Split SUSY at LHC and a 100 TeV collider

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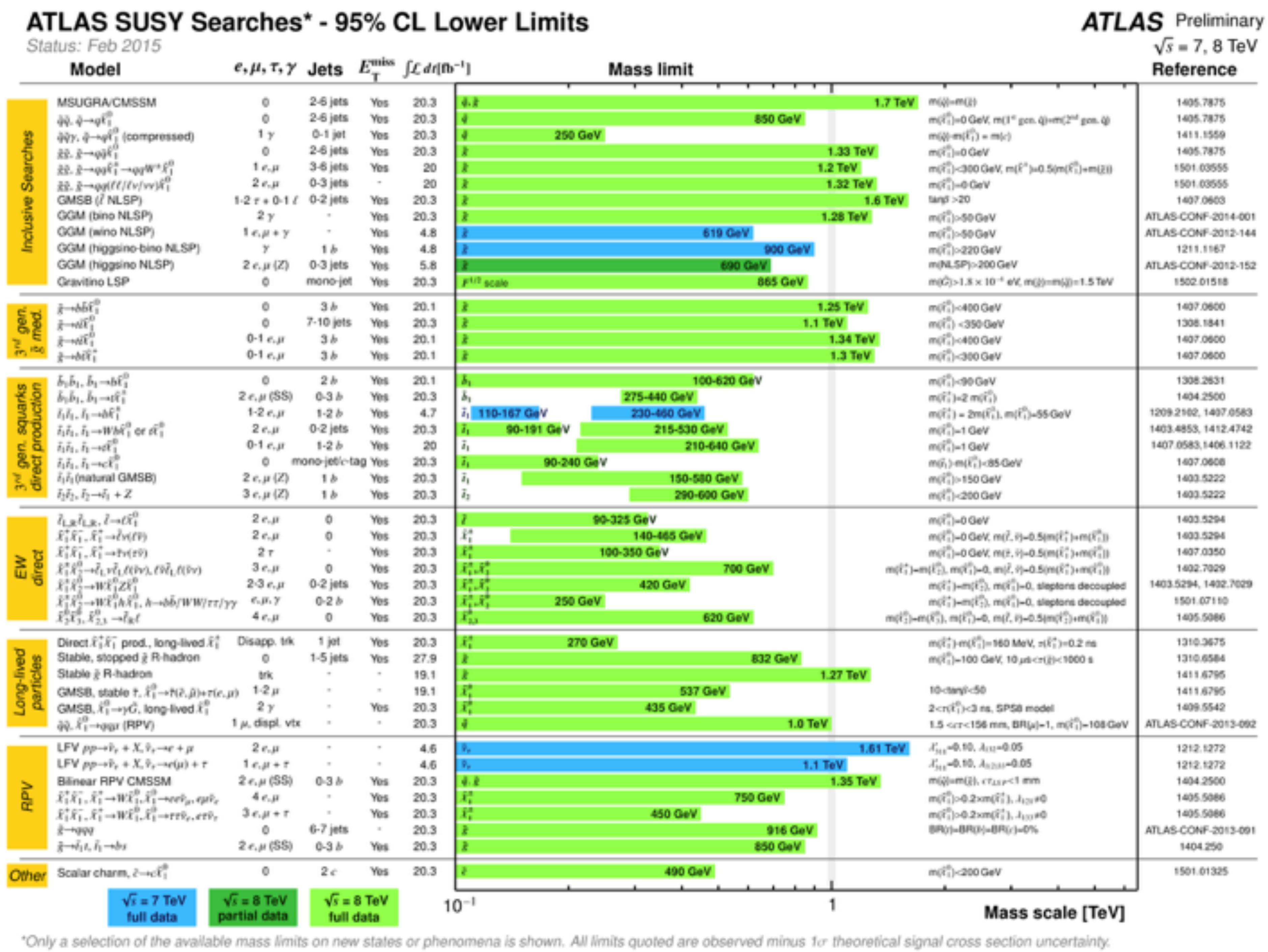
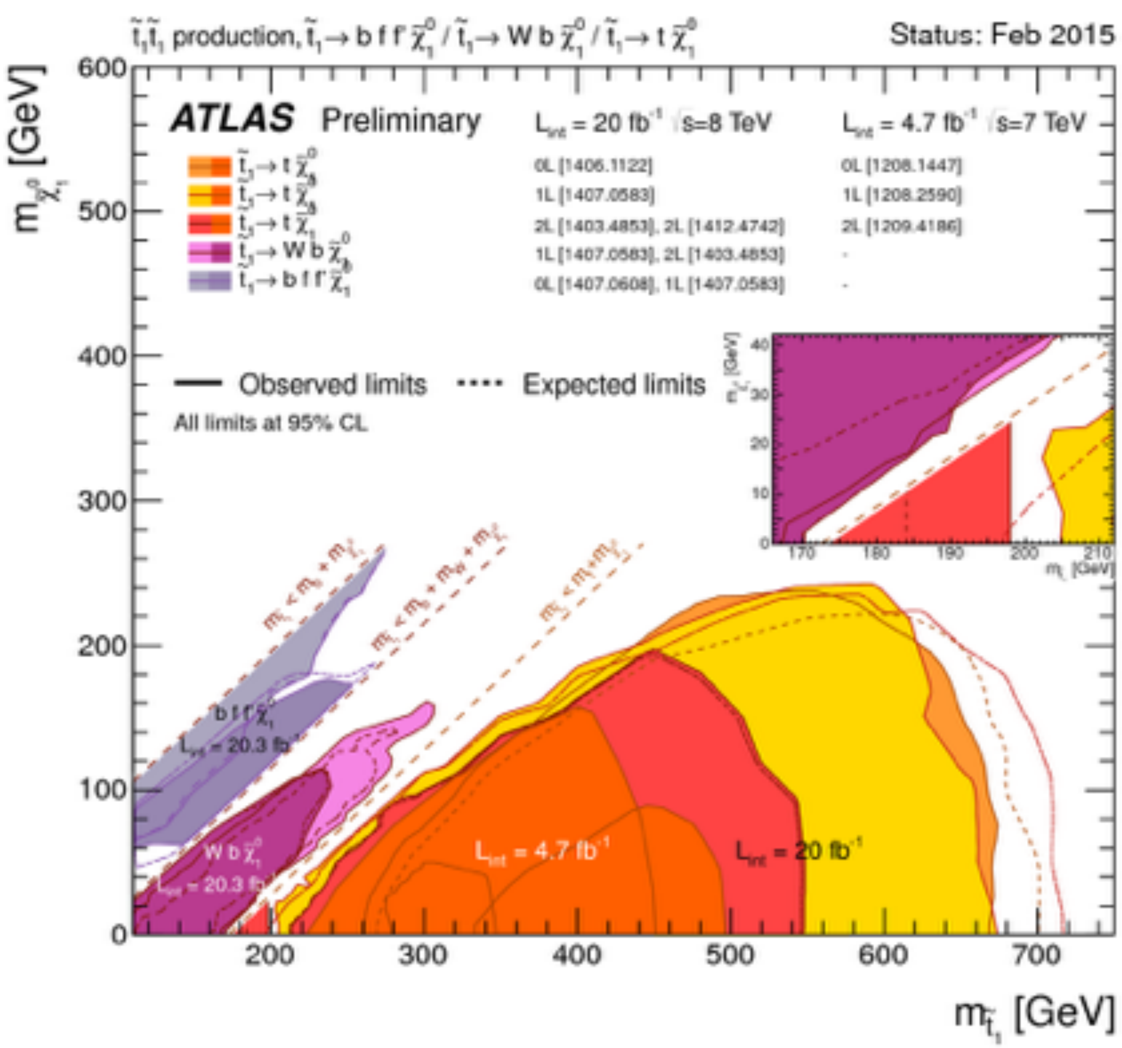
1503.03099

GGI - 2015

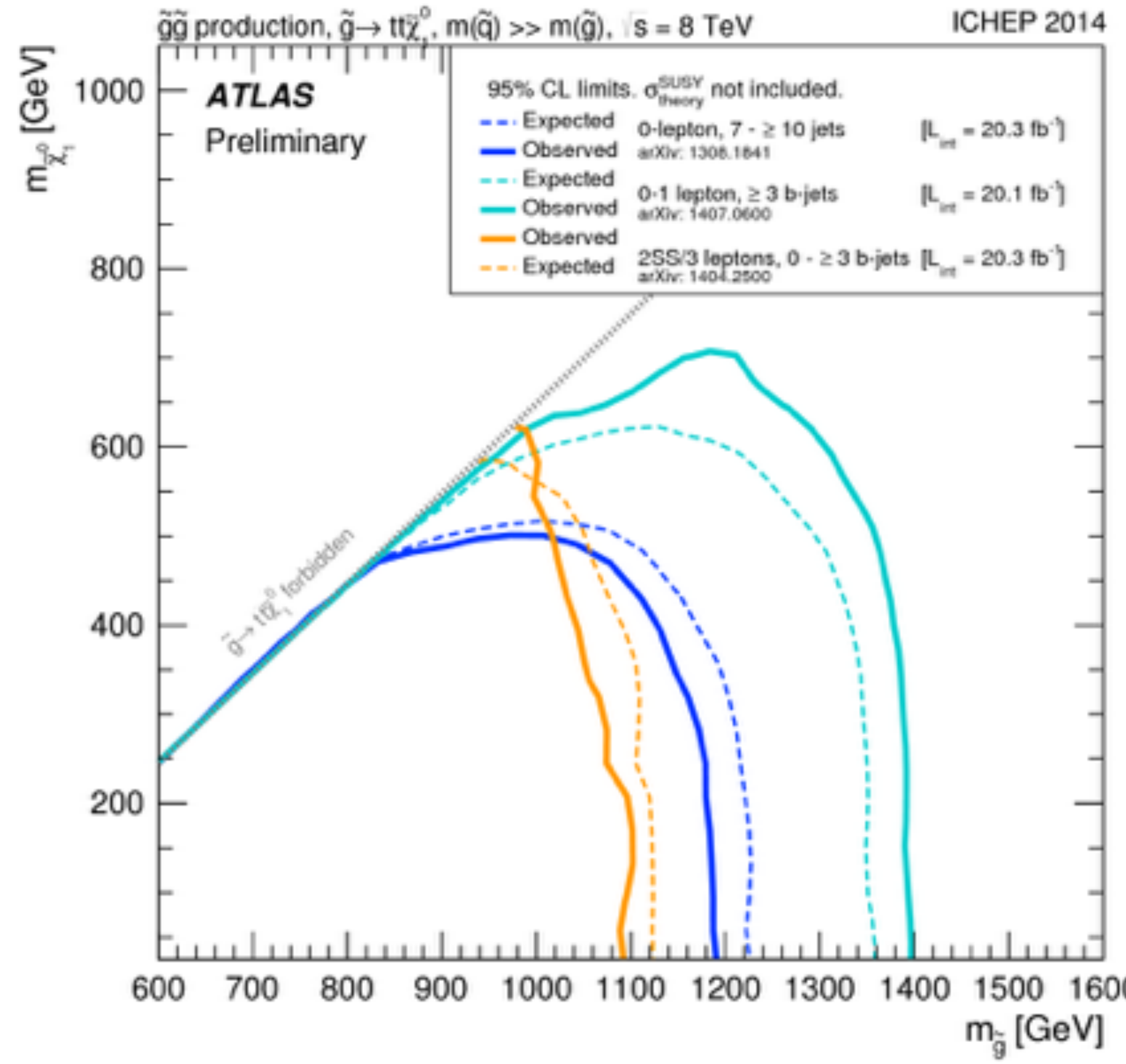
Status of Supersymmetry



stop searches



gluino searches



$$m_{\tilde{t}} \gtrsim 700\text{GeV}$$

$$m_{\tilde{g}} \gtrsim 1.4\text{TeV}$$

What does it mean for naturalness?

‘natural SUSY’ (stop,gluino,higgsino)

Papucci, Ruderman,Weiler ‘11

stop

$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log \left(\frac{\Lambda}{\mathrm{TeV}} \right)$$

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\mathrm{GeV} \left(\frac{\Delta^{-1}}{20\%} \right)^{-1/2}$$

gluino

$$\delta m_h^2 = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi} \right) M_3^2 \log^2 \left(\frac{\Lambda}{\mathrm{TeV}} \right)$$

$$M_3 \lesssim 900 \text{ GeV} \sin\beta \left(\frac{\Delta^{-1}}{20\%} \right)^{-1/2}$$

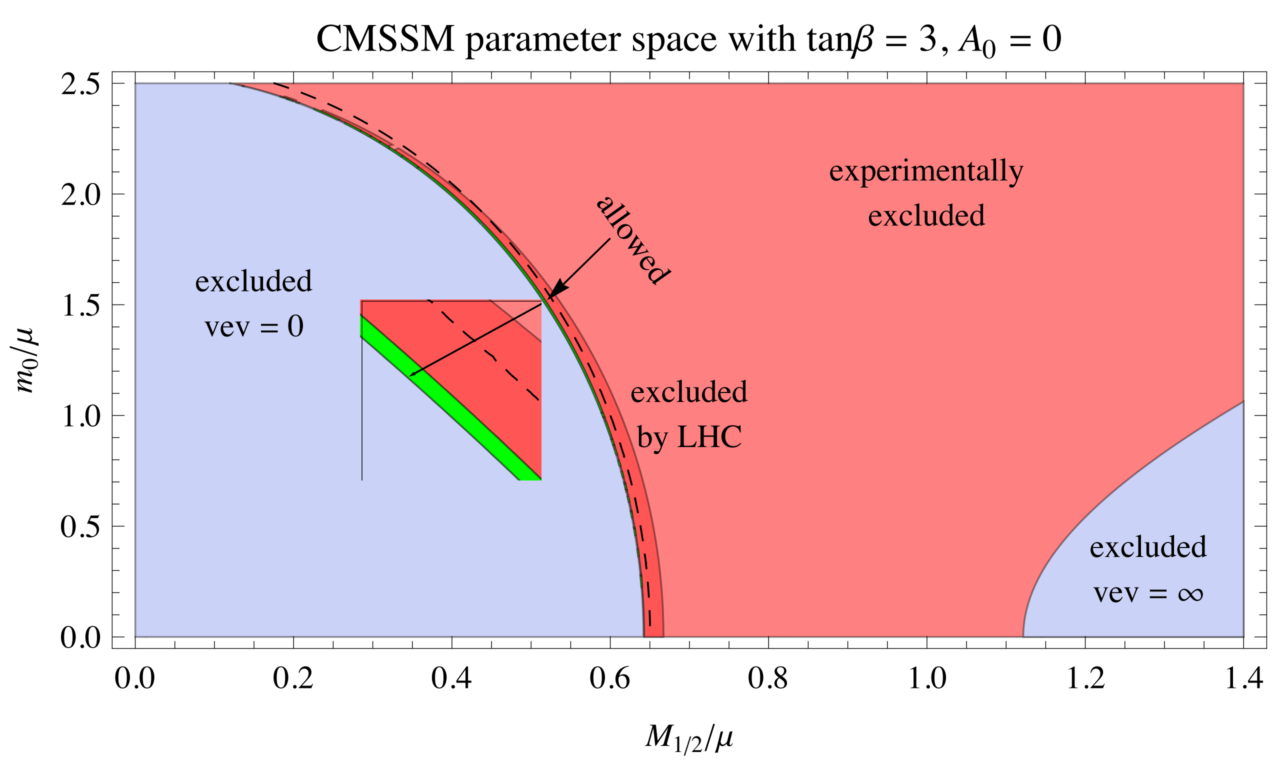
125 Gev Higgs : prefers heavy stops

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

~ 1-10 TeV stop depending on A-term

More complete models generally yield %-level fine-tuning

CMSSM



Strumia ‘11

NMSSM, split generation, low-scale mediation, Dirac gaugino, and R-parity breaking are generically tuned.

Arvanitaki, Baryakhtar, Huang, Tiburg, Villadoro ‘13

Better model building might save the day

Scherk-Schwartz SUSY breaking — Dimopoulos, March-Russell ‘14

Compressed spectrum — LeComte, Martin ‘11; Dimopoulos, March-Russell, Scoville ‘14

Stealth supersymmetry — Fan, Reece,Ruderman ‘11

Twin Higgs — Chacko, Goh, Harnik ‘05; Craig, Howe ‘13

Dirac gauginos

In the MSSM gauginos are Majorana

$$M\lambda\lambda$$

$$F_X\theta^2$$

$$\int d^2\theta X W_\alpha W^\alpha$$

Can be Dirac if new superfields are added

$$W^1_\alpha, W^2_\alpha, W^3_\alpha \qquad S, T, G$$

$$M_D \lambda \Psi$$

N=2 supersymmetry

extra-dimension

Supersoft SUSY breaking

Fox, Nelson, Weiner '02

$D'\theta_\alpha$

D-term breaking

$$\int d^2\theta W'_\alpha W_i^\alpha \Phi_i$$

Dirac gauginos do not feed into scalar masses through renormalization

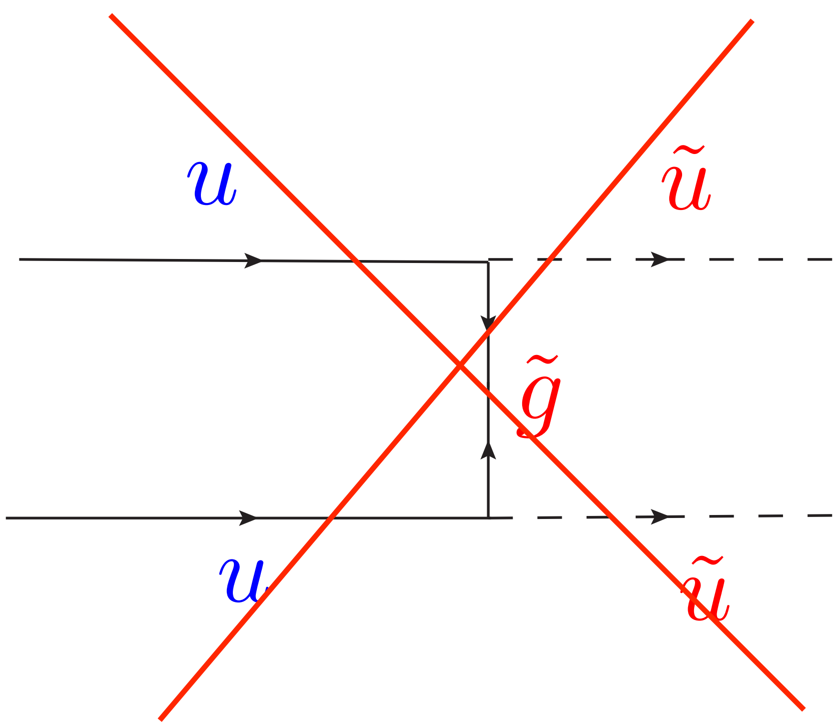
$$m^2 = \frac{C_i\left(r\right)\alpha_i m_i^2}{\pi}\log\left(\frac{\delta^2}{m_i^2}\right)$$

They can be naturally heavier than scalars

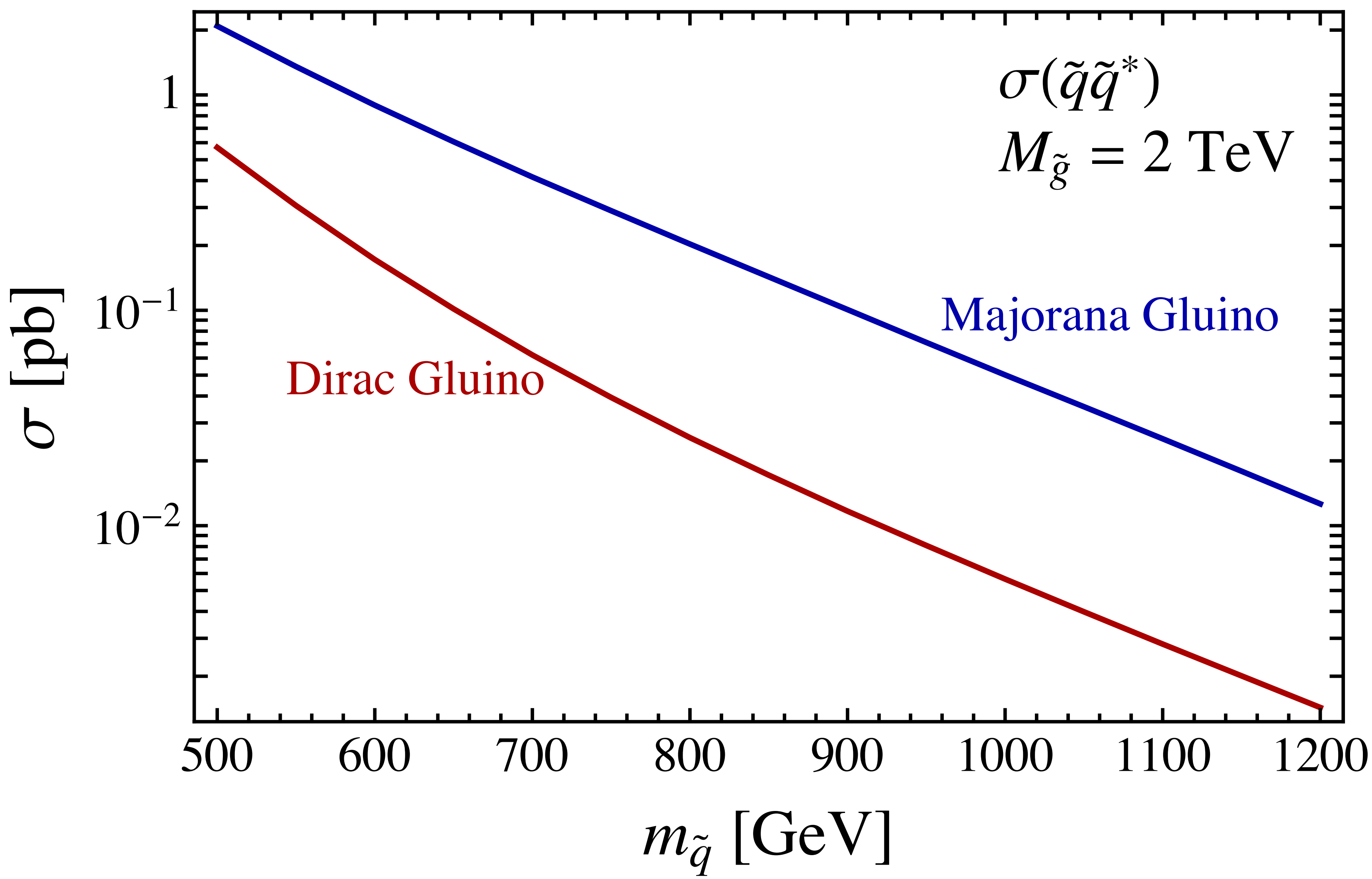
LHC will have a harder time seeing the gluino...

M. Heikinheimo, M. Kellerstein, V. Sanz '12
Kribs, Martin '12

...and squarks



Squark production



Frugiuele, T.G., Kumar, Ponton

R-symmetry

With Dirac gaugino: possible to impose an U(1) R-symmetry

$$M_D \lambda \Psi$$

Kribs,Poppitz,Weiner '02

- Bounds from FCNC are weaker: off diagonal m_{ij}

$$R[Q, U^c, D^c, L, E^c] = 1 \qquad R[H_u, H_d] = 0$$

$$\cancel{\mu H_u H_d}$$

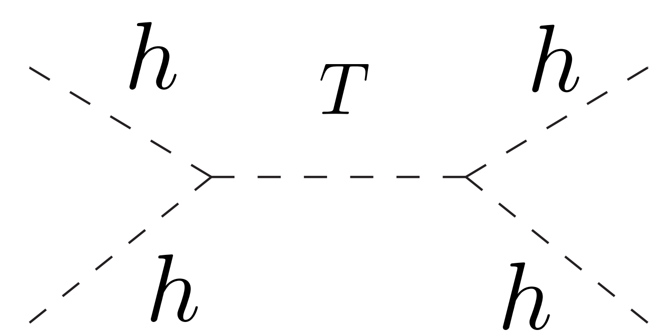
Higgs mass

Tree-level:

Reduced quartic, usual of Dirac gauginos

$$\int d^2\theta W'_\alpha W_i^\alpha \Phi_i \quad \longrightarrow \quad D_2 = M_2 T^a + H_u^\dagger \sigma^a H_u + \ldots$$

When the scalar T is integrated out:



$$\boxed{\lambda \to 0}$$

Higgs quartic

If the mass of T is set by M_2 and $\lambda_T = 0$

No help (at tree-level) from

$$\lambda_T H_u T R_d + \lambda_S H_u S R_d$$

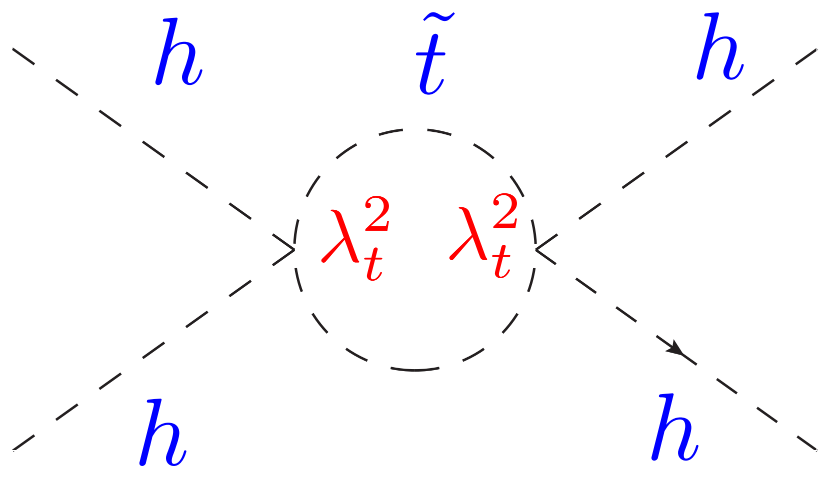
don't get a vev (In the limit of exact R-symmetry)

But do help in models without an R-symmetry

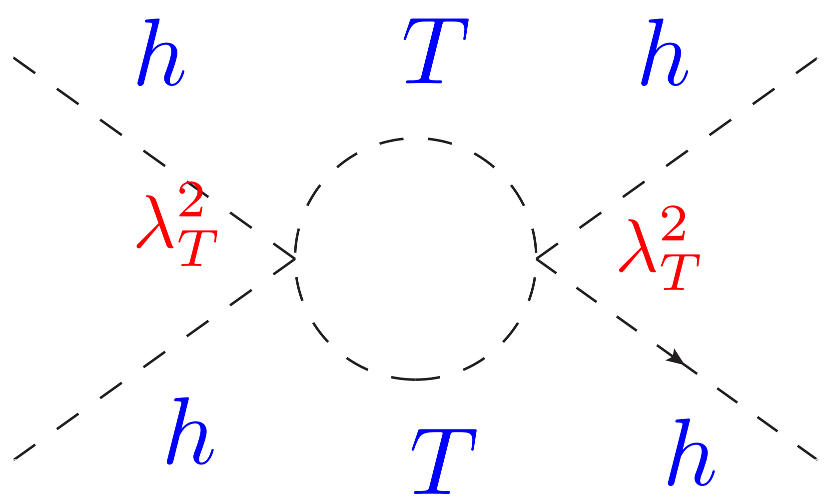
Benakli, Goodsell, Staub 1211.0552

Loop-level

Usual stop correction (but A-terms are 0)



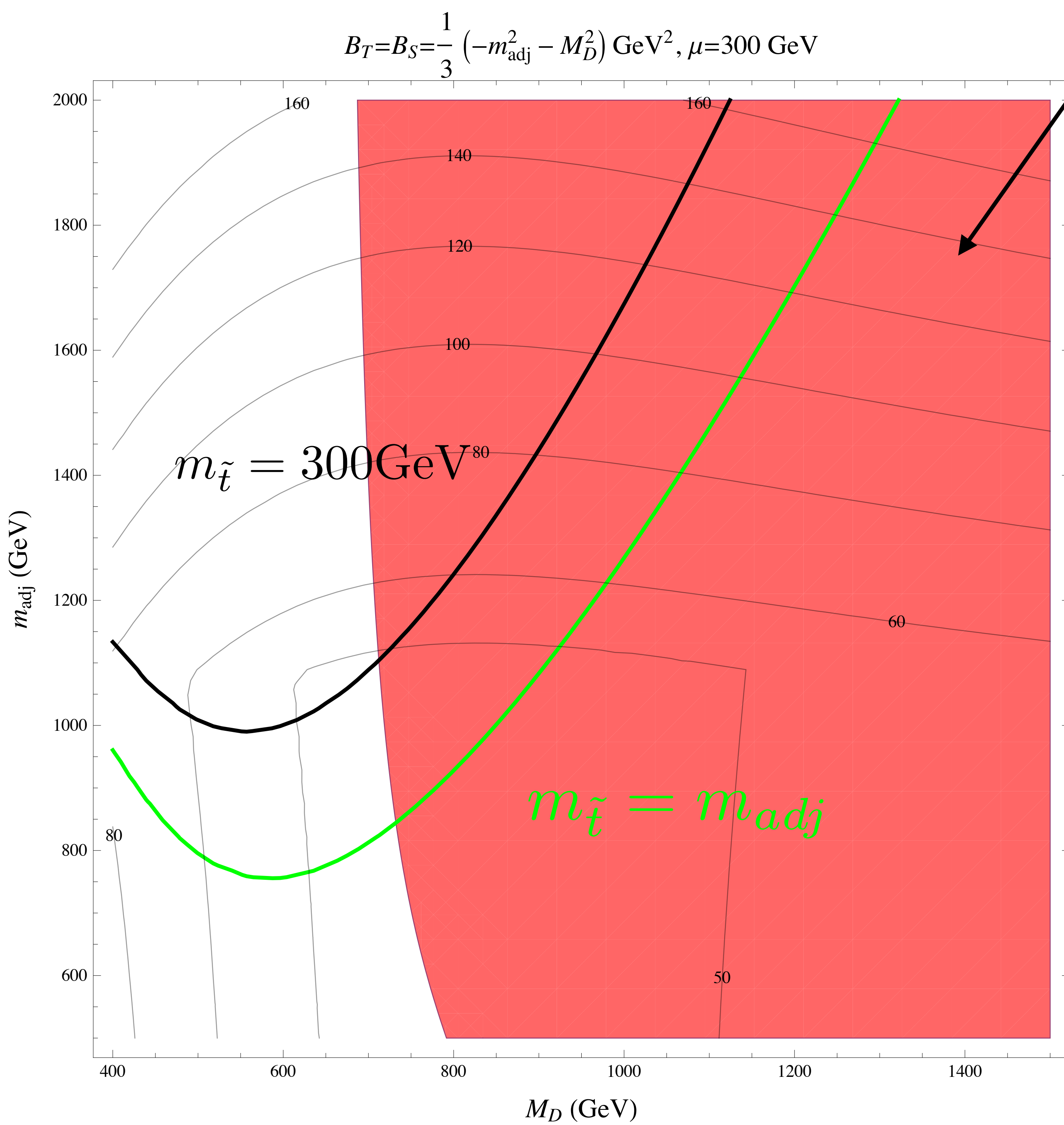
Similar loop from the triplet



$$V_{\mathrm{CW}} \sim \frac{1}{16\pi^2}\left(5\lambda_T^4 \log\frac{m_T^2}{M_2^2} + 3\lambda_t^4 \log\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

Very sensitive to λ_T

….but so are electroweak precision measurements allowed by EWPT



Bertuzzo, Frugiuele, T.G., Ponton

Arkani-Hamed, Dimopoulos '05

Split Supersymmetry

Naturalness might not be a good guide

SUSY might still be relevant

- Dark matter
- Gauge coupling unification
- 'UV' reasons

Gauginos and scalars might not be at the same mass scale

natural in for example anomaly mediation

Prediction for the Higgs mass

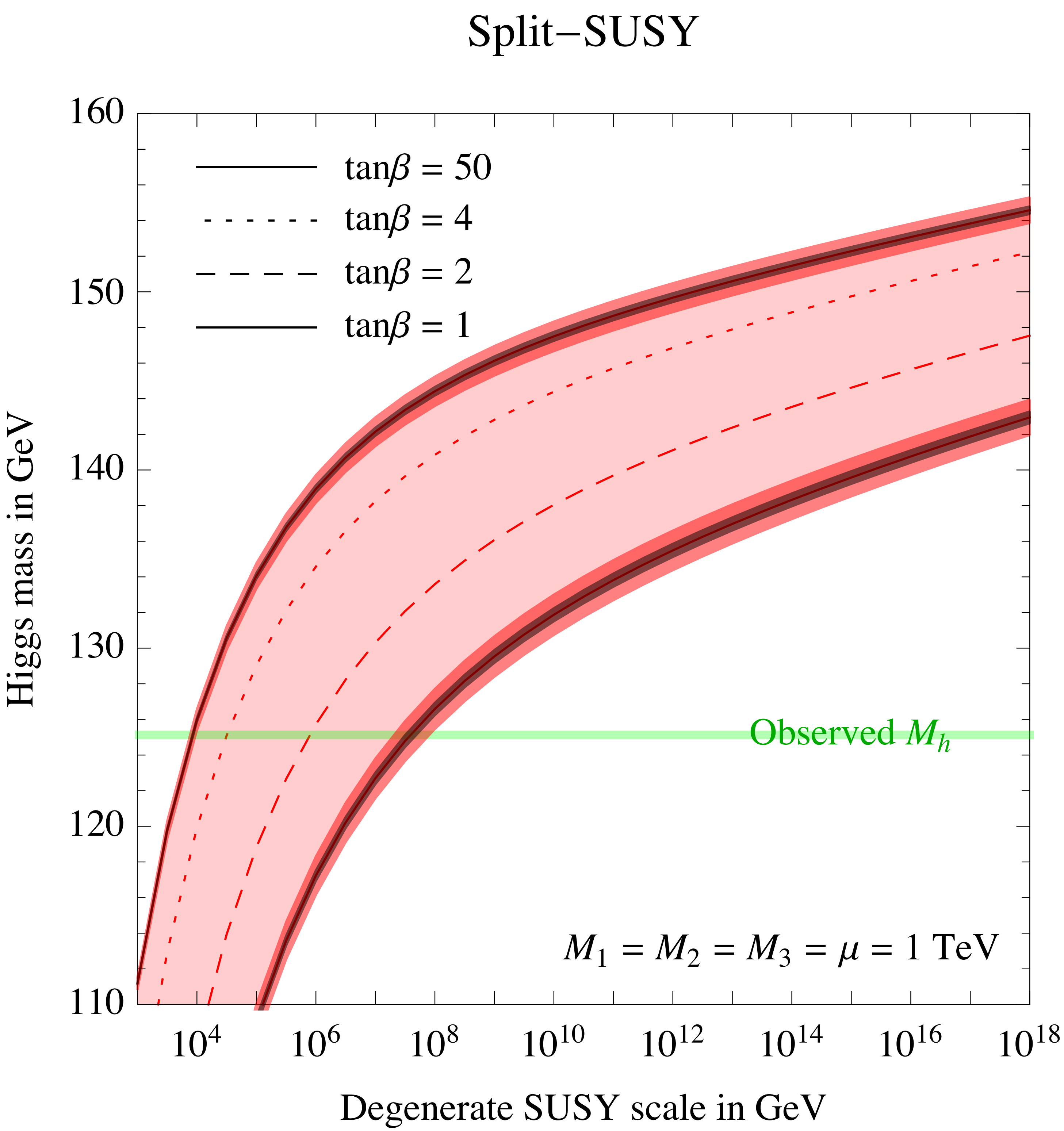
The Higgs quartic coupling is predicted at a high scale:

$$\lambda(m_{\rm scalar}) = \frac{1}{4}(g^2 + g'^2)\cos^2\beta \qquad \text{tree-level}$$

SUSY $\longrightarrow$ Split SUSY $\longrightarrow$ MSSM

thresholds running thresholds

Bagnaschi,
Giudice,Slavich,Strumia
'14



Bagnaschi, Giudice,Slavich,Strumia '14

Arvanitaki, Craig, Dimopoulos, Villadoro '12

Mini-split in anomaly mediation

scalar masses are generated by gravity mediation

$$\int d^4\theta \frac{X^\dagger X Q^\dagger Q}{M_{pl}^2} \qquad m^2 = m_{3/2}^2$$

but the gaugino masses are generated by AMSB

$$M_i = \frac{b_i}{16\pi^2} g_i^2 m_{3/2} \qquad \cancel{\int d^2\theta \frac{X W_\alpha W^\alpha}{M_{pl}}}$$

μ -term generated through Giudice-Masiero

conformal compensator

$$\int d^4\theta \phi^\dagger \phi H_u H_d$$

$$\mu \sim \frac{B_\mu}{\mu} \sim m_{3/2}$$

Heavy Higgsino

Similar spectrum could also arise in
gauge mediation

Arvanitaki, Craig, Dimopoulos, Villadoro '12
Buican, Meade, Seiberg, Shih '09

$$W = M_R\left(\phi_1\bar{\phi}_1 + \phi_2\bar{\phi}_2\right) + X\phi_1\phi_2$$

$$M_i \sim \frac{g_i^2}{16\pi^2}\frac{M}{M_R}\frac{F^3}{M_R^3} = \frac{g_i^2}{16\pi^2}\Lambda$$

We take the scalars at $\sim \Lambda$

Gaugino spectrum
(deflected AMSB)

Higgsino
threshold

$$M_{\tilde{B}} = M_1 \left[1 + \frac{C_\mu}{11} + \cdots\right]$$

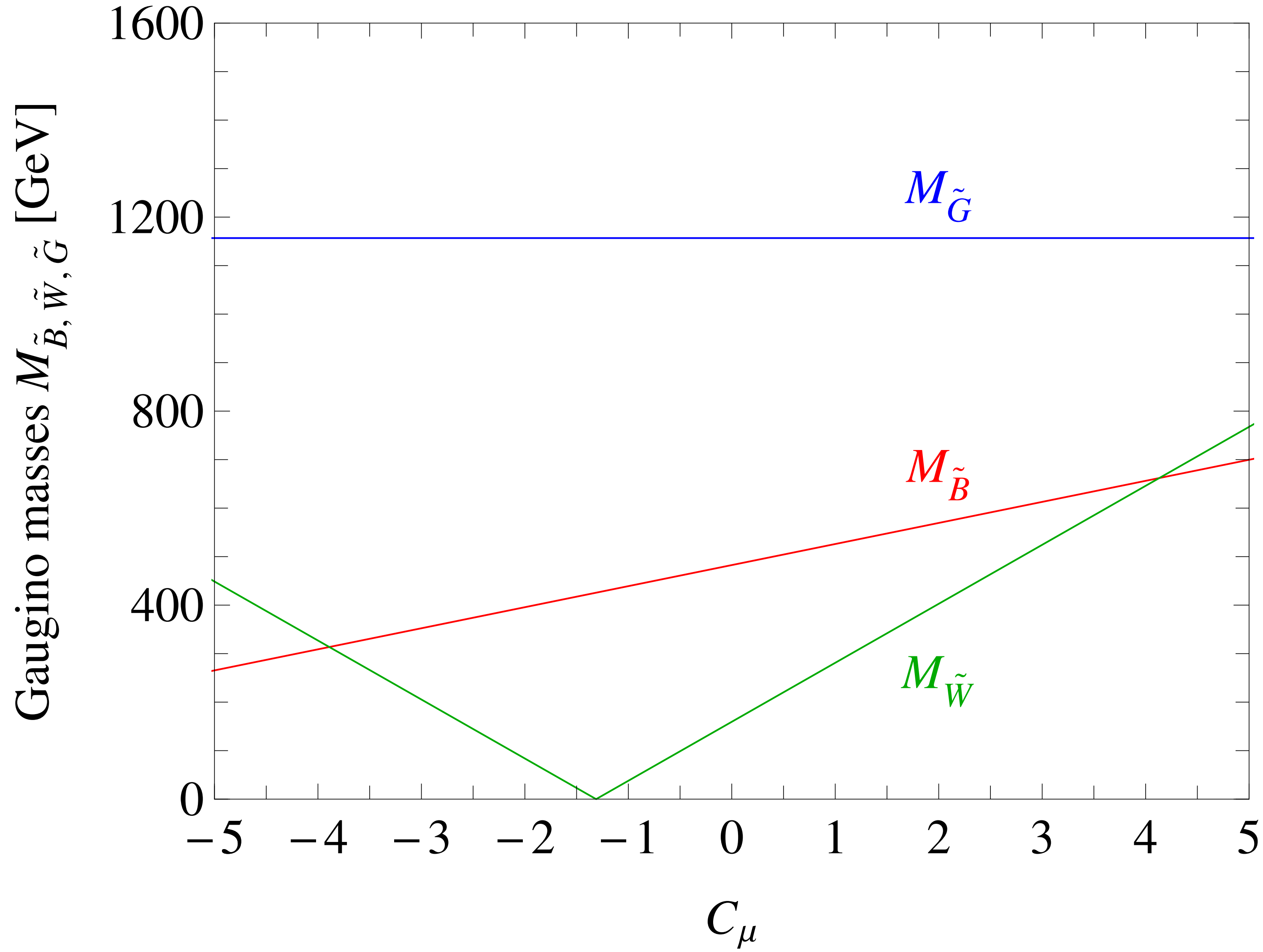
$$M_{\tilde{W}} = M_2 \left[1 + C_\mu + \cdots\right]$$

$$M_{\tilde{g}} = M_3 \left[1 + \cdots\right]$$

$$M_i = \frac{\beta_i}{g_i} m_{3/2} \qquad C_\mu = \frac{\mu}{m_{3/2}} \frac{m_A^2 \sin^2\beta}{m_A^2 - \mu^2} \ln \frac{m_A^2}{\mu^2}$$

AMSB Gaugino spectrum

Beauchesne, Earl, T.G. ‘15



Parametrize deflection from AMSB spectrum

Similar expressions for gauge mediation

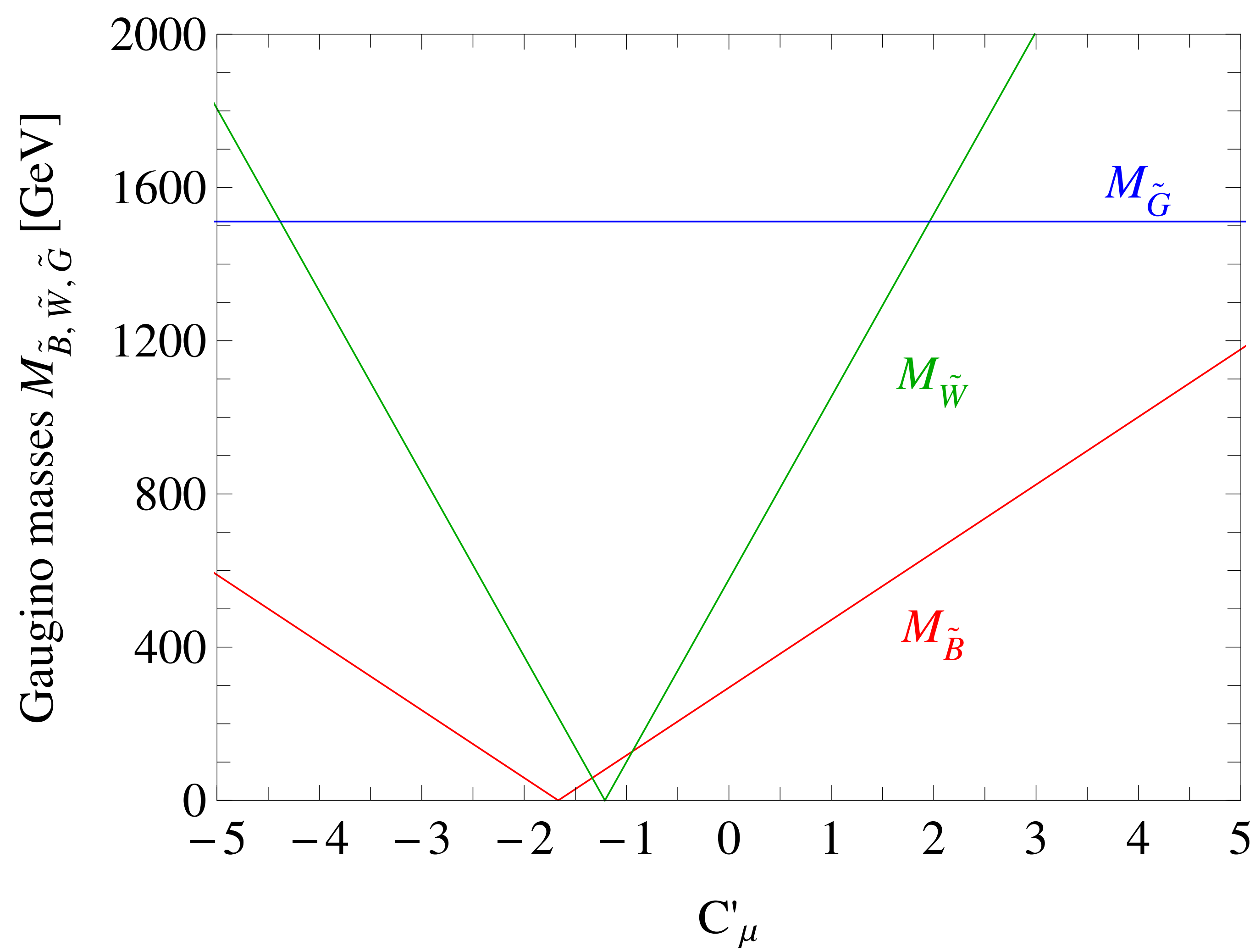
$$M_{\tilde{B}} = M_1 \left[1 + \frac{3C'_\mu}{5} + \cdots \right]$$

$$M_{\tilde{W}} = M_2 \left[1 + C'_\mu + \cdots \right]$$

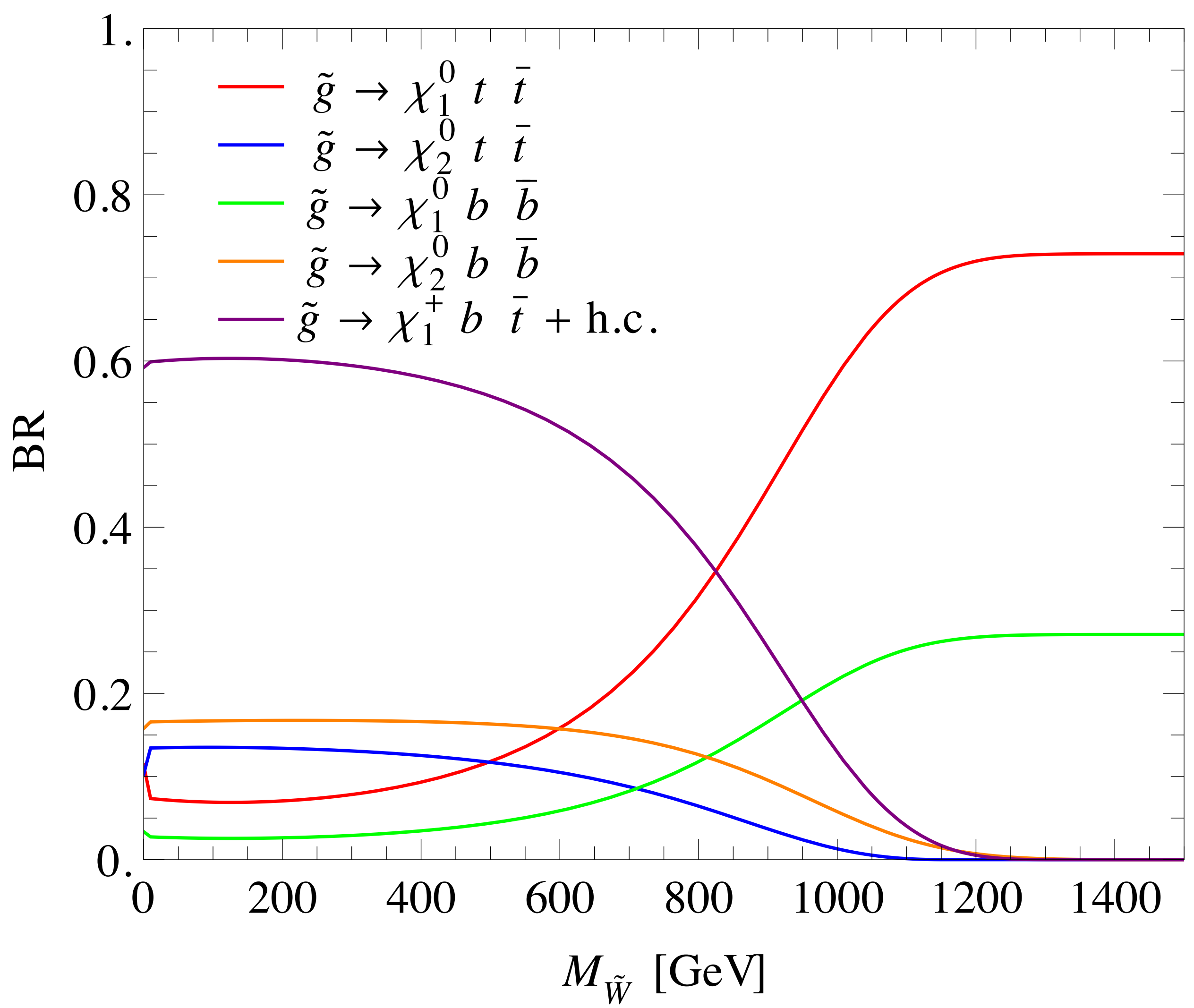
$$M_{\tilde{g}} = M_3 \left[1 + \cdots \right]$$

$$M_i = \frac{g_i^2}{16\pi^2}\Lambda \qquad C'_\mu = \frac{\mu}{\Lambda} \frac{m_A^2 \sin^2\beta}{m_A^2 - \mu^2} \ln \frac{m_A^2}{\mu^2}$$

Similar expressions for gauge mediation



Assume that gluino decay to 3rd generation quarks



$$m_{\tilde{B}} = 0 \text{ GeV}$$

$$m_{\tilde{G}} = 1.5 \text{ TeV}$$

Electroweakino decays

$$\tilde{W}^0 \to \tilde{B} h$$

$$\tilde{W}^+ \to W^+ \tilde{B}$$

bino LSP

$$\tilde{B} \to \tilde{W}^0 h$$

$$\tilde{W}^+ \to W^0 + \mathrm{soft}$$

wino LSP

Parameter space

parameters of the model:

$m_{3/2}$ μ $\tan\beta$ $m_{\rm scalar}$

choose: $m_{\rm scalar} \sim m_{3/2}$

set $\tan\beta$ to reproduce the Higgs mass

results in term of

C_μ and $m_{3/2}$

Recasting LHC bounds

Gaugino spectrum and branching ratios are obtained as a function of $m_{3/2}$ and C_μ.

we simulate the signal using MadGraph-Pythia-Delphes and recast LHC searches

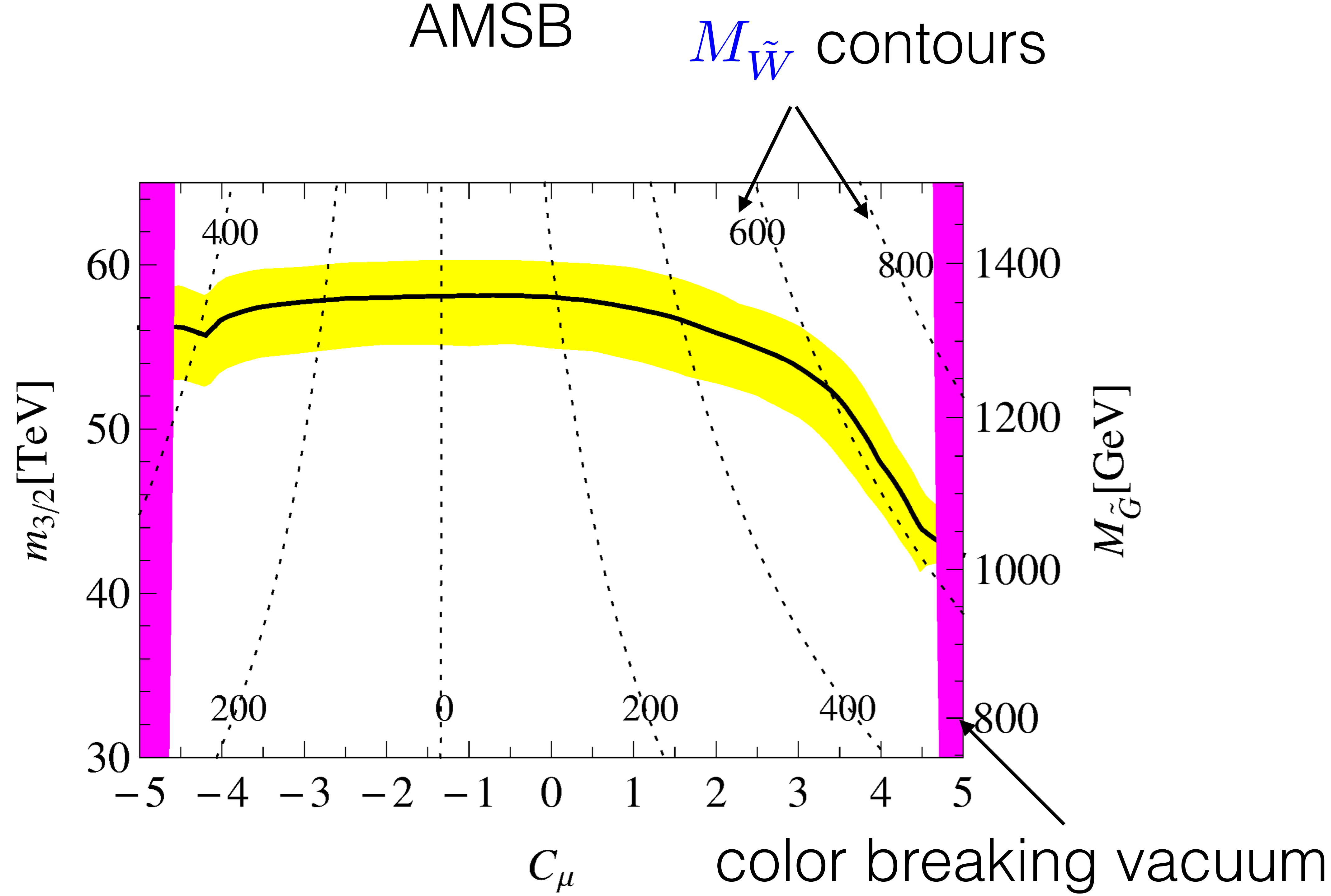
ATLAS multi-leptons+b-jets

ATLAS 0-1 lepton+b-jets

CMS high jets multiplicity

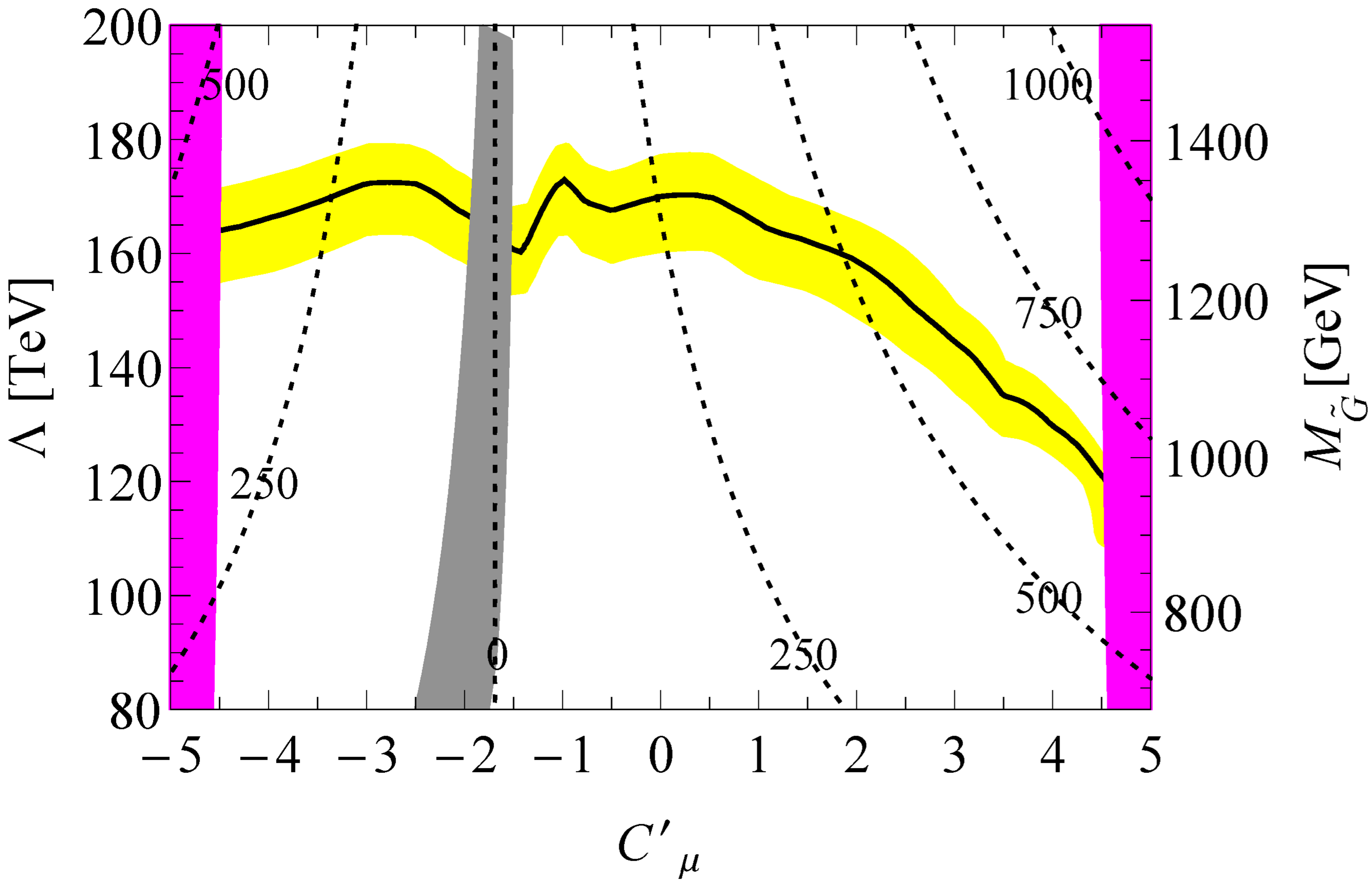
CMS 2 OS leptons+jets

AMSB



Beauchesne, Earl, T.G. '15

Gauge mediation



LHC 14 prospects

looked at 2 sets of cuts

same-sign dilepton

cohen et al. 1311.6480

- SSDL
- 2 b-jets or more
- 6 jets or more
- $H_T > 700\mathrm{GeV}$
- $E_T^{\mathrm{miss}} > 250\mathrm{GeV}$

8 signal regions

High missing energy

CMS-PAS-FTR-13-014

- 1 lepton
- 6 jets or more
- 1 b-jet
- $H_T > 500\mathrm{GeV}$
- $E_T^{\mathrm{miss}} + P_T^{\mathrm{lep}} > 450\mathrm{GeV}$

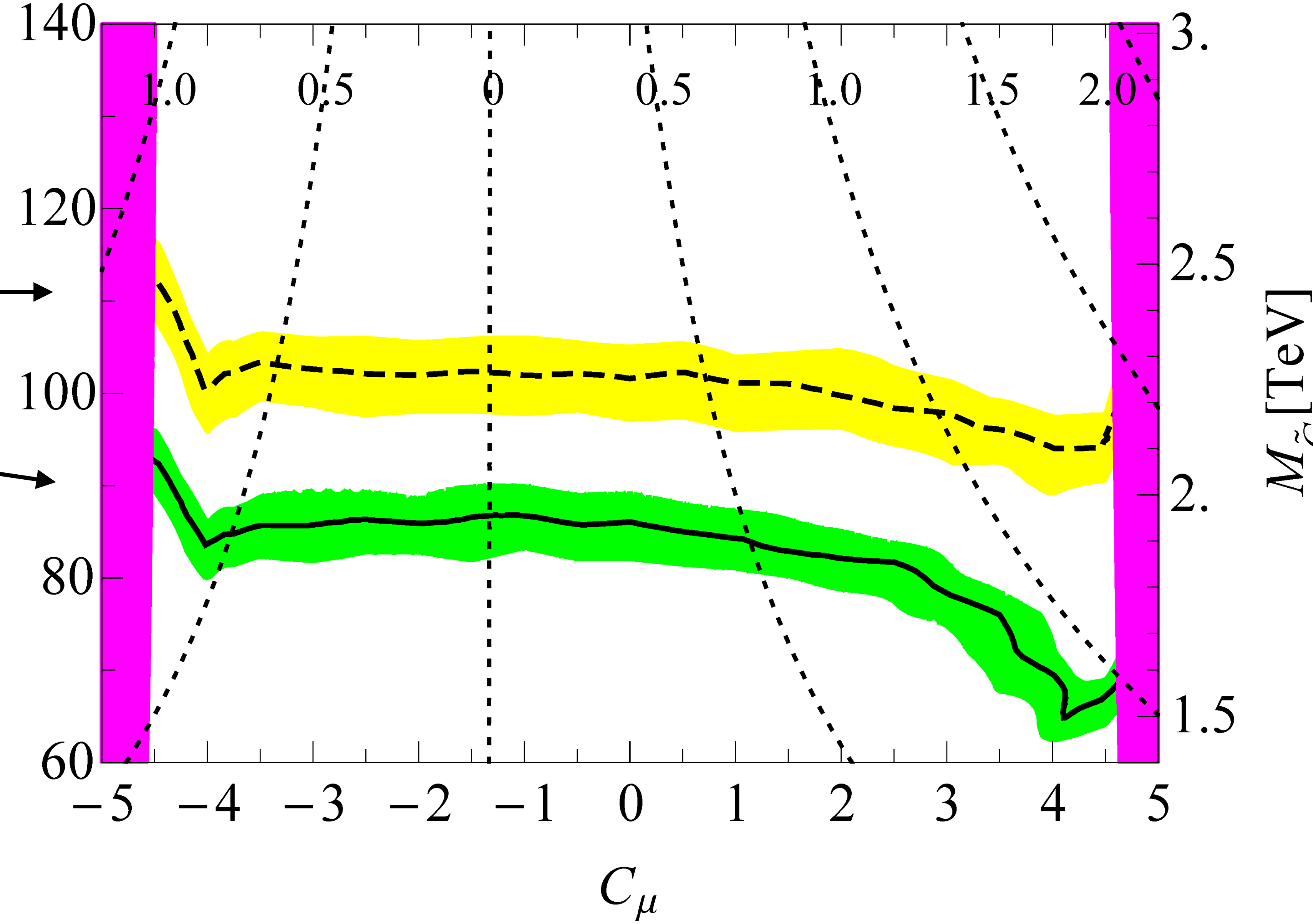
4 signal regions

AMSB (discovery) at LHC 14

$M_{\tilde{W}}$ contours

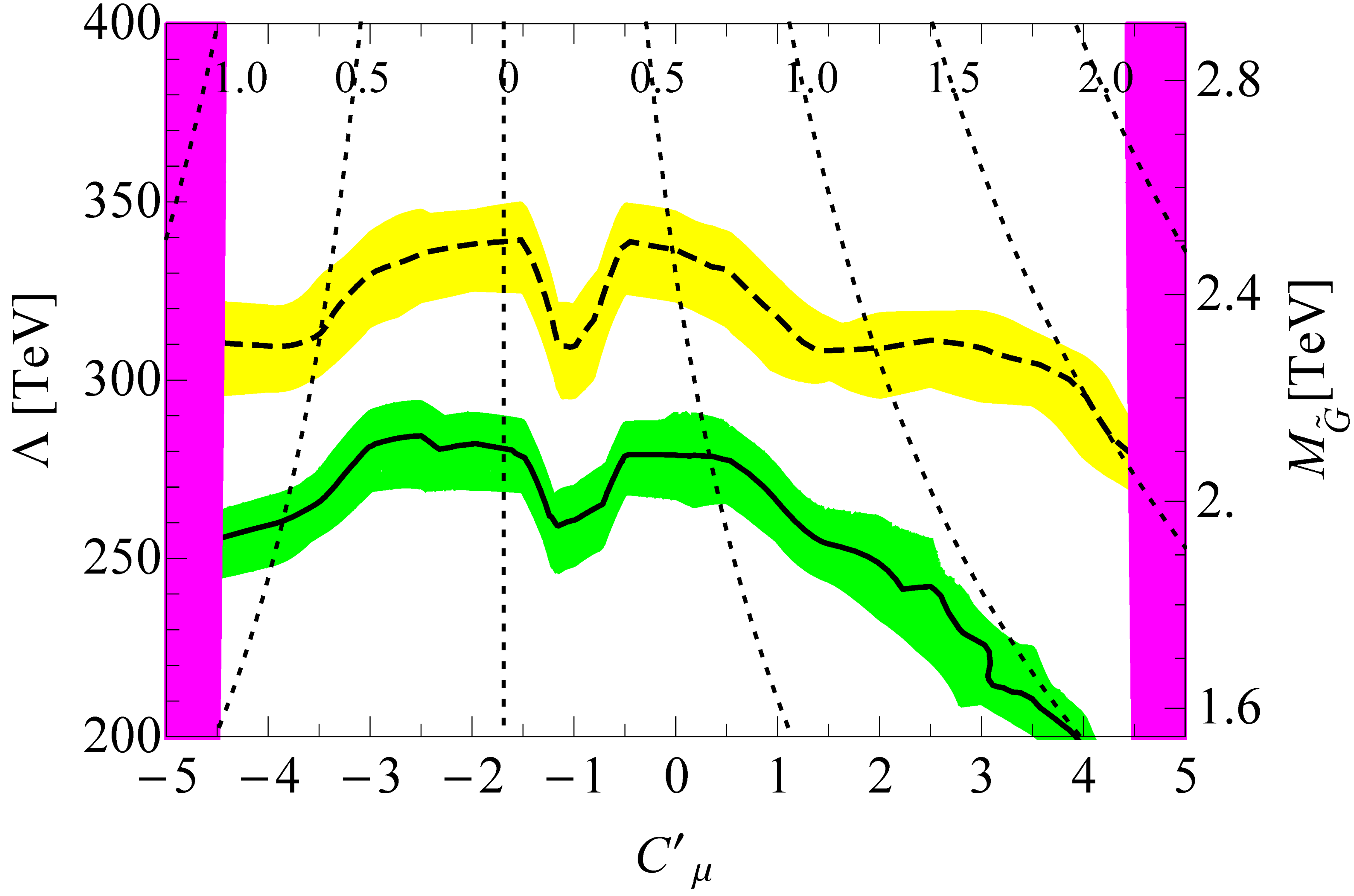
3000 fb

300 fb



GMSB (discovery) at LHC 14

$M_{\tilde{B}}$ contours



Prospect for a 100 TeV collider

same-sign dilepton

cohen et al. 1311.6480

- SSDL
- 3 b-jets or more
- 7 jets or more
- $H_T > 3000\mathrm{GeV}$
- $E_T^{\mathrm{miss}} > 800\mathrm{GeV}$

8 signal regions

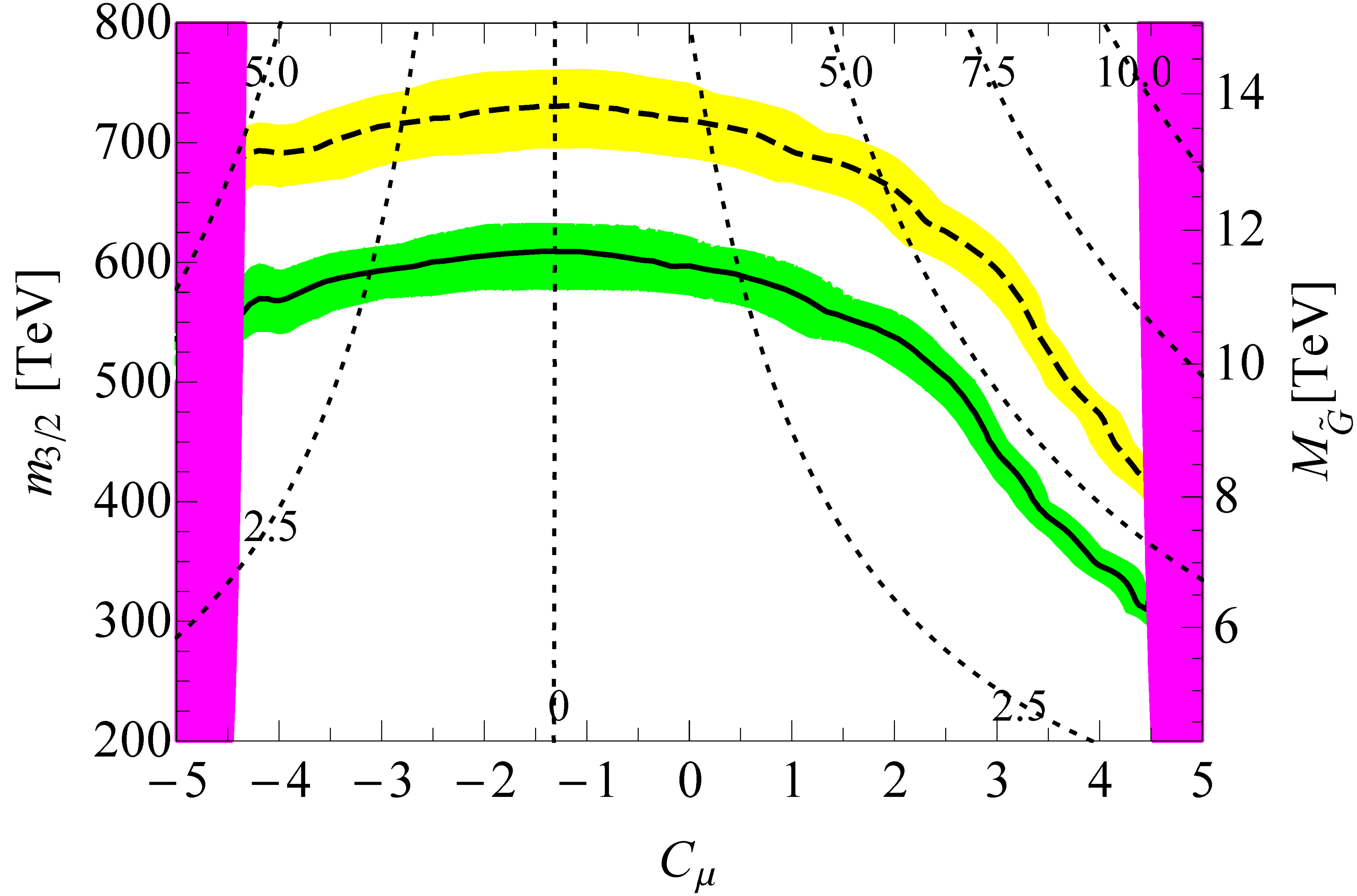
High missing energy

adapted from Jung, Wells '13

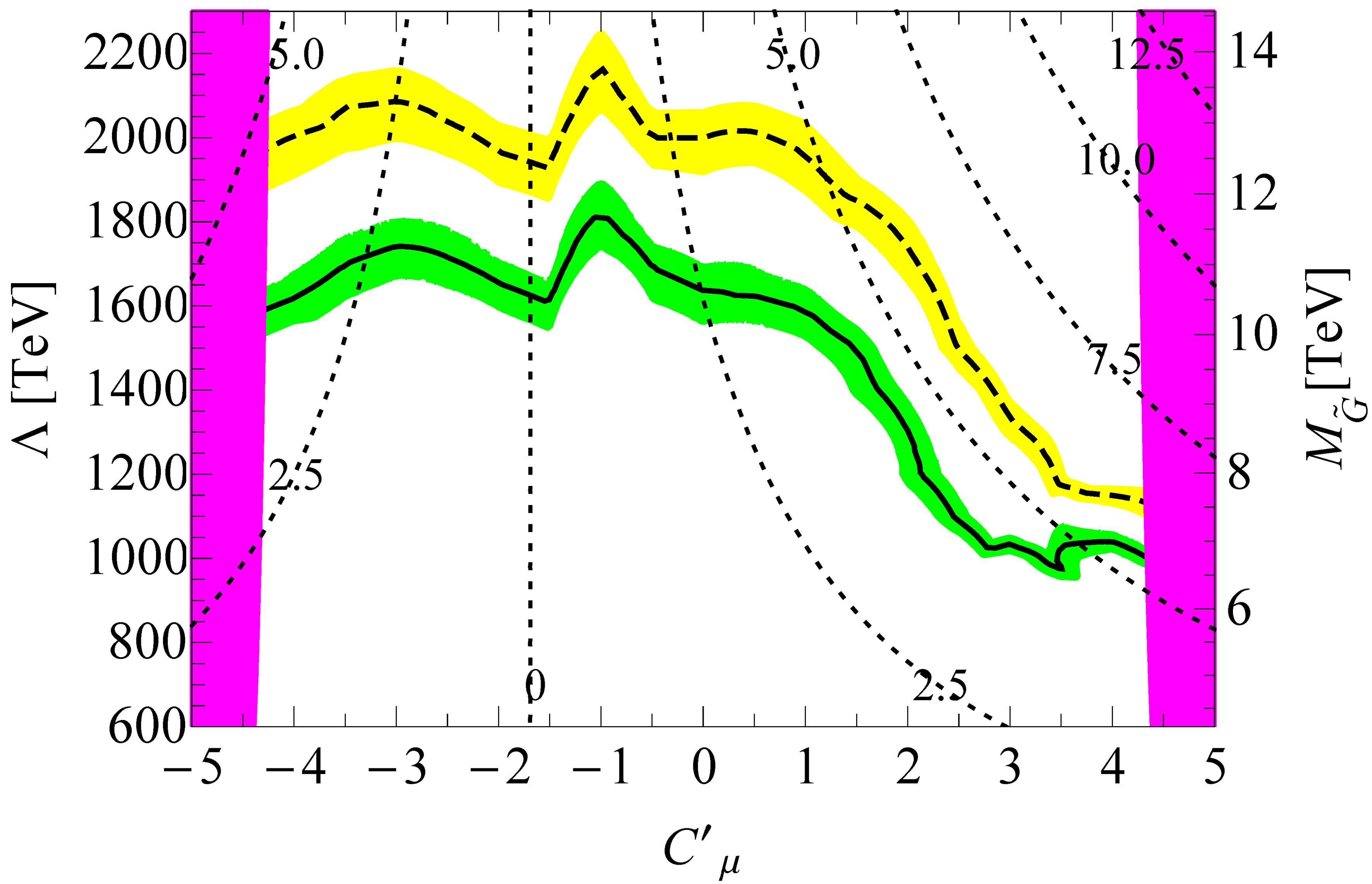
- 2 jets with $p_T > 0.1 M_{\mathrm{eff}}$
- no lepton
- $E_T^{\mathrm{miss}} > 0.2 M_{\mathrm{eff}}$
- $M_{\mathrm{eff}} > 15\mathrm{TeV}$
- 3 or more b-jest

5 signal regions

AMSB at a 100 TeV collider ($3ab^{-1}$)



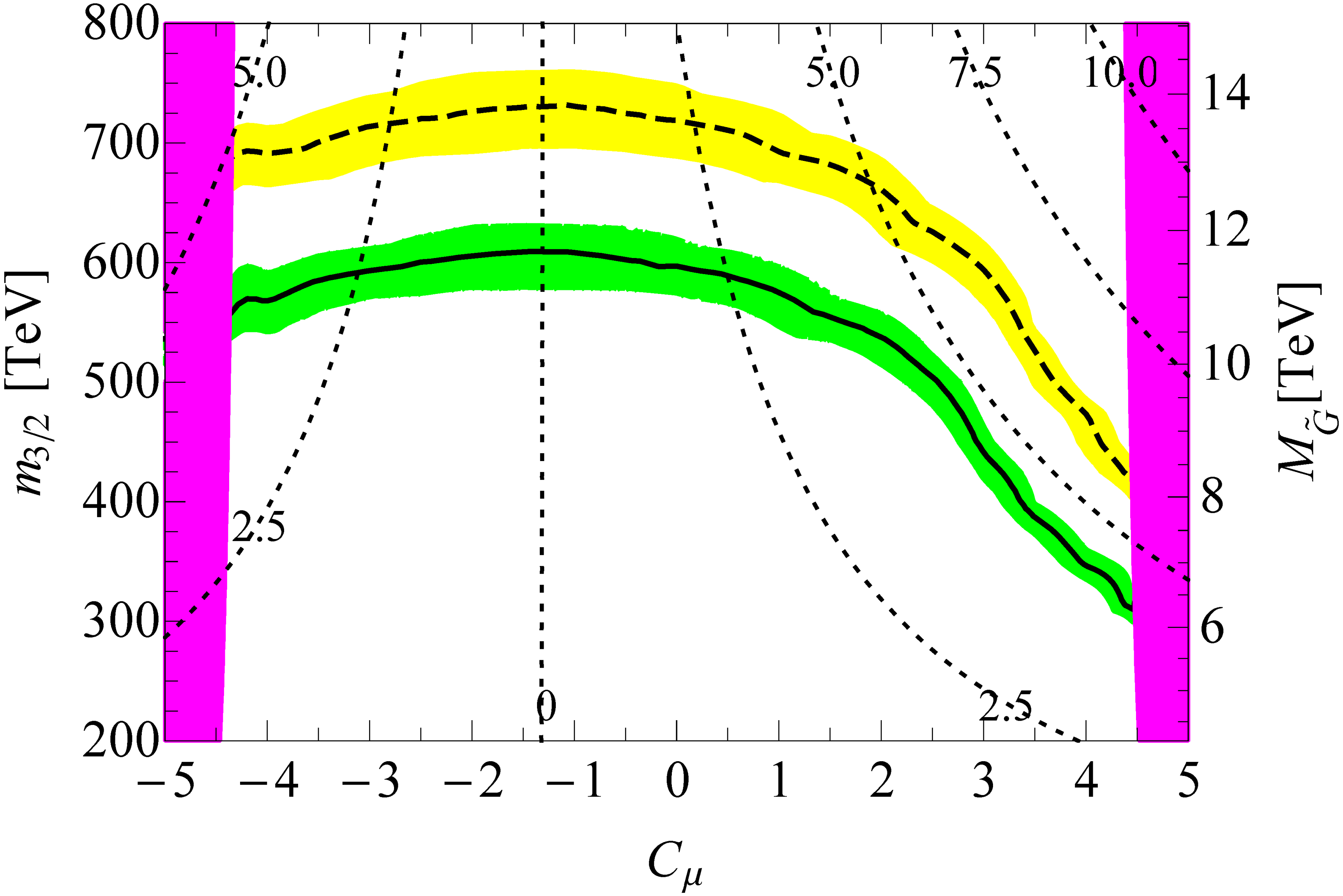
GMSB at a 100 TeV collider



Dark matter

If the LSP is a wino: need $M_{\tilde{W}} \sim 2.7\text{TeV}$

100 TeV collider



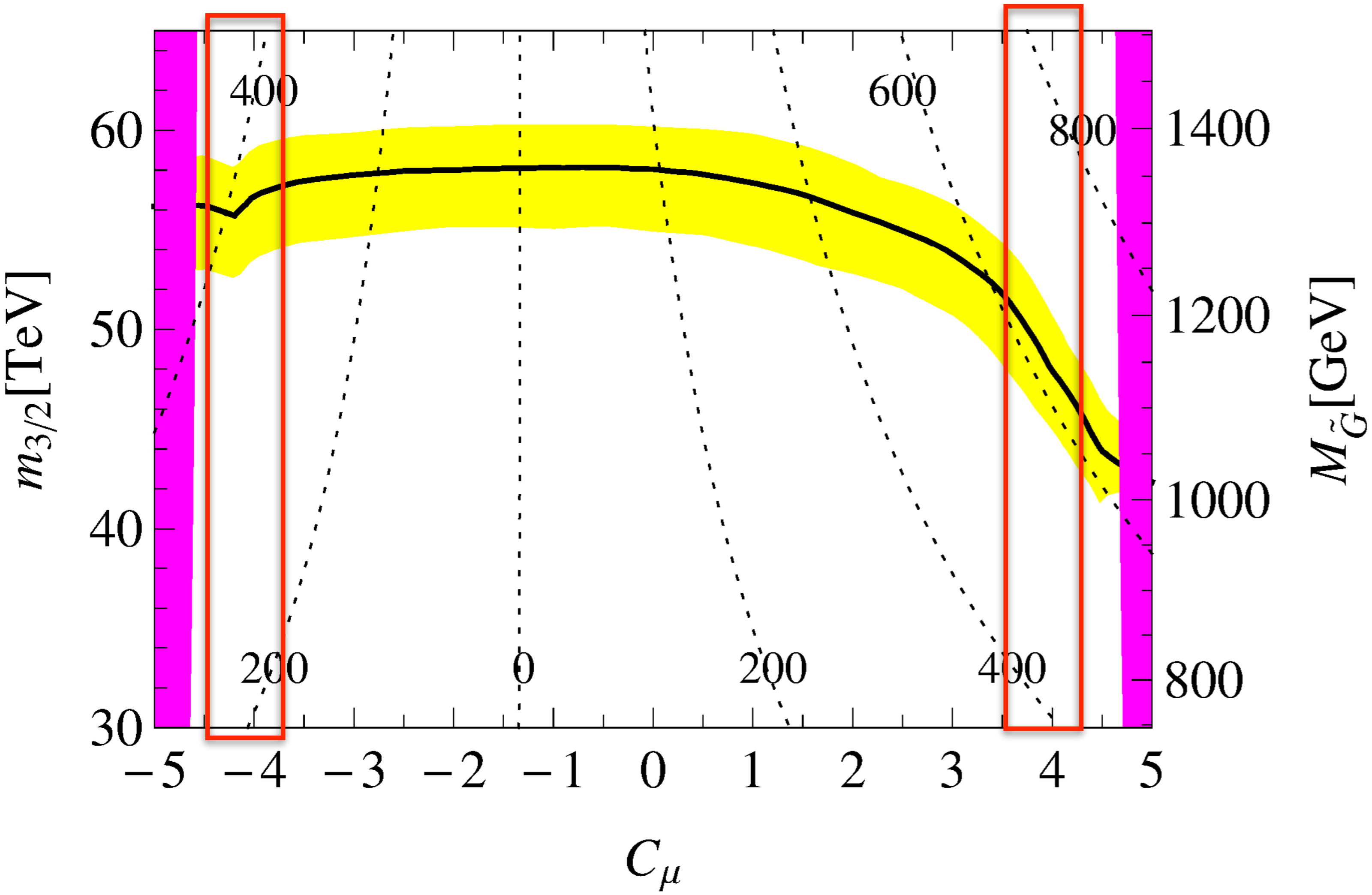
If the LSP is a bino: need dilution

If the LSP is a bino-wino mixture ($|C_\mu| \sim 4$):

M ~ several 100 GeV

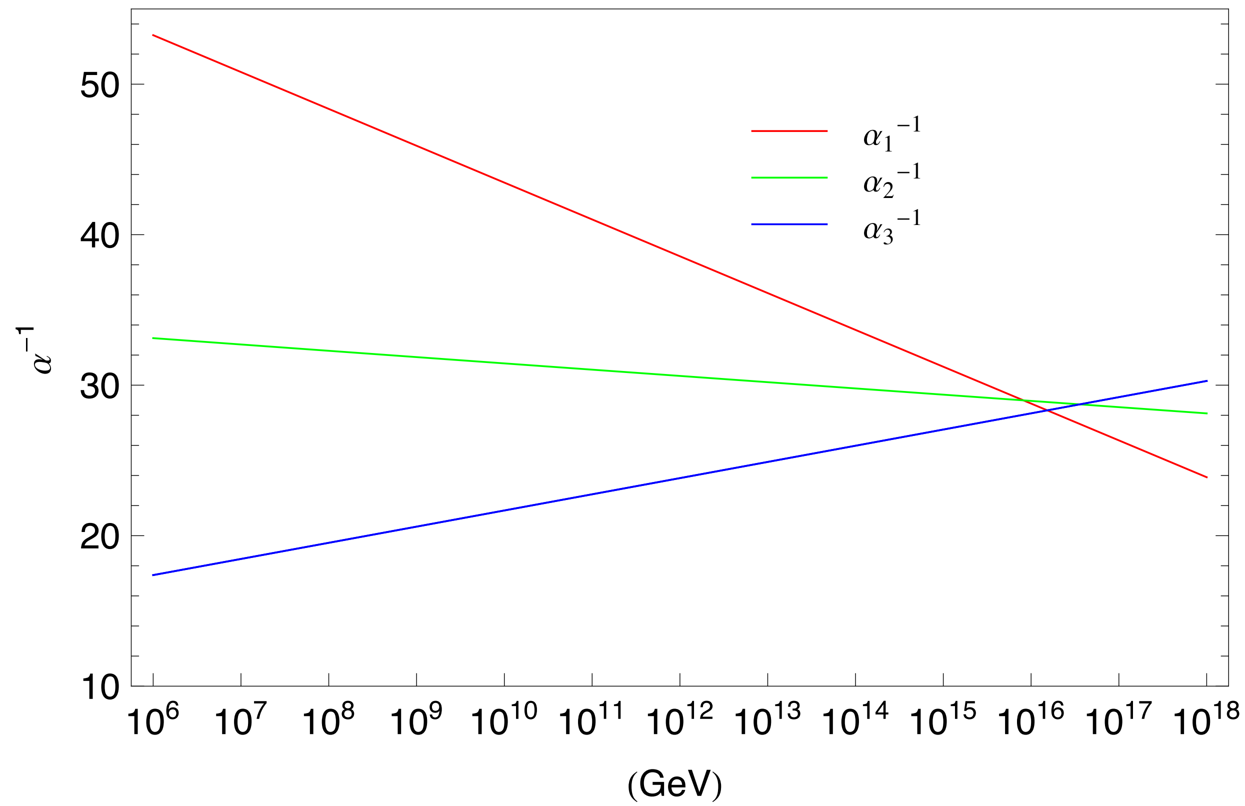
well-tempered neutralino

Arkani-Hamed,Delgado,Giudice



Gauge couplings unification

modified by heavy Higgsino,
but seems to work



Arkani-Hamed, Gupta,
Kaplan, Weiner, Zowarski