



# Models & signatures of extra dimensions at the LHC

March 2010

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# Motivations for extra dimensions

## bottom-up

1) address hierarchy problem of SM

2) can address :

- symmetry breaking (EW, SUSY) → boundary conditions
- SM fermions masses and mixing

EW observables precision measurements  
K and B physics (CP violation), rare decays, ...

**model building  
is challenging !**

## top-down

superstring theories (branes, duality, M-theory)

# **Models for extra dimensions**

many possible approaches

with different impact on phenomenology depending on

**how many extra dimensions ? 1 or more ?**

**which geometry ?**

**how large and which consequences?**

**which fields where ?**

# How many and which “geometry” ?

- **factorizable or 'flat'** (3 space + 1 time + D - 4 extra space dimensions)

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad \mu, \nu = 0, 1, 2, 3, \dots D$$

- **non factorizable or warped** (3 space + 1 time + 1 extra space dimension y)

$$ds^2 = a(y) (\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2 \quad \mu, \nu = 0, 1, 2, 3$$

warp factor

6D multiple warping ? arXiv:1001.2666

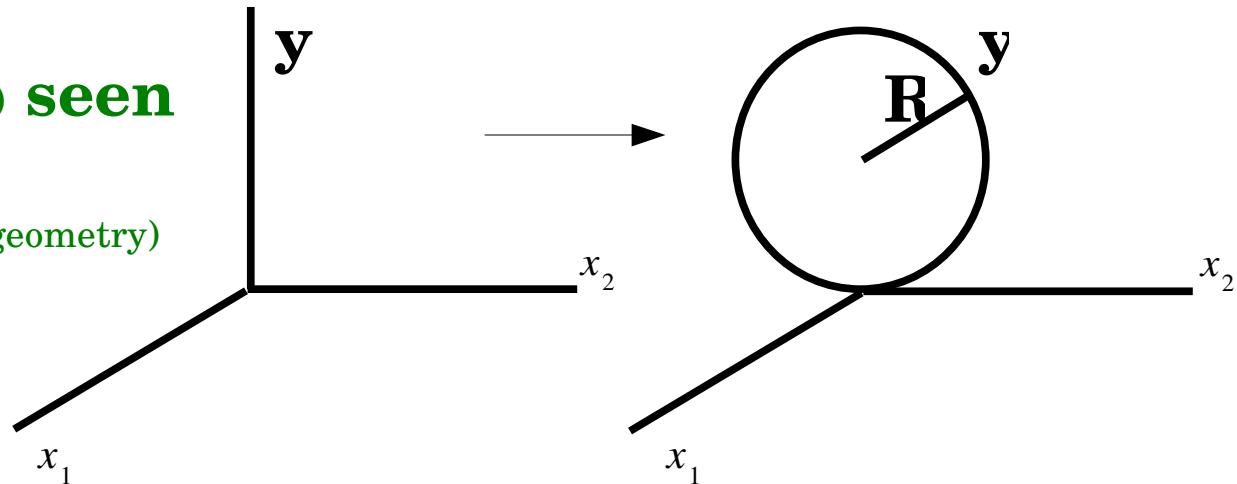
$$ds^2 = b(z) [a(y) \eta_{\mu\nu} dx^\mu dx^\nu + r_y^2 dy^2] + r_z^2 dz^2$$

see also Davoudiasl, Rizzo JHEP11(2008)013

# How Large and which consequence?

**Extra dimensions not (yet) seen**

→ must be 'small' (for 'flat' geometry)



→ **compact**

**compactified dimensions leads to periodicity conditions**

Fourier mode expansion of fields

$$\Phi(x, y) = \sum_k \phi^{(k)}(x) e^{\frac{iky}{R}}$$

infinite number of **Kaluza-Klein (KK)** modes/states/exitations

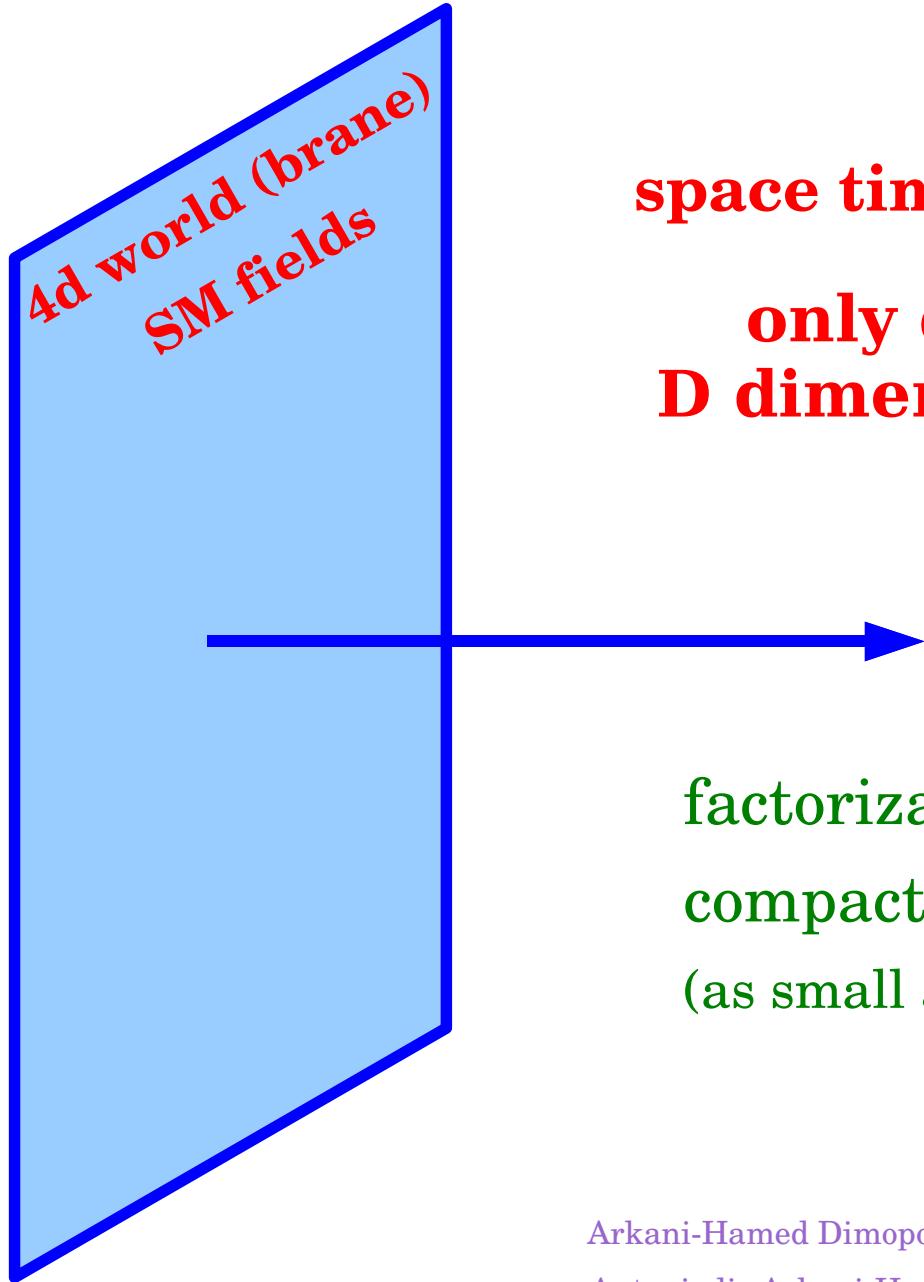
**$k^{\text{th}}$  mode mass**

$$m_k^2 = m_0^2 + \frac{k^2}{R^2}$$



**tower of KK states**

# which fields/particles and where ?



space time of  $D = 4 + n$  dimensions

only gravity propagates in  
 $D$  dimensional (*bulk*) full space

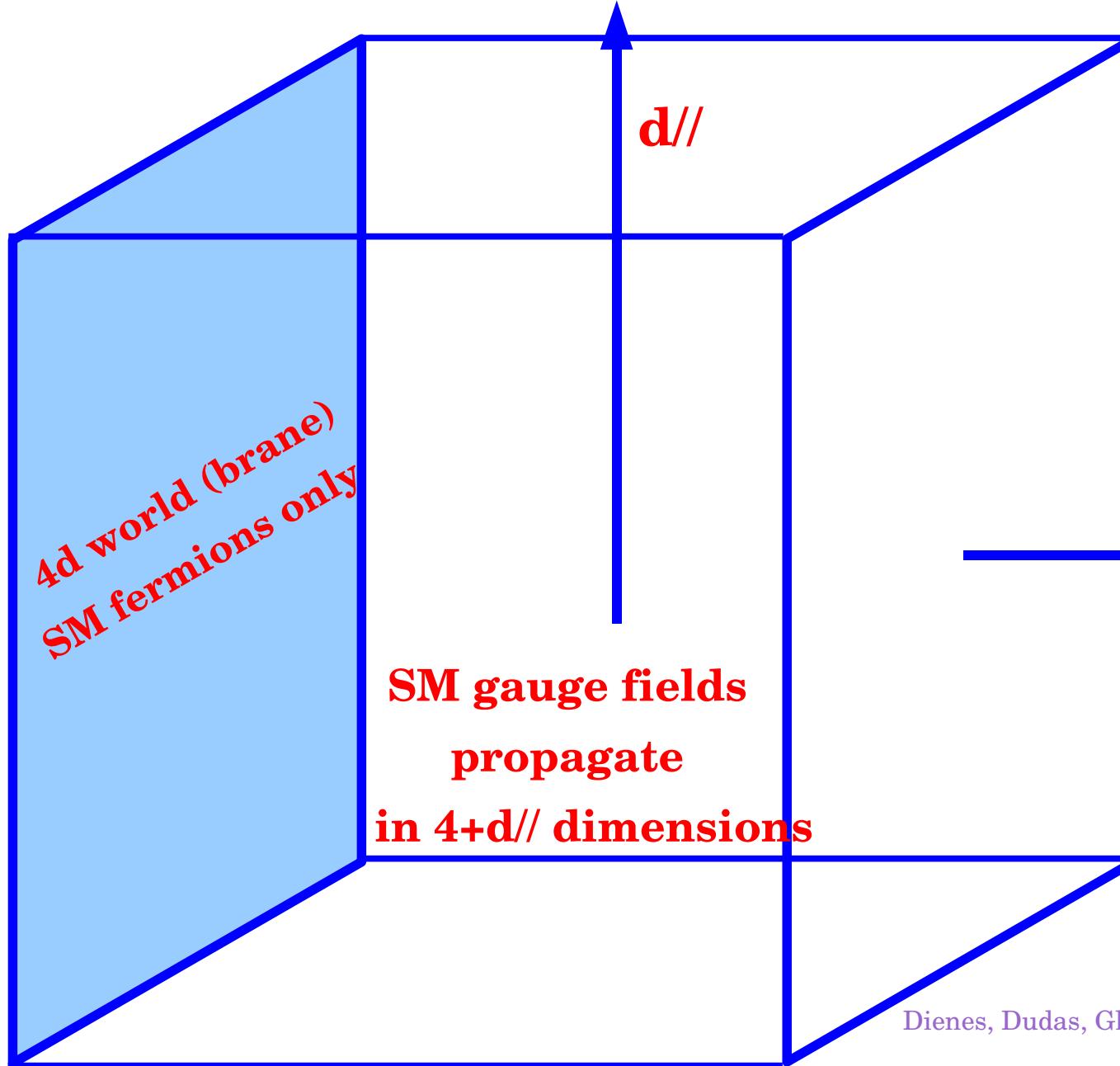
factorizable geometry

compactified  $n$  extra-dimensions  
(as small as  $\sim$  mm ?)

**ADD model**

Arkani-Hamed Dimopoulos Dvali, PLB 429 (1998) 263, PRD59 (1999) 086004  
Antoniadis Arkani-Hamed Dimopoulos Dvali, PLB 436 (1998) 257

# which fields/particles and where ?



$d//$  size:  $R^{-1} \approx TeV \approx 10^{-19} m$

## $\text{TeV}^{-1}$ models

~ ADD extension

gravity propagates in  
 $D = 4 + d// + d_{\perp}$  bulk

factorizable geometry  
compactified Xtradim

Antoniadis PLB246 (1990) 377

Antoniadis, Benakli, Quiros, PLB 331 (1994) 313

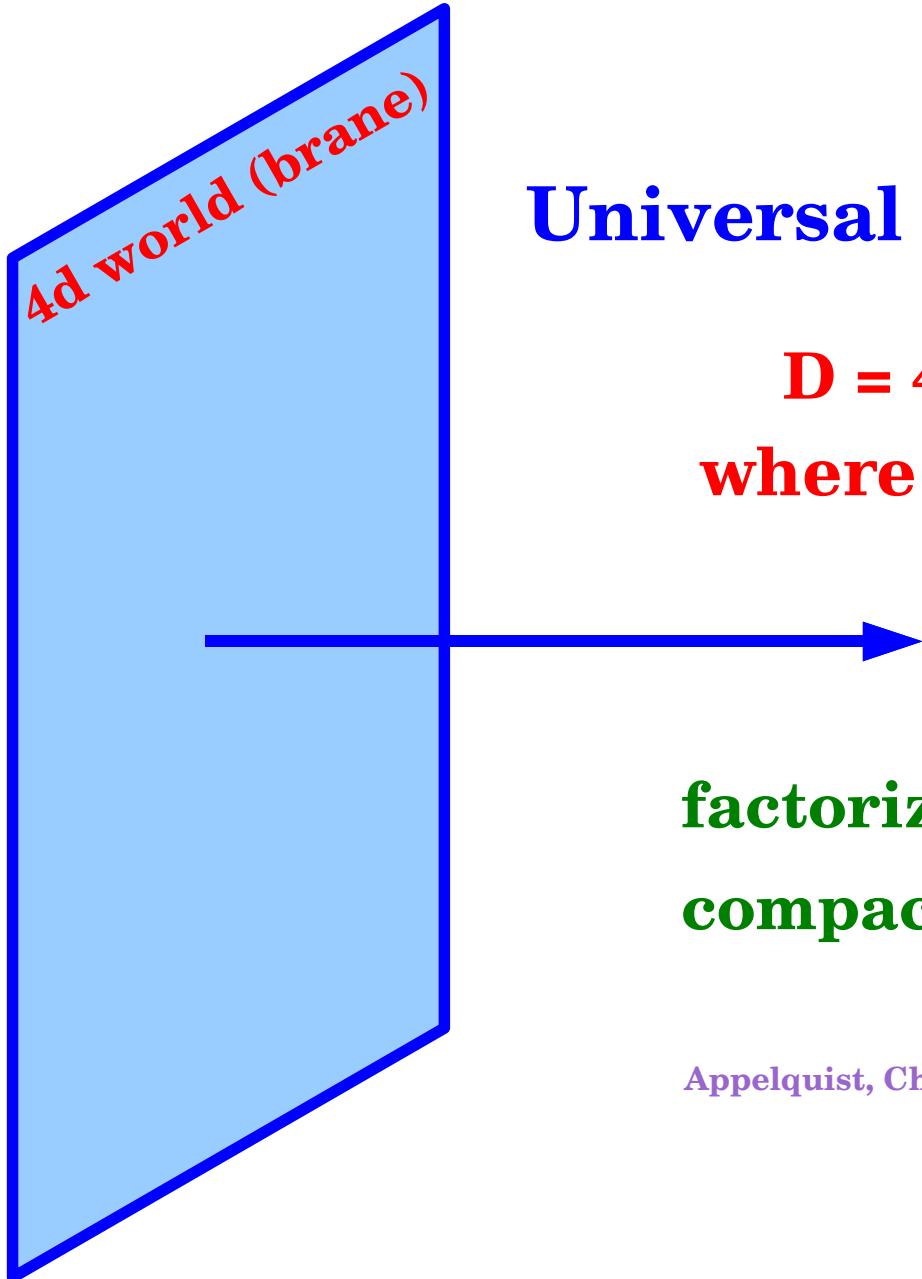
Dienes, Dudas, Gherghetta, PLB 436 (1998) 55, NPB 537 (1999) 47

Antoniadis, Benakli, Quiros, PLB 460 (1999) 176

Rizzo, Wells, PRD61, 016007

Cheung, Landsberg, PRD65, 076003

# which fields/particles and where ?



## Universal Extra-Dimensions (UED)

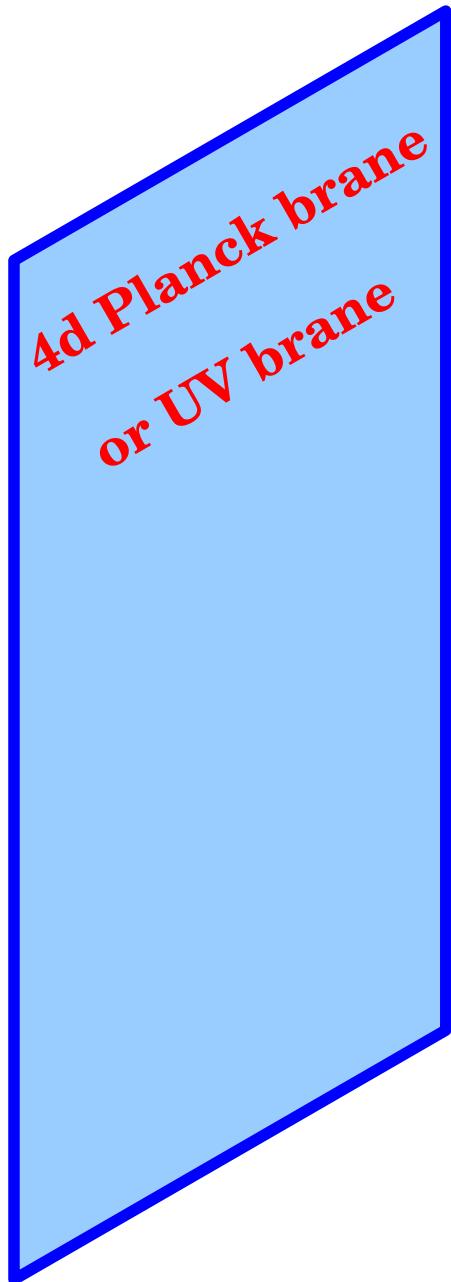
$D = 4 + n$  bulk (n=1 mostly)

where SM gauge AND fermion  
fields propagate

factorizable geometry  
compactified extra-dimensions

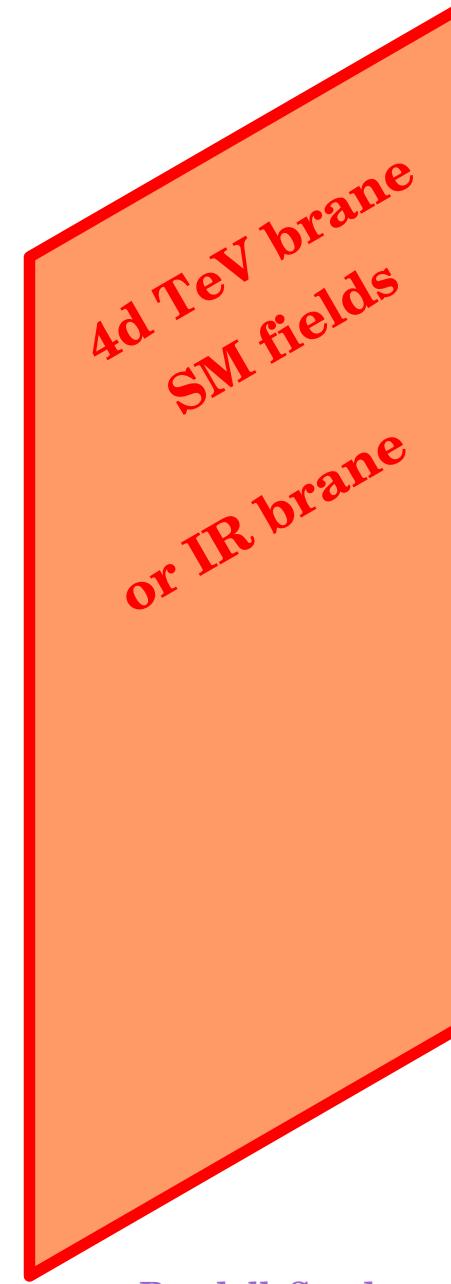
Appelquist, Cheng, Dobrescu, PRD64, 035002

# which fields/particles and where ?



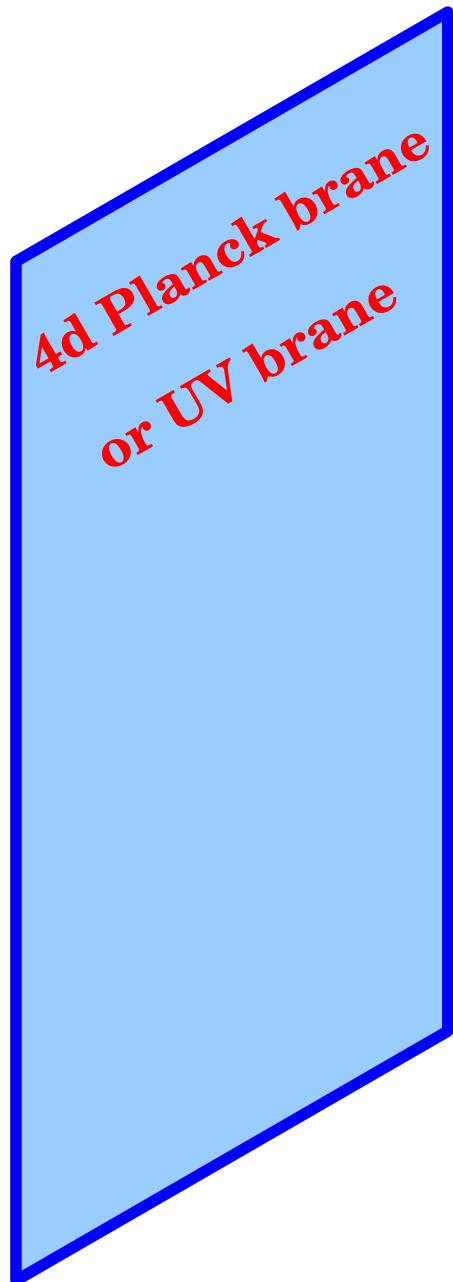
**gravity only  
propagates in a  
5D warped bulk**

**Minimal RS**

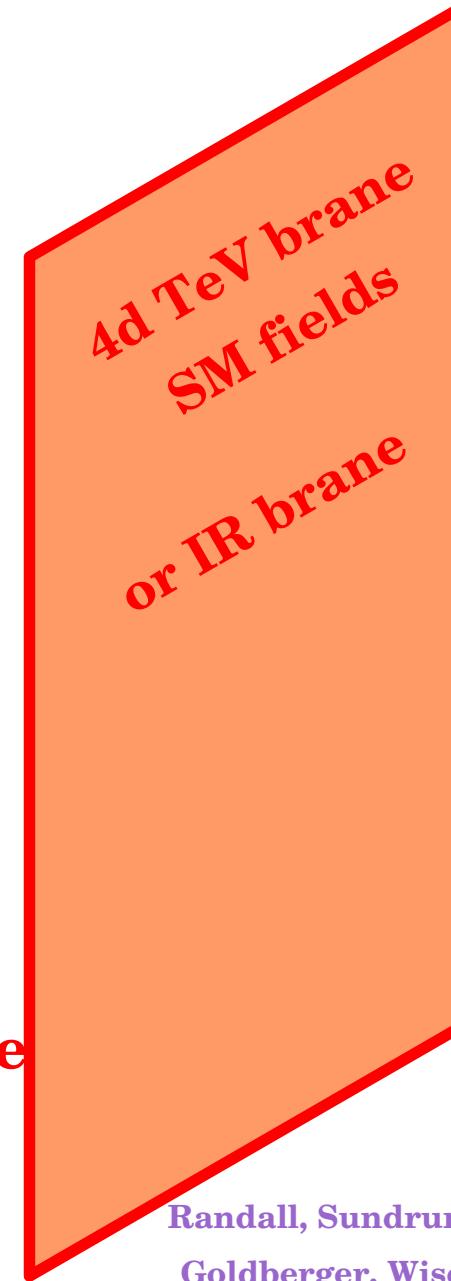


Randall, Sundrum, PRL 83 (1999) 3370

# which fields/particles and where ?

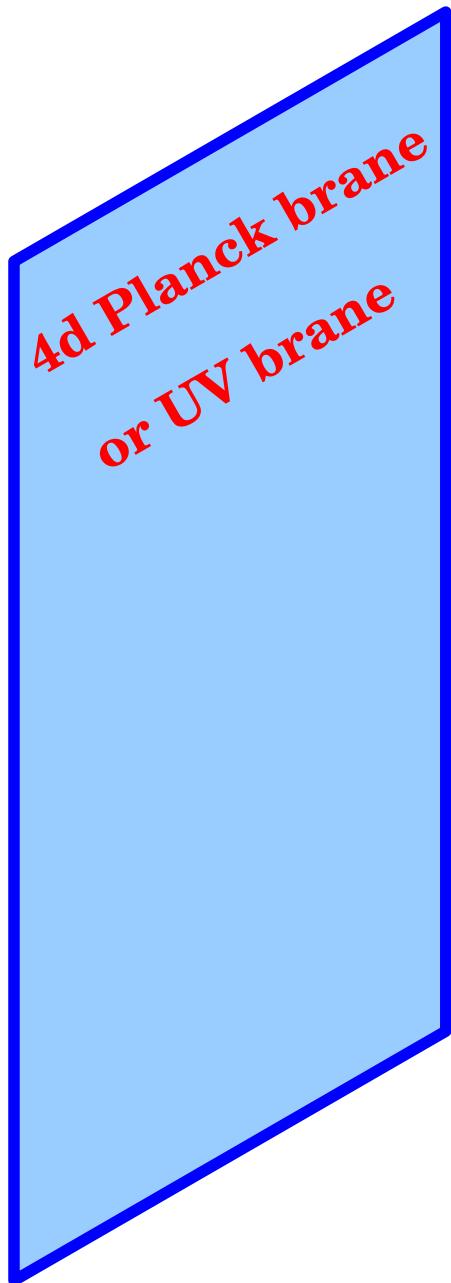


gravity  
propagates in a  
5D warped bulk  
+  
scalar for  
interbrane distance  
stabilization  
stabilized RS



Randall, Sundrum, PRL 83 (1999) 3370  
Goldberger, Wise, PRL 83 (1999) 4922,  
PRD 60, 107505,  
PBL 474 (2000) 275  
Moriond EW  
March 2010

# which fields/particles and where ?

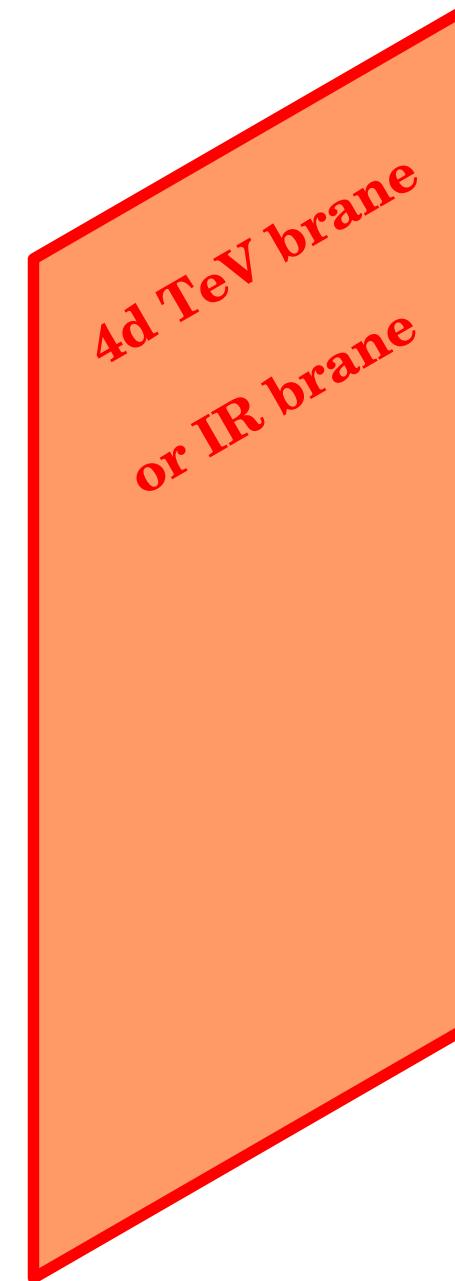


**not only gravity  
propagates in a  
5D warped bulk**

**but also  
fermion and  
gauge fields**

**Higgs localized  
close to TeV brane**

**Bulk RS**



see references later on

# OUTLINE

## - flat compactified extra-dim models family

**ADD** (only gravity in bulk)

**TeV<sup>-1</sup>** (SM gauge boson in a 'small' bulk  $1/R \sim \text{TeV}$ )

**minimal (n=1) Universal Extra dimensions:** **mUED** (SM gauge bosons and fermions in bulk)

## - warped extra-dim models family

**minimal RS** (**mRS**) (only gravity in bulk)

**stabilized RS** (**sRS**) (gravity + 1 scalar field in bulk)

**bulk RS** (**bRS**) (SM gauge bosons and fermions in bulk)

## - not in this talk

higgsless (backup), black holes (backup), string states, susy ED,  
models/signals from intersecting branes (at angle) .....

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# ADD approach

Arkani-Hamed Dimopoulos Dvali,  
PLB 429 (1998) 263, PRD59 (1999) 086004  
Antoniadis Arkani-Hamed Dimopoulos Dvali,  
PLB 436 (1998) 257

**gravity at TeV scale in a bulk of  $4 + n$  compactified dimensions**

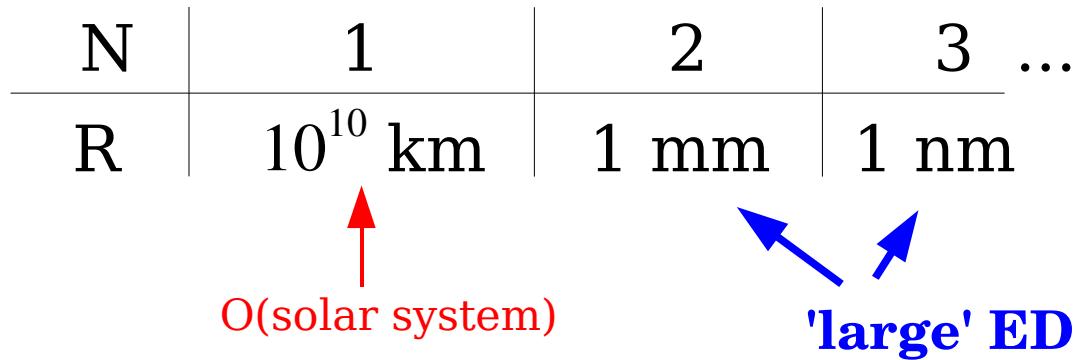
**SM fields confined in 4D brane**

one of 1<sup>st</sup> approach of the KK idea renewal after the string duality and brane revolution

**address the hierarchy problem**

$$M_{Pl(4)}^2 = M_{Pl(4+n)}^{n+2} R^n$$

for  $M_D \equiv M_{Pl(4+n)} = 1 \text{ TeV}$



**phenomenology and constraints from various areas:**

- short distance gravity measurement (backup)
- astrophysics and cosmology (backup)
- **collider physics**

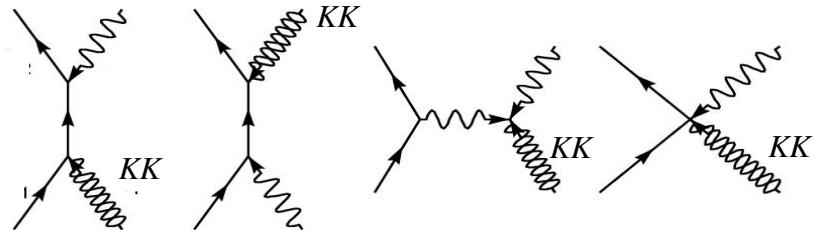
Han, Lykken, Zhang, PRD5 9, 105006  
Hewett, PRL 82 (1999) 4760

Giudice, Rattazzi, Wells, NPB 544 (1999) 3  
Mirabelli, Perelstein, Peskin, PRL 82 (1999) 2236

# ADD signatures at colliders in a nutshell

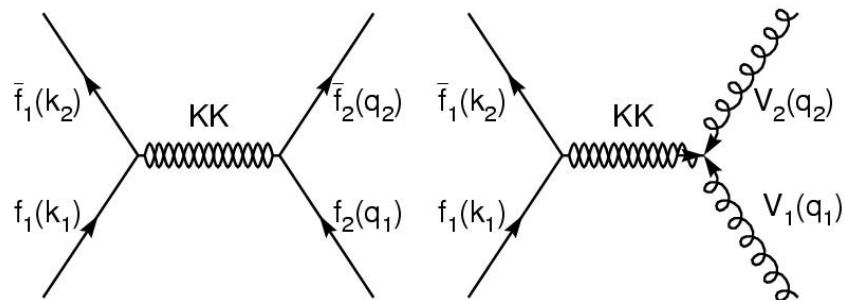
- direct searches  $\rightarrow$  KK graviton in final states  
states close to each other in mass  $O(\text{fraction of eV})$       quasi-continuum  
compensating  $\sim O(1/M_{\text{Pl}})$  coupling of each KK state to SM fields

look for jet + missing energy  
photon + missing energy  
 $Z$  + missing energy



sizeable Xsection directly related to  $n$  and scale  $M_D$   $\sigma \approx E^n / M_D^{n+2}$

- indirect searches  $\rightarrow$  no KK states in final states



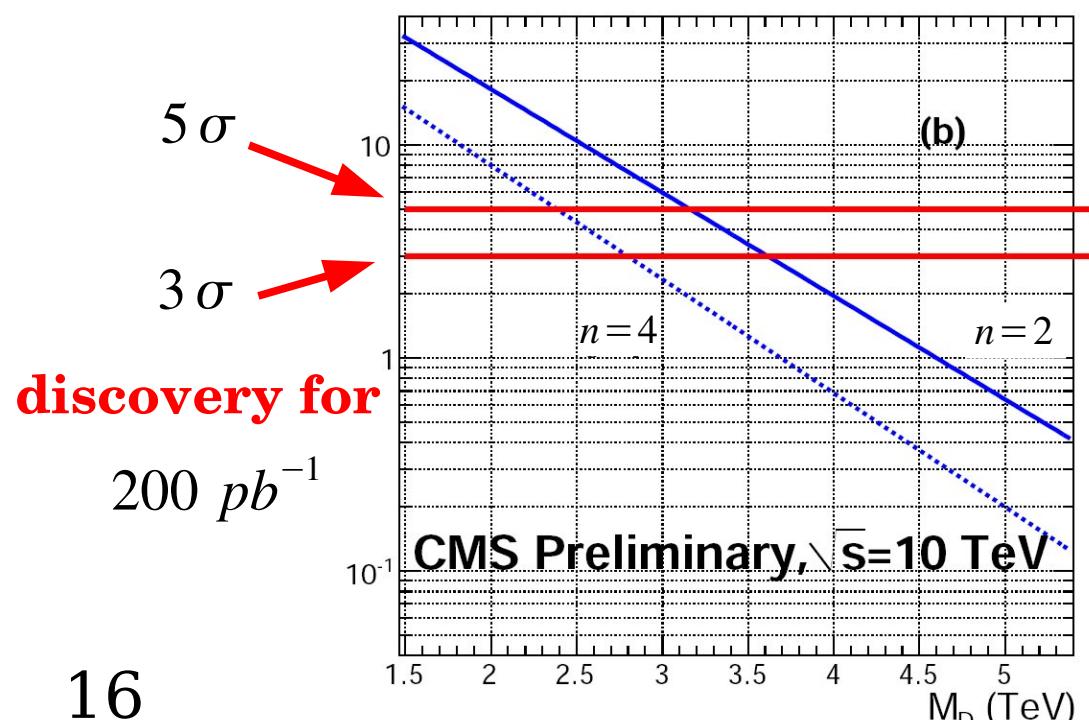
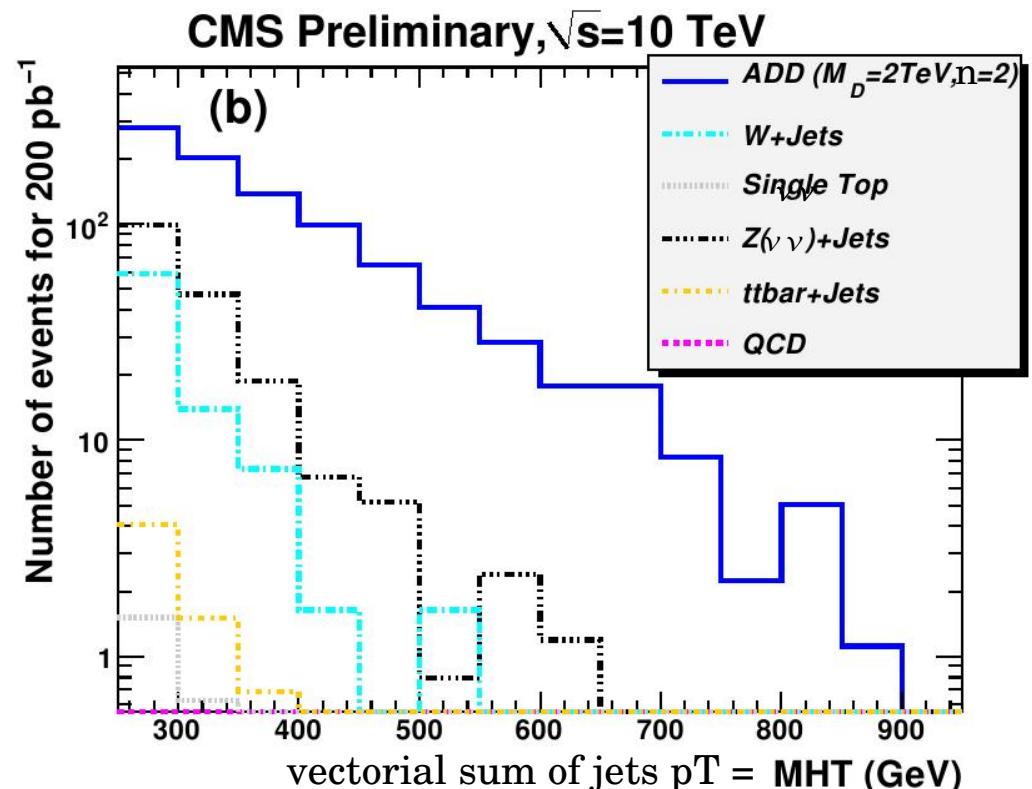
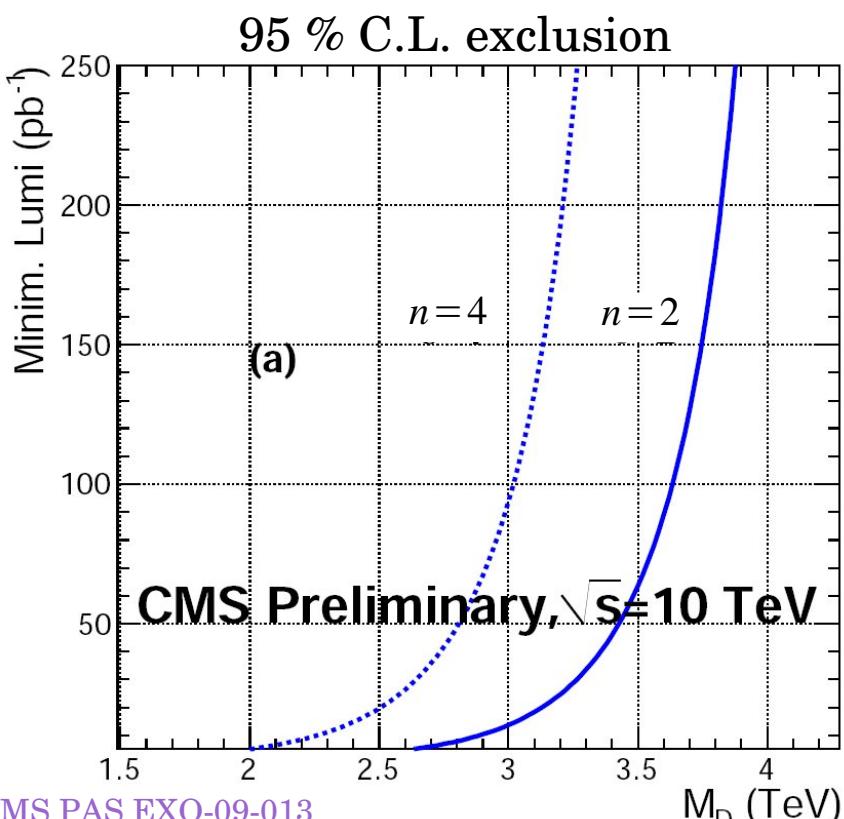
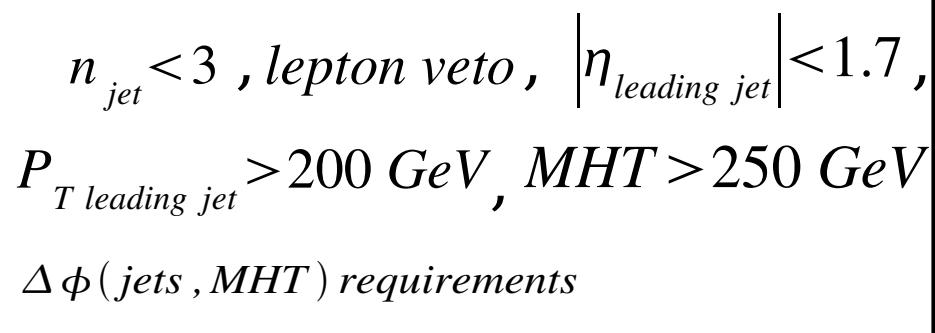
look for deviation in fermion or boson pairs production (diff.) Xsections measurements

Xsection divergent for  $n > 1$   $\rightarrow$  need a cutoff  
cut-off  $M_S$  not related to scale  $M_D$   $\rightarrow$  assume  $M_S \approx M_D$   
(possible regularization in string theories context)

current collider constraints on scales  $\sim O(1.6 - 2.1 \text{ TeV})$  for  $n = 2$

# ADD direct search

e.g.  $pp \rightarrow 1\ jet + MET$

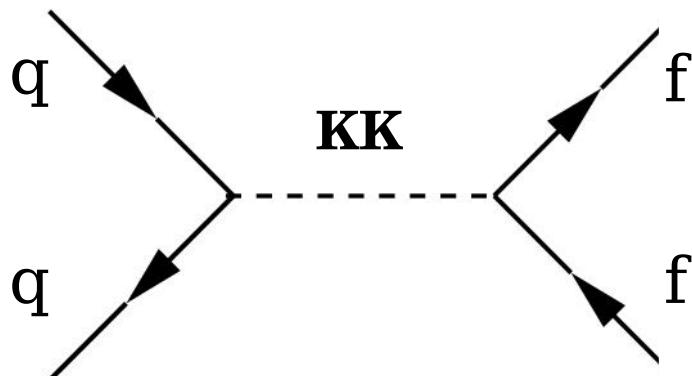


Antoniadis, Benakli, Quiros, PLB 331 (1994) 313  
 Dienes, Dudas, Gherghetta, PLB 436 (1998) 55, NPB 537 (1999) 47  
 Antoniadis, Benakli, Quiros, PLB 460 (1999) 176  
 Rizzo, Wells, PRD61, 016007  
 Cheung, Landsberg, PRD65, 076003

# $\text{TEV}^{-1}$ (KK gauge bosons)

- gauge bosons in 'flat' 5D bulk with  $R = O(\text{TeV}^{-1})$  extra dimension
- KK 0th mode identified with SM gauge bosons (can mix with non-zero modes)
- combined constraints from LEP, HERA, TEVATRON:  $M_{\text{KK}} = R^{-1} > 6.8 \text{ TeV}$   
Cheung, Landsberg, PRD65, 076003
- direct searches:**  $M_{\text{KK}} > O(1 \text{ TeV})$
- **resonant production if**  $M_{\text{KK}} < E_{CM}$   
 search for dilepton or dijet invariant mass peak  
 (or transverse mass jacobian peak from single lepton)  
**to look for the 1<sup>st</sup> mode at least**  
 $2^{\text{nd}}, 3^{\text{rd}}$  modes for KK pattern would be desirable
- **virtual effects (?) if**  $M_{\text{KK}} > E_{CM}$

Xsection deviations, asymmetries



Coupling: finite at 5D, divergent for > 5D  
 but regularized in specific string models

# $\text{TeV}^{-1}$ (KK gauge bosons)

## - generic Z' discovery potential

depends on particular models  
and detector performances (lept. id, mu align.)

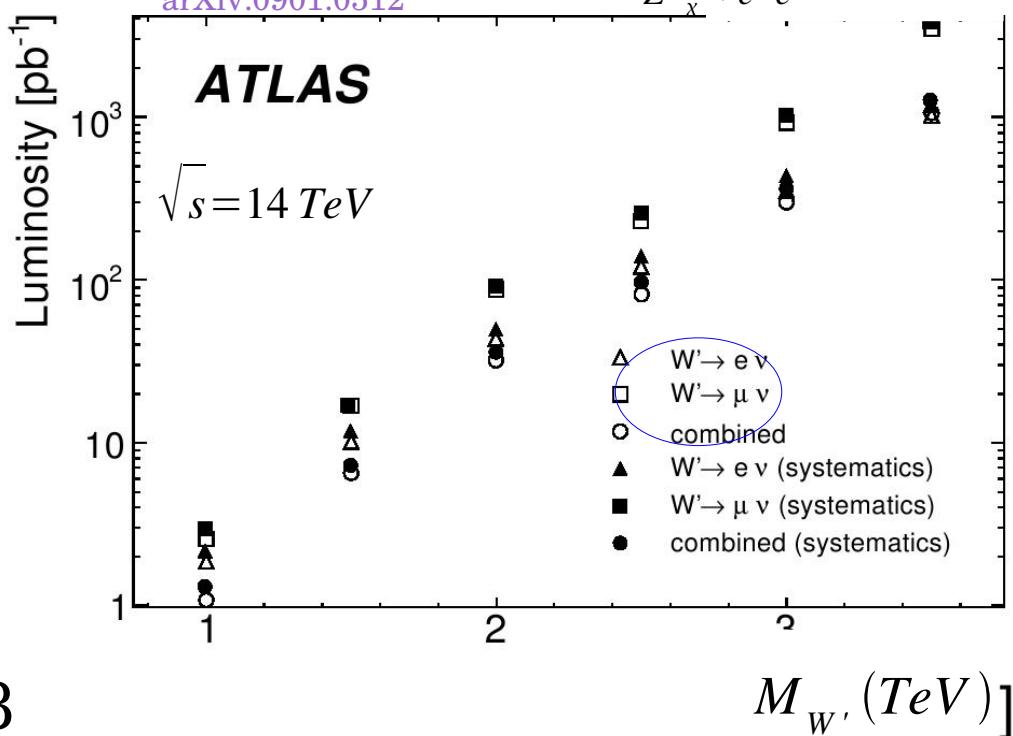
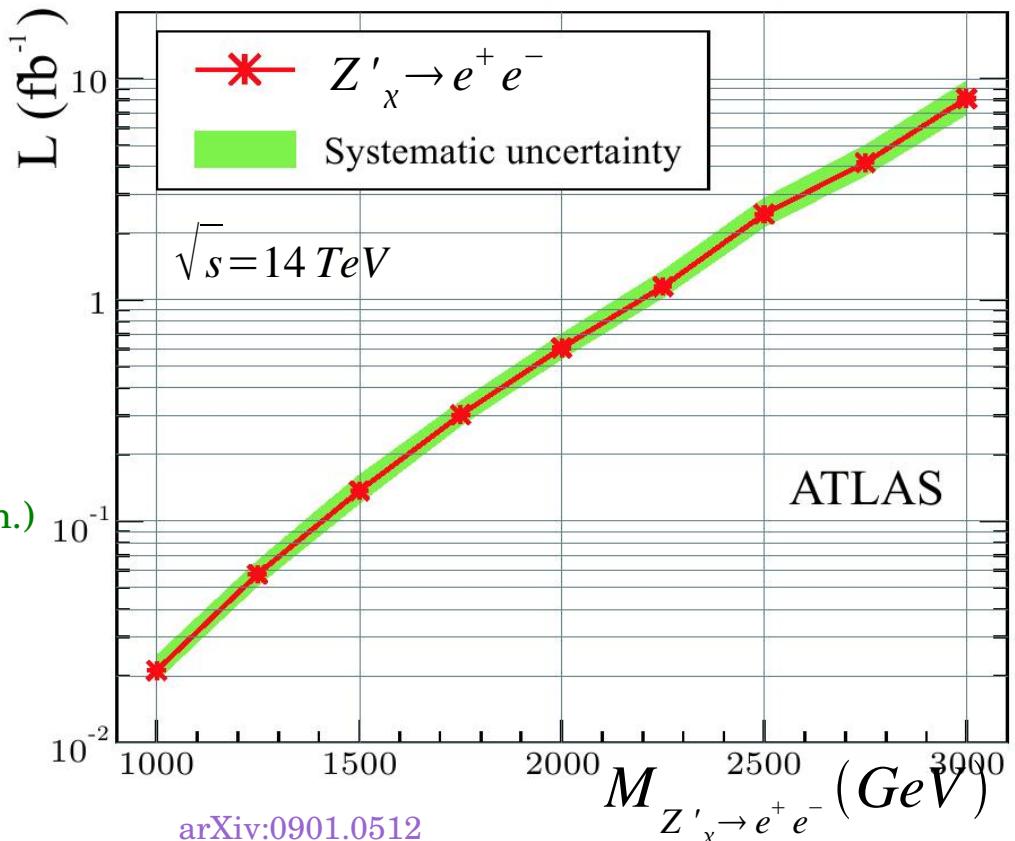
varies in the 1 – 3 TeV range

@ O(20-40 pb $^{-1}$ ) – O(10 fb $^{-1}$ )

## - W' discovery potential

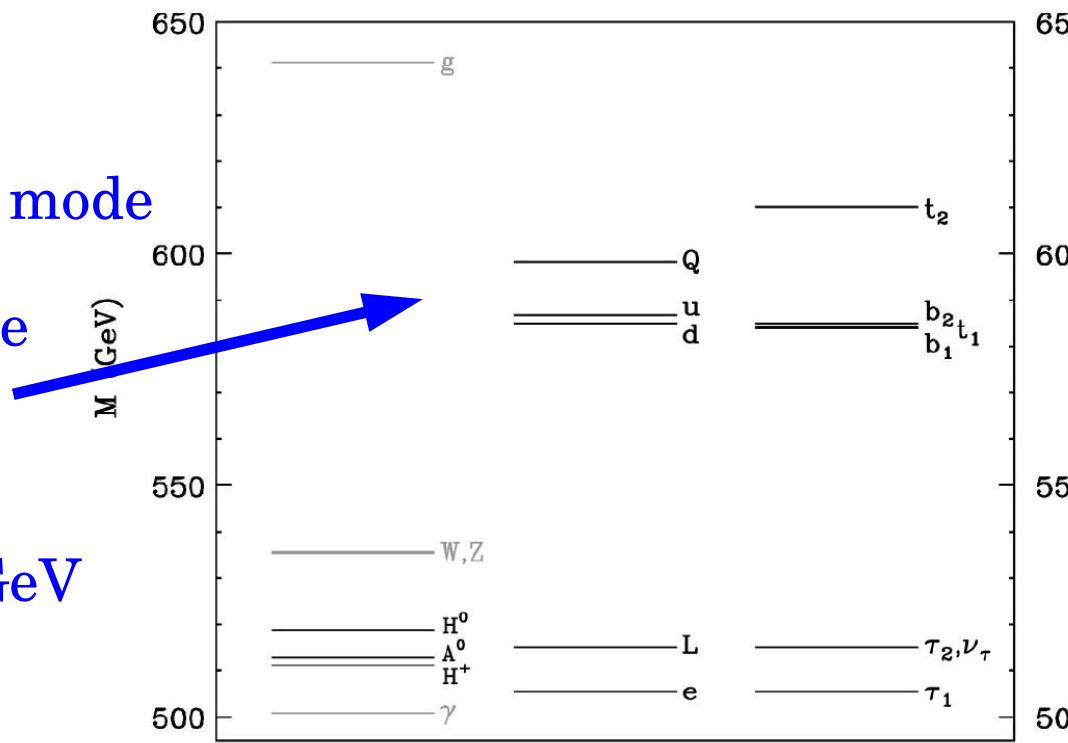
5 $\sigma$  discovery above 1 TeV  
possible with few tens of pb $^{-1}$

systematics: lepton id, MET resolution



# Minimal Universal Extra Dimensions (mUED)

- all SM fields in a 5D bulk  
further extension of  $\text{TeV}^{-1}$
- 4D SM particles identified to 0th KK mode
- 1<sup>st</sup> (and beyond) KK modes are massive
  - loop corrections involving bulk fields
  - lead to non degenerate mass spectrum
- EW constraints  $\rightarrow M > 300 - 600 \text{ GeV}$
- momentum conservation in bulk
  - KK-parity
  - pheno. similar to SUSY with conserved R-parity

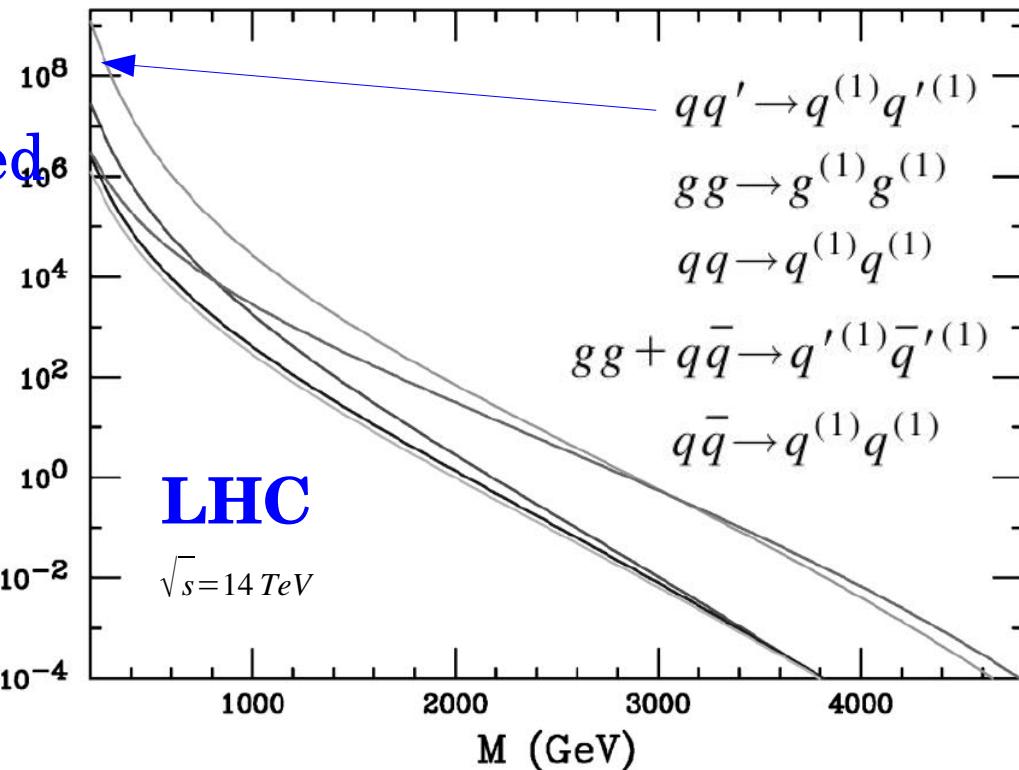
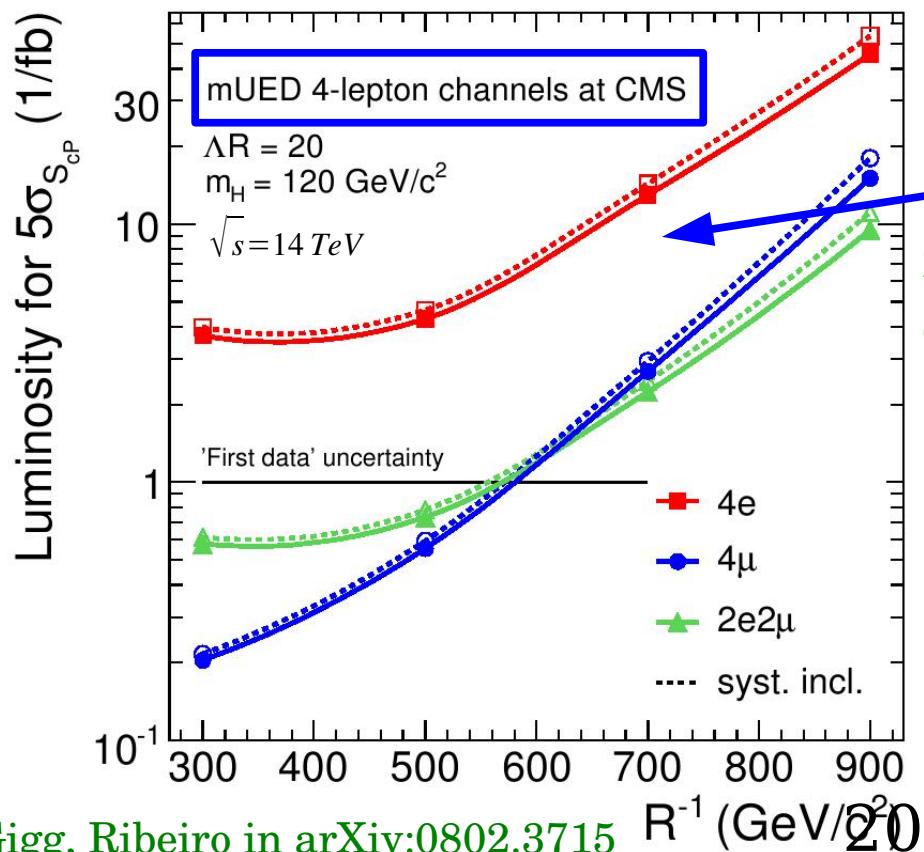


Cheng, Matchev, Schmaltz PRD66, 056006

- KK states produced in pairs
  - 1 KK + 1 SM in a KK state decay  
possible cascade decays
  - stable LKP (DM candidate)  
source of MET

# Minimal UED

- pair production of lightest coloured KK states (largest Xsection)
- possible signatures:
  - 4 leptons + MET
  - 3 (or 2 leptons ...) + jets + MET
  - 2 (or more) jets + MET



discovery potential

2 pairs of isolated and high pT (30, 40, 50 and 60 GeV)  
OS leptons, MET requirement ( $> 60 \text{ GeV}$ ), ZZ & b-jets veto

maximizing efficiency for  $R^{-1} = 900 \text{ GeV}$

$g_1$	$q_{L1}$	$u_{R1}$	$d_{R1}$	$l_{L1}$	$\gamma_1$
1114.25	1050.50	1028.84	1025.28	926.79	900.00

See also Beauchemin, Azuelos

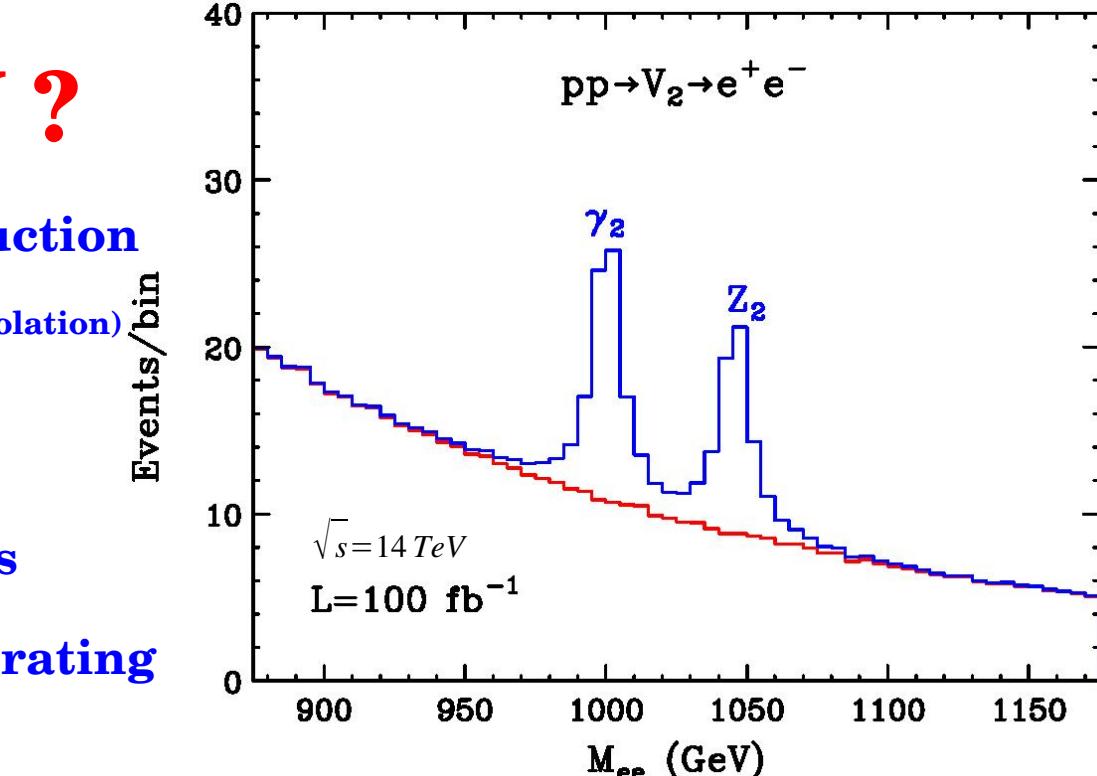
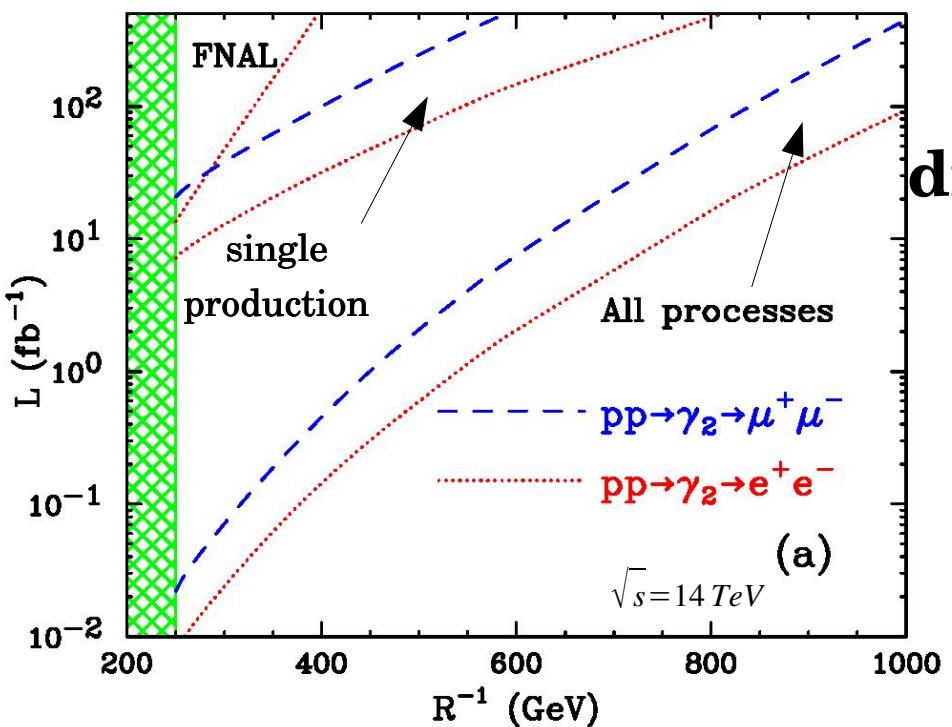
ATL-PHYS-PUB-2005-003 for 2 jets + MET **LKP**

# mUED w.r.t SUSY ?

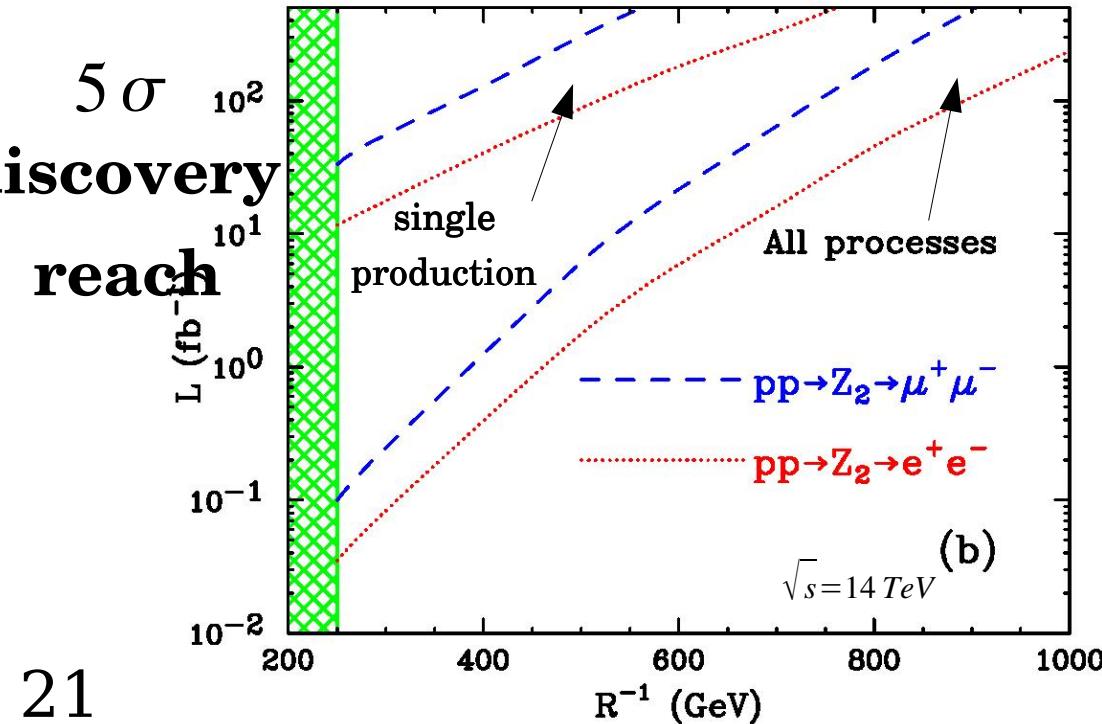
- look for level 2 KK gauge bosons production including single production (KK number violation)

$$pp \rightarrow V_2 \rightarrow f_0 \bar{f}_0 = f_{SM} \bar{f}_{SM}$$

- double peak structure in dilepton mass
- near mass-degeneracy further corroborating UED interpretation w.r.t susy or Z'



Datta, Kong, Matchev, PRD75 (2005) 096006



# OUTLINE

## - flat compactified extra-dim models family

**ADD** (only gravity in bulk)

**TeV<sup>-1</sup>** (SM gauge boson in a 'small' bulk  $1/R \sim \text{TeV}$ )

**minimal (n=1) Universal Extra dimensions:** **mUED** (SM gauge bosons and fermions in bulk)

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**minimal RS (mRS)** (only gravity in bulk)

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## - not in this talk

higgsless (backup), black holes (backup), string states, susy ED,  
models/signals from intersecting branes (at angle) .....

# Minimal RS

- **gravity only** in a 5D warped bulk (with 1 compact ED) and 2 4D branes

$$ds^2 = e^{-2kr_c\phi} (\eta_{\mu\nu} dx^\mu dx^\nu) + r_c d\phi^2 \quad \phi \in [0, \pi] \quad k \approx M_{Pl(4)}$$



- **warp factor** allows to generate TeV scale on one brane (**TeV Brane**) from Planck scale on the other brane (**Planck Brane**)

$$\Lambda_\pi = M_{Pl(4)} e^{-\pi k r_c} \longrightarrow \Lambda_\pi \approx 1 \text{ TeV} \quad \text{for} \quad k r_c \approx 12 \quad r_c = 10^{-32} \text{ m}$$

- **KK graviton** with O(TeV) spacing  $M_n = k x_n e^{-k r_c \pi}$   $x_1 = 3.83$   $x_n$  roots of Bessel function  $J_1$

- **SM fields on TeV brane coupling to massive KK graviton**  $1/\Lambda_\pi^2$

- phenomenology described by 2 parameters

$$M_1 \text{ mass of 1st mode, and } c = \frac{M_1}{x_1 \Lambda_\pi} \quad 0.01 < c < 0.1 \text{ theoretically reasonable range}$$

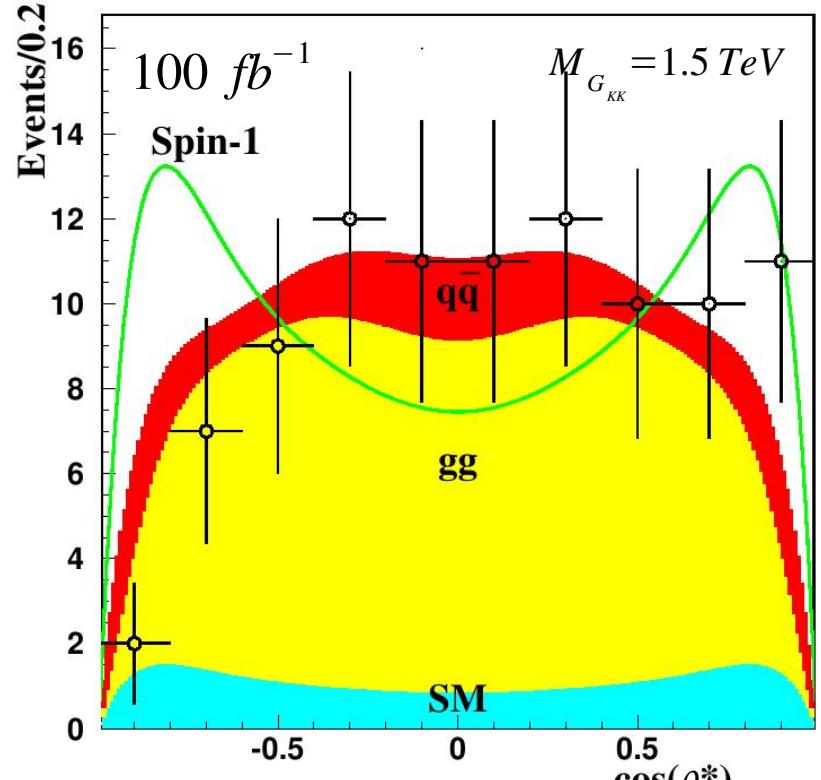
**search for narrow resonances**  $pp \rightarrow G_{KK} \rightarrow e^+ e^-, \mu^+ \mu^-, \gamma \gamma, ZZ$

# Minimal RS

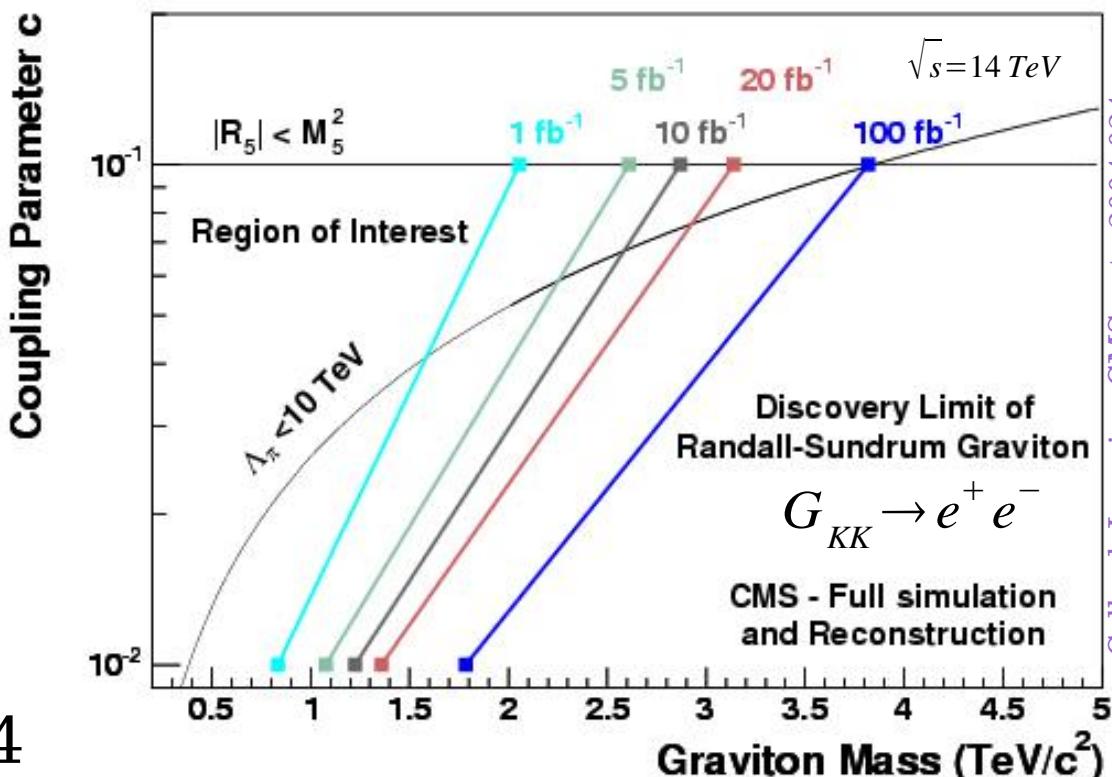
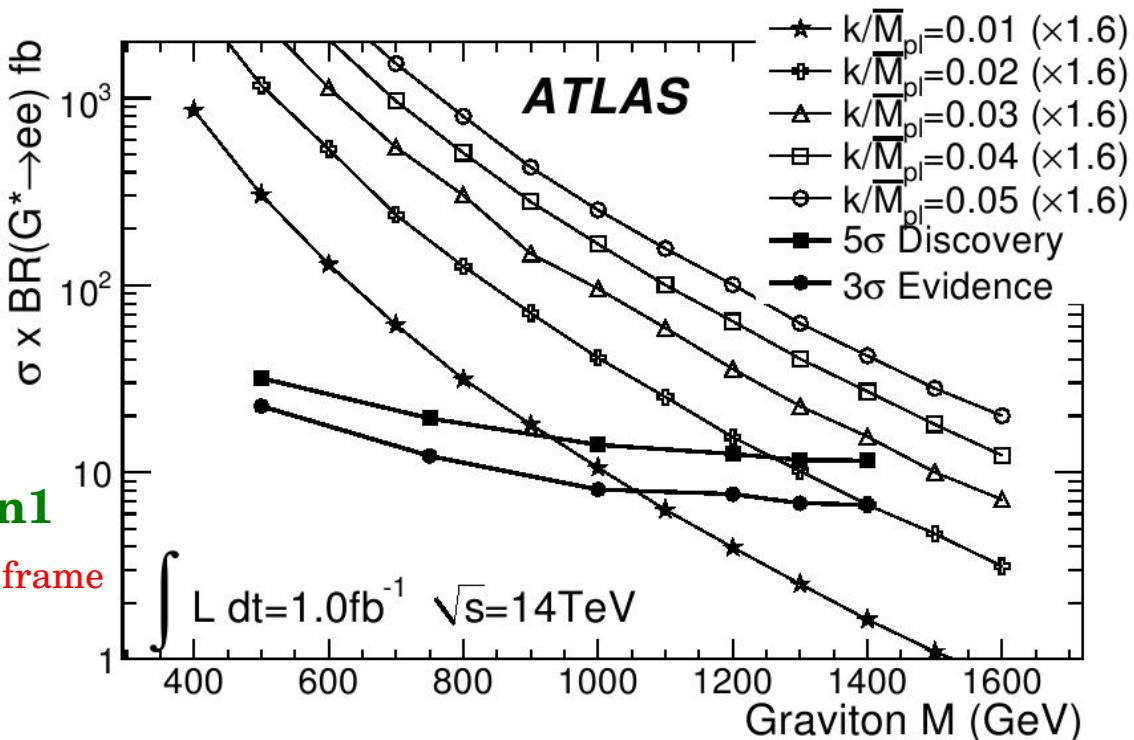
e.g. resonant  $G_{KK} \rightarrow e^+ e^-$

- LHC should be able to cover the region of interest with  $< 100 \text{ fb}^{-1}$
- possible to distinguish spin 2 vs spin 1  
different angular distribution in lepton lepton cms frame

Allanach, Odagiri, Parker, Webber, JHEP 09 (2000) 019



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# Stabilized RS

gravitational fluctuations around RS metric  $ds^2 = e^{-2kr_c\phi}(\eta_{\mu\nu}dx^\mu dx^\nu) + r_c d\phi^2$

- contain massless scalar mode (modulus)  $r_c \rightarrow T(x)$ : **the radion**
- v.e.v stabilizing the interbrane distance  $\langle T(x) \rangle = r_c$   
(Goldberger Wise mechanism)  
bulk scalar generating potential  
can stabilize the modulus  
at minimum of potential

radion must be massive to recover ordinary 4D Einstein gravity

in order to have  $k r_c \approx 12$  **radion should be lighter than O(TeV) KK graviton**

**radion likely the lightest state from RS models**  
**radion couples directly to gluon and photon**

**possible Higgs-radion mixing** (also in type I string)

parameterized by  $\xi$  with  $|\xi| \approx O(1)$

Goldberger, Wise, PRL 83 (1999) 4922

Goldberger, Wise, PRD 60, 107505

Goldberger, Wise, PBL 474 (2000) 275

Csaki, Graesser, Randall, Terning, PRD 62 (2000) 045015

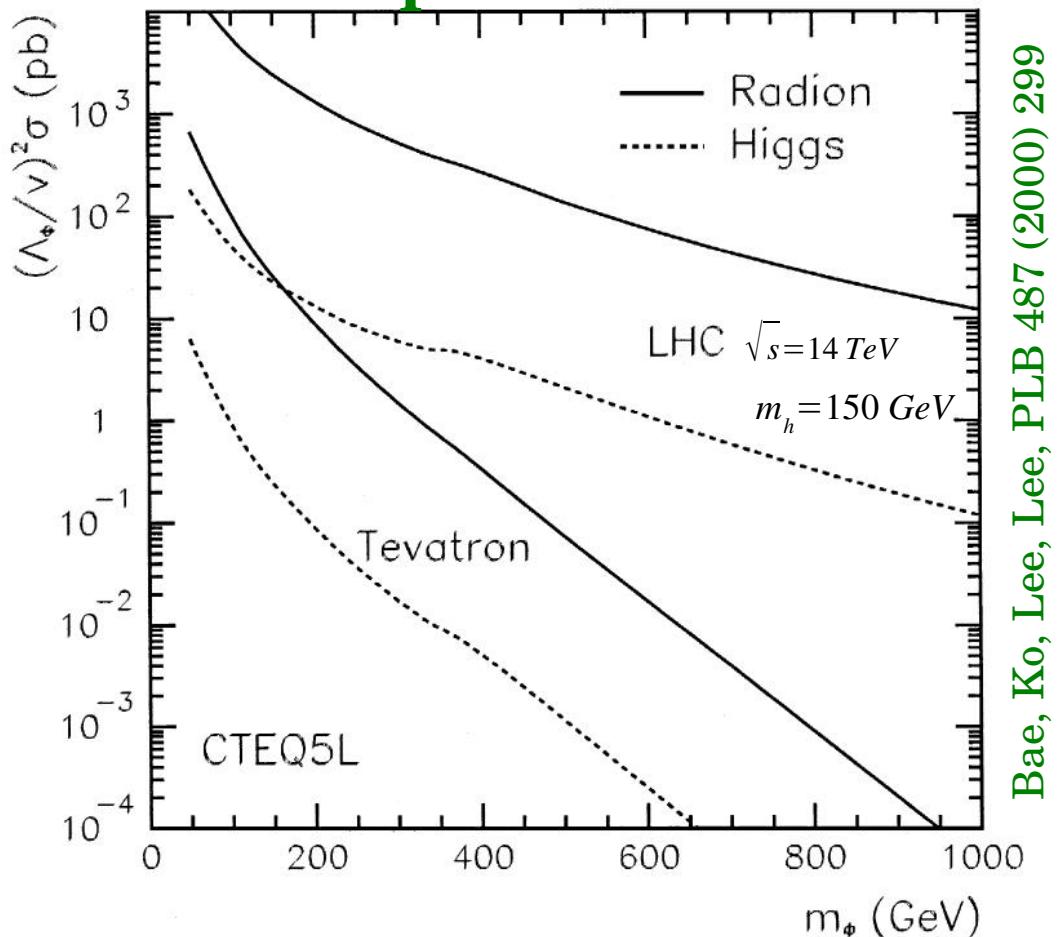
Charmousis, Gregory, Rubakov, PRD 62 (2000) 067505

# stabilized RS

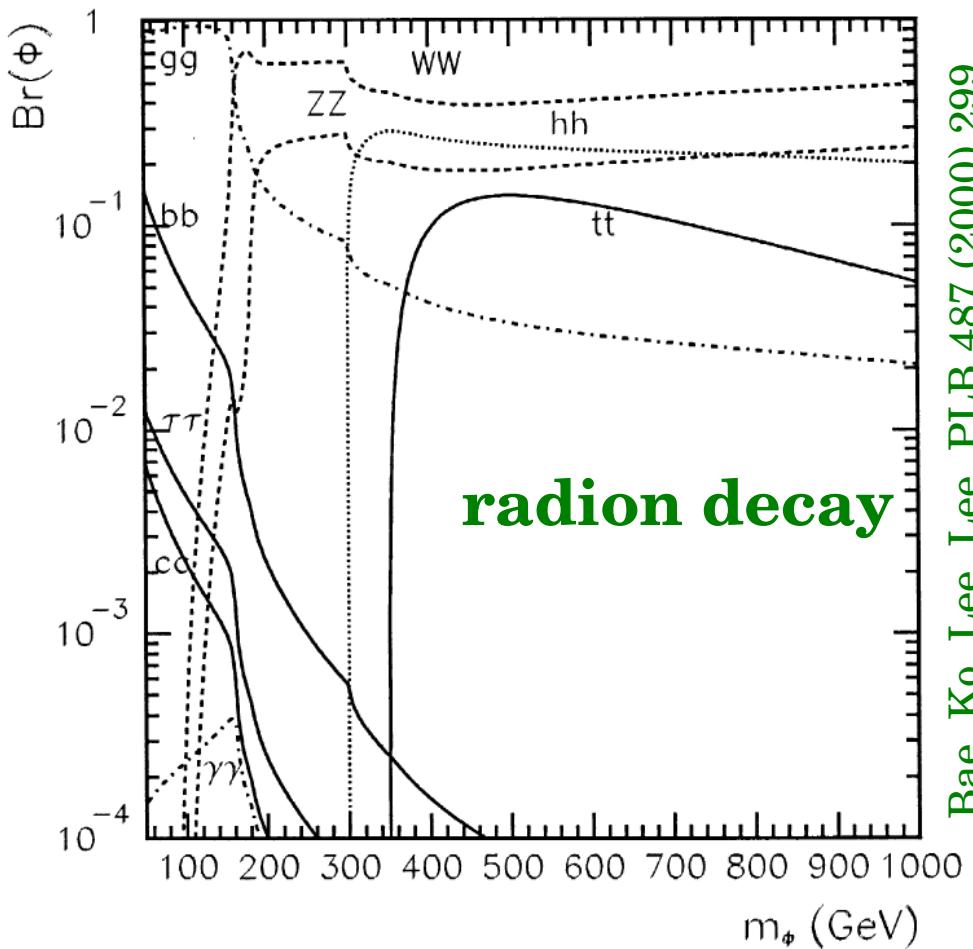
- Mahanta, Rakshit, PLB 480 (2000) 176  
 Mahanta, Datta, PLB 483 (2000) 196  
 Bae, Ko, Lee, Lee, PLB 487 (2000) 299  
 Mahanta, PRD 63, 076006  
 Cheung, PRD 63, 056007  
 Giudice, Rattazzi, Wells, NPB 595 (2001) 250  
 Rizzo, JHEP 06 (2002) 056  
 Bae, Lee, PLB 506 (2001) 147  
 Chaichian, Datta, Huitu, Yu, PLB 524 (2002) 161  
 Das, Mahanta, PLB 529 (2002) 253  
 Azuelos, Cavalli, Przysiezniak, Vacavant,  
 Eur. Phys. J. Direct C4 (2002) 16

- Csaki, Graesser, Kribs, PRD63, 065002  
 Han, Kribs, McElrath, PRD 64, 076003  
 Antoniadis, Sturani, NPB 631 (2002) 66  
 Gupta, Mahajan, PRD 65, 056003  
 Hewett, Rizzo, JHEP, 08 (2003) 028  
 Battaglia, De Curtis, De Roeck, Dominici, Gunion,  
 PLB 568 (2003), 92  
 Das, Mahanta, Mod. Phys. Lett. A19 (2004) 1855  
 Gunion, Toharia, Wells, PLB 585 (2004) 295  
 Cheung, Kim, Song, PRD69, 075011  
 Das, PRD 72,055009  
 Csaki, Hubisz, Lee, PRD 76,125005

## radion production



## radion decay



# stabilized RS

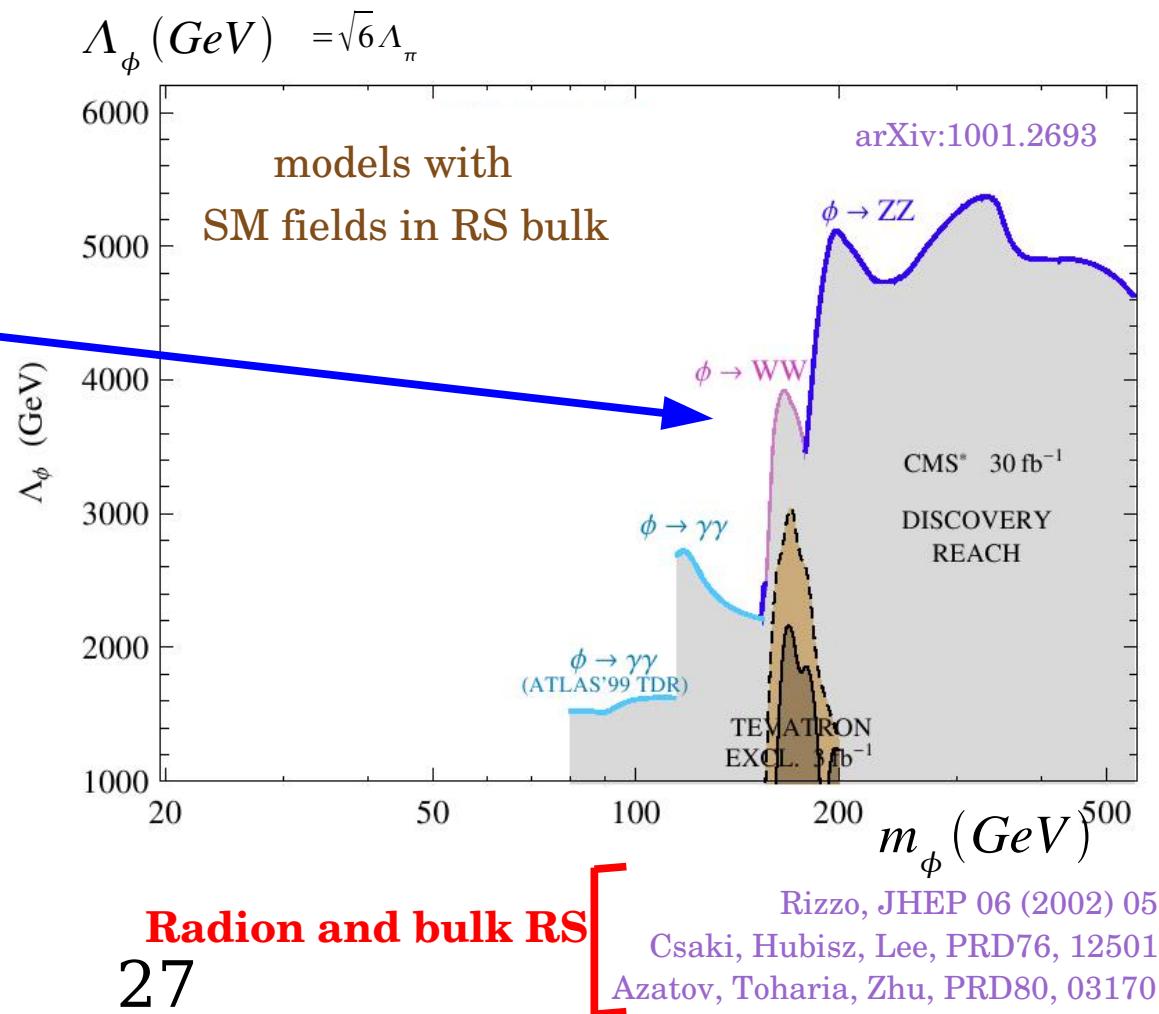
- pure radion effects on precision EW data are small

Gunion, Toharia, Wells, PLB 585 (2004) 295

- radion searches using  
SM Higgs searches

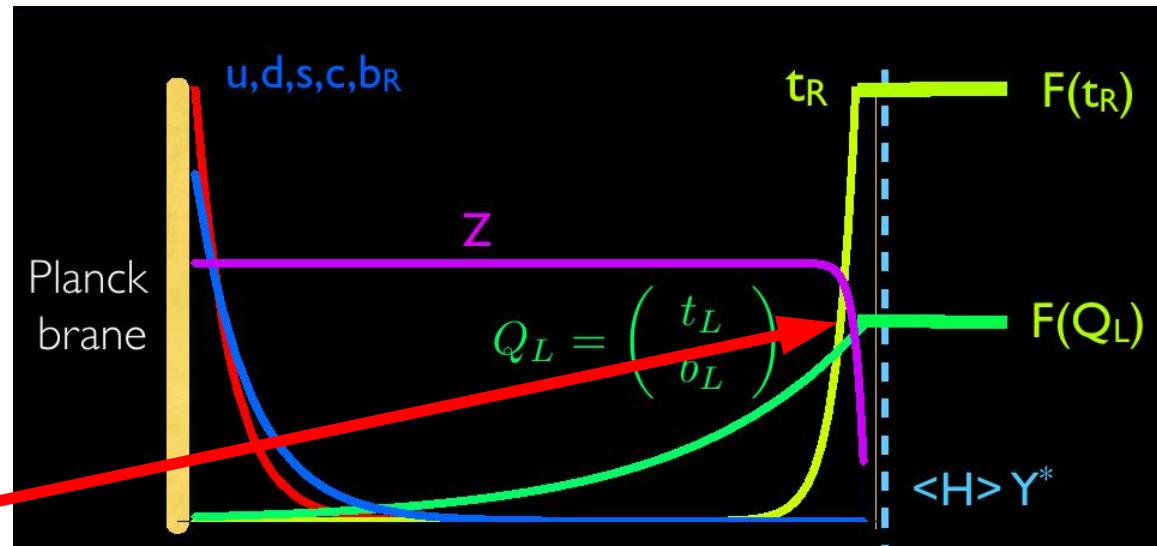
$\phi \rightarrow h h$  also possible

key difference w.r.t SM Higgs  
→ direct couplings to gluons



# Bulk RS models

- to solve hierarchy problem
  - only SM Higgs has to be localized on/near TeV Brane
- fermion and gauge fields allowed to propagate in the Xtra dim
- SM particles correspond to KK zero modes of 5D fields
  - bulk profile of SM fermion depends on its 5D mass parameter
- choose to localize 1<sup>st</sup> and 2<sup>nd</sup> generation fermions near Planck brane
  - FCNC from higher dim operator suppressed by scales >> TeV
  - SM Yukawa coupling hierarchies
    - 1<sup>st</sup> and 2<sup>nd</sup> generation small Yuk. coup.  
with Higgs localized near TeV brane
    - top quark can be localized near TeV brane  
to account for its large Yukawa coupling



from Weiler's talk at GDR Terascale (<http://terascale.in2p3.fr>)  
<http://indico.in2p3.fr/conferenceDisplay.py?confId=1617>

# constraints on Bulk RS models

from:

- EW precision data via Oblique parameters S T U
- FCNC (K physics, CPV, B physics, rare decays)
- $Z b_L \bar{b}_L$  ( $t_L, b_L$ ) not too close to TeV brane

and with various symmetries in the bulk

- larger bulk gauge symmetry i.e.  $SU(2)_L \times SU(2)_R \times U(1)_X$ ,  $SO(5) \times U(1)$ , ....
- flavor symmetries

→ KK gauge mass > 3 TeV

→ KK graviton mass > 2 - 4 TeV dependent on specific models  
w/o fermions in bulk and bulk symmetry > 23 TeV

→ Fermionic excitations > 1 – 2 TeV

Additional SU(2) doublet states with exotic charge (5/3) 0.5 – 0.8 TeV

# constraints on Bulk RS models

from:

- EW precision data via Oblique parameters S T U

- FCI

- ( $=\sqrt{6}$ )

and v

- large

- flavor



- Delgado, Pomarol, Quiros, JHEP (2000) 030
- Huber, NPB 666 (2003) 269
- Burdman, PLB 590 (2004) 86
- Agashe, Perez, Soni PRL 93 (2004) 201804, PRD71, 016002
- Moreau, Silva-Marcos, JHEP 03 (2006) 090
- Agashe, Contino, NPB 742 (2006) 59
- Cacciapaglia,Csaki, Galloway, Marandella, Terning, Weiler, JHEP 04 (2008) 006
- Casagrande, Goertz, Haisch, Neubert, Pfoh, JHEP 10 (2008) 094
- Santiago, JHEP 12 (2008) 046
- Csaki, Falkowski, Weiler, JHEP 09 (2008)008
- Fitzpatrick, Perez, Randall, PRL 100 (2008) 171604
- Bouchart, Moreau, NPB 810 (2009) 66
- Blanke, Buras, Duling, Gori, Weiler, JHEP03 (2009) 001
- Blanke, Buras, Duling, Gemmler, Gori, JHEP 03 (2009) 108
- Csaki, Perez, Surujon, Weiler, arXiv:0907.0474
- Bauer, Casagrande, Grunder, Haisch, Neubert, PRD79, 076001
- Csaki, Falkowski, Weiler, PRD 80, 016001
- .....

cays)

Flavour physics constraints  
striking hard →  
**huge activity in RS flavor  
models development**

pendent on specific models

Additional SU(2) doublet **states with exotic charge** (5/3) **0.5 – 0.8 TeV**

# Bulk RS models signatures

## - KK graviton

$$gg \rightarrow G \rightarrow t\bar{t}$$

$$gg \rightarrow G \rightarrow W_L W_L \rightarrow l\nu jj$$

$$gg \rightarrow G \rightarrow W_L W_L \rightarrow e^\pm \mu^\mp 2\nu$$

$$gg \rightarrow G \rightarrow Z_L Z_L \rightarrow 4l$$

## - KK Gluon

$$pp \rightarrow g^{(1)} \rightarrow t\bar{t}$$

## - KK EW neutral gauge boson

$$\begin{aligned} pp \rightarrow Z' \rightarrow WW \rightarrow 2l2\nu \\ \rightarrow l\nu jj \end{aligned}$$

## - KK EW charged gauge boson

$$pp \rightarrow W' \rightarrow t\bar{b} \rightarrow W\bar{b} b \rightarrow l\nu\bar{b}b$$

$$pp \rightarrow W'^+ \rightarrow W^+ h$$

## - KK fermions (e.g.)

$$pp \rightarrow g + g^{(1)} \rightarrow t^{(1)}\bar{t}^{(1)} \rightarrow W^+ b W^- \bar{b} \rightarrow l^- \nu b\bar{b} jj \quad (l=e, \mu)$$

Davoudiasl, Hewett, Rizzo, PLB 473 (2000) 43

Grossman, Neubert, PLB474 (2000) 361

Pomarol, PLB 486 (2000) 153

Chang, Hisano, Okada, Yamaguchi, PRD62, 084025

Randall, Schwartz, JHEP 11 (2001) 003

Huber, Shafi PRD 63, 045010, PLB 498 (2001) 256

Randall, Schwartz, PRL 88 (2002) 081801

Csaki, Erlich, Terning, PRD66 (2002) 064021

Hewett, Petriello, Rizzo, JHEP 09 (2002) 030

Agashe, Delgado, May, Sundrum, JHEP08 (2003) 050

Carena, Delgado, Ponton, Tait, Wagner, PRD68, 035010, PRD71, 015010

Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202, PRD76, 035006

Skiba, Tucker-Smith, PRD75, 115010

Aguilar-Saavedra, PLB 625 (2005) 234, PLB 633 (2006) 792

Agashe, Contino, Darold, Pomarol, PLB 641 (2006) 62

Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013

Agashe, Davoudiasl, Perez, Soni, PRD76, 036006

Holdom, JHEP 03 (2007) 063

Antipin, Atwood, Soni, PLB 666 (2008) 155

Antipin, Soni, JHEP10 (2008) 018

Lillie, Randall, Wang, JHEP 09 (2007) 074

Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003

Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

Baur, Orr, PRD 77, 114001

Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347

Lillie, Shu, Tait, PRD 76, 115016

Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003

Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, PRD76, 115015

Djouadi, Moreau, Singh, NPB 797 (2008) 1

Contino Servant, JHEP 06 (2008) 026

Antipin, Tuominen, PRD 79, 075011

Aguilar, Aguilar-Saavedra, Moretti, Piccinini, Pittau, Treccani,

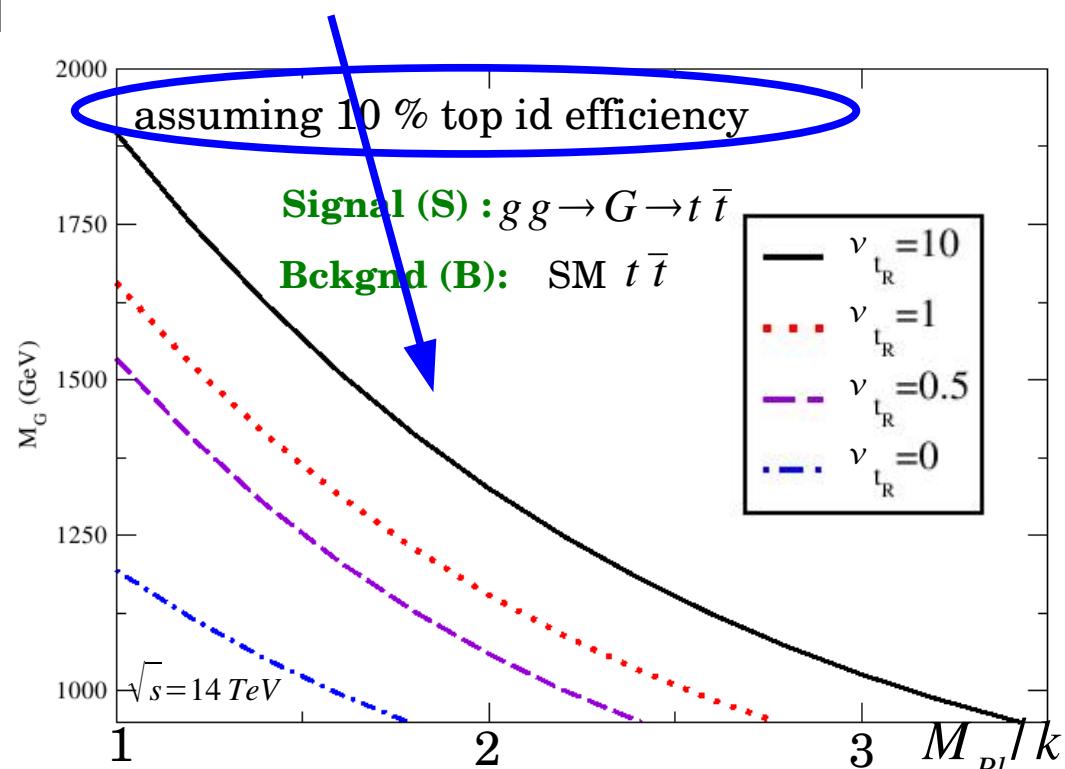
arXiv:0912.3799

# Bulk RS models

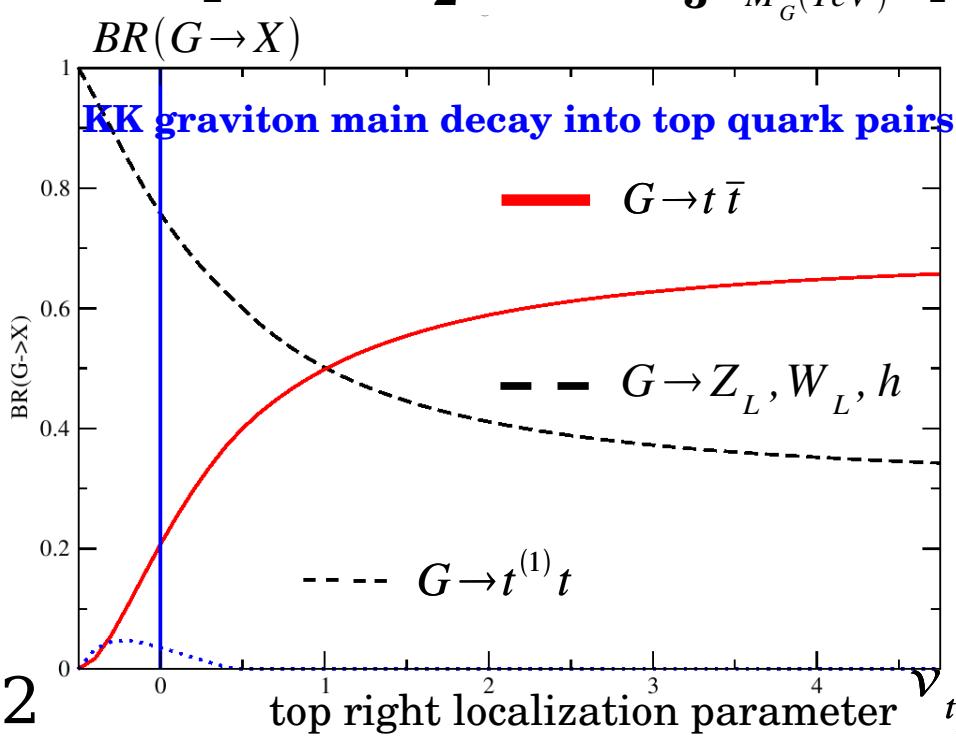
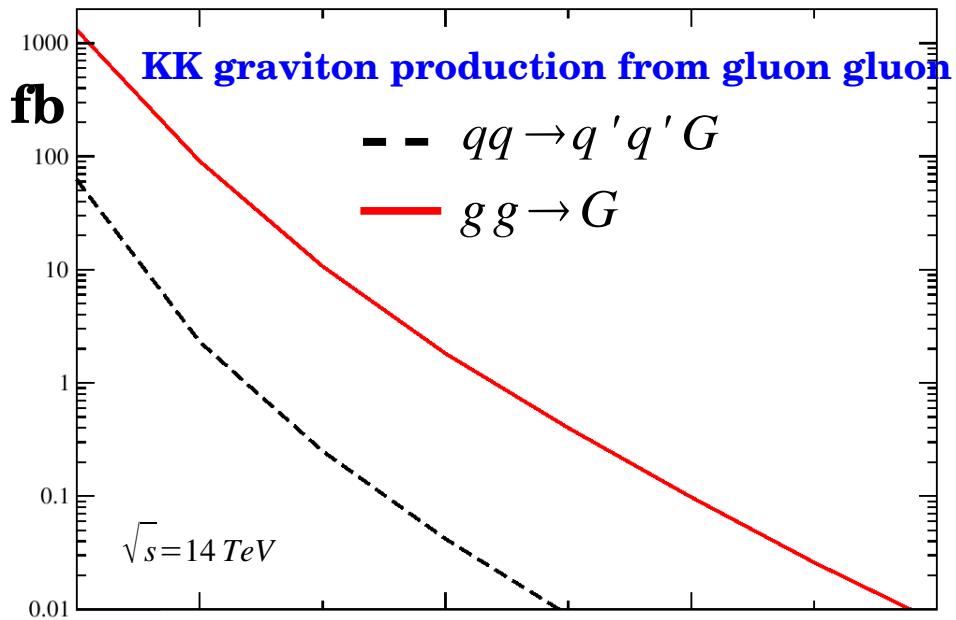
## KK Graviton search

- KK Graviton close to TeV Brane
- 1<sup>st</sup> (and 2<sup>nd</sup>) generation fermion near Planck brane  
i.e. small coupling with 1<sup>st</sup> and 2<sup>nd</sup> quark generation
- gluon profile is flat
- t and b quark close to TeV brane

$\frac{S}{\sqrt{B}} = 5$  reach for various t quark IR localization  $\nu_{tR}$  (the bigger the closer to IR brane)



Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013  
Agashe, Davoudiasl, Perez, Soni, PRD76, 036006  
Antipin, Atwood, Soni, PLB 666 (2008) 155  
Antipin, Soni, JHEP10 (2008) 018





# Summary

## wide spectrum of possible models/signatures

search for resonant and non resonant KK states (black holes, string states)

final states: mono-jet, mono-photon, dileptons, diphoton, WW, ZZ, top quark pairs, ...

## strong constraints from EW precision data and flavor physics

very challenging for (realistic) model building

## possible signal discovery with $O(100 \text{ pb}^{-1})$

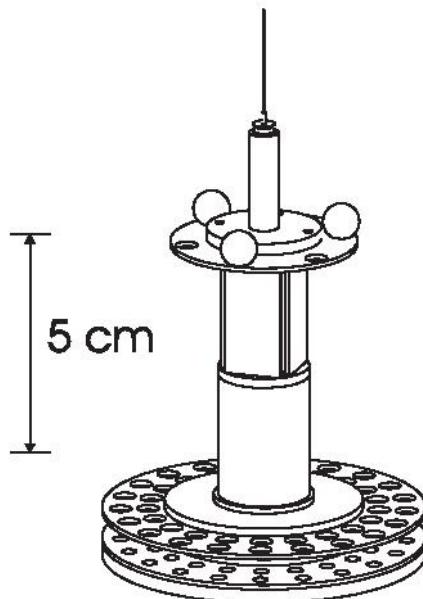
if lucky with models parameters and masses

ADD,  $\text{TeV}^{-1}$  (spin 1 resonance), mRS (spin 2 resonance)

## ED proof and further dedicated studies may need higher lumi

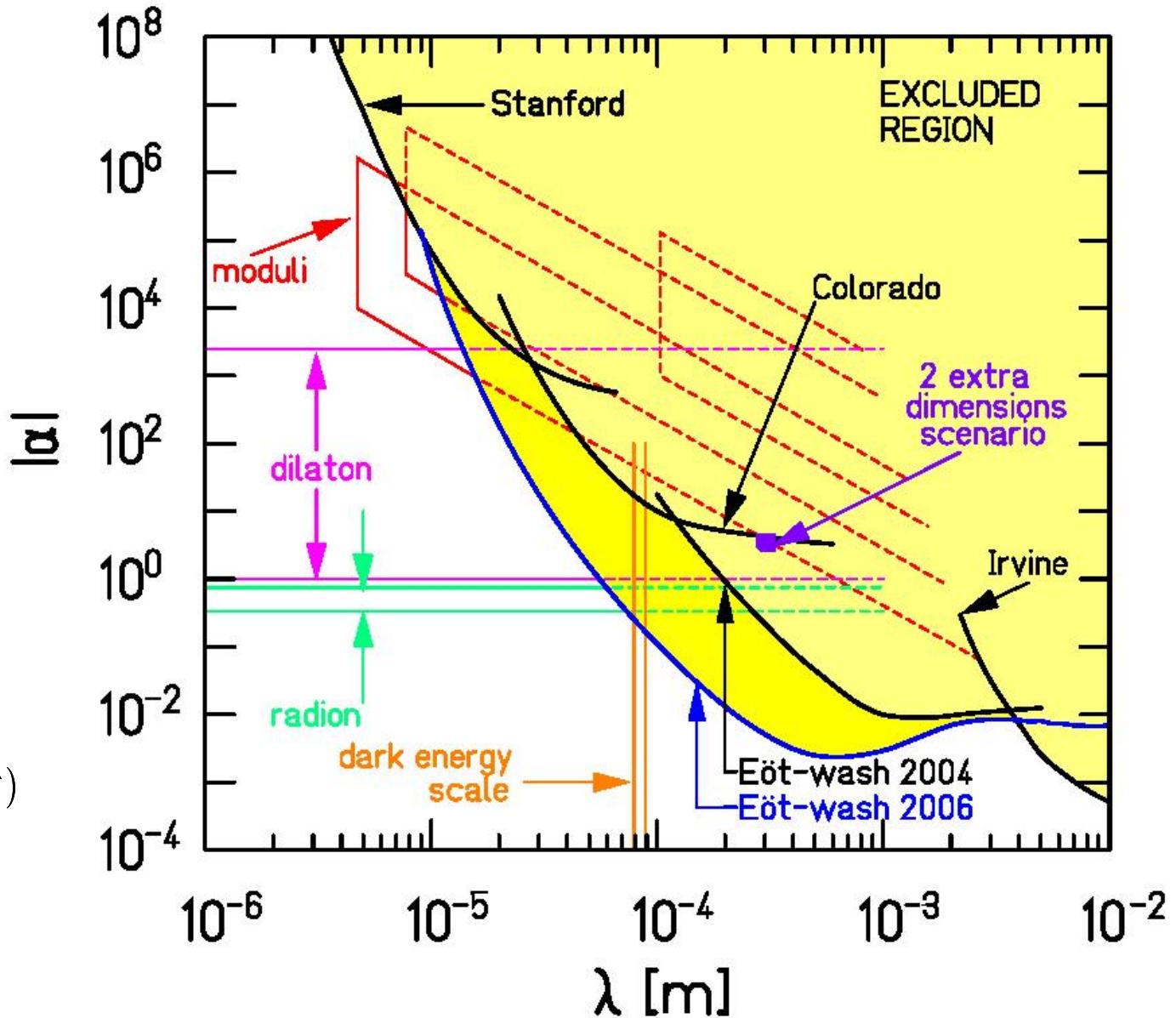
# **BACKUP**

# From torsion balance test of gravitational Inverse square law



$$V(r) = -G \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

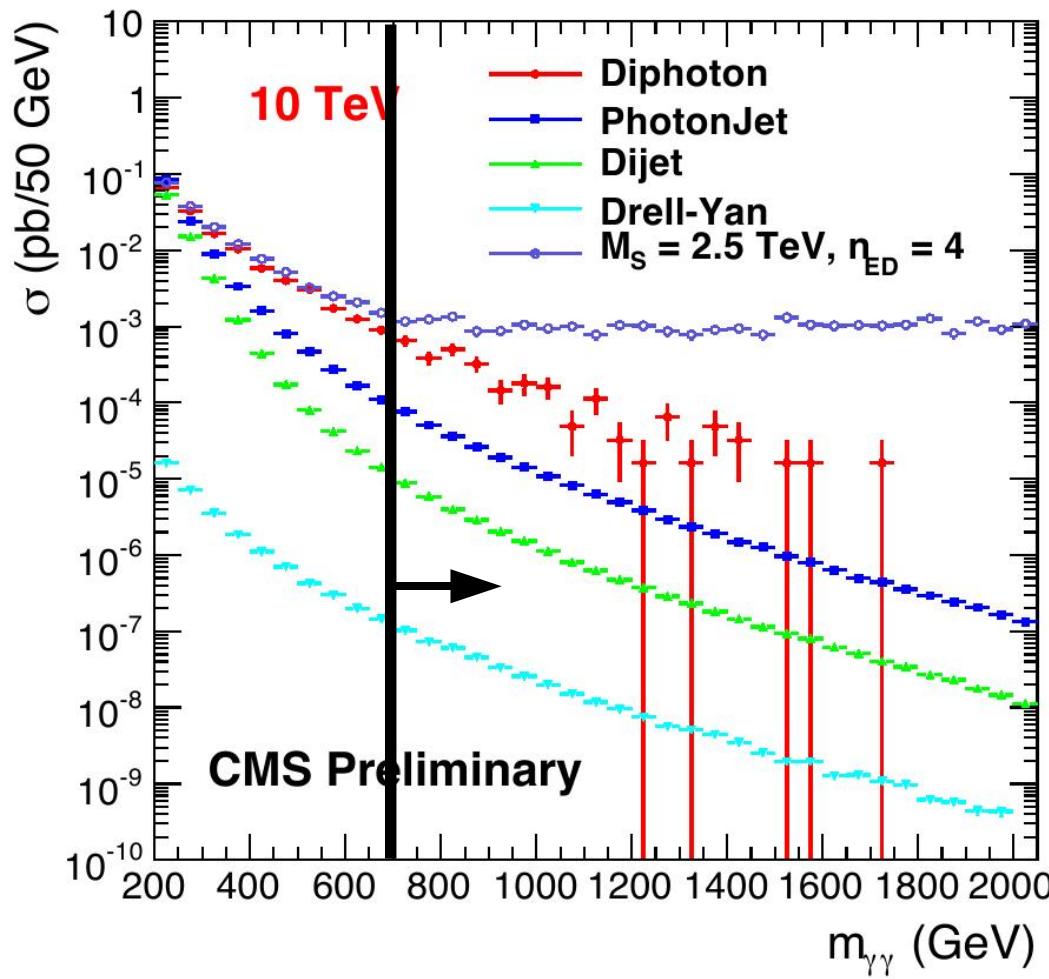
$R \lesssim 50$  microns



Kapner, Cook, Adelberger, Gundlach, Heckel, Hoyle, Swanson, PRL 98 (2007) 021101

# Astrophysical Constraints

	$M_D$	$M_D$
$\gamma$ ray from galactic bulge (from EGRET)	450 TeV (n=2) $3.8 \cdot 10^{-10} m$	1.9 TeV (n=3) $4.2 \cdot 10^{-12} m$
neutron star halo (KK decay) (from EGRET)	454 TeV (n=2)	27 TeV (n=3)
neutron star excess heat (from HST)	1680 TeV (n=2)	60 TeV (n=3)



95% C.L. exclusion

$M_S > 2.8 \text{ TeV}$  for  $n_{ED} = 4$  @  $100 \text{ pb}^{-1}$

5 $\sigma$  discovery up to

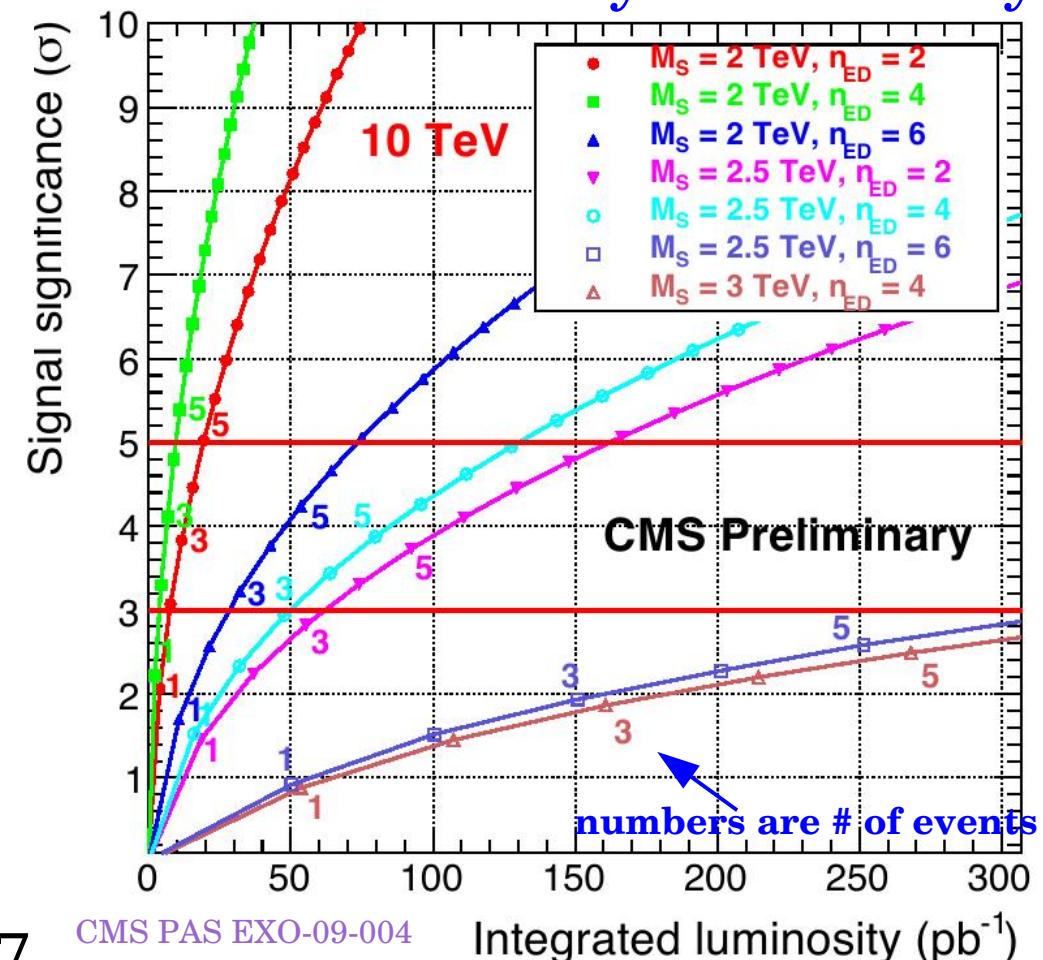
$M_S = 2.5 \text{ TeV}$  for  $n_{ED} = 4$  @  $130 \text{ pb}^{-1}$

# ADD indirect search

e.g.  $pp \rightarrow \gamma\gamma$

$m_{\gamma\gamma} > 700 \text{ GeV}$

luminosity for discovery



# ADD Formalism issues

## - Hewett

interference (sign and n dependence undetermined)

$$\pm \lambda / M_s^4 \quad \text{with} \quad \lambda \quad \text{conventionally} \quad \lambda = \pm 1$$

## - Giudice Rattazzi Wells

interference (sign fixed and n dependence undetermined)  $\sim 1 / \Lambda_T^4$

## - Han Lykken Zhang

interference (sign fixed)  $\sim F / M_{HLZ}^4$

$$F = \log \frac{M_{HLZ}^2}{S} \quad n=2$$

$$F = \frac{2}{n-2} \quad n>2$$

## - conversion rules

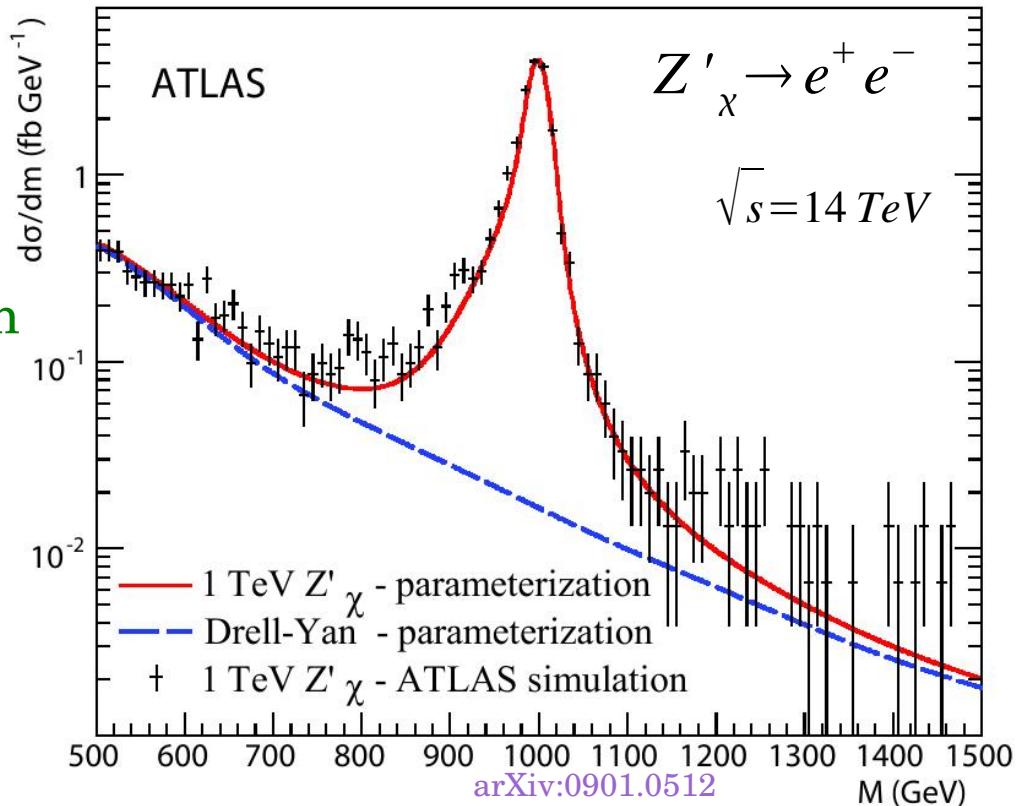
$$M_s [ \text{Hewett } \lambda = +1 ] = \left[ \frac{2}{\pi} \right]^{\frac{1}{4}} \Lambda_T ( \text{GRW} )$$

$$\frac{\lambda}{M_s^4 (\text{Hewett})} = \frac{\pi}{2} \frac{F}{M_{HLZ}^4}$$

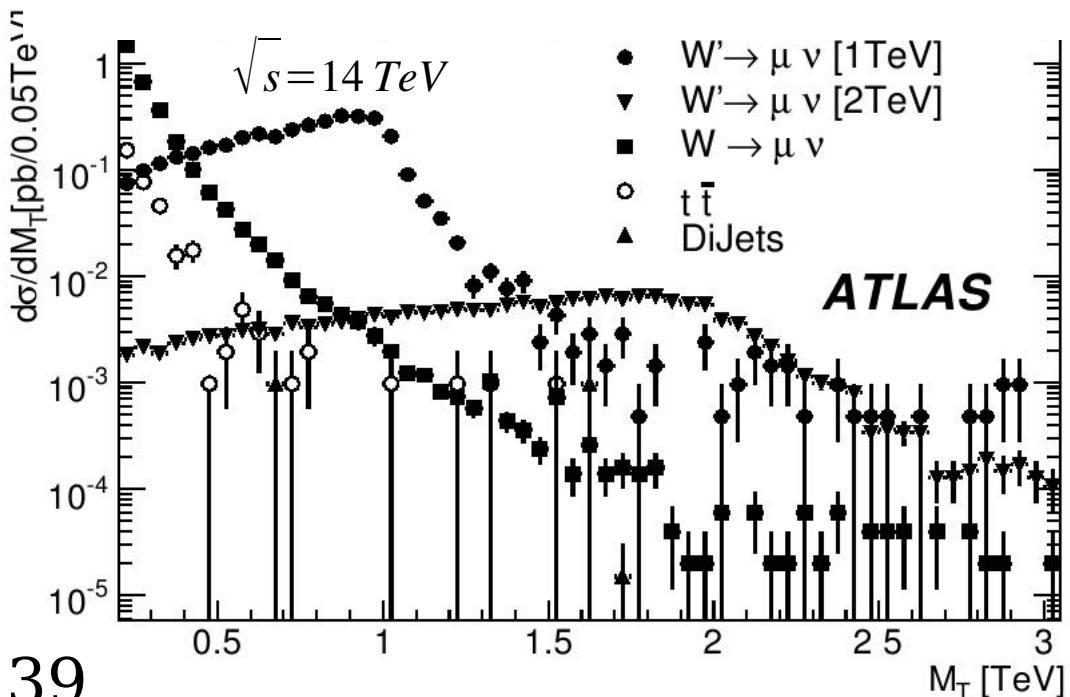
$$\frac{1}{\Lambda^4 (\text{GRW})} = \frac{F}{M_{HLZ}^4}$$

# KK gauge bosons ( $\text{TeV}^{-1}$ )

~ generic resonances search into dilepton



~ generic  $W' \rightarrow l \nu$  searches



# Minimal UED

*example of decay flow*

$$Br(g_1 \rightarrow Q_1 Q_1) \approx 0.5$$

$$Br(g_1 \rightarrow q_1 q_1) \approx 0.5$$

$$Br(q_1 \rightarrow q \gamma_1) \approx 1$$

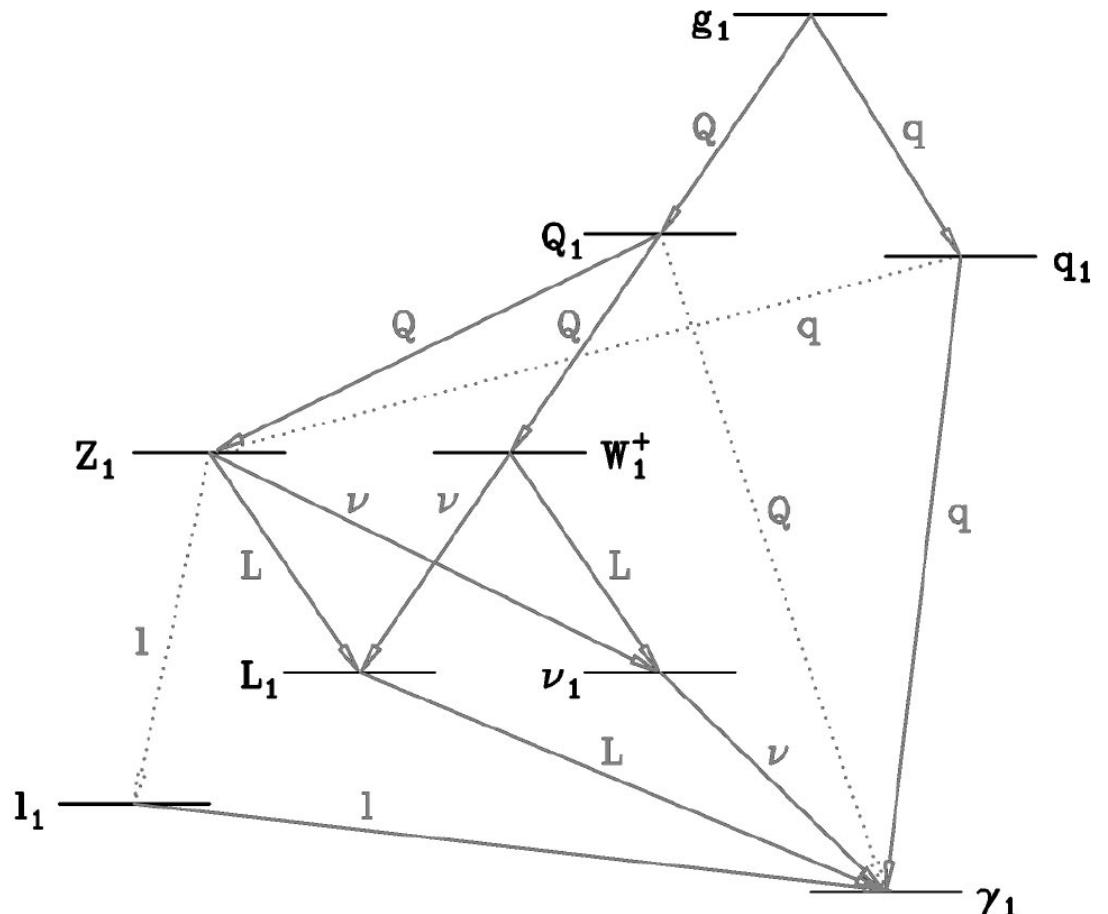
$$Br(Q_1 \rightarrow Q Z_1 : W 1 : \gamma_1) \approx 0.33 : 0.65 : 0.02$$

$$Br(W_1 \rightarrow \nu L_1 : \nu_1 L) \approx 1/6 : 1/6$$

$$Br(Z_1 \rightarrow \nu \nu_1 : LL_1) \approx 1/6 : 1/6$$

$$Br(L_1 \rightarrow \gamma_1 L) \approx 1$$

$$Br(\nu_1 \rightarrow \gamma_1 \nu) \approx 1$$



Cheng Matchev Schmaltz PRD66, 056006

# discriminating mUED

w.r.t SUSY ?

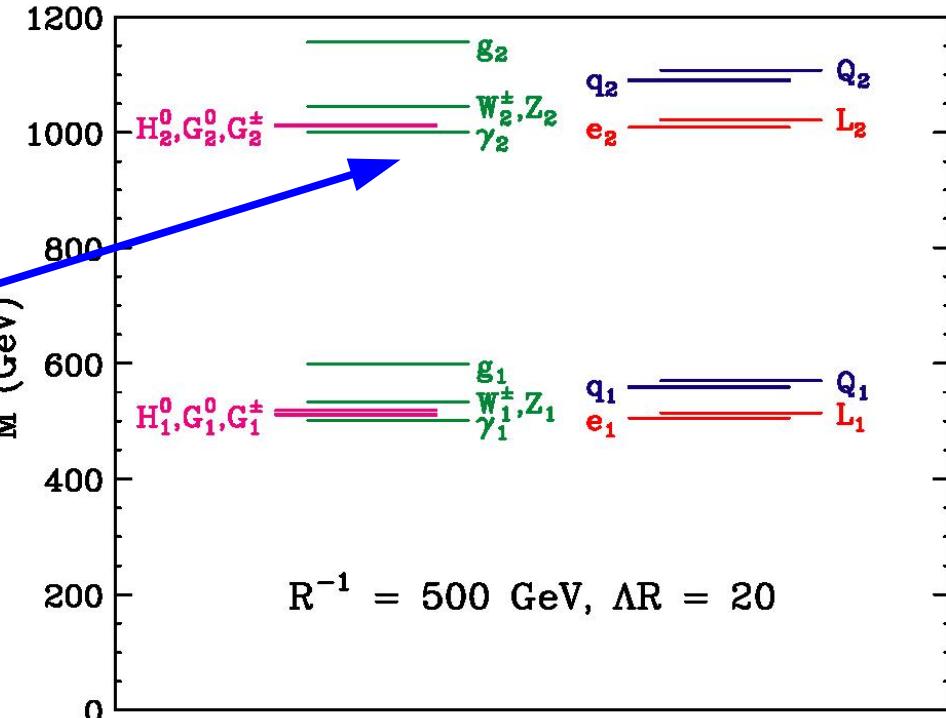
search for level 2 KK modes

i.e. search for KK tower structure

at similar masses

Xsection(UED) > Xsection(SUSY)

Datta, Kong, Matchev, PRD75 (2005) 096006



e.g. for s-channel production :

- both L and R handed SU(2) doublet KK fermions in UED (in susy only L handed SU(2) doublet squarks)
- integrating different angular distributions for fermions ( $1 + \cos^2 \theta$ ) vs scalars ( $1 - \cos^2 \theta$ )
- for production close to threshold (heavy particles)  
different Xsection threshold suppression for fermions ( $\beta$ ) vs scalars ( $\beta^3$ )

Level 2 KK-quarks (pairs or associated with KK gluons) can be produced directly

BUT Br (Nleptons + MET) • Xsection still challengingly small  
& challenging small statistics to distinguish from level 1 modes

# discriminating mUED w.r.t SUSY ?

**KK gauge bosons offer good prospects**

**prospects to discover level 2 structure**

KK number conservating interactions  
(and KK-parity conserved) allows for

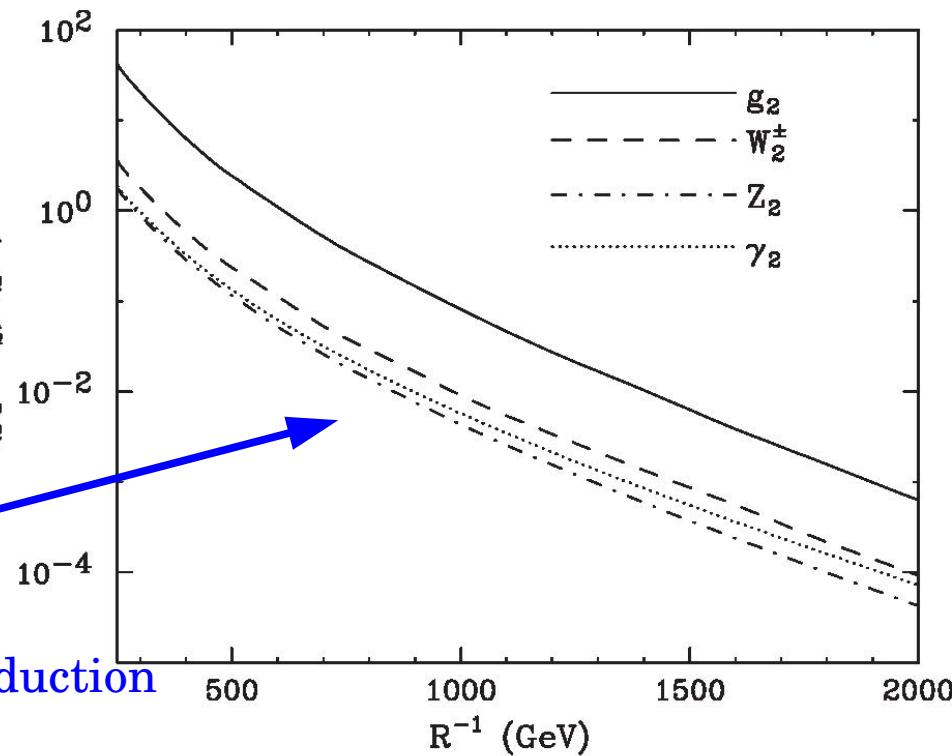
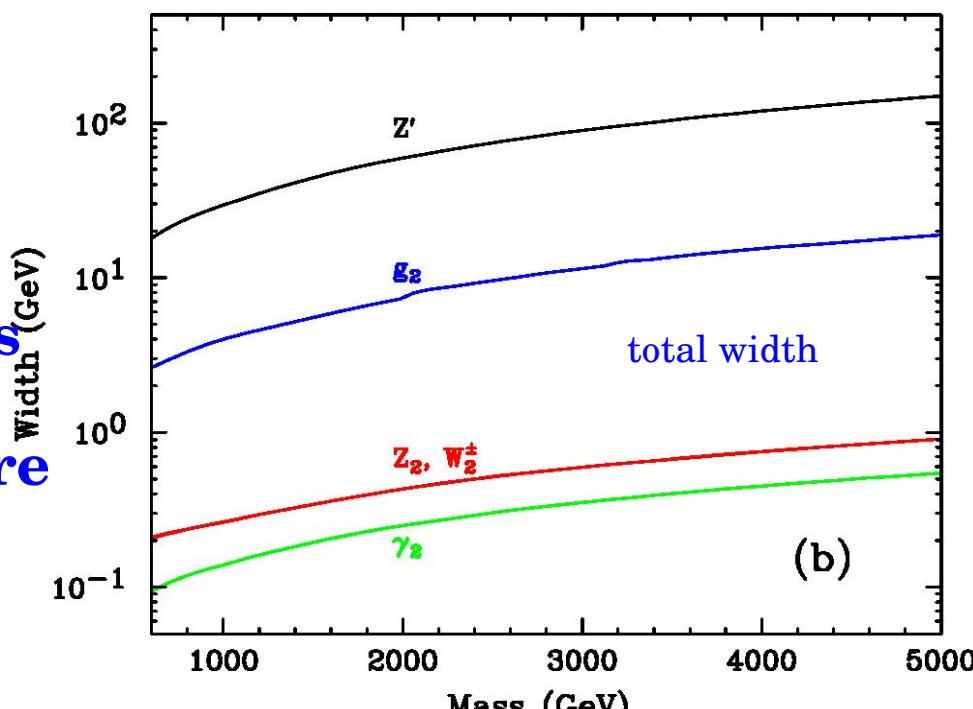
$$V_2 \rightarrow f_1 \bar{f}_1 \quad \text{or} \quad V_2 \rightarrow f_2 \bar{f}_0 = f_2 \bar{f}_{SM}$$

**level 2 KK gauge bosons have also  
KK number violating interaction**

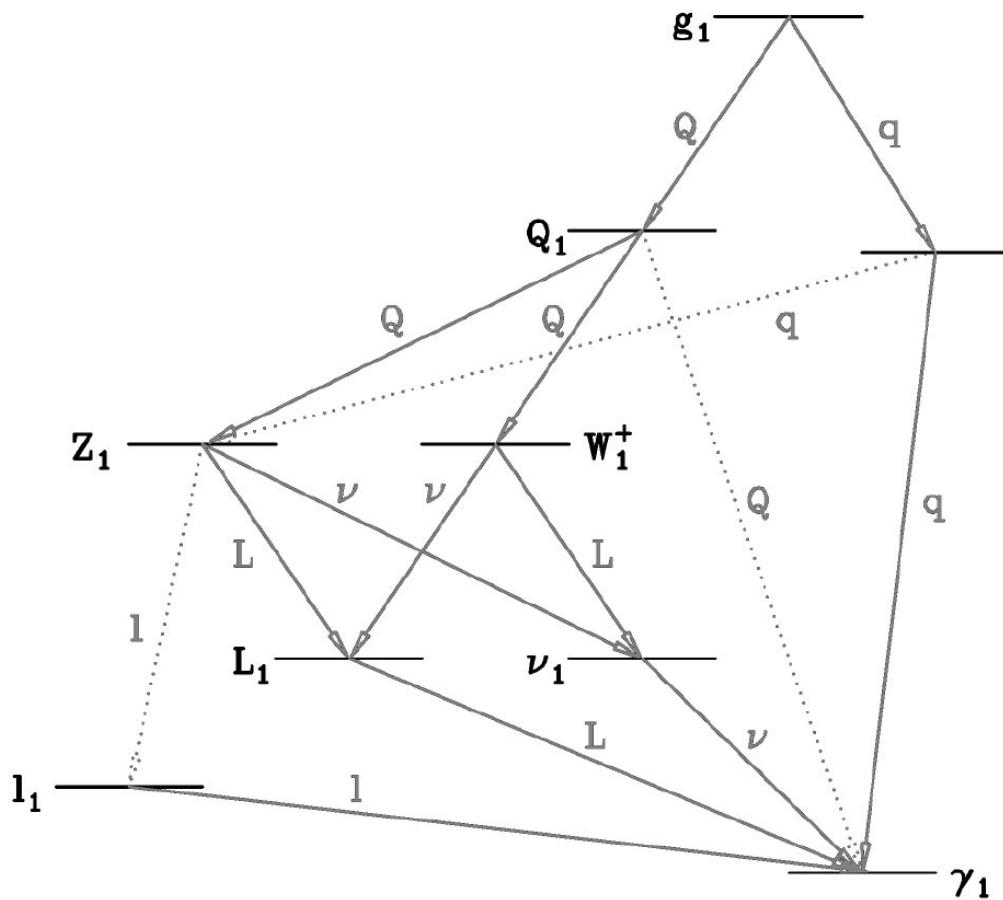
**allowing for**  $V_2 \rightarrow f_0 \bar{f}_0 = f_{SM} \bar{f}_{SM}$

**i.e. single production**

kinematically not suppressed w.r.t pair production

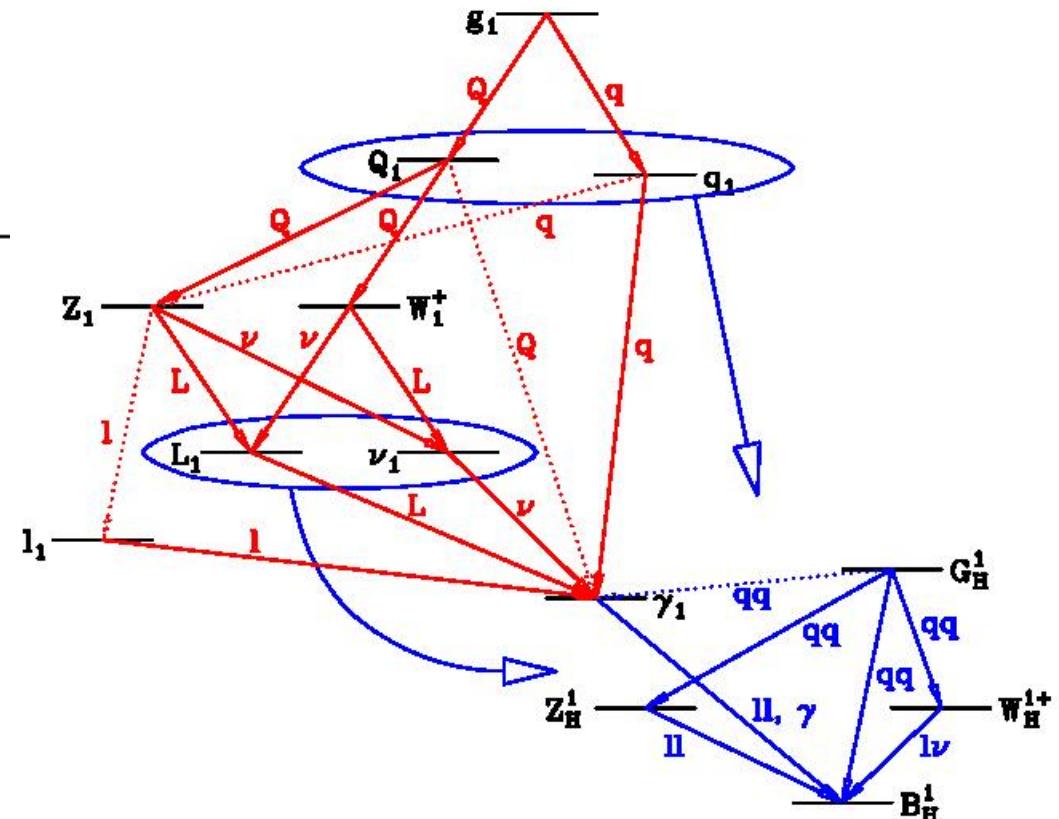


# n=1 and n=2 UED



Cheng Matchev Schmaltz PRD66, 056006

**mUED    n=1**

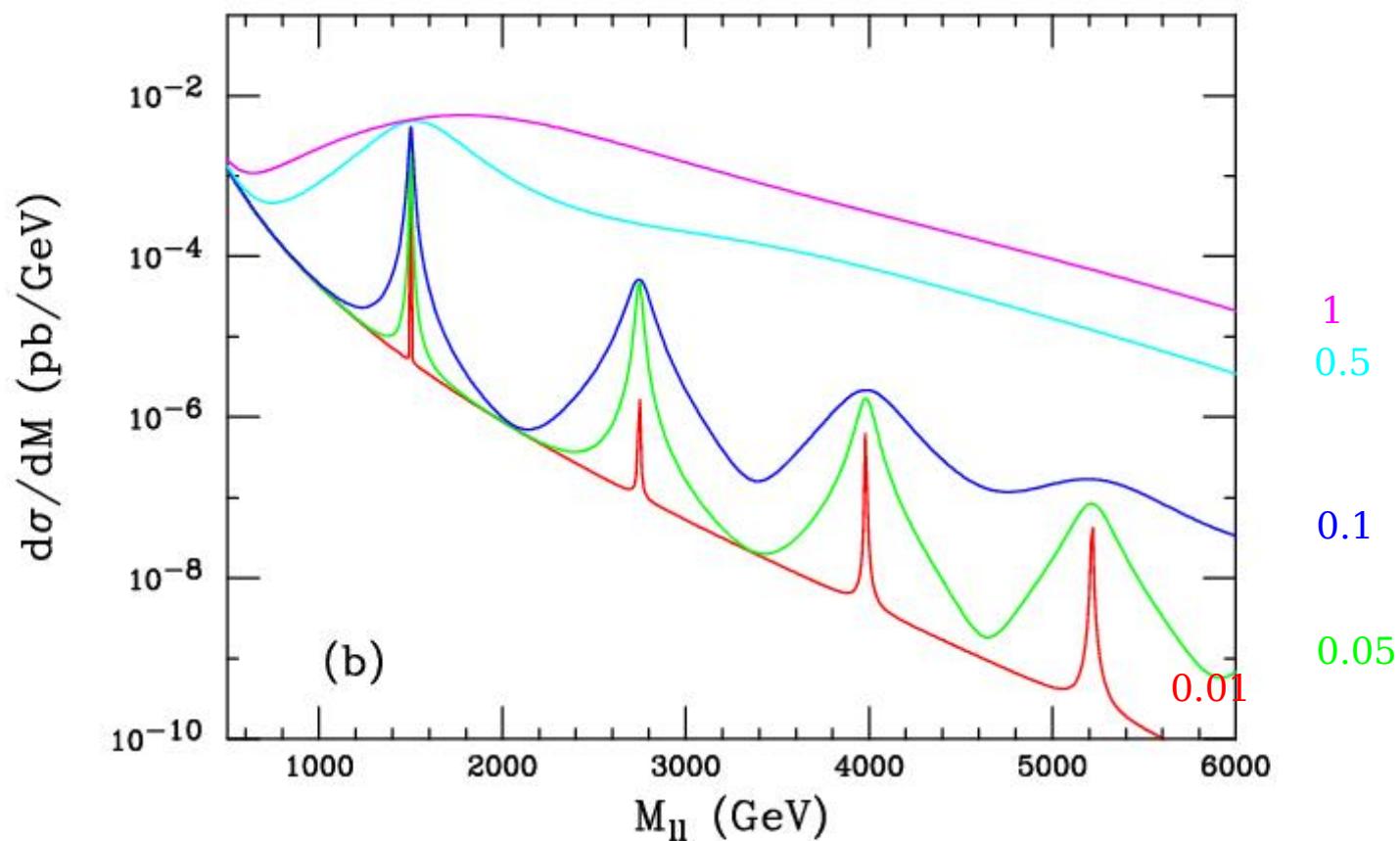


Freitas, Kong JHEP 02 (2008) 068

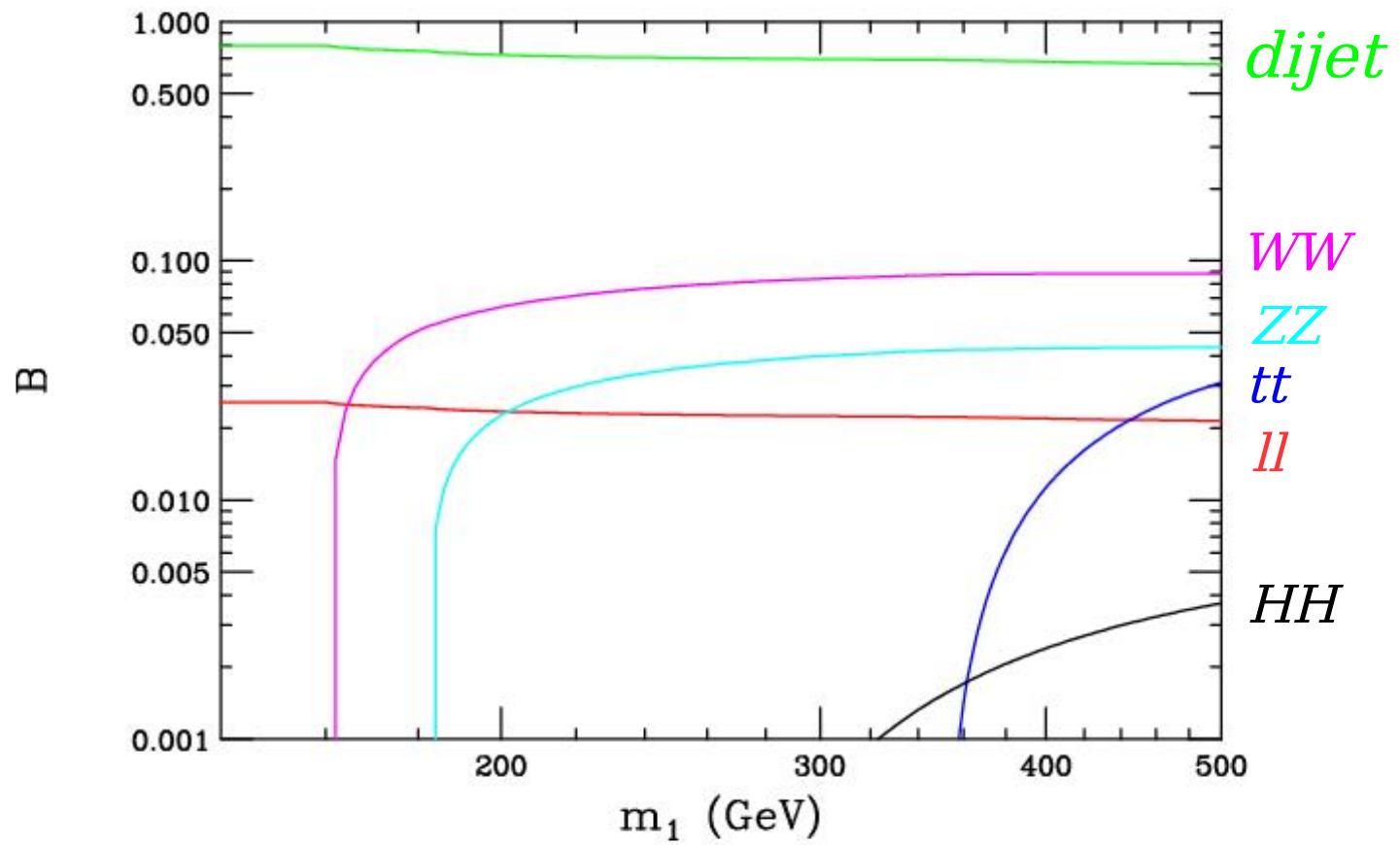
**n=2    UED**

# minimal RS

$G_{KK}$  production at LHC for various  $c$  parameter

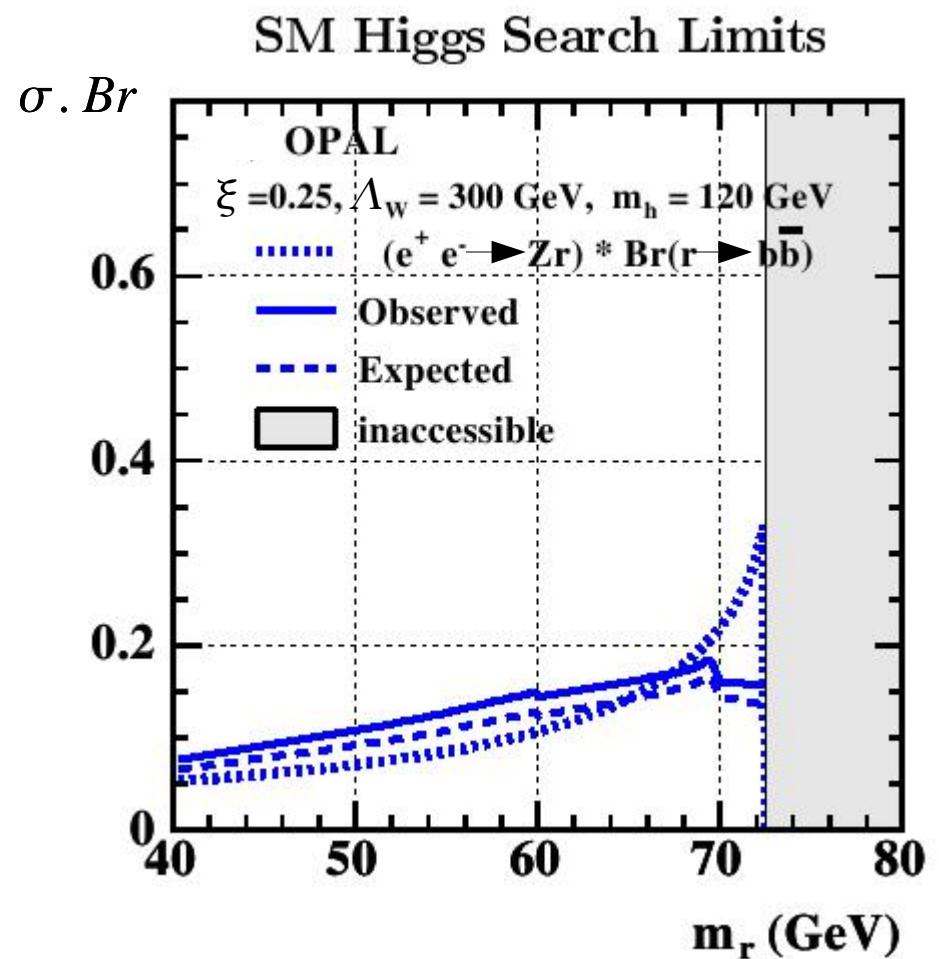


# Minimal RS: $G_{KK}$ decays



# Stabilized RS

## Constraints from LEP SM Higgs searches

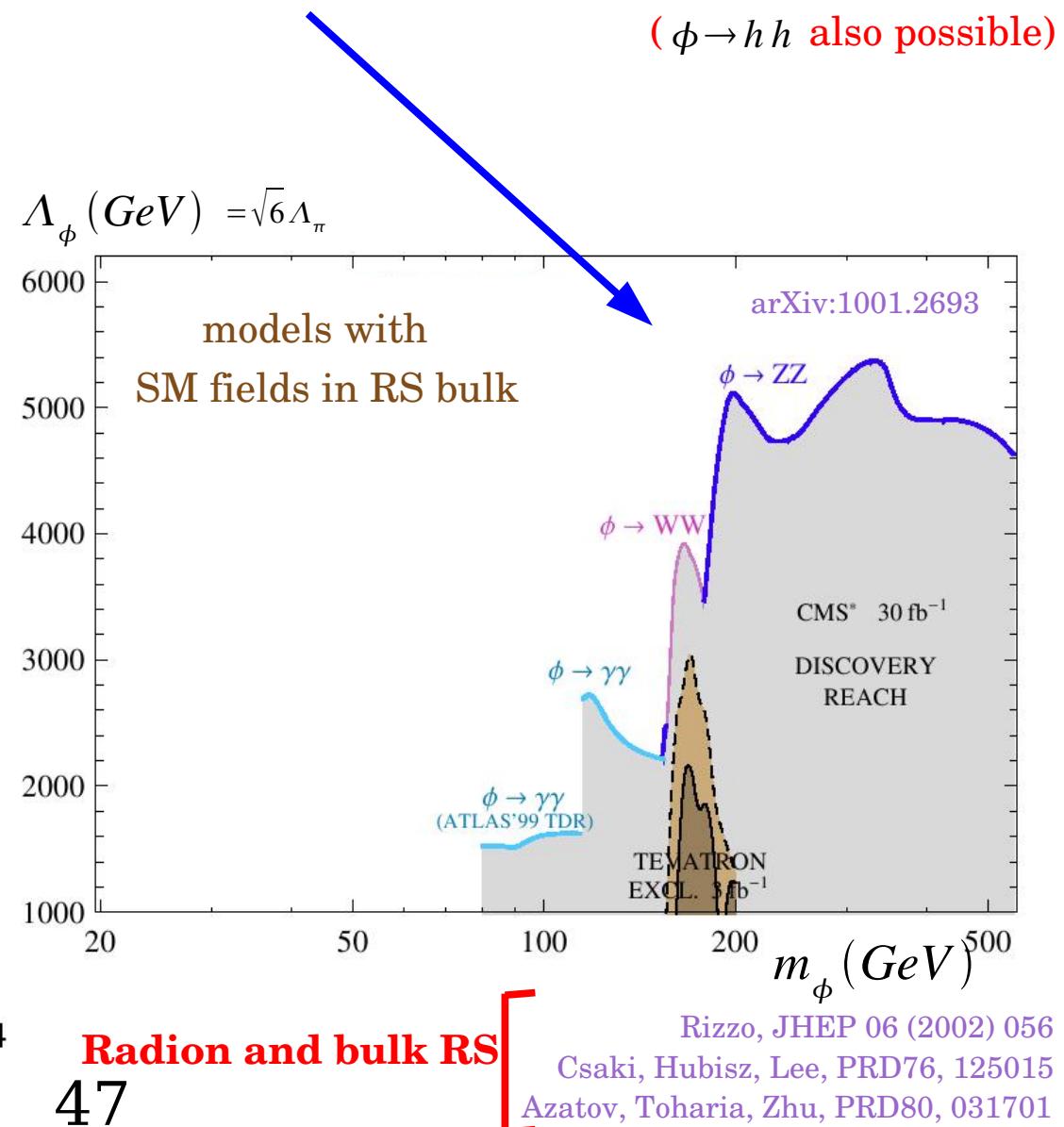
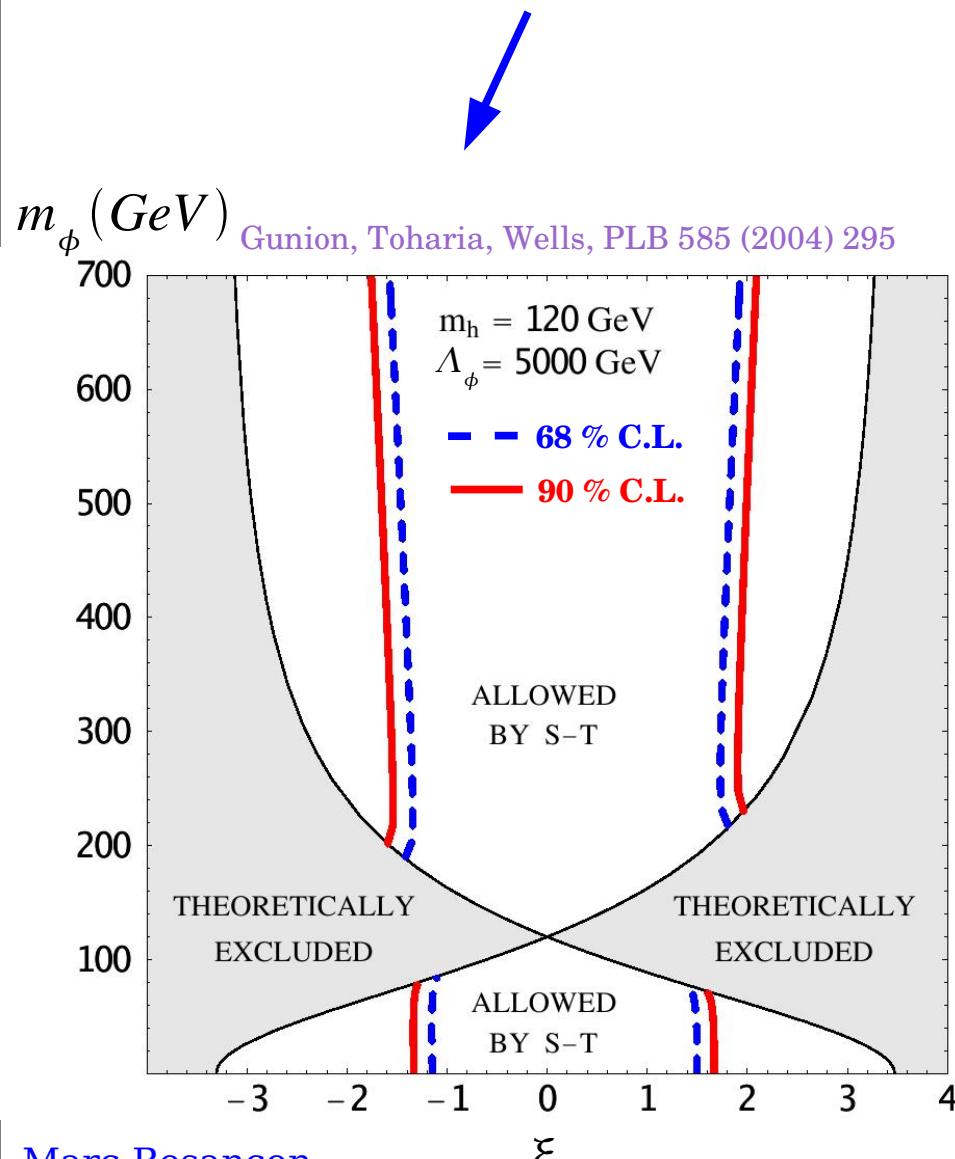


OPAL Collaboration, PLB609 (2005) 20, 637 (2006) 374

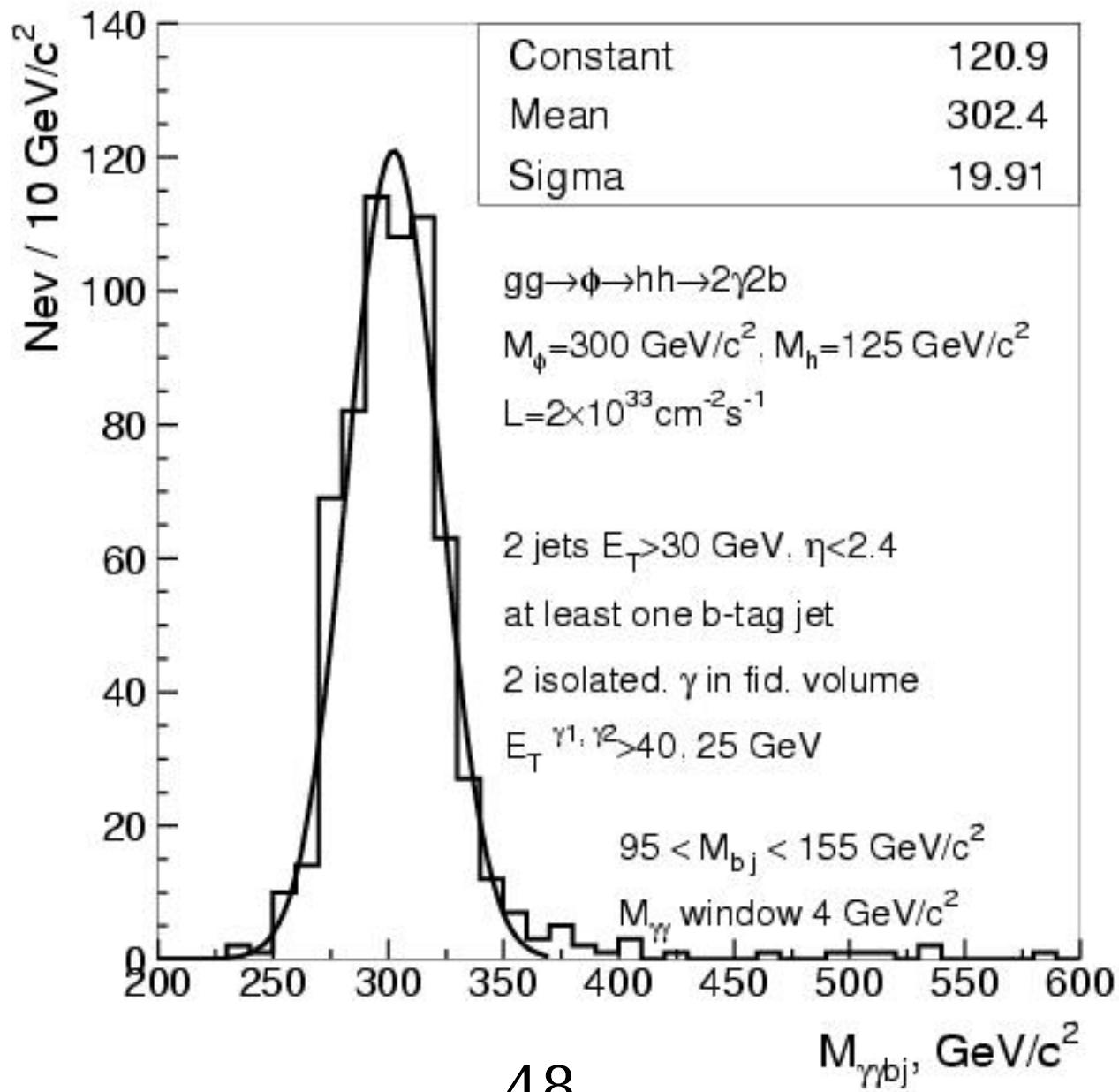
# stabilized RS

constraints  
from precision EW data

radion searches  
using SM Higgs searches

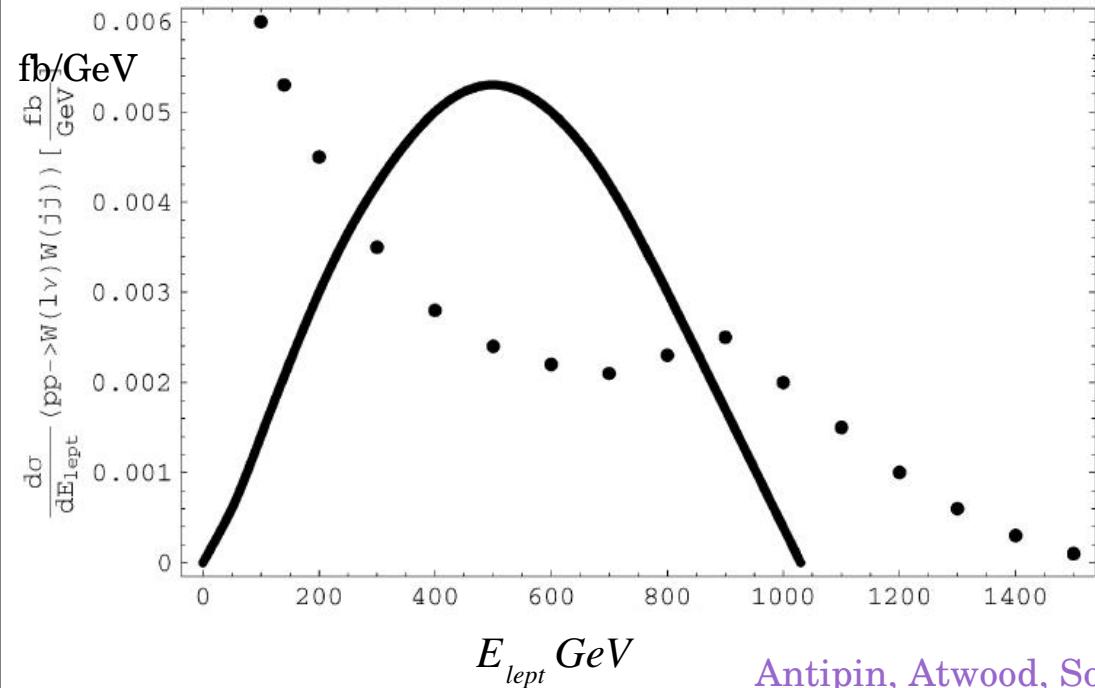


# Stabilized RS

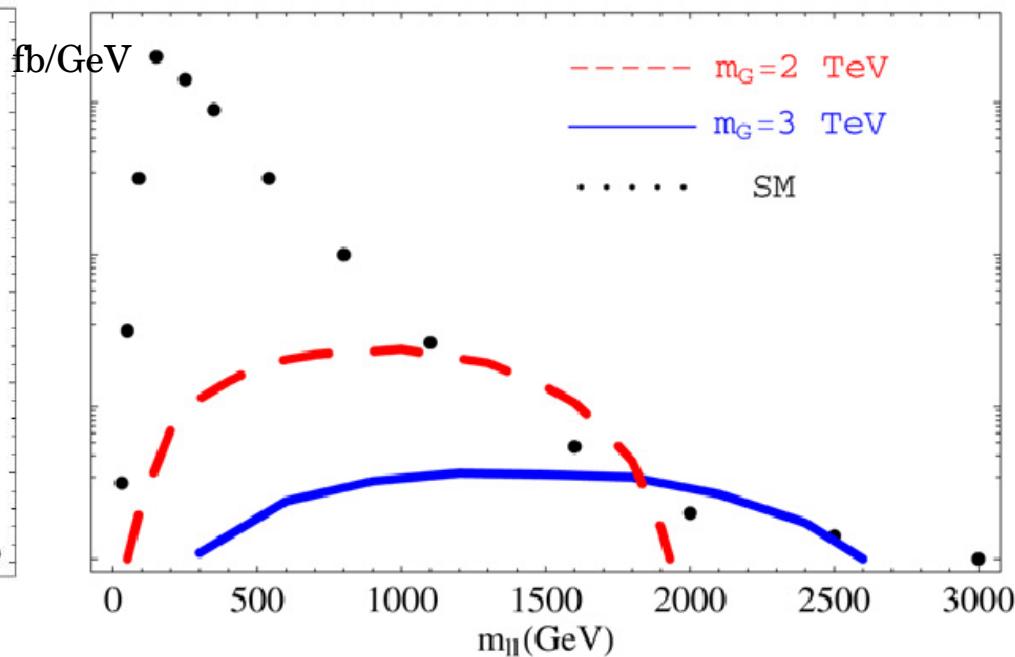


# Bulk RS models: KK graviton search

$gg \rightarrow G \rightarrow W_L W_L \rightarrow l \nu jj$



$gg \rightarrow G \rightarrow W_L W_L \rightarrow e^\pm \mu^\mp 2\nu$



$gg \rightarrow G \rightarrow W_L W_L \rightarrow l \nu jj$

$\sim 3.5$  TeV sensitivity @  $300 \text{ fb}^{-1}$  (jet mass cut window for further bckgd reduction)

$gg \rightarrow G \rightarrow W_L W_L \rightarrow e^\pm \mu^\mp 2\nu$

$\sim 3.5$  TeV sensitivity @  $300 \text{ fb}^{-1}$  (dilepton invariant mass cut for further bckgd reduction)

# Bulk RS models

## KK gluon

$g^{(1)}$  production suppressed

→ small coupling to proton constituents

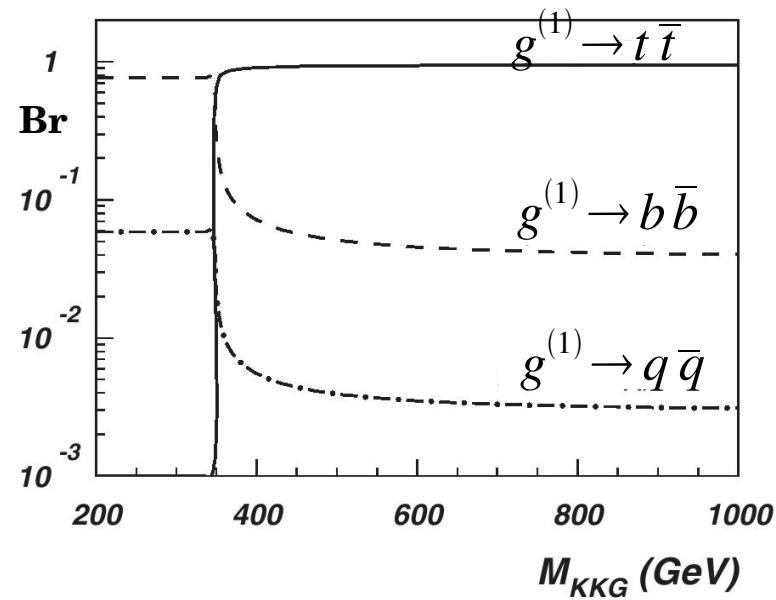
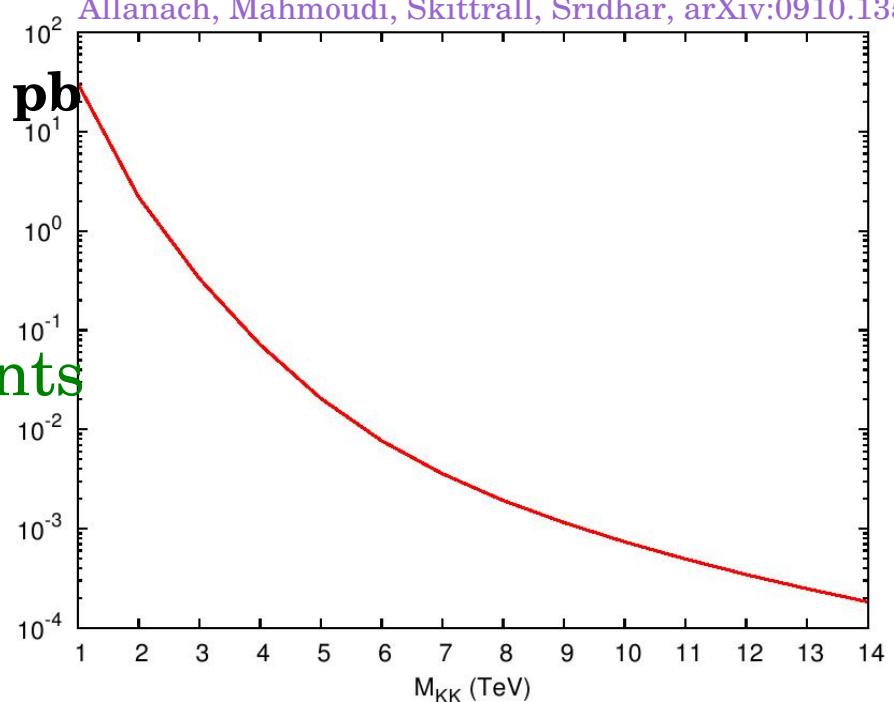
fermionic decay dominated by top quark

bias towards RH top

a heavy KK gluon is broad

above 1 TeV    width  $\sim M_{KK} / 6$

Lillie, Randall, Wang, JHEP 09 (2007) 074  
 Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003  
 Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347  
 Lillie, Shu, Tait, PRD 76, 115016  
 Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003  
 Baur, Orr, PRD 77, 114001  
 Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350



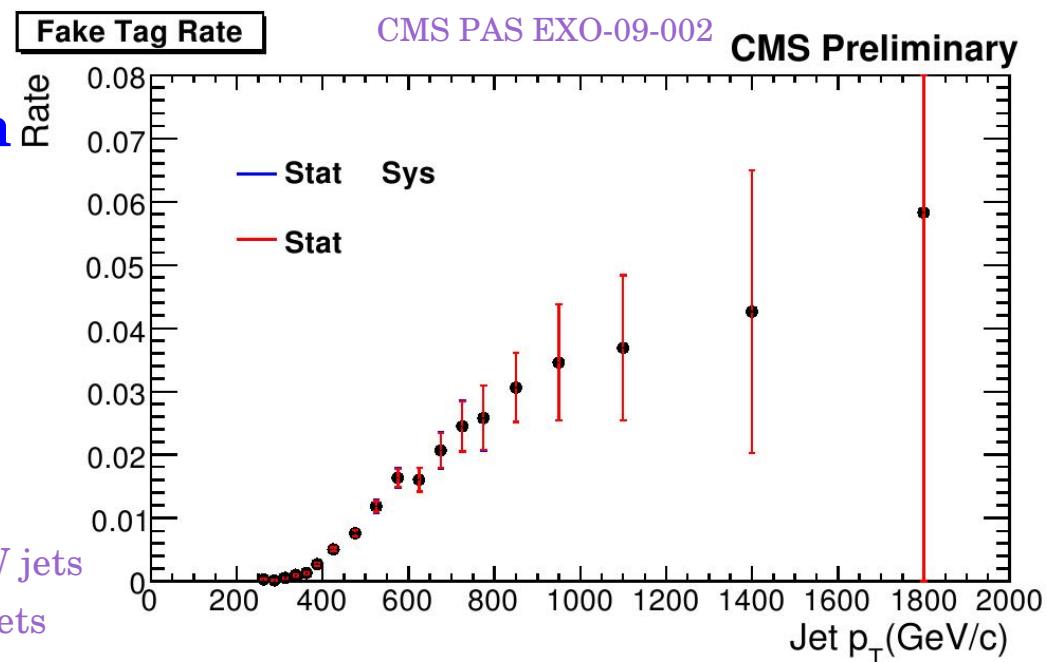
# Bulk RS models: KK gluon in all hadronic mode

$p p \rightarrow g^{(1)} \rightarrow t \bar{t} \rightarrow b \bar{b} j j j j$  need

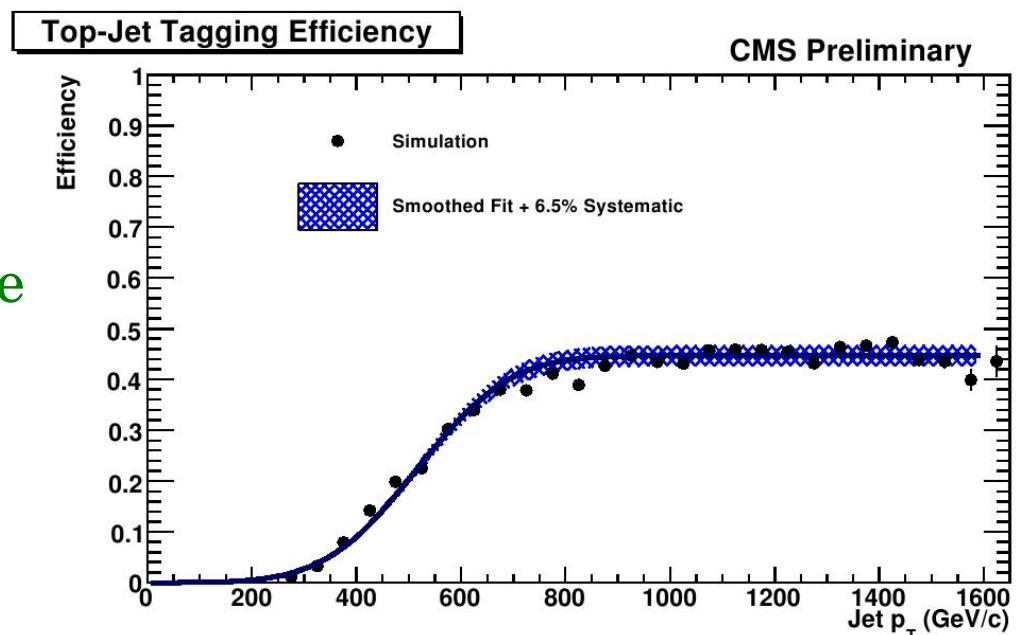
## boosted top-quark jets algorithm

using Dokshitzer, Leder, Moretti, Webber,  
JHEP 08 (1997) 001, i.e. CA algorithm and  
Kaplan, Rehermann, Schwartz, Tweedie,  
PRL 101 (2008) 142001

similar to: Butterworth, Davison Rubin Salam,  
PRL 100 (2008) 242001, for Higgs jets  
Butterworth, Cox, Fowshaw PRD65 (2002) 096014, for W jets  
Butterworth, Ellis, Raklev, JHEP 05 (2007) 033, for W jets



cluster using a large jet radius  
then iteratively decluster each jet  
to search for jet structure and impose  
kinematic constraints



# Bulk RS models : KK gluon in all hadronic mode

$$p p \rightarrow g^{(1)} \rightarrow t \bar{t} \rightarrow b \bar{b} j j j j$$

$w = 1\%$

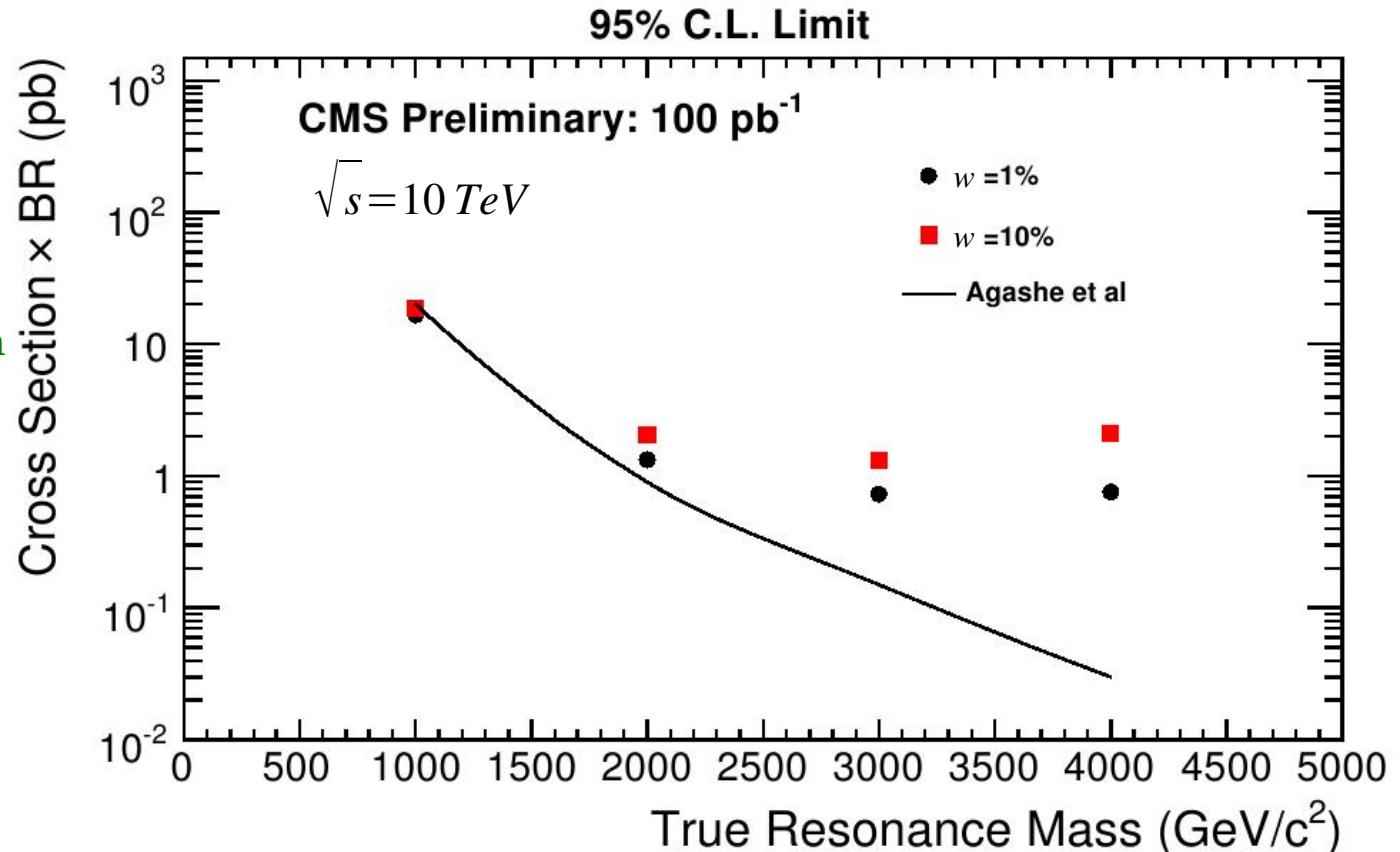
for the case where resonance is narrower than detector resolution

$w = 10\%$

for the case where resonance is wide

$\epsilon$ : top jet tagging efficiency

A: kinematic acceptance



Mass and Width (GeV/c <sup>2</sup> )	Background (events)	$\epsilon \cdot A \cdot BR$ (%)	95% C.L. limit (pb)	3 $\sigma$ Evidence (pb)	5 $\sigma$ Discovery (pb)
$M = 1000, w = 10$	$2.18 \pm 0.90$	$0.34 \pm 0.05$	17.2	23.0	43.6
$M = 2000, w = 20$	$5.81 \pm 2.18$	$6.06 \pm 0.85$	1.45	2.18	3.99
$M = 3000, w = 30$	$0.95 \pm 0.41$	$6.21 \pm 0.88$	0.74	0.97	1.62
$M = 4000, w = 40$	$0.11 \pm 0.12$	$4.62 \pm 0.66$	0.75	0.62	1.27
$M = 1000, w = 100$	$2.18 \pm 0.90$	$0.30 \pm 0.05$	19.3	25.7	48.6
$M = 2000, w = 200$	$9.04 \pm 3.31$	$4.90 \pm 0.69$	2.30	3.46	6.32
$M = 3000, w = 300$	$2.04 \pm 0.79$	$4.25 \pm 0.61$	1.34	1.87	3.28
$M = 4000, w = 400$	$0.98 \pm 0.41$	$2.21 \pm 0.34$	2.13	2.73	5.00

# Bulk RS models

Lillie, Randall, Wang, JHEP 09 (2007) 074

Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003

Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347

Lillie, Shu, Tait, PRD 76, 115016

Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003

Baur, Orr, PRD 77, 114001

Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

**KK gluon**  $p p \rightarrow g^{(1)} \rightarrow t \bar{t} \rightarrow b \bar{b} jj l \nu$

background: SM  $t \bar{t}$ , single top, W+jets

**for 100 pb<sup>-1</sup>**  $M_{g^{(1)}} = 3 \text{ TeV}$   $S/\sqrt{B} \approx 11$

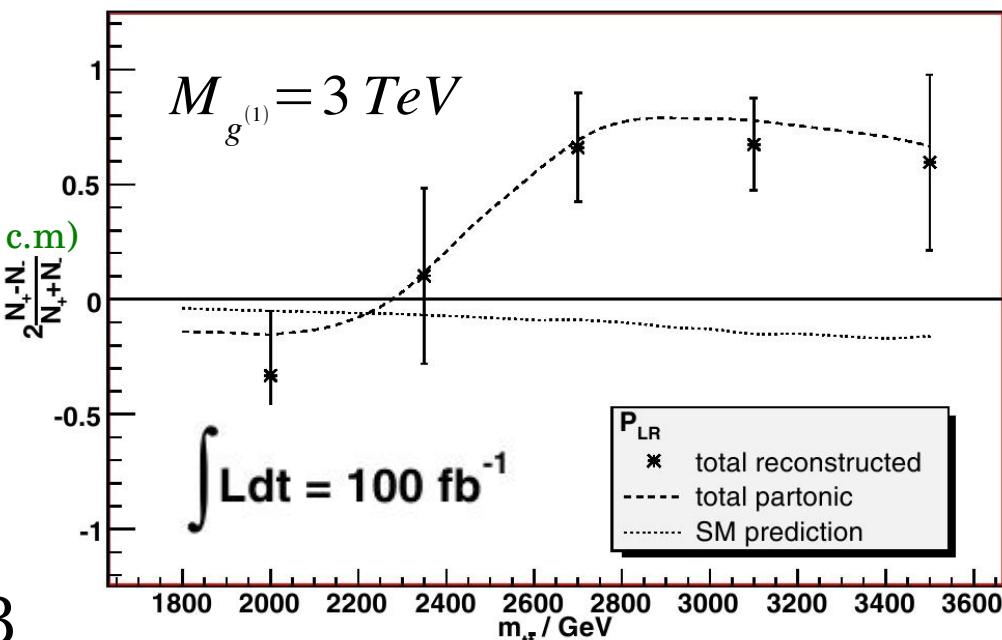
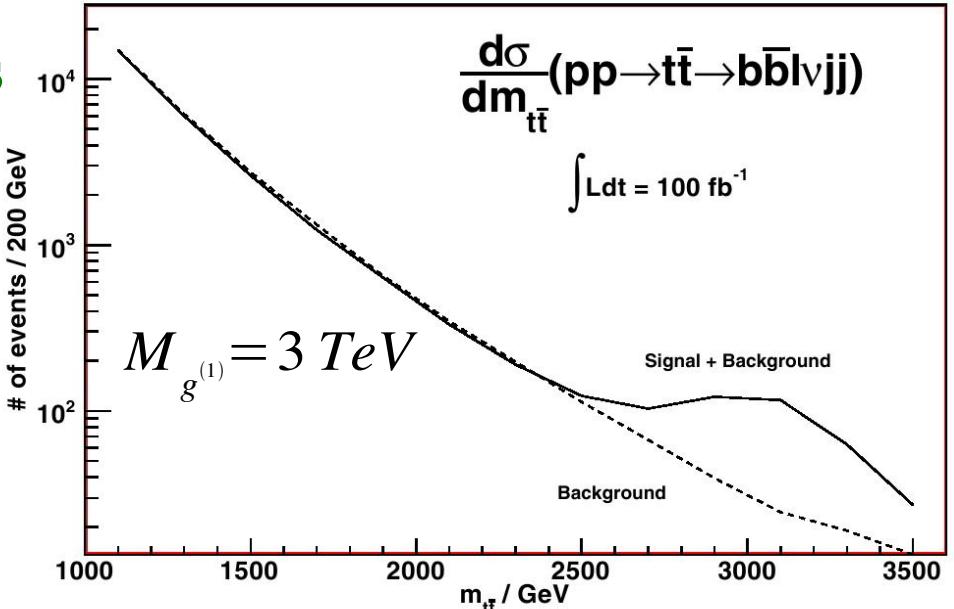
$M_{g^{(1)}} = 4 \text{ TeV}$   $S/\sqrt{B} \approx 4.2$

**reach < 4 TeV**

**asymmetry**  $2 \times \frac{N_+ - N_-}{N_+ + N_-}$

$N_-$  number of positron  
along direction of top-quark boost (in top pair c.m)

**expect strong bias towards RH top  
from KK gluon decay**



# Bulk RS models

Lillie, Randall, Wang, JHEP 09 (2007) 074  
 Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003  
 Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

## KK gluon

$$p\ p \rightarrow g^{(1)} \rightarrow t\bar{t} \rightarrow b\bar{b} jjl\nu$$

Selection	Variables	Cuts
Kinematic and acceptance	Lepton ≥ 2 jets Tagged $b$ -jets Missing energy ( $\nu$ ) Lepton isolation $b$ -jet lepton isolation	$p_T > 10$ GeV, $ \eta  < 2.5$ $p_T > 30$ GeV, $ \eta  < 2.5$ $\geq 1$ $p_T^{\text{miss}} > 20$ GeV $\Delta R \geq 0.4$ (non- $b$ jets) $\Delta R \geq 0.4$ or $m_{bl} \geq 40$ GeV
Reconstruction quality for #jets > 2, 2 $b$ -jets required	$ M_W^{\text{had}} - M_W $ $ M_t^{\text{had}} - M_t $ $ M_t^{\text{lep}} - M_t $ $ M_t^{\text{had}} - M_t $ “Top jet”	<50 GeV <50 GeV <50 GeV <50 GeV $p_{T^t} > 800$ GeV
Reconstruction quality a $b$ -jet + $t$ -jet		

one could use in addition the fowardness of the SM  $t\bar{t}$   
 i.e. dominant production via gluon fusion more forward

**KK gluons produced by quark annihilation**

# Bulk RS models

Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, PRD76, 115015

Djouadi, Moreau, Singh, NPB 797 (2008) 1

## Warped EW neutral gauge bosons

from underlying  $SU(2)_L \times SU(2)_R \times U(1)_X$  in the bulk

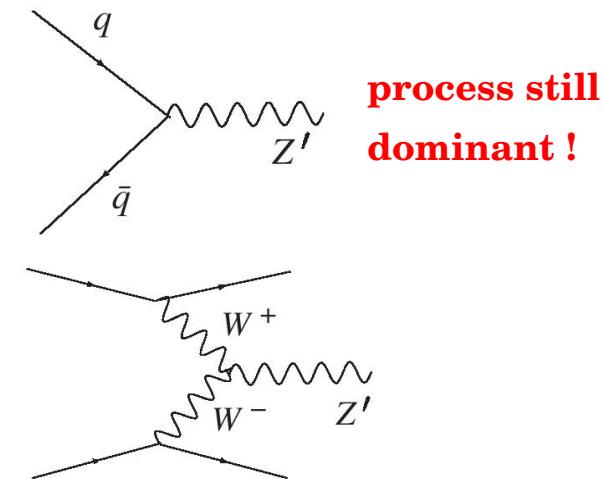
3 neutral KK gauge bosons tower from  $U(1)_{L,R,X}$

→  $A_1, Z_1, Z_{X1}$  (after mixing)  
→ generically  $Z'$

$Z'$  coupling to light quarks and leptons are suppressed

$Z'$  coupling to top and bottom are enhanced

$Z'$  coupling to longitudinal W, Z and Higgs enhanced



$Z'$  signatures into top and bottom overwhelmed by KK gluon decay into b and t

$Z' \rightarrow WW \rightarrow 2l2\nu$  sensitivity up to 2 TeV (3 TeV) with  $100 \text{ fb}^{-1}(1 \text{ ab}^{-1})$   
or  $\rightarrow l\nu jj$  luminosity upgrade crucial

luminosity upgrade also crucial for associate production with heavy quarks

## Warped EW charged gauge bosons

2 charged KK gauge bosons tower (mixing)  $\longrightarrow$  generically  $W'$

$W'$  coupling to light quarks and leptons are suppressed

$W'$  coupling to top and bottom are enhanced

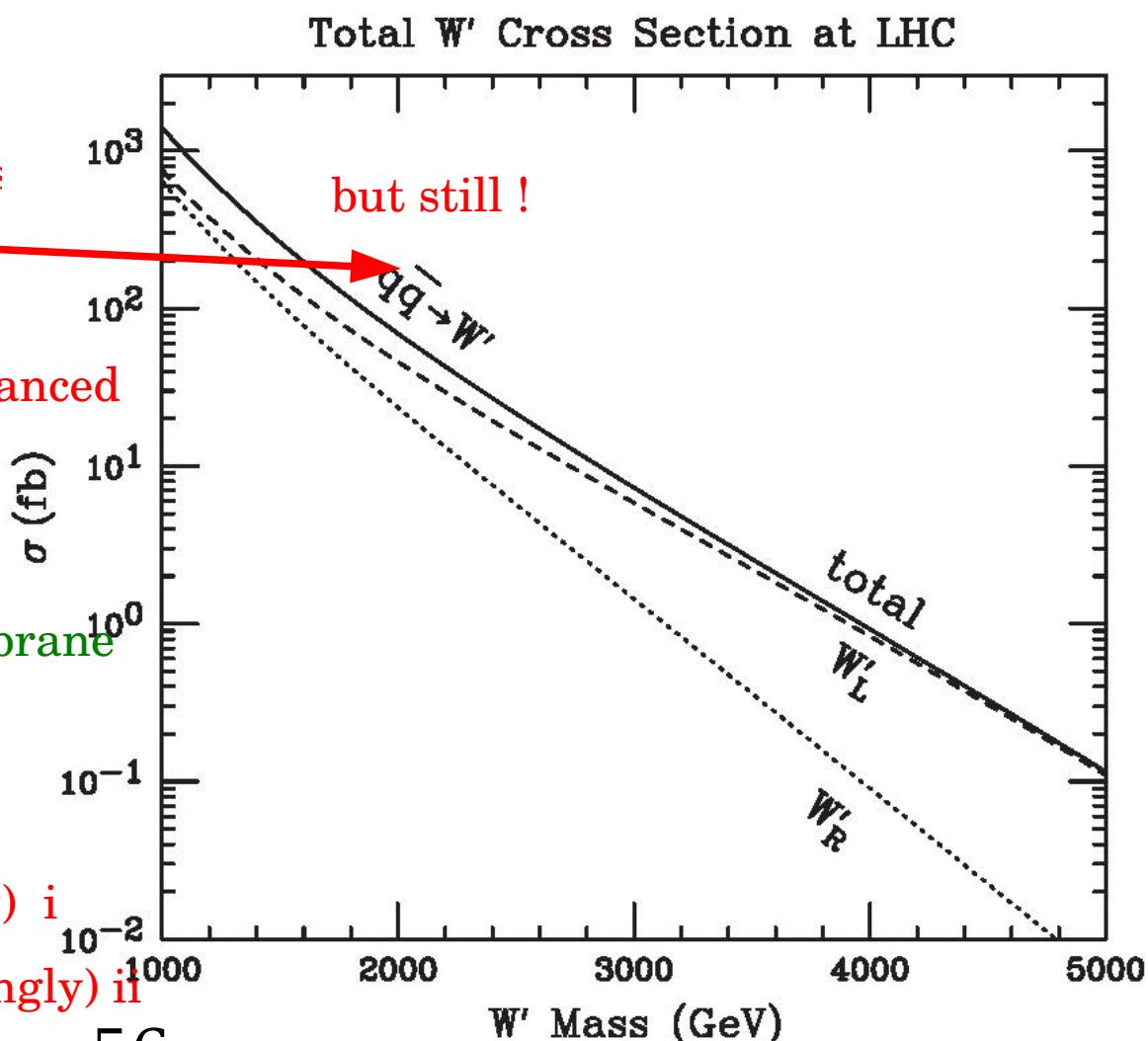
→ two cases :

case i)  $t_R$  close-to-flat profile in bulk and  $(t,b)_L$  profile close to TeV brane

case ii) vice-versa

EW precision tests tend to prefer (mildly) i

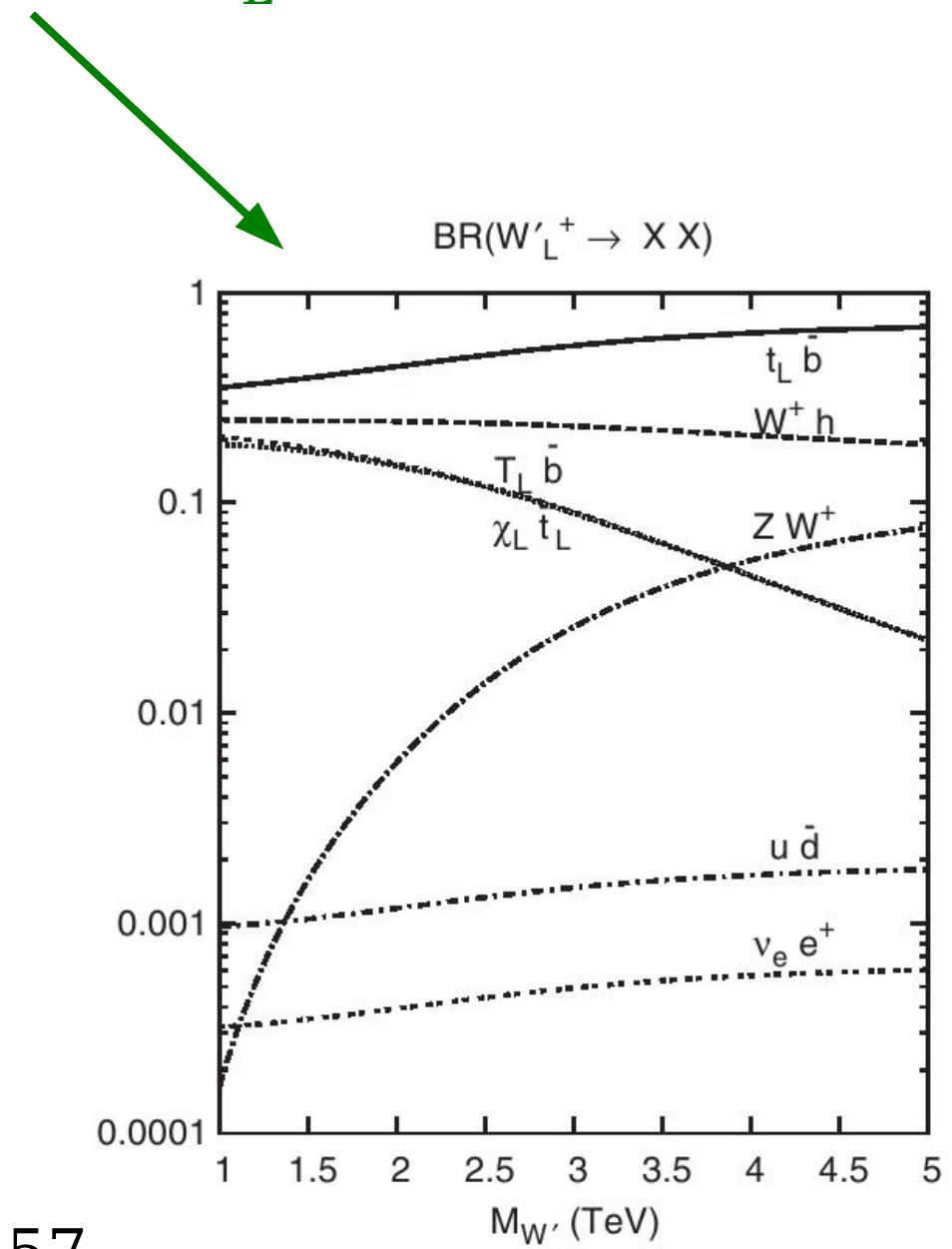
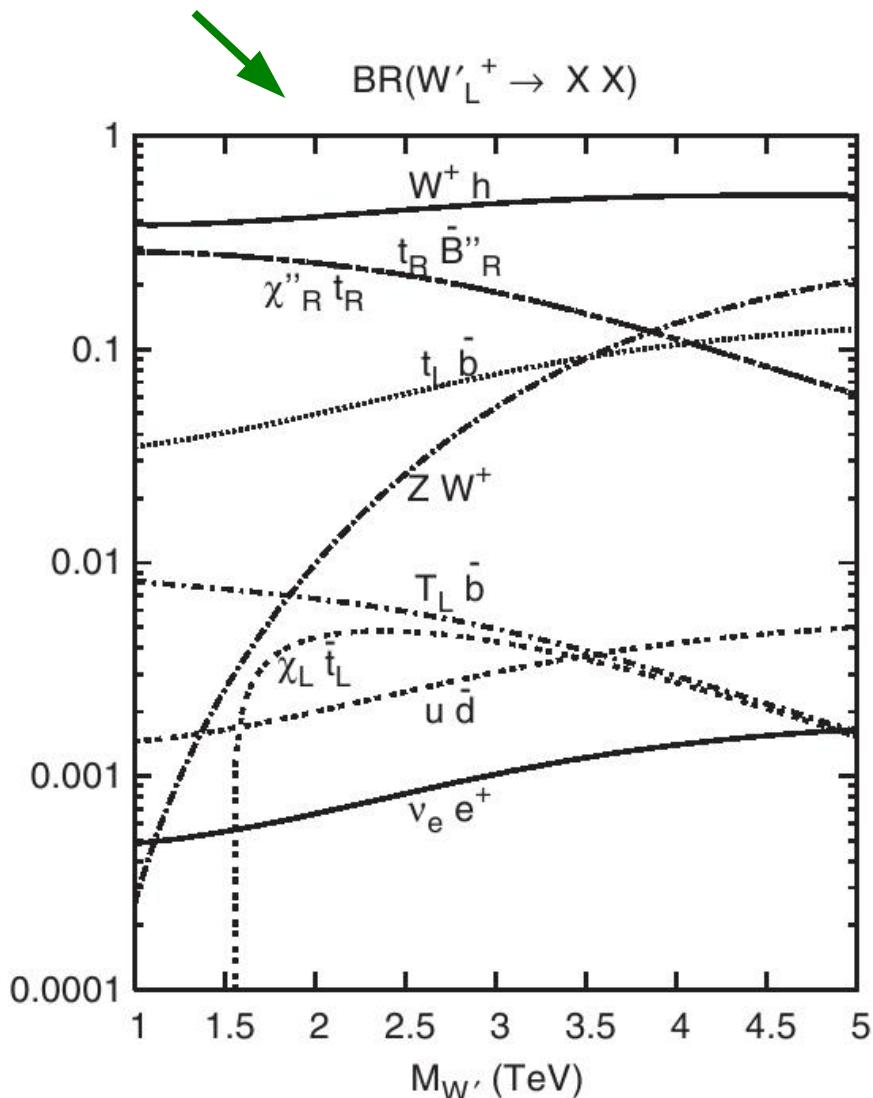
flavor precision tests tend to prefer (strongly) ii



## Bulk RS models

## Warped EW charged gauge boson decay

- i)  $t_R$  close-to-flat profile in bulk and  $(t,b)_L$  profile close to TeV brane
- ii) vice versa



# Bulk RS models

Agashe, Gopalakrishna, Han, Huang, Soni, PRD 80, 075007

## Warped EW charged gauge bosons

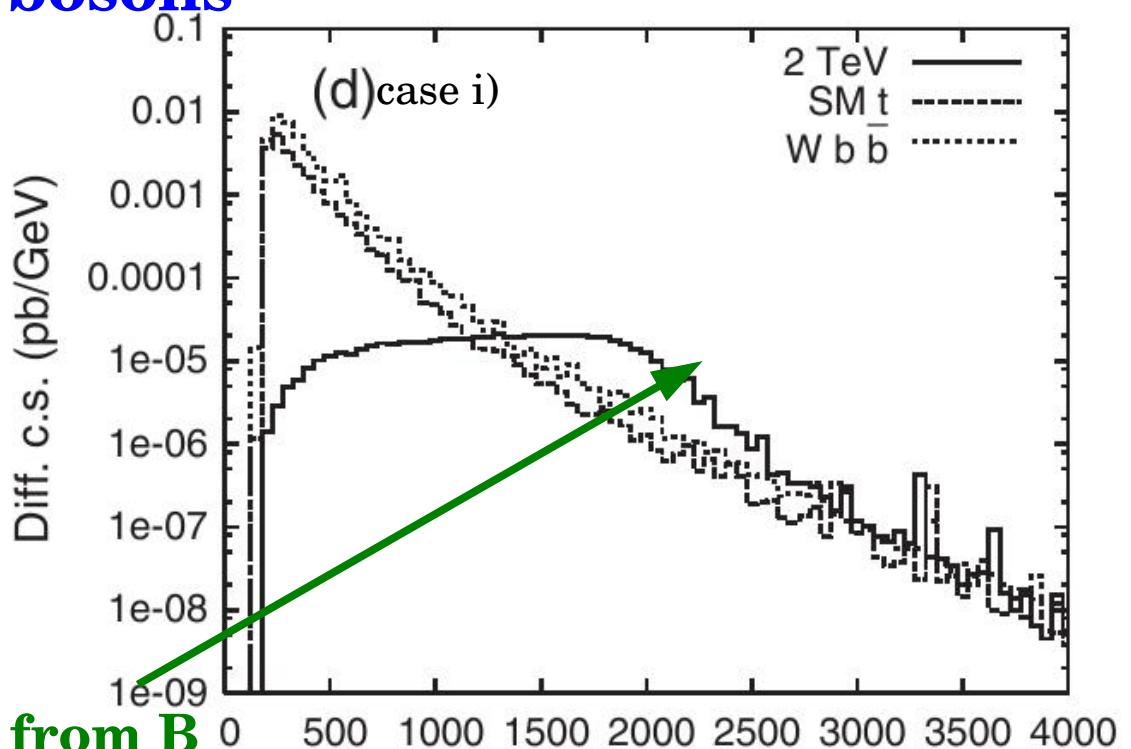
### tb channel

$$pp \rightarrow W' \rightarrow t\bar{b} \rightarrow W\bar{b}b \rightarrow l\nu\bar{b}\bar{b}$$

$(l=e,\mu)$

**main SM Backgrounds (B)**

→ single top and Wbb



**possible separation of Signal (S) from B**

Wb angle cut, jet-mass cut, 2 btags,

$$M_{TWb\bar{b}} = p_{Tb} + p_{T\bar{b}} + \sqrt{p_{TW}^2 + m_W^2}$$

$$M_{TWb} = (\sqrt{p_{TW}^2 + m_W^2} + p_{Tb})^2 - |P_{TW} + P_{Tb}|^2 \quad \text{and} \quad M_{TWb\bar{b}} \text{ mass window}$$

<b>case i)</b>	$M_{W'} = 2 \text{ TeV}$	$L = 100 \text{ fb}^{-1}$	(20 events)	$S/B = 2.5$	$S/\sqrt{B} = 7$
	$M_{W'} = 3 \text{ TeV}$	$L = 300 \text{ fb}^{-1}$	(7 events)	$S/B = 5.8$	$S/\sqrt{B} = 4.5$
<b>case ii)</b>	$M_{W'} = 2 \text{ TeV}$	$L = 1000 \text{ fb}^{-1}$	(30 events)	$S/B = 0.38$	$S/\sqrt{B} = 3.4$

# Bulk RS models

## 1 example of KK fermions search

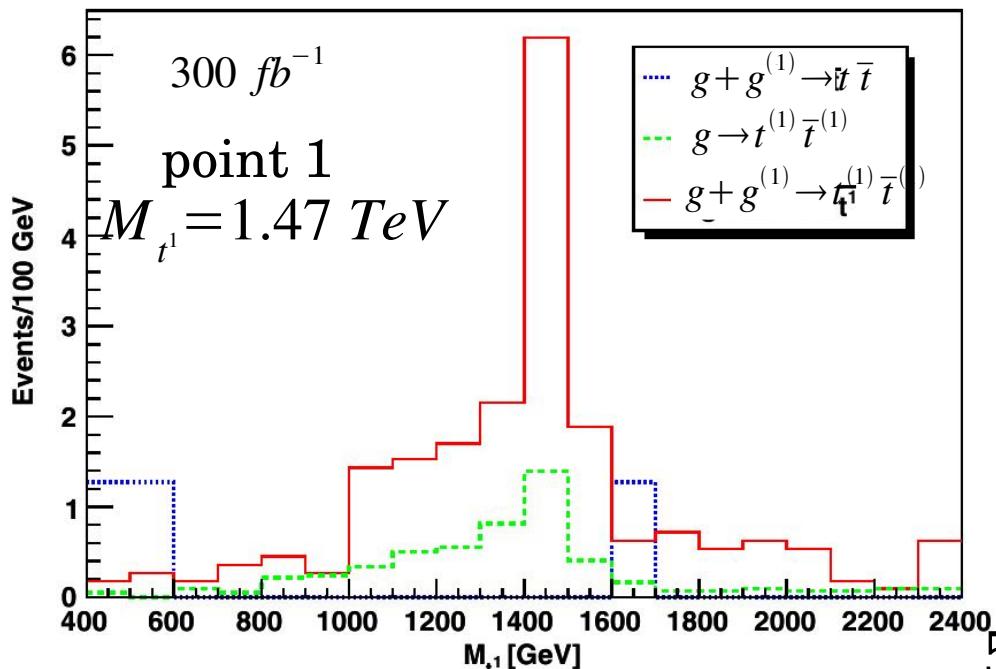
$$pp \rightarrow g + g^{(1)} \rightarrow t^{(1)} \bar{t}^{(1)} \rightarrow W^+ b W^- \bar{b} \rightarrow l^- \nu b \bar{b} jj (l=e, \mu)$$

### Backgrounds :

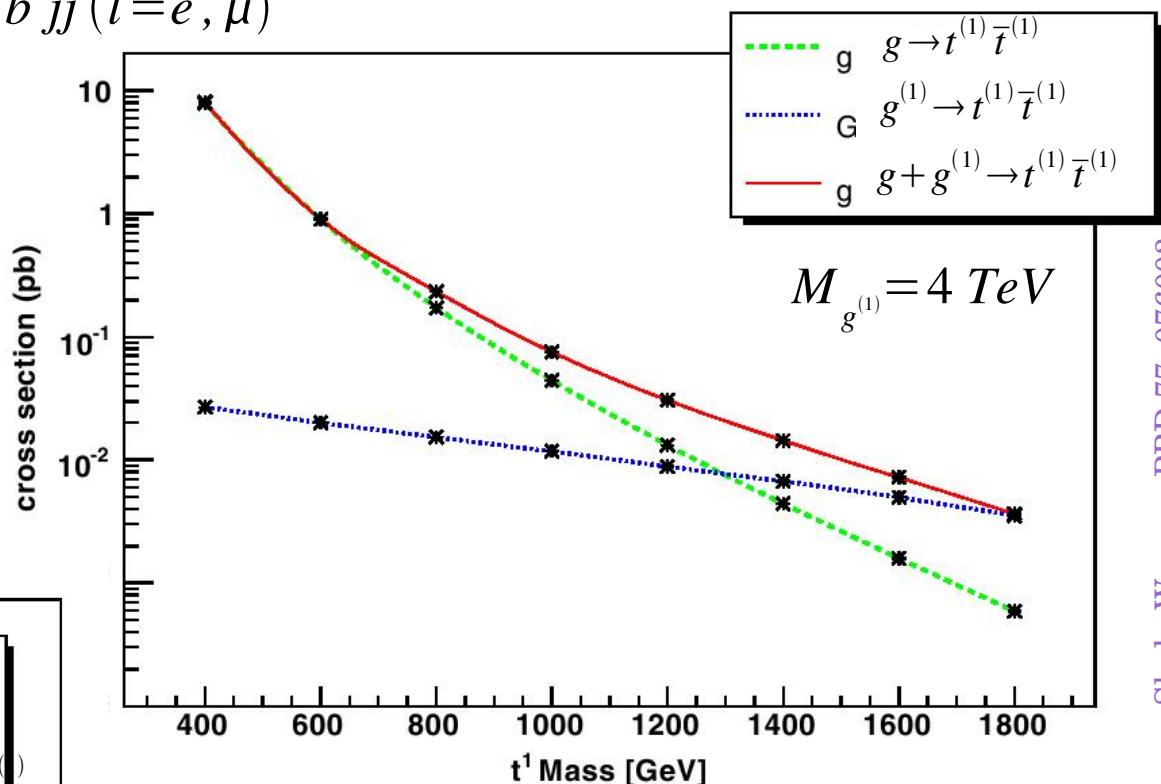
SM model top pair prod. and W/Z + jets  
top pair prod. from KK gluon decay (!)

high pT lepton, high pT jets, MET, Ht,  
2b-tags, single jet from boosted W and  
Wb system requirement i.e.

bottom having biggest  $\Delta R$  w.r.t W

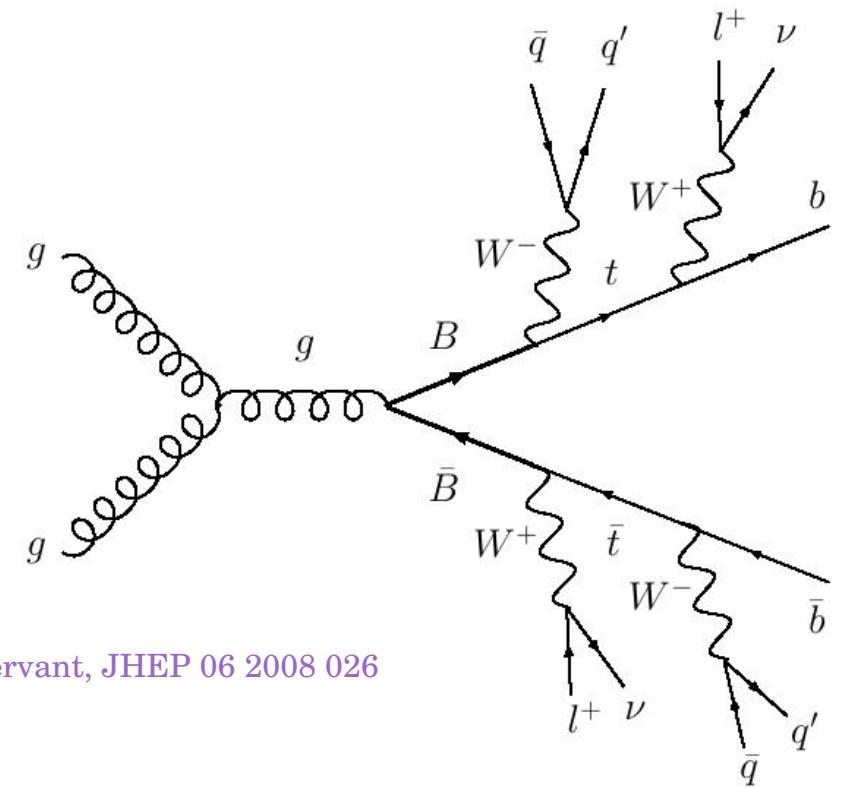
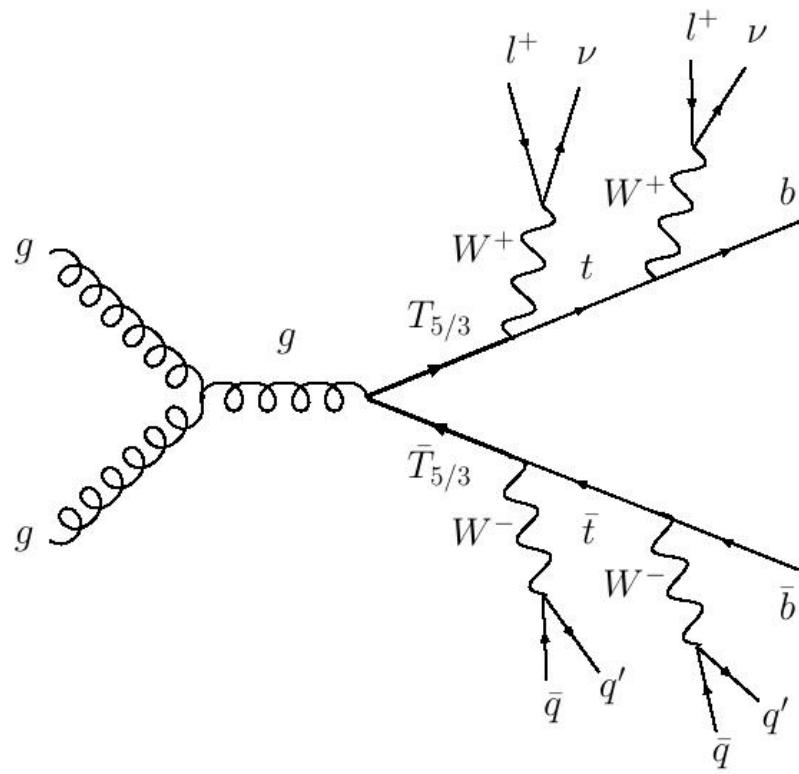


Aguilar-Saavedra, PLB 625 (2005) 234, PLB 633 (2006) 792  
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202  
Holdom, JHEP 03 (2007) 063  
Skiba, Tucker-Smith, PRD75, 115010  
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003  
Contino Servant, JHEP 06 (2008) 026



5 $\sigma$  significance  $S/\sqrt{S+B}$  at 300  $fb^{-1}$   
with K-factor = 1.5

# States with exotic charge



Contino, Servant, JHEP 06 2008 026

Agashe, Delgado, May, Sundrum, JHEP 08 (2003) 050  
 Csaki, Grojean, Murayama, Pilo, Terning, PRD 69, 055006  
 Csaki, Grojean, Pilo, Terning, PRL 92, 101802  
 Barbieri, Pomarol, Rattazzi, PLB 591 (2004) 141  
 Davoudiasl, Hewett, Lillie, Rizzo PRD 70, 015006  
 Cacciapaglia, Csaki, Grojean, Terning, PRD 71, 035015  
 Foadi, Gopalakrishna\_schmidt, PLB 606 (2005) 157  
 Cacciapaglia, Csaki, Grojean, Reece, Terning, PRD 72, 095018  
 Cacciapaglia, Csaki, Marandella, Terning, PRD 75, 015003

# Higgsless models

- gauge theory in a 5D RS warped bulk (with custodial SU(2) symmetry) e.g.

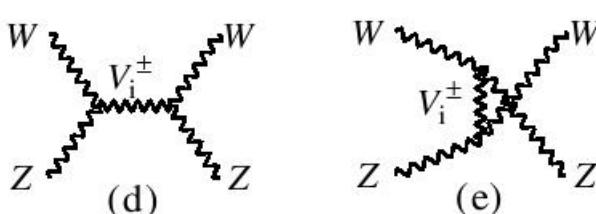
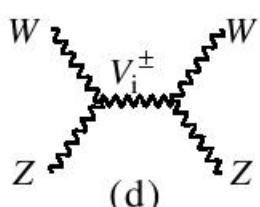
$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

in flat space  $\rightarrow$  violation of SU(2) custodial symmetry  $\rightarrow$  large deviation of  $\rho$  parameter from 1

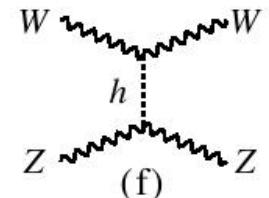
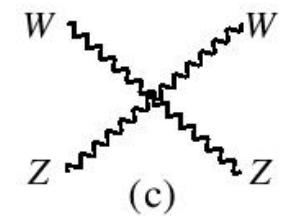
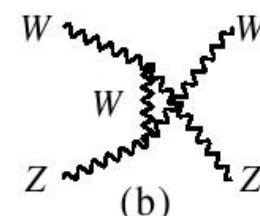
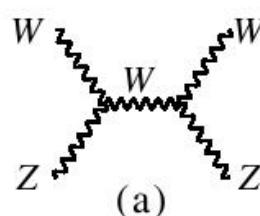
- EWSB  $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$  via boundary conditions of gauge fields at TeV and Planck brane positions (rather than via Higgs vev)

- unitarization of WW and WZ scattering amplitudes

due to W and Z KK modes exchange



rather than Higgs



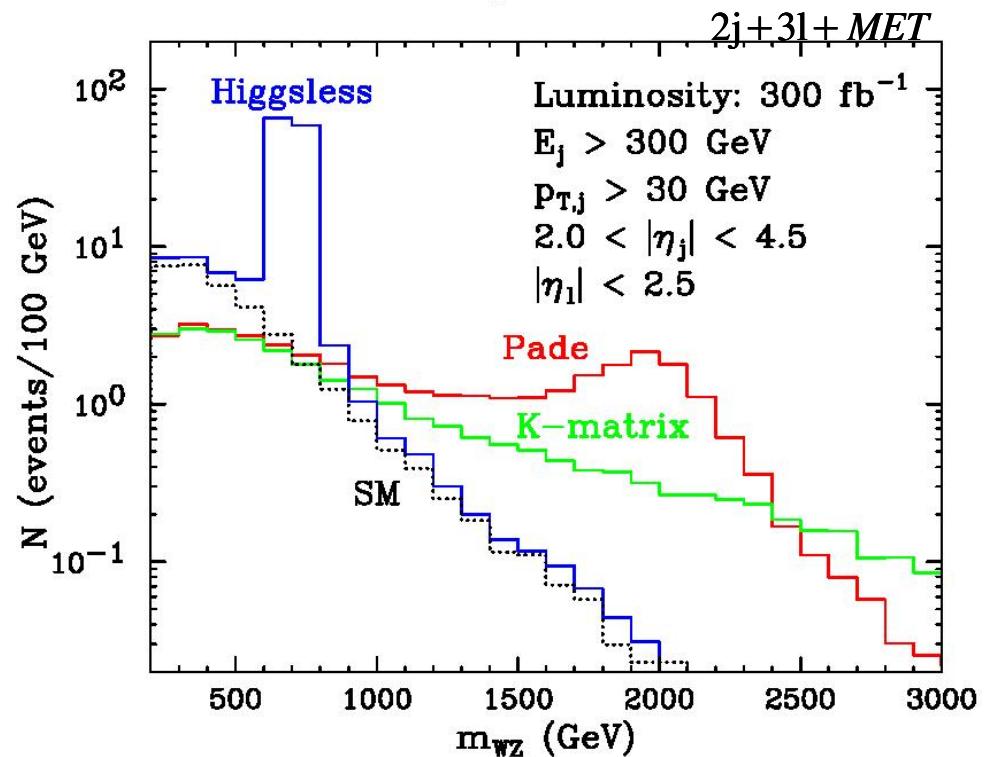
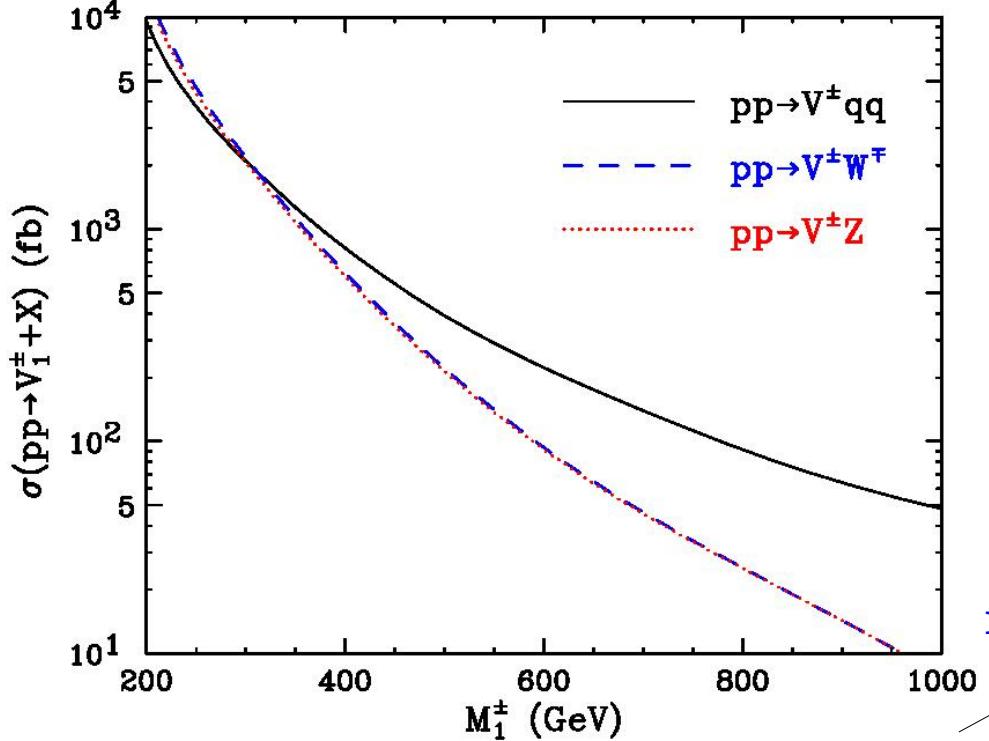
Agashe, Delgado, May, Sundrum, JHEP 08 (2003) 050  
Csaki, Grojean, Murayama, Pilo, Terning, PRD 69, 055006  
Csaki, Grojean, Pilo, Terning, PRL 92, 101802  
Barbieri, Pomarol, Rattazzi, PLB 591 (2004) 141  
Davoudiasl, Hewett, Lillie, Rizzo PRD 70, 015006  
Cacciapaglia, Csaki, Grojean, Terning, PRD 71, 035015  
Foadi, Gopalakrishna\_schmidt, PLB 606 (2005) 157  
Cacciapaglia, Csaki, Grojean, Reece, Terning, PRD 72, 095018  
Cacciapaglia, Csaki, Marandella, Terning, PRD 75, 015003

# Higgsless models

- EW precision data through oblique parameters **S, T, U very constraining**
  - **tension between EW data and unitarity**

EW precision data  $\rightarrow$  scale of KK modes  $\gtrsim 2 \text{ TeV}$   
Unitarity  $\rightarrow$  scale of KK modes  $\lesssim 2 \text{ TeV}$
- need extension or modification
  - induced kinetic terms on TeV brane  $\rightarrow$  but lowest Z KK mode  $\sim 300 \text{ GeV}$
  - **spreading fermions in the bulk and (enhanced) custodial symmetry**

OK with S parameter (and T, and U)  
large enough top quark without messing Zbb coupling



# Higgsless models

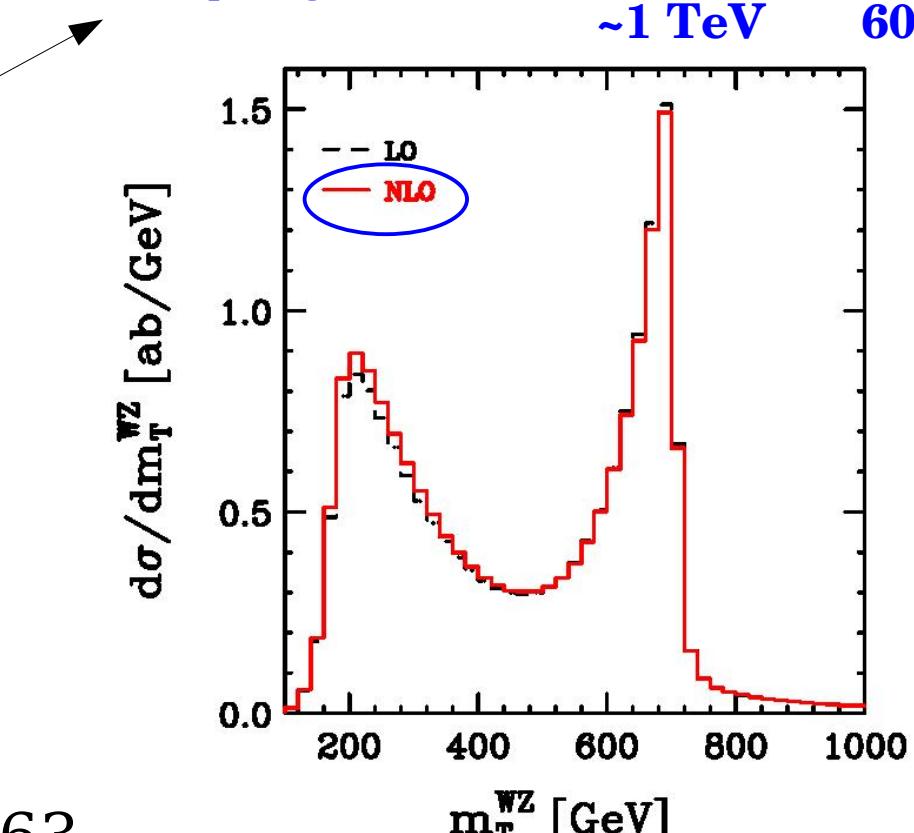
$W_{KK}$  or  $Z_{KK}$  exchange in  $VV \rightarrow VV$   
vector boson fusion processes

narrow width resonances

~ 20 narrower than SM  
Higgs of same mass

reach (requiring 10 evts at least)

~550 GeV  $10 \text{ fb}^{-1}$   
~1 TeV  $60 \text{ fb}^{-1}$



# Higgsless models

arXiv:0901.0512

from *generic* resonant weak vector boson scattering ( $VV \rightarrow VV$ ) searches

- **W+jets, Z+jets, QCD backgrounds**

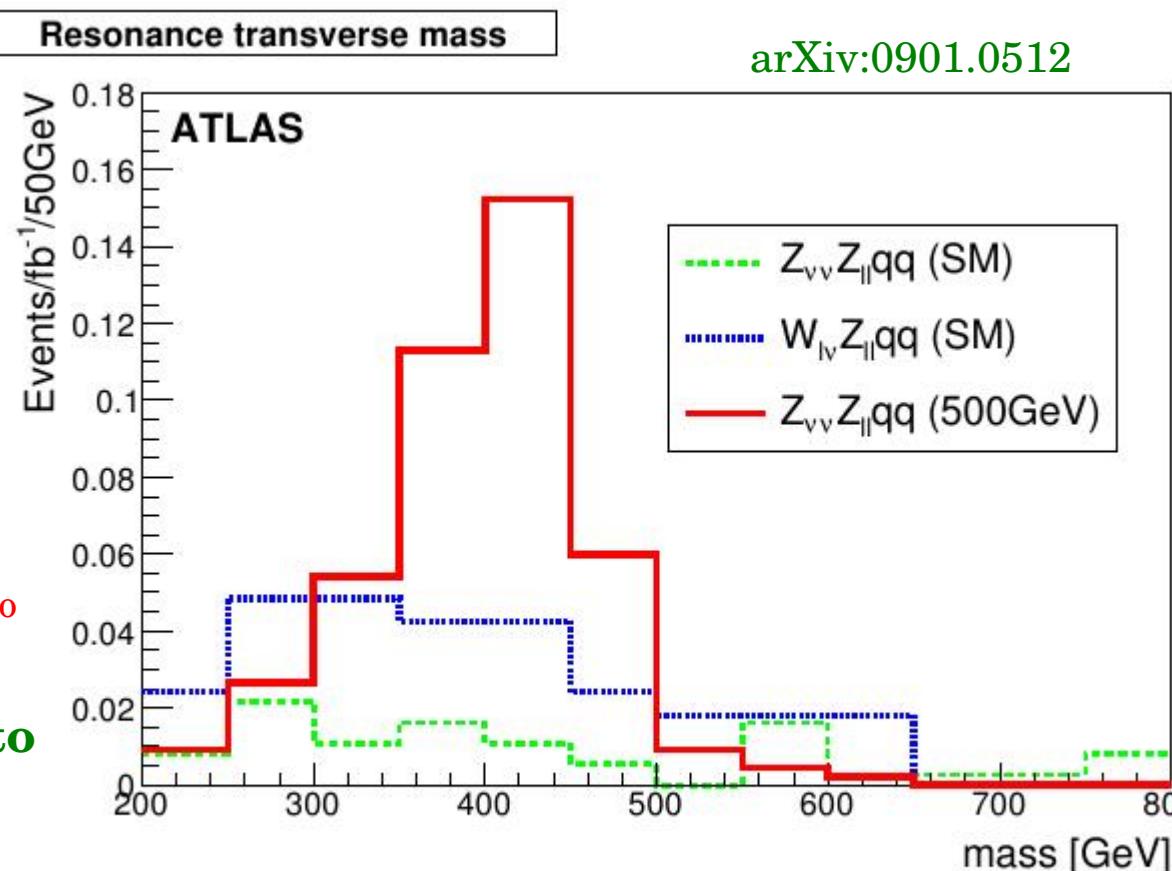
suppressed by single jet/dijet mass reconstruction techniques

hadronically decaying vector bosons collimated into single jet

- **tagged forward jet & central jet veto**

- **top quark rejection**

Wjet invariant mass far from top mass window



Process	Cross section (fb)		Luminosity (fb <sup>-1</sup> )		Significance for 100 fb <sup>-1</sup>
	signal	background	for 3 $\sigma$	for 5 $\sigma$	
$WW/WZ \rightarrow \ell\nu jj$ , $m = 500$ GeV	$0.31 \pm 0.05$	$0.79 \pm 0.26$	85	235	$3.3 \pm 0.7$
$WW/WZ \rightarrow \ell\nu jj$ , $m = 800$ GeV	$0.65 \pm 0.04$	$0.87 \pm 0.28$	20	60	$6.3 \pm 0.9$
$WW/WZ \rightarrow \ell\nu jj$ , $m = 1.1$ TeV	$0.24 \pm 0.03$	$0.46 \pm 0.25$	85	230	$3.3 \pm 0.8$
$W_{\ell\nu}Z_{\ell\ell}$ , $m = 500$ GeV	$0.40 \pm 0.03$	$0.25 \pm 0.03$	20	55	$6.6 \pm 0.5$
$Z_{vv}Z_{\ell\ell}$ , $m = 500$ GeV	$0.32 \pm 0.02$	$0.15 \pm 0.03$	20	60	$6.6 \pm 0.6$

# Higgsless models

Schwinn, PRD 71, 113005

## detection of KK resonance of top and bottom quark

- KK top search  $T^{(1)}$  resembling heavy top  $T$  from Little Higgs ?

$$\sigma_{Littlest-Higgs}(Wb \rightarrow T) = \frac{m^2}{m_b m_T} \frac{\lambda_1^2}{\lambda_2^2} \sigma_{Higgsless}(Wb \rightarrow T^{(1)})$$

$$\Gamma_T^{Littlest-Higgs} = \frac{4 m_t}{m_T} \frac{\lambda_1^2}{\lambda_2^2} \Gamma_{T^{(1)} \rightarrow tZ}^{Higgsless}$$

$T^{(1)} \rightarrow bW$  suppressed by  $\frac{2m_b}{m_t}$   
in Higgsless

at higher mass ~3 TeV  $T^{(1)}$  tends to be broader ( $> 240$  GeV) than  $T$

- heavy bottom  $B^{(1)}$  can be a feature distinguishing Higgsless from minimal implementation of little Higgs

both

$$q \bar{q} \rightarrow W^- \rightarrow B^{(1)} \bar{t} \quad (\text{kinematically suppressed})$$

$$q b \rightarrow q B^{(1)} \quad (\text{small coupling})$$

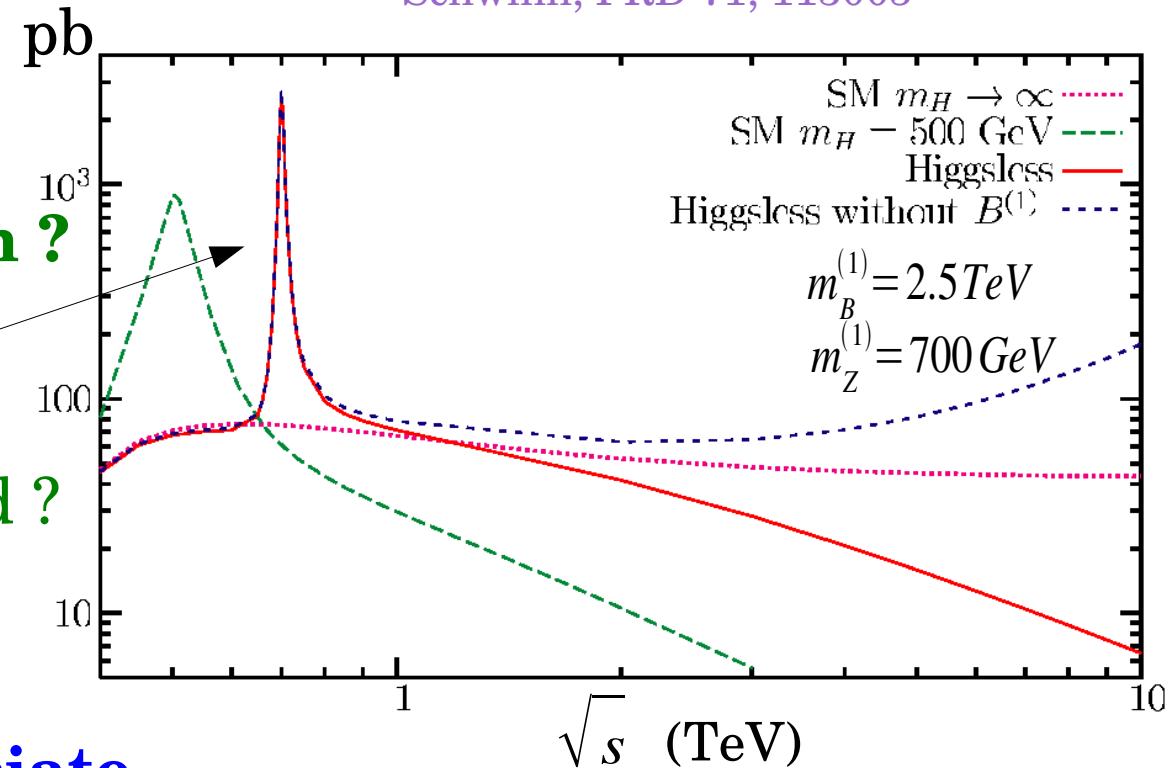
challenging at LHC

# Higgsless models

**other resonant production ?**

$$\sigma(ZZ \rightarrow t\bar{t}) \quad \sigma(W^+ W^- \rightarrow t\bar{t})$$

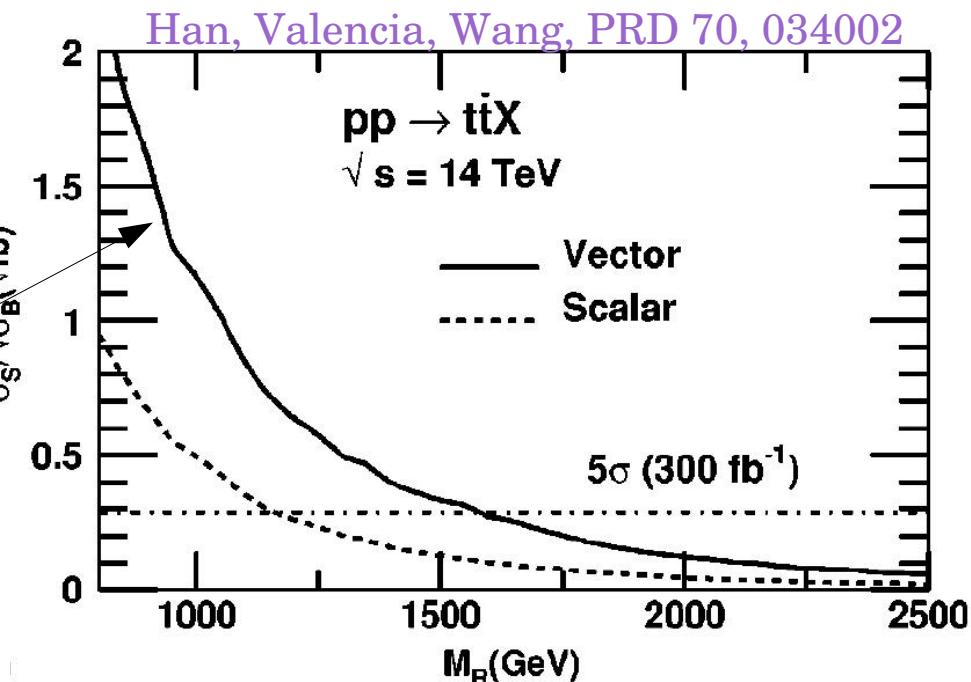
swamped by QCD background ?



**look alternatively at associate  
production ? :**

$$Wb \rightarrow t Z^{(1)}, \quad gg \rightarrow t\bar{t} Z^{(1)} \\ \rightarrow b\bar{b} Z^{(1)}$$

e.g. for a generic massive  
vector boson resonance  
with large new couplings  
to b and t quarks



# Black Holes

Myers, Perry, Annals. Phys. 172 (1986) 304  
 Argyres, Dimopoulos, March-Russel, PLB 441 (1998) 96  
 Banks, Fischler, hep-th/9906038  
 Emparan, Horowitz, PRL 85 (2000) 499  
 Giddings, Thomas, PRD65, 056010  
 Dimopoulos, Landsberg, PRL 87 (2001) 161602  
 Anchordoqui, Goldberg, Shapere, PRD 66, 024033  
 Dimopoulos, Emparan, PLB 526 (2002) 393  
 Kanti, Int.J.Mod.Phys. A19 (2004) 4899  
 Lect.Notes.Phys.769(2009)387

Schwarzschild radius ('flat' ED ~ ADD)

$$4\text{D} \quad R_s \approx \frac{2}{M_{Pl}^2} \frac{M_{BH}}{c^2}$$

$$R_s \ll 10^{-35} \text{ m}$$

$$(4+n)\text{D} \quad R_s \approx \frac{1}{M_d} \left( \frac{M_{BH}}{M_D} \right)^{\frac{1}{n+1}}$$

$$R_s \approx 10^{-19} \text{ m}$$

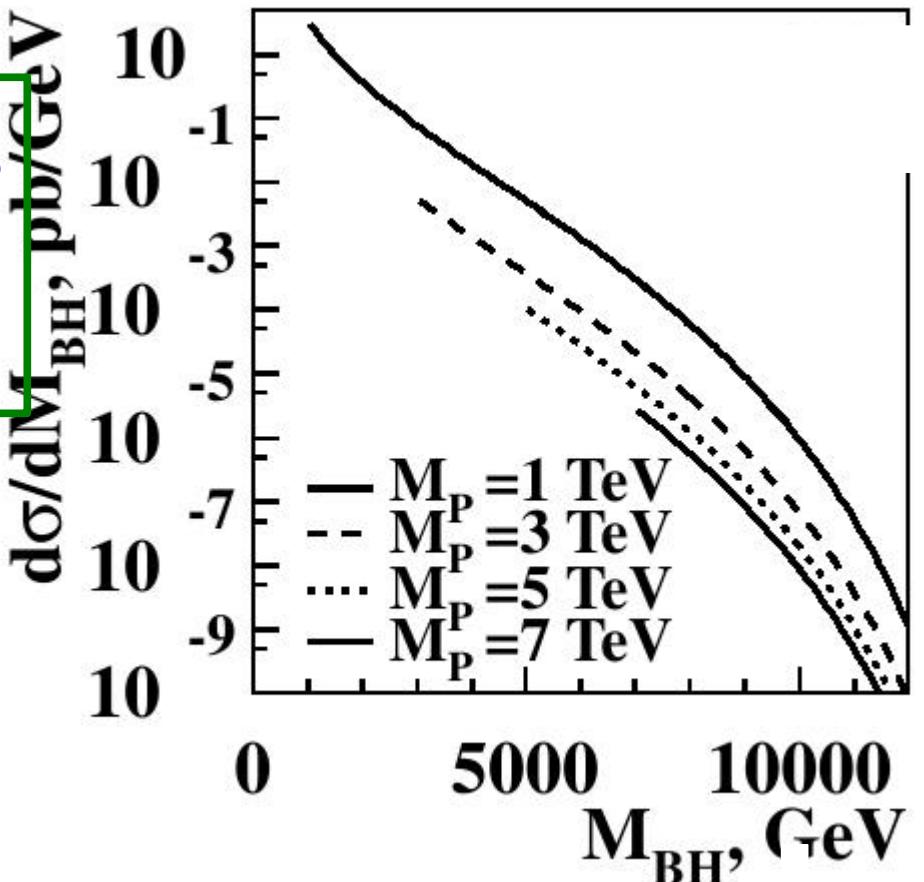
if **colliding parton impact parameter <  $R_s$**   
 and  $E_{CM} \sim M_{BH} > M_D$   
**a black hole can form**

Cross sections are large

$$\sigma(\text{parton}_i \text{ parton}_j \rightarrow BH) \approx \pi R_s^2$$

semi-classical approach

$$\sigma(pp \rightarrow BH) \approx 1 \text{ nb} - 1 \text{ fb}$$



Dimopoulos, Landsberg, PRL 87 (2001) 161602

# Black Holes decay

a highly asymmetric rotating created Black Hole goes through

## Balding phase

shedding of quantum numbers except a few i.e. M, Q ...  
invisible energy (15% of total energy ?)

## Spin-down phase

loss of angular momentum by Hawking radiation  
visible energy (25% of total energy ?)

## Schwarzschild phase $M_{BH} \gg M_D$

Hawking radiation at  $T_H \approx M_D \left(\frac{M_D}{M_{BH}}\right)^{\frac{1}{n+1}} (n+1)$

thermal evaporation black body spectrum + grey-body factors from strong. Grav. field)

visible energy (60% of total energy ?) → **mostly in SM particles on our brane**

## Planck phase $M_{BH} \approx M_D$ (**regime of quantum gravity**)

quanta emission ?

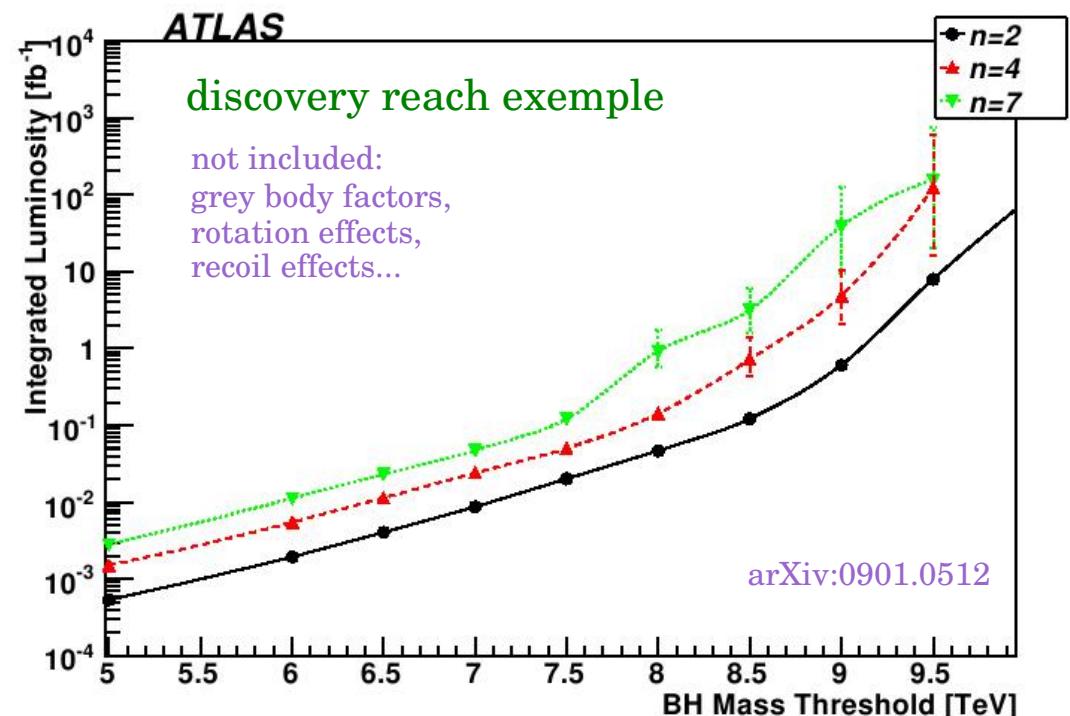
string ball formation and evaporation at Hagedorn temperature ?

# Black Holes

BH evaporate/decay democratically into SM particles (or SM+SUSY) mainly on the brane through Hawking radiation

decay is fast  $\sim 10^{-26}$  s  $\rightarrow$  Black Holes do not escape the detector

**spectacular signatures**  
**large multiplicities**  
**jets/leptons  $\sim 5$**   
**small missing energy**



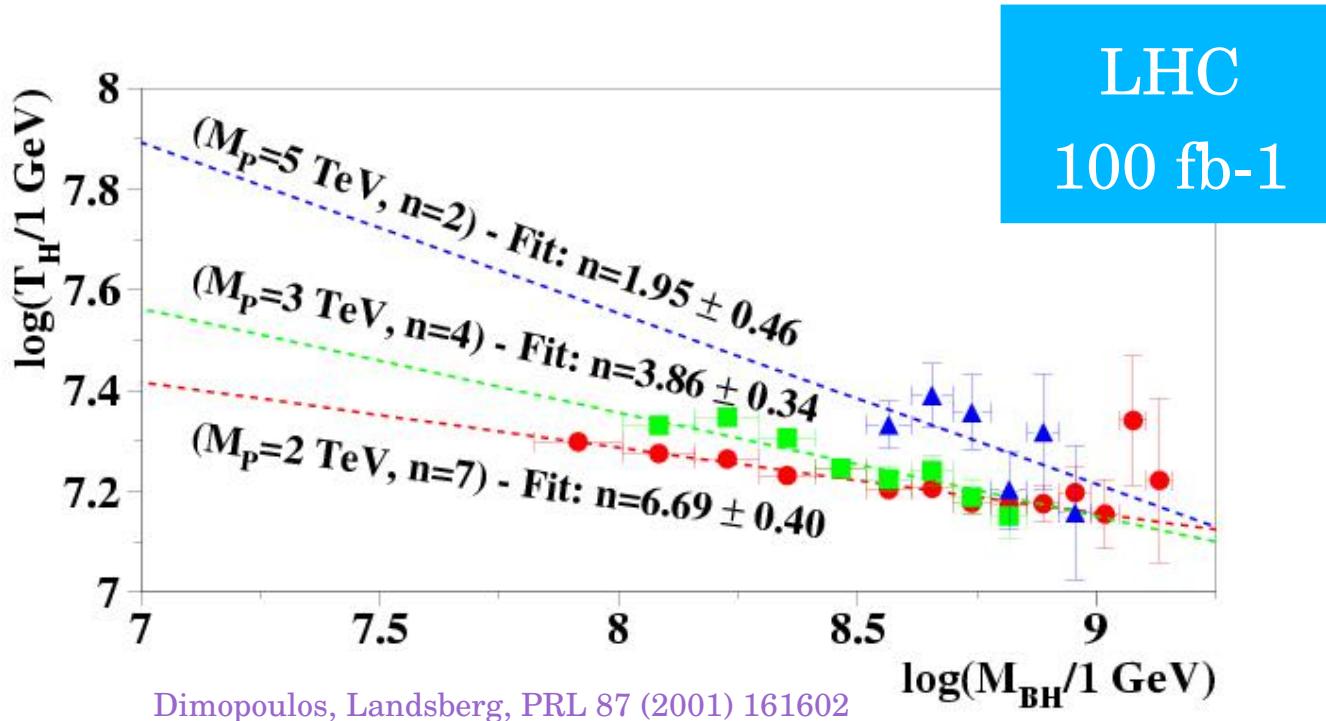
possible to carry dedicated studies  $\rightarrow$  dimensionality of space-time

# Measure Hawking temperature of Black Hole $T_{BH}$

(e.g. from energy spectrum of electron or photon tag)

as a function of its mass  $M_{BH}$   
(from total energy of all of its decay product)

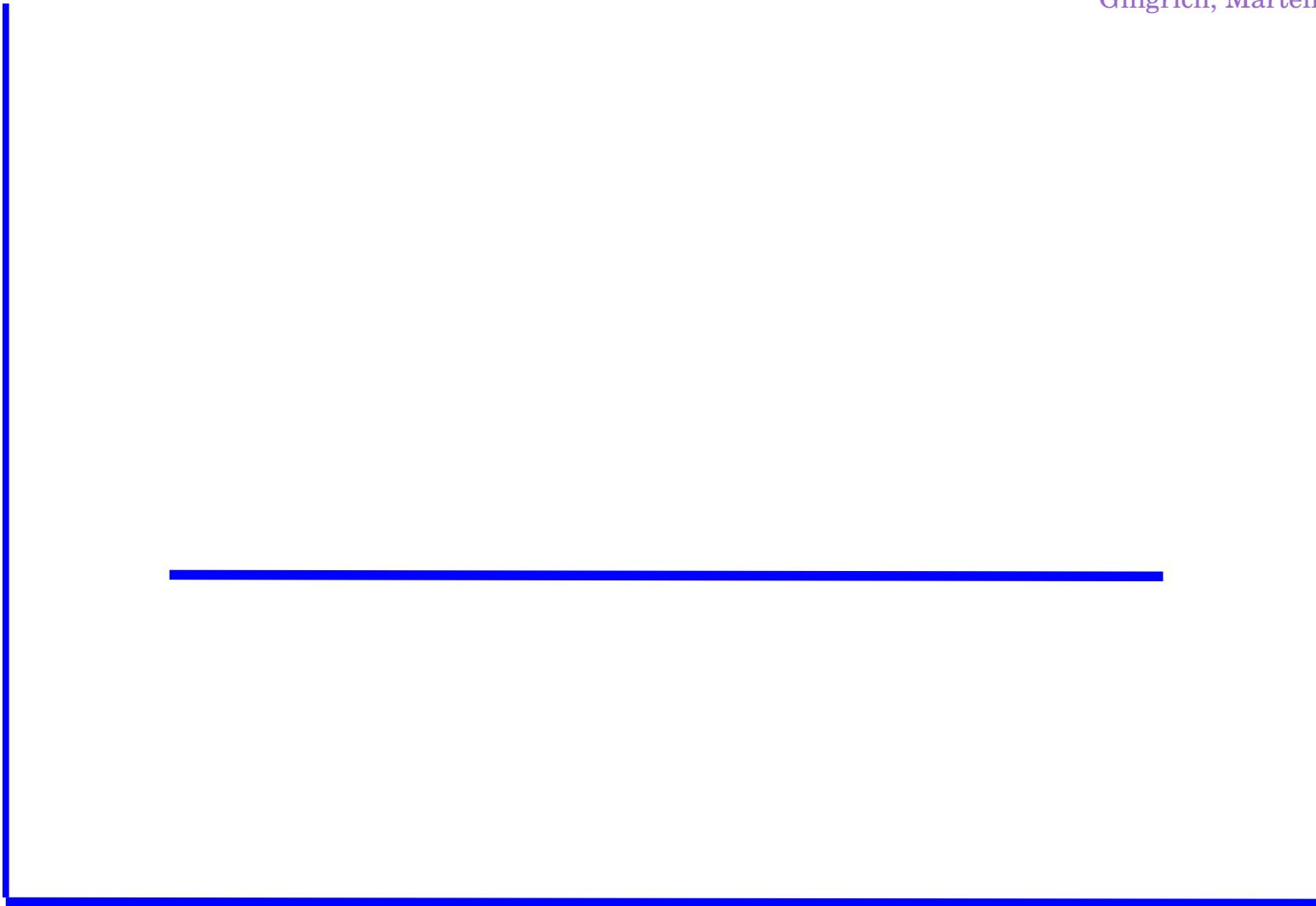
check that  $\log(T_{BH}) = -\frac{1}{n+1} \log(M_{BH}) + const$  (Xtra-dim equivalent of Wien law)



# String Ball

T

T<sub>Hagedorn</sub>



M