What does a Higgs Tell us about SUSY?

Based on work with
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Mitchell Workshop on Collider and Dark Matter Physics

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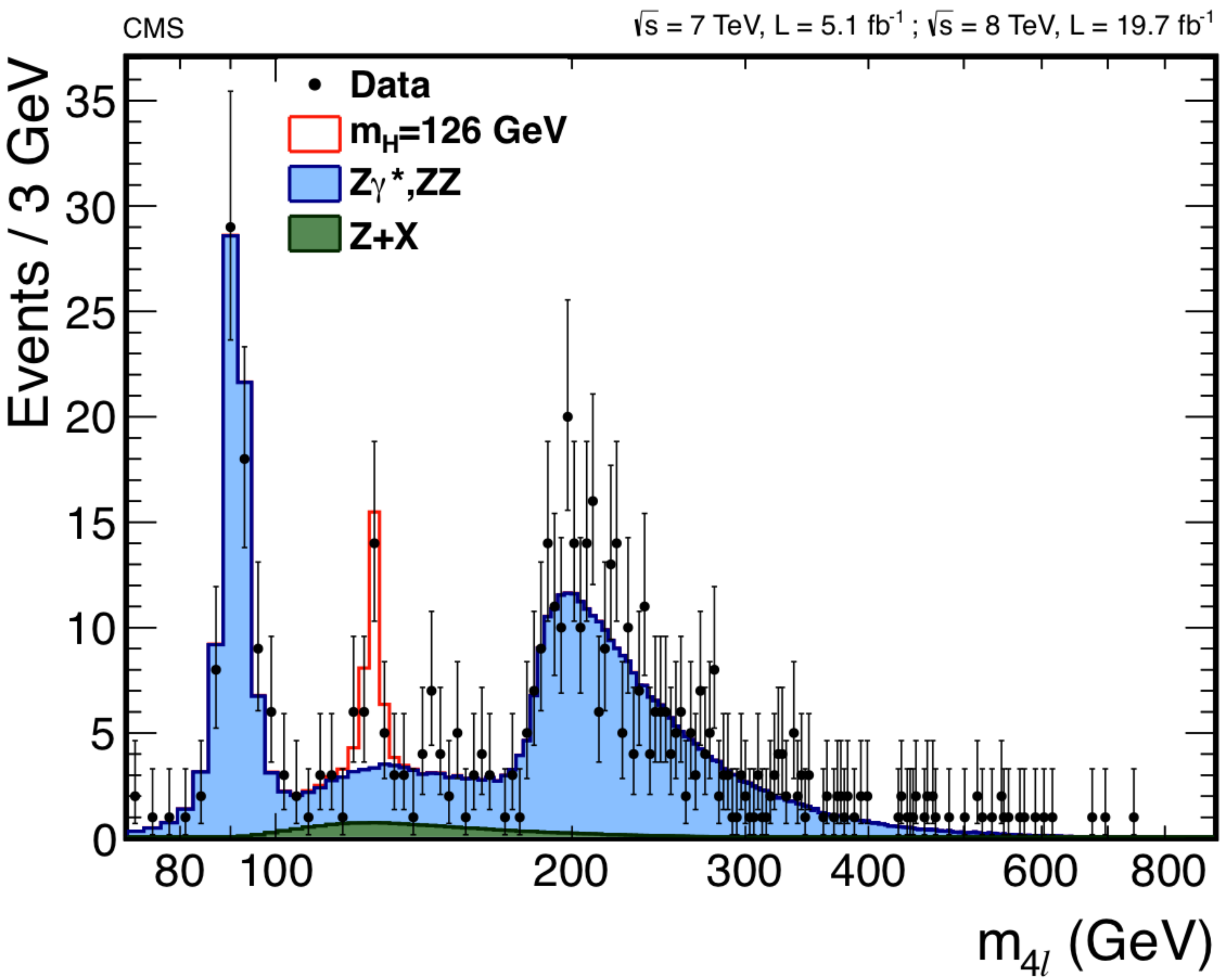
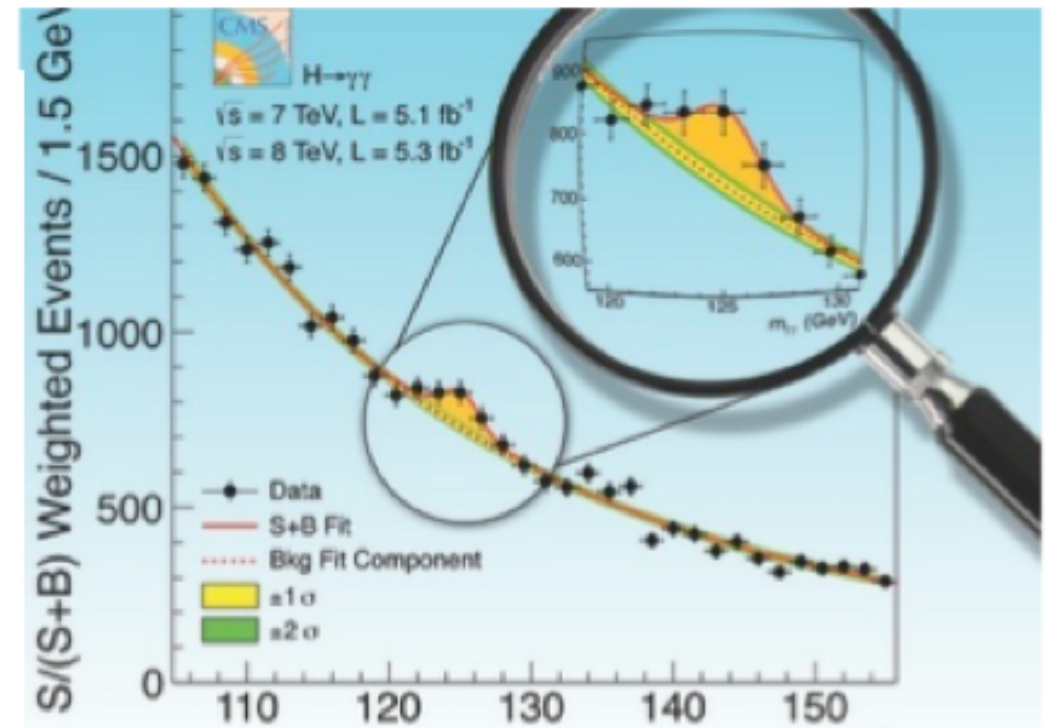
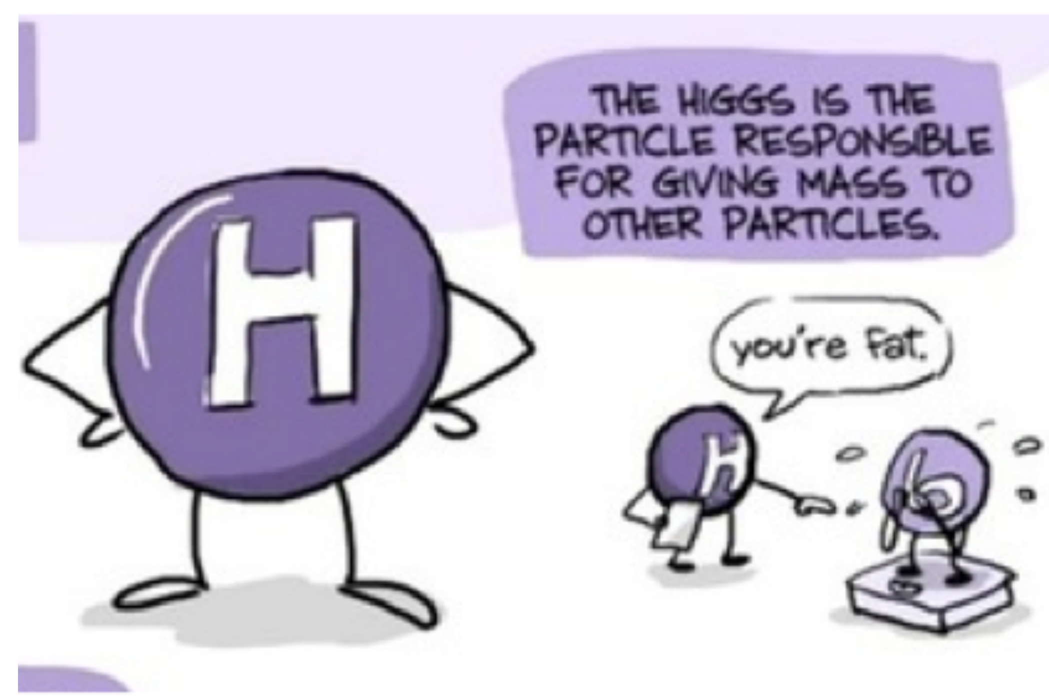
ANL & University of Chicago

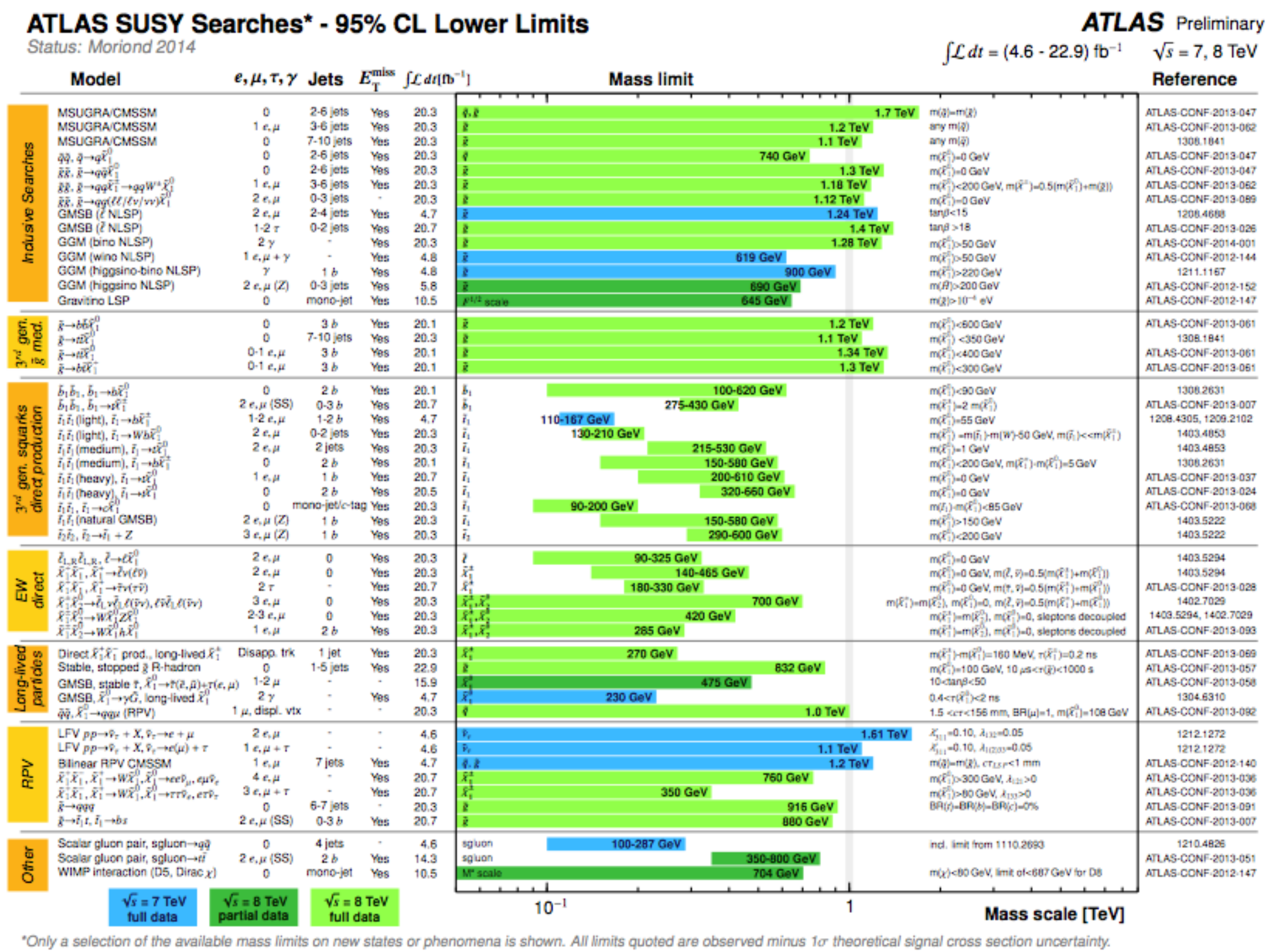
What do We Know about the Higgs?







What do We Know about SUSY?



What can We Learn about SUSY from Higgs?

- Calculate higgs mass in MSSM
- Consider the inverse problem, higgs to SUSY
- Search for SUSY with a higgs in the final states

Higgs Mass, MSSM

- Two higgs doublets H_u and H_d
- D-terms $\frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2$
- Tree level bound $m_h \leq m_Z cos 2\beta$
- Important quantum corrections to the higgs mass from stops and sbottoms/staus for large tanβ

Loop Corrections to the MSSM Higgs Mass

1 loop

- **CP-odd higgs mass m_A , tanβ, stop mass and mixing.**

$$M_{\tilde{t}} = \begin{pmatrix} m_{\tilde{t}_L^2} + m_t^2 + D_L & -m_t X_t \\ -m_t X_t & m_{\tilde{t}_R^2} + m_t^2 + D_R \end{pmatrix}$$

- **For moderate to large value of tanβ**

Polynomial dependence on the stop mixing

$$\boxed{m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3g^2}{8\pi^2}\frac{m_t^4}{m_W^2}[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2})]}$$

Logarithmic growth with stop mass

2 loop

A lot of efforts: Carena, Casas, Degrassi, Ellis, Espinosa, Haber, Heinemeyer, Hempfling, Hoang, Hollik, Martin, Quiros, Ridolfi, Slavich, Wagner, Weiglein, Zwriner, Zhang...

In public codes: FeynHiggs, Isajet, SuSpect, Softsusy, Spheno

Higher Order Corrections to Higgs Mass

- Diagrammatic calculations:
  - ❖ Up to partial three loop order

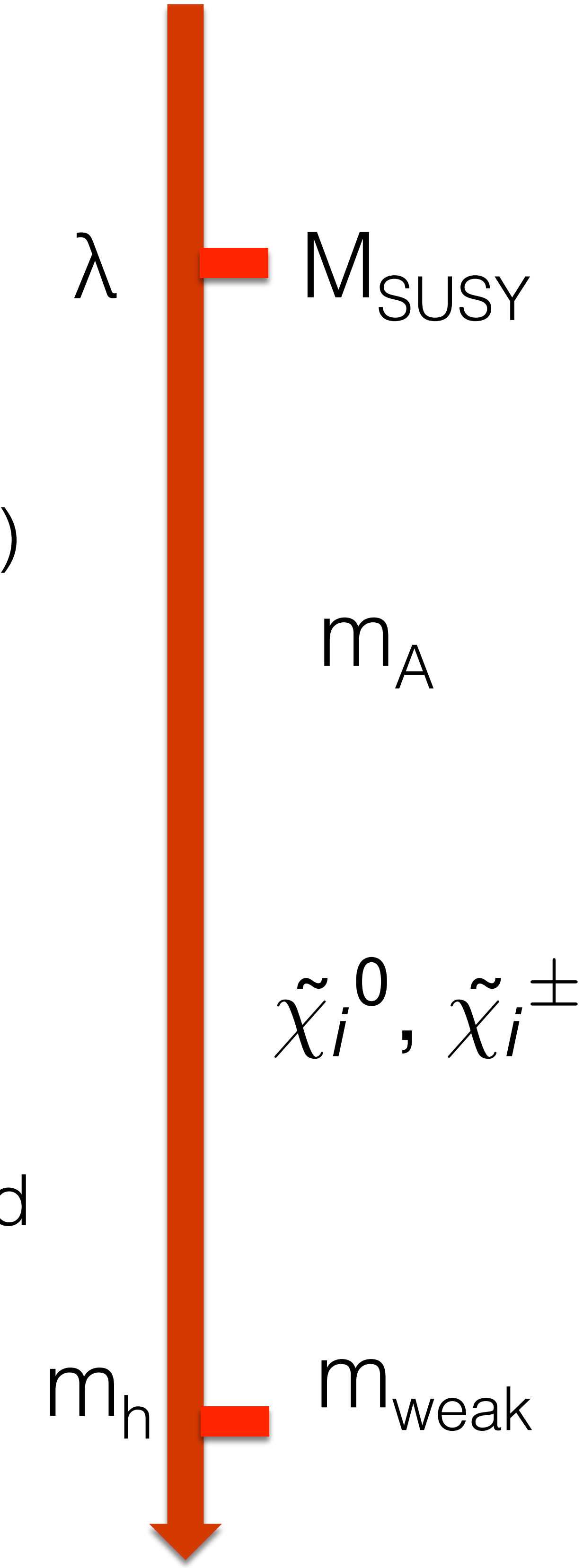
  —Harlander, Kant, Mihaila and Steinhauser.

  - ❖ In a mathematica code H3M
  - ❖ 6 particular mass hierarchies

- Effective potential method:
  - ❖ Derivatives of the MSSM potential V(h1,h2) evaluated at the vev
  - ❖ Zero external momentum approximation of the diagrammatic calculation
  - ❖ Up to partial three loop order, Martin

Higher Order Corrections to Higgs Mass

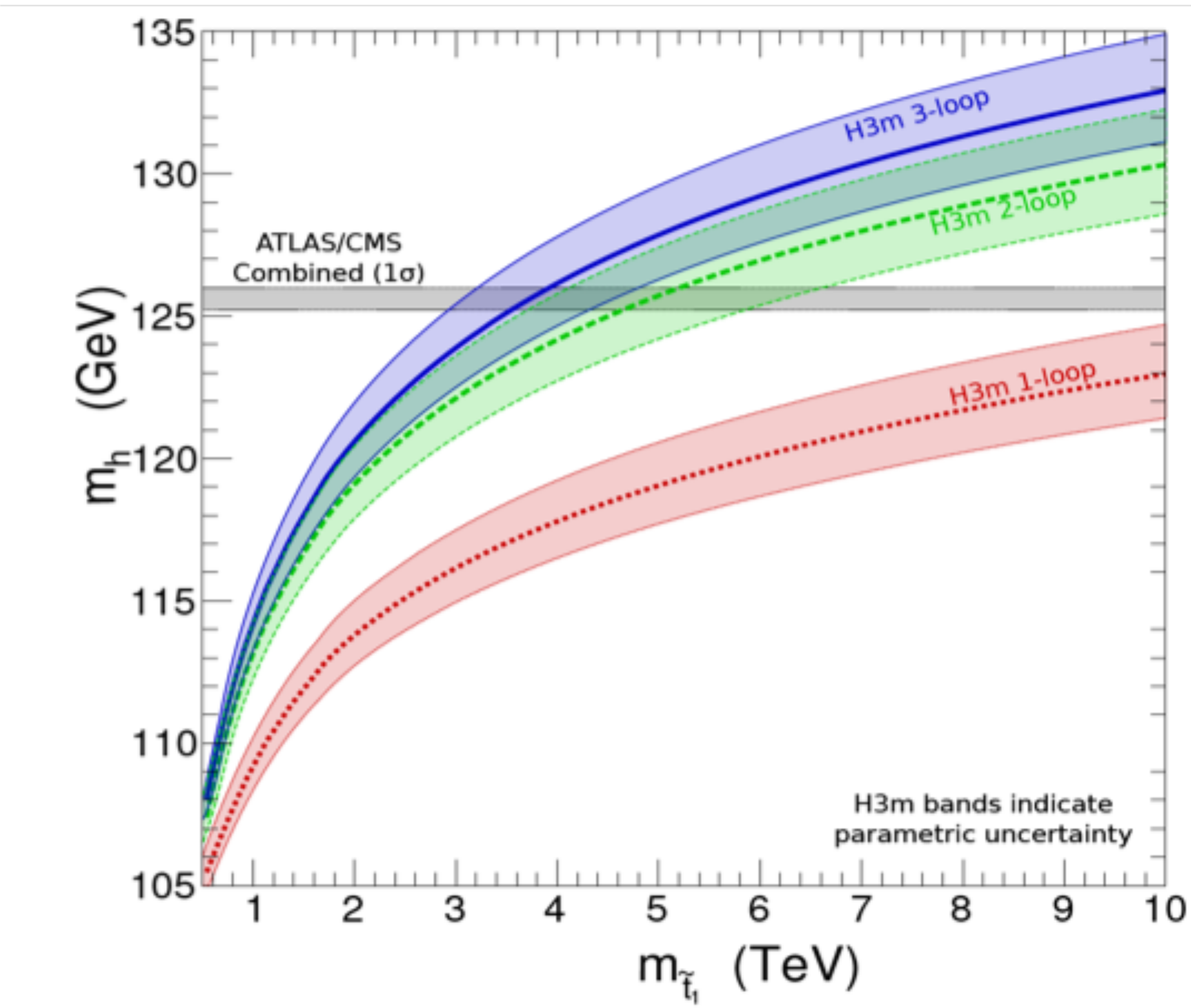
- Effective field theory analysis
  - Running the effective theory couplings(quartic couplings) down to the electroweak scale
  - Integrate out the MSSM particles at their thresholds
  - Evaluate the higgs pole mass at the electroweak scale
  - Partial three loop order, Degrassi, Di Vita, Elia-Miro, Espinosa, Giucidice, Isidori and Strumia; Draper, Lee and Wagner



Higher Order Corrections to Higgs Mass

- Low SUSY scales, fixed order calculations (diagrammatic calculations and effective potential method) are most accurate.
    - ❖ Keep a large set of non-logarithmic terms
- High SUSY scales, especially in the simplified models, EFT analysis is more accurate.
    - ❖ Resume large log terms

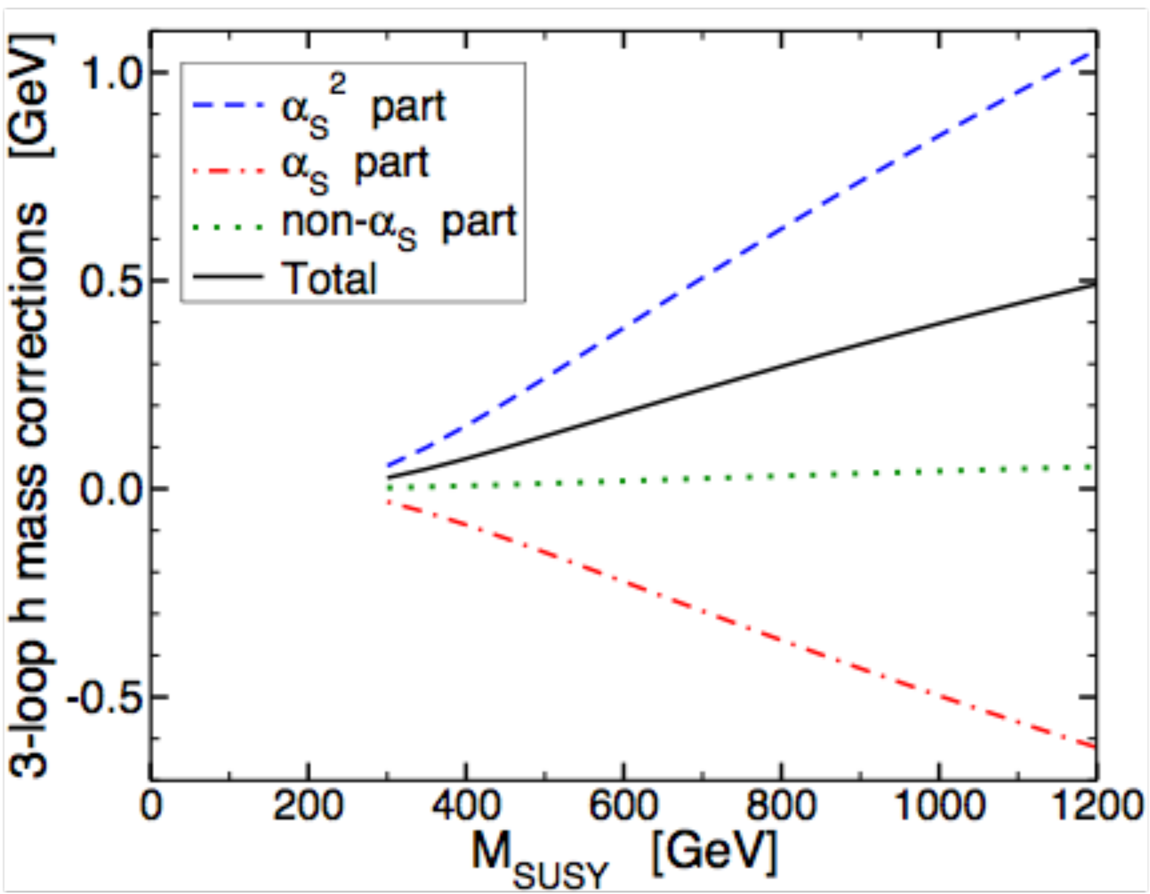
Higher Order Corrections to Higgs Mass, Diagrammatic Calculation



- Degenerate, non-mixed stops
- Gaugino mass unification and gluino mass is 1.5 TeV
- tanβ = 20, μ = 200 GeV
- The uncertainties are from top mass and $\alpha_s(m_Z)$
- Stop mass ~ 3 TeV

Feng, Kant, Profumo, Sanford, 2013

Higher Order Corrections to Higgs Mass, Effective Potential

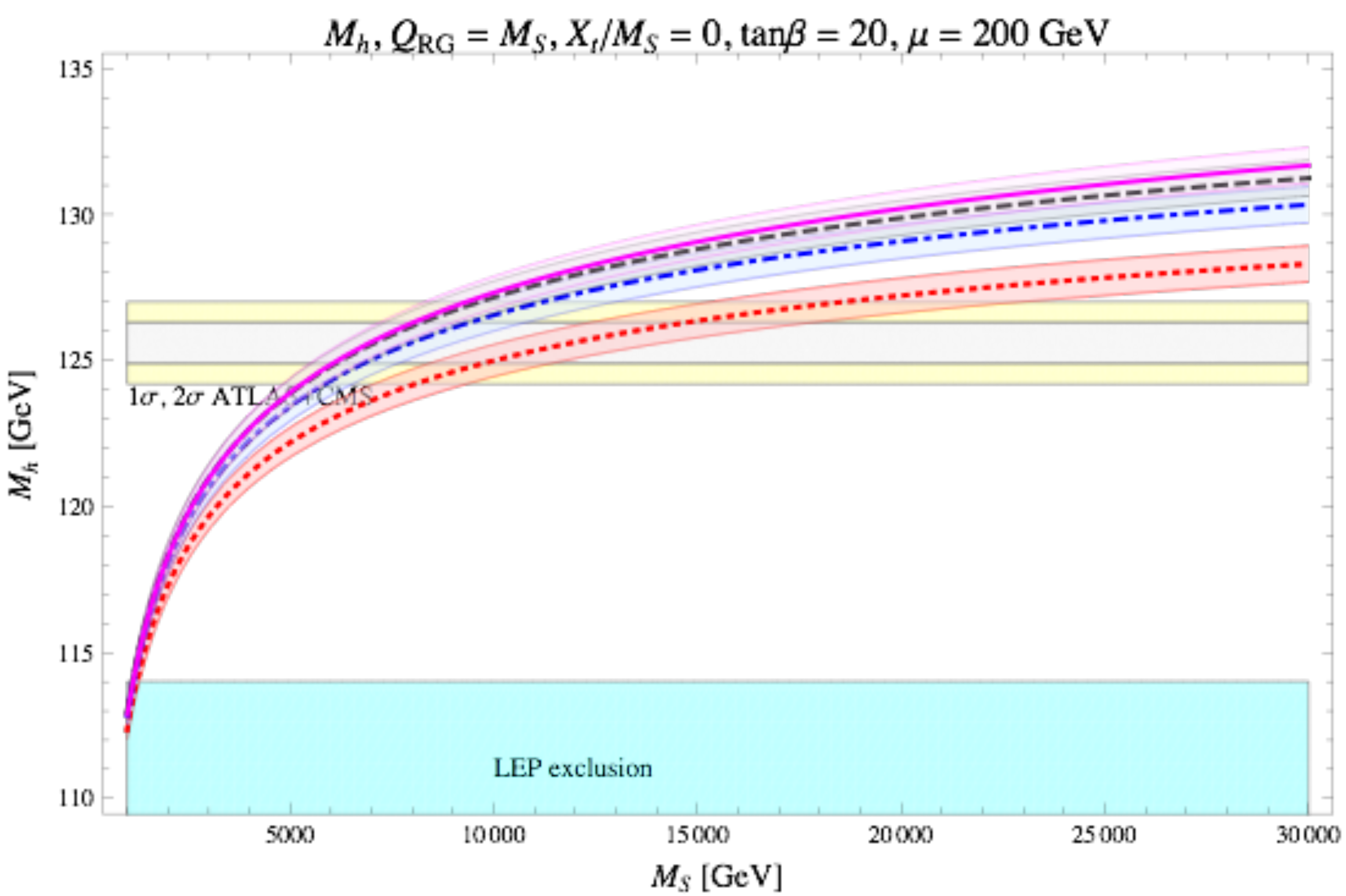


Martin, 2007

- Degenerate and non-mixed stops
- Large tanβ
- Leading logs
- Large stop mass

Higher Order Corrections to Higgs Mass, EFT Analysis

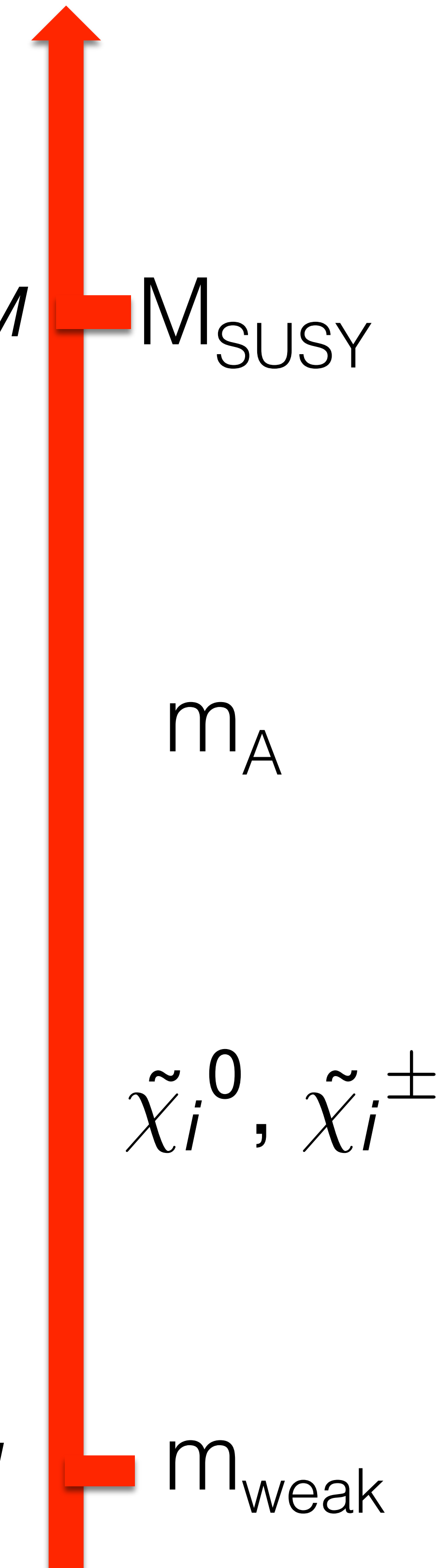
1loop 2loop 3loop



- Degenerate, non-mixed stops
- All other SUSY particles are decoupled
- $\tan\beta = 20$, $\mu = 200$ GeV
- Stop mass ~ 7 TeV

Draper, Lee and Wagner

What about the Inverse Problem?



- Start from the electroweak scale, calculate λ
- run λ, coupled with g_1, g_2, g_3, y_t up: $\lambda_{SM}(Q)$
- integrate out the MSSM particles at their threshold
- Calculate $\lambda_{MSSM}(Q, m_{\tilde{g}}, m_A, m_{\tilde{q}}...)$ from V_{eff}
- Estimate the SUSY scale:
  where λ_{SM} and λ_{MSSM} match

What about the Inverse Problem? Ingredients

- Higgs mass is known from the experiment
- Quartic coupling λ is known to 2 loop order

  Bezrukov, Kalmykov, Kniehl, and Shaposhnikov 2012

- β -fuction for higgs quartic coupling is known to 3 loop order

  Chetyrkin and Zoller, 2013

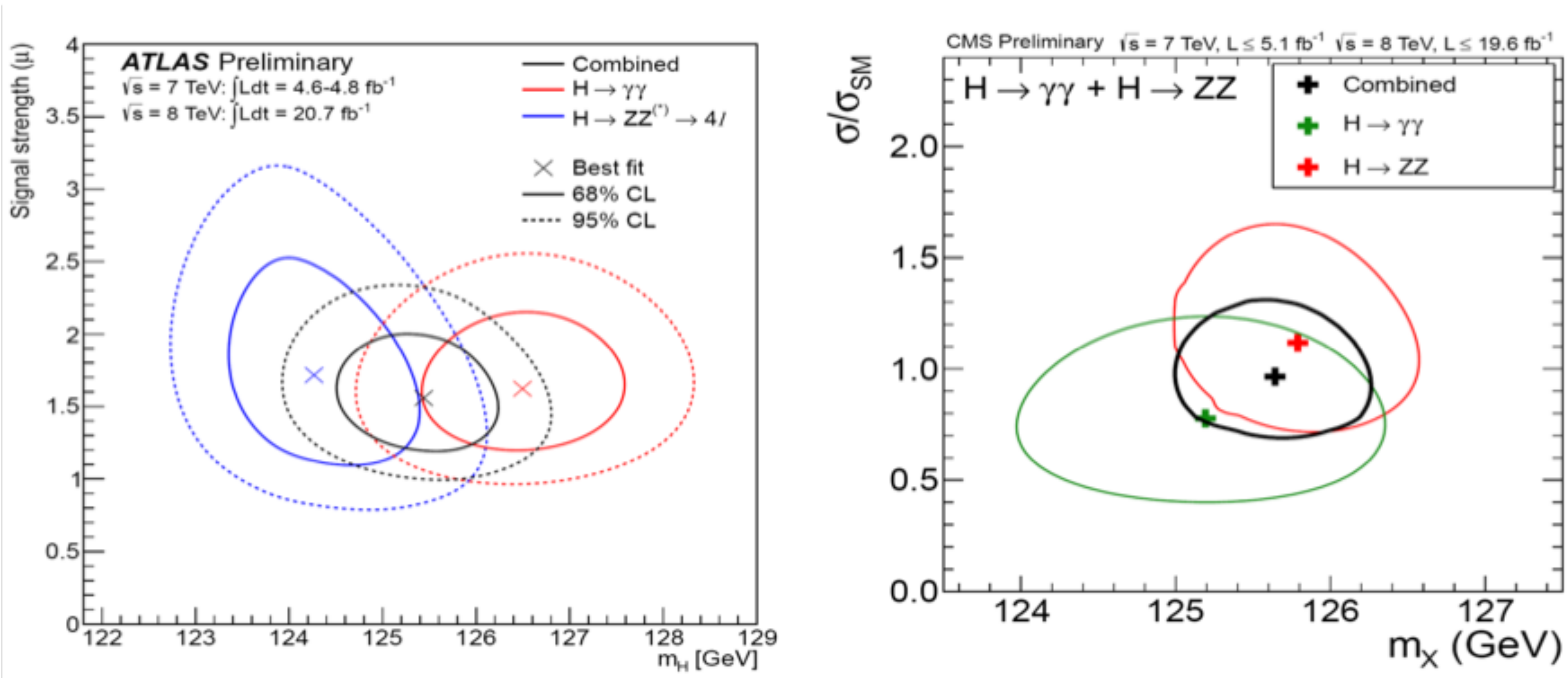
- SM RGE is known to 3 loop order

  Chetyrkin and Zoller, 2012

- MSSM effective potential is known to 2 loop order

  Espinosa and Zhang, 2001

Boundary Conditions at Weak Scale, Higgs Mass



$$\left.\begin{array}{r}\text{ATLAS (combined)}:\ 125.5 \pm 0.2\ {}^{+0.5}_{-0.6}\ \text{GeV}\\ \text{CMS (combined)}:\ 125.7 \pm 0.3 \pm 0.3\ \text{GeV}\end{array}\right\} \Rightarrow 125.6 \pm 0.4\ \text{GeV}$$

Boundary Conditions at Weak Scale

$$\alpha_s(m_Z) = 0.1184 \pm 0.0007$$

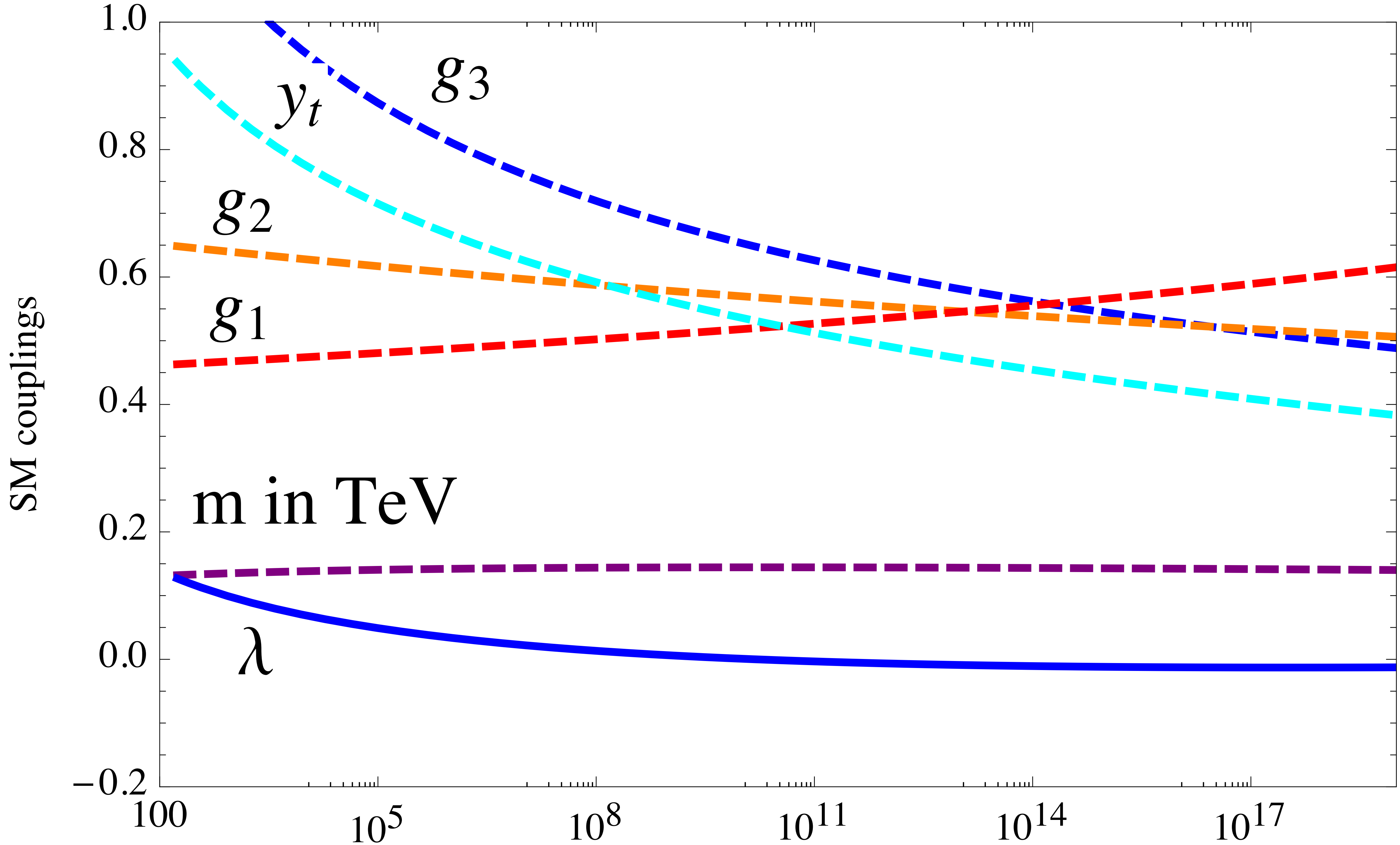
$$m_t = 173.2 \pm 0.87 \text{ (Tevatron)}$$

	LO 0 loop	NLO 1 loop	NNLO 2 loop
g_2	$2m_W/V$	full	full
g	$2\sqrt{m_Z^2 - m_W^2}/V$	full	full
y_t	$\sqrt{2}m_t/V$	$O(\alpha_s)$, $O(\alpha)$	$O(\alpha_s^2, \alpha_s\alpha_{1,2})$
λ	$m_h^2/2V^2$	full	full

$V \equiv (\sqrt{2}G_\mu)^{-1/2}$

Sirlin; Tarrach; Hempfling and Kneihl; Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio and Strumia

Running from Weak Scale to SUSY Scale



Matching at the SUSY Scale

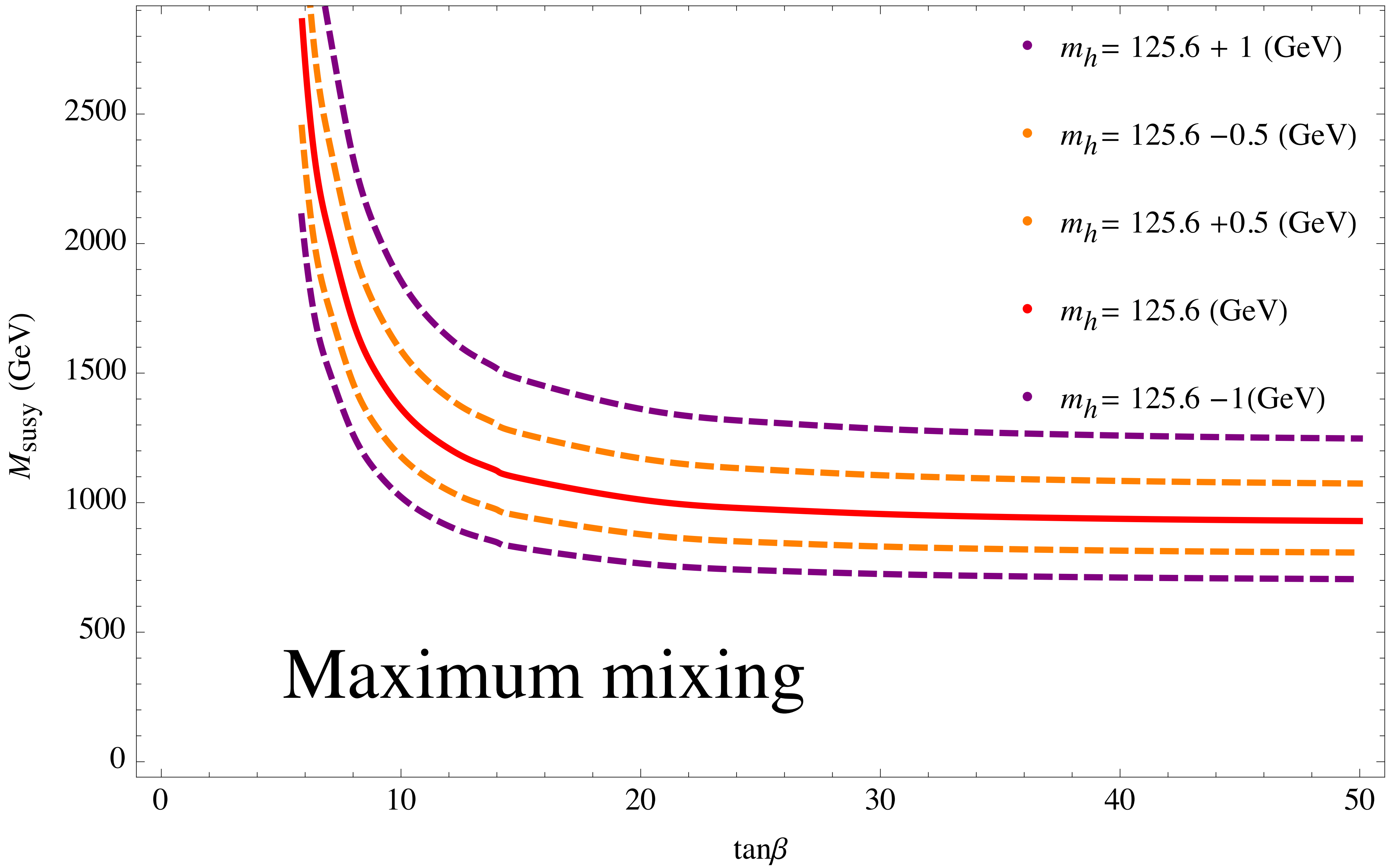
$$\lambda^0_{SUSY} = \frac{(g^2+g'^2)\cos 2\beta}{8}$$

$$V_{eff}(h) \equiv V_0(h) + V_{\rm loop}(h) = V_0(h) + V_1(h) + V_2(h) + \cdots$$

$$\lambda_{SUSY} = \lambda^0_{SUSY} + d\lambda^1 + d\lambda^2$$

$$\begin{aligned}
d\lambda \;=\;& g_Z^2 c_{2\beta}^2 \Delta Z_h^{\rm SUSY} + 6\kappa\left[\zeta_{m1}^2 \ln\frac{m_{\tilde t_1}^2}{Q^2} + \zeta_{m2}^2 \ln\frac{m_{\tilde t_2}^2}{Q^2} + \eta_m B(\tilde t_1, \tilde t_2)\right] + 6\kappa\left(\frac{g^2}{4} + \frac{g'^2}{12}\right)^2 c_{2\beta}^2 \ln\frac{m_Q^2}{Q^2} \\
&+ \kappa\frac{9g^4 + g'^4}{6} c_{2\beta}^2 \ln\frac{m_{Q_{12}}^2}{Q^2} + \kappa\frac{g'^4}{6} c_{2\beta}^2\left(2\ \ln\frac{m_{D_{1,2}}^2}{Q^2} + \ln\frac{m_D^2}{Q^2} + 8\ \ln\frac{m_{U_{1,2}}^2}{Q^2}\right) \\
&+ \kappa\frac{3(g^4 + g'^4)}{4} c_{2\beta}^2 \ln\frac{m_L^2}{Q^2} + \kappa\frac{3g'^4}{2} c_{2\beta}^2 \ln\frac{m_E^2}{Q^2} \\
&+ \frac{\kappa}{8}\left[\left\{4g^4 - 4g^2 g_Z^2 c_{2\beta}^2 + g_Z^4\left(2 + \frac{3}{2}s_{4\beta}^2\right)\right\}\ln\frac{m_A^2}{Q^2} - 3g_Z^4 s_{4\beta}^2\right] + d\lambda^{(1)}_{\tilde C_i} + d\lambda^{(1)}_{\tilde N_i} - \kappa\left(g^4 + \frac{g_Z^4}{2}\right) \\
&+ \kappa^2 36 h_t^6 s_\beta^6 X_t^2 B^{(1)}(\tilde t_1, \tilde t_2)\left[2\ln\frac{m_t^{T,2}}{Q^2} + \frac{16}{3} - \left(1 - \frac{X_t^2}{2s}\right)^2 \ln\frac{m_{\tilde t_1}^2}{Q^2} - \left(1 + \frac{X_t^2}{2s}\right)^2 \ln\frac{m_{\tilde t_2}^2}{Q^2} - \frac{X_t^4}{2s^2} B(\tilde t_1, \tilde t_2)\right] \\
&+ d\lambda^{(2)}_{\rm Yukawa} + d\lambda^{(2)}_{\rm QCD} + \kappa^2 24 \hat y_t^4\left[(g_3^2 c_{\mathcal{Y}_t} + \hat y_t^2 c'_{\mathcal{Y}_t})\left(2\ln\frac{m_t^{T,2}}{Q^2} + \frac{16}{3}\right) + g_3^2 c_{\mathcal{Y}_t} + \hat y_t^2 (c'_{\mathcal{Y}_t} + c_v)\right] \qquad (65)
\end{aligned}$$

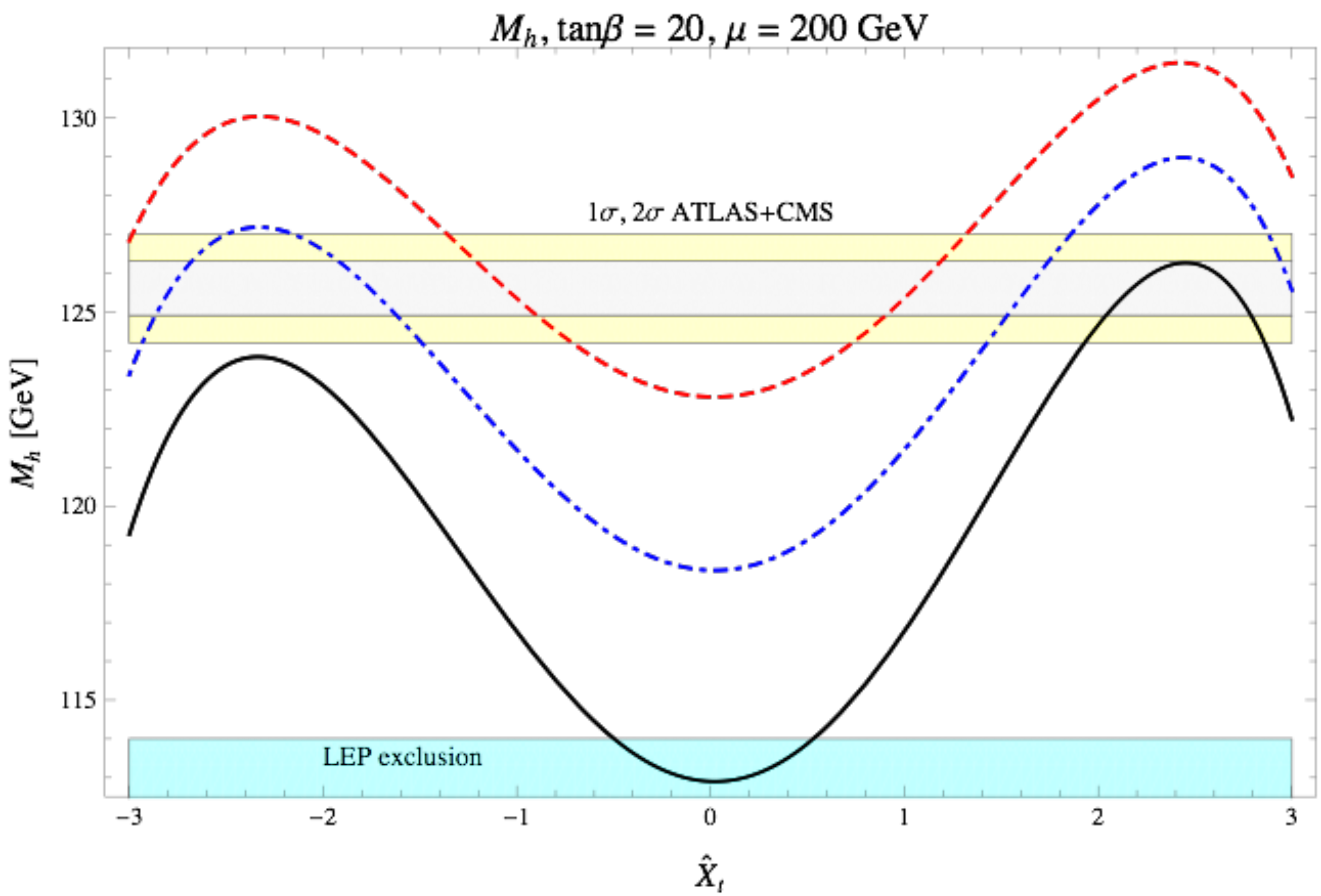
Results



Maximum mixing, large tanβ, stop mass ~1 TeV

Compare with EFT Analysis

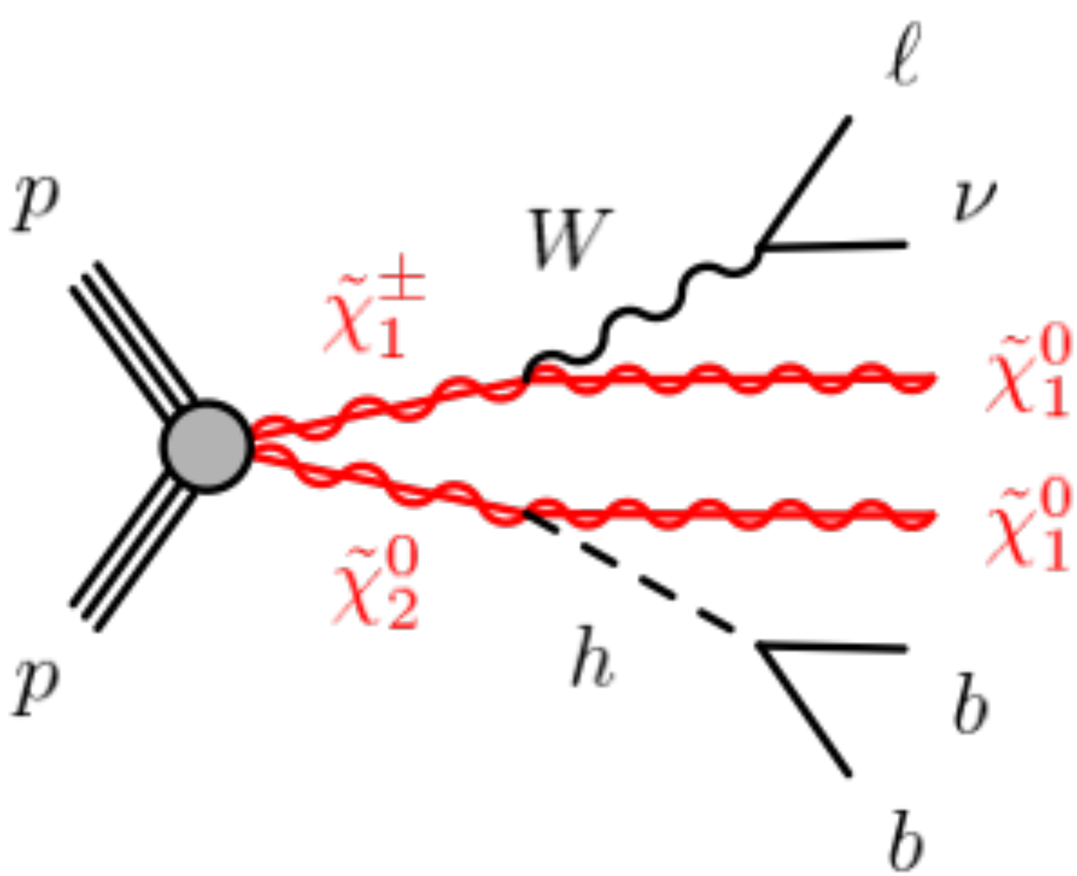
Draper, Lee and Wagner

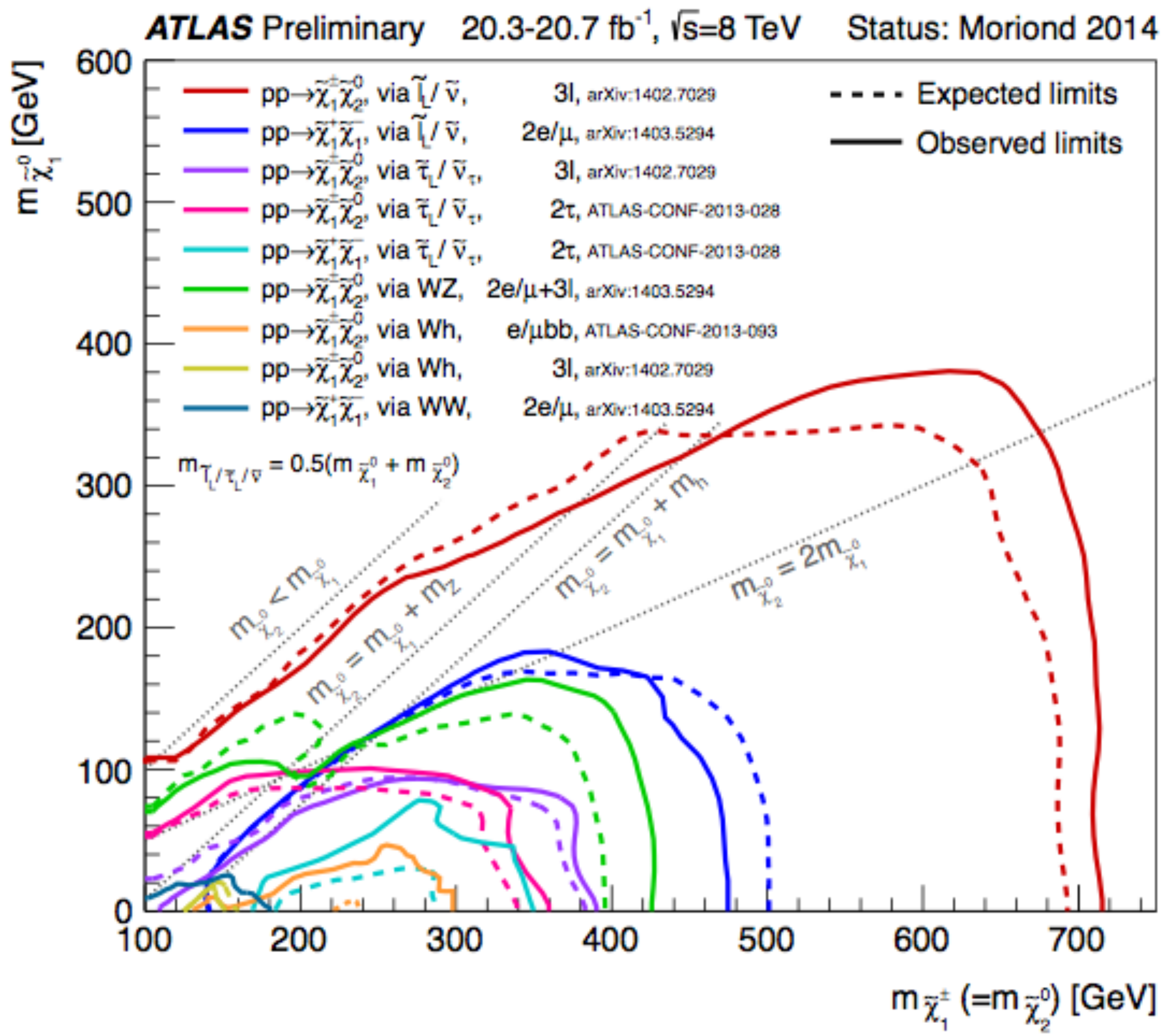


1 TeV
2 TeV
4 TeV

for large tanβ, stop mass around 1TeV

Search for SUSY with a Higgs in the Final State



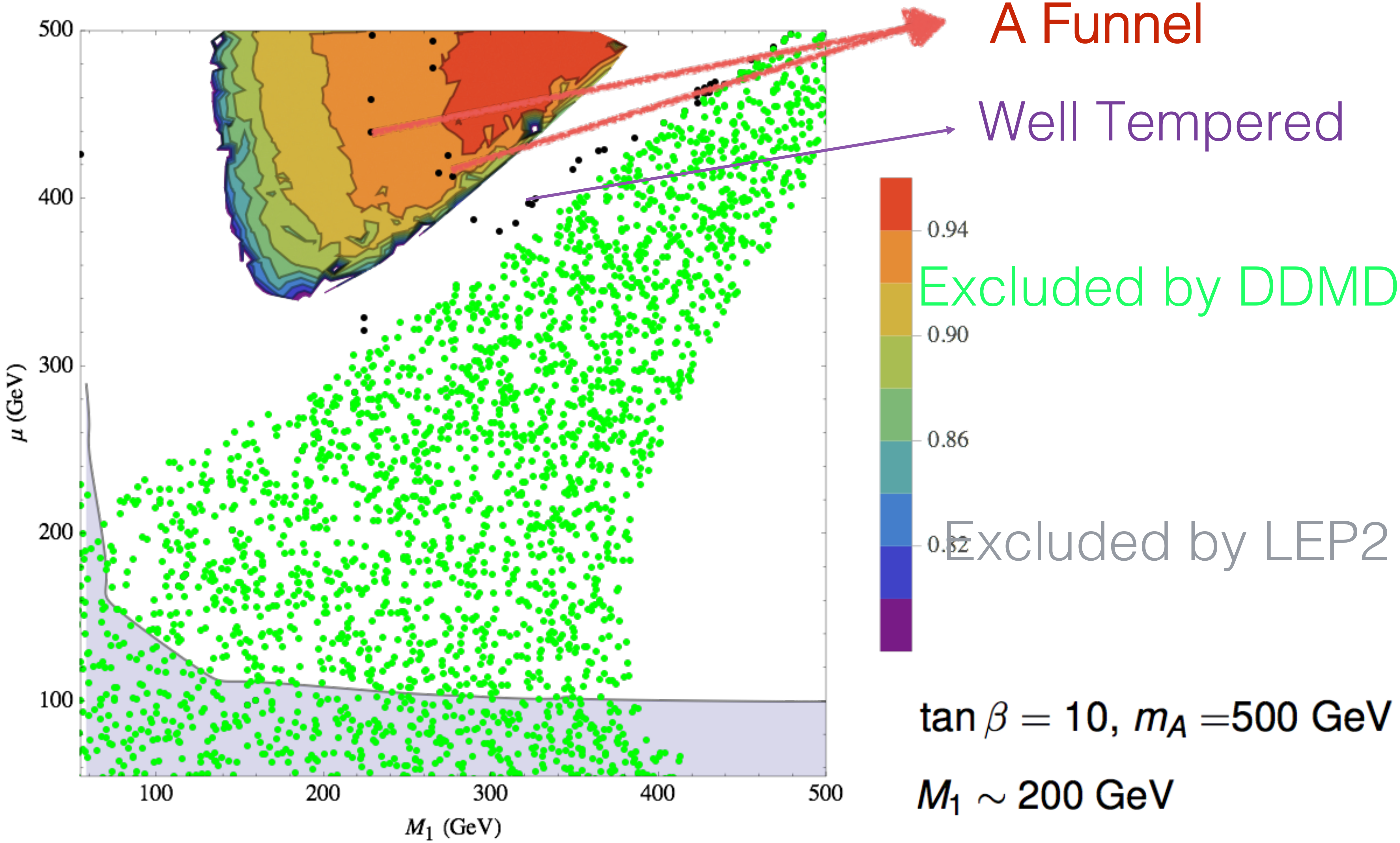


Parameter Space

- right relic density : Ωh^2 = 0.1138 $\pm$0.0045
- allowed by the direct detection experiments(LUX)
- allowed by CMS $H, A \to \tau\tau$ searhces
- higgs is the dominant decay mode for $\tilde{\chi}_i^0$ and/or $\tilde{\chi}_i^\pm$
- $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV, from LEP

Right Relic Density, Black

DDMD, Green

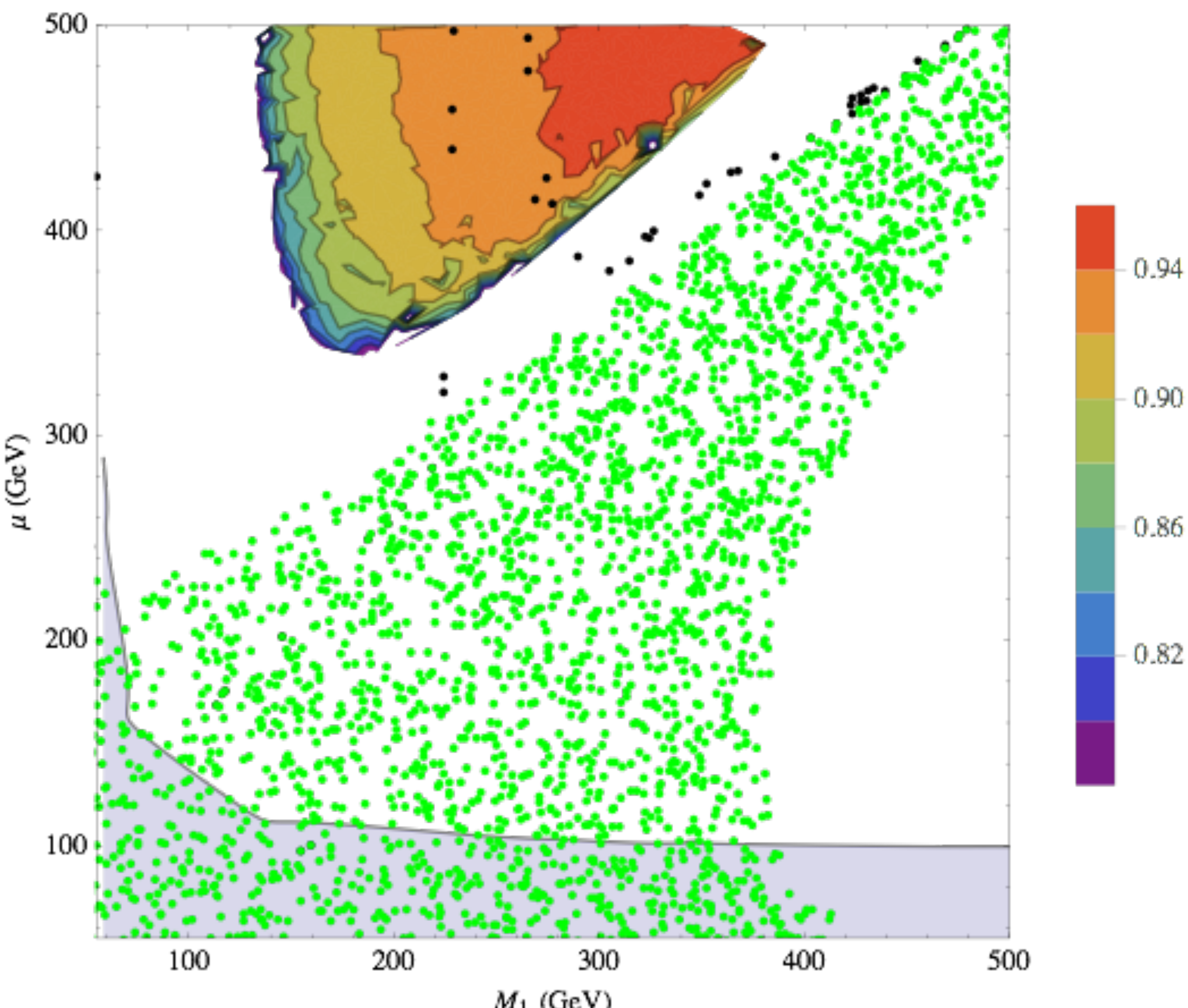


$\tan\beta = 10$, $m_A = 500$ GeV

$M_1 \sim 200$ GeV

Higgs in Neutralino and Chargino Decays, Contours

$$L = -D_\mu H_u^+ D^\mu H_u - i\bar{\tilde{H}}_u \not{D} \tilde{H}_u - \sqrt{2} g' Y_{H_u} \tilde{B} \tilde{H}_u H_u^* - \sqrt{2} g \tilde{W}^a \tilde{H}_u t^a H_u^* + (u \leftrightarrow d)$$



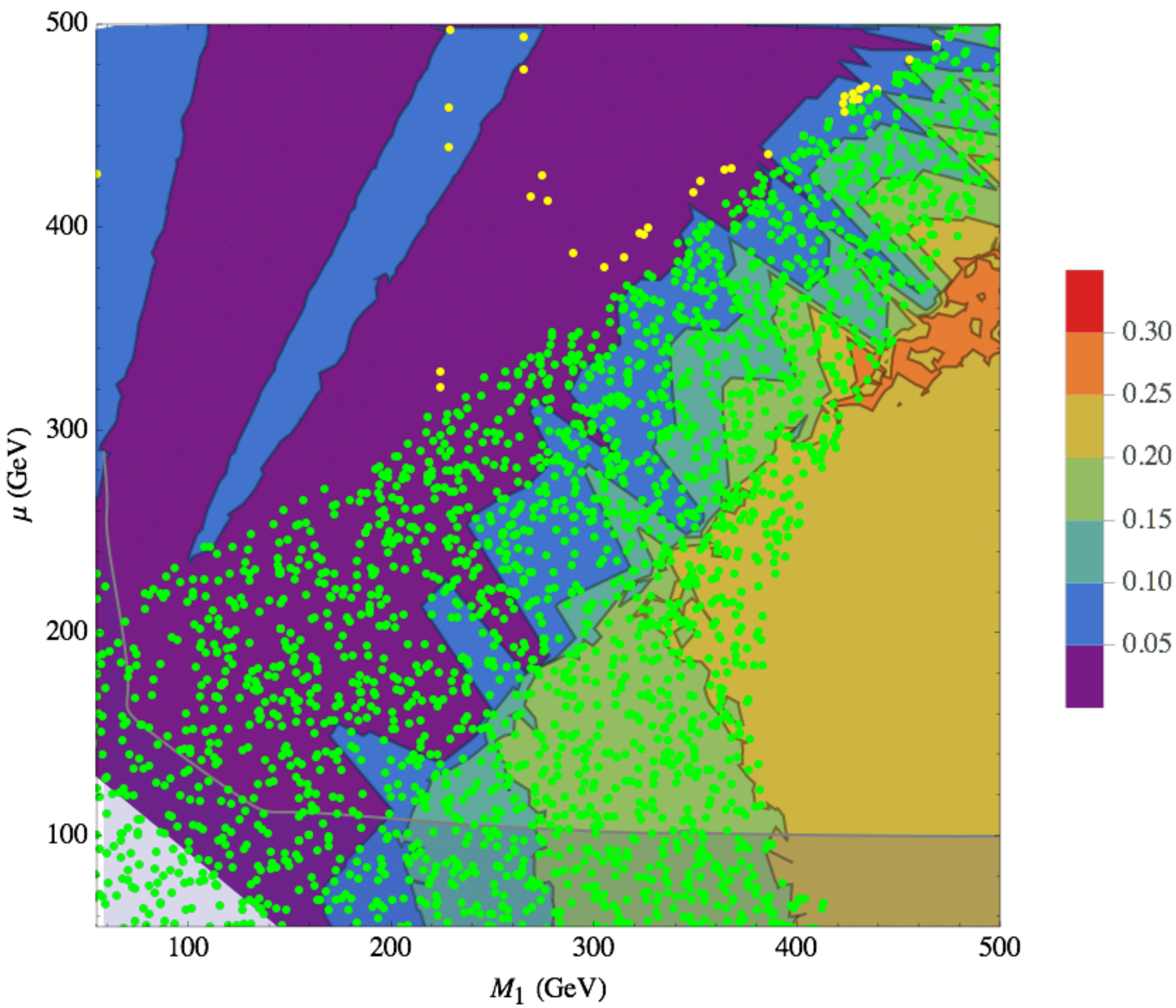
$$\tilde{\chi} = N_{i1}\ \tilde{B} + N_{i2}\ \tilde{W} + N_{i3}\ \tilde{H}_d + N_{i4}\ \tilde{H}_u$$

$$\tilde{\chi}_2{}^0 \rightarrow \tilde{\chi}_1{}^0 + h$$

from kinematics $M_2 - M_1 \approx M_1 > m_h$ and $\mu - M_1 > m_h$

Higgs in Neutralino and Chargino Decays, Contours

$$L = -D_\mu H_u^{+} D^\mu H_u - i\bar{\tilde{H}}_u \not{D}\tilde{H}_u - \sqrt{2}g' Y_{H_u}\tilde{B}\tilde{H}_u H_u^* - \sqrt{2}g\tilde{W}^a\tilde{H}_u t^a H_u^* + (u \leftrightarrow d)$$

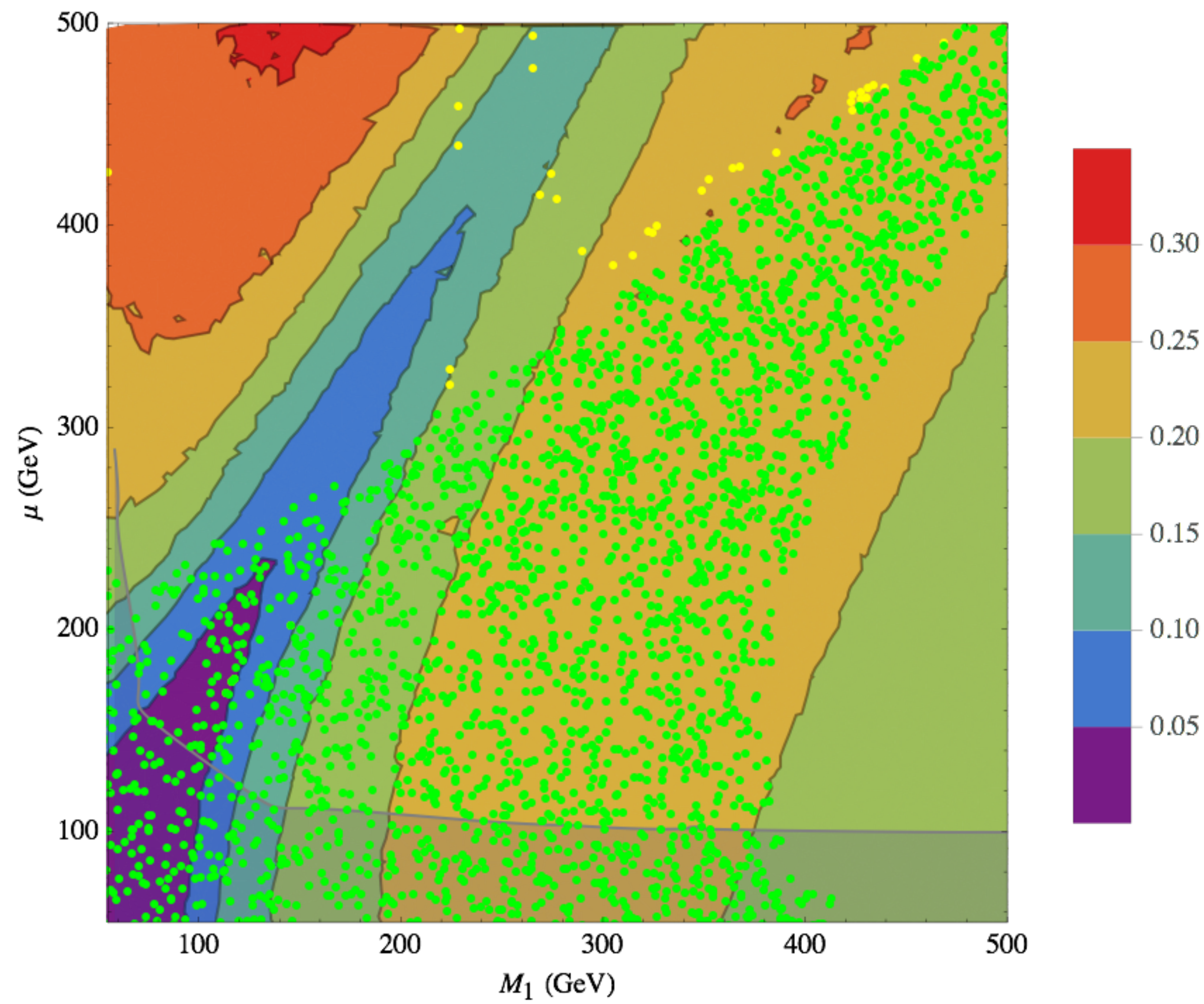


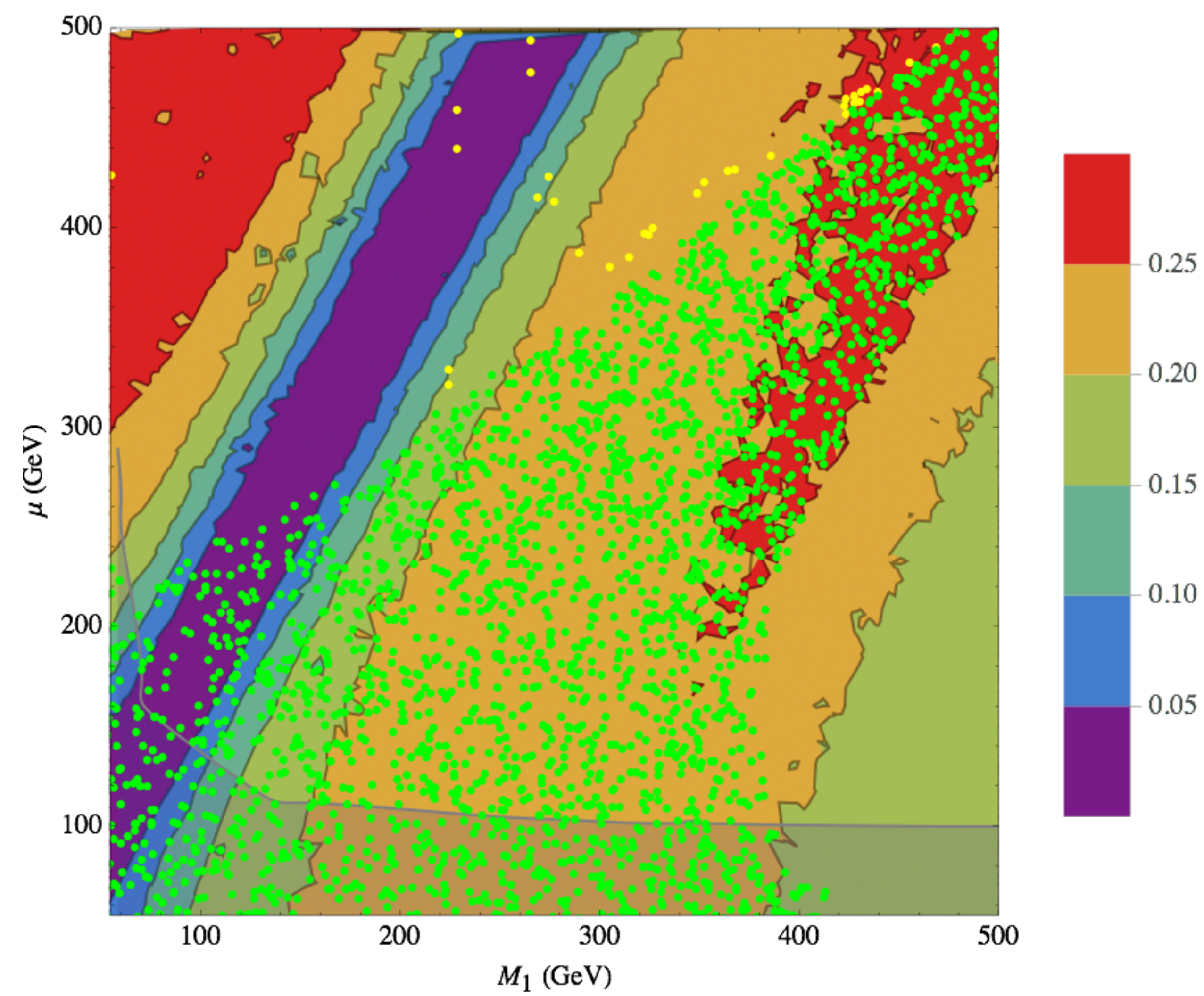
$$\tilde{\chi} = N_{i1}\ \tilde{B} + N_{i2}\ \tilde{W} + N_{i3}\ \tilde{H}_d + N_{i4}\ \tilde{H}_u$$

$$\tilde{\chi_3}^0 \to \tilde{\chi_1}^0 + h$$

Higgs in Neutralino and Chargino Decays, Winos

$$L = -D_\mu H_u^+ D^\mu H_u - i\bar{\tilde{H}}_u \not{D} \tilde{H}_u - \sqrt{2} g' Y_{H_u} \tilde{B} \tilde{H}_u H_u^* - \sqrt{2} g \tilde{W}^a \tilde{H}_u t^a H_u^* + (u \leftrightarrow d)$$

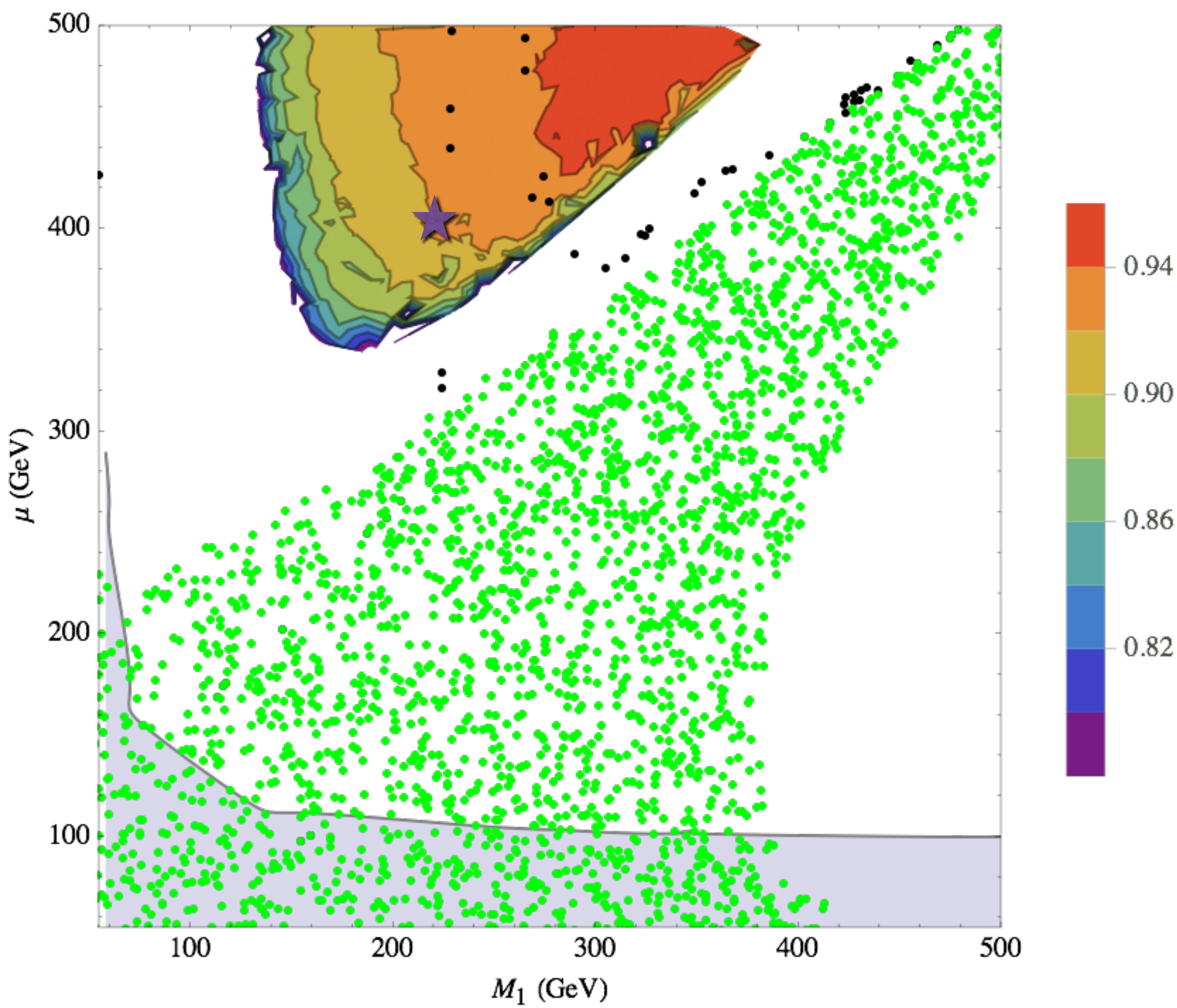




$\tilde{\chi}_4{}^0 \to \tilde{\chi}_i{}^0 + h$

$\tilde{\chi}_2{}^\pm \to \tilde{\chi}_1{}^\pm + h$

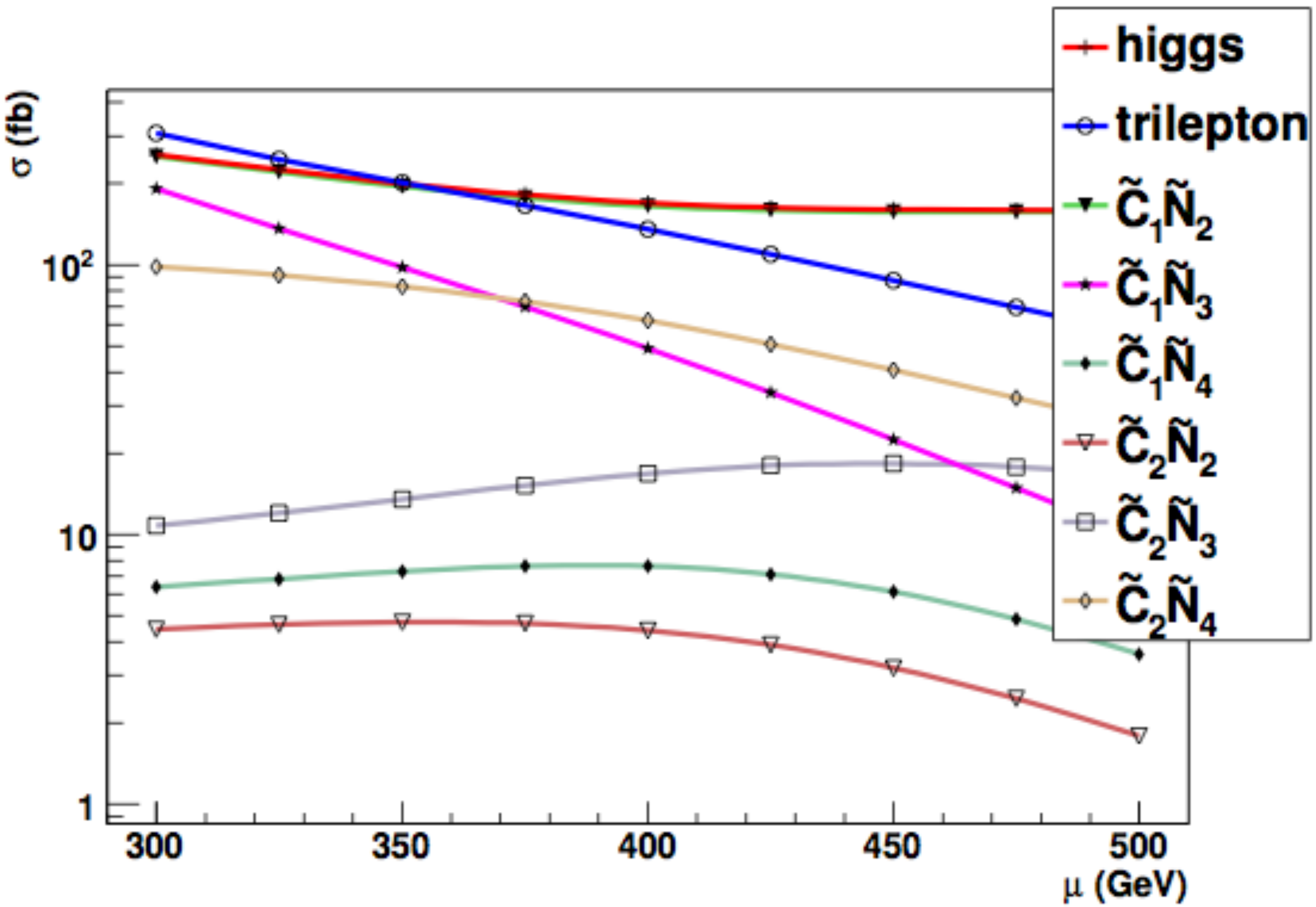
Collider Searches



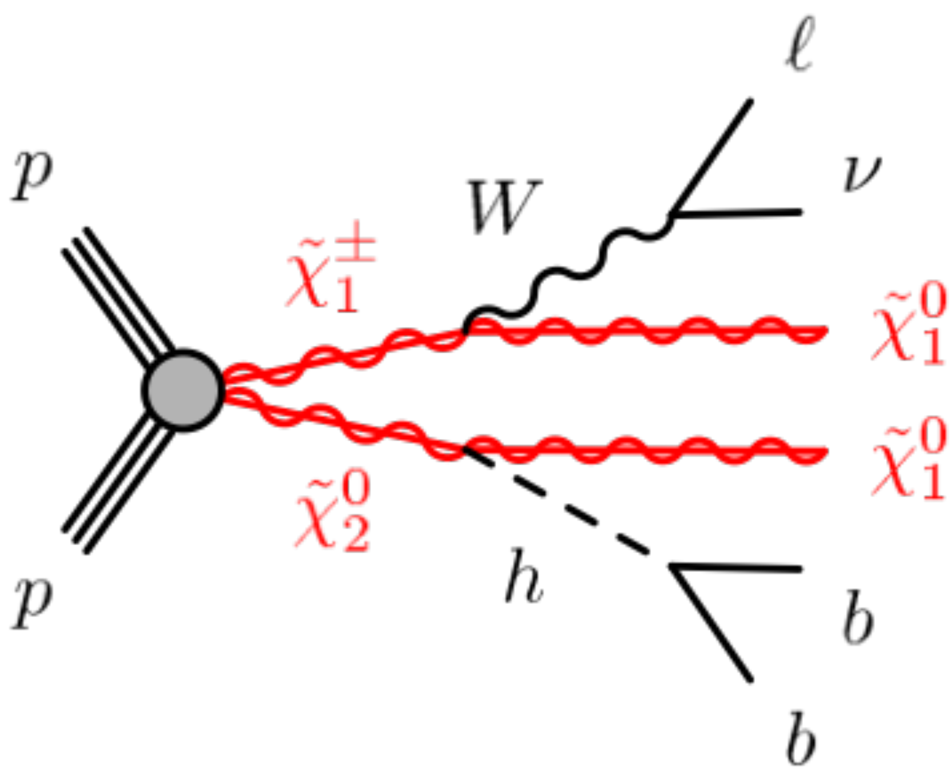
★ Benchmark

$M_1 \sim 220$ GeV

Collider Searches



Collider Searches



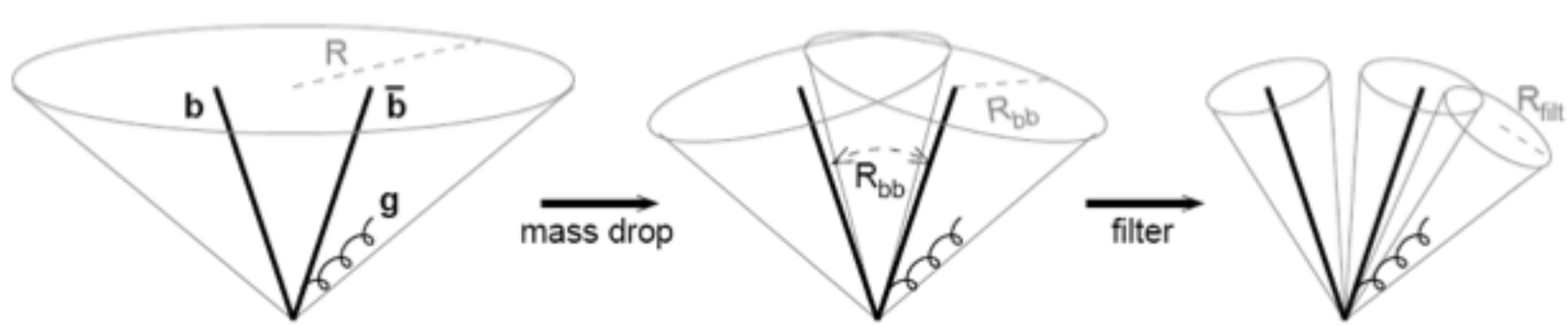
- Higgs can be boosted
- Look for 1 lepton, 1 fat jet that can be reconstructed as a higgs and missing energy

Reconstruct the Higgs

- Use the Cambridge-Aachen jet algorithm
  - ❖ Recombines the closest pair of objects in the events up to R
- For a boosted fat jet
  - ❖ Undo the last clustering step
  - ❖ Check "mass drop" and "subjet symmetry"

$$\mu = \frac{m_{j1}}{m_j} \qquad y = \frac{min(p_{T1}, p_{T2})\Delta R_{12}^2}{m_j^2}$$

  - ❖ If there are significant mass drop and symmetric subjet, recluster the remaining constituents with a smaller R(jet filter)



Collider Searches

- 1 isolated lepton, 1 fat jet reconstructed as a higgs($m_j = 125 \pm 4$ GeV) and $\not{E}_T > 100$ GeV
- main background: Wjj, dijet, $t\bar{t}$

S	Wjj+dijet	$t\bar{t}$	B	$S/\sqrt{B}$
27.8	10	88.5	99	2.8

100 fb^{-1}, 14 TeV

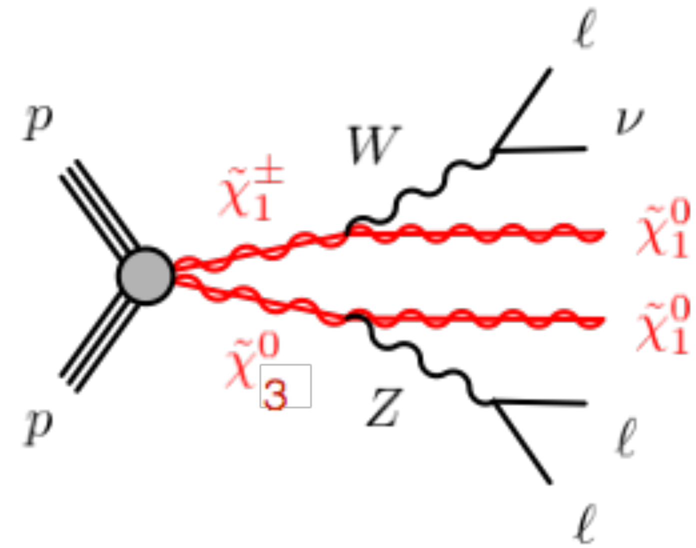
Tri-lepton Channel

ATLAS NOTE

ATLAS-CONF-2013-035

March 24, 2013

Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in 21 fb^{-1} of pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector



Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
m_{SFOS} [GeV]	<60	60–81.2	<81.2 or >101.2	81.2–101.2	81.2–101.2	81.2–101.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>50	>75	>75	75–120	75–120	>120
m_{T} [GeV]	–	–	>110	<110	>110	>110
p_{T} 3$^{\mathrm{rd}}$ ℓ [GeV]	>10	>10	>30	>10	>10	>10
SR veto	SRnoZc	SRnoZc	–	–	–	–

main background: WZ, ZZ, $t\bar{t}$V, tri-boson

safe at 8 TeV, 20.7 fb^{-1}, $S/\sqrt{B} \sim 1.7$ for 14 TeV 100 fb^{-1}

Conclusion

- Higgs mass is known to ~0.4 GeV level, which motivates higgs mass calculation to a higher order
- Run the quartic coupling up, and match to MSSM at SUSY scale, to predict the SUSY scale for given parameters
- New search channel for LHC: neutralino/chargino production with a boosted higgs in the decay chain