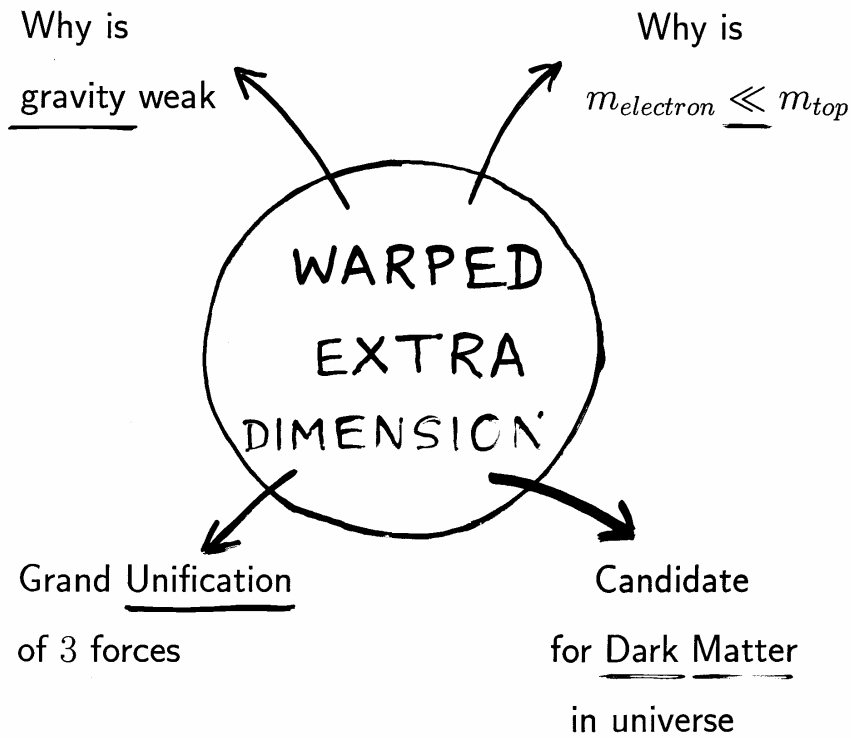


PARTICLE PHYSICS FROM A WARPED EXTRA DIMENSION

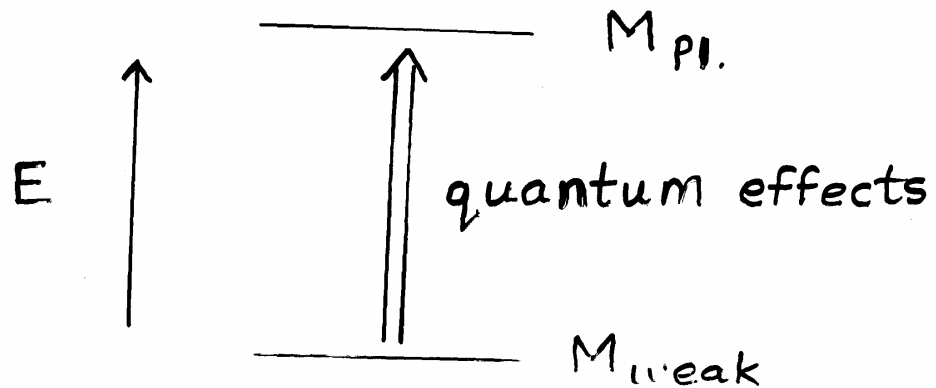
Kaustubh Agashe (Johns Hopkins University)

OPEN QUESTIONS: ADDRESSED BY
WARPED EXTRA DIMENSION!



Experiments will tell!

HIERARCHY PROBLEM IN HIGGS CONDENSATE



Quantum corrections \rightarrow

$$M_{weak} \sim 100 \text{ GeV} \ll M_{Pl} \sim 10^{19} \text{ GeV}$$

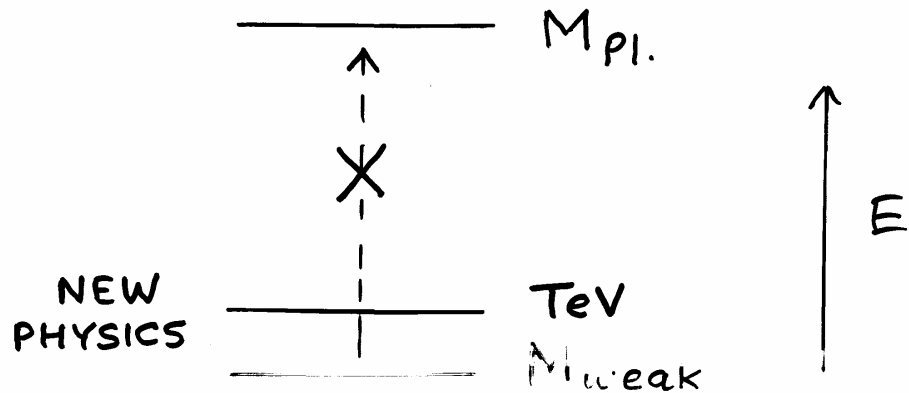
unstable!

(for spin-0)

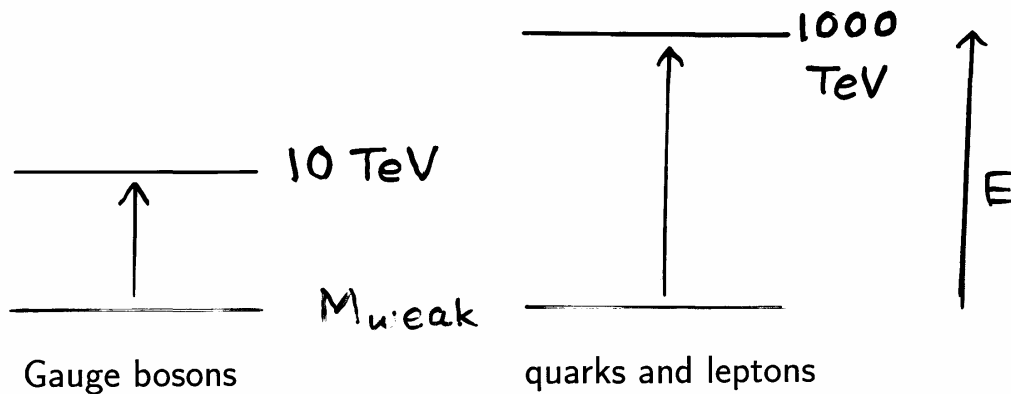
Biggest mystery for the last 20 years or so!

TENSION: SOLVING HIERARCHY PROBLEM VS. PRECISION TESTS

Solution to hierarchy problem: New Physics at \sim TeV



New Physics contributes to precision tests:



New Physics has to be special!

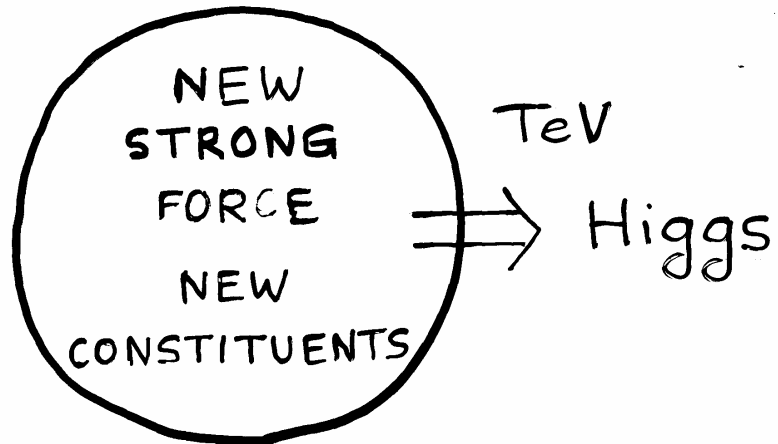
OUTLINE

1. Composite Higgs solves hierarchy problem
2. Dual description with 5th dimension!
3. Explain hierarchy of quark and lepton masses
(why $m_e \ll m_t$)
4. Tension with precision tests avoided by protective mechanisms (of SM) for New Physics
5. Grand Unification of 3 forces
6. Candidate for Dark Matter of universe
7. Conclusions

COMPOSITE
HIGGS

HIGGS IS COMPOSITE ABOVE TeV

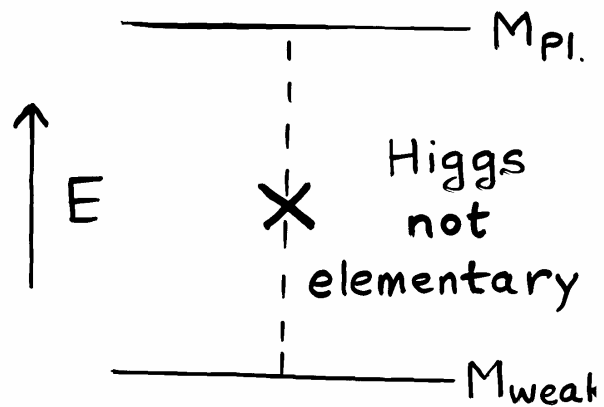
(a la quarks bound into proton by QCD/strong force)



Dynamical suppression of quantum corrections →

$$\underline{M_{weak}} \ll \underline{M_{Pl}} \text{ natural}$$

$$(a la \underline{\Lambda_{QCD}} \ll \underline{M_{Pl}})$$

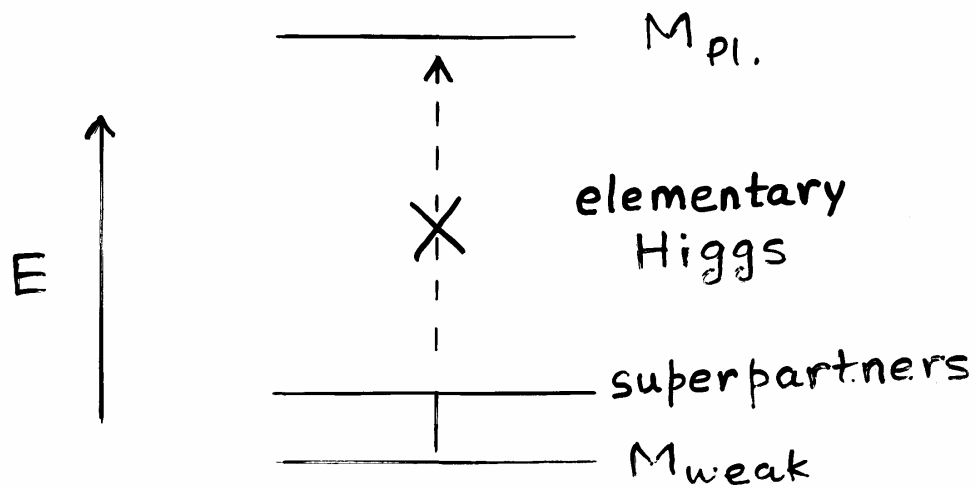


ALTERNATIVE TO SUSY

Add superpartners of SM:

Quantum corrections to Higgs condensate cancel

Higgs **elementary** till M_{Pl}



DUAL DESCRIPTION

DUAL TO EXTRA DIMENSION!

Difficult to calculate (\sim strong force):

constituents of Higgs strongly coupled

at best, incomplete models (Georgi, Kaplan)

AdS/CFT duality in String Theory

(Maldacena; Witten; Gubser, Klebanov, Polyakov):

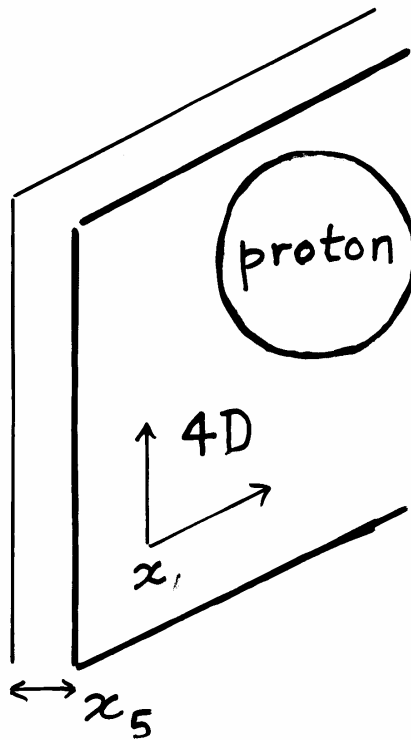
Strong interactions dual to extra spatial dimension!

Weakly coupled \rightarrow calculable!

WHY HAVEN'T WE SEEN EXTRA DIMENSION

$4D$ = (3 spatial D) + time

Tiny 5^{th} dimension!



MOTIVATION FOR DUALITY

Tower of bound states in 4D picture (with strong dynamics)



Particle in 5D (a la particle in 1D box)

\downarrow 4D point of view

- Lightest mode (SM) + heavier (Kaluza-Klein or KK) modes (*eigenmodes with $p_5 = n/L$*)

with profiles in 5th dimension

KK mass scale \approx TeV \rightarrow not yet seen!

WARPED SPACE-TIME

AdS/CFT duality \rightarrow $5D$ space-time is curved:

Warped space-time

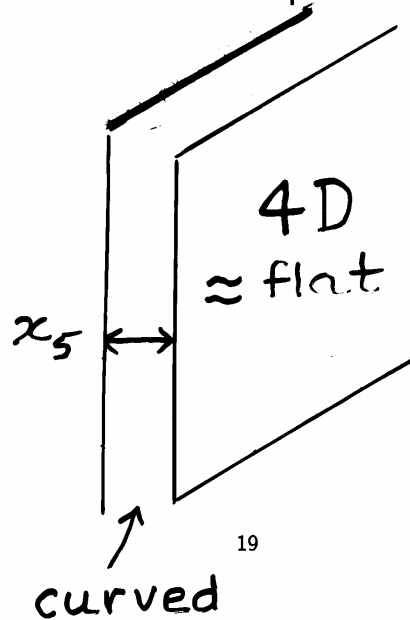
Einstein: gravity is curvature of space-time

usual curvature extremely small, gravity very weak

Warped space-time highly curved

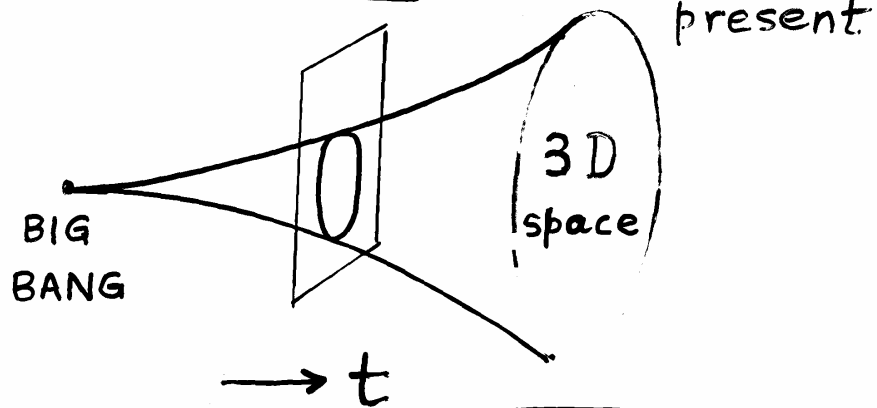
curvature hidden if extra dimension hidden

(tiny in size or KK scale $>$ present reach)!

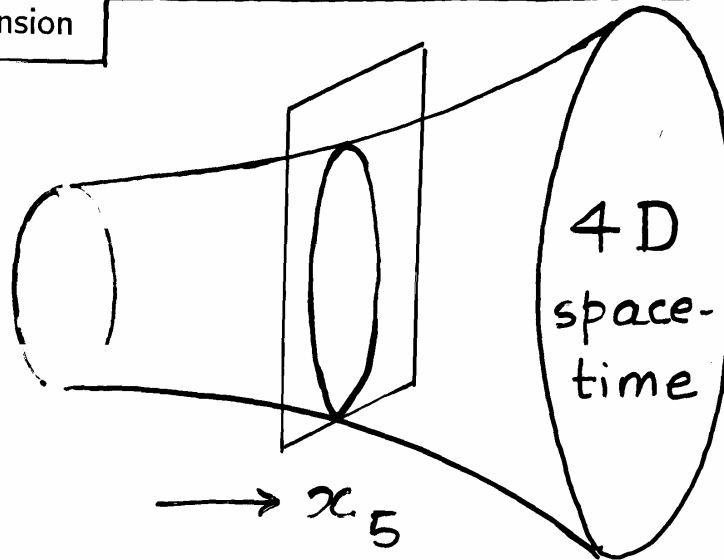


ANALOGY WITH EXPANDING UNIVERSE

3D space expands with time



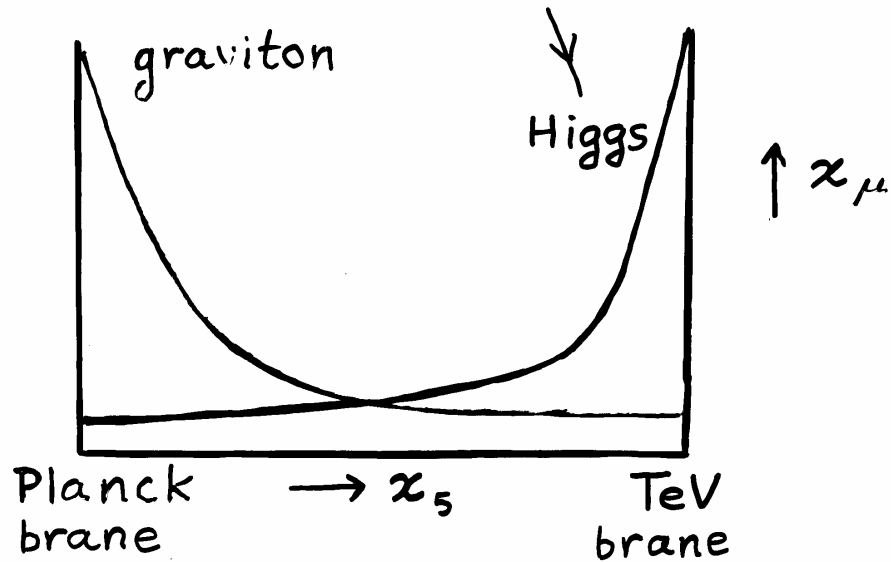
4D space-time expands with moving along 5th
dimension



WARPED EXTRA DIMENSION: GRAVITY AND HIGGS (Randall, Sundrum)

Profiles: solutions to wave equation in curved $5D$
space-time

(Contino, Nomura, Pomarol)



Small overlap of Higgs with gravitational field \rightarrow small
Higgs mass/condensate

- Planck-weak hierarchy problem solved!

SM FERMION

PROFILES

EXPLAIN

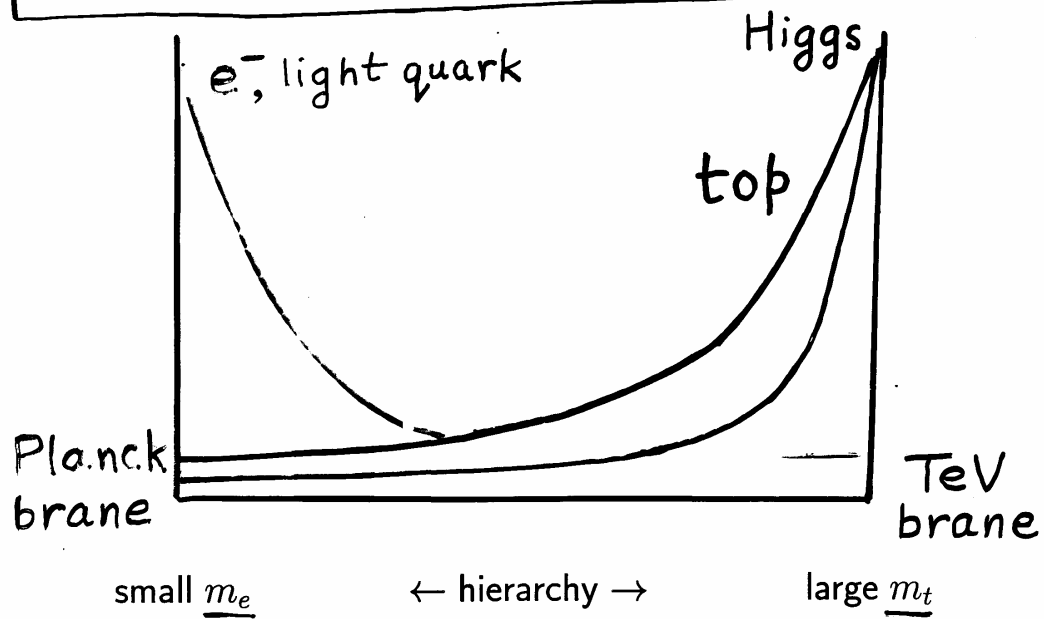
HIERARCHY

COUPLING \propto

WAVEFUNCTION OVERLAP

WARPED EXTRA DIMENSION: FERMIONS

$5D$ wave equation \rightarrow lightest mode (SM) profile
sensitive to $5D$ mass (Grossman, Neubert)

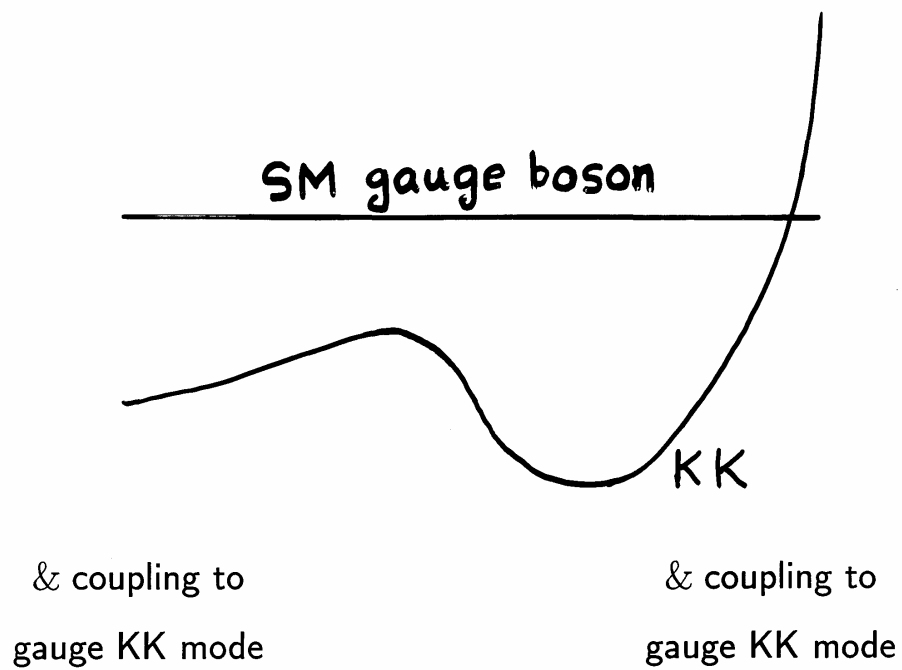


Elementary in $4D$ picture \leftrightarrow Planck brane

Composite in $4D$ picture \leftrightarrow TeV brane

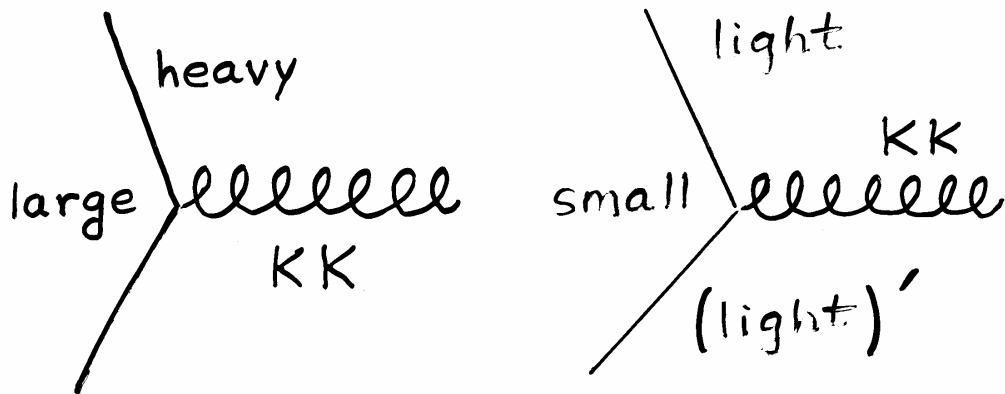
: AdS/CFT

**& GAUGE BOSONS (Davoudiasl, Hewett, Rizzo;
Pomarol)**



FLAVOR CONVERSION (Gherghetta, Pomarol)

Coupling of KK modes non-universal: $q \leftrightarrow q'$

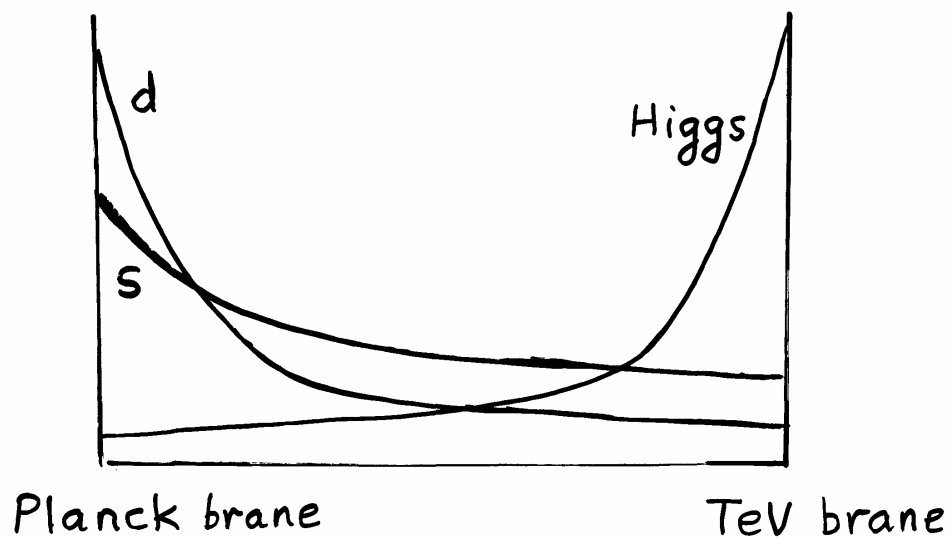
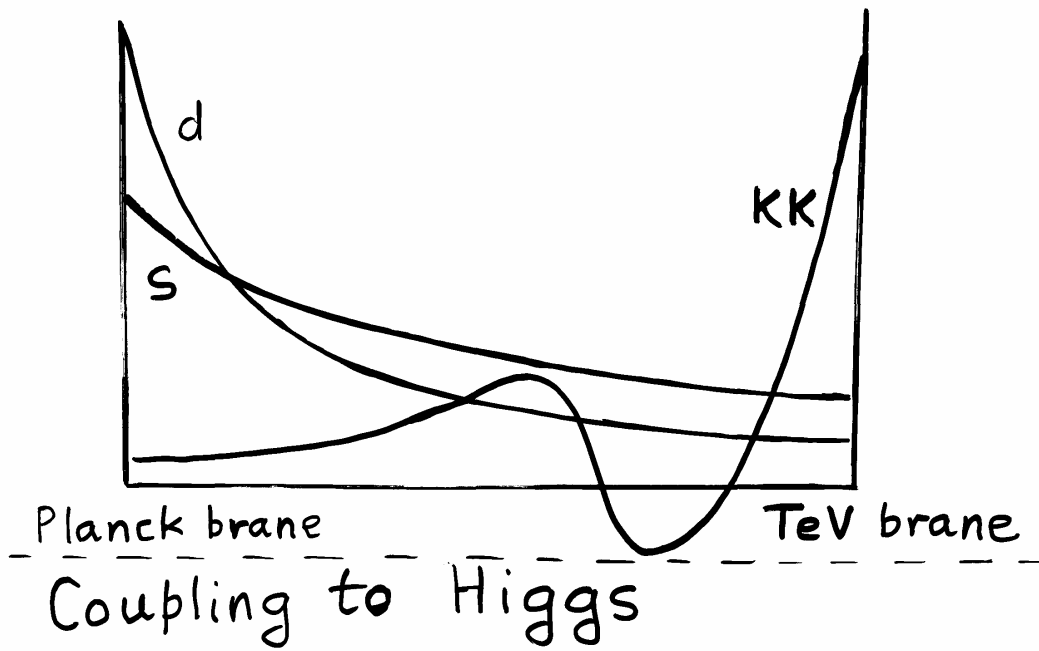


Flavor conversion \propto quark mass

a la SM (GIM mechanism)

Built-in mechanism to avoid **too** large flavor conversion!

Coupling to gauge KK mode



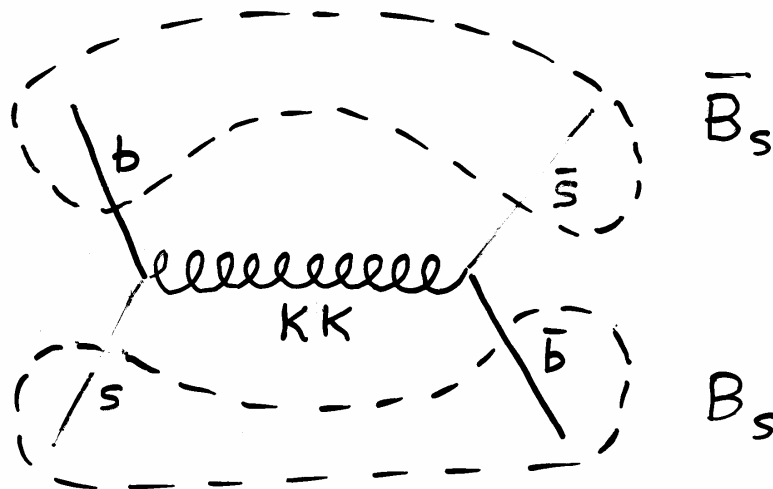
SIGNALS OF SOLUTION TO FLAVOR HIERARCHY

(KA, Perez, Soni, Phys. Rev. Lett. 93
(2004); KA et al.)^{to appear}

Large flavor conversion for top, bottom on edge of
current data



Signals at ongoing B-factories (BABAR, BELLE, Run
II of Tevatron), LHC (in few years)



100% deviation from SM in $B_s - \bar{B}_s$ oscillations

KK MASS SCALE: ISOSPIN SYMMETRY

(KA, Delgado, May, Sundrum, hep-ph/0412089
JHEP 0308 (2003); KA, Contino, Pomarol)

Natural solution to hierarchy problem:

compositeness/KK scale \sim TeV

KK contribute to precisely measured properties of W, Z

Isospin symmetry \rightarrow relation between M_W and M_Z :

\approx in SM

breaking magnified in extra dimension

\rightarrow KK scale \approx 10's TeV (Huber, Shafi;

Csaki, Erlich, Terning; Hewett, Petriello, Rizzo)



Extend **gauge** structure \ni isospin

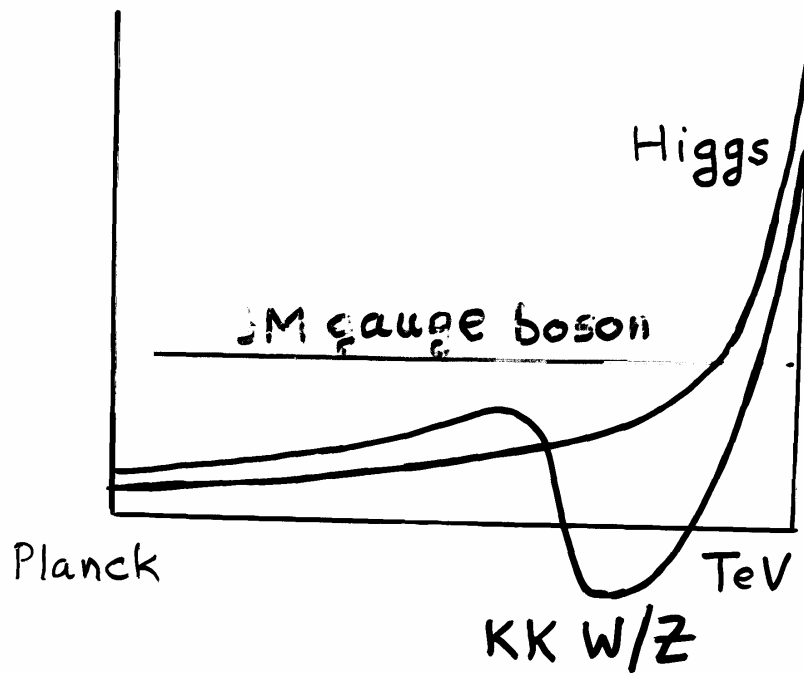
(extra gauge bosons massive)



KK mass ~ 3 TeV allowed

$\left. \begin{array}{l} \text{cf. Higgsless : KK mass} \sim 1 \text{ TeV} \\ \rightarrow \text{difficult to pass tests,} \end{array} \right\}$

Coupling of Higgs to KK W/Z



NO TENSION WITH PRECISION TESTS!

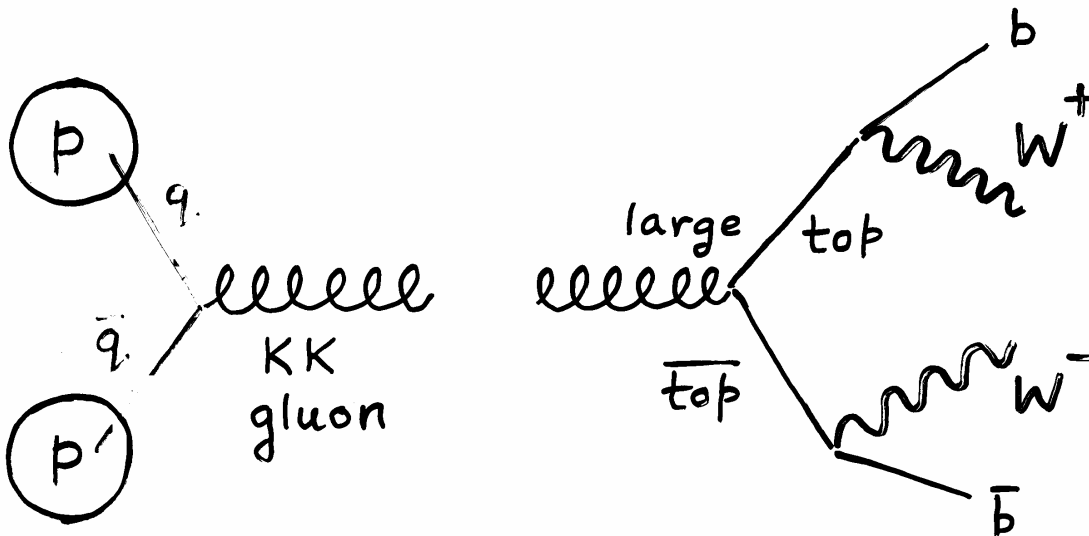
Preserve nice features of SM:

GIM mechanism (for quarks and leptons)

Isospin symmetry (for gauge bosons)

KK PRODUCTION AT LHC (c.m. energy = 14 TeV)

Production at LHC: KK gluon



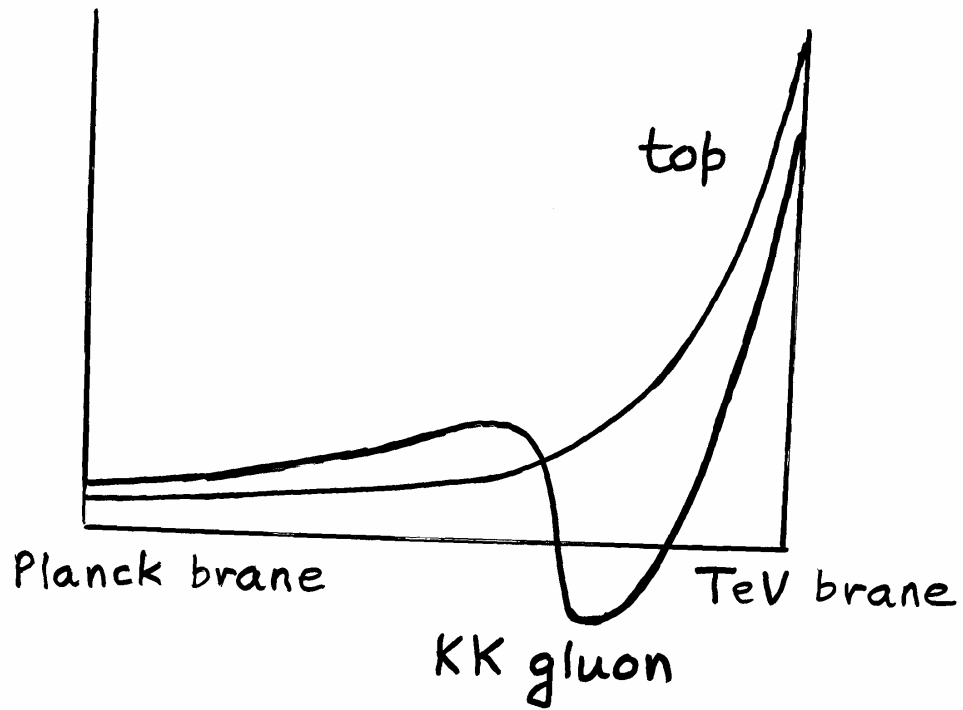
Decay: unique signature!

Top compositeness (a la Higgs) modifies its properties:

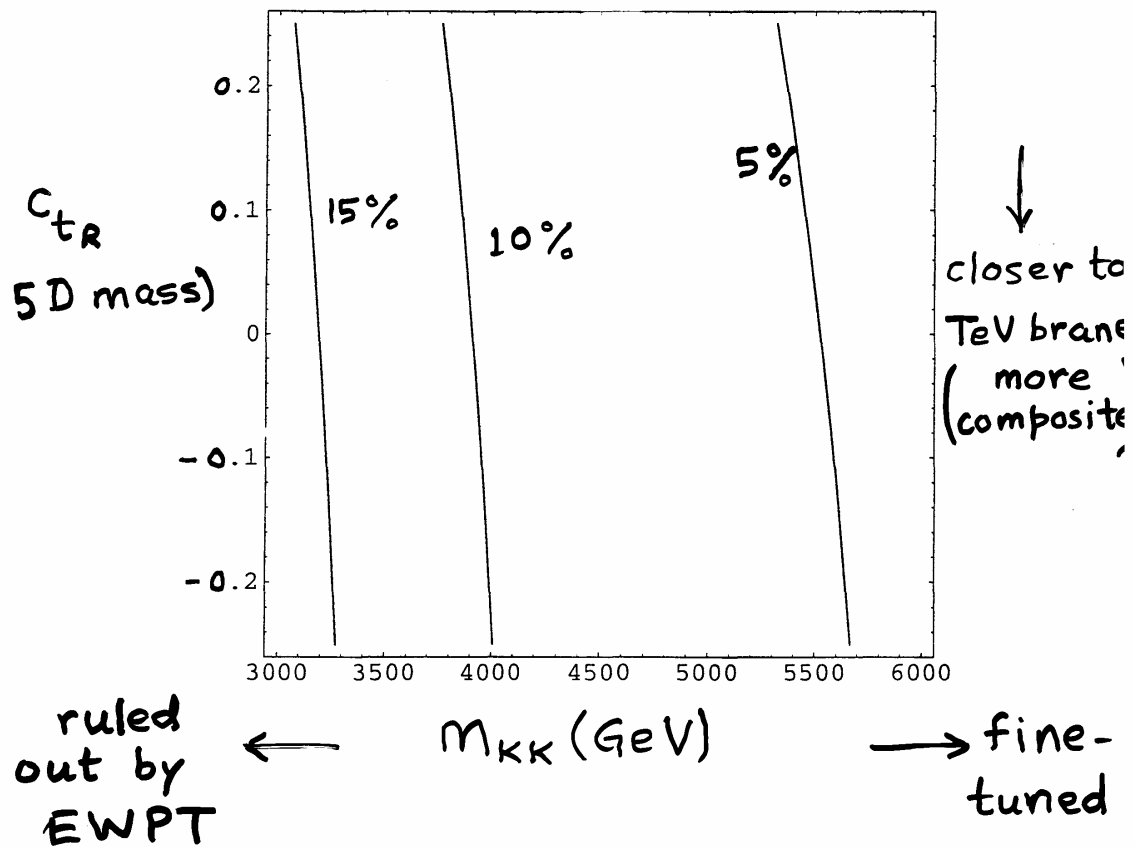
10% shift in coupling to Z (Linear Collider)

flavor conversion $t \rightarrow cZ$ (LHC, Linear Collider)

Coupling of top to KK gluon



Shift in $Z \bar{t}_R t_R$



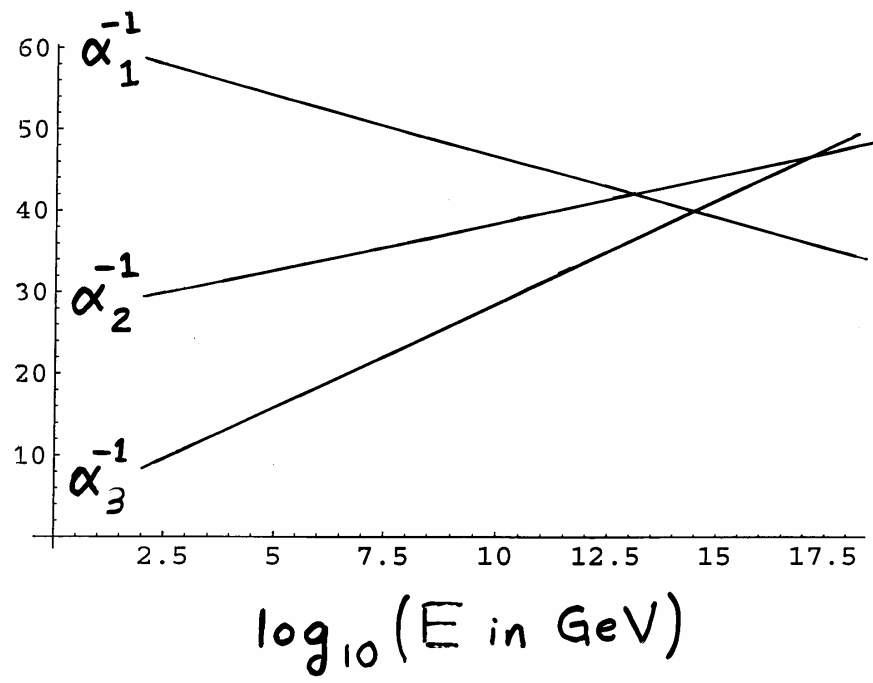
GRAND UNIFIED THEORY (GUT)

GUT IN SM

Couplings meet at high energy \rightarrow GUT!

SM: meeting not so good

SM



GUT WITH WARPED EXTRA DIMENSION

(KA, Contino, Sundrum) $hep-ph/0502222$

Evolution of couplings modified due to profiles for SM fermions

Top quark near TeV brane (heavy) \rightarrow modify starting at low energies

(KK modes do not modify **relative** evolution)

\leftrightarrow Strong dynamics with unified flavor symmetry

Top quark effect correct size and sign

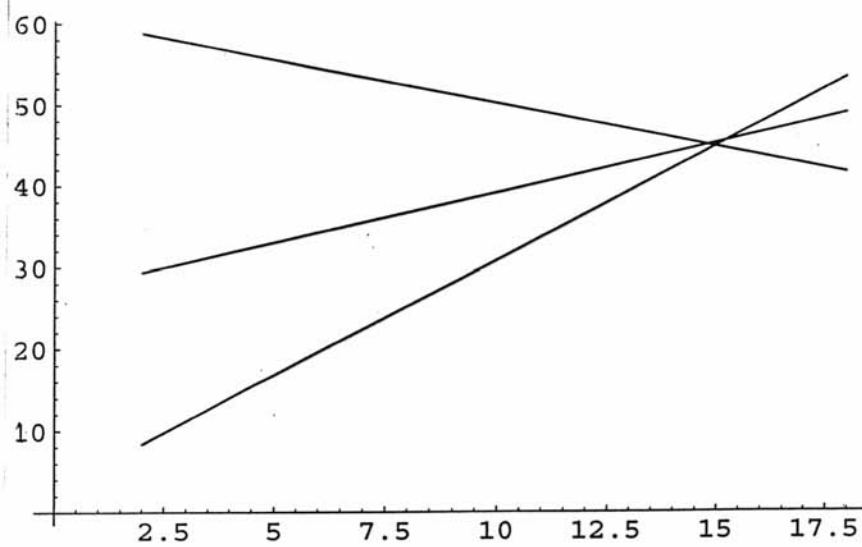


Precise meeting!

↑
heavy top

SUSY: precise meeting due to addition of superpartners

IN WARPED EXTRA DIMENSION

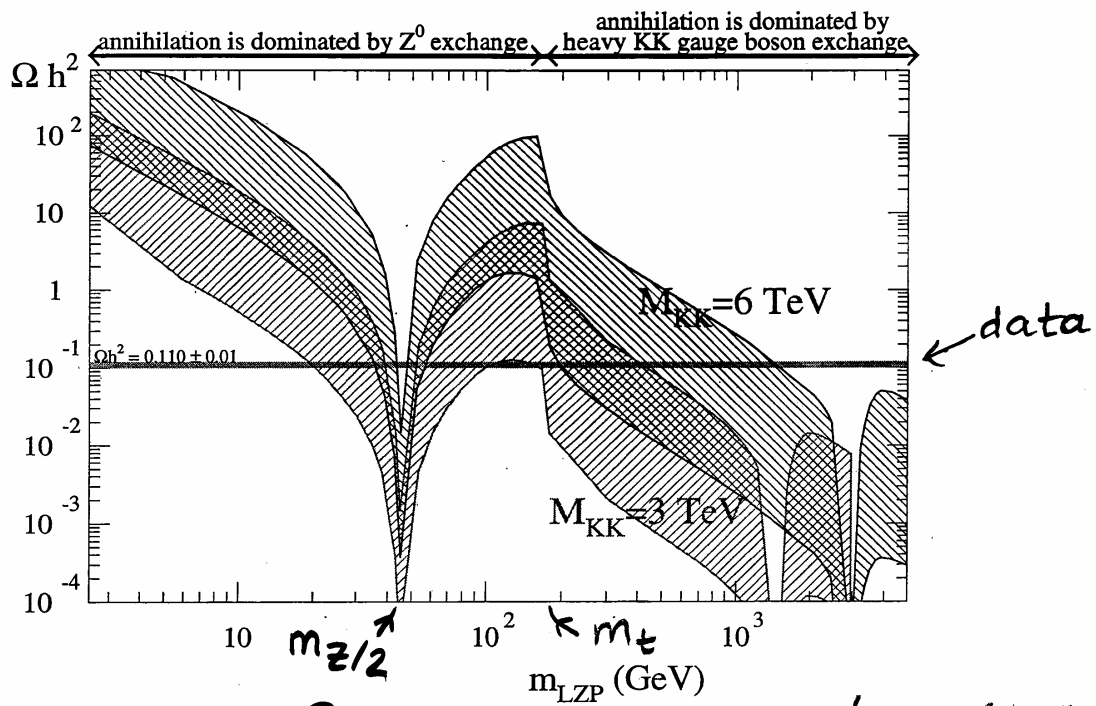


PROTON STABILITY
IN GUT

LEADS TO
DARK MATTER
(\sim SUSY)

(KA, SERVANT)

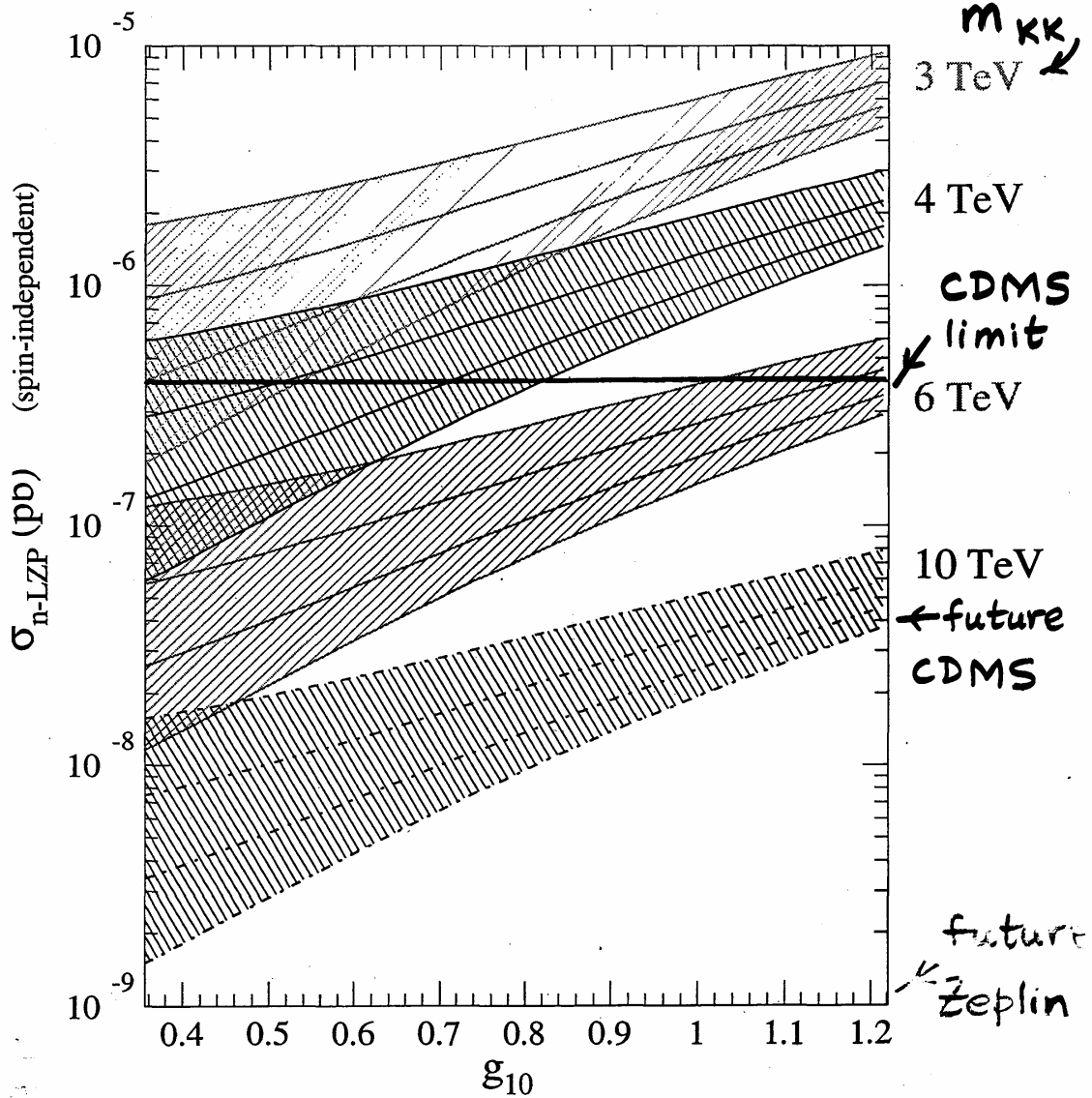
RELIC DENSITY PREDICTION



Range of Ω due to C_{tR} , g_{5D} (loop effects)

PREDICTIONS FOR DIRECT DETECTION

(RANGE OF σ due to C_{ν_R}, C_{τ_R})

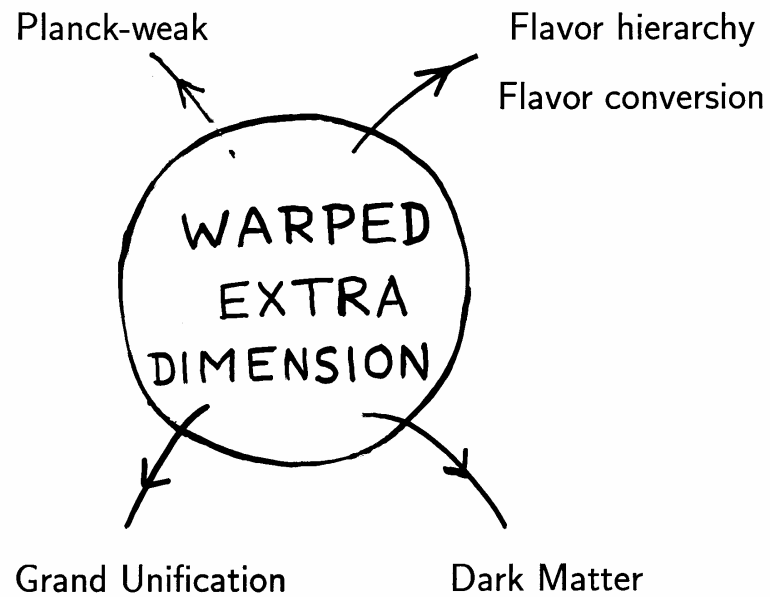


CONCLUSIONS

Composite Higgs:



solution to Planck-weak hierarchy problem of SM


WEAKLY COUPLED DUAL DESCRIPTION:
WARPED EXTRA DIMENSION



Solves puzzles of nature!

, TESTABLE!


KK at
LHC



B-factories,
LC, LHC


Direct detection (CDMS...)

We will know soon!