Open Questions for the New Physics Working Group (Theory)

Les Houches

Thursday 15th June, 2017

Matthew McCullough

Topics of Focus

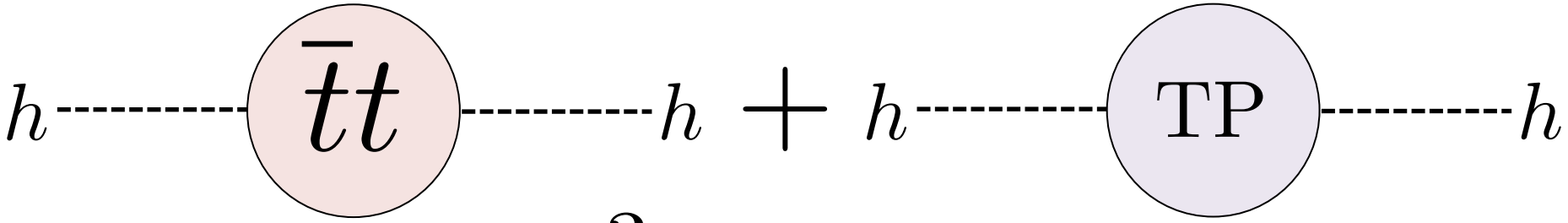
I am a model builder: Throughout I will illustrate the topics by considering specific models.

Topics of Focus

Beyond MET: Do we have full coverage of signatures not involving missing energy?

Generic Expectations

HP solutions typically involve a "Top Partner":



$$\approx \frac{3}{8\pi^2} m_{TP}^2 \log \Lambda$$

If top partner is near the weak scale, Higgs mass corrections logarithmically sensitive to new physics scales, hence naturally light Higgs.

For naturalness expect $m_{TP} \lesssim 400 \text{ GeV}$.

Supersymmetry

Supersymmetry extends SM fields to superfields, thus requiring a top partner:

$$\mathbf{t} = \tilde{t} + \sqrt{2}\theta \cdot t + \theta^2 F_t$$

Top Partner
Stop Squark

Top Quark

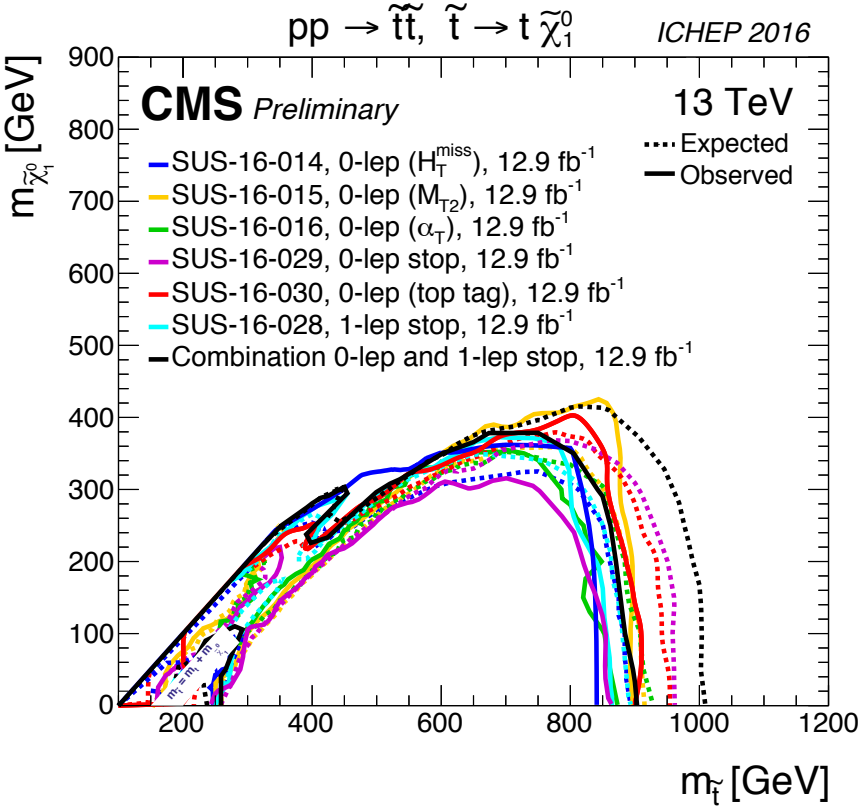
With interactions such as

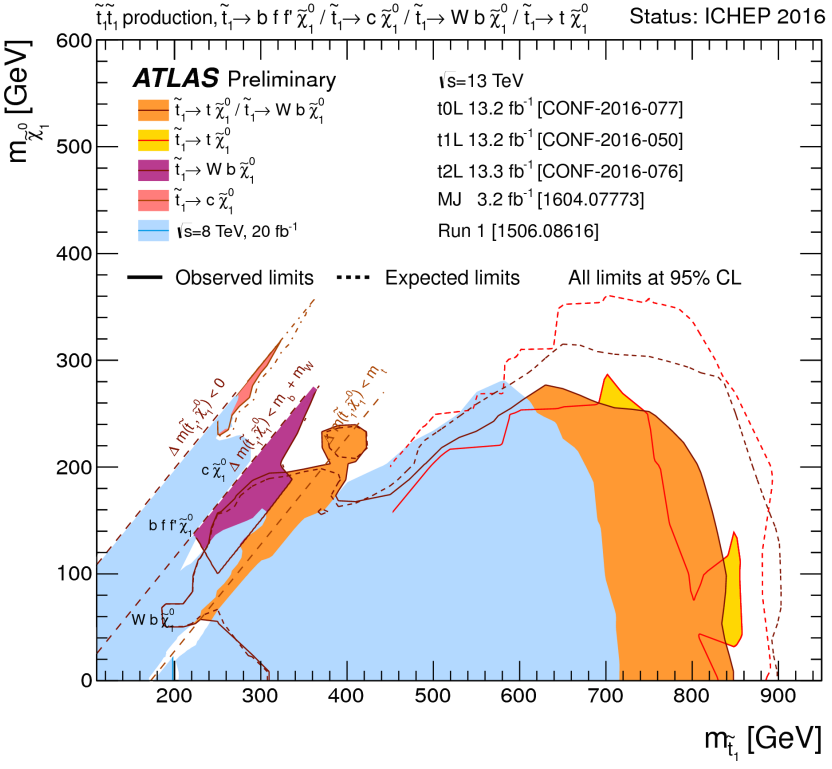
$$\mathcal{L} \sim \lambda_t h t_L t_R + h.c. + \frac{\lambda_t^2}{2} h^2 \left(|\tilde{t}_L|^2 + |\tilde{t}_R|^2 \right)$$

And $\mathcal{L} \sim \tilde{t}^c t \cdot \chi^0$ which enables decays.

Supersymmetry

MET searches in third generation go right for the jugular of SUSY naturalness:





Already considerable pressure on SUSY naturalness...

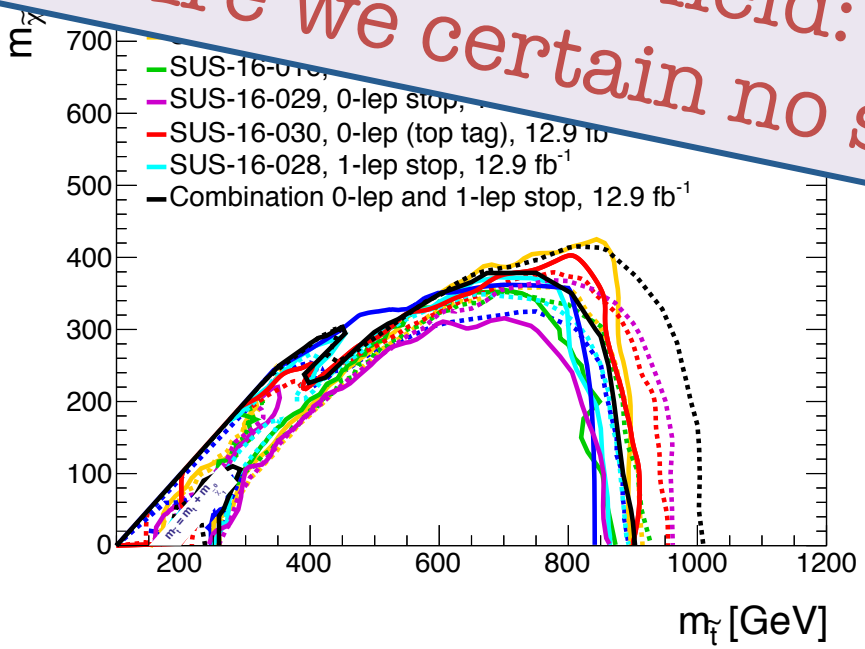
Supersymmetry

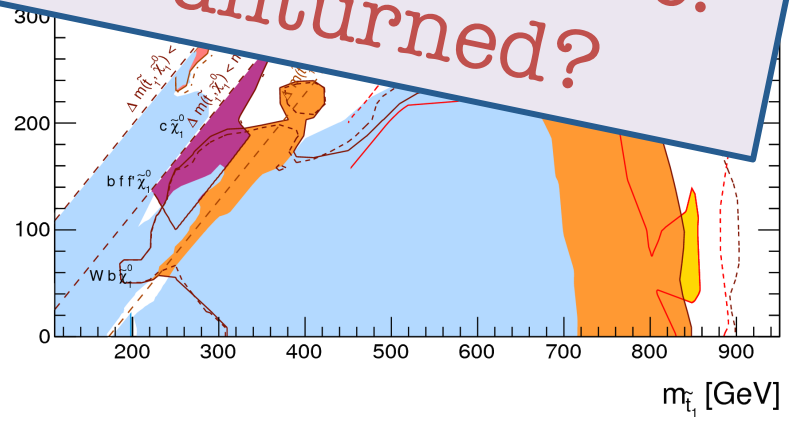
go right for the

Are these plots misleading us? Is SUSY hiding in signatures "Beyond MET"?

Well-developed field: RPV, Stealth, etc etc.

Are we certain no stone is unturned?





Already considerable pressure on SUSY naturalness...

Topics of Focus

Multiple Unknowns: Most searches for one new particle (or pair). Do we have coverage for multiple new particles?

Topics of Focus

Apology: Will illustrate with current work, but I think it gets the point across...

Multiple [illegible] new particle (or pair). Do we [illegible] multiple new particles?

A Clockwork Scalar

Choi & Im, Kaplan & Rattazzi

Action given by

"Interaction basis π"

$$\mathcal{L} = \frac{1}{2}\sum_{j=0}^{N}(\partial_\mu \pi_j)^2 - \frac{m^2 f^2}{2}\sum_{j=0}^{N-1}\left(e^{\frac{i}{f}(q\pi_{j+1}-\pi_j)} + h.c.\right)$$

Spontaneous symmetry breaking pattern:

$$\mathrm{U}(1)^{N+1} \to \emptyset$$

So expect $N+1$ Goldstones.

Explicit symmetry breaking:

$$\mathrm{U}(1)^{N+1} \to \mathrm{U}(1)$$

So expect N pseudo-Goldstones and one true Goldstone.

Can identify true Goldstone direction from remaining shift symmetry

$$\pi_j \to \pi_j + \kappa/q^j$$

A Clockwork Scalar

Choi & Im, Kaplan & Rattazzi

Peculiar spectrum, reminiscent of Condensed Matter...

Mass matrix

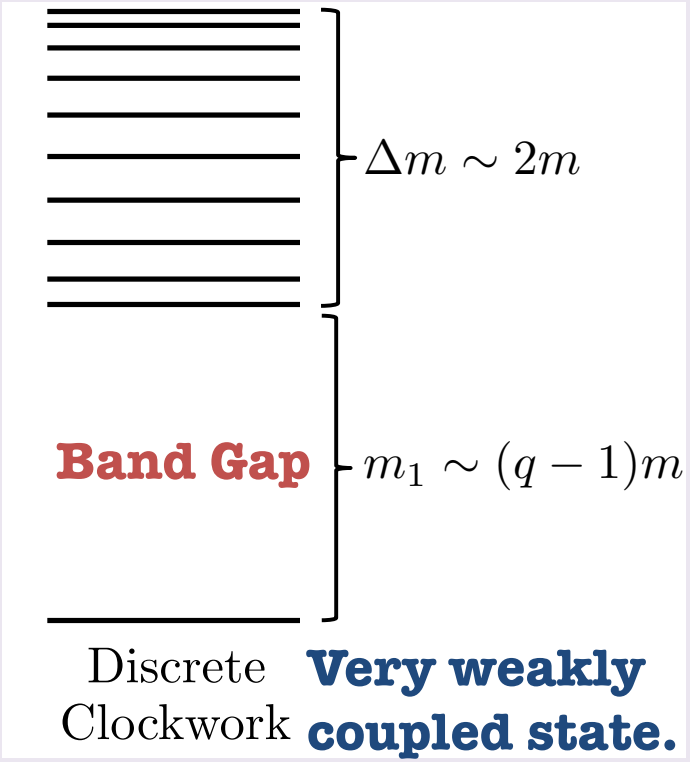
$$M_\pi^2 = m^2 \begin{pmatrix} 1 & -q & 0 & \cdots & & 0 \\ -q & 1+q^2 & -q & \cdots & & 0 \\ 0 & -q & 1+q^2 & \cdots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \cdots & -q & q^2 \end{pmatrix}.$$

Eigenvalues for "Clockwork Gears"

$$m_{a_k}^2 = \left(q^2 + 1 - 2q\cos\frac{k\pi}{N+1}\right) m^2$$

$$k = 1, .., N$$

Mass spectrum



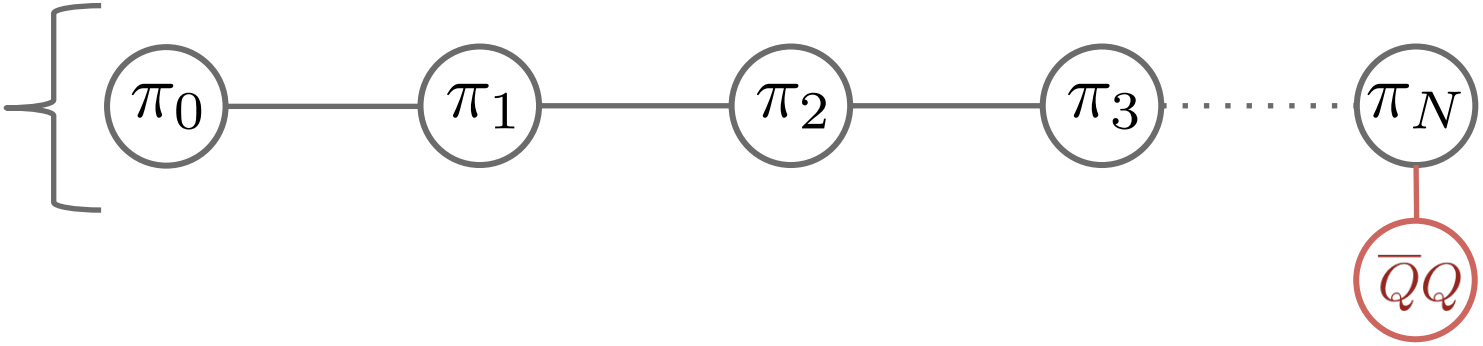
How might this be useful in practice?

A Clockwork Axion

See also Farina et al 2016.

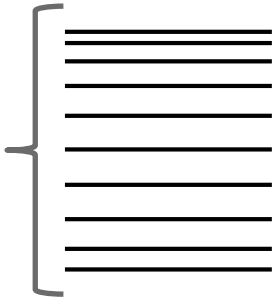
Imagine clockworking Peccei-Quinn at weak scale:

$$\langle \phi_j \rangle = \frac{f}{\sqrt{2}} \sim m_H$$



An invisible axion and band of weak-scale "gears":

$$m_{a_j} \sim m_H \ , \ \mathcal{L} \sim \frac{a_j}{f} \tilde{G} G$$

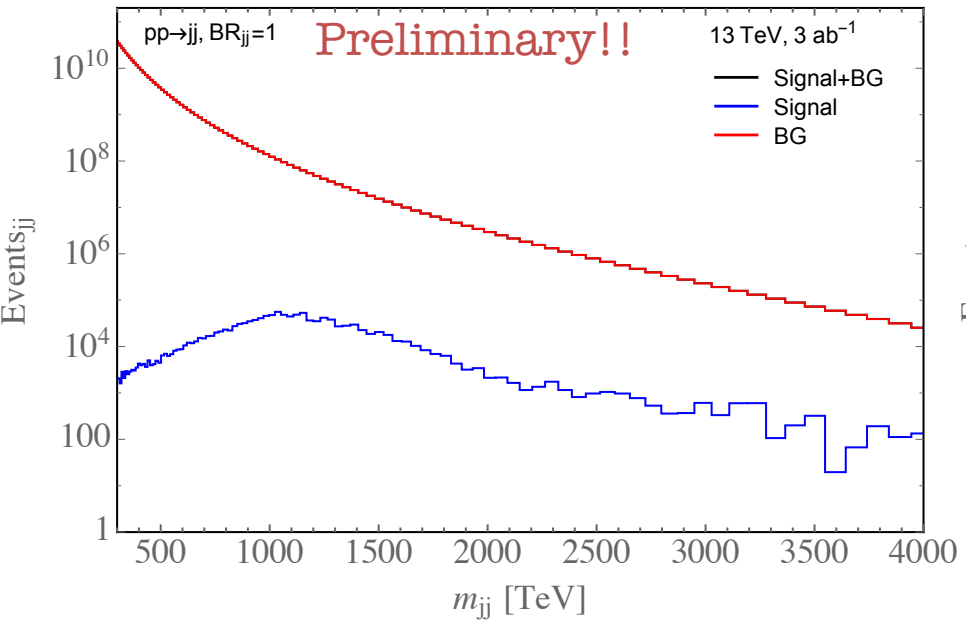


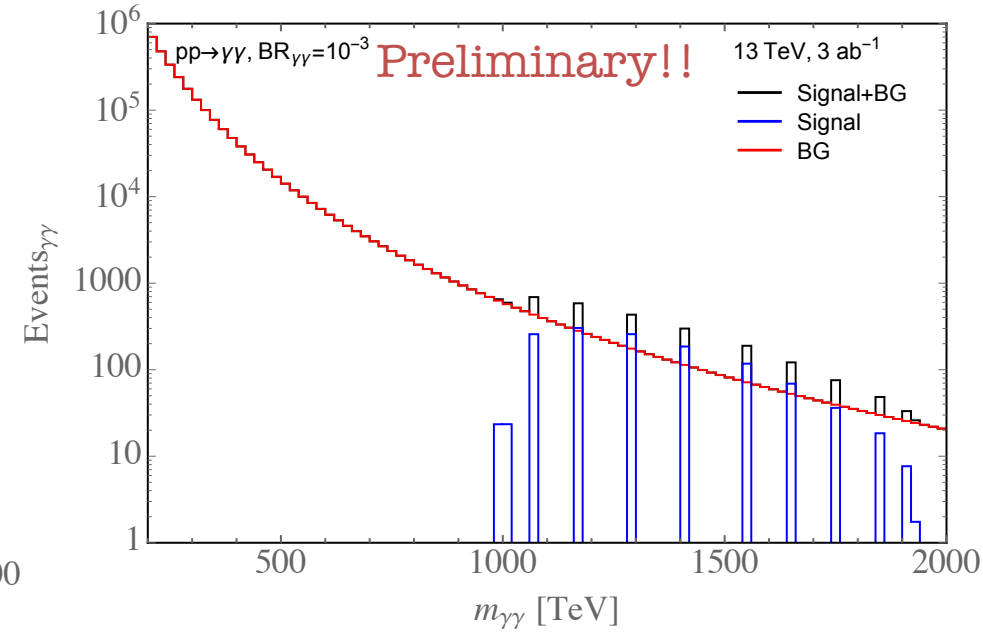
$$m_{a_j} \sim \frac{\Lambda_{QCD}^2}{q^N f} \ , \ \mathcal{L} \sim \frac{a_j}{q^N f} \tilde{G} G$$

- Clockwork gears could show up as a band of states at colliders.
- Cosmology / thermal history of invisible axion radically altered: stays in thermal equilibrium to late times.

A Clockwork Axion

The phenomenology of the clockwork gears would be very exotic:





Dijet spectrum likely too smeared, and background too large, to reveal anything here. Perhaps diphotons could reveal gears.

Linear Dilaton Model

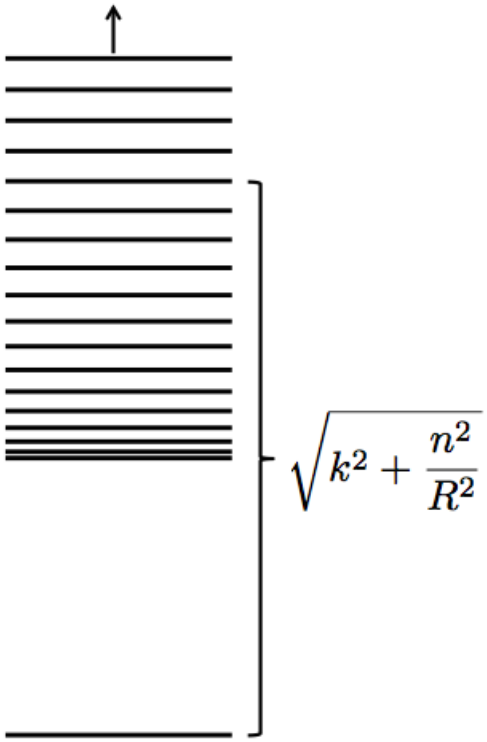
This theory shows up as the continuum limit of the clockwork models. Solves hierarchy problem as in extra dimensions.

In this theory Planck scale is:

$$M_P \sim \sqrt{\frac{M_5^3}{k}} e^{k\pi R}$$

So if all other parameters at the weak scale, require:

$$kR \sim 11$$



But the mass spectrum is given by:

$$m_n \sim k\left(1 + \frac{n^2}{2(kR)^2}\right)$$

Thus the first few states will always be split by %'s, with the relative splitting decreasing for heavier modes.

This splitting is a key prediction of the theory.

Linear Dilaton Model

Irre

In t
Pla

M_I

So i
par
wea

en by:

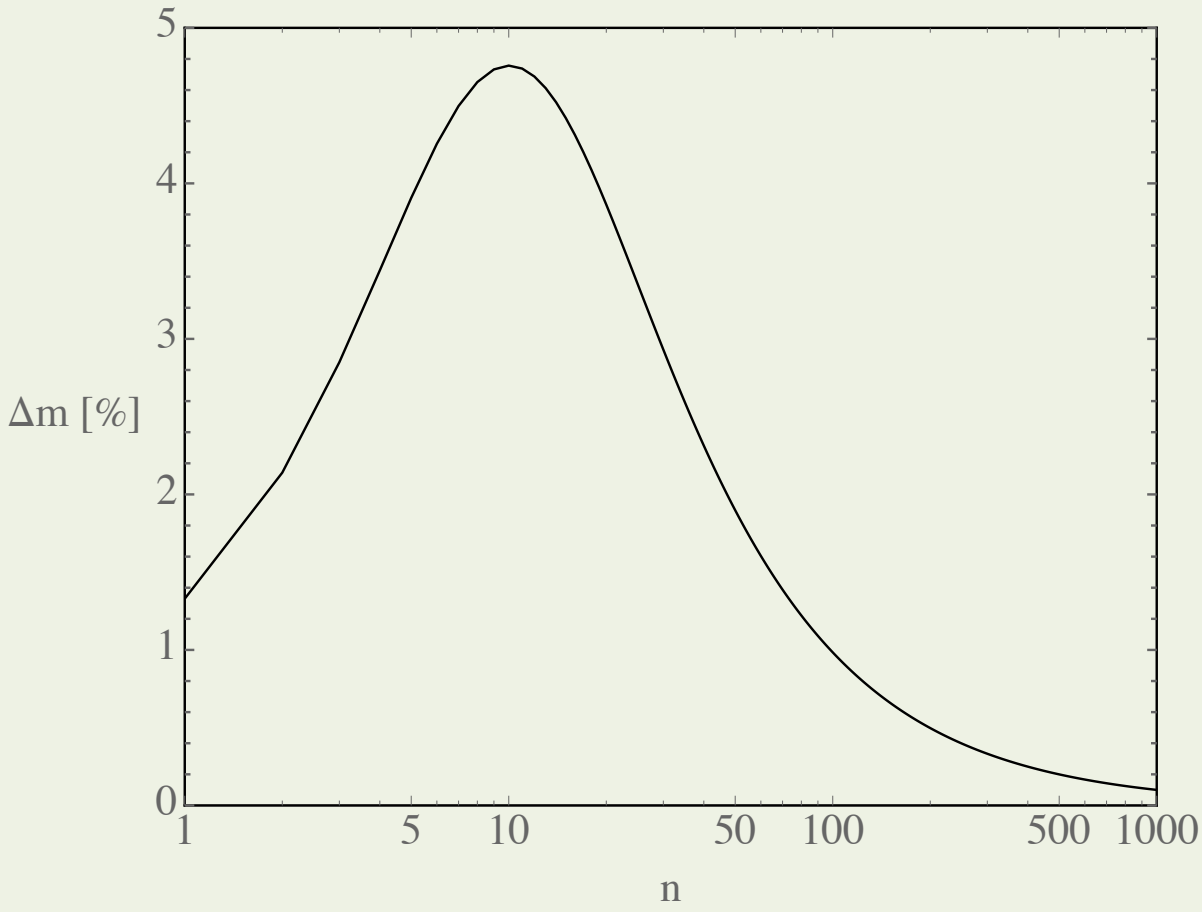
$\left(\frac{n^2}{kR)^2}\right)$

ew
ys be
h the
g

This

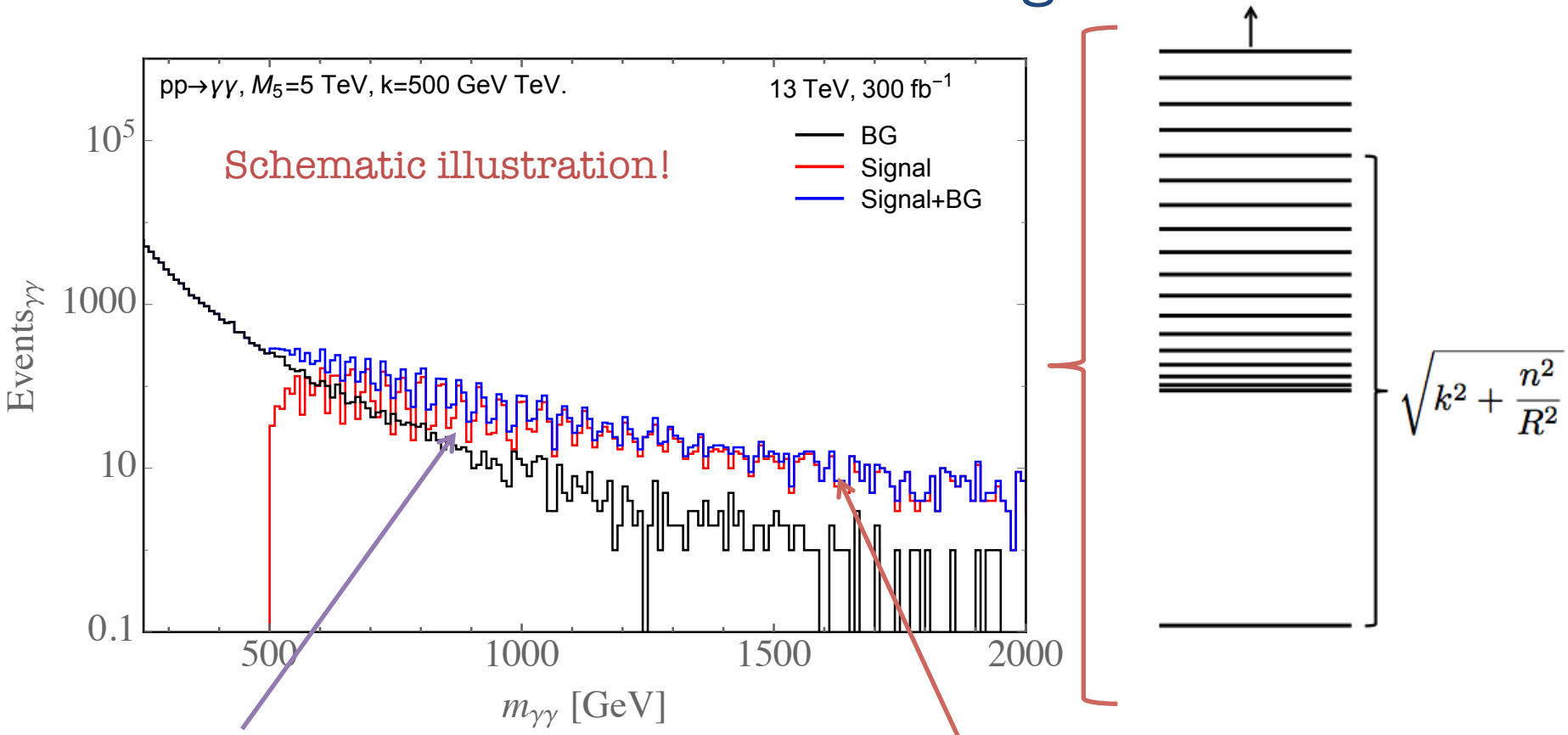
heory.

Mass splitting:



Linear Dilaton Model

At colliders would look something like:

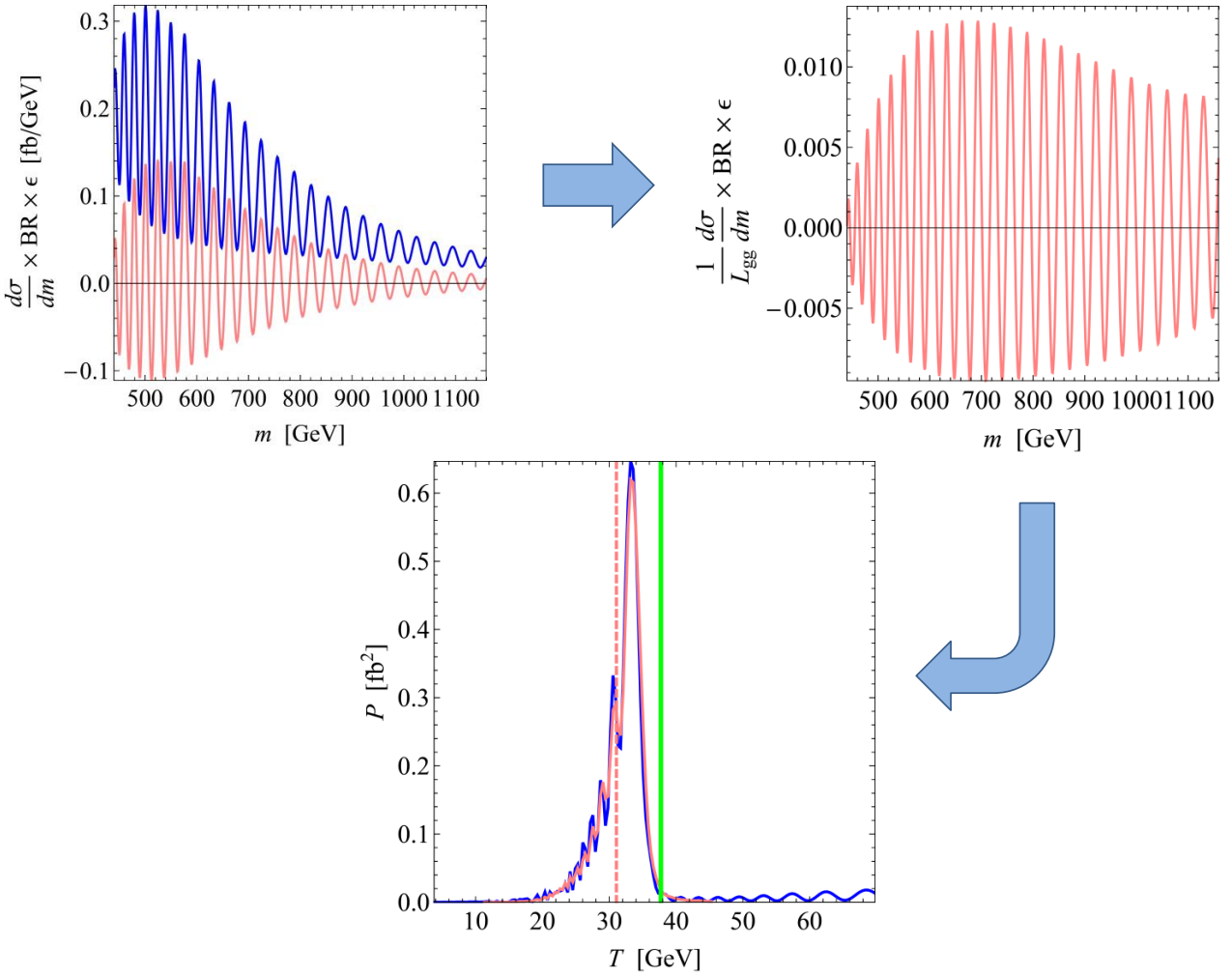


Most interestingly, due to splittings, signal appears to "oscillate". Thus get extra sensitivity by doing spectral analysis... The "power spectrum" of LHC data!

Can search for continuum spectrum at high energies. BG modelling essential...

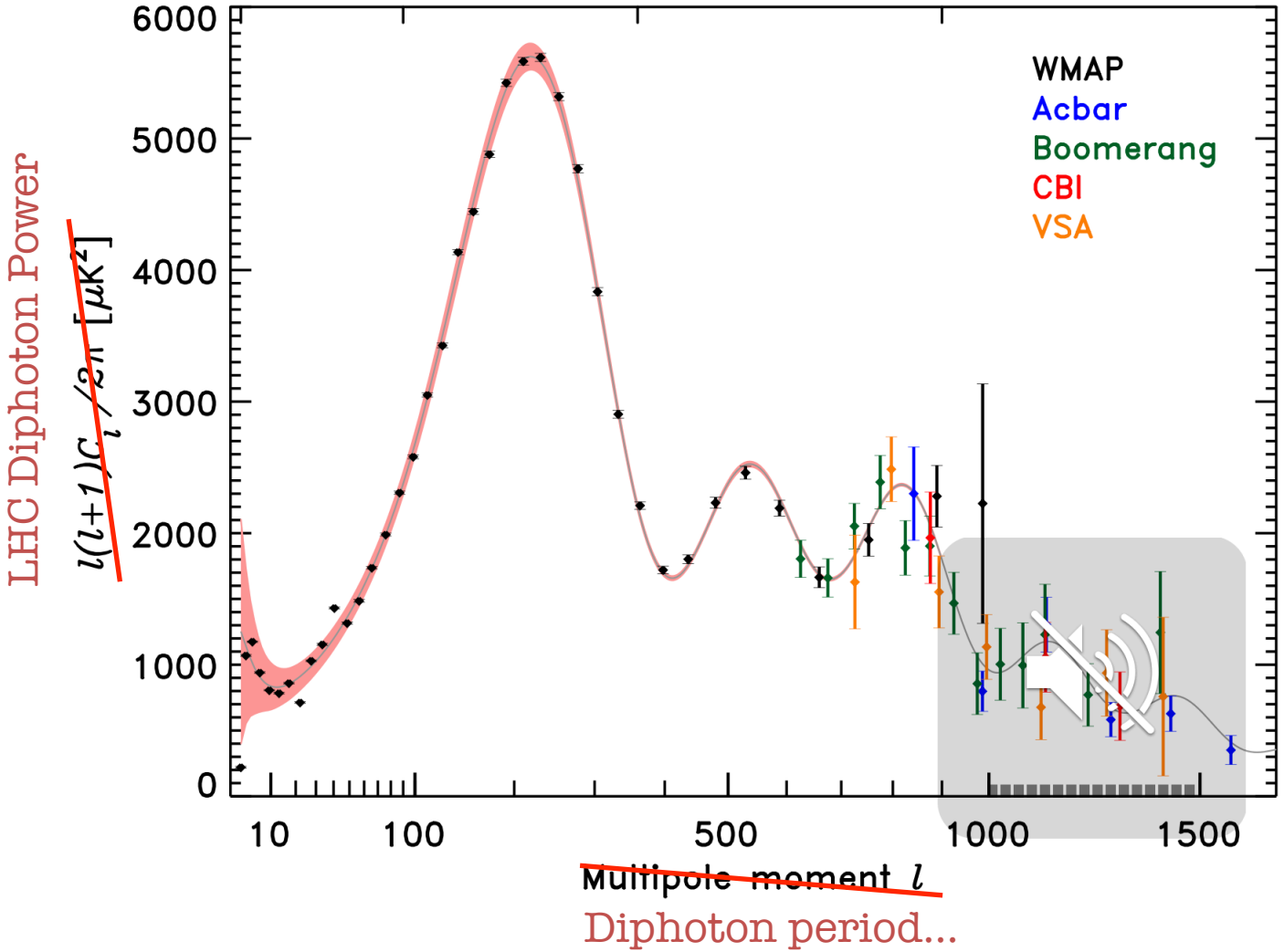
Phenomenology

The Fourier transform would then exhibit a peak:



Phenomenology

What is the power spectrum of the LHC?

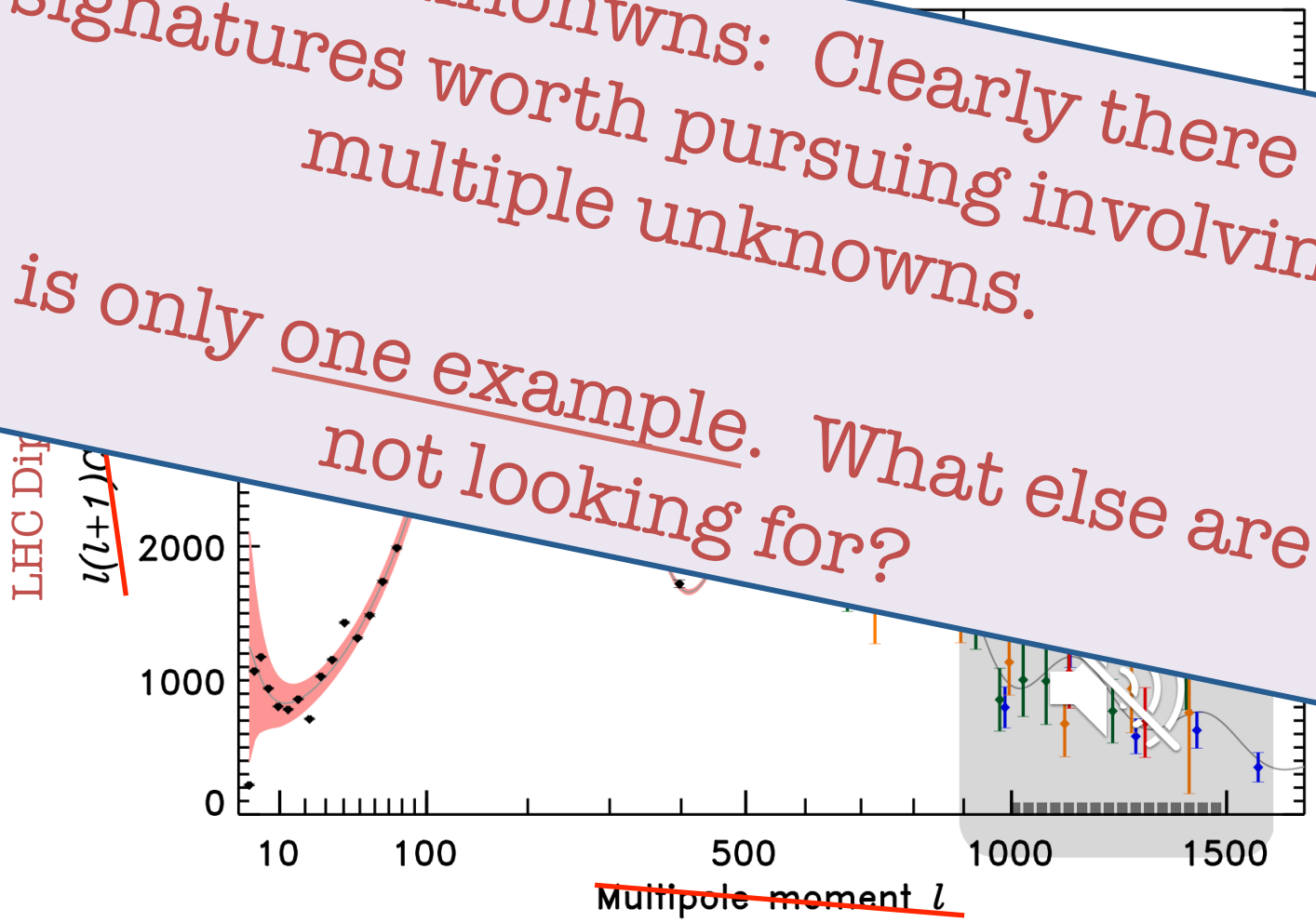


Phenomenology

W power spectrum of the LHC?

Multiple unknonwns: Clearly there are signatures worth pursuing involving multiple unknowns.

This is only one example. What else are we not looking for?



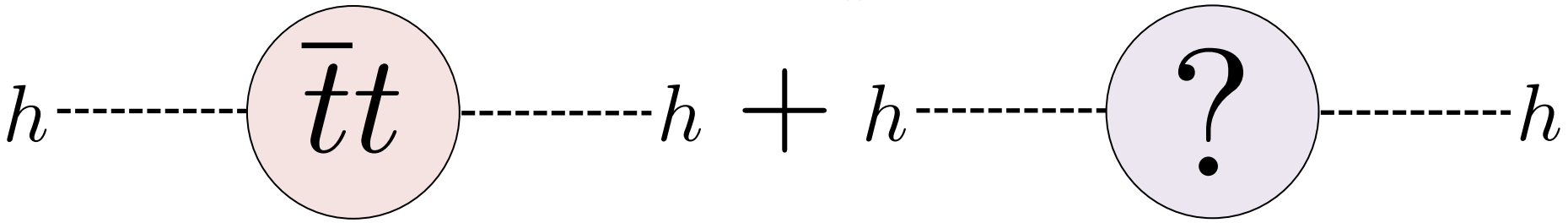
Diphoton period...

Topics of Focus

The lifetime frontier: How ubiquitous are Long-Lived Particles (LLPs)? Do we have/need the appropriate language to generalise search program?

LLPs in Naturalness

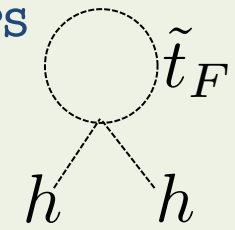
Could there be a hidden "Top Partner"?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners

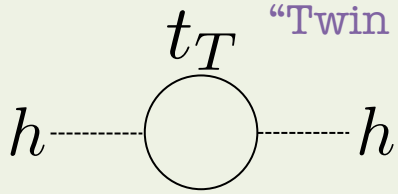


"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



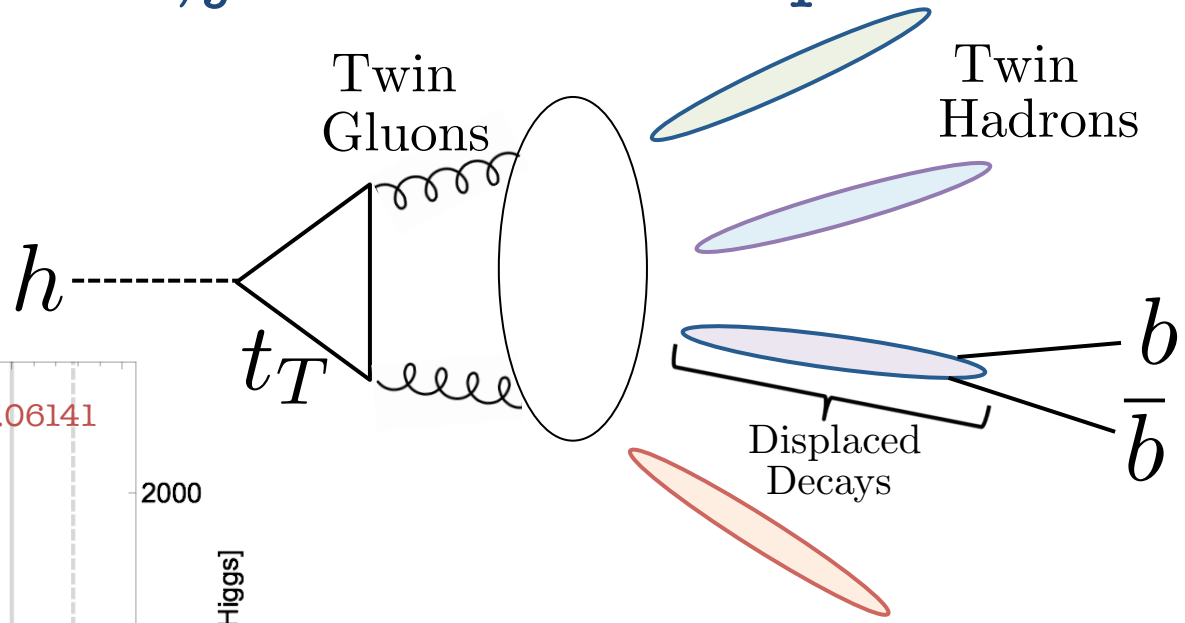
"Twin Tops"

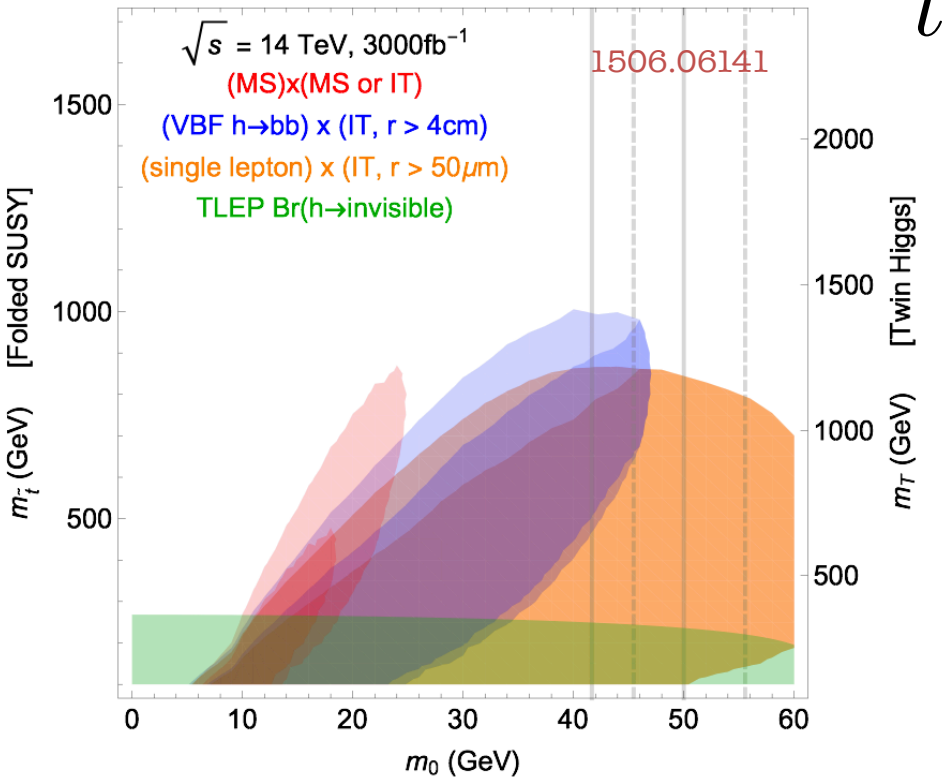
...but they must be charged under new hidden QCD'.

LLPs in Naturalness

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:

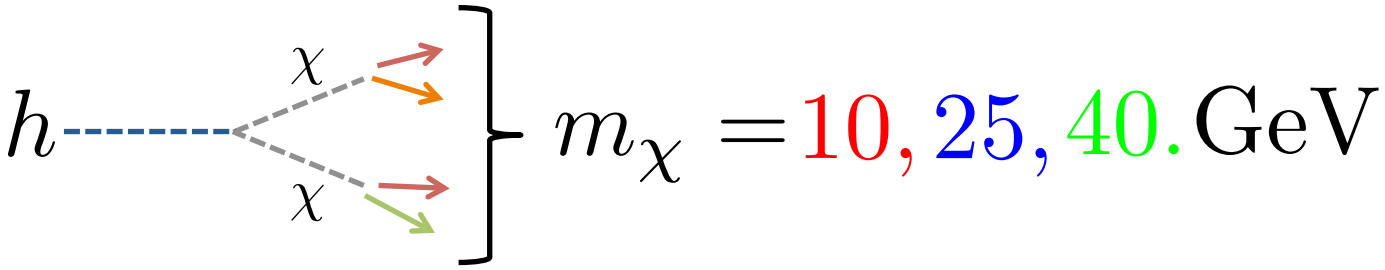


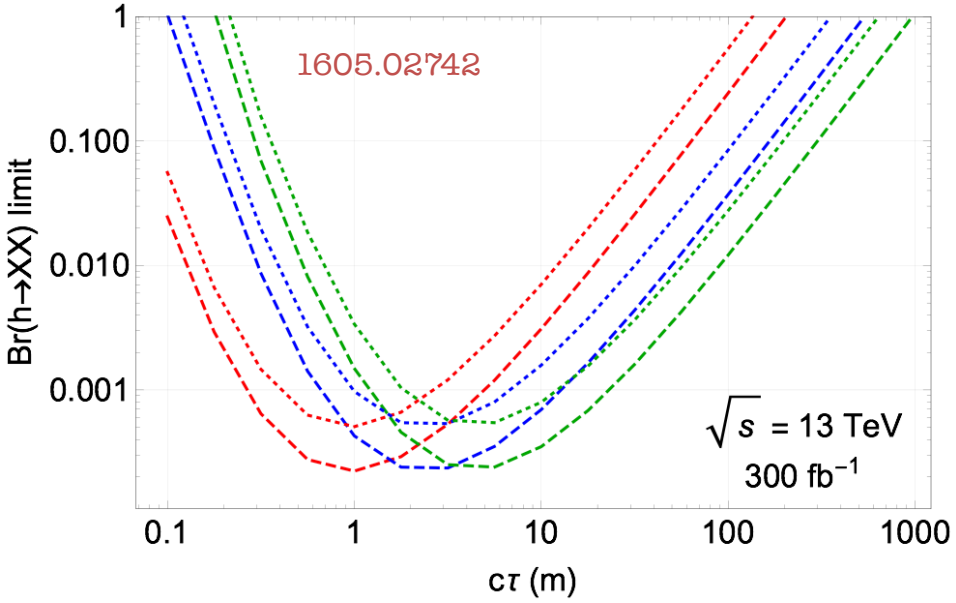


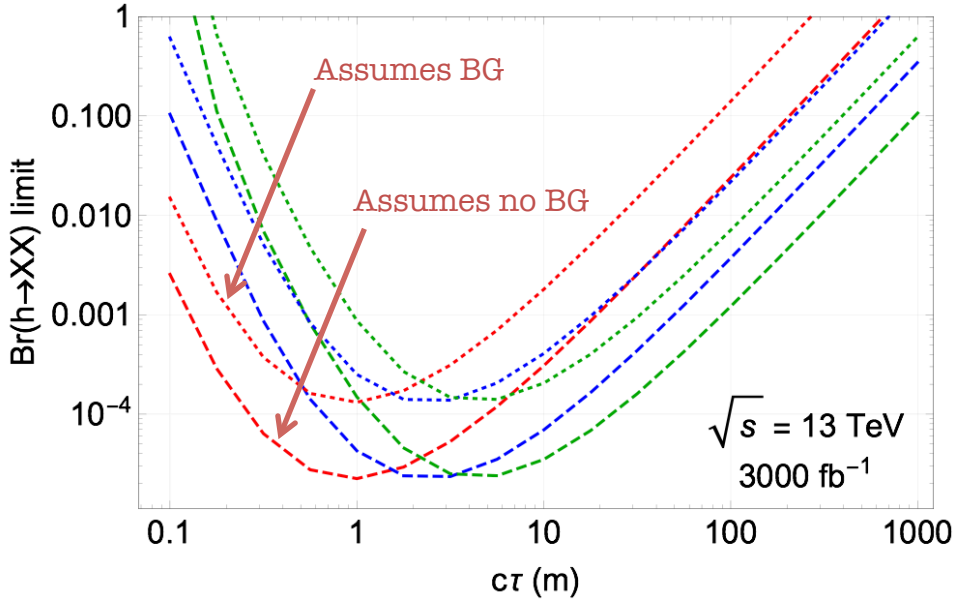
One striking signature these models motivate is displaced vertices, which may also be quite soft.

Exotic Higgs

Exotic Higgs decays provide a signature "standard candle"



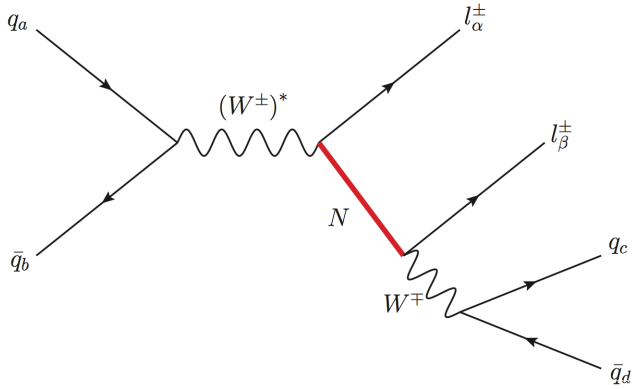




As expected, reach scaling well with luminosity!

Neutrino Masses

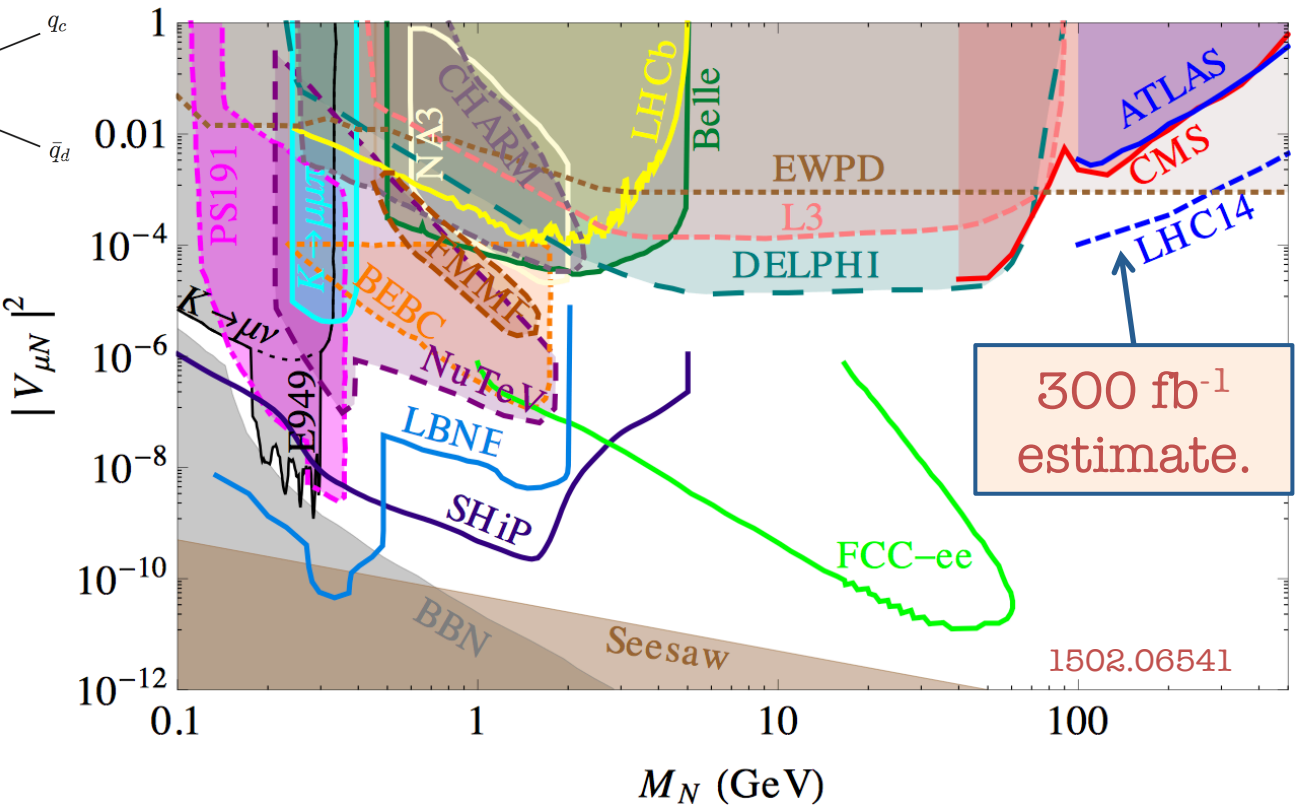
Certain classes of neutrino mass models have RHD neutrinos at weak scale.



Signatures are relatively clean: same-sign leptons+jets.

More generally, new neutral, weakly coupled, fields may show up in the lepton sector.

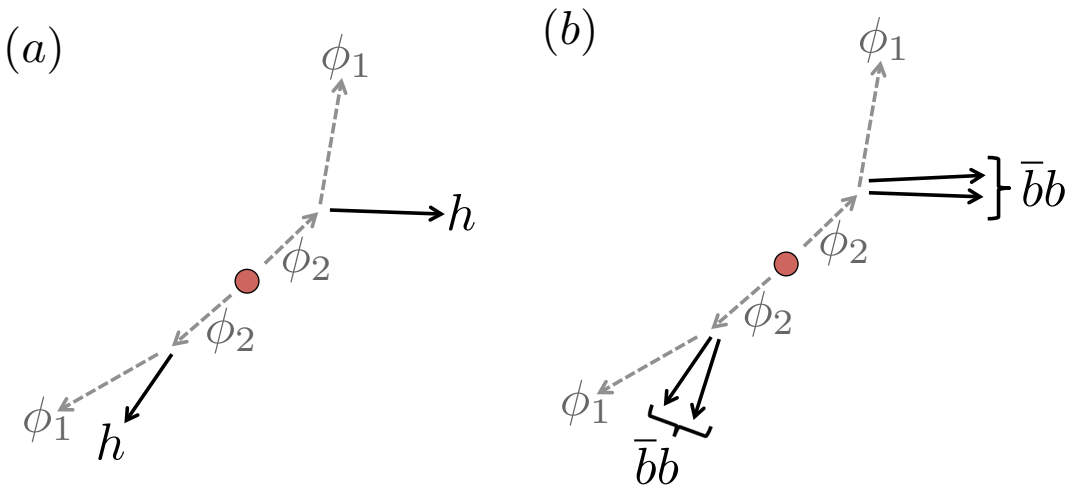
Signatures rare, with low SM backgrounds.



Displaced Dark Matter

There are generic classes of unexplored scenarios.

An example: $\mathcal{L}_{\rm Int} \sim \mathcal{O}_{\rm SM} \times \left(\phi_2^2 + \phi_1^2 + \epsilon\phi_2\phi_1\right)$



Exciting signatures:
- Paired displaced events!
- Soft displaced events.
- Missing energy
- Non-pointing displaced

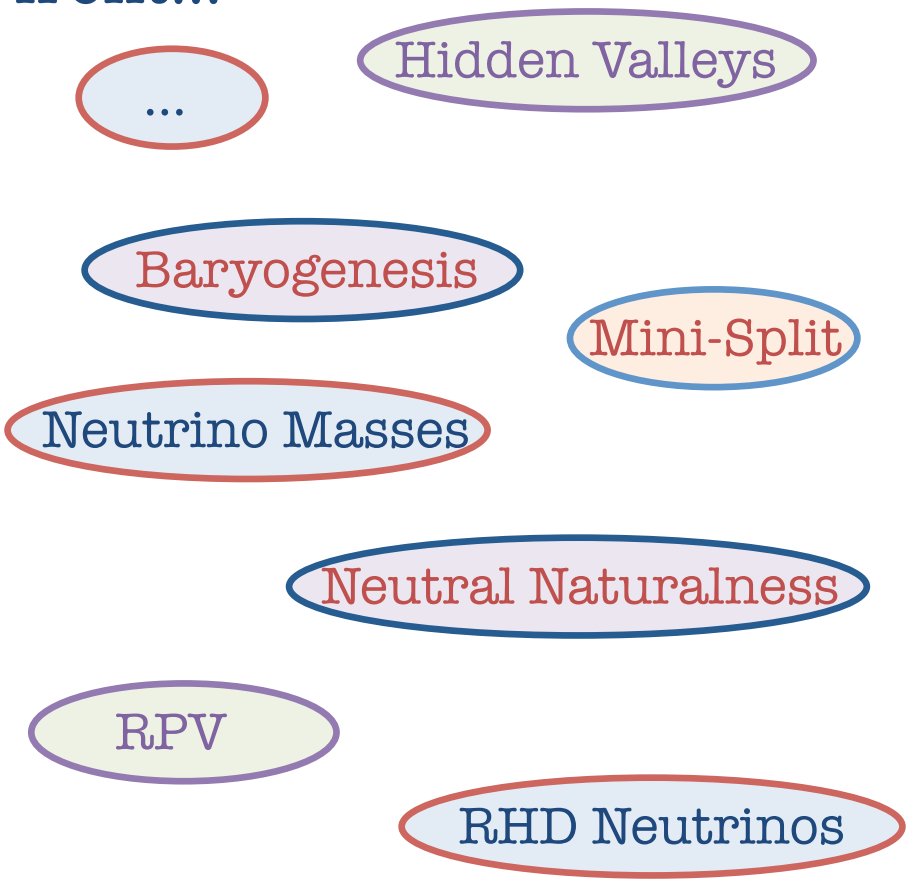
Clear detector goals:
- Triggering
- Tracking
- ???

Numerous unexplored theories that take full advantage of the added integrated luminosity.

LLPs

Long-lived particles come up in many models.

Many exciting and creative ideas on the theoretical front...



LLPs

LLPs are seemingly ubiquitous. They show up in:

a) The Standard Model (Precedent)

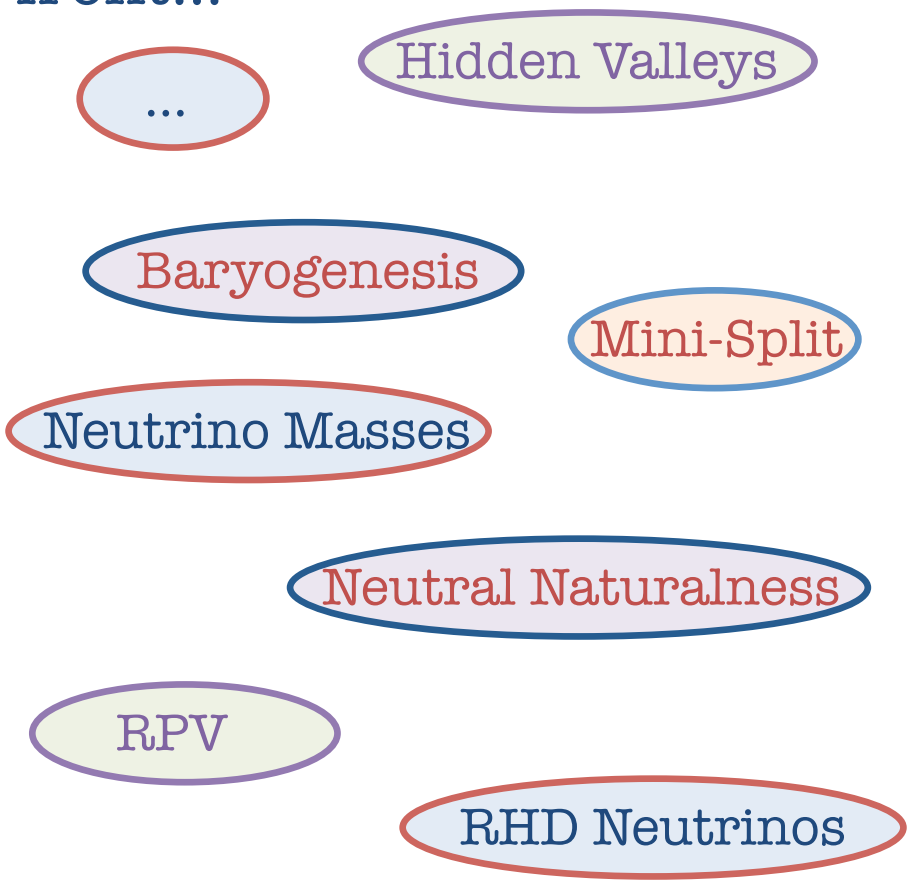
b) Pretty much any BSM scenario in some corner of parameter space.

Are there other BSM scenarios where we may be overlooking signatures? Composite Higgs?

LLPs

Long-lived particles come up in many models.

Many exciting and creative ideas on the theoretical front...



LLPs

Since they are ubiquitous, do we have an experimental program taking advantage of all the discovery opportunities?

Do we need to generalise now to simplified models?

Example for neutral LLPs: 1704.06515.

What about other scenarios?

LLPs

Long… come up in many models.

Many… ideas… from…

There is already a concerted effort in this direction: LHC LLP Community.

Recent workshop:
https://indico.cern.ch/event/607314/

What can we at Les Houches add to this effort? Tomorrow: Identify areas of opportunity and goals.

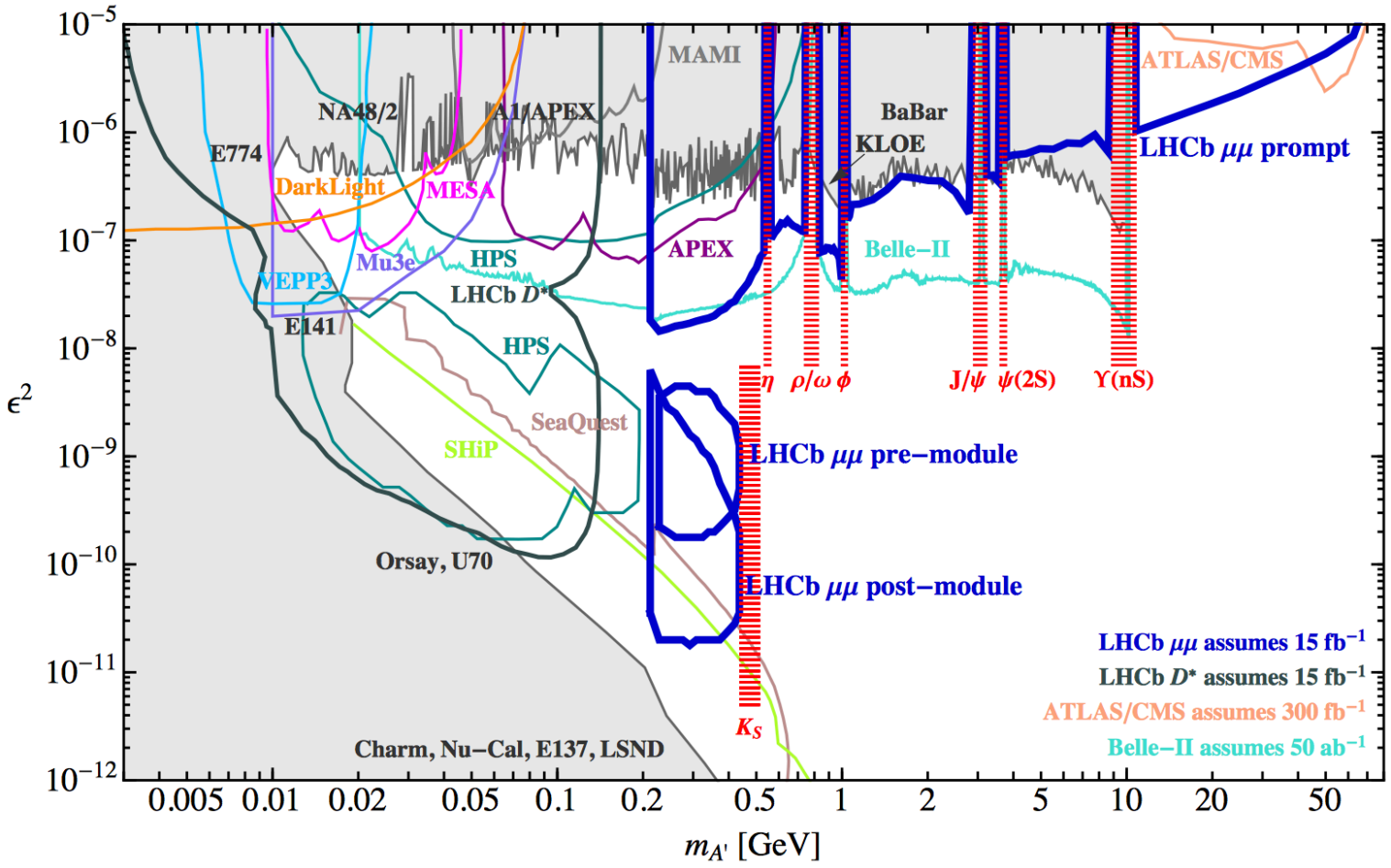
RPV

RHD Neutrinos

Topics of Focus

Beyond ATLAS and CMS: What more can be done with LHCb?

Beyond ATLAS and CMS



Last year 1603.08926 demonstrated LHCb is a superb intensity-frontier machine. In this case dark photon searches. What else can we use it for?

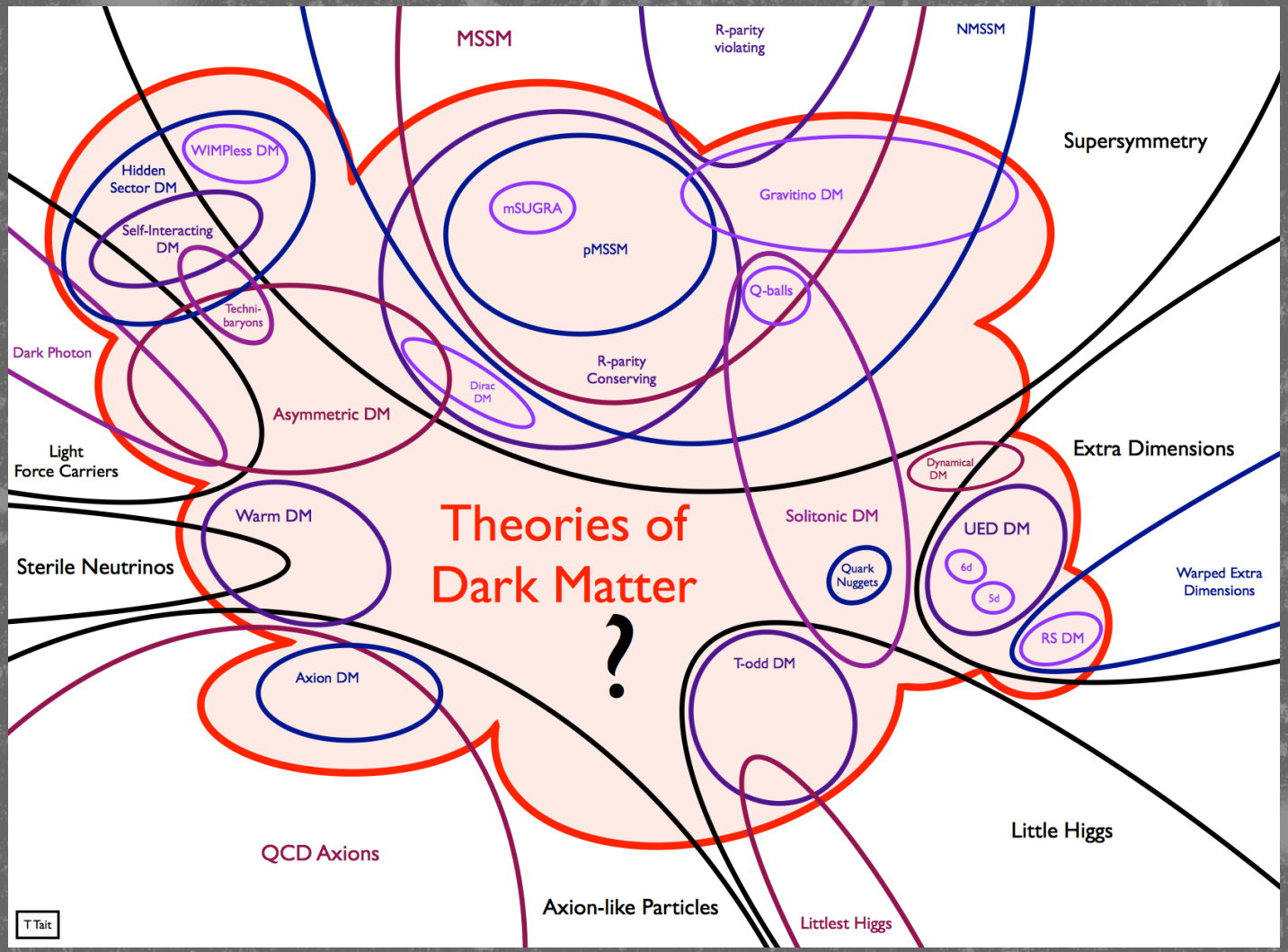
Topics of Focus

Colliders and multi-component dark matter:

- Are we taking relic abundance too seriously?
- Are we properly searching for sub-components?
- Are there collider signatures that are only possible with multi-component?

Dark Matters

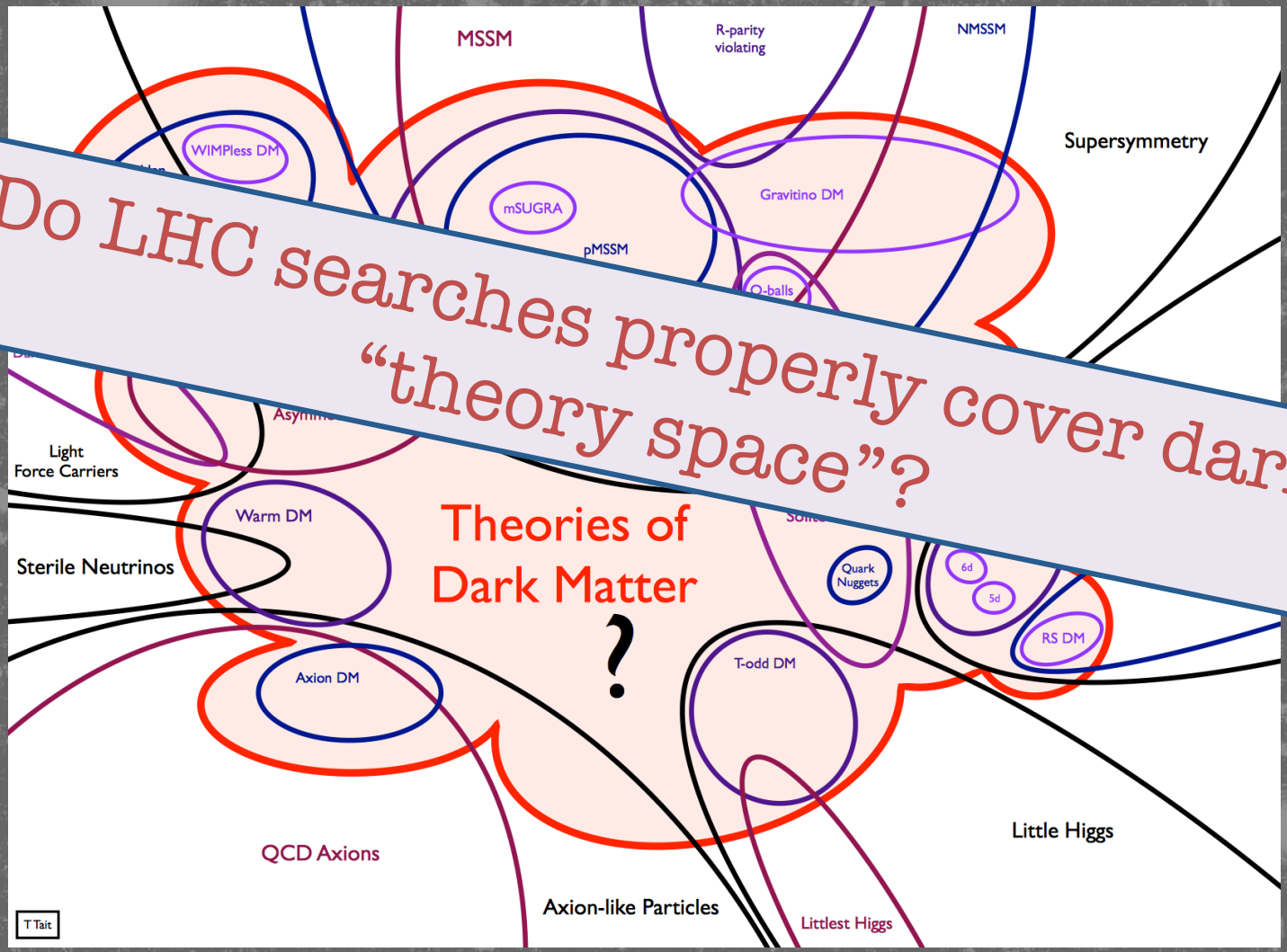
But there are some ideas...



Stolen from slides of Tim Tait

Dark Matters

But there are some ideas...



Do LHC searches properly cover dark "theory space"?

Stolen from slides of Tim Tait

Topics of Focus

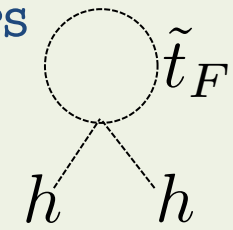
New ideas? New features from old ideas?

Neutral Naturalness

Personal perspective: These ideas are a decade old. Work since has been very valuable, but structurally not much has changed. Are there possibilities we haven't found yet? Are there signatures we are overlooking?

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners

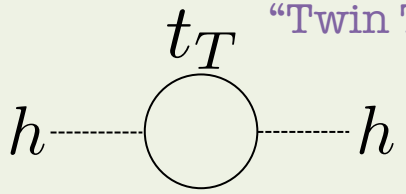


"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



"Twin Tops"

...but they must be charged under new hidden QCD'.

Topics of Focus

Flavour? B-meson anomalies... What else is left to study?

Summary

A collider search is a question:

"Does there exist..."

What questions are we not asking, and why not?