What Could We Learn From Future Colliders?

Matt Reece

June 24, 2014

drawing on the work of many people

Outline

- What will precision e+e- measurements at future colliders (e.g. ILC or TLEP) tell us about naturalness?

- What are some of the physics possibilities at a future 100 TeV proton-proton collider?

- What's the interplay between future experimental results on dark matter (indirect & direct detection) and future collider physics?

e^+e^-

e^+e^- precision physics

Proposed e+e- colliders like ILC, TLEP, or CEPC have limited energy reach for discovery compared to the LHC. To what extent can they be an improved probe of naturalness?

e.g.: reach for loop effects of stops? for composite Higgs?

If I'm very conservative, the LHC has only guaranteed factors of ~ 10 tuning for SUSY and ~ 100 for composite Higgs. **Most particular models are worse**, but it's hard to make completely generic arguments given LHC data.

Loophole Closing

LHC direct searches are powerful but can fail if decay modes are altered so that signals hide in SM backgrounds.

Stealth Supersymmetry

JiJi Fan,[1] Matthew Reece,[2] and Joshua T. Ruderman[1]

Displaced Supersymmetry

Peter W. Graham,[1] David E. Kaplan,[2] Surjeet Rajendran,[1,2] and Prashant Saraswat[1]

Hiding Missing Energy in Missing Energy

Daniele S. M. Alves,[1,2] Jia Liu,[1] and Neal Weiner[1]

Model builders can do amusing (or annoying, depending on your viewpoint) things to hide particles like stops. Would ILC and/or TLEP shut down these model-building games?

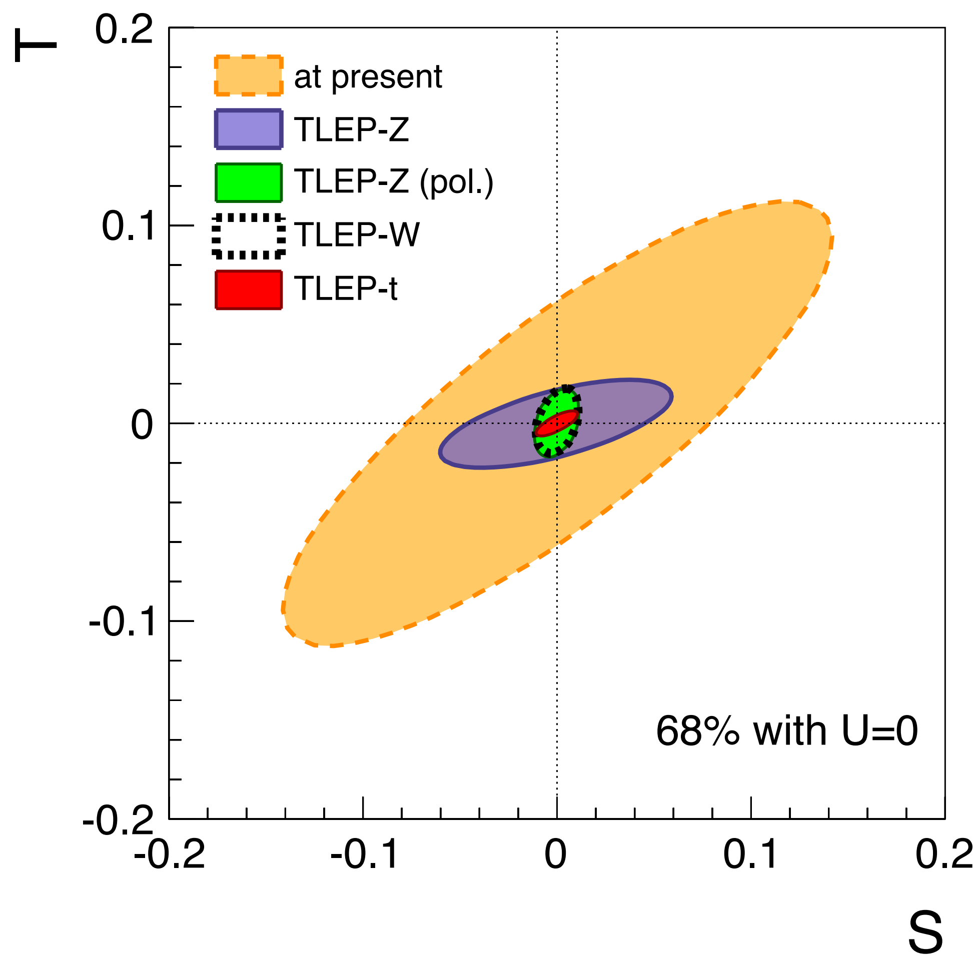
Precision Higgs

	Model-independent fit				Constrained fit		
Coupling	TLEP-240	TLEP		ILC	TLEP		ILC
g_{HZZ}	0.16%	**0.15%**	(0.18%)	0.9%	0.05%	(0.06%)	0.31%
g_{HWW}	0.85%	**0.19%**	(0.23%)	0.5%	0.09%	(0.11%)	0.25%
g_{Hbb}	0.88%	**0.42%**	(0.52%)	2.4%	0.19%	(0.23%)	0.85%
g_{Hcc}	1.0%	**0.71%**	(0.87%)	3.8%	0.68%	(0.84%)	3.5%
g_{Hgg}	1.1%	**0.80%**	(0.98%)	4.4%	0.79%	(0.97%)	4.4%
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)	2.9%	0.49%	(0.60%)	2.6%
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)	45%	6.2%	(7.6%)	45%
$g_{H\gamma\gamma}$	1.7%	**1.5%**	(1.8%)	14.5%	1.4%	(1.7%)	14.5%
BR_{exo}	0.48%	**0.45%**	(0.55%)	2.9%	0.16%	(0.20%)	0.9%

Higgs coupling measurements expected at TLEP and ILC, from the TLEP “First Look at Physics Case” paper 1308.6176.

EWPT Observables

SM scenario



from slides by Satoshi Mishima at the 6th TLEP workshop

$$\delta S \sim 7 \times 10^{-3}, \qquad \delta T \sim 4 \times 10^{-3}$$

Also: R_b at 2 to 5 × 10^{-5}.

Need to consider whether the machine runs on the *Z*-pole enough for GigaZ, TeraZ, etc. Key for maximizing new physics reach: a Higgs factory is not enough; also need to re-run LEP, only better.

Composite Higgs?

Tuning in Higgs VEV and Higgs mass. Specifically: for Higgs as a pseudo-Goldstone, expect a potential something like

$$V(h) \sim \frac{a\lambda^2}{16\pi^2}\cos(h/f) + \frac{b\lambda^2}{16\pi^2}\sin^2(h/f)$$

This has $v \sim f$ unless:

$$-2\cos(h/f) - (1+\epsilon)\sin^2(h/f) \Rightarrow \langle h \rangle^2 \approx 2\epsilon f^2$$

We tune $v << f$ by making $\epsilon << 1$.

(Exception: "little Higgs" with extended symmetry structure. Pay a big price in complexity.)

Composite Higgs?

Constraints: *S*-parameter $S \approx \frac{4\pi v^2}{m_\rho^2}, \quad m_\rho^{(NDA)} \sim \frac{4\pi f}{\sqrt{N}}$

Higgs couplings: $a = \frac{g_{VVH}}{g_{VVh}^{\rm SM}} = \sqrt{1 - \frac{v^2}{f^2}}$

Tuning: f^2/v^2 for the VEV; but **also** quadratically divergent W/Z loop cut off at the rho meson mass:

$$\Delta \sim \frac{2\delta m_H^2}{m_h^2} \approx \frac{9}{32\pi^2} g^2 \frac{m_\rho^2}{m_h^2} \sim \frac{9 g^2 f^2}{2 m_h^2 N}$$

Note: $2 < N < 10$; problems with first-order phase transition in cosmology at large *N*.
(e.g. Creminelli/Nicolis/Rattazzi hep-ph/0107141, Kaplan/Schuster/Toro hep-ph/0609012)

Composite Higgs?

Currently bounds from *S* and Higgs couplings translate to roughly

$$m_\rho \gtrsim 3 \text{ TeV}, \quad f \gtrsim \max(\sqrt{\frac{N}{3}} \times 400 \text{ GeV}, 550 \text{ GeV})$$

The Higgs VEV is a factor of ~5 tuning, but the Higgs mass tuning is ~ 12. So combined, it's percent-level tuning.

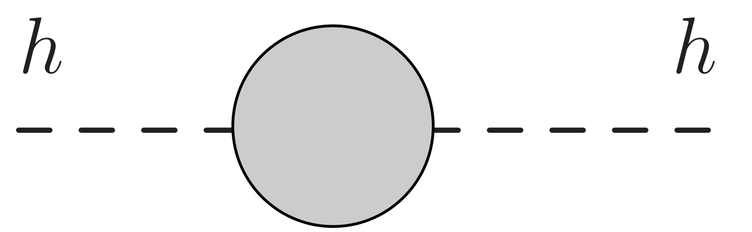
TLEP would bring the *ZZh* coupling measurement to the 0.1% level, probing *f* ~ 6 TeV and achieving **a factor of ~ 1000 tuning in the Higgs VEV *and* (independently) in the Higgs mass**. The *S*-parameter measurement will provide a comparable improvement in sensitivity.

Note: I haven't mentioned flavor (makes tuning worse).

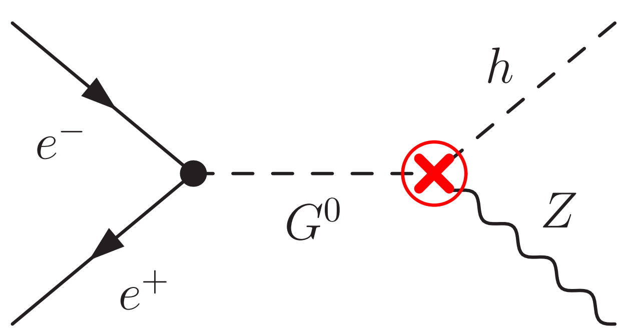
Higgs Wavefunction Renormalization

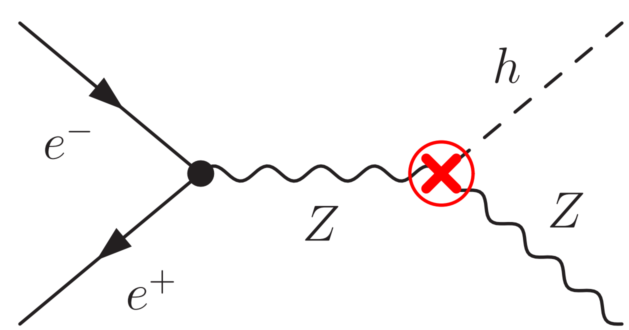
Craig, Englert, McCullough 1305.5251

$$\delta Z_h, \delta m_h^2 \sim$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu |H|^2 \partial^\mu |H|^2\right) + \dots$$





Probes *Any* Natural Physics

E.g. toy model:

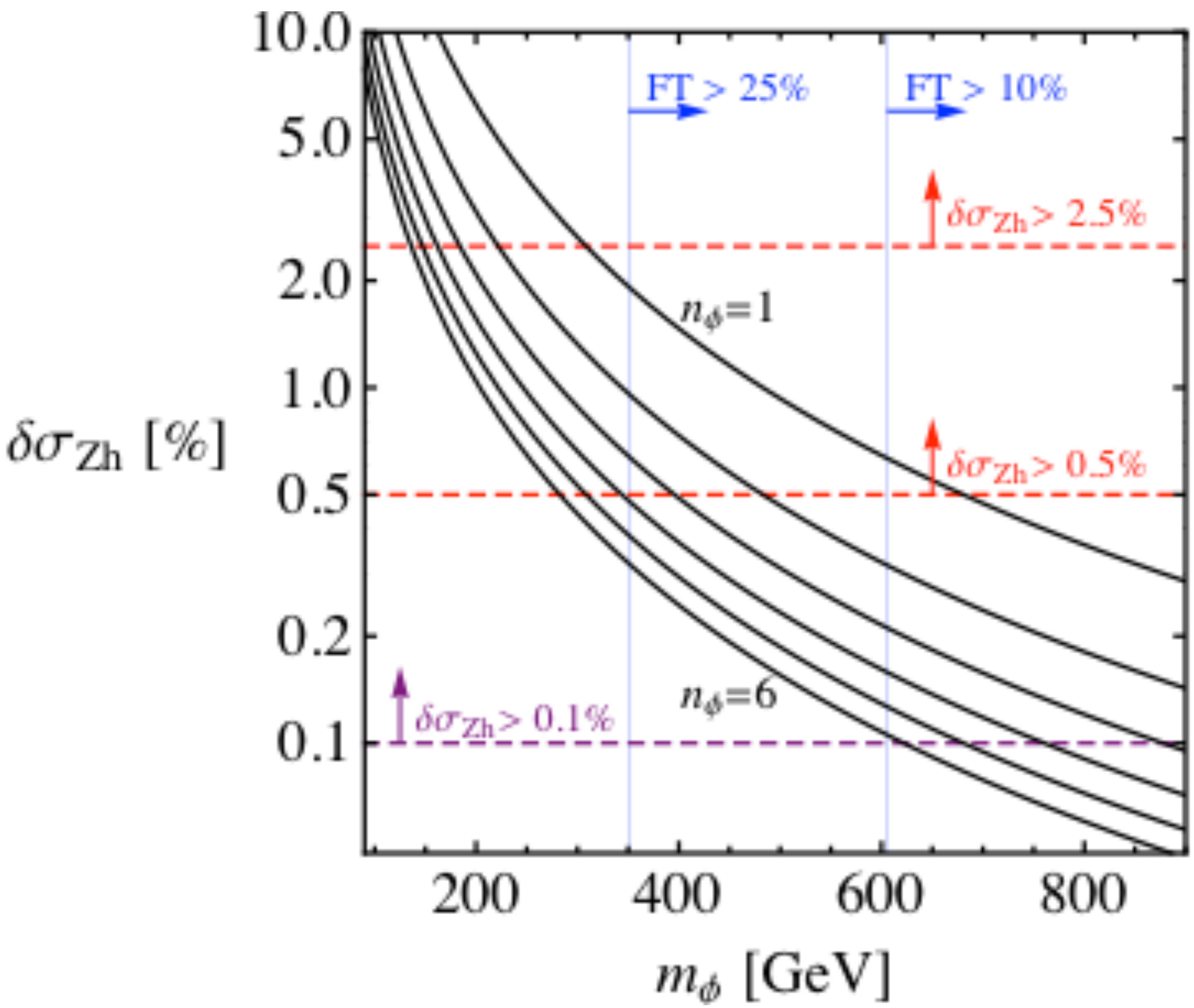
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \left(|\partial_\mu \phi_i|^2 - m_i^2 |\phi_i|^2 - \lambda_i |H|^2 |\phi_i|^2\right)$$

New singlets; undetectable; cancel divergences if:

$$\sum_i \lambda_i = 6\lambda_t^2$$

Less “toy” analogues include Twin Higgs or Folded Supersymmetry: cancel top loops with partner particles that do *not* have QCD color and so are hard to make directly.

Reach at ILC/TLEP



Craig, Englert, McCullough

≈ **TLEP: See recent papers**

(also useful to probe EW baryogenesis: e.g. Katz, Perelstein 1401.1827)

Higgs Constraints on Stops

A low-energy theorem tells us stops correct Higgs couplings to gluons or photons:

$$\mathcal{A}_{\tilde{t}-\text{loop}}(gg \to h) \propto \frac{\partial \log \det M_{\tilde{t}}^2}{\partial v} \sim y_t m_t \frac{\tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2 \beta}{\tilde{m}_Q^2 \tilde{m}_u^2 - X_t^2 m_t^2 \sin^2 \beta}$$

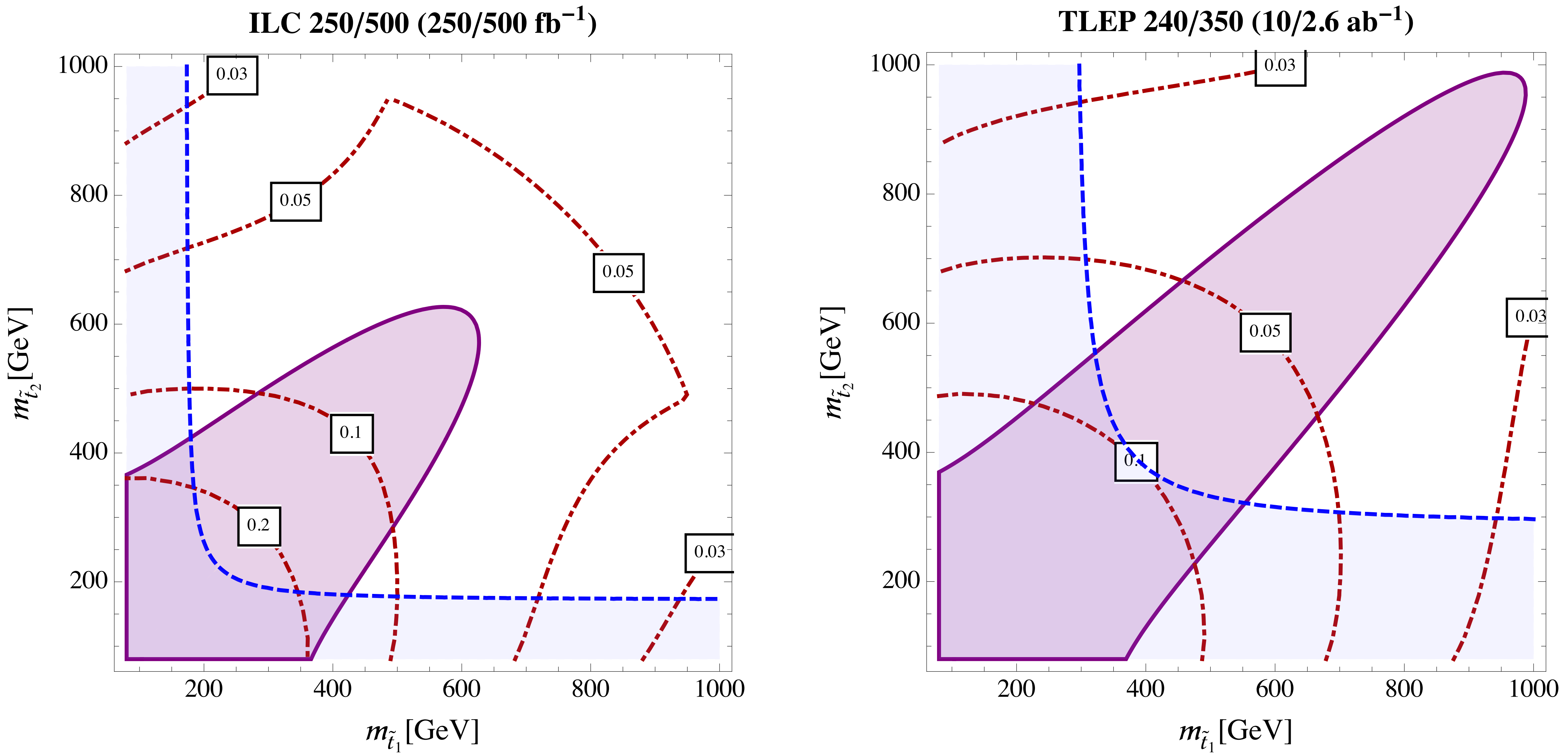
For light enough stops, can only avoid a big correction via a sizable mixing term X_t. Implies tuning of the coupling.

For any pair of *physical* stop masses, there's a *maximum* X_t. (On the diagonal, $X_t = 0$: symmetric matrix with off-diagonal term will *always* have two unequal eigenvalues.)

So: robust bound on light stops.

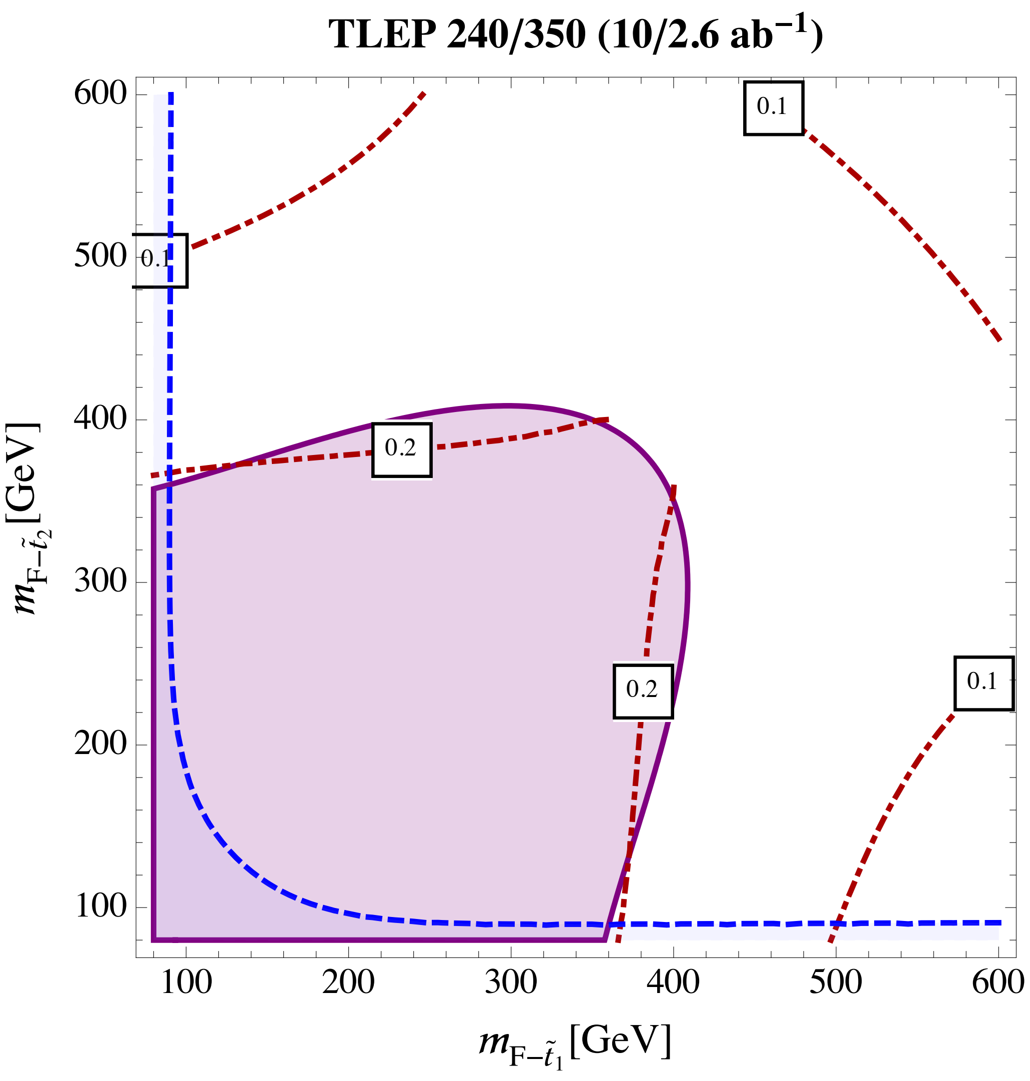
Future Bounds on Stops From hgg, hγγ

J. Fan, MR 1401.7671



Even TLEP won't probe down to 1% tuning. Can do better with additional precision observables. But first…

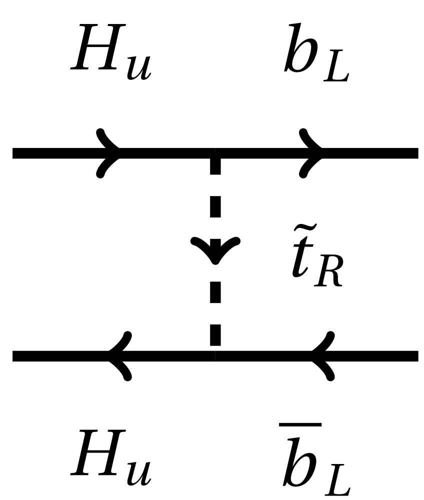
Future Bounds on **Folded** Stops From hγγ



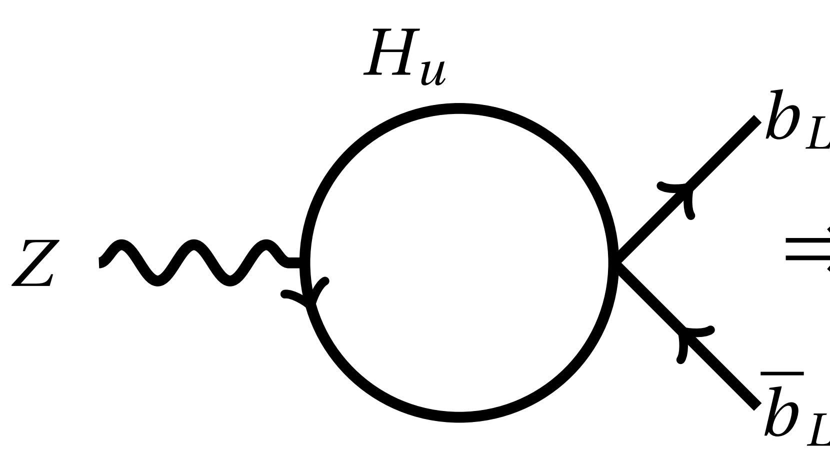
No color, just charge, so difficult to exclude. But complementary to the wavefunction renormalization effect.

Stop/Higgsino Loop for R_b

Rely on the large top Yukawa. Useful only if higgsinos are light (not so much in JMR's scenario from yesterday). Leading term from operator mixing:



$$\Rightarrow \frac{y_t^2}{m_{\tilde{t}_R}^2}\left(\tilde{H}_u^\dagger Q\right)\left(Q^\dagger \tilde{H}_u\right)$$



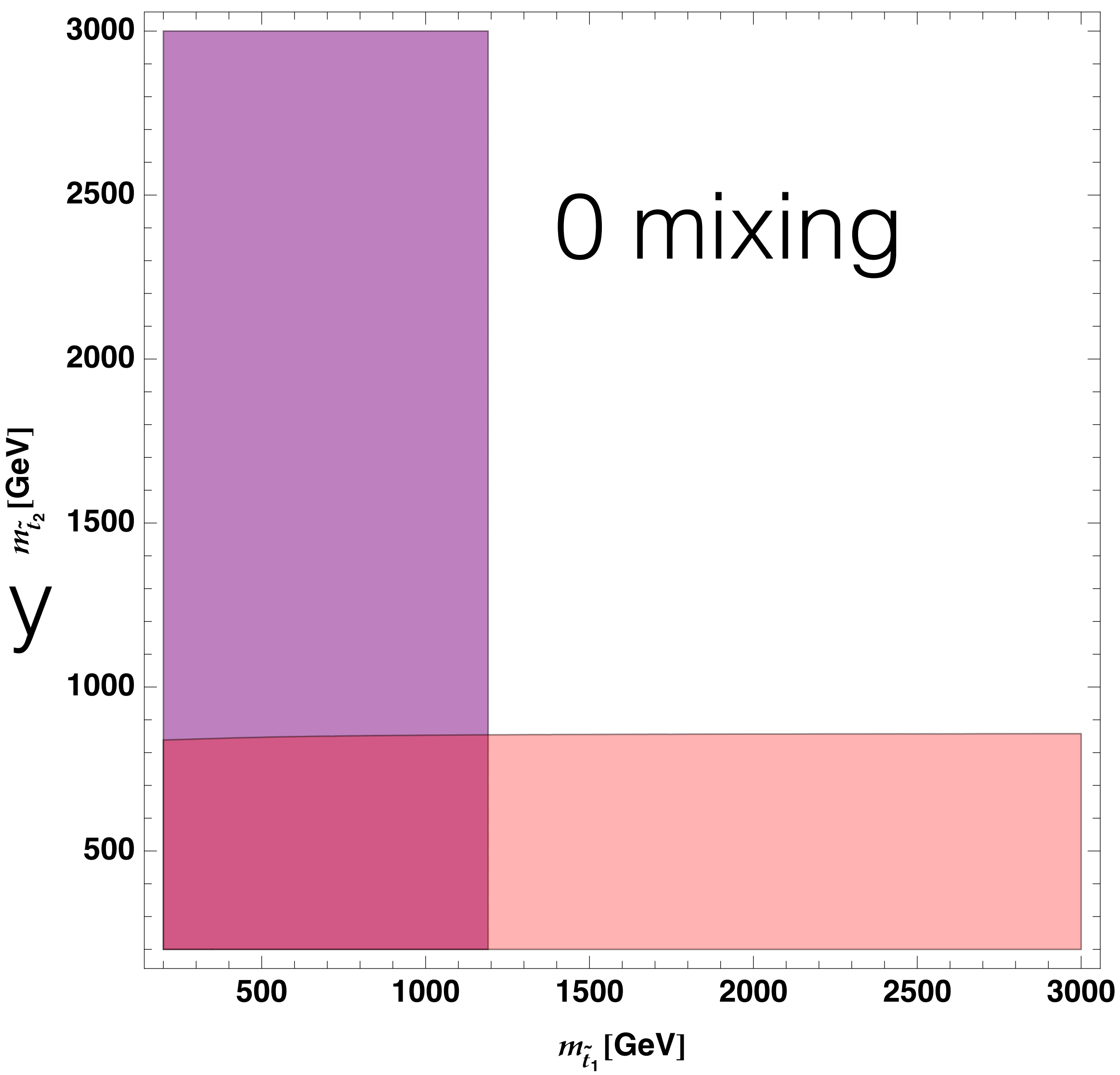
$$\Rightarrow \frac{y_t^2}{m_{\tilde{t}_R}^2} W^I_{\mu\nu} Q^\dagger \tau^I \overline{\sigma}^\mu i D^\nu Q \log\frac{m_{\tilde{t}_R}}{\mu}$$

Complementary Stop Constraints

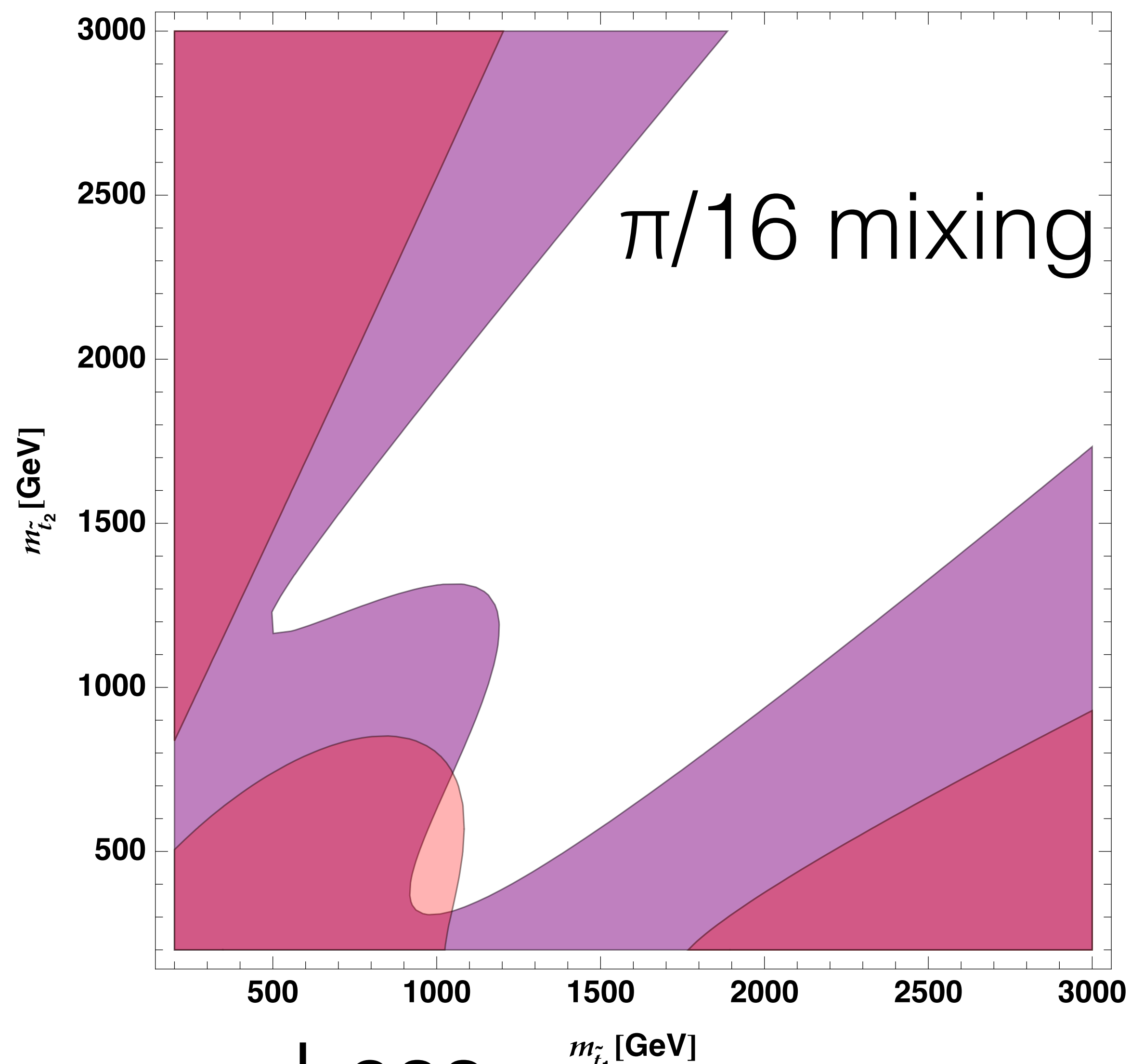
Work in progress with JiJi Fan and Lian-Tao Wang.

red = R_b; purple = T parameter

mostly LH



mostly RH



Less complementary with mixing

The Message

A combination of precision measurements of Higgs couplings, Z couplings, the W mass, etc. can be a powerful probe of naturalness.

Corrections that cancel in corners of parameter space (e.g. mixing angle dependence) for one observable will generally not cancel in another.

Can probably rule out stops up to ~1 TeV (~ 1% tuning) completely model-independently with a future e+e- collider. Work in progress with JiJi Fan and Lian-Tao Wang.

100 TeV

Gavin Salam's Rules of Thumb

G. Salam's slide from SLAC 100 TeV workshop

Rule of Thumb #1

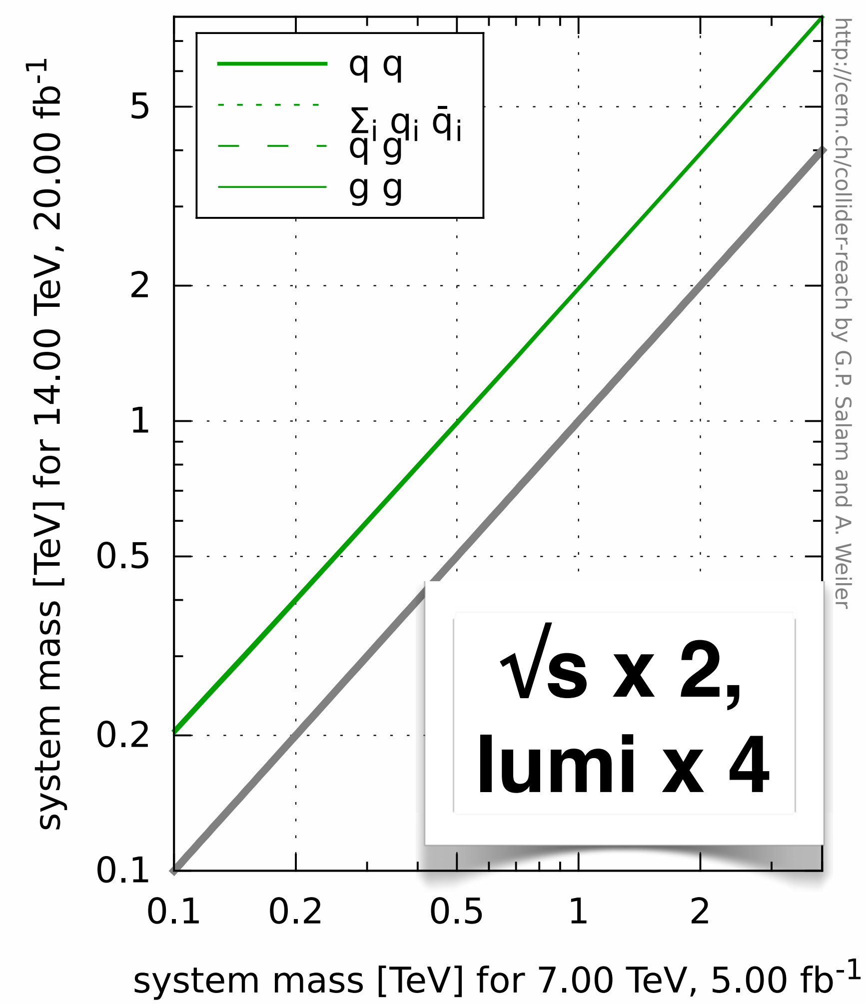
(well known among practitioners)

Increase collider energy by factor X
& increase luminosity by a factor X^2

→ **reach goes up by a factor X**

[Because you keep same Bjorken-x & luminosity increase compensates for $1/\text{mass}^2$ scaling of cross sections]

PDF scaling variations are small effect



Gavin Salam's Rules of Thumb

G. Salam's slide from SLAC 100 TeV workshop

Rule of Thumb #2

(apparently not widely known previously)

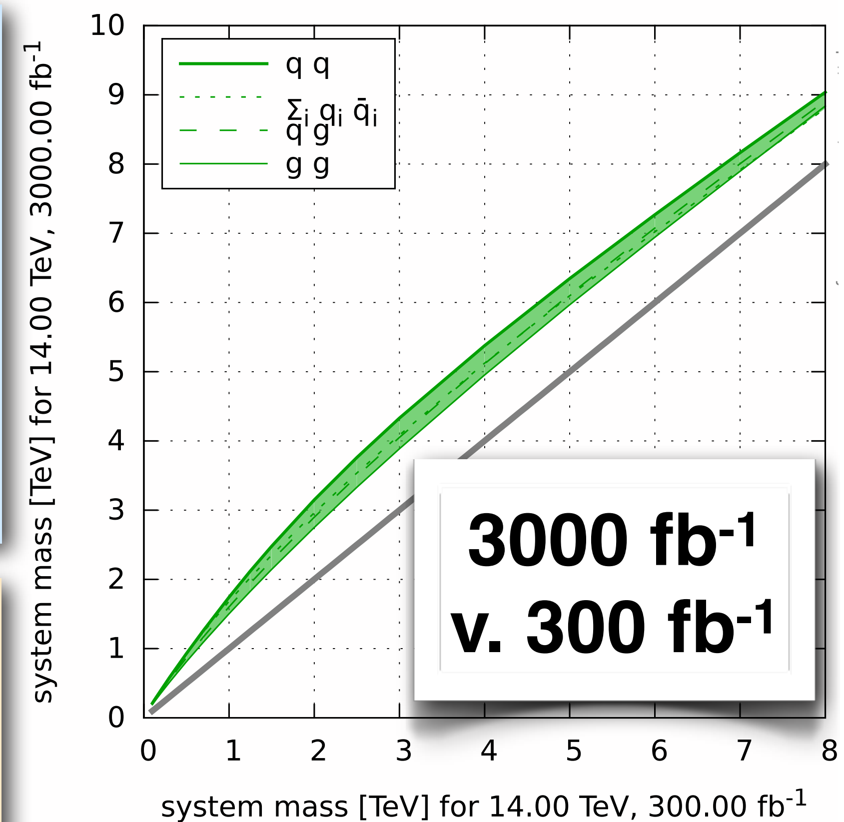
Increase luminosity by factor 10

→ reach increases by constant $\Delta m \simeq 0.07\sqrt{s}$

i.e. for $\sqrt{s}$=14 TeV, reach goes by up 1 TeV

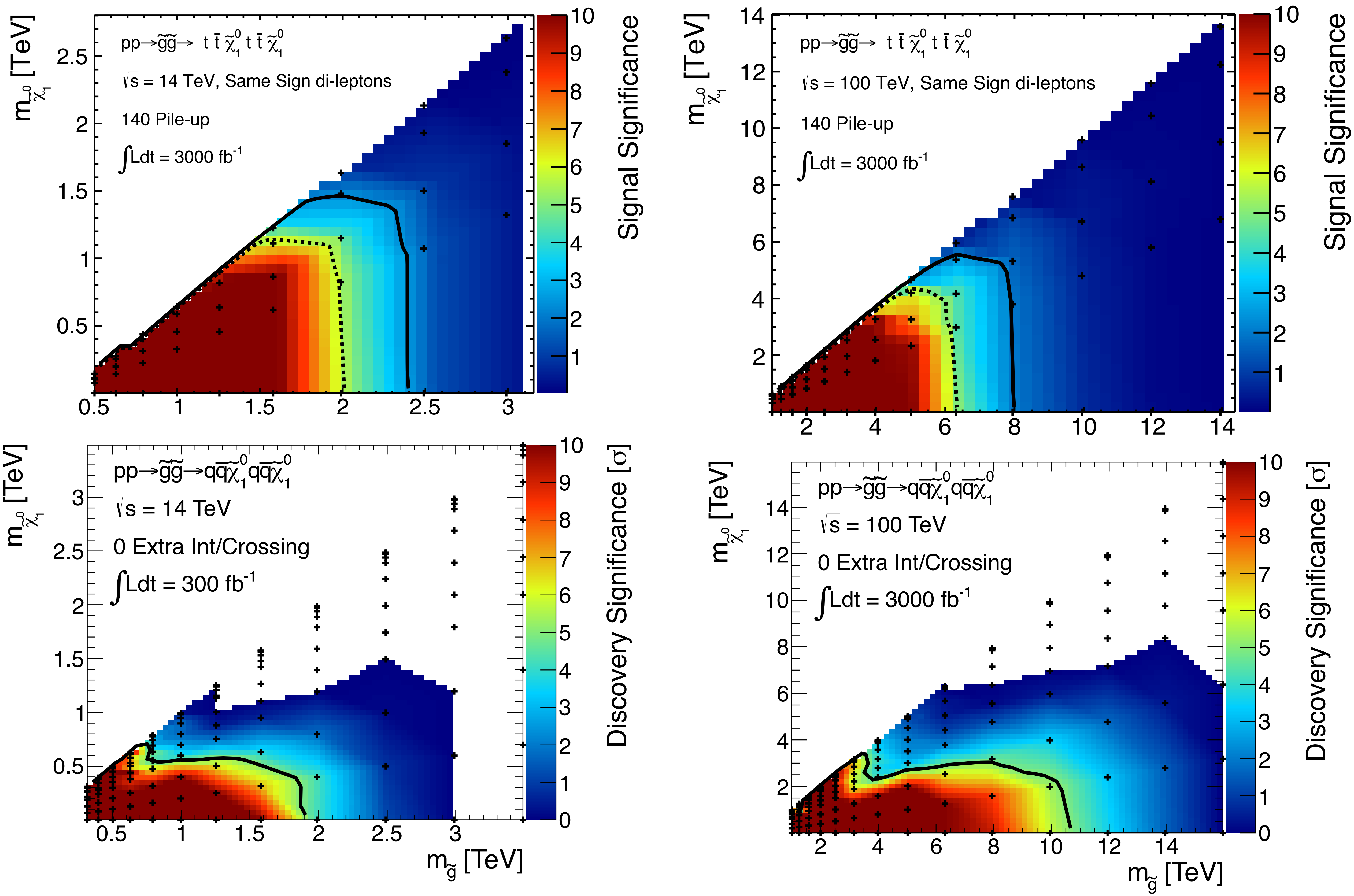
No deep reason — a somewhat random characteristic of large-x PDFs.

Only holds for $0.15 \lesssim M/\sqrt{s} \lesssim 0.6$



Gluino Reach

1311.6480 Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker



Gluino Reach

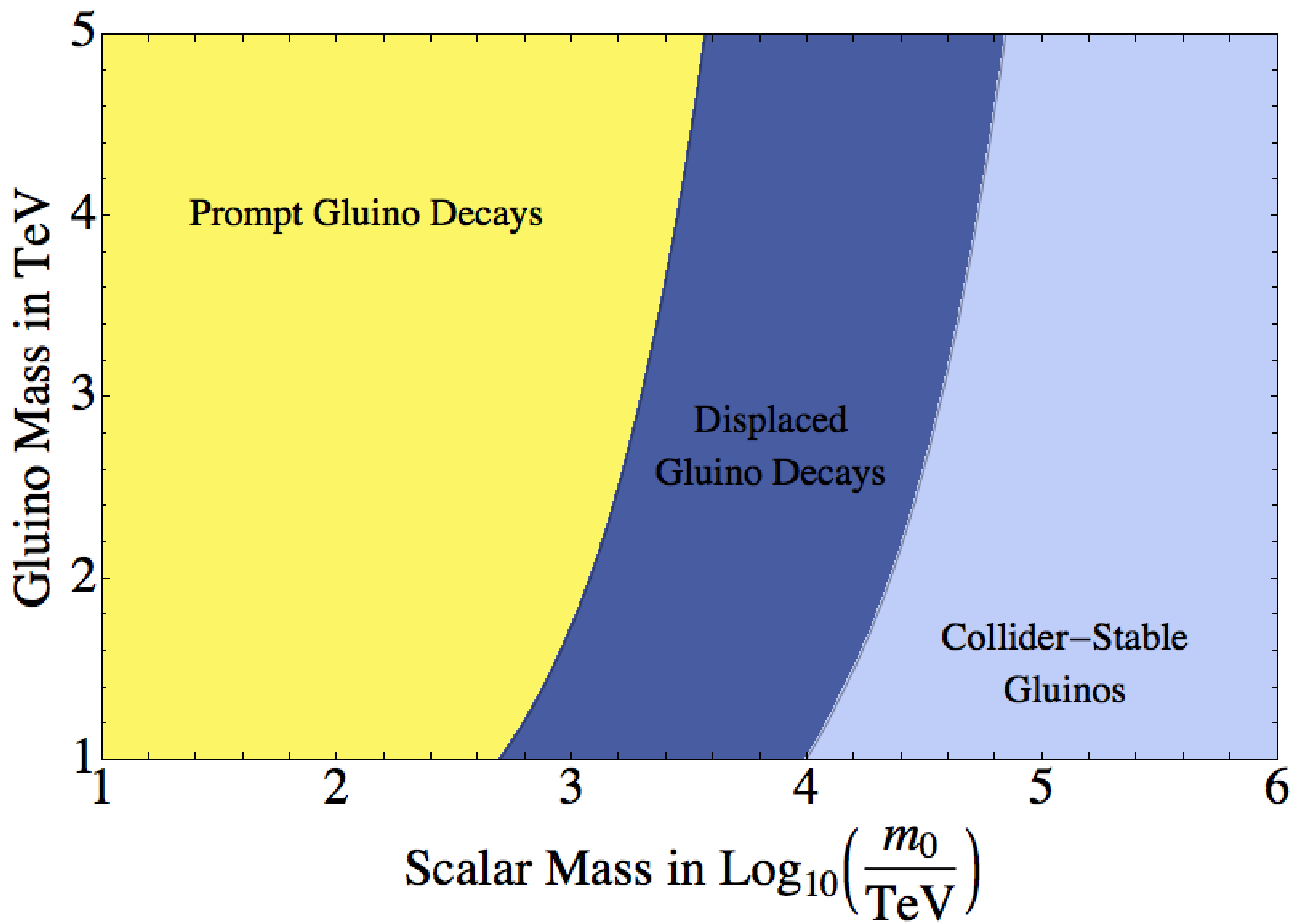
3000 fb^{-1} is being used as a benchmark number, but 10 times that could be better for maximizing reach.

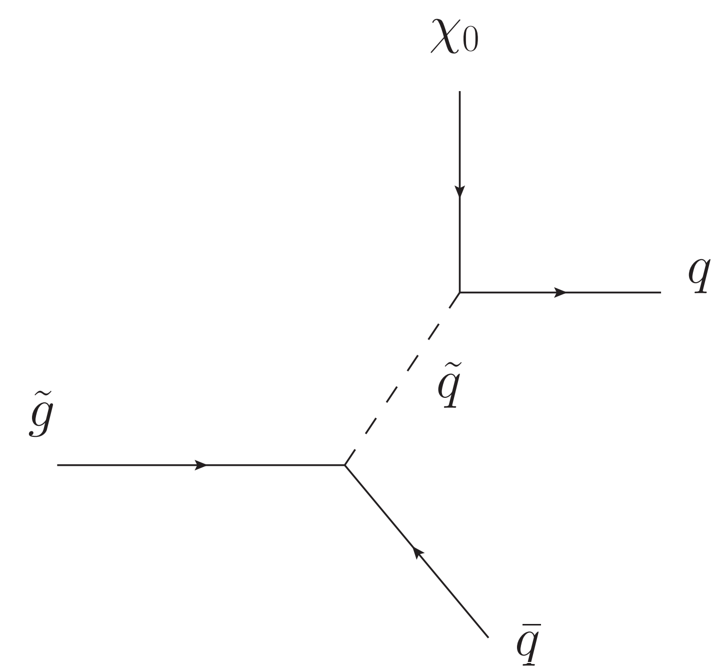
An 8 TeV gluino constraint corresponds to 2-loop tuning of the Higgs mass-squared by a **factor of about 500** (depending on the log in the running).

Potentially can push this up above 1000 with further work.

Gluino Lifetime

Important additional parameter that should be taken into account. Probes scalar masses.



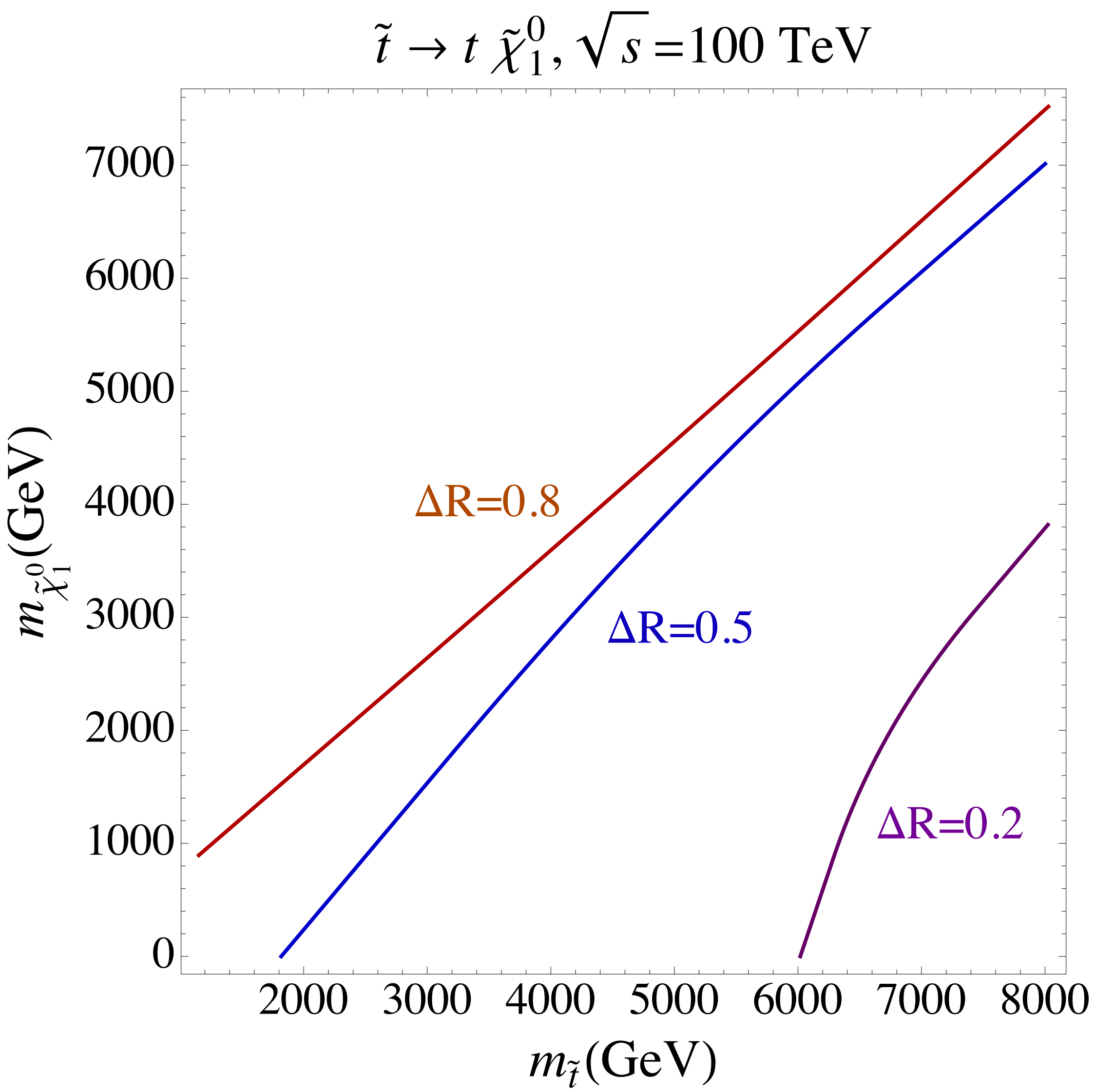


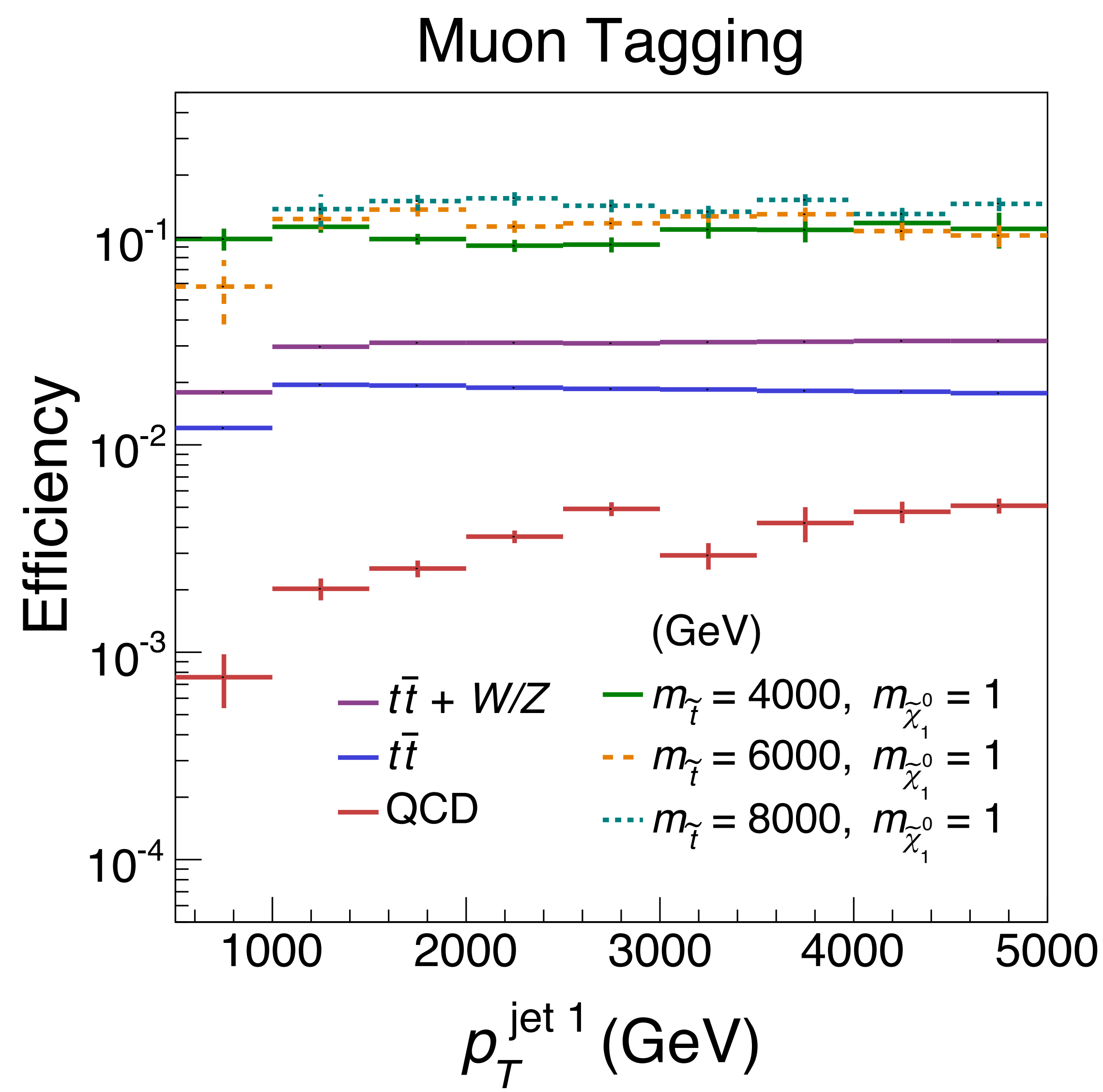
$$c\tau \approx 10^{-5}\mathrm{m}\left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4\left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 .$$

Arvanitaki, Craig, Dimopoulos, Villadoro 1210.0555; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski 1212.6971

Stop Detection

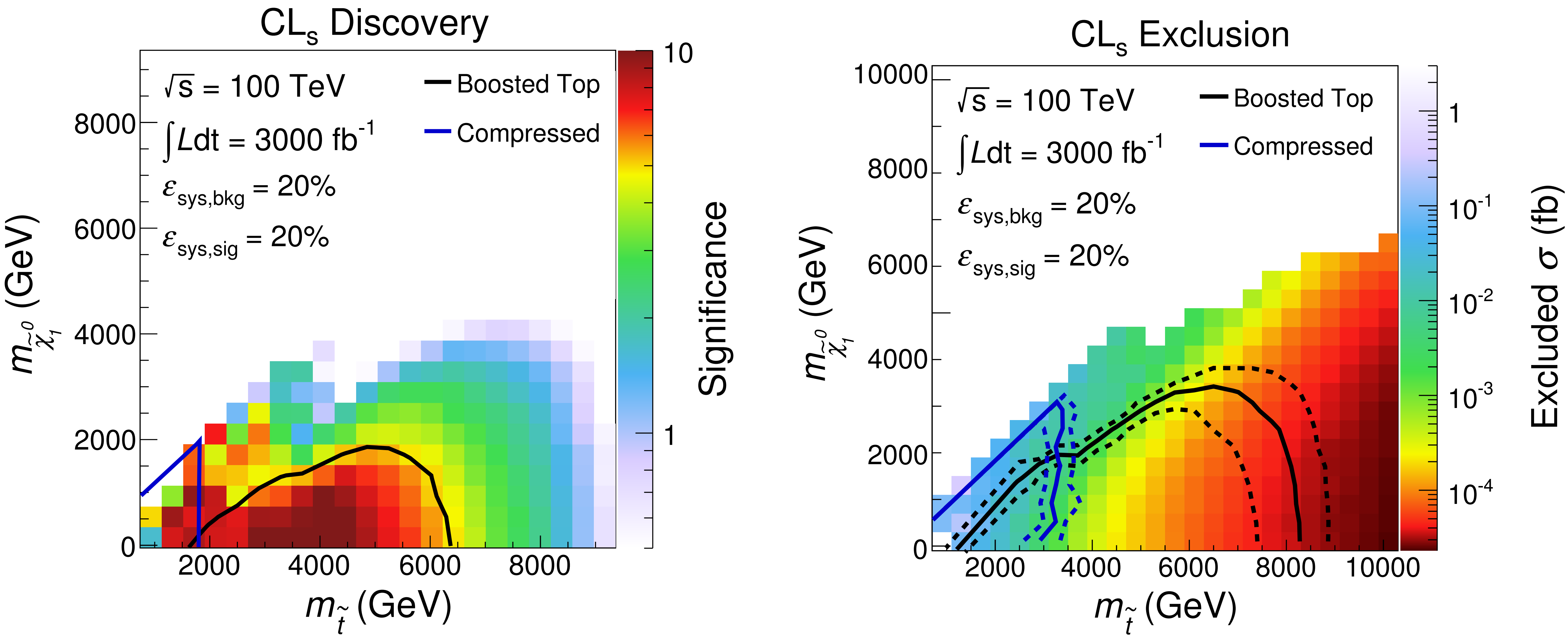
Cohen, D'Agnolo, Hance, Lou, Wacker 1406.4512





Collimated tops: *a top at 100 TeV is like a b-quark at the Tevatron.* Substructure difficult without very fine-grained calorimetry (is that feasible?). Tag it with a muon inside the jet.

Stop Reach

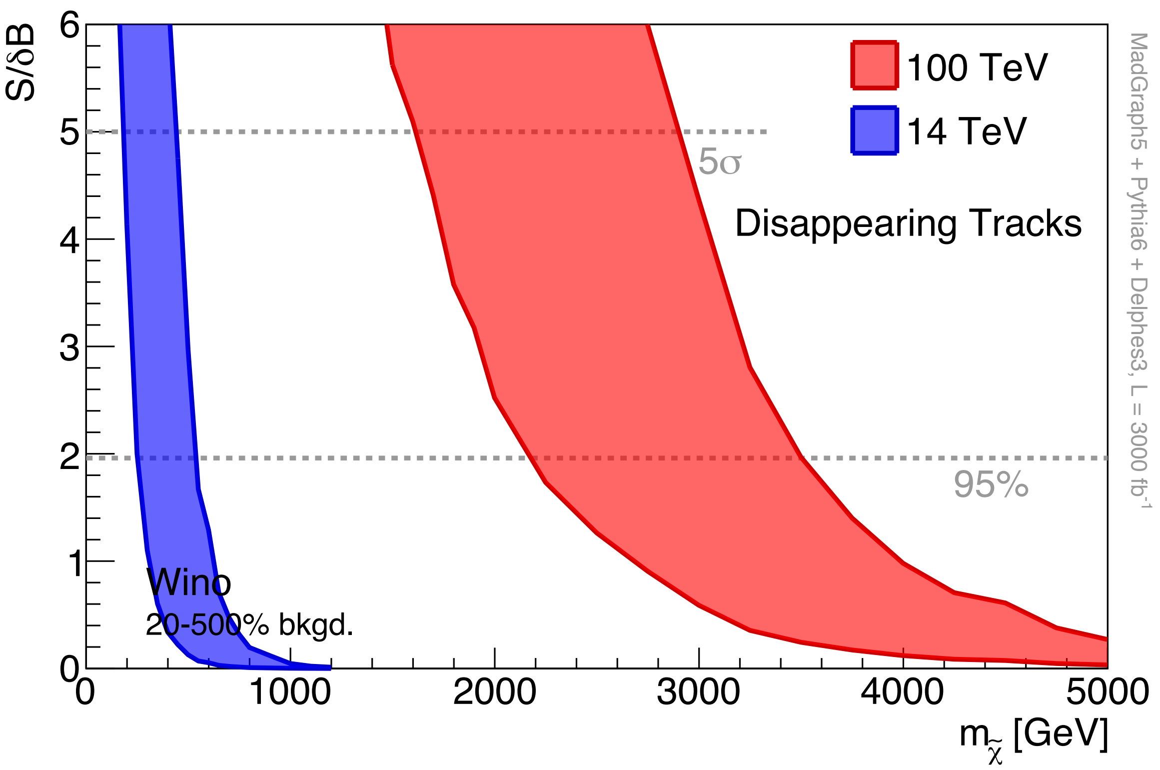


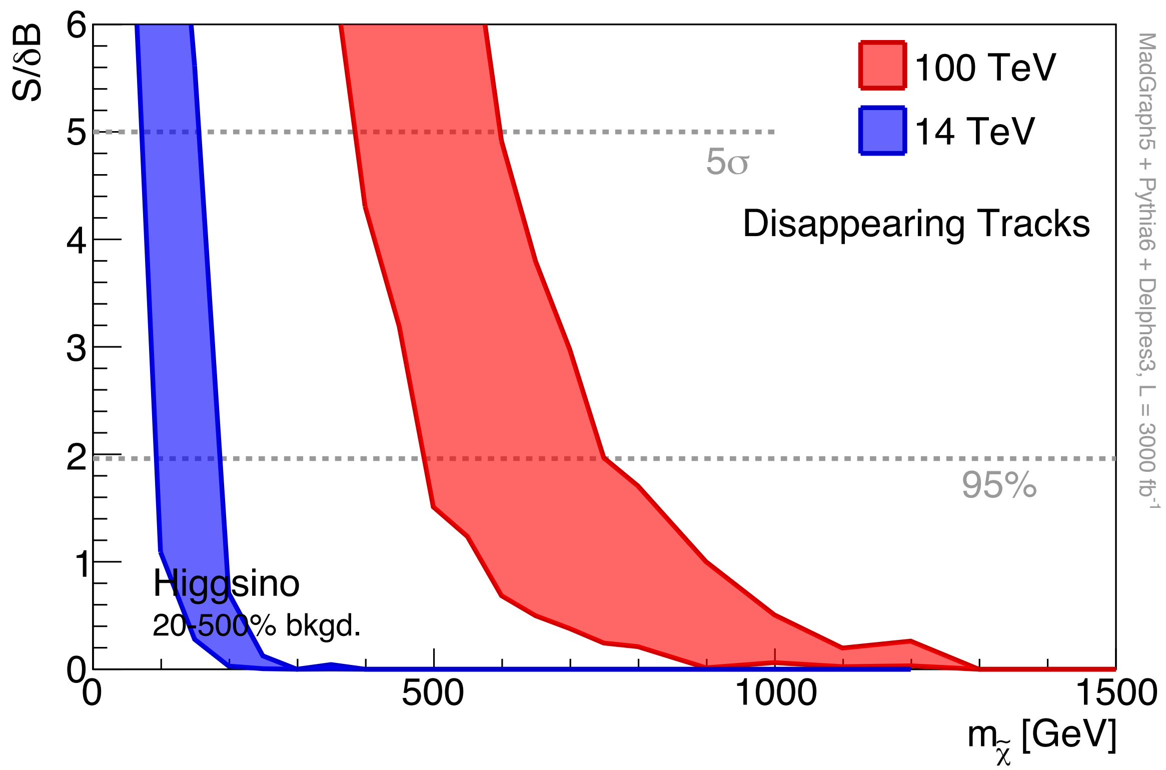
Cohen, D'Agnolo, Hance, Lou, Wacker 1406.4512

8 TeV stop bound: **factor of >1000 tuning**. (But need to improve compressed spectrum reach!)

Electroweakinos

Matthew Low & Lian-Tao Wang, 1404.0682

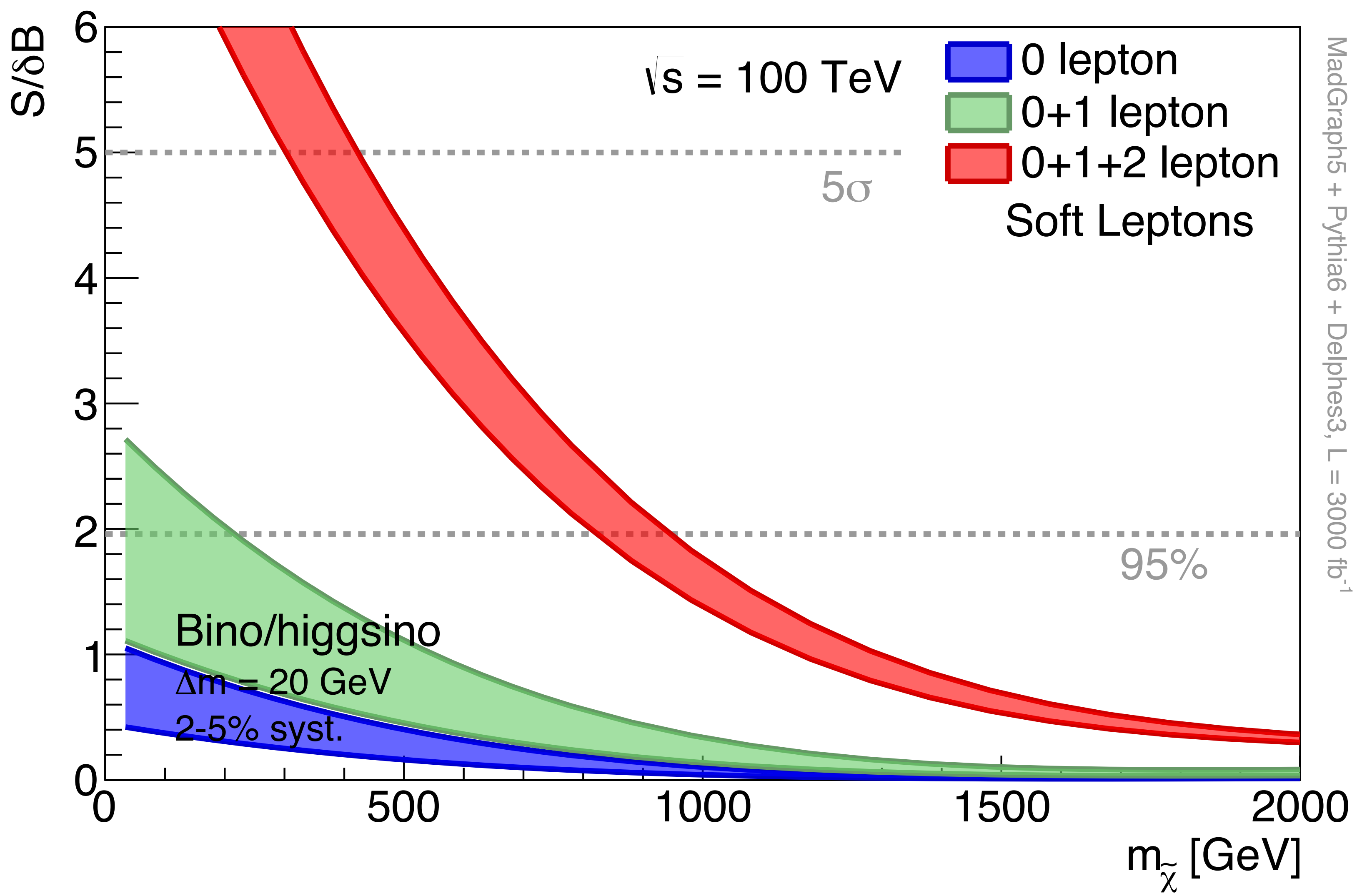




Disappearing track channel. More representative of winos than higgsinos, in general (dim-7 versus dim-5 tree-level splitting)

Electroweakinos

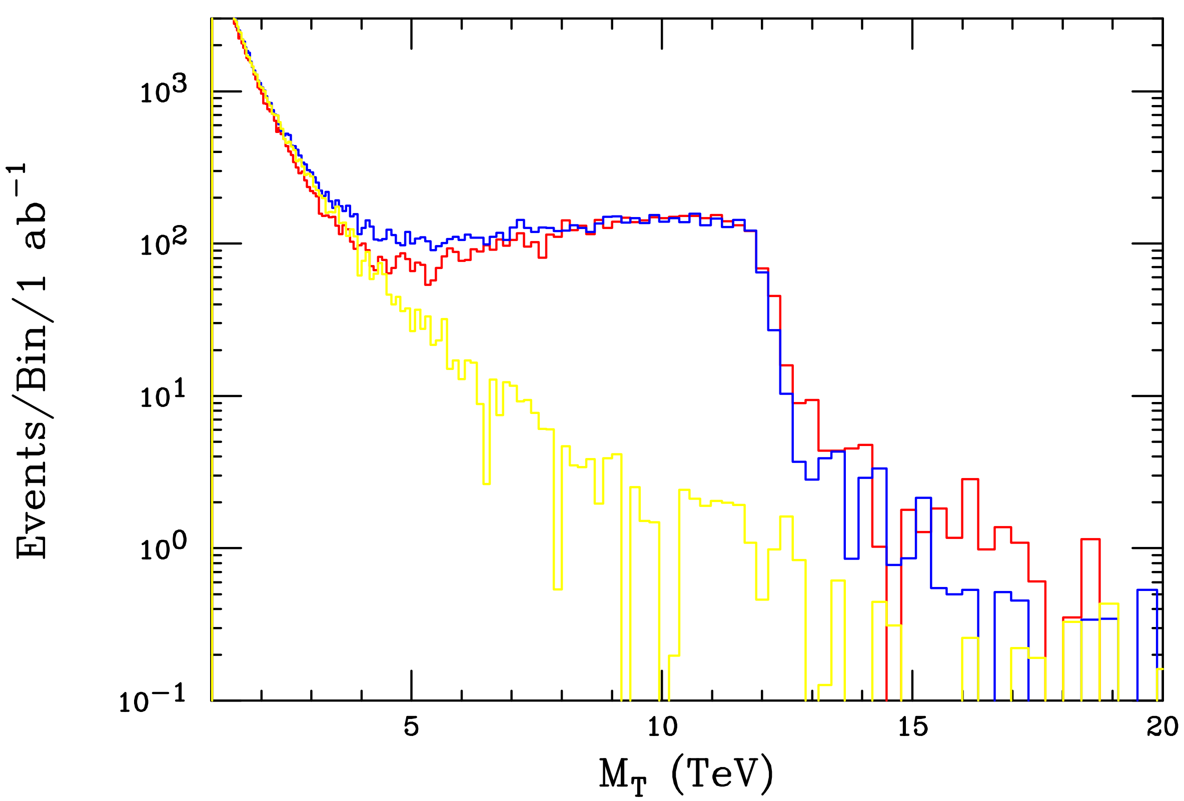
Matthew Low & Lian-Tao Wang, 1404.0682

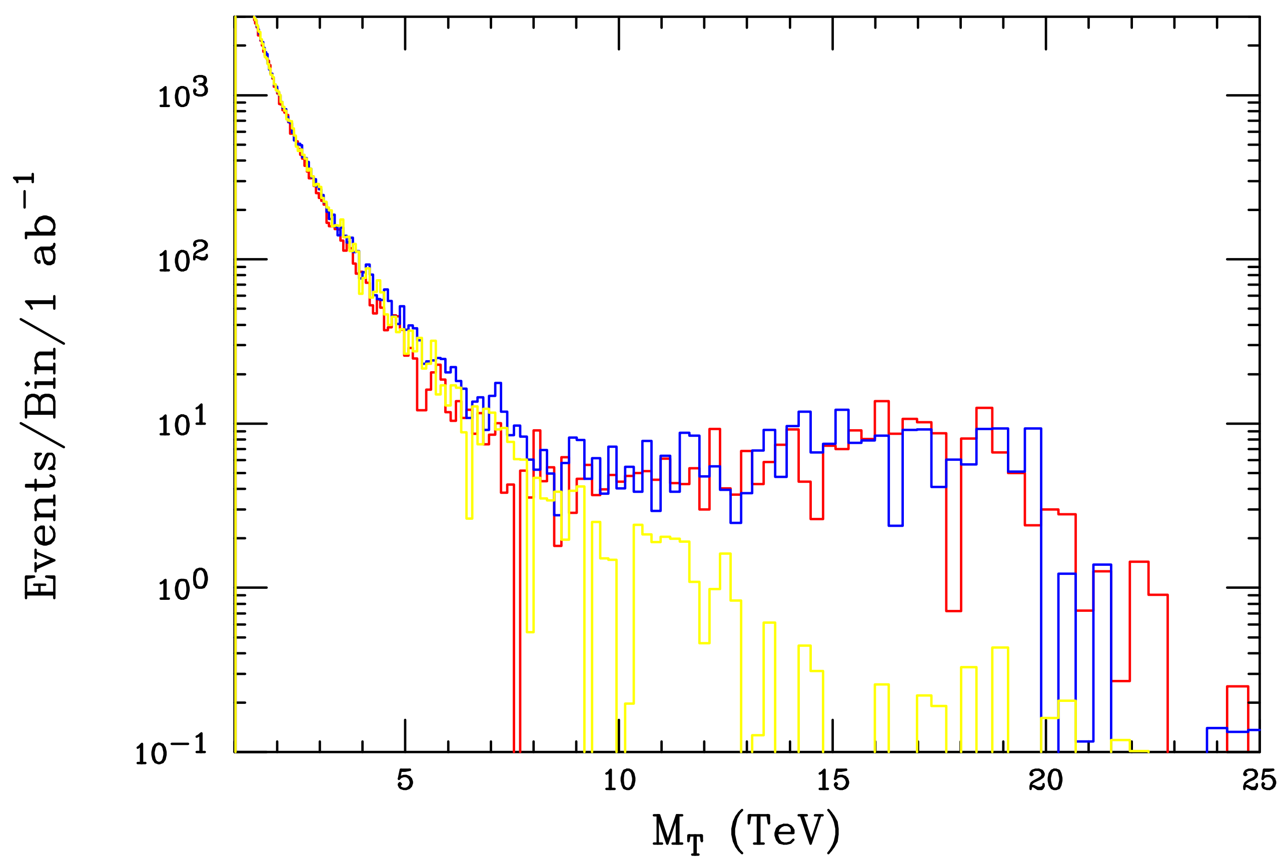


Supplementing monojet with soft leptons.

New Heavy Gauge Bosons

Tom Rizzo, 1403.5465





Potentially dramatic signals possible: here, a *W'* with Standard Model-like couplings.

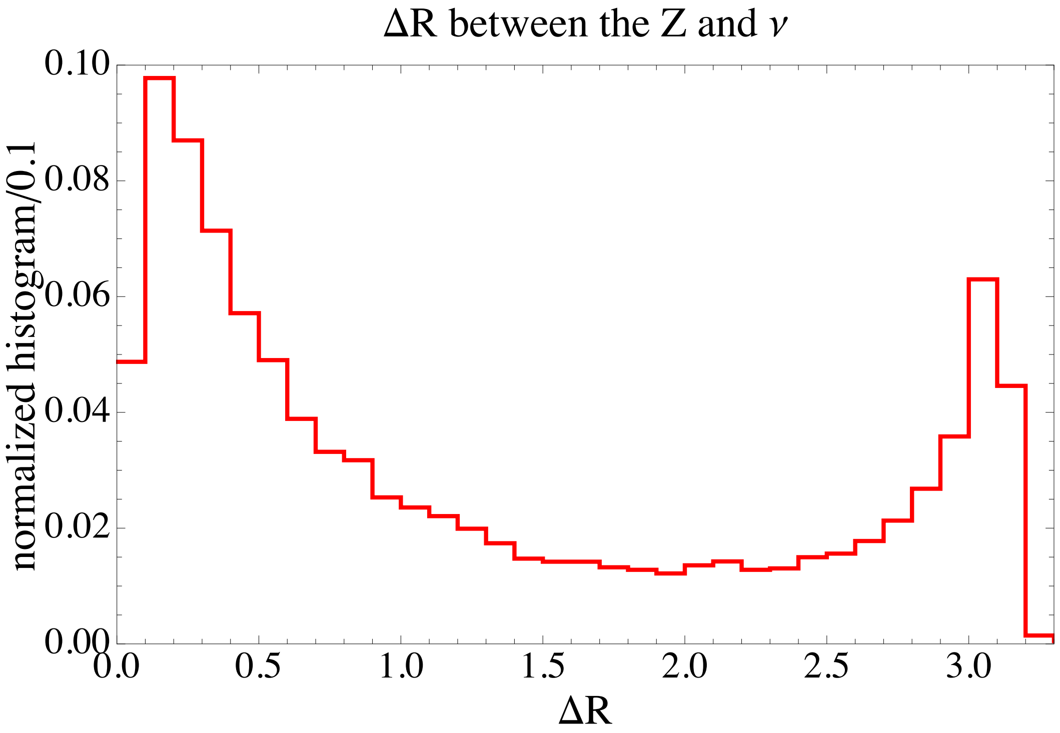
EWK Radiation

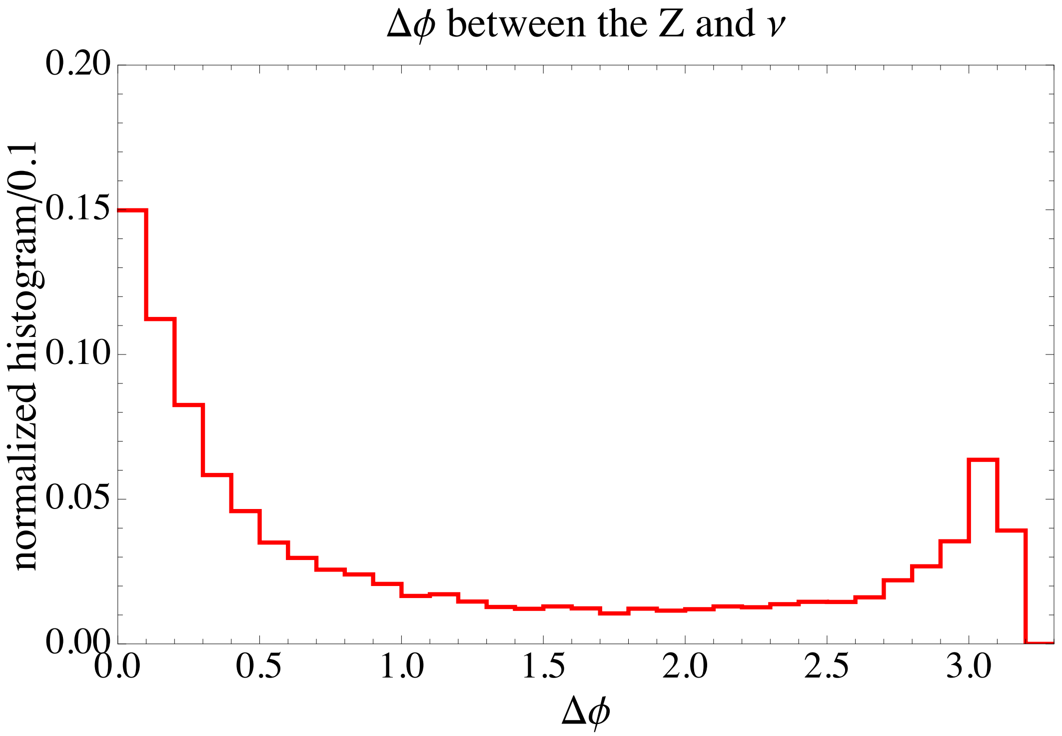
A. Hook, A. Katz (to appear)

Expect that at a 100 TeV collider, the electroweak symmetry should look approximately unbroken. Parton showers radiate not just photons, but *W* and *Z* bosons.

Neutrinos are visible.

$$W' \to \ell\nu^{(*)} \to \ell\nu Z$$

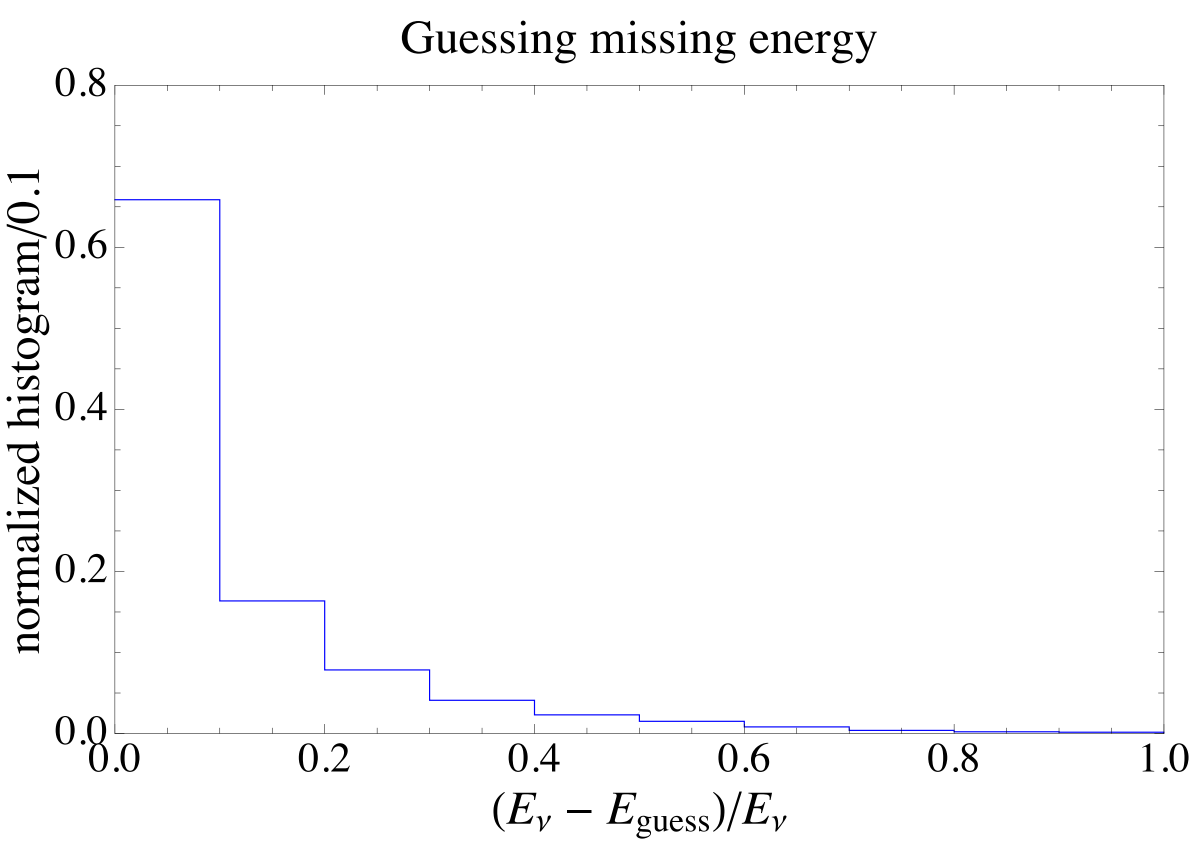


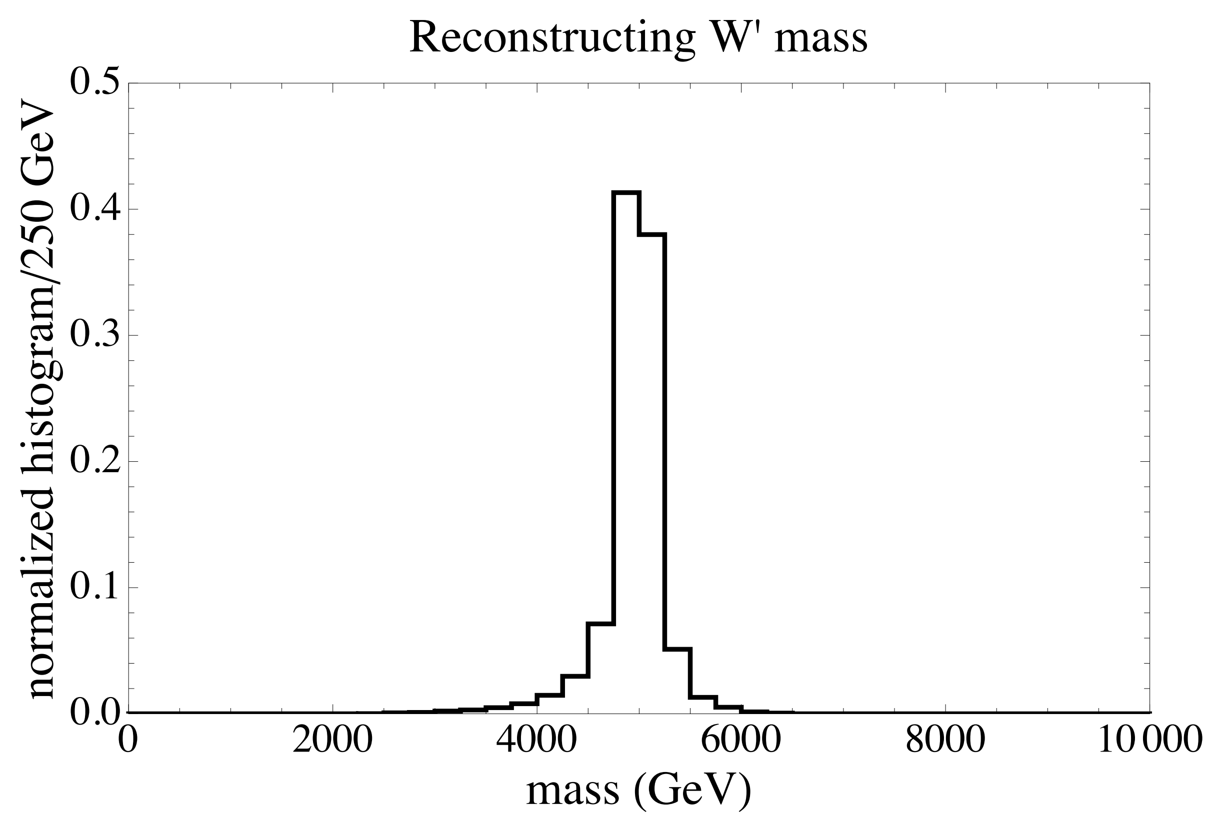


EWK Radiation

A. Hook, A. Katz, to appear

Picking up the Z radiated from a neutrino and approximating the missing energy (via collinearity assumption) allows one to plot a **W' mass**, not just transverse mass.





EWK Radiation

A. Hook, A. Katz, to appear

Also affects electroweakino searches: here look for neutralinos in the Z + MET channel.

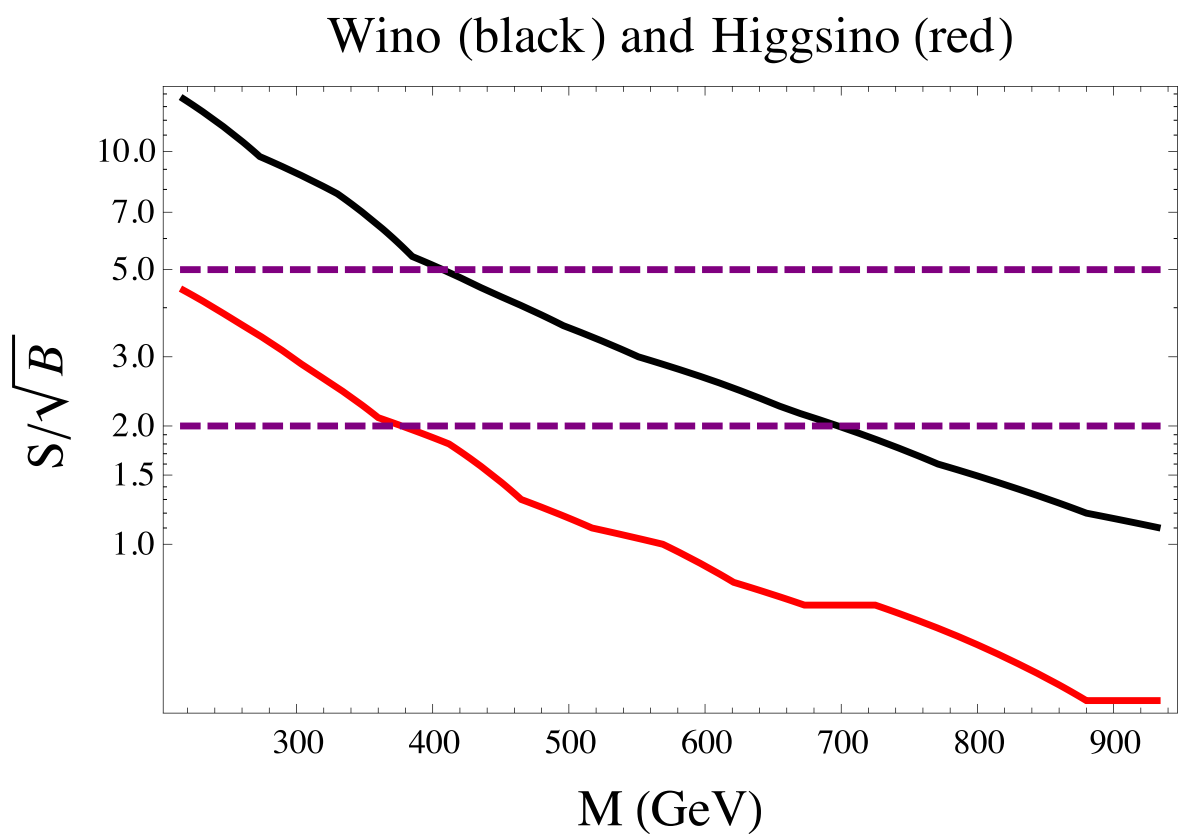


Figure 10. Expected reach for SUSY dark matter with a $Z_l + \not{E}_T$ search at 100 TeV collider with integrated luminosity $\mathcal{L} = 3\ \mathrm{ab}^{-1}$.

Measuring Running Weak Couplings

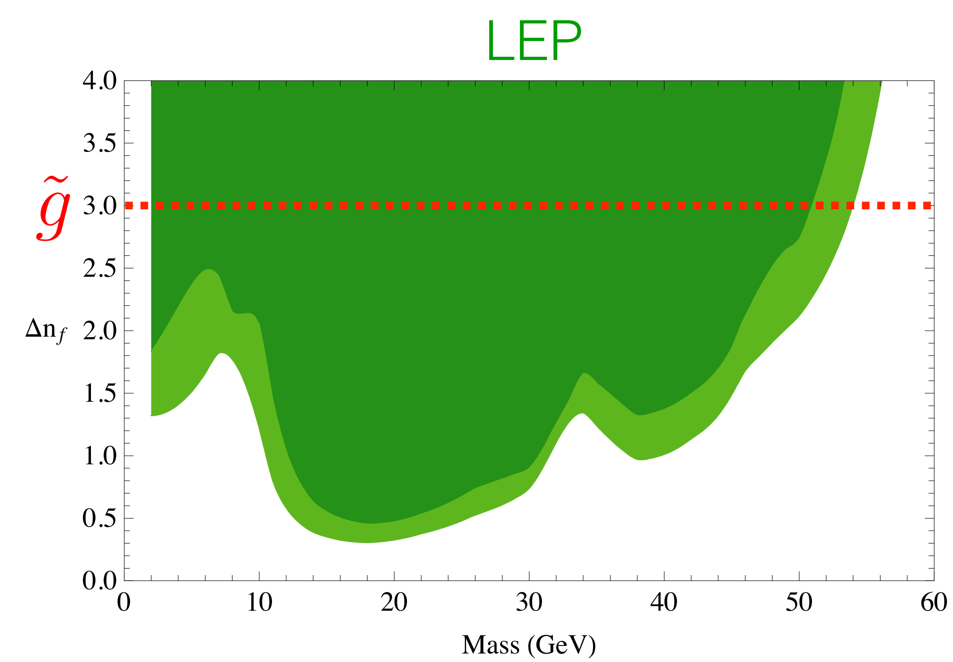
(at LHC14 / 100 TeV pp)

Daniele Alves, Jamison Galloway, Josh Ruderman, Jon Walsh
(to appear)

plots/slides contributed by Josh Ruderman

model independent gluino limit

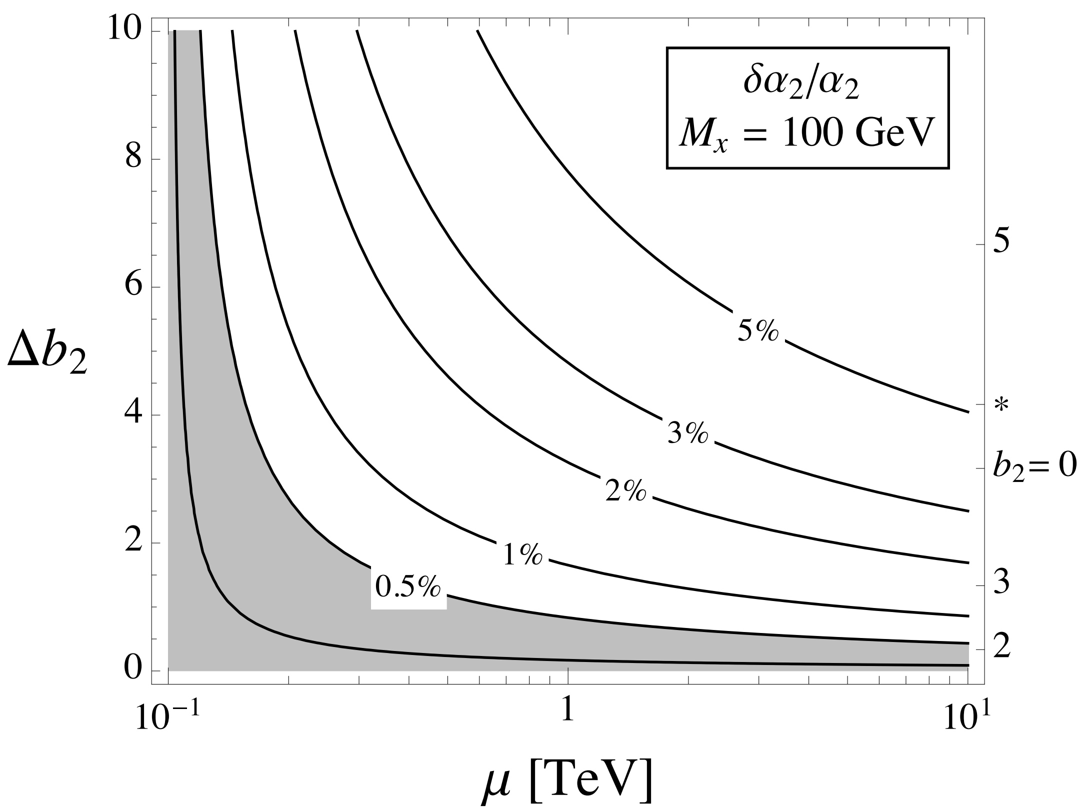
Goal: electroweak version of the gluino exclusion plot at right

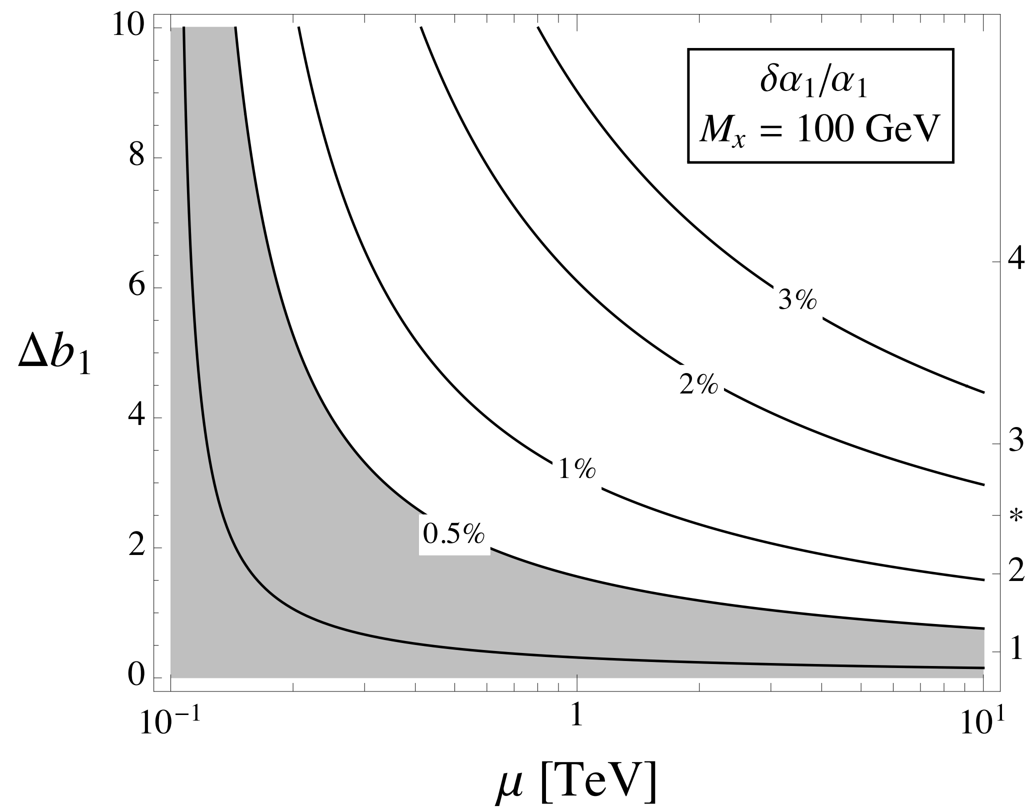


Kaplan and Schwartz 0804.2477

deviation from SM

with new physics at M =100 GeV





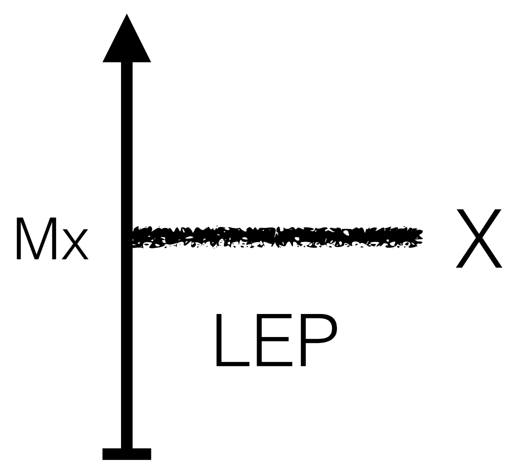
	Δb_2
2	1/3 = 0.33
3	4/3 = 1.33
5	20/3 = 6.67
7	56/3 = 18.7

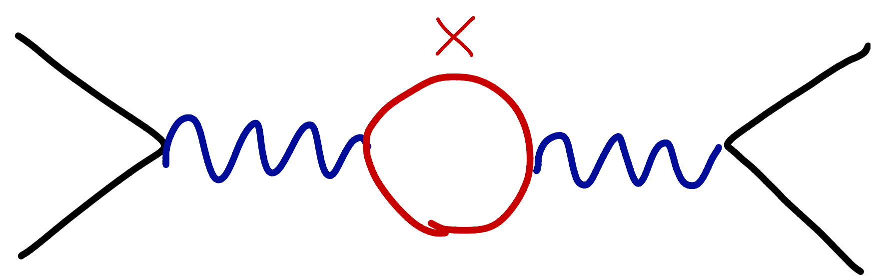
$$\Delta b_1 = \frac{2}{5} Y_i^2$$

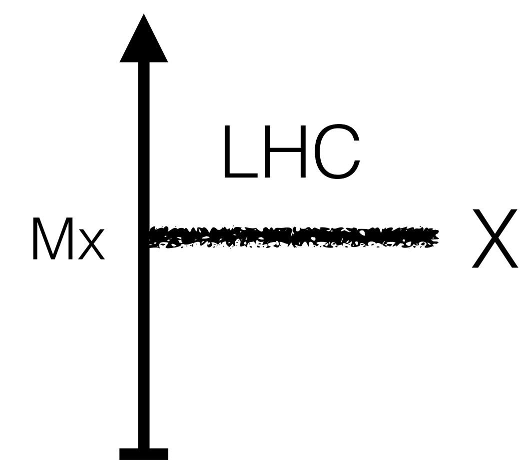
via Josh Ruderman

Precision Electroweak

below threshold vs. above threshold







$$\frac{\left(D_\rho W^a_{\mu\nu}\right)^2}{2g^2} \qquad \frac{\left(\partial_\rho B_{\mu\nu}\right)^2}{2g'^2}$$

$$W = \Delta b_2 \, \frac{\alpha_2}{20\pi} \, \frac{m_W^2}{M^2} \qquad Y = \Delta b_1 \, \frac{\alpha_1}{20\pi} \, \frac{m_W^2}{M^2}$$

$$W, Y \lesssim 10^{-3}$$

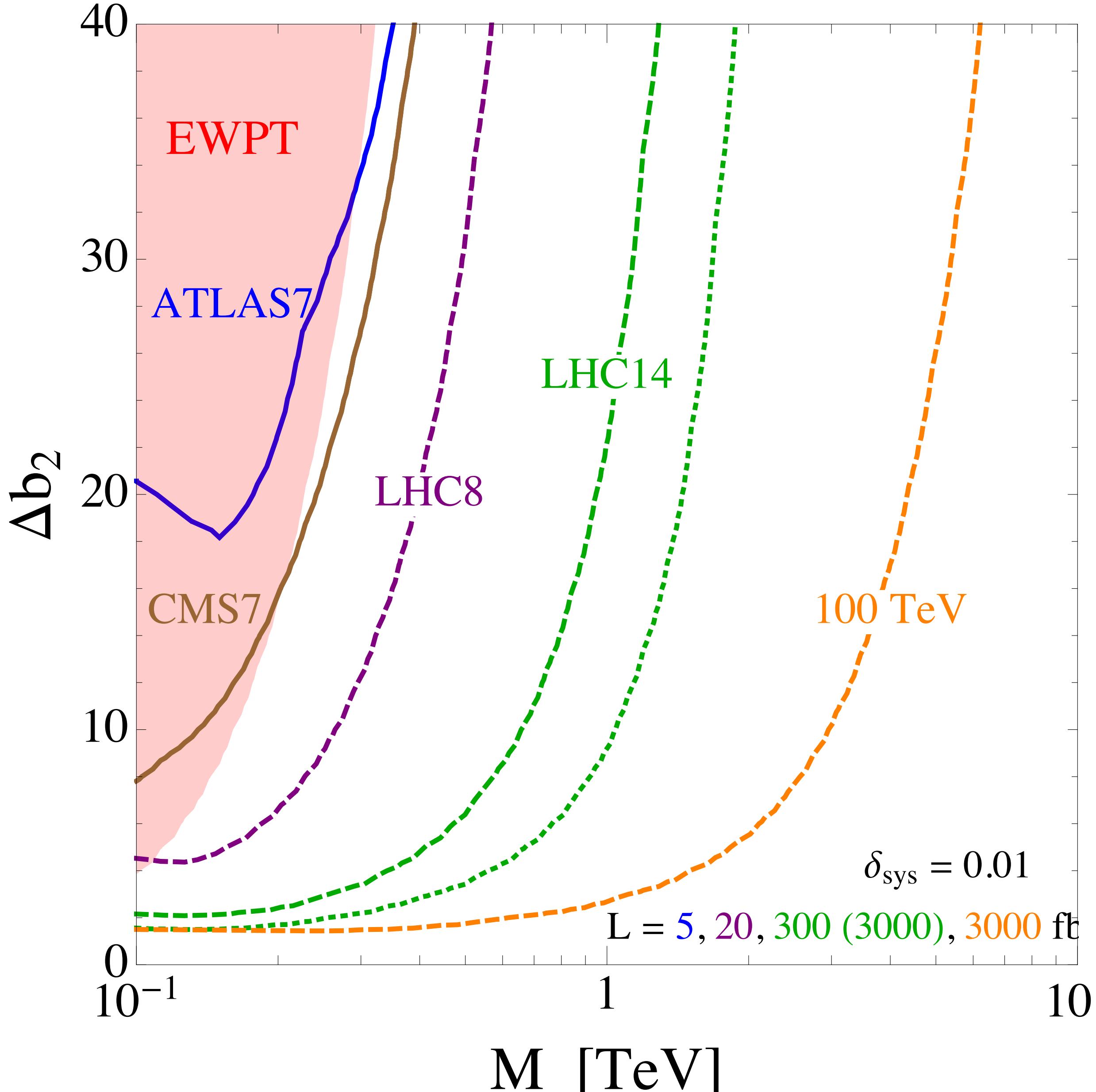
see for ex: Barbieri, Pomarol, Rattazzi, Strumia 0405040

$$\frac{\delta\sigma}{\sigma}(Q) \propto \Delta b_{1,2} \, \frac{\alpha_{1,2}}{\pi} \log\left(\frac{Q}{M}\right)$$

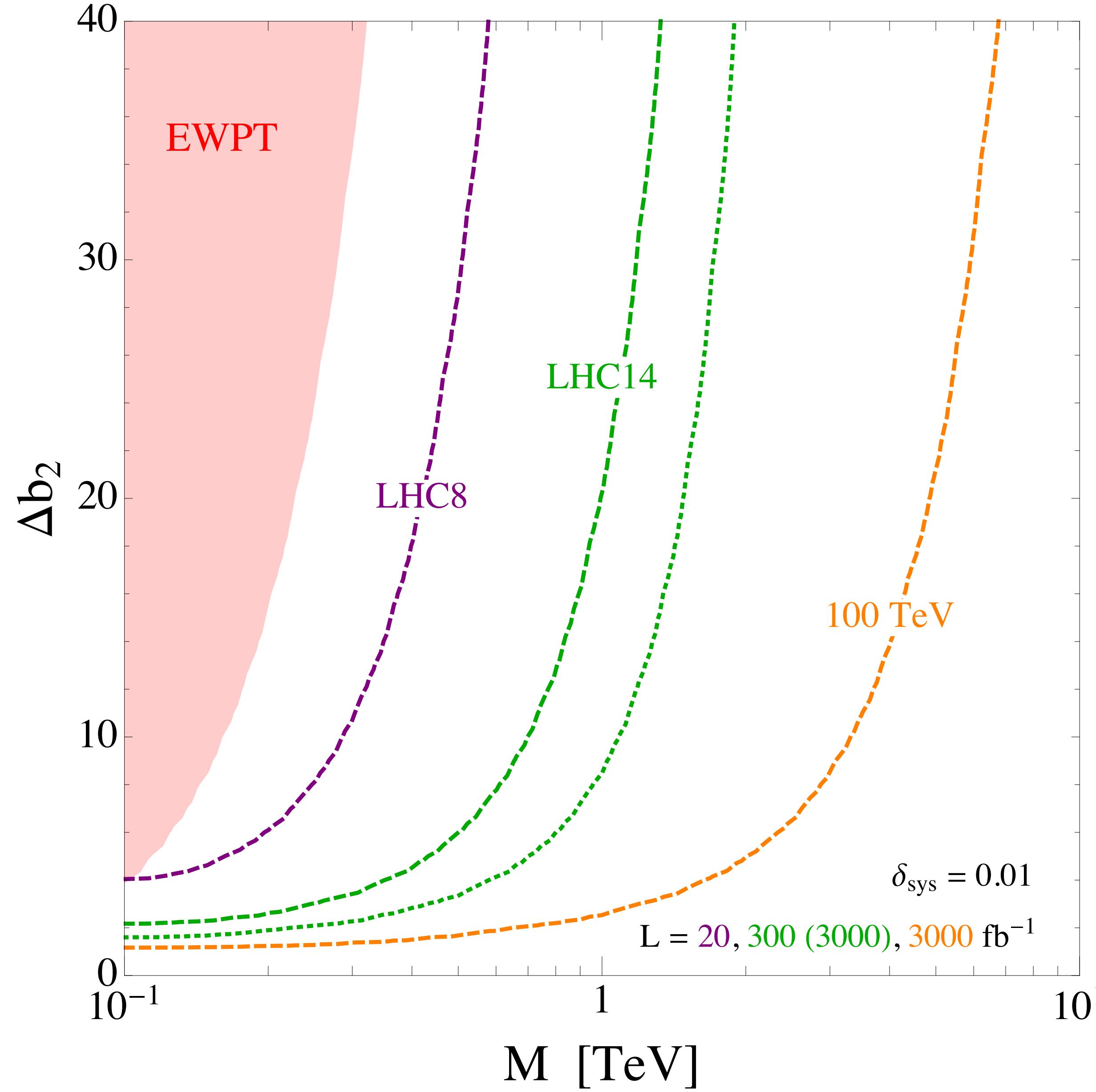
via Josh Ruderman

general limits

Z*/γ*



W*



via Josh Ruderman

Top Quark PDFs?

At a 100 TeV collider, top quarks play a role similar to bottom quarks at the Tevatron:

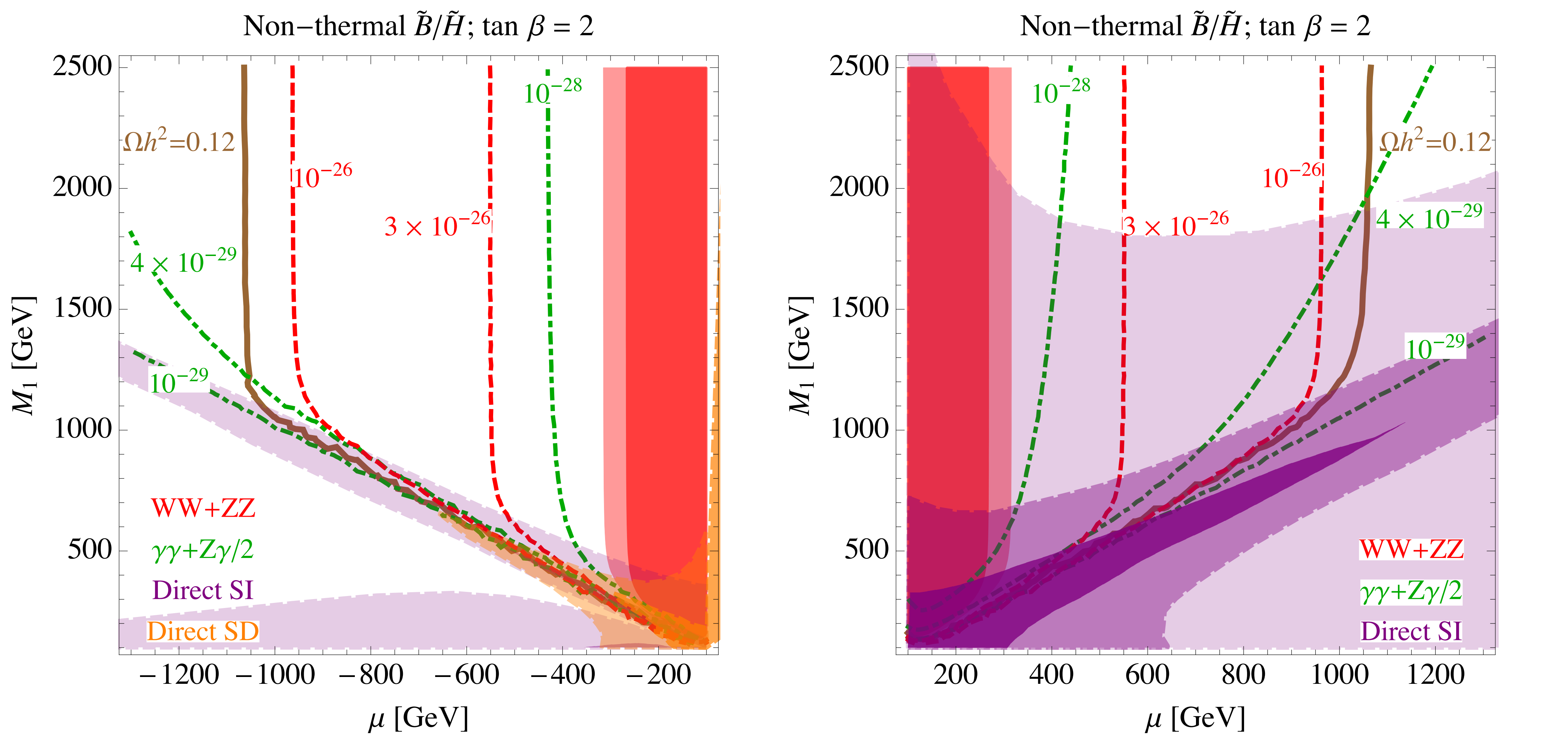
Tops @ 100 TeV: $E_{collider}/m_{top}$ ~ 100 TeV / 175 GeV ~ 570
B-quarks @ Tevatron: $E_{collider}/m_b$ ~ 2 TeV / 4.2 GeV ~ 480

So should we include the "top quark PDF" in the proton? Answer seems to be: **not really**. The collinear-enhanced coupling, $\alpha_s(E) \log \frac{E}{m_t}$, is still small at these energies.

Gluon splitting with 5-flavor PDFs is mostly right. For more see: S. Dawson, A. Ismail, I. Low 1405.6211

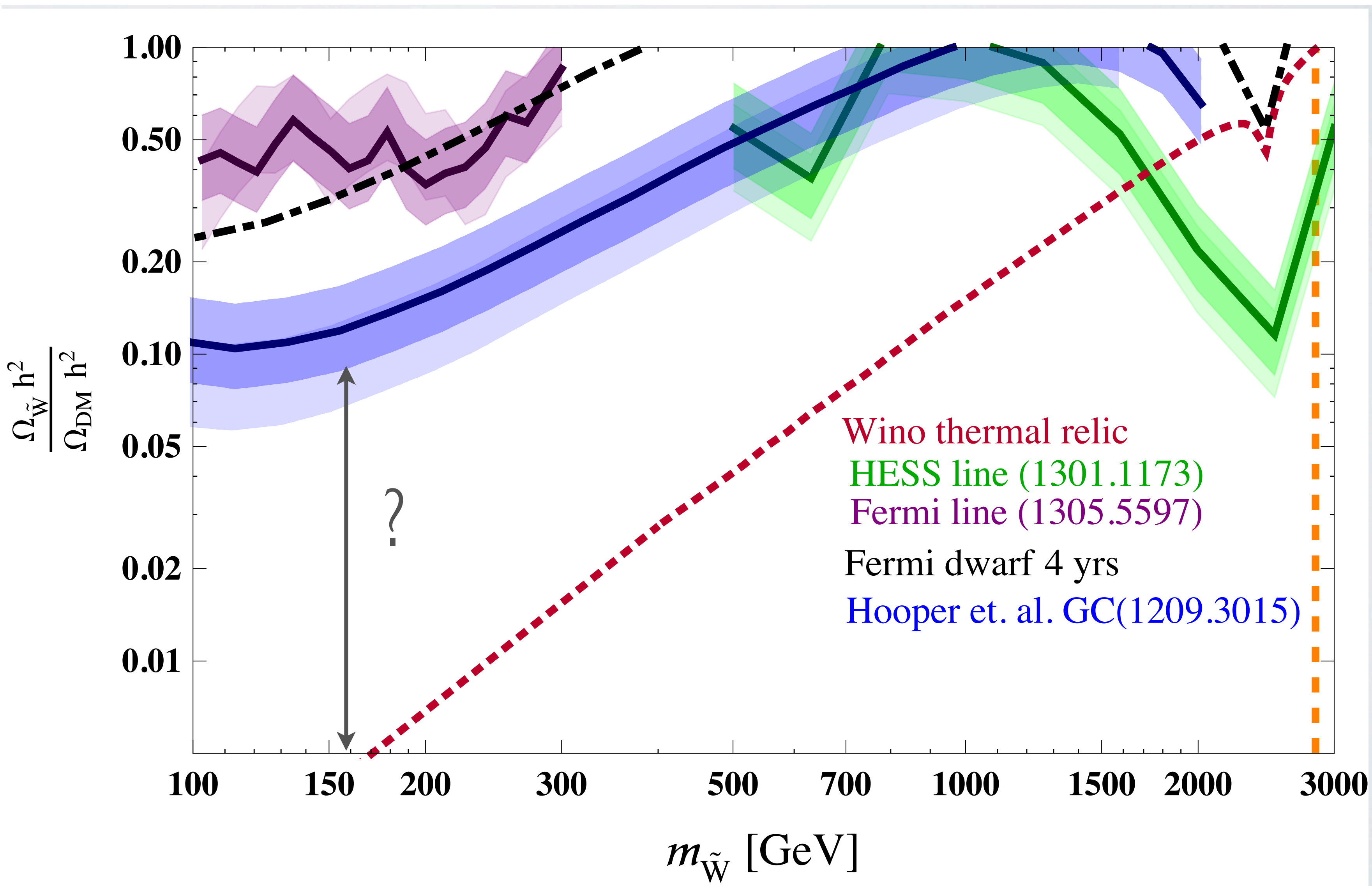
DM / Collider Interplay

SUSY Dark Matter in 20 Years?



The bino/higgsino plane. Direct detection, indirect detection, LHC (good at covering subdominant fractions) cover a lot.

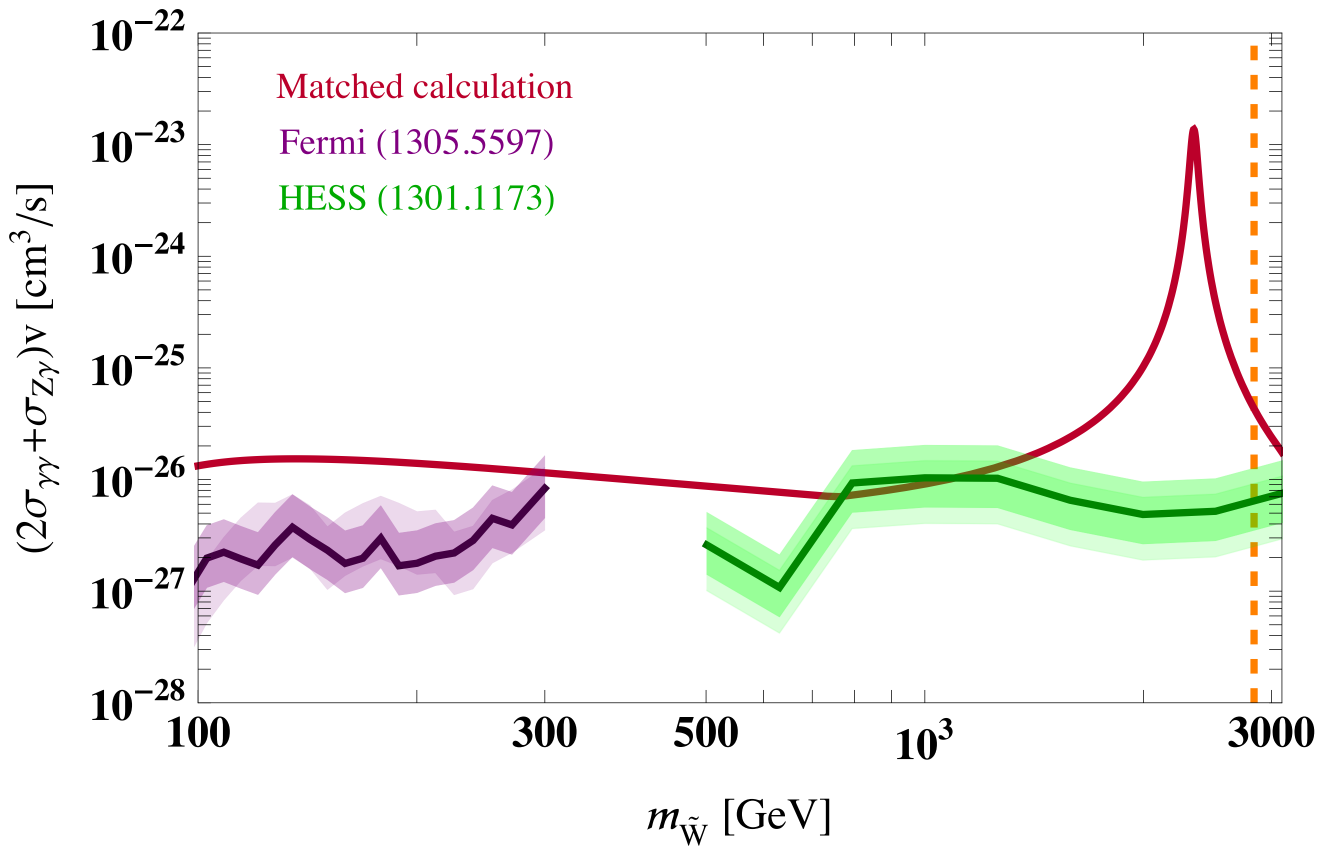
Fraction of Allowed Wino Dark Matter

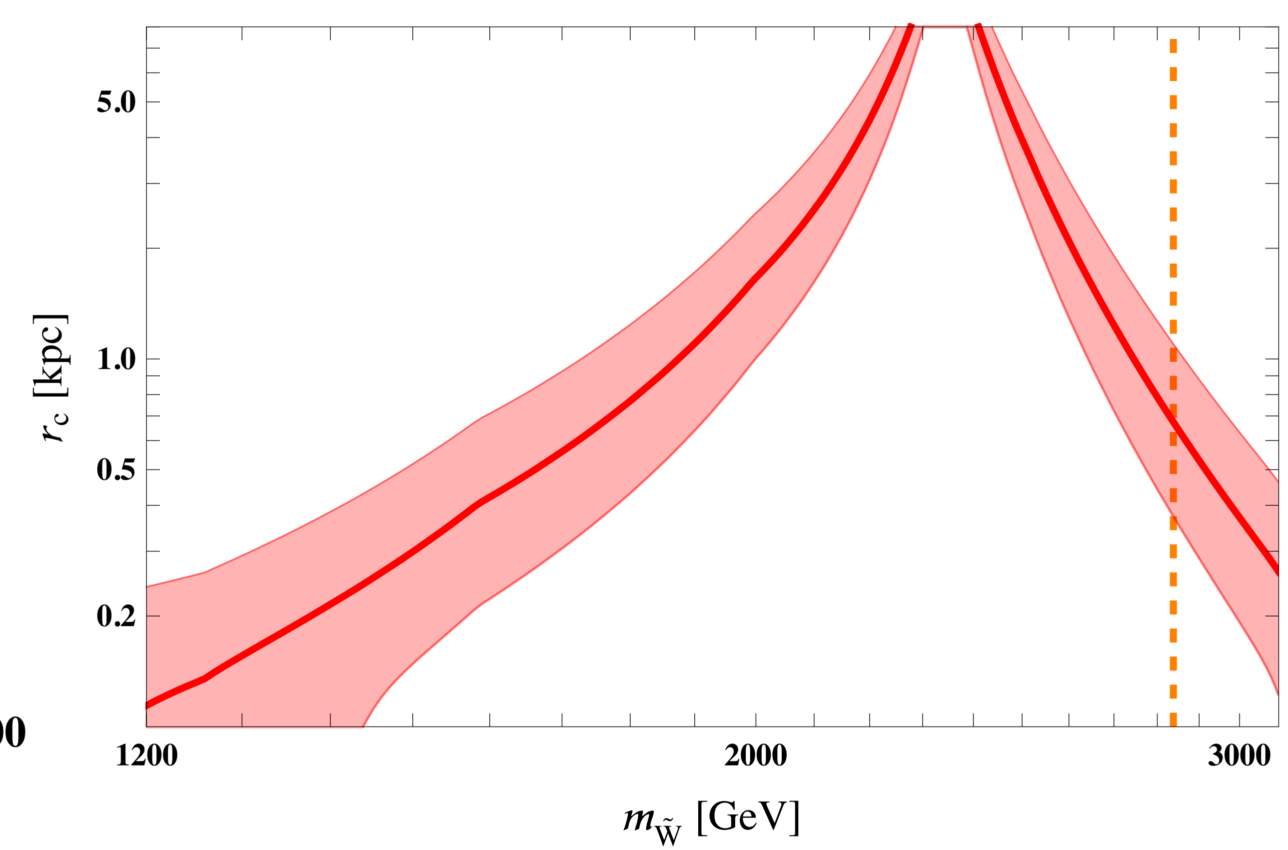


Gamma ray observations: winos are not all of the dark matter. Light winos aren't even a *tenth* of the dark matter.

J. Fan and MR, 1307.4400; see also Cohen, Lisanti, Pierce, Slatyer 1307.4082

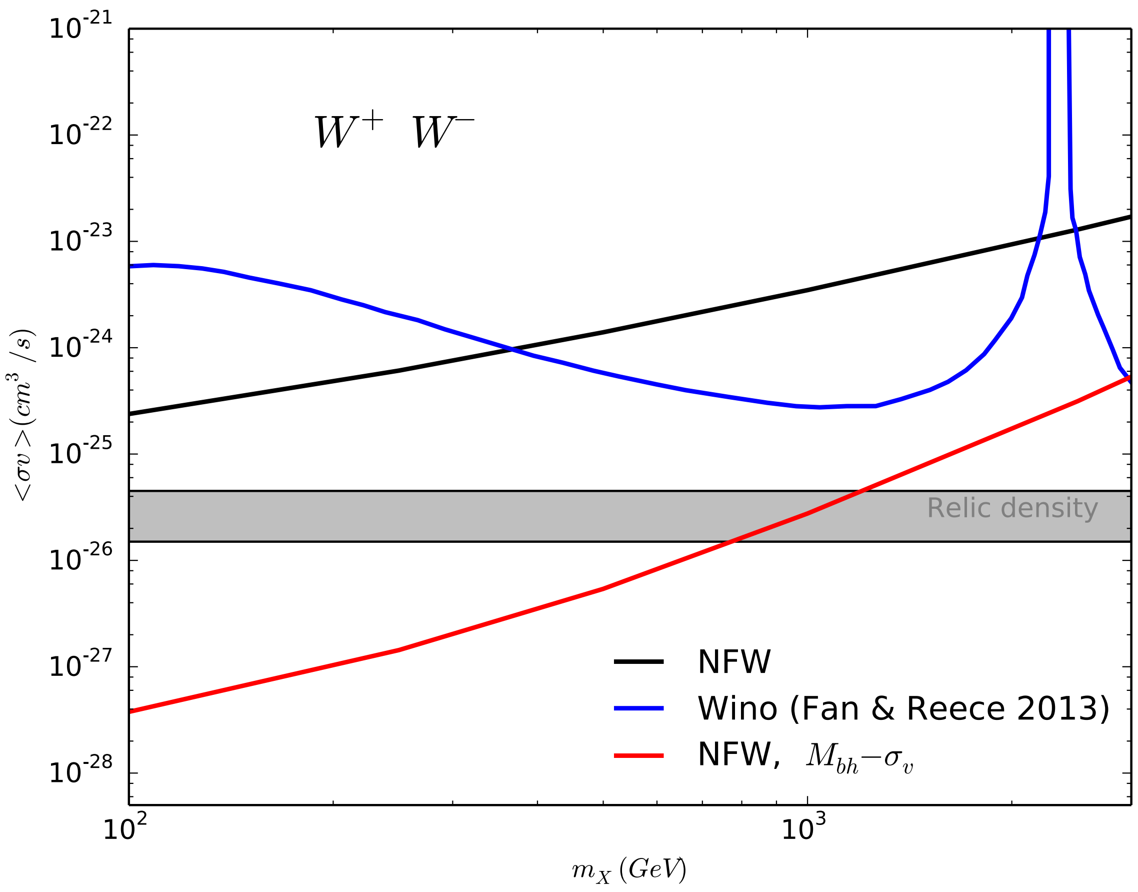
Astrophysical Uncertainties





Putting a “core” in the DM distribution in the galaxy can remove the limits over most of the heavy wino parameter space. At right: needed core size (~ kiloparsec).

DM Density Spikes?

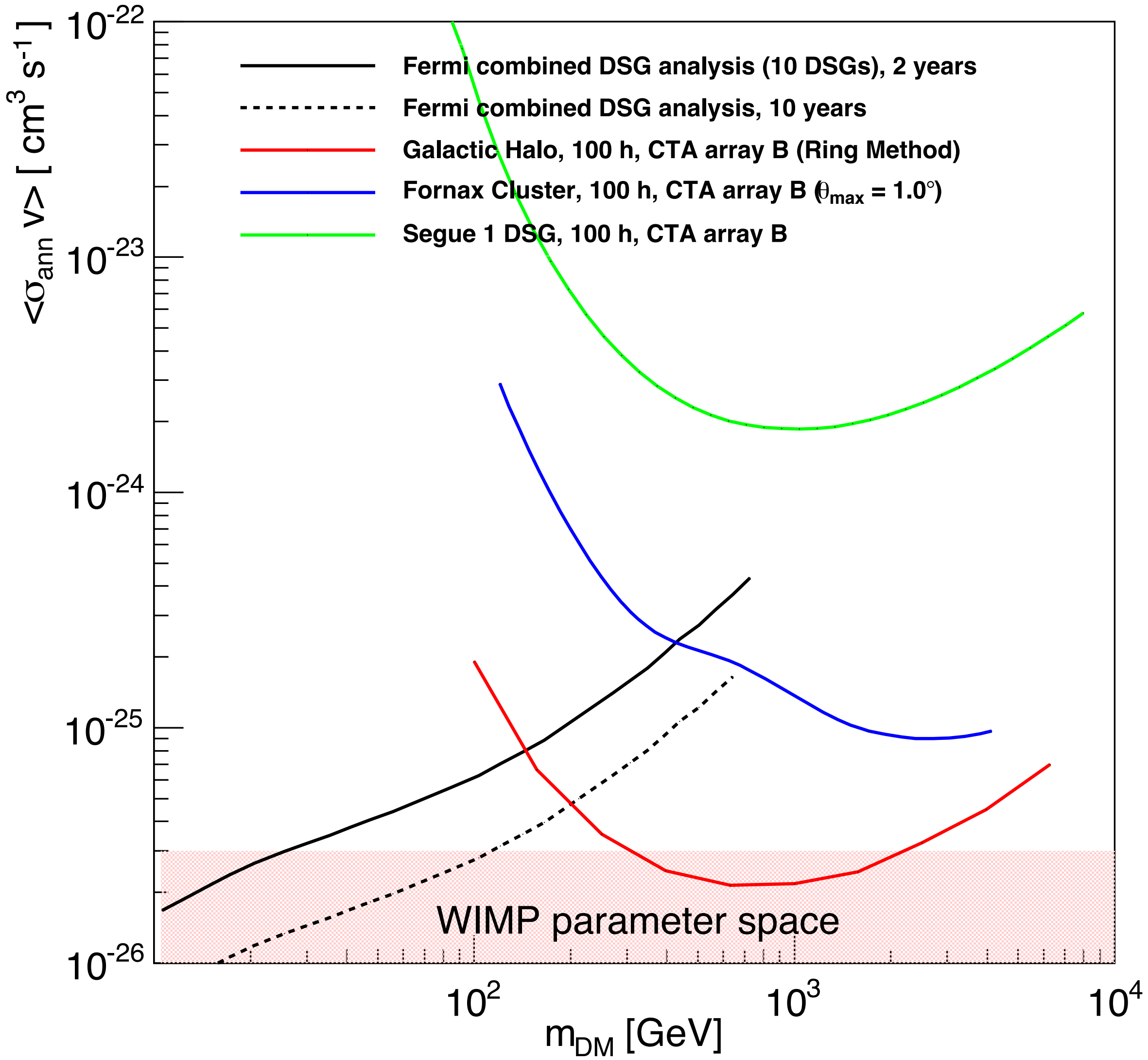


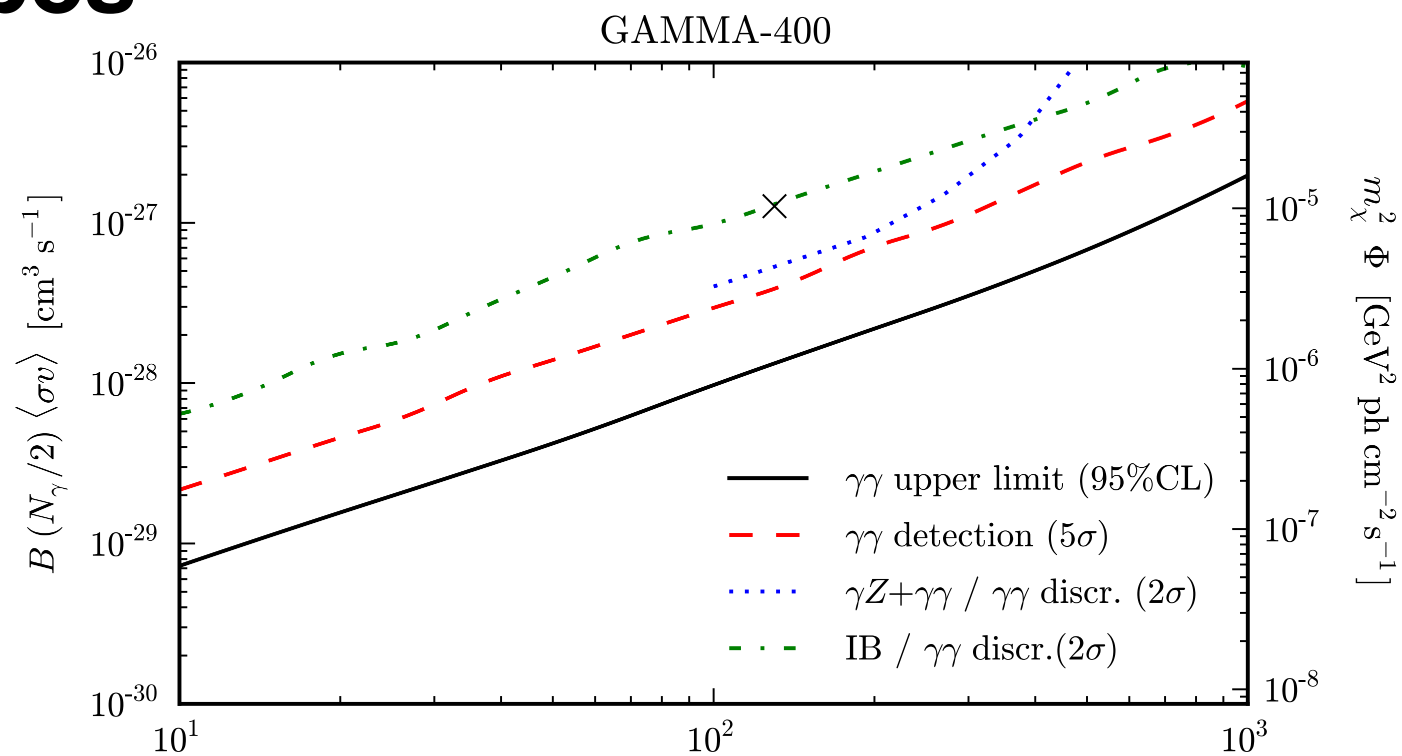
Gonzalez-Morales, Profumo, Queiroz, 1406.2424

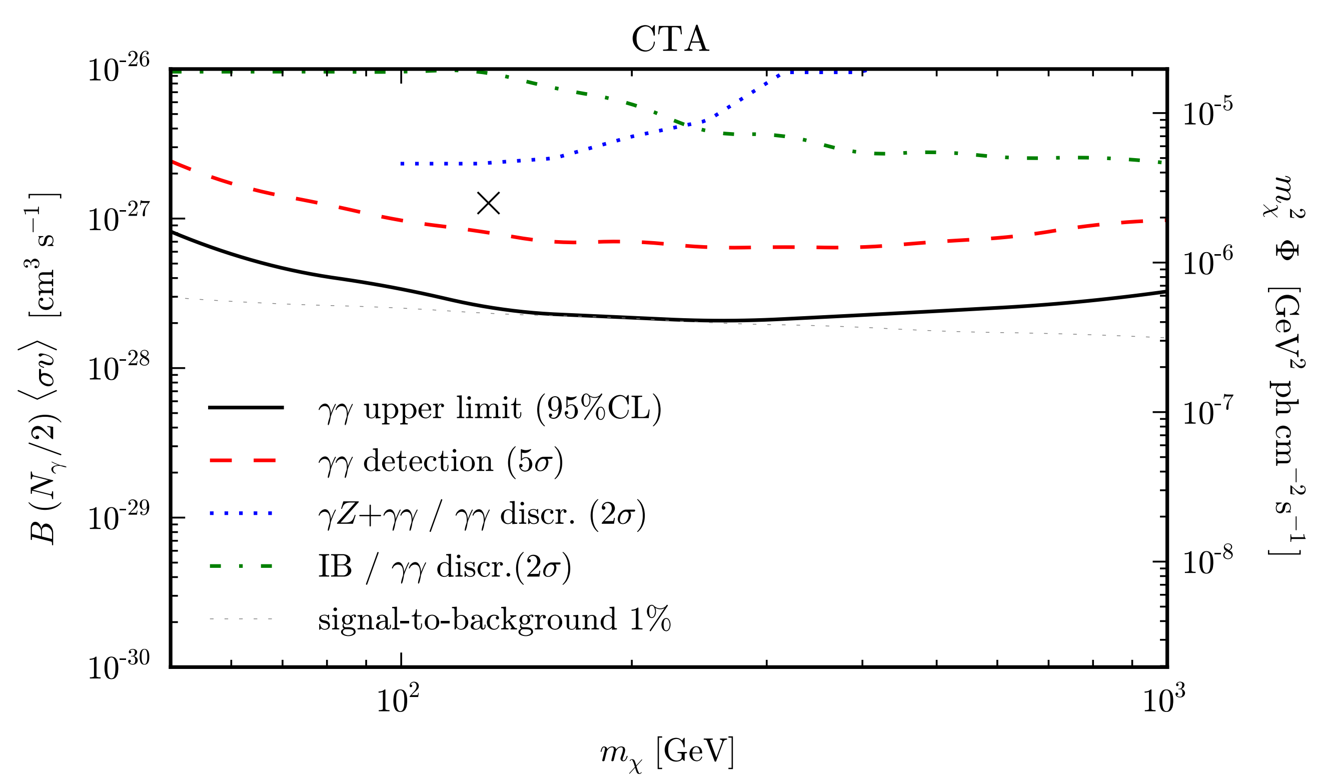
If intermediate-mass black holes exist and formed at the centers of dwarf galaxies, could we *already* have the data to rule out most SUSY dark matter?

Future Reach

crucial to decrease astrophysical uncertainties to make the most of these telescopes







above: CTA, 1208.5356
right: Bergstrom et al., 1207.6773

DM & Future Colliders

If indirect / direct detection exclude neutralino DM, you can always imagine it has a lifetime long on collider scales but short on cosmological scales. **Don’t stop looking for winos and higgsinos at colliders**.

But: it could become **much more interesting** to consider scenarios like **R-parity violation** or **decays to hidden sectors** if we have very strong constraints on neutralino dark matter. Long-lifetime searches, searches with cascades ending in lots of jets, all the “tricky” signals could become more important—even at 100 TeV, even if we’re not demanding strict naturalness.

Conclusions?

New colliders: push the constraints on naturalness well above the mild tuning the LHC requires.

Kill naturalness at percent (sub-percent?) level, decisively rule out (or confirm?) electroweak baryogenesis….

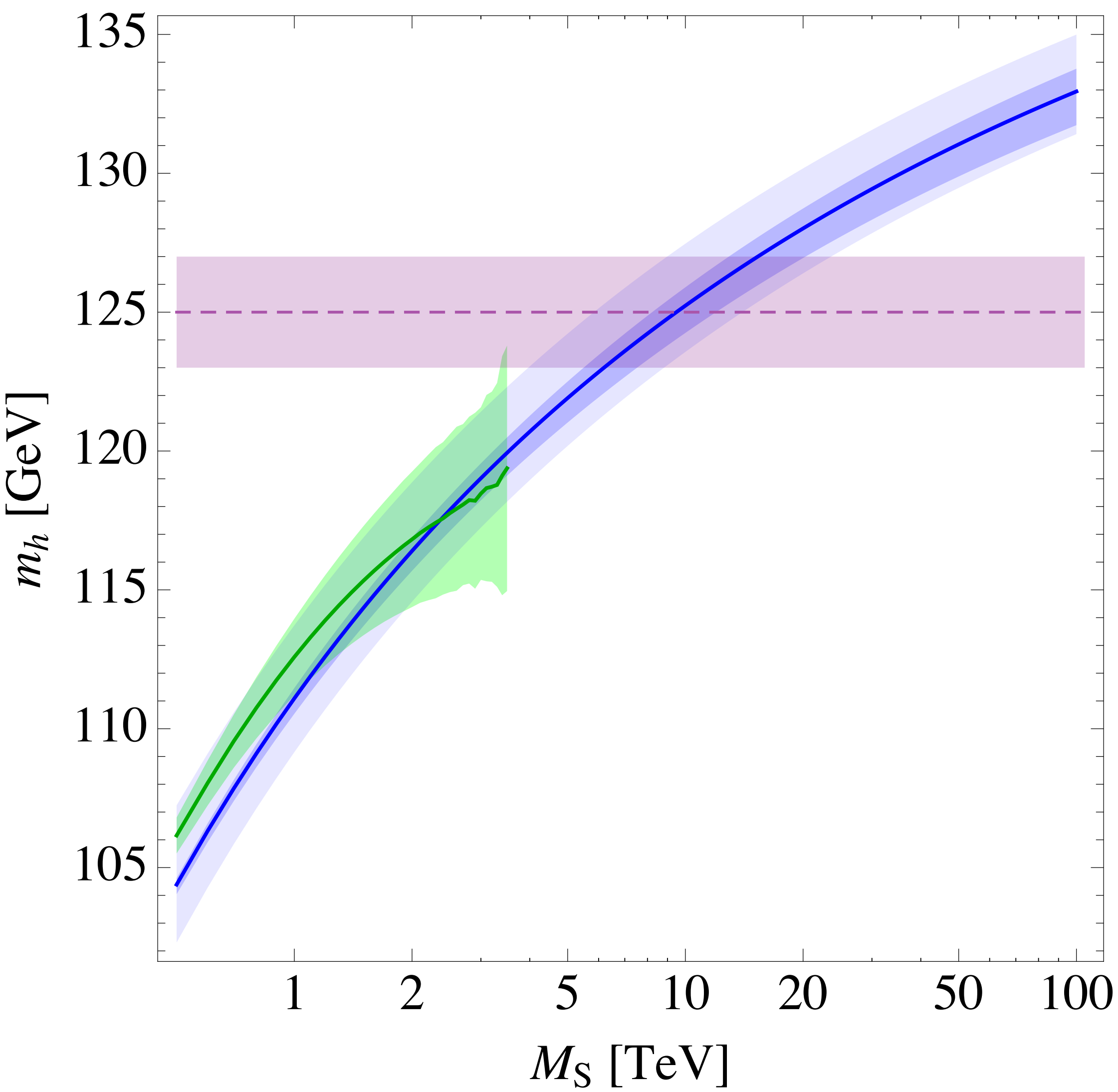
What scenarios are we optimistic about *discovering* at this machine? Mini-split SUSY? How strong is the argument for this particular scale? (e.g. anthropics?)

No conclusion for now; let's discuss….

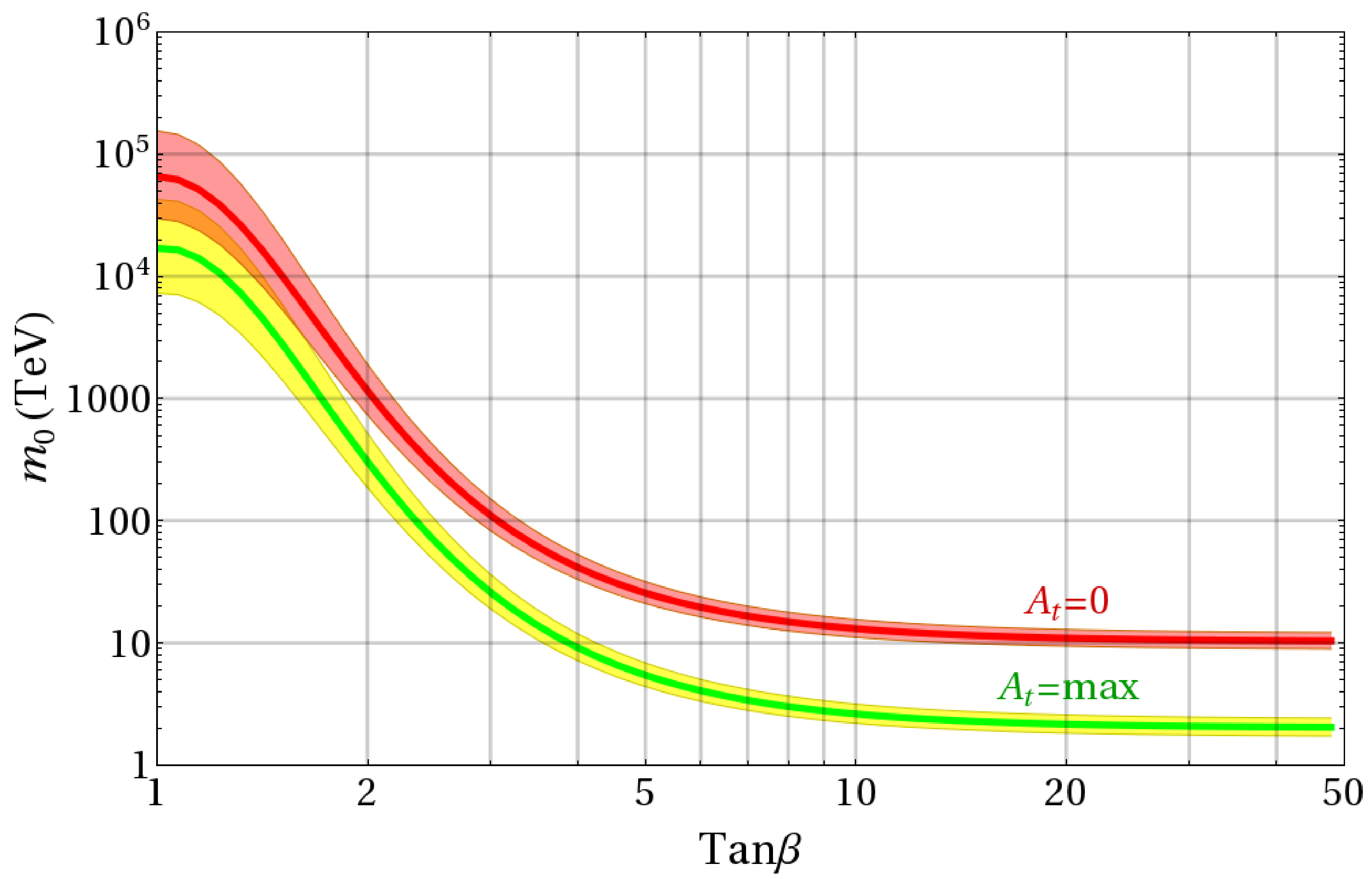
Backup Slides

Why Split?

Arkani-Hamed & Dimopoulos originally had in mind very heavy scalars. But what the data points to now may be only “mildly” split SUSY, with scalars at 10s—100s TeV.

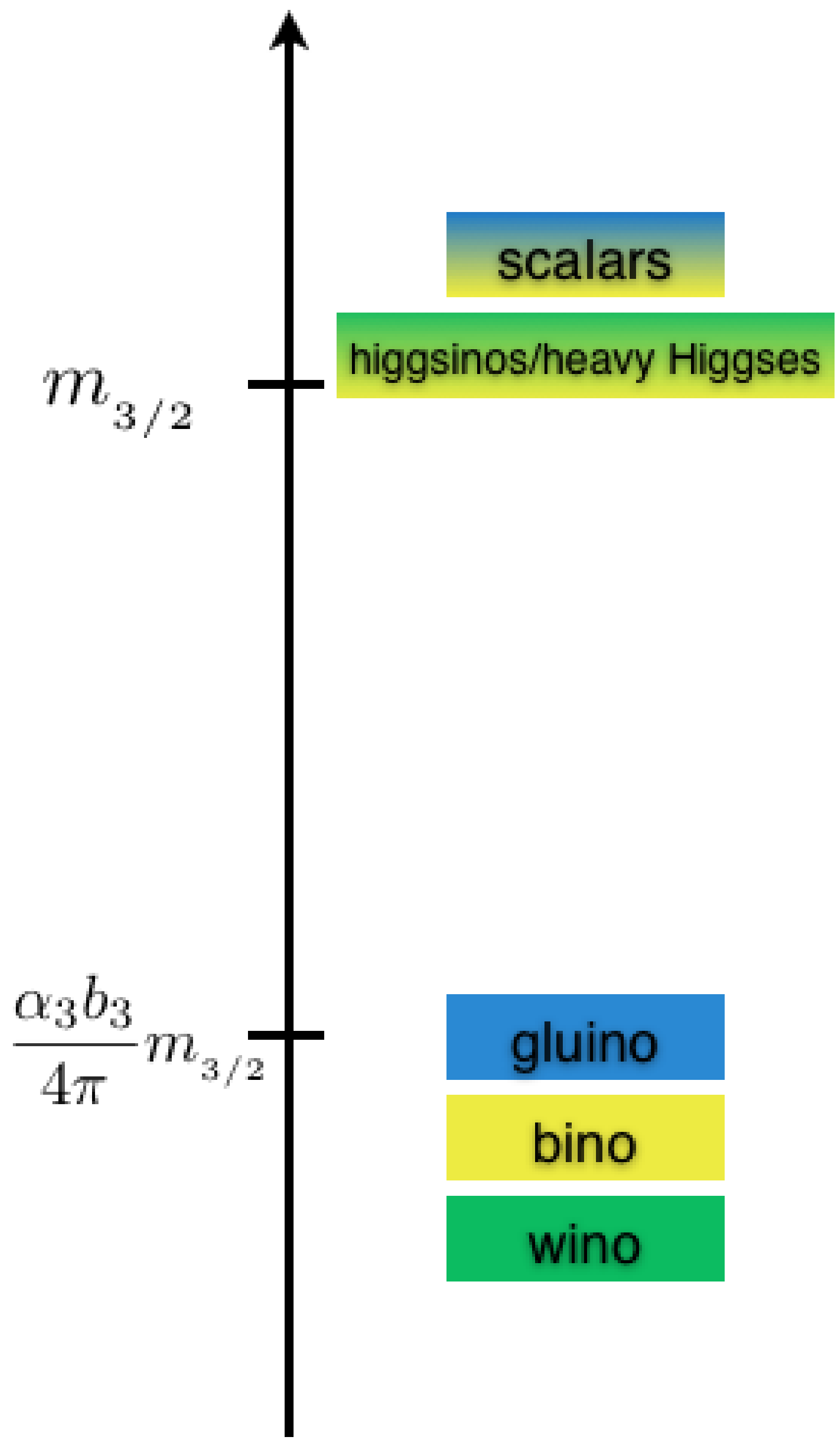


Draper, MR, Meade, Shih 1112.3068



Arvanitaki, Craig, Dimopoulos, Villadoro 1210.0555

Collider Targets?



A possible spectrum (Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski 1212.7961; see also Hall, Nomura, Shirai; Arvanitaki, Craig, Dimopoulos, Villadoro,…).

The obvious collider target is a gluino. But: how would it decay? Is there a lot of missing transverse momentum?

I want to argue for **split + RPV** as an understudied signature. Why? (Most) **dark matter is not made of winos.**

Anomaly Mediation and Mini-Split

The observed Higgs mass fits well with *anomaly mediation* or other scenarios (including many moduli-mediated scenarios) where gaugino masses are set by

$$m_\lambda \sim \frac{\alpha}{\pi} m_{3/2}$$

For plausible and typical models, in such a scenario scalars are ~ $m_{3/2}$ and the spectrum is split.

If gauginos are ~ TeV (and we know they aren't much lighter!), the scalars are in the right place for a 125 GeV Higgs. (1 TeV gluino means ~40 TeV gravitino & scalars)

Moduli

Moduli are scalar fields coupling with gravitational strength. In string constructions their VEVs determine couplings, e.g.

$$\mathcal{L} \supset c_\phi \frac{\phi}{M_{\rm Pl}} F_{\mu\nu} F^{\mu\nu}$$

These fields are often light: the natural scale for their masses is ~$m_{3/2}$. (Coughlan, Fischler, Kolb, Raby, Ross 1983; de Carlos, Casas, Quevedo, Roulet 1993).

Overclose the universe or ruin BBN unless their masses are > $(T_{\rm BBN}^2 M_{\rm Pl})^{1/3}$ ~ 100 TeV. **There's the 100 TeV scale again!**

Triple coincidence?

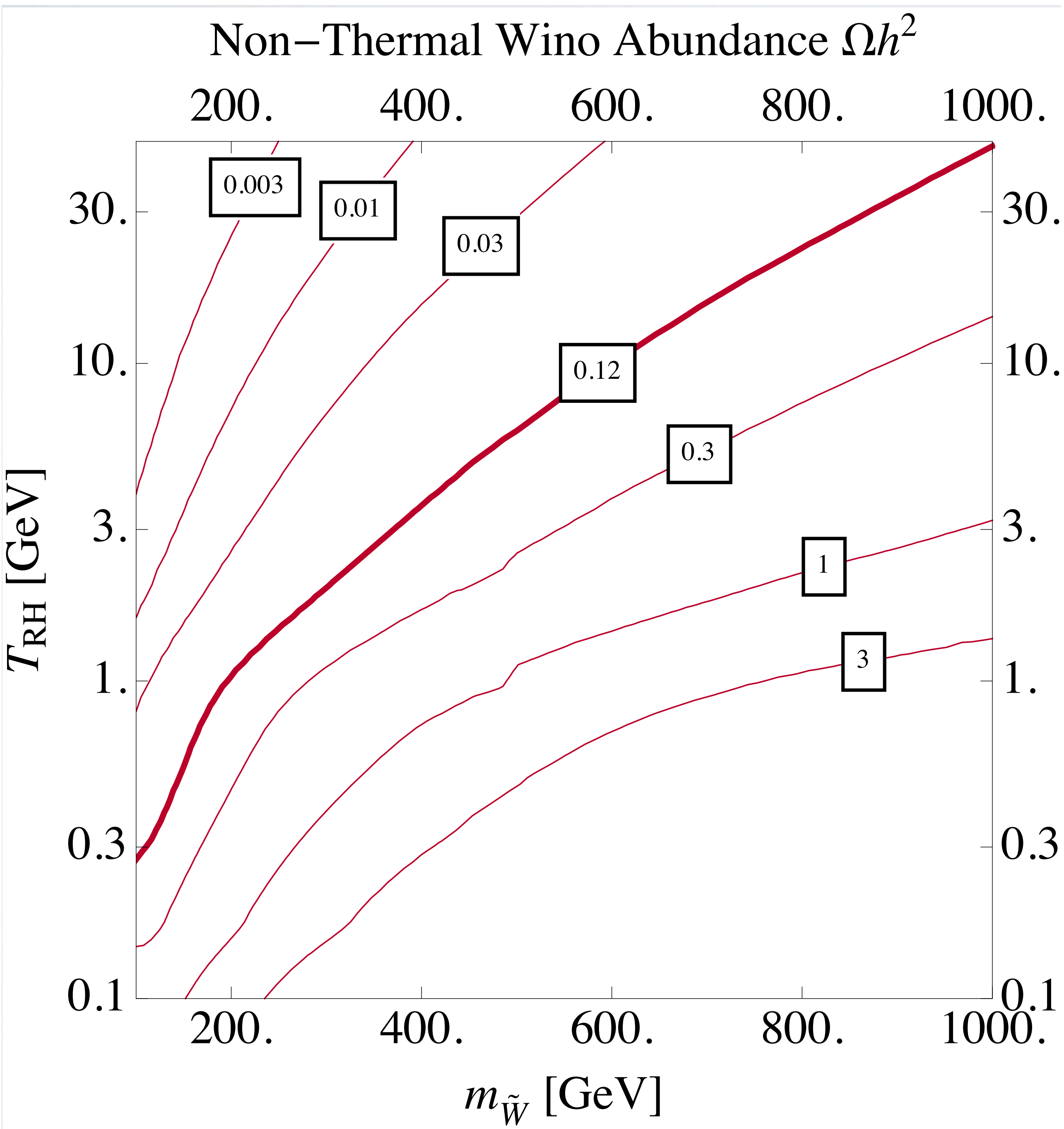
- If gauginos are at the 100 GeV to 1 TeV scale (and we know they aren't much lighter…), AMSB puts the gravitino at ~10 to 100 TeV.

- If we want moduli to reheat above BBN, this picks out a scale ~10 to 100 TeV.

- If we want to raise the Higgs mass to 125 GeV without large *A*-terms, for moderate to large tan beta this picks out scalar masses ~ 10s of TeV.

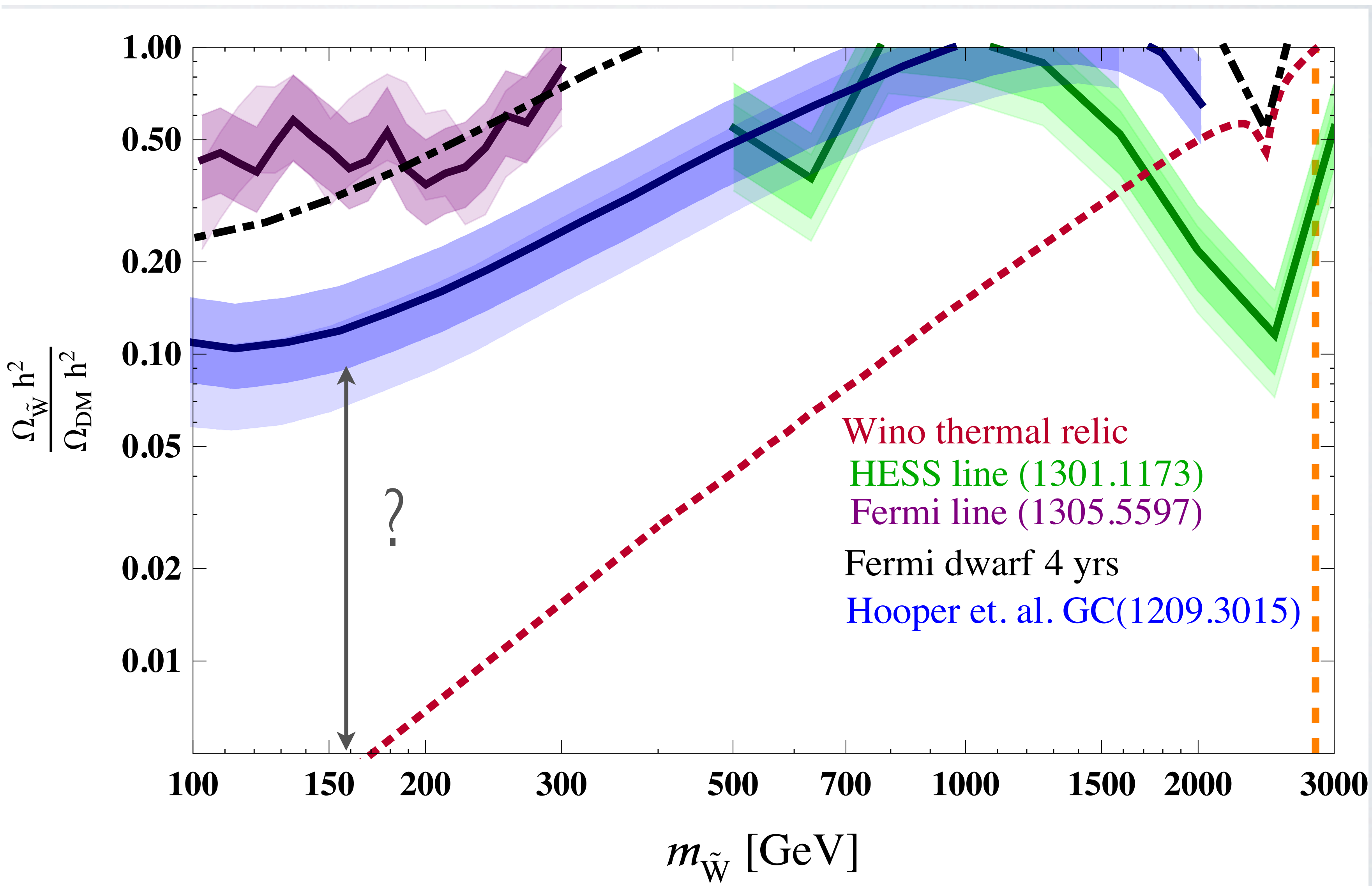
- It's a nice story, aside from the fine-tuning.

Non-thermal abundances



Light wino LSPs (e.g. from anomaly mediation) are bad dark matter candidates *unless* we have exactly the sort of non-thermal cosmology moduli could provide. (Moroi & Randall, recently Gordy Kane & collaborators, Yanagida & collaborators, etc)

Fraction of Allowed Wino Dark Matter



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R-parity violation

RPV has received a lot of attention recently in the context of natural SUSY (hiding superpartners from the LHC).

I think we should also be thinking about RPV *in the unnatural, mini-split SUSY context*. Removes the wino DM problem. Produce **winos**, which **decay**. How do they decay?

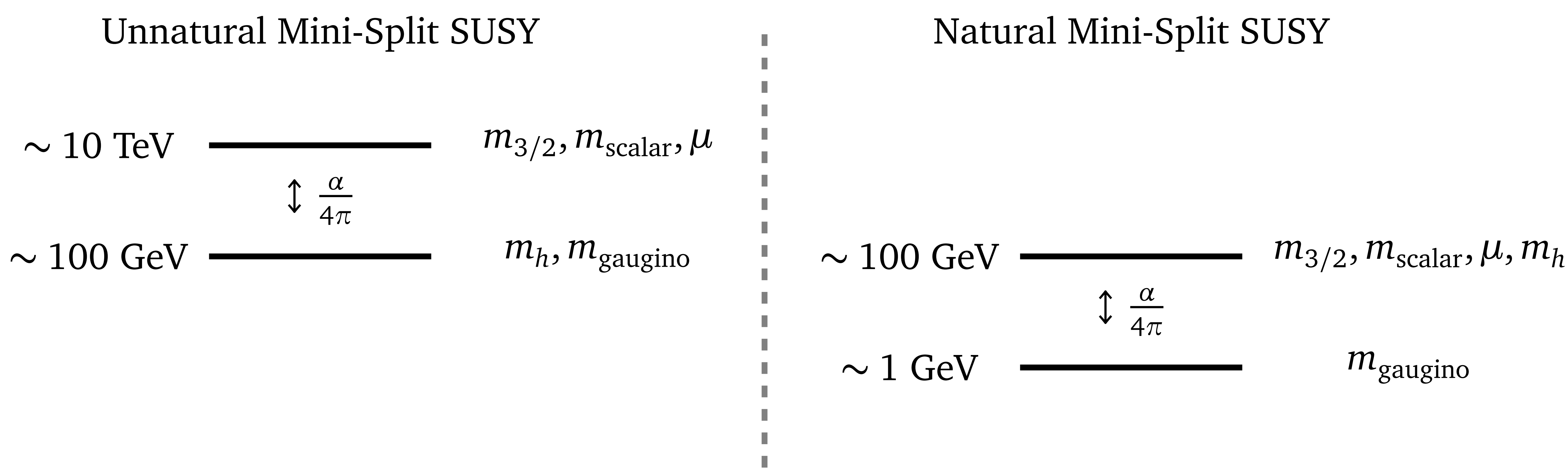
$W_{RPV} = u^c d^c d^c$ has gotten a lot of recent attention (e.g. MFV RPV). Good for hiding from LHC searches (multi-jet signals).

One option that received less recent attention (but see papers by JWF Valle): bilinear RPV, with 2-body wino decays at LHC.

(for older work: see hep-ph/9612447 by Mukhopadyaya and Roy; hep-ph/0410242 by Chun and Park; also, for 3-body decays in bilinear RPV, Graham, Kaplan, Rajendran, Saraswat, 1204.6038)

The Anthropic Question

Our picture raises a question: SUSY could have been split *and* natural.

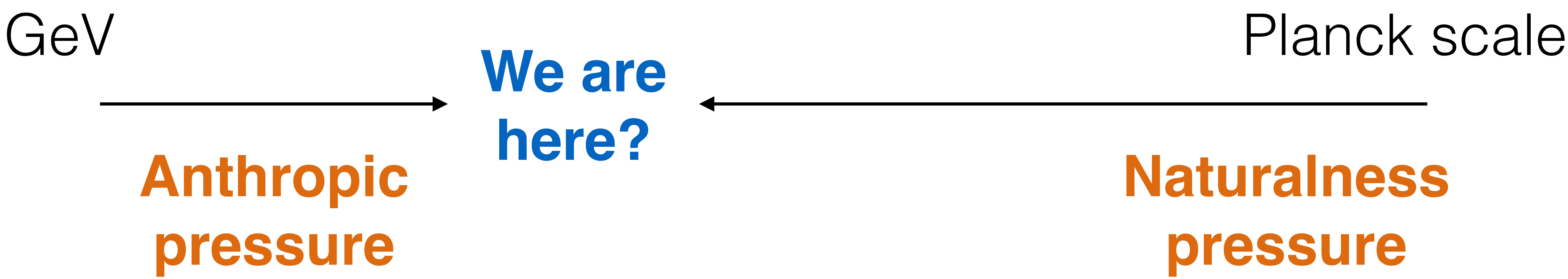


Is there a good reason why we might find ourselves living in the universe at left instead of the natural one at right?

Maybe cosmological (moduli) answers (work with J Pradler)

The Big Picture?

SUSY may solve most of the hierarchy problem. What we see conflicts with our notions of naturalness because we could not live in the natural world. Balance of two pressures:



Sounds philosophical, but the hope is for an anthropic story that relates to cosmology in a *predictive* way. Still work in progress….