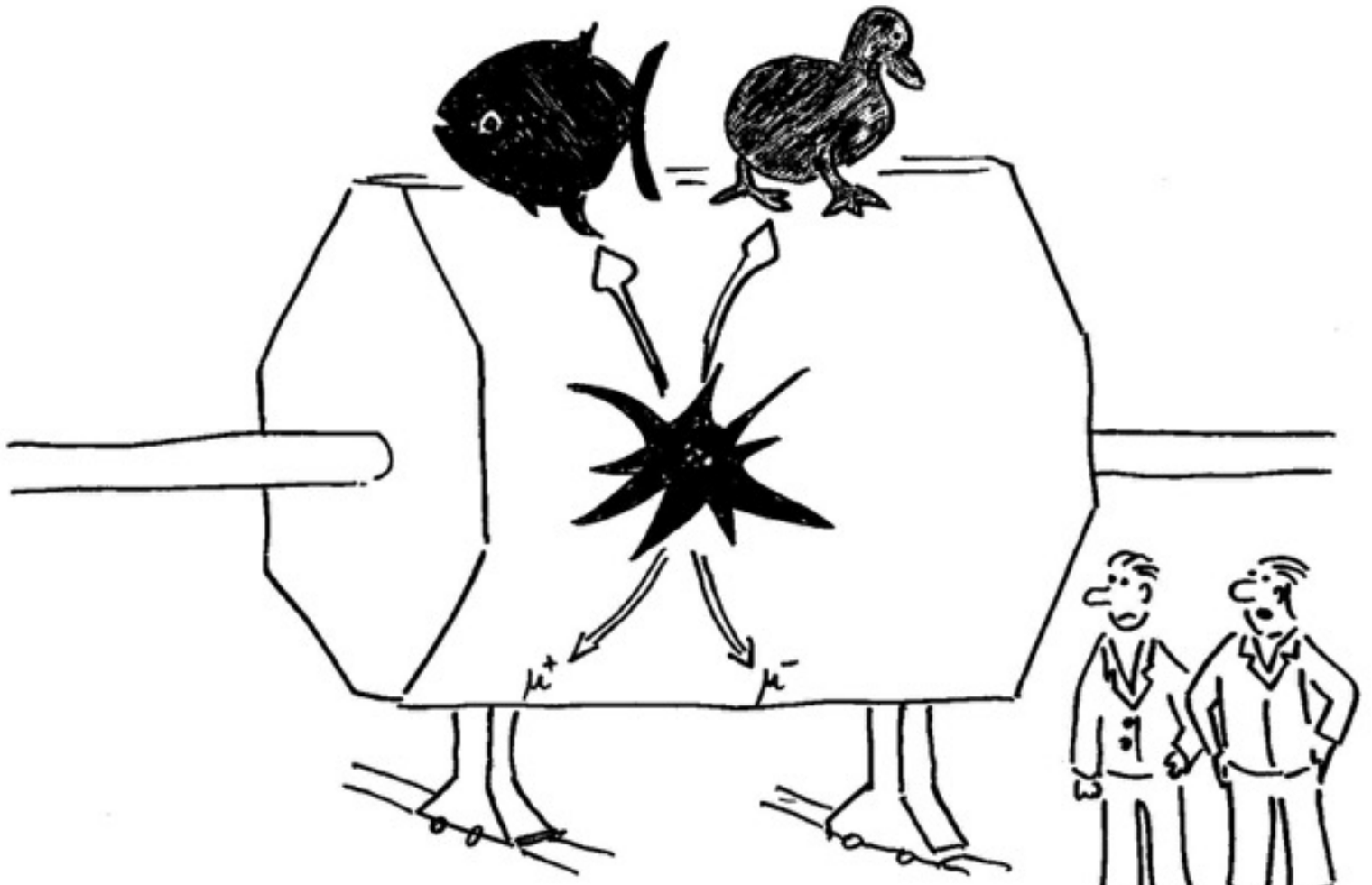
Exotic Higgs decays in Neutral Naturalness



"This is not exactly, what theory predicted for the Higgs decay!"

Simon Knapen
UC Berkeley & LBNL

This talk

"General introduction to Neutral Naturalness and it's relevance for exotic Higgs decays"

Also

Warm-up for

David Curtin — Phenomenology of Neutral Naturalness

Eric Kuflik — Displaced decays

This talk

"General introduction to Neutral Naturalness and it's relevance for exotic Higgs decays"

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Warm-up for

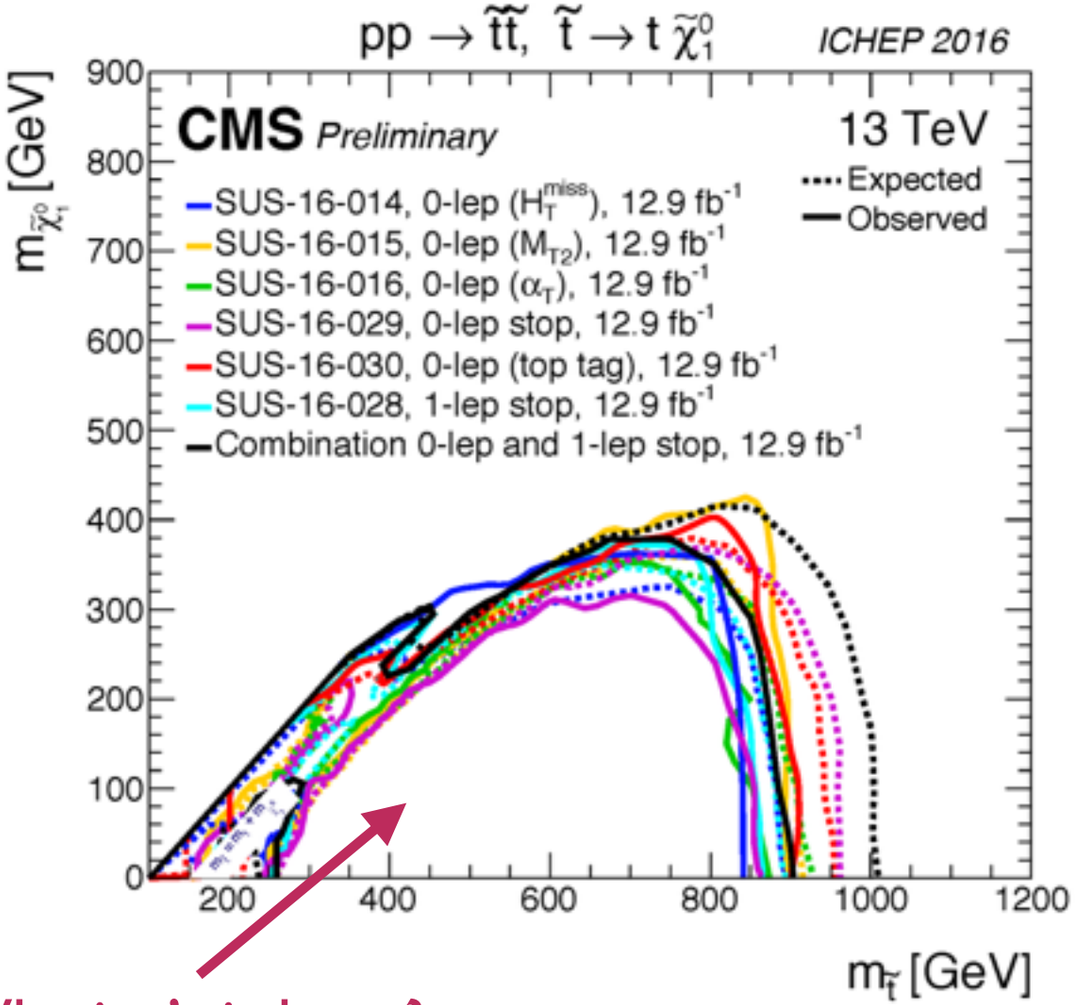
David Curtin — Phenomenology of Neutral Naturalness

Eric Kuflik — Displaced decays

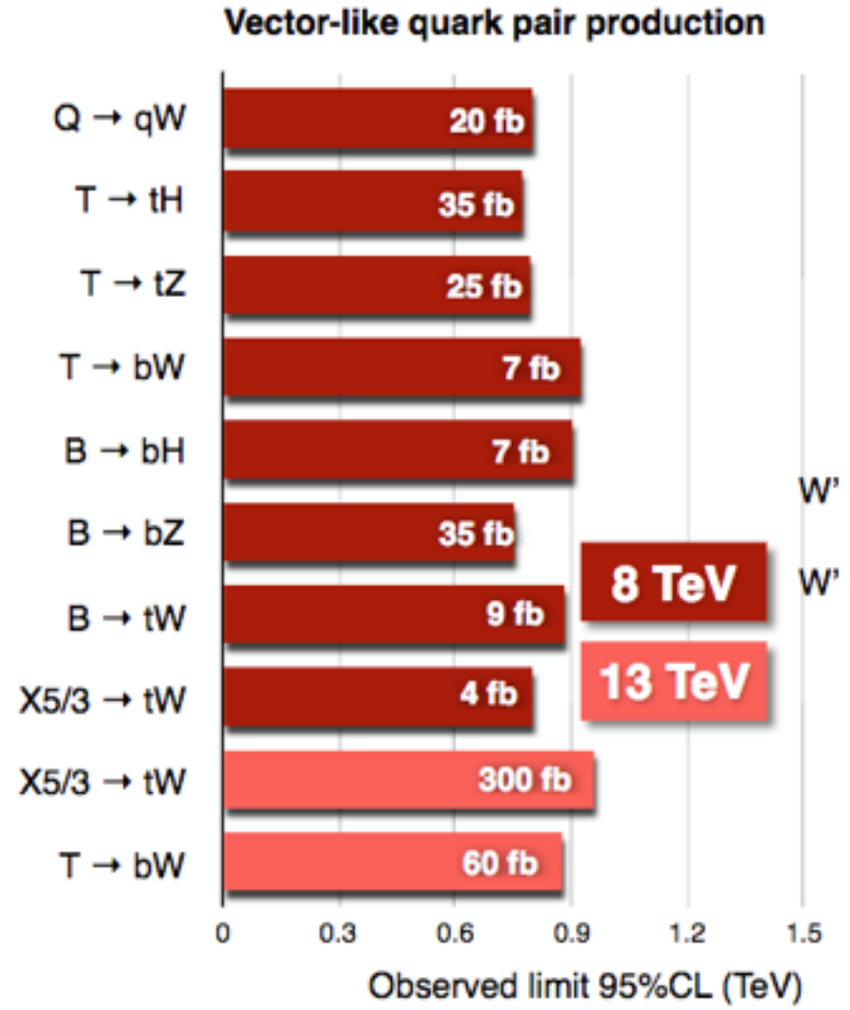
- Heavy bias towards Exotic Higgs decays
- (Nearly) nothing about models, UV completions,…
- Experts may learn nothing new…

Lots of (interesting) subtleties under the carpet

Top partners?



Why isn't it here?



Hide it

- RPV
- Stealth
- Squeezed
- …

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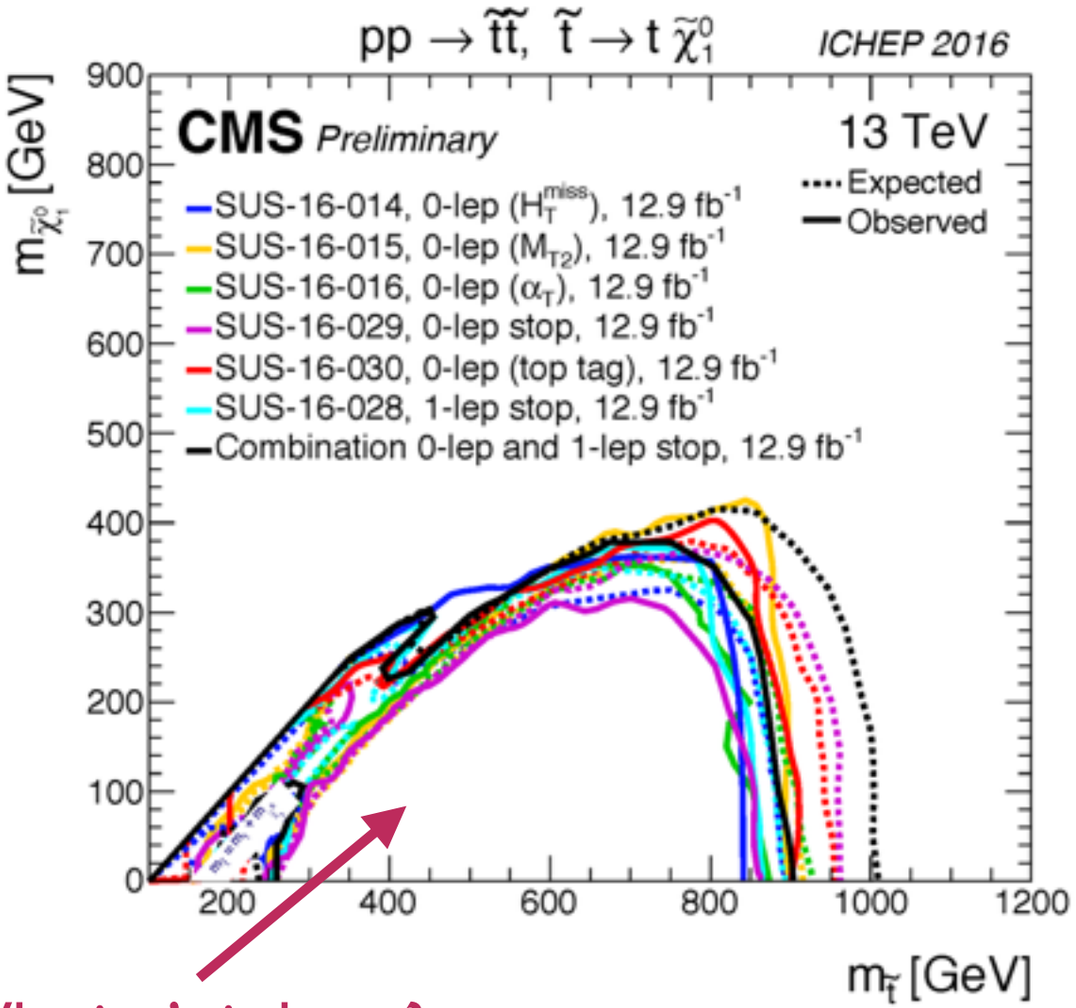

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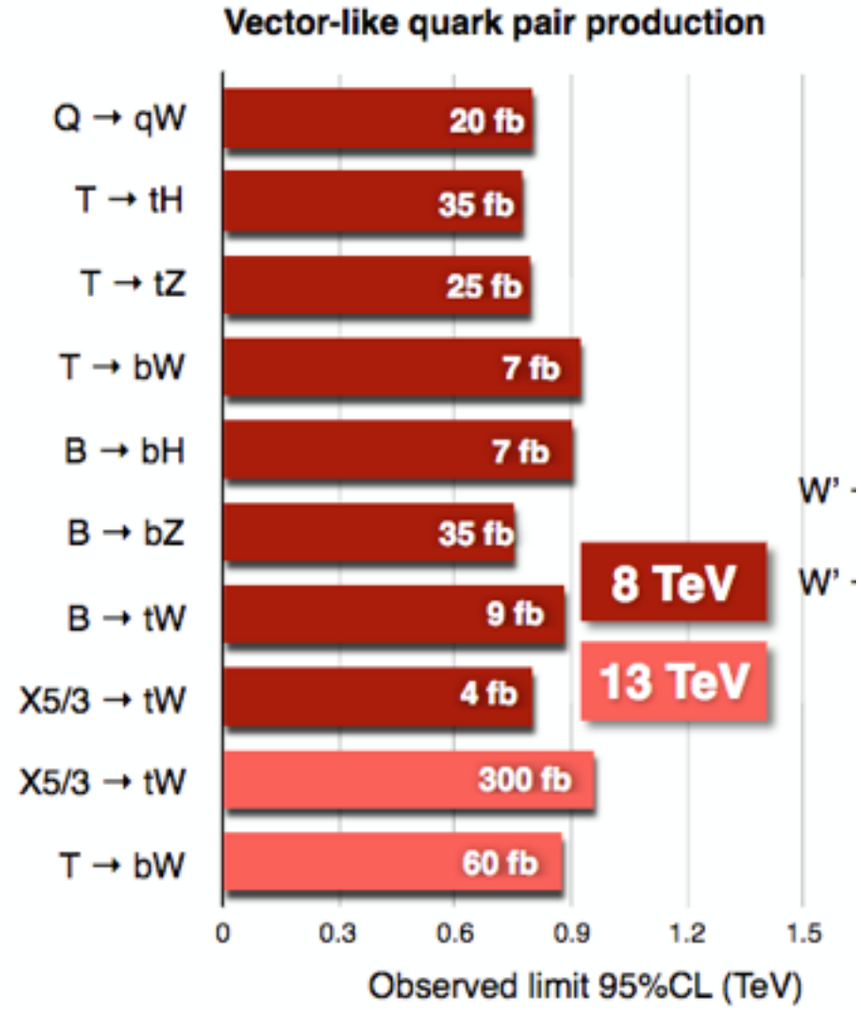

Hide it

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OR

Kill production cross section

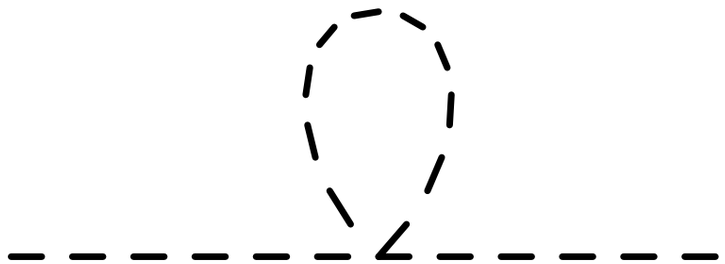
↓

Color neutral top partners

Canceling the divergence

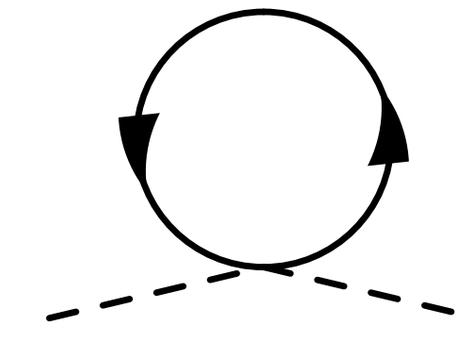
Symmetries protect the Higgs mass

supersymmetry



$$\sim \frac{N_c}{16\pi^2} y_t^2 \Lambda^2$$

global symmetry



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At 1 loop, only the number of colors enters

Canceling the divergence

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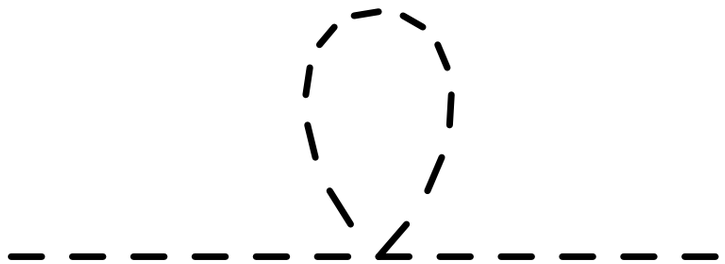

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Folded supersymmetry

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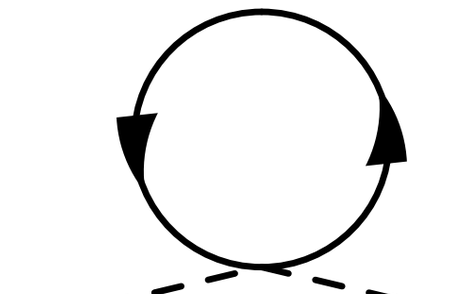

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Twin Higgs

Uncolored top partners?

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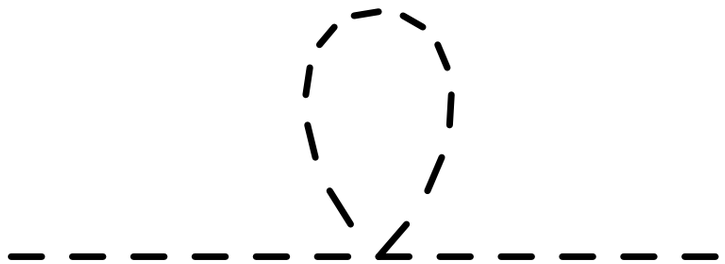

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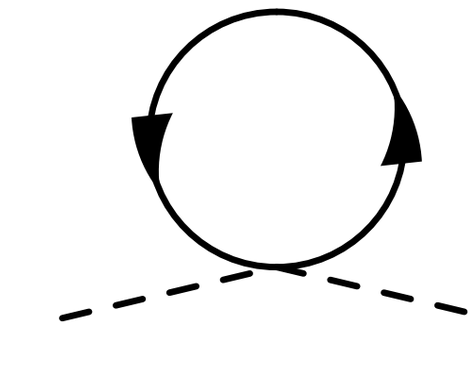

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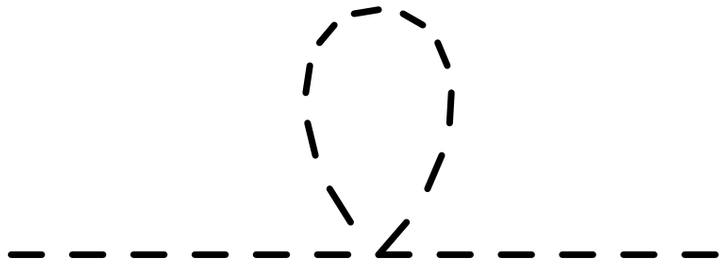

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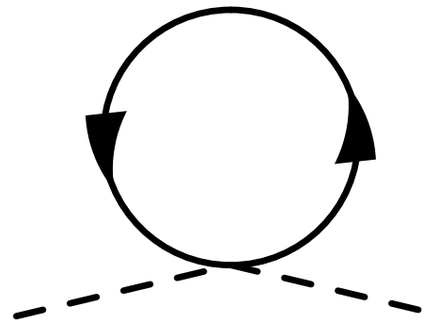

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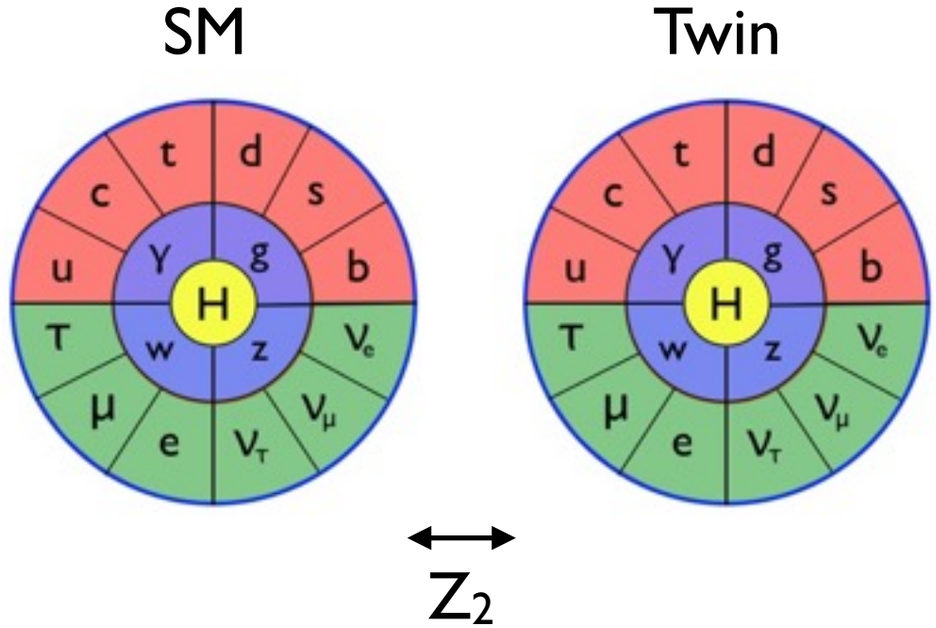
The Twin Higgs

<u>Ingredients:</u>

1. Fully dark, but otherwise identical copy of the Standard Model

2. SU(4) symmetry for the Higgs potential



Z. Chacko, H. Goh, R. Harnik, '05

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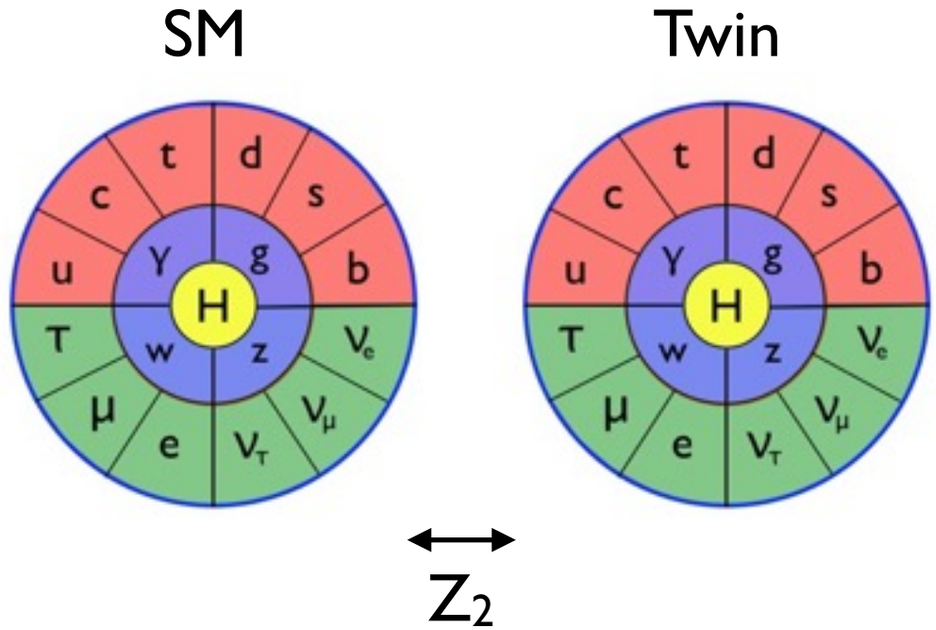

$$V(H) = -m^2|H|^2 + \lambda|H|^4 + \delta\left(|h_A|^4 + |h_B|^4\right) \qquad H = \begin{pmatrix} h_A \\ h_B \end{pmatrix}$$

Spontaneously breaks SU(4) → SU(3)

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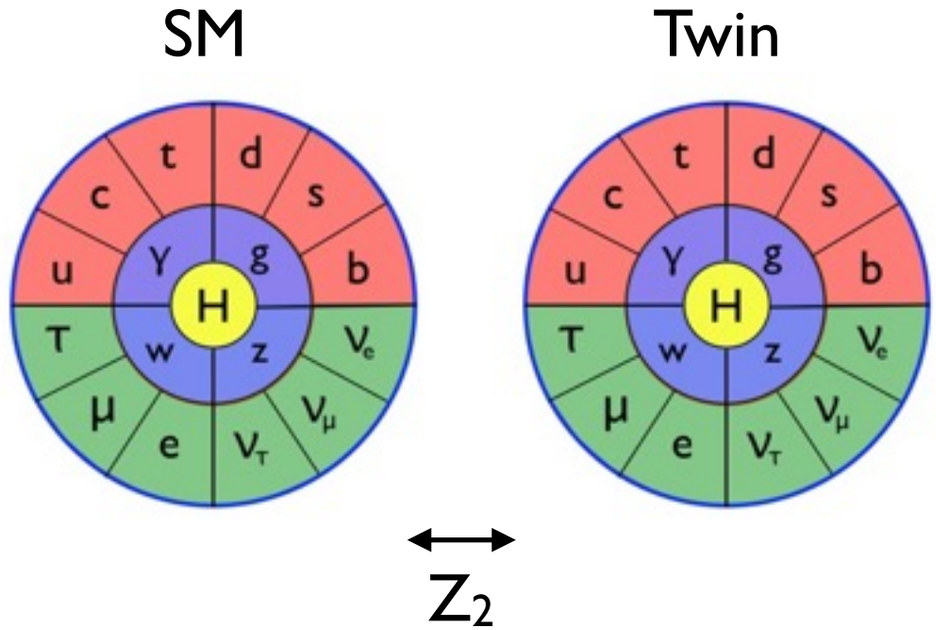

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Spontaneously breaks SU(4) → SU(3)

7 Goldstone bosons:

- 3 eaten by our Z,W
- 3 eaten by twin Z,W
- 1 light scalar @ 125 GeV

1 radial mode ($\gtrsim$ 1 TeV)

Z. Chacko, H. Goh, R. Harnik, '05

...

The Twin Higgs

$$V(H) \supset -m^2|H|^2 + \lambda|H|^4 + \underset{\text{SM top}}{y_t h_A q_A u_A} + \underset{\text{Twin top}}{y_t h_B q_B u_B}$$

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125 GeV scalar is a mixture of the SM Higgs and the Twin Higgs

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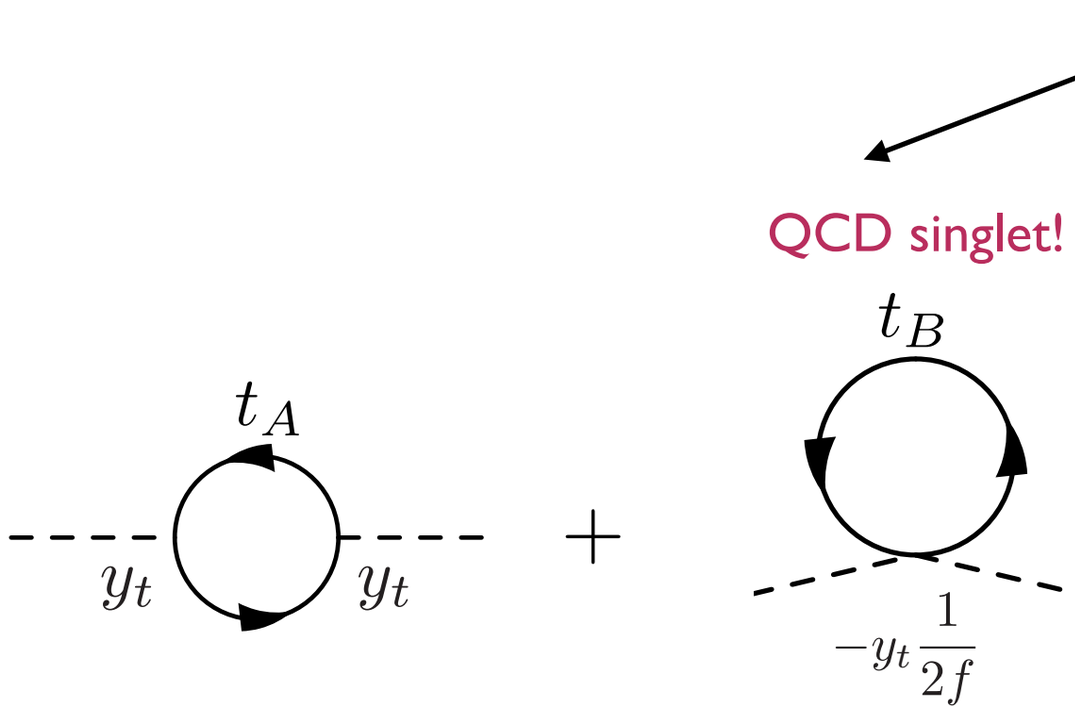

Twin top cancel the quadratic divergence

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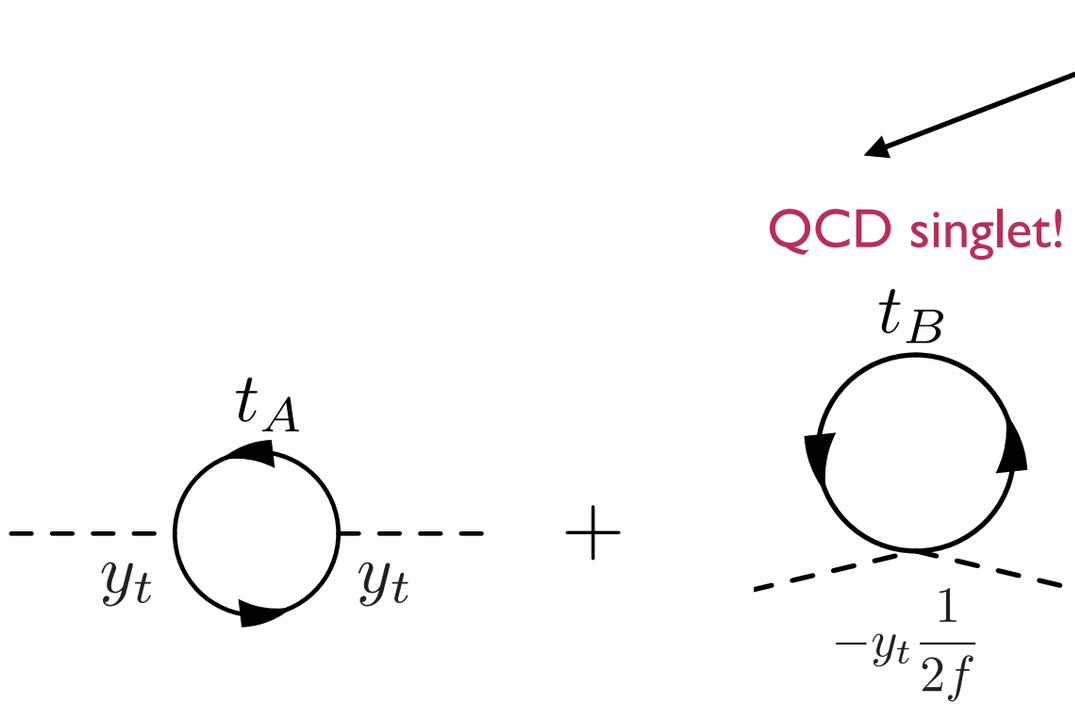


Twin top cancel the quadratic divergence

Exotic Higgs decays +
Deviations in Higgs couplings

↓

only* signatures of

Twin Higgs models!

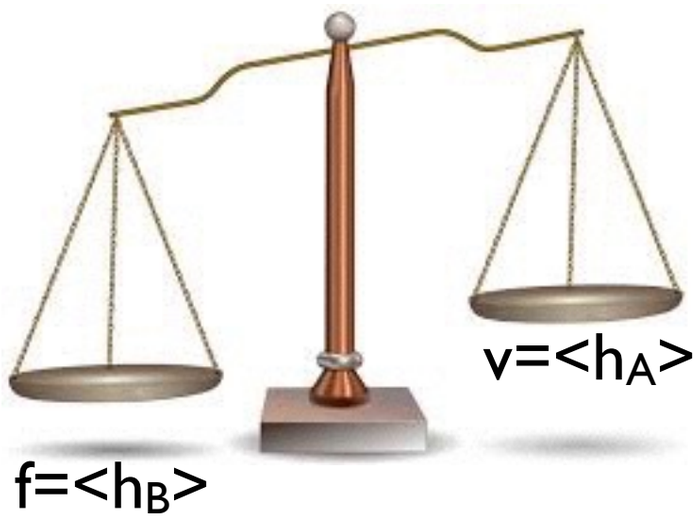
(No new states charged under the SM)

* unless you are very lucky with the UV completion

Higgs couplings

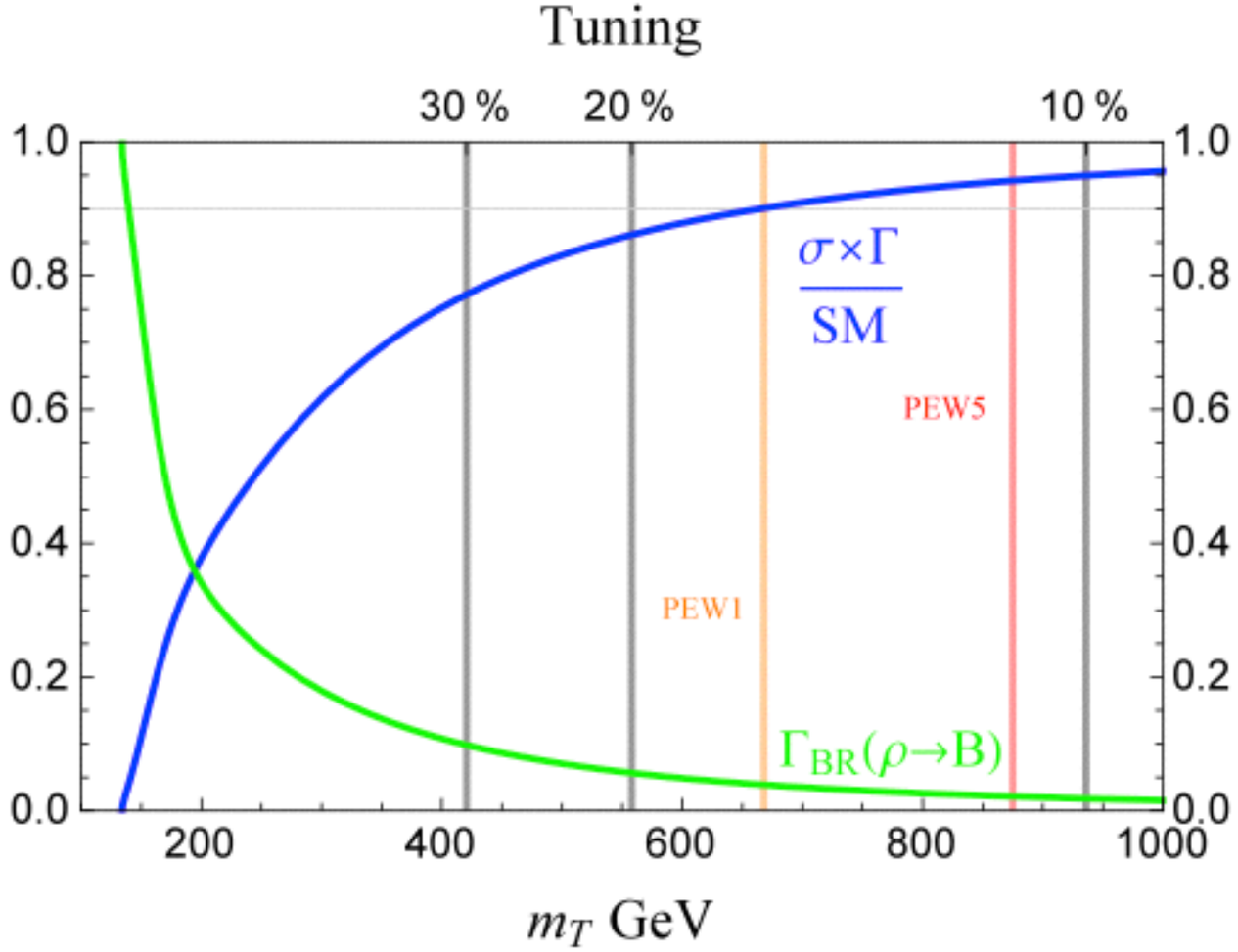
Generically, SM and Twin Higgs maximally mixed

Order one deviations in the Higgs couplings



Tuning ~ (f / v)^2

(Generic feature of pNGB Higgs models)



1411.3310: G. Burdman, Z. Chacko, L. de Lima, R. Harnik, C. B. Verhaaren

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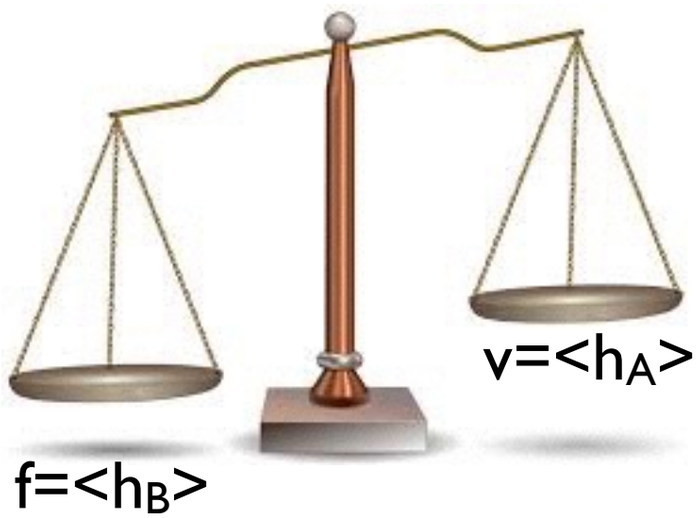

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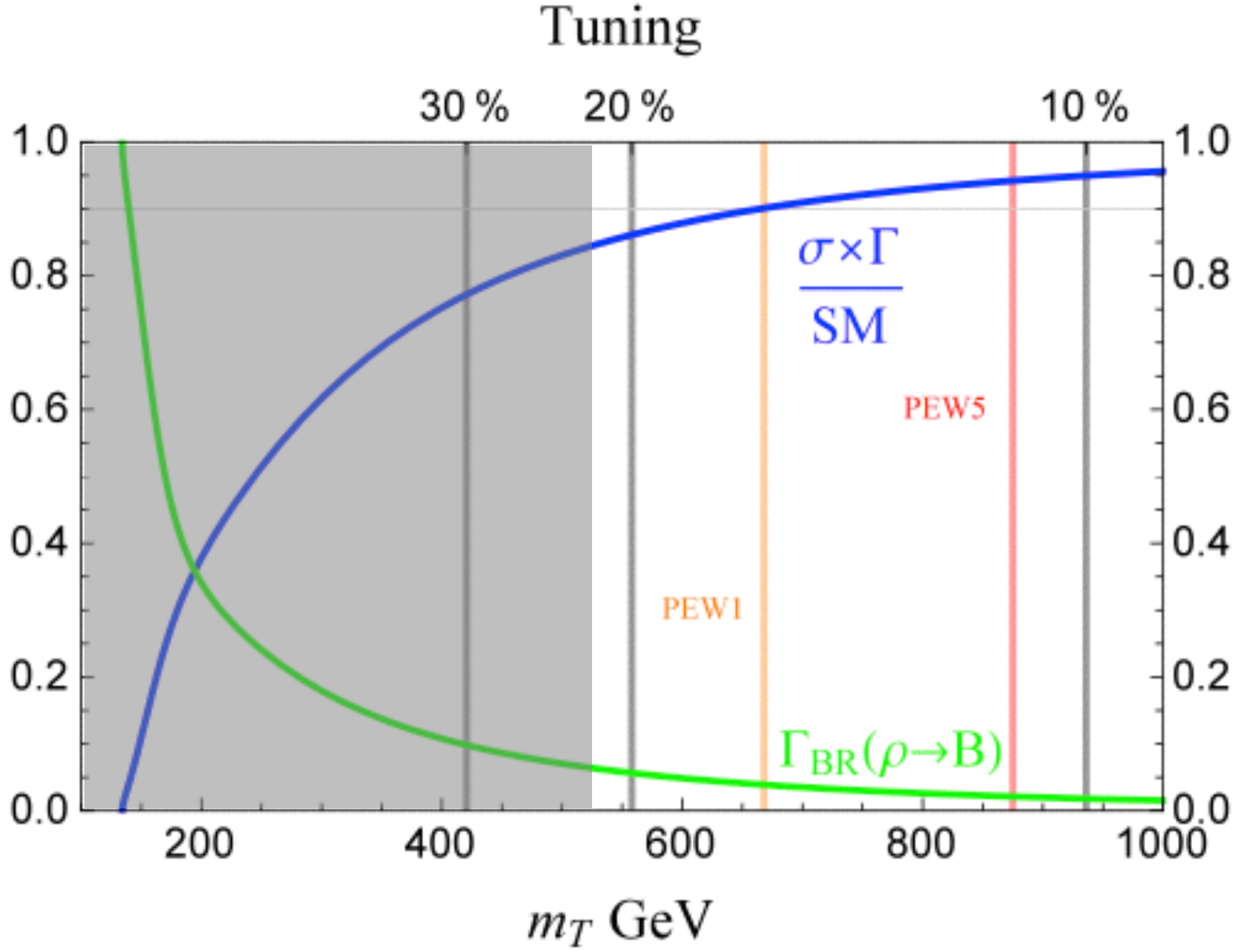

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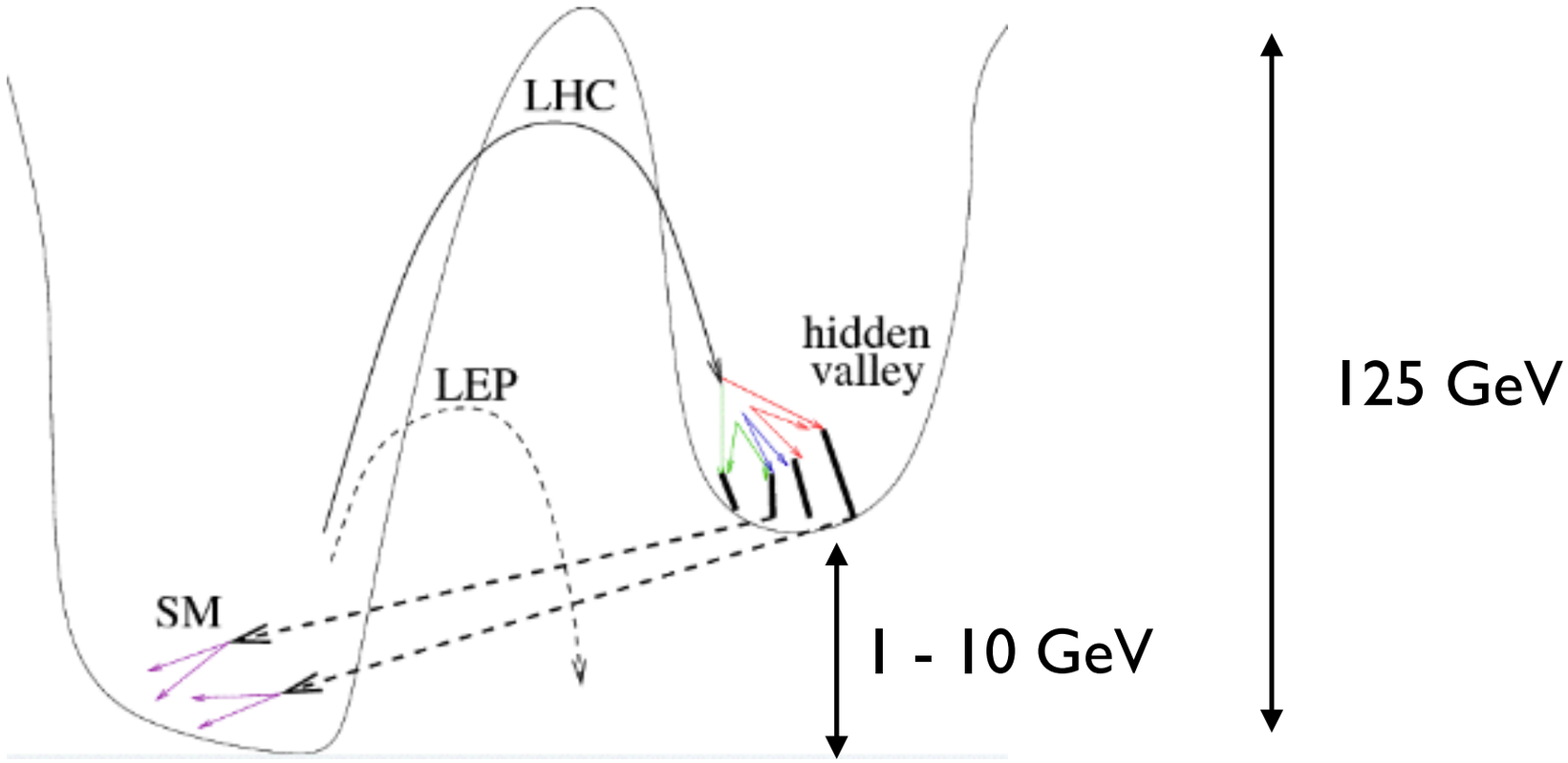
The Twin Higgs = Hidden Valley



Twin Higgs is much more predictive than generic Hidden Valley

Still, there are a number of options

M. Strassler, K. Zurek : 0604261, 0605193, 0607160
…

Anatomy of a Twin Higgs model

Natural Supersymmetry

- Higgsino < 400 GeV
- Stop & sbottom < 500 GeV
- Gluino < 1.5 TeV

- Wino
- Bino
- Sleptons
- Squarks

Can be decoupled

Anatomy of a Twin Higgs model

Natural Supersymmetry			Twin Higgs	
• Higgsino	< 400 GeV	⟷	• Twin Higgs	(small vev)
• Stop & sbottom	< 500 GeV	⟷	• Twin top & twin bottom	< 500 GeV
• Gluino	< 1.5 TeV	⟷	• Twin QCD scale	< 10 GeV
• Wino • Bino • Sleptons • Squarks	Can be decoupled	⟷	• Twin W / Z • Twin photon • Twin leptons • Twin quarks	< 300 GeV Can be decoupled / omitted

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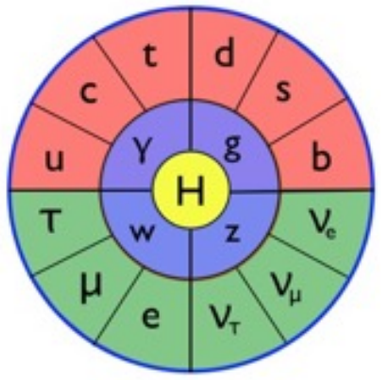
Pheno depends strongly on

Lightest Supersymmetric Particle (LSP)

Lightest Twin Particle (LTP)

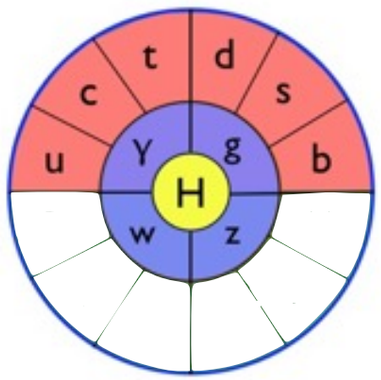
Scenario's



Z_2 symmetric twin

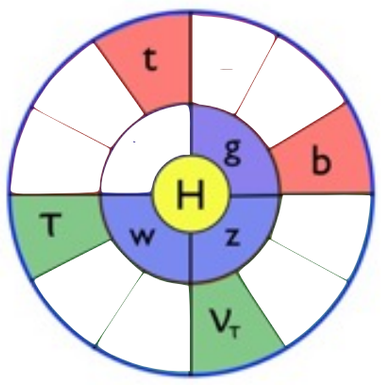
<u>Lightest Twin Particle (LTP)</u>

twin lepton



Hadro-symmetric twin

twin pion

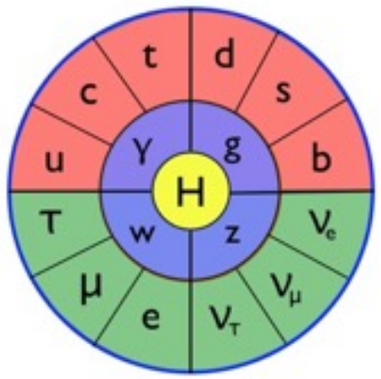


Fraternal twin

twin glueball / bottomium

(Variations of course possible)

Scenario's



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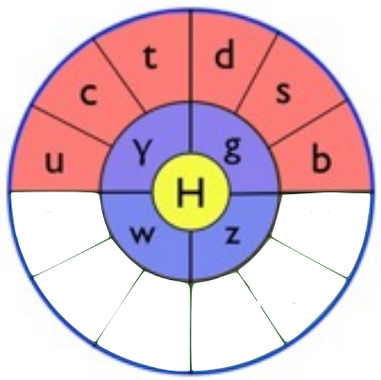

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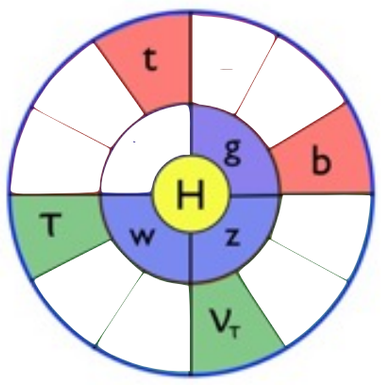

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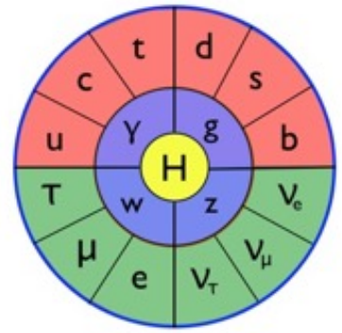
Complexity

(Variations of course possible)

Z_2 symmetric Twin



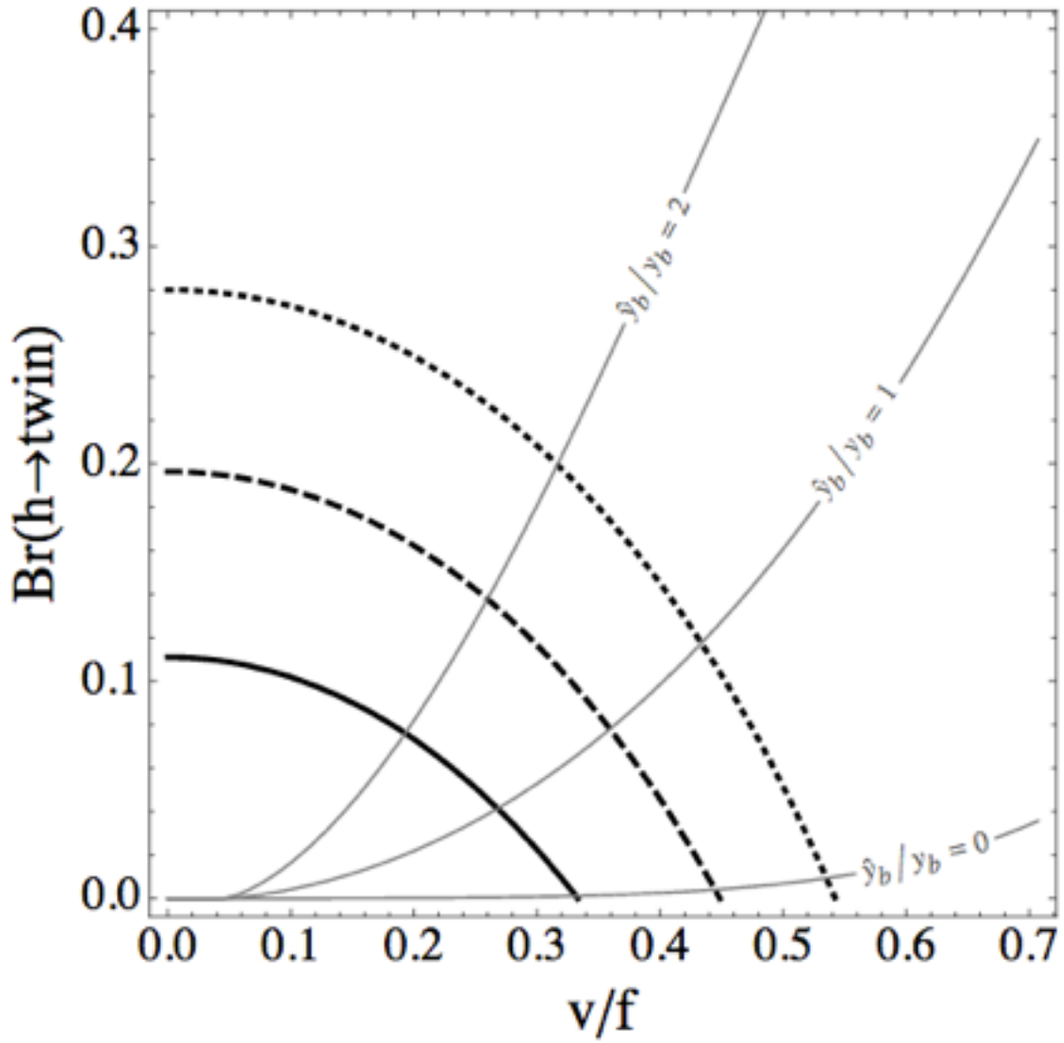
LTP : Twin leptons / Twin photon
(Stable)

<u>Exotic Higgs decay:</u> $h \to b_B \bar{b}_B$

Showers into fully invisible twin b-jets

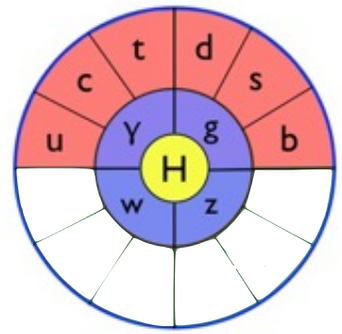
Standard cosmology ruled out

- Modify the spectrum
- Or dilute the twin sector



1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

Hadro-symmetric Twin



LTP : Twin pions

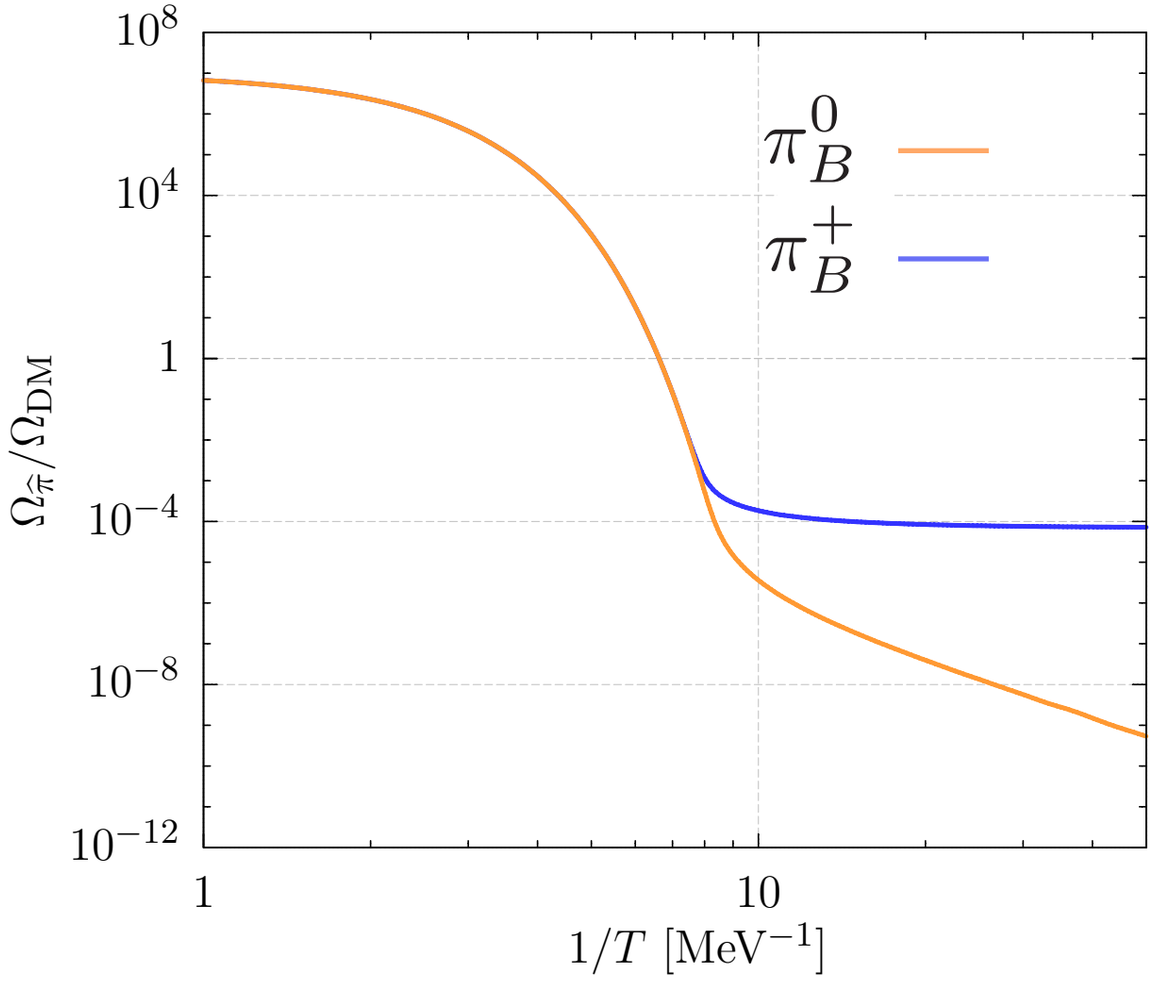
π_B^+ stable

π_B^0 metastable

Avoid matter domination during BBN

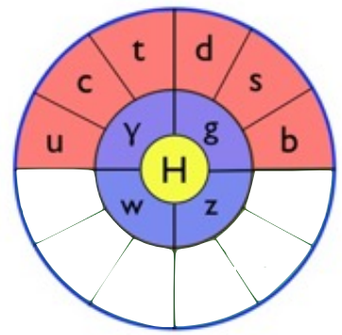
↓

π_B^0 lifetime < 1 second



M. Freytsis, SK, D. Robinson, Y. Tsai: 1601.07556

Hadro-symmetric Twin



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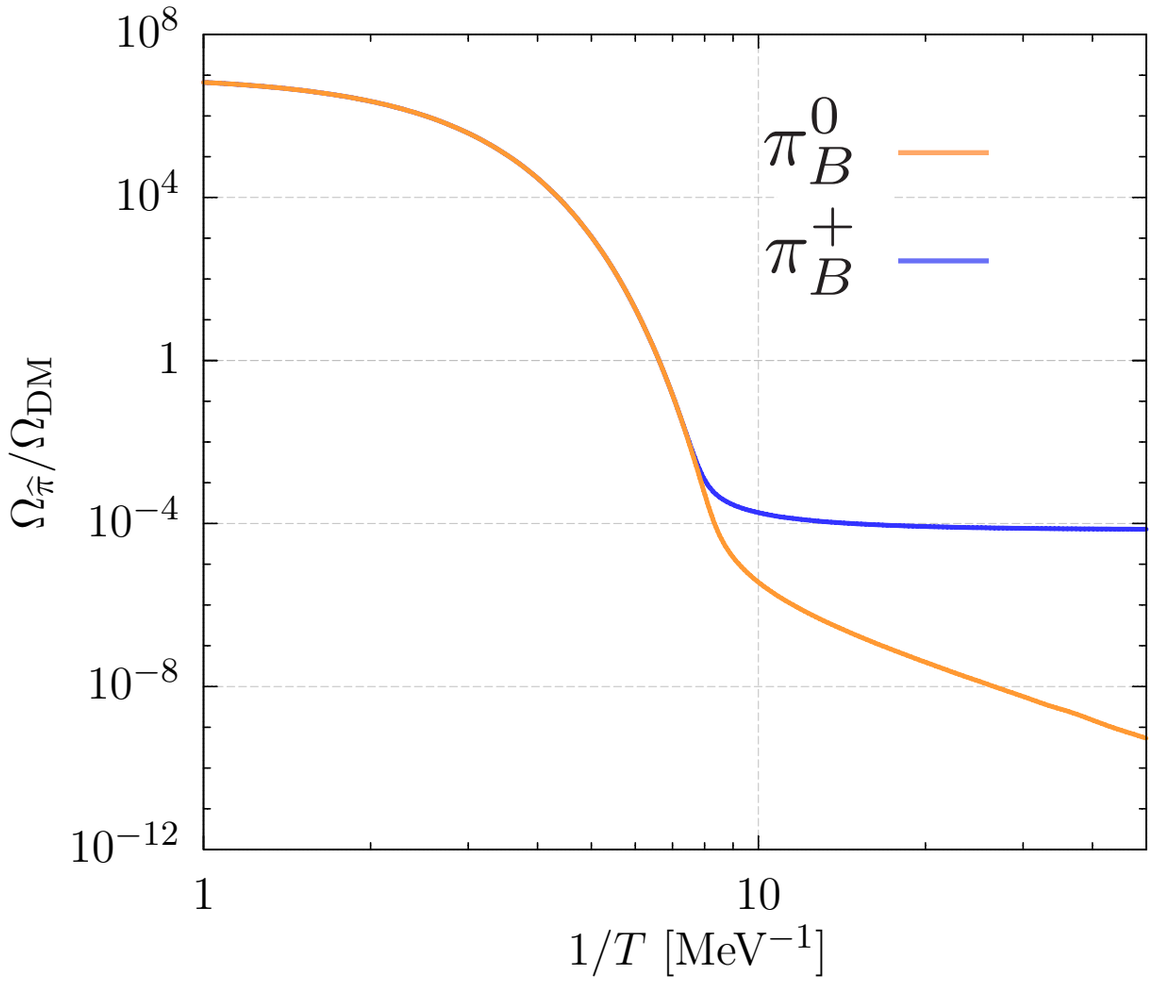


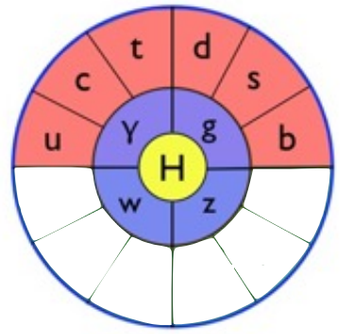
Possible decay modes:

$$\pi_B^0 \to 2\gamma$$
$$\pi_B^0 \to 2\ell$$
$$\pi_B^0 \to 4\ell$$

→ Cosmic ray experiments

M. Freytsis, SK, D. Robinson, Y. Tsai: 1601.07556

Hadro-symmetric Twin



$\pi_B^0 \to 2\gamma$

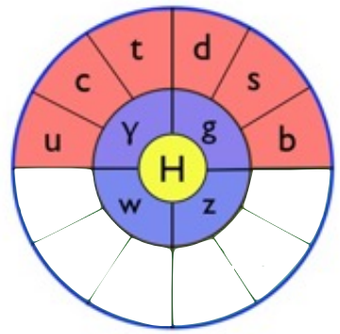
$\pi_B^0 \to 2\ell$

$\longrightarrow$ Always very displaced

$\pi_B^0 \to 4\ell$ $\longrightarrow$ Prompt possible

J. Chou, D. Curtin, H. Lubatti: 1606.06298

Hadro-symmetric Twin



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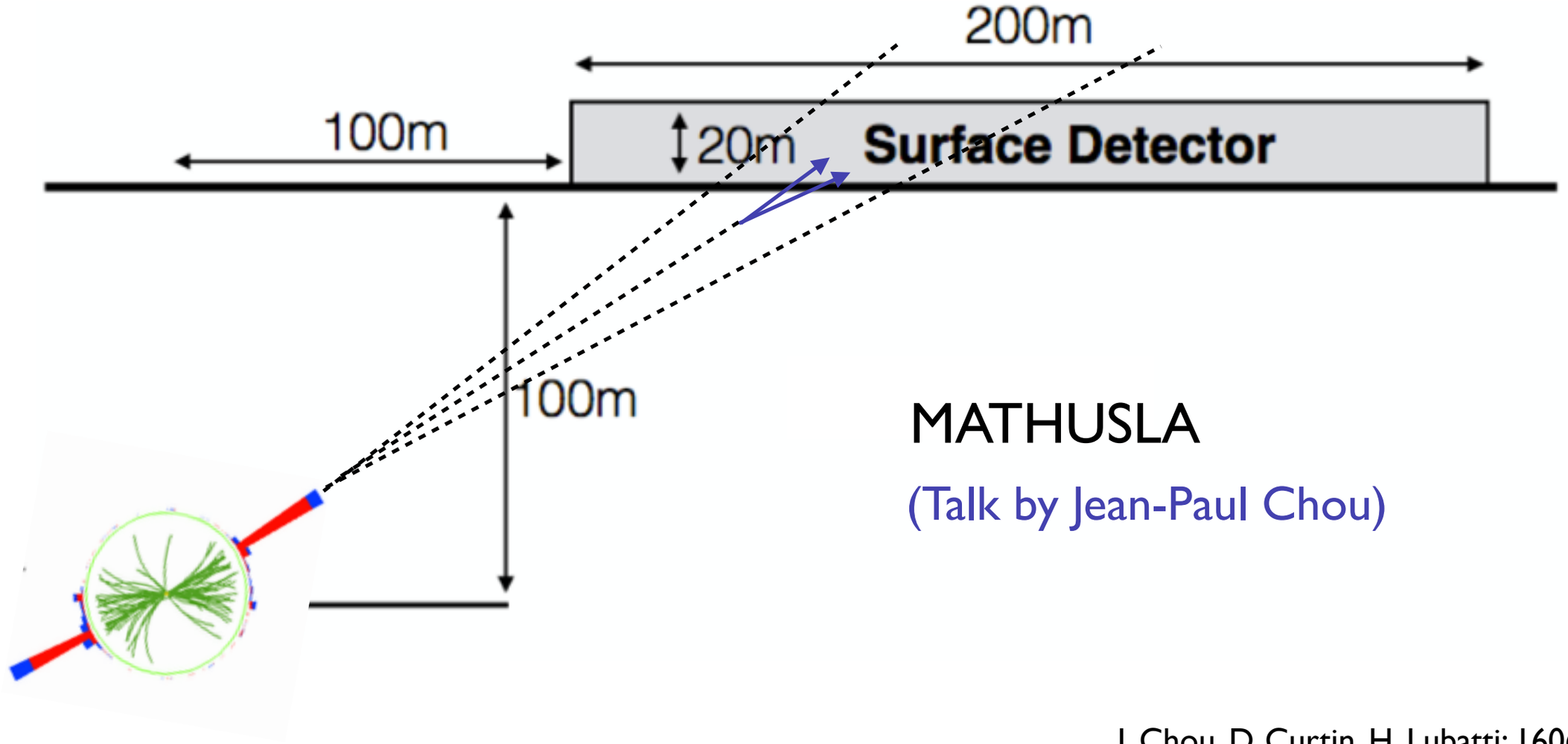
→ Always very displaced

$\pi_B^0 \to 4\ell$ → Prompt possible

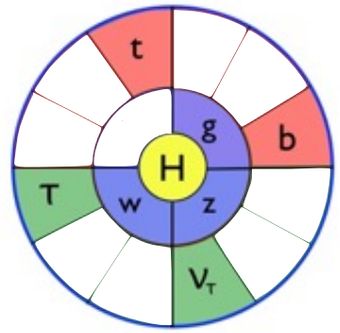


MATHUSLA

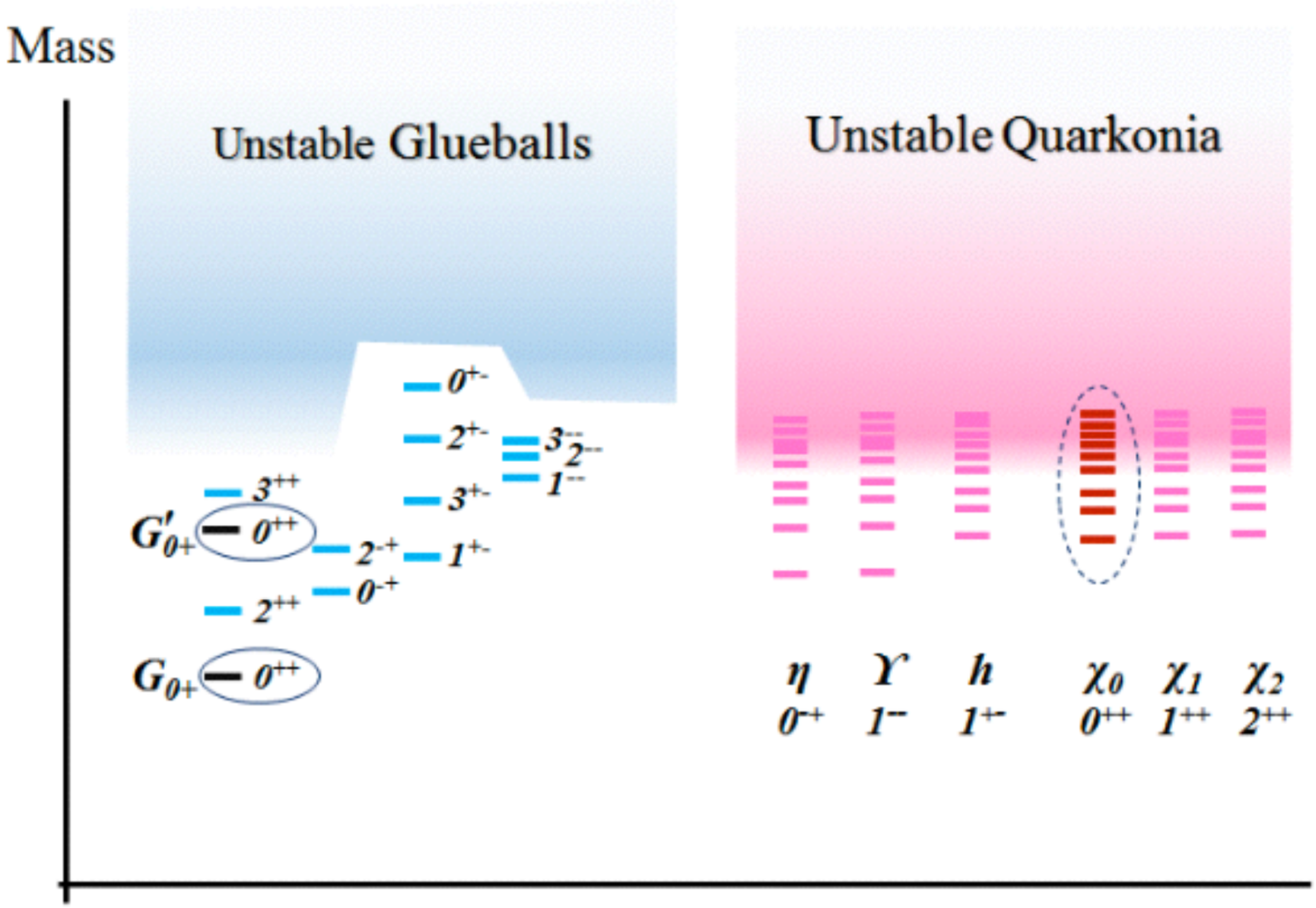
(Talk by Jean-Paul Chou)

J. Chou, D. Curtin, H. Lubatti: 1606.06298

Fraternal Twin



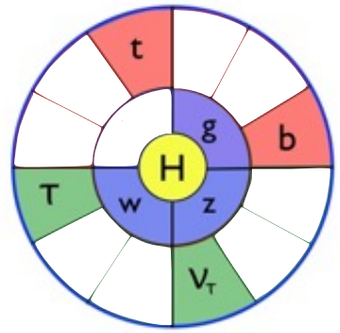
LTP : Twin glueball or bottomonium

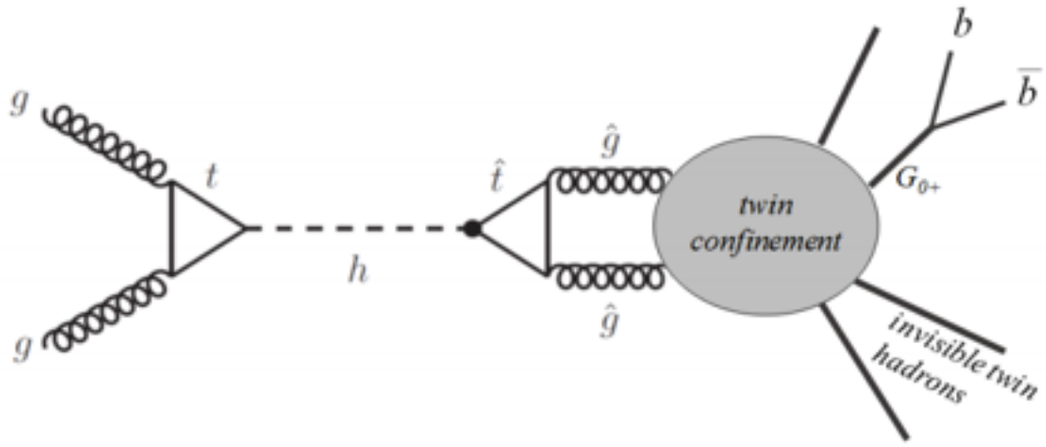


0^{++} states can decay by mixing with the Higgs

1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

Fraternal Twin





Glueball LTP

Life-time spans 18 orders of magnitude!

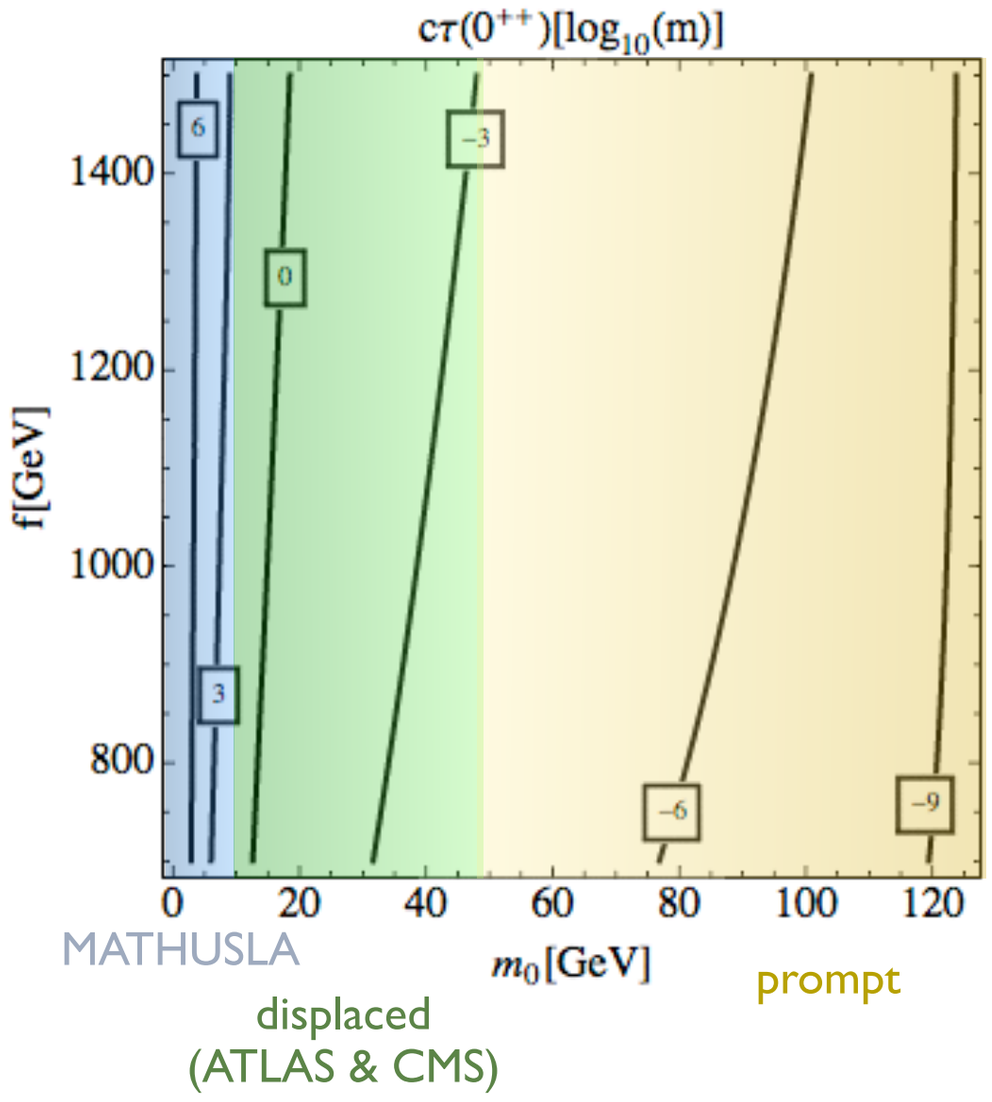
$$c\tau \sim 18\ \mathrm{m} \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7$$

Later this afternoon

David Curtin	(Theory)
Eric Kuflik	(Theory)
Henry Lubatti	(ATLAS)
Jamie Antonelli	(CMS)
Jean-Paul Chou	(MATHUSLA)

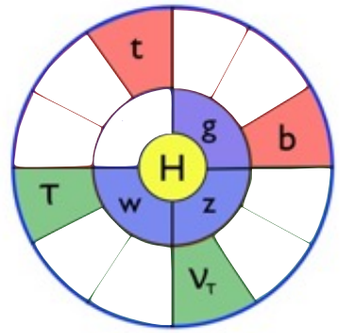
$h \rightarrow (bb)^n$ + MET

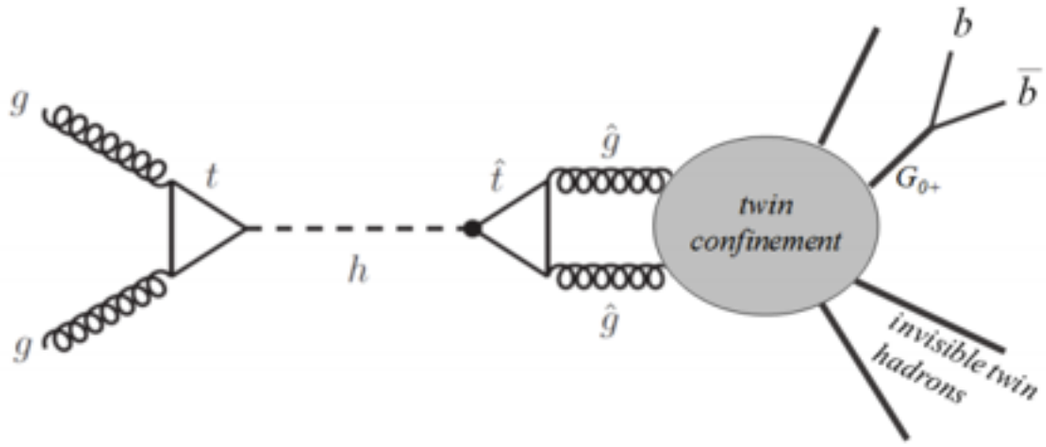
prompt or displaced



1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

Fraternal Twin





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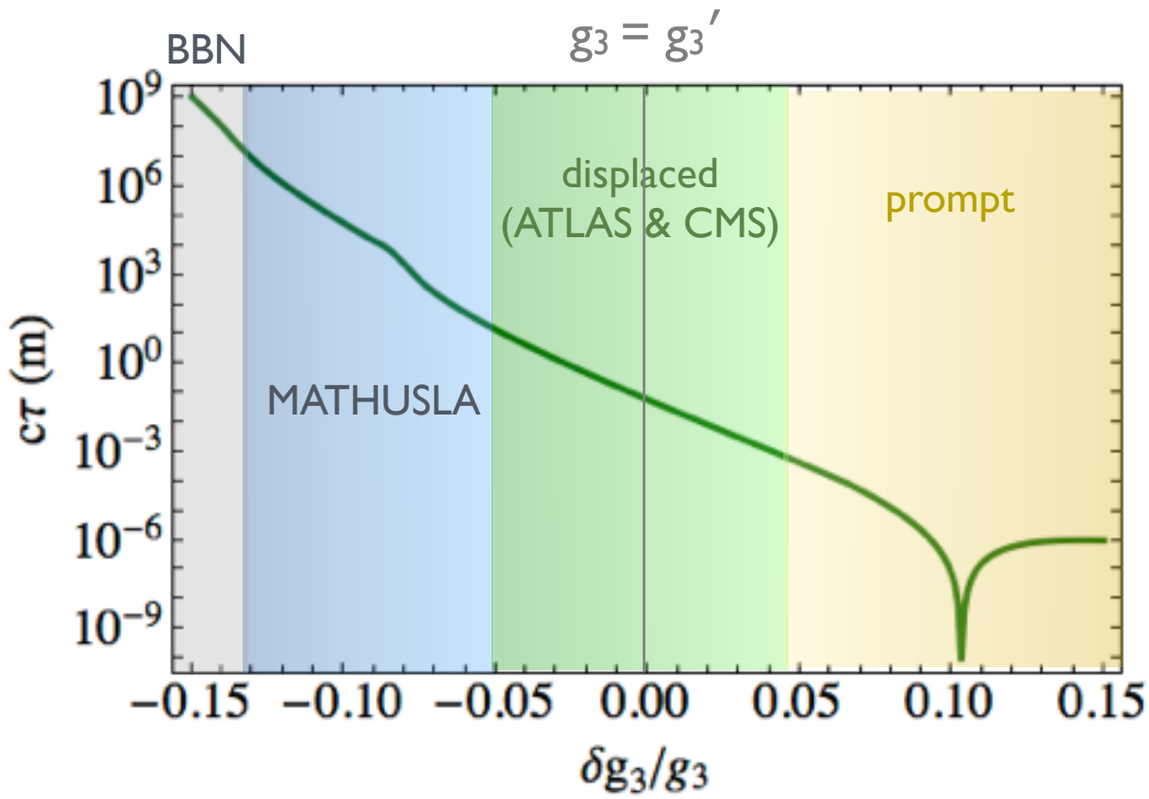


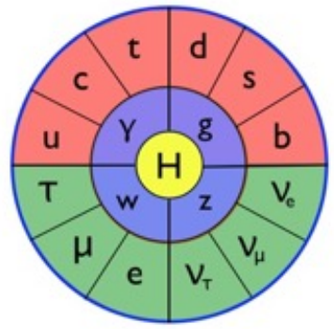
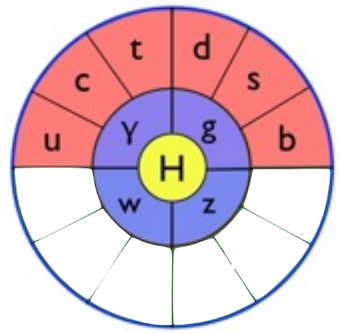
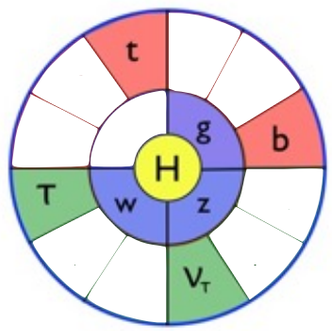
Possibly very complex dynamics (Hadronization)

1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

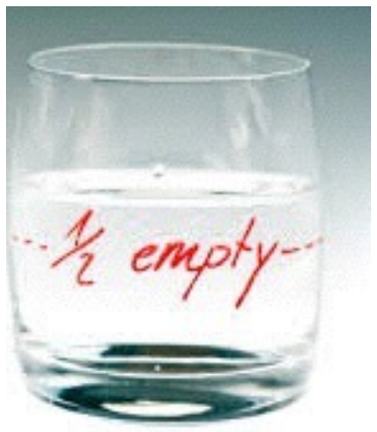
Later this afternoon

David Curtin (Theory)
Eric Kuflik (Theory)
Henry Lubatti (ATLAS)
Jamie Antonelli (CMS)
Jean-Paul Chou (MATHUSLA)

Summary

Observable \ Twin sector	 LTP: twin leptons	 LTP: twin pions	 LTP: twin glueball
Higgs couplings	$f/v \gtrsim 3$	$f/v \gtrsim 3$	$f/v \gtrsim 3$
Higgs decays	invisible	invisible / (very displaced) leptons	invisible / (displaced) b-jets
CMB	$\Delta N_{eff} \gtrsim 7$	$\Delta N_{eff} \gtrsim 0.075$	$\Delta N_{eff} = 0$
BBN	/	pion lifetime	Depends on spectrum
Intensity frontier	Dark photon searches	Dark photon searches	No signal
Dark Matter (Direct detection)	/	Higgs portal	Higgs portal
Dark Matter (Indirect detection)	/	$\gamma\gamma,\ \ell^+\ell^-$ (soft)	$bb,\ \tau^+\tau^-$

The bottom line

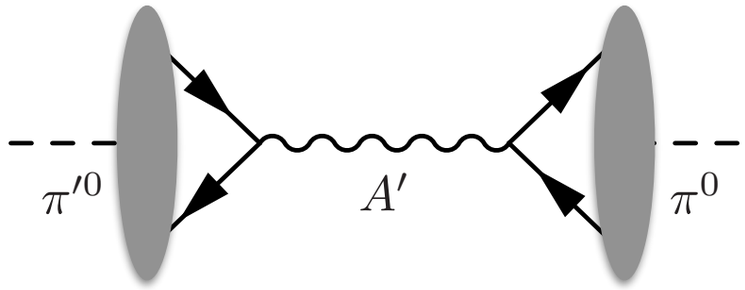


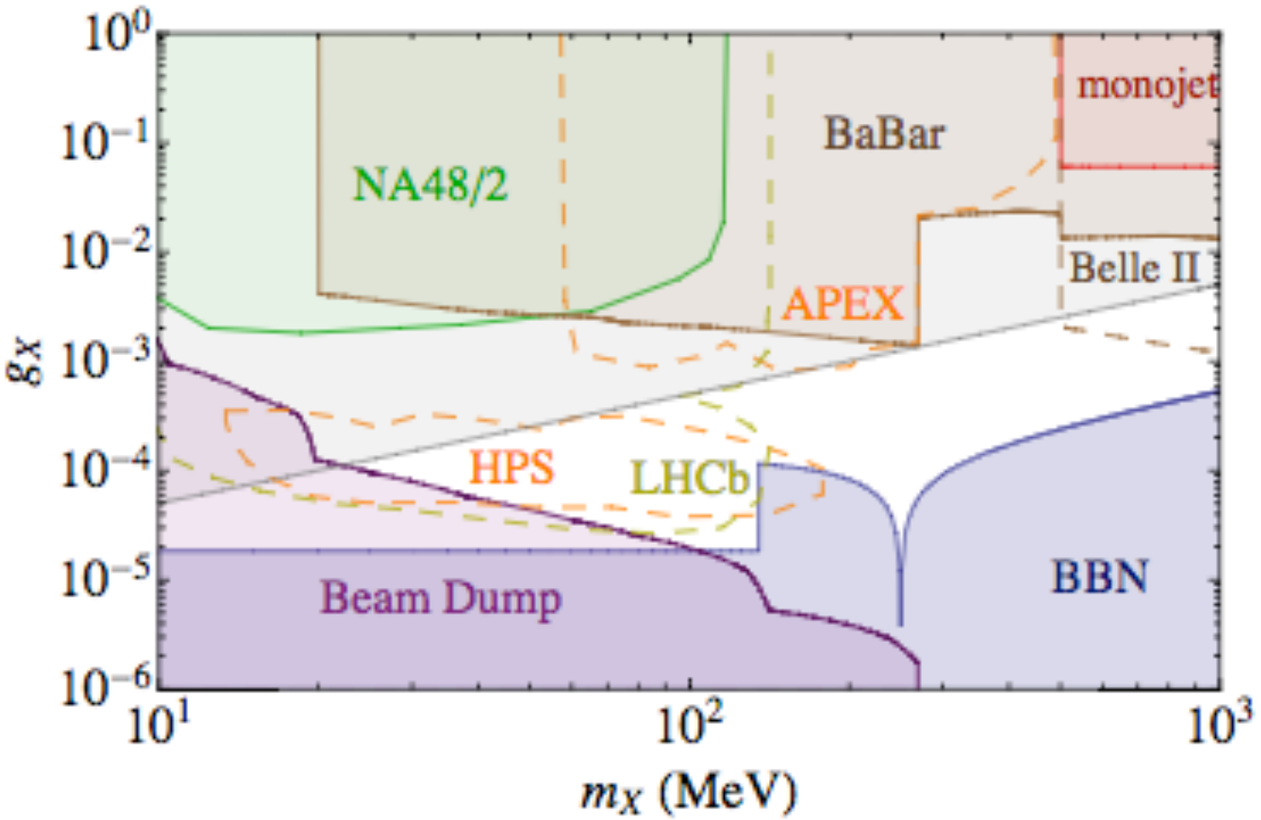
The twin Higgs could easily hide from us…
(…except at a Higgs factory)

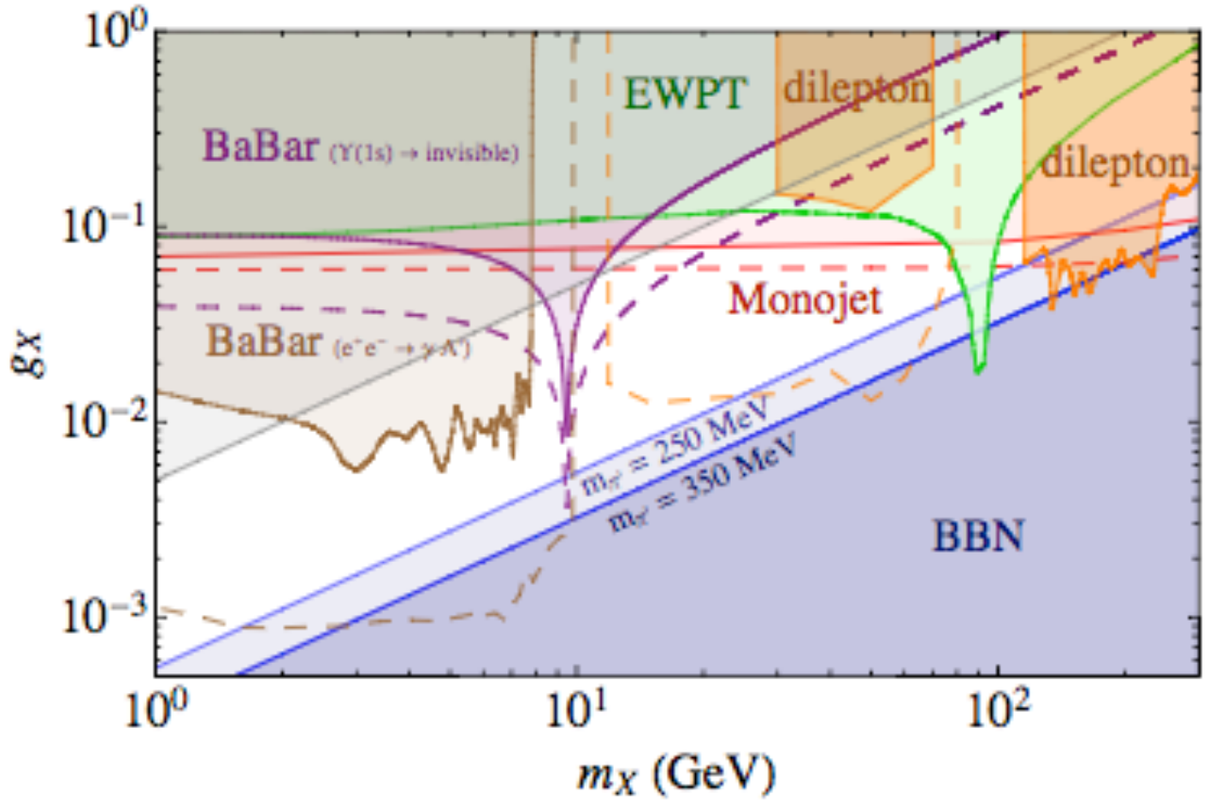
The twin Higgs could be found in exotic Higgs decays
or cosmology / astrophysics

back-up slides

Axial Z′

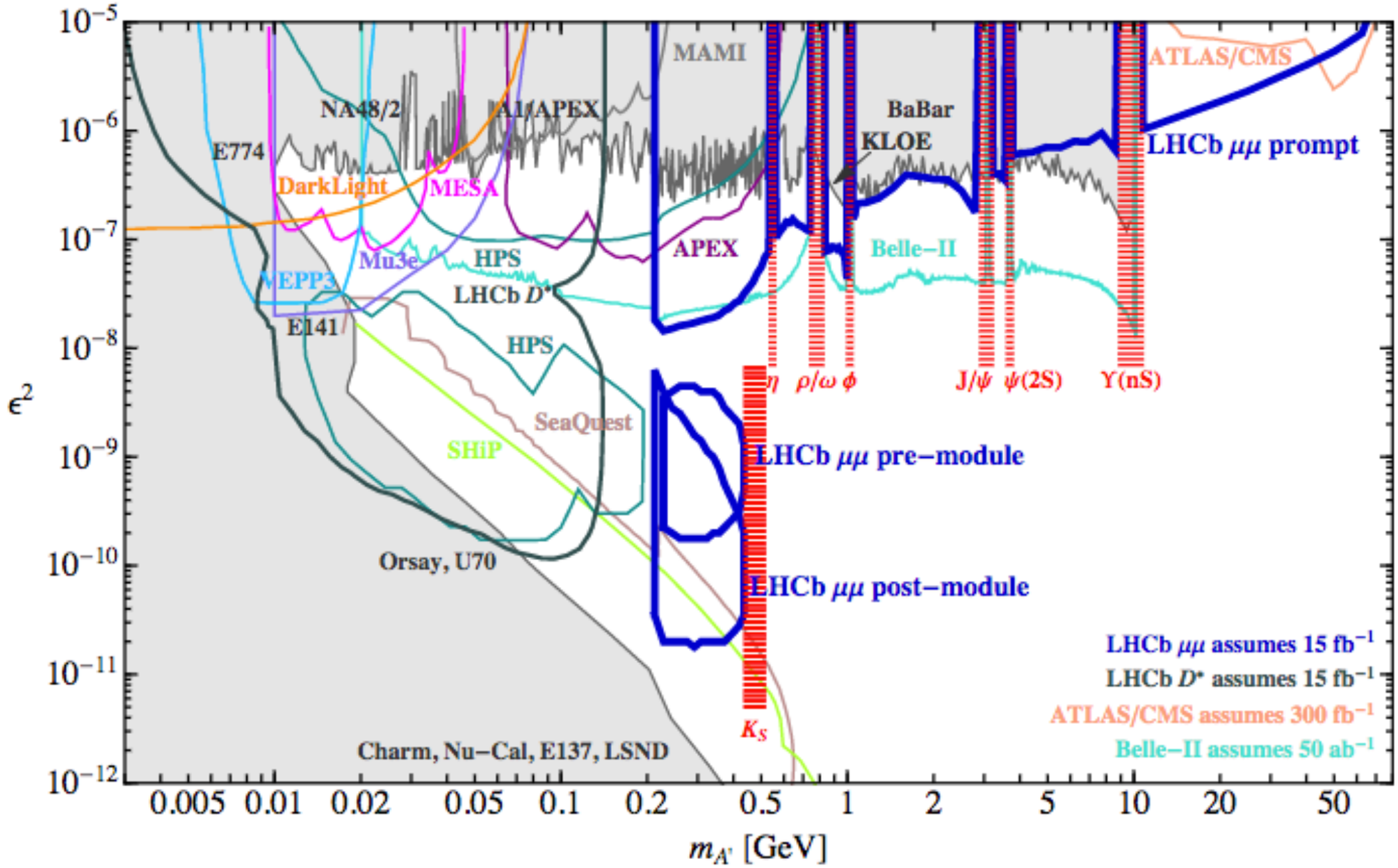






M. Freytsis, SK, D. Robinson, Y. Tsai: 1601.07556

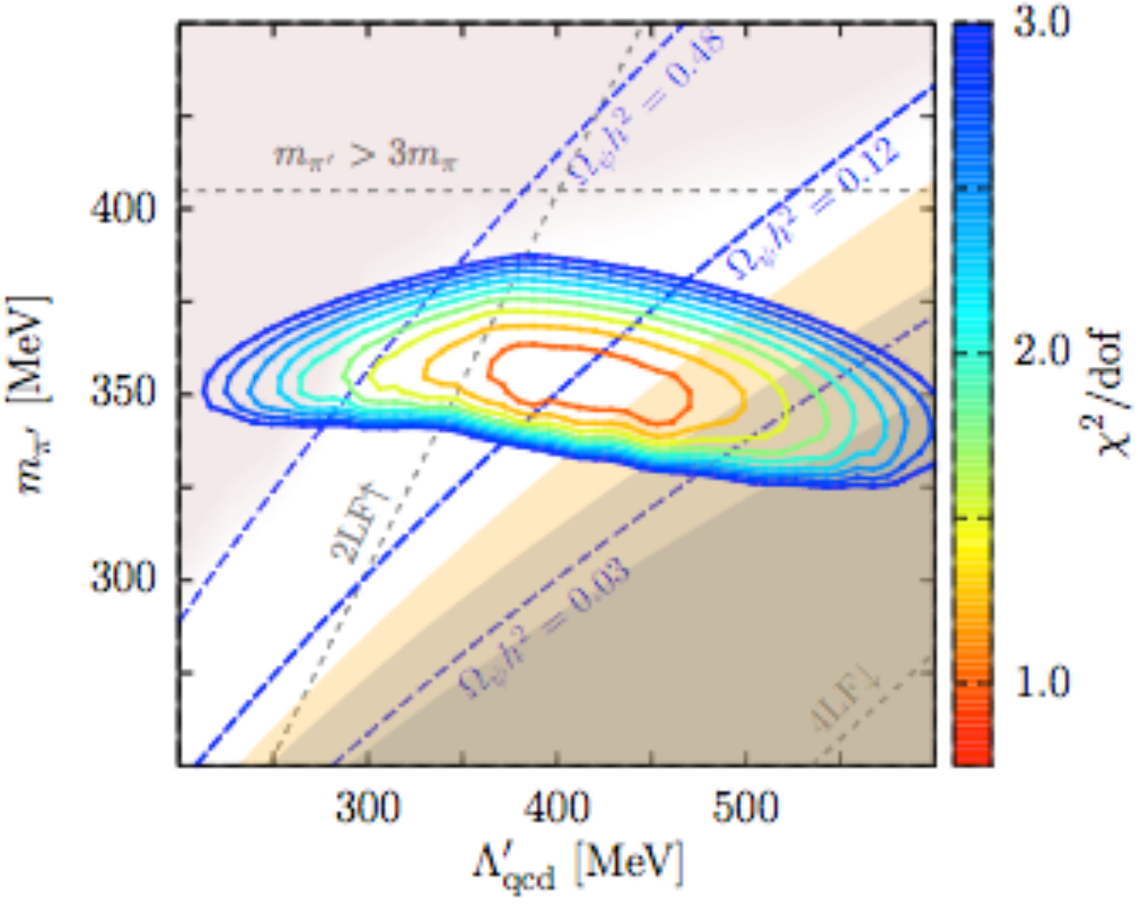
Dark photons



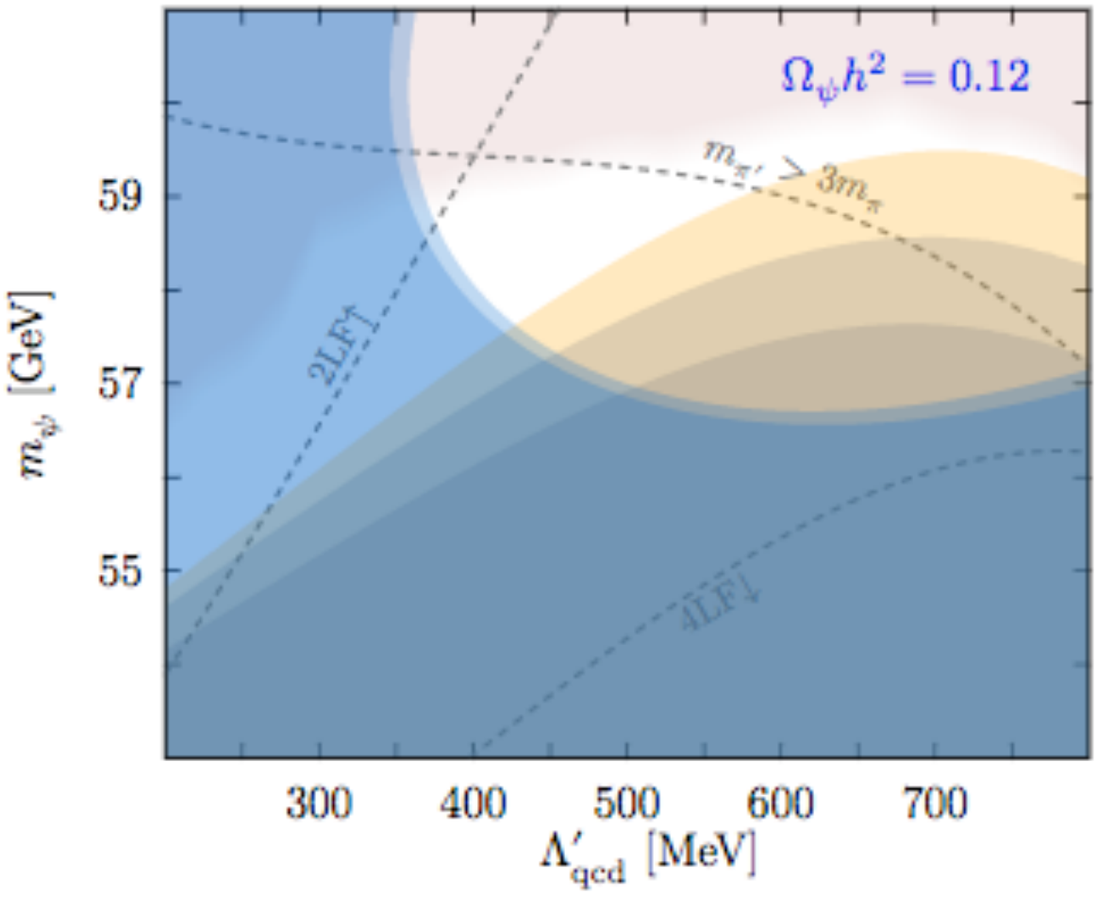
P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue: 1603.08926

Gamma rays

Galactic center excess

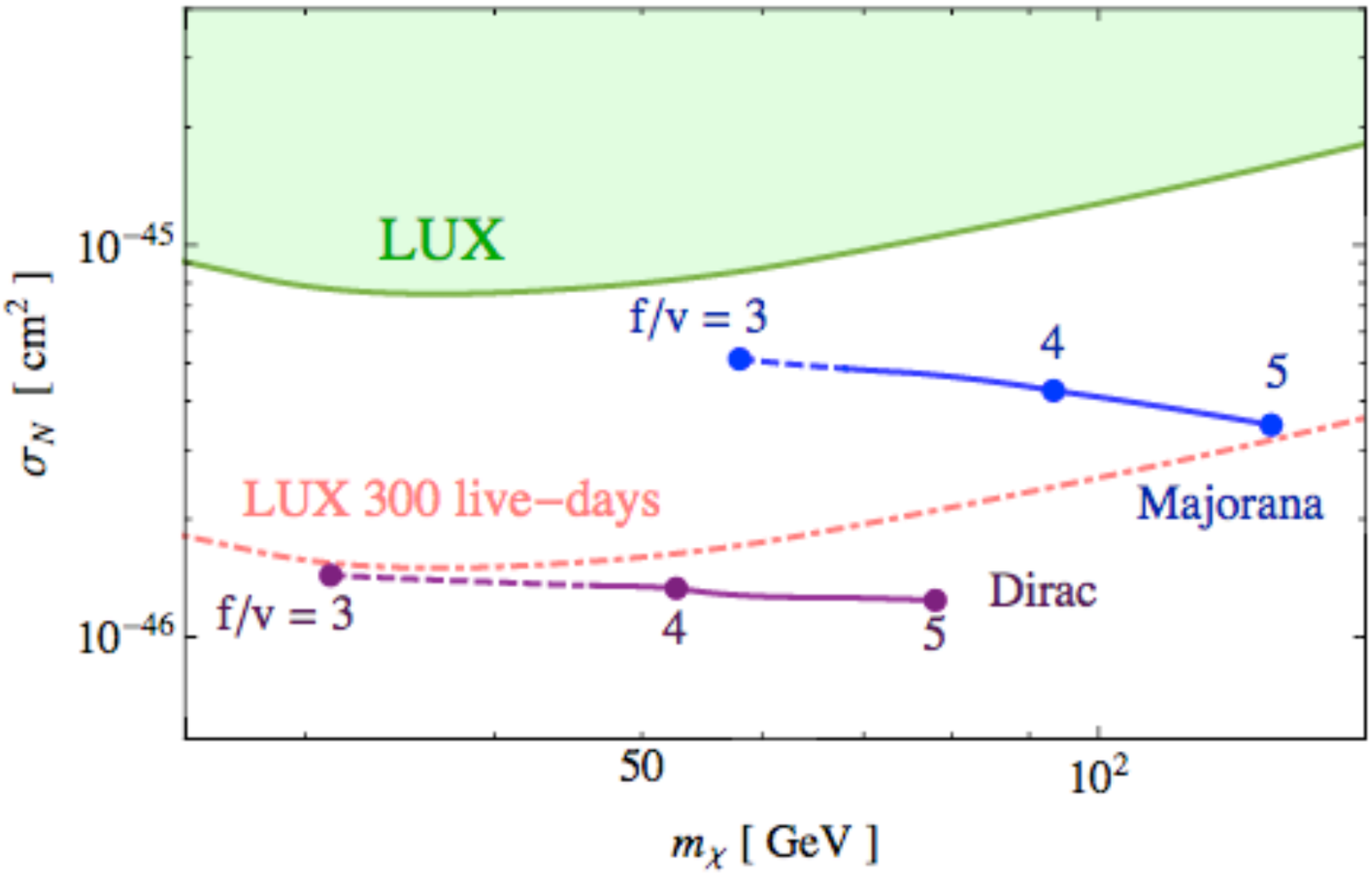


Gamma ray constraints



M. Freytsis, SK, D. Robinson, Y. Tsai: 1601.07556

Direct Detection



M. Freytsis, SK, D. Robinson, Y. Tsai: 1601.07556