“Light” Higgs and warped models; Possible clues for future directions in HEP

[Case for a GIGANTIC INTERNATIONAL HADRON COLLIDER]

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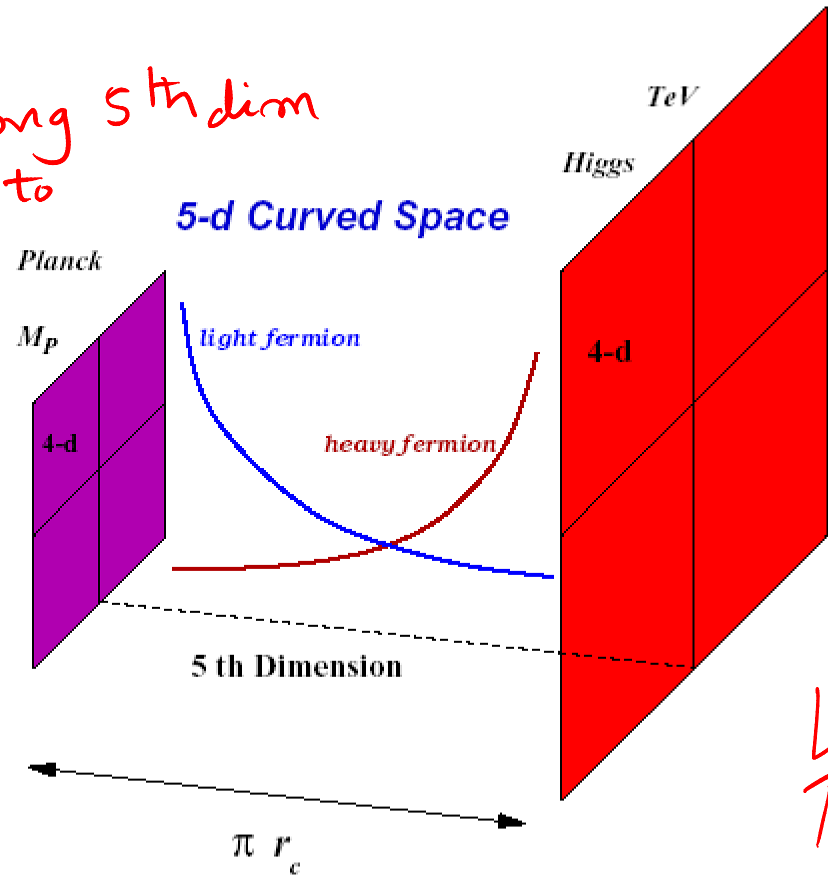
Outline

- Light SM-like Higgs strengthens case for mKK > ~ 10 TeV in warped framework
- Provides a compelling simultaneous resolution of weak-planck hierarchy and flavor puzzle via an elegant geometric interpretation
- With mKK> 10 TeV resulting set up is simpler and economical but at LHC only radion signal possible
- Provides a strong rationale for higher energy hadron collider for direct experimental verification of underlying warped set up

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

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



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

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

$$\sigma = k r_c \pi$$

$k r_c \sim 12$

TeV, M_P

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

Fermion "geography" (localization) naturally explains:

Grossman&Neubert; Gherghetta&Pomarol; Davoudiasl, Hewett & Rizzo

- **Why they are light (or heavy)**
- **How due to the exponential warp factor small changes in the fermion 5d mass parameter can lead to large hierachies in their 4d masses**
- **FCNC for light quarks are severely suppressed**
- **RS-GIM MECHANISM (Agashe, Perez,AS'04) flavor changing transitions though at the *tree level* (resulting from rotation from interaction to mass basis)are suppressed roughly to the same level as the loop in SM**
- **Most flavor violations are driven by the top**

Thus remarkably RS-leads to lowering of Λ_{flavor} from ~1000 TeV to < 20 TeV (possibly just a few TeV if you allow small amount of tuning)

See Buras et al '08; Neubert et al '08

5 d mass parameter of the 3-families of quarks

$$c_{Q_1} = -0.579\,, \quad c_{Q_2} = -0.517\,, \quad c_{Q_3} = -0.473$$
$$c_{u_1} = -0.742\,, \quad c_{u_2} = -0.558\,, \quad c_{u_3} = +0.339$$
$$c_{d_1} = -0.711\,, \quad c_{d_2} = -0.666\,, \quad c_{d_3} = -0.553$$

Table from M. Neubert @Moriond09

Repercussions of a SM-like 125 GeV Higgs

- Assuming a "SM-like" (125 GeV) Higgs is confirmed[meaning BR and other properties consistent with SM expectations], then interpreted in the context of a warped scenario, mKK > around 10 TeV ["MKK10"] satisfying EWPC.[see Azatov et al '10; Goertz et al '11; Carena et al '12]
- Warped model with MKK10 are simple and economical but imply a tuning of O(10^-3) but automatically satisfy Kaon mixing and other flavor constraints
- To ameliorate tuning to O(10^-2) Agashe et al '03 imposed "custodial symmetry" by extending gauge group from SU(2) X U(1) to SU(2)XSU(2)XU(1) with the addition of many new particles
- EWPC then allow mKK > 3 TeV and chance of signals @ LHC

- But flavor constraints esp from Delta S=2 K^0 mixing still demand KK masses lot bigger than 3 TeV anyway
- So excepting tuning at 10^-3, MKK > ~ 10 TeV with the bonus of more economical KK setup seems attractive.
- Moreover SM-like light Higgs is not consistent with light mKK anyway
- With mkk at 10 TeV, it'd seem there is no chance of

experimental verification at LHC but this is not necessarily true as a radion (ϕ) of mass << mKK, possibly several hundred GeV is predicted by the Goldberger-Wise stabilization mechanism.

- Recall ϕ represents quantum fluctuations of the IR brane and interacts through its couplings with the trace of the

energy momentum tensor

$$\mathcal{L}_V = -\frac{\phi}{\Lambda_\phi}\sum_i a_i\Big[\mu_i^2 V_\mu^{(i)} V^{(i)\mu} + \frac{1}{4kL} V_{\mu\nu}^{(i)} V^{(i)\mu\nu}\Big], \quad (1)$$

where $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$, $a_W = 2$, $a_Z = 1$, and

$$\mu_i^2 = m_i^2\Big[1 - \frac{kL}{2}\Big(\frac{m_i}{\tilde{k}}\Big)^2\Big]. \quad (2)$$

Here, $\tilde{k} \equiv k\lambda$ sets the scale of the lightest KK masses and corrections to $\mathcal{L}_V$ are suppressed by powers of $m_i^2/\tilde{k}^2$.

A massless gauge field A_μ couples to ϕ via

$$\mathcal{L}_A = -\frac{\phi}{4\Lambda_\phi kL}\Big[1 + \frac{\alpha_G}{2\pi} b_G kL\Big] F_{\mu\nu}F^{\mu\nu}, \quad (3)$$

where b_G denotes the one-loop β-function coefficient below $m_\phi/2$ and $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$. In this work, the relevant gauge fields are γ ($G =$ EM) and g ($G =$ QCD). We have $b_{\rm EM} = b_2 + b_Y - F_W - 4F_t/3$, with $b_2 = 19/6$, $b_Y = -41/6$. To a good approximation, $F_W = 7$ for $m_\phi < 2m_W$, $F_t = -4/3$ for $m_\phi < 2m_t$, and both functions are zero when ϕ is heavier than twice the mass of the respective particle. For gluons, $b_{\rm QCD} = 11 - 2N_F/3$, where N_F is the number of quark flavors.

The coupling of ϕ to SM fermion f of mass m_f depends on its bulk profile parameters $c_{L,R}$, corresponding to the left and right 4D chiralities, respectively [15,20]:

$$-\frac{\phi}{\Lambda_\phi} m_f [I(c_L) + I(c_R)](\bar{f}_L f_R + \bar{f}_R f_L), \qquad (4)$$

where

$$I(c) \equiv \frac{1 - 2c}{2(1 - \lambda^{1-2c})} + c. \qquad (5)$$

In our convention, fermions with $c_{L,R} > 1/2$ have UV-localized zero modes.

Finally, the coupling of the radion to a brane-localized Higgs scalar is given by [12]

$$-\frac{\phi}{\Lambda_\phi}(-\partial_\mu h \partial^\mu h + 2m_h^2 h^2), \qquad (6)$$

where h is the physical Higgs of mass m_h. We will next discuss the relevant LRS parameters for our analysis.

ELECTROWEAK CONSTRAINTS

$$S_{\rm tree} \approx 2\pi \left(\langle H\rangle/\tilde{k}\right)^2 \left[1 - \frac{1}{kL} + \xi(c)\right] \tag{5}$$

and

$$T_{\rm tree} \approx \frac{\pi}{2\cos\theta_W^2}\left(\langle H\rangle/\tilde{k}\right)^2 \left[kL - \frac{1}{kL} + \xi(c)\right], \tag{6}$$

where

$$\xi(c) \equiv \frac{(2c-1)/(3-2c)}{1-e^{kL(2c-1)}}\left(2kL - \frac{5-2c}{3-2c}\right) \tag{7}$$

is a function of fermion localization parameter c and $\cos^2\theta_W \simeq 0.77$. For fermion profiles that lead to a realistic flavor pattern we have $\xi(c) \ll 1$.

$\delta S \sim 0.02$, $\delta T \sim 0.4$ for $10^5 < k < 10^{17}$ TeV

General light dilatons

- **In theories where the EW symmetry breaking originates from a spontaneously broken,nearly conformal sector, there is also a narrow scalar resonance, the psuedo-GB (pseudo-dilaton) of conformal symm breaking, properties like Higgs.**
- **For collider signatures & distinction from Higgs, see: Goldberger,Grinstein,Skiba'07;Fan, Goldberger,Ross,Skiba'08**
- **Relation to walking technicolor, Applequist & Bai '10**

BR Vs Mass of Radion

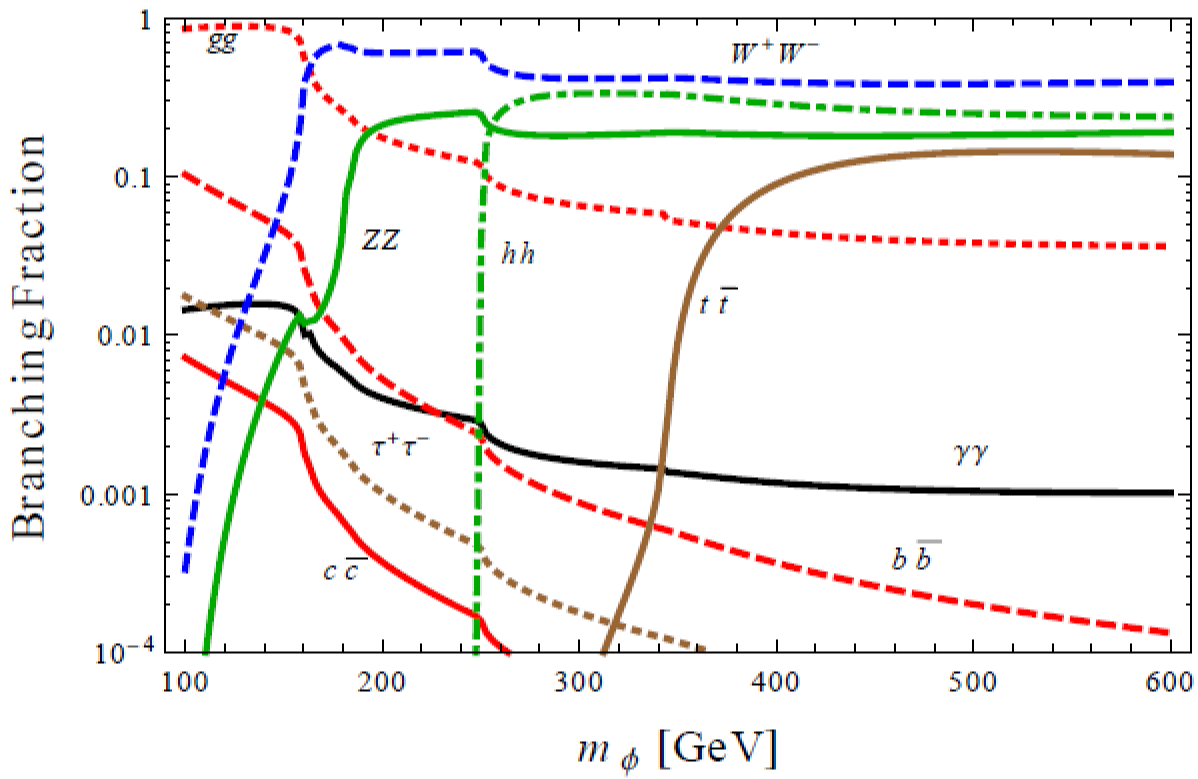


FIG. 1: Branching fractions of the radion as a function of radion mass, assuming $m_H = 125$ GeV, $kL = 10$, and $\Lambda_\phi = 10$ TeV.

Radion versus Higgs

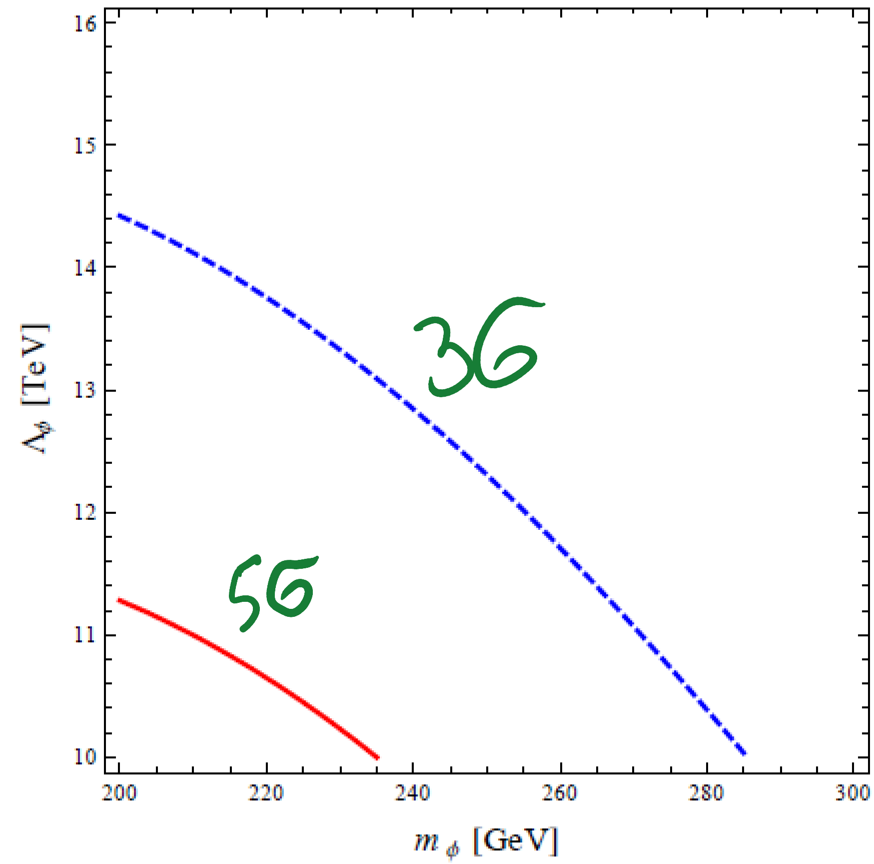
- **For mass ~ 125 GeV, Radion Br to 2 gammas is around %, Higgs is smaller by O(10). Radion width is few hundred KeV ; SM-Higgs is larger by X O(10)**

- **For mass ~600 GeV, Radion width is ~ 1GeV; SM-Higgs is ~ 120 GeV**

Radion O(fewX100GeV) signal @ LHC14

LHC14 Reach Via $\phi \to WW \to l\nu l\nu$

100/fb



kL = 10

k ~ 10^5 TeV

FIG. 2: The 3σ (dashed) and 5σ (solid) contours, in the (m_ϕ, Λ_ϕ) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with 100 fb^{-1} at 14 TeV, with $kL = 10$.

Cuts & Such

We impose the following cuts, somewhat similar to those used in Higgs searches at the LHC [58, 59]. We require exactly two oppositely charged leptons (e or μ), each with pseudorapidity $|\eta| < 2.5$, and no accompanying jets. One of the leptons must have transverse momentum $p_T > 20$ GeV, while the other must have $p_T > 15$ GeV. The two leptons must have an invariant mass $m_{ll} > 10$ GeV and be separated by $\Delta R > 0.4$, where $\Delta R \equiv \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$ is the separation in azimuthal angle φ and pseudorapidity η. When both leptons have the same flavor (e^+e^- or $\mu^+\mu^-$), we further require that $m_{ll} > 15$ GeV and $|m_{ll} - m_Z| > 15$ GeV, in order to suppress the Drell-Yan background. Additionally, we require large missing transverse energy E_T^{miss}, which we identify as the vector sum of the neutrinos' transverse momenta: $E_T^{\text{miss}} > 25$ GeV for $e^\pm\mu^\mp$ events and $E_T^{\text{miss}} > 45$ GeV for e^+e^- and $\mu^+\mu^-$ events.

Finally, we consider a transverse mass variable m_T, defined by

$$m_T^2 \equiv \left(\sqrt{|\mathbf{p}_T^{ll}|^2 + m_{ll}^2} + E_T^{\text{miss}}\right)^2 - |\mathbf{p}_T^{ll} + \mathbf{p}_T^{\text{miss}}|^2, \qquad (10)$$

where $\mathbf{p}_T^{ll}$ is the transverse momentum of the lepton pair, $\mathbf{p}_T^{\text{miss}}$ is the missing transverse momentum, and $E_T^{\text{miss}} = |\mathbf{p}_T^{\text{miss}}|$ [59, 60]. The definition of m_T is such that $m_T \leq m_\phi$ for all signal events. Because of this relation between m_T and m_ϕ, the distribution of m_T can be used to provide an estimate of m_ϕ. It may be possible to obtain an improved estimate by considering alternative transverse-mass variables that bound m_ϕ more tightly [61]. However,

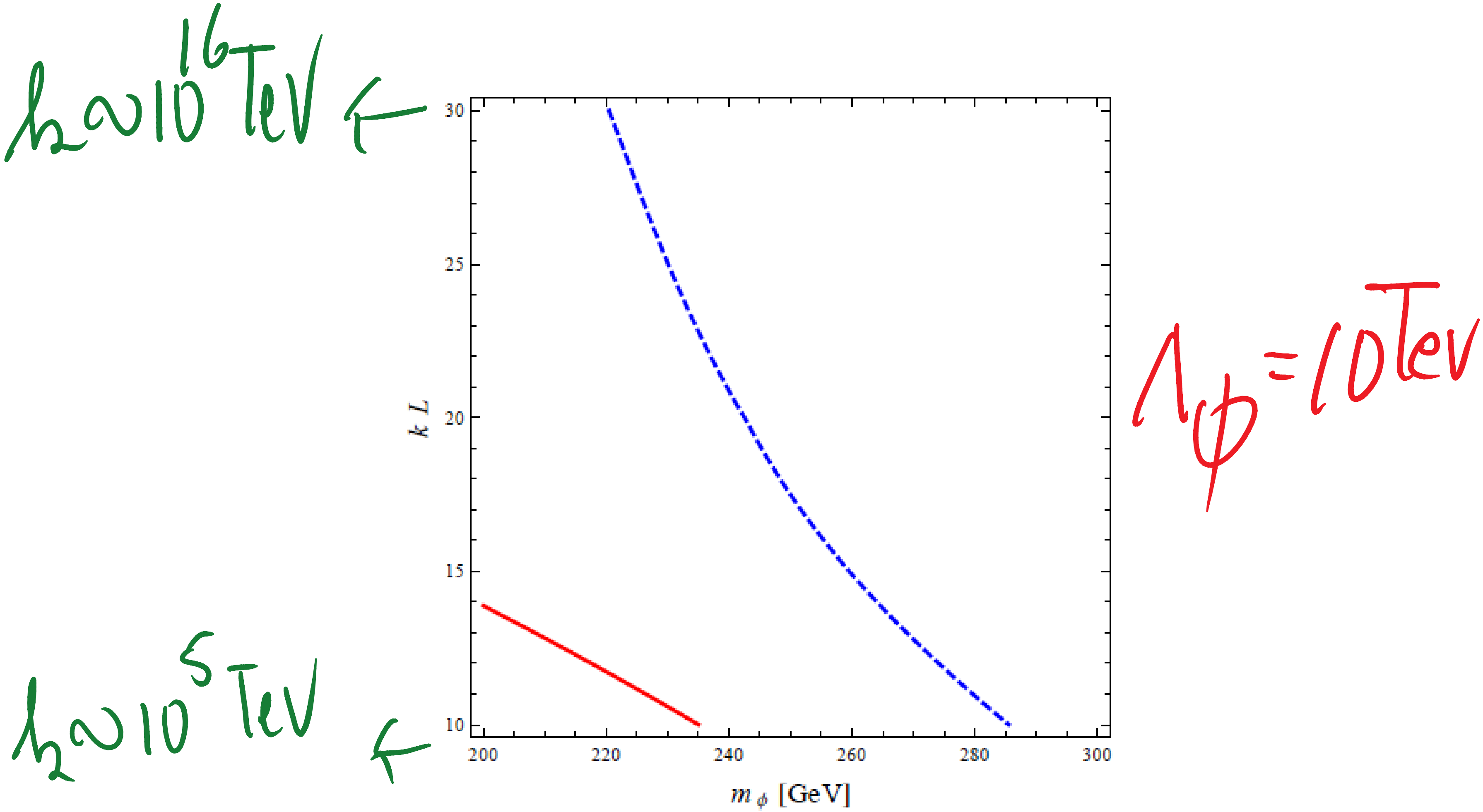
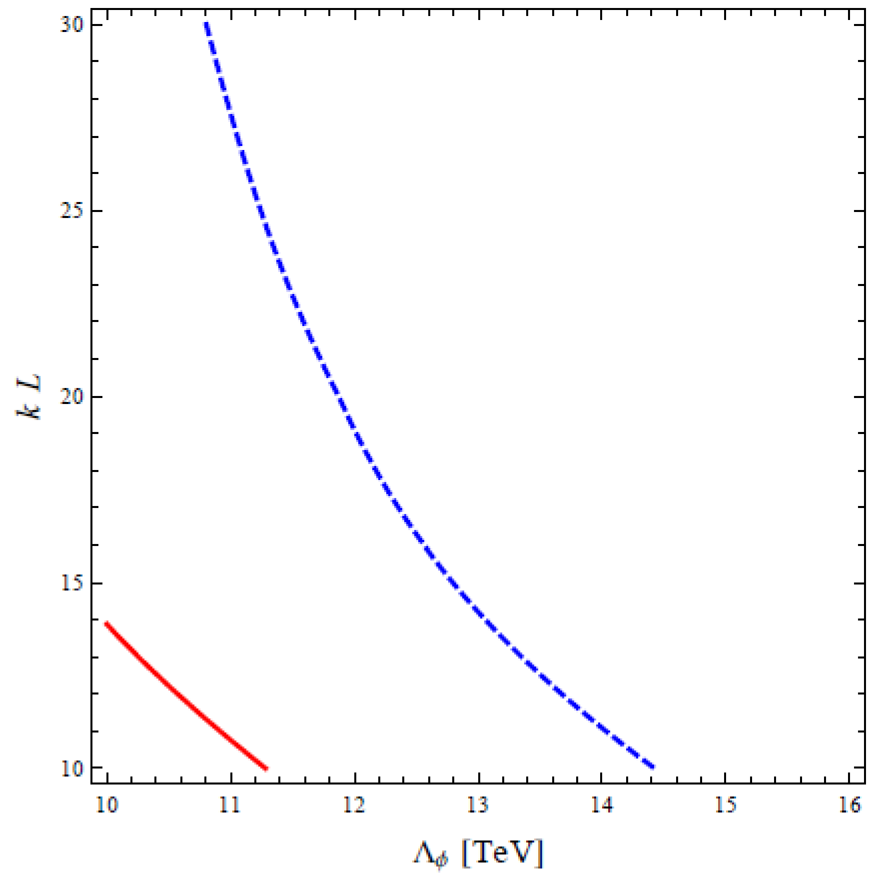


FIG. 3: The 3σ (dashed) and 5σ (solid) contours, in the (m_ϕ, kL) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with 100 fb^{-1} at 14 TeV, with $\Lambda_\phi = 10$ TeV.



m_ϕ=200 GeV

FIG. 4: The 3σ (dashed) and 5σ (solid) contours, in the (Λ_ϕ, kL) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with 100 fb^{-1} at 14 TeV, with $m_\phi = 200$ GeV.

LHC14 with 100/fb

$\Lambda_\phi = 10$ TeV

$\phi \to \gamma\gamma$

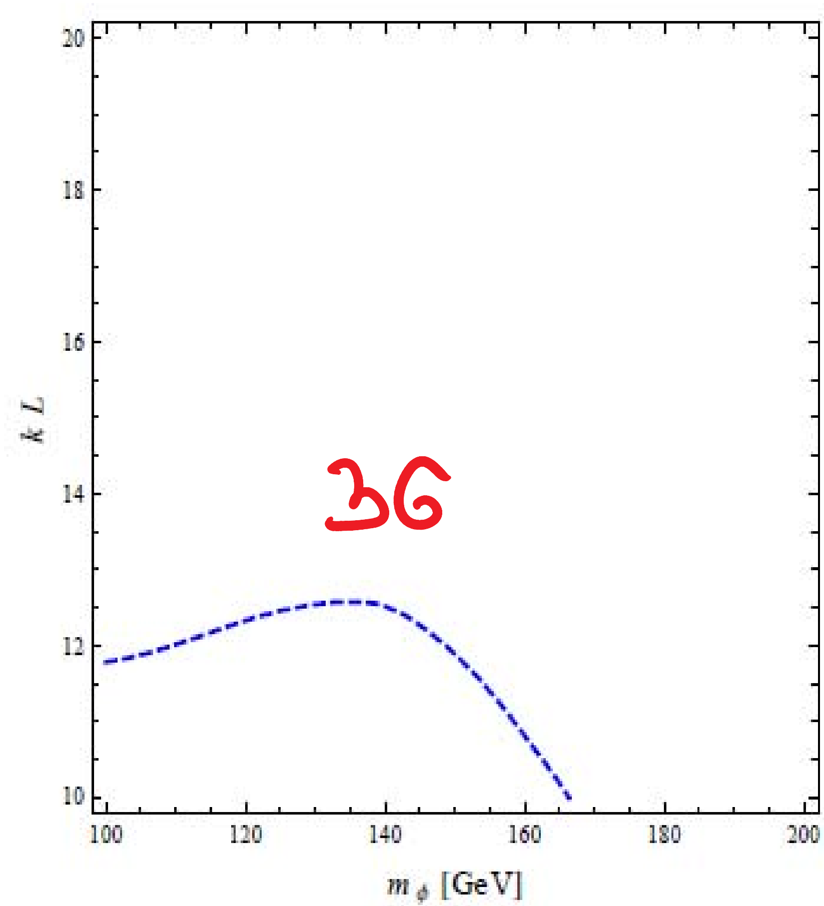


FIG. 5: The 3σ contour, in the (m_ϕ, kL) plane, for $\phi \to \gamma\gamma$ at the LHC with 100 fb^{-1} at 14 TeV, with $\Lambda_\phi = 10$ TeV.

Recall even with mKK O(3 TeV), LHC14 reach for direct verification of a warped set up is limited

FOLLOWS from extensive works done in past ~ 5 years

[26] See, for example: K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D **77**, 015003 (2008) [hep-ph/0612015]; A. L. Fitzpatrick, J. Kaplan, L. Randall and L. -T. Wang, JHEP **0709**, 013 (2007) [hep-ph/0701150]; B. Lillie, L. Randall and L. -T. Wang, JHEP **0709**, 074 (2007) [hep-ph/0701166]; K. Agashe, H. Davoudiasl, G. Perez and A. Soni, Phys. Rev. D **76**, 036006 (2007) [hep-ph/0701186]; A. Djouadi, G. Moreau and R. K. Singh, Nucl. Phys. B **797**, 1 (2008) [arXiv:0706.4191 [hep-ph]]; K. Agashe, H. Davoudiasl, S. Gopalakrishna, T. Han, G.-Y. Huang, G. Perez, Z.-G. Si and A. Soni, Phys. Rev. D **76**, 115015 (2007) [arXiv:0709.0007 [hep-ph]]; O. Antipin, D. Atwood and A. Soni, Phys. Lett. B **666**, 155 (2008) [arXiv:0711.3175 [hep-ph]]; K. Agashe, S. Gopalakrishna, T. Han, G.-Y. Huang and A. Soni, Phys. Rev. D **80**, 075007 (2009) [arXiv:0810.1497 [hep-ph]]; H. Davoudiasl, T. G. Rizzo and A. Soni, Phys. Rev. D **77**, 036001 (2008) [arXiv:0710.2078 [hep-ph]]; H. Davoudiasl, S. Gopalakrishna and A. Soni, Phys. Lett. B **686**, 239 (2010) [arXiv:0908.1131 [hep-ph]].

KK-Particle Masses

$J_1(x_n) = 0$

$$m_n = x_n k e^{-kr_c\pi}, \tag{18}$$

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

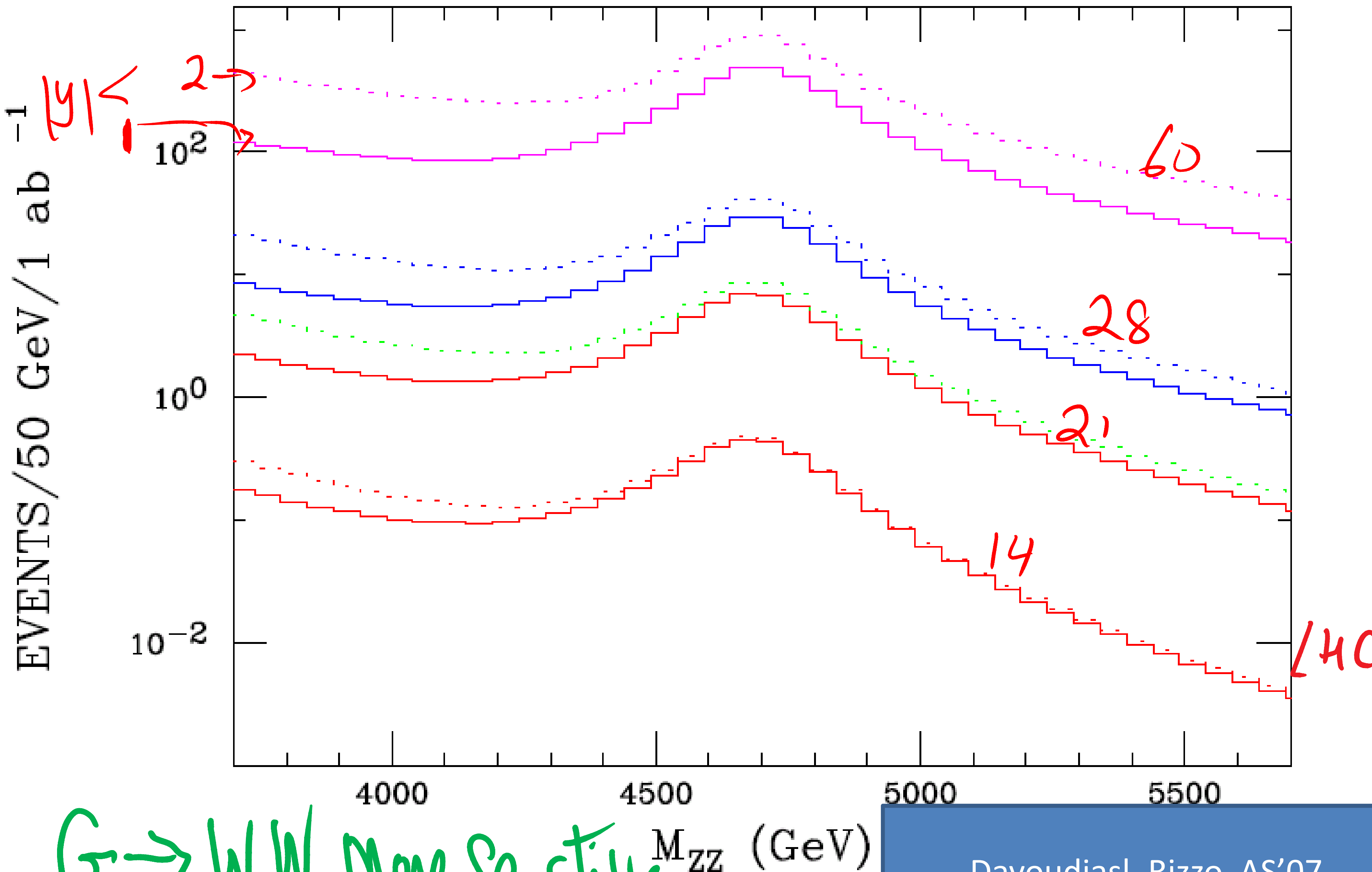
EWPT $\Rightarrow m_{KK} \gtrsim 3$ TeV Agashe DMS '03

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

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

GOLD-Plated G→ZZ

Z BR Not inc.



G→WW More Sensitive

Davoudiasl, Rizzo, AS'07

Associated Production of PAIR of KK Fermions

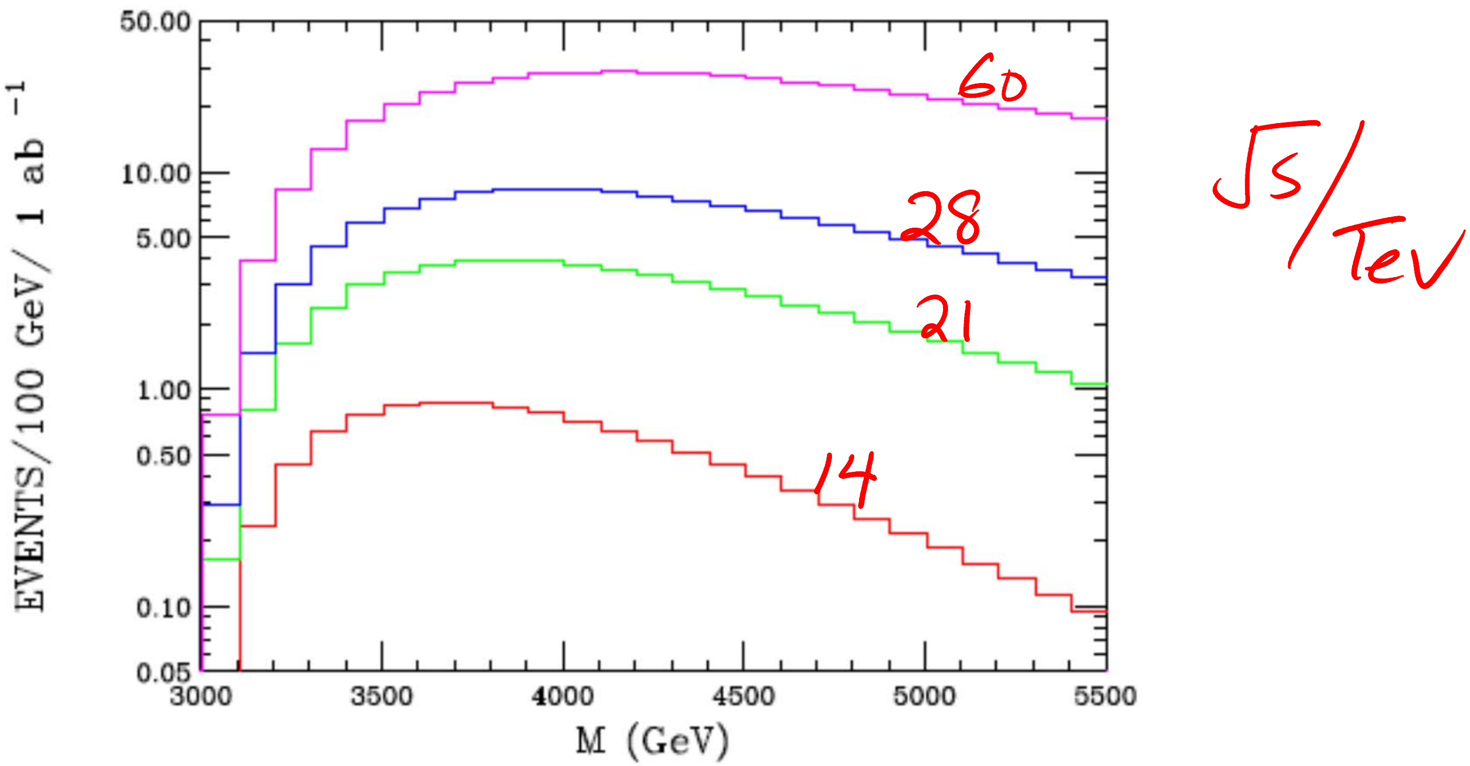


FIG. 2: Same as the last figure but now for different values of $\sqrt{s}$ and taking the first gluon KK and fermion KK masses to be degenerate at 3 TeV. From bottom to top the histograms correspond to $\sqrt{s} = 14$, 21, 28 and 60 TeV, respectively.

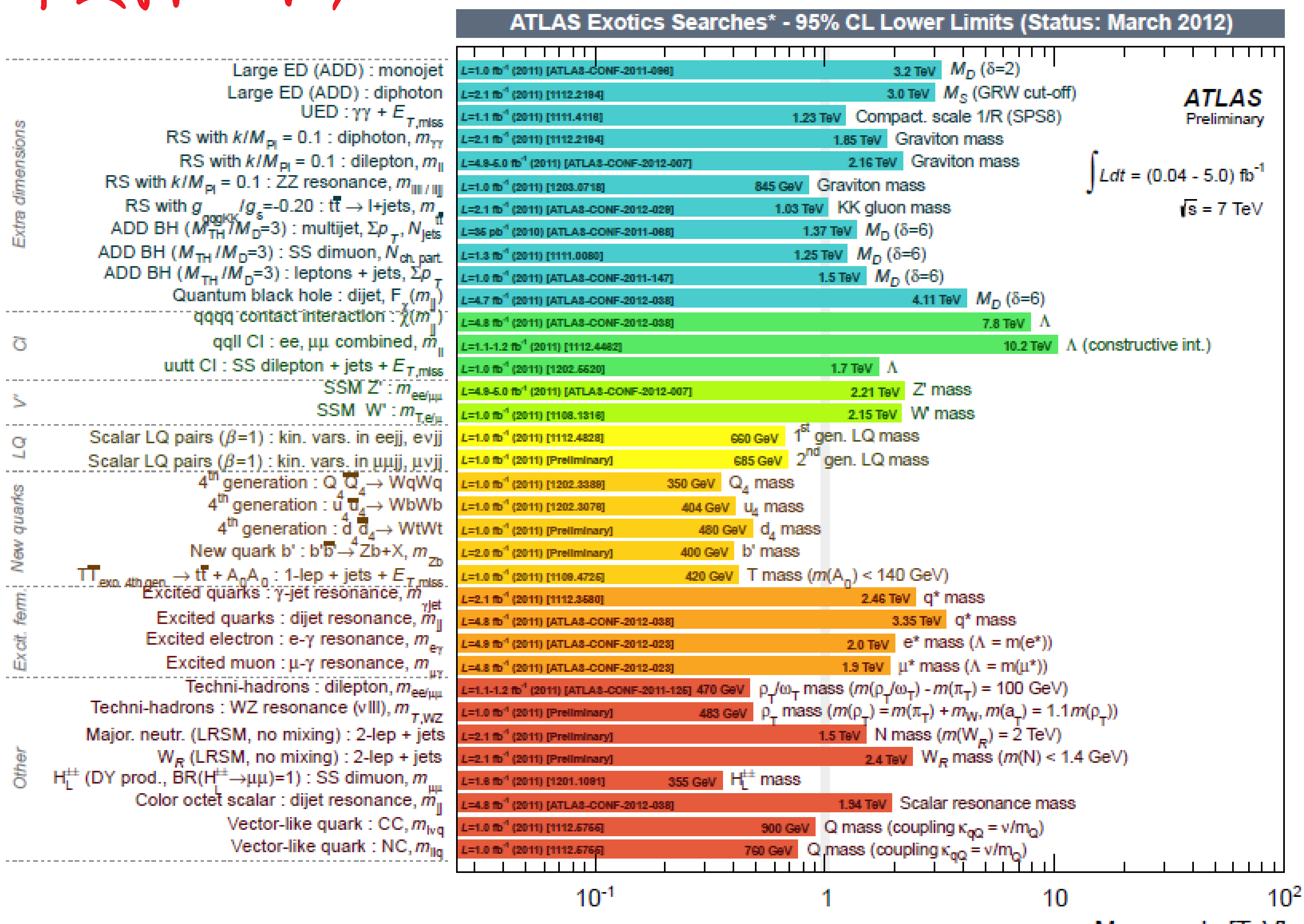
"Direct verification" (i.e. KK-graviton and/or KK-fermion) at LHC will be very difficult unless we can learn to lower m_{KK} appreciably or go to higher cm energies

old

CONFIRMATION of SM-like light Higgs

⇒ m_{KK} CANNOT Be lowered

ATLAS EXOTICS LIMIT ~ MAR. 2012



*Only a selection of the available mass limits on new states or phenomena shown

Lesson learnt from ν's

~ Circa 1983, after long and arduous efforts, Δm^2 upper bound used to be around a few ev^2 but efforts to Search oscillations continued basically because there was no good theoretical reason for m_ν to be zero.

- ***Recall it took more than a decade beyond '83*** **and Δm^2 had to be lowered by almost 4 orders of magnitude (!) before osc were discovered.**

SSC 40 TeV ~ 1990

MAY WELL NEED SERIOUSLY THINKING of

GIGANTIC INTERNATIONAL HADRON COLLIDER

~ 100 TeV CM

Conclusions & outlook

- Warped space ideas provide an almost compelling framework for simultaneously addressing hierarchy and flavor puzzles
- With ~125 GeV SM-like Higgs, EW precision & flavor constraints strongly suggest mKK masses above ~ 10 TeV
- Radion with mass few hundered GeV is one important footprint accessible to LHC14 which can cover most of the parameter space
- As the next step in our adventure, it may be time to start thinking of a GIGANTIC INTERNATIONAL HADRON COLLIDER

XTRAS