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# BEYOND HIGGS & SUSY

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GRAHAM KRIBS

UNIVERSITY OF OREGON

SLAC SUMMER SCHOOL

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THE FIRST QUESTION YOU'RE NO DOUBT ASKING:

THIS TALK ABOUT BEYOND HIGGS & SUSY

HAS NOT EVEN GONE BEYOND TRANSPARENCIES?

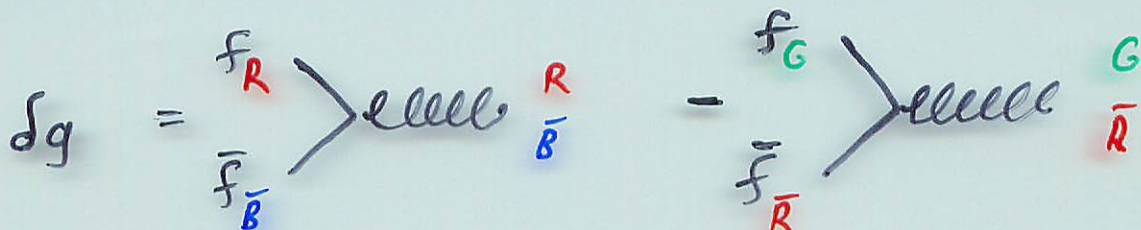
(YES.)

# WHY CARE ABOUT THEORY?

THEORY PROVIDES A SIMPLIFYING FRAMEWORK THAT WE IMPLICITLY OR EXPLICITLY USE TO MAKE PROGRESS UNDERSTANDING DATA.

## EXAMPLES:

IMPLICIT: WE "TAKE FOR GRANTED" THAT  $SU(3)_c$  IS EXACT. NO ONE TRYS TO MEASURE "HARD BREAKING":



EXPLICIT: LHC COLLISION RATE:  $10^9$  Hz

LHC EVENT WRITING RATE:  $10^2$  Hz

SELECTION BIAS HAS PLENTY OF (SPECULATIVE) THEORY INPUT.

BOTH: DATA ANALYSES USE MONTE CARLO PROGRAMS

WHICH HAVE VARIOUS THEORETICAL ASSUMPTIONS FROM THE

MODEC TO SHOWERING TO HADRONIZATION.

# STANDARD MODEL

( BRIEF REVIEW OF SOME SALIENT FACTS  
THAT GUIDE & RESTRICT BSM PHYSICS )

# STANDARD MODEL ON ONE PAGE

$$S_{\text{GAUGE}} = \int d^4x \quad F_{\mu\nu}^Y F^{\mu\nu Y} + F_{\mu\nu}^{\alpha} F^{\alpha\mu\nu} + F_{\mu\nu}^c F^{\mu\nu c}$$

HYPERCHARGE                      SU(2)<sub>L</sub>                      SU(3)<sub>C</sub>

$$S_{\text{FERMIONS}} = \int d^4x \quad \sum_{\text{GENERATIONS}} \sum_{f=Q,u,d,L,e} (\bar{f} \not{D} f)$$

$$S_{\text{HIGGS}} = \int d^4x \quad (D_{\mu} H)^{\dagger} (D^{\mu} H) - V(H)$$
$$V(H) = -m^2 |H|^2 + \lambda |H|^4$$

$|H|^2 \equiv H^{\dagger} H$

$$S_{\text{YUKAWA}} = \int d^4x \quad Y_u Q u^c H + Y_d Q d^c H^{\dagger} + Y_e L e^c H^{\dagger}$$

$$\left( + S_{\text{GRAVITY}} = \int d^4x \sqrt{g} [M_{\text{pl}}^2 R + \Lambda_{\text{cc}}^4] \right)$$

# GAUGED SYMMETRIES

COLOR

ELECTROWEAK

$SU(3)_c$

$\times$

$SU(2)_L \times U(1)_Y$

		ELECTROWEAK		
		$SU(2)_L$	$U(1)_Y$	
MATTER FERMIONS	Q	3	2	$\frac{1}{6}$
	$u^c$	$\bar{3}$	1	$-\frac{2}{3}$
	$d^c$	$\bar{3}$	1	$+\frac{1}{3}$
	L	1	2	$-\frac{1}{2}$
	$e^c$	1	1	+1

PLUS GRAVITY, WHICH WE UNDERSTAND AS

GAUGED GENERAL COORDINATE INVARIANCE.

# GLOBAL FLAVOR SYMMETRIES

SM MATTER SECRETLY HAS A LARGE SYMMETRY:

$$U(45)$$

$$\begin{pmatrix} Q_1 \\ u_1 \\ d_1 \\ L_1 \\ e_1 \\ \vdots \\ \vdots \\ \vdots \\ 2 \\ \vdots \\ \vdots \\ \vdots \\ 3 \end{pmatrix}$$

ROTATE 45 FERMIONS INTO EACH OTHER

EXPLICITLY BROKEN BY CHARGING 3-2-1

$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

$$Q_{1,2,3} \quad u_{1,2,3}^c \quad d_{1,2,3}^c \quad L_{1,2,3} \quad e_{1,2,3}^c$$

ROTATE AMONG GENERATIONS

EXPLICITLY BROKEN BY QUARK YUKAWAS + CKM

$$U(1)_B$$

BARYON NUMBER

EXPLICITLY BROKEN BY CHARGED LEPTON YUKAWAS

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

NEUTRINO MASSES

LEPTON NUMBER

$U(1)_e$   
(OR NOTHING)

← DIRAC

← MAJORANA

EXCESSIVELY VIOLATING FLAVOR SYMMETRIES IS A BIG CONCERN FOR BEYOND-SM PHYSICS!

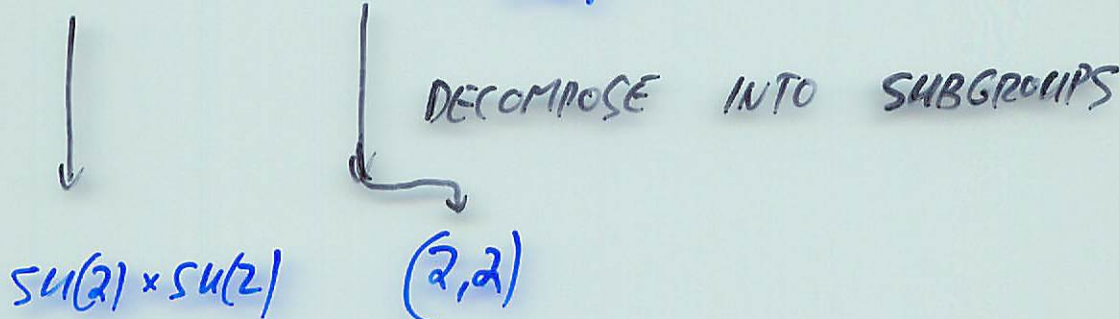
# GLOBAL SYMMETRIES OF HIGGS SECTOR

HIGGS DOUBLET:  $\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$

FOUR REAL  
DEGREES OF FREEDOM

SECRETLY TRANSFORMS AS A

$SO(4)$   $4 = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$



IDENTIFIED AS  $SU(2)_L$  OF ELECTROWEAK

REMAINING GLOBAL SYMMETRY

GAUGING  $U(1)_Y$  EXPLICITLY BREAKS

$SU(2)_{GLOBAL} \rightarrow$  nothing

ORDER PARAMETER FOR  $SU(2)_{GLOBAL}$  IS HYPERCHARGE  $g'$

$\frac{M_W^2}{M_Z^2} = \frac{g^2}{g^2 + (g')^2} \rightarrow 1$  AS  $g' \rightarrow 0$   
( $W^+, Z, W^-$  TRIPLET)

AGAIN, NEW PHYSICS MAY EXCESSIVELY BREAK  $SU(2)_{GLOBAL}$   
"CUSTODIAL SYMMETRY"



# SM FERMIONS ARE CHIRAL

FERMIONS CANNOT "PAIR UP" WITH ONE ANOTHER,

I.E. MASS TERMS ARE FORBIDDEN  $m \bar{f}_L f_R$ ,

SINCE NO TWO FERMIONS CARRY OPPOSITE QUANTUM NUMBERS!

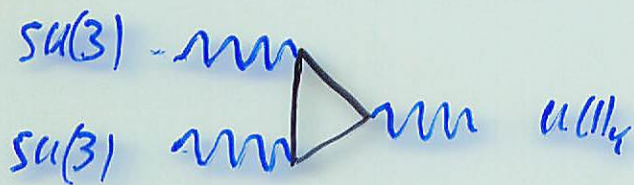
TRY IT!

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$(Q u^c)$	1	2	$-\frac{1}{2}$
$(Q d^c)$	1	2	$+\frac{1}{2}$
$(Q L)$	3	1	$-\frac{1}{3}$
$(Q e)$	3	2	$\frac{1}{6}$
$(u^c d^c)$	$\bar{3} \times \bar{3}$	1	$-\frac{1}{3}$
$(u^c L)$	$\bar{3}$	2	$-\frac{2}{3}$
$(u^c e)$	$\bar{3}$	1	$-\frac{5}{3}$
$(d^c L)$	$\bar{3}$	2	$+\frac{1}{3}$
$(d^c e)$	$\bar{3}$	1	$\frac{2}{3}$
$(L e)$	1	2	$\frac{1}{2}$

FOR FERMION MASSES TO RESPECT SM GAUGE INVARIANCE,  
THEY MUST COME FROM DIMENSION 4 (HIGGS) OR  
LARGER OPERATORS IN THE THEORY.

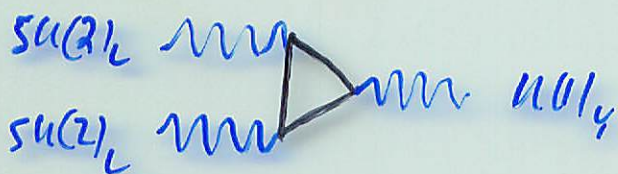
5. CHIRAL GAUGE THEORIES HAVE HIGHLY NONTRIVIAL  
GAUGE QUANTUM NUMBERS FOR ANOMALY  
CANCELLATION

LET'S CHECK THE SM:



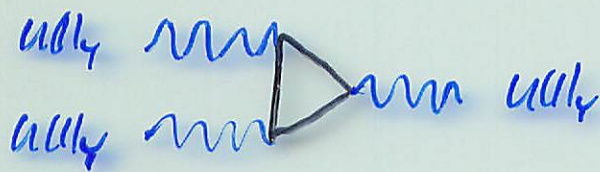
$$3 \left[ 2 \cdot \left(\frac{1}{6}\right) + \left(-\frac{2}{3}\right) + \left(+\frac{1}{3}\right) \right] = 0$$

$Q$ 
 $u^c$ 
 $d^c$



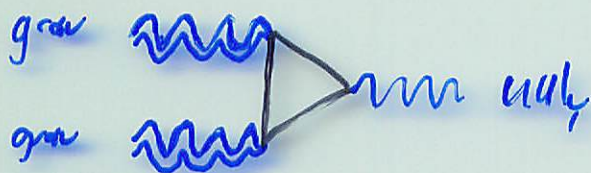
$$3 \left[ 3 \cdot \left(\frac{1}{6}\right) + \left(-\frac{1}{2}\right) \right] = 0$$

$Q$ 
 $L$



$$3 \left[ 6 \cdot \left(\frac{1}{6}\right)^3 + 3 \left(-\frac{2}{3}\right)^3 + 3 \left(\frac{1}{3}\right)^3 + 2 \left(-\frac{1}{2}\right)^3 + 1^3 \right] = 0$$

$Q$ 
 $u^c$ 
 $d^c$ 
 $L$ 
 $e$



$$3 \left[ \frac{1}{6} + \left(-\frac{2}{3}\right) + \left(\frac{1}{3}\right) + \left(-\frac{1}{2}\right) + 1 \right] = 0$$

$Q$ 
 $u^c$ 
 $d^c$ 
 $L$ 
 $e$

CANNOT ADD "JUST" ANOTHER QUARK OR LEPTON

UNLESS IT IS ACCOMPANIED BY EITHER

→ CHIRAL PARTNERS E.G. FOURTH GENERATION

→ VECTOR-LIKE PARTNER E.G.  $t, t^c$  TOP PARTNERS  
IN LITTLE HIGGS MODELS

# SM REVIEW

- Gauge Symmetry

$$SU(3)_c \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{BROKEN}}$$

↑  
EXACT →  $U(1)_{EM}$

- Flavor Symmetry

$$U(3)^5$$

↓ EXPLICITLY BROKEN BY  
YUKAWA COUPLINGS (SMALL  
PARAMETERS)

$$U(1)_B \times U(1)_L (?)$$

- Custodial Symmetry

$SU(2)_{\text{custodial}}$  OF HIGGS SECTOR

BROKEN BY HYPERCHARGE

SUCH THAT  $\rho = \frac{M_W^2}{g_W^2 M_Z^2} = 1$

- CHIRAL FERMIONS

NEED HIGGS OR HIGHER-D OPERATORS

- Gauge ANOMALIES

RESTRICT QUANTUM NUMBERS  
OF NEW FERMIONS

STANDARD MODEL IS AN EFFECTIVE FIELD THEORY

AN EFFECTIVE FIELD THEORY HAS A FINITE RANGE OF APPLICABILITY IN ENERGY:



ALL INTERACTIONS CONSISTENT w/ GAUGED SYMMETRIES ARE PERMITTED, INCLUDING HIGHER DIMENSIONAL OPERATORS WHOSE MASS DIMENSION IS COMPENSATED FOR BY POWERS OF  $\Lambda$ .

WHAT SETS THE CUTOFF SCALE  $\Lambda$ ?

WHAT IS THE THEORY ABOVE THE CUTOFF?

NEW PHYSICS

"BEYOND THE SM"

THREE PARADIGMS:

1) SM PARAMETER(S) UNNATURAL

=> NEW PHYSICS INTRODUCED TO "NATURALIZE"

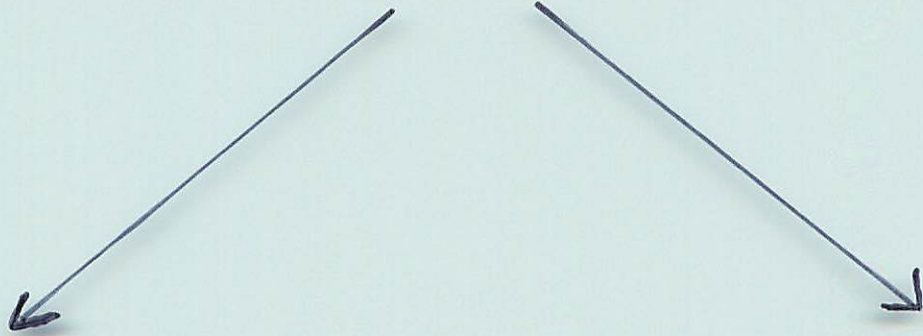
2) SM GAUGE / MATTER CONTENT COMPLICATED

=> NEW PHYSICS INTRODUCED TO SIMPLIFY

3) DEVIATION FROM SM OBSERVED IN EXPERIMENT

=> NEW PHYSICS INTRODUCED TO EXPLAIN

# HOW (UN)NATURAL ARE THE SM PARAMETERS?



## "TECHNICALLY NATURAL"

- FERMION MASSES  
(YUKAWA COUPLINGS)
- GAUGE COUPLINGS
- CKM

LOGARITHMICALLY SENSITIVE  
TO CUTOFF SCALE

## "TECHNICALLY UNNATURAL"

- HIGGS (MASS)<sup>2</sup>
- COSMOLOGICAL CONSTANT
- QCD VACUUM ANGLE

POWER-LAW SENSITIVITY  
TO CUTOFF SCALE

(FOR HIGGS & C.C.)

THE NATURALNESS PROBLEM WITH WHAT  
HAS PROBABLY THE GREATEST IMPACT ON  
COLLIDER PHYSICS IS THE

HIGGS (MASS)<sup>2</sup> PROBLEM

OR  
"HIERARCHY PROBLEM"

# ELECTROWEAK HIERARCHY PROBLEM

HIGGS (MASS)<sup>2</sup> IS QUADRATICALLY DIVERGENT.

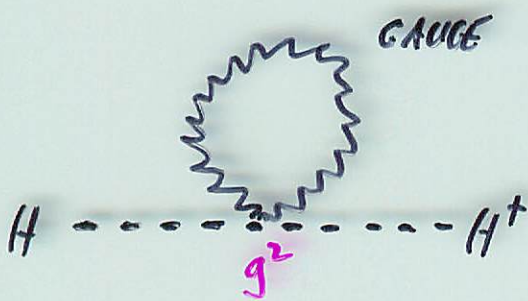
SYMMETRY ARGUMENTS ALREADY TOLD US THAT

$$m_H^2 \propto |H|^2$$

$$m_H \rightarrow 0$$

NOT SYMMETRY ENHANCED POINT.

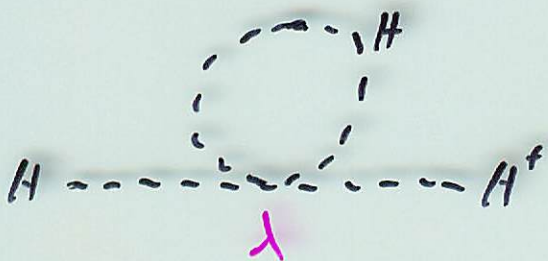
DIAGRAMMATICALLY:



$$\frac{g^2}{16\pi^2} \int_0^\Lambda d^4 q \frac{g^2}{q^2 - M_G^2 + i\epsilon} \sim \frac{g^2}{16\pi^2} \Lambda^2$$



$$\frac{y_f^2}{16\pi^2} \int_0^\Lambda d^4 q \frac{1}{(q - M_f)^2} \sim \frac{y_f^2}{16\pi^2} \Lambda^2$$



$$\frac{\lambda}{16\pi^2} \int_0^\Lambda d^4 q \frac{1}{q^2 - m_H^2 + i\epsilon} \sim \frac{\lambda}{16\pi^2} \Lambda^2$$

LET'S NOW CONCENTRATE ON SPECIFIC IDEAS TO ADDRESS THIS PROBLEM.



BUT WAIT ...

DO WE REALLY NEED A HIGGS SECTOR?

# FIRST THINGS FIRST.

DO WE REALLY NEED A HIGGS SECTOR?

SUPPOSE WE SIMPLY PUT FERMION & GAUGE BOSON MASSES BY HAND INTO THE ACTION, EXPLICITLY BREAKING THE GAUGE SYMMETRY.

THEN CALCULATE SCATTERING PROCESS

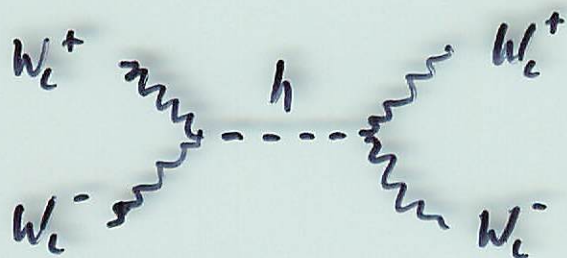


$$A = a \frac{s}{M_W^2} + \dots$$

$E_C^2$  of M.

DIVERGENT!

HIGGS GIVES AN IMPORTANT CONTRIBUTION:



$$A = -a \frac{s - m_h^2}{M_W^2} + \dots$$

LEADING TO

$$A = a \cdot \frac{m_h^2}{M_W^2}$$

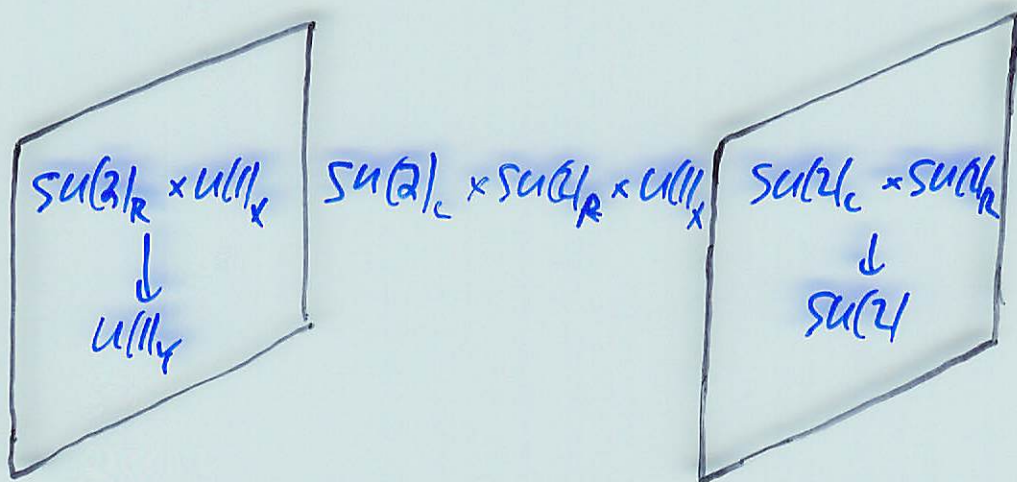
(SIMILAR ARGUMENTS ALSO APPLY FOR <sup>"HARD"</sup> FERMION MASSES)

## THIS IS AN IMPORTANT LESSON:

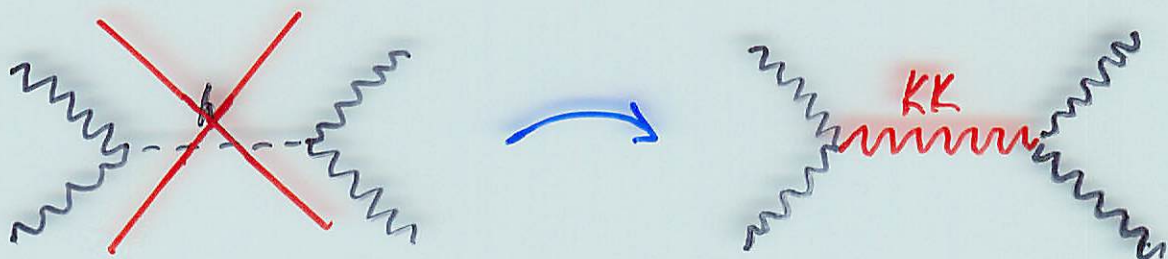
- EXPLICIT SYMMETRY BREAKING, IN EW CASE, LEADS TO DIVERGENT AMPLITUDES, HENCE THEORY MUST BE CUTOFF AT  $\Lambda \sim 4\pi M_w$
- HIGGS SOFTENS THIS DIVERGENCE, BUT THE AMPLITUDE SCALES AS  $\frac{m_h^2}{M_w^2}$  AND THUS  $m_h \lesssim 4\pi M_w$  SO THAT EFFECTIVE THEORY WITH AN ELEMENTARY (NOT STRONGLY-COUPLED) HIGGS MAKES SENSE.

# (ASIDE: "HIGGSLESS" THEORIES?)

THERE ARE INTRIGUING PROPOSALS TO BREAK THE ELECTROWEAK SYMMETRY THROUGH BOUNDARY CONDITIONS OF A WARPED EXTRA DIMENSION.



THE ROLE OF THE HIGGS IS REPLACED WITH THE EXCHANGE OF ADDITIONAL KALUZA-KLEIN GAUGE BOSONS



THESE MODELS FACE MANY CHALLENGES, GETTING FERMION MASSES (particularly, top) WHILE AVOIDING EXCESSIVE CONTRIBUTIONS TO PRECISION EW (VERY RECENT PAPER SHOW PROMISE!)

FOR THE REMAINDER OF THE LECTURES  
I WILL GIVE BRIEF INTRODUCTIONS TO  
FOUR PROPOSALS: (ALL QUALITATIVELY DIFFERENT)

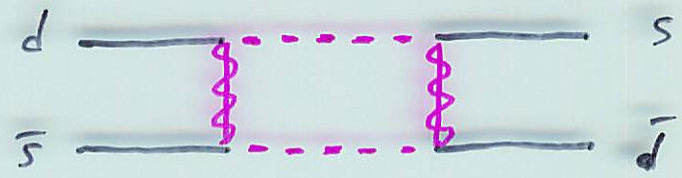
TECHNICOLOR

LARGE EXTRA DIMENSIONS

WARPED EXTRA DIMENSIONS

LITTLE HIGGS

# WHY NOT SUSY?

- 1) HAS NOT BEEN FOUND! (SAME GOES FOR OTHER PROPOSALS)
- 2) MUST BE CAREFULLY BROKEN WITH A "HIDDEN SECTOR", CAREFULLY SEQUESTERED FROM MSSM
- 3) SUSY IN MSSM GENERICALLY LEAD TO EXCESSIVE FLAVOR VIOLATION  

- 4) SUSY GENERICALLY MAKES STRONG CP PROBLEM WORSE THAN SM (GAUGINO MASS PHASES)
- 5) NEW PHASES GENERICALLY LEAD TO EXCESSIVE CONTRIBUTIONS TO EDMs (e, n, Hg, ...)
- 6) BOUND ON HIGGS MASS FROM LEP  $m_h > 115$  GeV IN TENSION WITH EW SIZE OF SUSY
- 7) GENERIC B, L VIOLATION (FORBIDDEN BY R-PARITY) AT DIM-4; DIM-5 A DISASTER
- 8) GRAVITINO GENERICALLY A COSMOLOGICAL NUISANCE

# TECHNI COLOR

"REPORTS OF MY DEATH WERE GREATLY  
EXAGGERATED"  
M. TWAIN

# TECHNICOLOR

## BASIC POSTULATES:

- ELECTROWEAK BREAKING IS DYNAMICAL IN ORIGIN, ANALOGOUS TO CHIRAL SYMMETRY BREAKING IN QCD
- NO HIGGS SECTOR, THUS NO (FUNDAMENTAL) SCALARS IN THEORY
- WE'VE SEEN ALL THIS BEFORE!  
(LOW ENERGY QCD)

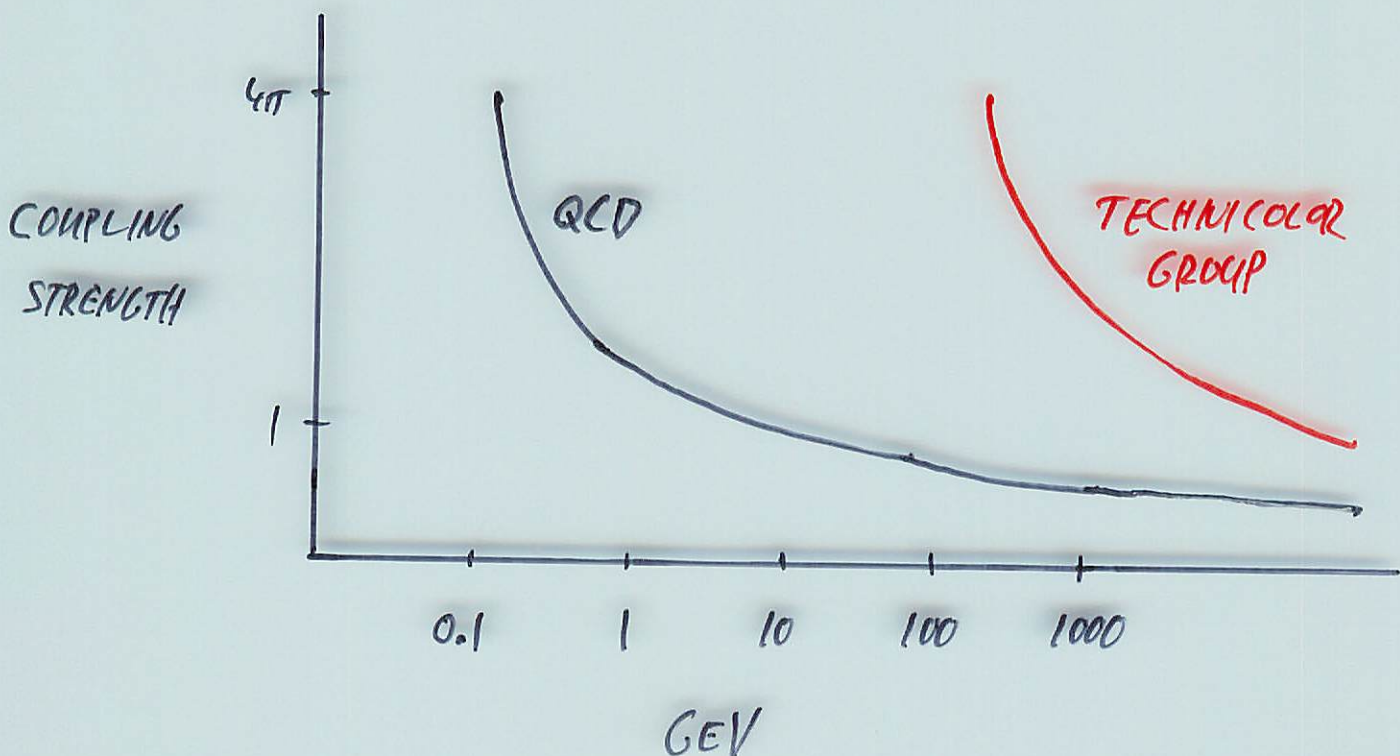


## MINIMAL TECHNICOLOR

THE CONTENT OF THE MODEL NEEDED TO BREAK EW SYMMETRY IS VERY SIMPLE:

	$SU(2)_{TC}$	$SU(2)_C$	$U(1)_Y$
$T_L$	2	2	0
$T_R = \begin{pmatrix} ++ \\ +- \end{pmatrix}$	2	1	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$

$SU(2)_{TC}$  IS POSTULATED TO GET STRONG @ EW SCALE:



# FERMION CONDENSATION

MECHANISM FOR TC TO BREAK EW SYMMETRY SAME AS HOW QCD BREAKS CHIRAL SYMMETRY:

IN QCD, QUARKS BIND VIA  $SU(3)_c$ , LEADING TO A CONDENSATE:



THE CONDENSATE SPONTANEOUSLY BREAKS CHIRAL SYMMETRY  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{diag}$  LEAVING 3 GOLDSTONE BOSONS ( $\pi^+, \pi^0, \pi^-$ )

IN TECHNICOLOR, TECHNIQUARKS BIND VIA  $SU(4)_{TC}$  LEADING TO



BREAKING EW SYMMETRY ("CHIRAL SYM" FOR TECHNIQUARKS)

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$$

LEAVING 3 WOULD-BE GOLDSTONE BOSONS (TECHNIPIONS)

THAT ARE EATEN BY  $(W^+, Z, W^-)$

TECHNIPIONS, LIKE THEIR QCD COUSINS,  
ARE COMPOSITE, MADE OUT OF TECHNICALLY  
NATURAL FERMIONS.

NO HIERARCHY PROBLEM IN TECHNICOLOR BECAUSE  
THERE IS NO HIGGS!

## TECHNICOLOR (9) COLLIDERS

- TECHNIHADRON : BOUND STATES OF TECHNI-FERMIONS

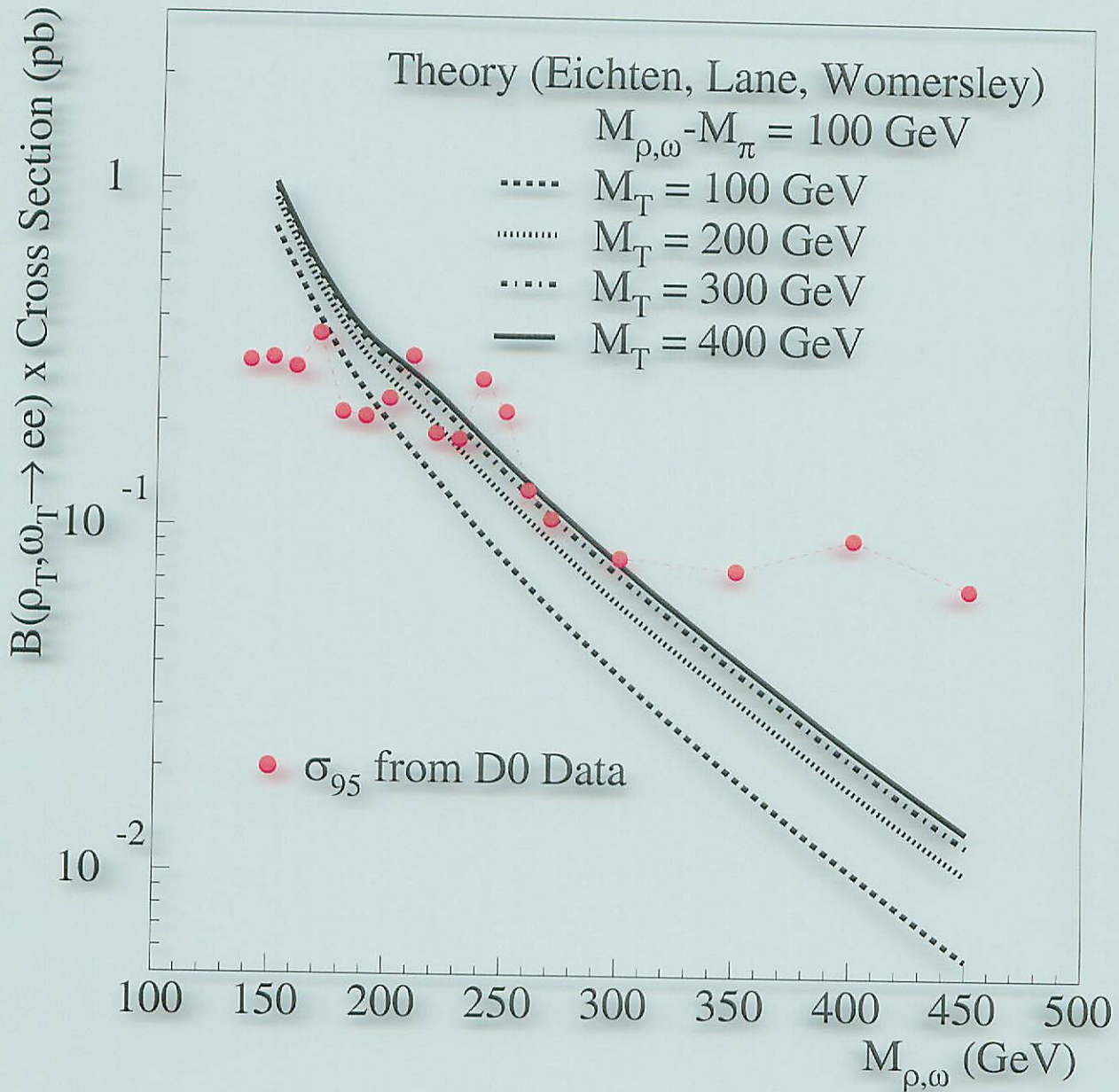
LOTS OF PARTICLES :  $\pi_T, \rho_T, \rho_{T8} \dots$

DECAY CHAINS ARE MODEL DEPENDENT

- PSEUDO-GOLDSTONE BOSONS: SCALARS THAT APPEAR AFTER SPONTANEOUS BREAKING OF A LARGER GLOBAL SYMMETRY FOR  $SU(N_{TC})$   $N_{TC} > 2$

(  $SU(N_{TC}/L) \times SU(N_{TC}/R) \rightarrow$  OBTAIN  $N_{TC}^2 - 1 - 3$  PHYSICAL PARTICLES )

# TECHNICOLOR LIMITS FROM TEVATRON



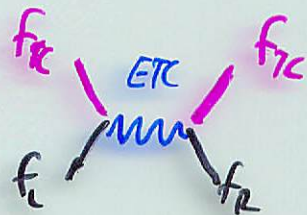
## PROBLEMS WITH TECHNICOLOR

FERMION MASSES ARISE THROUGH DIMENSION-6 OPERATOR

$$\frac{f_{TC} f_{TC} f_L f_R}{\Lambda^2} \rightarrow \frac{\langle f_{TC} f_{TC} \rangle}{\Lambda^2} f_L f_R$$

WHICH IMPLIES  $m_f = \frac{\Lambda_{TC}^3}{\Lambda^2}$ .

THREE PROBLEMS WITH THIS:



1) WHAT HAPPENS AT  $\Lambda$ ?

$\Rightarrow$  ~~DO NOT~~ "UV COMPLETE" INTO NEW EXTENDED TECHNICOLOR GAUGE INTERACTION THAT CONFINES AT  $\Lambda$

2) WHAT ABOUT TOP QUARK?

$\Rightarrow$  HARD TO LOWER  $\Lambda$  TO EXPLAIN SIZE OF TOP MASS WHILE NOT AFFECTING OTHER THINGS

3) GENERICALLY GET WAY-TOO-LARGE FCNC.

$$\frac{f f f f}{\Lambda^2}$$

AUTOMATICALLY GENERATED BY ETC INTERACTIONS.

## THERE ARE PROPOSED SOLUTIONS

- EXTENDED TECHNICOLOR
- WALKING TECHNICOLOR
- TOP COLOR
- TOP COLOR ASSISTED TECHNICOLOR

# ELECTROWEAK PRECISION DATA VS. TC?

FOR A SMALL NUMBER OF **TECHNICOLORS** AND  
A SMALL NUMBER OF **TECHNIFERMIONS**, RESULT  
IS NOT SO BAD.

BECAUSE TC IS STRONGLY COUPLED @ 1 TEV,  
GENERICALLY WOULD HAVE EXPECTED DEVIATIONS IN  
VARIOUS PRECISION DATA, BUT NO RELIABLE WAY  
TO CALCULATE!

ESTIMATE:

$$S \text{ PARAMETER} \approx \frac{N_{TC} N_F}{12\pi} \approx \frac{1}{10}$$

T PARAMETER  $\rightarrow$  UNCALCULABLE

WELL WITHIN EXPT.  
UNCERTAINTIES.

SU(2) w/  $N_F = 2$

$\downarrow$

$\frac{1}{10}$





LARGE EXTRA DIMENSIONS

# LARGE EXTRA DIMENSIONS

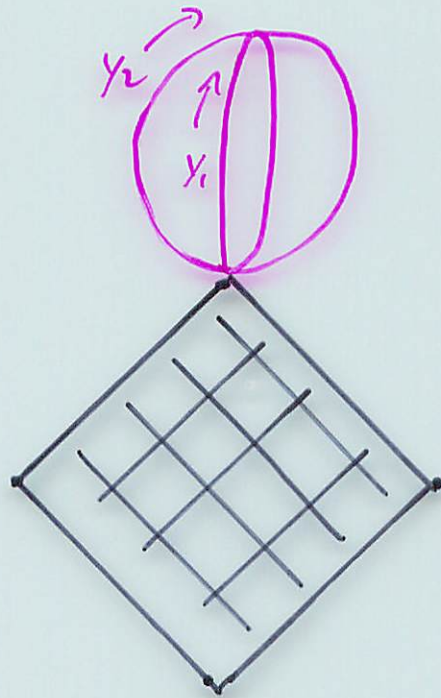
## BASIC POSTULATES:

- THERE ARE EXTRA "LARGE" COMPACTIFIED SPATIAL DIMENSIONS FELT ONLY BY GRAVITY
- EFFECT OF EXTRA DIMENSIONS IS TO DRAMATICALLY REDUCE THE QUANTUM GRAVITY SCALE
- LOWERED QUANTUM GRAVITY SCALE IS THE CUTOFF SCALE OF SM

$$M_* = \Lambda = \text{TeV}$$

THERE IS NO HIERARCHY ( $m_h \ll \Lambda$ )  
AND SO NO HIERARCHY PROBLEM

# BASIC PICTURE



EXTRA SPATIAL  
(COMPACTIFIED) DIMENSIONS

OUR 4-D  
SPACE TIME

(w/ MATTER, GAUGE, HIGGS  
FIELDS)

$$S_{\text{GRAVITY}} = \underbrace{\int d^4x}_{4\text{-D}} \underbrace{\int d^n y}_{\text{EXTRA D}} M_*^{n+2} R^{(5)}$$

SUPPOSE ALL EXTRA DIMENSIONS SAME SIZE  $r$

SO THAT  $y_i \rightarrow y_i + 2\pi r$  (PERIODIC).

AT LOW ENERGIES (DISTANCES LONGER THAN  $r$ ),

CAN "INTEGRATE OUT" EXTRA DIMENSIONS

$$\int^{4\text{-D}} = \int d^4x M_*^{n+2} (2\pi r)^n R^4$$

AND IDENTIFY

$$M_{\text{Pl}}^2 = M_*^{n+2} (2\pi r)^n$$

QUALITATIVELY, THE RELATION

$$M_{pl}^2 = M_*^{n+2} (2\pi r)^n$$

SAYS

$$\left( \begin{array}{c} \text{WEAK 4-D} \\ \text{GRAVITY} \end{array} \right) = \left( \begin{array}{c} \text{STRONG (4+n)-D} \\ \text{GRAVITY} \end{array} \right) \times \left( \begin{array}{c} \text{EXTRA D} \\ \text{VOLUME DILUTION} \end{array} \right)$$

SETTING  $M_* = 1 \text{ TEV}$ , SIZE OF EXTRA DIMENSIONS:

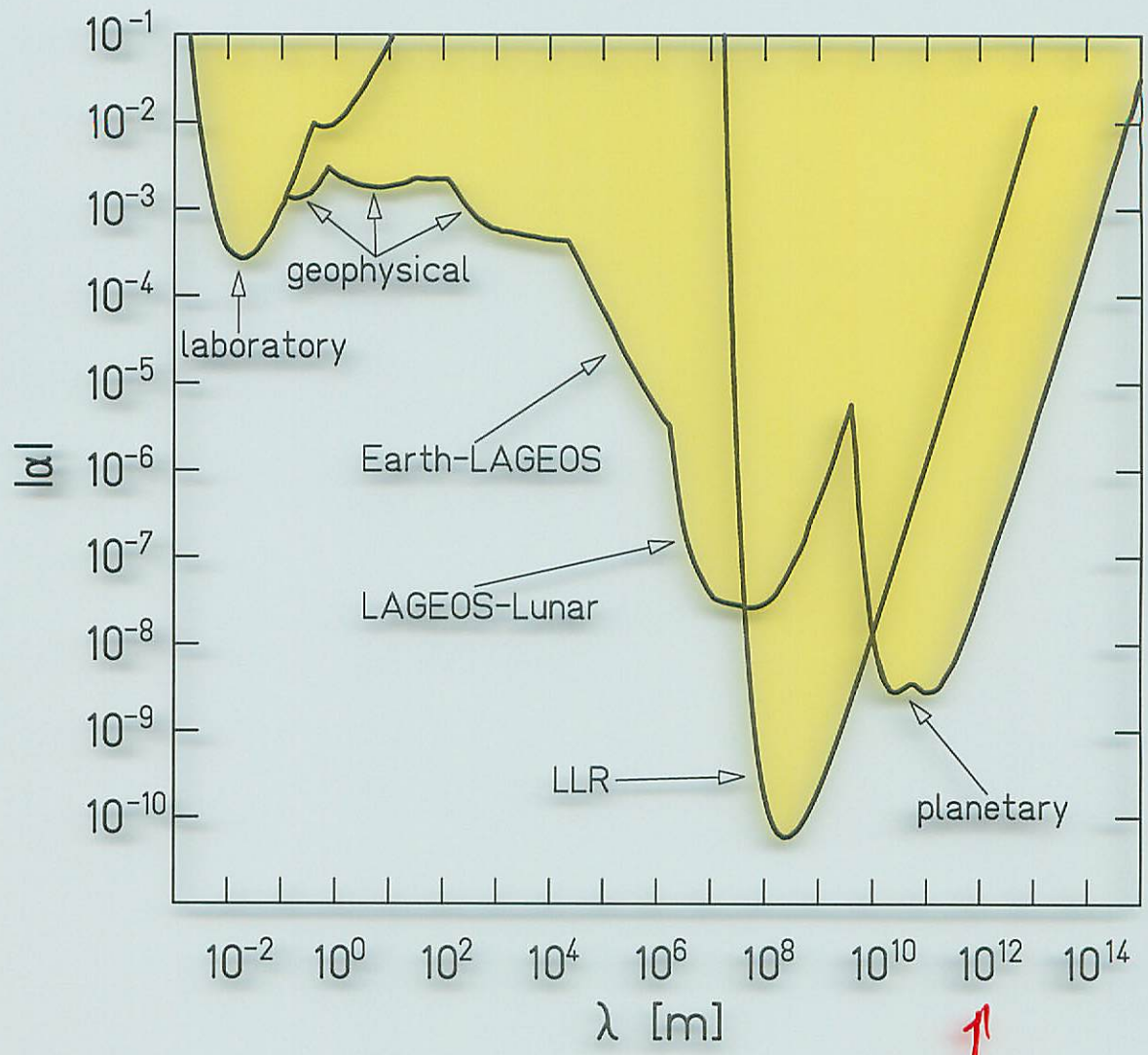
# OF EXTRA DIMENSIONS	$n$	RADIUS OF EXTRA-D	$r$
1		$10^{12}$	m
2		$10^{-3}$	m
3		$10^{-8}$	m
⋮		⋮	
6		$10^{-11}$	m

THE DISTANCE SCALE  $r$  CORRESPONDS TO THE

TRANSITION FROM 4-D TO (4+n)-D GRAVITY

$$\text{NEWTONIAN POTENTIAL } V(r') = \begin{cases} -G_N \frac{m_1 m_2}{r'} & r' > r \\ -G_N \frac{m_1 m_2}{(r')^{4+n}} & r' < r \end{cases}$$

$n=1$ , ONE EXTRA DIMENSION OF SIZE  $10^{12}$  m,  
IS NOT SURPRISINGLY RULED OUT

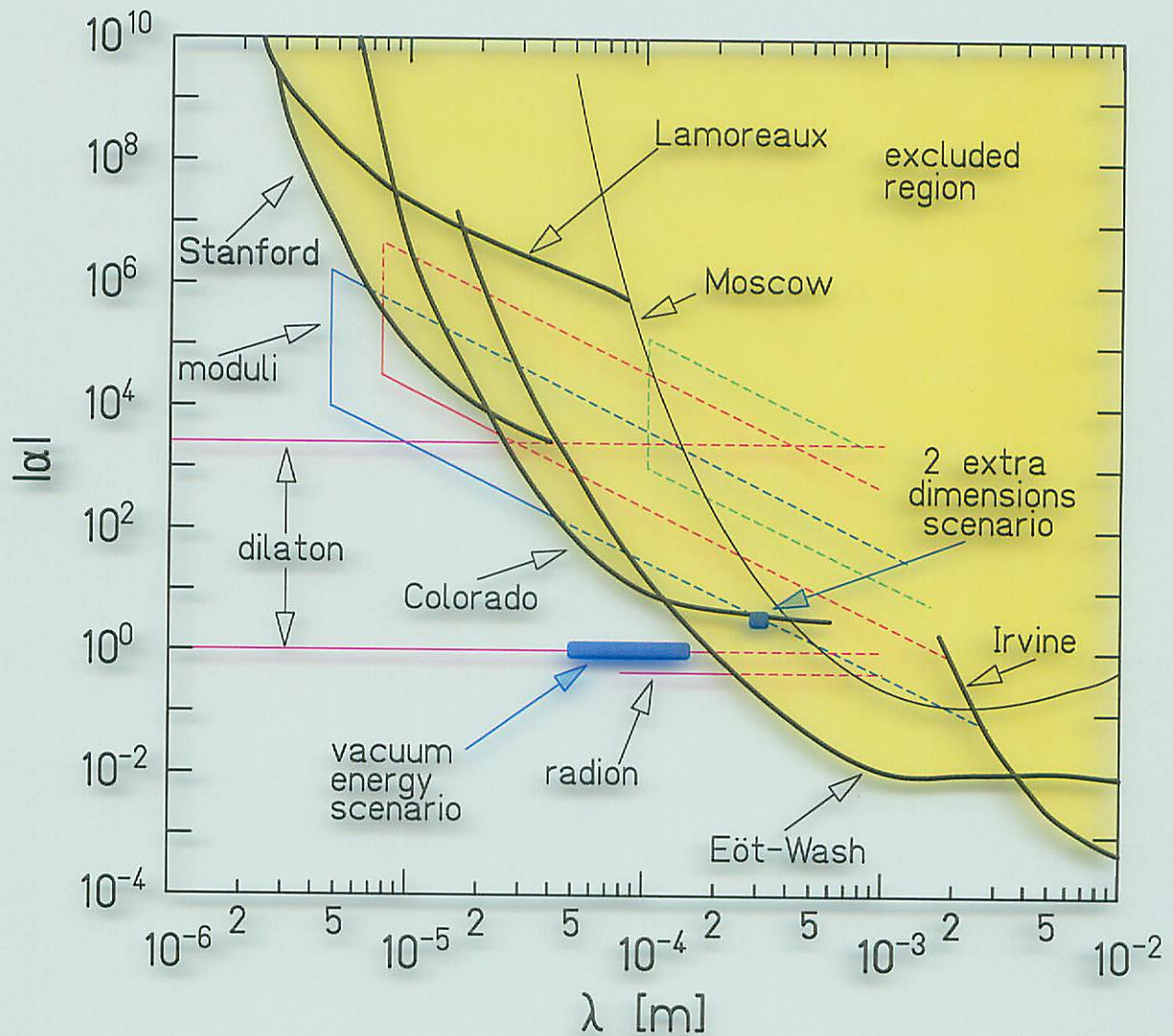


$\alpha, \lambda$  PARAMETRIZE A DEVIATION FROM

NEWTONIAN GRAVITY:

$$V_{\text{MODIFIED}}(r') = V_{\text{NEWTONIAN}}(r') \cdot (1 + \alpha e^{-r'/\lambda})$$

AT SHORTER DISTANCES, THE CONSTRAINTS ON GRAVITY RAPIDLY BECOME RATHER WEAK:



NEVERTHELESS, THE EÖT-WASH EXPERIMENT HAS RULED OUT  $n=2$  FOR  $M_* = 1$  TEV

# KALUZA-KLEIN GRAVITONS

AT HIGH ENERGY COLLIDERS, THE SIGNAL TO LOOK FOR IS THE METRIC FLUCTUATIONS OF THE EXTRA DIMENSIONS. **FOURIER EXPANDING**

$$h_{AB}(x; y) = \sum_{m_1=-\infty}^{\infty} \cdots \sum_{m_n=-\infty}^{\infty} h_{AB}^{(m)}(x) e^{i \frac{m_j y_j}{r}}$$

$(4+n)$ -D GRAVITON

INFINITE TOWER OF 4-D "KALUZA-KLEIN" PARTICLES

[	GRAVITONS	$h_{\mu\nu}^{(m)}$
	GRAVI-PHOTONS	$h_{\mu 5}^{(m)}, h_{\mu 6}^{(m)}, \dots$
	SCALARS	$h_{56}^{(m)}, \dots$

KK GRAVITONS ARE THE MAIN PLAYERS (COUPLING TO US)

MASS SPLITTING BETWEEN KK MODES:

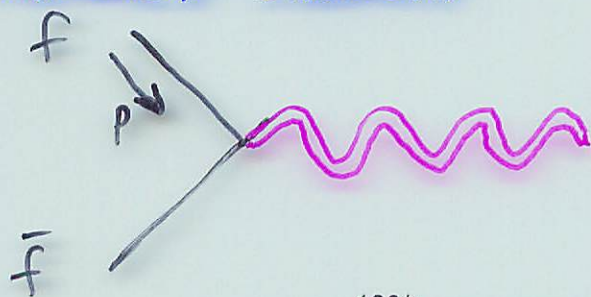
$$\Delta m \sim \frac{1}{r} \sim \begin{cases} 0.003 \text{ eV} & n=2 \\ 0.1 \text{ MeV} & n=4 \\ 0.05 \text{ GeV} & n=6 \end{cases}$$

TINY SPLITTING!

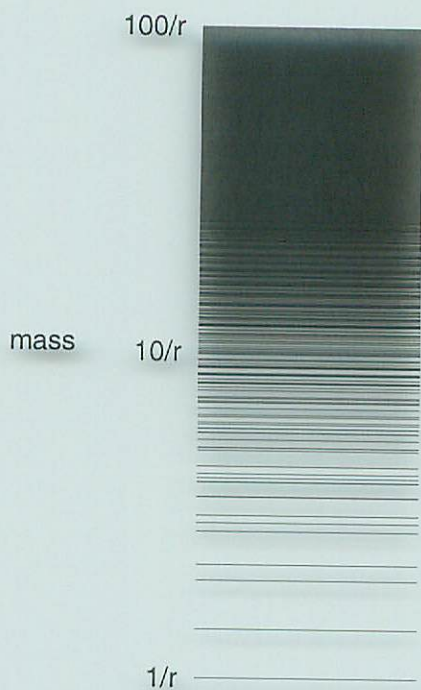
# STRENGTH & NUMBERS

EACH KK GRAVITON IS EXTREMELY WEAKLY COUPLED

(GRAVITATIONAL STRENGTH



$$\sim \frac{p}{M_{pl}}$$



THE DENSITY OF STATES, HOWEVER, GROWS AS A POWER LAW, COMPENSATING FOR THE  $\frac{1}{M_{pl}}$  SUPPRESSION

$$\sigma_i(pp \rightarrow G_i + \gamma) \propto \frac{1}{M_{pl}^2}$$

WHILE SUMMING OVER STATES GIVES:

$$\sum_i \sigma_i(pp \rightarrow G_i + \gamma) \propto \frac{M_{pl}^2}{M_*^2} \cdot \frac{1}{M_{pl}^2} \propto \frac{1}{M_*^2}$$



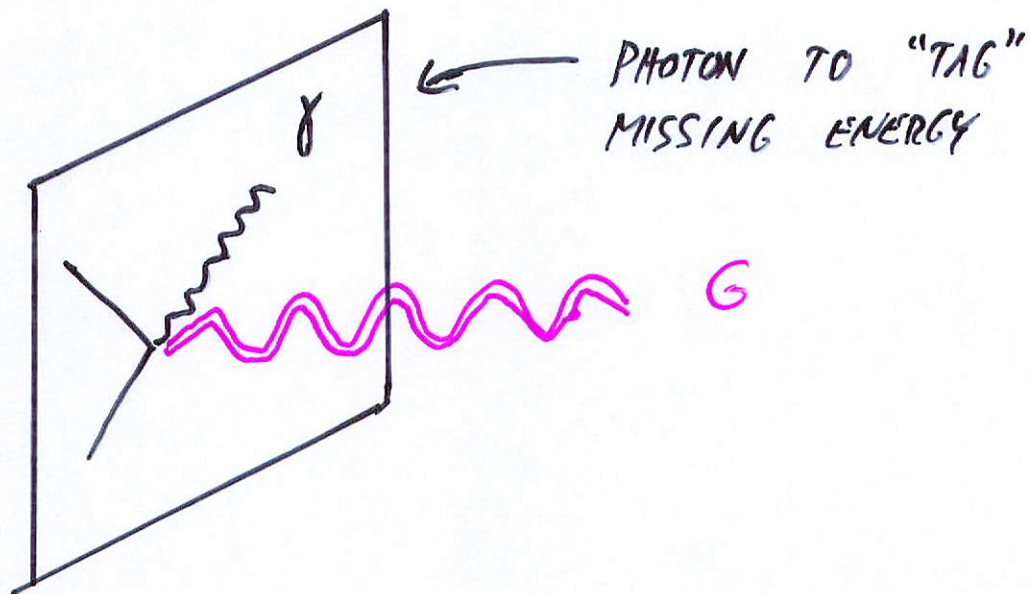
THE NATURALNESS PROBLEM WITH WHAT  
HAS PROBABLY THE GREATEST IMPACT ON  
COLLIDER PHYSICS IS THE

HIGGS (MASS)<sup>2</sup> PROBLEM  
OR  
"HIERARCHY PROBLEM"

## KK GRAVITON SIGNAL @ COLLIDERS

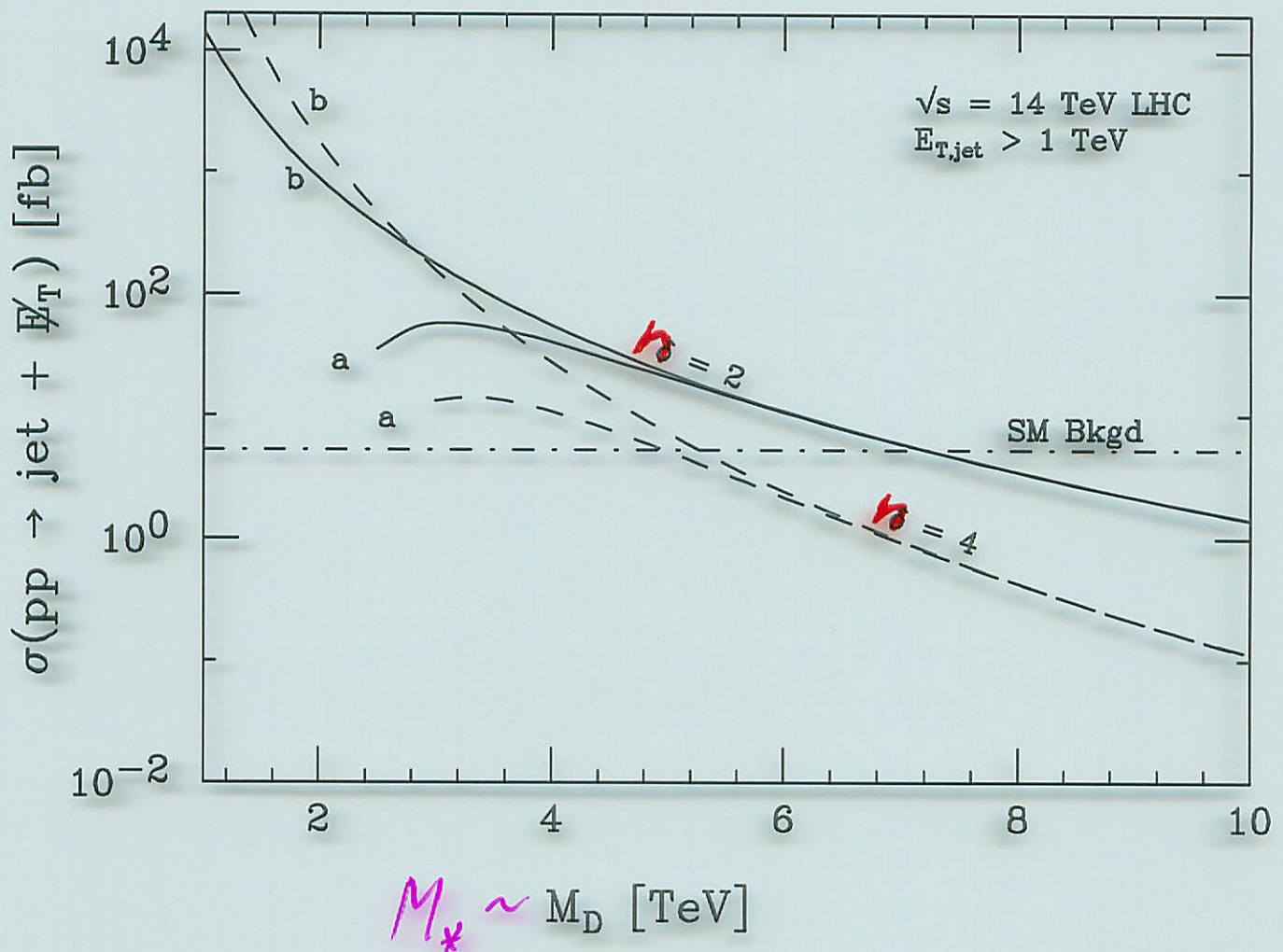
WHILE THE CROSS SECTION TO PRODUCE SOME GRAVITON IS LARGE, ANY INDIVIDUAL GRAVITON HAS  $\frac{1}{M_{pl}}$  SUPPRESSED COUPLINGS WITH MATTER, AND THUS ESCAPES THE DETECTOR.

THE  $(4+n)$ -D INTERPRETATION OF THIS IS THAT A HIGHER DIMENSIONAL GRAVITON "ESCAPES INTO THE BULK"



# MISSING ENERGY SIGNAL @ LHC

HERE A SINGLE JET WAS USED TO "TAG" THE MISSING ENERGY



LHC CAN EXPLORE UP TO  $M_* \sim 5 \rightarrow 6$  TeV

## BLACK HOLES @ LHC

THERE IS ANOTHER SIGNAL FOR LARGE EXTRA DIMENSIONS THAT IS TRULY SPECTACULAR:

BLACK HOLE FORMATION (AND HAWKING EVAPORATION)



SUFFICIENTLY ENERGETIC PARTONS THAT GET WITHIN

$d \sim \frac{1}{M_*}$  WILL FORM A TINY BH THAT RAPIDLY EVAPORATES.

FOR  $m_{BH}$  MUCH LARGER THAN  $M_*$  (NOT MORE THAN

ABOUT 5 @ LHC), EVAPORATION IS QUASI-THERMAL,

EMITTING LARGE NUMBERS OF PARTICLES (THE ENTRY OF THE BH).

# WHAT'S THE PROBLEM WITH A LOW CUTOFF?

EXPERIMENTS HAVE ALREADY INDIRECTLY PROBED HIGHER MASS SCALES THROUGH HIGHER DIMENSIONAL OPERATORS:

## ELECTROWEAK:

E.G.  $\frac{(H^\dagger D_\mu H)^2}{\Lambda^2}$   $\rho$  PARAMETER  $\Lambda \gtrsim 10$  TGV

## FLAVOR VIOLATION

E.G.  $\frac{d\bar{s}d\bar{s}}{\Lambda^2}$   $K^0 \leftrightarrow \bar{K}^0$  MIXING  $\Lambda \gtrsim 1000$  TeV

## SCALE VIOLATION

$\frac{(LH)^2}{\Lambda}$  MAJORANA NEUTRINO MASS ( $m_\nu \lesssim 1$  eV)  $\Lambda \gtrsim 10^{13}$  GeV

## BARYON & LEPTON NUMBER VIOLATION

E.G.  $\frac{QQQL}{\Lambda^2}$  PROTON DECAY  $\Lambda \gtrsim 10^{16}$  GeV

# EXTRA DIMENSIONS VERSUS HIGHER-D OPERATORS

PHENOMENOLOGICAL : ASSUME COEFFICIENTS OF HIGHER-D OPERATORS VIOLATING SM GLOBAL SYMMETRIES ARE SUFFICIENTLY SMALL.

SPECIFIC MODELS: (FEW EXAMPLES)

- 
- IMPOSE DISCRETE SYMMETRY, ANALOGOUS TO R-PARITY IN SUSY ( SOLVE  $\beta, \mu$  BUT NOT OBVIOUSLY FLAVOR)

- 
- SPLIT FERMIONS : SPATIALLY SEPARATE  
QUARKS FROM LEPTONS  
QUARKS FROM QUARKS

SUPPRESSES DANGEROUS

HIGHER-D OPS



NOVEL SIGNALS!

CROSS SECTIONS BECOME EXPONENTIALLY SUPPRESSED AT HIGH ENERGIES

- 
- UNIVERSAL EXTRA DIMENSIONS

MATTER, GAUGE, HIGGS IN  $\text{TeV}^{-1}$  SIZED DIMENSION

CAN SUPPRESS OPS (6D MODELS); NOVEL PHENOMENOLOGY, CONFUSINGLY SIMILAR TO SUSY!