Extra Dimensions at the LHC

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(Chuo Univ.)

7/23/2010 Workshop@YITP

このトークの目的
(世話人からのリクエスト)

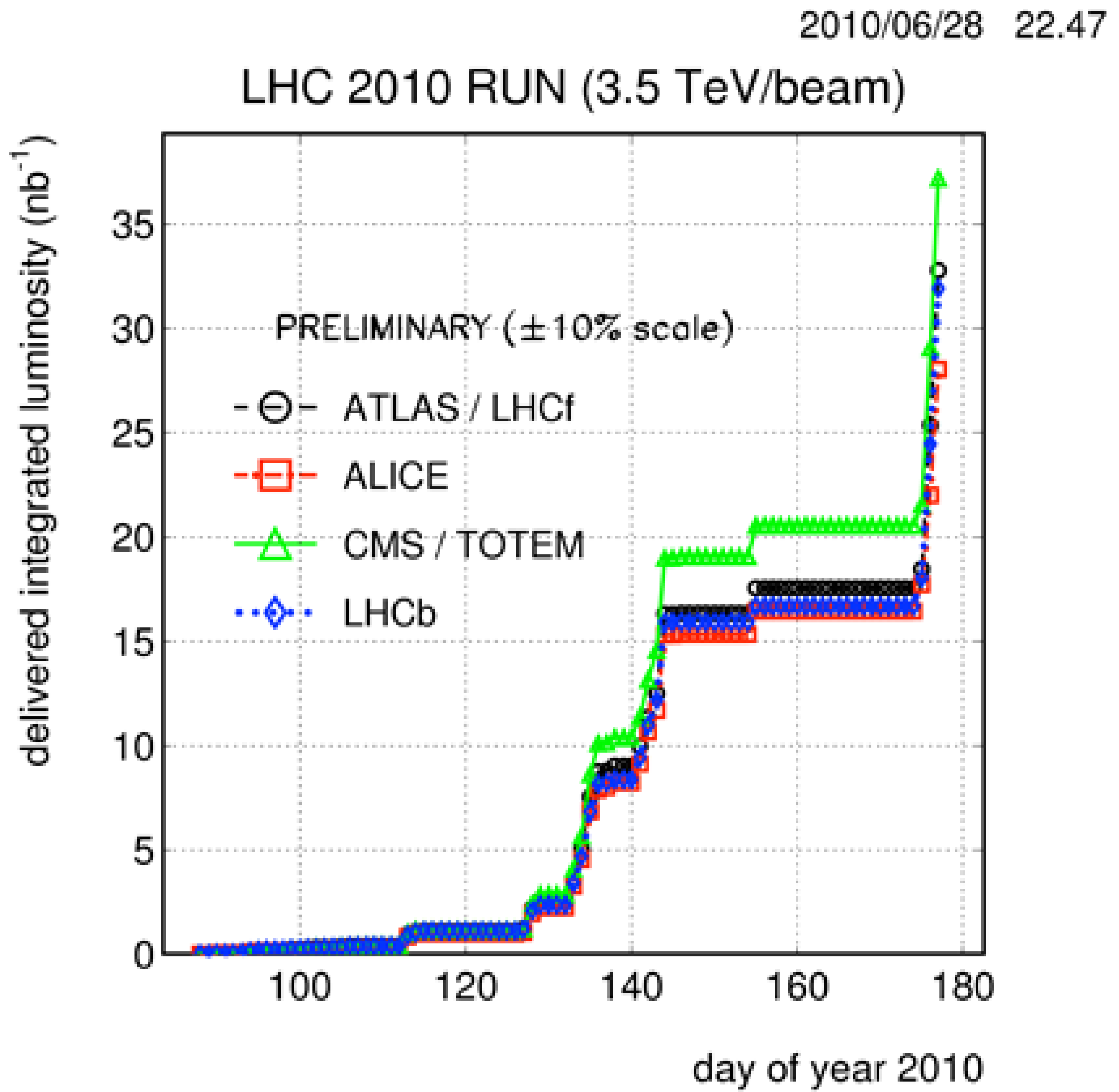
“LHCで新しい物理が発見される前夜の今の時代に

どういう高次元模型があり、
どのような将来性があり、
どのような特徴があるのか、
高次元理論からの実験的予言とは
どのようなものがあるのか、

など高次元理論のオーバーヴュー”

Introduction

Now LHC is working!!


2010/06/28 22.47
LHC 2010 RUN (3.5 TeV/beam)
delivered integrated luminosity (nb⁻¹)
PRELIMINARY (±10% scale)
ATLAS / LHCf
ALICE
CMS / TOTEM
LHCb
0
5
10
15
20
25
30
35
100
120
140
160
180
day of year 2010

The purpose of LHC is to search for NEW PHYSICS
as well as Higgs hunting

One of the guiding principles to go beyond the SM
$\Rightarrow$ hierarchy problem

$$M_W << M_P$$

- Dynamics: Technicolor
- Symmetry: Supersymmetry

The purpose of LHC is to search for NEW PHYSICS
as well as Higgs hunting

One of the guiding principles to go beyond the SM
⇒ hierarchy problem

$$M_W \ll M_P$$

- Dynamics: Technicolor
- Symmetry: Supersymmetry
- Geometry: Extra Dimensions

General strategy of collider physics

Step 1: Looking for a new particle "X"
with coupling to the SM fields

Step 2: Identify the most promising production processes
for X (QCD processes are better)

Step 3: Calculate $\sigma(pp \to X)$

Step 4: (1) X is stable

(a) EM charged $\to$ X behave like μ

(b) Color charged $\to$ X hadronized (many BKGs)

(c) Weakly charged $\to$ X like ν as missing energy

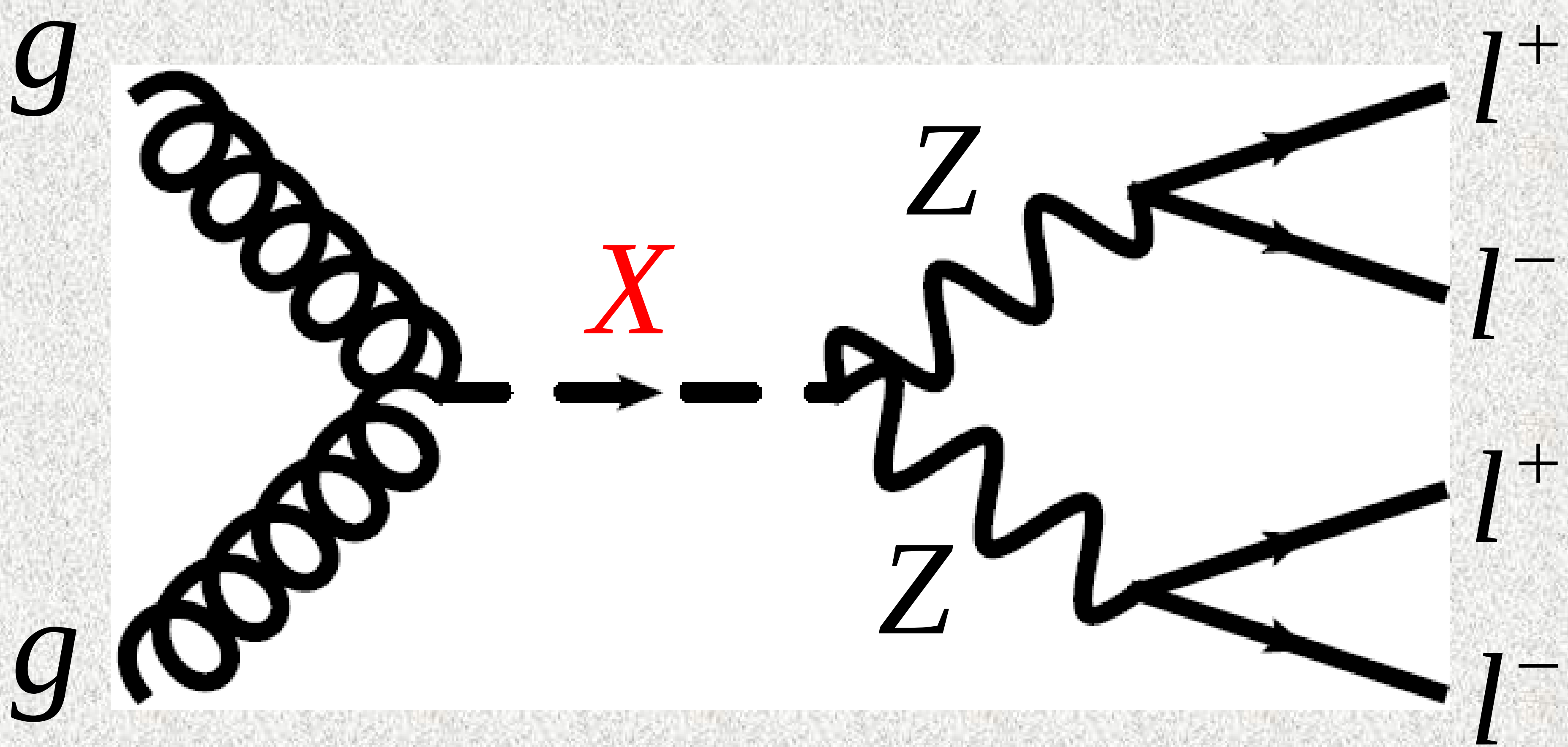
(2) X is unstable $\Rightarrow$ decay to the SM fields
(coloress processes are better)

Compute the branching ratio

Step 5: Compute σ(SM background processes)

Best way

Production from color particles
+ Decay to colorless states



In this talk,
we discuss collider signatures of
various models based on extra dimensions

We introduce basic ideas of each model,
and does not discuss the model in detail

Off course, we cannot cover all signatures,
so focus on the model independent ones

Plan

1: Introduction

2: KK Graviton
- Large Extra Dimensions
- Warped Extra Dimension
- Black Holes

3: Universal Extra Dimensions

4: Gauge-Higgs Unification

5: Higgsless Models

6: Higgs

7: Radion

8: Summary

KK Graviton

"Quantum Gravity and Extra Dimensions at High-Energy Colliders"
G.F. Giudice, R. Rattazzi & J.D. Wells, NPB544 (1999) 3

"Indirect Collider Signals for Extra Dimensions"
J.L. Hewett, PRL82 (1999) 4765

"Searching for the Kaluza-Klein Graviton in Bulk RS Models"
A.L. Fitzpatrick, J. Kaplan, L. Randall & L.T. Wang
JHEP 0709 (2007) 013

"Warped Gravitons at the CERN LHC and Beyond"
K. Agashe, H. Davoudiasl, G. Perez & A. Soni, PRD76 (2007) 036006

Large Extra Dimensions

"The Hierarchy Problem and
New Dimensions at a Milimeter"

N. Arkani-Hamed, S. Dimopoulos and G. Dvali
PLB429 (1998) 263

Lowering the higher dim. Mp to TeV by large extra dimensions to solve the hierarchy problem

(4+n)-dim gravity compactified on n-dim compact space

(SM fields are confined on 3-brane)

$$S = -\frac{1}{2} M_*^{2+n} \int d^{4+n}x \sqrt{-g^{(4+n)}}\, \mathrm{R}^{(4+n)} = -\frac{1}{2} \underbrace{M_*^{2+n} V_n}_{M_P^2} \int d^4x \sqrt{-g^{(4)}}\, \mathrm{R}^{(4)}$$

$$\Rightarrow R = \frac{1}{2\pi} \left(\frac{M_P^2}{M_*^{2+n}} \right)^{1/n} \text{(n-dim torus)}$$

If

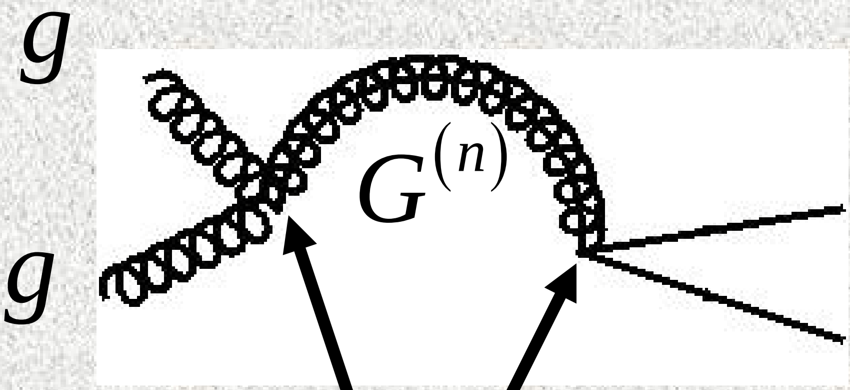
$$M_* = 1\,TeV$$

# of XD	R
n = 1	10^12 m
n = 2	1 mm
n = 3	10 nm
:	:
n = 6	10^-11 m

Excluded (n = 1, 2)
(No deviations up to 200 μm)

Signatures for KK gravitons

1: Virtual graviton exchange



$$l^+ l^- = \frac{1}{M_P^2}\sum_n \frac{T_{\mu\nu}P^{\mu\nu\rho\sigma}T_{\rho\sigma}}{s-(n/R)^2}$$

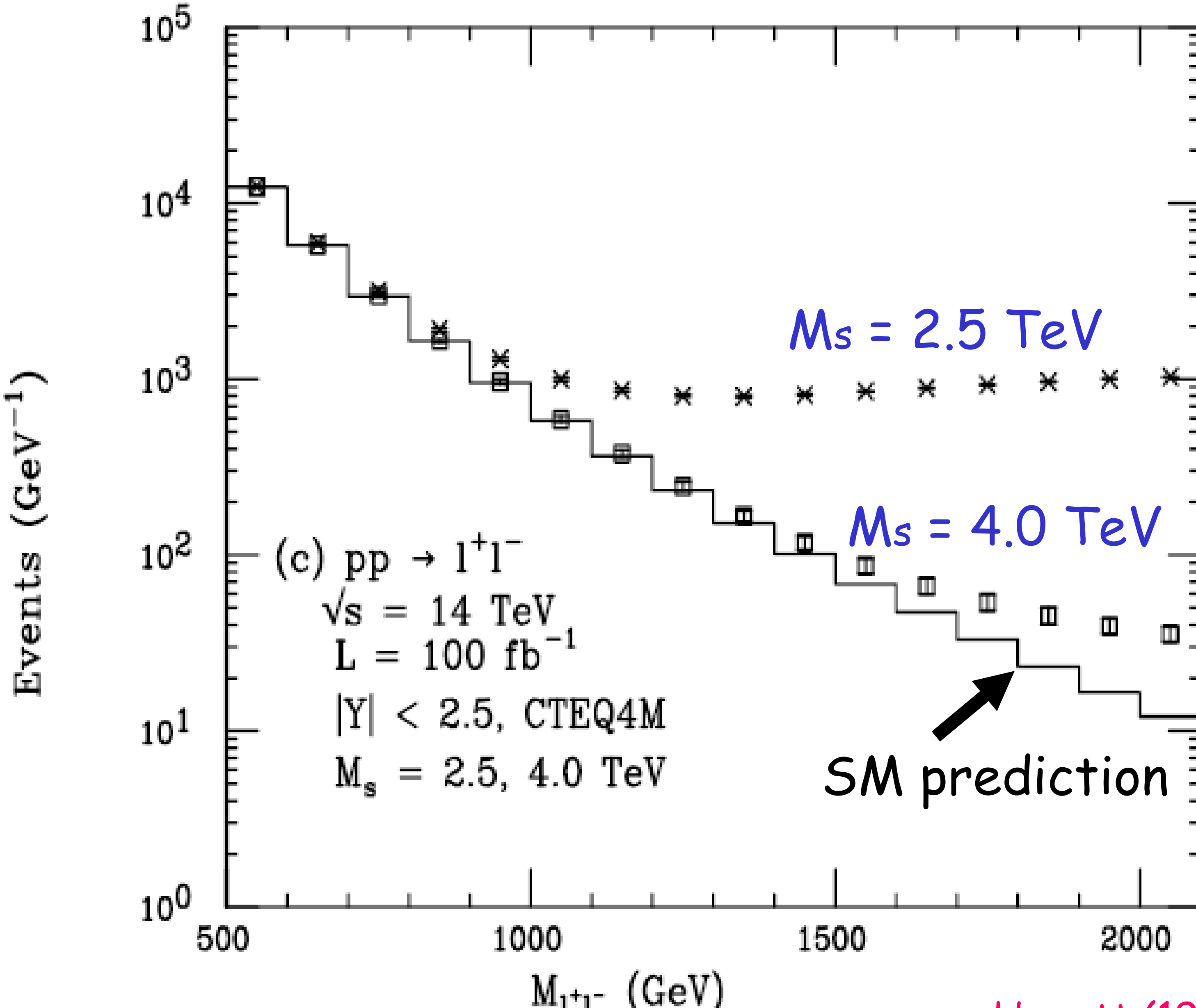
Spin sum of the polarization tensors

Log div. for n=2
Power div. for n > 2

$$\int d^4x d^n y \frac{h_{\mu\nu}(x,y)T^{\mu\nu}(x)}{M_*^{n/2+1}}$$

$$= \frac{-4\lambda}{M_s^4}\bar{f}(p')[(p'-p)_\mu\gamma_\nu + (p'-p)_\nu\gamma_\mu]f(p)$$
$$\times \{k'_\alpha(k_\mu\eta_{\beta\nu} + k_\nu\eta_{\beta\mu}) + k_\beta(k'_\mu\eta_{\alpha\nu} + k'_\nu\eta_{\alpha\mu}) - \eta_{\alpha\beta}(k'_\mu k_\nu + k_\mu k'_\nu) + \eta_{\mu\nu}(k'\cdot k\,\eta_{\alpha\beta} - k_\beta k'_\alpha)$$
$$- k\cdot k'(\eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\mu\beta}\eta_{\nu\alpha})\}\epsilon_g^\beta(k')\epsilon_g^\alpha(k).$$

Cutoff by the string scale Ms λ:O(1) constant

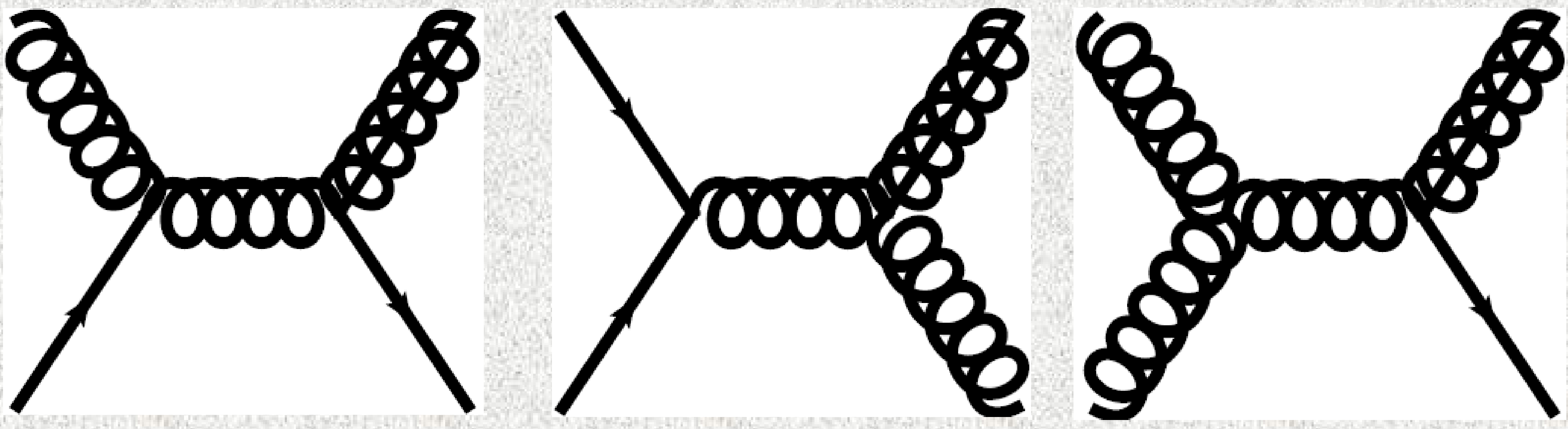


Hewett (1999)

ADD contributions to the Drell-Yan process@LHC

2: Real graviton emission → Missing energy

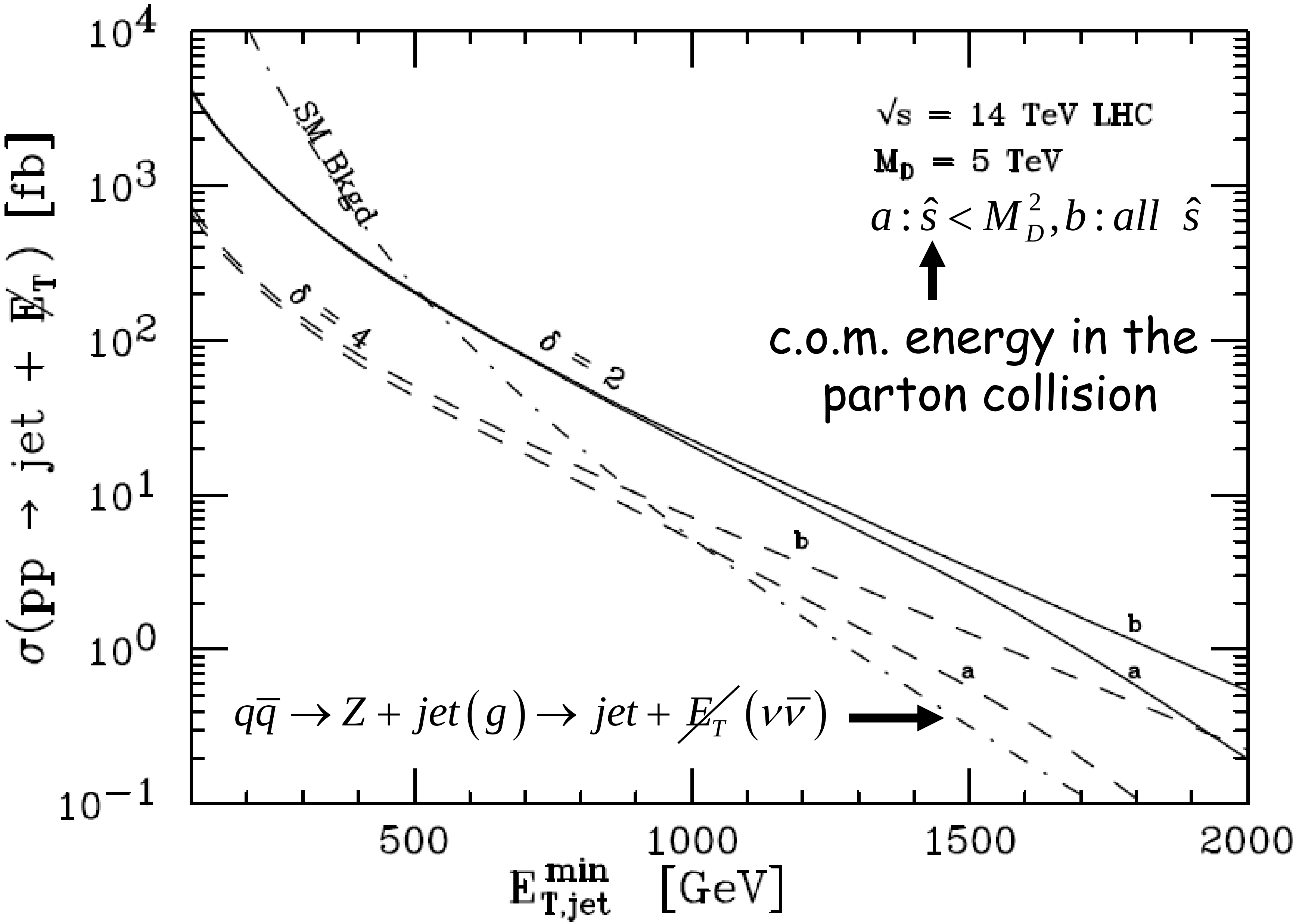
$$pp \to jet + \not{E}_T$$



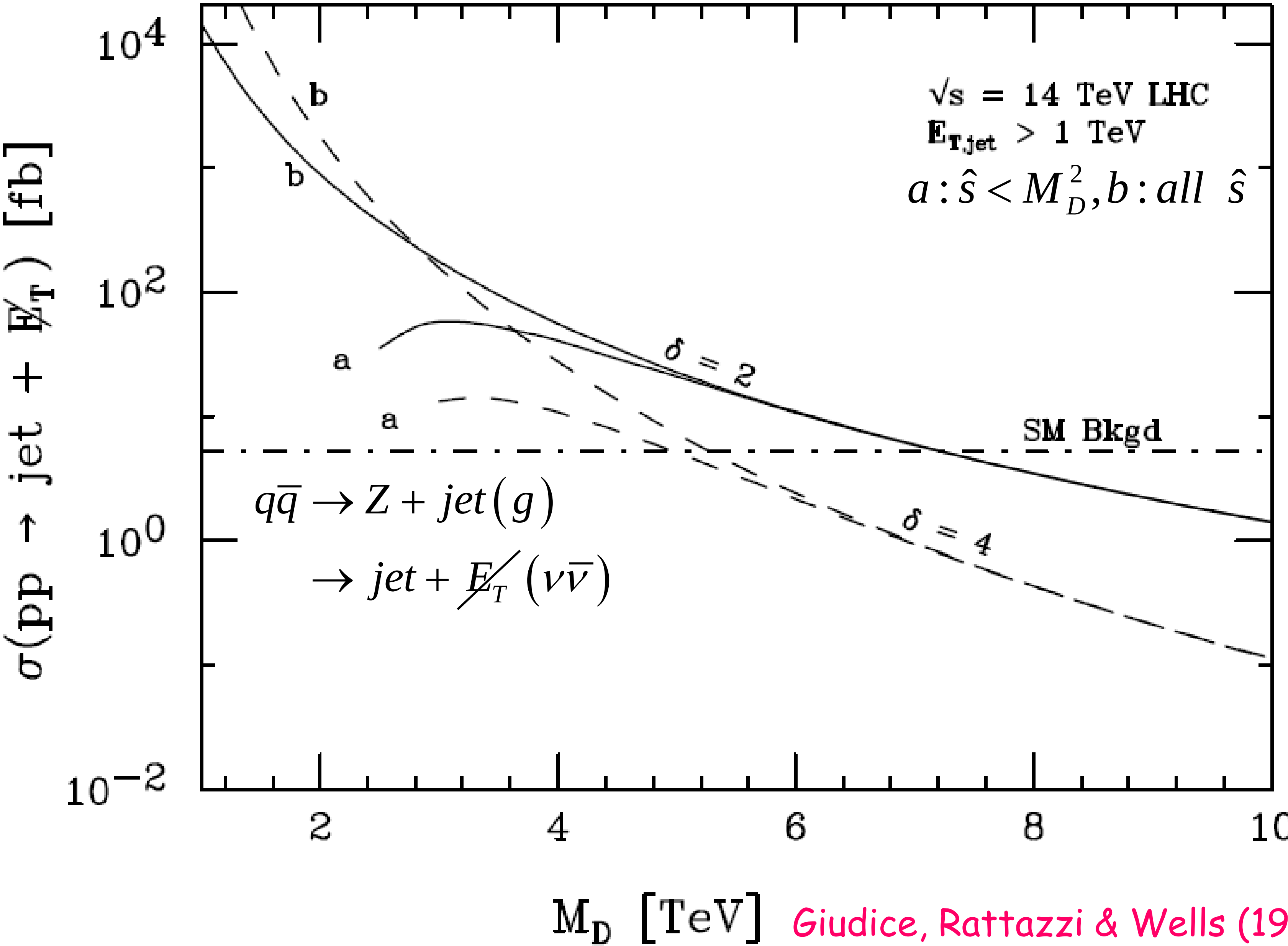
$qg \to qG^{(n)}$ — Dominant process

$q\bar{q} \to gG^{(n)}$

$gg \to gG^{(n)}$



Giudice, Rattazzi & Wells (1999)



Giudice, Rattazzi & Wells (1999)

Warped Extra Dimension

"A Large Mass Hierarchy
from a Small Extra Dimension"(RS1)

"An Alternative to Compactification"(RS2)

L. Randall and R. Sundrum
PRL83 (1999) 3370; PRL83 (1999) 4690

RS1

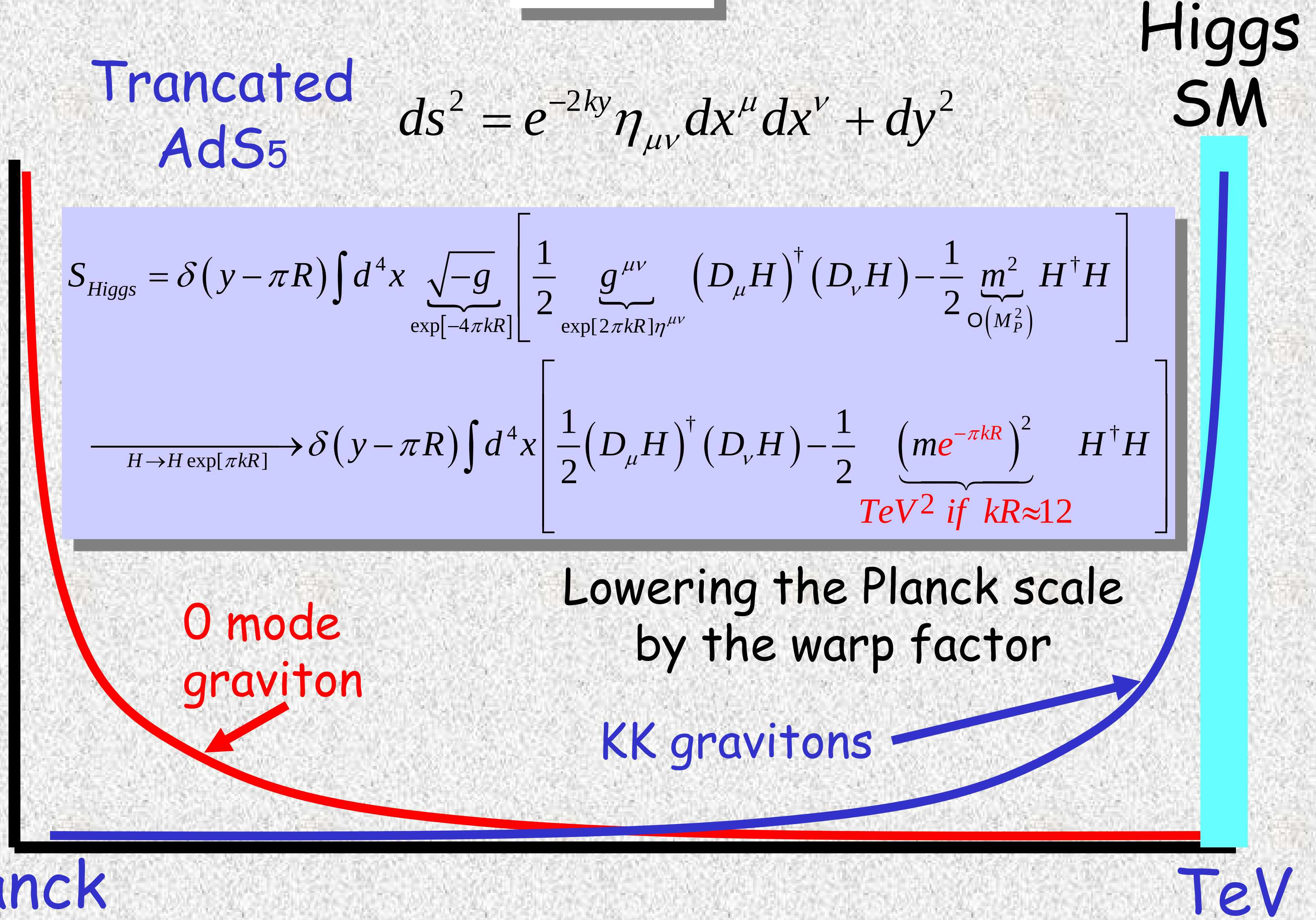
Trancated AdS5

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$S_{Higgs} = \delta(y-\pi R)\int d^4x \underbrace{\sqrt{-g}}_{\exp[-4\pi kR]}\left[\frac{1}{2}\underbrace{g^{\mu\nu}}_{\exp[2\pi kR]\eta^{\mu\nu}}(D_\mu H)^\dagger(D_\nu H) - \frac{1}{2}\underbrace{m^2}_{\text{o}(M_P^2)} H^\dagger H\right]$$

$$\xrightarrow[H\to H\exp[\pi kR]]{}\delta(y-\pi R)\int d^4x\left[\frac{1}{2}(D_\mu H)^\dagger(D_\nu H) - \frac{1}{2}\underbrace{\left(me^{-\pi kR}\right)^2}_{TeV^2\ if\ kR\approx 12} H^\dagger H\right]$$

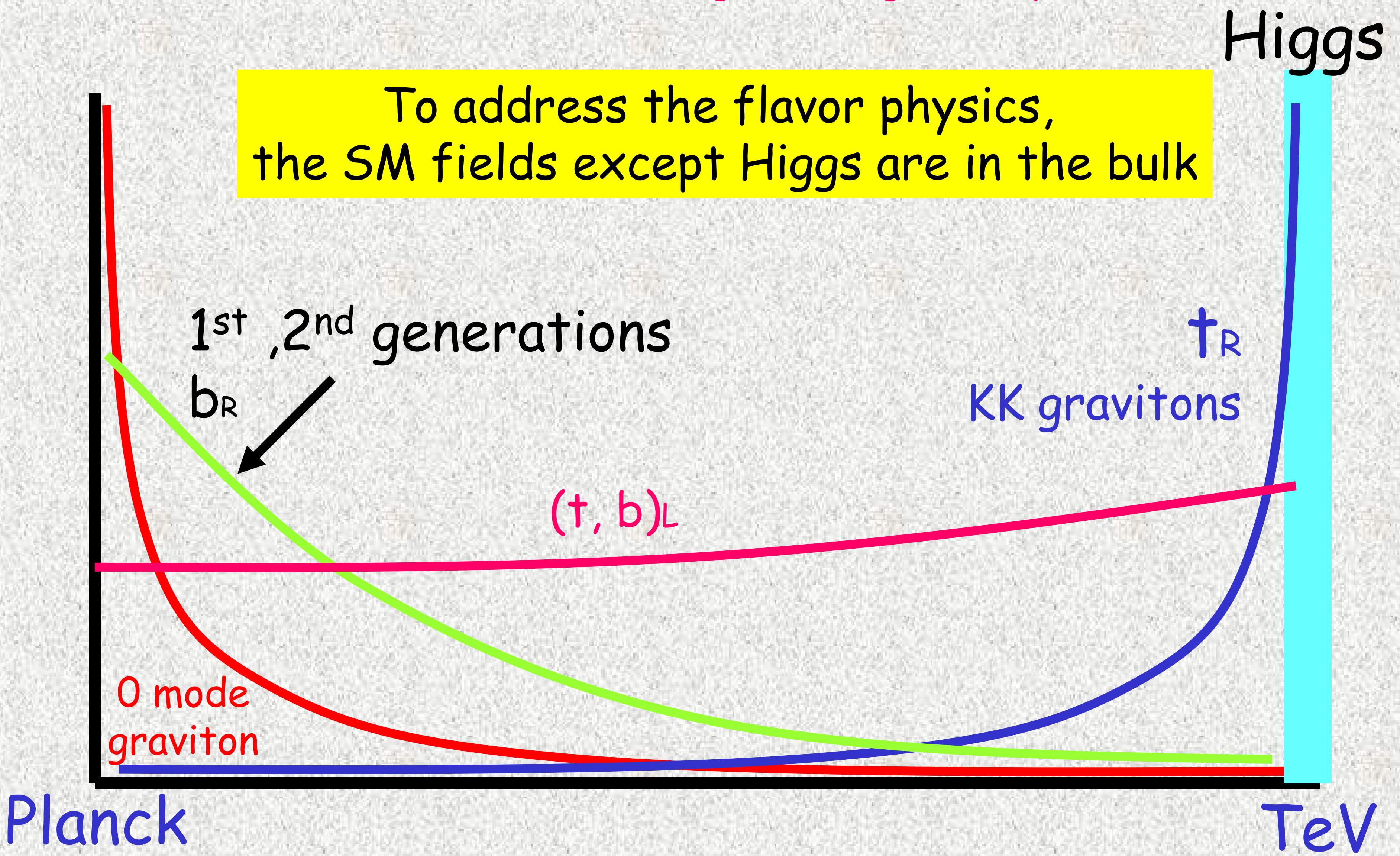
Lowering the Planck scale by the warp factor



Bulk SM in RS

Agashe, Delgado, May & Sundrum (2003)

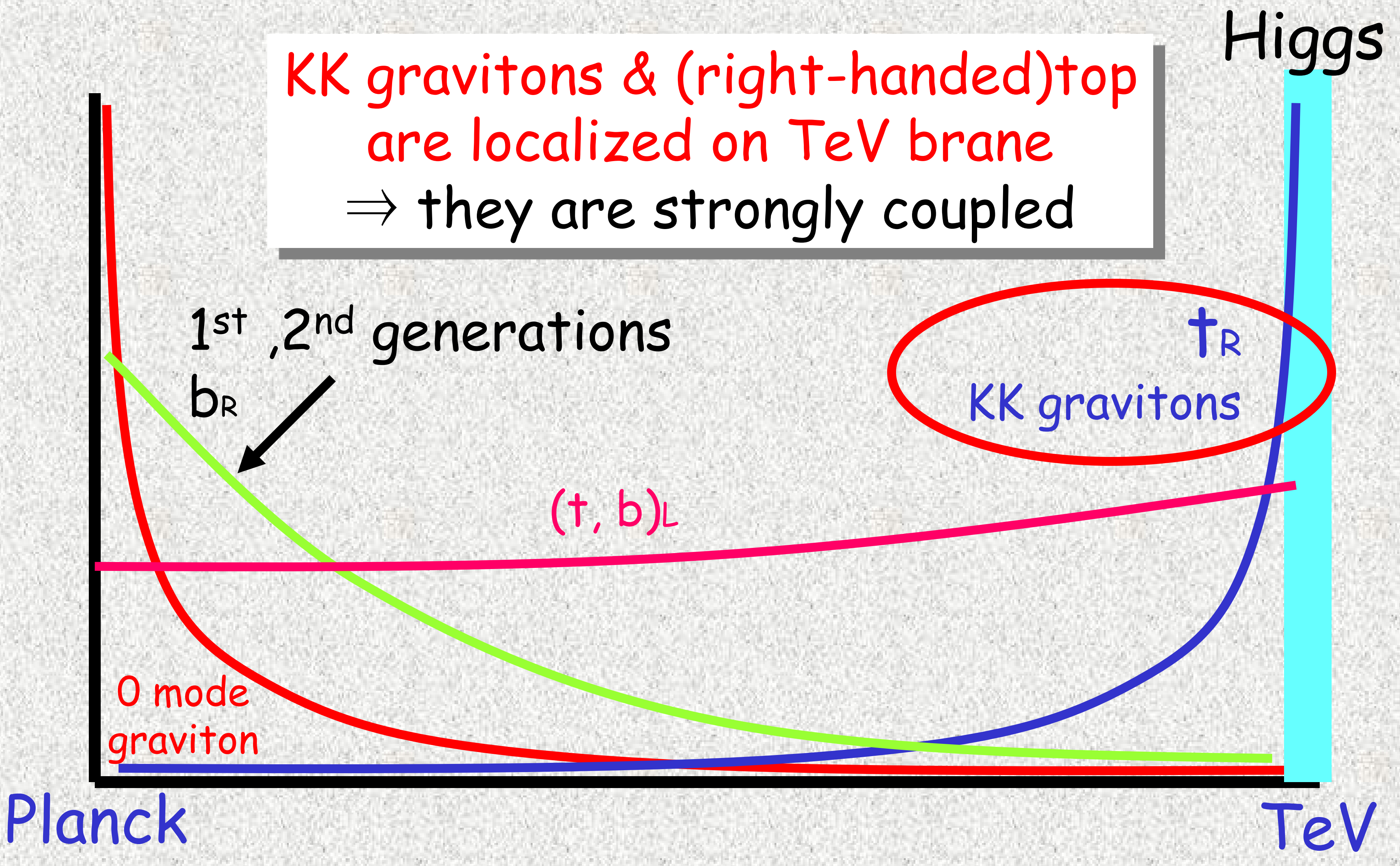
To address the flavor physics,
the SM fields except Higgs are in the bulk



$$gg \to G^{(1)} \to t\bar{t}\,(\mathrm{RS})$$

KK gravitons & (right-handed)top are localized on TeV brane

$\Rightarrow$ they are strongly coupled



All coupling to the KK gravitons can be written as

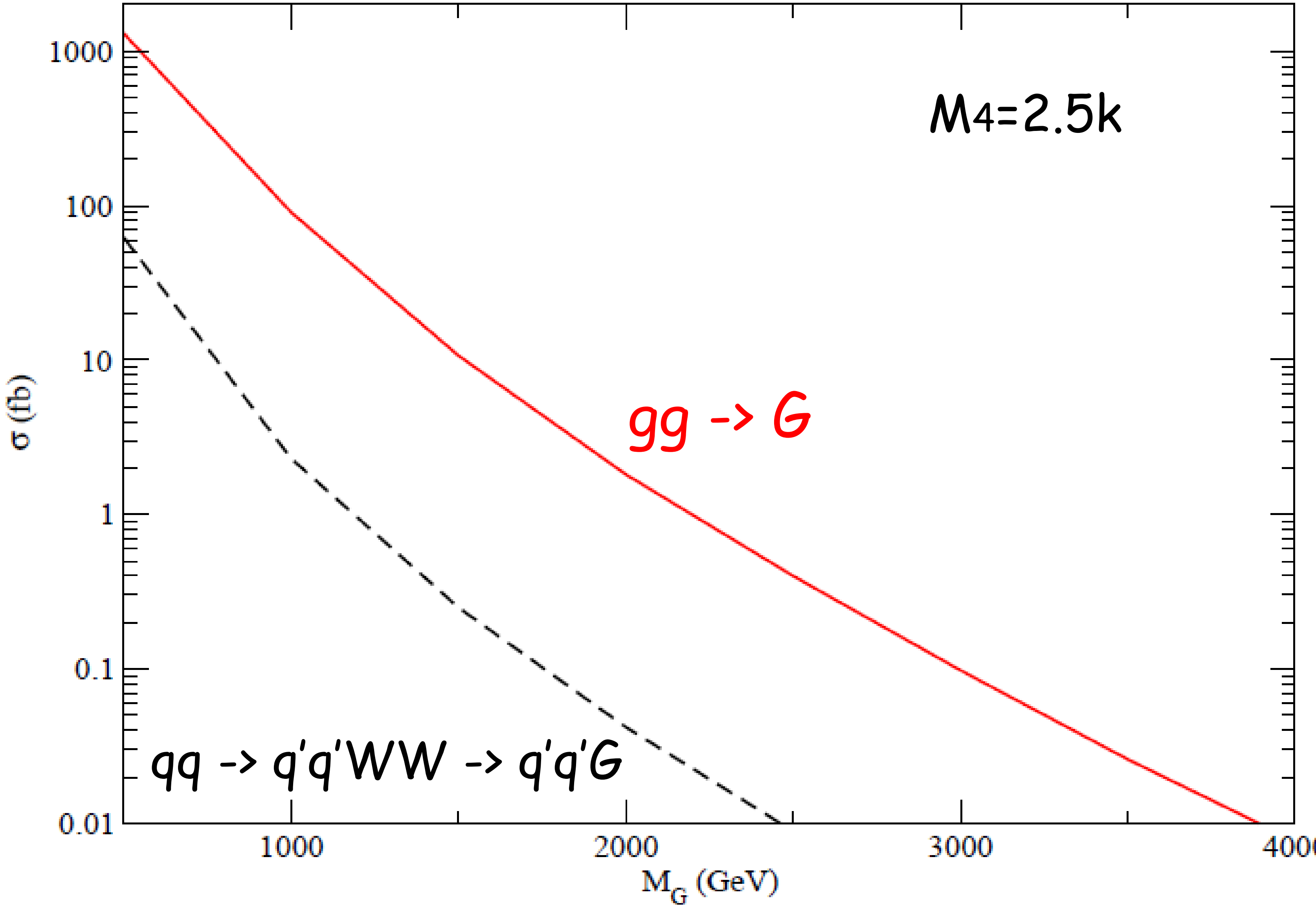
$$C_{XXG}\int d^4x h_{\mu\nu}T^{\mu\nu}_{XX}$$

(XX: a pair of fermions or gauge fields)

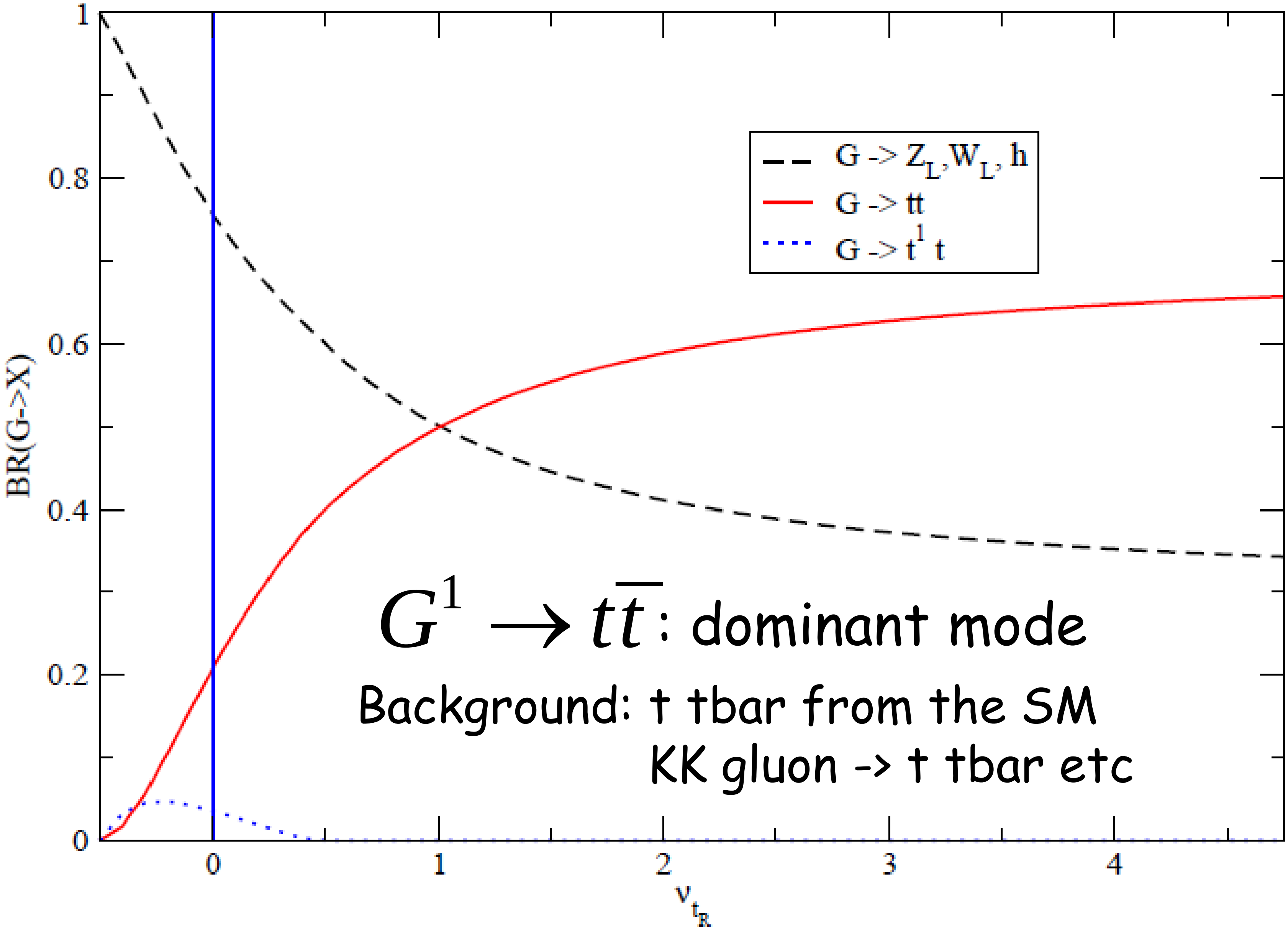
XX	$T^{\mu\nu}_{XX}$	C_{XXG}
ss	$\frac{1}{2}\partial^\mu\phi\partial^\nu\phi$	$C_{ssG}=\frac{2}{(M_4L)TeV}$
$f\bar{f}$	$i\psi^\dagger\bar{\sigma}^\mu D^\nu\psi$	$C_{f\bar{f}G}=\frac{1}{(M_4L)TeV}\left(\frac{1+2\nu}{1-e^{-\pi kr_c(1+2\nu)}}\right)\frac{\int_0^1 dyy^{2+2\nu}J_2(3.83y)}{J_2(3.83y)}$
$t\bar{t}_1$	$i\psi^\dagger\bar{\sigma}^\mu D^\nu\psi$	$C^{101}_{f\bar{f}G}=\frac{1}{(M_4L)TeV}\sqrt{\frac{2(1+2\nu)}{1-e^{-\pi kr_c(1+2\nu)}}}\int_0^1 dyy^{\nu+5/2}\frac{J_{\nu-1/2}(x_1^L y)}{J_{\nu-1/2}(x_1^L)}\frac{J_2(3.83y)}{\lvert J_2(3.83y)\rvert}$
gg	$F^{\mu\rho}F^\nu_\rho$	$C_{ggG}=\frac{1}{\pi kr_c(M_4L)TeV}\frac{\int_0^1 dyy^{2+2\nu}J_2(3.83y)}{J_2(3.83y)}\approx\frac{0.47}{\pi kr_c(M_4L)TeV}$

Cross section of KK graviton production

Fitzpatrick, Kaplan, Randall & Wang (2007)



Branching ratios for KK graviton decay



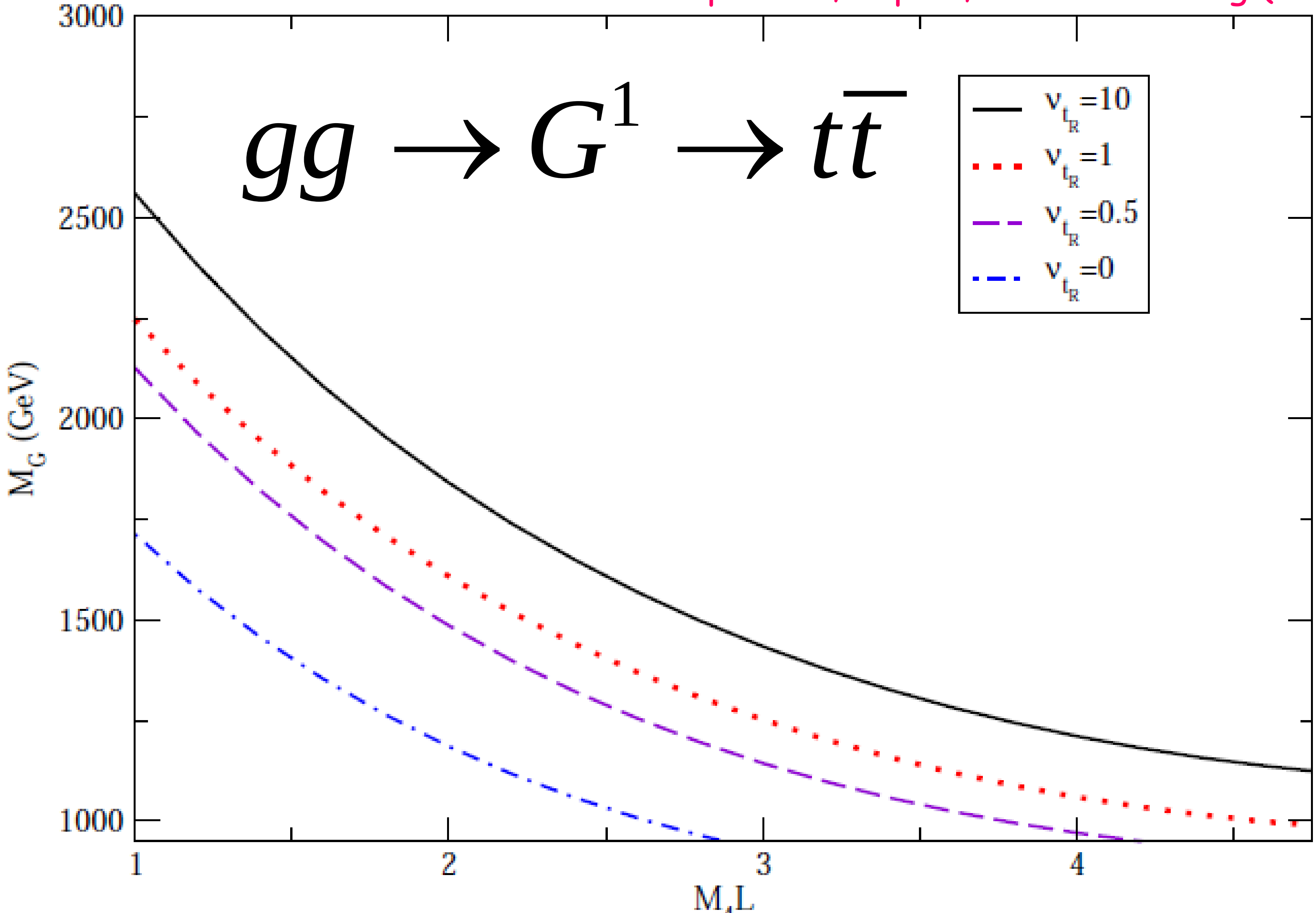
$G^1 \to t\overline{t}$: dominant mode

Background: t tbar from the SM

KK gluon -> t tbar etc

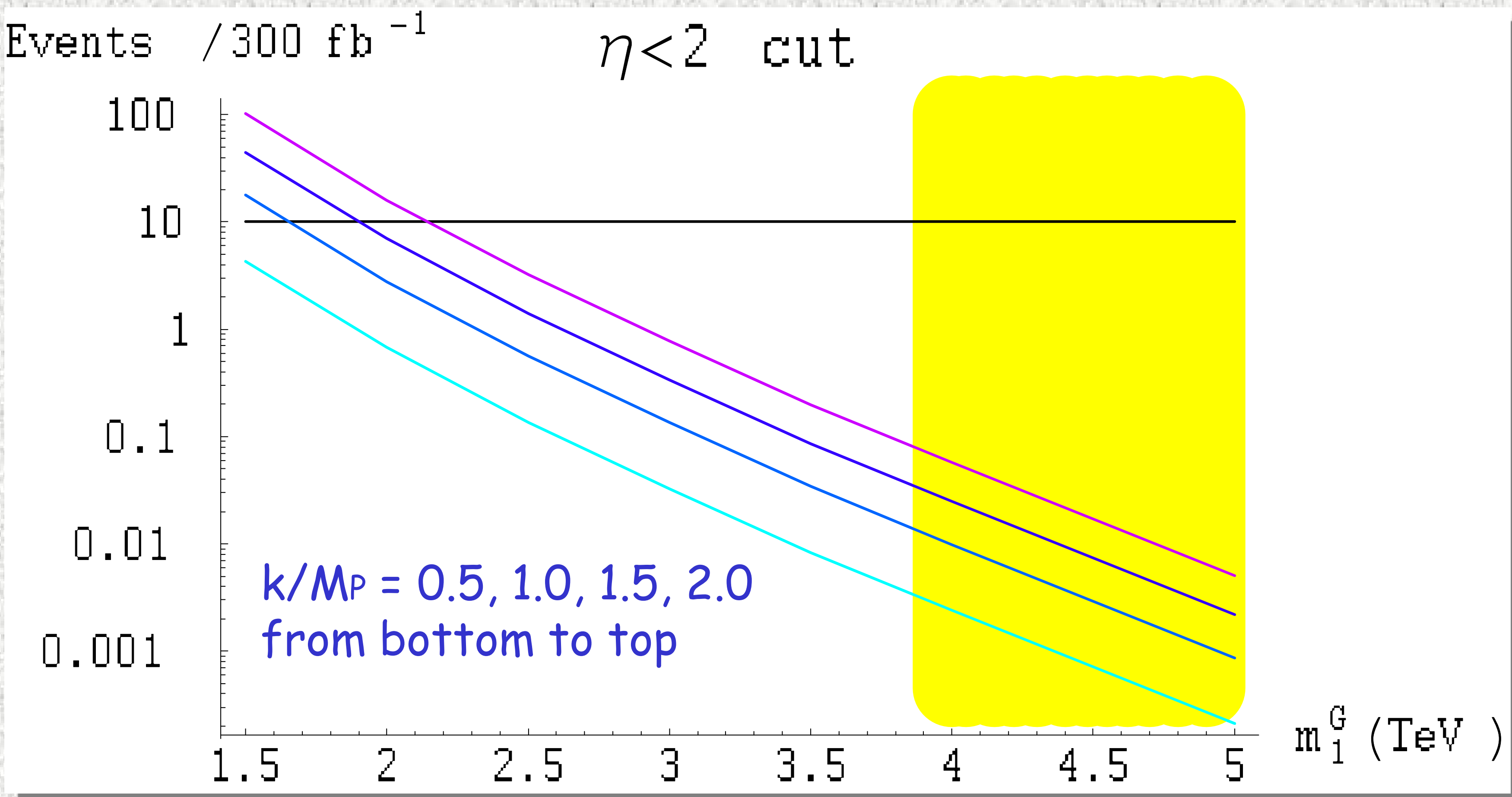
Discovery reach 5σ

Fitzpatrick, Kaplan, Randall & Wang (2007)



$$gg \to G^{(1)} \to Z_L Z_L \to 4l \left(l = e, \mu\right)$$

Agashe, Davoudiasl, Perez & Soni (2007)



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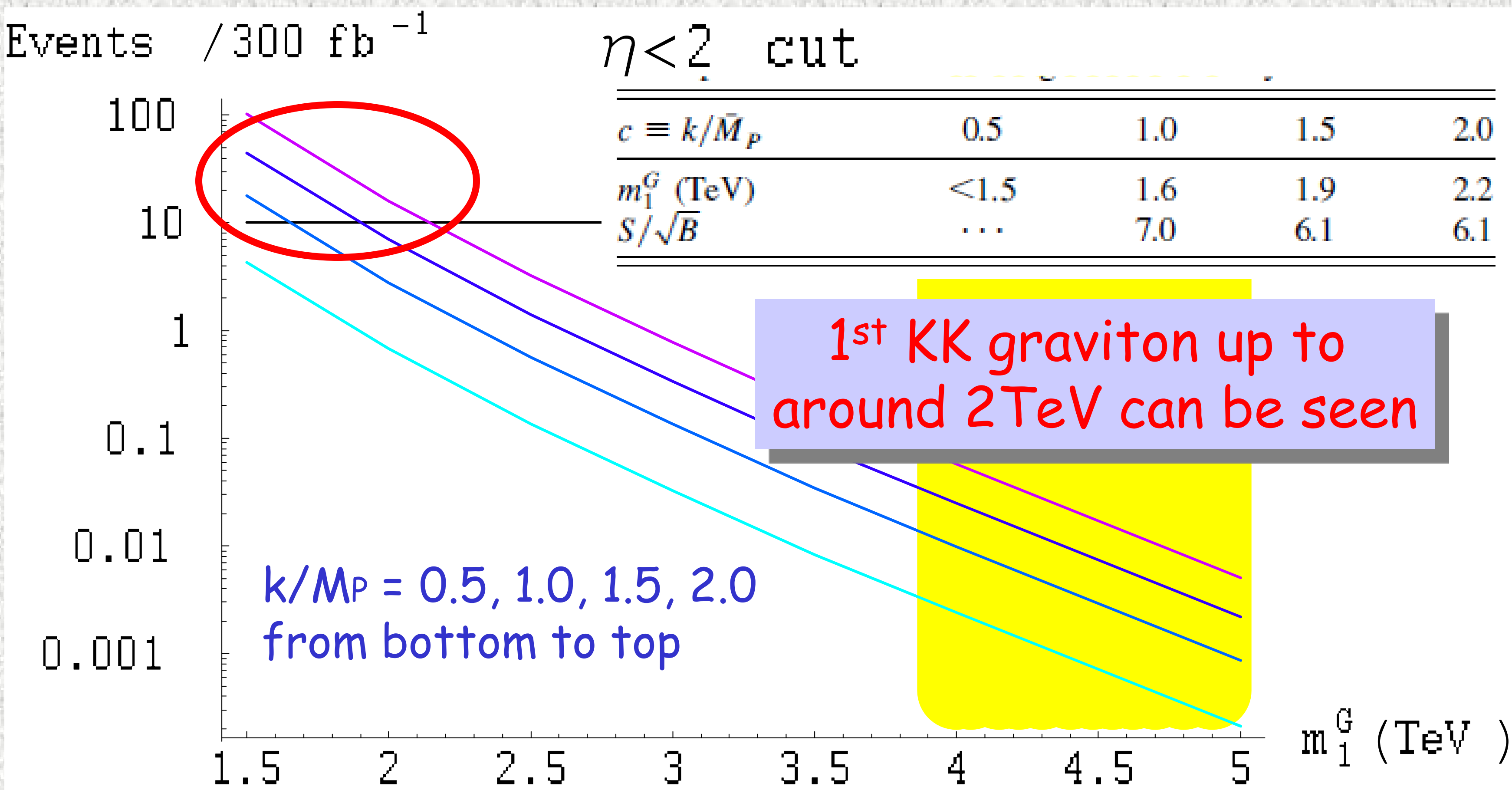


$c \equiv k/\bar{M}_P$	0.5	1.0	1.5	2.0
m_1^G (TeV)	<1.5	1.6	1.9	2.2
$S/\sqrt{B}$	⋯	7.0	6.1	6.1

Black Hole

"Black Holes at the Large Hadron Collider"

S. Dimopoulos & G. Landsberg

PRL87 161602 (2001)

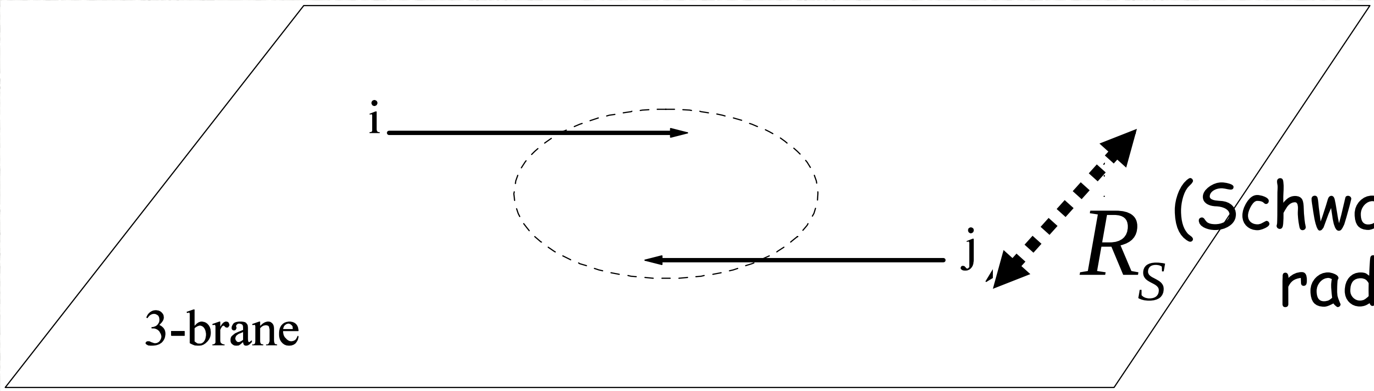
"High Energy Colliders as Black Hole Factories: The End of Short Distance Physics"

S.B. Giddings & S. Thomas

PRD65 056010 (2002)

Production

Two partons with $\sqrt{\hat{s}} = M_{BH}$ moving in opposite directions



R_S (Schwarzshild radius)

If the impact parameter < R_S, a BH with M_{BH} forms

Total cross section

$$\sigma(M_{BH}) \approx \pi R_S^2 = \frac{1}{M_*^2}\left[\frac{M_{BH}}{M_*}\left(\frac{8\Gamma((n+3)/2)}{n+2}\right)\right]^{2/(n+1)}$$

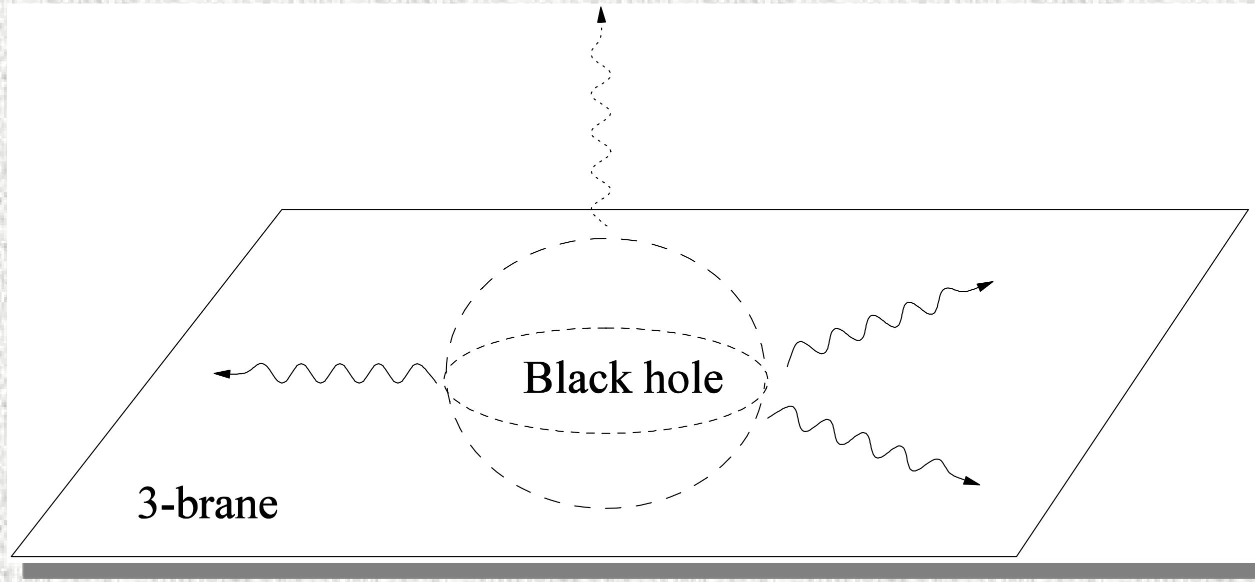
$M_* \approx$ TeV with $30 fb^{-1}/y \Rightarrow 10^7$ BH production/year!!

(comparable to Z production@LEP)

Decay

BHs, once produced, evapolate
@Hawking temp.

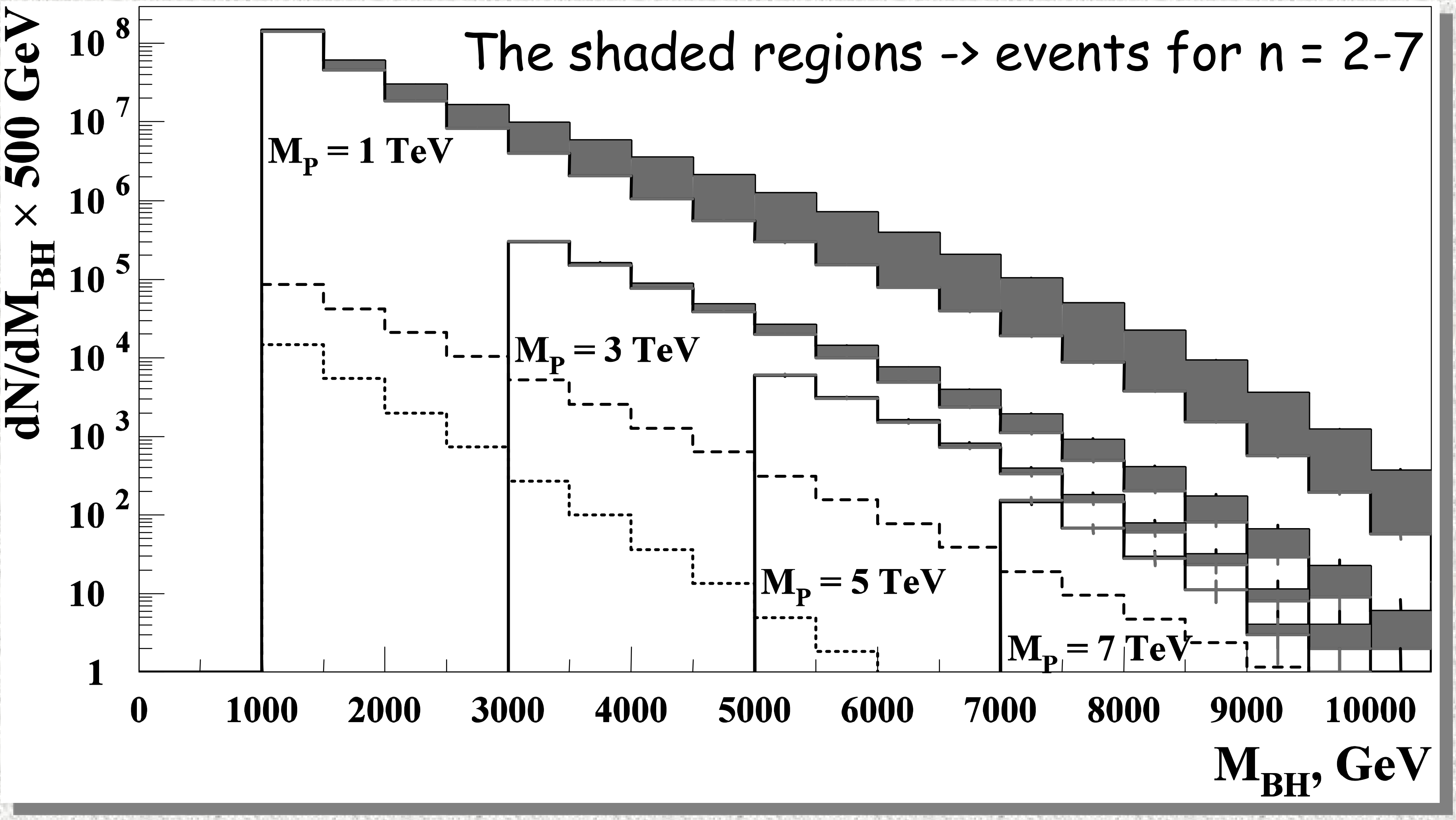
$$T_H = \frac{n+1}{4\pi R_S} \approx 100\ GeV$$



BH decay to SM particles with rough equal probability:

G, q: 72%, l: 11%, Z, W: 8%,
ν, graviton: 6%, H: 2%, γ: 1%

of BHs produced @LHC in e or γ decay channel with 100 fb^-1 of integrated luminosity



– – – – – SM bkg from Z(ee) + jets & γ+ jets

.... SM bkg from Z(ee) + X

Universal Extra Dimension

"Bounds on Universal Extra Dimensions"

T. Appelquist, H-C. Cheng & B. Dobrescu

PRD64 035002 (2001)

Universal Extra Dimension (UED) model is just a higher dim. extension of the Standard Model

↓

All of the SM fields propagate in extra dimensions of size $1/R \sim$ TeV

(In ADD & RS, some or all of them are confined to 3-brane)

Motivations for UED (although not a solution of the hierarchy problem...)

1: KK parity

KK parity which is a remnant of KK momentum is conserved even after orbifold $(-1)^n$

ex. Reflection symmetry w.r.t. the center of line segment for S^1/Z_2 orbifold

☆KK parity relaxes the constraints from EWPT

⇒ 1/R > 300 GeV (5D on S^1/Z2) testable @colliders

Appelquist, Cheng & Dobrescu (2001)

☆KK parity naturally predicts a candidate of dark matter

"lightest KK particle (LKP)" like a LSP in SUSY w/ R-parity

∵ 1st KK modes are always produced in pairs

2: # of generations from anomaly cancellation (6D)

Dobrescu & Poppitz (2001)

Witten anomaly:

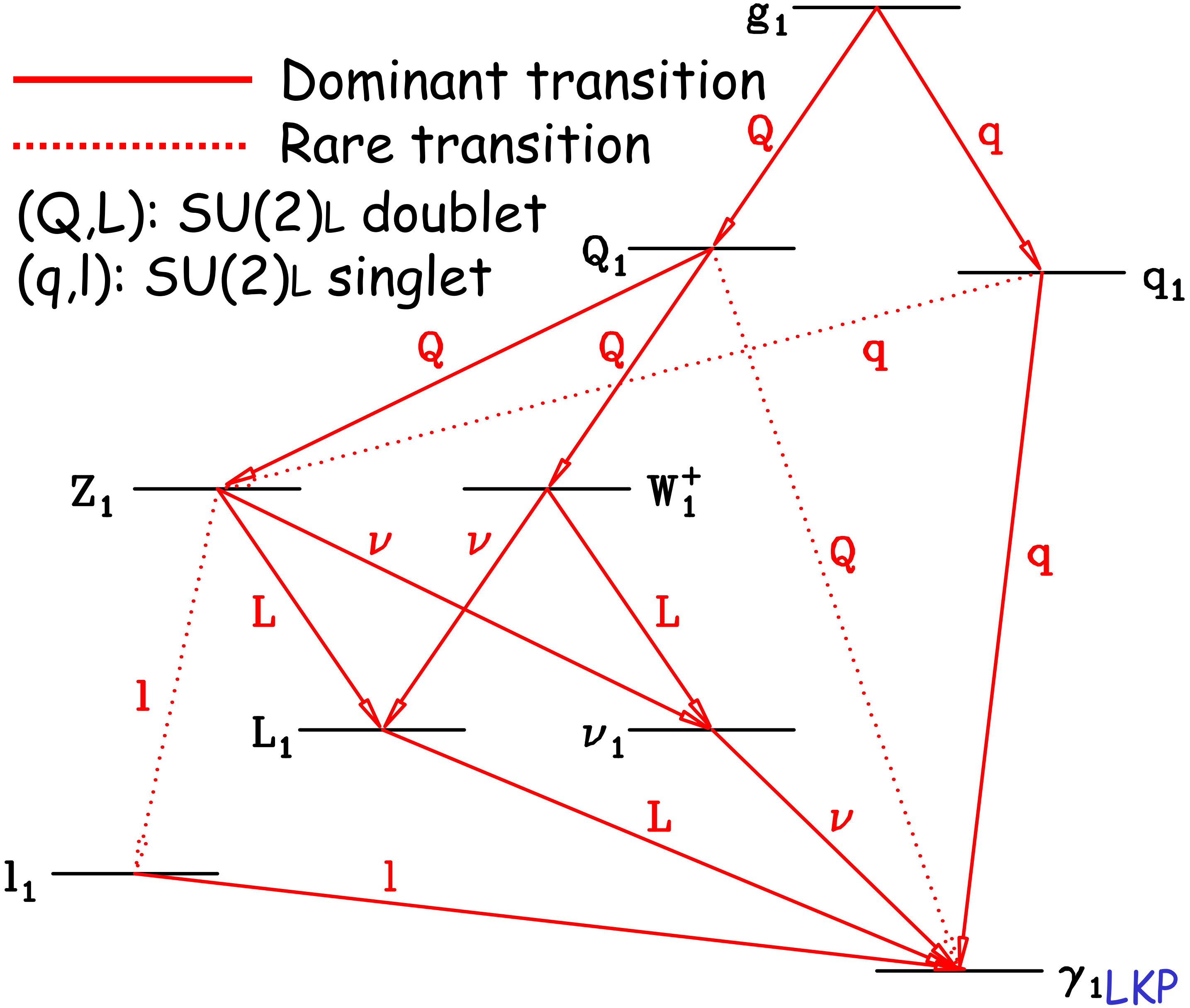
$$\Pi_6\left(SU(2)_W\right) = N(2_+) - N(2_-) = 0 \mod 6 \Rightarrow n_g = 0 \mod 3$$

3: Proton stability by Lorentz subgroup (6D)

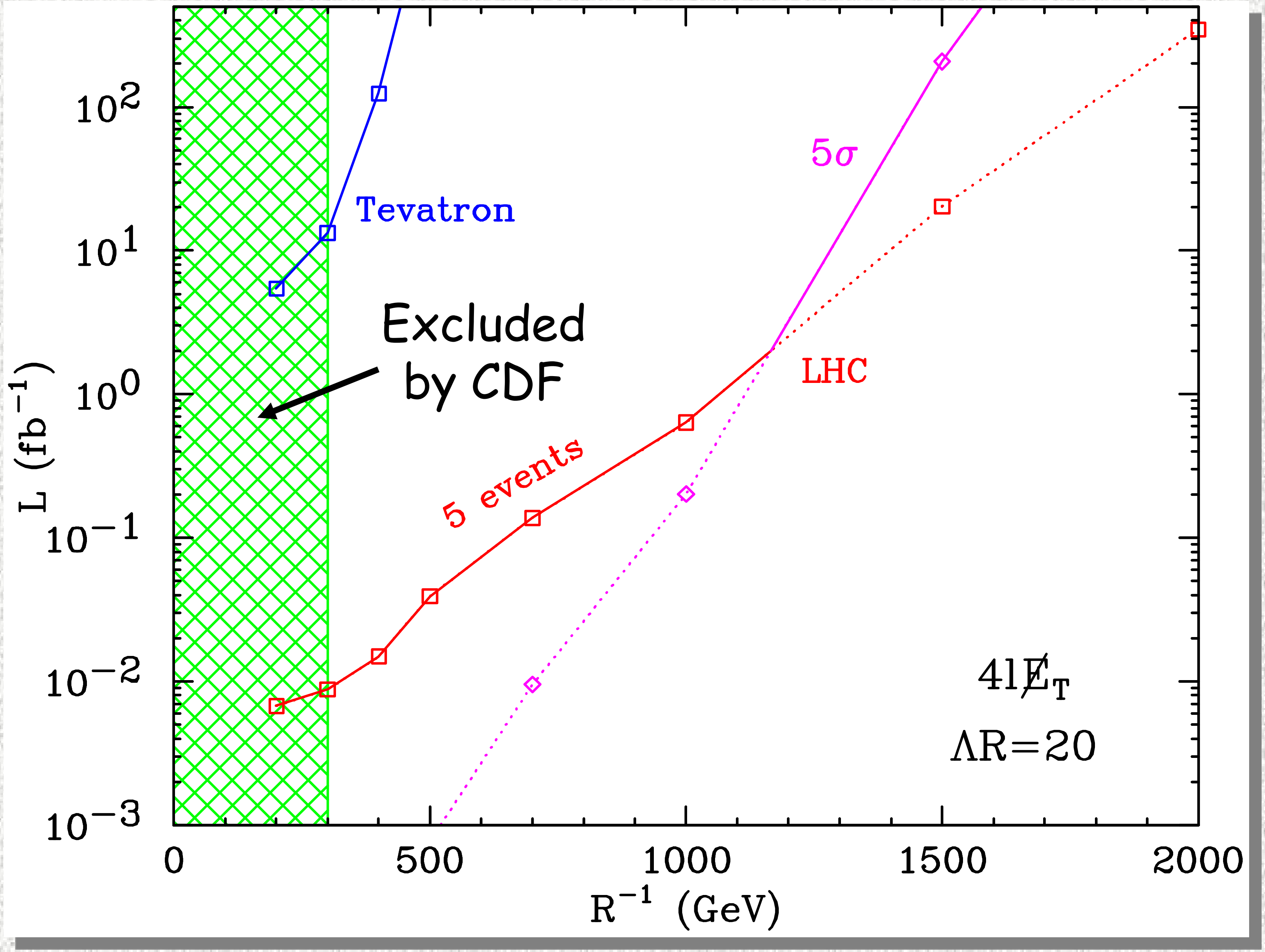
$$Z_8 \subset T^2/Z_2$$

Appelquist, Dobrescu, Ponton & Yee (2001)

Decays & products of 1st KK modes (5D on S^1/Z2)



Discovery reach for 5D UED in Q1Q1 -> 4l + missing energy



Gauge-Higgs Unification

"LHC Signals for Coset Electroweak Gauge Bosons in Warped/Composite PGB Higgs Models"

K. Agashe, A. Azatov, T. Han, Y. Li, Z-G. Si & L. Zhu

PRD81 096002 (2010)

Gauge-Higgs unification

Identified with Higgs in the SM → A_y ⇔ A_μ

Higher dimensional Lorentz invariance

Mass term is forbidden by the gauge symmetry

Higher dimensional gauge symmetry

Higgs potential is generated @1-loop and finite due to the higher dim. gauge symmetry

↓

EW scale is stabilized

Gauge symmetry breaking:

$G \to H \supseteq SU(2) \times U(1)$ by an orbifold (ex. S^1/Z2)

Parity assignments of gauge sector

H subgroup

$$\begin{cases} A_\mu^H(-y) = A_\mu^H(y) \\ A_y^H(-y) = -A_y^H(y) \end{cases} \Leftrightarrow \begin{cases} \partial_y A_\mu^H(y) = 0 \\ A_y^H(y) = 0 \end{cases}$$

G/H coset

$$\begin{cases} A_\mu^{G/H}(-y) = -A_\mu^{G/H}(y) \\ A_y^{G/H}(-y) = A_y^{G/H}(y) \end{cases} \Leftrightarrow \begin{cases} A_\mu^{G/H}(y) = 0 \\ \partial_y A_y^{G/H}(y) = 0 \end{cases}$$

Only even mode has a massless mode

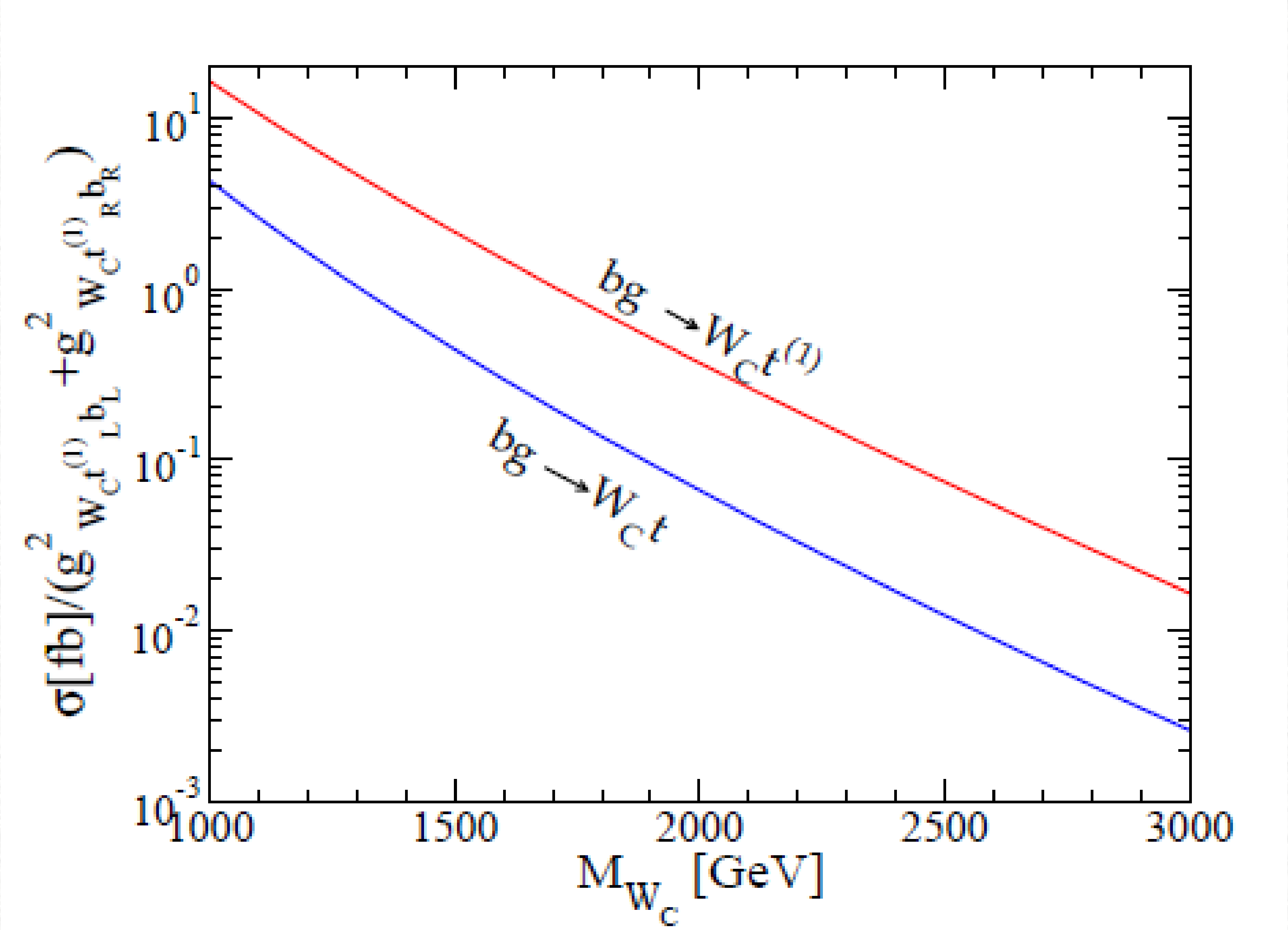
A_μ^H : SU(2) x U(1) Gauge fields

$A_y^{G/H}$: Higgs

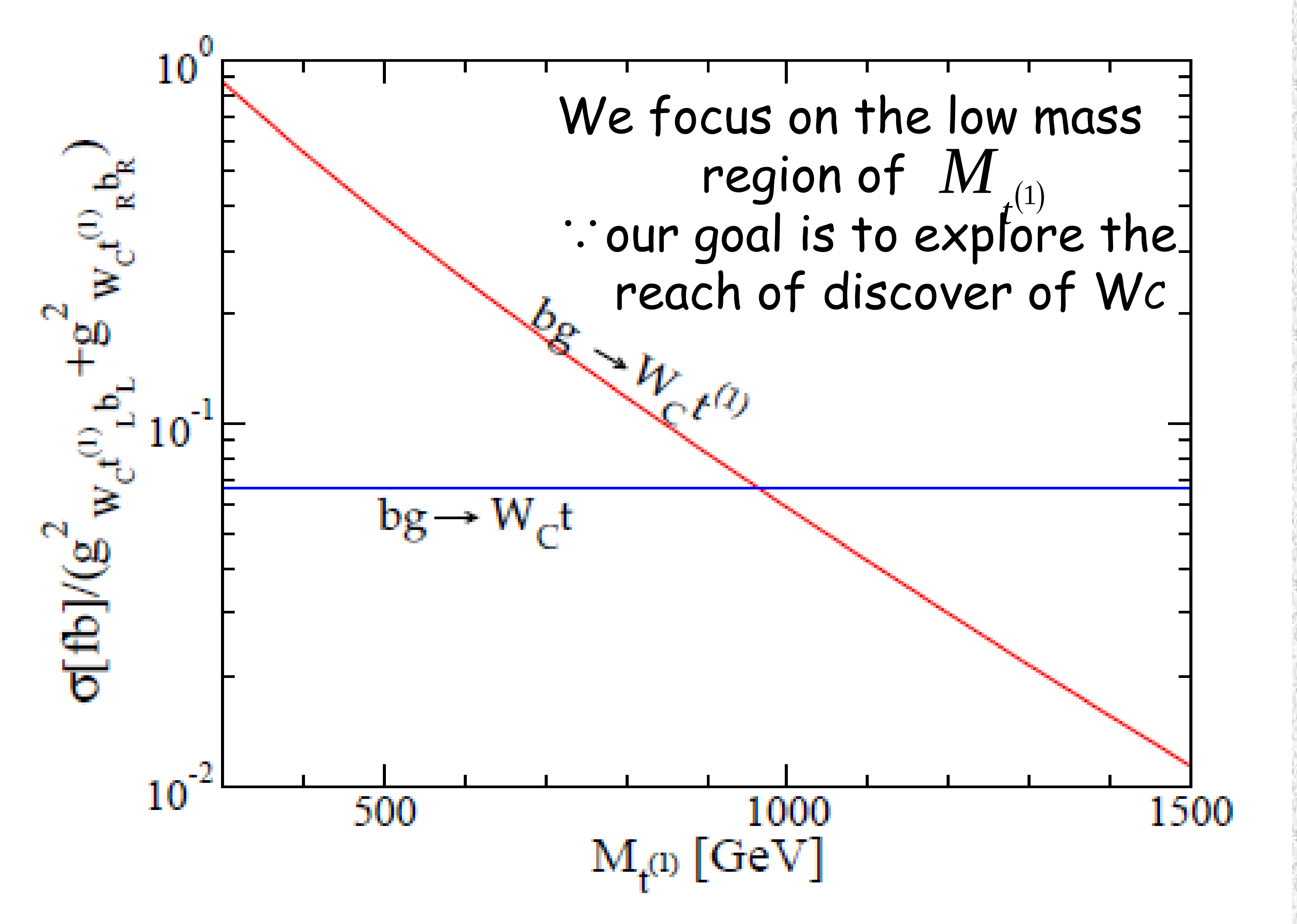
Model independent new fields

$\Rightarrow$ SU(2) doublet coset gauge boson partner of Higgs $A_\mu^{G/H}$

$pp \to W_C^{\pm} t^{(1)}$ vs $pp \to W_C^{\pm} t$

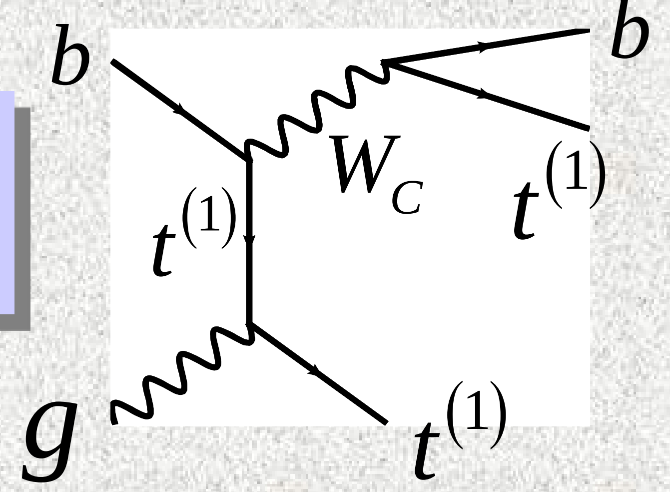


$pp \to W_C^{\pm} t^{(1)}$ vs $pp \to W_C^{\pm} t$

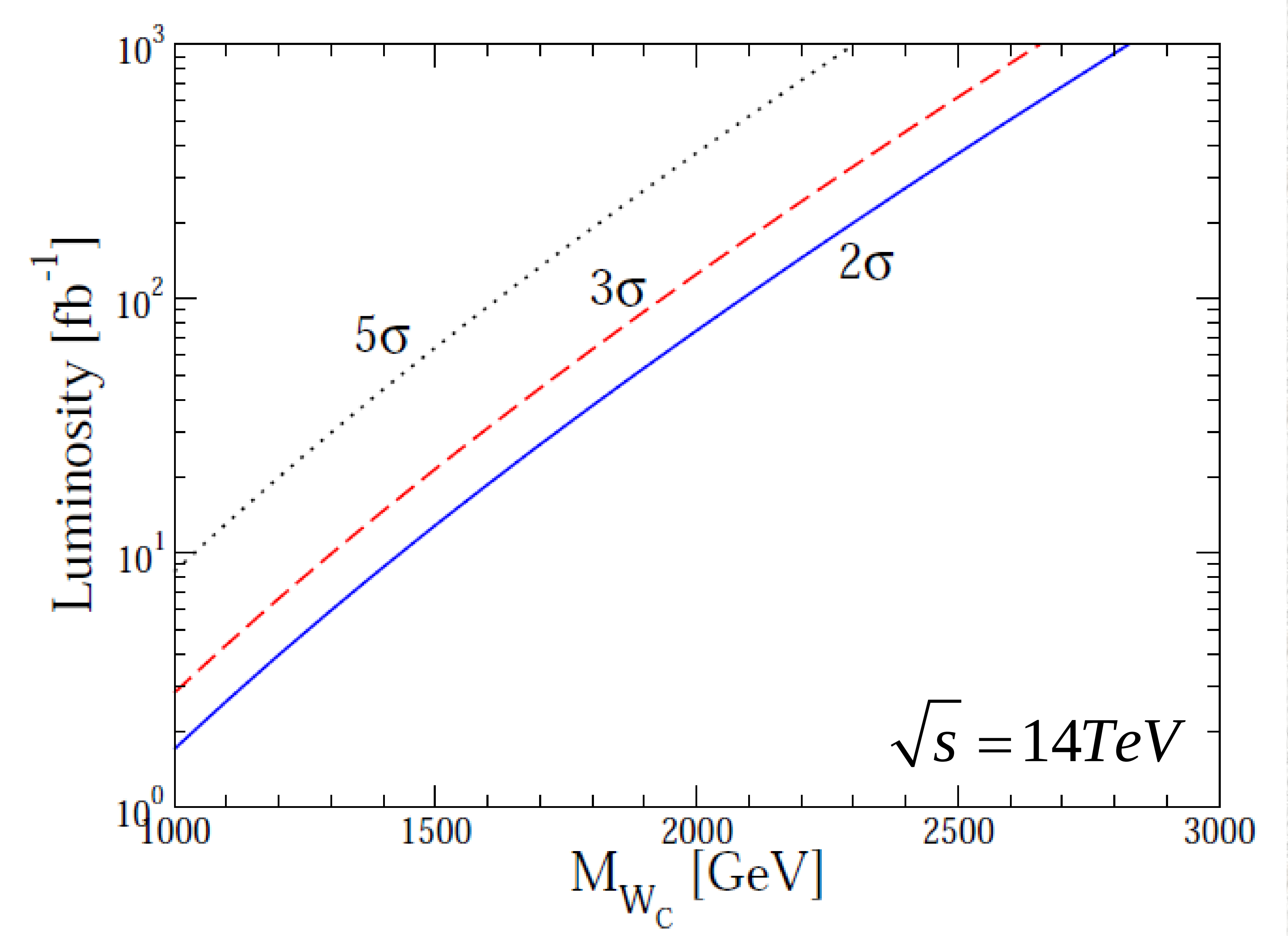


Dominant channels of Wc production & its decay

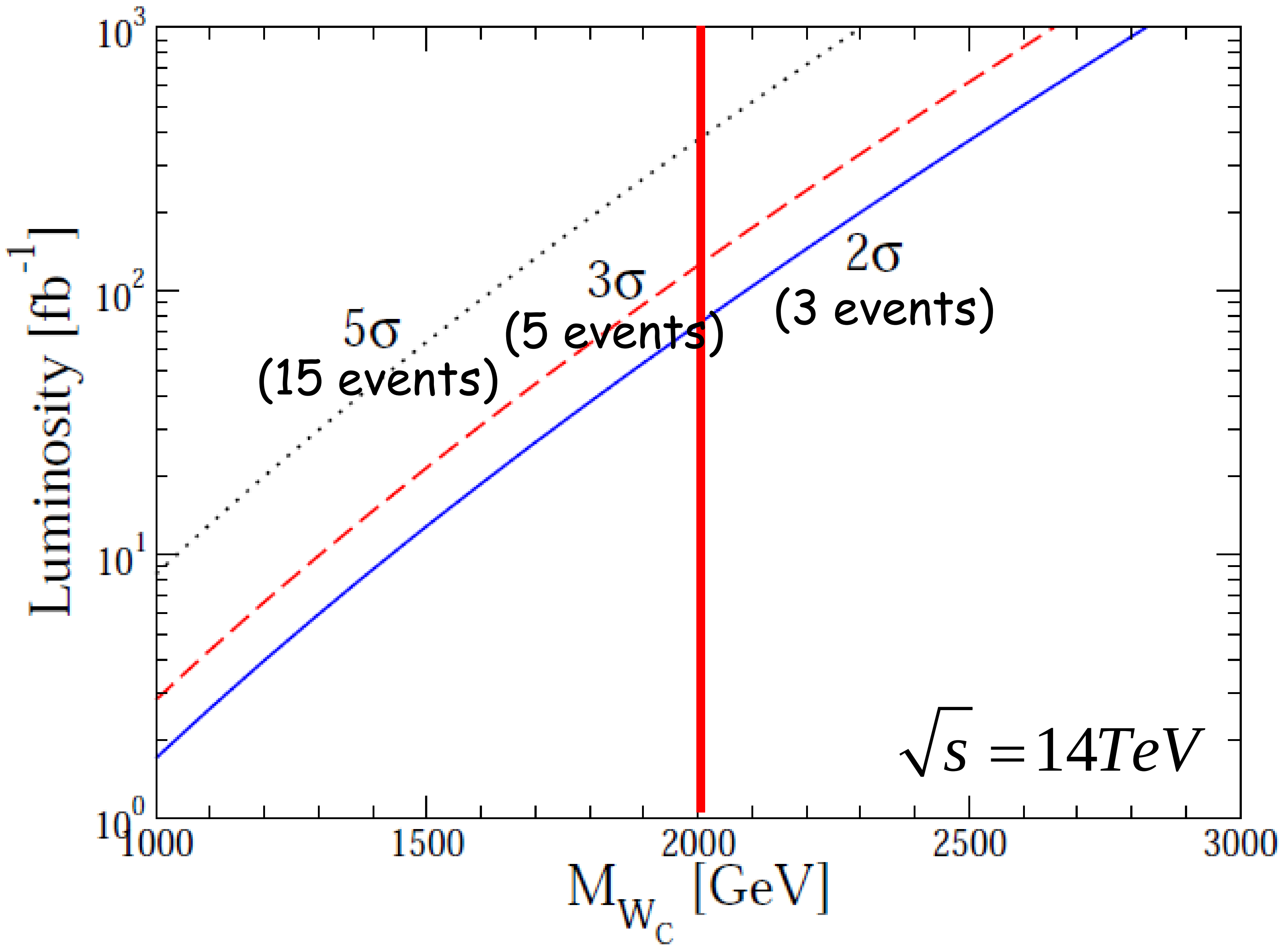
$$bg \to W_C t^{(1)} \to b t^{(1)} t^{(1)}$$



$$t^{(1)} \to \begin{cases} bW \\ tH\left(tZ\right) \end{cases} \to \begin{cases} 1: 3b + 2W \to l\nu + 5\,jets \\ \quad Br\left(W_C \to t^{(1)}b\right) \times \left(Br\left(t^{(1)} \to bW\right)\right)^2 \approx 90\% \times \left(50\%\right)^2 = 22.5\% \\ 2: bbWtH\left(Z\right) \to l\nu + 7\,jets \\ \quad 2 \times Br\left(W_C \to t^{(1)}b\right) \times Br\left(t^{(1)} \to bW\right) \times Br\left(t^{(1)} \to tH, tZ\right) \\ \quad \approx 2 \times 90\% \times \left(50\%\right)^2 = 45\% \\ 3: btH\left(Z\right)tH\left(Z\right) \to l\nu + 9\,jets \\ \quad Br\left(W_C \to t^{(1)}b\right) \times \left(Br\left(t^{(1)} \to tH, tZ\right)\right)^2 \approx 90\% \times \left(50\%\right)^2 = 22.5\% \end{cases}$$



Luminosity [fb^-1]
10^3
10^2
10^1
10^0
1000
1500
2000
2500
3000
M_{W_C} [GeV]
5σ
3σ
2σ
√s = 14TeV



Luminosity [fb^{-1}]
10^3
10^2
10^1
10^0
1000
1500
2000
2500
3000
M_{W_C} [GeV]
5σ
(15 events)
3σ
(5 events)
2σ
(3 events)
$\sqrt{s} = 14 TeV$

Higgsless Models

"Collider Phenomenology of the Higgsless Models"

A. Birkedal, K. Matchev & M. Perelstein,

PRL94 191803 (2005)

Higgsless model???

In extra dimensions,
the gauge symmetry can be broken by BCs
⇒ New possibility

SU(2) x U(1) -> U(1)em by BCs
without a Higgs boson???

Immediate question:
How unitarizes W/Z scattering amplitudes
without Higgs???

(Warped) Model

Csaki, Grojean, Pilo & Terning (2003)

AdS5 on an interval $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to U(1)_{em}$

$SU(2)_L \times U(1)_{B-L}$
$\downarrow$
$U(1)_Y$

$$A_\mu^{R\pm} = 0$$

$$g_5{}' B_\mu - g_5 A_\mu^{R3} = 0$$

$$\partial_5 \left(g_5 B_\mu + g_5{}' A_\mu^{R3} \right) = 0$$

$SU(2)_L \times SU(2)_R$
$\downarrow$
$SU(2)_D$

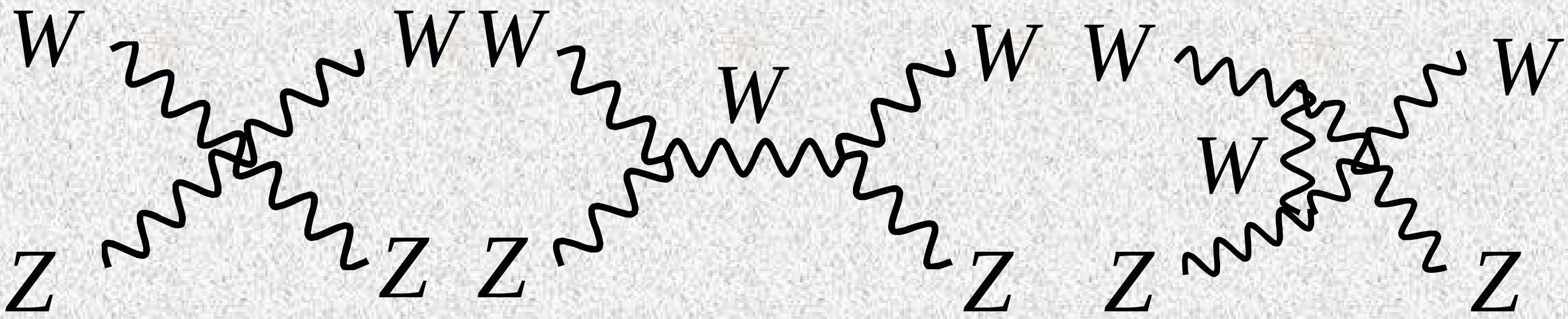
$$A_\mu^{La} - A_\mu^{Ra} = 0$$

$$\partial_5 \left(A_\mu^{La} + A_\mu^{Ra} \right) = 0$$

Planck

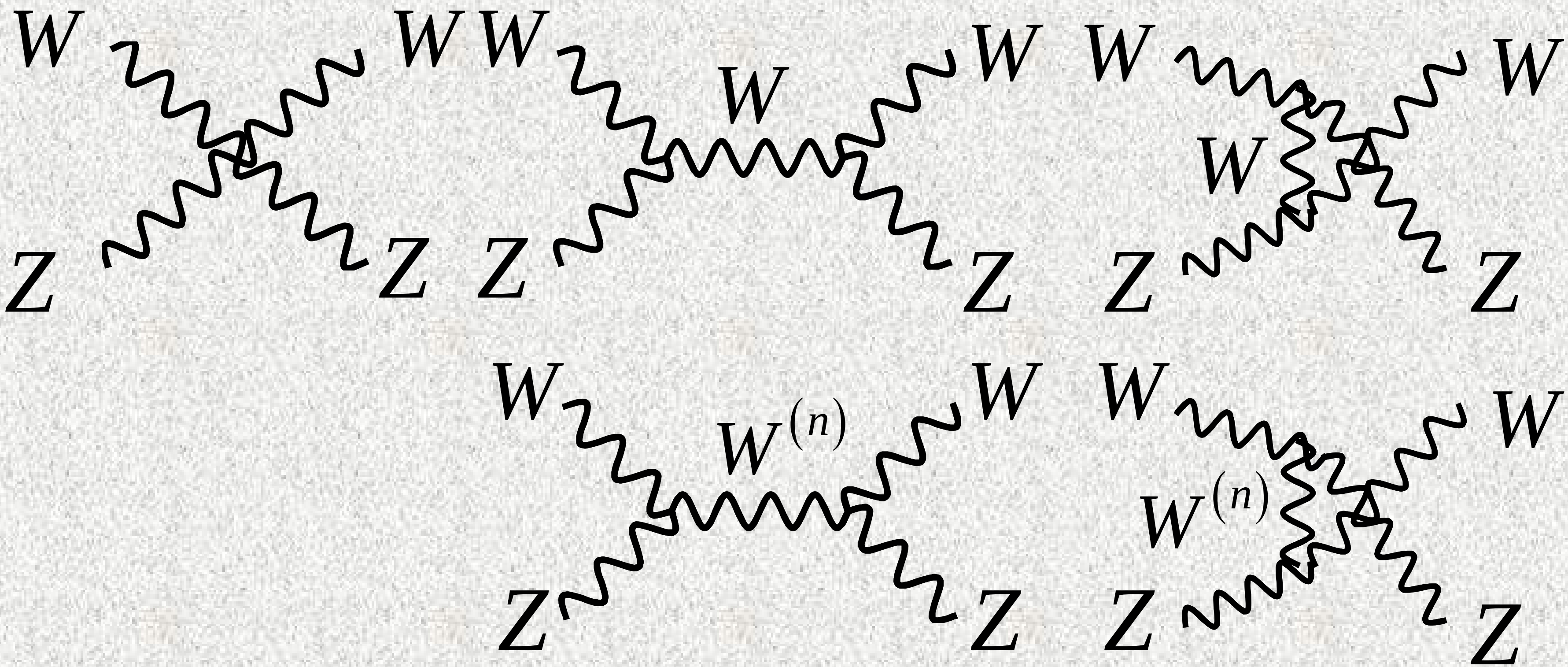
TeV

$$W_L^{\pm} Z_L \to W_L^{\pm} Z_L$$



$$\mathcal{A} = A^{(4)} \left(\frac{E}{M_n} \right)^4 + A^{(2)} \left(\frac{E}{M_n} \right)^2 + A^{(0)} + \mathcal{O}\left(\frac{M_n^2}{E^2} \right) \left(E \gg M_n \right)$$

$$W_L^{\pm} Z_L \to W_L^{\pm} Z_L$$



$$\mathcal{A} = A^{(4)}\left(\frac{E}{M_n}\right)^4 + A^{(2)}\left(\frac{E}{M_n}\right)^2 + A^{(0)} + \mathcal{O}\left(\frac{M_n^2}{E^2}\right) \quad (E \gg M_n)$$

Necessary conditions for unitarity

$$g_{WWZZ} = g_{WWZ}^2 + \sum_n \left(g_{WZW^{(n)}} \right)^2 \leftarrow O\left(E^4\right) = 0$$

$$2\left(g_{WWZZ} - g_{WWZ}^2\right)\left(M_W^2 + M_Z^2\right) + g_{WWZ}^2 \frac{M_Z^4}{M_W^2}$$

$$= \sum_n \left(g_{WZW^{(n)}} \right)^2 \left[3\left(M_{W^\pm}^{(n)}\right)^2 - \frac{\left(M_Z^2 - M_W^2\right)^2}{\left(M_{W^\pm}^{(n)}\right)^2} \right] \leftarrow O\left(E^2\right) = 0$$

These sum rules are automatically satisfied by higher dimensional gauge invariance

This sum rule can be satisfied by only the 1st KK mode in a good approximation

$$g_{WZW^{(1)}} \le \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W^\pm}^{(1)} M_W}$$

$$g_{WZV}^{(1)} \le \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W^\pm}^{(1)} M_W}$$

$g_{WZW^{(1)}} \le 0.04$ for

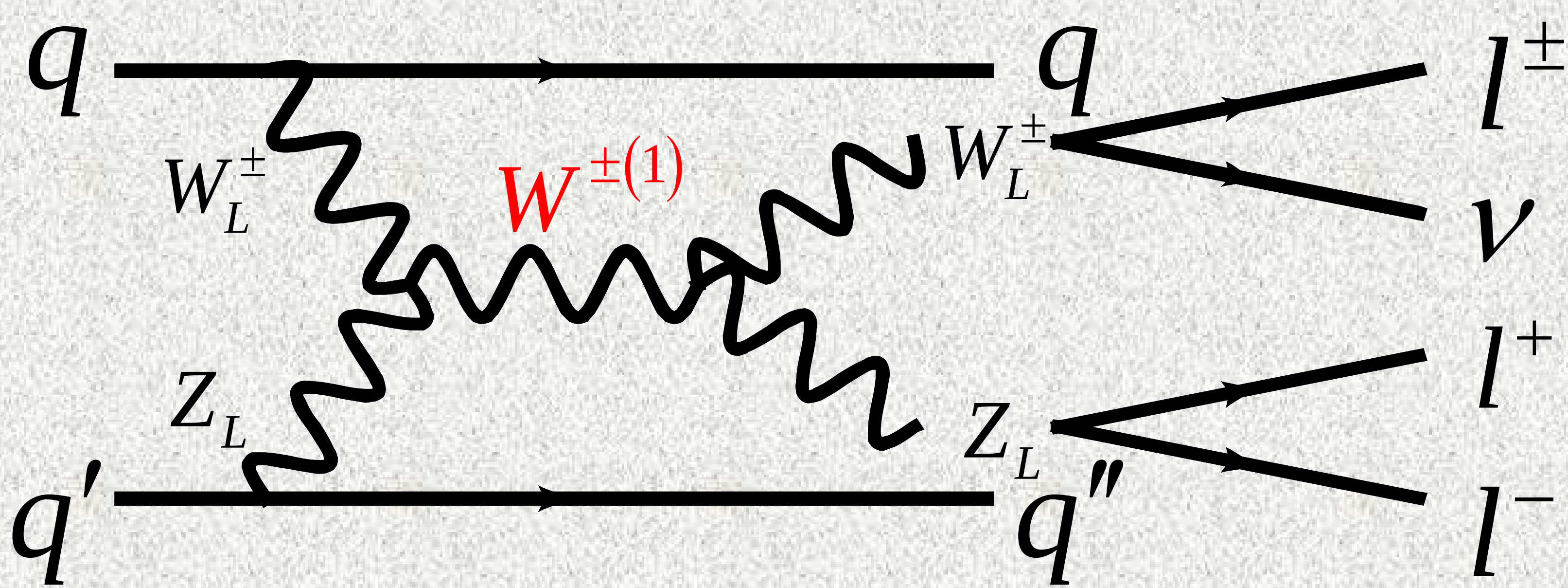
$M_{W^\pm}^{(1)} \ge 700 GeV \left(CDF \right)$

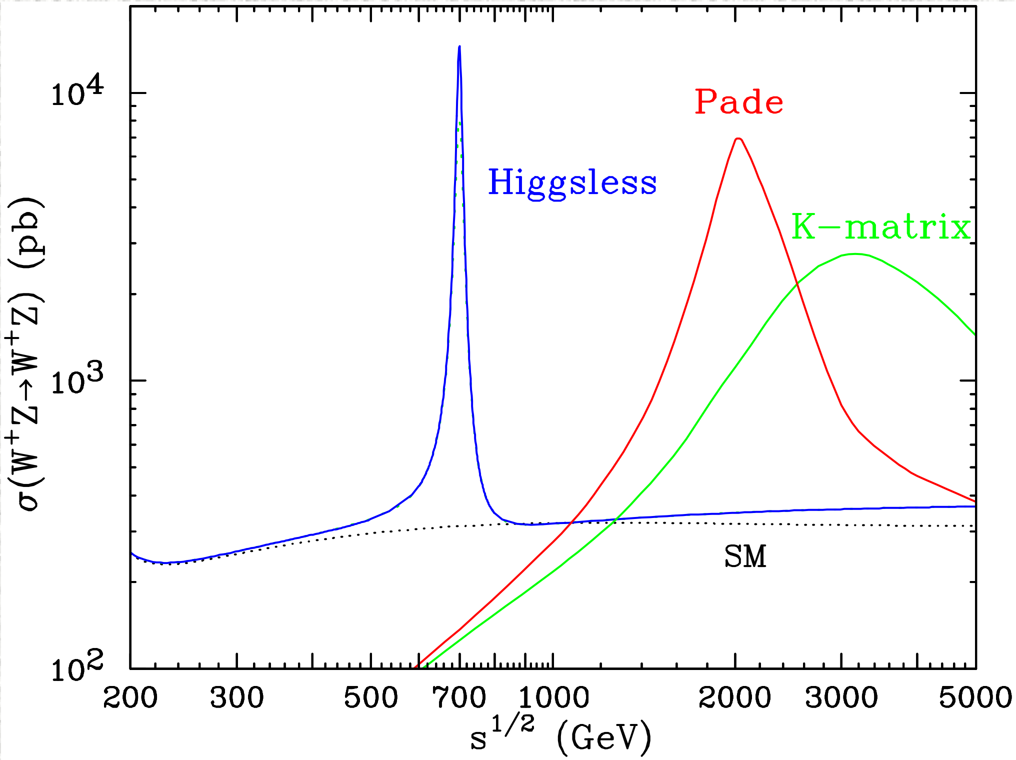
Check this rule by measuring $M_{W^\pm}^{(1)}$ and $g_{WZW^{(1)}}$

(Independent of model-building details)

"gold-plated" events

$$W^{\pm(1)} \to W^\pm Z \to 3l + \nu$$





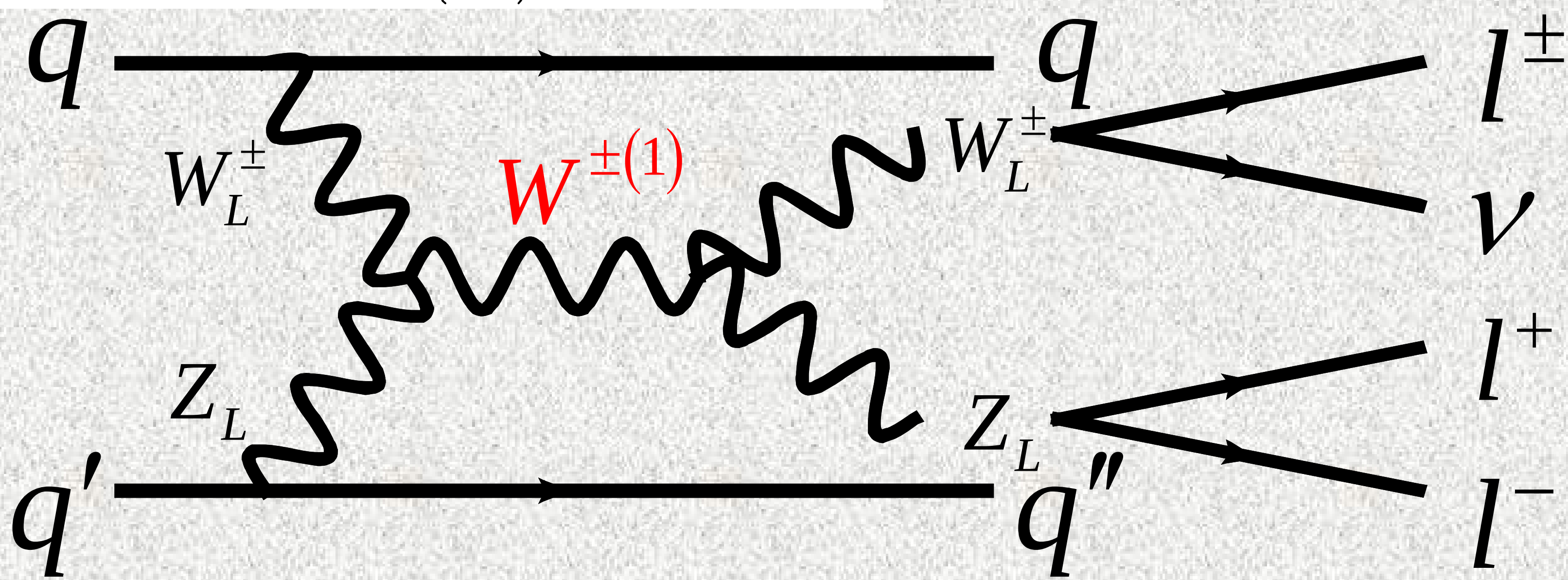
$g_{WZW^{(1)}} \leq 0.04$ for

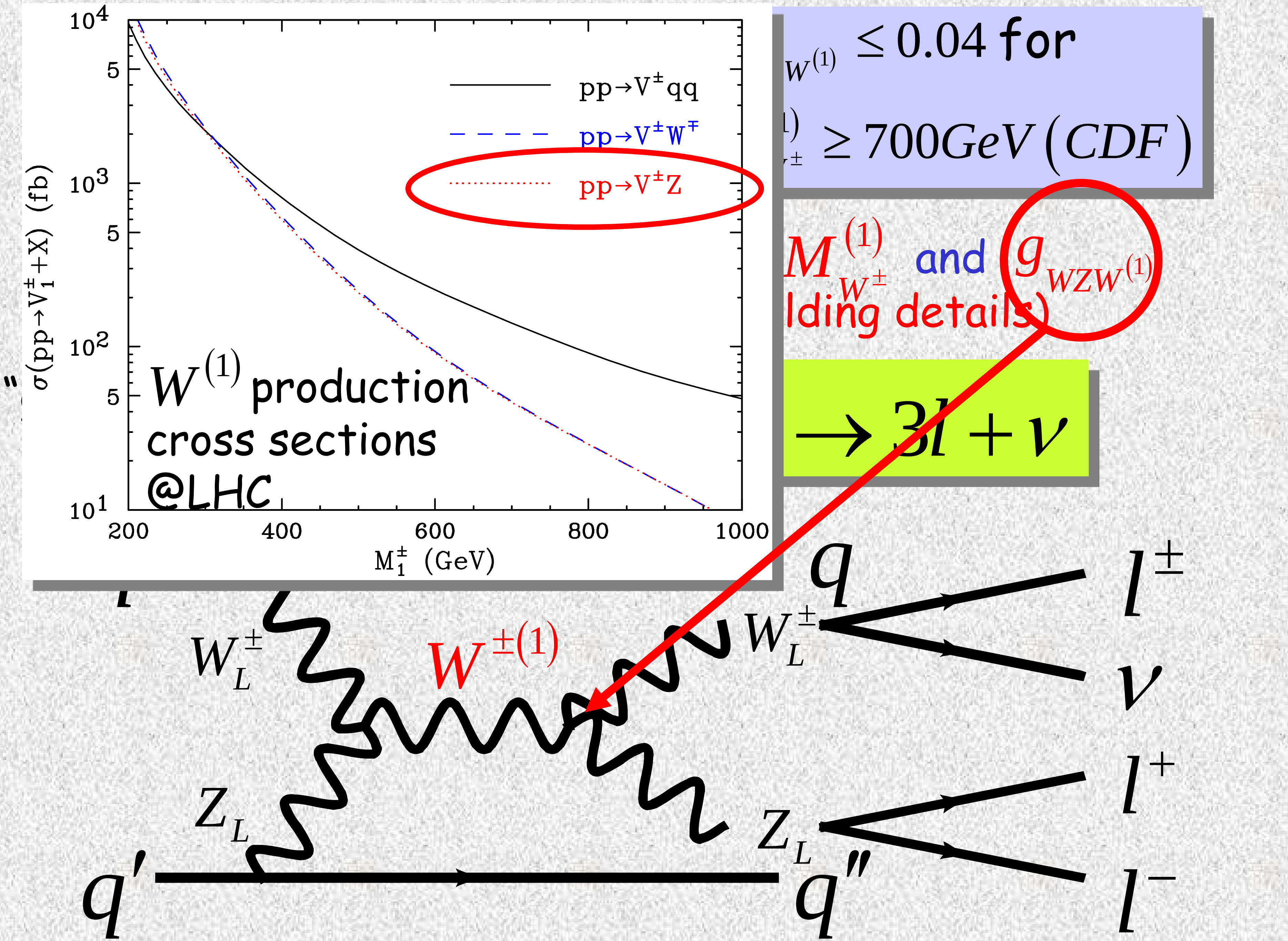
$M_{W^\pm}^{(1)} \geq 700 GeV\,(CDF)$

ing $M_{W^\pm}^{(1)}$ and $g_{WZW^{(1)}}$

-building details)

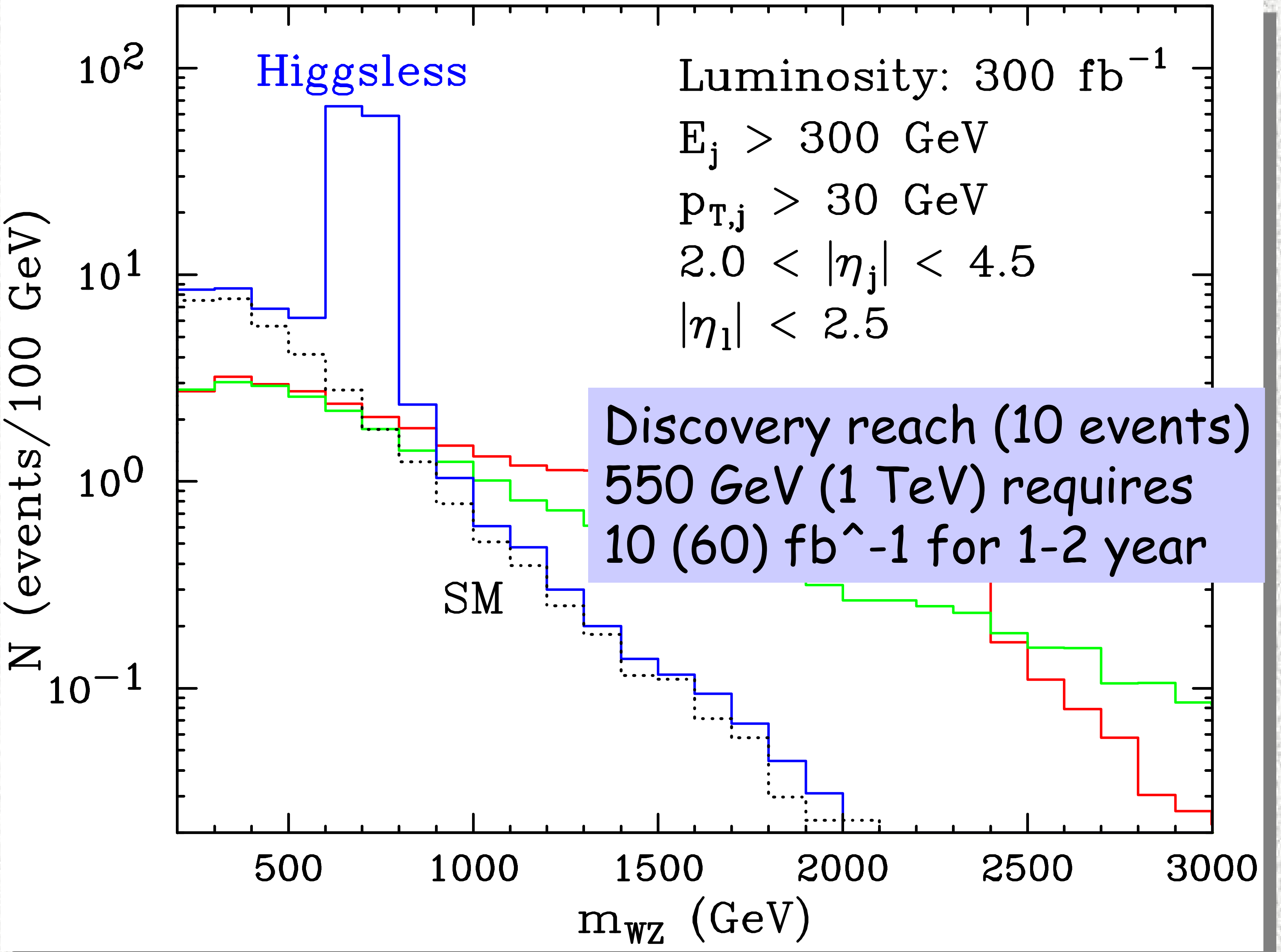
${}^\pm Z \to 3l + \nu$





$W^{(1)}$ ≤ 0.04 for
$\geq 700 GeV\,(CDF)$
$M_{W^{\pm}}^{(1)}$ and $g_{WZW^{(1)}}$
lding details)
$\rightarrow 3l + \nu$
10^4
5
10^3
5
10^2
5
10^1
200
400
600
800
1000
$M_1^{\pm}$ (GeV)
$\sigma(pp\rightarrow V_1^{\pm}+X)$ (fb)
$pp\rightarrow V^{\pm}qq$
$pp\rightarrow V^{\pm}W^{\mp}$
$pp\rightarrow V^{\pm}Z$
$W^{(1)}$ production
cross sections
@LHC
q
$l^{\pm}$
$W_L^{\pm}$
ν
$W^{\pm(1)}$
$W_L^{\pm}$
Z_L
Z_L
l^{+}
l^{-}
q'
q''

of events in the 2jet + 3l + v channel



Discovery reach (10 events)
550 GeV (1 TeV) requires
10 (60) fb^-1 for 1-2 year

Higgs

"Kaluza-Klein Effects on Higgs Physics in Universal Extra Dimensions"

F.J. Petriello, JHEP05 (2002) 003

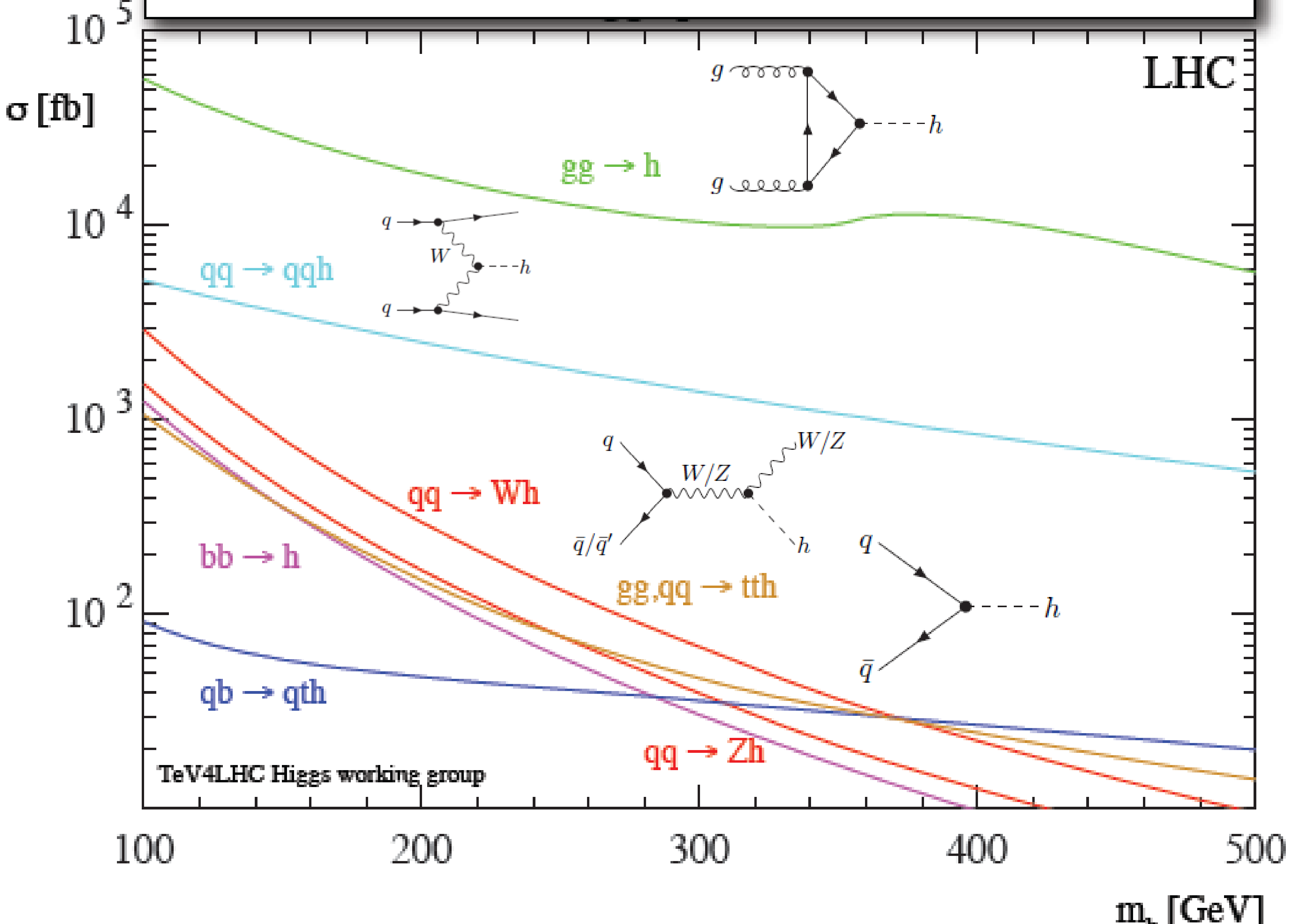
"Gauge-Higgs Unification at the CERN LHC"

N. Maru & N. Okada, PRD77 (2008) 055010

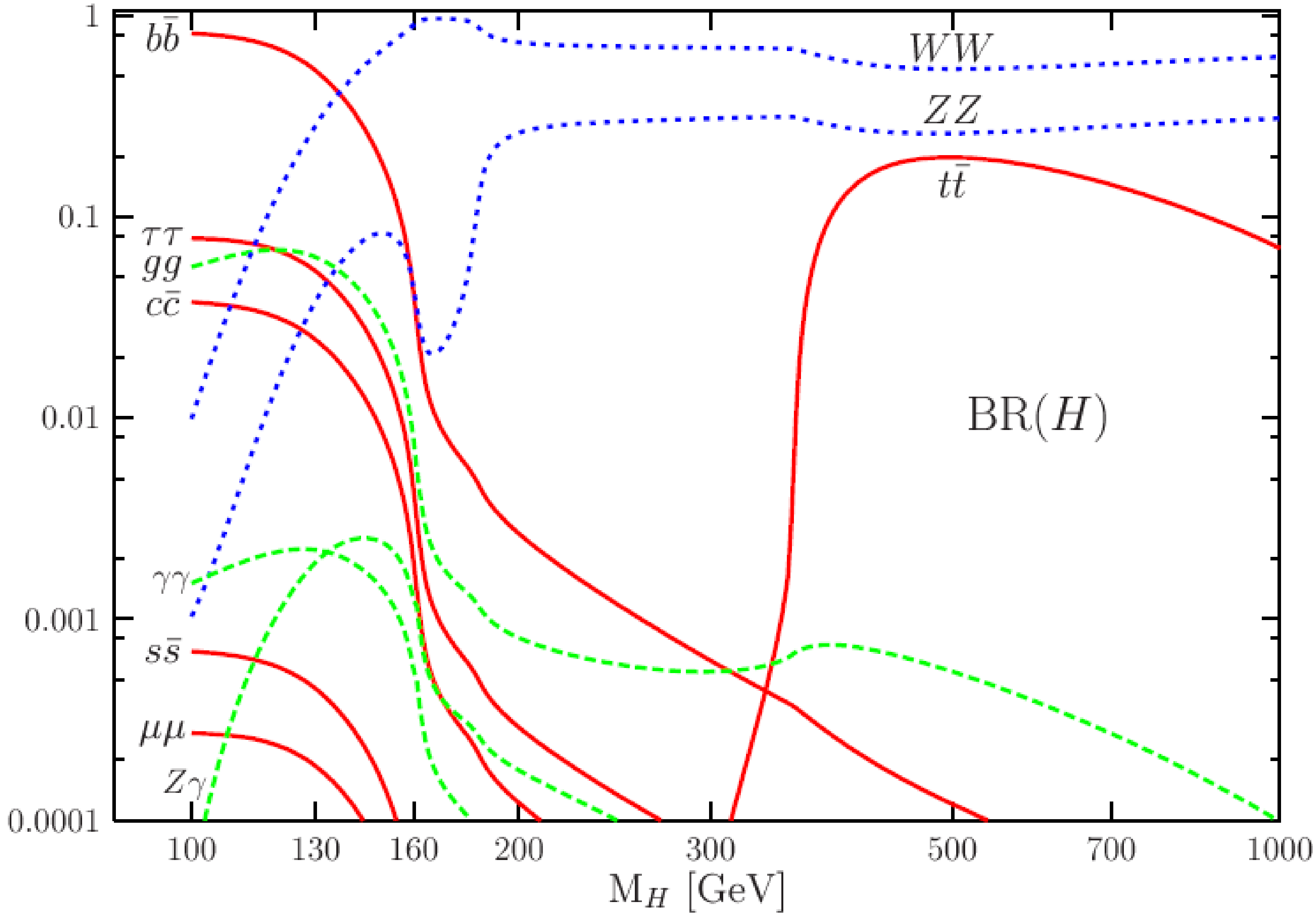
"Higgs Production from Gluon Fusion in Warped Extra Dimensions"

A. Azatov, M. Toharia & L. Zhu, arXiv:1006.5939

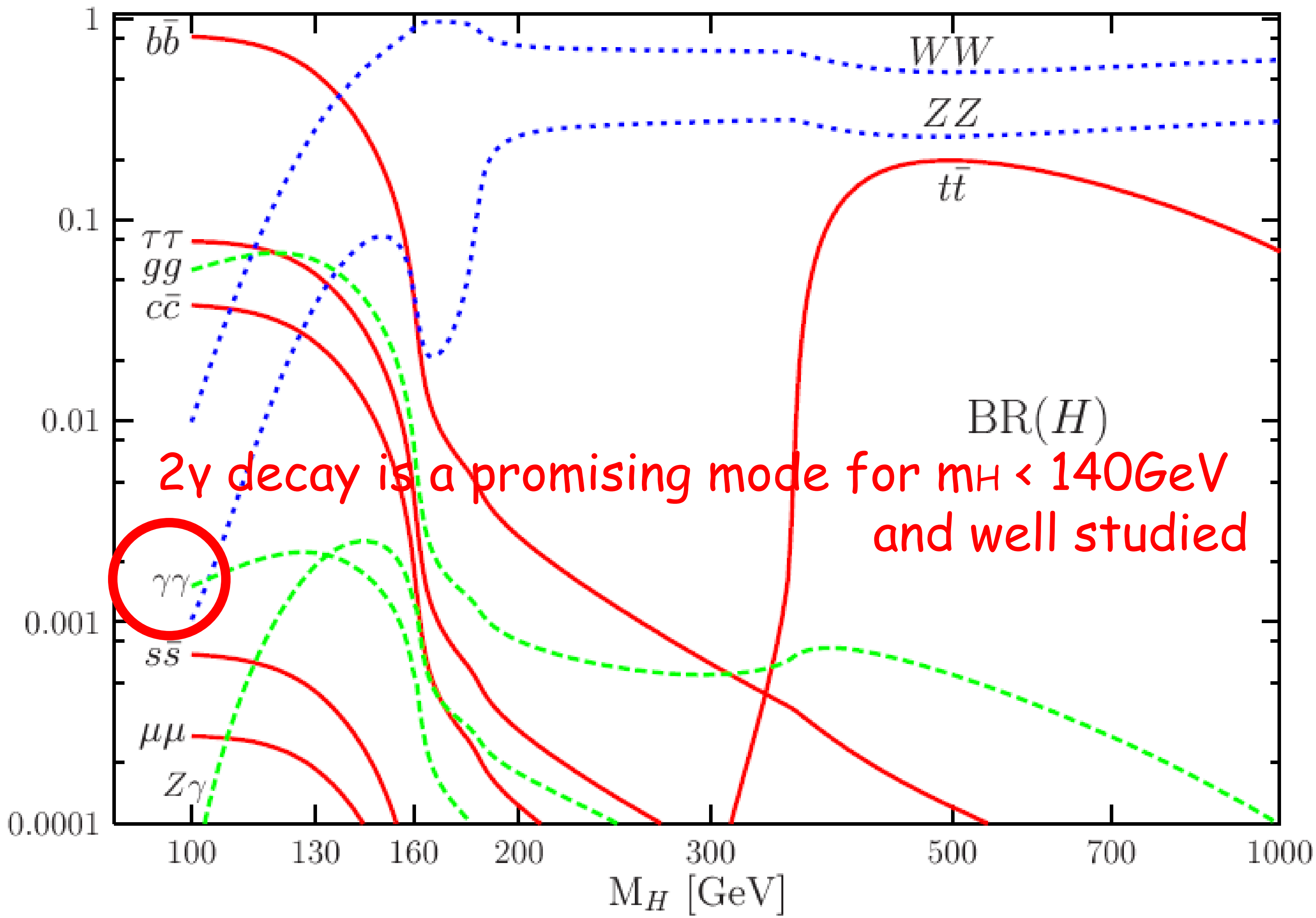
Higgs production cross-section



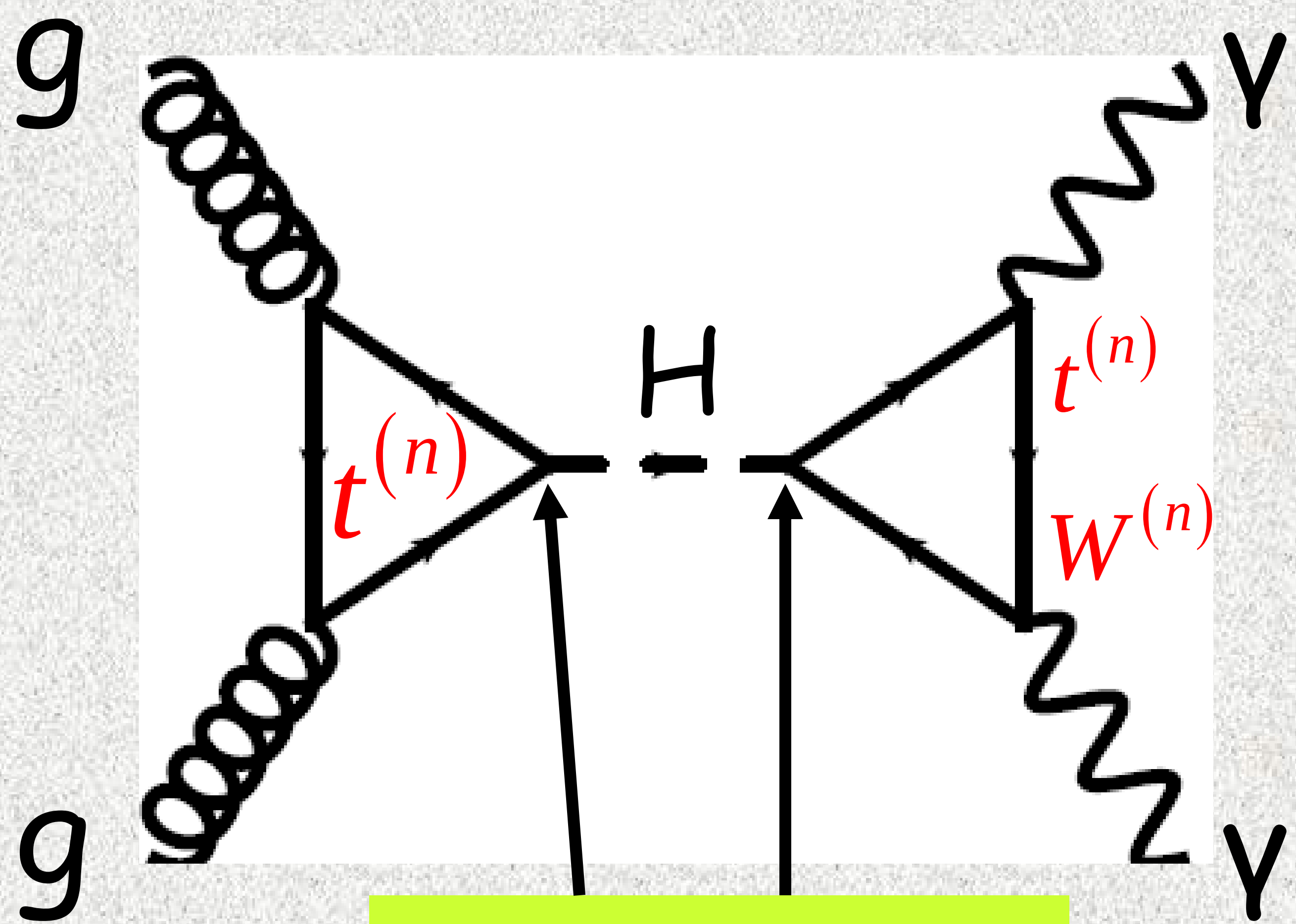
Discovery Mode



Discovery Mode



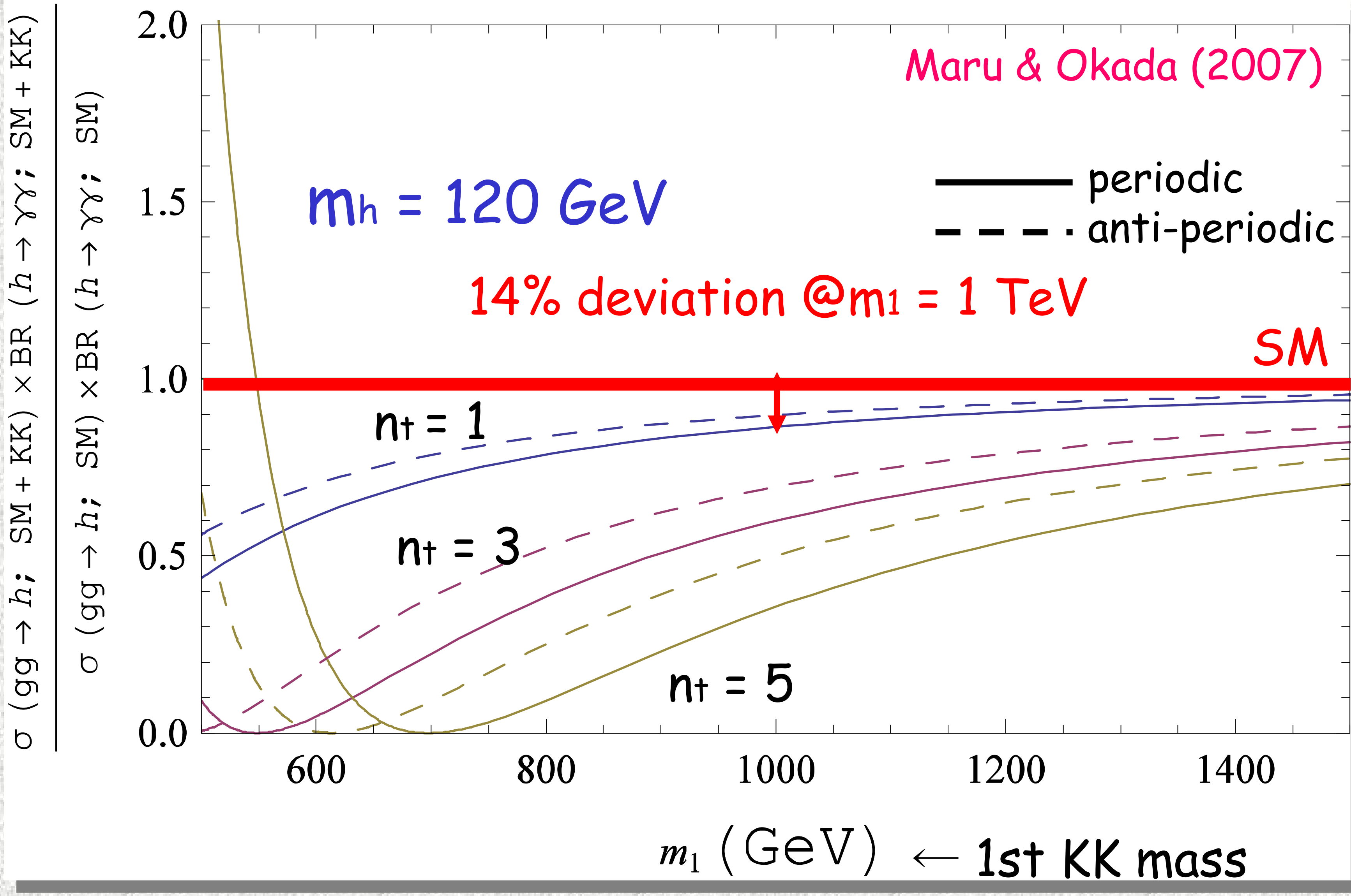
gg -> H -> γγ



Model information

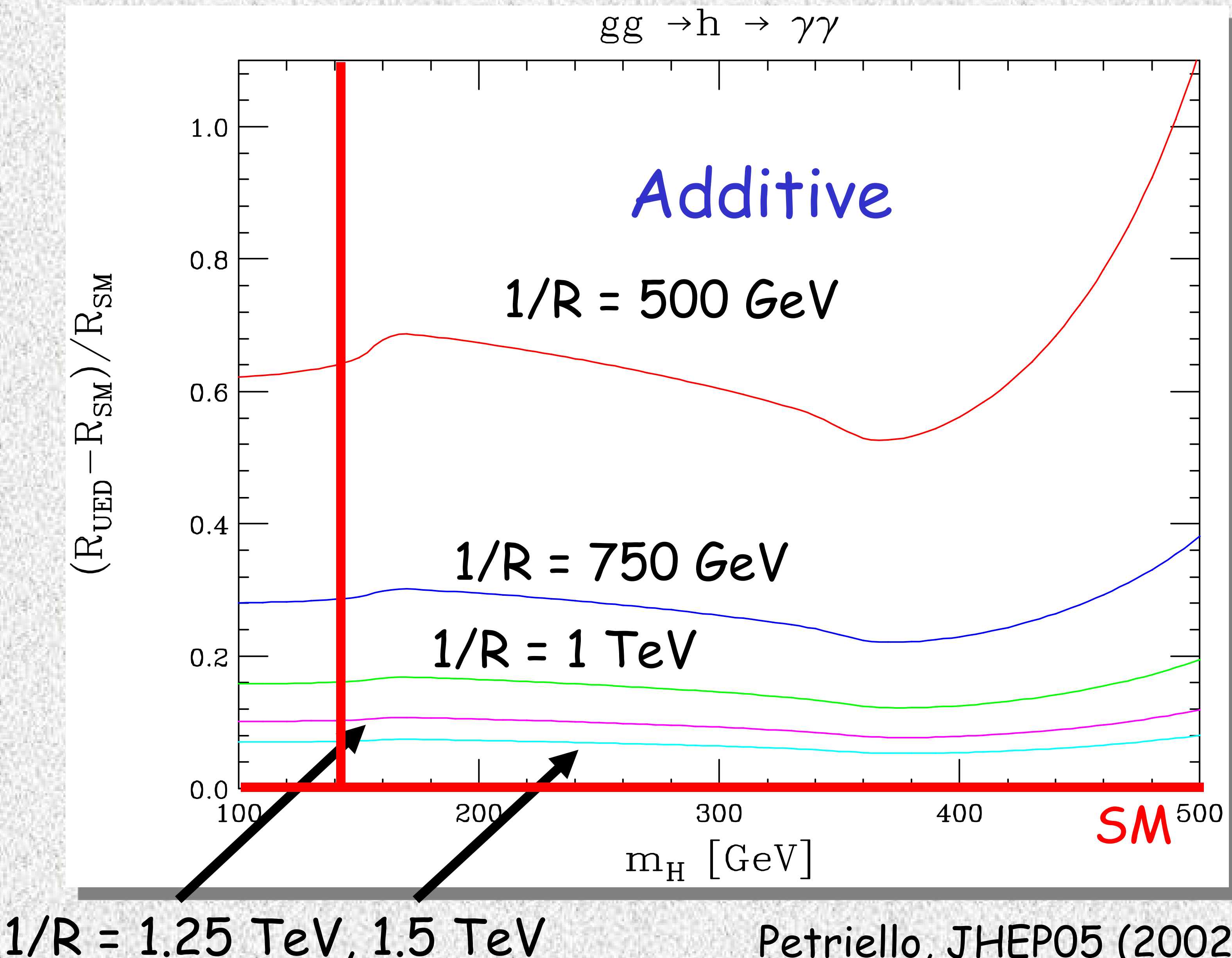
$$y_t, g_W, m_n^{t,W}$$

GHU (5D SU(3))



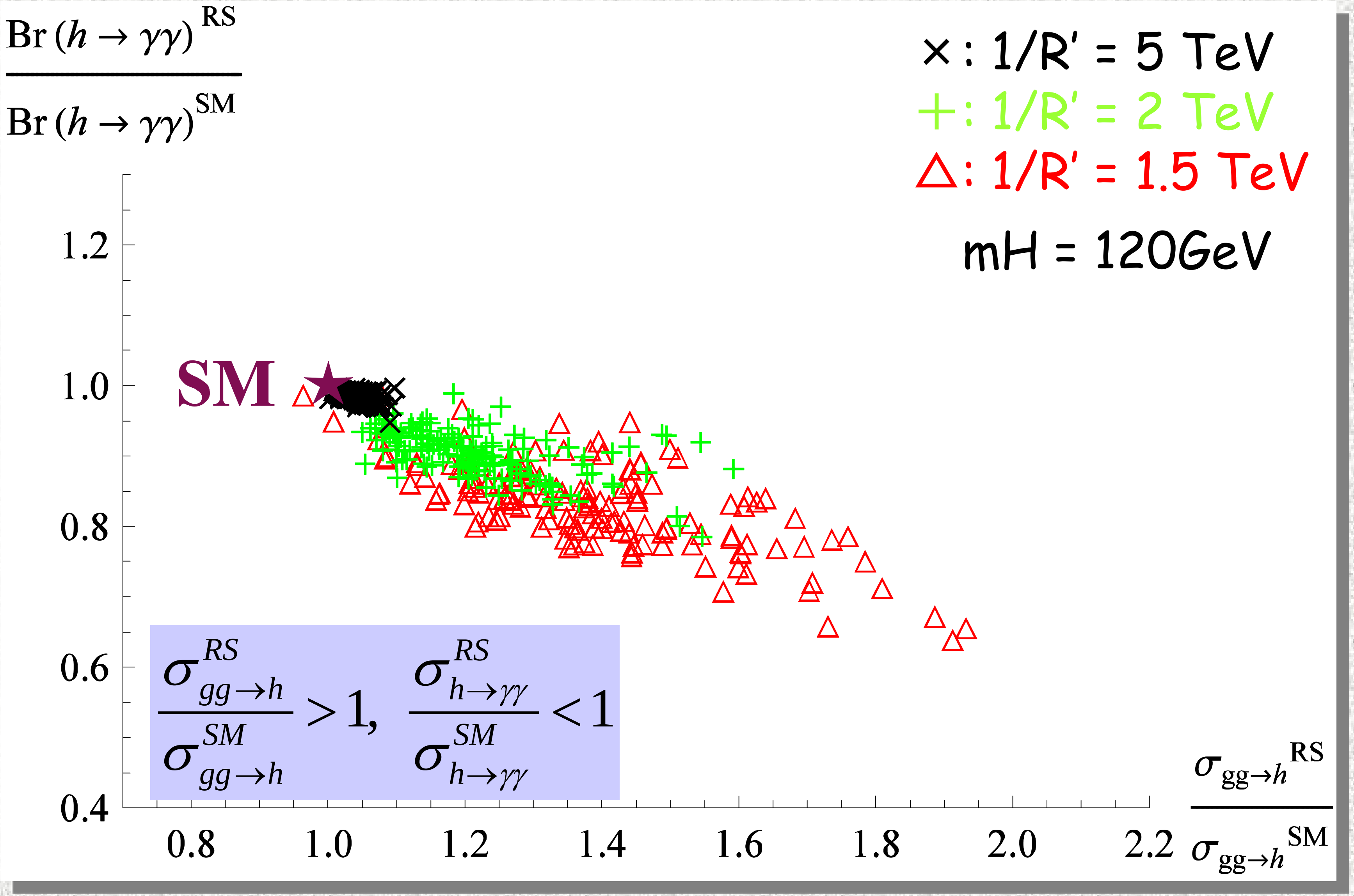
Maru & Okada (2007)
mh = 120 GeV
periodic
anti-periodic
14% deviation @m1 = 1 TeV
SM
nt = 1
nt = 3
nt = 5
2.0
1.5
1.0
0.5
0.0
600
800
1000
1200
1400
σ (gg → h; SM + KK) × BR (h → γγ; SM + KK)
σ (gg → h; SM) × BR (h → γγ; SM)
m1 (GeV) ← 1st KK mass

UED (5D)



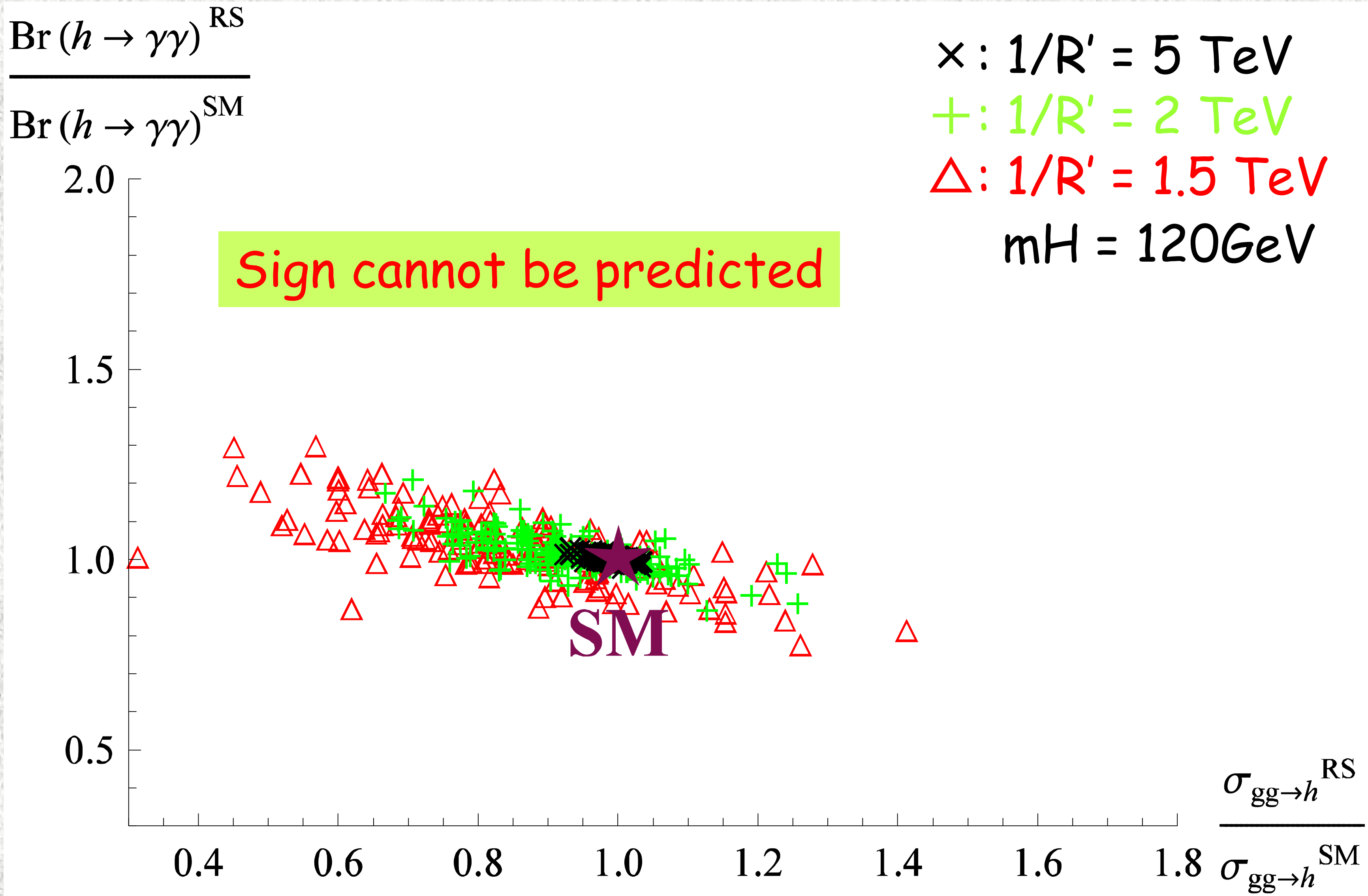
Petriello, JHEP05 (2002) 003

RS with Bulk Higgs



Azatov, Toharia & Zhu, 1006.5939

RS with Brane Higgs



Azatov, Toharia & Zhu, 1006.5939

Radion

"Graviscalars from Higher-Dimensional Metrics and Curvature-Higgs Mixing"

G.F. Giudice, R. Rattazzi & J.D. Wells

"Radion Phenomenology on Realistic Warped Space Models"

C. Csaki, J. Hubisz & S.J. Lee, PRD76 (2007) 125015

Radion is a scalar perturbation of the metric which cannot be gauged away

$$ds^2 = e^{-2(ky+F)}\eta_{\mu\nu} - (1+2F)^2 dy^2$$
$$= \left(\frac{R}{z}\right)^2 \left(e^{-2F}\eta_{\mu\nu}dx^\mu dx^\nu - (1+2F)^2 dz^2\right) \quad \left(R(=1/k) < z < R'(=TeV^{-1})\right)$$

Radion-Matter interaction

$$S_{radion} = -\frac{1}{2}\int d^5x\sqrt{g}T^{MN}\delta g_{MN}$$
$$= \frac{1}{\Lambda_r}\int d^5x\sqrt{g}\left[\left(\frac{z}{R'}\right)^2 r(x)\left(T^\mu_\mu - 2T^{55}g_{55}\right)\right]$$

4D canonically normalized radion r(x)

$$F(z,x) = \frac{1}{\sqrt{6}}\frac{R^2}{R'}\left(\frac{z}{R}\right)^2 r(x) = \frac{r(x)}{\Lambda_r}\left(\frac{z}{R'}\right)^2, \Lambda_r \equiv \frac{\sqrt{6}}{R'}(\approx TeV)$$

Localized on TeV brane

Coupling to the SM fermions

$$\frac{m}{\Lambda_r}\left(c_L - c_R\right) r\bar{\psi}_{UV}\psi_{UV}\left(others\right) \qquad \frac{m}{\Lambda_r} r\bar{\psi}_{IR}\psi_{IR}\left(t_{L,R}, b_L\right)$$

Coupling to massive gauge bosons (W, Z)

$$\left(-1+\frac{3M_W^2}{\Lambda_r^2}\log\left(kR'\right)\right)\frac{2}{\Lambda_r}M_W^2 rW_\mu W^\mu + \left(-1+\frac{3M_Z^2}{\Lambda_r^2}\log\left(kR'\right)\right)\frac{1}{\Lambda_r}M_Z^2 rZ_\mu Z^\mu$$

Coupling to massless gauge bosons (γ, g)

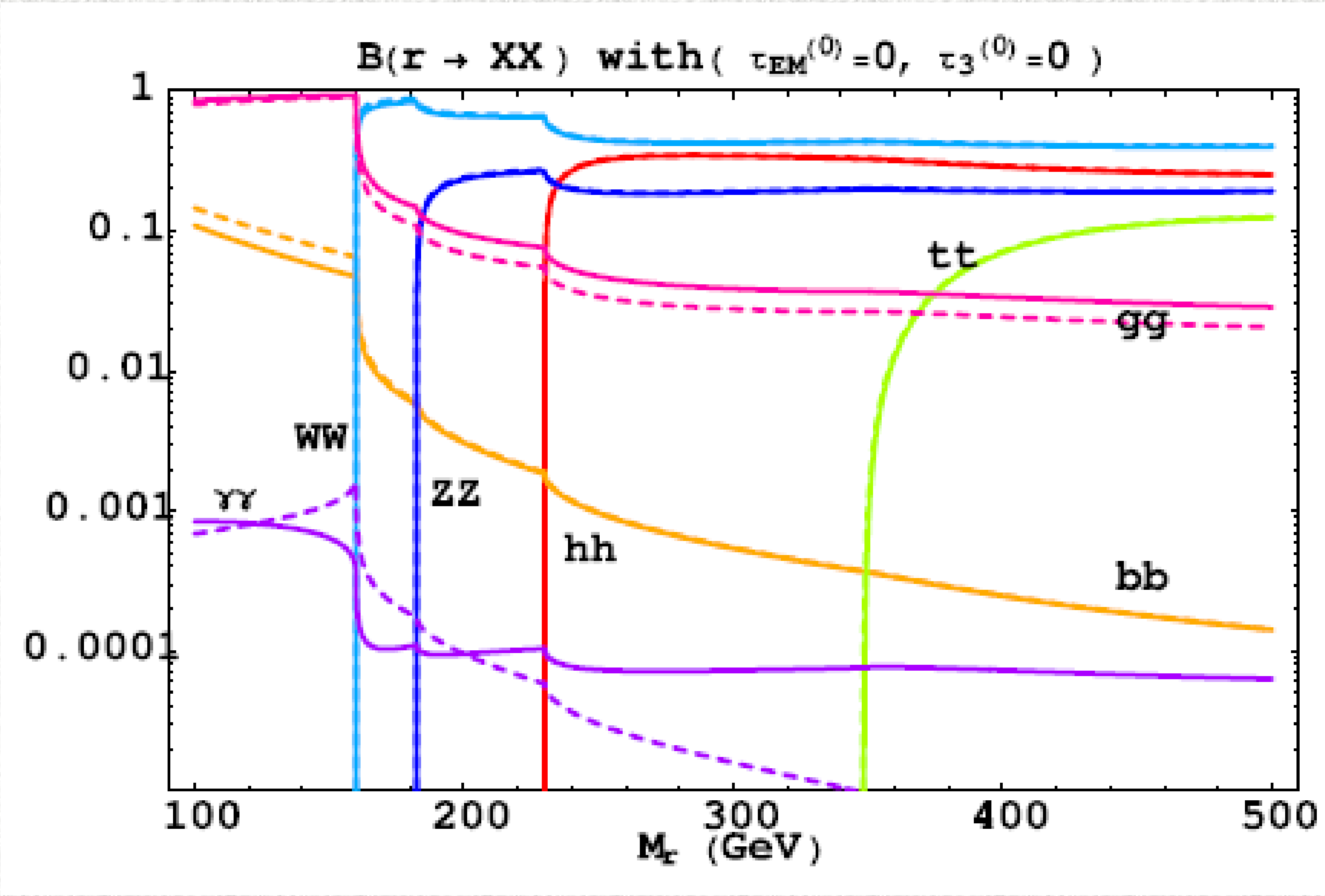
$$-\left[\frac{1-4\pi\alpha\left(\tau_{UV}^{(0)}+\tau_{IR}^{(0)}\right)}{4\log\left(kR'\right)}+\frac{\alpha}{8\pi}\left(b-\sum_i \kappa_i F_i\left(\tau_i\right)\right)\right]\frac{r}{\Lambda_r}F_{\mu\nu}F^{\mu\nu}$$

1-loop effects

Brane kinetic term

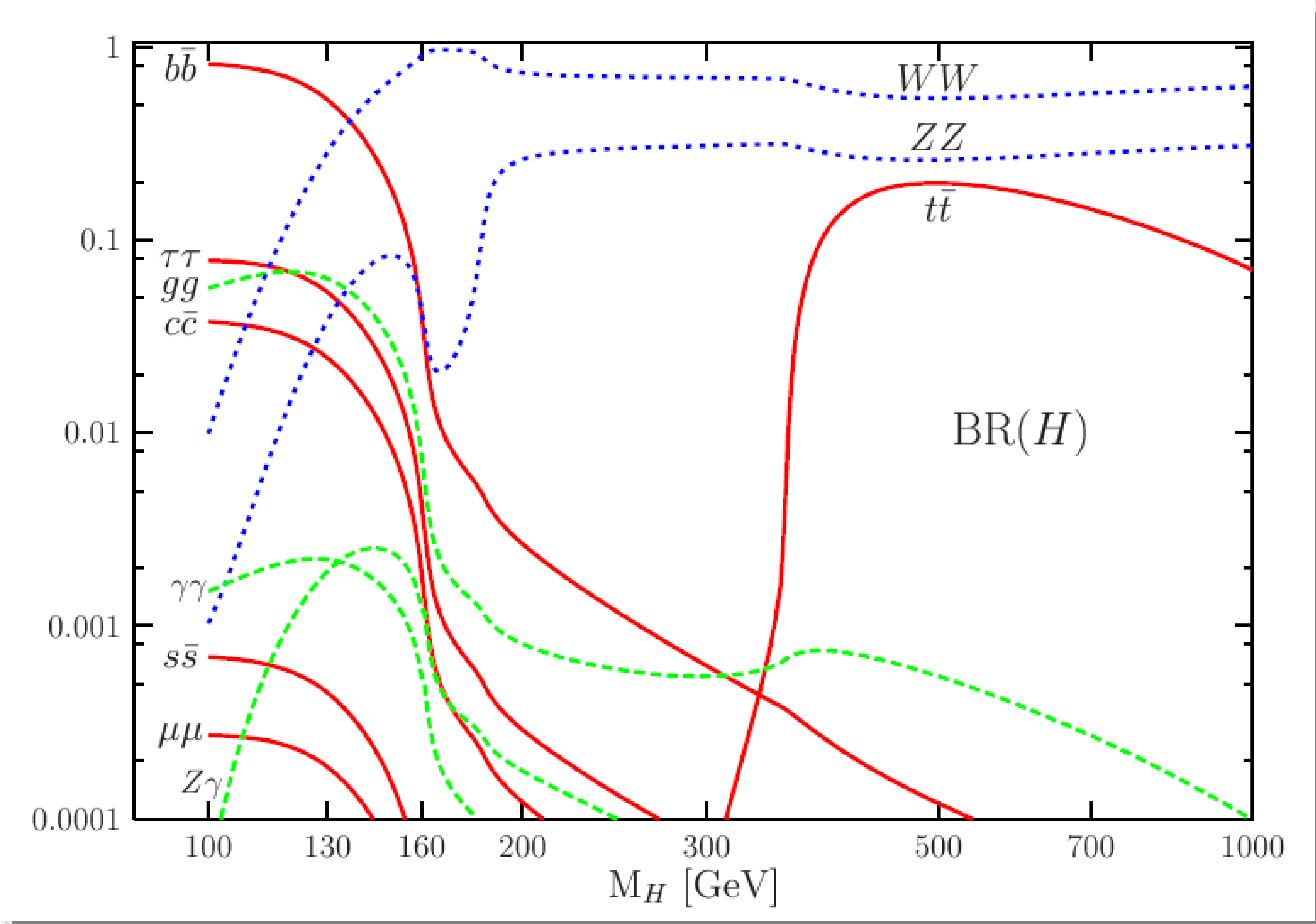
Trace anomaly

Branching fraction of the radion

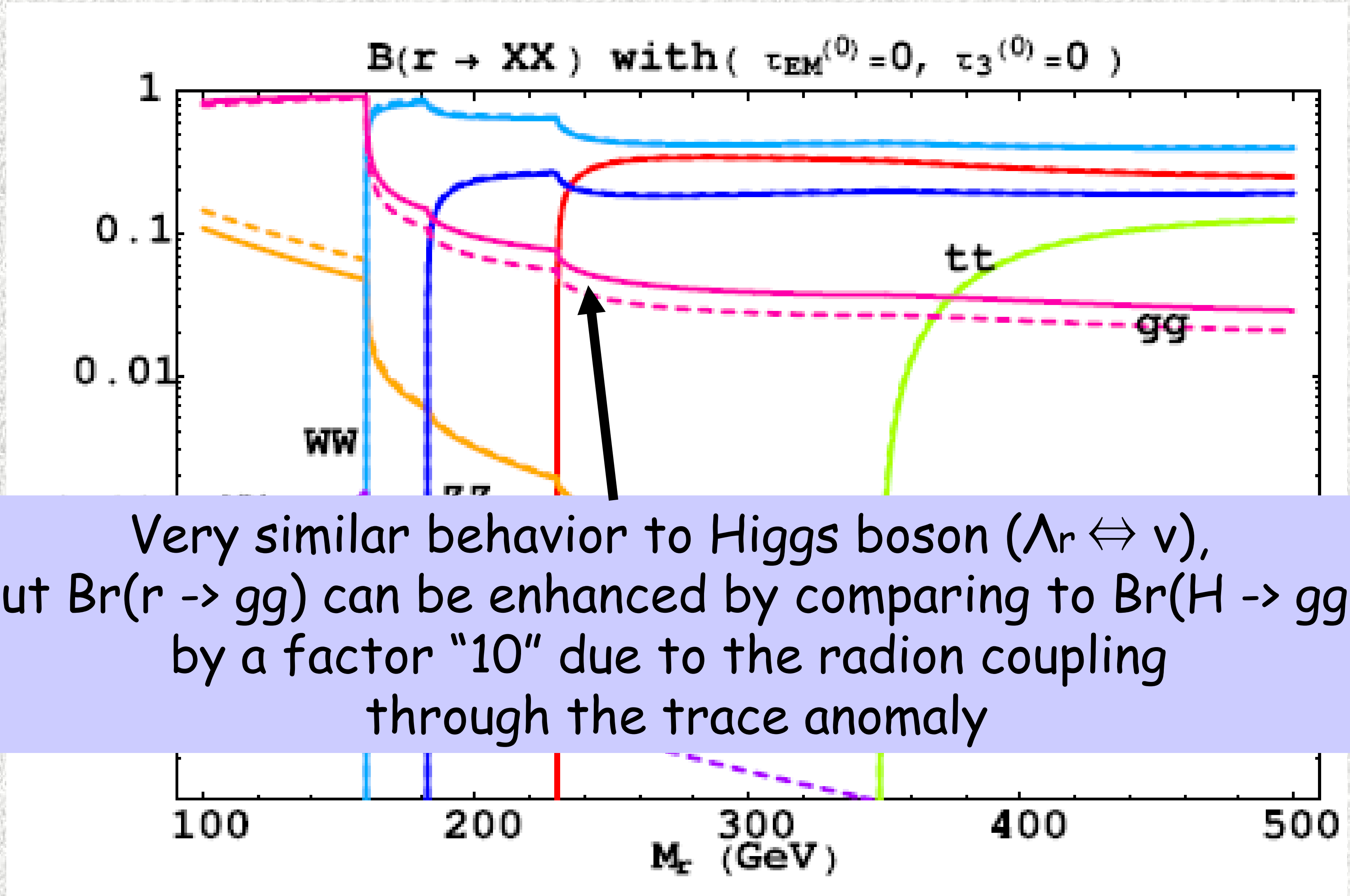


Λ_r = 2 TeV —— Bulk RS1 .... RS1

Branching fraction of Higgs



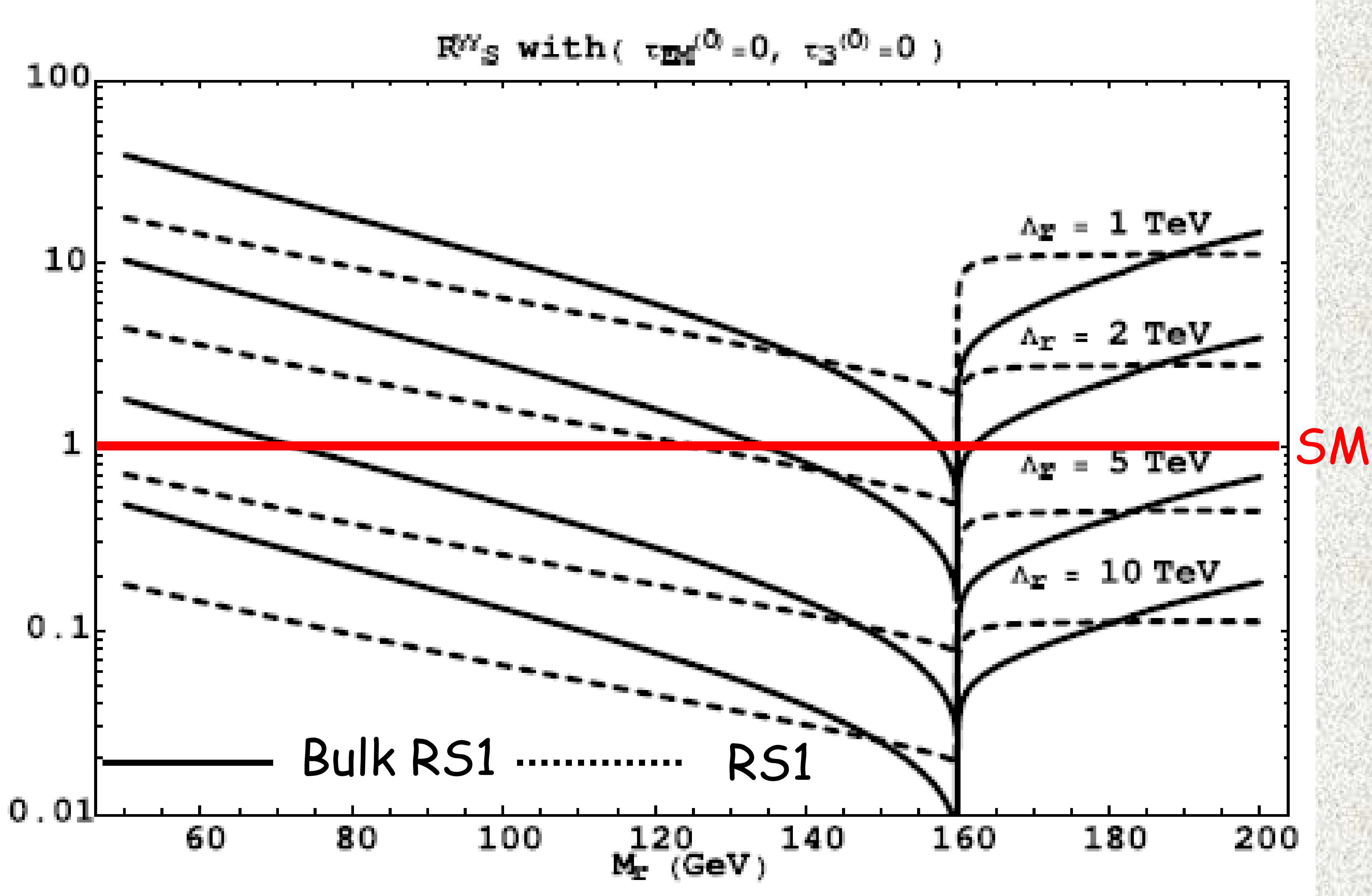
Branching fraction of the radion



Very similar behavior to Higgs boson ($\Lambda_r \Leftrightarrow v$),
but Br(r -> gg) can be enhanced by comparing to Br(H -> gg)
by a factor "10" due to the radion coupling
through the trace anomaly

Λ_r = 2 TeV ——— Bulk RS1 .... RS1

Ratio of gg -> r -> γγ/gg -> H -> γγ



Summary

Now, "Extra Dimensions" as an alternative to solution to the hierarchy problem is no longer alternative

⇒ **KK particles with TeV mass**

These give rise to various collider signatures@LHC!!

Let us expect that the news of discovery of extra dimensions will come soon!!

Backup

KK Gluon

"The Bulk RS KK-gluon at the LHC"

B. Lillie, L. Randall & L-T. Wang, JHEP09 (2007) 074

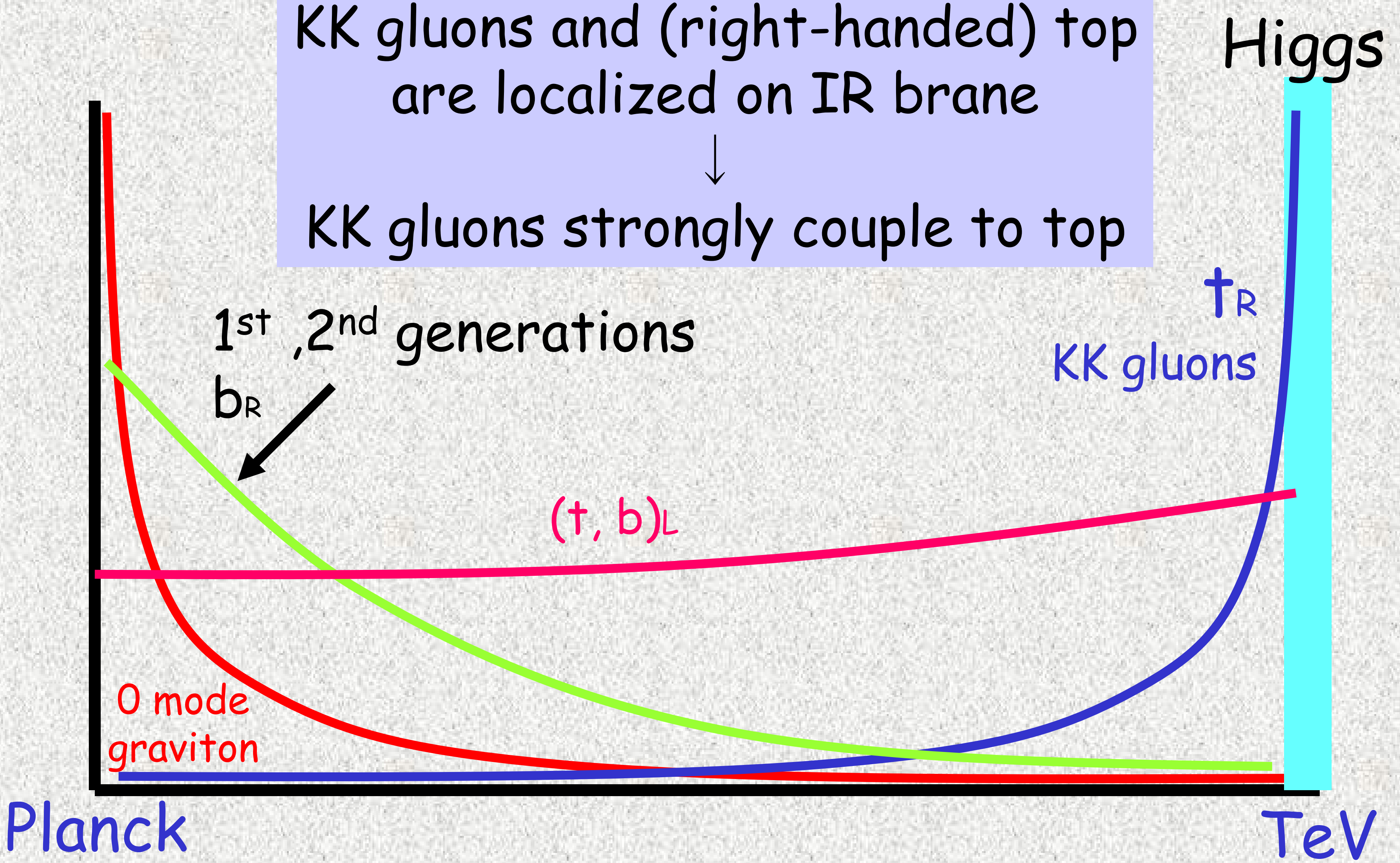
"CERN LHC Signals from Warped Extra Dimensions"

K. Agashe, A. Belyaev, T. Krupovnicas, G. Perez & J. Virzi

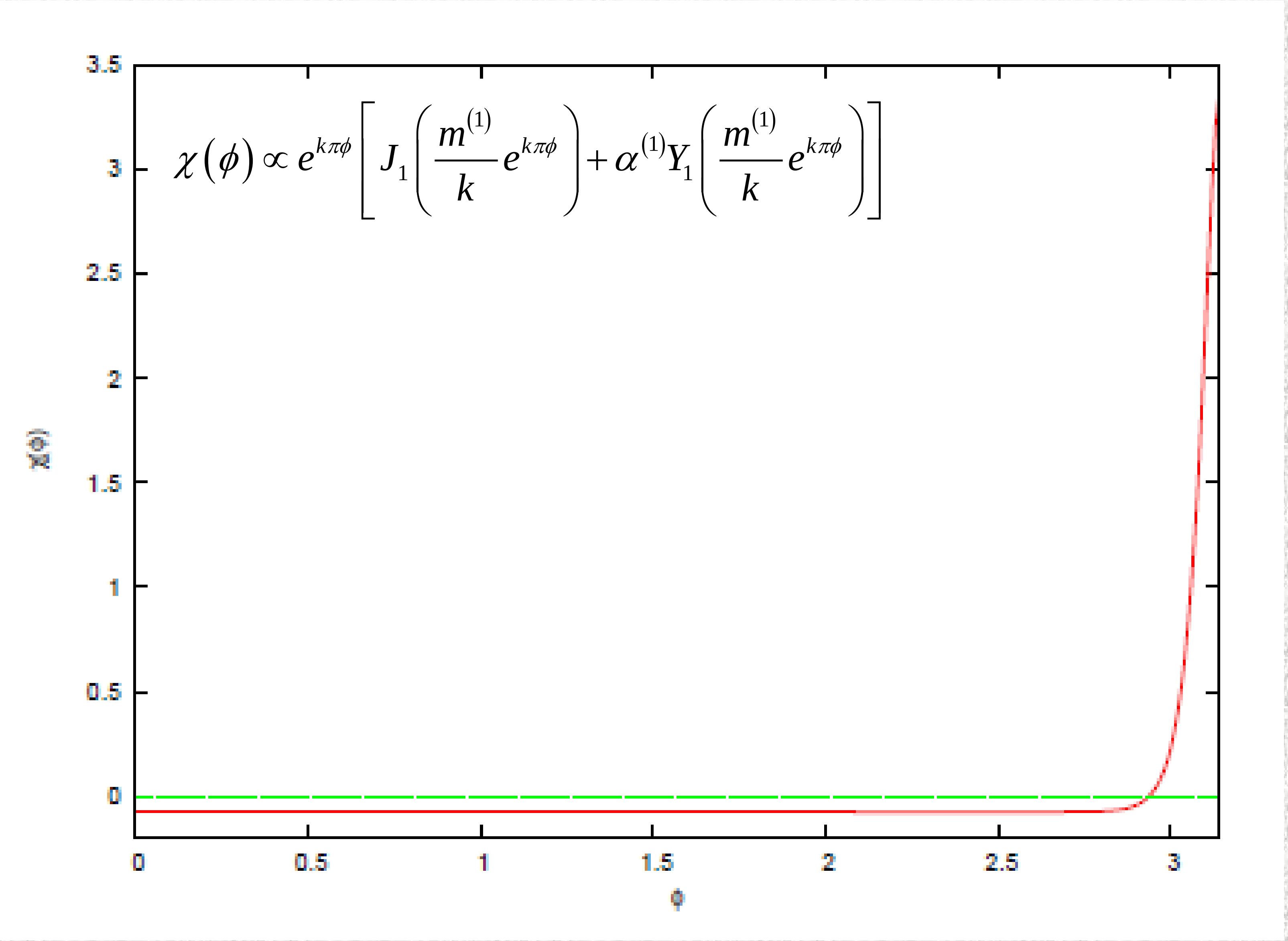
PRD77 (2008) 015003

Bulk SM in RS

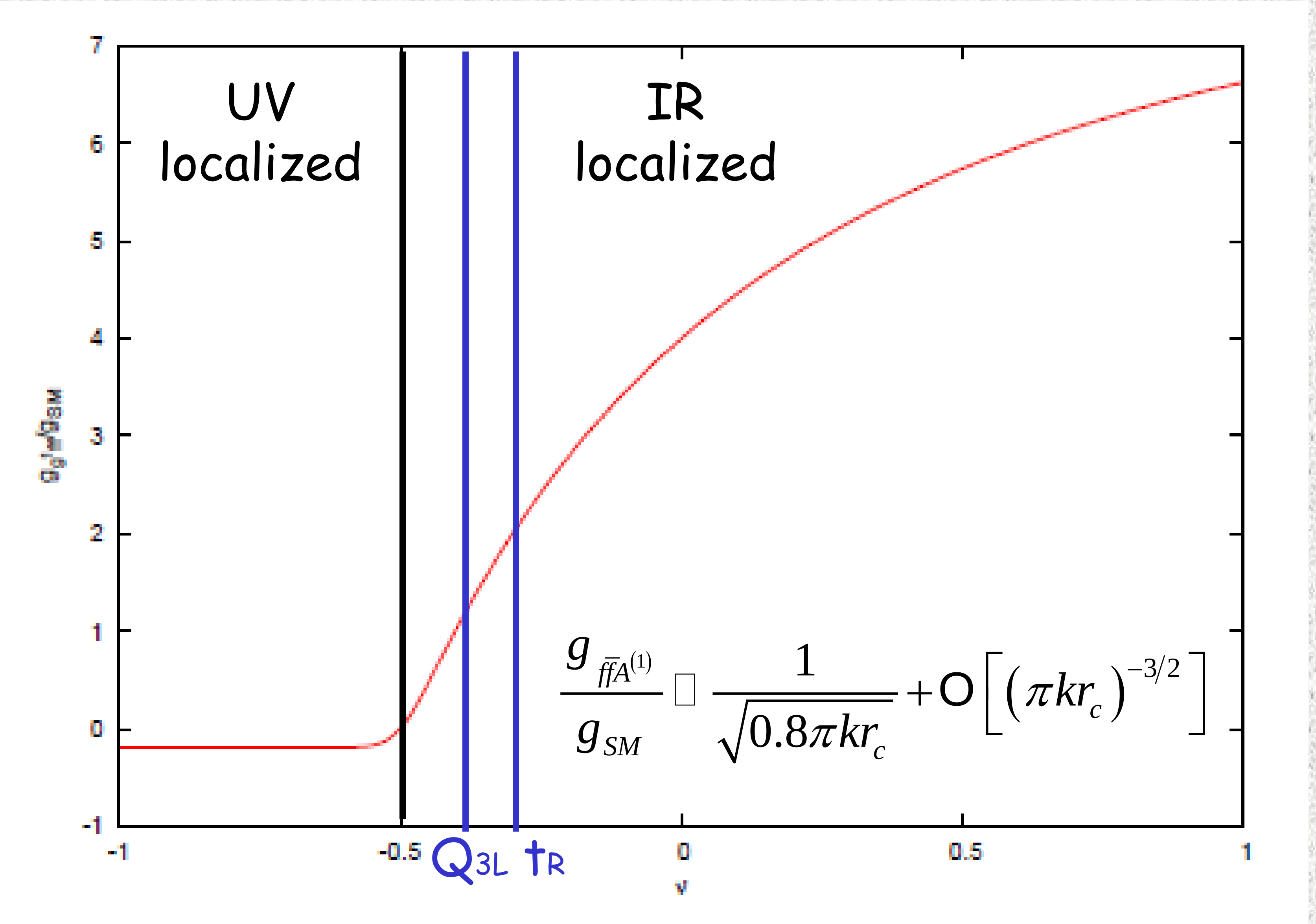
KK gluons and (right-handed) top are localized on IR brane
↓
KK gluons strongly couple to top



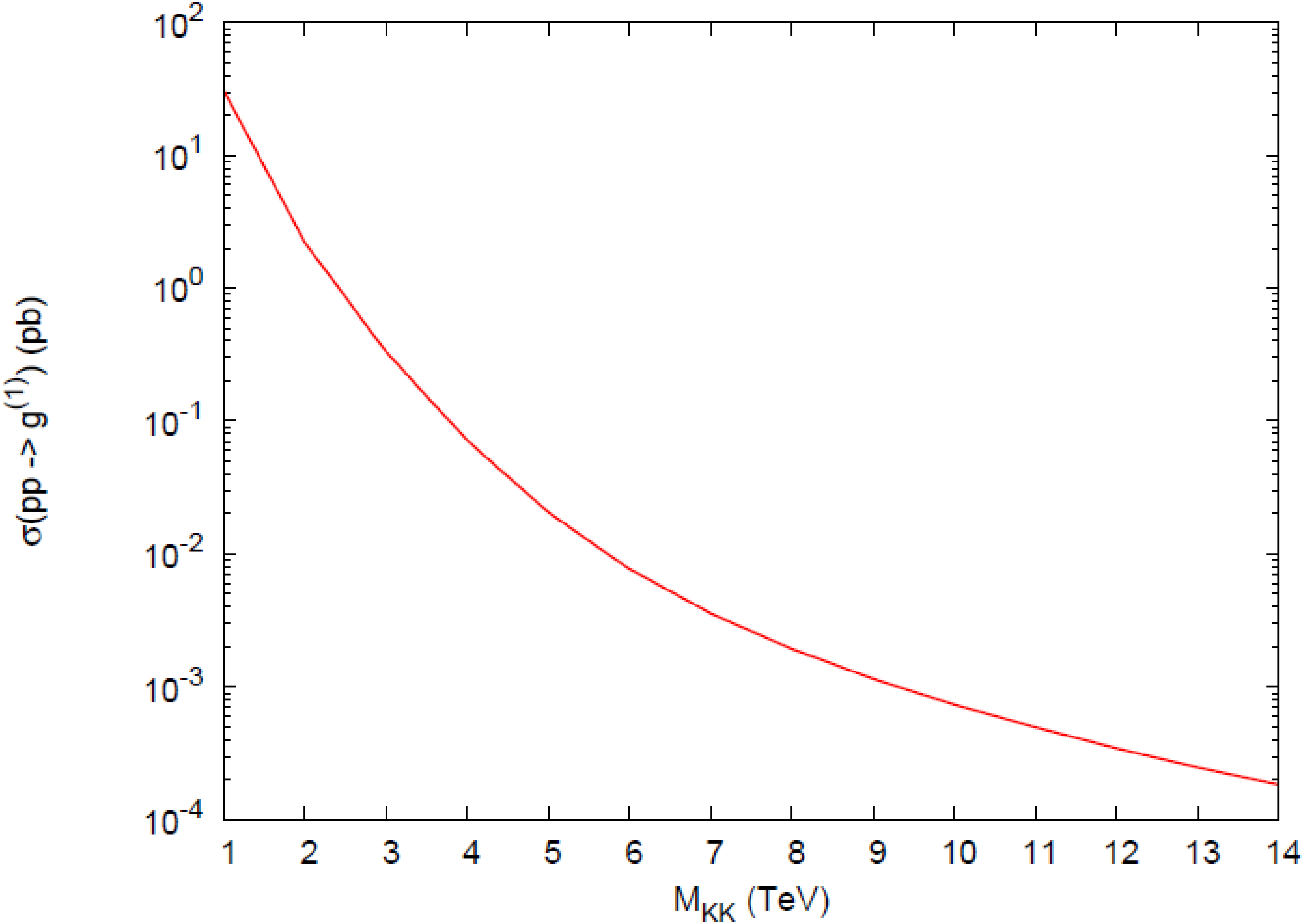
Wave function of 1st KK gluon



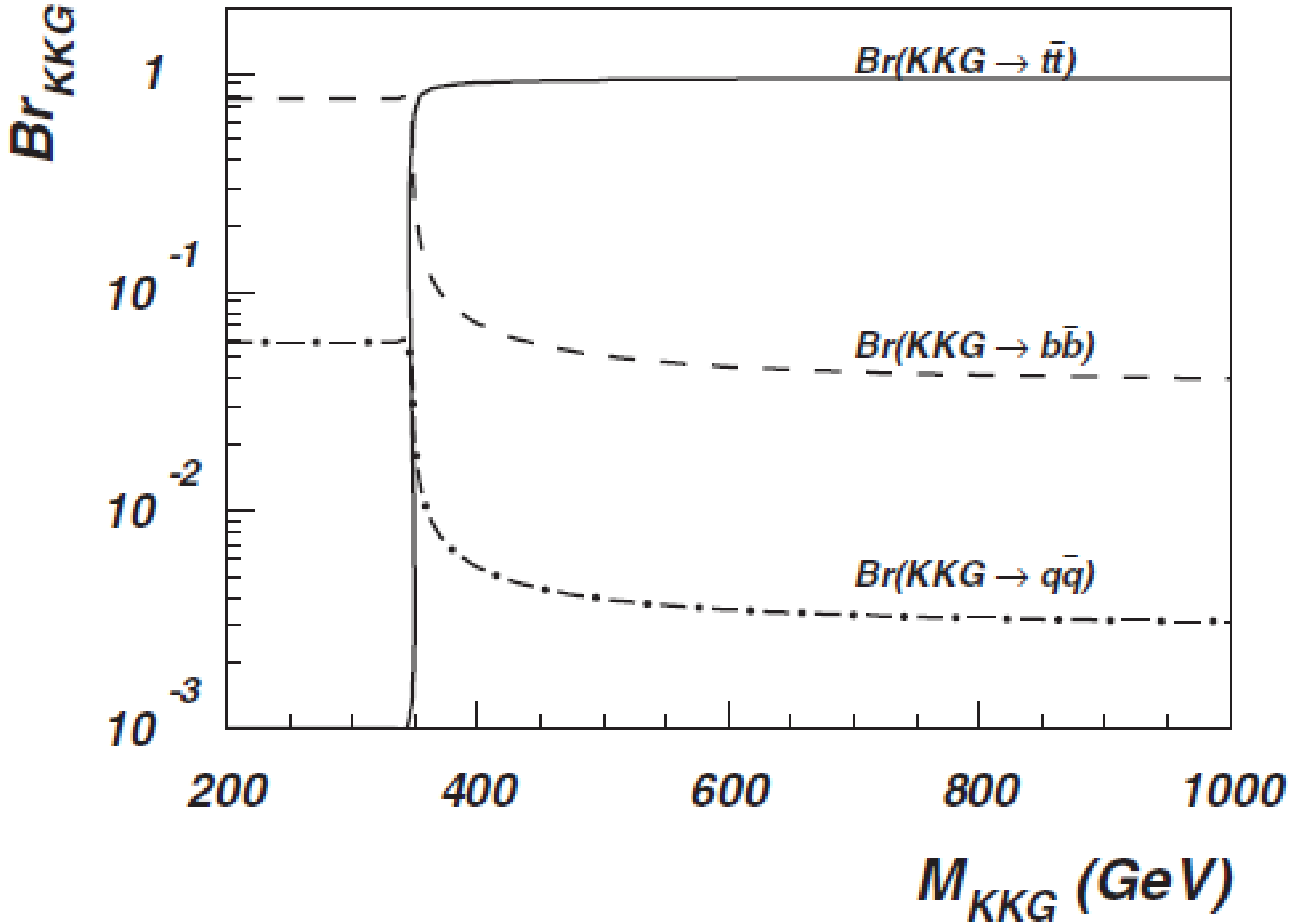
Coupling of 1st KK gluon to zero mode fermion



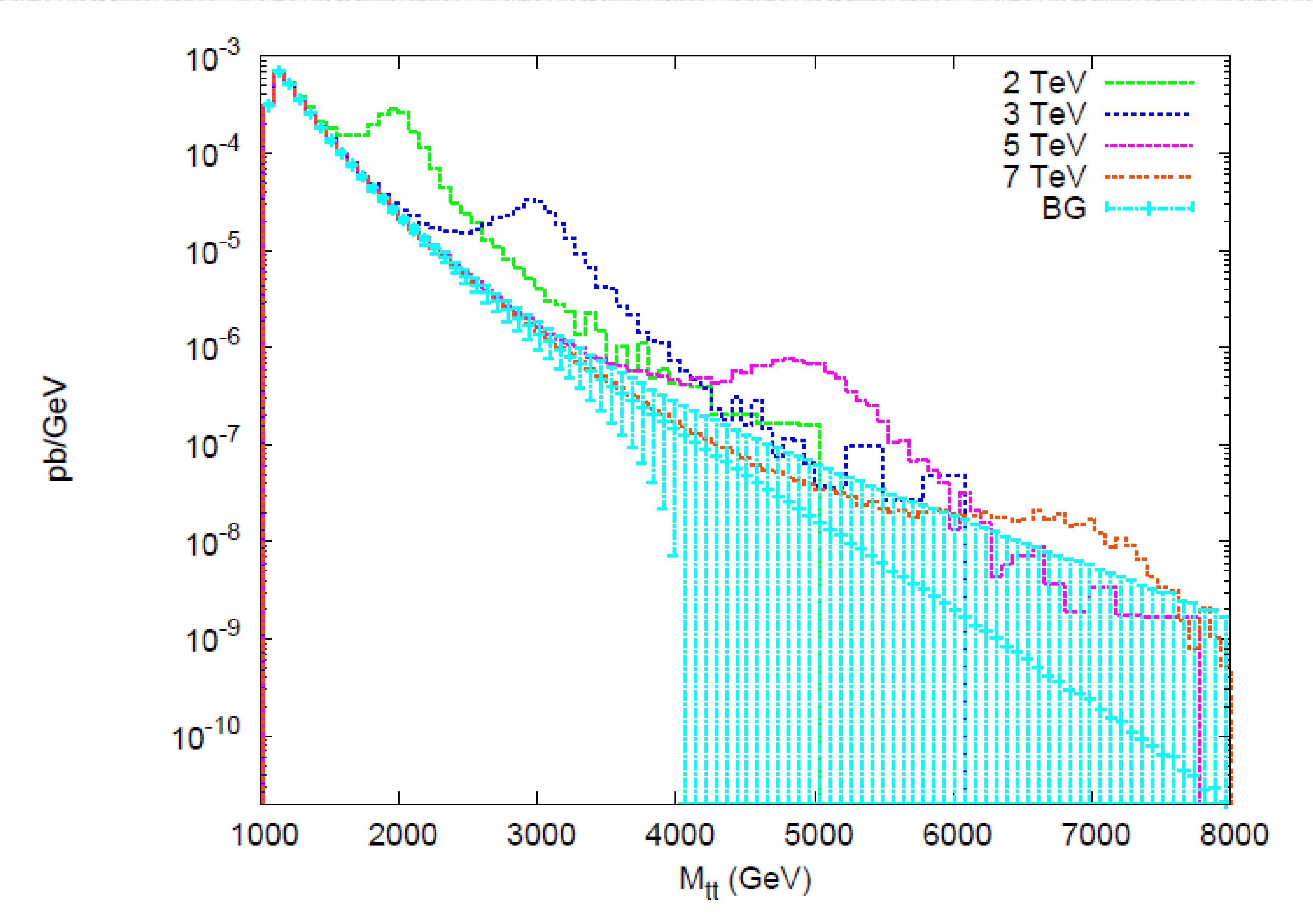
Cross section for production of 1st KK gluon

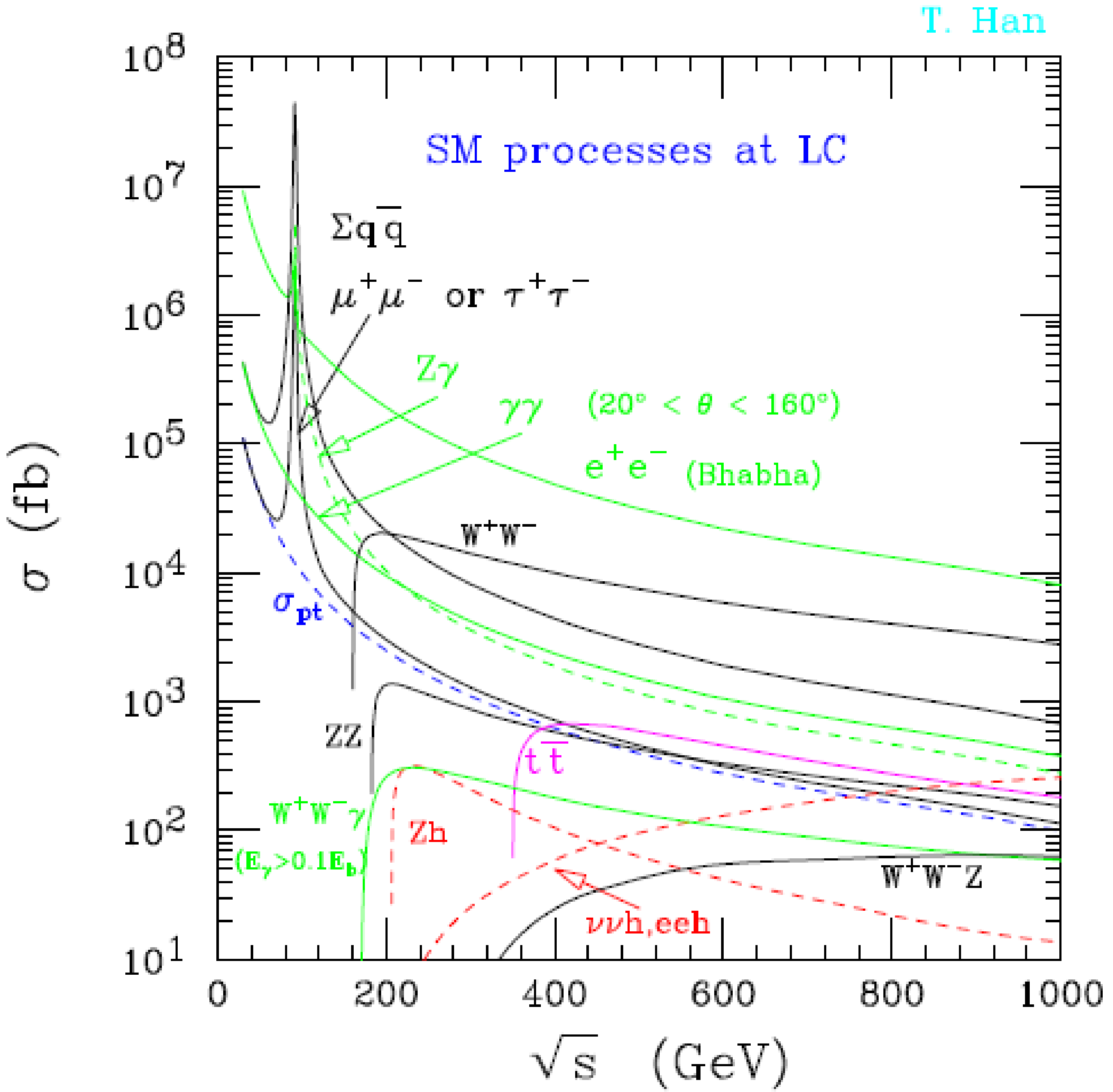


Branching ratio of 1st KK gluon



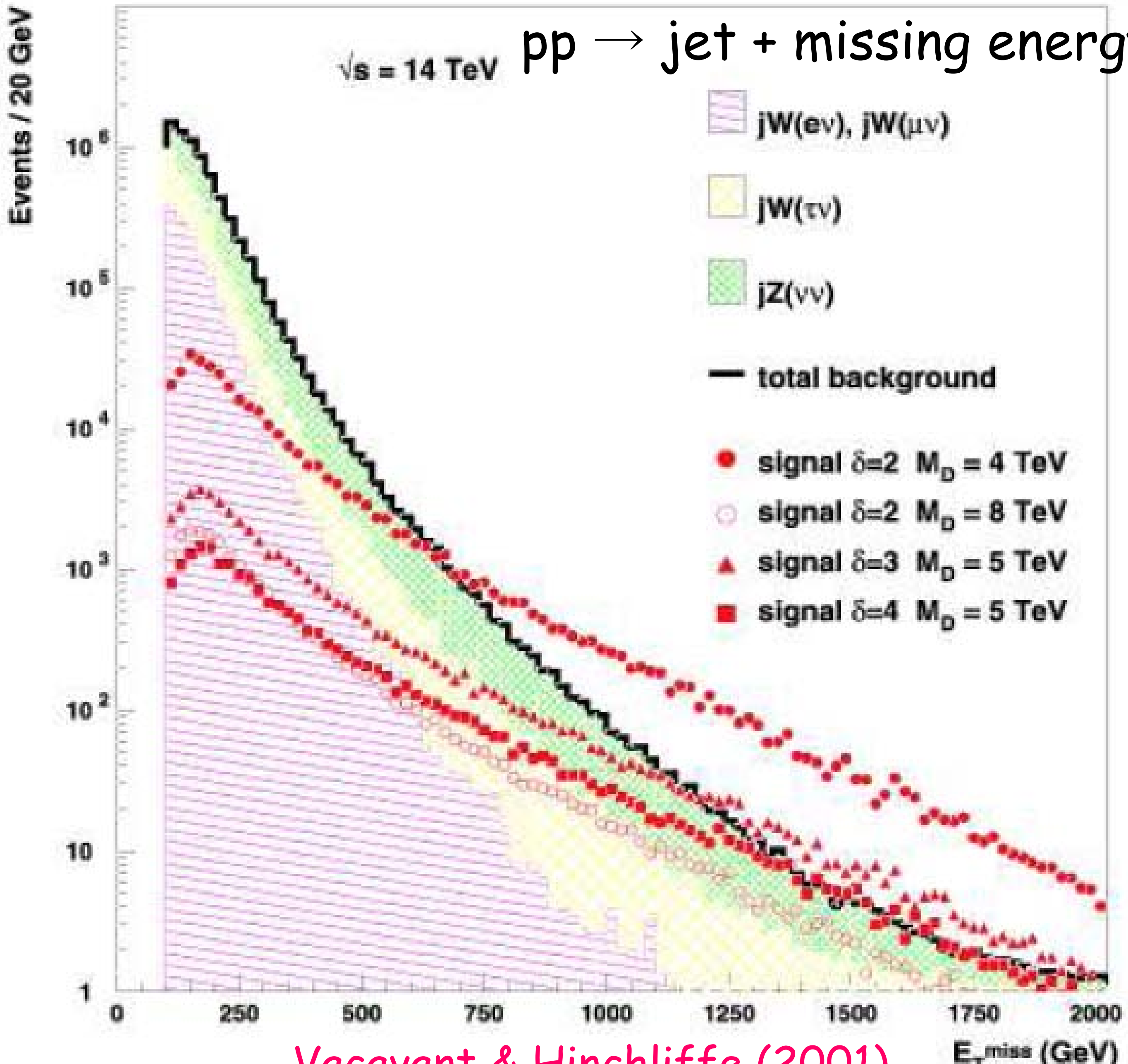
Invariant mass distribution of $g^{(1)} \to t\bar{t}$





T. Han
SM processes at LC
$\Sigma q\bar{q}$
$\mu^+\mu^-$ or $\tau^+\tau^-$
$Z\gamma$
$\gamma\gamma$
$(20° < \theta < 160°)$
e^+e^- (Bhabha)
W^+W^-
σ_{pt}
ZZ
$t\bar{t}$
$W^+W^-\gamma$
$(E_\gamma > 0.1E_b)$
Zh
W^+W^-Z
$\nu\nu h, eeh$
σ (fb)
$\sqrt{s}$ (GeV)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
0
200
400
600
800
1000

pp → jet + missing energy



Vacavant & Hinchliffe (2001)

Spin sum of polarization tensors

$$\sum_s e_{\mu\nu}(k,s)\, e_{\alpha\beta}(k,s) = P_{\mu\nu\alpha\beta}(k)$$

$$P_{\mu\nu\alpha\beta}(k) = \frac{1}{2}\left(\eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\mu\beta}\eta_{\nu\alpha} - \eta_{\mu\nu}\eta_{\alpha\beta}\right)$$
$$+\frac{1}{6}\left(\eta_{\mu\nu} + \frac{2}{m_n^2}k_\mu k_\nu\right)\left(\eta_{\alpha\beta} + \frac{2}{m_n^2}k_\alpha k_\beta\right)$$
$$-\frac{1}{2m_n^2}\left(\eta_{\mu\alpha}k_\nu k_\beta + \eta_{\nu\beta}k_\mu k_\alpha + \eta_{\mu\beta}k_\nu k_\alpha + \eta_{\nu\alpha}k_\mu k_\beta\right)$$

Anomaly cancellation

Arkani-Hamed, Cheng, Dobrescu & Hall (2000)
Dobrescu & Poppitz (2001)

6D Anomaly = One-loop Square diagram

$SU(3)_C$ $\Rightarrow$ $\sum_{+} Tr\left(T^a T^b T^c T^d\right) - \sum_{-} Tr\left(T^a T^b T^c T^d\right)$ $\Rightarrow$ $Q \Leftrightarrow U, D$ Opposite chirality

Gravitational $\Rightarrow$ $N_+ = N_-$

➡ 4 possibilities

$Q_+, U_-, D_-, L_-, E_+, N_+$ & $(+ \Leftrightarrow -)$
$Q_+, U_-, D_-, L_+, E_-, N_-$ & $(+ \Leftrightarrow -)$

$SU(2)_W \times U(1)_Y$ sector

$SU(2)_W \times U(1)_Y$ anomalies cannot be canceled by the SM matter, but GS mechanism helps

$[SU(2)_W]^4$, $[U(1)_Y]^4$, $[SU(2)_W]^2[SU(3)_C]^2$, $[SU(3)_C]^2[U(1)_Y]^2$, $[SU(2)_W]^2[U(1)_Y]^2$

$[SU(2)_W]^3 = 0$ (identically),

$[SU(3)_C]^3 U(1)_Y = 0$ (per generation)

Global anomaly

$\Pi_6(G)$: nontrivial if $G = SU(3), SU(2), G_2$

$\Pi_6[SU(3)]$: trivial $\because$ $SU(3)_C$ is vector-like

$SU(2)_L$: $N(2_+) - N(2_-) = 0 \bmod 6$

$\rightarrow n_g [N(2_+) - N(2_-)] = 0 \bmod 6 \Rightarrow n_g = 0 \bmod 3$

$[\because N(Q)=3, N(L)=1]$

Reducible anomalies

$$\left[SU(3)\right]^3 U(1) = \frac{1}{6}A(Q) + \frac{2}{3}A\left(\bar{U}\right) - \frac{1}{3}A\left(\bar{D}\right) = \left(\frac{2}{6} - \frac{2}{3} + \frac{1}{3}\right)A(3) = 0$$

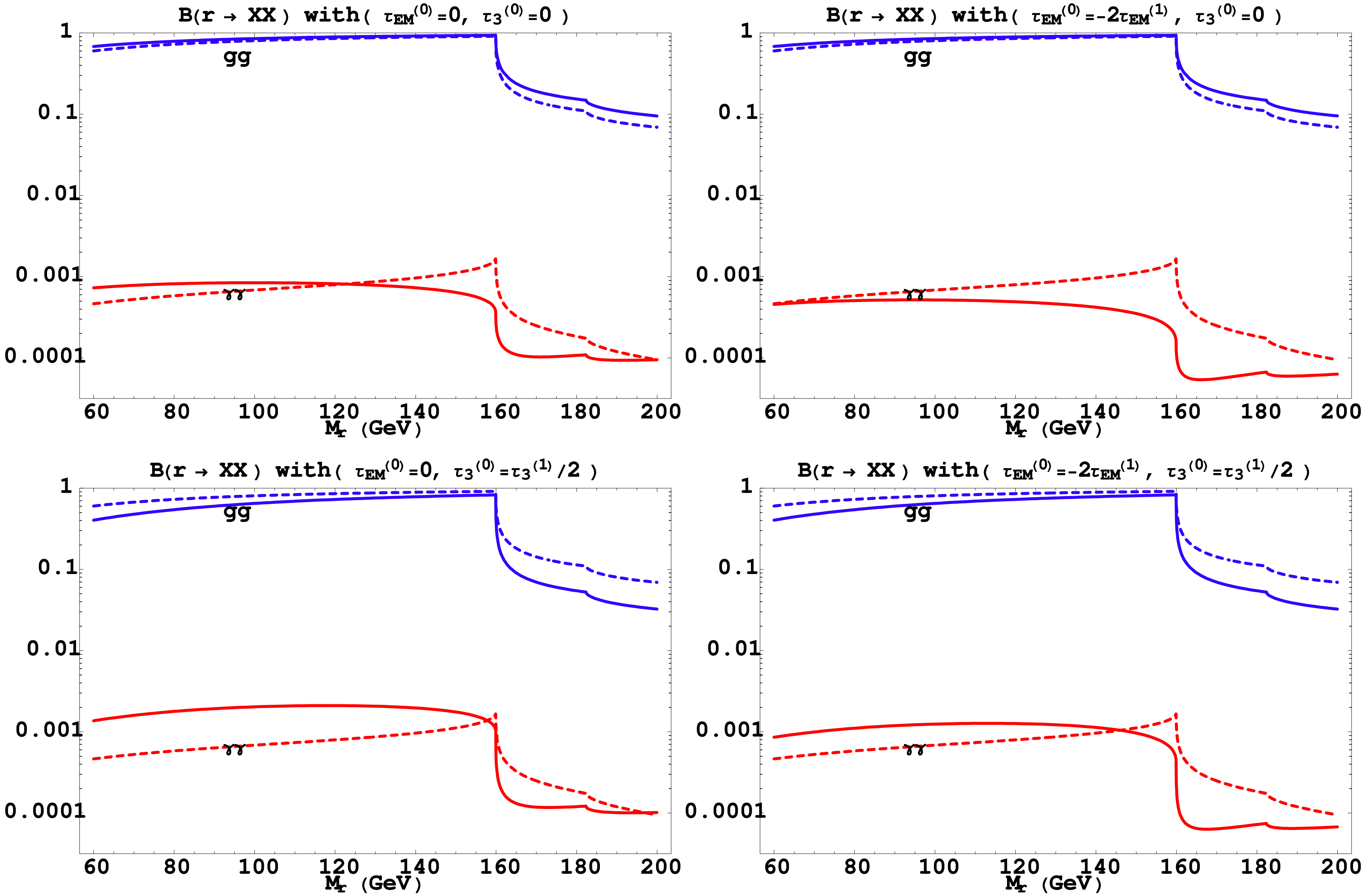
$$\left[SU(3)\right]^2 \left[U(1)\right]^2 = \frac{1}{36}C(Q) - \frac{4}{9}C\left(\bar{U}\right) - \frac{1}{9}C\left(\bar{D}\right) = \left(\frac{2}{36} - \frac{4}{9} - \frac{1}{9}\right)C(3) = -\frac{1}{2}C(3)$$

$$\left[U(1)\right]^4 = \frac{6}{6^4} + \frac{16\times 3}{3^4} + \frac{3}{3^4} + \frac{2}{2^4} + 1 = \frac{1+136+243}{216} = \frac{95}{54}$$

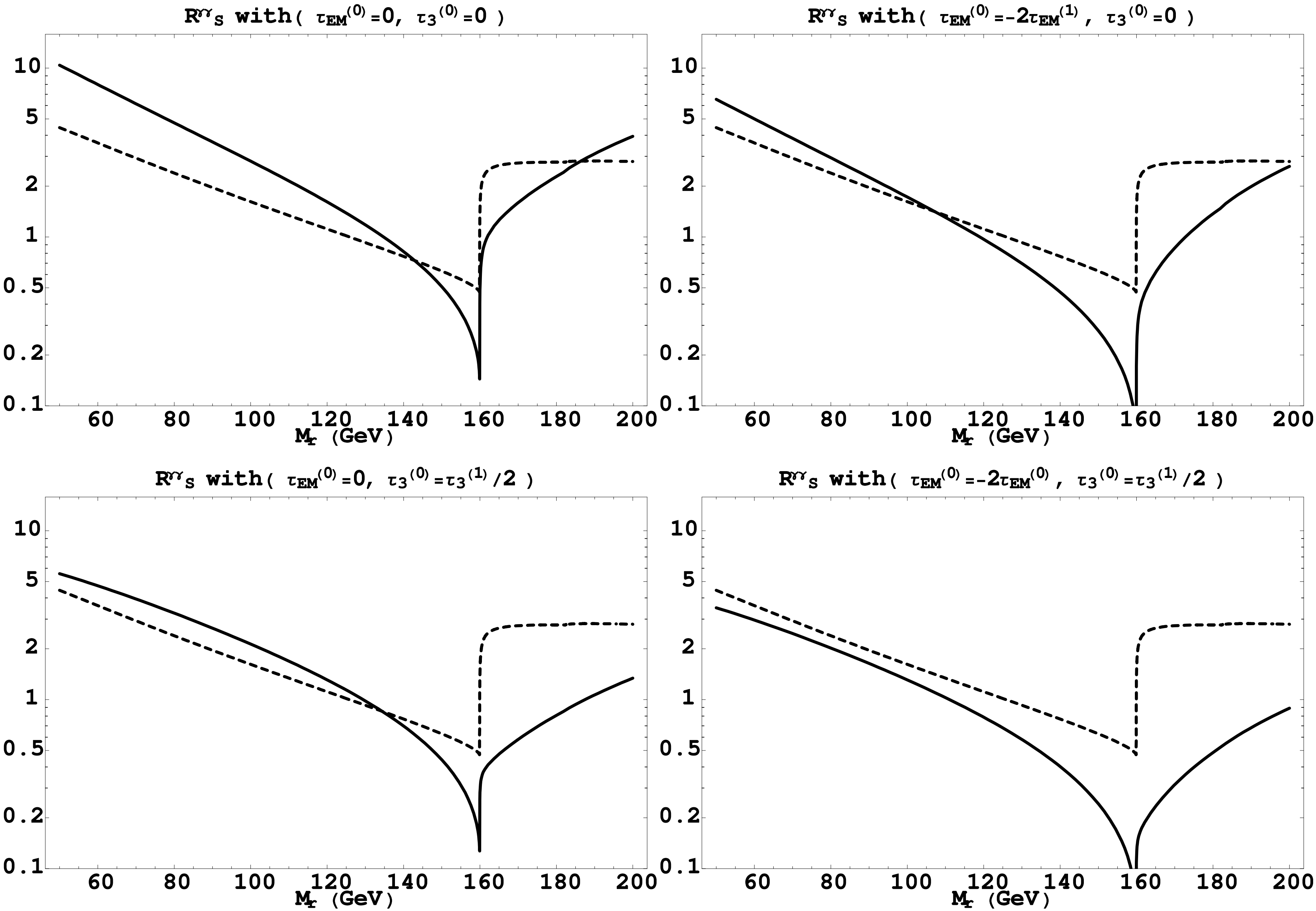
$$\left[SU(3)\right]^2 \left[SU(2)\right]^2 = C(3)C(2) = \frac{1}{2}C(3) = \frac{1}{2}C(2)$$

$$\left[SU(2)\right]^2 \left[U(1)\right]^2 = \frac{3}{36}C(2) \pm \frac{1}{4}C(2) = \frac{1}{3}C(2) \text{ or } -\frac{1}{6}C(2)$$

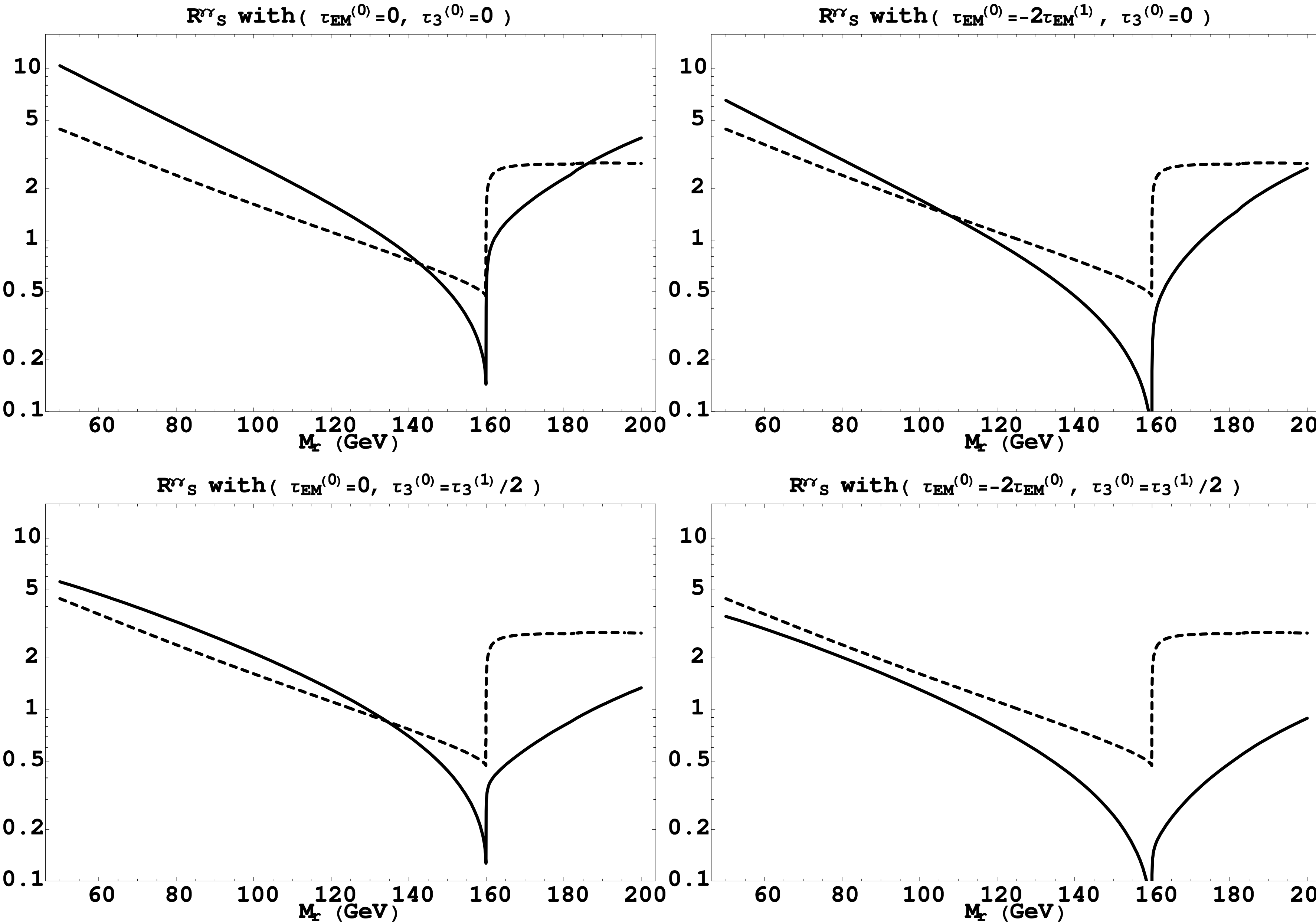
$$\left[SU(2)\right]^2 \left[SU(2)\right]^2 = 3\left(C(2)\right)^2 \pm \left(C(2)\right)^2 = 2C(2) \text{ or } C(2)$$



B(r → XX) with(τEM(0) =0, τ3(0) =0)
B(r → XX) with(τEM(0) =-2τEM(1) , τ3(0) =0)
B(r → XX) with(τEM(0) =0, τ3(0) =τ3(1) /2)
B(r → XX) with(τEM(0) =-2τEM(1) , τ3(0) =τ3(1) /2)
gg
γγ
1
0.1
0.01
0.001
0.0001
60
80
100
120
140
160
180
200
Mr (GeV)

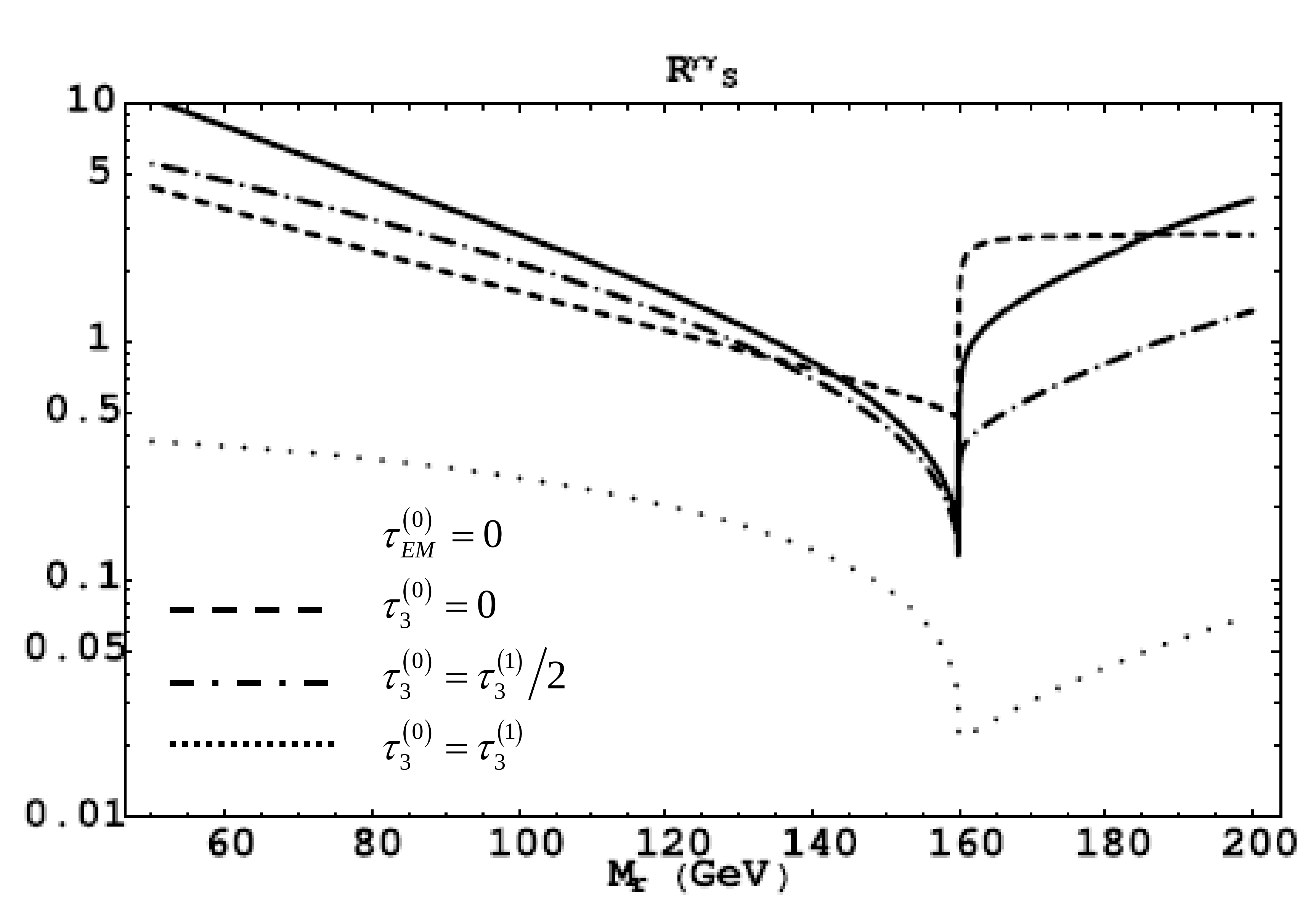


Rγγ S with(τEM(0)=0, τ3(0)=0)
Rγγ S with(τEM(0)=-2τEM(1), τ3(0)=0)
Rγγ S with(τEM(0)=0, τ3(0)=τ3(1)/2)
Rγγ S with(τEM(0)=-2τEM(0), τ3(0)=τ3(1)/2)
10
5
2
1
0.5
0.2
0.1
60
80
100
120
140
160
180
200
Mr (GeV)

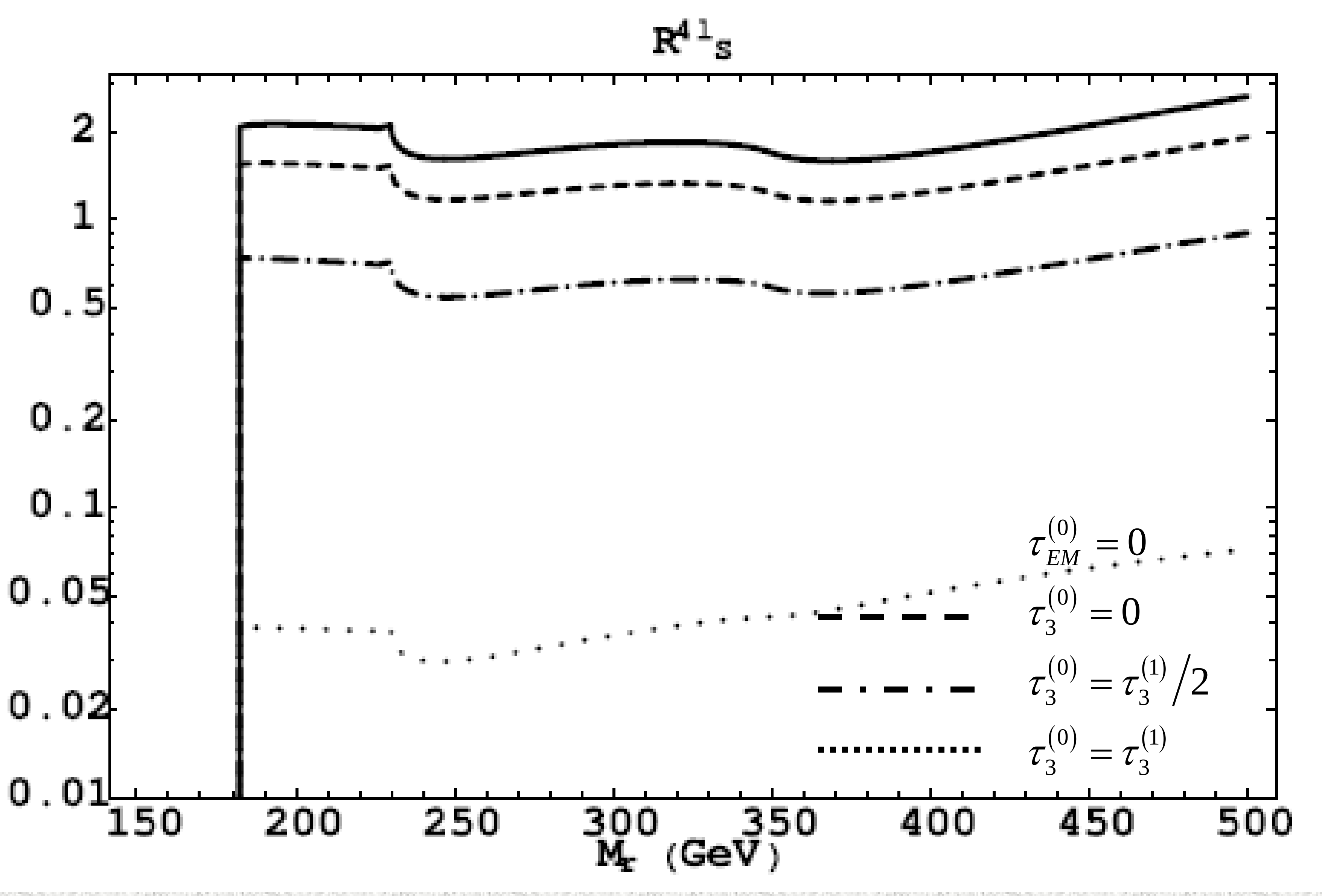


Rγγ_S with(τ_EM^(0)=0, τ3^(0)=0)
Rγγ_S with(τ_EM^(0)=-2τ_EM^(1), τ3^(0)=0)
Rγγ_S with(τ_EM^(0)=0, τ3^(0)=τ3^(1)/2)
Rγγ_S with(τ_EM^(0)=-2τ_EM^(0), τ3^(0)=τ3^(1)/2)
10
5
2
1
0.5
0.2
0.1
60
80
100
120
140
160
180
200
Mr (GeV)

Discovery significance of gg -> r -> γγ



Discovery significance of gg -> r -> ZZ -> 4l



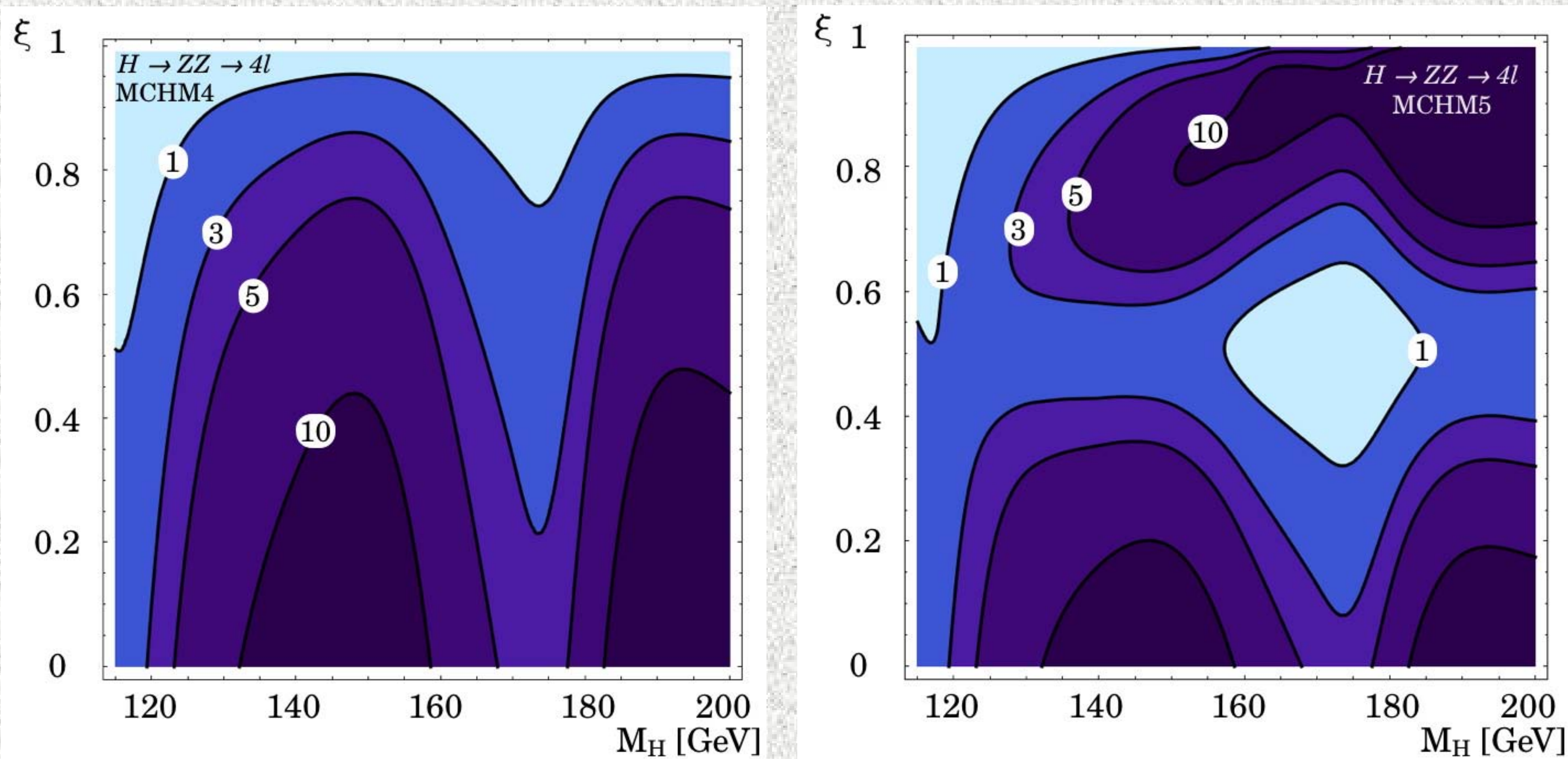
Sum Rules

$$g_{WWZZ} = g_{WWZ}^2 + \sum_n \left(g_{WZV}^{(n)} \right)^2 \leftarrow A^{(4)} = 0$$

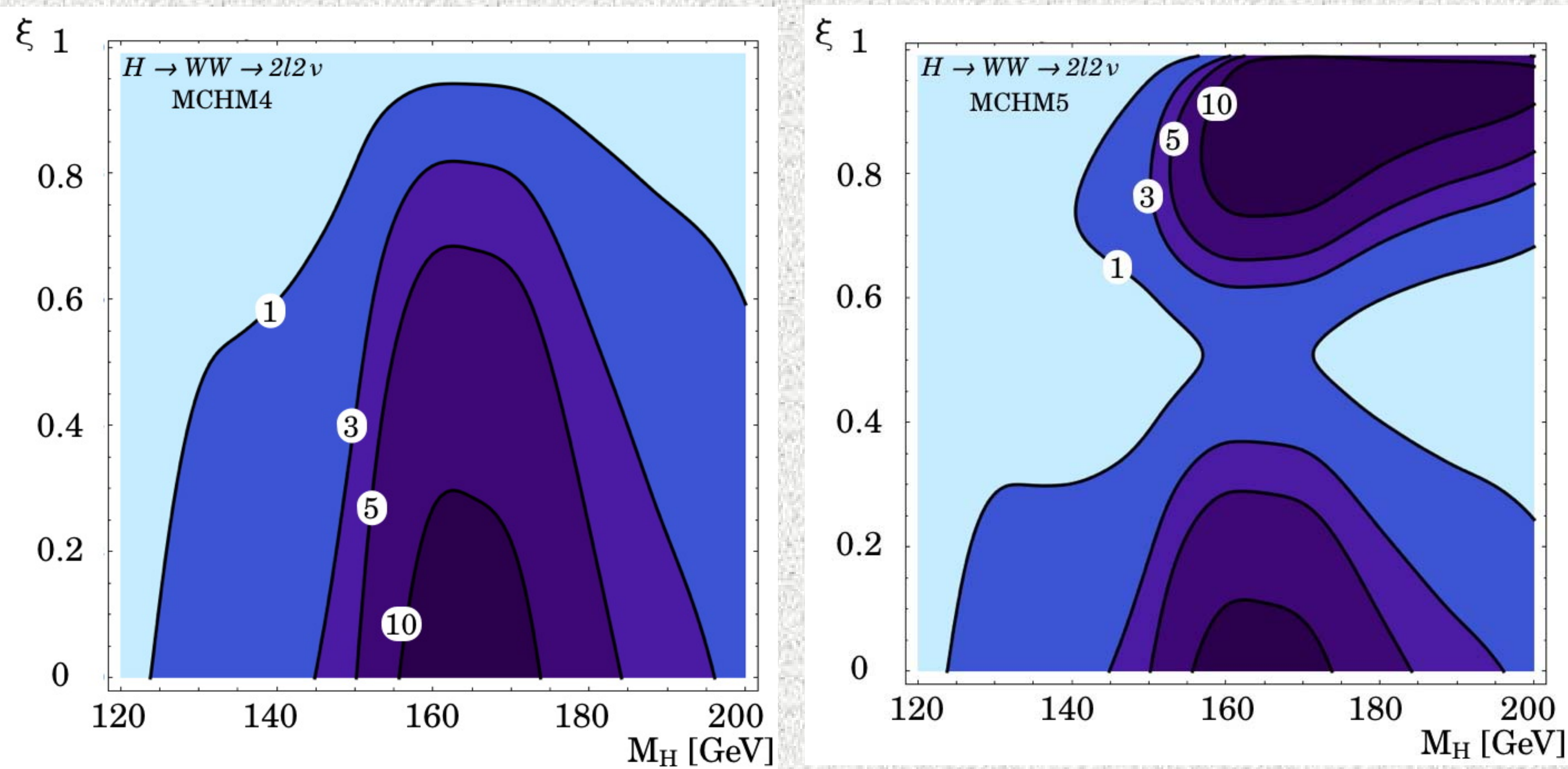
$$2\left(g_{WWZZ} - g_{WWZ}^2 \right)\left(M_W^2 + M_Z^2 \right) + g_{WWZ}^2 \frac{M_Z^4}{M_W^2} = \sum_n \left(g_{WZV}^{(n)} \right)^2 \left[3\left(M_W^{\pm(n)} \right)^2 - \frac{\left(M_Z^2 - M_W^2 \right)^2}{\left(M_W^{\pm(n)} \right)^2} \right] \leftarrow A^{(2)} = 0$$

$$g_{WWWW} = g_{WWZ}^2 + g_{WW\gamma}^2 + \sum_i \left(g_{WWV}^{(i)} \right)^2$$

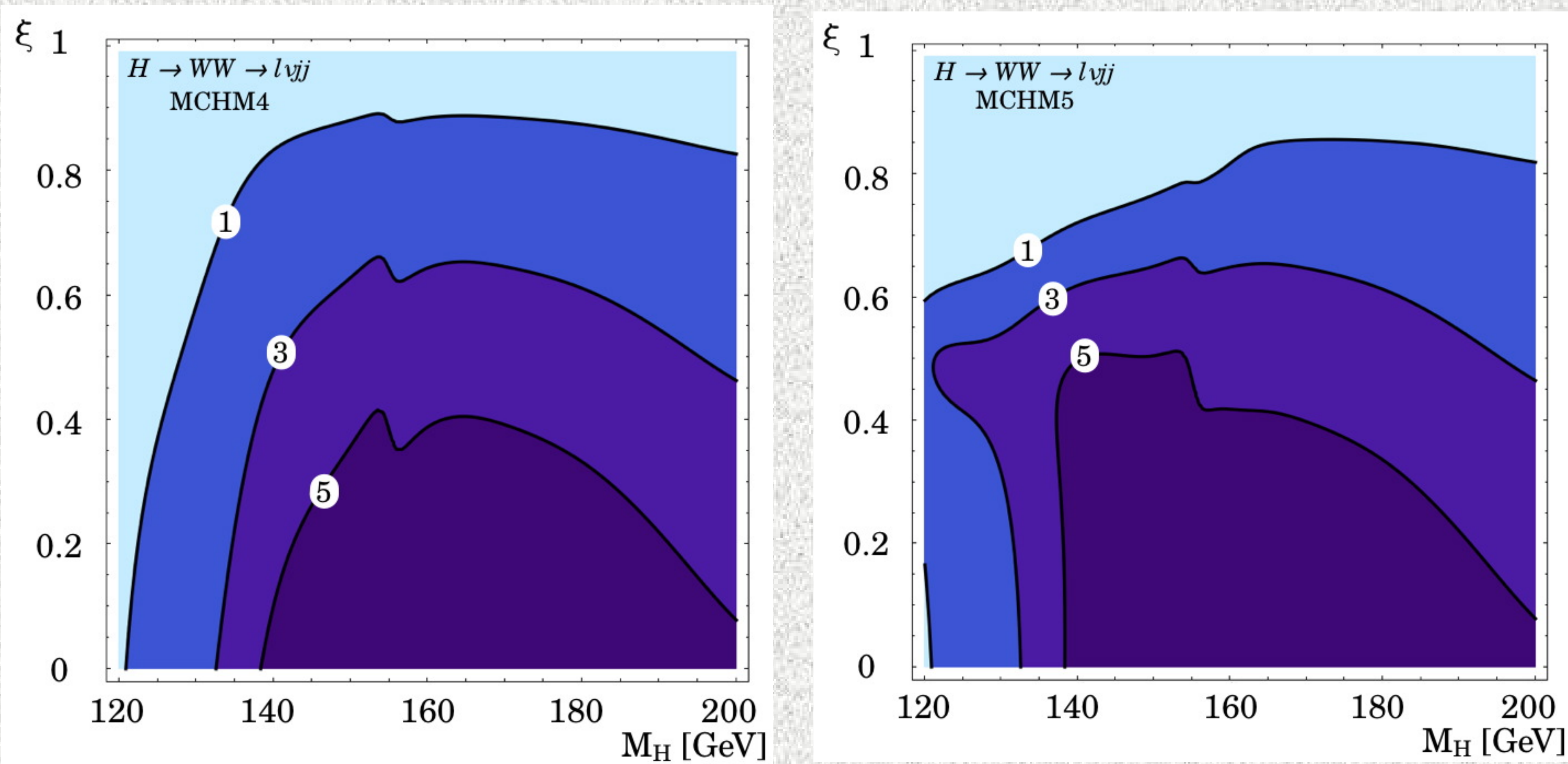
$$4 g_{WWWW} M_W^2 = 3\left[g_{WWZ}^2 M_Z^2 + \sum_i \left(g_{WWV}^{(i)} \right)^2 \left(M_i^0 \right)^2 \right]$$



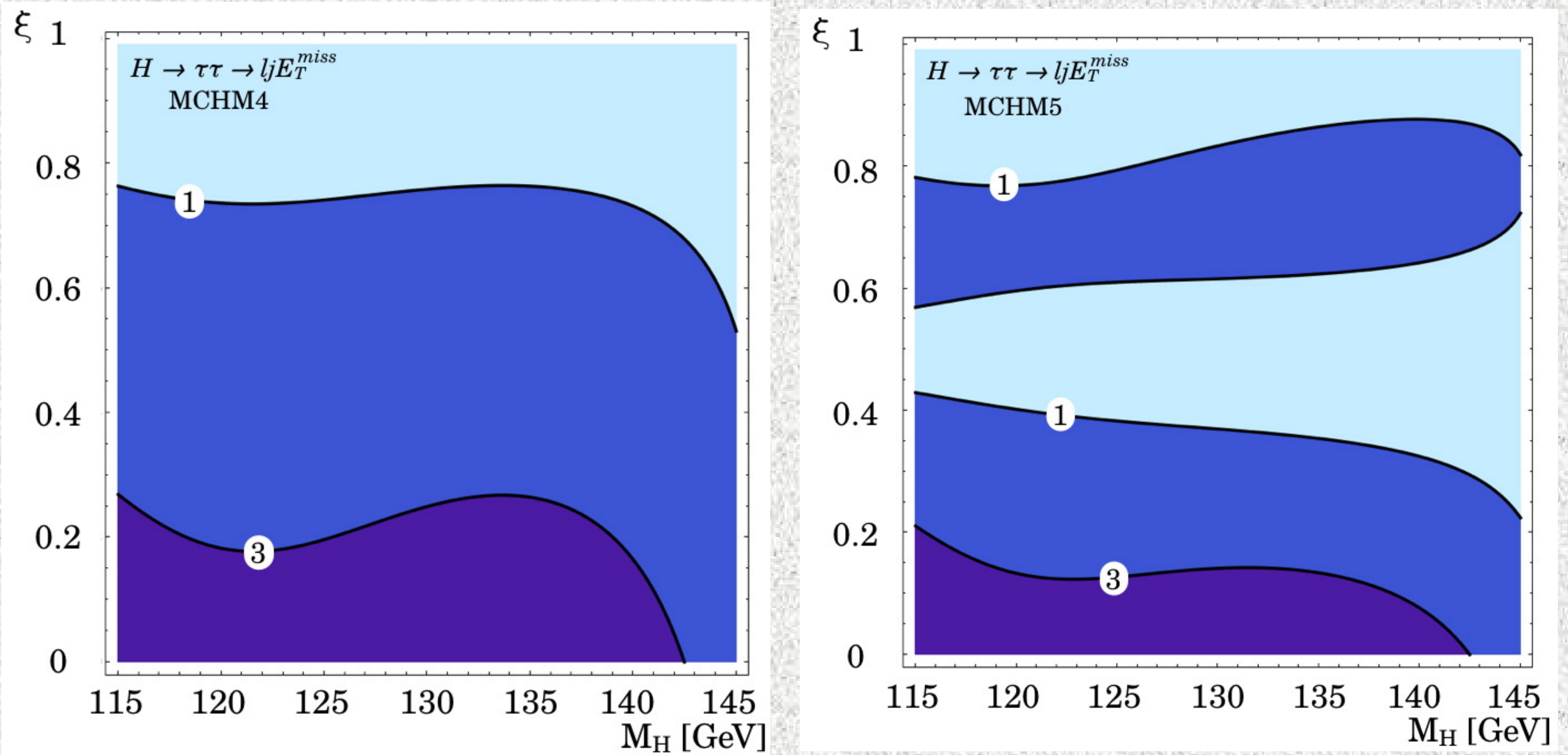
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → ZZ → 4l
MCHM4
1
3
5
10
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → ZZ → 4l
MCHM5
10
5
3
1
1



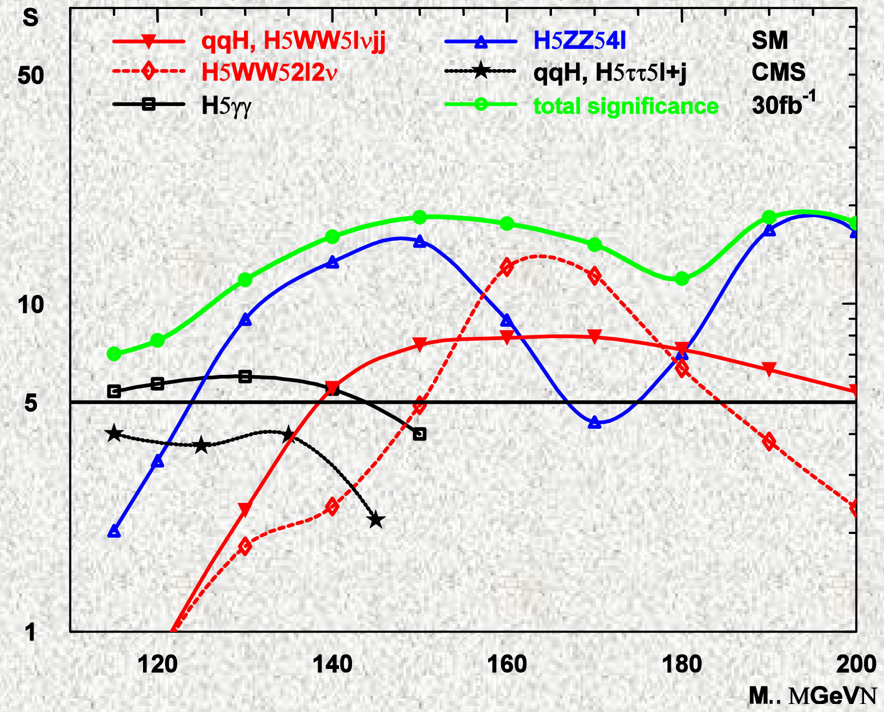
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → WW → 2l2ν
MCHM4
1
3
5
10
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → WW → 2l2ν
MCHM5
10
5
3
1



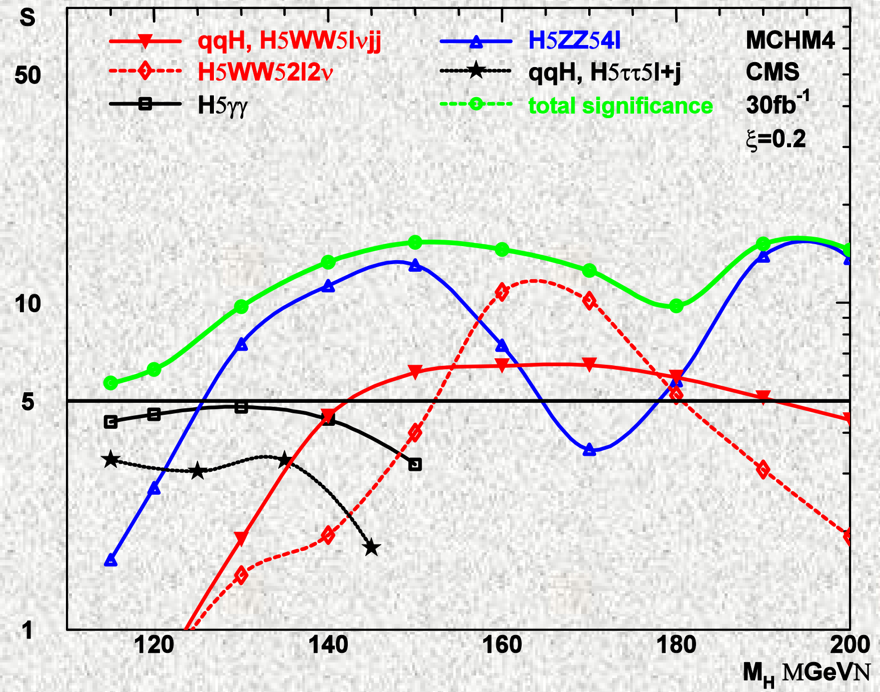
ξ
1
0.8
0.6
0.4
0.2
0
H → WW → lνjj
MCHM4
1
3
5
120
140
160
180
200
M_H [GeV]
ξ
1
0.8
0.6
0.4
0.2
0
H → WW → lνjj
MCHM5
1
3
5
120
140
160
180
200
M_H [GeV]



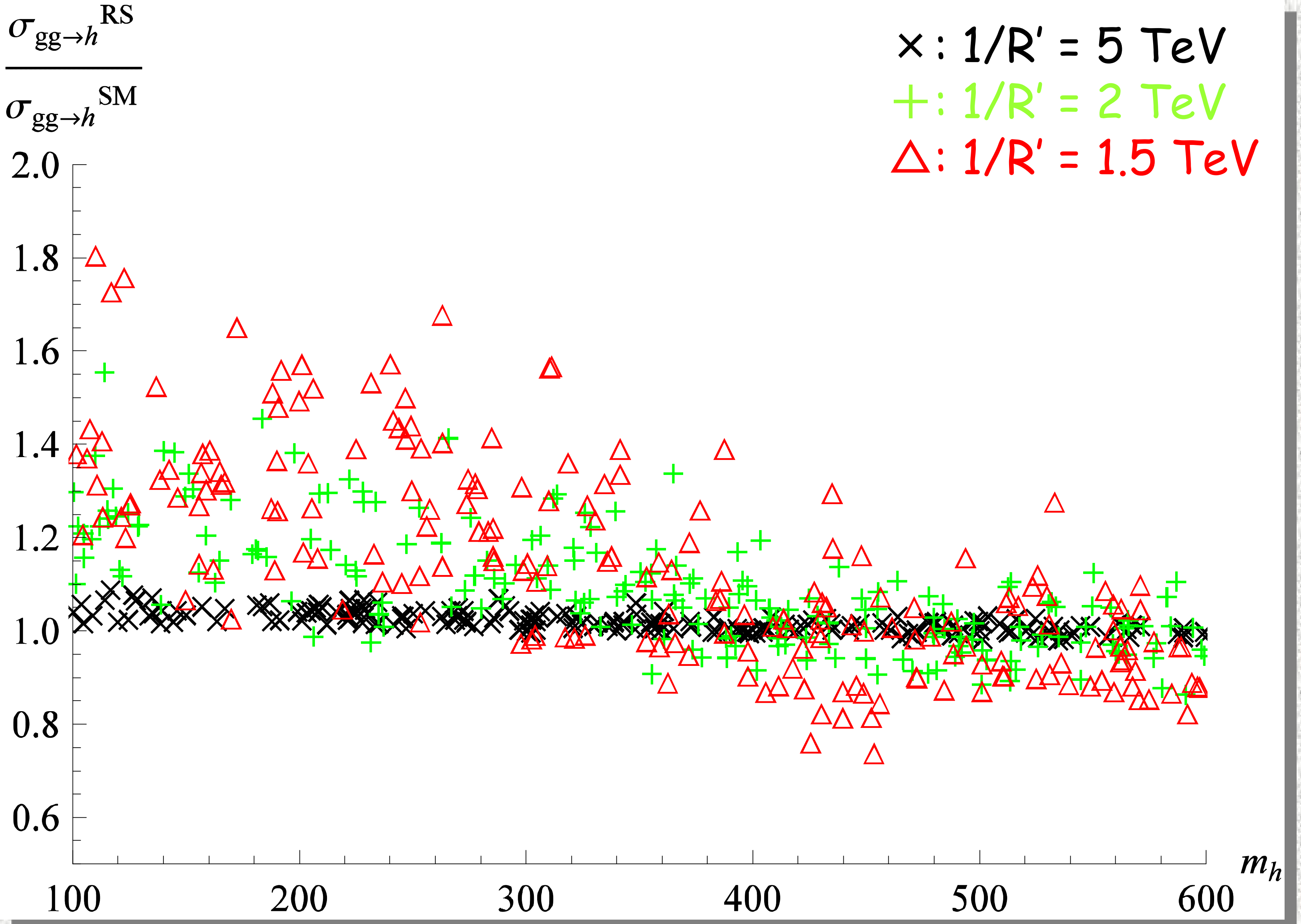
$H \to \tau\tau \to lj E_T^{miss}$
MCHM4
ξ
1
0.8
0.6
0.4
0.2
0
115
120
125
130
135
140
145
M_H [GeV]
3
$H \to \tau\tau \to lj E_T^{miss}$
MCHM5



S
50
10
5
1
qqH, H5WW5lνjj
H5WW52l2ν
H5γγ
H5ZZ54l
qqH, H5ττ5l+j
total significance
SM
CMS
30fb-1
120
140
160
180
200
M.. MGeVN

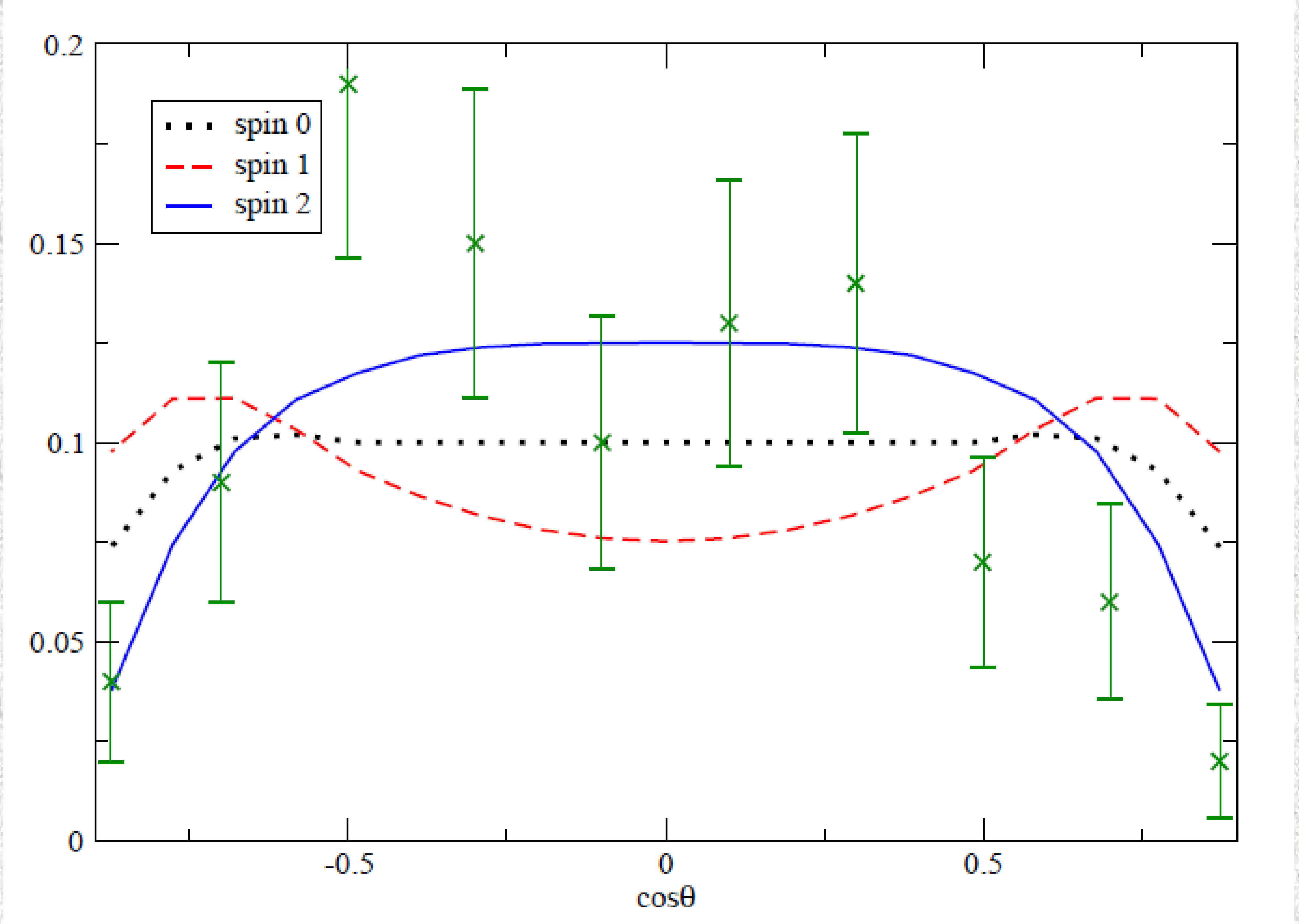


S
50
10
5
1
qqH, H5WW5lνjj
H5WW52l2ν
H5γγ
H5ZZ54l
qqH, H5ττ5l+j
total significance
MCHM4
CMS
30fb-1
ξ=0.2
120
140
160
180
200
MH MGeVN



Azatov, Toharia & Zhu, 1006.5939

Angular dependences of gg -> G(V,S) -> t tbar



Branching fractions

$$B\left(g_1 \to Q_1 Q_0\right) \approx B\left(g_1 \to q_1 q_0\right) \approx 0.5$$

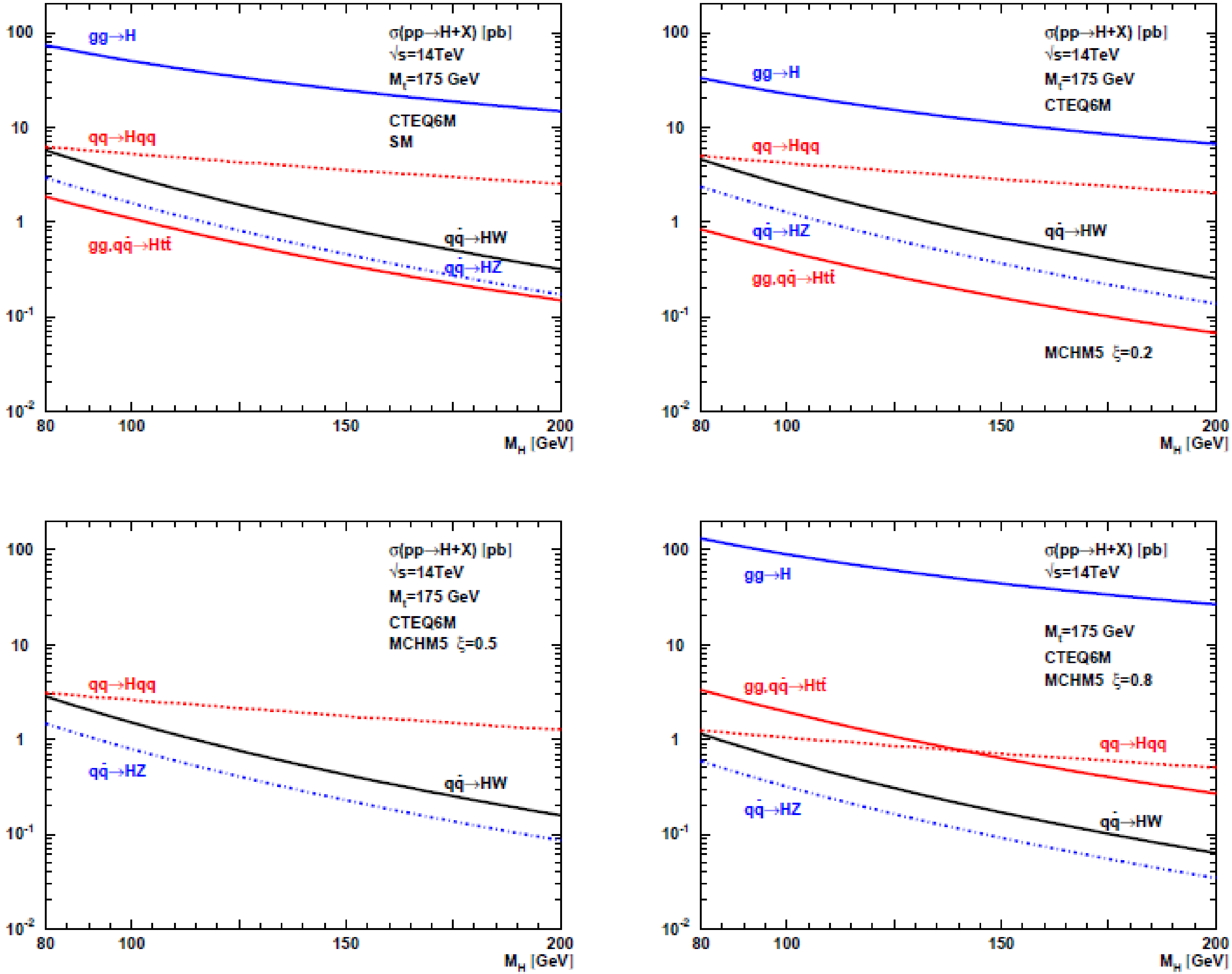
$$B\left(Q_1 \to W_1^{\pm} Q_0\right) \approx 0.65 \quad B\left(q_1 \to Z_1 q_0\right) \approx 10^{-2} - 10^{-3}$$

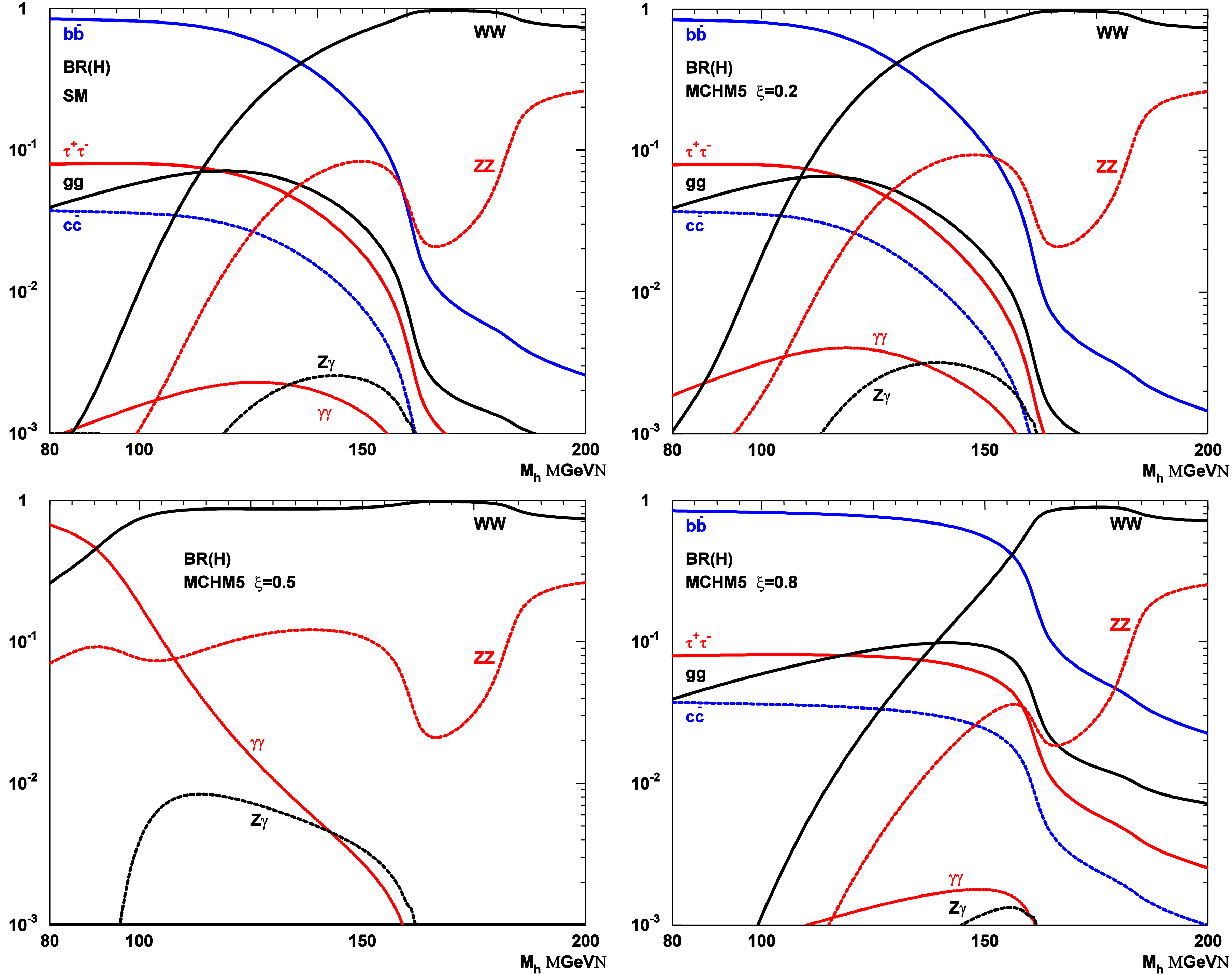
$$B\left(Q_1 \to Z_1 Q_0\right) \approx 0.33 \quad B\left(q_1 \to \gamma_1 q_0\right) \approx 1$$

$$B\left(Q_1 \to \gamma_1 Q_0\right) \approx 0.02$$

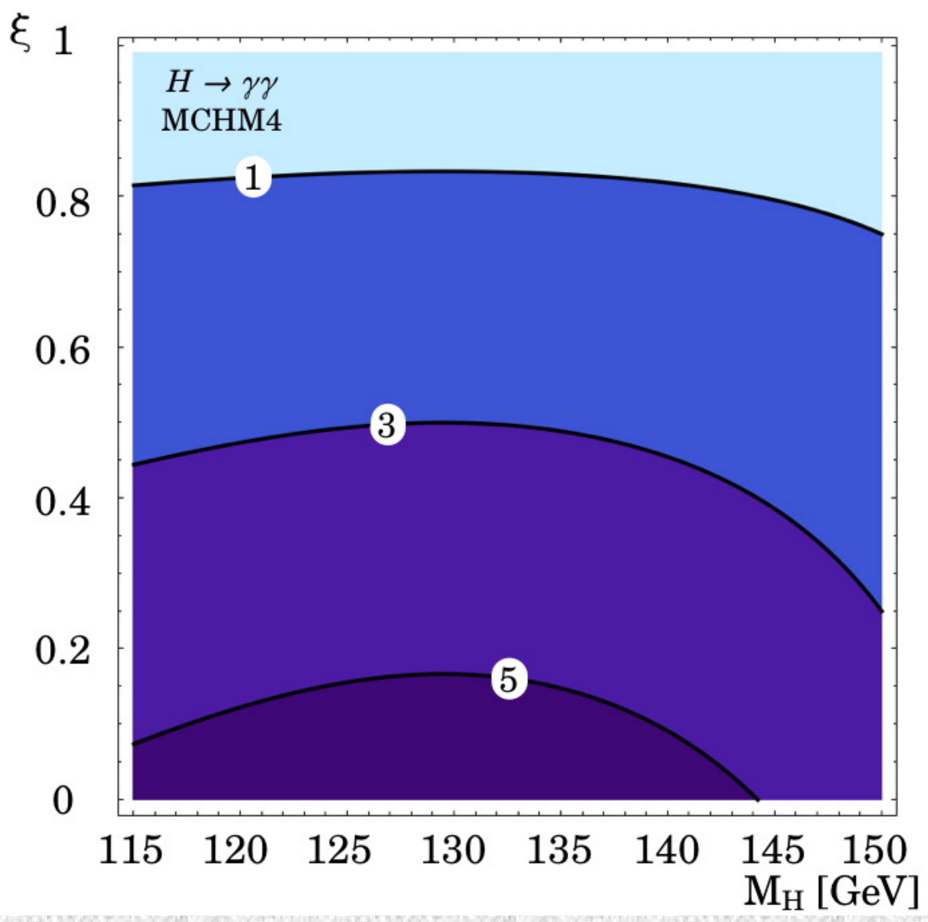
$$B\left(W_1^{\pm} \to \nu_1 L_0^{\pm}\right) = B\left(W_1^{\pm} \to L_1^{\pm} \nu_0\right) = 1/6$$

$$B\left(Z_1 \to \nu_1 \overline{\nu}_0\right) = B\left(Z_1 \to L_1^{\pm} L_0\right) \approx 1/6$$

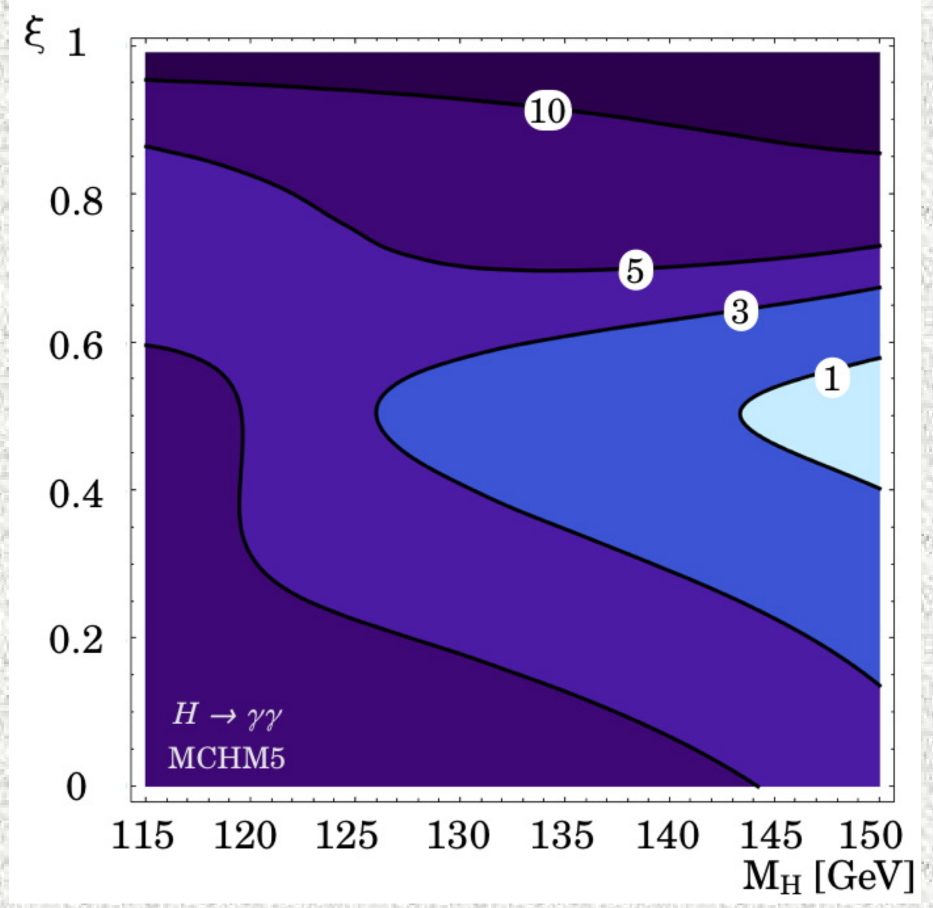

σ(pp→H+X) [pb]
√s=14TeV
M_t=175 GeV
CTEQ6M
SM
gg→H
qq→Hqq
gg,qq̄→Htt̄
qq̄→HW
qq̄→HZ
MCHM5 ξ=0.2
MCHM5 ξ=0.5
MCHM5 ξ=0.8
M_H [GeV]



BR(H)
SM
bb̄
WW
$\tau^+\tau^-$
ZZ
gg
cc̄
Zγ
γγ
BR(H)
MCHM5 ξ=0.2
BR(H)
MCHM5 ξ=0.5
BR(H)
MCHM5 ξ=0.8
1
10^{-1}
10^{-2}
10^{-3}
80
100
150
200
M_h MGeVN



ξ
$H \to \gamma\gamma$
MCHM4
1
3
5
0
0.2
0.4
0.6
0.8
1
115
120
125
130
135
140
145
150
M_H [GeV]

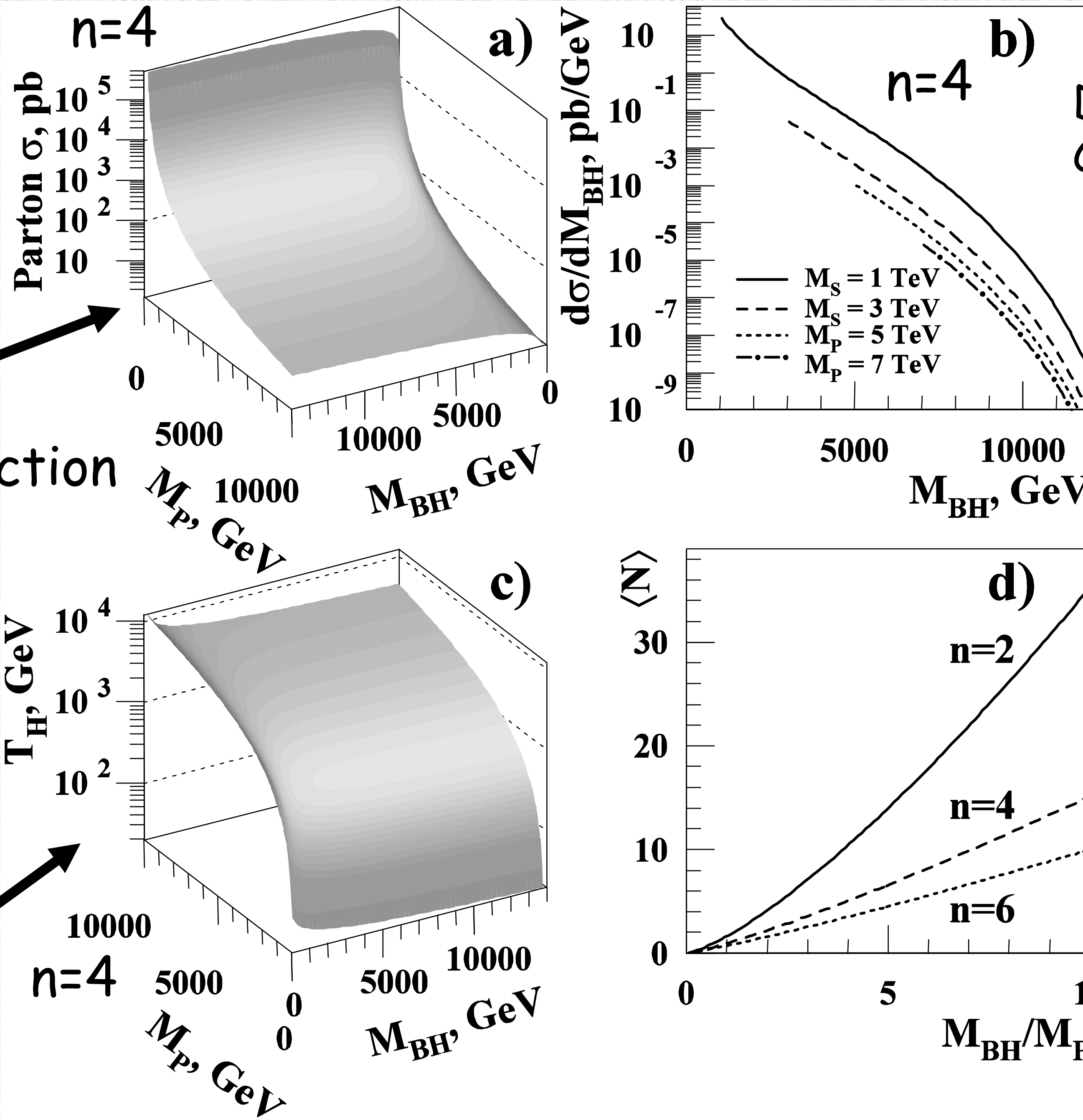


ξ
10
5
3
1
$H \to \gamma\gamma$
MCHM5
0
0.2
0.4
0.6
0.8
1
115
120
125
130
135
140
145
150
M_H [GeV]

$$\frac{d\sigma_m}{dt}(q\overline{q} \to gG) = \frac{\alpha_S}{36}\frac{1}{sM_P^2}F_1\left(\frac{t}{s},\frac{m^2}{s}\right), \quad \frac{d\sigma_m}{dt}(qG \to gG) = \frac{\alpha_S}{96}\frac{1}{sM_P^2}F_2\left(\frac{t}{s},\frac{m^2}{s}\right)$$

$$\frac{d\sigma_m}{dt}(gg \to gG) = \frac{3\alpha_S}{16}\frac{1}{sM_P^2}F_3\left(\frac{t}{s},\frac{m^2}{s}\right)$$

$$\begin{aligned}
F_1(x,y) &= \frac{1}{x(y-1-x)}\left[-4x(1+x)(1+2x+2x^2)+\right. \\
&\quad \left. y(1+6x+18x^2+16x^3) - 6y^2x(1+2x) + y^3(1+4x)\right], \\
F_2(x,y) &= -(y-1-x)\, F_1\left(\frac{x}{y-1-x}, \frac{y}{y-1-x}\right) = \\
&\quad \frac{1}{x(y-1-x)}\left[-4x(1+x^2) + y(1+x)(1+8x+x^2)\right. \\
&\quad \left. -3y^2(1+4x+x^2) + 4y^3(1+x) - 2y^4\right], \\
F_3(x,y) = &\quad \frac{1}{x(y-1-x)}\left[1+2x+3x^2+2x^3+x^4\right. \\
&\quad \left. -2y(1+x^3) + 3y^2(1+x^2) - 2y^3(1+x) + y^4\right].
\end{aligned}$$

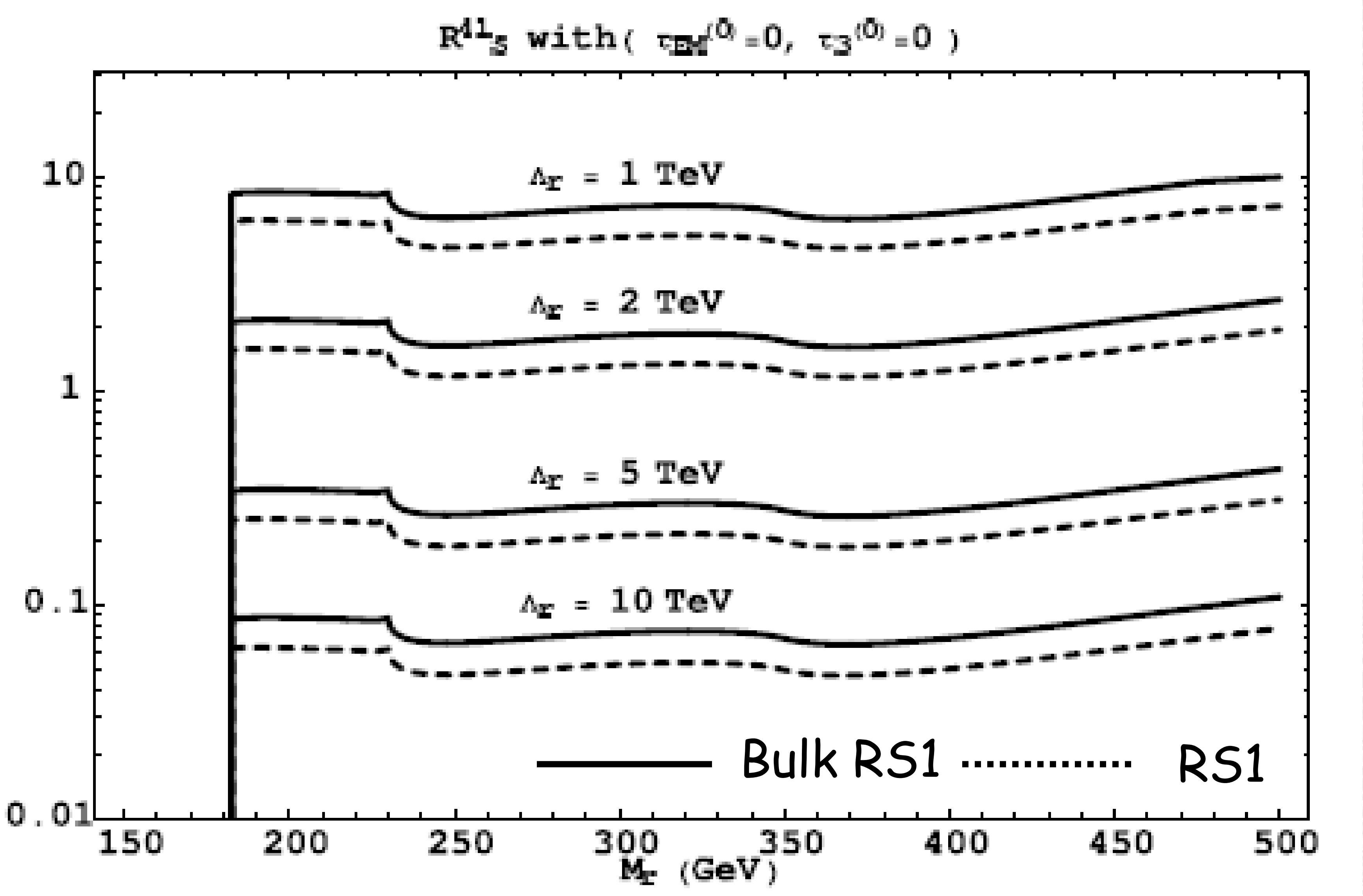


Differential Cross section

Total cross section

Hawking Temp.

Ratio of gg -> r -> ZZ-> 4l/gg -> H -> ZZ -> 4l



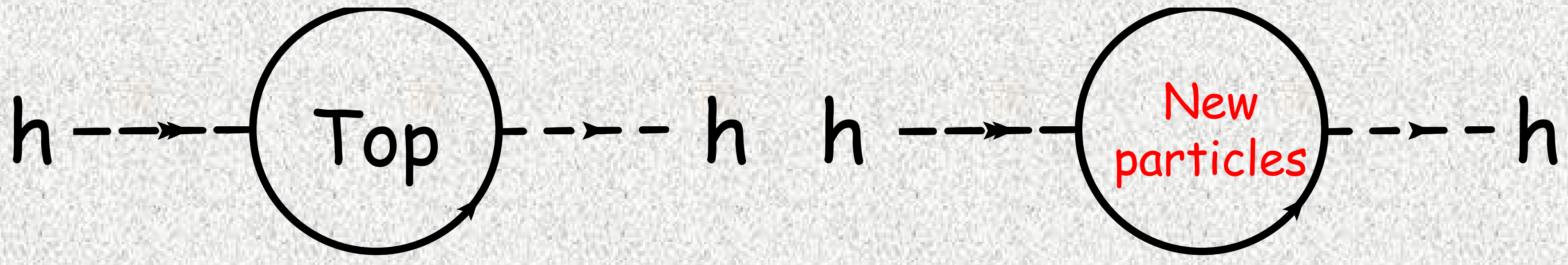
Similar type of deviations from the SM are also seen in

1: SUSY model — Djouadi, PLB453 (1998) 101

2: Little Higgs model — Han, Logan, McElrath & Wang, PLB563 (2003) 191

Common feature among GHU, SUSY & LH is that the quadratic divergence in m_h^2 is canceled

This can be seen diagrammatically as follows



Start with Higgs self-energy diagram with a relative minus sign

Similar type of deviations from the SM are also seen in

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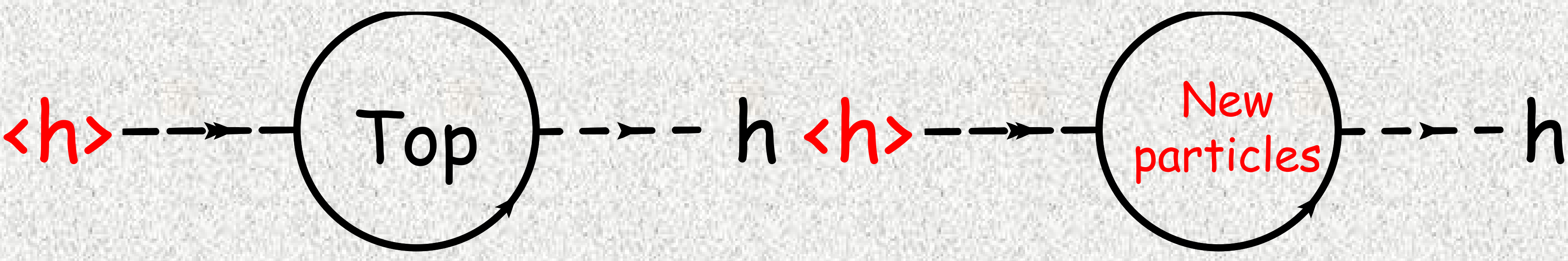


Replace one of the Higgs by its VEV

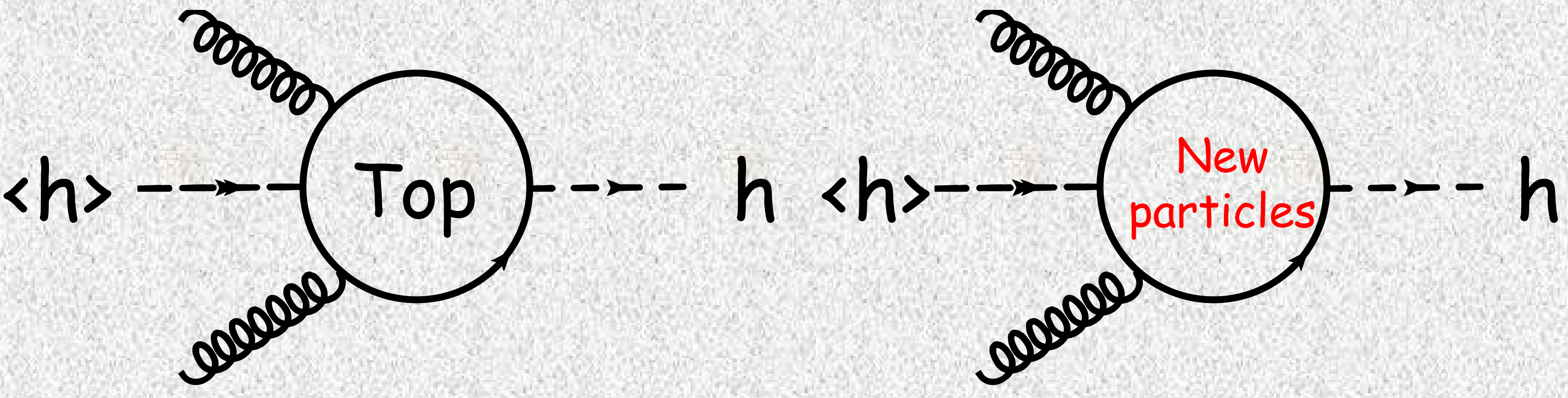
Similar type of deviations from the SM are also seen in

1: SUSY model — Djouadi, PLB453 (1998) 101

2: Little Higgs model — Han, Logan, McElrath & Wang, PLB563 (2003) 191

Common feature among GHU, SUSY & LH is that the quadratic divergence in m_h^2 is canceled

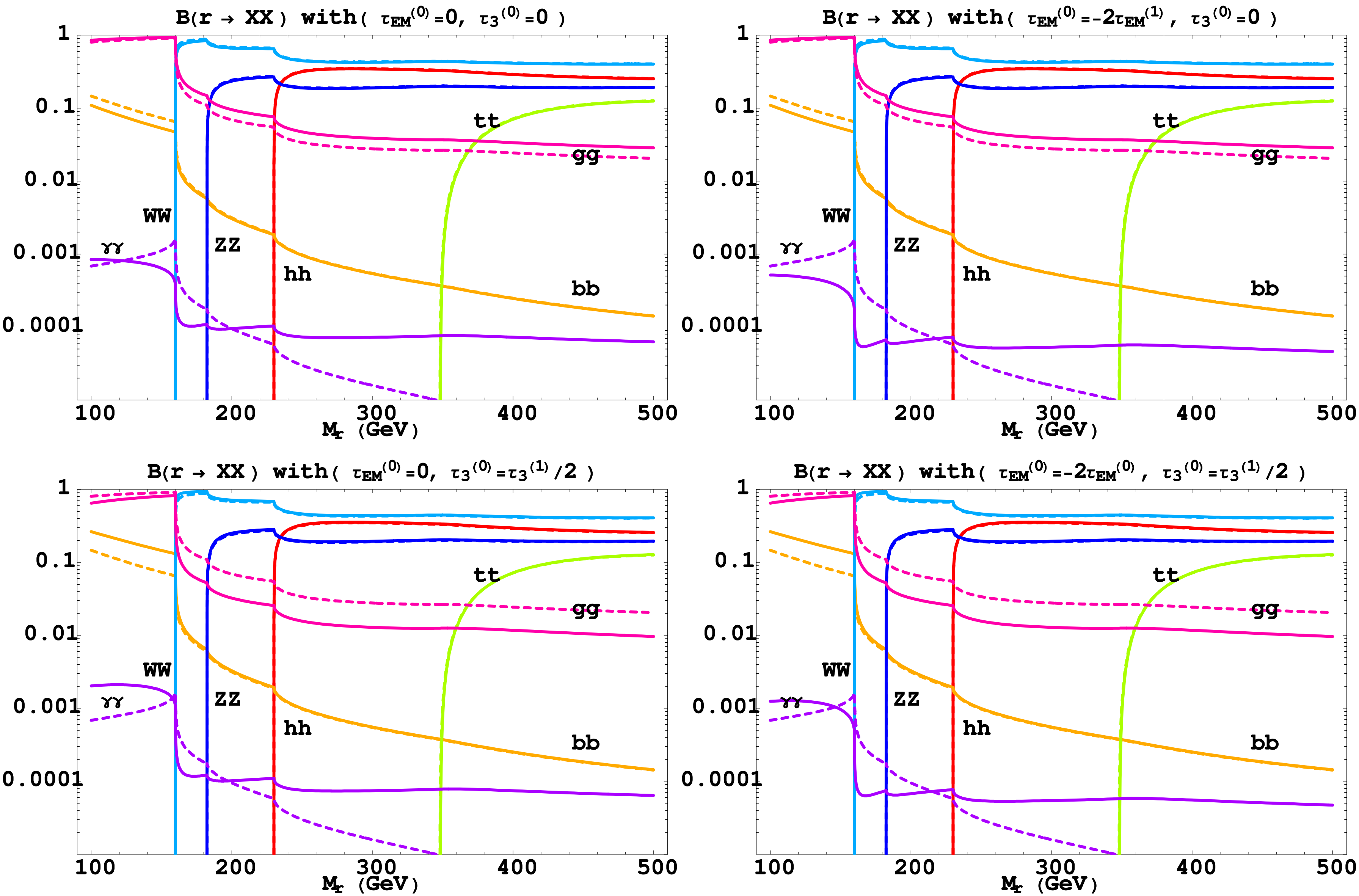
This can be seen diagrammatically as follows



Attaching 2 gluon lines

⇒ gluon fusion diagram with a relative minus sign

Branching fraction of the radion



Λ_r = 2 TeV ——— Bulk RS1 .... RS1