A Chiral Fourth Generation

Meets Precision and Higgs Physics

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Kribs, Plehn, Spannowsky, TT
hep-ph/0706.3718, PRD

Columbia University
October 10, 2007

What will we find at the LHC?


WIDESCREEN COLLECTION
DVD
BING CROSBY
DONALD O'CONNOR
JEANMAIRE
MITZI GAYNOR
PHIL HARRIS
ANYTHING GOES

A 4^{th} Generation??

"A 4^{th} generation of ordinary fermions is excluded to 99.999% CL on the basis of the S parameter alone."

PDG 2006

So maybe not *anything*...

Outline

- The PDB's conclusion is wrong!
- Constraints on a 4th generation.
- Parameter space where 4th generation avoids (minimizes) all constraints.
- Consequences for Higgs physics.

We concentrate on the low energy effective theory (cut-off $\Lambda << M_{pl}$).
Some effects well-known, some known (but not appreciated), some new!

Constraints on a 4th Generation

- $Z \to \nu\bar{\nu}$ at LEP I.
- CKM and MNS mixings.
- Tevatron and LEP II direct searches.
- Electroweak precision measurements.
- Vacuum stability and triviality.

Invisible width $Z \to \nu\overline{\nu}$

Easily avoided. We add a singlet ν_{R4} with

$$\mathcal{L} \supset \lambda L_4 H \nu_{R4}^c$$

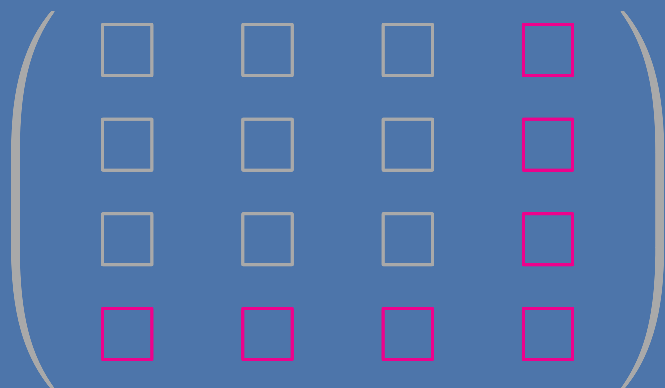
The 4th generation neutrino acquires Dirac mass:

$$m_D = \lambda v$$

(We can also add $M_{44}\, \nu_{R4}\, \nu_{R4}$: a Majorana mass;
a bit more to say on this later)

Flavor physics

Quark mixing constraints can be approximated by enforcing unitarity of the 4x4 CKM matrix:



$$|V_{ud4}|^2 = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \simeq 0.0008 \pm 0.0011$$
$$|V_{cd4}|^2 = 1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 \simeq 0.032 \pm 0.181$$
$$|V_{t4d}|^2 = 1 - |V_{ud}|^2 - |V_{cd}|^2 - |V_{td}|^2 \simeq -0.001 \pm 0.005$$

PDB

This requires, roughly,

$$\begin{aligned} |V_{ud4}| &\lesssim 0.03 \\ |V_{d4u}| &\lesssim 0.04 \\ |V_{cd4}| &\lesssim 0.2 \end{aligned}$$

resulting in acceptably small deviations in quark flavor physics. 3-4 mixing could be larger, and is bounded by D0's (and recently CDF too) observation of single top production:

$$|V_{tb}| \gtrsim 0.68$$

D0, arXiv:hep-ex/0612052

which allows for roughly 50% 3-4 quark mixing.

More precise constraints from analyses of 4th generation effects on specific processes, for example...

$$|V_{ud4}| \lesssim 0.03$$

$$|V_{d4u}| \lesssim 0.04$$

$$|V_{cd4}| \lesssim \not{0.2}$$

0.04 ($D0-\overline{D0}$ mixing)

J. Hewett et al, arXiv:0705.3650

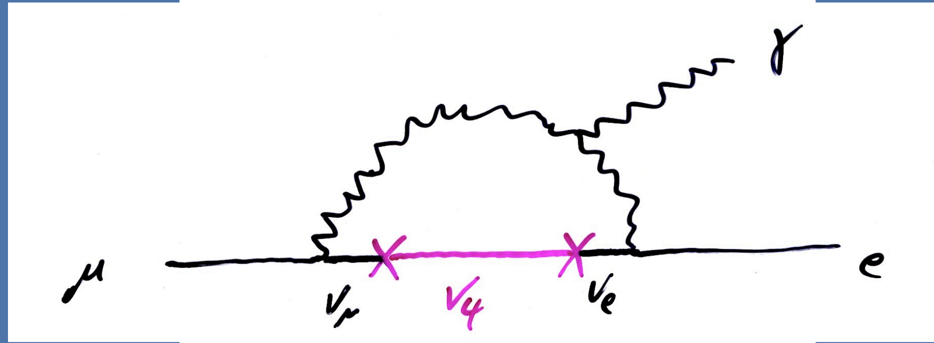
Charged Lepton Flavor Mixing

- μ -> e γ and similar processes restrict PMNS elements.
- Assuming Dirac neutrino masses, we find

$$|U_{e4}U_{\mu 4}|^2 \lesssim 10^{-8}$$

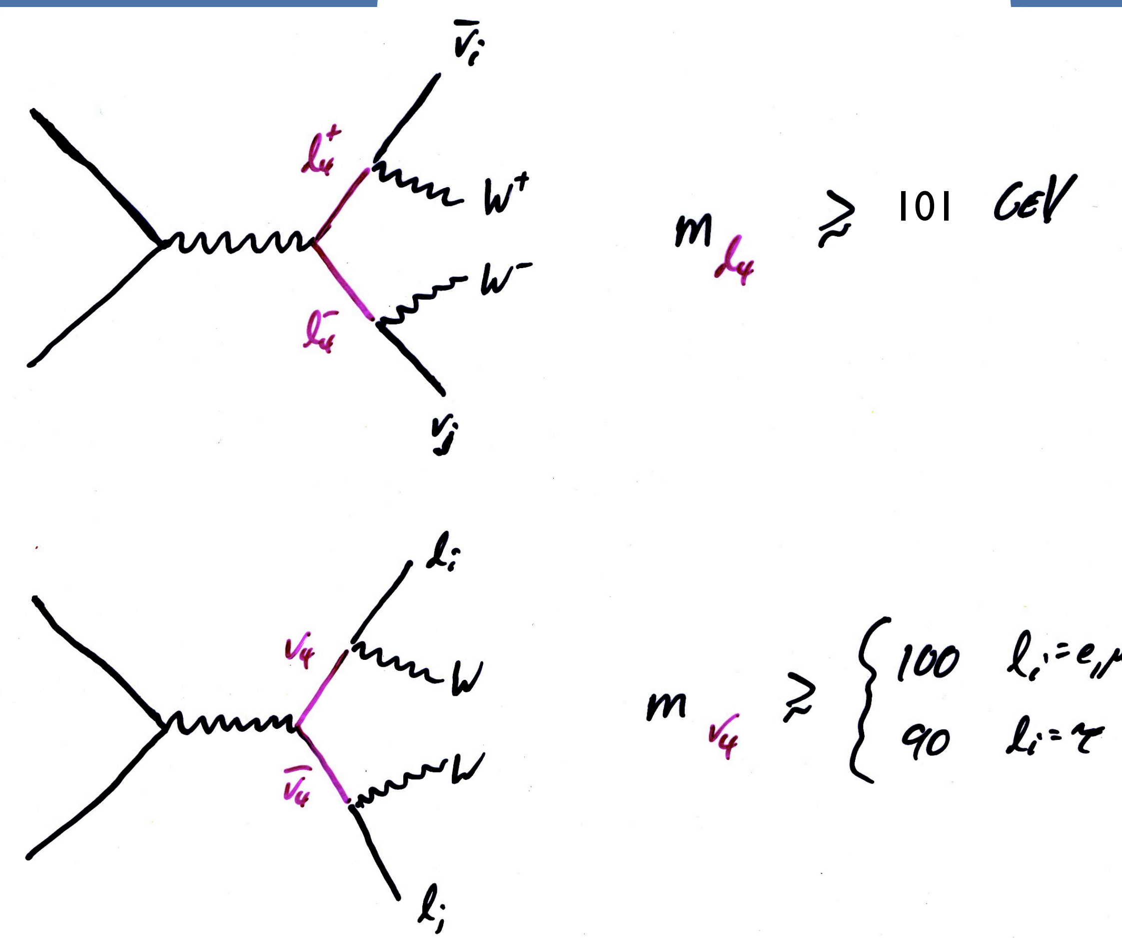
- So that:

$$|U_{e4}|, |U_{\mu 4}| \lesssim 0.01$$

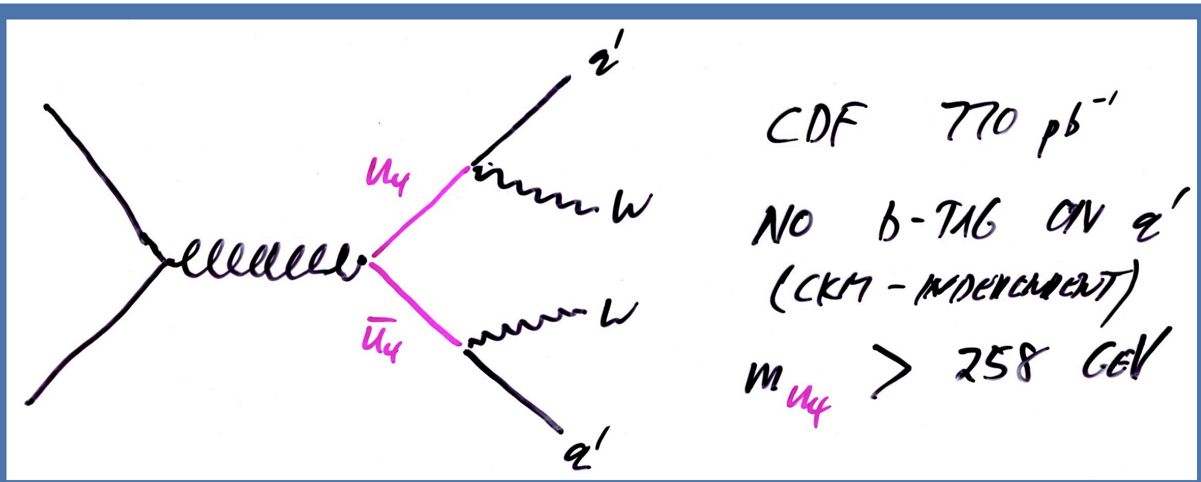


LEP II Direct Search

- LEP II would have noticed pair production of the fourth generation leptons,
- They can decay into ordinary charged leptons and missing energy and/or jets.
- Tevatron bounds would probably be a little better (similar to charginos/neutralinos) but difficult to interpret.



Tevatron Direct Limits: CDF t-prime Search

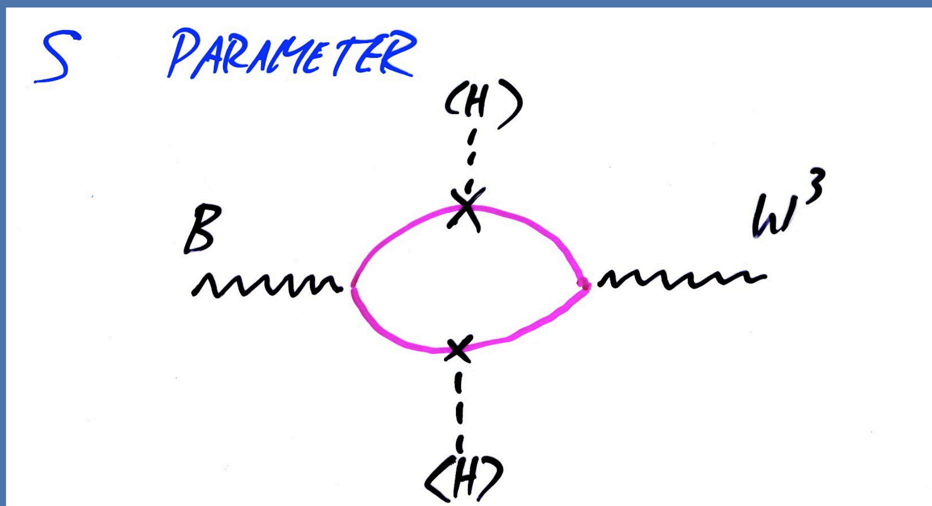


No comparable published bound on d_4 (except when d_4 -> b Z dominates)

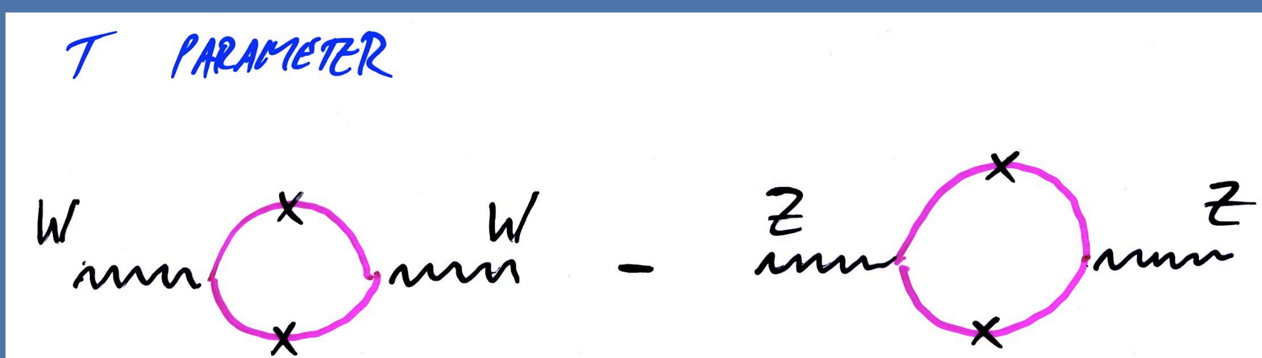
However, for $m_{d4} < m_t + m_W$, CDF search for u_4 also applies to d_4 (just gluon production); for $m_{d4} > m_t + m_W$, expect ttWW signal

We take: $m_{u4,d4} > 258$ GeV

Electroweak Precision



Counts number of EW doublets getting mass from EWSB



Isospin violation; measures mass splitting within doublets

U=0 as usual...

S Parameter

In the "limit", $m_{u,d} >> M_Z$

$$\Delta S = \frac{N_f}{6\pi}$$

↳ 0.21 for 4th generation

S Parameter

In the limit, $m_{u,d} \gg M_Z$

$$\Delta S = \frac{N_c \, \not{N_f}}{6\pi} \left(1 - 2Y \ln \frac{m_u^2}{m_d^2} \right)$$

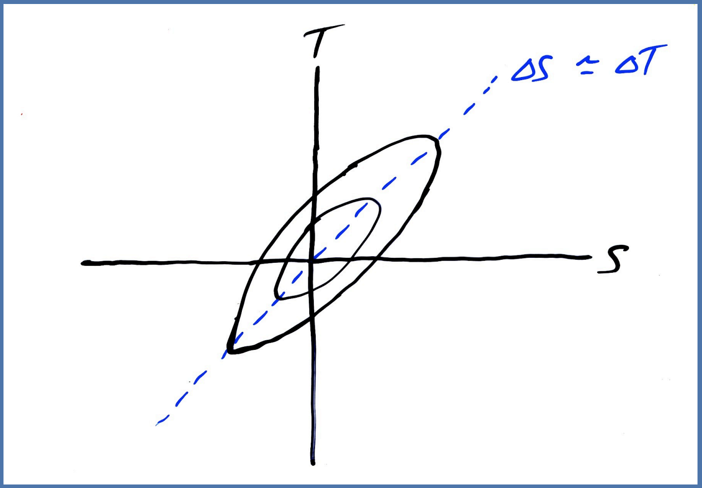
↳ 0.21 for 4th generation

which suggests a strategy to minimize S! Take:

$m_{u4} > m_{d4}$ $(Y = +1/6)$

$m_{\nu 4} < m_{l4}$ $(Y = -1/2)$

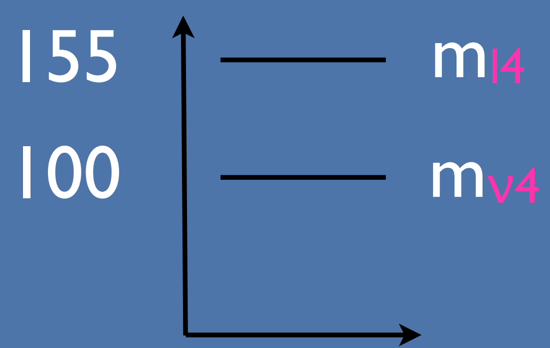
- The price to pay is a contribution to T.
- We can exploit the well-known relative experimental insensitivity to the $S \simeq T$ direction in the S-T plane.



Leptons

Taking $m_{l4} - m_{\nu 4} = 50\text{-}55$ GeV, the lepton contribution to S can be eliminated.

For example:



$\Delta S = 0.00$

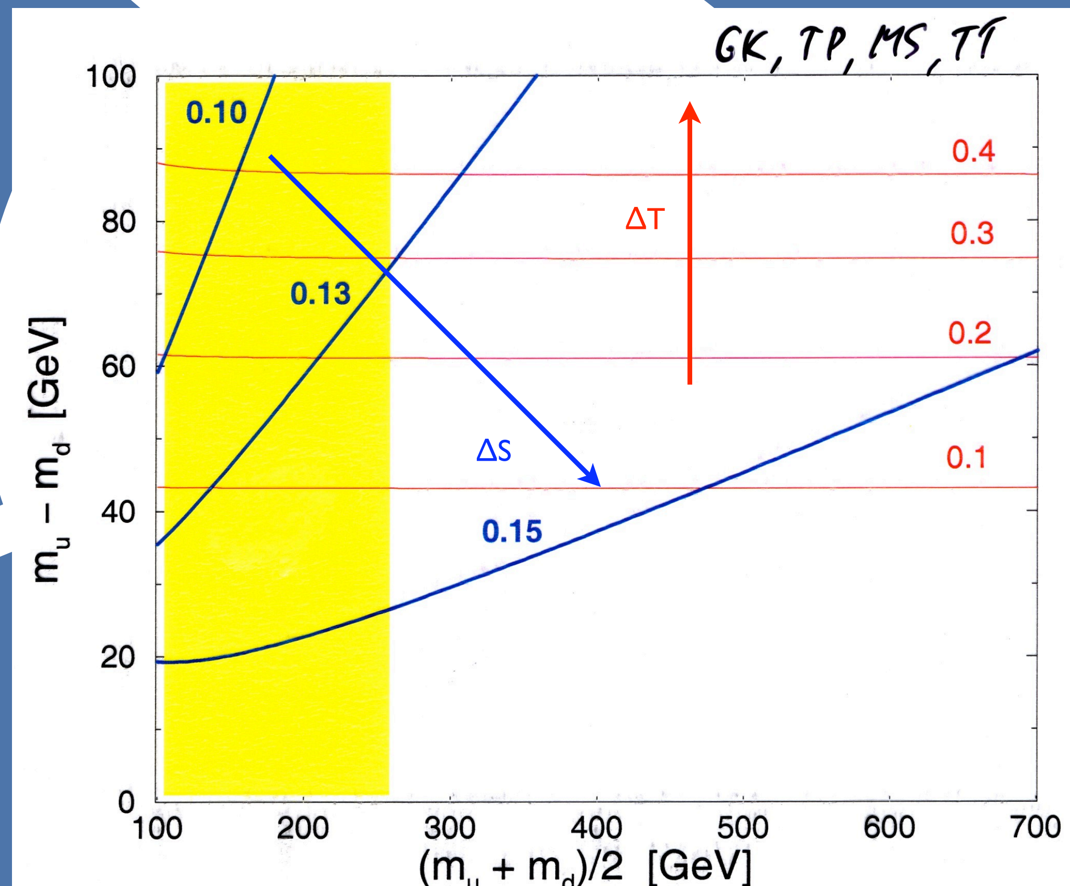
$\Delta T = 0.05$

(one-loop exact expressions used to calculate)

(A Majorana mass for $\nu 4$ enlarges the parameter space, but does not substantially reduce S.)

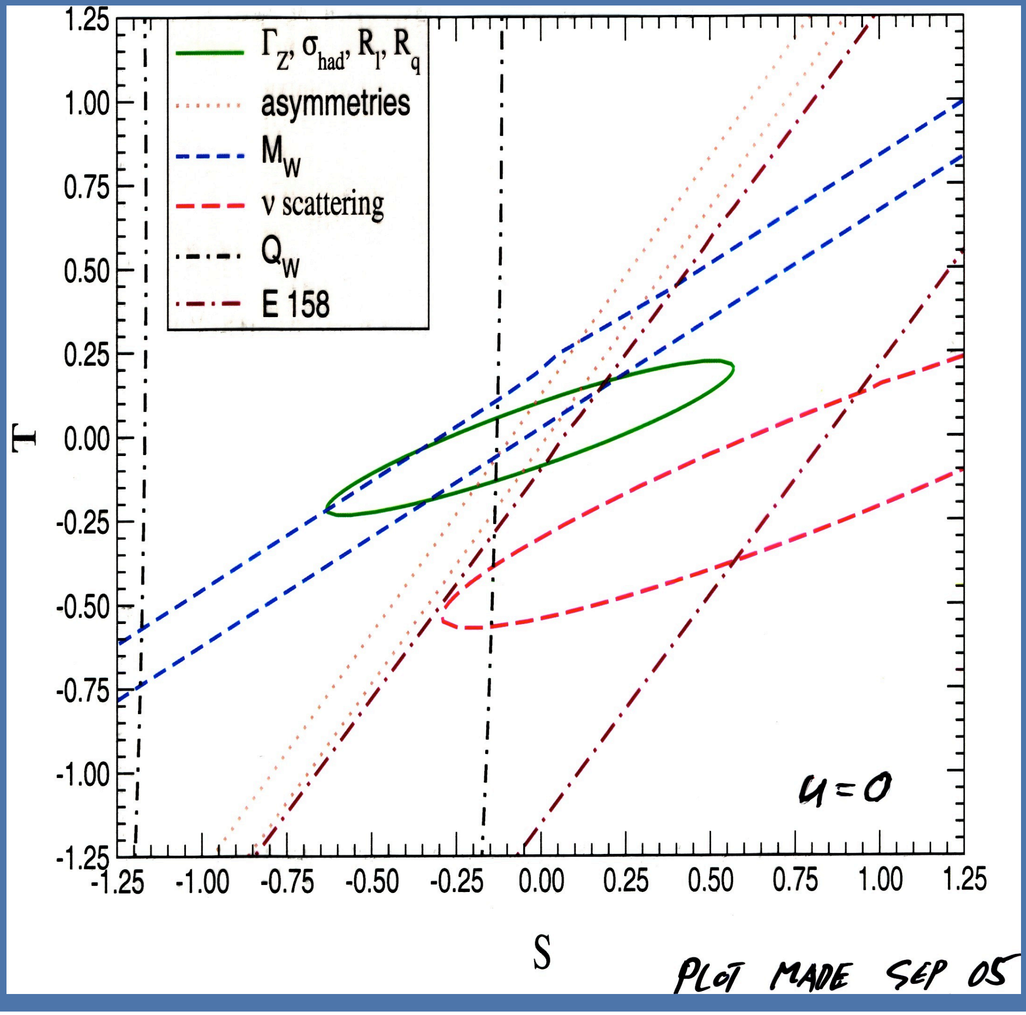
Quarks

The small quark hyper-charge (Y=+1/6) makes balancing S and T together a challenge.

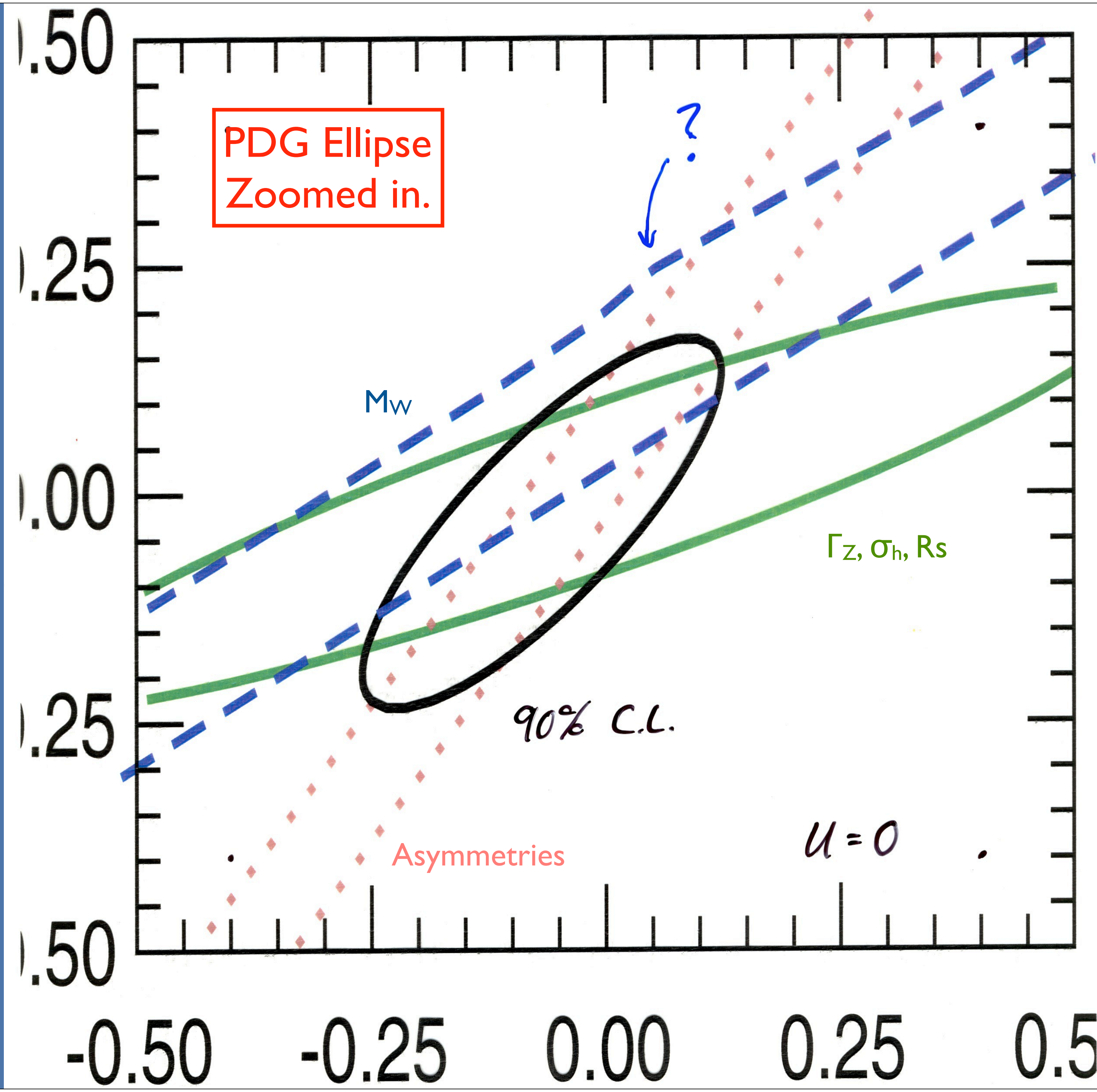


We can adjust S and T. The question becomes, can we adjust them suitably together and what does this do to the Higgs mass.

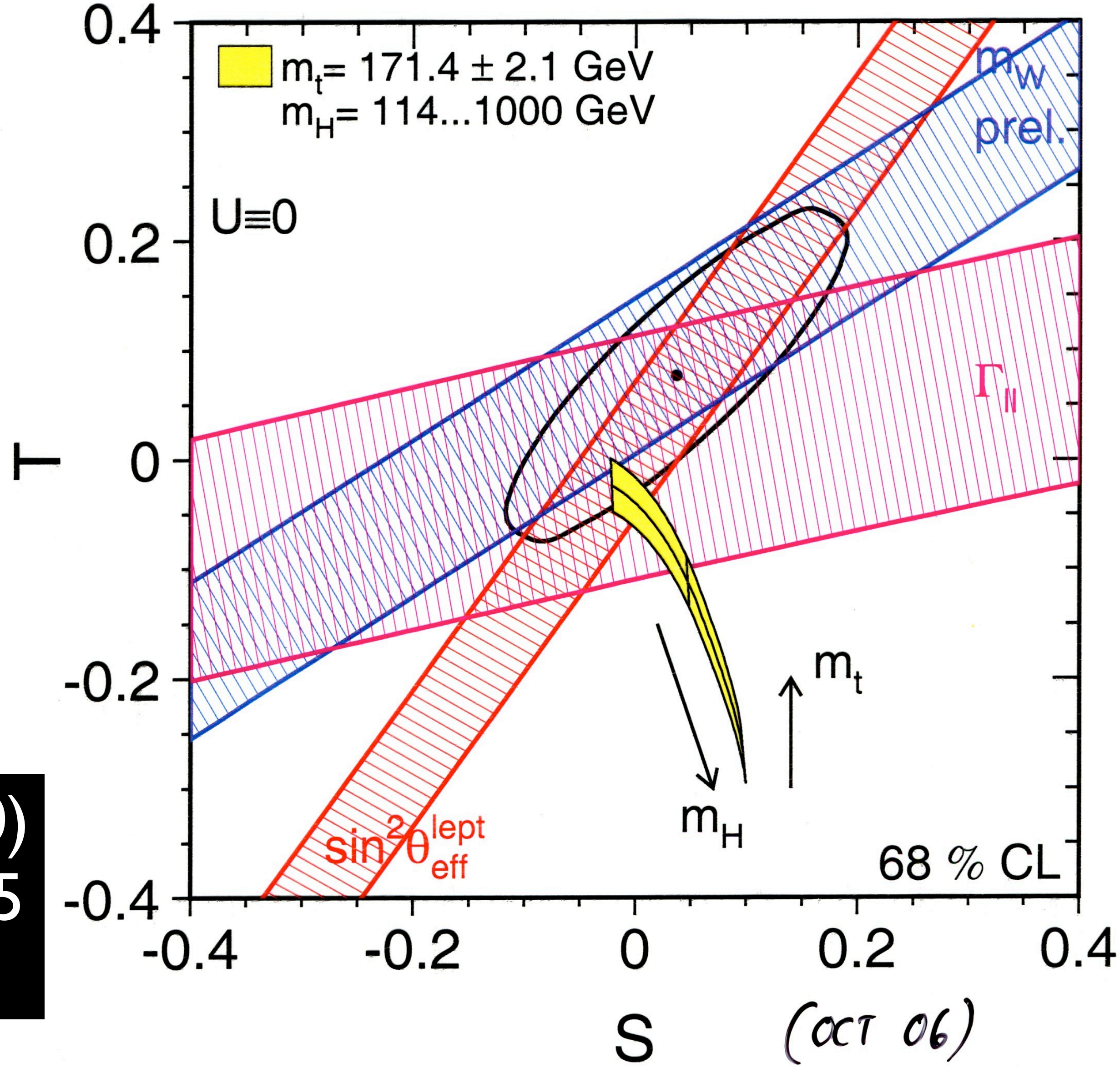
PDG 2006



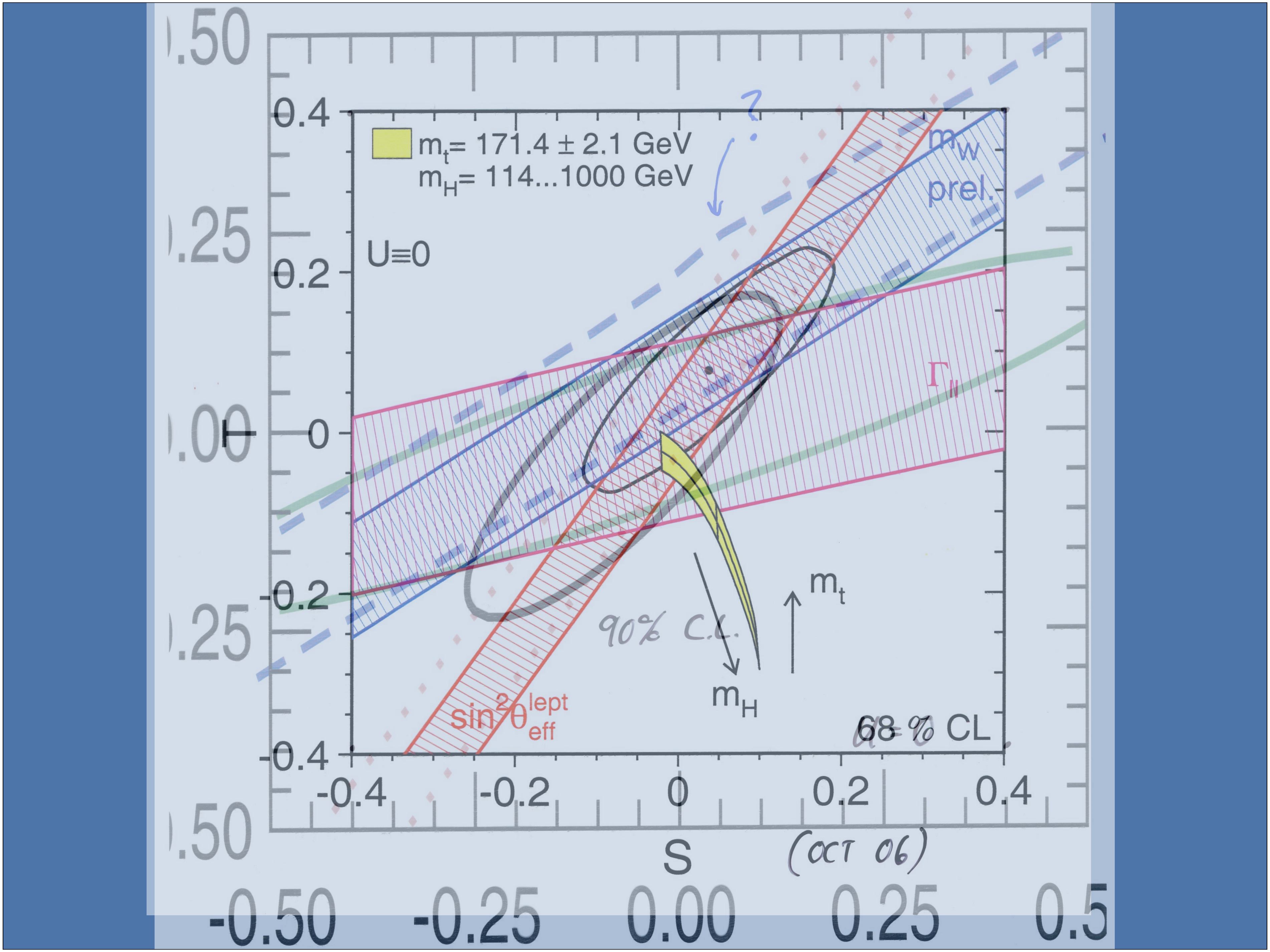
Γ_Z, σ_{had}, R_l, R_q
asymmetries
M_W
ν scattering
Q_W
E 158
T
S
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
u=0
PLOT MADE SEP 05


PDG Ellipse
Zoomed in.
?
MW
ΓZ, σh, Rs
90% C.L.
Asymmetries
U=0
.50
.25
.00
.25
.50
-0.50
-0.25
0.00
0.25
0.5

LEP EWWG

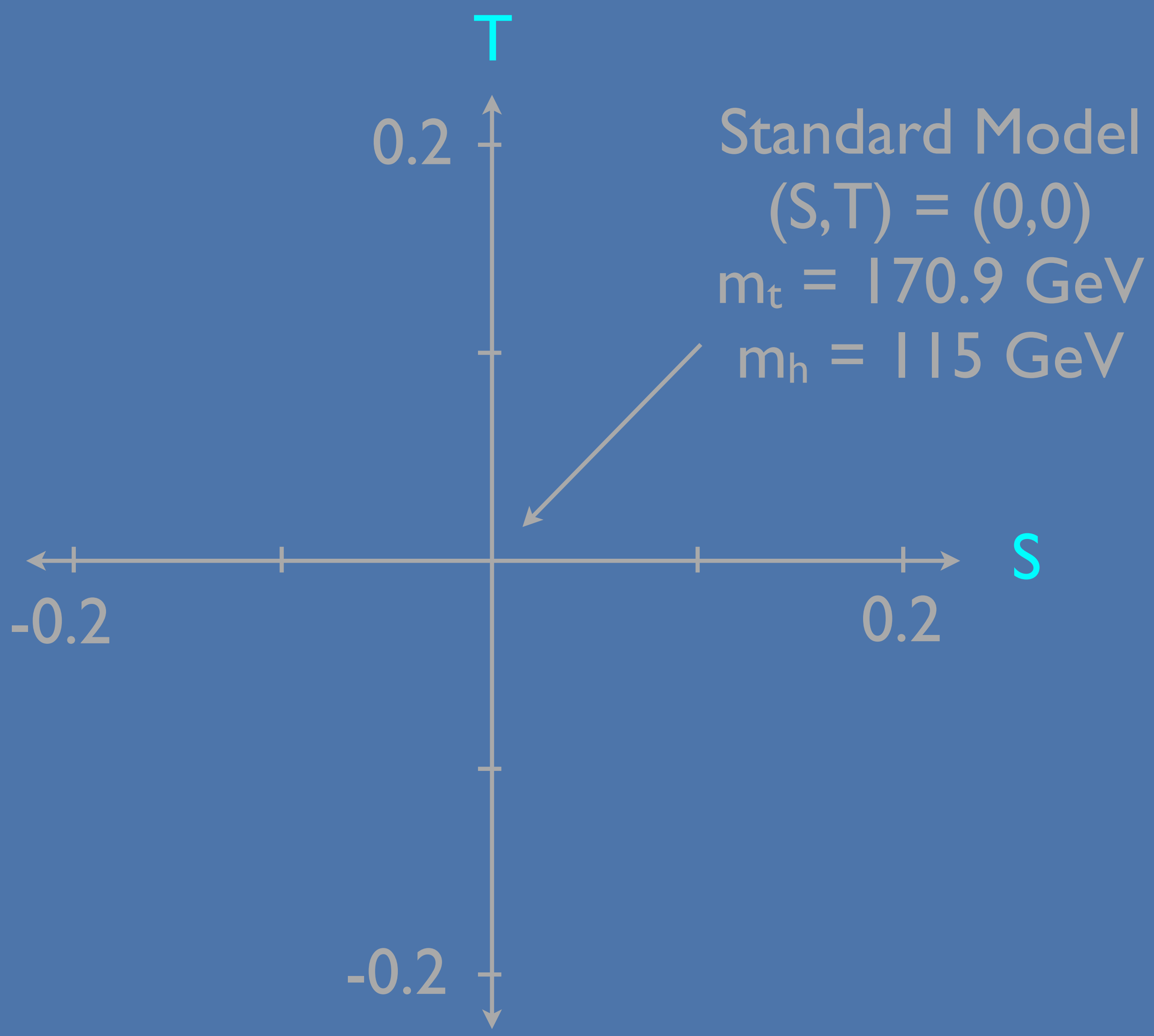


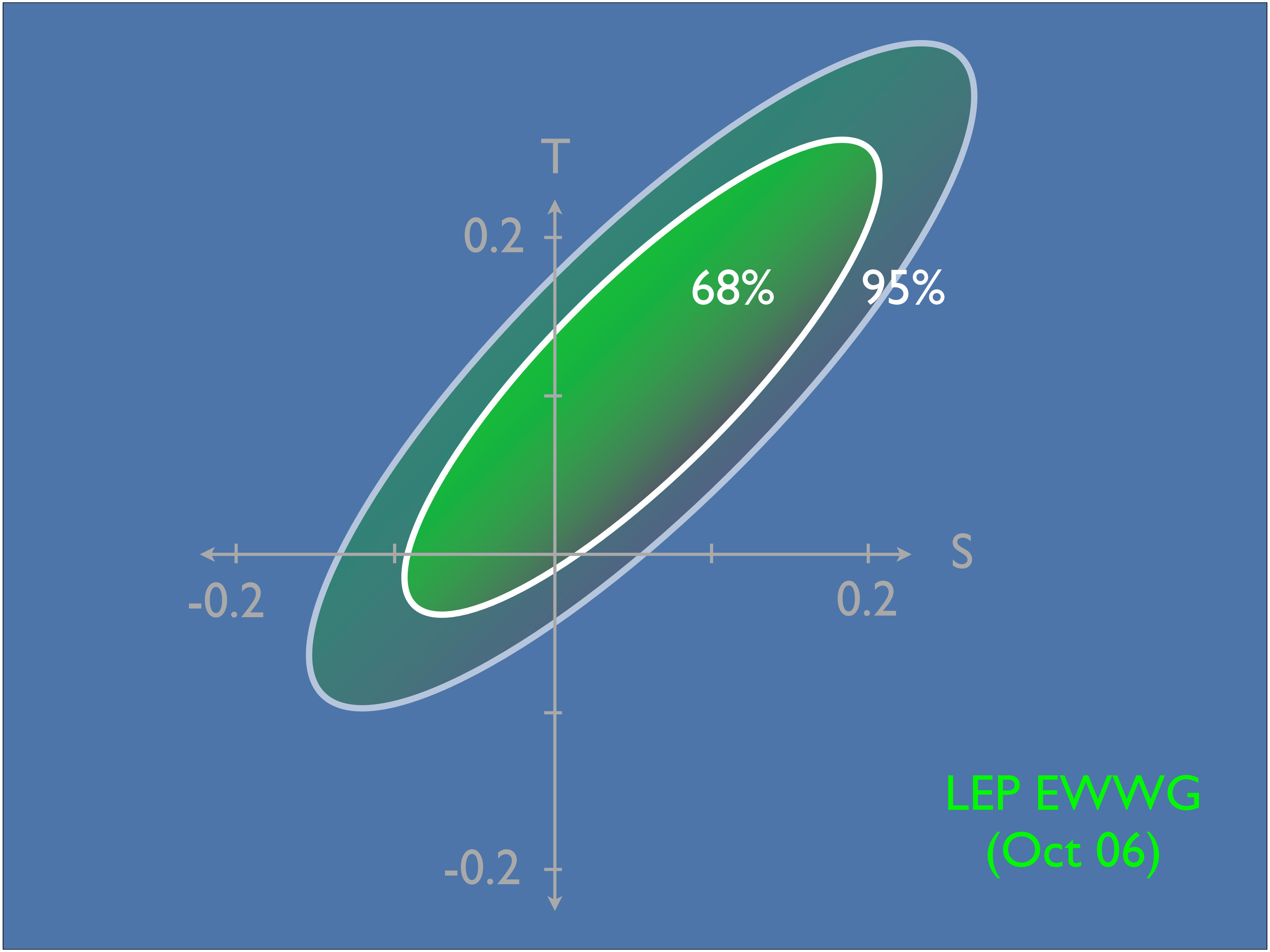
(S,T)=(0,0)
at mt=175
mh=150

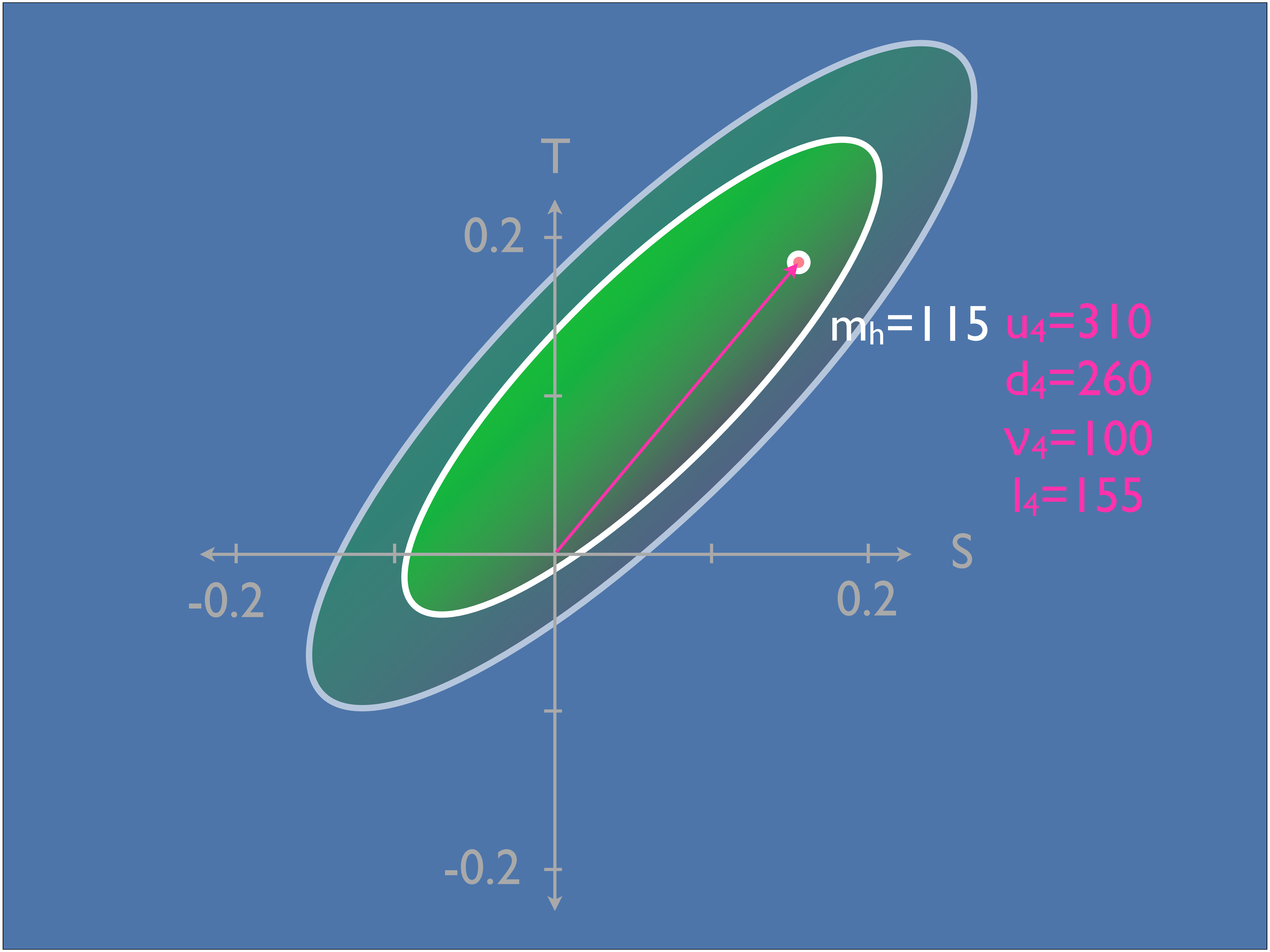


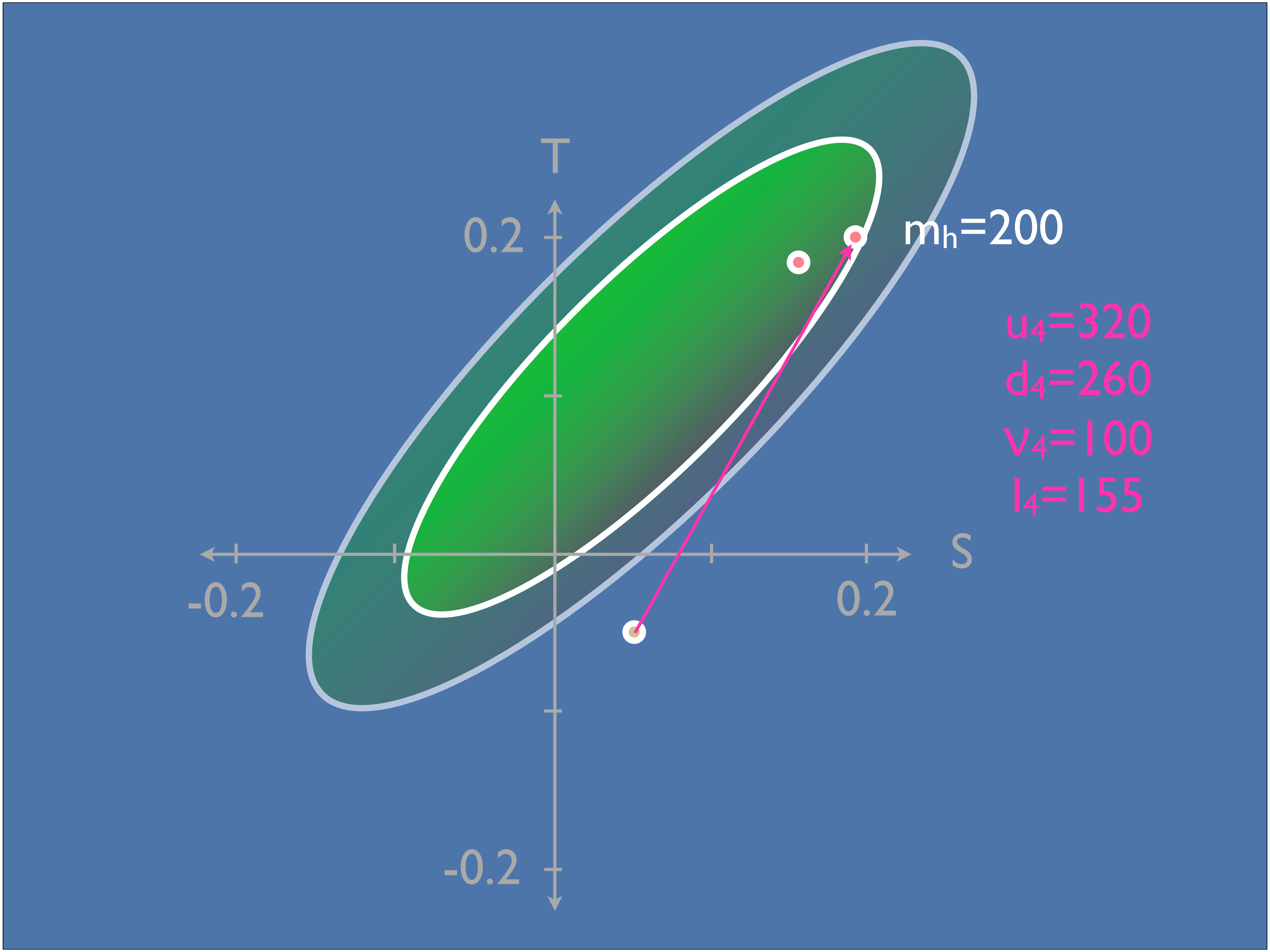
m_t= 171.4 ± 2.1 GeV
m_H= 114...1000 GeV
U≡0
m_W prel.
Γ_ll
sin²θ^lept_eff
m_t
m_H
90% C.L.
68 % CL
T
S
(OCT 06)

The S-T Plane

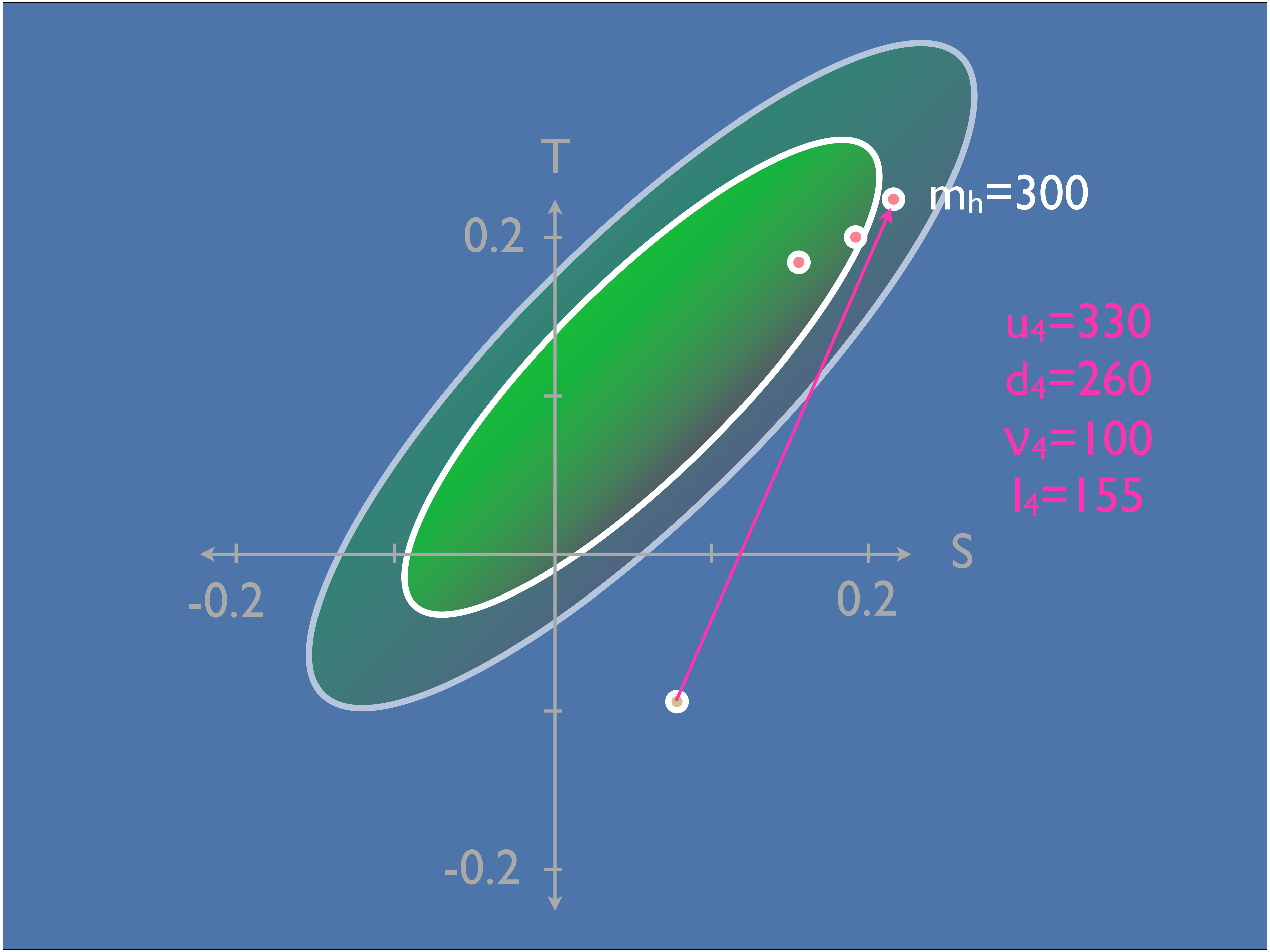



T
0.2
68%
95%
S
-0.2
0.2
-0.2
LEP EWWG
(Oct 06)

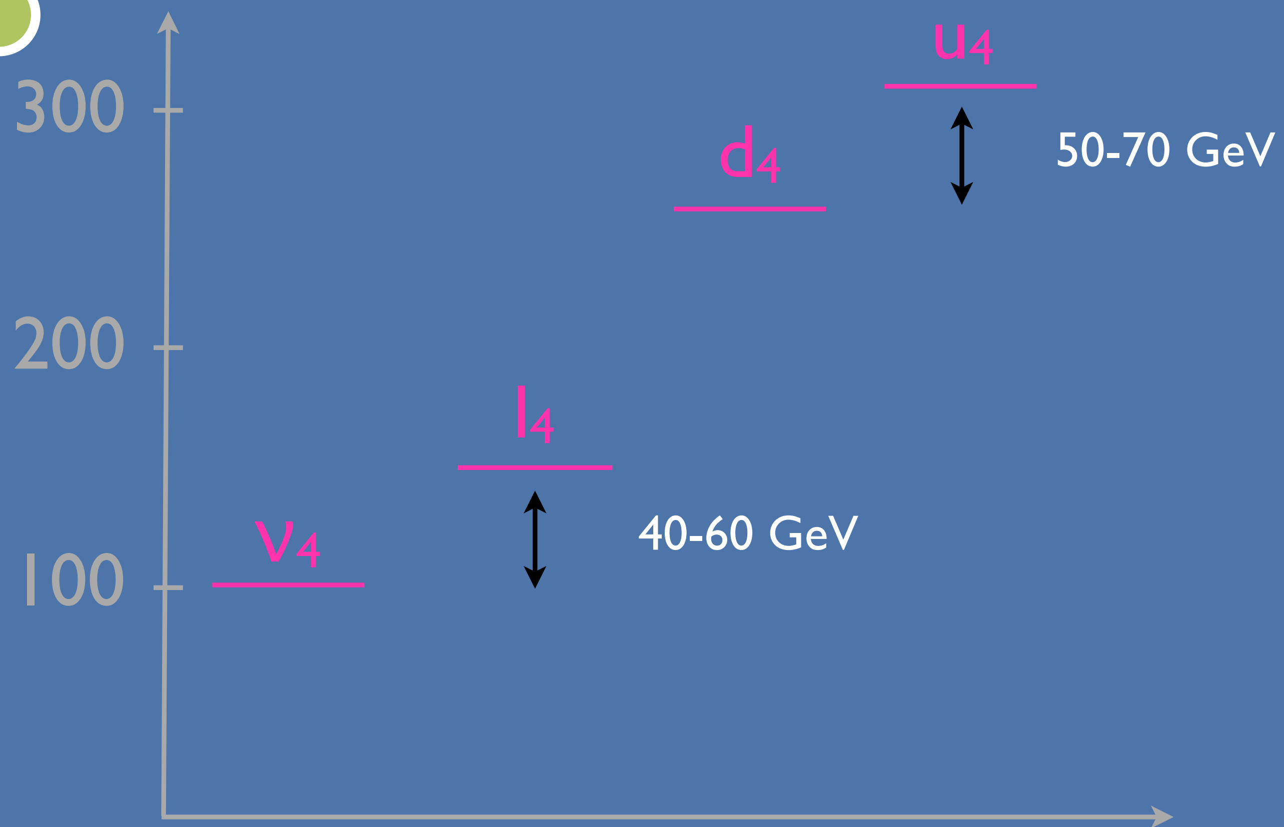

T
0.2
-0.2
S
-0.2
0.2
m_h=115
u_4=310
d_4=260
ν_4=100
l_4=155



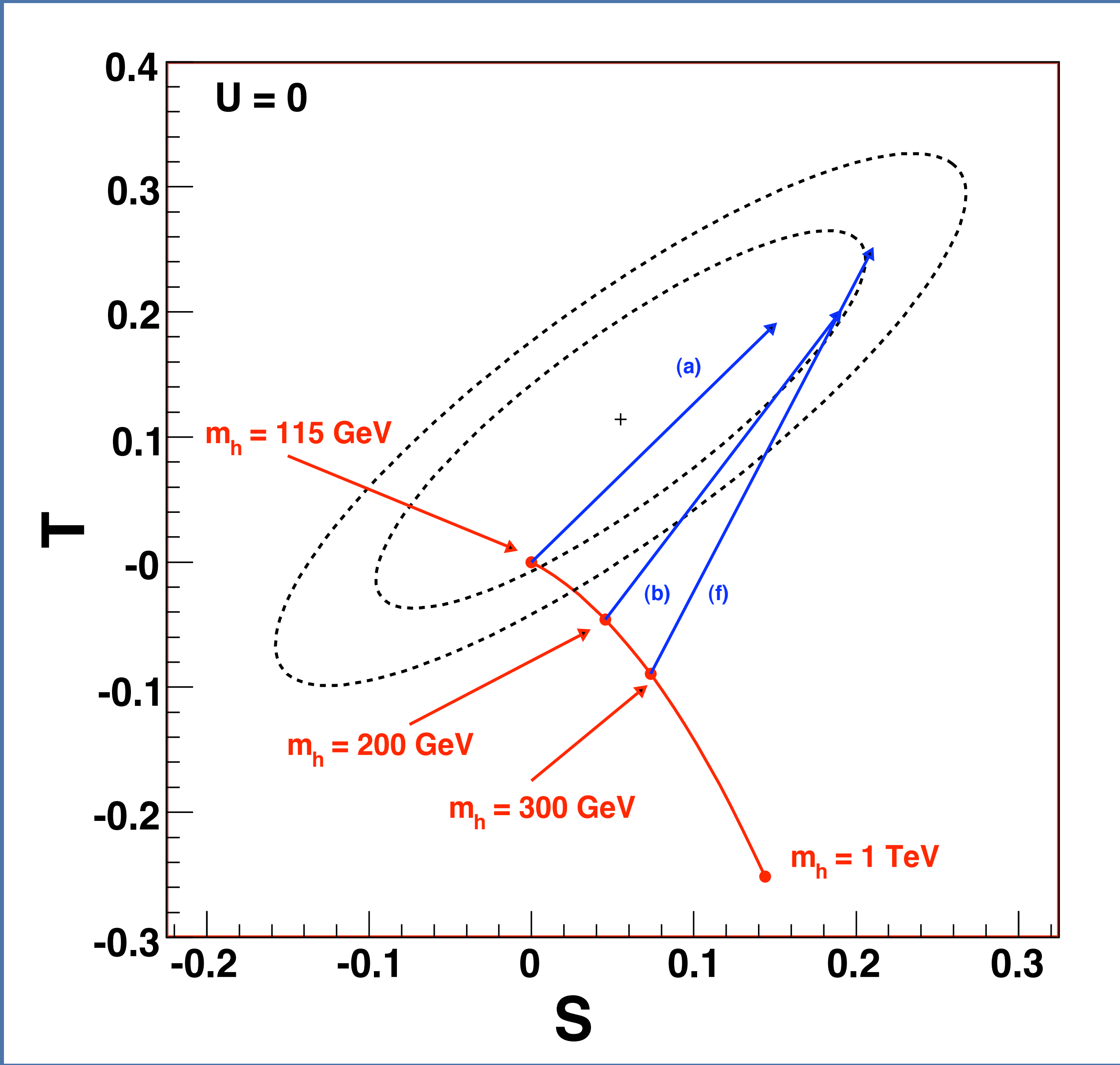
T
0.2
-0.2
S
-0.2
0.2
mh=200
u4=320
d4=260
ν4=100
l4=155


T
0.2
-0.2
S
-0.2
0.2
mh=300
u4=330
d4=260
ν4=100
l4=155

Fourth Generation Spectrum



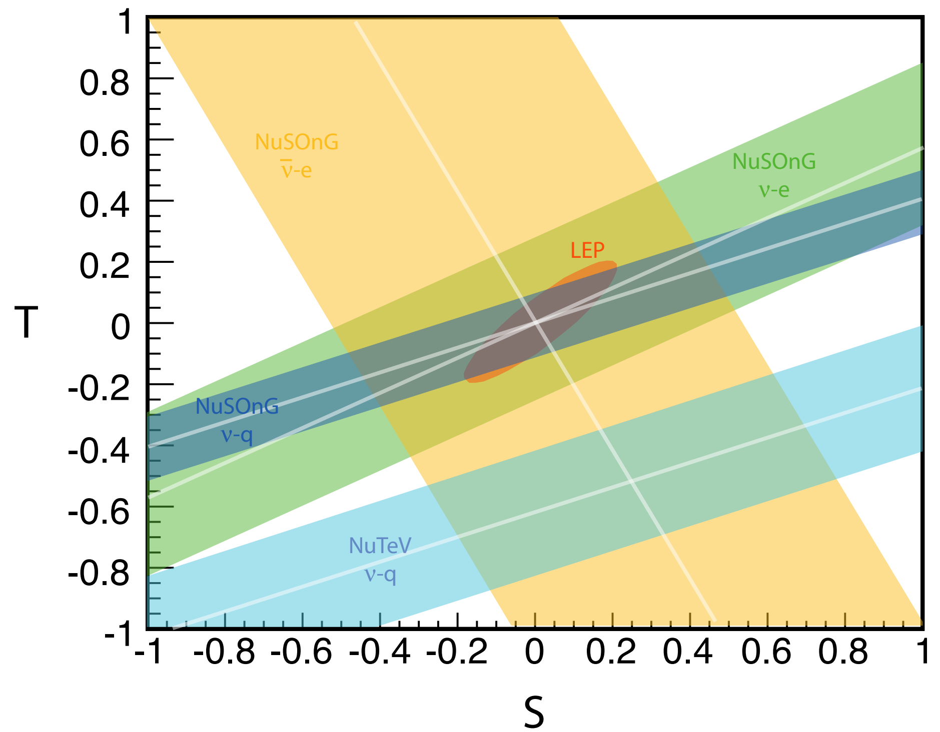
CKM/PMNS mixings $\lesssim 0.01$



The fourth generation compensates for a heavier Higgs.

Future EW Measurements

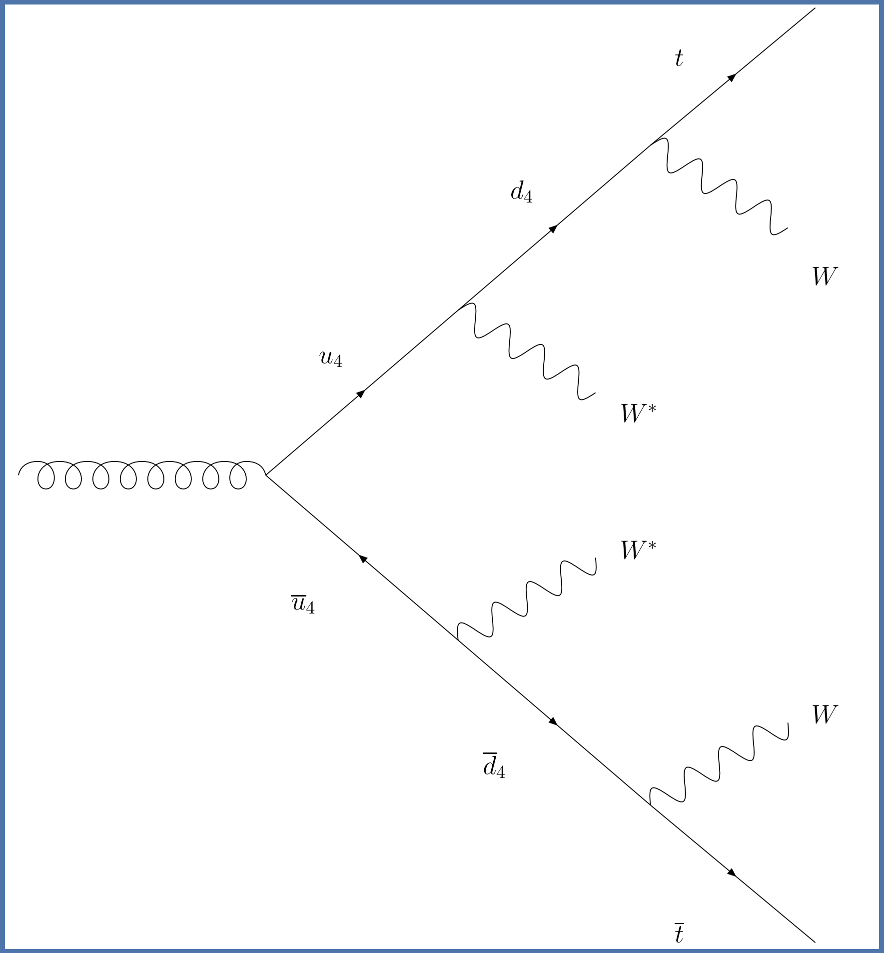
- The precision of the Z-pole data can be improved upon in the foreseeable future.
- Precise measurements of neutrinos scattering on hadrons can improve on the LEP Ellipse.
- Note the 4th generation liked to live on the ellipse's "upper corner", indicating small reductions in errors on S-T are significant!



NuSOnG, Expression of Interest

Striking LHC Signals...

u_4 production:



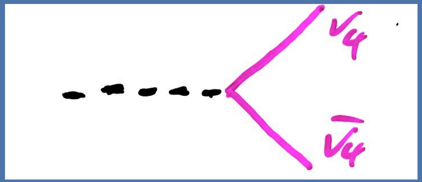
Six W's and 2 b's!?!...
a bewildering array of riches...

Effects on Higgs Physics

- Higgs mass range: 115 < mh < { 315 to 68% CL; 750 to 95% CL

- Non-decoupling loops affect production and decay:

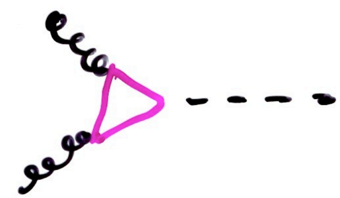
- New decay modes:

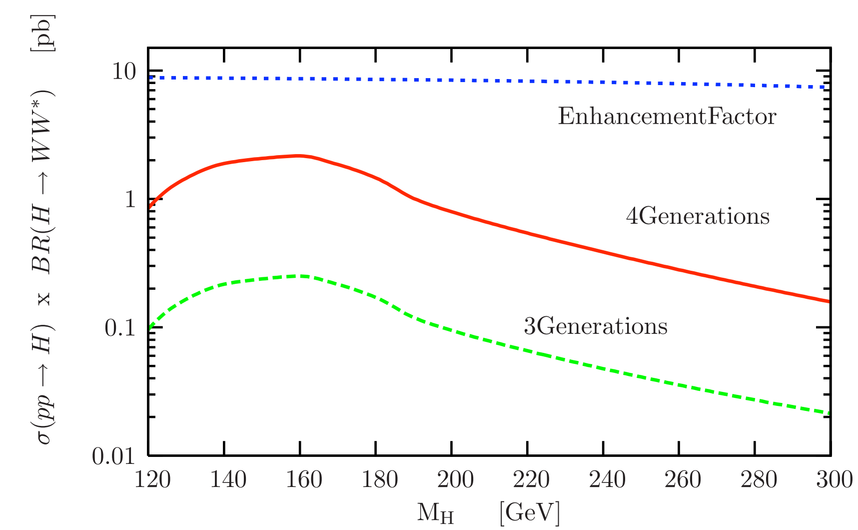


- Vacuum stability and cut-off scale

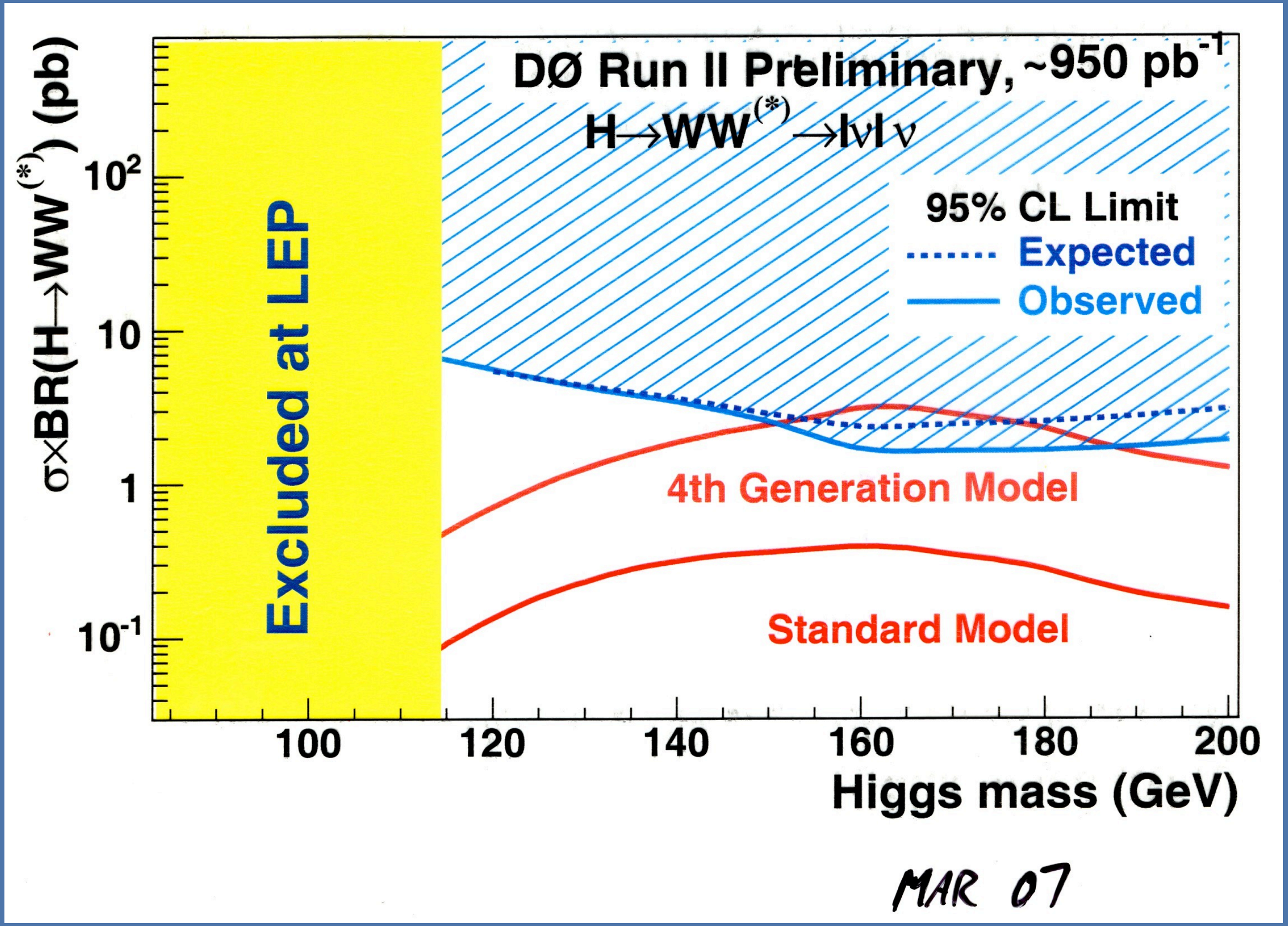
Loop Enhancement!

- Loops of the new quarks contribute to the effective H-g-g vertex.
- For the masses of interest, the effect is captured by the "decoupling" limit.
- The new quarks add to the top contribution:
  - $\sigma_{4th}(gg\text{->}h) \simeq 9\ \sigma_{SM}(gg\text{->}h)$
  - For m_h < 130 GeV, BR(h->gg) can **dominate**!
- H->γγ remains (as in SM) dominated by the W loops, but the new fermions interfere destructively, reducing it.

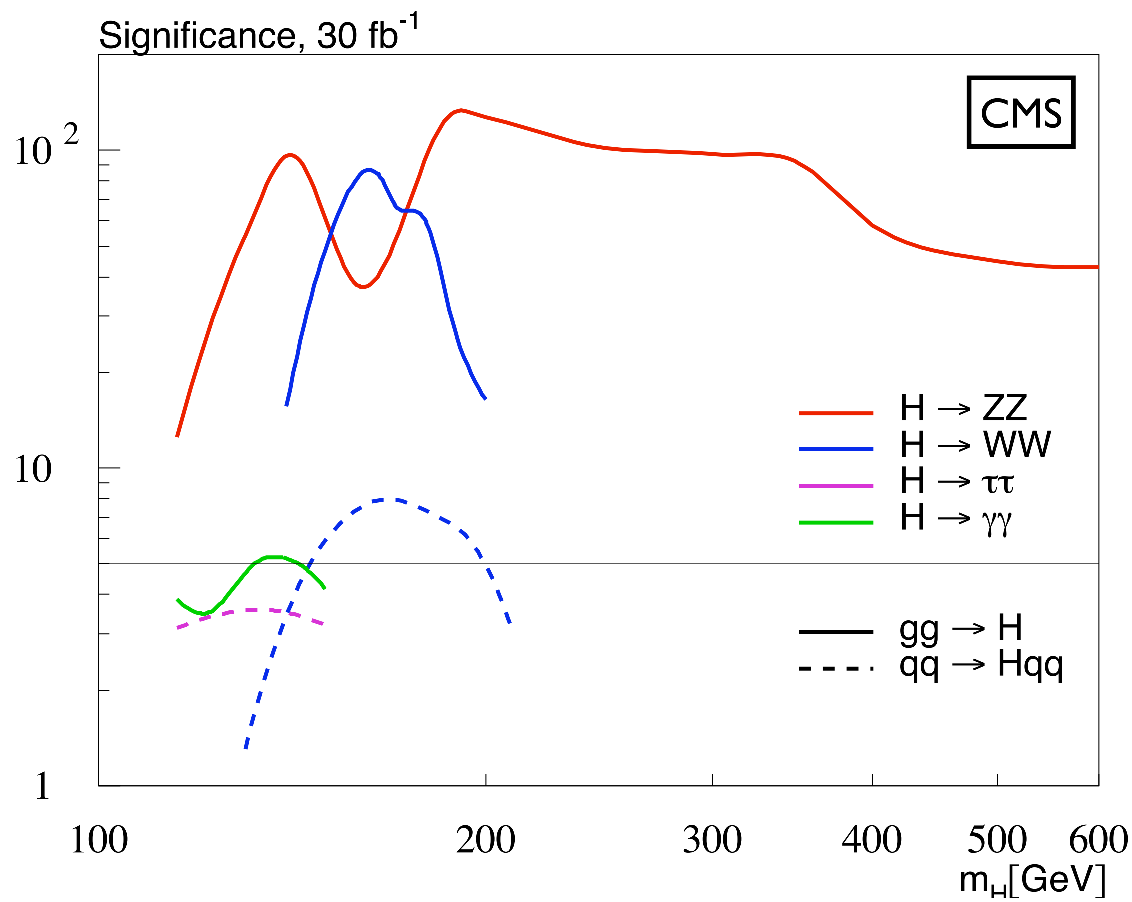




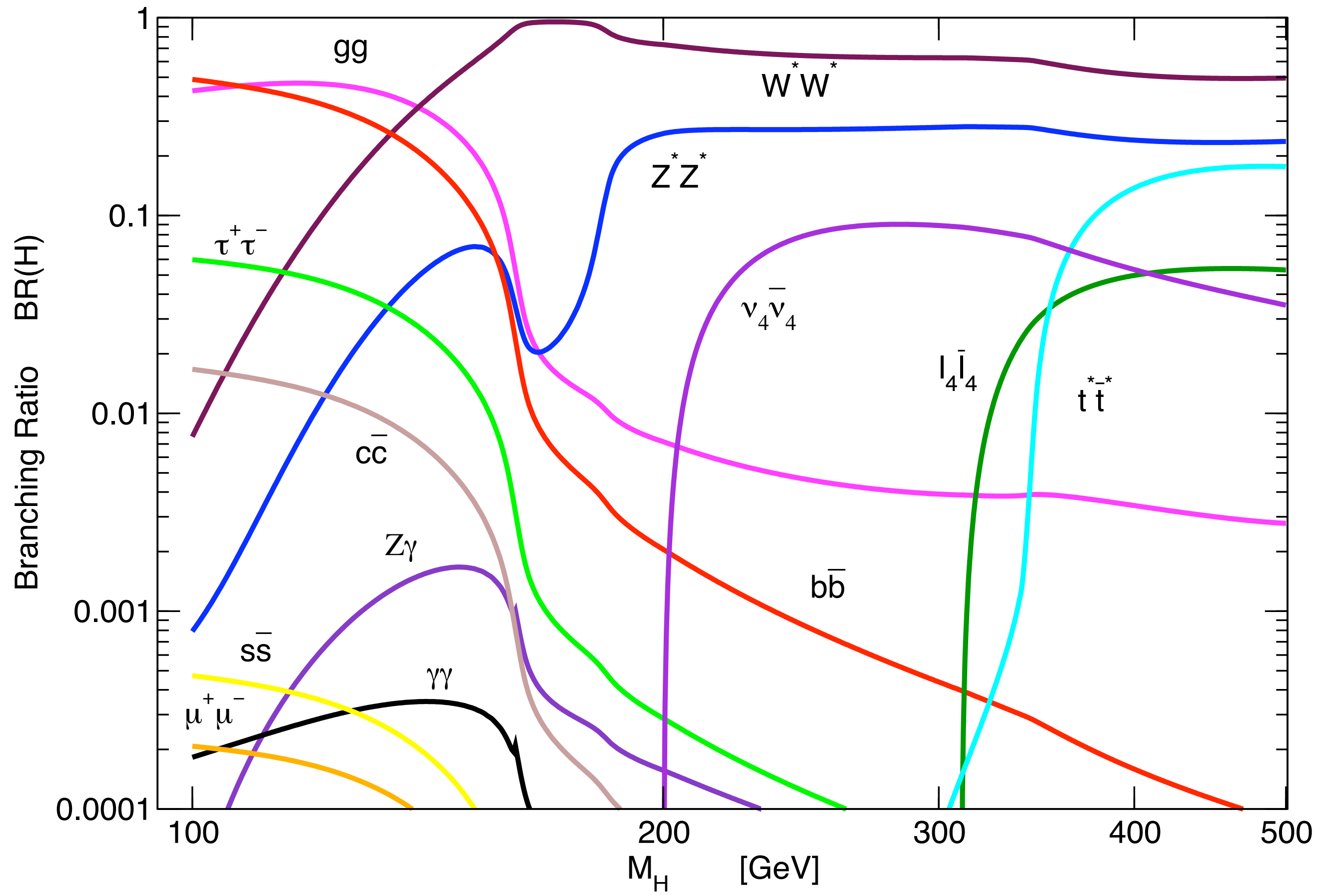
Already important at D0...



To say nothing of at ATLAS / CMS!

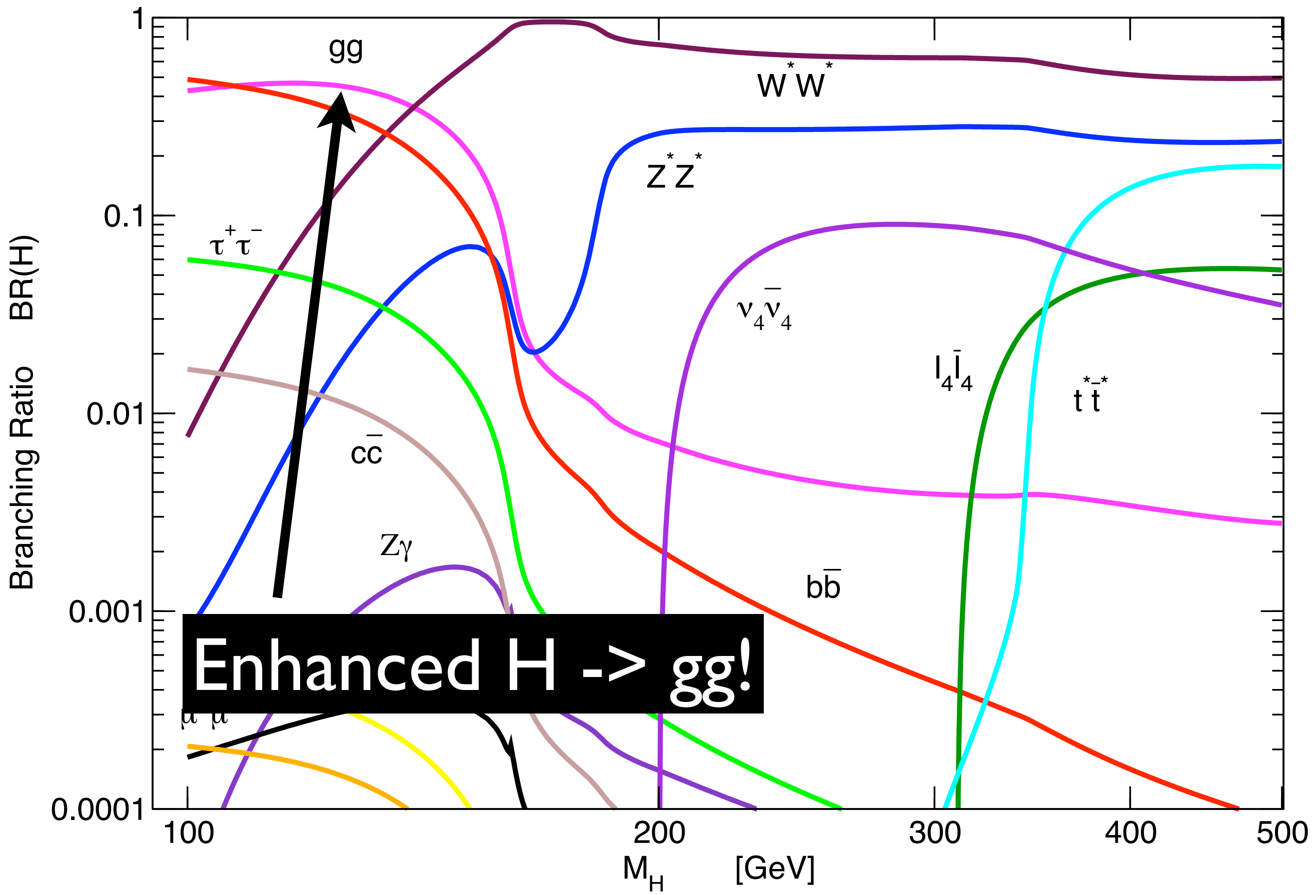


Higgs Branching Ratios



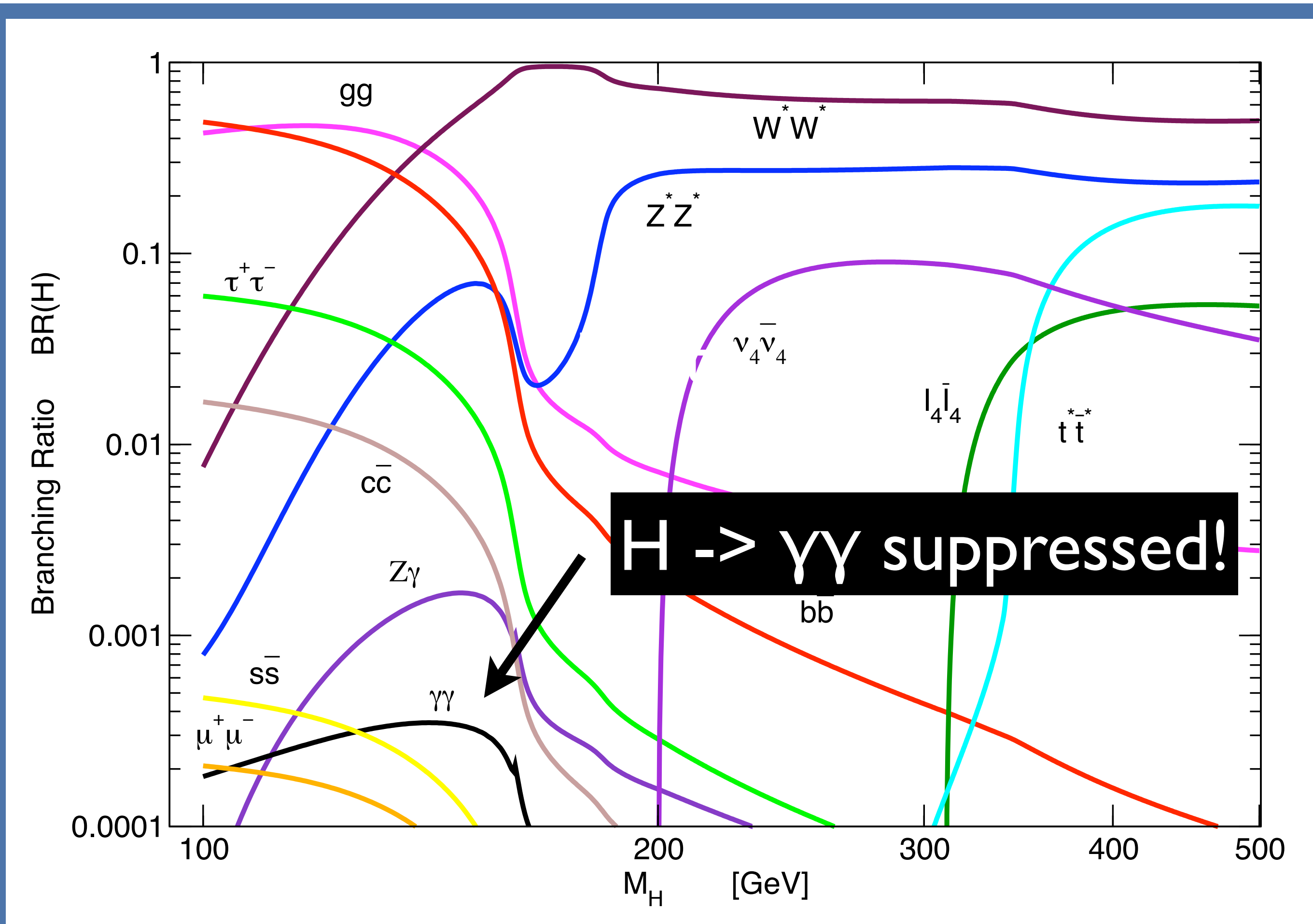
Modified HDECAY

Higgs Branching Ratios



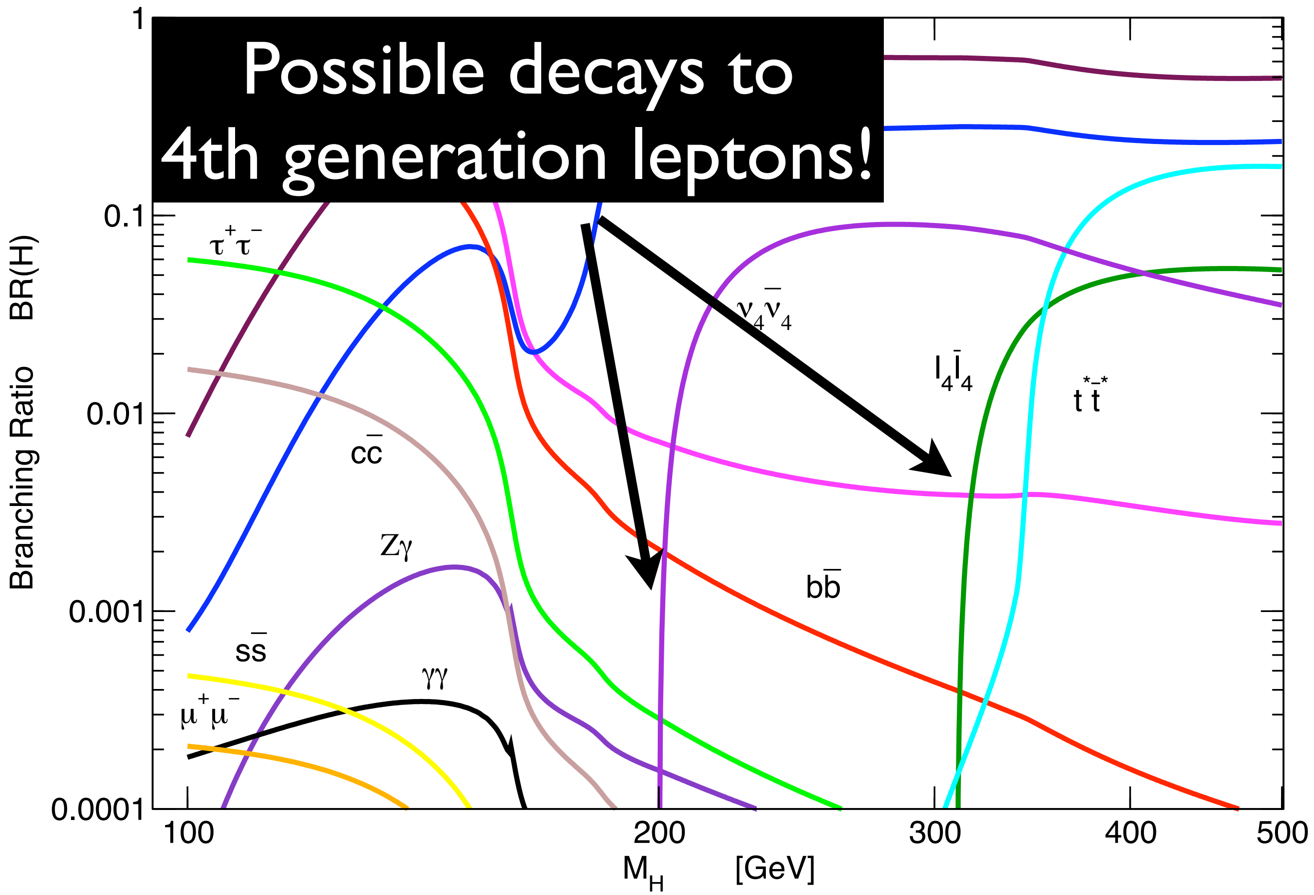
Modified HDECAY

Higgs Branching Ratios



Modified HDECAY

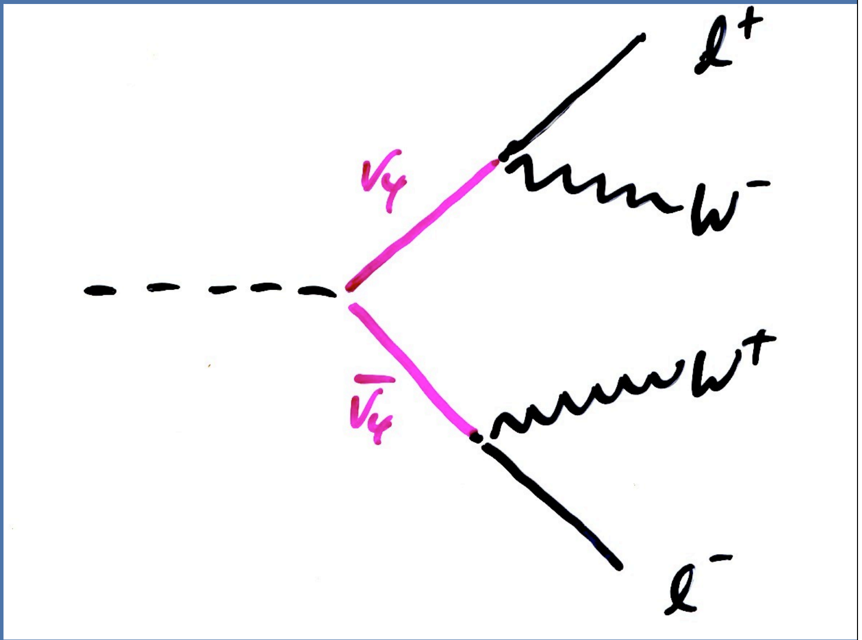
Higgs Branching Ratios



Modified HDECAY

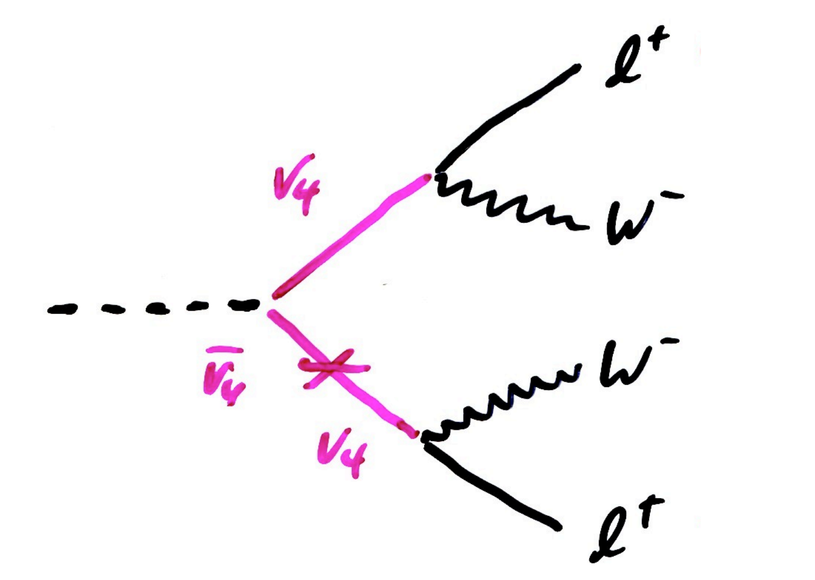
Unusual Higgs Decays

- The Higgs could even have a large (~ 0.1) branching ratio into 4th family neutrinos.
- The decay leads to charged leptons and W bosons. We can reconstruct the Higgs and ν_4 masses.
- The BR depends on the interplay between Majorana and Dirac neutrino masses in the 4th family.



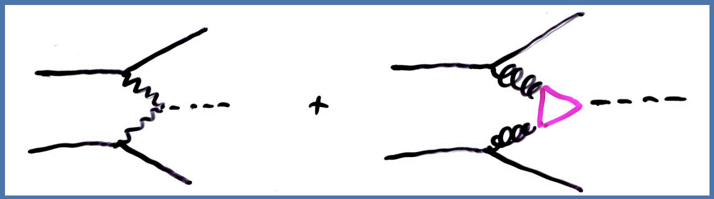
(More) Unusual Higgs Decays

- A Majorana neutrino mass opens the door for even more exotic Higgs decays.
- A Majorana mass insertion allows for the leptons (and the Ws) to have the same sign.
- EW precision (and the possibility of neutrinos as dark matter) favor comparable Majorana & Dirac masses.

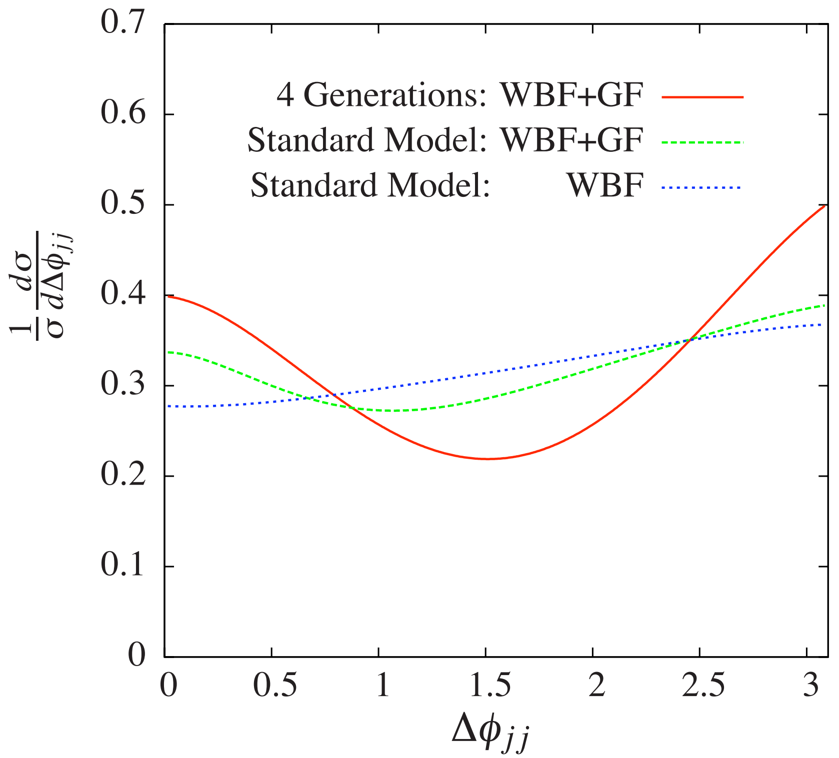


Modification to VBF

- The large enhancement to g-g-H can lead to a modification of the vector boson fusion kinematics.

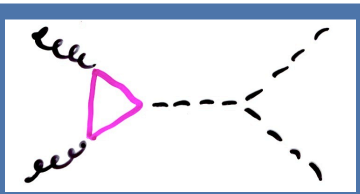


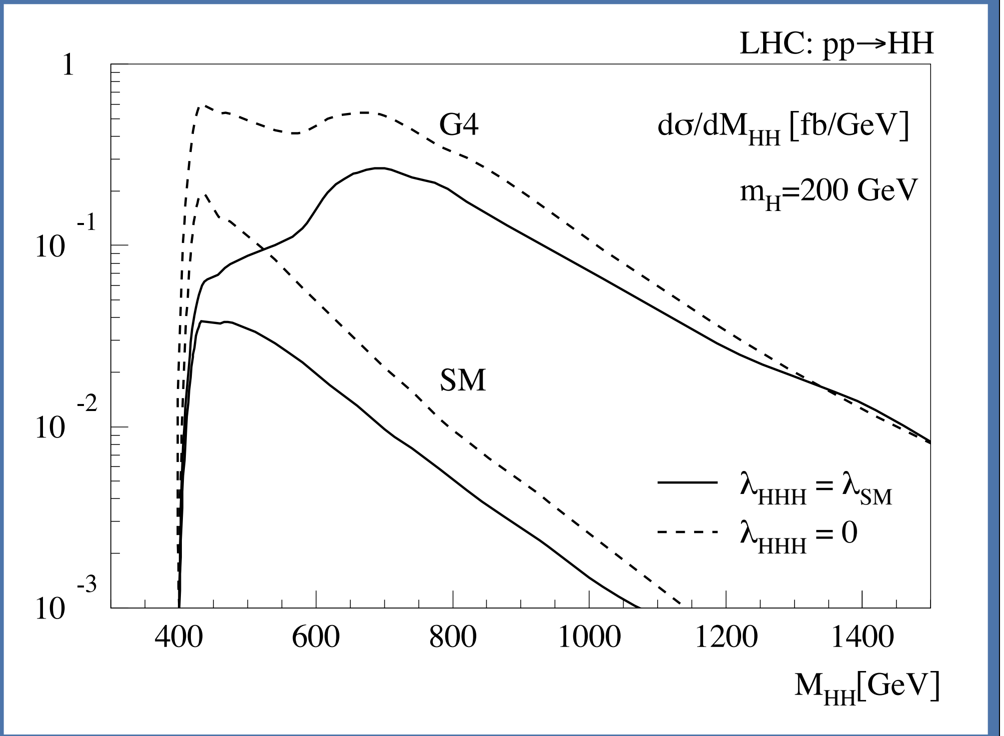
- The different admixture leads the fourth generation to predict an angular distribution between the jets which is more “gluon fusion”-like than “vector boson fusion”-like.



Di-Higgs Production

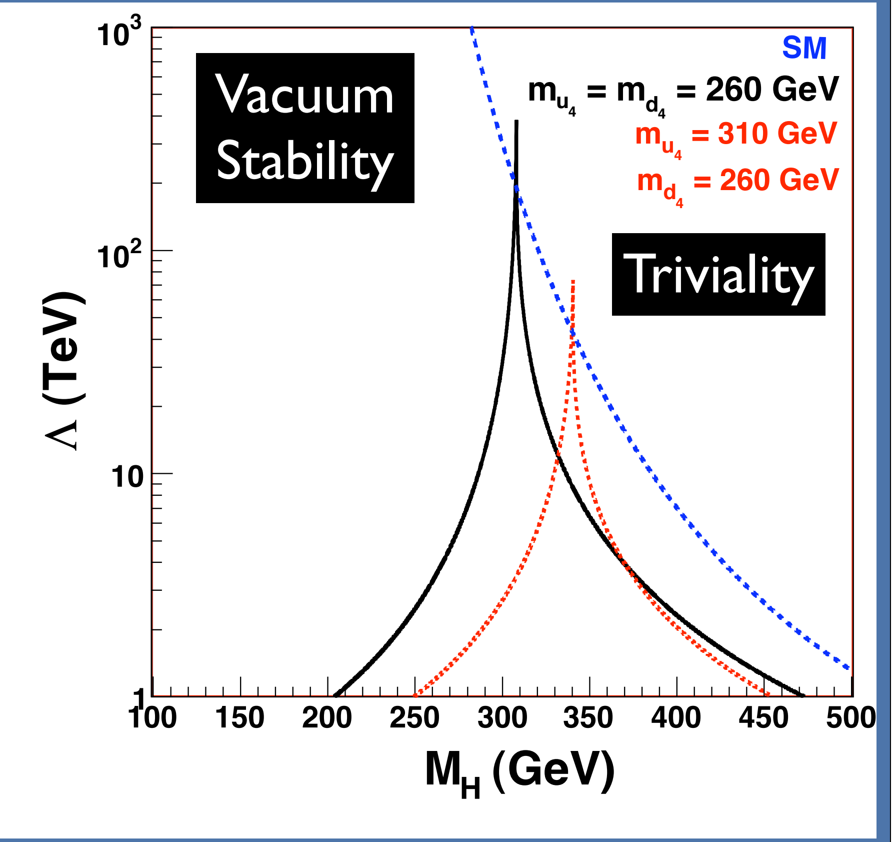
- The enhanced H-g-g coupling is also important for di-Higgs production.
- Di-Higgs has been proposed to measure the H-H-H interaction (the Higgs quartic in the SM).
- The large enhancement improves sensitivity to the coupling, and also makes the measurement possible at the LHC.



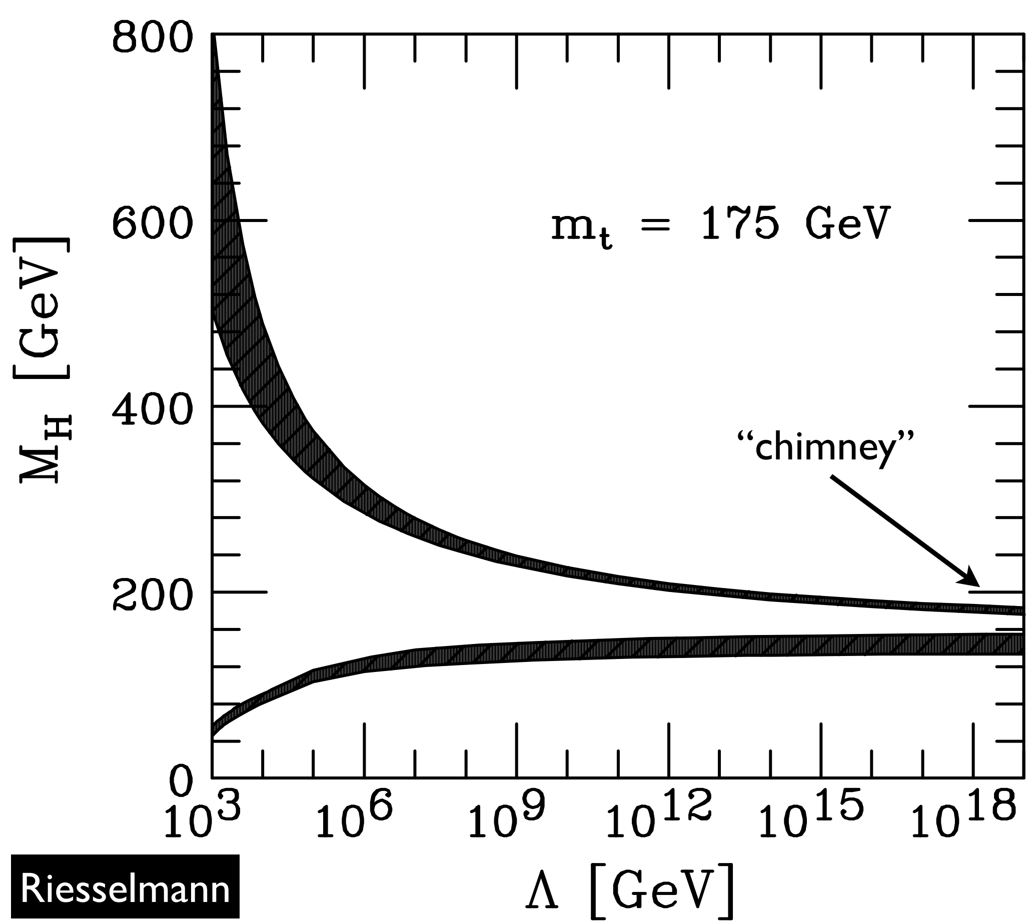


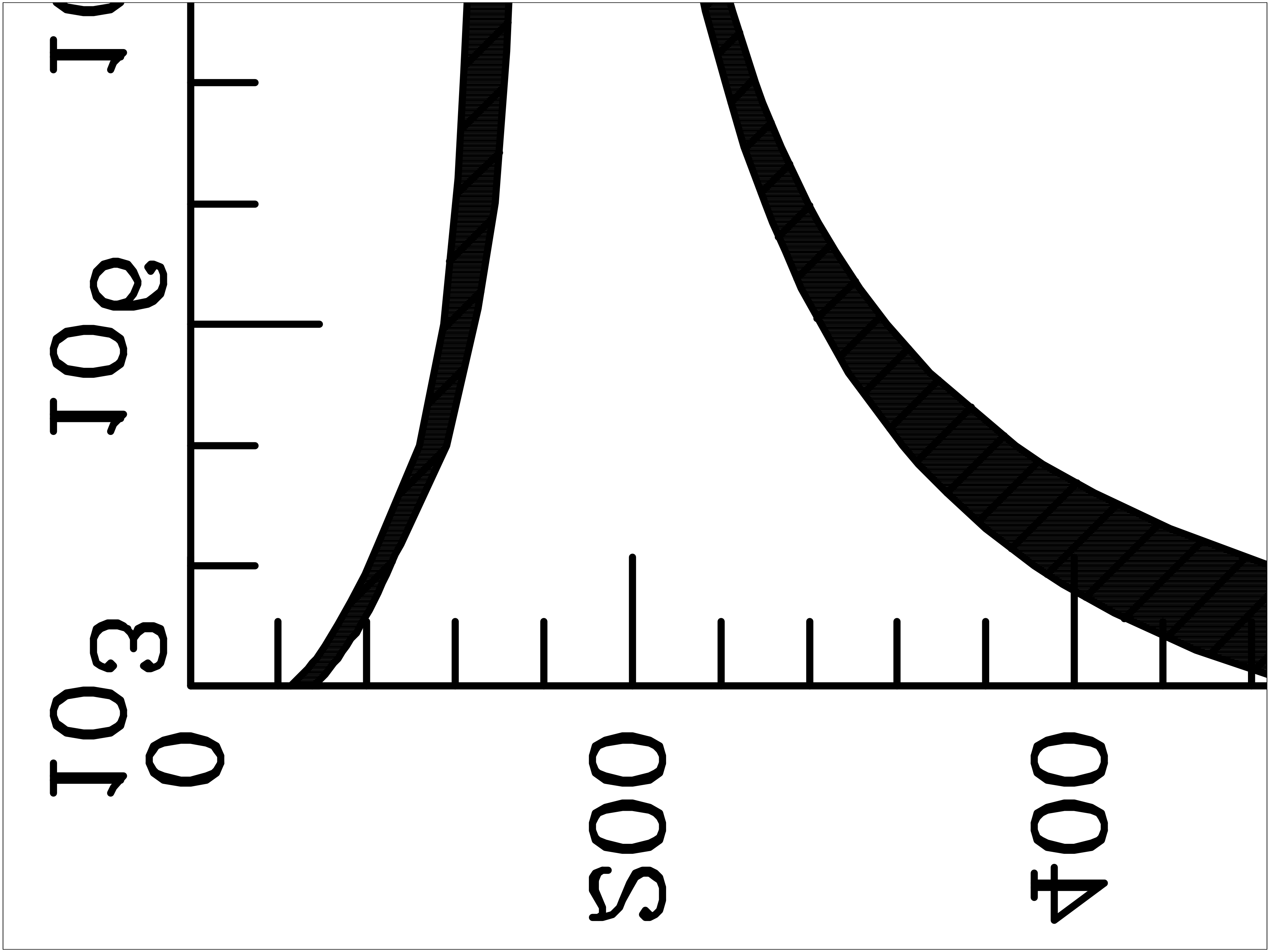
Higgs Potential & New Physics

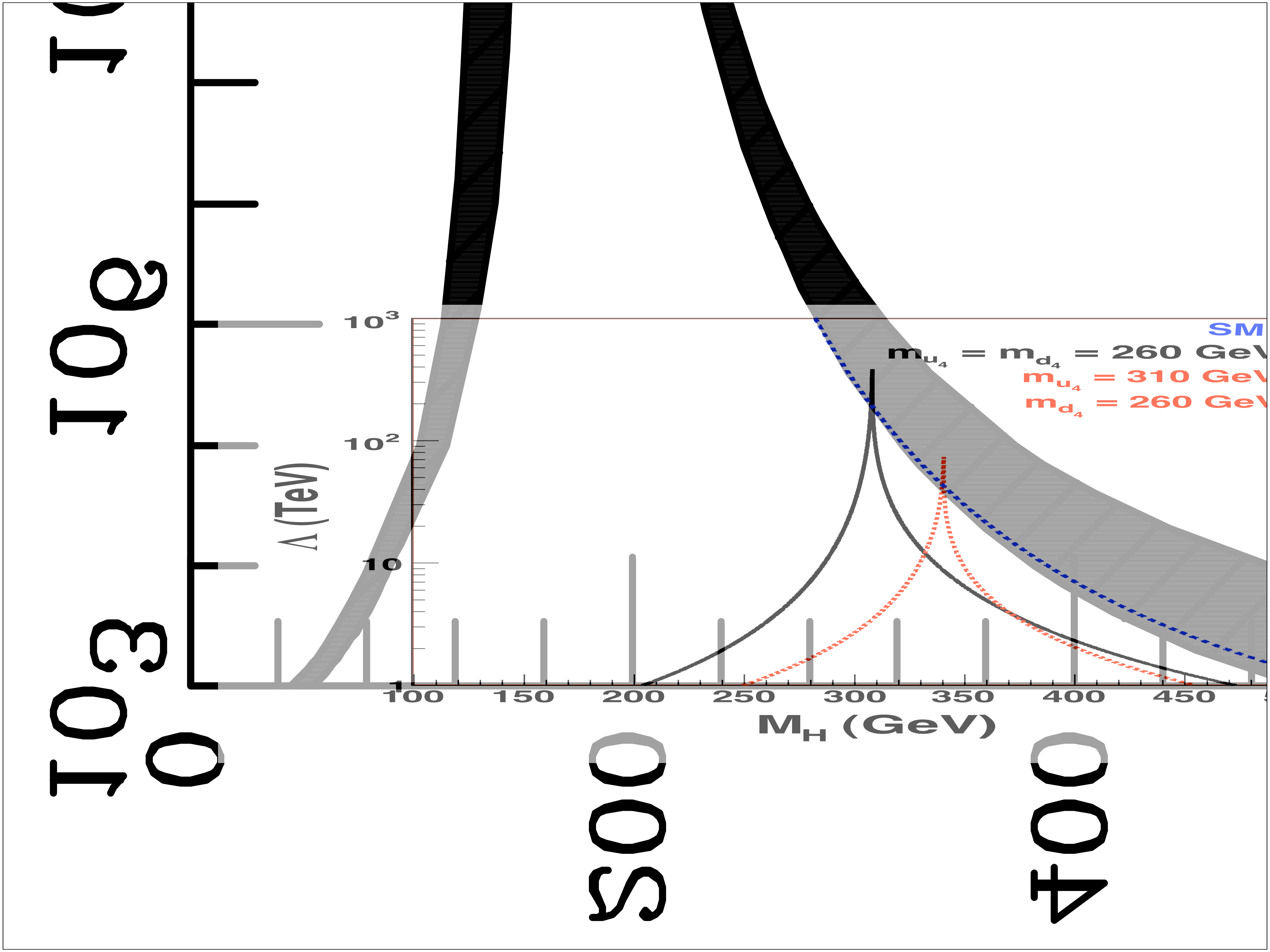
- As in the SM, we can find out where our effective theory breaks down by studying the Higgs potential using the RGEs.
- For small Higgs masses, the loops of the fermions can drive the Higgs quartic term negative at high scales, leading to an unstable vacuum.
- For large Higgs masses, the quartic interaction can blow up at some intermediate scale.



Standard Model




0
200
400
10^3
10^6



SM
Λ (TeV)
M_H (GeV)
100
150
200
250
300
350
400
450
10

Applications?

- The new fermions, strongly coupled to the Higgs, can drive the EW phase transition in the early Universe to be first order; baryogenesis?
- The fourth generation neutrino could be dark matter if it is stable for long enough.
- The fourth generation quarks can be used in composite Higgs models, cousins of top-color.

Conclusions / Summary

- A fourth generation is not ruled out! A combination of judicious choices of masses and choice of the Higgs mass render it consistent at about one sigma with the EW fits.
- Parameter space is limited, but not overly tuned.
- Mixings with the light quarks and leptons should be small, but are allowed.

Conclusions / Summary

- A fourth generation leads to visible signals of the new fermions at the LHC.
- Large effects are possible in Higgs physics, including enhancement of gg -> H and di-Higgs production, suppression of the decay to gamma gamma, and new decay modes.

Bonus Material

contribution to the oblique electroweak parameters is $\Delta S \simeq \Delta T \gtrsim 0.3$ and thus outside the 95% CL ellipse.

[2] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33**, 1 (2006).

[3] P. H. Frampton, P. Q. Hung and M. Sher, Phys. Rept. **330**, 263 (2000) [arXiv:hep-ph/9903387].

[4] H. J. He, N. Polonsky and S. f. Su, Phys. Rev. D **64**, 053004 (2001) [arXiv:hep-ph/0102144].

[5] M. Maltoni, V. A. Novikov, L. B. Okun, A. N. Rozanov and M. I. Vysotsky, Phys. Lett. B **476**, 107 (2000) [arXiv:hep-ph/9911535].

[6] Direct search experiments have ruled out a stable fourth generation Dirac neutrino with a cosmological relic density (as well as densities much lower than even this) [59]. Whether the thermal relic abundance can be arranged to sufficiently small so as to contribute insignificantly to cosmological dark matter (and thus avoid the direct search bounds) depends on how large the annihilation cross section can be made, which in turn depends on several parameters including the Majorana mass of the neutrino. See [58] for a recent discussion.

[7] V. A. Novikov, L. B. Okun, A. N. Rozanov and M. I. Vysotsky, Phys. Lett. B **529**, 111 (2002) [arXiv:hep-ph/0111028].

[8] V. A. Novikov, L. B. Okun, A. N. Rozanov and M. I. Vysotsky, JETP Lett. **76**, 127 (2002) [Pisma Zh. Eksp. Teor. Fiz. **76**, 158 (2002)] [arXiv:hep-ph/0203132].

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