Corrections to precision Higgs Physics from a warped extra dimension

Ben Lillie

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BL	In progress

Outline

- Introduction and motivation
- Formalism
- Precision Electroweak constraints
- Higgs physics
- Other collider signatures
- Conclusion

Motivation

Randall-Sundrum Model

One extra dimension with a warped background:
$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$, $R = 1/k$,
k is the AdS curvature.

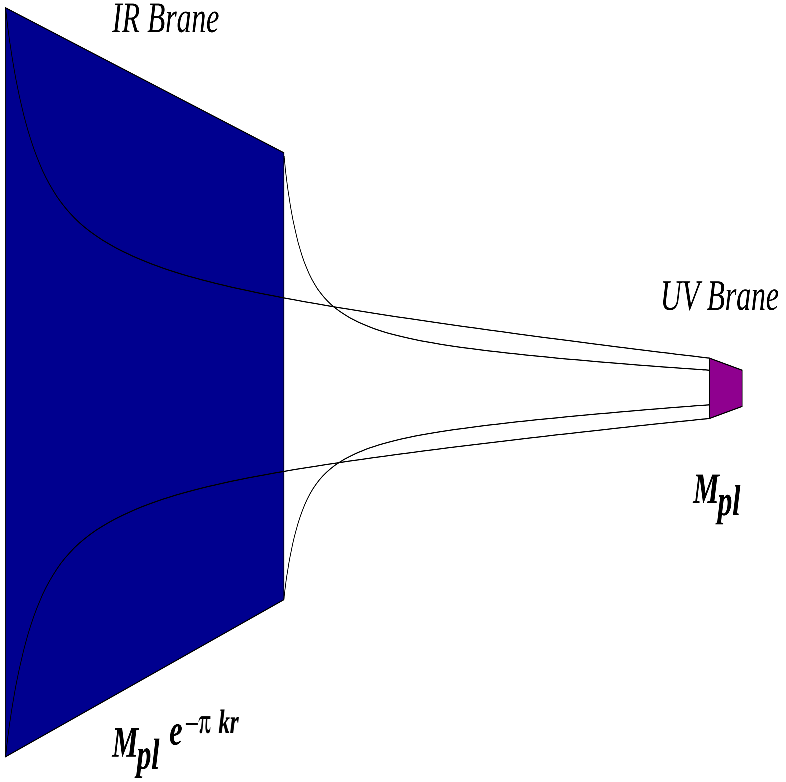
Two branes, one at R, the other at $R' = \frac{M_{Pl}}{TeV} R$.

Masses get scaled by $M \longrightarrow \frac{R}{R'} M$.

Solves the Hierarchy Problem!

$\Rightarrow \log(R'/R) \approx 35$.

(Will often use $\epsilon = \frac{R}{R'} \sim 10^{-16}$.)



Randall, Sundrum hep-ph/9905221

Where do the SM fields go?

On TeV brane $\Rightarrow$ large 4-fermi opperators: $\frac{\lambda}{\Lambda^2_{\mathrm{TeV}}}\psi\bar{\psi}\psi\bar{\psi}$.

Solution to Hierarchy problem $\Rightarrow$ need to leave Higgs on TeV brane.

Also phenomenological problems with Higgs in bulk

Davoudiasl, Hewett, Rizzo hep-ph/0006041

Can move fermions to Planck brane $\Rightarrow$ 4-fermi operators supressed by M_{Pl}.

But EWSB on TeV brane $\Rightarrow$ fermions in bulk $\Rightarrow$ gauges in bulk.

Gauge bosons in the bulk can lead to gauge coupling unification

Agashe, Delgado, Sundrum hep-ph/0212028 Agashe, Servant hep-ph/0411254

Need a way to enforce $SU(2)_{\rm custodial}$

With just the SM gauge group, there are large corrections to $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta}$.

Expand gauge group: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

Break $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ on Planck brane,

$SU(2)_L \times SU(2)_R \to SU(2)_D$ on TeV brane

$\Rightarrow$ only $U(1)_Q$ completely unbroken.

Note $SU(2)_{\rm Custodial} = SU(2)_D$

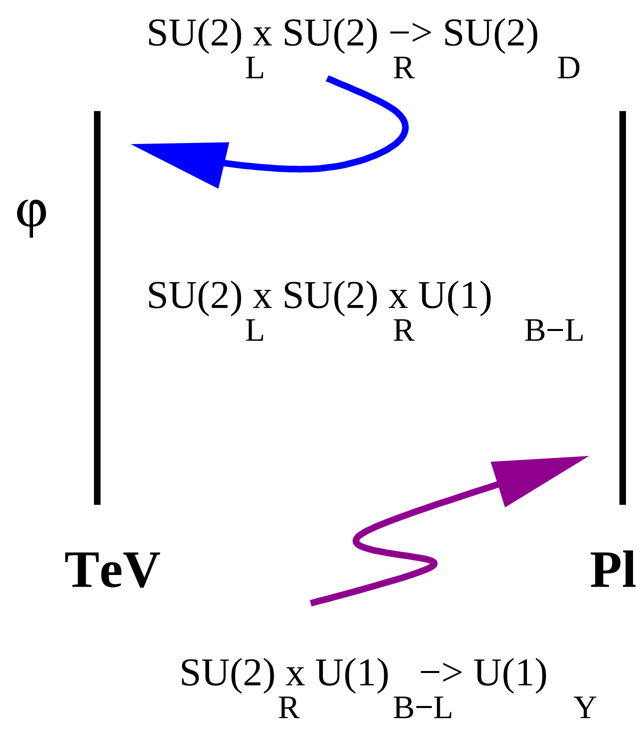
$\longrightarrow$ only broken on Planck brane.

Put right-handed fermions into $SU(2)_R$ multiplets.

$$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}.$$

Define $\kappa = \frac{g_{5R}}{g_{5L}}$, $\lambda = \frac{g_{5B}}{g_{5L}}$.

Agashe, Delgado, May, Sundrum hep-ph/0308036



KK Expansions

We can write gauge fields as $A(x,z) = \sum_n \zeta_A^{(n)}(z) A^{(n)}(x)$ with

$$\zeta_A^{(n)}(z) = z(a_A^{(n)} \mathrm{J}_1(x_A^{(n)} \epsilon z/R) + b_A^{(n)} \mathrm{Y}_1(x_A^{(n)} \epsilon z/R))$$

5D fermions are a-chiral, write as $\Psi = \begin{pmatrix} \chi_\Psi \\ \xi_\Psi \end{pmatrix}$.

Expansion is $\chi(x,z) = \sum_n z^{(3/2)} \psi_\chi^{(n)}(z) \chi_\Psi^{(n)}(x)$, etc.

$$\psi_\chi^{(n)}(z) = z(a_\chi^{(n)} \mathrm{J}_{c_\Psi+1/2}(x_\Psi^{(n)} \epsilon z/R) + b_A^{(n)} \mathrm{J}_{-c_\chi-1/2}(x_\Psi^{(n)} \epsilon z/R))$$

$$\psi_\xi^{(n)}(z) = z(a_\xi^{(n)} \mathrm{J}_{c_\Psi+1/2}(x_\Psi^{(n)} \epsilon z/R) + b_A^{(n)} \mathrm{J}_{-c_\xi-1/2}(x_\Psi^{(n)} \epsilon z/R))$$

Gauge Boundary Conditions:

At $z = R$

$$\begin{aligned} \partial_z \zeta_{A_L} &= 0 \\ \zeta_{A_R^\pm} &= 0 \\ \partial_z((\kappa/\lambda)\zeta_B + \zeta_{A_R^3}) &= 0 \\ \zeta_B - (\kappa/\lambda)\zeta_{A_R^3} &= 0 \end{aligned}$$

And at $z = R'$

$$\begin{aligned} \partial_z(\kappa\zeta_{A_L} + \zeta_{A_R}) &= 0 \\ \partial_z(\zeta_{A_L} - \kappa\zeta_{A_R}) &= -\frac{g_{5L}^2 v^2 \epsilon}{4}(\zeta_{A_L} - \kappa\zeta_{A_R}) \\ \partial_z \zeta_B &= 0 \end{aligned}$$

Fermion Boundary Conditions. Boundary conditions will mix two fields, Ψ_L, Ψ_R.

At $z = R$

$$\xi_L = 0$$
$$\chi_R = m^{(n)} R \alpha \xi_R$$

And at $z = R'$

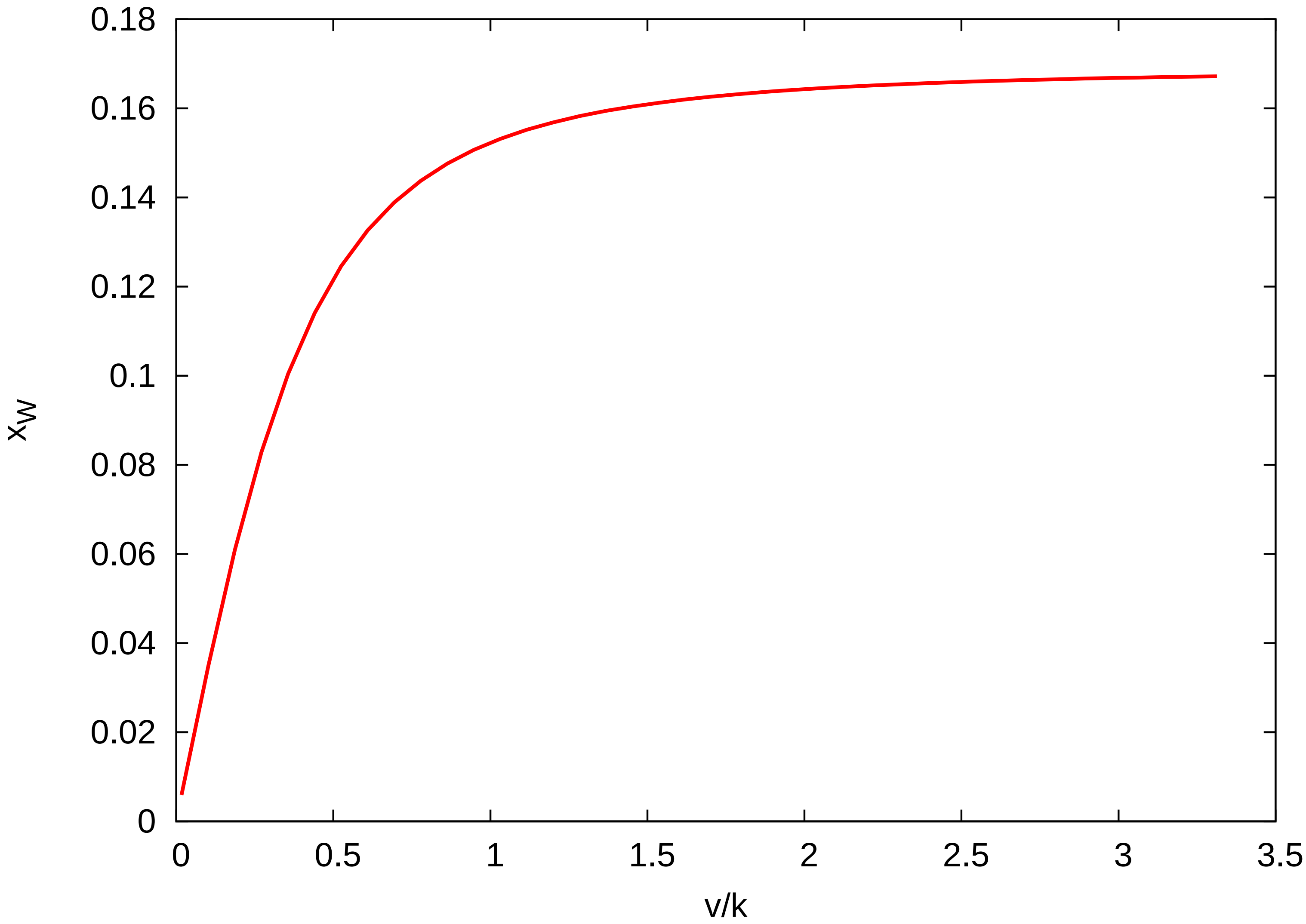
$$\xi_L = -M_D R' \xi_R$$
$$\chi_R = M_D R' \chi_L$$

$M_D = \lambda_f v$. Note $\lambda_t = \lambda_b$ by $SU(2)_D$.

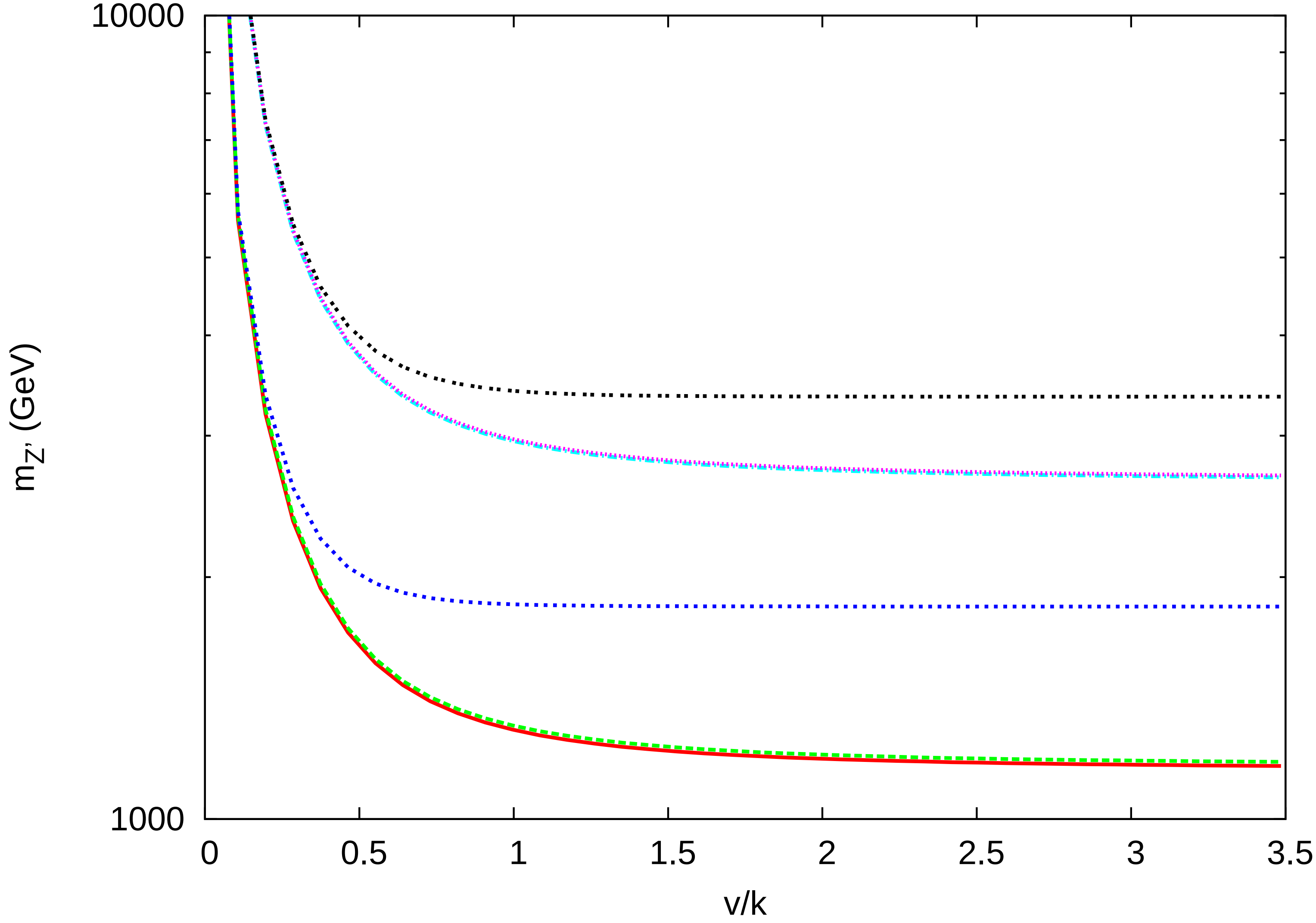
α is related to mixing with planck brane localized fermions. Needed for top-bottom splitting.

Csaki, Grojean, Hubisz, Shirman, Terning `hep-ph/0310355`

$$m_W/k\epsilon$$



$Z' Masses$



Electroweak Constraints

- Require *rough* agreement with tree-level SM relations. In our scheme:

$$1 - \sin^2\theta_{\rm os} \equiv \frac{m_W^2}{m_Z^2}. \qquad \lambda(= g_{5B}/g_{5L}) \text{ fixed by } M_Z$$

We can also define:

$$\sin^2\theta_{eg} \equiv \frac{e^2}{g^2_{\mu\bar{\nu}W_1}} \qquad \text{Could be any light fermion}$$

From the coupling of the neutral KKs to fermions, as measured on the Z-pole:

$$\sqrt{\rho^Z_{\rm eff,f}}\,\frac{g_{f\bar{f}W_1}}{c_W^{\rm os}}\left(T_{3\rm L} + \sin^2\theta_{R,f}T_R^3 - \sin^2\theta_{\rm eff,f}Q\right)$$

- In the SM at *tree-level*, all these must be equal.

- Note

$$\rho^Z_{\rm eff,f} = g^2_{Z_1 f\bar{f}}/g^2_{W_1 f\bar{f}}.$$

We can match this onto the 5D covariant derivative:

$$\int_R^{R'} \frac{dz}{z}\, g_{5L} \left(T^{aL} A^{aL} + \kappa T^{aR} A^{aR} + \lambda \frac{B-L}{2} B \right)$$

For neutral bosons $\longrightarrow$

$$\underbrace{g_{5L}(I^{3L} - \lambda I^B)}_{g_{f\bar{f}Z^{(n)}}} \left(T^{3L} + \kappa \underbrace{\frac{(\kappa I^{3R} - \lambda I^B)}{(I^{3L} - \lambda I^B)}}_{\sin^2\theta_{R,f}} T^{3R} + \underbrace{\frac{\lambda I^B}{(I^{3L} - \lambda I^B)}}_{-\sin^2\theta_{\mathrm{eff,f}}} Q \right) Z$$

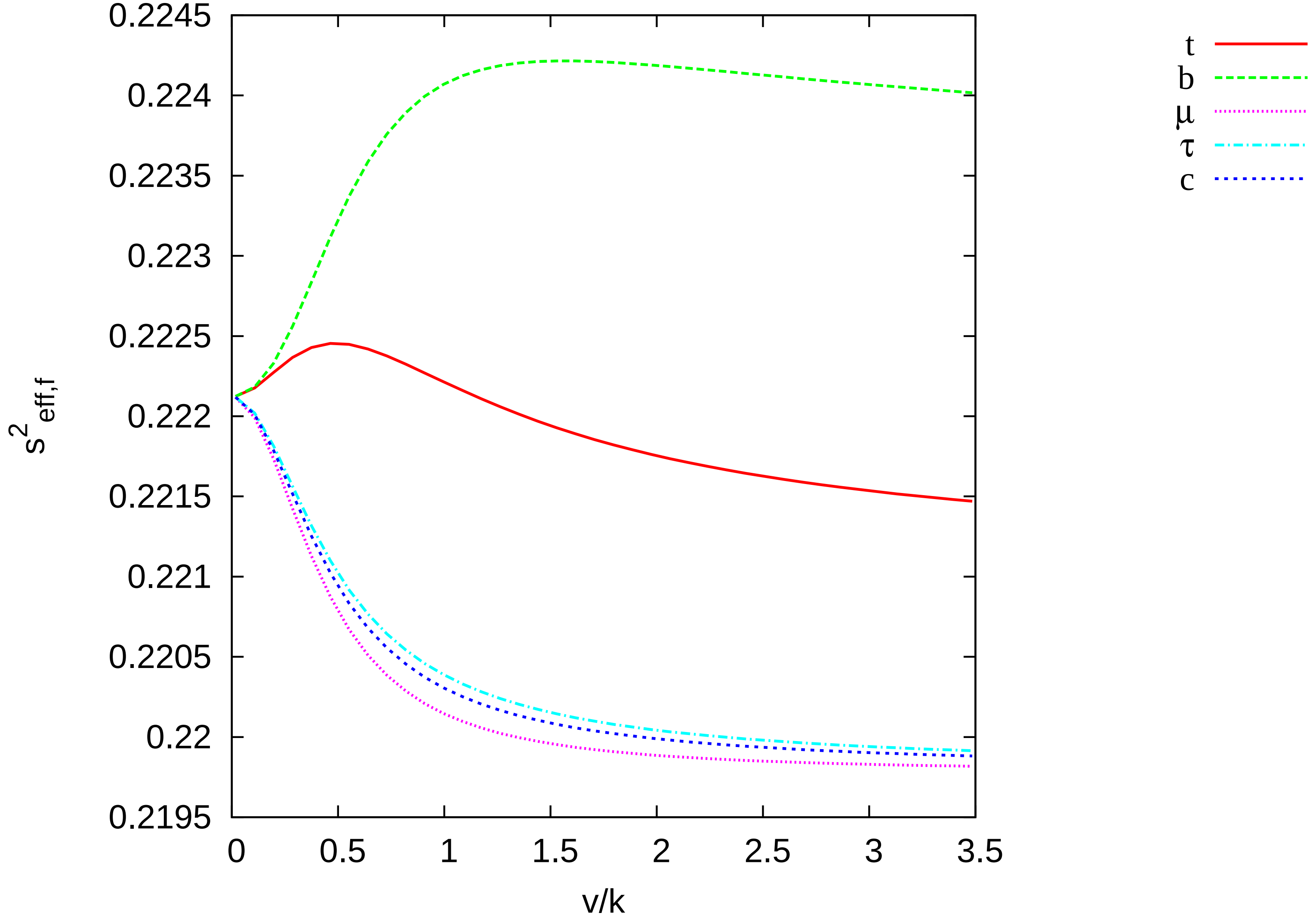
Where $I^i = \int_R^{R'} dz/z\, \zeta_i \psi_f \psi_{\bar{f}}$.

$\sin^2\theta_{R,f} = 0$ for planck brane fermions.

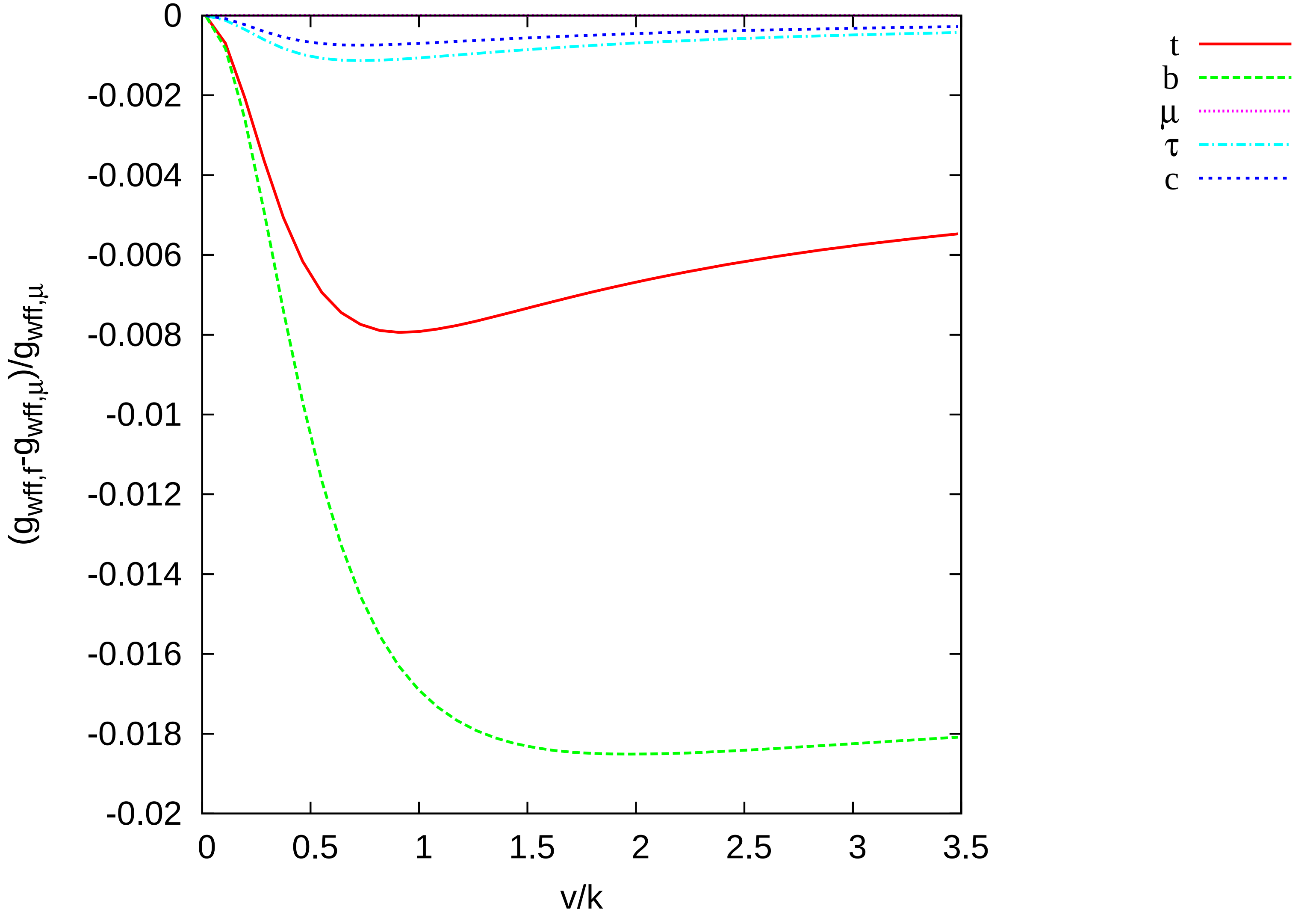
Similarly for charged bosons.

Cacciapaglia, Csaki, Grojean, Terning `hep-ph/0409126`

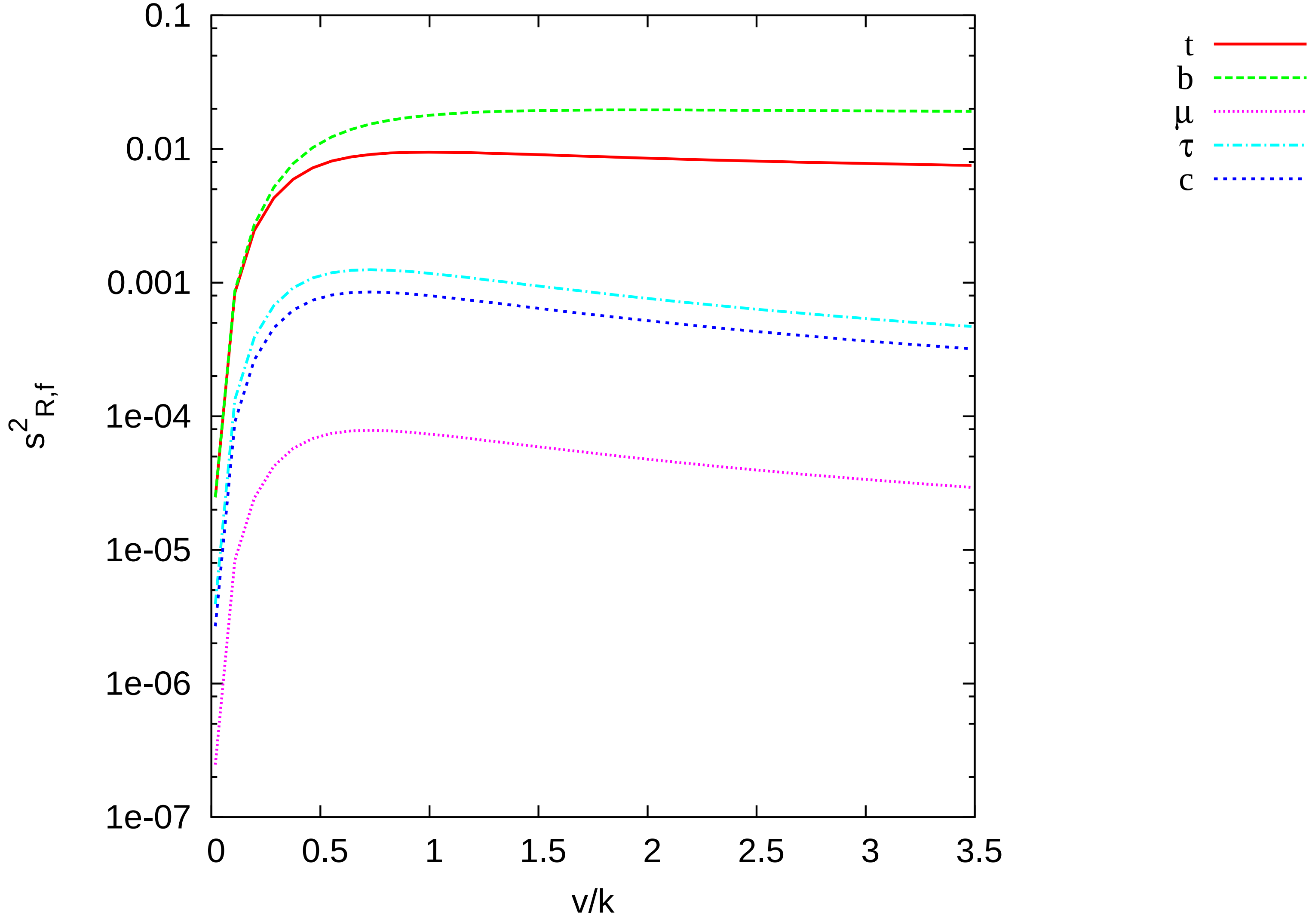
$$\kappa = g_{5R}/g_{5L} = 1$$



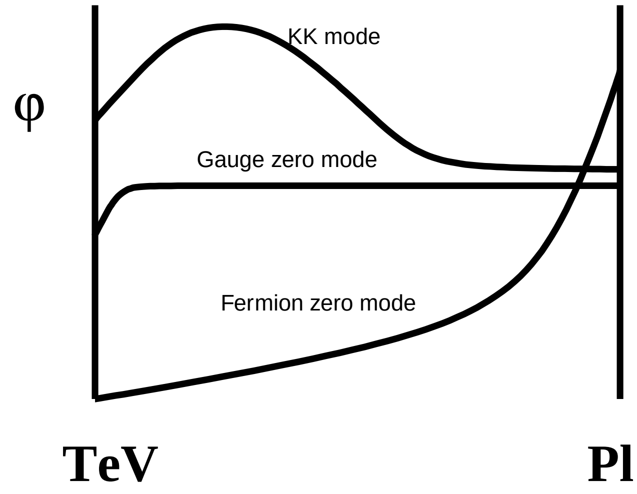
Left handed currents



Right handed currents



Why we expect strange Higgs physics



- Wavefunctions distorted

  $\Rightarrow$ masses for gauge bosons

  $\Rightarrow g_{hWW}$ is supressed.

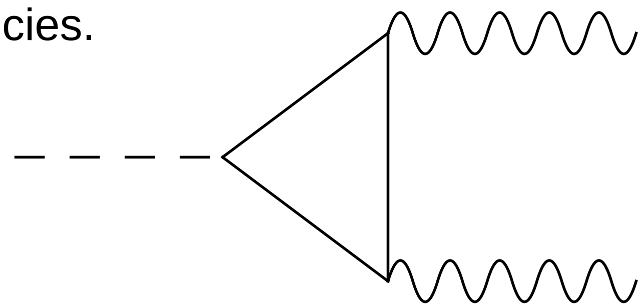
- No supression of $\lambda_{hf_1\bar{f}_1}$.

- *Enhancement* of KK fermion couplings

$$\lambda_{hf_n\bar{f}_n} \sim \sqrt{\log(R'/R)}\lambda_{hf_1\bar{f}_1}.$$

- $\mathcal{O}(1)$ Yukawas

  $\Rightarrow$ Large couplings for KK-states of *all* fermion species.



So we expect supression of $h \to WW, ZZ$

enhancement of $h \to gg, \gamma\gamma$.

Fermion spectrum and couplings

Impose explicit Z_2 left-right symmetry, so $c_L = -c_R$.

Large Dirac mass $\Rightarrow$ **light** first KK state

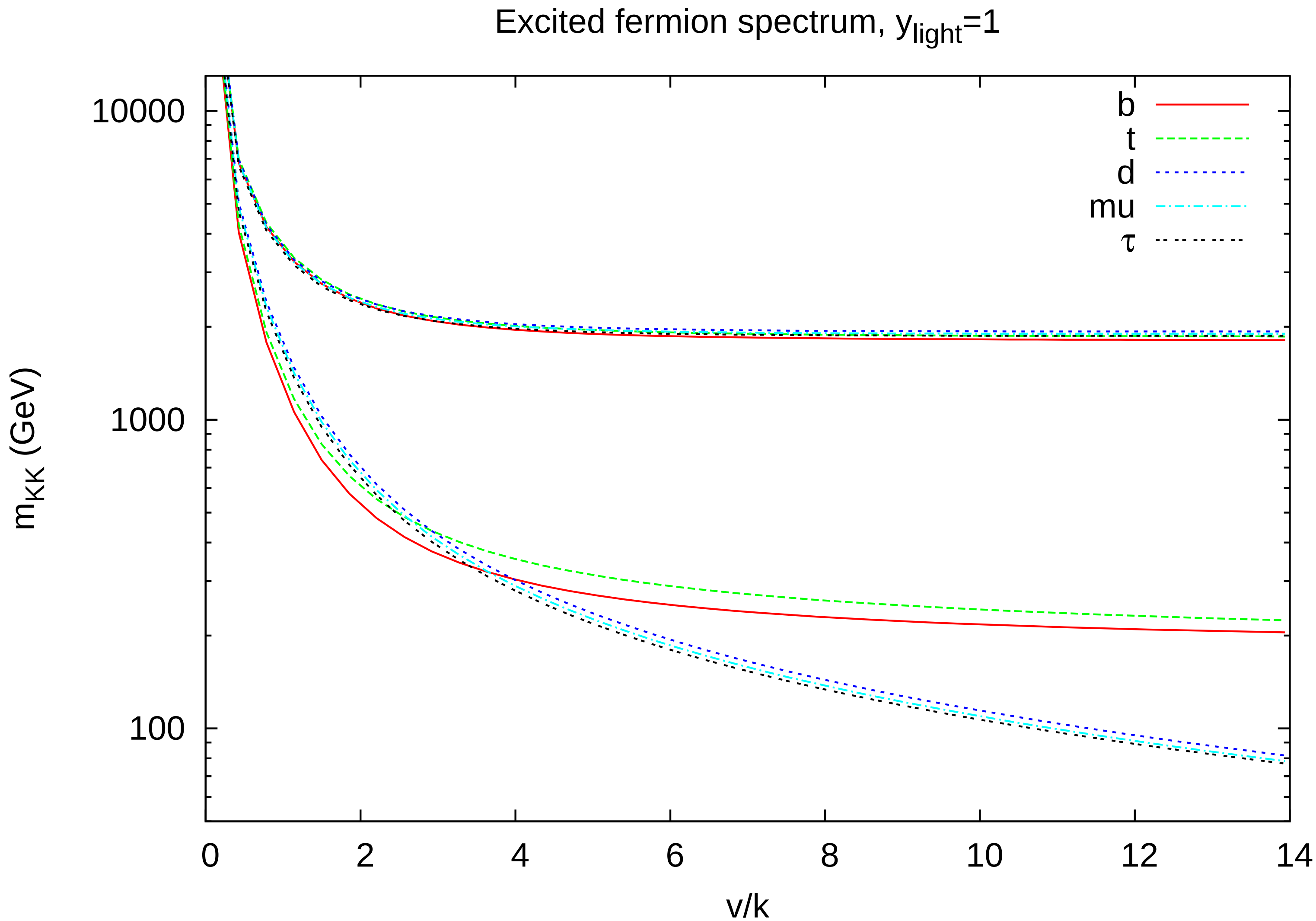
Agashe, Servant `hep-ph/0403143`

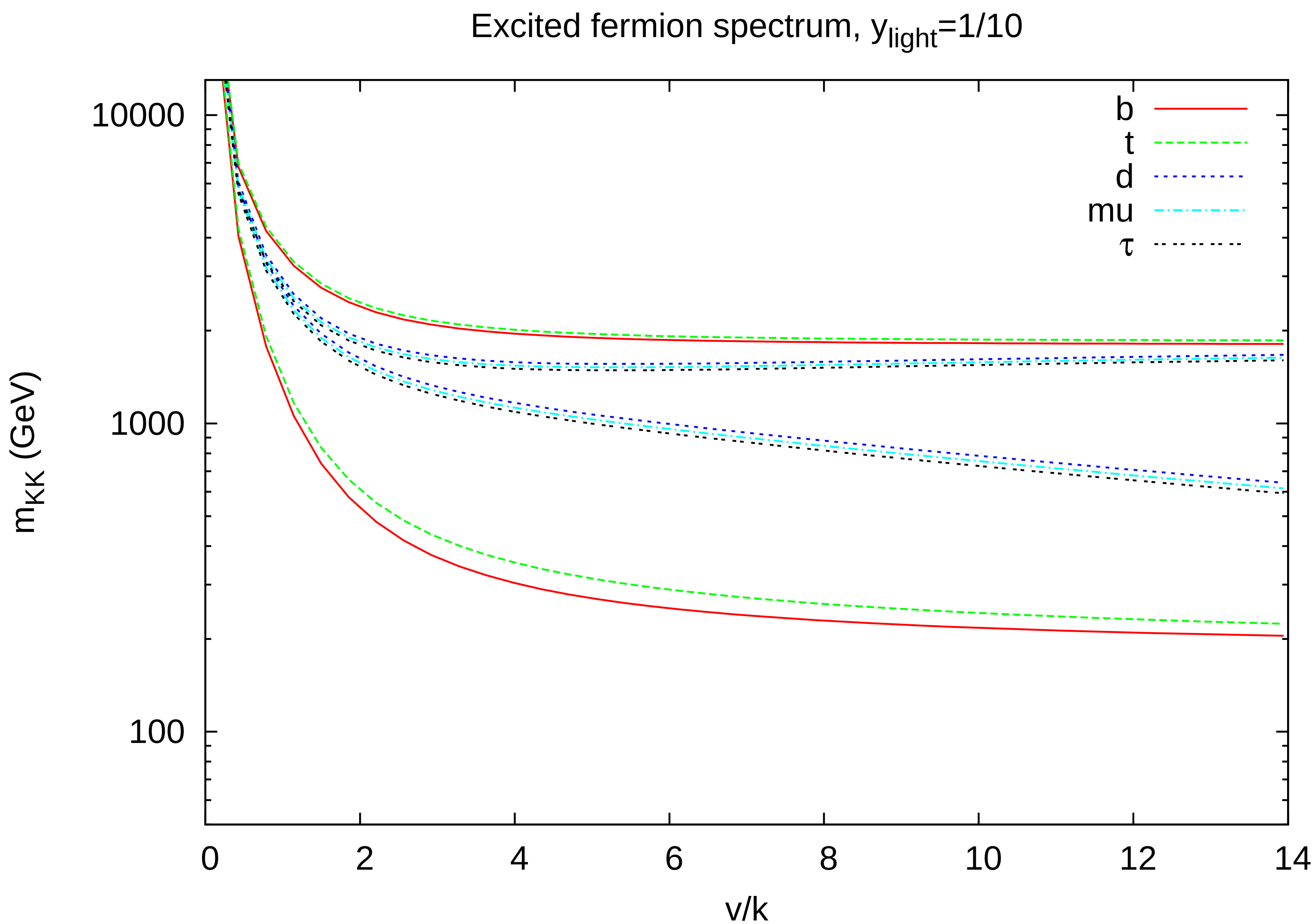
KK state coupling to TeV localized field

$\Rightarrow \sqrt{\log(R'/R)}$ enhancement.

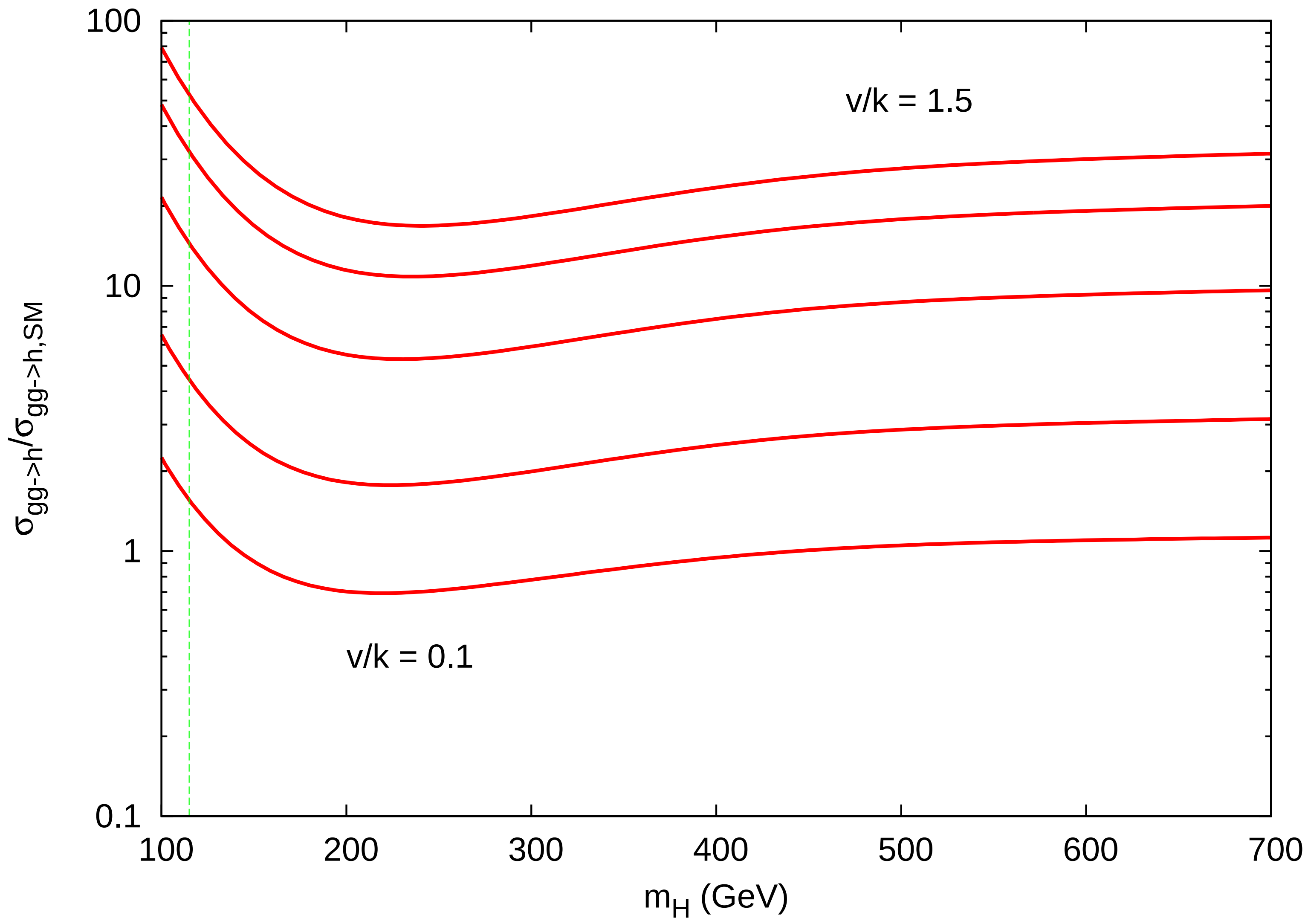
use fundamental Yukawa couplings $\lambda_{t,b} = 1.5$.

$$\lambda_{\text{others}} = \lambda_{light}.$$

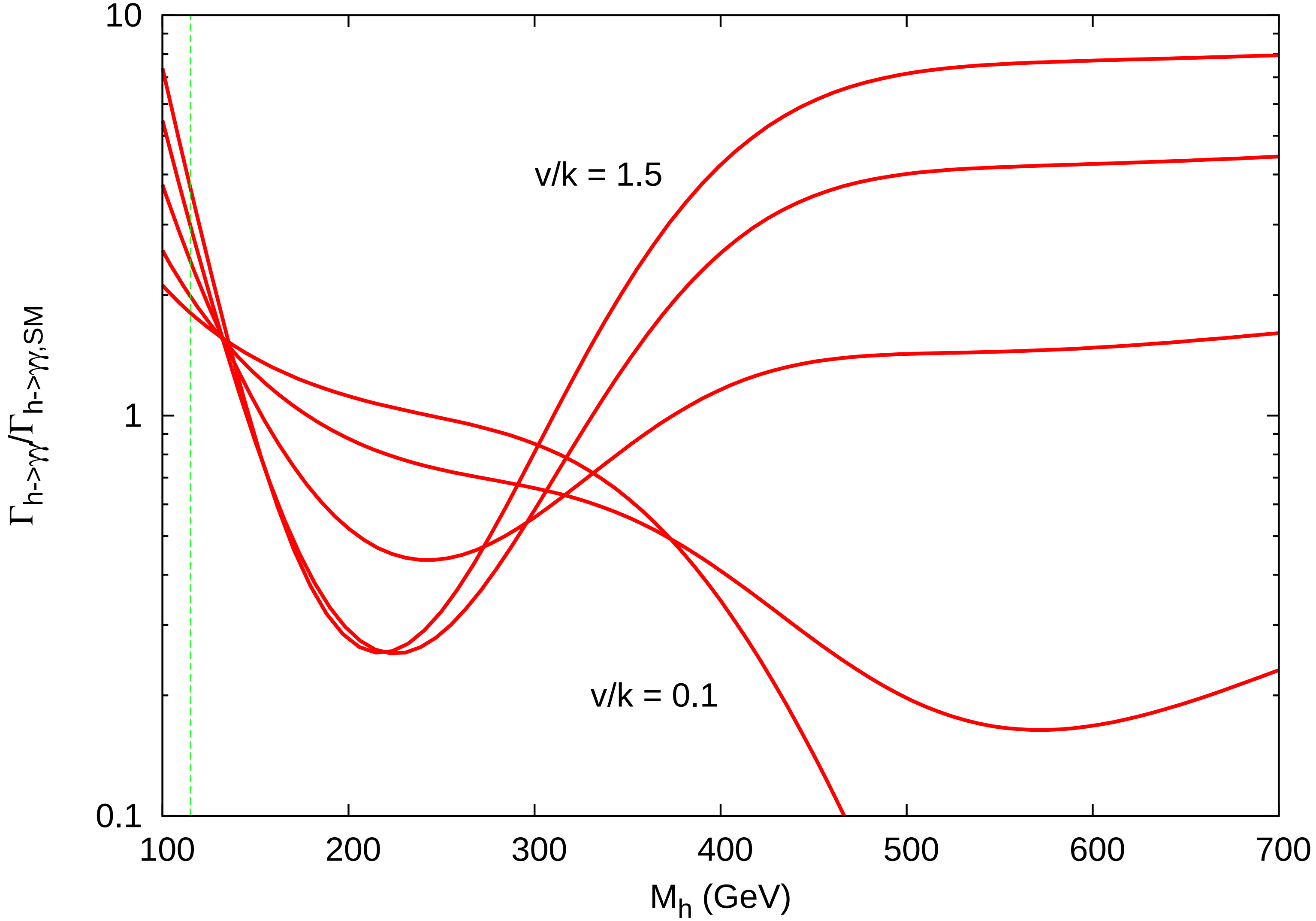

Excited fermion spectrum, y_light=1
m_KK (GeV)
10000
1000
100
0
2
4
6
8
10
12
14
v/k
b
t
d
mu
τ

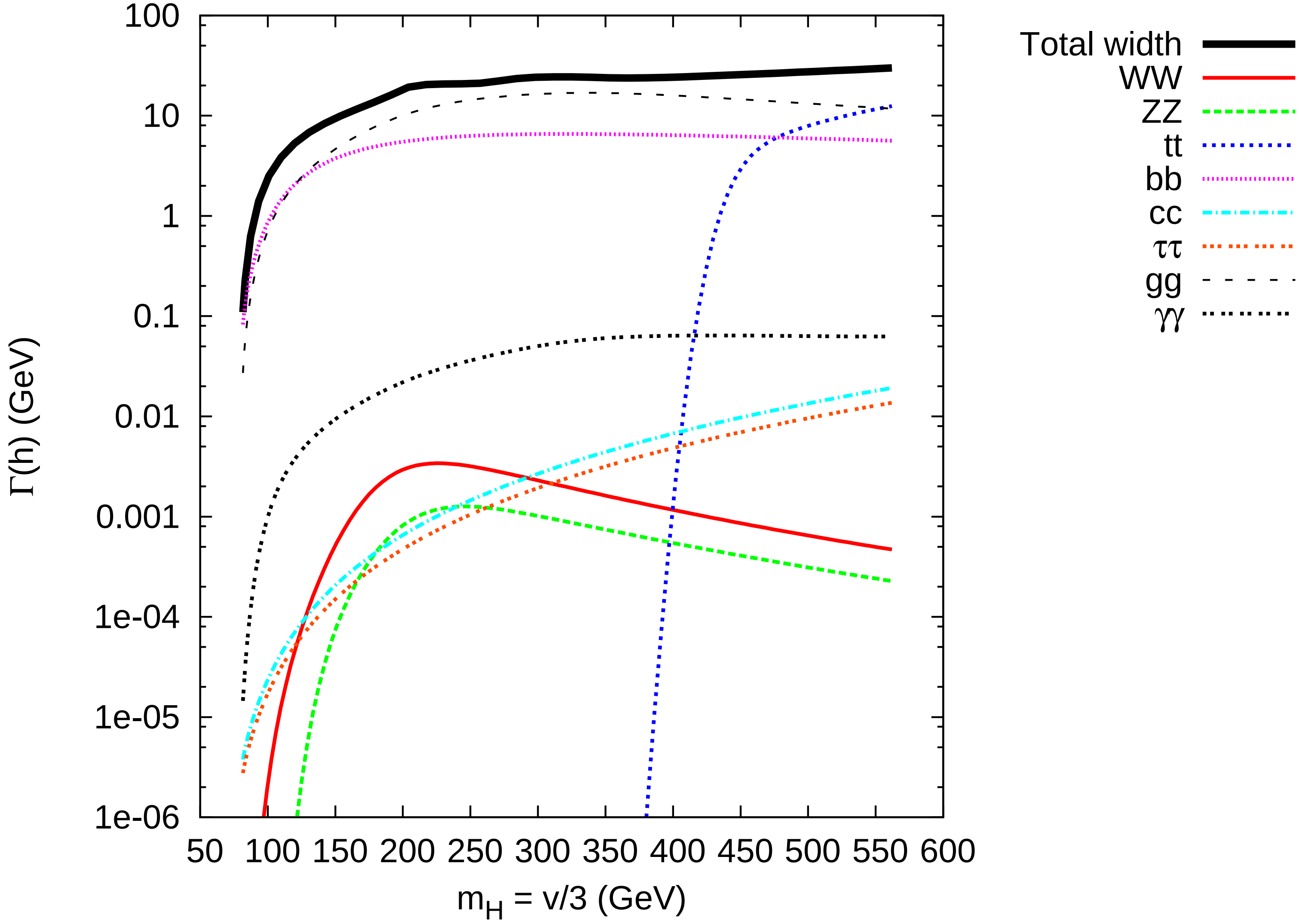

Excited fermion spectrum, y_light=1/10
10000
1000
100
m_KK (GeV)
0
2
4
6
8
10
12
14
v/k
b
t
d
mu
τ

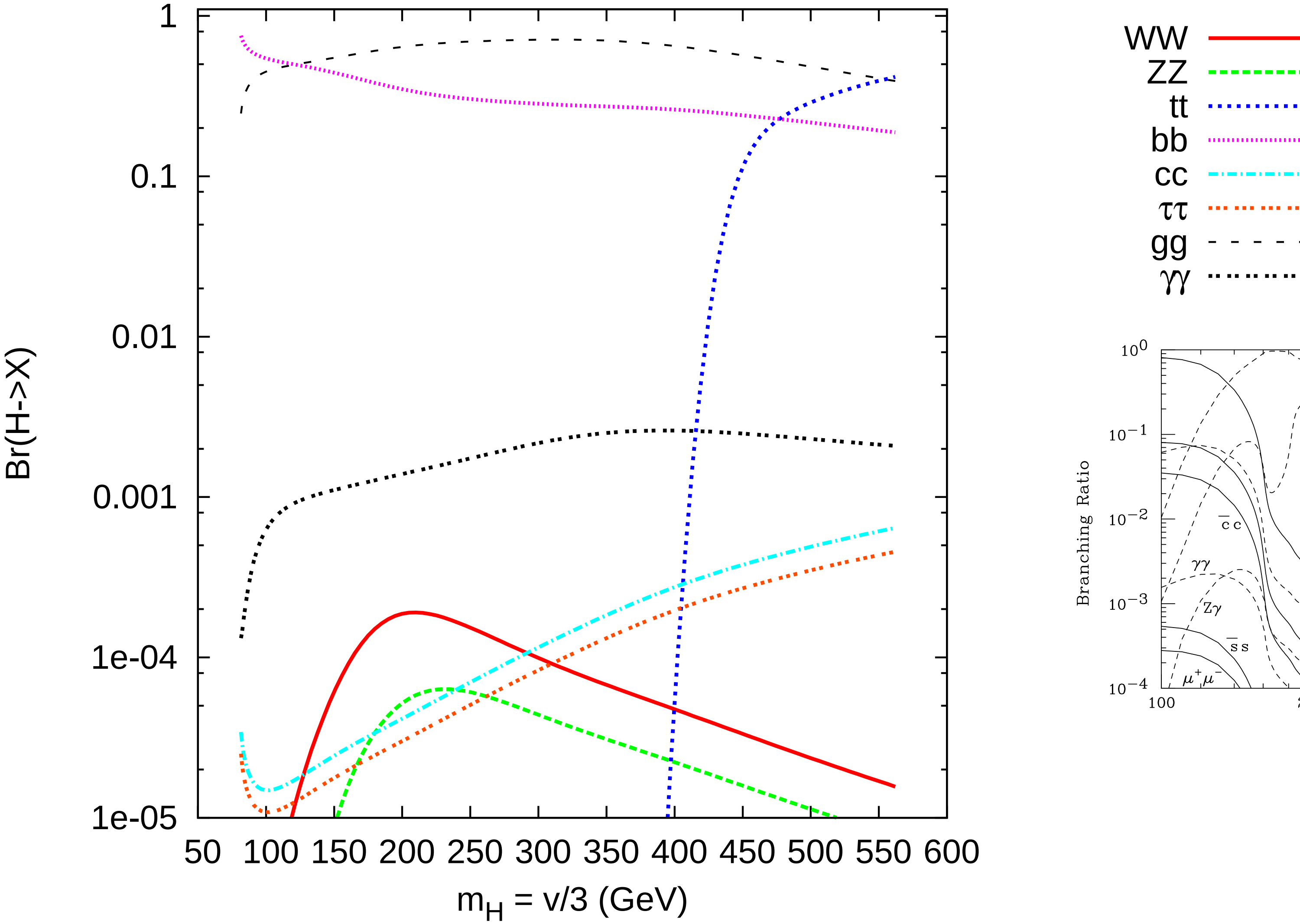
Enhancement of $gg \rightarrow h$, $y_{\mathrm{light}} = 1/10$

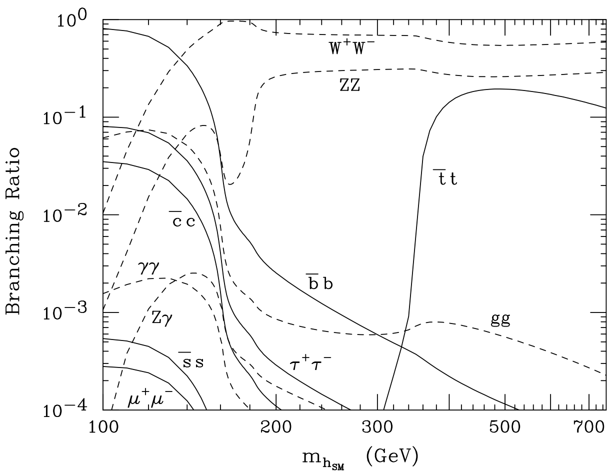


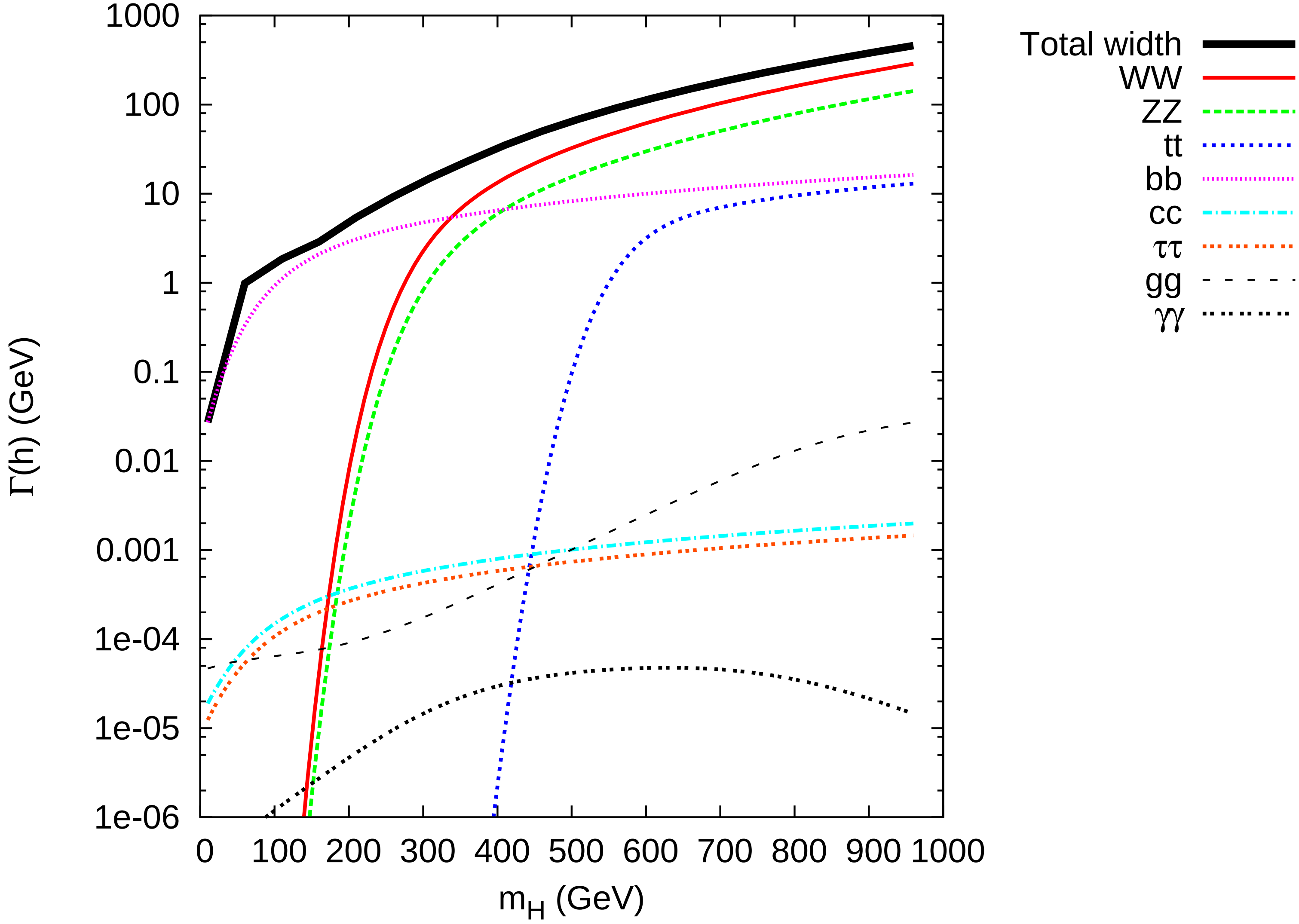
Enhancement of $g \to \gamma\gamma$, $y_{\rm light} = 1/10$



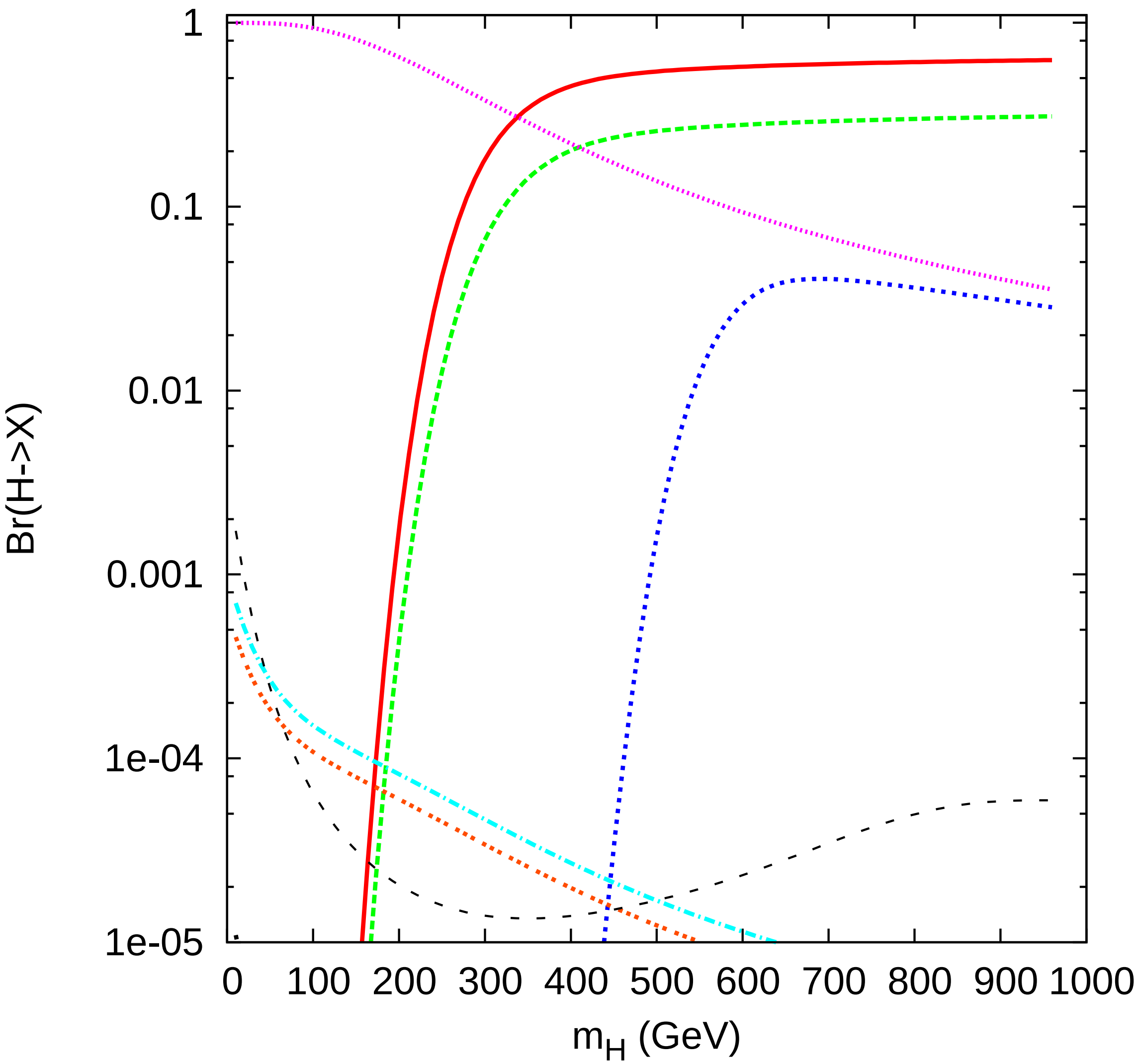

100
10
1
0.1
0.01
0.001
1e-04
1e-05
1e-06
50 100 150 200 250 300 350 400 450 500 550 600
Γ(h) (GeV)
m_H = v/3 (GeV)
Total width
WW
ZZ
tt
bb
cc
ττ
gg
γγ


Br(H->X)
1
0.1
0.01
0.001
1e-04
1e-05
50 100 150 200 250 300 350 400 450 500 550 600
m_H = v/3 (GeV)
WW
ZZ
tt
bb
cc
ττ
gg
γγ

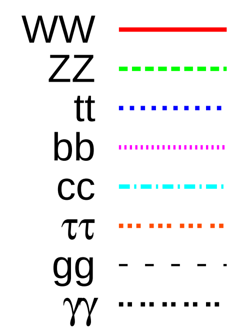

Branching Ratio
10^0
10^-1
10^-2
10^-3
10^-4
W+W-
ZZ
t̄t
c̄c
b̄b
γγ
Zγ
s̄s
τ+τ-
μ+μ-
gg
100 200 300 500 700
m_hSM (GeV)



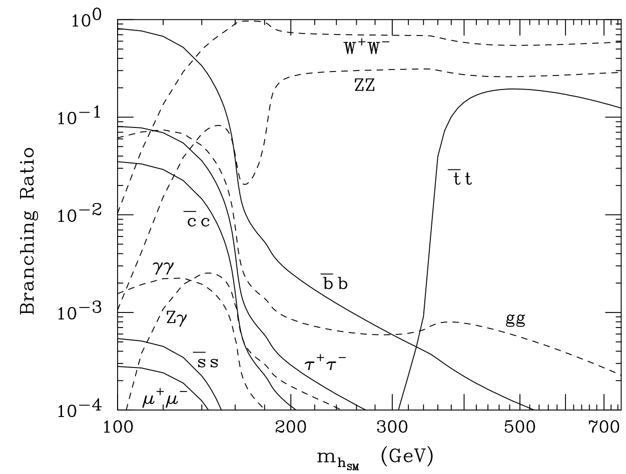
1000
100
10
1
0.1
0.01
0.001
1e-04
1e-05
1e-06
Γ(h) (GeV)
0 100 200 300 400 500 600 700 800 900 1000
m_H (GeV)
Total width
WW
ZZ
tt
bb
cc
ττ
gg
γγ



Br(H->X)
1
0.1
0.01
0.001
1e-04
1e-05
0 100 200 300 400 500 600 700 800 900 1000
m_H (GeV)



WW
ZZ
tt
bb
cc
ττ
gg
γγ



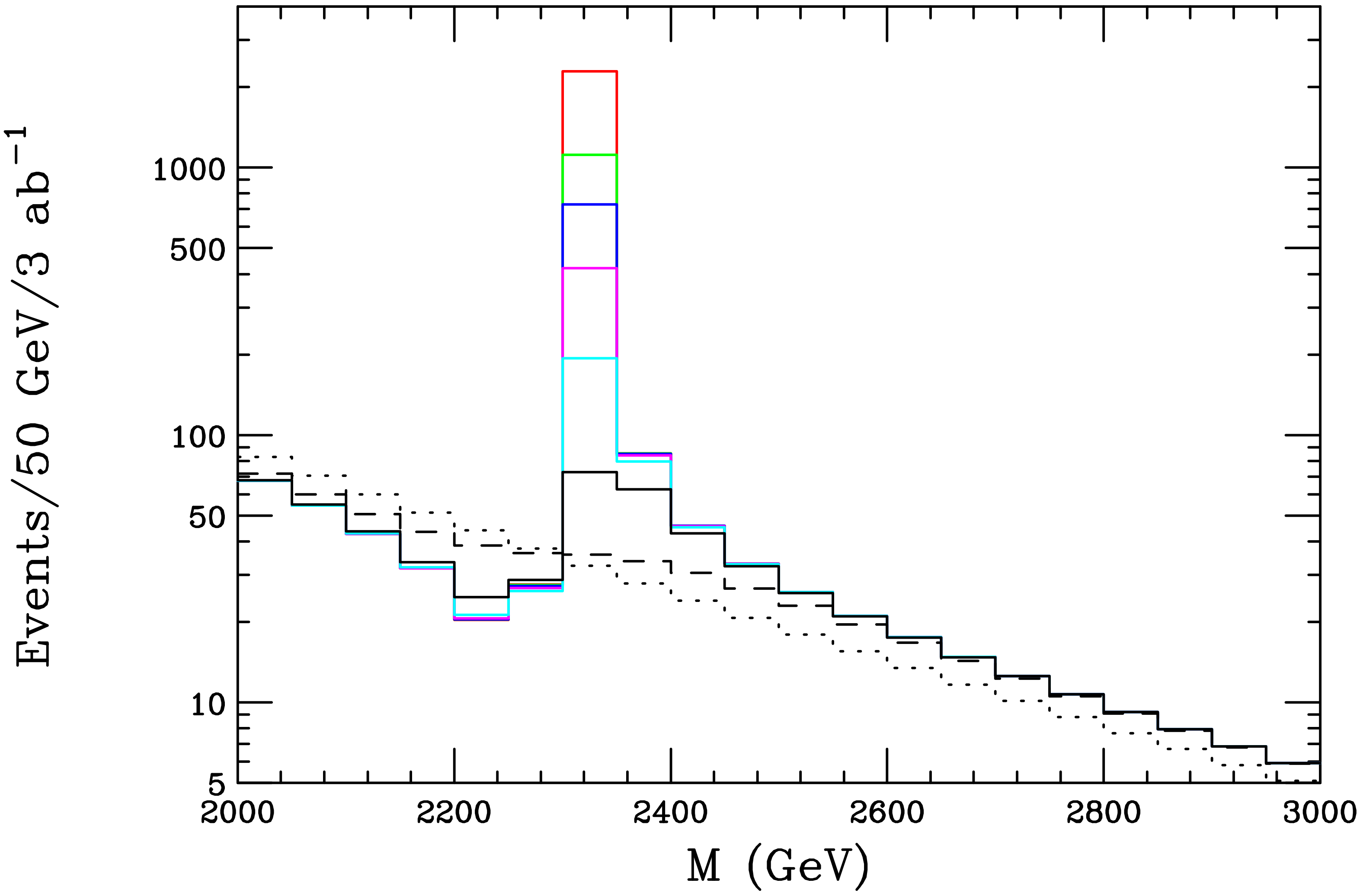
Branching Ratio
10^0
10^−1
10^−2
10^−3
10^−4
W+W−
ZZ
t̄t
c̄c
γγ
b̄b
Zγ
gg
s̄s
τ+τ−
μ+μ−
100 200 300 500 700
m_hSM (GeV)

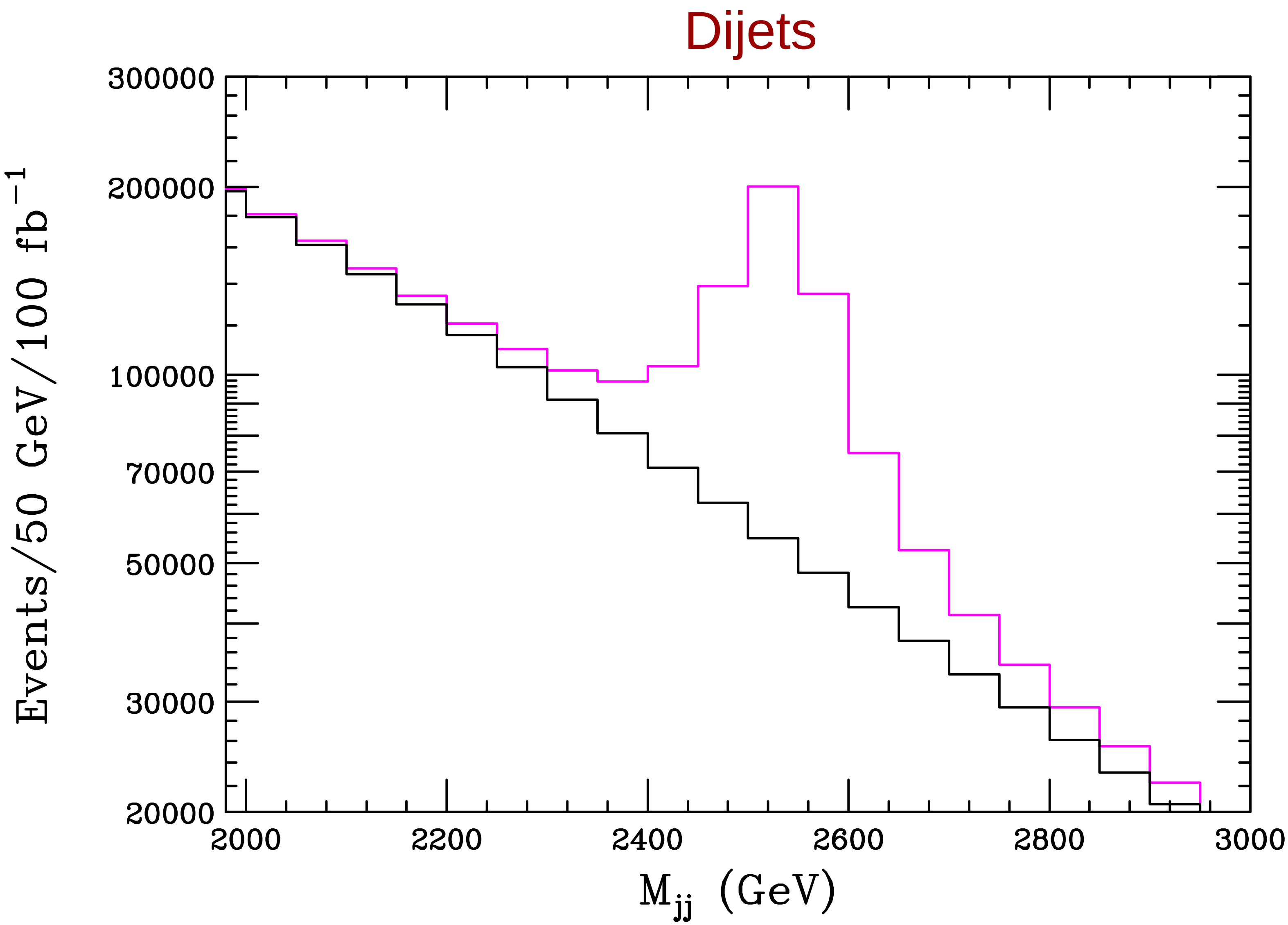
Generic Collider Signatures

What does this model look like at colliders?

- First one or two electroweak gauge boson KK modes visible at the LHC
- First two or three gluon KK modes highly visible at LHC
- Light new fermions, should be visible
- Graviton KK resonances at best difficult to see
- Strong $W_L W_L$ scattering?

Drell-Yan production




Dijets
300000
200000
100000
70000
50000
30000
20000
2000
2200
2400
2600
2800
3000
Events/50 GeV/100 fb^{-1}
M_{jj} (GeV)

Conclusions

- Regions of parameter space are consistent with all precision electroweak and collider constraints
- Signals are easily visible at the LHC and possibly ILC
- Higgs production has large enhancement at LHC, $\gamma\gamma$ colliders, reduction at ILC
- Higgs decays are substantially modified