Electroweak Baryogenesis and Supersymmetry

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TRIUMF

with

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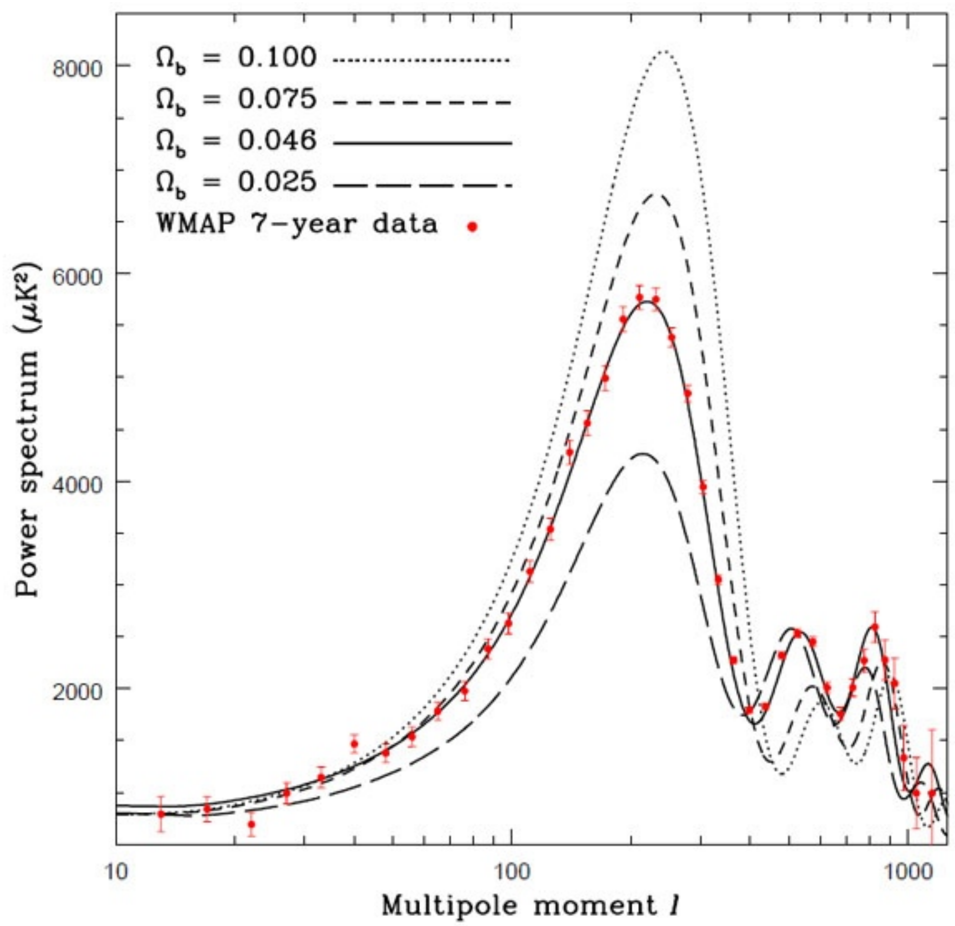
Baryons > Antibaryons

$$\Omega_B = 0.0486 \pm 0.0011$$

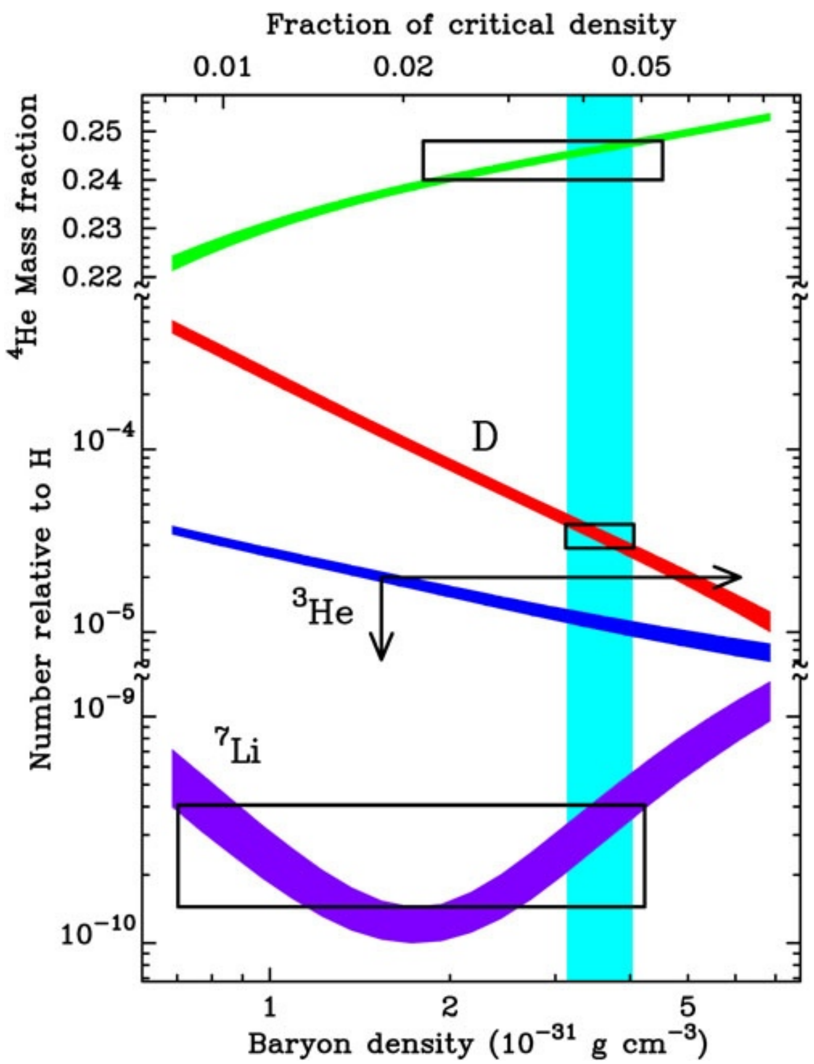
$$\eta \equiv \frac{n_B}{n_\gamma} \simeq (7.04)\frac{n_B}{s} \simeq 6.1 \times 10^{-10}$$

CMB



[Garrett+Duda '10]

BBN



[Cyburt *et al.* '97]

Baryogenesis Ingredients [Sakharov '67]

1. Baryon Number Violation
2. C and CP Violation
3. Departure from Equilibrium

Ingredients are not enough:

$+$

$\neq$

A mechanism for baryogenesis is needed.

Electroweak Baryogenesis

[Kuzmin, Rubakov, Shaposhnikov ’87]

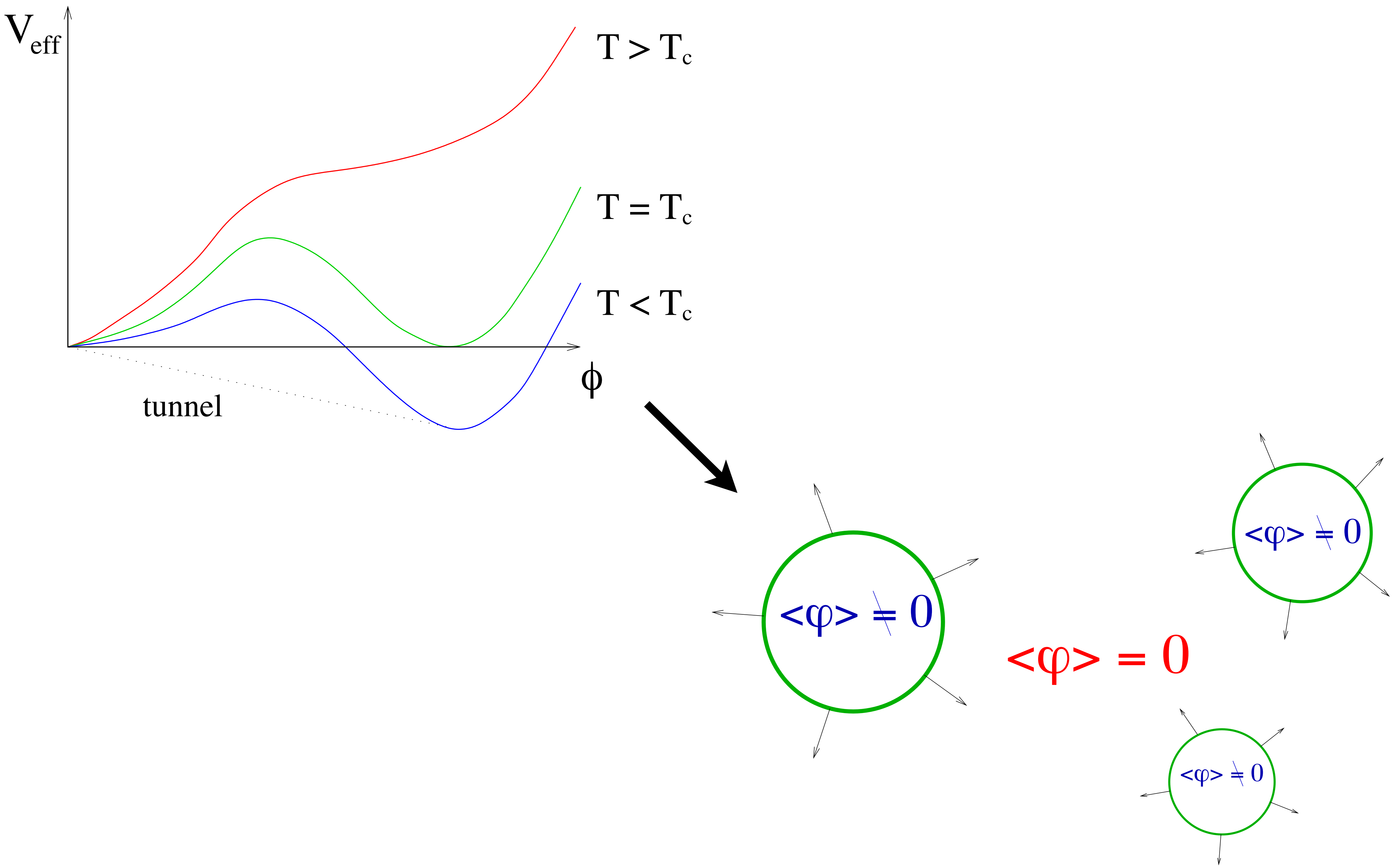
[Cohen, Kaplan, Nelson ’90-’95]

Three Steps:

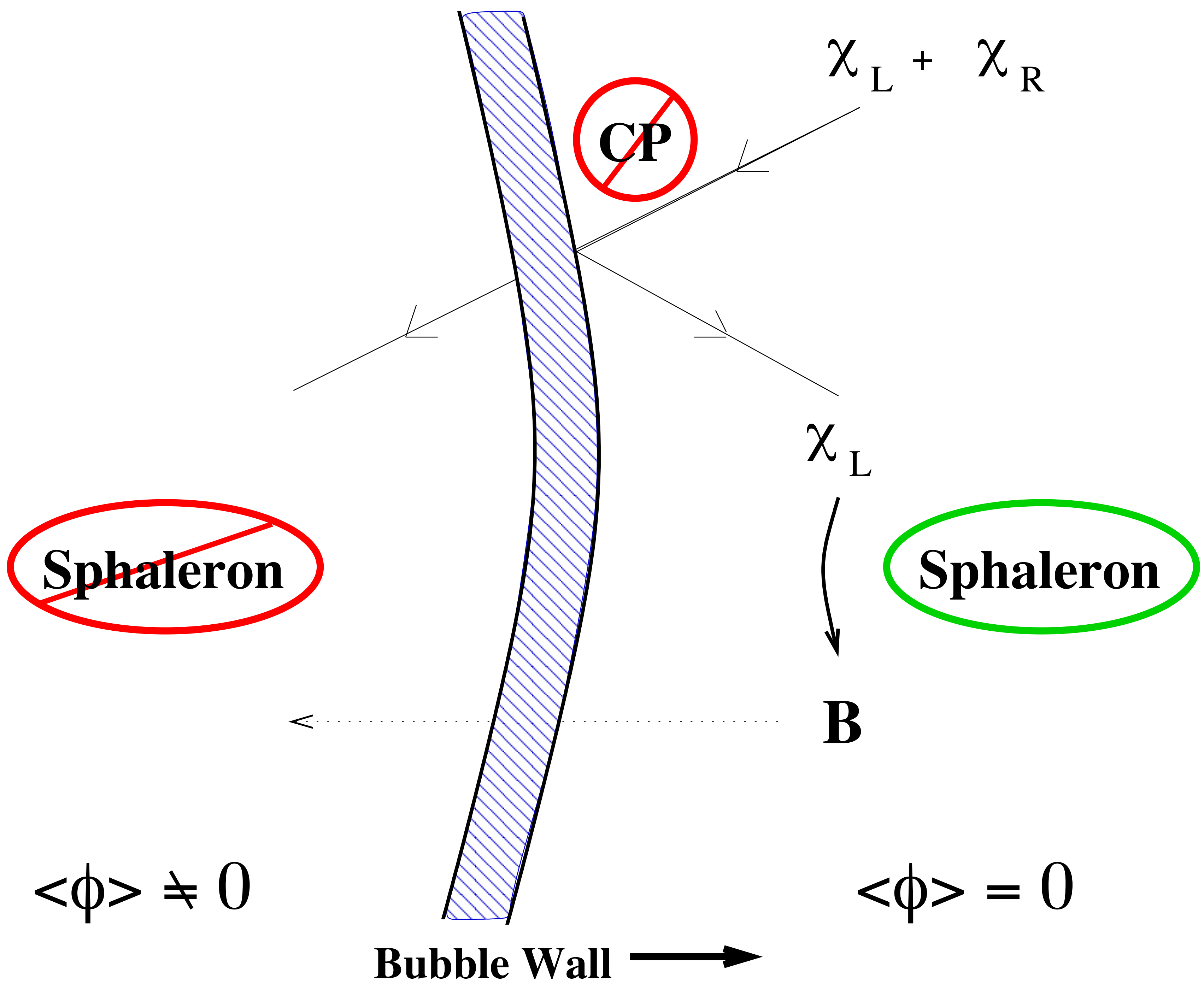
1. First-order EW PT produces expanding bubbles.
2. C and CP violation near the bubble wall induce chiral asymmetries.
3. Electroweak sphalerons convert this to a baryon charge.

Could this explain baryogenesis within the SM?!

Non-Equilibrium: Bubbles



C and CP Violation



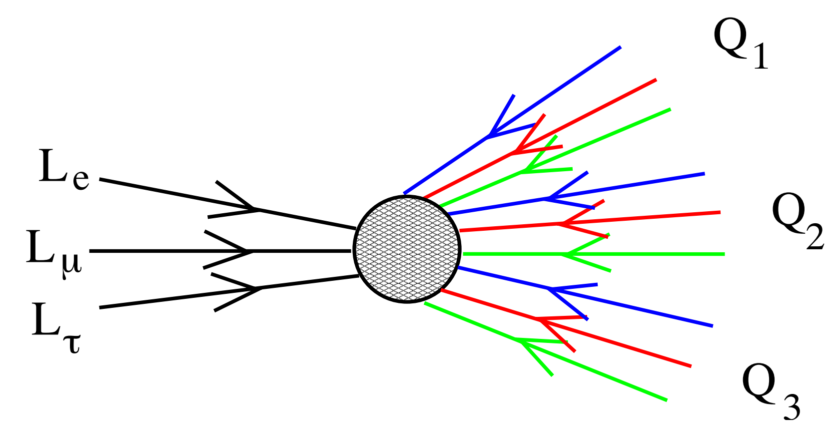
Baryon Creation

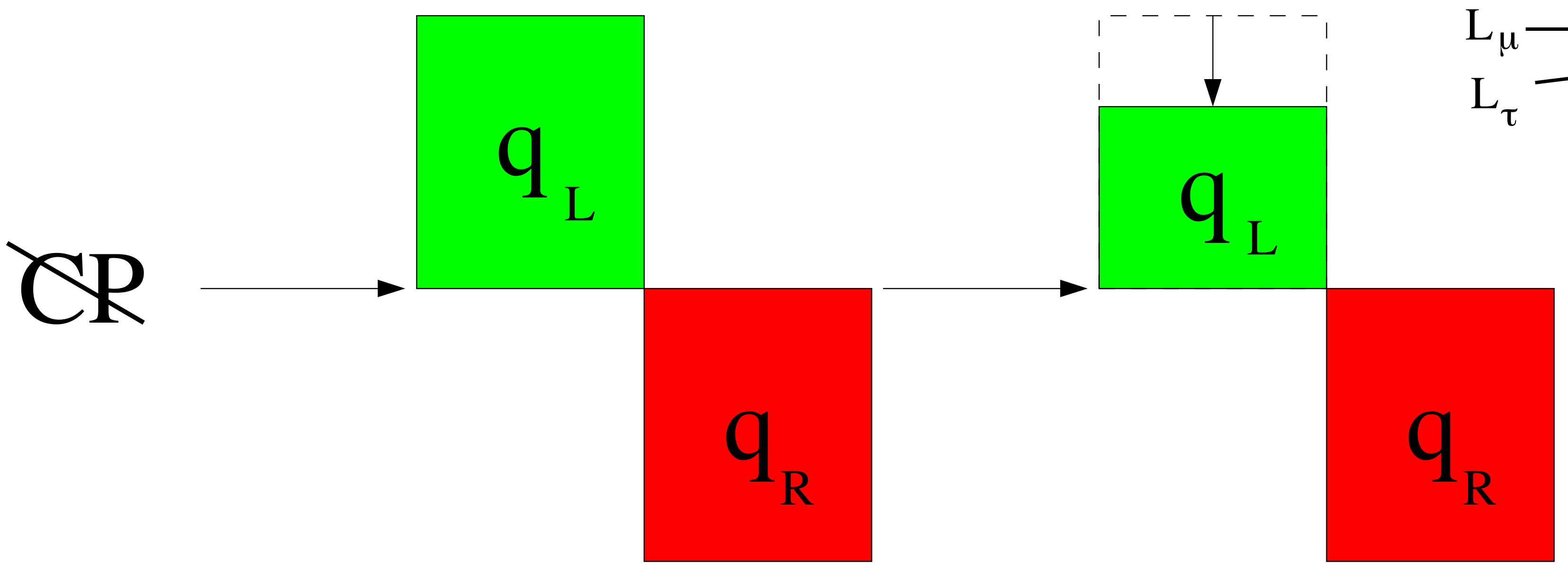
Sphaleron = non-perturbative $SU(2)_L$ transition.

Violates (B+L) by 3 units.

Active in the unbroken phase.
Suppressed in the broken.

$$\Gamma/V \sim \begin{cases} (\alpha_w T)^4 \\ T^4 \exp(-8\pi\langle H\rangle/g_w T) \end{cases}$$





EWBG in the Standard Model

- It doesn't work for two reasons
  1. The EW PT is not first order for m_h = 125 GeV.
     [Kajantie, Laine, Rummukainen, Shaposhnikov '98]
  2. Not enough effective CP violation.
     [Gavela, Hernandez, Orloff, Pene'94; Huet + Sather '95]

- EWBG could work with new physics.
  e.g. Minimal Supersymmetric Standard Model (MSSM)

EWBG in the Supersymmetric SM (MSSM)

- Fixes

  1. A strongly first-order PT from a light stop.

     [Carena, Quiros, Wagner '96; Delepine, Gerard, Gonzalez Felipe, Wyers '96]

  2. New sources of CP violation from soft terms.

     [Carena, Quirós, Riotto, Vilja, Wagner '97; Cline + Kainulainen '97]
     [Konstandin, Prokopec, Schmidt, Seco '05; Cirigliano, Ramsey-Musolf, Tulin, Lee '06]

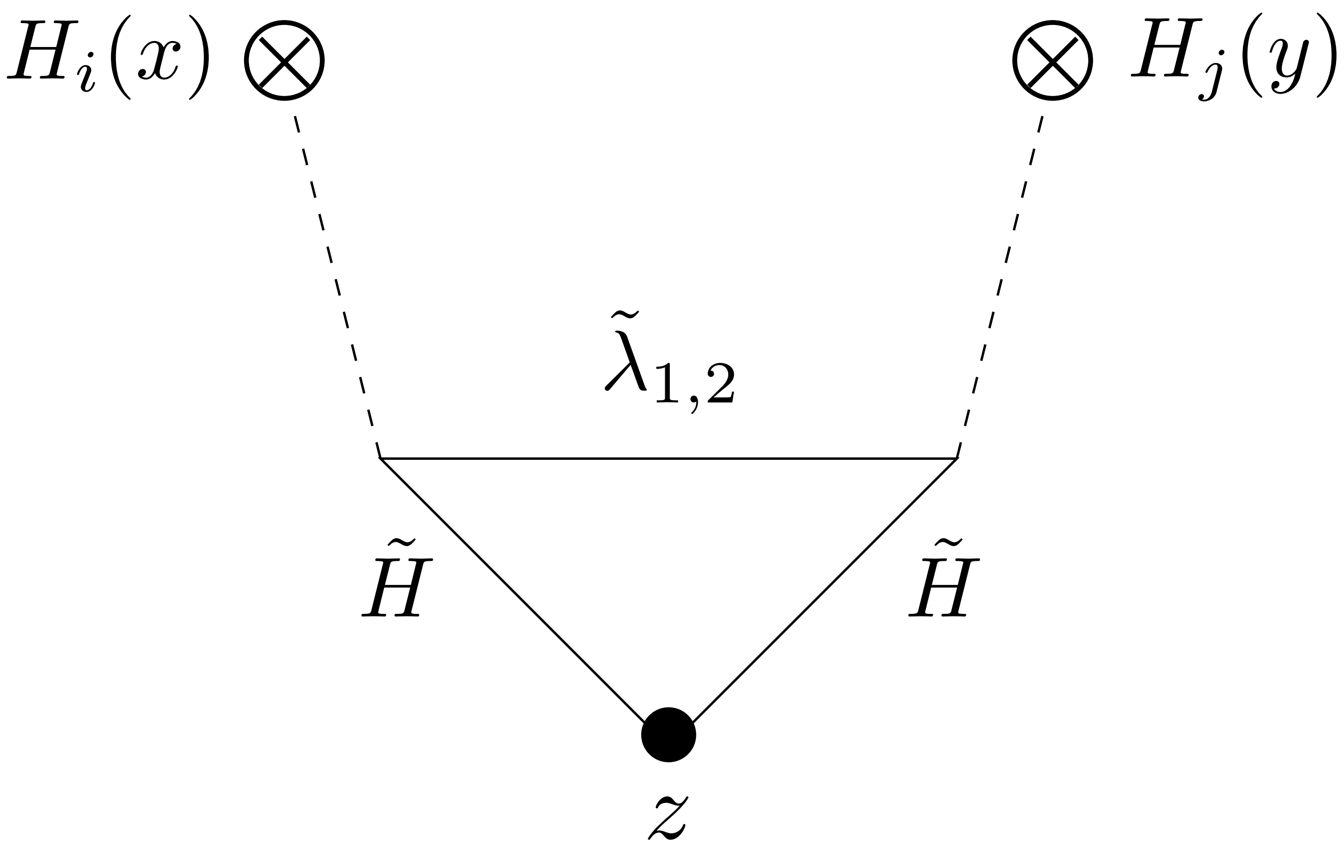
- LHC measurements have strongly constrained this minimal SUSY realization of EWBG.

- EWBG is still viable in MSSM extensions.

New Sources
of
CP Violation

CP Violating Sources

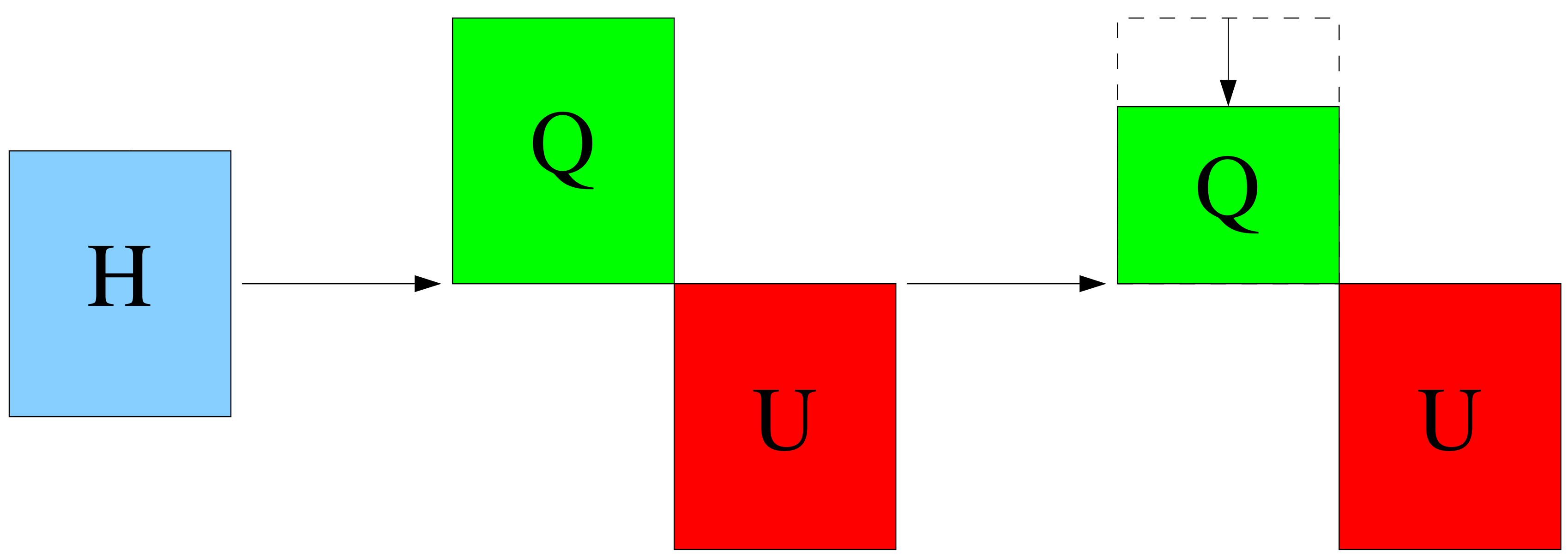
MSSM: Charginos and Neutralinos $(\widetilde{H}_u, \widetilde{H}_d, \widetilde{W}^a, \widetilde{B}^0)$



$$
\begin{aligned}
S^{\tilde{H}}_{CPV} &= \partial_0 J^0_{\tilde{H}}(z) \\
&\propto Im(\mu\, M_i)\, \partial_z f(v_u(z), v_d(z))
\end{aligned}
$$

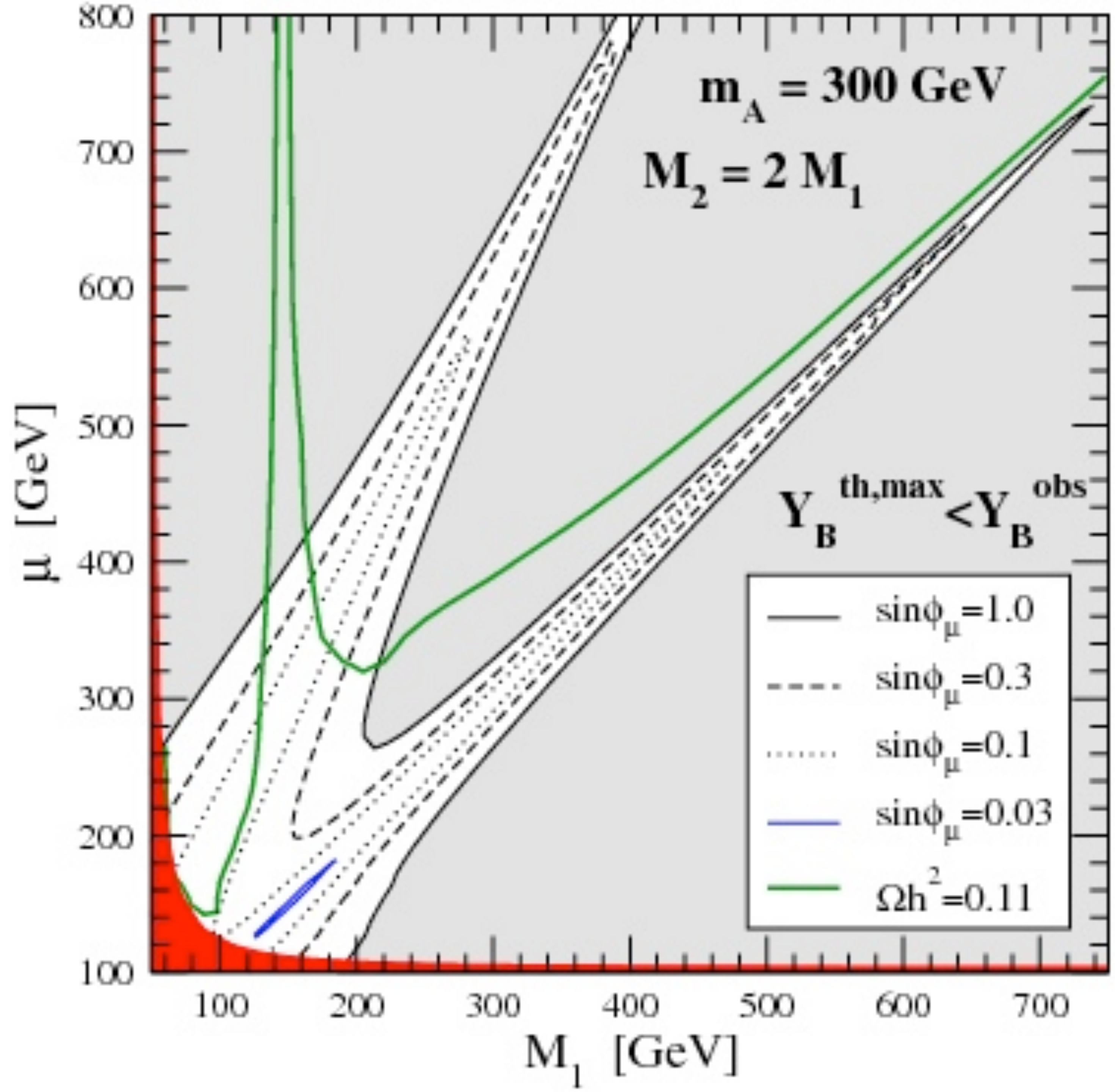
Transfer of Sources to B

- Higgsino source is transferred to tops and stops.
- LH asymmetries bias weak sphalerons to make B.
- (Quark asymmetries are washed out by strong sphalerons.)



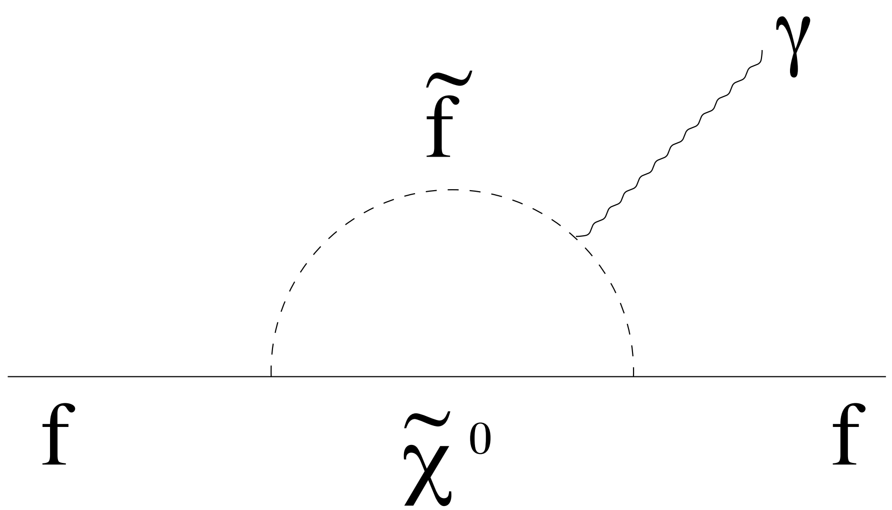
$\not{C}$, $\not{C}\!P$ $\quad y_t\, Q H_u U^c \quad$ Sphalerons

Results [Cirigliano, Li, Profumo, Ramsey-Musolf '09]



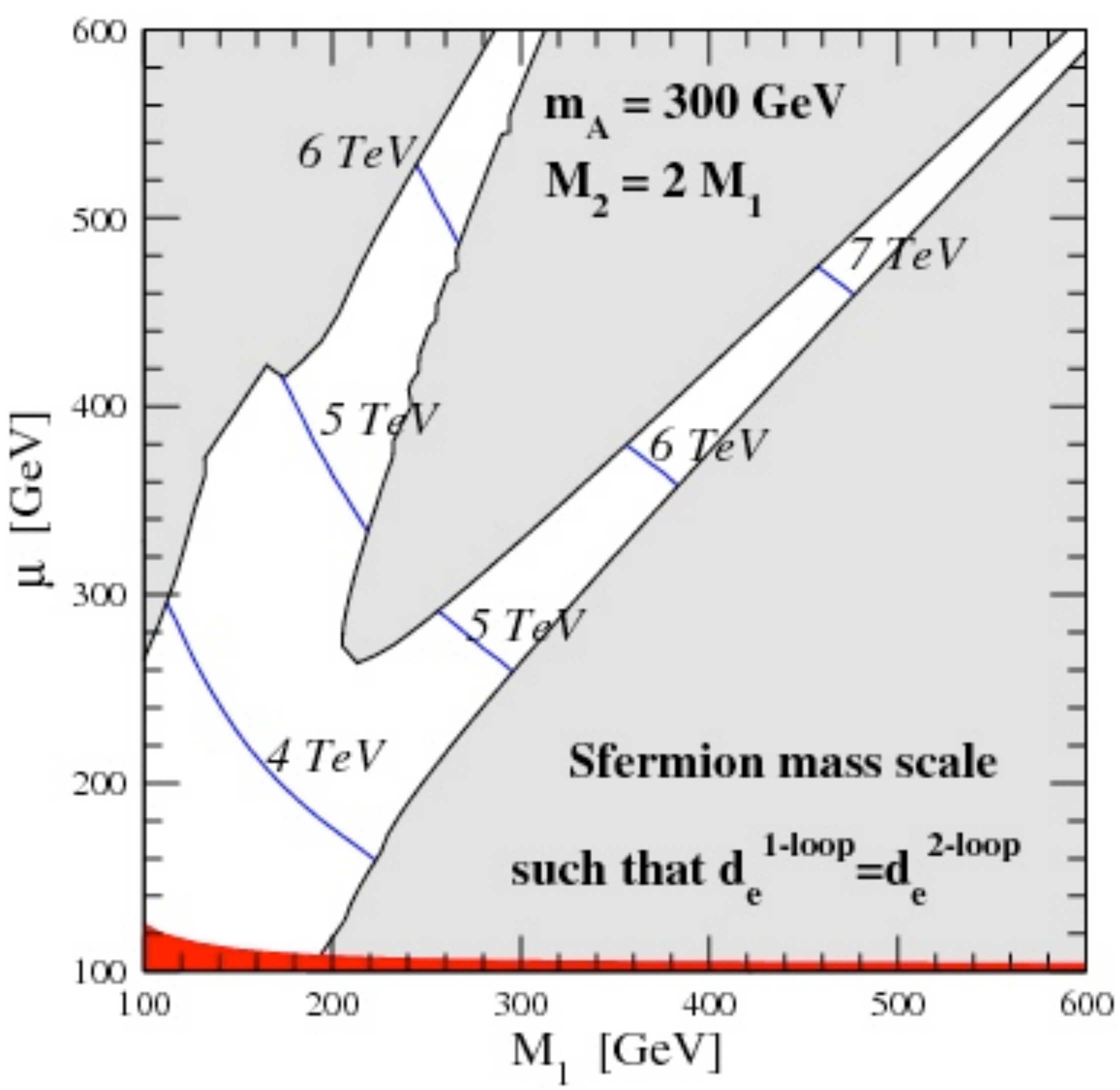
Electric Dipole Moments (EDM)

- One loop:



+ . . .

[Cirigliano, Li, Profumo, Ramsey-Musolf '09]

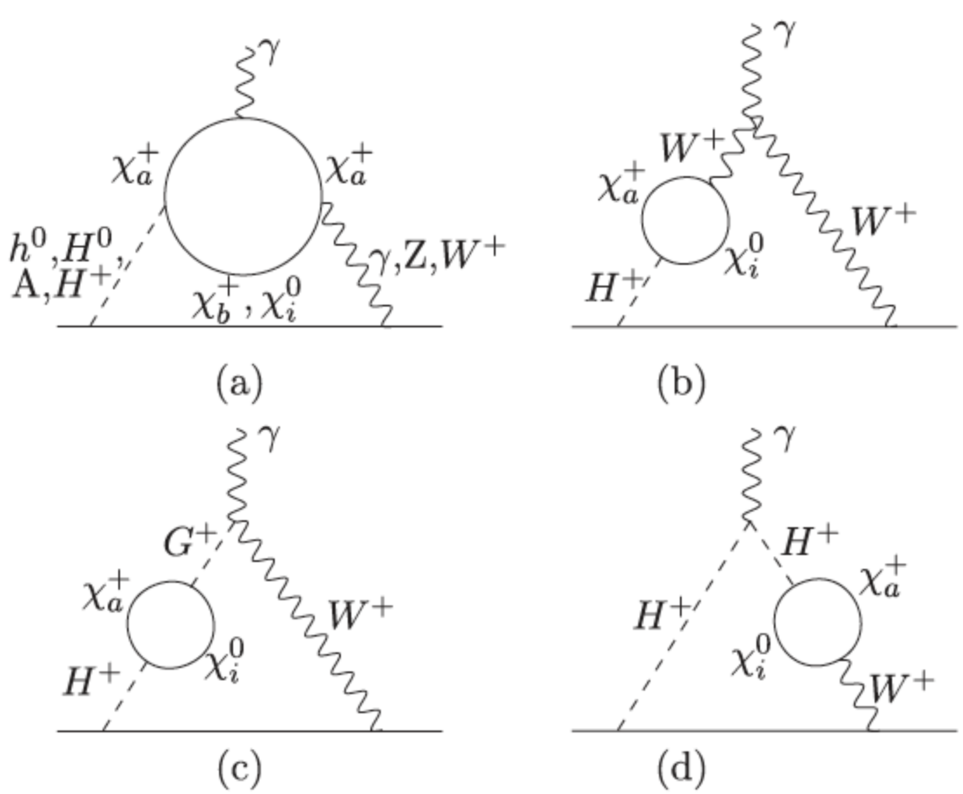


- Decouples for $m_{\tilde{f}} \gtrsim 10\,\mathrm{TeV}$.

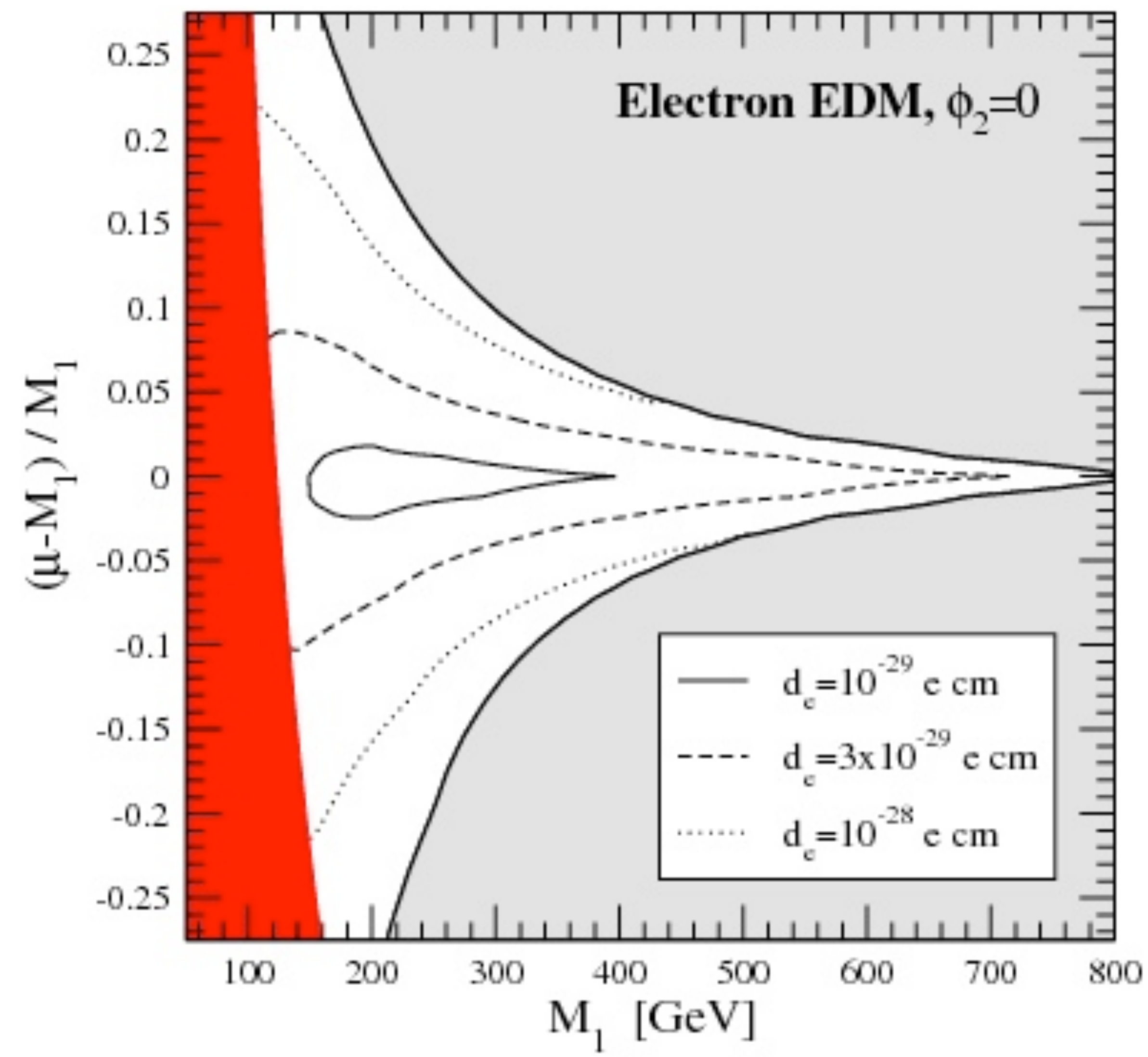
Electric Dipole Moments (EDM)

- Two loop:

  [Chang, Keung, Pilaftsis '98; ...]

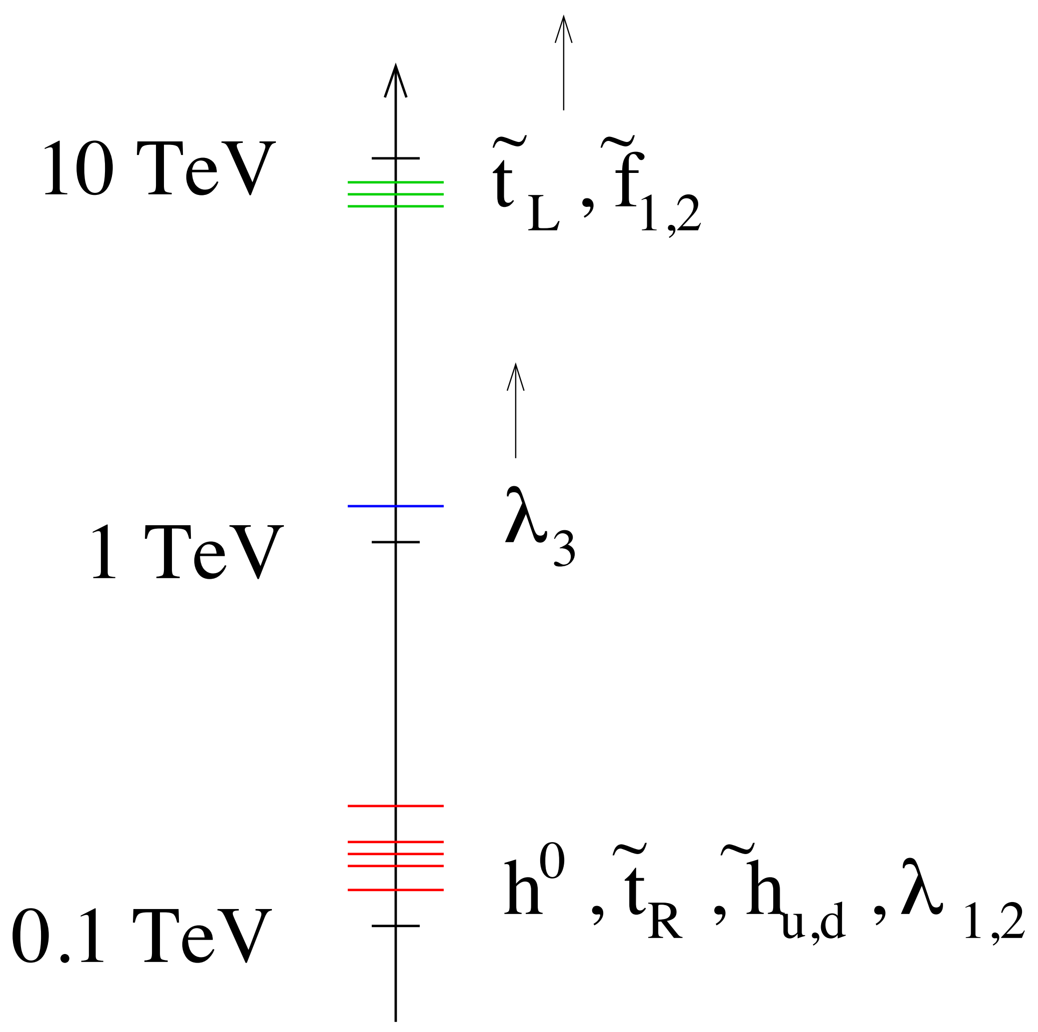


[Cirigliano, Li, Profumo, Ramsey-Musolf '09]



- Does not decouple!
- ACME: $d_e < 8.7 \times 10^{-29}\,\mathrm{e\ cm}$

MSSM EWBG Spectrum



Mini-stop-split spectrum.

A Strongly First-Order Electroweak Phase Transition

Light Stops

- Stop mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t^* \\ m_t X_t & m_{U_3}^2 + m_t^2 + D_R \end{pmatrix}$$

- Mass eigenstates: $\tilde{t}_1, \tilde{t}_2$ with $m_{\tilde{t}_1} \leq m_{\tilde{t}_2}$.

  Mixing angle: $\theta_{\tilde{t}}$.

Light Stops and the EW Phase Transition

- Assume $m_{U_3} \ll m_{Q_3}, m_A$.

$$-\mathscr{L}_{eff} \supset m_U^2 |\tilde{t}_1|^2 + Q |H|^2 |\tilde{t}_1|^2$$

with

$$m_U^2 \simeq m_{U_3}^2$$

$$Q \simeq |y_t|^2 \sin^2\beta \left(1 - \frac{|X_t|^2}{m_{Q_3}^2}\right) + \frac{1}{3} g'^2 \cos 2\beta$$

[Carena, Nardini, Quirós, Wagner '08]

- Thermal effective potential:

$$V_{eff}(\varphi, T) \simeq -(\mu^2 - \xi\, T^2)\, \varphi^2 - \frac{T}{4\pi} \left[m^2_{\tilde{t}_1}(\varphi, T)\right]^{3/2} + \frac{\lambda}{4}\varphi^4$$

where

$$m^2_{\tilde{t}_1}(\varphi, T) \simeq Q\, \varphi^2 + \underbrace{m_U^2 + \xi\, T^2}_{\delta m^2}$$

- Large Q , $\delta m^2 \to 0$ yield a strongly first-order transition.

$$\text{Strength}(\delta m^2 = 0) \;\sim\; \frac{``\langle \varphi_c \rangle''}{T_c} \;\sim\; \frac{Q^{3/2}}{\lambda} \;\gtrsim\; 1$$

Light Stops and the Higgs

- Stop Mass:

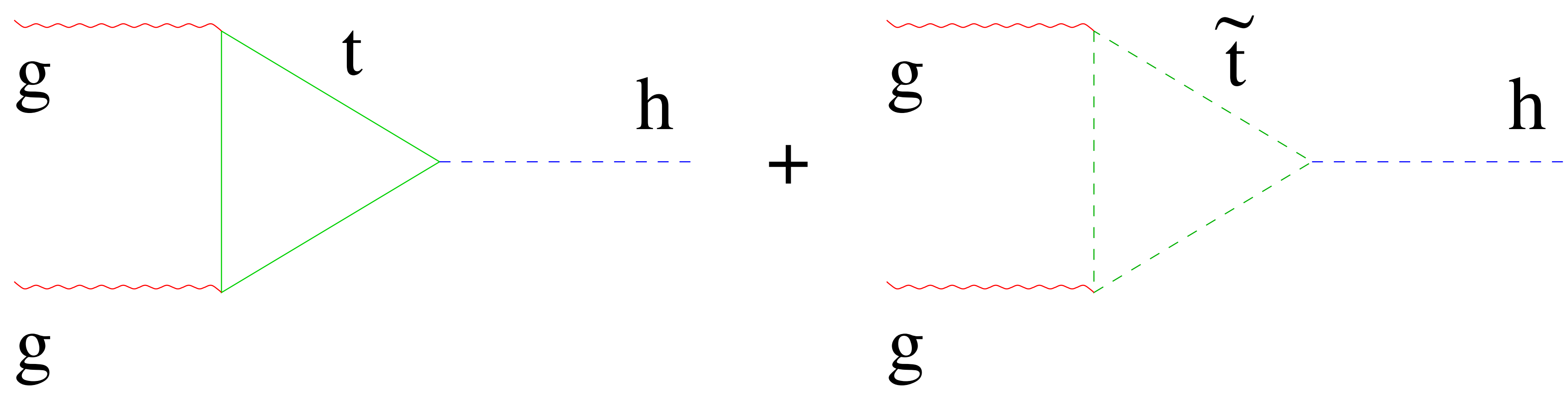
$$m_{\tilde{t}_1}^2 = m_U^2|\tilde{t}_1|^2 + Qv^2|\tilde{t}_1|^2$$

- Contribution to h^0gg , $h^0\gamma\gamma$ couplings goes like

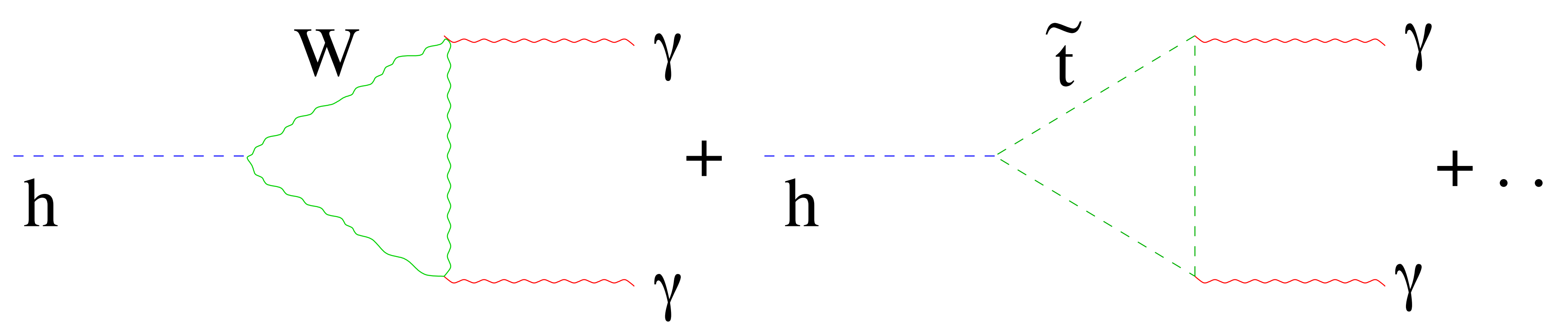
$$\Delta C_{hVV} \propto \frac{v^2}{m_{\tilde{t}_1}^2}\frac{\partial m_{\tilde{t}_1}^2}{\partial v^2} = \frac{Qv^2}{m_U^2 + Qv^2}$$

- Diagrammatically: [Menon, DM '09]

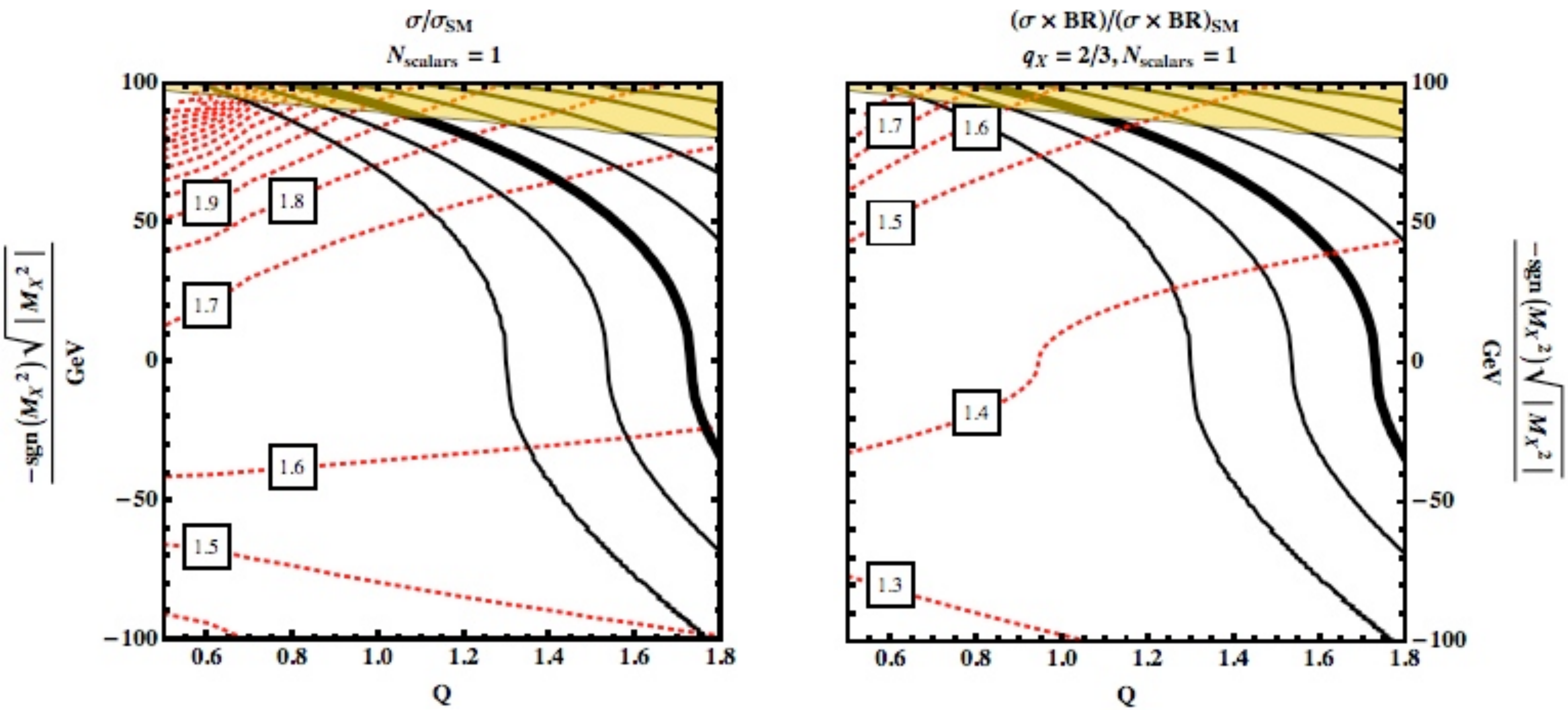
$\sigma(gg \to h^0)$: constructive with top loop for $Q > 0$.



$\Gamma(h^0 \to \gamma\gamma)$: destructive with W loop for $Q > 0$.



Phase Transition vs. Higgs Rates



[Cohen, DM, Pierce ’12]

- Inconsistent with measured Higgs rates.

[Curtin, Jaiswal, Meade ’12; Katz + Perelstein ’14]

- Caveats:

  1. Interference with other superpartners (stau, chargino), or invisible decays to neutralinos might work.
     [Carena, Nardini, Quirós, Wagner '12]

  2. Lattice studies find a stronger phase transition than perturbative calculations.
     [Laine, Nardini, Rummukainen '13]

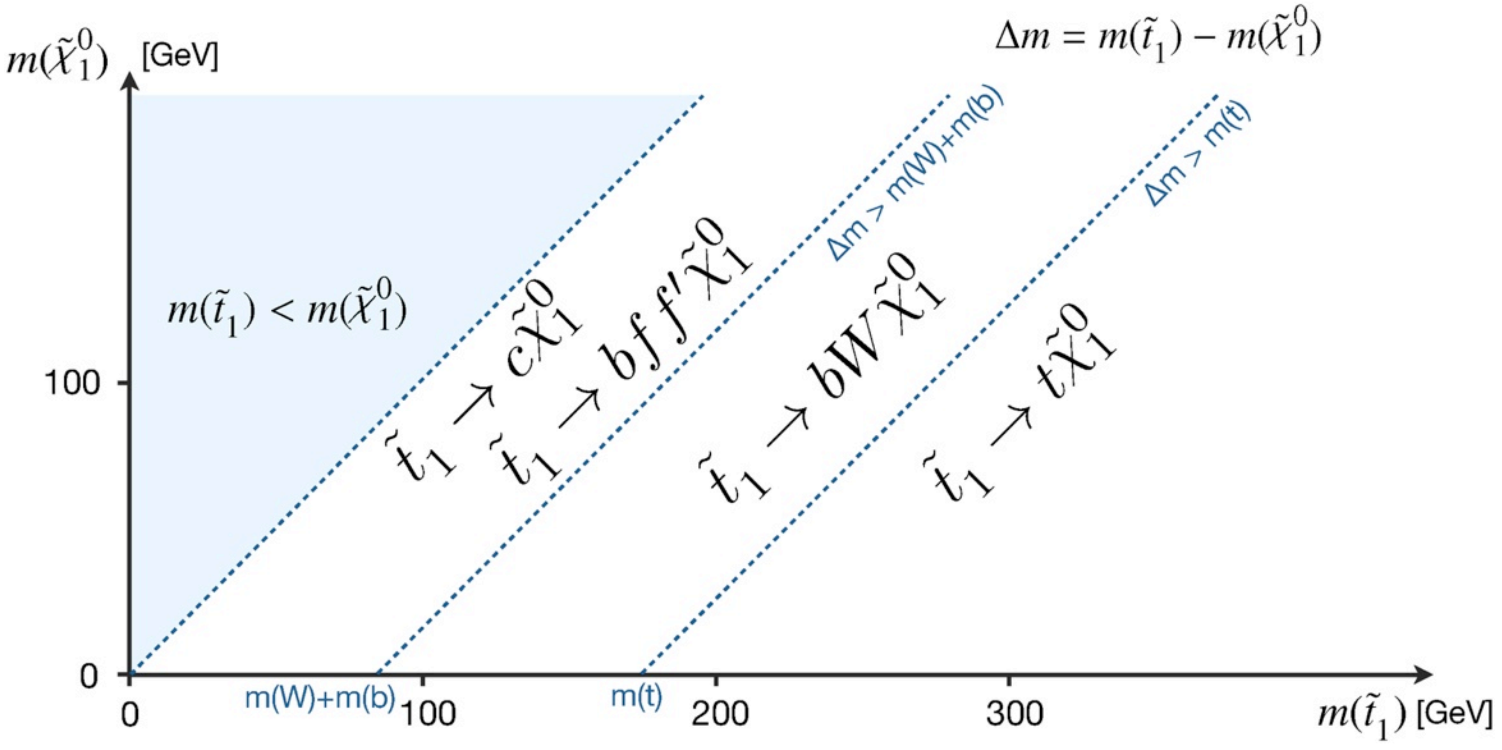
     But $m_{\tilde{t}_1} \lesssim 155\,\mathrm{GeV}$ still seems to be required.

- Direct stop searches?

  [Kumar, DM '12; Delgado, Giudice, Isidori, Pierini, Striumia '12]

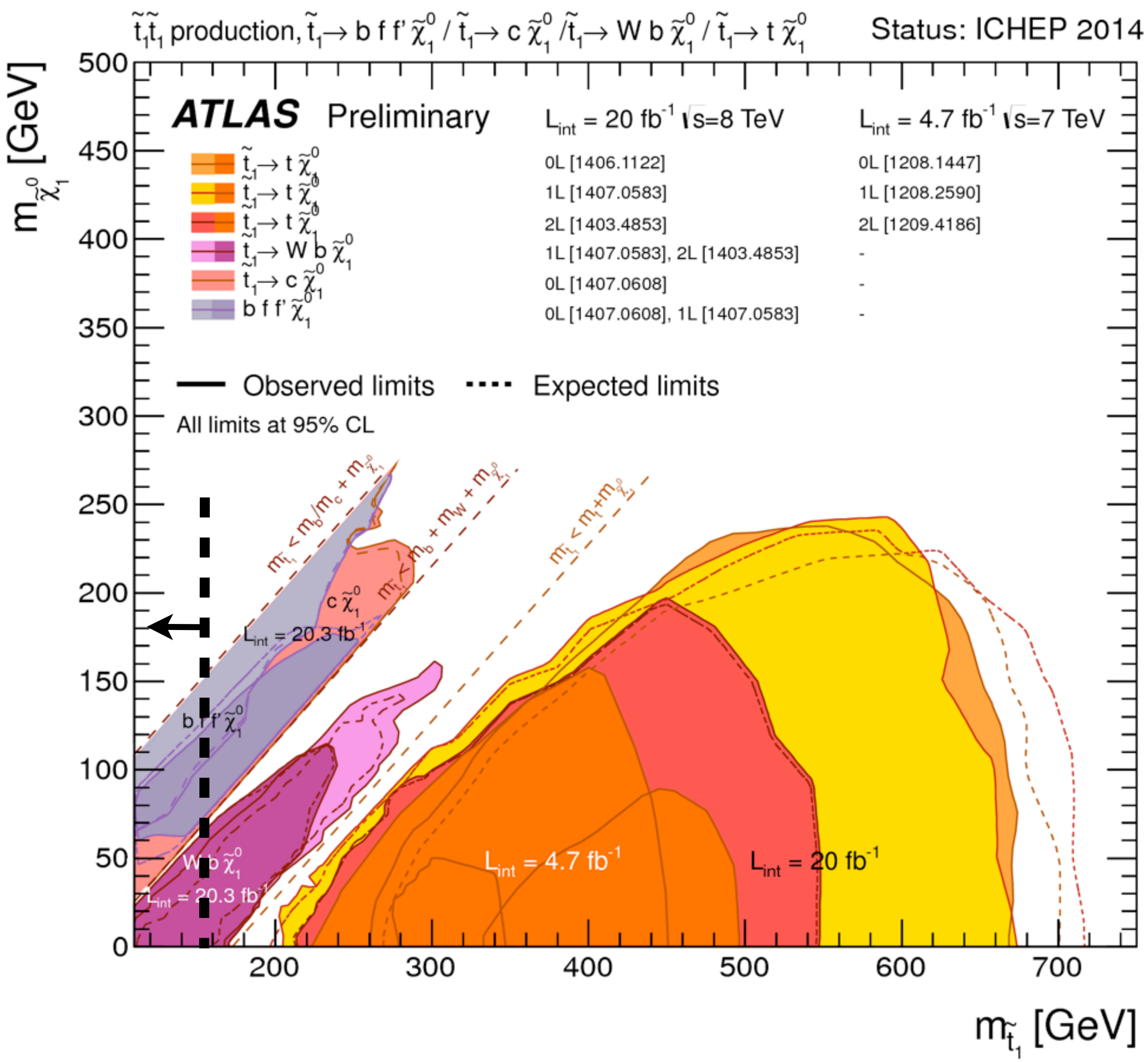
Direct Stop Searches: Light Stop Decays

- Two Body: $\tilde{t} \to t\,\chi_1^0, \qquad \tilde{t} \to b\,\chi_1^+$
- Three/Four Body: $\tilde{t} \to b\,\chi_1^0\,W^{+(*)}$
- Flavor Violating: $\tilde{t} \to c\,\chi_1^0$
- Generally, 2B > 3B > 4B, FV.



[ATLAS]

Direct Stop Searches at the LHC



CMS has similar exclusions.

- More Caveats:

  1. Searches assume stops decay promptly.
     4B and FV modes are frequently displaced.*
     [Hiller+Nir '08]

  2. Weaker limits with RPV?
     [Evans+Kats'12]

* LHC searches for long-lived stops rule out $m_{\tilde{t}} \lesssim 600\,\mathrm{GeV}$.

[CMS 1205.0272]

Beyond the MSSM

Beyond the MSSM

- EWBG can still work in MSSM extensions.
- MSSM EWBG problem:
  A light stop is needed for a strong phase transition.
  This is ruled out by Higgs data and direct searches.
- Stops can be heavier if the PT is driven by other dynamics:

  1. {N}MSSM
  2. R-symmetric SUSY
  3. ...

- MSSM extensions can also provide new sources of CPV.

e.g.1: {N}MSSM [Pietroni '92; Davies *et al.* '96; Huber+Schmidt '00; Menon *et al.* '04; ...]

- {N}MSSM = MSSM + singlet (S):

$$W \supset \lambda S H_u \cdot H_d + \ \ldots$$

- Singlet VEV: $\mu_{eff} = \lambda \langle S \rangle$
- The singlet can induce a strongly first-order EWPT driven partly by tree-level effects with:

[Huang *et al.* '14; Kozaczuk *et al.* '14]

  - $m_h \simeq 125\,\mathrm{GeV}$.
  - Higgs rate corrections consistent with data.
  - Viable Bino-Singlino dark matter.
- Higgs rate corrections are still expected.

e.g. 2 : R-Symmetric SUSY [Kumar+Pontón '11; Fok, Kribs, Martin, Tsai '12]

- Extend the SM to preserve a global $U(1)_R$:
  - Dirac gaugino masses, need adjoints Φ_A.
  - Vanishing mu term, need doublets R_u , R_d .

$$W \supset \lambda_A^u \Phi_A H_u R_u + \lambda_A^d \Phi_A H_d R_d$$

- New bosons in loops, modified Higgs potential can produce a strong EWPT with $m_h \simeq 125\,\mathrm{GeV}$.
- Higgs rates can still be consistent with data. [Katz+Perelstein '14]
- CP violation from new couplings is consistent with EDMs.

EWBG and SUSY

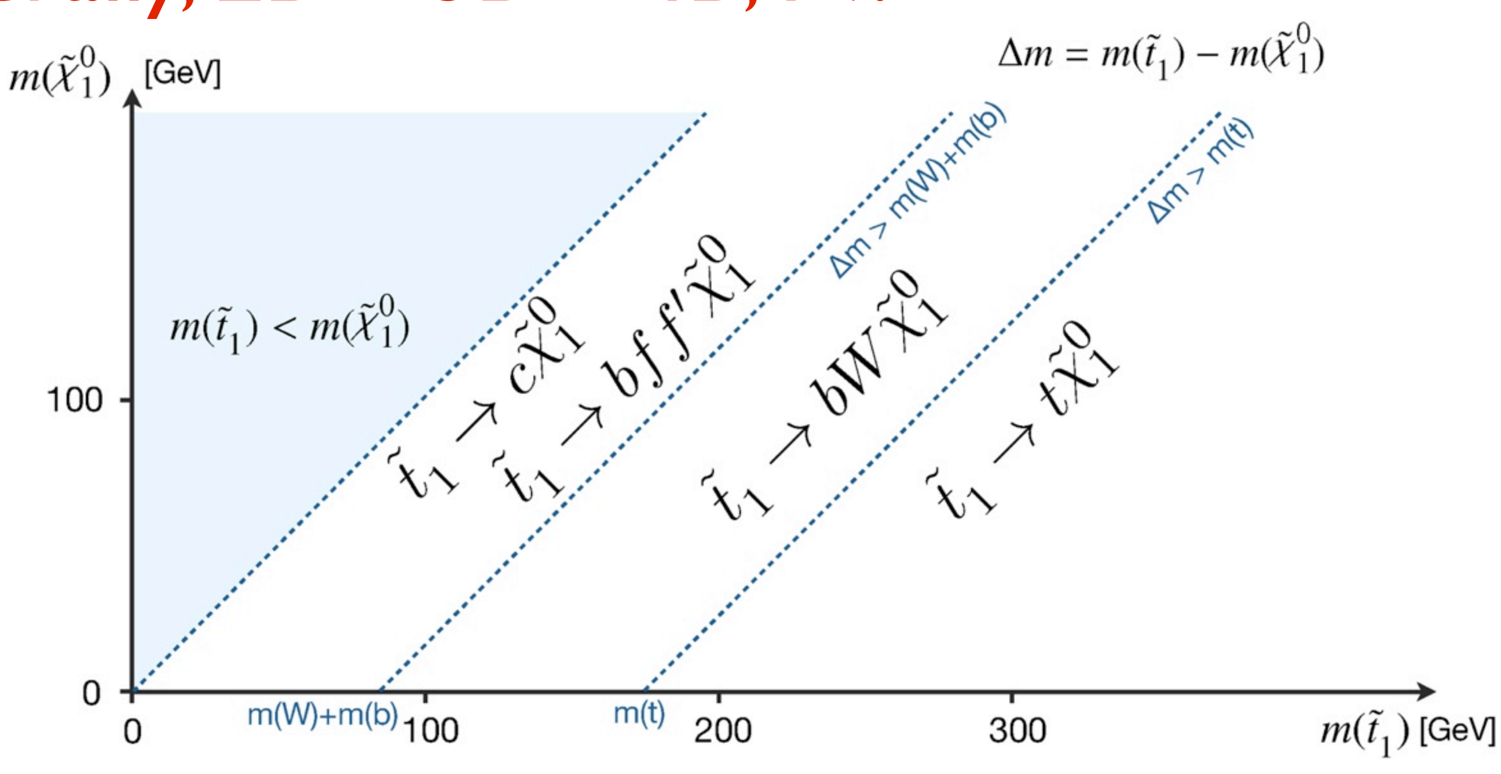
- MSSM EWBG is seriously constrained:
  - EDM bounds are challenging.
  - Light stop, $m_{\tilde{t}} \lesssim 155\,\mathrm{GeV}$, for a first-order EWPT.
  - Very hard to satisfy Higgs rates and direct searches.

- It can still work in extended scenarios ({N}MSSM, Rsym).
- Places to look:
  - EDM searches.
  - Deviations from SM Higgs rates, new scalars.

Extra Slides

Light Stop Decays

- Two Body: $\tilde{t} \to t\,\chi_1^0, \qquad \tilde{t} \to b\,\chi_1^+$
- Three/Four Body: $\tilde{t} \to b\,\chi_1^0\,W^{+(*)}$
- Flavor Violating: $\tilde{t} \to c\,\chi_1^0$
- Generally, 2B > 3B > 4B, FV.



[ATLAS]

Light Stop Decays

- Setup:
  - Heavy gluino, sleptons, light-flavor squarks: $m \geq 1.5\,\mathrm{TeV}$
  - Lighter electroweakinos: $\mu,\ M_2 \gtrsim M_1$
  - Moderate $\tan\beta = 10,\ 30$.
  - Smaller $m^2_{U_{33}}$ or $m^2_{Q_{33}}$.
- Assume Minimal Flavor Violation (MFV) for squark mixing.
  [...; d'Ambrosio, Guidice, Isidori, Strumia '02]

- MFV: $SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$ global symmetry.

- Spurions: $Y_u = (3, \bar{3}, 1), \quad Y_d = (3, 1, \bar{3})$

$$
\begin{aligned}
m_Q^2 &= \tilde{m}^2(a_1 \mathbb{I} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + b_3 Y_d {Y_d}^\dagger Y_u {Y_u}^\dagger) \\
m_{U^c}^2 &= \tilde{m}^2(a_2 \mathbb{I} + b_5 {Y_u}^\dagger Y_u + c_1 {Y_u}^\dagger Y_d {Y_d}^\dagger Y_u) \\
m_{D^c}^2 &= \tilde{m}^2(a_3 \mathbb{I} + b_6 {Y_d}^\dagger Y_d) \\
a_u &= A(a_4 \mathbb{I} + b_7 Y_d {Y_d}^\dagger) Y_u \\
a_d &= A(a_5 \mathbb{I} + b_8 Y_u {Y_u}^\dagger) Y_d
\end{aligned}
$$

- Tuning b_1 and b_5 allows $m_{Q_{33}}^2, m_{U_{33}}^2 \ll \tilde{m}^2$.

- All off-diagonal terms are fixed by CKM.

FV Decay Width [Hiller + Nir '08]

$$-\mathscr{L}_{c\tilde{t}\tilde{\chi}_1^0} = \bar{c}(y_L P_R + y_R P_L)\tilde{\chi}_1^0 \tilde{t} + \text{h.c.}$$

$$\begin{aligned} y_L &= \frac{\lambda_b^2 V_{cb} V_{tb}^*}{m_{\tilde{t}}^2 - m_{\tilde{c}_L}^2} (\tilde{m}^2 b_2 c_{\tilde{t}} + A v_u b_7 \lambda_t s_{\tilde{t}})(-\frac{g'}{3\sqrt{2}} N_{11} - \frac{g}{\sqrt{2}} N_{21}) \\ y_R &= \mathcal{O}(\lambda_c) \end{aligned}$$

$$Y = \sqrt{|y_L|^2 + |y_R|^2}$$

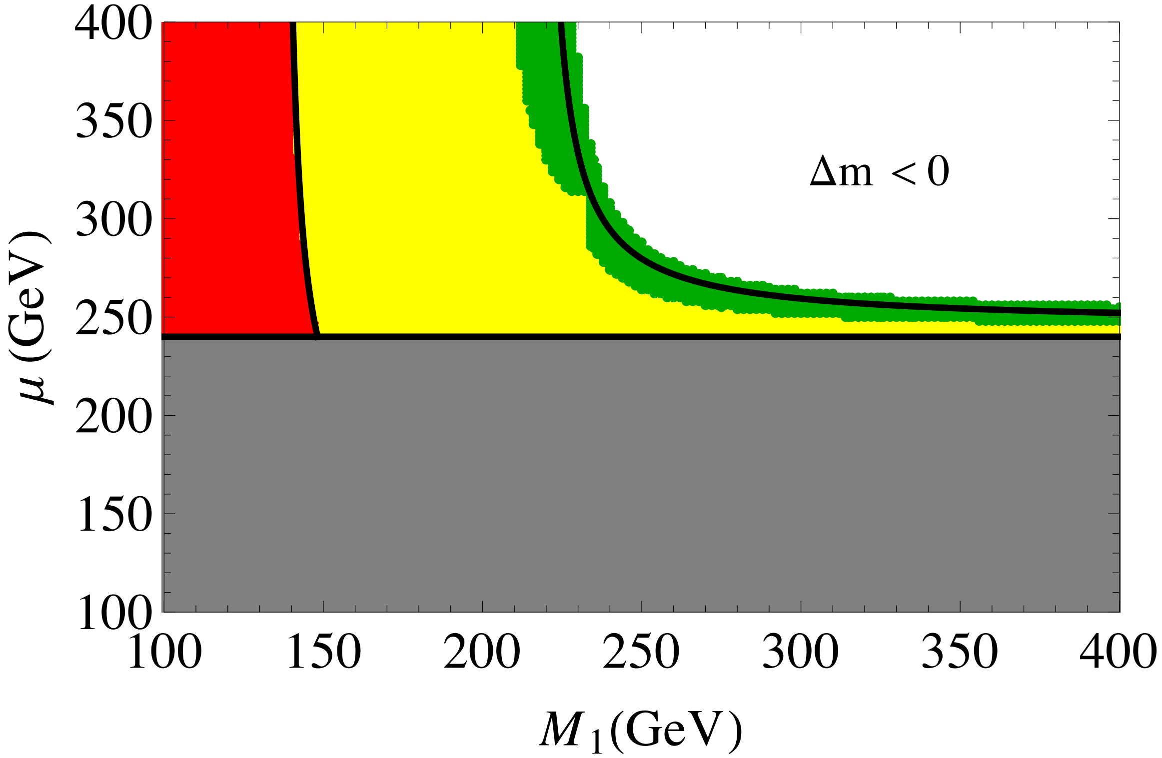
$$\begin{aligned} \Gamma_{FV} &= \left(Y^2/16\pi\right) m_{\tilde{t}} \left(1 - m_{\chi_1^0}^2/m_{\tilde{t}}^2\right)^2 \\ &\to \left(Y^2/4\pi\right) (\Delta m)^2/m_{\tilde{t}} \end{aligned}$$

4B Decay Width [Delgado, Giudice, Isidori, Pierini, Strumia '12]

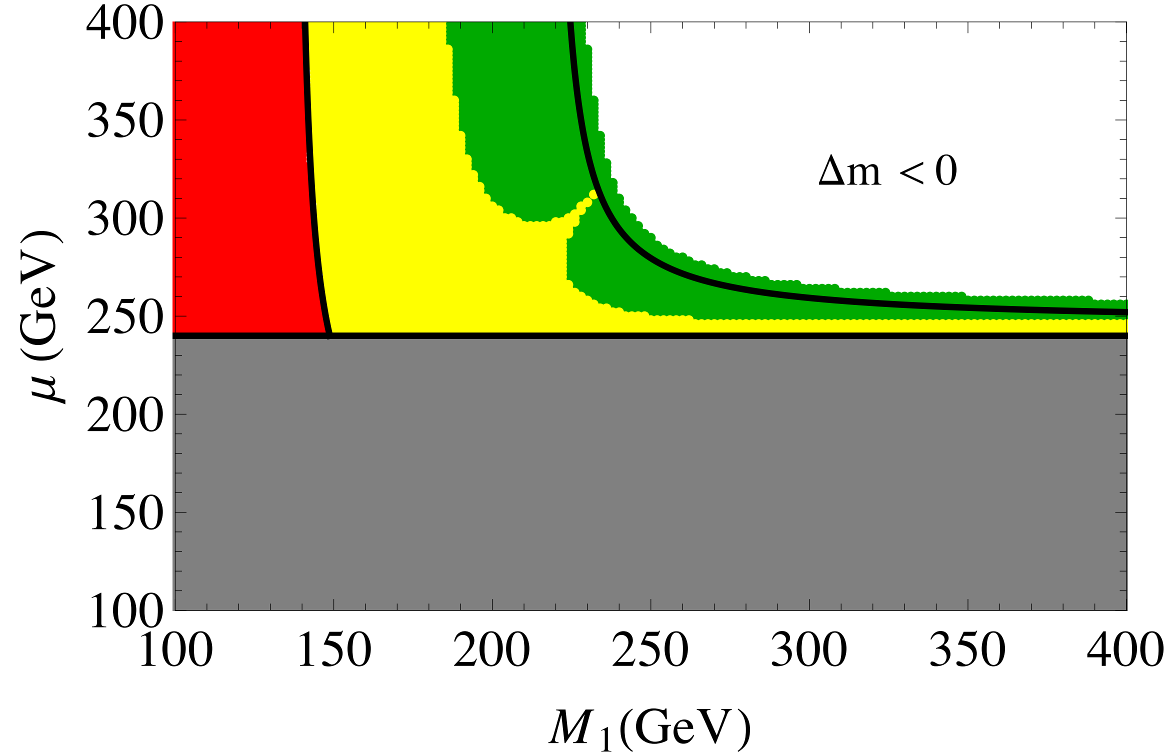
$$\Gamma_{4B} \simeq \frac{3g^2 t_W^2}{70(6\pi)^5} \frac{(\Delta m)^8}{m_W^4 m_t^2 m_{\tilde{t}}}$$

- Decays for: $m_{\tilde{t}_1} = 225\,\text{GeV},\ \tan\beta = 10,\ M_2 = 350\,\text{GeV}$.

[Kumar, DM '12]



$\cos\theta_{\tilde{t}} = 0.1$



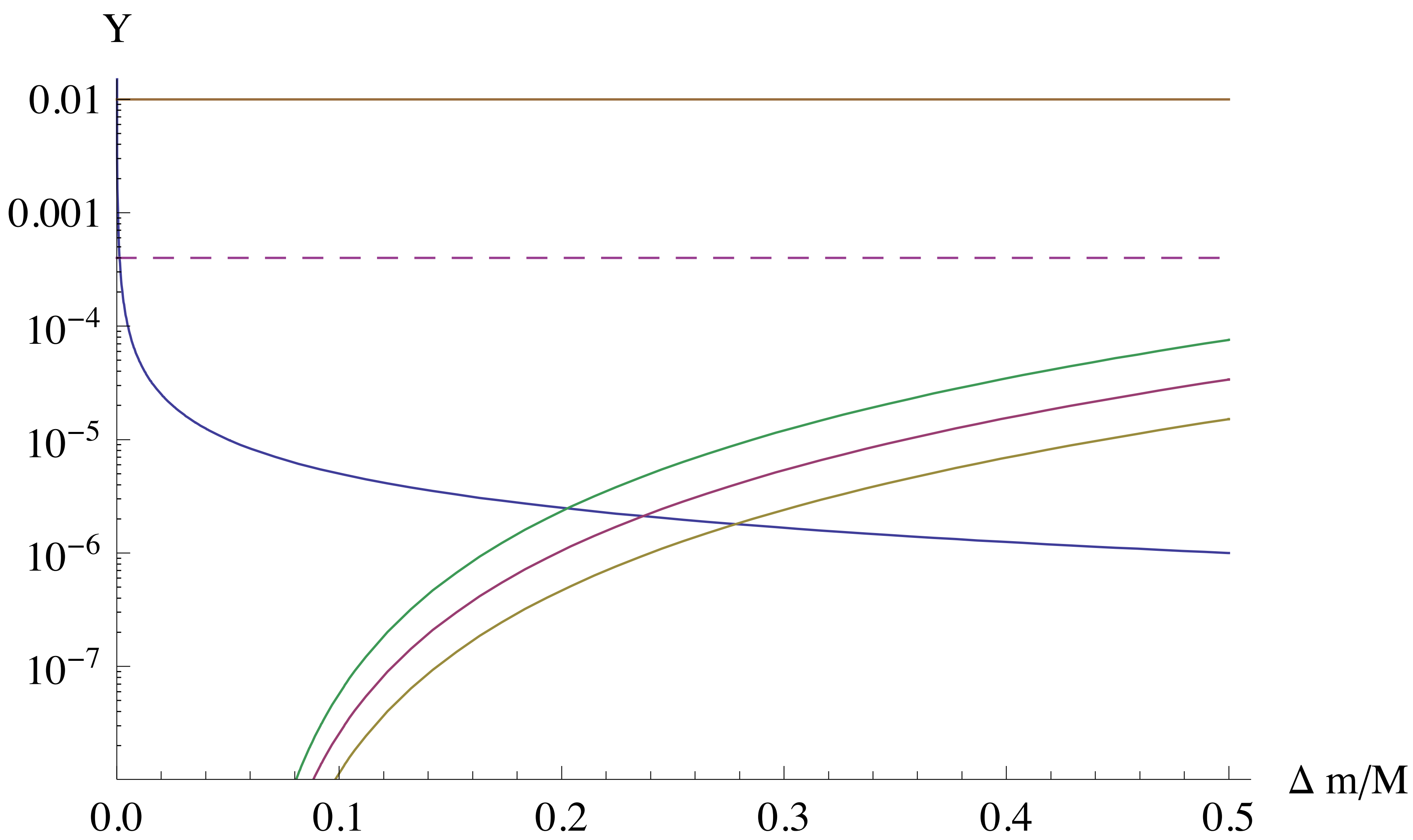
$\cos\theta_{\tilde{t}} = 0.7$

- 4B beats FV for small mass splittings.

- $\Gamma_{FV} = (Y^2/16\pi)\, m_{\tilde{t}} \left(1 - m^2_{\chi^0_1}/m^2_{\tilde{t}}\right)^2$.

- Displaced vertices likely for small $\Delta m = (m_{\tilde{t}_1} - m_{\chi^0_1})$.

  [Hiller + Nir '08]

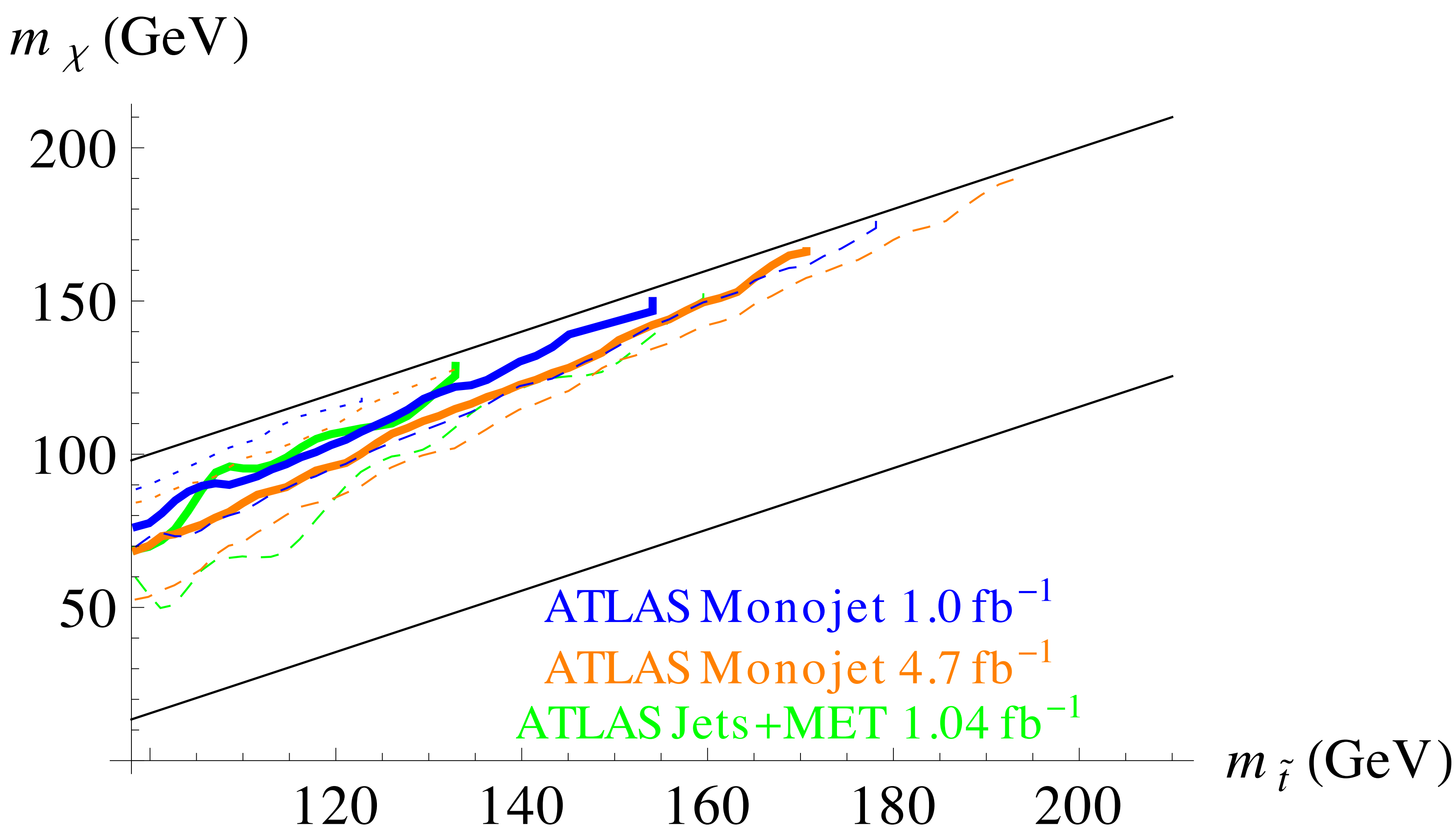


LHC Sensitivity Estimates [Kumar, DM '12]

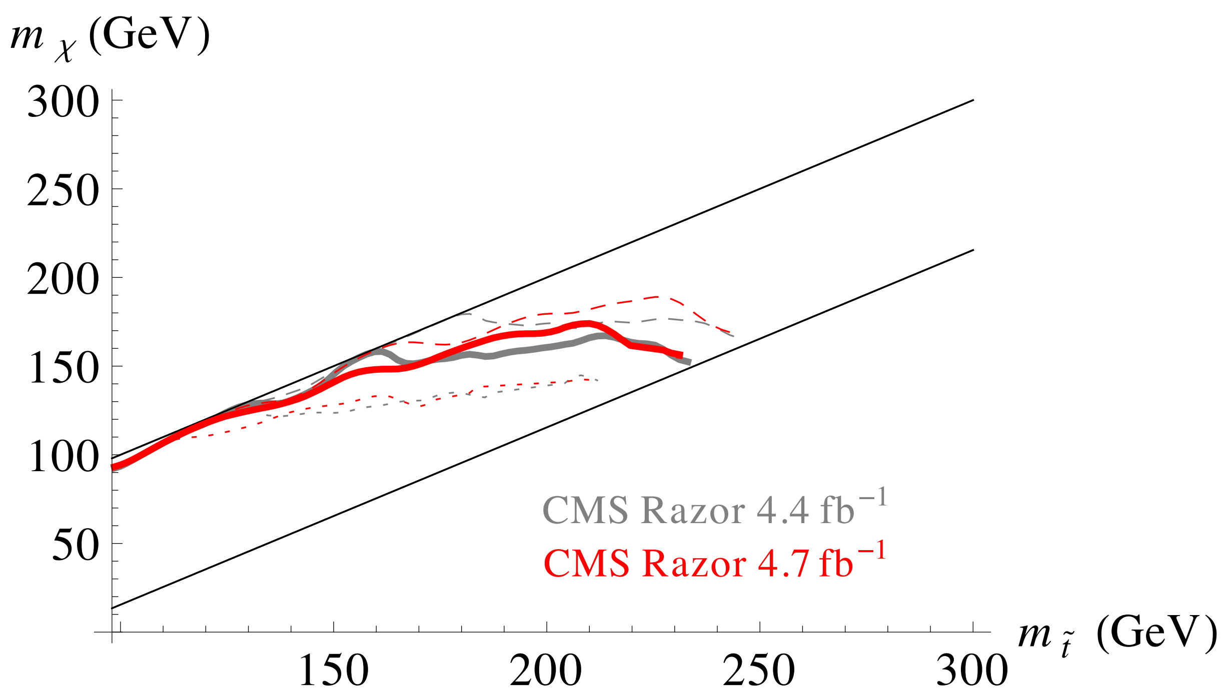
- Signal: Madgraph5 + Pythia 6.4 + MLM matching (0,1,2 *j*)
- Delphes as a detector simulator with anti-k_T jets.
- ATLAS Searches:
  - monojet
  - *jets* + n*l* + m*b* + *MET* (n, m $\geq$ 0)
- CMS Searches:
  - monojet
  - *jets* + n*l* + m*b* + *MET* (n, m $\geq$ 0)
  - Razor, MT2, α_T

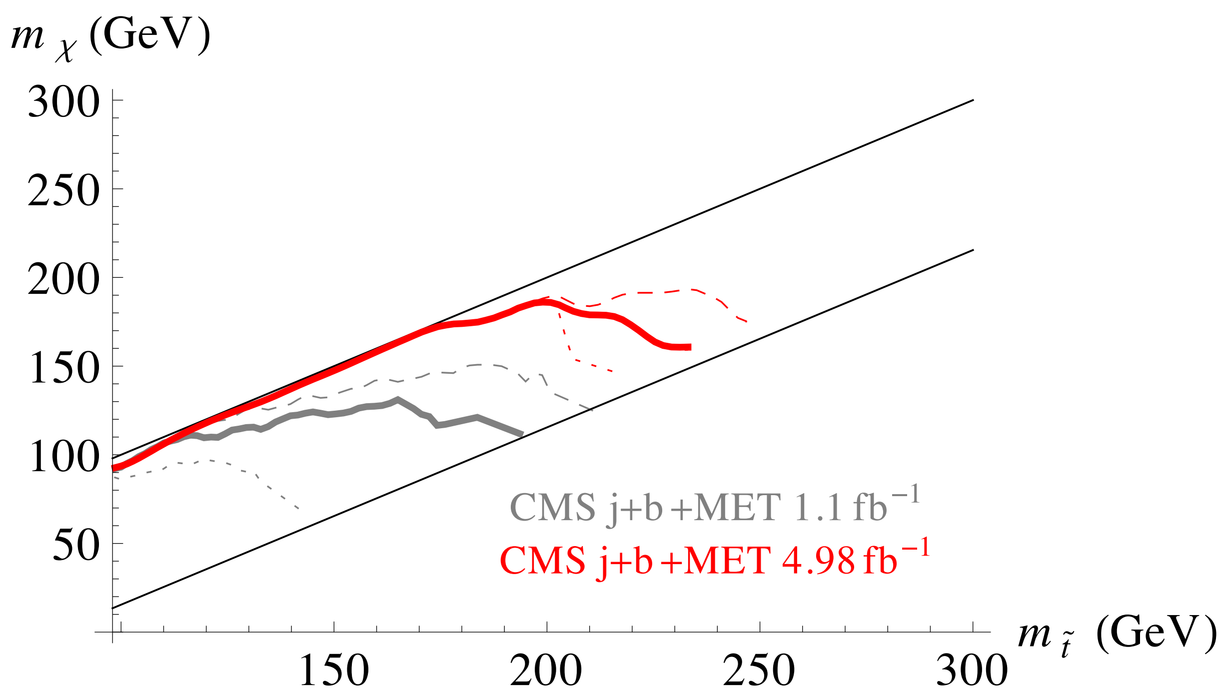
FV Stop Decays

- Assume BR = 1, prompt.
- Monojets constrain small $\Delta m = (m_{\tilde{t}_1} - m_{\chi_1^0})$. Also: [Carena, Freitas, Wagner '08; He, Li, Shafi '11; Drees et al. '12]



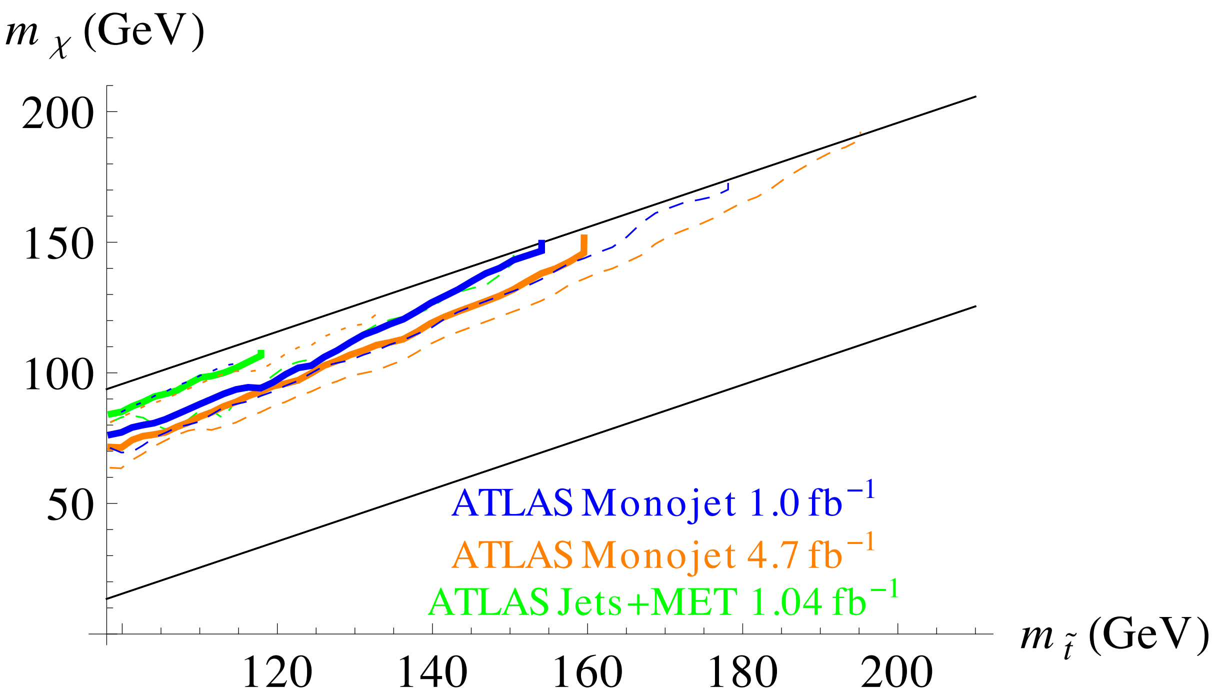
- Razor and *jets+b+MET* are better for larger Δm .
- Mistagging *c* as *b* gives a signal in b channels.

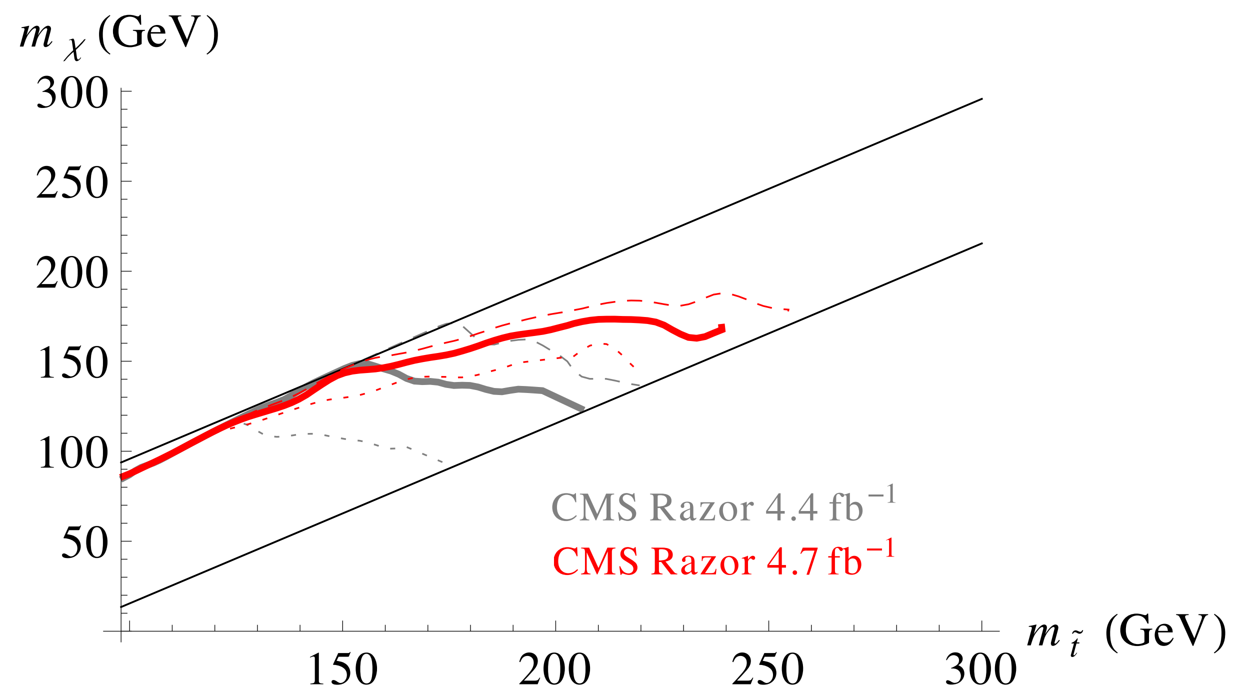




4B Stop Decays

- Softer decay products but similar LHC limits.

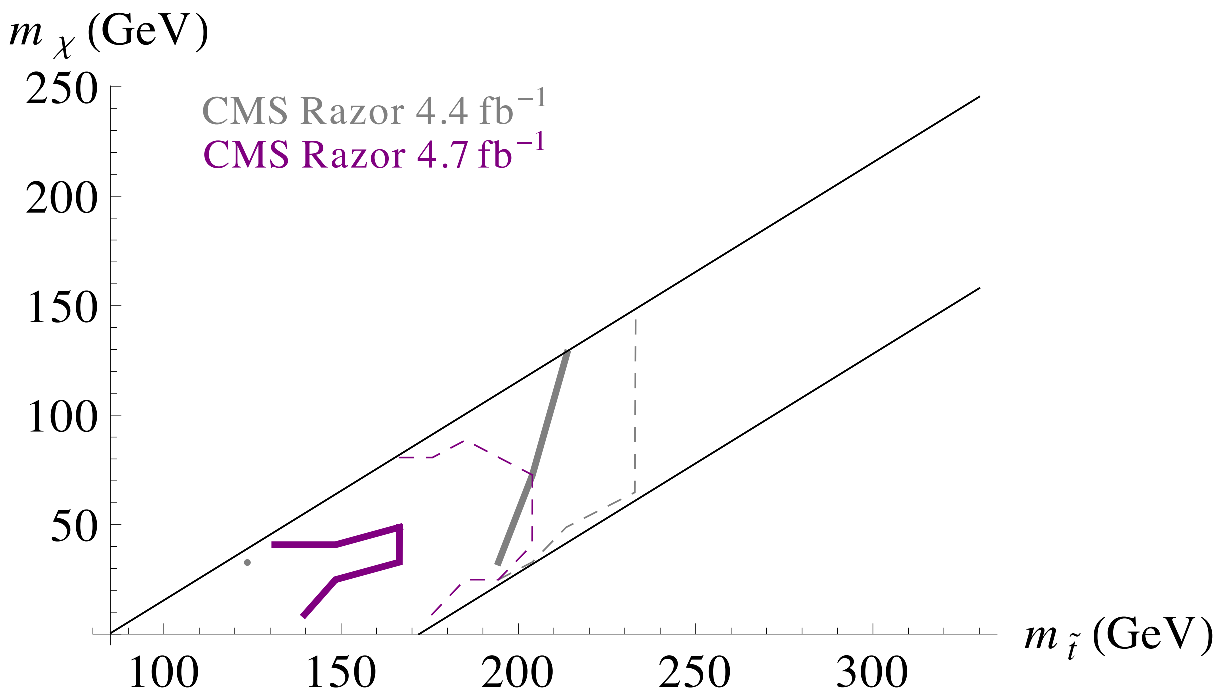


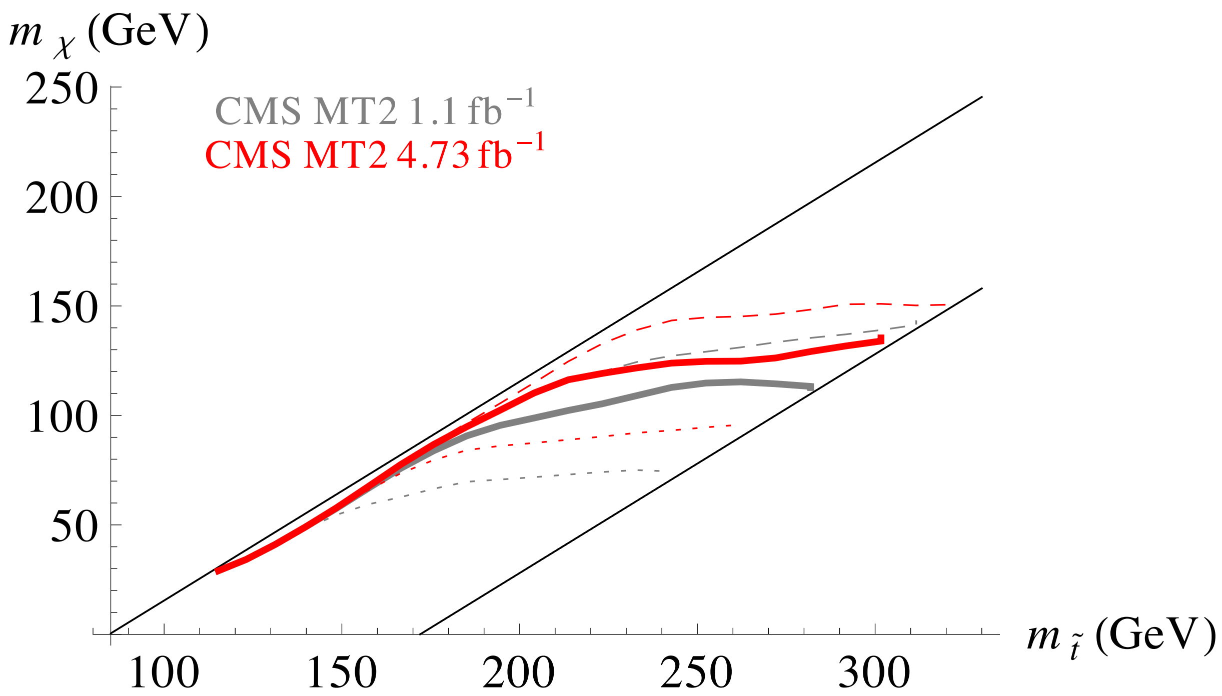


- Similar result in [Delgado, Giudice, Isidori, Pierini, Strumia '12] .

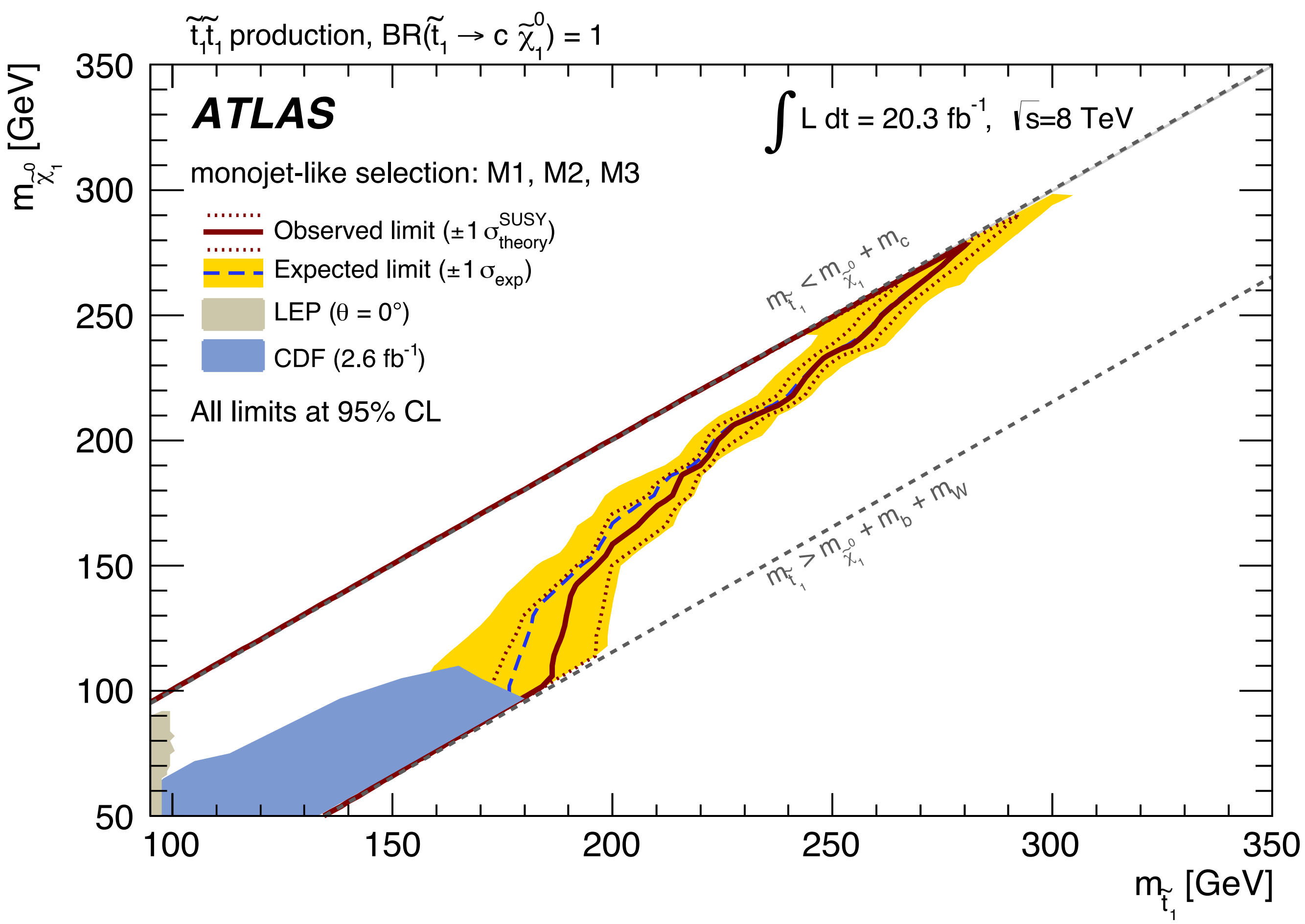
3B Stop Decays

- Covers a different kinematic region.

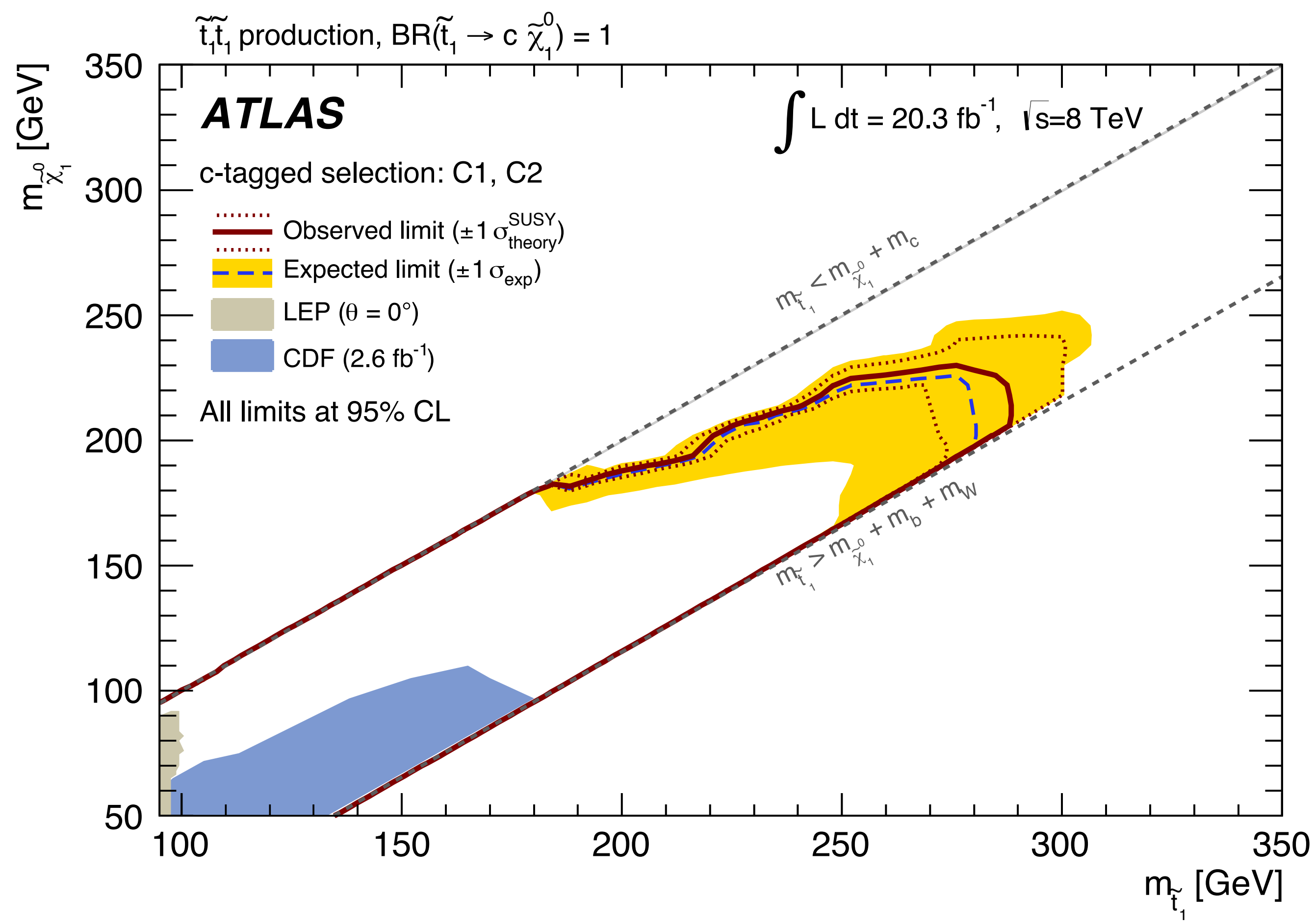




ATLAS FV Stop Searches

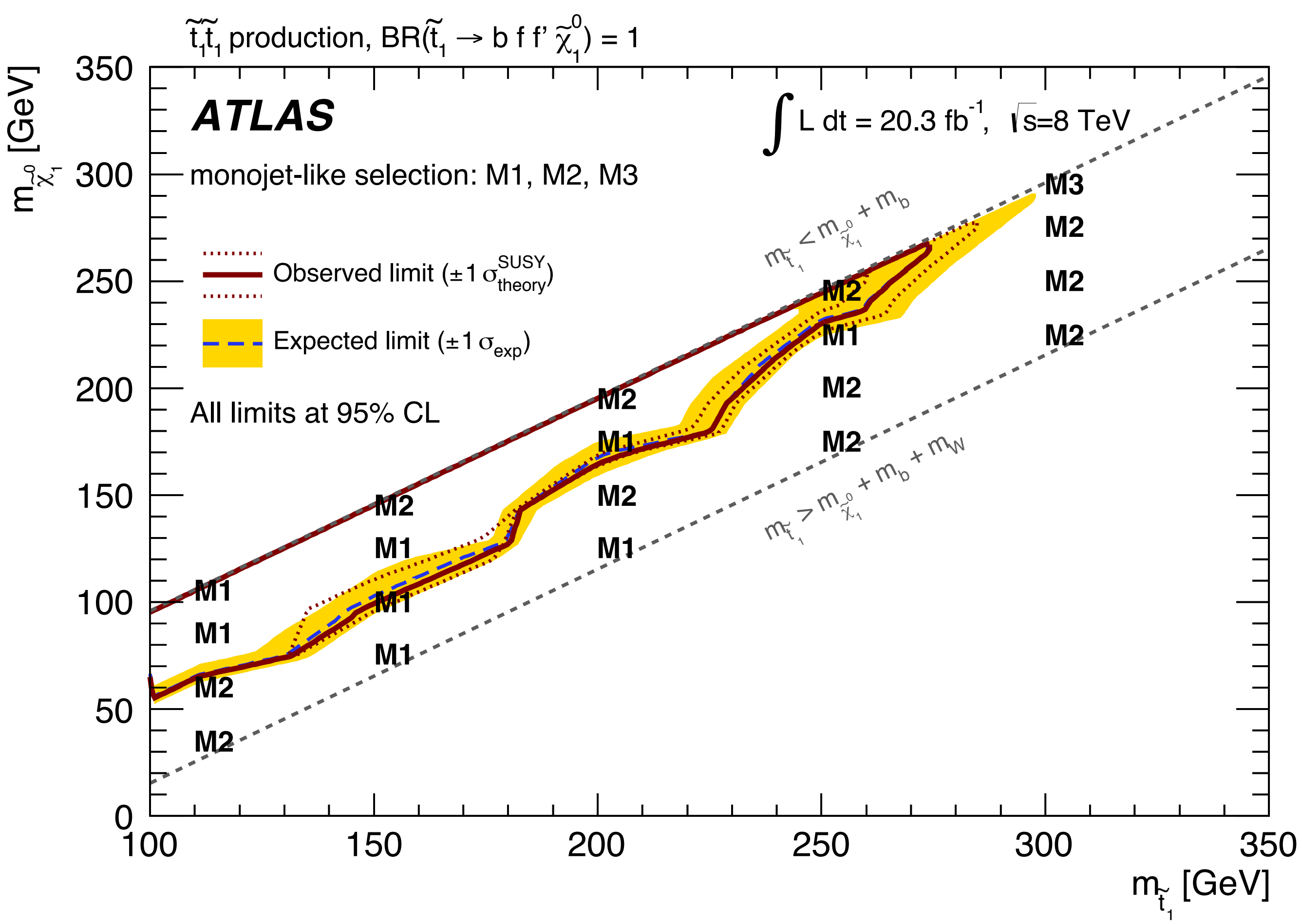


monojet

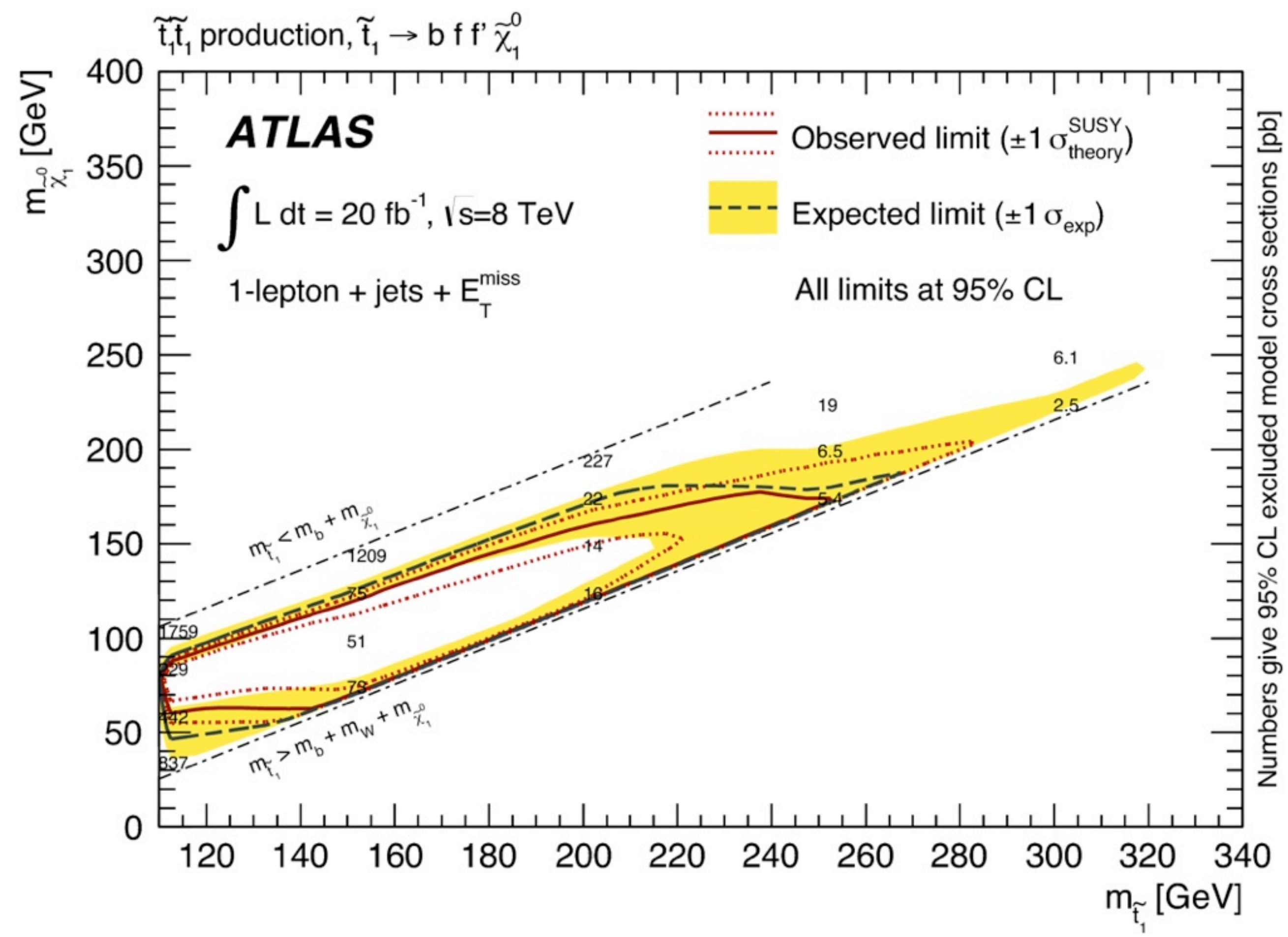


c-tag

ATLAS 4B Decay Searches



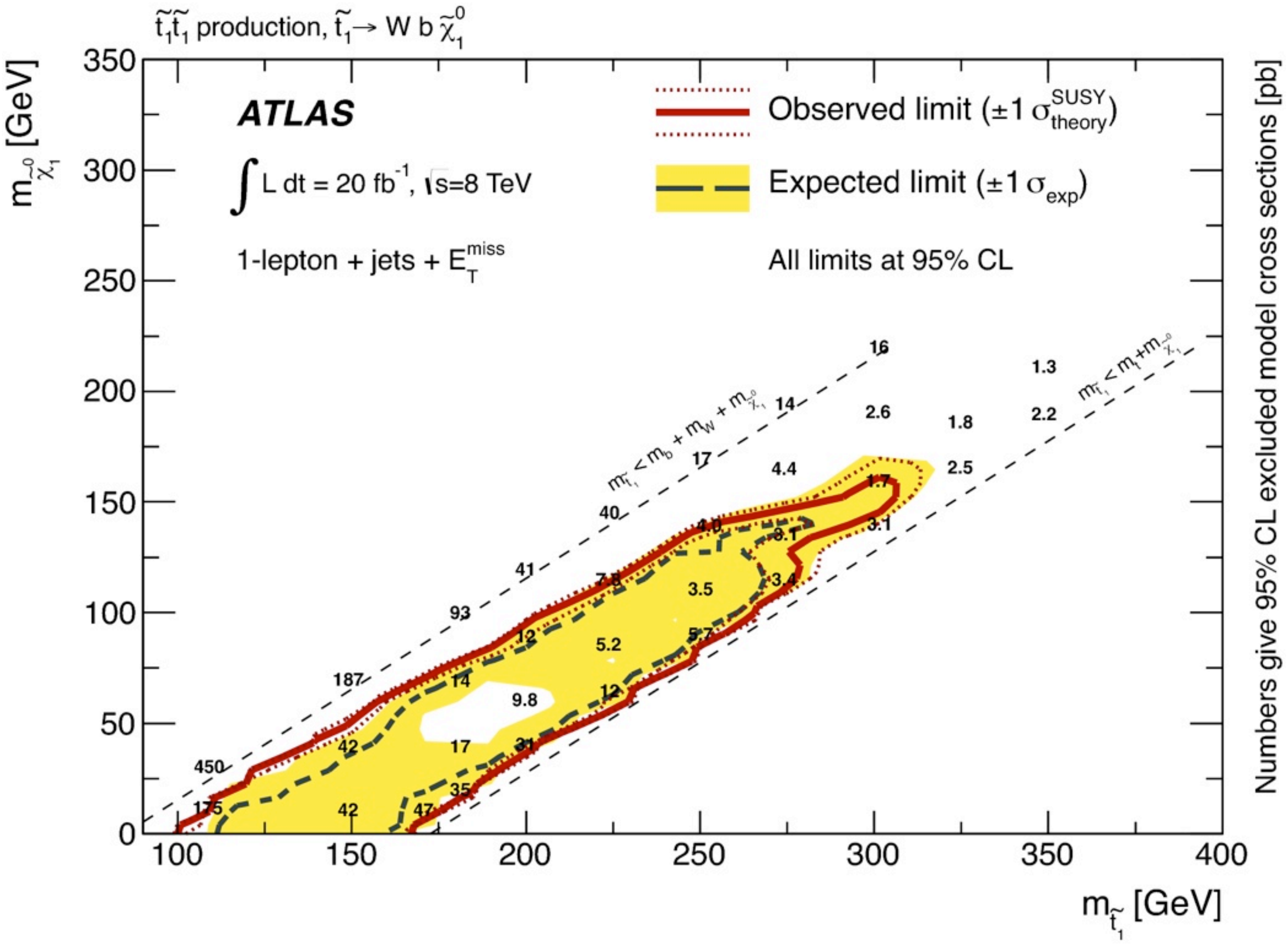
monojet

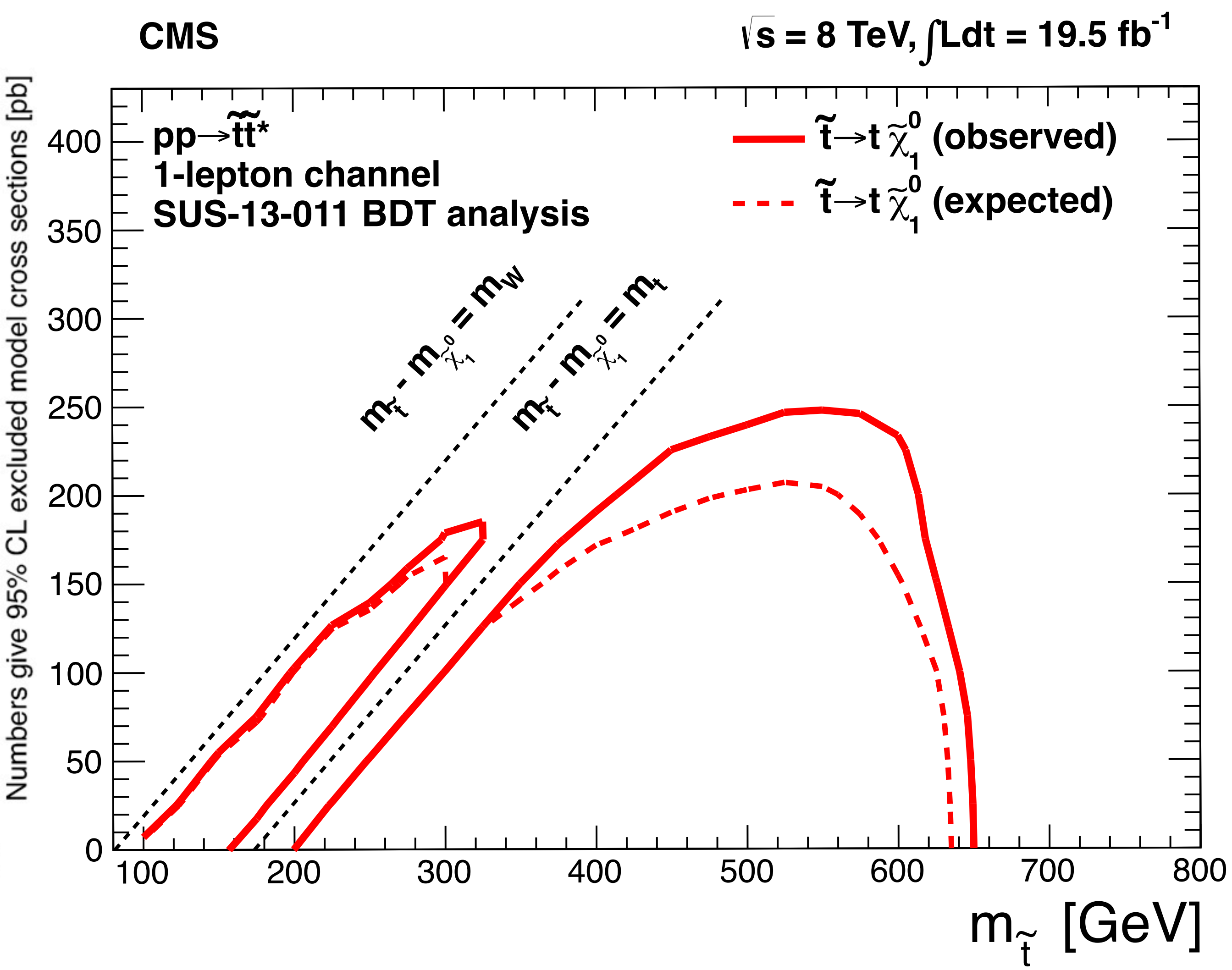


b + l + MET

TRIUMF

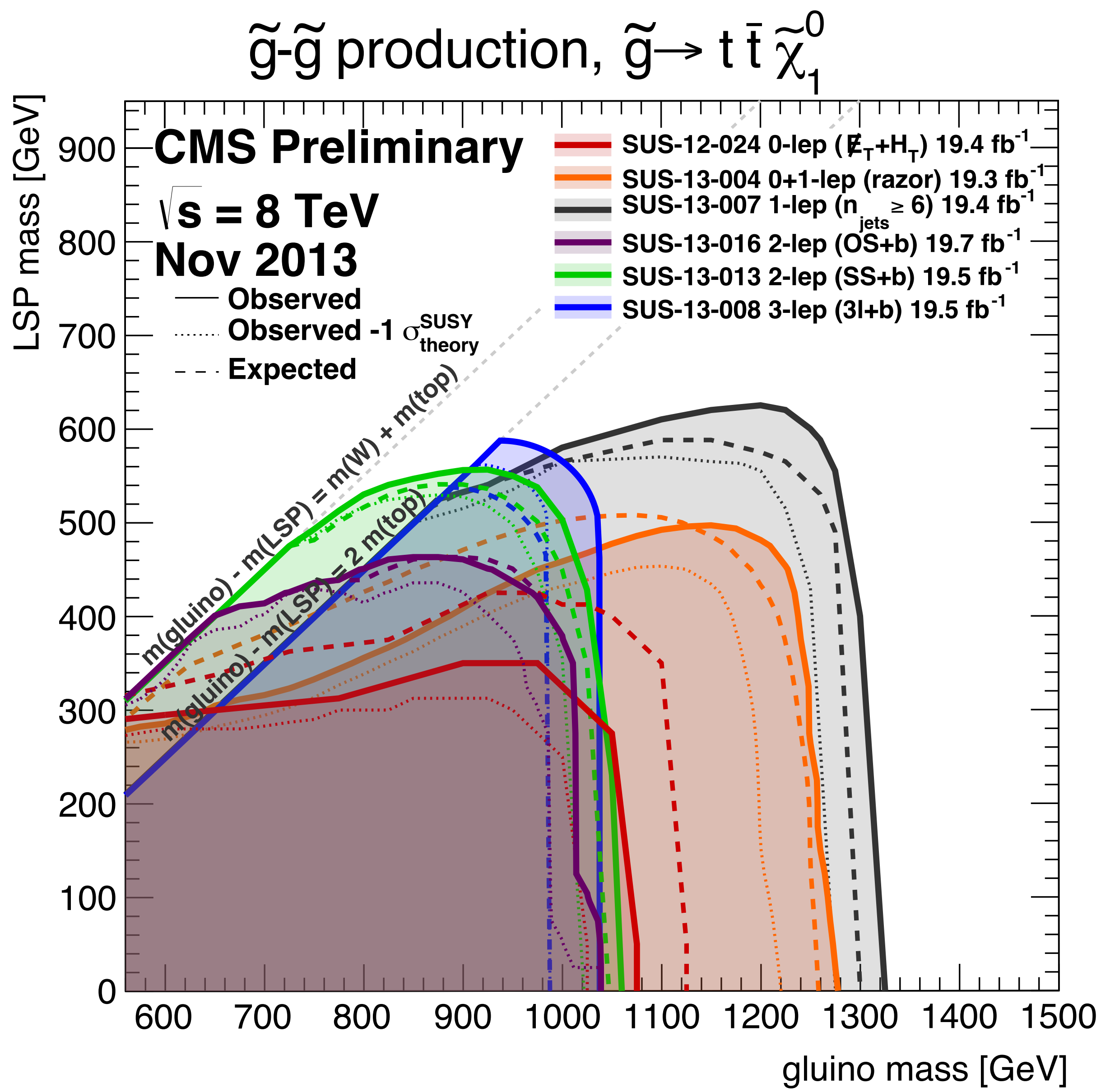
ATLAS/CMS 3B Searches in b + (1,2)l + MET





LHC Gluino to Top-Stop [Kraml+Raklev '06]

- Assumes $pp \to \tilde{g}\tilde{g}$ with $\tilde{g} \to \tilde{t}t,\ \tilde{t} \to t\chi_1^0$.



- Limits should weaken if stops decay differently.

Stoponium [Drees+Nojiri '97; Martin '08; Barger, Ishida, Keung '11]

- $\eta_{\tilde{t}_1} = \tilde{t}_1^* \, \tilde{t}_1^*$ bound state.

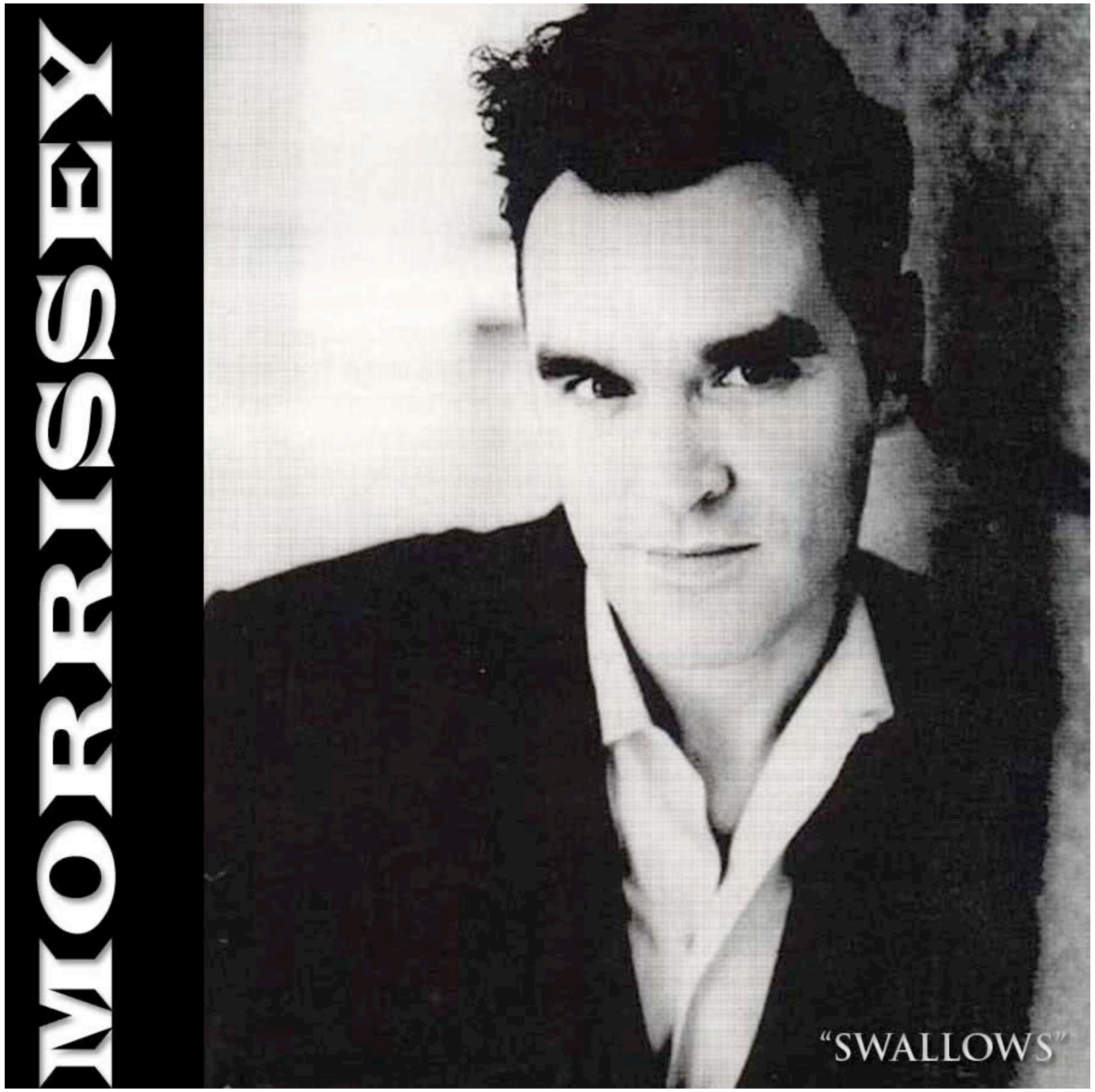
- $\underbrace{\Gamma_{\tilde{t}_1 \to c\chi_1^0}}_{\sim \mathrm{eV}} \ll \underbrace{\eta_{\tilde{t}_1} = \text{binding energy}}_{\sim \mathrm{GeV}}$

- $\eta_{\tilde{t}_1} \to \gamma\gamma, \, WW, \, ZZ$ via stop-Higgs coupling

  $\eta_{\tilde{t}_1} \to gg, \, \gamma\gamma$ via direct stop couplings

- But $\eta_{\tilde{t}_1} \to hh$ can be a spoiler mode.

A Famous Mancunian



No relation (as far as I know).