Beyond the Standard Model at the LHC

Status and Prospects

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Rencontres de Blois 2017

Goal of the talk

Huge subject I will inevitably fail to do justice to.

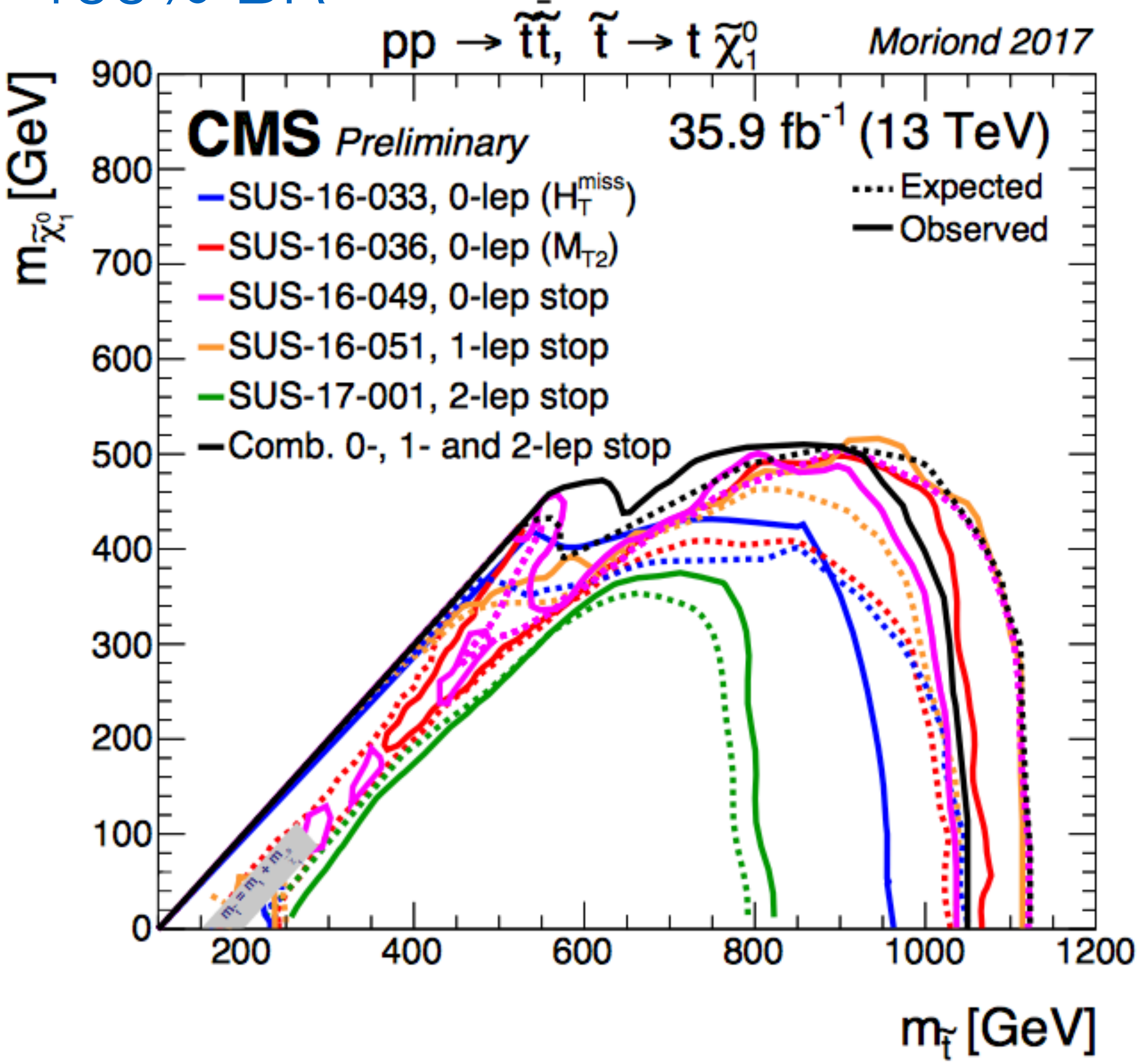
Highlight a range of BSM physics at LHC, from standard topics like SUSY to a variety of fun and exciting recent work.

I apologize in advance for omissions—there are many important things I don't have sufficient time or knowledge of to include.

Pursue naturalness

Stop parameter space

100% BR



Naturalness: expected stop below ~ 1 TeV*

Big progress with 13 TeV data: mass reach 1 TeV.

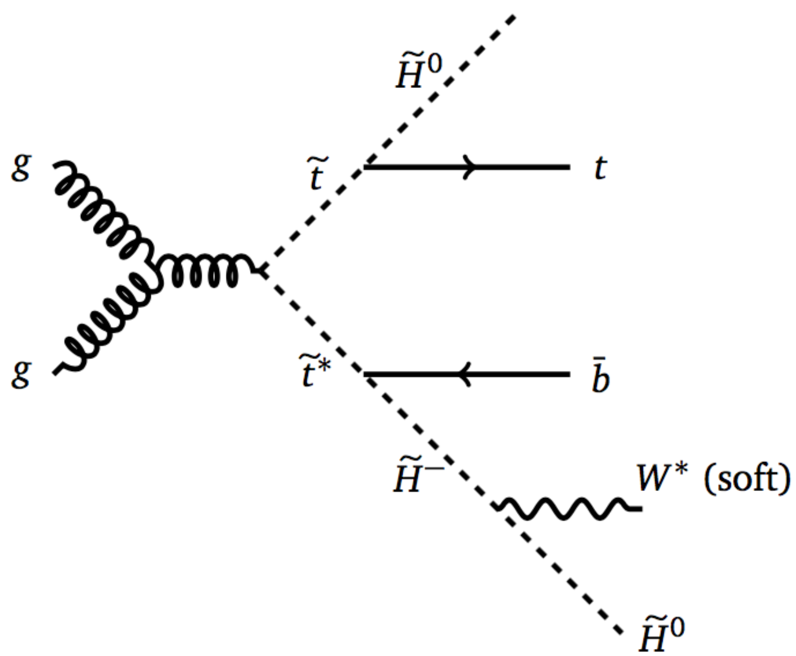
Solid exclusion of the compressed region (both ATLAS and CMS).

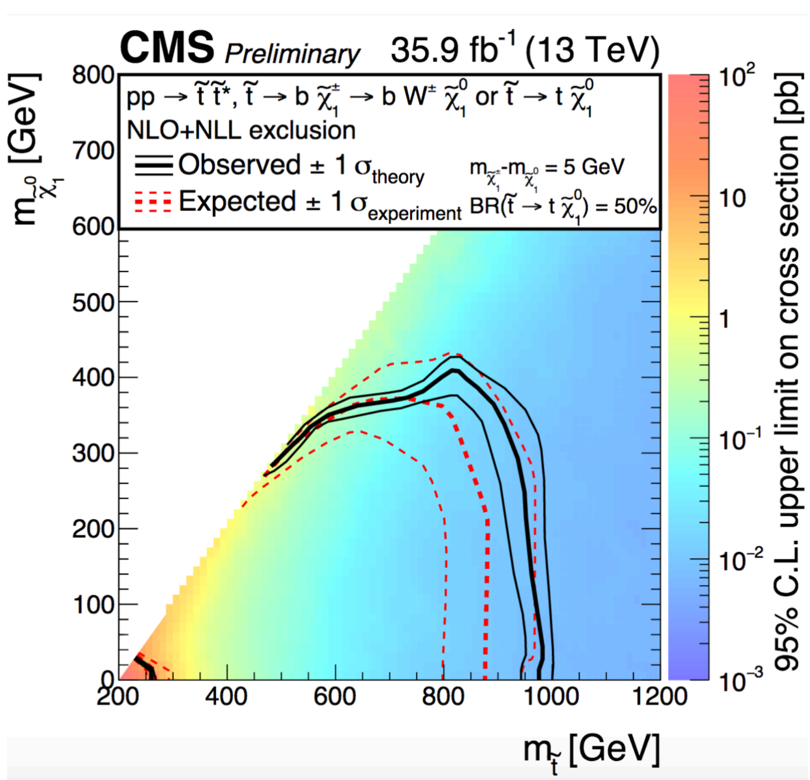
Compressed Region Theory:
Hagiwara, Yamada 1307.1553
An, Wang 1506.00653
Macaluso, Park, Shih, Tweedie 1506.07885

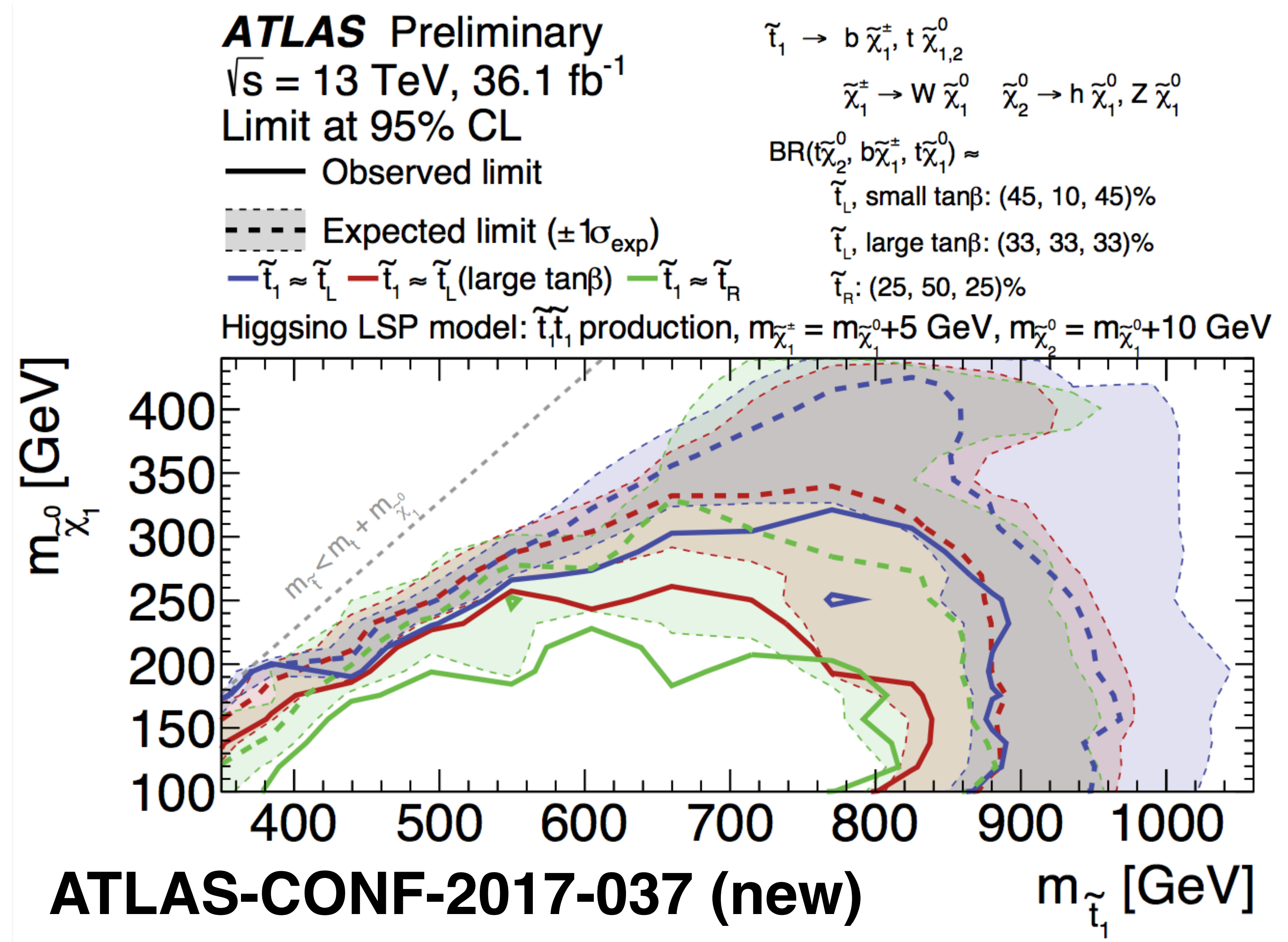
*Precise number depends on higher-loop effects; see Buckley, Monteux, Shih 1611.05873

Stop: multiple decays possible

The most natural* of the simplified stop models is the stop/higgsino simplified model. Asymmetric branching (Graesser, Shelton '12)







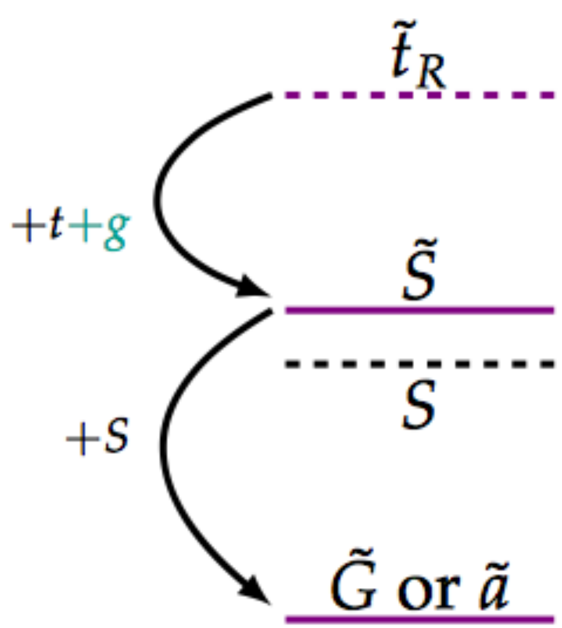
Branching ratios *matter*!

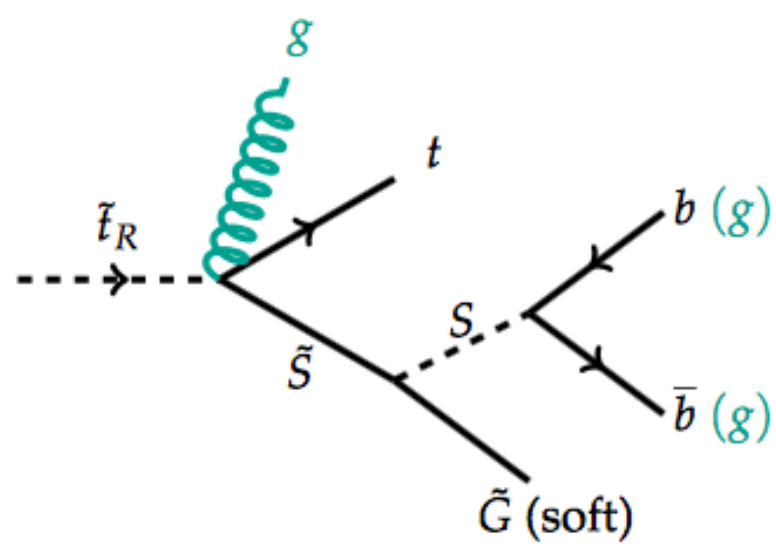
* without further model-building to decouple the higgsino safely, e.g. Cohen, Kearney, Luty 1501.01962

Stealth SUSY Stops

several new simplified models

Fan, Krall, Pinner, MR, Ruderman
arXiv:1512.05781

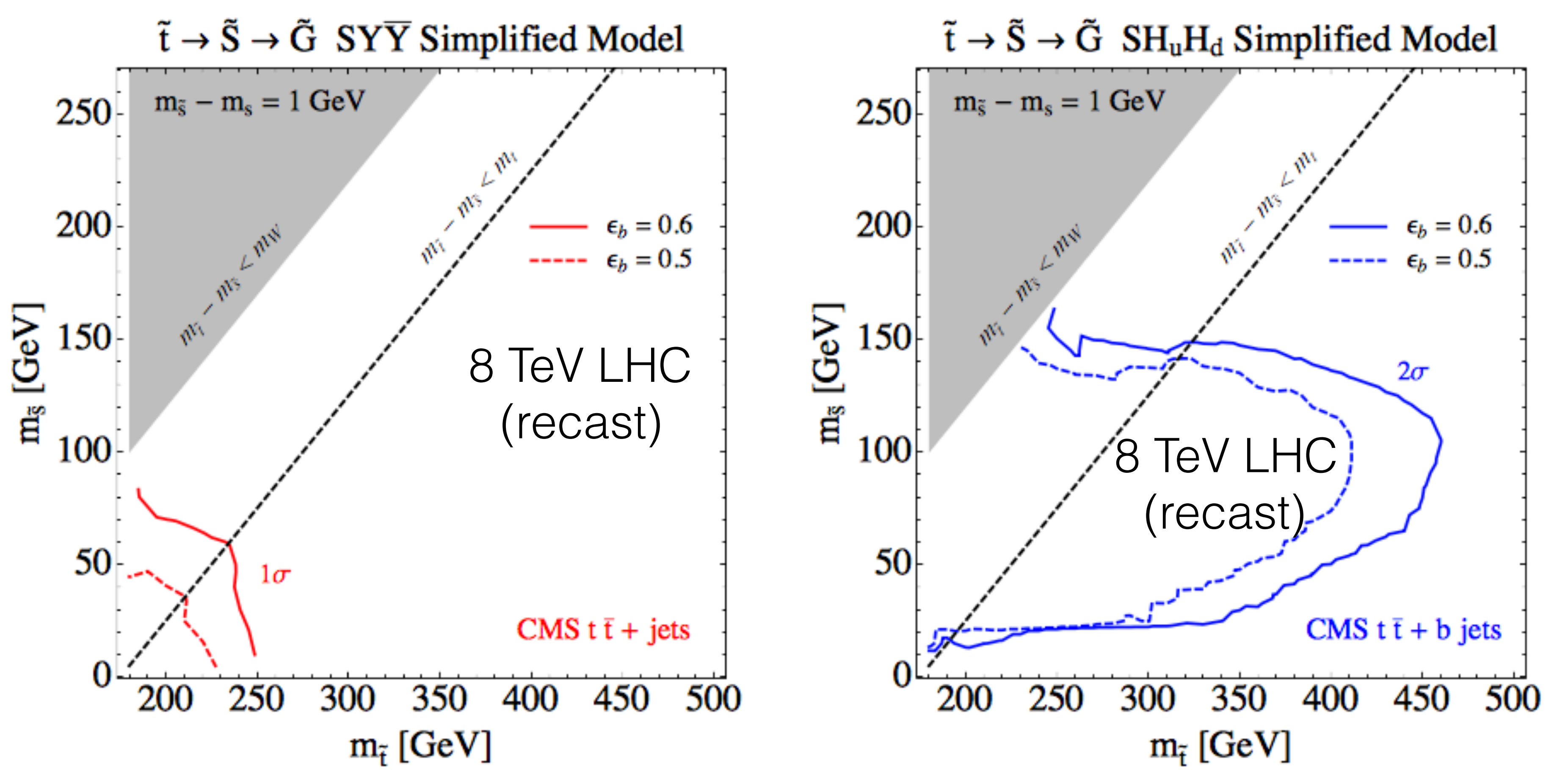




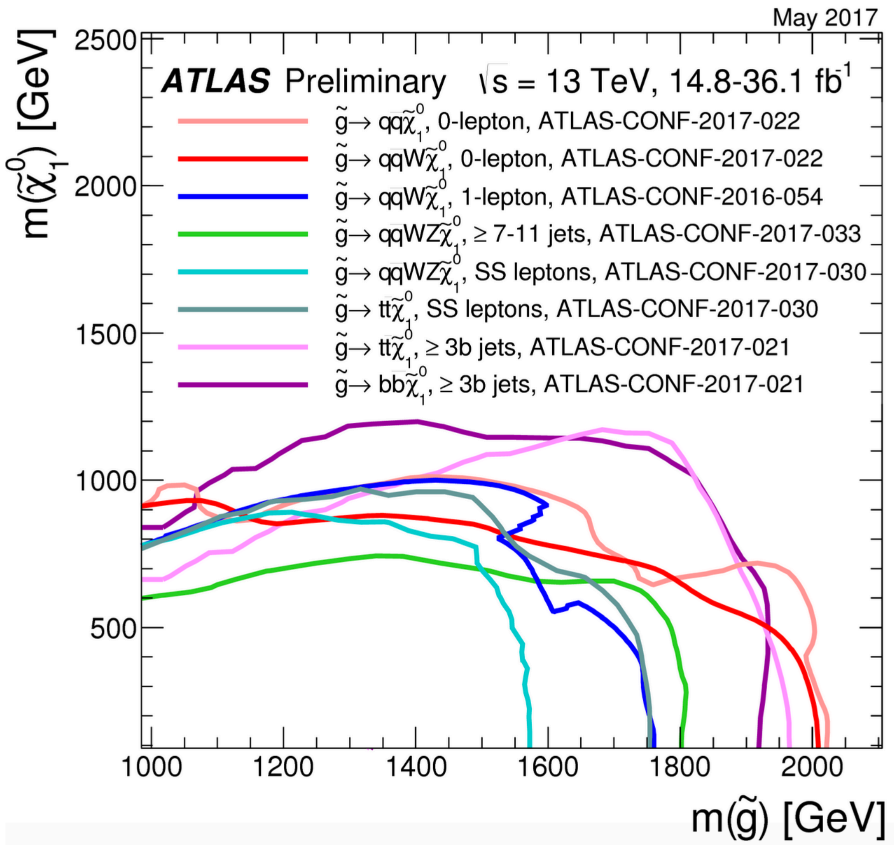
Stealth SUSY:
Approx. SUSY in hidden sector suppresses missing momentum.

Recast of 8 TeV searches.

ttbar + jets signal. Need better understanding of SM background.

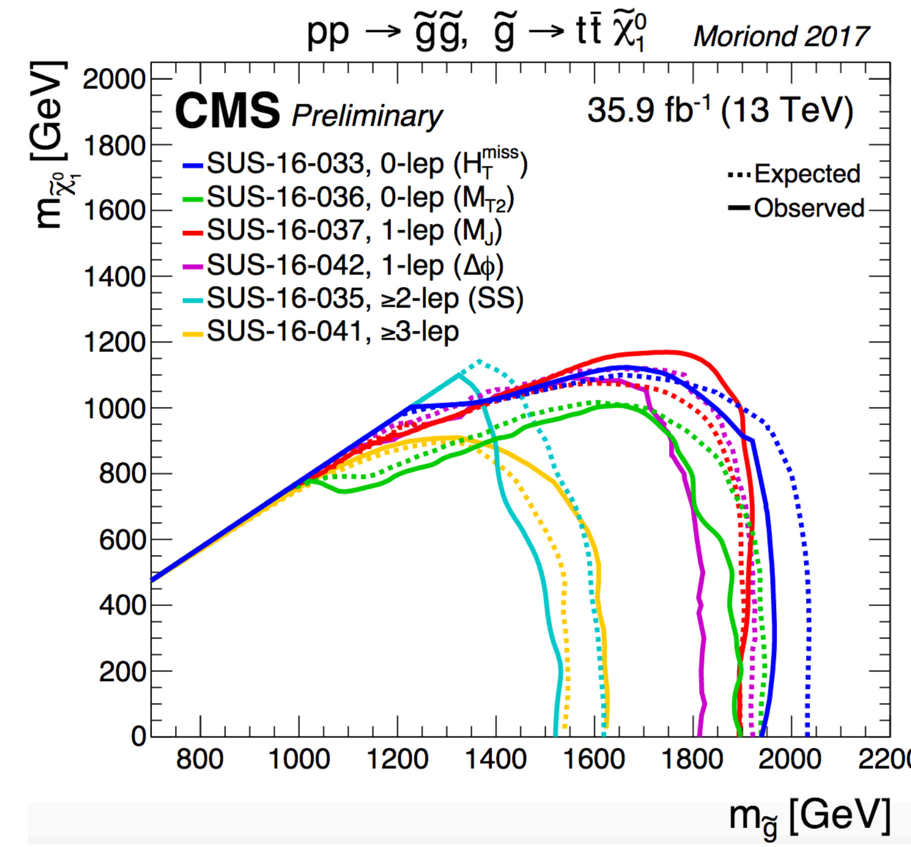


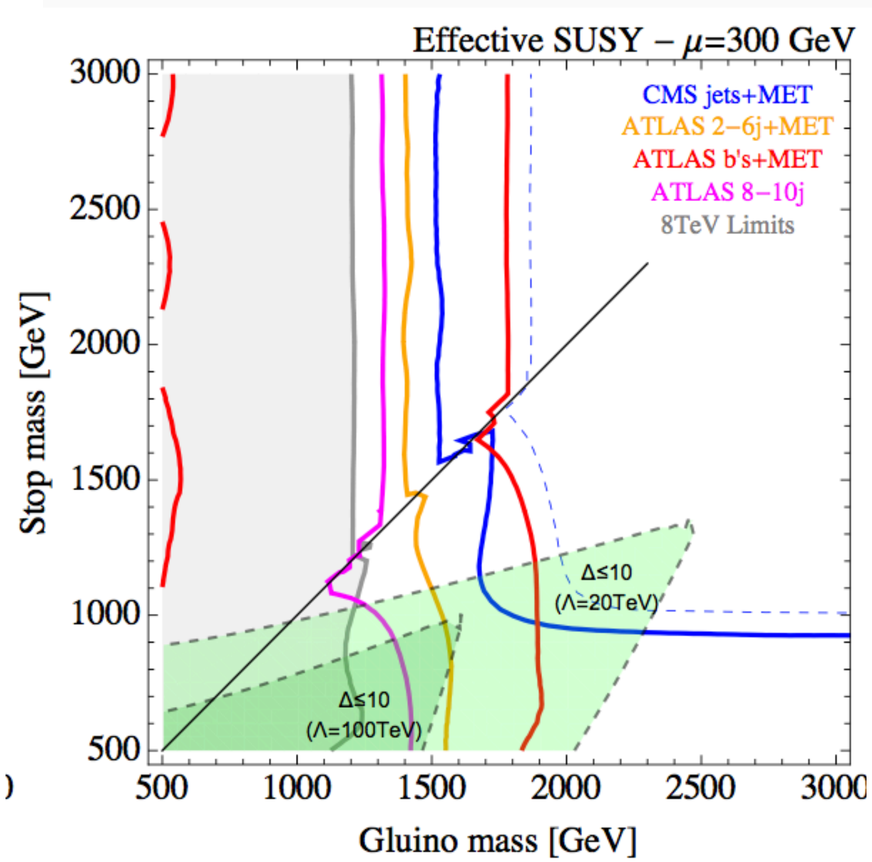
Gluino searches: the bottom line, so far

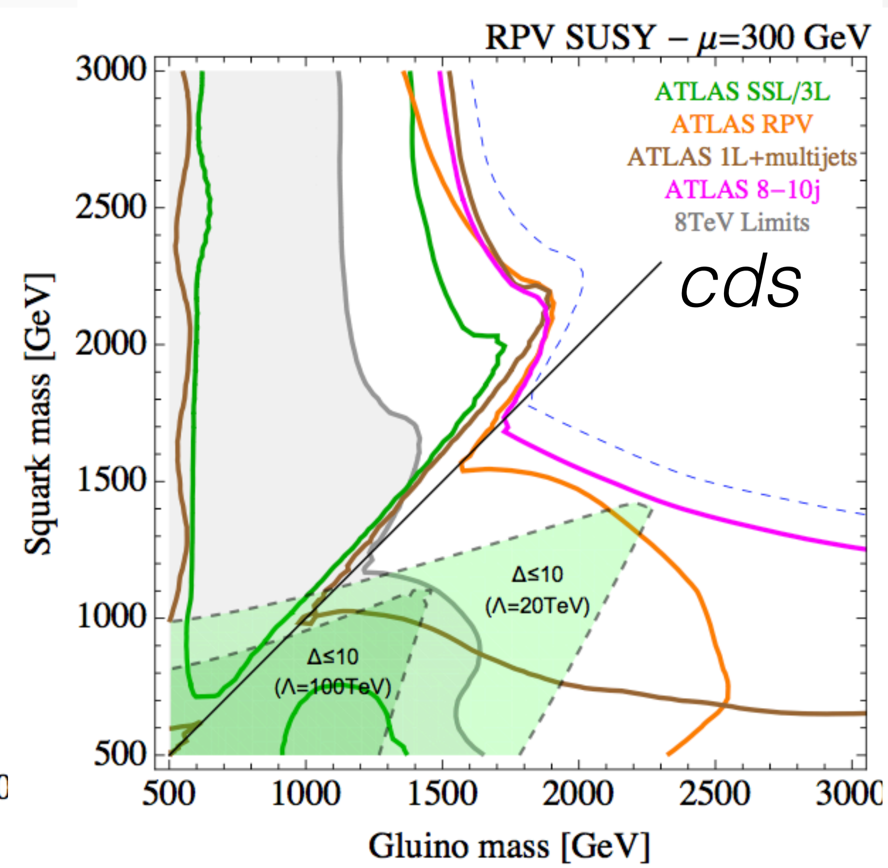


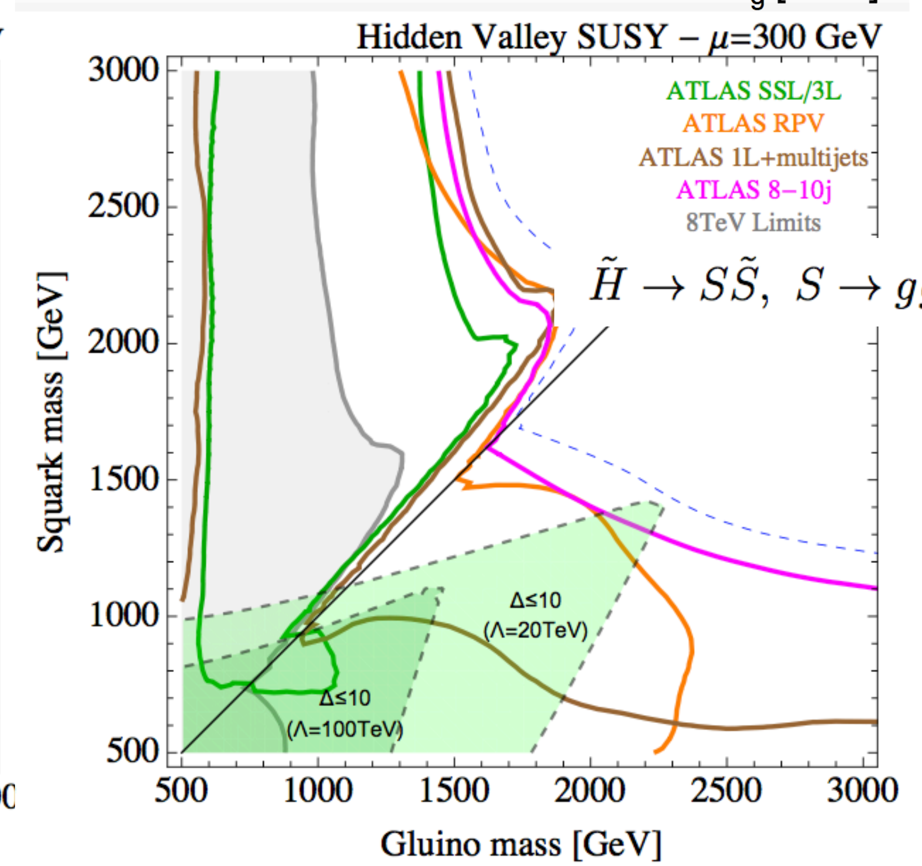
Fairly robust to variations on the SUSY model.

Biggest tension with naturalness.







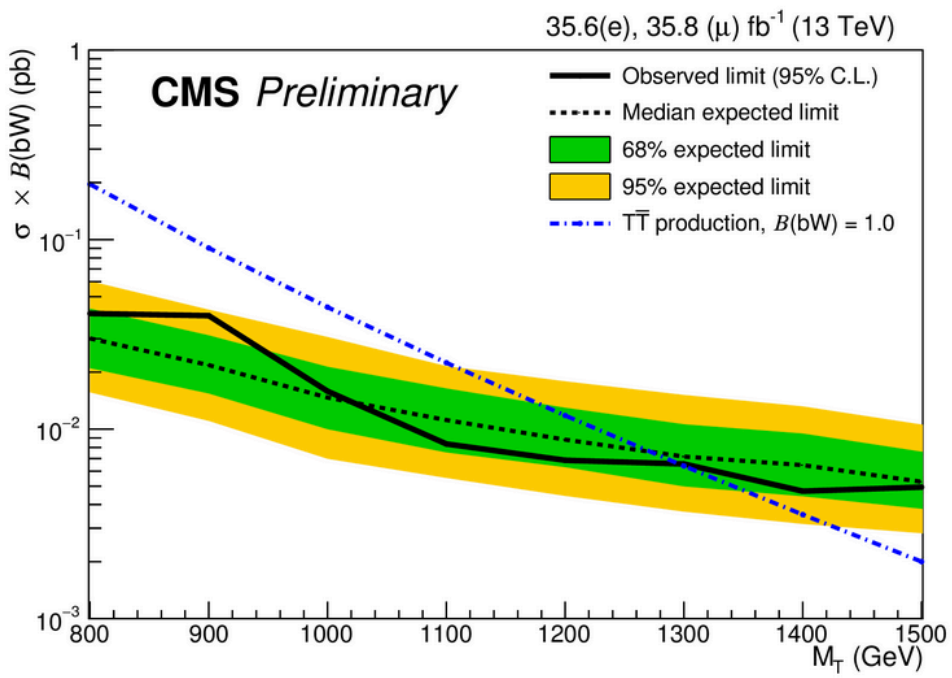


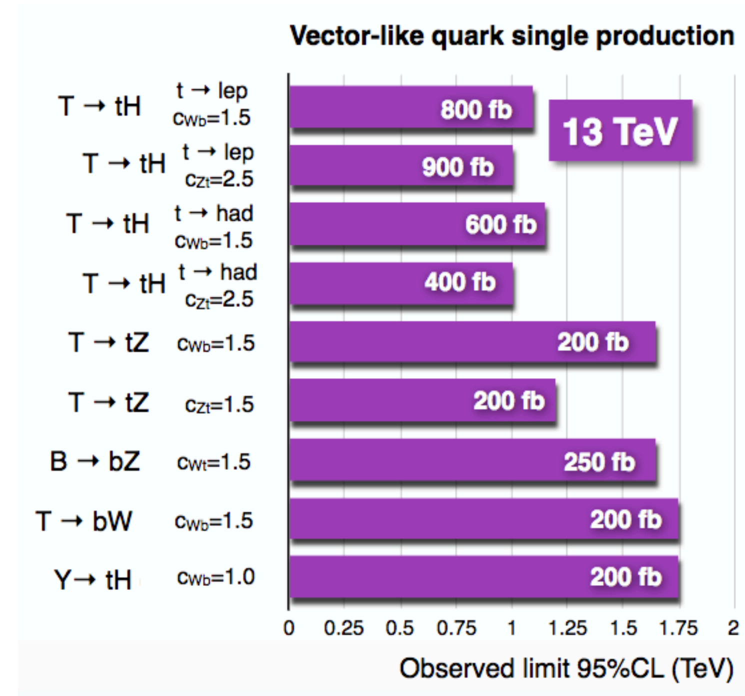
Buckley, Feld, Macaluso, Monteux, Shih 1610.08059

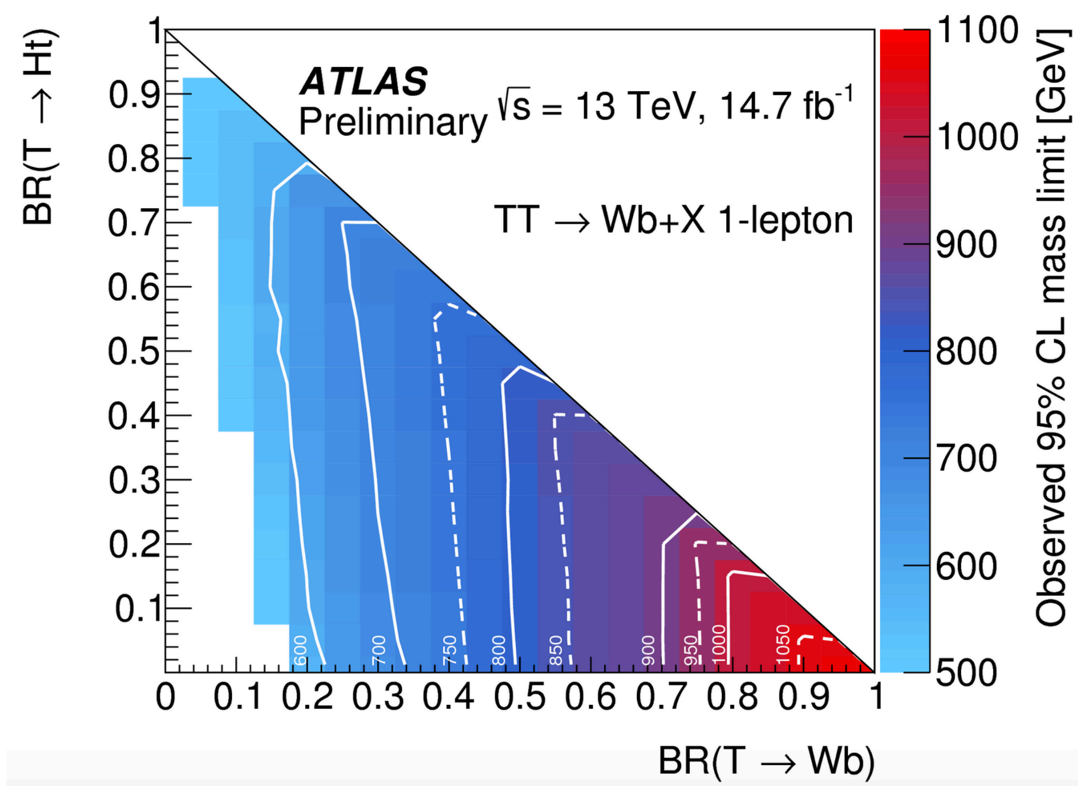
Fermionic top partners

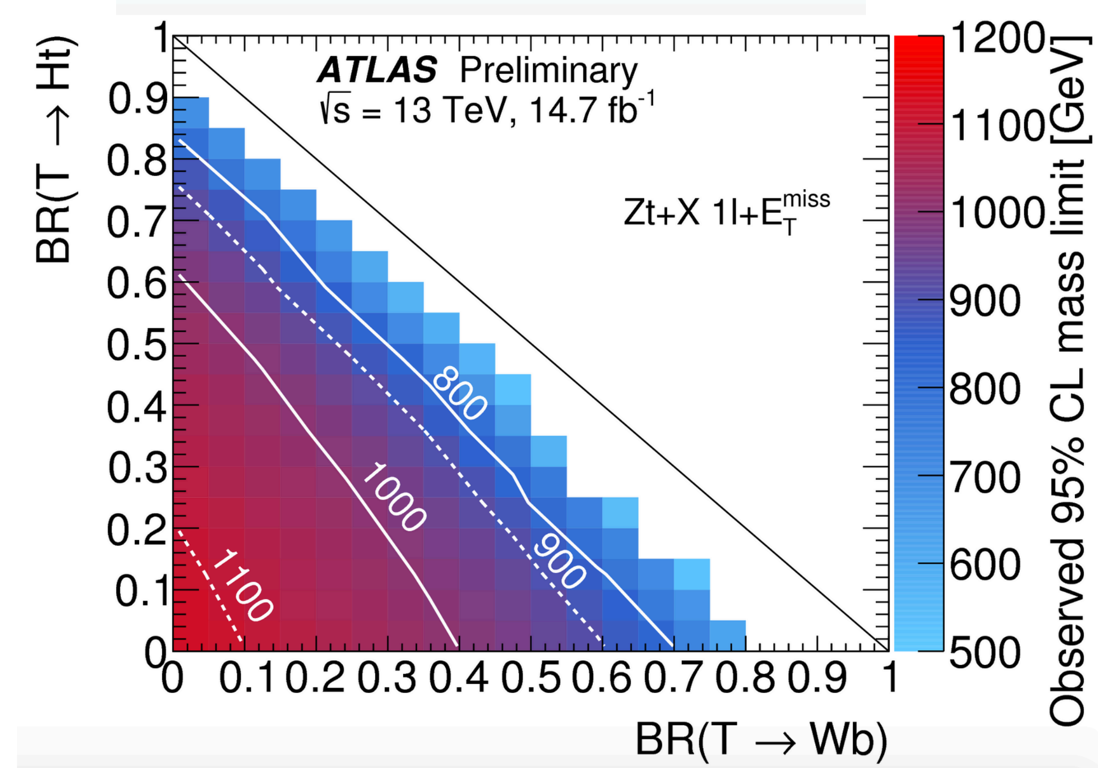
Expected to be light given Higgs mass: Matsedonskyi, Panico, Wulzer arXiv:1204.6333

Strong exclusion limits above 1 TeV have been achieved in standard channels: $T \to th, tZ, bW^+, B \to bh, bZ, tW^-$

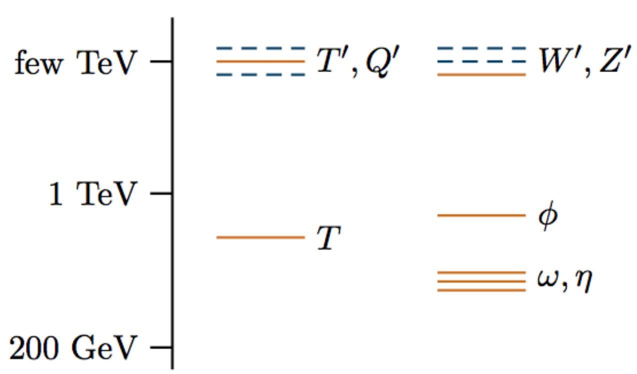


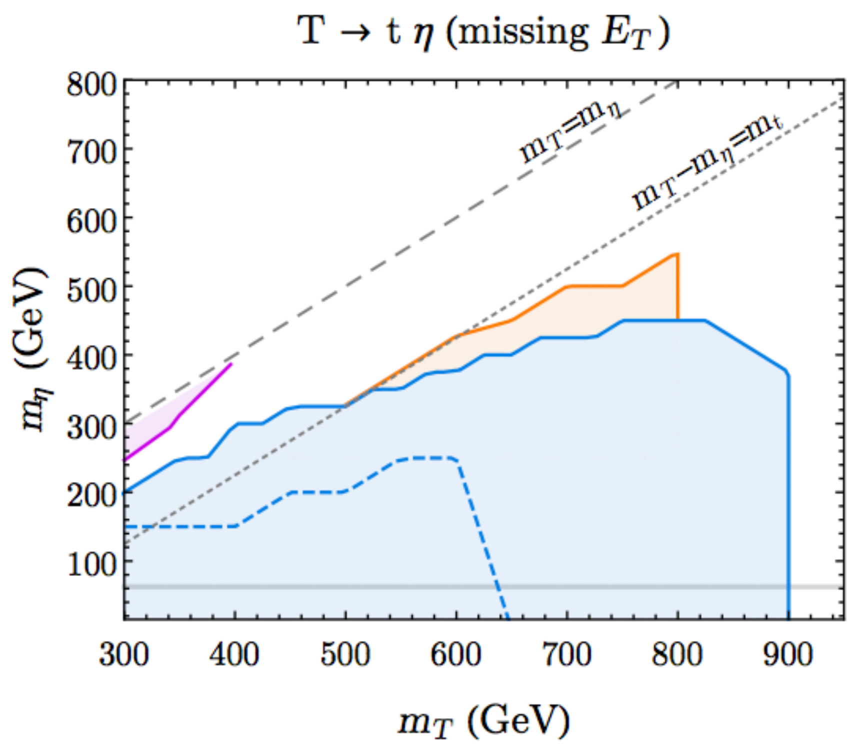


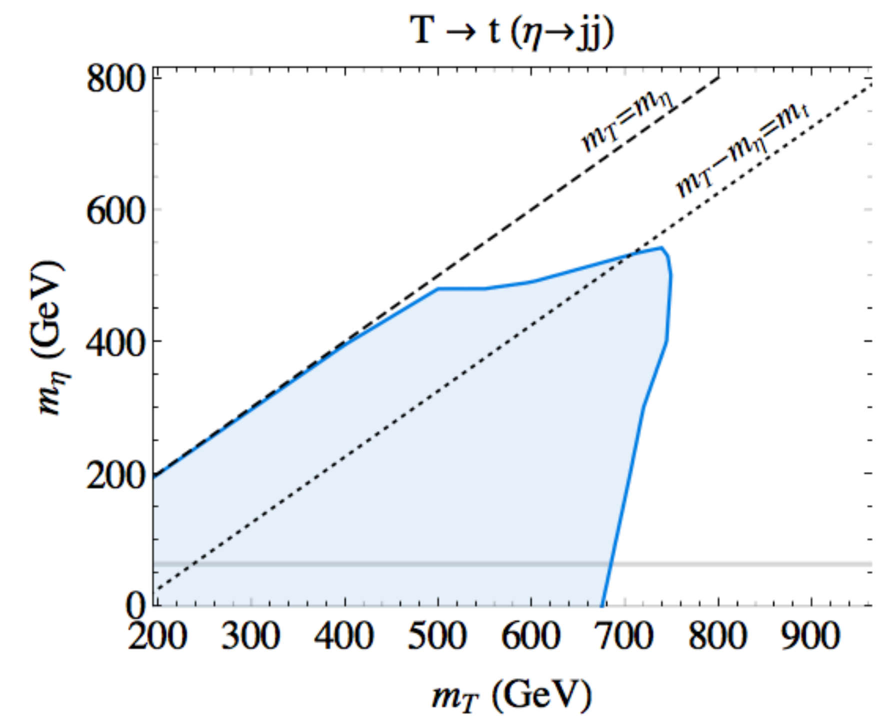




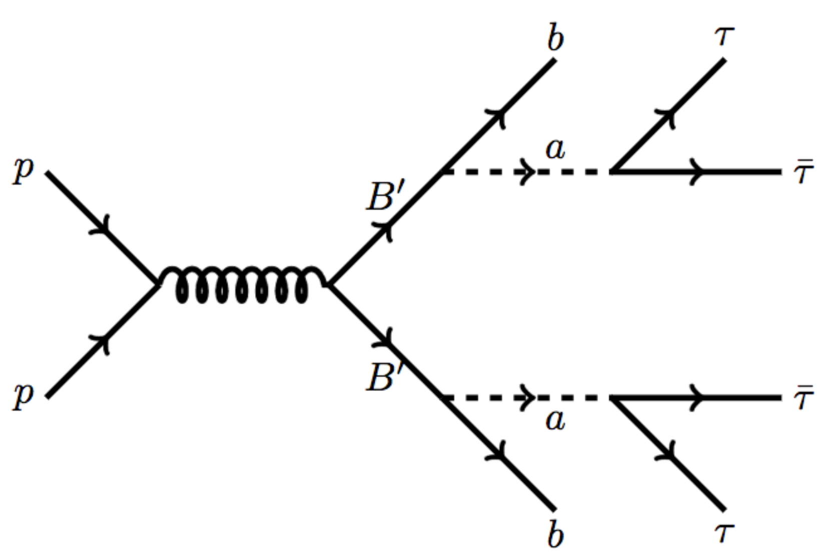
Top partners, less simplified

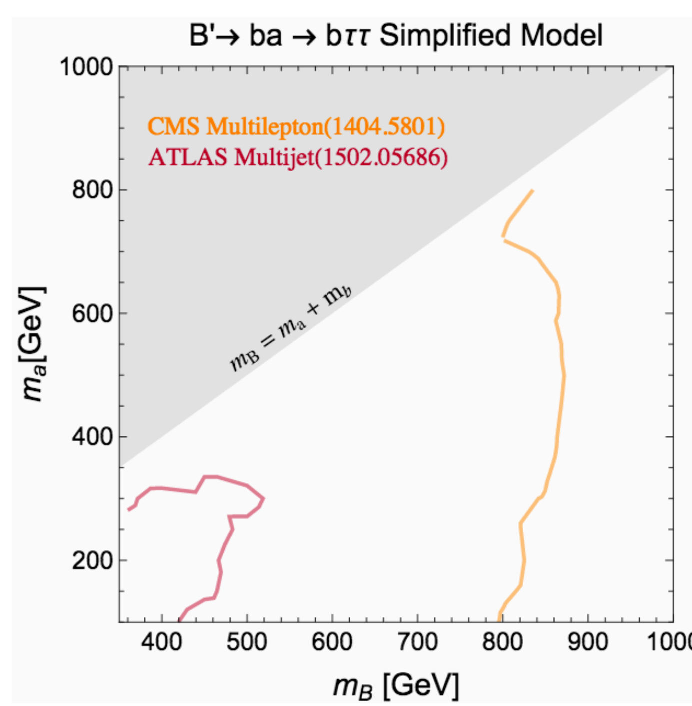






Anandakrishnan, Collins, Farina, Kuflik, Perelstein 1506.05130
(also Serra, 1506.05110)



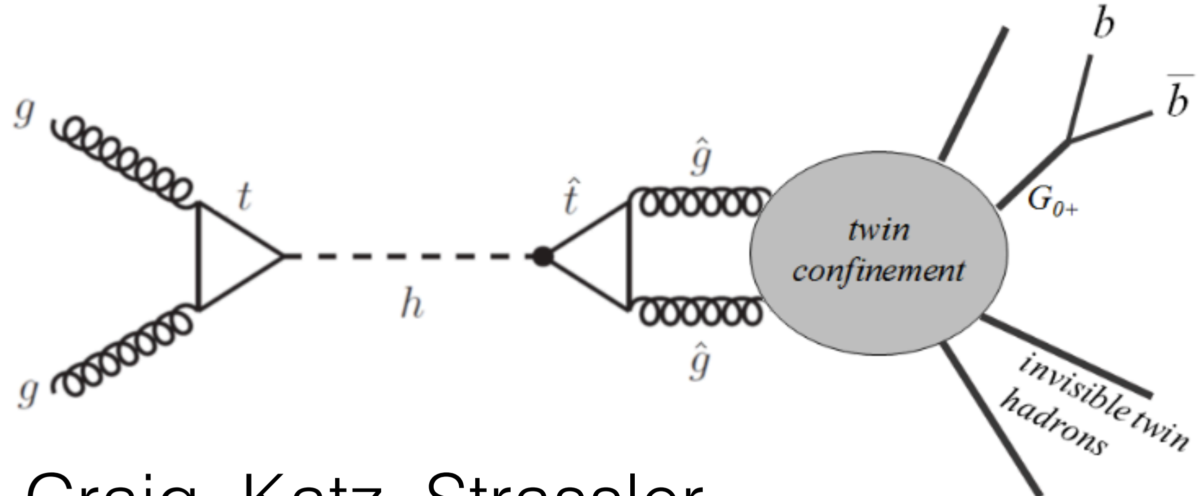


Good coverage already, but could do more targeted searching?

Fan, Koushiappas, Landsberg 1507.06993

Neutral naturalness

Rebranding of Twin Higgs (Chacko, Goh, Harnik hep-ph/0506256) and related ideas.



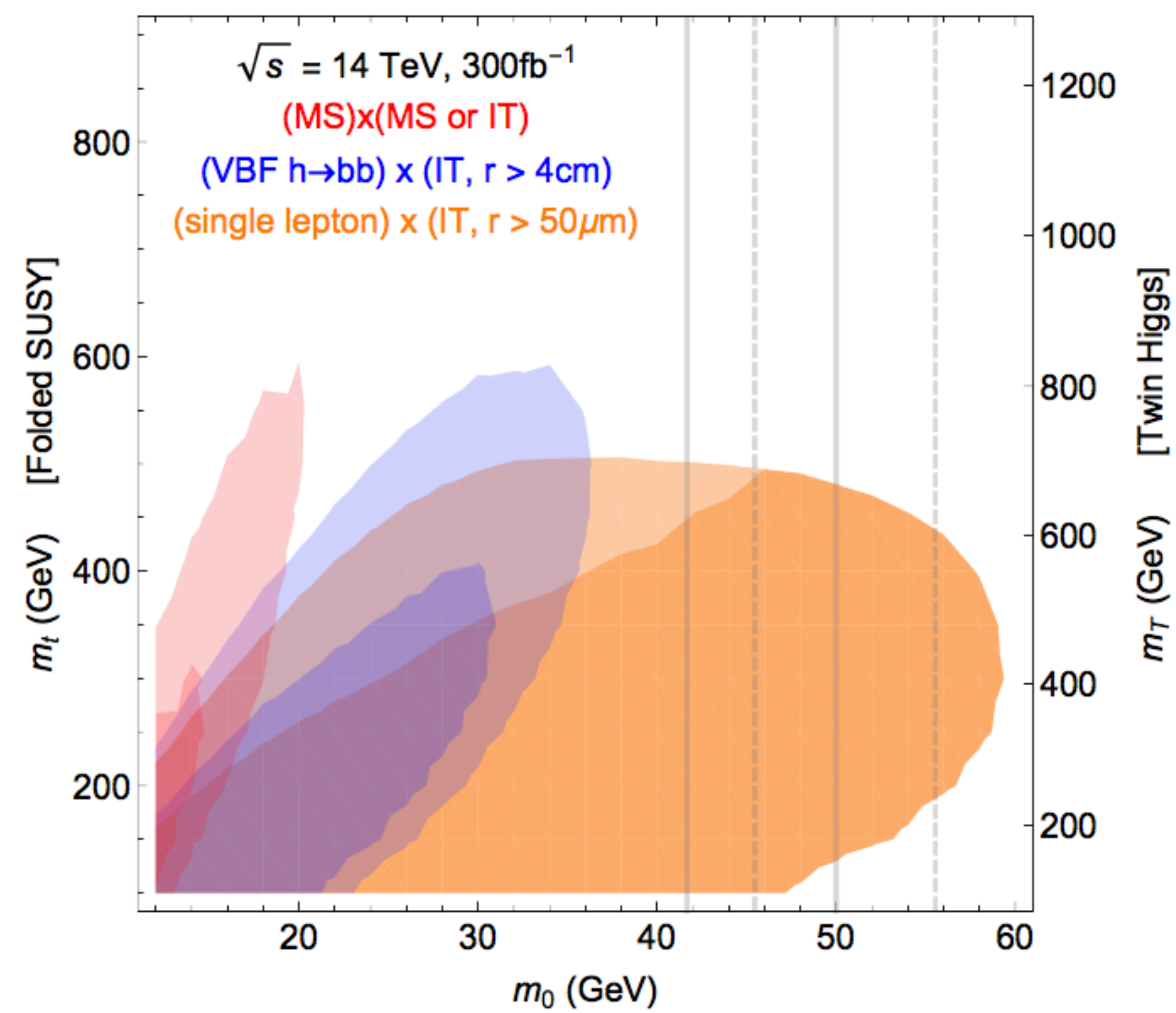
Craig, Katz, Strassler, Sundrum 1501.05310

These models are constructed to solve *only* the *little* hierarchy problem; they need a UV completion.

More work to do on constructing nice UV completions and consistent cosmologies for these theories.

Hidden Valley signatures: twin glueball a key particle

Curtin, Verhaaren 1506.06141



Dark Matter

Dark matter at the LHC

I think it's useful to organize these searches into two categories:

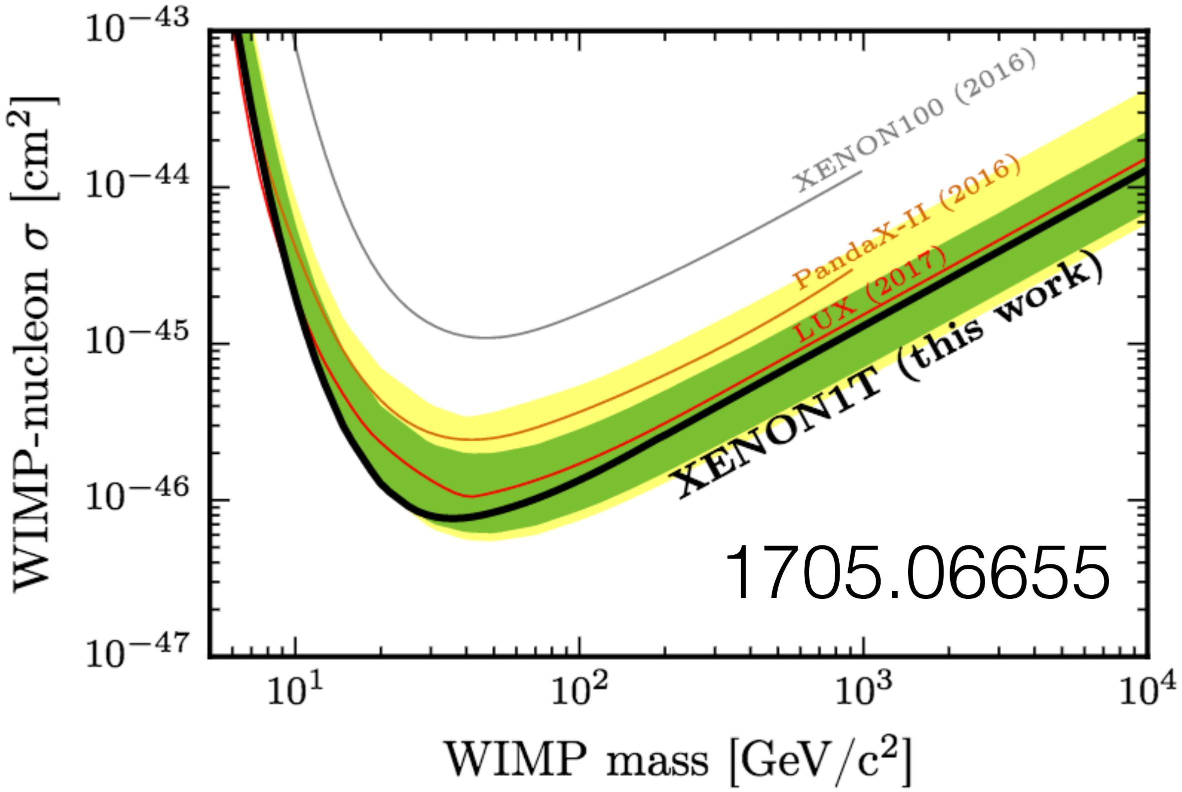
DM with no new mediator

Higgs portal (in the case of scalar dark matter)
SU(2) multiplets or mixtures
example: SUSY neutralinos/charginos

DM with new mediator

Z' mediators
(Pseudo)scalar mediators
"Completons": most of these theories don't make sense without adding additional new particles that might have striking signals of their own.

The WIMP is not yet dead

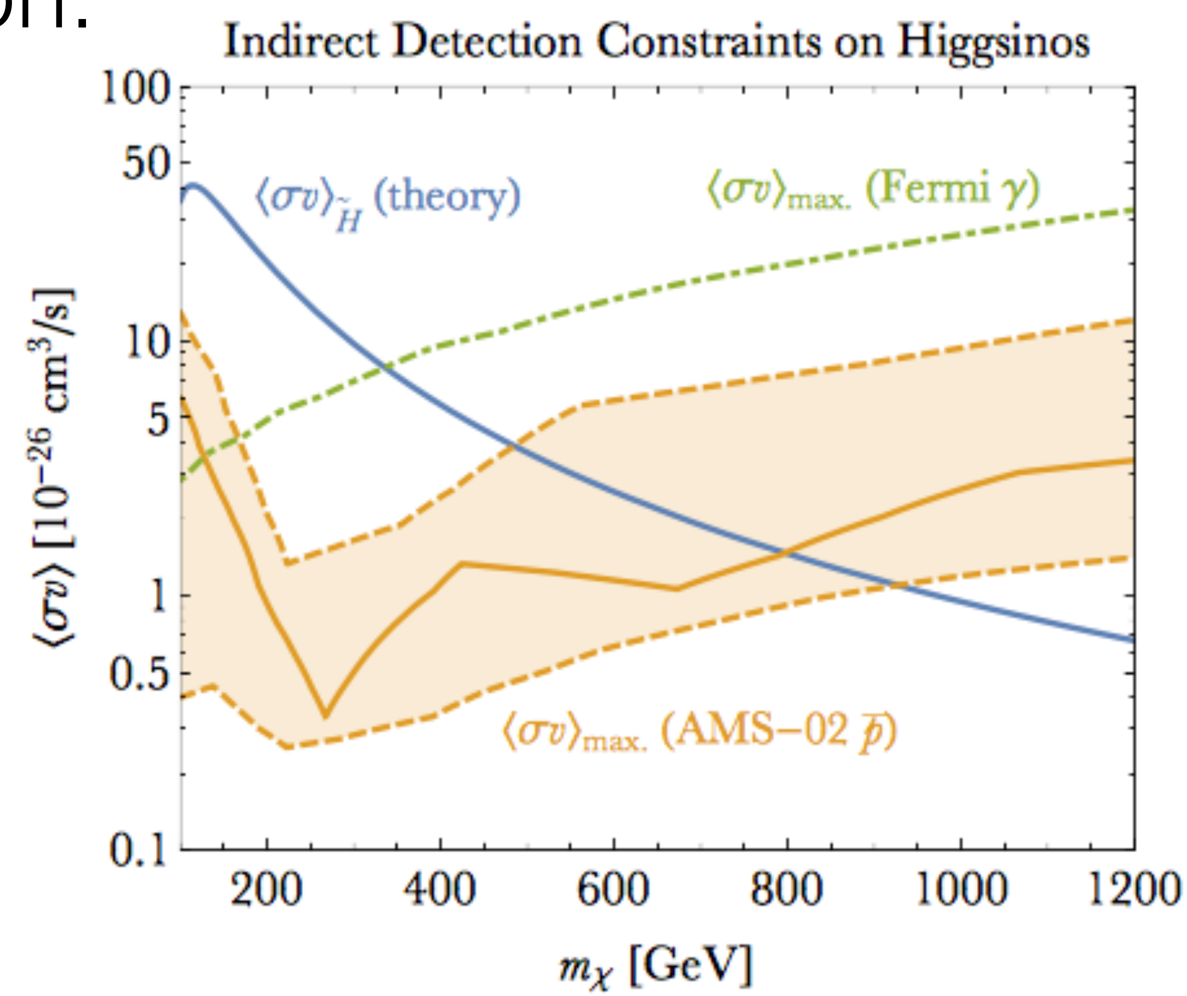


The xenon based experiments have strongly constrained WIMPs coupling to the Higgs boson.

WIMPs in pure SU(2) multiplets have

$$\tilde{\chi}^0\tilde{\chi}^0 \to W^+W^-$$

annihilation. Indirect detection severely constrains winos*; constrains ***higgsinos*** mildly.



Krall, MR 1705.04843, using work of Cuoco, Krämer, Korsmeier 1610.03071

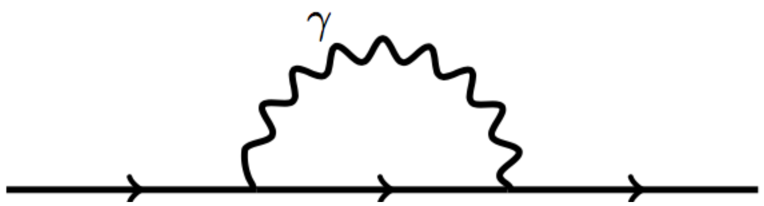
* Cohen, Lisanti, Pierce, Slatyer 1307.4082

* Fan, MR 1307.4400

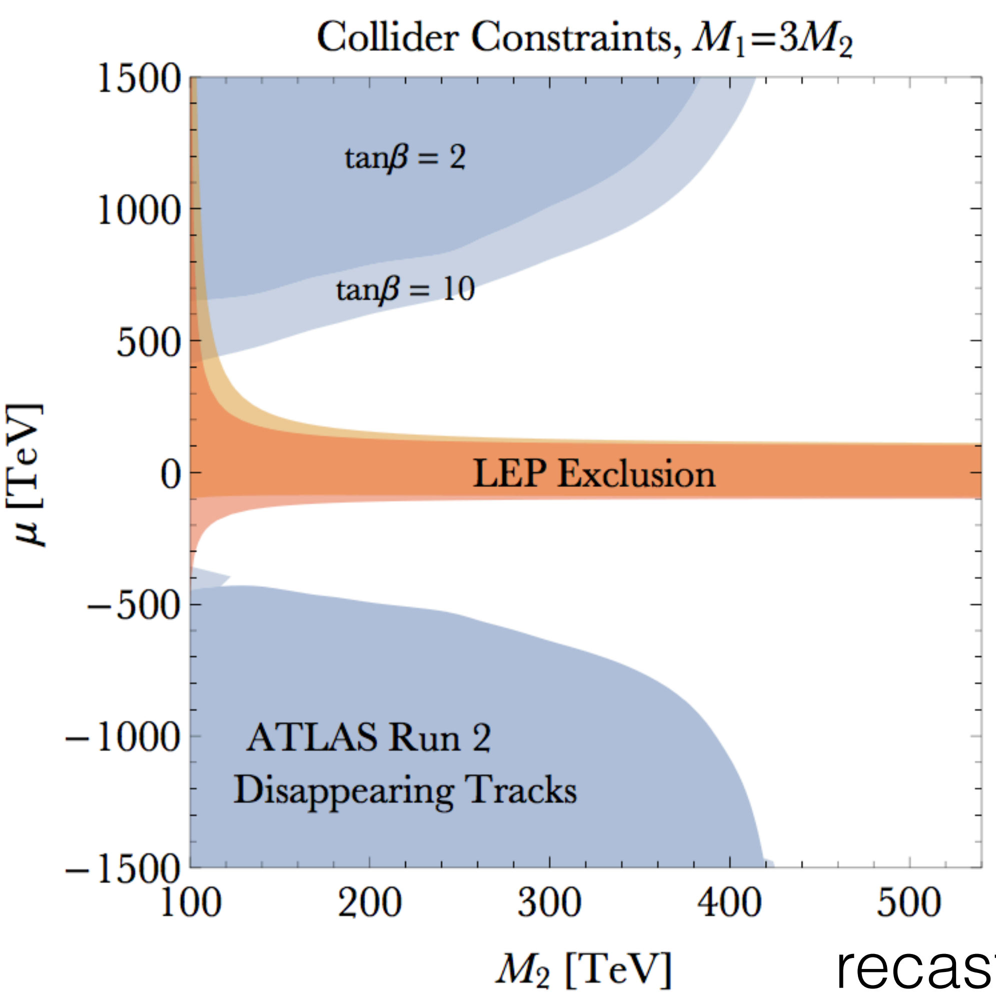
A Compelling LHC Dark Matter Result

Disappearing tracks:

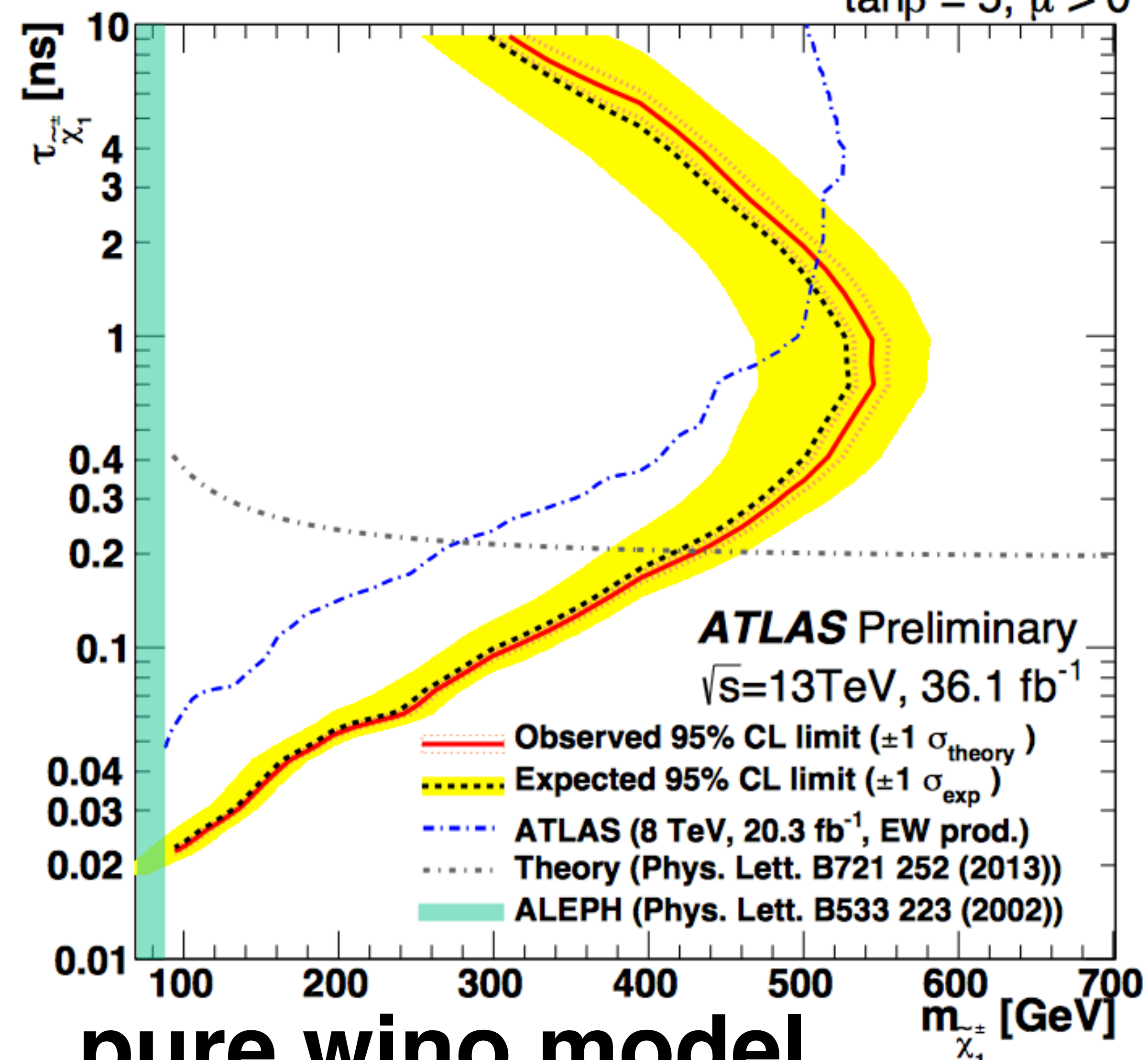
$$m_{\chi^+} - m_{\chi^0} \sim 100 \text{ MeV}$$



$$\tilde{\chi}^+ \to \tilde{\chi}^0 + \pi^+$$



ATLAS-CONF-2017-017



pure wino model

Moral: searches with powerful DM implications might not always *look* like standard DM searches.

recast: Krall, MR 1705.04843

Dark Matter EFT

- DM EFT with $1/\Lambda^2$ couplings: if weakly coupled, breaks down at lower scale $q^2 \sim M^2 = g_A\, g_B\, \Lambda^2$.

- In some analyses, **cuts on momenta** are used to focus attention only on the events where $q^2 << M^2$.

- But that requires assuming we know size of couplings like $g_A\, g_B$! (Otherwise, how to disentangle M from Λ?)

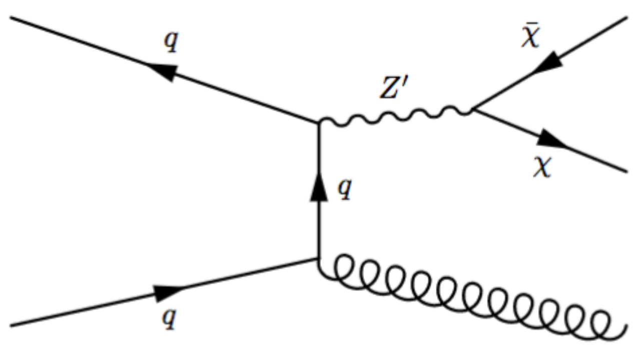
  Not fully "model-independent," unless we only use events with q below any possible mediator scale of interest.

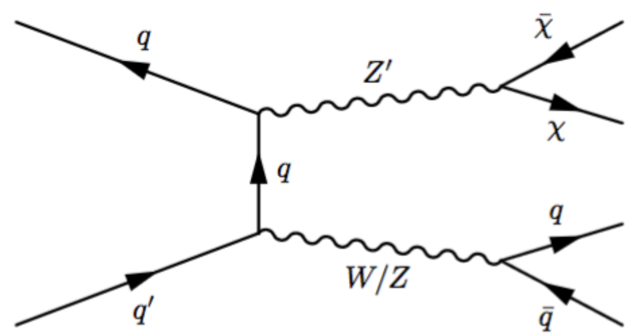
- If we're making such assumptions *anyway*, should we jump all the way to just studying specific models?

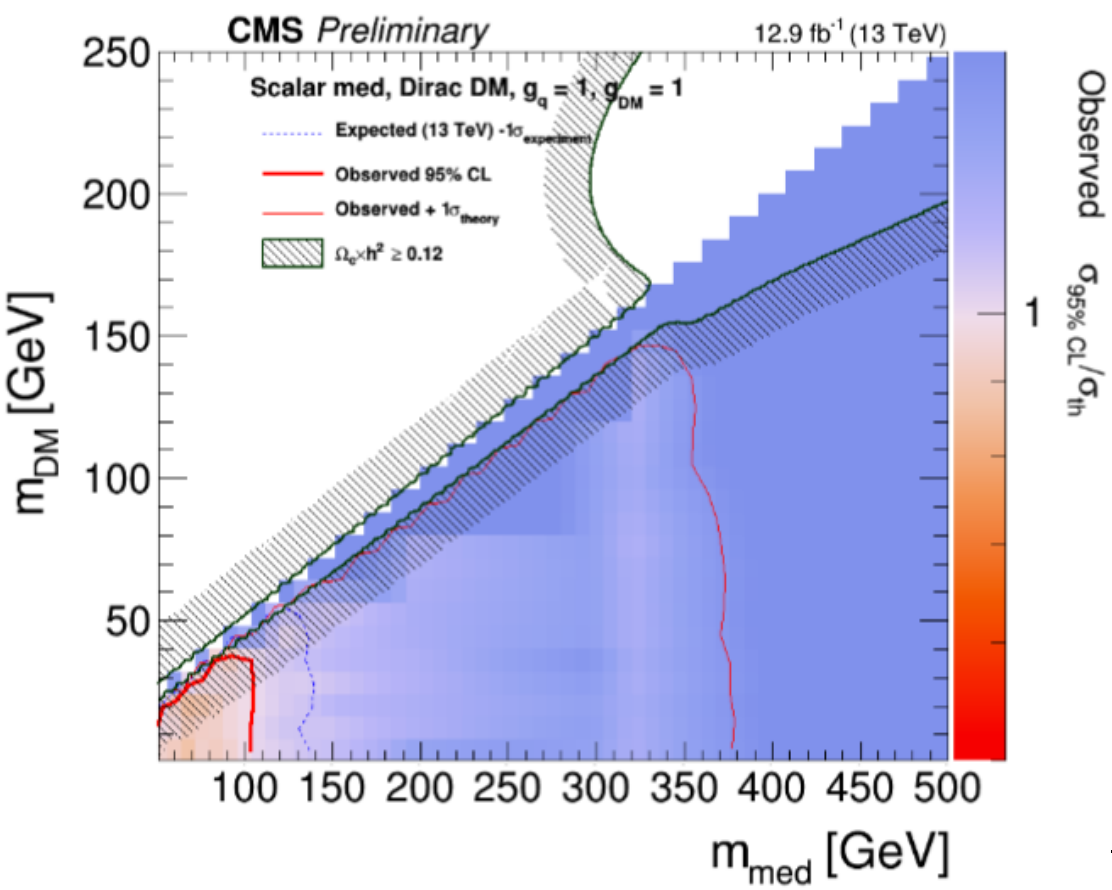
- The **"simplified model"** approach is a nice **compromise** between detailed models and overly simple assumptions.

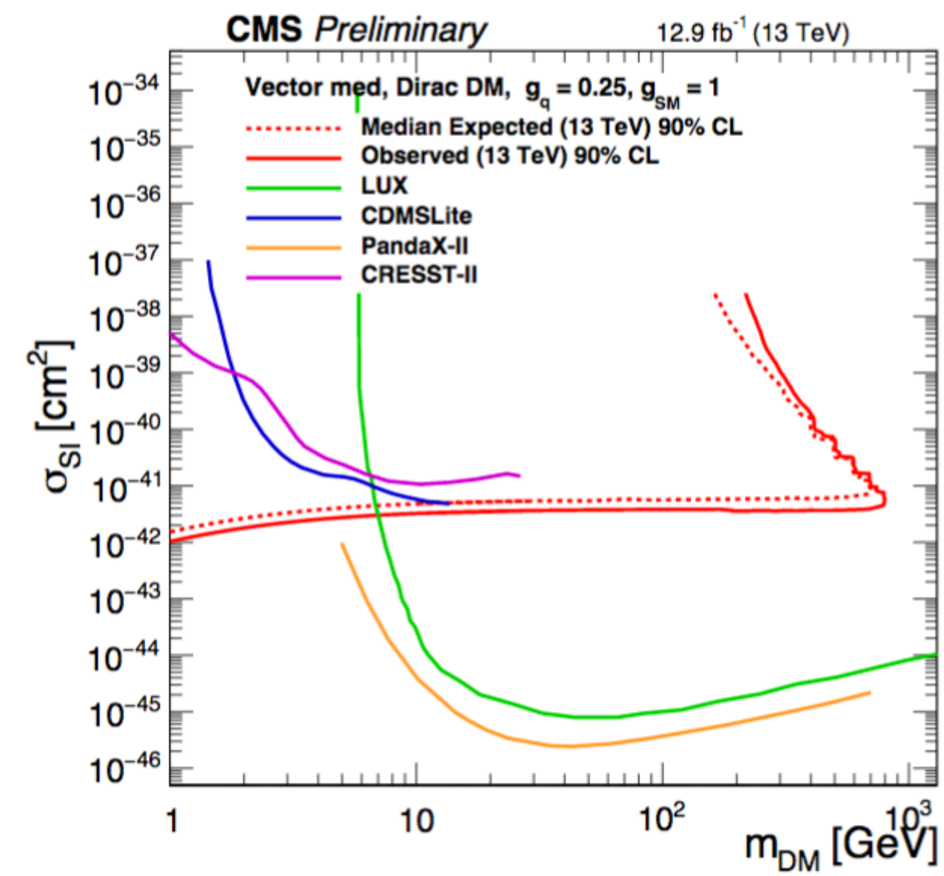
Simplified Models

Coming into wider use in the DM context. One recent example: CMS EXO-16-037: monojet or mono-W/Z (hadronic)





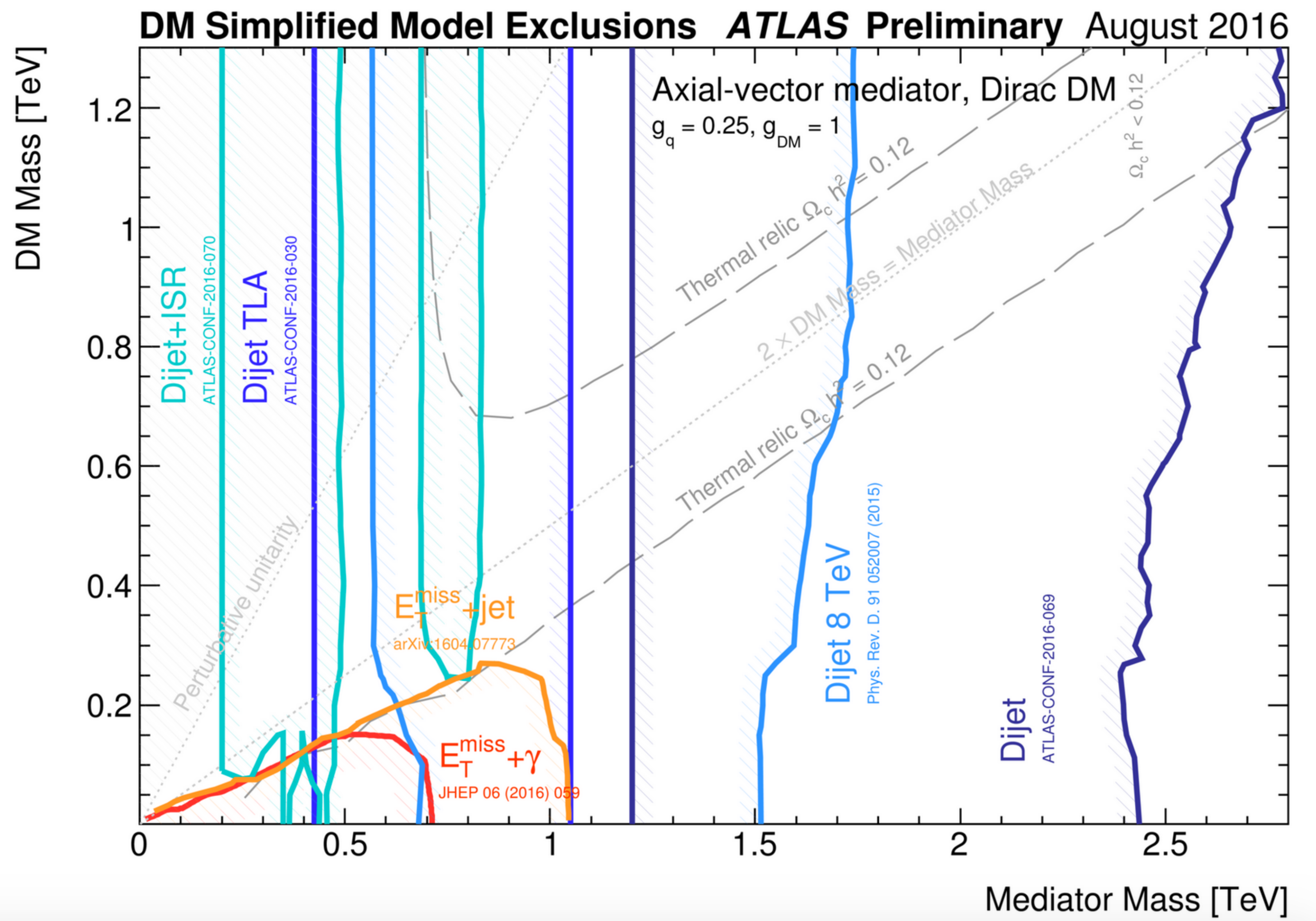




DM of low mass can be better covered by colliders than by direct detection (**so far!** lots of recent thought on low-mass DM direct detection)

refs: Abdallah et al. 1409.2893, 1506.03116; ATLAS/CMS Dark Matter Forum 1507.00966; de Simone & Jacques 1603.08002; Bauer et al. 1607.06680; ….

Mediators as Resonances



Invoking a new mediator in a simplified model might regulate the EFT problem, but it's often **highly** constrained by resonance searches!

Are Simplified Models Simple?

It's easy to say that we want to consider, e.g., a pseudoscalar mediator, writing down terms like

$$\mathrm{i} g a \bar{q} \gamma^5 q$$

but this operator **does not exist** given electroweak symmetry. In other words, it's secretly a **nonrenormalizable** operator with a Higgs inserted, e.g.

$$\mathrm{i}\frac{g}{v} a q^\dagger H u^c + \mathrm{h.c.}$$

and so if *g* is not *very* small, have to complete this operator with other weak-scale physics.

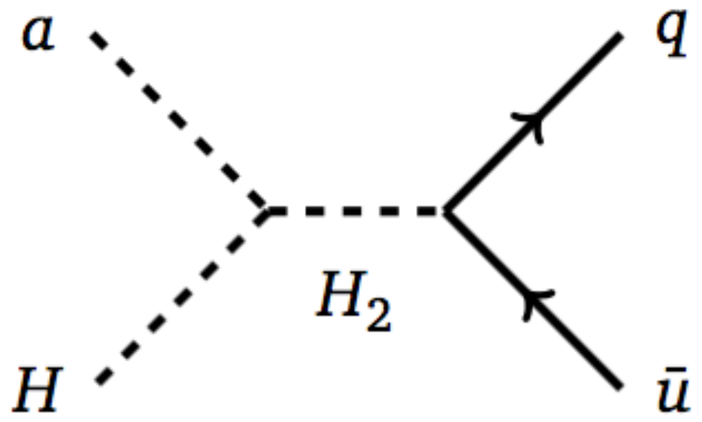
Similar issues arise for Z' mediators, especially if they don't obey anomaly cancelation conditions.

“Completons” of Simplified Models

Given the dimension 5 operator

$$\mathrm{i}\frac{g}{v} a q^\dagger H u^c + \mathrm{h.c.}$$

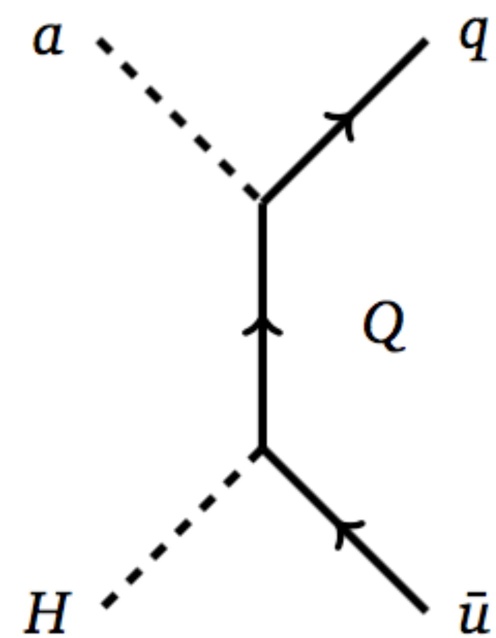
we can integrate in new tree-level physics in two ways:



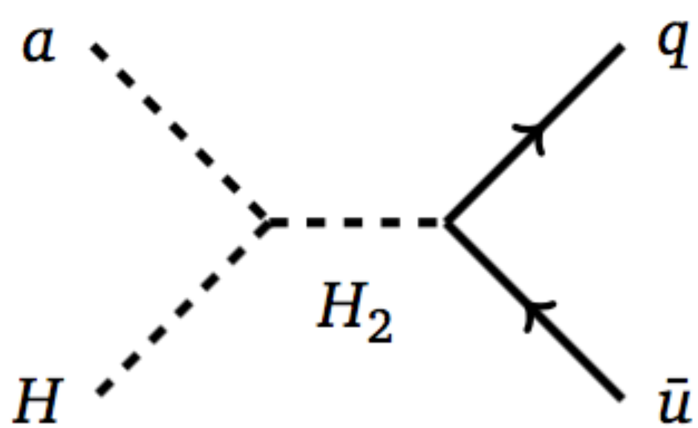
New Higgs doublet (2HDM)

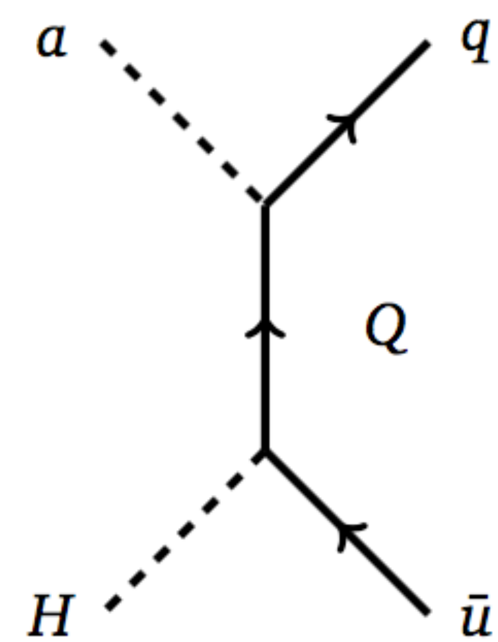
examples:
Ipek, McKeen, Nelson 1403.3716
Izaguirre, Krnjaic, Shuve 1404.2018
Fan, Koushiappas, Landsberg 1507.06993
Gonçalves, Machado, No 1611.04593

Vectorlike quark
(could also be U)



“Completons” of Simplified Models





Thus something as innocuous as “Dirac fermion dark matter with a pseudoscalar mediator” *really* means at least a 2HDM or a VLQ in addition to the mediator.

Furthermore these “completon” particles have new **nonminimal decays** to the mediator.

New signals! Sometimes easier to search for than the simplified model you started with.

B anomalies

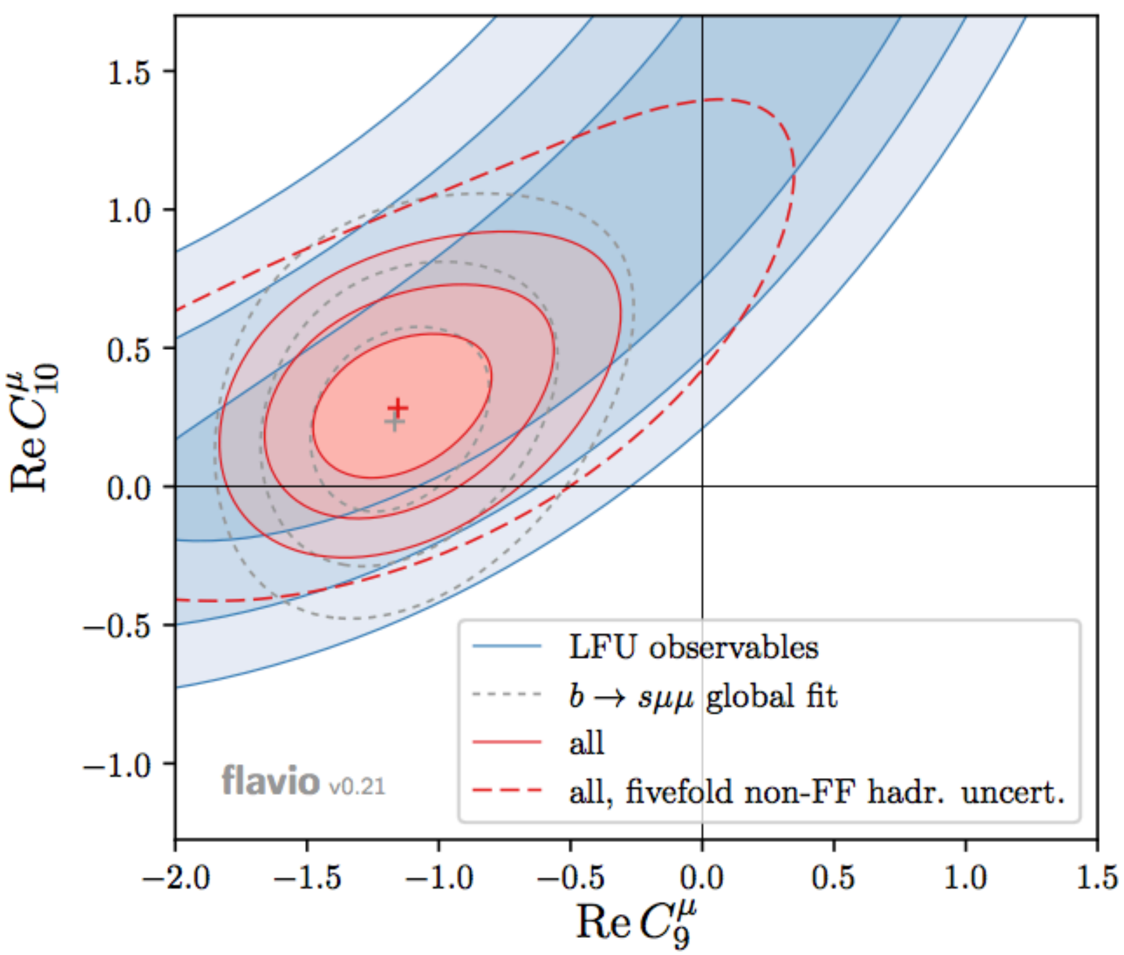
B to K: Lepton Flavor Universality Violation?

Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ (P_4', P_5')

arXiv:1303.5794 Descotes-Genon, Hurth, Matias, Virto

Branching ratios of $B^{0\pm} \to K^{(*)0,\pm}\mu^+\mu^-$

$B_s \to \mu^+\mu^-$ constrains scalar operators



Altmannshofer, Stangl, Straub
arXiv:1704.05435

$$\mathcal{O}^{\ell}_{9(10)} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu(\gamma_5)\ell)$$

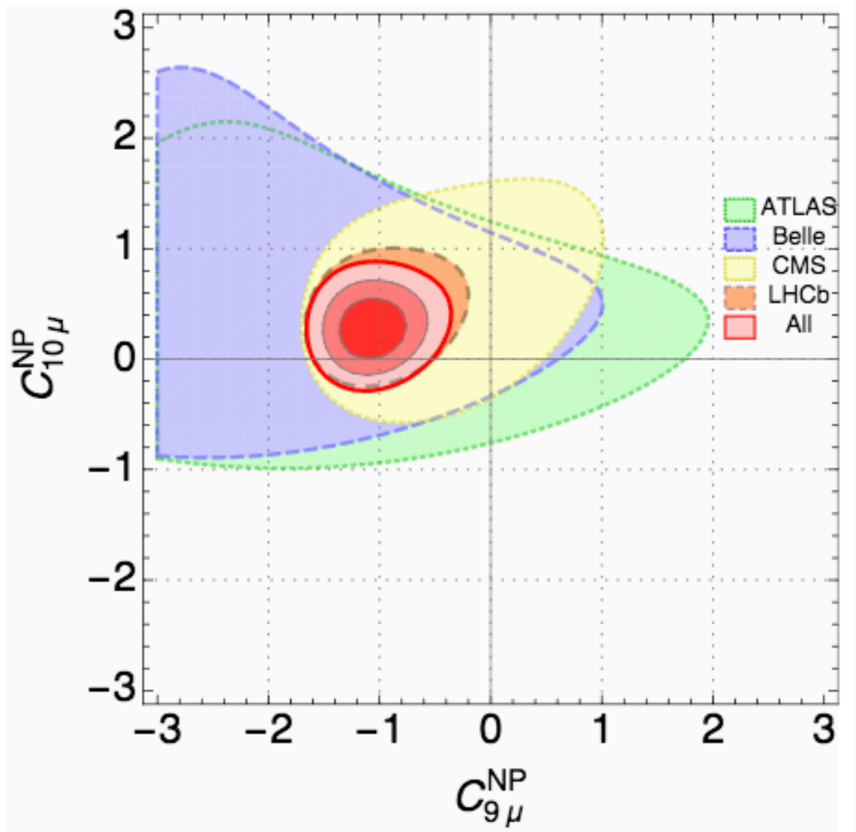
Good fits with order one

$$C_9, C_{10}, C_9 = -C_{10}$$

i.e. coefficient of order $\dfrac{2}{v^2} V_{tb} V_{ts}^* \dfrac{e^2}{16\pi^2}$

B to K: Lepton Flavor Universality Violation?

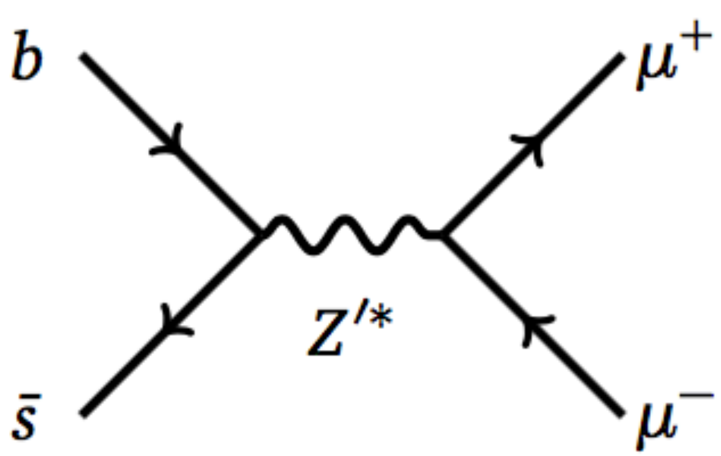
The discrepancy from the SM is driven mostly by results from LHCb.



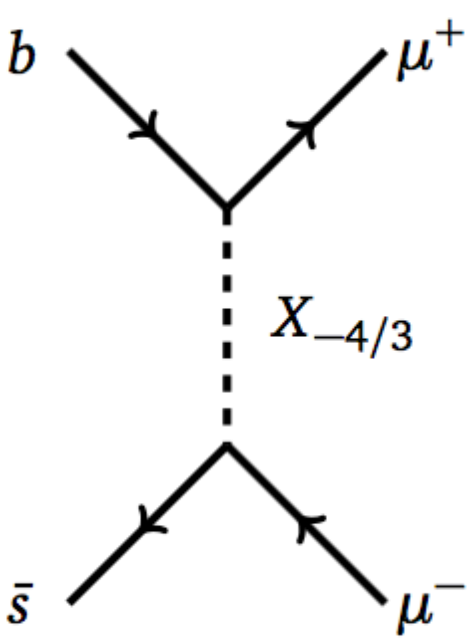
Capdevila, Crivellin, Descotes-Genon, Matias, Virto arXiv:1704.05340

Tree-level BSM explanations:

Z' boson coupling to both quarks and leptons



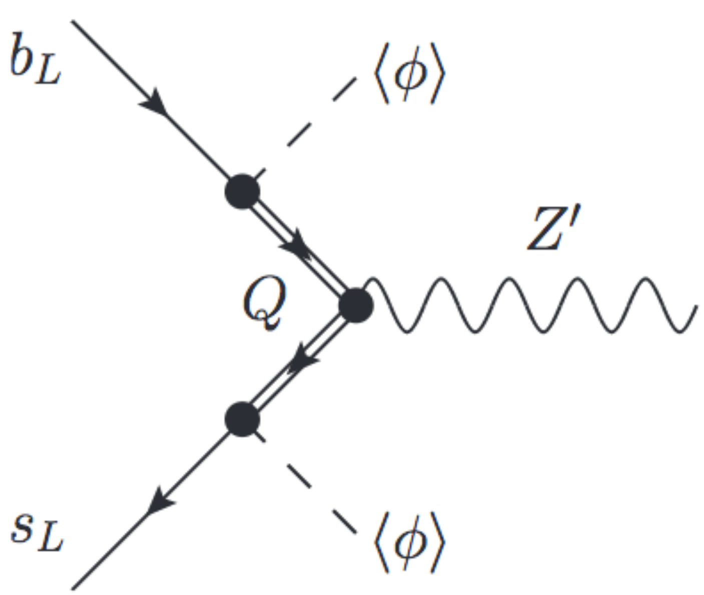
Charge -4/3, color triplet scalar leptoquark



B to K: Models

As in the dark matter simplified models, need to complete these effective operators into gauge-invariant quantities.

Leptoquark case: scalar in the $(\mathbf{3},\mathbf{3})_{-1/3}$ of SM.
Three fundamental gauge indices! Would be very new.
(Hiller, Schmaltz 1408.1627)



Z' case: could gauge $L_\mu - L_\tau$

Quark couplings from **vectorlike quarks** charged under the Z': **completons** again.
(Altmannshofer, Gori, Pospelov, Yavin 1403.1269)

Or try to directly gauge an anomaly-free group including quark charges, but then forced to add **new Higgs bosons** to get fermion masses. (Crivellin, D'Ambrosio, Heeck 1503.03477)

Comment on the Completons

There are many traditional searches for Z’ bosons, mostly in Drell-Yan production, assuming they couple to light flavor quarks.

There are traditional leptoquark searches, often organized around assumptions about the flavor-dependent couplings (e.g. “third generation leptoquark.”)

The **Z’** and **leptoquark** particles relevant for fitting the *B* anomalies **do not couple so simply.** For instance, **Z’ could couple only to heavier generations**. Independent of chasing any particular ambulance, it would be worthwhile to broaden the search strategies as much as is feasible.

Semileptonic B decays to D mesons

One of the largest tensions with the SM is in the observable

$$R(D^{(*)}) = \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell\bar{\nu})}, \qquad \ell = e, \mu$$

where the latest HFAG average of results from BaBar, Belle, and LHCb (http://www.slac.stanford.edu/xorg/hfag/semi/moriond17/RDRDs.html) is

$$R(D^*)_{\mathrm{obs}} \approx 0.310 \pm 0.015 \pm 0.008$$
$$R(D^*)_{\mathrm{SM}} \approx 0.252 \pm 0.003$$

3.4σ

$$R(D)_{\mathrm{obs}} \approx 0.403 \pm 0.040 \pm 0.024$$
$$R(D)_{\mathrm{SM}} \approx 0.300 \pm 0.008$$

2.2σ

The combination is discrepant at 3.9σ!

Operator analysis: Freytsis, Ligeti, Ruderman, 1506.08996

$$\mathcal{O}'_{V_L} = (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu) \qquad \mathcal{O}_{S_R} - \mathcal{O}_{S_L} \sim (\bar{c}\gamma^5 b)(\bar{\tau} P_L \nu)$$

Lifetimes

Why displaced vertices

Long lifetimes happen quite generally when decays proceed only through higher-dimension operators or slightly broken symmetries (think of the muon, the charged pion, the neutron). E.g. dimension 6:

$$c\tau \sim \frac{8\pi M^4}{\alpha^2 m^5} \approx 100\ \mu\mathrm{m} \times (M/10\ \mathrm{TeV})^4\,(100\ \mathrm{GeV}/m)^5$$

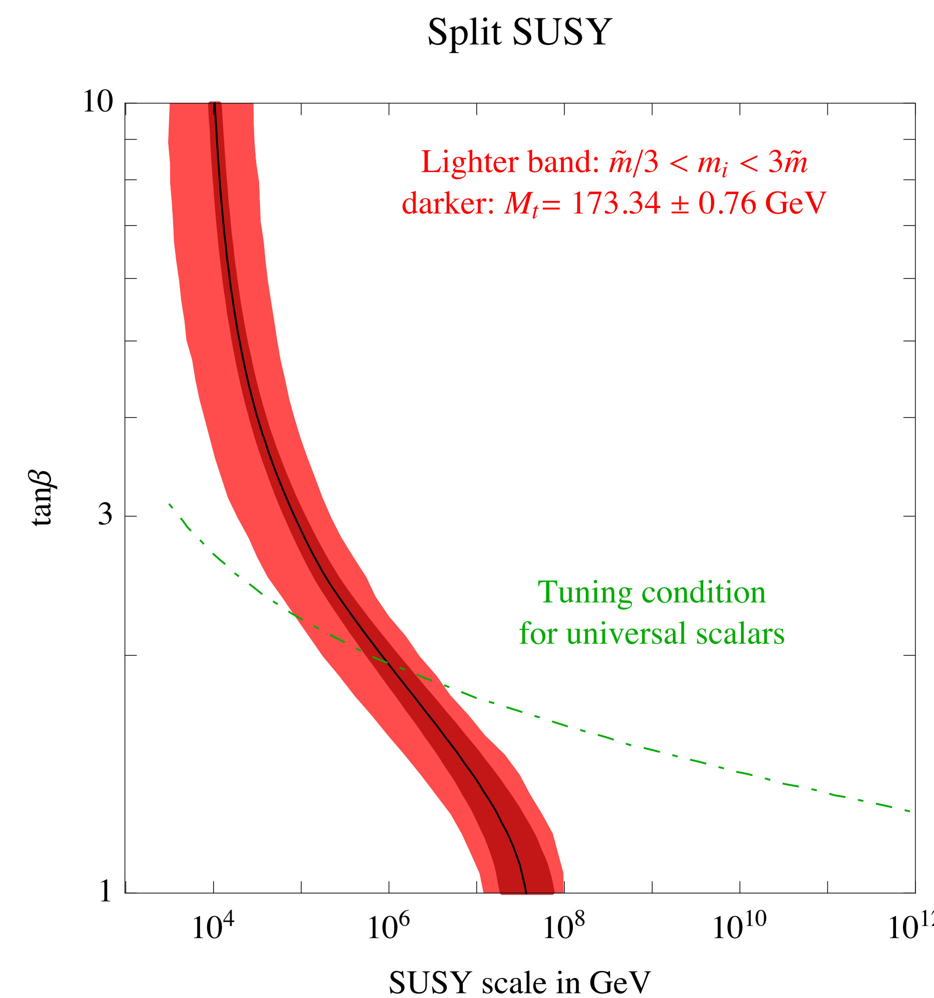
This happens, for instance, in **gauge-mediated SUSY breaking**, or in many **Hidden Valley models** (also **Twin Higgs**)

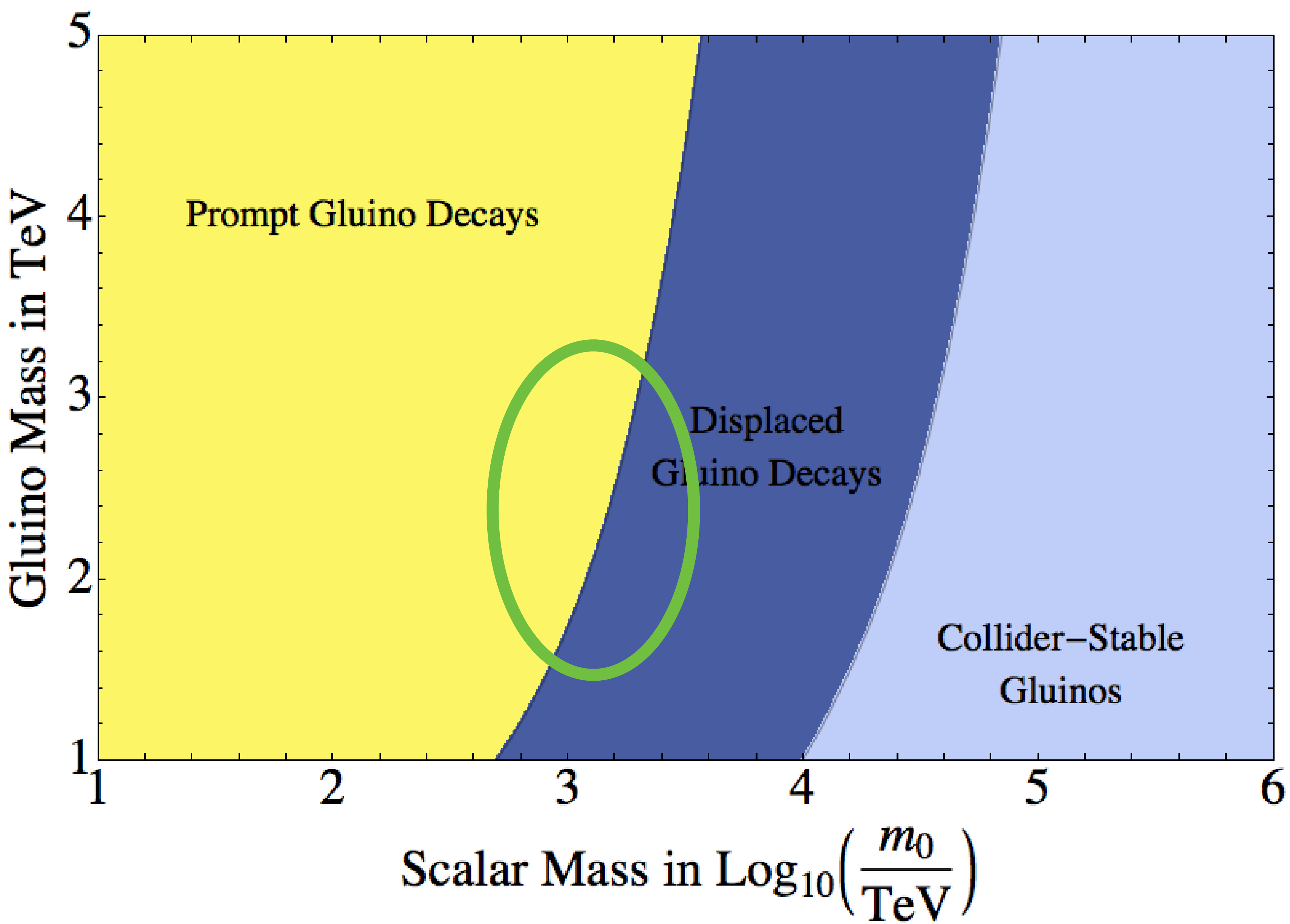
A request for experimentalists

Not always easy to tell when a mild displacement (centimeters) will cause events to be thrown out by "event cleaning" cuts. Would be useful to try to always publicize this information—a wide range of searches could be applied to mildly displaced events.

Split SUSY displacements

The extreme version of split SUSY with very long gluino lifetimes is disfavored by the Higgs mass, in the MSSM. A more plausible scenario has mild displacement. (Bagnaschi, Giudice, Slavich, Strumia 1407.4081)



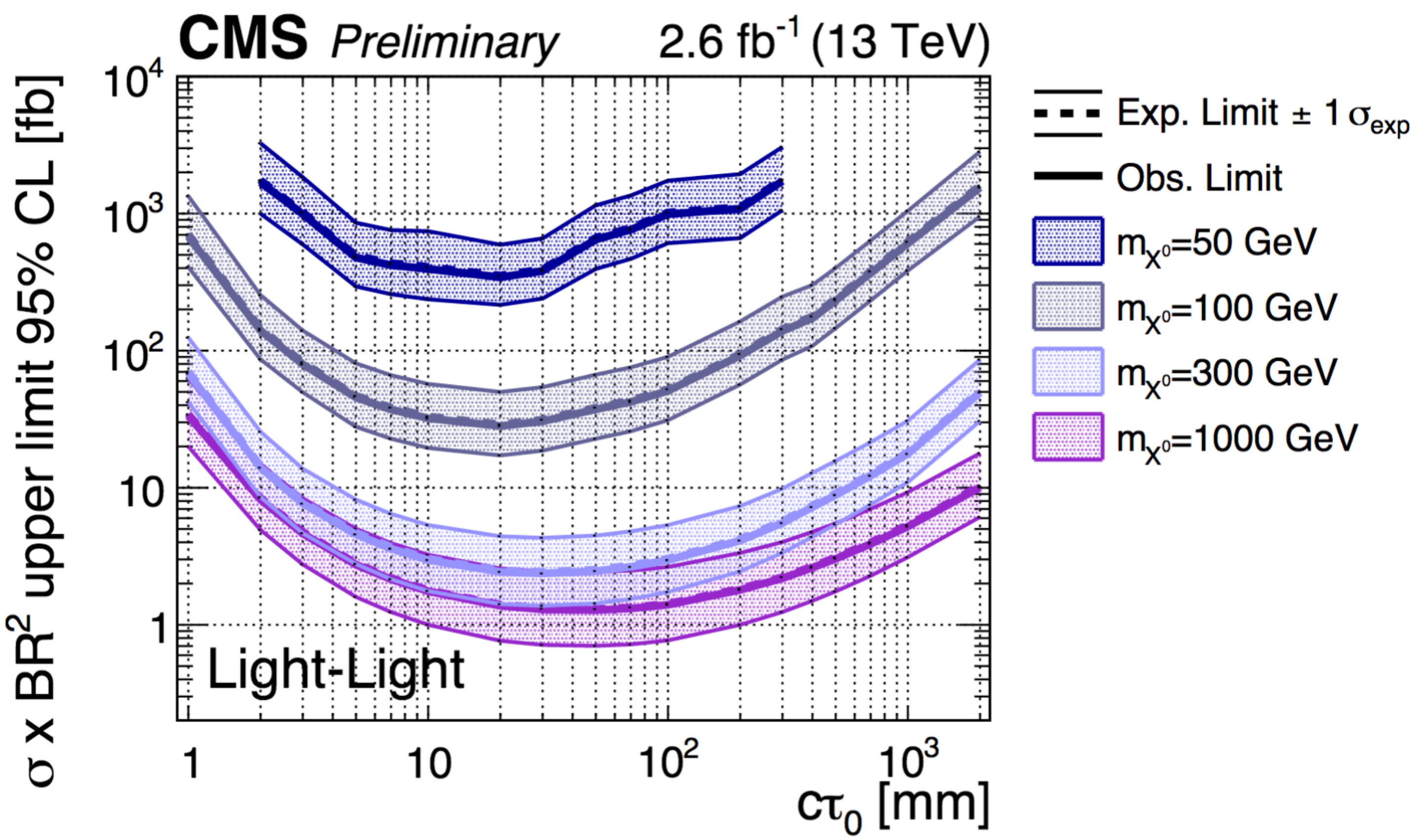


(Arvanitaki, Craig, Dimopoulos, Villadoro '12)

On the border, ~100 μm decay lengths. Experimentally challenging, but possible?

When do we lose events in standard searches?

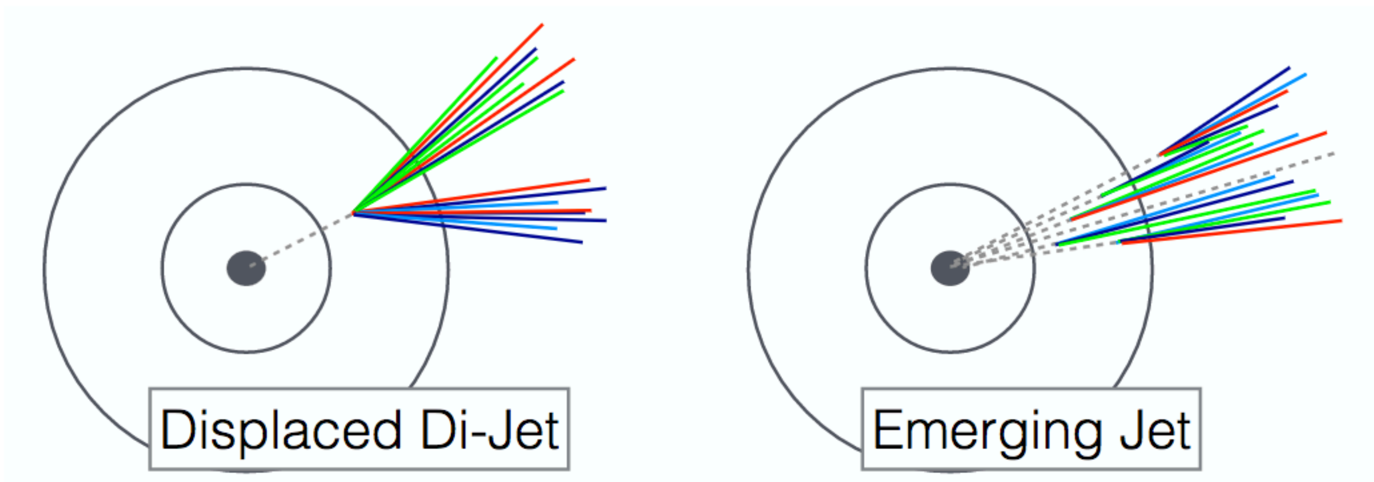
Displaced jets



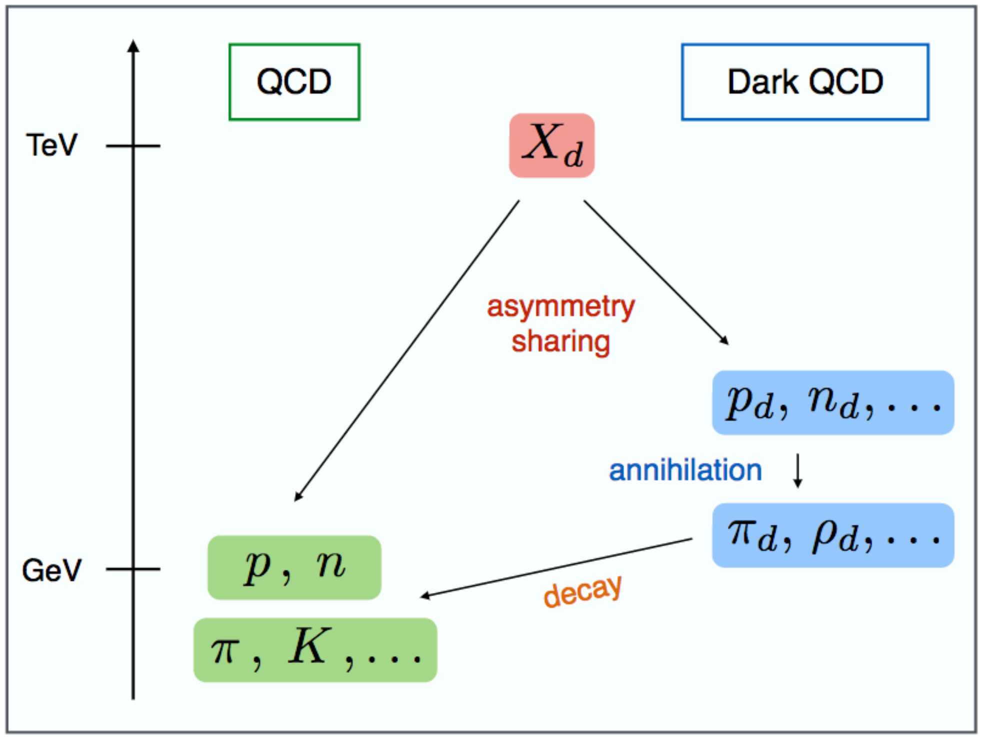
Some nice, quite general searches have happened at ATLAS and CMS, such as a generic displaced dijet search (CMS PAS EXO-16-003).

Very constraining, e.g. for R-parity violating SUSY.

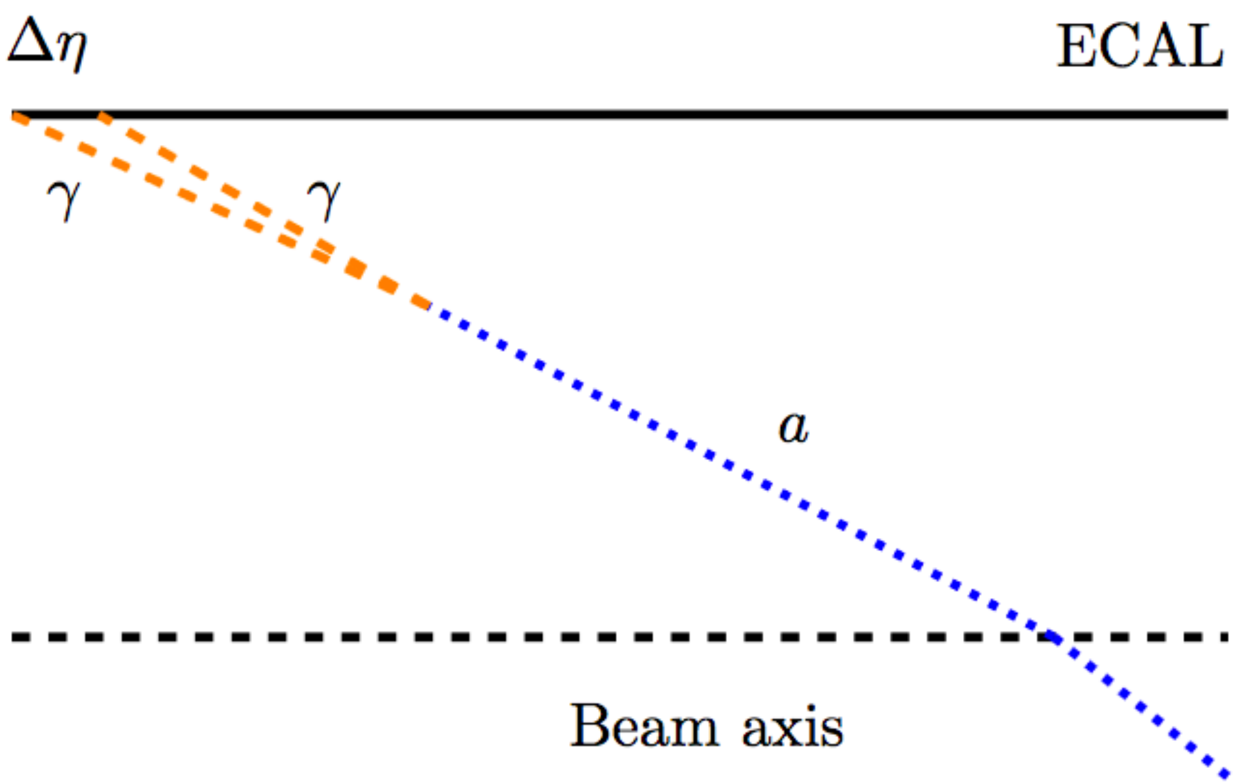
Emerging jets



Schwaller, Stolarski, Weiler 1502.05409



Diphotons from Tetraphotons

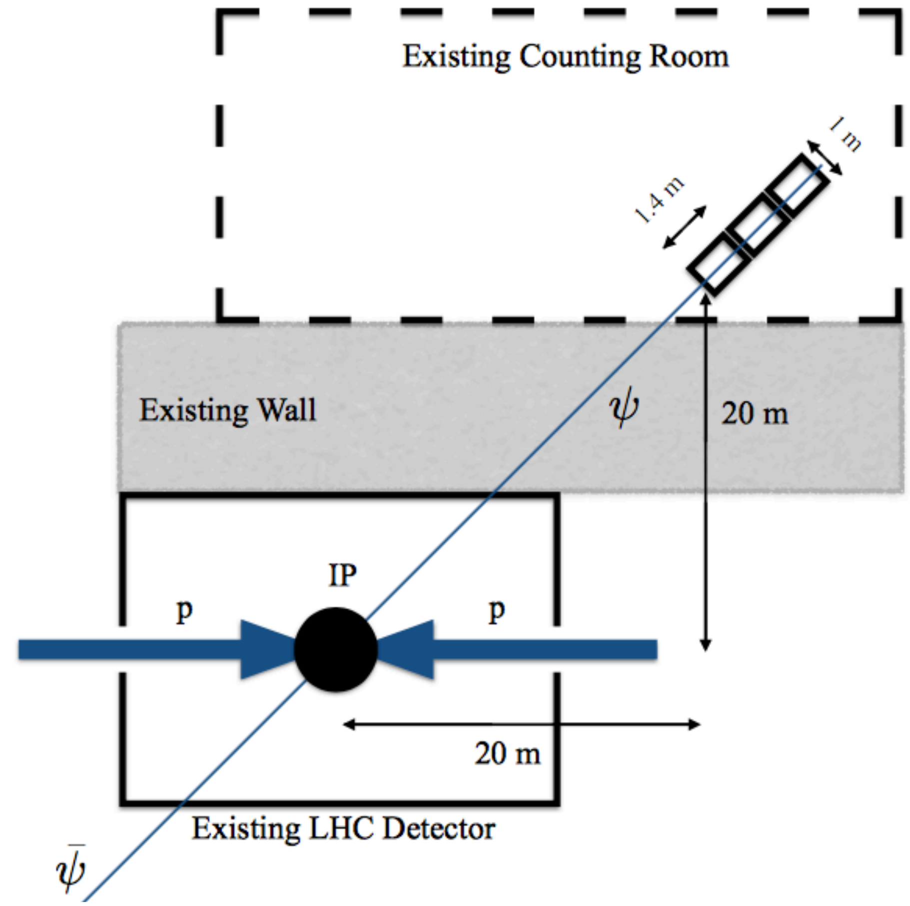


Dobrescu, Landsberg, Matchev hep-ph/0005308
Draper, McKeen 1204.1061
Knapen, Melia, Papucci, Zurek 1512.04928
Agrawal, Fan, Heidenreich, MR, Strassler 1512.05775

This idea has been around for a while, but became briefly a center of attention again during the 750 GeV hoopla.

Independent of that, it's worth asking: how well can experiments find particles decaying into two highly overlapping photons?

“Parasitic” experiments



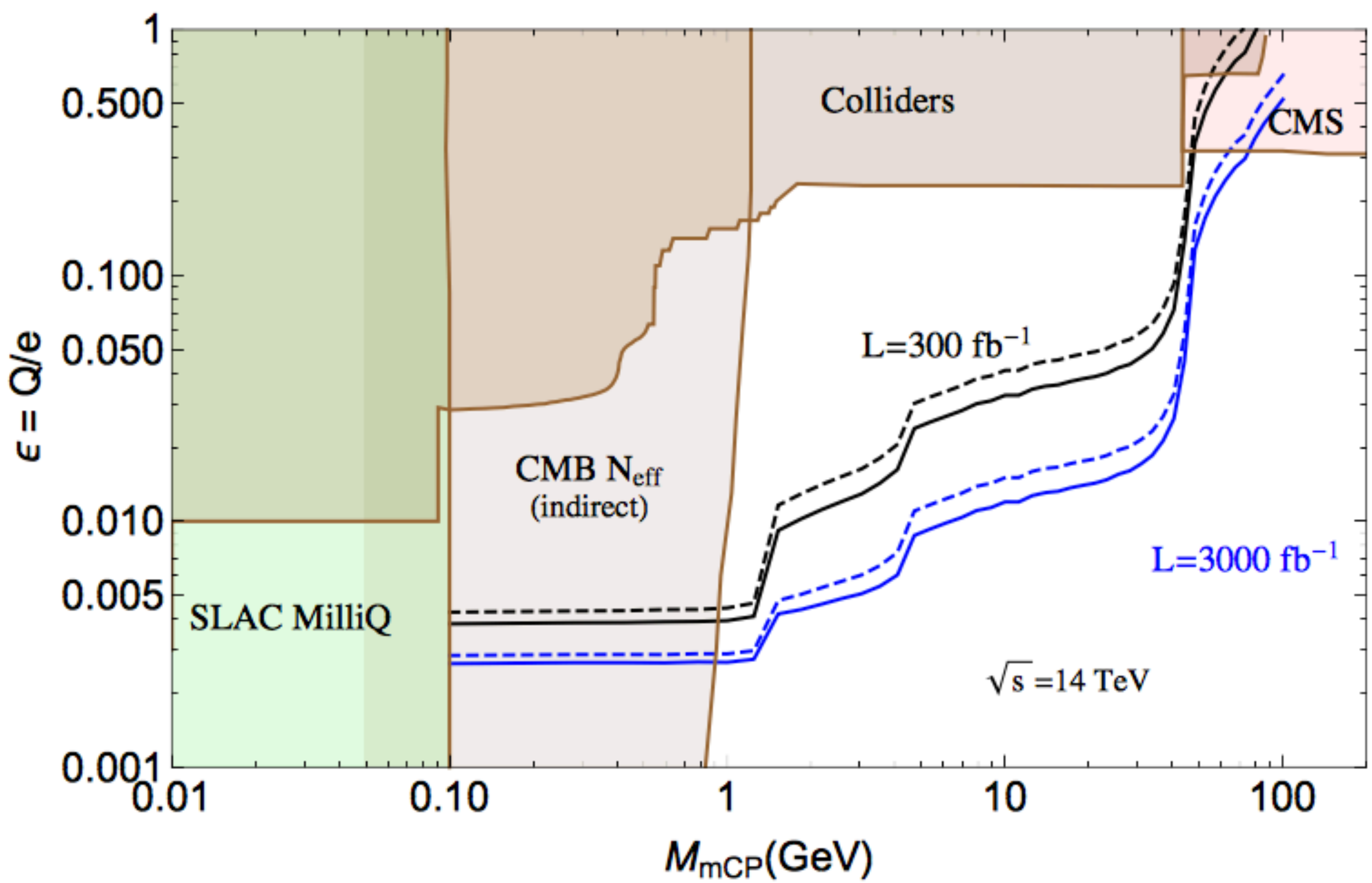
Can the LHC allow for small-scale experiments not otherwise possible?

MilliQan experiment: A. Haas, C. Hill, E. Izaguirre, I. Yavin arXiv:1410.6816; Izaguirre & Yavin 1506.04760; letter of intent 1607.04669

Use existing space in CMS drainage gallery.

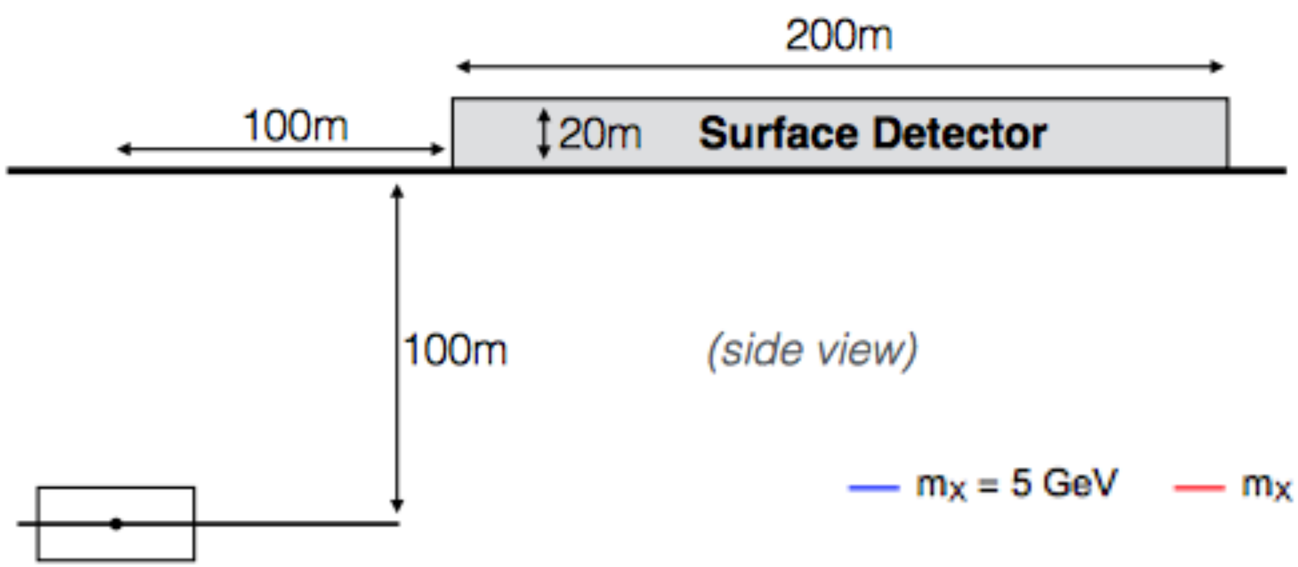
Plastic scintillator bars (~meter) and PMTs. About 1 photoelectron per 10^{-3} charge particle passage.

Operate during Run 3 (2022-2025).



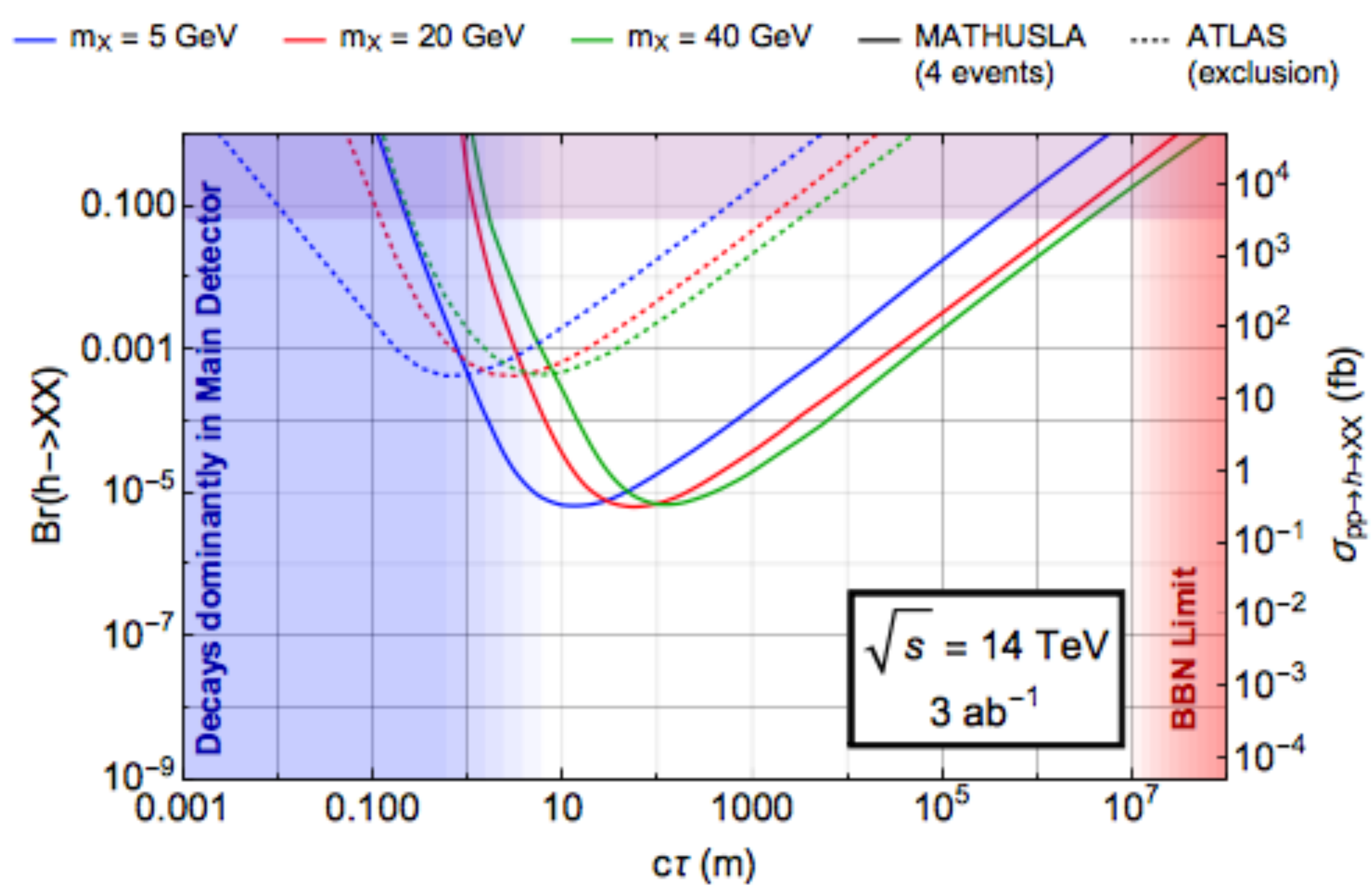
MATHUSLA experiment

Chou, Curtin, Lubatti arXiv:1606.06298; Curtin, Sundrum 1702.02524; Curtin, Peskin 1705.06327



Idea:
Surround a large volume with inexpensive scintillator as a veto; put a tracking detector inside.

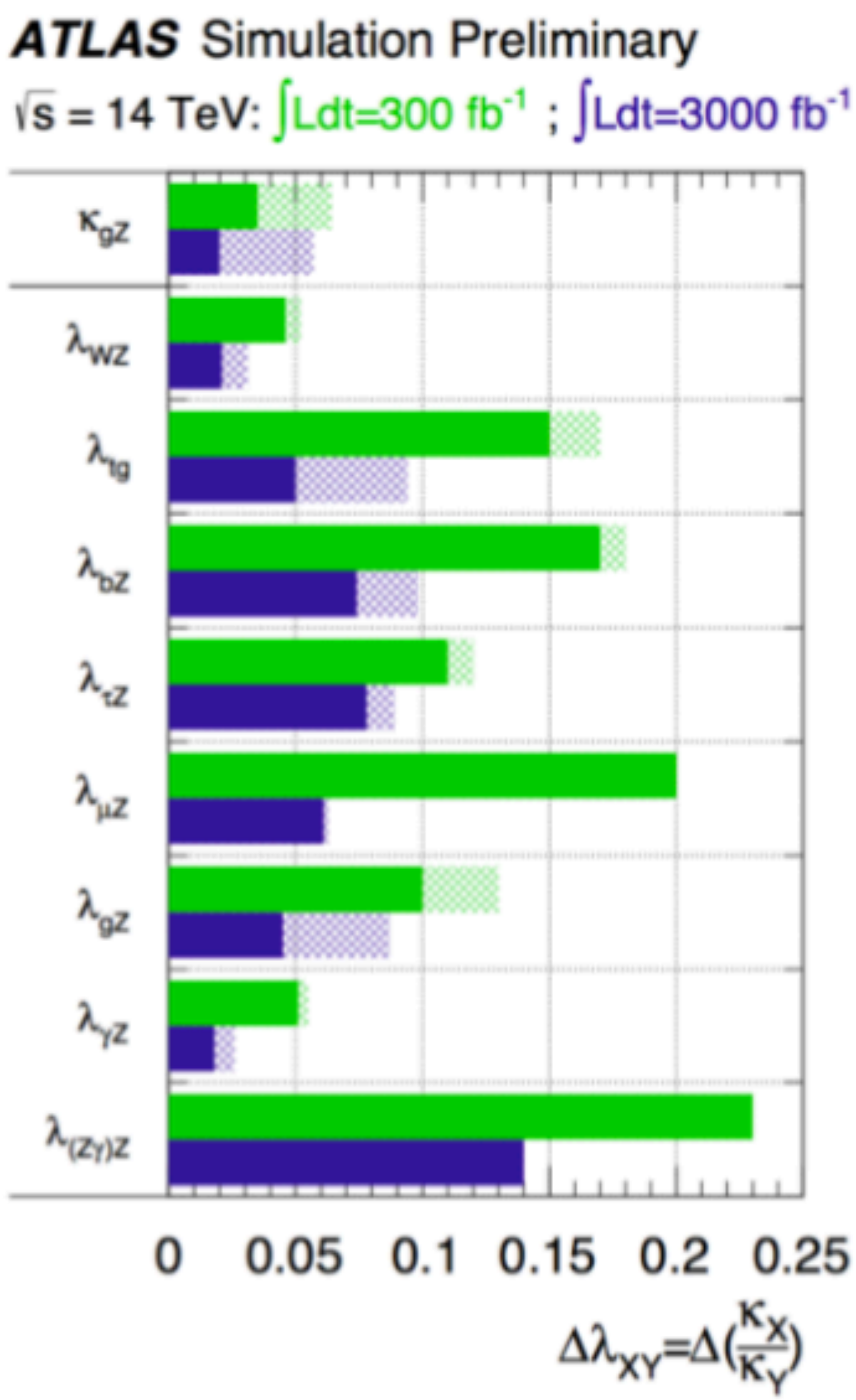
For particles with large production rates (e.g. from Higgs decays), could even probe **BBN lifetime**. But best coverage in the **10 meter to kilometer range.**



Precision

Higgs couplings at the LHC

Remember: ***a natural Higgs is not a Standard Model Higgs.*** We expect ***order-one*** deviations in Higgs properties.



The high luminosity LHC will measure certain *ratios* of Higgs couplings with great precision.

The photon-to-Z coupling ratio will be measured particularly precisely (important input to future e^+e^- Higgs factories!)

Electroweak precision at the LHC

CP-even operators with higgses and gauge fields:

$$\mathcal{O}_W = \frac{ig}{2}(h^\dagger \sigma^i D_\mu h) D^\nu W^i_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}(h^\dagger D_\mu h)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{WW} = g^2 |h|^2 W^i_{\mu\nu} W^{i\mu\nu}$$

$$\mathcal{O}_{WB} = g g' h^\dagger \sigma^i h W^i_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 h^\dagger h B_{\mu\nu} B^{\mu\nu}$$

Peskin-Takeuchi *S* depends on:

$$S: \quad C_{WB}, C_W, C_B$$

well-constrained by LEP.

$$h \to \gamma\gamma, h \to Z\gamma:$$
$$C_{WW}, C_{BB}, C_{WB}$$

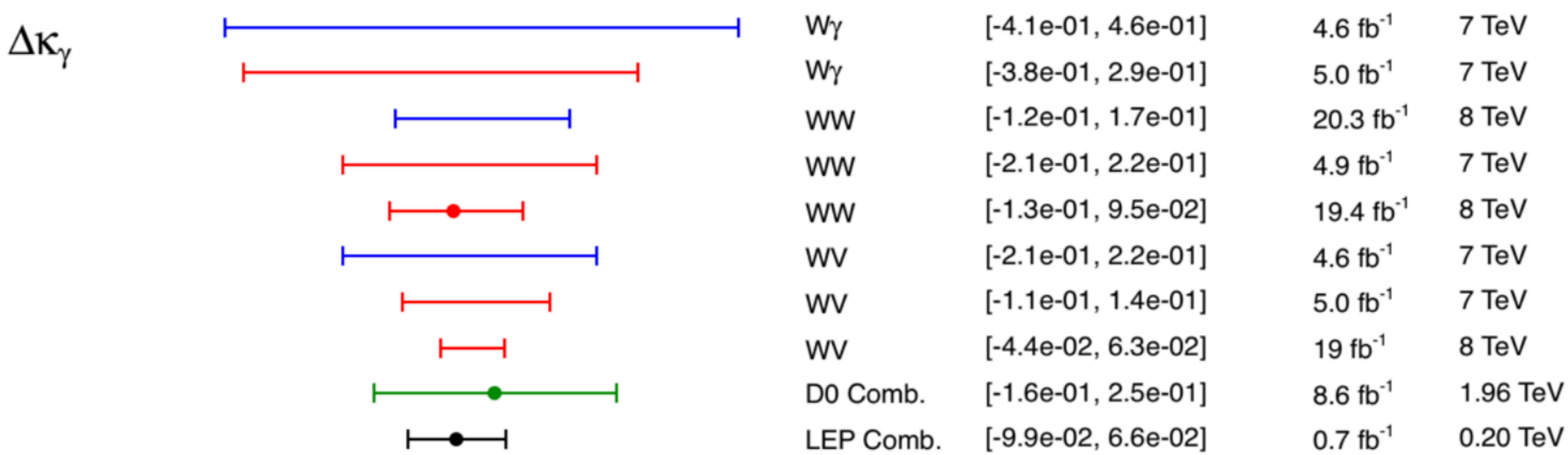
TGCs: $ig \cos\theta_W (\Delta g_1^Z) Z^\nu (W^+_{\mu\nu} W^{-\mu} + \text{h.c.}), \quad \Delta g_1^Z \propto C_W$

$(\Delta\kappa_\gamma) \sin\theta_W A^{\mu\nu} W^+_\mu W^-_\nu / 2, \quad \Delta\kappa_\gamma \propto C_{WB}$

many papers, many bases; see e.g.
Elias-Miró, Grojean, Gupta, Marzocca 1312.2928
Wells, Zhang 1510.08642

Electroweak precision at the LHC

By measuring both Higgs branching ratios and Triple Gauge Couplings, can try to explore the whole space of these operators (supplementing LEP). TGCs already competing with LEP, e.g.:



Other purely-electroweak (no Higgs) operators:

$(D^\mu W_{\mu\nu})^2 \sim j_{W\,\mu} j_W^\mu$ test with Drell-Yan

(Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer 1609.08157)

$\mathrm{tr}(W^3)$ additional TGC, tiny in all models I know

(but perhaps not in hypothetical “Remedios” models: Liu, Pomarol, Rattazzi, Riva 1603.03064)

Exploit SM progress

Jet physics

Lots of recent advances in pileup removal, jet grooming (filtering, trimming, pruning), quark/gluon discrimination, top tagging, and so on.

Example:
Soft Drop to remove soft and wide angle radiation.

Larkoski, Marzani, Soyez, Thaler 1402.2657

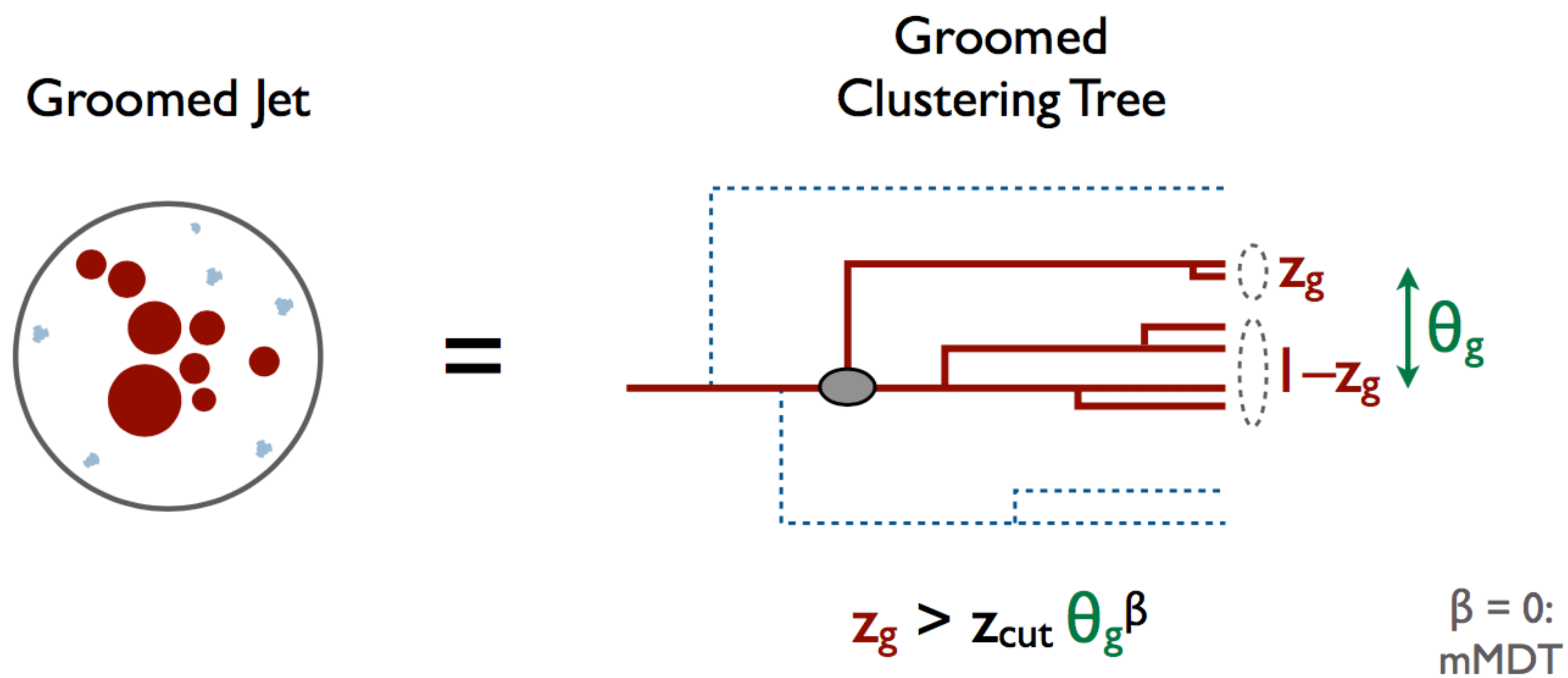
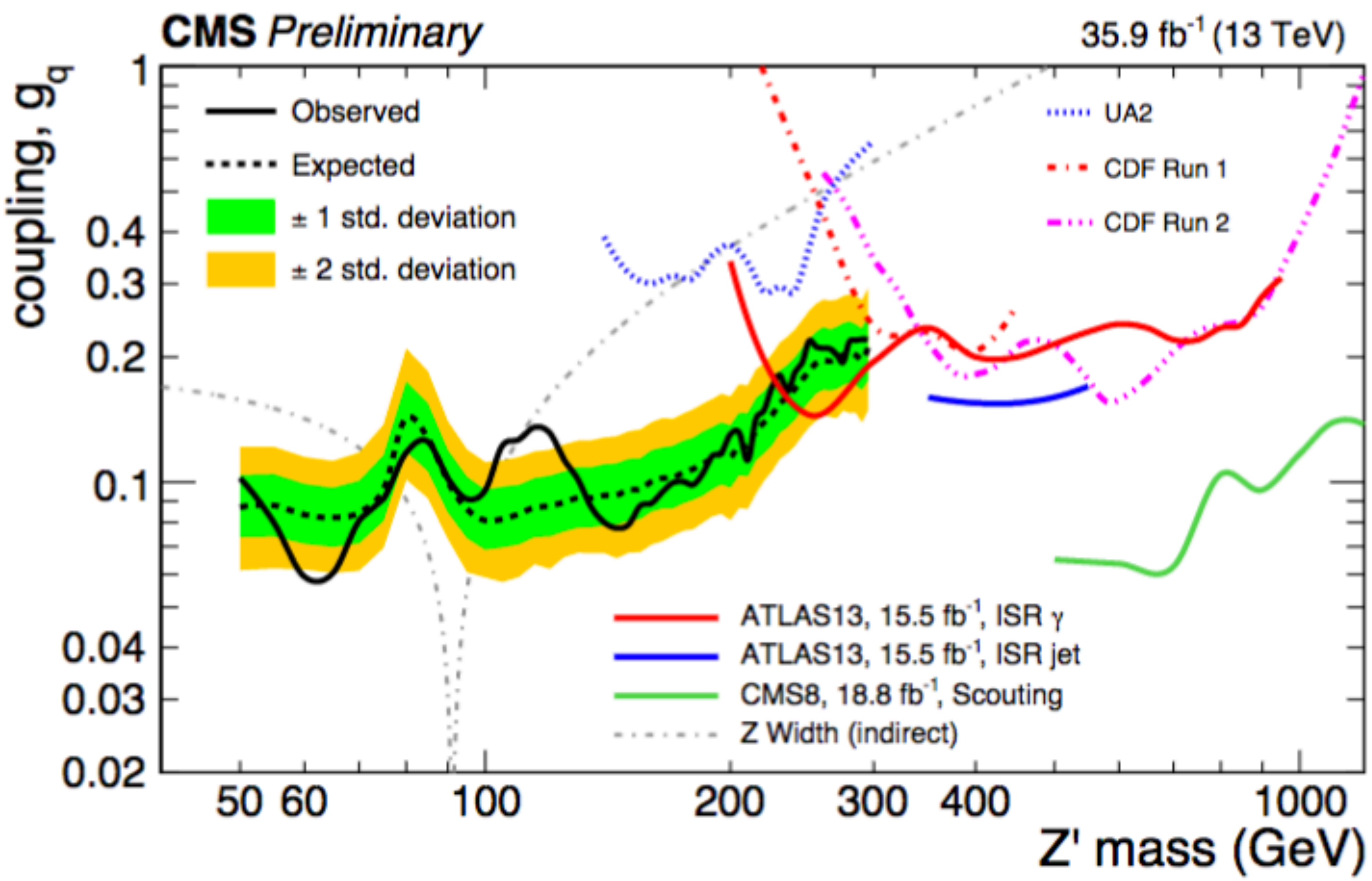


figure from Jesse Thaler's winter Aspen 2017 talk

Jet physicists have developed a large toolkit of ideas. It's time to really put it to work for doing more searches for BSM physics.

Example: new CMS search for light Z'



CMS PAS EXO-17-001

Looks for

$$Z' \to q\bar{q}$$

in a single high-p_T jet.

Low-mass region not well studied even at Tevatron or UA2!

Builds on recent ideas from theorists:

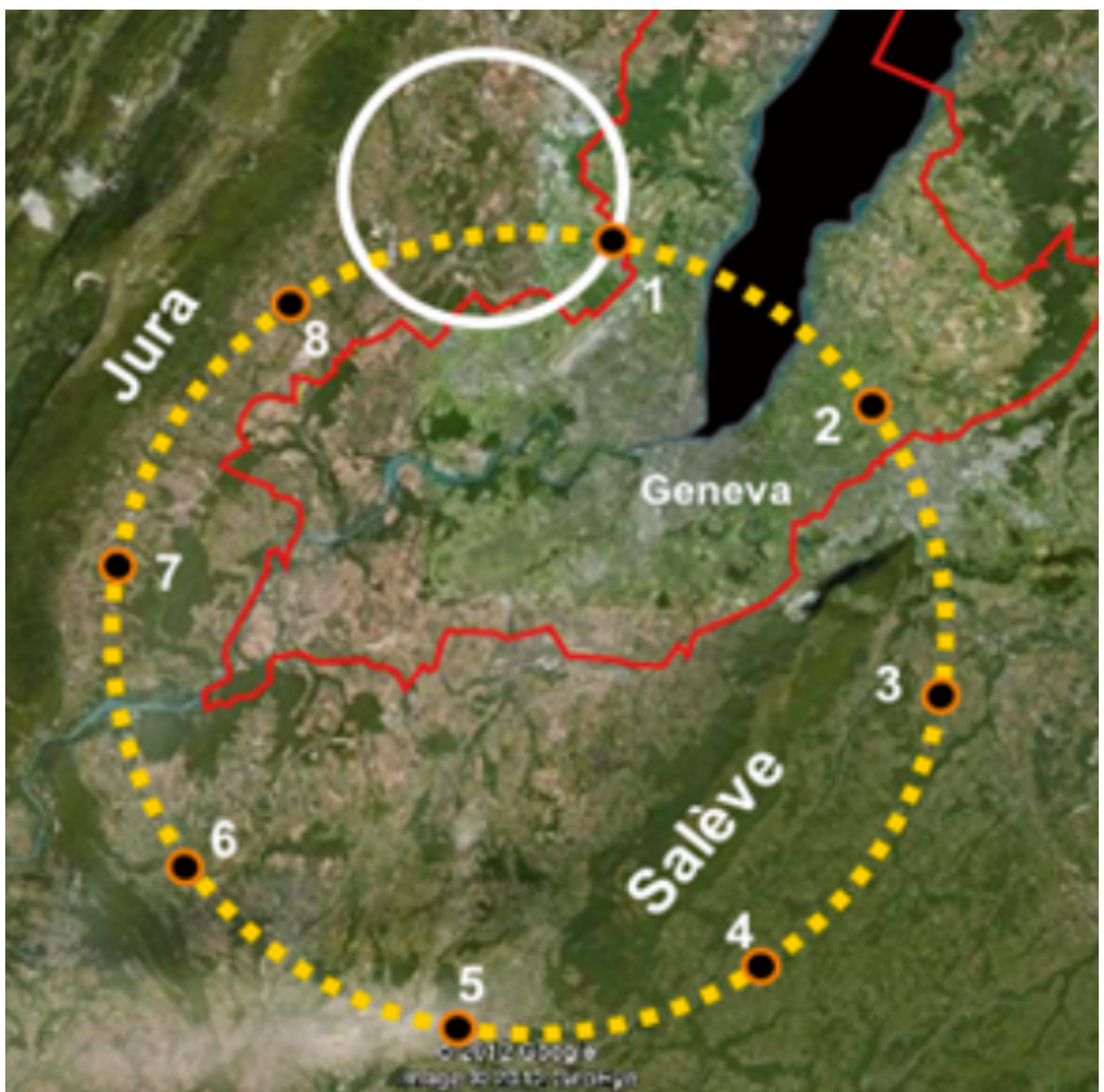
- PUPPI (Pileup per particle identification)
  Bertolini, Harris, Low, Tran 1407.6013
- Soft drop jet grooming
  Dasgupta, Fregoso, Marzani, Salam 1307.0007
  Larkoski, Marzani, Soyez, Thaler 1402.2657
- N^1_2 variable (ratio of energy correlation functions)
  Moult, Necib, Thaler 1609.07483

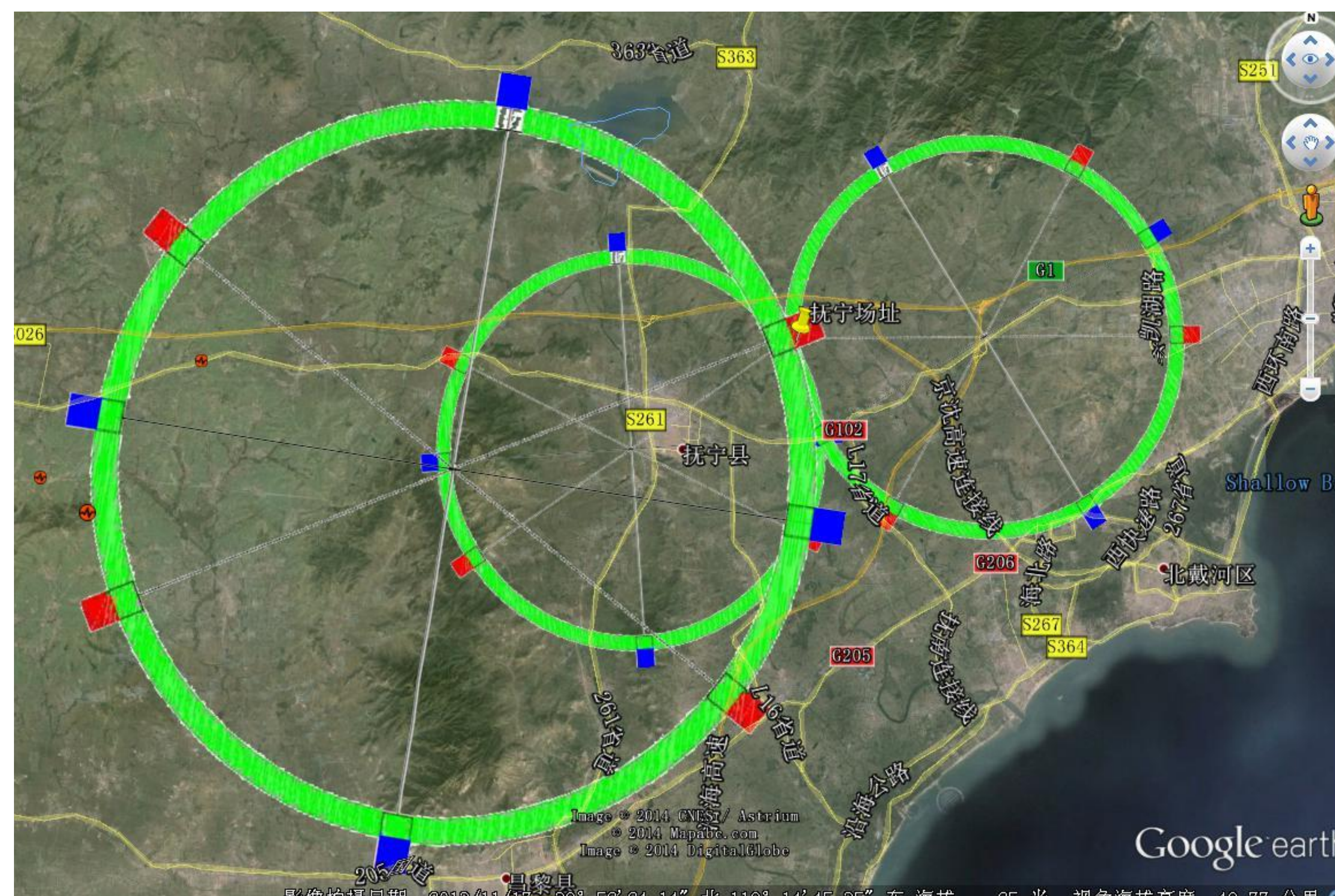
BSM BLHC

The next colliders?

Lots of planning:

ILC, FCC-ee/hh, CEPC/SPPC
Healthy competition

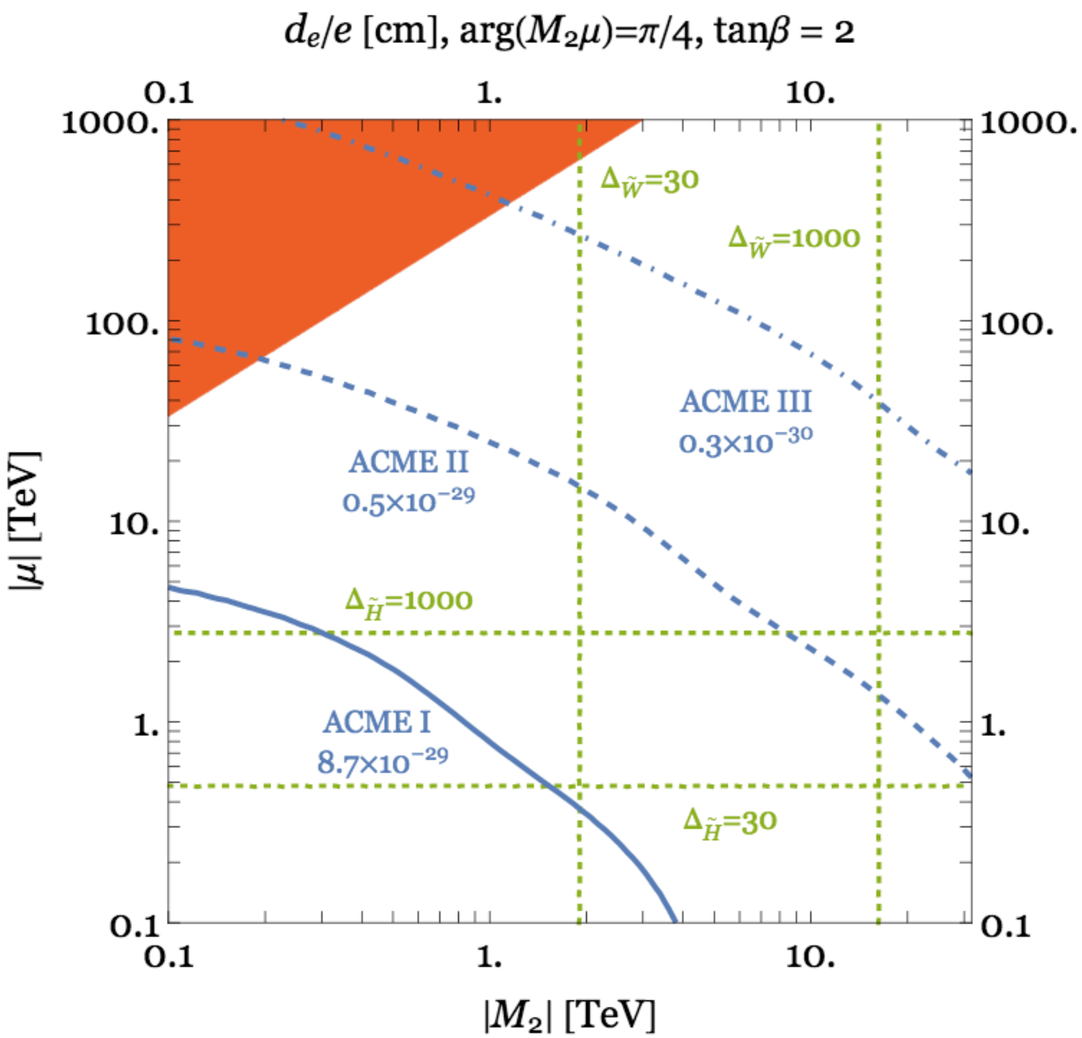




Elsewhere…

The LHC might not provide our first sign of new physics.

One of many possible examples:



Electron EDM could exist, indicating new EWK physics (e.g. split SUSY) figure from Y. Nakai, MR 1612.08090

Projections from John Doyle

ACME II result expected **in 2017**

Important to keep in mind, when thinking about future colliders, that we could get concrete information about the new physics energy scale from many places in the coming decade!

Outlook

Some possible lessons:

Important to look beyond minimal decays, explore non-100% branching fractions, and generally cover gaps.

“Completons”—particles introduced to make simplified models make sense—are often vectorlike quarks, leptoquarks, extra Higgses. These are all good things to look for *broadly*, independent of any particular model.

Experimental edge cases: What happens to events with modestly displaced vertices? What happens when two photons overlap? Can be good places to look for exotica.

The BSM community can always benefit from what the QCD/jet community is doing.

Conclusion

The fully natural solution to the hierarchy problem, with spectacular signals in the first tens of fb^{-1}, did not appear, but our search is not over.

A mostly-natural theory is still more plausible than 30 decimal places of fine-tuning. This is no time to give up. It ***is*** a time to consider novel ideas, for instance linking cosmology to the hierarchy.

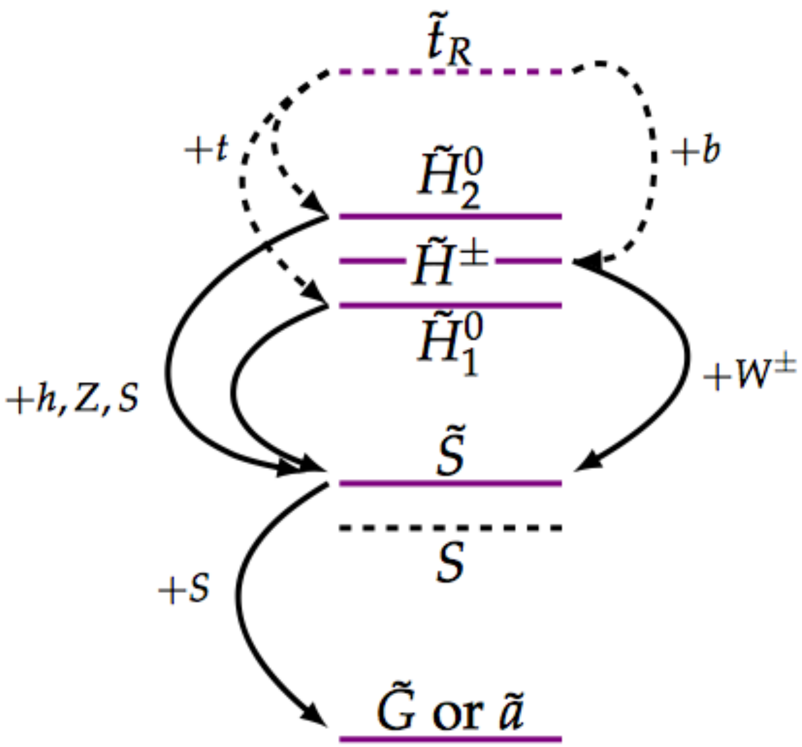
We have seen, for the first time, what appears to be a ***fundamental, weakly-coupled scalar***, and this is an important clue about nature. We must pursue the underlying ***mechanism***.

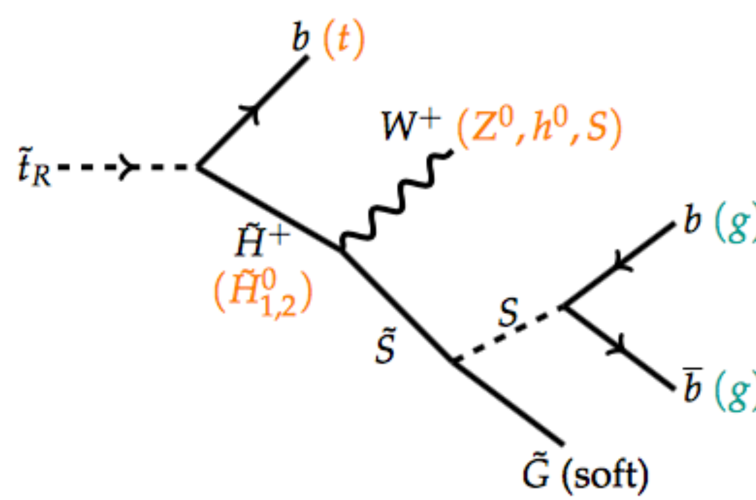
Backup/Useful

Stealth SUSY Stops

cascade through higgsino

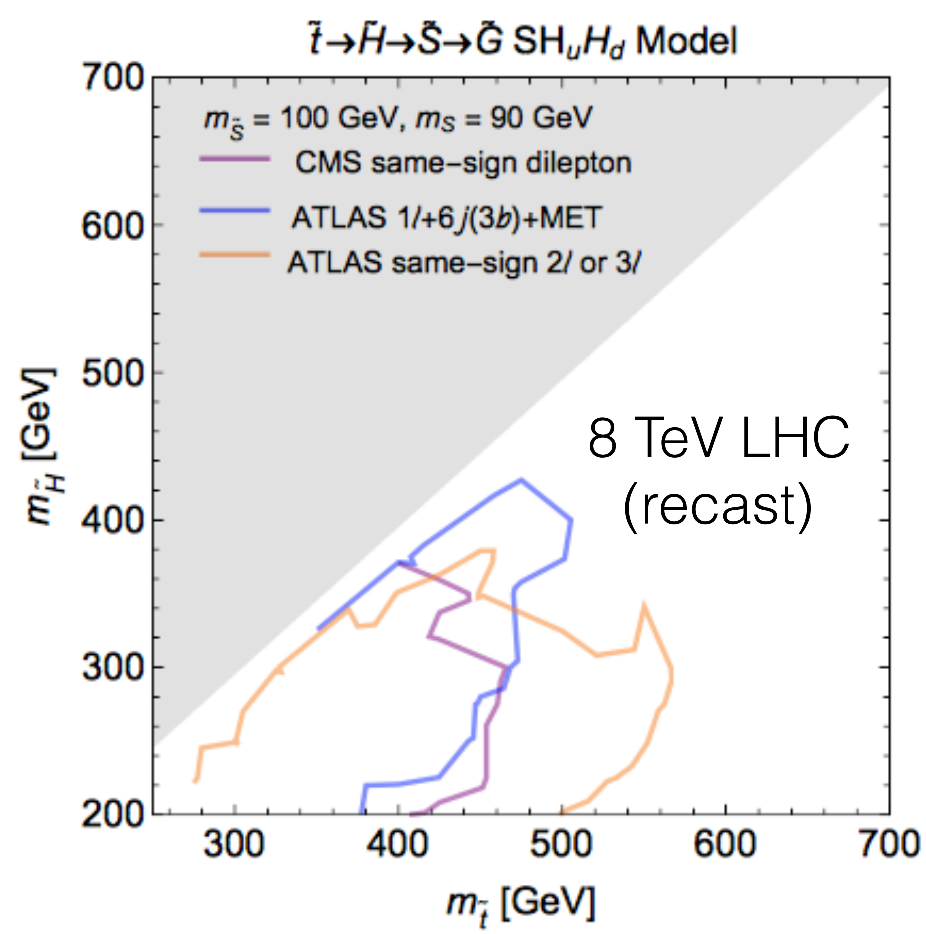
Fan, Krall, Pinner, MR, Ruderman
arXiv:1512.05781

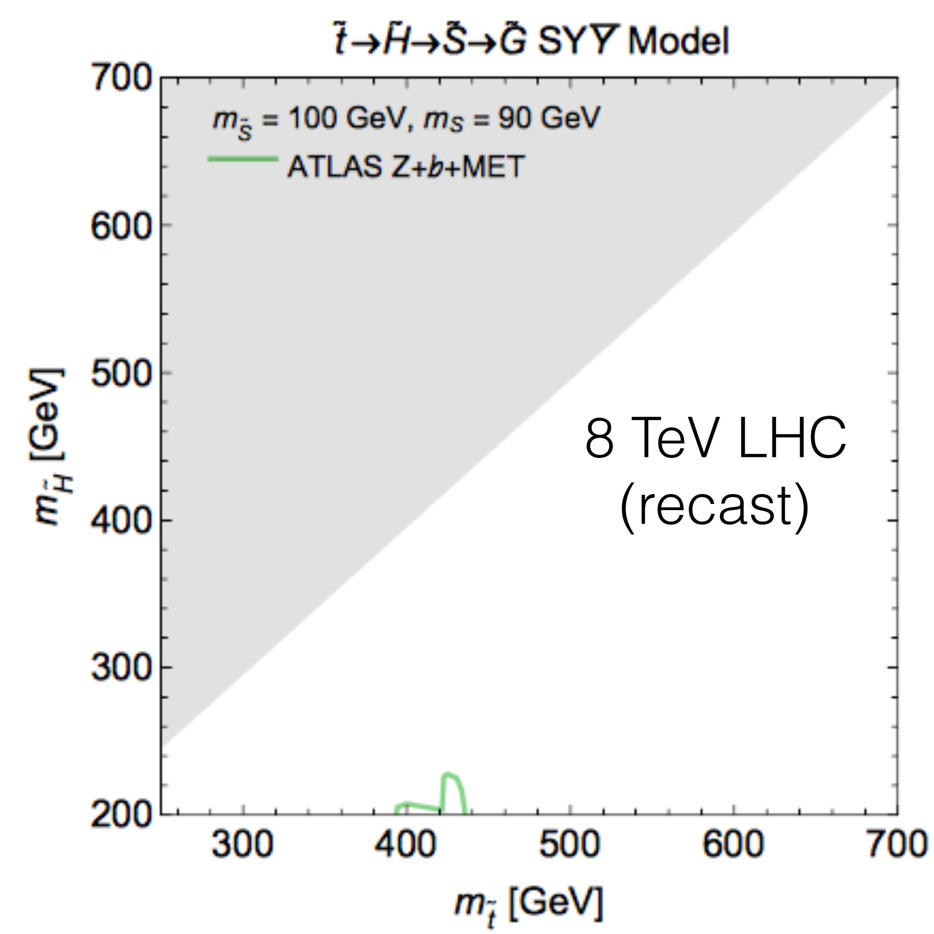




Stealth SUSY:
Approx. SUSY in hidden sector suppresses missing momentum.

Recast of 8 TeV searches. Bound depends on number of *b*-jets in final state.





What are angular observables in B decays?

arXiv:1303.5794 Descotes-Genon, Hurth, Matias, Virto

Integrals of J_4, J_5 over q^2 ranges

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big], \qquad (3)$$

R(D*) New Physics Possibilities

A general operator analysis is in Freytsis, Ligeti, Ruderman, 1506.08996.

Differential distributions can distinguish different operators. Good fits from e.g.:

$$\mathcal{O}'_{V_L} = (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu)$$

$$\mathcal{O}_{S_R} - \mathcal{O}_{S_L} \sim (\bar{c}\gamma^5 b)(\bar{\tau} P_L \nu)$$