

BEYOND HIGGS & SUSY

(PART 2)

GRAHAM KRIBS

OREGON

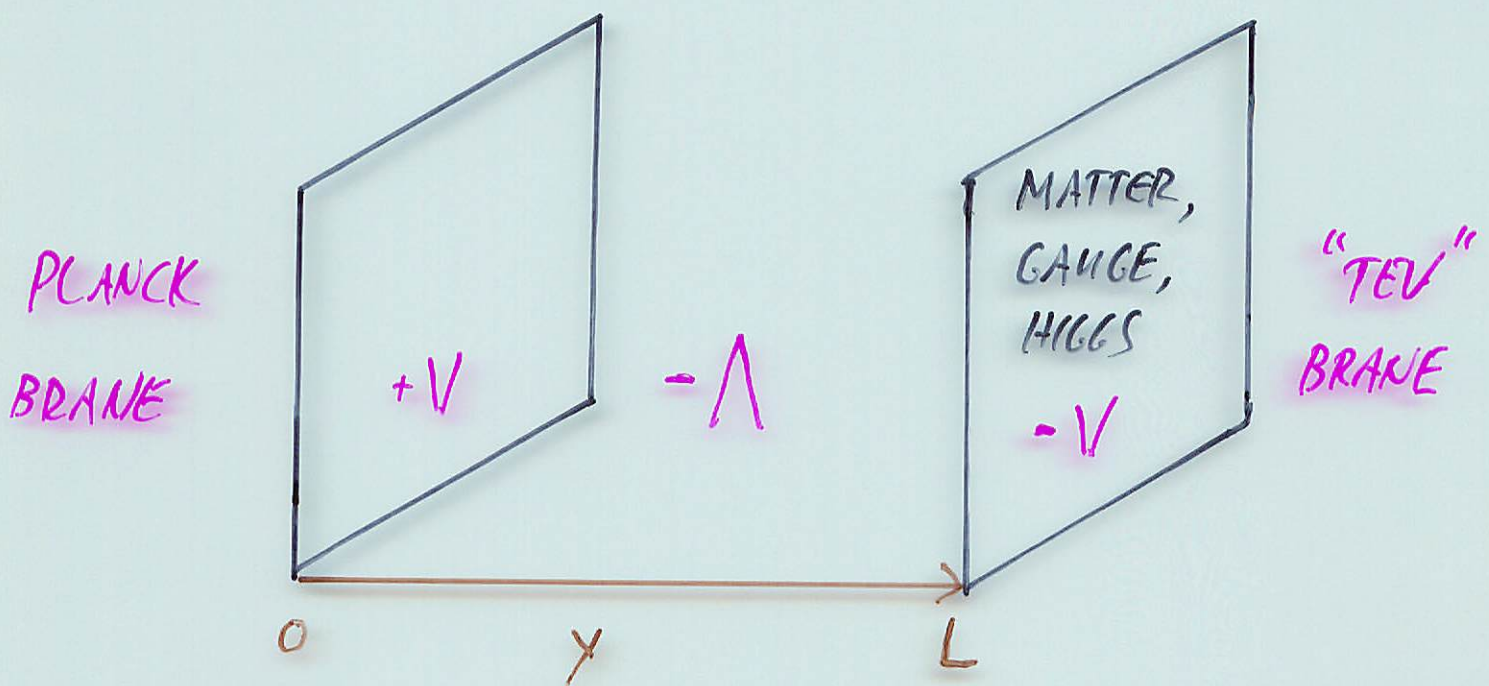
SCAC SUMMER INSTITUTE

JULY 2006

WARPED EXTRA DIMENSIONS

WARPED EXTRA DIMENSION

BASIC PICTURE OF ORIGINAL "RANMCC - SANDRWT" MODEL:



- ONE EXTRA DIMENSION w/ SM ON A BRANE
- BULK CONTAINS JUST GRAVITY, BUT ALSO WITH A NEGATIVE COSMOLOGICAL CONSTANT
- BOUNDARIES CONTAIN EQUAL BUT OPPOSITE BRANE TENSIONS (BOUNDARY C.C.'s)

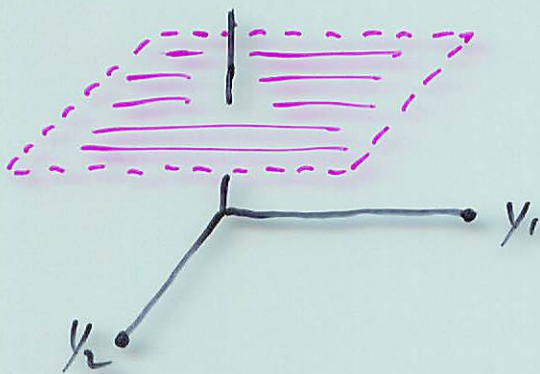
BULK, BOUNDARY C.C.'s CAUSE y -DIMENSION TO BE CURVED ("WARPED"), WHILE 4-D SPACE IS FLAT.

GRAVITON WAVEFUNCTION

THE WARPING HAS A DRAMATIC EFFECT ON THE SHAPE OF THE GRAVITON MODES

LARGE X-D

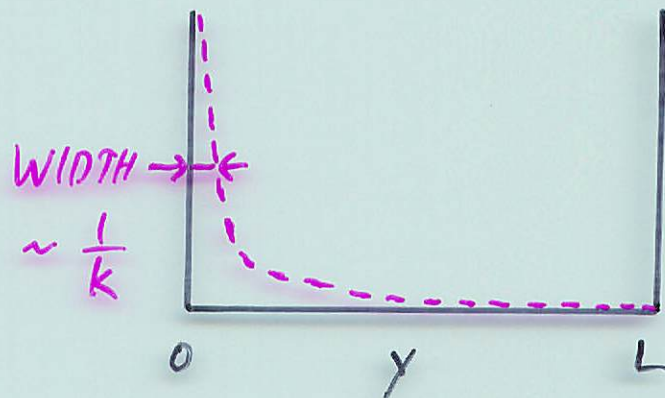
(TWO DIMENSIONS)



GRAVITON ZERO-MODE FLAT.

WEAKNESS OF GRAVITY IS
DUE TO GRAVITON SPREAD
OUT IN (COMPARITIVELY)
LARGE DIMENSIONS

WARPED X-D



GRAVITON ZERO-MODE EXPONENTIALLY
FALLS TOWARD TEV BRANE

WEAKNESS OF GRAVITY IS
DUE TO EXPONENTIAL FALL-OFF
OF GRAVITON WAVEFUNCTION

SOLVING THE HIERARCHY PROBLEM

THE FUNDAMENTAL PARAMETERS OF THE MODEL,

$$M_*^{RS} \sim k \sim M_{pl} \quad (\text{USUAL } 10^{18} \text{ GeV}).$$

THE SPATIAL CURVATURE

$$ds^2 = e^{-2ky} g_{\mu\nu} dx^\mu dx^\nu - L^2 d\tilde{y}^2$$

ENTERS INTO THE SM ACTION

$$\begin{aligned} S_{\text{TEV BRANE}} &= \int d^4x \sqrt{-g} \left[g^{\mu\nu} (D_\mu H)^\dagger D_\nu H - \lambda (H^\dagger H - v^2)^2 + \dots \right] \\ &= \int d^4x e^{-4kL} \left[e^{2kL} (D_\mu H)^\dagger (D^\mu H) - \lambda (H^\dagger H - v^2)^2 + \dots \right] \end{aligned}$$

NOW RESCALE FIELDS, $H \rightarrow e^{kL} \tilde{H}$

$$= \int d^4x \left[(D_\mu \tilde{H})^\dagger (D^\mu \tilde{H}) - \lambda (H^\dagger H - (e^{-kL} v)^2)^2 + \dots \right]$$

ALL MASS SCALES ON TEV BRANE ARE

EXPONENTIALLY SUPPRESSED BY WARP FACTOR.

TAKE: $v \sim 0.1 M_{pl}$

$$L \sim 35/k$$

$$\tilde{v} \equiv e^{-kL} v \sim 10^2 \text{ GeV}$$

WARPED @ COLLIDERS

- KALUZA-KLEIN GRAVITONS COUPLE WITH $\frac{1}{\text{TeV}}$ STRENGTH AND HAVE $\mathcal{O}(\text{TeV})$ MASSES

$$m_{KK}^{(j)} = x^{(j)} \underbrace{k e^{-kL}}_{\sim \text{TeV}}$$

3.8	$j=1$	SOLUTIONS OF $J(x_j) = 0$
7.0	$j=2$	
10.2	$j=3$	
⋮		

UNEVENLY SPACED KK MODES!

- SCALAR FLUCTUATION IN SIZE OF EXTRA DIMENSION

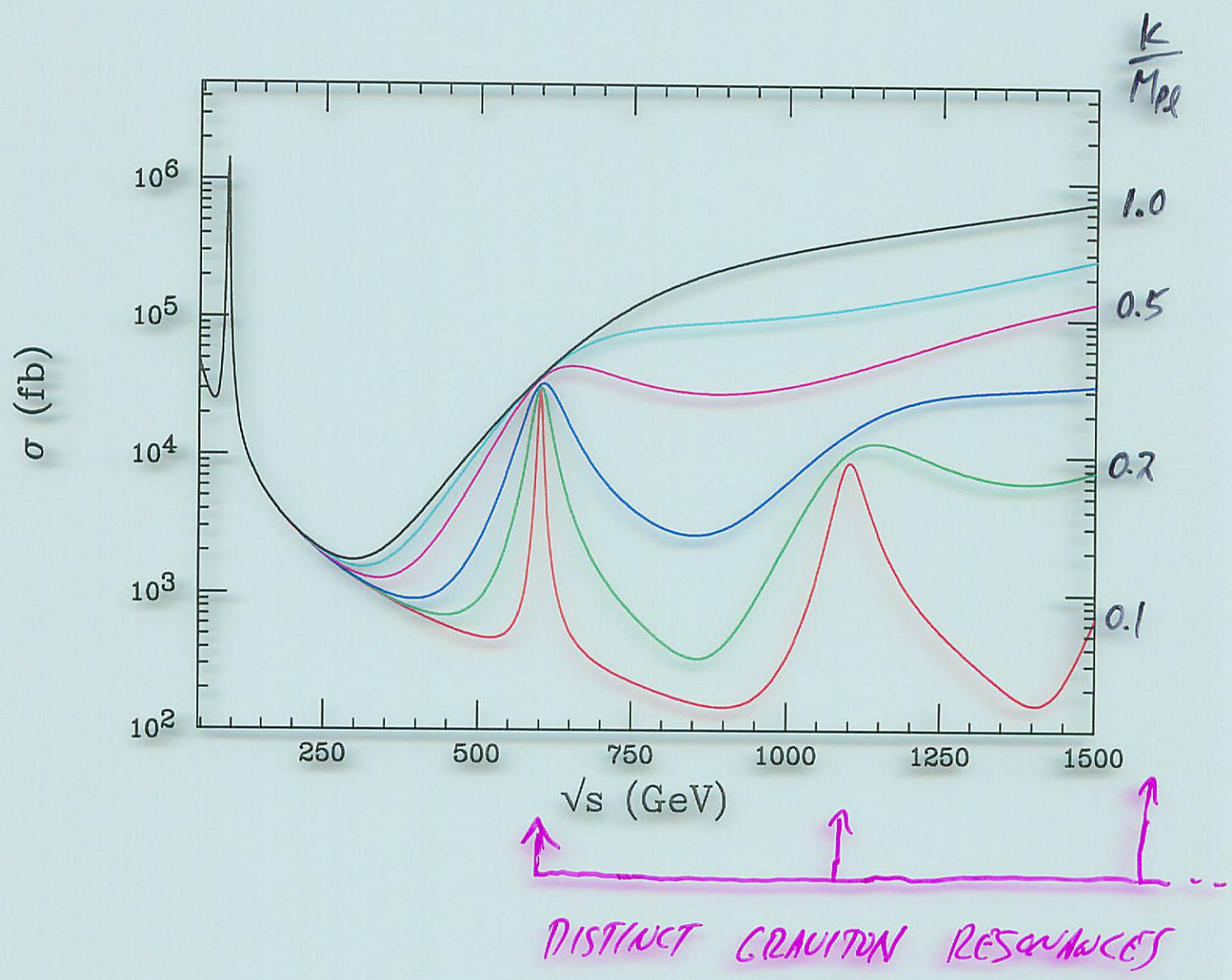
$$m_\phi \sim \epsilon \frac{1}{\sqrt{kL}} M_{\text{Pl}} e^{-kL} \quad \text{"RADION"}$$

$$\sim 0.1 \cdot (\text{TeV})$$

AND COUPLES WITH $\frac{1}{\text{TeV}}$ STRENGTH TO THE

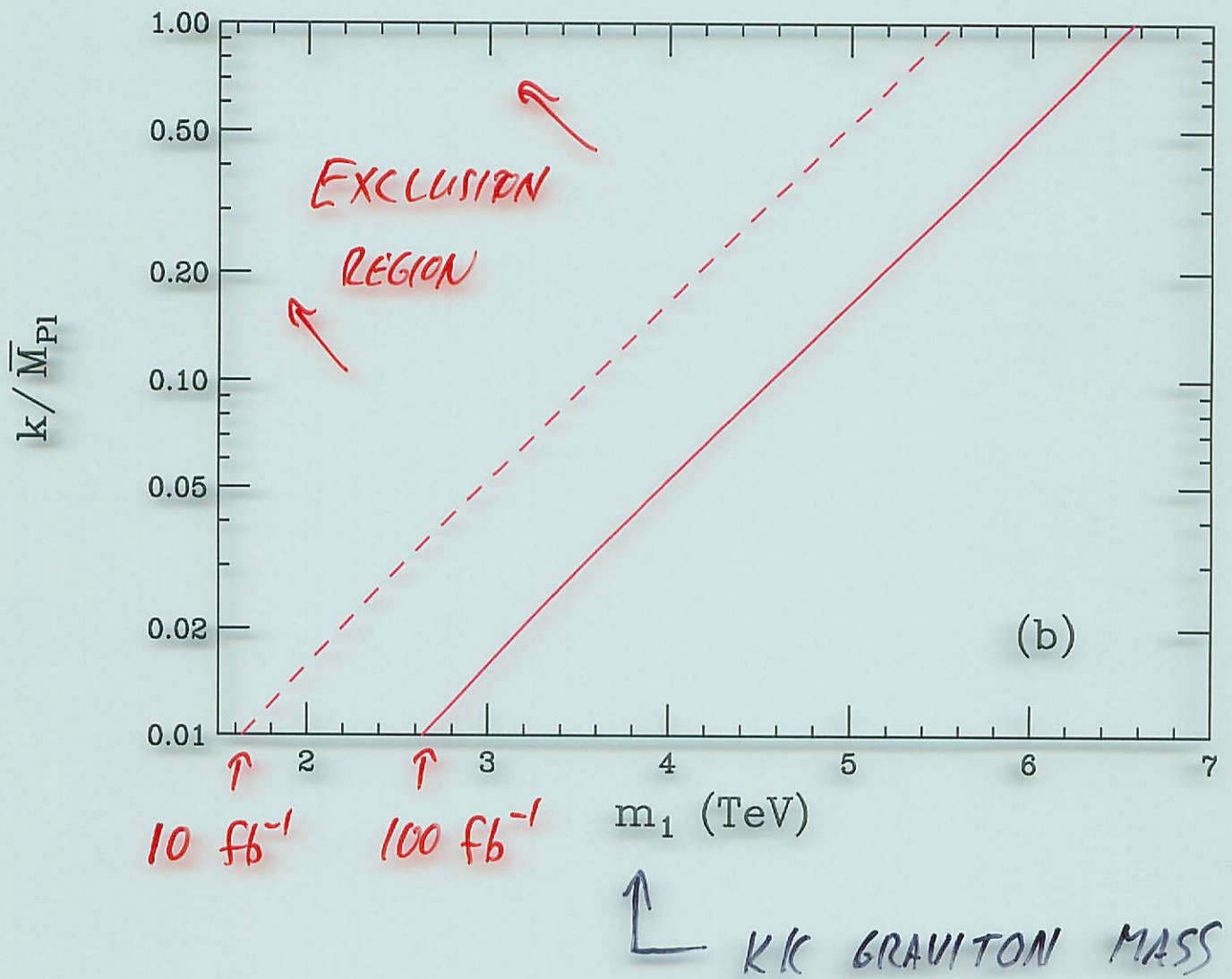
TRACE OF E-M TENSOR $\frac{\phi}{\text{TeV}} T_{\mu\nu}^{\text{SM}}$

TOTAL e^+e^- CROSS SECTION AT A LINEAR COLLIDER INTO $\mu^+\mu^-$



FROM: DAVIDIASC, HEGEPT, RIZZO

EXCLUSION REGION OF RESONANCE PRODUCTION OF FIRST KK GRAVITON @ LHC



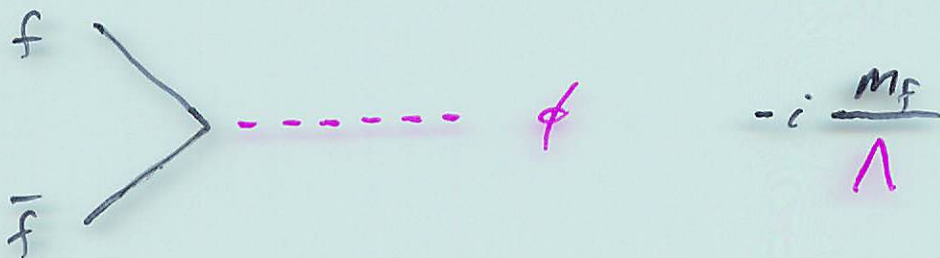
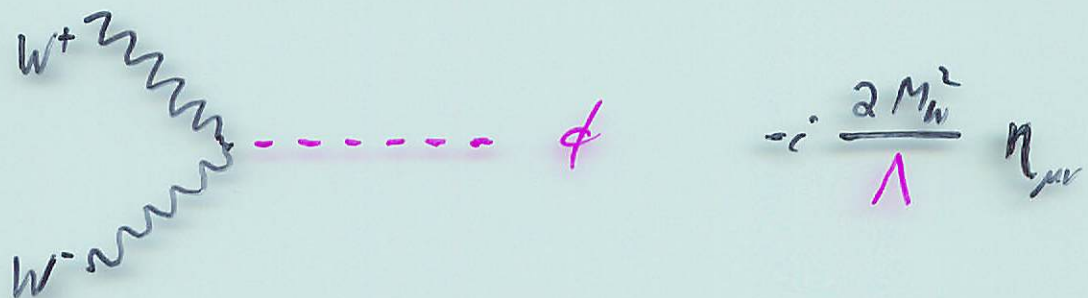
FROM: DAVIDIASI, HEWETT, RIZZO

RADION PHENOMENOLOGY

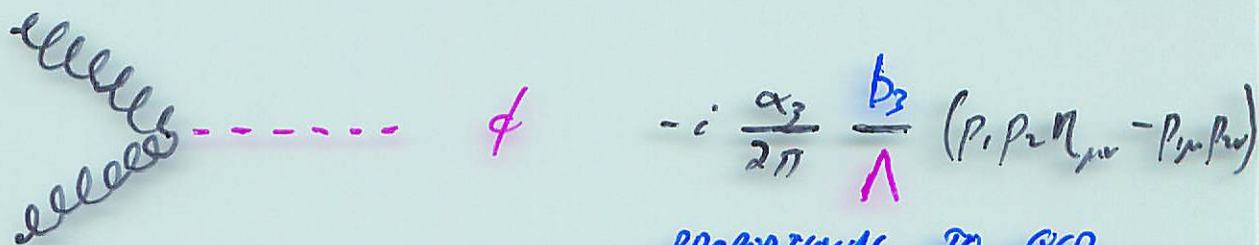
• THE RADION IS LIKELY THE LIGHTEST NEW STATE IN THE RS MODEL.

• TREE-LEVEL COUPLINGS IDENTICAL TO HIGGS, BUT WITH v REPLACED BY $\Lambda \sim M_{Pl} e^{-kL}$

EXAMPLES!



WHILE COUPLINGS ARE QUALITATIVELY DIFFERENT @ 1-LOOPS



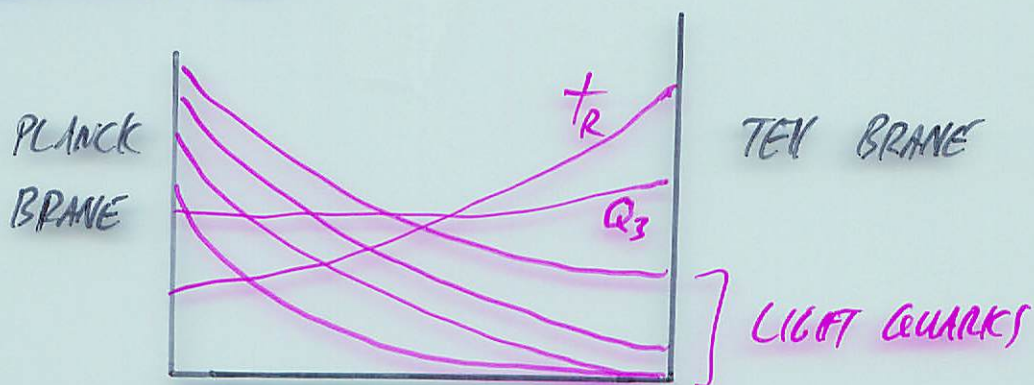
PROPORTIONAL TO QCD
 β -FUNCTION COEFF $b_3 = 7!$

RADION COULD BE CONFUSED w/ HIGGS!

WARPED PROBLEMS; WARPED VARIATIONS

TeV BRANE CUTOFF SCALE OPERATORS LEAD TO SAME PROBLEMS (VIOLATE GLOBAL SYMMETRIES OF SM) AS LARGE EXTRA DIMENSIONS.

PUTTING FERMIONS & GAUGE BOSONS IN THE BULK, ONE CAN SIGNIFICANTLY IMPROVE ON THESE FLAVOR PROBLEMS. THE SM YUKAWA COUPLINGS BECOME RE-INTERPRETED AS



GAUGE BOSONS IN THE BULK LEAD TO ELECTROWEAK PRECISION CORRECTIONS THAT ARE LARGE, UNLESS CUSTODIAL SYMMETRY IS "BUILT INTO" THE BULK.

LITTLE HIGGS THEORIES

LITTLE HIGGS THEORIES

A NEW APPROXIMATE GLOBAL SYMMETRY PROTECTS
HIGGS MASS AGAINST ONE LOOP QUADRATIC DIVERGENCES

OR

$$m_h^2 \sim \frac{\Lambda^2}{(16\pi^2)^2}$$

THIS SOLVES (MOST) OF THE LITTLE HIERARCHY PROBLEM
BY PUSHING $\Lambda \rightarrow 10 \rightarrow 20$ TEV WITHOUT ANY MORE
FINE-TUNING THAN THE SM WITH $\Lambda_{SM} \rightarrow 1 \rightarrow 2$ TEV

BASIC IDEA

- THE HIGGS BECOMES ONE COMPONENT OF A LARGER MULTIPLY OF SCALARS Σ (OR $\Sigma_1, \Sigma_2, \dots, \Sigma_n$)
- Σ_i TRANSFORMS NON-LINEARLY UNDER A NEW GLOBAL SYMMETRY
- NEW GLOBAL SYMMETRY IS SPONTANEOUSLY BROKEN, LEAVING THE HIGGS AS A GOLDSTONE
- GAUGING SOME OF THE GLOBAL SYMMETRY IMPLIES HIGGS IS NOT EXACT GOLDSTONE ("PSEUDO-GOLDSTONE")
- CAREFULLY GAUGING CAN ARRANGE THAT HIGGS DOES NOT ACQUIRE ONE-LOOP DIVERGENCE

$$\left(\text{THUS, } \delta m_H^2 \sim \frac{\Lambda^2}{(16\pi^2)^2} \text{ IMPLYING } \Lambda \gtrsim 10 \rightarrow 20 \text{ TEV} \right)$$

TWO LOOP !!

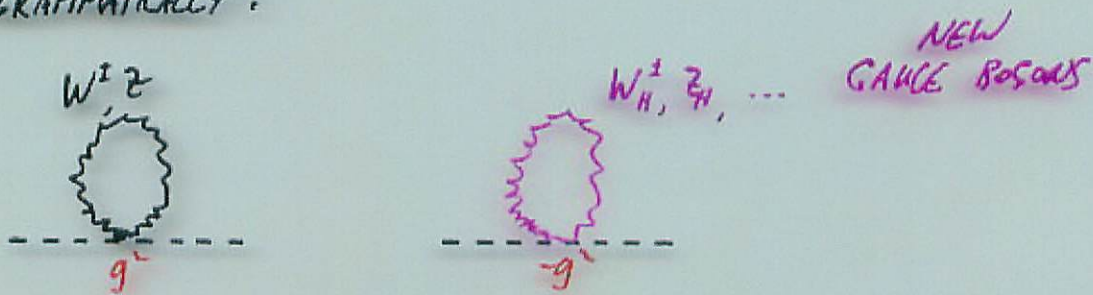
AND THUS SOLVES LITTLE HIERARCHY PROBLEM!

LITTLE HIGGS MODELS

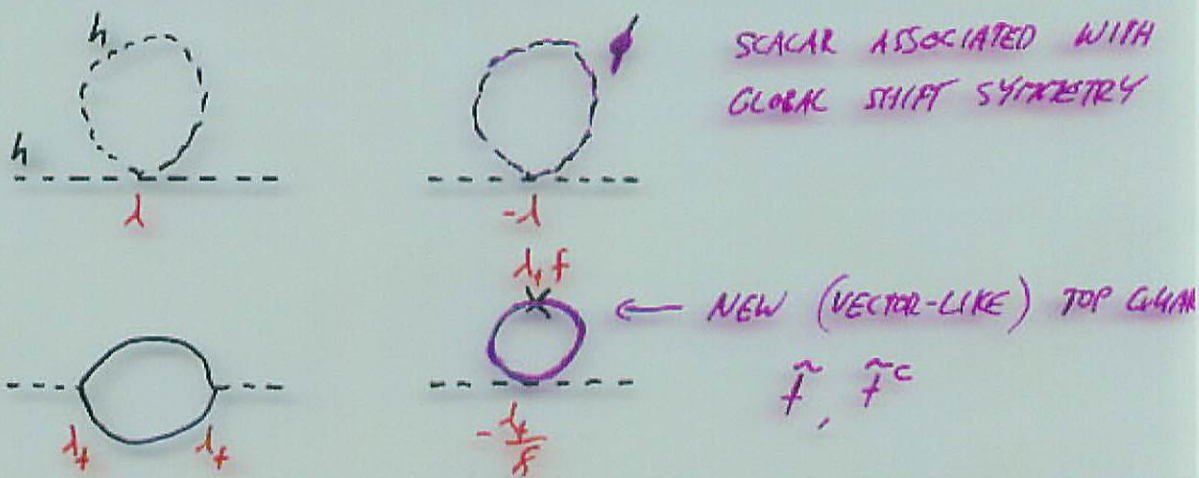
Name	Global Symmetry	Gauge Symmetry	# of light Higgs doublets	Higgs triplet? VEV
Littlest Higgs [ACKN]	$SU(5)$	$[SU(2) \times U(1)]^2$	1	yes!
Minimal Moose [ACGKNW]	$[SU(3)]^8$	$SU(3) \times SU(2) \times U(1)$	2	yes!
Antisymmetric condensate [LSS]	$SU(6)$	$[SU(2) \times U(1)]^2$	2	<u>no.</u>
Simple Group [KS]	$[SU(4)]^4$	$SU(4) \times U(1)$	2	<u>no.</u>
Minimal Moose Variant [CW]	$[SO(5)]^8$	$SO(5) \times SU(2) \times U(1)$	2	yes!
Two Little Higgs [ST]	$SU(4)$	$SU(3) \times U(1)$	2	<u>no.</u>
Custodial $SU(2)$ [C]	$SO(9)$	$[SU(2)]^3 \times U(1)$	1	yes ^u
T-parity LH [CL]	$[SO(5)]^{10}$	$[SU(2) \times U(1)]^3$	2	<u>no.</u>

ONE-LOOP CANCELLATIONS

THE SLICK SYMMETRY ARGUMENT CAN BE VERIFIED ~~DIAGRAMMATICALLY~~
 DIAGRAMMATICALLY:



A SIMILAR ANALYSIS SHOWS THAT: (ROUGHLY):



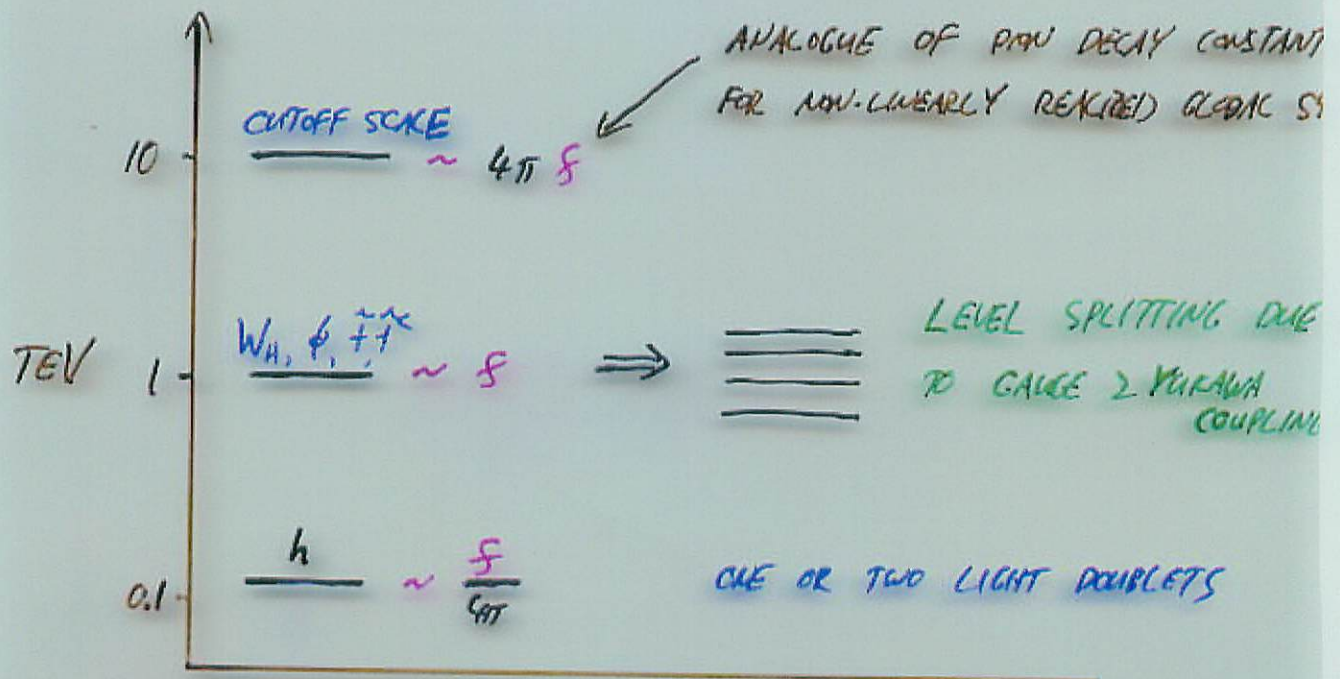
THESE NEW PARTICLES ARE REQUIRED TO IMPLEMENT
 THE GLOBAL SYMMETRY SO THAT ALL DANGEROUS QUADRATIC
 DIVERGENCES (PROPORTIONAL TO $O(1)$ COUPLINGS) ARE CANCELED.

PHENOMENOLOGY

SEVERAL NEW PARTICLES MUST APPEAR NEAR ~ 1 TEV
TO CANCEL QUADRATIC DIVERGENCES:

- NEW GANGE BOSONS
- NEW SCALARS
- NEW (VECTOR-LIKE) QUARKS

AND MANY MODELS HAVE TWO (LIGHT) HIGGS DOUBLETS.



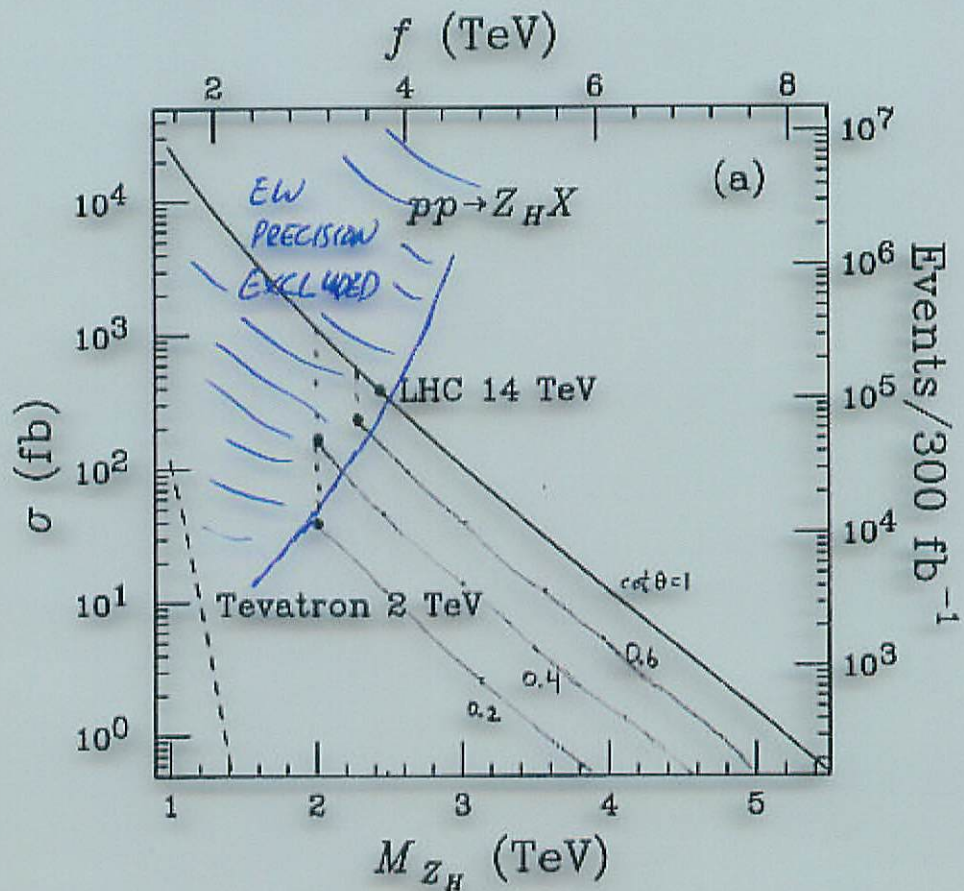
PHENOMENOLOGY II

WHAT ARE THE EXPERIMENTAL IMPLICATIONS OF THE NEW PARTICLES NEEDED TO IMPLEMENT A LITTLE HIGGS MODEL

- **INDIRECT EFFECTS ON EW PRECISION OBSERVATIONS**
 - NEW GAUGE BOSONS THAT $\left\{ \begin{array}{l} \text{MIX WITH SM GAUGE BOSONS} \\ \text{COUPLE TO LIGHT FERMIONS} \end{array} \right.$
 - SCALAR $SU(2)$ TRIPLET ACQUIRES $v_{EW} \sim \frac{v_{EW}^2}{f}$ (IN SOME MODELS)
 - $\tan \beta \neq 1$ LEADS TO A FINAL SOURCE OF CONCERN (CUSTODIAL $SU(2)$) (IN 2HDMs)
[CHKMT1, CHKMT2, HPR, GSW]
- **DIRECT PRODUCTION AT FUTURE HADRON COLLIDER**
 - HEAVY W^\pm, Z $\left\{ \begin{array}{l} \text{[HPR, BPP, HLMW...]} \end{array} \right.$
 - HEAVY \tilde{t}, \tilde{t}^c $\left. \begin{array}{l} \end{array} \right\}$
 - MODIFIED $h \rightarrow gg, h \rightarrow \gamma\gamma$ [HLMW, DRZ]
 $b \rightarrow s\gamma$ [HZ]
- **VERIFY COLLECTIVE BREAKING** [PIP]
- **DARK MATTER CANDIDATE** [BW, BHKW]

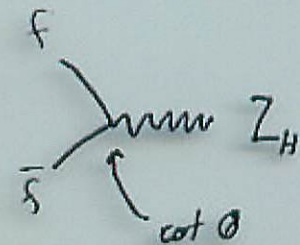
PRODUCTION OF Z_H AT LHC

LITTLEST HIGGS MODEL; GAUGE ONLY $[SU(2)]^2 \times U(1)_Y$



solid line : $\cot \theta = 1$

$$\sigma \propto \cot^2 \theta$$



[COURTESY OF HEATHER LOGAN]

PROBLEMS WITH LITTLE HIGGS THEORIES

THEY ARE NOT "UV COMPLETE". UV COMPLETIONS ARE TYPICALLY TECHNICOLOR OR SUSY, BUT STILL FACE MANY PROBLEMS FOUND BEFORE (FLAVOR, ...).

NEW GAUGE BOSONS CAN LEAD TO SIZEABLE CONTRIBUTIONS TO PRECISION ELECTROWEAK DATA.

(THERE ARE MODELS THAT AVOID THIS THROUGH TUNING OR MODEL-COMPLICATIONS, BUT NOT ENTIRELY CLEAR IF THERE IS A SIMPLE SOLUTION)

SIGNIFICANT STRUCTURE JUST FOR TWO LOOPS.

DOING BETTER, WHILE GETTING EVERYTHING TO WORK PHENOMOLOGICALLY, APPEARS TO BE HARD.

RELATIONSHIPS BETWEEN THEORIES!

DECONSTRUCTION

EXTRA DIMENSIONAL
THEORIES



4-D THEORIES

e.g.

- BULK GAUGE BOSON

$$A_{\mu}^{(KK \#)}$$

- HIGGS AS 5th
COMPONENT OF
GAUGE FIELD

- PRODUCT GAUGE THEORY

$$U(1) \times U(1) \times U(1) \times \dots$$

- LITTLE HIGGS THEORIES

AdS / CFT

THEORIES IN AdS
(BULK NEGATIVE C.C.)



4-D CONFORMAL
FIELD THEORIES

- WARPED X-D w/
BULK GAUGE BOSONS
- TEV BOUNDARY FIELDS

- VARIATION OF
WALKING TECHNICOLOR
- COMPOSITES OF CFT

SUMMARY

EFFECTIVE FIELD THEORY PROVIDES FRAMEWORK FOR UNDERSTANDING STRUCTURE OF SM & HOW TO GO BEYOND.

ORIGIN OF ELECTROWEAK SYMMETRY BREAKING
BIG PUZZLE IN STANDARD MODEL.

SEVERAL FASCINATING IDEAS, NONE DEVOID OF PROBLEMS.

OBVIOUSLY CRUCIAL TO GET DATA, AND UNDERSTAND IT,
SO THAT WE MOVE ON TO THE POST-LHC STANDARD
MODEL, WHATEVER IT IS!

A FEW REFERENCES TO LECTURES / REVIEWS

EFFECTIVE FIELD THEORY

LECTURES BY DAVID B. KAPLAN: $\left\{ \begin{array}{l} \text{nucl-th/9506035} \\ \text{nucl-th/0510023} \end{array} \right.$

LECTURES BY IRA ROHSTEIN: [hep-ph/0308266](https://arxiv.org/abs/hep-ph/0308266)

TECHNICOLOR

LECTURES BY SEKHAR CHIVUKULA: [hep-ph/0011264](https://arxiv.org/abs/hep-ph/0011264)

PHYS REPT BY HILL & SIMMONS: [hep-ph/0203079](https://arxiv.org/abs/hep-ph/0203079)

RPP BY CHIVUKULA & WOMERSLEY: pdg.lbl.gov

LARGE & WARPED EXTRA DIMENSIONS

LECTURES BY CSABA CSÁKI: [hep-ph/0404096](https://arxiv.org/abs/hep-ph/0404096)

LECTURES BY RAMAN SUNDRUM: [hep-ph/0508134](https://arxiv.org/abs/hep-ph/0508134)

LECTURES BY GDK: [hep-ph/0605325](https://arxiv.org/abs/hep-ph/0605325)

HIGGSLESS EWSB

LECTURES BY CSÁKI (w/ HUBISZ, MEADE): [hep-ph/0510275](https://arxiv.org/abs/hep-ph/0510275)

LITTLE HIGGS

LECTURES BY SCHMALTZ (w/ SMITH): [hep-ph/0502182](https://arxiv.org/abs/hep-ph/0502182)