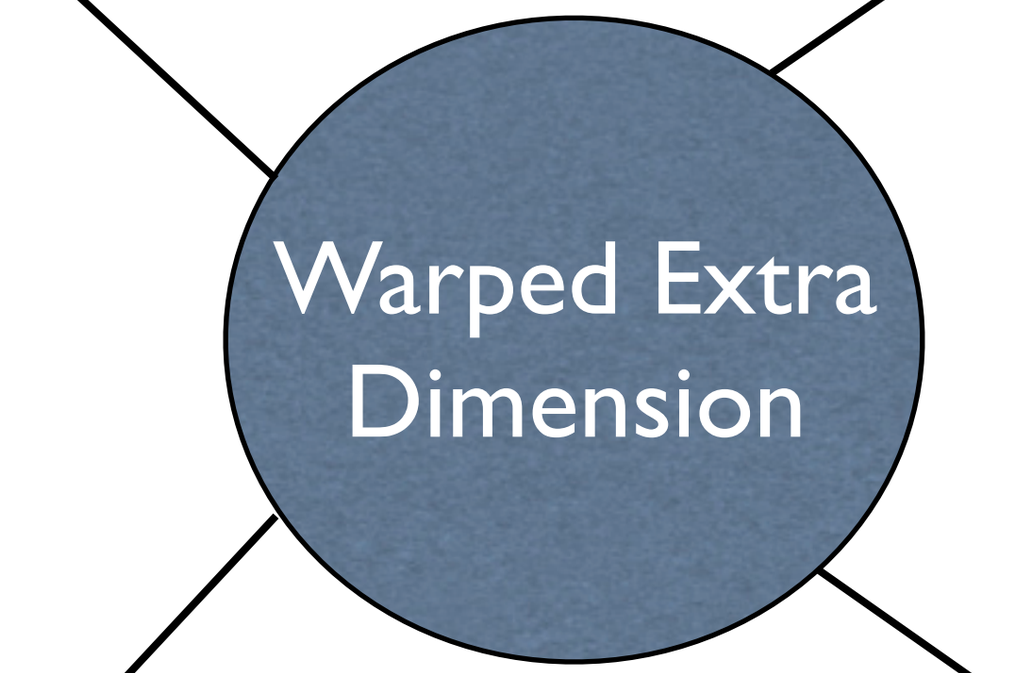
PARTICLE PHYSICS FROM A WARPED EXTRA DIMENSION

Kaustubh Agashe (University of Maryland)

Open questions of Standard Model of Particle Physics...addressed by warped extra dimension

Why is gravity weak

Why is up quark lighter than top



Grand Unification of 3 forces

Candidate for Dark Matter of Universe

Range of experiments will test...

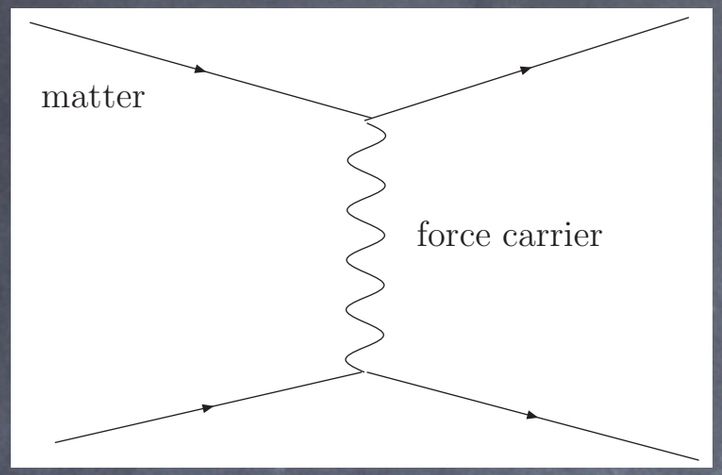
Alternative to SUSY

- Supersymmetry (SUSY) relates fermions (spin-1/2...) to bosons (spin-0...)
- New structure of space-time (like extra dimension)

Review of Standard Model (SM)

Theory of interactions of elementary particles

- Forces due to exchange of spin-1 gauge bosons



(Feynman diagram)

strong	EM	weak
gluon	photon	W, Z

- Fermionic (spin-1/2) matter

"flavors"

Quarks (strong interactions)

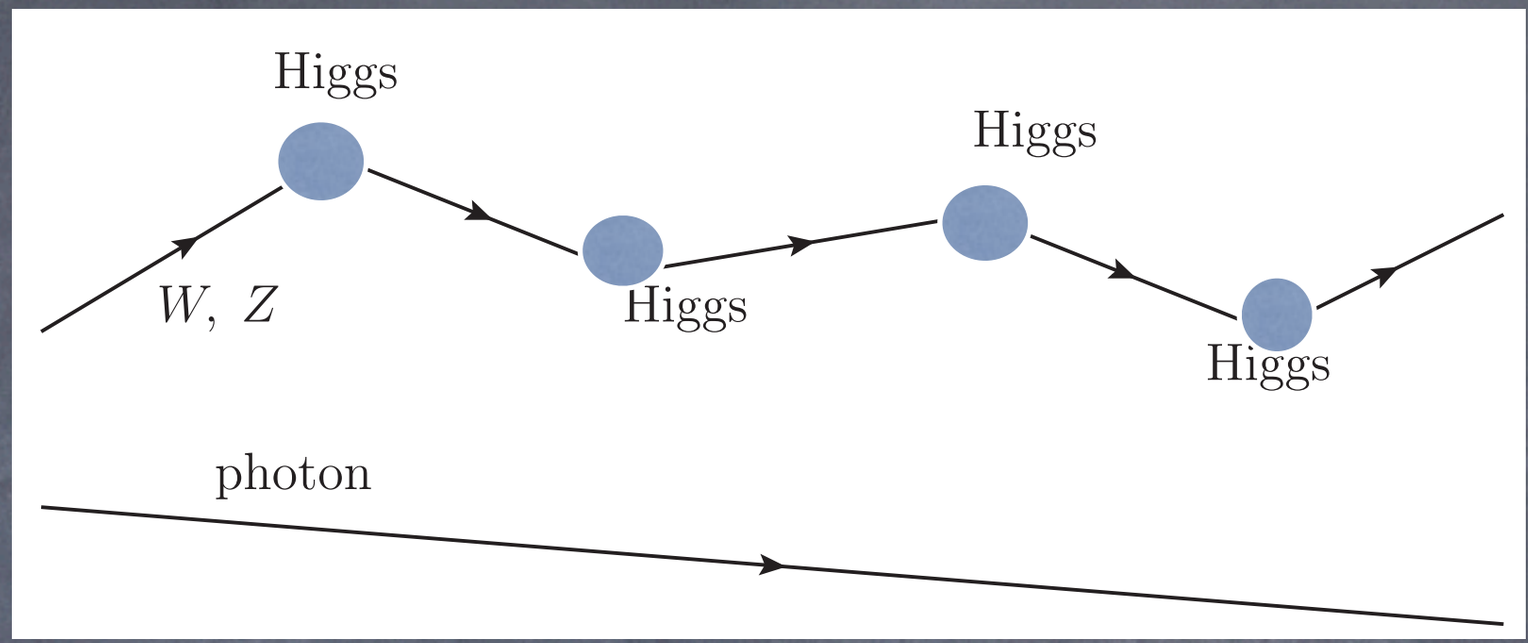
$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

leptons (no strong...)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Higgs boson (origin of masses...)

- EM and Weak unified into ElectroWeak force



- W, Z massive (short range for weak force) via coupling to Higgs (spin-0) condensate
- photon massless (Higgs condensate is neutral)

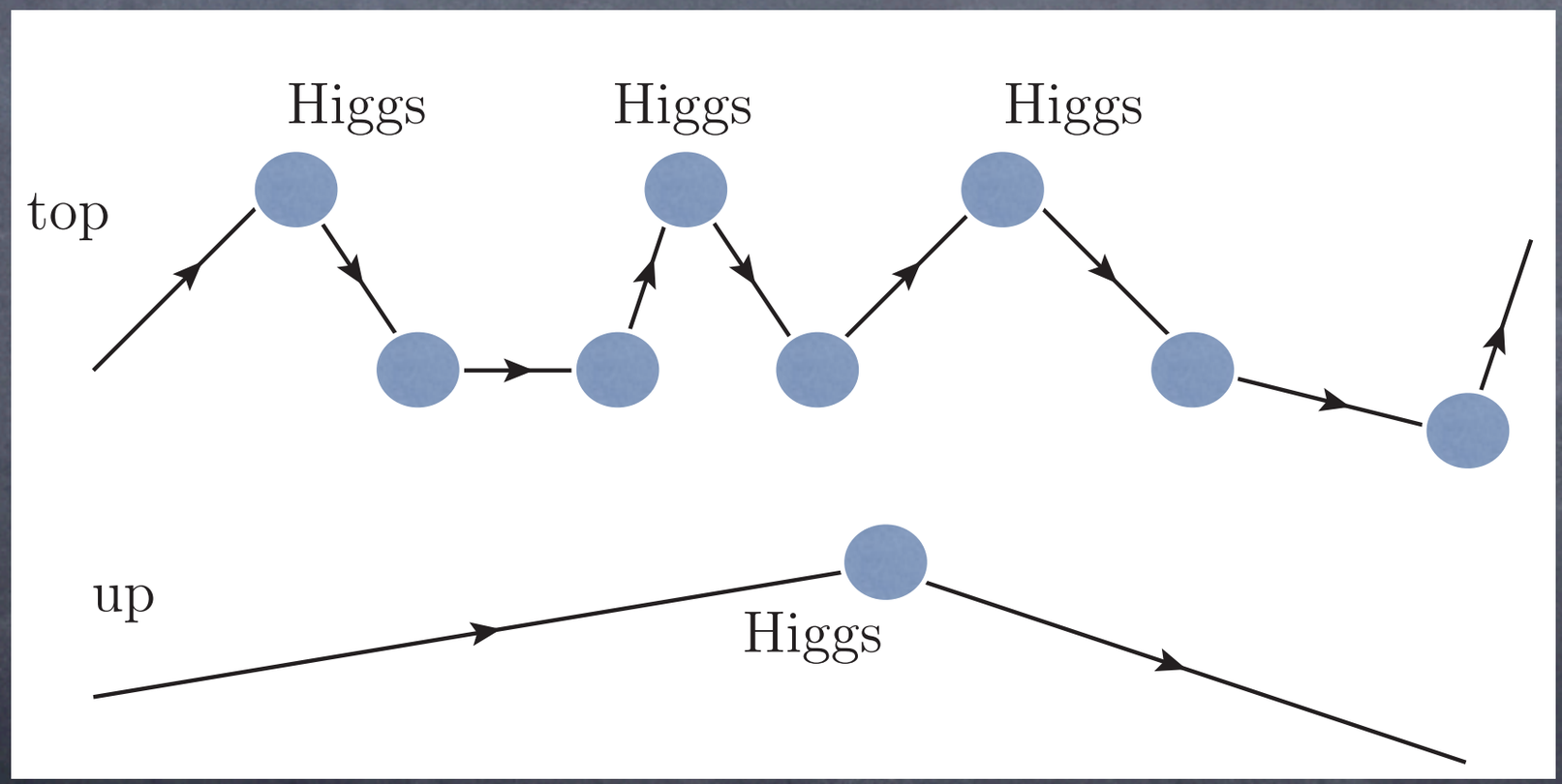
(a la superconductor: massive photon via coupling to condensate of Cooper pairs)

Size of Higgs condensate

- Mass $\sim$ condensate x coupling $\Longrightarrow$ dimensionless $(h = 2\pi,\ c = 1)$

Condensate $M_{weak} \sim 100$ GeV from W,Z masses and couplings

- Fermions: Top (up quark) is heavy (light) due to large (small) coupling to Higgs condensate



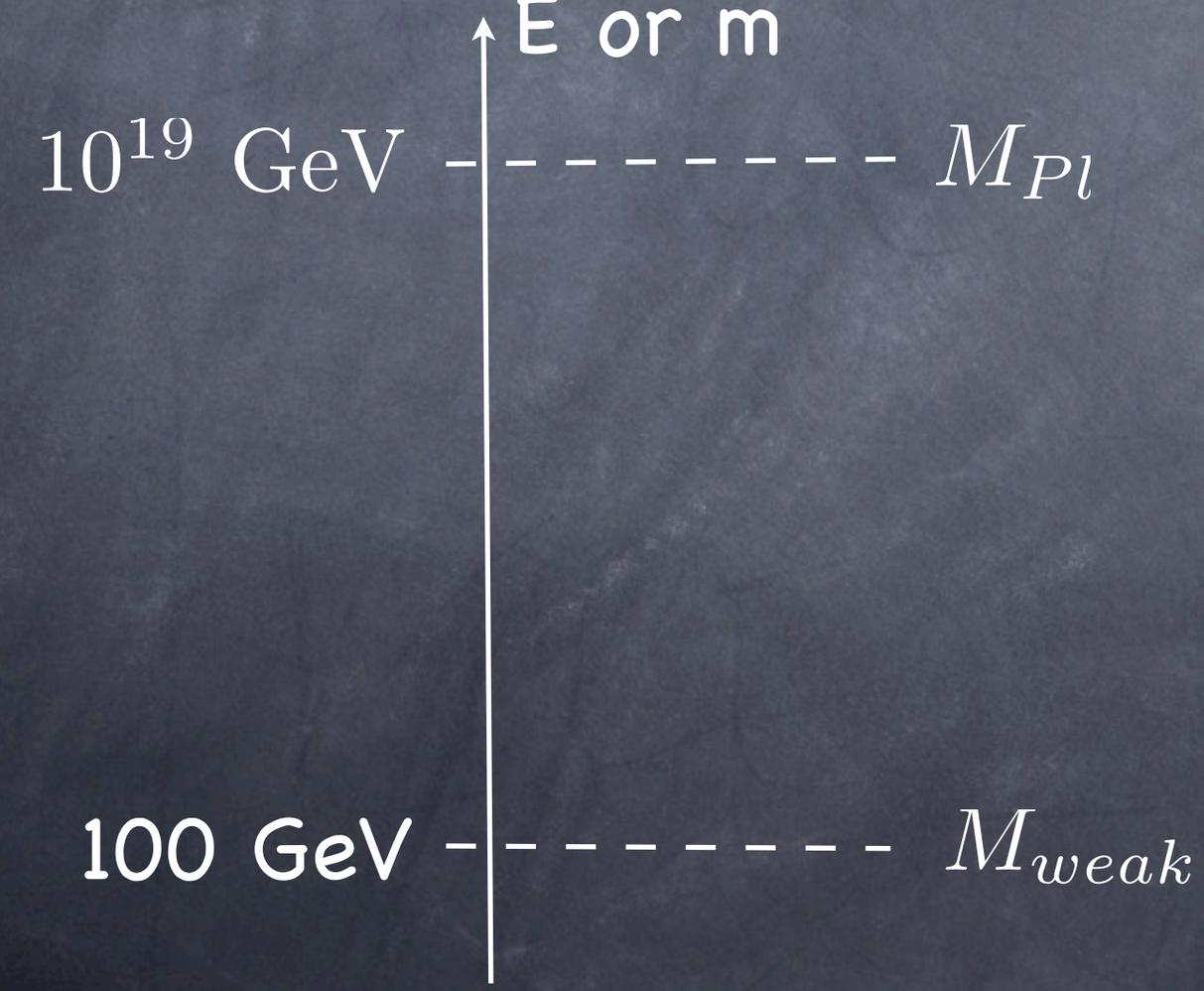
- M_{weak} $\sim$ mass scale of heaviest SM particles
- reach of current colliders (LHC)$\sim$ 1 TeV = 1000 GeV

Hierarchy Problem

Evidence for higher mass scales

- Quantum gravity ⟹ new physics at

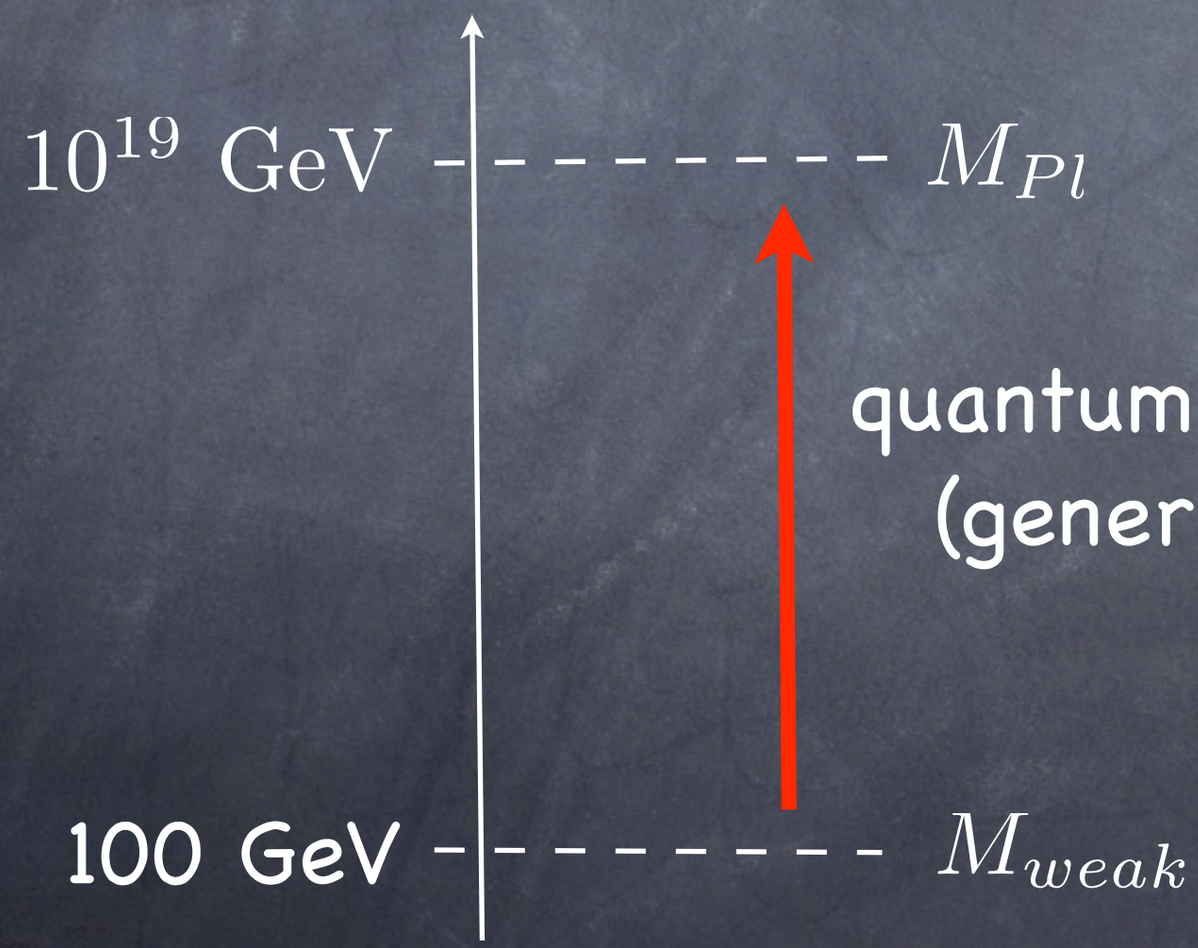
$$M_{Pl} \sim \sqrt{\hbar c^5 G_N^{-1}} \sim 10^{19}\ \mathrm{GeV}$$



Higgs condensate ⟶ higher scale

- Quantum corections (spin-0) ⟹

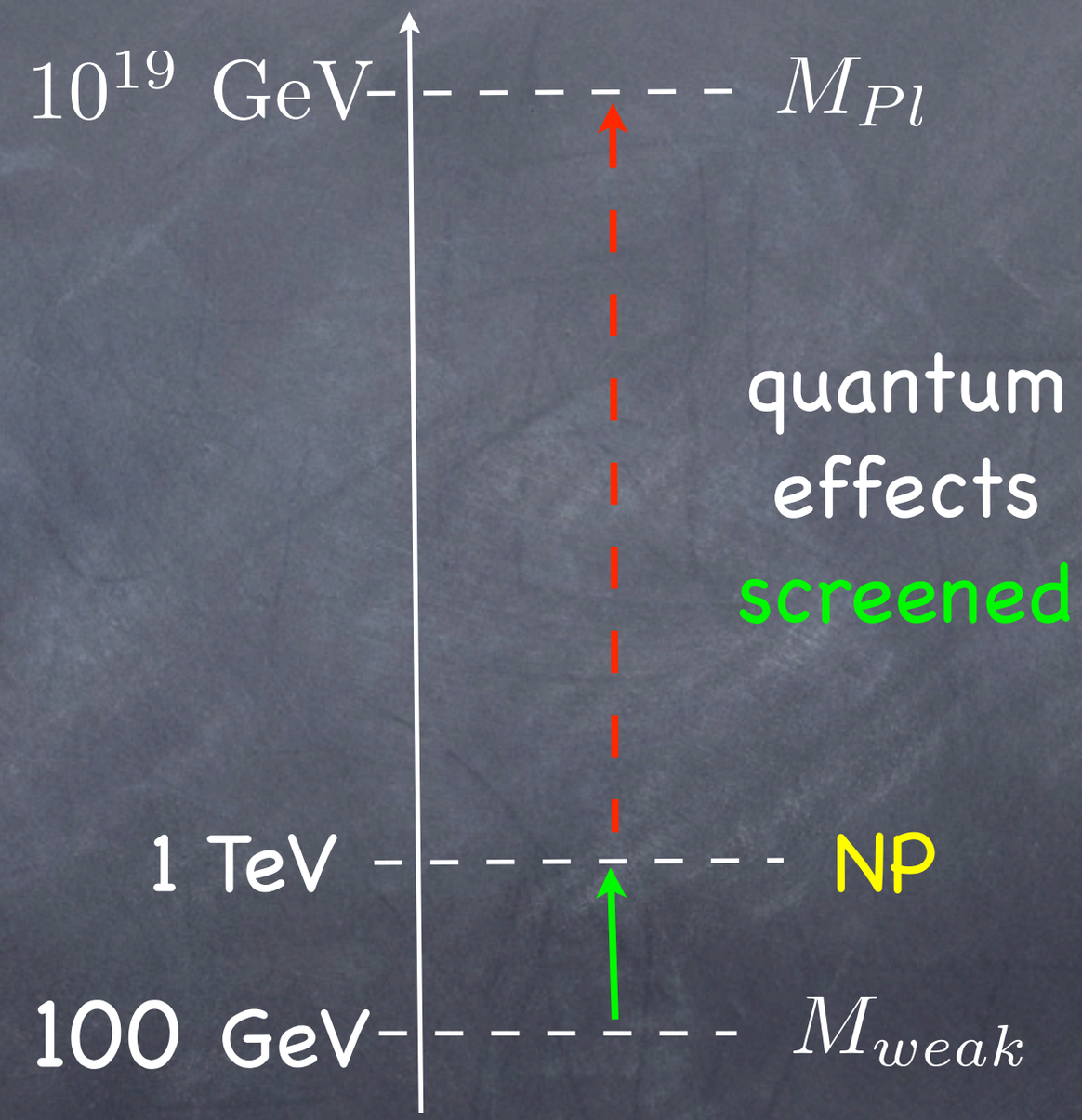
$M_{weak} \sim 100$ GeV $<< M_{Pl} \sim 10^{19}$ GeV is unstable



- Biggest mystery for past 30 years!

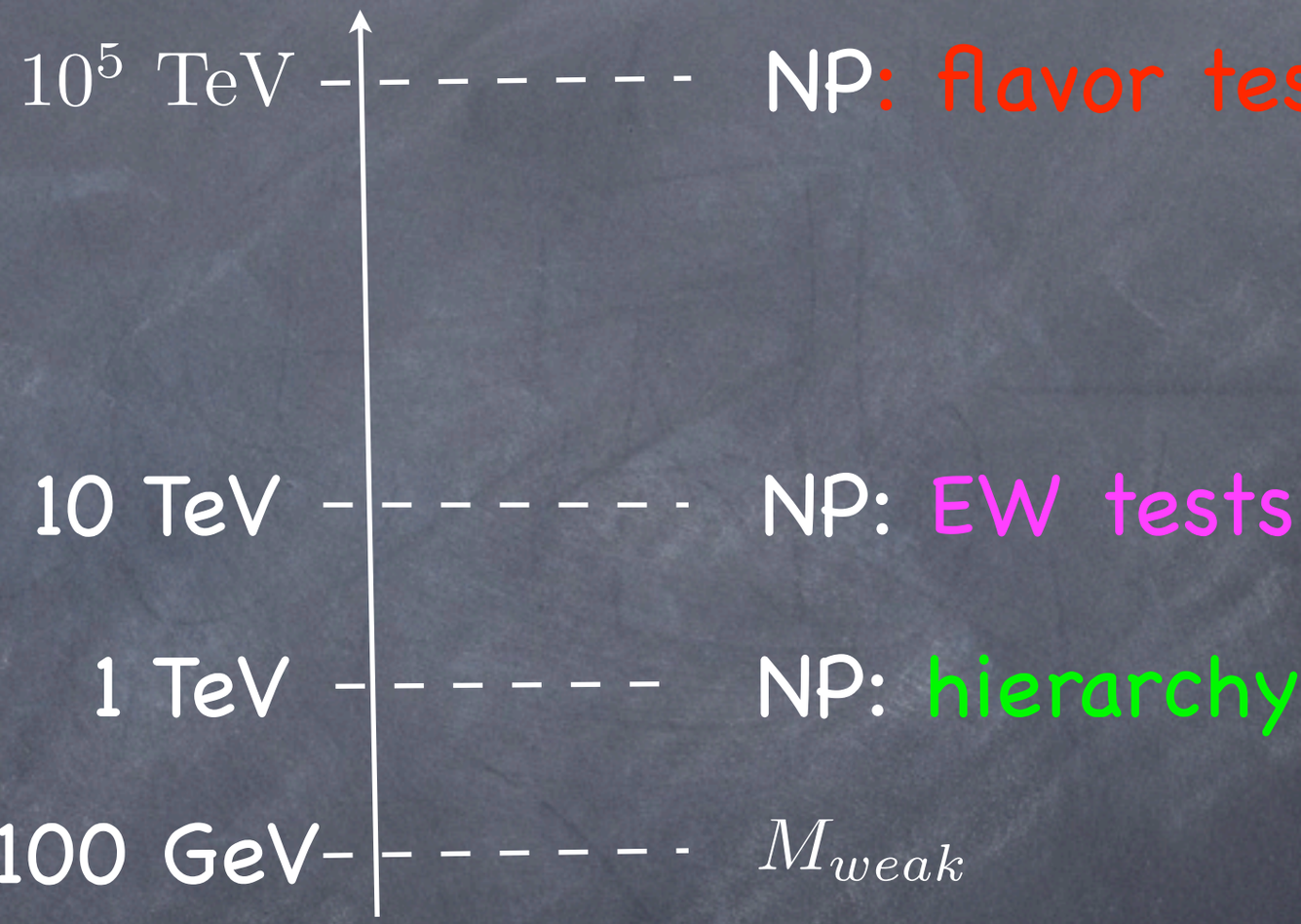
Solution to hierarchy problem

- New physics (NP) at TeV scale

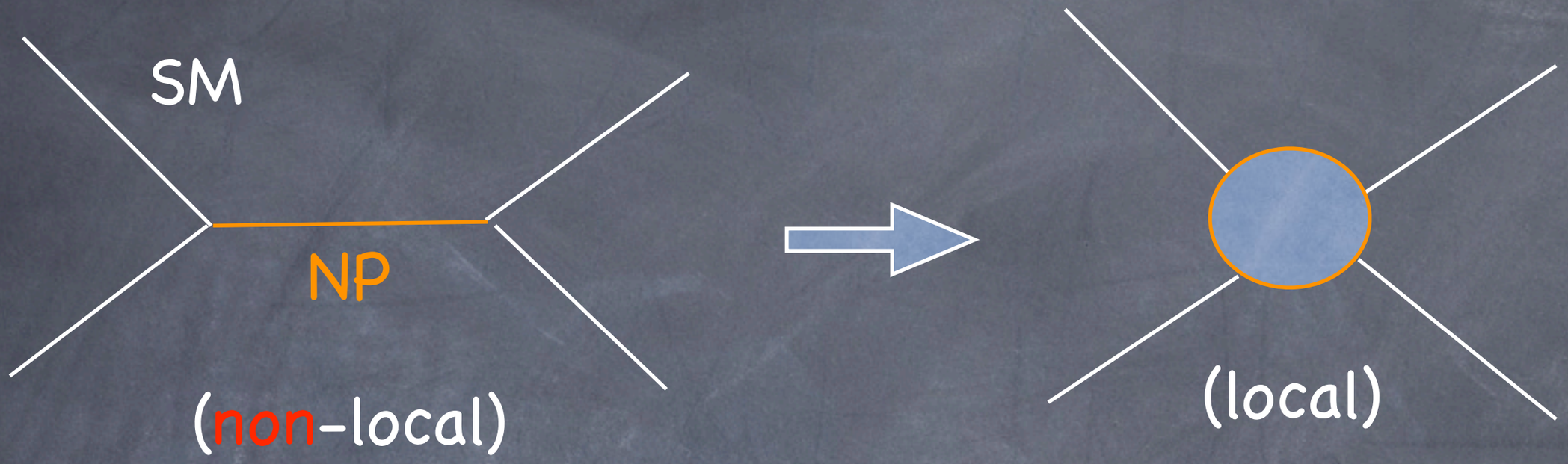


No hierarchy, but tension with precision tests

- New physics contributes to precision tests
- ElectroWeak tests (gauge bosons) sensitive to 10 TeV
- Flavor tests (quarks and leptons) 100,000 TeV
- New physics has to be special!



Indirect effect of New Physics



- Energy << mass of new particle
  short range/suppressed force
  (like low-energy weak force from W exchange)

- Sensitivity to new physics by measuring properties of SM particles precisely

Outline

- Warped Extra Dimension solves Planck-weak hierarchy problem
- addresses hierarchies of quark and lepton masses
- (Severe) tension with precision tests avoided by extending protective mechanisms of SM

↓

Signals (at energy and intensity frontier)

- Grand Unification of 3 forces

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Dark Matter

↓

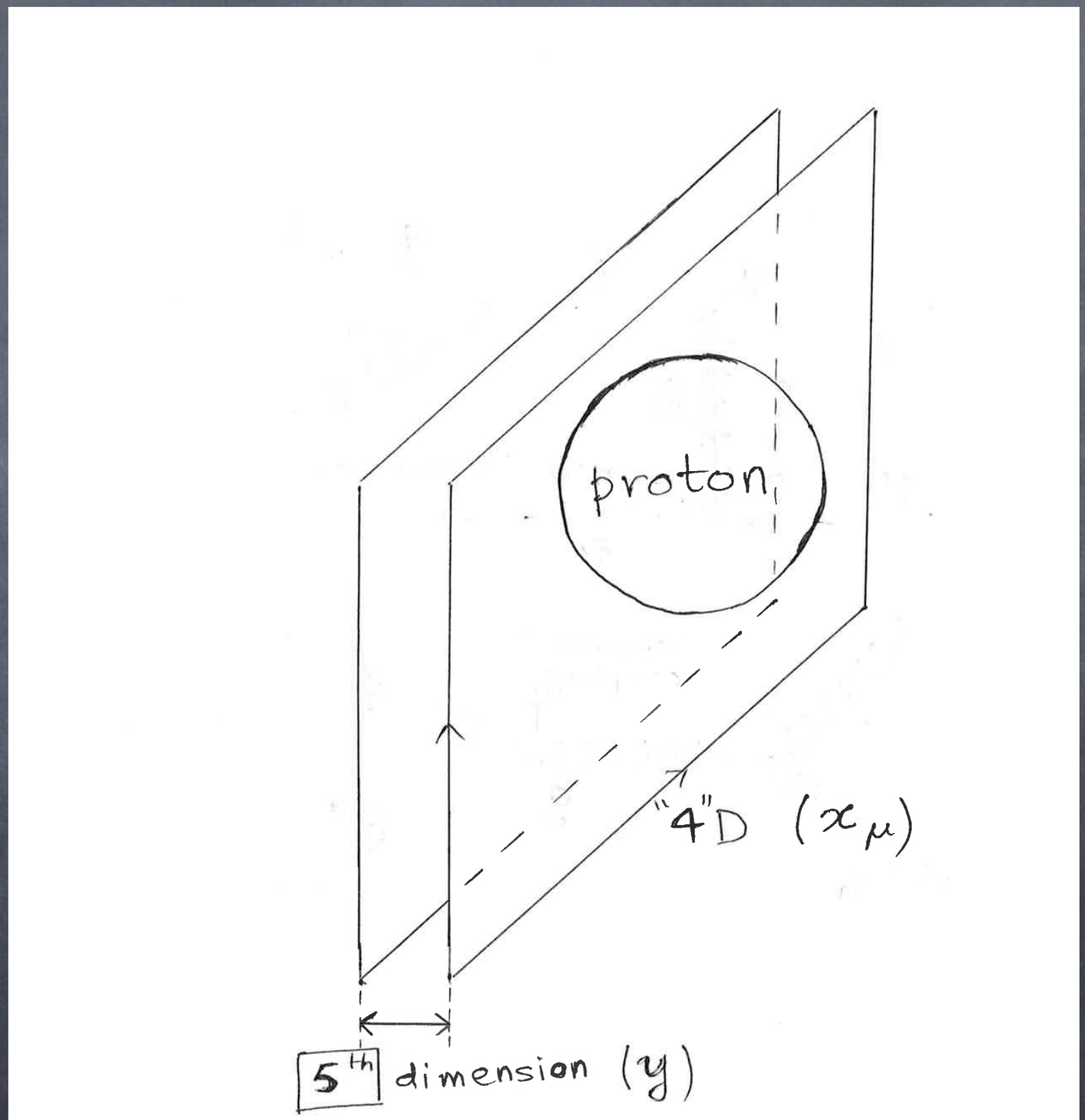
Direct detection

(General) extra

dimension

Why haven't we "seen" it (yet)?

- It's small!



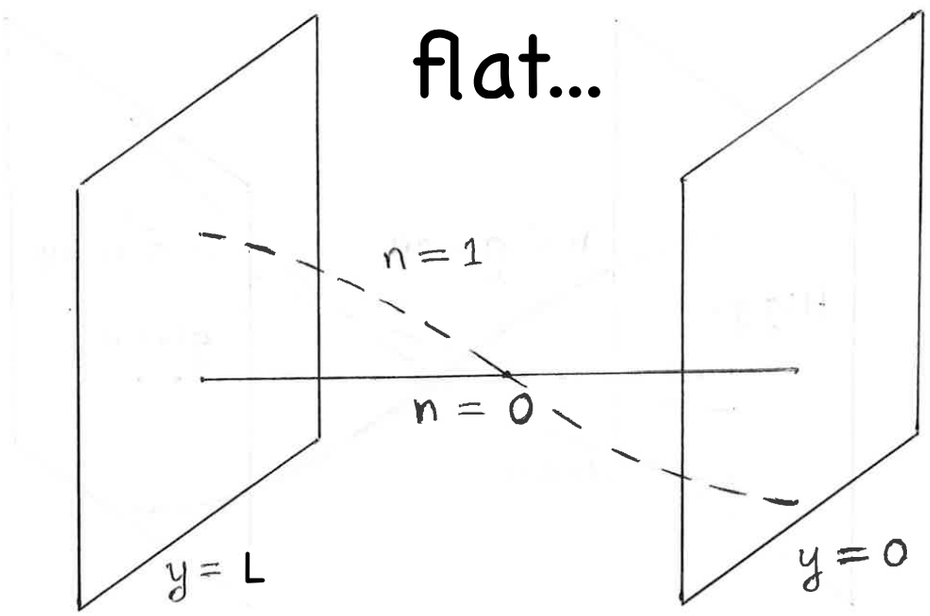
Why should it be compact/``small"?

- 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 μ m

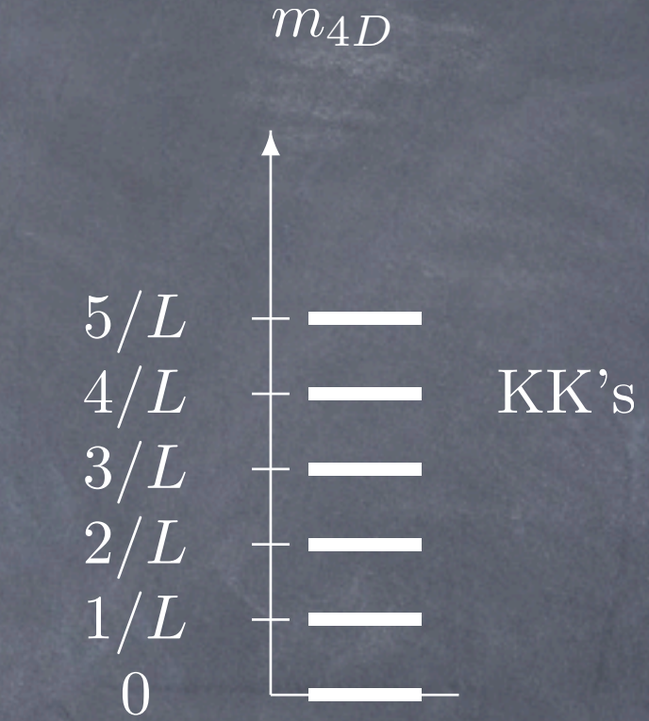
What can we see in future (I)?

- 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 $p_5 \sim n/L$



What can we see in future (II)?

$E^2 = |\bar{p}|^2 + m_{4D}^2$ becomes (set to 0)
$E^2 = |\bar{p}|^2 + p_5^2 + M_{5D}^2 \Rightarrow$
$\bar{p} = 0$ mode (at rest in 3D): $E \sim n/L \Rightarrow$
(rest) mass, $m_{4D} \sim n/L$



- Each KK mode like massive field (particle upon quantization) from 4D viewpoint:
- 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 >~1 TeV, haven't seen it yet!

Summary

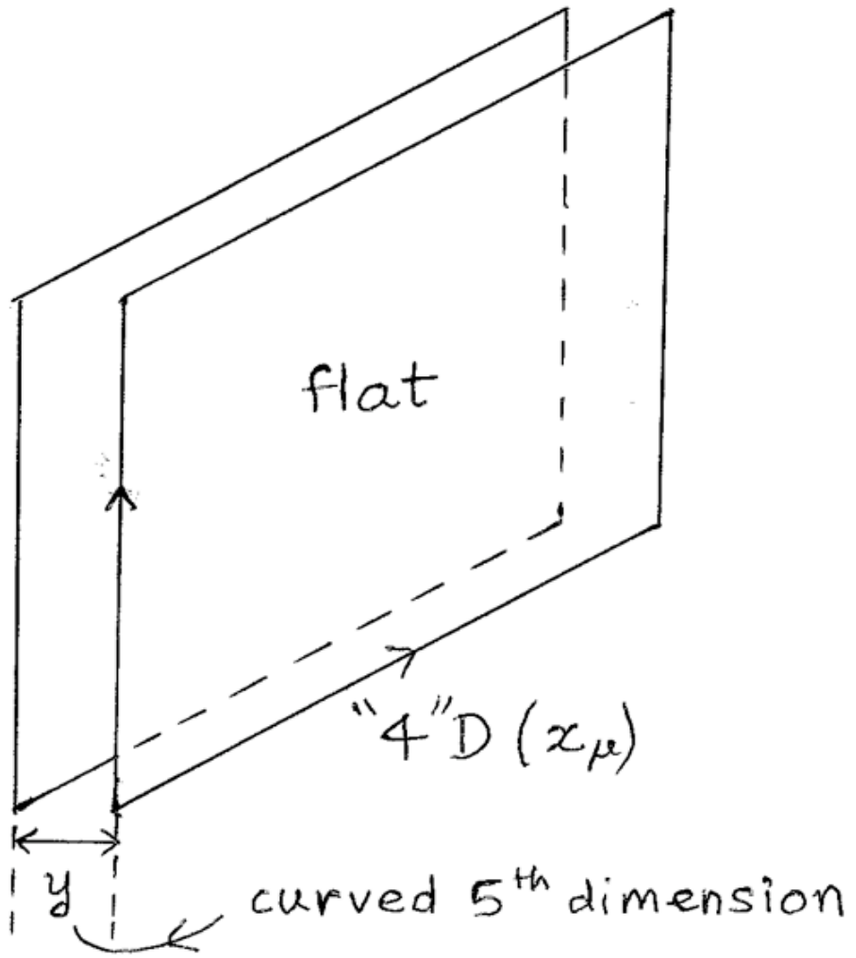
- 5D field ⟹ tower of (massive) KK modes (from 4D viewpoint)
- profiles from (generalized) wave equation in 5D space-time
- Coupling of particles $\propto$ overlap of profiles

Warped Extra Dimension

(general)

Where's the curvature?

- Einstein: gravity is curvature of space-time: usual curvature extremely small, gravity very weak
- Warped space highly curved: curvature hidden if extra dimension hidden (tiny in size or KK scale > TeV)



Warped extra dimension intuitively

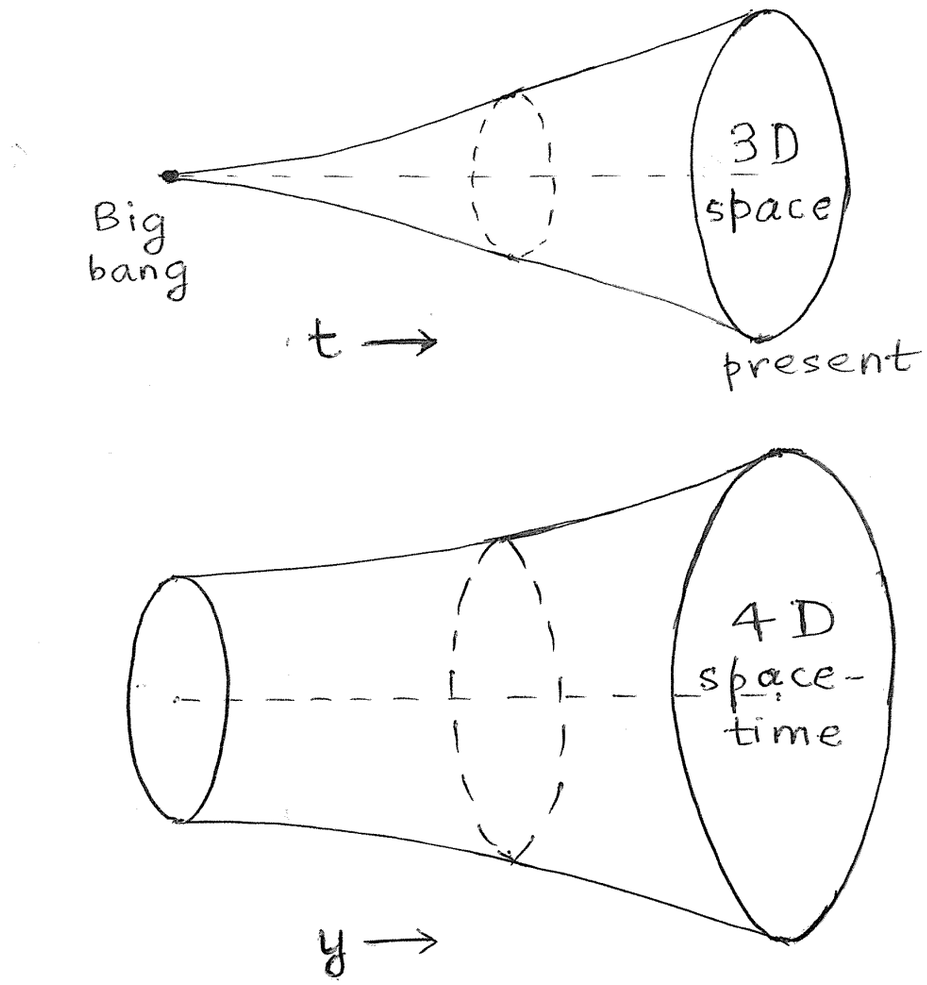
- Analogy with expanding universe

Nobel, '11 for acceleration now!

(flat) 3D space expands with time (``exponentially" during inflation: $N_e \sim 60$)

(flat) 4D space-time ``expands" (exponentially) with moving along 5th dimension

- gravitational red-shift generates hierarchies in mass scale between different positions in 5th dimension



Warped Extra Dimension: gravity and Higgs

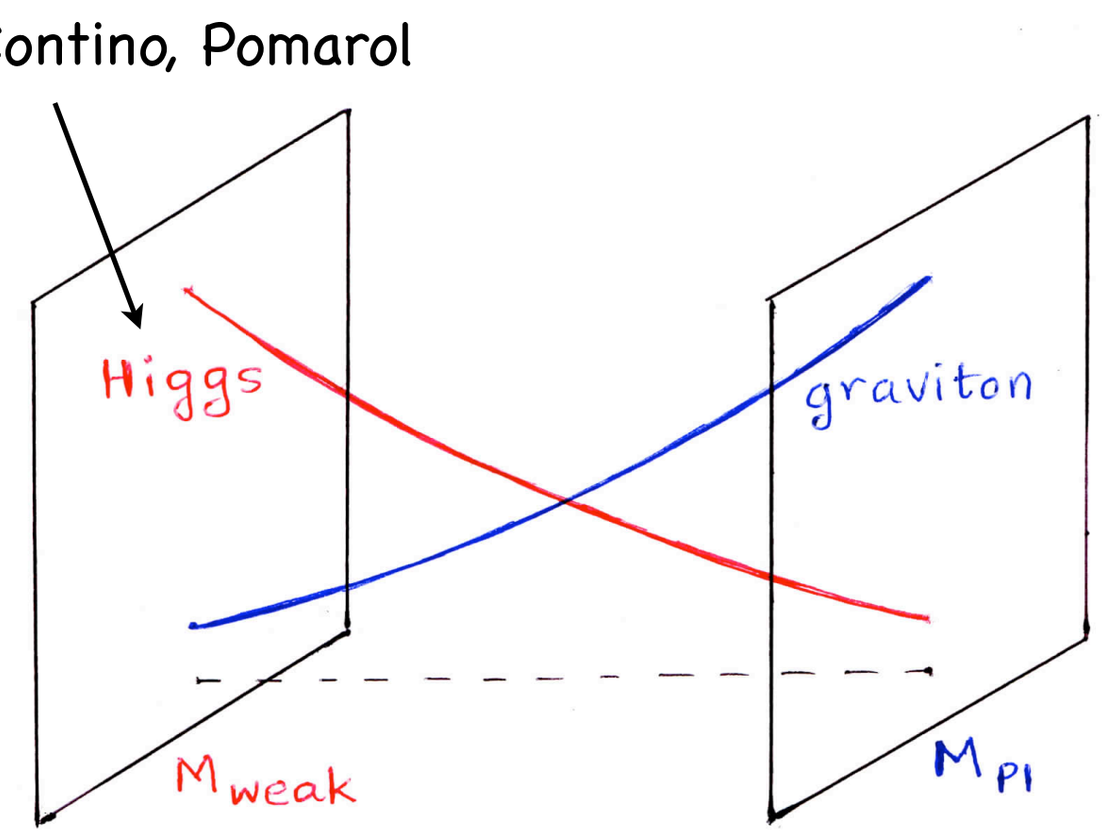
Solution to (Planck-weak) hierarchy problem (Randall-Sundrum model)

- specifically, gravitational red-shift of Planck scale to weak: $N_e \sim O(10)$

- equivalently, profiles (wave equation in curved space-time)

- small overlap of Higgs with gravitational field ⇨ small Higgs mass/ condensate << M_{Pl}

Contino, Nomura, Pomarol;
KA, Contino, Pomarol

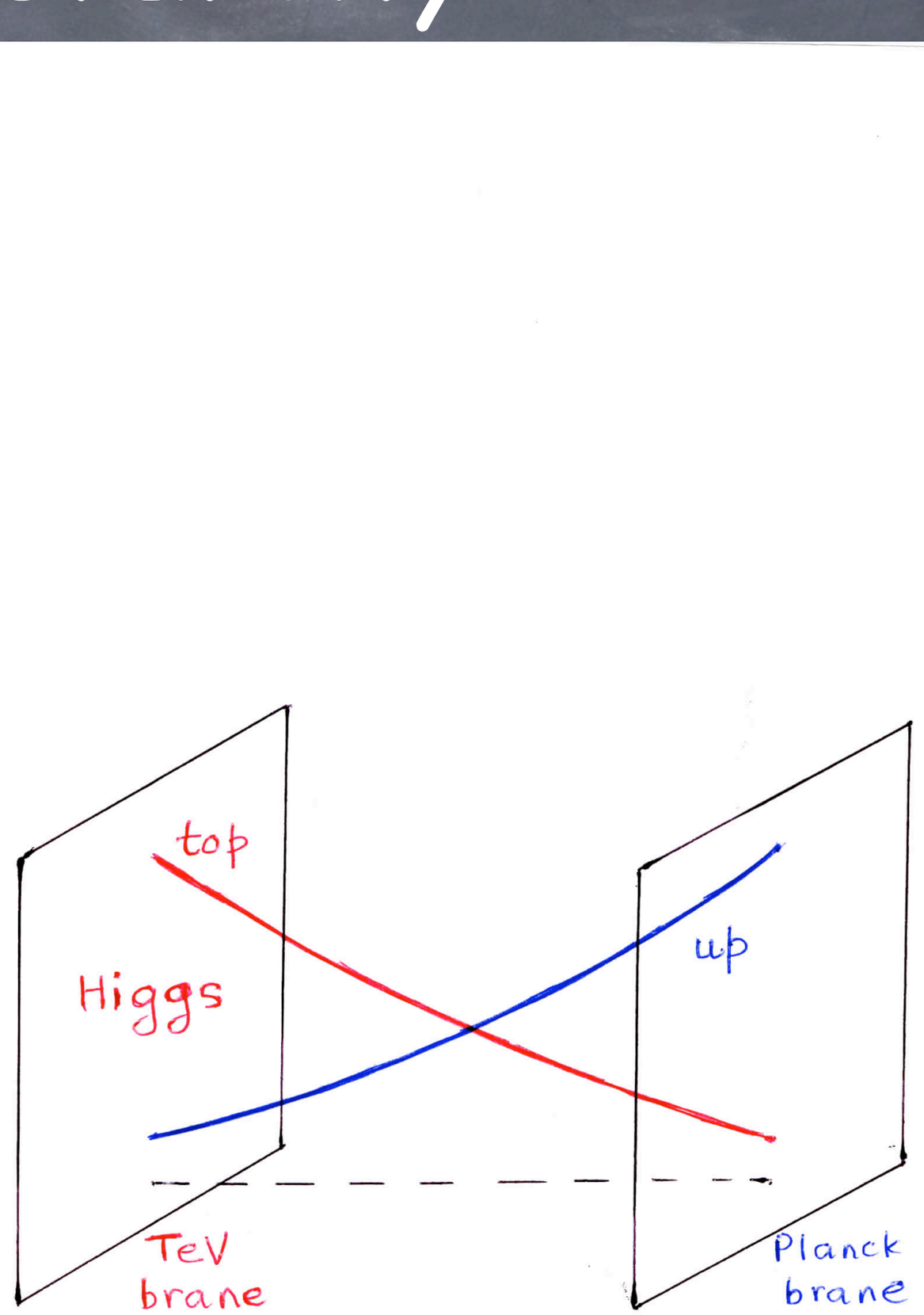


Warped Extra Dimension: Fermions and Gauge Bosons

Fermion mass hierarchy

- 5D wave equation: lightest profile sensitive to M_{5D} and boundary conditions (Grossman, Neubert; Gherghetta, Pomarol; Huber, Shafi)

- small up quark vs. large top mass from overlap with Higgs



Coupling of modes $\propto$

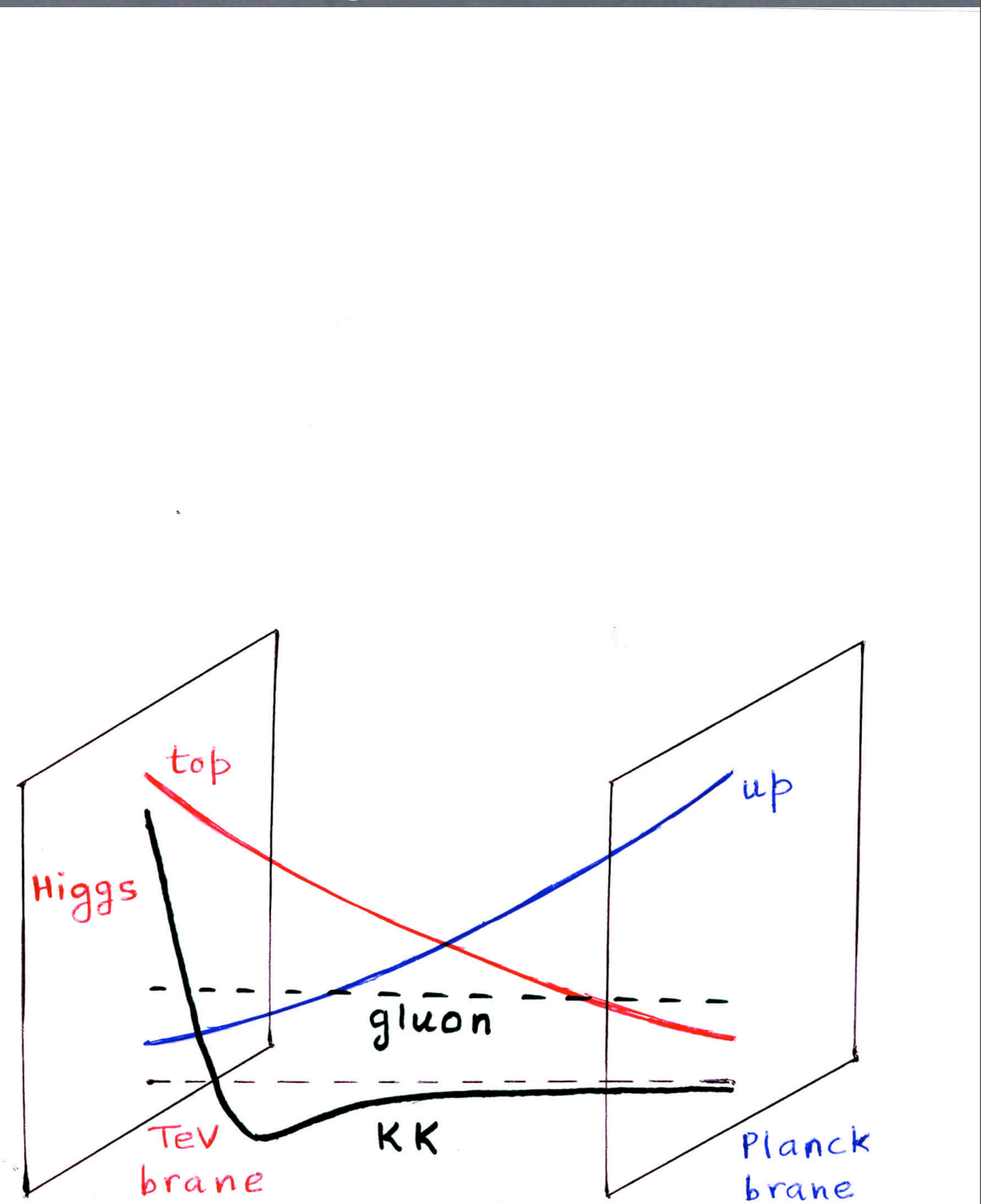
overlap of profiles

Bulk Gauge Bosons

(Davoudiasl, Hewett, Rizzo;
Chang, Hisano, Nakano, Okada, Yamaguchi; Pomarol)

- KK's localized near TeV brane with mass ~TeV (from wave equation)
- gauge KK "like" Higgs: large (small) coupling to top (up) quark

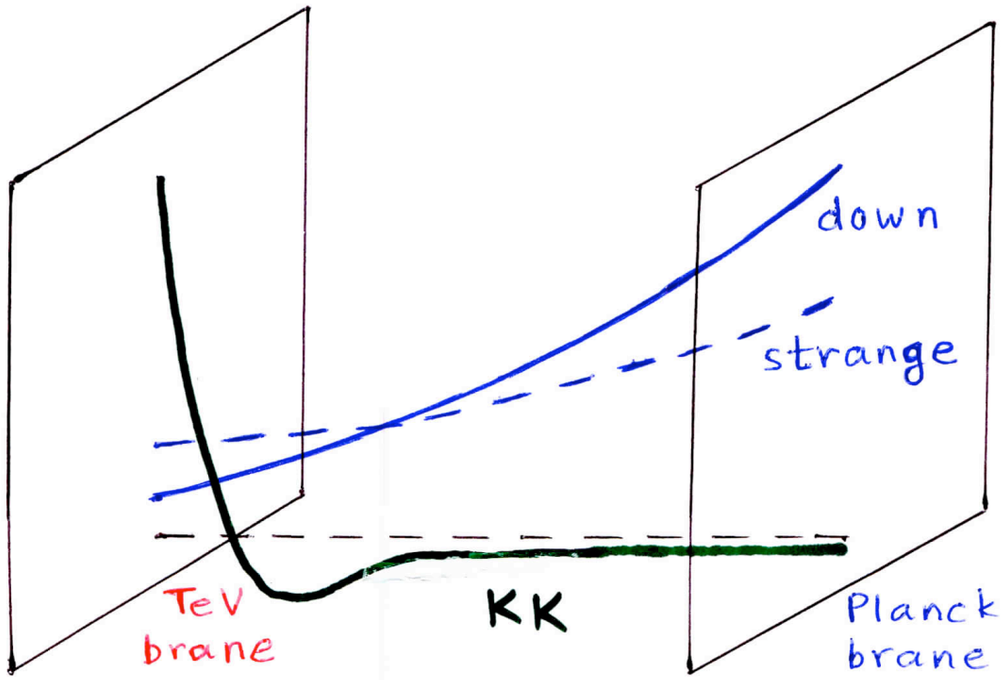
gauge KK's couple
$\propto$ fermion mass

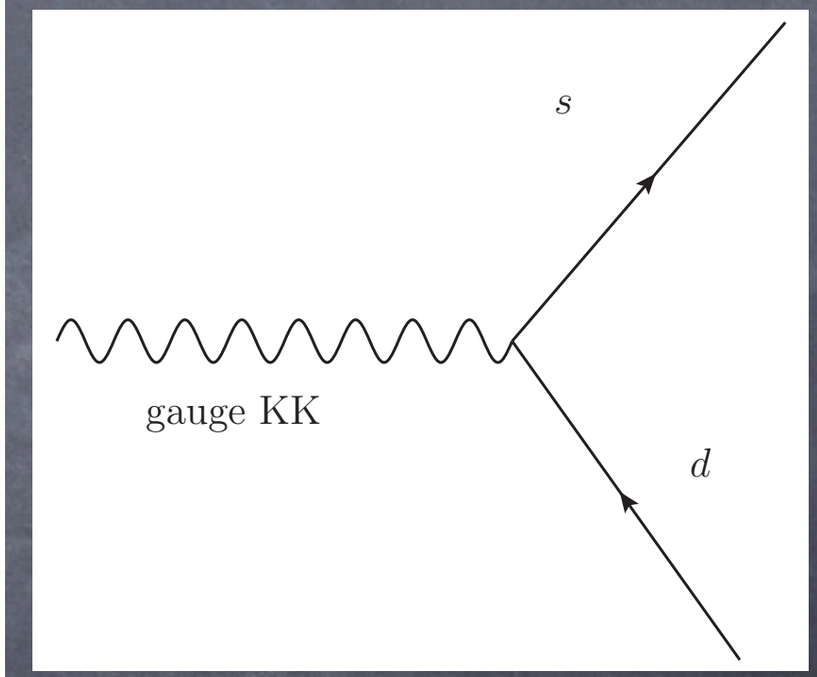


FLAVOR TESTS

Why flavor conversion (⇒ test)?

- Coupling of KK modes non-universal ⇒
  d↔s (flavor conversion)

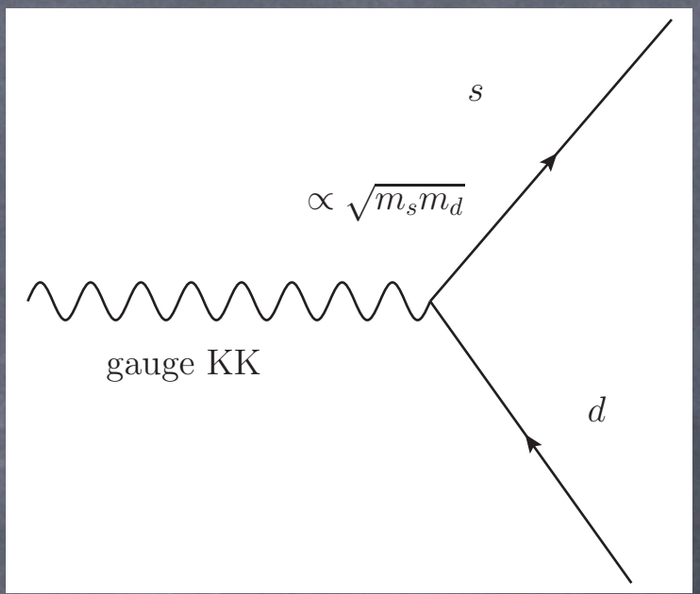


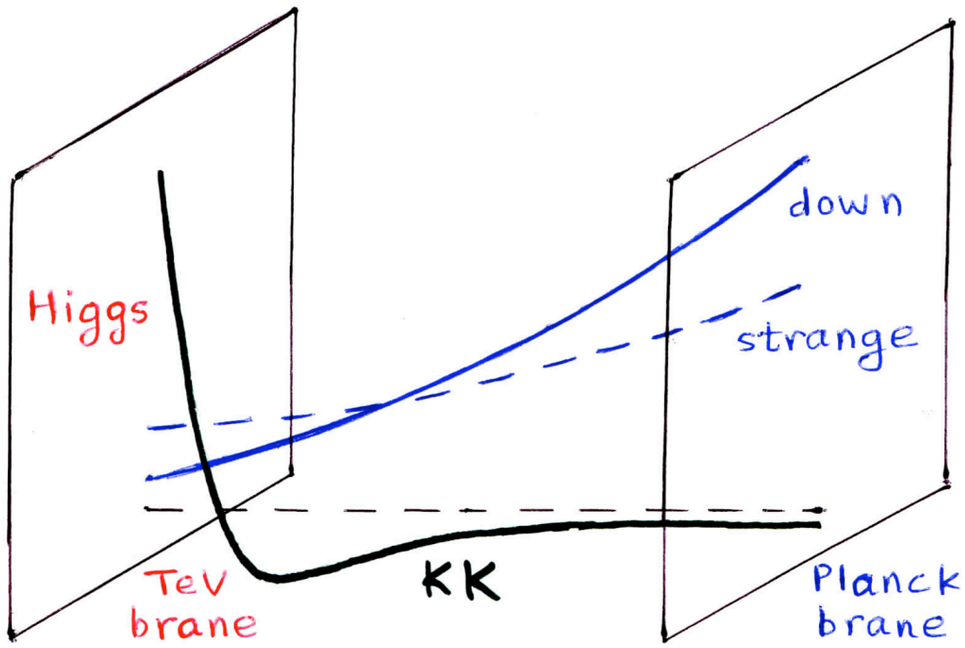


(Severe) tension avoided...

(Gherghetta, Pomarol; Huber. Shafi; KA, Perez, Soni)

- Flavor conversion $\propto$ quark mass (a la GIM mechanism of SM)





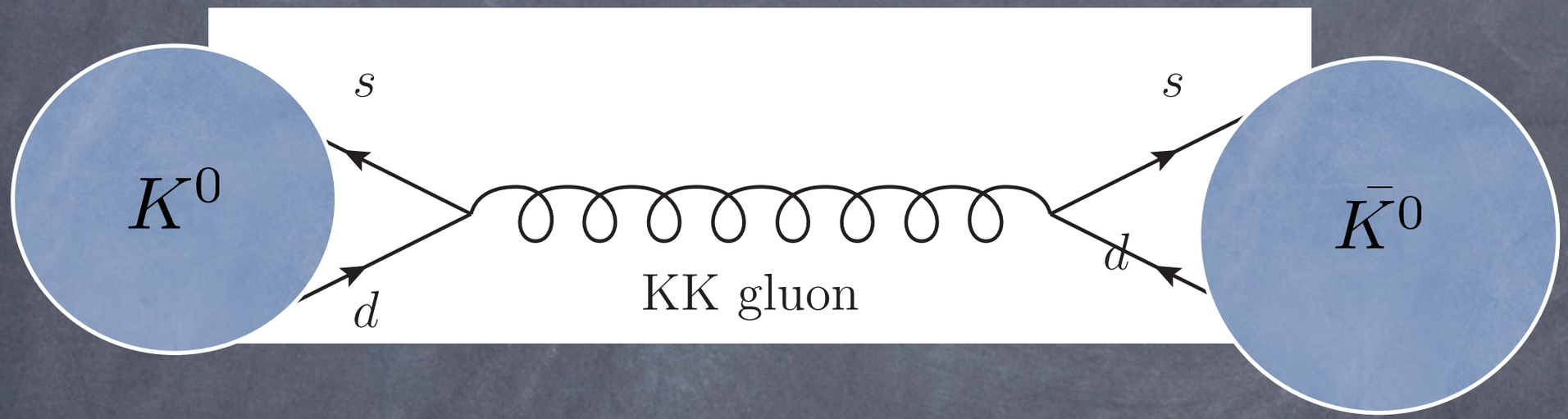
Built-in mechanism to avoid (severe) tension!

Lesson…

- New physics preserves (automatic here) feature of SM (GIM mechanism) to preserve agreement with precision data

...still tension with natural solution to hierarchy problem

- minimal model: KK >~10 TeV (generically) from



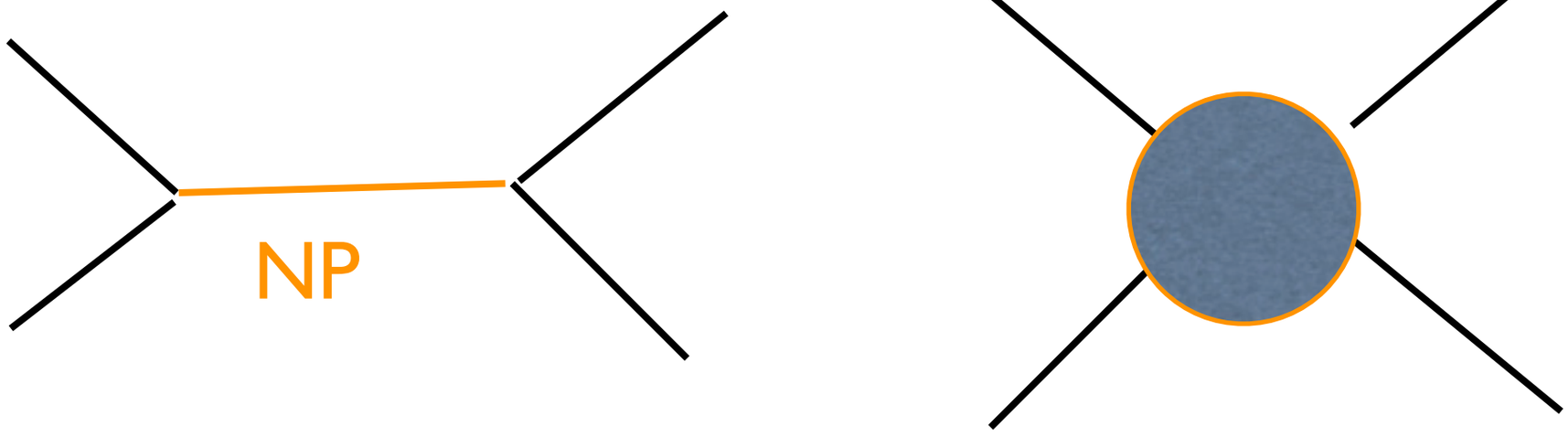
(Csaki, Falkowski, Weiler)

- ...but 3 TeV (within LHC reach) still allowed in part of parameter space

(Blanke, Buras, Duling, Gori, Weiler; KA, Azatov, Zhu)

FLAVOR SIGNALS

Intensity frontier



- Focus on indirect effects of new physics...

Low energy: directly produce SM, but not new particle

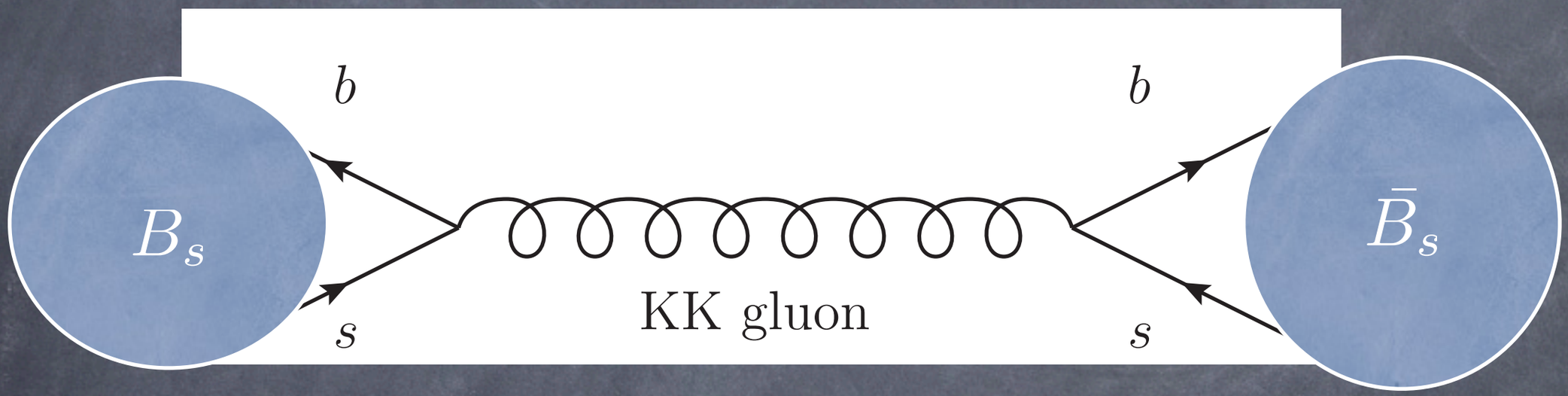
- if high precision (intensity), sensitive to new physics beyond direct (LHC) reach

(Back to warped...KK particles)

"Living on the edge" of flavor tests

⇒ signals

- LHCb: $B_s \leftrightarrow \bar{B}_s$ (Burdman; KA, Perez, Soni)



- $t \to cZ$ (KA, Perez, Soni); Htc (KA, Contino) at LHC (energy and intensity frontier!)

Jawahery colloquium

- Future:

super-B; projectX: $\mu \to e$...(Huber; KA, Blechman, Petriello)

(B/top/lepton-physics "cleaner" than Kaon...)

Motivation for experimental proposal

- LOI by Mu2e collaboration (FERMILAB-TM-2396-AD-E-TD)
- sensitive to KK mass $\sim$ 20 TeV (beyond LHC reach)

FERMILAB-TM-2396-AD-E-TD

Letter of Intent

A Muon to Electron Conversion Experiment at Fermilab

The Mu2e Collaboration

28 September 2007

...

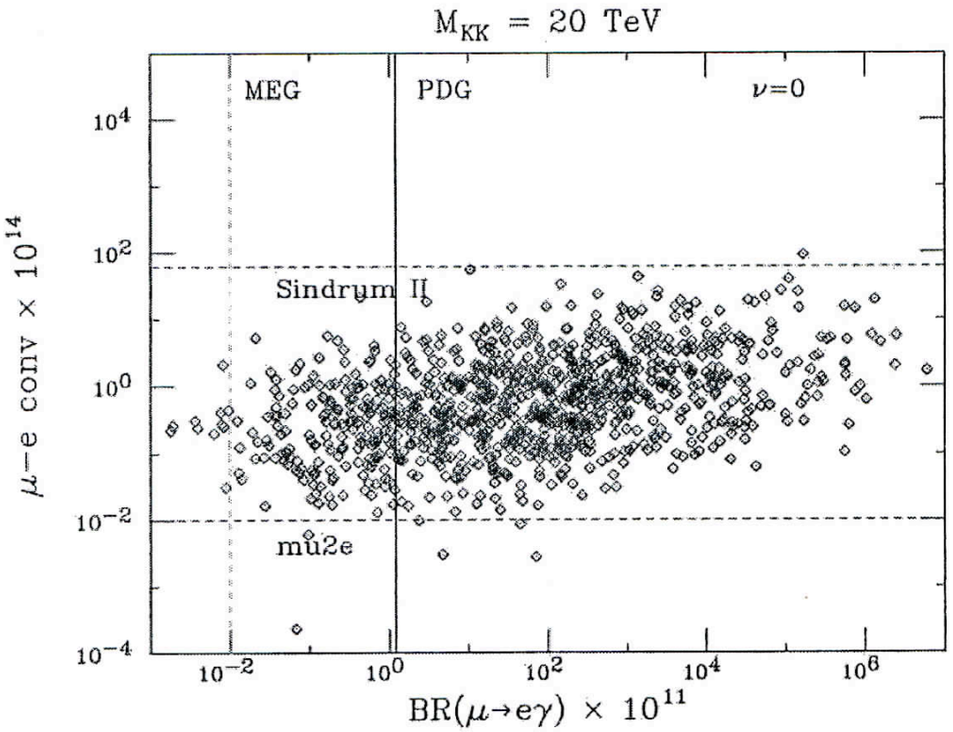
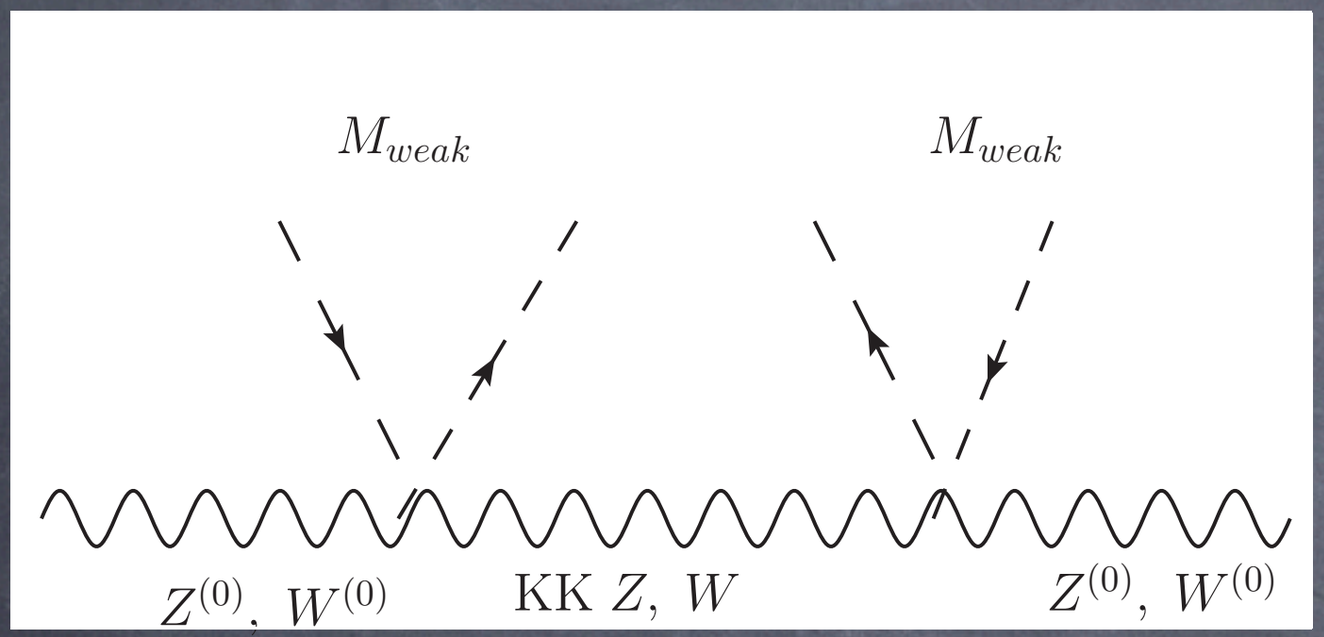


Figure 1.4: $\mu^+ {}^{48}\mathrm{Ti} \rightarrow e^+ {}^{48}\mathrm{Ti}$ rate as a function of Br($\mu \rightarrow e+\gamma$) for the Randall-Sundrum model with one warped, compact extra dimension, in the scenario where the Higgs boson is allowed to propagate in the bulk.

ELECTROWEAK PRECISION TESTS

Problem (I)!

- KK's contribute to precisely measured/predicted mass ratio of W,Z



KK > 10's of TeV (robust cf. flavor)

(beyond LHC reach + vs. <~1 TeV for natural solution to hierarchy problem)

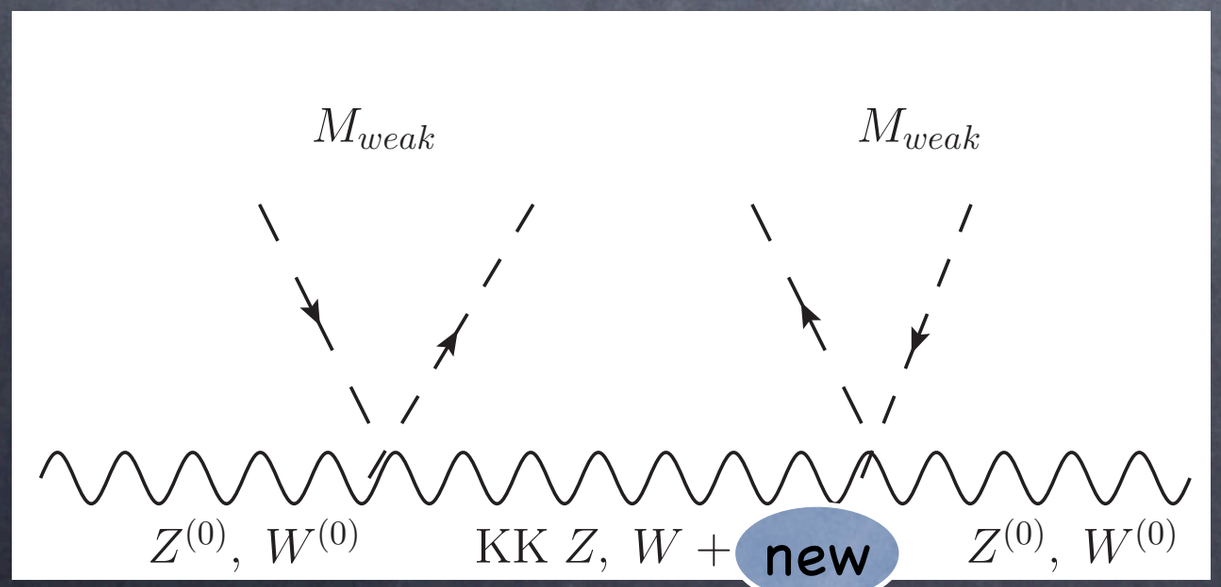
Isospin symmetry saves the day

(KA, Delgado, May, Sundrum)

- relation between W, Z masses in SM due to isospin symmetry (W, Z triplet...)

- small breaking in SM magnified in extra dimension

- (re)introduce isospin symmetry: extend gauge structure in extra dimension (extra gauge bosons massive)



KK~ 3 TeV allowed

Lesson learned!

- New physics preserve features of SM: GIM mechanism (quarks and leptons) and isospin symmetry (gauge bosons)

DIRECT KK PRODUCTION (@LHC: ENERGY FRONTIER)

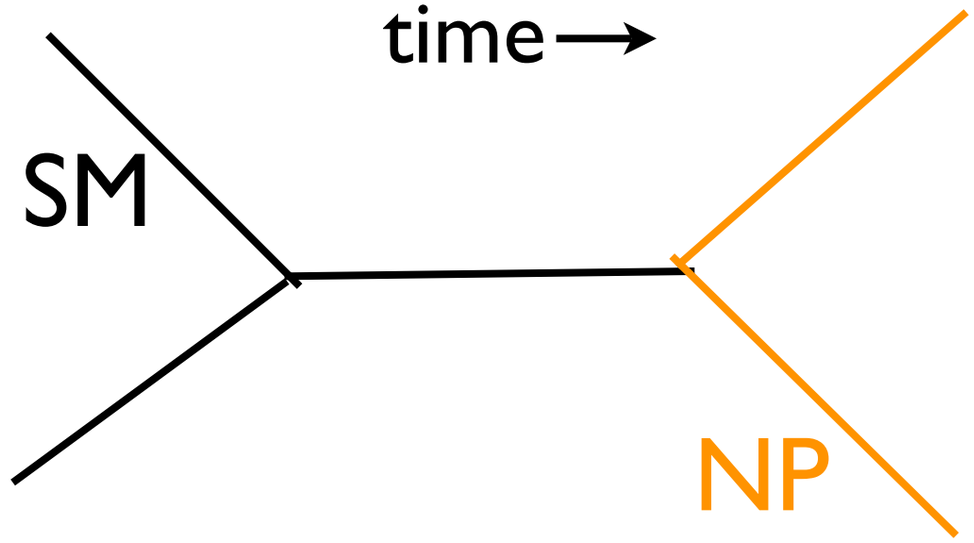
Resonant (no missing energy) vs. pair production (with missing energy)

- New particles are charged under (new) symmetry

lightest stable (dark matter?)

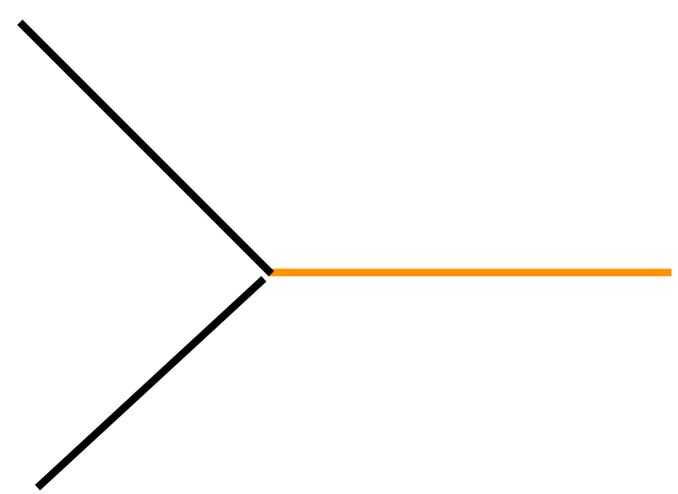
pair produce other particles

``mother'' decays into dark matter (missing energy) + SM



SUSY (superpartner of SM with spin differing by 1/2) is prototype

- ....vs. no symmetry for new particles



resonant/single production

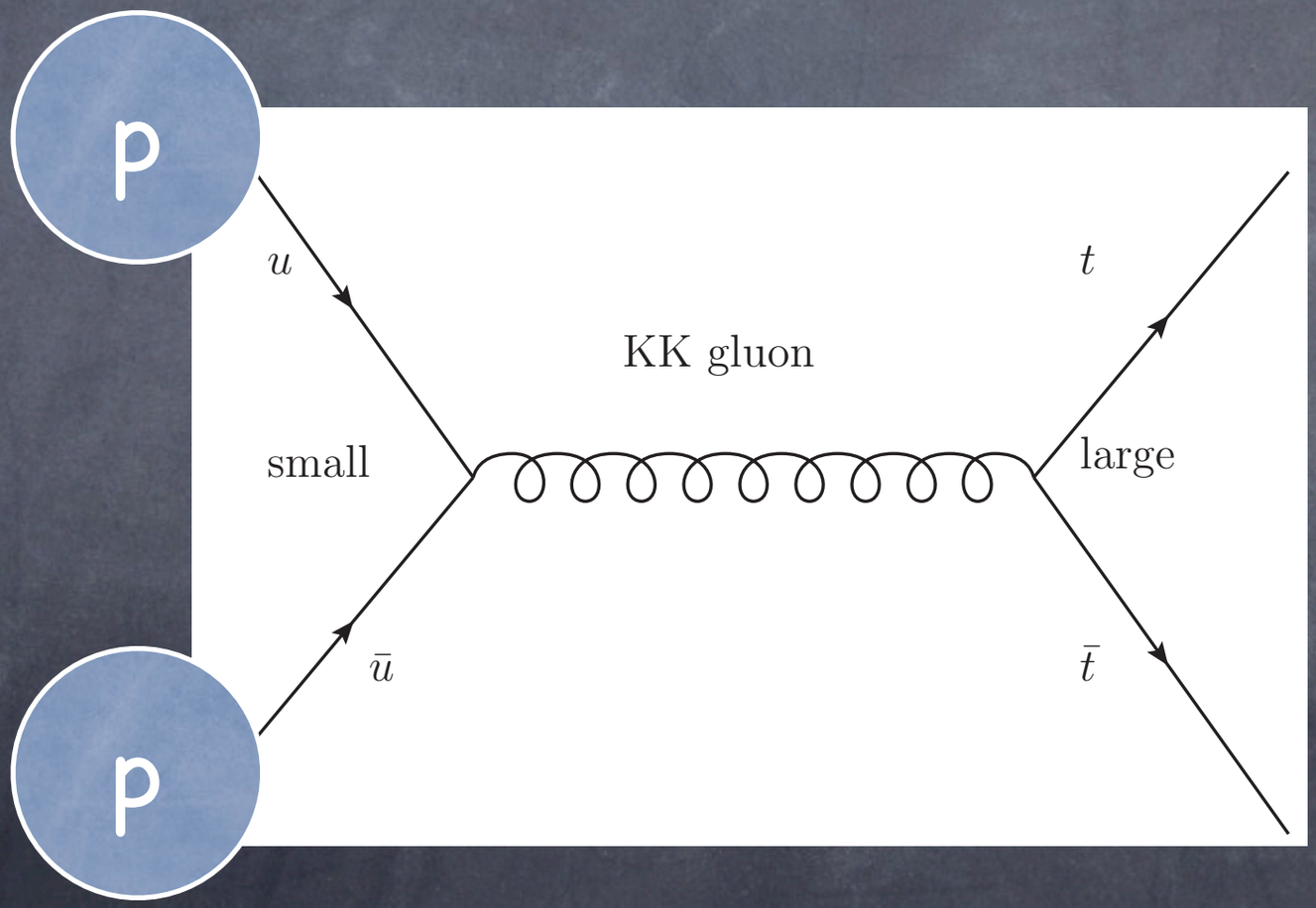
decay to only SM (no missing energy)

e.g., Extra dimension

(Back to warped...KK particles)

(1). KK gluon decays to tops

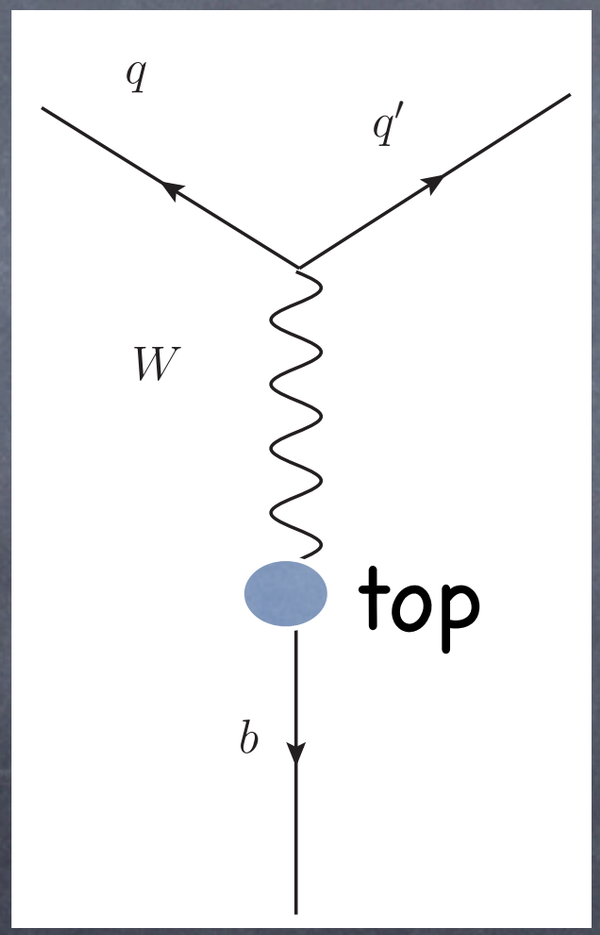
(KA, Belyaev, Krupovnickas, Perez, Virzi)



- Coupling to up (top) quark small (large)

Top identification before LHC

- top $\sim$ at rest (in lab frame)

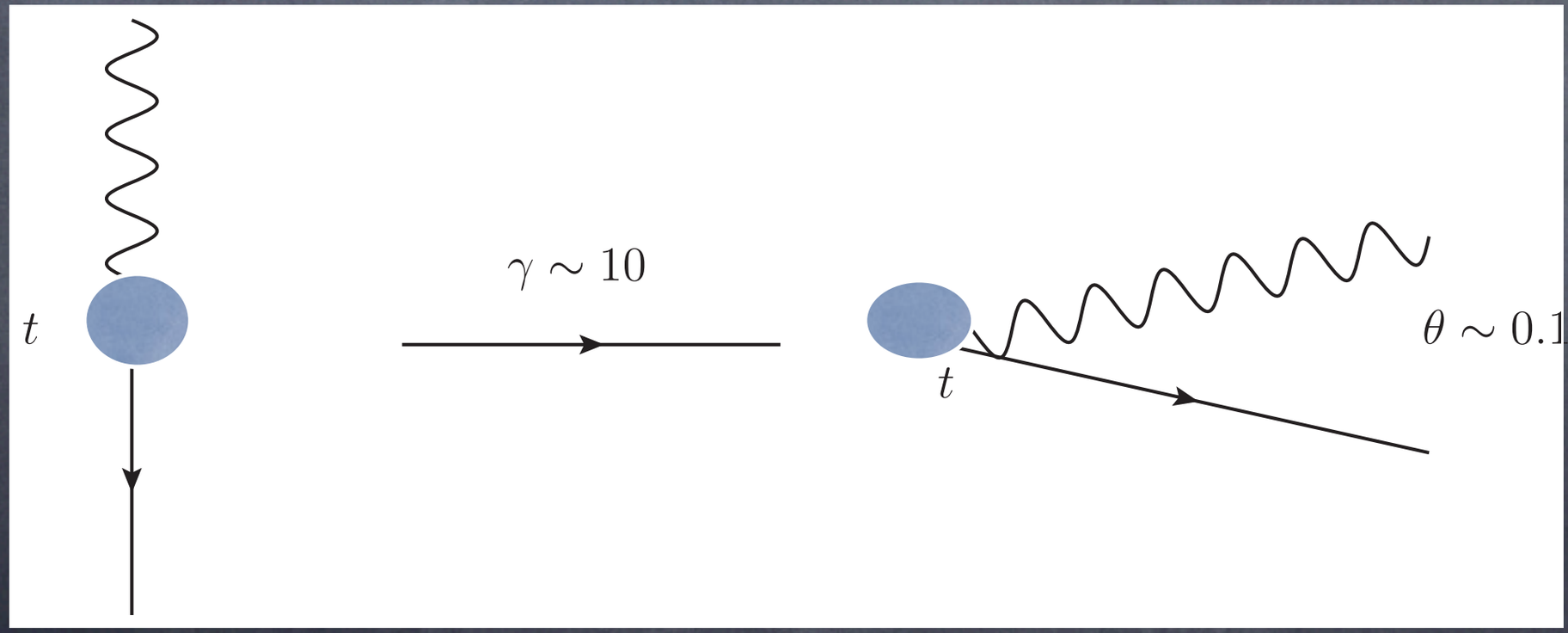


- b and W decay products well-separated

Problem: tops from KK gluon

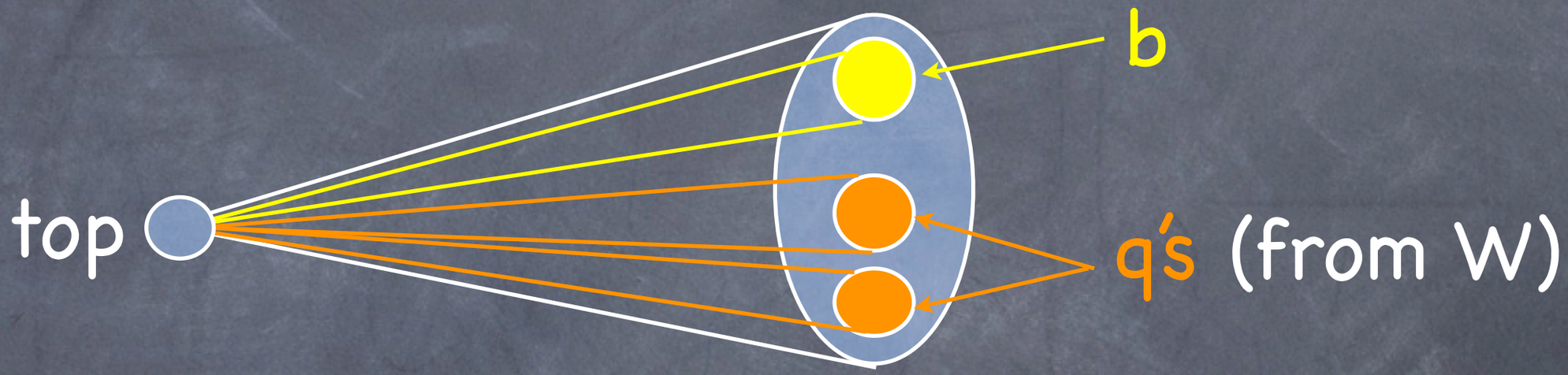
boosted (KA, Belyaev, Krupovnickas, Perez, Virzi)

$\gamma_{top} \sim E_{top}/m_{top} \sim (3\ \mathrm{TeV}/2)/170\ \mathrm{GeV} \sim 10$ ⇒
opening angle between b and W $\sim 1/\gamma_{top} \sim 0.1$



- b and W (and W decay products) merge: top-jet

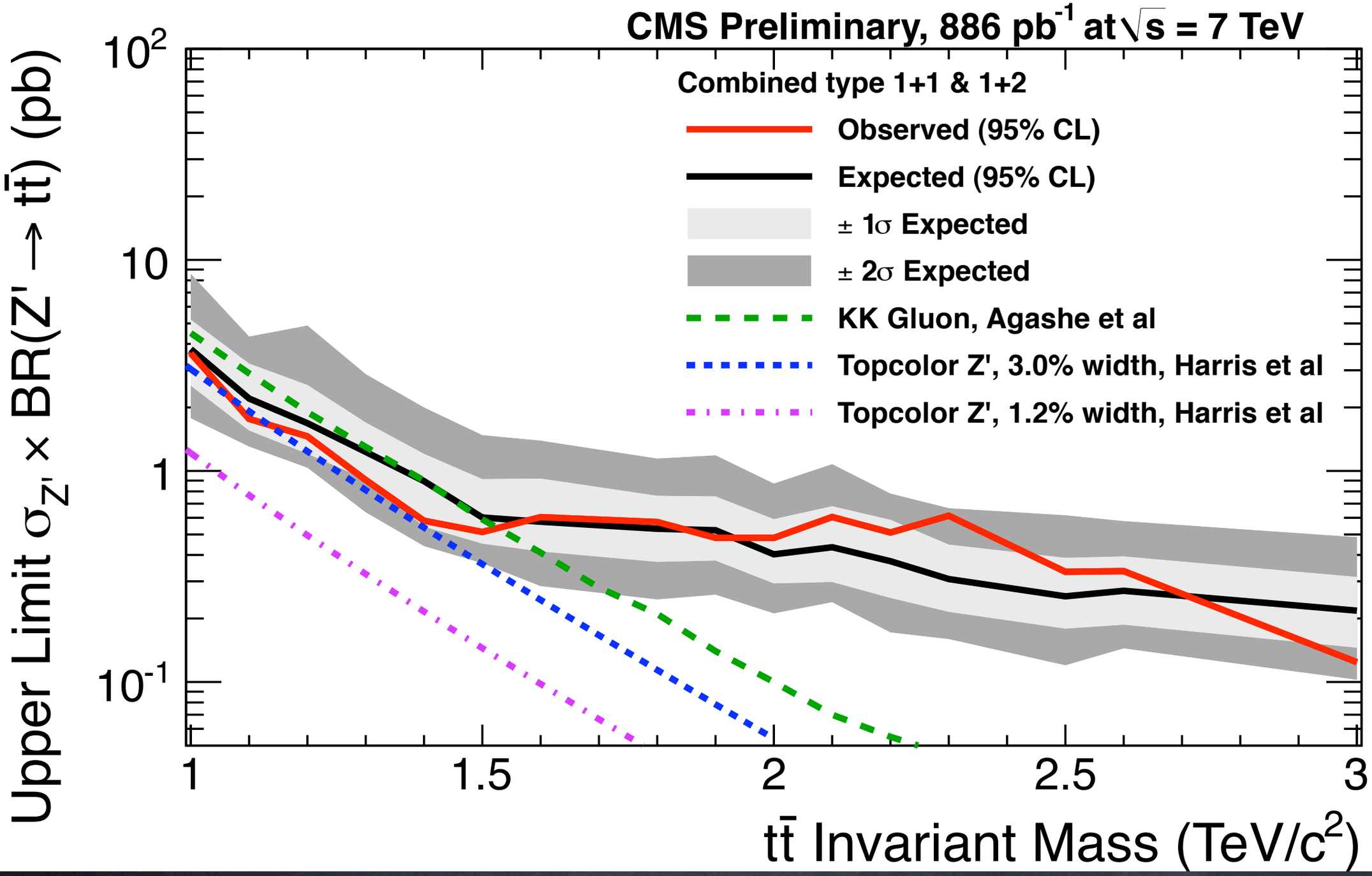
Solution: special identification strategy



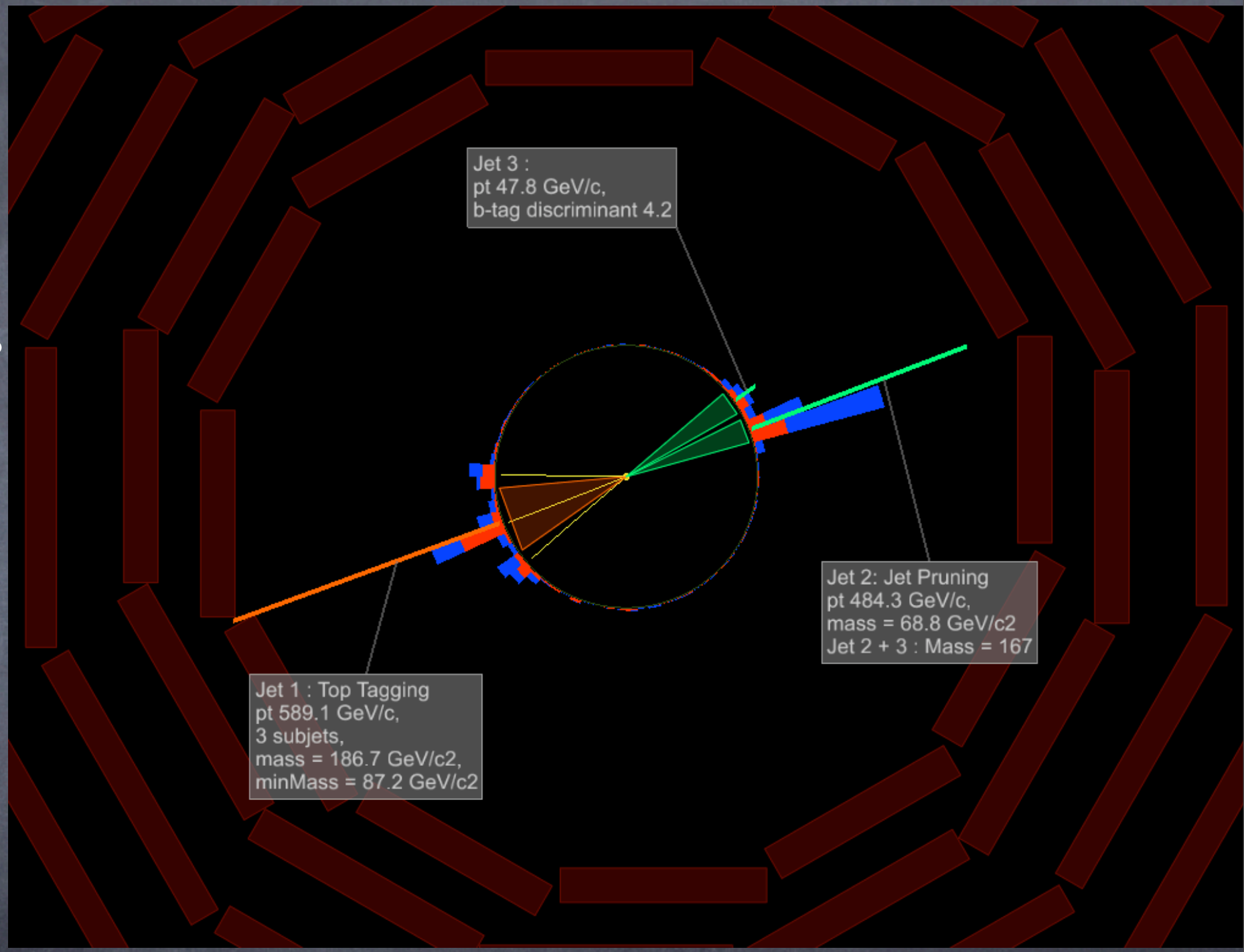
- jet substructure (joint effort: theorists/ phenomenologists and experimentalists)
- ``Boost" conference: meet annually (from 2009)to deal with boosted ``objects" (top, W, Z, Higgs...)

LHC search results

- ...getting to the boosted top regime (KK gluon mass ~ a few TeV) (CMS PAS EXO-11-006)



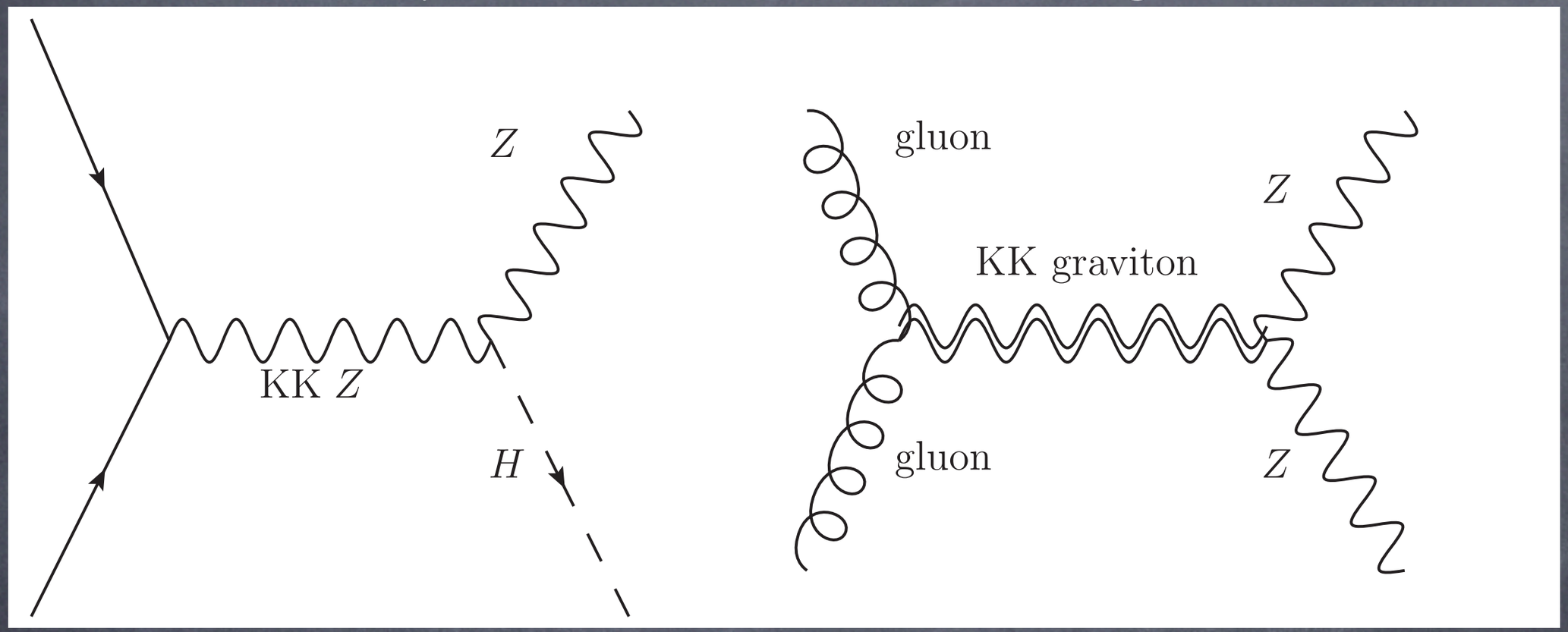
Real boosted top event!



- 1352.5 GeV invariant mass
- 1 jet with 3-sub-jets on one side (b and 2 jets from W merged)
  2 jets on other side (2 jets from W merged, but b not)

(2) Boosted W/Z/Higgs from KK W/Z/graviton

(KA, Davoudiasl, Perez, Soni;
KA, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni;
KA, Gopalakrishna, Han, Huang, Soni)



- ElectroWeak KK decay to W, Z, H(iggs) (and top)...but not to ZZ, HH
- KK graviton decays to ZZ, HH
- ...with $W,\ Z \to \bar{q}q'$...which merge...

Warped Extra Dimension:

GUT

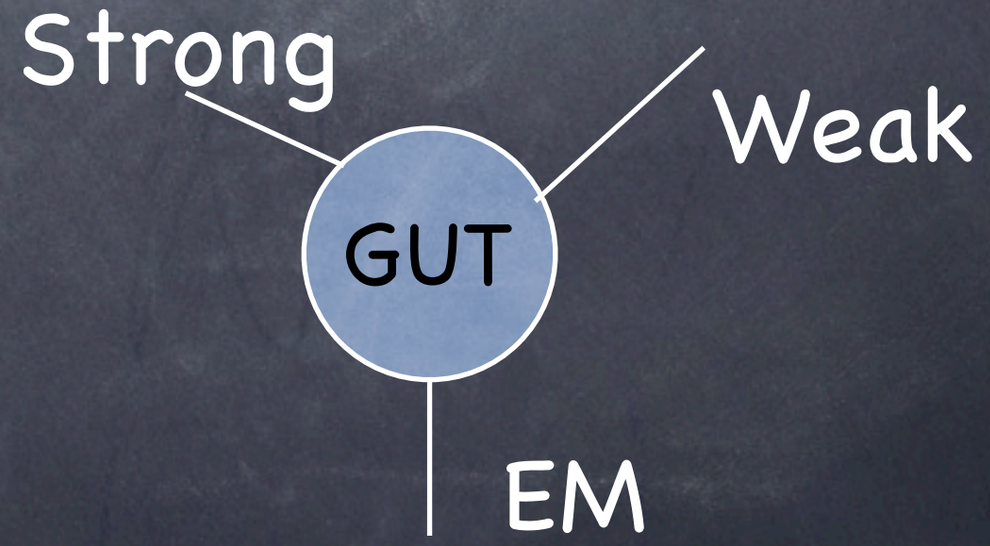
Strength of forces not constant!

- 3 strengths different at observed distance scales (energies)
- Strengths evolve with energy due to quantum effects:

$$1/r^2 \to 1/r^2 \ \log r$$

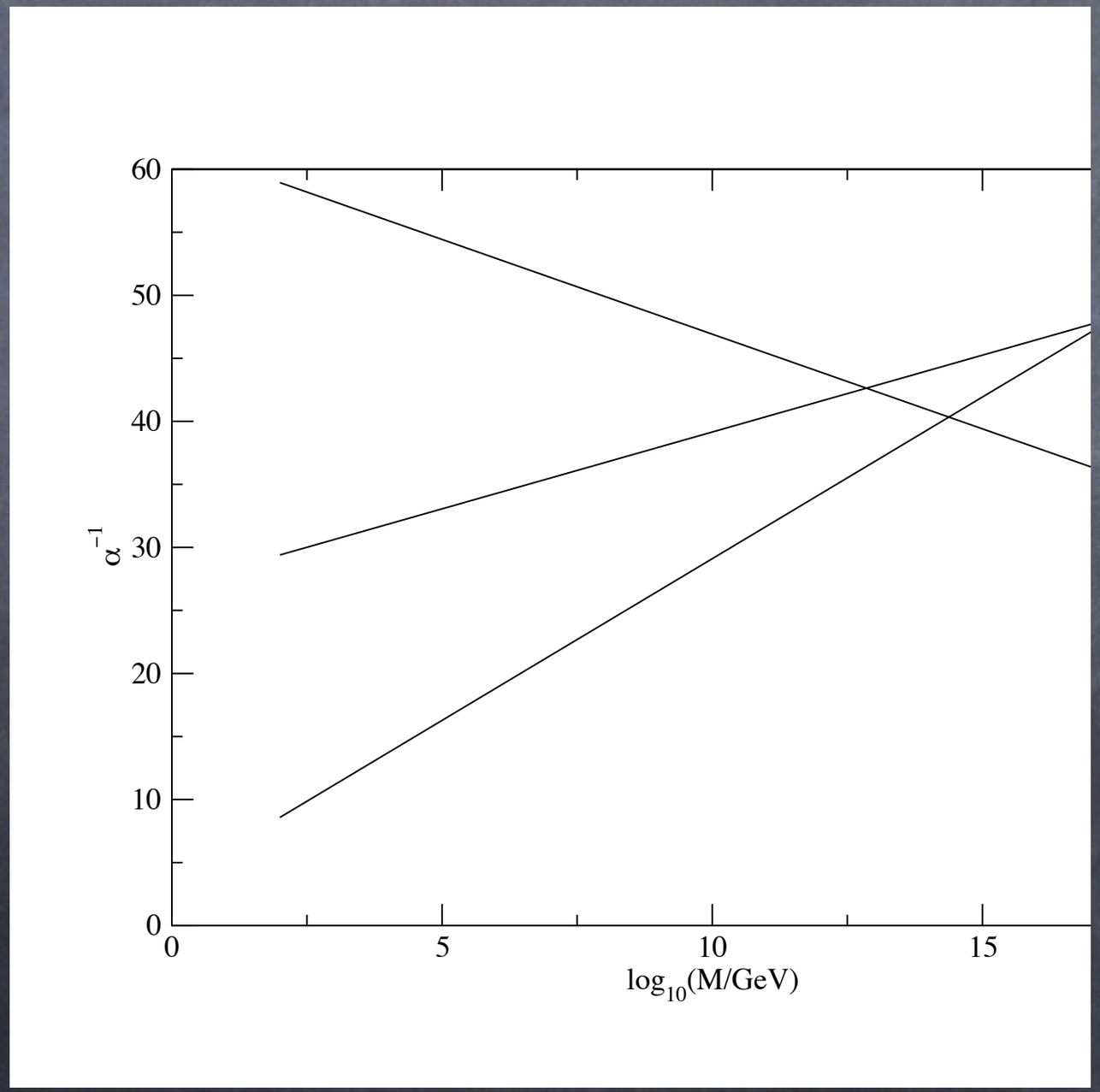
- ...that too differently for 3 forces of SM

3 forces unified into Grand Unified Theory (GUT)?



GUT in SM

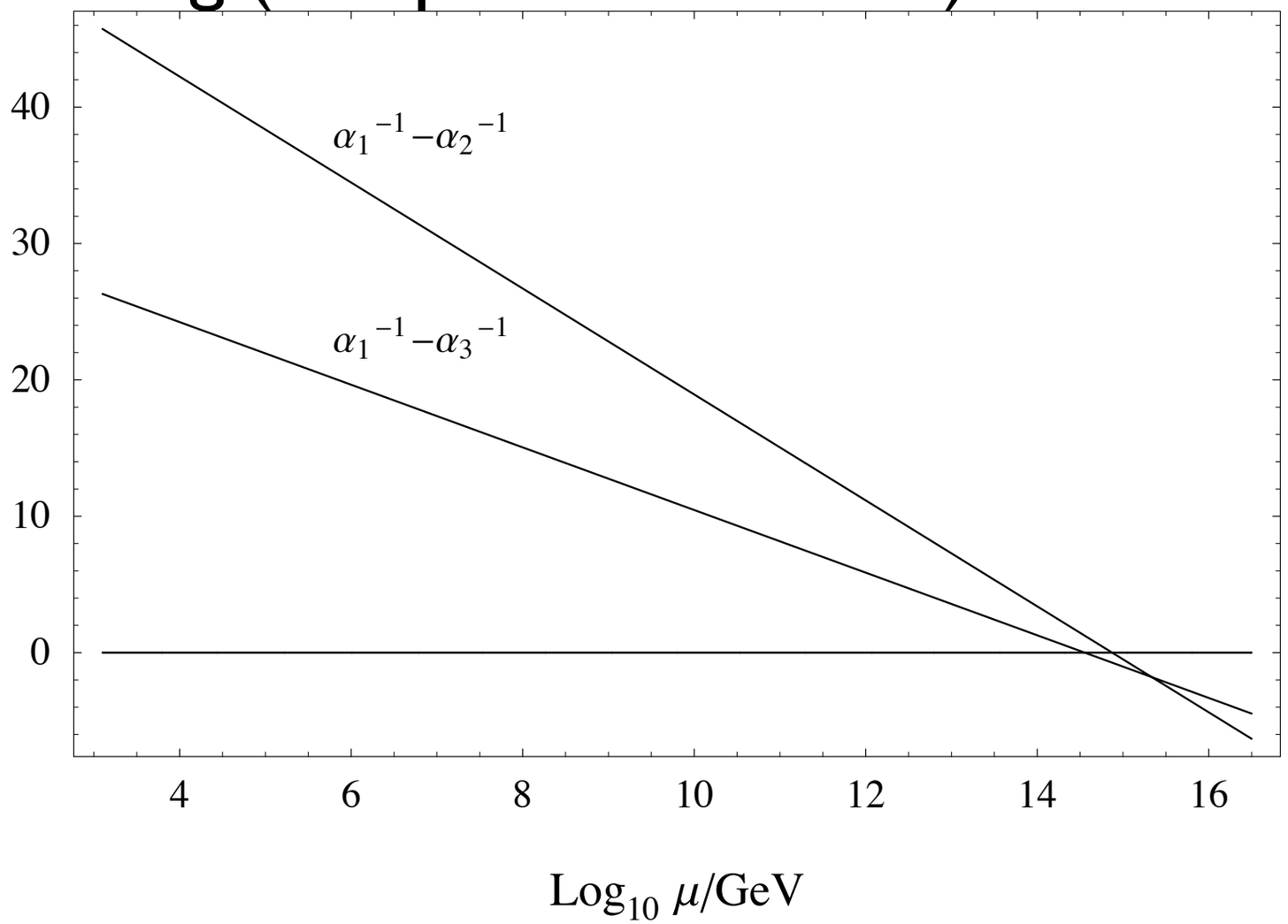
- ...couplings need to meet..
- ...good...but not so good given precision on couplings..



Warped GUT (KA, Contino, Sundrum)

- Evolution of couplings modified due different fermion profiles
- Top quark (heavy) near TeV brane → modify starting at TeV
  (KK's in unified multiplet do not modify relative evolution)
- Top quark effect ``correct'' sign/size →

  Precise meeting (comparable to SUSY)



Warped Extra Dimension:

GUT ⇒ DM

"Need" stable WIMP!

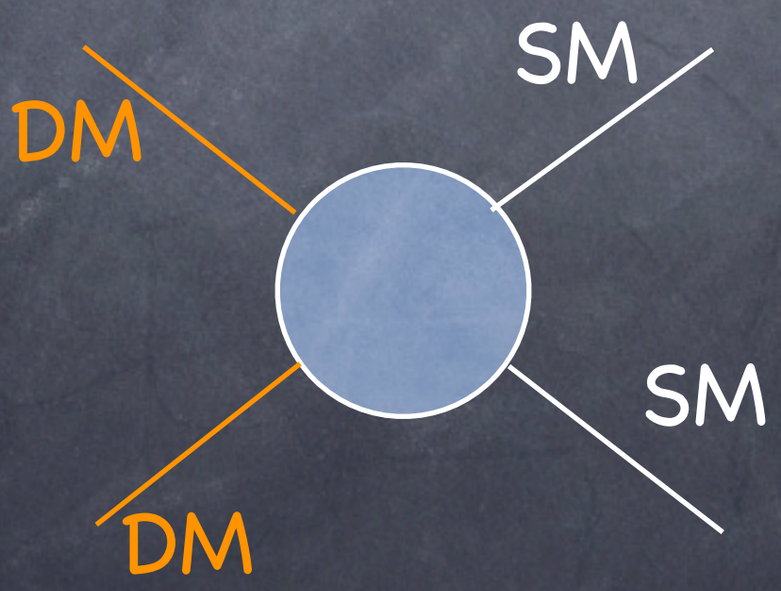
- Evidence for Dark Matter: galaxy rotation curves, WMAP...

- Stable (new) particle

- Weakly Interacting Massive Particle (WIMP):

Mass~100 GeV

Annihilation rate of weak strength

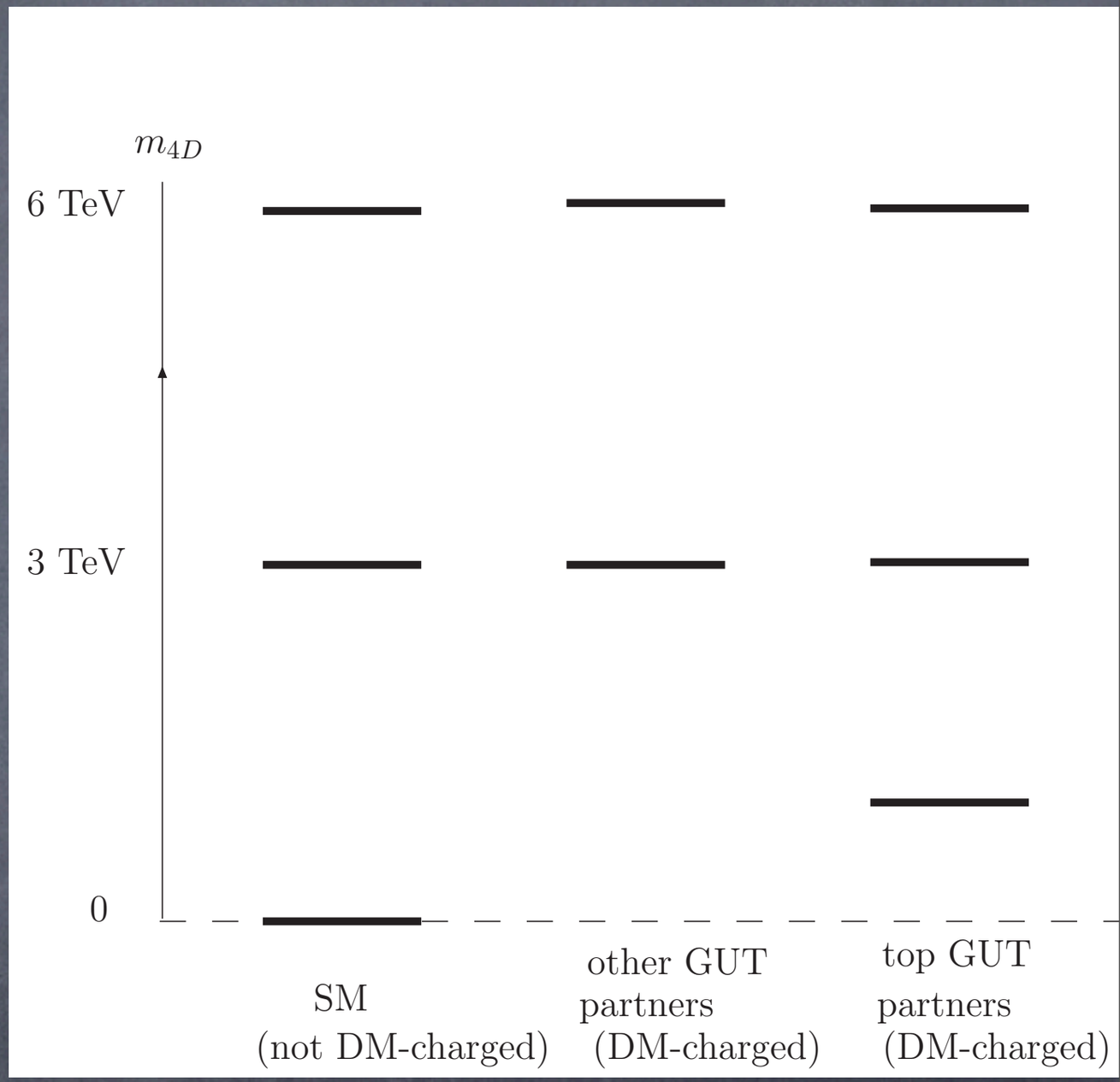


correct abundance (thermal freeze-out)

Stable particle in Warped GUT

(KA, Servant)

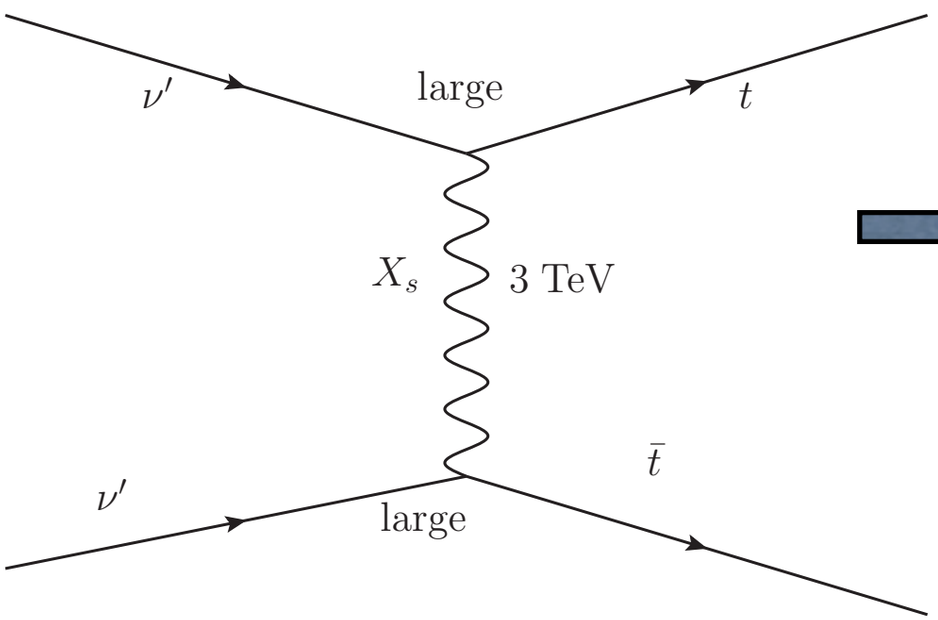
- Spin-off of extra symmetry imposed to suppress proton decay (like SUSY)
- "Exotic" neutrino (ν'): GUT partner of top (others are colored...)
- Mass ~100 GeV << KK scale of 3 TeV naturally (from wave equation + heavy top profile)

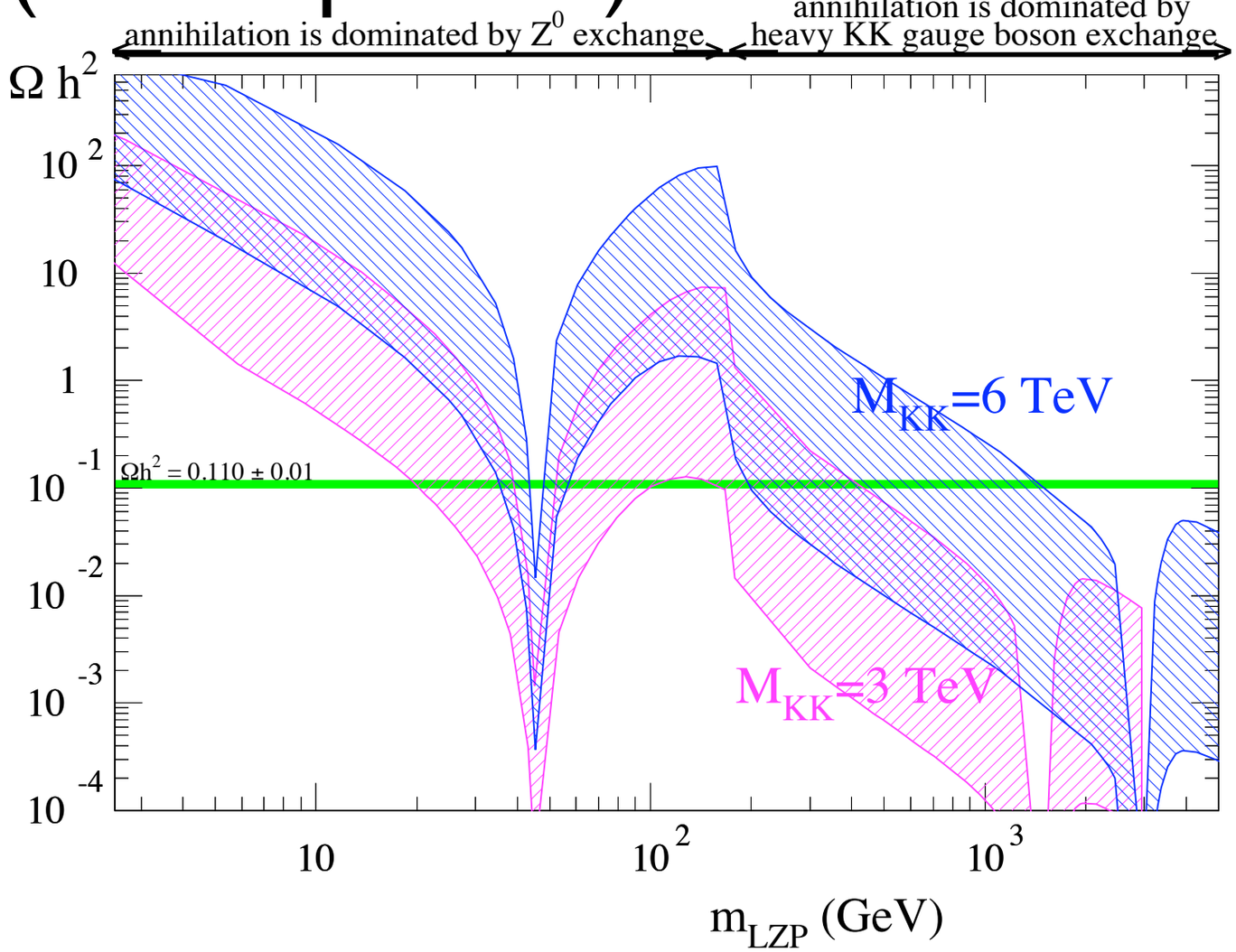


(Stable) WIMP in Warped GUT

(KA, Servant)

- Annihilation via exchange of 3 TeV (``>>" weak scale) KK, but strong coupling (due to profiles)



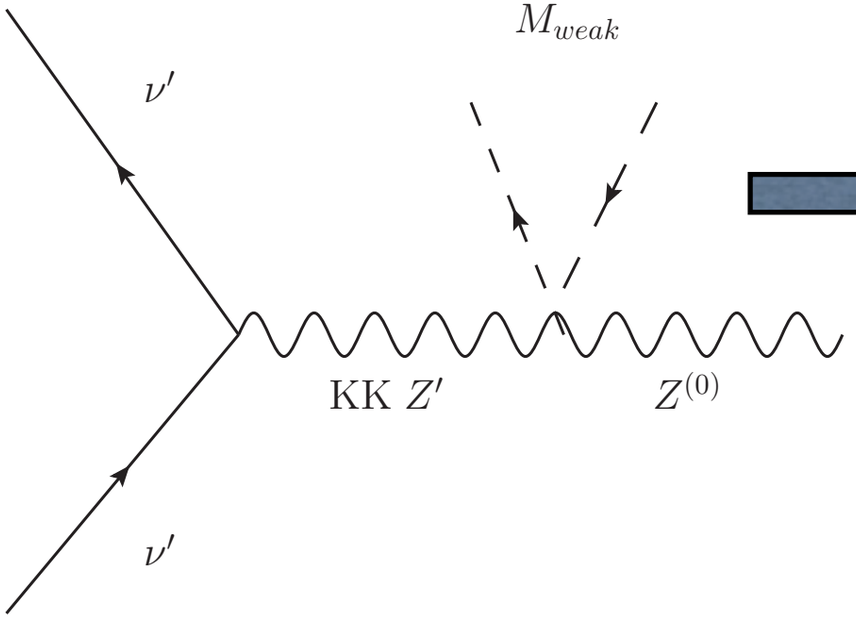


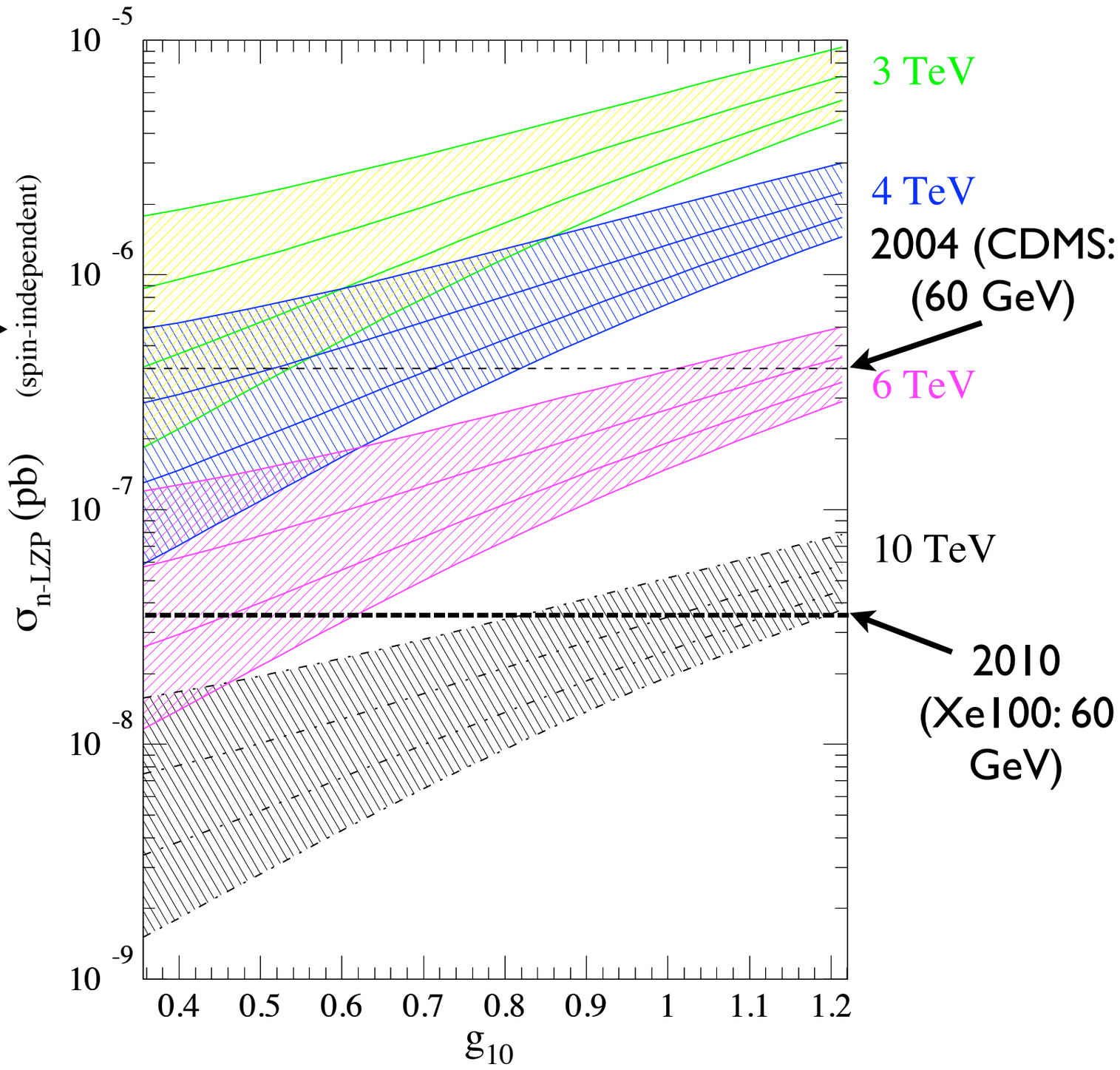
- (Stable) ``neutrino" is a WIMP ⇒ Dark Matter

DM SIGNALS

(Standard) direct detection

(KA, Servant)

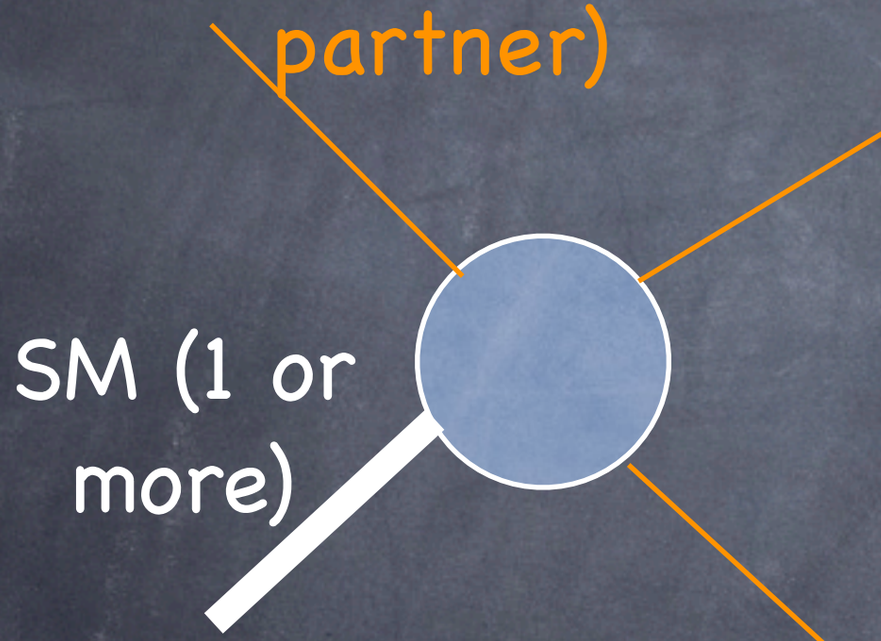




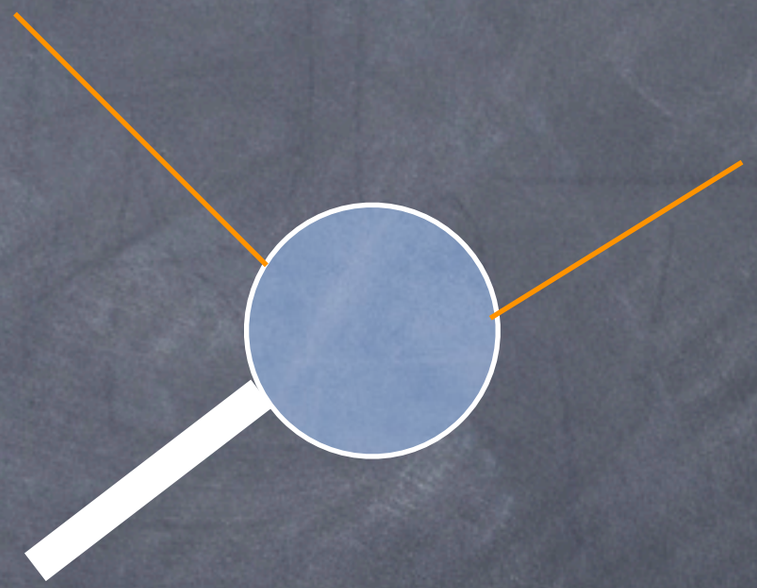
- ...(mild) tension for minimal model!

Non-standard effects

- Z_3 symmetry (warped GUT) vs. Z_2 (e.g., SUSY)



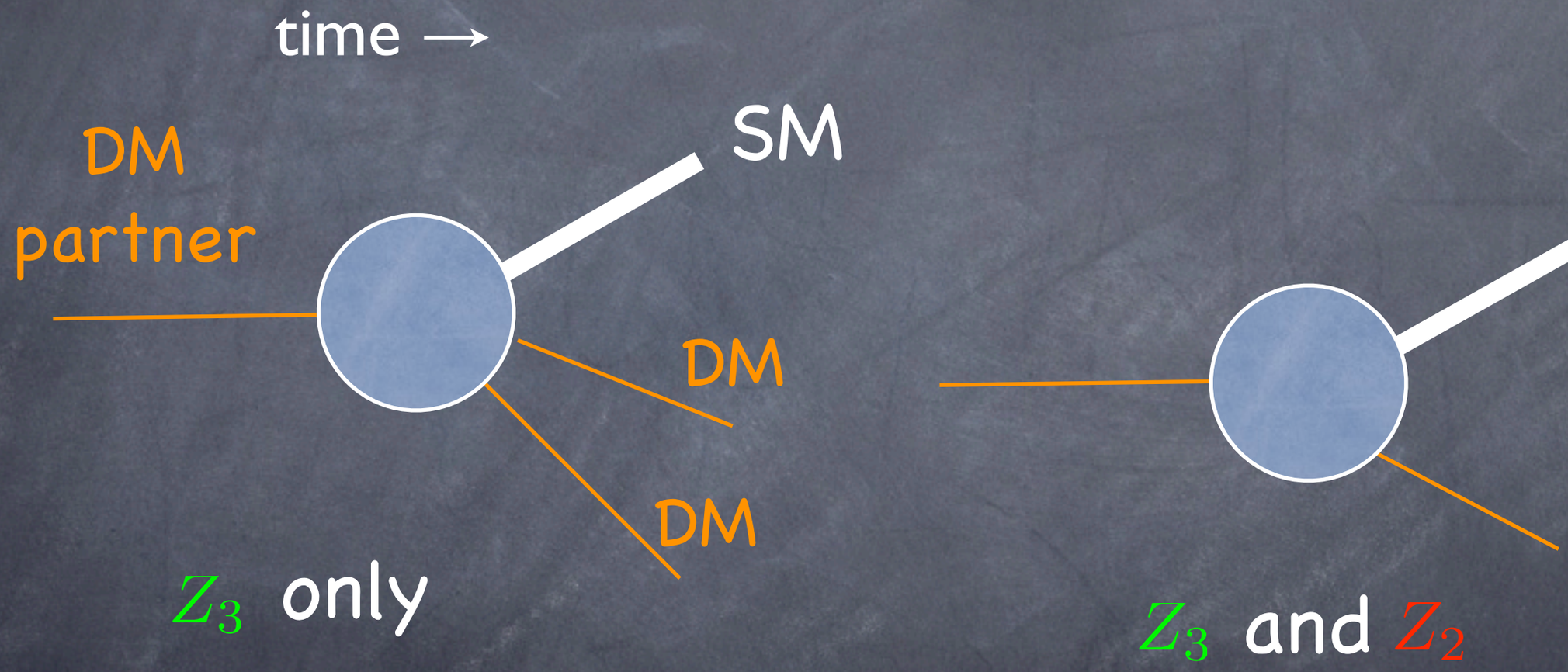
Z_3 only



Z_3 and Z_2

(I) At colliders (Dark Matter invisible)

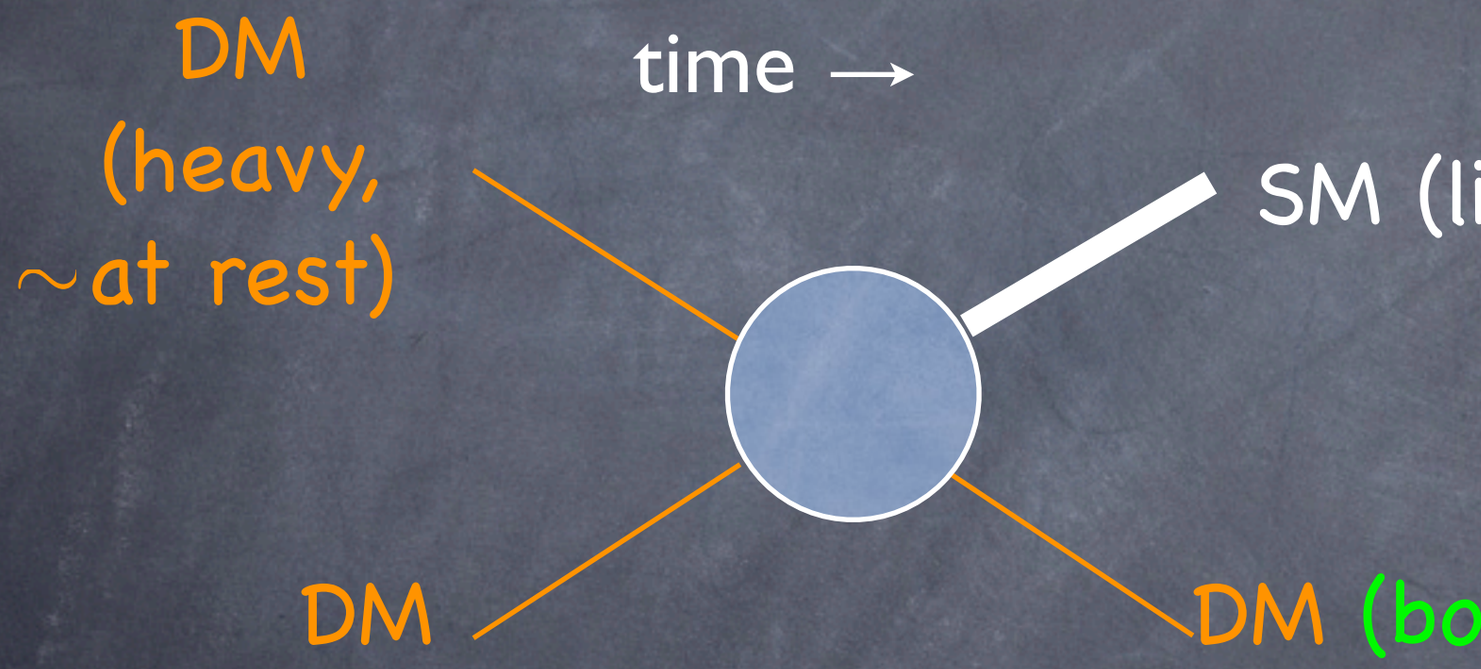
(KA, Kim, Toharia, Walker; KA, Kim, Walker, Zhu; KA, Franceschini, Kim, Wardlow)



- New decay chain for DM partner in Z_3 vs. Z_2

(II) Dark Matter Detection: Boosted Dark Matter (in progress...)

- only in Z_3: (semi) annihilation (in Sun)



- vs. (usual) ~ at rest Dark Matter

CONCLUSIONS

Testable solutions to puzzles of nature

Why is gravity weak

KK at LHC: boosted top/W/Z/H

Why is up quark lighter than top

LHCb; super-B; project X...

Charge 5/3 top/bottom partner

Warped Extra Dimension

Neutrino anarchy

$no\ 0\nu\beta\beta$

Grand Unification of 3 forces

(Top) GUT partners at LHC

Candidate for Dark Matter of Universe

Xe100; PandaX; LUX; boosted?

BACK-UPs

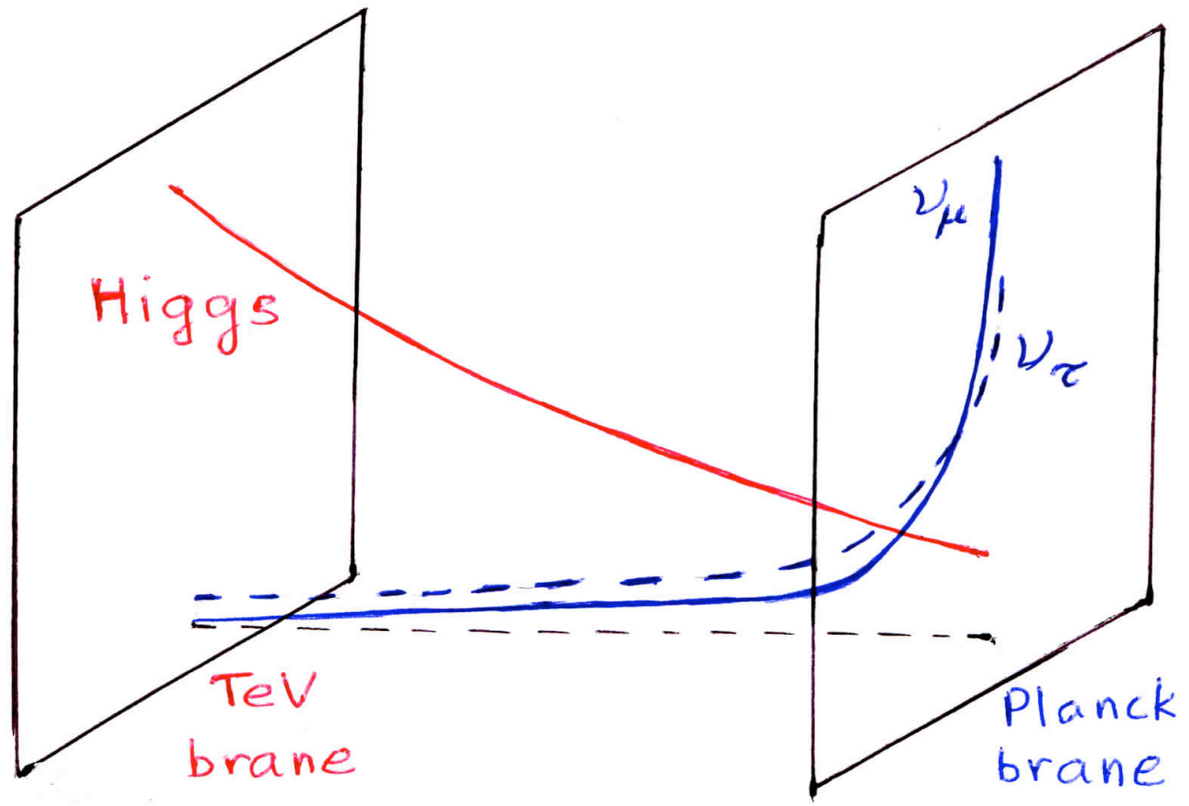
Neutrino anarchy (KA, Okui, Sundrum)

- Fermion profile very close to Planck... ⇒ overlap "switches" to dominated near Planck brane ⇒

- very small coupling to Higgs/mass (Higgs tail)

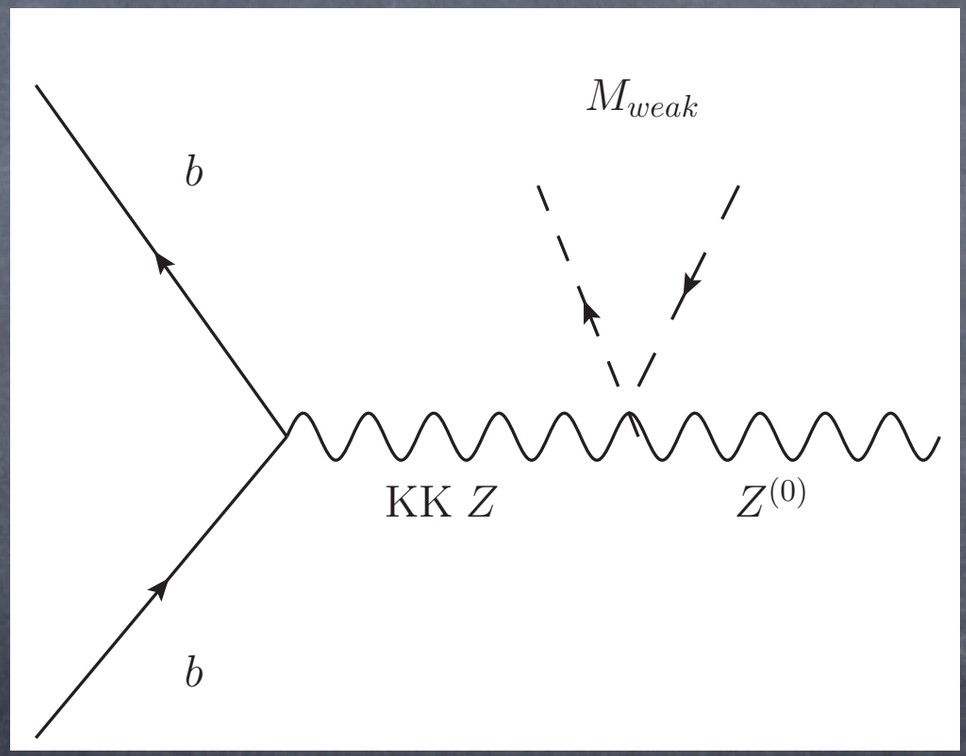
- non-hierarchical coupling/mass (profiles similar size)

- "Signal": works only for Dirac ν ⇒ no $0\nu\beta\beta$ decay!



ElectroWeak Precision Tests (II)

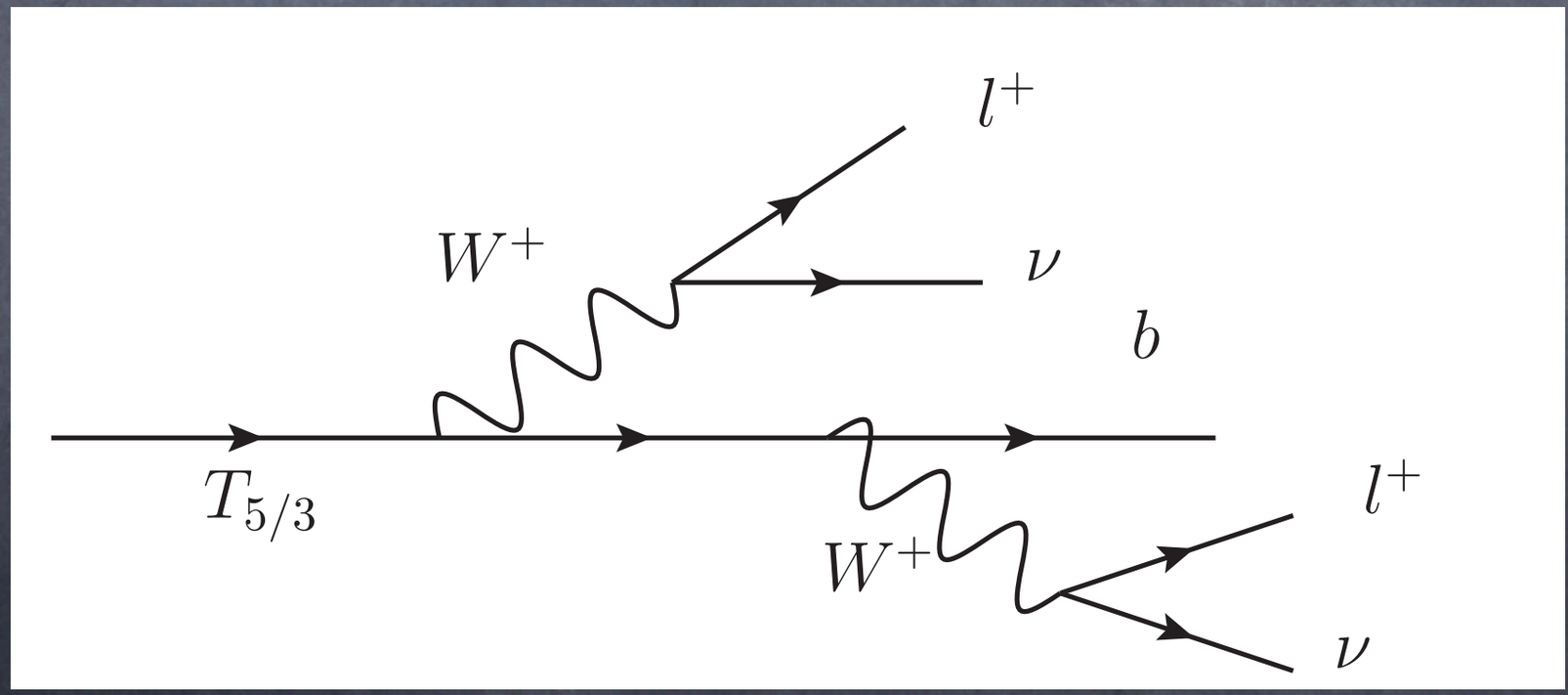
- Another problem: $Zb\bar{b}$ coupling
  due to isospin partner of b (top) being heavy
  (near TeV brane)



- extend isospin symmetry (KA, Contino, DaRold, Pomarol)

(3). Exotic charged particles

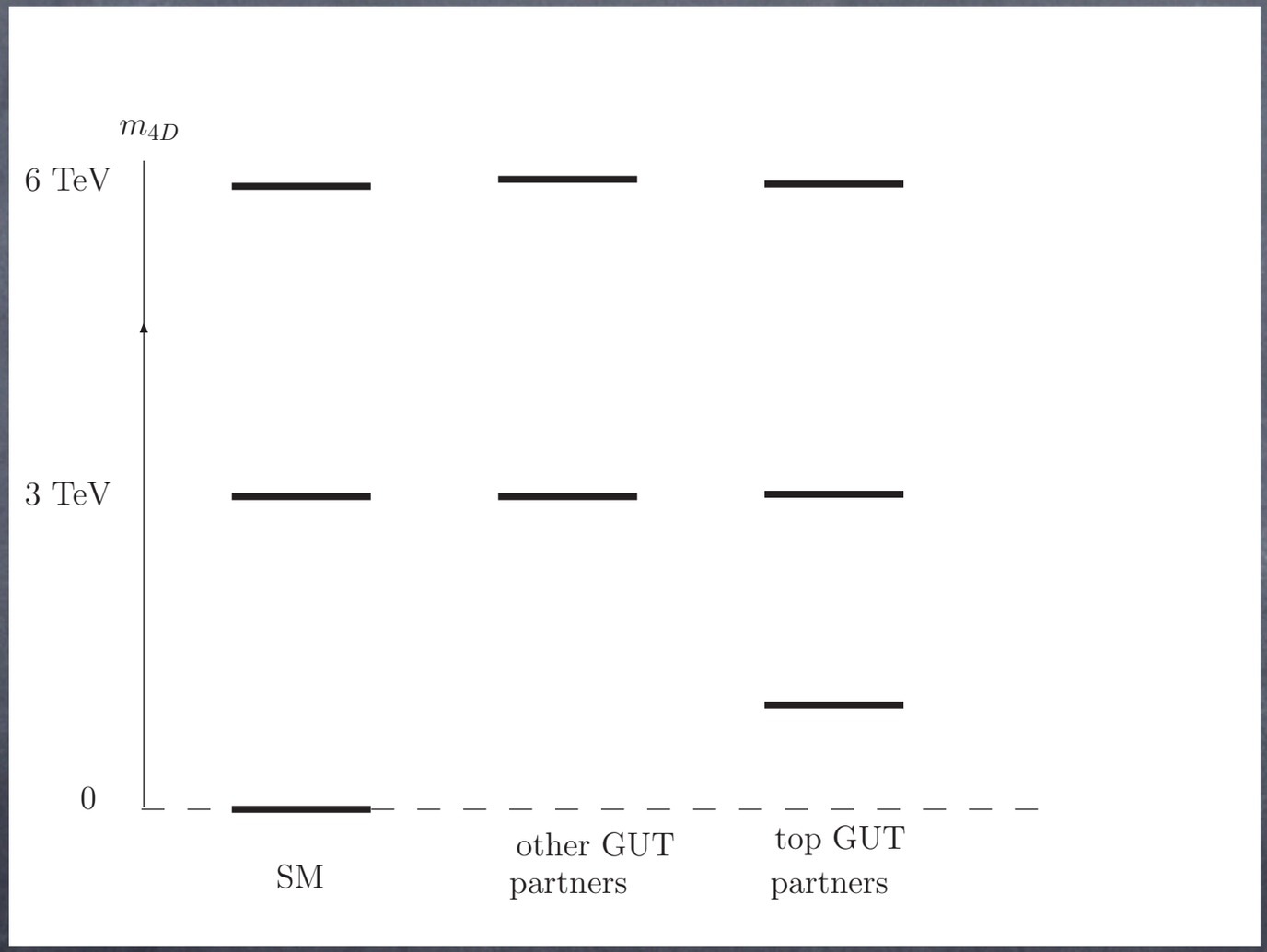
- predicts charge 5/3 fermionic partner of top/bottom quark
- decays to same sign W's/dilepton
  (Contino, Servant; Mrazek, Wulzer)



WARPED GUT SIGNALS

Light GUT partners of top

- <~1 TeV naturally (from wave equation + choice of profile for heavy top) even if other KK (minimal model)~3 TeV



- produce at LHC (even if other KK's beyond reach)

Dark Matter?!

- no new symmetry in (minimal) warped model ⇨
  no dark matter (unlike SUSY)

- ...but, Dark Matter (naturally) in extension to GUT