SUSY 02
DESY

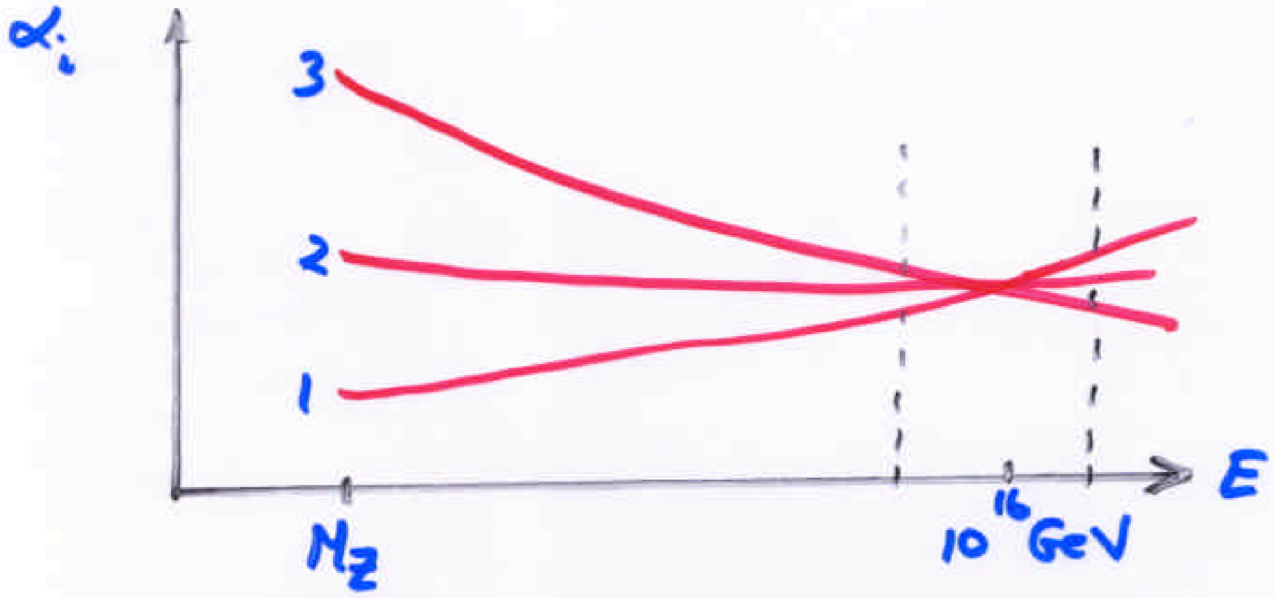
GRAND UNIFICATION IN HIGHER DIMENSIONS.

Lawrence Hall

UC Berkeley

WORKSHOPS ON GRAND UNIFICATION → (c. 1990) → SUSY CONFERENCES

Evidence for weak scale susy > Evidence for grand unification



1. WHAT IS THE PHYSICS AT UNIFICATION?

2. HOW CAN IT BE TESTED?

(I) FEATURES OF 4D GUTs

(II) NEW VIEWPOINT FOR UNIFICATION

hep-ph/0103125

(III) A MINIMAL MODEL

hep-ph/0111068

(IV) EXPERIMENTAL SIGNALS

hep-ph/0205067

with Yasunori Nomura.

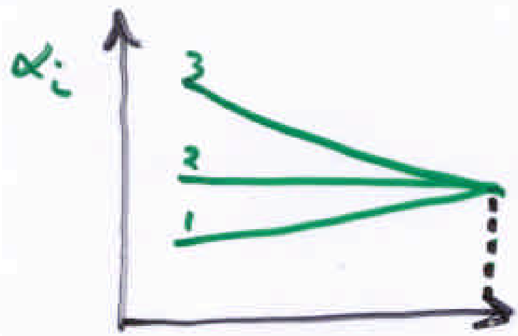
THE DICHOTOMY

UNIFICATION FITS

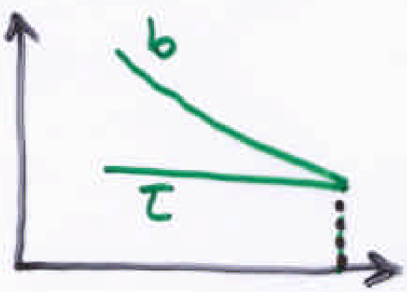
Light matter

$$\begin{pmatrix} q \\ u \\ d \\ \ell \\ e \\ \nu \end{pmatrix}$$

Numerical Prediction



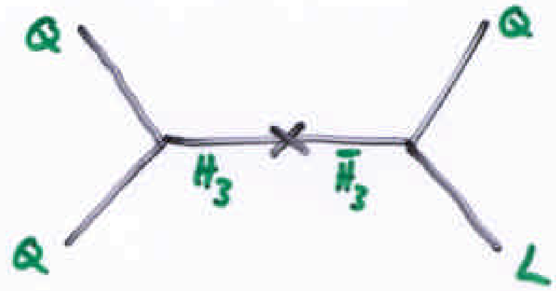
Quark-lepton masses

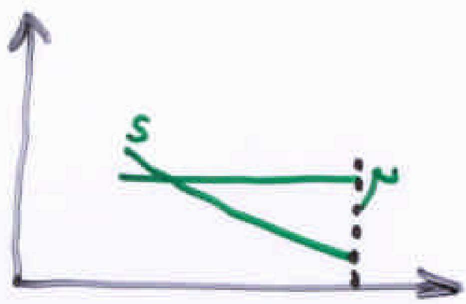


ABHORS UNIFICAT

Light Higgs

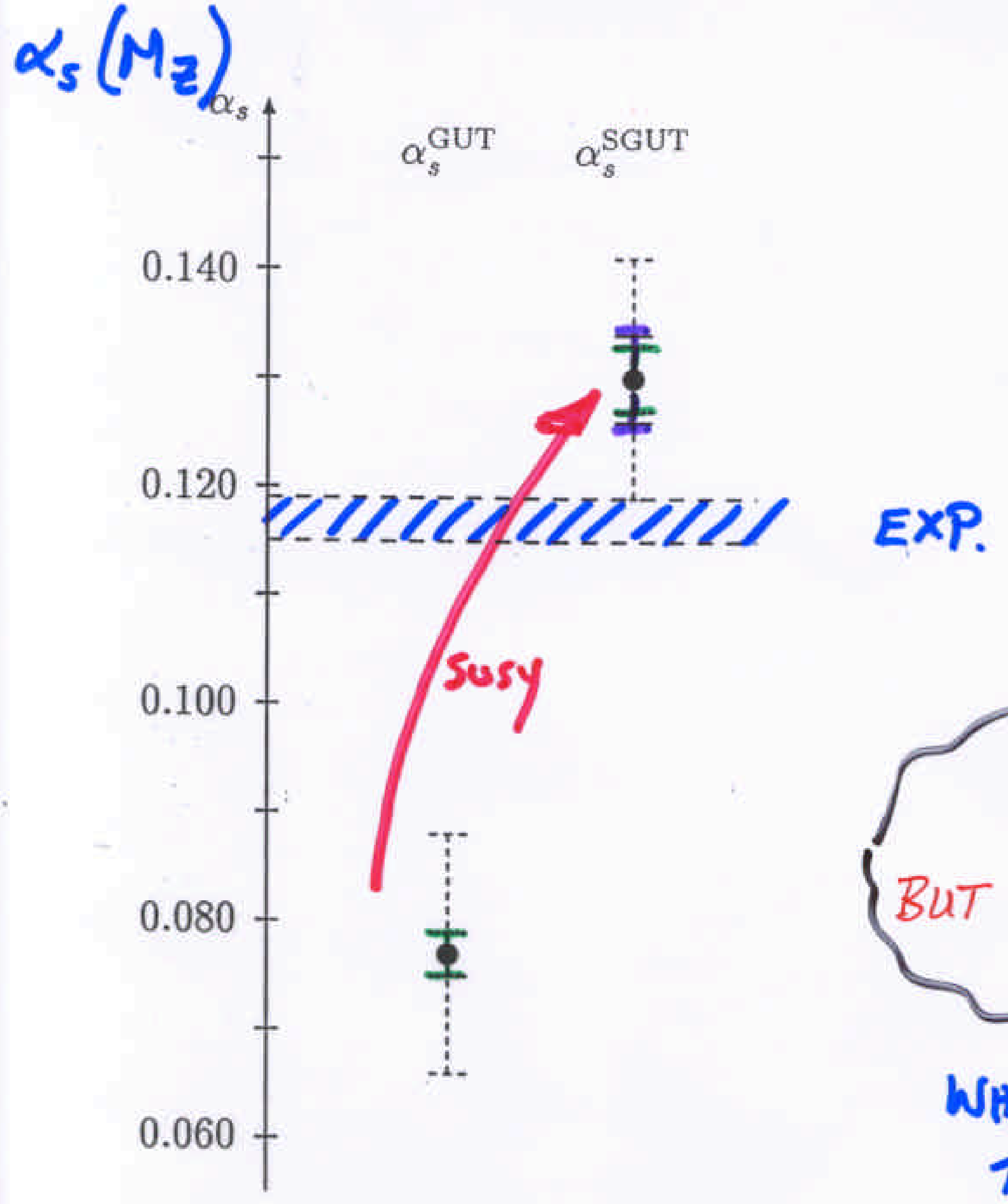
$$\begin{pmatrix} h_2 \\ \cdot \end{pmatrix} \quad \begin{pmatrix} \bar{h}_2 \\ \cdot \end{pmatrix}$$





RECONCILIATION ?

PREDICTION OF α_s



GOOD

BUT NOT PERFECT

WHAT IS THIS TELLING US?

GUT threshold corr.ⁿ (5+$\bar{5}$, unit log spl…

Estimate of supersym. threshold corr.ⁿ

MINIMAL 4D SUPERSYM. SU(5):

- No understanding of why h_2 light.
- Excluded by experimental limit on τ_p

One is forced to invent mechanisms ....

... a better way forward?

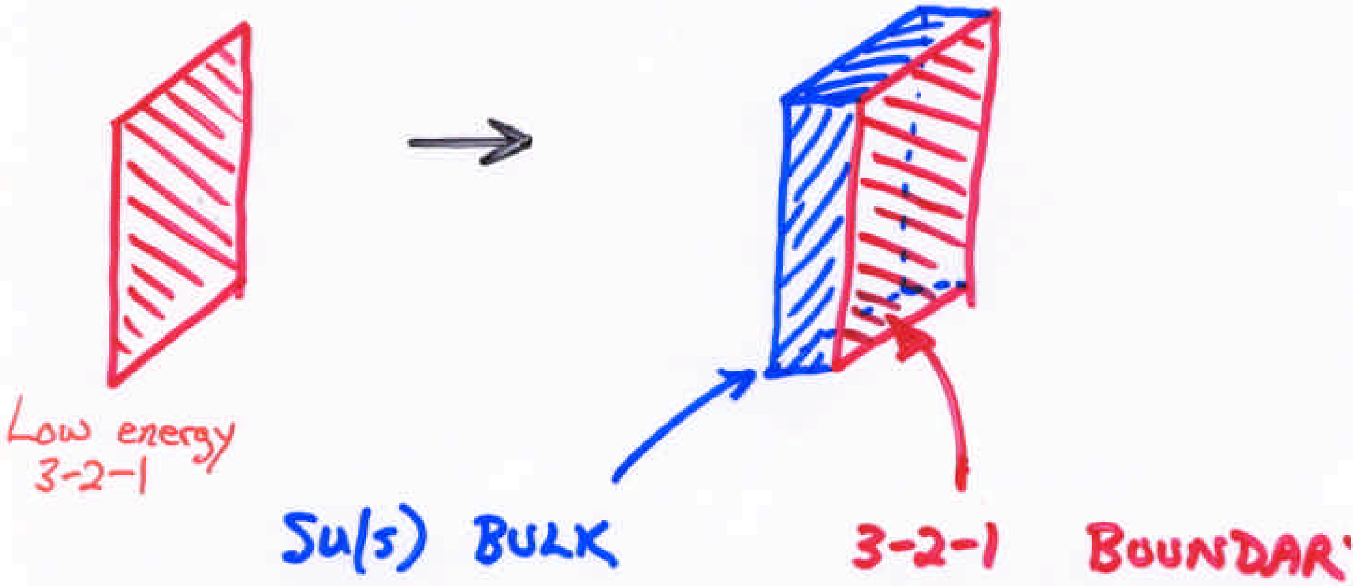
II

A NEW PHYSICS OF UNIFICATION

OLD TOOLS ⟹ A NEW THEORY FROM $10^{15} - 10^{17}$ GeV

HIGHER DIMENSIONS

$$x \longrightarrow (x, y)$$



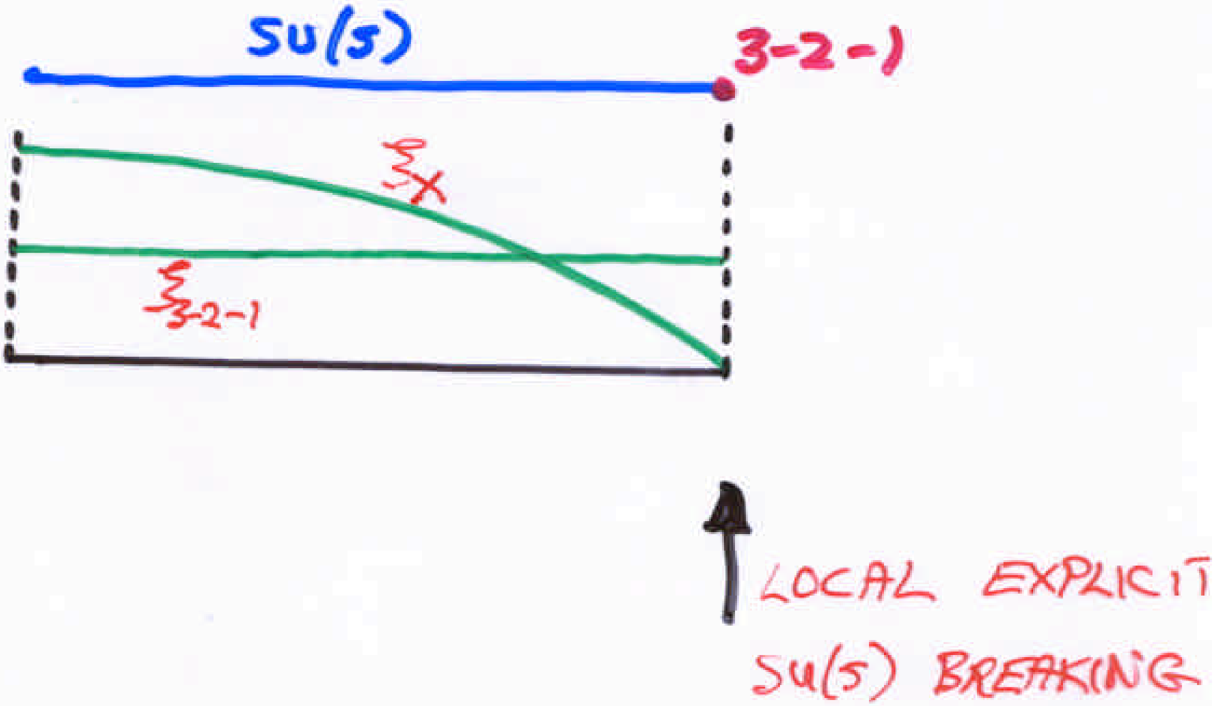
Suppress x:

Fit unification	Matter Q.N.	Higgs Q.N.	Abhor unificat
	α_s prediction		
	b/τ	s/μ	

p decay.

ORIGIN OF 3-2-1 POINT DEFE

RESTRICTED GAUGE SYMMETRY FROM BOUNDARY CONDITIONS : FIELD THEORY IN A BOX :



A NEW CLASS OF PREDICTIVE GAUGE THEORIES.

- SAME UNITARITY BEHAVIOUR AS 

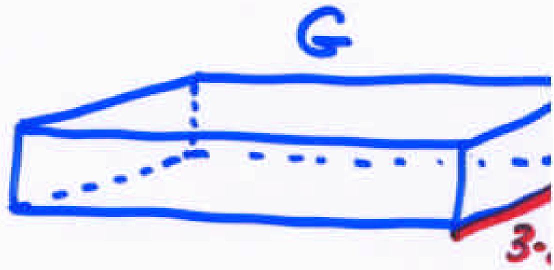
- *NO NEED TO BREAK THE UNIFIED GAUGE SYM

THE SET UP

- Assume

  Fixed geometry

  Boundary conditions

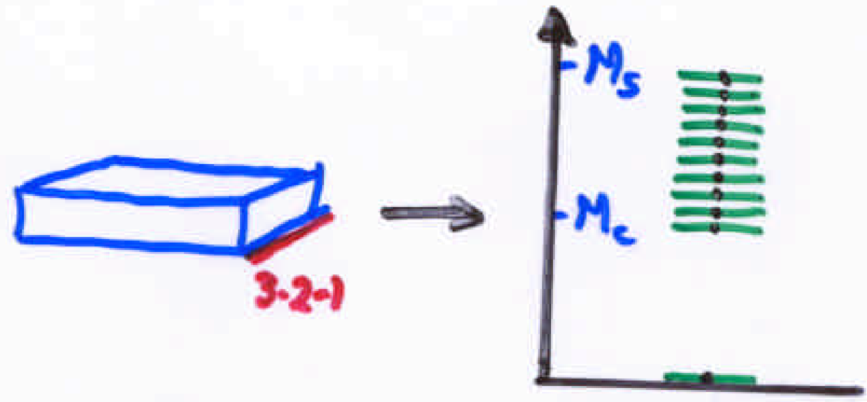


- Introduce

  $\phi(y)$ & general action

- "Machine"

$\phi(y)$ →



GEOMETRY / B.C. → KK STRUCTURE

STRUCTURE OF BULK ← EXPERIMENT

- No need for mass terms or spontaneous symmetry break

CONSEQUENCES FOR:

- Gauge coupling unification
- Why h_2 light
- p decay
- quark-lepton mass ratios.

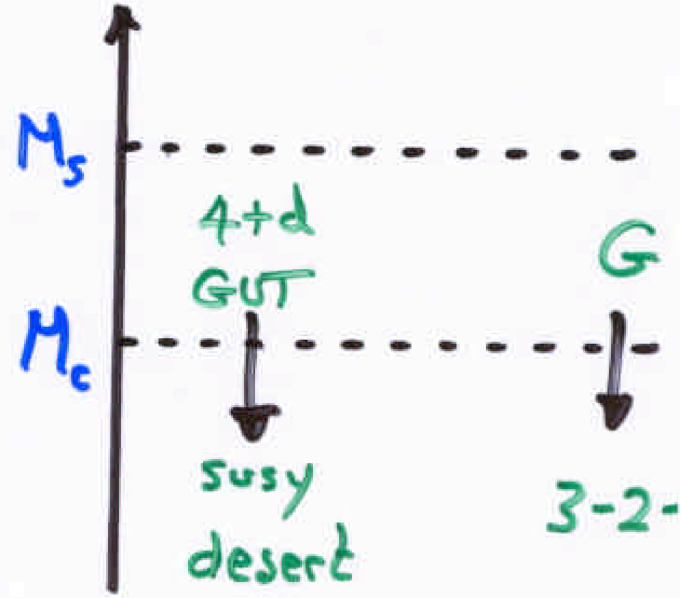
In each case the situation is quite unlike 4D:

HIGHER DIM GUTs $\neq$ 4D GUTs

Consequences for Gauge Coupling Un

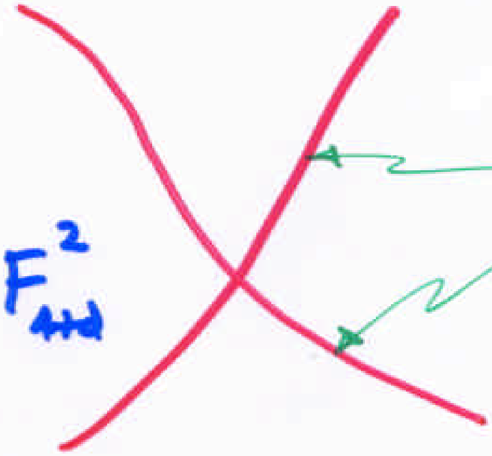
Cutoff for 4+d GUT →

1/R (Could be several) →



G

$\frac{1}{g_{4+d}^2} F_{4+d}^2$

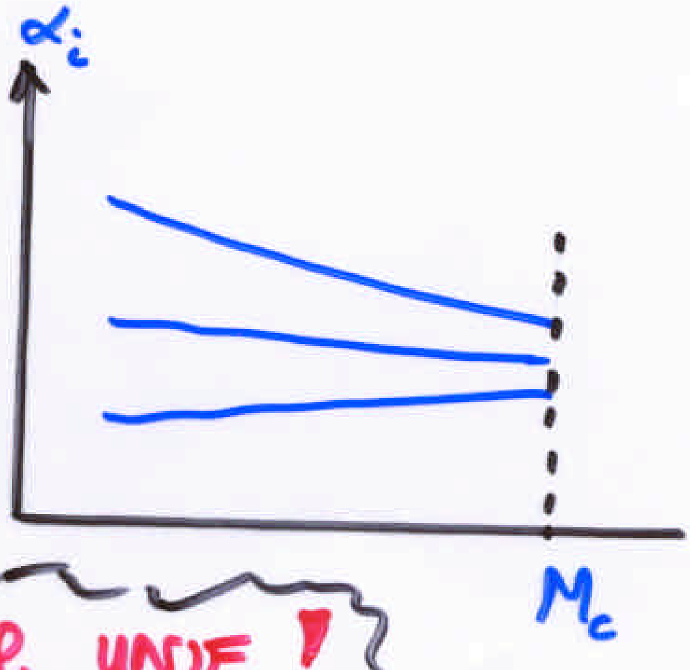


SUBSPACES WITH RESTRICTED GAUGE SYMMETRY:

$$\frac{1}{g_i^2} F_i^2$$

$\int dy$:

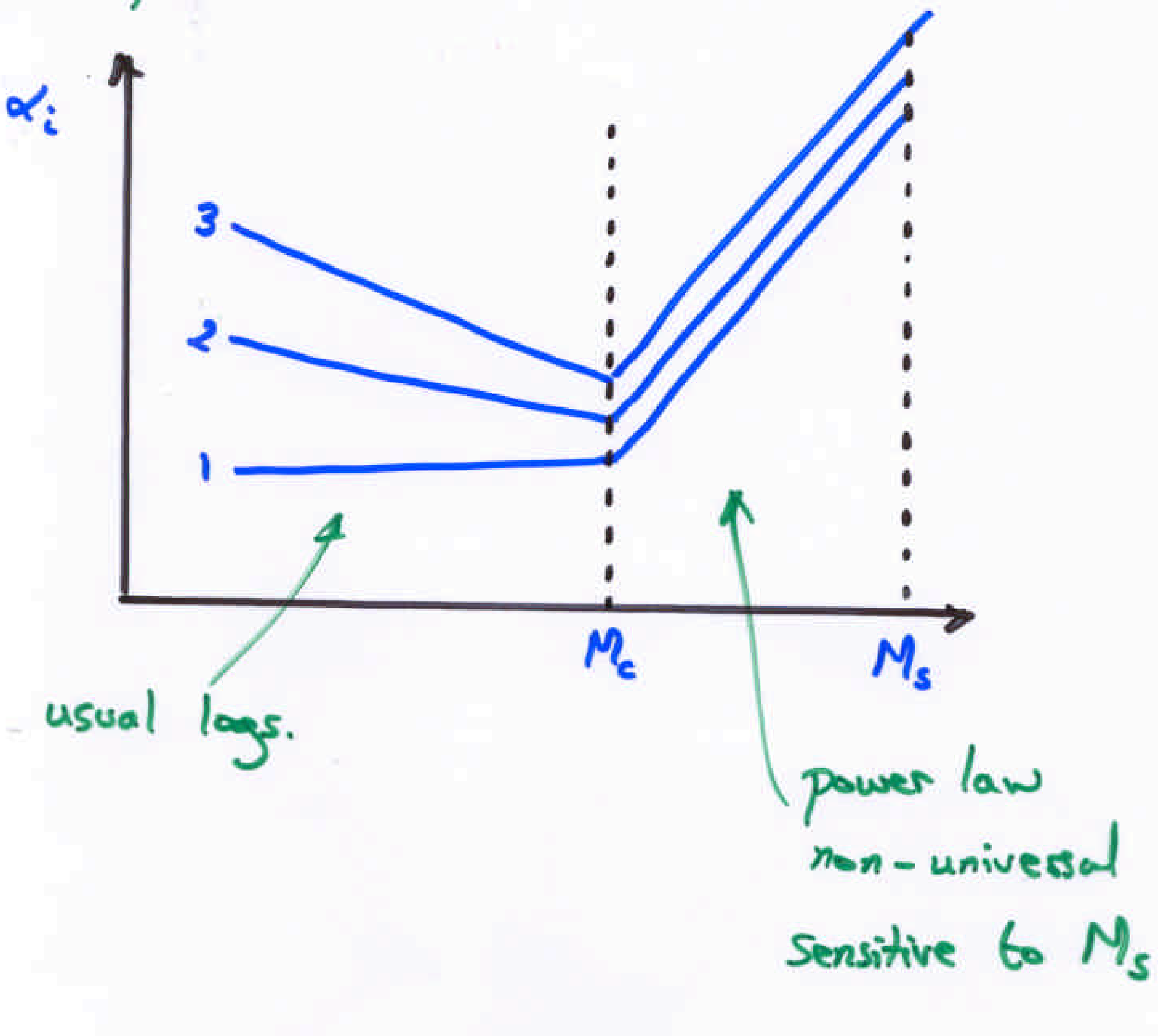
$$\frac{1}{g_i^2} = \frac{R^d}{g_{4+d}^2} + \frac{R^{d'}}{\bar{g}_i^2}$$



NO GAUGE COUP. UNIF !

RADIATIVE CORR.

4D viewpoint

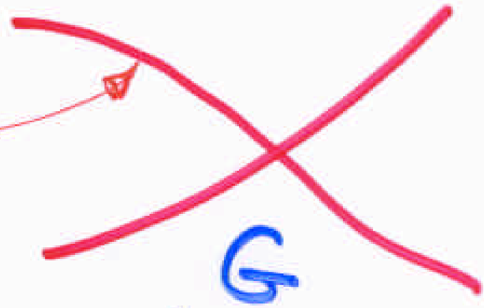


4+d GUT with RESTRICTED GAUGE SYMMETRY ⇒ EXPLICIT LOCAL BREAKING OF G ⇒ UNIF. α_i LOST

NEW PHYSICS OF UNIFICATION

Hall, Nomura (01)

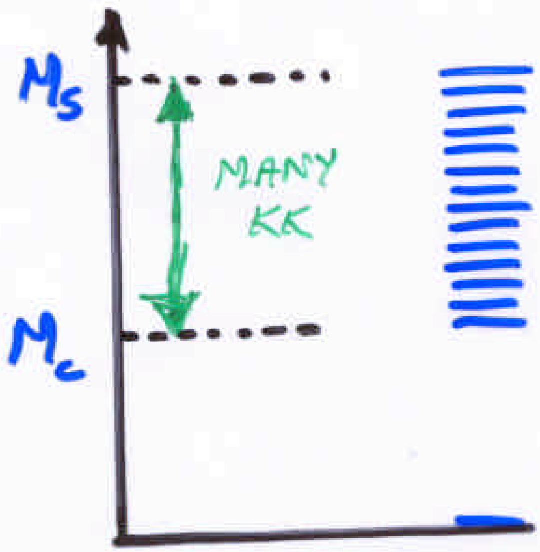
$$\frac{1}{g_i^2} = \frac{R^d}{g_{4+d}^2} + \frac{R^{d'}}{\tilde{g}_i^2}$$



① Large vol. of bulk

$$R M_s = \frac{M_s}{M_c} \gg 1$$

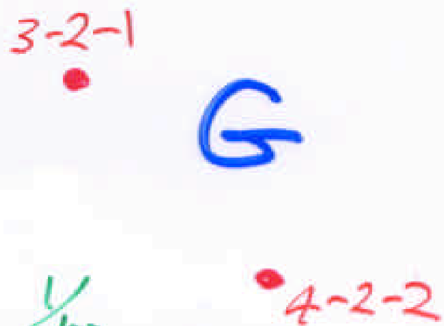
M_s AT/CLOSE TO STRONG COUPLING



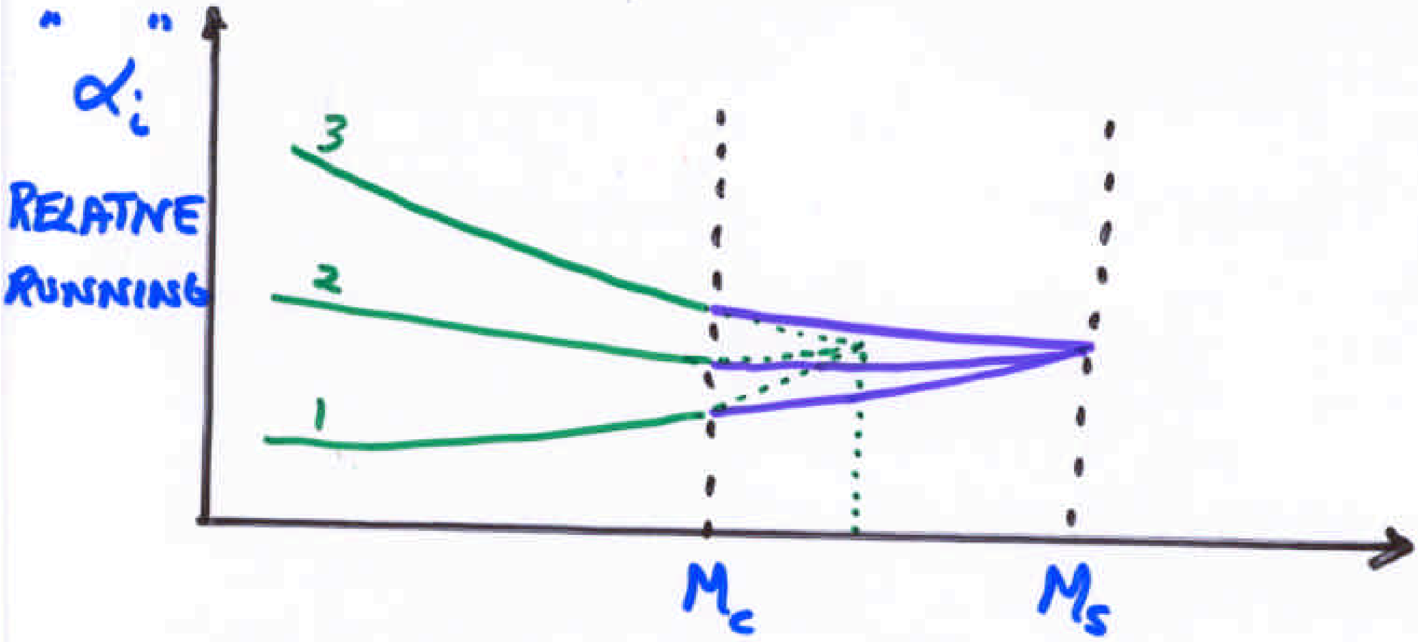
② Local Breaking To 3-2-1 at POINTS

⇒ RELATIVE RUNNING ABOVE M_c IS LOG

⇒ SENSITIVITY TO PHYSICS AT M_s IS 1/log



HOW CAN 2 STAGE UNIF. BE PREDICTIVE



$$\frac{1}{\alpha_i(M_Z)} = b_i^{susy} \ln \frac{M_c}{M_Z} + b_i^{KK} \ln \frac{M_s}{M_c} + \frac{1}{\alpha_G}$$

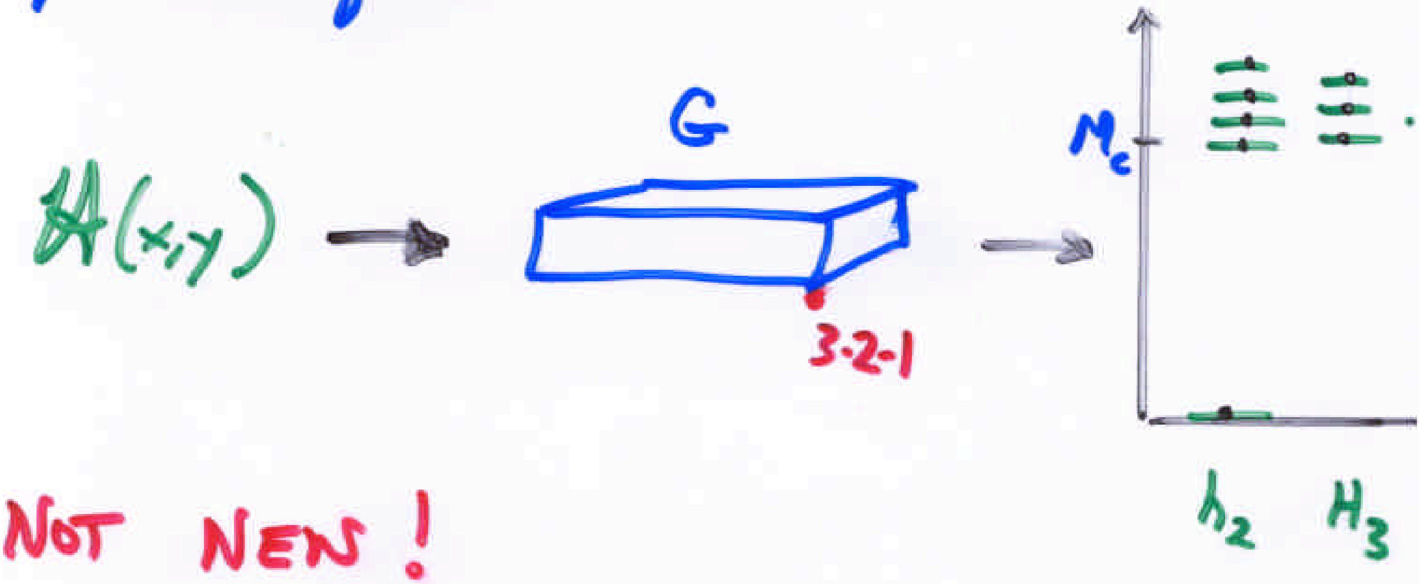
$\frac{M_s}{M_c}$ determined by strong coupling :

$$C \frac{g^2(M_c)}{16\pi^2} \left(\frac{M_s}{M_c}\right)^d \approx 1$$

$$\boxed{\alpha_s = \alpha_s\left(d,\ B.C.,\ \Phi(y)\right)}$$

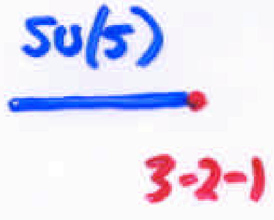
SPLIT MULTIPLETS: THE LIGHT h_2

The "machine" automatically creates split multiplets.



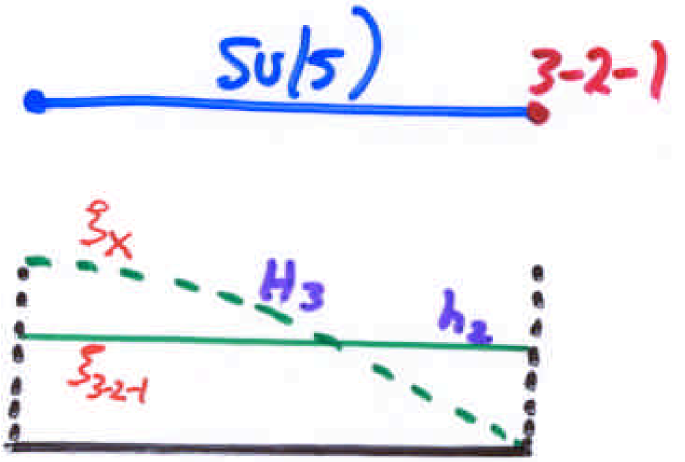
NOT NEWS!

Candelas, Horowitz, Strominger, Witten (85)
Dixon, Harvey, Vafa, Witten (85)
Ibanez, Kim, Nilles, Quevedo (87)
⋮
Kawamura (00)



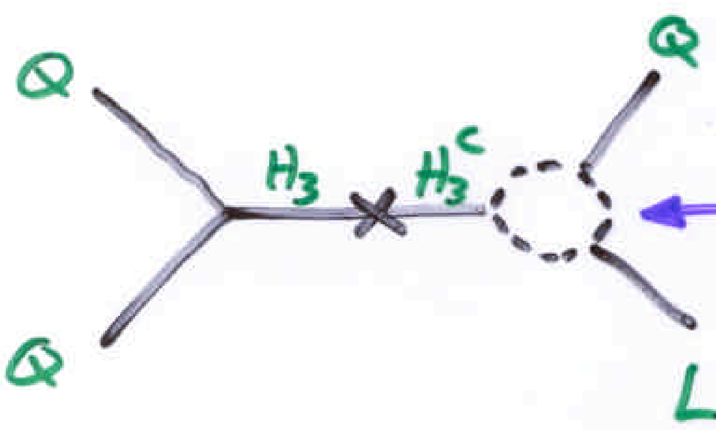
d = 5 PROTON DECAY

Study masses for H_3:



$$\mathcal{L} \supset H_3 \partial_y H_3^c \longrightarrow H_3 \frac{n}{R} H_3^c \quad , \; n \neq$$

N=2 partne

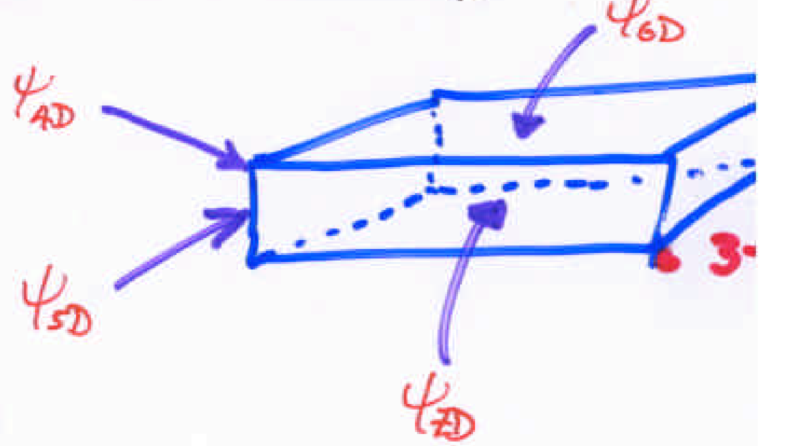


No coupling by R symmetry

d = 4,5 ABSENT BY SYM.	d = 6 $M_X = M_c = ?$

QUARK-LEPTON MASS RELATIONS

- DEPENDS ON LOCATION:



- Yukawas in 4d $\delta^d(\bar{y}-\bar{y}_0)\,\psi_1\,\psi_2\,H$

- $m_{12} \propto \frac{1}{\sqrt{V_1}}\frac{1}{\sqrt{V_2}}$ if both touch $\bar{y}_0$

* HEAVIEST FERMIONS LIVE IN 4D & HAVE UNIFIED MASS REL (IF AWAY FROM

* LIGHTER FERMIONS LIVE IN BULK & DON'T HAVE UNIFIED MASS REL. (IF TOUCH 321

III

THE MINIMAL MODEL

Conceptual framework

⇓

Calculable, predictive theories

α_s SUGGESTS SU(5) IN 5D

Seek: $\alpha_s(\text{BULK}, \text{B.C.}, G, H) \rightarrow 0.117 \pm .002$ (Exp. at M_Z)

Recall $\alpha_s^{SGUT} \simeq 0.130$

Find

$d < 3$

H in bulk (not part of V)

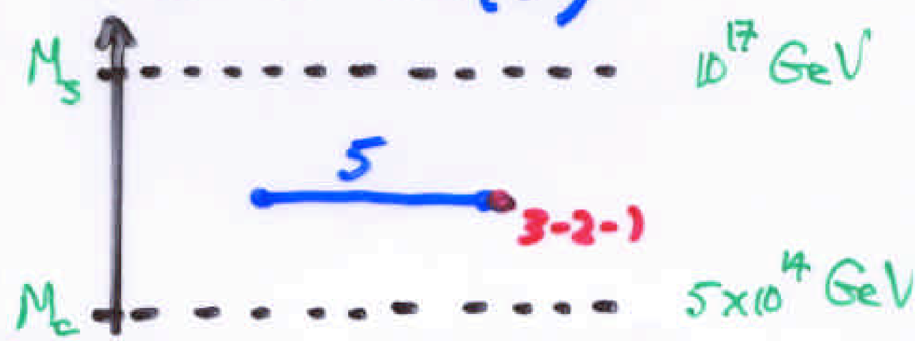
$$\delta\alpha_s = -\frac{1}{2\pi}\,\alpha_s^2\,\frac{12}{7m}\,\ln\frac{M_s}{M_c} \qquad \left\{ \begin{array}{l} T^2/Z_m \\ \text{or} \\ m=2 \\ \text{for } d= \end{array} \right.$$

Best if

$$d = 1 \Rightarrow \left\{ \begin{array}{l} M_s/M_c \simeq 200 \\ G = SU(5) \end{array} \right.$$

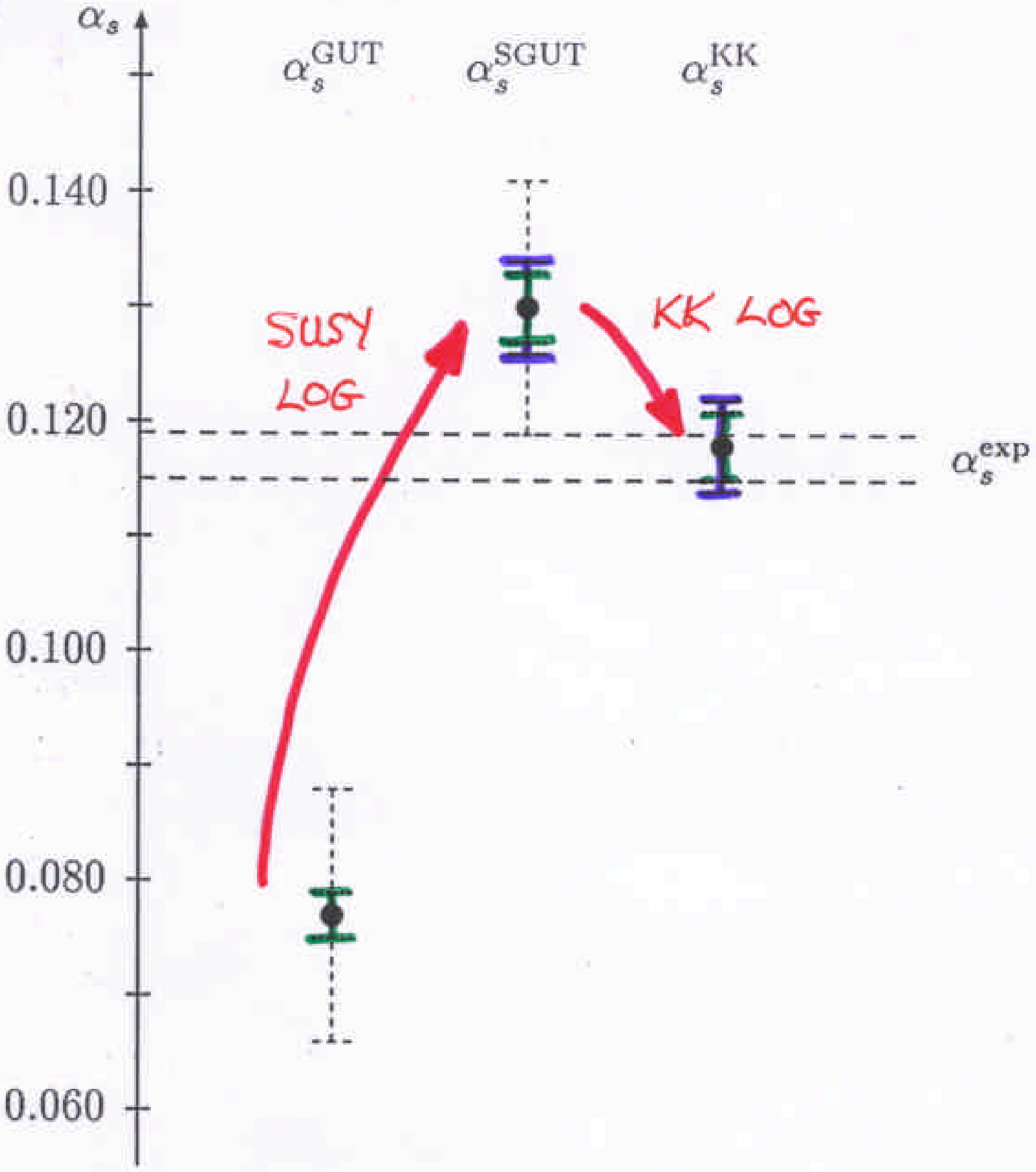
Simplest Model

is selected over a large energy interval.



THE α_s PREDICTION

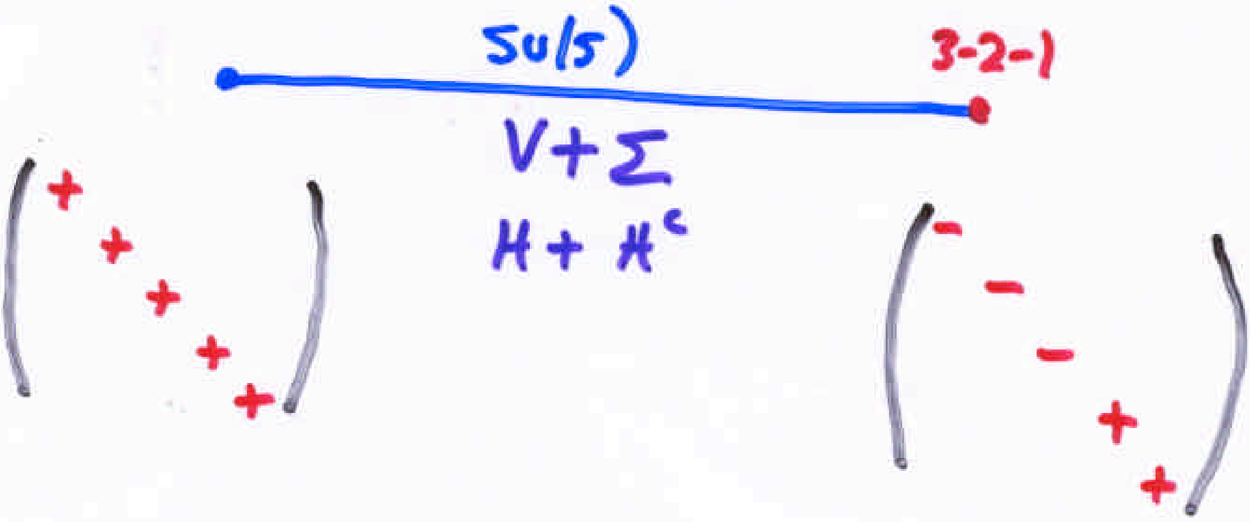
$\alpha_s(M_Z)$

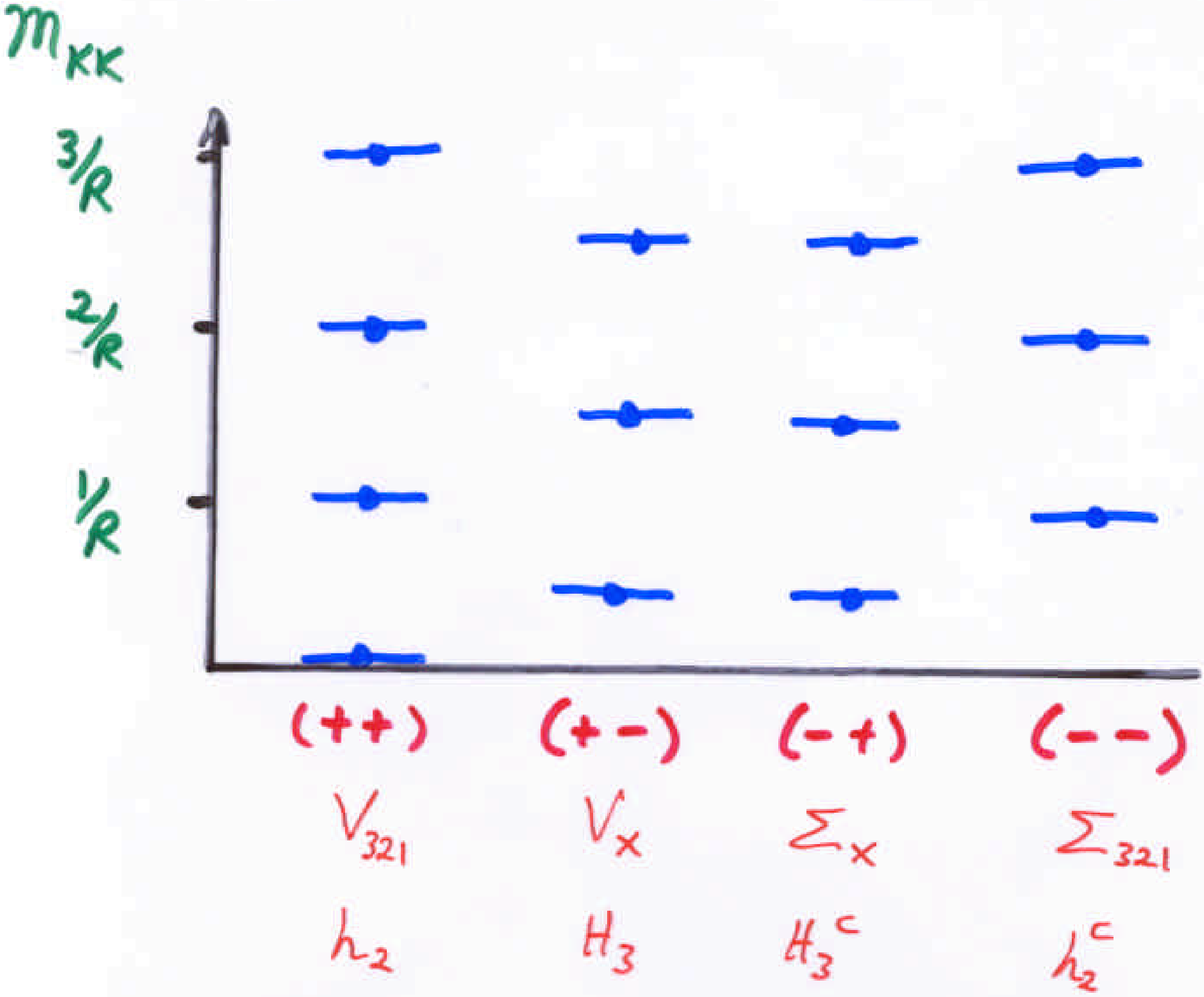


- uncertainty from non-log corr.^{n} at high scale
- uncertainties from susy scale

- 5D Theory with large M_s/M_c is best fit t…
- Other theories not excluded

THE KK MODES





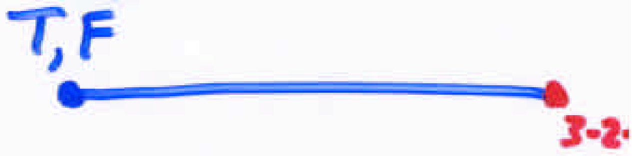
cf Kawamura (2000)

MATTER LOCATION

"Boundary" Matter

"UNIFIED"

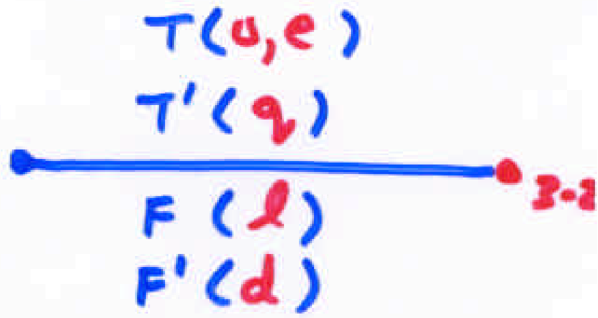
$$\delta(y)\{TTH + TFH\}$$



"Bulk" Matter

"non-UNIFIED"

$$\delta(y)\left\{\begin{array}{l} TTH + TT'H + \dots \\ TF\bar{H} + TF'\bar{H} + \dots \end{array}\right\}$$



Boundary	$1/R^{1/2}$	SU(5) REL.
Bulk	$1/R^{3/2}$	NO REL.

Hall, Nomura ph/0103
Hebecker, March-Russell ph/0106

T_3 must be on boundary

F_3 on boundary for b/τ

BOUNDARY INTERACTIONS

4D, N=1 allows:

	FH, $\bar{H}H$	NO
	TTH, $TF\bar{H}$	YES
	TFF	NO
	$TTTF$	NO

N=2 possesses continuous R sym.

$$\text{eg } [\, \underset{(0)}{H} \; \partial_y \underset{(2)}{H^c} \,]_F$$

Extend to boundary interactions:

$T(1)$ $F(1)$ $H(0)$ $\bar{H}(0)$ $H^c(2)$ $\bar{H}^c(2)$

Complete sol^n to

- $\Delta B, \Delta L \neq 0$ at $d=4,5$
- h_2 massless

IV EXPERIMENTAL SIGNALS

- $d=6$ p decay

- Theories of quark & lepton masses.

  Hall, March-Russell, Okui, Smith ph/0108161

  Hebecker, March-Russell ph/0205143

  Talk by John March-Russell

<u>If</u> supersym. breaking has high messenger sc

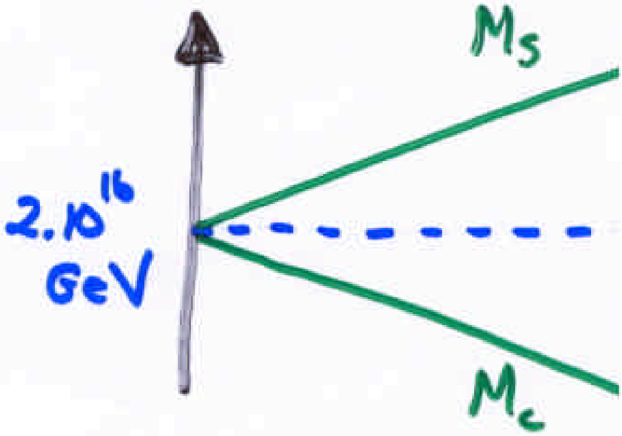
- Superpartner spectrum

- Lepton flavor violation

$d = 6$ PROTON DECAY

(1)

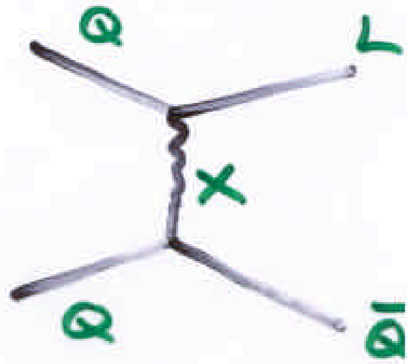
$M_X = M_c$



(2)

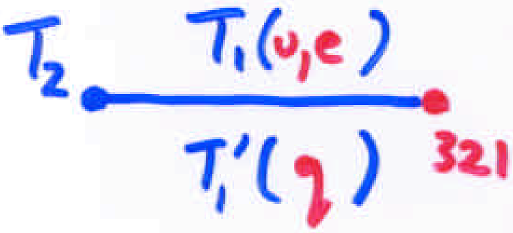
can give

$p \to e^+ \pi^0$



(3)

For large $\frac{M_s}{M_c}$, T_1 must be in bulk



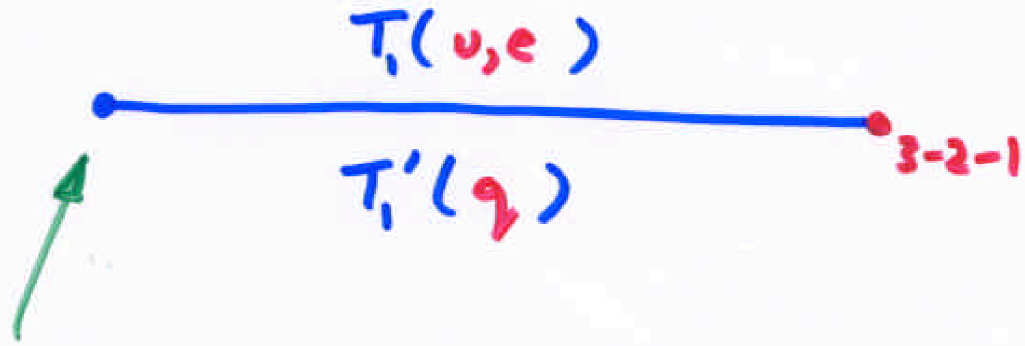
$p \longrightarrow K^+ \nu$

via CKM mixing.

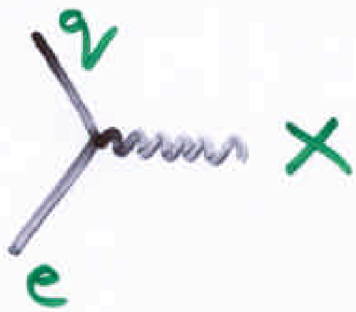
Nomura ph/0108170

Hebecker, March-Russell ph/0204037

④ Boundary Gauge Interactions



$\delta(y)\, T_1^{+} T_1' \quad \Rightarrow$



Minimal model gives

$\tau_p \approx 10^{34}$ yrs for $\ell^+\pi^0$, ℓ^+K^0; $\bar{\nu}\pi^+$, $\bar{\nu}K$

(ℓ = e or μ)

~~SUSY~~ : $M_{mess} > M_c$

Various possibilities for T_2, F_1, F_2

$$U(3)_T \times U(3)_F \xrightarrow[\text{location}]{\text{matter}} \ldots\ldots$$

Expect:

- Non-universal squark/slepton masses
- FCNC from superpartner exchange

Hall, Nomura ph/0205067

Ex: SUSY breaking B.C.

"$SU(2)_R$ twist"

$$\begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \text{ on } \begin{pmatrix} \lambda \\ \psi_\Sigma \end{pmatrix} \quad \begin{pmatrix} A \\ A^{c*} \end{pmatrix}$$

$\alpha \sim 10^{-13}$!

DYNAMICS OF F
COMPONENT OF RADION

Marti Pomarol th/0106

SOFT OPS. AT M_c

All bulk superpartners: $\tilde{m} = \dfrac{\alpha}{R}$

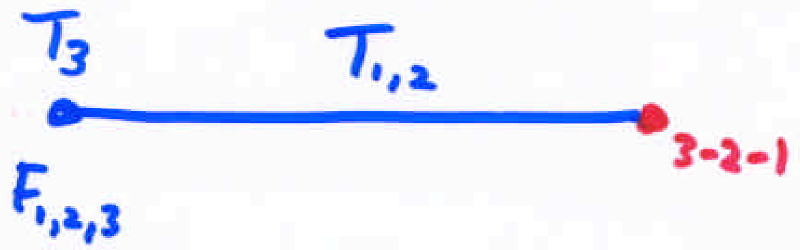
All boundary superpartners: 0

Trilinear A parameters: $1, 2, 3$

(counts # scalars in bulk,

CONSEQUENCES

Unique matter locations :



Param. $\tilde{m}, \mu, B \xrightarrow{\text{ENSB}} \tilde{m}, \tan\beta$

$\downarrow$

superpartne
spectrum

PREDICTIONS FOR

$$\begin{pmatrix} \cos\alpha & \sin \\ -\sin\alpha & \cos \end{pmatrix}$$

Probe matter location:

Boundary squarks light → $\tilde{d}$, $\tilde{l}$

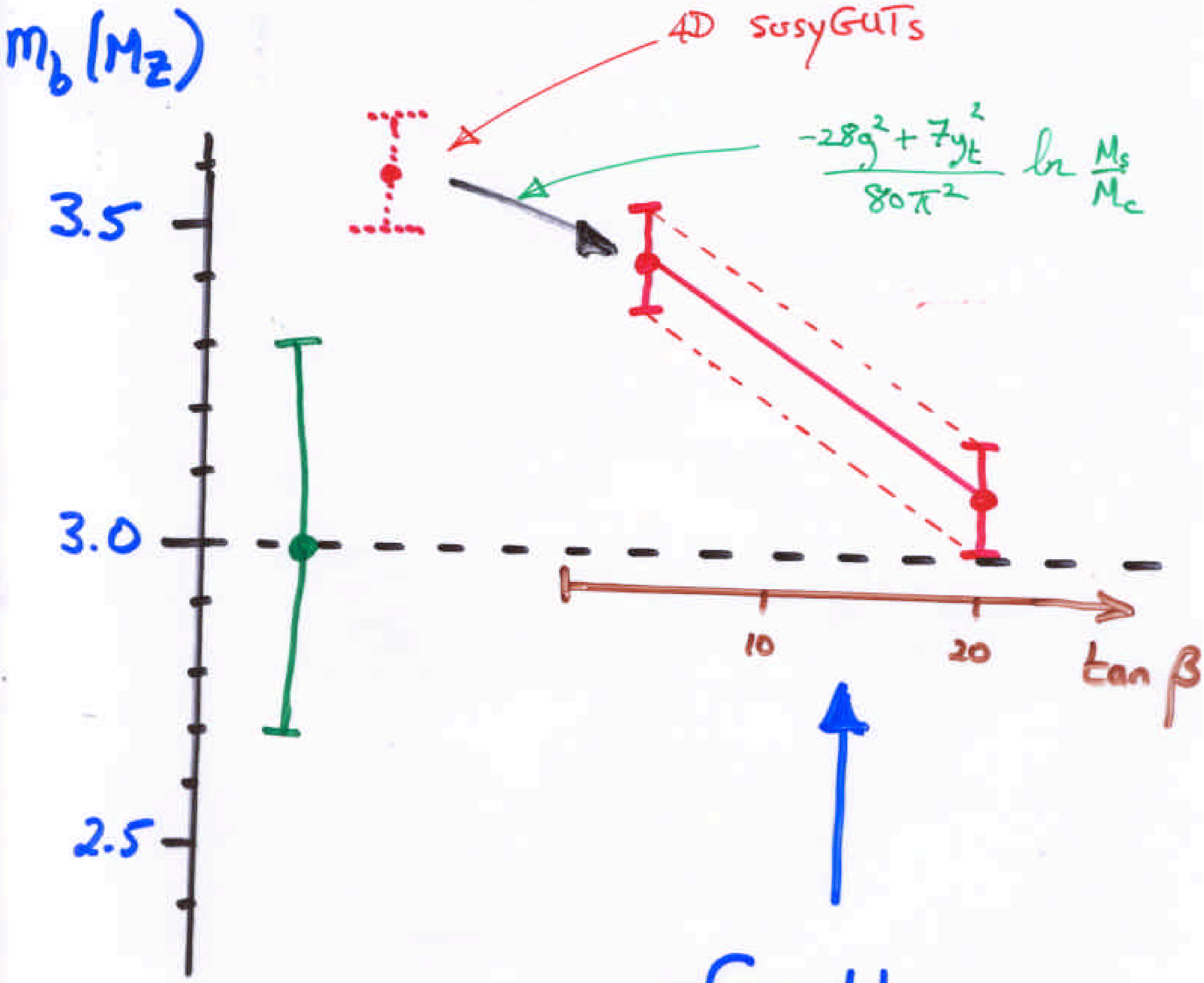
Boundary sleptons light. → $\tilde{l}$, $\tilde{\tau}_1$, $\tilde{\tau}_2$

$\tilde{m}$ / $\tan\beta$	300 / 5	400 / 10
$\tilde{g}$	699	911
$\tilde{\chi}_1^{\pm}$	251	334
$\tilde{\chi}_2^{\pm}$	427	531
$\tilde{\chi}_1^0$	130	175
$\tilde{\chi}_2^0$	251	334
$\tilde{\chi}_3^0$	417	518
$\tilde{\chi}_4^0$	422	528
$\tilde{q}$	701	915
$\tilde{u}$	675	880
$\tilde{d}$	602	780
$\tilde{l}$	209	277
$\tilde{e}$	317	422
$\tilde{t}_1$	425	547
$\tilde{t}_2$	619	780
$\tilde{b}_1$	563	727
$\tilde{b}_2$	601	774
$\tilde{\tau}_1$	106	126
$\tilde{\tau}_2$	214	280
h	118	128
A	552	690
H^0	553	690
$H^{\pm}$	558	695
$\alpha_s(M_Z)$ $\{\pm 0.003\}$	0.119	0.118
$m_b(M_Z)$ $\{\pm 0.10\}$	3.37	3.26
$\mathrm{Br}(\mu \to e\gamma)$	6×10^{-12}	8×10^{-12}
$\mathrm{Br}(\mu \to 3e)$	4×10^{-14}	5×10^{-14}
$\mathrm{Cr}(\mu \to e; {}^{48}_{22}\mathrm{Ti})$	4×10^{-14}	5×10^{-14}
$\mathrm{Br}(\tau \to \mu\gamma)$	1×10^{-8}	1×10^{-8}

MASS EIGENVALUE IN GEV

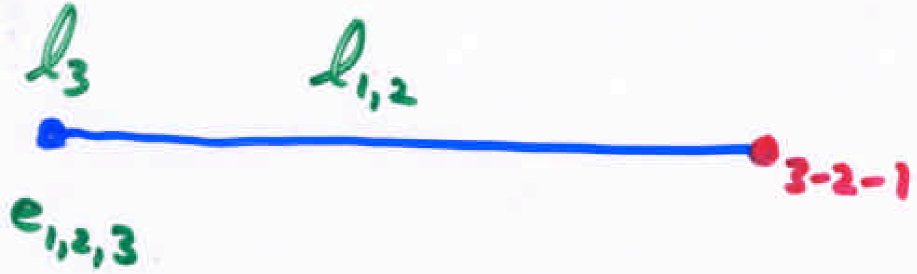
includes susy threshold corrections

b / τ MASS RELATION



Complete success for moderate $\tan\beta$.

LEPTON FLAVOR VIOLATION



$$m_E^2 = 0, \quad m_L^2 = \begin{pmatrix} \tilde{m}^2 & & \\ & \tilde{m}^2 & \\ & & 0 \end{pmatrix}, \quad A_E = \begin{pmatrix} 2 & & \\ & 2 & \\ & & 1 \end{pmatrix}$$

$U(3)_L \xrightarrow{\text{lepton location}} U(2)_L$

O(1) tree-level effect !

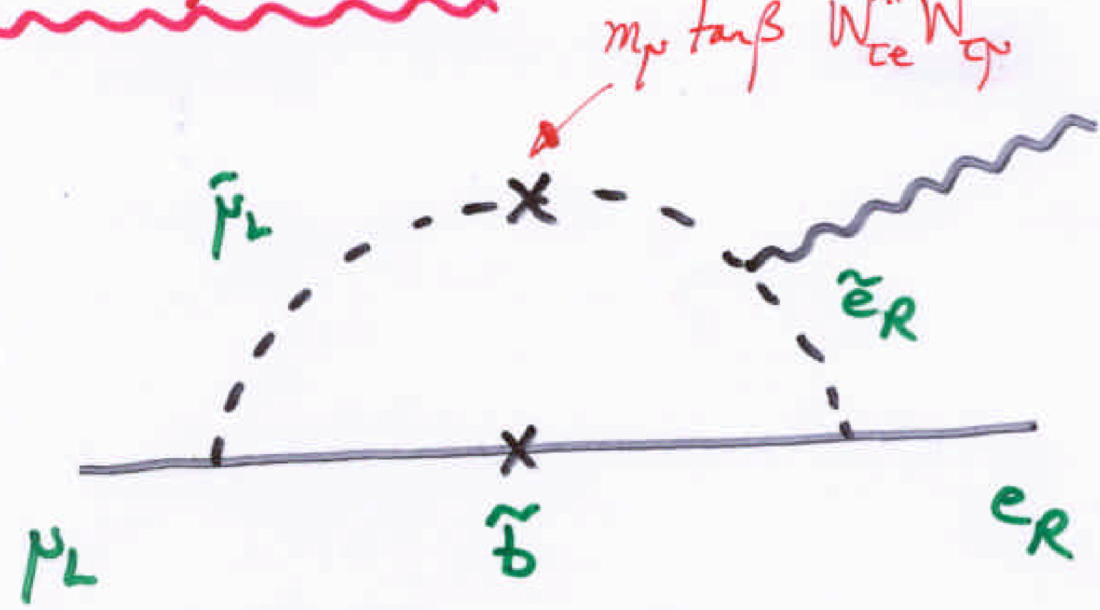
Much larger than $O\left(\frac{y_t^2}{16\pi^2}\right)$

4D susyGUT effect

Hall, Kostelecky, Raby (8

Barbieri, Hall (94)

e.g. $\mu \to e$



1.2×10^{-11} —PSI→ 10^{-14}

4.3×10^{-12} —MECO→ 10^{-16}

1.1×10^{-6} —B factories→ 10^{-7}

VERY POWERFUL PROBE

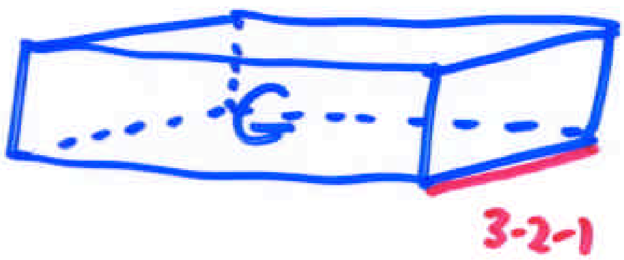
$$\mathrm{Br}(\mu \to e\gamma) \simeq \underline{3 \times 10^{-11}} \left(\frac{200\ \mathrm{GeV}}{\tilde{m}}\right)^4 \left(\frac{|W^e_{\tau\mu}|}{0.04}\right)^2 \left(\frac{|W^e_{\tau e}|}{0.01}\right)^2 \left(\frac{\tan\beta}{5.0}\right)^2$$

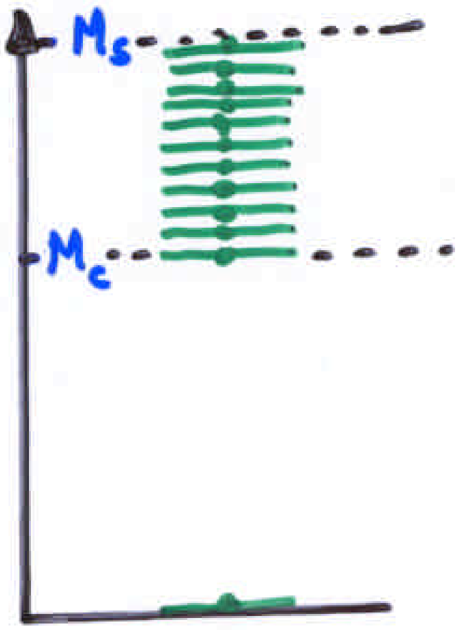
$$\left.\begin{array}{l}\mathrm{Br}(\mu \to 3e) \\ \mathrm{Cr}(\mu \to e; {}^{48}_{22}\mathrm{Ti})\end{array}\right. \simeq \underline{2 \times 10^{-13}} \left(\frac{200\ \mathrm{GeV}}{\tilde{m}}\right)^4 \left(\frac{|W^e_{\tau\mu}|}{0.04}\right)^2 \left(\frac{|W^e_{\tau e}|}{0.01}\right)^2 \left(\frac{\tan\beta}{5.0}\right)^2$$

$$\mathrm{Br}(\tau \to \mu\gamma) \simeq \underline{5 \times 10^{-8}} \left(\frac{200\ \mathrm{GeV}}{\tilde{m}}\right)^4 \left(\frac{|W^e_{\tau\mu}|}{0.04}\right)^2 \left(\frac{|W^e_{\tau\tau}|}{1.0}\right)^2 \left(\frac{\tan\beta}{5.0}\right)^2.$$

CONCLUSIONS

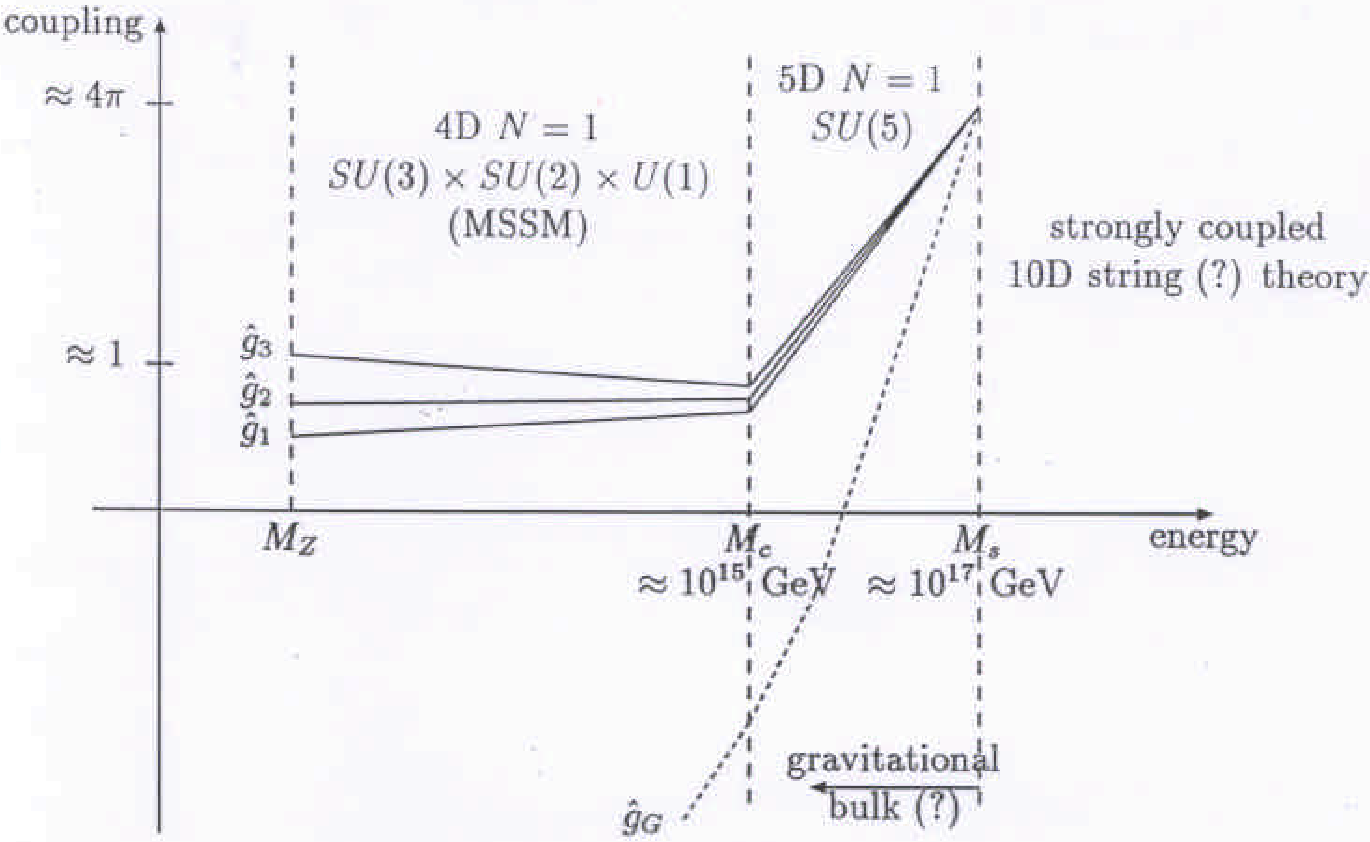
- Alternative physics for unification at 10^{16} GeV





- Solves dichotomy of 4D susy GUTs
  - $d=5$ p decay: $U(1)_R$
  - q–ℓ mass rel. only for heavy g
  - $h_2 - H_3$ splitting

MINIMAL MODEL WORKS BEST



Exp

- $\alpha_s(M_Z) = .118 \pm .003$ $.117 \pm .00$
- $m_b(M_Z) = 3.3 - .02(\tan\beta - 10)$ GeV $3.0 \pm$
- Some of flavor from $M_s/M_c \approx 10^2$
- $d=6$ p decay $p \to \ell^+\pi^0, \ldots$

* Predictive superpartner spectrum
* $\mu \to e$ transitions

} large M_m