Berkeley Workshop:
SUSY Searches @ LHC
October 2011

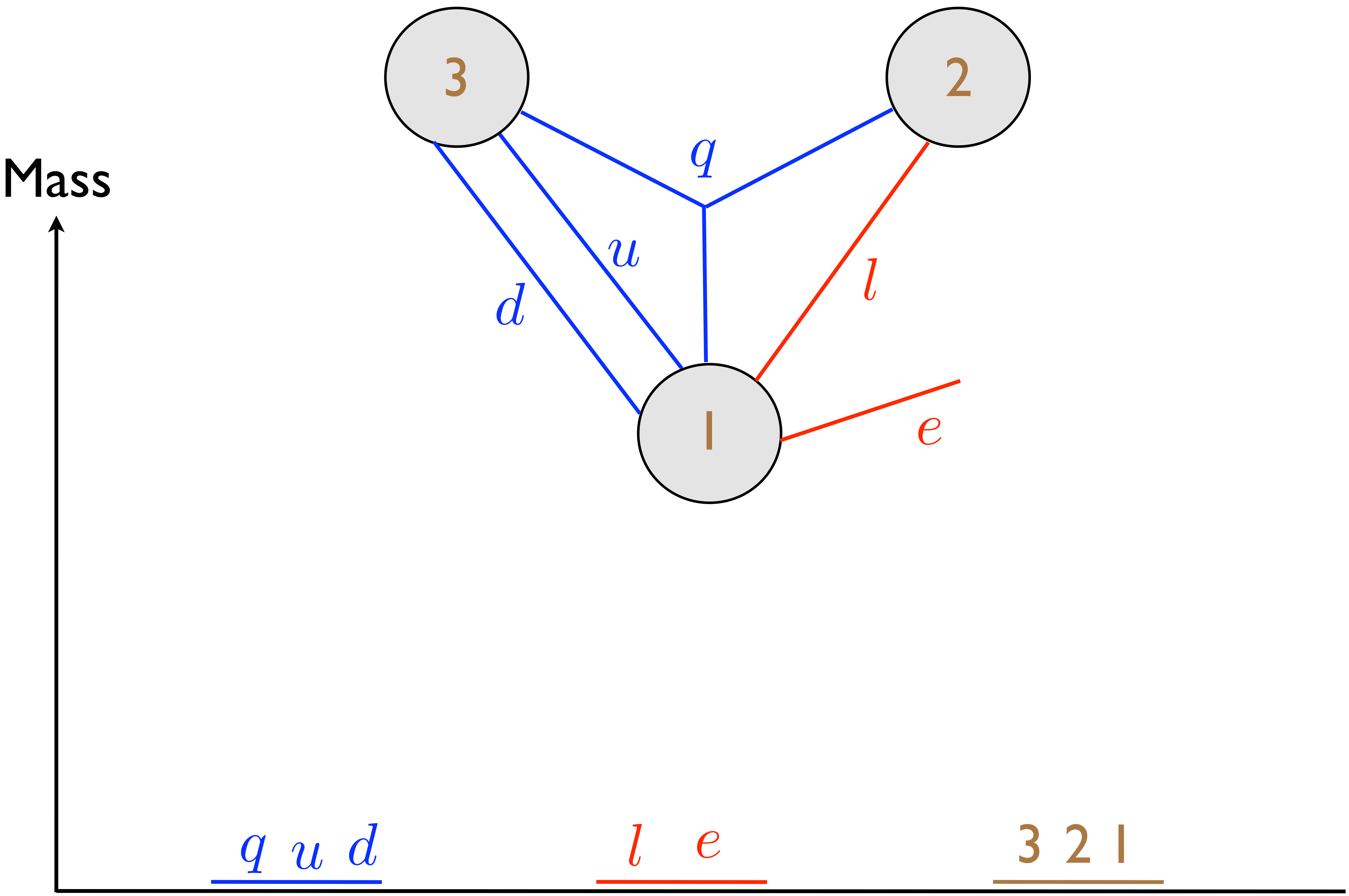
Where Do We Stand With SUSY?

Lawrence Hall
UC Berkeley & LBNL

BERKELEY CENTER FOR THEORETICAL PHYSICS

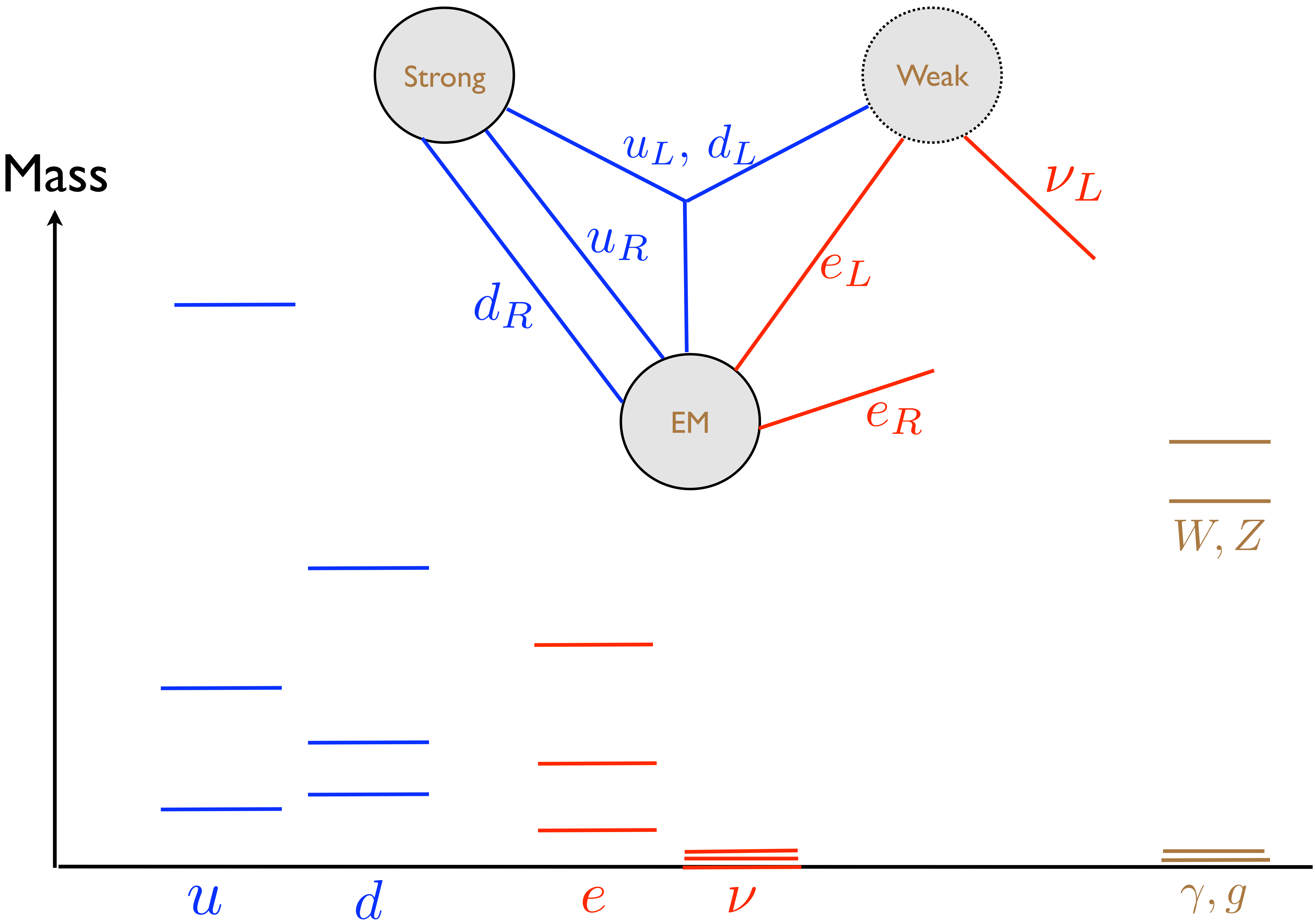
The Prime Goal of LHC

Our theoretical knowledge



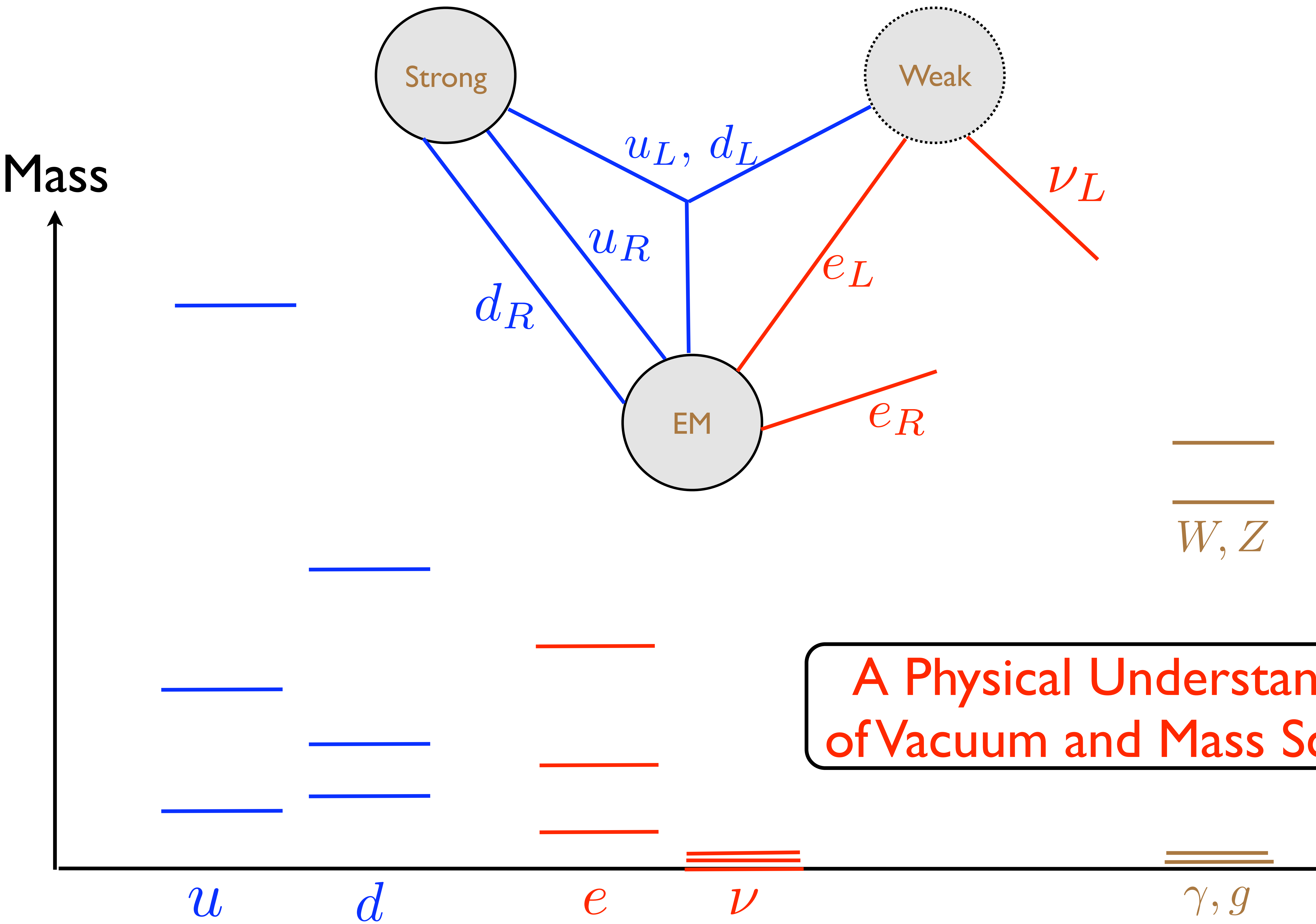
The Prime Goal of LHC

Our observed knowledge



The Prime Goal of LHC

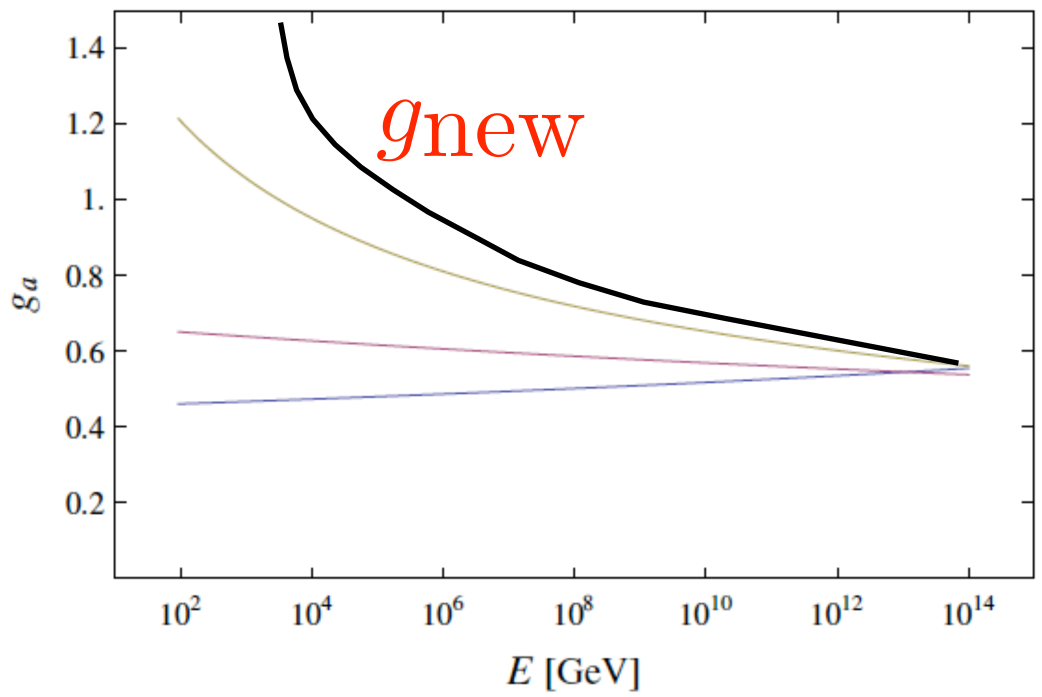
Our observed knowledge



A Physical Understanding of Vacuum and Mass Scale, v

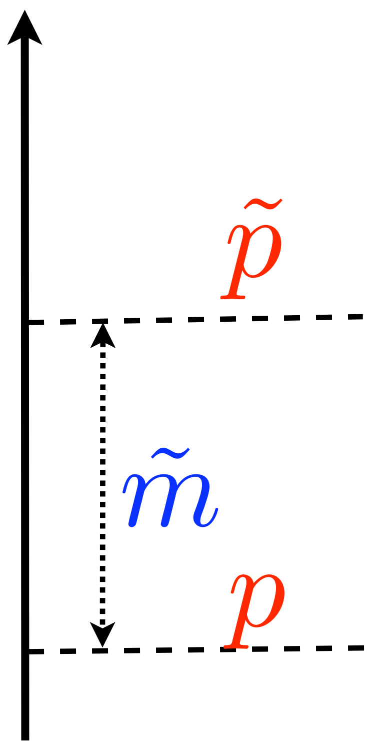
The Contenders

Dynamical



$$v = (\ldots)\Lambda_{\text{new}}$$

Susy



$$v = (\ldots)\,\tilde{m}$$

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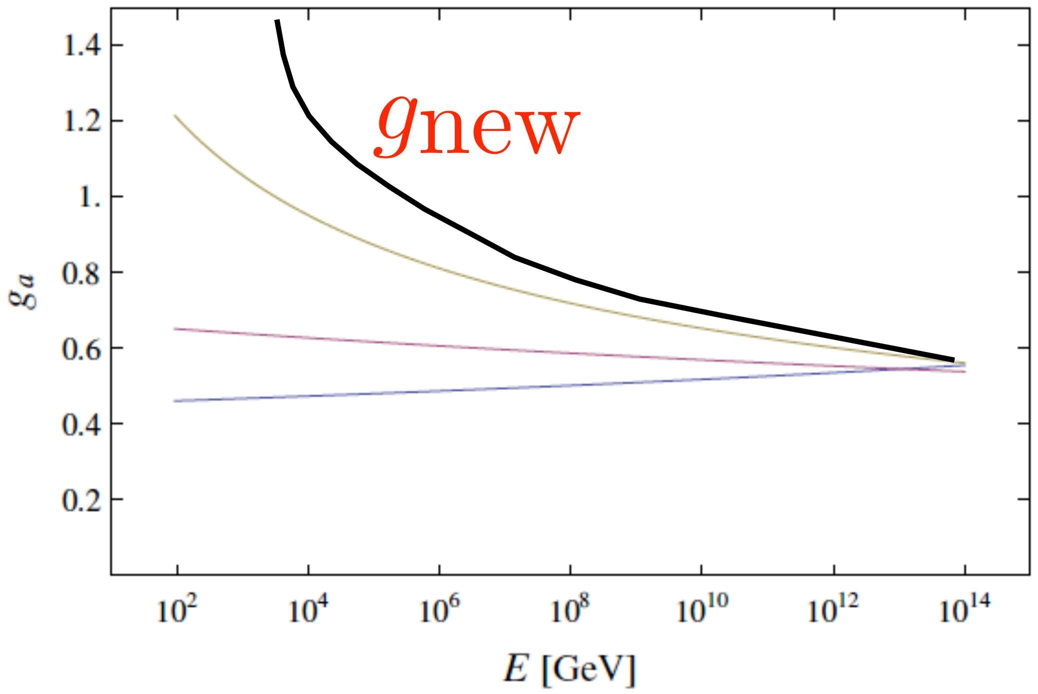

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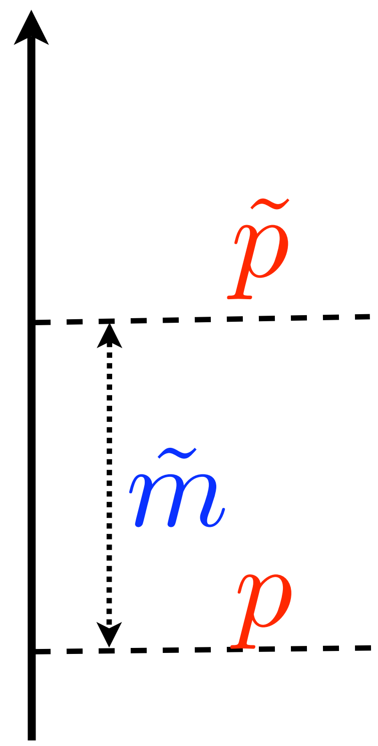

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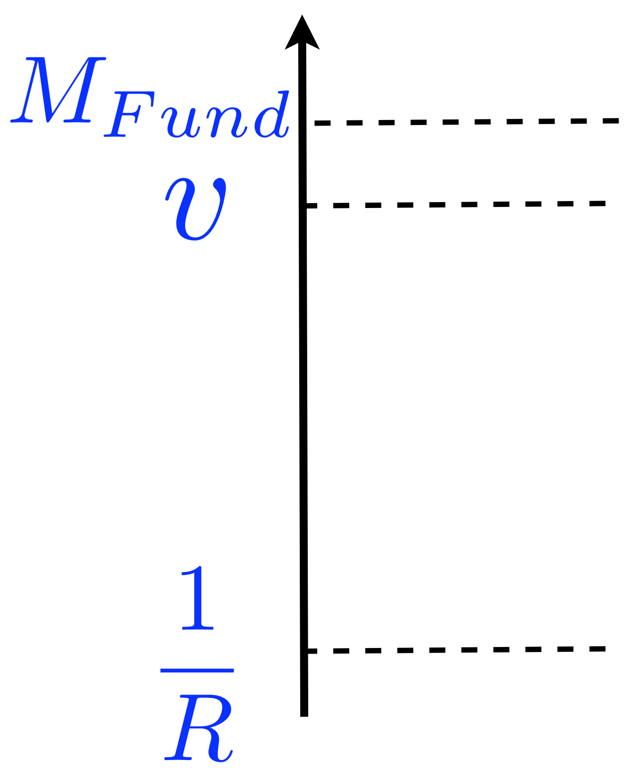
Large Extra Dim



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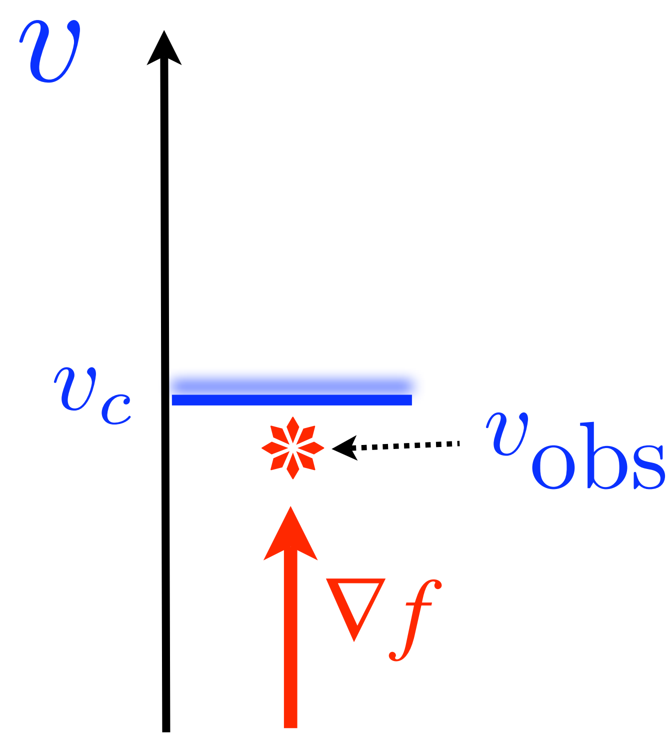
Multiverse



v_{obs} near v_c

The Contenders

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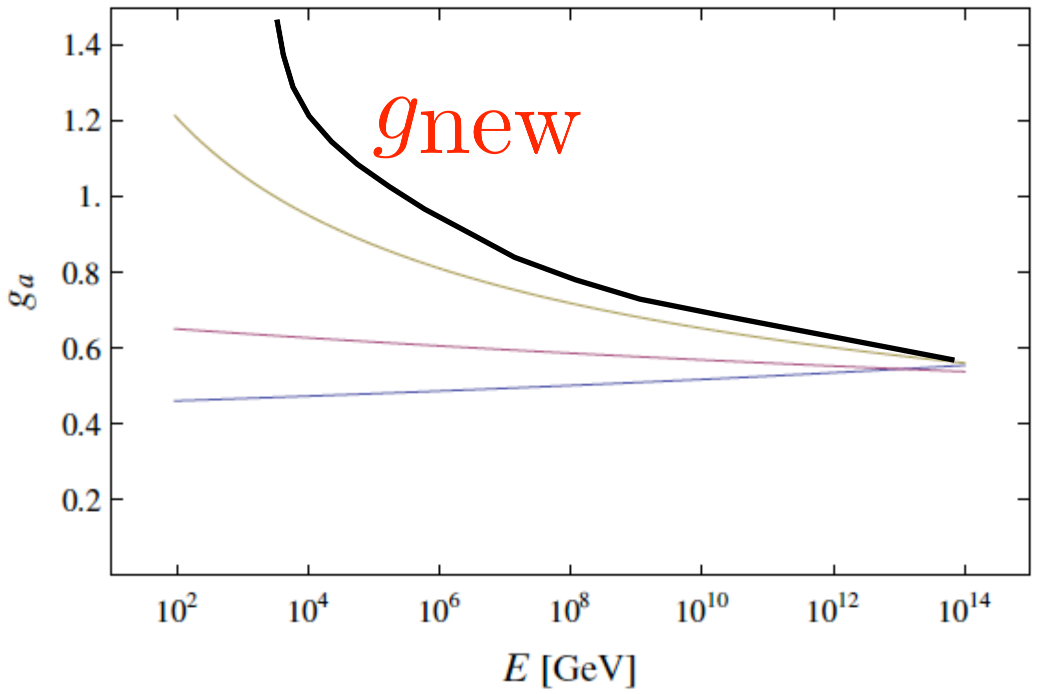

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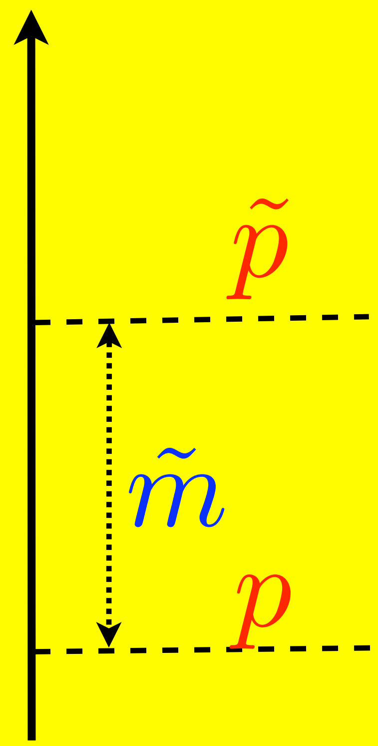

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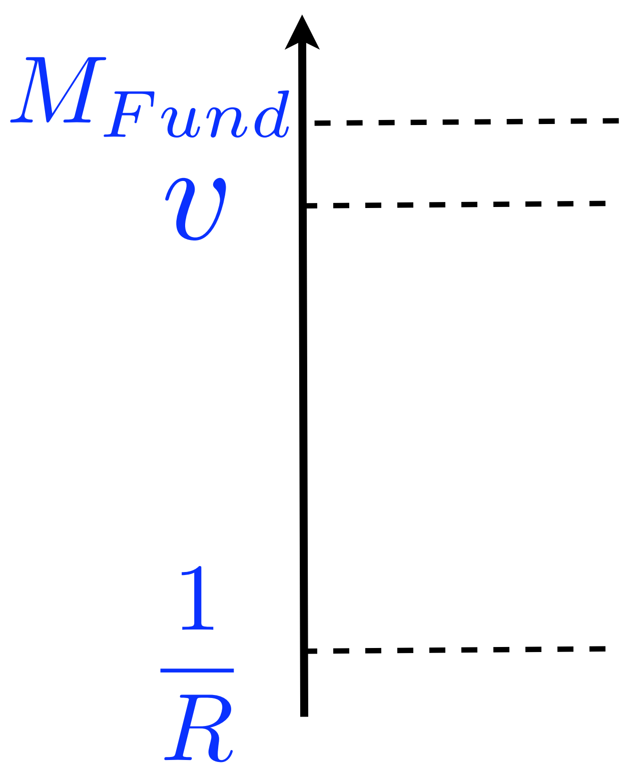

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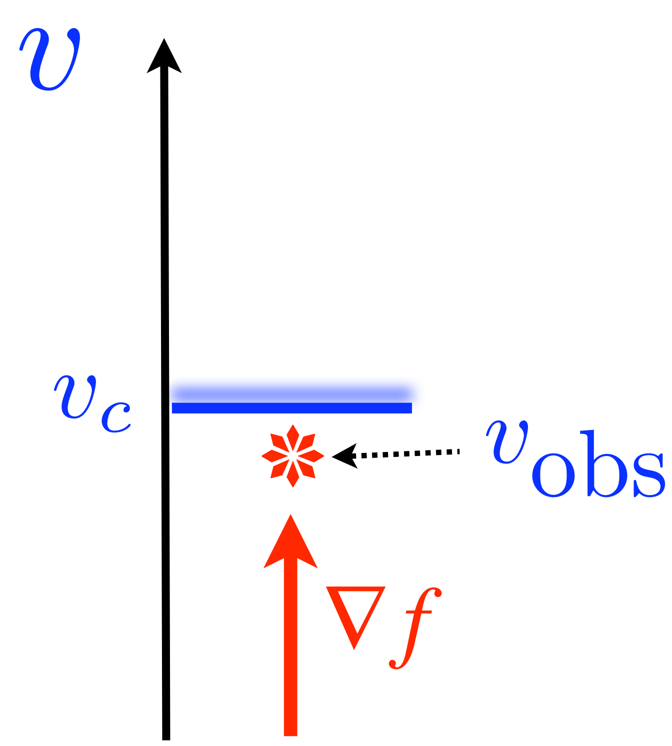
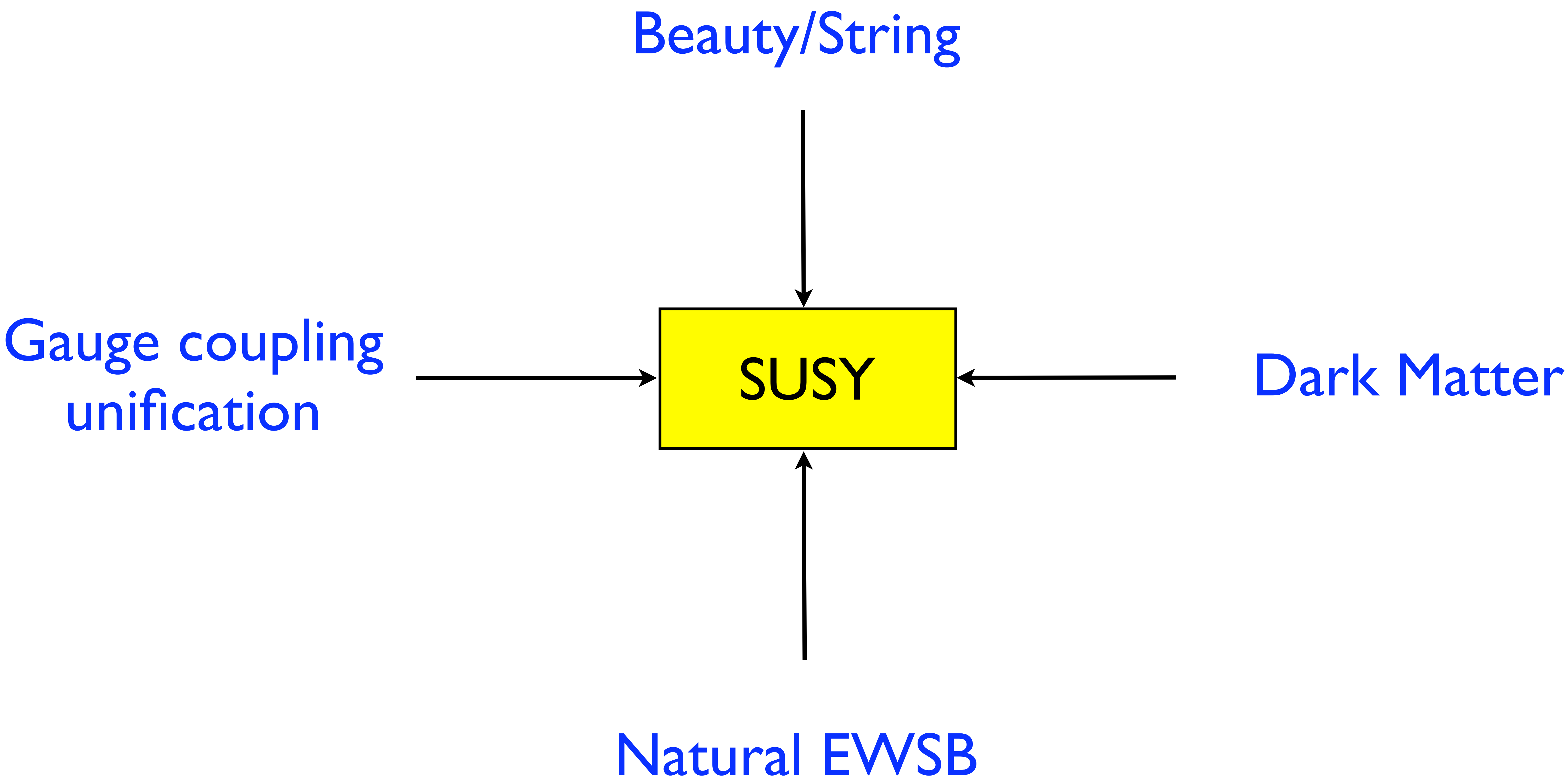


$v_{\rm obs}$ near v_c

Motivation for Supersymmetry



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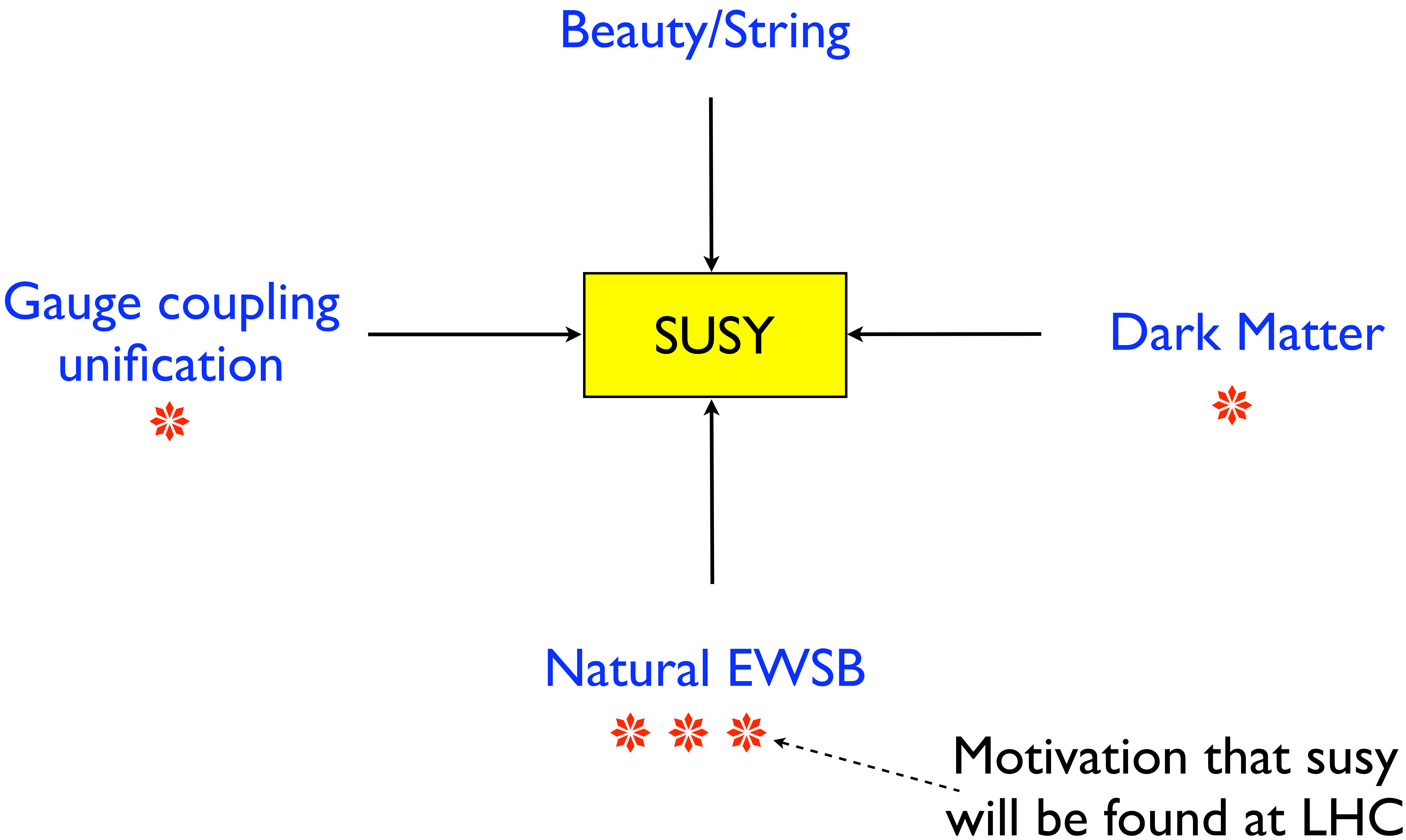

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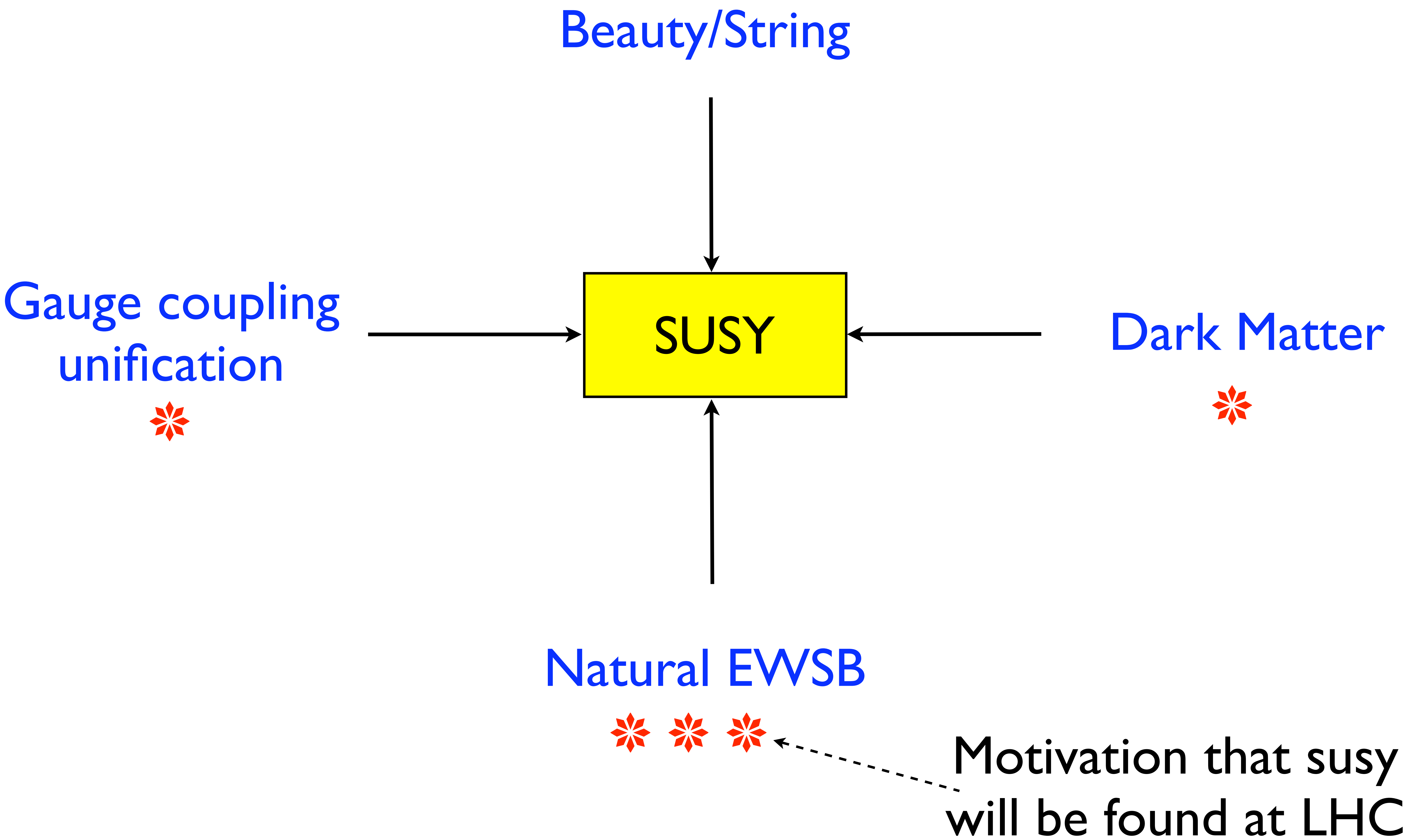

Cannot avoid naturalness/fine-tuning

Problems for Weak Scale SUSY

- Baryon and Lepton Conservation not automatic
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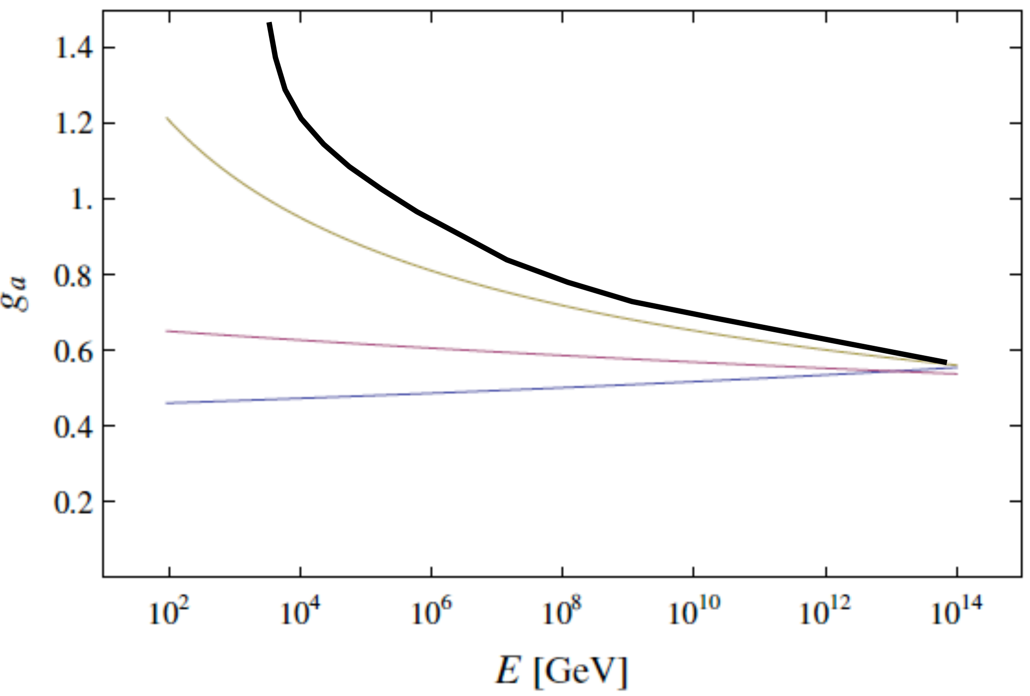
Give up on susy? The other contenders also problematic!!

The Bottom Line

Dynamical



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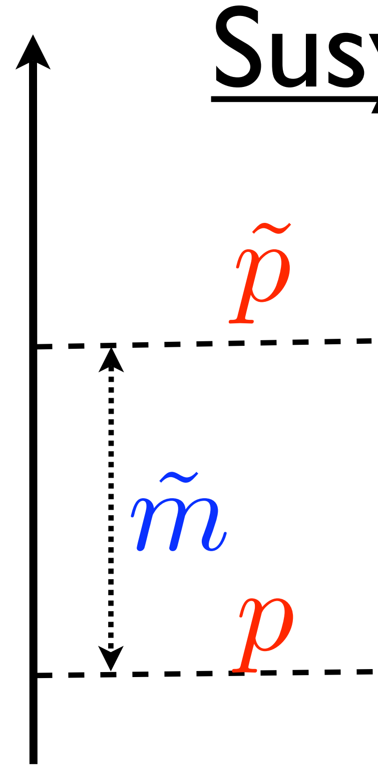
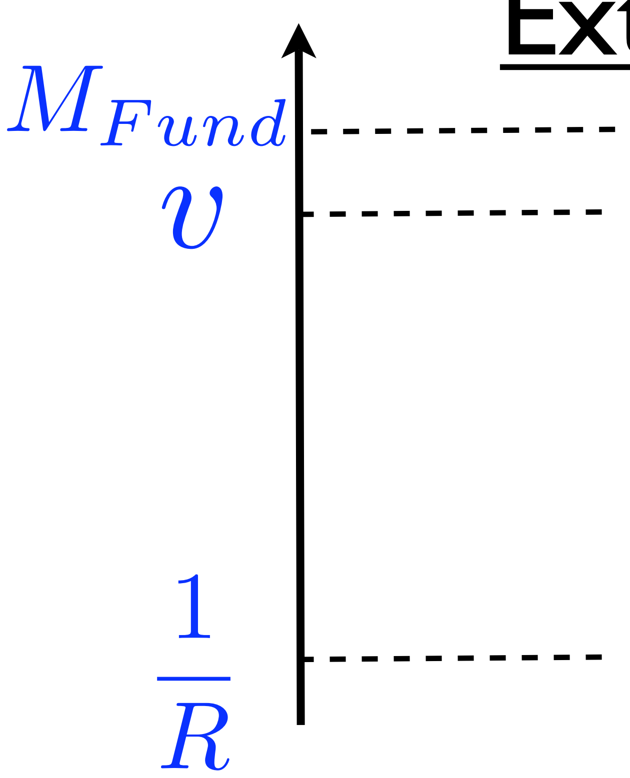


I really don't know.
That's the excitement
of the LHC.

Large Extra Dim



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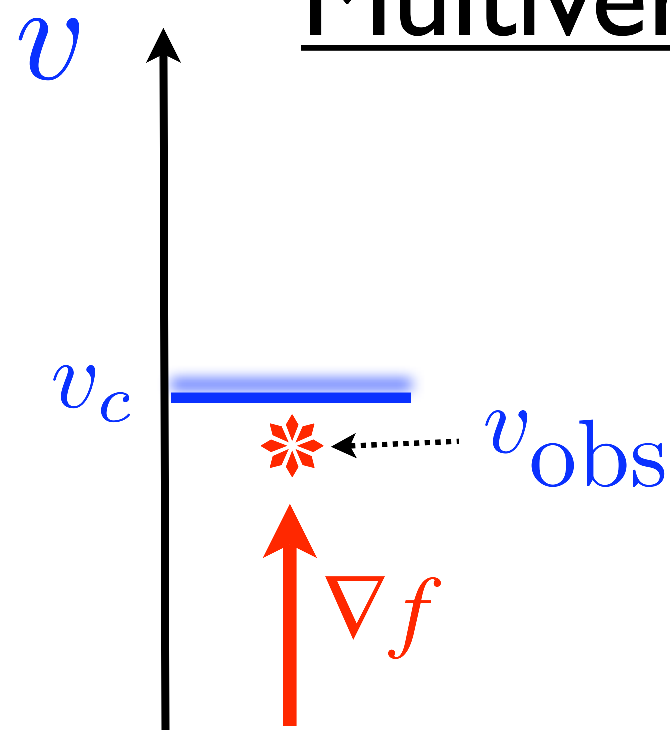


I

High-Scale Mediation

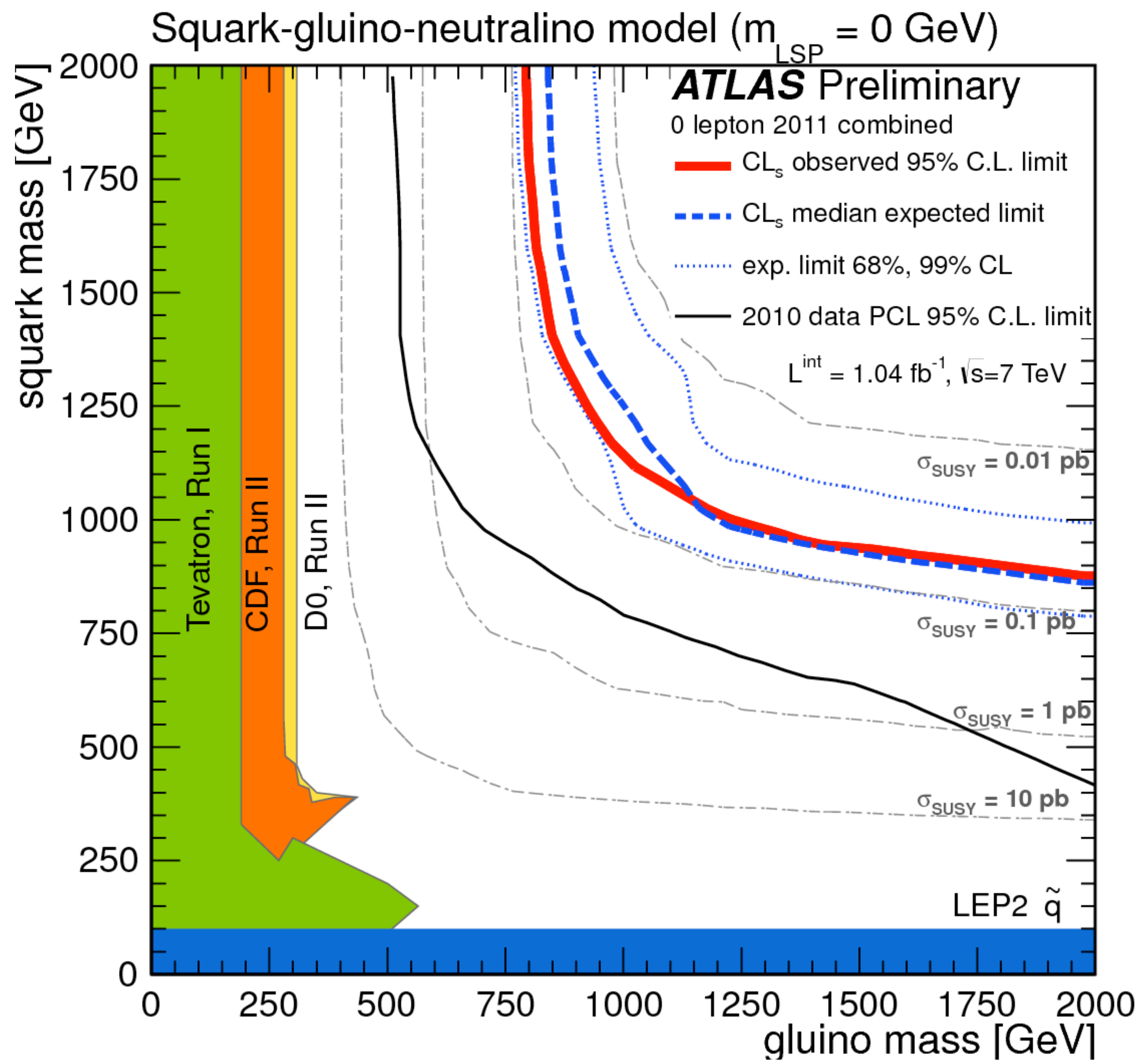
(No decays within detector to gravitinos)

Key Missing Energy Search

Jets + missing E_T

$$\tilde{g} \rightarrow \bar{q} q \, \tilde{\chi}$$

$$\tilde{q} \rightarrow q \, \tilde{\chi}$$



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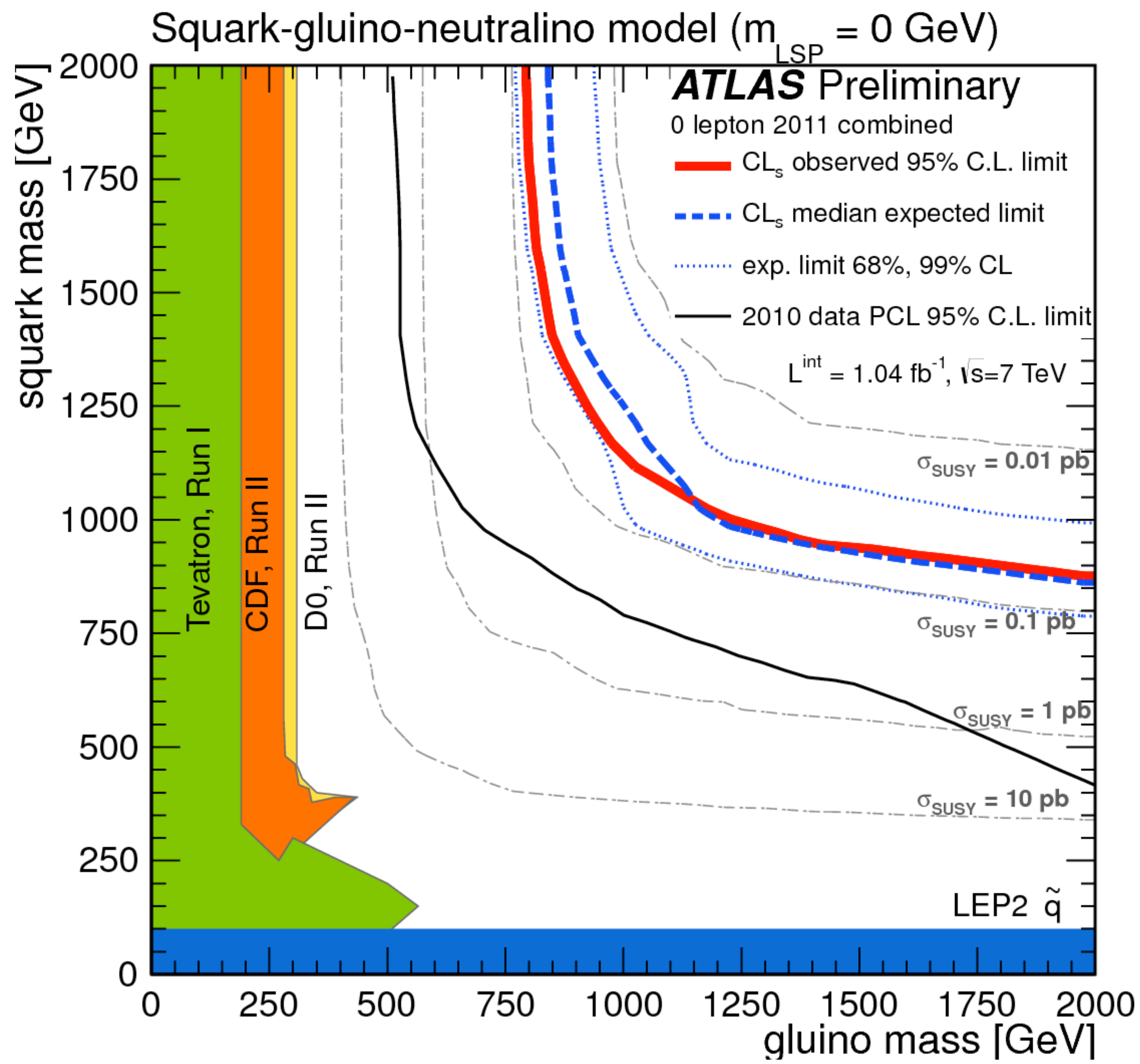

Important result:

- Some simple theories are now much less interesting
- Other theories are not yet probed

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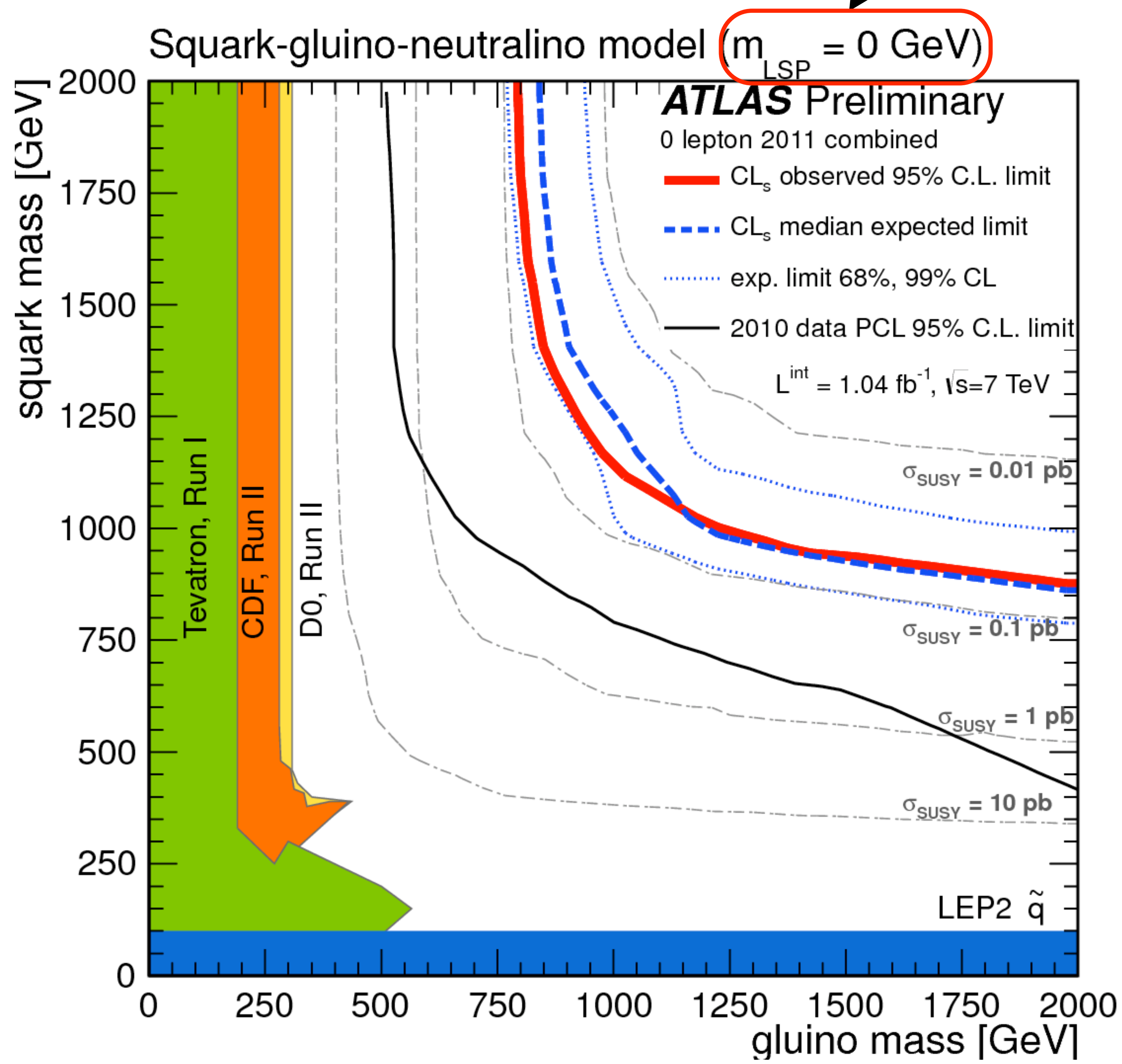

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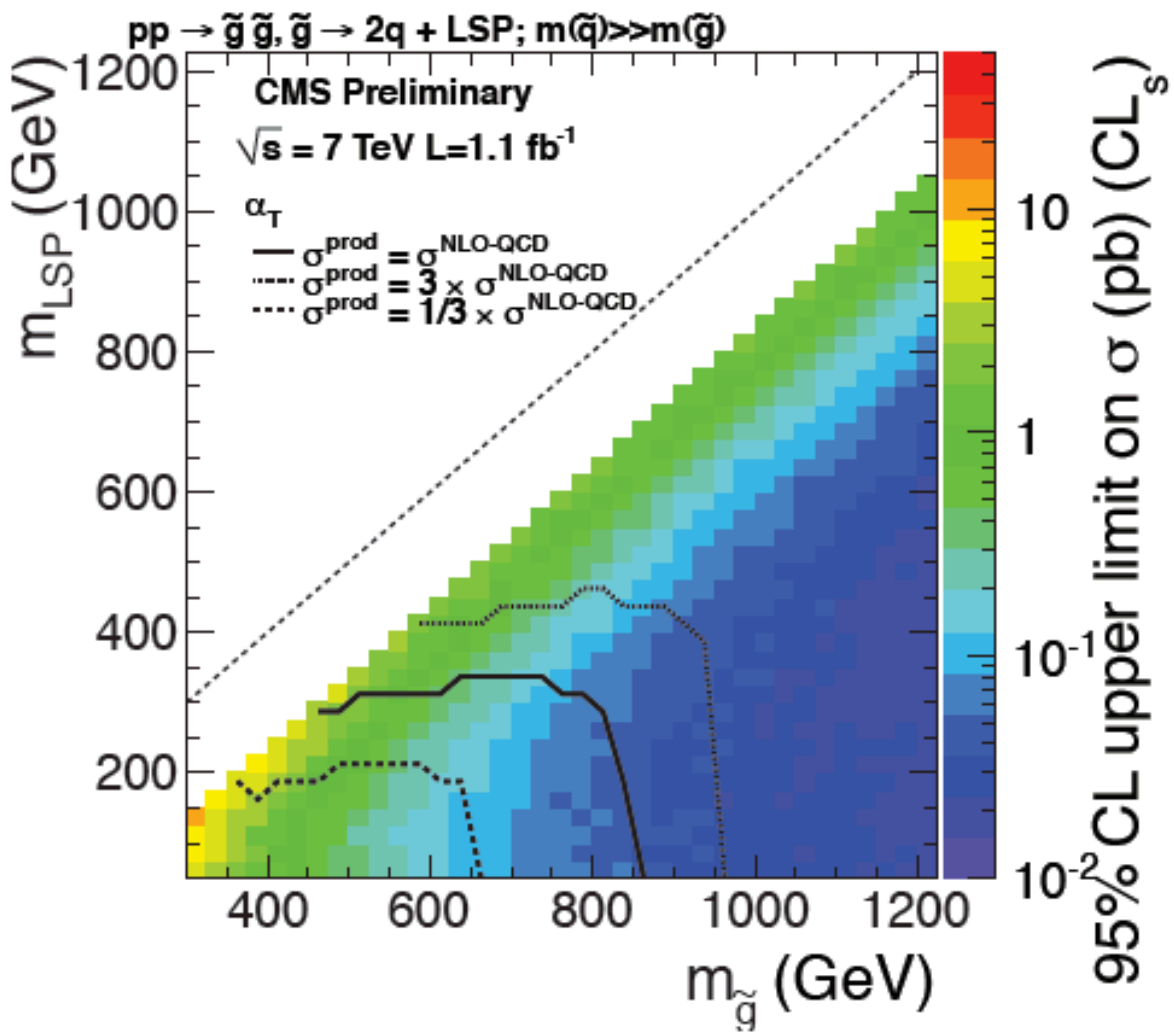
Dependence on LSP mass



No limit for $m_{LSP} \geq 350\,\mathrm{GeV}$

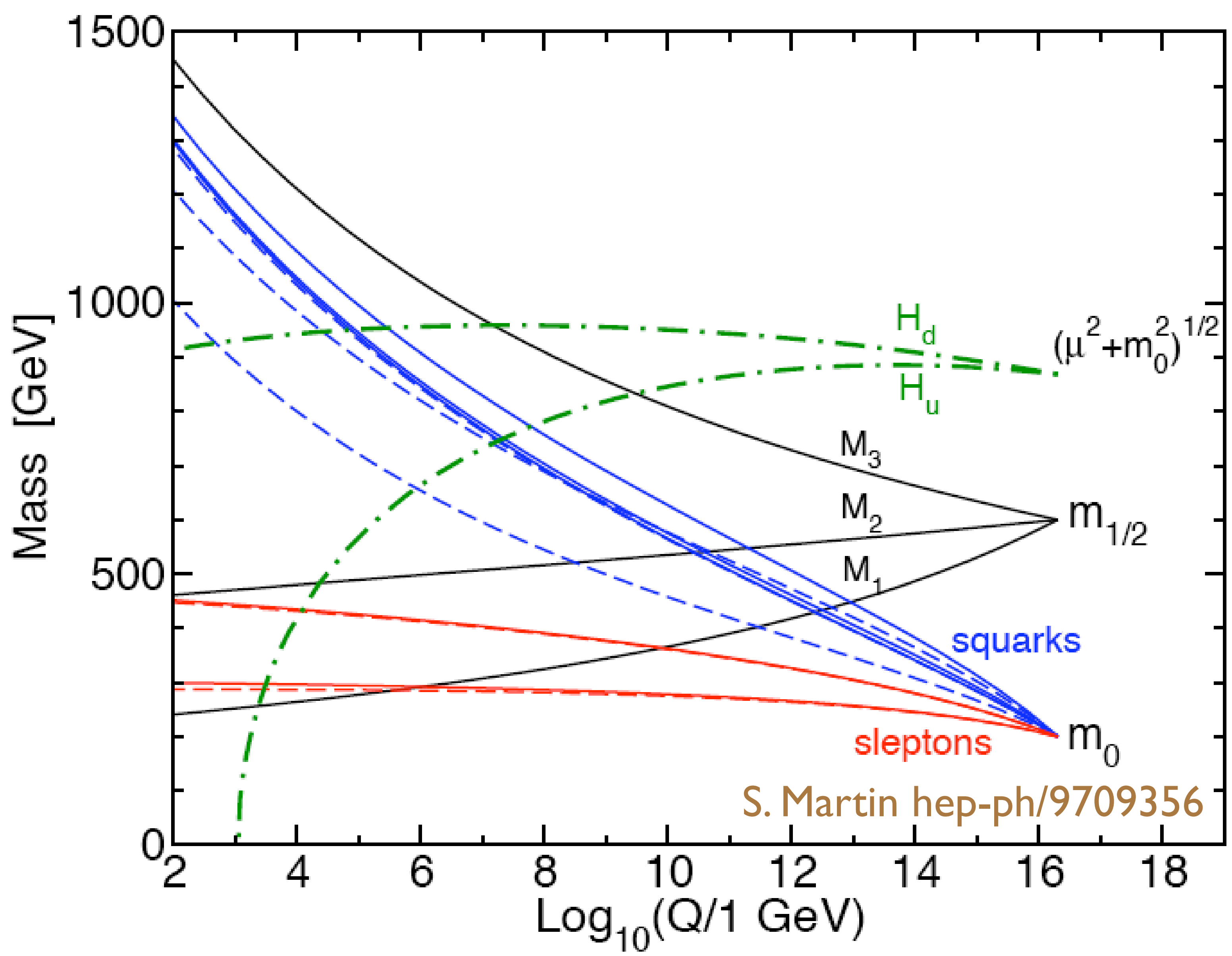
ie if $\mu \geq 350\,\mathrm{GeV}$

$M_i \propto \alpha_i$

Min SUGRA

High-scale boundary condition: $m_0,\ M_{1/2},\ A,\ B,\ \mu$

Radiative EWSB



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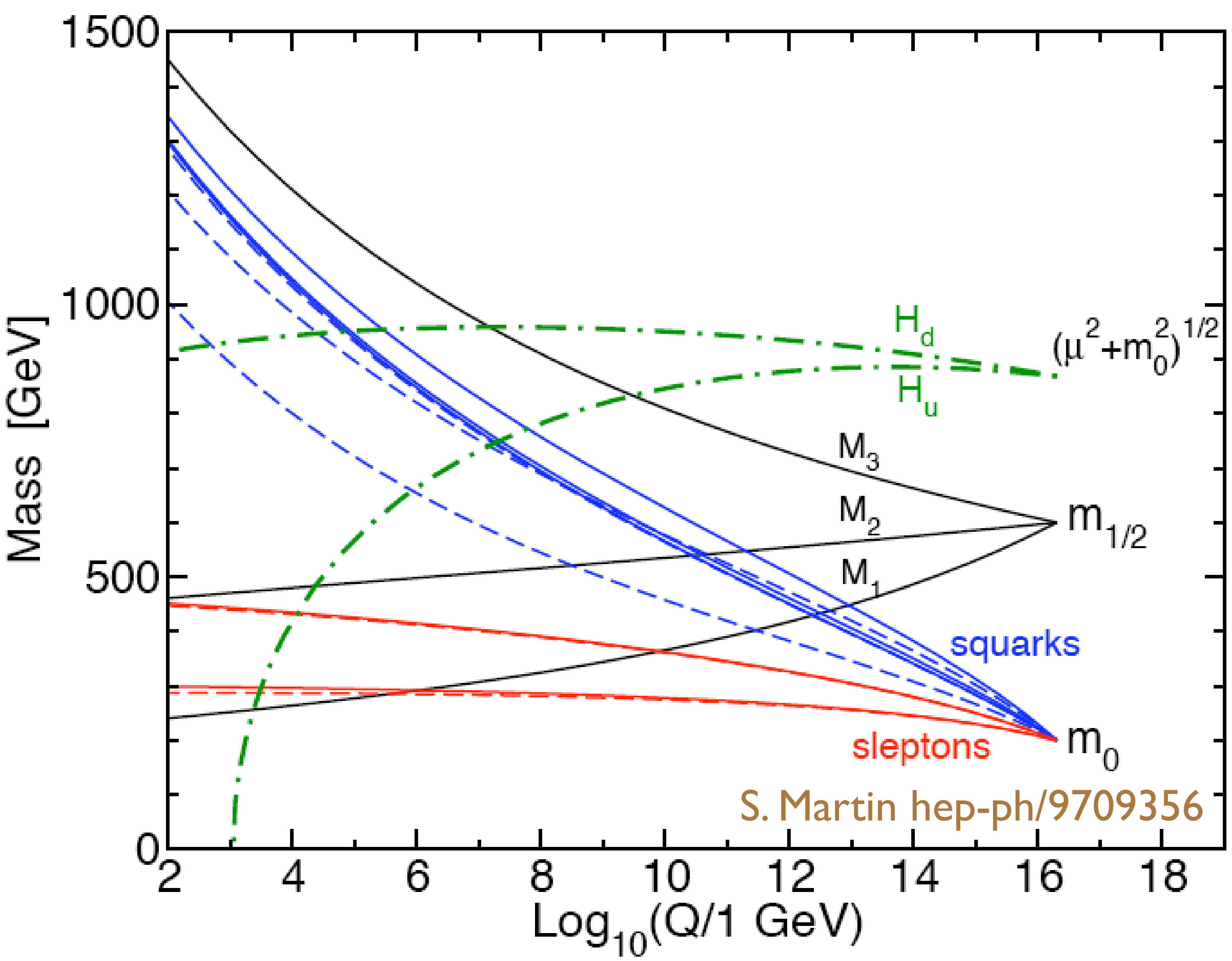

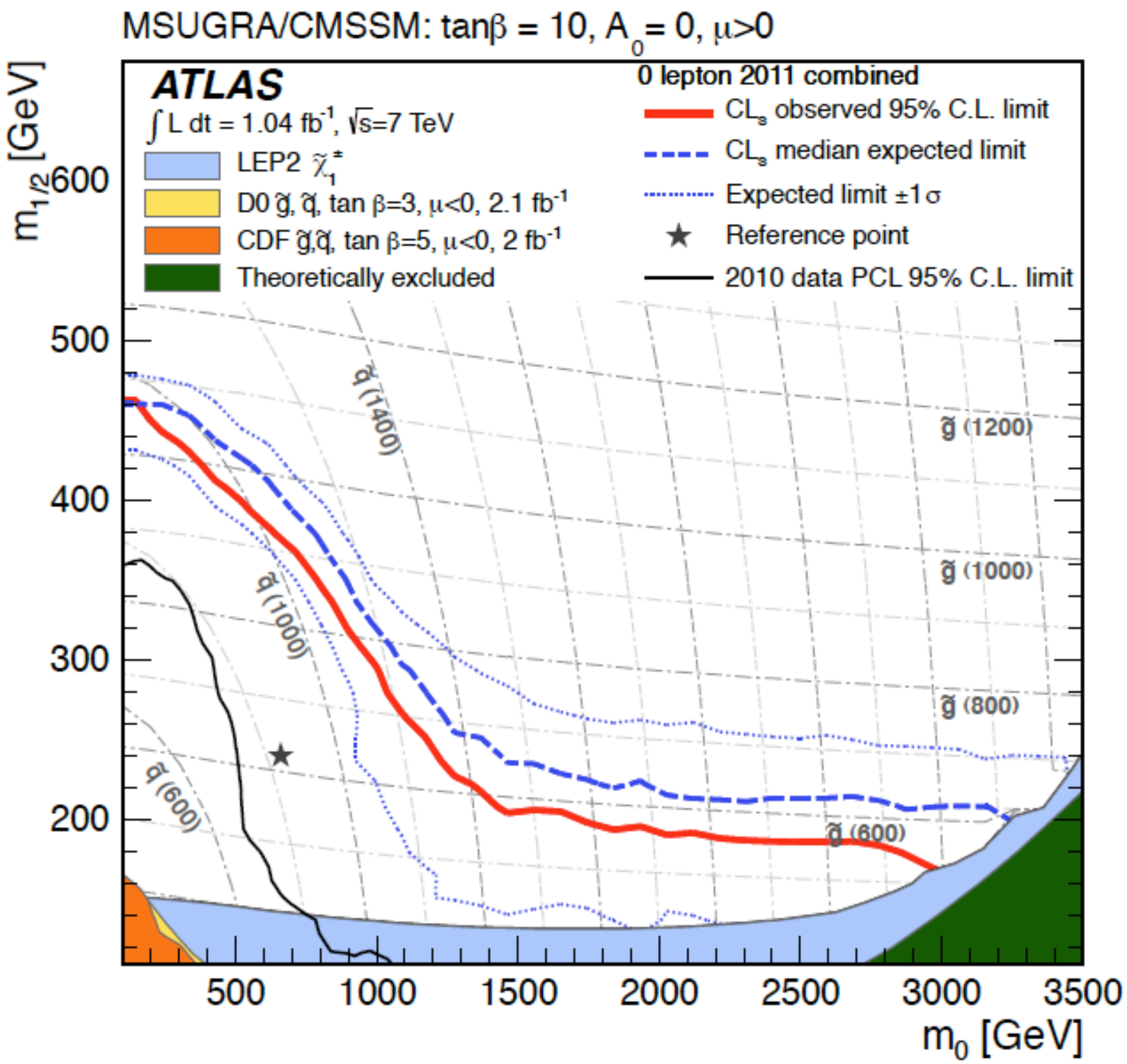

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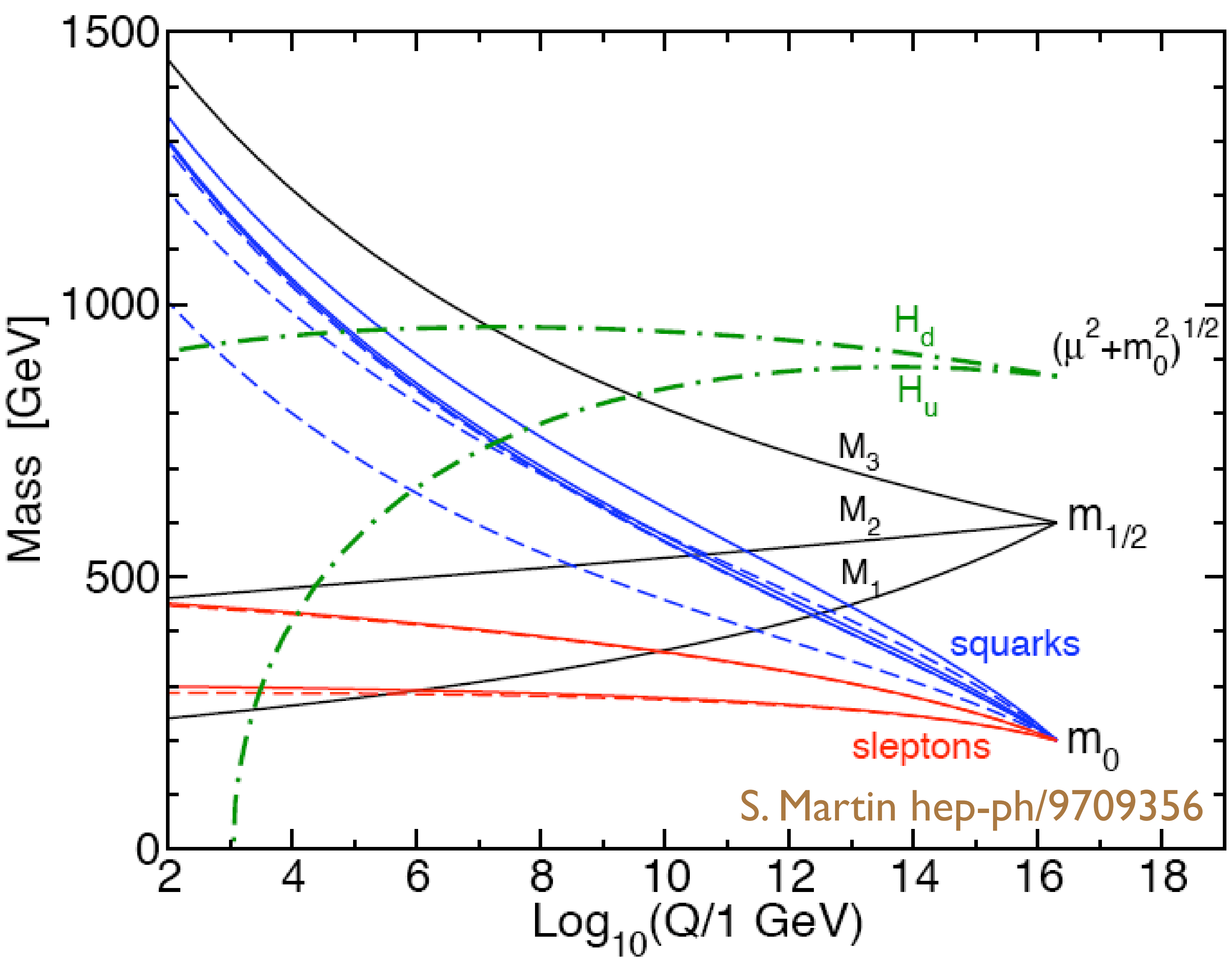
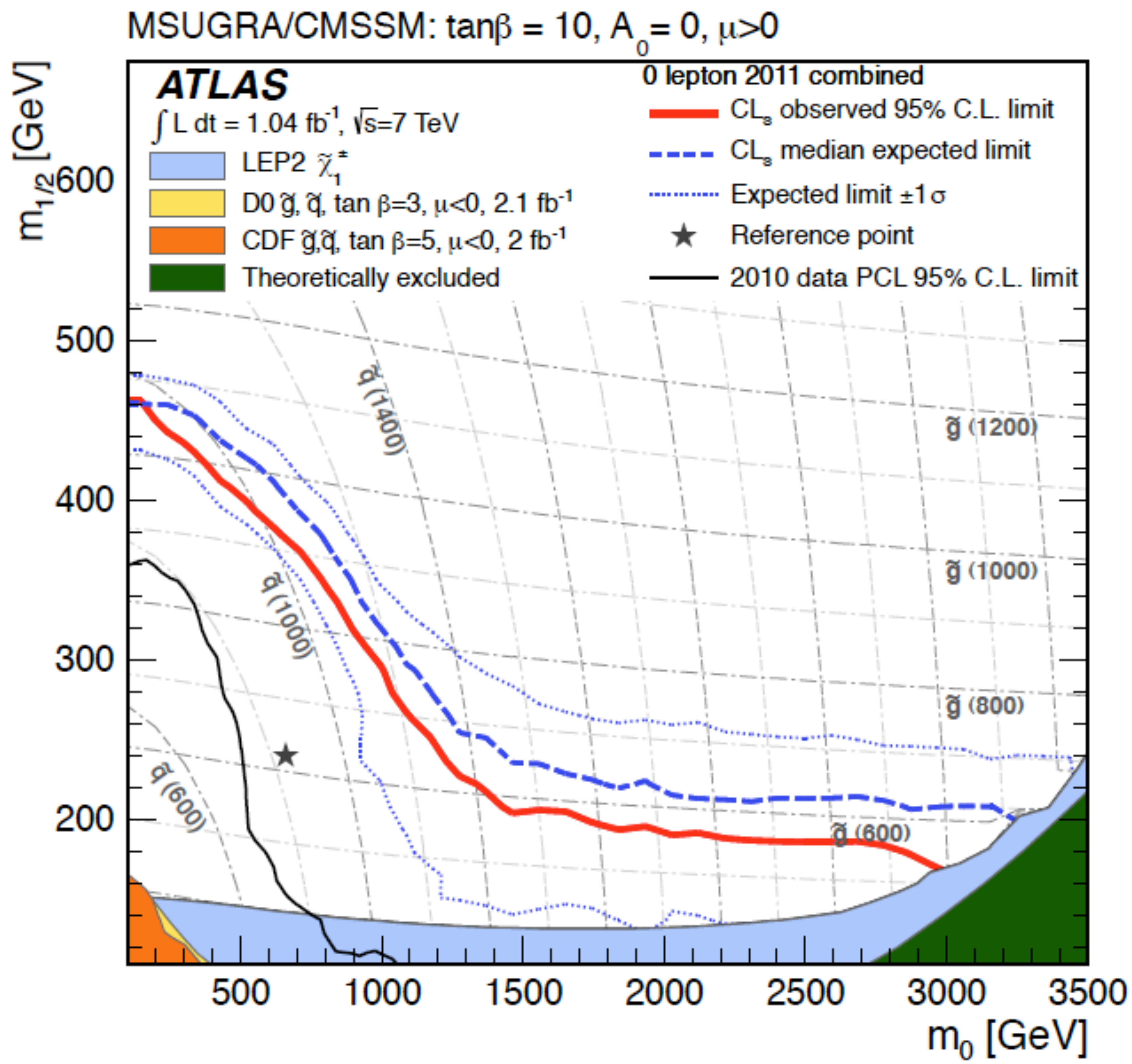
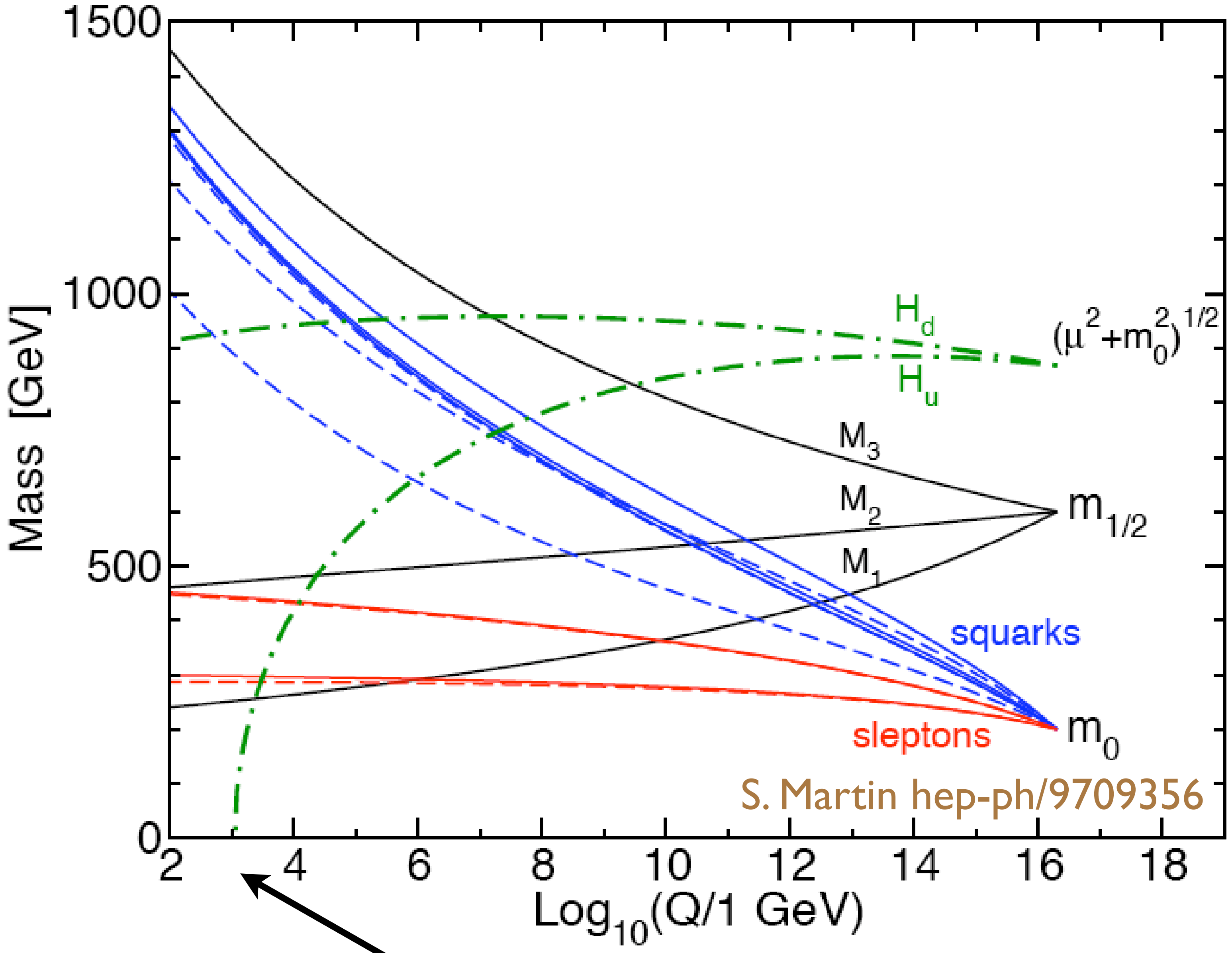




How fine-tuned?

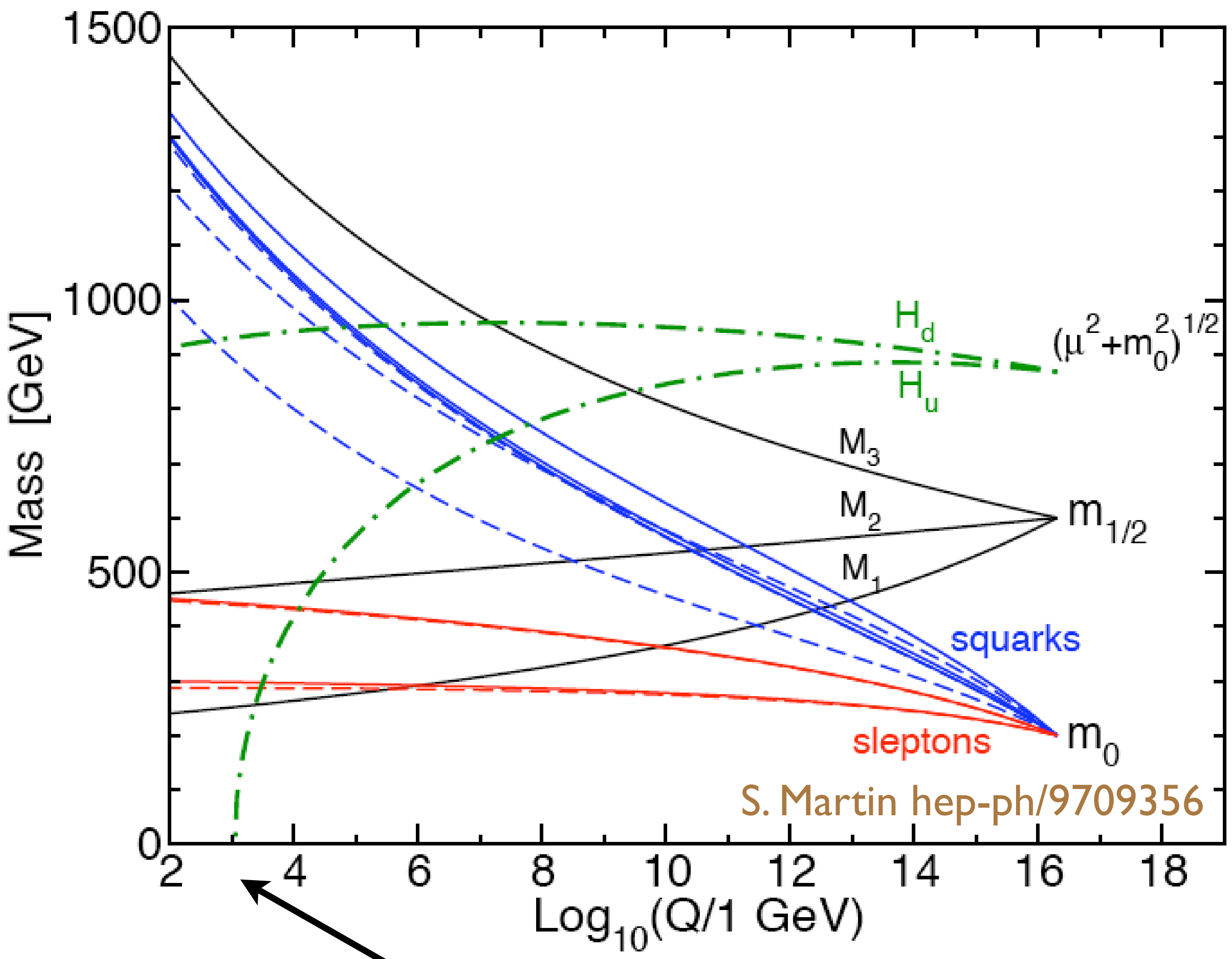
Min SUGRA: Fine-tuning

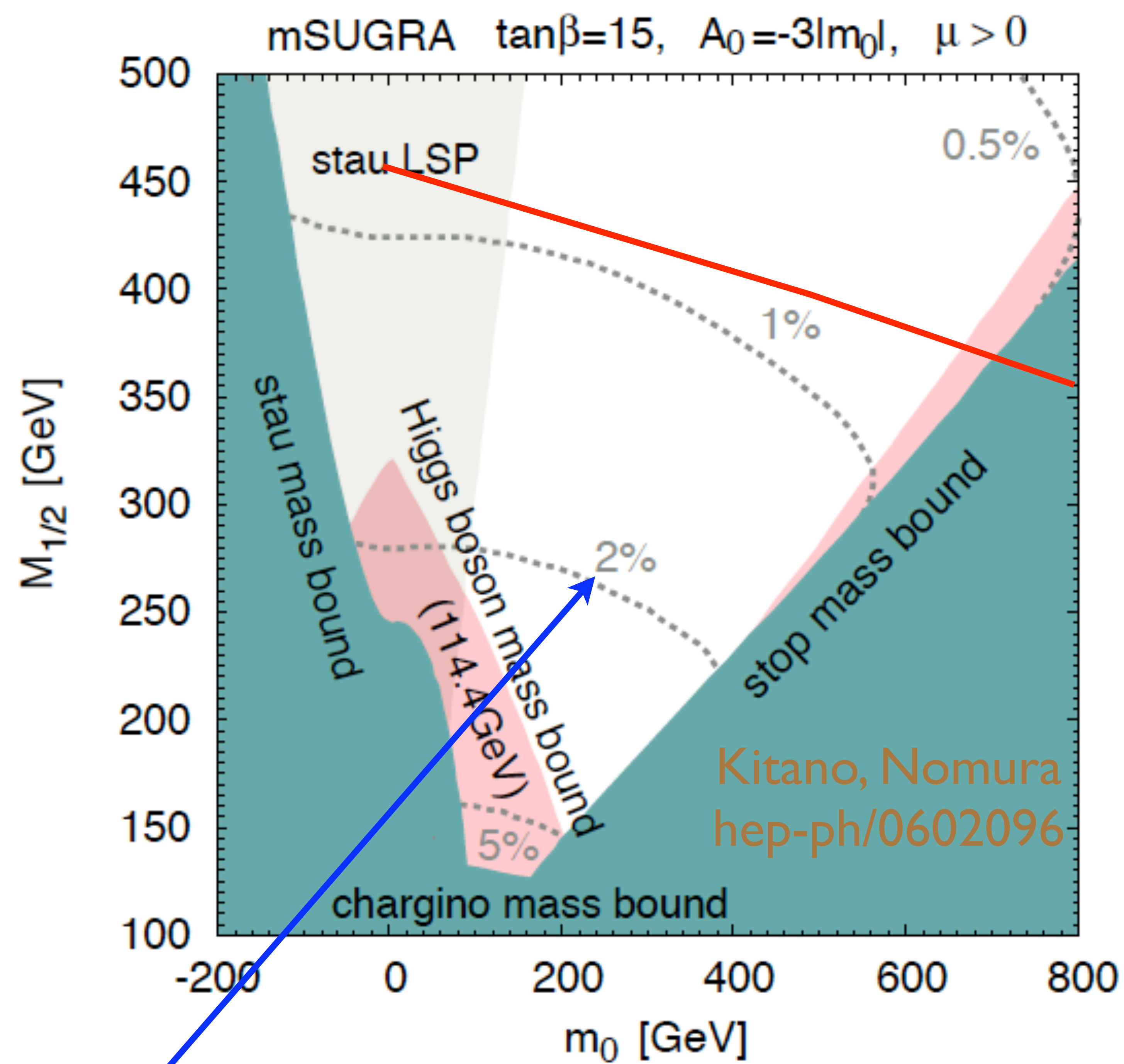


$$\frac{M_Z^2}{2} \approx -|\mu|^2 + |m_{H_u}^2|$$

Cancellation

Min SUGRA: Fine-tuning





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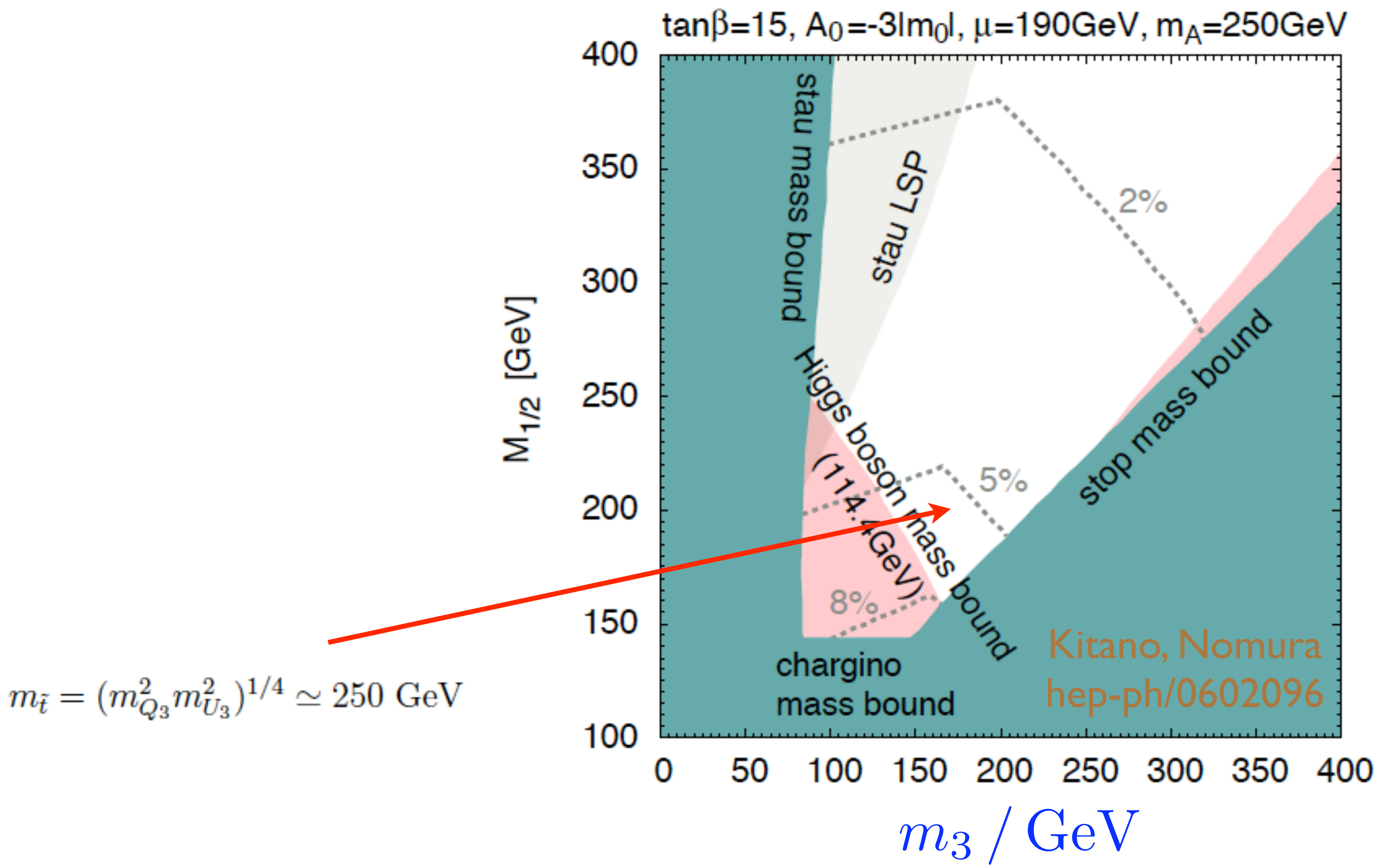
Cancellation

Worse than 1 in 100

SUGRA: non-universal scalar masses

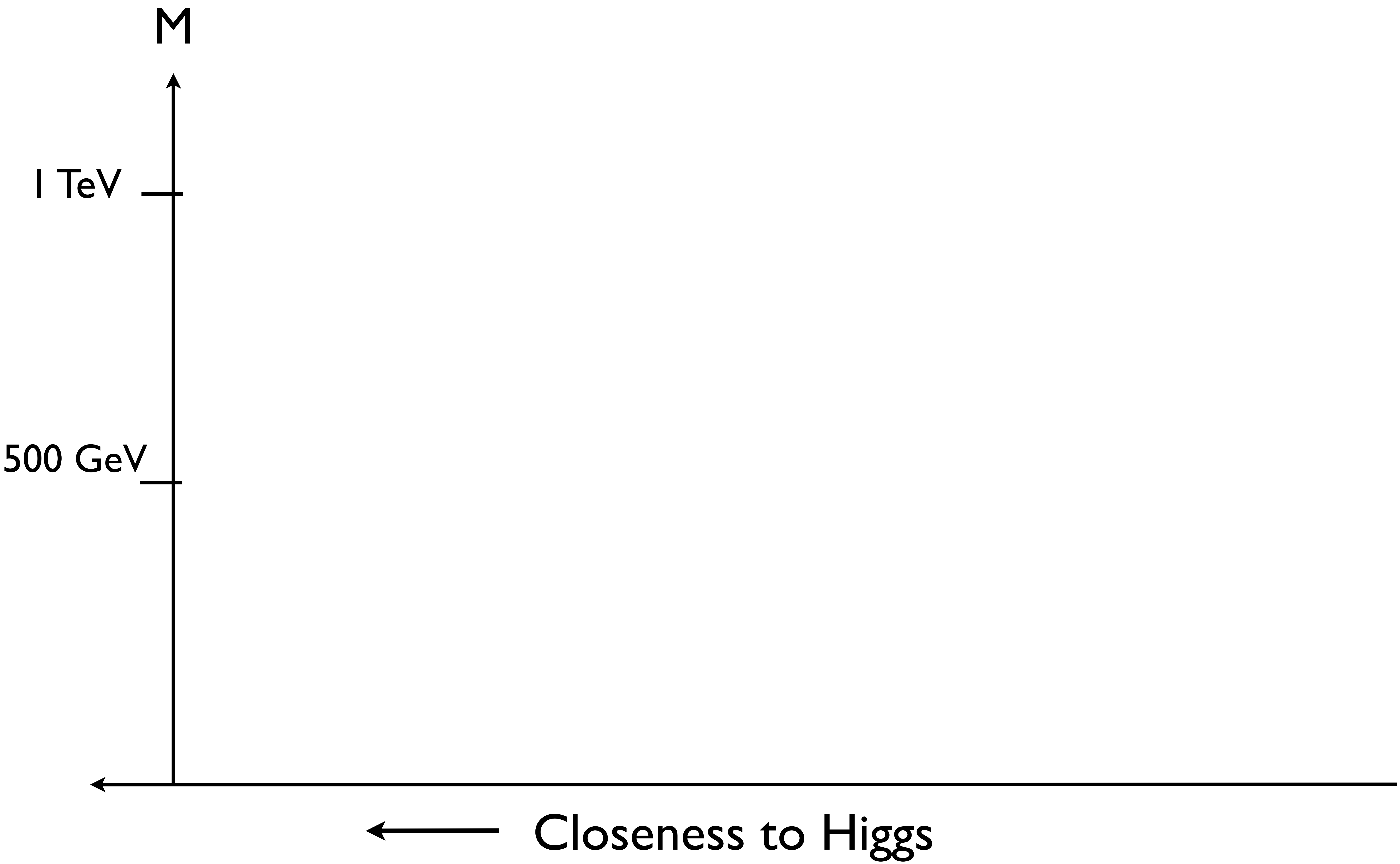
High-scale boundary condition: $M_{1/2},\ A,\ B,\ \mu$

$m_0 \ \rightarrow \ m_{H_u},\ m_{H_d},\ m_{1,2},\ m_3$



A Natural Spectrum

General “bottom-up” viewpoint



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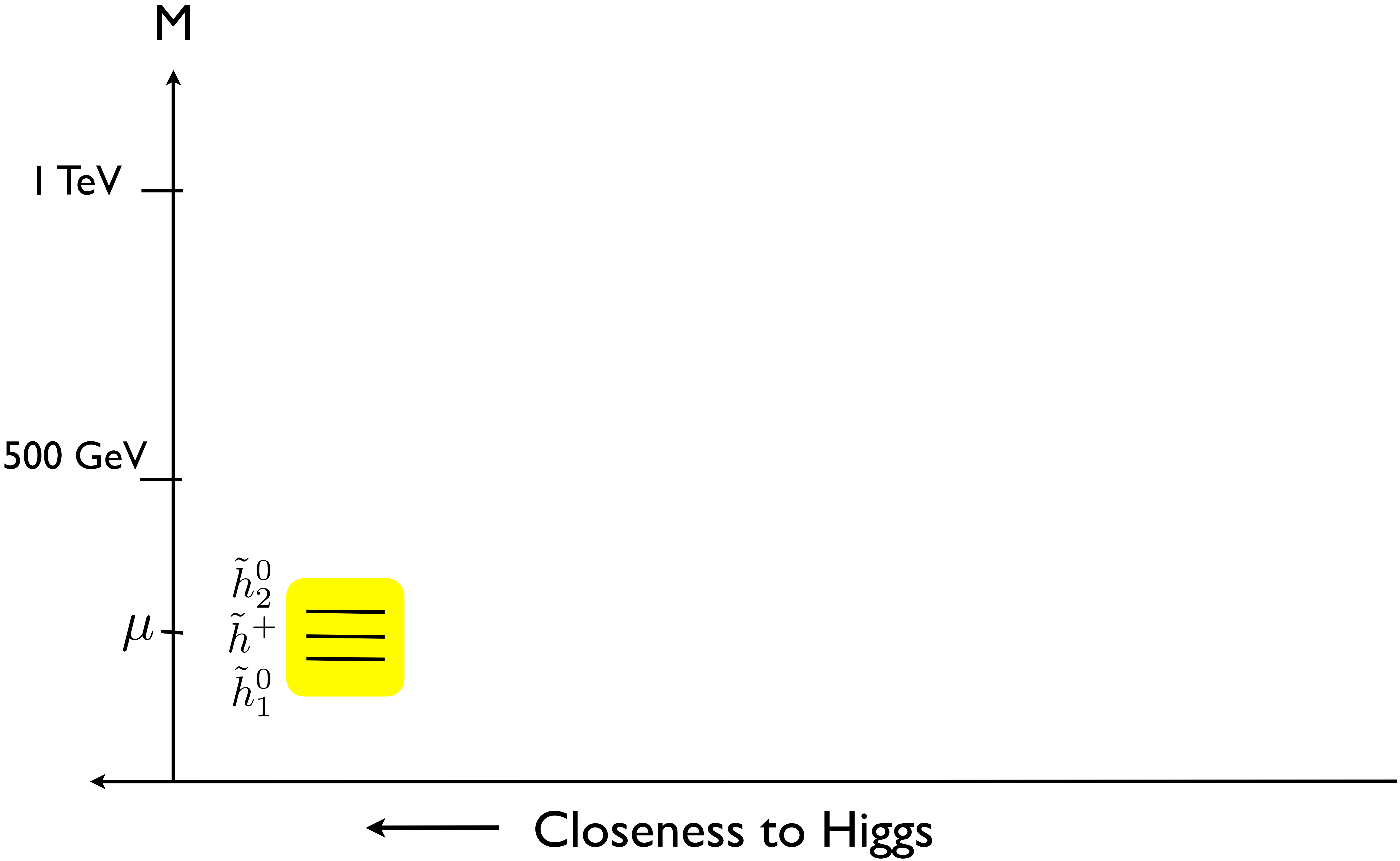

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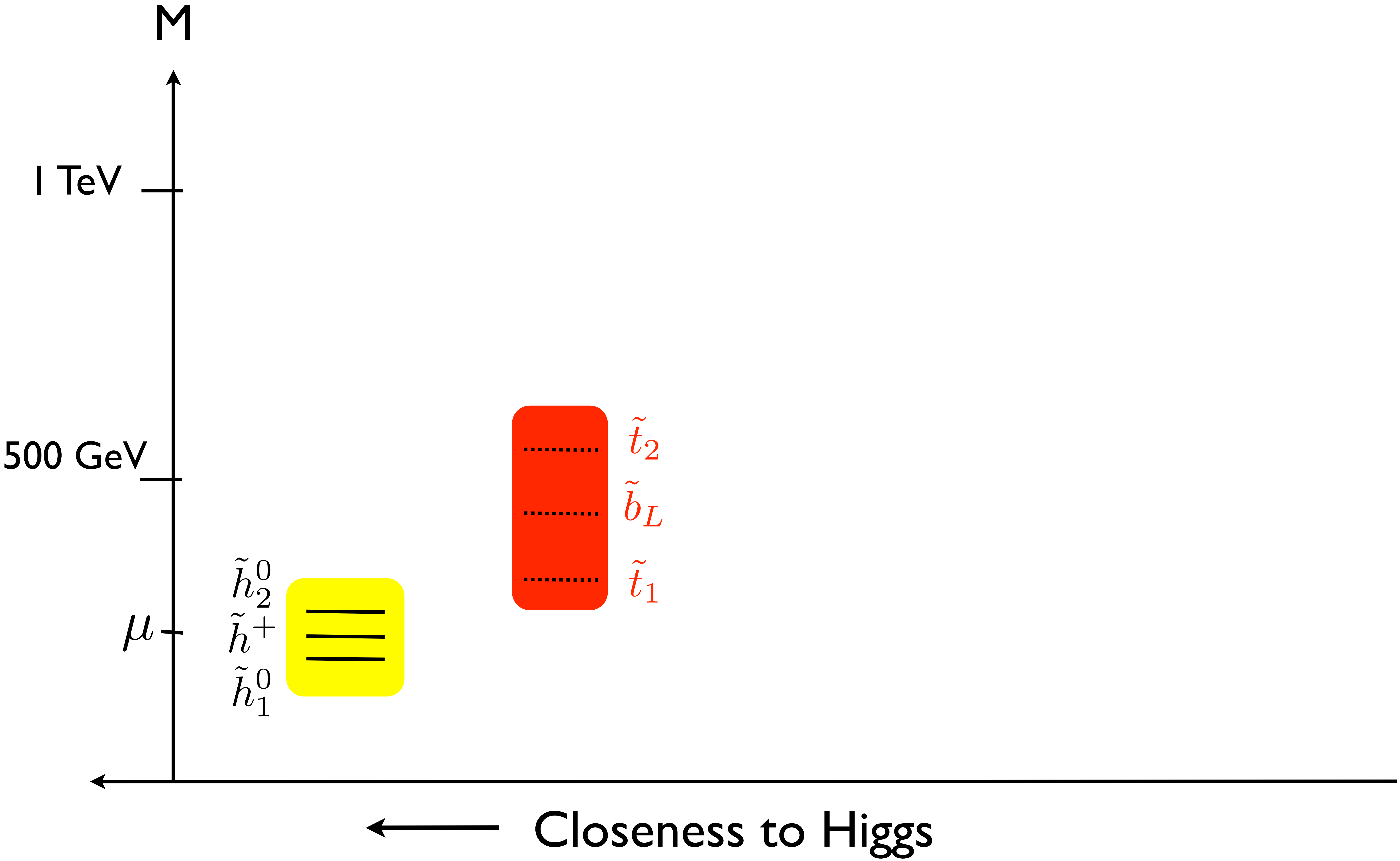

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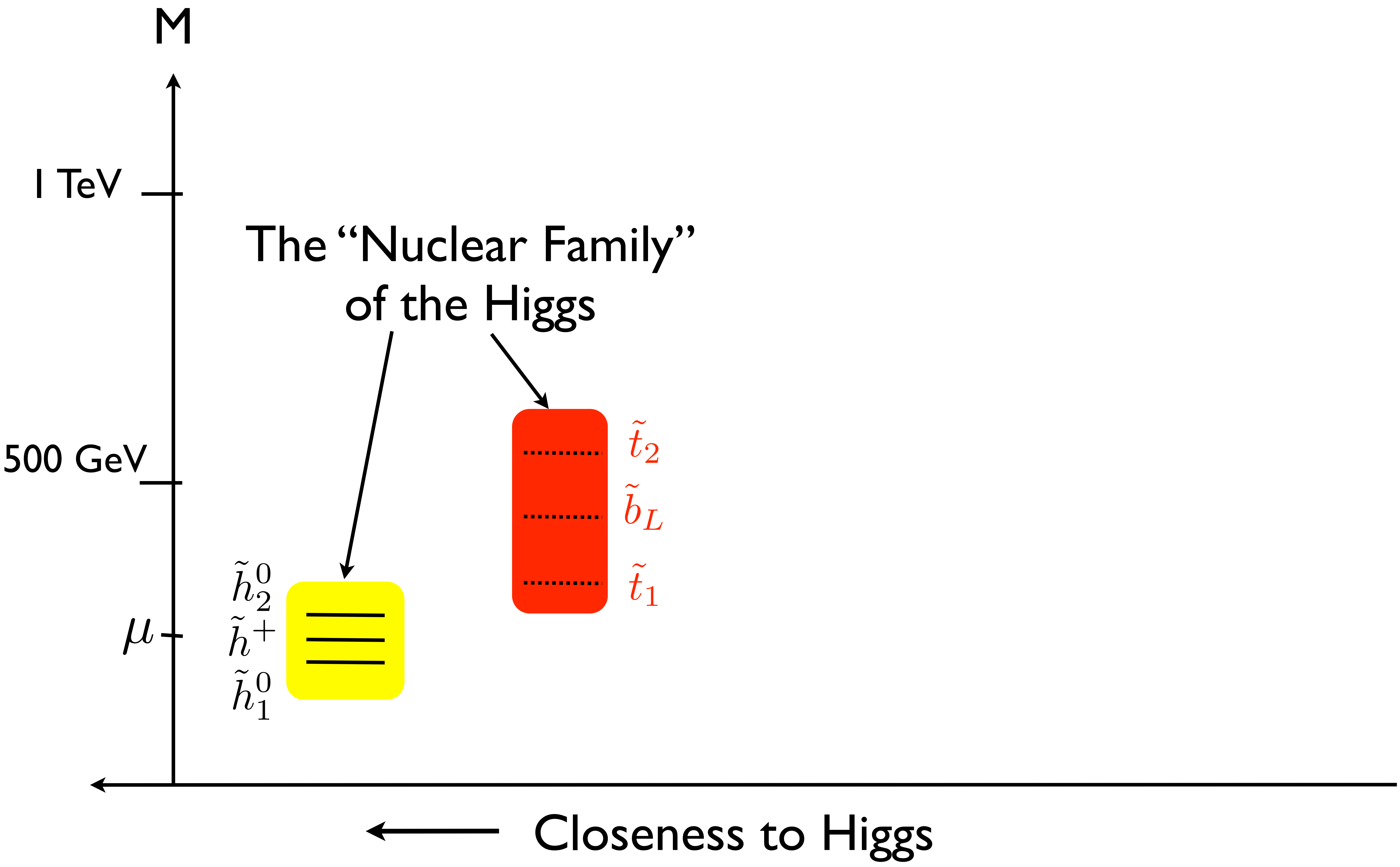

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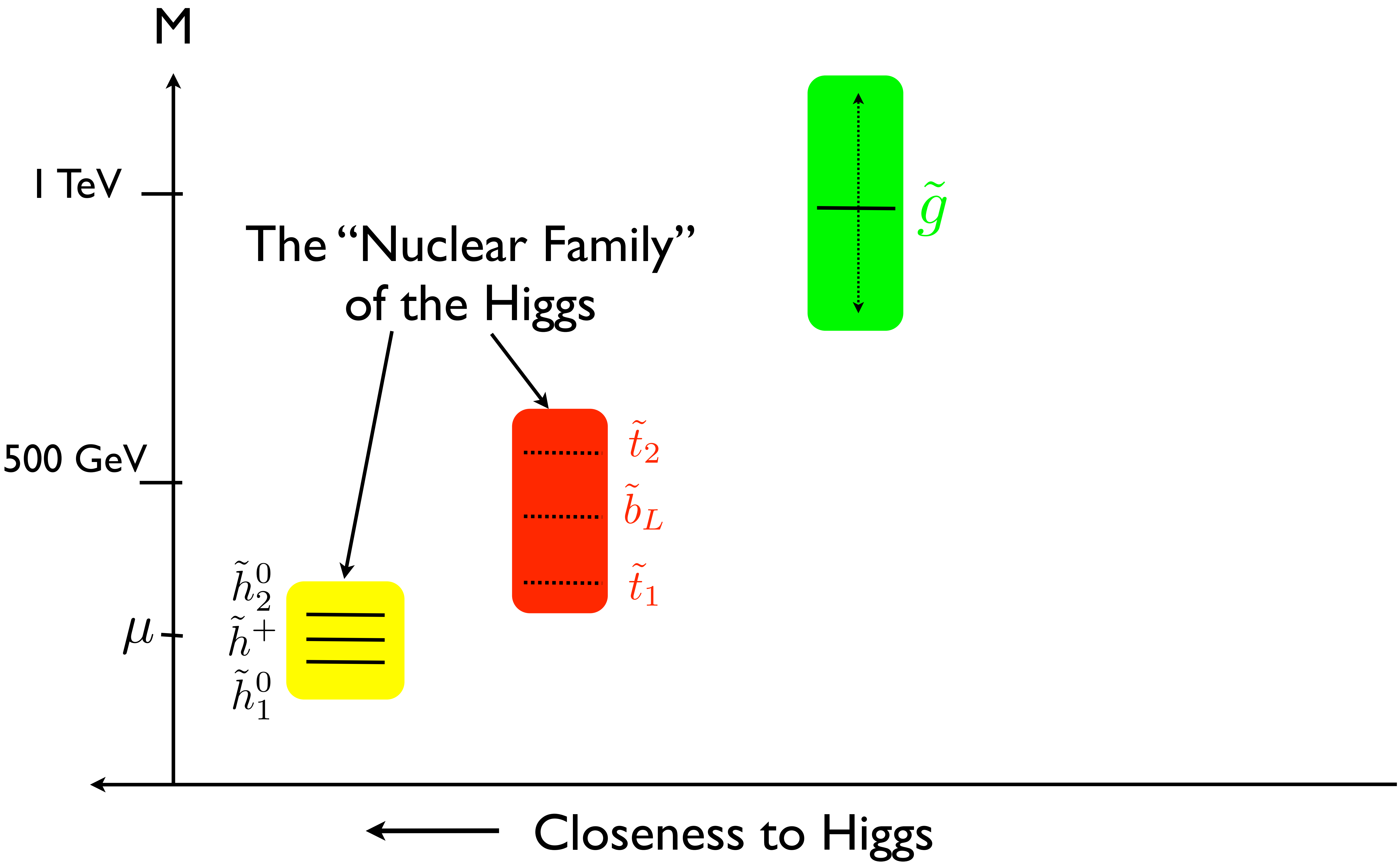

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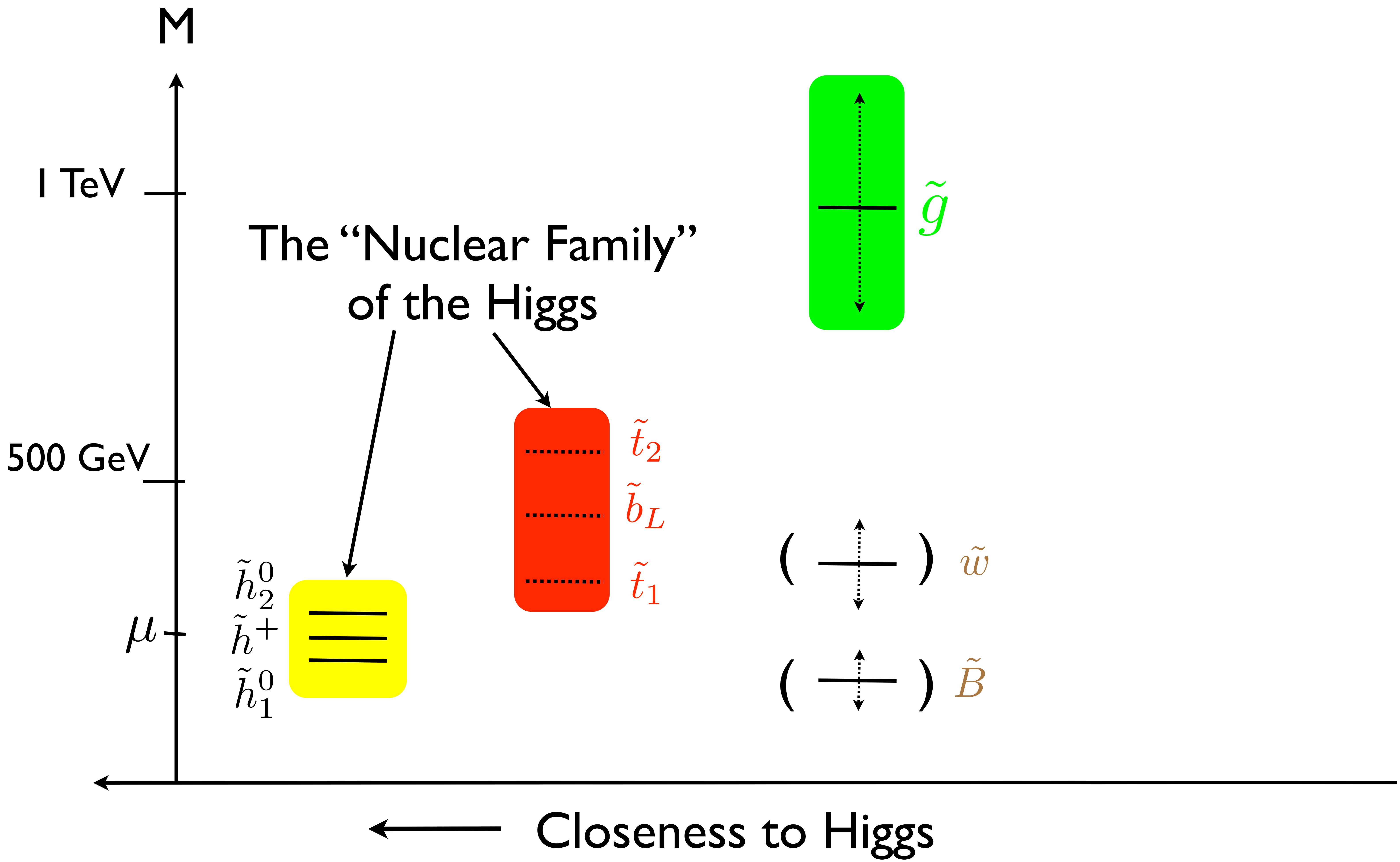

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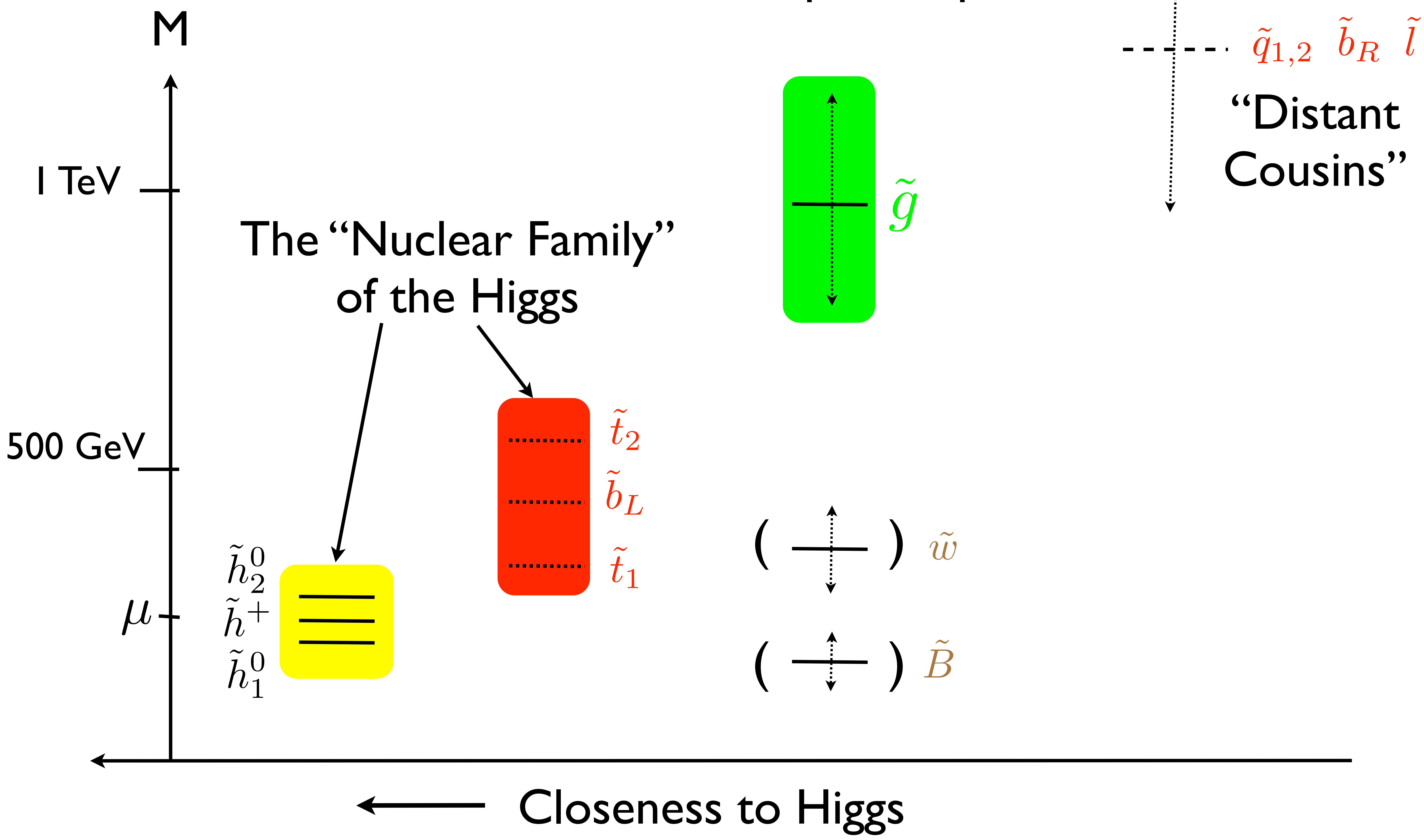

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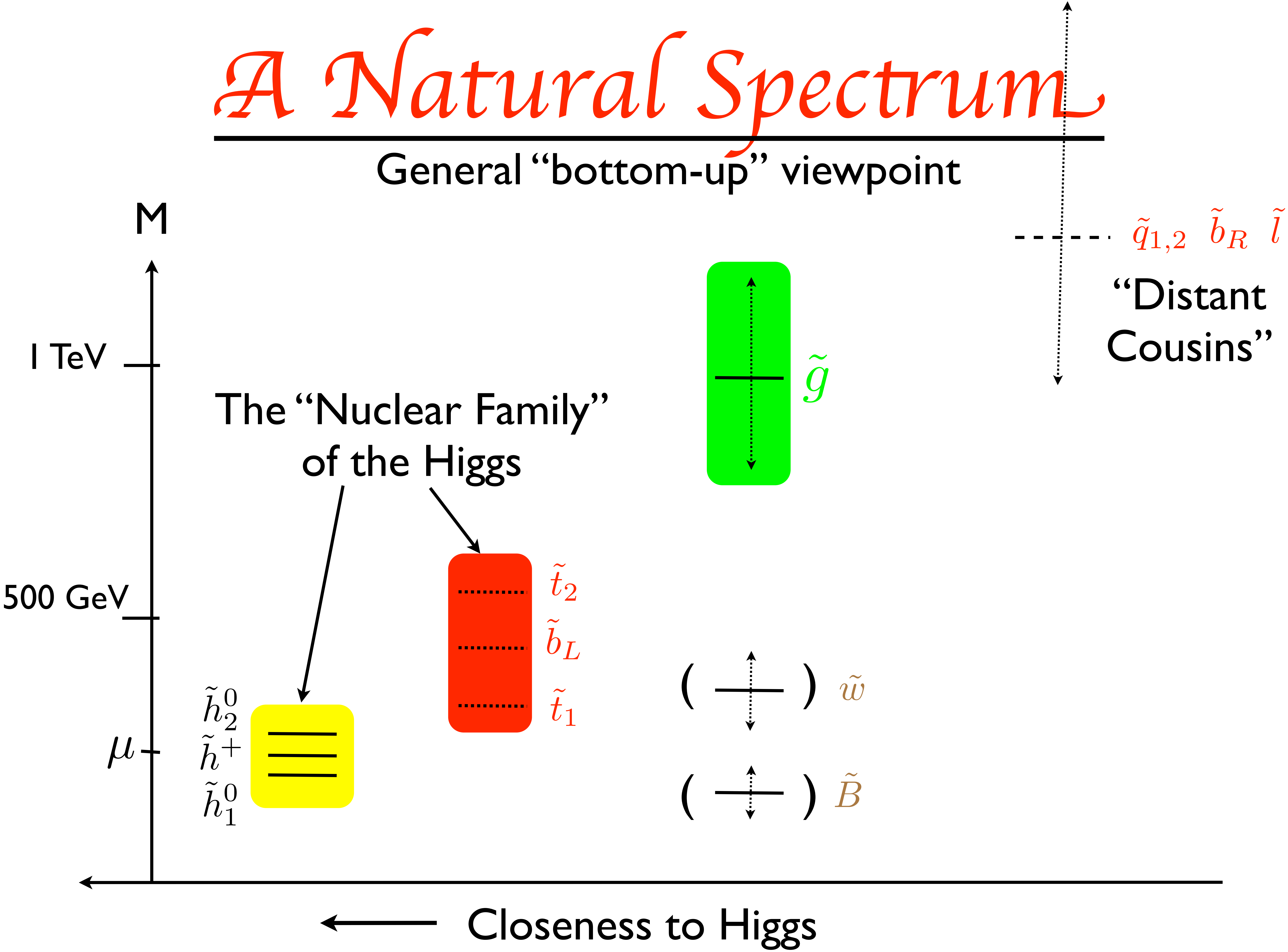

Would I prefer a factor of 3 lower?

A Natural Spectrum

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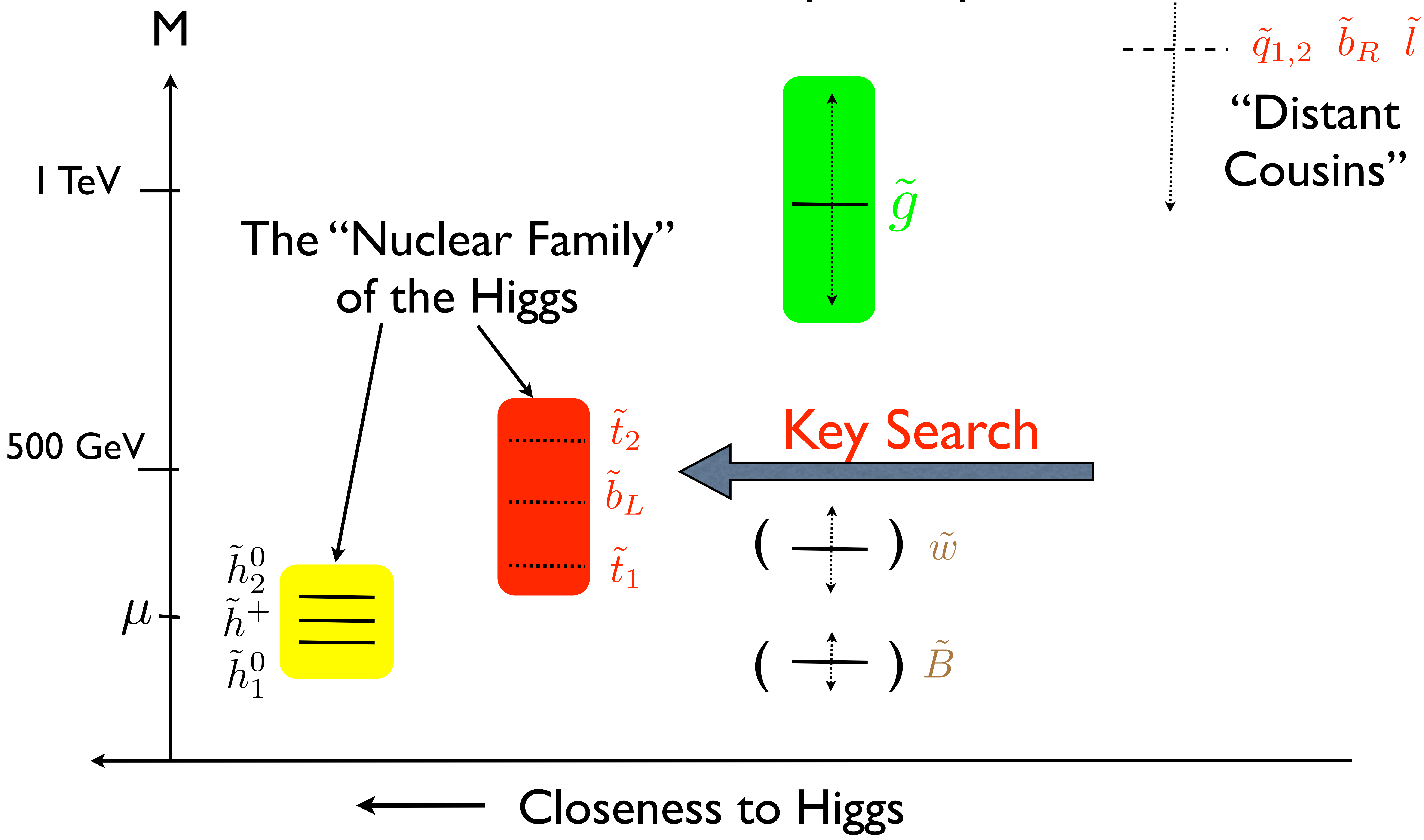

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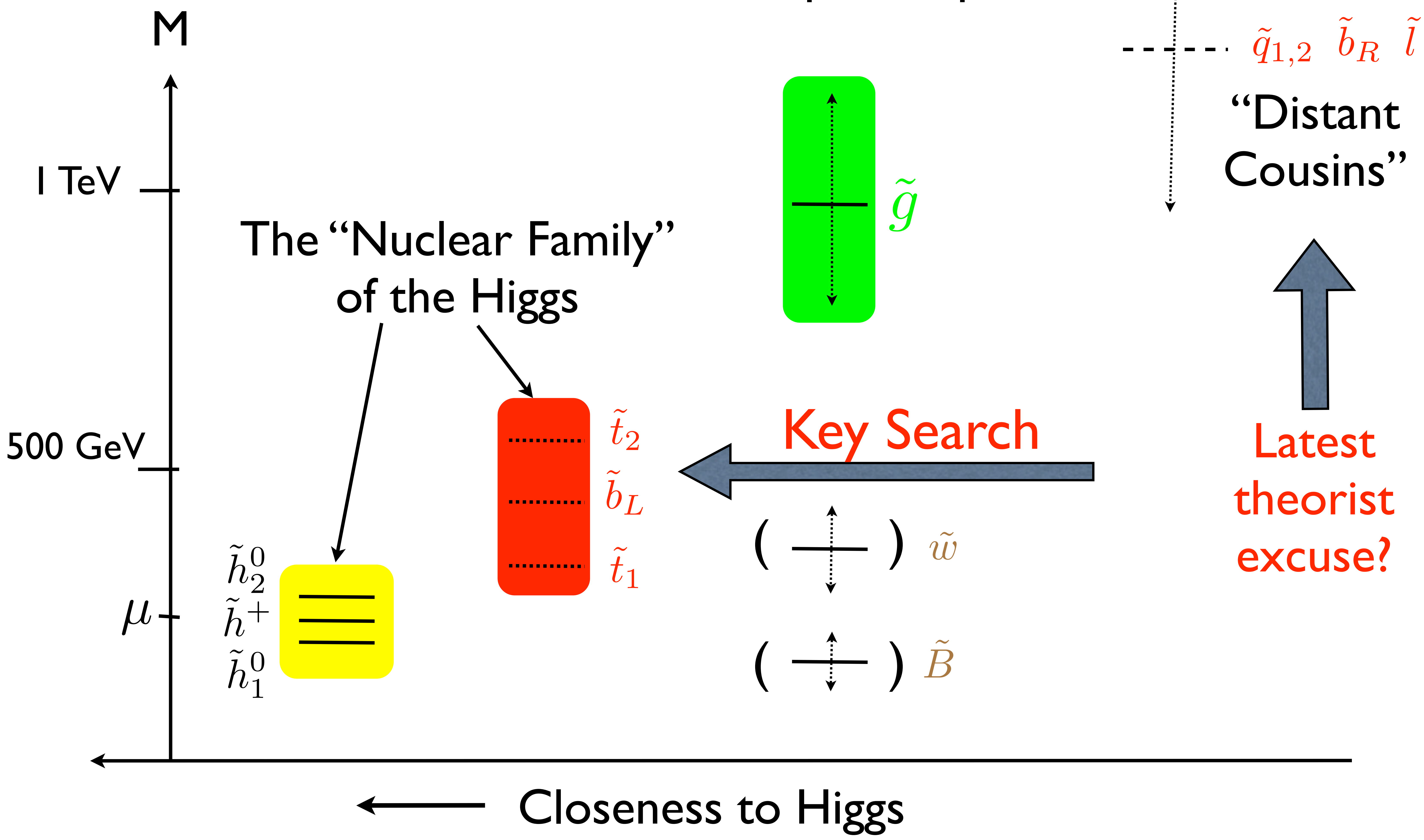

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A Common Scalar Mass m_0 ?

So long as we are careful to break the supersymmetry by adding a common mass to all the matter bosons with the same quantum numbers, this diagram is suppressed by a super-GIM mechanism.

$$V_{\text{eff}} = \sum_\alpha \left| \frac{\partial f_{\text{eff}}}{\partial z^\alpha} \right|^2 + 2\,\text{Re}(m_g'^{\,*} f^{(3)}) + 4\,\text{Re}(m_g^* f^{(2)})$$

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Softly Broken Supersymmetry and SU(5).
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"Natural Spectrum" is 15-20 years old

Jets + MET

Jets + missing E_T

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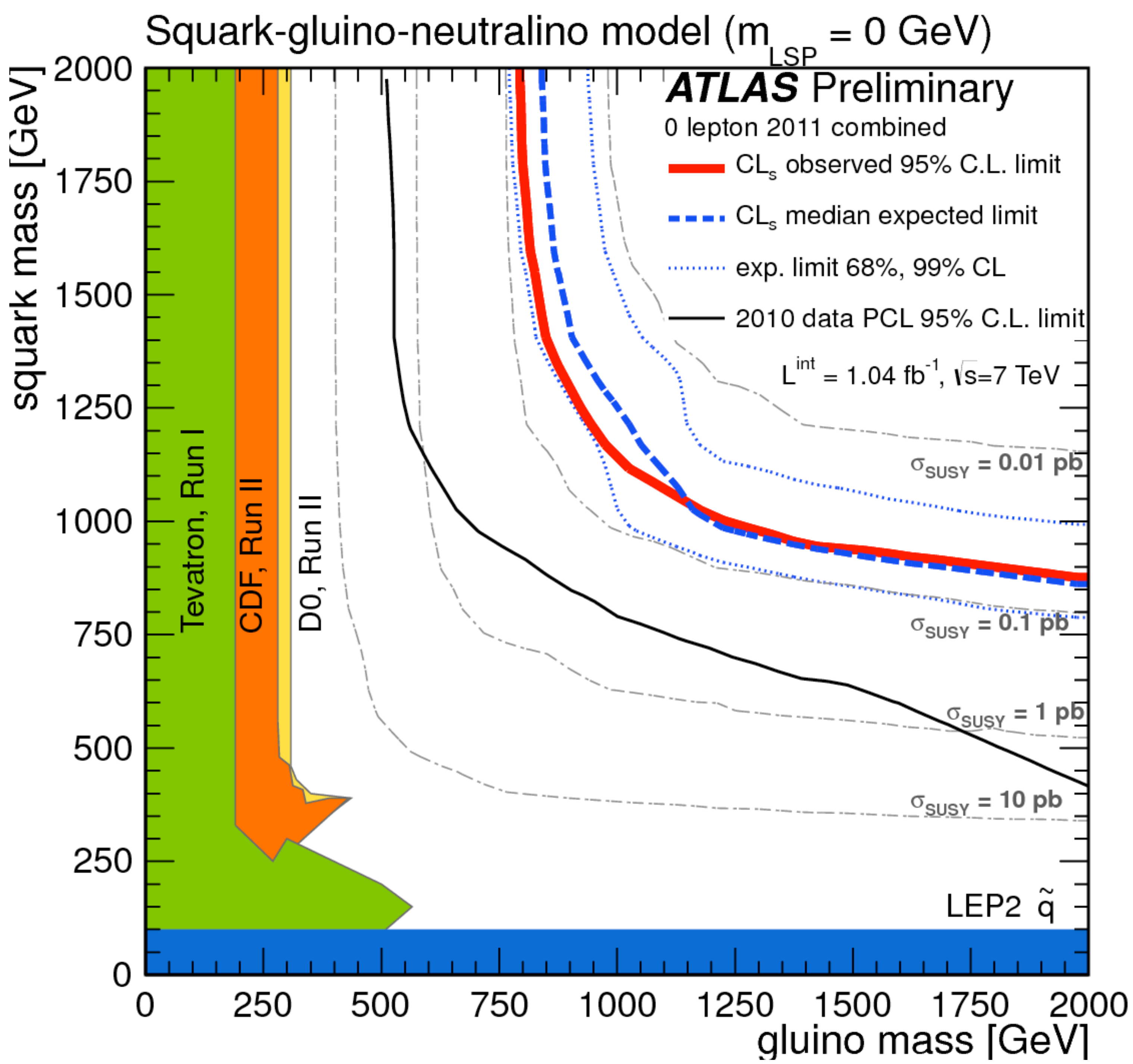


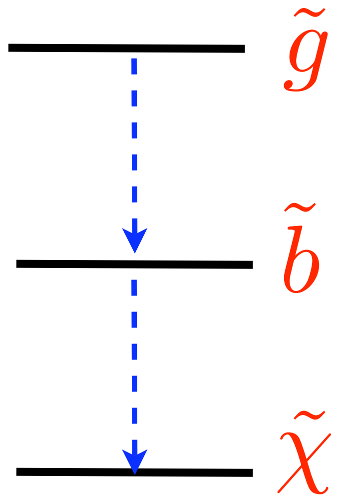
$m_{\tilde{\chi}} < 200\,\mathrm{GeV}$

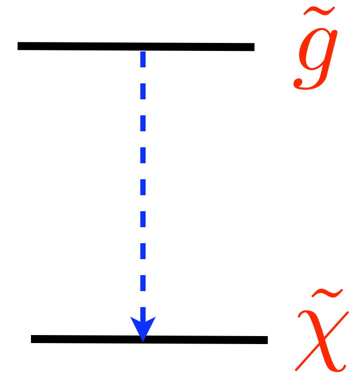
Probes $\tilde{u},\ \tilde{d},\ \tilde{c},\ \tilde{s}$

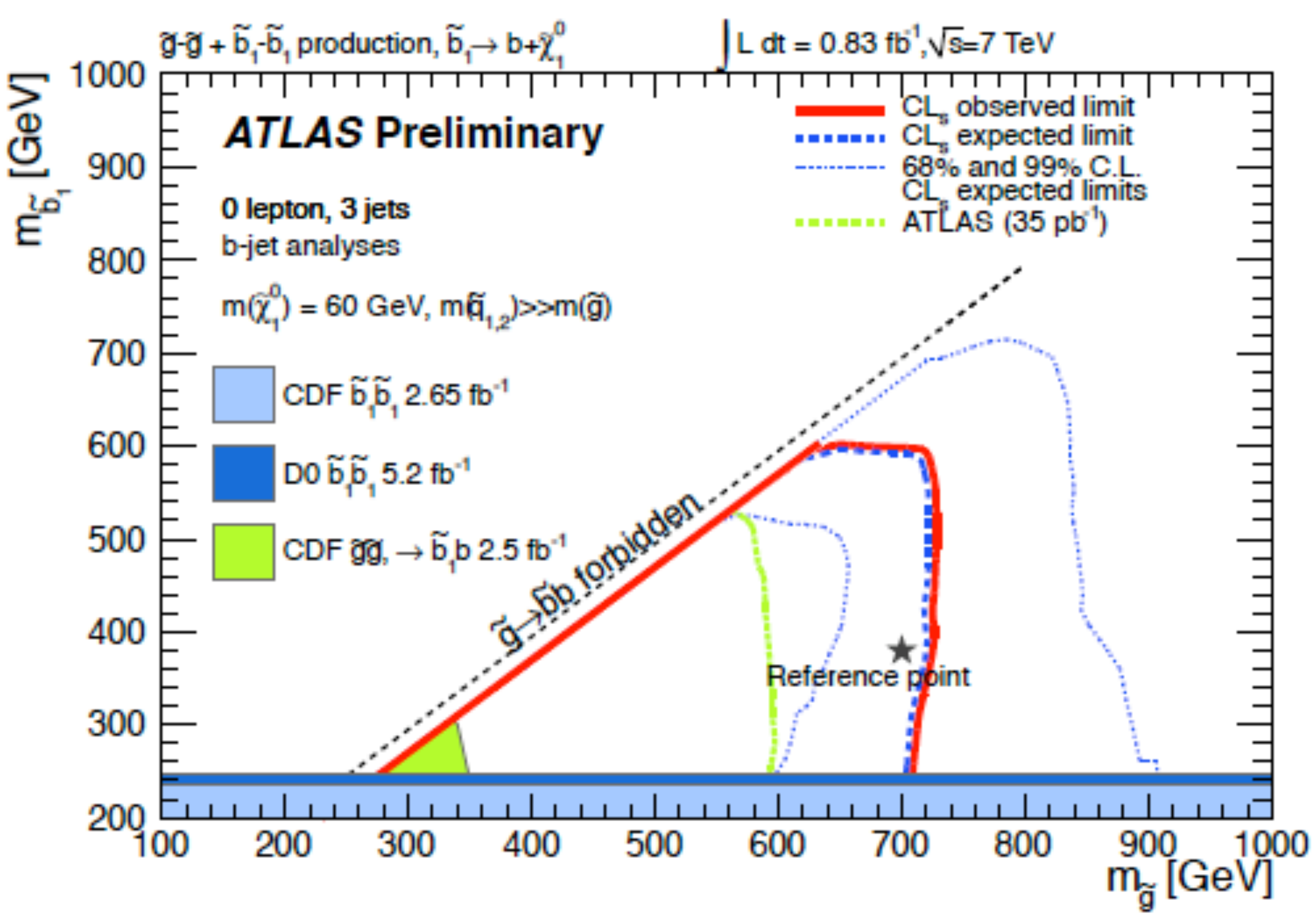
not $\tilde{t},\ \tilde{b}$

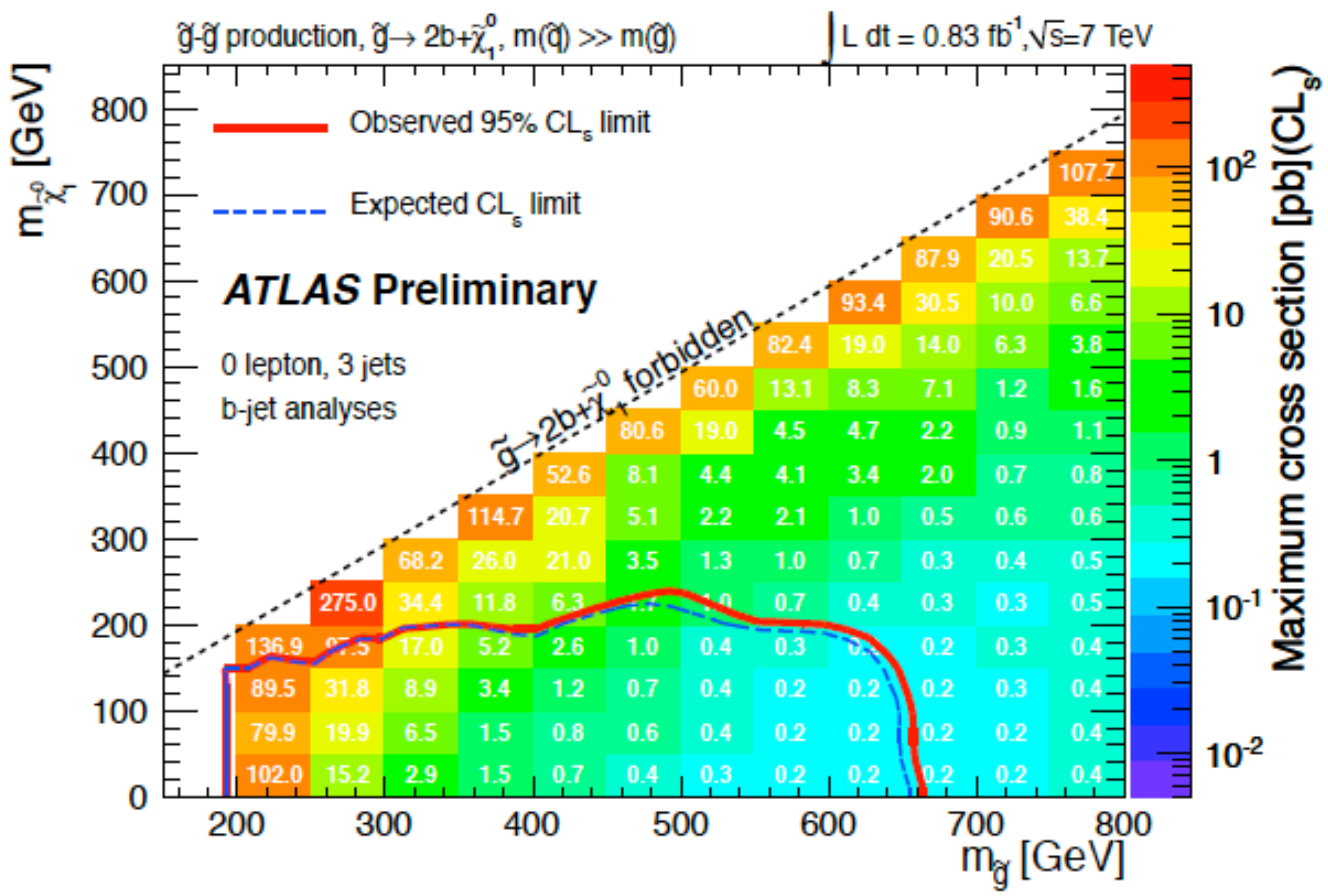
Search in b Jets

$0\, l, b\text{-jets}, E_{T miss}$



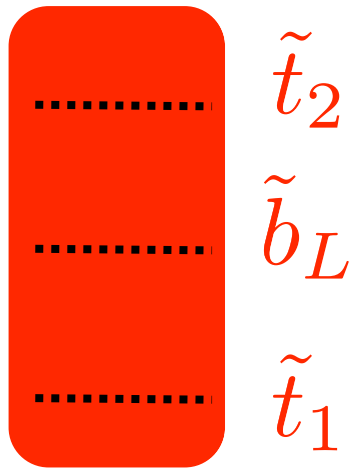




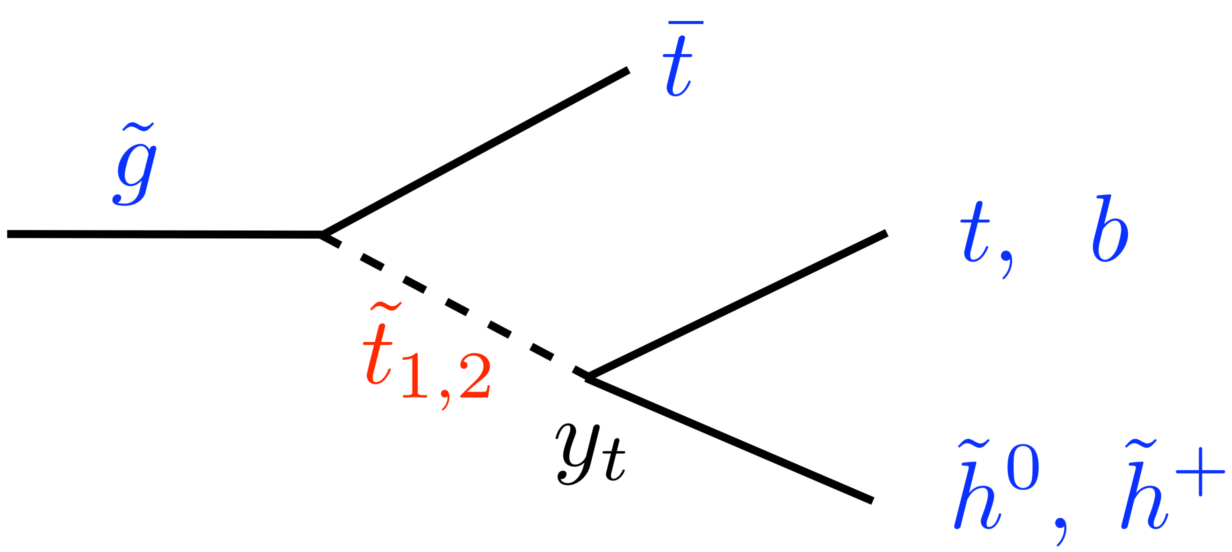


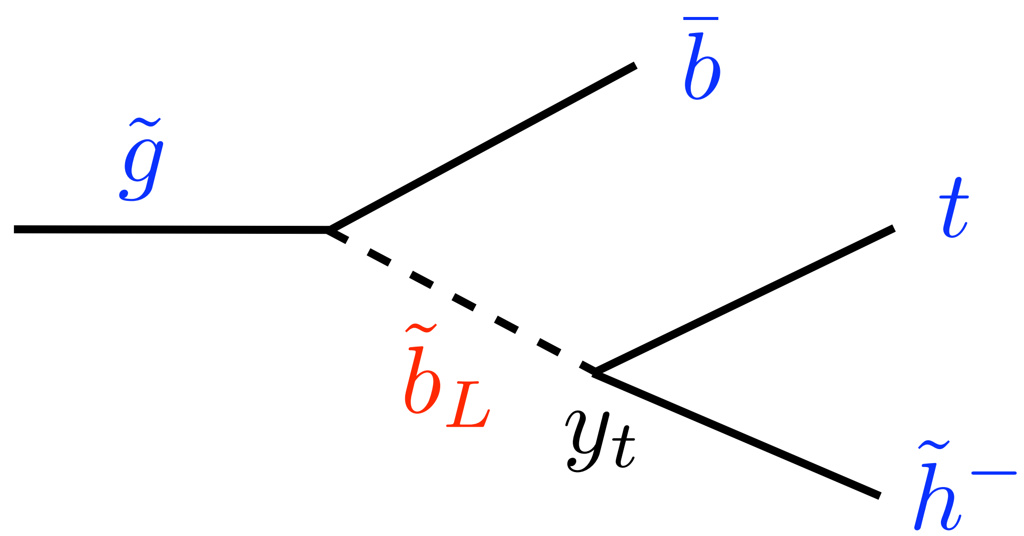
$\tilde{g} \to \bar{b}b\,\tilde{\chi}$ *is sub-dominant*

Nuclear family



decay dominantly via y_t





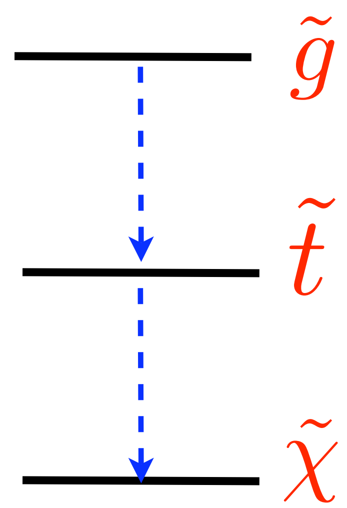
Dominant modes

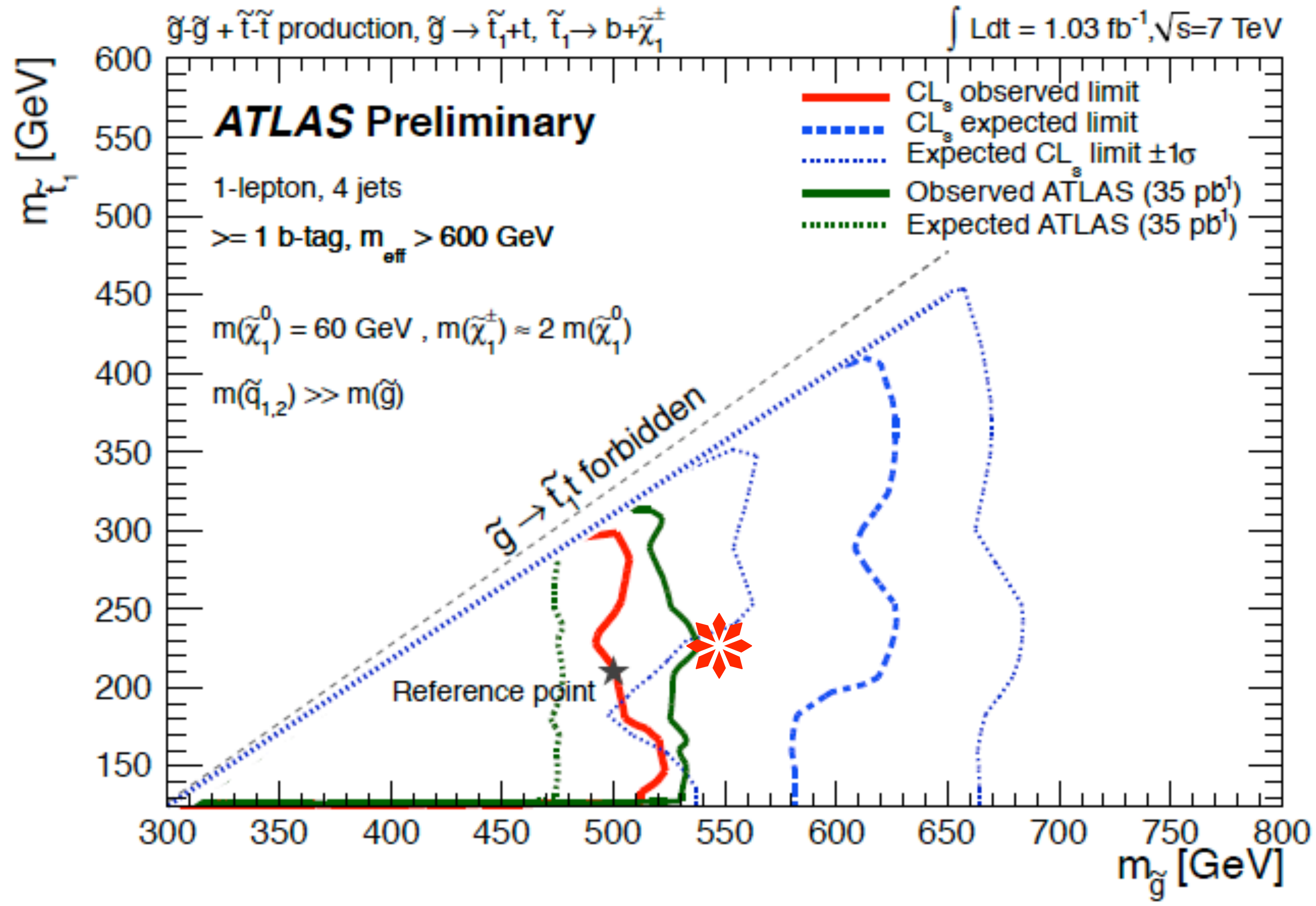
$$\tilde{g} \to \bar{t}t\,\tilde{\chi}^0$$

$$\tilde{g} \to \bar{t}b\,\tilde{\chi}^+$$

Search for Light $\tilde{t}$

$\tilde{g} \to \bar{t} b \, \tilde{\chi}^+$

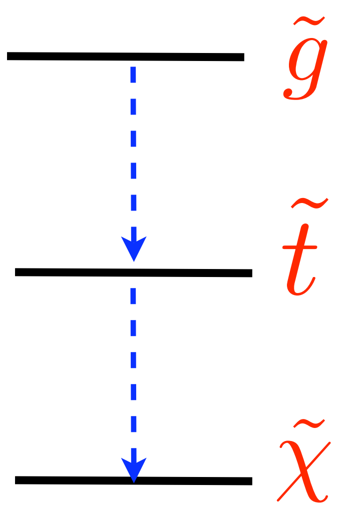


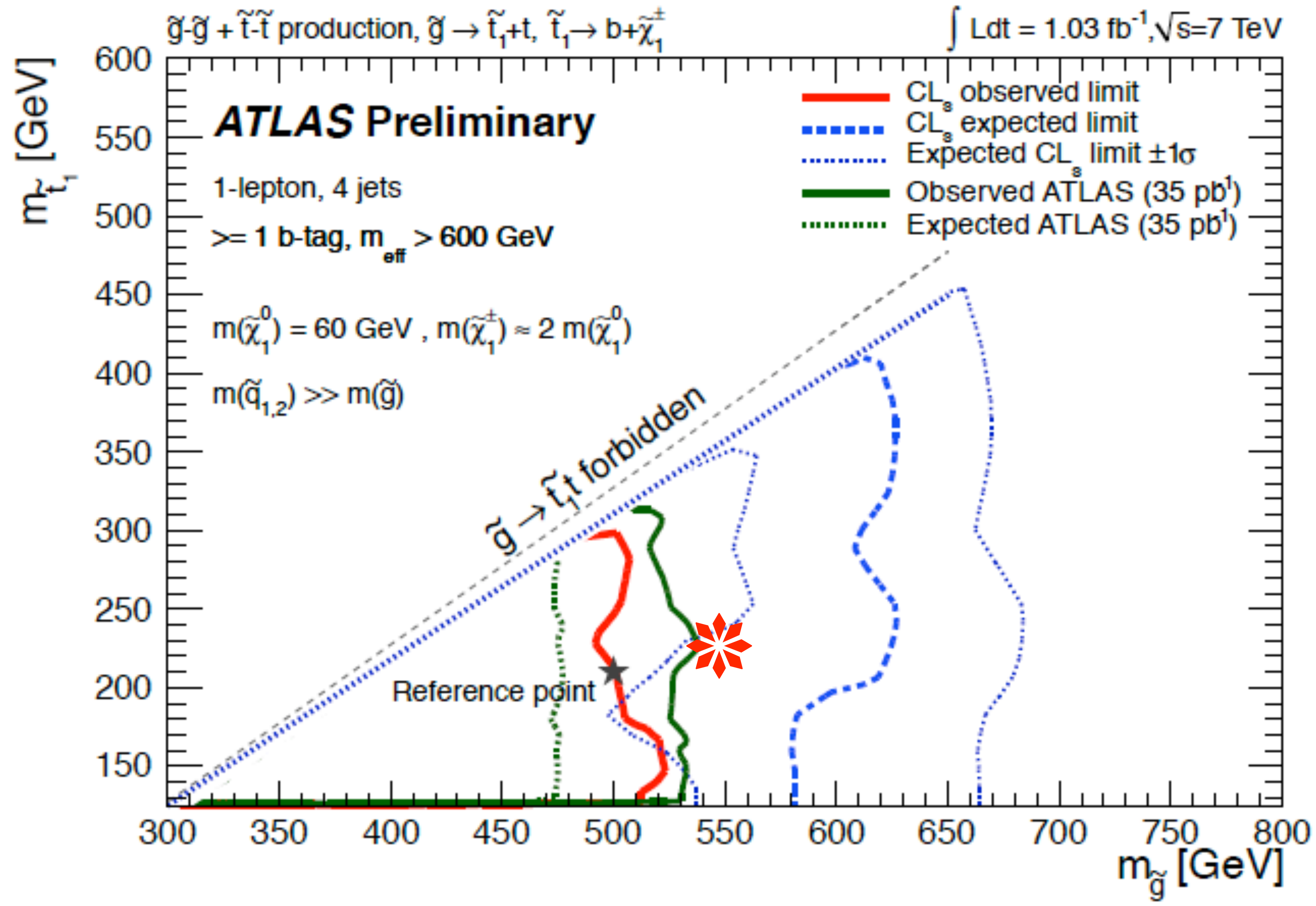


❈ Low values of $m_{\tilde{g}}, m_{\tilde{t}}$ allowed

Search for Light $\tilde{t}$

$\tilde{g} \to \bar{t} b \, \tilde{\chi}^{+}$

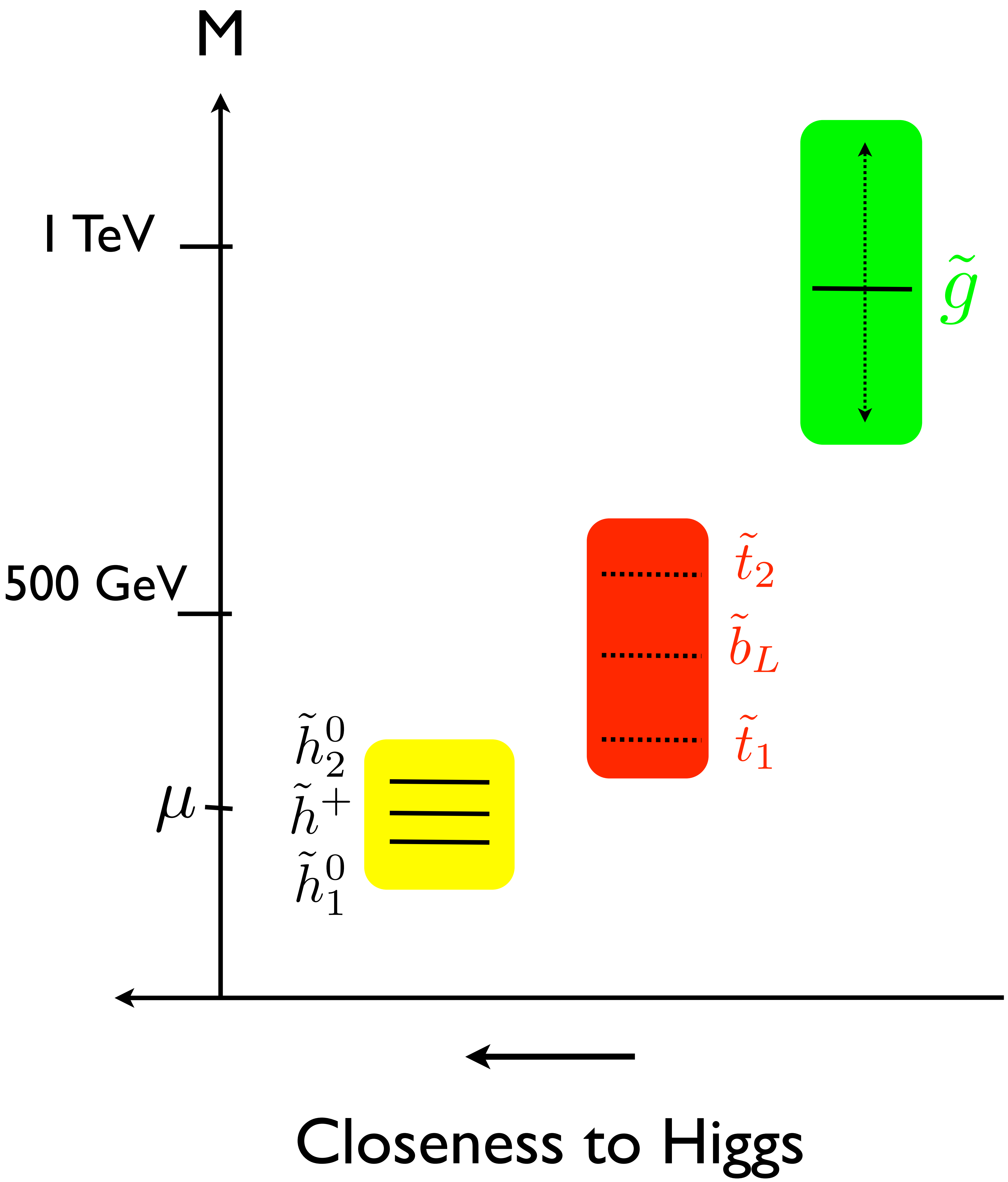




✻ Low values of $m_{\tilde{g}}, m_{\tilde{t}}$ allowed

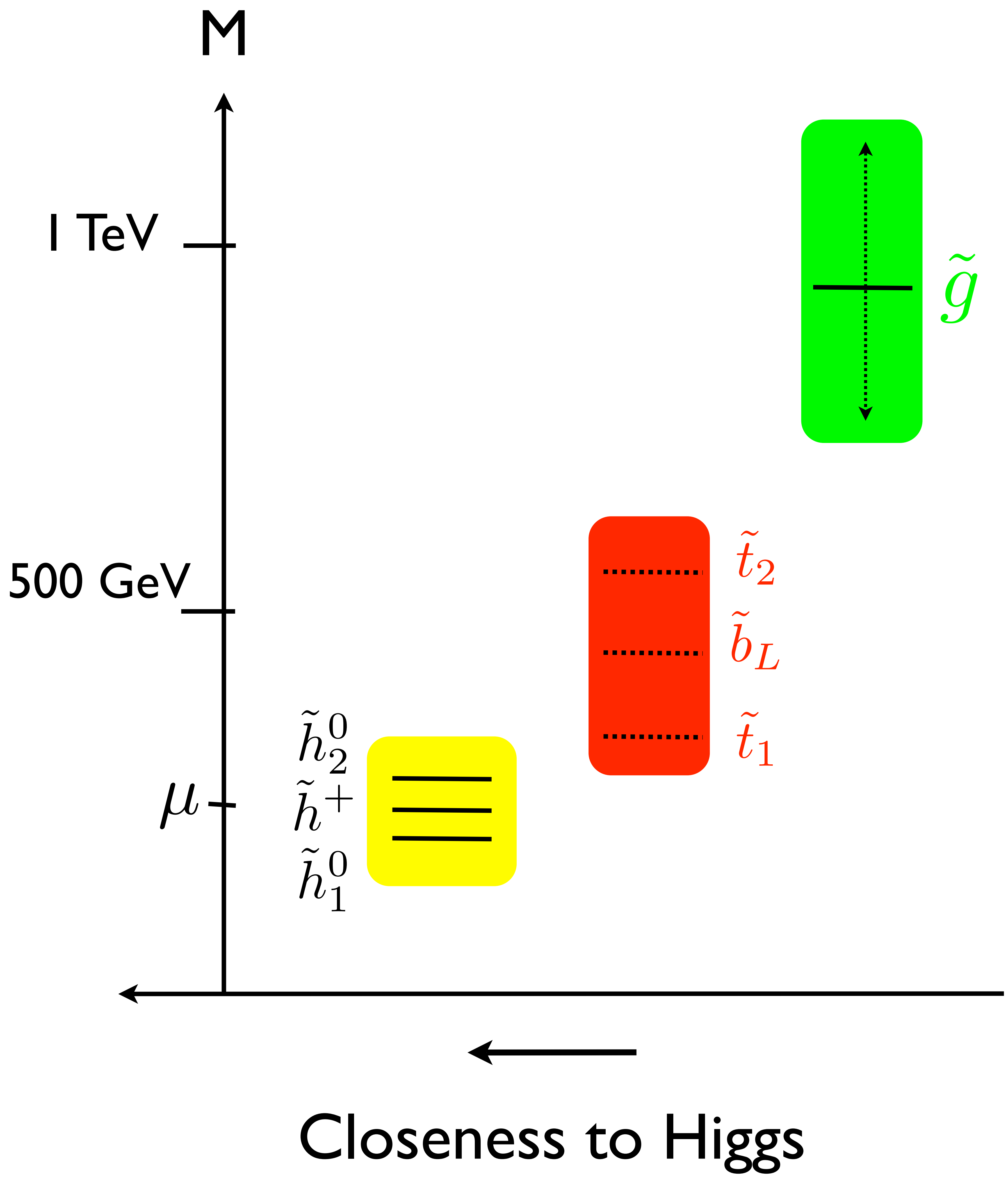
Further searches are underway & eagerly awaited.

Bottom-Up Viewpoint



We already bought something like this after LEP

Bottom-Up Viewpoint

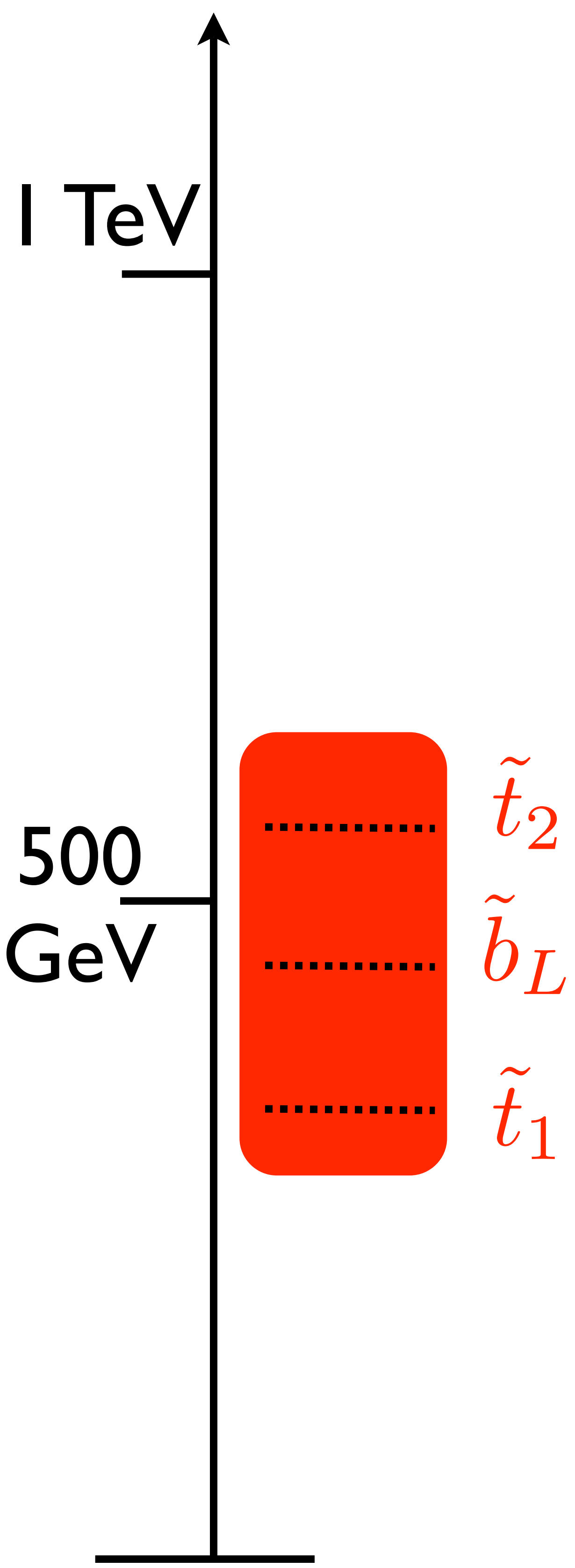


We already bought something like this after LEP

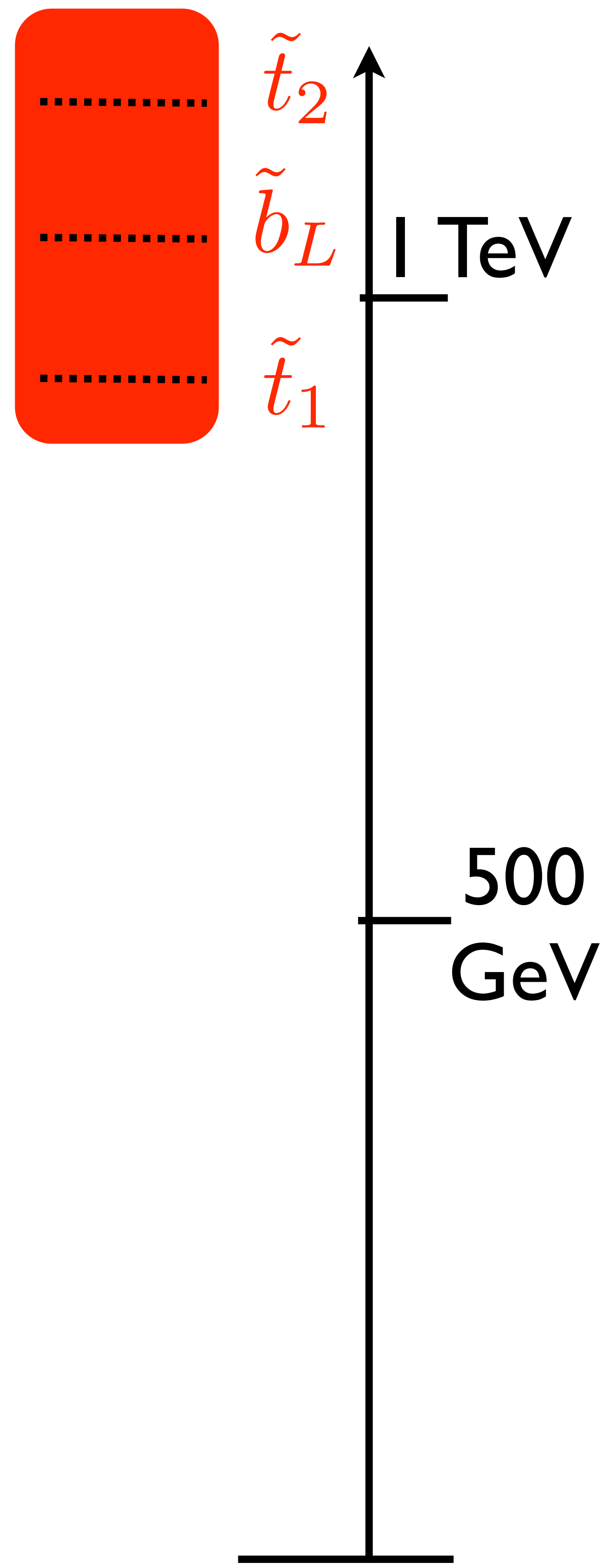
This natural spectrum has not been excluded, and may take 5+ years to probe

What if (Light Stop + MET) Absent?

Reduced Missing Energy



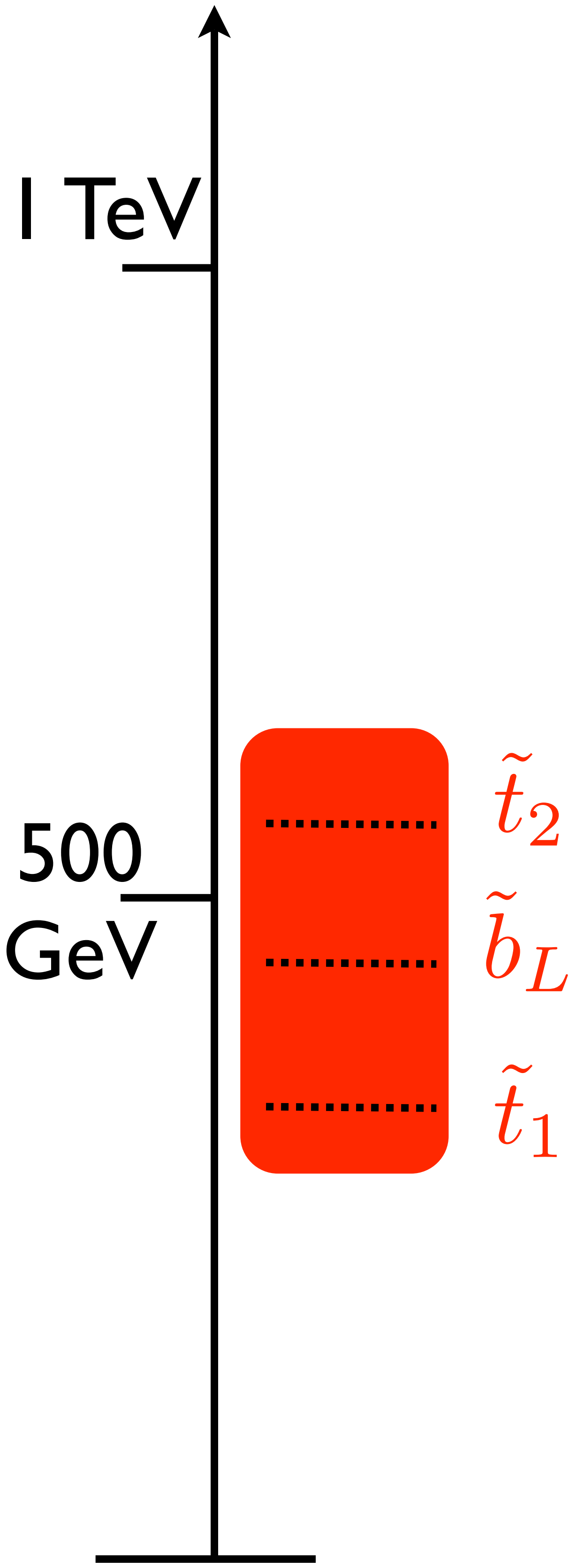
Stops are Naturally Heavy



What if (Light Stop + MET) Absent?

Reduced Missing Energy

❋

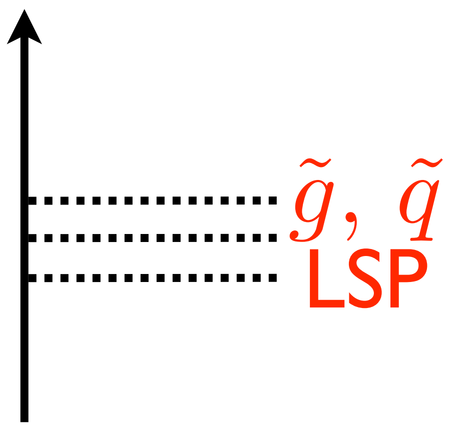


R Parity Violation

eg

$$\chi \to \begin{array}{l} tbs \\ \nu\bar{b}b \\ \tau\bar{b}t \\ \tau W \\ \nu Z \end{array}$$

❋ Squashed susy spectrum



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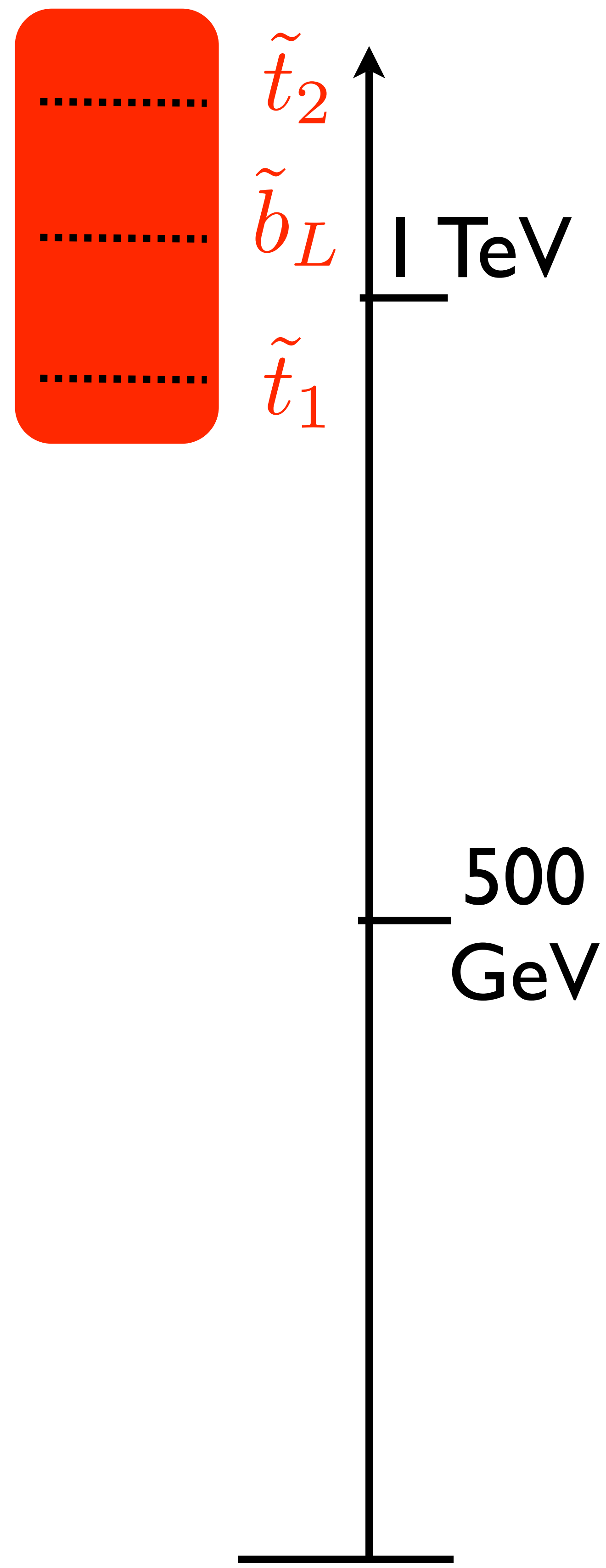

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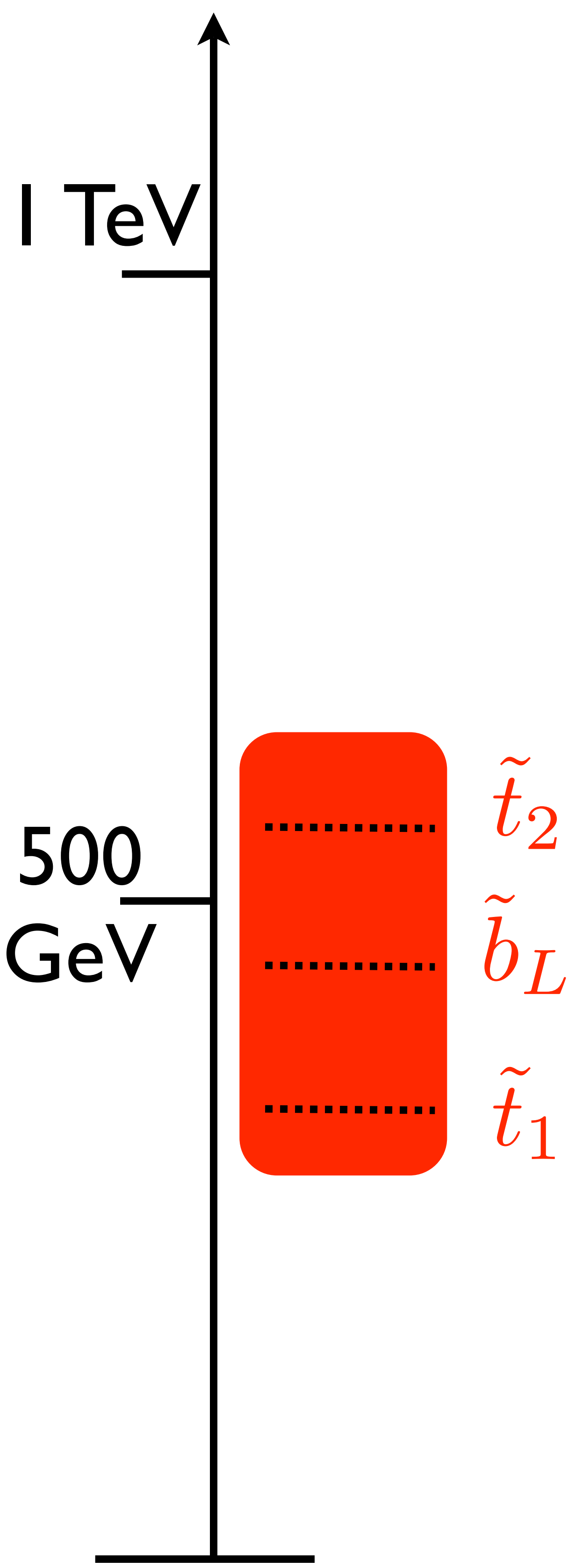
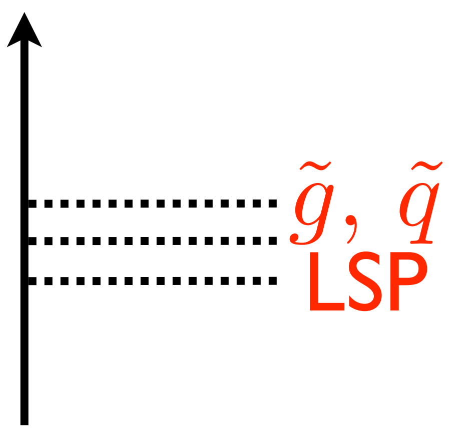


Reduced Missing Energy

- R Parity Violation

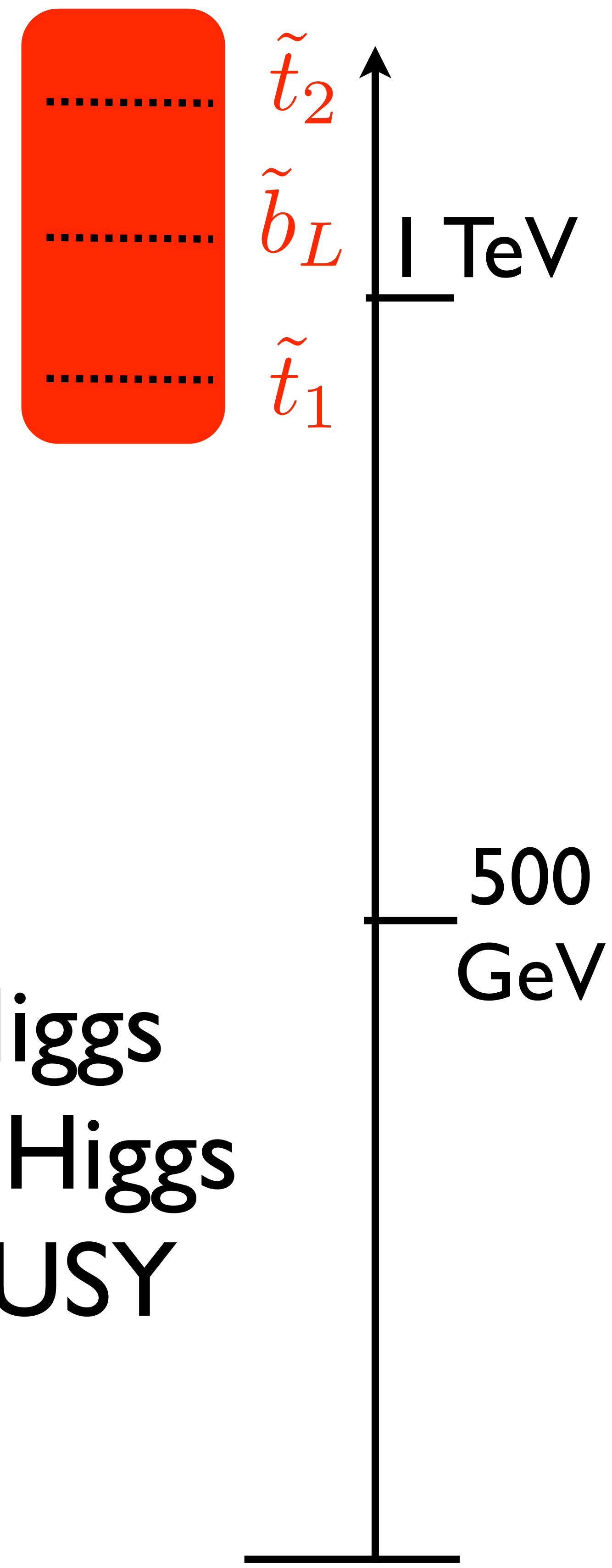
  eg $\chi \rightarrow$ tbs, $\nu\bar{b}b$, $\tau\bar{b}t$, τW, νZ

- Squashed susy spectrum



Stops are Naturally Heavy

- Focus Points



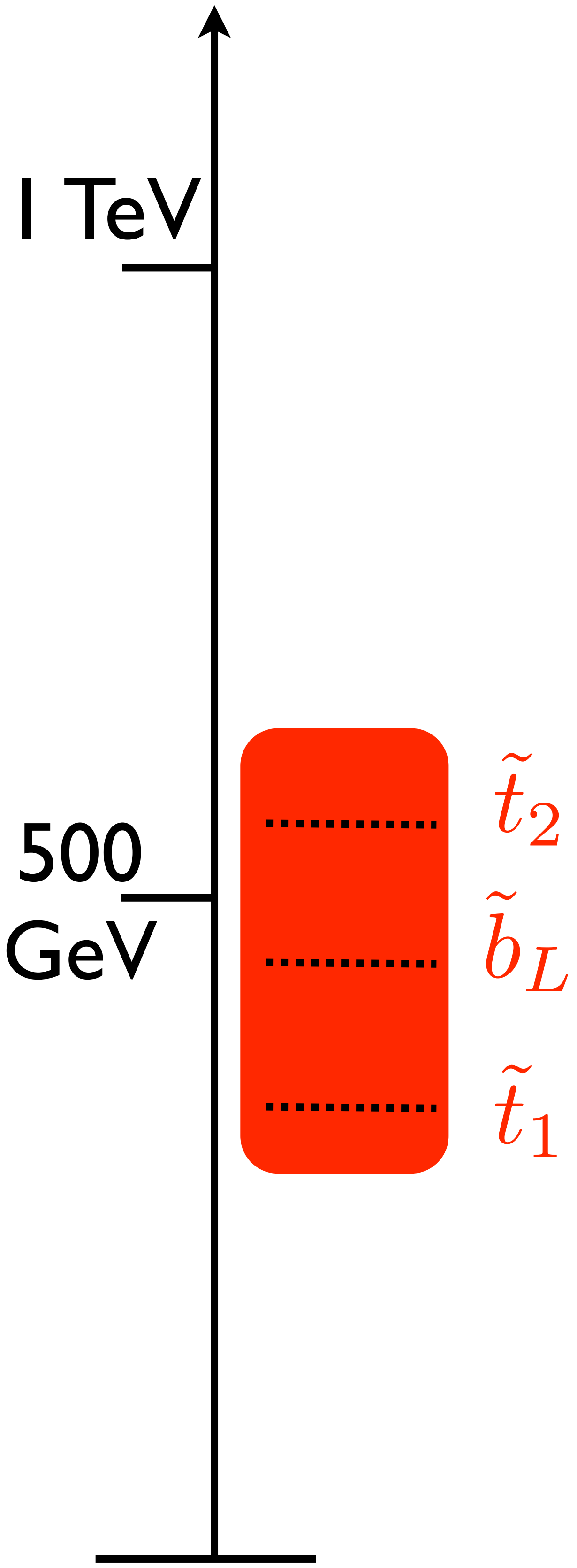
- Heavier Higgs

  Fat Higgs

  λ-SUSY

What if (Light Stop + MET) Absent?

Reduced Missing Energy



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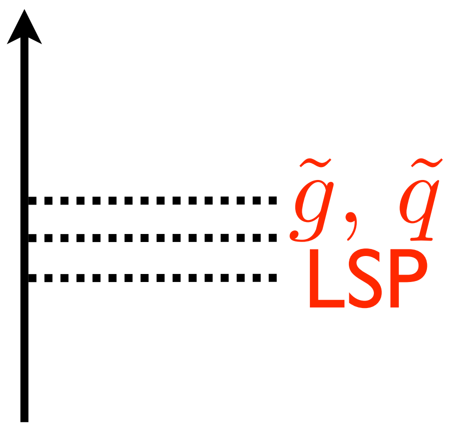

Stops are Naturally Heavy

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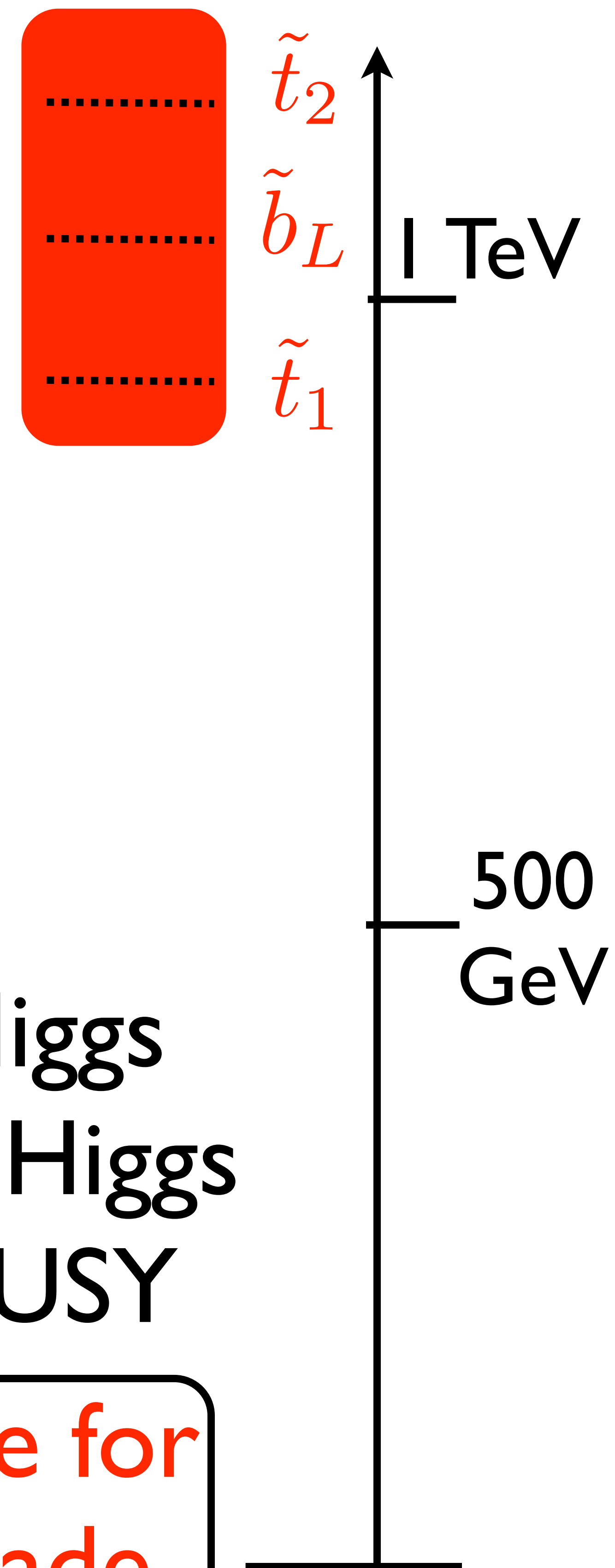

- Heavier Higgs
  - Fat Higgs
  - λ-SUSY

Plenty to explore for the coming decade

II

Low-Scale Mediation

Naturalness

Generically a factor 10 more natural

$$m_{\tilde{t}}^2 \lesssim (450 \text{ GeV})^2 \frac{1}{1+\frac{x^2}{2}} \left(\frac{20\%}{\Delta^{-1}}\right) \left(\frac{3}{\ln \frac{M_{\text{mess}}}{m_{\tilde{t}}}}\right)$$

Plenty of room for Gravitino LSP

Naturalness

Generically a factor 10 more natural

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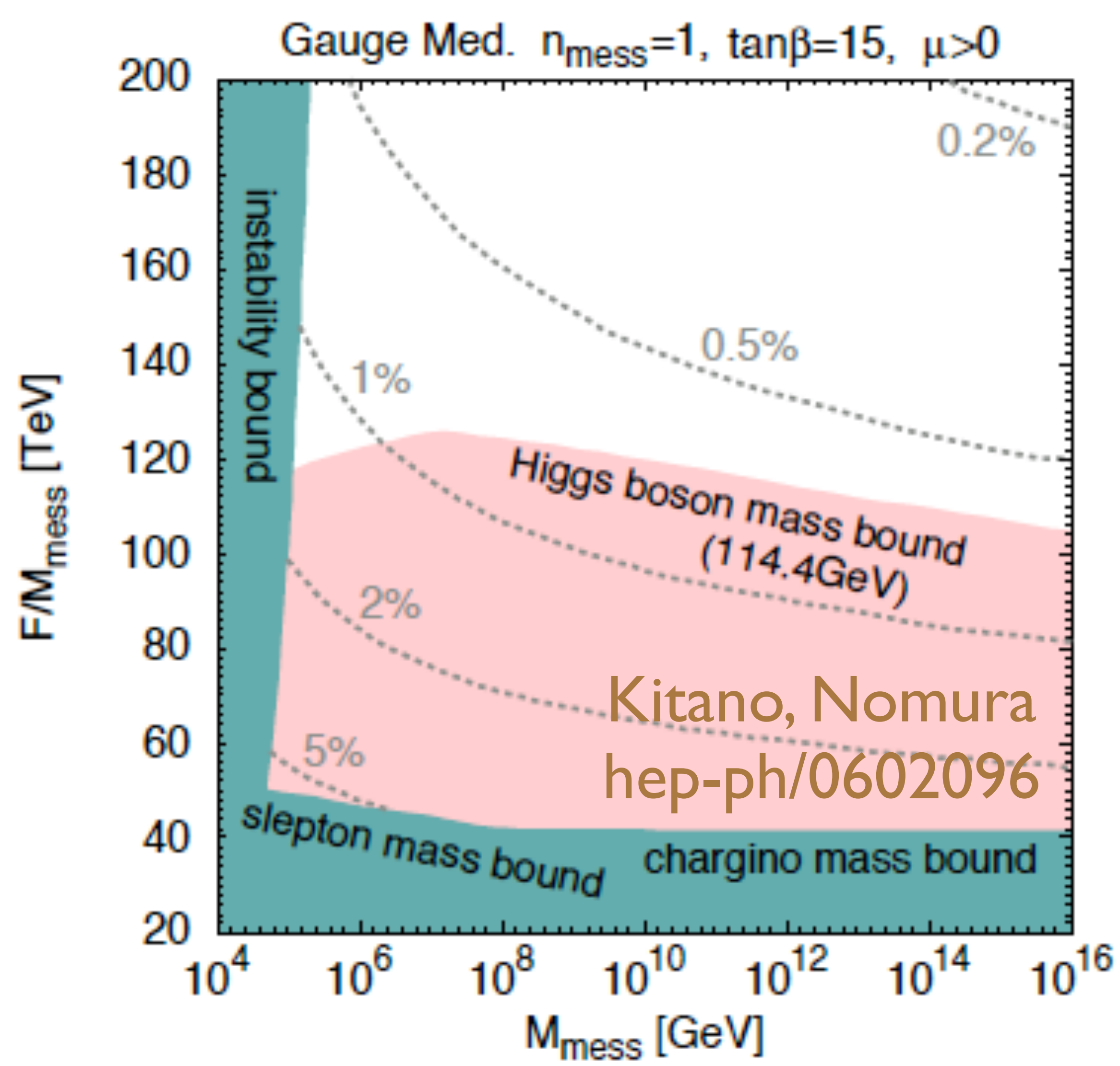
Plenty of room for Gravitino LSP

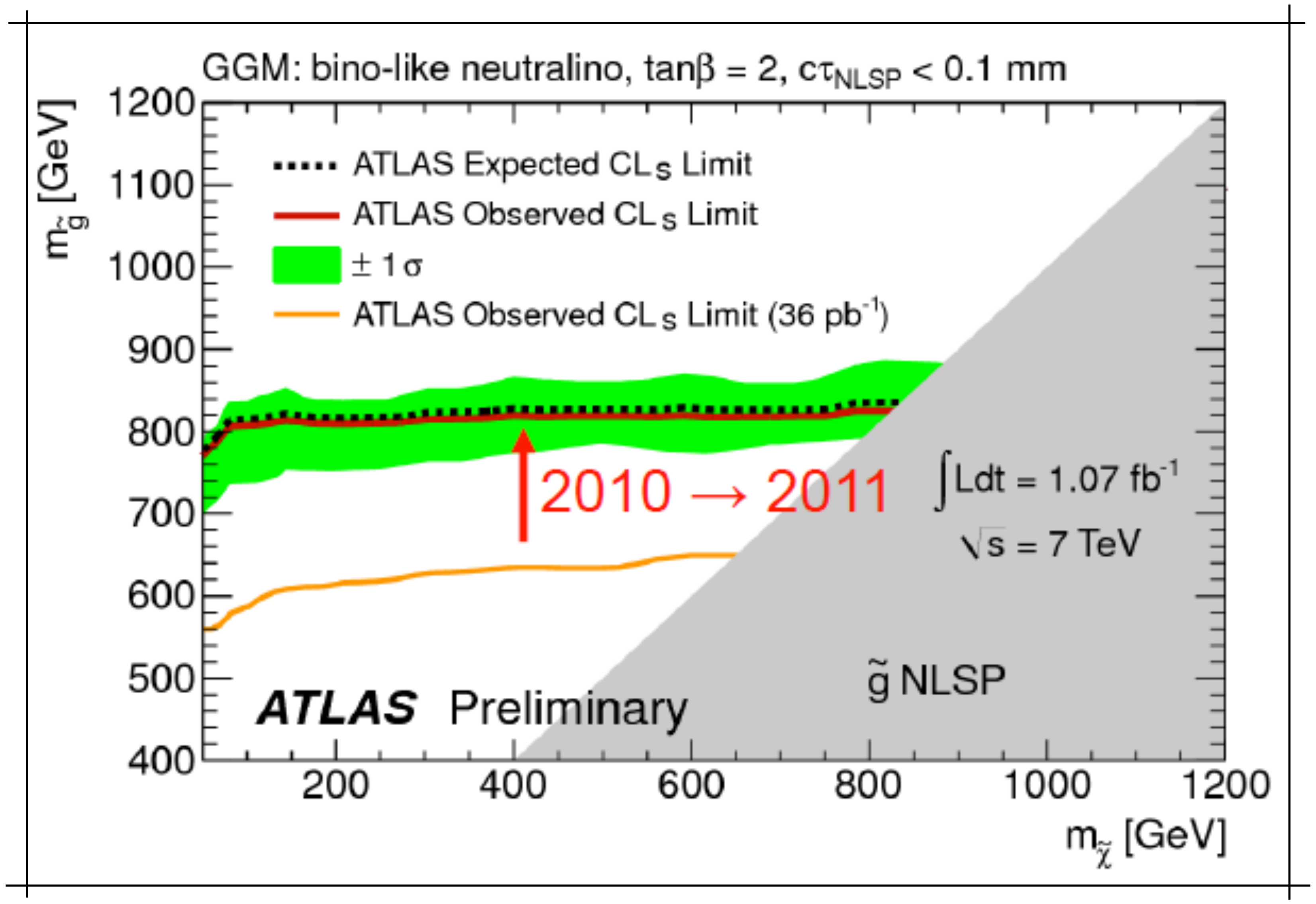
But not in minimal gauge mediation models (a theorists problem)



Key Missing Energy Searches

$$\gamma\,\gamma + \text{missing}\, E_T$$

$$\tilde{g} \;\rightarrow\; \bar{q}q\,\tilde{B} \searrow \tilde{G}_{3/2} \;+\; \gamma$$



Minimal gauge-mediated models: no worse

Natural models: no problem with stop at 300 GeV

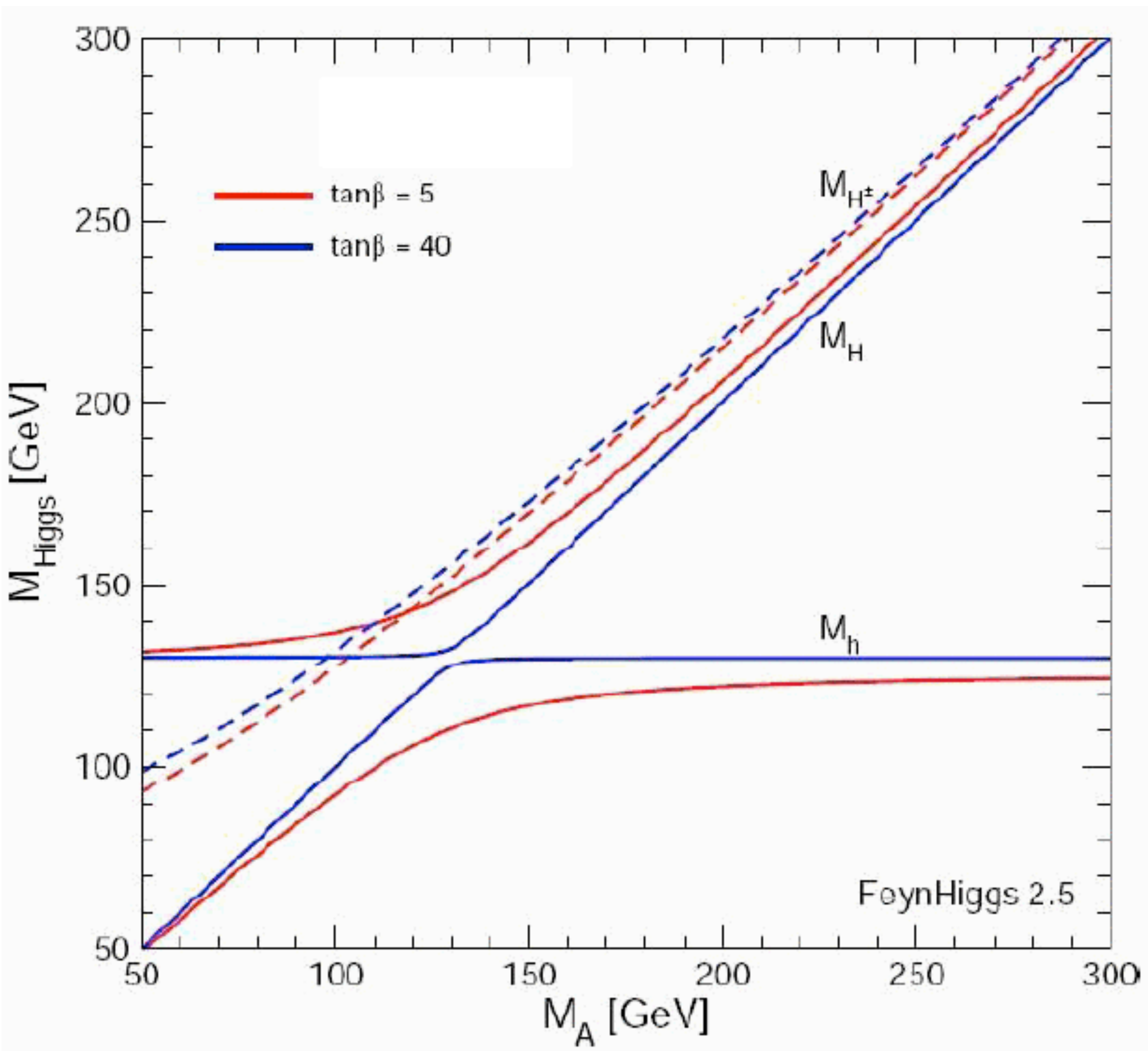
III

SUSY Higgs

SUSY Higgs

$$h_{SM} \to h, H, A, H^+$$

$$m_{h_{SM}} \to \tan\beta, m_A$$

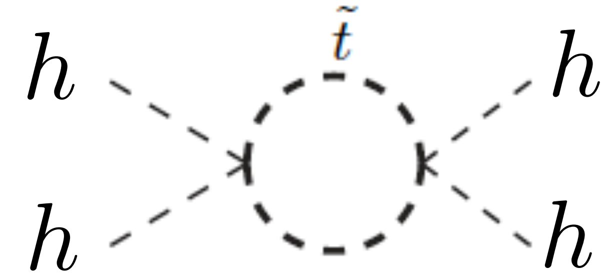


SUSY Higgs

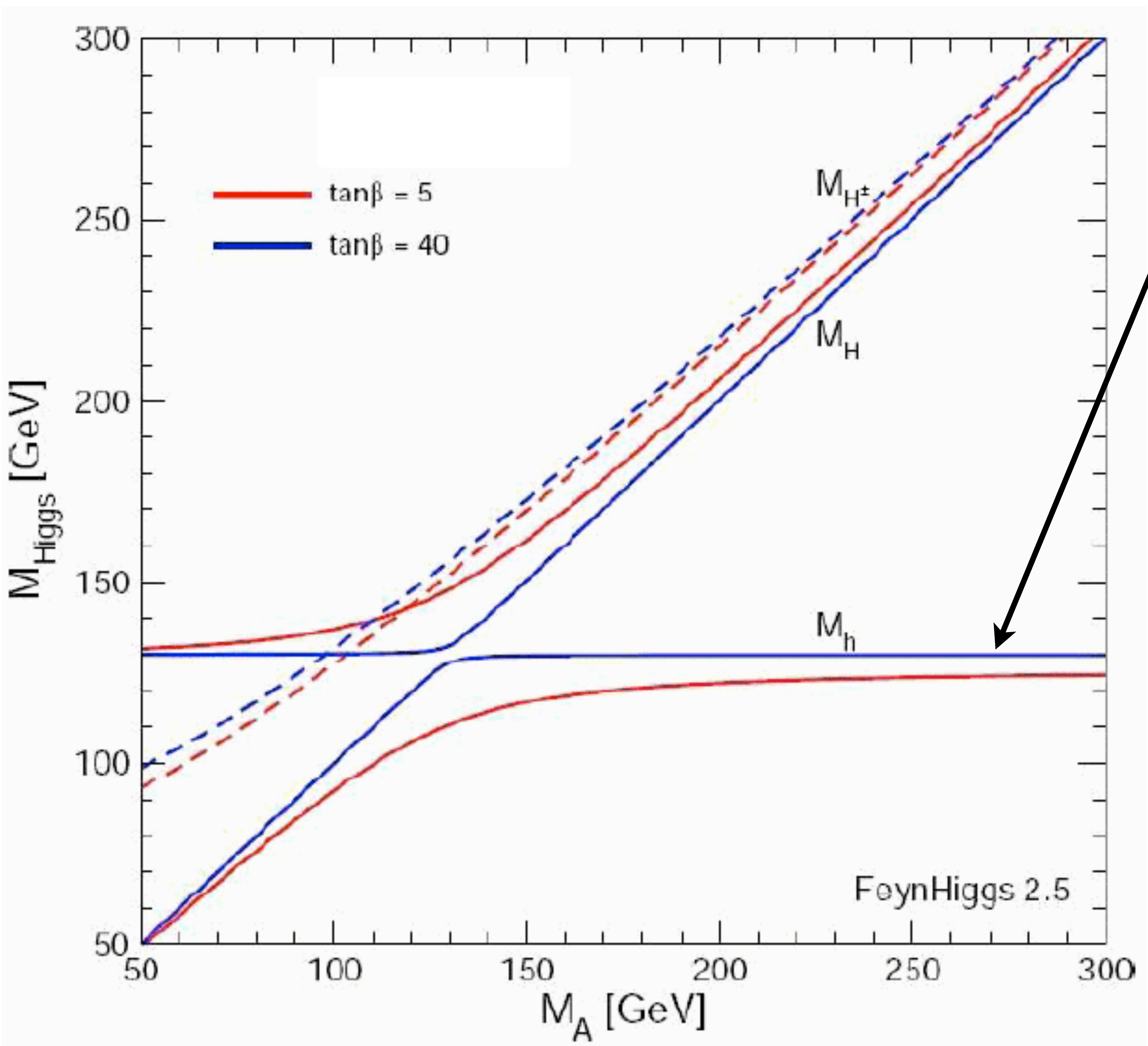
$$h_{SM} \to h, H, A, H^+$$

$$m_{h_{SM}} \to \tan\beta, m_A$$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_{top}$$



Need heavy $\tilde{t}$!



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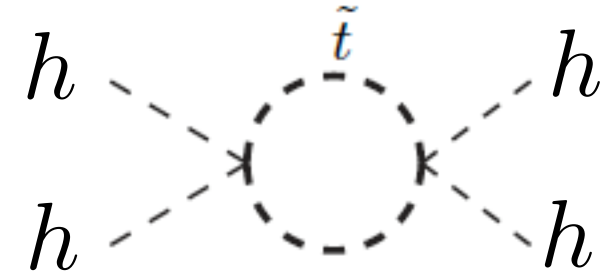

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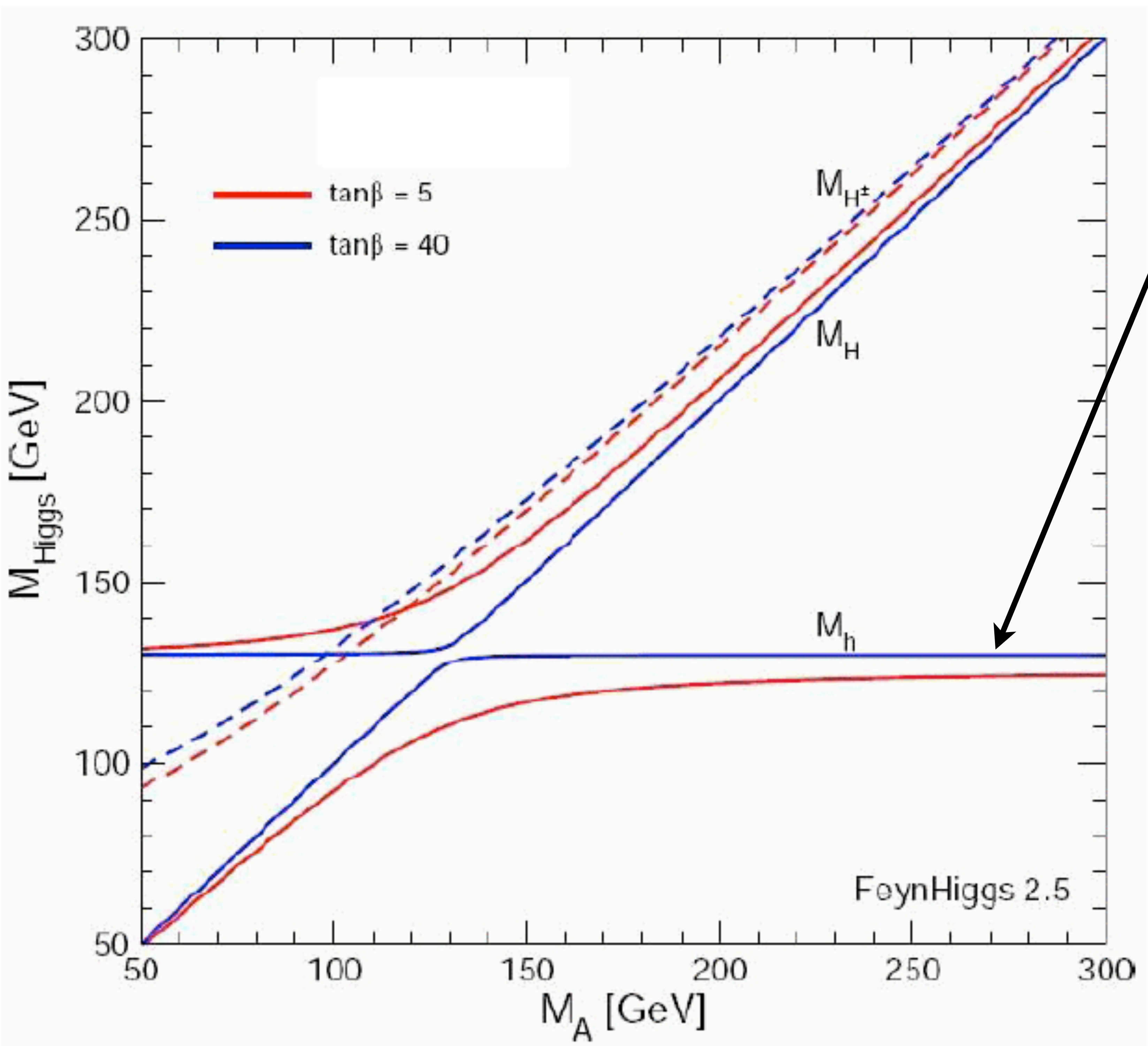

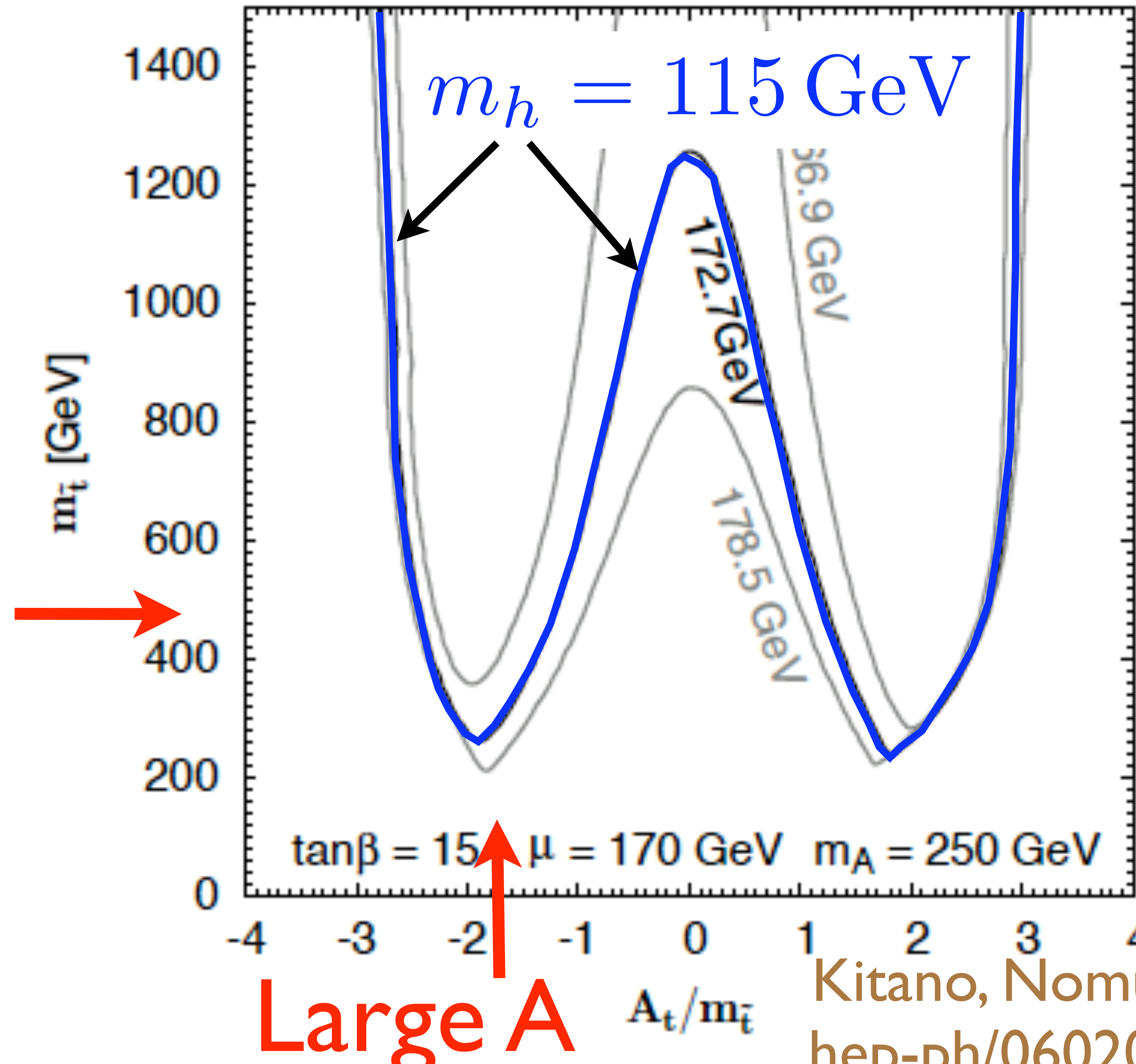

Kitano, Nomura
hep-ph/0602096

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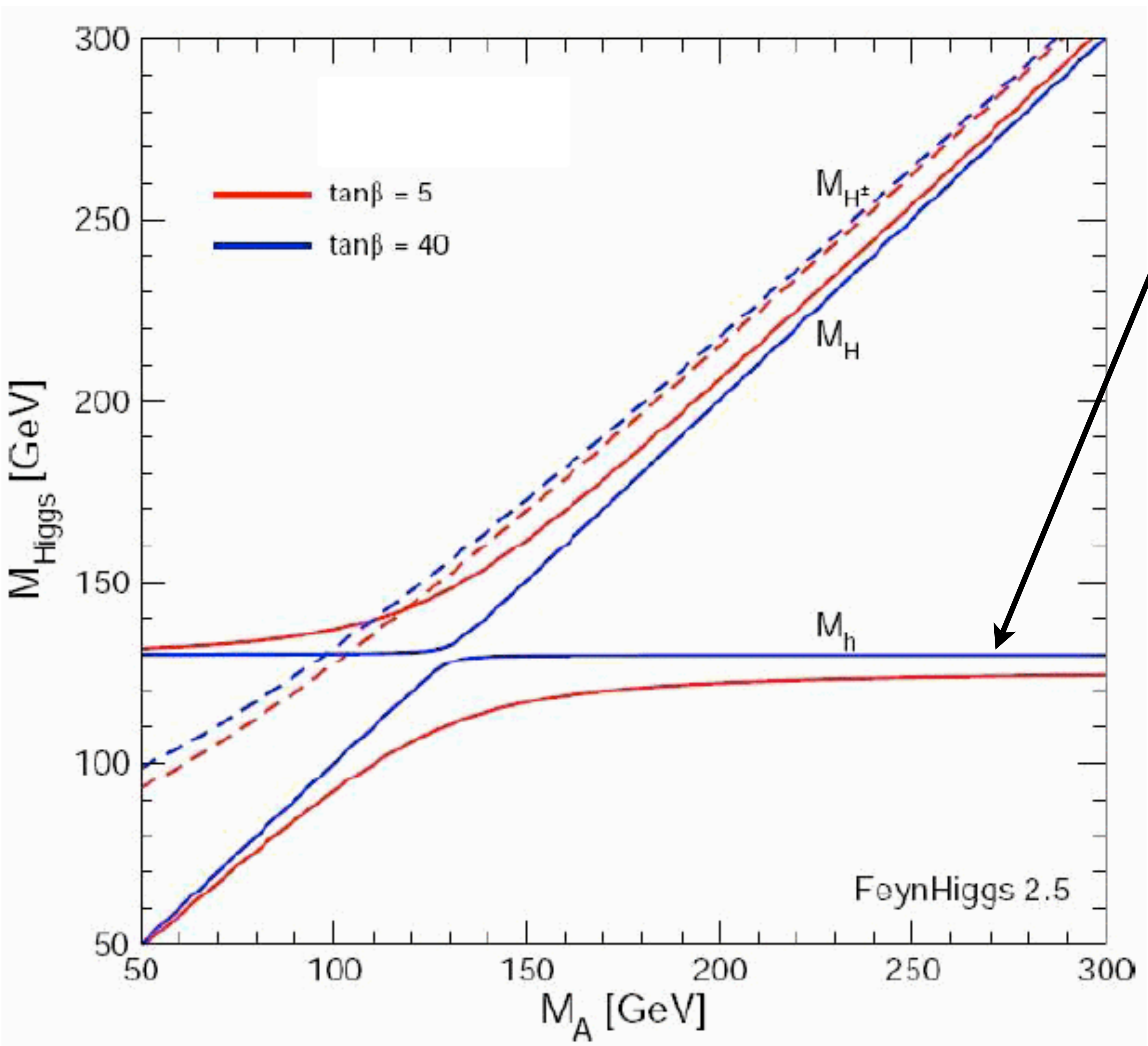

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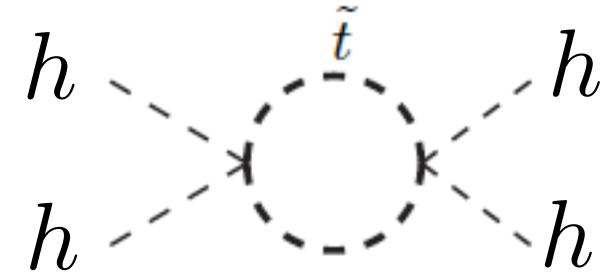

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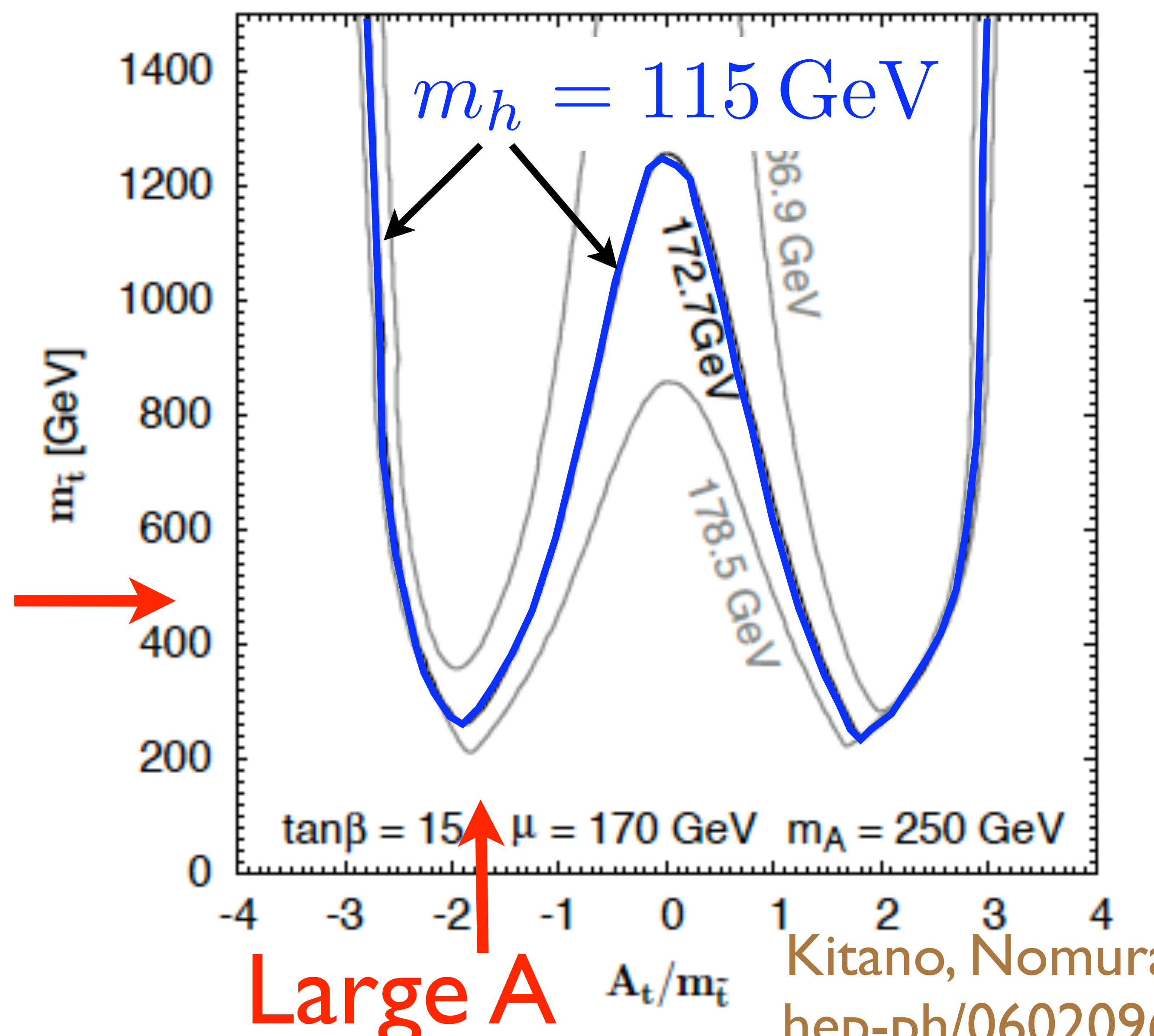

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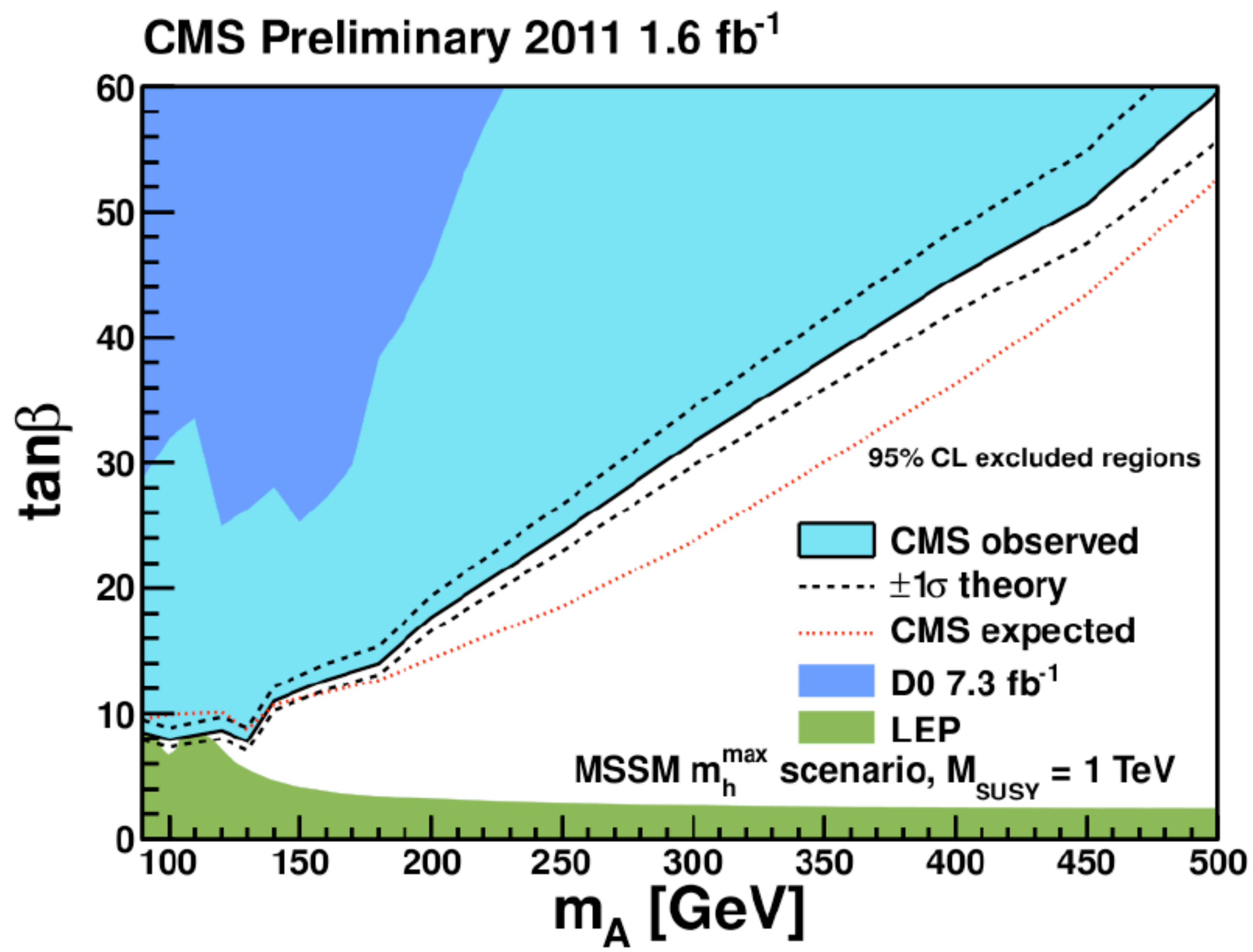
Or $\mu \to S$

Search for H,A of MSSM

H,A couplings to b, τ
enhanced at large $\tan\beta$

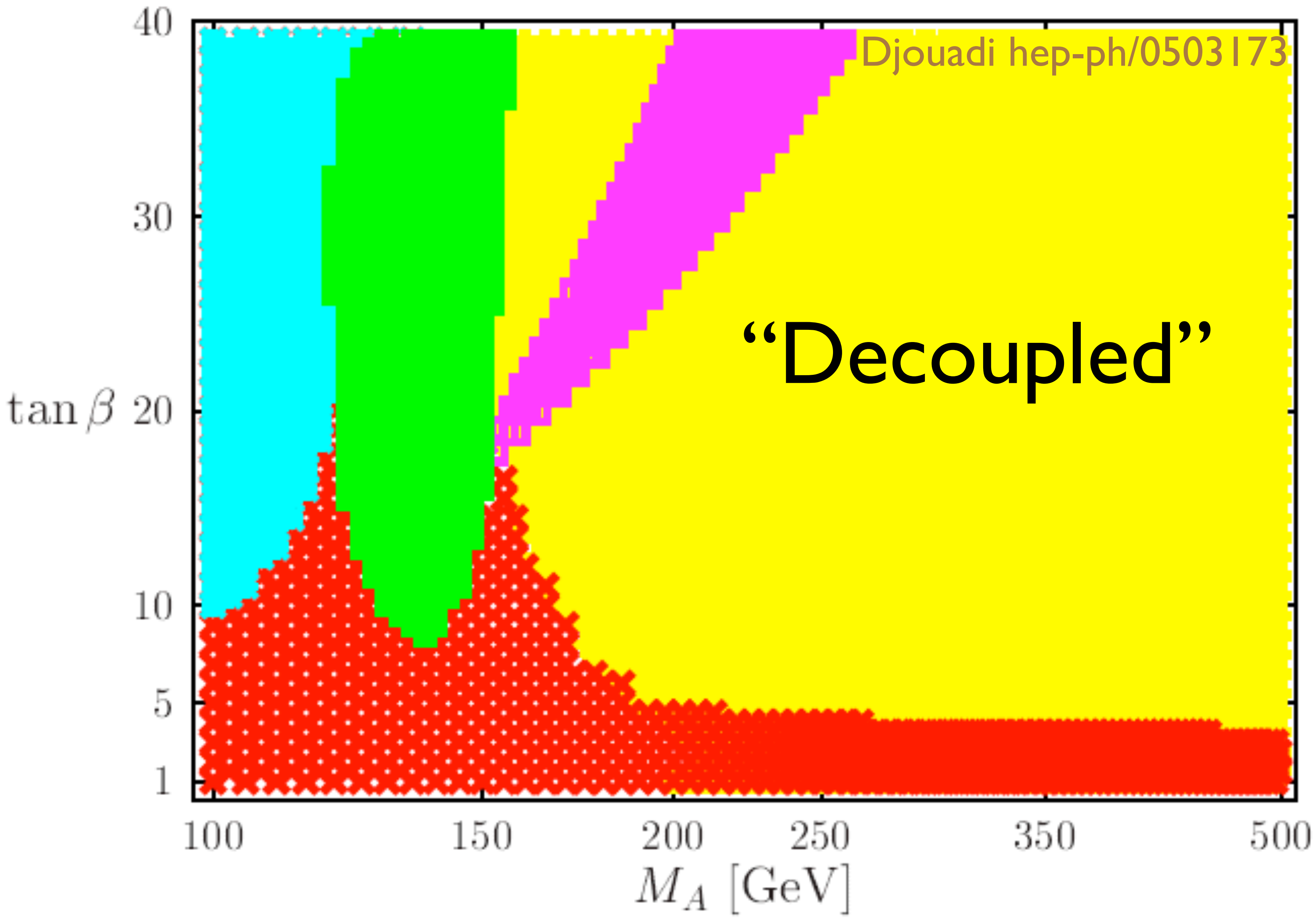
$$H, A \rightarrow \tau^+\tau^-$$

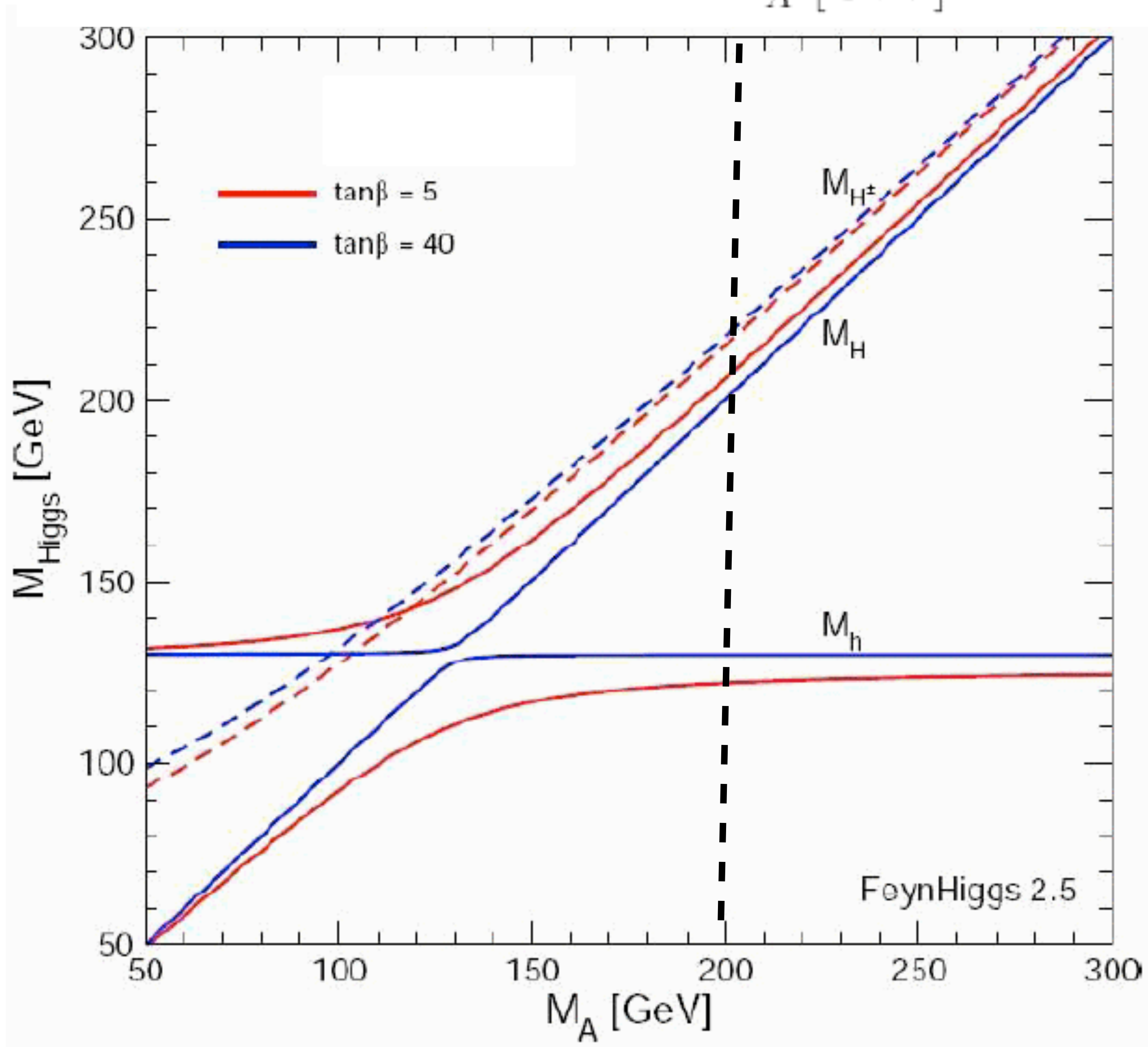


Search for h

$$m_{h_{SM}} \rightarrow \tan\beta, m_A$$

$$h_{SM} \rightarrow h, H, A, H^+$$





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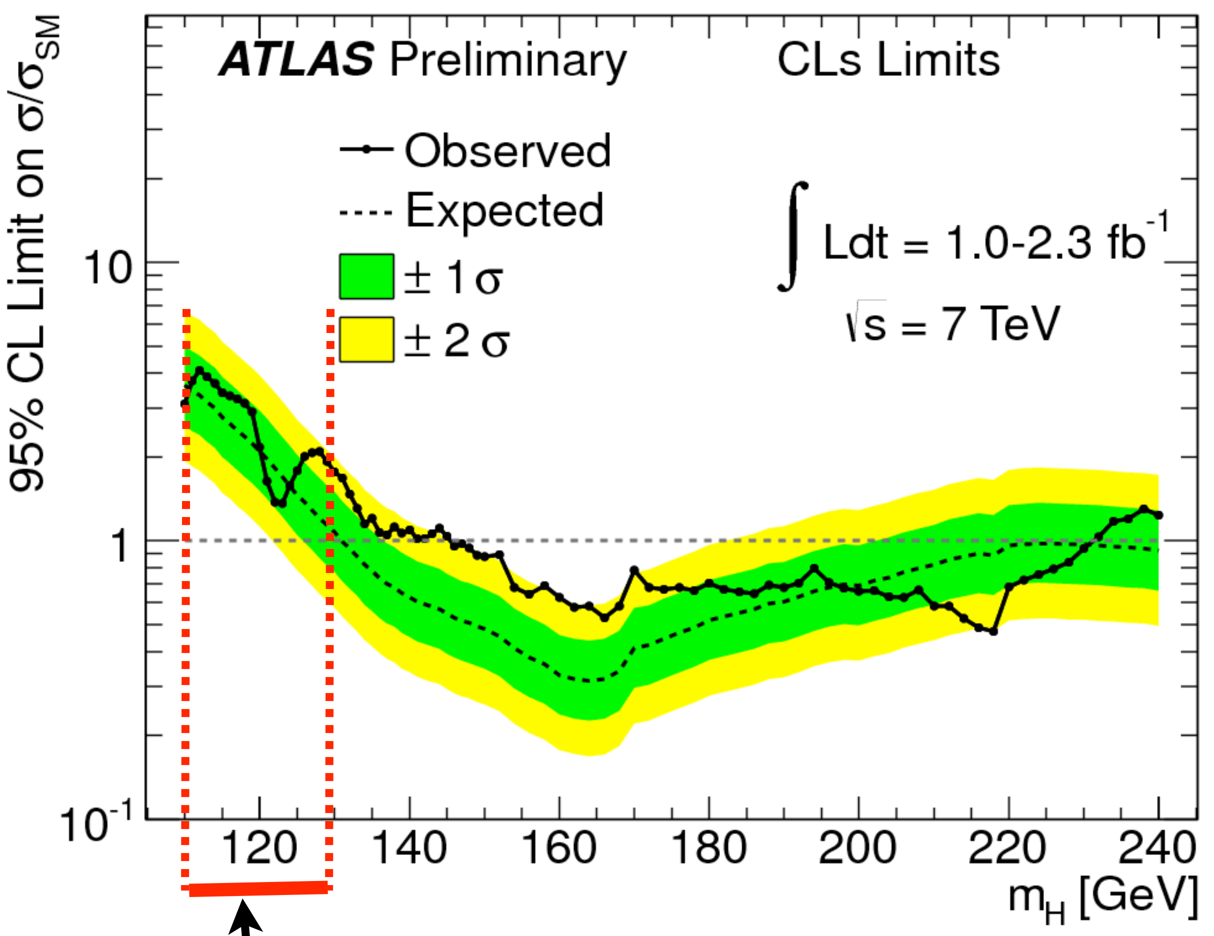
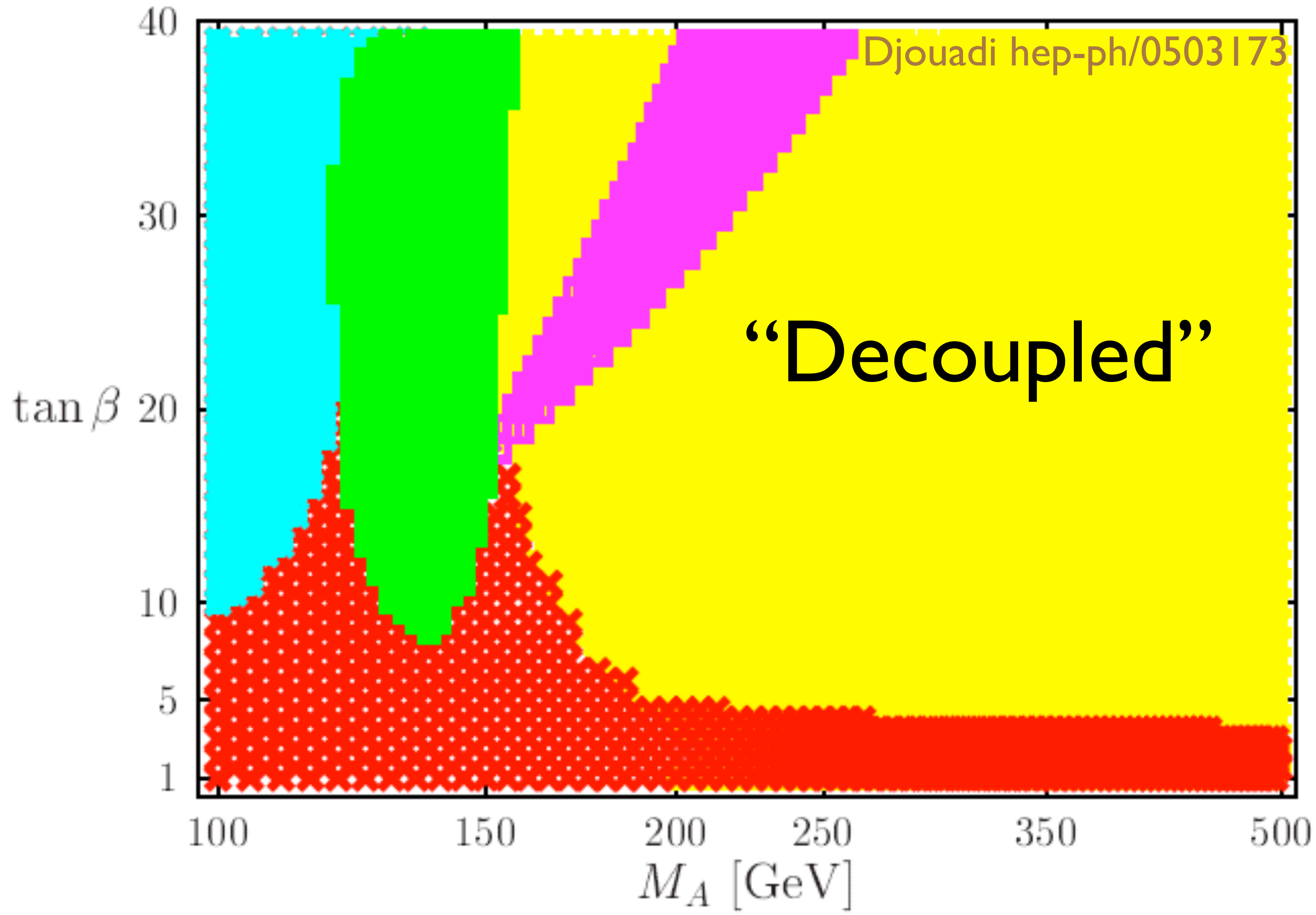
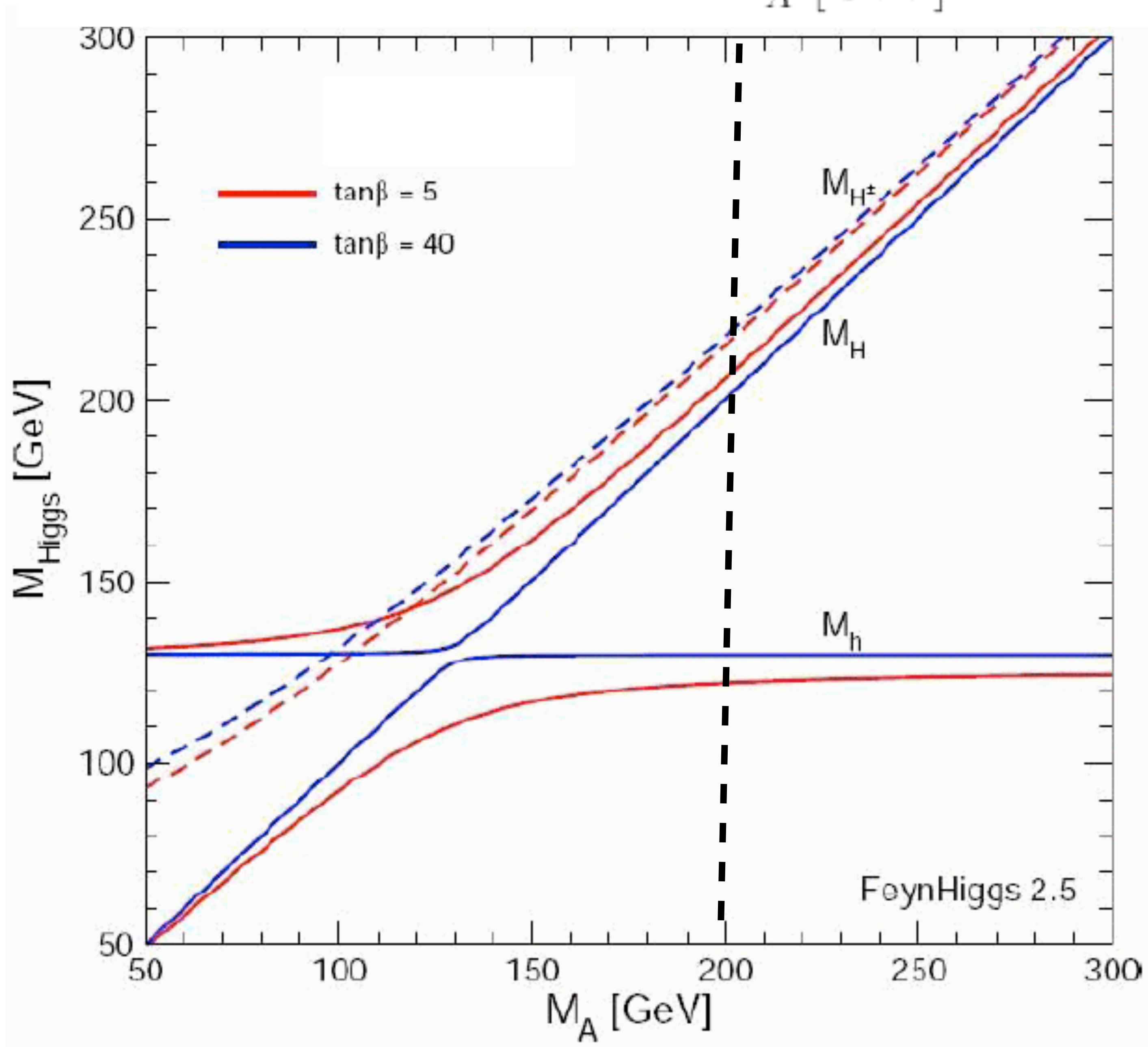


Should show up here "soon" !!





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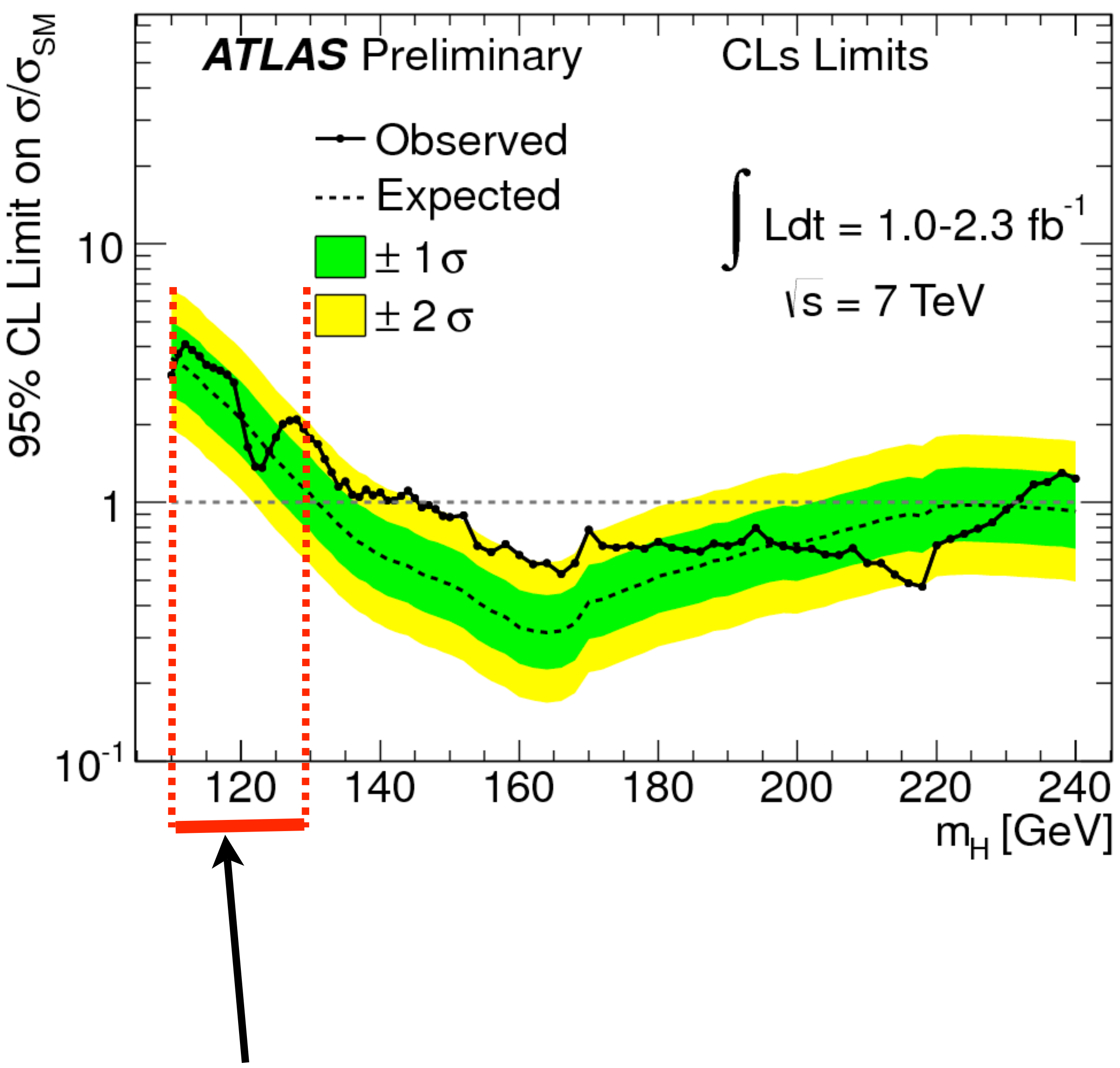
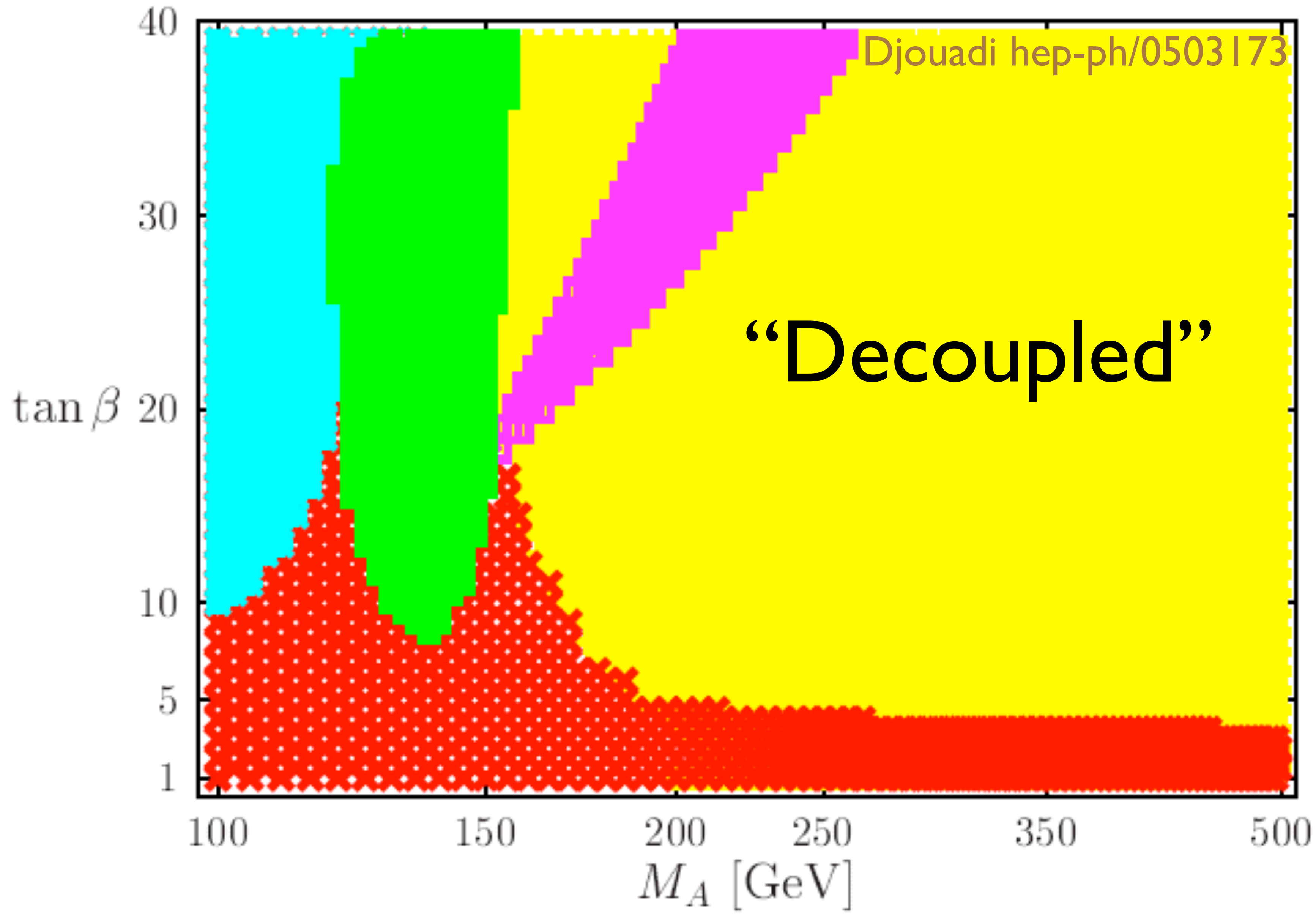
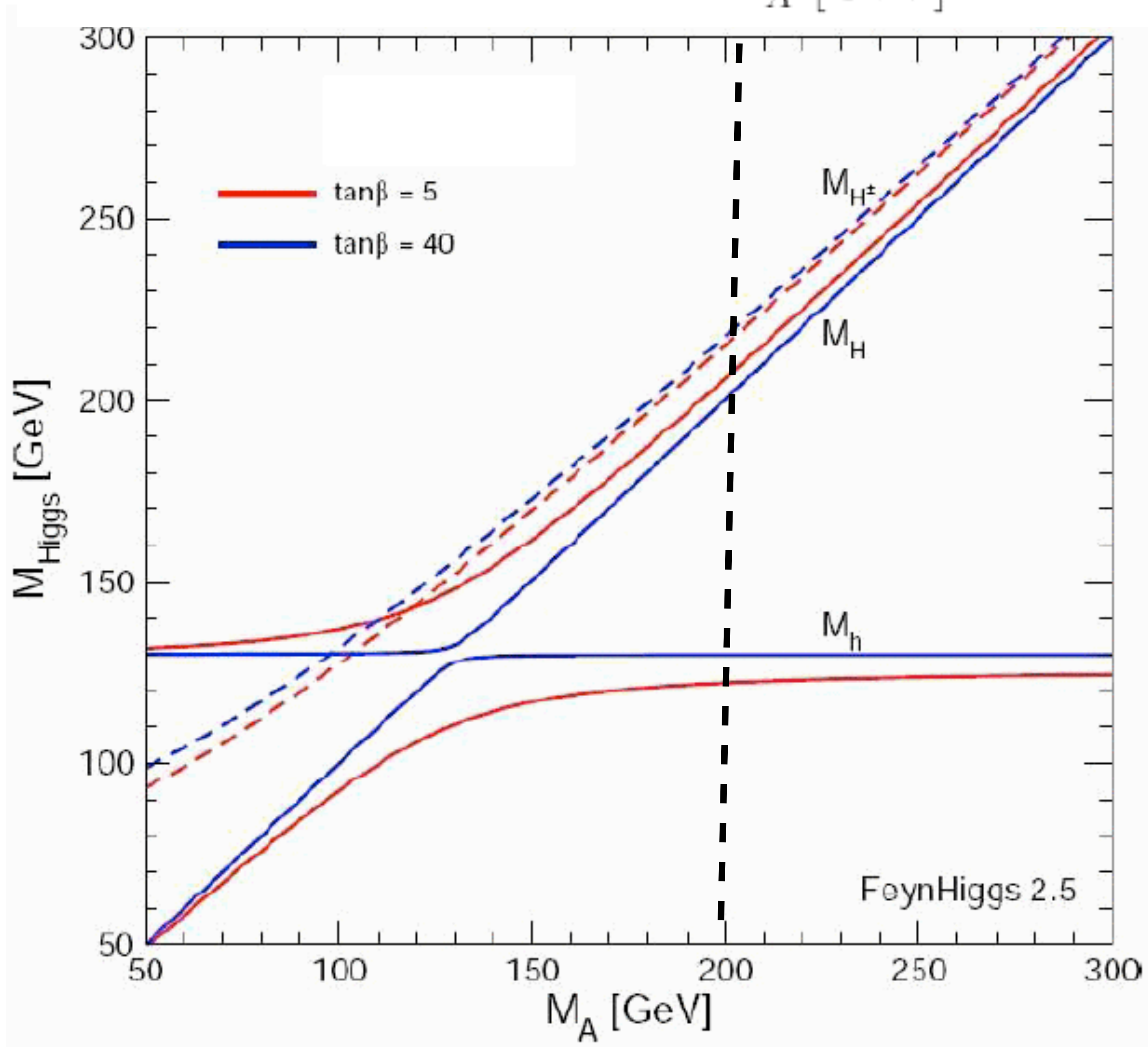


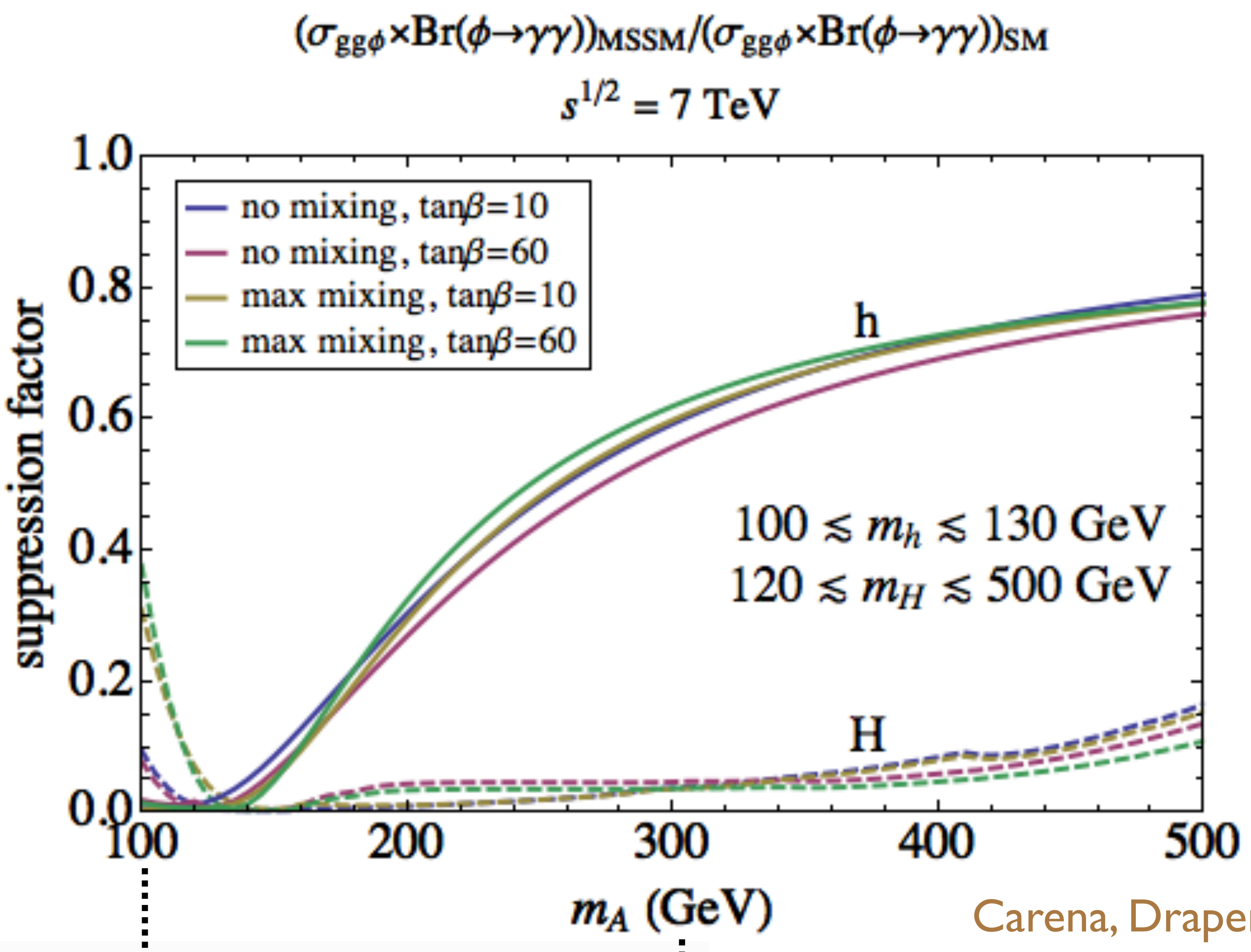
Should show up here "soon" !!

What if it doesn't?

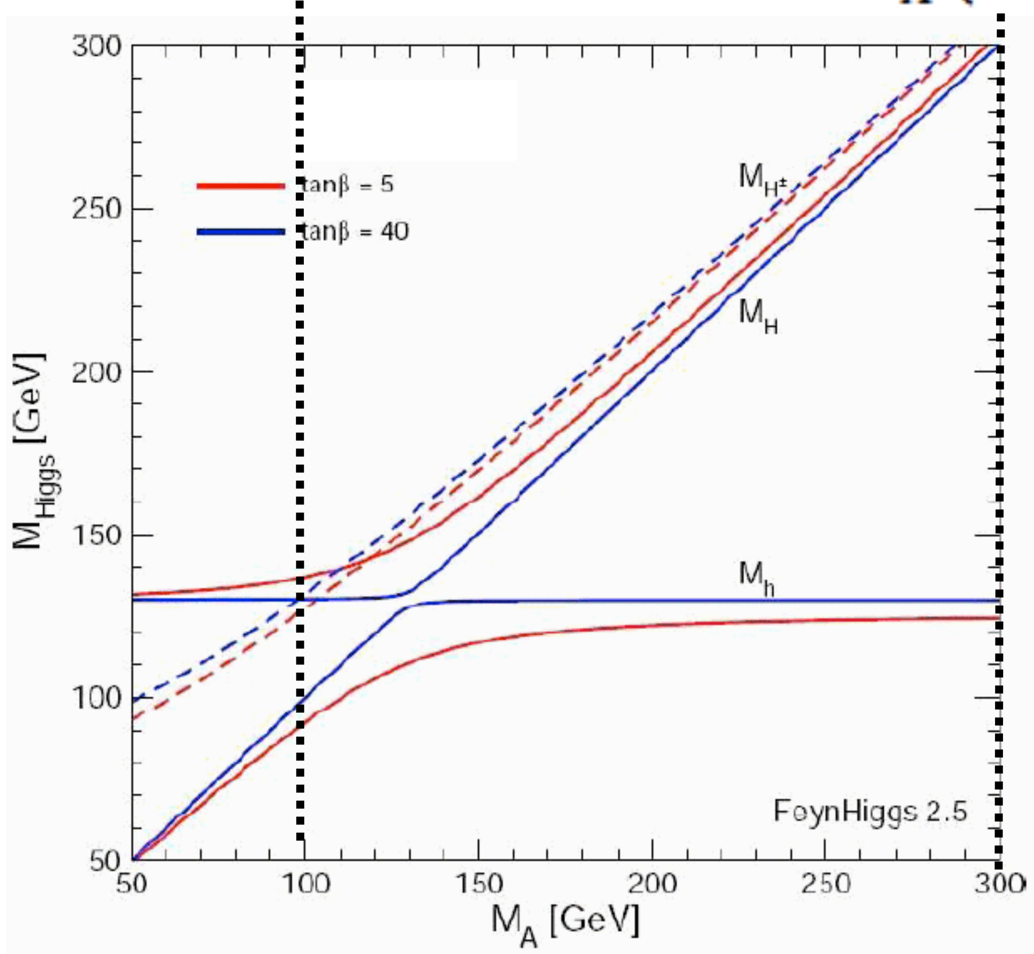




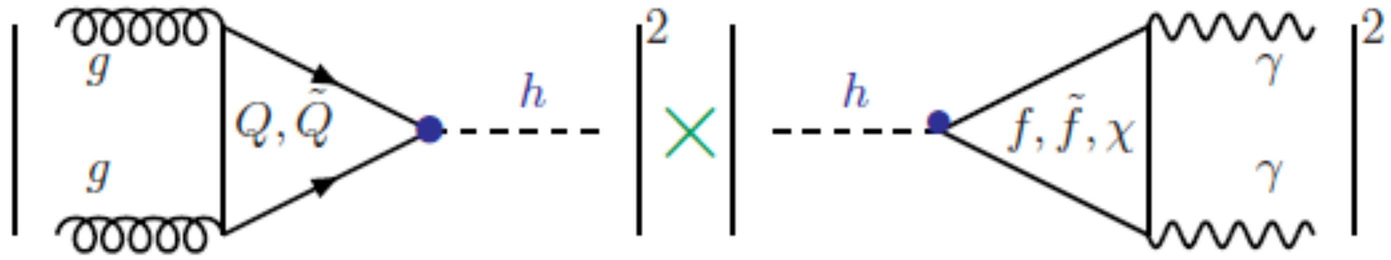
Not In Decoupled Region



Carena, Draper, Liu, Wagner
1107.4354

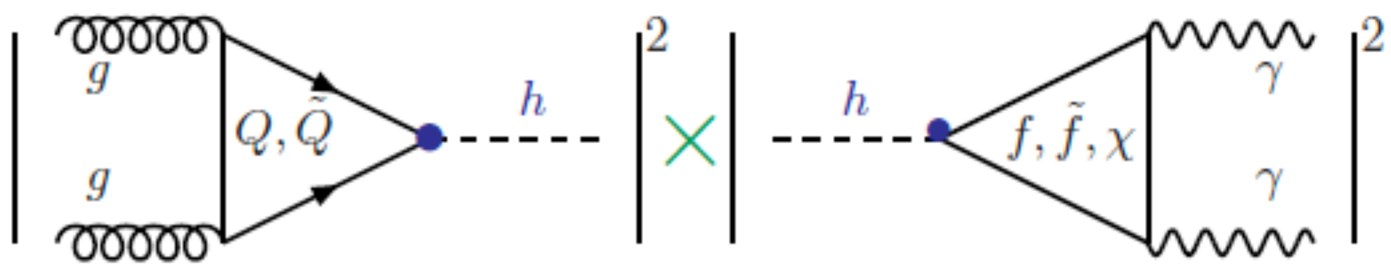


Effect of Light $\tilde{t}$ on $h \rightarrow \gamma\gamma$ Signal Rate



modifies rate by $B\,\sigma$

Effect of Light $\tilde{t}$ on $h \to \gamma\gamma$ Signal Rate



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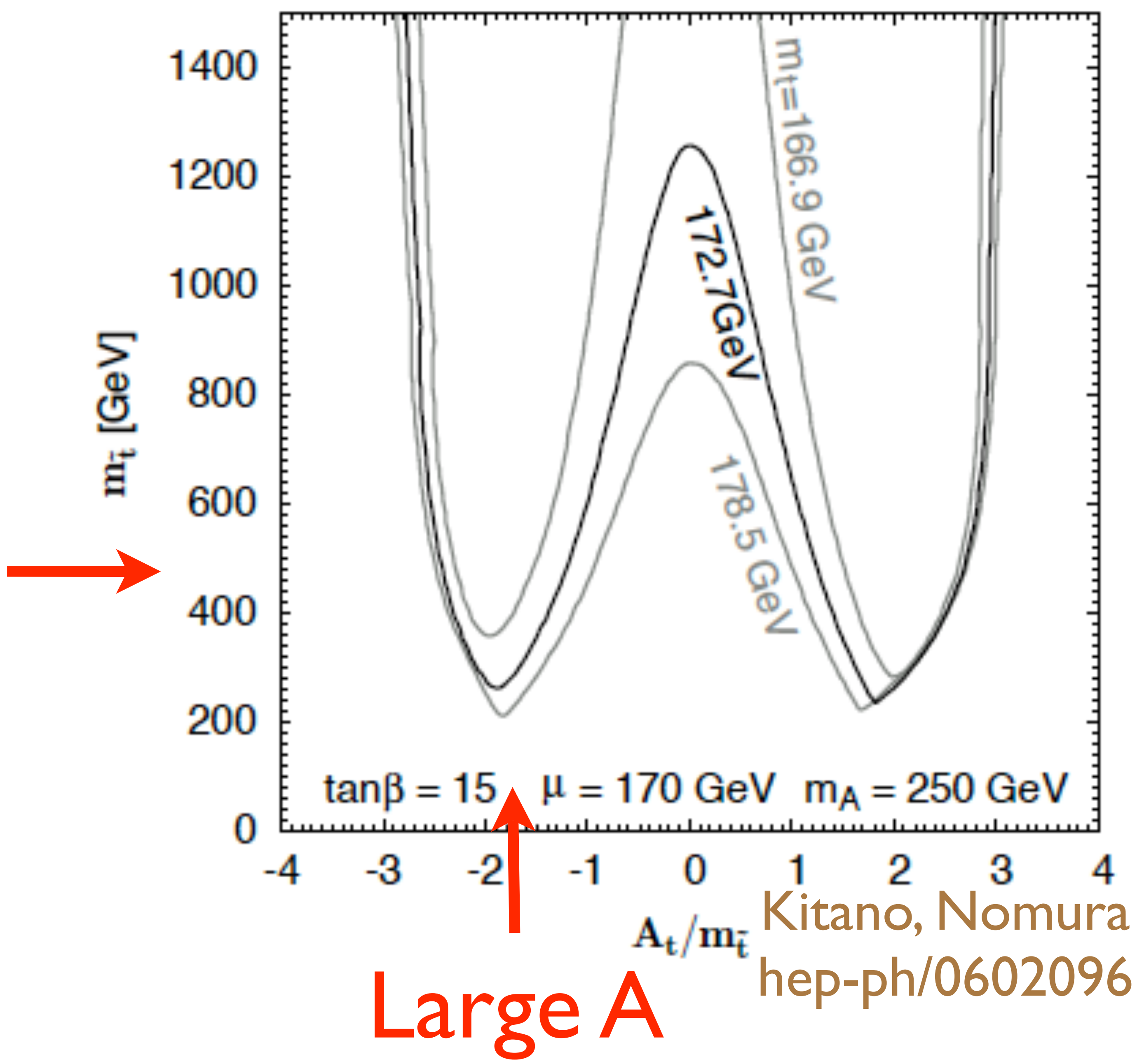
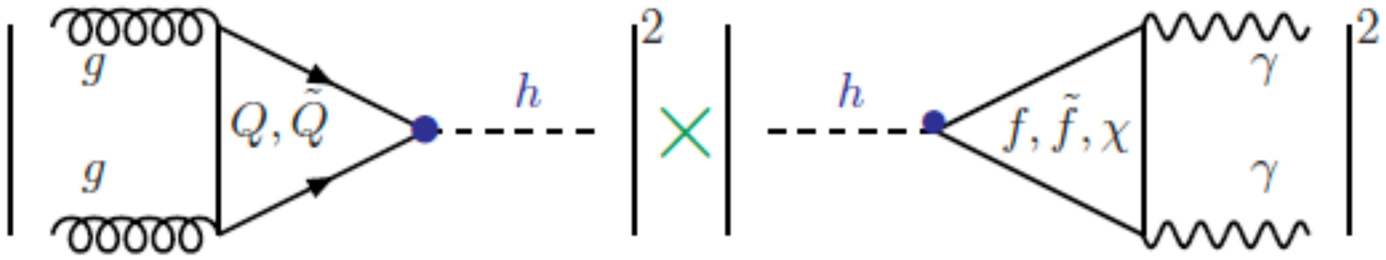


Kitano, Nomura
hep-ph/0602096

Effect of Light $\tilde{t}$ on $h \to \gamma\gamma$ Signal Rate



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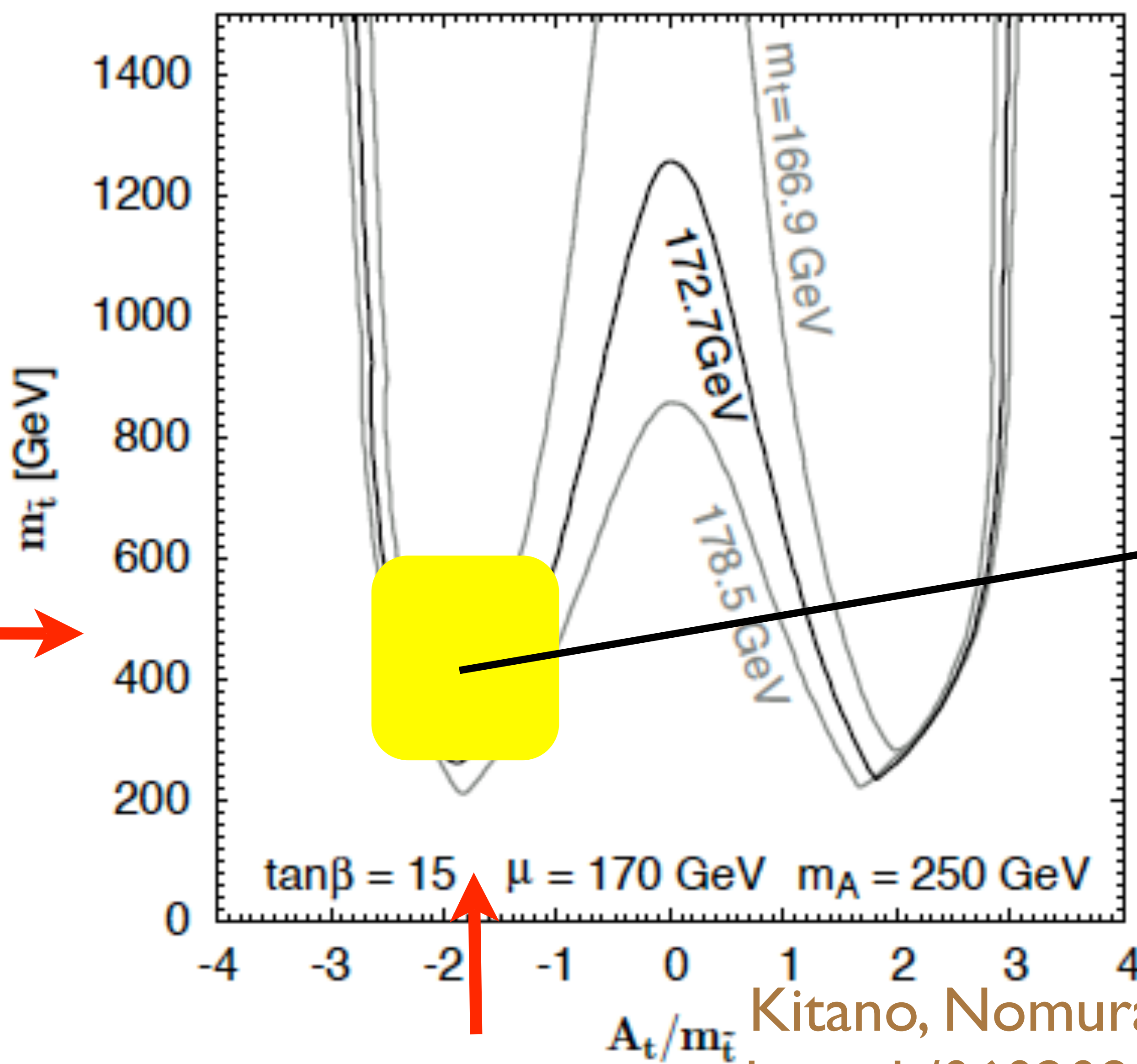

Large A

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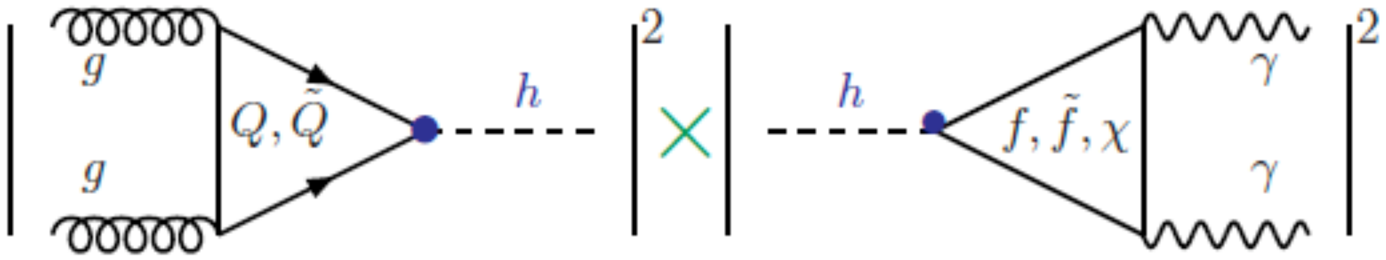
Effect of Light $\tilde{t}$ on $h \to \gamma\gamma$ Signal Rate



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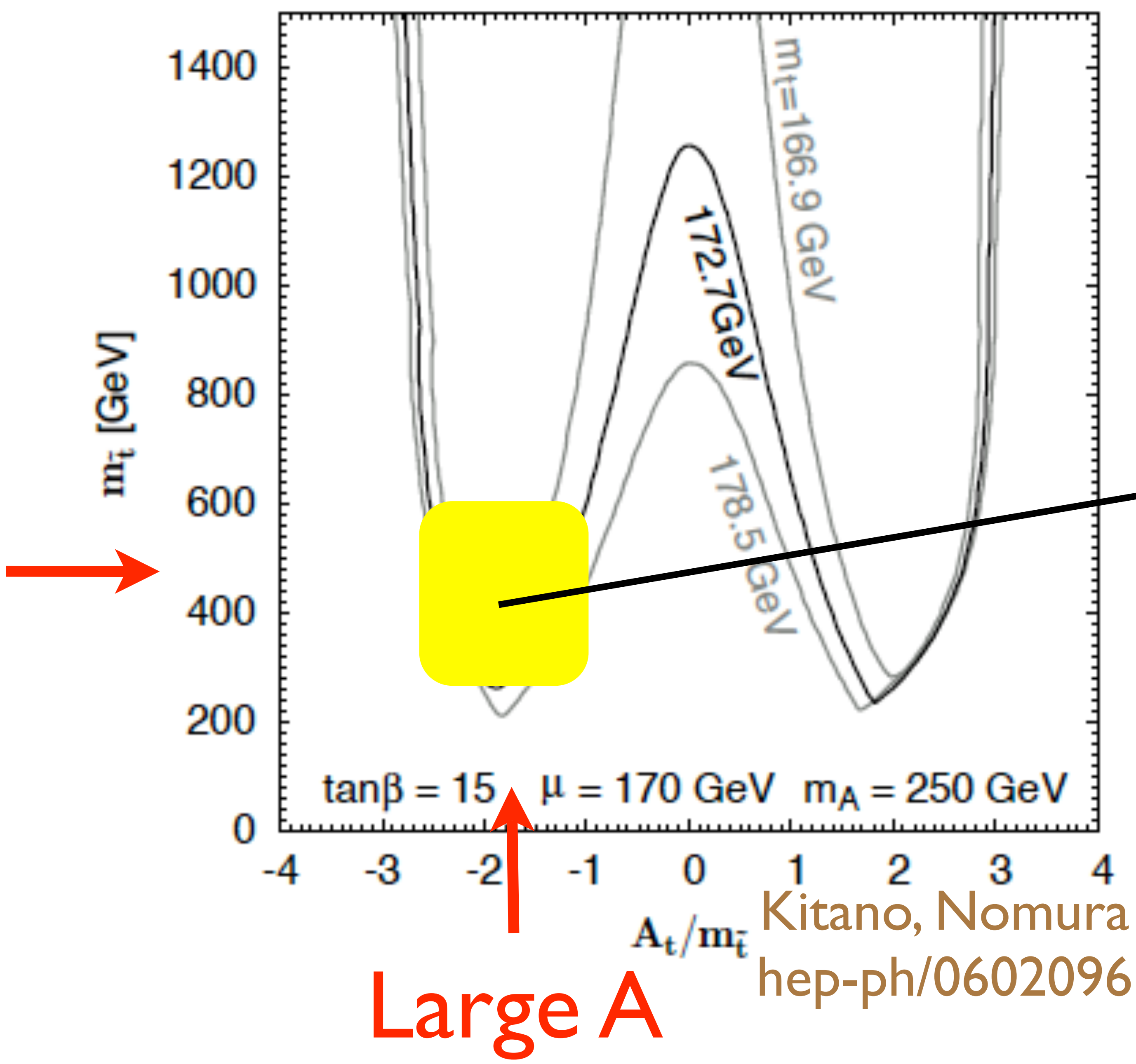

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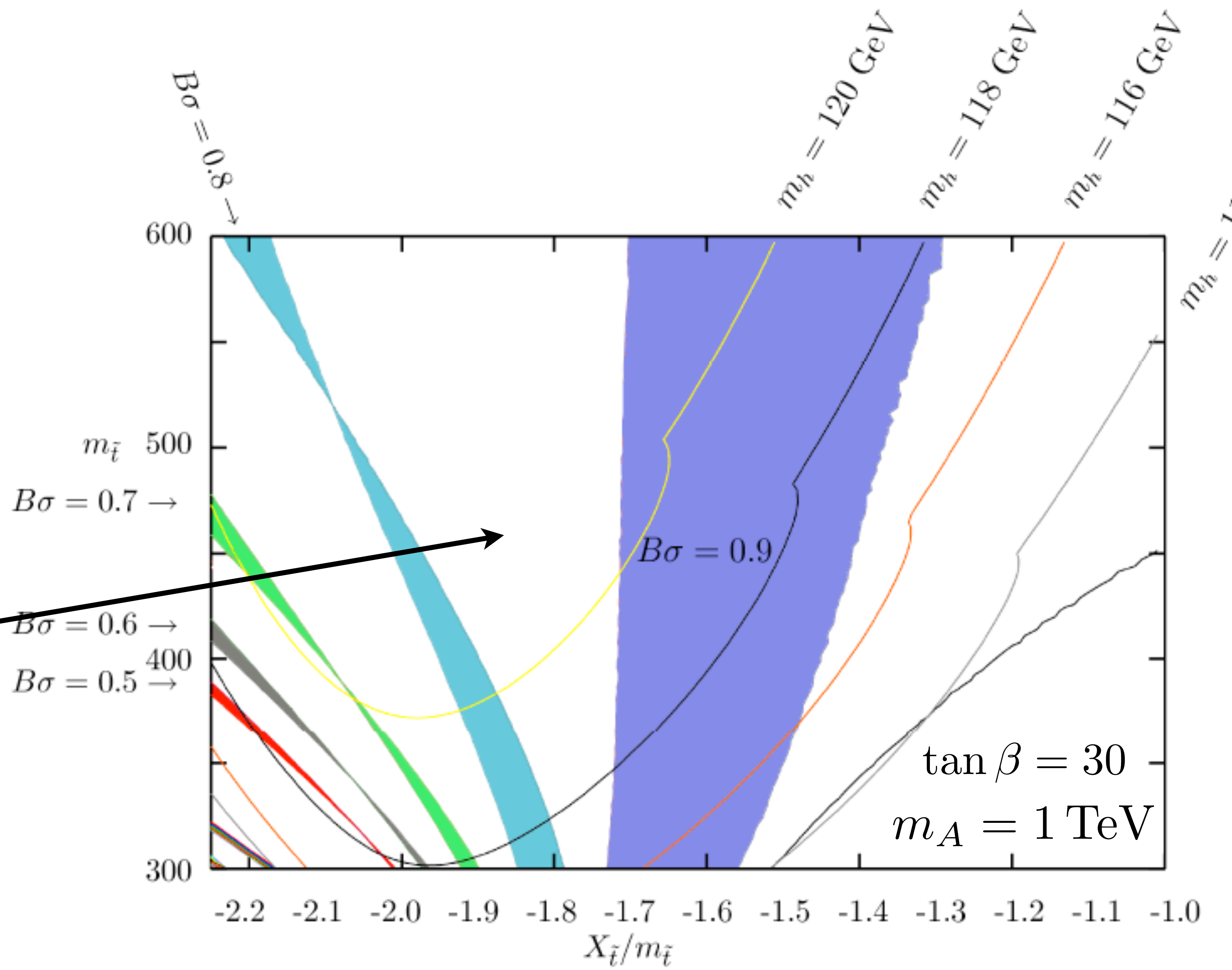
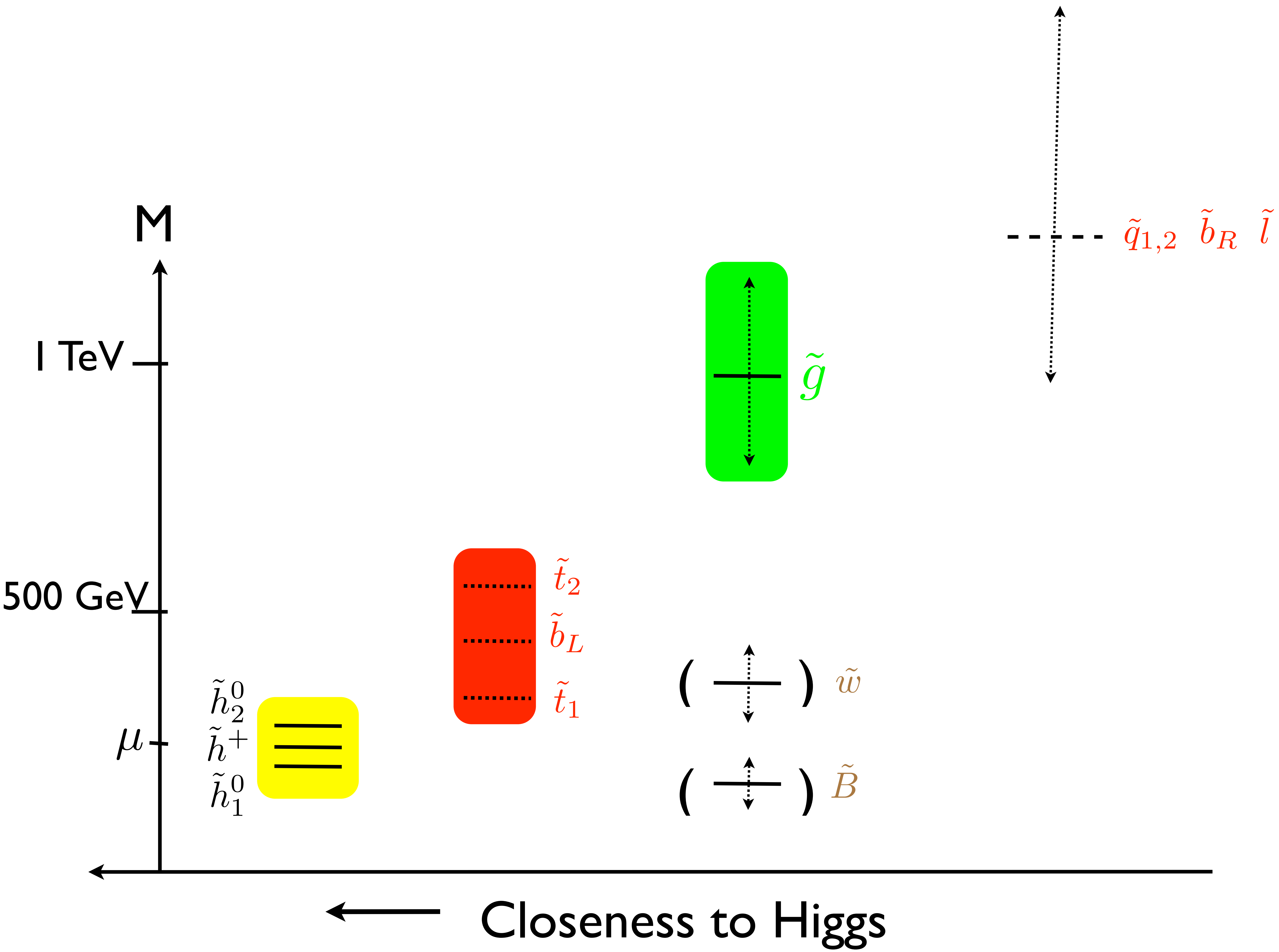


Low, Shalgar 0901.0266

Shaded regions from varying μ

Natural Spectrum and Dark Matter



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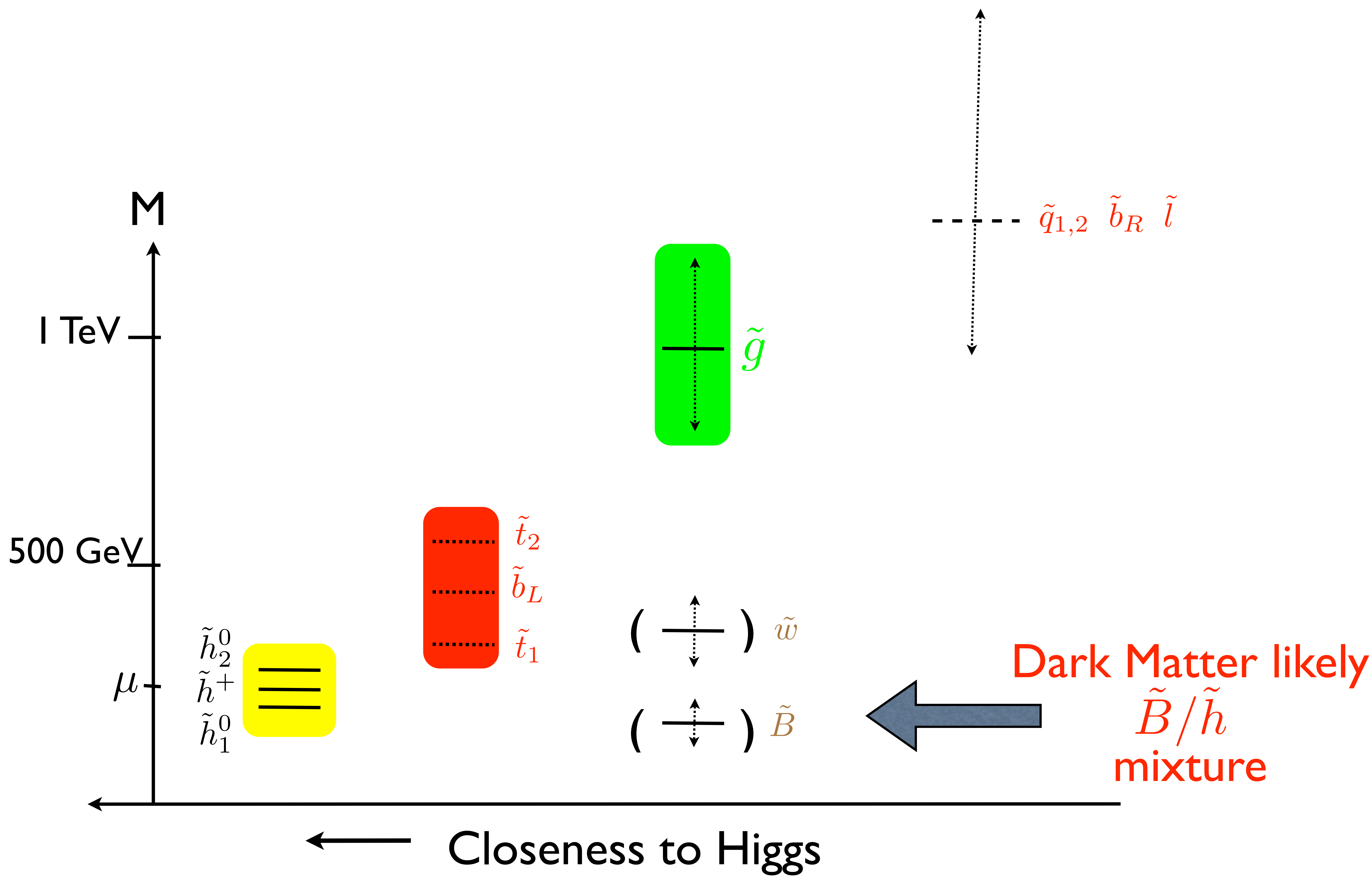
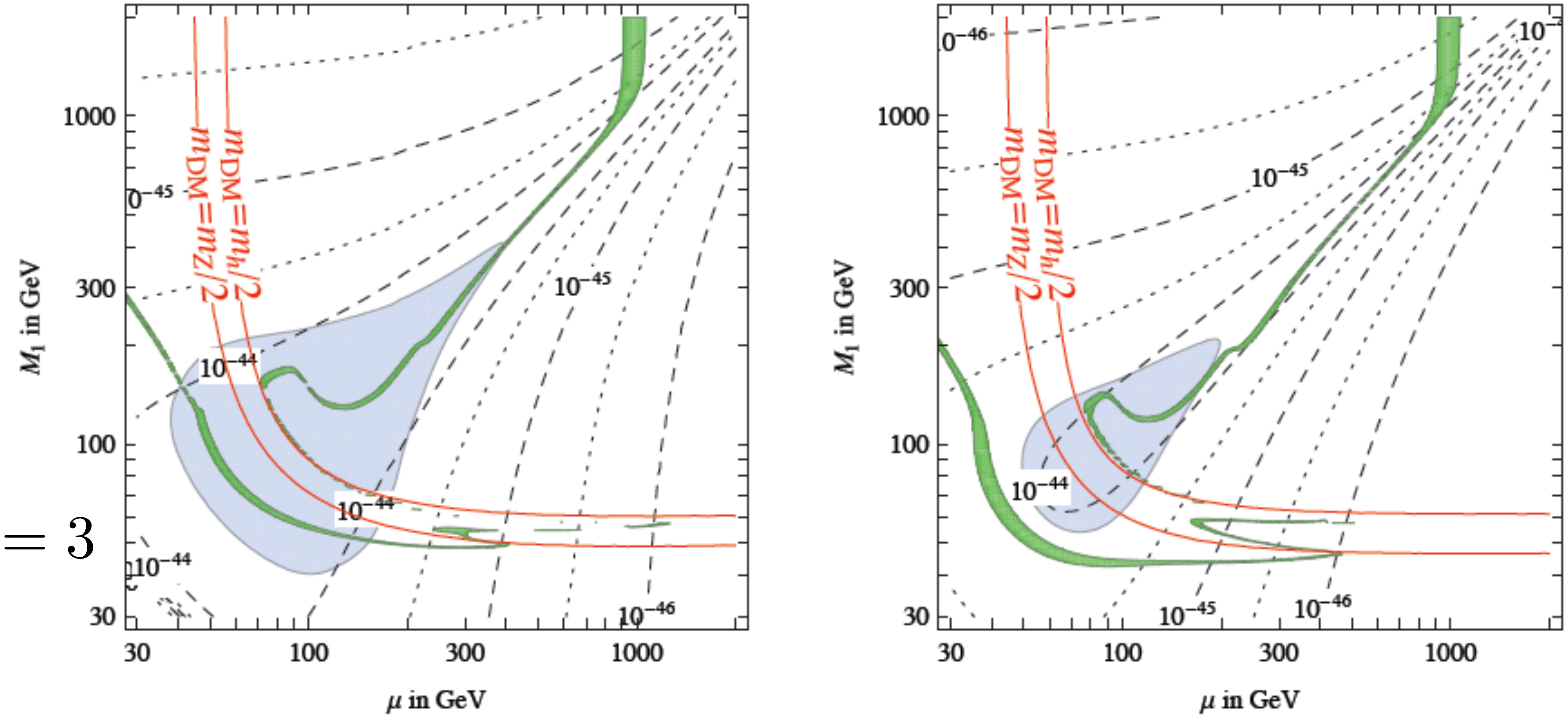


Higgs Decays to Neutralino Dark Matter

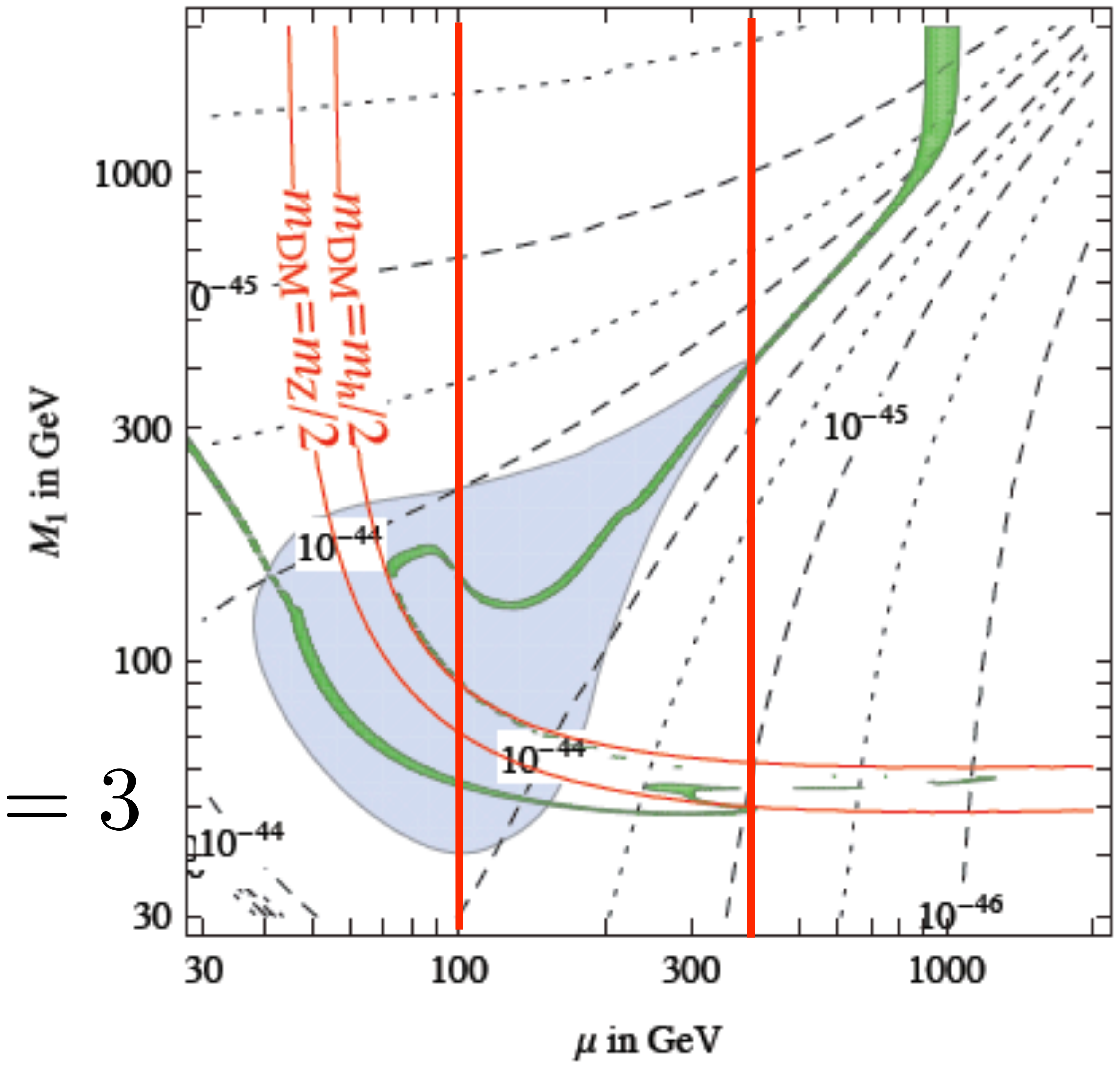


$\tan\beta = 3$

$\tan\beta = 10$

Farina, Kadastik, Pappadopulo, Pata, Raidal, Strumia 1104.3572

Higgs Decays to Neutralino Dark Matter



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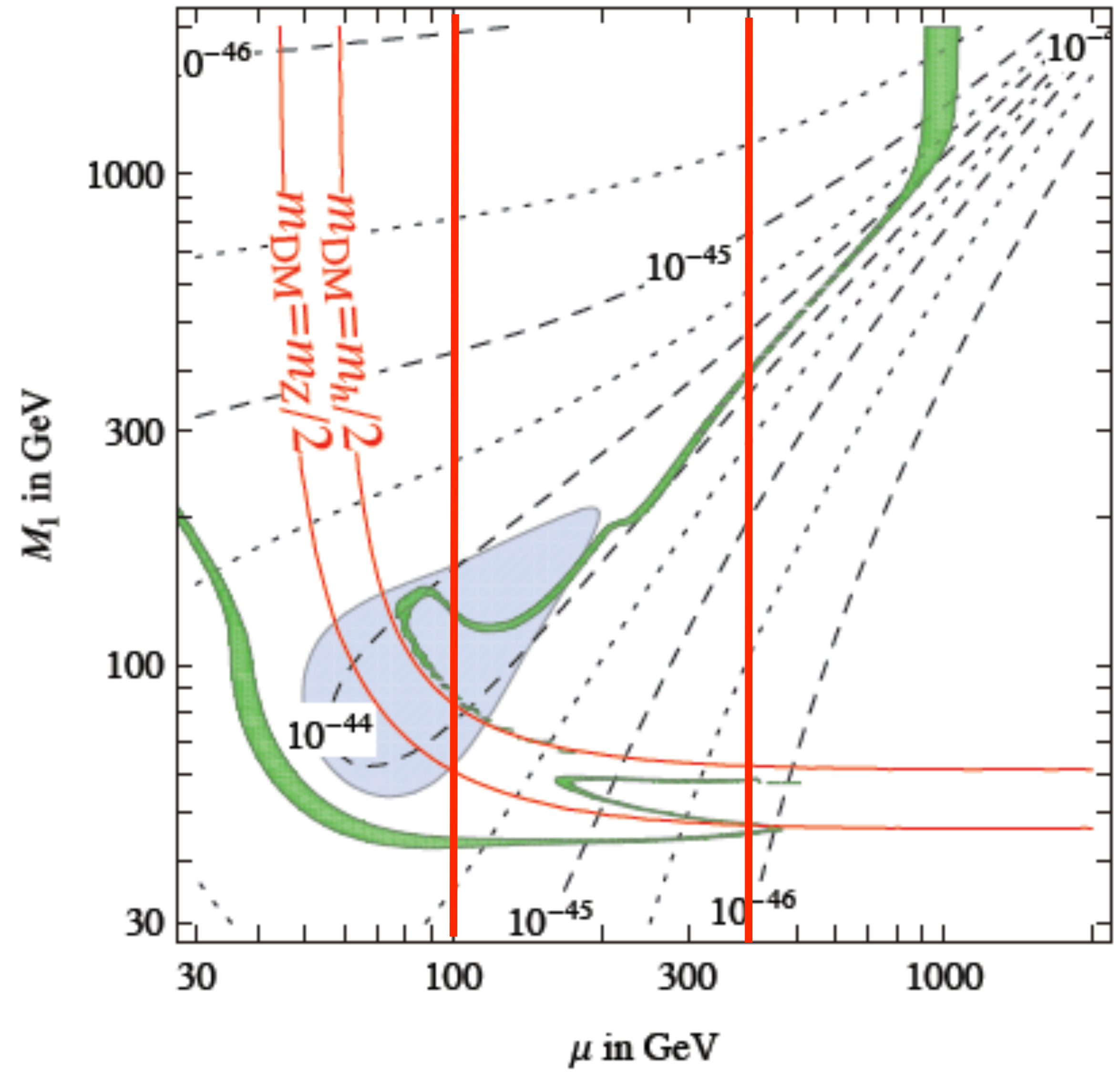

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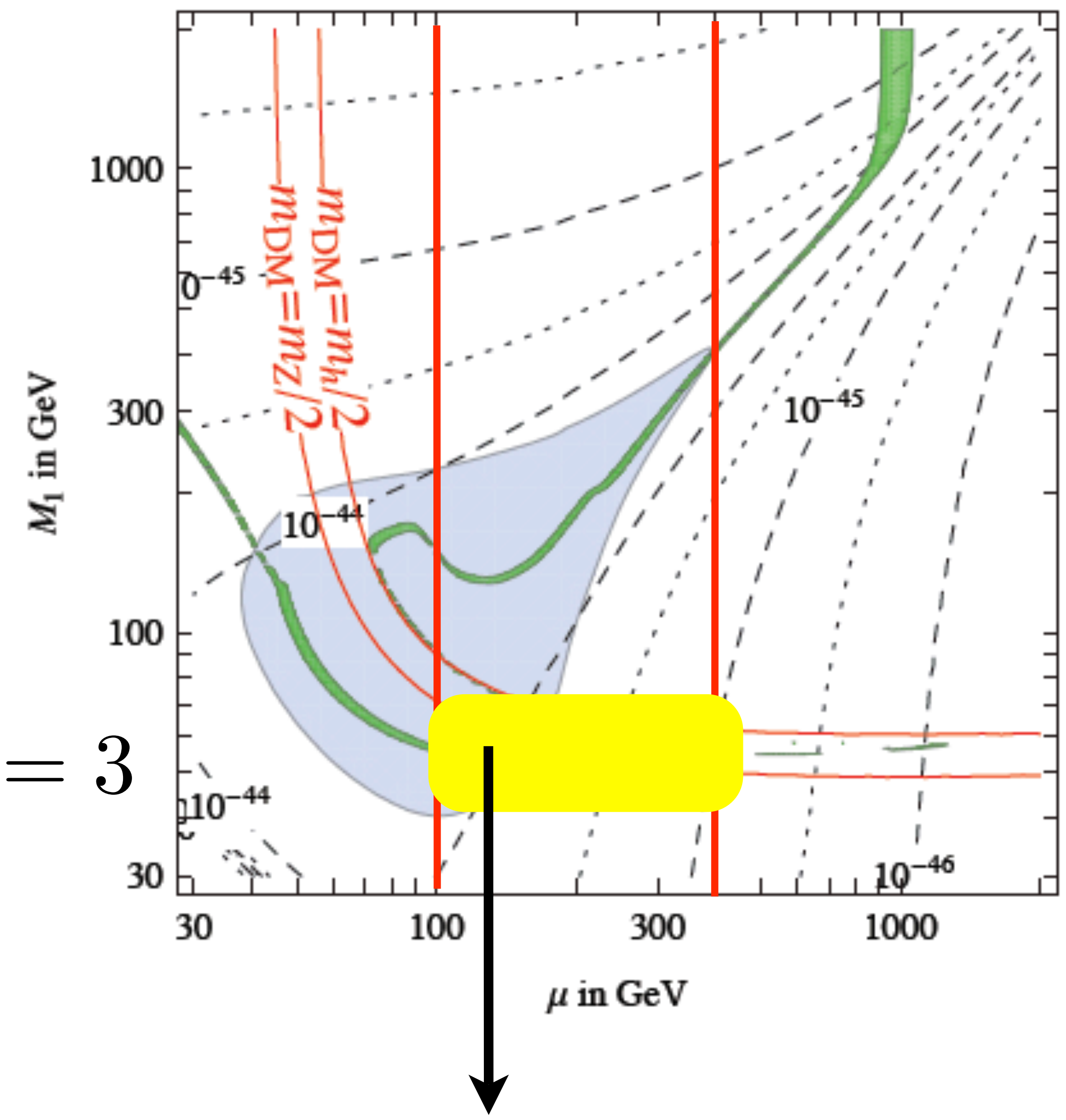

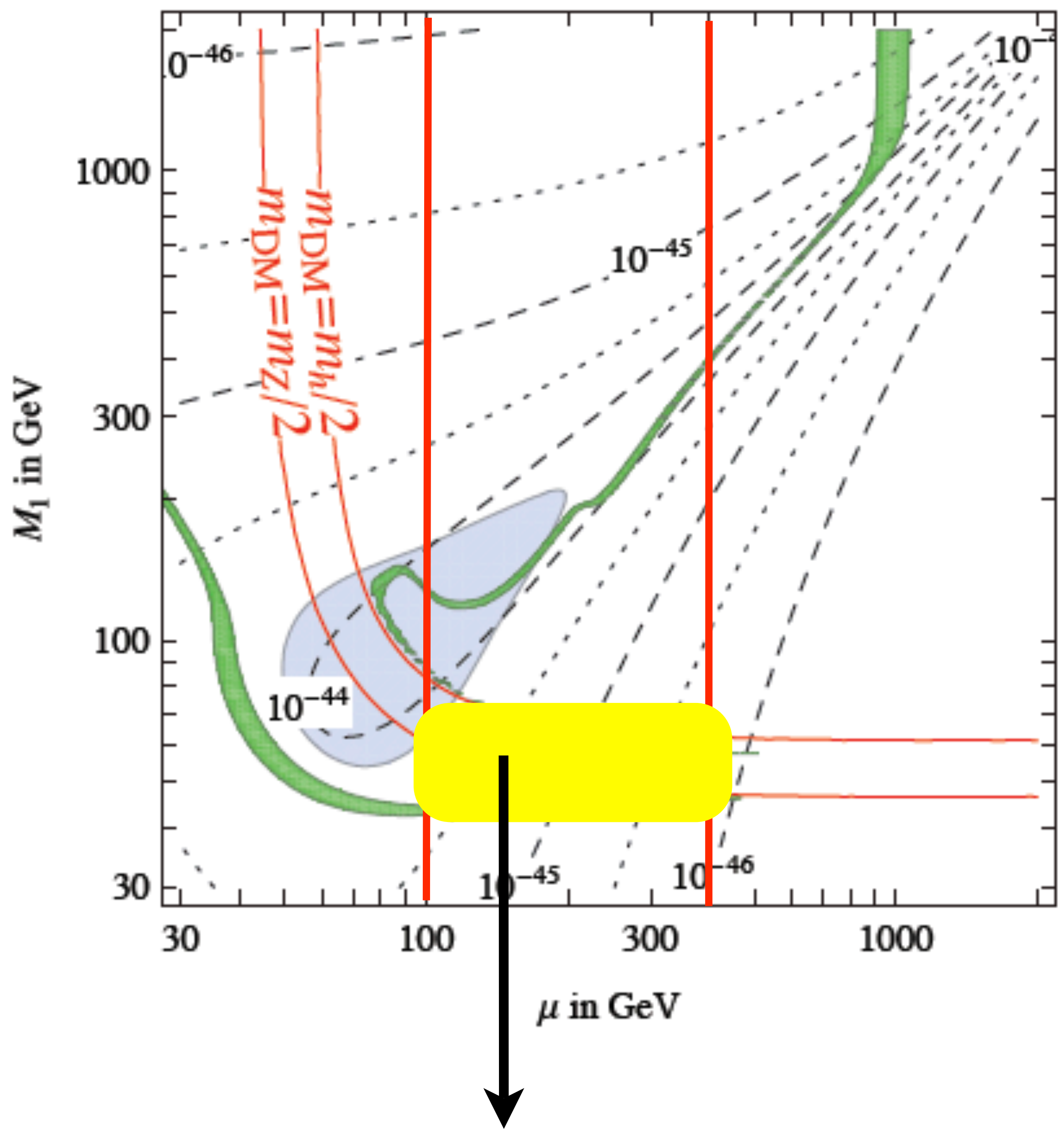

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Farina, Kadastik, Pappadopulo, Pata, Raidal, Strumia
1104.3572

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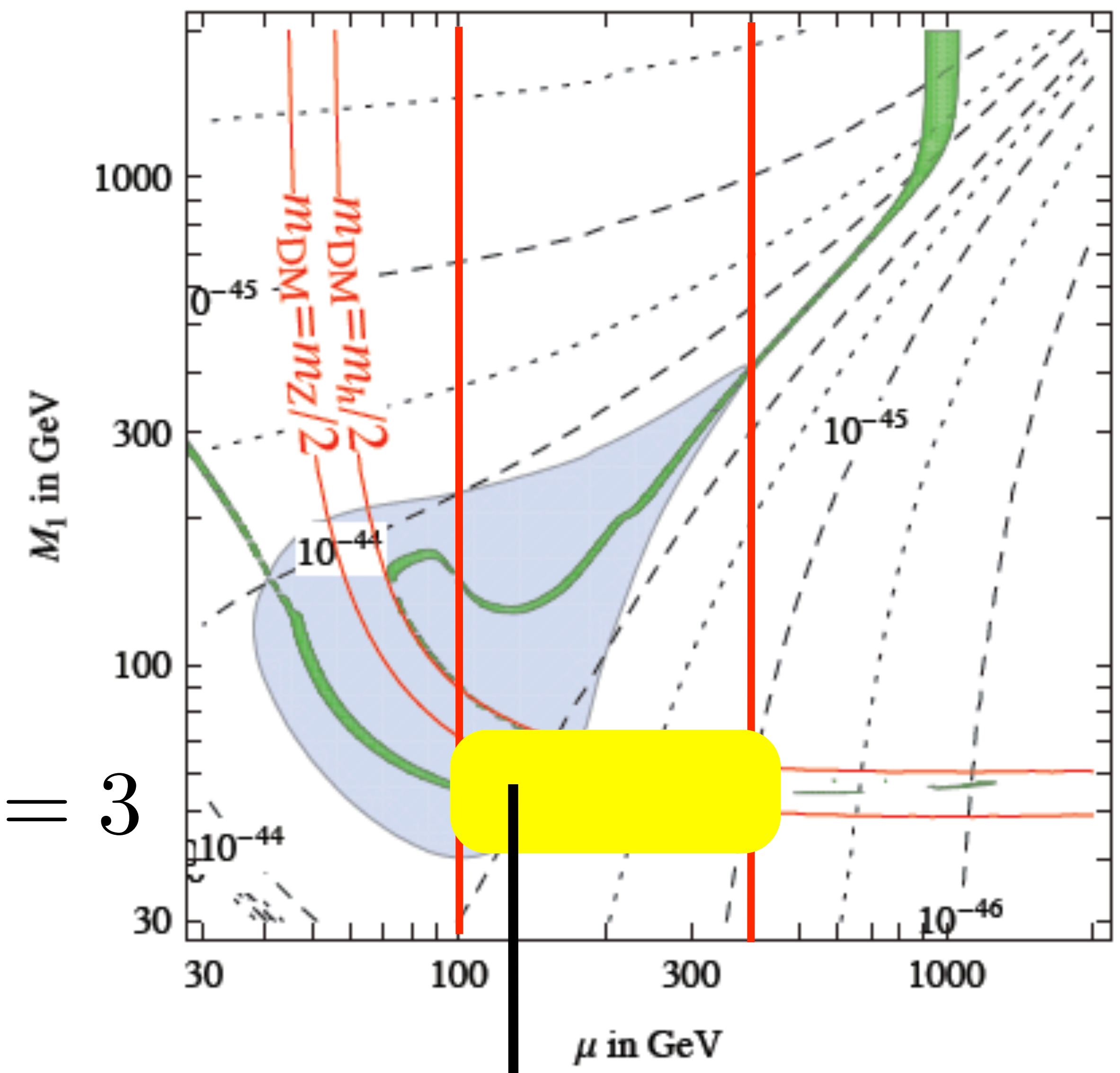

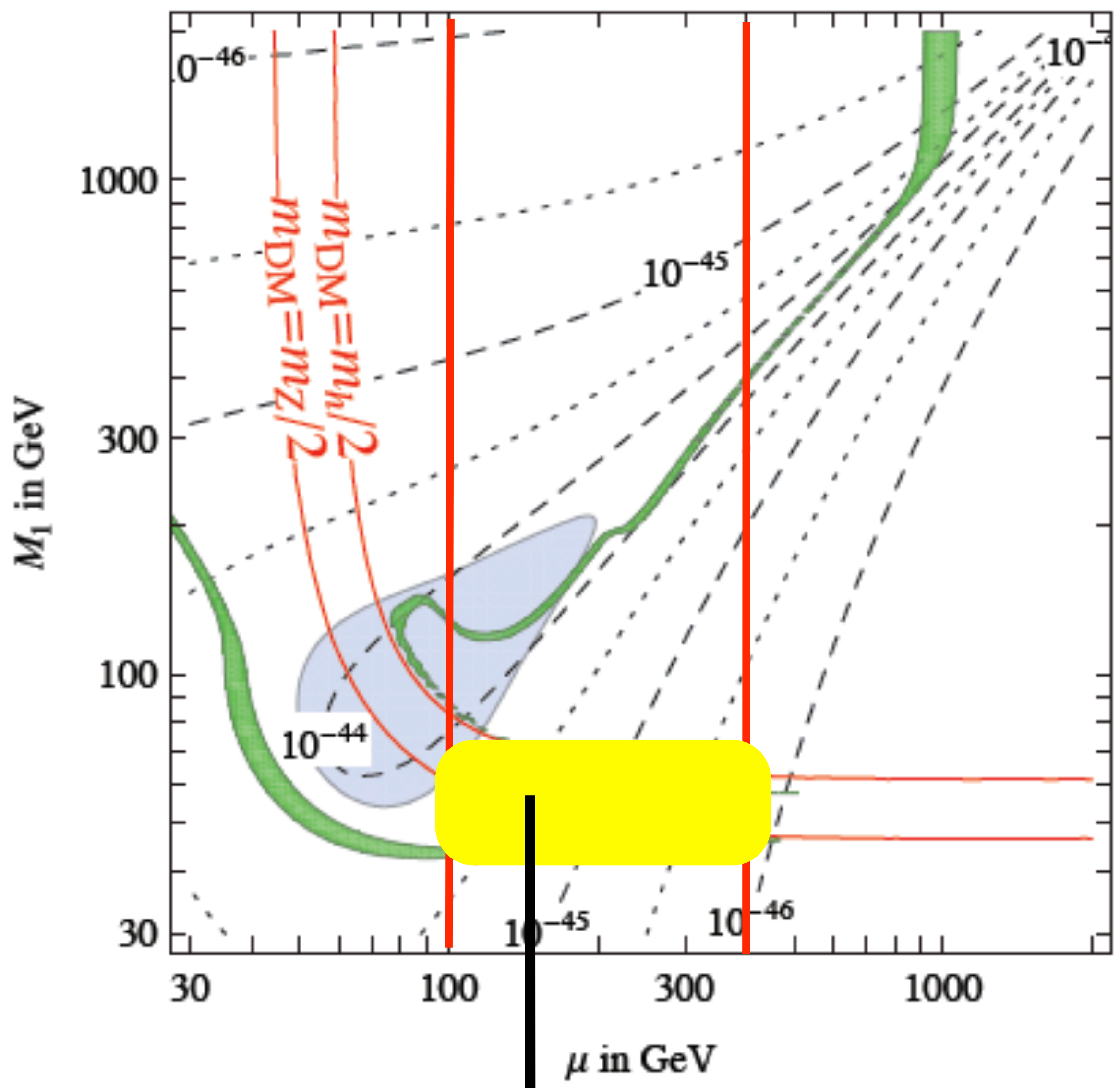

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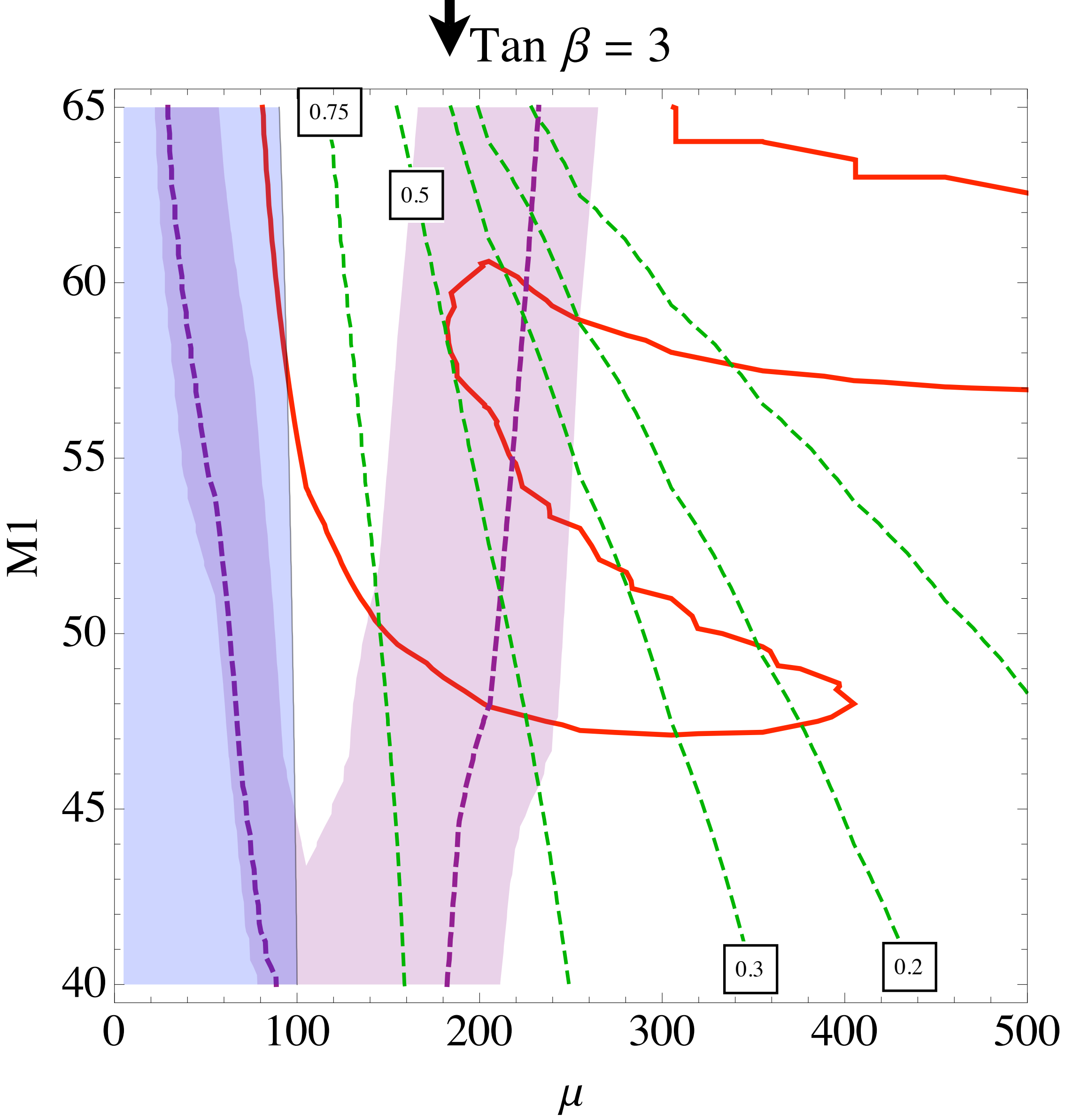
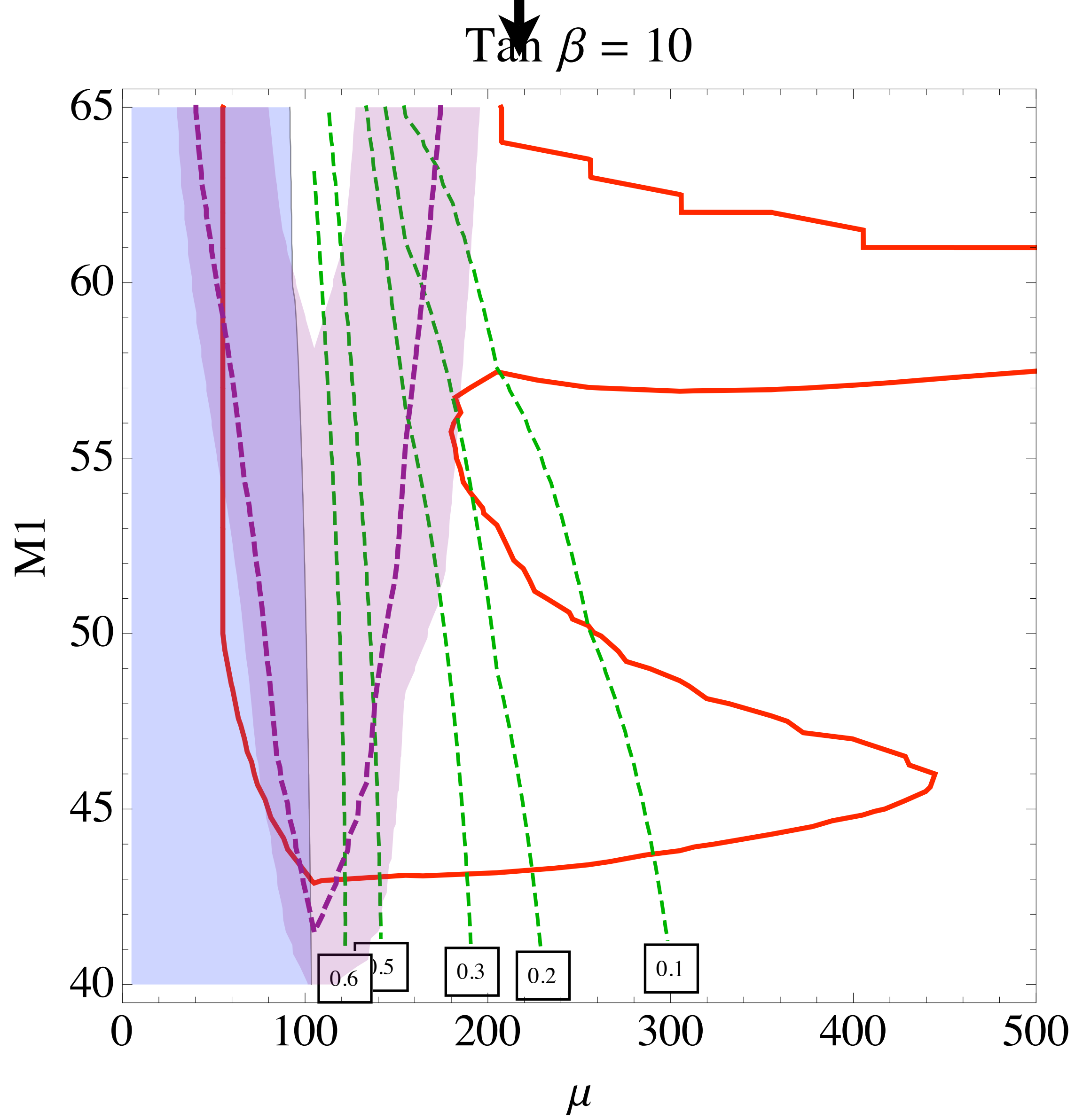
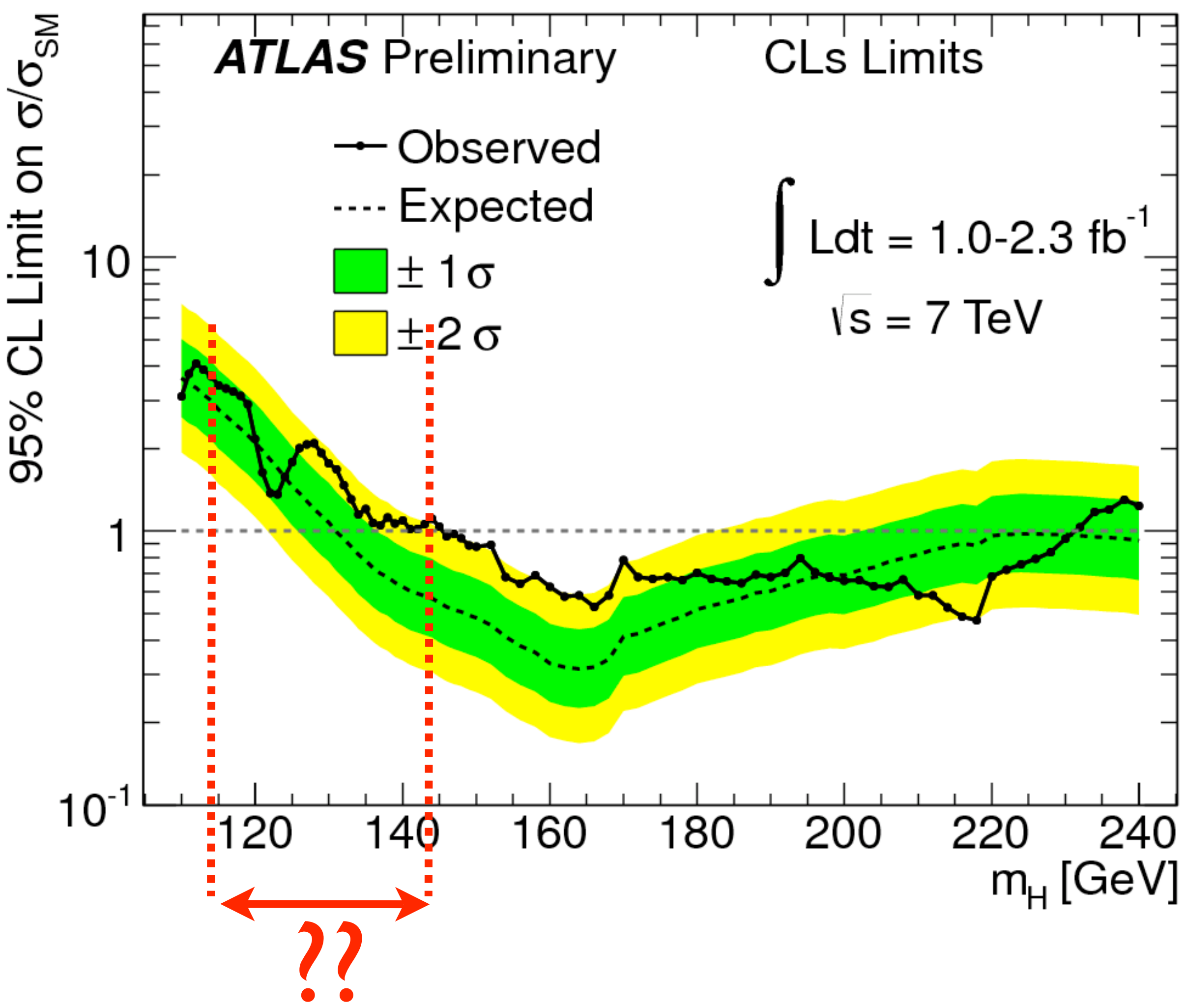
Farina, Kadastik, Pappadopulo, Pata, Raidal, Strumia 1104.3572





Gilly Elor, Lawrence Hall, David Pinner, Josh Ruderman

Is h in Light Window?



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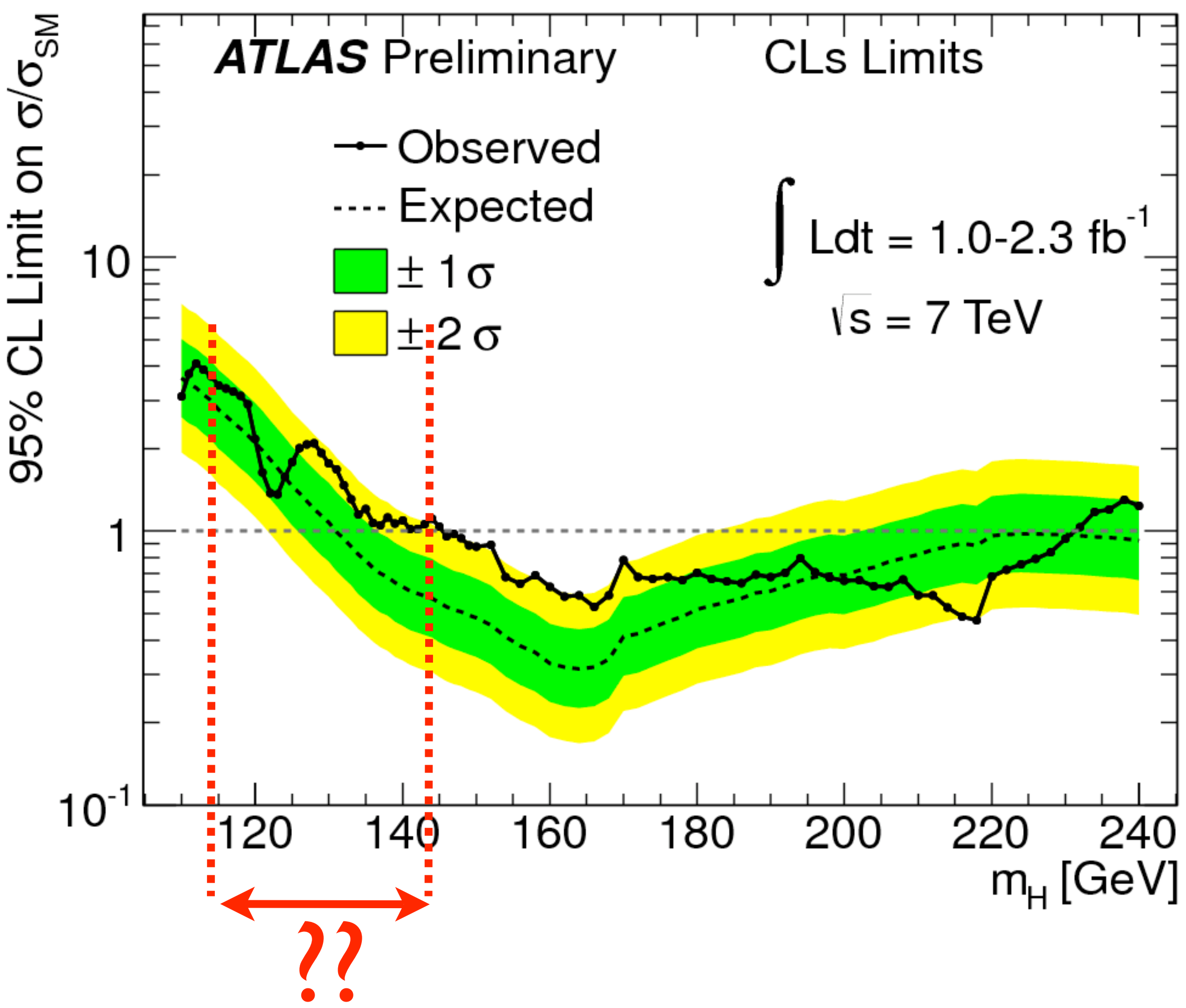

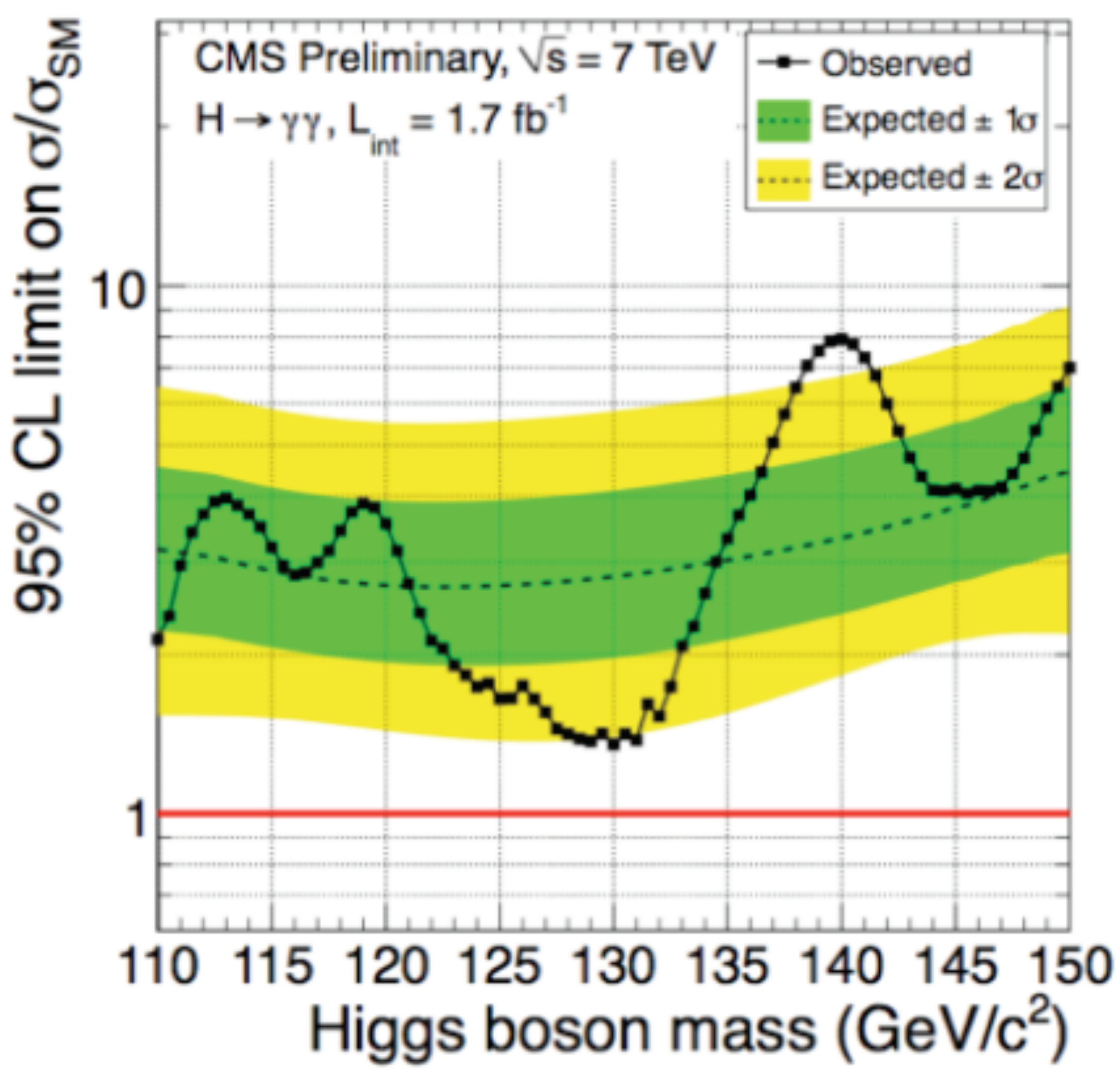

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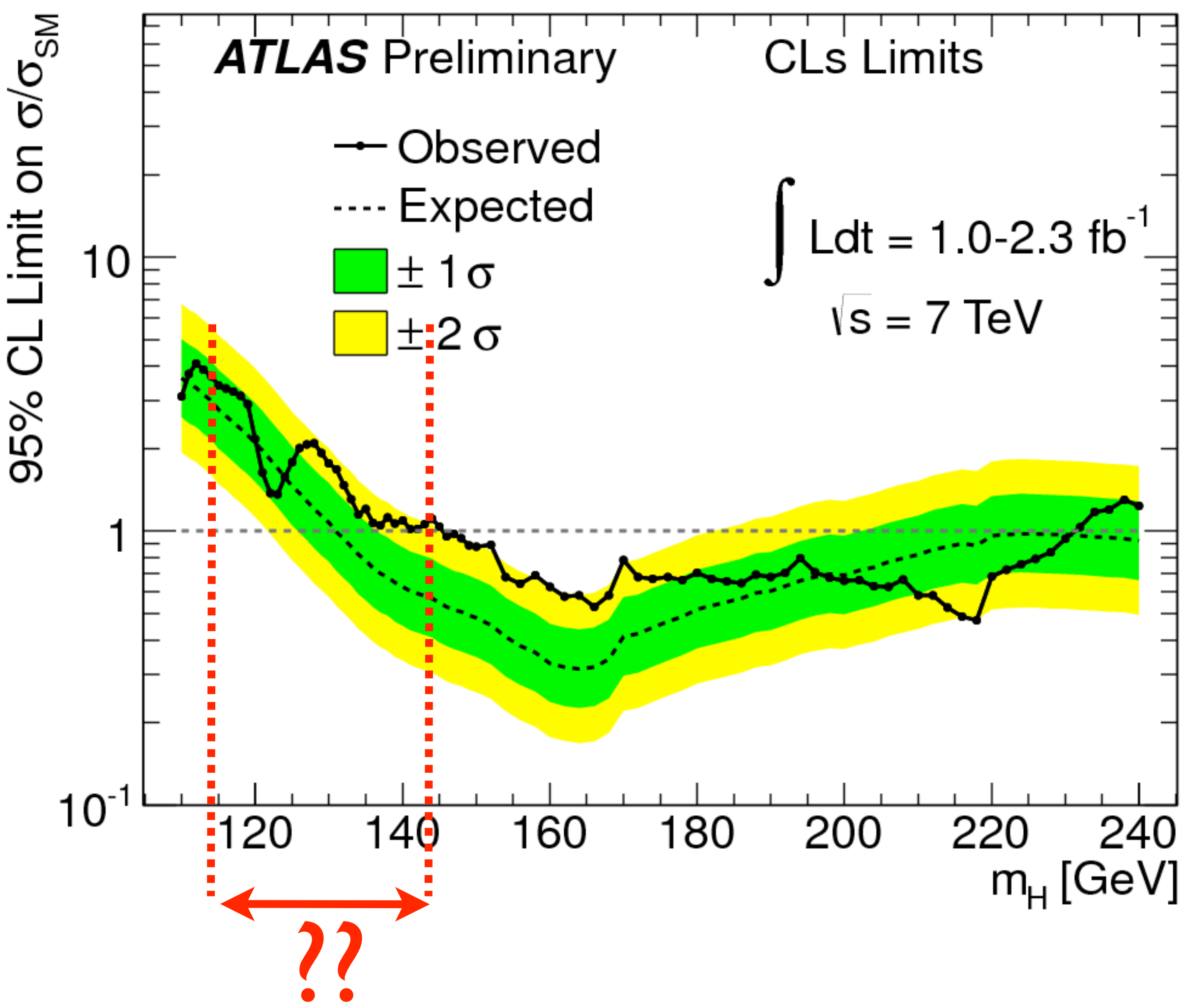
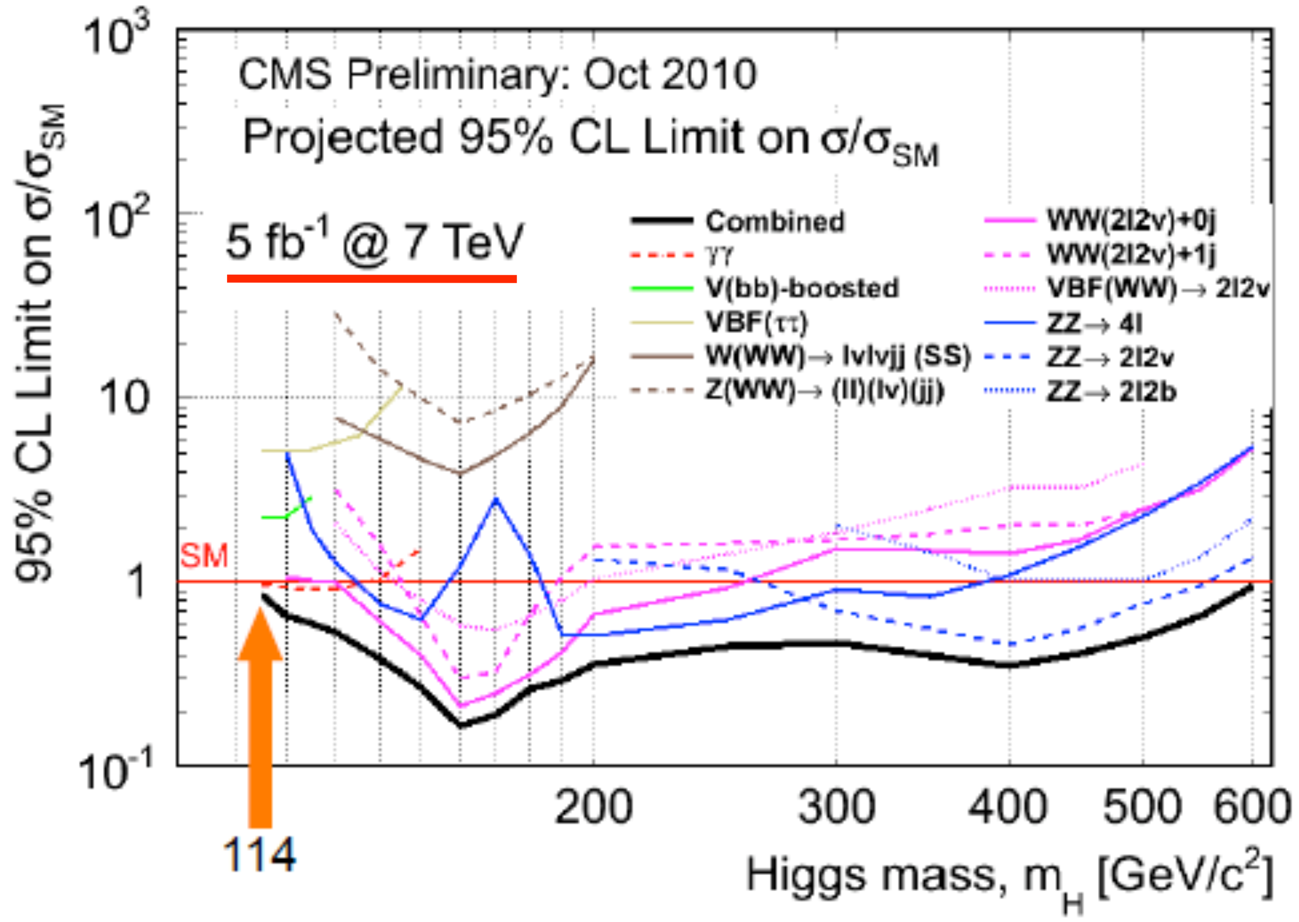
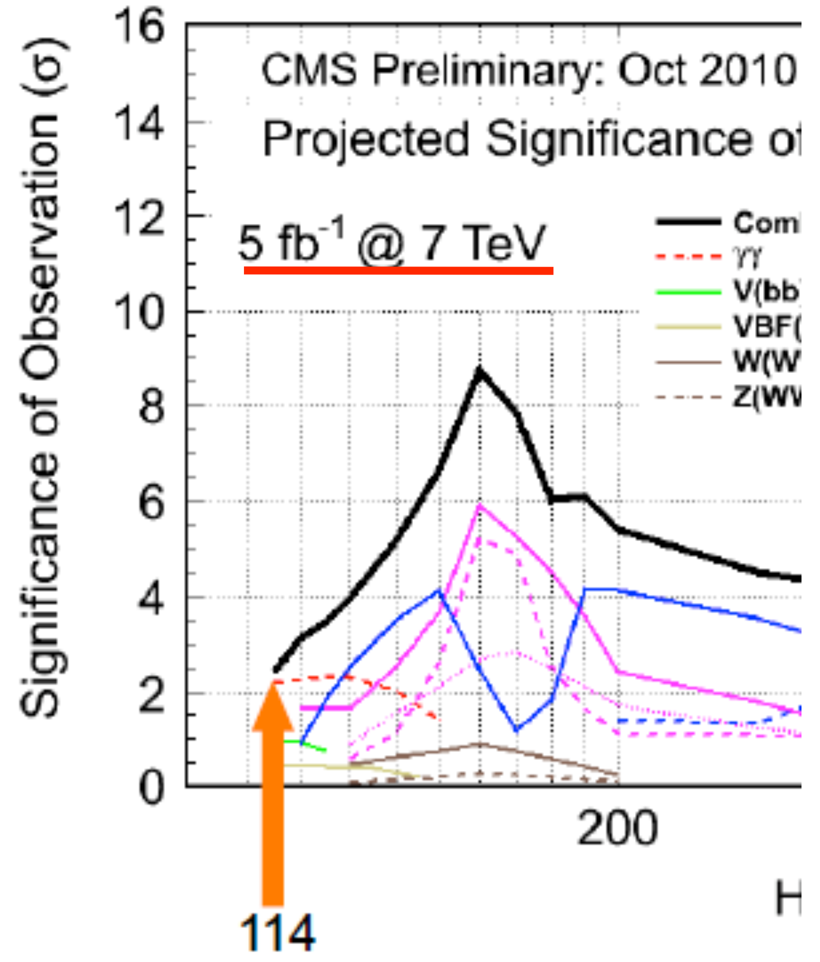
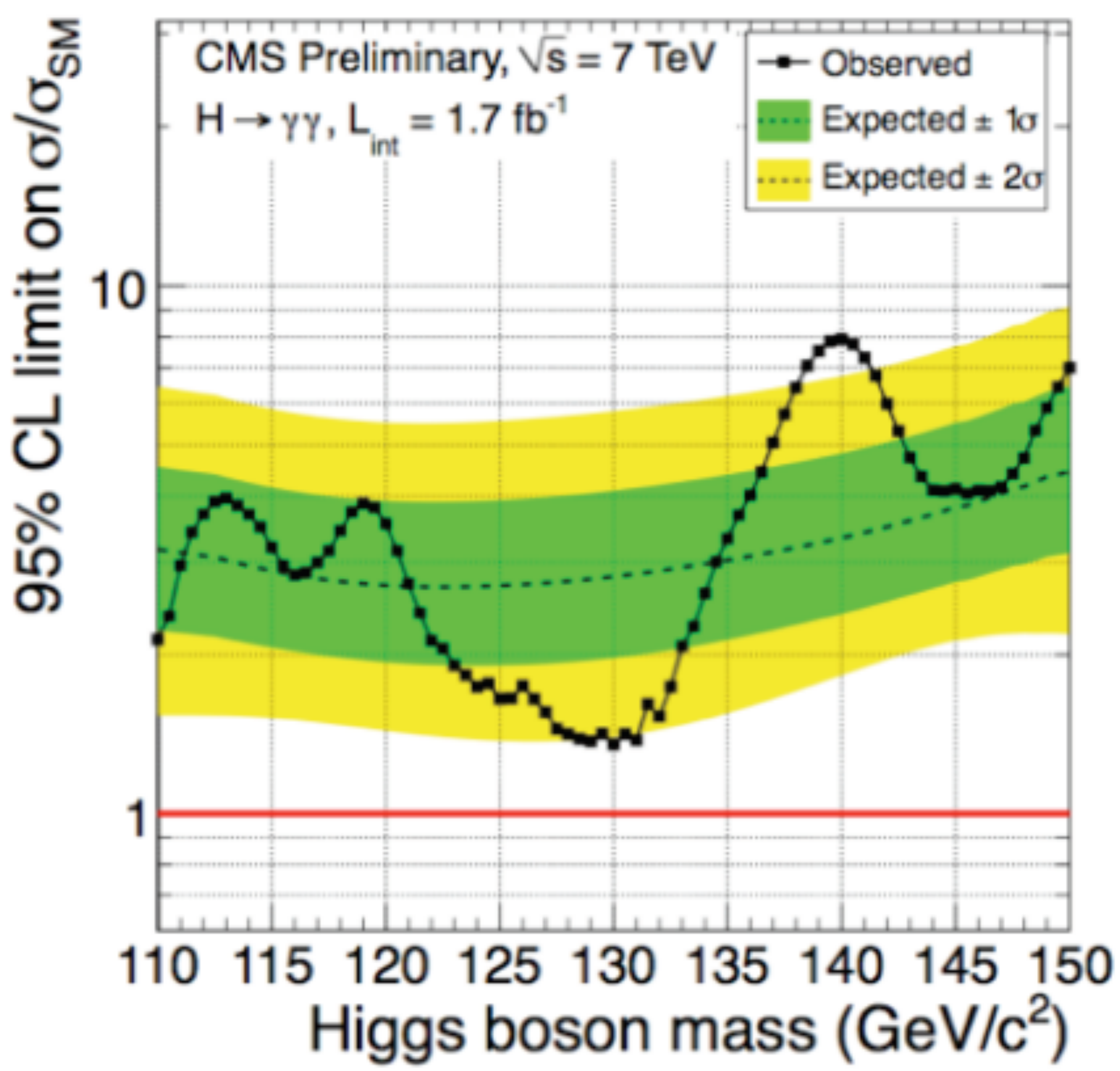


Limit?



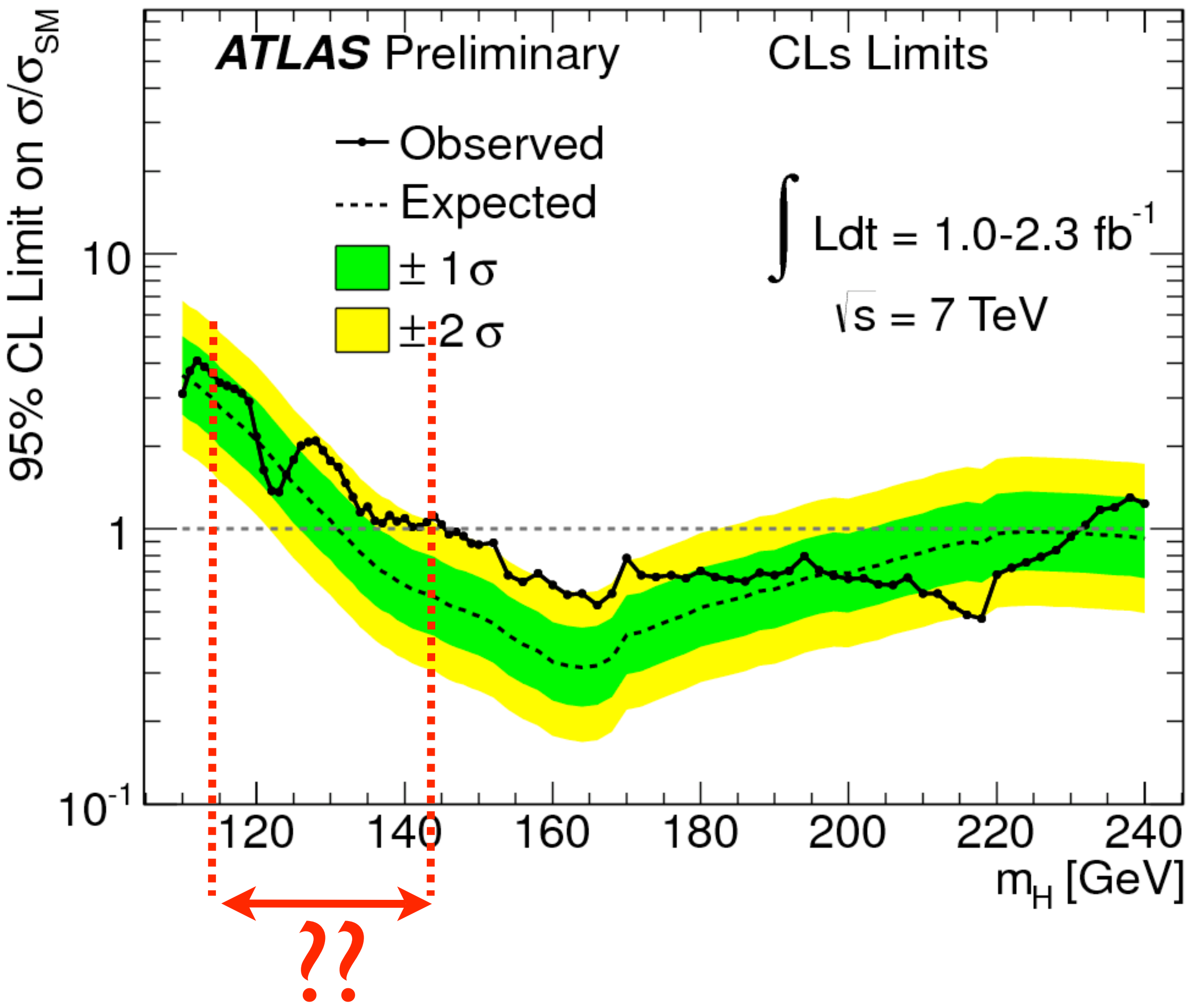
Hint?





Our Field Is Approaching a Defining Moment

Is h in Light Window?



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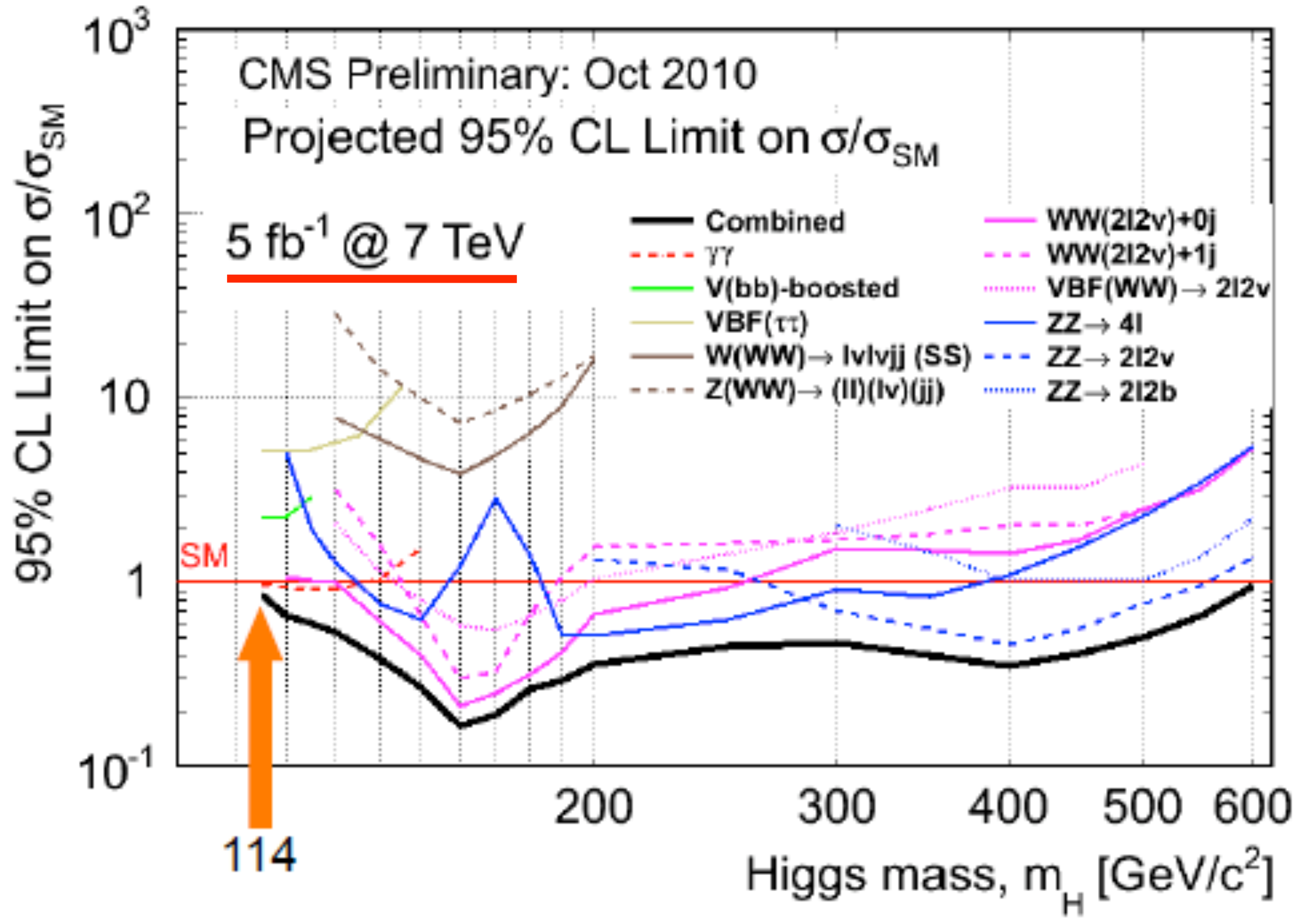

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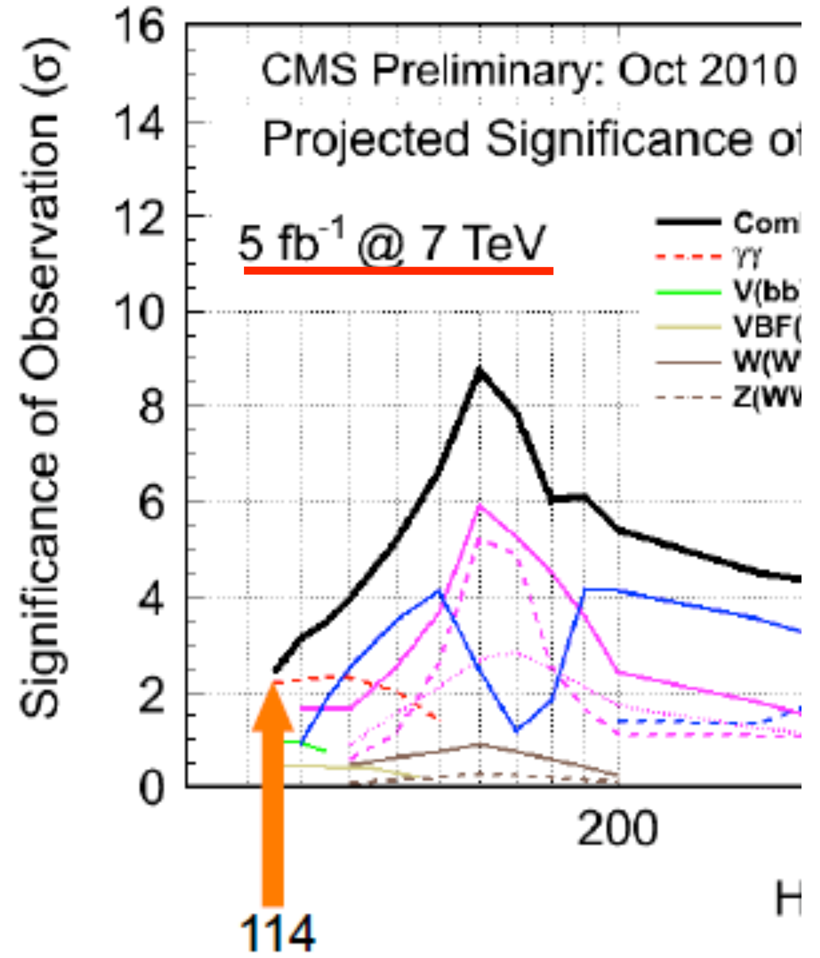
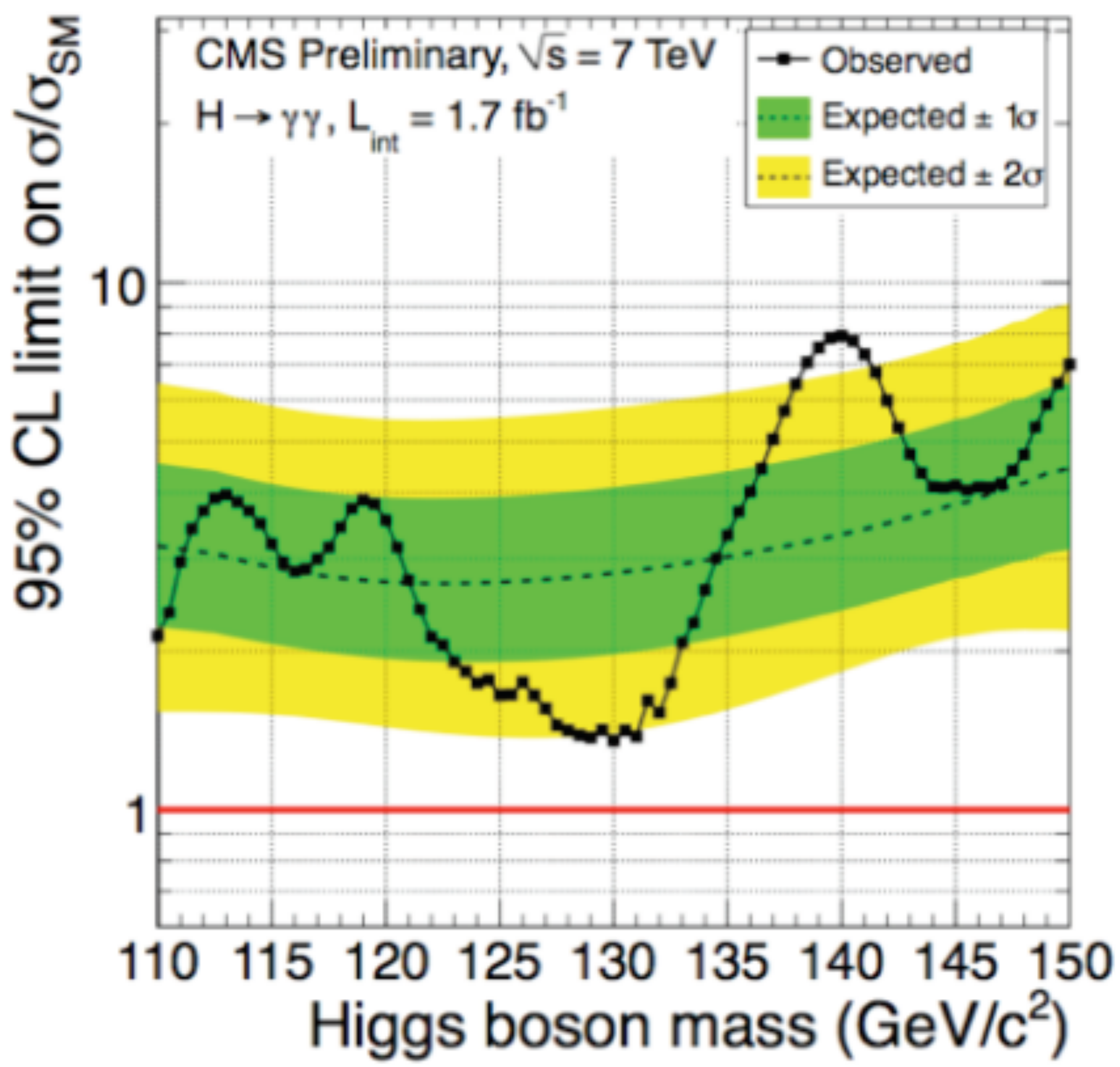


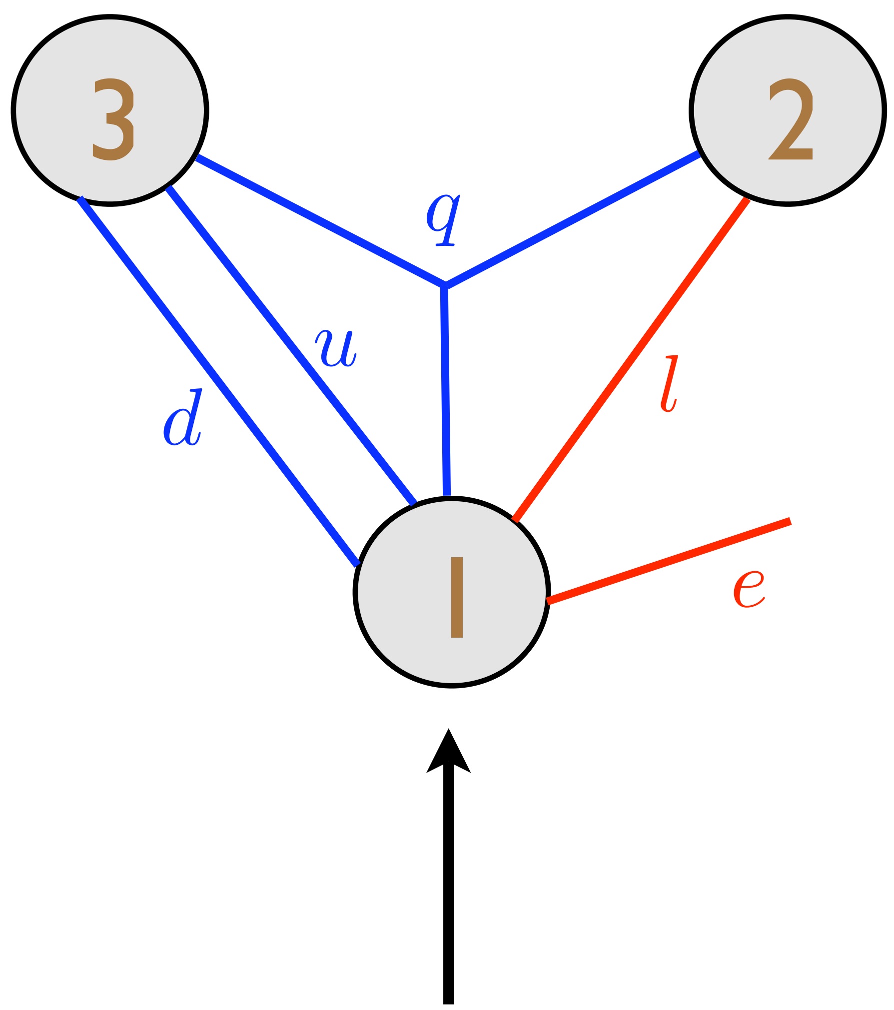


Our Field Is Approaching a Defining Moment

	Yes	No
SM (1 Higgs)	Alive	Excluded
SUSY	Look for deviations from h_{SM}	H $\tilde{t}$ $\tilde{\chi}$ light $\lambda S H_u H_d$ large

CONCLUDE:

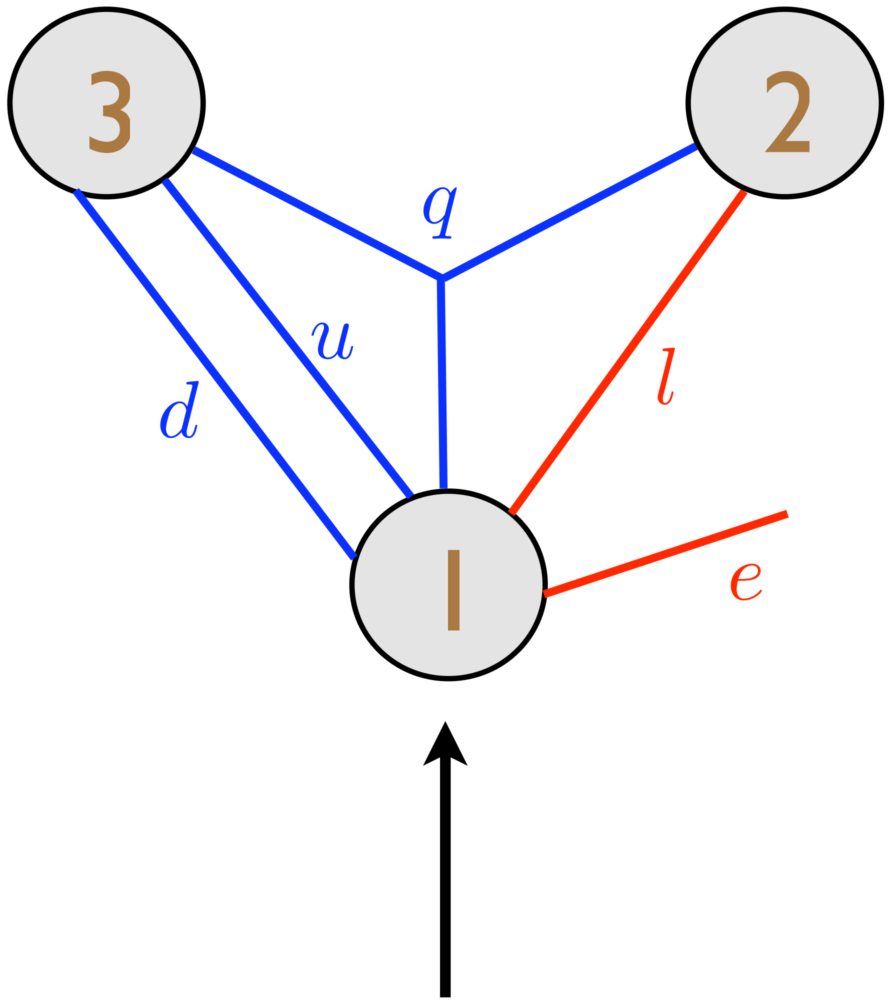
The Excitement of the LHC



Origin and scale of
EW Symmetry Breaking

CONCLUDE:

The Excitement of the LHC



Origin and scale of
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Contenders:

Weak scale supersymmetry

New strong dynamics

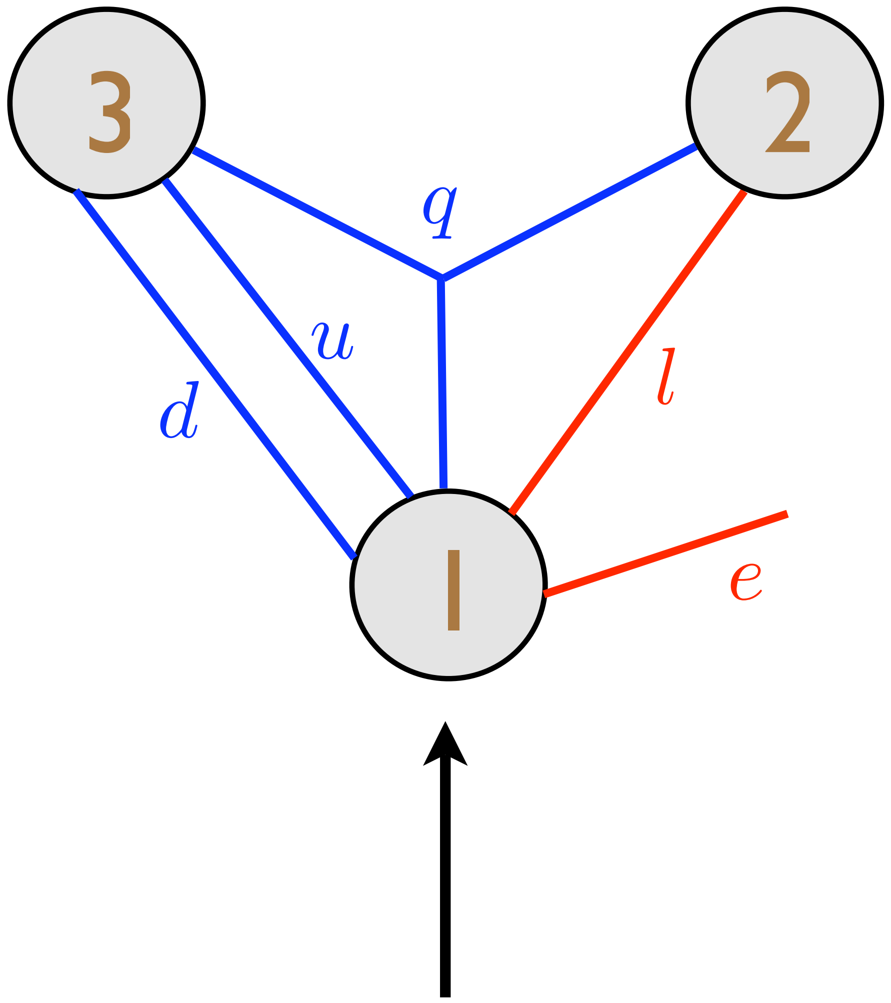
Multiverse

Large Extra Dimensions

We really don't know!

CONCLUDE:

The Excitement of the LHC



Origin and scale of
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Contenders:

Weak scale supersymmetry

New strong dynamics

Multiverse

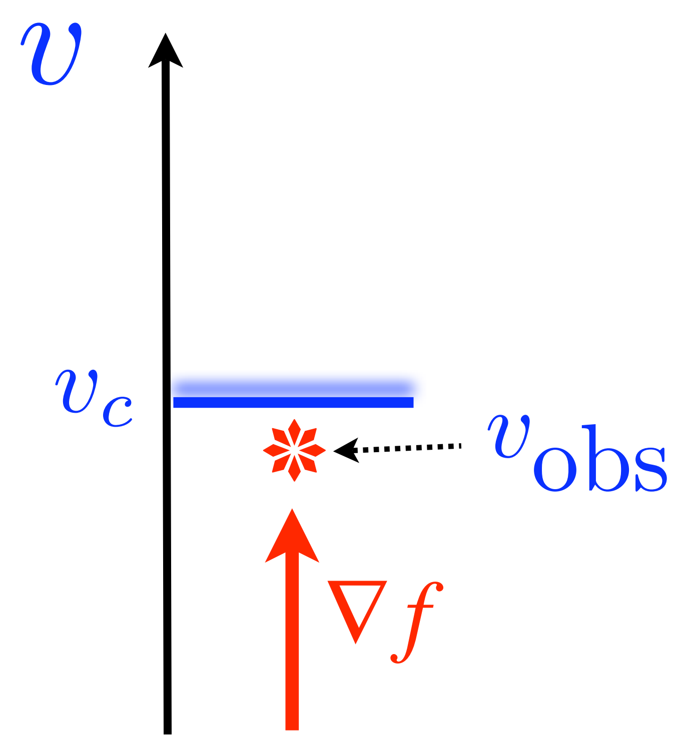
Large Extra Dimensions

We really don't know!

Supersymmetry will be probed deeply
in the coming months and years.
It may take a while.

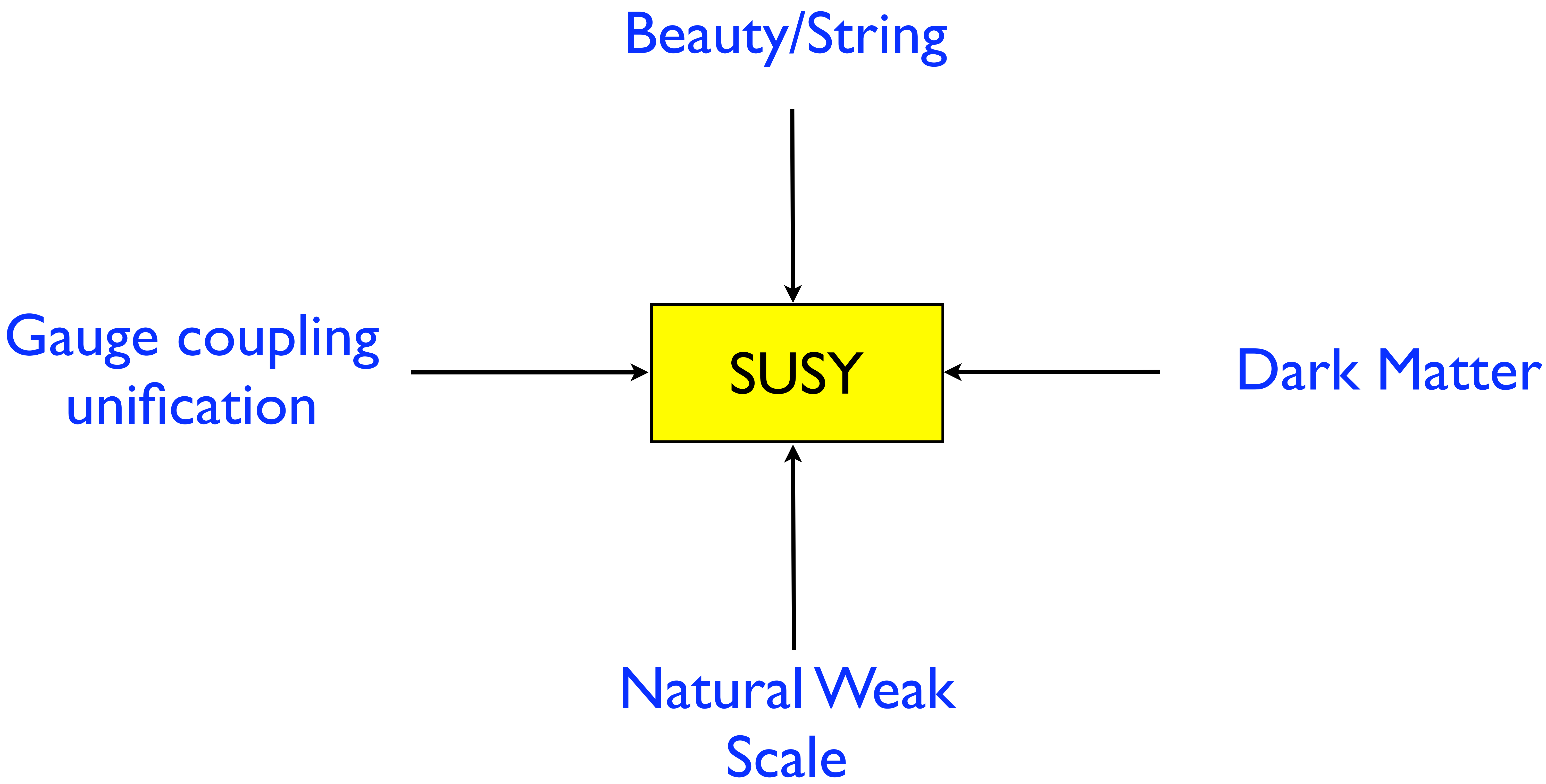
IV

Multiverse



v_{obs} near v_c

Motivation for Supersymmetry



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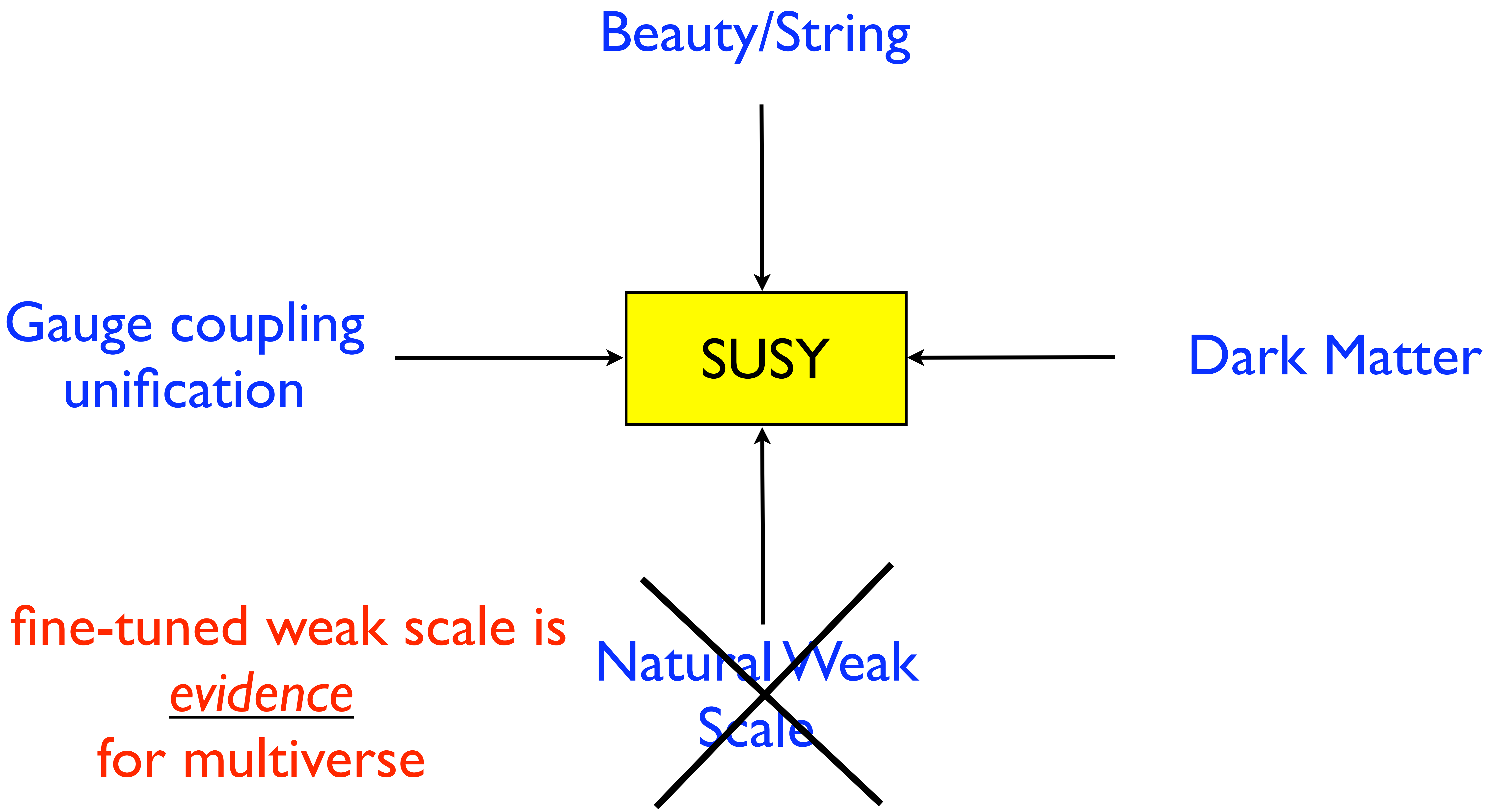

A fine-tuned weak scale is
evidence
for multiverse

$$\tilde{m} \gg v$$

The Higgs Mass Prediction

$\tilde{m} \gg v$

Some superpartners at weak scale?

Yes (fermionic): Split Supersymmetry

Arkani-Hamed, Dimopoulos, hep-th/0405159

WIMP DM

No: High-Scale Supersymmetry

Hall. Nomura arXiv:0910.2235

Axion DM

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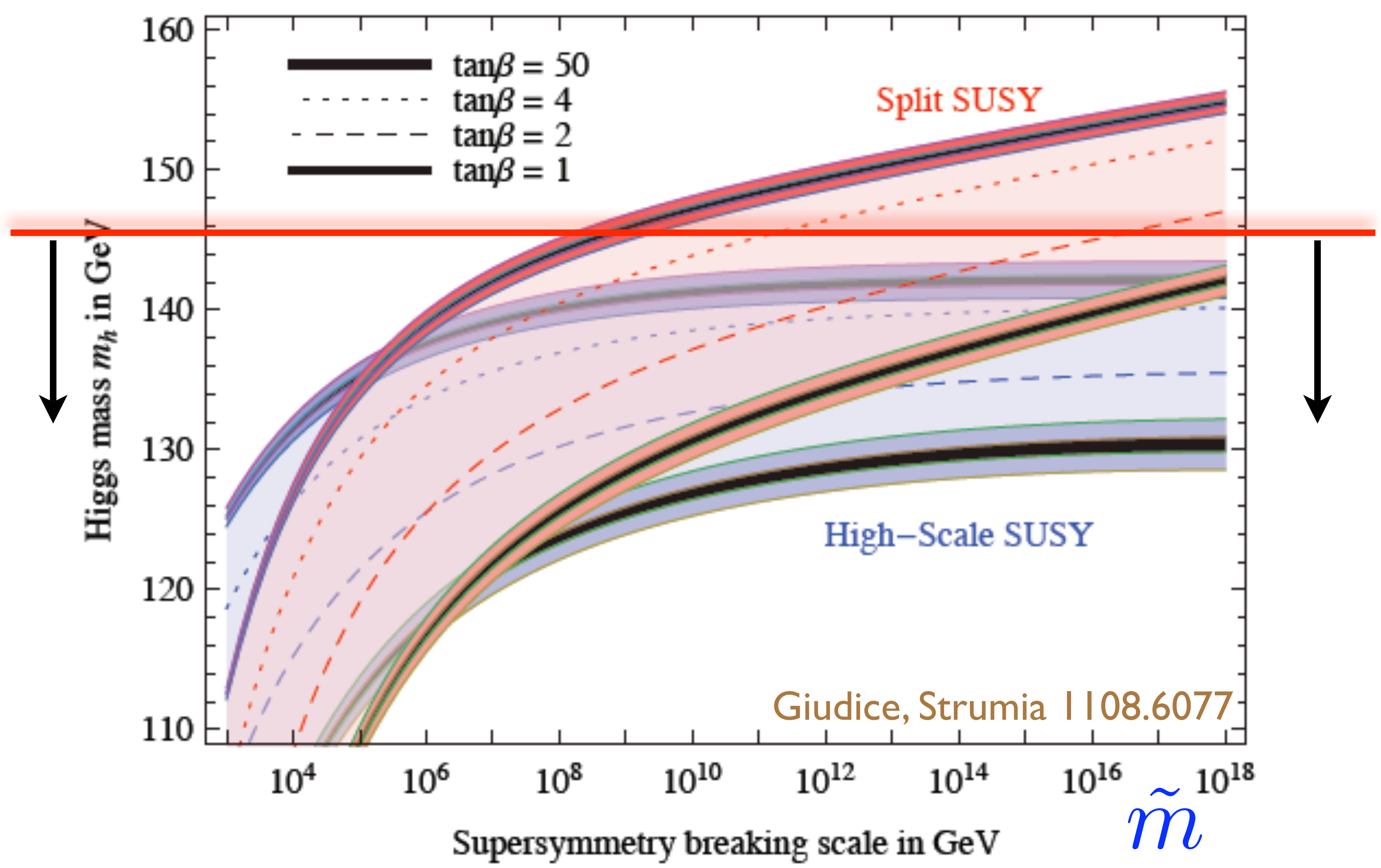

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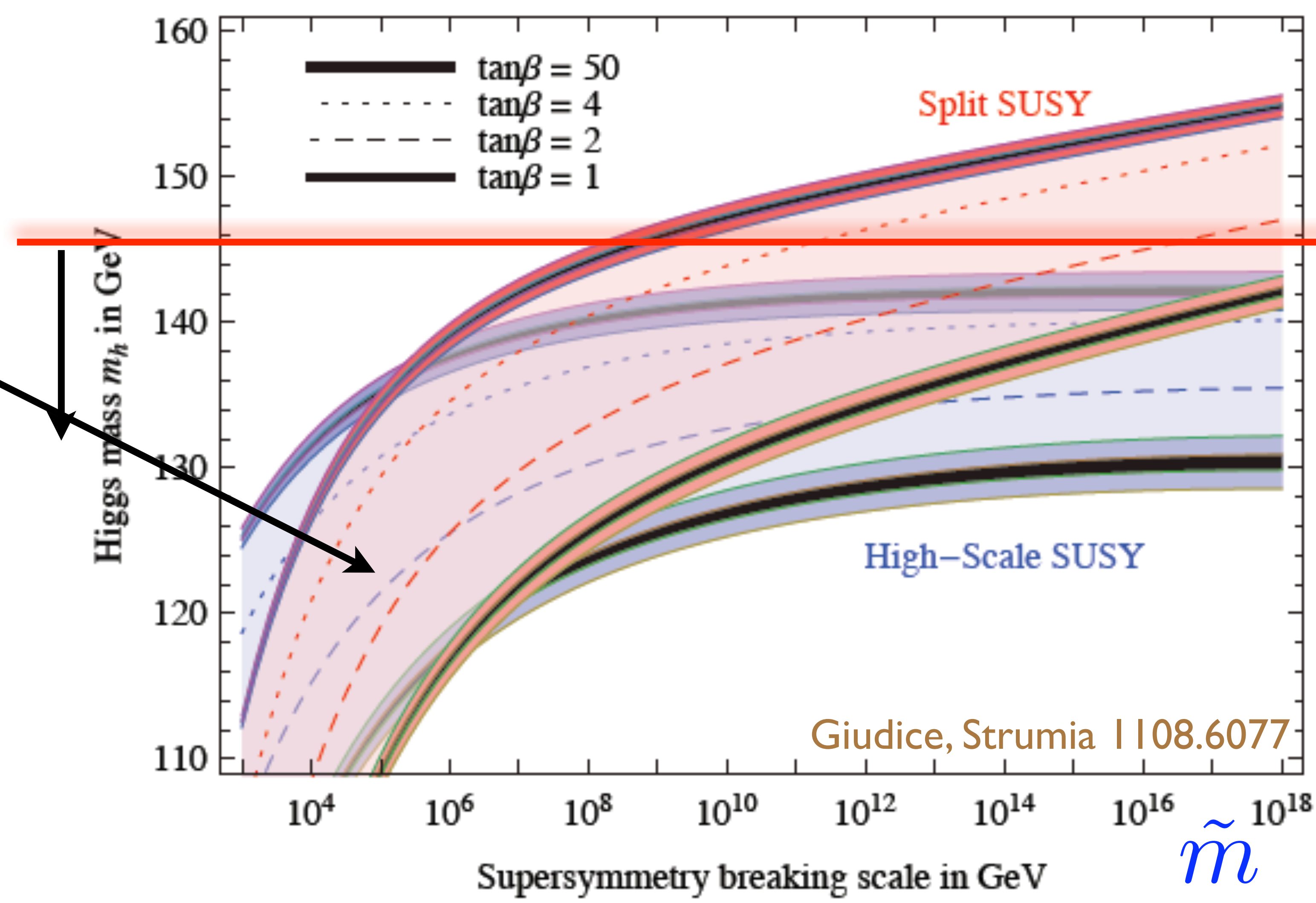
Hall. Nomura arXiv:0910.2235

Axion DM

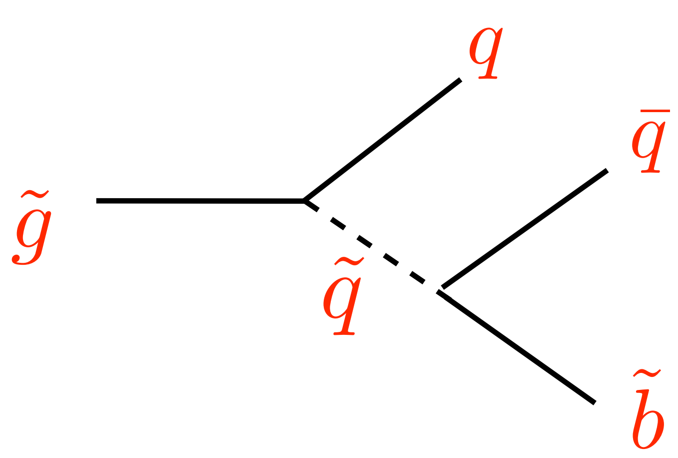
Hard to hide the Higgs:

no h/H mixing

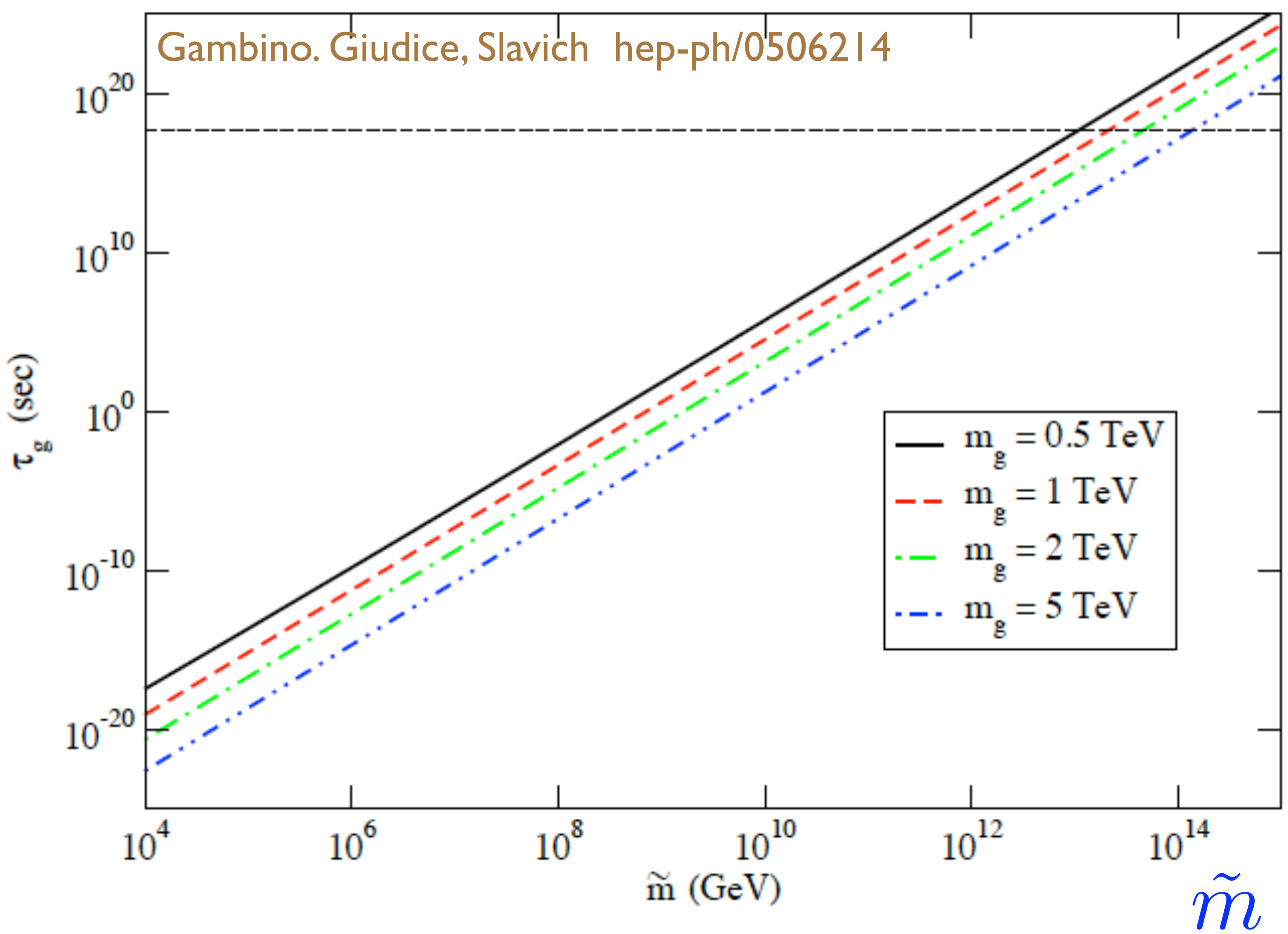
no h production from squark loop



Long-Lived Gluinos In Split SUSY



$\tilde{m} \gg v$



$\tilde{m}$

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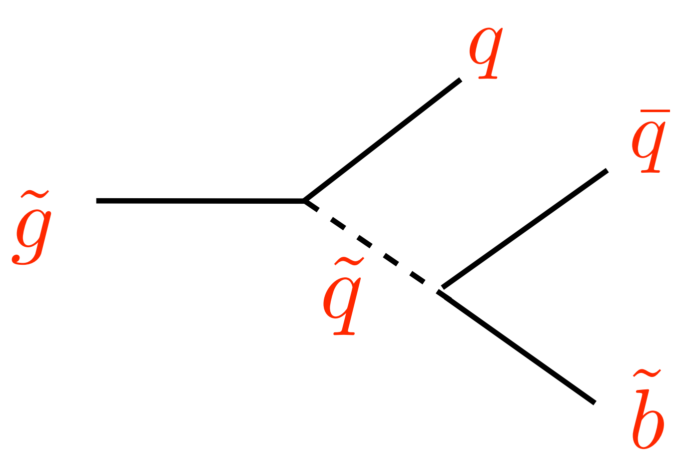

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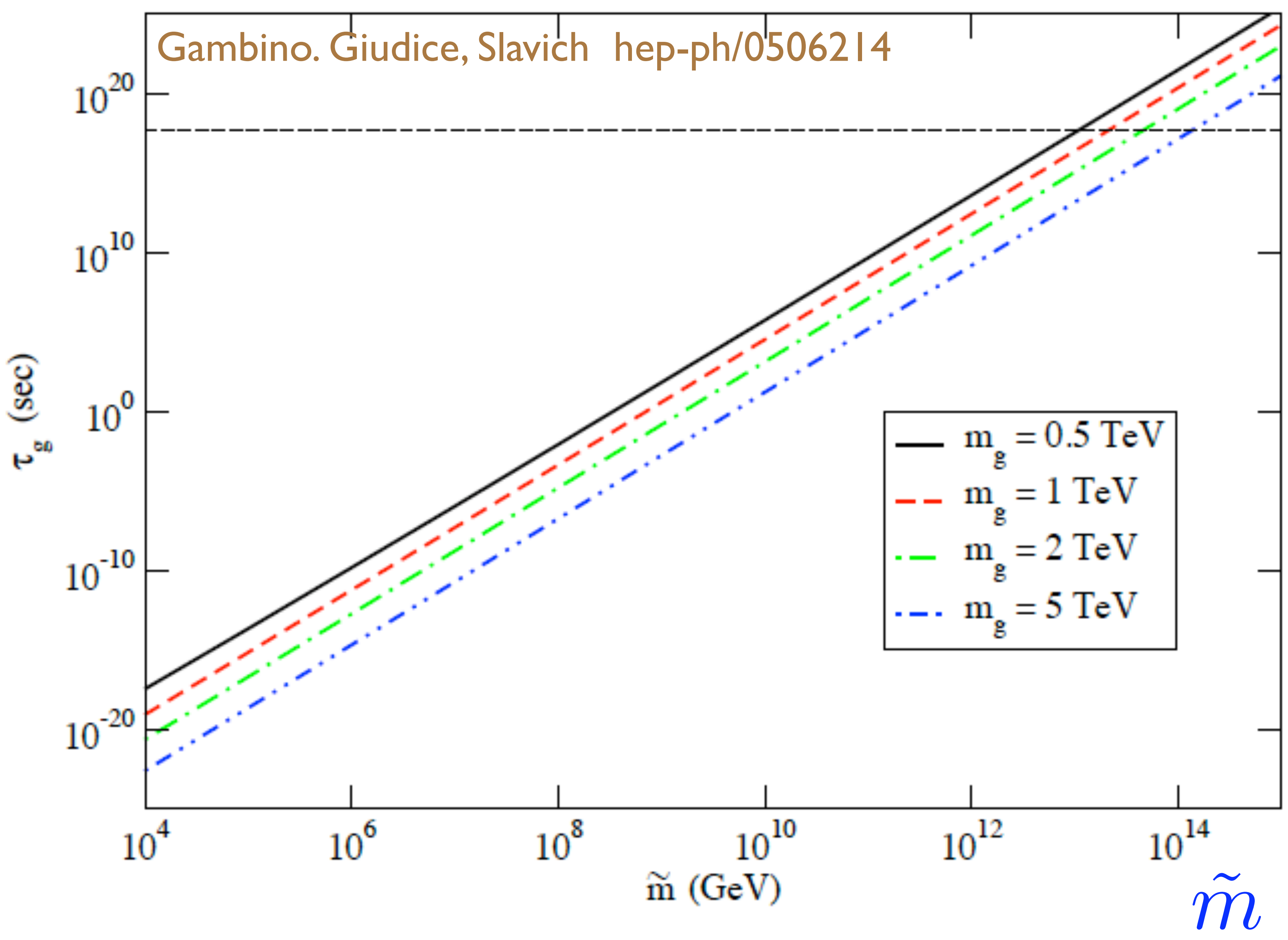

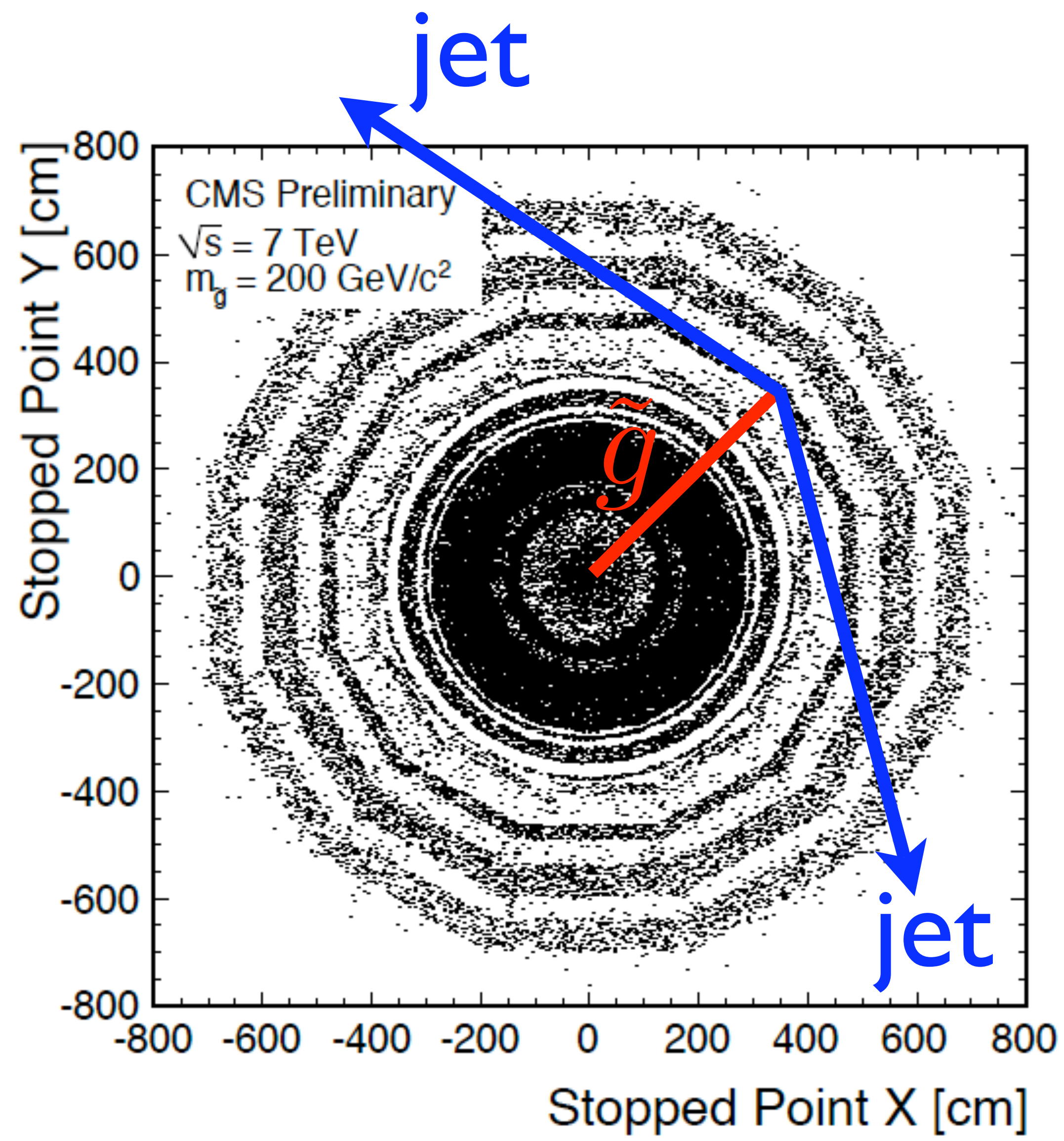

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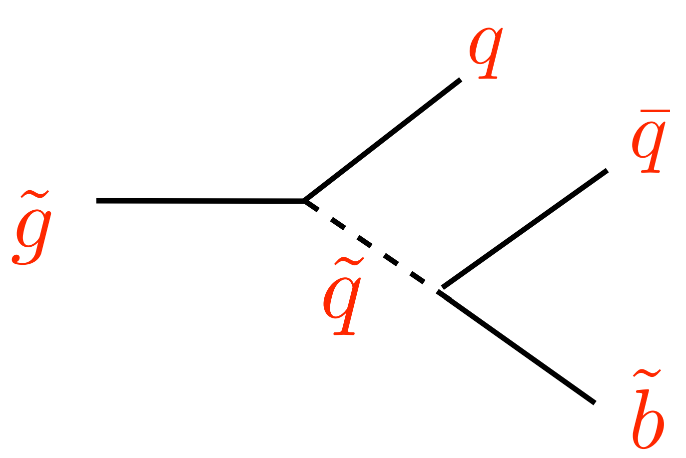

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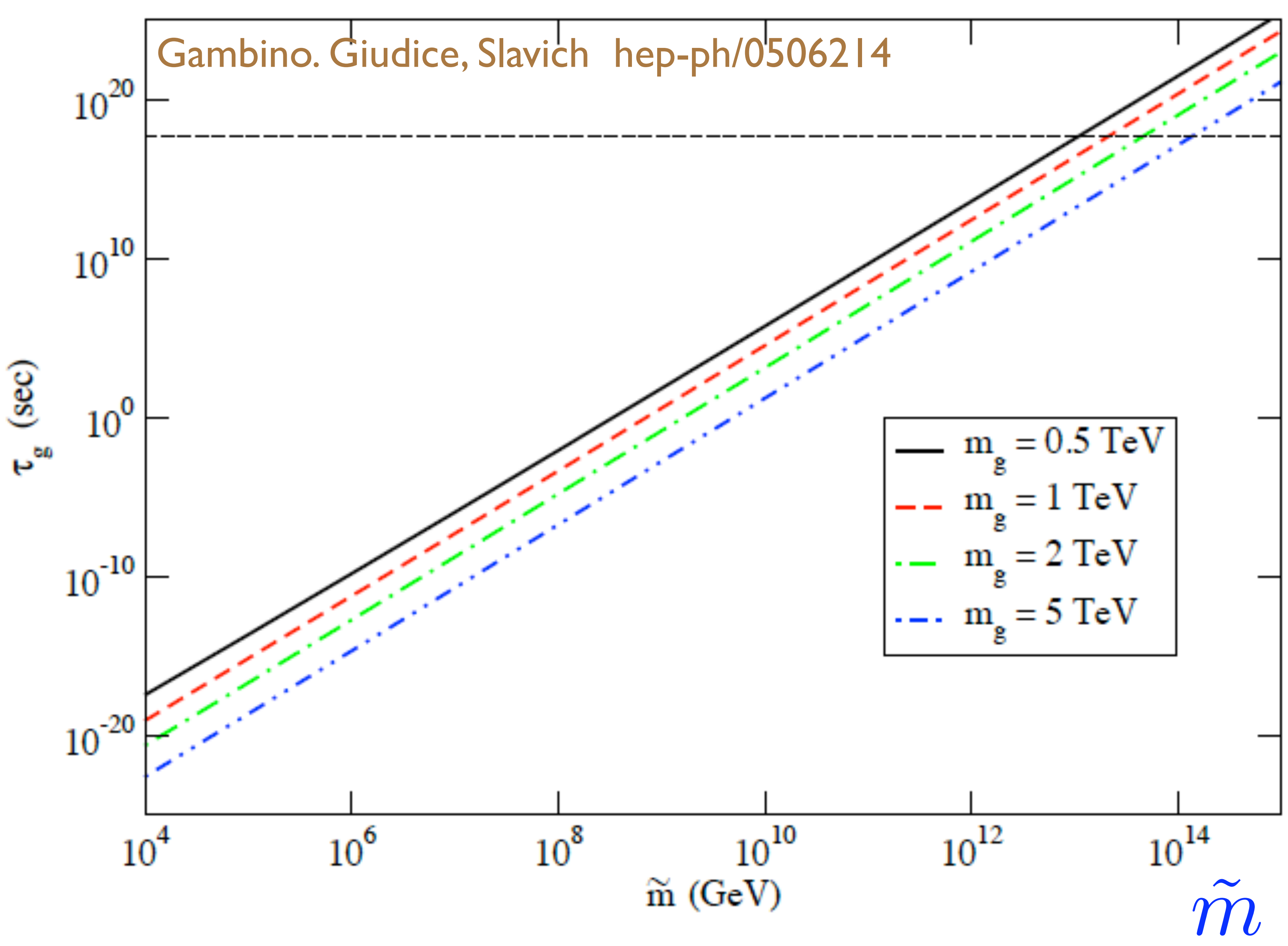

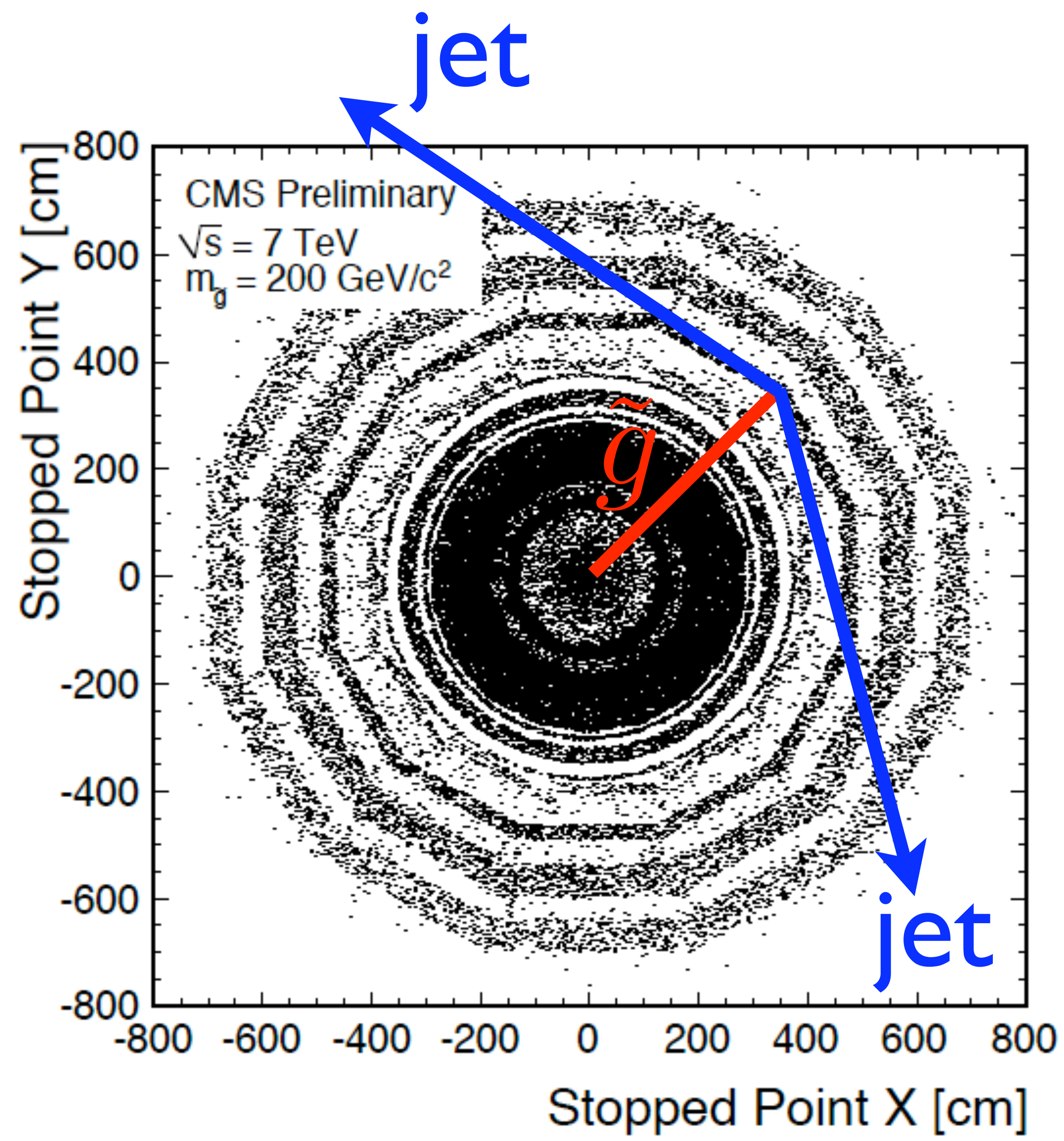

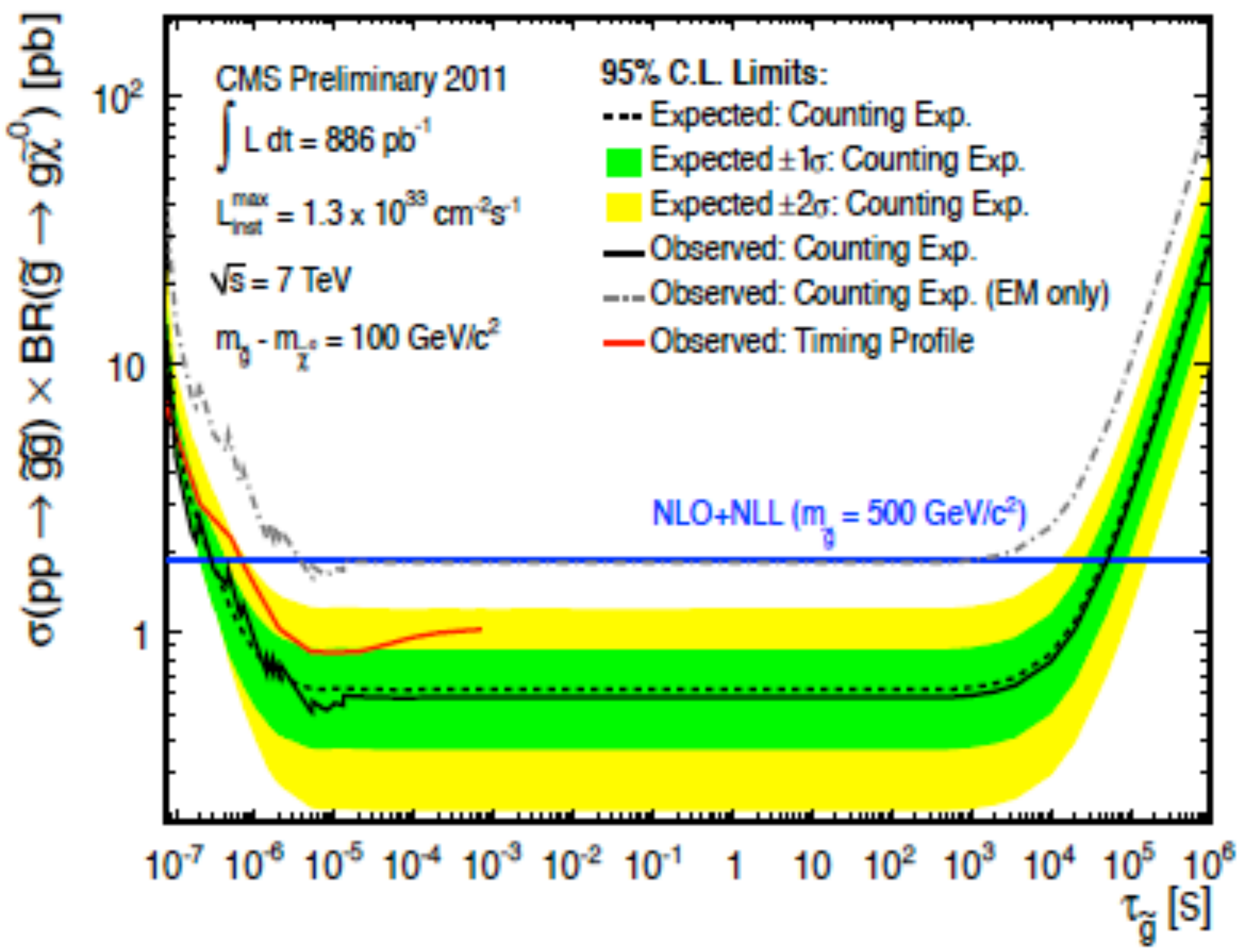

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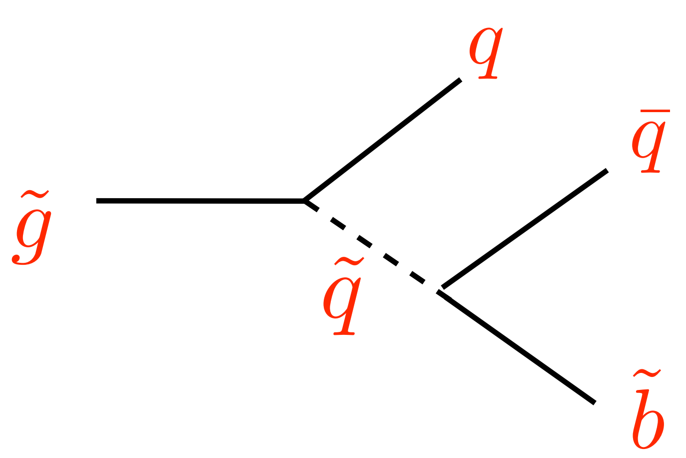

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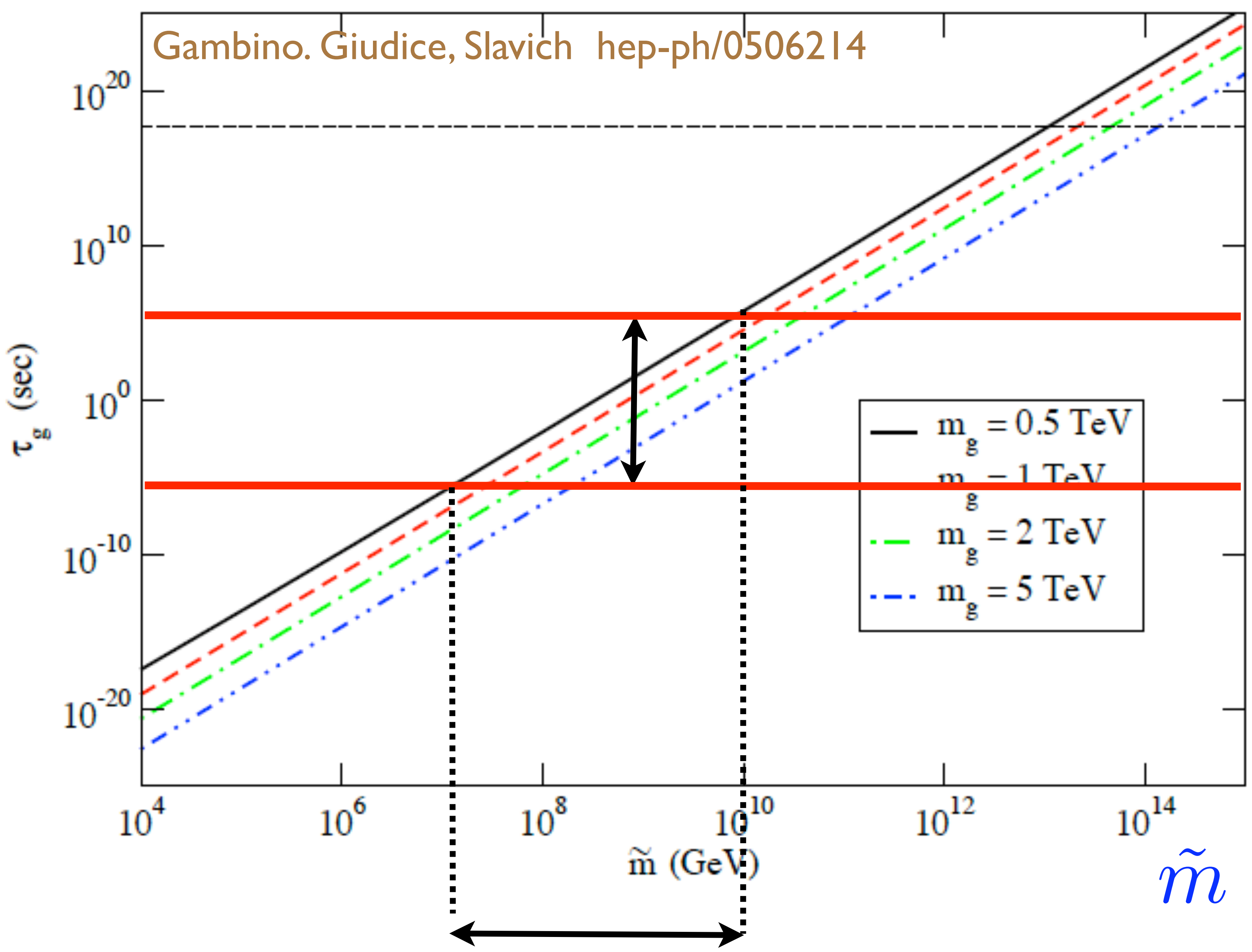
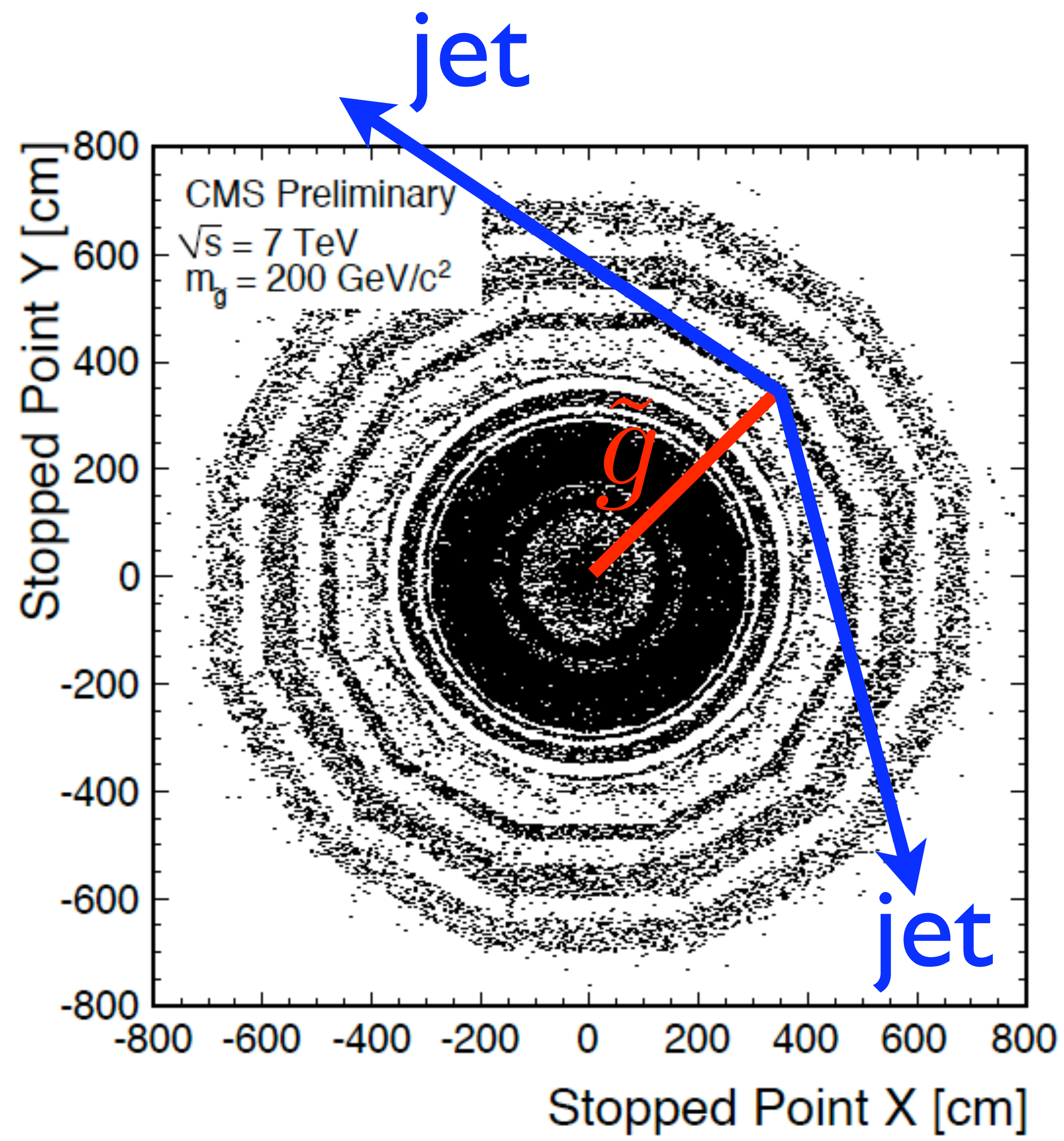
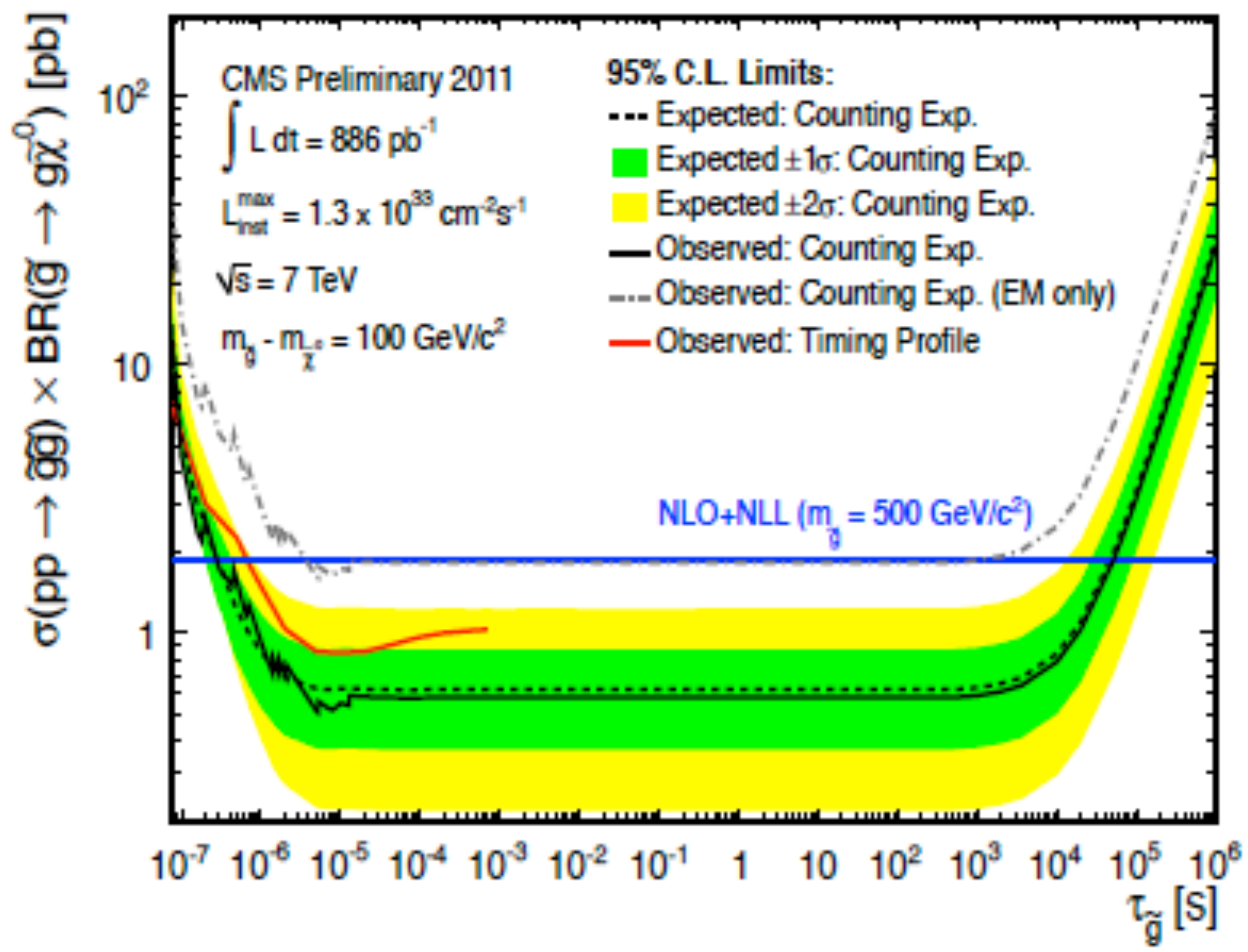


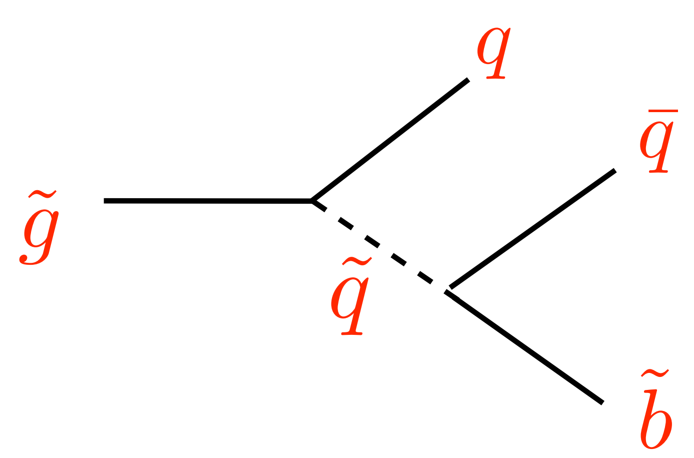
Excluded

$m_{\tilde{g}} < 500\,\mathrm{GeV}$



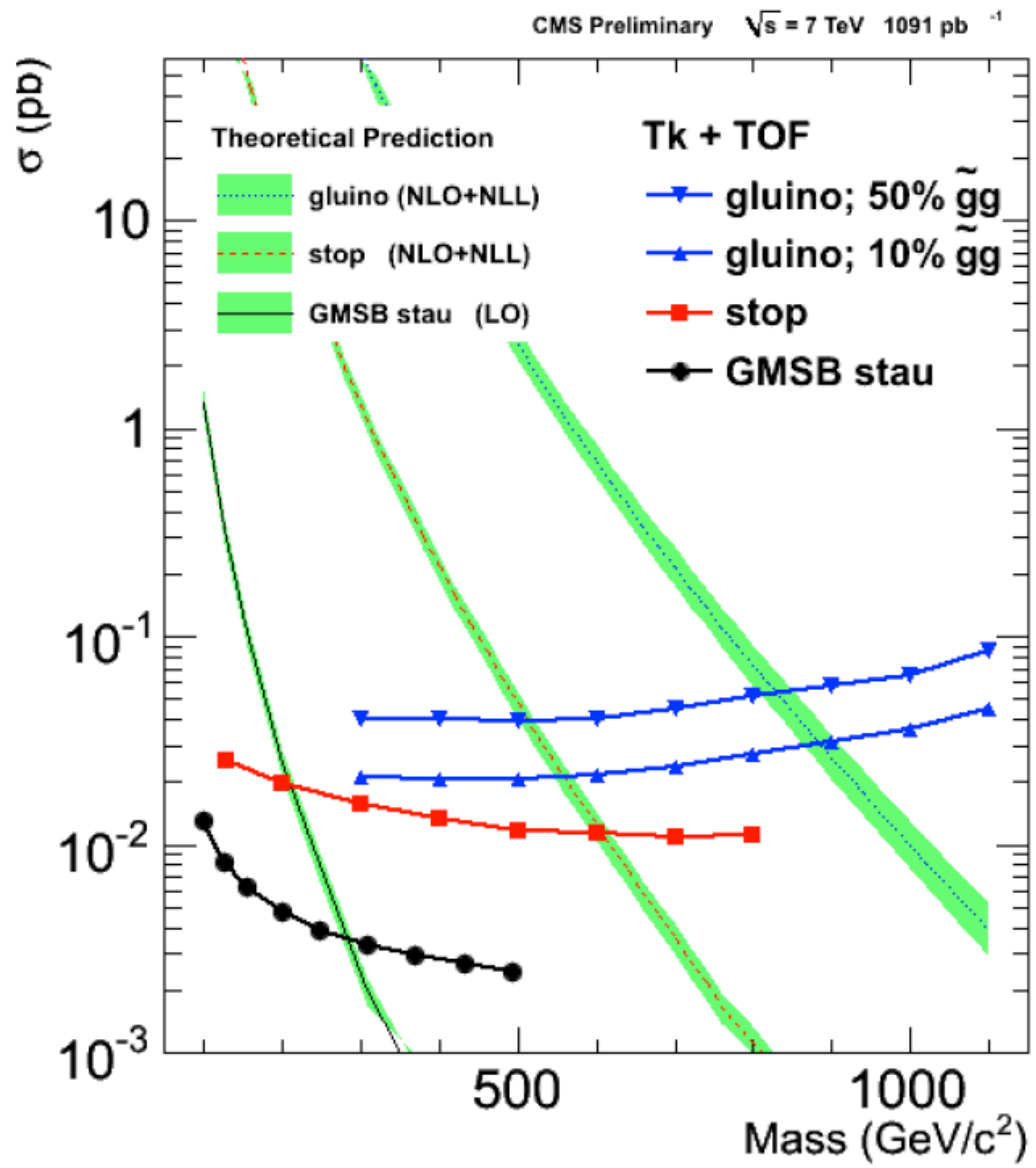


Gluino R Hadron Charged Tracks



$\tilde{m} \gg v$

Heavy Stable
Charged Particle Tracks



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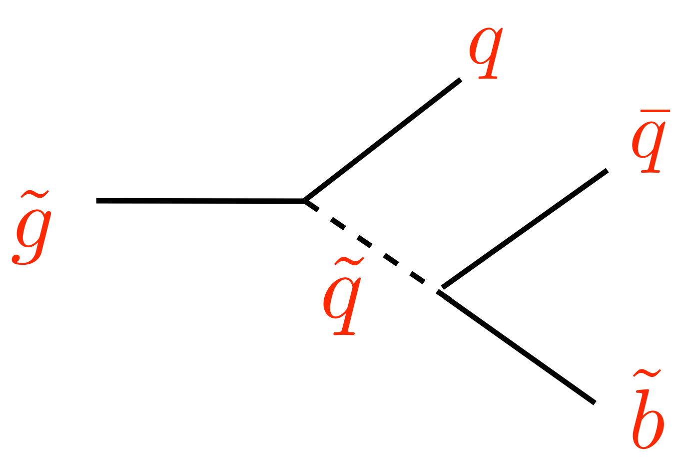
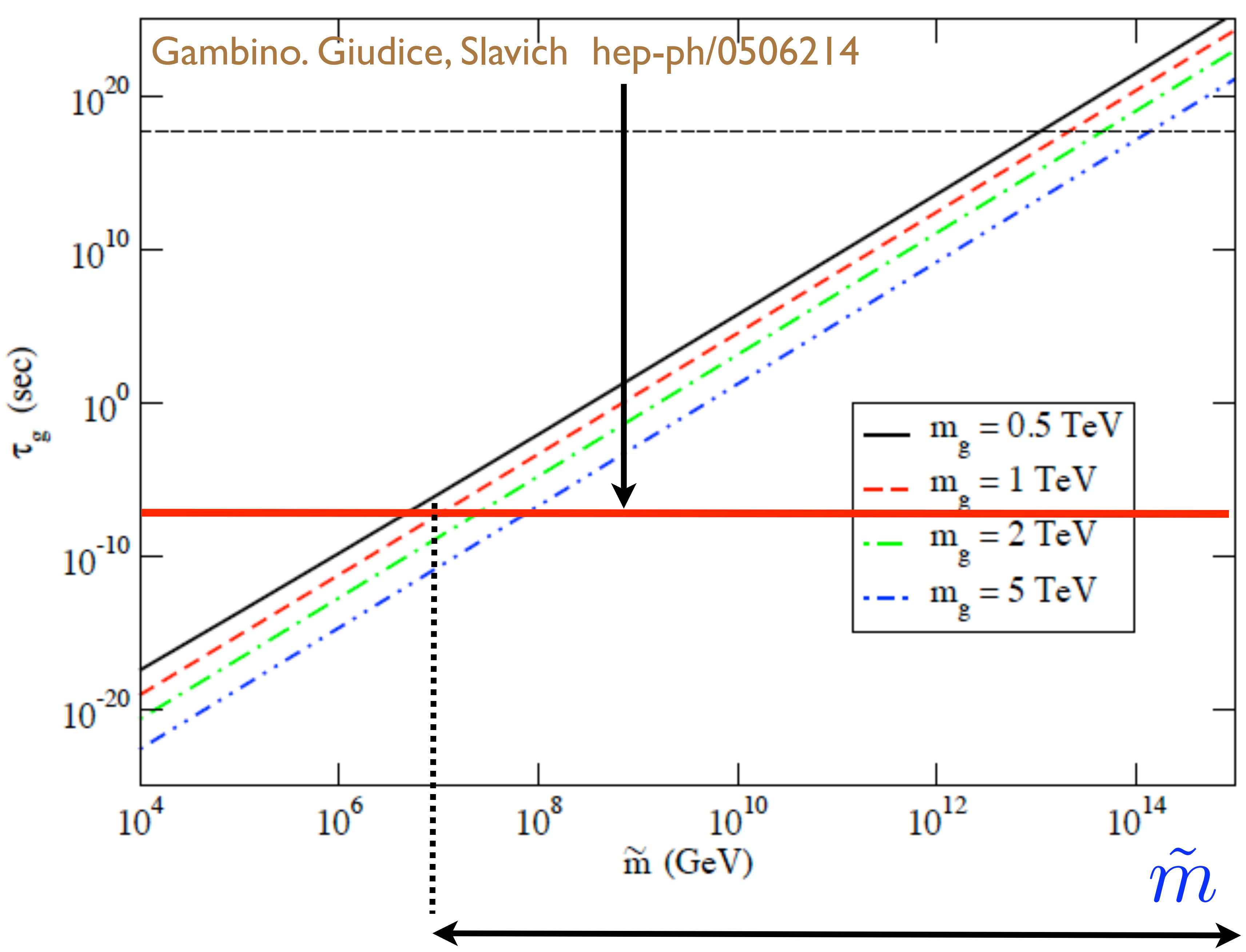


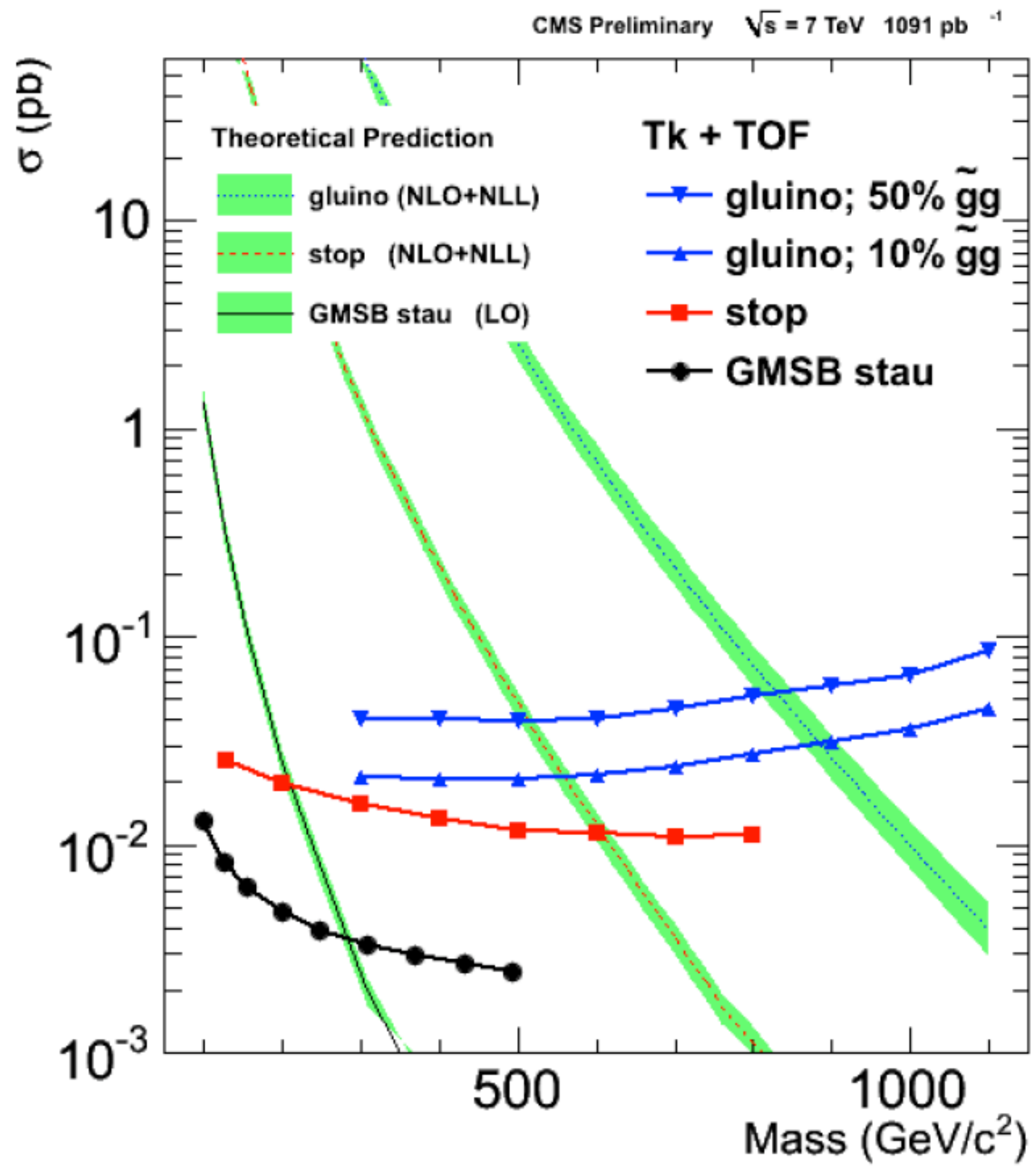
$$\tilde{m} \gg v$$



Excluded

$$m_{\tilde{g}} < 850\,\text{GeV}$$

Heavy Stable Charged Particle Tracks



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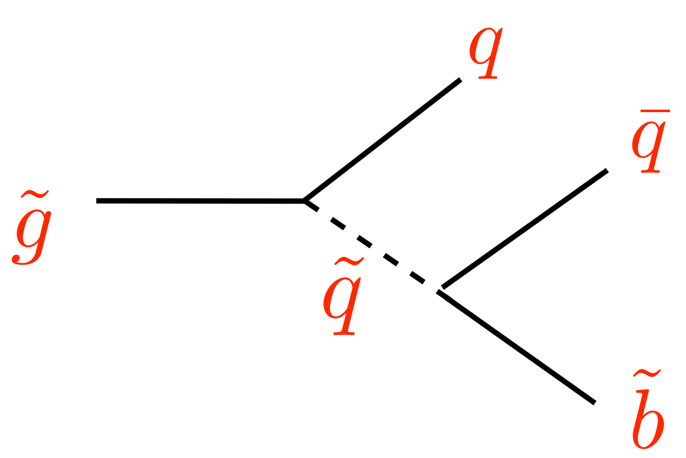

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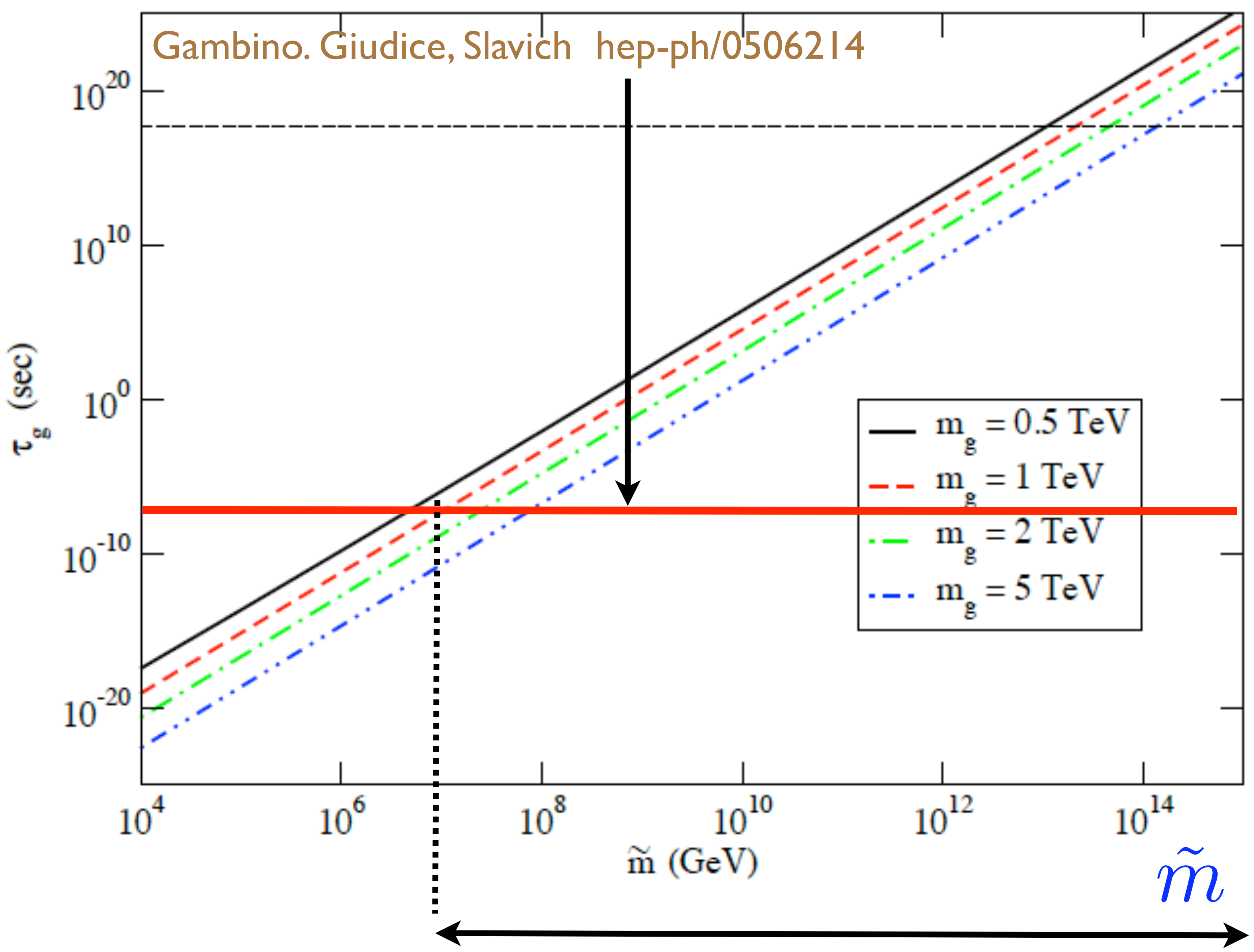

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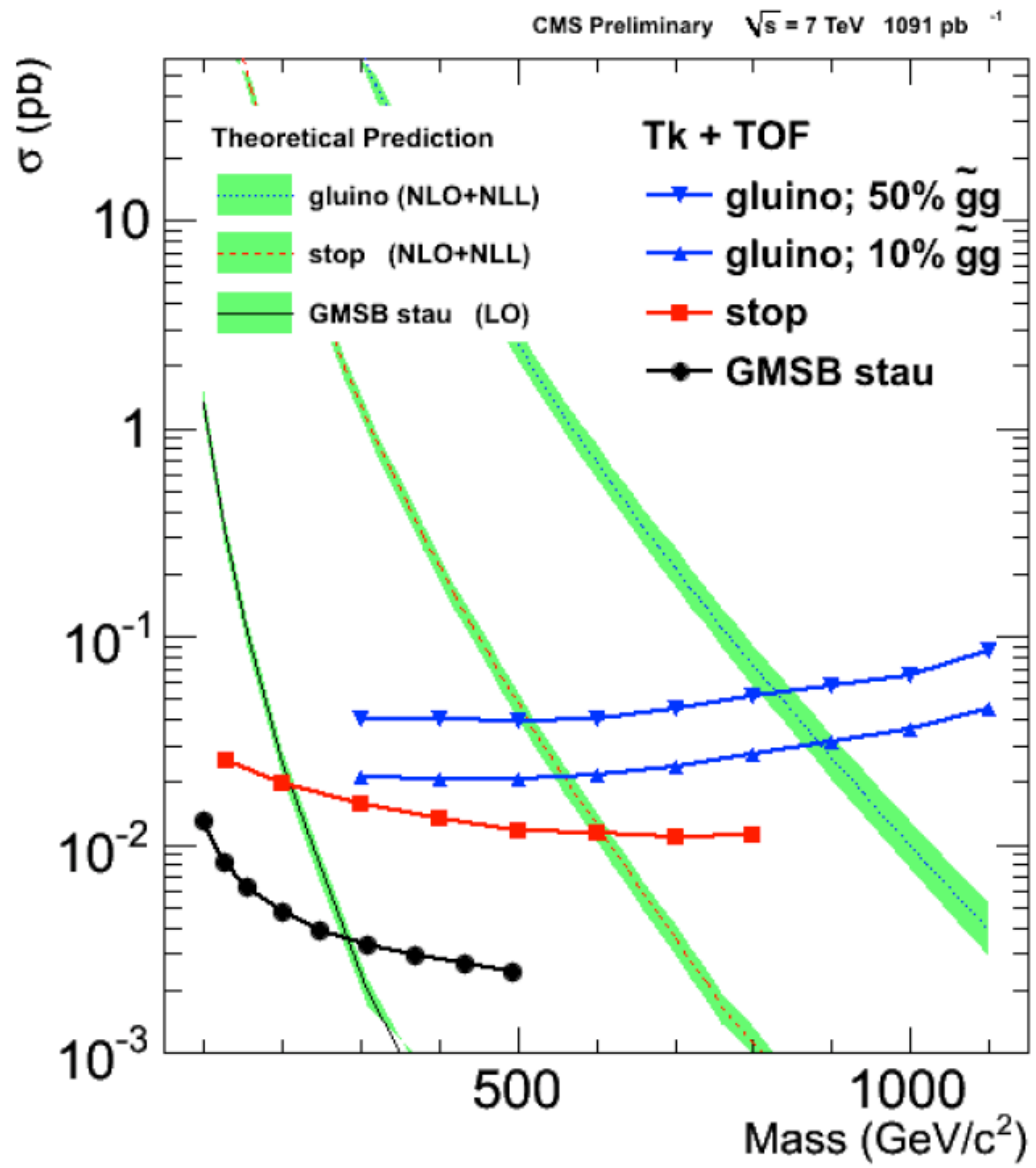

Problem:

$m_{\tilde{g}}$ not constrained by naturalness