BEYOND THE SM (II)

Kaustubh Agashe (University of Maryland)

Hierarchy problems (from lecture 1)

- Planck-weak hierarchy problem
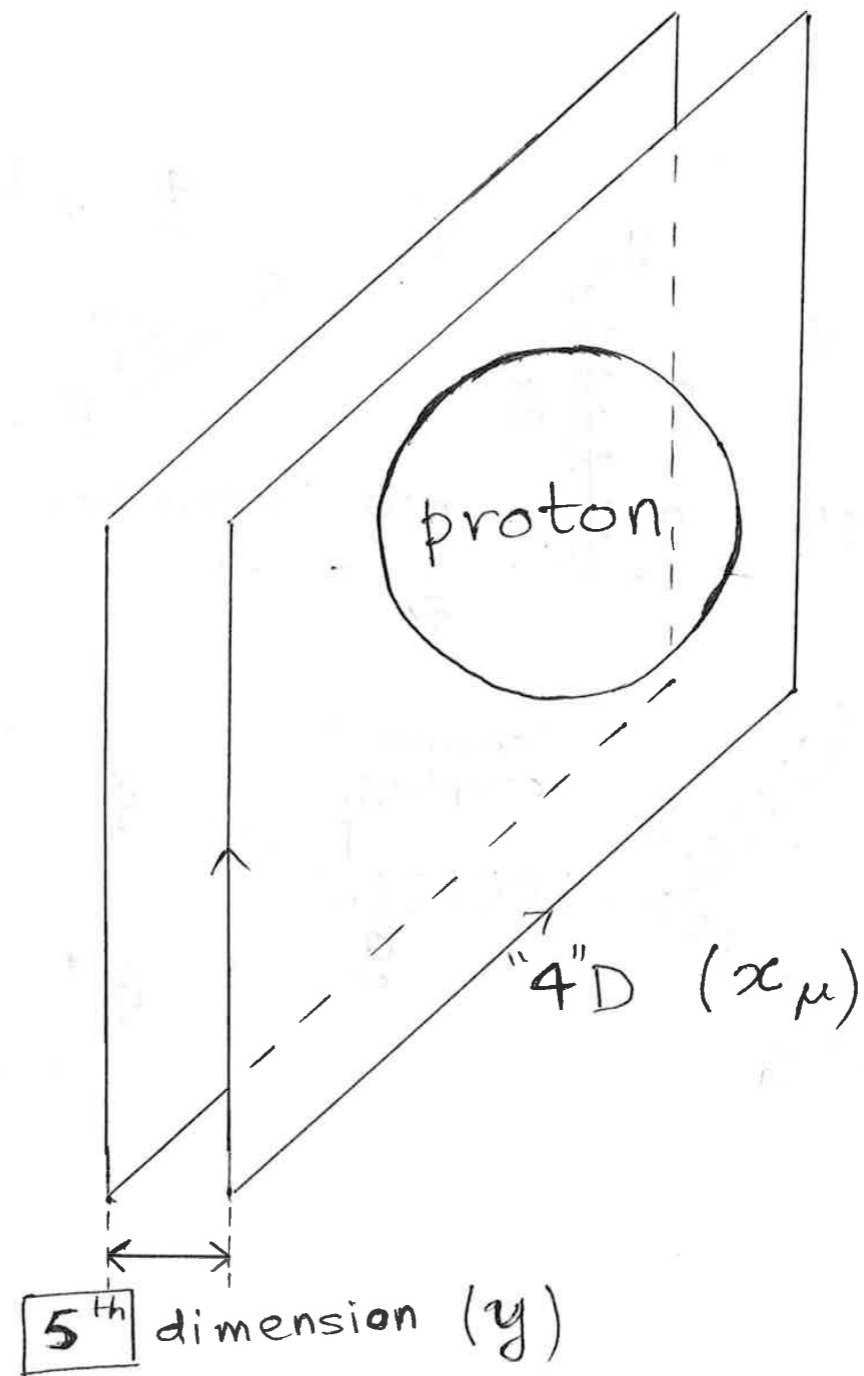
- Flavor (hierarchy) puzzle

...Extra dimensions can address both...

Extra dimensions: basic idea

(reviews in hep-ph/0404096, hep-ph/0510275, hep-th/0508134, hep-ph/0605325,...)

Why haven't we "seen" it?

It's small!

proton

"4"D (x_μ)

5th dimension (y)

Why should it be compact/"small"?

- If 5th dimension was infinite, Newton's law $\propto 1/r^3$ (Gauss' law)

- we have measured it to be $\propto 1/r^2$ down to $100\,\mu$ m

What can we see in future (I)?

- SM field (x_μ, y):
  Fourier expand (compact) y

- From 4D viewpoint,
  dynamics in y similar to
  quantum mechanics of
  particle in 1D infinite
  potential well

- Kaluza-Klein (KK) modes
  (still function of x) with
  profile in y and
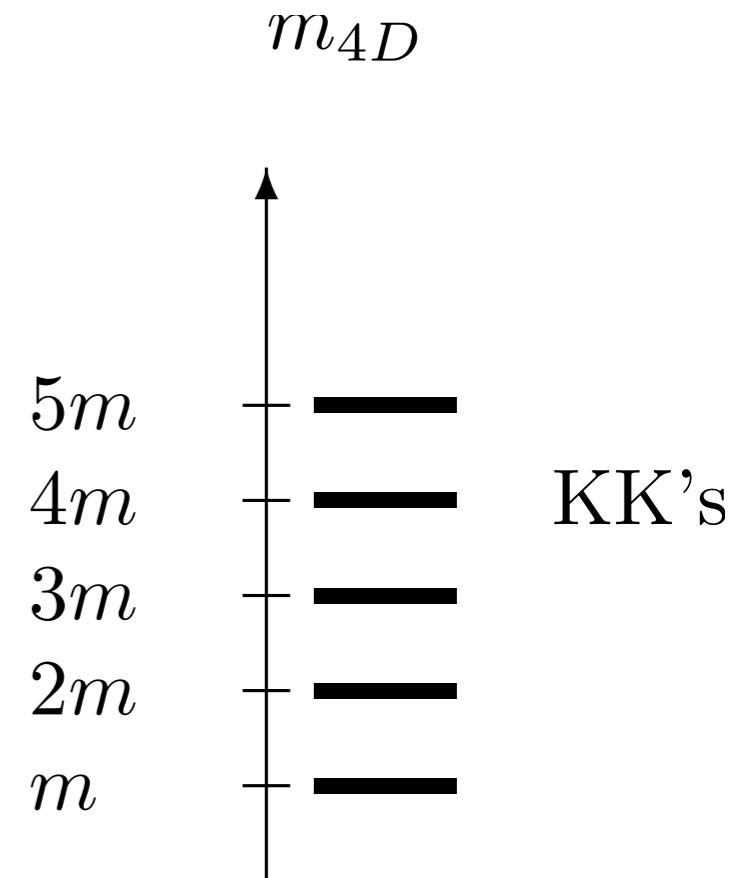 quantized $p_5 \sim n/R$
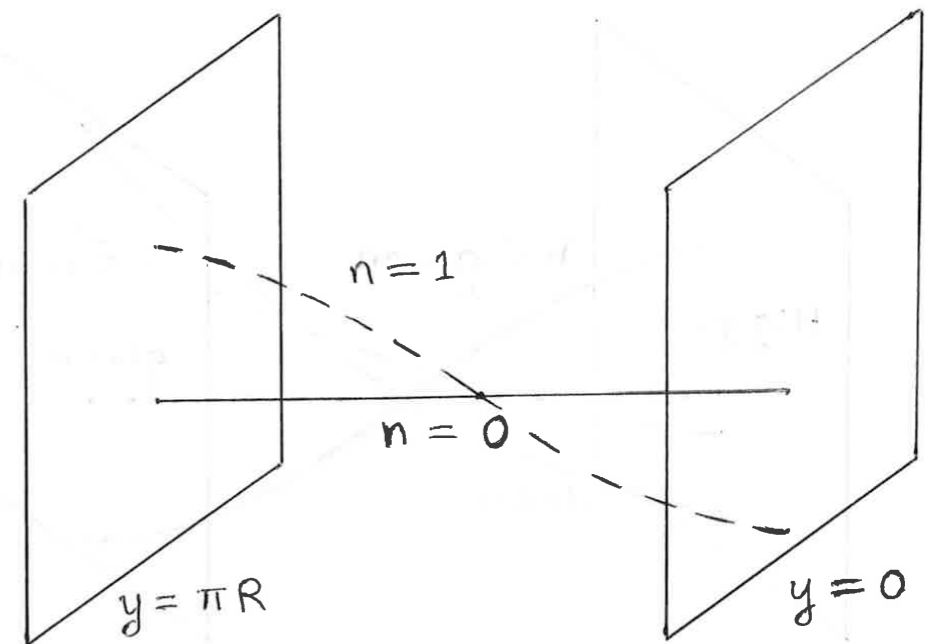
What can we see in future (II)?

- Each mode like massive field (particle upon quantization) from 4D viewpoint:

m_{4D}

set to 0

$$E^2 = |\bar{p}|^2 + p_5^2 + M_{5D}^2 \Rightarrow$$

$\bar{p} = 0$ mode (at rest in 3D): $E \sim n/R \Rightarrow$

(rest) mass, $m_{4D} \sim n/R$

$5m$

$4m$ — KK's

$3m$

$2m$

m

- p_5 "converted" to 4D mass

- lightest mode ($n = 0$) identified with observed/SM

- heavier (KK) modes ($n \neq 0$):
  new particles (signals + solve problems)

- KK mass scale $> \sim$ I TeV, haven't seen it yet!

Technically: (real) scalar field on circle

$$S_{5D} = \int d^4x \int dy \left[(\partial^M \Phi)(\partial_M \Phi) - M_{5D}^2 \Phi \Phi \right]$$

- Compacfity on a circle (S^1):
  $-\infty < y < \infty$ with $y \equiv y + 2\pi R$

Periodic boundary condition: $\Phi(y = 2\pi R) = \Phi(y) \Rightarrow$

$$\Phi = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{n=+\infty} \phi^{(n)}(x) e^{iny/R}$$

Substitute into S_{5D}, use orthogonality of profiles:

$$S_{4D} = \int d^4x \sum_n \left[\left(\partial_\mu \phi^{(n)} \right) \left(\partial^\mu \phi^{(n)} \right) - \left(M^2 + \frac{n^2}{R^2} \right) \phi^{(n)} \phi^{(n)} \right]$$

- 4D viewpoint: Tower of $4D$ fields (KK modes),
  $\phi^{(n)}$ with mass^2: $m_{4D\ n}^2 = M_{5D}^2 + n^2/R^2$ (n^2/R^2 from ∂_5 acting on profile)

Technically: Fermion field on orbifold

- on circle: fermion zero-modes not chiral (both LH and RH) (unlike SM: LH doublet, RH singlet) ⟹

- go to orbifold to project out one zero-mode:

$$S^1/Z_2: y \leftrightarrow -y \text{ in addition to } y \equiv y + 2\pi R$$

- exponential profile for fermion zero-modes (cf. flat for scalar earlier) due to 5D mass term:

$$\text{not } m_{4D}$$

$$\sim e^{-M_{5D\,L}y}, e^{+M_{5D\,R}y}$$

(Solve more general wave equation to obtain modes: can get exponential profile for zero-mode even for scalar)

Technically: gauge field...

$$\mathcal{A}_M = \mathcal{A}_{\mu=0,1,2,3} + \mathcal{A}_5$$

- $\mathcal{A}_\mu$ modes behaves as vectors (spin-1) from 4D viewpoint

- $\mathcal{A}_5$ modes behaves as scalars from 4D viewpoint (Higgs?...see later)

- zero-mode flat; KK sin/cos...

Interactions...

5D Dirac matrices

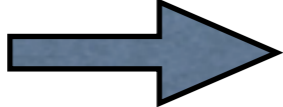$$\int d^4x \, dy \, g_{5D} \bar{\Psi} \underline{\Gamma^M} \mathcal{A}_M \Psi \Rightarrow$$

$$\int d^4x \, g_{4D \; mnp} \psi_L^{(m)} A_\mu^{(n)} \gamma^\mu \psi_L^{(p)} :$$

$$g_{4D \; mnp} \sim g_{5D} \int dy \; \left(m^{th} \text{profile}\right) \times \left(n^{th} \text{profile}\right) \times \left(p^{th}...\right)$$

$\Rightarrow$

- coupling between modes $\propto$ overlap of profiles

Summary

- 5D field $\Longrightarrow$ tower of (massive) KK modes (from 4D viewpoint)

- profiles from (generalized) wave equation in 5D space-time

- Coupling of particles $\propto$ overlap of profiles

Extra dimensions: "application"

Solution to flavor (hierarchy) puzzle

Yukawa coupling: $\Gamma_{4D} \sim \Gamma_{5D} \times \int dy\, e^{(-M_{5D\ L} + M_{5D\ R} + M_{5D\ \phi})y}$

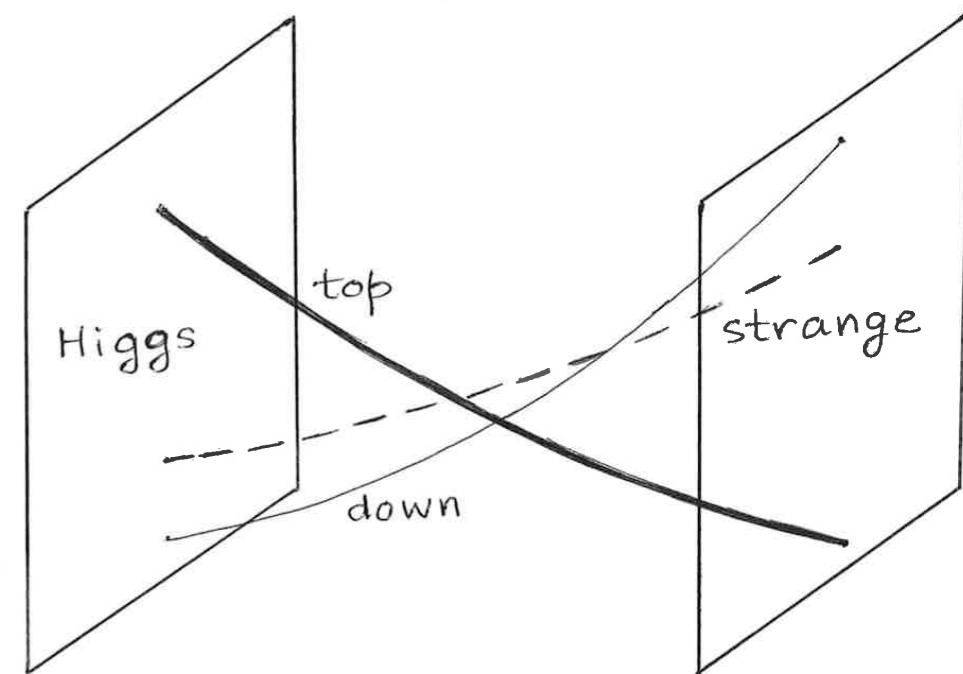- choose M's so that overlap near Higgs brane dominates

  ⟹

- $m_d \ll m_s$ due to hierarchical fermion profiles at Higgs brane:

  $\Gamma_{4D} \sim \Gamma_{5D}\, e^{(-M_{5D\ L} + M_{5D\ R})\pi R}$

  (do not need hierarchies in 5D Yukawa or M_{5D} for fermions)

- 1-2 (Cabbibo) mixing also small:

  $\Gamma_d^{22} \gg \Gamma_d^{12} \gg \Gamma_d^{11}$

What about neutrino mass?

- Add ν_R with profile...similar to quarks?

- ...but neutrino masses VERY small and mixing large!

- choose $M_{5D\ \nu_R}$ so that overlap near other brane dominates:

$$\Gamma_{4D} \sim \Gamma_{5D}\ e^{(-M_{5D\ \phi})\pi R}$$

- very small neutrino mass due to Higgs tail:

NOT due to smallness of ν profiles at Higgs brane: cf. quarks and charged leptons

- mixing large since all 3 profiles similar near other brane:

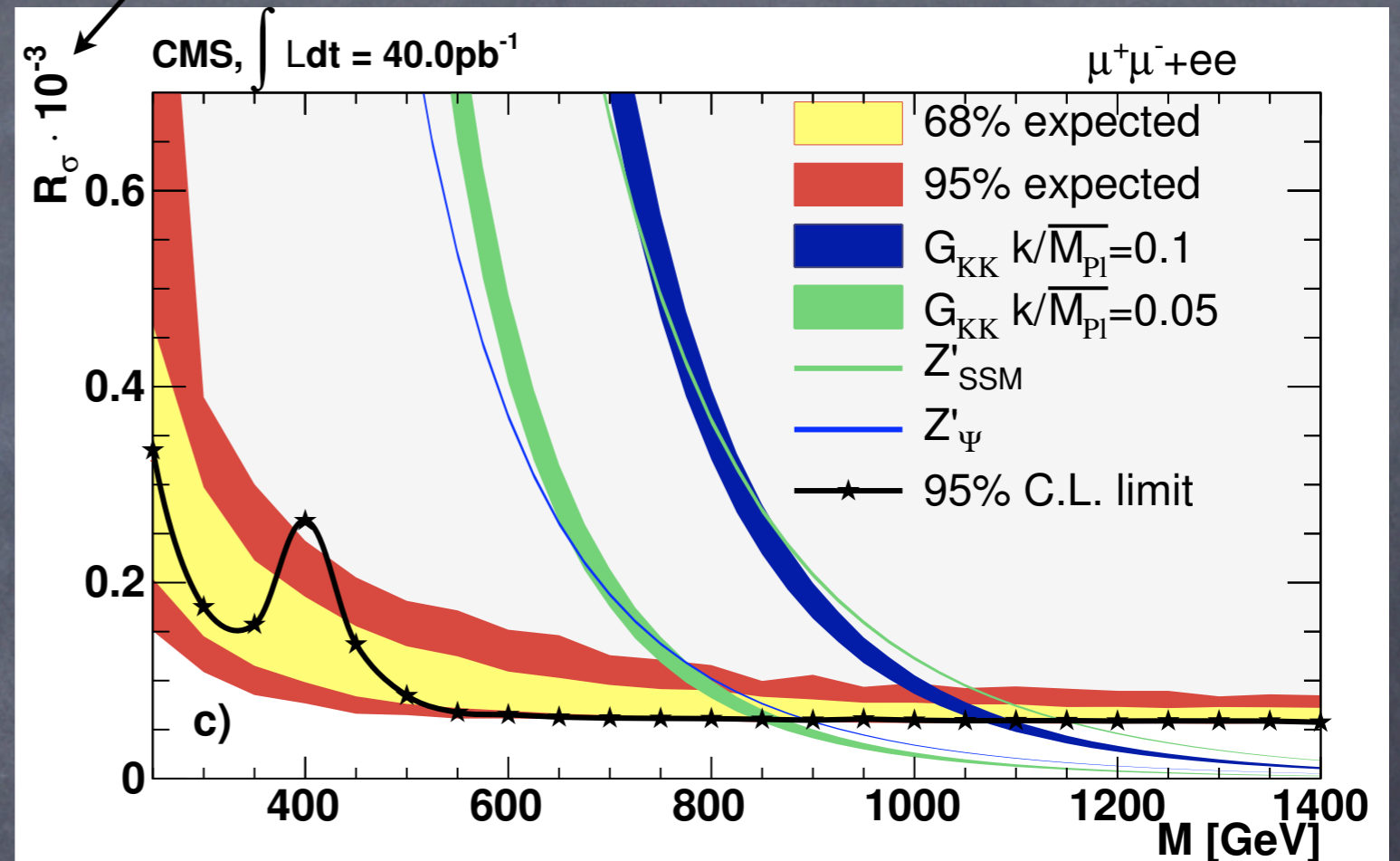$$\Gamma_\nu^{33} \sim \Gamma_\nu^{23} \sim \Gamma_\nu^{22}$$

Signals for KK modes (I)

- resonant production of single KK gauge mode a la SM Z:

$$q\bar{q} \rightarrow \text{KK } Z \rightarrow l^+ l^-$$

- peak in dilepton invariant mass...

- adapt LHC Z′ search (include appropriate couplings)
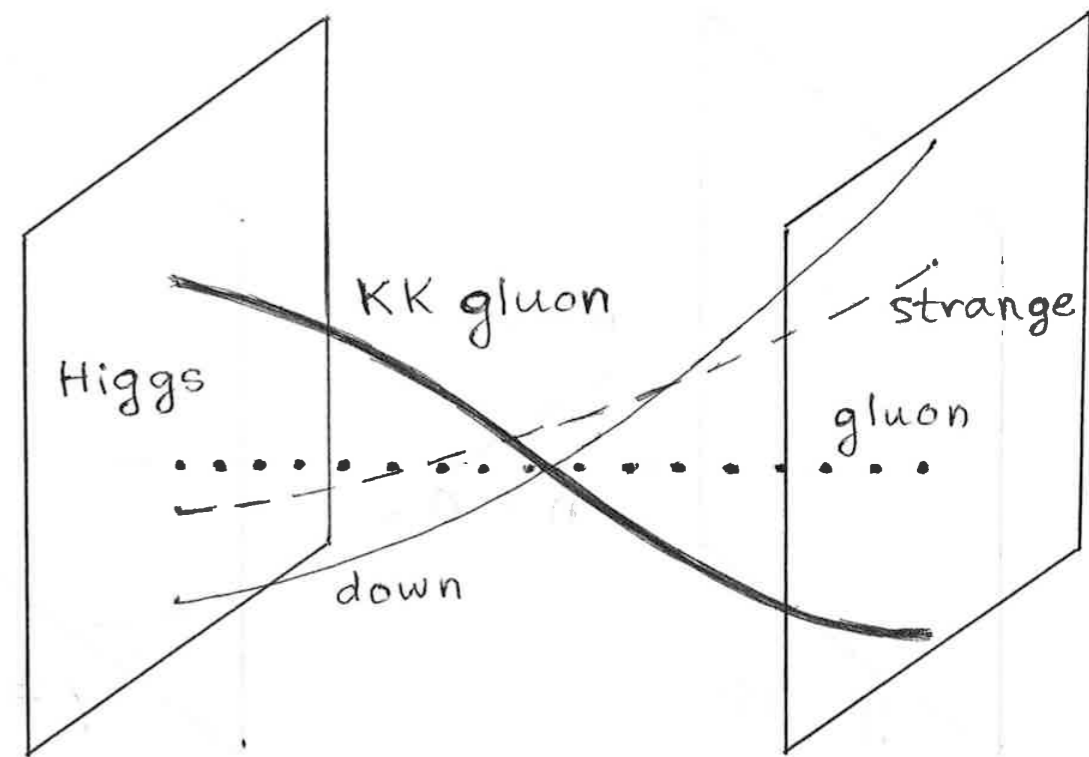
ratio of Z′ and SM Z cross-section x BR

CMS, $\int$ Ldt = 40.0pb^{-1} $\mu^+\mu^-$+ee

- 68% expected
- 95% expected
- G_{KK} k/$\overline{M_{Pl}}$=0.1
- G_{KK} k/$\overline{M_{Pl}}$=0.05
- Z′$_{SSM}$
- Z′$_{\Psi}$
- 95% C.L. limit

$R_\sigma \cdot 10^{-3}$
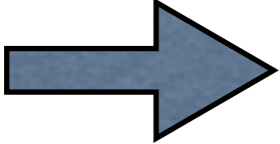
M [GeV]

c)

(from 1103.0981)

Signals for KK modes (II)

- Coupling to KK gauge mode is flavor-dependent: in overlap, KK common, but fermion varies

- cf. coupling to gauge zero-mode (flat) is universal

  (see later: flavor problem; KK gluon decays mostly to top quarks)

Summary

- solution to flavor (hierarchy) puzzle based on fermion profiles in extra dimension...

- ⟹ KK/massive gluon, Z... resonances

- LHC sensitive only if KK mass scale $\sim$ TeV...

- ...but (so far) can be (much) heavier (smaller ruled out by current limits)

- ...it IS TeV if use extra dimension to also solve Planck-weak hierarchy problem...

Extra dimensions: "complete" model

Extra dimension solves Planck-weak hierarchy problem (I)

- KK particles cut-off Higgs mass divergence...like superpartners, KK's must be <~TeV

- Principle is: Higgs is $\mathcal{A}_5$ mode ("extra" component of 5D gauge field)

- no quadratic divergence from $E \gtrsim \text{KK mass scale } (5D \text{ regime})$: (5D) gauge invariance protection "extended" from spin-1 to 0 (the two 4D spins are related via 5th dimension)

...cf. SUSY...

- (chiral) symmetry protection for fermion... extended to scalar...

- ...the two spins (differing by 1/2) related by SUSY

Extra dimension solves Planck-weak hierarchy problem (II)

- Like SUSY, "new" hierarchy problem:
  KK mass scale $\ll M_{Pl}$?

- Solution: warped extra dimension...

Warped extra dimension intuitively

- Analogy with expanding universe

- gravitational red-shift generates hierarchies in mass scale between different positions in 5th dimension
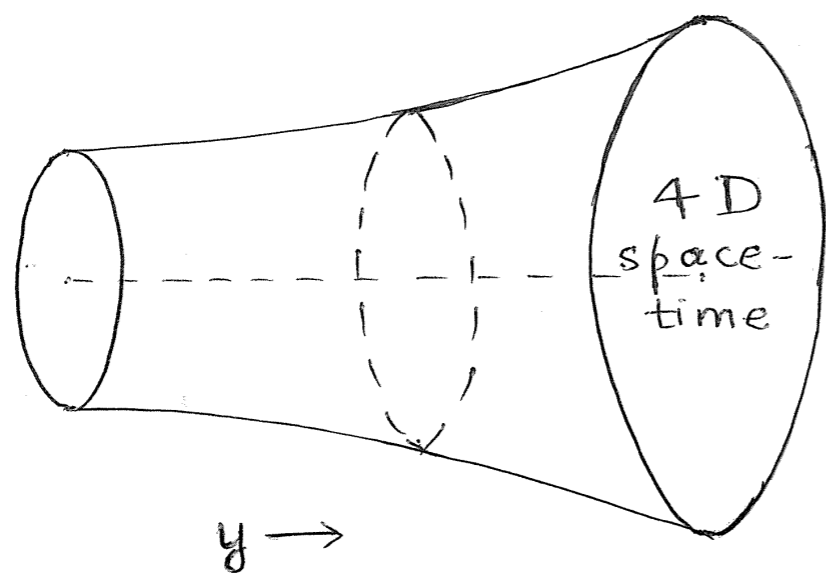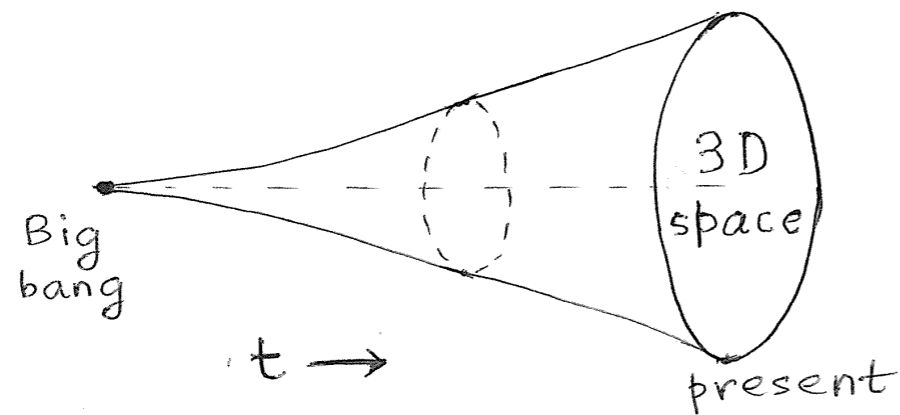
3D space expands with time

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

Warped extra dimension technically (I)

- Bulk + brane cosmological constants $\Rightarrow$

flat 4D

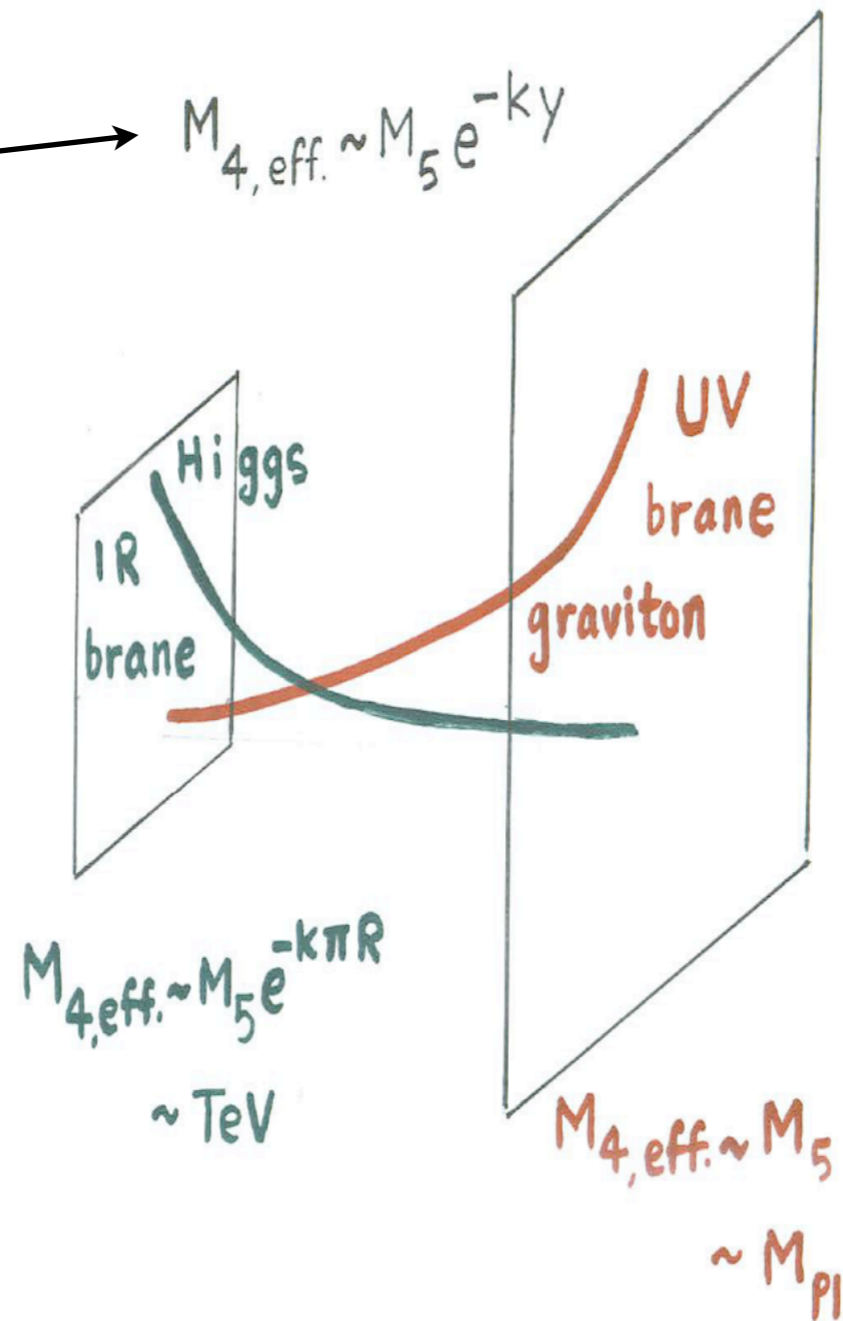$$(ds)^2 \;=\; e^{-2ky}\eta_{\mu\nu}(dx)^\mu(dx)^\nu + (dy)^2$$

- Master equation:

$$M_{4D,\,\text{eff.}}(y) \;\sim\; M_{5D,\,\text{fund.}} \times e^{-ky}\ (\text{warp factor})$$

- Gravity and Higgs: Randall-Sundrum (RS1) model

apply master...at 2 ends...

$M_{4,\,eff.} \sim M_5 e^{-ky}$

Higgs

IR brane

UV brane

graviton

$M_{4,eff.} \sim M_5 e^{-k\pi R}$

$\sim$ TeV

$M_{4,\,eff.} \sim M_5$

$\sim M_{Pl.}$

Need $kR \sim \log\left(M_{Pl}/\text{TeV}\right)/\pi \sim 10$:
Exponential $4D$ hierarchy
from $O(10)$ hierarchy in $5D$ theory!

- ...due to curvature (cf. flat extra dimension earlier)

- KK mass ~ Higgs brane scale (~ TeV)

- KK's couple strongly to Higgs, top
(weakly to light fermions): based on overlap of profiles
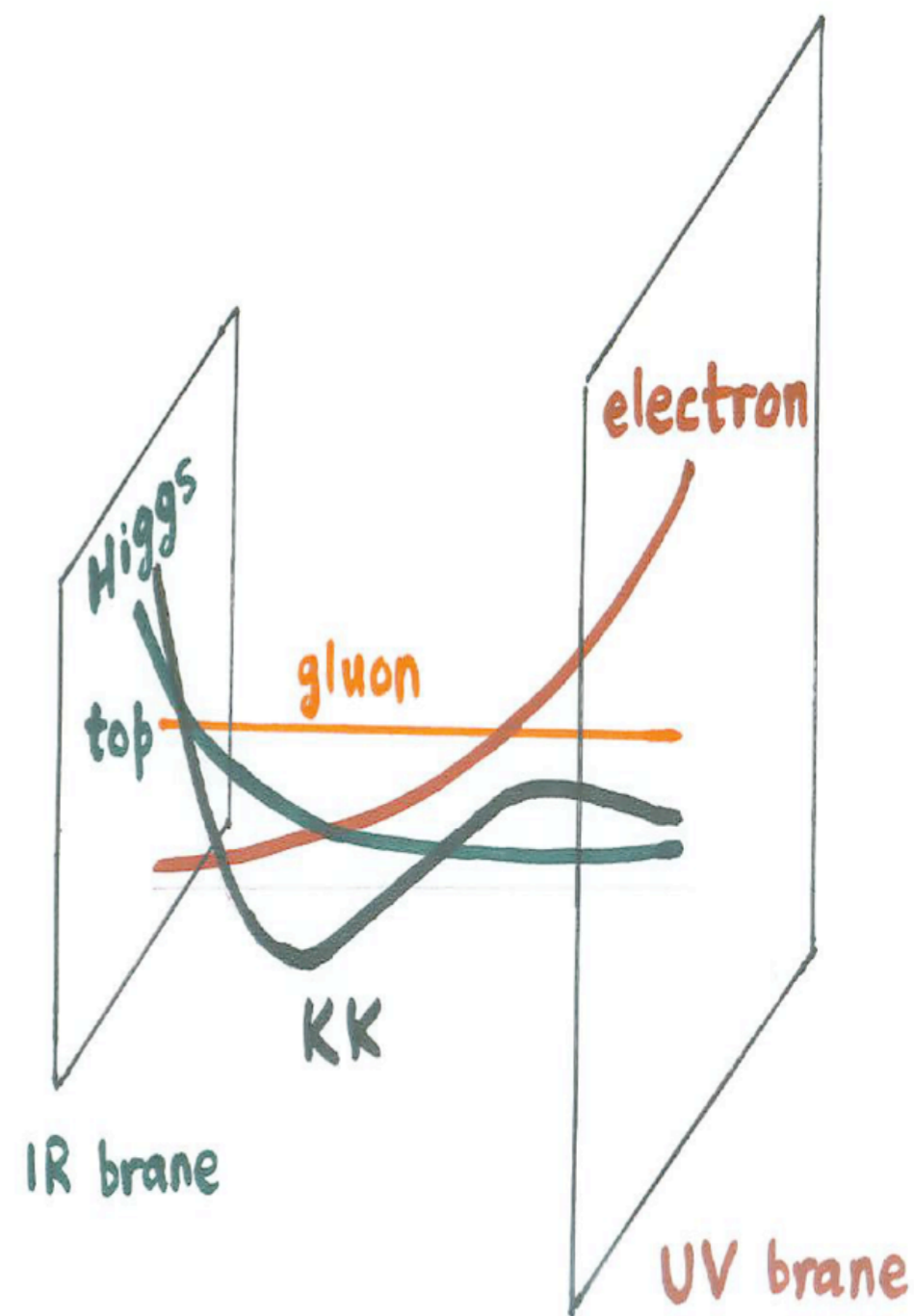
KK gluon signal: decays to top

- production suppressed due to small coupling to proton

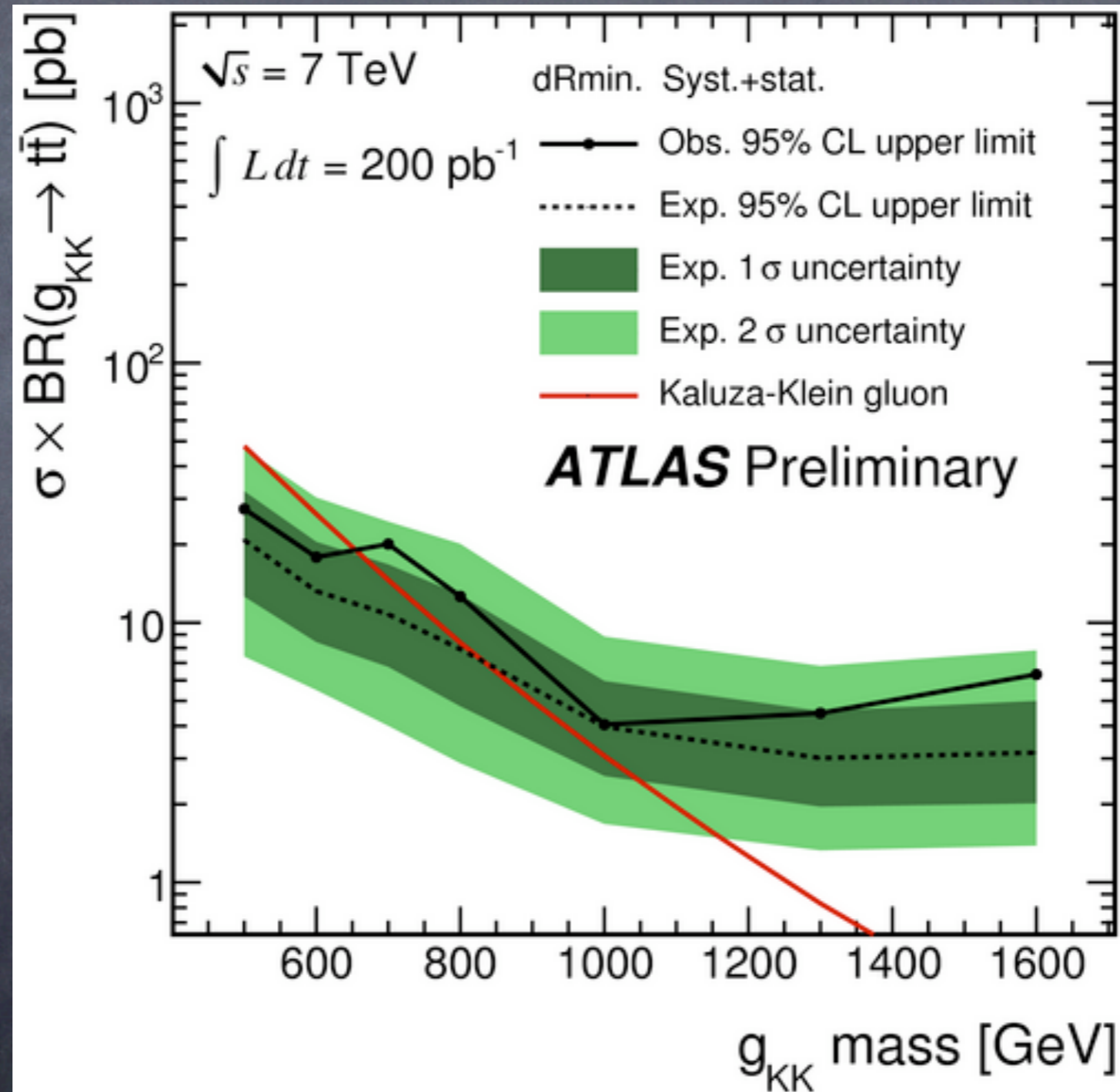- decay dominated by top quark with stronger coupling
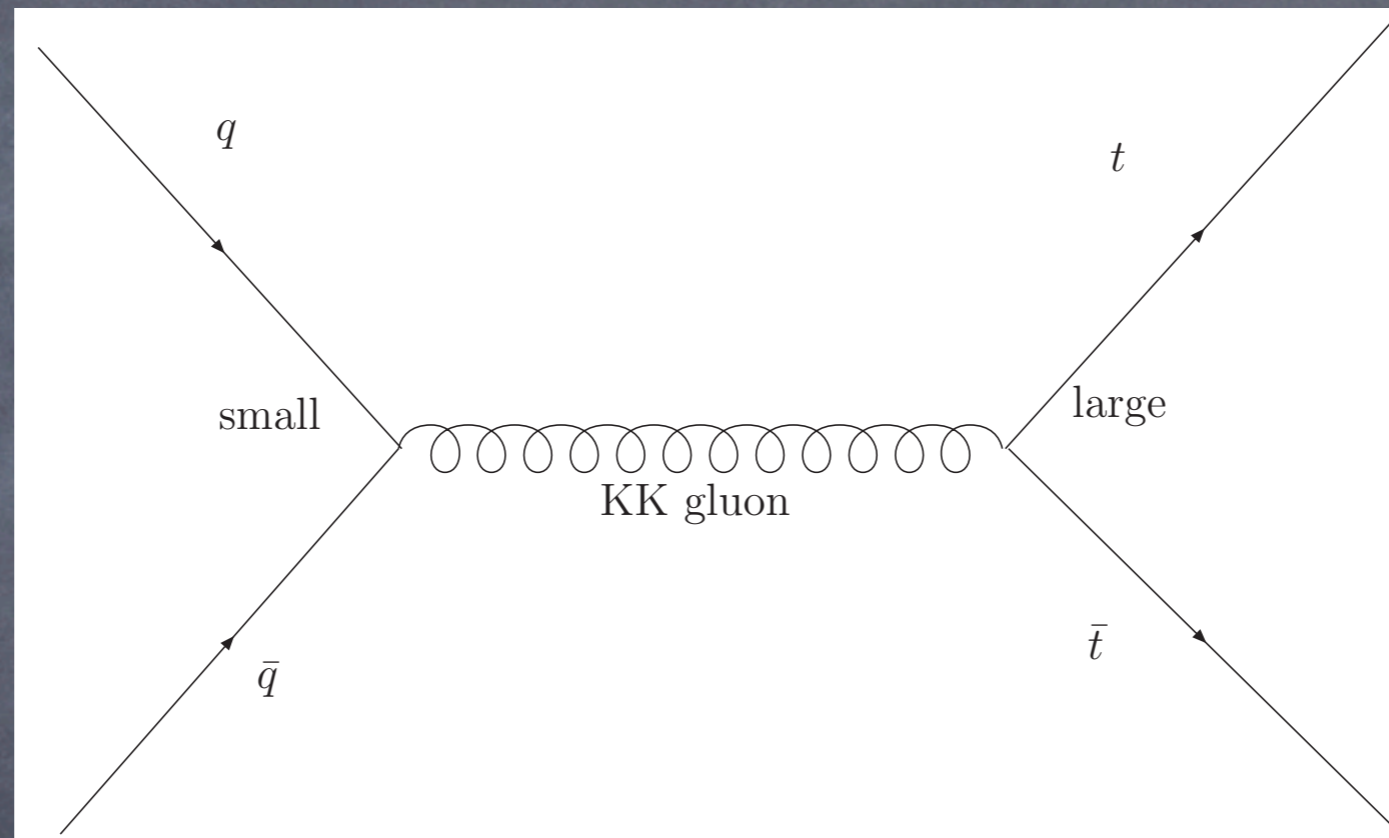
- mass $> \sim 3$ TeV due to constraints from virtual effects (see later)

KK gluon signal: decays to boosted top

- E of each top quark is 1.5 TeV

- top decay products (bW; W->...) collimated

- looks like QCD jet at 0th order

- jet substructure (see Soper's lectures)to distinguish the two
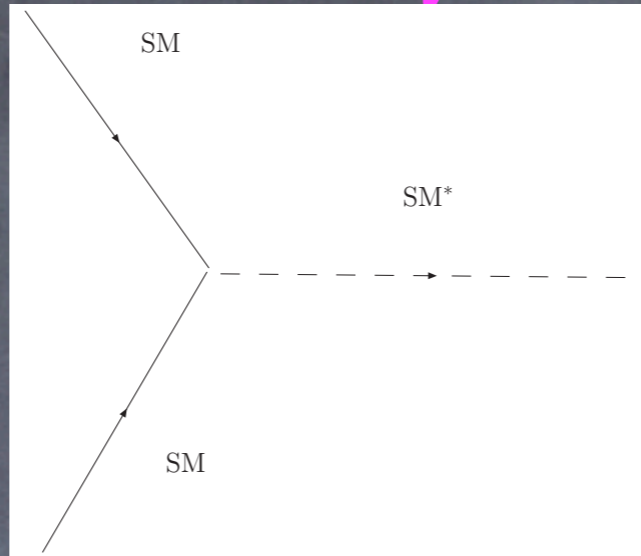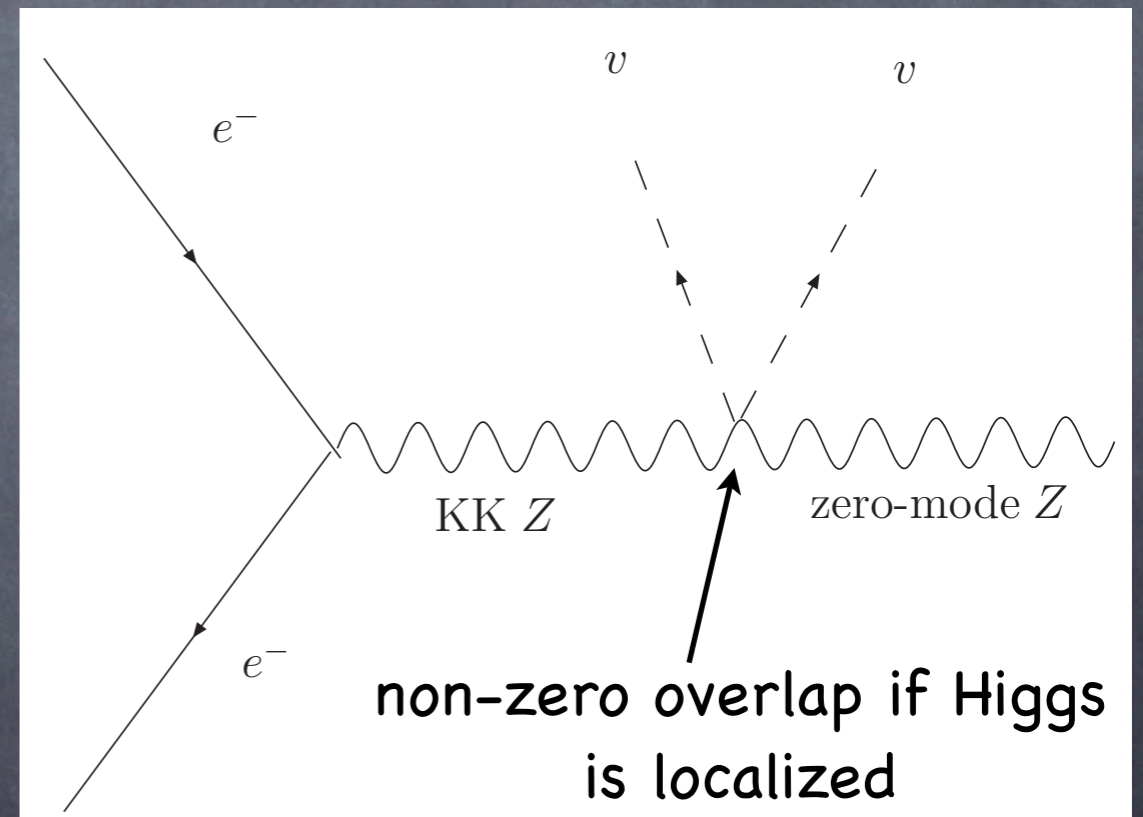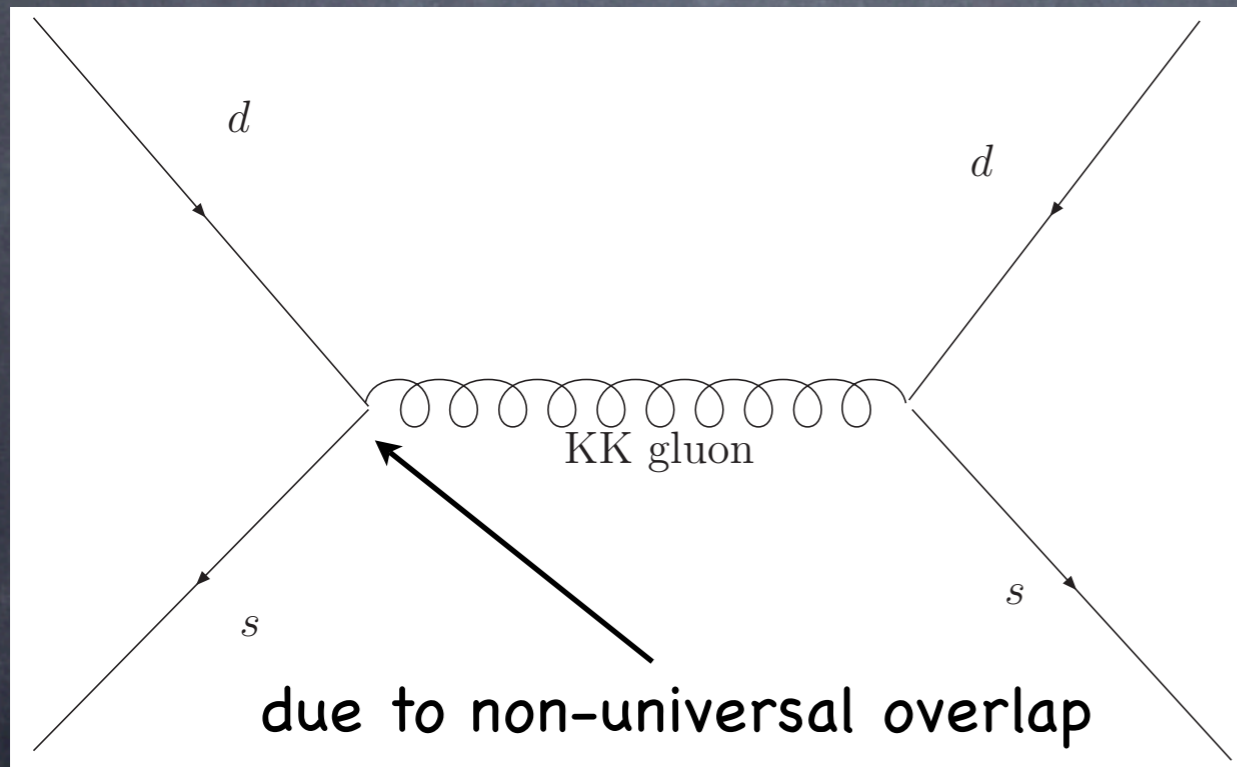
...not there yet...

from ATLAS-CONF-2011-087

Virtual effects of KK modes

Summary (rough)

- no parity

- tree-level contributions to flavor and EW precision tests

due to non-universal overlap

non-zero overlap if Higgs is localized

- limit on KK scale:~$O(10)$ TeV [built-in mechanism: cf. $O(1000)$ TeV in SUSY] → $O(3)$ TeV model-building/mild tuning

AdS/CFT "duality"

- tower of KK's like tower of hadrons from (purely) 4D strong dynamics

- warped extra dimension solution dual to Higgs compositeness at TeV scale