Asymmetric (S)tops

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work in progress *with* M. Graesser

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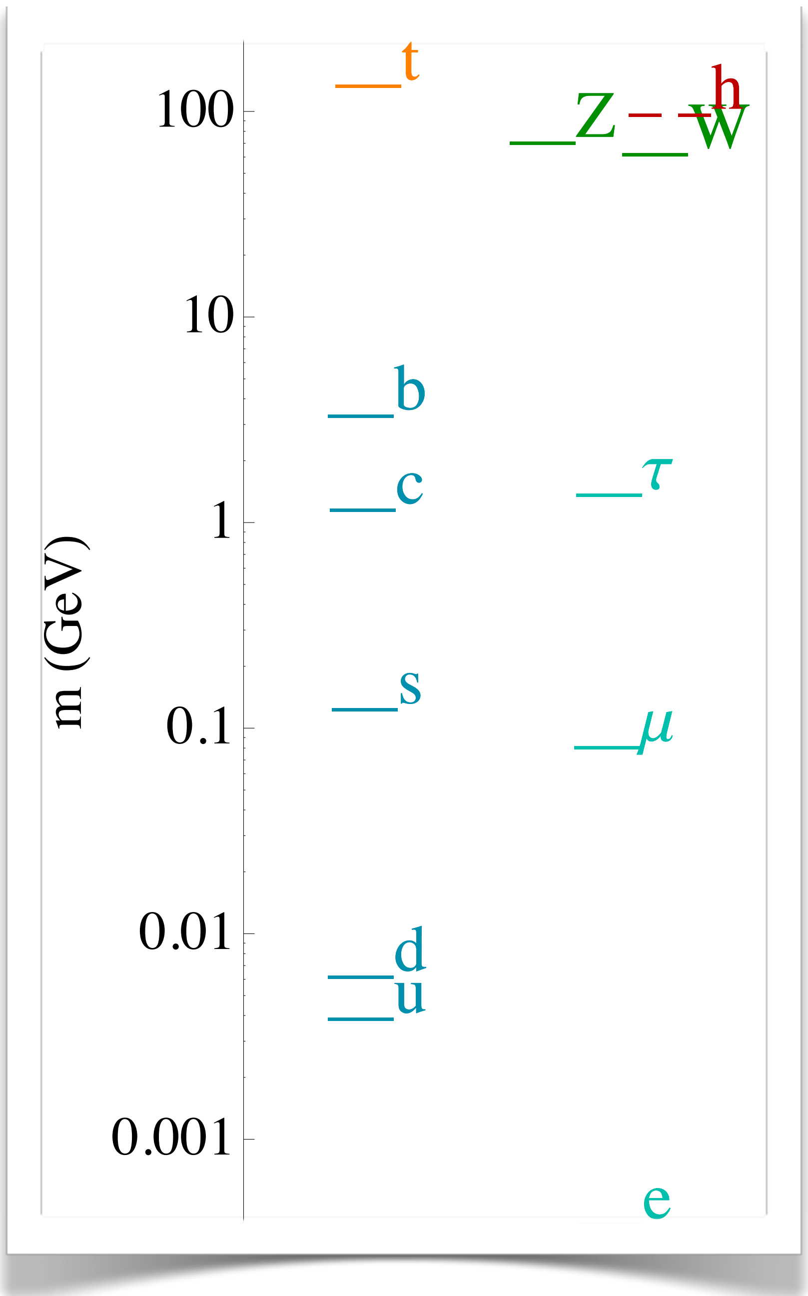
Fermilab, October 25, 2012

Tops, new physics, and the LHC

Heaviness of top quark makes it uniquely interesting to study from both theoretical and practical standpoints.



- The top plays a privileged role in electroweak symmetry breaking: $\lambda_t \approx 1$
- Top also potentially has large couplings to flavor-symmetry breaking physics
- Top properties are among the least well measured in the SM: more room for new physics
- Rapid EW decay means many kinematic handles in top-like final states...
- ...and access to angular properties

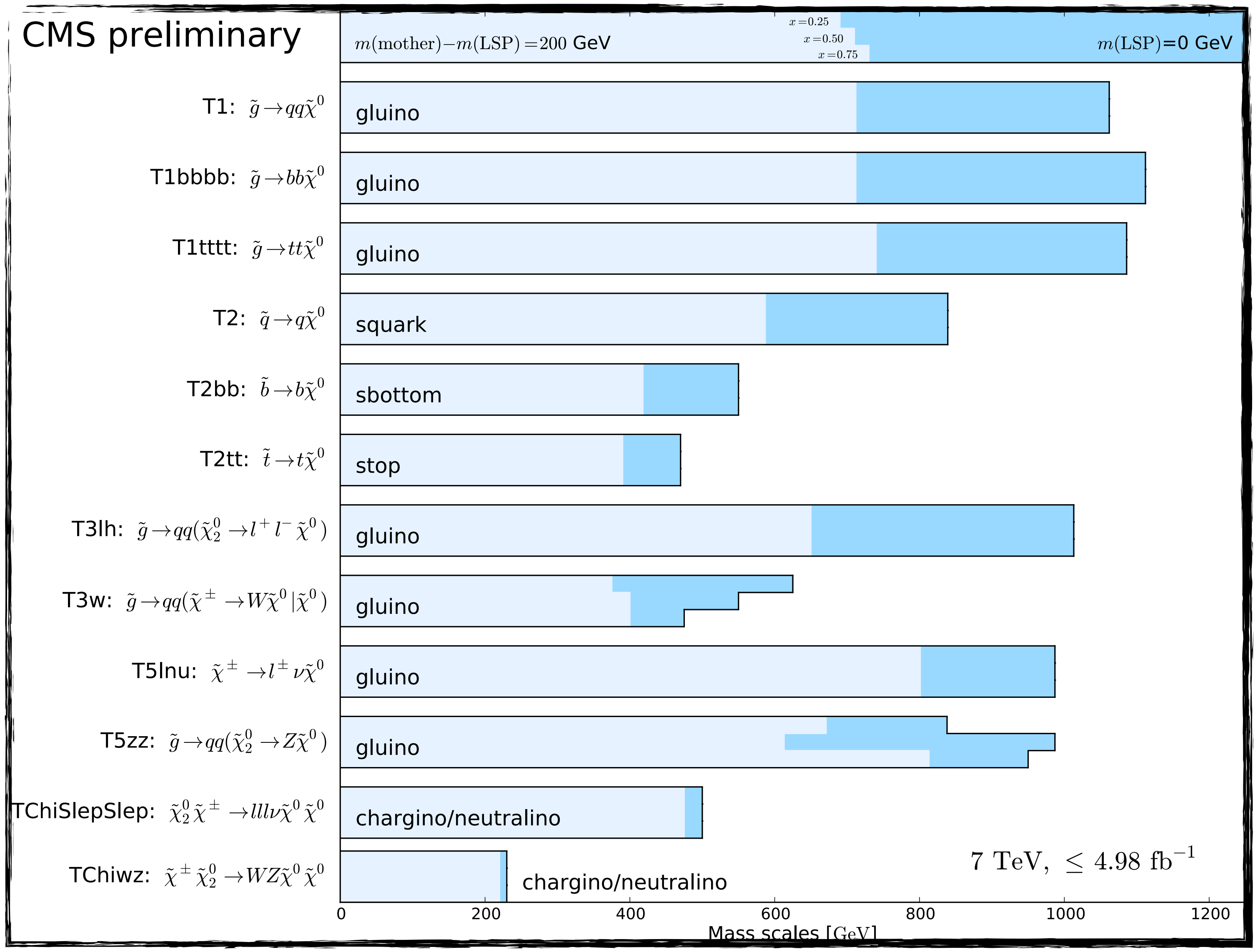
Tops, new physics, and the LHC

- Two particular reasons to think about new physics in top quarks
  - top-down: we have found a weakly-coupled Higgs (or something very like it). Does anything protect the EW scale?
  - bottom-up: persistent hints from the Tevatron of new physics in top pair production.
- So far, LHC has seen no significant deviations from SM.
  - Searches and models in light of this?

1. Top down: the hunt for stops

Tops, stops, and the electroweak scale

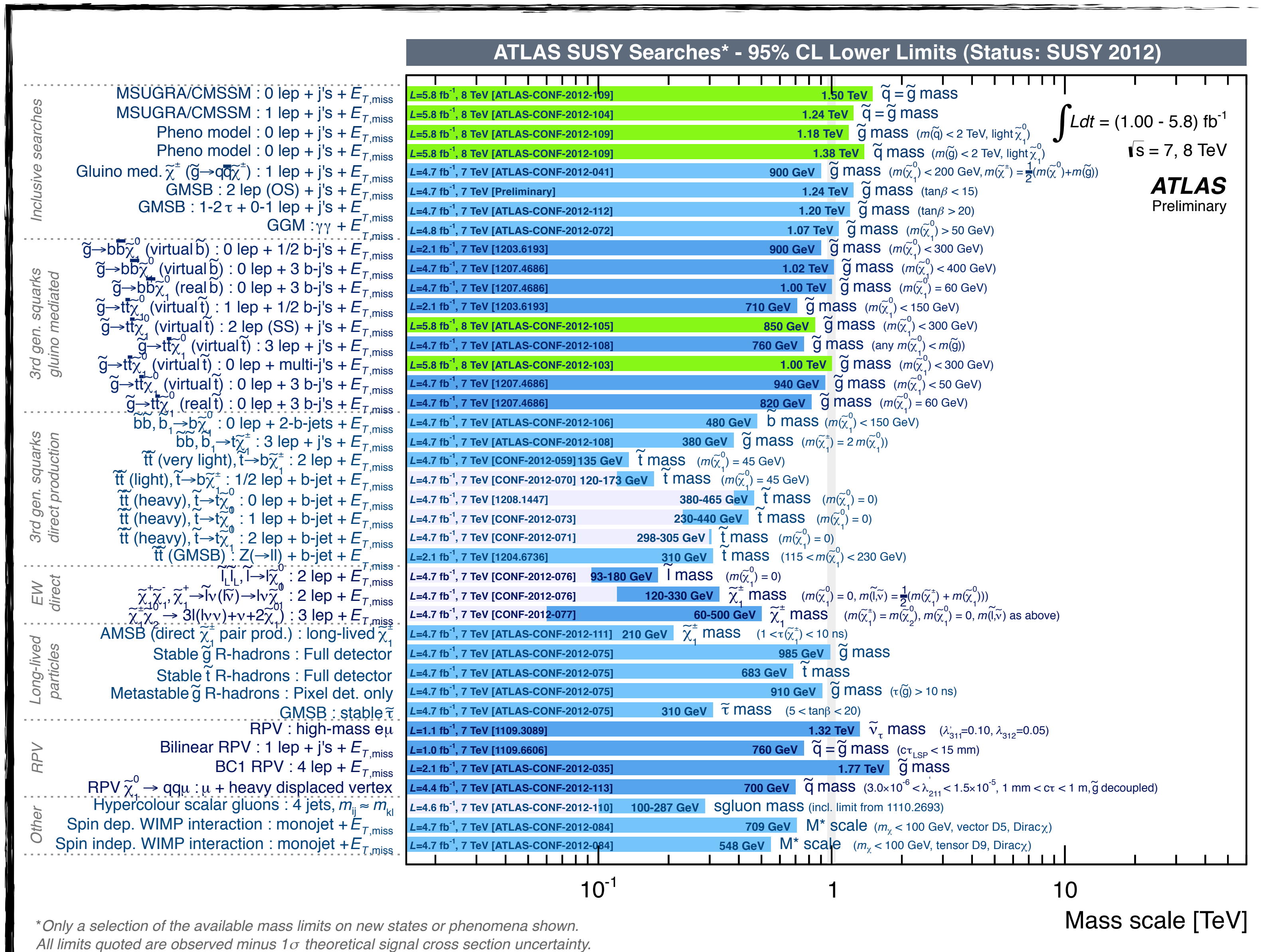
- Weak-scale SUSY: elegant* solution to the hierarchy problem



- At LHC as at Tevatron, LEP, ..., have learned only that if weak-scale SUSY exists, it doesn't look like simplest expectations

Tops, stops, and the electroweak scale

- Weak-scale SUSY: elegant* solution to the hierarchy problem



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Tops, stops, and the electroweak scale

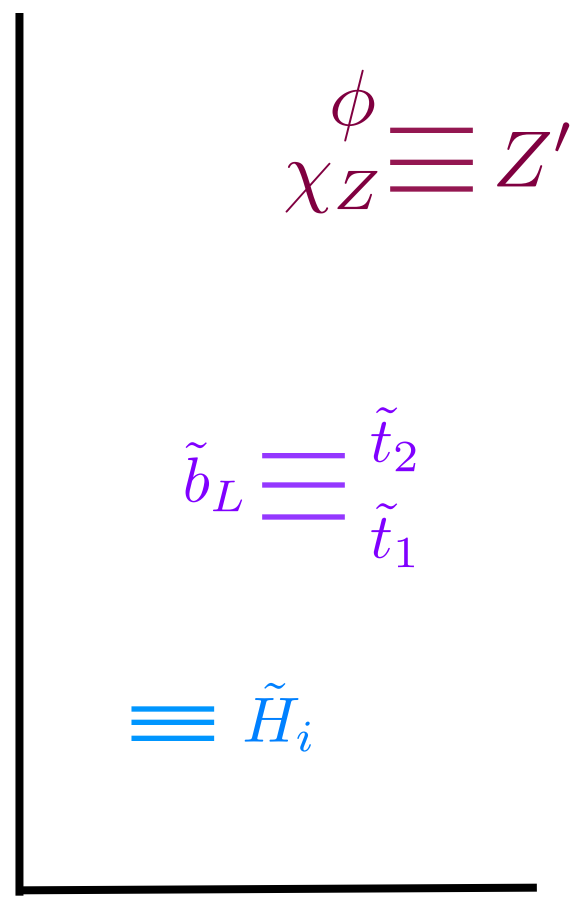
- Still ways for weak-scale SUSY to evade LHC limits.
  - RPV? Especially all-hadronic searches
  - "Natural" or "Effective" SUSY (Cohen, Kaplan, Nelson; Kats, Meade, Reece, Shih; Papucci, Ruderman, Weiler; Brust, Katz, Lawrence, Sundrum; ...)
    - Not all superpartners are equally important for radiative stability: top and EW partners
    - Higgsinos: $m \approx \mu \lesssim 200\,\mathrm{GeV}$
    - Stops and LH sbottom: $m \lesssim 400\,\mathrm{GeV}$
    - Gluino: $m \lesssim 1\,\mathrm{TeV}$

Naturalness and light stops

- Higgs at 125 GeV squeezes SUSY no matter what:

Relax minimality:

- Take naturalness seriously as a guide to weak-scale spectrum
- three light third-generation squarks
- require extended Higgs sector to augment quartic (D-term, F-term...)



Relax naturalness:

- Set stop parameters to obtain 125 GeV with minimal possible tuning
- one light, well-mixed stop

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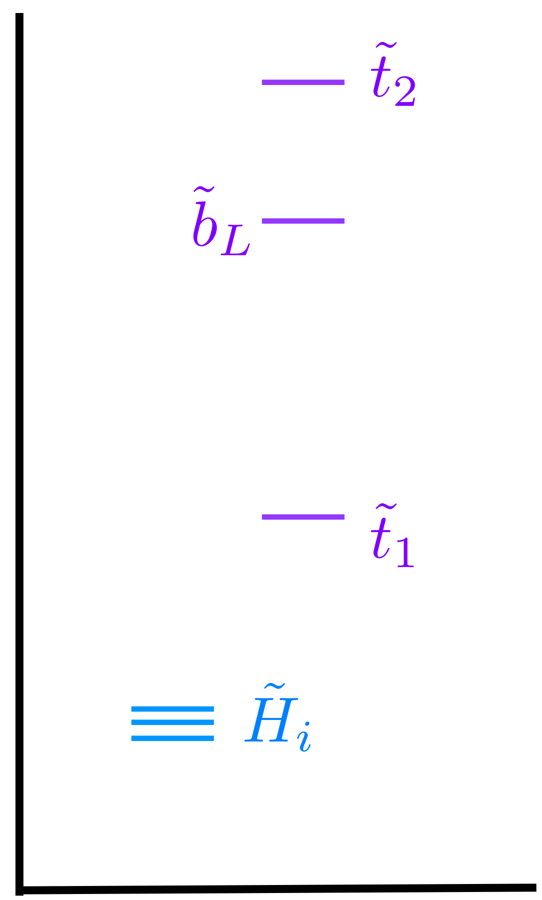

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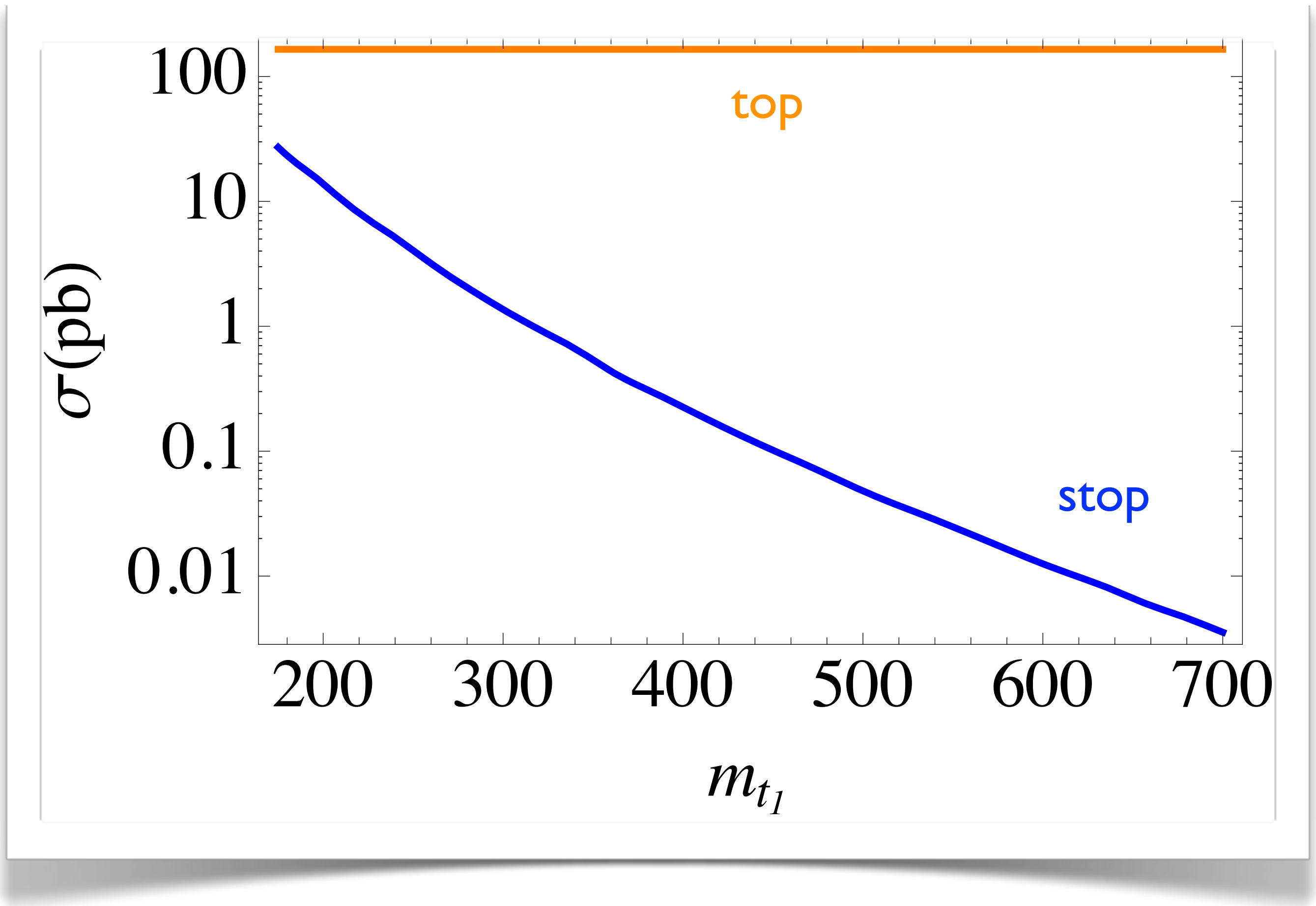
Direct Stop Searches

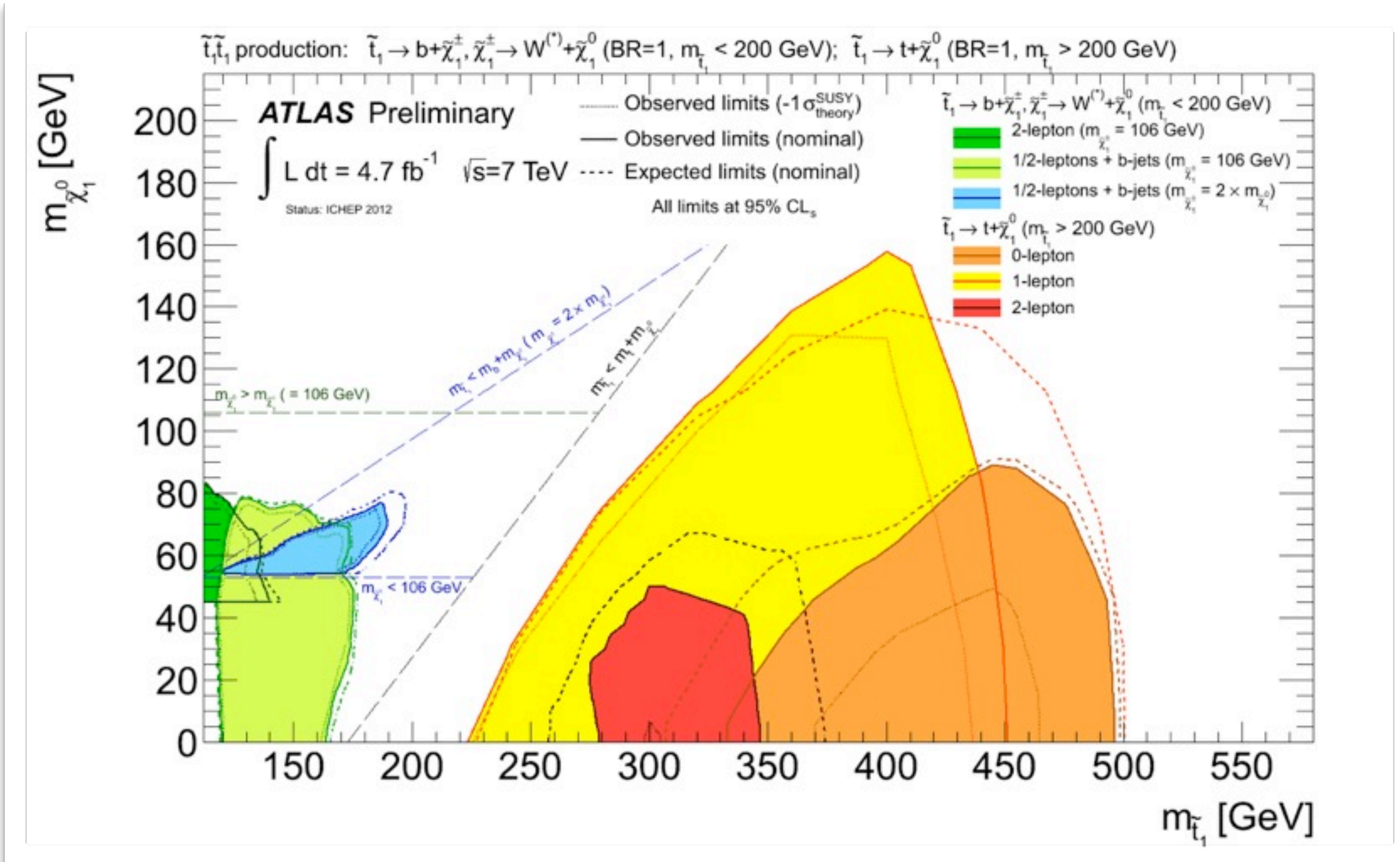
- Probing stops without help from gluinos is hard:



7 TeV NLO pair production cross-sections

Direct Stop Searches

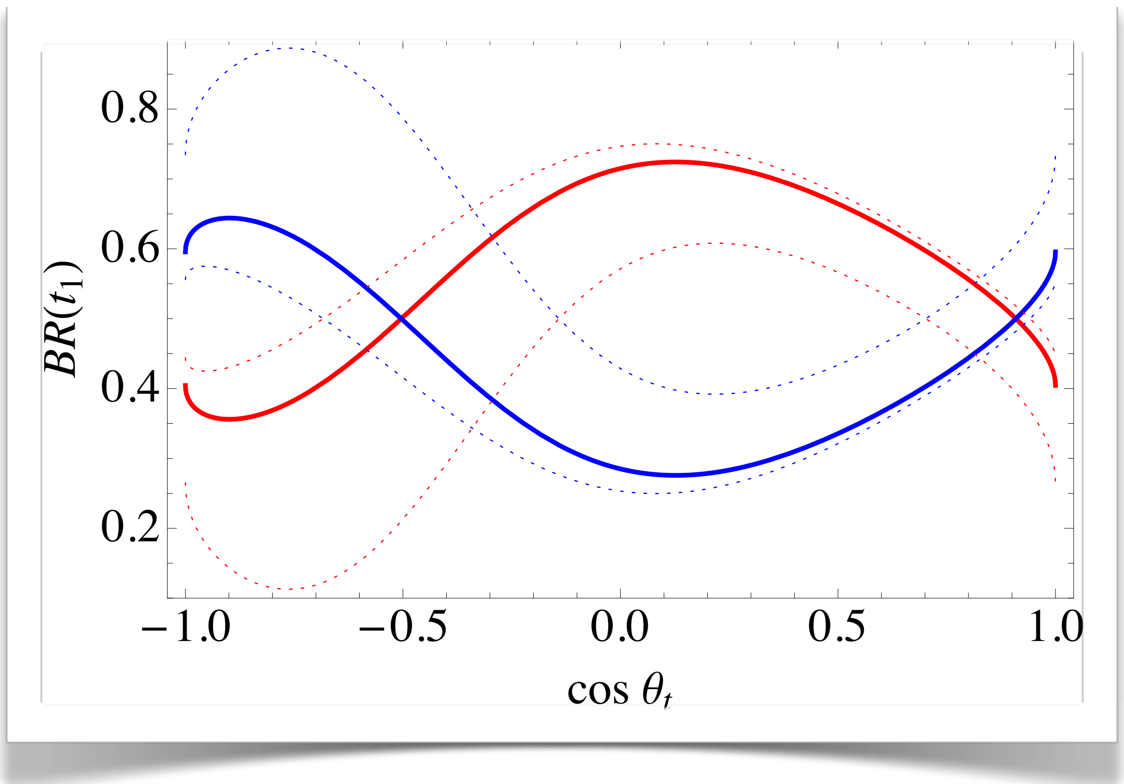
- ...but we are starting to have sensitivity



Searches with a natural SUSY spectrum

In a natural SUSY spectrum, mixed stop (sbottom) decays are generic:

- Charged and neutral branching fractions of squarks are similar
- Near-degenerate Higgsinos all appear as (mostly) MET



b

t

$\mu = 200$
$\tan\beta = 20$

right ⟵ left ⟶ right

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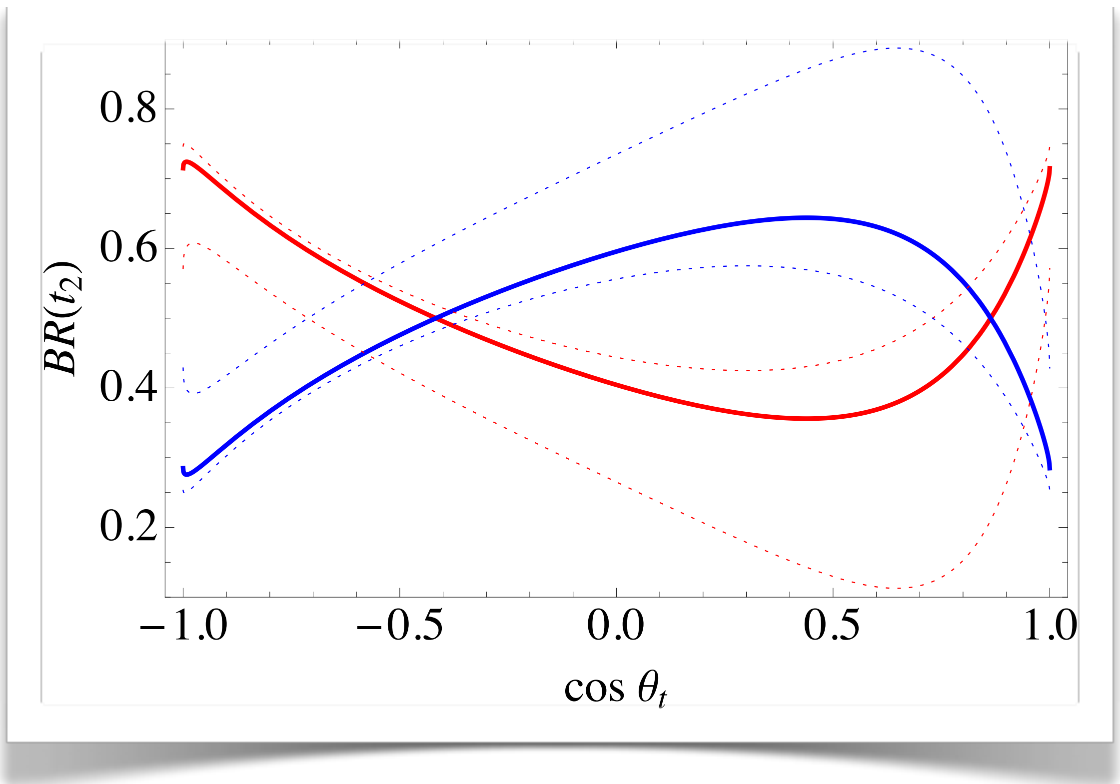

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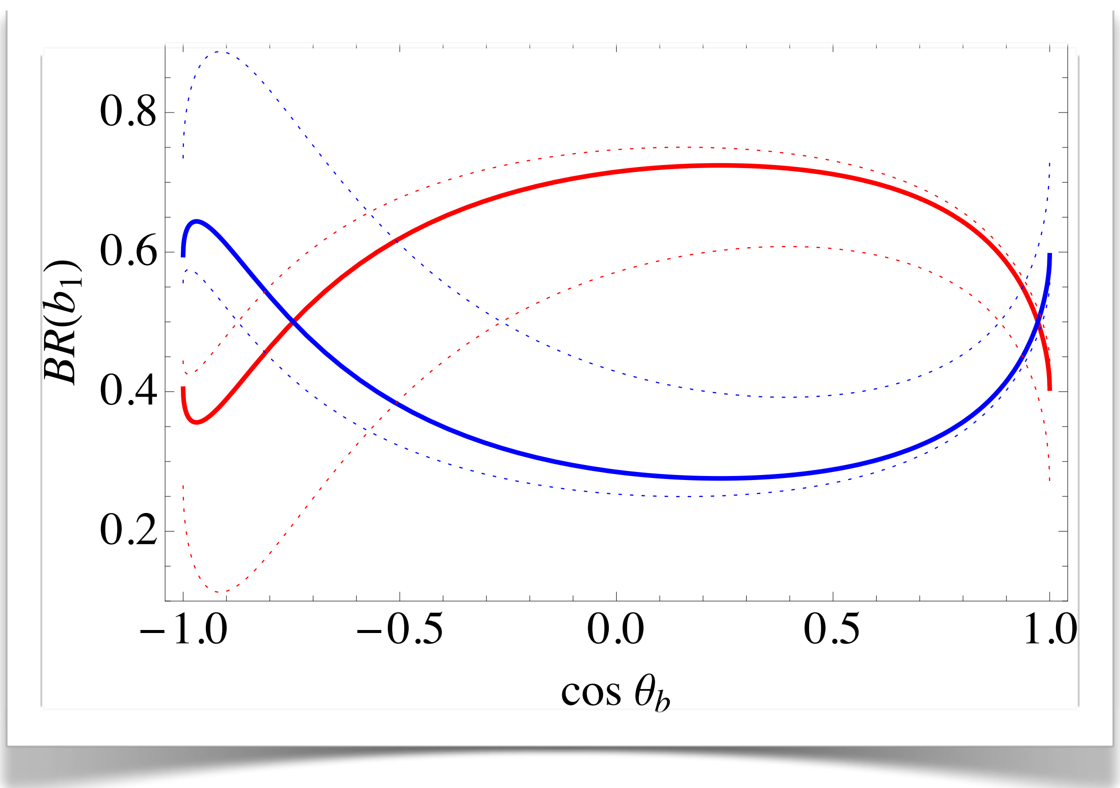

b

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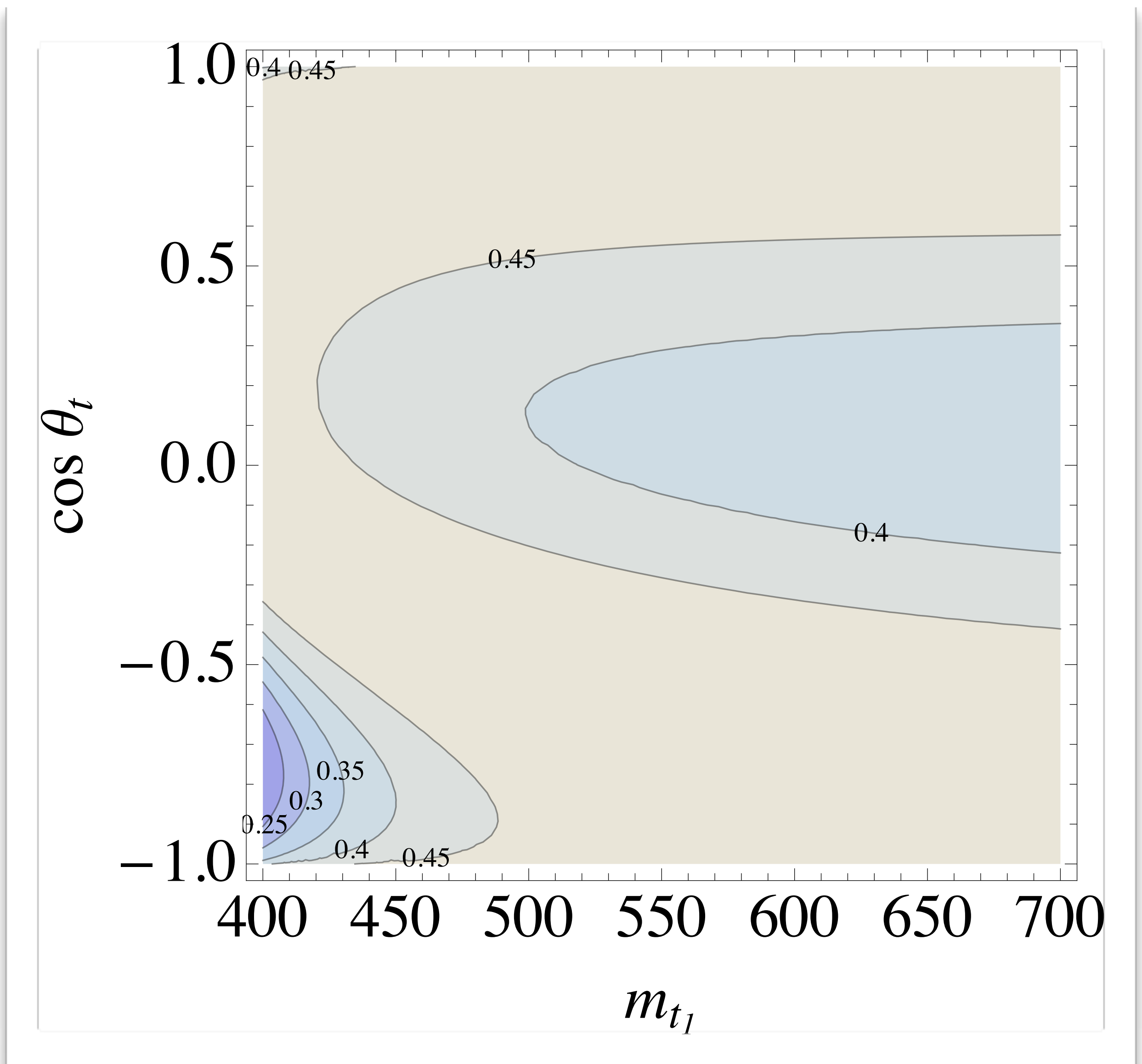
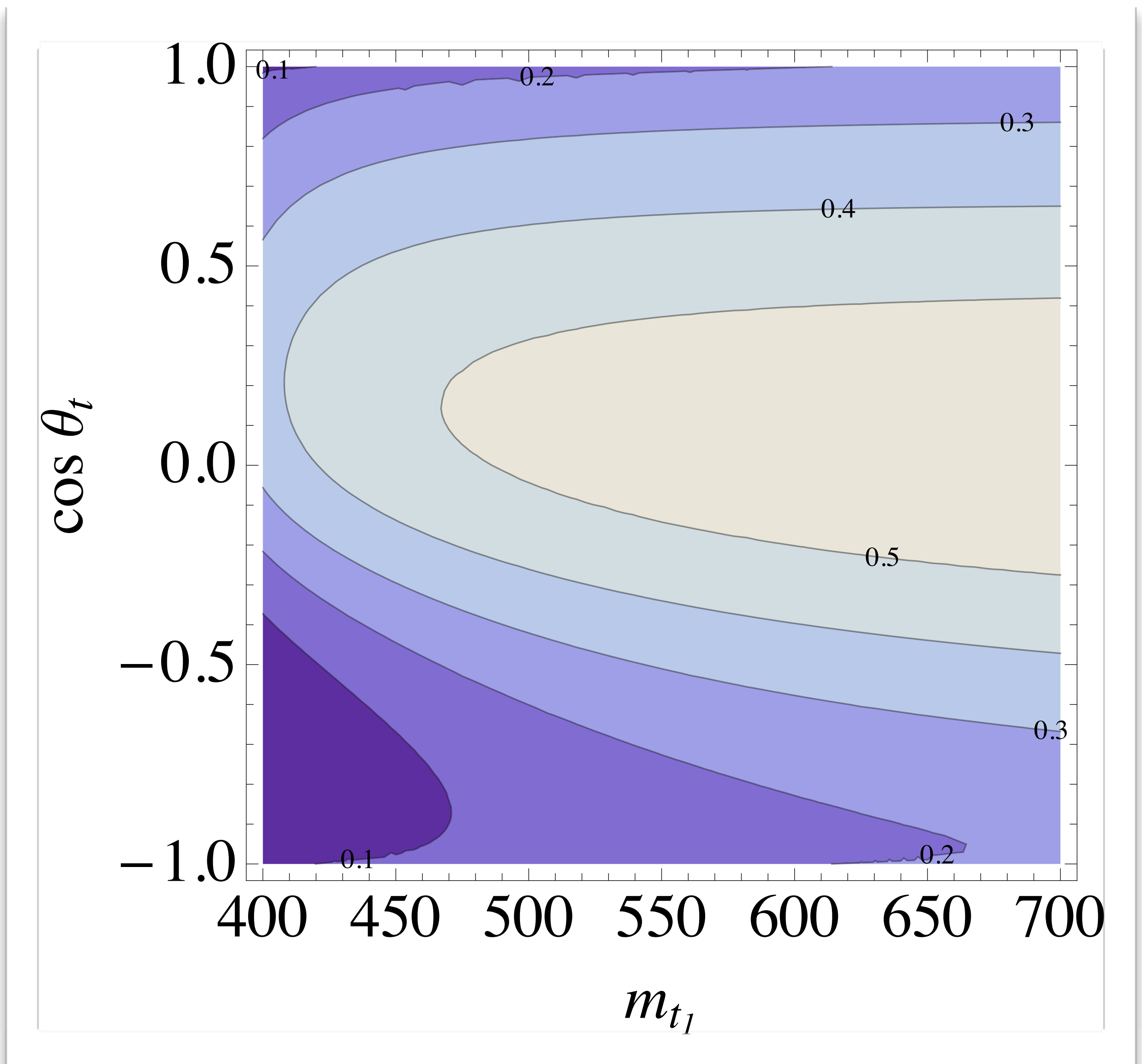
$$\Rightarrow t\, b + \not{E}_T$$

Rate into *tb+MET* final state

For one light stop



BR(tb+MET)



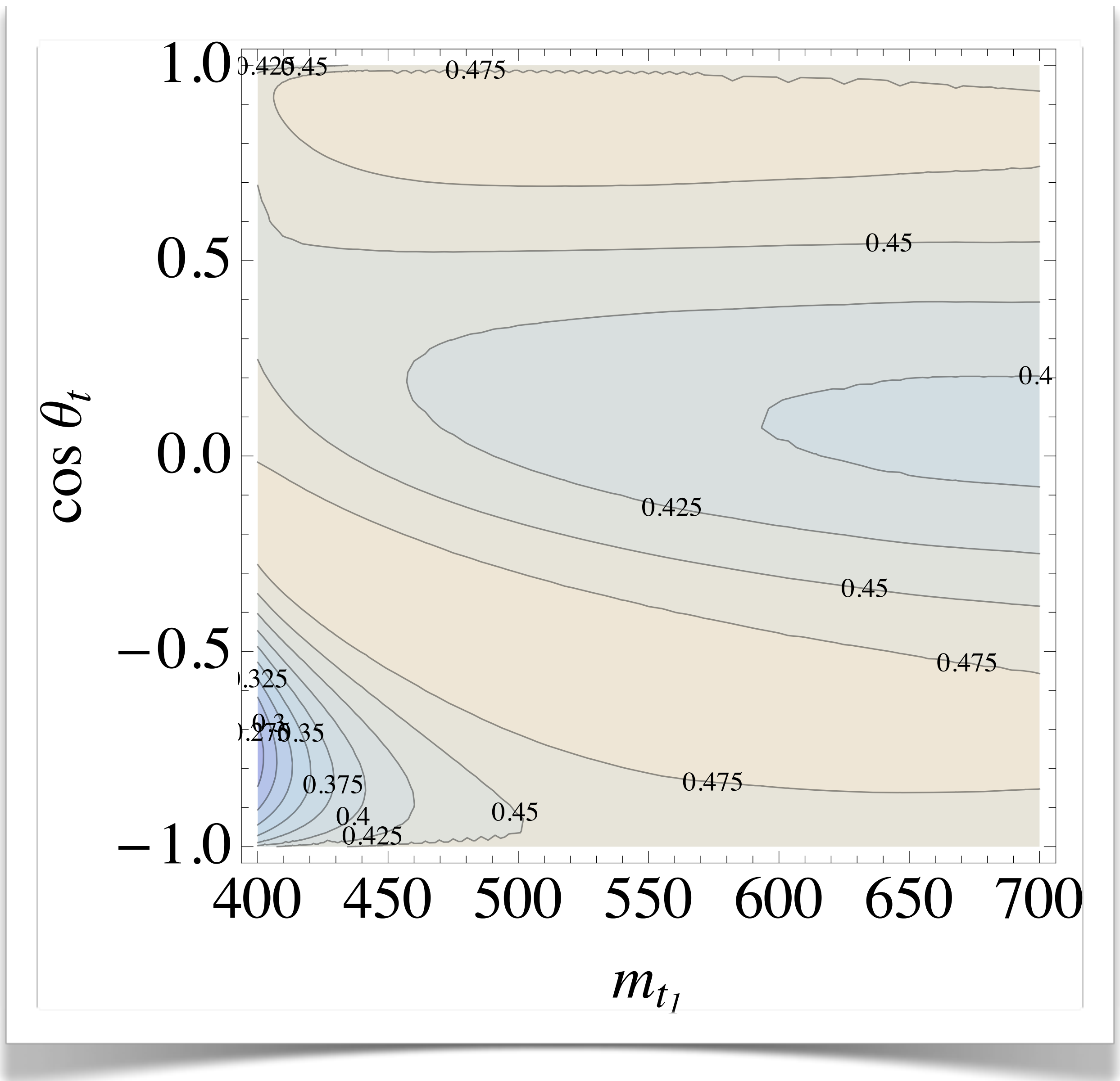
BR(tt+MET)

$\tan\beta = 20$

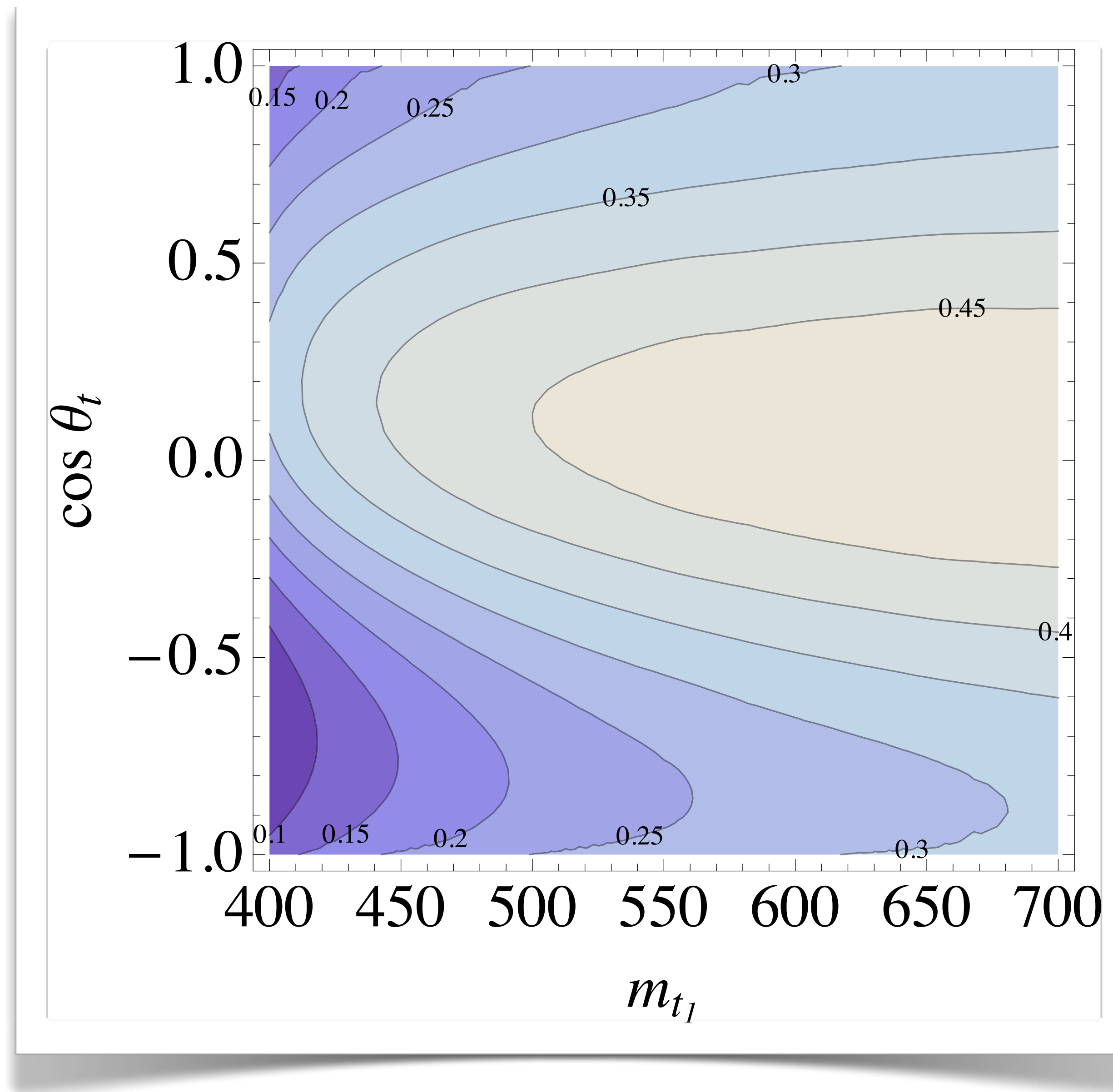
$m_\chi = 200\,\mathrm{GeV}$

Rate into *tb+MET* final state

For three light squarks ($\Delta m = 100\,\text{GeV}$)



BR(tb+MET)



BR(tt+MET)

$\tan\beta = 20$

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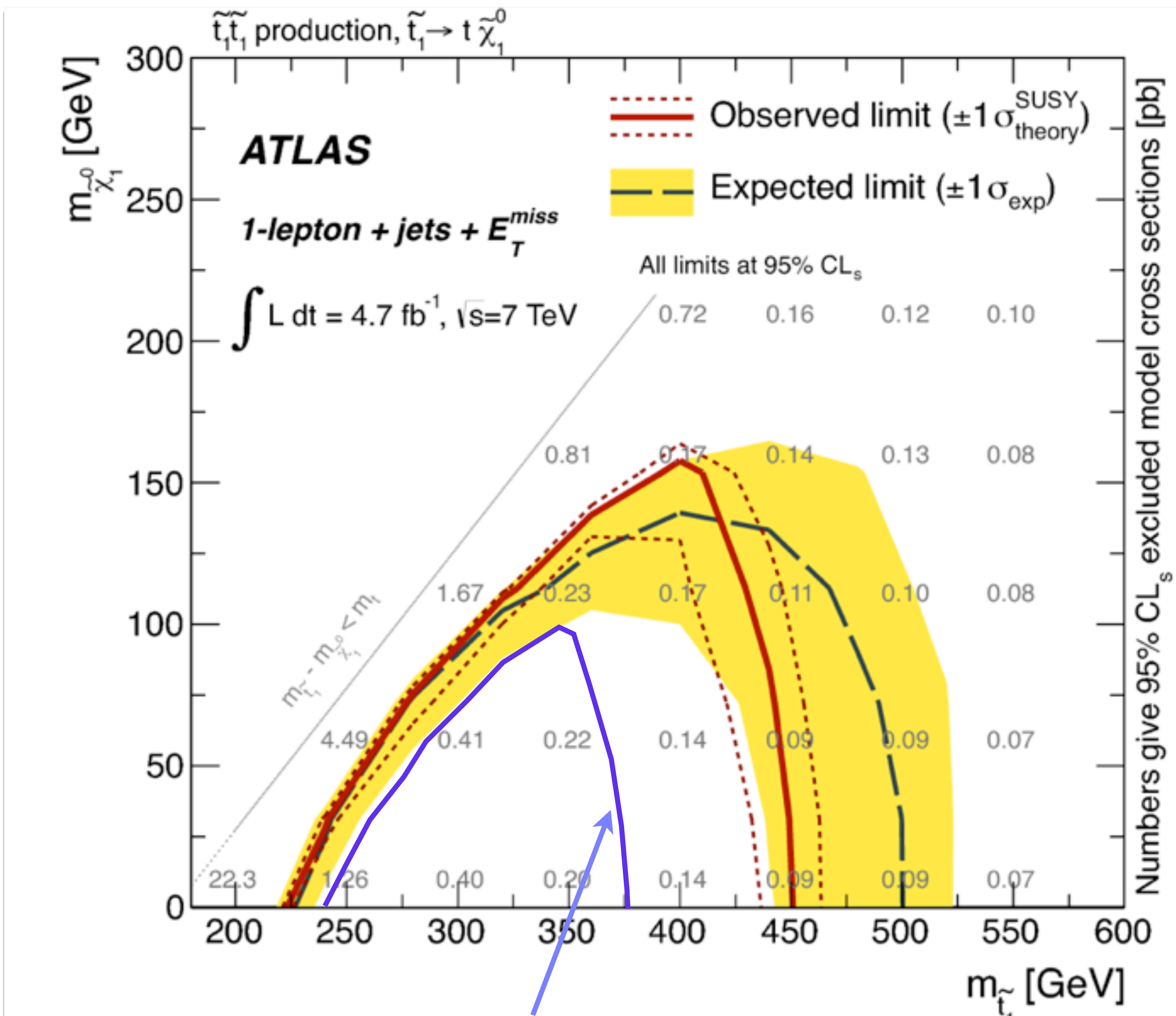
Limits from Direct Stop Searches

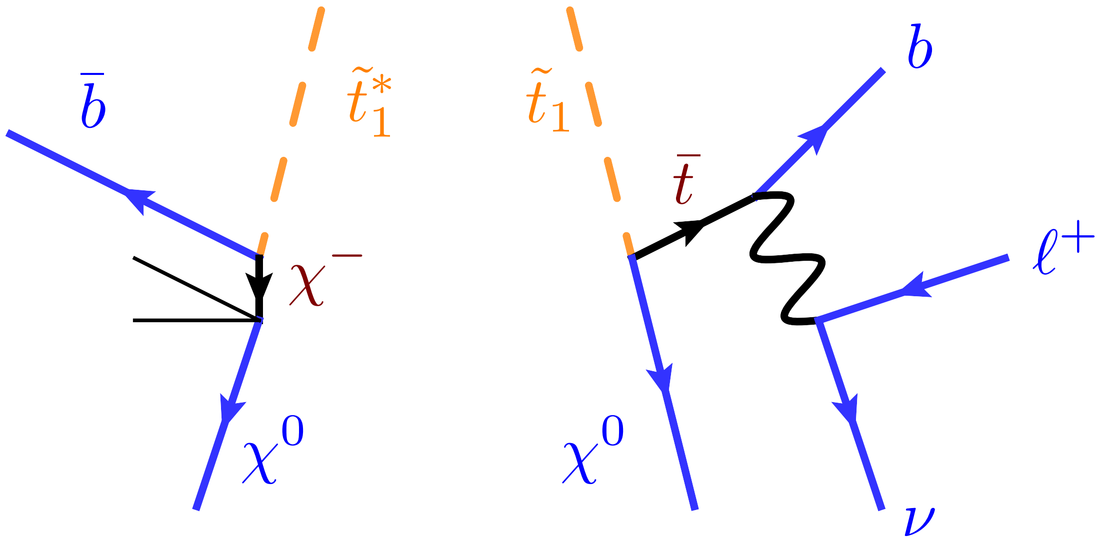


$BR(\tilde{t}_1\tilde{t}_1^* \to t\bar{t} + MET) = 0.5$

arXiv:1208.2590

Hunting asymmetric stops

Design a search targeting the mixed decay:



$$b\, b\, \ell + \not{E}_T$$

Backgrounds:

- W+jets
- top pair with one identified lepton
- single top

Will see: transverse mass $m_T(\ell, \not{E}_T)$ powerful tool to suppress any background where MET comes from single W

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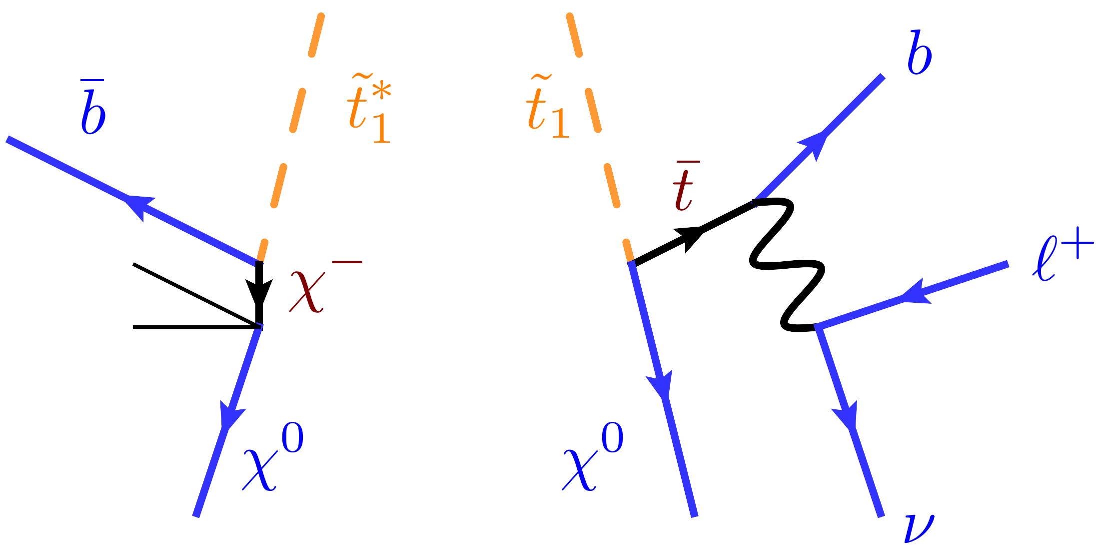


Backgrounds:

- W+jets
- top pair with one identified lepton
- single top

W+ 2 j (contrast semi-leptonic $t\bar{t} + \chi_1^0\chi_1^0$): require b-tag for additional suppression

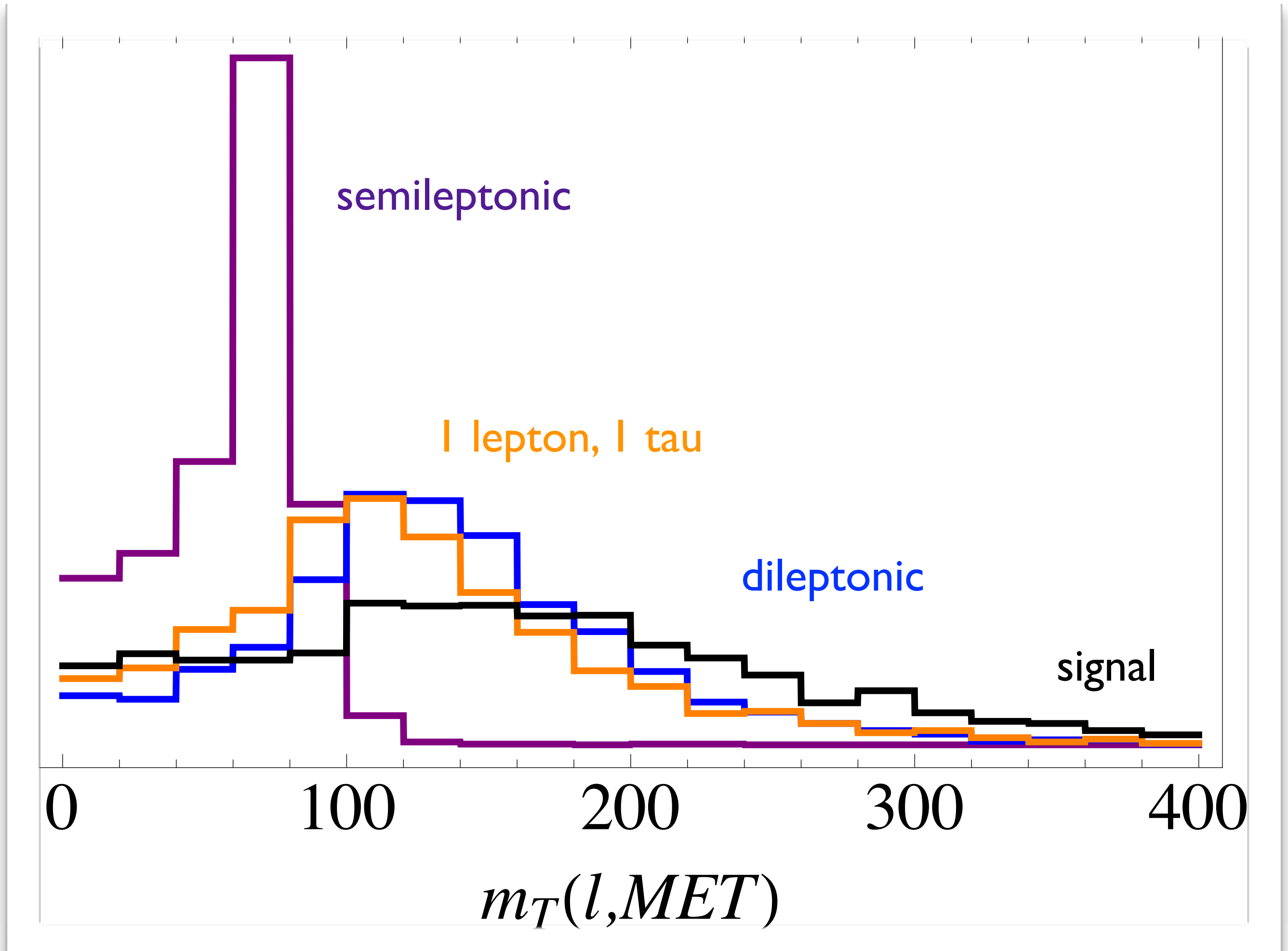
Will see: transverse mass $m_T(\ell, \not{E}_T)$ powerful tool to suppress any background where MET comes from single W

The fine print: event generation

- Events are generated in MadGraph, showered in Pythia, and clustered in FastJet using R=0.4 anti-k_T.
- B-tagging: apply flat 0.7 probability for *b*-jets with p_T>25 GeV, $|\eta| < 2.5$
- Lepton isolation criteria:
  - $p_{T,l} > 0.2 \sum p_{T,i}$ for particles within $R_{iso}= 0.2$
- Hadronic tau ID:
  - for hadronic taus with visible $p_T > 20$ GeV,
  - check isolation; criteria chosen to reproduce $\approx$50% tau efficiencies

Transverse mass cuts

Transverse mass cut removes semileptonic top background:



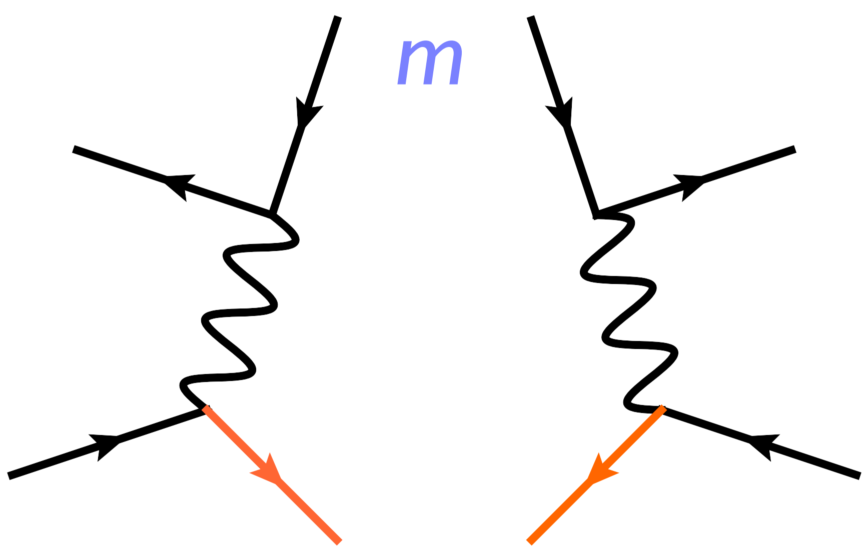
Unit-normalized transverse mass distributions

Dominant background: top with a missing lepton

Reducing dileptonic top background

- Top background has many kinematic handles: m_W, m_t
- M_{T2}: exploiting kinematic constraints in events with missing energy (Barr, Lester, Summers)
  - Since $m_T \leq m$,

$$m \geq [\max(M_{T,1}, M_{T,2})]$$



$\not{p}_{T1} + \not{p}_{T2} = \not{p}_T$

- M_{T2} : Minimum m consistent with kinematic constraints

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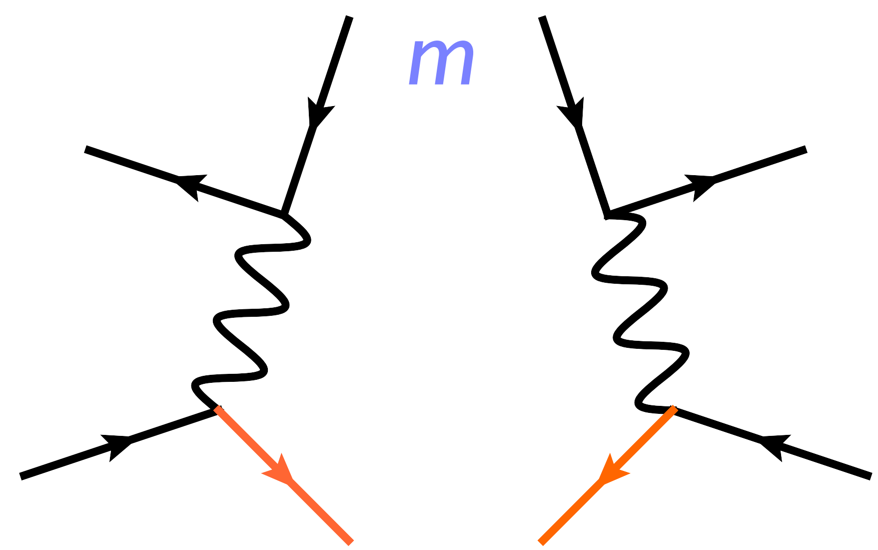

$$m \geq \min_{\not{\vec{p}}_{T1},\not{\vec{p}}_{T2}} [\max(M_{T,1}, M_{T,2})]$$

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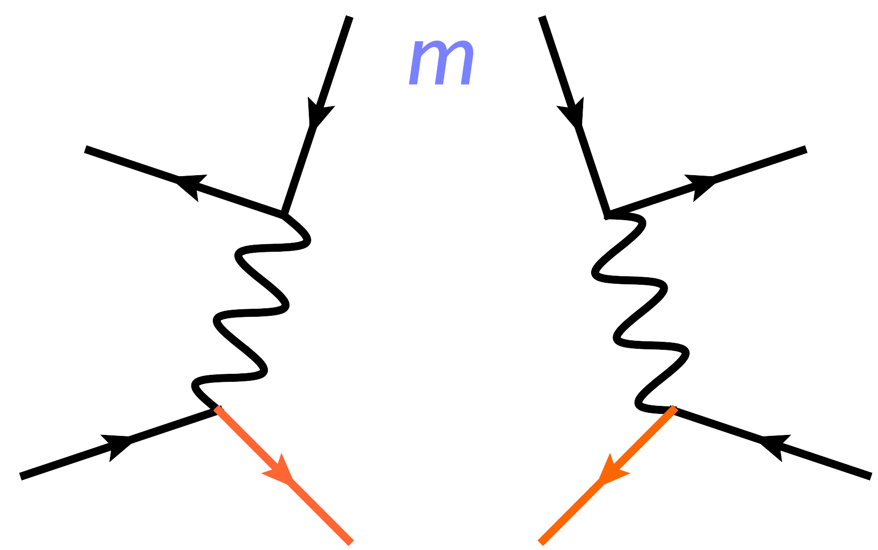


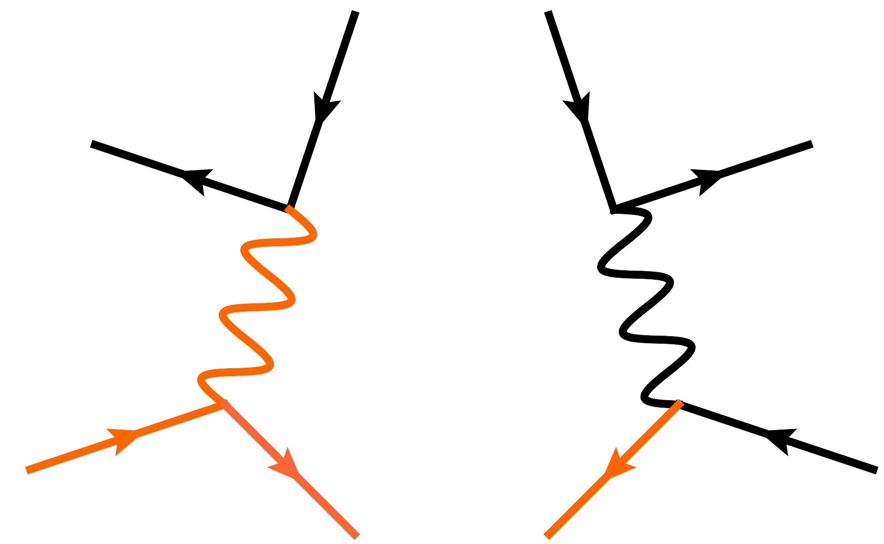
$$M_{T2} \equiv \min_{\not{p}_{T1},\not{p}_{T2}} [\max(M_{T,1}, M_{T,2})]$$

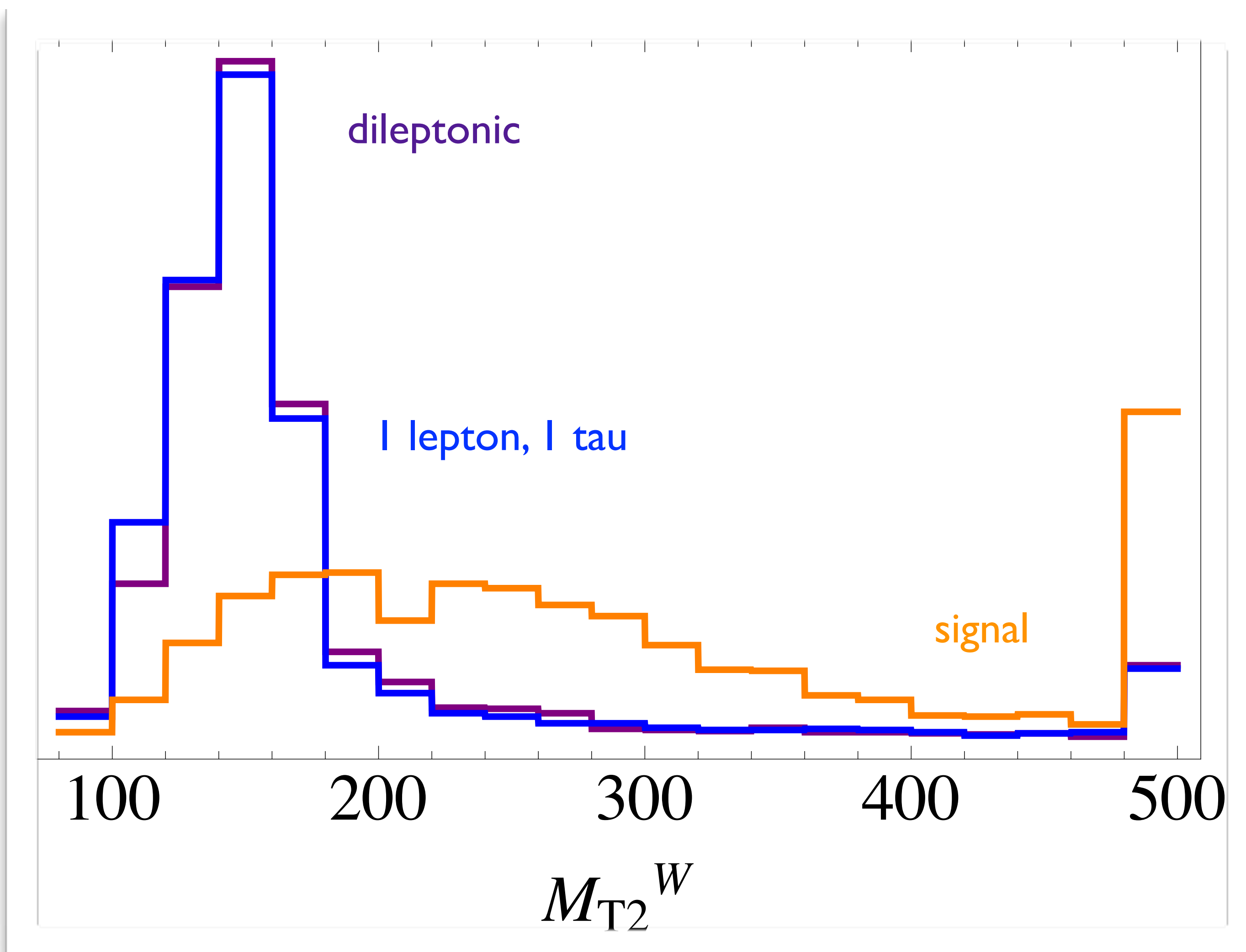
$$\not{p}_{T1} + \not{p}_{T2} = \not{p}_T$$

- M_{T2} : Minimum m consistent with kinematic constraints

Reducing dileptonic top background

- Natural generalization to backgrounds with a missed lepton:
  (Bai, Cheng, Gallicchio, Gu)
- $M_{T2}{}^{W}$: Minimum m consistent with asymmetric kinematic constraints



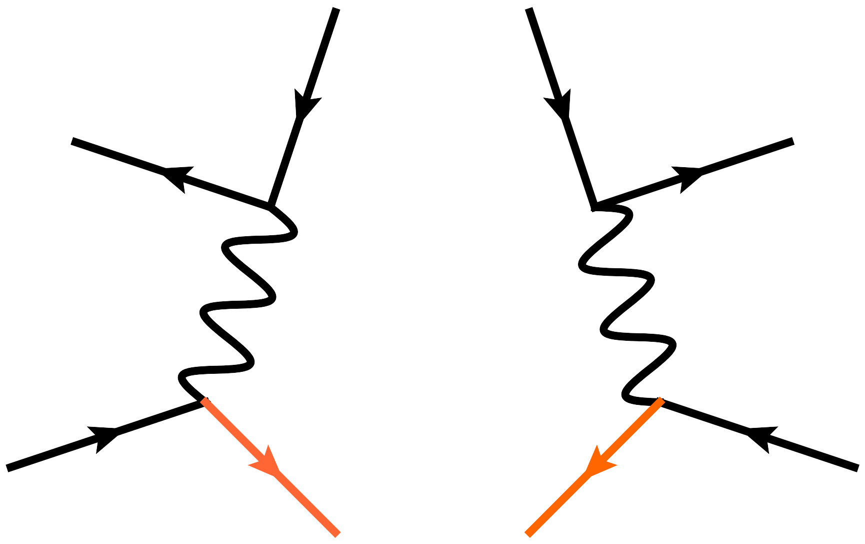


Unit normalized $M_{T2}{}^{W}$ distributions (500 GeV stops, 200 GeV higgsinos);

at least 1 *b*-tag; summed over combinatoric assignments and possible non-*b* jets

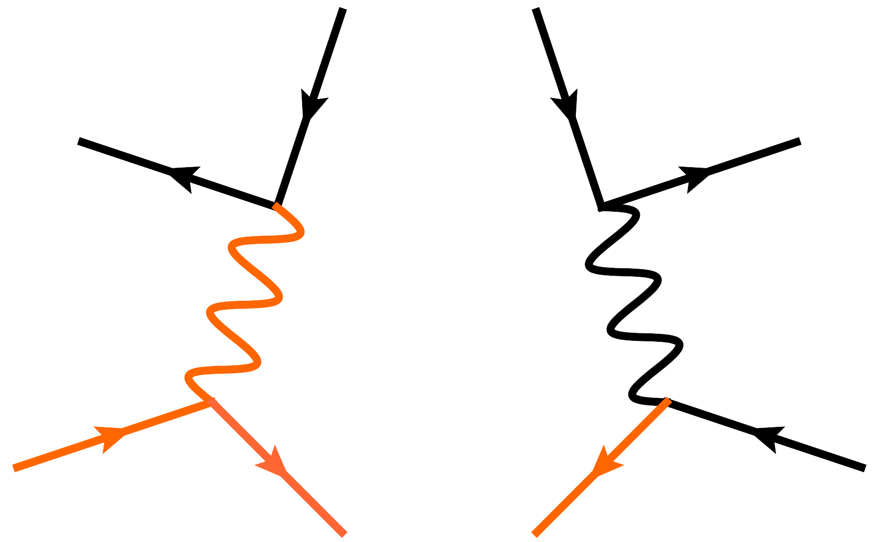
Thanks to tools made public by Bai, Cheng, Gallicchio, Gu

Reducing dileptonic top background



Dileptonic top: have enough mass shell constraints to completely reconstruct the event

Reducing dileptonic top background



Dileptonic top: have enough mass shell constraints to completely reconstruct the event

After losing a lepton, no longer true.

Can instead choose solutions that minimize $\sqrt{s}$

Quantifying "Topness"

- To implement, construct a function S that quantifies degree of departure from top hypothesis:

$$S(p_{\nu,z}, p_{W,x}, p_{W,y}, p_{W,z}) = \frac{(m_W^2 - (p_\ell + p_\nu)^2)^2}{a_W^4} + \frac{(m_t^2 - (p_\ell + p_\nu + p_{j_1})^2)^2}{a_t^4}$$

$$+ \frac{(m_t^2 - (p_W + p_{j_2})^2)^2}{a_t^4} + \frac{(4m_t^2 - (\sum p_i)^2)^2}{a_{CM}^4}$$

- Denominators set relative weight and should not exceed resolution:

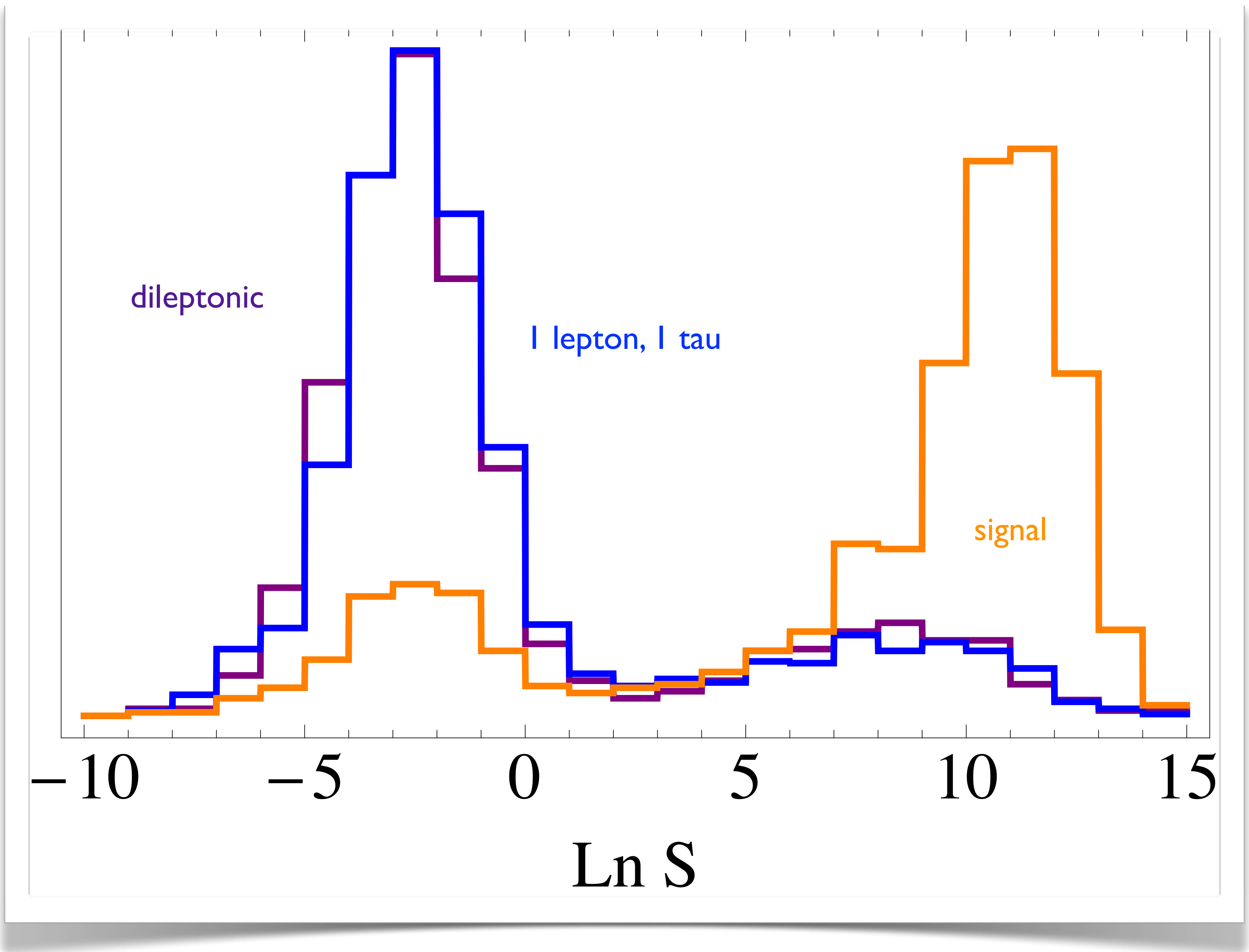
a_W =5 GeV $\quad$ a_t =15 GeV $\quad$ a_{CM} = TeV

- Again, sum over combinatoric assignments, jet possibilities...

Quantifying "Topness"

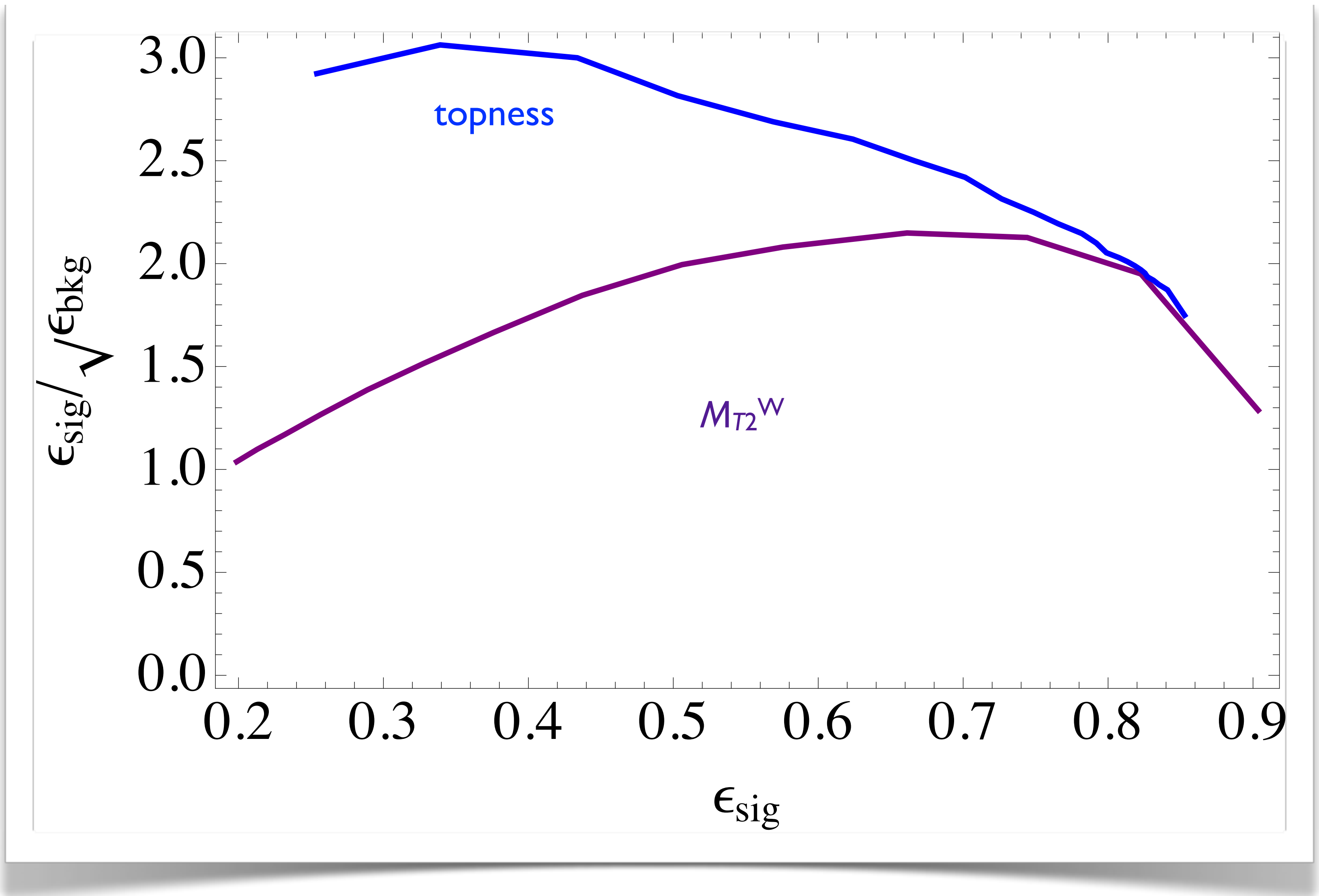
- Discriminating variable: Min S
- Finding global minimum is a nontrivial technical challenge
  - use 10 iterations of Nelder-Mead per event: trade-off between speed and reliability
  - This is generally not sufficient to find the global minimum
  - But: does finds minimum within our numerical tolerance of the global minimum: at worst, percent-like variation in *ln S*.

Quantifying "Topness"



Unit normalized distributions; 500 GeV stops, 200 GeV higgsinos

Relative Performance



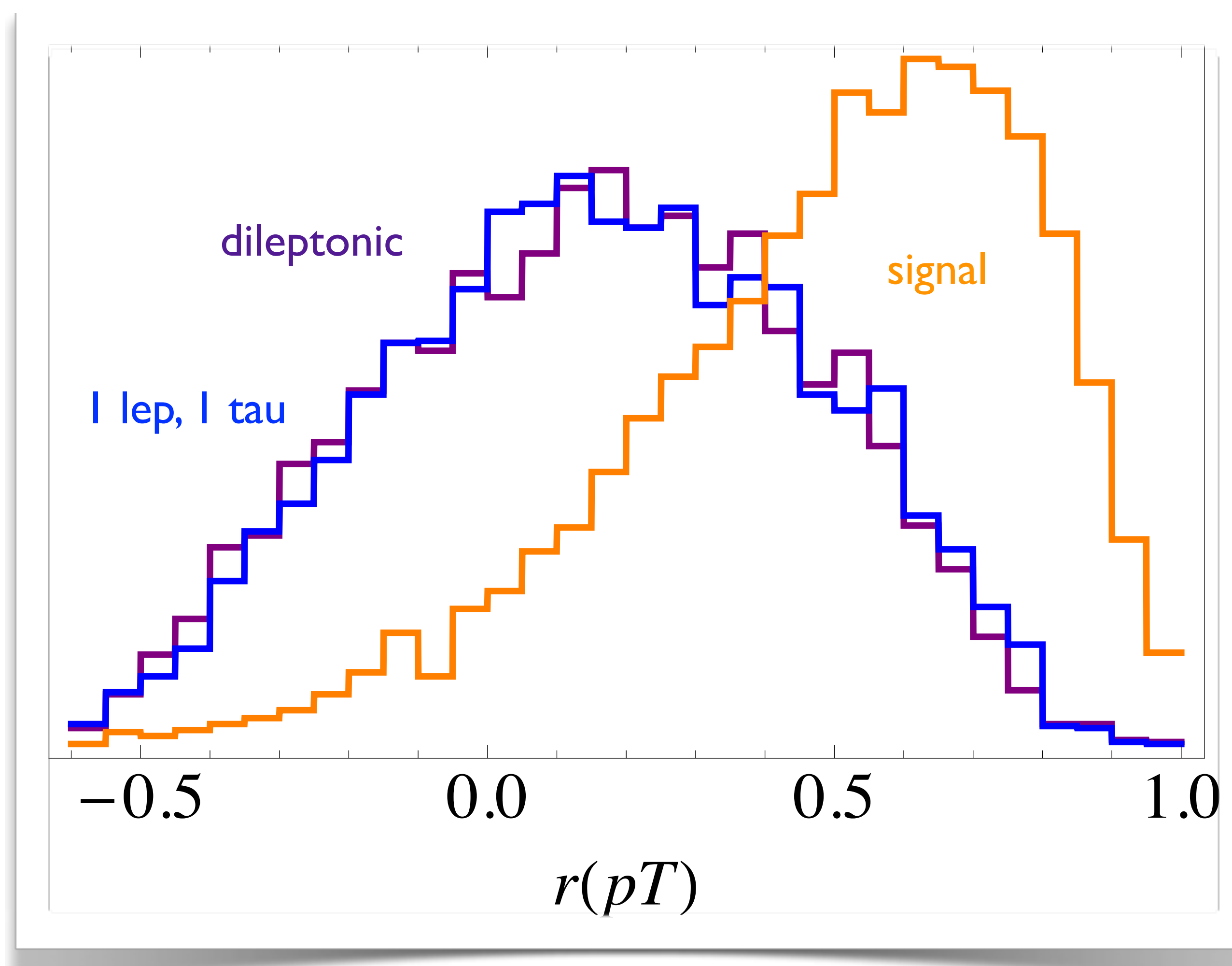
Proportional change in significance versus signal efficiency.

Event selection includes m_T cut and MET > 200 GeV.

Targeting asymmetric stop decays

- Other features of signal:
  - usual hardness cuts on jets, MET
  - asymmetric kinematics
- Difference in top and stop daughter p_T is a good discriminant:

$$r_{p_T} = \frac{p_{T,j_1} - p_{T,\ell}}{p_{T,j_1} + p_{T,\ell}}$$



Lepton vetoes

- ATLAS' stop search vetoes on soft leptons
  - may worry: do soft χ_2^0 , χ_1^+ decay products spoil this?
  - No. Kinematics ok:

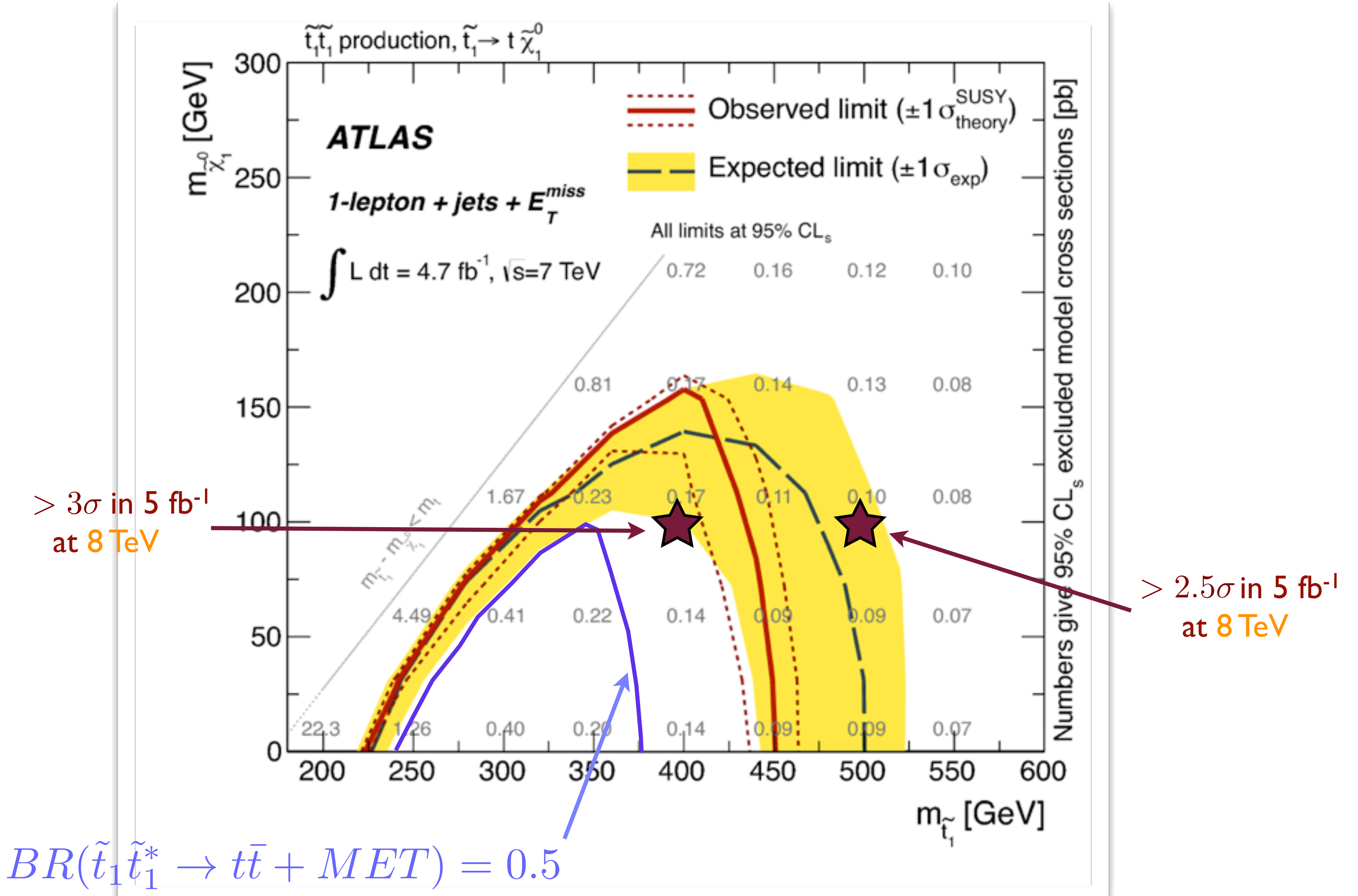
$$p_{T,soft} \sim p_{T,\chi^+} \times \frac{m_{\chi^+}^2 - m_{\chi^0}^2}{m_{\chi^+}^2}$$

  - Impose soft lepton vetoes at $p_{T,l} > 15$ GeV, $p_{T,tau} > 20$ GeV; do not consider more aggressive semi-isolated track veto used by ATLAS, which specifically targets 1-prong taus
  - reductions of 0.75 (dileptonic), 0.84 (one lepton, one tau) for (almost) no price in signal

Search reach in asymmetric stops

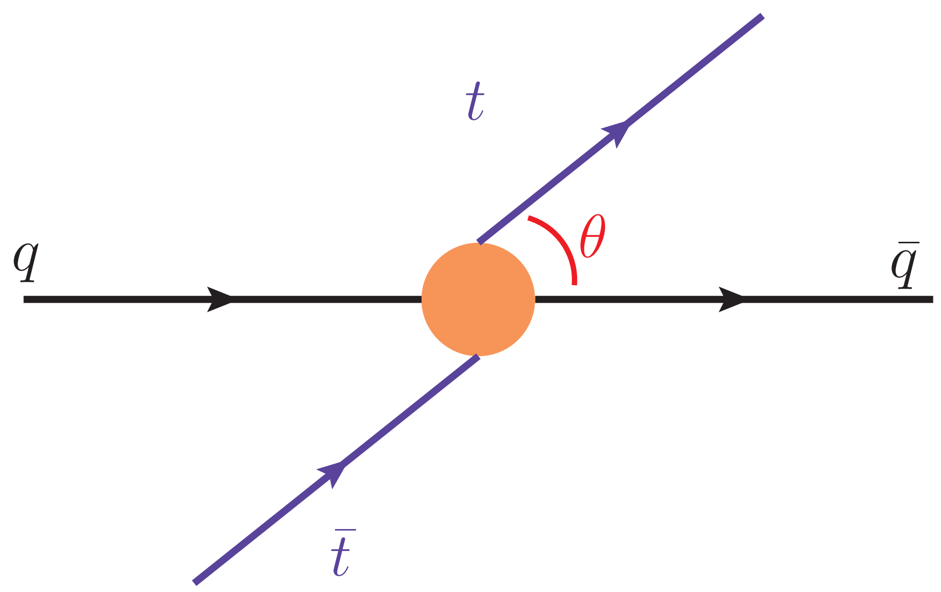
- Still work in progress. (Background statistics...)
- Low event rate: evaluate significance using Poisson
- As branching ratios to χ_1^0, χ_2^0 vary over parameter space, important that efficiencies for different neutralinos are nearly identical.
- Reach for 50% *BR* reference scenario looks broadly comparable to traditional $t\bar{t} + MET$ (with 50% *BR*)
    - caveat I: apples and oranges
    - caveat II: not a final statement...

Limits from Direct Stop Searches



II. Bottom up: the top forward-backward asymmetry

The Tevatron anomaly in A^t_{FB}



$$\mathcal{A}^t_{FB} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}$$

- QCD predicts a small but non-zero asymmetry in $q\bar{q} \to t\bar{t}$:
  - A^t_{FB} = 0.05$\pm$0.015 (Antunano, Kuhn, Rodrigo);
  - A^t_{FB} = 0.066$\pm$0.015 (Almeida, Sterman, Vogelsang)
- EW corrections increase the asymmetry by a factor ~ 1.5 (Hollik, Pagani; Kuhn, Rodrigo)

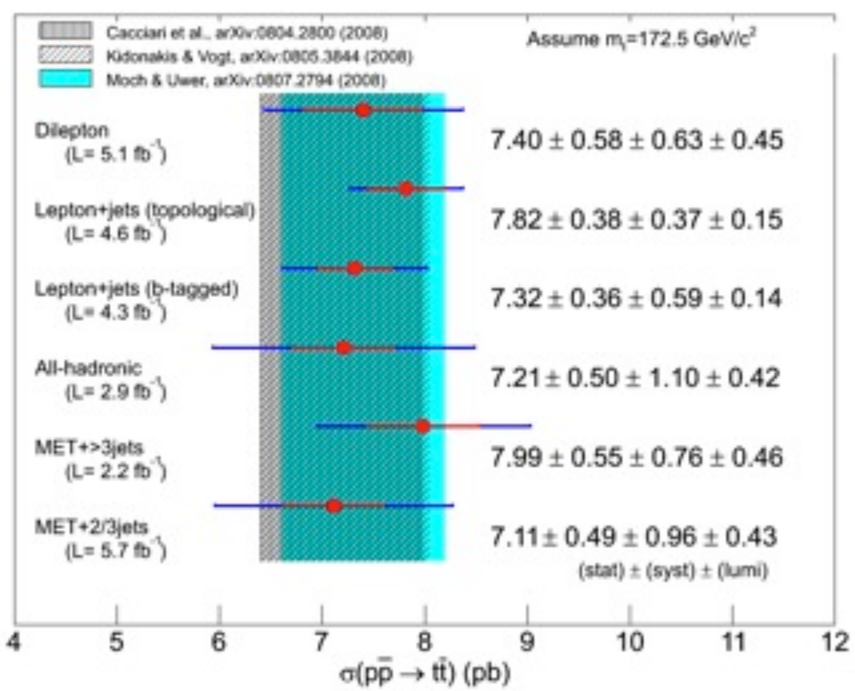
The Tevatron anomaly in A^t_{FB}

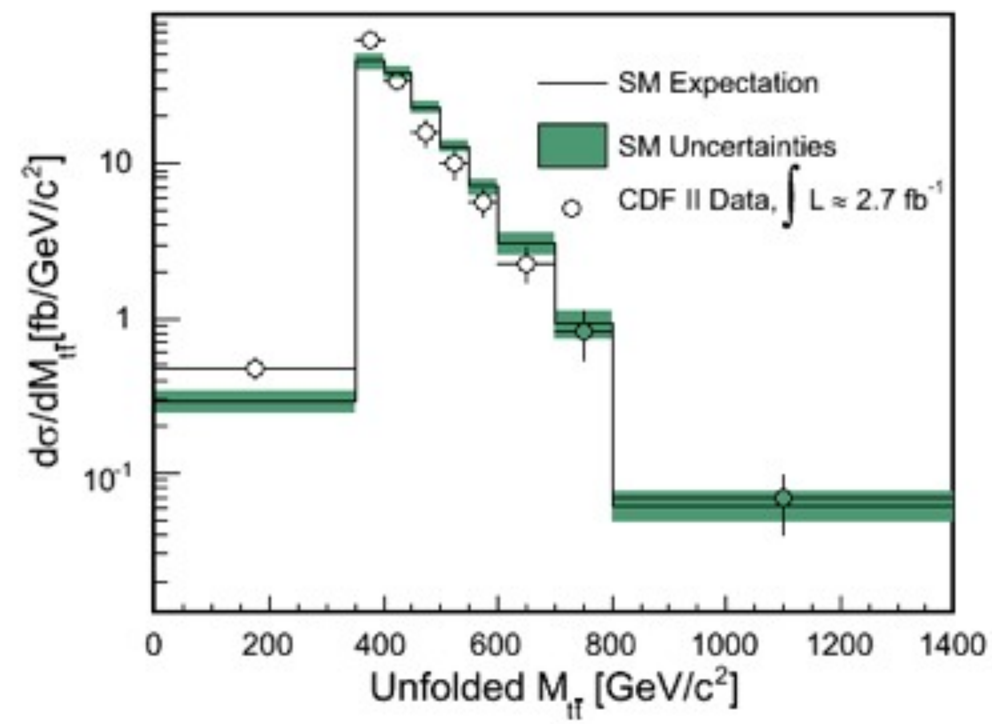
D0, CDF have consistently observed anomalously large values for A^t_{FB} at ~2 sigma level

- Current central values:
  - CDF: $A^t_{FB} = 0.162 \pm 0.041 \pm 0.022$ (production level)
  - D0: $A^t_{FB} = 0.196 \pm 0.065$ (production level)
- 3 sigma discrepancies in interesting subregions have mitigated with more data
  - CDF high mass: was 3.4 sigma (5 fb^{-1}), is now 2.9 sigma (full dataset)
  - D0 lepton: was 3.3 sigma (5 fb^{-1}), is now 2.2 sigma (with dileptonic and EW SM)

New physics for A^t_{FB}

- Model-building tightly constrained by excellent agreement of other top properties with SM predictions...





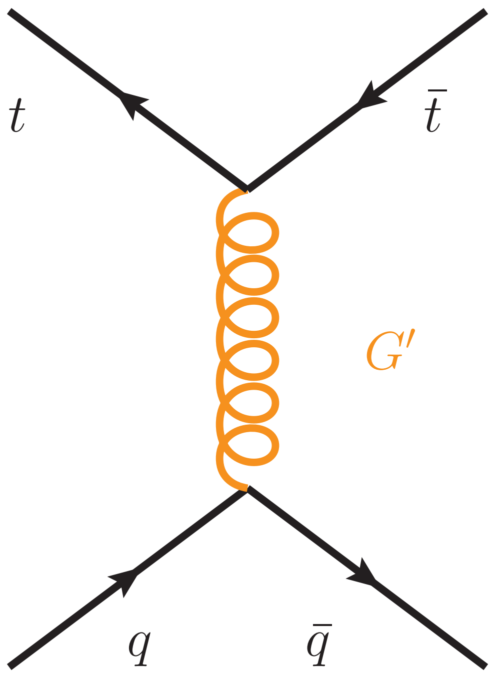
- ...and by lack of signals at LHC
- Surviving models must hide by invoking additional hadronic or invisible decay modes for the BSM particles (Tavares, Schmaltz; Drobnak et al.)

Light broad axigluons

- Axigluons can interfere with SM tree amplitude to generate asymmetry

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}\mathcal{M}_{SM}\mathcal{M}^*_{NP} + |\mathcal{M}_{NP}|^2$$

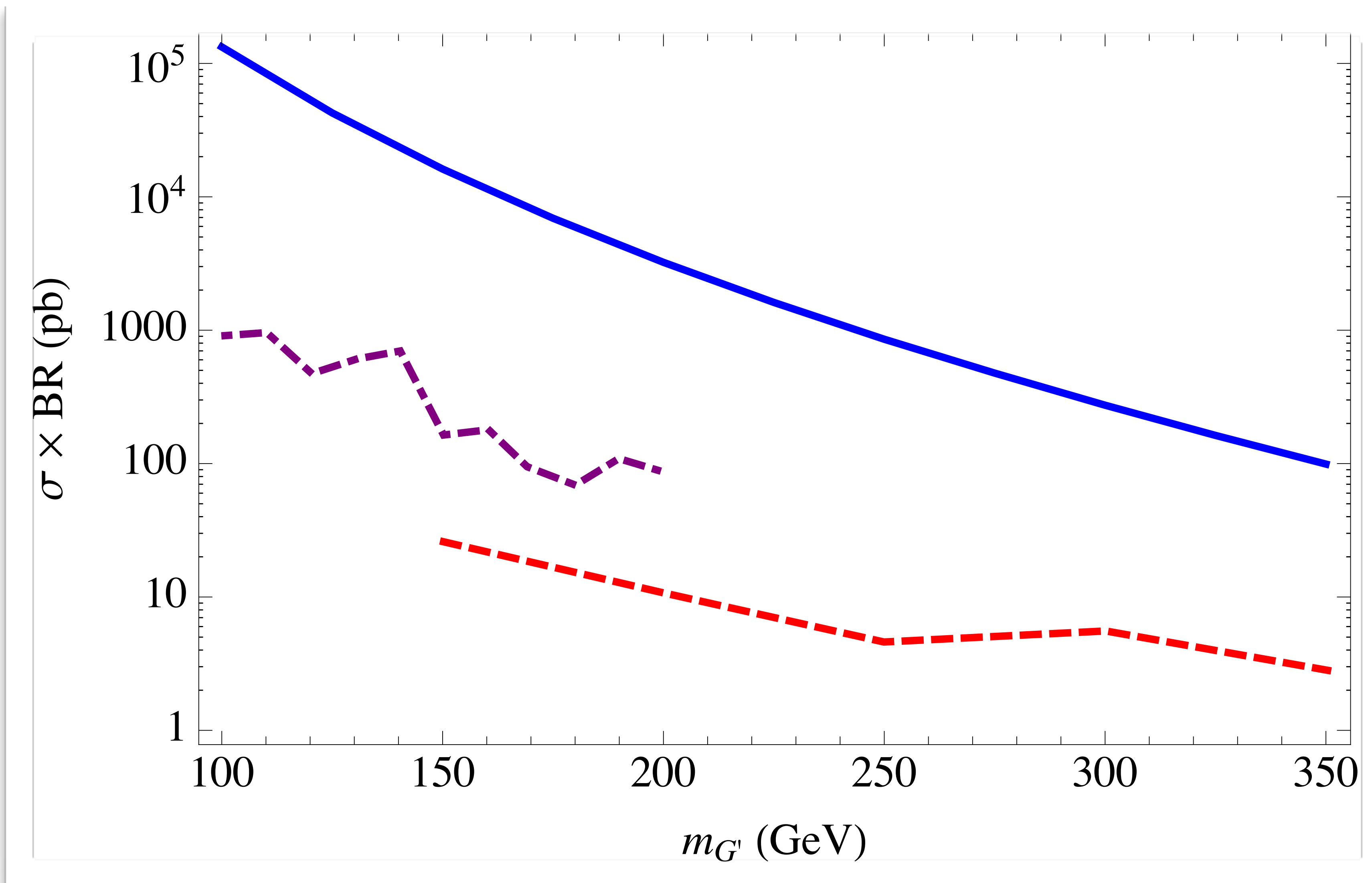
  - Sign of asymmetry: $\propto -\frac{g_A^{u,d} g_A^t}{m_{G'}^2 - \hat{s}}$
  - Light axigluons: ameliorate flavor constraints, tension with cross-section



(Frampton, Shu, Wang; Bai, Hewett, Kaplan, Rizzo; Tavares, Schmaltz; Krnjaic)

Light broad axigluons

...but must add additional new degrees of freedom as natural decay modes are conclusively excluded: (Tavares, Schmaltz)



(Rescaled) limits on octet vectors from ATLAS paired dijet searches

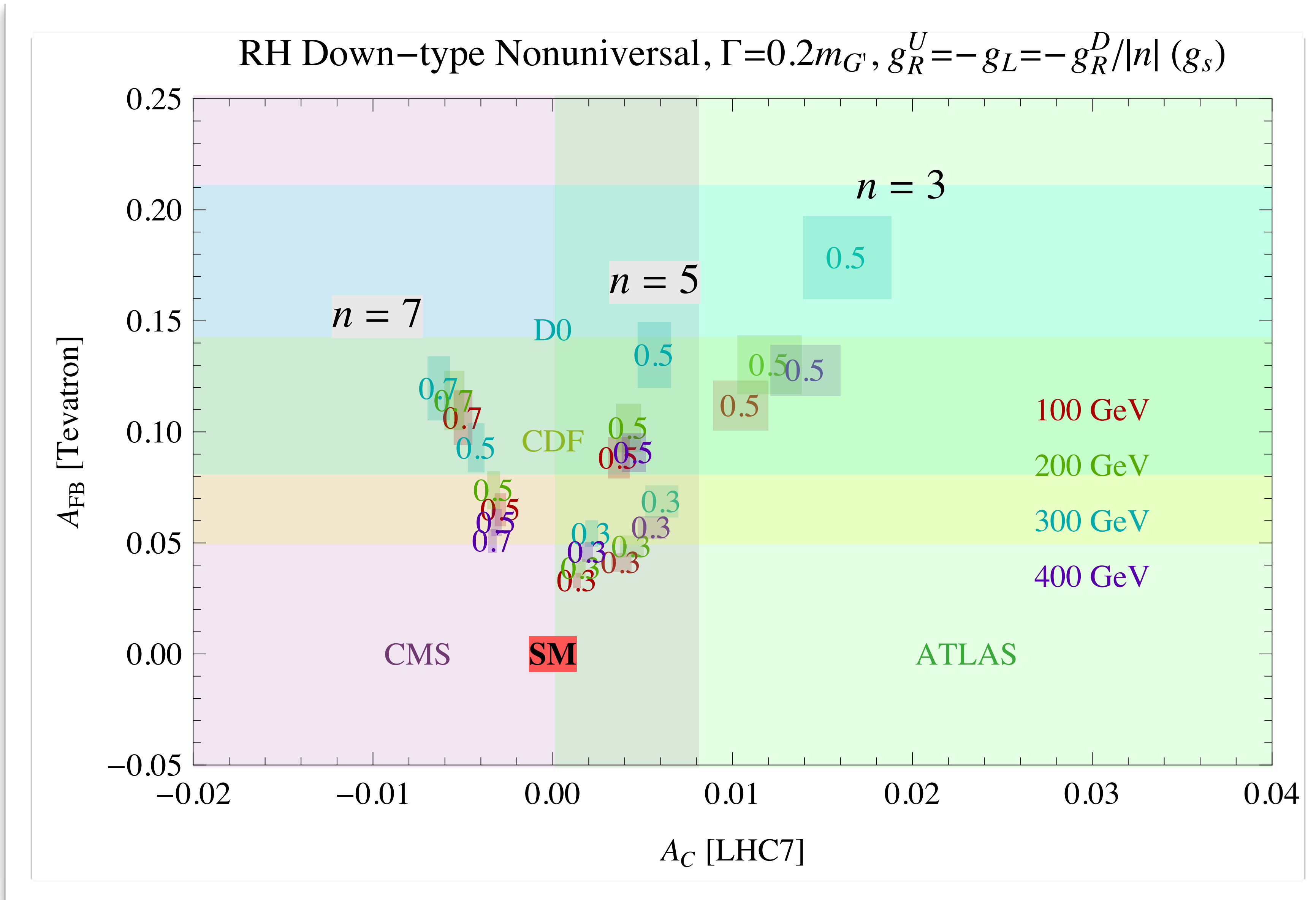
Indirect constraints on light broad axigluons

- Hunting for a broad multi-jet excess at hadron colliders is hard (but see Gross, Tavares, Spethmann, Schmaltz)
- Indirect constraints may have first conclusive word
  - A_{FC} at LHC
  - Precision electroweak is dependent on UV completion, but minimal model of SSB makes definite predictions (in progress)
- Three flavor structures of interest:
  - universal
  - down-type non-universal: win with A_{FC}, lose with PEW
  - top-type non-universal: win with PEW, lose with A_{FC}

LHC A_{FC} from light axigluons

Tevatron versus LHC charge asymmetries

LHC A_{FC} from light axigluons



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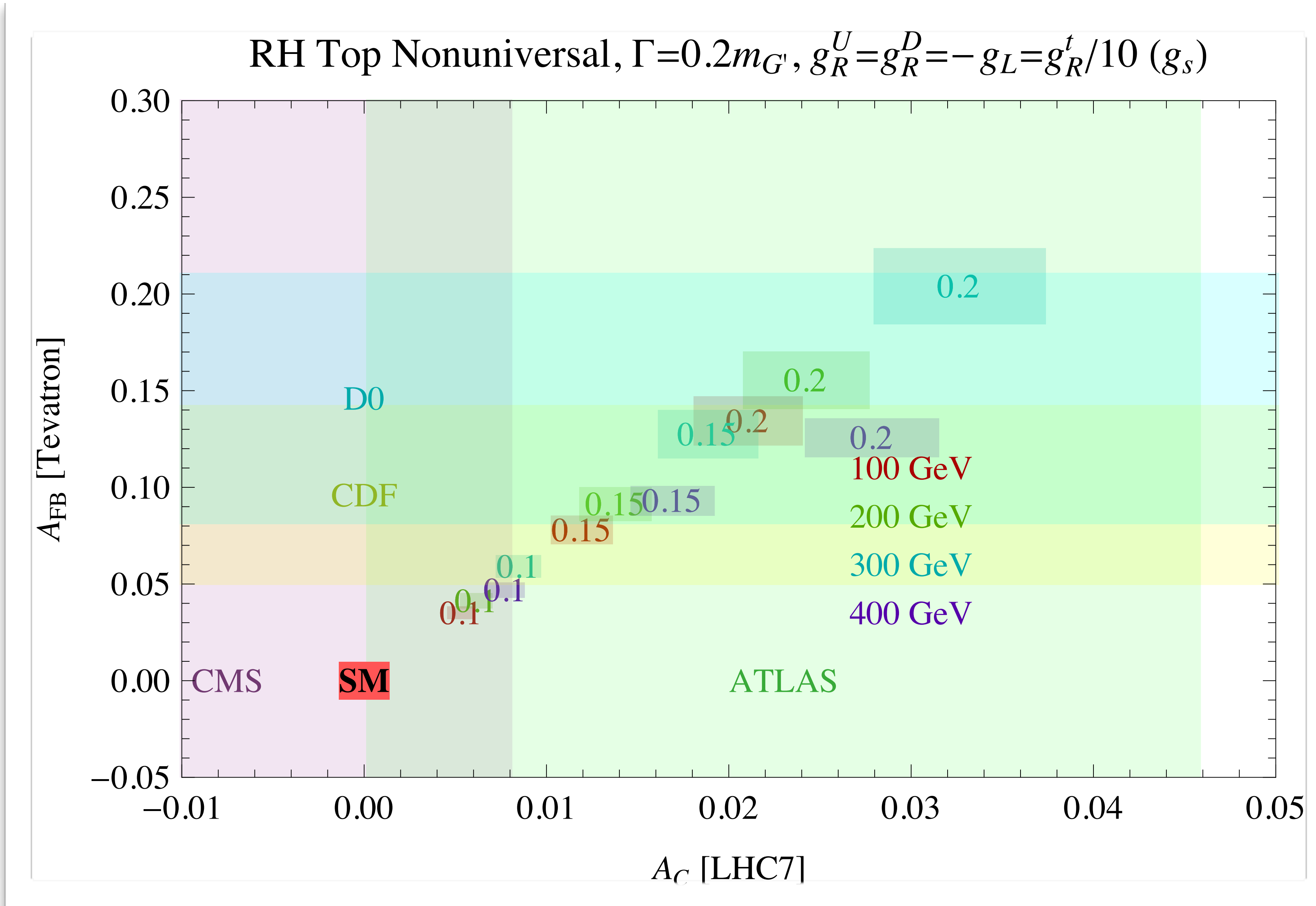

Tevatron versus LHC charge asymmetries

Summary of constraints

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Precision EW constraints

- Most stringent constraints come from corrections to *Z-q-q* vertex: axigluon loop increases g_Z^q (see also: Haisch, Westhoff)

- But for light axigluons, must have additional matter to achieve phenomenologically acceptable couplings (Dobrescu, Kong, Mahbubahni; Cvetic, Halverson, Langacker; Gross, Tavares, Spethmann, Schmaltz)

  - Minimal UV completion $SU(3)_1 \times SU(3)_2 \to SU(3)_c$

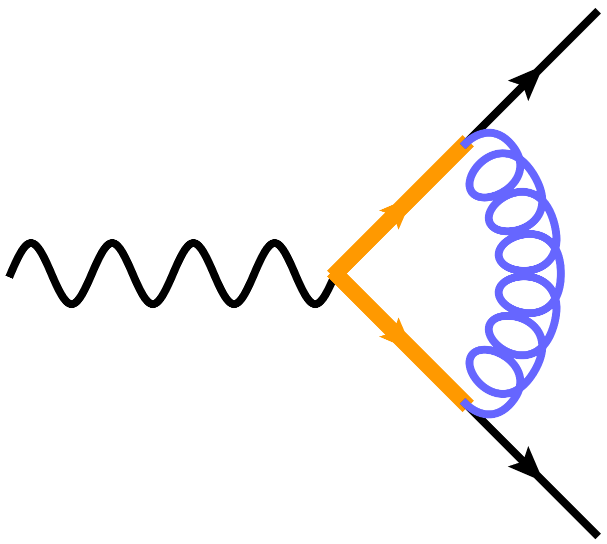
  - Quark embeddings? Possible minimal embeddings give

$$g_s \tan\theta \qquad\qquad -g_s \cot\theta$$

  - To get both $g_{L,R} < g_s$ and $g_R \neq g_L$, require mixing with new heavy quarks

Precision EW constraints

- Additional contributions to Z-q-q vertex from minimal UV completion:

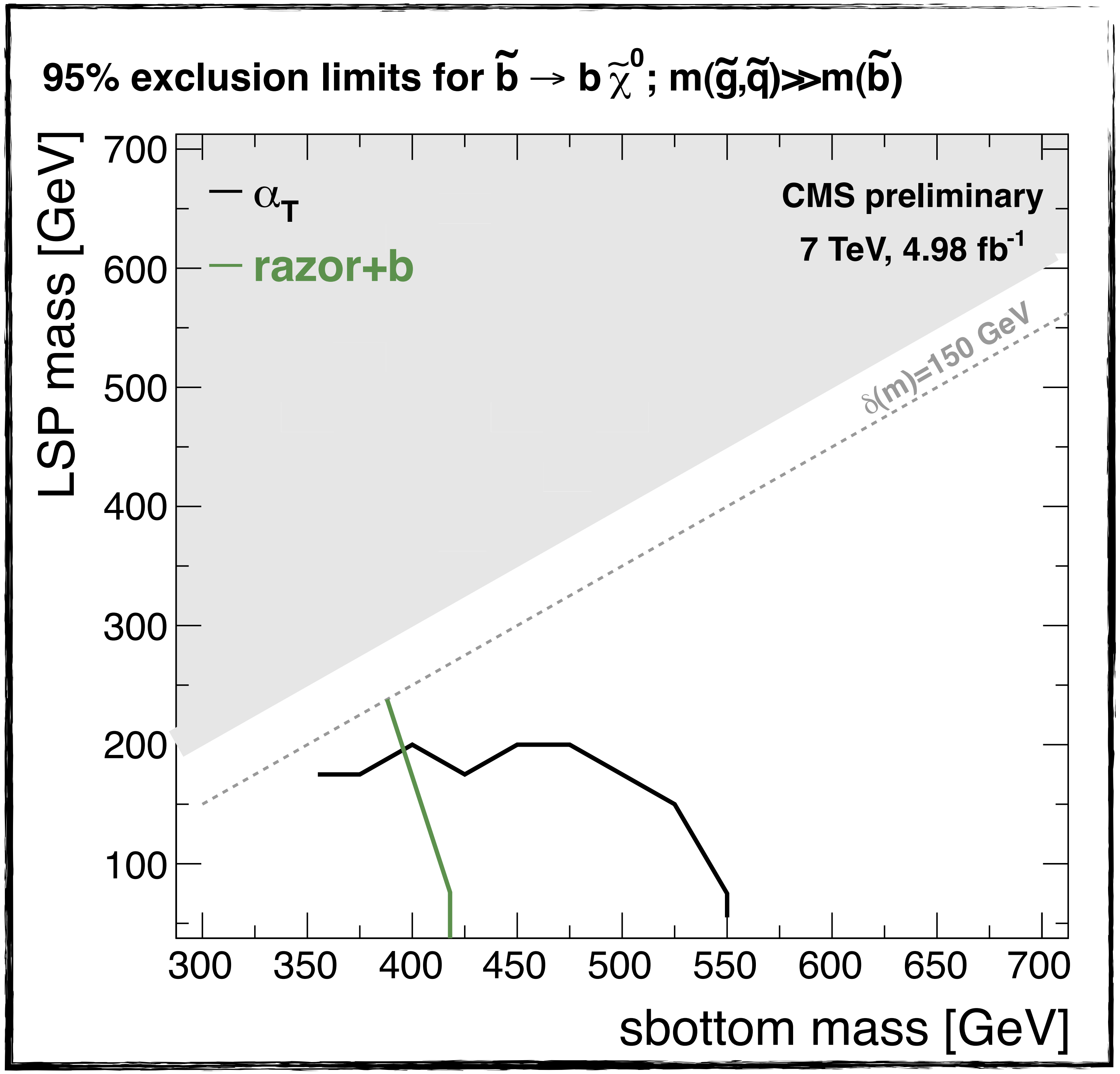


- Quark couplings to axigluon fix all parameters but m_f
- in progress!

Conclusions

- LHC fulfilling its promise as top factory
- Asymmetric stop decay signature is generic product of modular natural SUSY spectrum
  - targeted searches can recover sensitivity to light stops in scenarios with mixed decays
- New, generally applicable technique for suppressing dileptonic top background to lepton + *MET*+ jets searches
- Discussed evolving status of top A^t_{FB} and advertised future results on surviving parameter space for light, hidden axigluons

Backup: *bb+MET*



Probing interesting mass range, but pairwise BRs are small