CERN
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Fun with Four Generations

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What will the LHC find?

4^{th} Generation??

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

PDG 2006

Outline

This conclusion is wrong.

- Constraints on a 4th generation
- Parameter space where 4th generation avoids (minimizes) all constraints
- Consequences for Higgs physics

Concentrate on the low energy effective theory (there will be a cutoff $\Lambda << M_{pl}$).
Some effects well-known, some known (but not appreciated), some new!

Constraints on a 4th Generation

- Z -> νν at LEP I
- CKM, MNS mixing
- Tevatron, LEP II direct search
- Electroweak precision (S parameter)
- Vacuum stability; triviality

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

Easily avoided. Add ν_{R4} with

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

4th generation neutrino acquires Dirac mass

$$m_D \;=\; \lambda v$$

(can also add $M_{44}\nu_{R4}\nu_{R4}$ 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

$$\begin{pmatrix} \square & \square & \square & \square \\ \square & \square & \square & \square \\ \square & \square & \square & \square \\ \square & \square & \square & \square \end{pmatrix}$$

$$|V_{ud4}|^2 = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \simeq 0.0008 \pm 0.0011$$

$$|V_{cd4}|^2 = 1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 \simeq 0.032 \pm 0.181$$

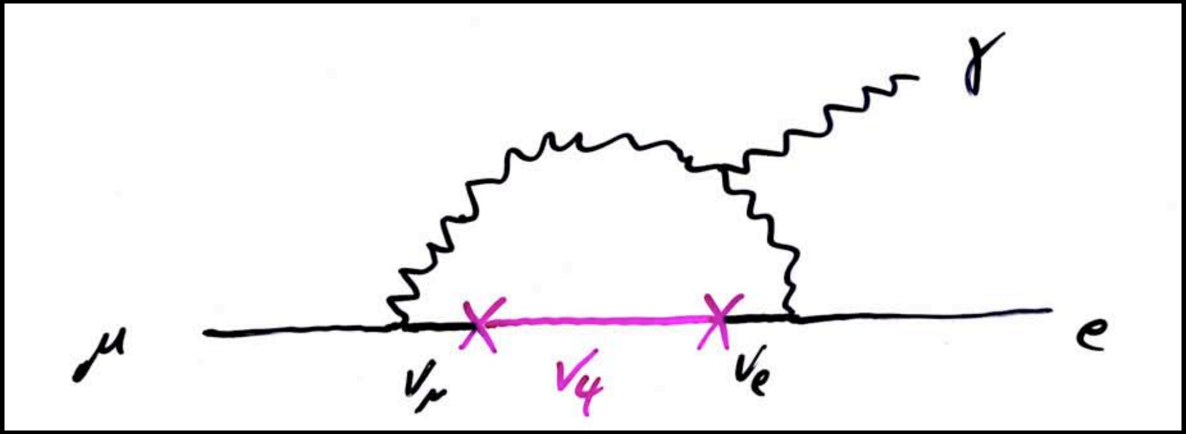
$$|V_{t4d}|^2 = 1 - |V_{ud}|^2 - |V_{cd}|^2 - |V_{td}|^2 \simeq -0.001 \pm 0.005$$

Roughly,

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

is sufficient.

Charged Lepton Flavor Mixing



This and similar processes restrict PMNS elements.

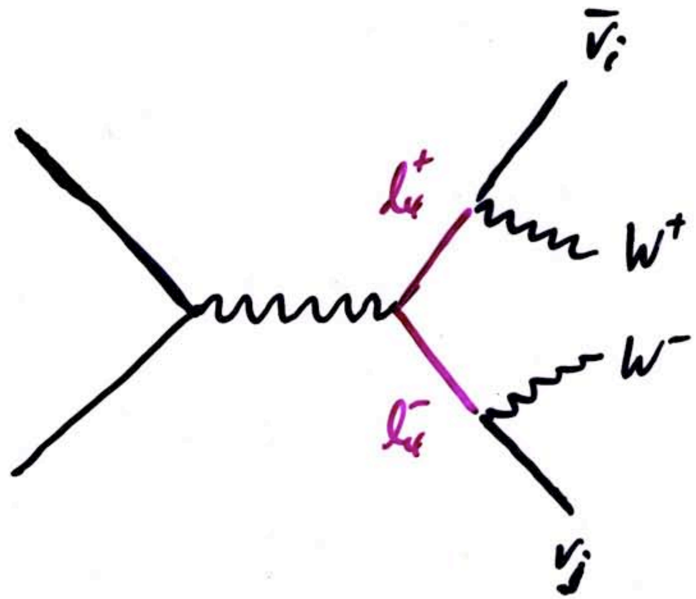
We find

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

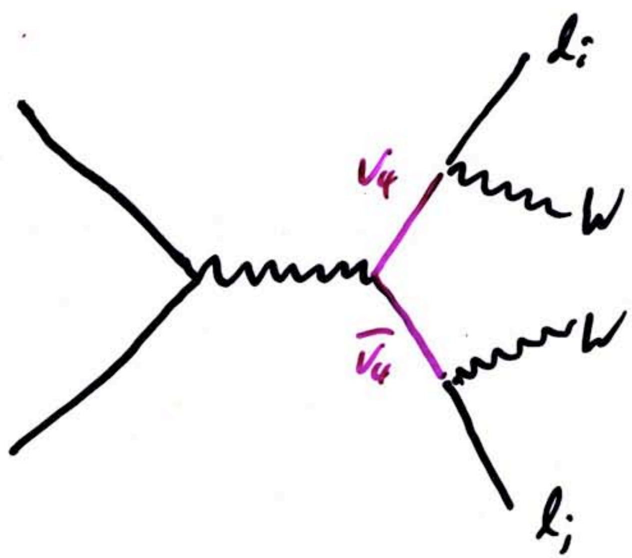
So that

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

LEP II Direct Search

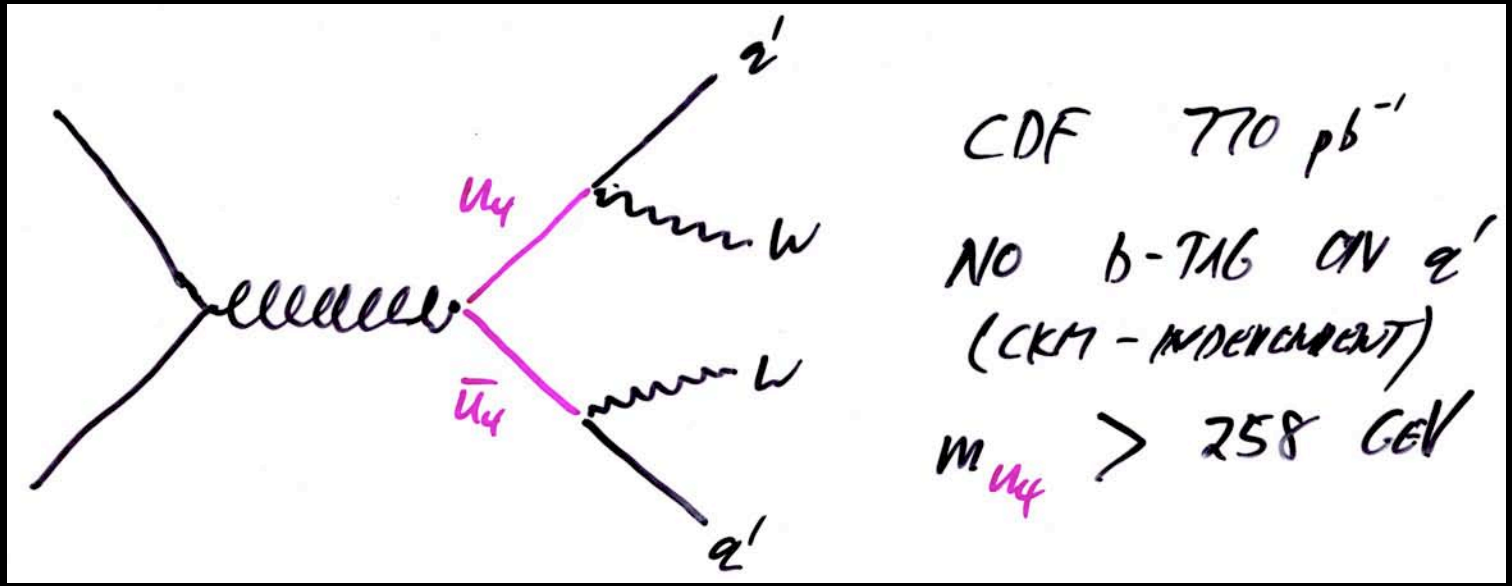


$$m_{l_4} \gtrsim 101 \text{ GeV}$$



$$m_{\nu_4} \gtrsim \begin{cases} 100 & l_i = e, \mu \\ 90 & l_i = \tau \end{cases}$$

Tevatron Direct Search

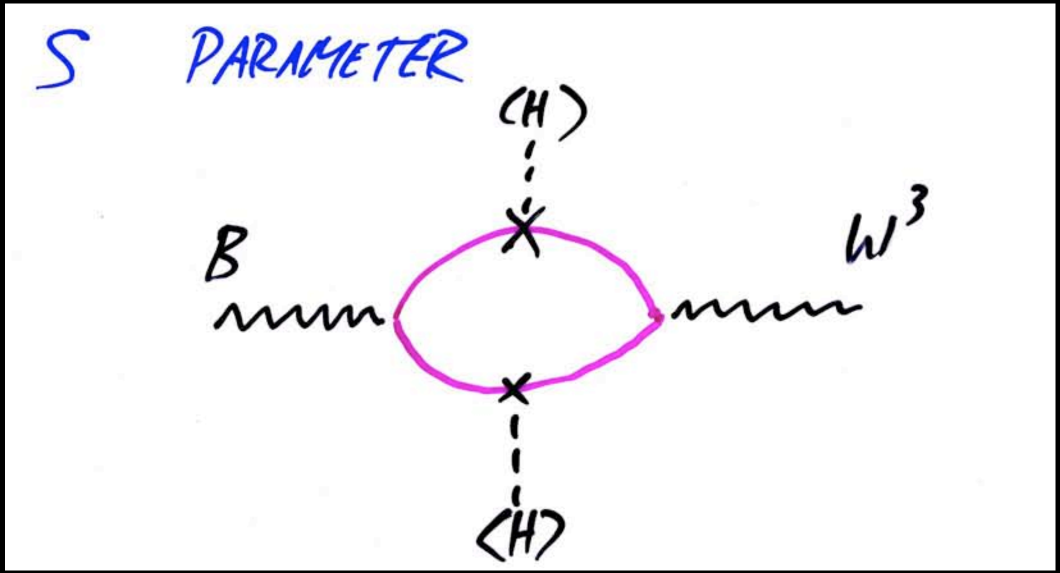


No comparable published bound on d_4.

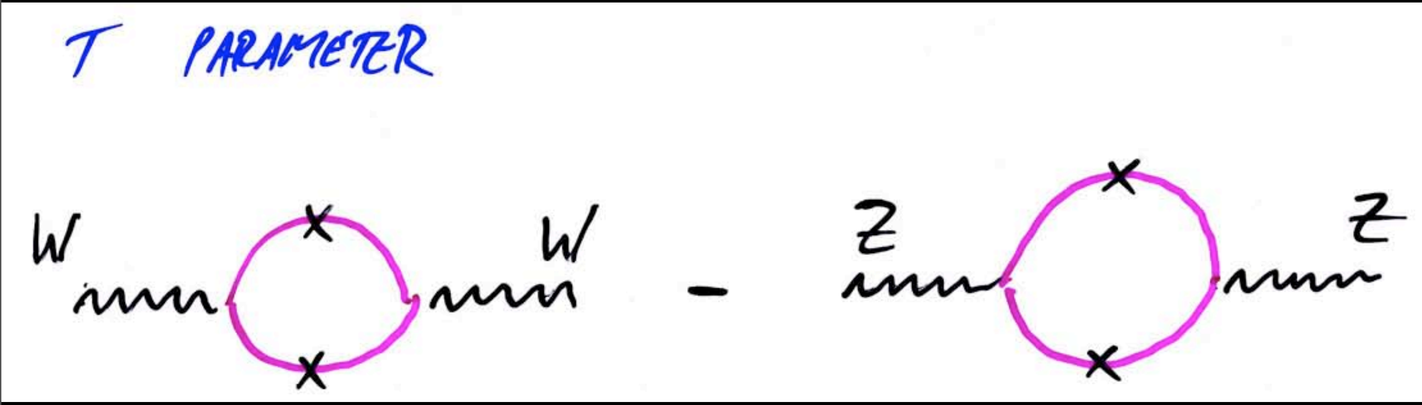
However, for $m_{d4} < m_t + m_W$, CDF search for u_4 also applies to d_4 (just gluon production); for $m_{d4} > m_t + m_W$, expect $t\bar{t}WW$ signal

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

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", $m_{u,d} \gg M_Z$

$$\Delta S = \frac{\overset{N_c}{\cancel{N_f}}}{6\pi}\left(1 - 2\,Y \ln\frac{m_u^2}{m_d^2}\right)$$

~~0.21 for 4th generation~~

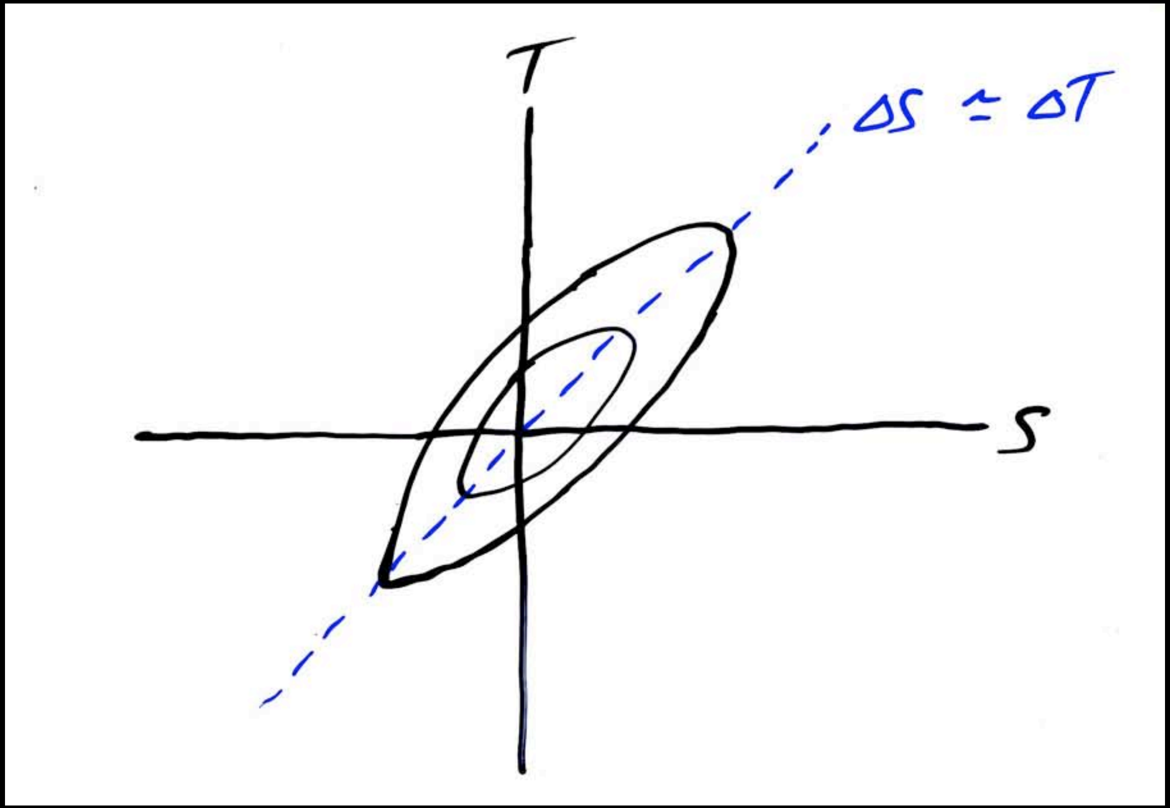
Suggests a strategy to minimize S. Take:

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

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

The price to pay is a contribution to T.

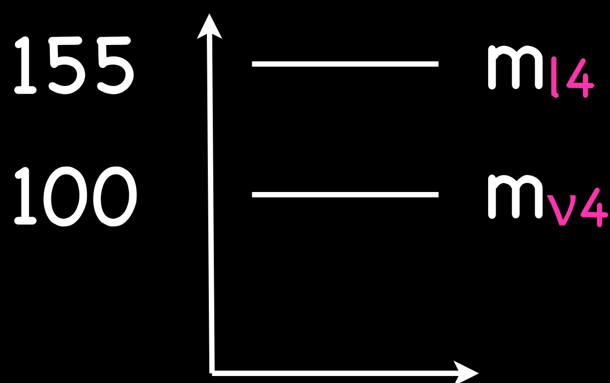
We can exploit the well-known relative experimental insensitivity to the $S \simeq T$ direction.



Leptons

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

For example:



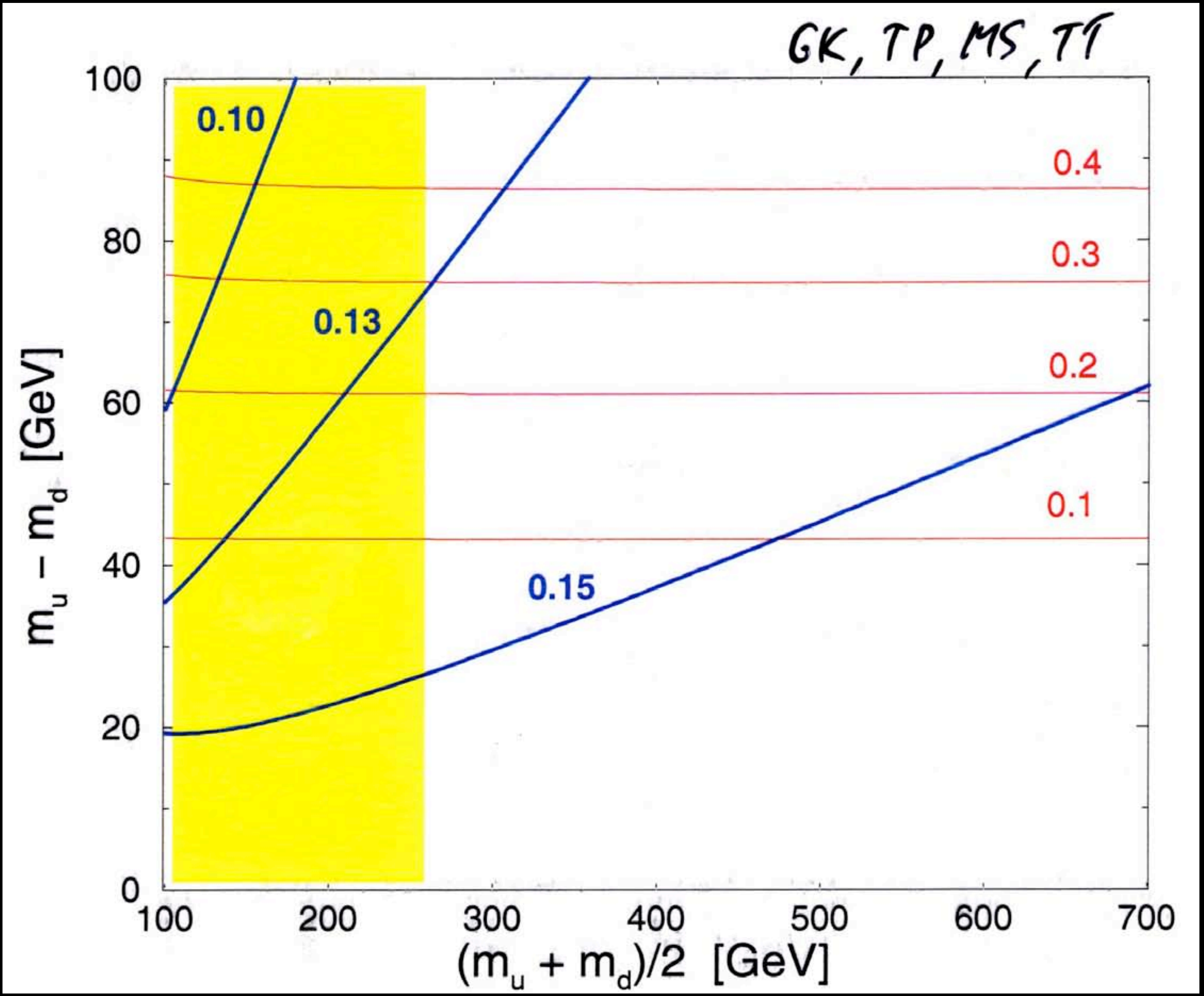
$\Delta S = 0.00$

$\Delta T = 0.05$

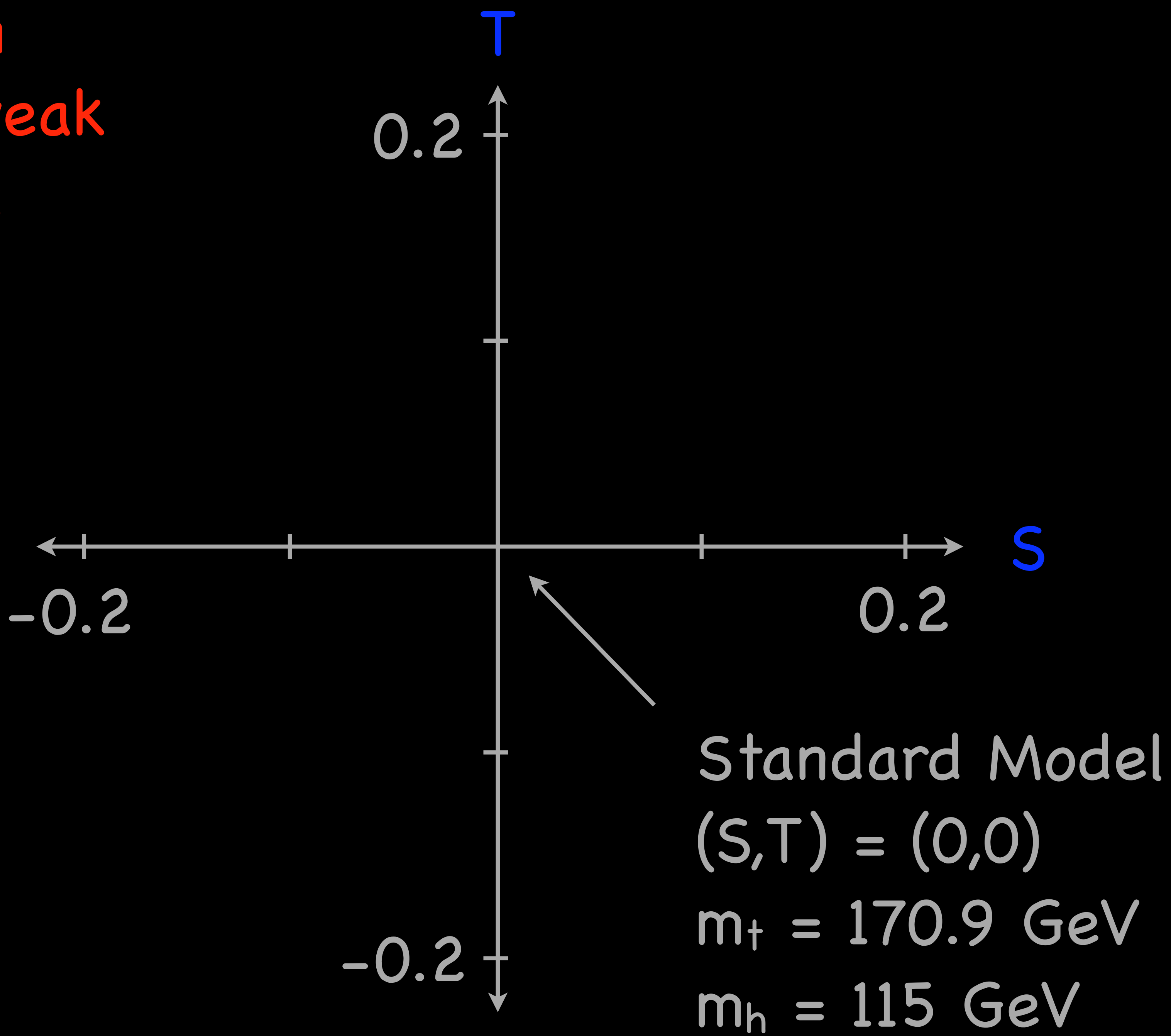
(one-loop exact used to calculate)

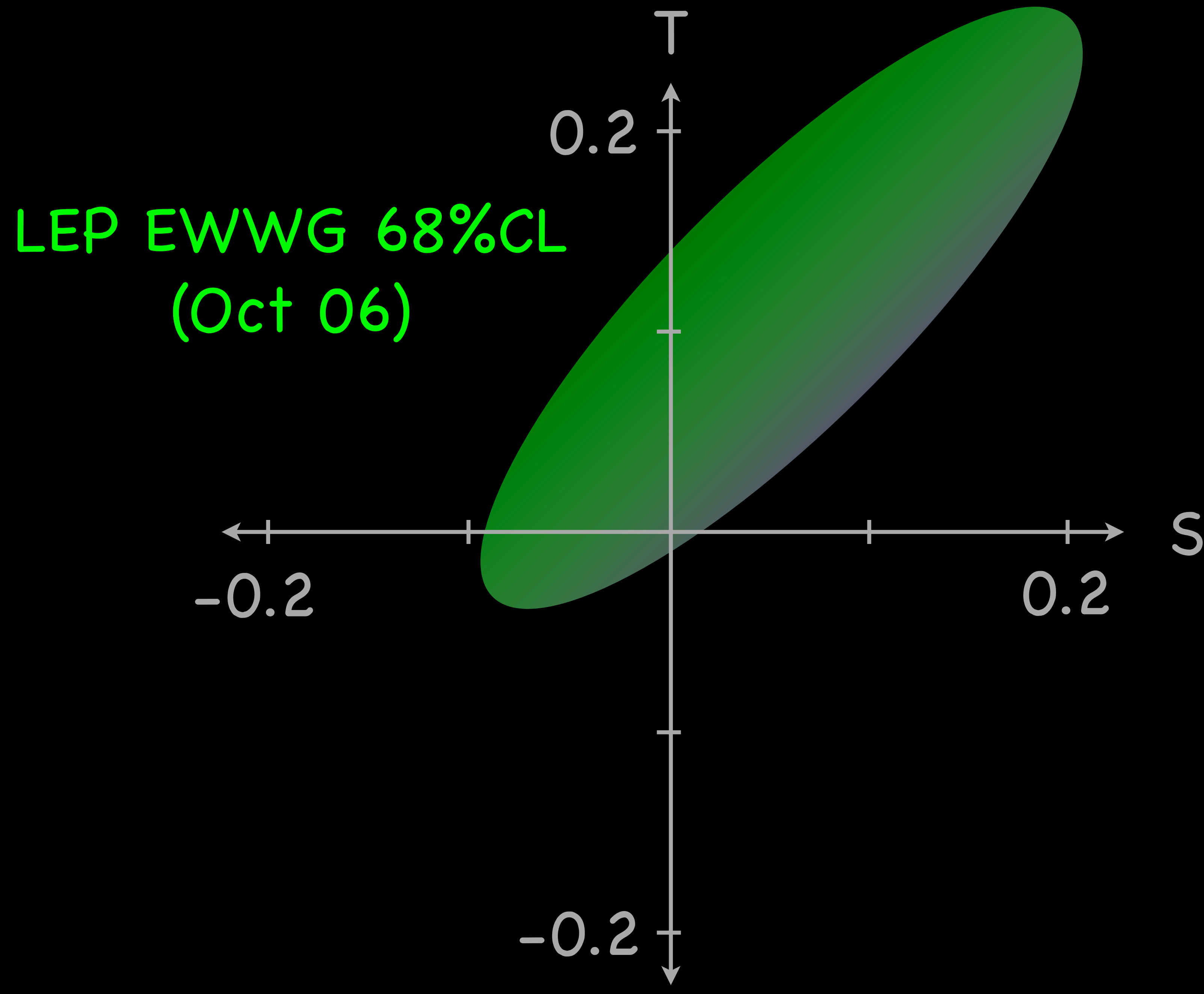
(A Majorana mass for $\nu 4$ enlarges the parameter space, but does not substantially reduce S.)

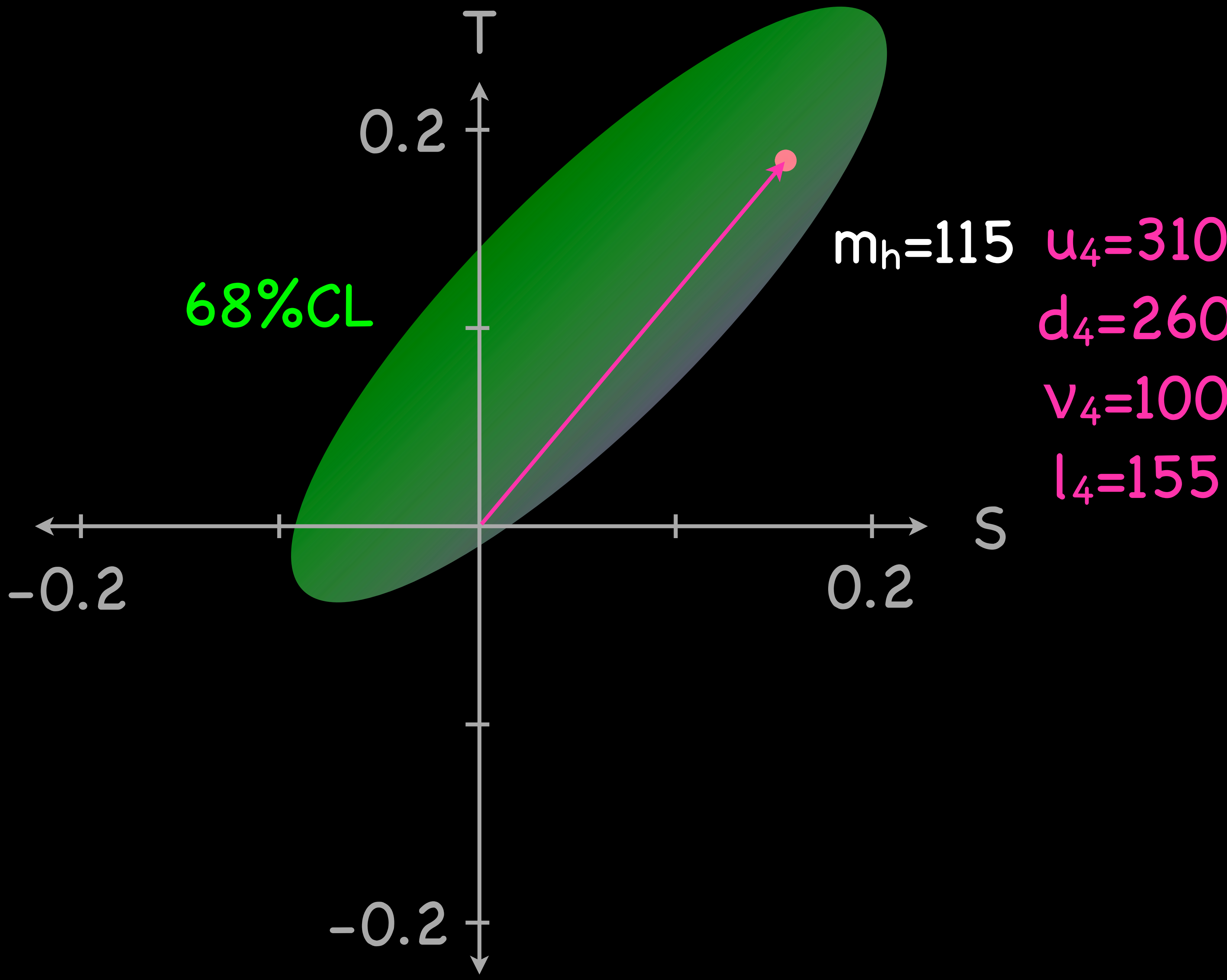
Quarks

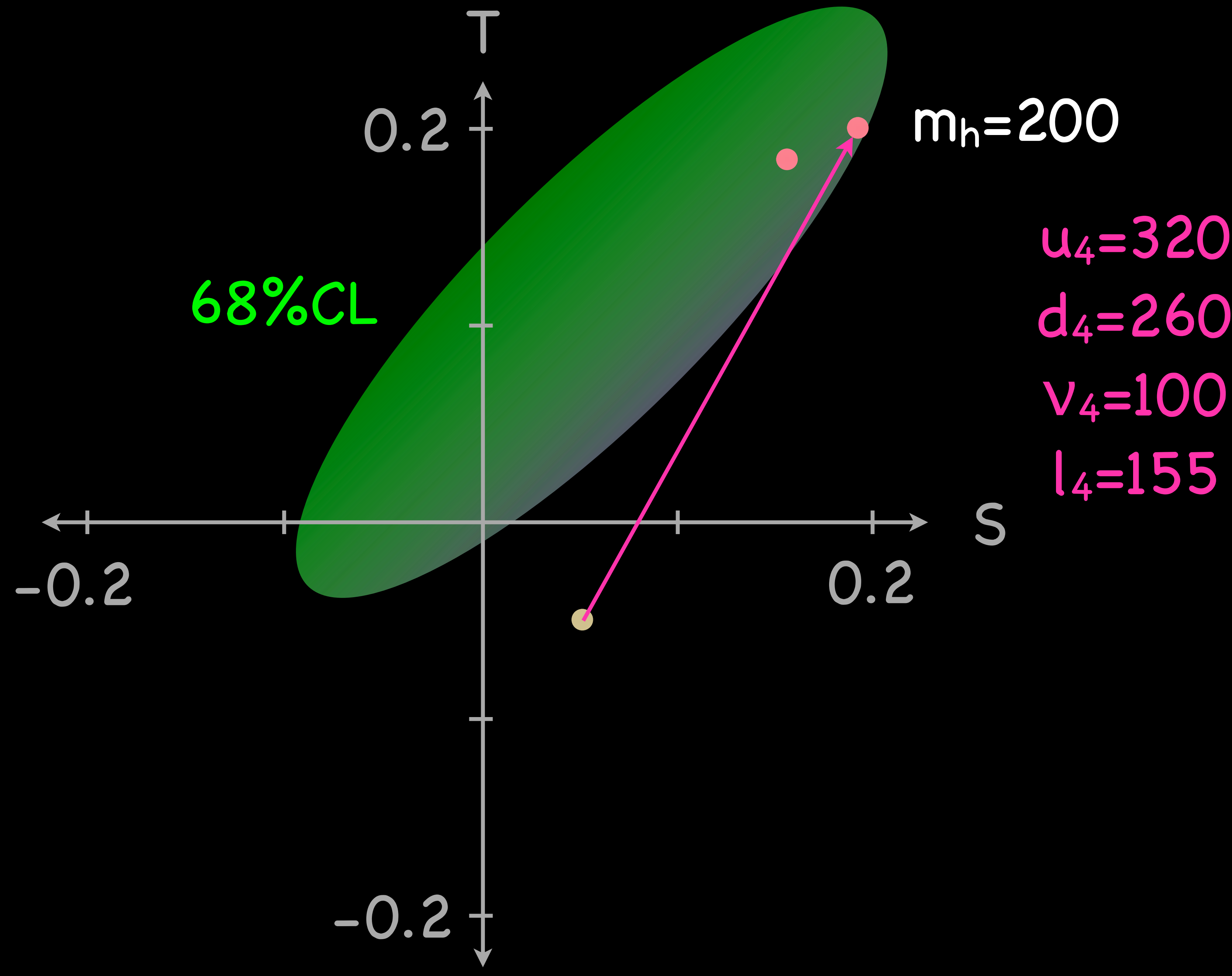

GK, TP, MS, TT
0.10
0.13
0.15
0.4
0.3
0.2
0.1
100
80
60
40
20
0
100
200
300
400
500
600
700
$m_u - m_d$ [GeV]
$(m_u + m_d)/2$ [GeV]

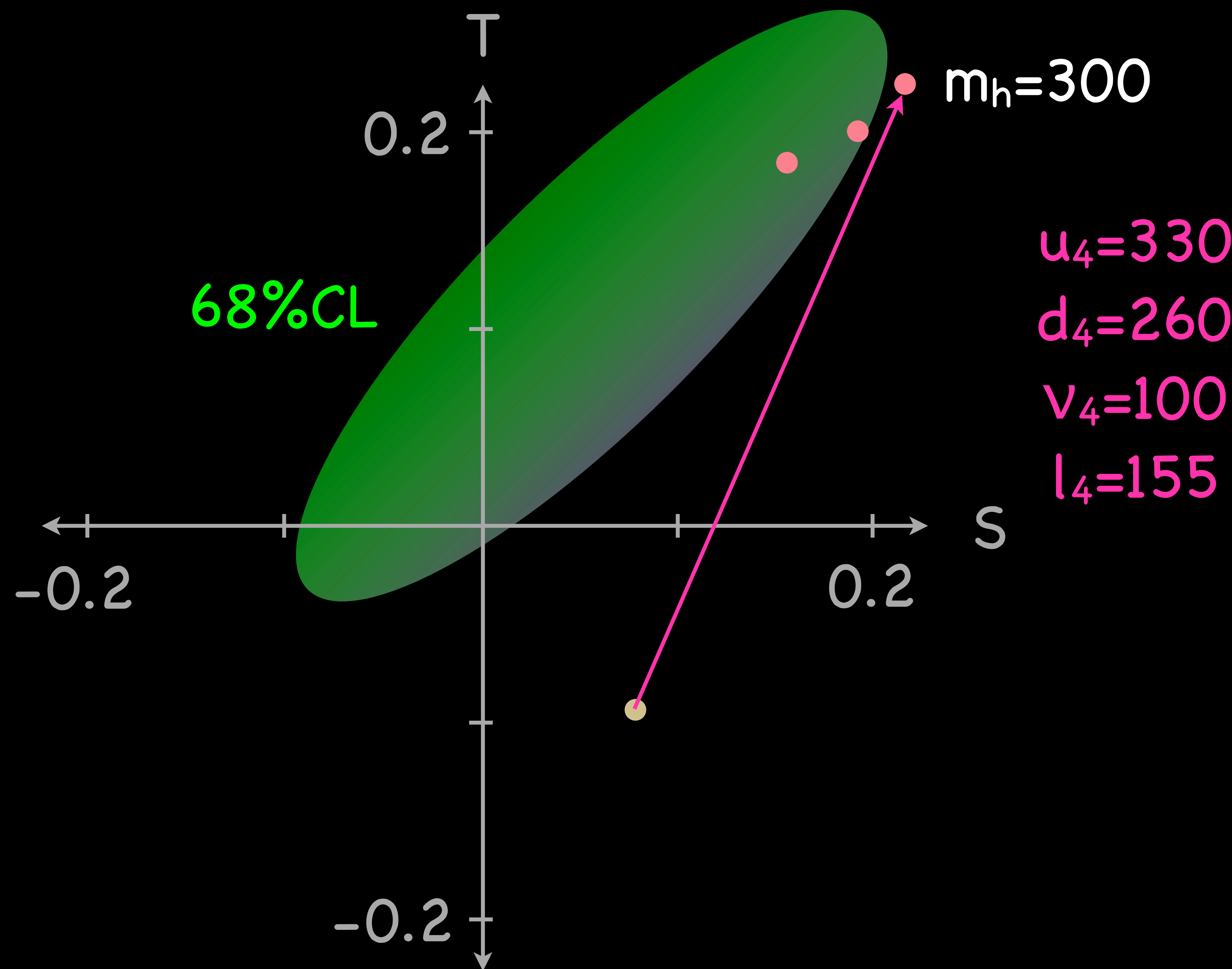
Precision Electroweak (oblique):



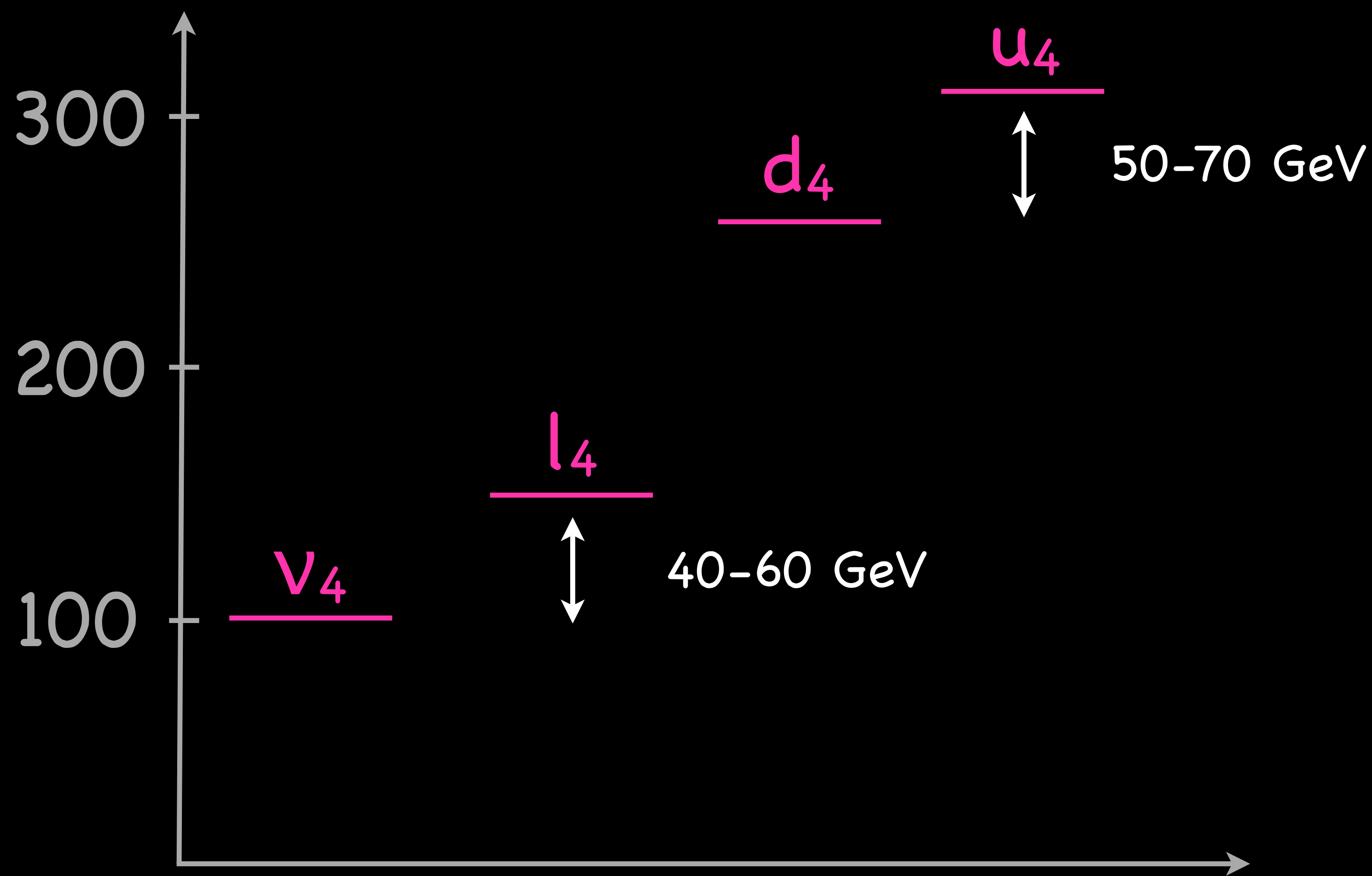

LEP EWWG 68%CL
(Oct 06)
T
0.2
-0.2
S
-0.2
0.2


T
0.2
-0.2
S
-0.2
0.2
68%CL
m_h=115
u_4=310
d_4=260
ν_4=100
l_4=155


T
0.2
m_h=200
u_4=320
d_4=260
ν_4=100
l_4=155
68%CL
S
-0.2
0.2
-0.2


T
0.2
-0.2
S
-0.2
0.2
68%CL
m_h=300
u_4=330
d_4=260
ν_4=100
l_4=155

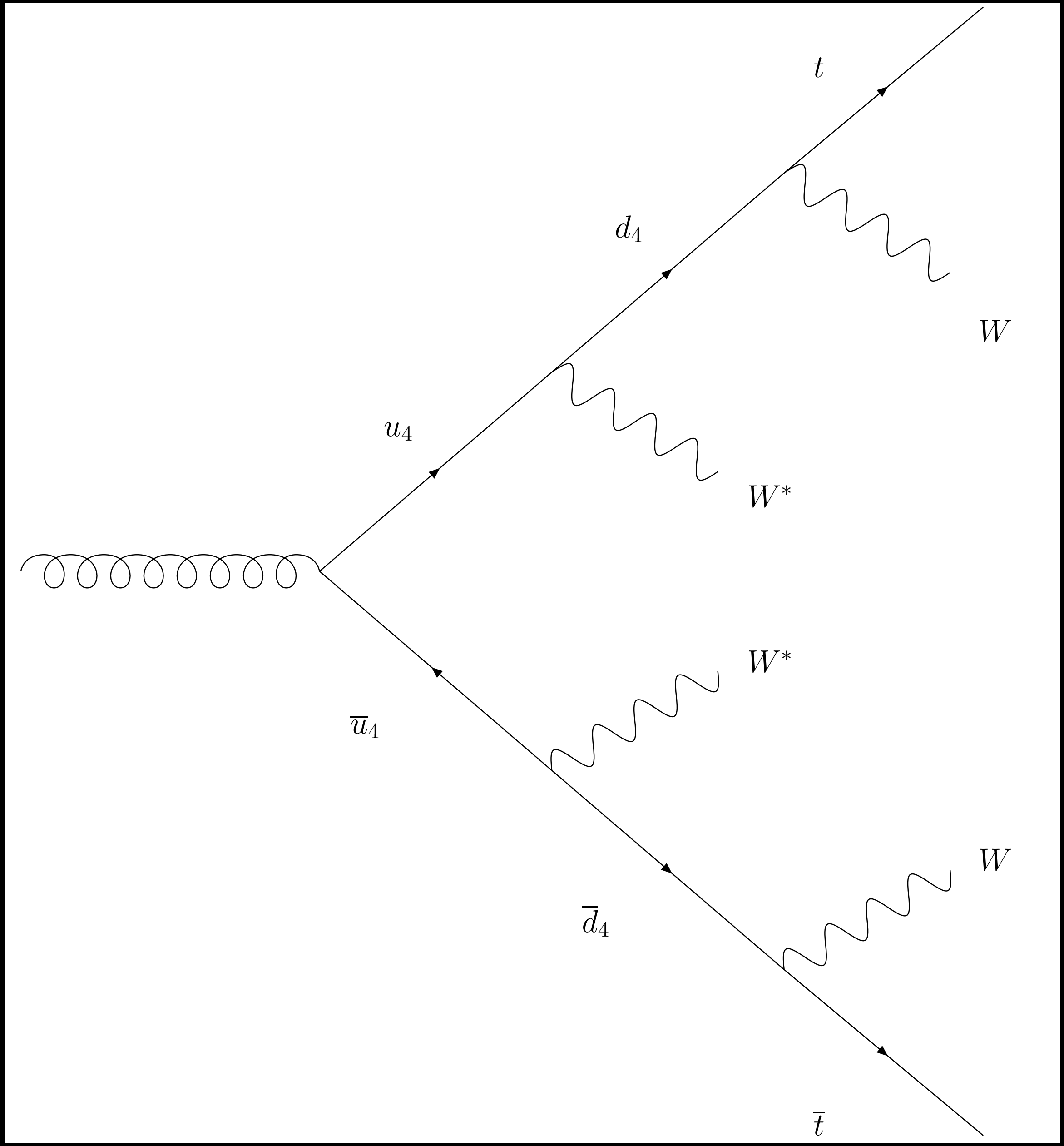
Fourth Generation Spectrum



CKM/PMNS mixings $\lesssim 0.01$

Striking Signals

u_4 production:

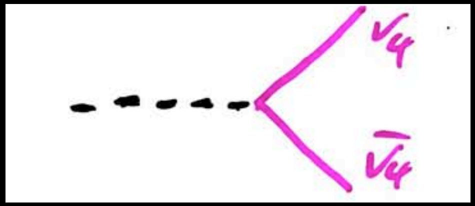


Effects on Higgs Physics

1) Higgs mass range: $115 < m_h < \begin{cases} 315 & \text{to } 68\% \text{ CL} \\ 750 & \text{to } 95\% \text{ CL} \end{cases}$

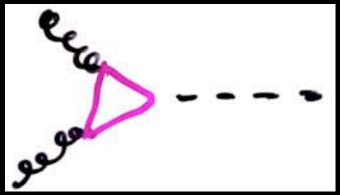
2) Non-decoupling loop effects affect Higgs production and decay:

3) New decay modes:



4) Vacuum stability; cutoff scale

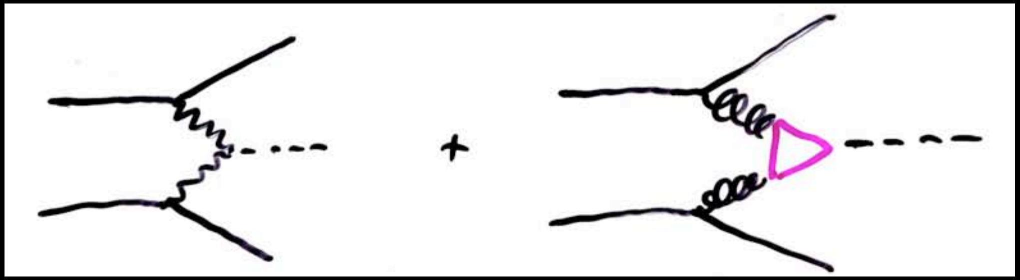
Loop enhancement:



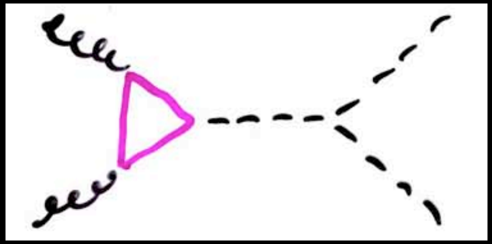
1) $\sigma^{4th}(gg\to h) \simeq 9\sigma^{SM}(gg\to h)$

2) For $115 < m_h < 140$ GeV: $BR(h\to gg) \simeq 0.5$

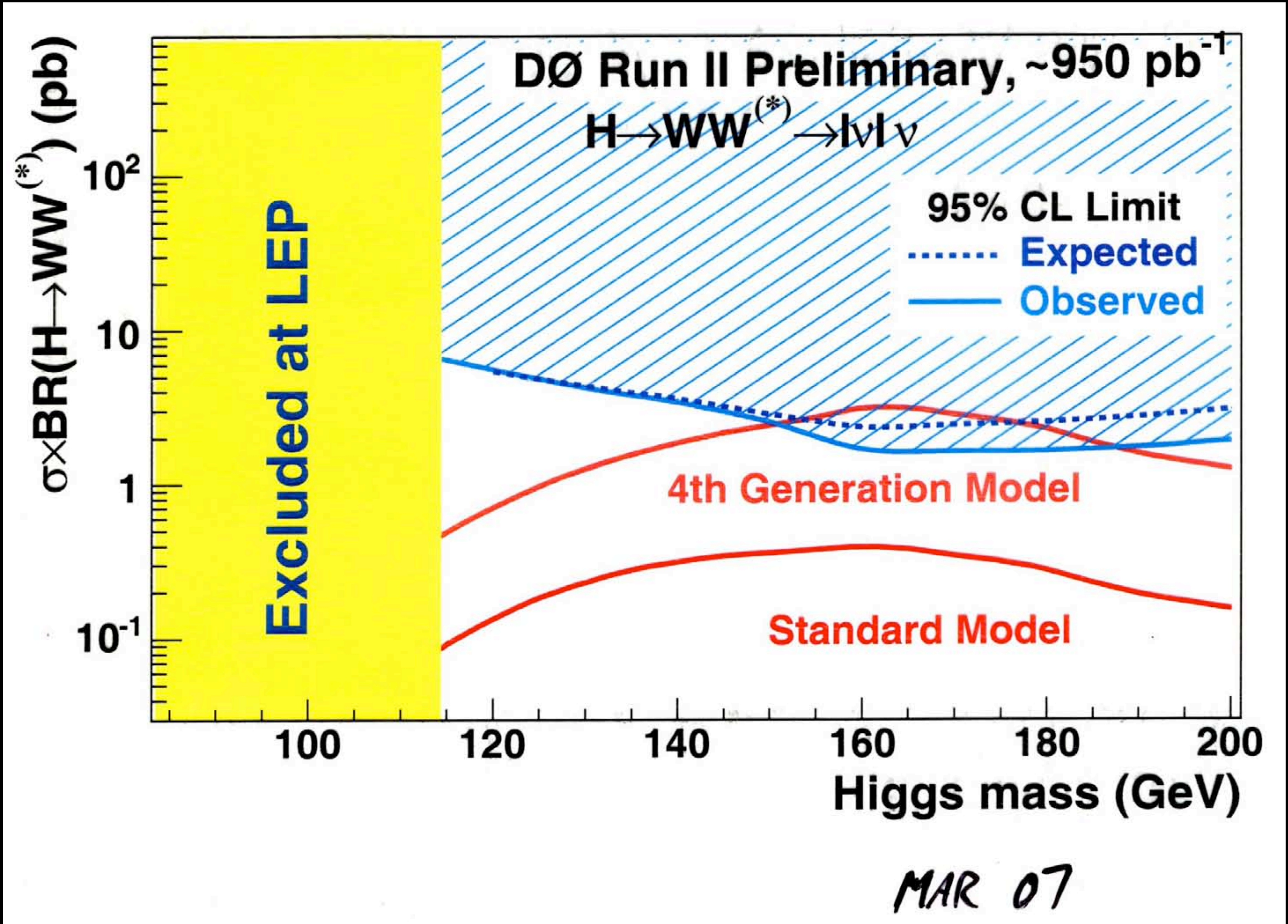
3) Modified angular distribution for VBF:



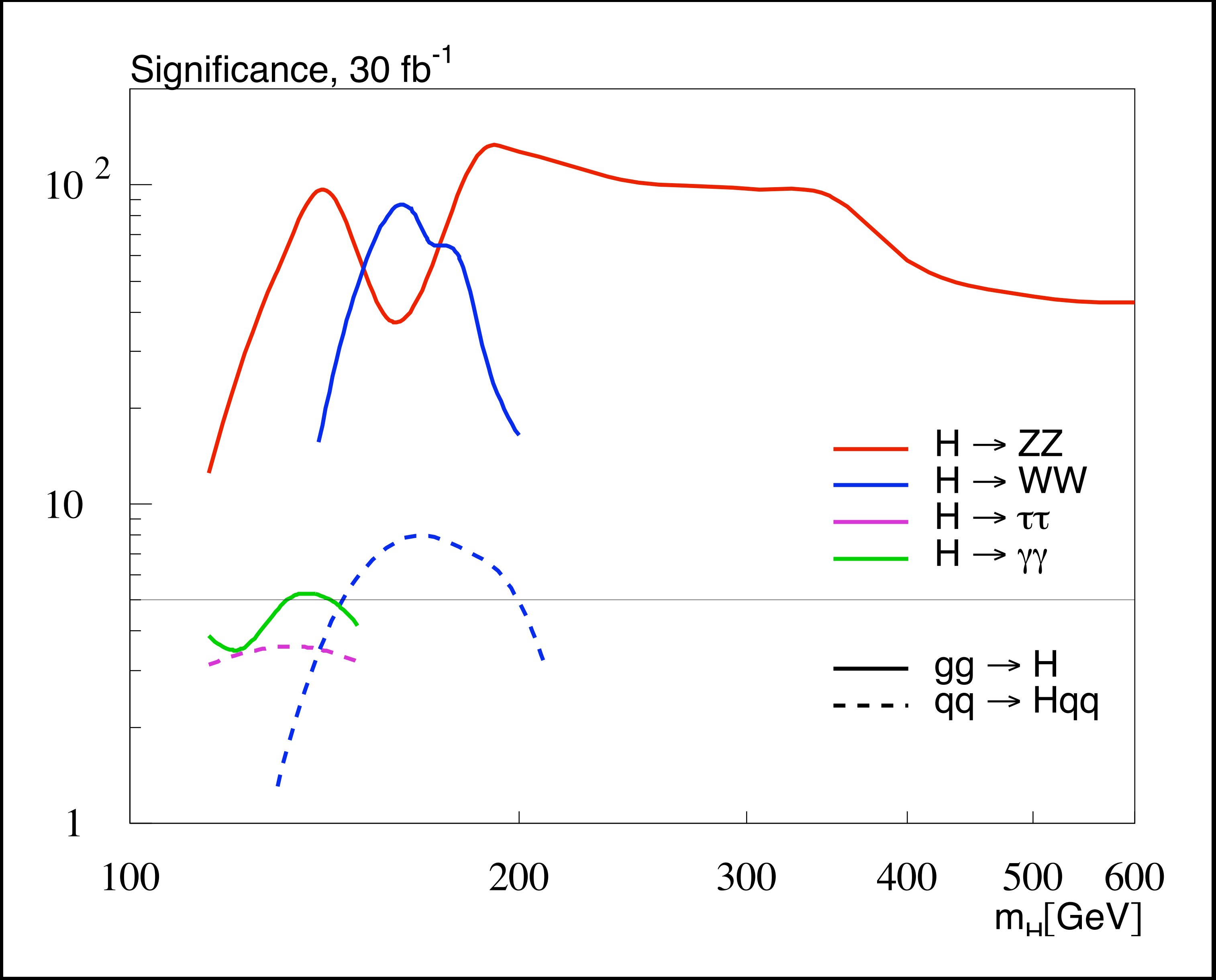
4) Large increase in di-Higgs production:



Higgs Production Enhancement

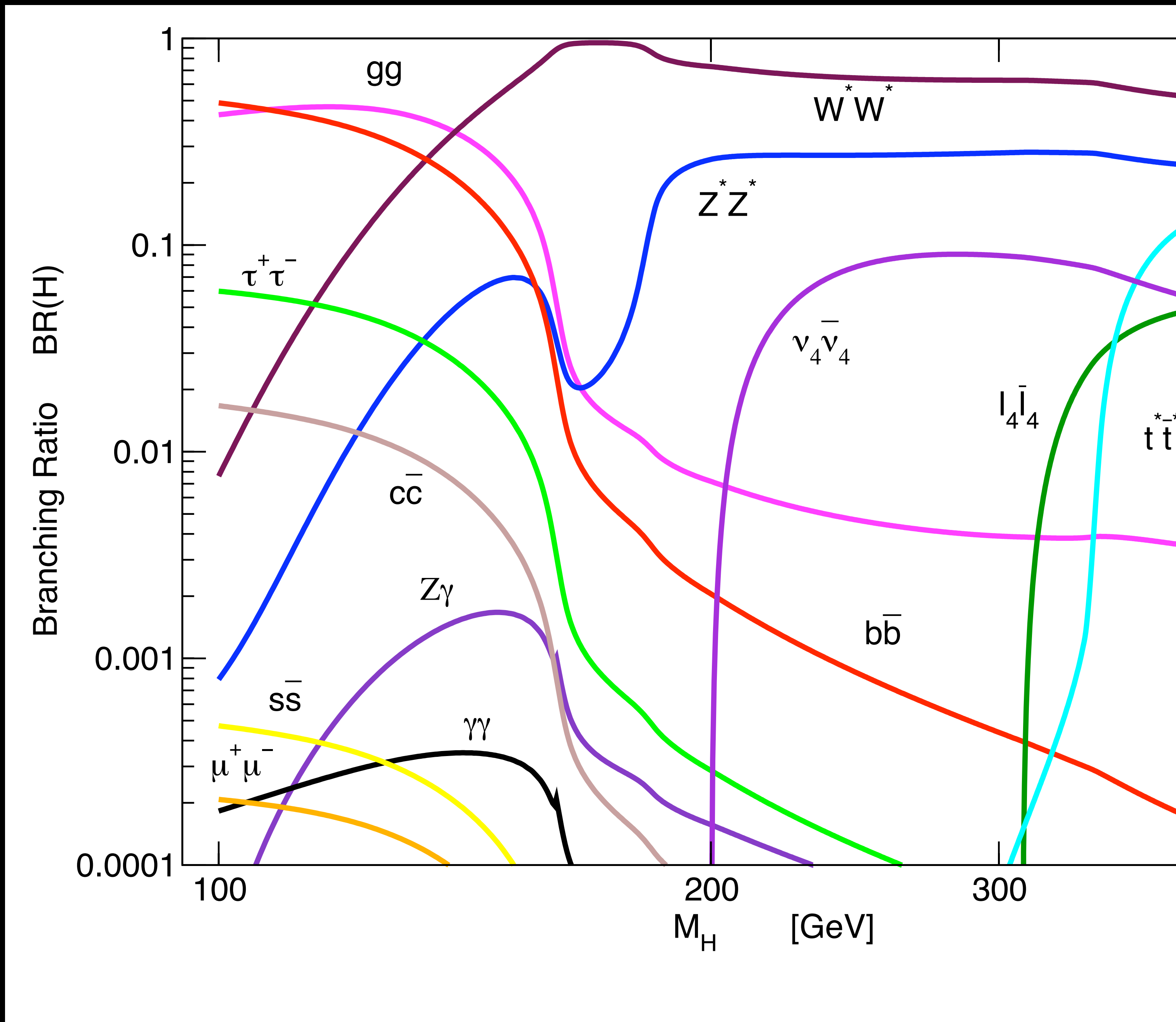


Higgs Signals -- Rescaled CMS Significance



GK,TP,
MS,TT

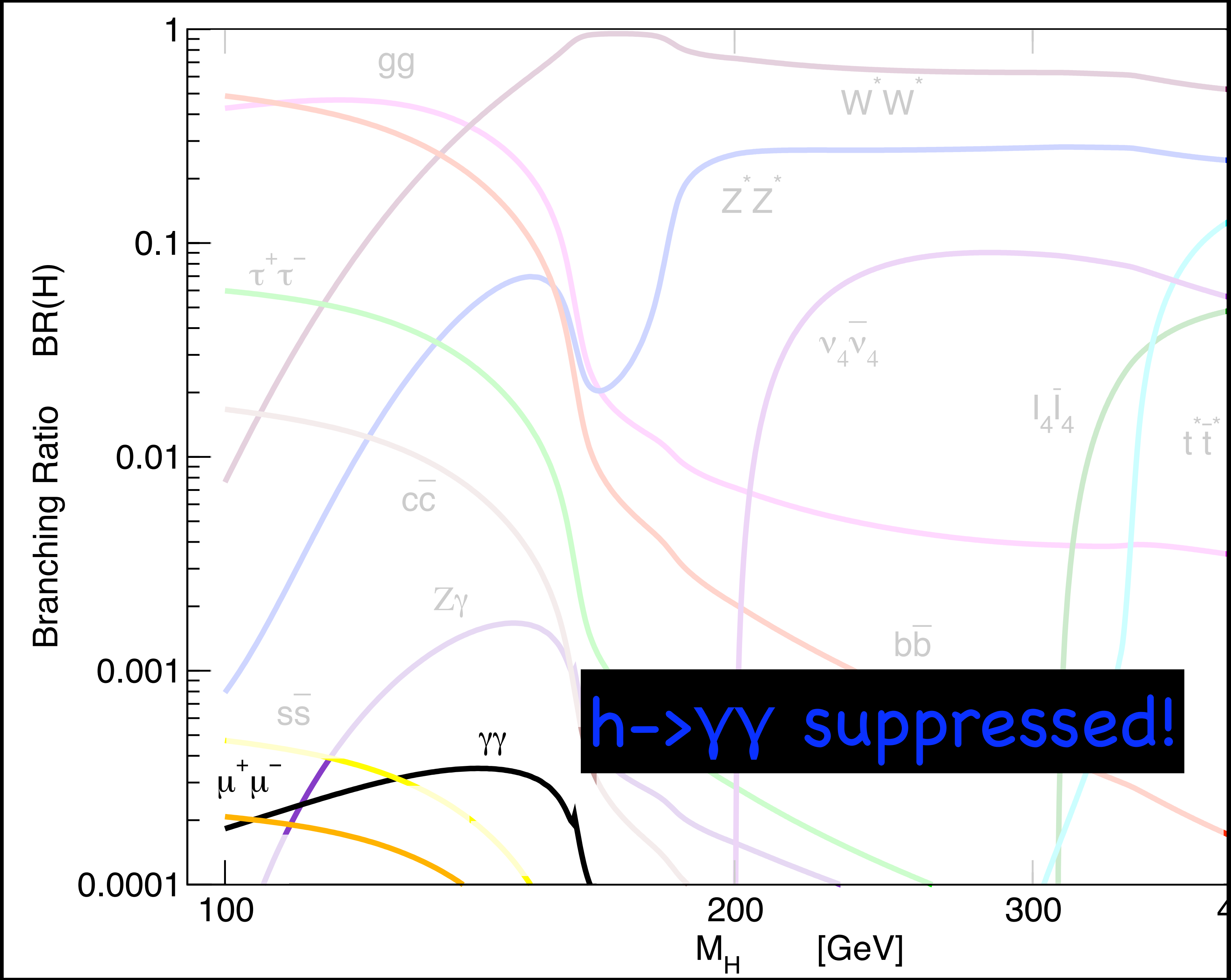
Higgs Branching Ratios



Modified HDECAY

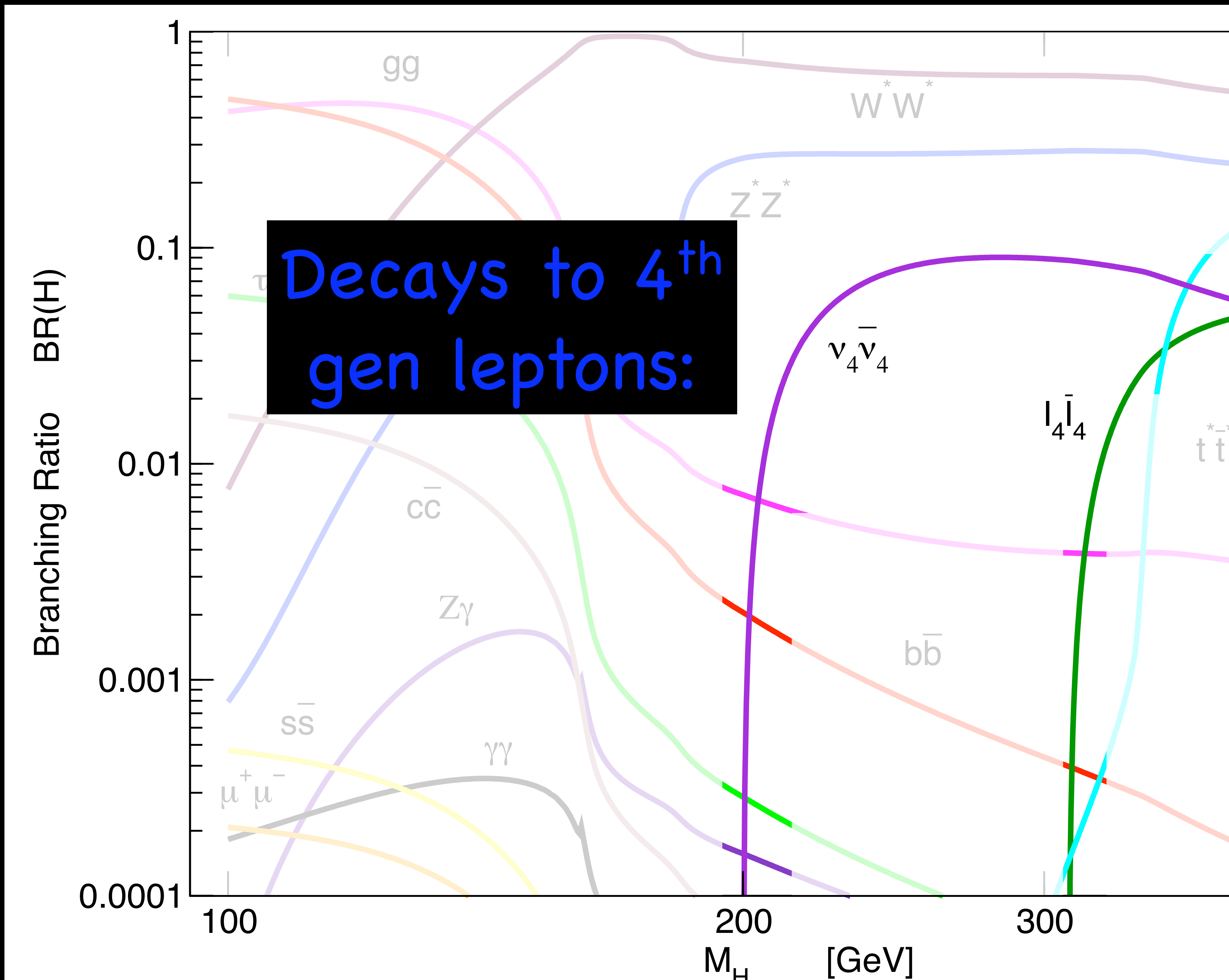
GK,TP, MS,TT

Higgs Branching Ratios



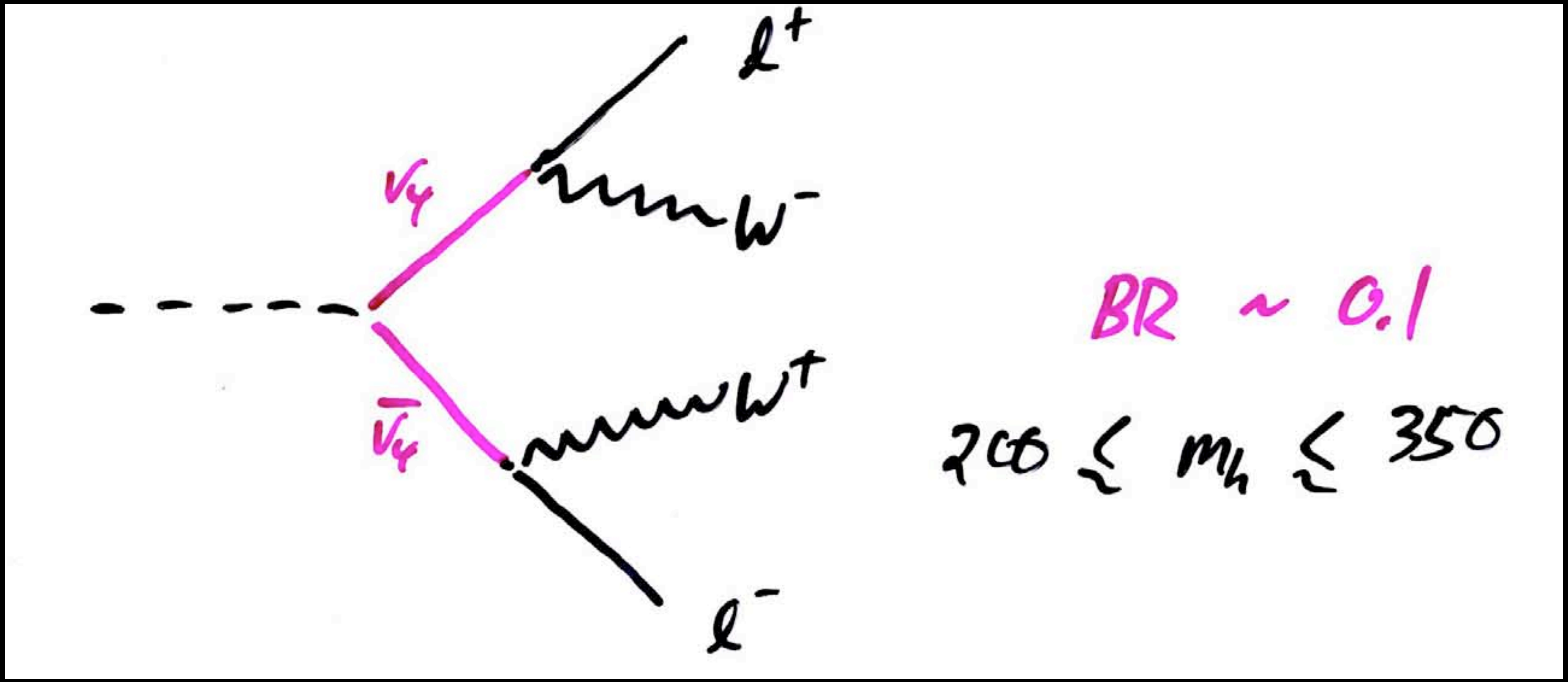
GK,TP,
MS,TT

Higgs Branching Ratios

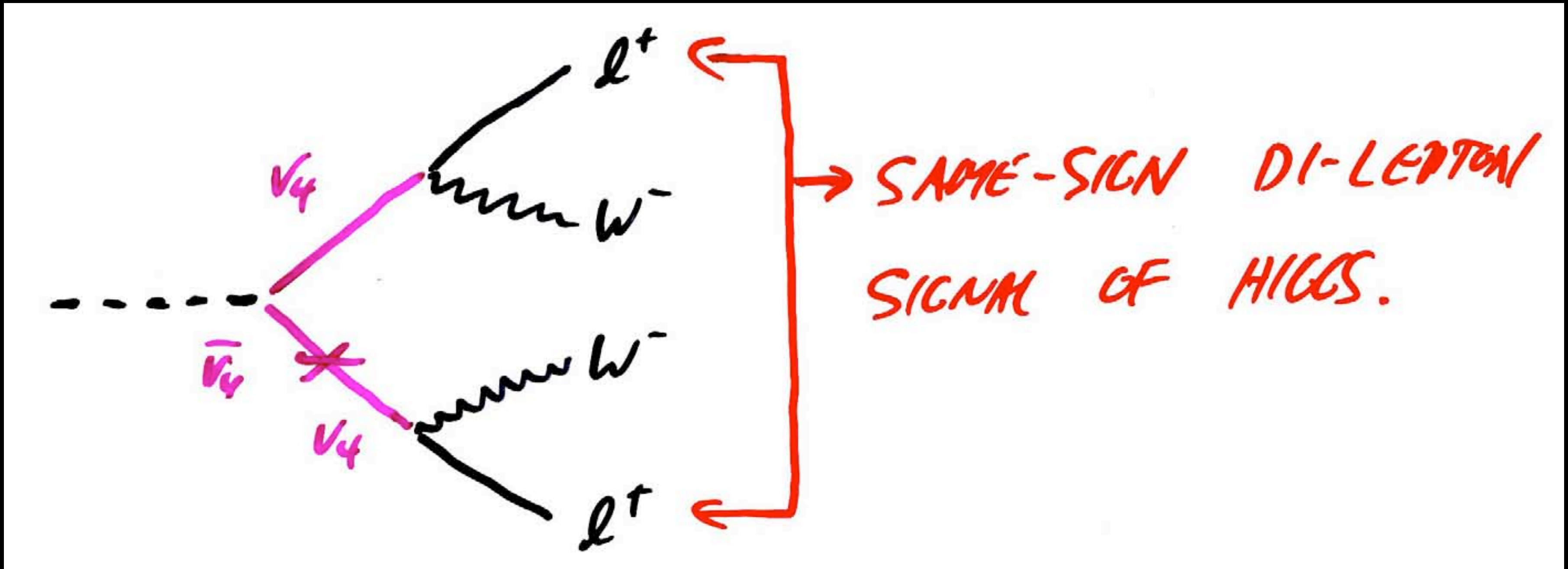


GK,TP,
MS,TT

Unusual Higgs Decays

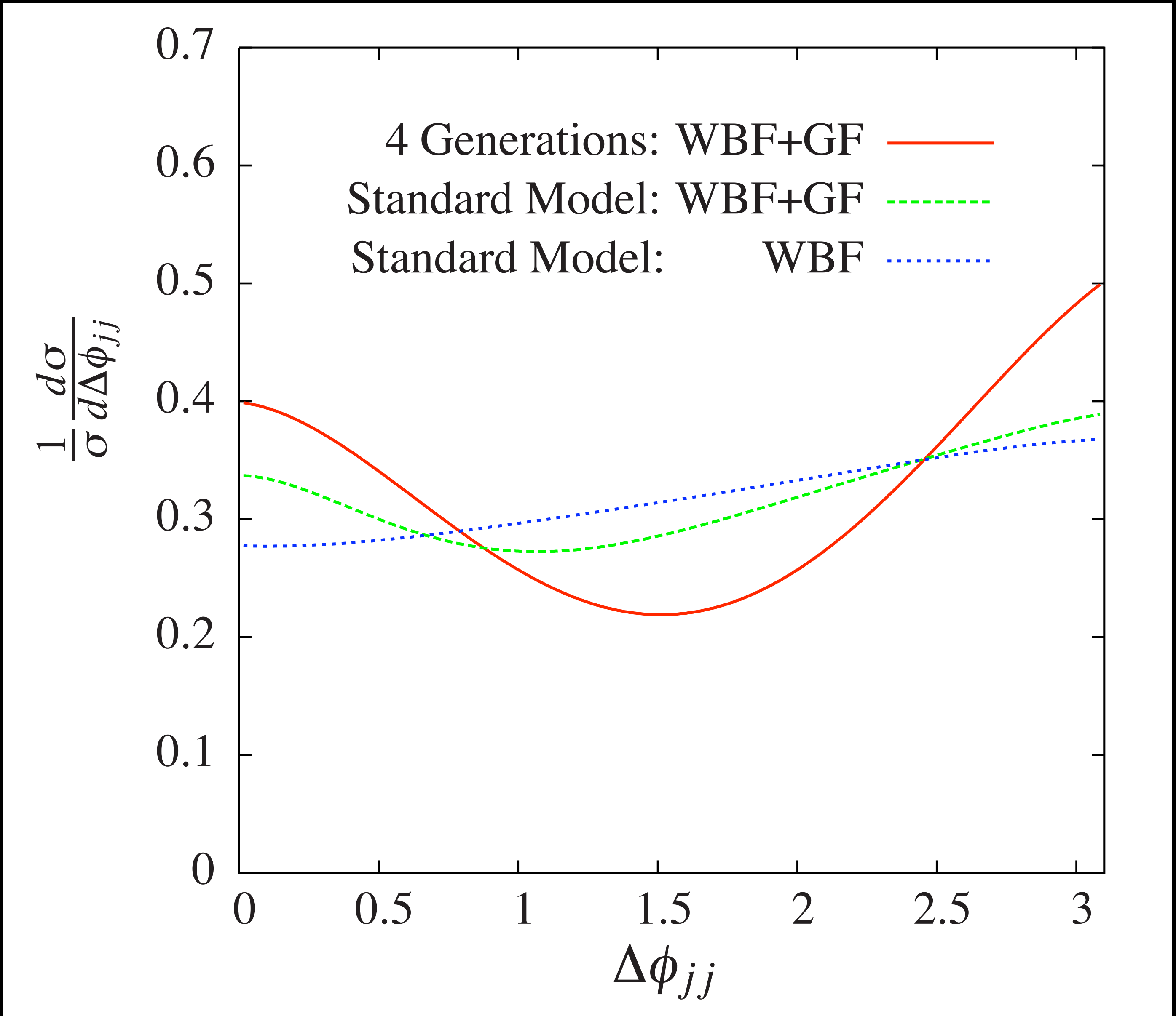


If the 4th generation neutrino has a Majorana mass



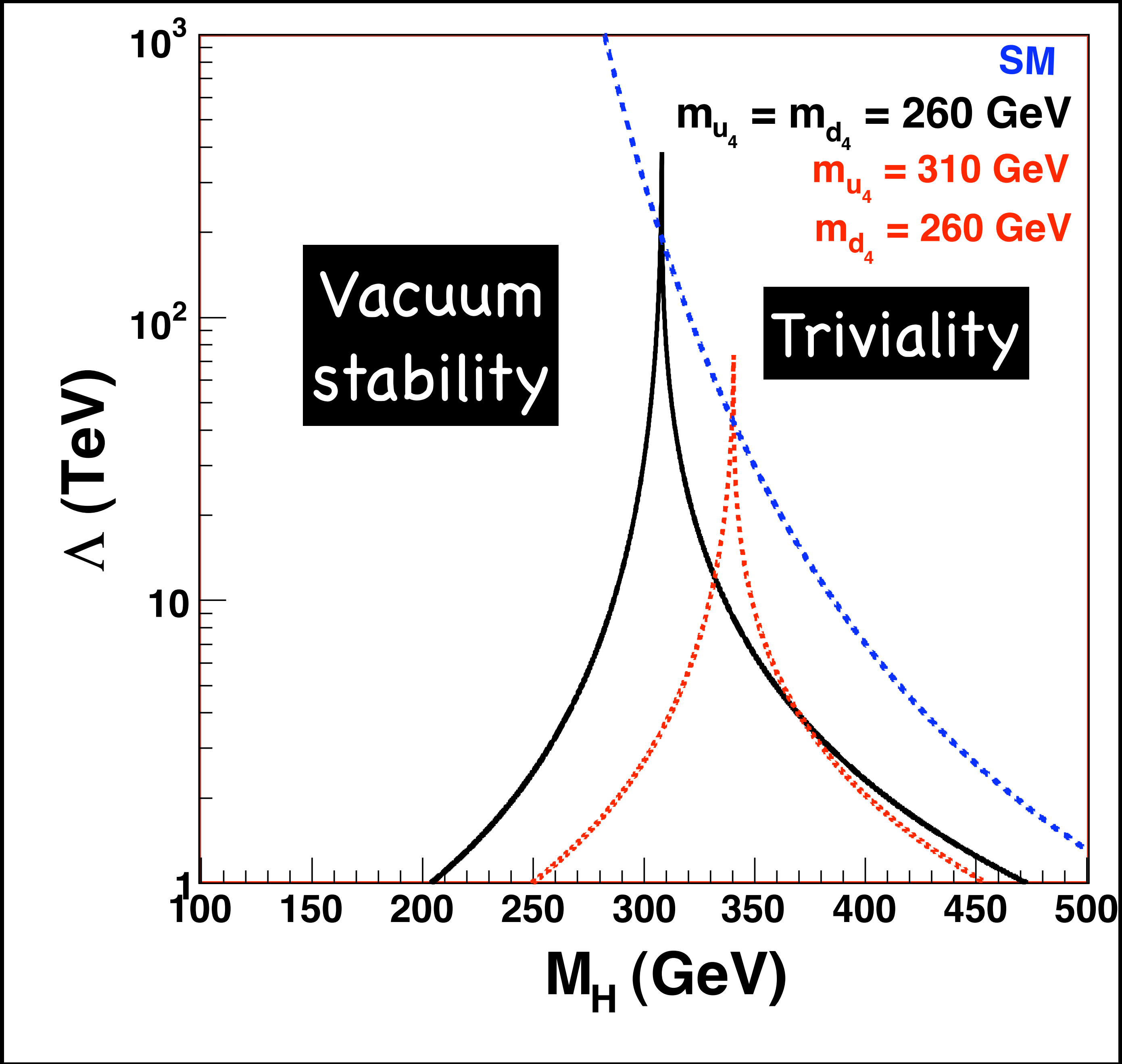
(EW precision allows $M_{44} \simeq m_D$; ν_4 as DM favors it)

Modification to the VBF Angular Distribution



GK,TP,
MS,TT

Higgs Potential



Vacuum stability requires new physics...
but need not be strongly coupled!
(e.g., supersymmetry)

(so, 4^{th} generation effects on the Higgs sector should remain unscathed by the UV completion)

Applications

EW phase transition modified; can be enhanced due to fermion decoupling (work in progress)

(discussed in a different context in Carena, Megevand, Quiros, Wagner)

ν_4 as DM: with Majorana mass, no direct detection constraint. Stability? Low thermal abundance?

(Z' models, e.g., Belanger, Pukhov, Servant)

Summary

4th generation allowed by all direct and indirect constraints within a well-defined parameter space.

Pattern of masses that minimize EW precision

$m_{u4} - m_{d4} = 50\text{–}70$ GeV

$m_{l4} - m_{\nu4} = 40\text{–}60$ GeV

Dramatic effects on Higgs sector:

- gluon fusion x 9; VBF modified; di-Higgs enhanced
- unusual decays (l^+l^-WW; l^+l^+WW if Majorana)

Discover (rule out) quarks and Higgs will be fast. Higgs rate, angular dist, unusual decays distinguish from vector-like quarks.

Extra

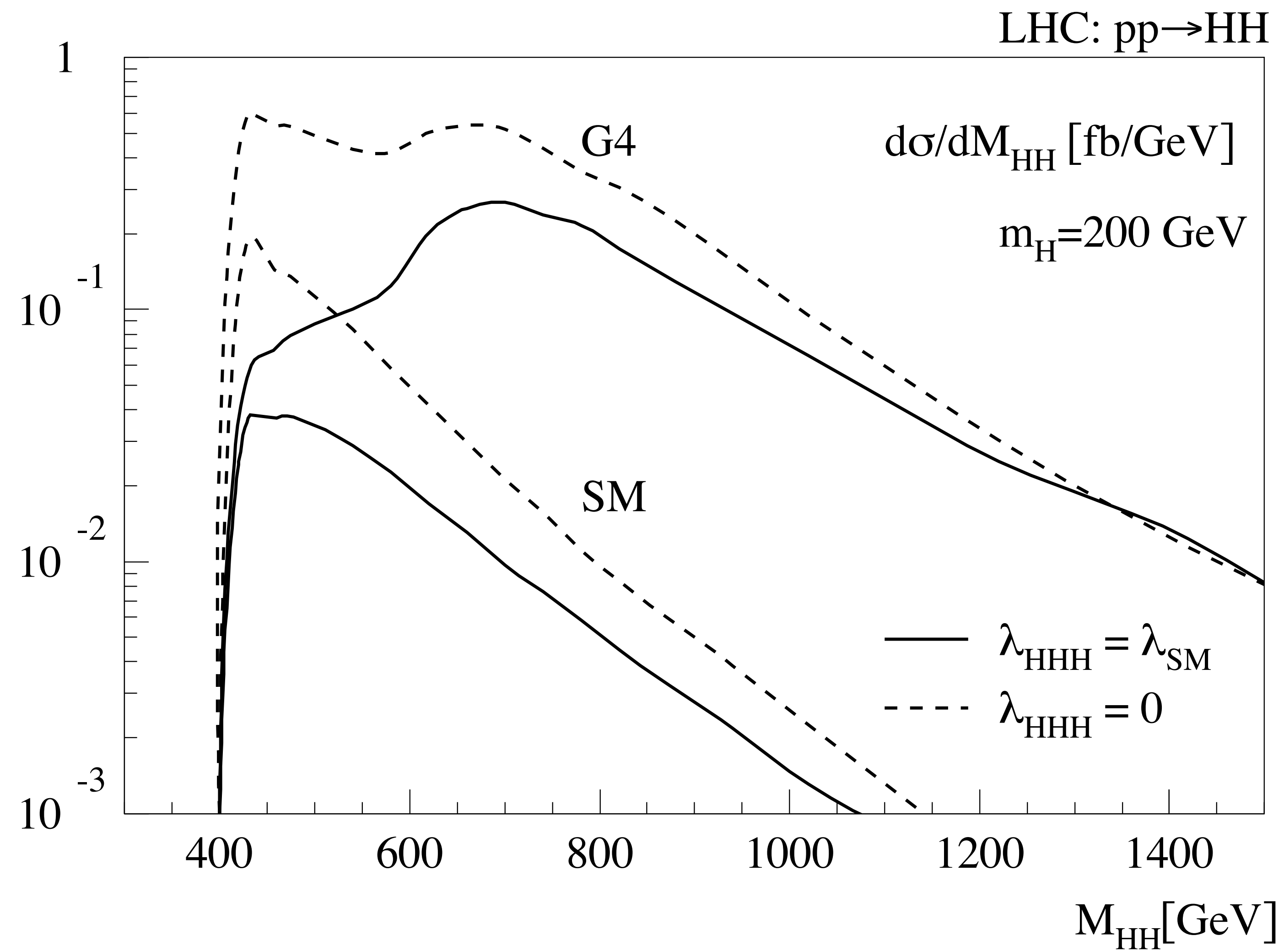


FIG. 6: Invariant mass distribution for Higgs pair production at the LHC. We show the Standard Model and fourth–generation curves in the reference point (b). For the dashed line the Higgs self coupling is set to zero.