observables.
Also has consequences for leptogenesis.

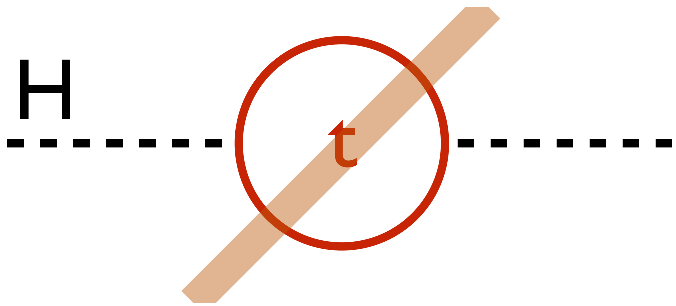


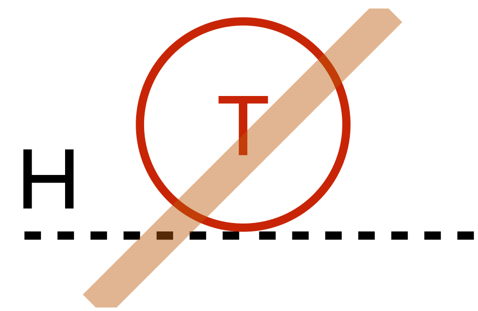


Let’s talk about weird LHC signatures..

Neutral Naturalness

The Hierarchy Problem





… can be solved by top partners

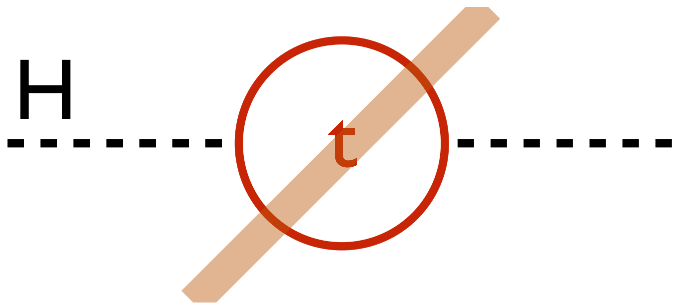
top quark t $\xrightarrow{\text{continuous symmetry}}$ top partner T

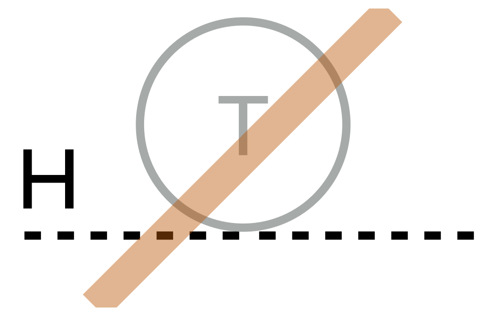
carries
color charge

e.g.

Supersymmetry*, modern* ***composite Higgs*** *models (Little Higgs), etc…*

The Hierarchy Problem





The symmetry need not commute with SM color!

top quark t $\xrightarrow{\text{continuous symmetry}}$

$\downarrow$ discrete symmetry

top partner T

COLOR NEUTRAL!

e.g.

Folded SUSY *(EW-charged stops)*, ***Twin Higgs*** *(SM singlet T-partners)*

hep-ph/0609152 Burdman, Chacko, Goh, Harnik

hep-ph/0506256 Chacko, Goh, Harnik

The Hierarchy Problem

H

The

Top partners are SM-uncolored!

(Hence avoid LHC constraints)

New BSM QCD’ gauge force!

Naturalness motivation for Hidden Valleys!

top partner T

e.g.

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hep-ph/0609152 Burdman, Chacko, Goh, Harnik

hep-ph/0506256 Chacko, Goh, Harnik

LLPs in Neutral Naturalness

Scenario with Simplest Pheno:

(FSUSY, QLH, some FTH)

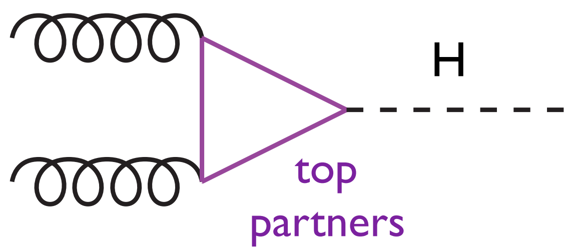
top partners

maybe other states

QCD' glueballs
$< \sim$ 60 GeV

Higgs talks to mirror glue via top partner loops:

$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2}\, H^\dagger H \,\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

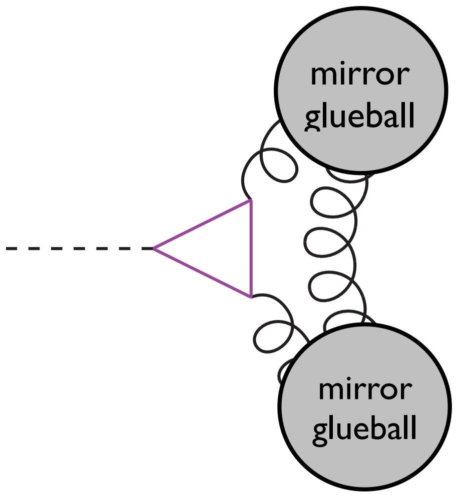


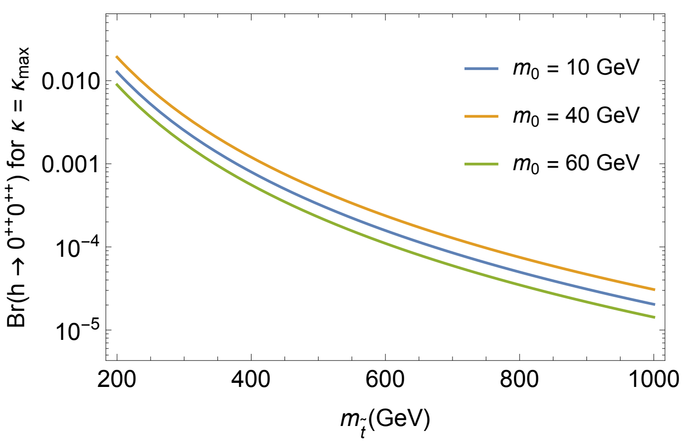
Craig, Katz, Strassler, Sundrum 1501.05310

DC, Verhaaren 1506.06141

LLPs in Neutral Naturalness

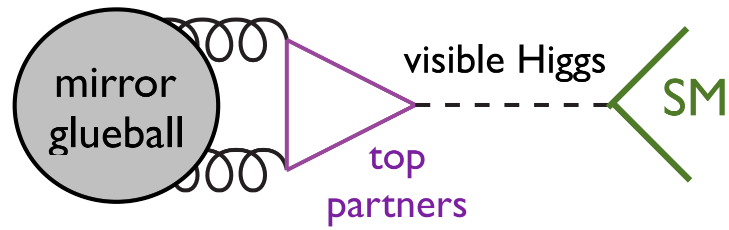
Can produce lots of glueballs in Exotic Higgs Decays:

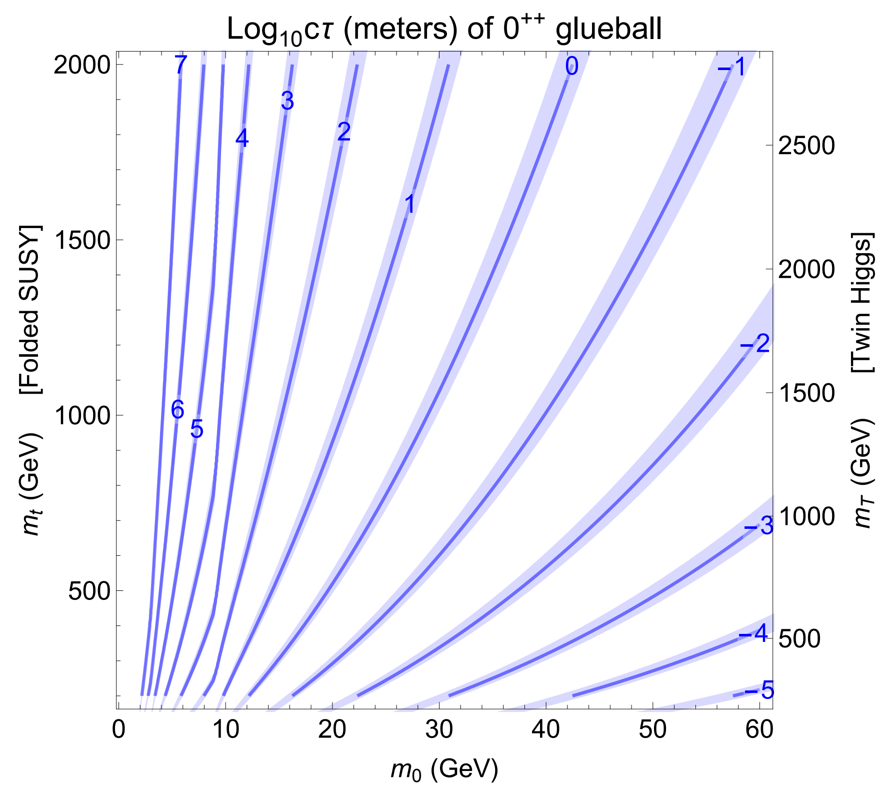




Craig, Katz, Strassler, Sundrum 1501.05310
DC, Verhaaren 1506.06141

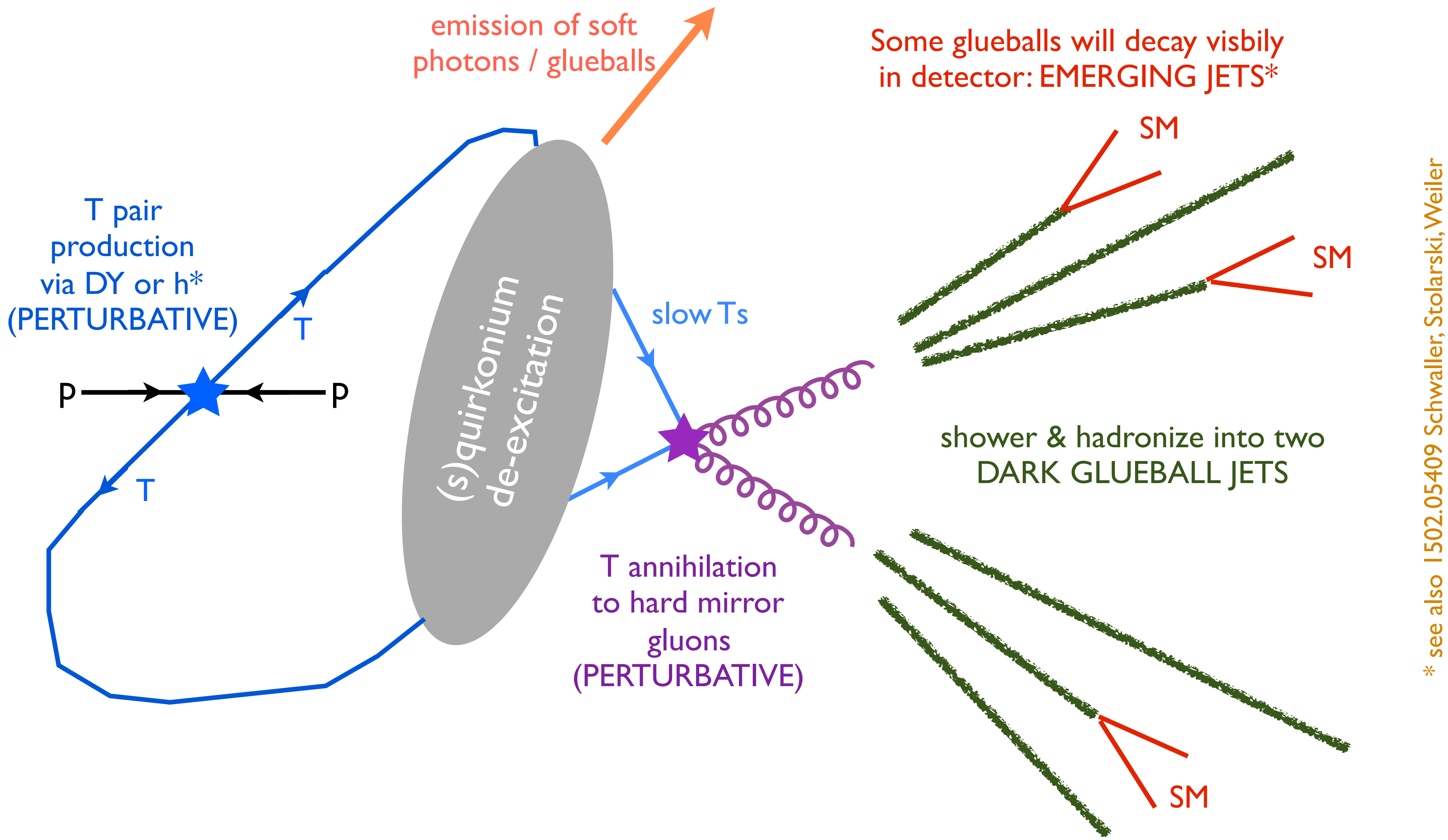
Glueballs are LLPs!





→ Striking displaced decay signatures!

Quirks in Neutral Naturalness



Chacko, DC, Verhaaren, 1512.05782

Chacko, DC, Verhaaren, 16XX.XXXXX

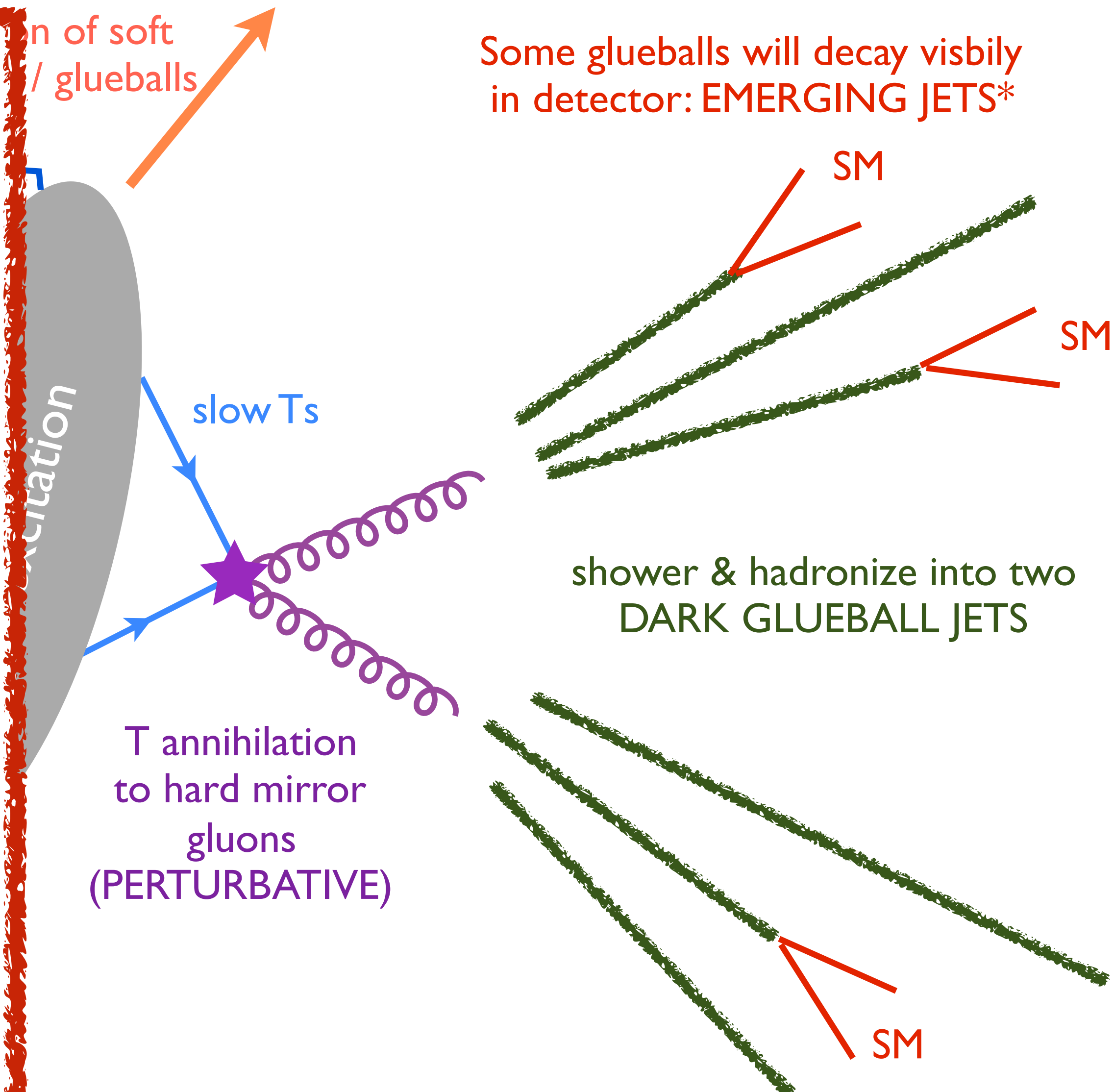
Can give complicated/spectacular multi-LLP signals

Quirks in Neutral Naturalness

Quirk annihilation is also a promising source of **Di-Bosons Signals!**

Would be vital in precise mass & coupling determination

→ Nailing down Neutral Naturalness Mechanism!



Can give complicated/spectacular multi-LLP signals

* see also 1502.05409 Schwaller, Stolarski, Weiler

Chacko, DC, Verhaaren, 1512.05782

Chacko, DC, Verhaaren, 16XX.XXXXX

Neutral Naturalness is just one motivation for…

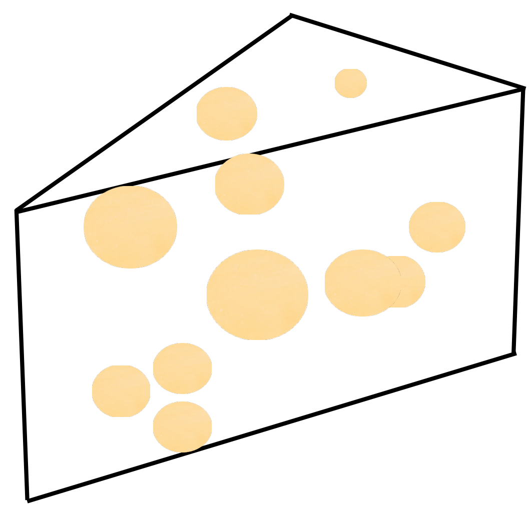
Long-Lived Particle Searches

Neutral Naturalness is just one motivation for…

Long-Lived Particle Searches

not yet

more like



LLP Searches

Existing LLP searches at ATLAS or CMS either

- look for distinctive LLP decay products (leptons)
- look for 'hard' LLPs in tracker (high mass/p_T)
- look for **2** decays, at least 1 in Muon System/HCAL *(longish lifetime)*

More work needed! Currently missing sensitivity to low-scale LLP production (e.g. Higgs), especially hadronic LLP decays.

Most important new searches that are required/feasible:

1. searches for a single LLP in tracker + VBF/lepton
   this will give sensitivity to LLP production in ***exotic Higgs decays***
2. searches for LLPs with very short lifetimes
   re-purpose b-taggers!
3. searches for LLPs with very long lifetimes
   single decay in outer detector subsystems

LLP Searches

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Need to examine inclusive VBF/Vh Higgs production!

More work need[illegible]sing sensitivity to low-scale LLP production (e.g. Hig[illegible]ecially hadronic LLP decays.

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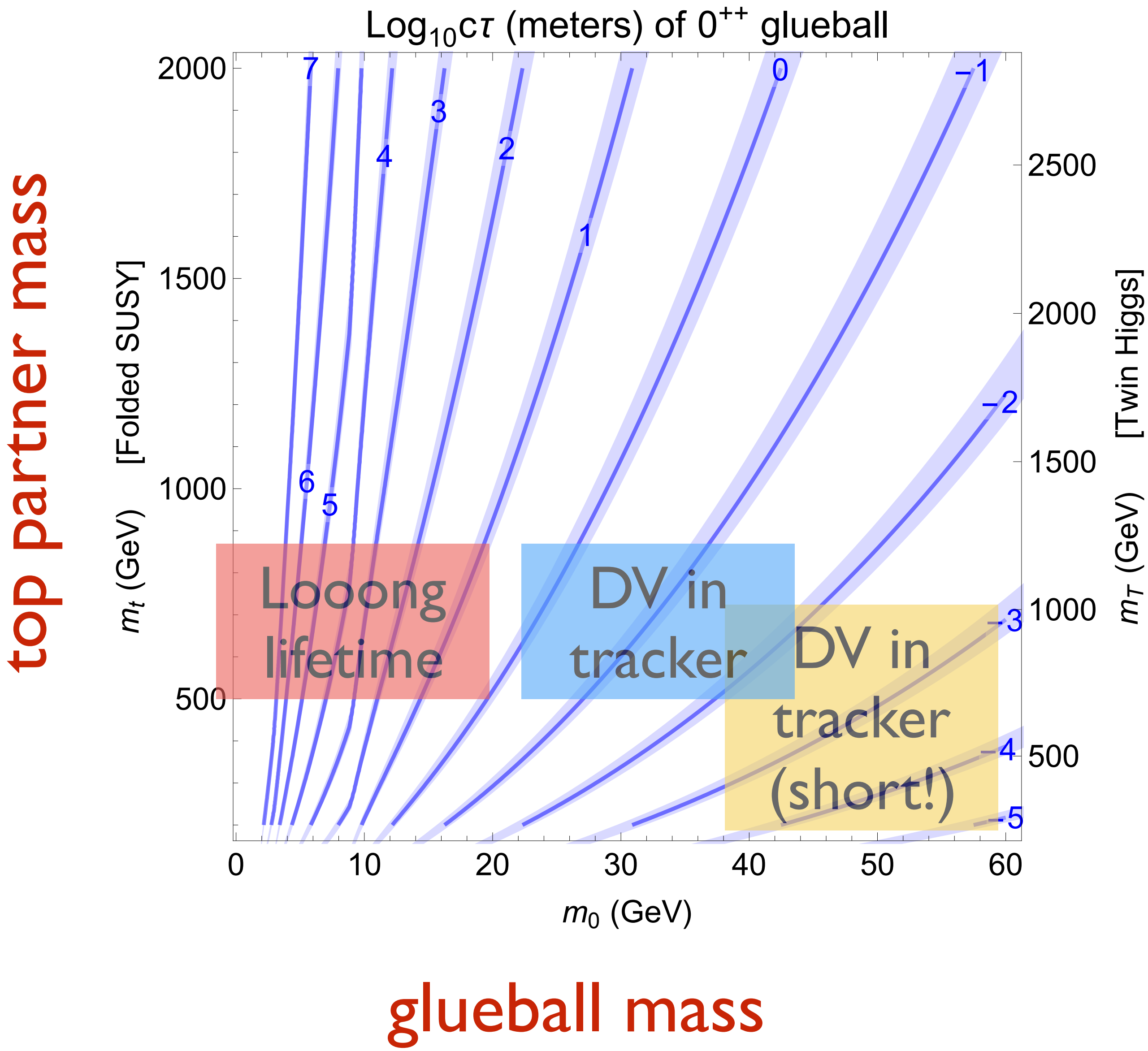
Neutral Naturalness @ HL-LHC

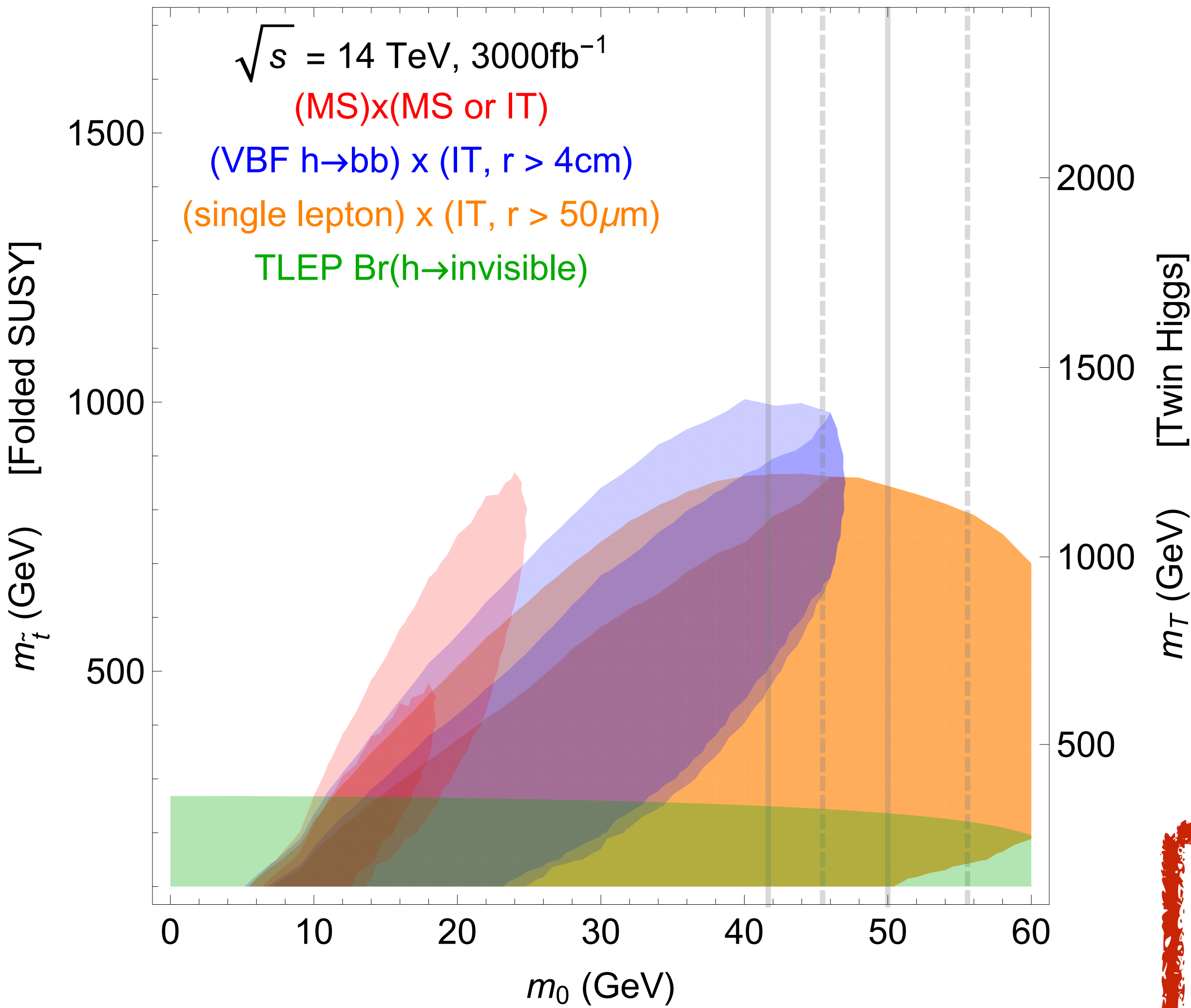


Need entire array of LLP search strategies to cover parameter space

DC, Verhaaren 1506.06141

Neutral Naturalness @ HL-LHC

top partner mass



glueball mass

DV searches in tracker* or Muon System

*need VBF or lepton for triggering.

TeV Top Partner Mass Reach from LLP searches!

DC, Verhaaren 1506.06141

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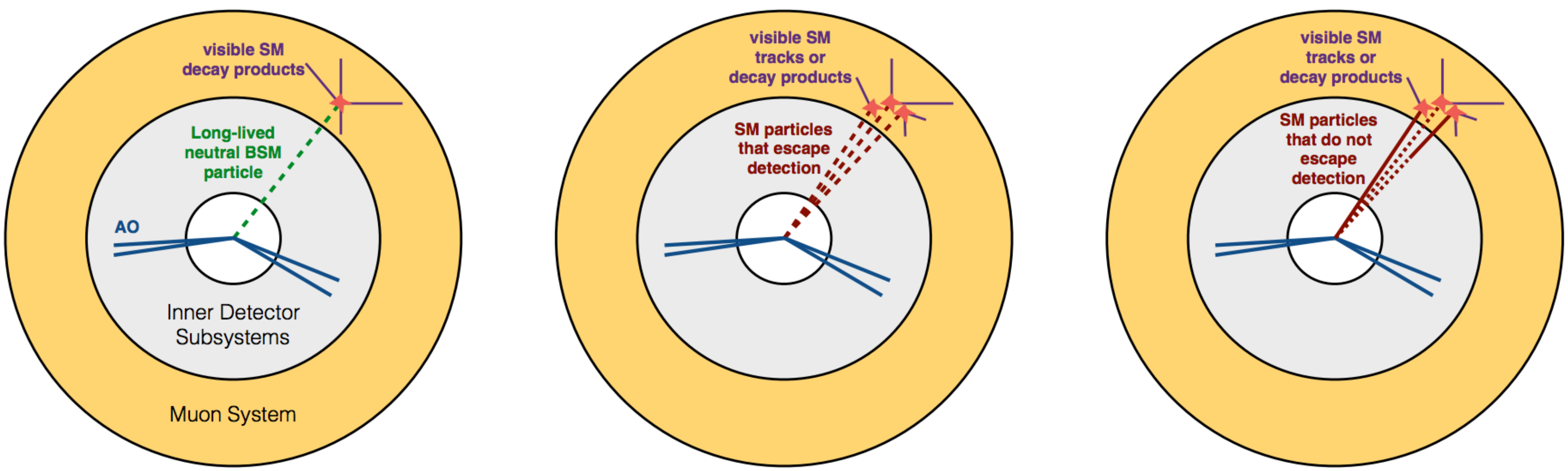
LLP Search for Long Lifetimes

Probably the best we can do at the LHC:
search for a single DV in the ATLAS Muon System.



Signal Trigger
iso event from BSM
(a)

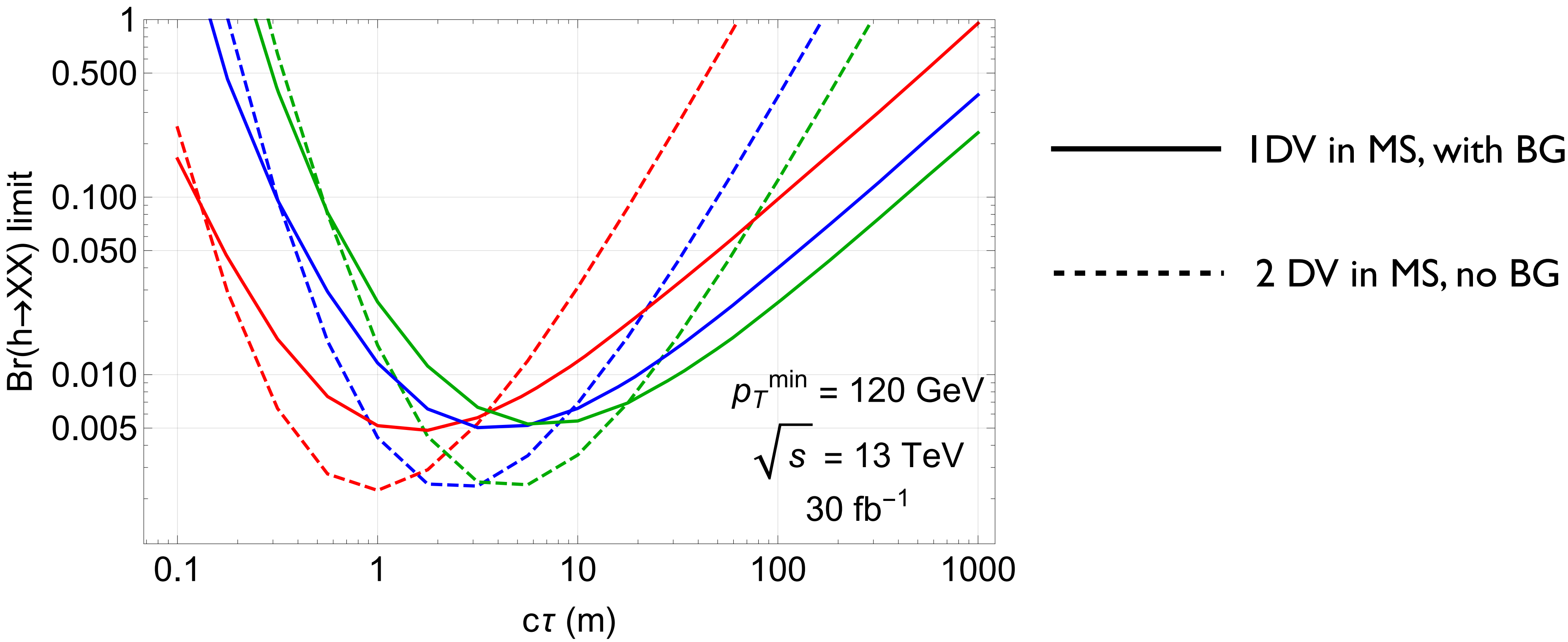
Signal Trigger
iso event from SM QCD
(b)

Orthogonal Trigger
non-iso event from SM QCD
(c)

Very challenging search! Have to obtain fully differential data-driven background estimates.

1605.02742 Andrea Coccaro, DC, Henry Lubatti, Heather Russell, Jessie Shelton

Projected Sensitivities: single DV in ATLAS MS



Projected limits of 1DV in MS search far superior at **long lifetimes** compared to existing 2DV search.

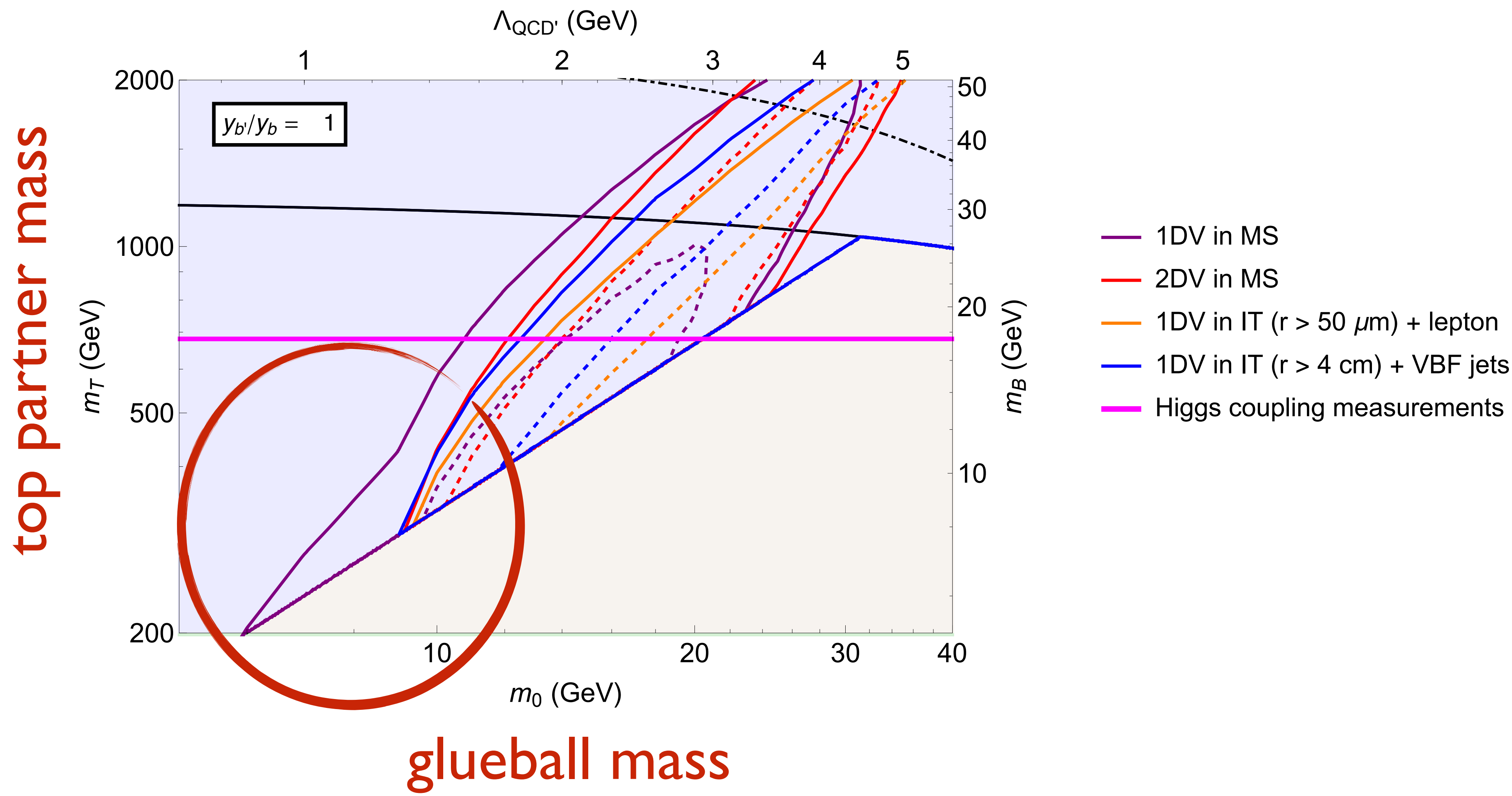
Hopefully will be implemented at run 2!

1605.02742 Andrea Coccaro, DC, Henry Lubatti, Heather Russell, Jessie Shelton

Resulting Neutral Naturalness Sensitivity

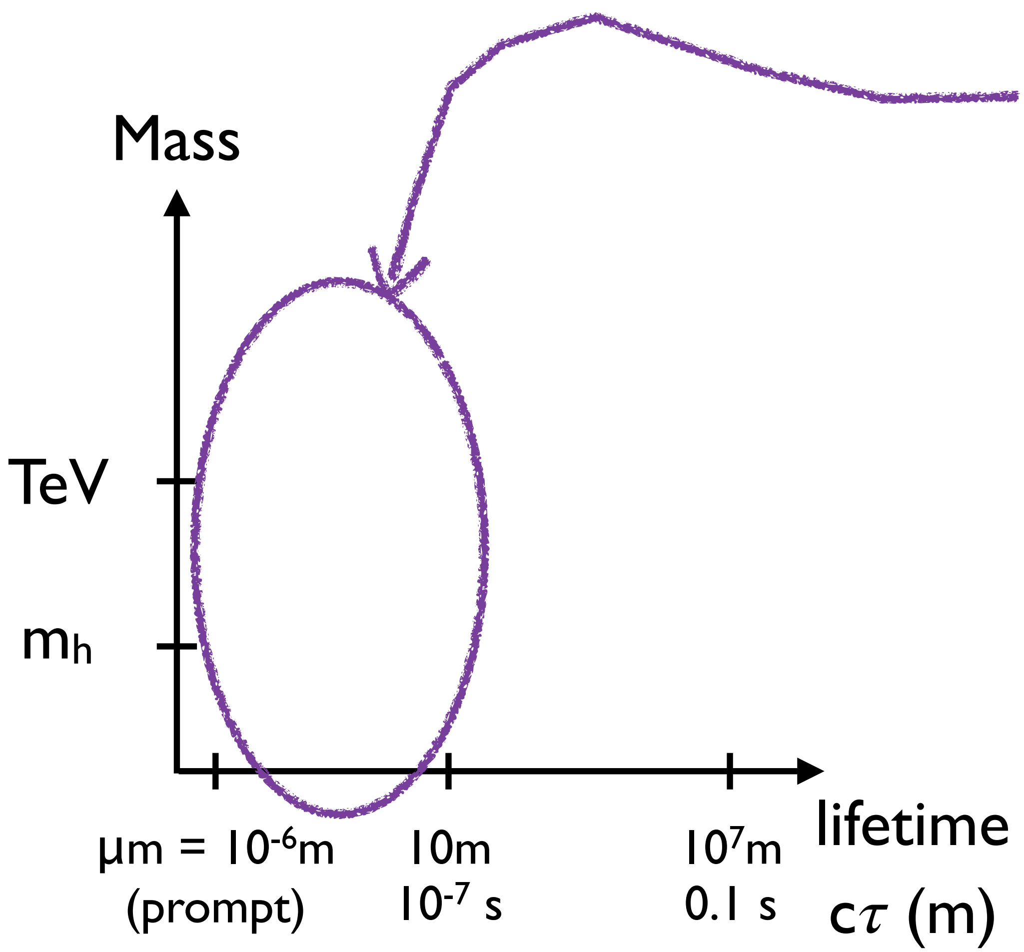
Twin Higgs

1605.02742 Andrea Coccaro, DC, Henry Lubatti, Heather Russell, Jessie Shelton



Allows us to probe ~ 5 GeV Glueballs! (very long-lived)

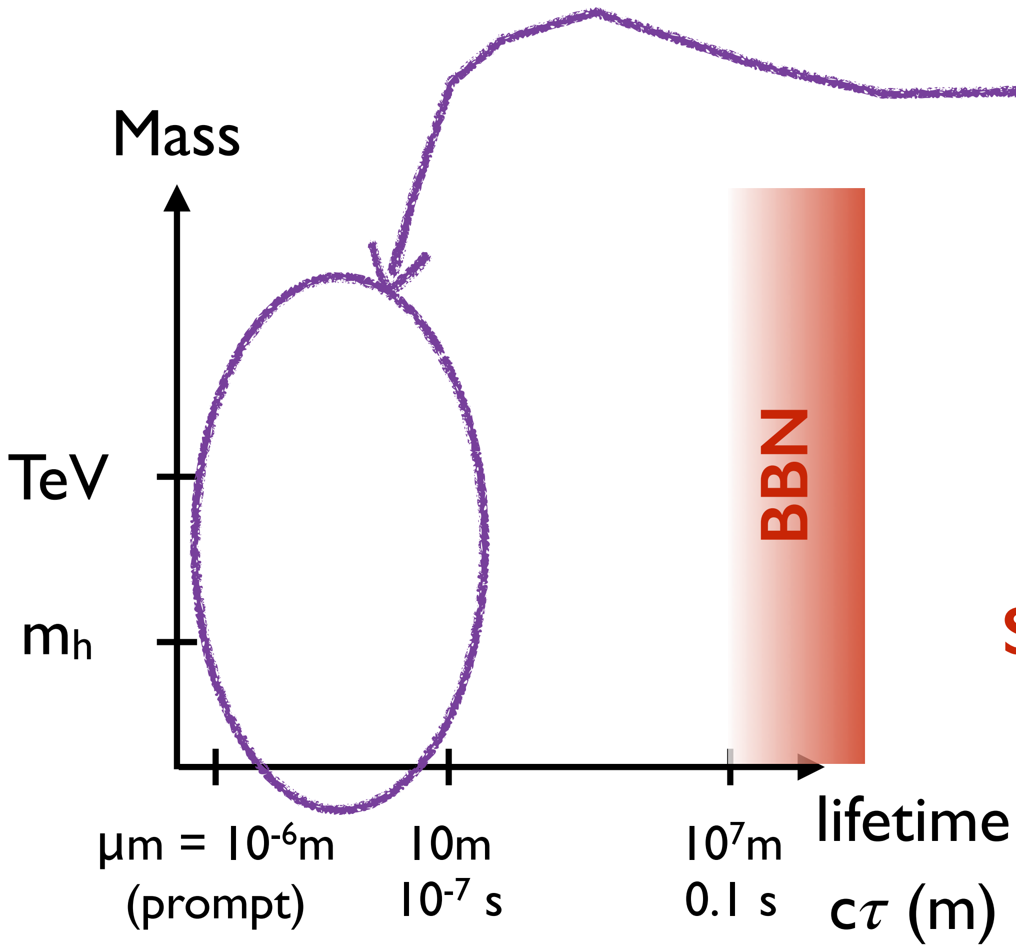
Reach in BSM particle lifetime



LLP searches can be conducted at various colliders, but they are very challenging!

→ Significant Recent Progress!

Reach in BSM particle lifetime



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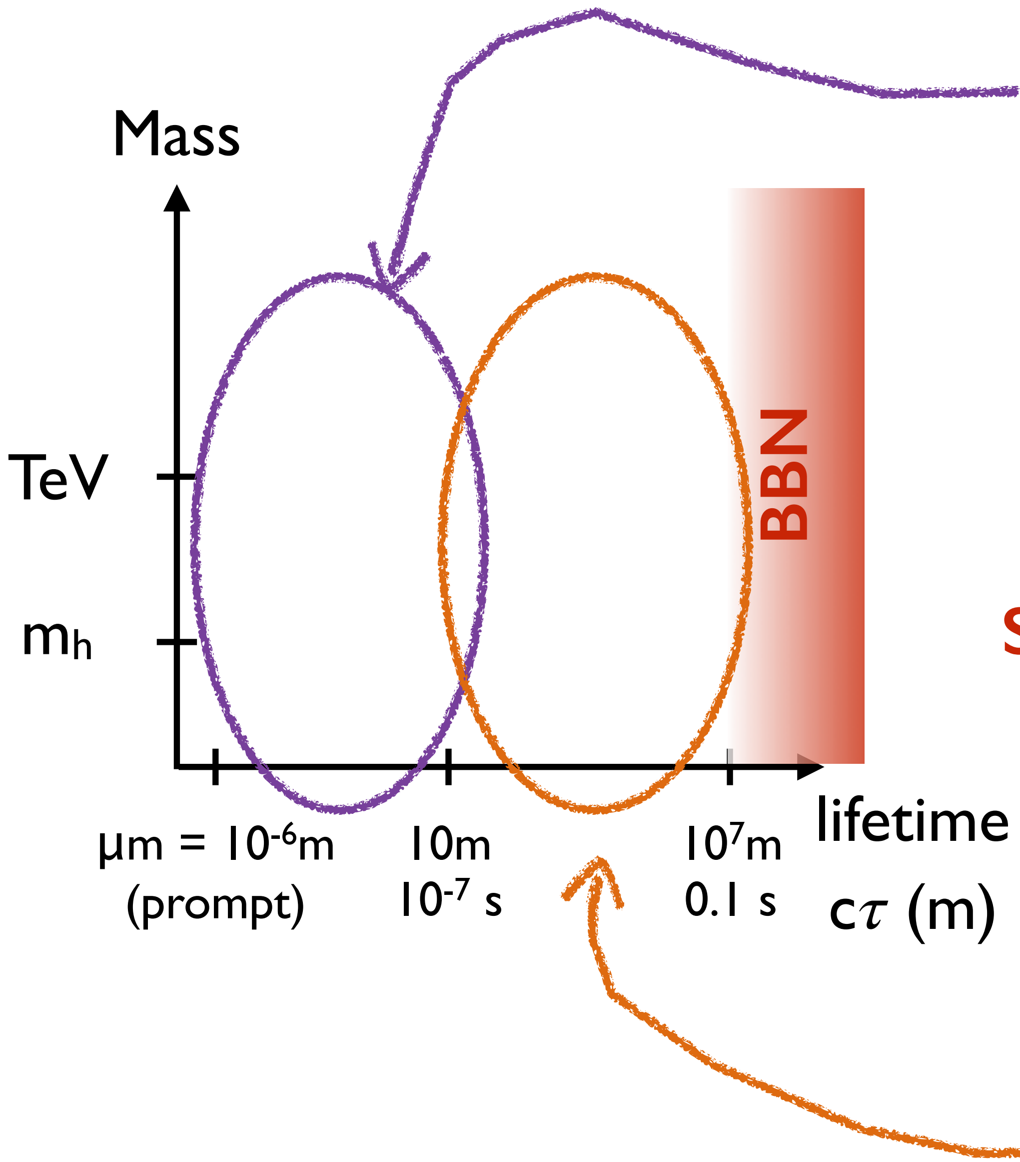
→ Significant Recent Progress!

Special parameter space: FINITE*!

Reach in BSM particle lifetime



LLP searches can be conducted at various colliders, but they are very challenging!

→ Significant Recent Progress!

Special parameter space: FINITE*!

How oh how… do we explore this region?

MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti
1606.06298

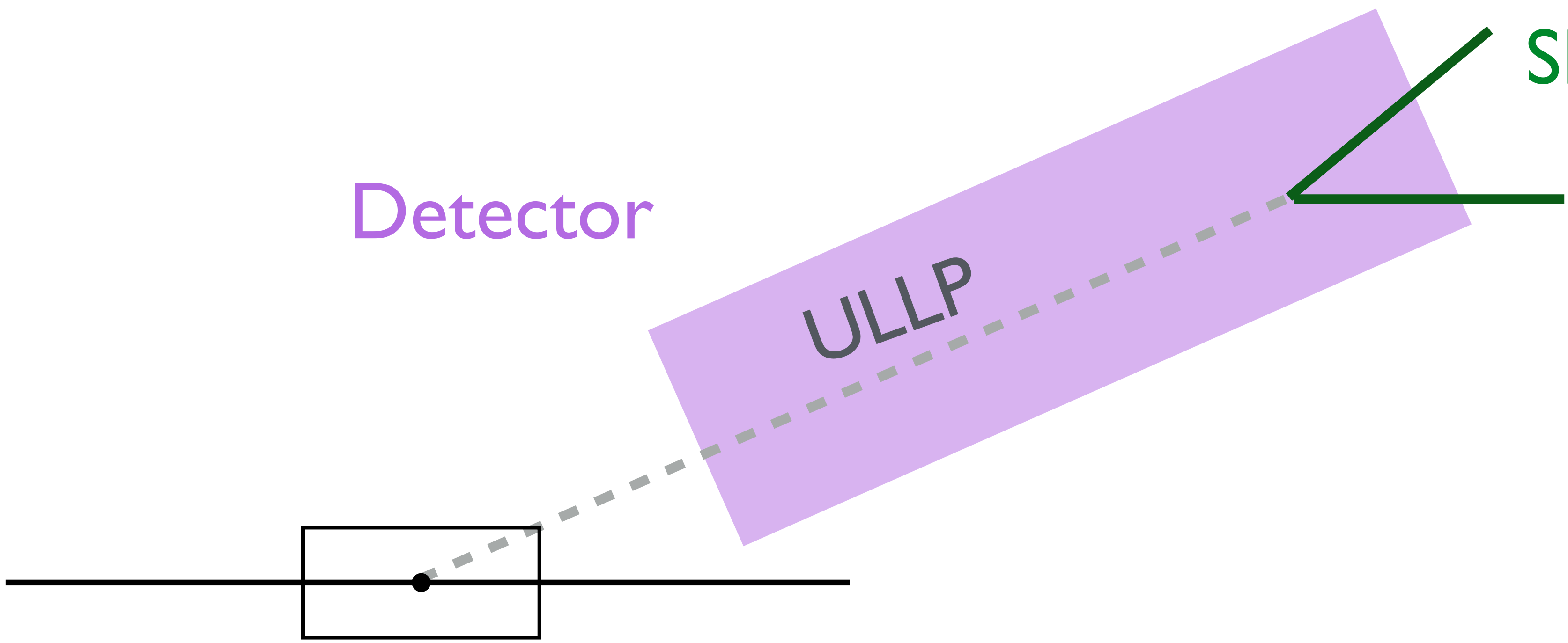
MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

Methuselah (Hebrew: מְתוּשֶׁלַח / מְתוּשָׁלַח, Modern *Metušélaẖ* / *Metušálaẖ* Tiberian *Məṯûšélaḥ* / *Məṯûšālaḥ* ; "Man of the dart/spear", or alternatively "his death shall bring judgment"[1]) is the man reported to have lived the longest at the age of 969 in the Hebrew Bible.[2]

How to detect very long lifetimes?

There's *nothing* clever you can do.

You simple have to instrument a volume of sufficient LENGTH.



The lifetime is anything from (say) 10^3m to 10^7 or 10^8 m

How much volume do we need?

Want to have a chance of seeing a few decays with lifetime near BBN limit: $c\tau \sim 10^7$m

Assume ULLPs are produced in exotic Higgs decays

Require detector of length:

$$L \sim (20\ \mathrm{m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\mathrm{geometric}}}\right) \frac{0.3}{\mathrm{Br}(h \to \mathrm{ULLP})}.$$

ATLAS or CMS could satisfy this requirement!
($L \sim 1$ m, $\epsilon \sim 1$)

Yes, but there's lots of background to an inclusive LLP search

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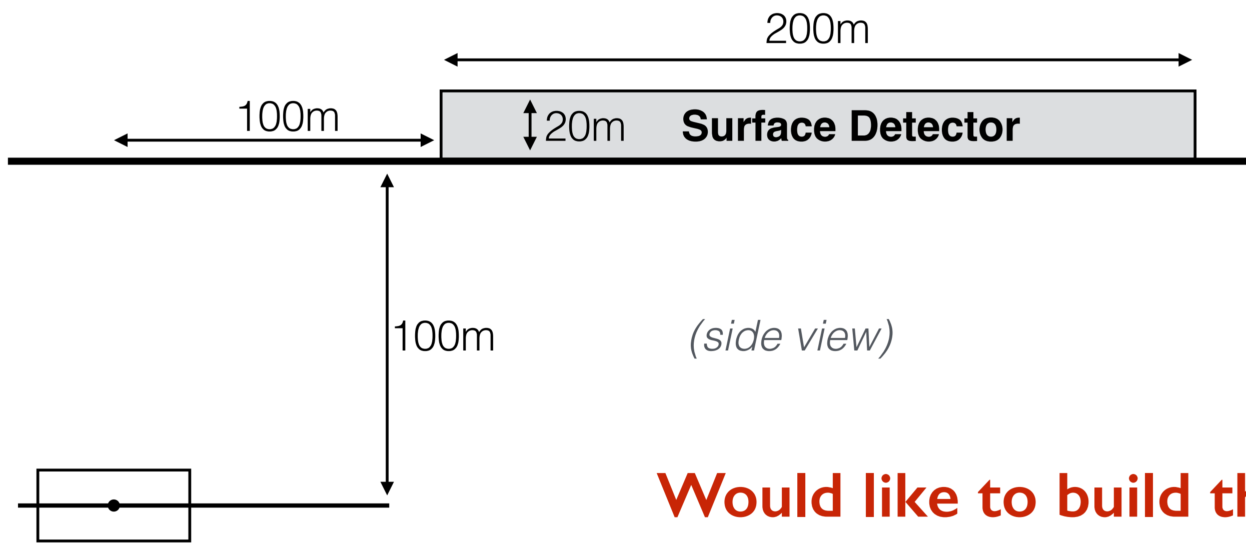
The defining characteristic of a dedicated ULLP detector is not (only) enormous size, but shielding from the main collision point to provide a background-free environment.

⇒ Has to be separated from main detector by > 20 m of rock!

MATHUSLA Surface Detector



Would like to build this in time for the HL-LHC upgrade!

Crazy expensive? Nope!

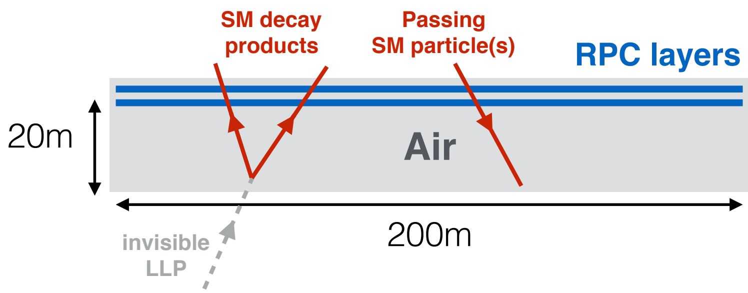
Hallow! Air-filled! Room-T!
Low-rate high-threshold environment.

Only the **outside area** of the detector volume needs to be instrumented with relatively simple detectors.

Available Space

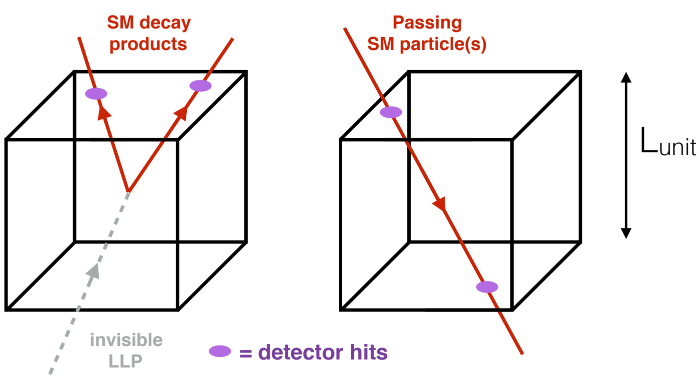
need ~ one
nearby farm plot

A few design sketches



Layers of RPCs in the roof act as a directional **tracker**.
~ns timing, ~cm position resolution.

Reconstructed vertex of ULLP decay distinguishable from e.g. passing cosmics.



Hermetic Scintillator Units of 10-30m size with crude position/timing resolution (m, 10ns).

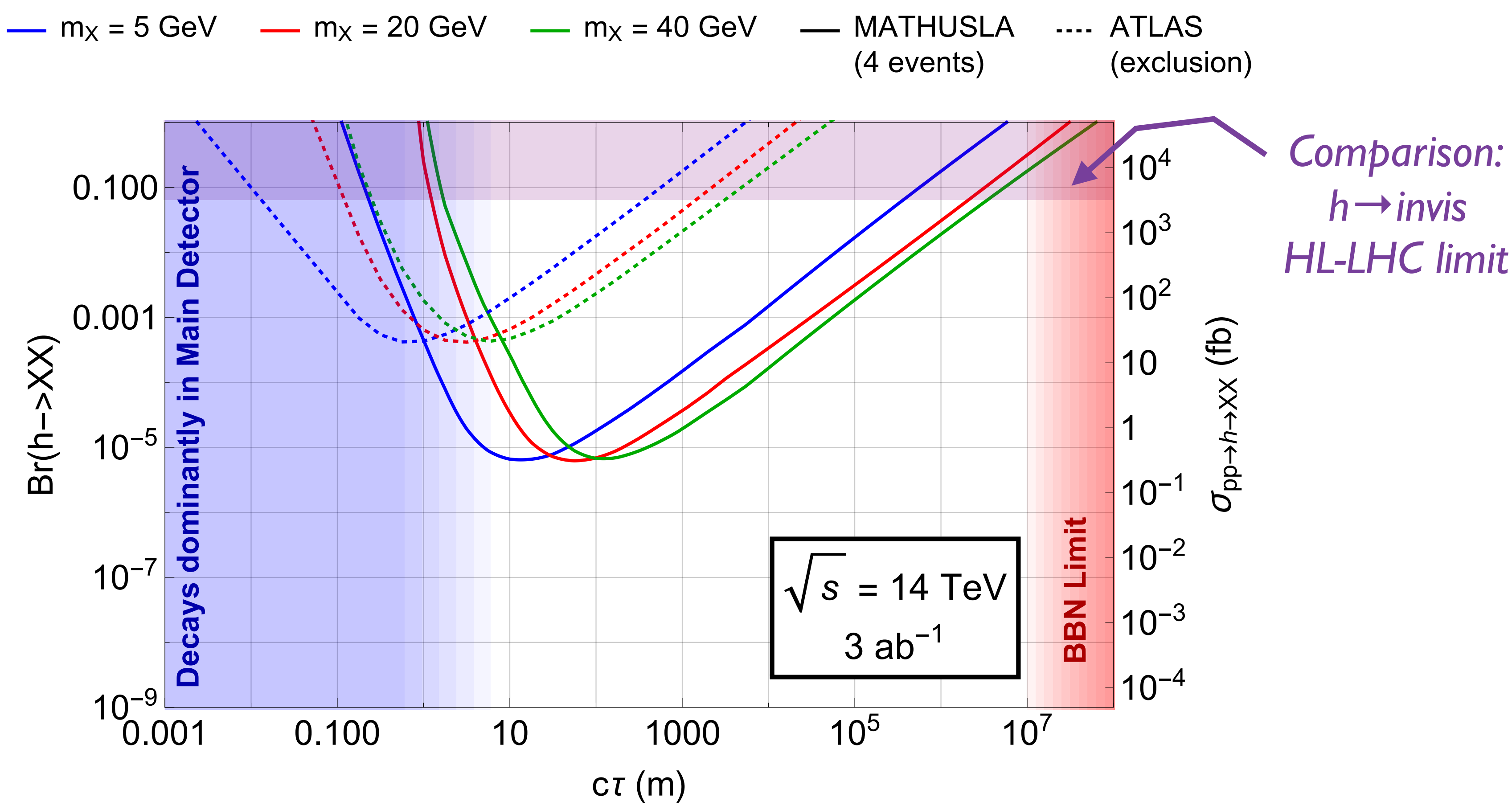
Can tell if something 'appeared' on the inside vs passed through.

Both of these toy-concepts carry a sensor cost of O(20 million USD)

In reality, would want hybrid design for both robust tracking and background vetoes.

Achievable Sensitivity

h→XX simplified signal model for LLP production



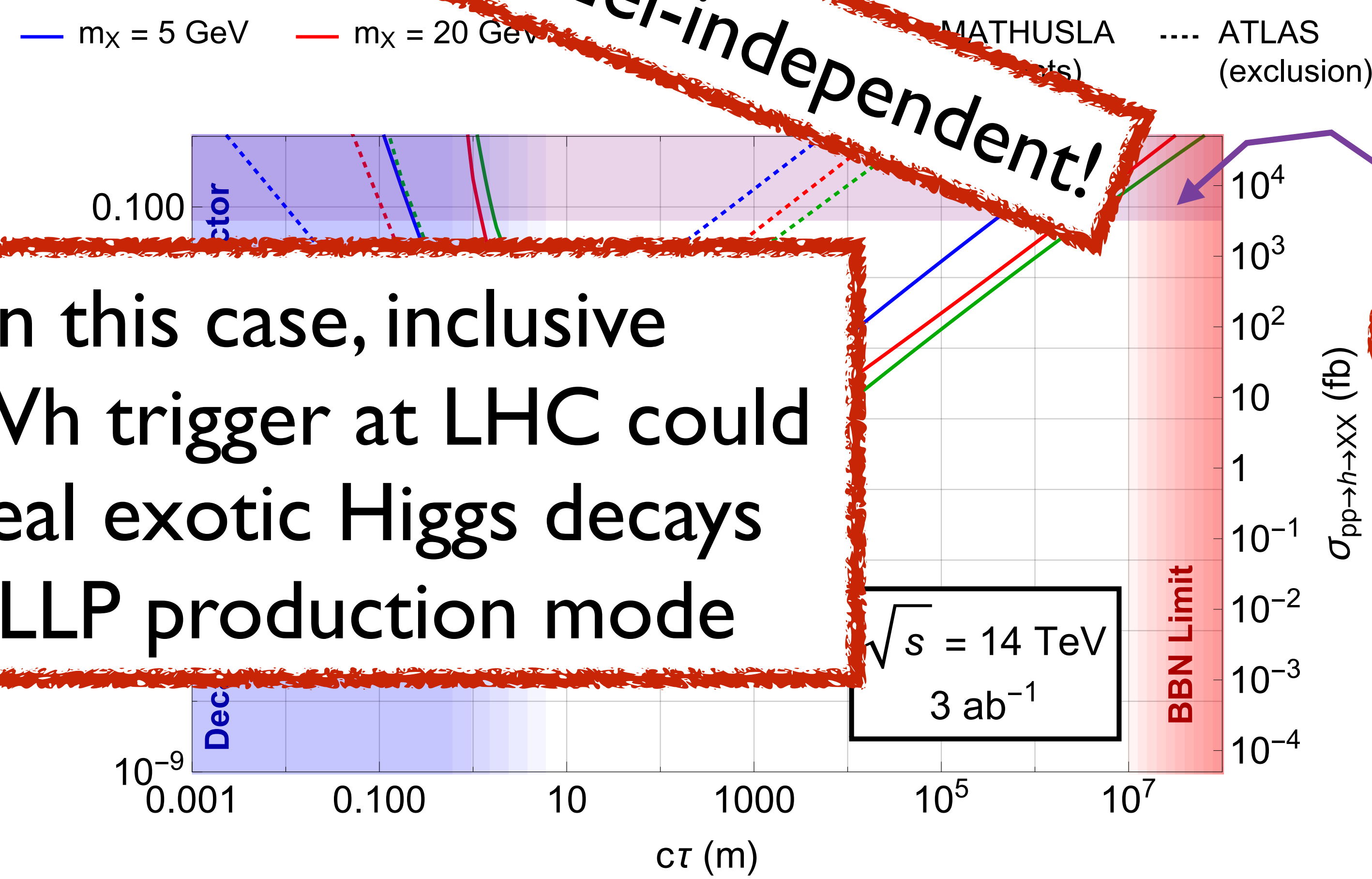
3 orders of magnitude better than ATLAS search for single DV in MS due to **absence of backgrounds!**

Very close to BBN limit!

Achievable Sensitivity

h→XX simplified model for LLP production

Very model-independent!



Comparison: h→invis HL-LHC limit

In this case, inclusive VBF/Vh trigger at LHC could reveal exotic Higgs decays as LLP production mode

3 orders of magnitude better than ATLAS search for single DV in MS due to **absence of backgrounds!**

Very close to BBN limit!

To Do:

Understand potential backgrounds:

Very Preliminary, under study!

Neutrino-Air scattering could fake DVs?
Fluxes seem very manageable and rejectable…

Experiment: Build Prototype:

In talks with various experimental/hardware groups.
Aim: take test data & write letter of intent 2017!

Theory: Make more detailed physics case:

Editors: DC, Matthew McCullough, Patrick Meade,
Michele Papucci, Jessie Shelton
Aim: release comprehensive report early 2017!

If you are an experimentalist
and want to build a new detector
CONTACT US!

If you are a theorist
and want to contribute your LLP model or study
to the MATHUSLA Physics case
CONTACT US!

Spread the word!

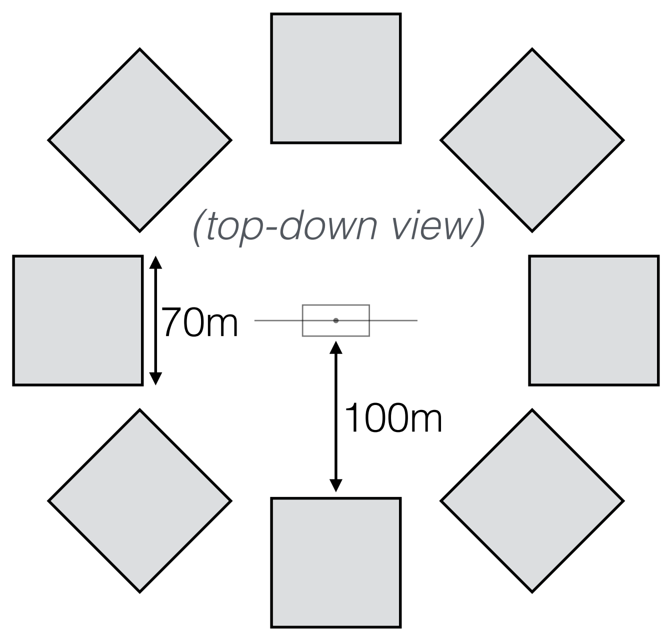
Thank you!

Backup

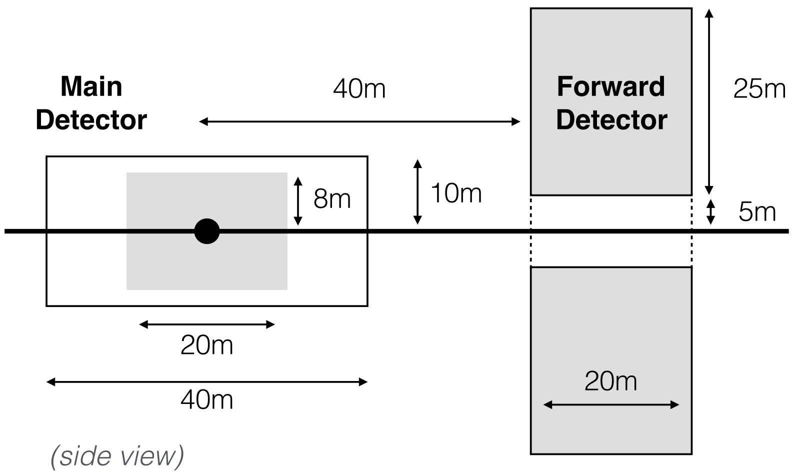
Available Space

Geometry is very flexible!

Could have distributed design,
even split between ATLAS and CMS sites!

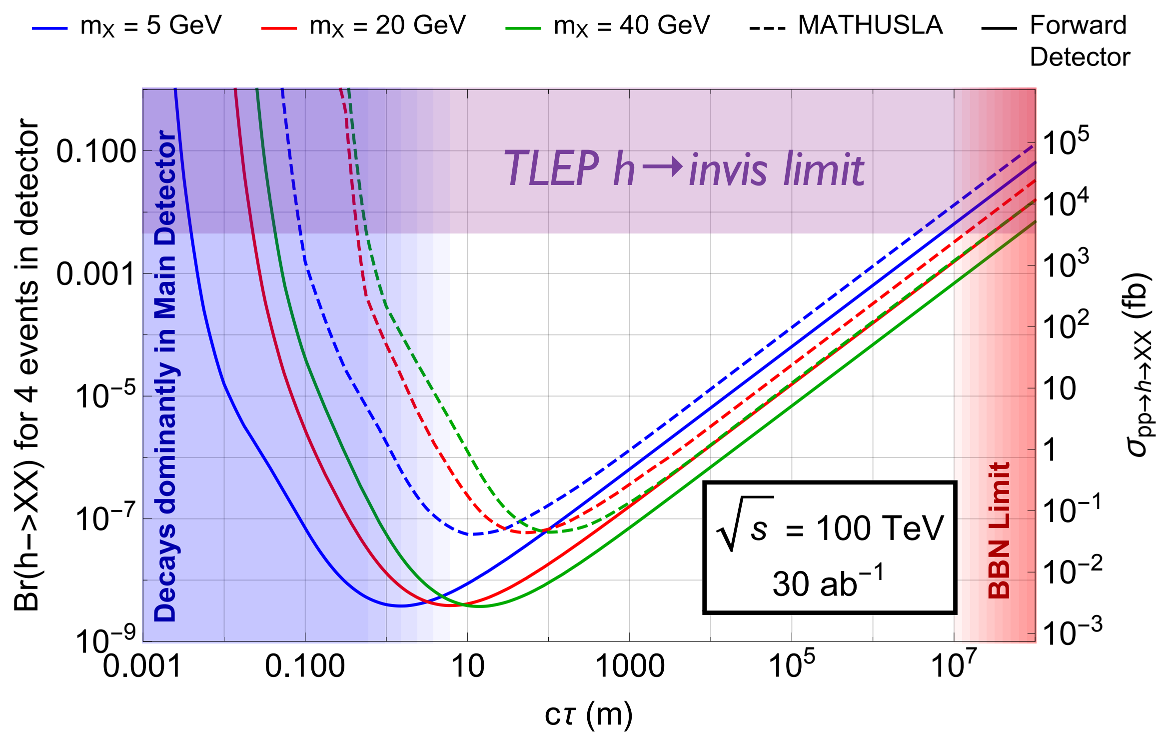


Aside: Start Planning for 100 TeV!



When digging a new tunnel, cavity for dedicated ULLP detector carries very little additional cost!

Compact sub-surface design can achieve much better sensitivity than TLEP for any ULLPs from exotic Higgs decays



Experiment: Small-Scale Prototype

Need to demonstrate feasibility and study backgrounds to anchor various estimates & simulations.

In talks with various detector groups.

Experimentalists:
Join us in building the prototype and developing a letter of intent for a full-scale LHC detector!

Would like to start collecting data by **April 2017!**
(before shutdown)

Theory: make the physics case

CERN-TH-2016-XX

Detecting Ultra-Long-Lived Particles: The MATHUSLA Physics Case

Editors:
David Curtin[1], *Matthew McCullough*[2], *Patrick Meade*[3], *Michele Papucci*[4], *Jessie Shelton*[5]

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Abstract

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Would like to complete this by ~ **Jan 2017!**