BERKELEY CENTER FOR THEORETICAL PHYSICS

What have we learned from the LHC so far

Hitoshi Murayama (IPMU & Berkeley)

YIPQS Symposium @ YITP, Kyoto, Feb 6, 2012

Large Hadron Collider (LHC)

on Collider
HC)

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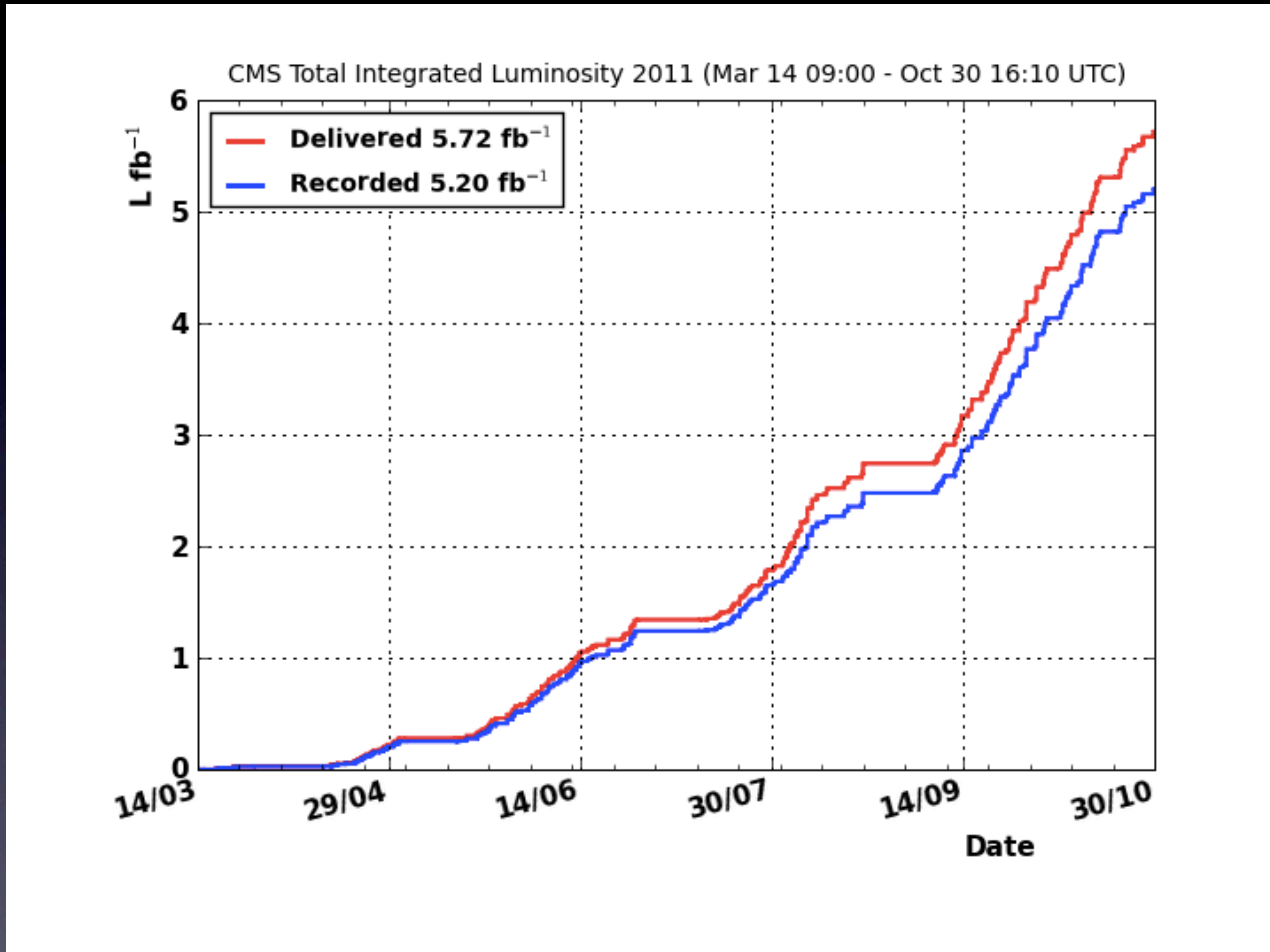
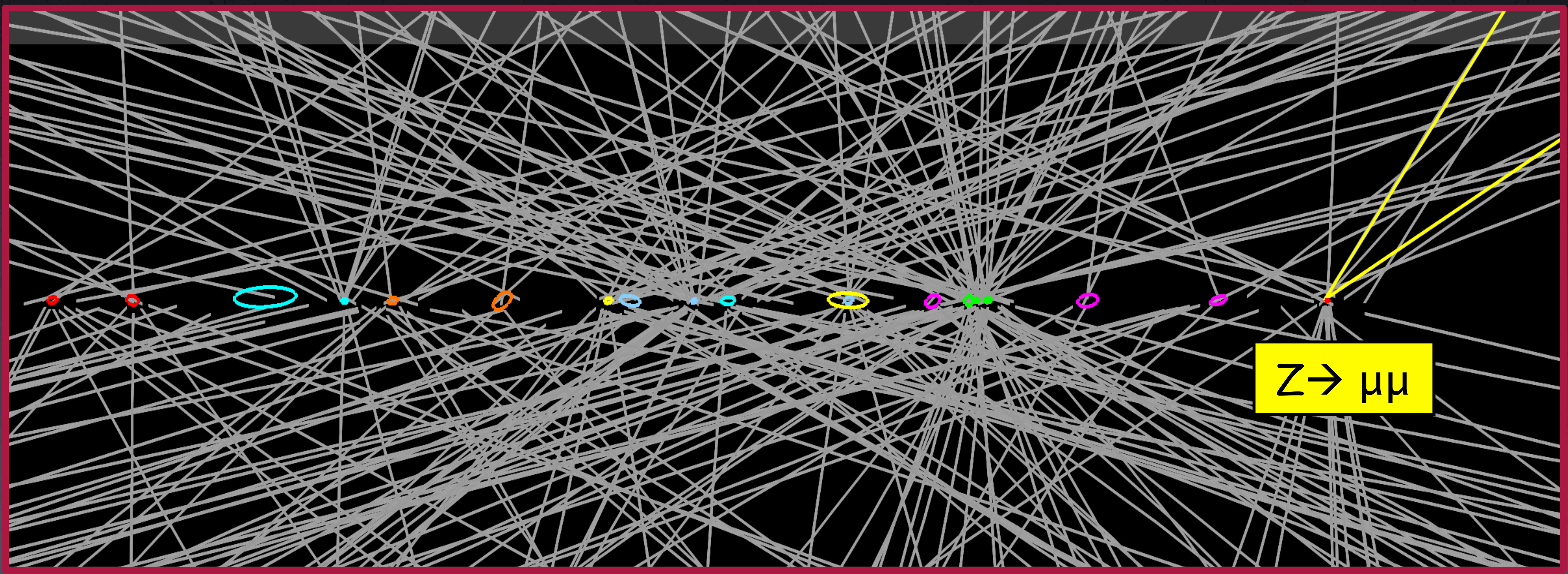
g Big Bang

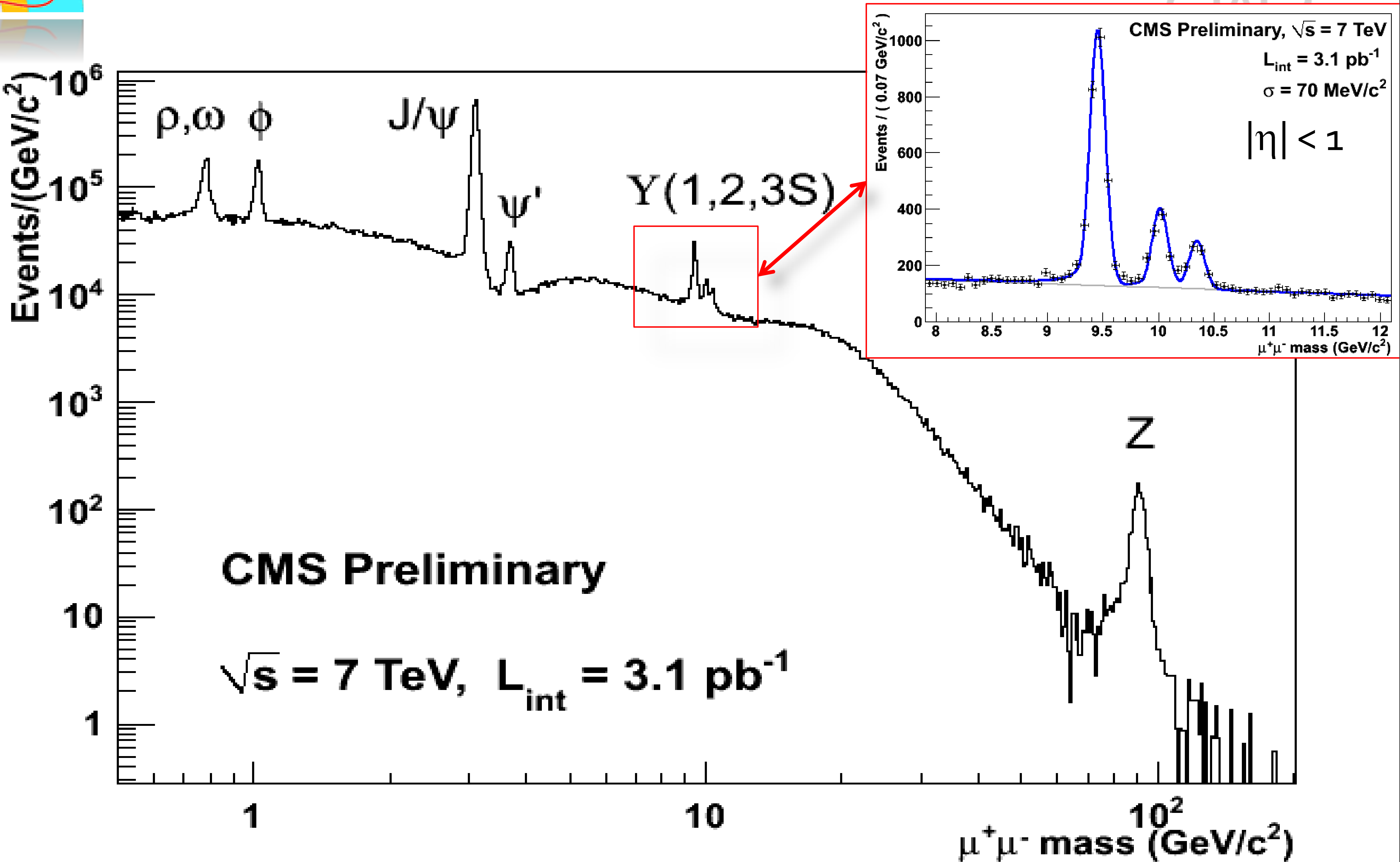

CMS Total Integrated Luminosity 2011 (Mar 14 09:00 - Oct 30 16:10 UTC)
Delivered 5.72 fb^{-1}
Recorded 5.20 fb^{-1}
L fb^{-1}
0
1
2
3
4
5
6
14/03
29/04
14/06
30/07
14/09
30/10
Date

what LHC events look like

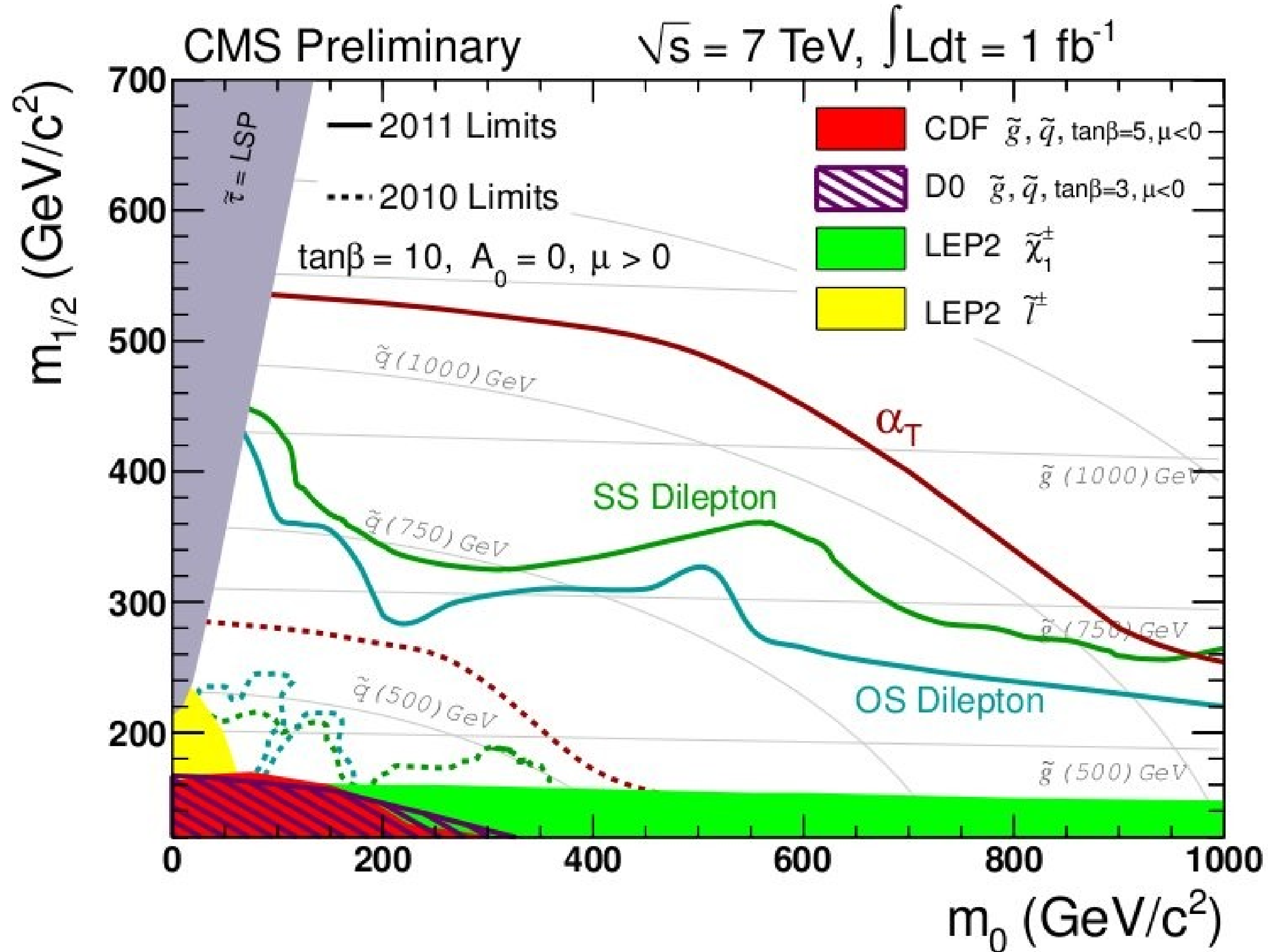


ATLAS

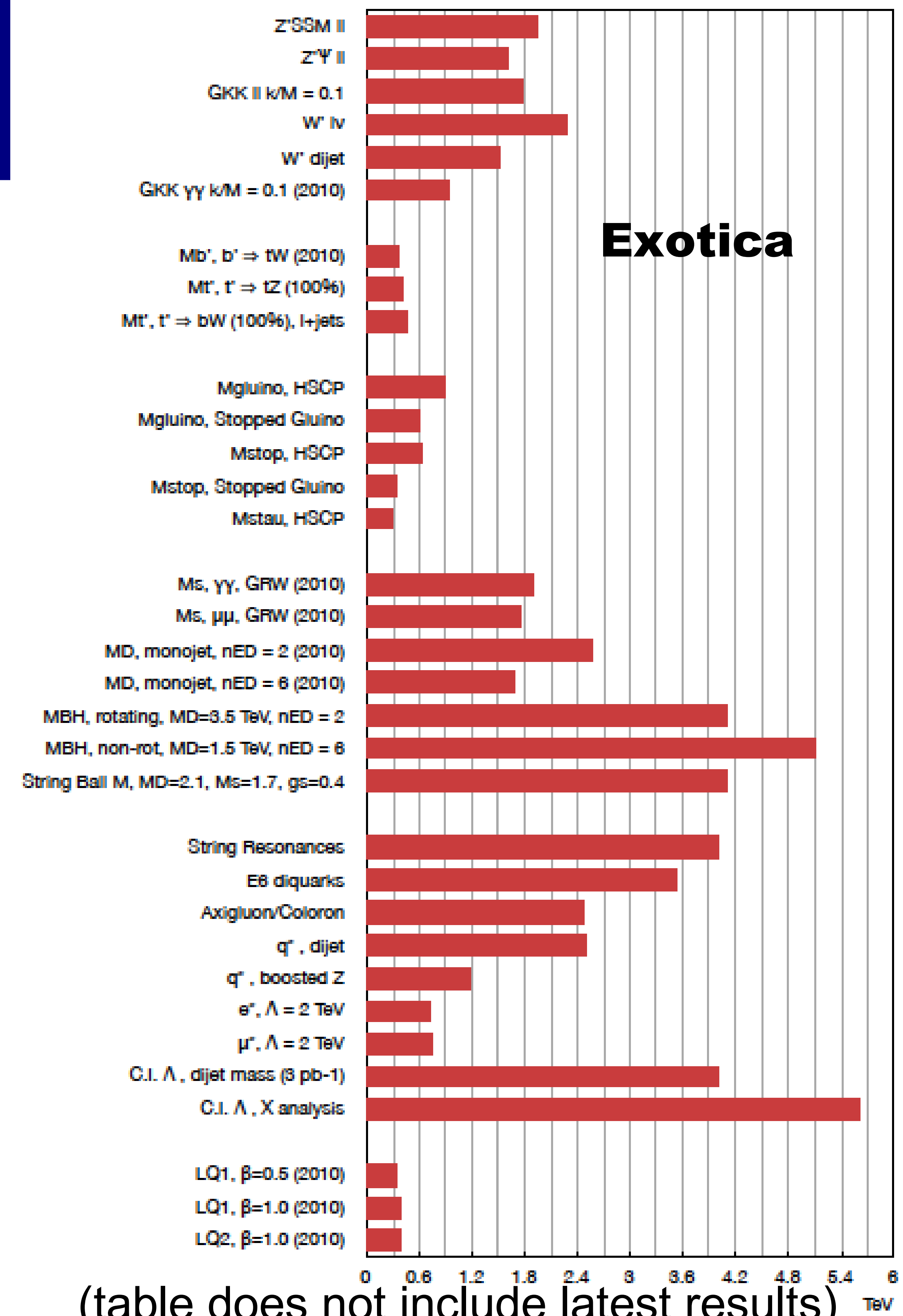
|η|<1: Yields ® (1,2,3) = 2440±61, 757±40, 464±34



Summary (CMS)



SUSY



(only a selection of results)

(table does not include latest results)

BBC NEWS

SCIENCE & ENVIRONMENT

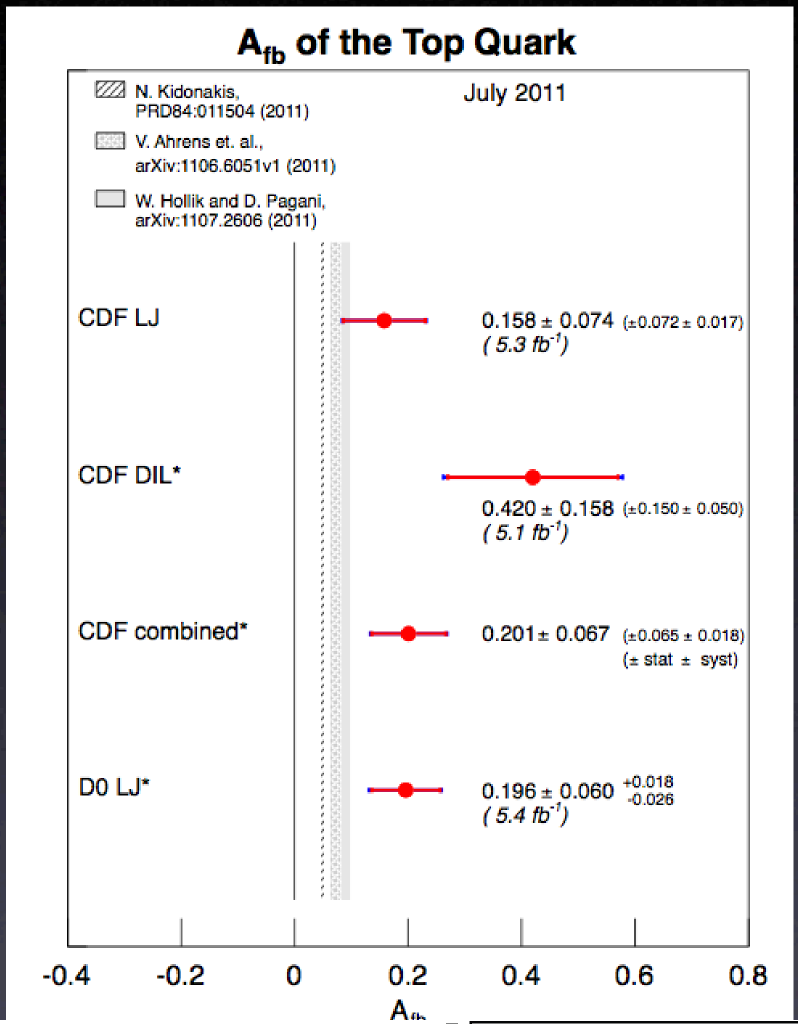
27 August 2011 Last updated at 02:41 ET

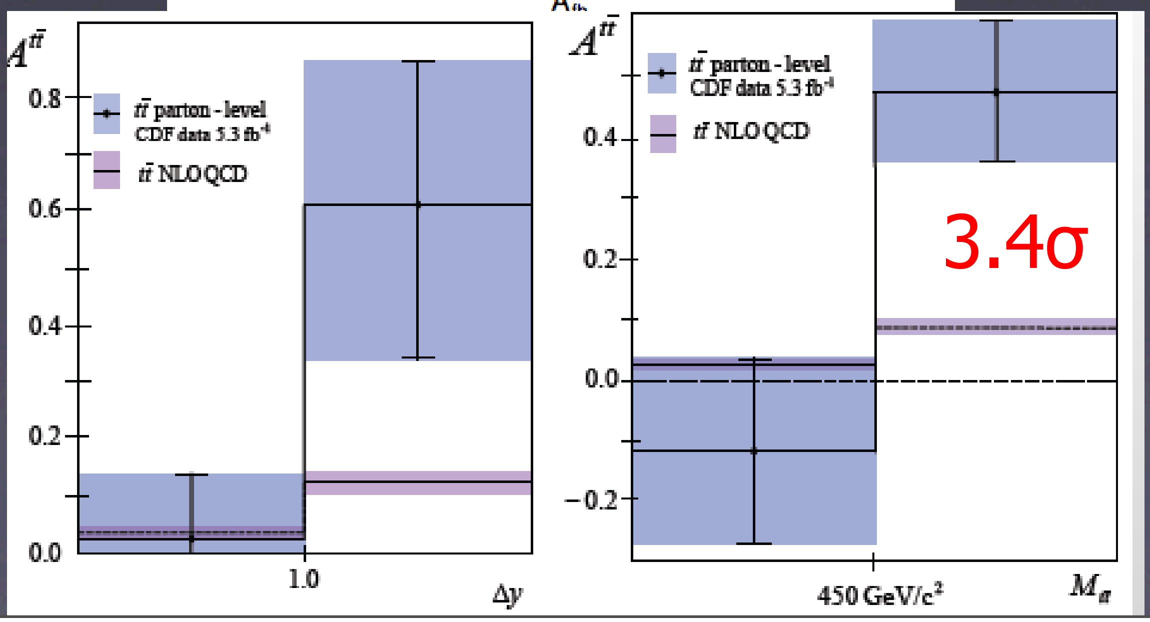
LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

top quark A_{FB}





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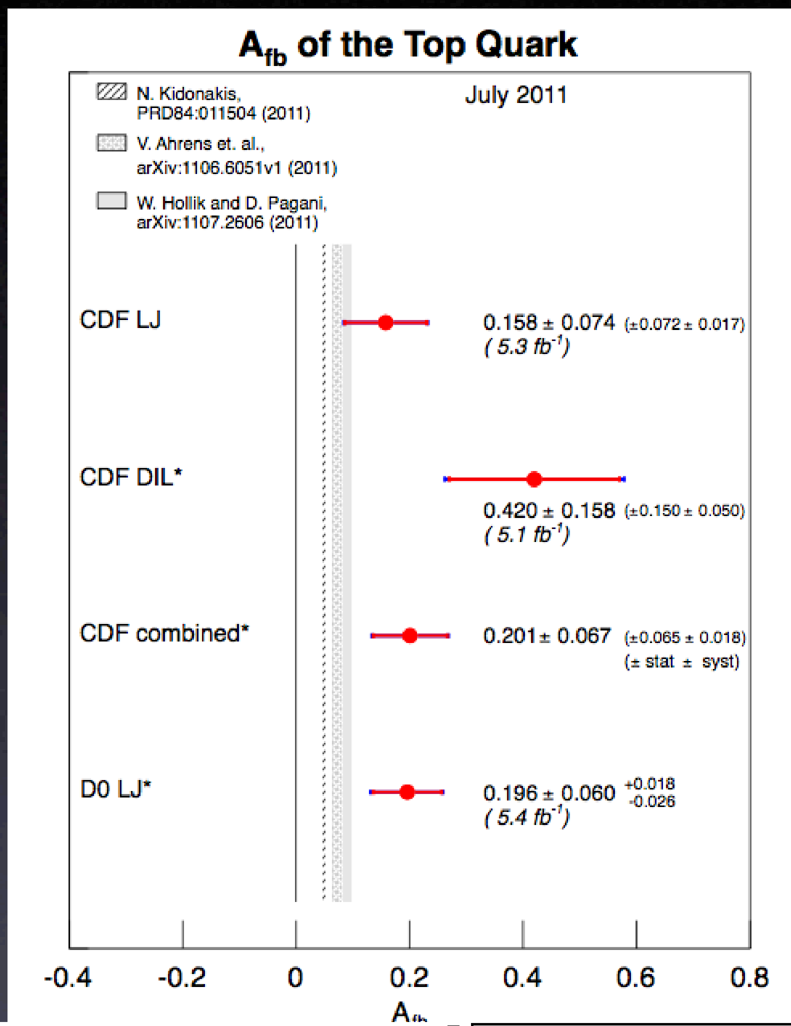
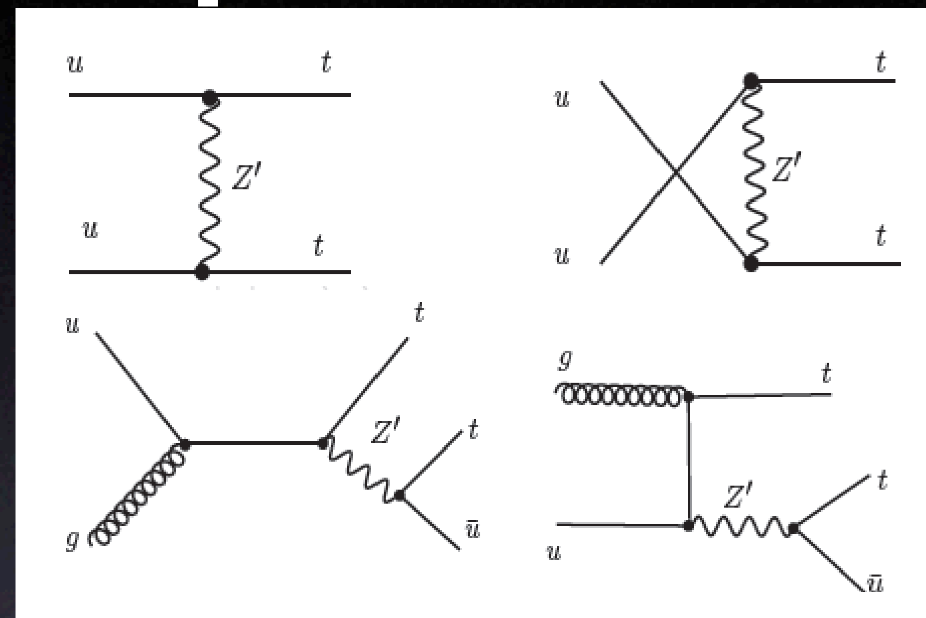
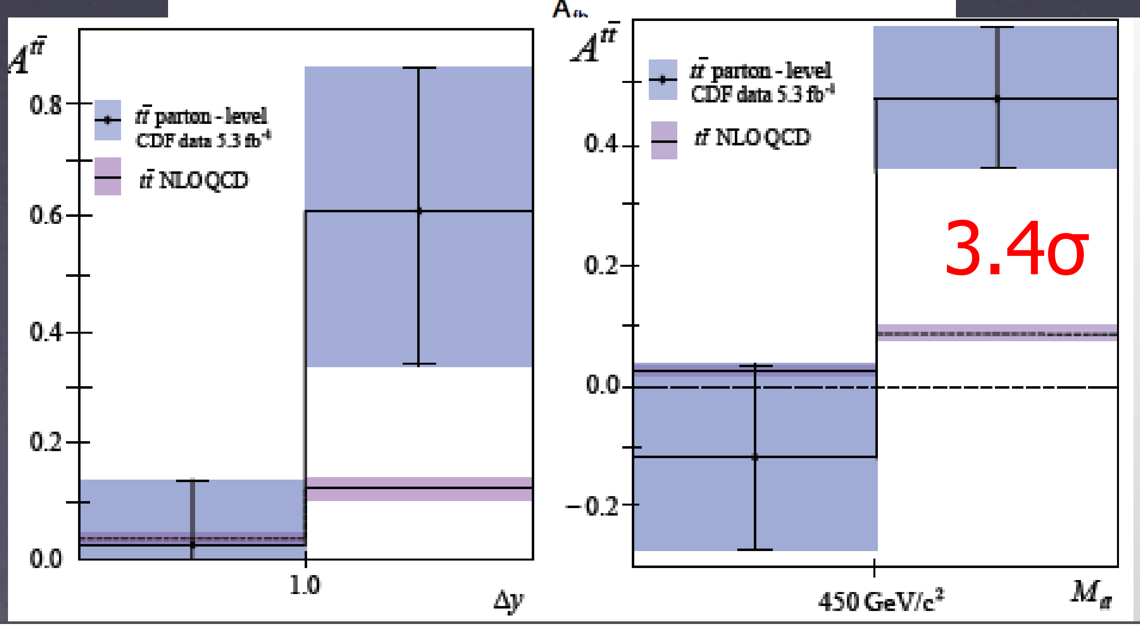




Jung, HM, Pierce, Wells
0907.4112



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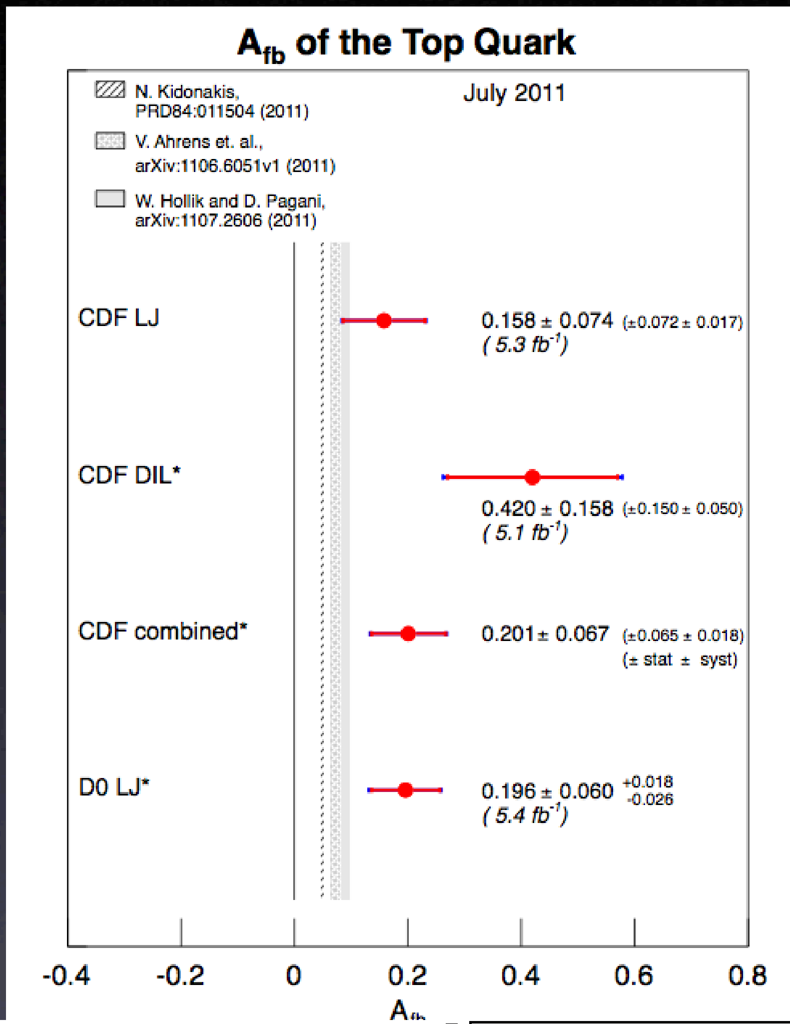

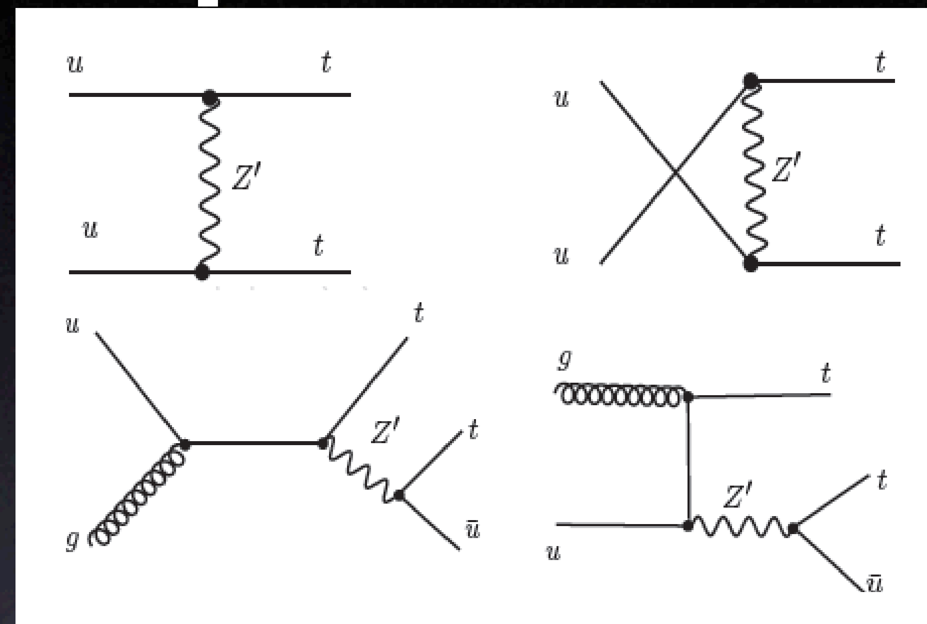

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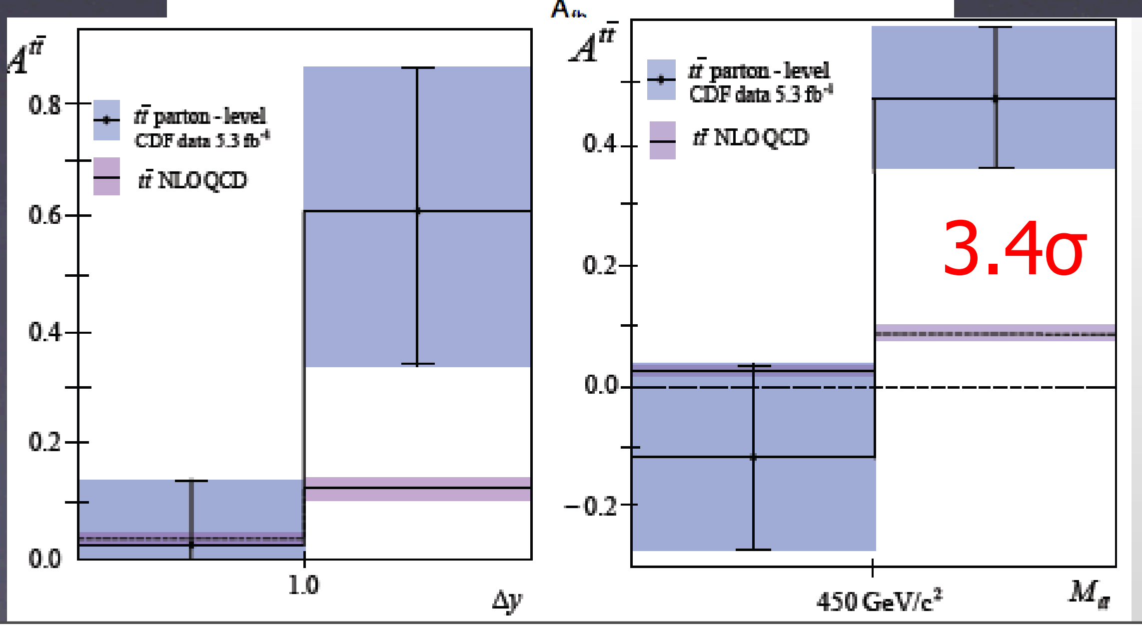

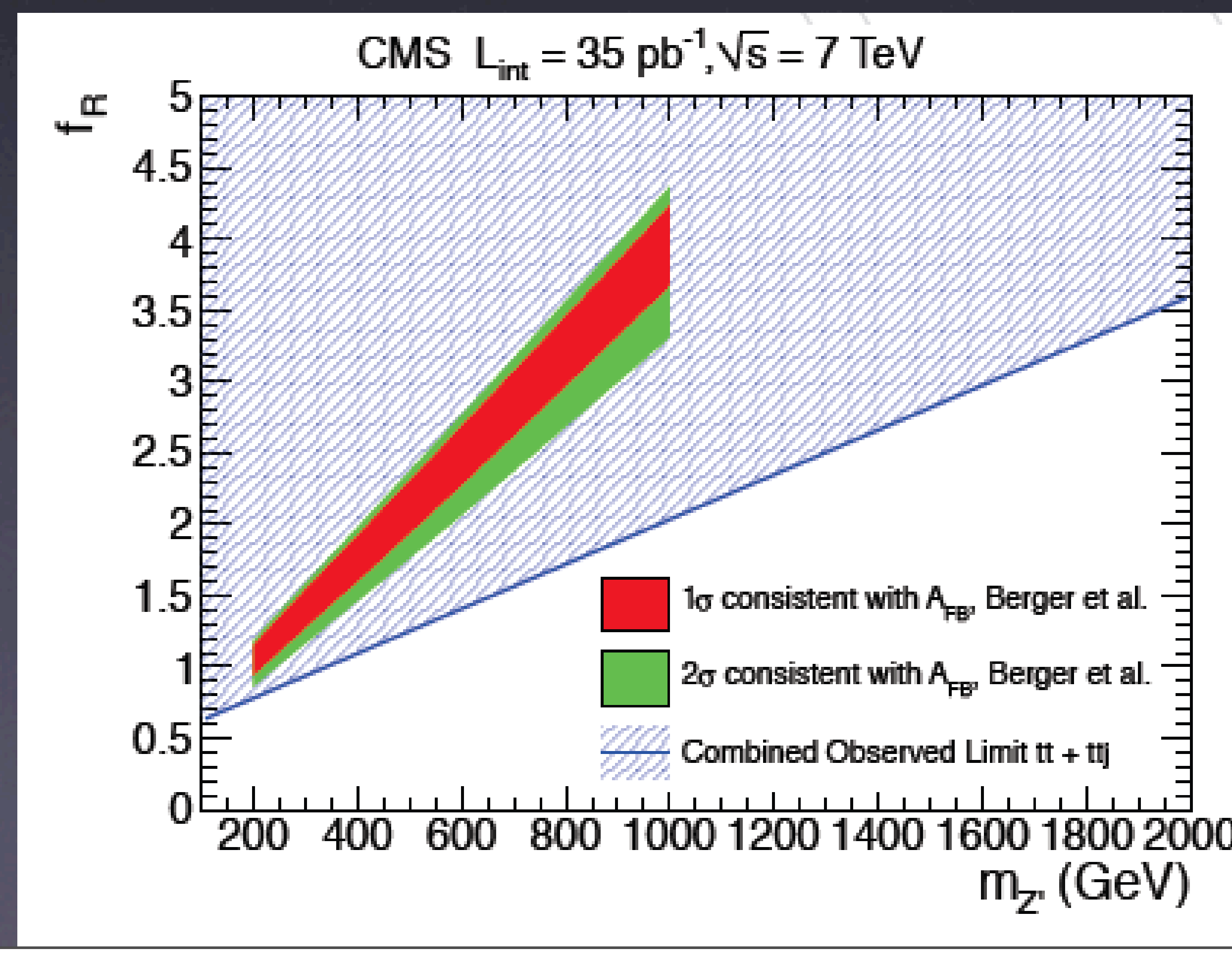

Do we still expect anything at the LHC?

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Where we are going

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- Complete the Standard Model
  - dream since 60's, finally there
  - need to clear the Terascale fog

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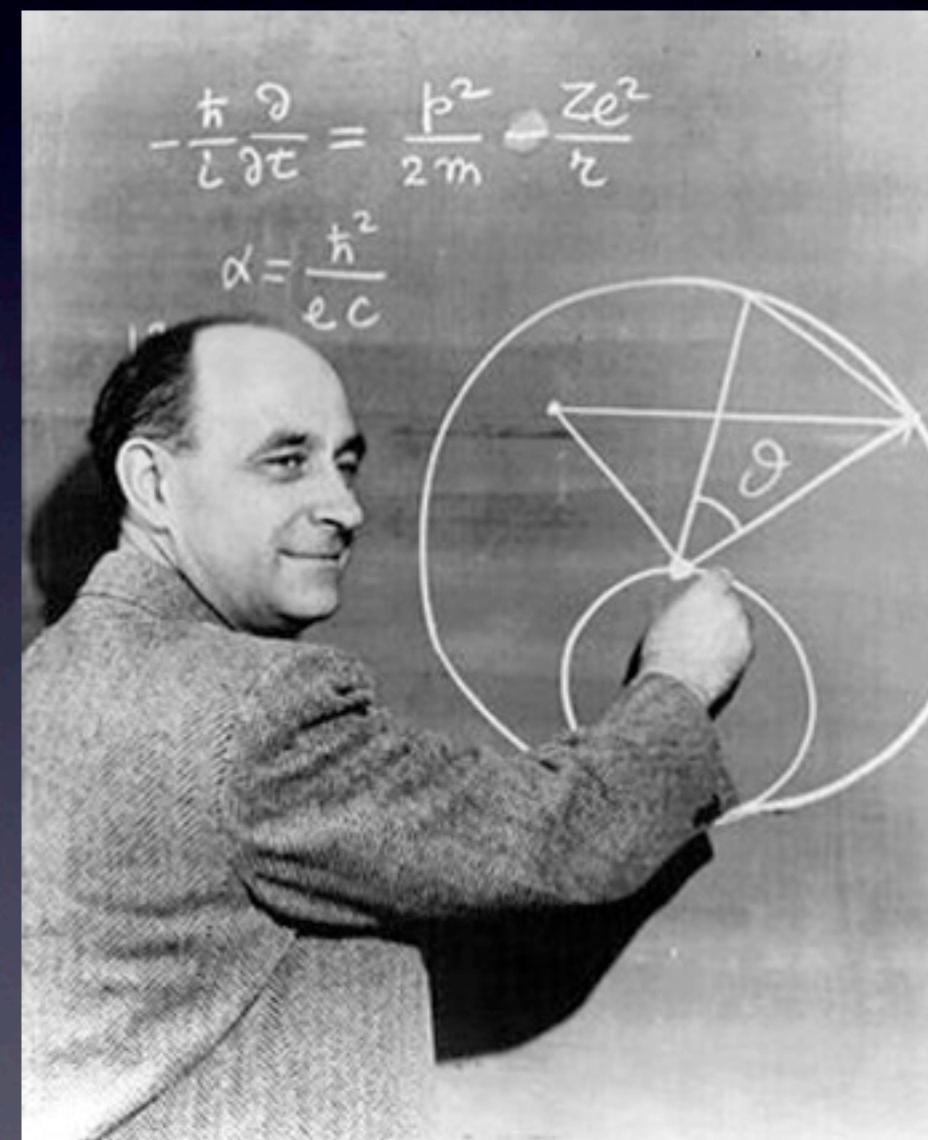
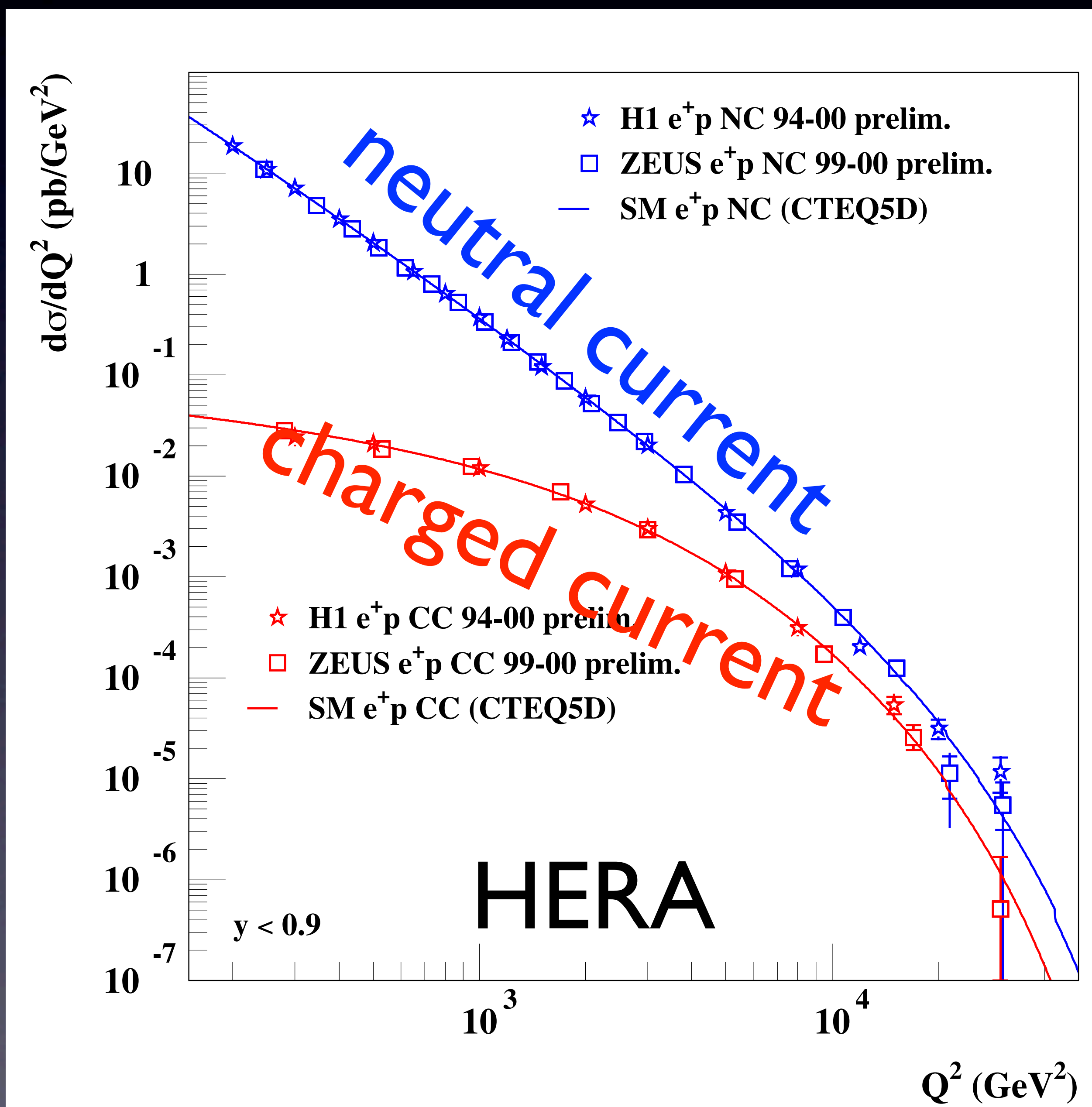
- Complete the Standard Model
  - dream since 60's, finally there
  - need to clear the Terascale fog
- Find physics beyond the standard model
  - naturalness, unification
  - dark matter, baryogenesis

Terascale

- Fermi formulated the first theory of the weak force (1932)
- *The required energy scale to study the problem known since then:* ~TeV
- We are finally getting there!



Terascale


H1 e+p NC 94-00 prelim.
ZEUS e+p NC 99-00 prelim.
SM e+p NC (CTEQ5D)
neutral current
charged current
H1 e+p CC 94-00 prelim.
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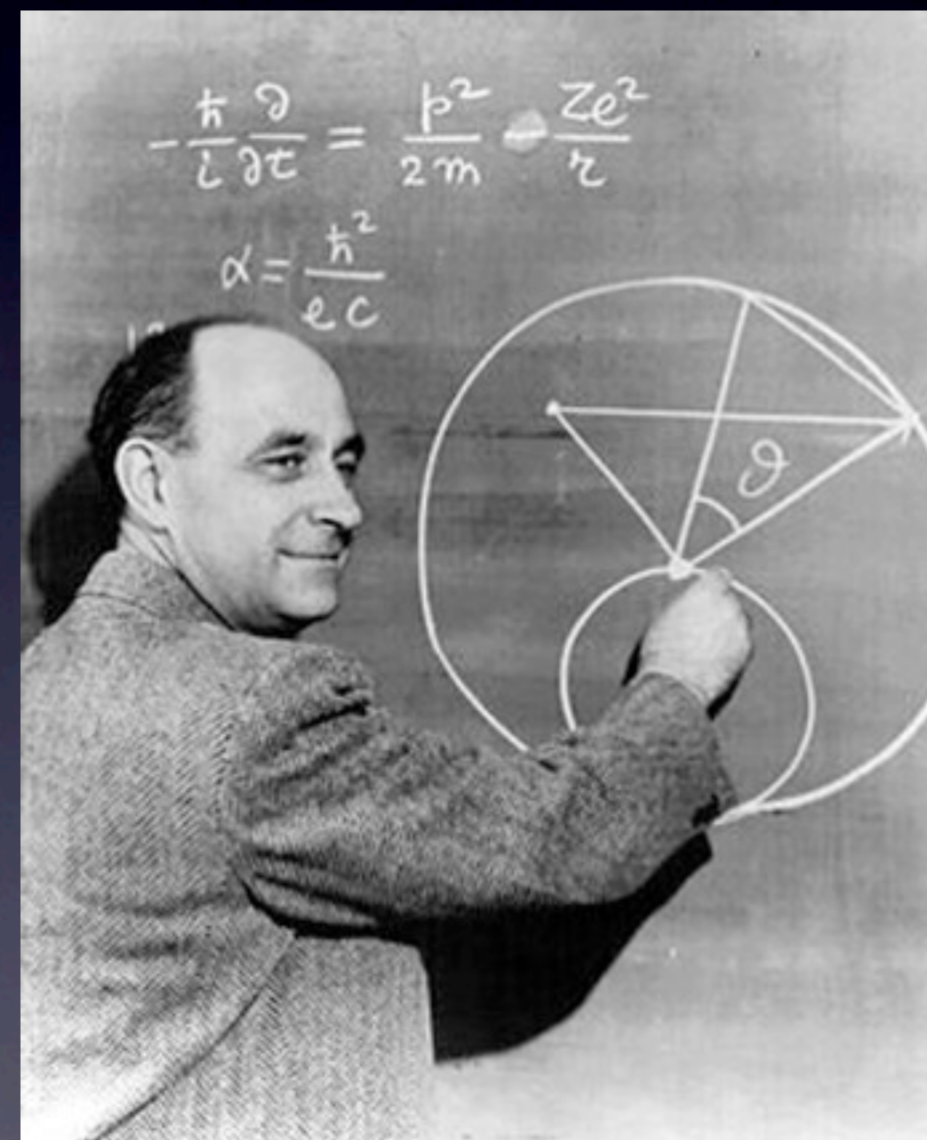
SM e+p CC (CTEQ5D)
HERA
y < 0.9
dσ/dQ2 (pb/GeV2)
Q2 (GeV2)



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- We'll start with Higgs boson(s)

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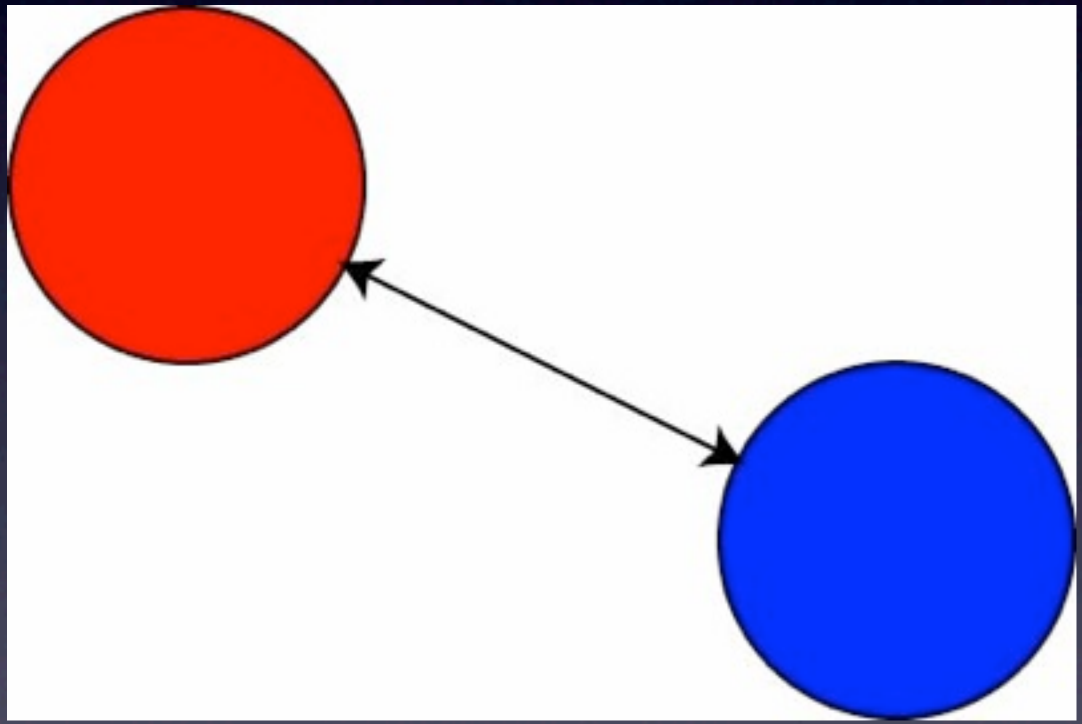
Why the Terascale?
—weak interaction—

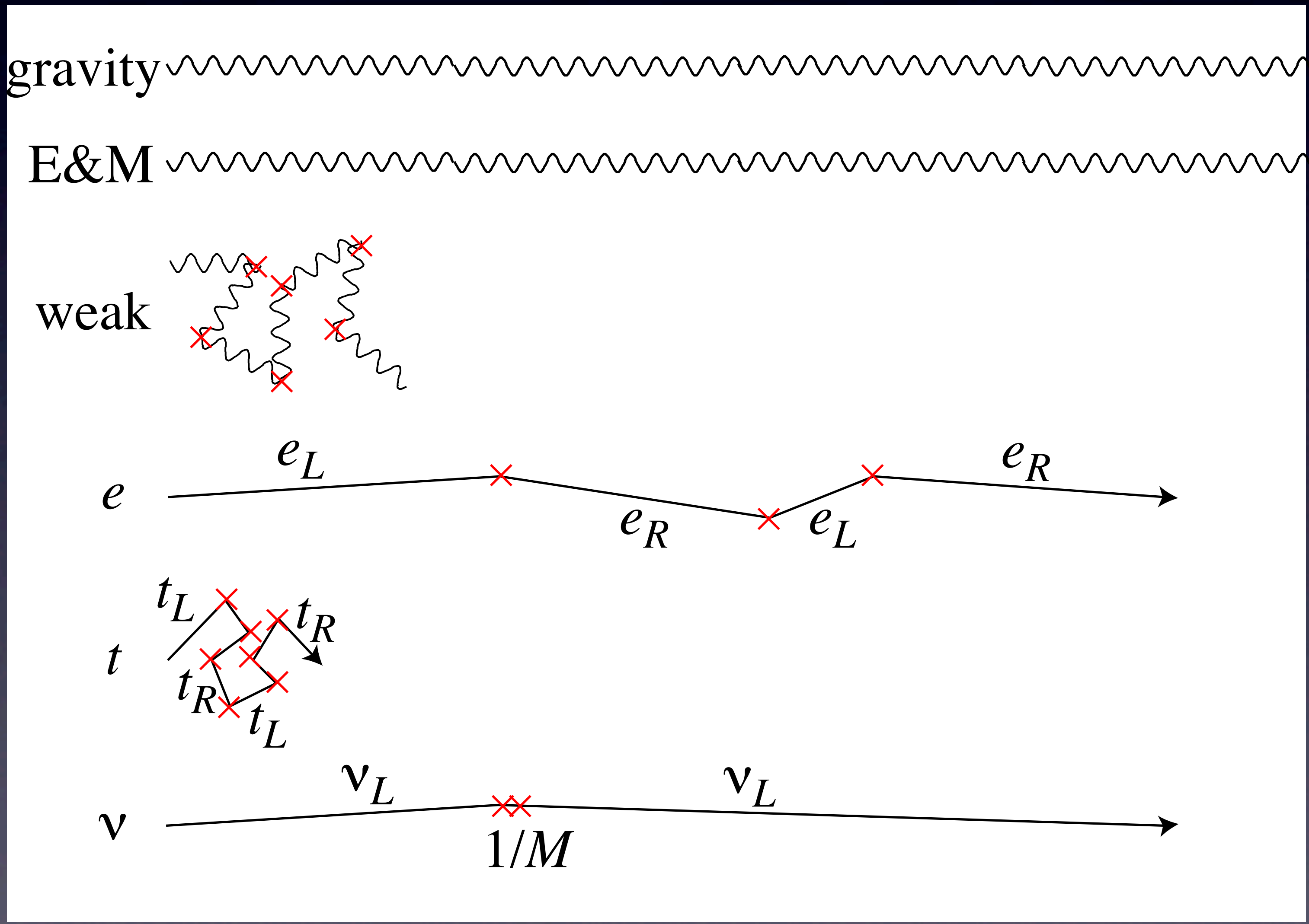
Mystery of the weak force

- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer
- We know the energy scale: ~0.3 TeV using $\hbar$ and c



We are swimming in a quantum liquid

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??



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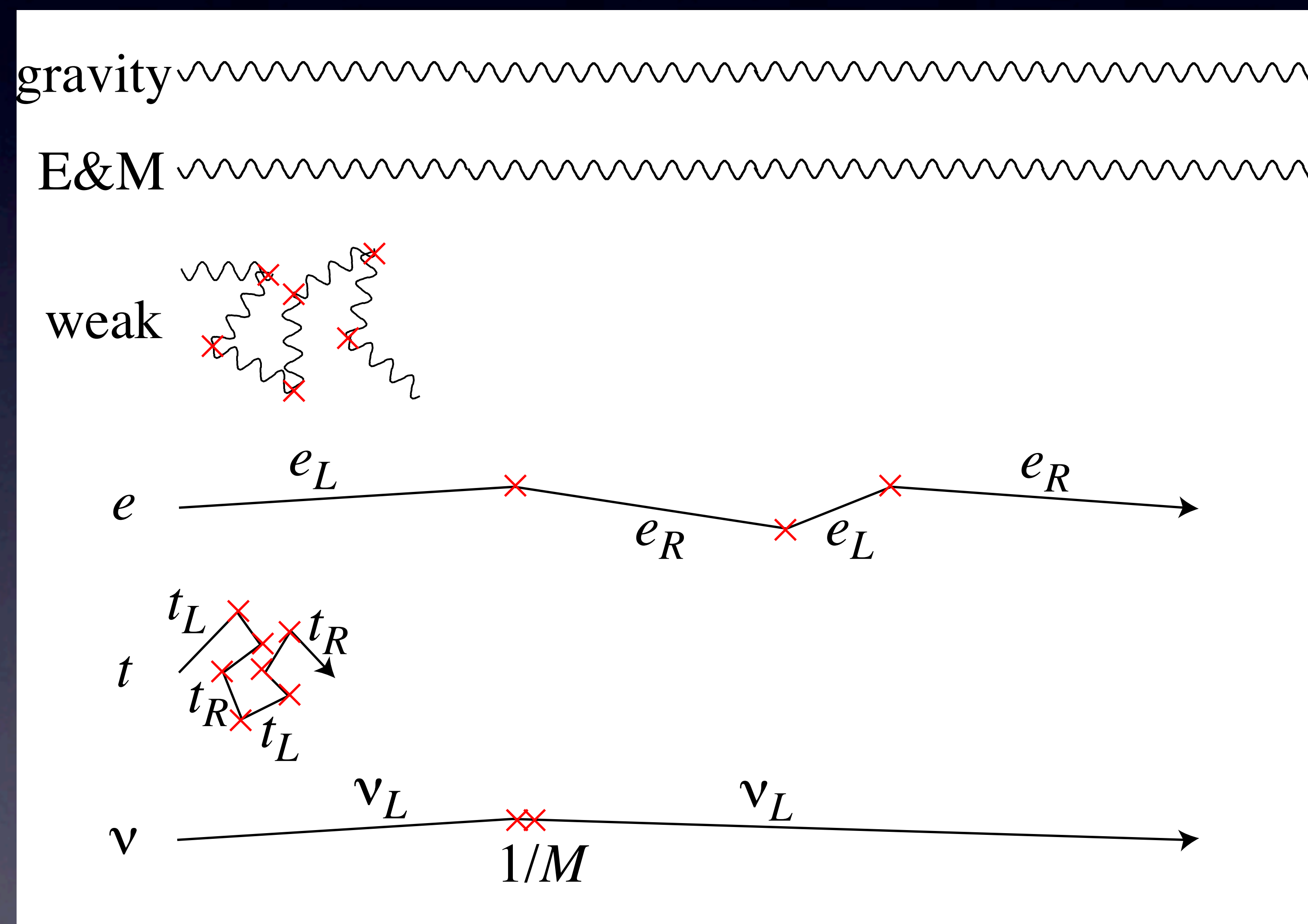


Cosmic Superconductor

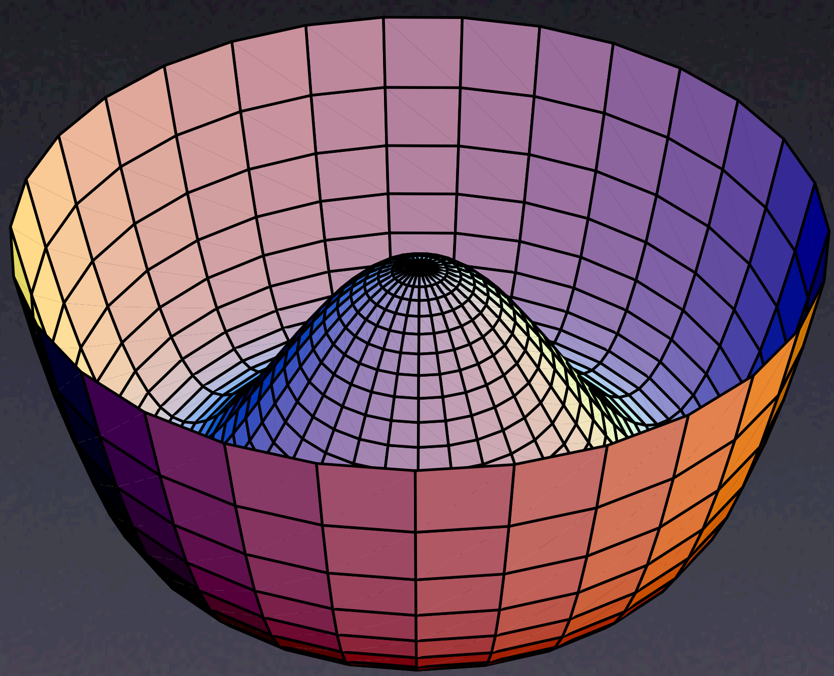
- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"

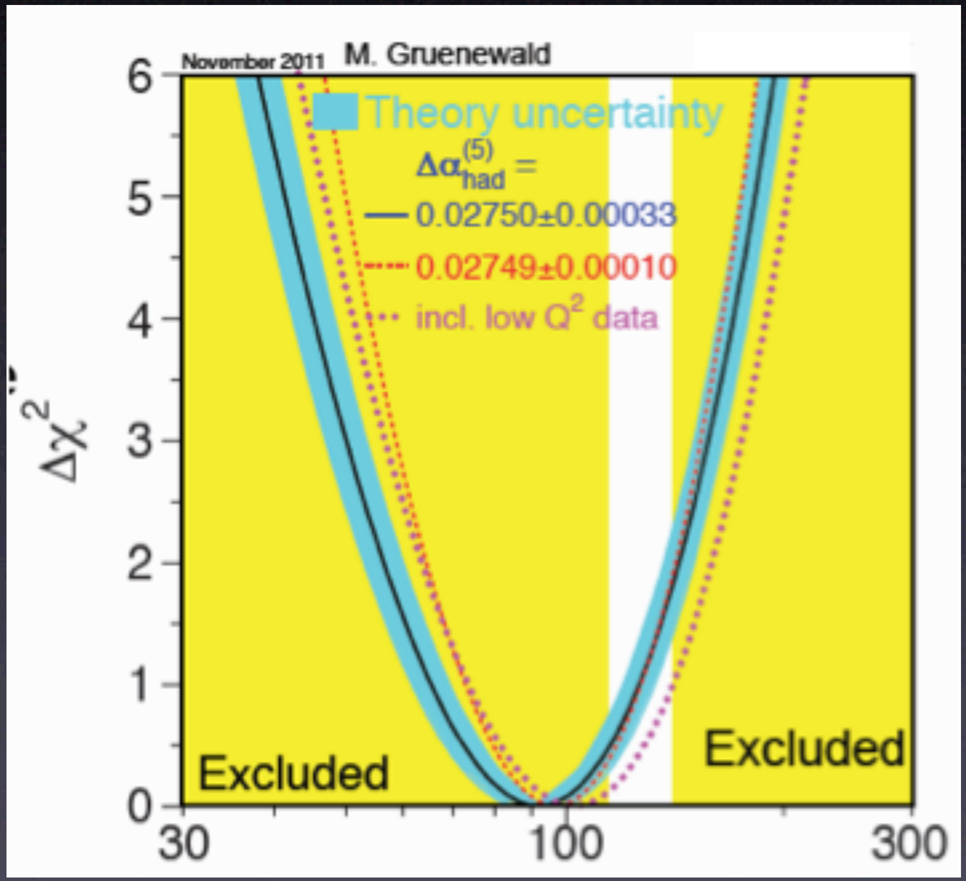
  ⇒ Magnetic field is short-ranged!

- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Didn't have enough energy (gap) to break up Cooper pairs

That's the stage where we are!

Higgs boson mass in the Standard Model



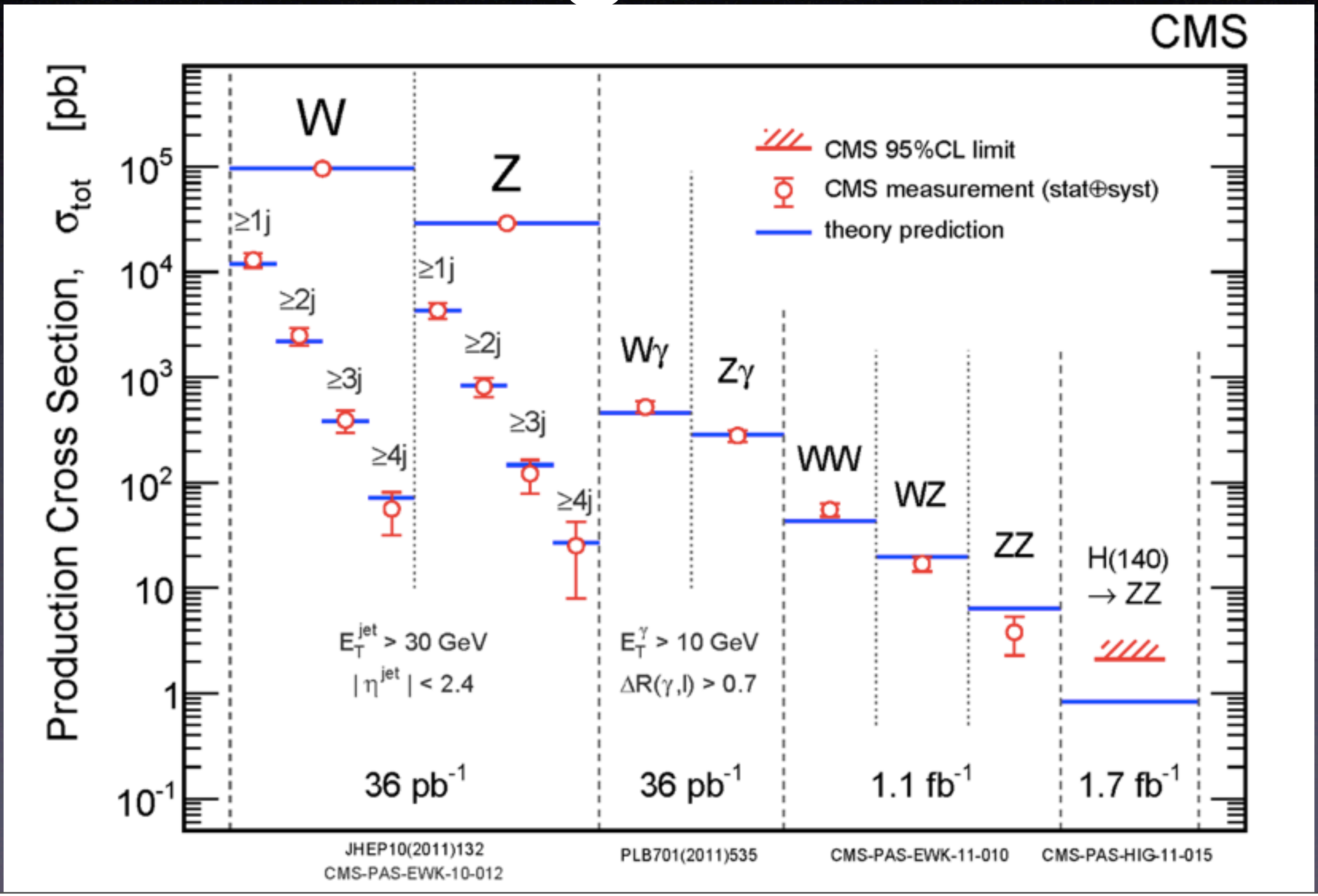


$$V = -\mu^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2 = \frac{\lambda}{2}(H^\dagger H - v^2)^2 + c.c.$$

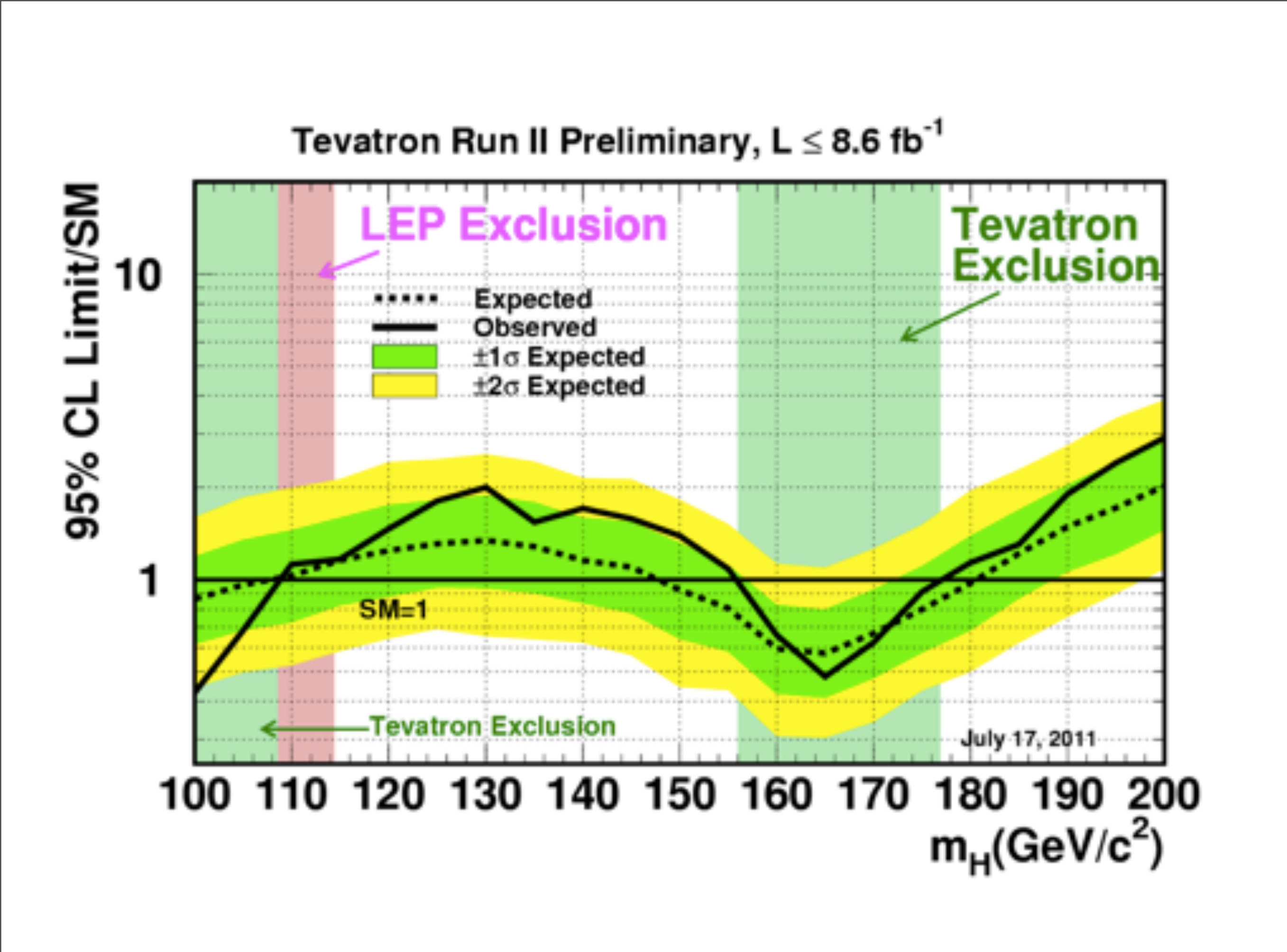
$$v \approx 175\text{GeV}, \quad m_h \propto \lambda v$$

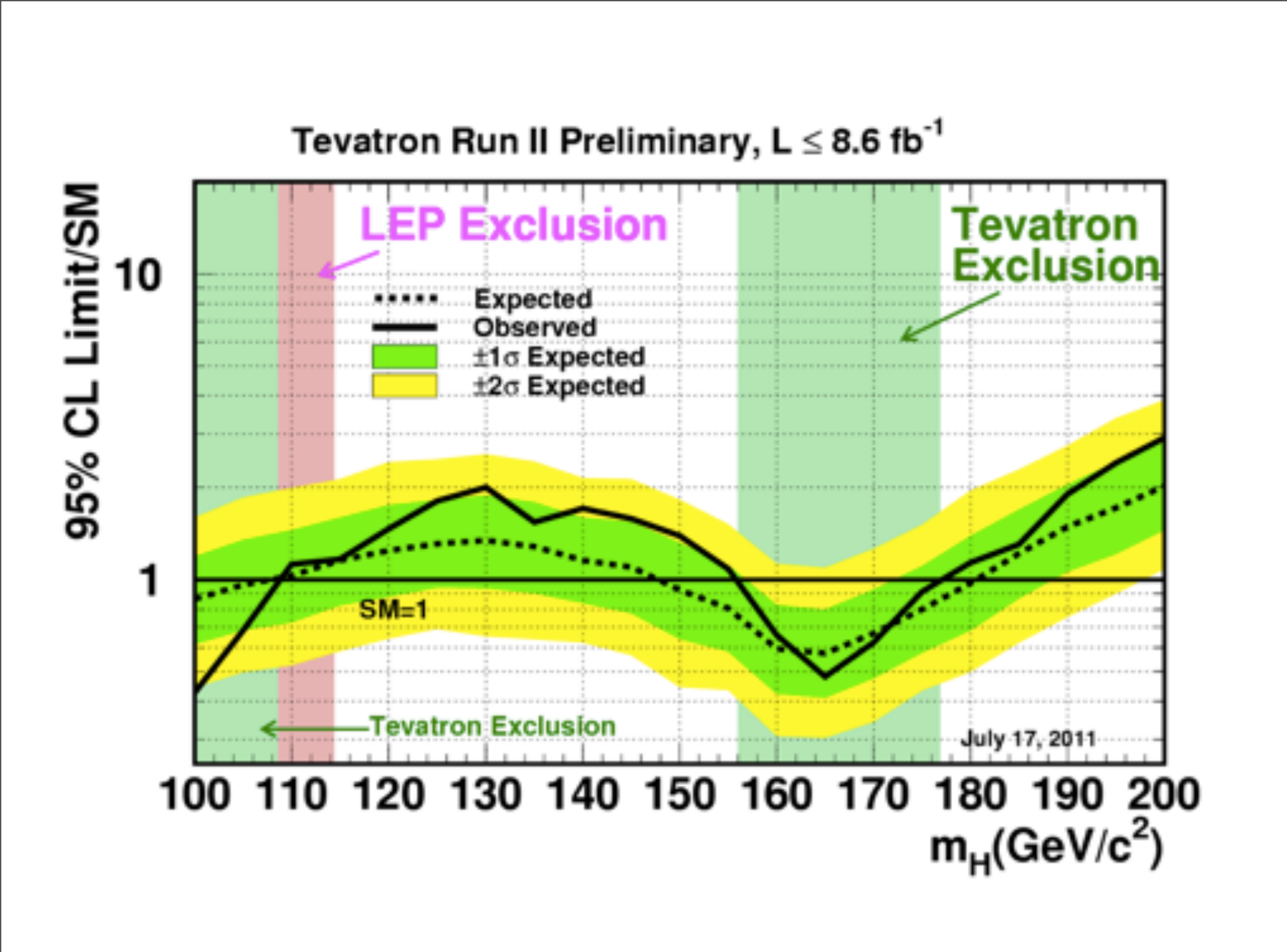
Some of the SM backgrounds

$\sigma_{pp} \sim 2 \times 10^{11}$ pb



Dec 13, 2011 @ CERN


Tevatron Run II Preliminary, L ≤ 8.6 fb-1
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
10
1
100 110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)



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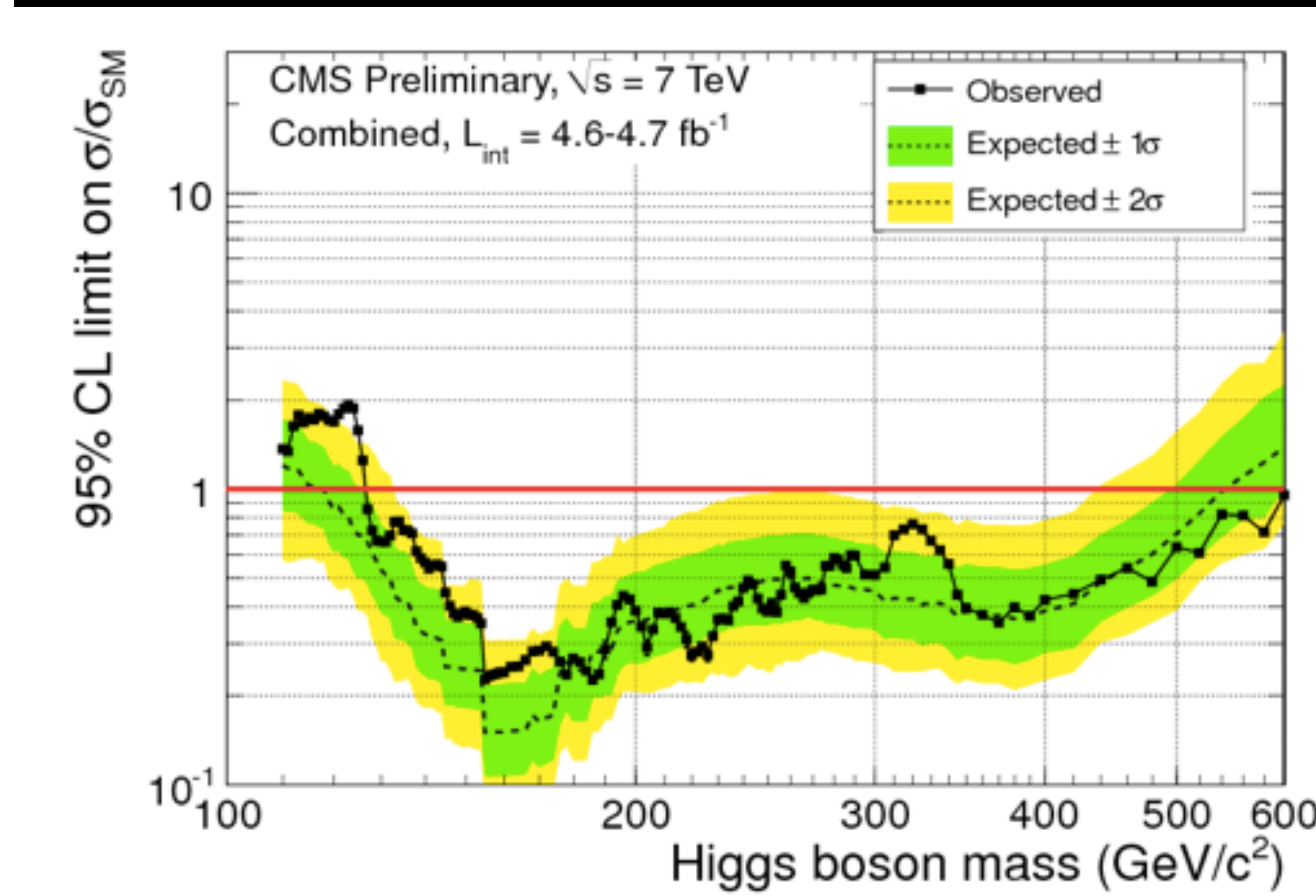

CMS Preliminary, √s = 7 TeV
Combined, Lint = 4.6-4.7 fb-1
Observed
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95% CL limit on σ/σSM
10
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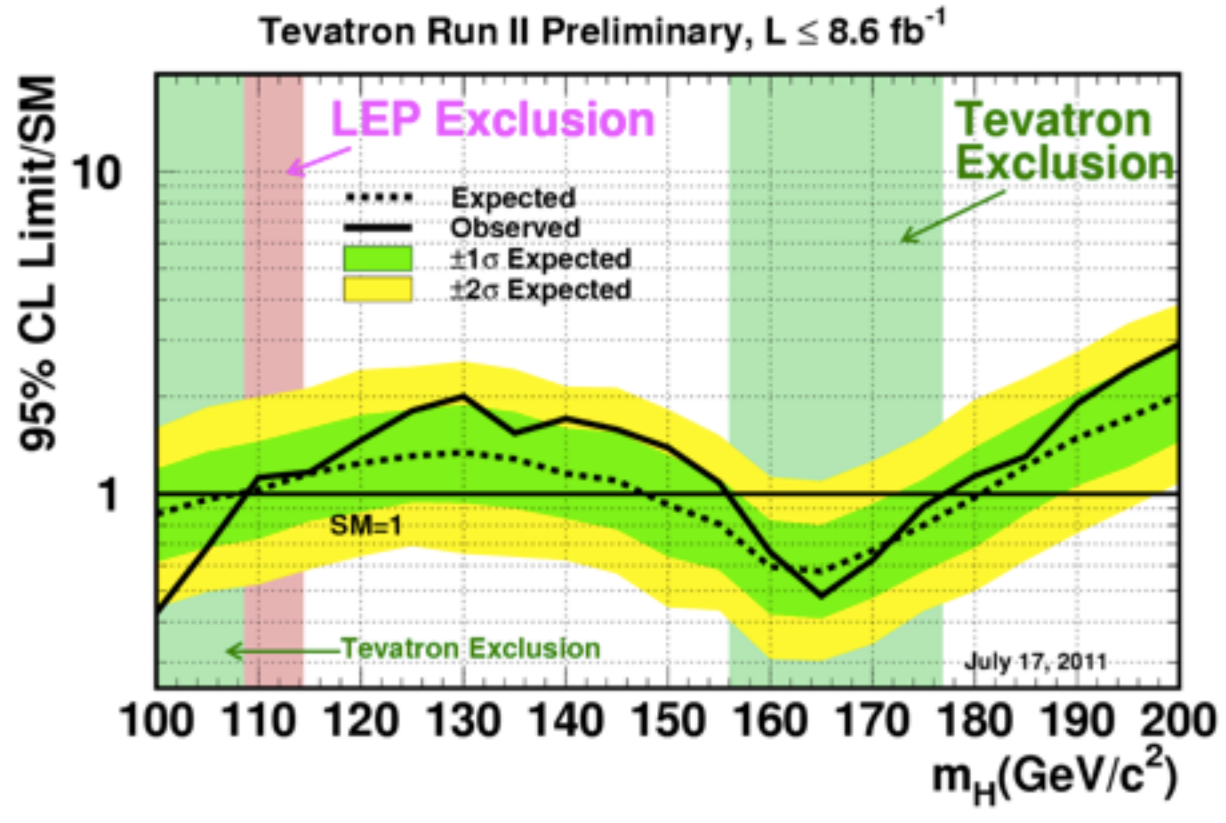
Higgs boson mass (GeV/c2)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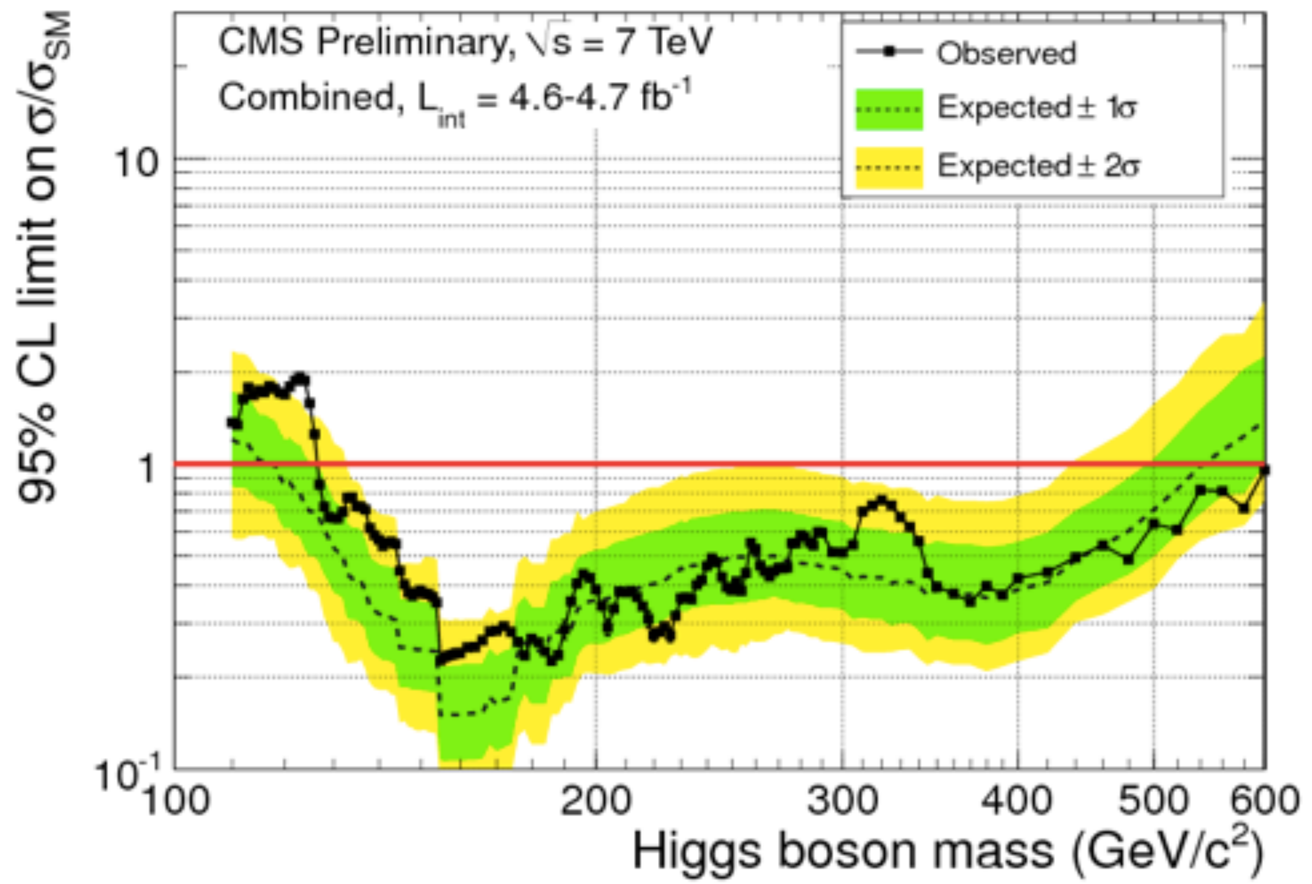
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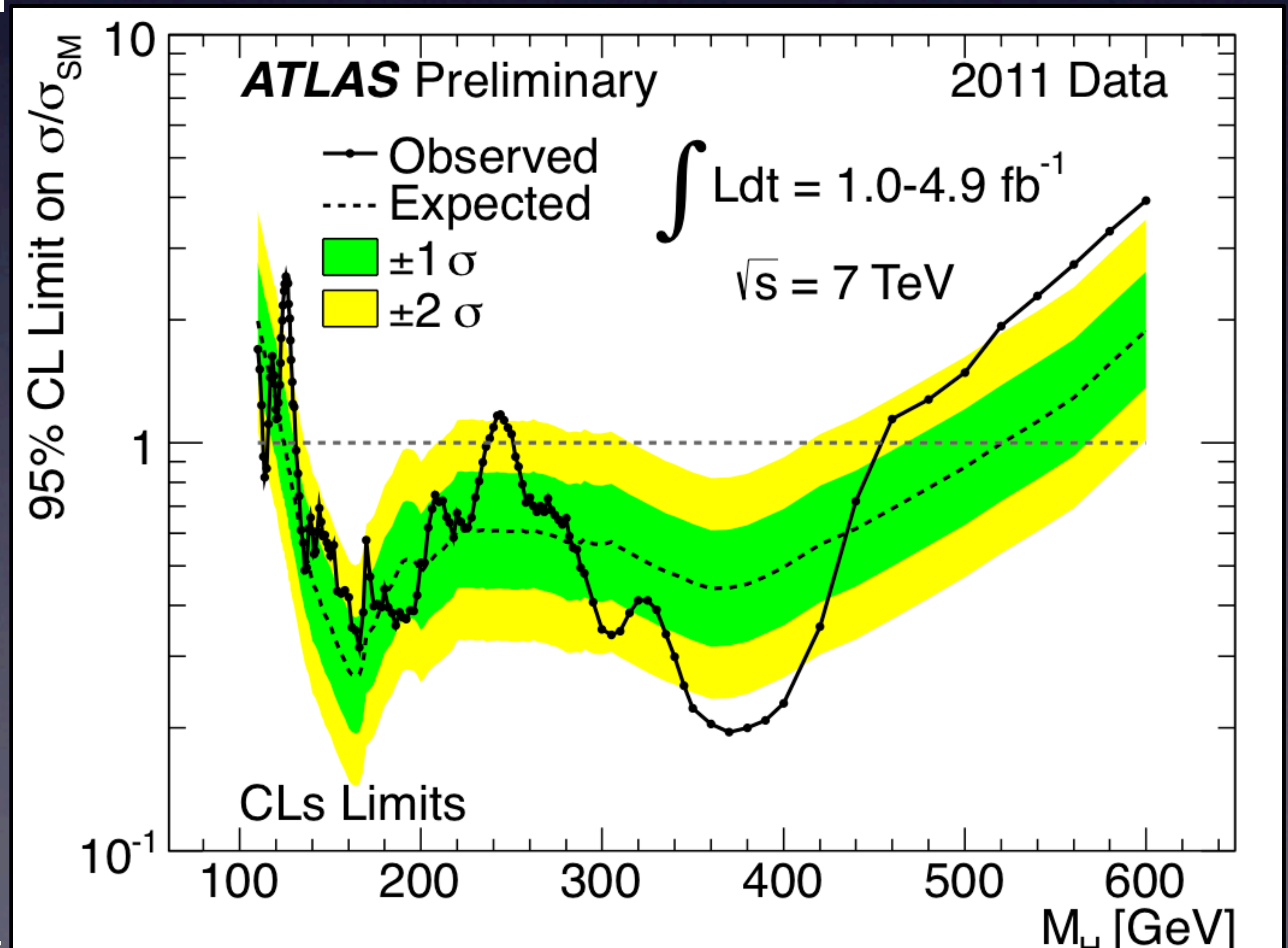
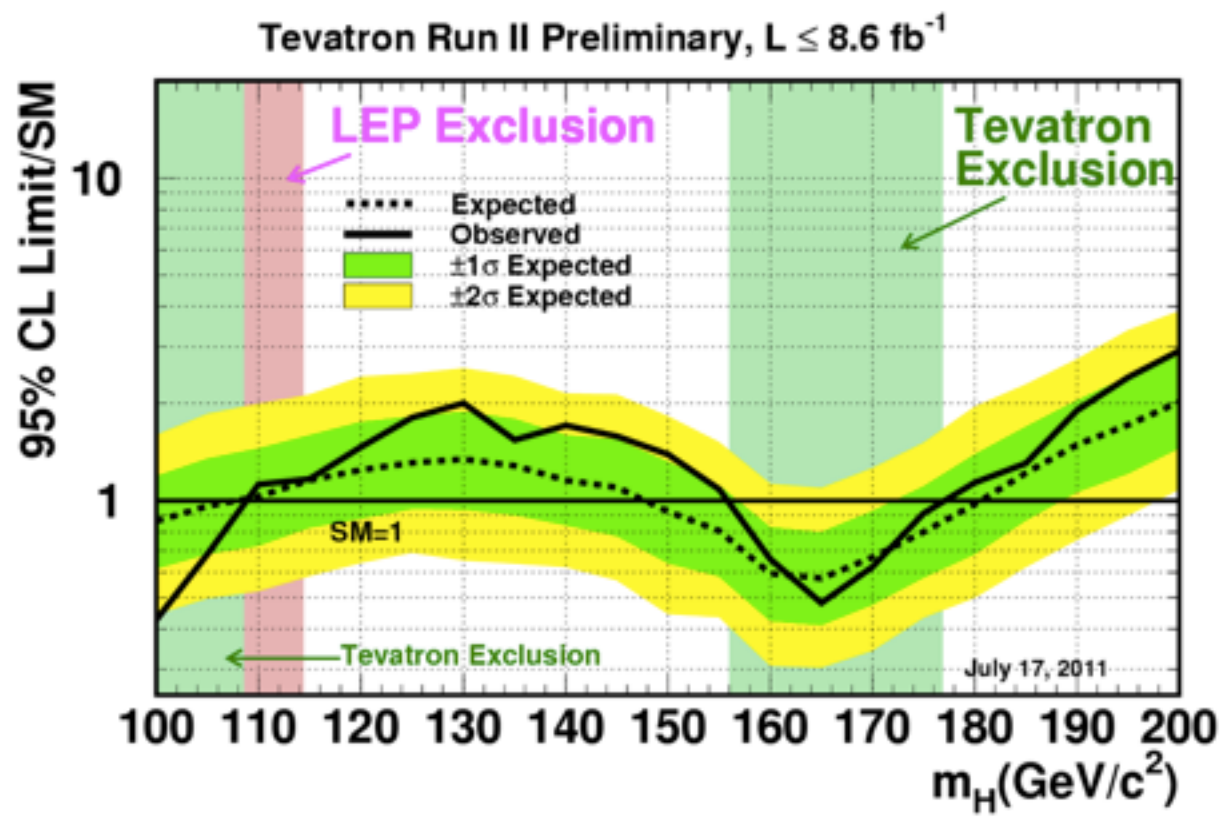
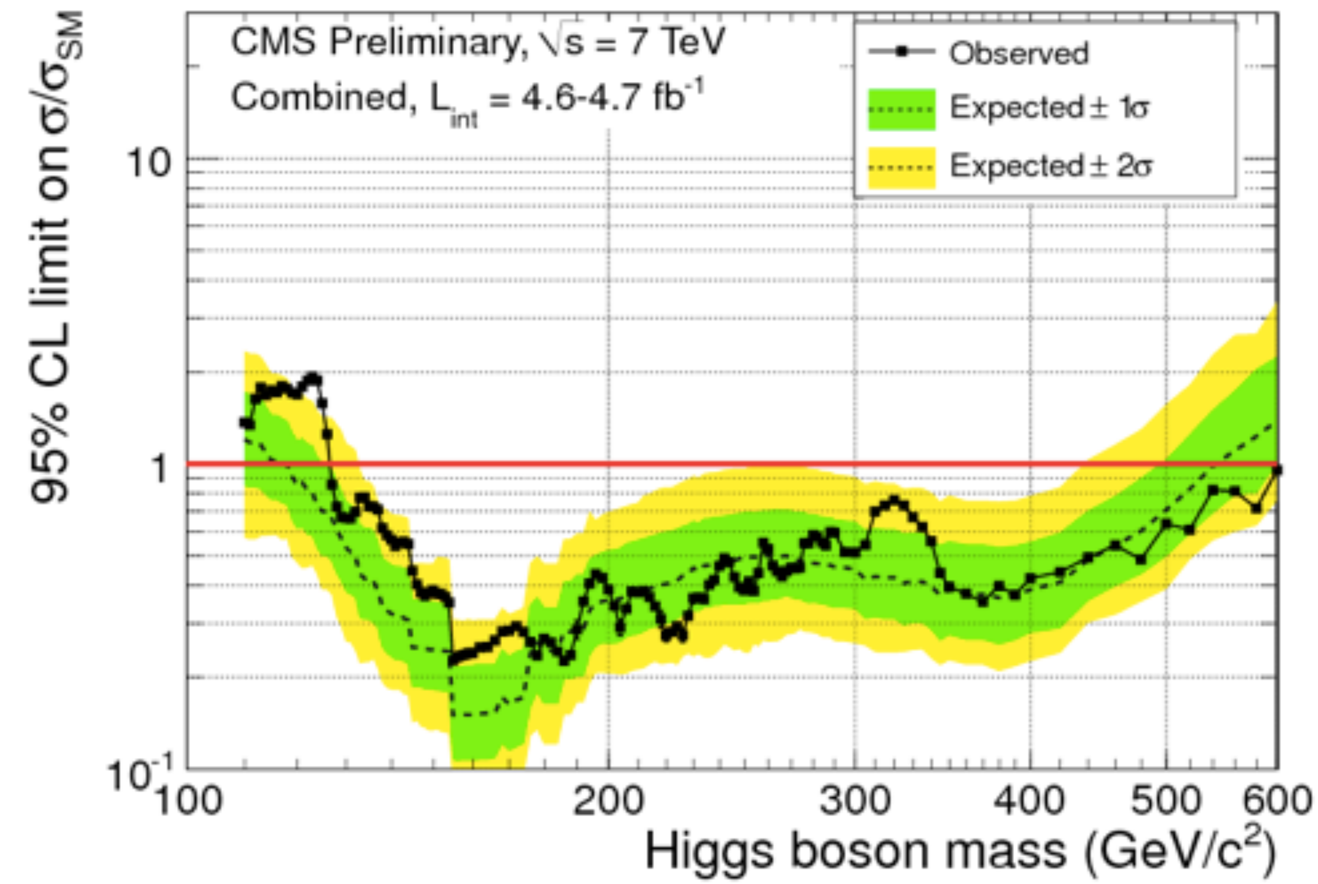
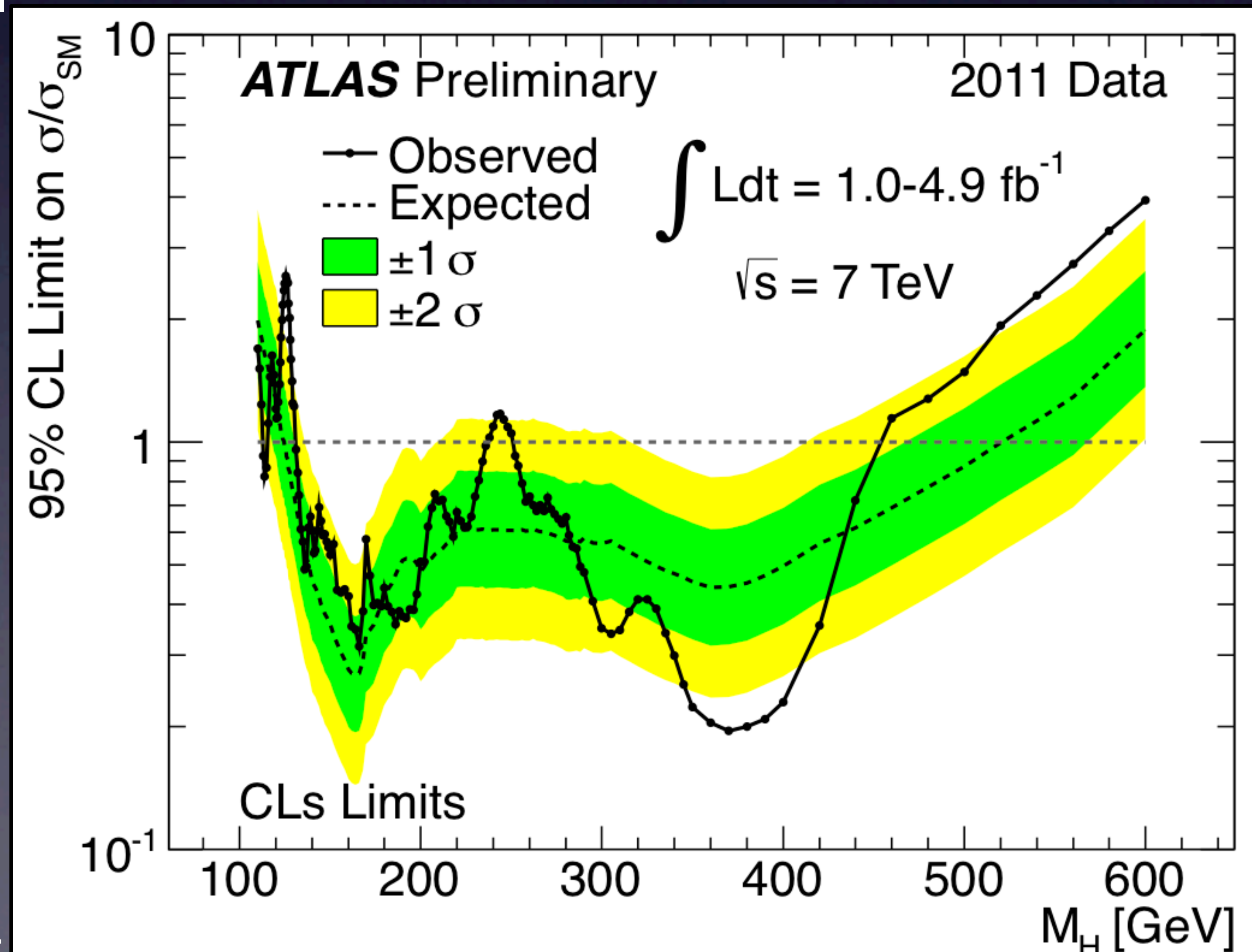
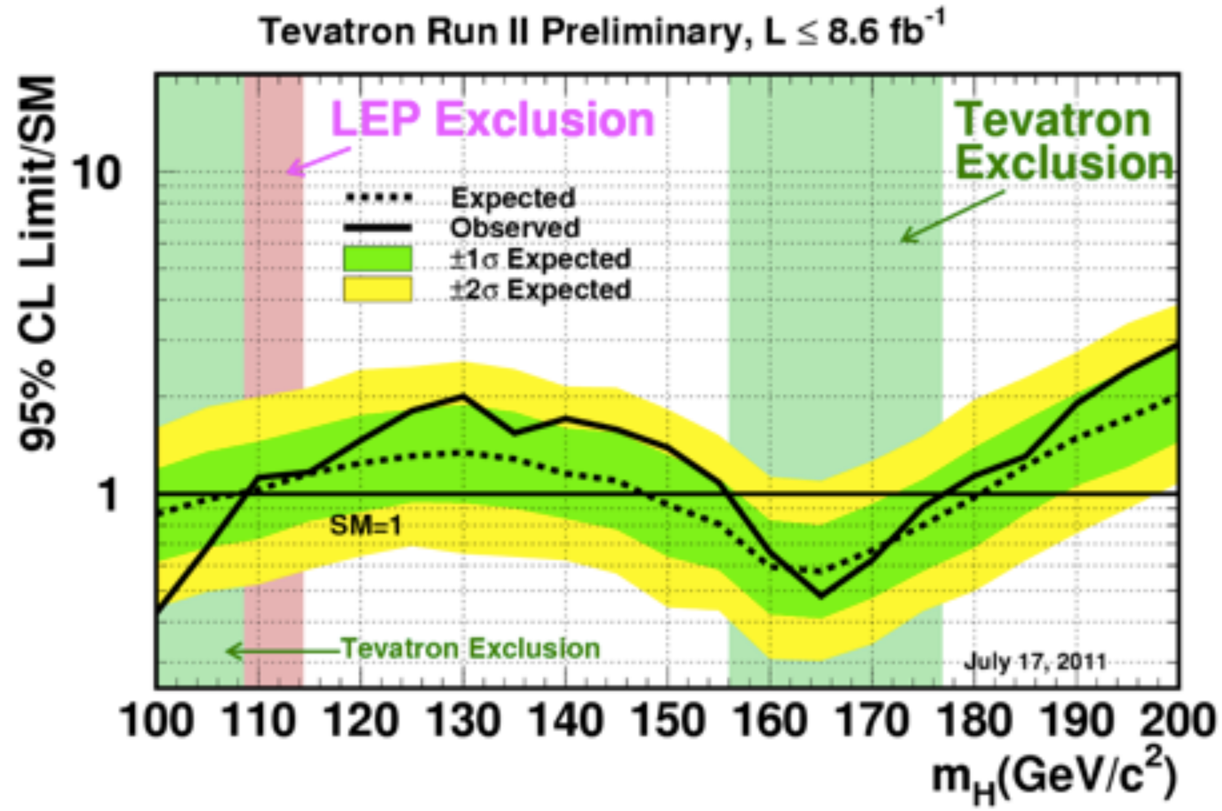

ATLAS Preliminary
2011 Data
Observed
Expected
±1 σ
±2 σ
∫Ldt = 1.0-4.9 fb-1
√s = 7 TeV
CLs Limits
95% CL Limit on σ/σSM
MH [GeV]

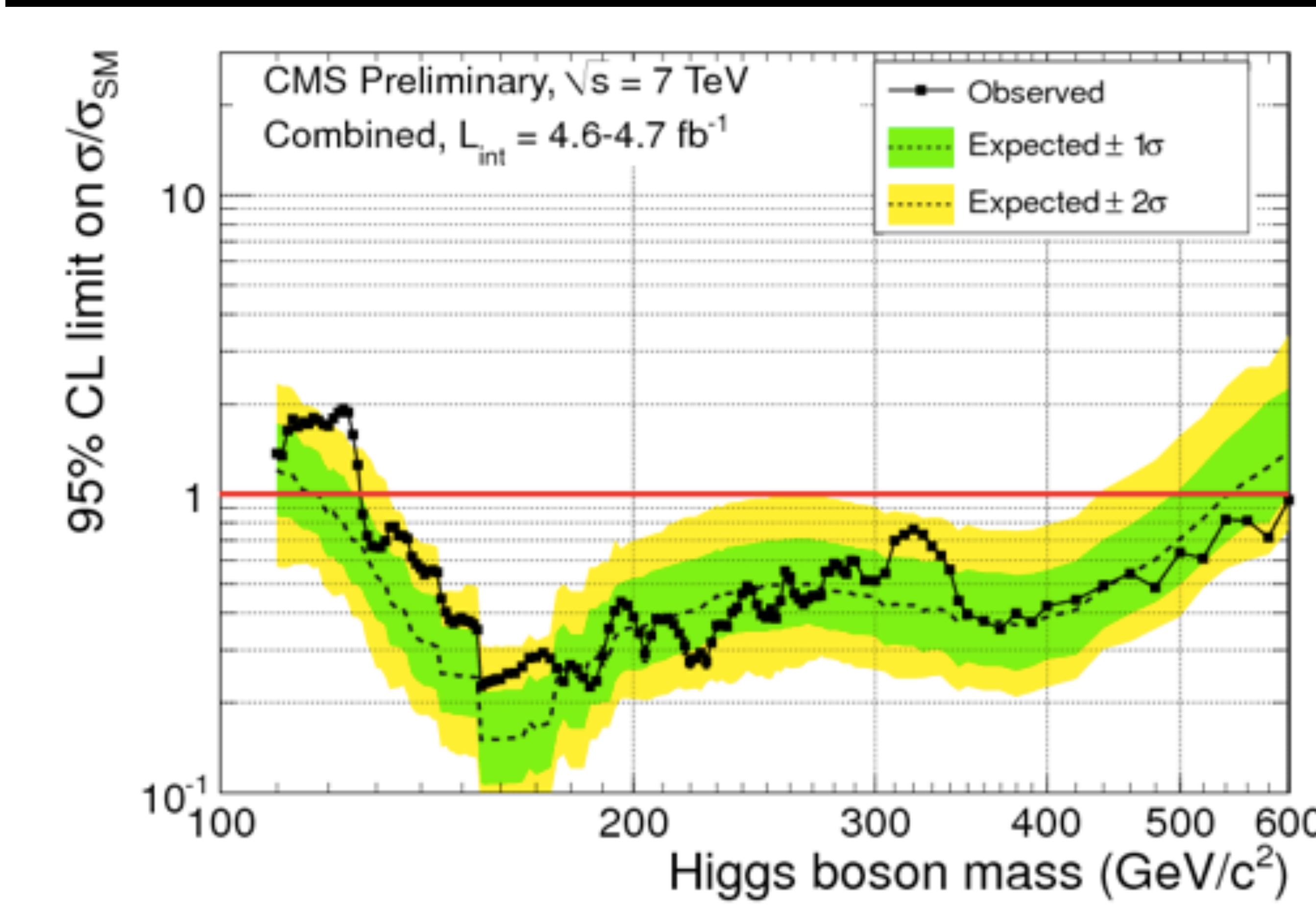


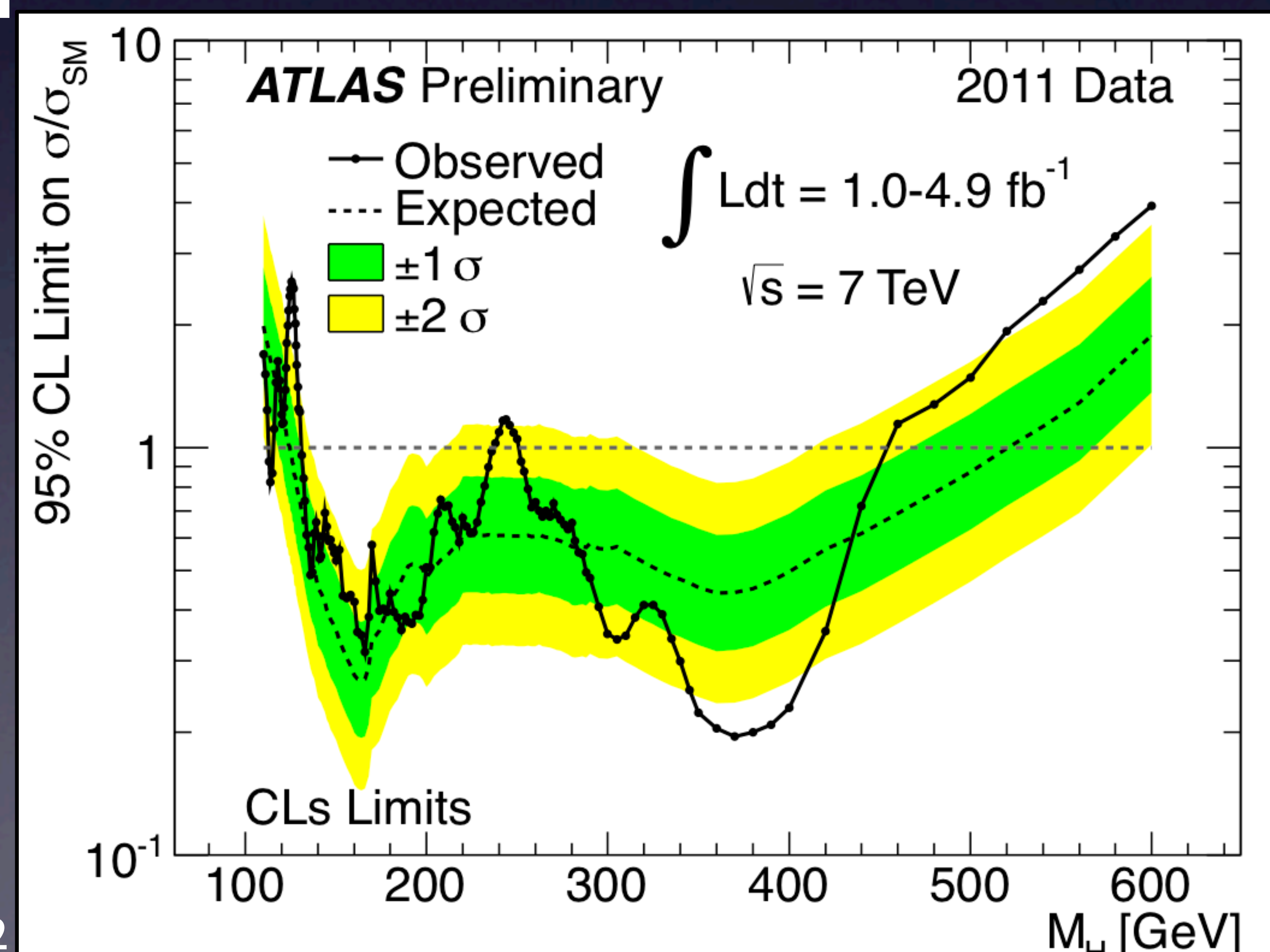




- truly impressive progress







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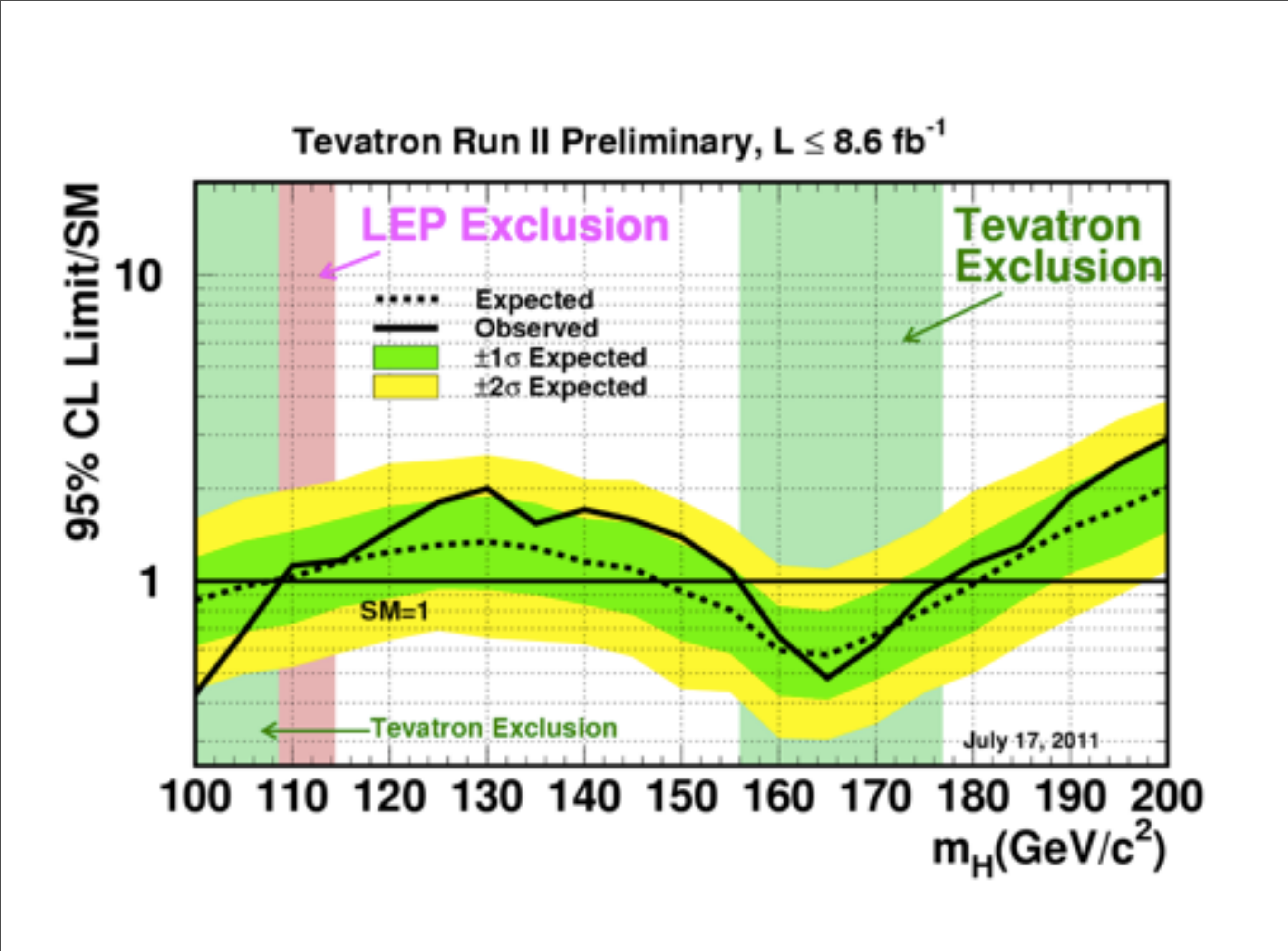
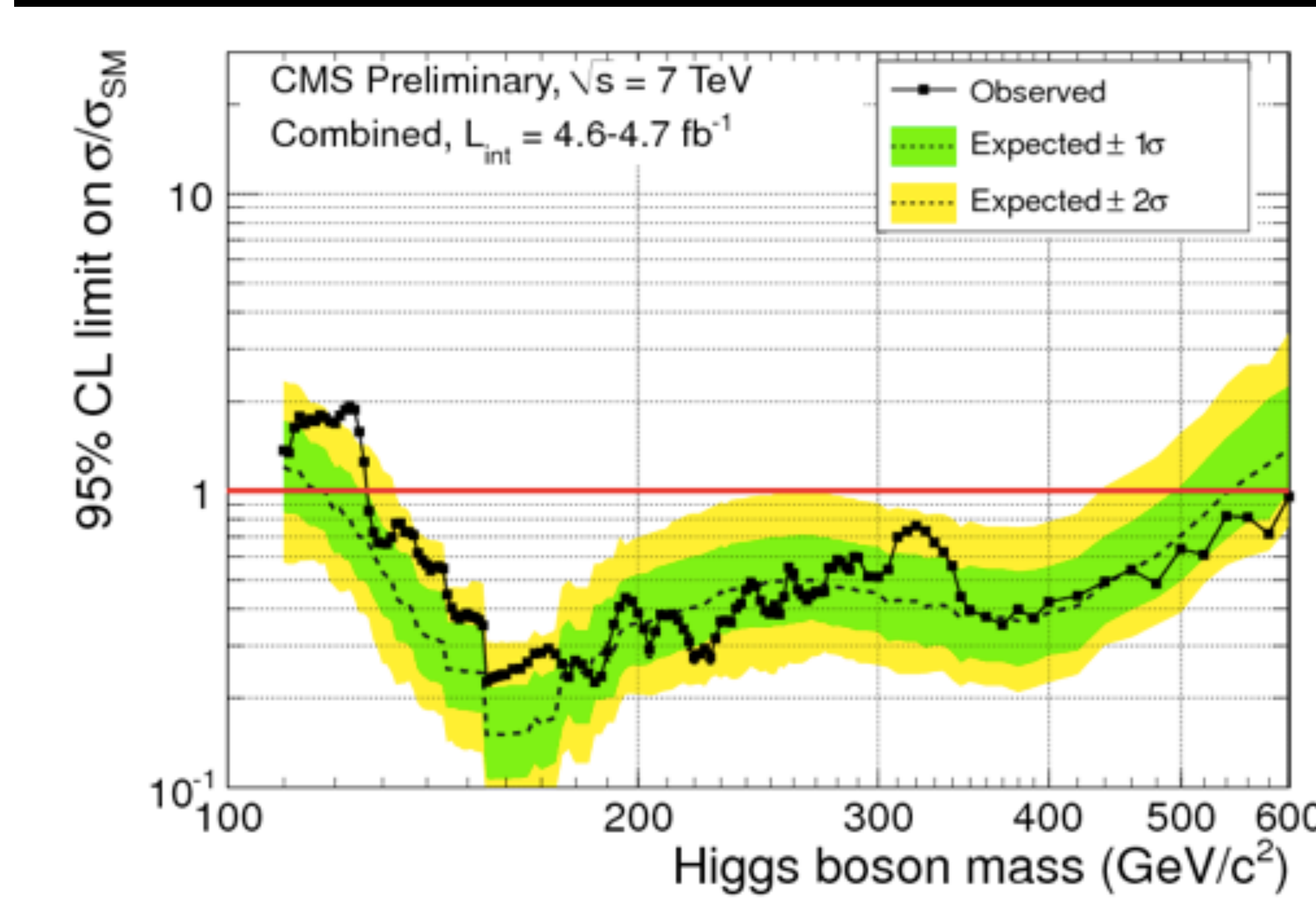
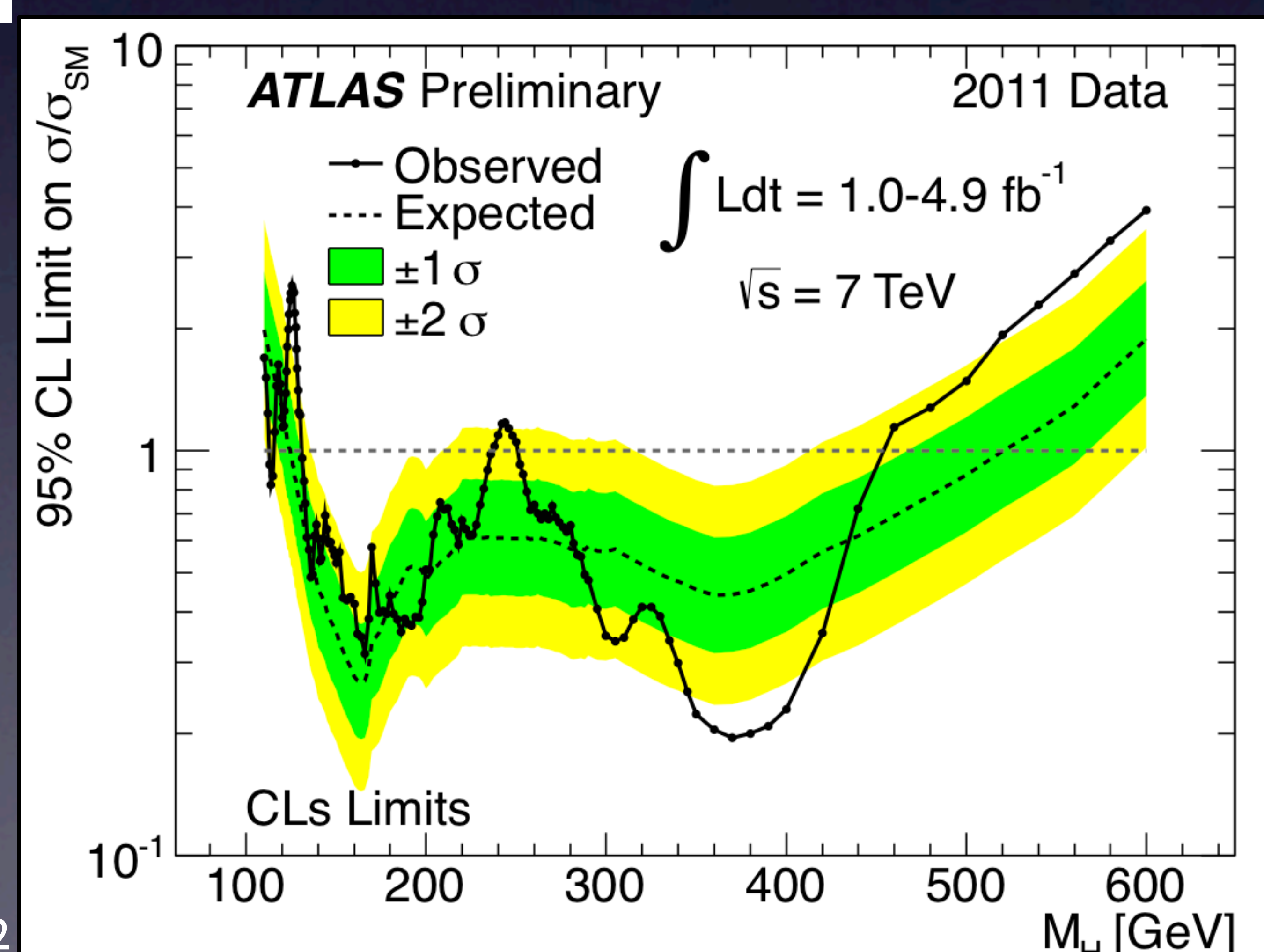
- 115.5<m_h<127 or >600







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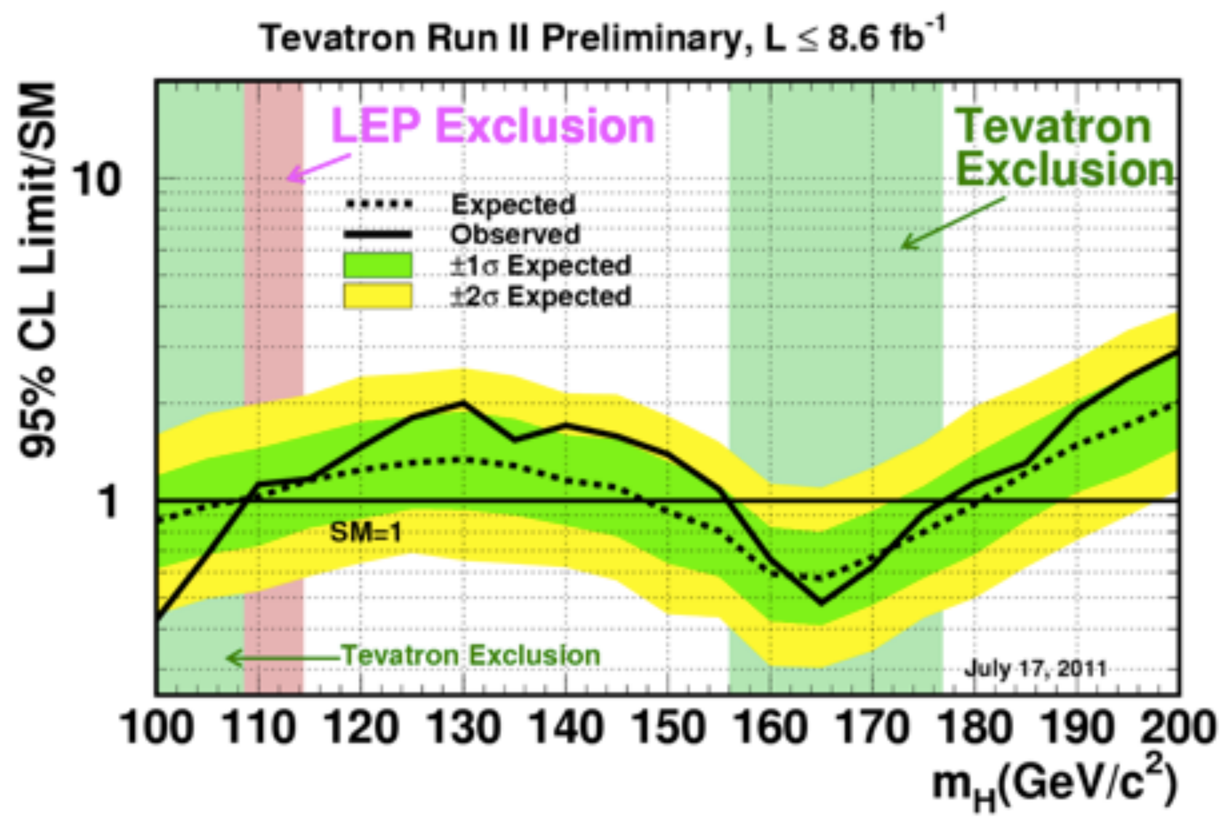
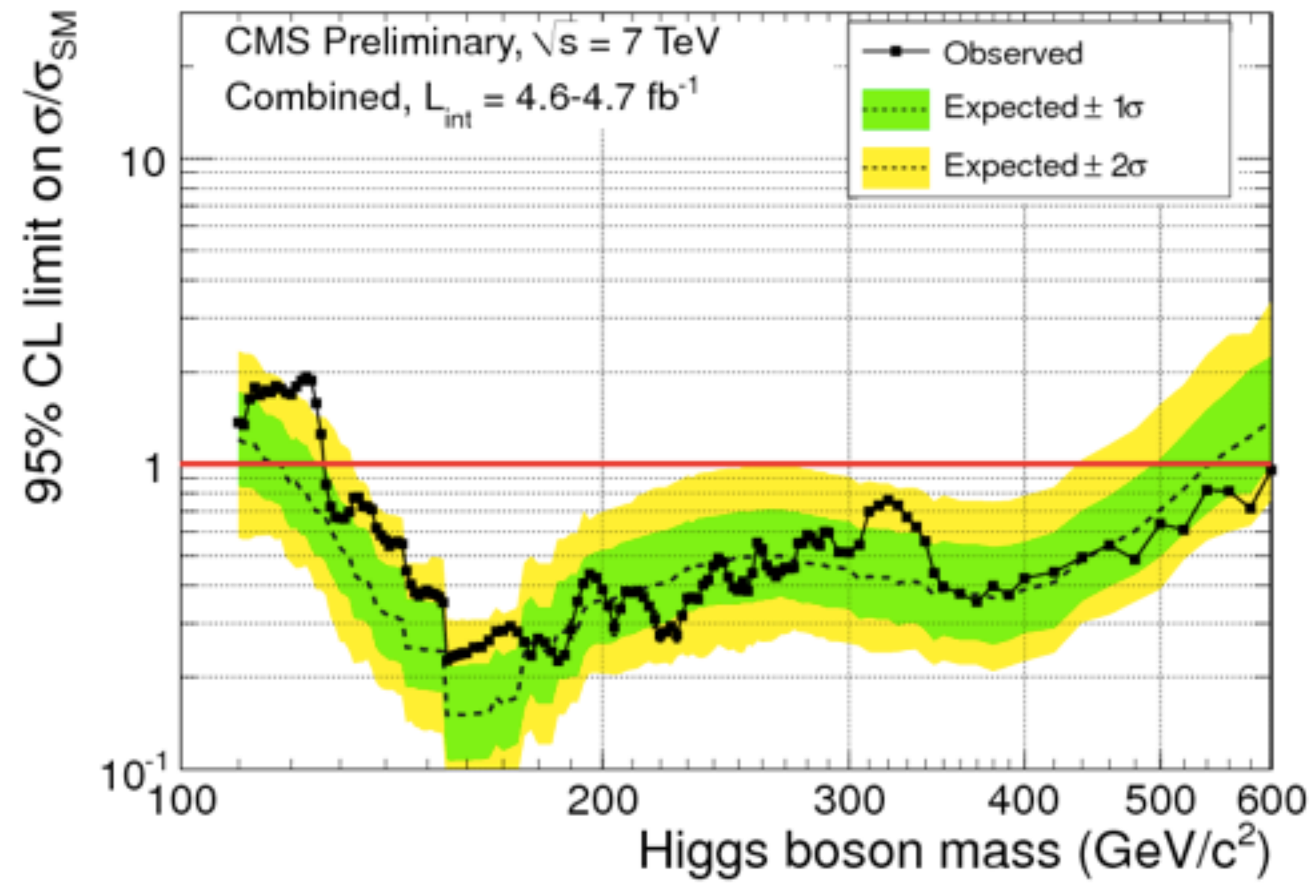
- $115.5 < m_h < 127$ or >600
- If $m_h > 130$, MSSM dead!





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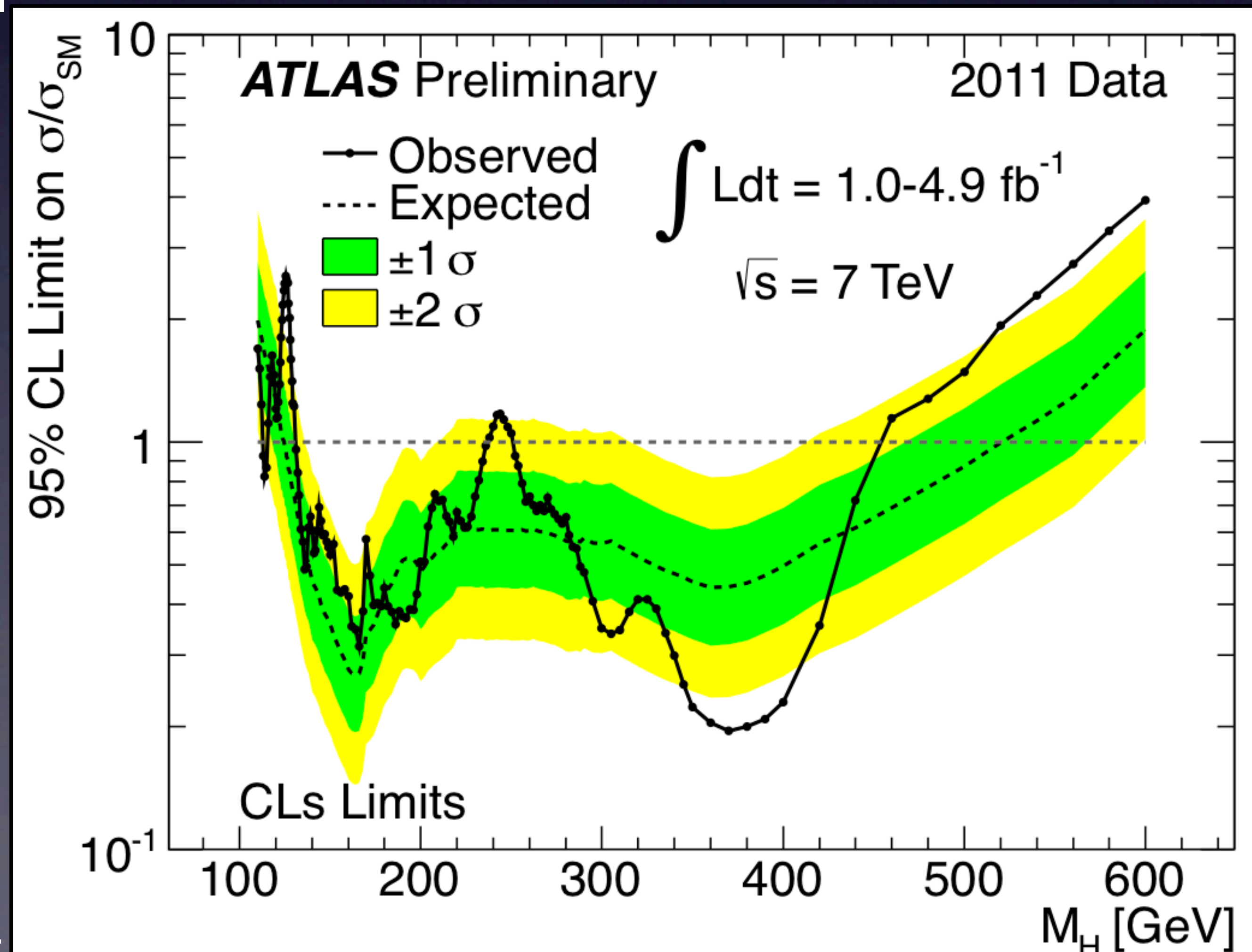
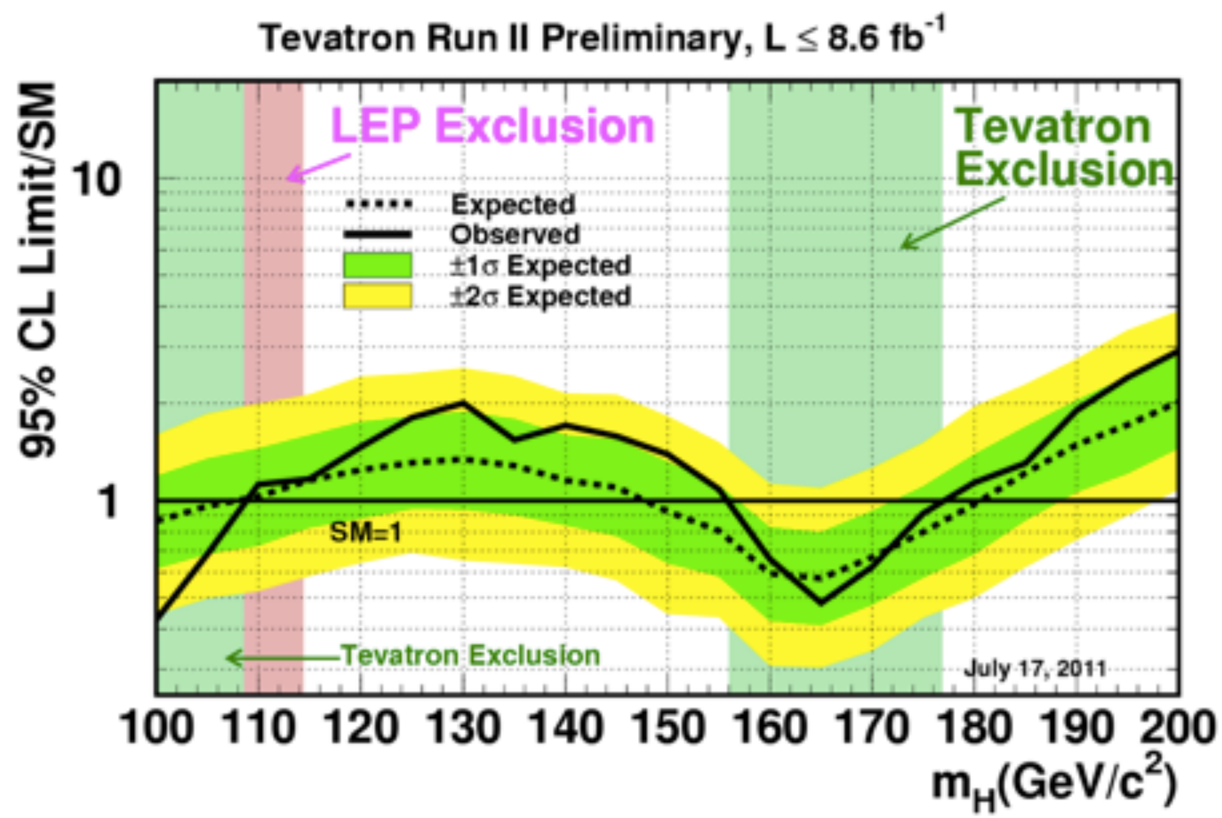
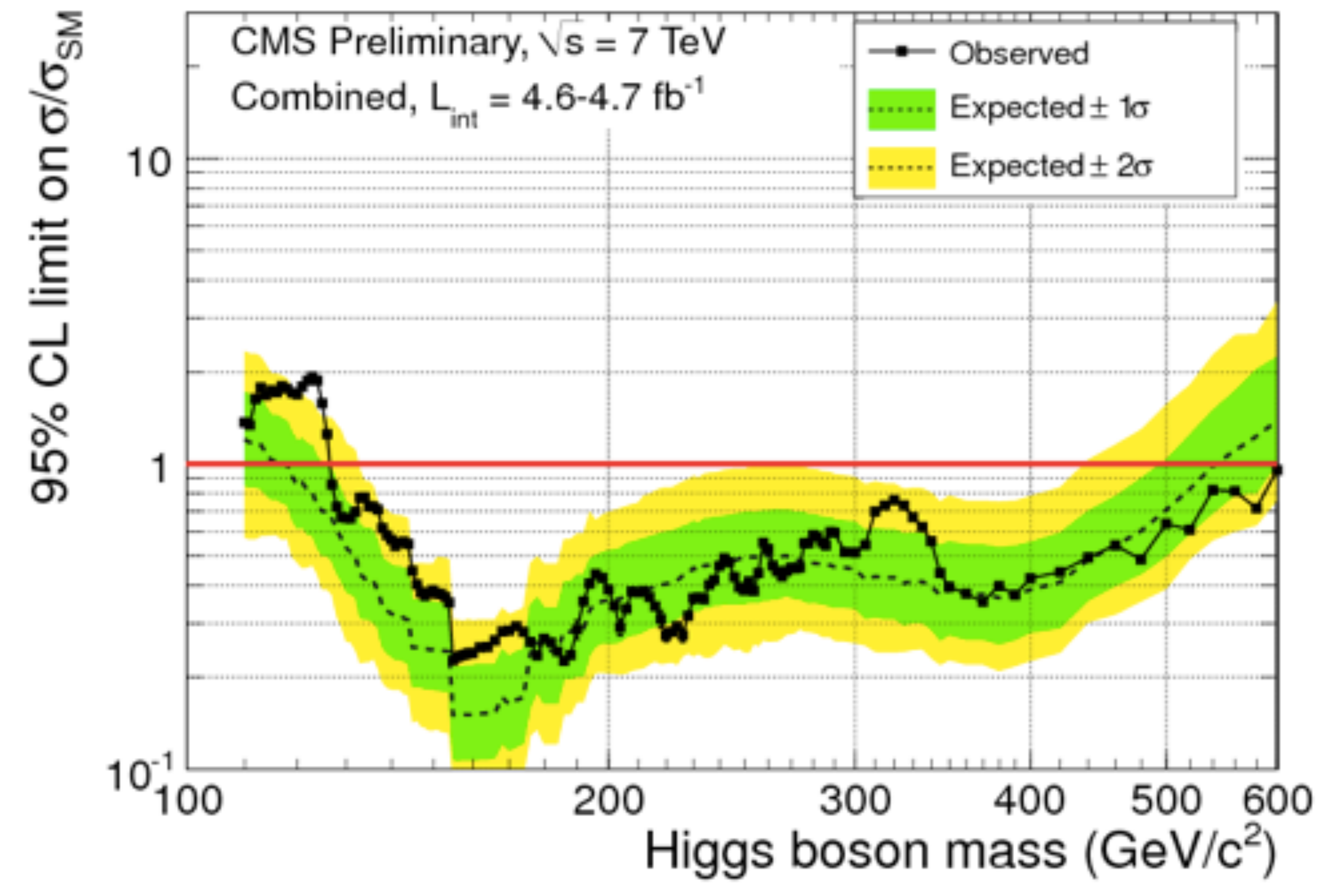
- If m_h>466, need BSM!







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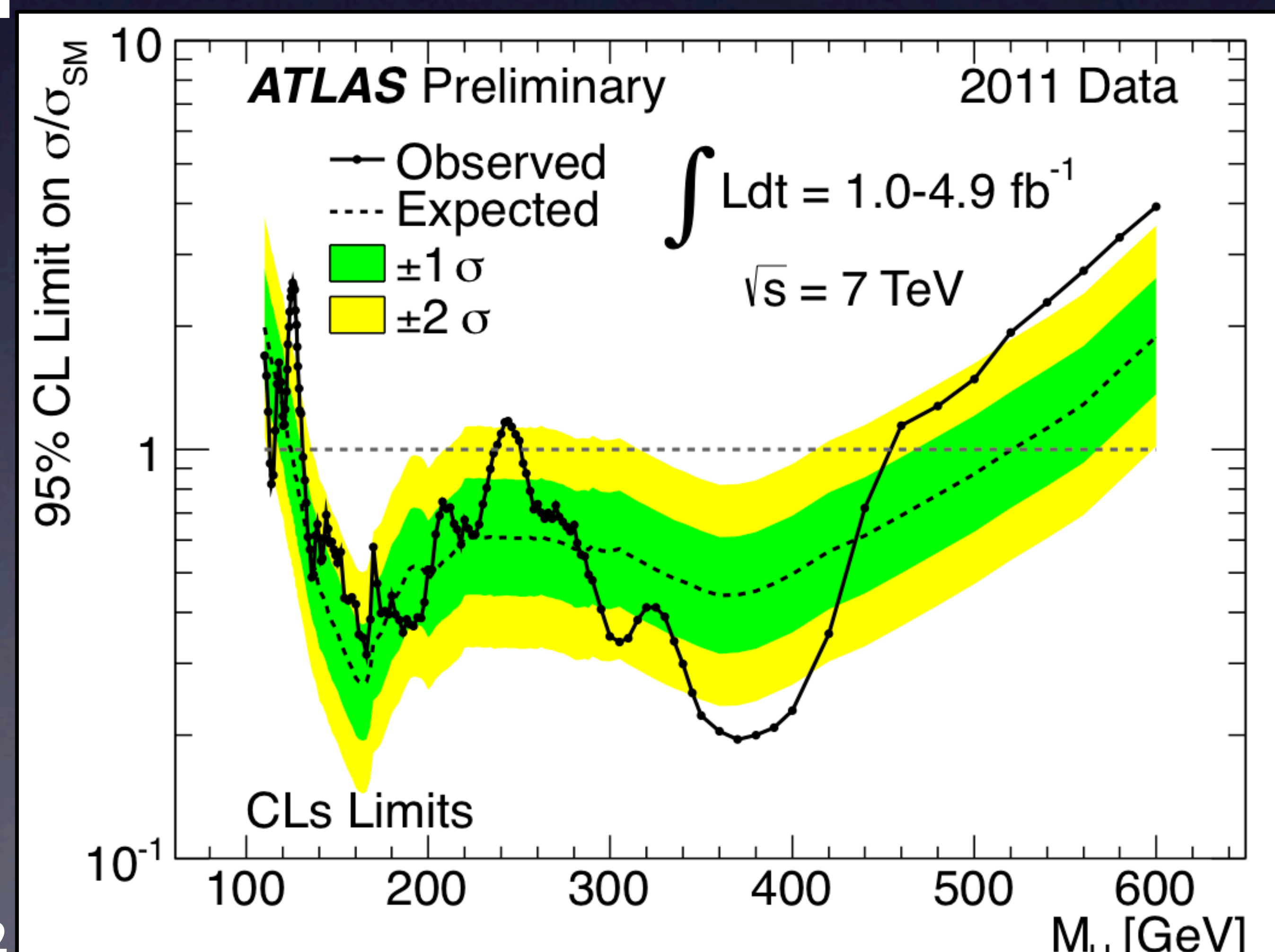
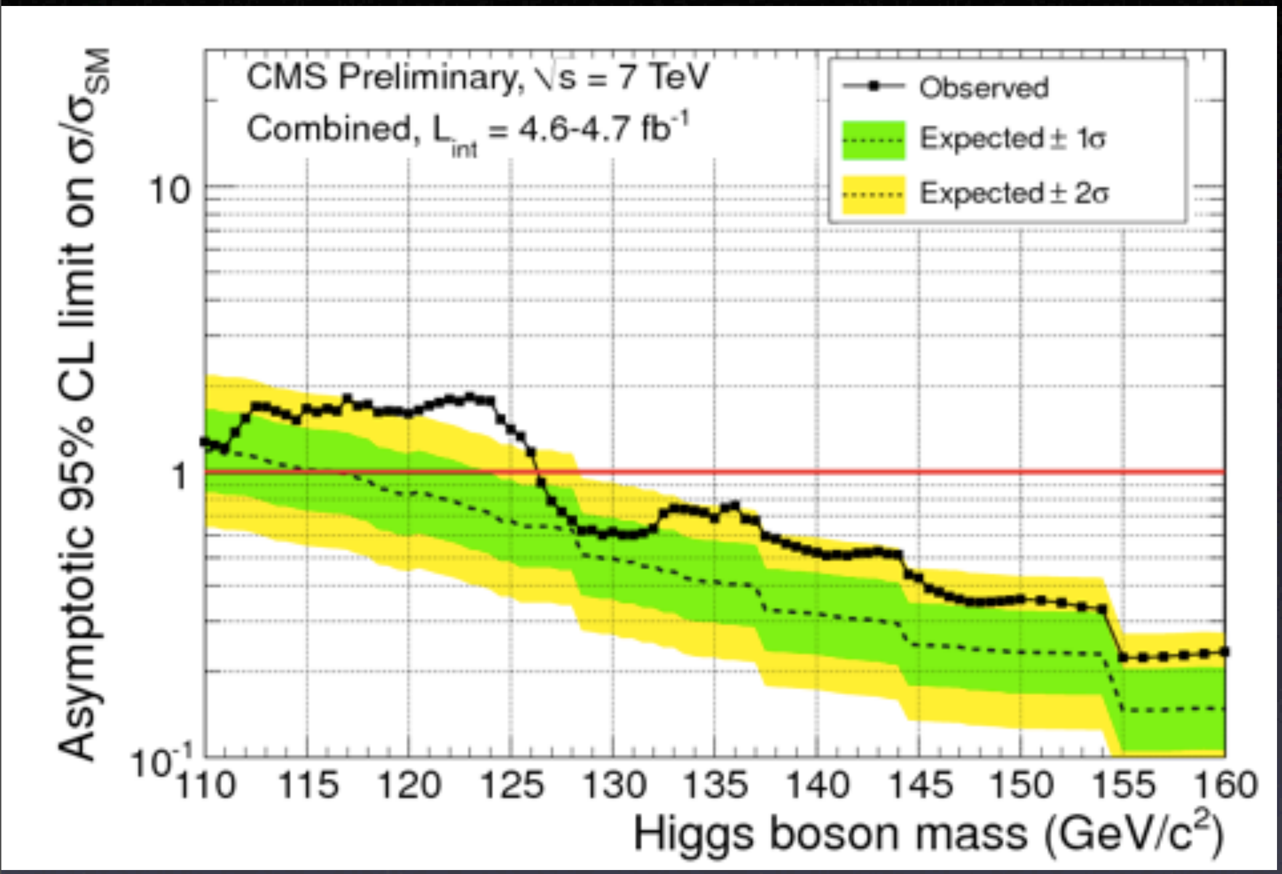
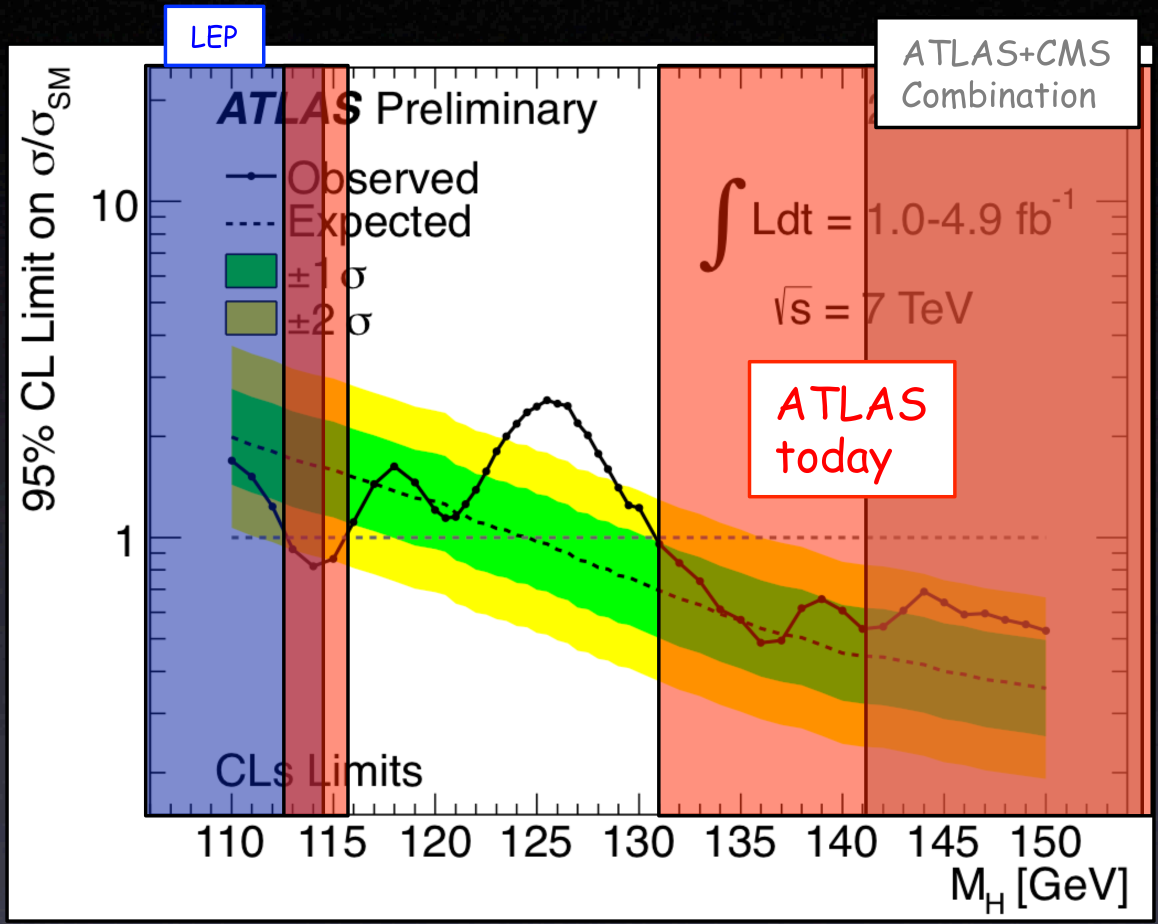
- If m_h>466, need BSM!
- Anyway, a lot to look forward to!



observed?





CMS exclusion
127GeV-600GeV

maximum local significance 2.6σ
1.9σ global after correcting for the LEE in the low mass region

ATLAS exclusion
$112.7 < m_H < 115.5$ GeV
$131 < m_H < 453$ GeV
except 237-251 GeV
excess 2.4 σ local, ~ 2.3 σ with LEE

CERN official statement

Taken individually, none of these excesses is any more statistically significant than rolling a die and coming up with two sixes in a row. What is interesting is that there are multiple independent measurements pointing to the region of 124 to 126 GeV. It's far too early to say whether ATLAS and CMS have discovered the Higgs boson, but these updated results are generating a lot of interest in the particle physics community.

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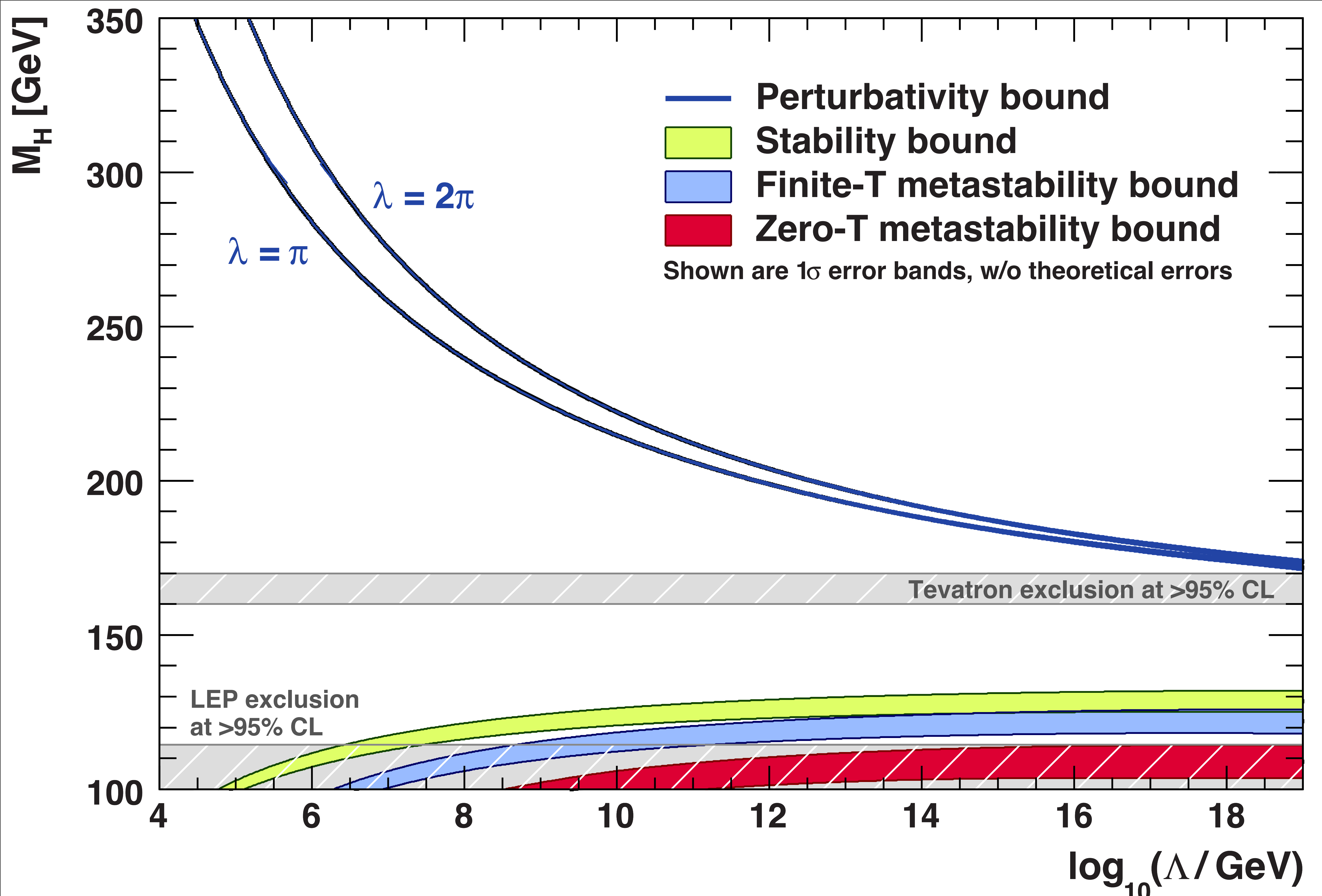
- didn't stop theorists from speculating!

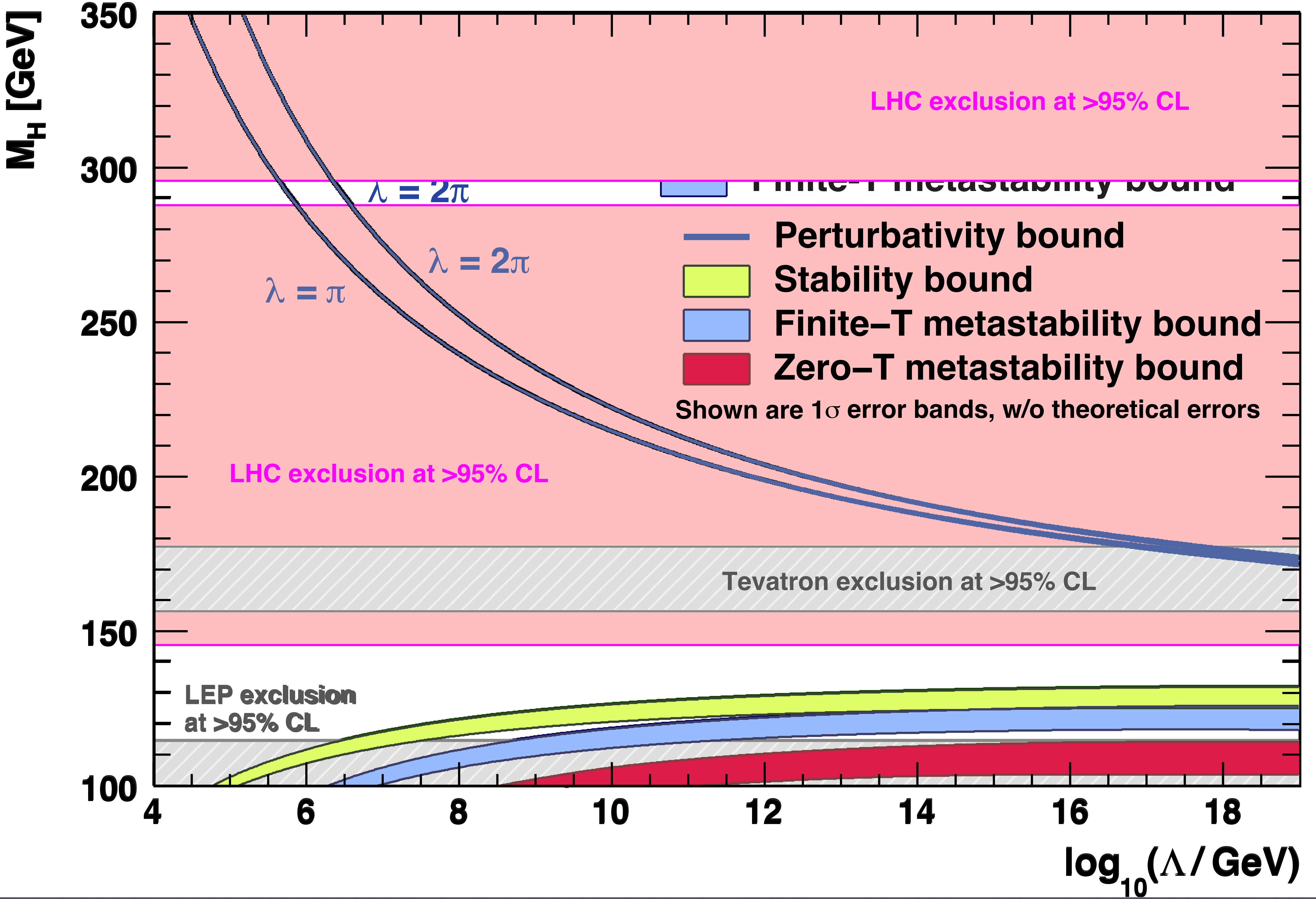
What do we learn from the Higgs boson mass?

Higgs allows a look into higher energies

- Higgs self-coupling can $\frac{d}{dt}\lambda \sim +\lambda^2 + g^2\lambda - h_t^4$
  - grow if big □ Landau pole, composite?
  - go negative if small □ instability $m_h \propto \lambda v$
- If m_H>600 GeV, it grows very quickly, basically with a few TeV cutoff
  - need new physics < a few TeV because of the inconsistency with low-energy data
- most focused on the light window



Harigaya, Matsumoto, HM



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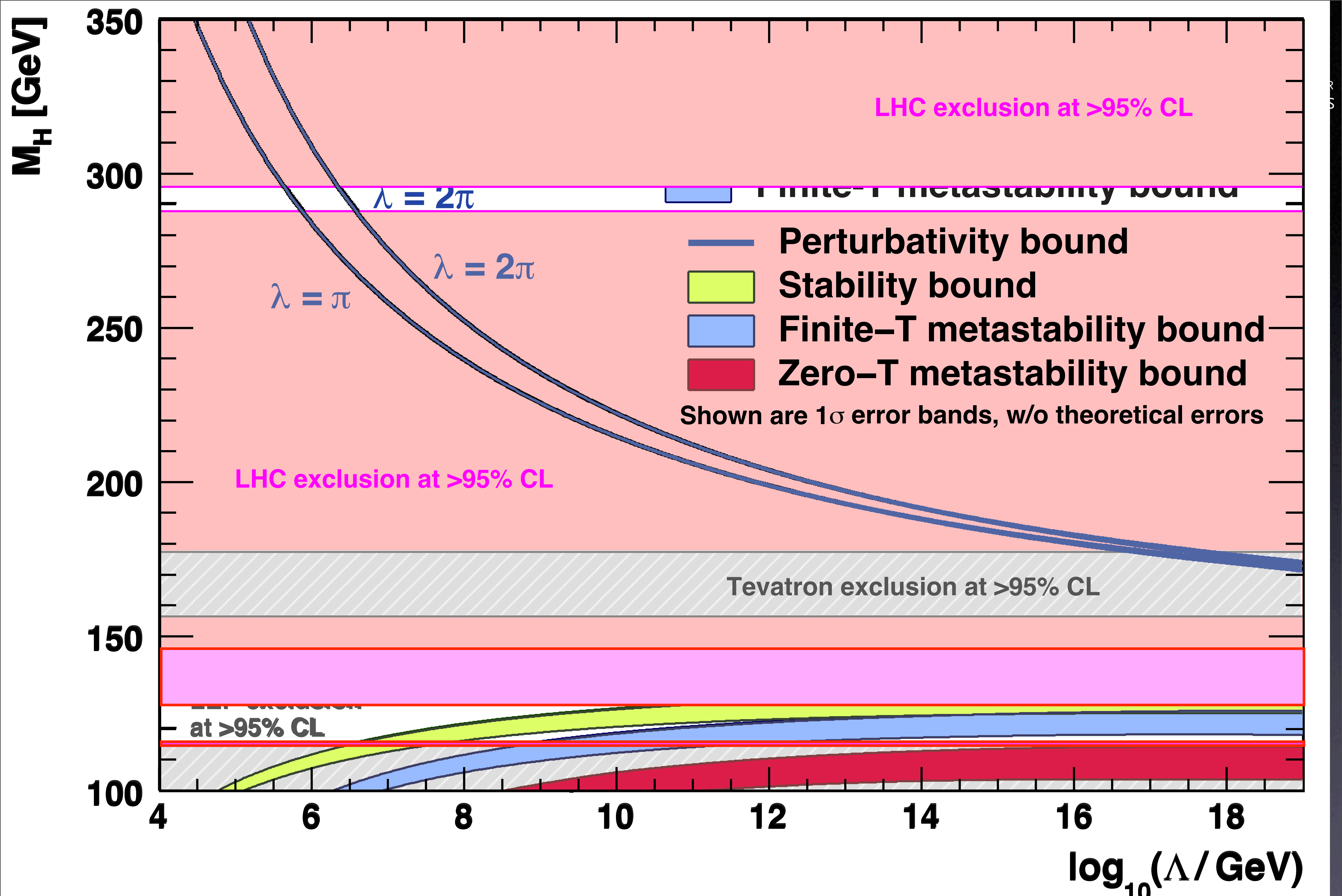


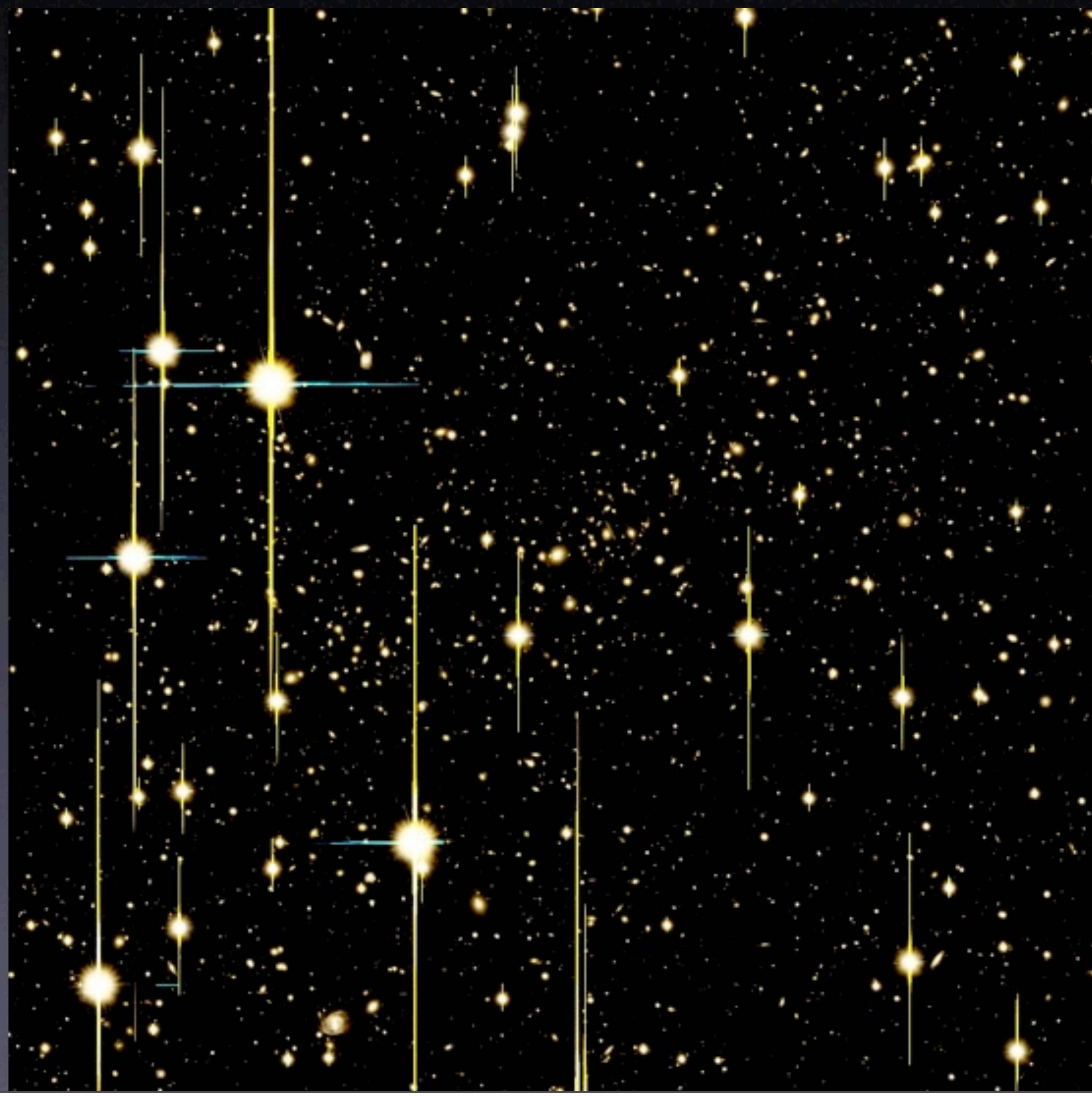
Harigaya, Matsumoto, HM

a few points

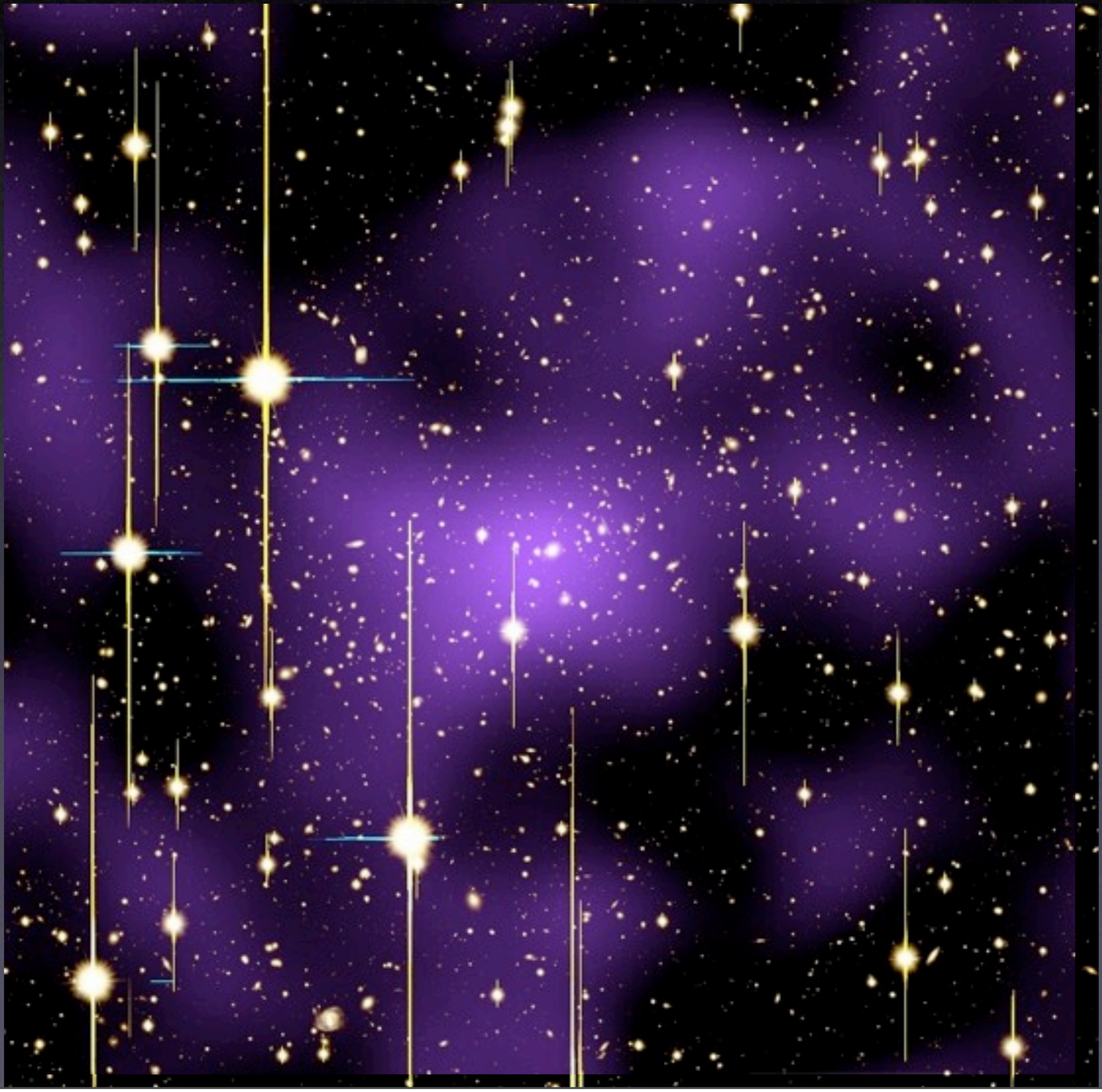
- The experimentally suggested Higgs boson mass is consistent with weak-coupled theory up to very high energies
  - grand unification
  - supersymmetry
- if on low end, need new physics below 10^8GeV to prevent us from decaying

Why the Terascale?
—dark matter—

"Seeing" invisible dark matter



“Seeing” invisible dark matter



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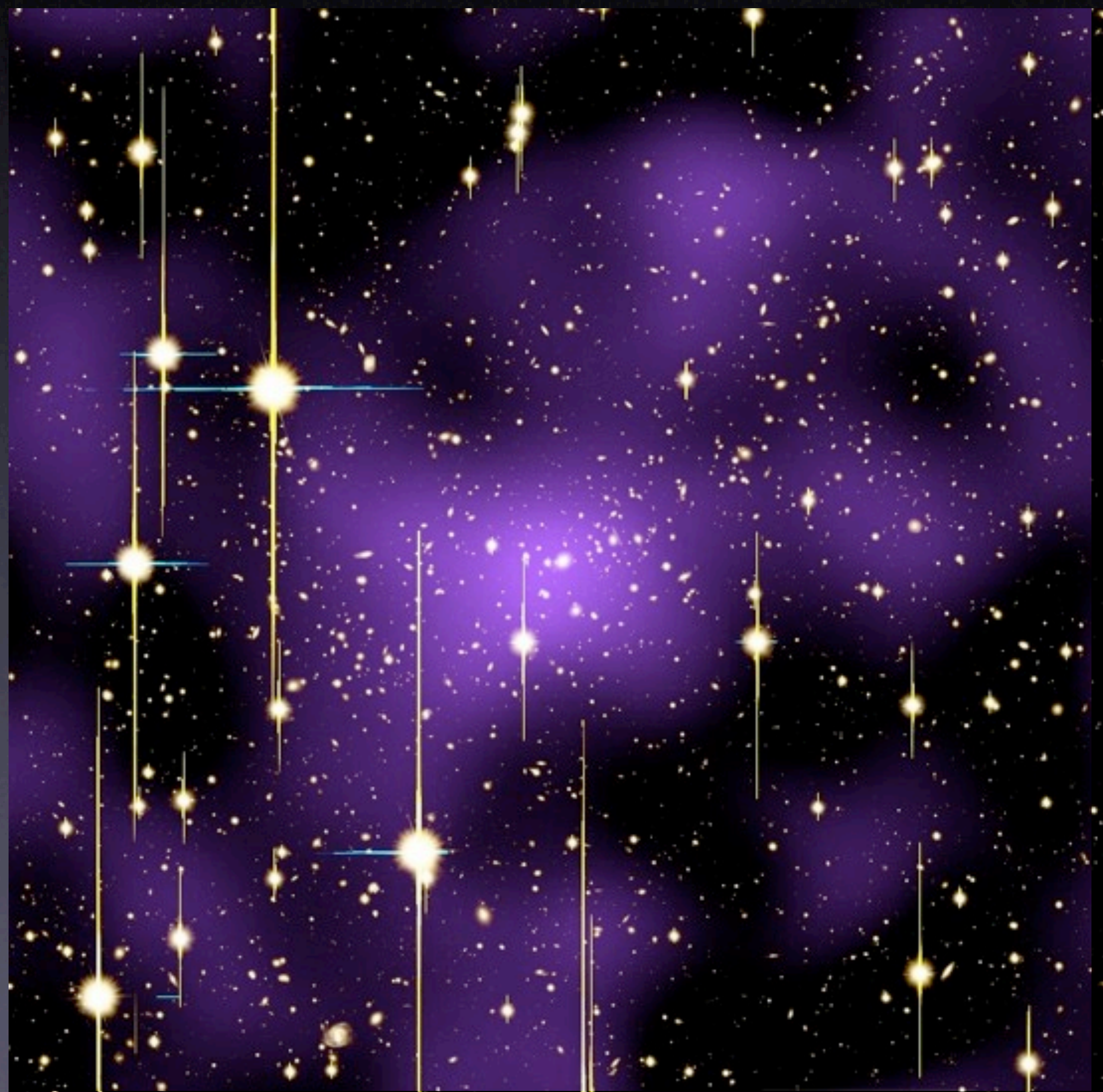

22% of the Universe

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)

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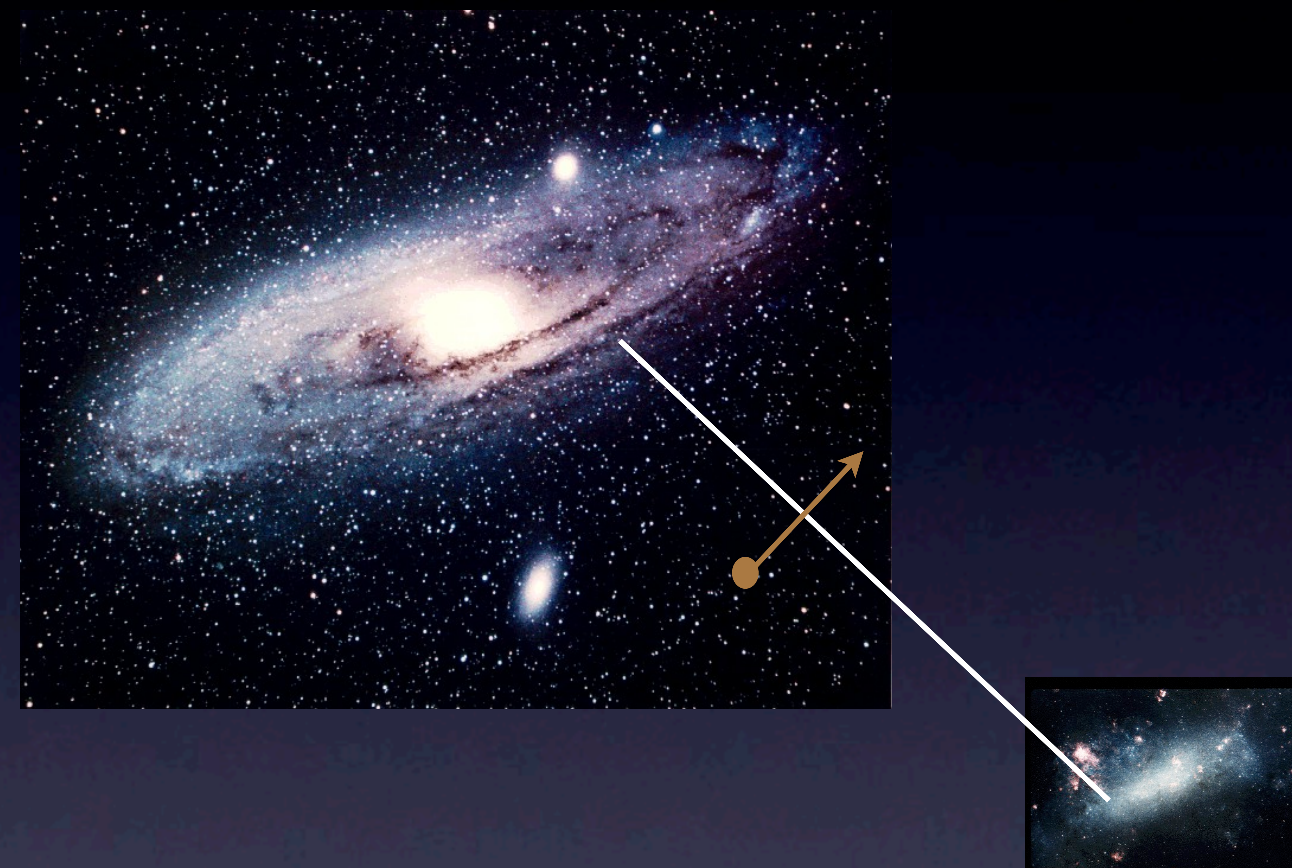

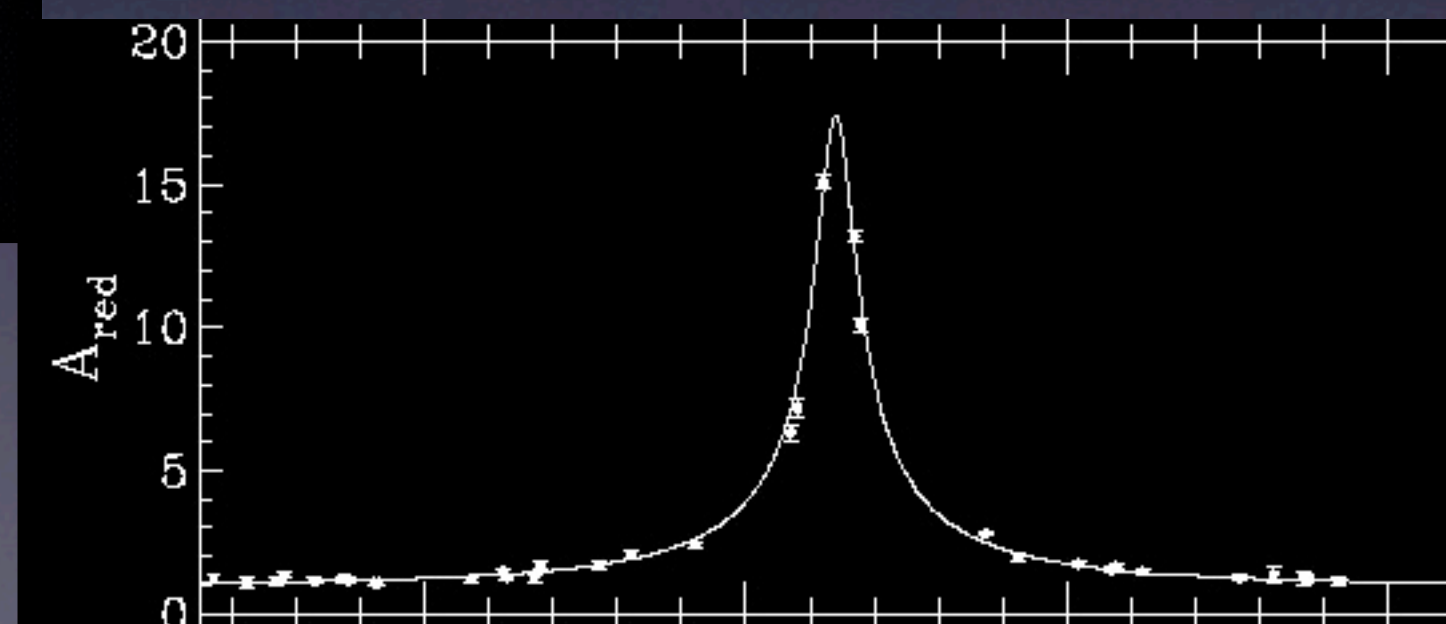

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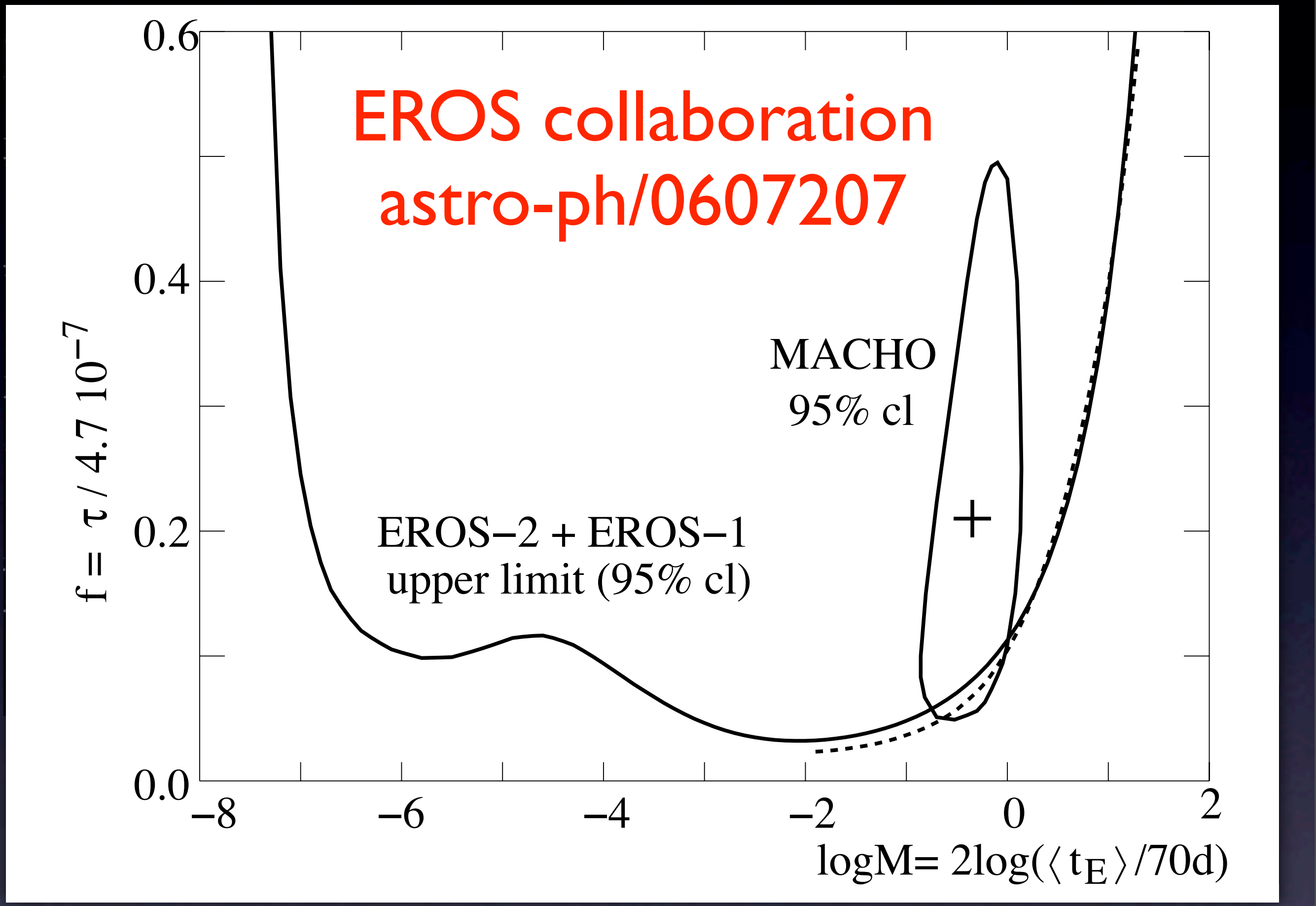

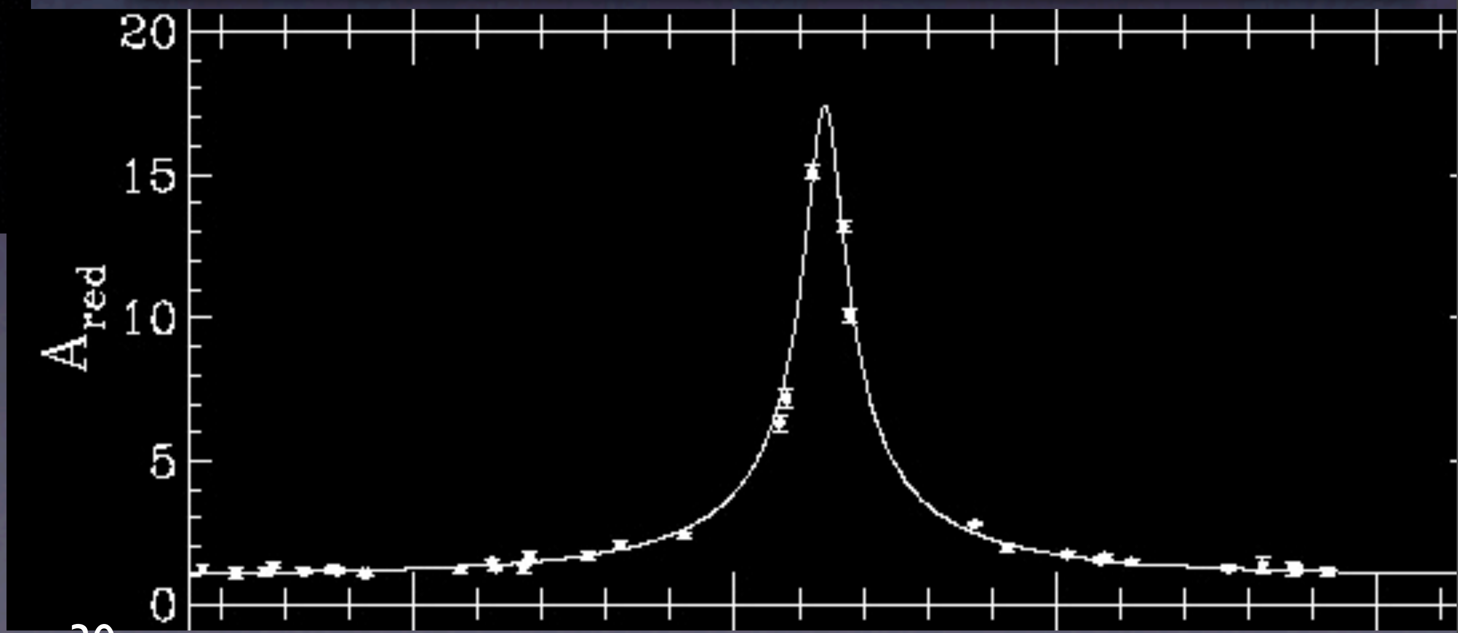

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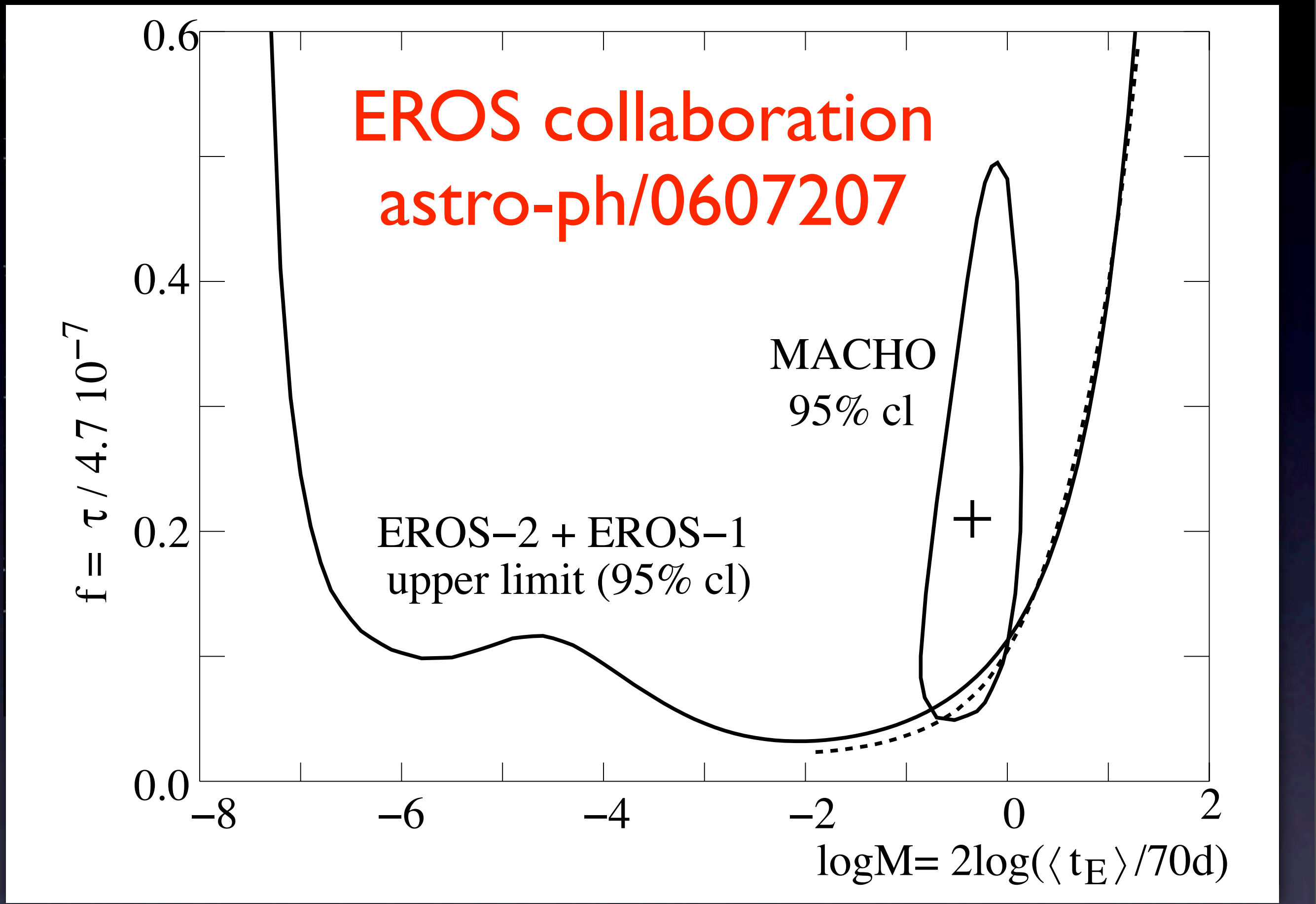

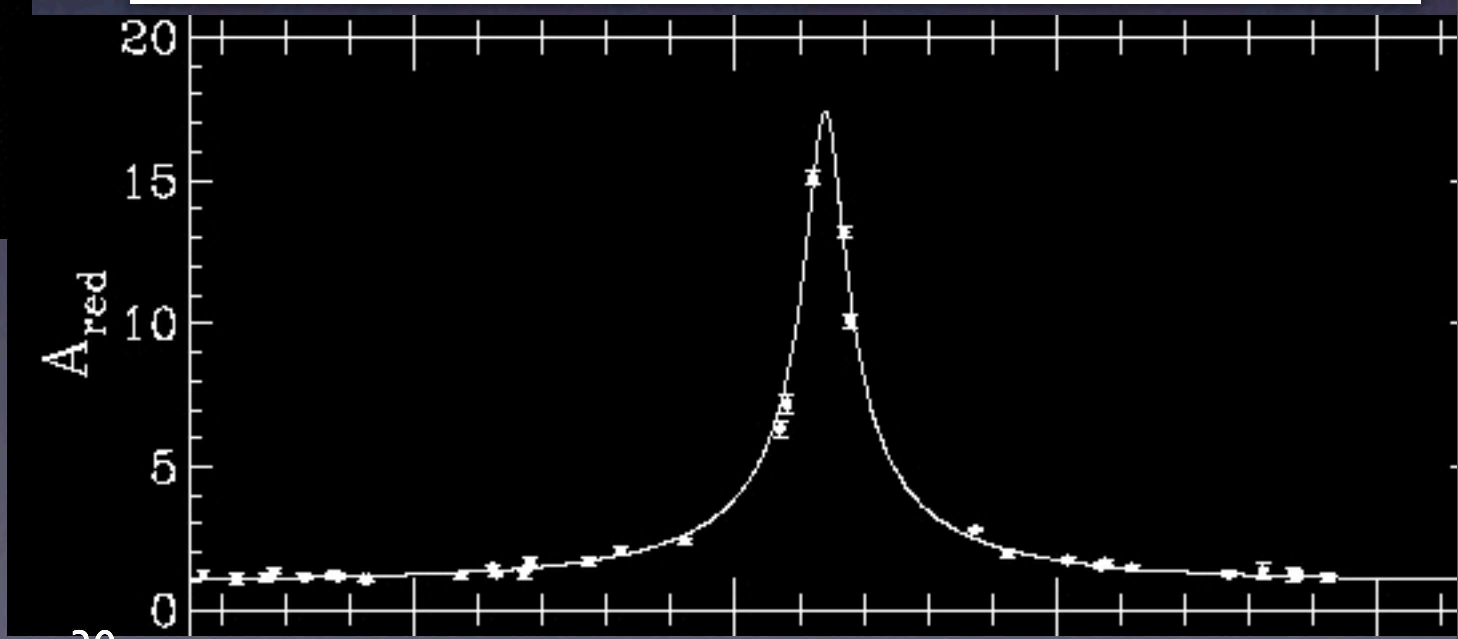

Not enough of them!

Mass Limits

"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

Mass Limits

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- 10^{-31} GeV to 10^{50} GeV

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- we narrowed it down to within 81 orders of magnitude

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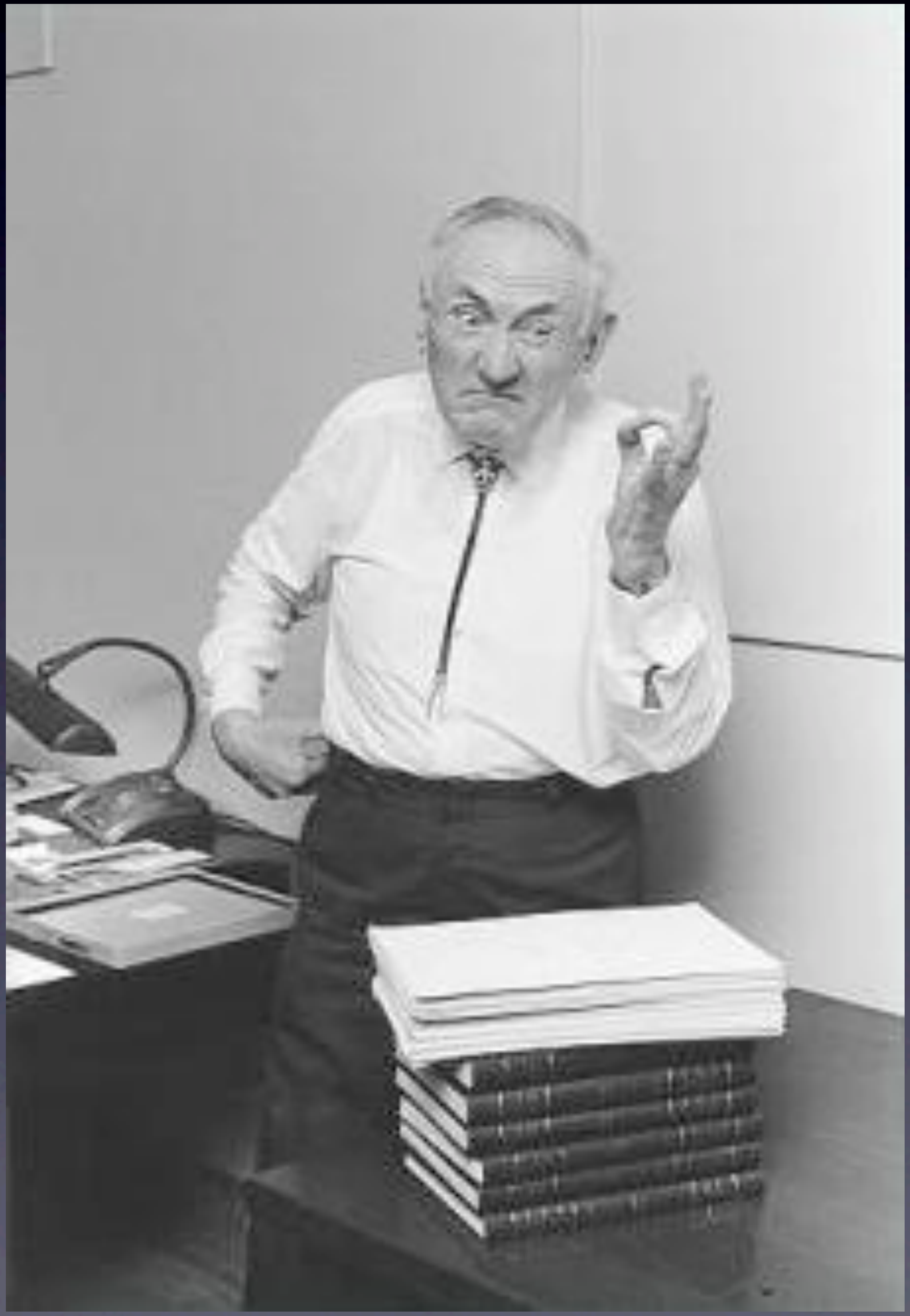
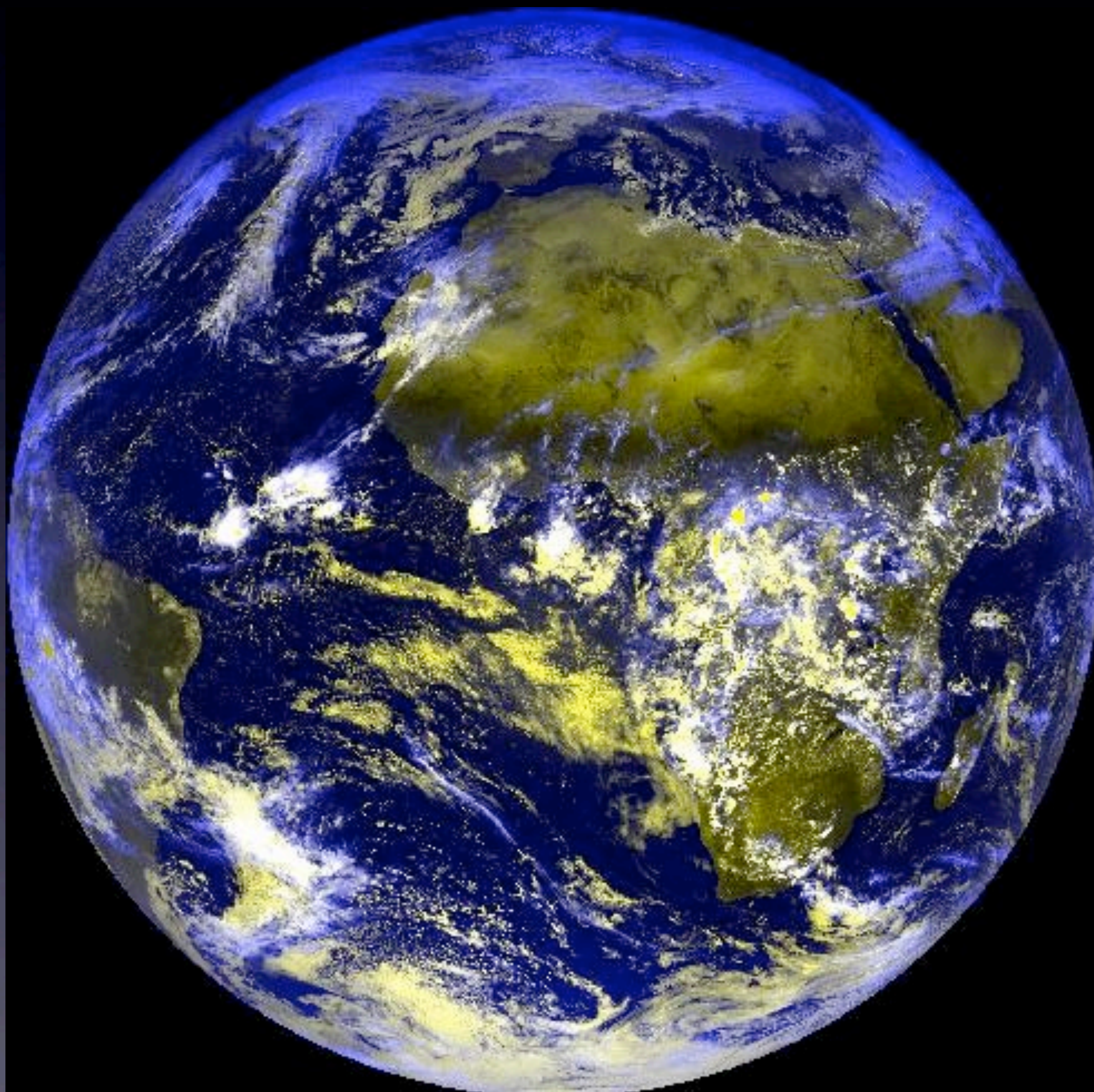
- 10^{-31} GeV to 10^{50} GeV
- we narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



WIMP



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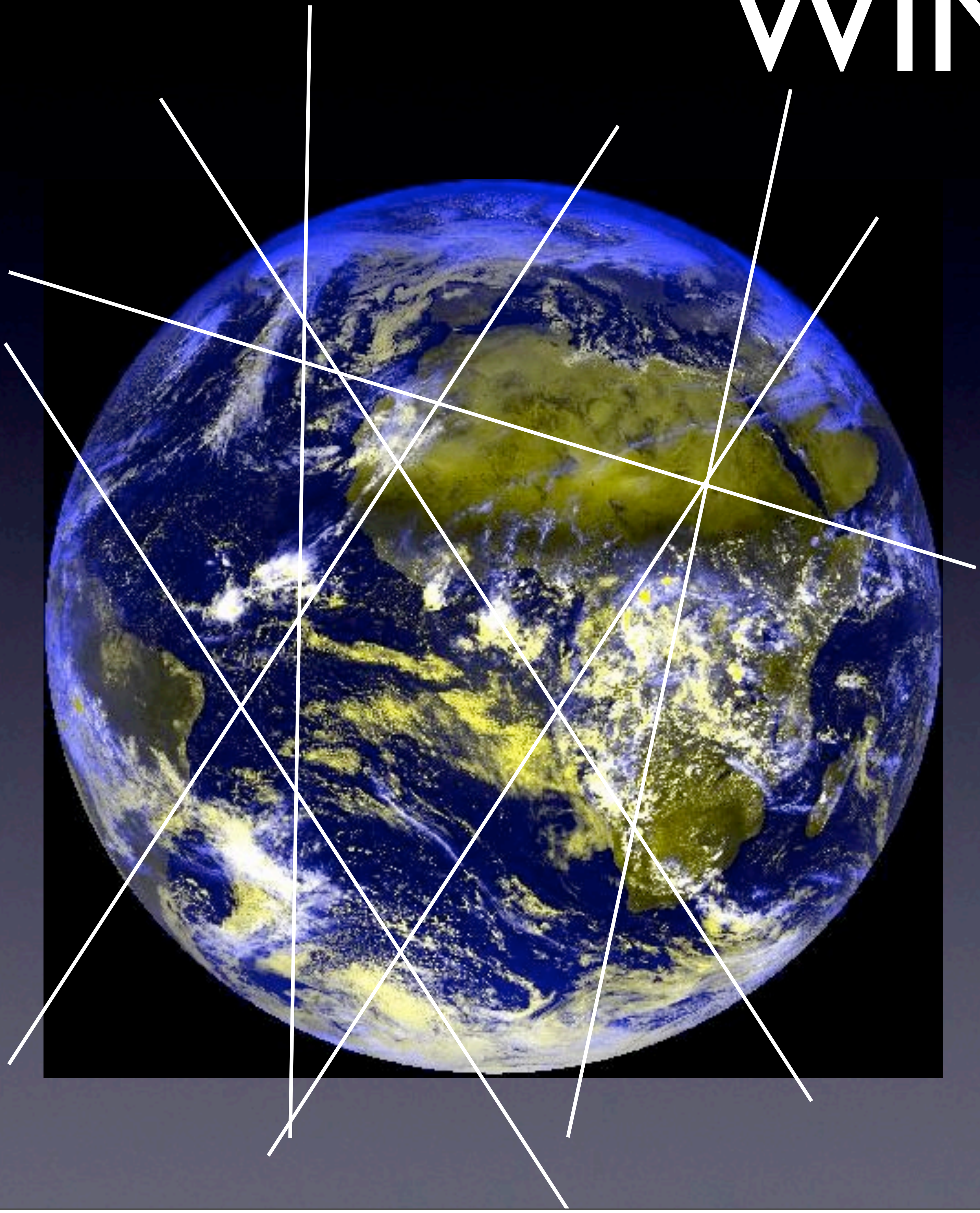

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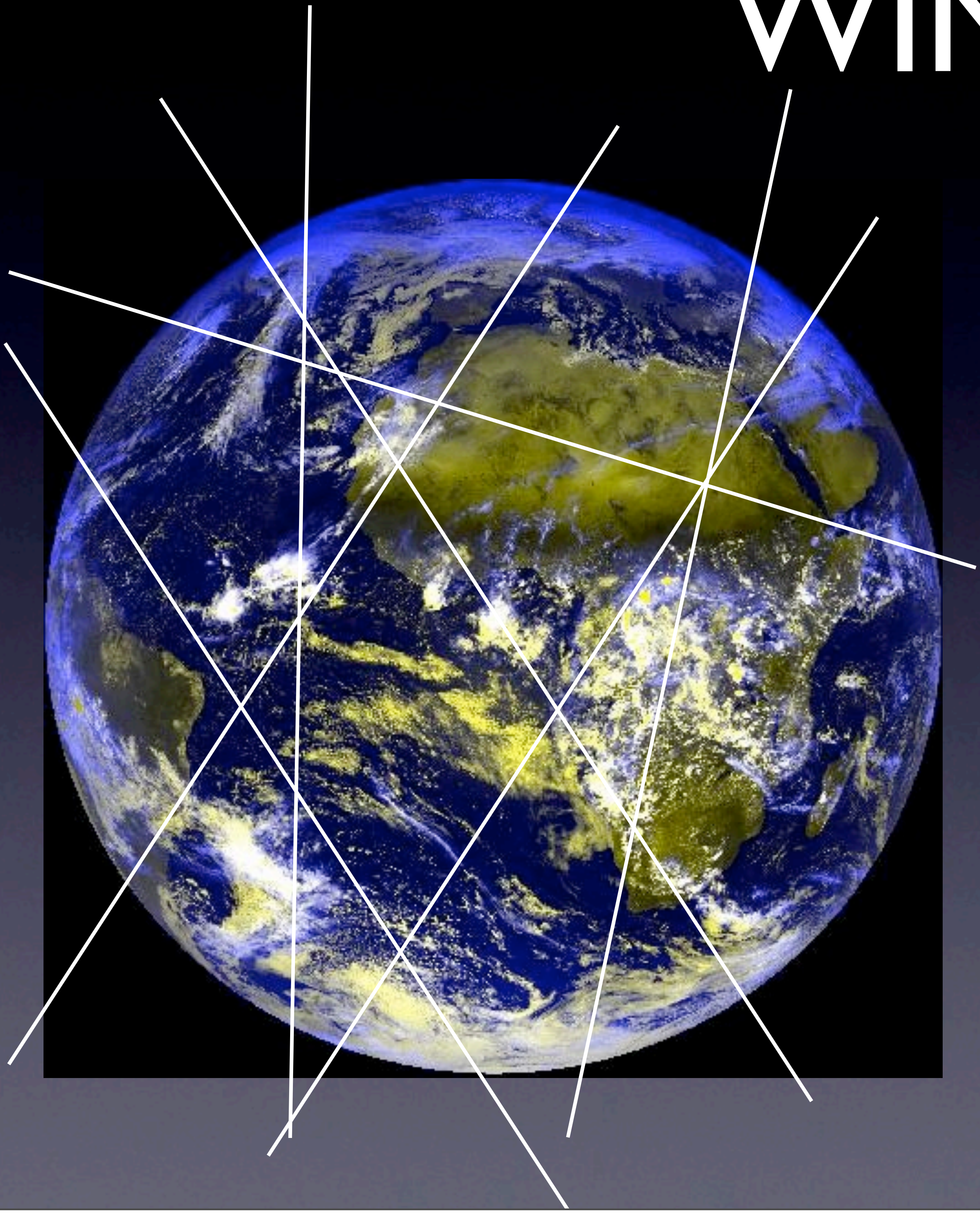
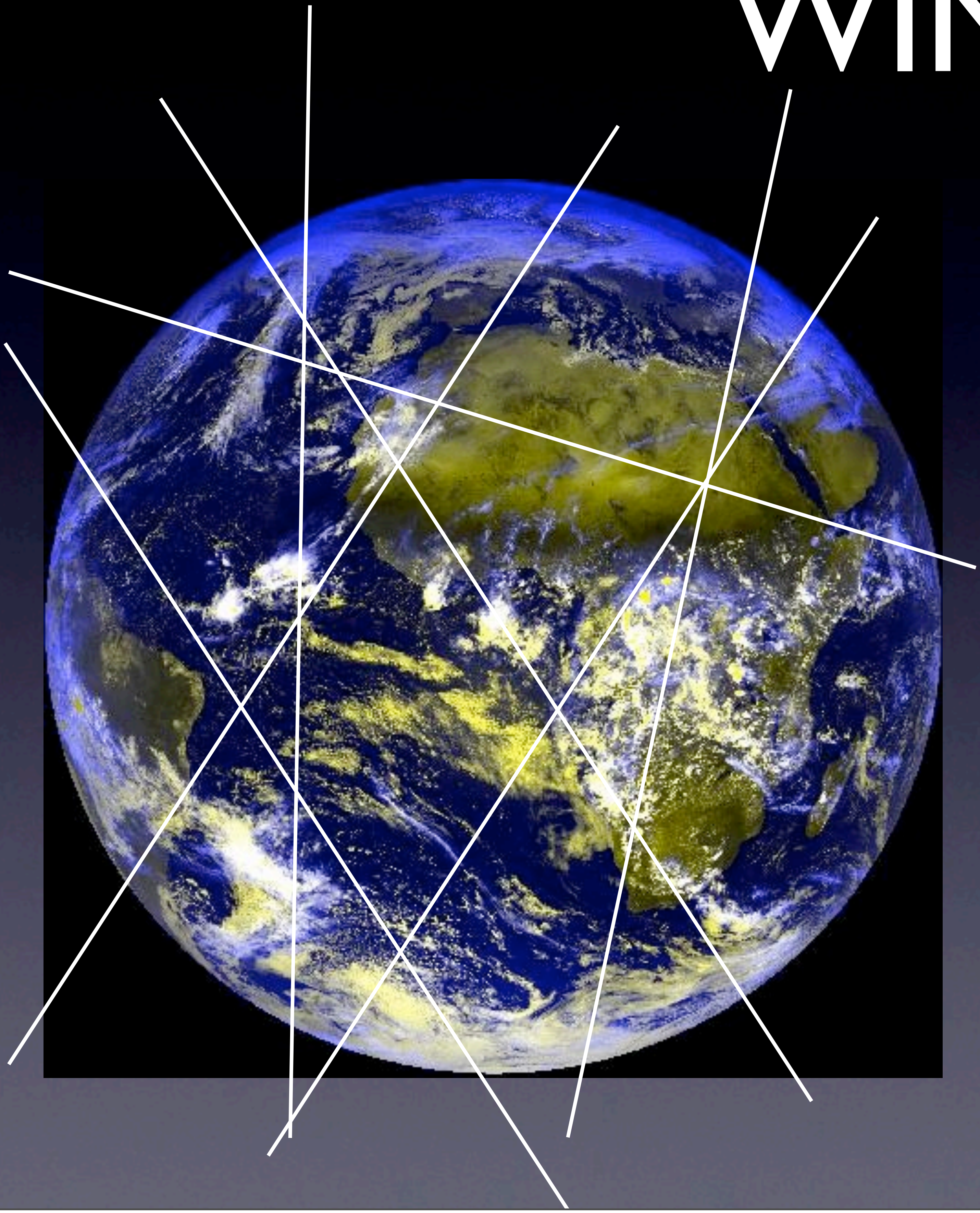


- *The dominant paradigm:* *WIMP (Weakly Interacting Massive Particle)*

WIMP



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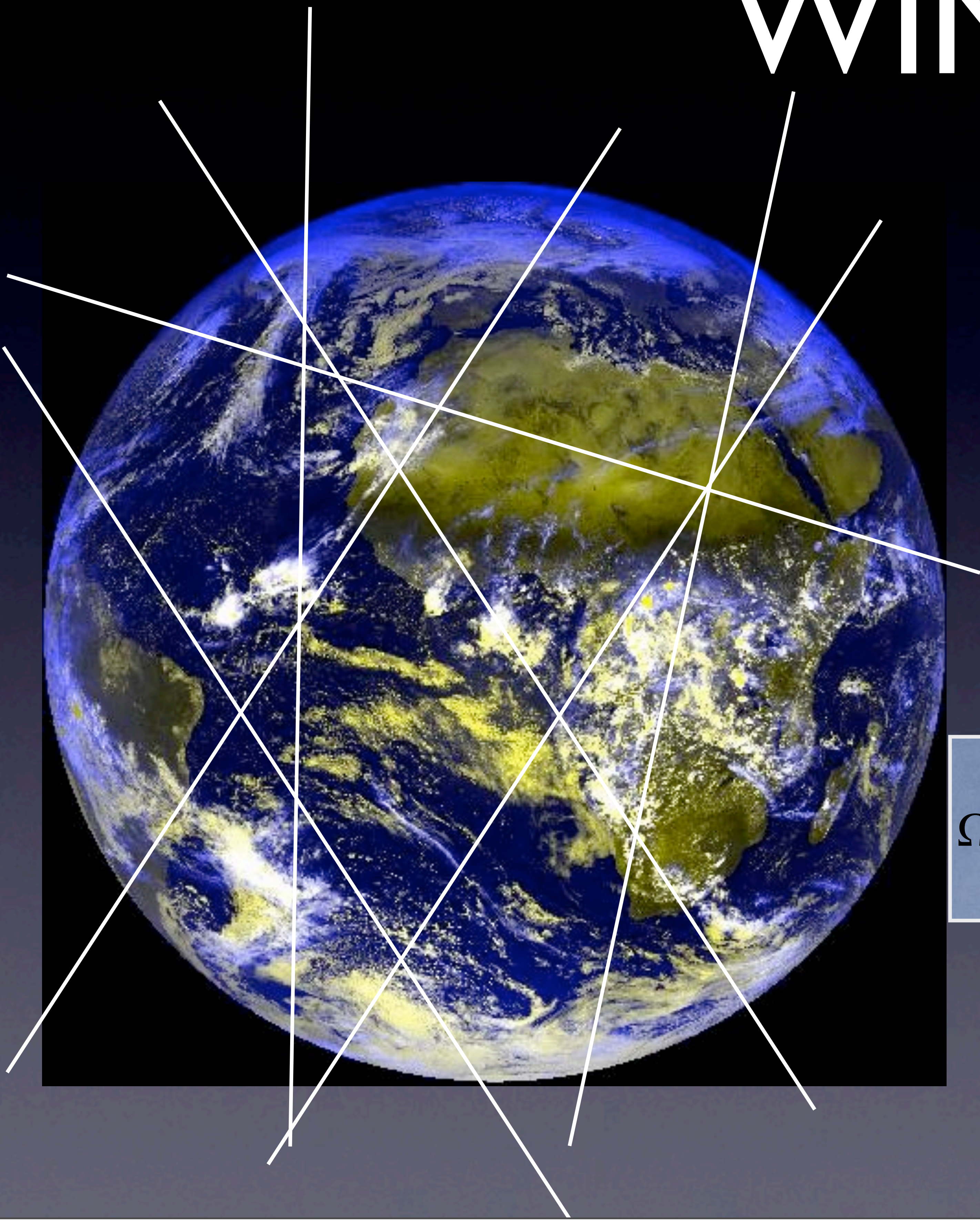
WIMP



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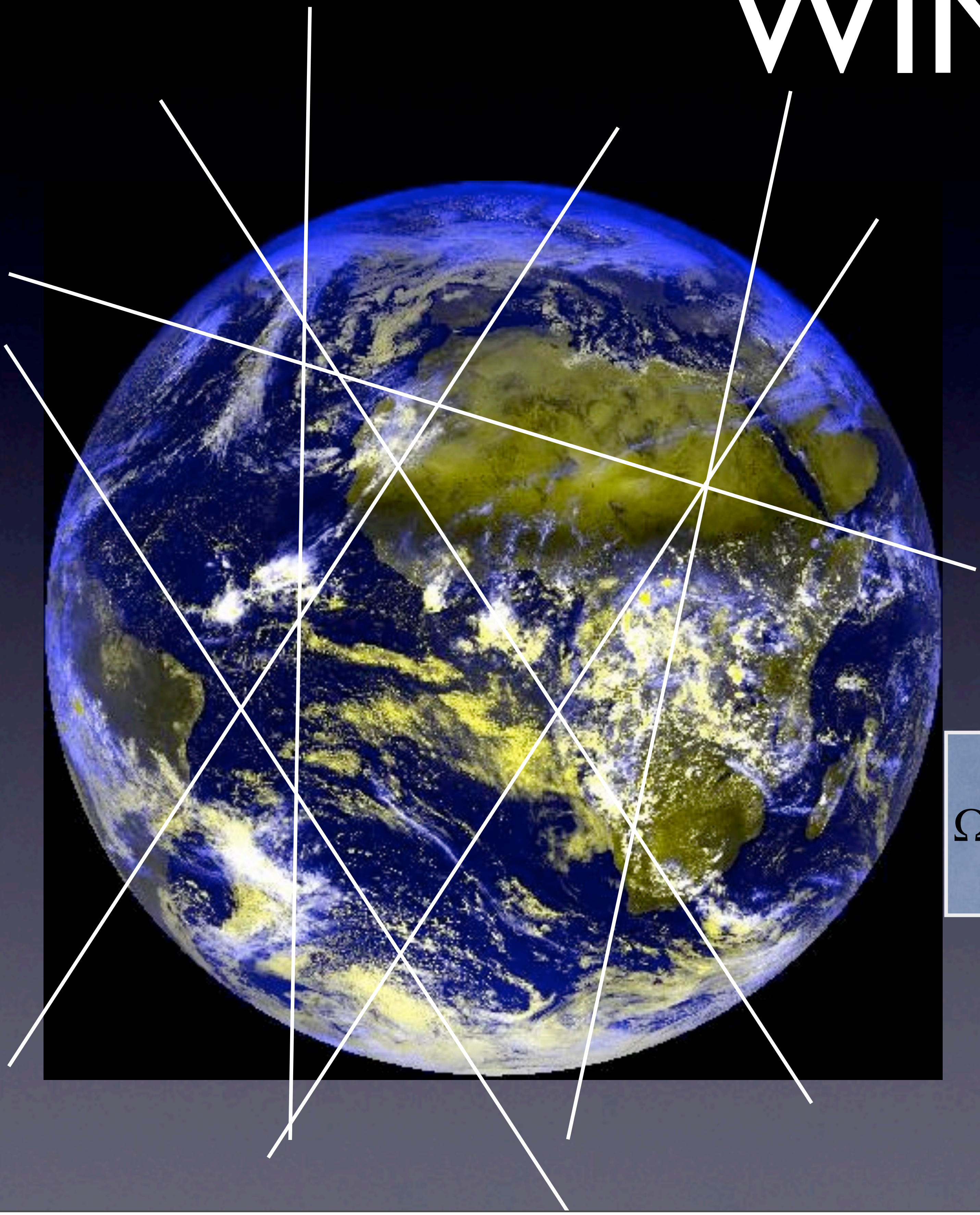

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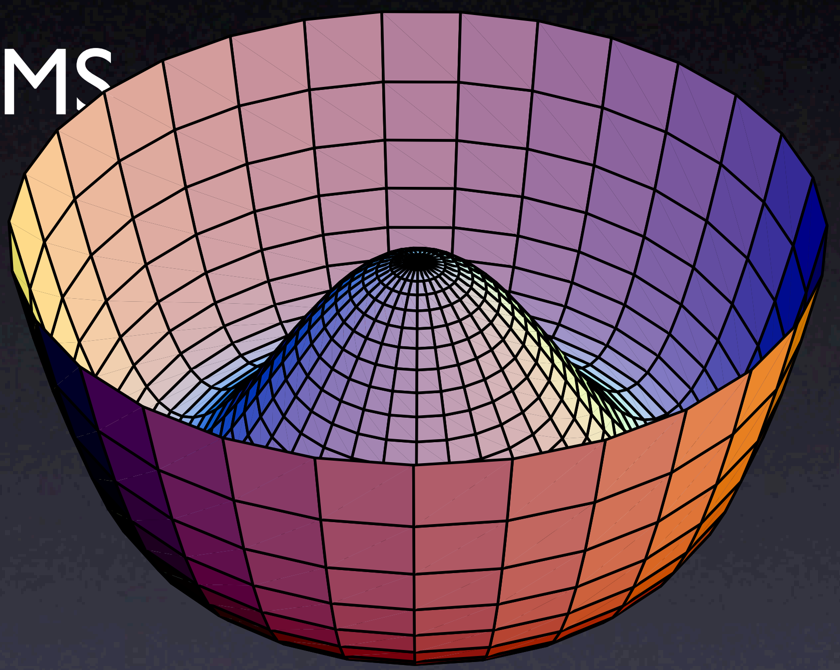
- messngers from other dimensions? SUSY?

Why the Terascale?

—naturalness—

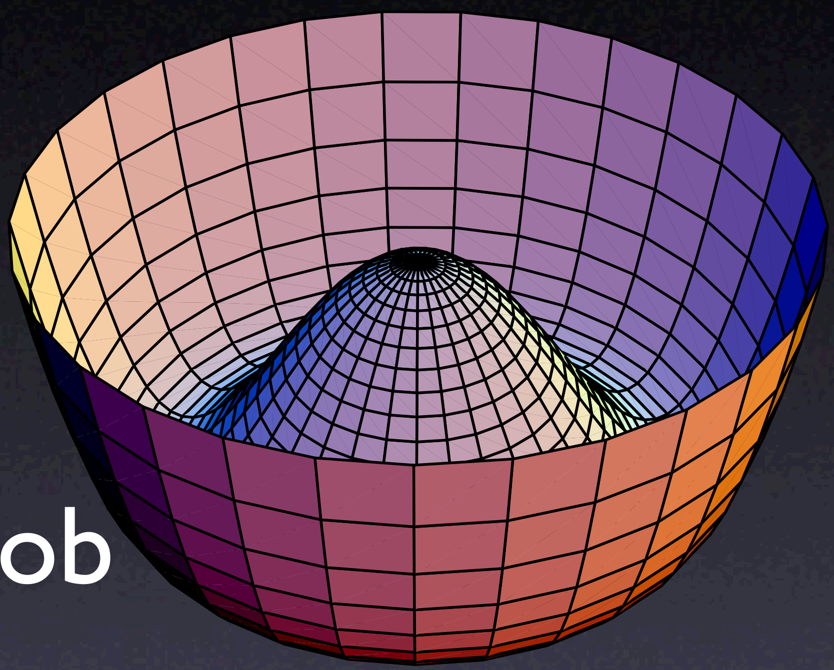
Post-Higgs Problem

- robust discovery reach by ATLAS/CMS
- We will see "what" is condensed
- But we still won't know "why"
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation ~TeV$\ll M_{Pl}=10^{15}$TeV



- Explanation most *likely* to be at ~TeV scale because this is the relevant energy scale

Strange



- Higgs boson is the *only spin 0 particle* in the standard model
  - one of its kind
  - but does the most important job
- looks rather artificial
- *Higgsless theories*: possible but not favored by EW precision data
- another problem: naturalness

Once upon a time, there was a naturalness problem...

- At the end of 19th century: a “crisis” about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

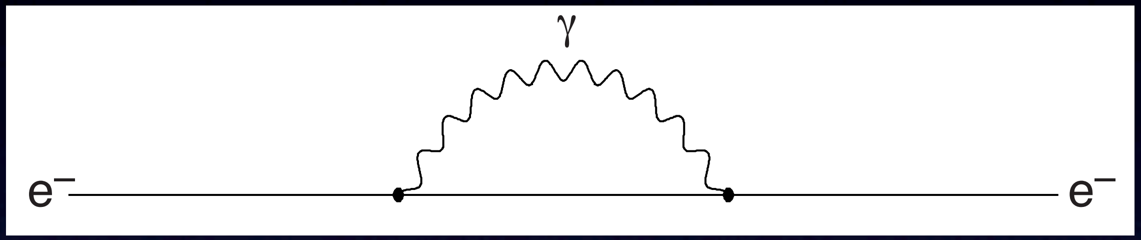
$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism

$\Rightarrow$ Can’t discuss physics below 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble



⇒ only 10% of mass even

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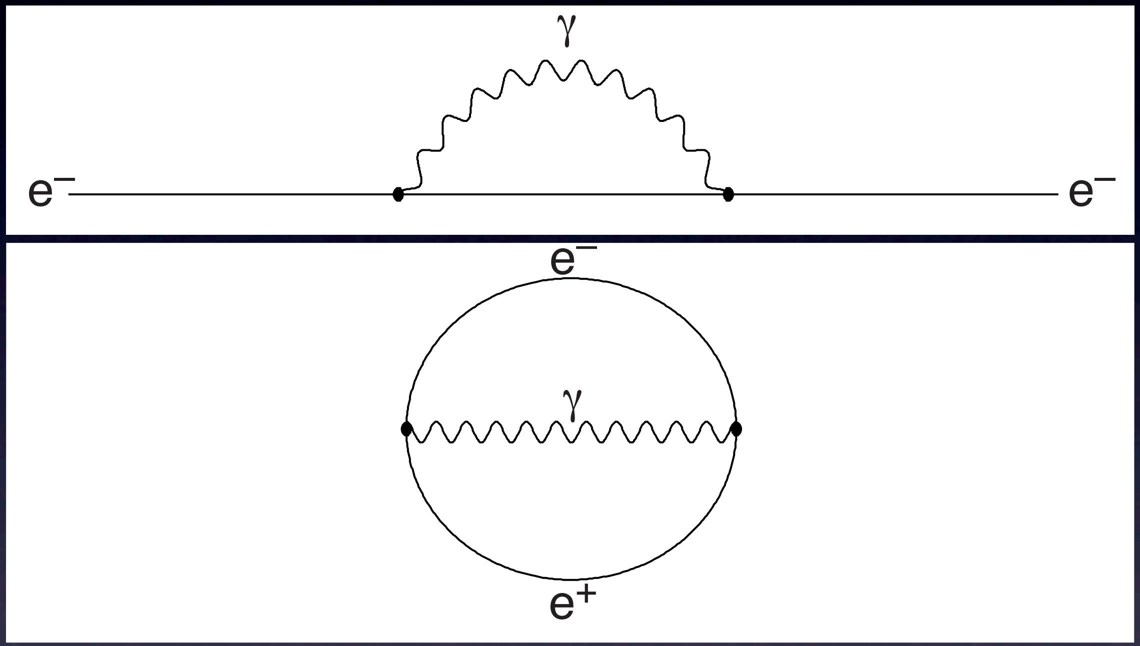

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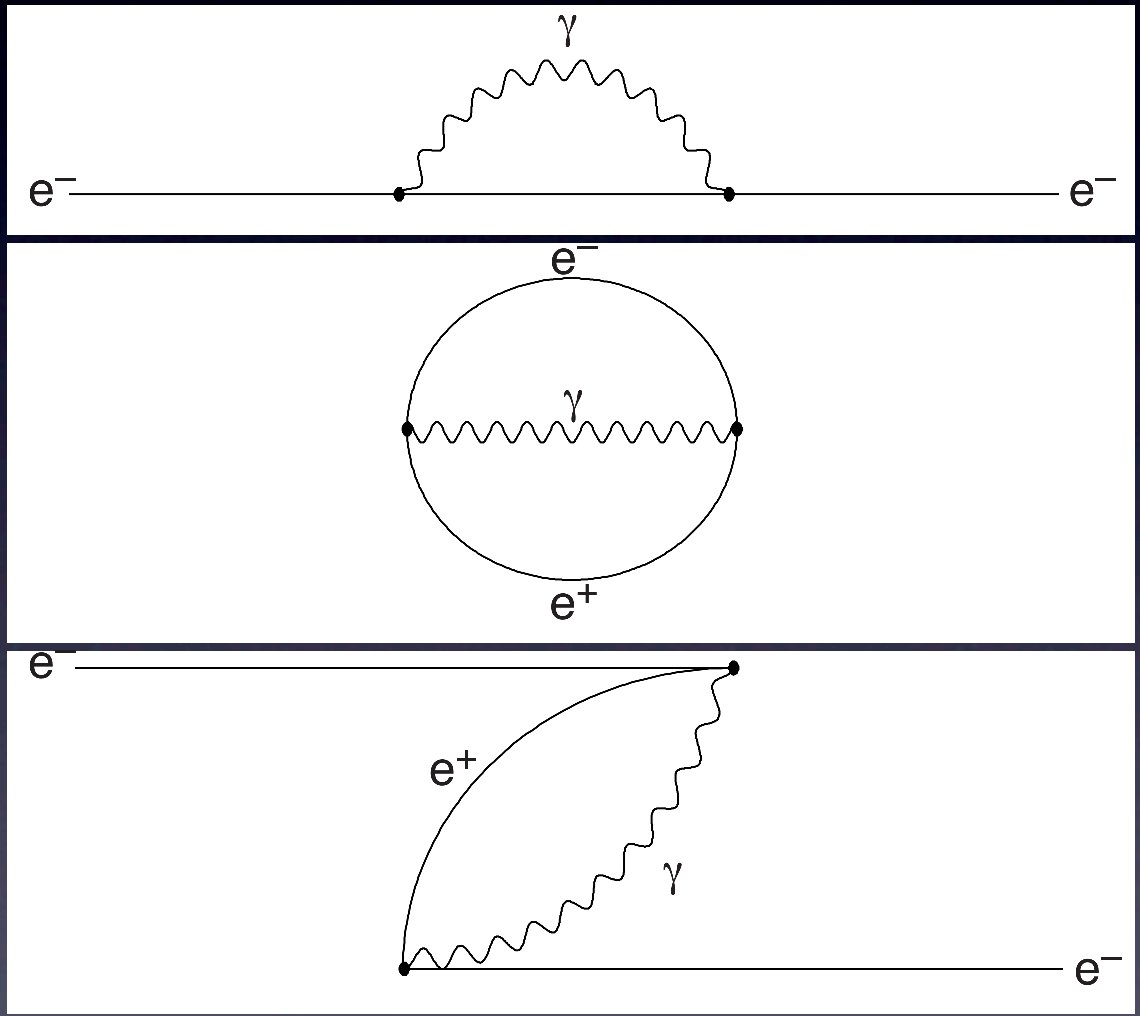

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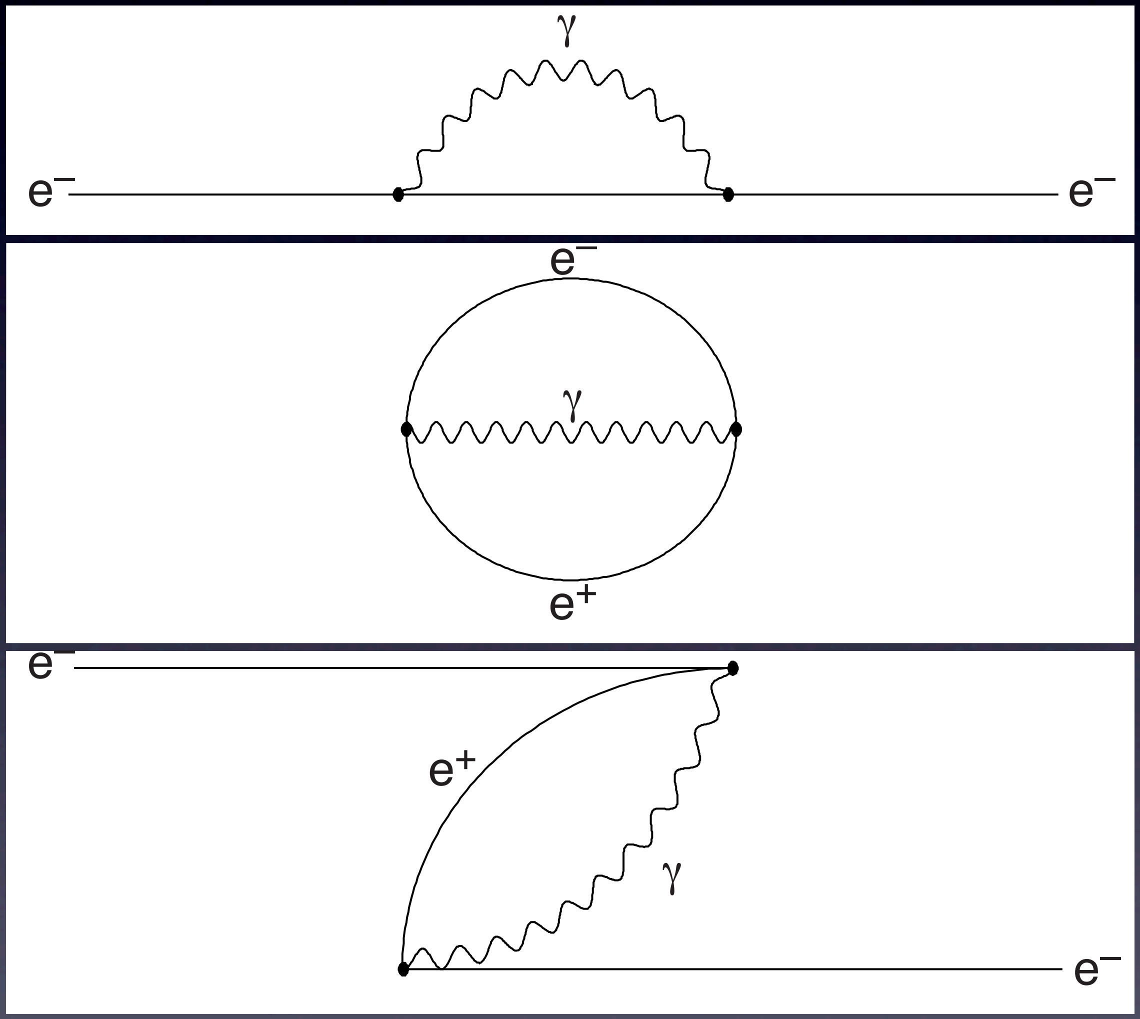
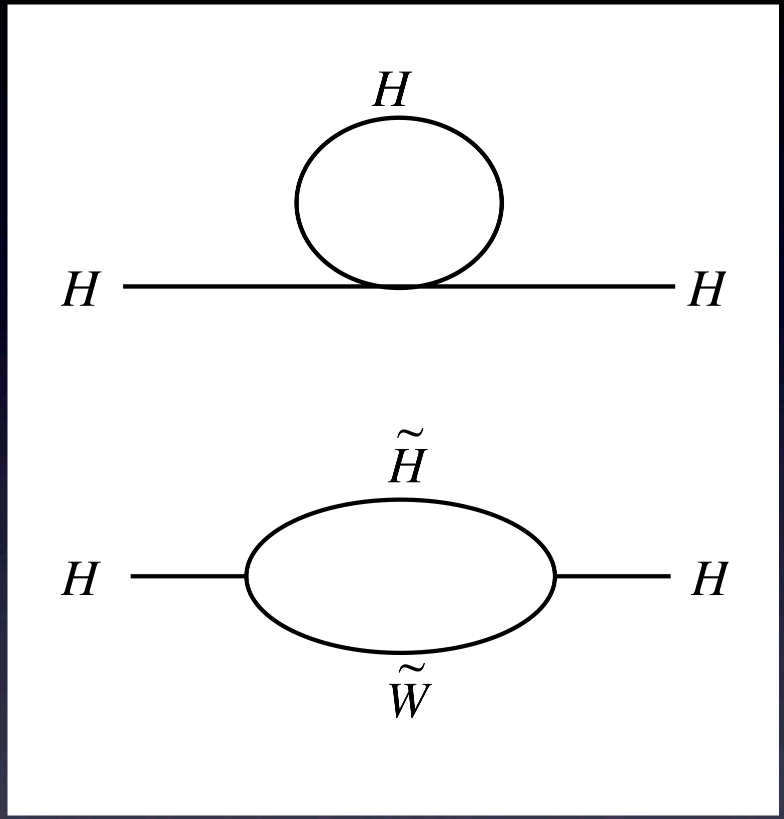


$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

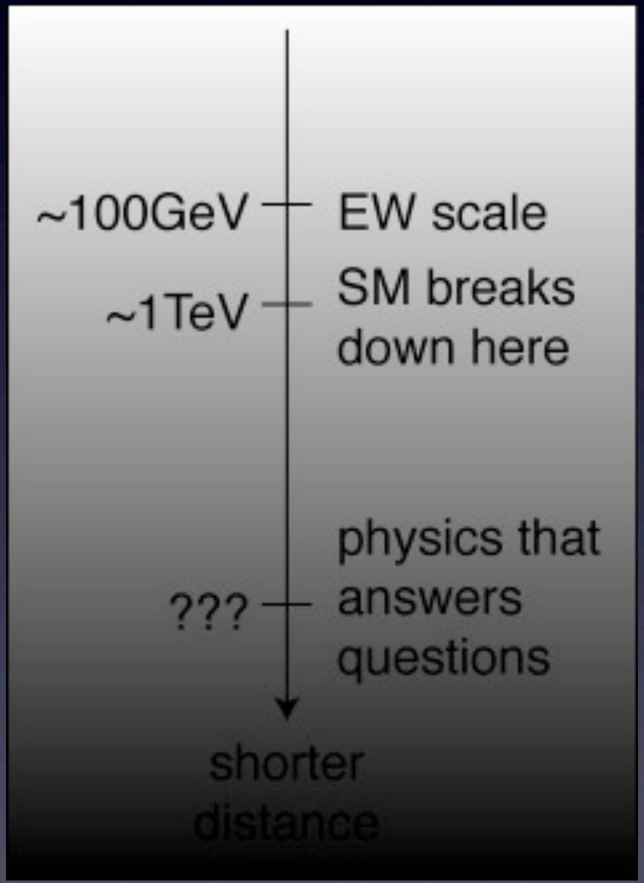
History repeats itself?

- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- "Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

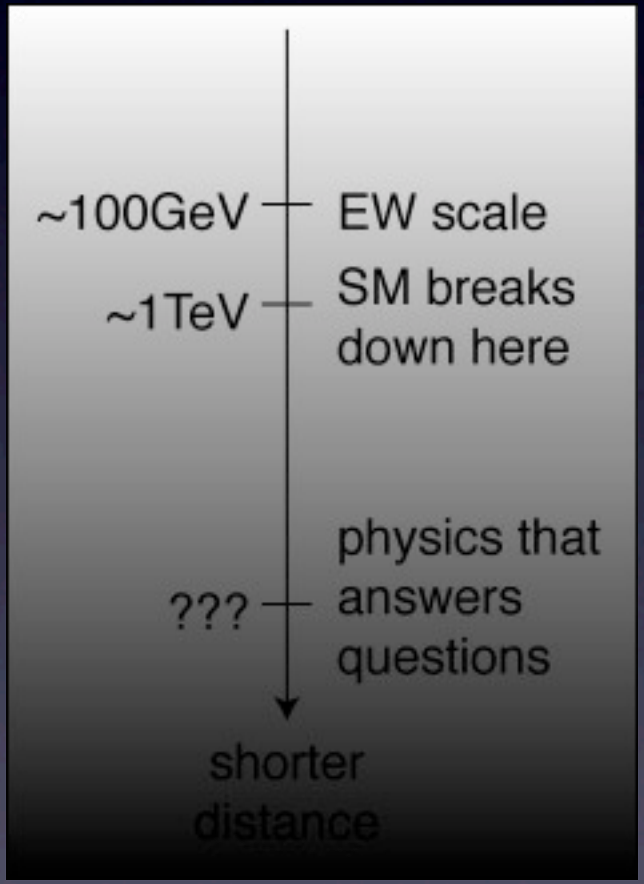
Opening the door



Opening the door

- Once the naturalness problem solved, we can get started to discuss physics at shorter distances and earlier universe.
- It opens the door to the next level:

Hope to probe yet higher energies



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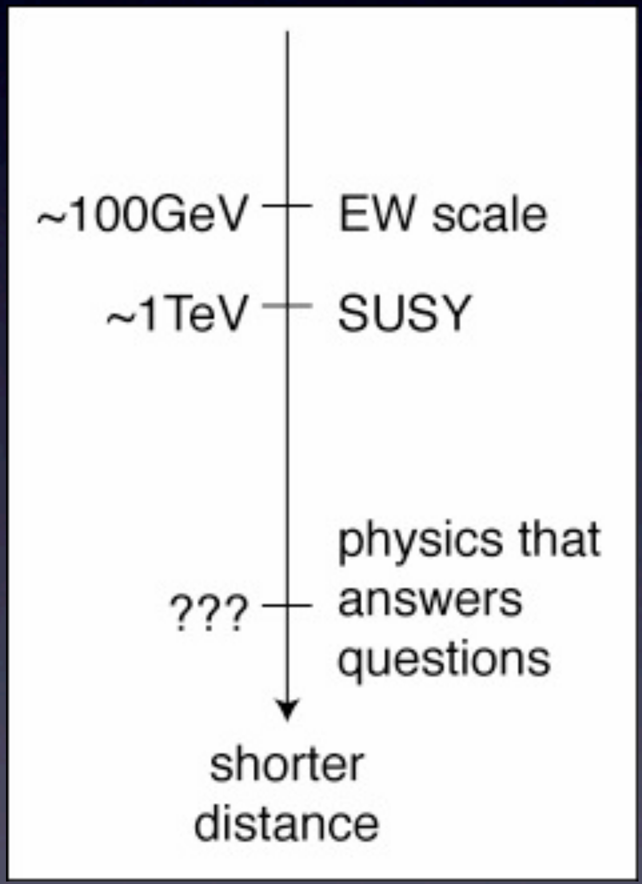

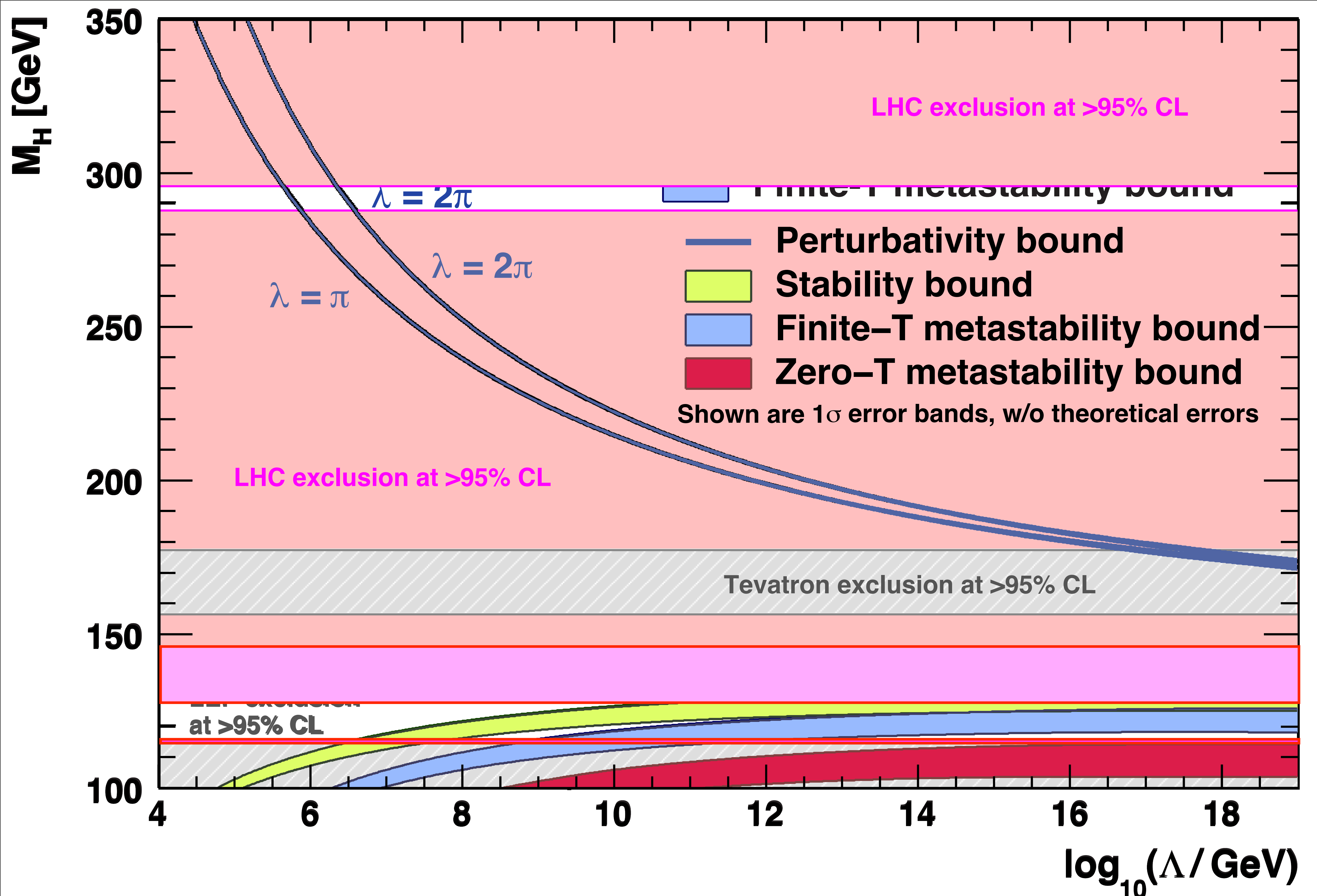

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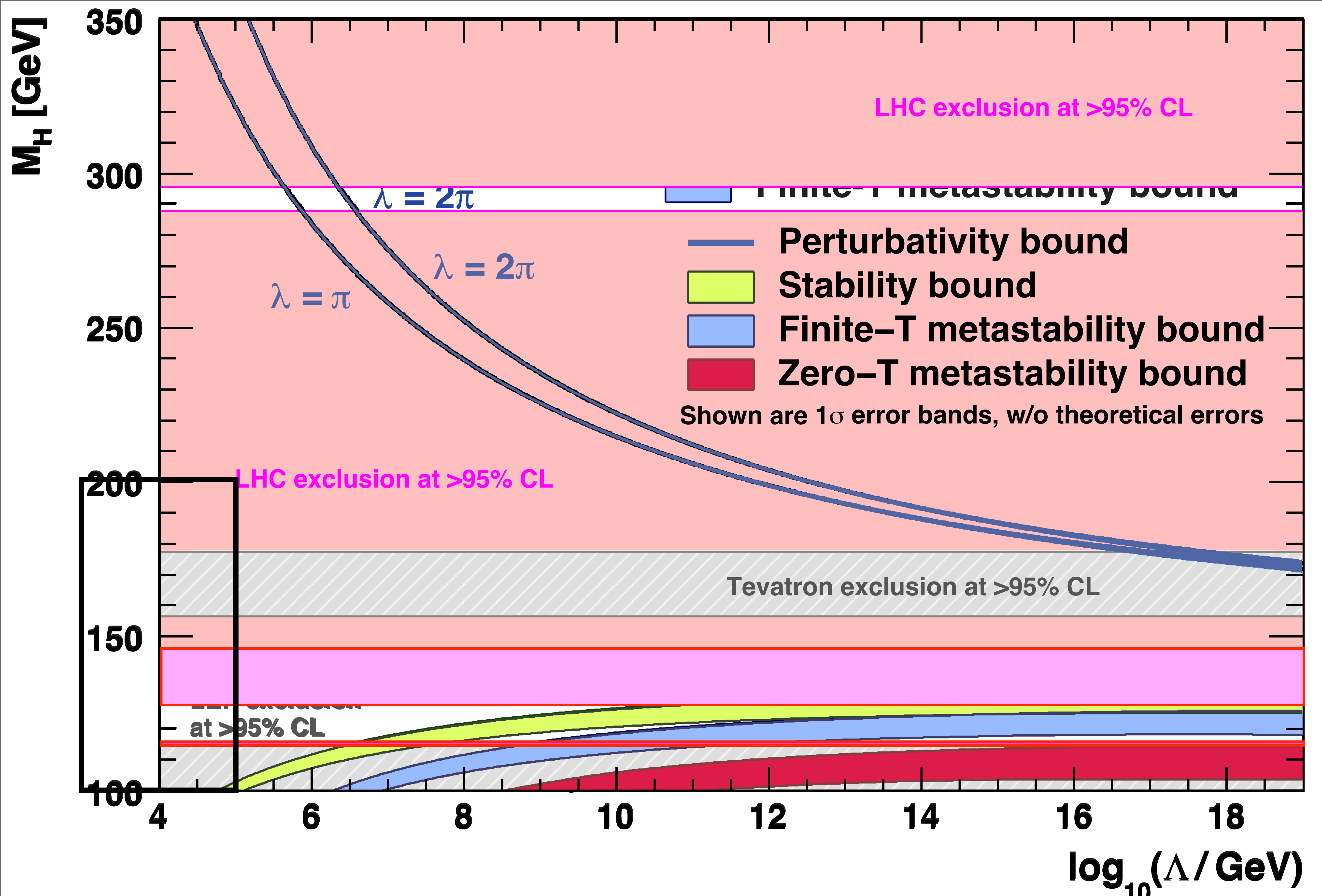

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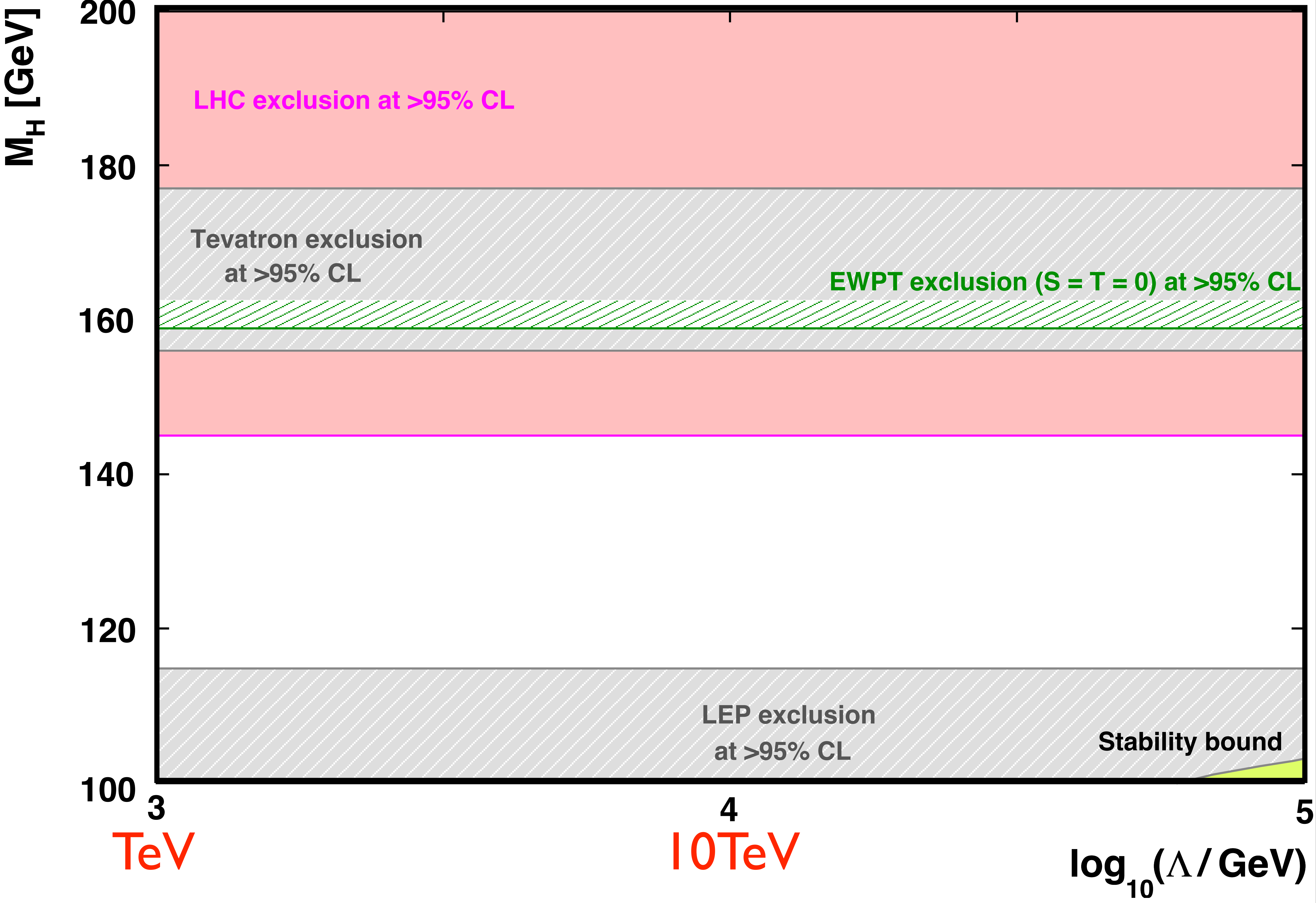

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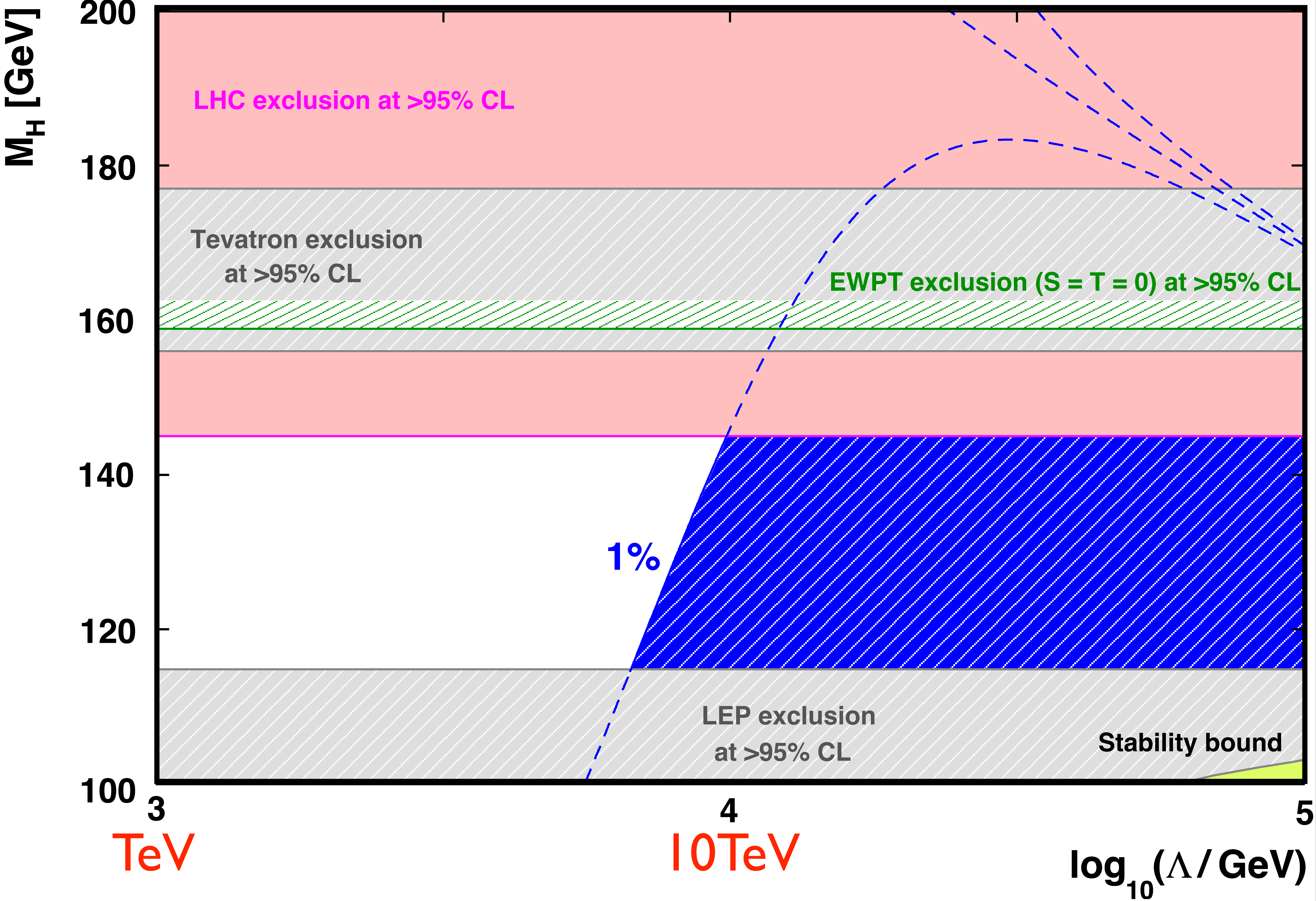

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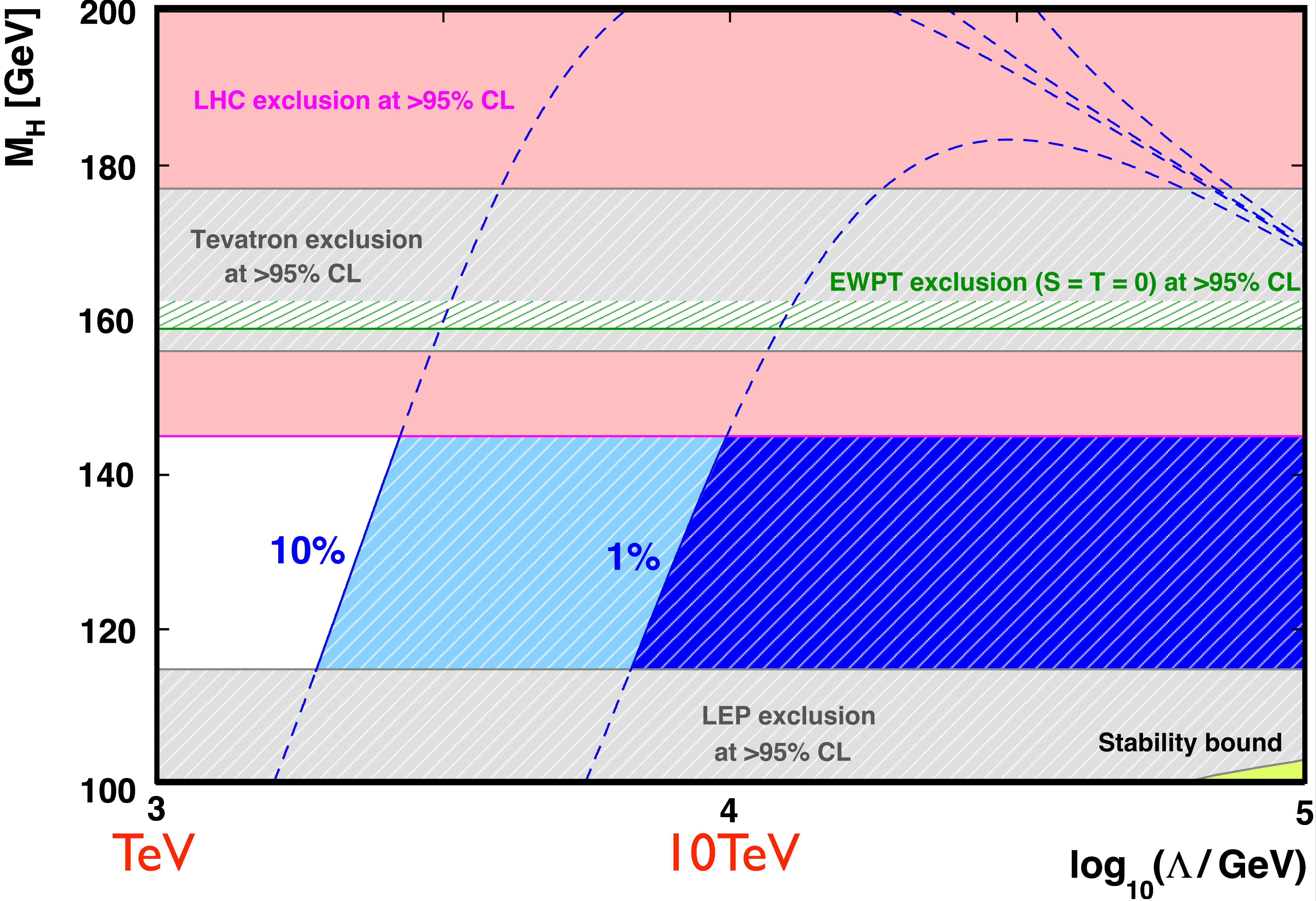

Three Directions

IPMU

BERKELEY CENTER FOR THEORETICAL PHYSICS

Three Directions

Supersymmetry

- Higgs just one of *many* scalar bosons
- SUSY loops make m_h^2 negative

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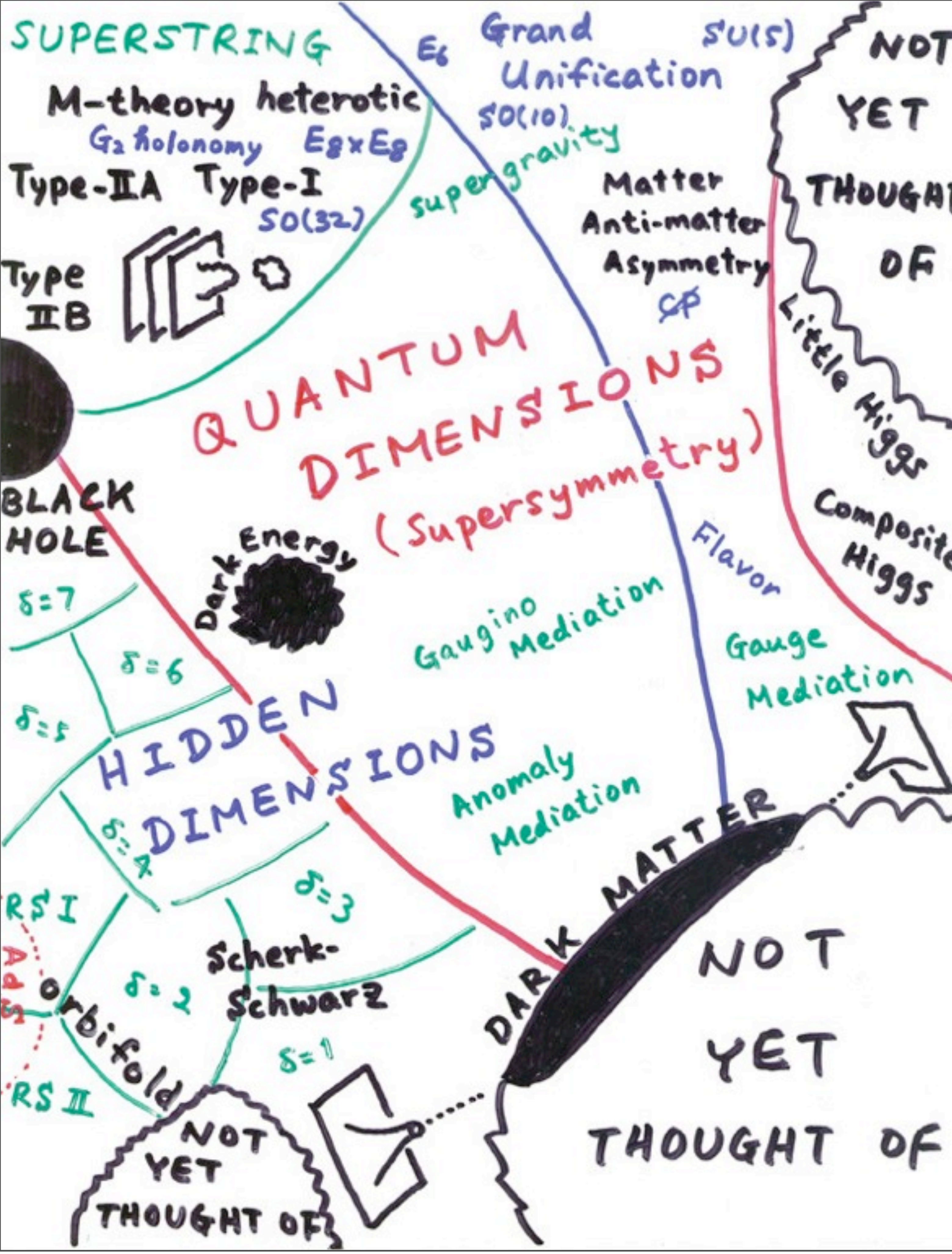
Extra dimension

- Higgs spinning in extra dimensions
- new forces from particles running in extra D


SUPERSTRING
M-theory heterotic
G2 holonomy E8xE8
Type-IIA Type-I
SO(32)
Type IIB
E6
Grand Unification
SU(5)
SO(10)
Supergravity
Matter Anti-matter Asymmetry
NOT YET THOUGHT OF
BLACK HOLE
QUANTUM DIMENSIONS (Supersymmetry)
Little Higgs
Composite Higgs
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
HIDDEN DIMENSIONS
Anomaly Mediation
DARK MATTER
RS I
AdS
orbifold
RS II
Scherk-Schwarz
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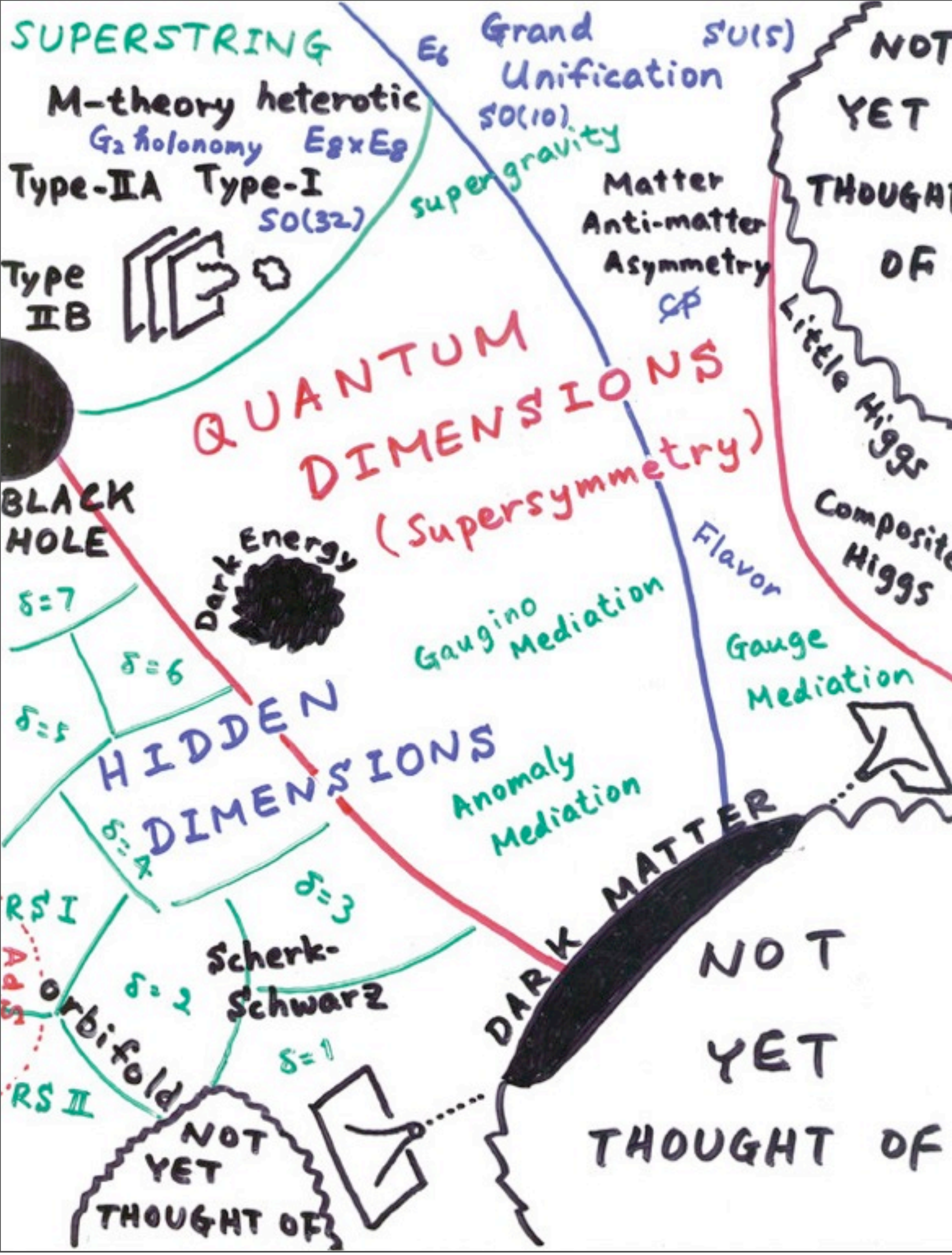
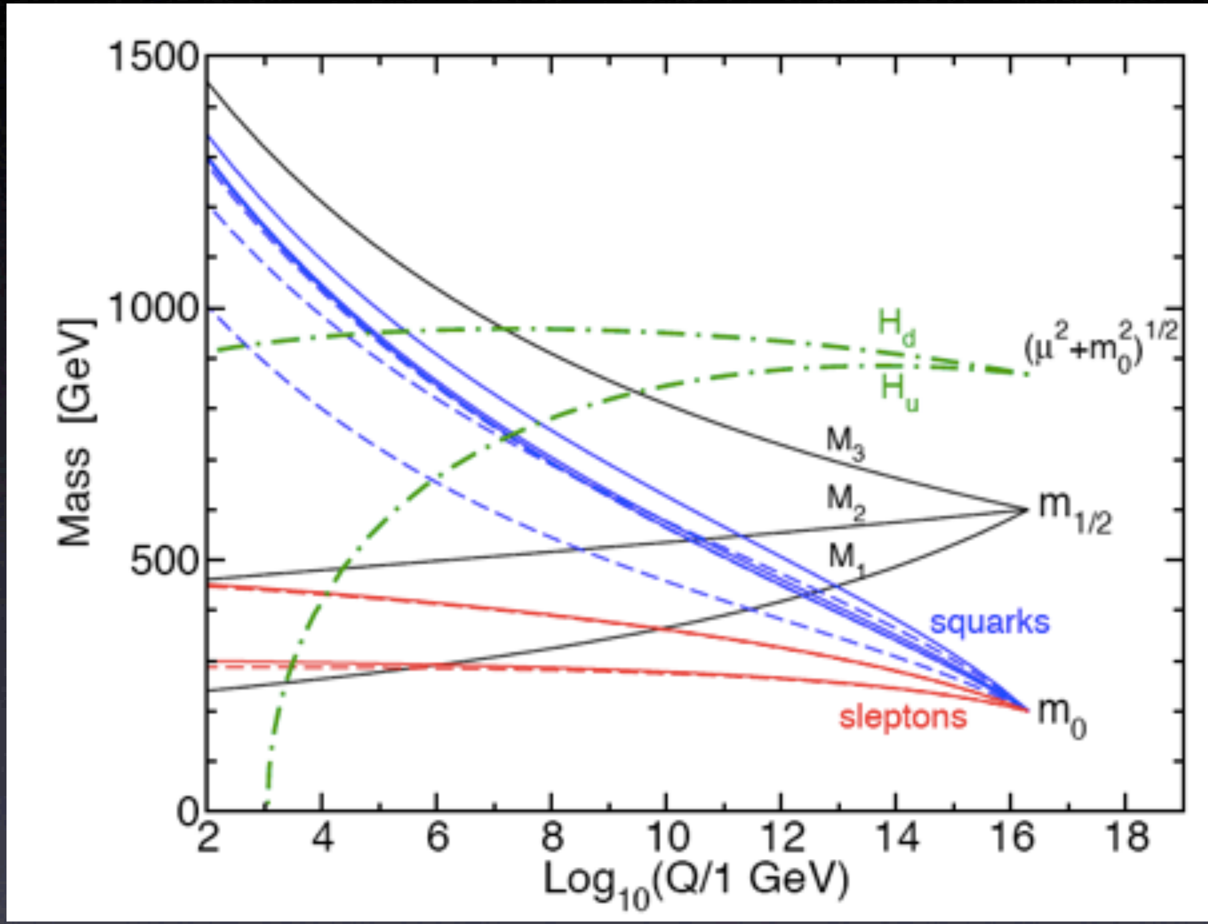


- We really don't know what is going on at TeV
- stupid theorists!
- Can we zoom in onto a point on this map?
- Expect the unexpected

SUSY naturalness limit



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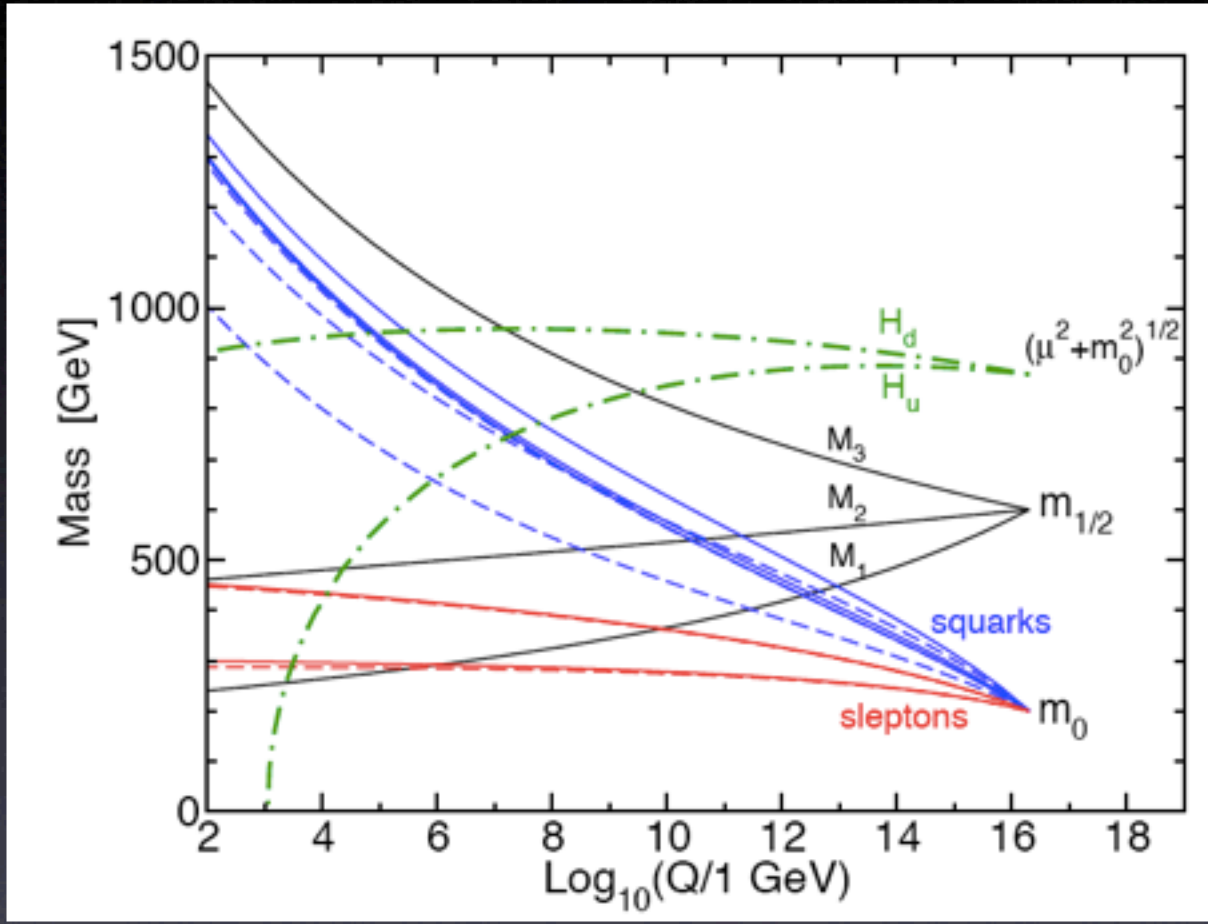

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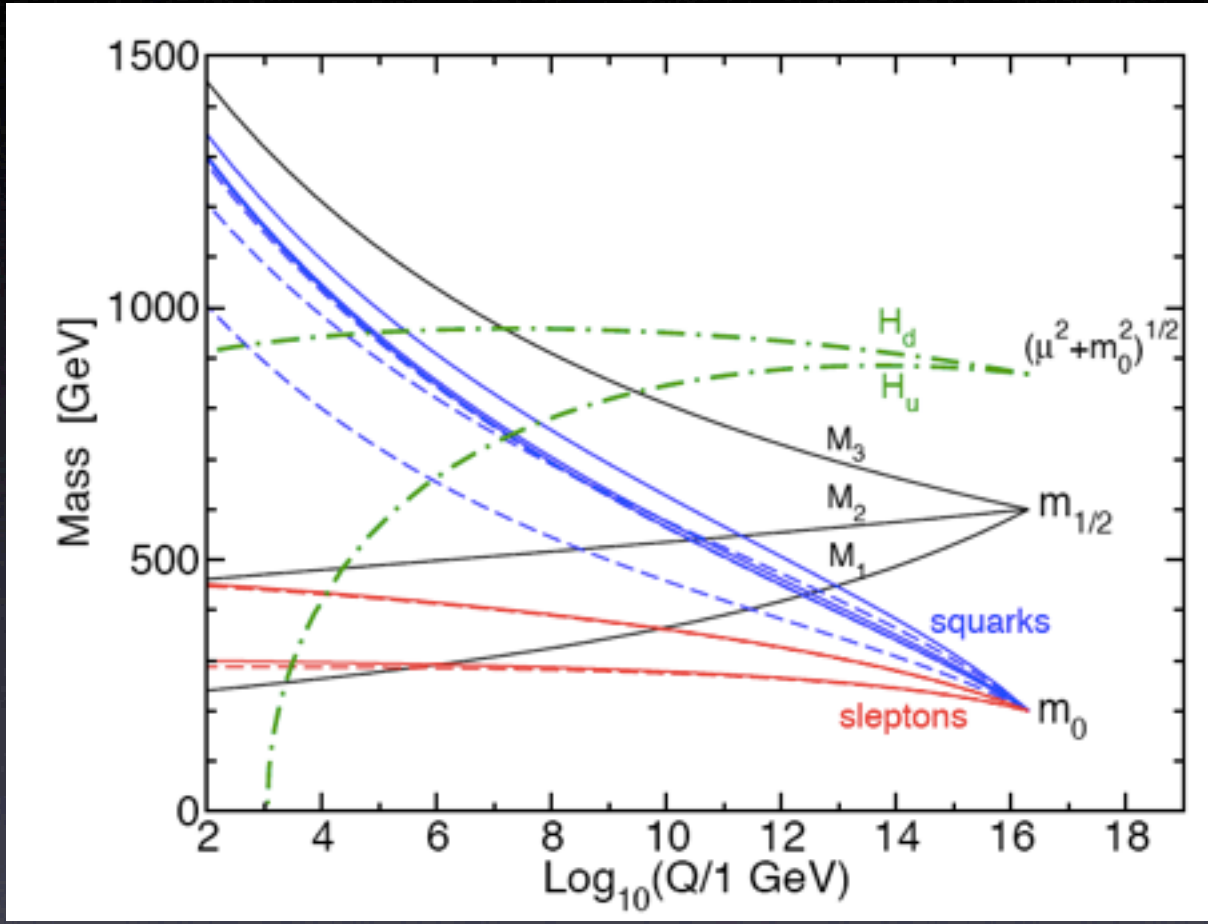

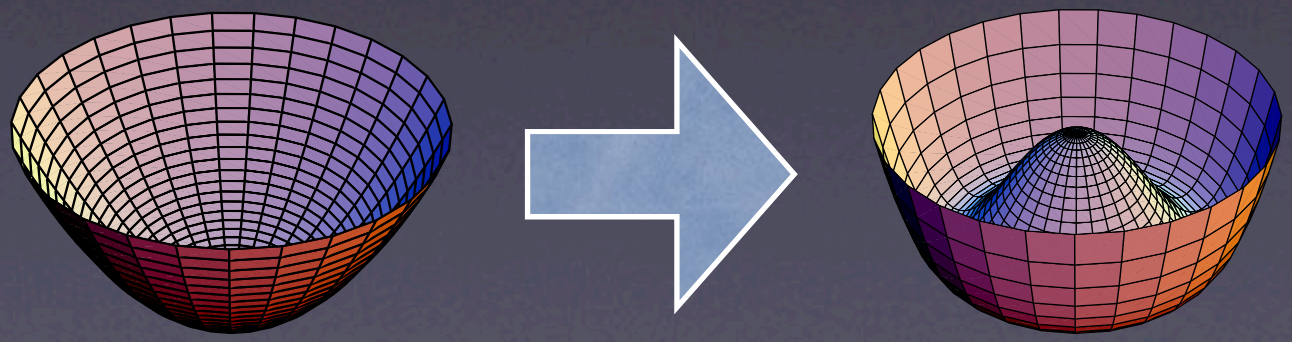

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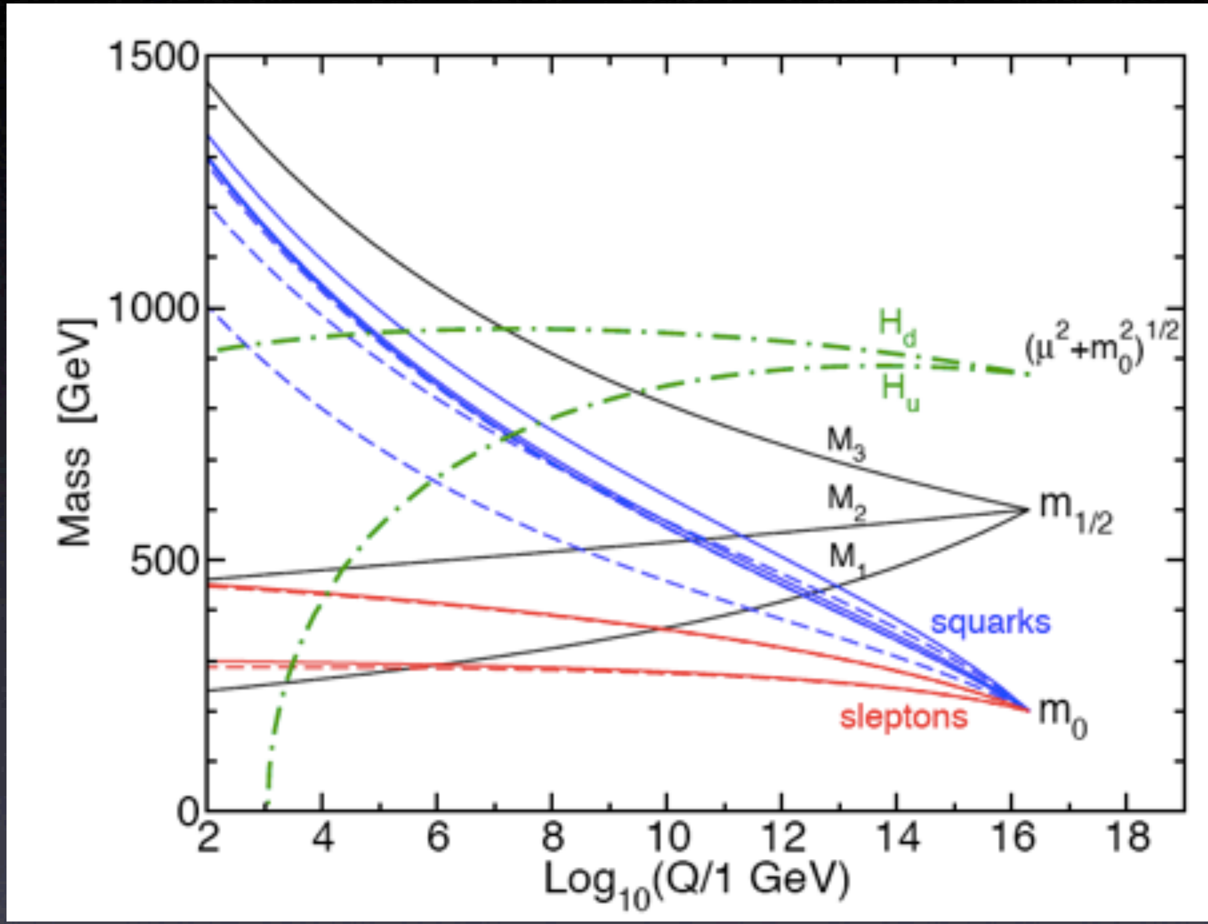

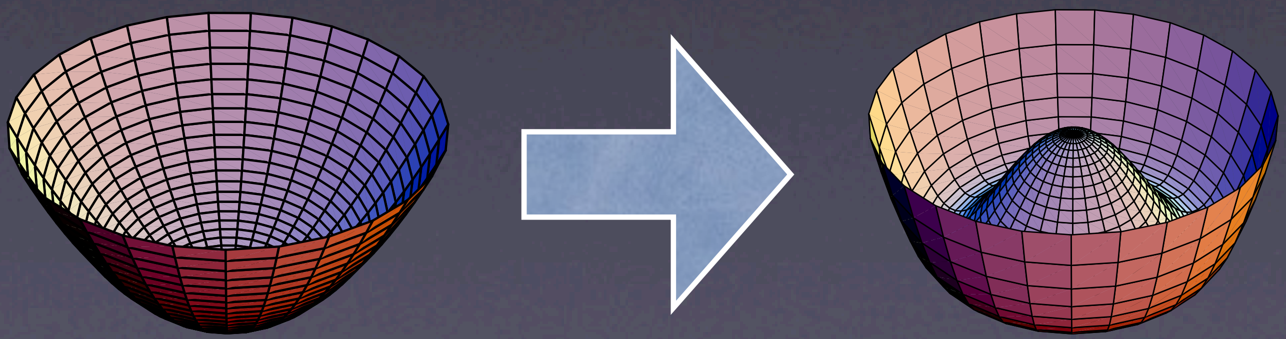

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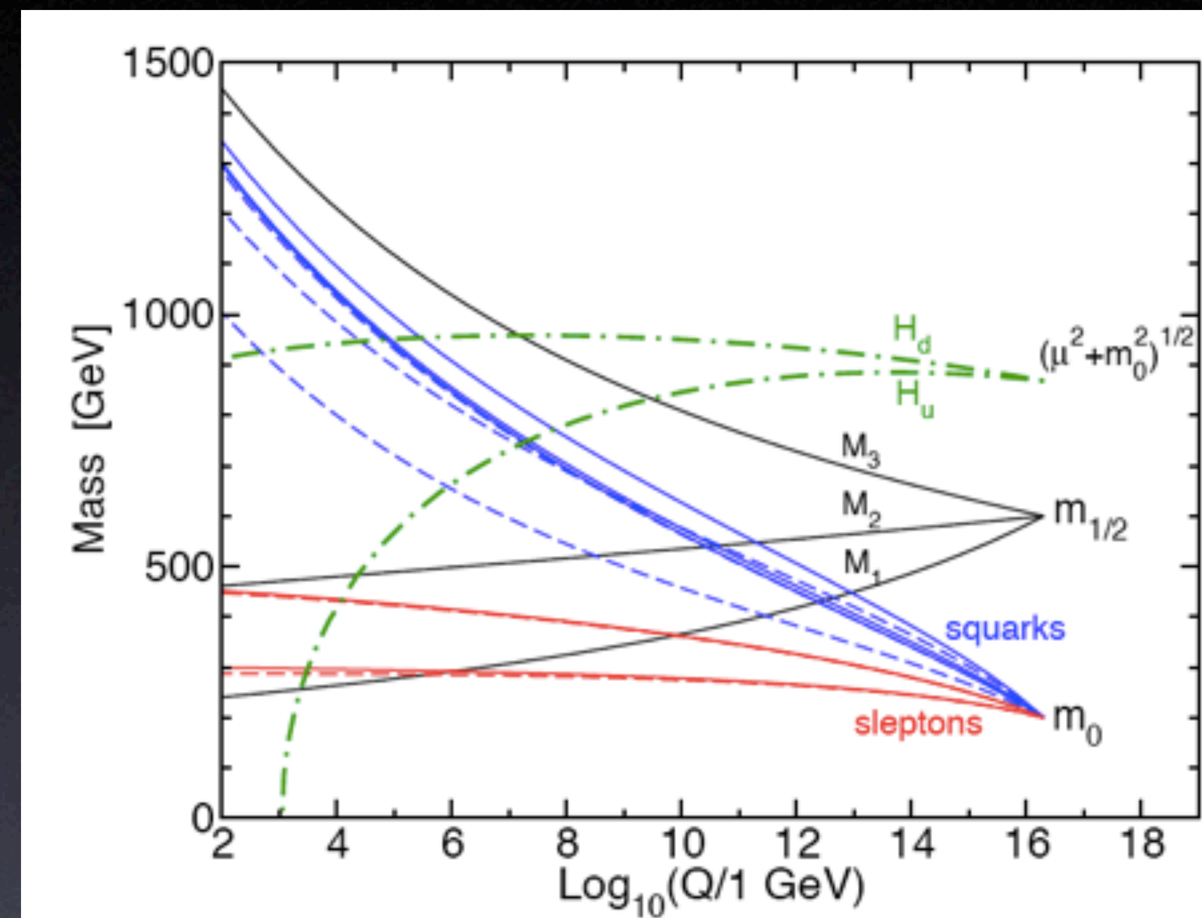

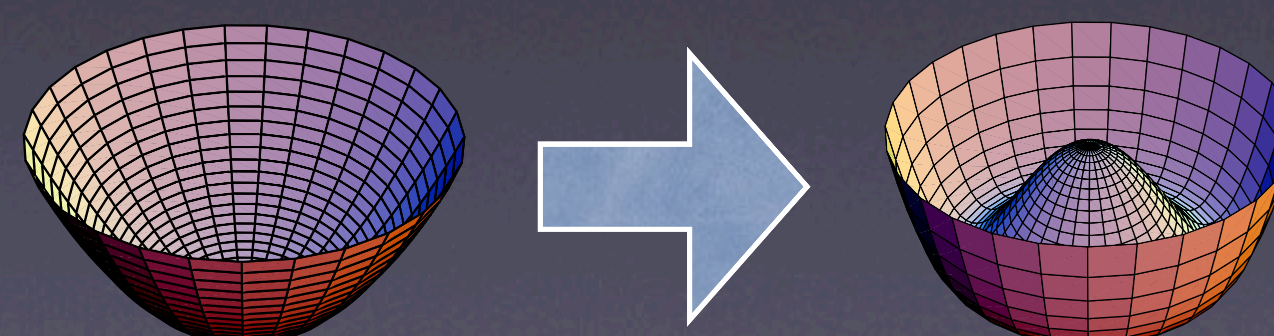

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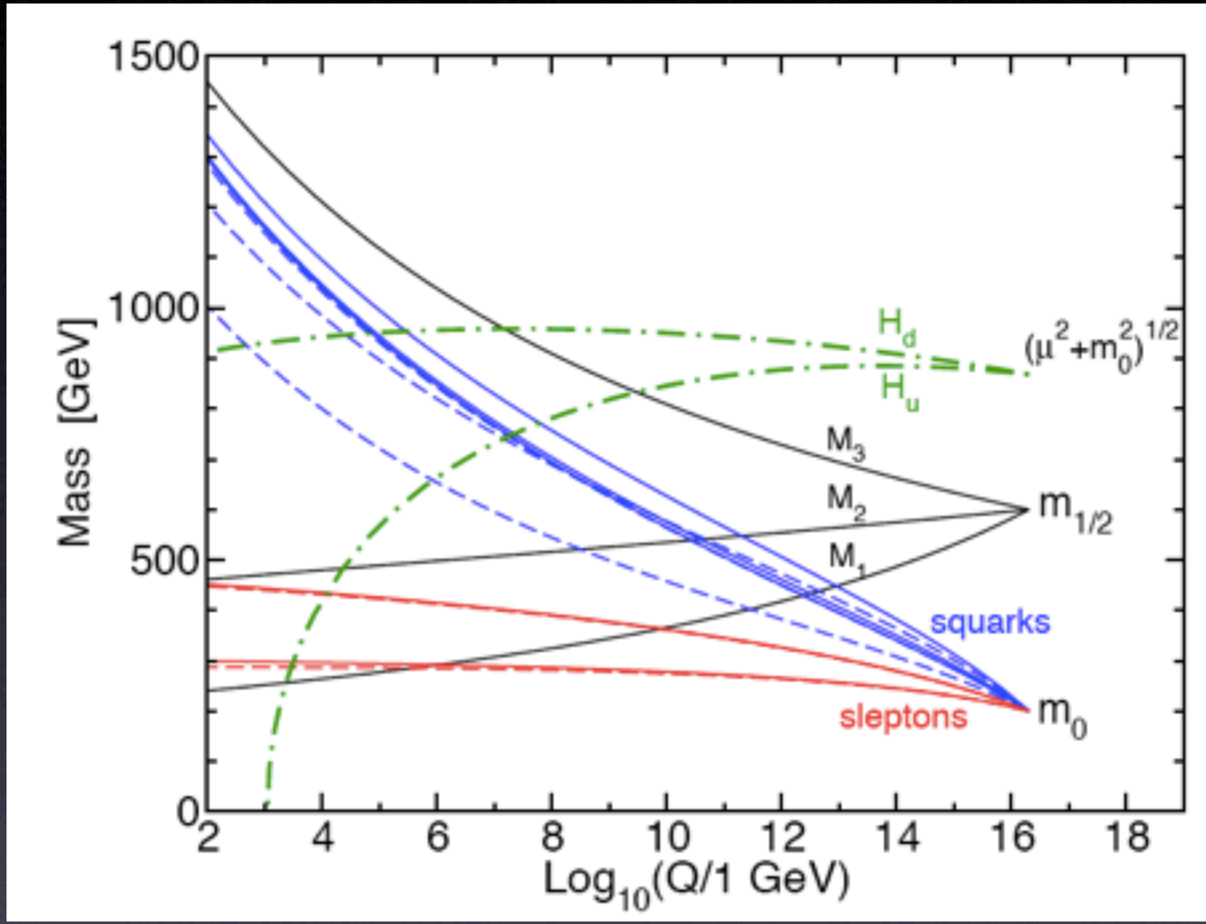

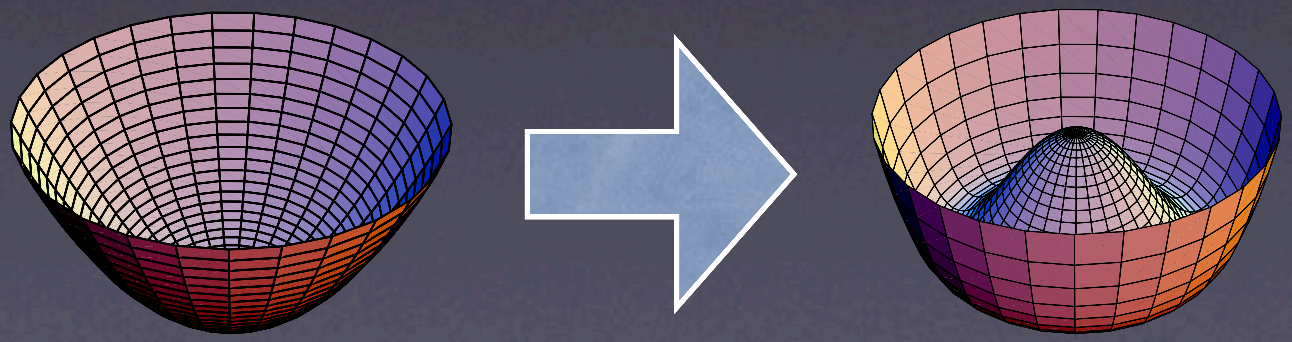

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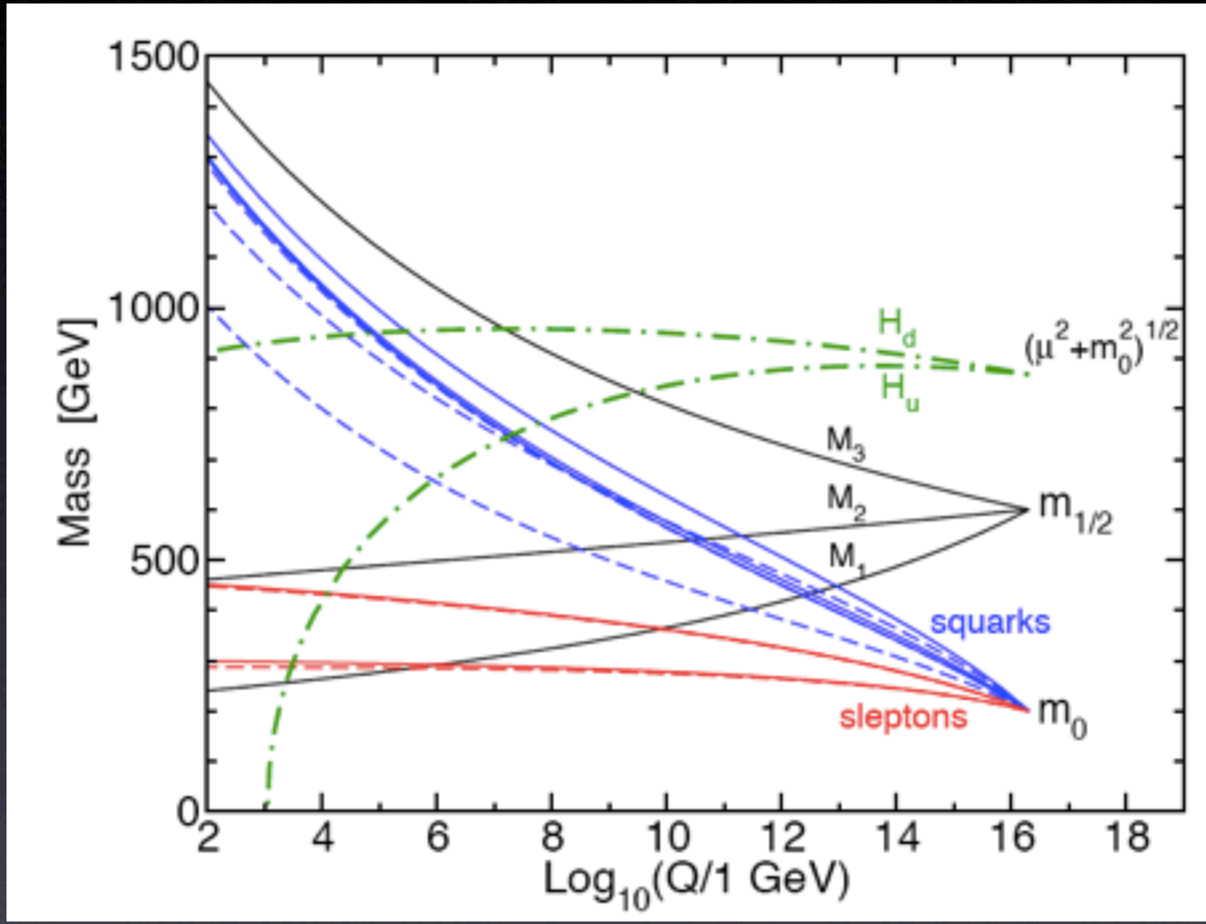
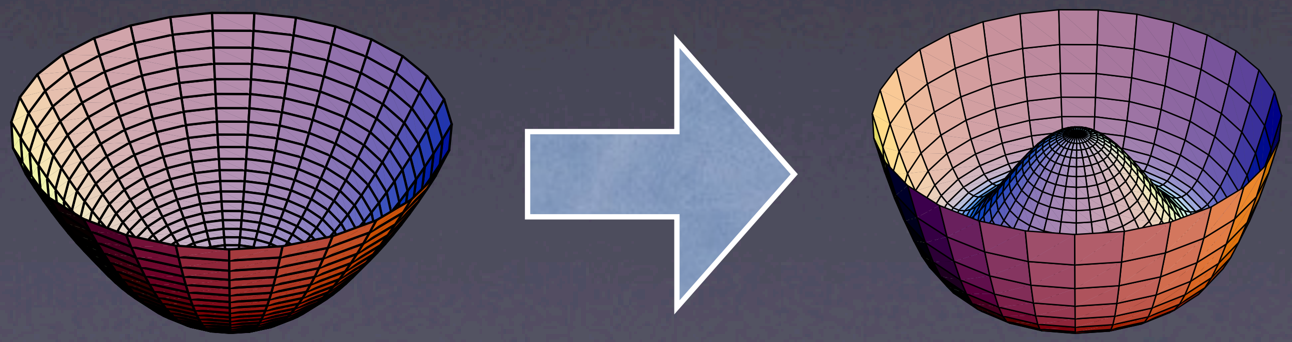
- m_{stop} < 200 GeV?





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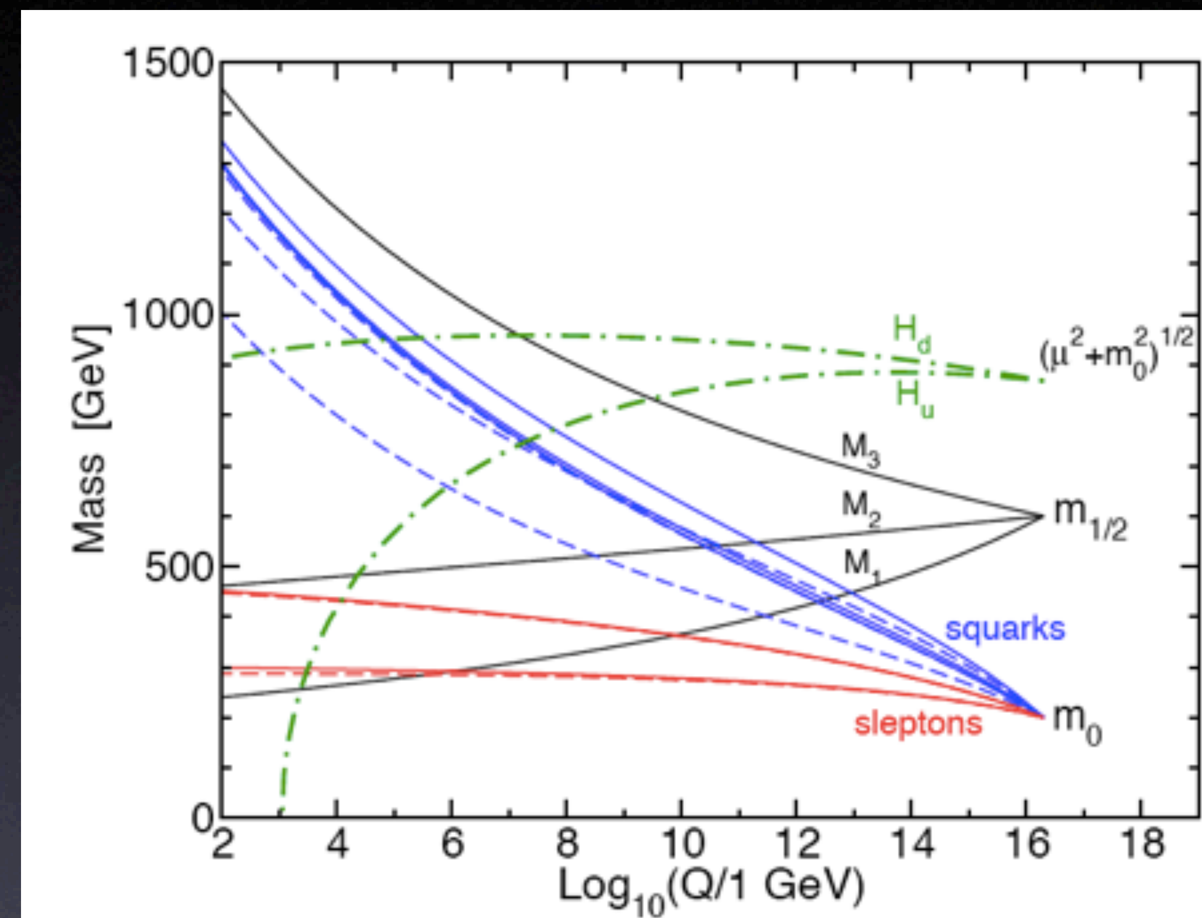

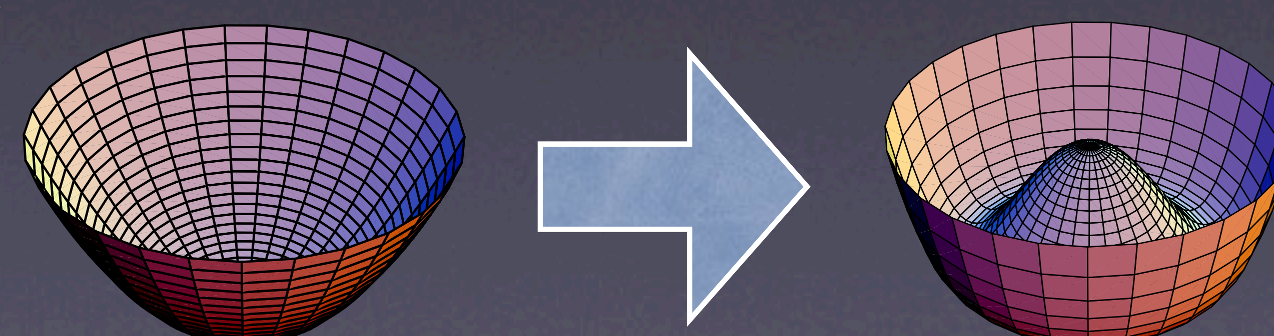

$$m^2_{\tilde{q}} \simeq m_0^2 + 0.7 M^2_{\tilde{g}}$$

SUSY naturalness limit

- Higgs mass squared driven negative by squark loop (Inoue et al)
- natural origin of EWSB!
- if stop too heavy, Higgs mass driven too negative

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- m_{stop} < 200 GeV?
- m_{gluino} < 300 GeV?

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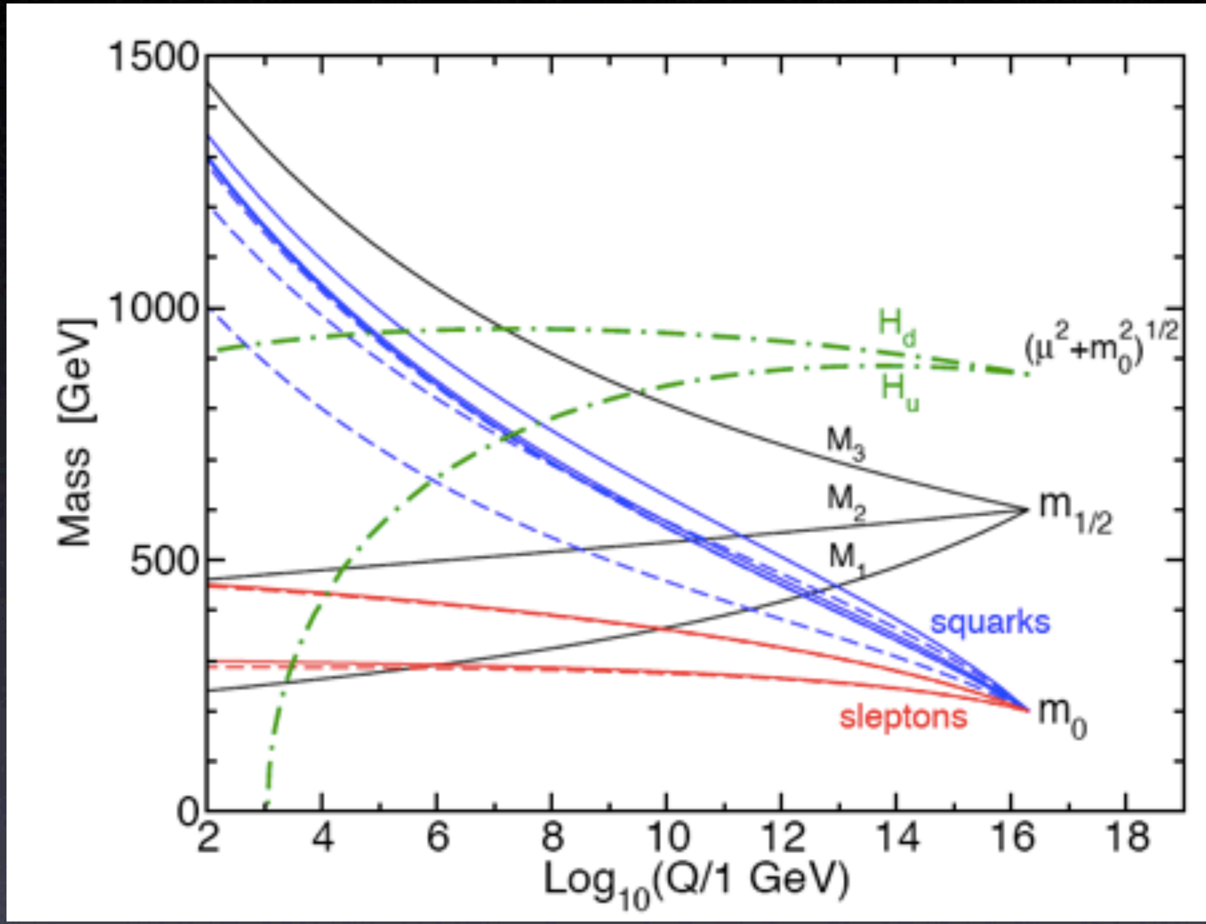

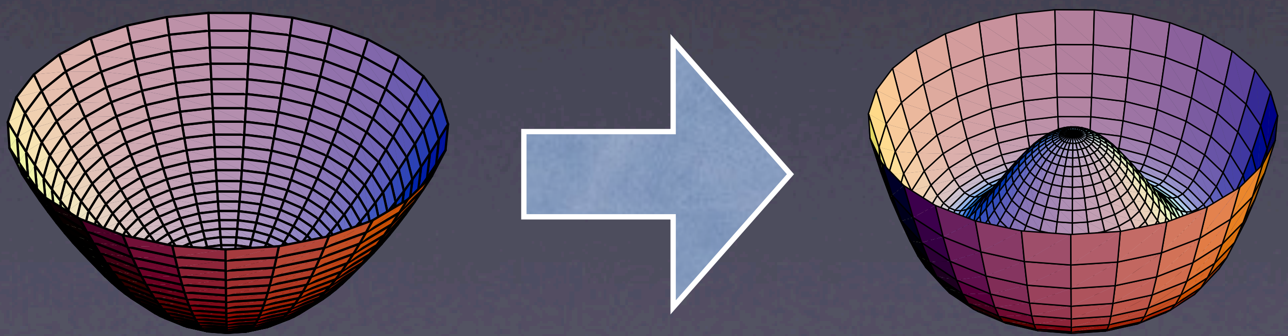

Monday, 6 February 12

Oversimplified summary

Unfortunately, no hint of New Physics in the LHC data (yet)

	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV

Oversimplified summary

Unfortunately, no hint of New Physics in the LHC data (yet)

in most cases, LHC limits just surpassed
EW precision limits = LEP +Tevatron

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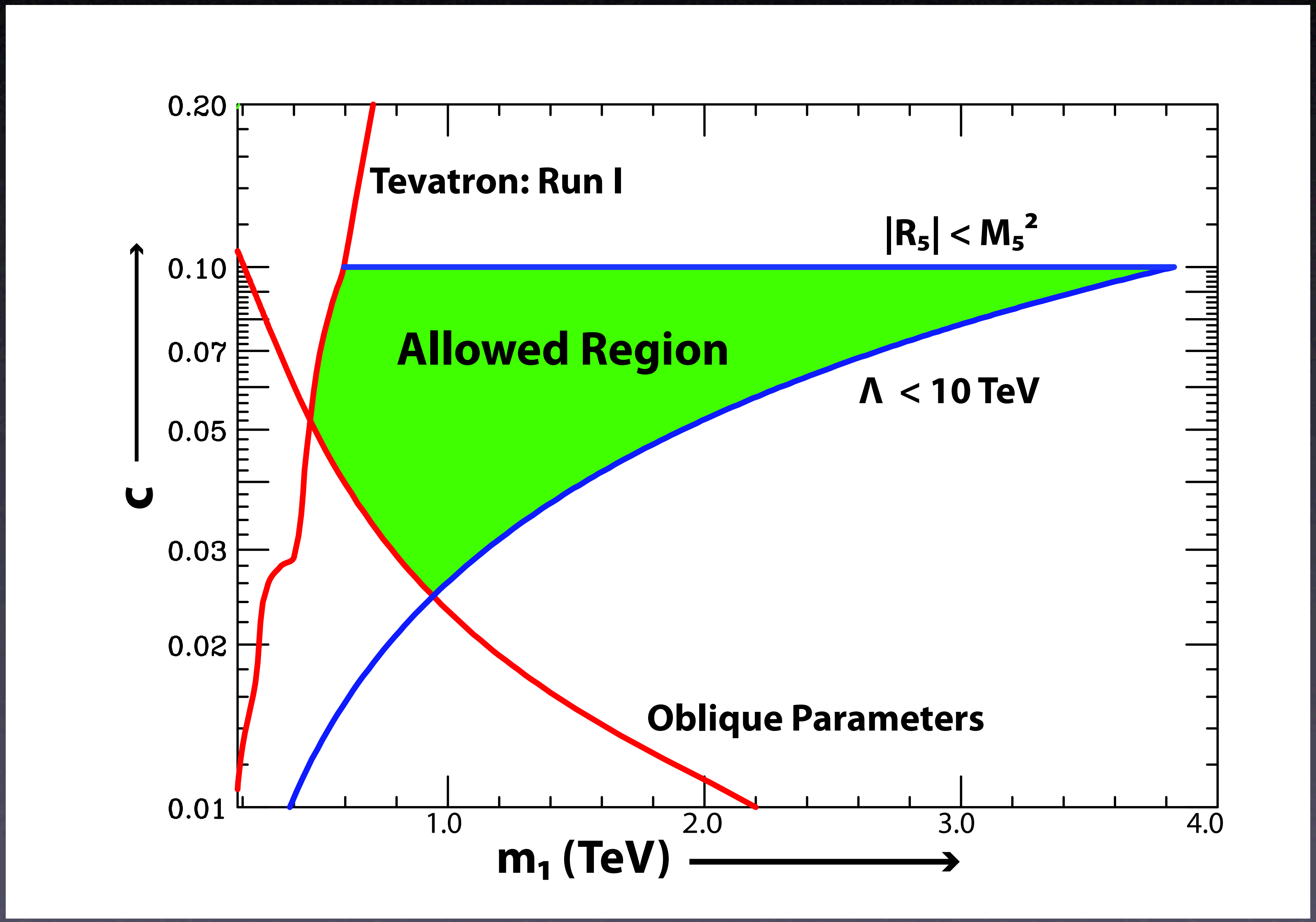
KK graviton warped extra dim



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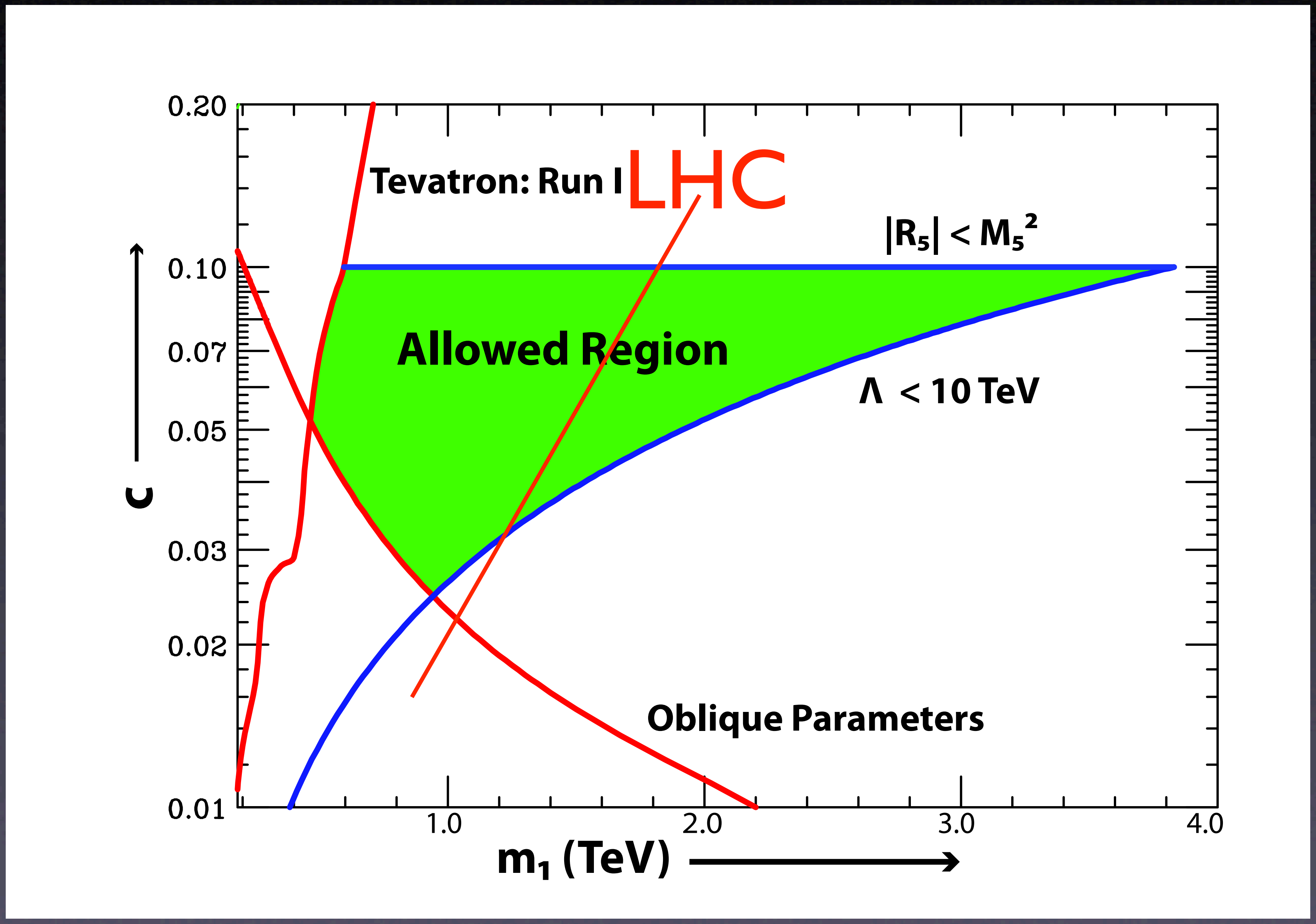
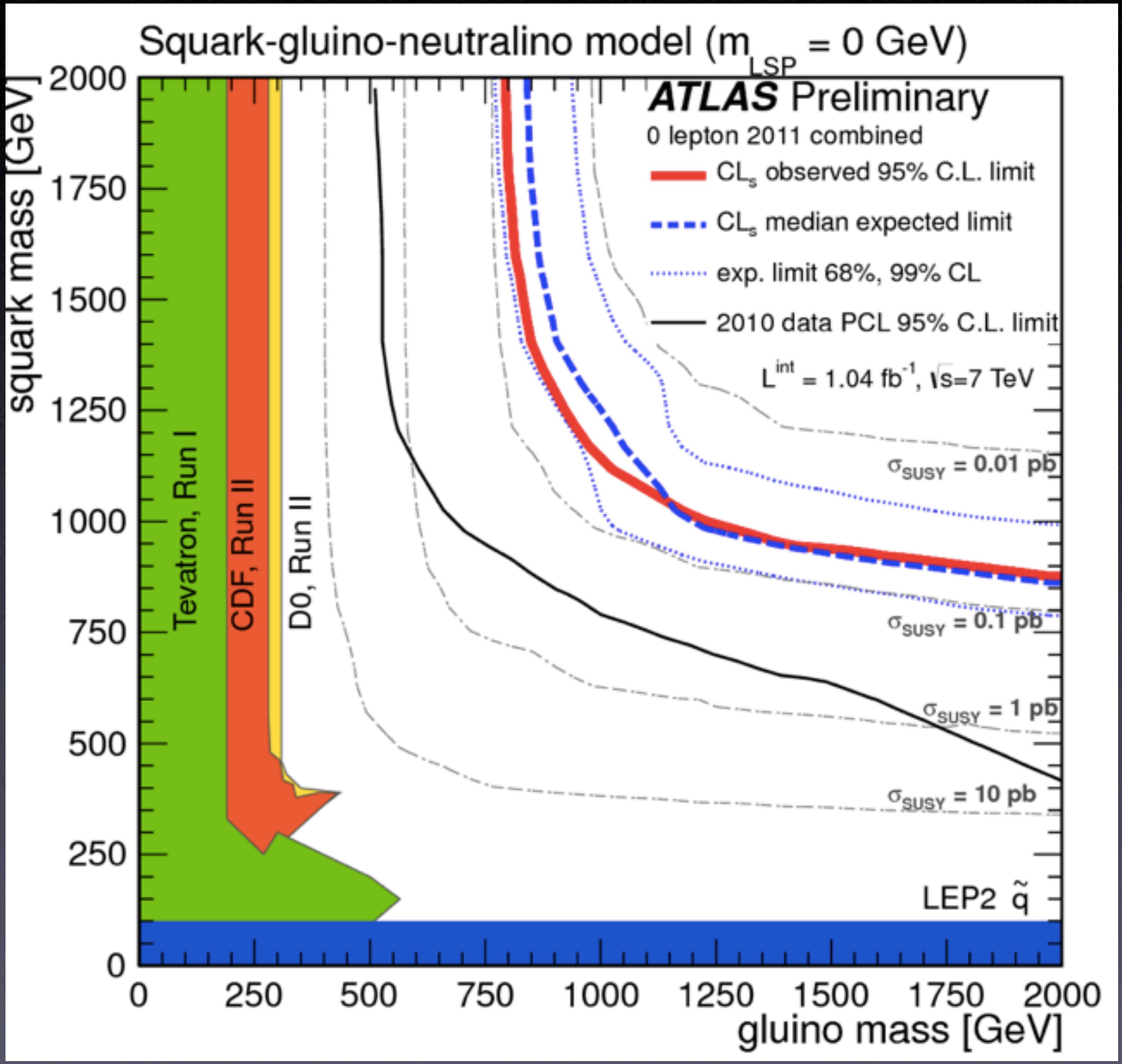
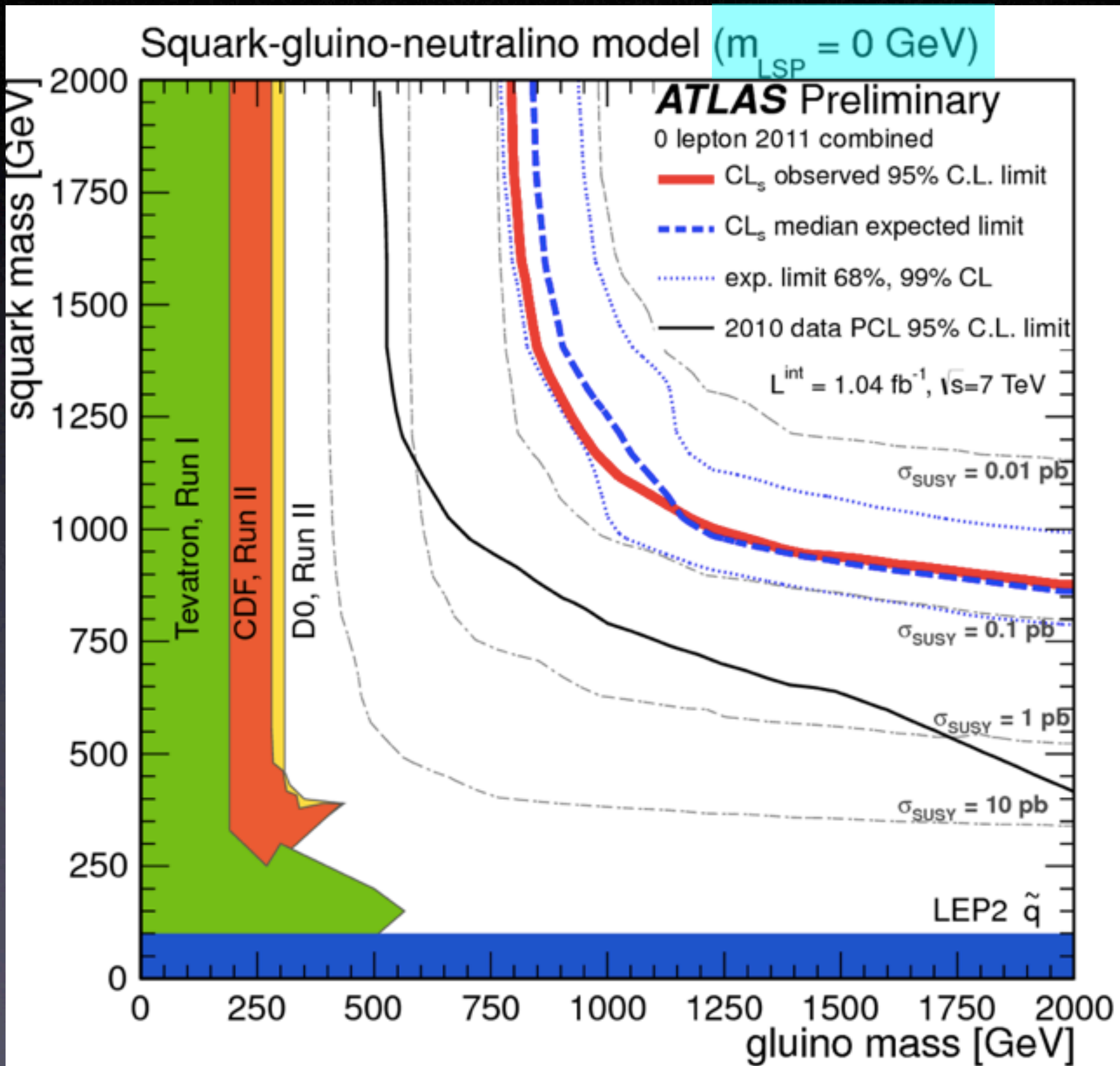


Is naturalness dead?



>0.8–1 TeV

Henri Bachacou, Lepton-Photon 2011



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Henri Bachacou, Lepton-Photon 2011

Is SUSY dead?

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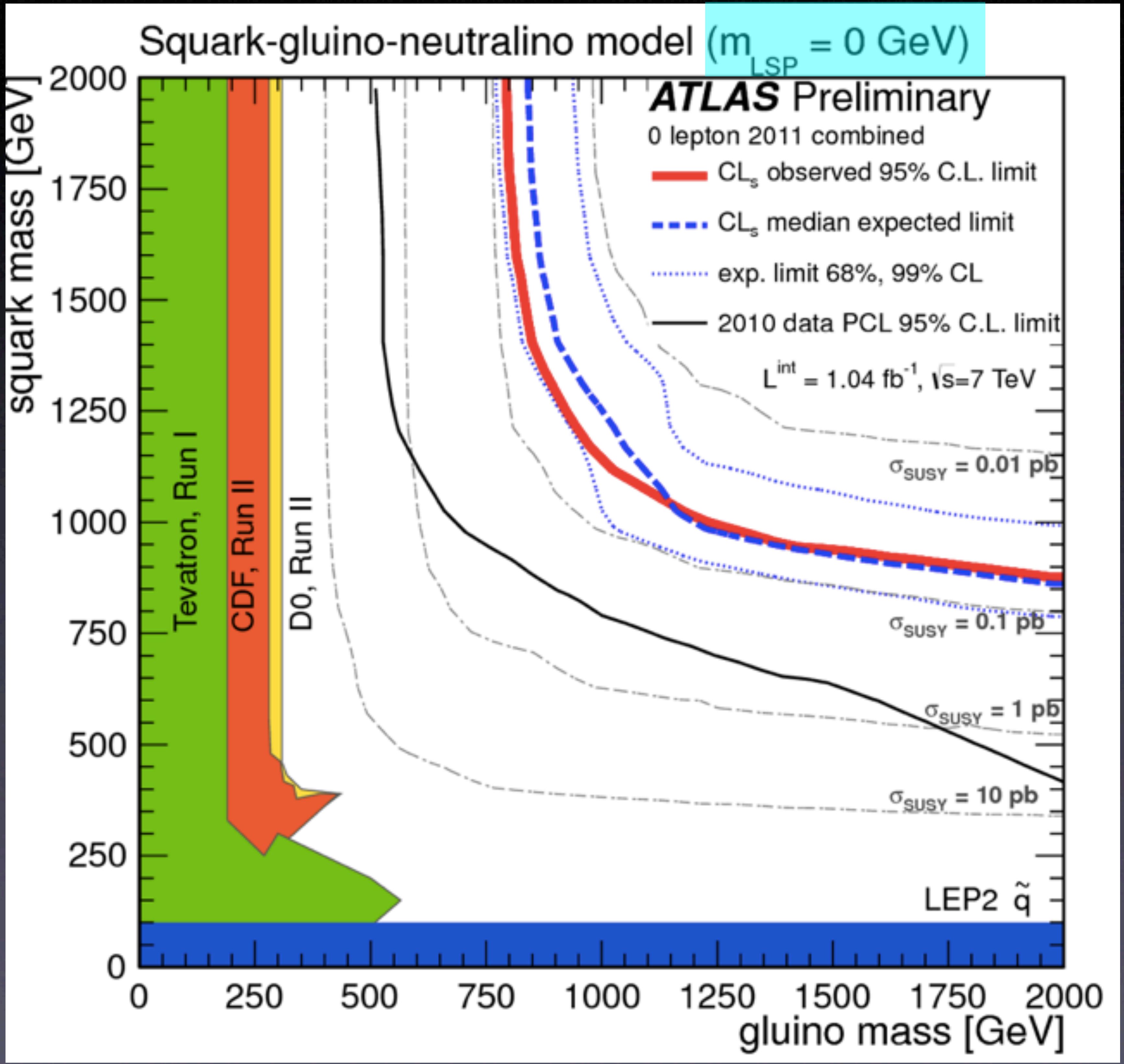

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Minimal Supersymmetric SM

- MSSM has a special relationship between the Higgs self-coupling and the gauge coupling $\lambda = g_2^2 + g_1'^2$
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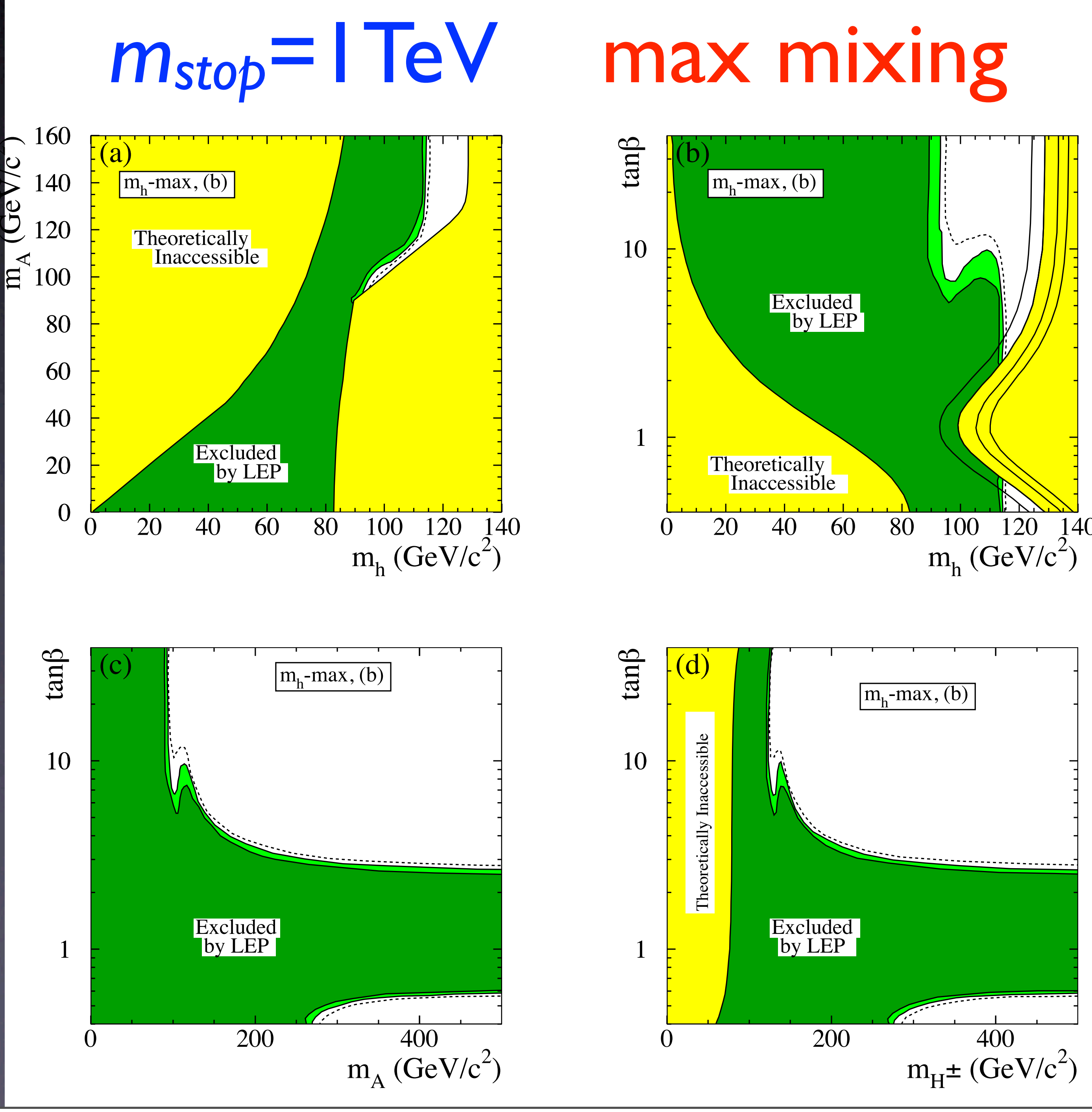
MSSM already fine-tuned

LEP combined hep-ex/0602042

MSSM predicts
$m_h < m_Z$@tree-level

need heavy stop to increase
Higgs boson mass



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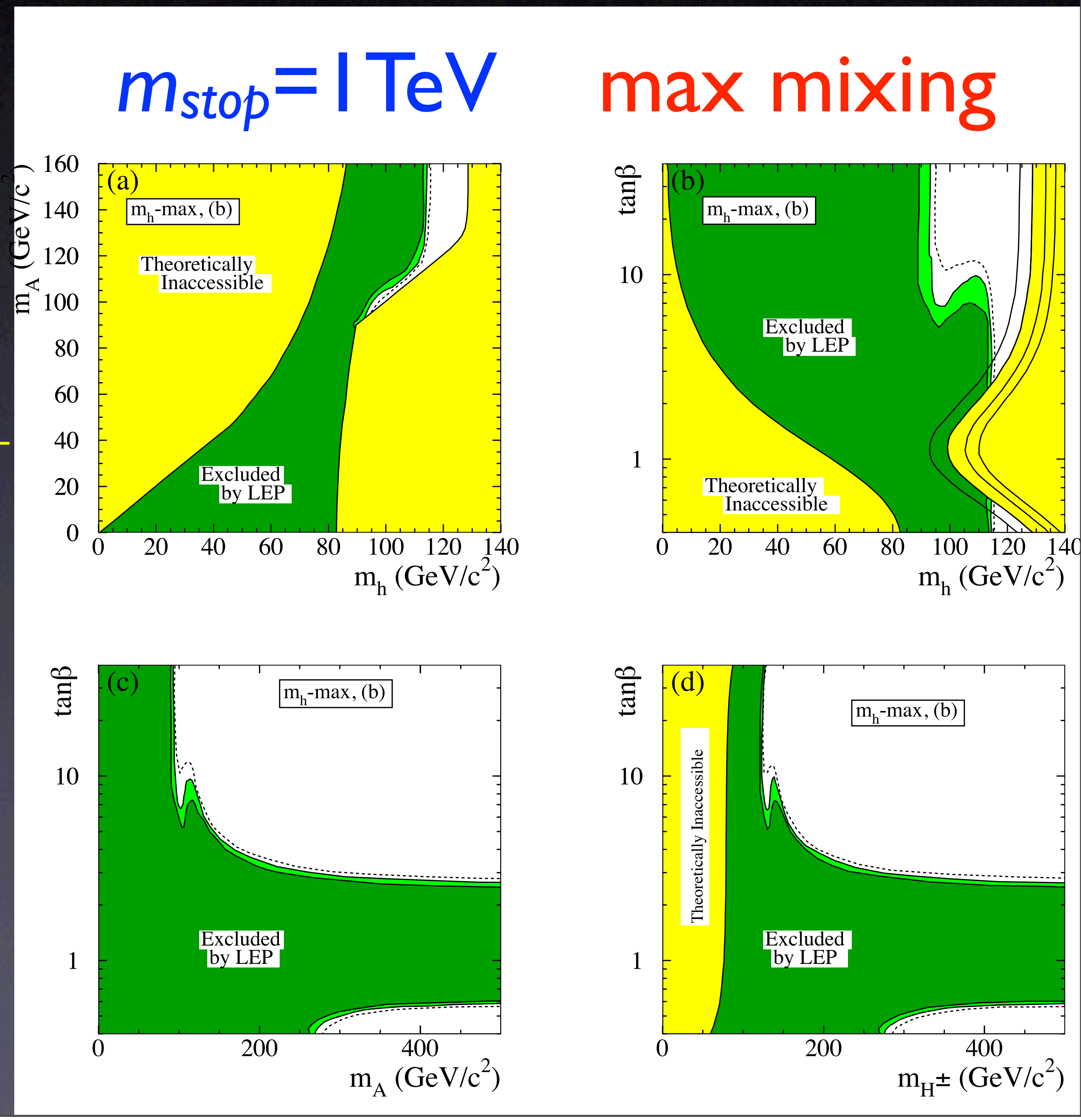
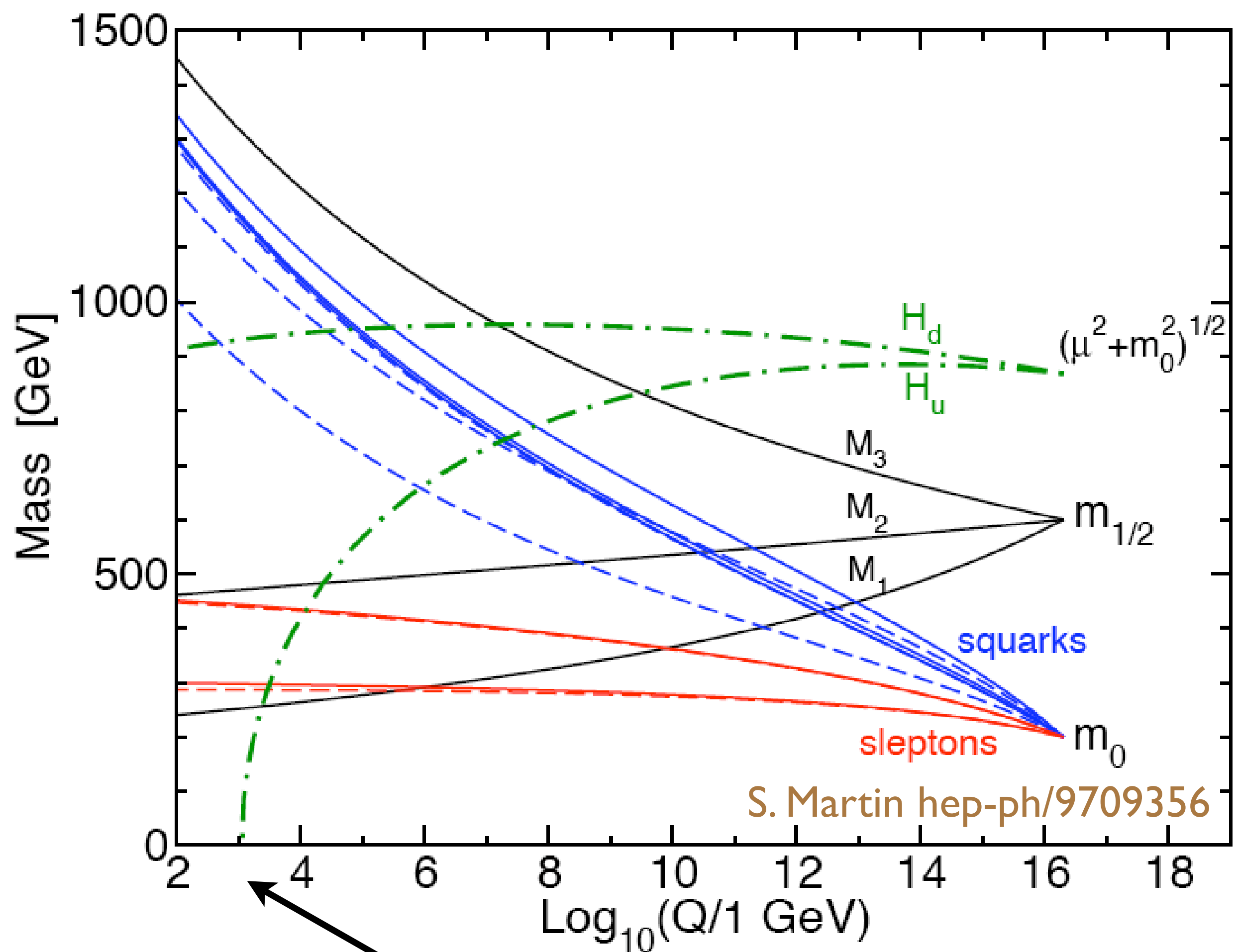
$$m_{h^0}^2 \simeq m_Z^2 + \frac{3}{4\pi^2} h_t^4 v^2 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

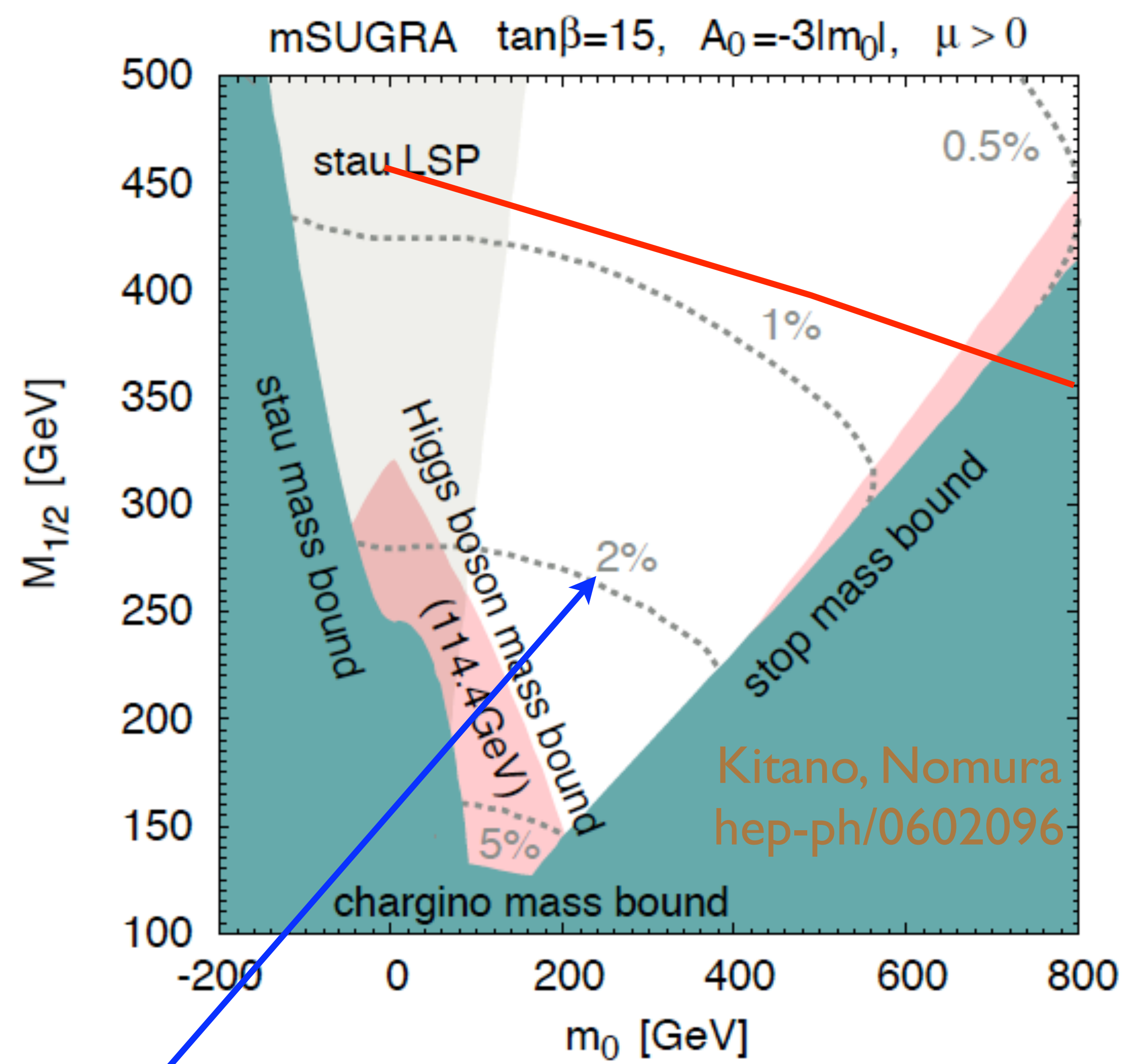
need heavy stop to increase Higgs boson mass



Min SUGRA: Fine-tuning

Lawrence Hall





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

Cancellation

Worse than 1 in 100

Growing Concern among theorists

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- No established deviations in
  - precision electroweak
  - flavor physics
  - LEP/Tevatron/LHC searches

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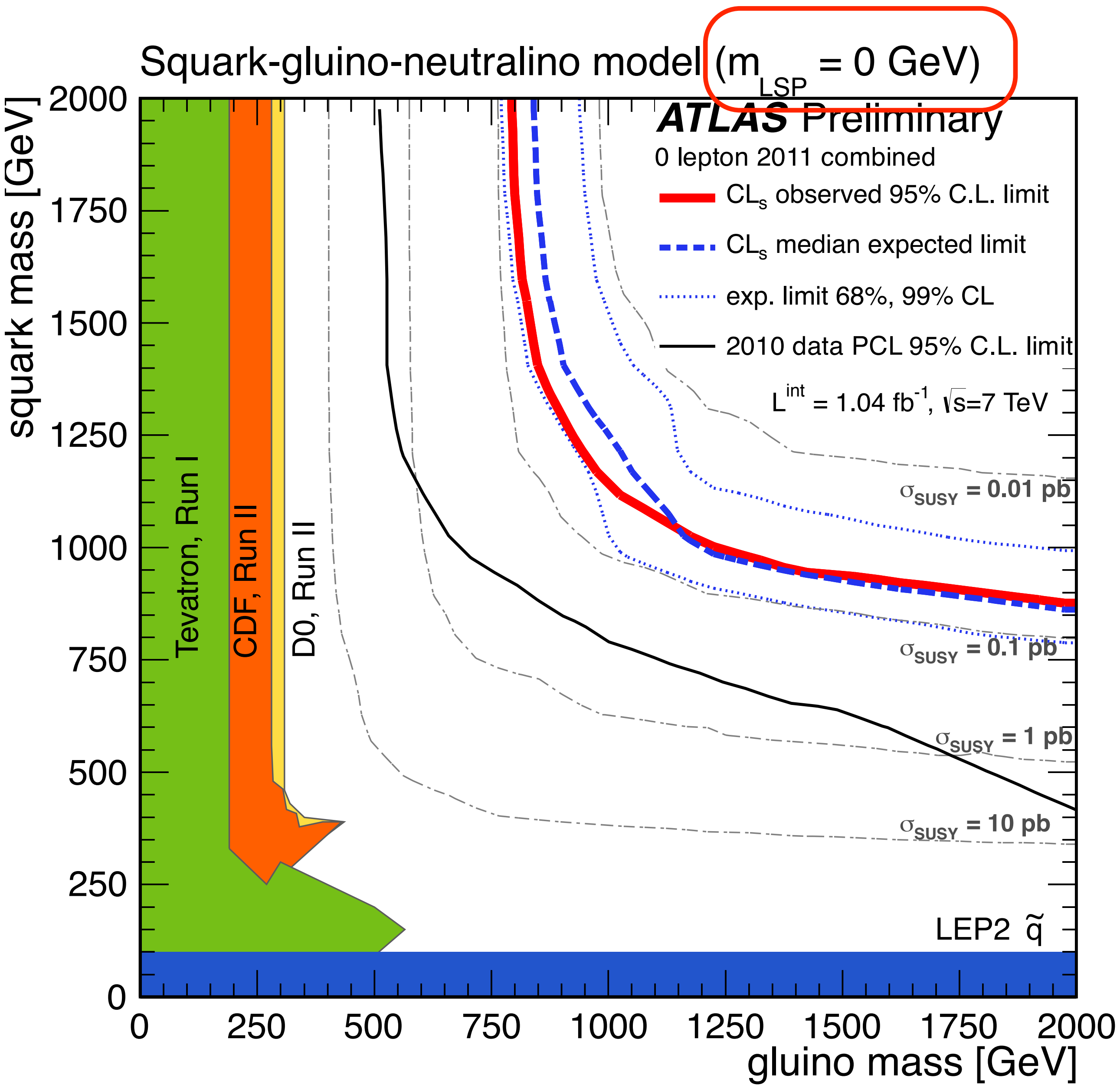
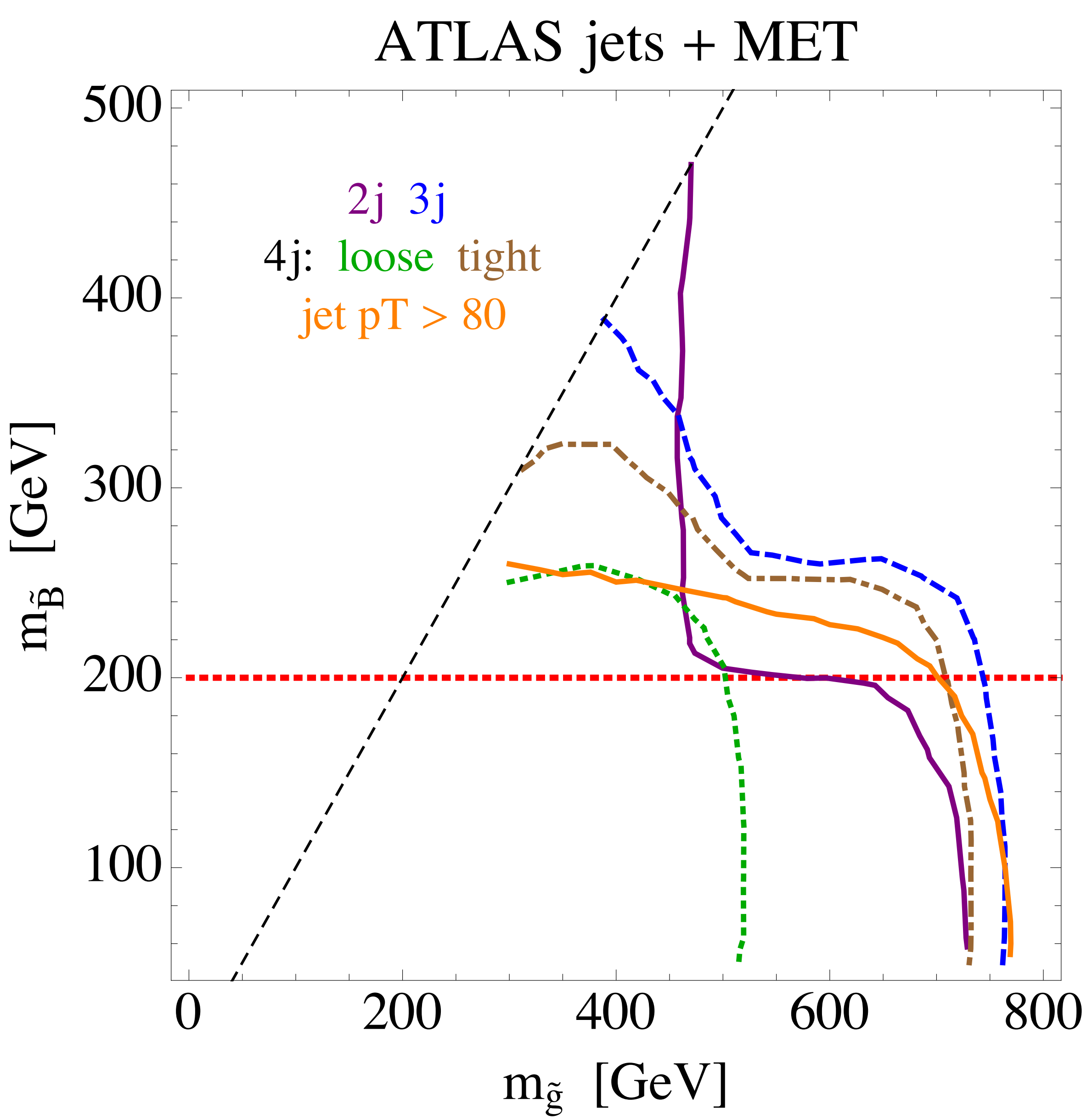
- after all, cosmological constant tuned 10^{-120}
- maybe there isn't anything beyond the Standard Model? → *There definitely is!*

Two attitudes

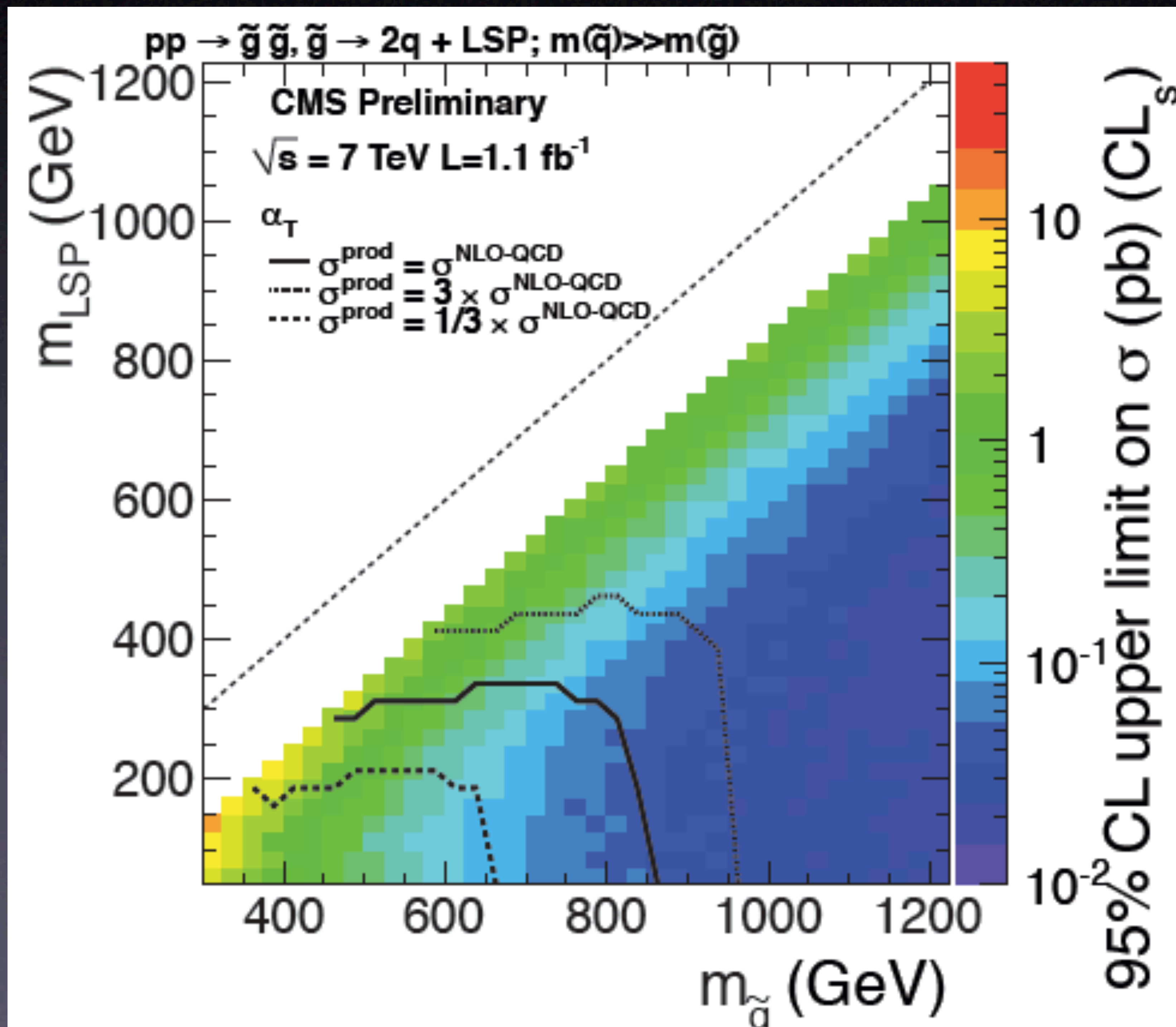
- change the SUSY spectrum so that it can be lighter still allowed by LHC data, trying to maintain naturalness in the Higgs sector
- abandon naturalness and allow for heavy masses for (some of) the SUSY particles, rely on anthropic principle for $v \ll M_{Pl}$
- always an interplay between SUSY vs Higgs

weaker limit with larger LSP mass





No limit if LSP>350GeV



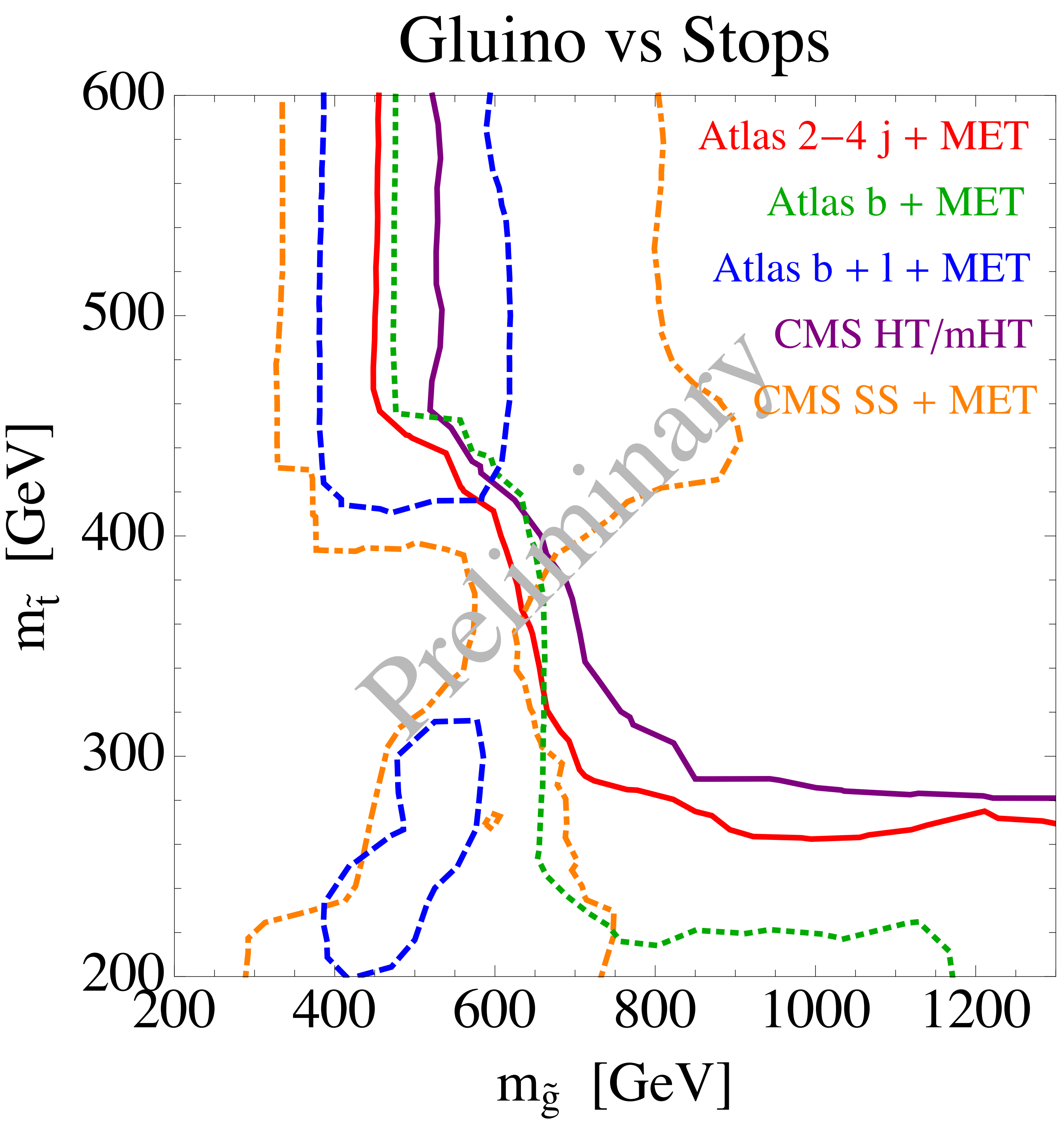
Josh Ruderman (Berkeley)

gluino v stop

here we fix,

$M_1 = 100$ GeV

$\mu = 200$ GeV



$m_{\tilde{g}} \gtrsim 800$ GeV

$m_{\tilde{t}} \gtrsim 300$ GeV

is OK

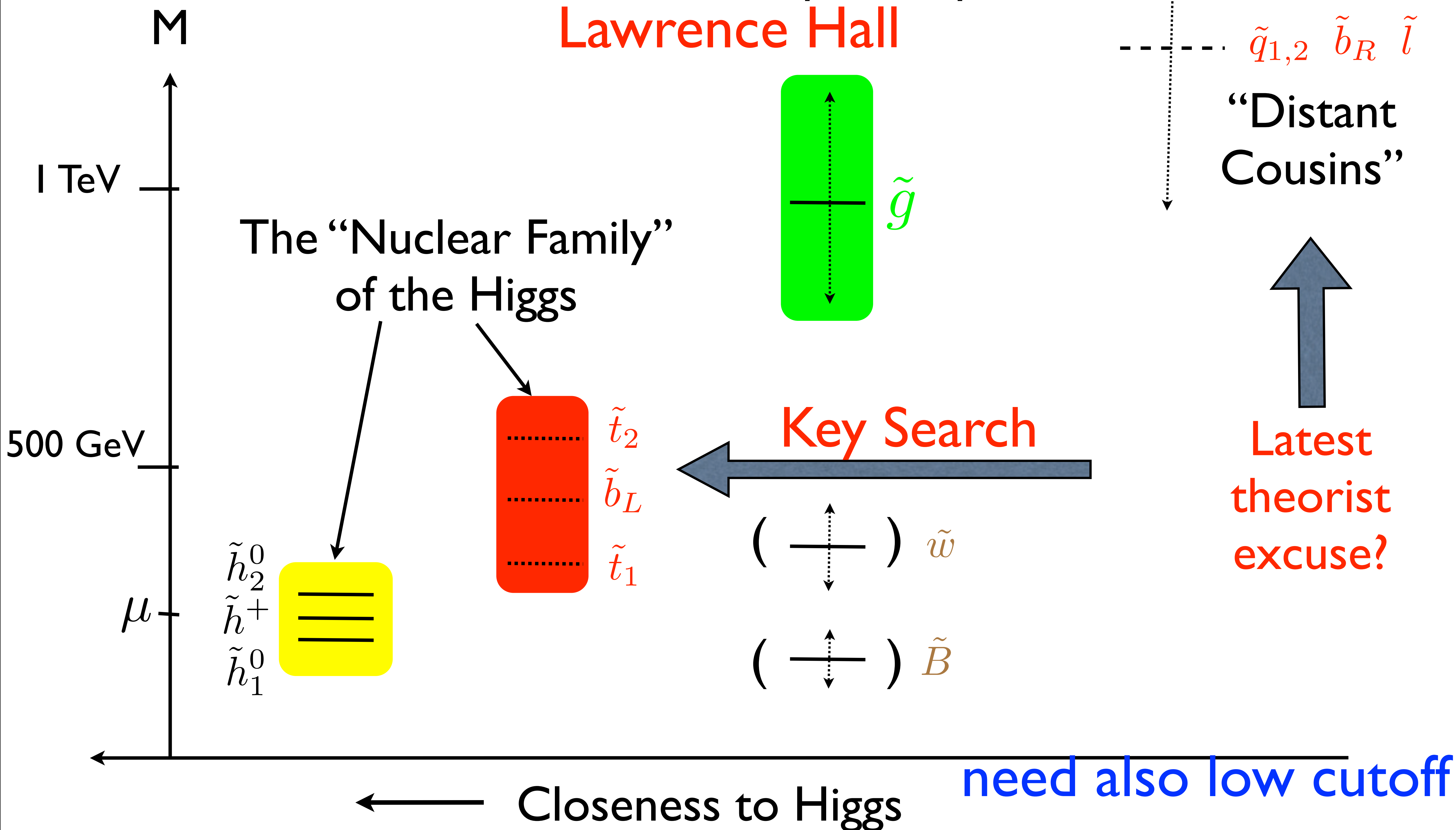
there is starting to be borderline fine tuning...

or, said differently, things are now becoming interesting!

A Natural Spectrum

General "bottom-up" viewpoint

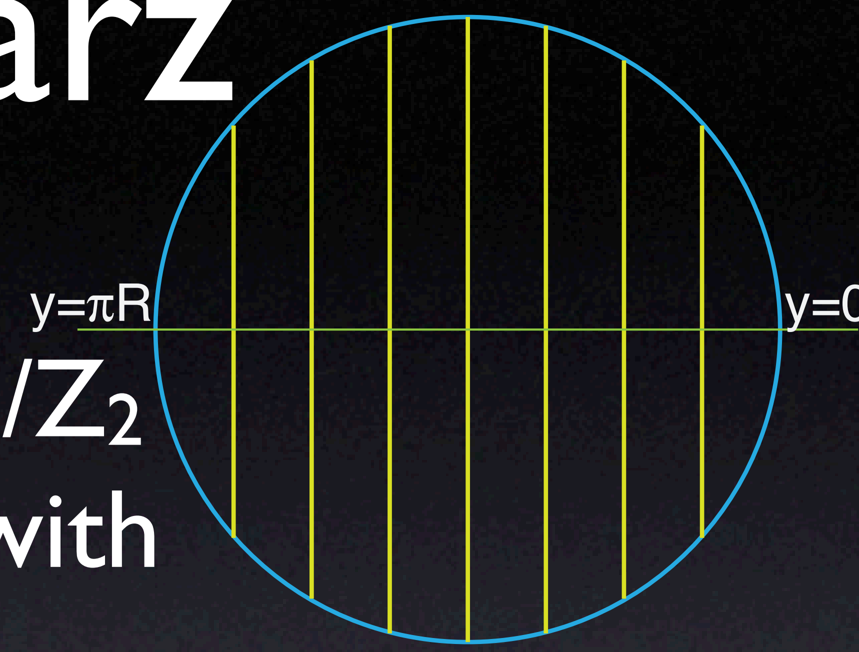
Lawrence Hall



need also low cutoff

Would I prefer a factor of 3 lower?

Scherk-Schwarz



- For MSSM living on 5D with S^1/Z_2 orbifold, one can break SUSY with boundary conditions $PTP = T^{-1}, \quad P^2 = 1$
- @tree level, all SUSY particles degenerate at α/R ($\alpha<1$, can be very small) $T = e^{i\alpha}$
- all Kaluza-Klein particles degenerate at $1/R$
- SUSY as light as 500 GeV still OK

HM, Nomura, Tobioka

Minimal Supersymmetric SM

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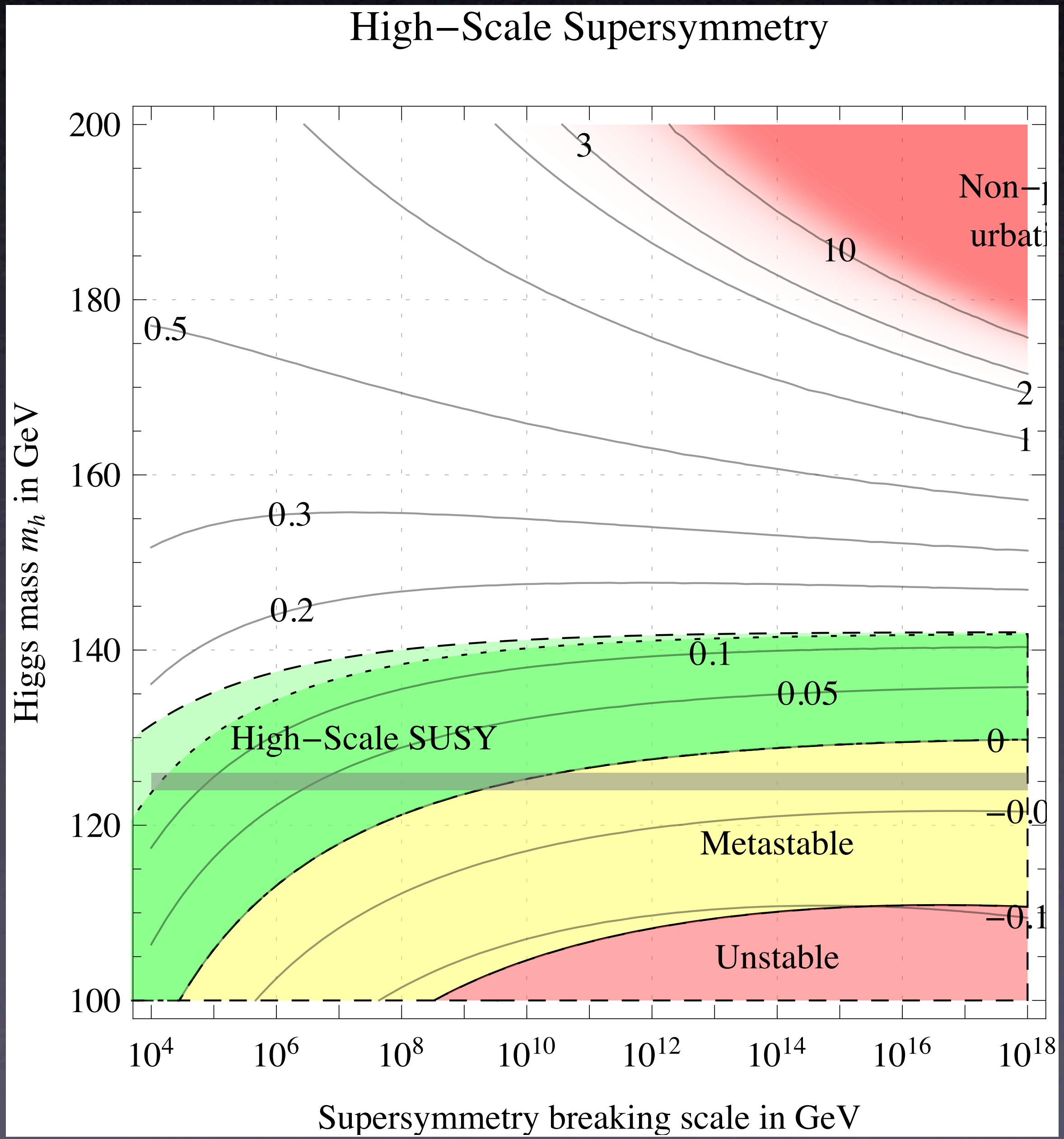
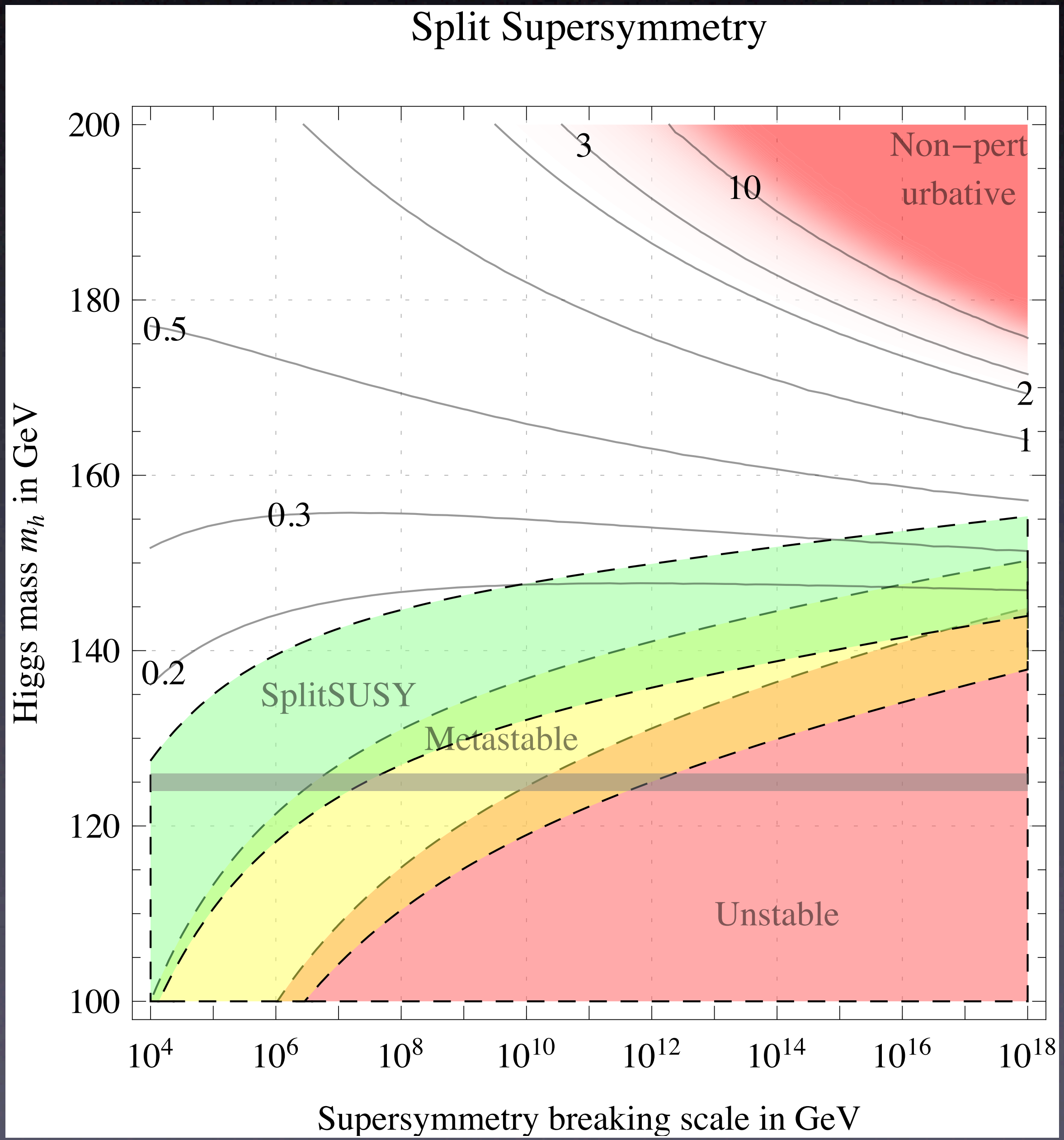
☐ prefer heavier SUSY

Giudice-Strumia

SUSY all heavy



SUSY scalars all heavy



Giudice-Strumia

Ibe-Yanagida

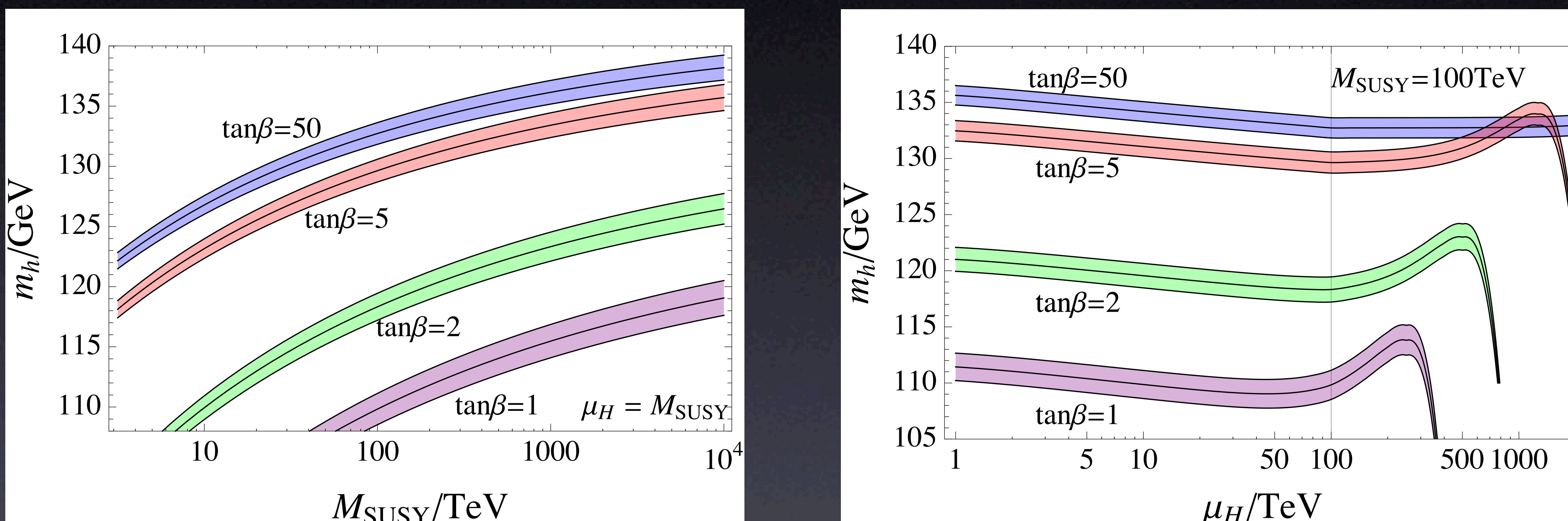


Figure 1: *Left) The lightest Higgs boson mass as a function of* $M_{\rm SUSY}$ *with* $\mu_H = M_{\rm SUSY}$. *The result is slightly lighter than the one in Ref. [25] due to the large* μ*-term (see the right panel). Right) The lightest Higgs boson mass as a function of* μ_H *for* $M_{\rm SUSY} = 100$ *TeV. In both panels, the color bands show the* 1σ *error of the top quark mass,* $m_{\rm top} = 173.2 \pm 0.9$ *GeV [26], while we have taken the central value of the strong coupling constant* $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ *[27]. We have also fixed the gaugino masses to* $M_1 = 900$ *GeV,* $M_2 = 300$ *GeV and* $M_3 = -2500$ *GeV as reference values, although the predicted Higgs boson mass is insensitive to the gaugino masses.*

anomaly-mediated SUSY breaking
with heavy scalars, higgsinos

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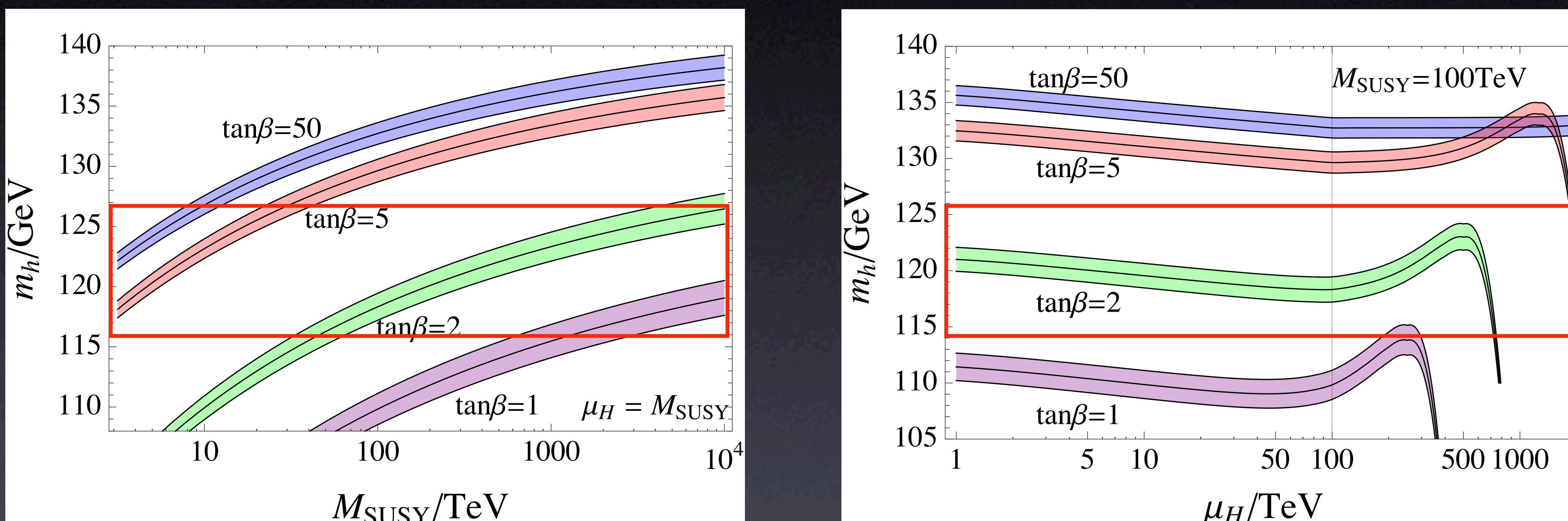
Ibe-Yanagida



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uneasiness in cosmology

- Before COBE, upper limit on CMB anisotropy kept getting better and better
- Before 1998, the universe appeared younger than oldest stars
- cosmologists got antsy
- "crisis in standard cosmology"
- it turned out a little "fine-tuned"
  - low quadrupole
  - dark energy

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"Big Bang not yet dead but in decline"
Nature 377, 14 (1995)

"Bang! A Big Theory May Be Shot"
A new study of the stars could rewrite the history of the universe
Times, Jan 14 (1991)

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The galaxy M100, as seen by the Hubble Space Telescope. Images like this and other new discoveries are turning theories of the cosmos upside down.

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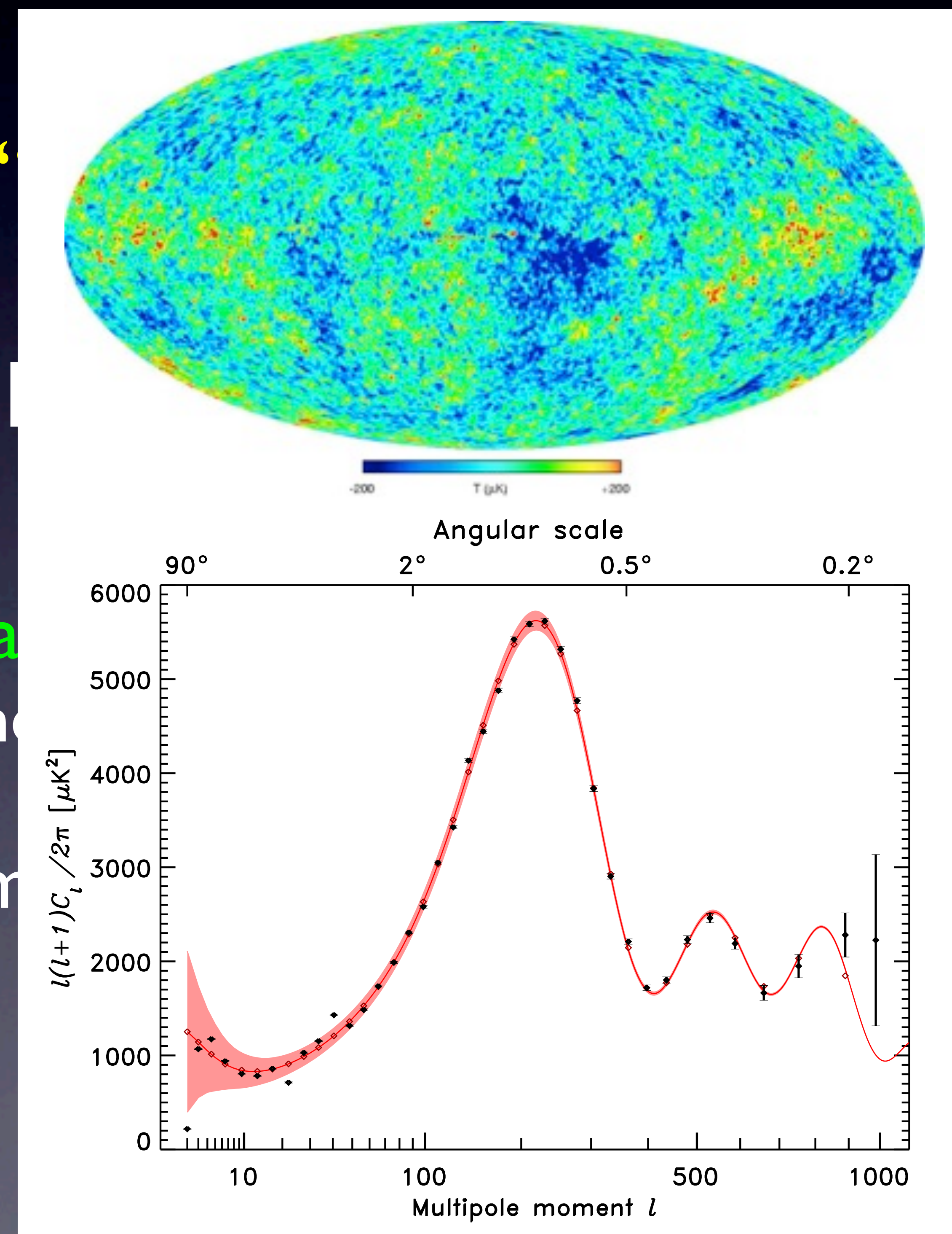

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patience

It took 10 years for CDF to discover the top quark.

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4] S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] P. Auchincloss,[26] F. Azfar,[22] P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26] A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] P. Bartalini,[24] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[24] S. Behrends,[3] S. Belforte,[24] G. Bellettini,[24] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[24] D. Bortoletto,[25] J. Boudreau,[23] G. Brandenburg,[9] L. Breccia,[2] C. Bromberg,[18] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[13] C. Campagnari,[7] M. Campbell,[17] A. Caner,[7] W. Carithers,[15] D. Carlsmith,[34] A. Castro,[21] G. Cauz,[24] Y. Cen,[26] F. Cervelli,[24] H. Y. Chao,[29] J. Chapman,[17] M.-T. Cheng,[29] G. Chiarelli,[24] T. Chikamatsu,[32] C. N. Chiou,[29] L. Christofek,[11] S. Cihangir,[7] A. G. Clark,[24] M. Cobal,[24] M. Contreras,[5] J. Conway,[28] J. Cooper,[7] M. Cordelli,[8] C. Couyoumtzelis,[24] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] J. D. Cunningham,[3] T. Daniels,[16] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[24] M. Dell'Orso,[24] L. Demortier,[27] B. Denby,[24] M. Deninno,[2] P. F. Derwent,[17] T. Devlin,[28] M. Dickson,[26] J. R. Dittmann,[6] S. Donati,[24] R. B. Drucker,[15] A. Dunn,[17] N. Eddy,[17] K. Einsweiler,[15] J. E. Elias,[7] R. Ely,[15] E. Engels, Jr.,[23] D. Errede,[11] S. Errede,[11] Q. Fan,[26] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[19] J. Freeman,[7] J. Friedman,[16] H. Frisch,[5] T. A. Fuess,[1] Y. Fukui,[14] S. Funaki,[32] G. Gagliardi,[23] S. Galeotti,[24] M. Gallinaro,[21] M. Garcia-Sciveres,[15] A. F. Garfinkel,[25] C. Gay,[9] S. Geer,[7] D. W. Gerdes,[17] P. Giannetti,[24] N. Giokaris,[27] P. Giromini,[8] L. Gladney,[22] D. Glenzinski,[13] M. Gold,[19] J. Gonzalez,[22] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[27] H. Grassmann,[7,*] L. Groer,[28] C. Grosso-Pilcher,[5] G. Guillian,[17] R. S. Guo,[29] C. Haber,[15] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[34] R. M. Hans,[35] K. Hara,[32] B. Harral,[22] R. M. Harris,[7]

too early to tell

- SM Higgs boson most likely be settled with this year's data
- but it could take longer if not SM
- no sign of SUSY or other new physics
- not much better than what we already knew from LEP
- limits would improve ~200 GeV this year

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  - “twice in a century” opportunity!

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- LHC won’t stand alone: need other probes to reveal the picture at Terascale and beyond

I feel lucky to
live in this era!

experiments


theorist
ATLAS
CMS

healthy field!