Title: A simple proof of the threshold for fault-tolerant quantum computation

Date: Mar 24, 2005 04:00 PM

URL: http://pirsa.org/05030123

Abstract:

WARPED COMPACTIFICATIONS: FLAVOR, UNIFICATION AND DARK MATTER

Kaustubh Agashe (Johns Hopkins University)

with

G. Perez and A. Soni,
Phys. Rev. Lett. 93, 201804 (2004) and
Phys. Rev. D71, 016002 (2005)

R. Contino and R. Sundrum, ~~to appear~~ hep-ph/0502222

G. Servant, Phys. Rev. Lett. 93, 231805 (2004) and
hep-ph/0411254 (to appear in JCAP)

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- **POST-LEP: SUSY SOLVES PLANCK-WEAK HIERARCHY OF SM**

Gauge coupling unification: evidence for SUSY?

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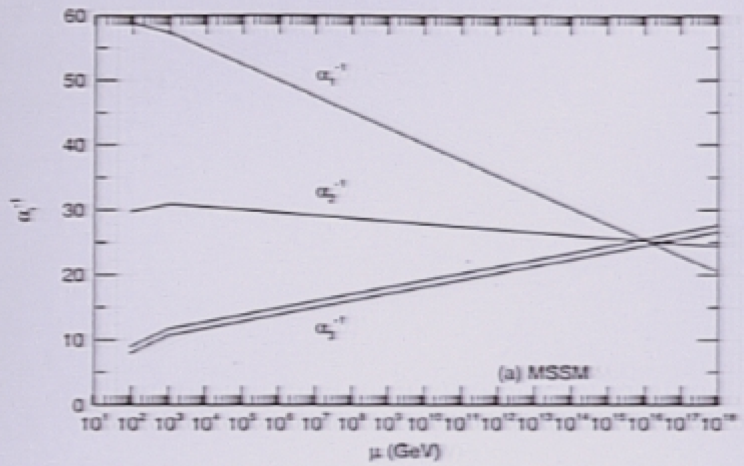
Gauge coupling unification: evidence for SUSY?

Running of gauge couplings



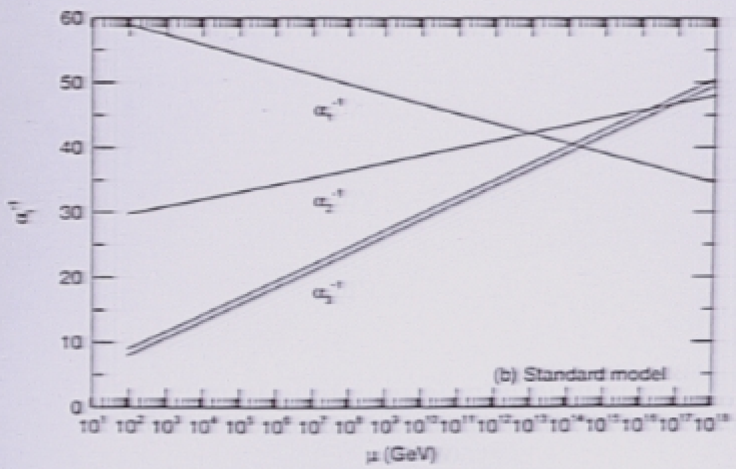


Figure 2.2: Renormalization group flow of the coupling constants of $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ gauge group for the case of (a) the MSSM, and (b) the standard model. Here, we use two loop renormalization group equations, and take the SUSY scale at 1TeV for the MSSM case.

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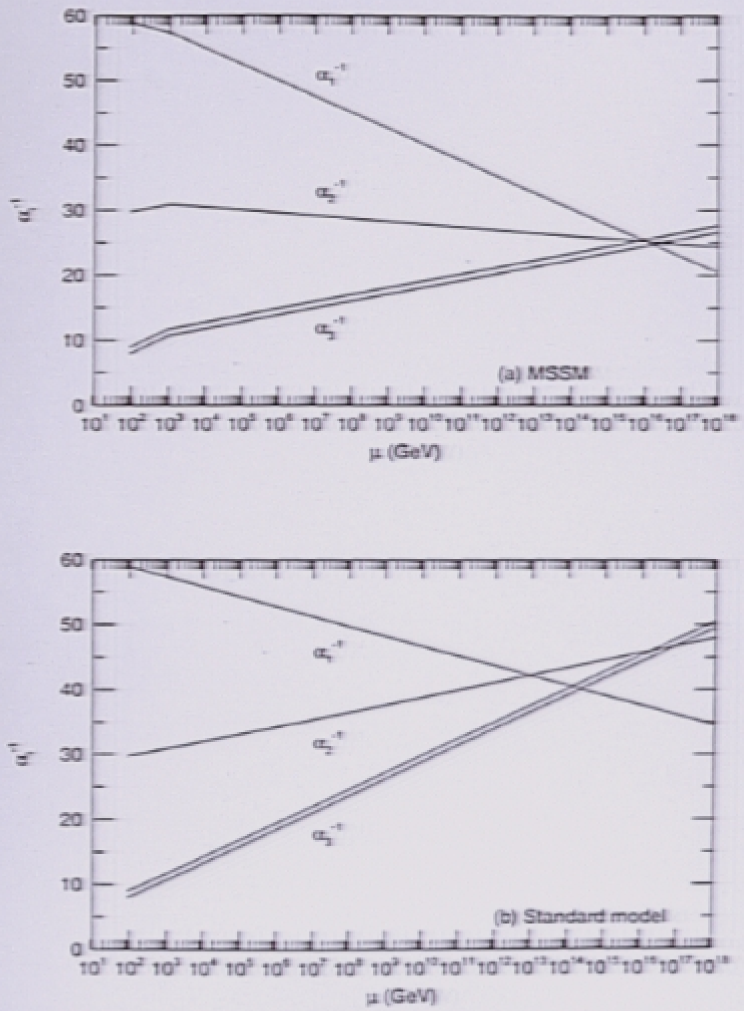

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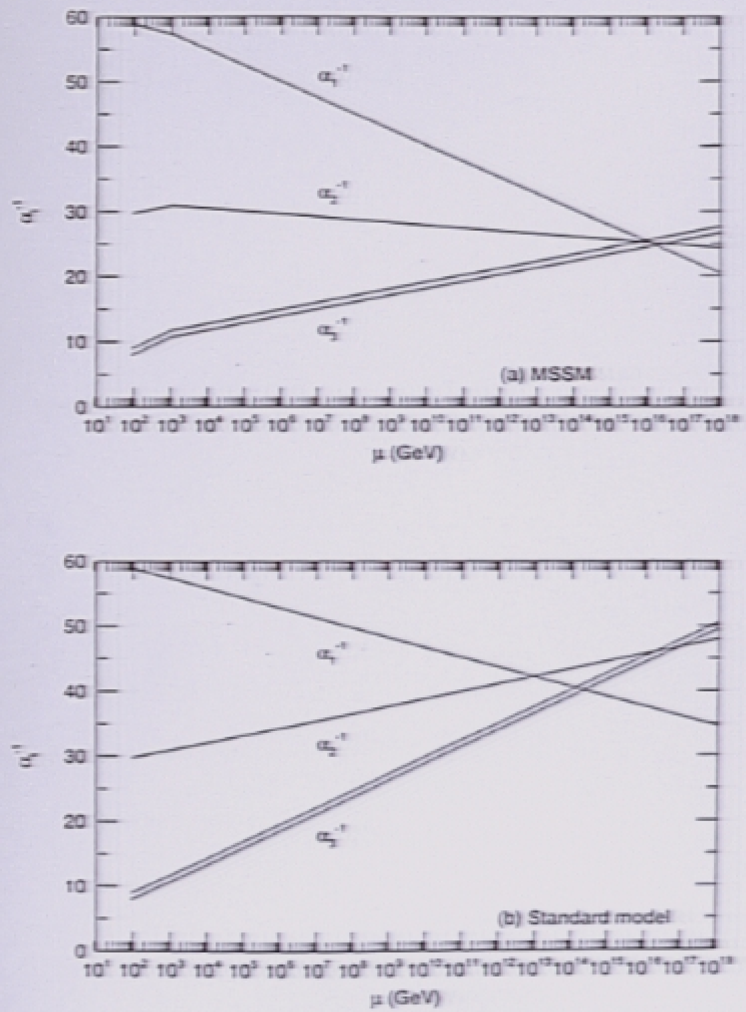

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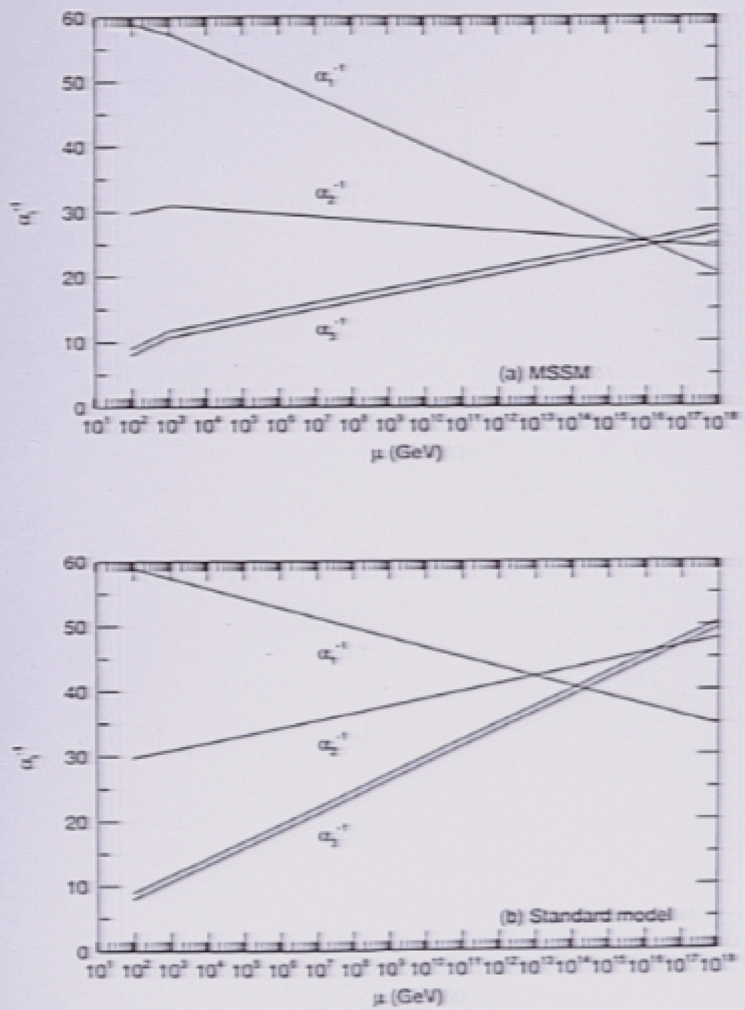

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OTHER PROS OF SUSY

- Dark matter (DM) from proton stability (R-parity)

- Small corrections to Precision Electroweak Data:

  loop level + weak couplings

PROBLEMS OF MSSM

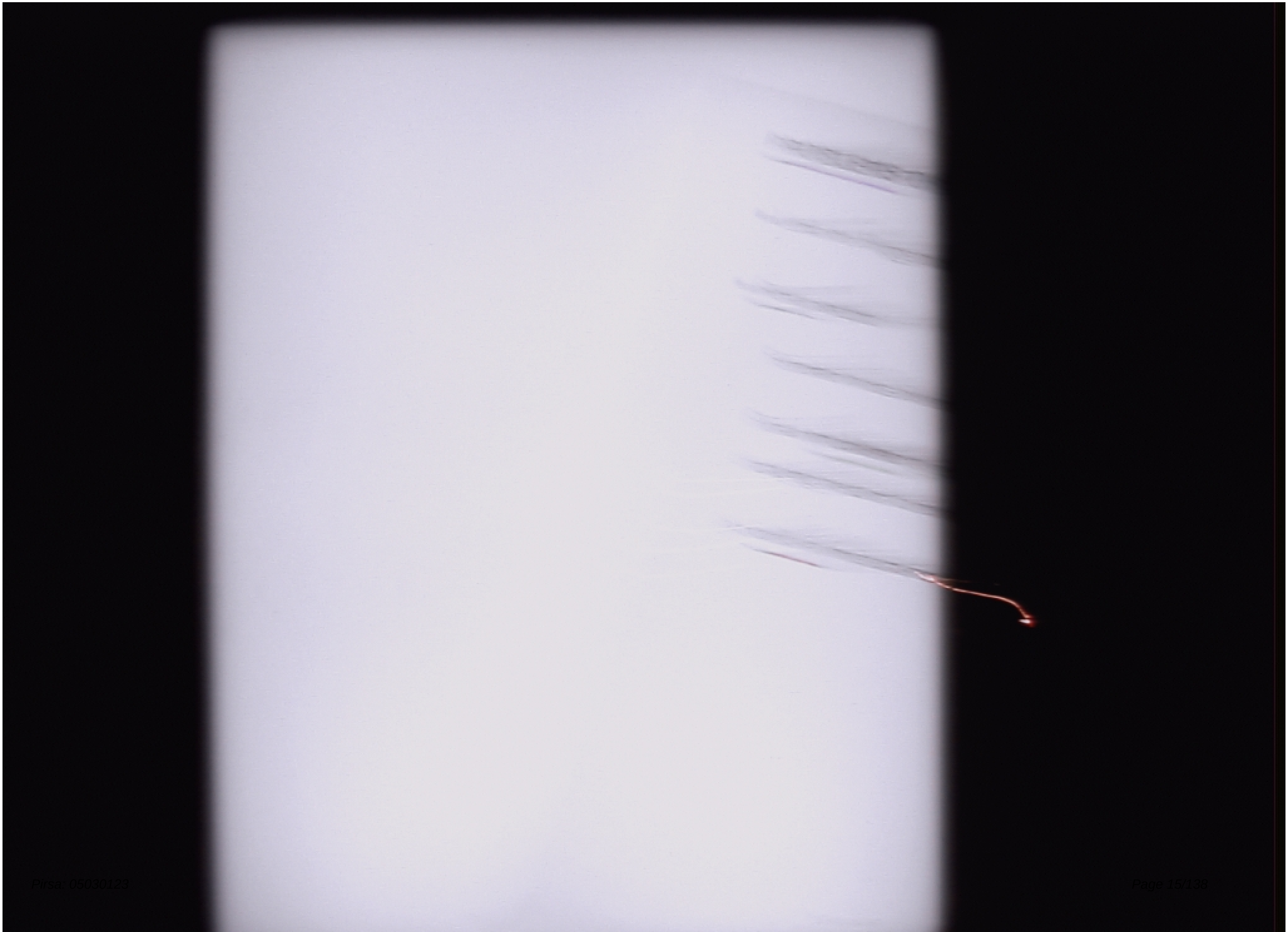
- Limit on Higgs mass $\rightarrow$ fine-tuning $\sim$ few %

- Flavor sector:

  Fermion mass hierarchy by hand (flavor puzzle)

  Flavor **problem**: generic SUSY breaking $\rightarrow$ flavor changing neutral currents (FCNC's): $K - \bar{K}$...

  (no built-in mechanisms)



OUTLINE

Non-**SUSY solution: warped extra dimension**

(Randall-Sundrum models)

SM (except Higgs) in **bulk**

- Fermion profiles **solve** flavor **puzzle**

  No flavor problem: GIM mechanism

  Couplings of **left**-handed b (and $t_{L,R}$) ~~GIM~~ due to m_t ($\sim$ SM) $\rightarrow$ Signals at B-factories

- Fermion profiles in GUT's $\rightarrow$ unification $\sim$ SUSY

- Proton stability in GUT's $\rightarrow$ stable particle ($\sim$ SUSY)

  Exotic RH-neutrino as DM (good for detection)

Conclusions: **direct** signal at LHC

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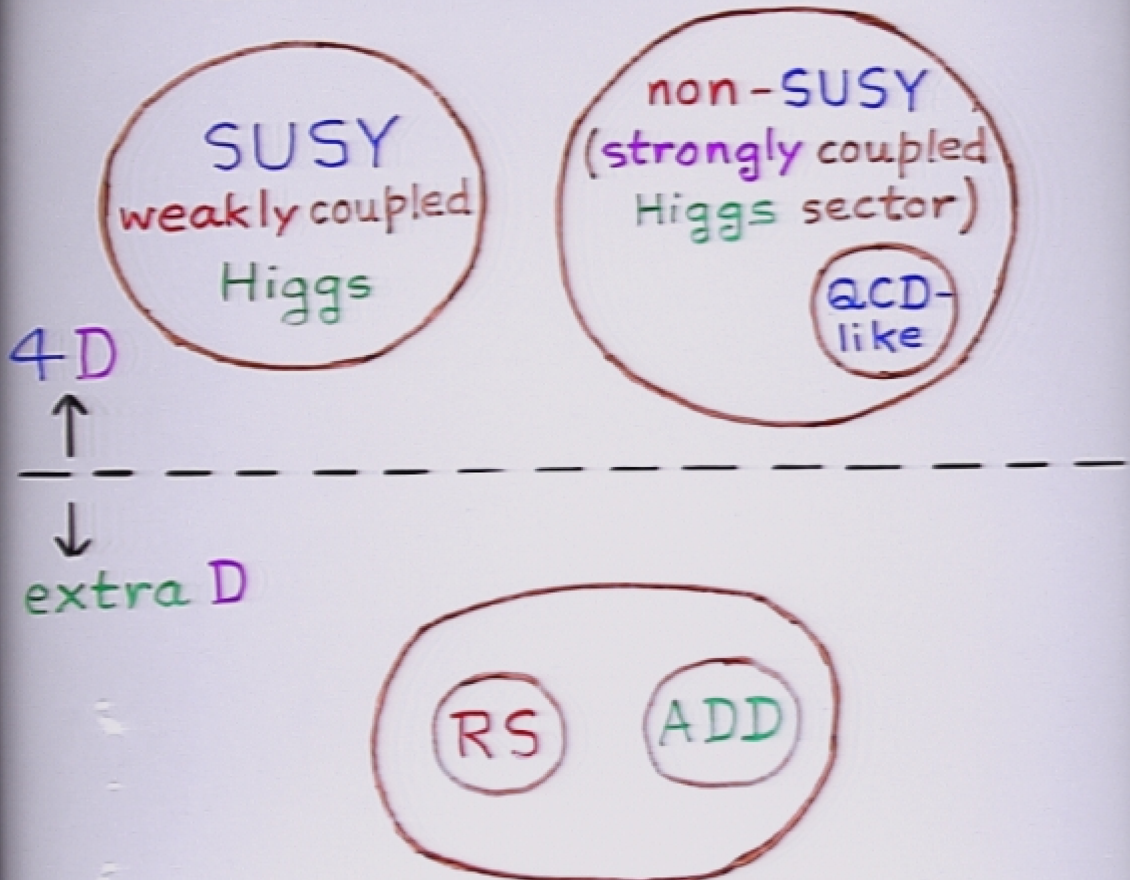
SOLUTIONS TO PLANCK-WEAK HIERARCHY PROBLEM



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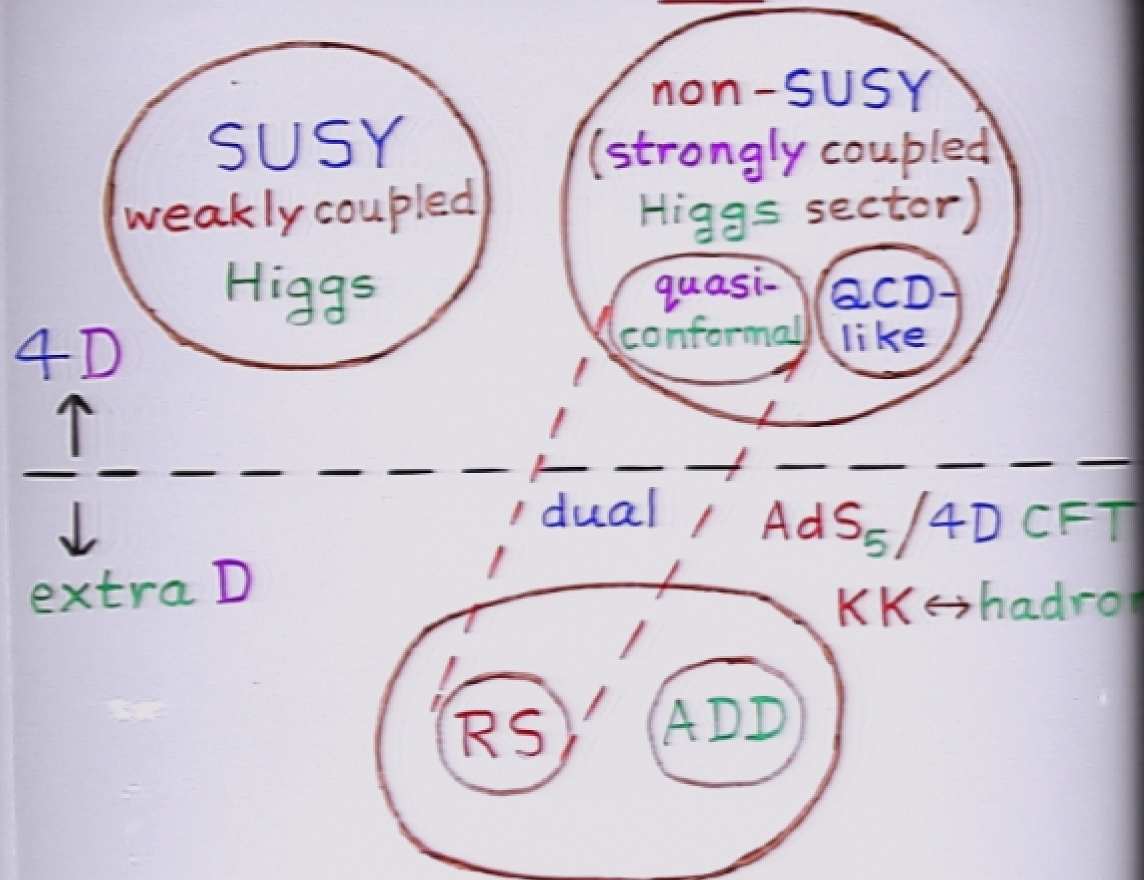
SOLUTIONS TO PLANCK-WEAK HIERARCHY PROBLEM : REAL PICTURE



- RS: **weakly** coupled tool for a $4D$ **strongly** coupled Higgs sector

9

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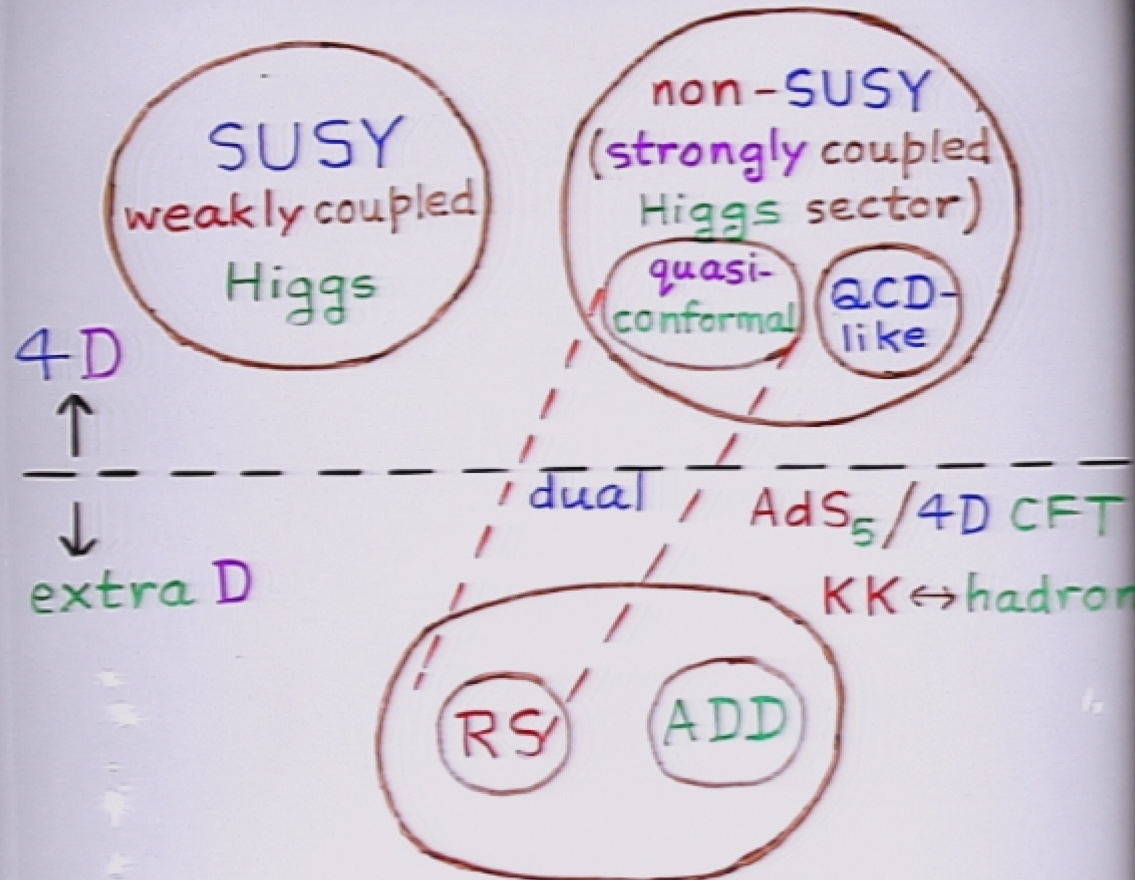

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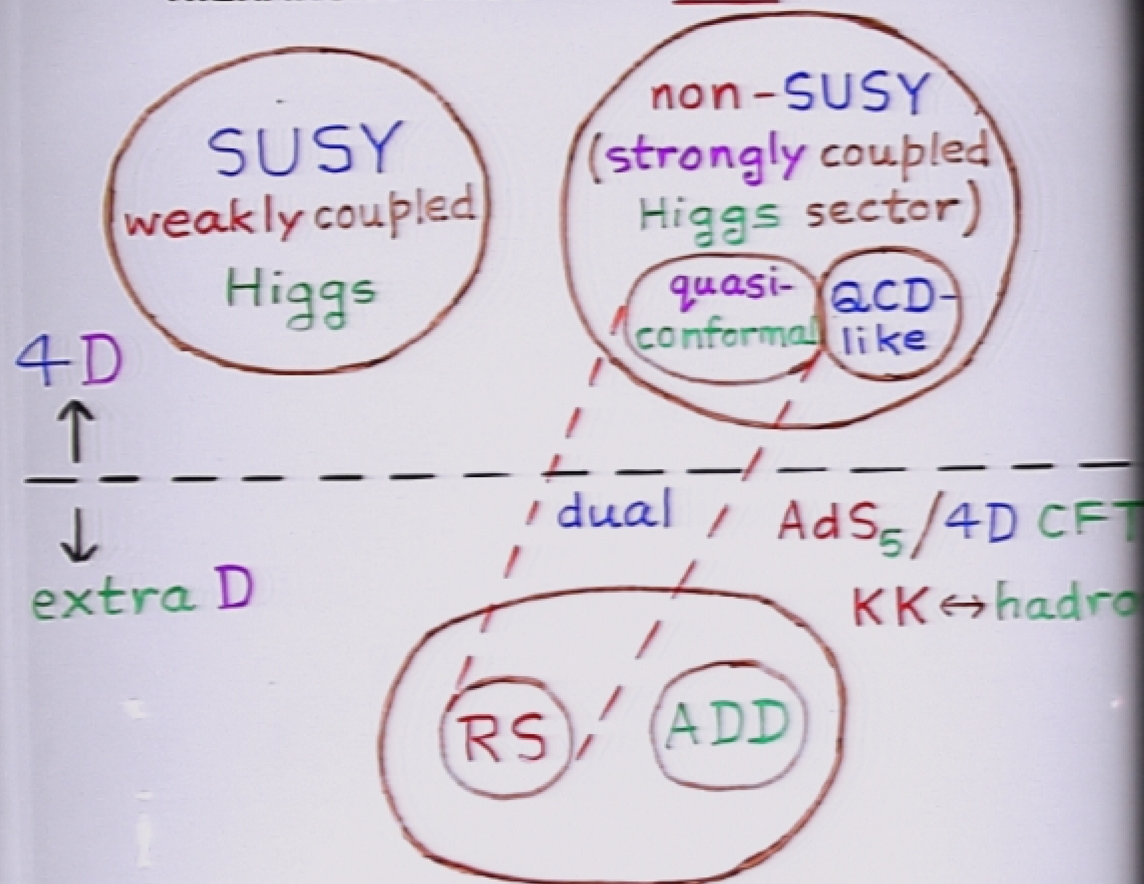

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REVIEW

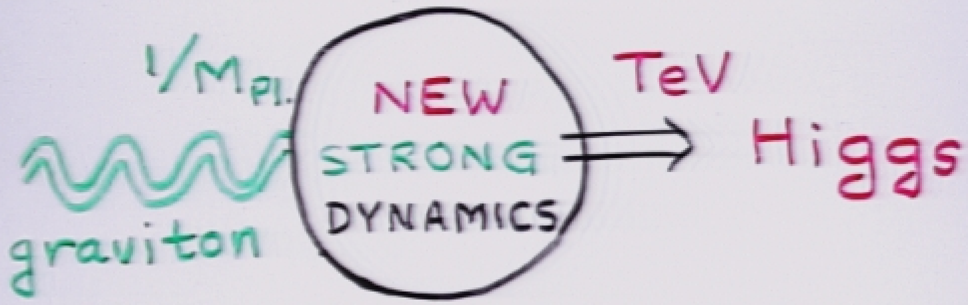
OF

RS1

$\boxed{4D}$ COMPOSITE HIGGS MODEL

New strong dynamics condenses at $\sim$ TeV (a la QCD at $\sim$ GeV)

Higgs is a (light) composite (a la π)



tower of **massive** composites

- difficult to calculate: constituents of "hadrons" strongly coupled

4

graviton

tower of massive compo

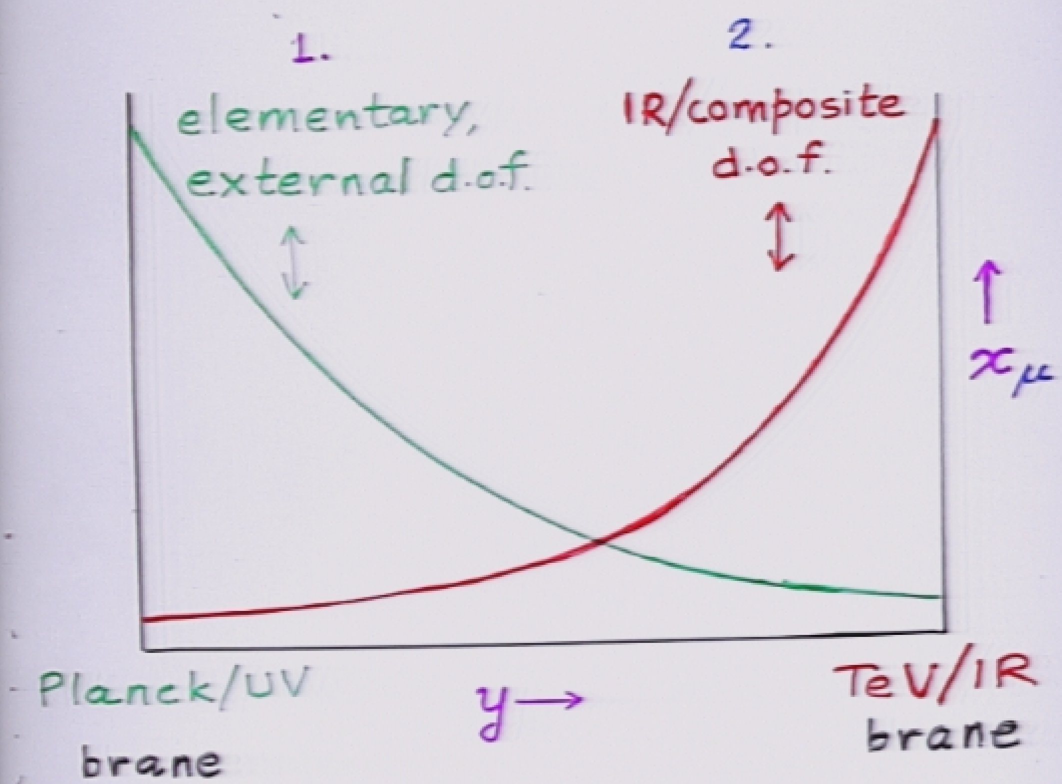
* difficult to calculate; consti

strongly coupled

WEAKLY COUPLED (DUAL) PICTURE:

WARPED (CURVED) EXTRA DIMENSION

$5D$ AdS/$4D$ CFT correspondence: KK $\leftrightarrow$ hadron



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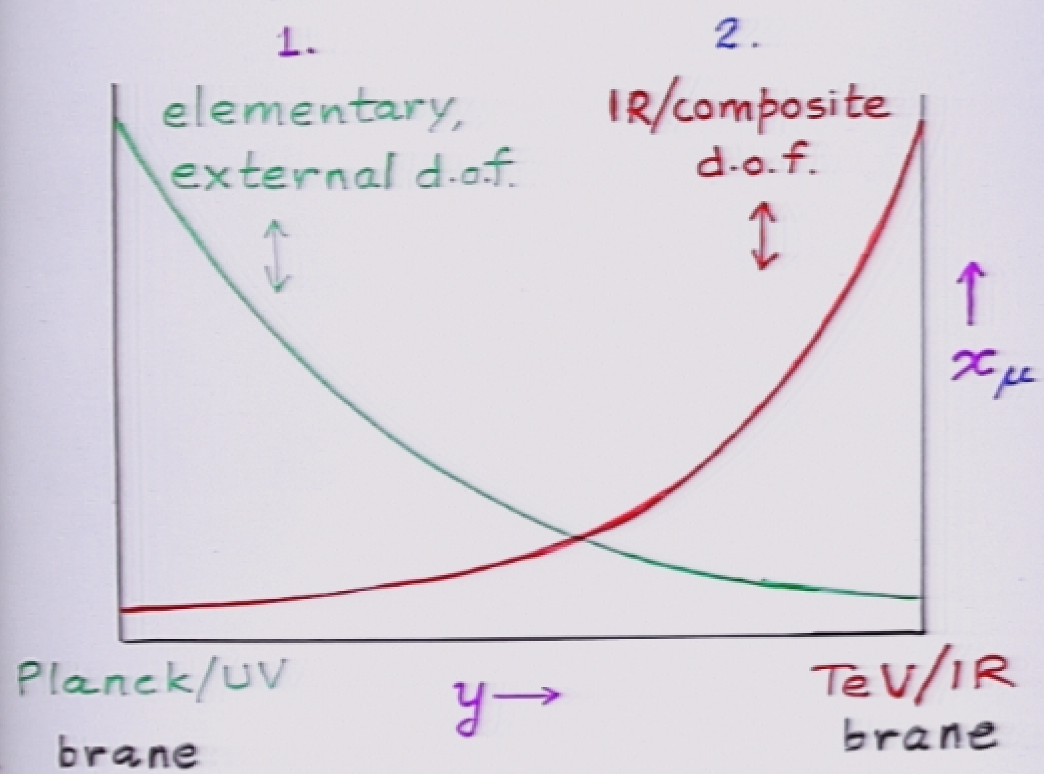

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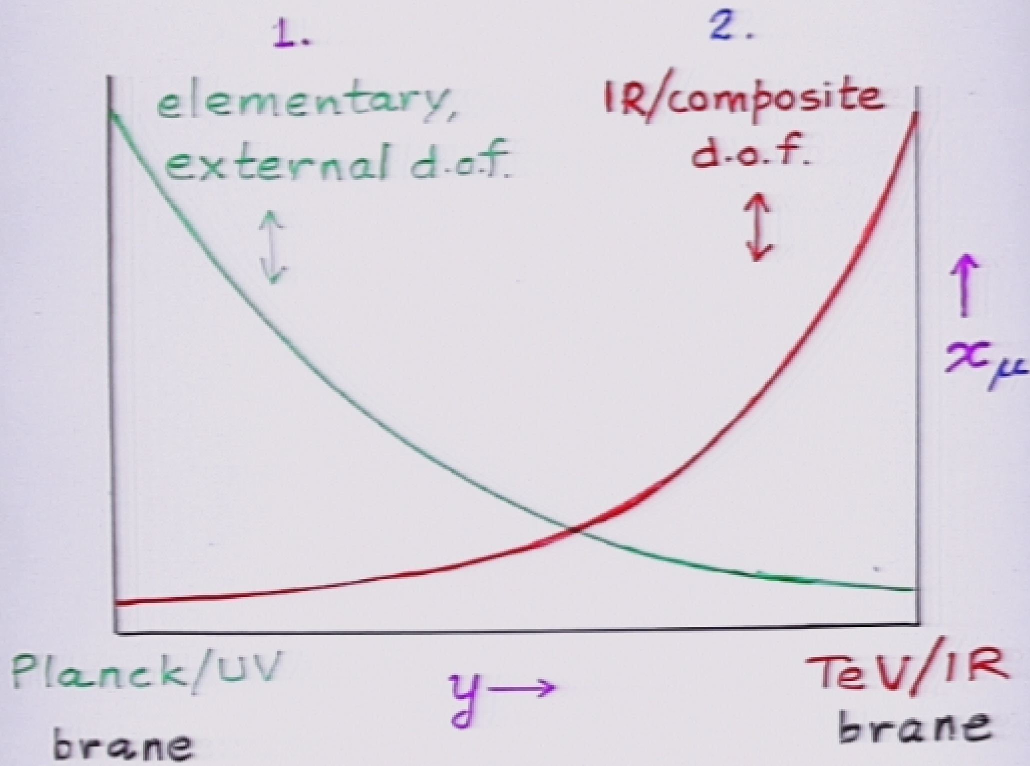

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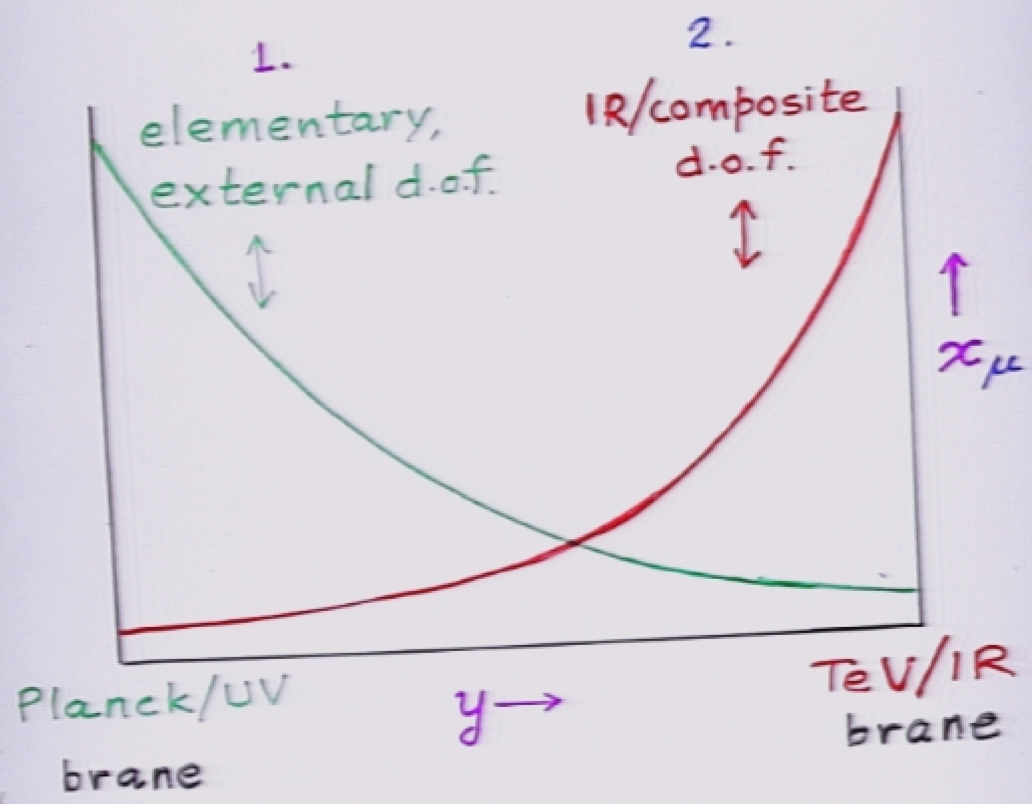

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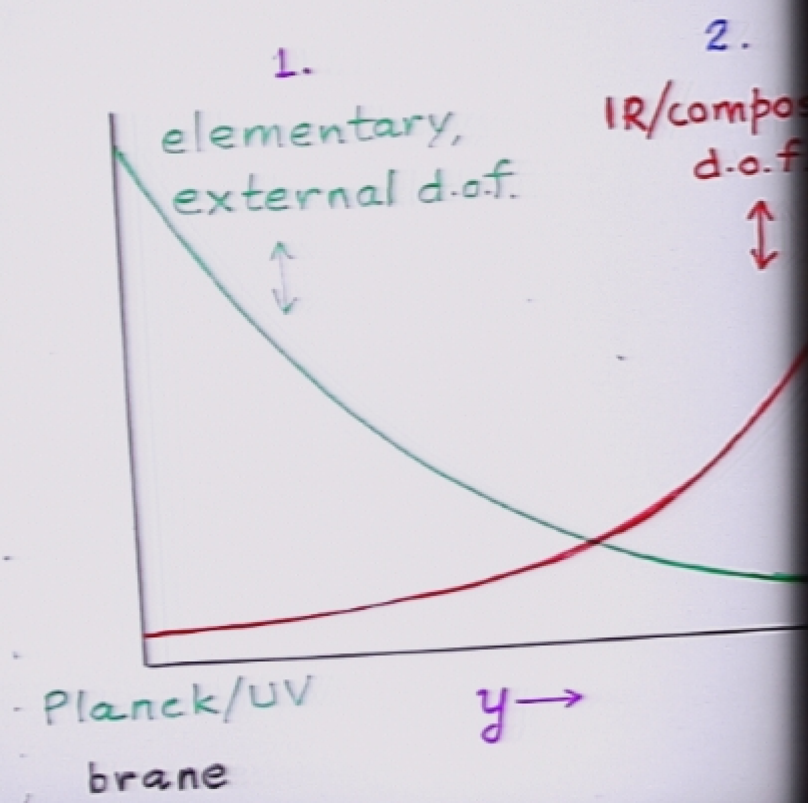
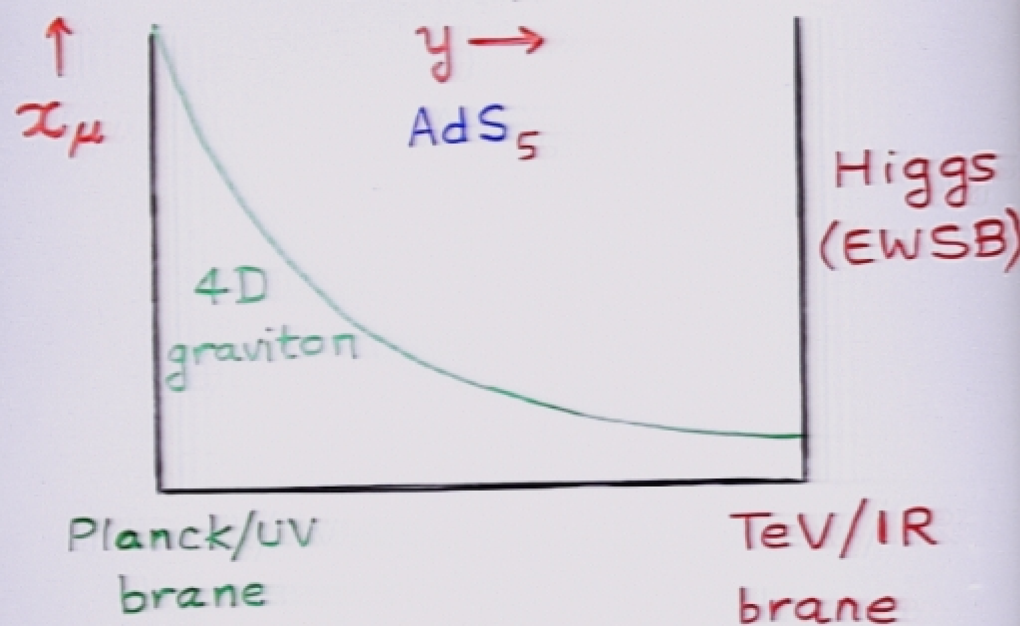
$5D$ AdS/$4D$ CFT correspondence: KK ←



• **RS1 MODEL** (Randall, Sundrum)



$G_N^{-2} \sim M_{Pl}^2$ ← due to warping → cut-off for $m_H \sim$ TeV

Profiles: solve wave equation in $5D$ **curved** space-time

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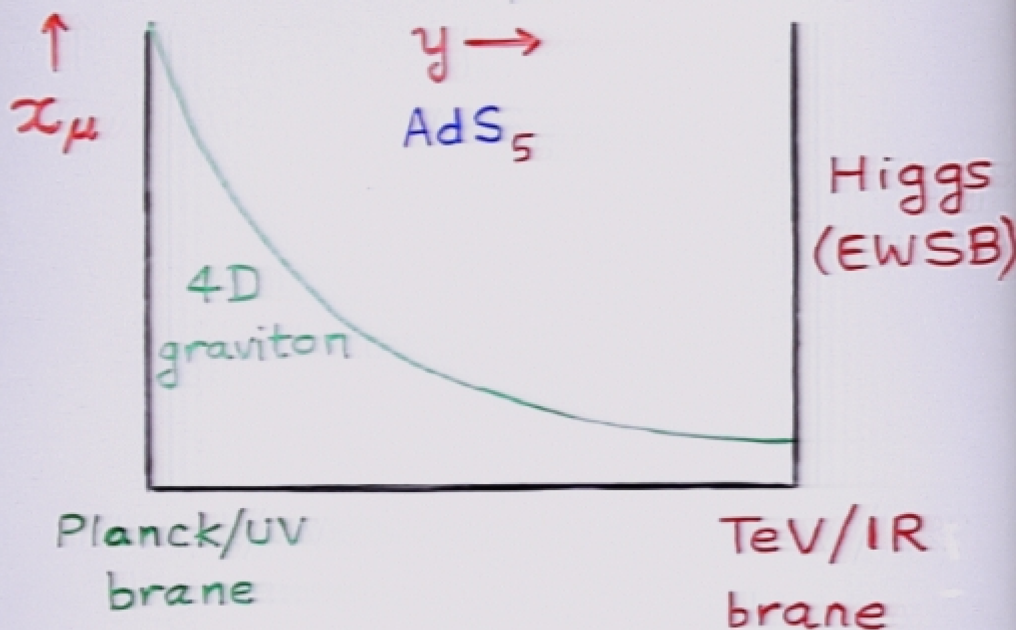

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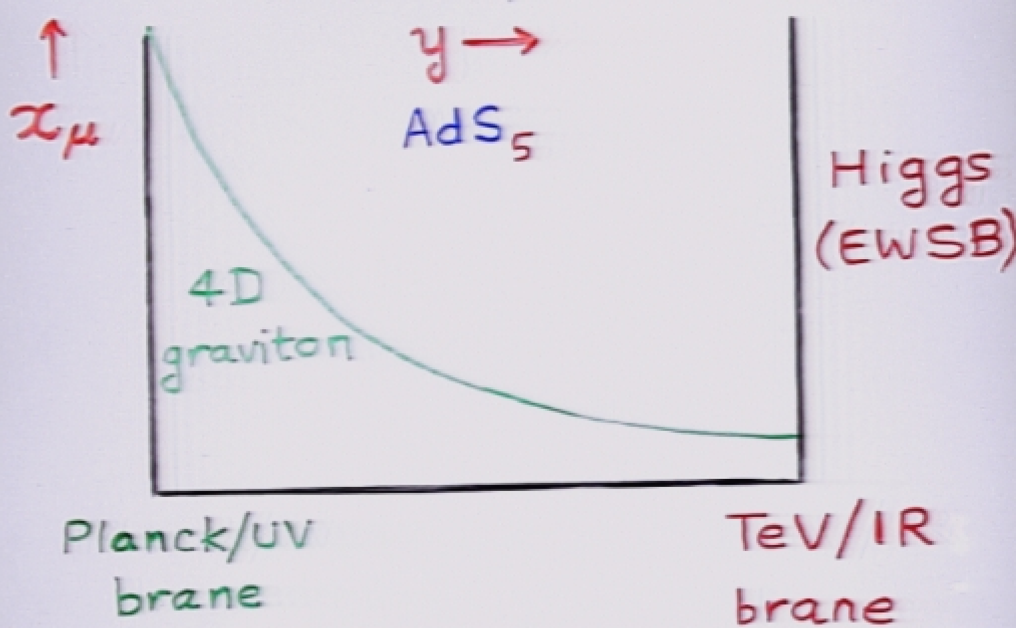

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Profiles: solve wave equation in $5D$ **curved** space-time

SM IN BULK

↓

SOLUTION TO

FLAVOR PUZZLE

WITHOUT

FLAVOR PROBLEM

SM IN B

↓

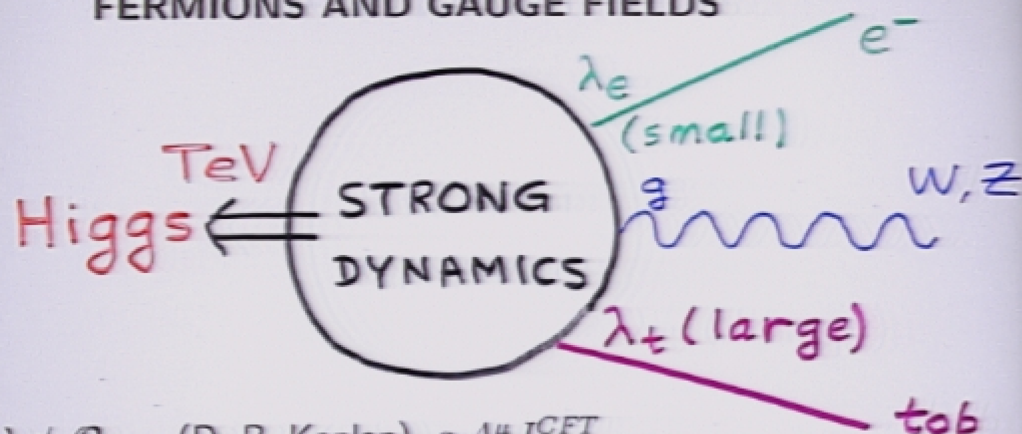
SOLUTION

FLAVOR PU

WITHOUT

FLAVOR PRO

• $\boxed{4D}$ COMPOSITE HIGGS MODEL: FERMIONS AND GAUGE FIELDS



$\lambda\,\psi\,\mathcal{O}_{CFT}$ (D. B. Kaplan), $g\, A^\mu J_\mu^{CFT}$

$\boxed{\text{SM} \sim \text{external} \oplus \text{composite}}$ (a la $\gamma - \rho$)

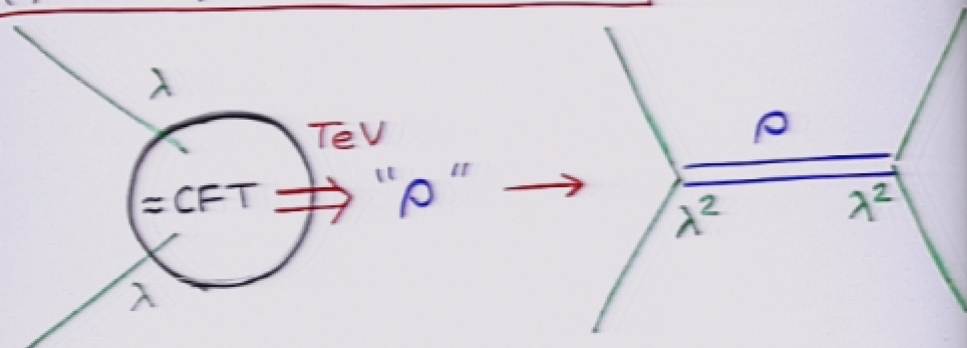
mixing $\sim [\mathcal{O}_{CFT}]$

$\boxed{\text{fermion mass} \propto (\text{mixing})^2 \sim \lambda^2}$

light fermions	top quark
irrelevant (small λ)	relevant (large λ)
fundamental	composite

- **FCNC:** $\underline{4D}$ **PICTURE** (KA, Perez, Soni)

$$\boxed{\text{Coupling of massive } (\sim \text{TeV}) \text{ composites ("}\rho\text{-mesons") to SM fermions} \propto \text{mixing}}$$



$\Rightarrow \boxed{\text{FCNC} \propto \lambda^4 \propto m_f^2}$

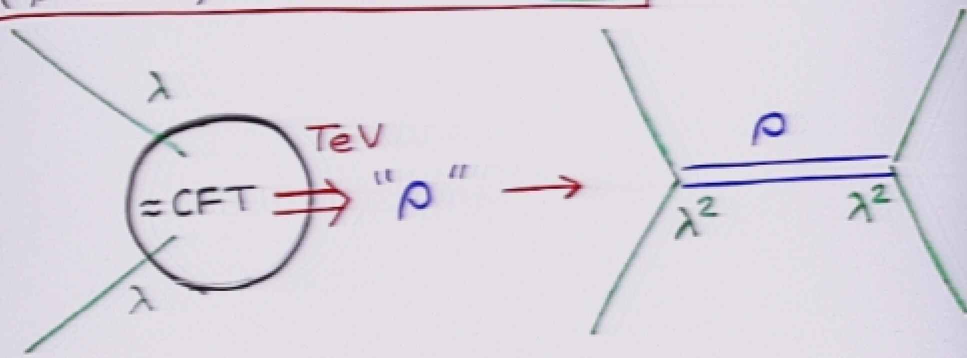
Glashow-Iliopoulos-Maiani (GIM) in SM:

loop level meson mixing $\propto m_q^2$

- **built-in GIM mechanism (absent in generic SUSY model)!**

- **FCNC:** $4D$ **PICTURE** (KA, Perez, Soni)

Coupling of massive ($\sim$ TeV) composites ("ρ-mesons") to SM fermions $\propto$ mixing



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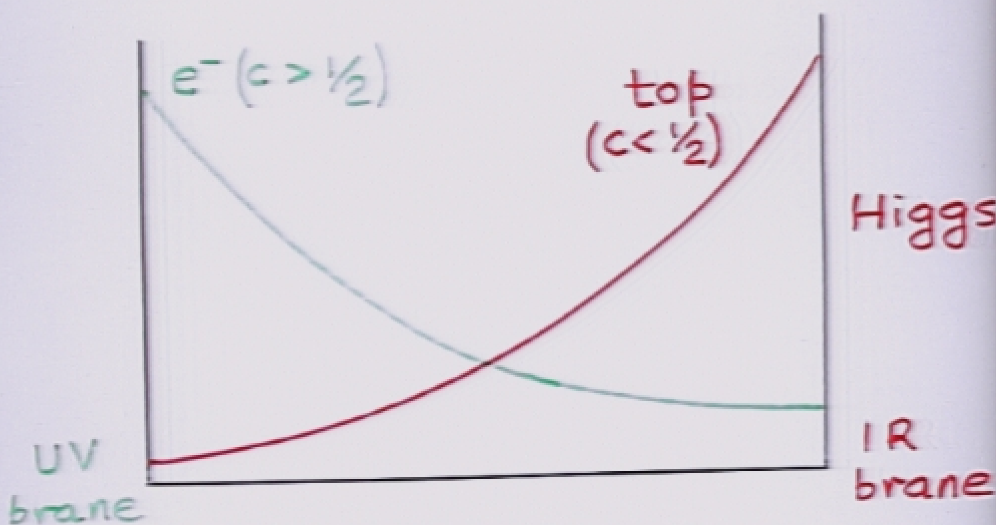
$5D$ mass (c parameter) $\sim$ domain wall: localizes **zero**-mode

(Grossman, Neubert; Gherghetta, Pomarol)



small y_e $\leftarrow$ y_{5D} same $\rightarrow$ large y_t

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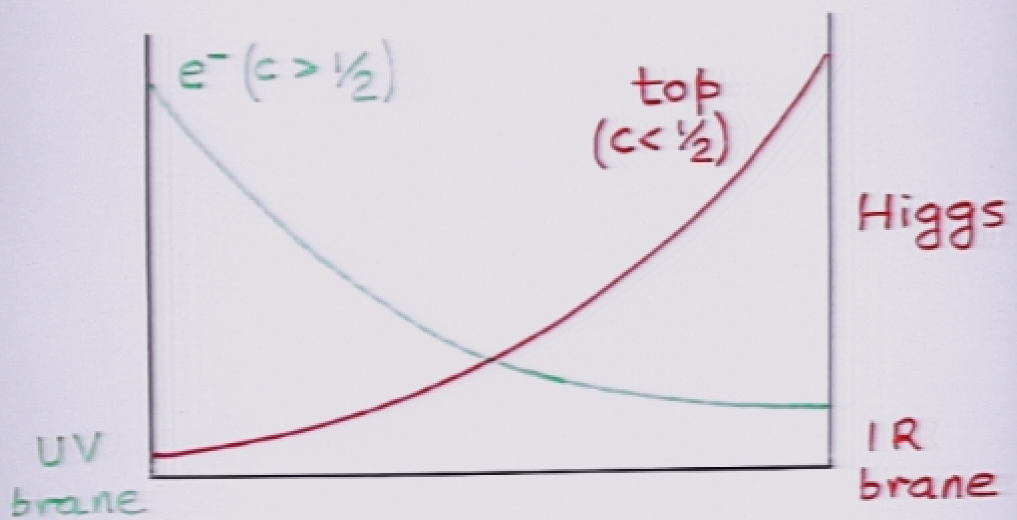

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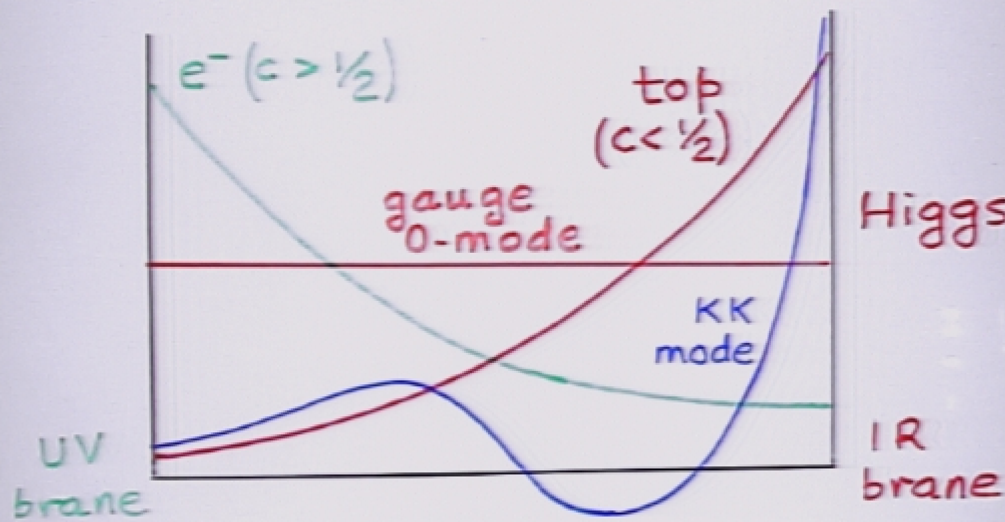
(Grossman, Neubert; Gherghetta, Pomarol)

$c_{eff.} = 1/2$ for gauge fields

(Davoudiasl, Hewett, Rizzo; Pomarol)



small y_e & coupling to gauge KK mode

$\leftarrow y_{5D}$ same $\rightarrow$

large y_t & coupling to gauge KK mode

Profiles: solution to $5D$ wave equation

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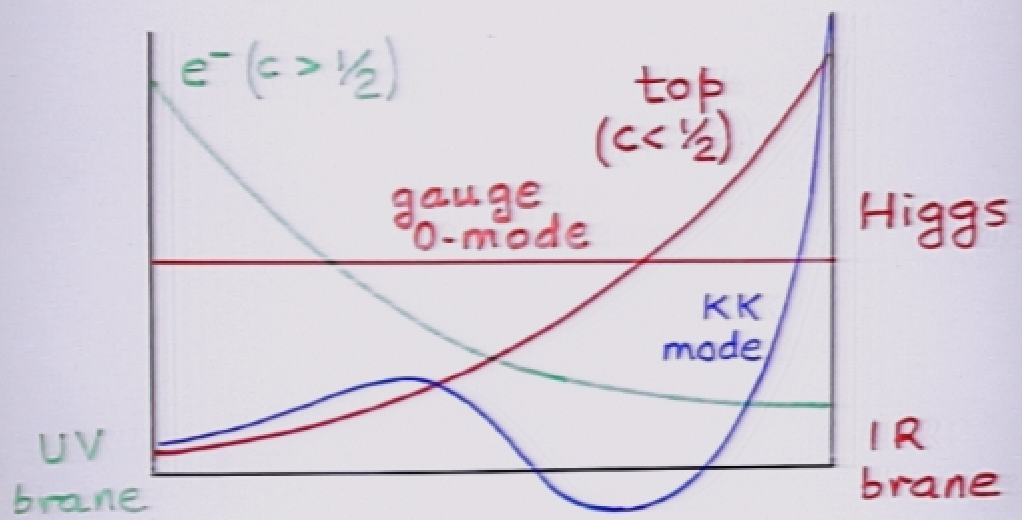

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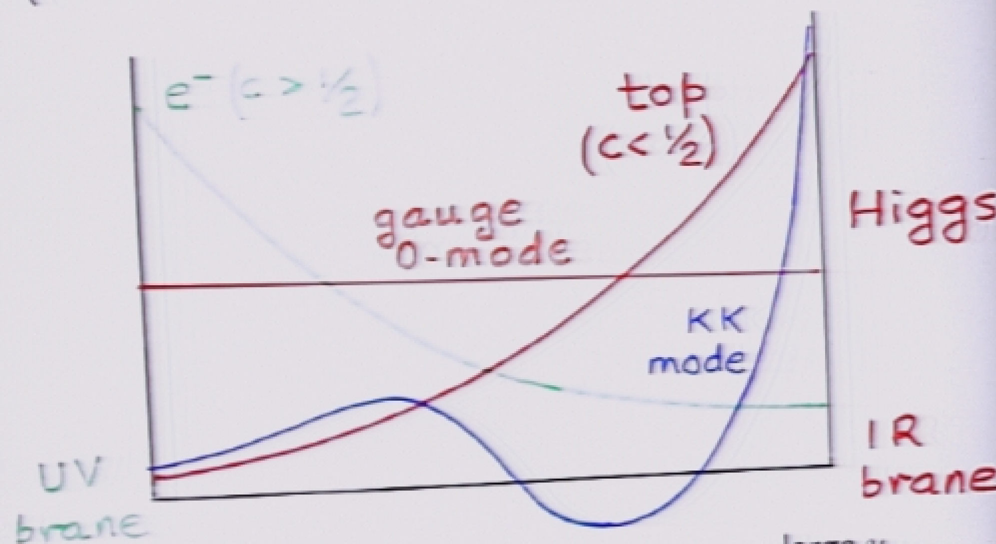

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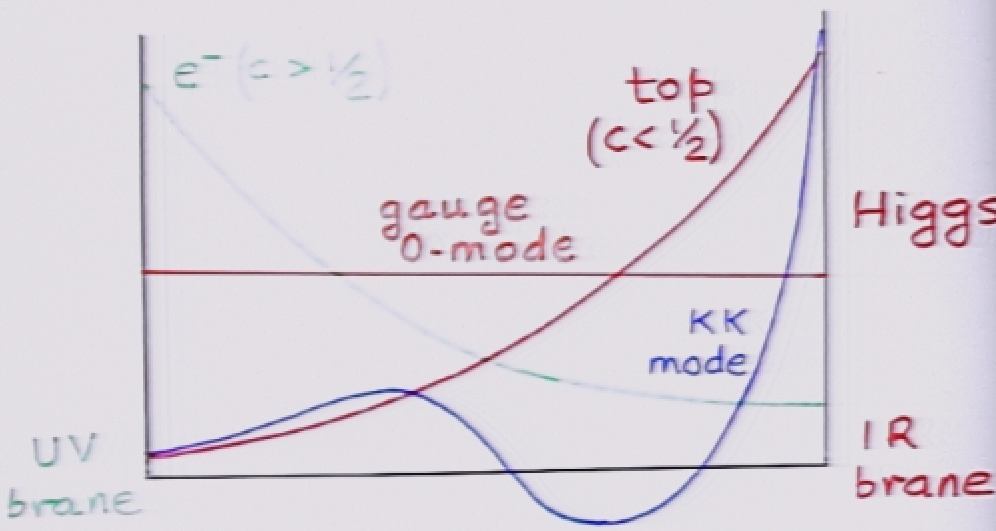

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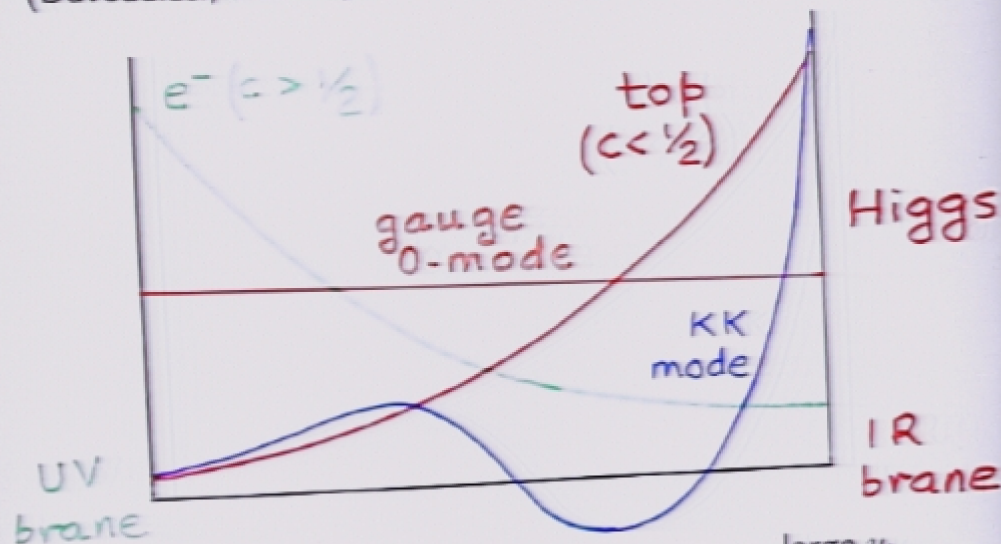

small y_e & coupling to gauge KK mode

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Profiles: solution to $5D$ wave equation

RH TOP

IS

COMPOSITE

RH TO

is

PRECISION TESTS: CUSTODIAL ISOSPIN

(KA, Delgado, May, Sundrum)

T parameter (or ϵ_1) $\Rightarrow$ **global** $SU(2)_L \times \boxed{SU(2)_R}$ symmetry for strong dynamics

$\updownarrow$

Electroweak $5D$ **gauge** symmetry:

$SU(2)_L \times \boxed{SU(2)_R} \times U(1)_{B-L}$

$3-4$ TeV KK masses consistent with S (or ϵ_3), T

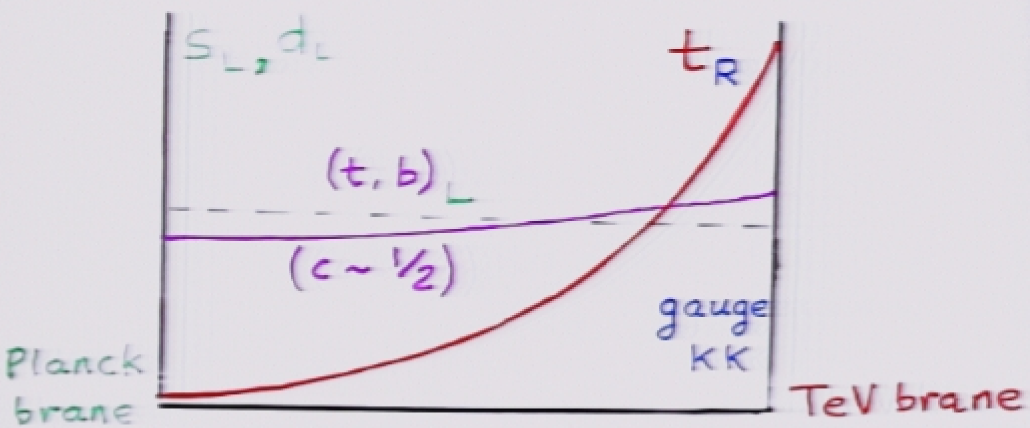
($\gtrsim$ 10 TeV without $SU(2)_R$: Huber, Shafi; Csaki, Erlich, Terning; Hewett, Petriello, Rizzo)

Preserve features of SM: GIM, custodial isospin

• TOP AND BOTTOM QUARKS

Top quark **heavy** — near TeV brane (composite)

$\boxed{\text{shift in } Z - b_L b_L \lesssim 0.5\% \to \text{KK mass} \sim 3-4 \text{ TeV}}$



• RH top quark near TeV brane ($c \lesssim 0$) (composite)

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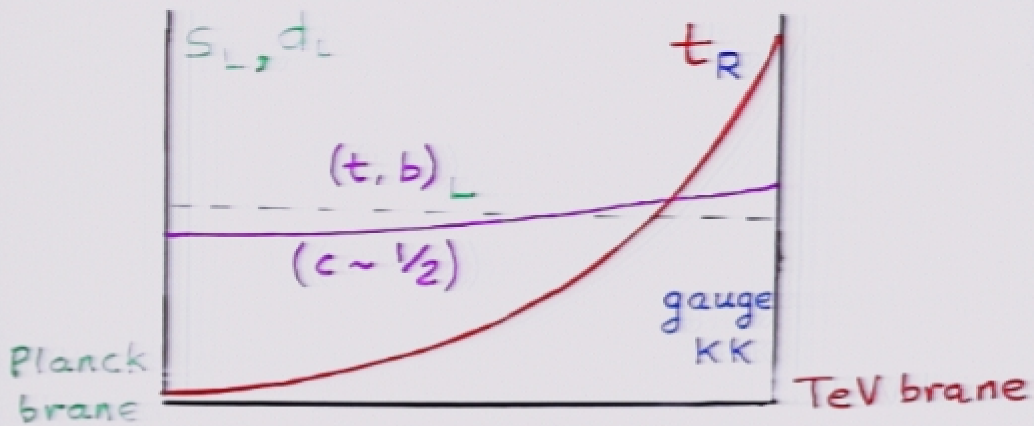
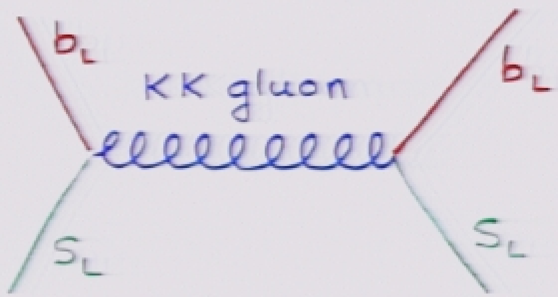


• RH top quark near TeV brane ($c \sim 0$) (composite)

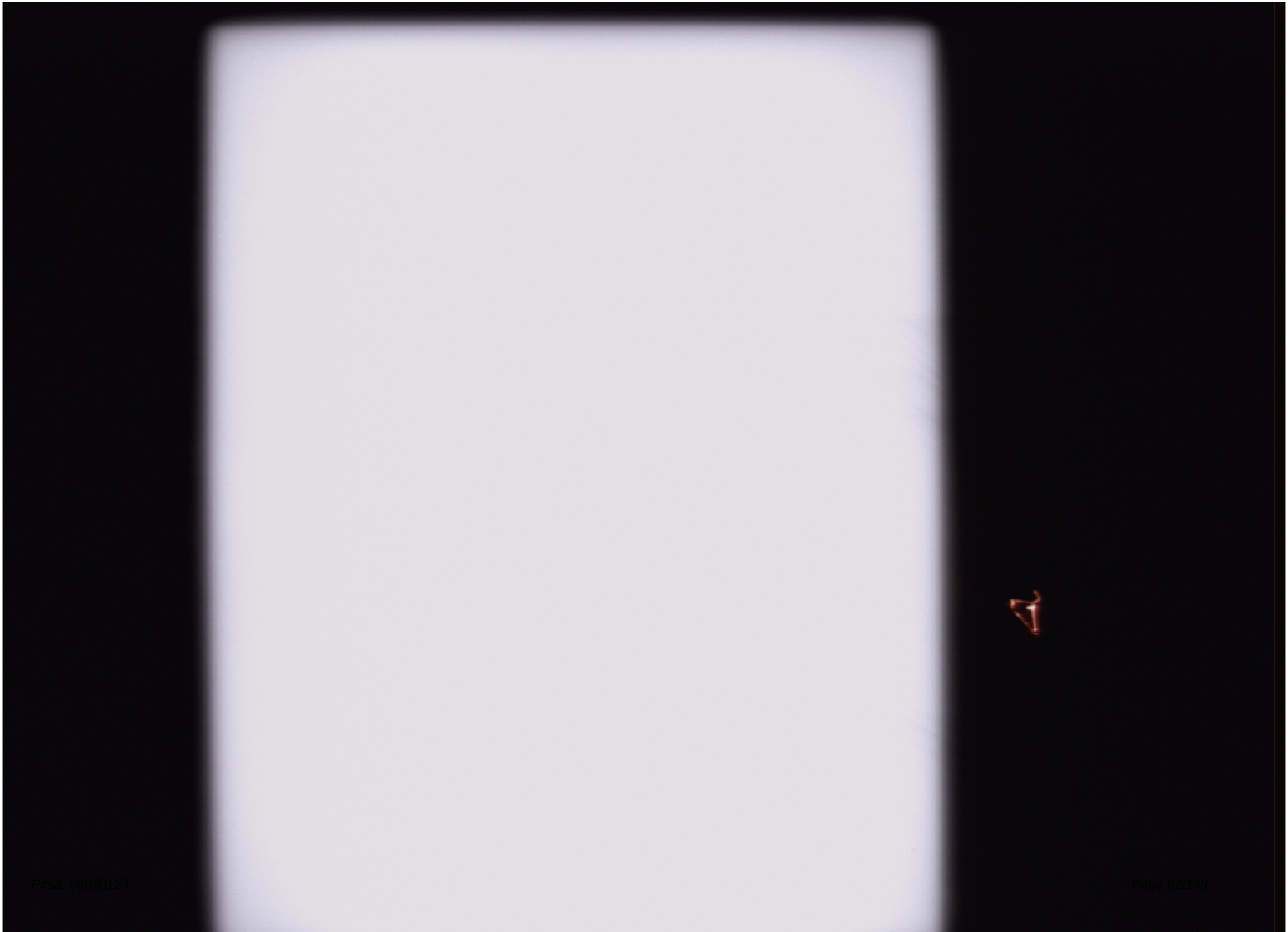
- **Couplings of b_L ~~GIM~~ due to m_t**

Coupling of b_L to gauge KK mode large [$\sim g_{SM}$]

$\gg$ couplings to s_L, d_L



$\rightarrow$ FCNC's involving b_L



- **SIGNALS AT B-FACTORIES** (KA, Perez, Soni; KA et al.)

KK mass $\sim 3-4$ TeV $\Rightarrow$

(i) $\Delta F = 2$:

$O(1)$ deviation from SM in Δm_{B_s}, $O(1)$ $S_{J/\psi\phi}$

(at Run II, LHC)

(40% allowed in $B_d - \bar{B}_d$ mixing)

(ii) $\Delta F = 1$ Z penguin:

$O(1)$ deviation from SM in BR, A_{FB} and $O(1)$ A_{CP}

in $b \to s l^+ l^-$

(errors in BR: theory, BABAR & BELLE $\sim 20\%$ each)

(iii) $\Delta F = 1$ Radiative Decays:

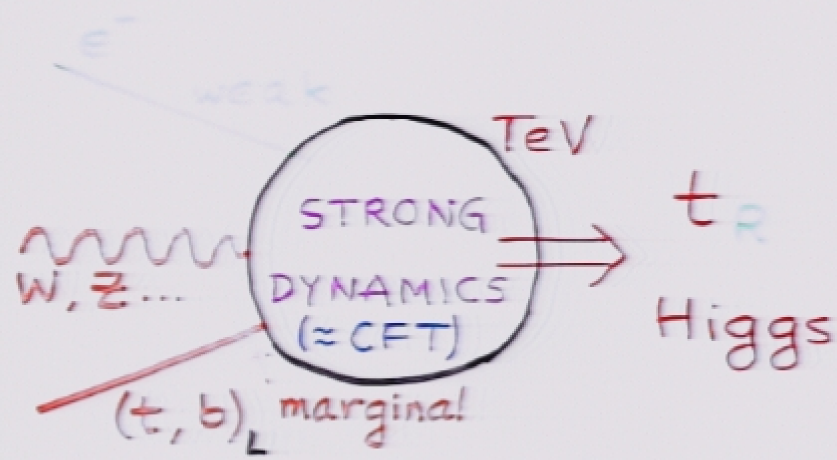
$O(1)$ mixing-induced (time-dependent) CP

asymmetry in $b \to (s, d)\gamma$

(BABAR: $S_{K^*\gamma} \approx 0.25 \pm 0.7$)

MODEL AT A GLANCE

- Higgs + t_R composite $\longleftrightarrow$ (near) TeV brane
- Light fermions elementary $\longleftrightarrow$ (near) Planck brane
- Gauge bosons + $(t, b)_L$ in-between $\longleftrightarrow$ ~ flat profile



...on to GUT's

t_R

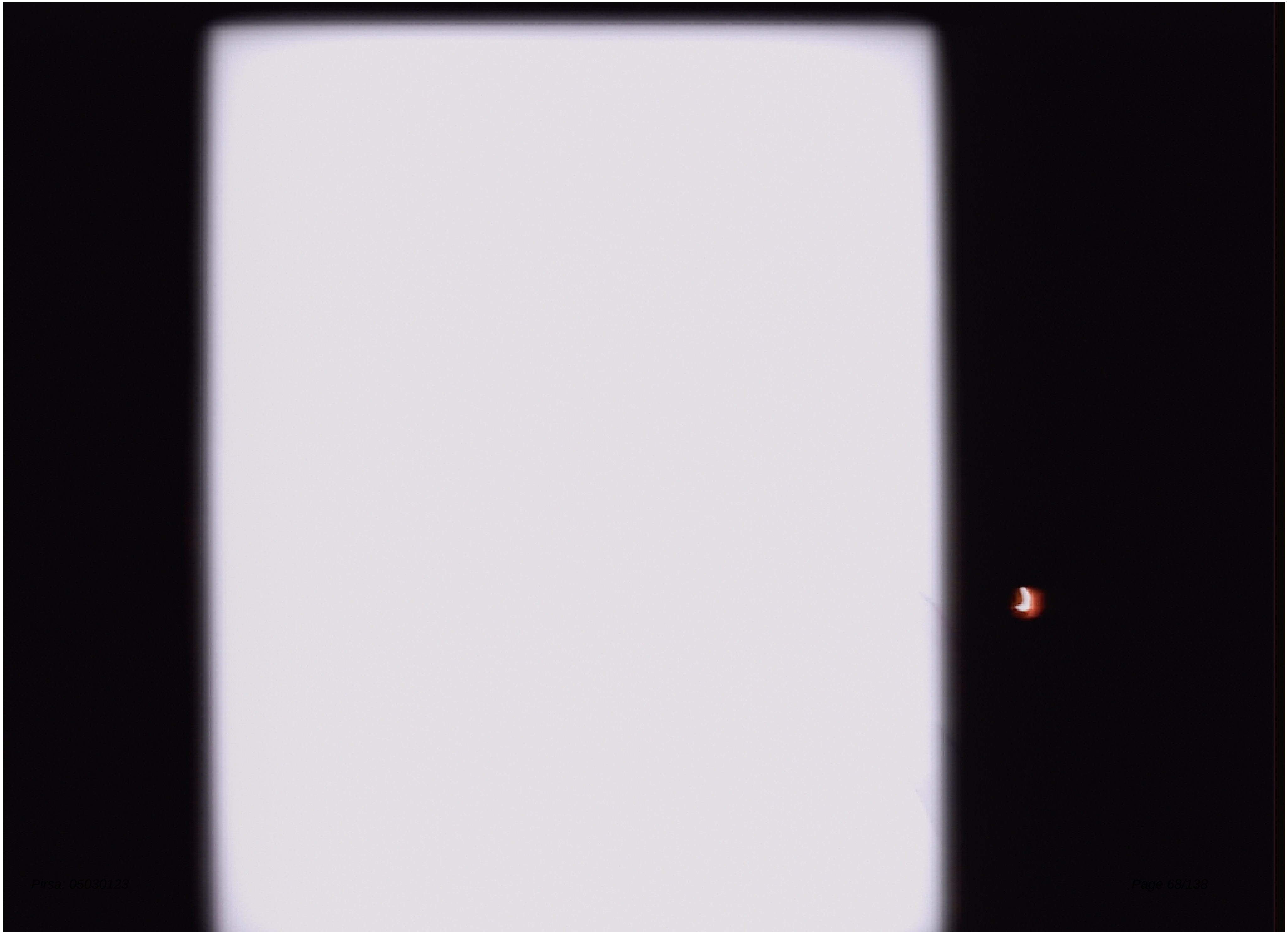
composite

UNIFICATION

~ SUSY

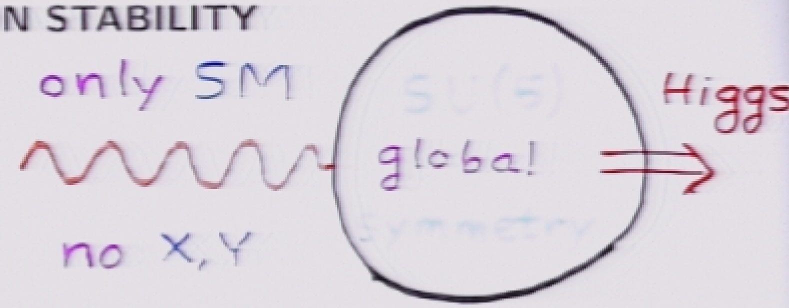
+ proton stability

DARK MATTER

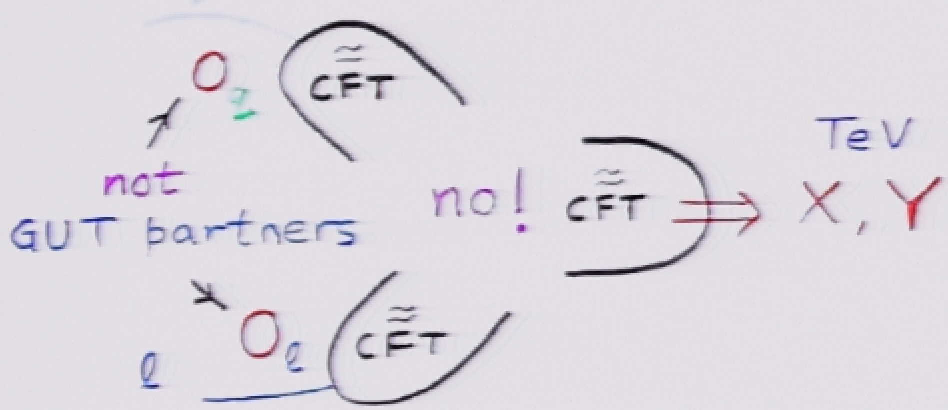


• SPLIT FERMION MULTIPLETS FOR

PROTON STABILITY



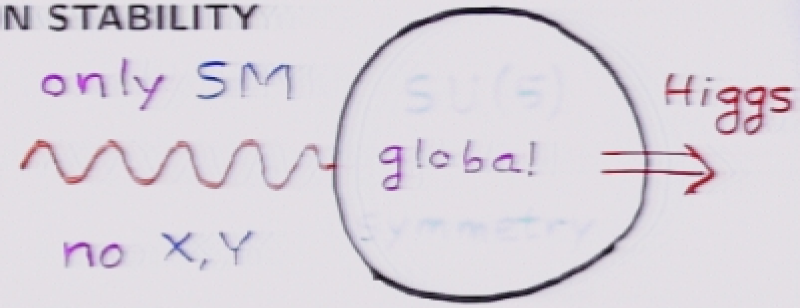
SM quarks and leptons are not GUT partners



Charge quantization: operators $\bar{5}$, 10 of $SU(5)$

(Contino, Creminelli, Trincherini; Goldberger, Nomura, Smith; KA, Delgado, Sundrum)

• SPLIT FERMION MULTIPLETS FOR PROTON STABILITY



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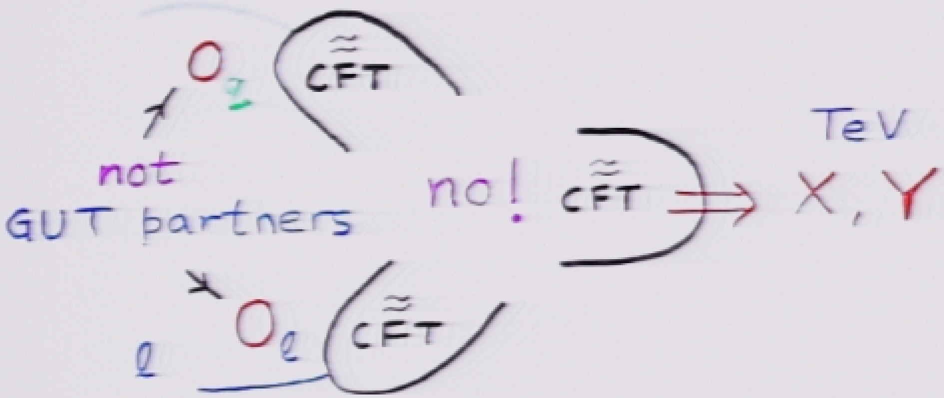

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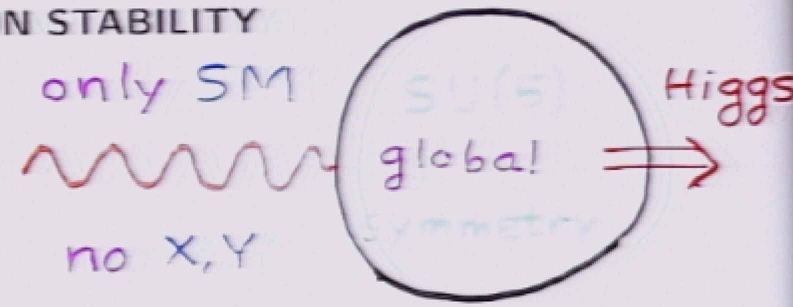

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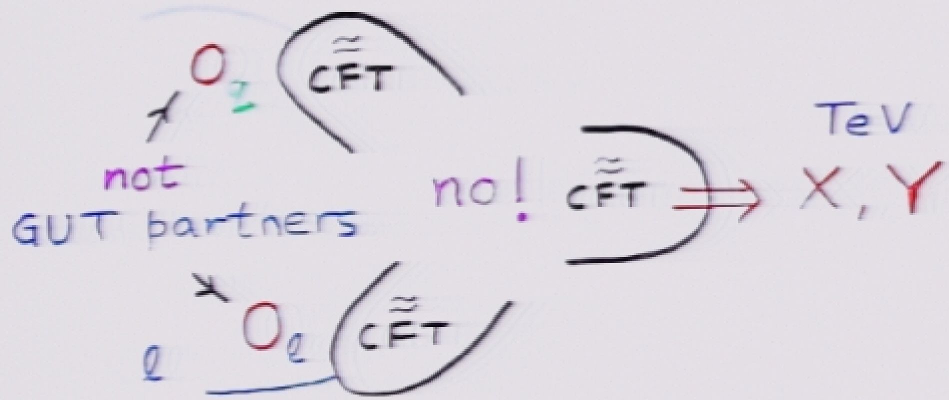

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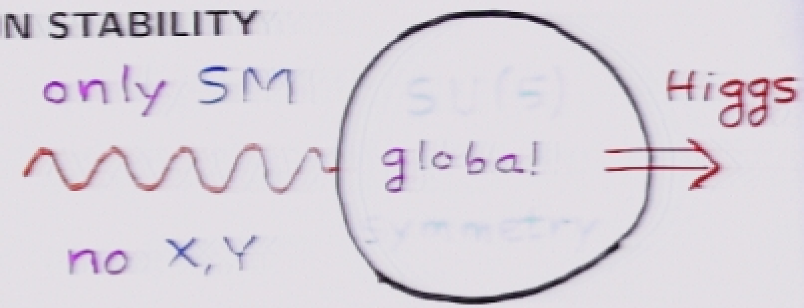

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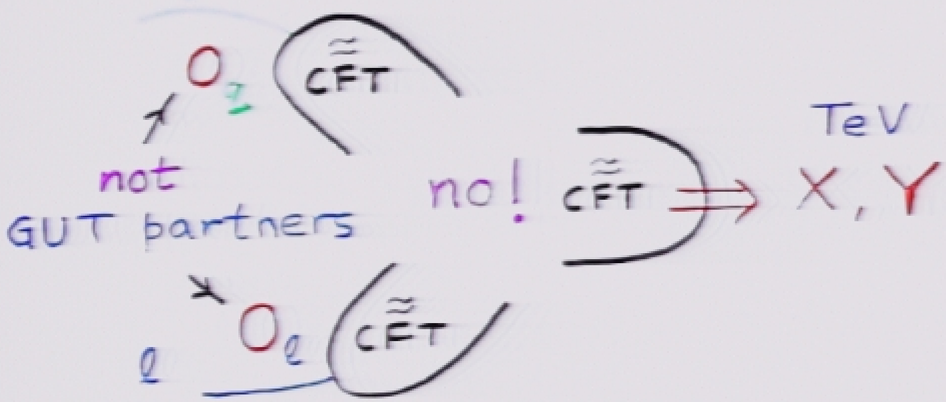

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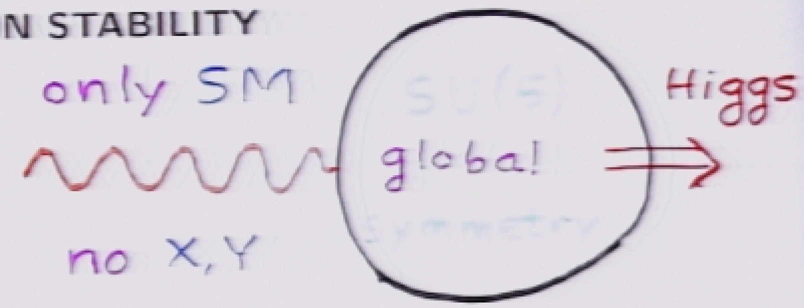

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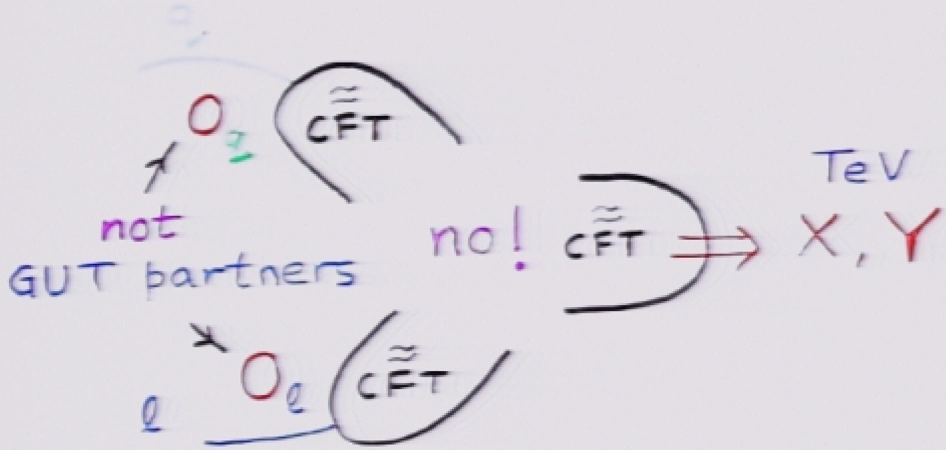

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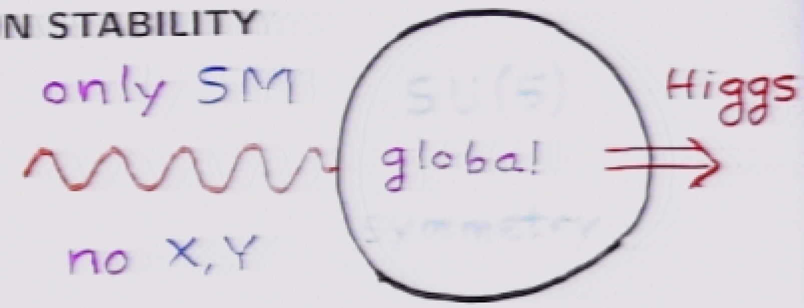

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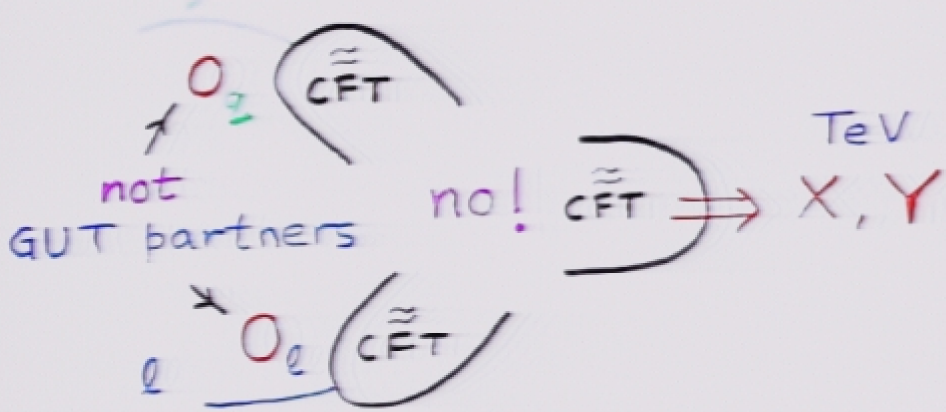

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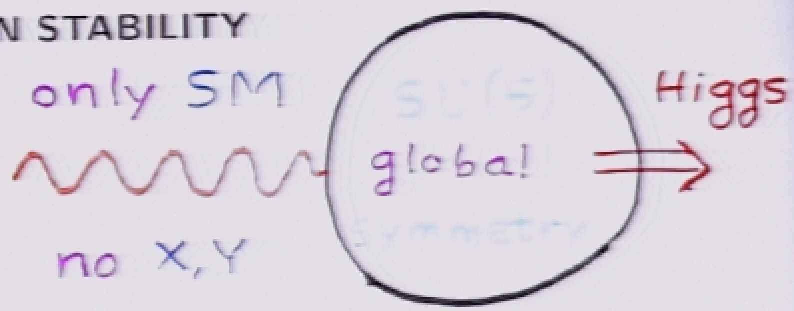

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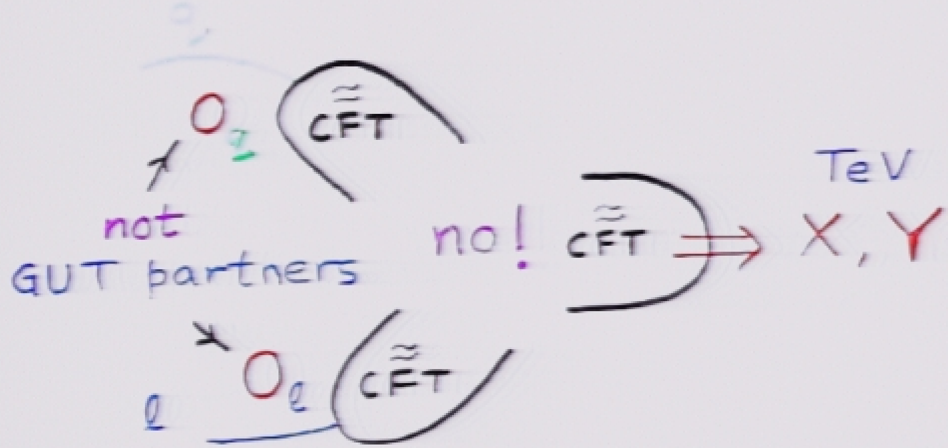

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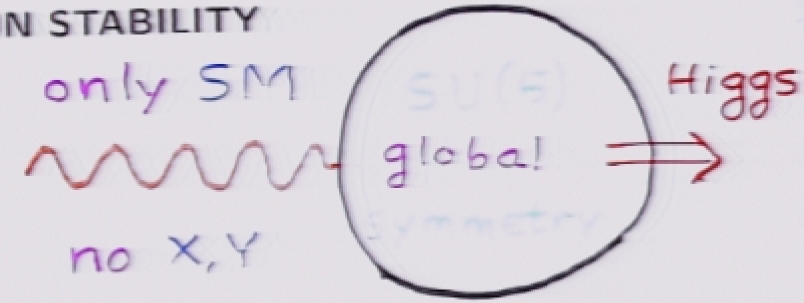

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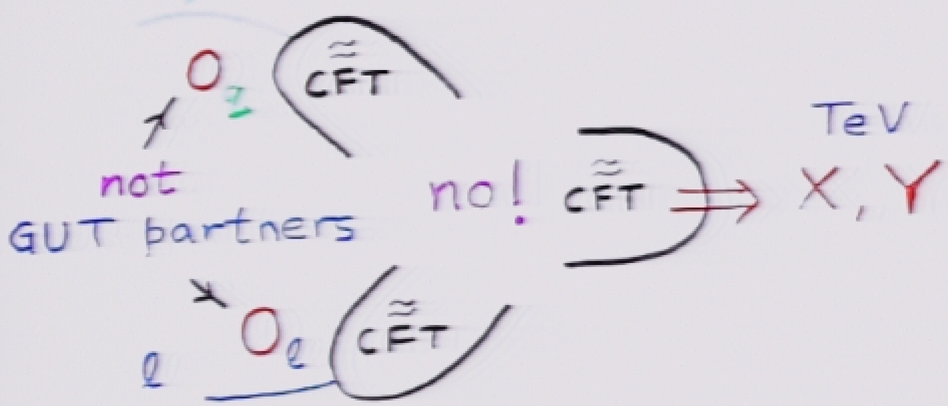

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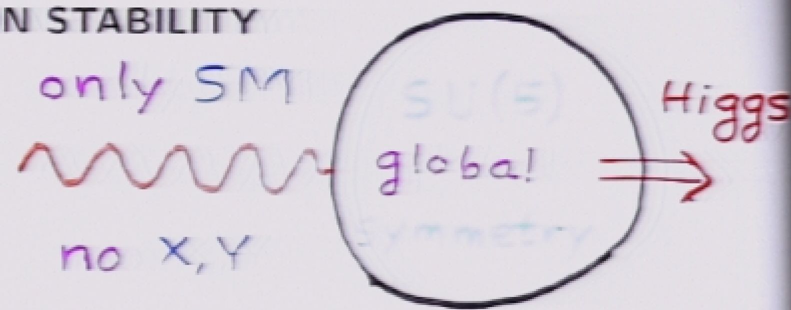

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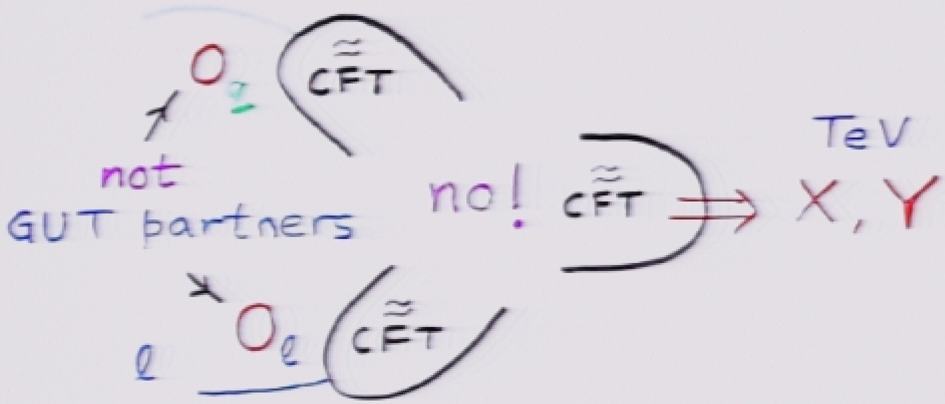

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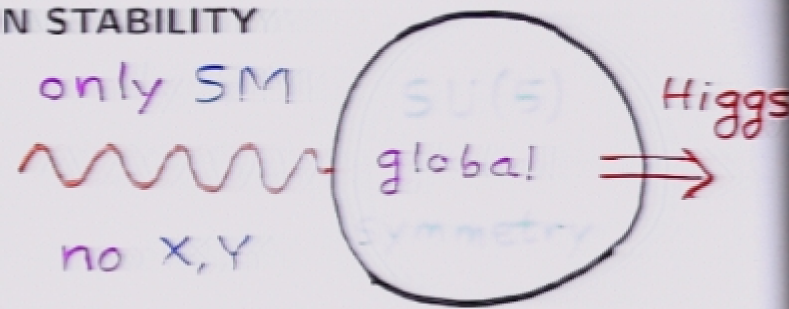

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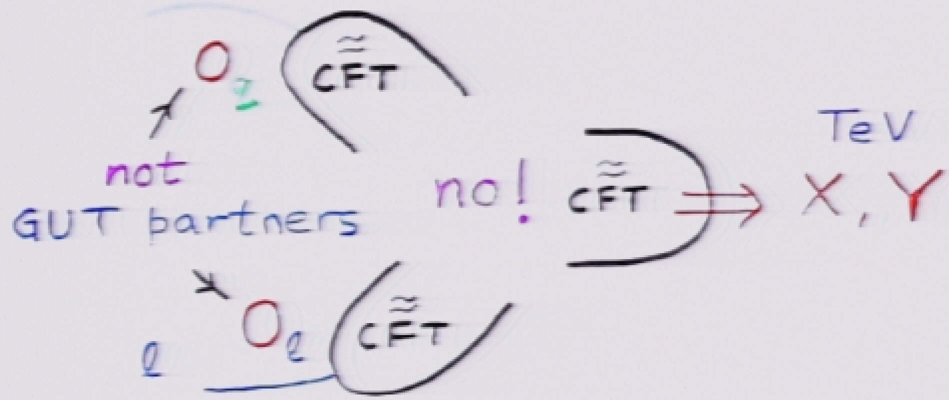

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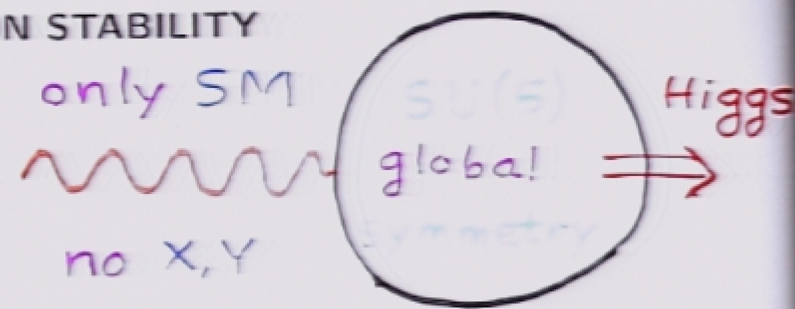

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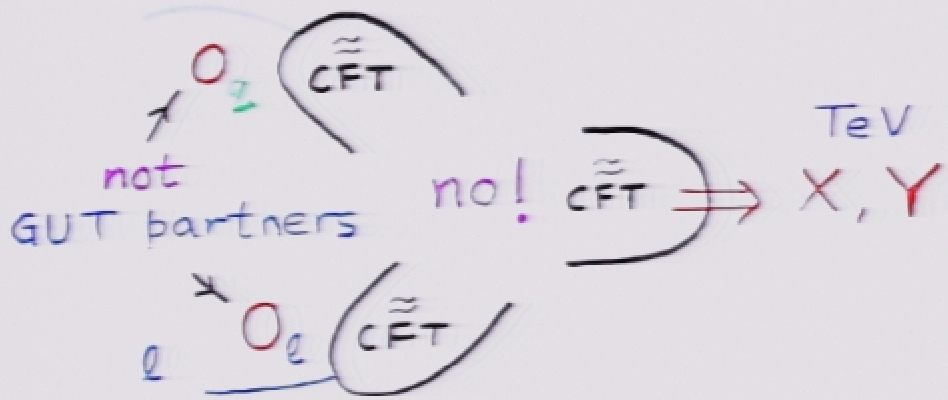

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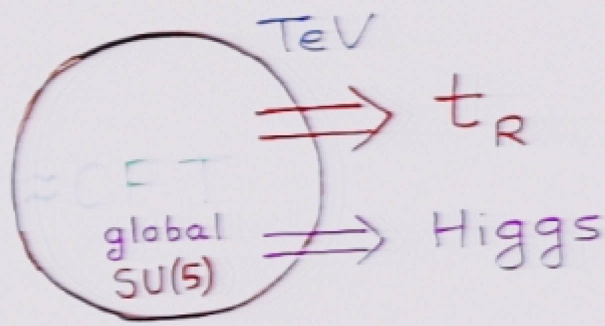
(Contino, Creminelli, Trincherini; Goldberger, Nomura, Smith; KA, Delgado, Sundrum)

1. (a) NO RUNNING FROM RH TOP QUARK, HIGGS

- **Differential** running:

$$\boxed{\text{SM} \ominus [t_R - \text{Higgs (composites)}]}$$

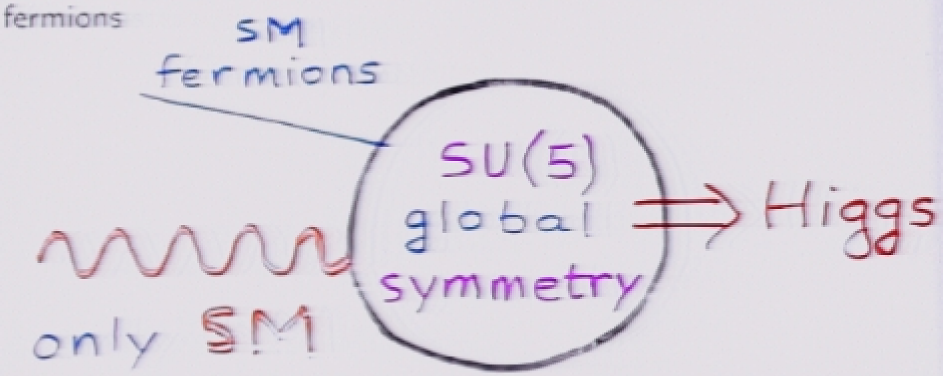
improves unification!



SM LEVEL OF UNIFICATION

Differential running as in SM (except Higgs):

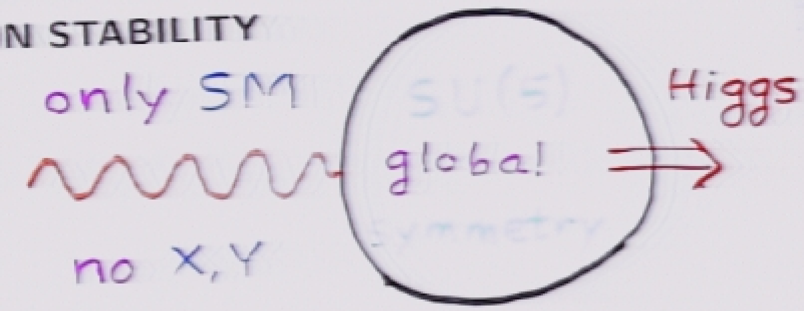
universal running from strong dynamics and SM fermions



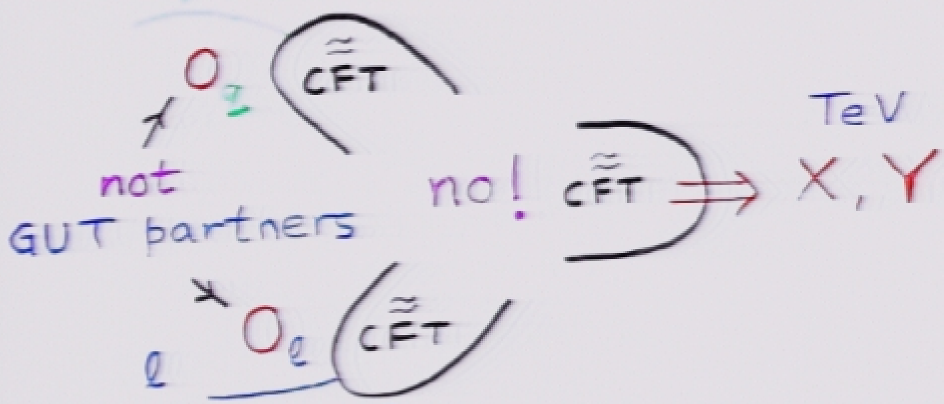
$\sim$ [illegible] unification

(Pomarol; Randall, Schwartz; Contino, Creminelli, Trincherini; Goldberger, Nomura, Smith; KA, Delgado, Sundrum)

- **SPLIT FERMION MULTIPLETS FOR PROTON STABILITY**



SM quarks and leptons are not GUT partners



$\boxed{\text{Charge quantization}}$: operators $\bar{5}$, 10 of $SU(5)$

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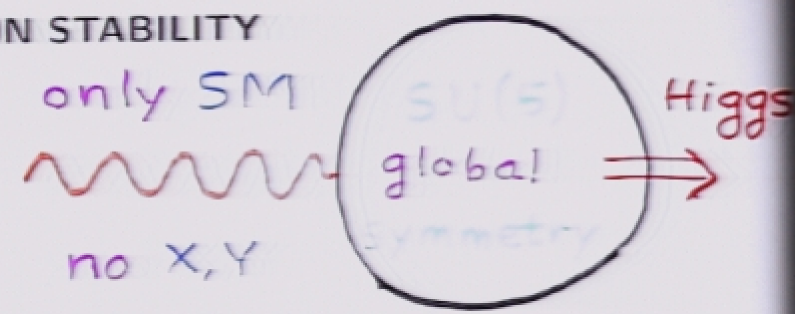

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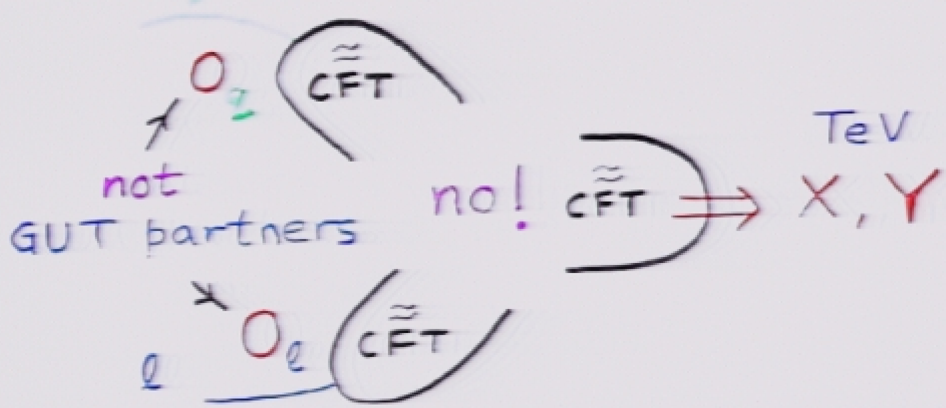

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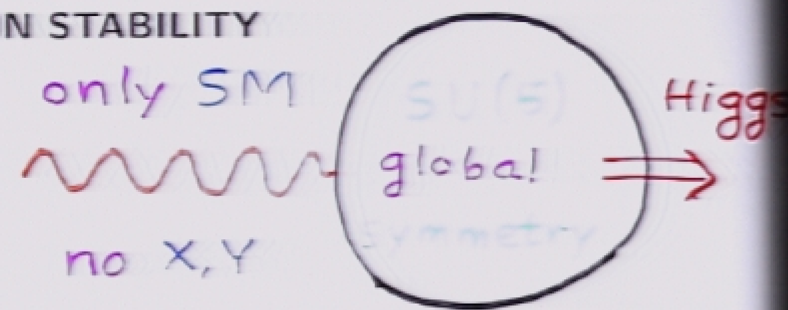

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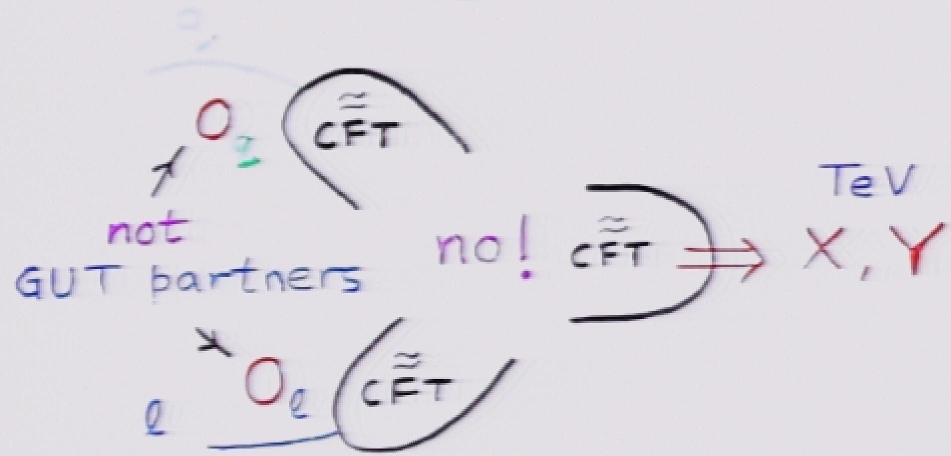

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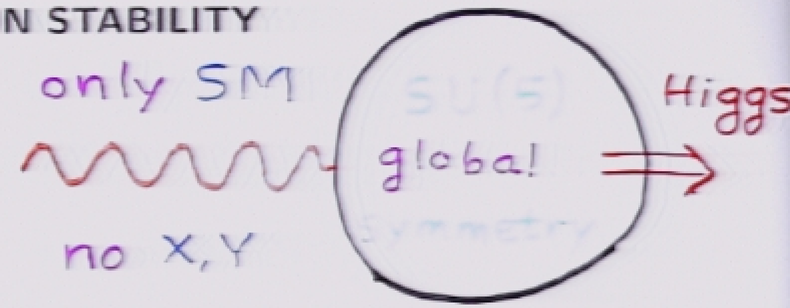

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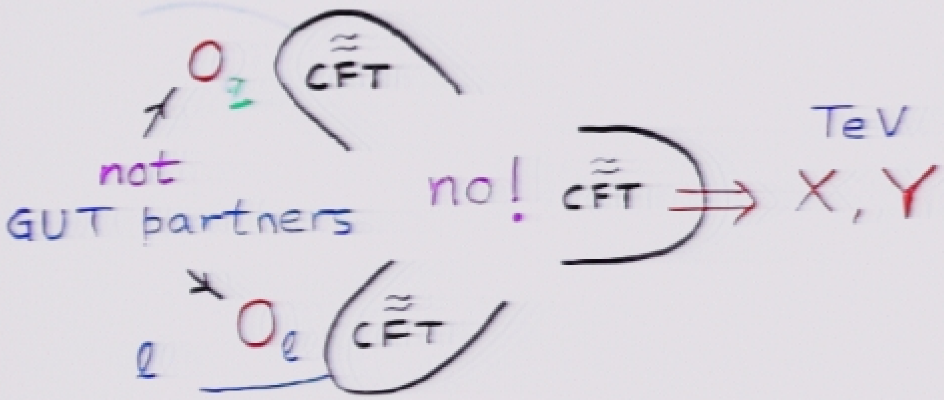

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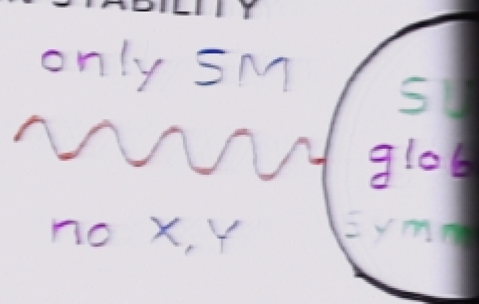
- **SPLIT FERMION MULTIPLETS FO**
  PROTON STABILITY



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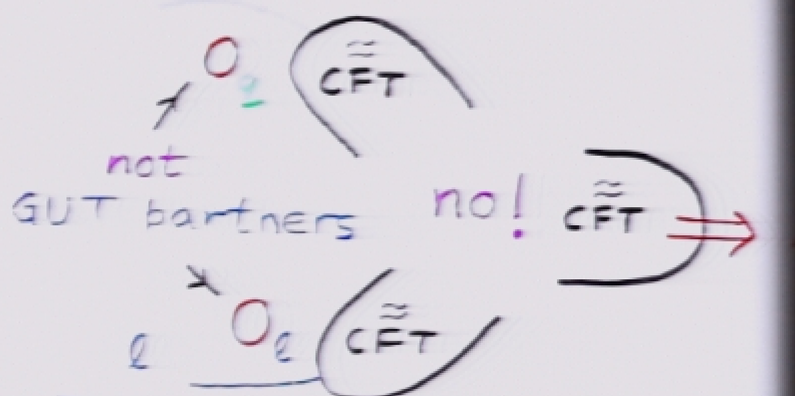

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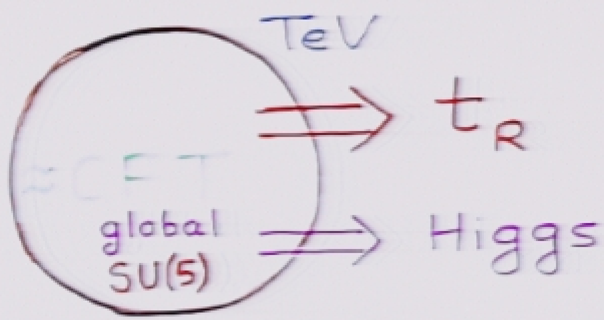
$\boxed{\text{SM} \ominus [t_R + \text{Higgs (composites)}]}$

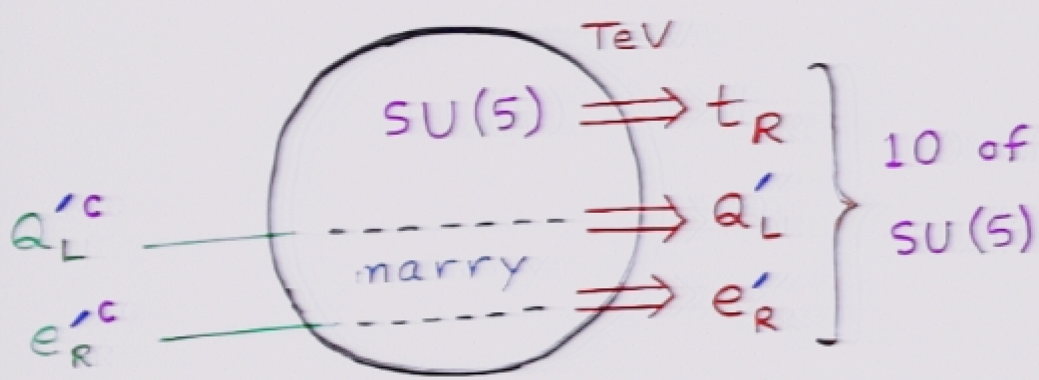
improves unification!



- **ELEMENTARY GUT PARTNERS OF t_R**

  (ANTI-GENERATION)

Whole **10** of $SU(5)$ (containing t_R) composite



Elementary Q'_R, e'_L marry composite partners of t_R

(cannot be SM lepton)

1. (b) RUNNING DUE TO ELEMENTARY GUT PARTNERS OF TOP QUARK (ANTI-GENERATION)

Marginal (irrelevant) coupling $\leftrightarrow c \sim -1/2$ $(c < -1/2)$

$\downarrow$

Add running due to elementary Q'_R and e'_L

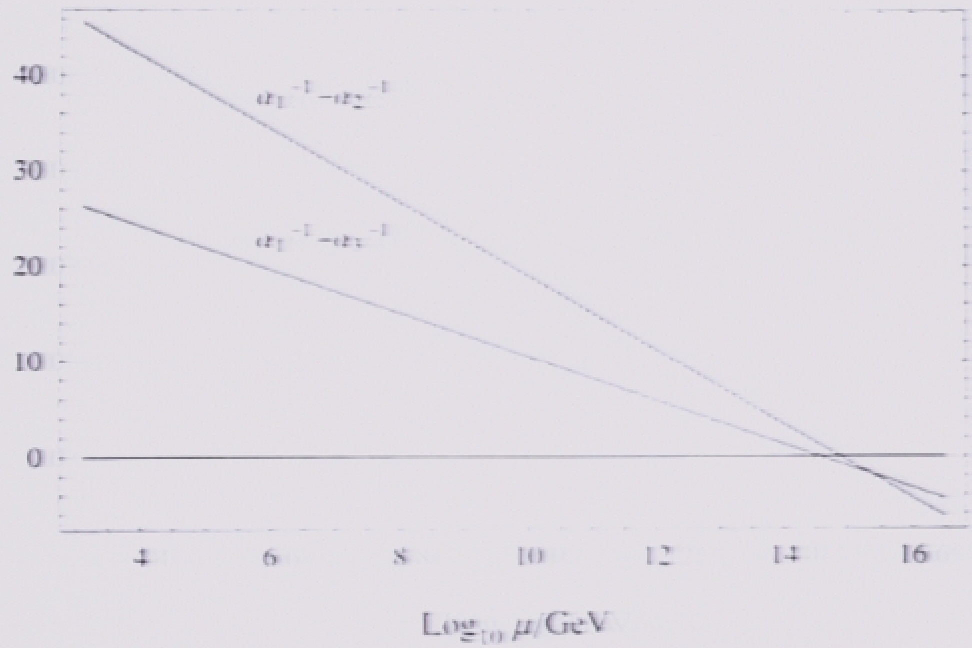
$\downarrow$

- $[\text{SM} - \text{Higgs} - t_R] + \boxed{(Q'_R - e'_L)} \equiv \text{SM} - \text{Higgs} - 2t_R$

  improves unification further!

Irrelevant $(c_{t_R} < -1/2)$: too light GUT partners

LO differential running of SM gauge couplings



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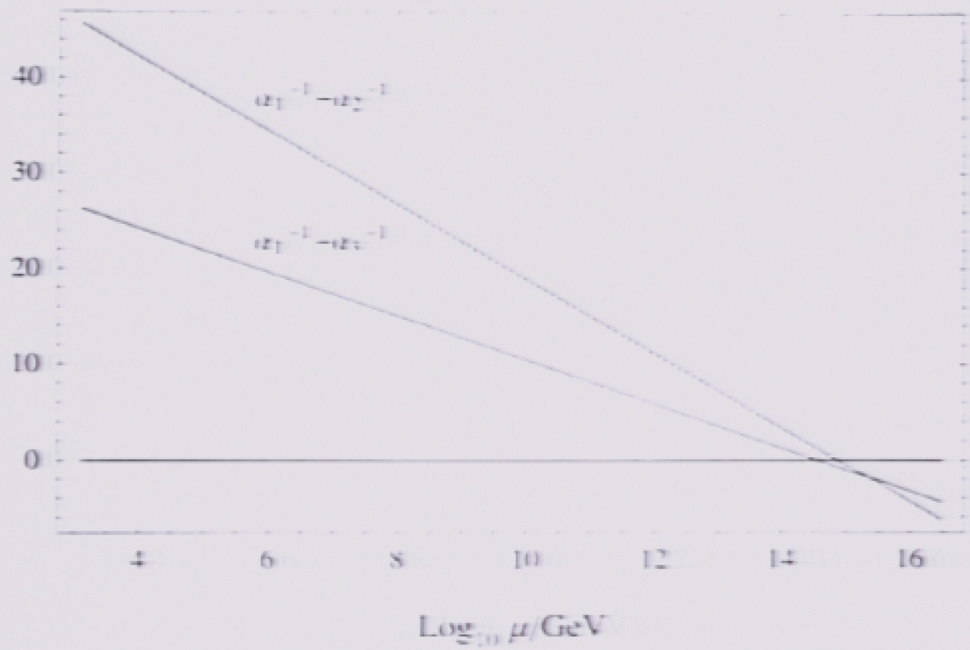
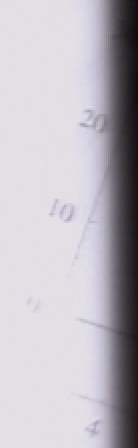
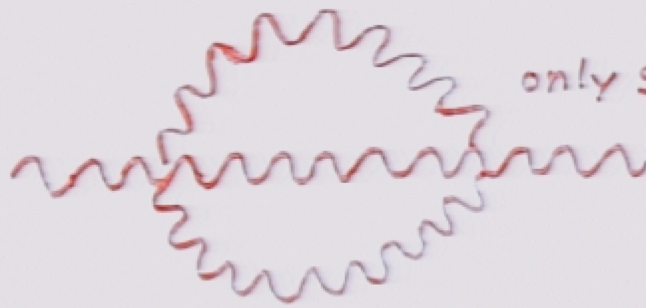



20
10
4

• 2. (a) 2-LOOP SM RUNNING HELPS



2-loop correction, $\theta < 0$ (as in SM):

sign good ($\Delta_{1-loop} \boxed{<} 0$)

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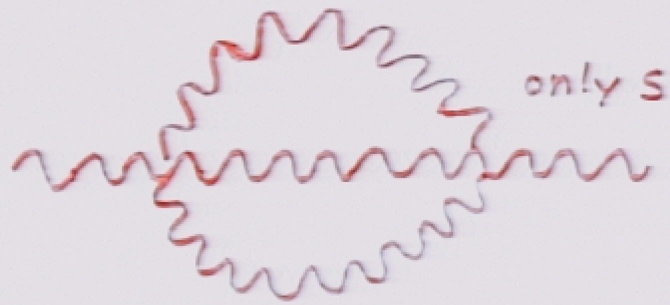

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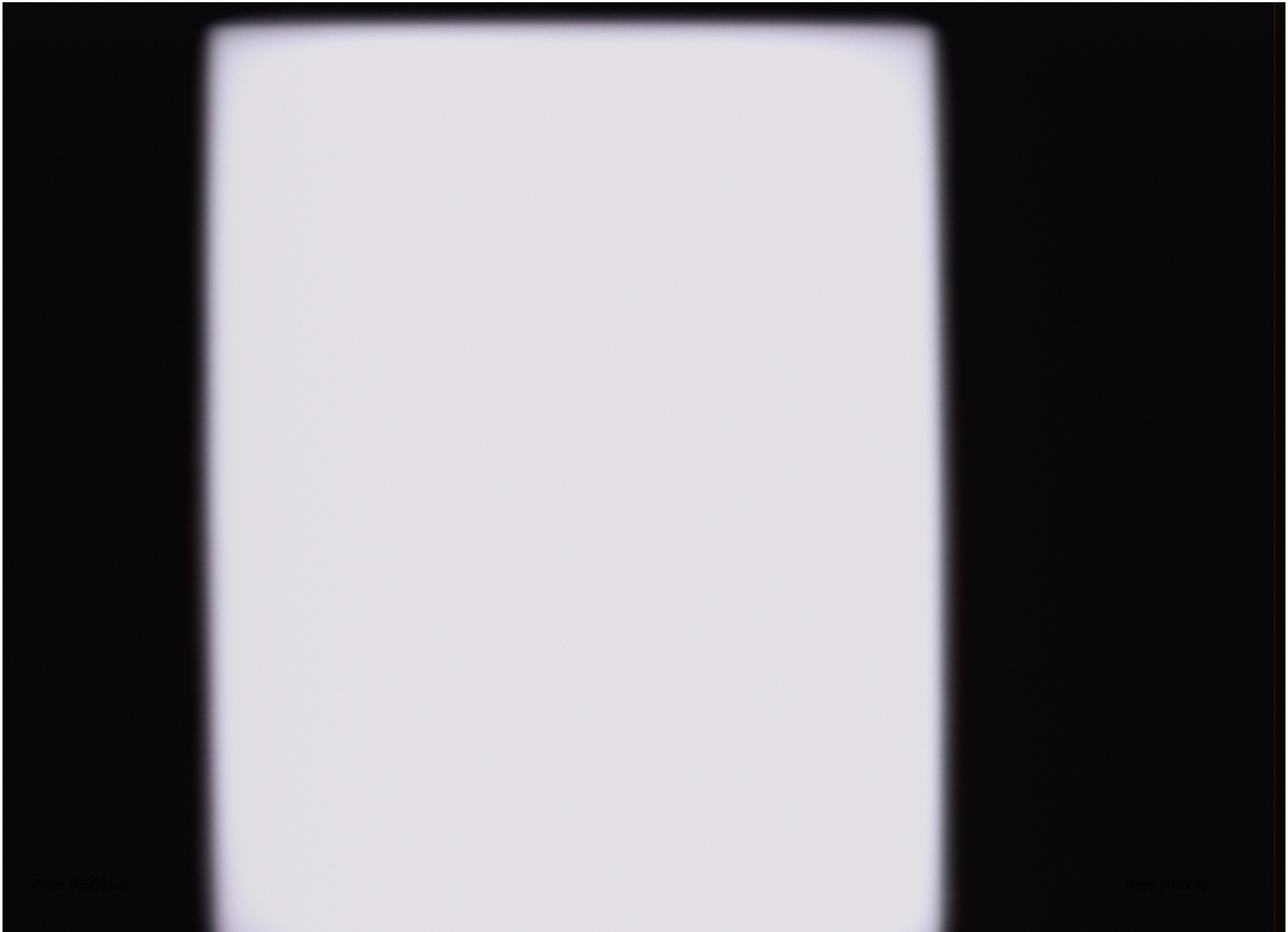

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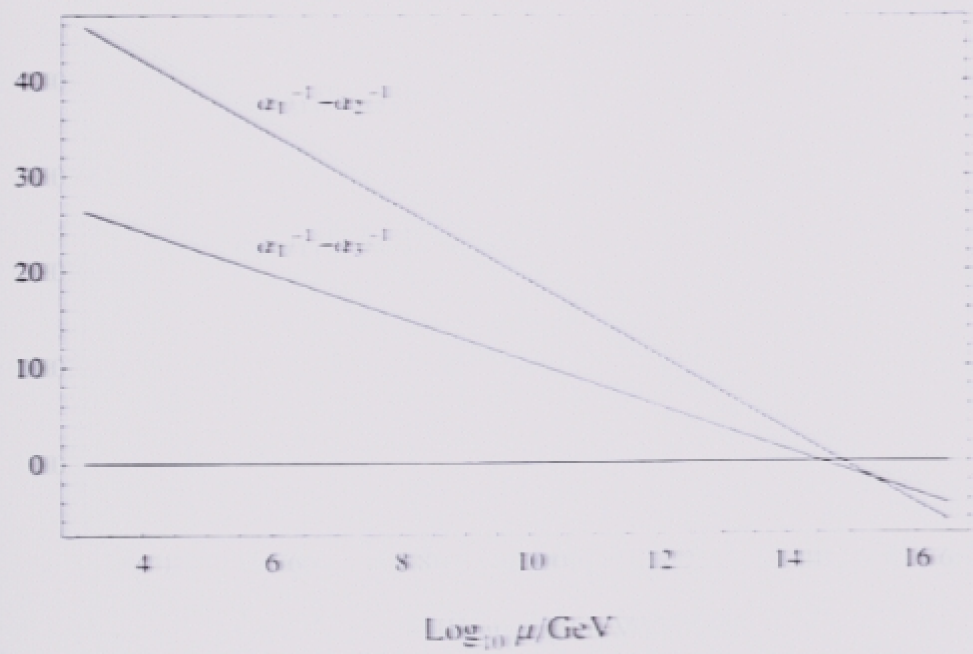

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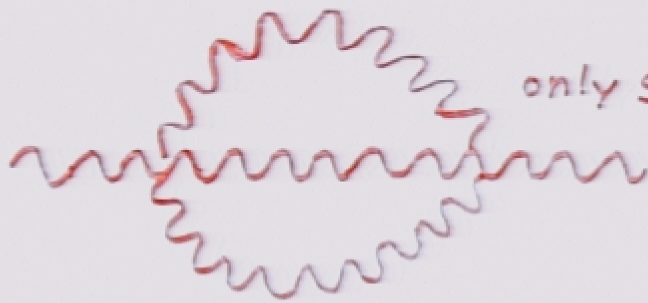

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• GRAND FINALE: FEW % UNIFICATION!

← error

SM: $-10\% \pm$ a few %

MSSM: $+2\% \pm$ a few %

threshold fix

$c_{t_R} \sim -1/2$ (marginal coupling for anti-generation):

$\boxed{\sim 0 \pm \text{a few } \%}$ (error ~ SM 2-loop running)

• $\boxed{\text{Unification} \approx \text{SUSY}}$

↑

$\boxed{t_R \text{ composite}}$

↑

large m_t + $\delta(Z \to b_L b_L) \approx 0.5\%$!

40

- **GRAND FINALE: FEW % UNIFICATION!**

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MSSM: ~ 2 % $\pm$ a few %

← threshold fix

(marginal coupling for anti-generation).

$\boxed{\sim \pm \text{ a few } \%}$ (error $\sim$ SM 2-loop running)

- $\boxed{\text{Unification} \not\approx \text{SUSY}}$

composite

large m_t ...

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40

PROTON STABILITY

IN GUT

LEADS TO

DARK MATTER

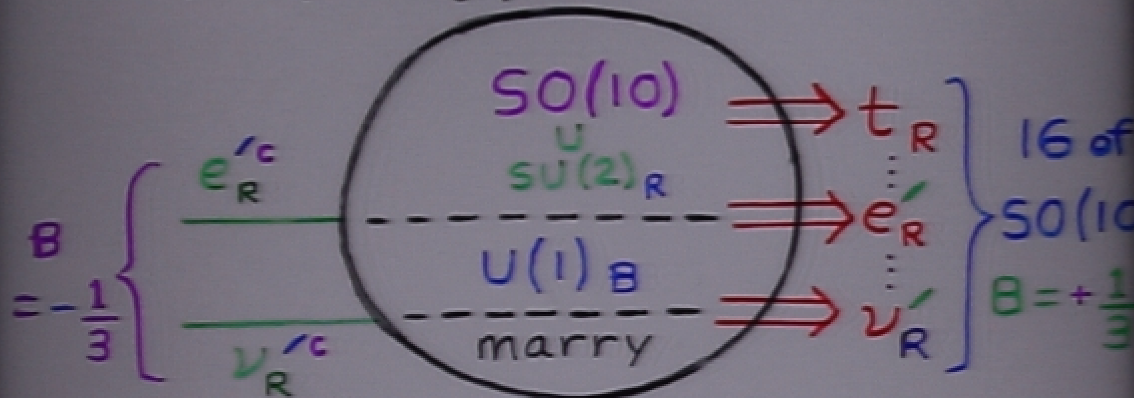
(~ SUSY)

(KA, SERVANT)

EXOTIC PARTICLES WITH Z_3 CHARGE

Proton decay via string states forbidden by $U(1)_B$

symmetry of strong dynamics



- "Wrong" combination of color and baryon-number:

  no color, $B = 1/3 \rightarrow$

$\boxed{\text{Lightest } Z_3\text{-charged particle (LZP) stable!}}$

Moderate coupling $\rightarrow$ light GUT partners of t_R

(a few 100 GeV)

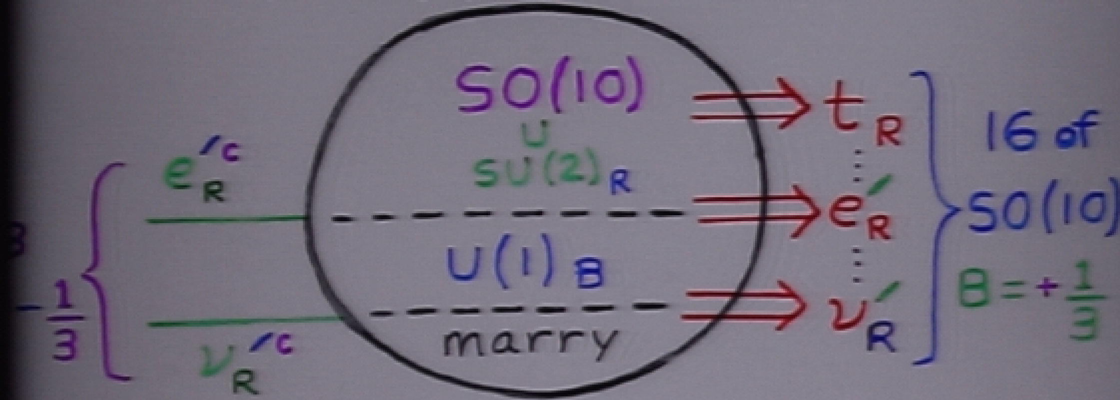
$\downarrow$

$\boxed{\nu_R' \text{ is stable!}}$ (due to **heavy** top)

EXOTIC PARTICLES WITH Z_3 CHARGE

Proton decay via string states forbidden by $U(1)_B$

symmetry of strong dynamics



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$\downarrow$

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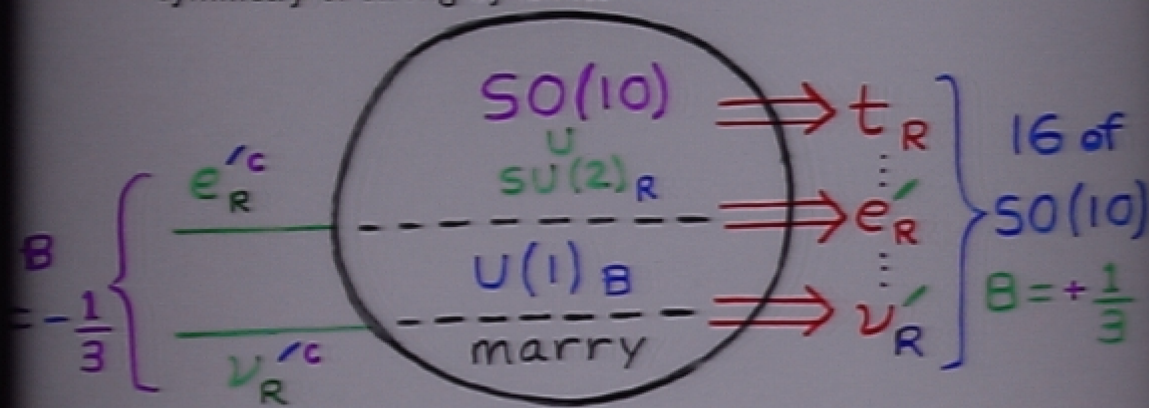
42

EXOTIC PARTICLES WITH Z_3 CHARGE

Proton decay via string states forbidden by $U(1)_B$

symmetry of strong dynamics



- "Wrong" combination of color and baryon-number:

  no color, $B = 1/3 \rightarrow$

  Lightest Z_3-charged particle (LZP) stable!

Moderate coupling $\rightarrow$ light GUT partners of t_R

(a few 100 GeV)

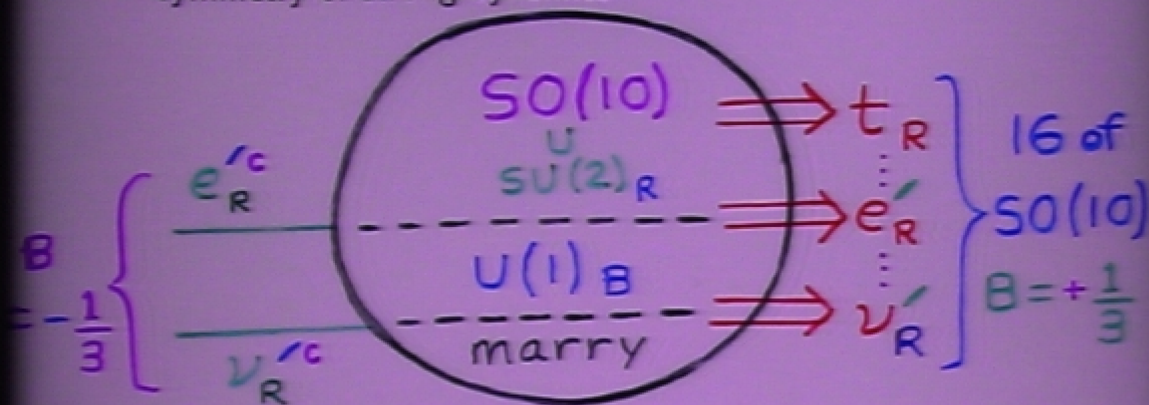
$\downarrow$

ν'_R is stable! (due to **heavy** top)

EXOTIC PARTICLES WITH Z_3 CHARGE

Proton decay via string states forbidden by $U(1)_B$

symmetry of strong dynamics



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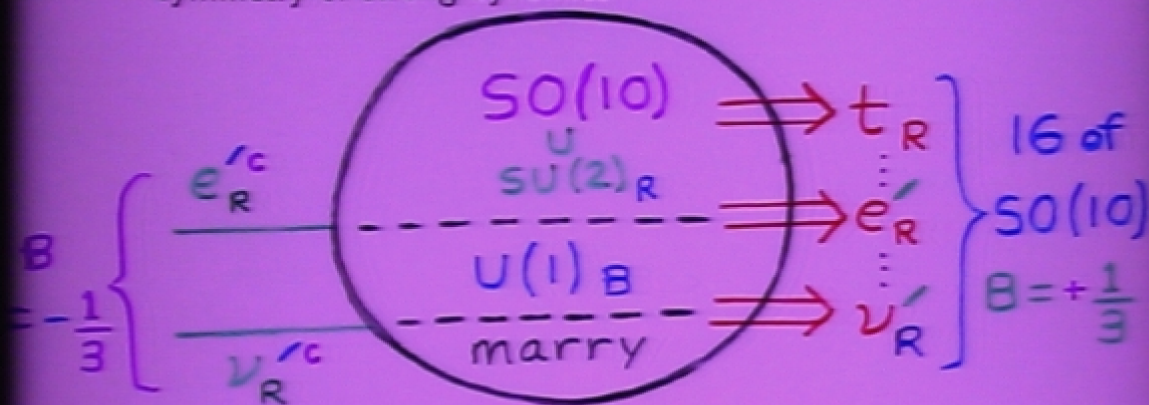
42

EXOTIC PARTICLES WITH Z_3 CHARGE

Proton decay via string states forbidden by $U(1)_B$

symmetry of strong dynamics



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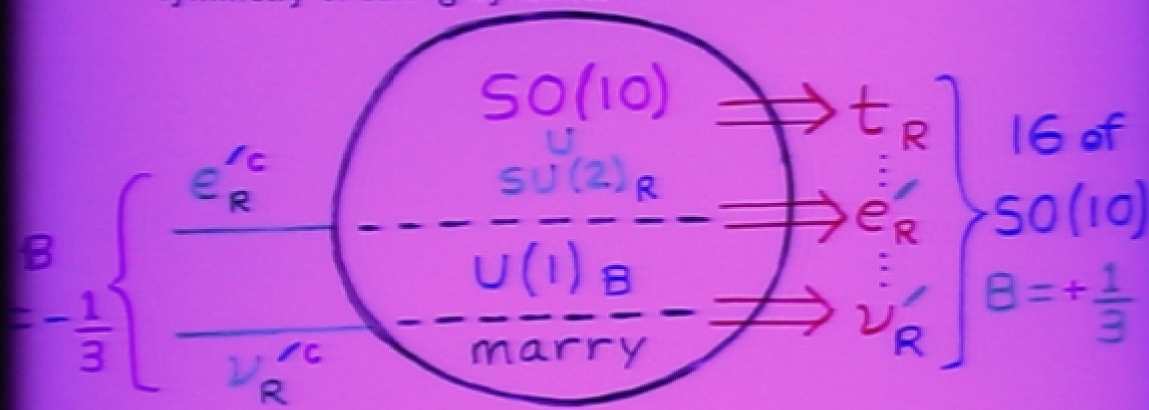

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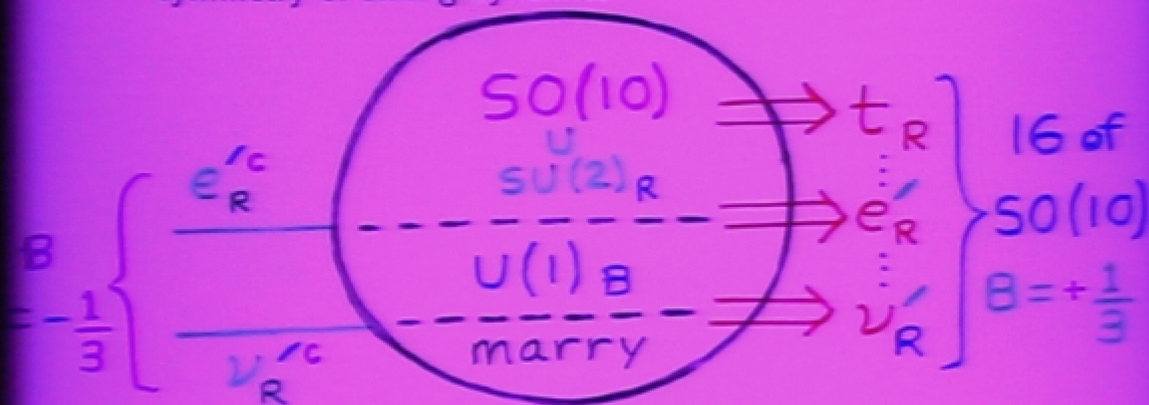

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42

Exo…

Photon…

symme…

- "Wrong" combina…

no coupl… $B' = 1/…$

$\boxed{\text{Lightest } Z_2\text{-charged…}}$

Moderate coupling → light …

(a few …

↓

$\boxed{\nu_R \text{ is stable!}}$

(due t…

EXOTIC ν_R (LZP)

AS

WIMP DM

(KA, SERVANT)

EXOTIC

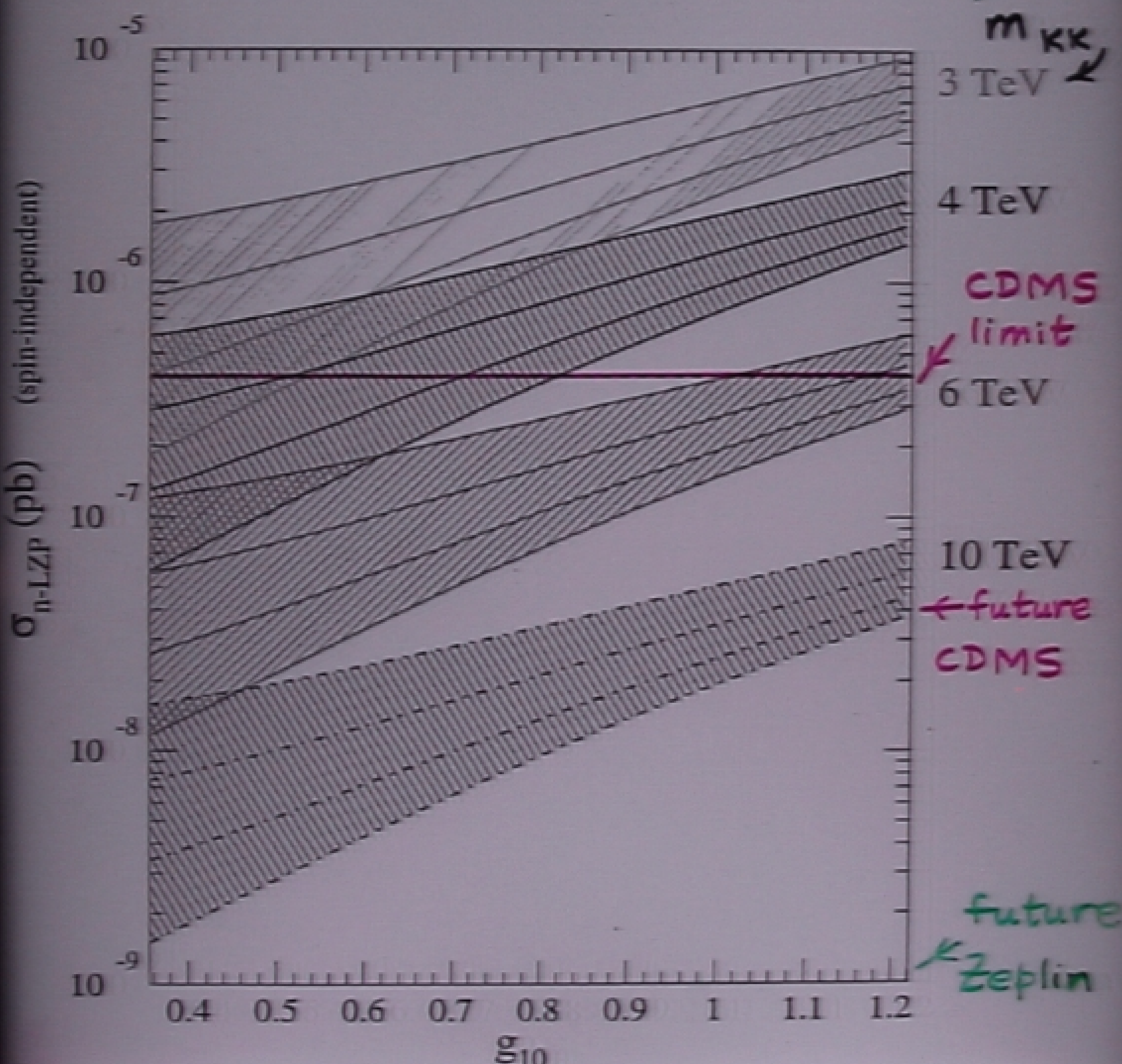
AS

WIMP

(KA, SERVA

PREDICTIONS FOR DIRECT DETECTION

(RANGE OF σ due to $c_{\nu'_R}$, c_{t_R})



brane terms modify σ by ~2

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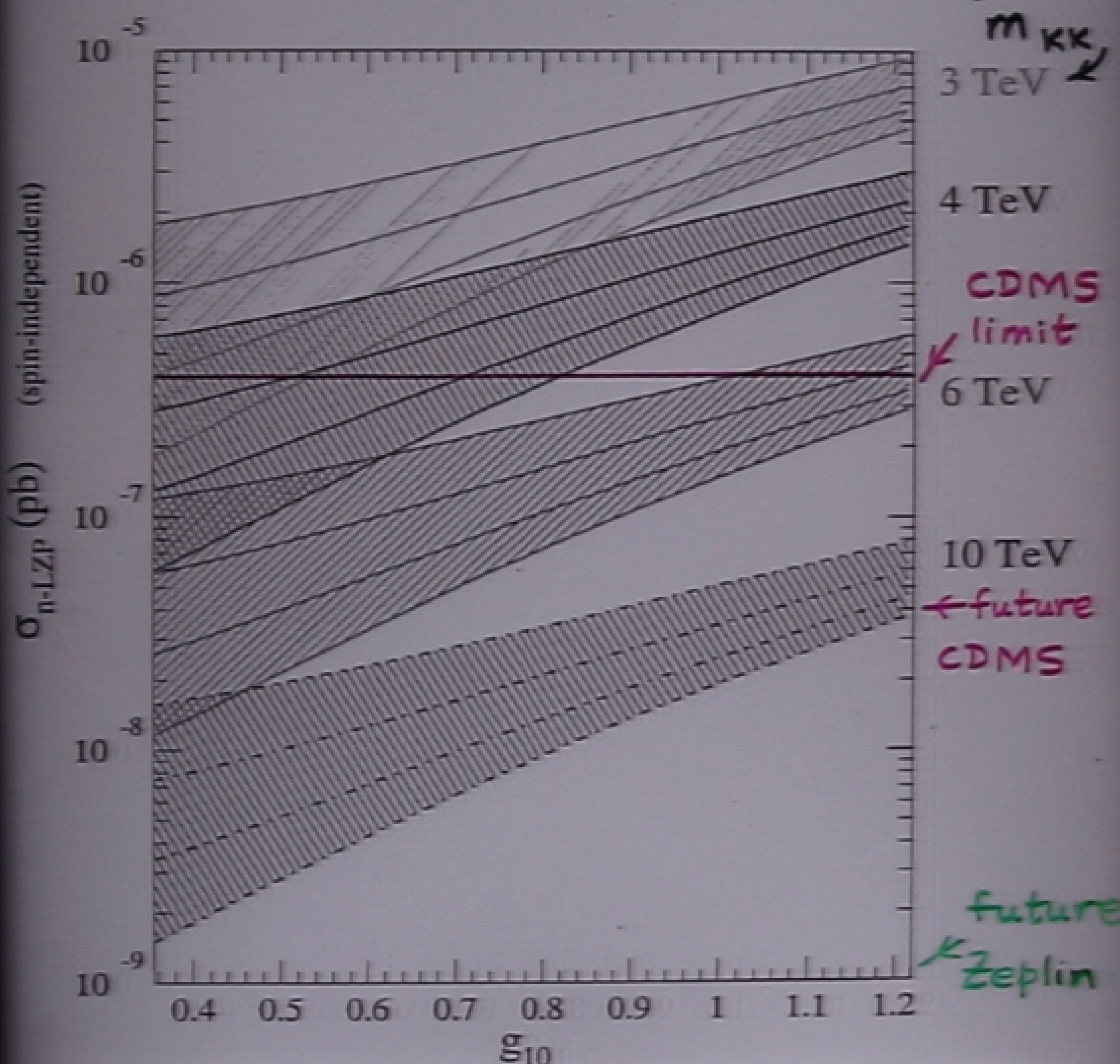

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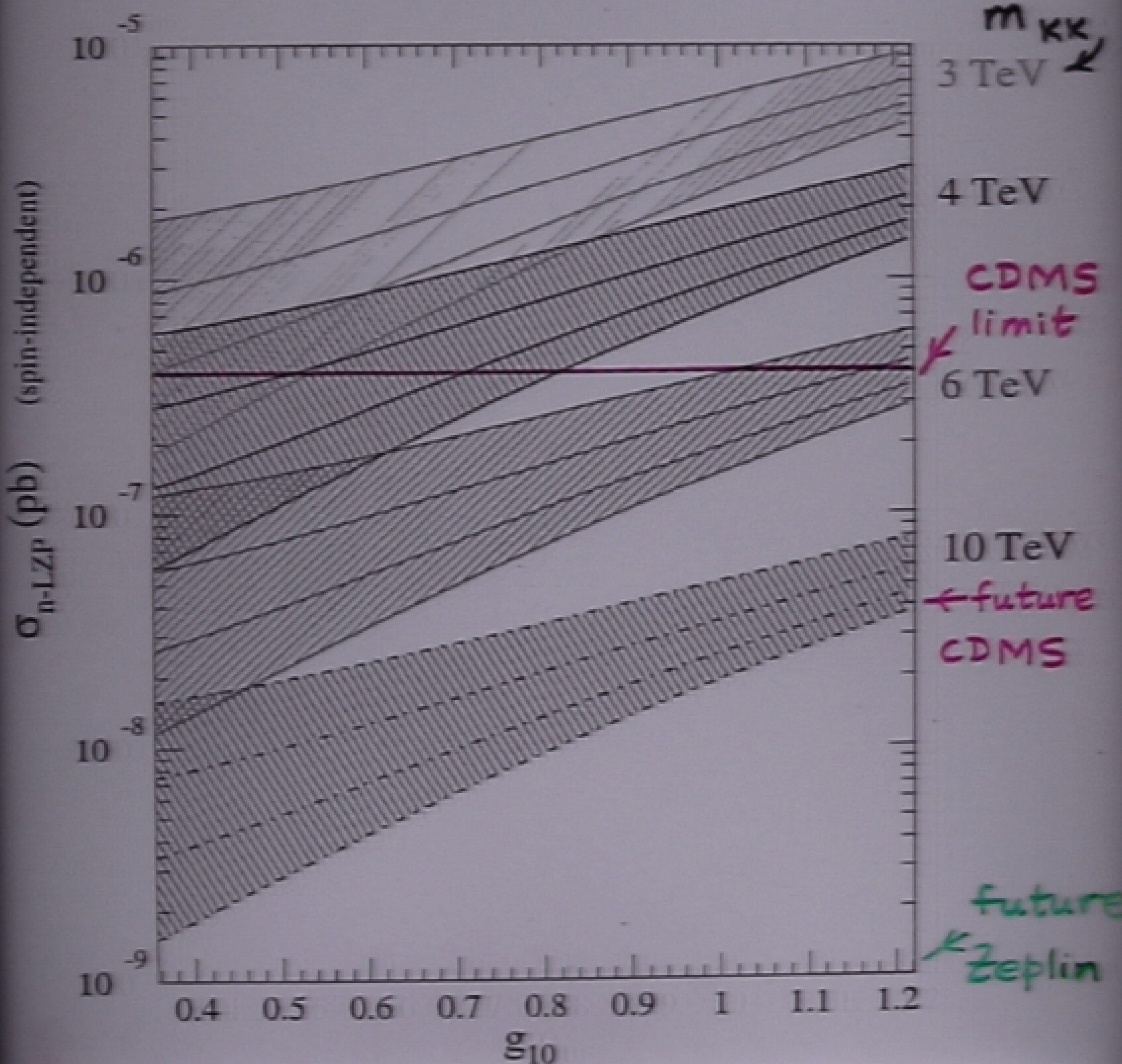

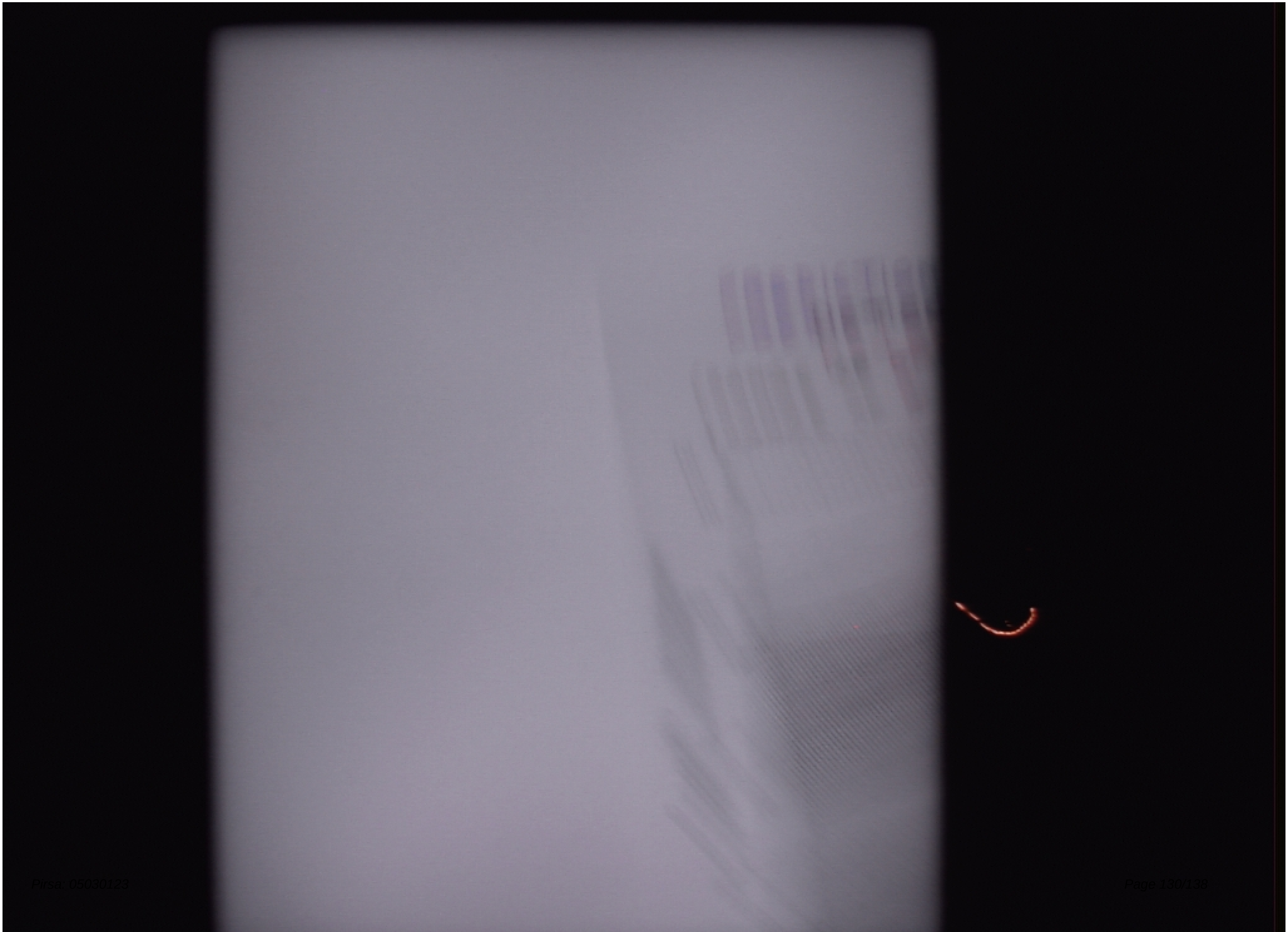

CONCLUSIONS

Strong dynamics in EWSB

- $\boxed{\text{tool: warped extra dimension}}$

Viable!

- EW data: composite Higgs ($\sim 10\%$ fine-tuning)
- Flavor: partial compositeness ($\leftrightarrow$ fermion profiles)

  explain fermion mass + mixing hierarchies and suppression of FCNC's

t_R COMPOSITE

radiative EWSB

(SPIN-OFFS)

t_R COMPOSITE

radiative EWSB

Unification at few % level

+Proton stability → Dark matter

- SUSY:
  - Flavor ✗
  - Unification ✓
  - Dark matter ✓
  - Fine-tuning: $\lesssim 10\%$

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INDIRECT SIGNALS

B-factories:

B_s mixing (Run II, LHC)

$b \to s l^+ l^-$, $b \to (s, d)\gamma$ (BABAR AND BELLE)

t_R compositeness:

shift in $Z t_R \bar{t}_R \sim 10\%$ (LC)

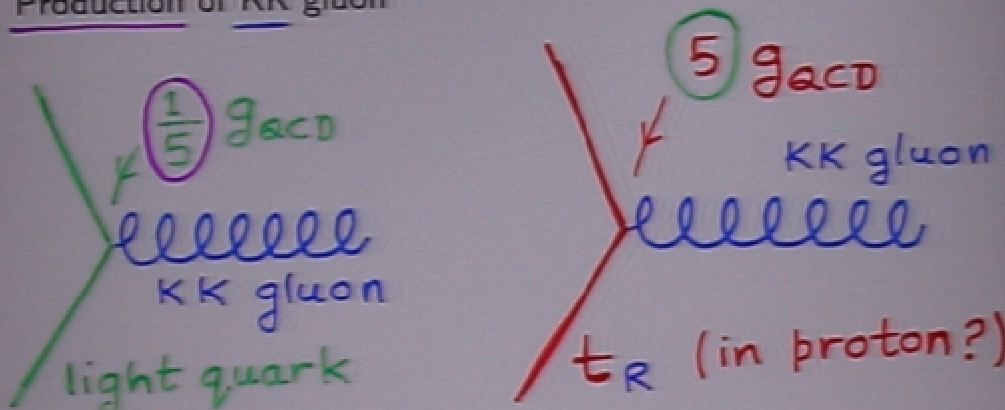
BR $(t_R \to c_R Z) \sim 10^{-5}$ (LC, LHC)

Dark matter detection (CDMS, Edelweiss, Zeplin)

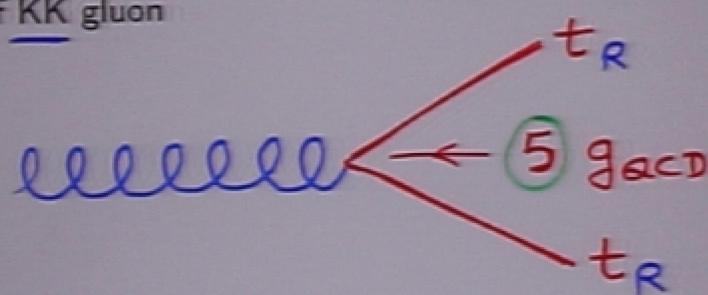
+ other light GUT partners of t_R (Run II, LHC)

DIRECT SIGNAL AT LHC: CHALLENGING!

Production of KK gluon



Decay of KK gluon



- $\boxed{\text{WE NEED TO BE READY}}$:

Previous RS1 and Technicolor studies not enough!