Warped Xtra Dimensions & the LHC

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Flavour as a Window to New Physics
at the LHC

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CERN, Th. Colloquim 6/11/08

Outline

- Intro, theoretical motivation
- Any hints
- Possible repurcussions for LE flavor physics
- LEET candidate: an example
- Signals @ LHC
- RS vs. LRS
- Outlook & Summary

Intro…

updated 9:10 a.m. EDT, Fri May 9, 2008

Colliding with nature's best-kept secrets

STORY HIGHLIGHTS

- Nima Arkani-Hamed, a theoretical physicist, predicts large extra dimensions
- The Large Hadron Collider in Switzerland may confirm his ideas
- LHC results may change ideas of spacetime for the first time since Einstein
- String theory postulates that the building blocks of matter are vibrating strings

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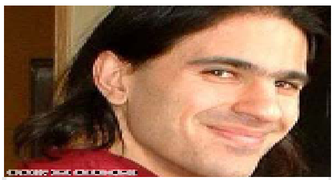
READ EXPLAINER

By Elisabeth Landau
CNN

(CNN) -- Visiting a particle accelerator is like a religious experience, at least for Nima Arkani-Hamed.



Nima Arkani-Hamed, a leading theoretical physicist, thinks the universe has at least 11 dimensions.

1 of 2

Immense detectors surround the areas where inconceivably small particles slam into one another at super-high energies, collisions that may confirm Arkani-Hamed's predictions about undiscovered properties of nature.

Arkani-Hamed is only in his mid-30s, but he has already distinguished himself as one of the leading thinkers in the field of particle physics.

His revolutionary ideas about the way the universe works will finally be put to the test later this year at Switzerland's Large Hadron Collider, which, when completed, will be the world's most powerful particle accelerator.

The accelerator, estimated to cost between $5 billion and $10 billion, could provide answers to questions physicists have had for decades. Thousands of scientists from around the world are collaborating on the project at the European Organization for Nuclear Research, or CERN.

If the results confirm any of Arkani-Hamed's predictions, they would be the first extension of our notions of spacetime since Albert Einstein.

"We're essentially guaranteed that there's going to be something surprising," Arkani-Hamed said of the Large Hadron Collider, which will operate inside a 17-mile circular tunnel. See what's planned for the collider »

Don't Miss

- Rough landing
- Hubble mission delayed
- SciTechBlog

Regarded as a "gem," Arkani-Hamed is "opening our minds and creating a new world of ideas that challenge deep-grained preconceptions about spacetime," said Chris Tully, professor of physics at Princeton University, who is working on the Compact Muon Solenoid experiment at the Large Hadron Collider.

"From the point of view of the big experiments at the LHC, there is no amount of money or craftsmanship that would produce the kind of insight that comes from sharing LHC data with a true visionary like Nima Arkani-Hamed," Tully said.

Formerly a professor at Harvard, Arkani-Hamed currently sits on the faculty at the prestigious Institute for Advanced Study in Princeton, New Jersey, where Einstein served from 1933 until his death in 1955.

"He was lured from Harvard to the IAS -- I'm sure that's considered quite a coup," said Daniel Marlow, a physics professor at Princeton who is also collaborating on the CMS experiment.

Arkani-Hamed has had a hand in explaining how the world can operate according to Einstein's theory of general relativity, which describes the universe on a very large scale, and at the same time follow quantum mechanics, laws that describe the universe on a scale smaller than the eye can see.

Some of the key mysteries that stem from these clashing theories include why gravity is so weak, relative to the other fundamental physical forces such as electromagnetism, and why the universe is so large. These issues come up because on an inconceivably small scale, the particles that make up our world seem to behave completely differently than one might imagine.

For example, if you are driving a car, your GPS tells you where you are, and your speedometer tells you how fast you are moving. But on the scale of particles like electrons, it is impossible to know both position and speed at once -- the very act of trying to find out requires incredible amounts of energy.

If it takes so much energy just to try to pin down a particle, then, in theory, all particles should have temporary energy changes around them called "quantum fluctuations." This energy translates into mass, since Einstein famously said that mass and energy are interchangeable through the equation $E=mc^2$.

"It makes it extremely mysterious that the electron, or indeed, everything else that we know and love and are made of, isn't incredibly more massive than it is," Arkani-Hamed said.

A theory that has emerged in recent decades that claims to bring some relief to physics mysteries like these is

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Introduction & Theoretical Motivation

- Basic idea of XtraDim long history:

Nordstrom(1914), Kaluza('21), Klein('26)

Efforts to unify GR with EM

- More Recently
- String Theory since the '80's: consistency required 10 or 11 dimension
- In Particle Physics since the '90's a recurring theme: Main Motivation EW-P hierarchy, $M_W/M_P \sim 10^{-17}$!

  - Antoniadis, 1990: TeV^{-1} extra dimensions and SUSY breaking.
  - Weak scale superstrings, Lykken, 1996.
  - Large Extra Dimensions; Arkani-Hamed, Dimopoulos, Dvali, 1998: $m_W \lesssim M_F$.
  - A Warped Extra Dimension; Randall, Sundrum, 1999: $m_W \sim e^{-k\pi r_c} M_P$; $k\pi r_c \sim 36$.

- SM with a Higgs: quadratic sensitivity to Λ_{UV}.

- EW precision: $\Lambda_{UV} \gtrsim 10$ TeV; "little hierarchy".

- Flavor data: $\Lambda_{UV} \gtrsim 10^3$ TeV; "flavor-weak hierarchy".

- Gravity: $\Lambda_{UV} \sim M_P \sim 10^{19}$ GeV; "Planck-weak" hierarchy.

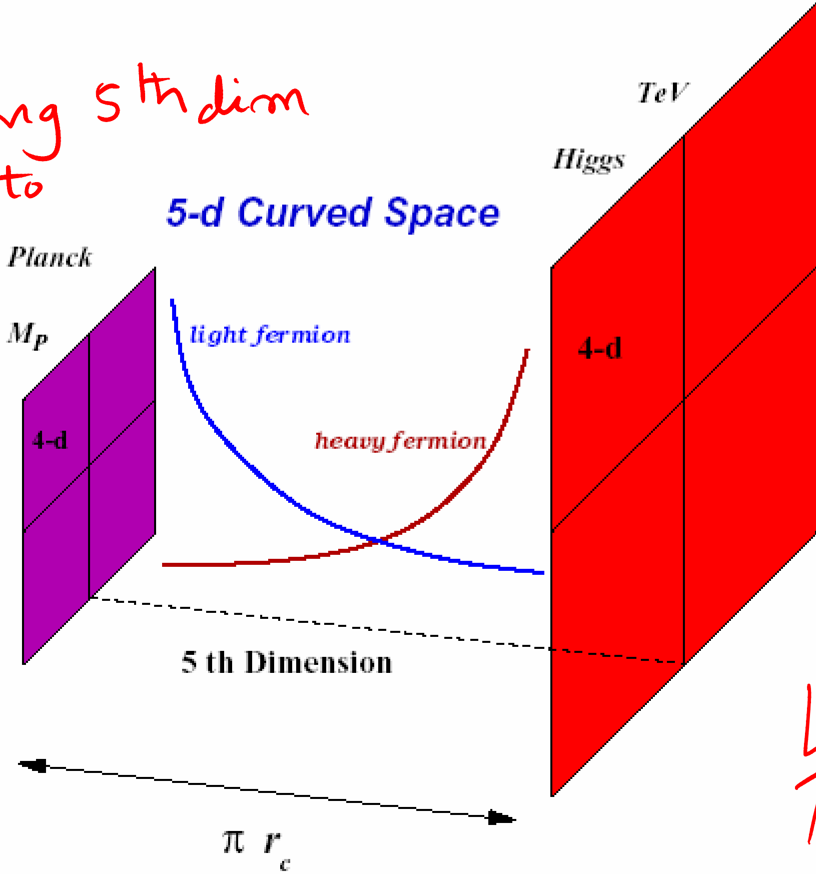
- Randall-Sundrum (RS) model (1999): Planck-weak hierarchy.

SM in 5D bulk, fermion masses through localization, warped model of flavor
Grossman & Neubert; Gherghetta & Pomarol
Possible to simultaneously address EW-Planck and EW-Flavor hierarchies

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

Points along 5th dim correspond to diff. eff. 4d scale!



$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$

$$\langle H_4\rangle = e^{-\sigma}\langle H_5\rangle$$

$\langle H_4\rangle$ → TeV, $\langle H_5\rangle$ → M_P

$$\sigma = k r_c \pi$$

$k r_c \sim 12$

Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

Simultaneous resolution to hierarchy and flavor puzzles

WAY 2 FINANCE New Colliders ?

MEANS 2 Seek answers to a burning timeless question for many a (wo)man in the street

MAY B XDIM IS WHERE THE SOUL GOES !

PROS & Cons

- The possibilty to simultaneously address
- EW-PI and EW-FI puzzles renders the basic warp idea extremely appealing

BUT

- Specific model(s) that can be used to make reliable predictions are not yet there
- SEEK GENERIC CLUES & TARGETS

Gold-mines@ H&L energies

- LHC:G->Z(ll) Z(l'l'), WW
- LHC et al: t \bar t due $(G,g,Z..)_{KK}$
- LHC: Top polarization, FB-asym?
- LHC: t-> c Z…….
- t-edm
- LC(ILC,CLIC,muLC…): Some items clearly More important/relevant for LC et al (e.g. t-edm, tcz f-B asym…)
- N-edm
- D^0 mixing & CP (dir & TD)
- B_S (CP) ->ψφ….
- B_d -> (φ,η'……)$K_{S,,}$ γ K^* ….TDCP

Ultimately an experimental question

- Analogy with Guts….expedited pushing searches for proton lifetime resulting in improvement of bounds by ~$O(10^4)$

Any Hints?

- **While a compelling & conclusive evidence for breakdown of SM in flavor physics cannot be made at present , in the last few years several interesting (and perhaps strong) hints have emerged.**
- **Although, taking too seriously every little deviation is not desirable and may be counterproductive;**
- **disregarding or overlooking the hints can be equally unwise and in fact can be more damaging. Following these up in flavor & collider physics and in theory may prove beneficial.**

{ based in part on Enrico Lunghi + A. S. arXiv:0707.0212; arXiv:0803.4340}

II. A tale of four numbers

- **Tantalizing (possible) signs of a BSM-CP-odd phase (L&S'07)**

I. A tale of two numbers

I. $S_{BF}(t)\,[B^0 \to \text{"}\psi\text{"} K_s] \Rightarrow \sin 2\beta\big|_{BF} = .674 \pm .026$

II. a) $\epsilon_K + B_K$

2) "f_B" $+ B_d\text{-}\bar{B}_d$ (also B_s)

3) $\dfrac{b \to ue\nu}{b \to ce\nu}$

- - - - - -

EXPT + "LATTICE" $\Rightarrow \sin 2\beta\big|_{SM} = .78 \pm .04$

Lunghi+AS,arXiv.0707.0212

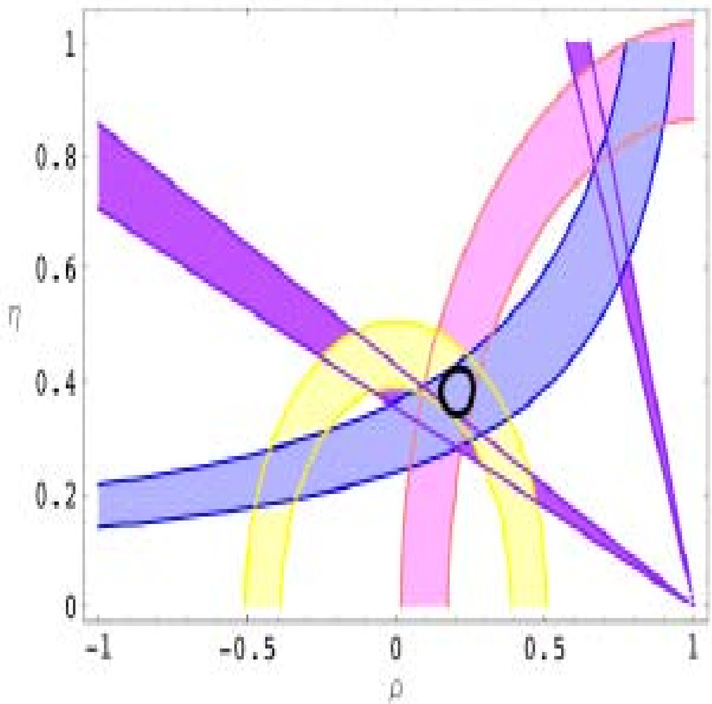


Figure 1: Unitarity triangle fit in the SM. The constraints from $|V_{ub}/V_{cb}|$, ε_K, $\Delta M_{B_s}/\Delta M_{B_d}$ are included in the fit; the region allowed by $a_{\psi K}$ is superimposed.

Continuing saga of Vub

- For past 2 years or so exclusive & inclusive ~small discrepancy:
- Exc ~ (3.7 +-.2+-.5)X10^{-3}
- Inc ~ (4.3 +-.2+-.3)X10^{-3}
- More recently (LP'07) Neubert suggests source is m_b extraction from b s gamma; disregarding that m_b shows incl. Vub quite consistent i.e. 3.98+-.15+-.30 X10^{-3}

-> ***Let's try NOT use Vub***

Leave out Vub

Sin 2 β = 0.82+-.09{Lunghi+AS,hep-ph/08034340}

(became possible only due significantly reduced error in Bk)

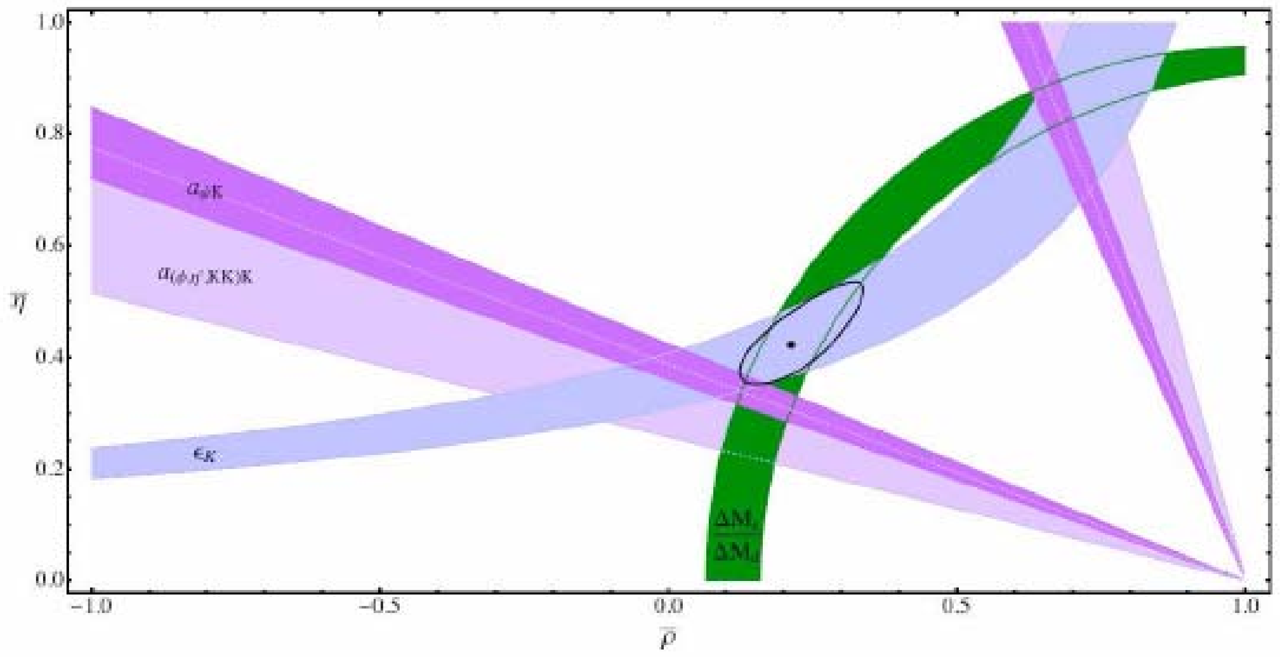


FIG. 1: Unitarity triangle fit in the SM. All constraints are imposed at the 68% C.L.. The solid contour is obtained using the constraints from ε_K and $\Delta M_{B_s}/\Delta M_{B_d}$. The regions allowed by $a_{\psi K}$ and $a_{(\phi+\eta'+2K_s)K_s}$ are superimposed.

Significance of fit w/o Vub

- Because of reduction of error in Bk

Now non-trivial constraint on sin2beta(SM) obtainable w/o Vub

Lattice calculation of Bk and SU3 breaking ratios(also B's) do NOT require any momentum injection in sharp contrast to semi-leptonic form factor needed for Vub…Also, B's are quite insensitive to quenching (though BK is in full QCD) .Progonosis

for further improvements in B-parameters is therefore quite good.

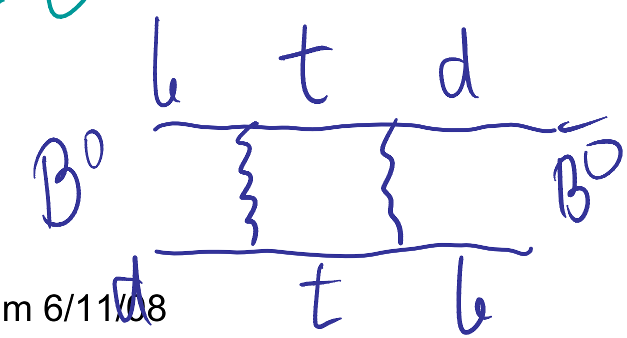
{for BK see D. Antonio et al (RBC-UKQCD), 0702042; For ζ see,e.g. Becirevic, 0310072}

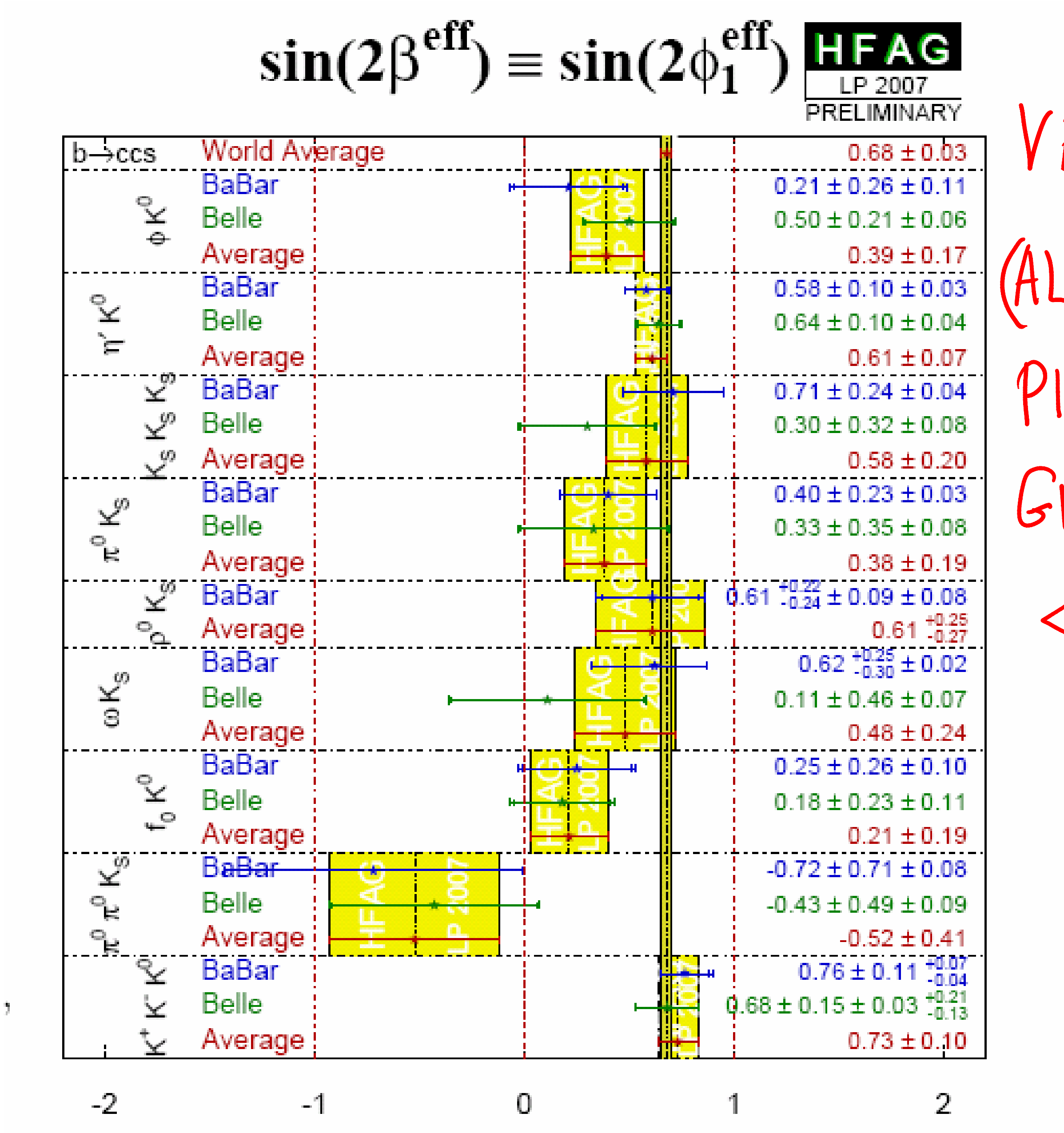
$$\Delta S \equiv S_{penguin} - S_{\psi K_S} = O(\lambda^2)$$

$$S^{Decay}_{peng} \simeq O(\lambda^2) \sim \text{few}\,\%$$

$$S^{Decay}_{\psi K_S} = 0$$

OSC is common





VERY INTRIGUING

(ALMOST) ALL PINGUIN MODES GIVE $\sin 2\beta < (\sin 2\beta)$!

$4K_s$

TABLE I: Some expectations for ΔS in the cleanest modes.

Mode	QCDF+FSI [20, 21]	QCDF [23]	QCDF [24]	SCET [25]
$\eta' K^0$	$0.00^{+0.00}_{-0.04}$	0.01 ± 0.01	0.01 ± 0.02	-0.019 ± 0.009 -0.010 ± 0.001
ϕK^0	$0.03^{+0.01}_{-0.04}$	0.02 ± 0.01	0.02 ± 0.01	
$K_S K_S K^0$	$0.02^{+0.00}_{-0.04}$			

CLEANEST MODES

Although, at the moment it is not a conclusive effect,
it may well become a serious blunder on the part
of our community to ignore it!
We can try learn some lessons from history.

It is extremely important to understand
that basically it is a very good test of the SM
and it should be followed vigorously to a decisive
conclusion ASAP.

DRELL-YAN @ its INFANCY!

pp → $\mu^+\mu^-$ X @ BNL

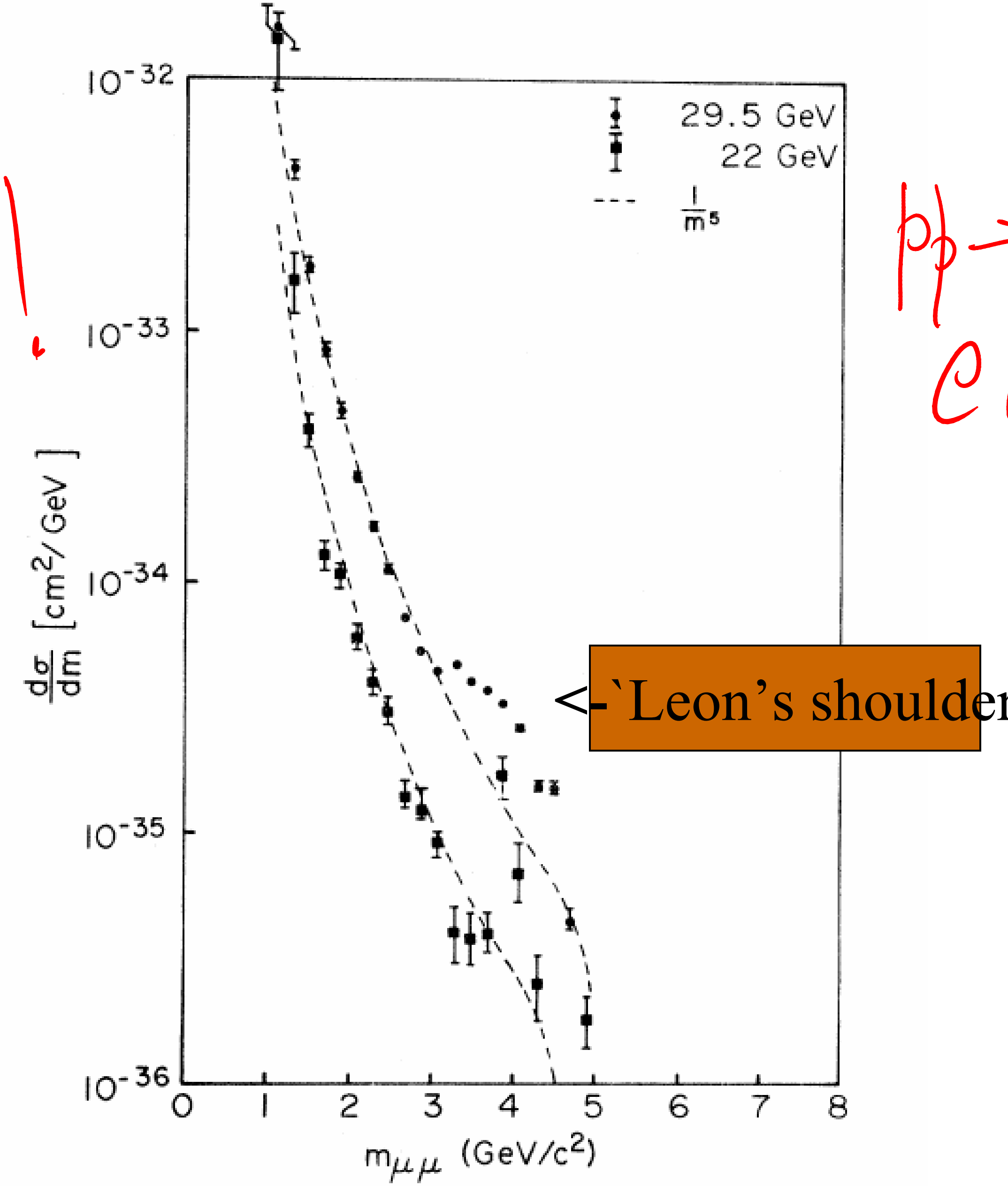


FIG. 15. Experimental cross sections at two energies compared with a simple $1/m^5$ continuum.

Christenson,Hicks,Lederman,Limon,Pope & Zavattini
PRD 8,2016 '72

mass range of 3–5 GeV/c^2, there is a distinct excess of the observed cross section over the reference curve. If this excess is assumed (certainly not required) to be the production of a resolution-broadened resonance, the cross-section–branching-ratio production σB would be approximately 6×10^{-35} cm^2, subject to the cross-section uncertainties discussed above. Alternatively the excess may be interpreted as merely a departure from the overly simplistic (and arbitrarily normalized) $1/m^5$ dependence. In this regard, we should remark that there may be two entirely different processes represented here: a low-Q^2 part which has to do with vector mesons, tail of the ρ, bremsstrahlung, etc., and a core yield with a slower mass dependence, which may be relevant to the scaling argument discussed below.

The "heavy photon" pole that has been postulated[32] to remove divergence difficulties in quan-

cles produced in the initial proton-uranium collision. In principle, these secondary particles could also create muon pairs. In this case, the observed spectrum would represent the inseparable product of the spectrum of the secondary particle and its own yield of muon pairs. In exploratory research of this kind this disadvantage is largely offset by the fact that the variety of initial states provides a more complete exploration of dimuon production in hadron collisions.

2. *Real Photons*

Real photons produced in the target (presumably from the decay of neutral pions) yield muon pairs by Bethe-Heitler or Compton processes. Estimates were made for the photon flux on the basis of pion-production models,[27,28] and this method of calculating the flux was checked against the experimental data of Fidecaro *et al.*[33] The argument

So far 3 numbers

- I) Expt [ε_K , B-mixing, b->uev…] + Lattice WME -> $\sin 2\beta_{SM}$ =0.78+-.04
- II)BF measurements [B -> "ψ" K_S]=0.674+-0.026
- III) BF measurements [B-> (φ, η',3) K_S]=0.57+-.06
- ***-> Deviations 2.2(I-II) - 3(I-III) sigmas***

NO GOOD REASON to IGNORE THIS

Last but quite significant #

$$A_{CP}(B^0 \to K^+\pi^-) = -9.7 \pm 1.2\,\%$$

$$A_{CP}(B^+ \to K^+\pi^0) = 4.7 \pm 2.6\,\%$$

$$\Delta A_{CP} = (14.4 \pm 2.9)\,\%$$

4th IMPORTANT # CAVEAT

(Naively) SM predicts $\Delta A_{CP} \approx 0$

Lunghi + AS ('07)

$$A_{CP}(B^- \to K^-\pi^0) = \left(7.1^{+1.7+2.0+0.8+9.0}_{-1.8-2.0-0.6-9.7}\right)\% \quad (1)$$

$$A_{CP}(\bar{B}^0 \to K^-\pi^+) = \left(4.5^{+1.1+2.2+0.5+8.7}_{-1.1-2.5-0.6-9.5}\right)\% \,, \quad (2)$$

where the first error corresponds to uncertainties on the CKM parameters and the other three correspond to variation of various hadronic parameters; in particular, the fourth one corresponds to the unknown power corrections. The main point is that the uncertainties in the two asymmetries are highly correlated. This fact is reflected in the prediction for their difference; we find:

$$\Delta A_{CP} = A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+) = (2.5 \pm 1.5)\% \,. \quad (3)$$

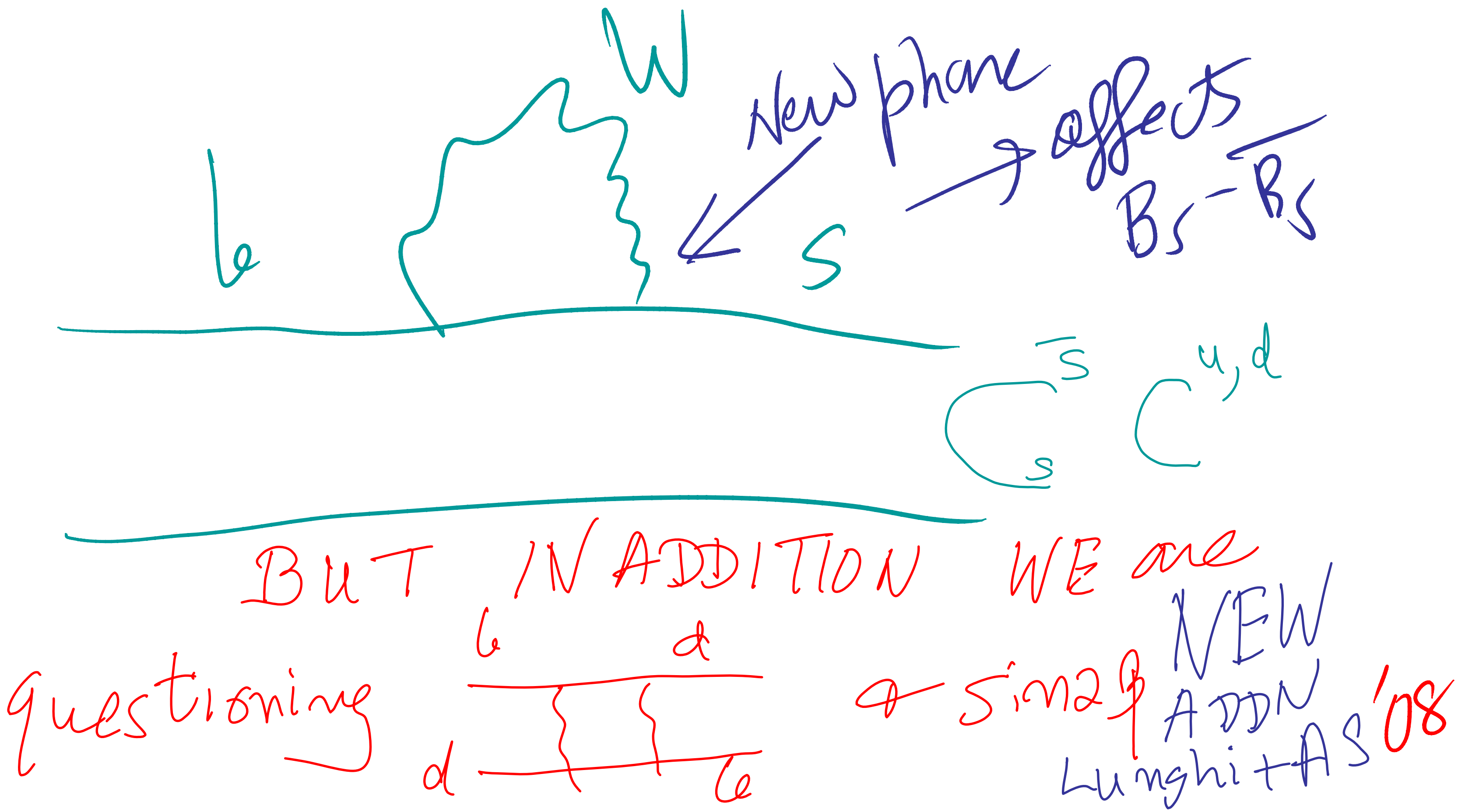
In evaluating the theory error for this case, we followed the analysis presented in Ref. [31] and even allowed for some extreme scenarios (labeled S1-S4 in Ref. [31]) in which several inputs are simultaneously pushed to the border of their allowed ranges. The comparison of the SM prediction in Eq. (3) to the experimental determination of the same quantity [14]

$$\Delta A_{CP}^{\rm exp} = (14.4 \pm 2.9)\% \,, \quad (4)$$

yields a 3.5σ effect.

BENEKE+NEUBERT
0308039

Central ROLE:Penguin & Box graph



THUS

- The CKM-paradigm of CP violation accounts for the observed CP patterns to an accuracy of about 15%!
- Remarkably in the past few years several B-factories results exhibit 2 -3 σ deviations from the SM-CKM paradigm requiring a new CP-odd phase!!

MORE Recently B_s shows related effects due to $b \to s$ NP-phase

See UTFIT 08030659

WHODUNIT?

Honest answer &

- **Don't really know (too many possibilities…)**
- **But theoretically the most interesting possibility is that we may be witnessing**

Dawning of the age of

"Warped Quantum Flavordynamics"

→ DUAL to STRONG DYNAMICS

Numerous other possibilities

NOT ordered

- **1) another (4th) generation**
- **2)2nd Higgs doublet…e.g. T2HDM**
- **3) LR Models**
- **4) Z'**
- **5) SUSY**

Fermion masses through localization

Yukawa term in the 5-d action will take the form

$$S_{\Upsilon}^{5} = \int d^4x\, d\phi \sqrt{-g}\, \frac{\lambda_5}{k} H(x) \Psi_L^D \Psi_R^S \delta(\phi - \pi), \qquad (12)$$

where $\lambda_5 \sim 1$ is a dimensionless 5-d Yukawa coupling and $\Psi^{D,S}$ are doublet left- and singlet right-handed 5-d fermions, respectively. After the rescaling $H \longrightarrow e^{kr_c\pi} H$, the 4-$d$ action resulting from Eq.(12) is

$$S_{\Upsilon}^{4} = \int d^4x\, \sqrt{-g}\, \lambda_4 H(x) \psi_L^{(D,0)} \psi_R^{(S,0)} + \ldots, \qquad (13)$$

where the 4-d Yukawa coupling for the corresponding zero-mode SM fermion is given by [3]

$$\lambda_4 = \frac{\lambda_5}{kr_c} \left[\frac{e^{(1-c^D+c^S)kr_c\pi}}{N_0^{D,L} N_0^{S,R}} \right], \qquad (14)$$

with $c^{D,S}$ denoting the 5-d mass parameters for $\Psi^{D,S}$. Thus, in the quark sector, there are, in general, 9 different values for c's: 3 for the doublets and 6 for the singlets. One can see that the exponential form of the effective Yukawa coupling λ_4 can accommodate a large hierarchy of values without the need for introducing unnaturally small 5-d parameters.

Examples of Mass Parameters

q	c^D	c^S	m_q (GeV)
		$-.7$	4.8×10^{-3}
d	$.5$		
		$-.61$	0.11
s	$.5$		
		$-.52$	4.1
b	$.4$		

Due to the warped scale Fermion masses far below the weak scale can be naturally obtained w/o the need for introducing any tiny 5d-yukawa couplings

Flavor structure in a warped framework

(Agashe,Perez,Soni,hep-ph/0406101(PRL);0408134 (PRD))

- RS with a WARPED EXTRA DIMENSION (WEXD) provides an elegant solution to the HP
- In this framework, due to warped higher-dimensional spacetime, the mass scales (i.e. flavors) in an effective 4D description depend on location in ED. Thus, e.g. the light fermions are localized near the Plank brane where the effective cut-off is much higher than TeV so that FCNC's from HDO are greatly suppressed.. The top quark,on the other hand is localized on the TeV brane so that it gets a large 4D top Yukawa coupling.

Electroweak Precision Measurements

- These require m_{KK} > ~ 3 TeV (Agashe, Delgado, May & Sundrum, 0308036)
- But need impose custodial symmetry thru extending to $SU(2)_L X SU(2)_R X U(1)$

Key features of WEXD

- Amielorating the Flavor Problem. This provides an understanding of hierarchy of fermion masses w/o hierarchies in fundamental 5D params. Thus “solving” the SM flavor problem.

Flavor violations Most flavor-violating effects arise due to the violation of RS-GIM mechanism by the large top mass.

This originates from the fact that $(t,b)_L$ is localized on the TeV brane.

*P*ossible B-Factory Signals from WEXD with anarchic assumption

At least O(1) uncertainties

ALSO IMPLIES SIZABLE D° MIX & CP

DIFFICULTIES: nedm, ϵ_K

	Δm_{B_s}	$S_{B_s \to \psi\phi}$	$S_{B_d \to \phi K_s}$	$Br[b \to s l^+ l^-]$	$S_{B_{d,s} \to K^*, \phi\gamma}$	$S_{B_{d,s} \to \rho, K^*\gamma}$
RS1	$\Delta m_{B_s}^{SM}[1+O(1)]$	$O(1)$	$\sin 2\beta \pm O(.2)$	$Br^{SM}[1+O(1)]$	$O(1)$	$O(1)$
SM	$\Delta m_{B_s}^{SM}$	λ_c^2	$\sin 2\beta$	Br^{SM}	$\frac{m_s}{m_b}\left(\sin 2\beta, \lambda_c^2\right)$	$\frac{m_d}{m_b}\left(\lambda_c^2, \sin 2\beta\right)$

MODELS ARE NOT YET Developed to be precise

Warped models of hierarchy & flavor naturally lead to NMFV *

- **Agashe,PPP,hep-ph/050911; Fox ,LLPS 0704.482;Agashe,PS,hep-ph/0408134**
- NMFV : NP due to EWSB scale dominantly couples to the 3rd gen. in part. top quark
- Such NP is quasi-aligned with the 1st gens.
- And therefore despite the relative low scale of around a few TeV bounds from FCNC from them are largely evaded.
- {* see, however, Csaki et al 0804.006; 0804.1954}

Difficulties of anarchic assumption

- Anarchy: Assumption that all entries in the 5D Yukawa matrices are complex and O(1).

Induced LR currents cause conflict with ε_K unless $m_{KK} > \sim 10$ TeV

Model has a CP-problem in that tends to give about nedm too large by ~10-20 compared to Expt.

Recent warped models of hierarchy &/or flavor bypass difficulties of anarchic simplicity

- Fitzpatrick, Perez and Randall, arXiV. 0710.1869
- Cacciapaglia, Csaki, Galloway, Marandella Terning,Weiler, 0709.1714
- Davoudiasl, Perez and Soni, 0802.0203

DISTINCTIVE HALLMARKS

of (RS) NMFV :

$t \to cZ$ . . . . w or w/o CP

$D^0 - \bar{D}^0$ . . ''

t -> c Z

Effective Lagrangian from WED

$$\mathcal{L}^t_{\rm FC} \ni \left(g_1 \bar{t}_R \gamma_\mu c_R + g_2 \bar{t}_L \gamma_\mu c_L \right) Z^\mu g_Z$$

with

$$g_{1,2} \sim \left[5 \cdot 10^{-3} \frac{(U_R)_{23}}{0.1}, 4 \cdot 10^{-4} \frac{(U_L)_{23}}{0.04} \right] \left(\frac{3\ \text{TeV}}{m_{KK}} \right)^2 ;$$

expect O(1)

AGASHE et al

EWPT JHEP '03

$\Rightarrow m_{KK} \sim 3\,\text{TeV}$

Experimental signals @ the LHC

$$\mathrm{BR}\,(t \to cZ) \sim 10^{-5} \left(\frac{3 \ \mathrm{TeV}}{m_{KK}}\right)^4 \left(\frac{(U_R)_{23}}{0.1}\right)^2$$

~ 1

At the LHC expect 10^8 top pairs so should be accessible.
Specifically with 100 fb^{-1} ,upper limit on BR(t->cZ)~10^{-5} is feasible (ATLAS)
With enough statistics angular analysis would also be very informative.
WED predicts predominantly RH couplings.

SLHC

t -> c γ,glu

The dipole operators give

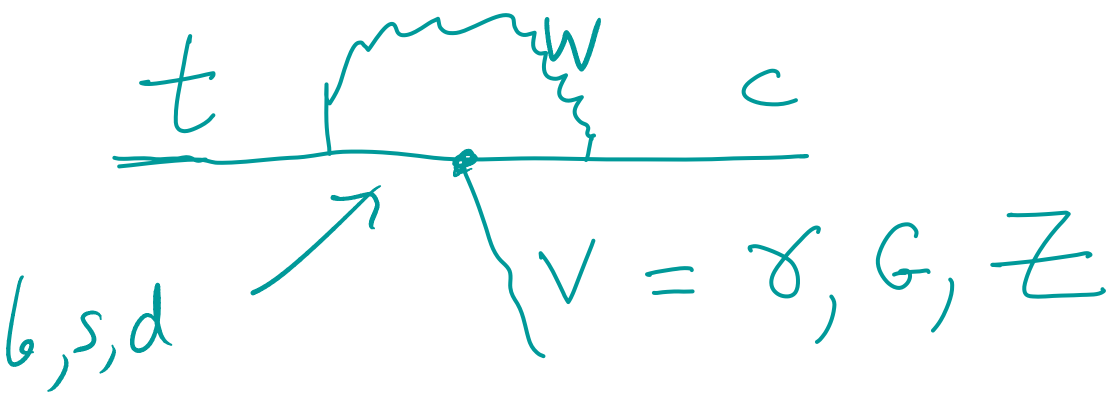
$$\mathrm{BR}\,(t \longrightarrow c\gamma, G) \;\sim\; 10^{-10,-9} \times \left(\frac{3\ \mathrm{TeV}}{m_{KK}}\right)^2 \left(\frac{(U_R)_{23}}{0.1}\right) \left(\frac{\lambda_{5D}}{4}\right)^4$$

At the LHC expected sensitivity for these is BR(t->c γ,G) ~ 10^{-5} , $^{-4}$ so not promising

Comparison with the SM

- In SM & in 2HDM BR (t -> c V) with V= γ , G, Z computed long ago (Eilam, Hewett, A.S, PRD'91)

In the SM 1-loop graph is extremely GIM suppressed as $\{(m_b , m_s , m_d)^2 / m_t^2) \to 0 \}$



COMPARISONS

	WED(1)	SM(2)	2HDM(2)	SUSY(3)
$t \to cZ$	$\lesssim 10^{-5}$	$\sim 10^{-13}$	$\lesssim 10^{-11}$	$\lesssim 10^{-6}$
$t \to c\gamma$	$\lesssim 10^{-10}$	$\sim 10^{-12}$	$\lesssim 10^{-11}$	$\leq 10^{-6}$
$t \to cg$	$\lesssim 10^{-9}$	$\sim 10^{-10}$	$\lesssim 10^{-10}$	$\leq 10^{-4}$

SIGNIFICANT DIFFERENCES

1) APS hep-ph 0606293. 2) EILAM, Hewett + AS '91
3) LIU, LI, YANG, JIN: "UNCONSTRAINED MSSM" 040155

MODEL Independent Analysis

Constraints on top FCNC operators

	C^u_{LL}	C^h_{LL}	C^w_{RL}	C^b_{RL}	C^w_{LR}	C^b_{LR}	C^u_{RR}
direct bound	9.0	9.0	6.3	6.3	6.3	6.3	9.0
LHC sensitivity	0.20	0.20	0.15	0.15	0.15	0.15	0.20
$B \to X_s\gamma,\ X_s\ell^+\ell^-$	$[-0.07, 0.036]$	$[-0.017, -0.01]$ $[-0.005, 0.003]$	$[-0.09, 0.18]$	$[-0.12, 0.24]$	$[-14, 7]$	$[-10, 19]$	—
$\Delta F = 2$	0.07	0.014	0.14	—	—	—	—
semileptonic	—	—	—	—	$[0.3, 1.7]$	—	—
best bound	0.07	0.014	0.15	0.24	1.7	6.3	9.0
Λ for $C_i = 1$ (min)	3.9 TeV	8.3 TeV	2.6 TeV	2.0 TeV	0.8 TeV	0.4 TeV	0.3 TeV
$\mathcal{B}(t \to cZ)$ (max)	7.1×10^{-6}	3.5×10^{-7}	3.4×10^{-5}	8.4×10^{-6}	4.5×10^{-3}	5.6×10^{-3}	0.14
$\mathcal{B}(t \to c\gamma)$ (max)	—	—	1.8×10^{-5}	4.8×10^{-5}	2.3×10^{-3}	3.2×10^{-2}	—
LHC Window	Closed*	Closed*	Ajar	Ajar	Open	Open	Open

[Fox, ZL, Papucci, Perez, Schwartz, arXiv:0704.1482]

- B factory data constrain some of the operators beyond the LHC reach
- If top FCNC seen, LHC & B factories together can probe the NP responsible for it

Implications of tc(u)NC for the LC

- $e^+ e^- \to t\,c$: **A unique, clean signal may be possible**.

The importance of this reaction for searching fcnc was 1st stressed in Atwood, Reina & A.S, PRD'96.

Extensively studied since then, See e.g.
Bar-Shalom & Wudka, PRD'99 (eff. Lag);
J.A.Aguilar-Saavedra,PLB'01 (Exptal aspects TESLA vs LHC);
Han & Hewett, PRD'99 (eff. Lag)
Cao,Xiong & Yang, NPB'03 (SUSY)
Yue,Wang,Di & Yang,PLB'05 (littlest Higgs);
Arhrib & Hou, JHEP'06 (4th family)…….

$e^+ e^- \to t\, c$ @ the LC

Agashe, Perez, AS '04

$$R_{tc} = \frac{\zeta_{tc}(a^2_{Ztc} + b^2_{Ztc})(a^2_{Zee} + b^2_{Zee})}{\left[(1 - m^2_Z/s)4\pi\alpha_{em}\right]^2}$$

$$R_{tc} = \frac{\sigma(e^+e^- \to [t\bar{c} + c\bar{t}])}{\sigma(e^+e^- \to \gamma \to \mu^+\mu^-)} \qquad \zeta_{tc} = \frac{9}{2} y_c^2 y_t \left[1 + \frac{y_c}{3y_t}\right]$$

R_{tc} is around $2X10^{-5}$ for Ecm~200GeV and increases to ~ $2X10^{-4}$ at higher energies

Forward-Backward Asymmetry in $e^+ e^-$ -> t c, a key prediction of WEXD

For unpolarized beams:

$$A_{FB}(e^+e^- \to t\bar{c}) = \frac{2\,\zeta_{FB}\; a_{Ztc} b_{Ztc} a_{Zee} b_{Zee}}{(a^2_{Ztc} + b^2_{Ztc})(a^2_{Zee} + b^2_{Zee})}$$

$$\zeta_{FB} = \frac{1+(y_c/y_t)}{1+[y_c/(3y_t)]}$$

A_{FB} is ~7% @ low energies and increases with energy to ~11%; higher with pol. beams. A distinctive feature of WED is that it predicts A_{FB} positive due to dominance of RH coupling.

$e^+ e^-$ -> t c: Some notable features

- fcnc searches with b s (or in general q q' , light flavors)…At ILC these are extremely difficult to detect due to the overwhelming background from b b (q q) X (mis) tagging efficiency….
- CONTRAST this with tc….Here fcnc reaction can be studied simply extremely efficiently by staying at cm energies of about 200-335GeV. Then t t is NOT possible.

- **Thus physics of crucial importance is possible with a LOW ENERGY OPTION for the LC**

- At such energies, due to its huge mass, E_t is significantly more than Ecm/2 ….
- The opposite side is an effectively massless "charm" jet carrying energy appreciably less than Ecm/2
- AND IT MUST NOT CONTAIN A b-jet. So lots of handles.
- Recall also top decays are very efficient analyzers of its polarization.. which can be a very helpful diagnostic of the underlying dynamix.

Prospects for CP violation

- In general, in RS1 scenarios, the mixing coeffs. e.g. $(U_R)_{23}$ are complex ; therefore should expect new CP-odd phase(s)

- Top decay to b W and charm jet so FS has several momenta (inc. W Pol.) allowing construction of T_N odd observables which can be used for extracting info on new CP-odd phase(s) associated with WEXD

Possibilty of top-quark edm with WEXD

Seems DIFFICULT @ LHC

- In RS direct KK-exchanges can endow CP-odd phase(s) to flavor-daigonal processes.
- This can lead to top-quark edm: @ 1-loop

$$d_t \sim 10^{-19} \left(\frac{3 \ \text{TeV}}{m_{KK}} \right)^2 \left(\frac{\lambda_{5D}}{4} \right)^2 \text{e-cm}$$

At the LC with the parameters mentioned, using $e^+ e^- \to t\,(b\,W^+)\,\bar{t}(b\,W^-)$ edm form-factors >~ 10^{-20} e-cm seem accessible.
{See Atwood, Bar-Shalom, Eilam, +AS, PR'01}

‘CP-Problem’ in WEXD scenarios

(ii) With regard to the CP-odd phases a concern in the RS1 type scenario is that in fact one naturally expects neutron electric dipole moment (NEDM) of $O\,(10^{-25}$e-cm) which exceeds existing experimental bounds by about $O(10)$; therefore there is a CP “problem” [11]. However, there can be significant differences in the size of the CP phases since the ones that enter the NEDM are from different sectors D_R, U_R, U_L, D_L than the ones which are relevant to this paper (which mostly arise from U_R, U_L).

In WEXD (as in many other BSM scenarios), nedm is expected to be close to current exptal bounds (~10^{-26} e-cm) & >> SM (<10^{-30} e-cm)

RS models are supposed to be dual to models of strong dynamics

- Can we find an example

Recall

- ADS/QCD <-> QCD -> LEET (ChPT)
- Is their a ChPT analogue of RS
- A nice example of such a LEET is T2HDM
- So the correspondence is

RS <-> perhaps ETC/TC/hypercolor…<->T2HDM

(STRONG DYNAMICS)

T2HDM

- A LEET that shares many features of RS(NMFV)

Two Higgs Doublet Models with Natural Flavor Conservation

The charged Higgs boson interactions with the quark sector are governed by the Lagrangian

$$\mathcal{L} = \frac{g}{2\sqrt{2}M_W} H^{\pm} \left[V_{ij} m_{u_i} A_u \bar{u}_i (1-\gamma_5) d_j + V_{ij} m_{d_j} A_d \bar{u}_i (1+\gamma_5) d_j \right] + h.c.\,,$$

where g is the usual SU(2) coupling constant and V_{ij} represents the appropriate CKM element. In model I, $A_u = \cot\beta$ and $A_d = -\cot\beta$, while in model II, $A_u = \cot\beta$ and $A_d = \tan\beta$, where $\tan\beta \equiv v_2/v_1$ is the ratio of vev

Part of SUSY

T2HDM: 2HiggsDM for the top quark

[see Das,Kao('96);Kirers,Wu,AS('99)…]

- **2nd doublet couples only to top (& 1st doublet**

  to all else), so that with V_2/V_1 >>1, natural way to get a very heavy top

T2HDM Possibly disproves SUSY?

$$\mathcal{L}_Y = -\bar{L}_L \phi_1 E l_R - \bar{Q}_L \phi_1 F d_R - \bar{Q}_L \tilde{\phi}_1 G \mathbf{1}^{(1)} u_R - \bar{Q}_L \tilde{\phi}_2 G \mathbf{1}^{(2)} u_R + \mathrm{H.c.},$$

Here ϕ_1 are the two Higgs doublets; E, F and G are 3 X 3 Yukawa matrices giving masses respectively to the charged letptons, the down and up type quarks; $\mathbf{I}^{(1)} \equiv diag(1,1,0)$ and $\mathbf{I}^{(2)} \equiv diag(0,0,1)$ are the two orthogonal projectors onto the 1st two and third family respectively. Q_L and L_L are the usual left-handed quark and lepton doublets.

(b) T2HDM should be viewed as LEET that parametrizes through the yukawa interactions some high energy dynamics which generates the top quark mass as well as the weak scale...

(c) In addition to largish $\tan\beta$ the model has restrictive FCNC (since it belongs to type III) amongst only the up-type

C Kiers, Wu & AS:
D^0-mixing
$\sin 2\beta$ deviations
B_s CP

H^{+-} phenomenology in T2HDM

H^{+-} interactions with U_R and D_L

$$\frac{g_2 m_c \tan\beta}{\sqrt{2} m_W} \begin{pmatrix} \xi'^{*} V_{td} & \xi'^{*} V_{ts} & \xi'^{*} V_{tb} \\ \xi^{*} V_{td} - V_{cd} & \xi^{*} V_{ts} - V_{cs} & \xi^{*} V_{tb} - V_{cb} \\ V_{td}\cot^2\beta/\epsilon_{ct} + \epsilon_{ct}\xi V_{cd} & V_{ts}\cot^2\beta/\epsilon_{ct} + \epsilon_{ct}\xi V_{cs} & V_{tb}\cot^2\beta/\epsilon_{ct} \end{pmatrix}$$

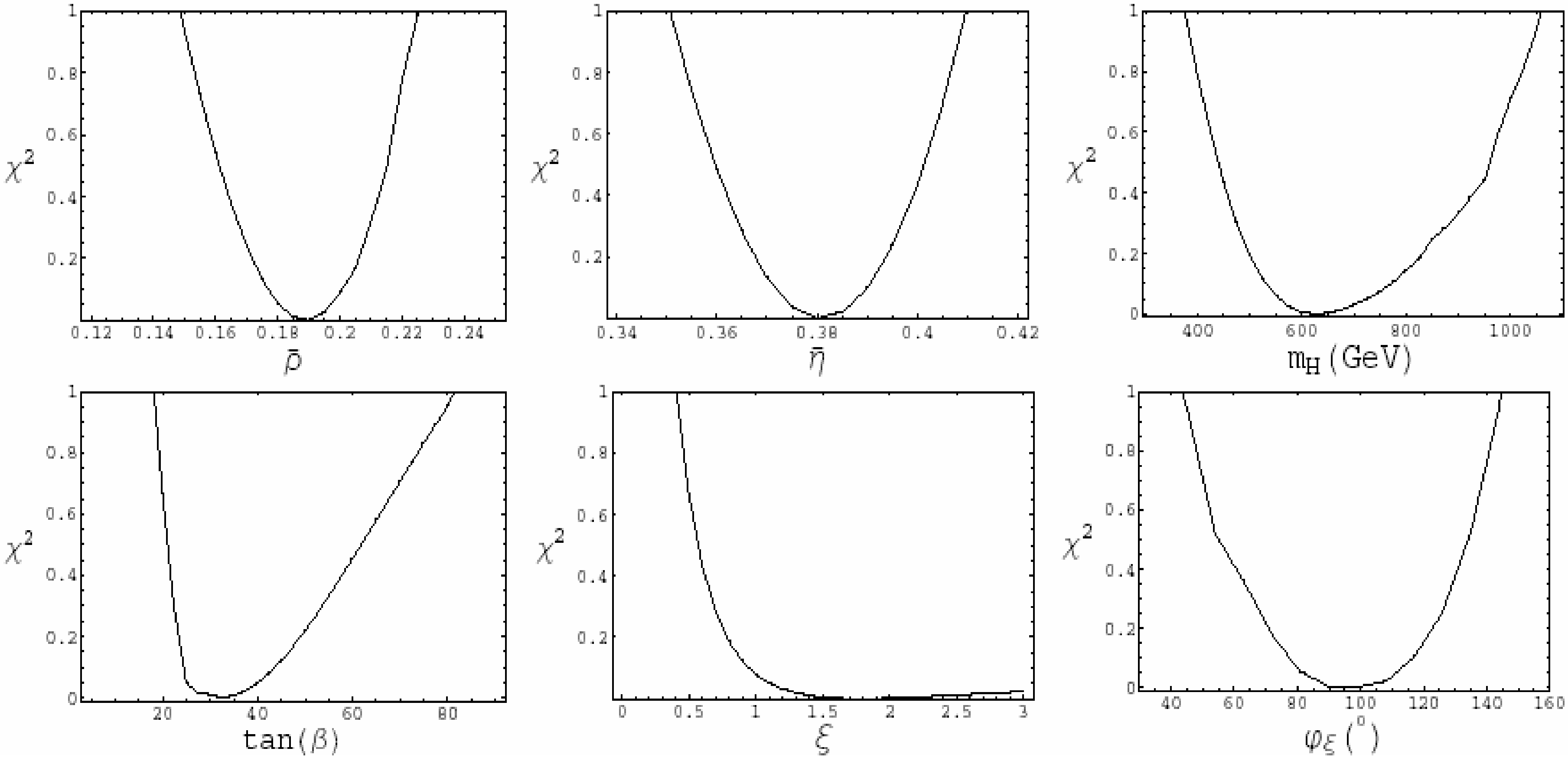
EXTENSIVE ANALYSIS: LUNGHI + A.S '07

IMP. PARAMETERS: $m_{H^\pm}$, $\tan\beta$, $\xi = |\xi| e^{i\varphi_\xi}$, $\bar{\rho}$, $\bar{\eta}$

CLEAN INPUT PROCESSES

$|V_{ub}/V_{cb}|$, $\Delta M_{B_s}/\Delta M_{B_d}$, $a_{\psi K}$, ε_K, $B \to X_s\gamma$, $B \to \tau\nu$

LUNGHI+AS '07



AT16: $m_H = 600^{-200}_{+400}$ GeV; $\tan\beta = 30^{-10}_{+50}$; $\phi_\xi = 100^{-40}_{+40}$

New Phase

Next to Minimal FV (NMFV)

Agashe,PPP,hep-ph/050911; Fox ,LLPS 0704.482;
Agashe,PS,hep-ph/0408134

- Large class of RS based models of flavor naturally tend to flow to NMFV
- In these NP couples dominantly only to the

  3rd generation quarks and is quasi-aligned with the up and down Yukawa matrices
- Interestingly T2HDM shares this important charcteristic (that top quark drives FCNC) with RS-based NMFV…
- Further strengthening the argument that T2HDM is LEET representative of RS model of flavor and is a nice concrete lab for exploring the phenomenology.

In fact corresponds to Fitzpatrick, Perez & Randall

RS-signals @LHC

KK-Particle Masses

$J_1(x_n) = 0$

$$m_n = x_n k e^{-k r_c \pi}, \qquad (18)$$

where for gauge fields $x_n = 2.45, 5.56, 8.70, \ldots$ and for the graviton $x_n^G = 3.83, 7.02, 10.17, \ldots$.

EWPT $\Rightarrow m_{KK} \gtrsim 3$ TeV

Agashe DMS '03

$m_G \sim 1.6\, m_{glu}$, $m_{KKF} \sim 1.5\, m_{glu}$

$Z', W' \sim m_{glu}$

Complementary study: Single top production at LHC

(Aquino, Burdman & Eboli, PRL98,131601,'07)

$$pp \to G_\mu^{a(1)} \to tq$$

S-channel production of the first KK excitation of the gluon with subsequent tree-level flavor changing decays to tc and tu

Process	σ − (11)	σ − (12)	σ − (13)
$pp \to tj$	148 fb	103 fb	103 fb
$pp \to Wjj$	243 fb	42.0 fb	21.0 fb
$pp \to Wbb$	11.1 fb	4.07 fb	3.19 fb
$pp \to tb$	1.53 fb	0.70 fb	0.61 fb
$pp \to t\bar{t}$	44.4 fb	15.1 fb	14.2 fb
Wg fusion	32.0 fb	5.23 fb	5.23 fb

APS $u_R^{tq} \sim 0.1$

TABLE II: Signal and background cross sections for a KK gluon of $M_{G(1)} = 1$ TeV, after the successive application of the cuts defined in (11), (12) and (13). Efficiencies and b tagging probabilities are already included. Here we used $U_R^{tq} = 1$.

Process	σ − (11)	σ − (12)	σ − (13)
$pp \to tj$	5.10 fb	2.18 fb	2.18 fb
$pp \to Wjj$	25.4 fb	3.79 fb	0.95 fb
$pp \to Wbb$	0.97 fb	0.45 fb	0.06 fb
$pp \to tb$	0.04 fb	0.02 fb	0.02 fb
$pp \to t\bar{t}$	1.60 fb	0.29 fb	0.24 fb
$W\,g$ fusion	1.20 fb	0.10 fb	0.10 fb

TABLE III: Signal and background cross sections for a KK gluon of $M_{G(1)} = 2$ TeV. Efficiencies and b tagging probabilities are already included. Here we used $U_R^{tq} = 1$

M_G [TeV]	$30fb^{-1}$	$100fb^{-1}$	$300fb^{-1}$
1	0.24	0.18	0.14
2	0.65	0.50	0.36

TABLE IV: Reach in U_R^{tq} for various integrated luminosities.

KKGluon

hep-ph/0612015

Kaustubh Agashe[1], Alexander Belyaev[2], Tadas Krupovnickas[3], Gilad Perez[4] and Joseph Virzi[5]

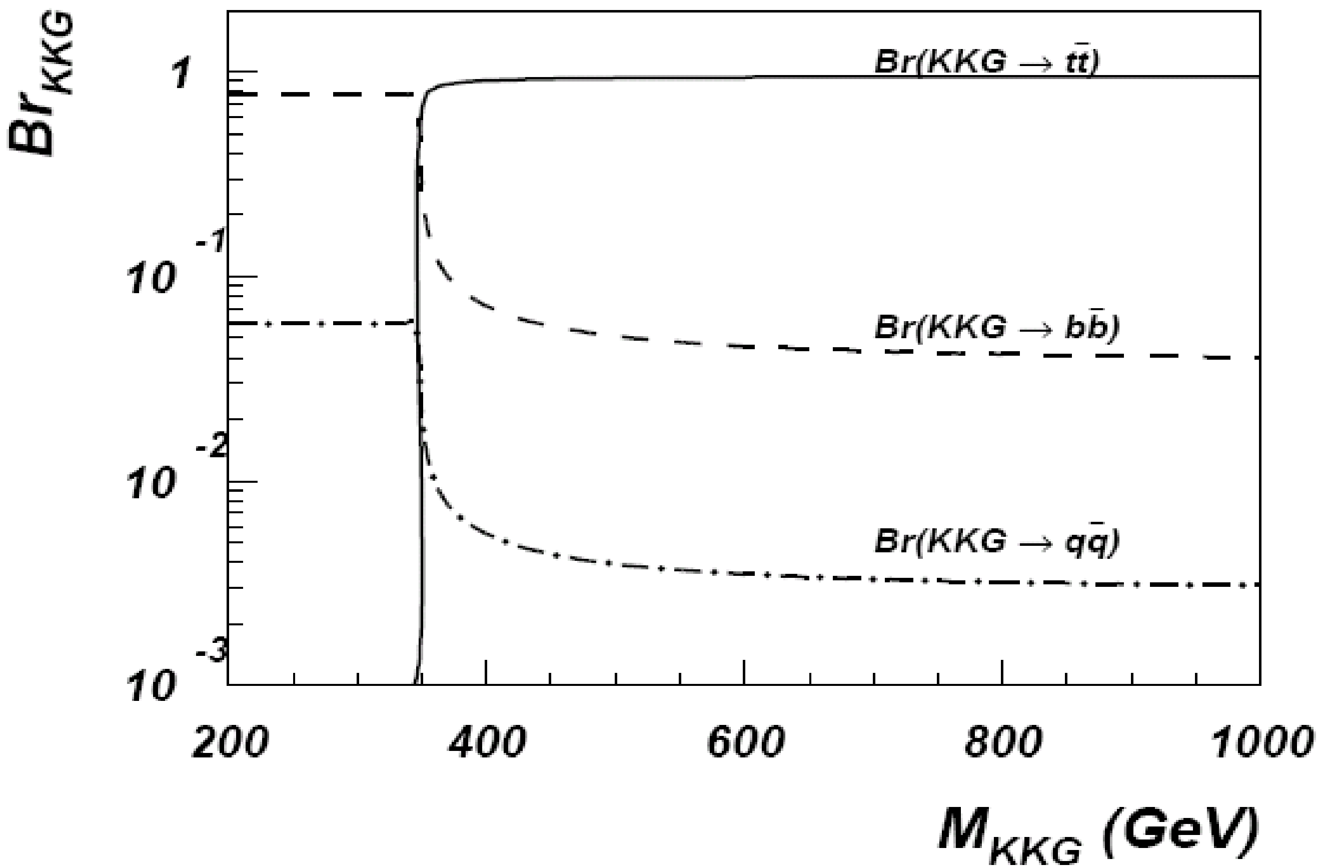


FIG. 2: The branching ratios of the KK gluon as a function of its mass.

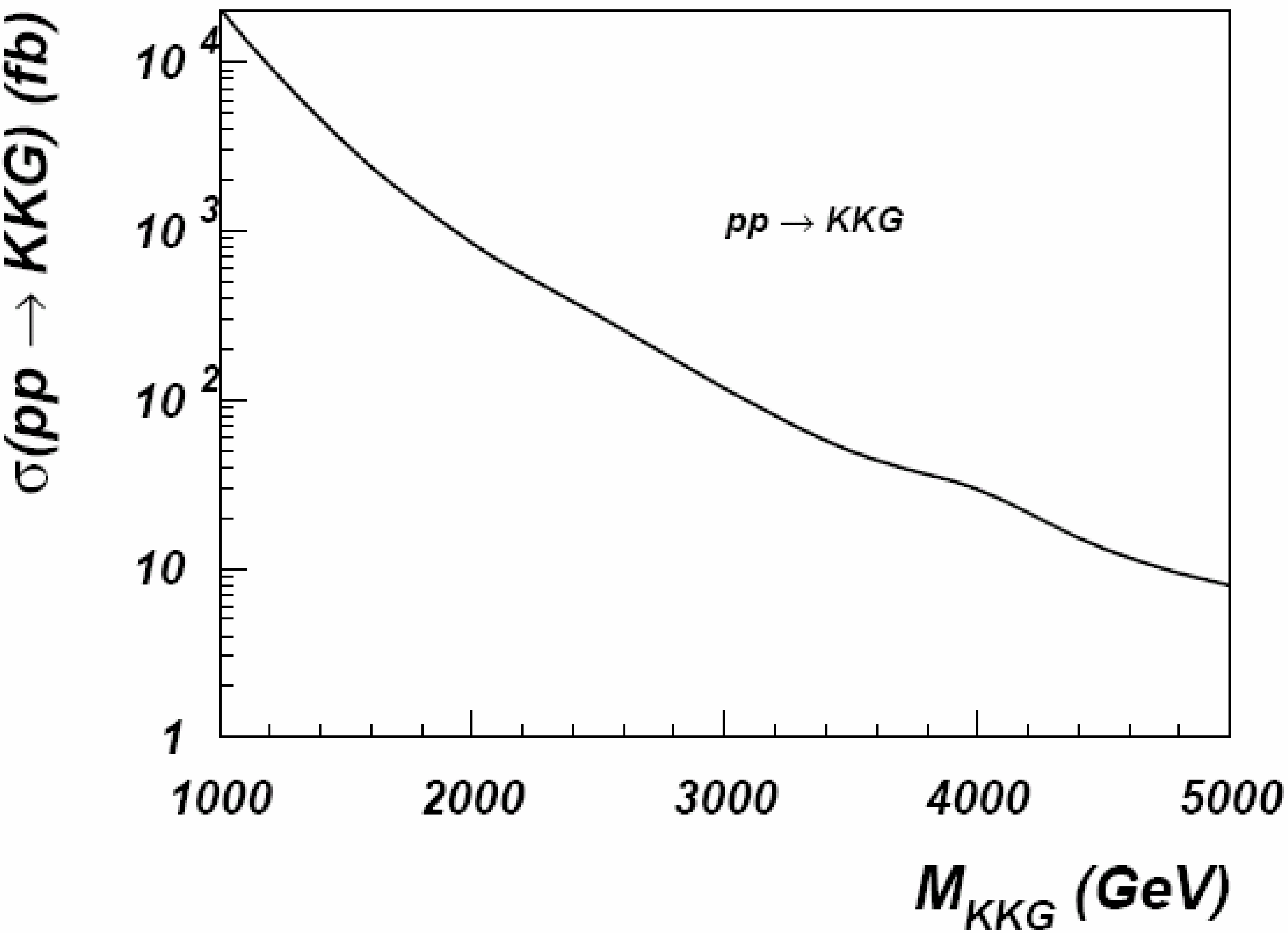
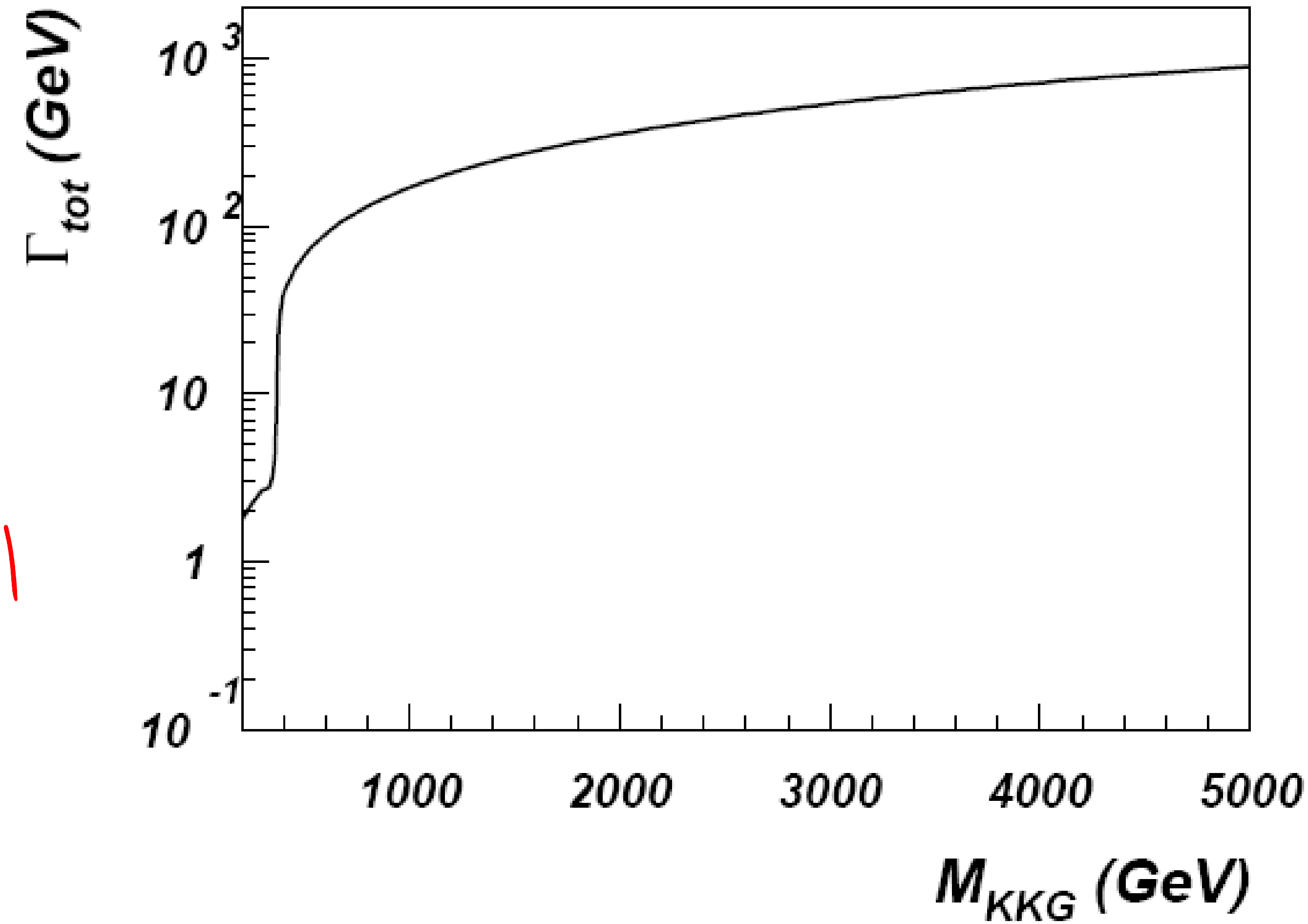


FIG. 1: The total cross section of KK gluon production at the LHC as a function of its mass (M_{KKG}).



$\frac{\Gamma}{m} \sim 0.1$ for $m \gtrsim 3$ TeV

FIG. 3: The total decay width of KK gluon as a function of its mass

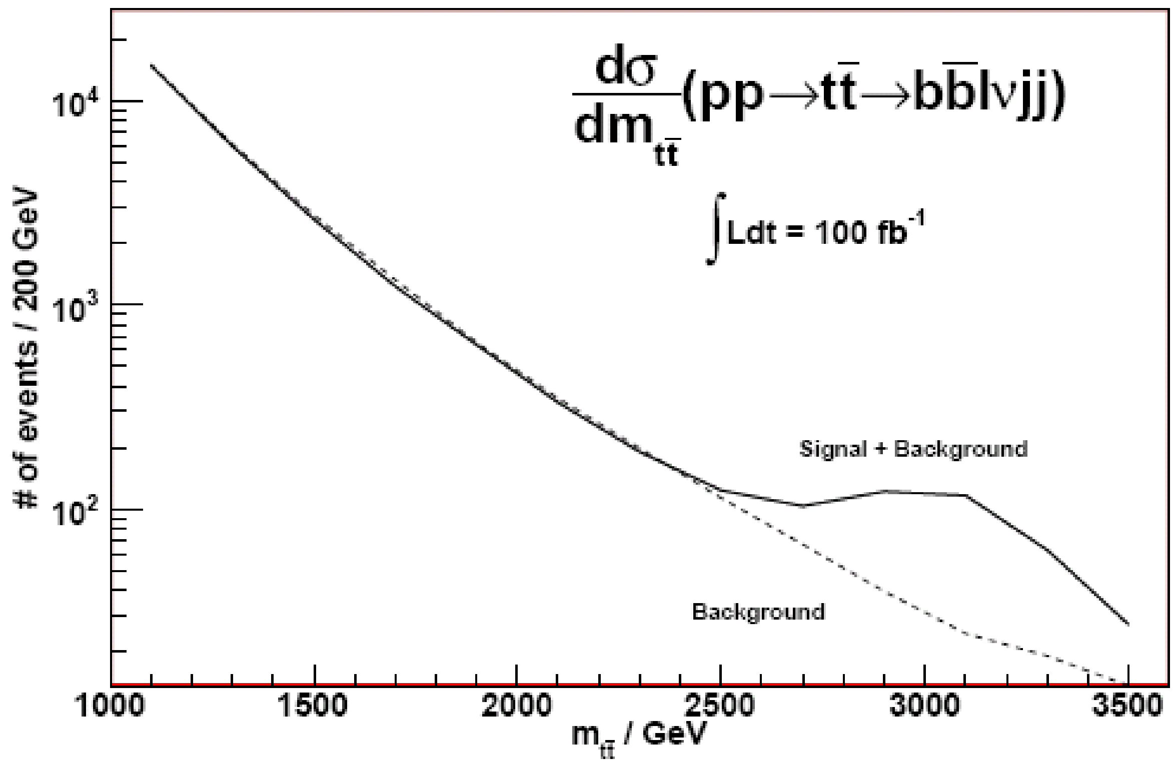


FIG. 4: Invariant $t\bar{t}$ mass distribution for $M_{KKG} = 3\,\mathrm{TeV}$ production at the LHC. The solid curve presents signal+background distribution, while the dashed curve presents the $t\bar{t}$ SM background, based on partonic level analysis.

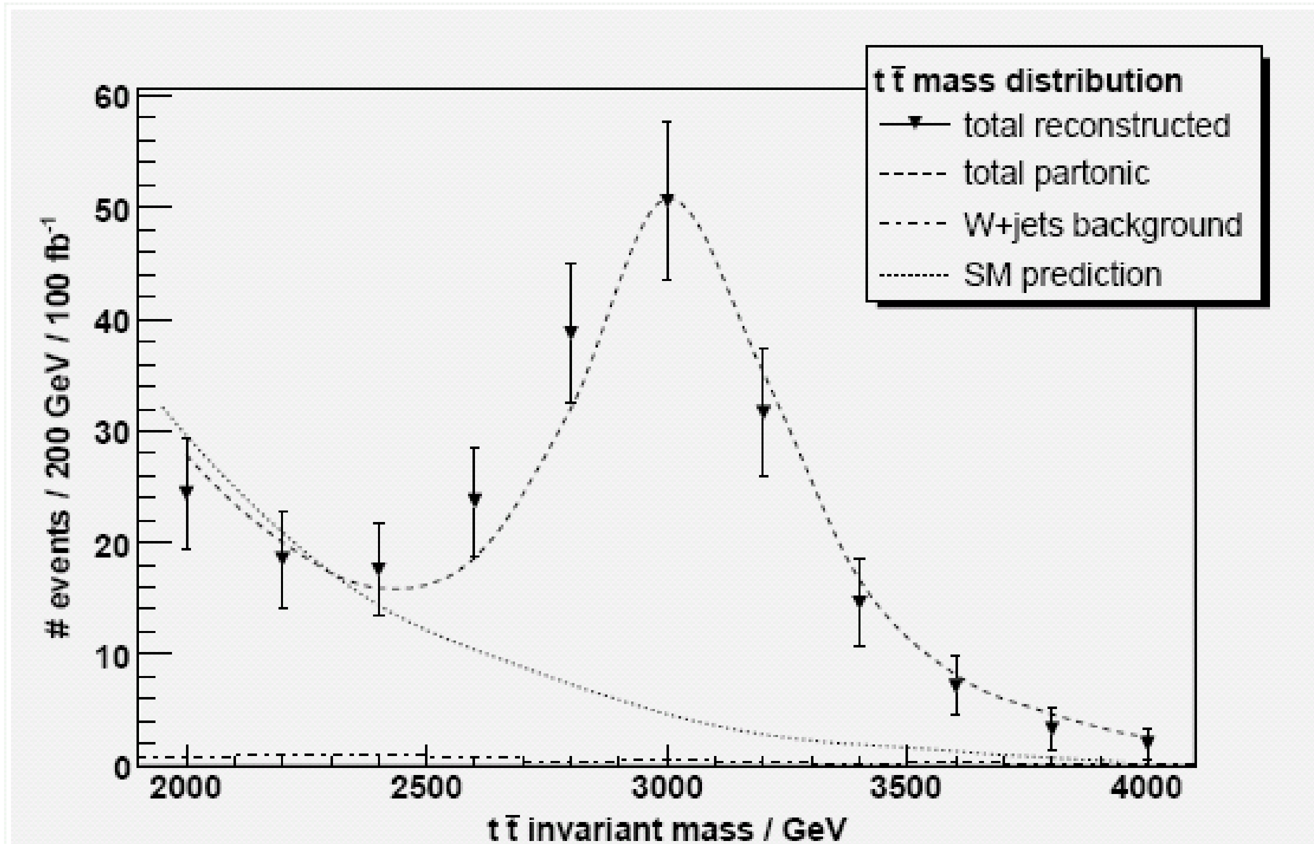


FIG. 5: Invariant $t\bar{t}$ mass distribution for 3 TeV KKG, focusing on the area near the peak. The error bars correspond to statistical uncertainties and represent our particle level analysis. The dotted line stands for the SM prediction. The dashed-dotted line shows the Wjj background. The dashed line shows the signal+background from Sherpa's partonic level analysis.

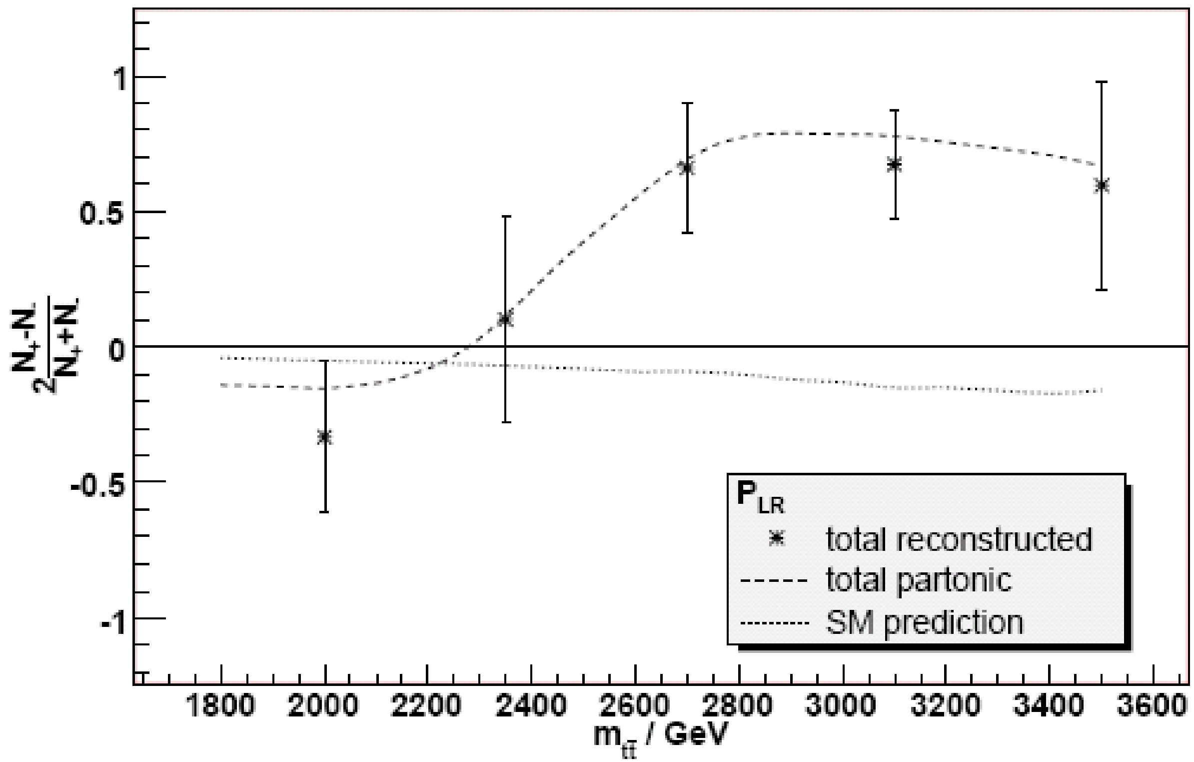


FIG. 6: $P_{LR}(m_{t\bar{t}})$ for $M_{KKG} = 3\,\text{TeV}$: The error bars correspond to statistical uncertainties and represent particle level analysis. The dotted line stands for the SM prediction. The dashed line shows the signal+background from Sherpa's partonic level analysis.

KK-Graviton: A Unique signal of RS

KK gravition -> Decays

GRAVITON: $\to t_R t_R (3), W_L W_L (2), Z_L Z_L (1), hh (1)$

SM fields	C_{00n}	Partial decay widths for n=1 graviton
gg(gluons)	$\frac{c}{2\pi kR\mu}$	negligible
$W_L W_L$	$2c/\mu$	$(cx_1^G)^2 m_1^G/480\pi$
$Z_L Z_L$	$2c/\mu$	$(cx_1^G)^2 m_1^G/960\pi$
$t_R \bar{t}_R$	c/μ	$N_c(cx_1^G)^2 m_1^G/320\pi$
h h	$2c/\mu$	$(cx_1^G)^2 m_1^G/960\pi$

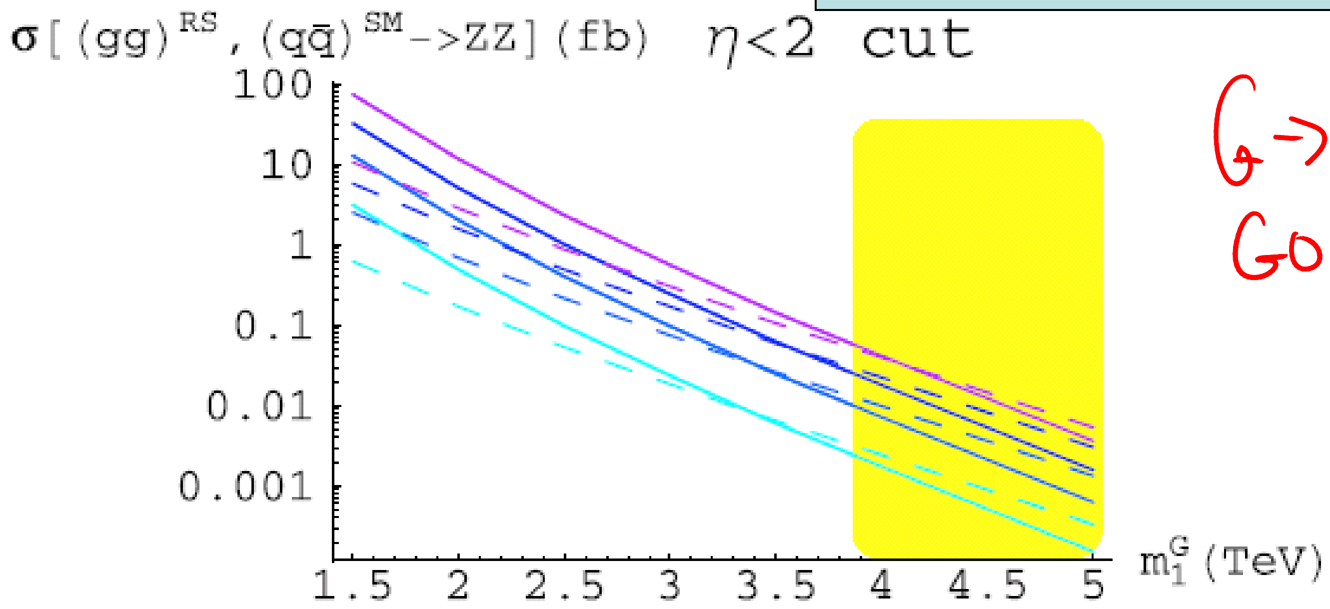
Antipin, Atwood & A.S., arXiV:0711.3175

$c = k/M_{PL}$

$\mu = k\, e^{-\pi k r}$

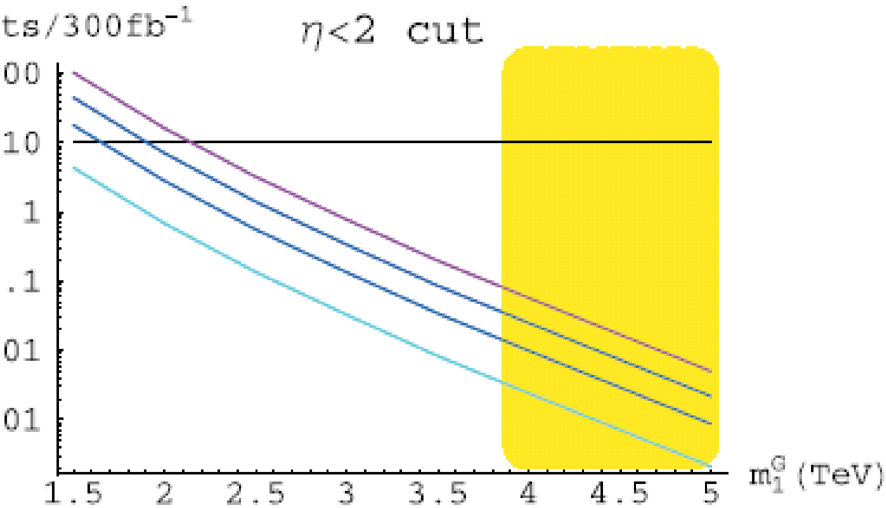
FIG. 1 (color online). The cross sections (integrated over one width) for $gg \to ZZ$ via KK gravitons (solid lines) and the corresponding SM background (dashed lines). We show the cross sections for $c \equiv k/\bar{M}_P = 0.5, 1, 1.5, 2$ (from bottom to top). See the text for an explanation of the upper limit on c. The shaded region shows where we expect the KK graviton mass to be in the simplest models according to relation in Eq. (3) and the limit on gauge KK mass from precision tests.

Agashe,Davoudiasl, Perez & A.S.arXiv:0701.186



G->Z_L Z_L
GOLD PLATED

G->ZZ: Agashe et al



(color online). The total number of expected events for rely leptonic decay mode for Z pairs from KK graviton using 300 fb^{-1} with $\eta < 2$. See also Fig. (1).

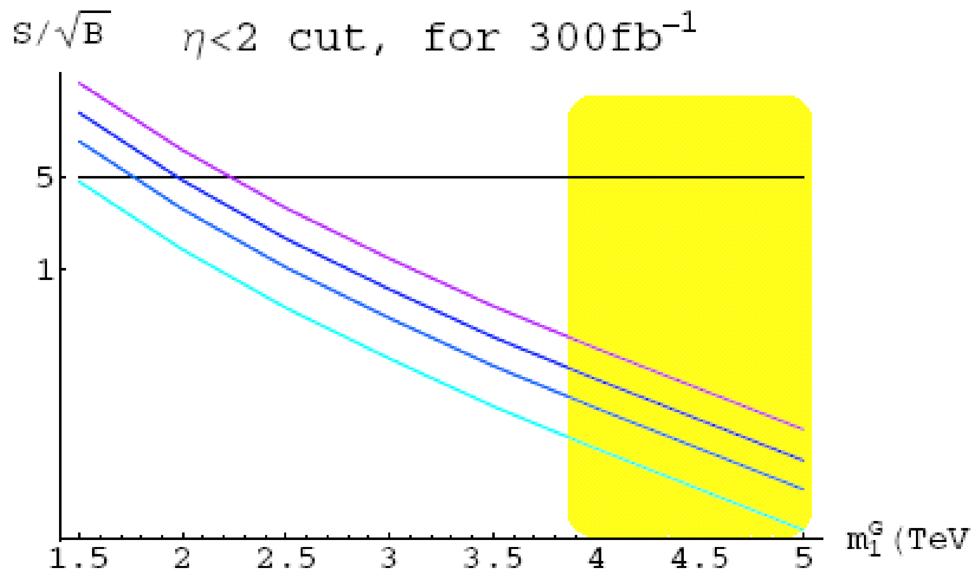


FIG. 5 (color online). Same as Fig. 4, but with $\eta < 2$.

Agashe et al

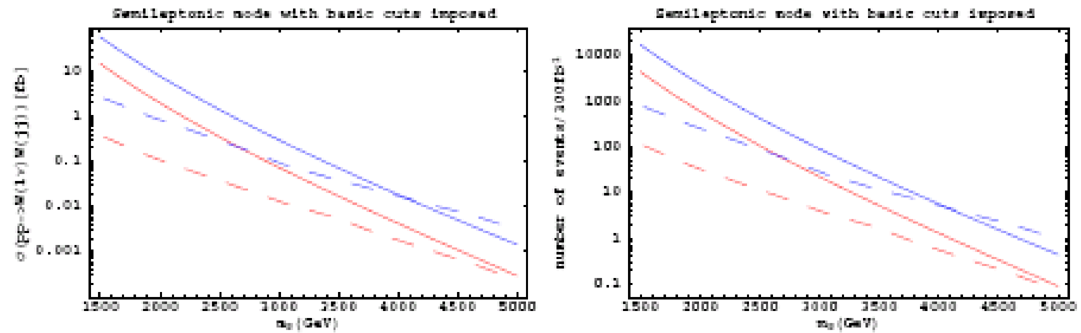
TABLE I. The mass of the first KK graviton for which the number of signal events is 10 at the LHC, for various choices of c. See the text for an explanation of the upper limit on c. The significance $S/\sqrt{B}$ of each result is also given. These numbers correspond to 300 fb^{-1} of integrated luminosity.

$c \equiv k/\bar{M}_P$	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

TABLE II. Same as Table I, except for the SLHC with 3 ab^{-1} of integrated luminosity.

$c \equiv k/\bar{M}_P$	0.5	1.0	1.5	2.0
m_1^G (TeV)	1.9	2.3	2.6	2.9
$S/\sqrt{B}$	6.1	4.3	4.3	4.3

SLHC NEEDED



Antipin, Atwood+A.S

FIG. 5: (Color online) (a) The total signal (solid) and SM background (dashed) cross-section (integrated in $m_G \pm \Gamma_G$ window) for $pp \to W(l\nu)W(jj)$ after $|\eta_W| < 1$ cuts were applied for c=1 (red) and c=2 (blue) values, (b) Corresponding number of events for 300 fb^{-1}.

$G \to WW$, $\to l\nu$, $\to q\bar{q}$

TABLE III: Semileptonic mode signal cross-sections [in fb] and S/B ratios along with W + 1 jet and WW SM backgrounds. Signal 1 and the corresponding W + 1 jet background results were obtained after cuts in Eqs.7,8 were imposed and $m_G \pm \Gamma_G/2$ integration region was chosen. Signal 2 and corresponding WW background results were obtained after $|\eta_W|$ <1 cut and integrated in $m_G \pm \Gamma_G$ window.

2 TeV	Cuts	# of events/300 fb^{-1}	S/B	S/$\sqrt{B}$
Signal 1 [c=1]	1.7	510	1.04	23
W + 1 jet background [c=1]	1.64	492		
Signal 2 [c=1]	2.0	600	13.3	90
WW background [c=1]	0.15	45		
Signal 2 [c=2]	7.8	2340	7.8	135
WW background [c=2]	1.0	300		
3.5 TeV	Cuts	# of events/300 fb^{-1}	S/B	S/$\sqrt{B}$
Signal 1 [c=1]	0.01	3	0.33	1
W + 1 jet background [c=1]	0.03	9		
Signal 2 [c=1]	0.02	6	2.9	4.1
WW background [c=1]	0.007	2.1		
Signal 2 [c=2]	0.07	21	1.4	5.4
WW background [c=2]	0.05	15		

"Semileptonic"

HIGHLY COLLIMATED Jets.

$$\frac{\sigma B_{W\to jj} B_{W\to l\nu}}{\sigma B_{Z\to ll} B_{Z\to ll}} \sim 150$$

MAY REACH 3.5 TeV with WW

KK-Z'(W')

KK W' & Z'

FINAL STATES IN DECAYS

Decay modes	W'	Z'
$W_L H$	0.47	-
$W_L W_L$	-	0.08
$W_L Z_L$	0.36	-
$Z_L H$	-	0.81
$t\bar{t}$	-	0.11
tb	0.17	-

COUPLING to light quarks (& leptons) disfavored.

"Semileptonic" Decays of KKZ → W W → ℓν, → jets.

⇒ HIGHLY COLLIMATED jets.

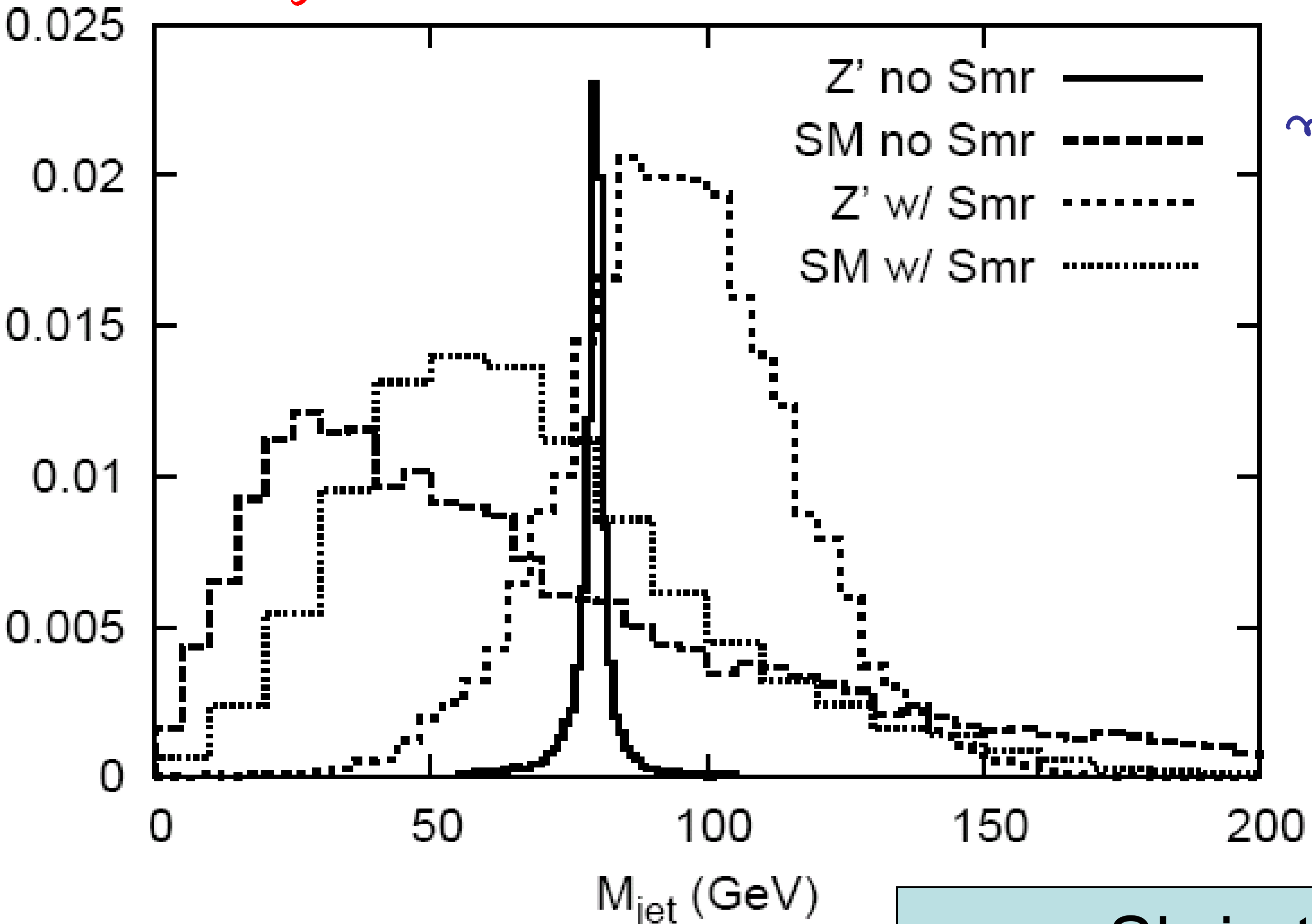
Table 3: $pp \to \ell^\pm \not{E}_T + 1$ jet cross-section (in fb) for $M_{Z'}$ =2 and 3 TeV, and background, with cuts applied successively. The number of events is shown for $\mathcal{L} = 100$ fb^{-1} for 2 TeV, and 1000 fb^{-1} for 3 TeV.

$M_{Z'} = 2$ TeV	p_T	$\eta_{\ell,j}$	M_{eff}	M_{TWW}	M_{jet}	# Evts	S/B	$S/\sqrt{B}$
Signal	4.5	2.40	2.37	1.6	1.25	125	0.39	6.9
W+1j	1.5×10^5	3.1×10^4	223.6	10.5	3.15	315		
WW	1.2×10^3	226	2.9	0.13	0.1	10		
$M_{Z'} = 3$ TeV								
Signal	0.37	0.24	0.24	0.12	-	120	0.17	4.6
W+1j	1.5×10^5	3.1×10^4	88.5	0.68	-	680		
WW	1.2×10^3	226	1.3	0.01	-	10		

Shrihari Gopalakrishina et al;arXiv:0709.0007

"JET-MASS": A Powerful Discriminator against backgrounds.

Jet-mass ≡ combined invariant mass of the vector sum of all hadrons making up the jet



Shri et al

Prospects for gold-plated modes(Z'->ll)

Table 1: Partial widths and decay branching ratios for $M_{Z'} = 2$ TeV.

	A_1		$\tilde{Z}_1$		$\tilde{Z}_{X1}$	
	Γ(GeV)	BR	Γ(GeV)	BR	Γ(GeV)	BR
$\bar{t}t$	55.8	0.54	18.3	0.16	55.6	0.41
$\bar{b}b$	0.9	8.7×10^{-3}	0.12	10^{-3}	28.5	0.21
$\bar{u}u$	0.28	2.7×10^{-3}	0.2	1.7×10^{-3}	0.05	4×10^{-4}
$\bar{d}d$	0.07	6.7×10^{-4}	0.25	2.2×10^{-3}	0.07	5.2×10^{-4}
$\ell^+\ell^-$	0.21	2×10^{-3}	0.06	5×10^{-4}	0.02	1.2×10^{-4}
$W_L^+W_L^-$	45.5	0.44	0.88	7.7×10^{-3}	50.2	0.37
$Z_L h$	-	-	94	0.82	2.7	0.02
Total	103.3		114.6		135.6	

Table 2: $pp \to \ell^+\ell^-\not{E}_T$ cross-section (in fb) for the signal with $M_{Z'} = 2$, 3 TeV and the WW and $\tau\tau$ backgrounds, with cuts applied successively (M_{eff} and M_T are in TeV). The number of events and statistical significance are shown for 100 fb^{-1} ($M_{Z'} = 2$ TeV) and 1000 fb^{-1} (3 TeV), respectively.

2 TeV	Basic cuts	$\|\eta_\ell\| < 2$	$M_{eff} > 1$ TeV	M_T >1.75 TeV	# Evts	S/B	$S/\sqrt{B}$
Signal	0.48	0.44	0.31	0.26	26	0.9	4.9
WW	82	52	0.4	0.26	26		
$\tau\tau$	7.7	5.6	0.045	0.026	2.6		
3 TeV	**Basic cuts**	**$\|\eta_\ell\| < 2$**	**$1.5 < M_{eff} < 2.75$**	**$2.5 < M_T < 5$**	**# Evts**	**S/B**	**$S/\sqrt{B}$**
Signal	0.05	0.05	0.03	0.025	25		
WW	82	52	0.08	0.04	40	0.6	3.8
$\tau\tau$	7.7	5.6	0.015	0.003	3		

$[\theta\, G_{\mu\nu} \tilde{G}^{\mu\nu}]$ hep-ph07050151

Strong CP, Up-Quark Mass, and the Randall-Sundrum Microscope

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The fermion mass hierarchy can be obtained with $O(1)$ parameters in the Randall-Sundrum (RS) model, via exponential bulk profiles. In particular, a tiny up quark mass $m_u \ll$ MeV does not require a chiral symmetry or fine-tuning in this setup. Therefore, the RS model can provide a natural geometric resolution of the strong CP problem, while addressing the hierarchy and flavor puzzles. In simple realizations, this hypothesis can be tested at future colliders, like the LHC, by measuring the spectrum of level-1 Kaluza-Klein (KK) quarks. In this sense, these KK states act as a "microscope" for probing light fermion masses.

Is m_u=0 ruled out(by the lattice)?

- C. Aubin et al (MILC) PRD'04
- m_u / m_d =0.43(0)(1)(8)

VERY Serious Study

(0) → stat; (1) → syst; (8) → em

SCEPTCISM LIMITED TO just $m_u/m_d \neq 0$

1. NO CHARM
2. "NNLO" Not NNLO
3. ROOTED STAGGERED

Quarks	c^D	c^S	m_q(SM) (GeV)	$m_q^{\rm KK}/m_g^{\rm KK}$
$\begin{pmatrix} u \\ d \end{pmatrix}$	0.5	$\begin{pmatrix} -1.4 \\ -0.7 \end{pmatrix}$	$\begin{pmatrix} 3.5 \times 10^{-14} \\ 4.8 \times 10^{-3} \end{pmatrix}$	1.0, $\begin{pmatrix} 1.5 \\ 1.1 \end{pmatrix}$
$\begin{pmatrix} c \\ s \end{pmatrix}$	0.5	$\begin{pmatrix} -0.53 \\ -0.61 \end{pmatrix}$	$\begin{pmatrix} 1.2 \\ 0.11 \end{pmatrix}$	1.0, $\begin{pmatrix} 1.0 \\ 1.0 \end{pmatrix}$
$\begin{pmatrix} t \\ b \end{pmatrix}$	0.46	$\begin{pmatrix} - \\ -0.5 \end{pmatrix}$	$\begin{pmatrix} 171.2 \\ 4.1 \end{pmatrix}$	1.0, $\begin{pmatrix} - \\ 1.0 \end{pmatrix}$

TABLE I: Sample values for a realistic set of SM bare quark masses. The doublet and singlet profile parameters are denoted by c^D and c^S, respectively. To get the top mass, a 5-d Yukawa coupling $\lambda_5^t = 4.8$ has been assumed; all other $\lambda_5 = 1$. The resulting zero-mode SM quark masses are given in GeV. The last column is the ratio of the level-1 (Doublet, Singlet) KK quark masses to that of the KK gluon (gauge boson). With m_u set to a small value that resolves the $SCPP$, the level-1 singlet u-quark KK state is nearly 50% heavier than any other of its counterparts. Mass splittings from KK-fermion Yukawa couplings have been ignored here.

COLLIDER SIGNATURE

$q^S_{KK} \to H + q^D$

$\hookrightarrow$ jet

Prospects for Direct Verifiction of a warped nature

Davoudiasl, Rizzo, AS,’07

CERN, Th. Colloquim 6/11/08

Associated Production of PAIR of KK Fermions

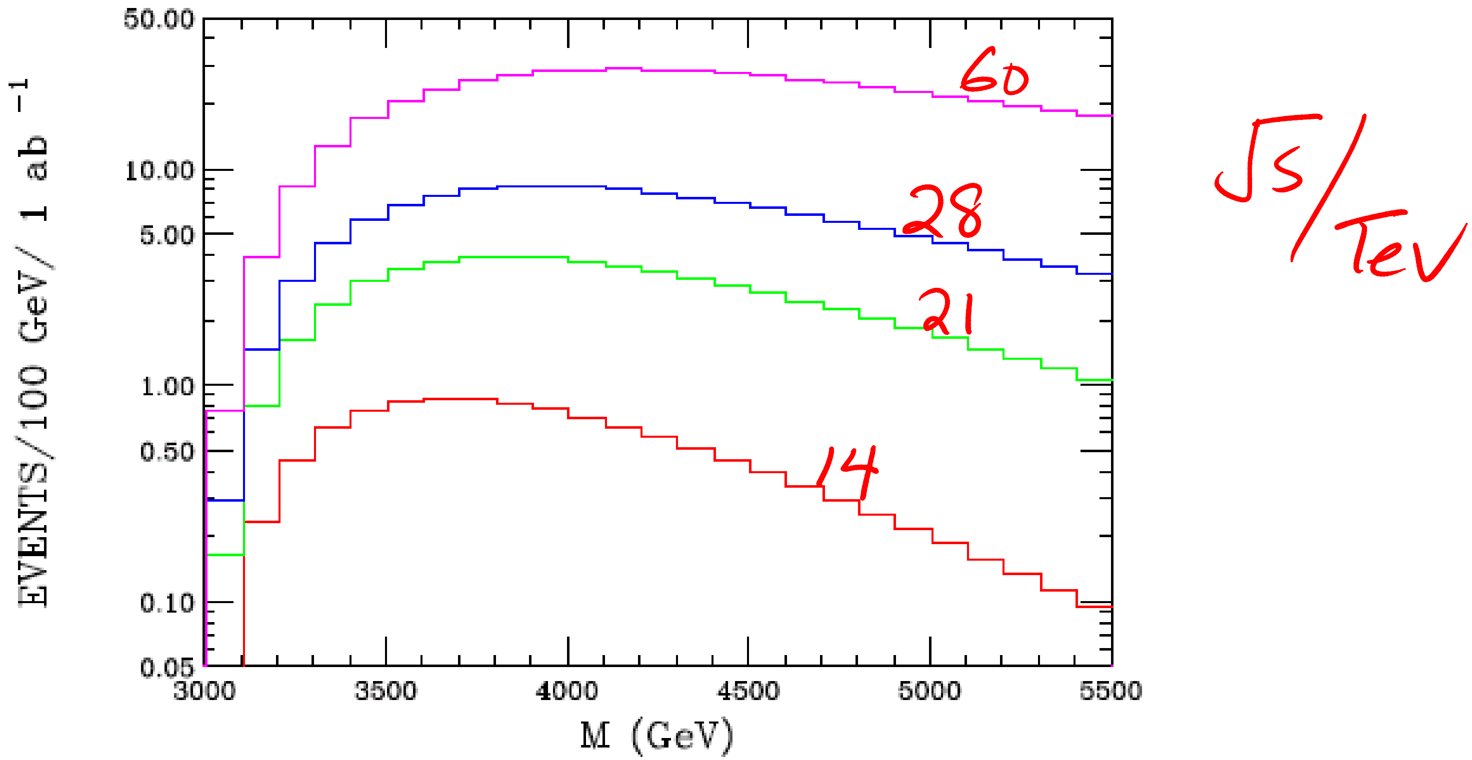
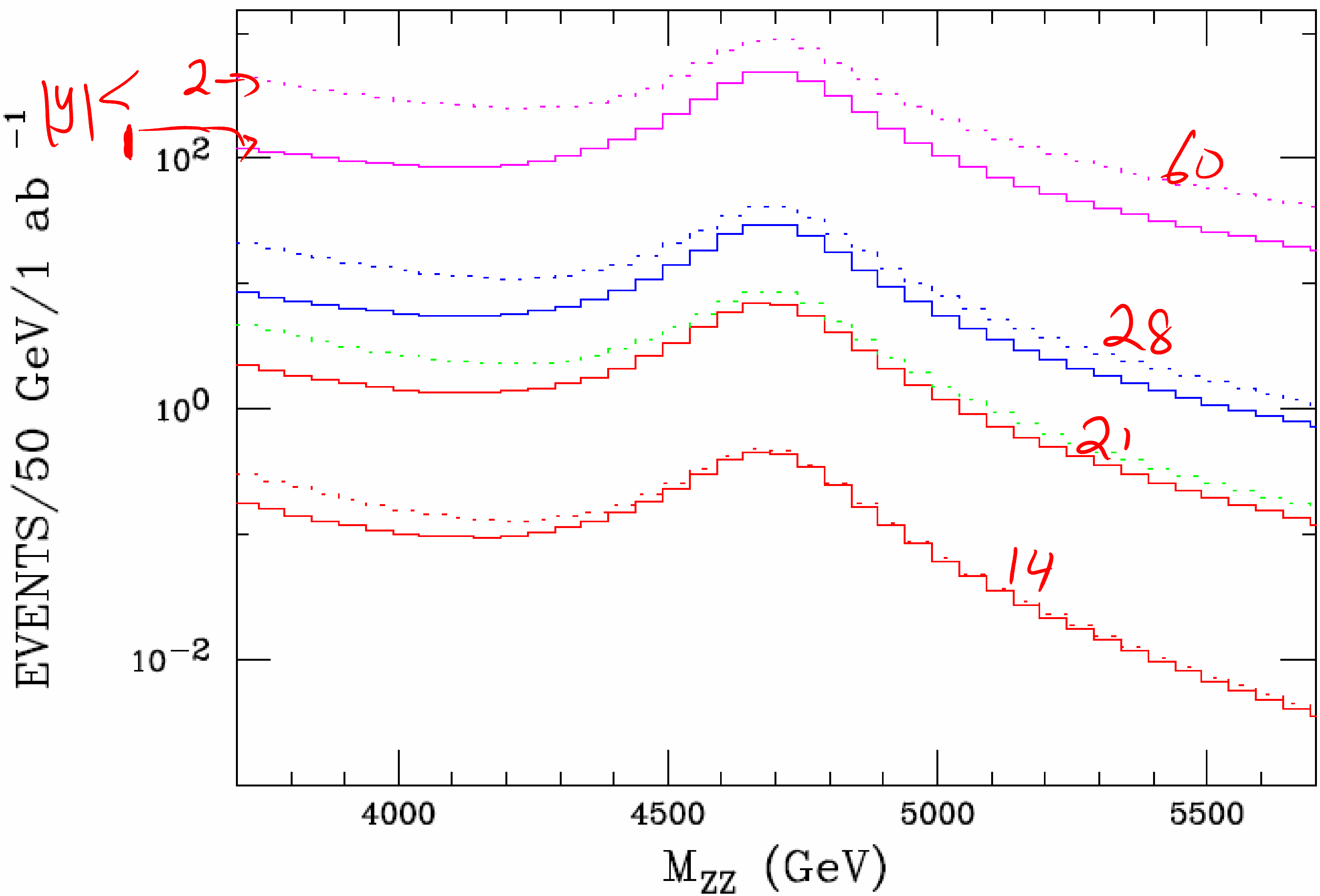


FIG. 2: Same as the last figure but now for different values of $\sqrt{s}$ and taking the first gluon KK and fermion KK masses to be degenerate at 3 TeV. From bottom to top the histograms correspond to $\sqrt{s} = 14$, 21, 28 and 60 TeV, respectively.

GOLD-Plated G → ZZ

Z BR Not inc.



"Direct verification" (i.e. KK-graviton and/or KK-fermion) at LHC will be very difficult unless we can learn to lower m_{KK} appreciably

LRS@LHC (davoudiasl,perez,AS,0802.0203)

- LRS=Little Randall-Sundrum – a WARPED THEORY Of FLAVOR
- While the RS construction has a compelling appeal, as it allows a simultaneous resolution of SM (EW-Planck) and (EW-Flavor) puzzles, it is premised on a very strong assumption:
- Warping extends over many orders of magnitude w/o any basic change in physics, from the weak scale all the way to the Planck scale. Surely this assumption, no matter how appealing needs to be put to an experimental test.
- Is it possible, e.g. that the basic warped idea is used only for understanding EW-Flavor (~10^3 TeV) hierarchy via fermion localization, leaving open avenues for UV completion to Planck?

Let's B Modest

OBLIQUE CORRECTIONS IN RS

$$S_{tree} \approx 2\pi\,(v/\kappa)^2 \left[1 - \frac{1}{kr_c\pi} + \xi(c)\right],$$

$$T_{tree} \approx \frac{\pi}{2\cos\theta_W^2}(v/\kappa)^2 \left[kr_c\pi - \frac{1}{kr_c\pi} + \xi(c)\right],$$

Agashe, D, M Sundrum

$$y \equiv \frac{kr_c\pi\big|_{RS}}{kr_c\pi\big|_{LRS}} \approx 6.$$

LRS Phenomenology and Golden Modes

Courtesy HD

- $g_{KK}|_{UV} \sim g_4/\sqrt{kr_c\pi}$, $\quad g_{KK}|_{IR} \sim g_4\sqrt{kr_c\pi}$.

(i) Broad KK states become narrower by y.

(ii) Width into light states $(e^+e^-, u\bar{u}, \ldots)$ enhanced by $y \to$ BR$\sim y^2$.

(iii) $\sigma(f_i\bar{f}_j \to KK \to f_k\bar{f}_l) \propto \Gamma(KK \to f_i\bar{f}_j)\text{BR}(KK \to f_k\bar{f}_l)$

(i) $\oplus$ (ii) $\oplus$ (iii) $\Rightarrow \mathcal{S} \sim y^3$ and $\mathcal{B} \sim 1/y$ (over the width); $\mathcal{S}/\mathcal{B} \sim y^4$.

LRS, $y \approx 6 \Rightarrow \mathcal{S} \to \mathcal{O}(100)\mathcal{S}$; $\mathcal{S}/\mathcal{B} \to \mathcal{O}(1000)\mathcal{S}/\mathcal{B}$!

$M_{Z'} \sim 4$ TeV and L = 100 fb^{-1}: $Z' \to \ell^+\ell^-$, $\ell = e, \mu$.

Compare with RS: $M_{Z'} \sim 2$ TeV and L = 1000 fb^{-1}. Agashe *et al.*, 2007

Revived prospects for golden modes!

constraint	RS	LRS
T parameter	3	3
S parameter	3	3
$Z \to b\bar{b}$	3	3^*
ϵ_K	8	3
$\mathcal{S}/\mathcal{B}$ for $Z' \to l^+l^-$	0.3	60

TABLE II: Summarized comparison of constraints between the RS and the LRS scenarios. For simplicity and definiteness, the Higgs is assumed to be on the IR-brane. The numbers corresponds to lower bounds on gauge KK masses, in TeV. Here, we assume a custodial symmetry for the T parameter; a left-right Z_2 symmetry is imposed to protect the $Zb\bar{b}$ coupling, unless denoted by *.

t->cZ ,(D^0 mixig) in LRS

- In RS there are 2 types of distinct contributions that are roughly of the same size:
- 1) mixing of Z with Z_KK..this will be suppressed in LRS by y~6 compared to RS and therefore small
- 2)mixing between t_R and t_L^KK. This mixing is cotrolled by the 5D yukawa which is unchanged in LRS and therefore BR(t->cZ) is again ~10^{-5}…good prospects for LHC.
- Correspondingly potential for D^0 mixing and CP remain in LRS as in RS

Summary & Outlook

- WEXD a fascinating possibilty for BSM:

  Address EW-Pl and/or EW-Fl hierarchies (RS or LRS)
- Unfortunately, for now, explicit, robust models for

  reliable numerical predictions not available
- Generic tests still possible
- Typically flow to NMFV with FCNC driven by the top
- and/or (t,b) …RS framework provides natural understanding of severe suppression of FCNC in light quarks though models are dual to strong binding

LE tests: Typically yield enhanced D^0 mixing with or w/o CP,

(Bd-> "phi" Ks, K* gamma, Bs->psi phi …) TDCP, nedm very good probes

HE tests: t-> c Z…, G (graviton perhaps the most unique signature)->ZZ,WW,tt and significant suppression to light fermions (l l)

Z' -> WW, ZH, tt, again suppressed l l

Z'-> l l powerful monitor of UV scale : is it Planck, Fl, or whatever else