New/Alternative Physics WG Summary Report

LCWS 2000 @ FNAL

C. S. Kim

(w/ G. Wilson, S. Tkaczyk)

I. Introduction

II. Report

III. Discussion & Conclusions

I

Komamiya's "Charge to Participants"

⇒ WG-P5 : New/Crazy idea (physics)

How crazy is real-Crazy?

- Planck-scale on your finger tip?
- (natural) composite Higgs and EWSB?
- D.S.B. — degenerate BESS?
- W', Z', Heavy Majorana Neutrinos?
- geometry of Universe ; Universal Torsion ; violation of Equivalence principle?
- ~~CP~~-ing Higgs-gauge boson coupling?
- non-commutative field theory?
- maximal weirdness?

⋮

Who are the crazy guys? and crazy ideas?

New and Alternative Physics Session P5
25-26 October 2000

Wednesday 25 October 2000		Parallel Session P5: New and Alternative Physics
12:00		Lunch
1	Joe Lykken	TBF
1:40	JoAnne Hewett	Signals for non-commutative field theories (Non-Commutative)
2:15	Hooman Davoudiasl	Probing the geometry of the Universe at the NLC (ED)
2:40	Tom Rizzo	Probing the Randall-Sundrum Warped Extra Dimensions Scenario at LC (ED)
3:05	Tatsu Takeuchi	Universal Torsion Induced Interactions from Large Extra Dimensions (ED)
3:30		Coffee
4:00-5:00		Fermilab Colloquium: Large Extra Dimensions
5:30-5:50	H-C Cheng (Chicago)	Electroweak Symmetry Breaking and Extra Dimensions (Composite Higgs)
6:00		Tours to Tours of Main Injector, CDF, D0, MiniBooNE, KTeV, etc.
7:00		Dinner
Thursday 26 October 2000		Parallel Session P5: New and Alternative Physics
1:00	Daniele Dominici	Signals of new vector resonaces at future colliders (D-BESS)
1:30	Pat Kalyniak	Discovery and Identification of W' and Z' Bosons at High Energy e+e- Colliders (Extra W, Z)
2:00	Sabine Riemann	Indications of New Physics in Fermion Pair Production (New Physics Search)

2:30	Marco Battaglia	Direct Searches for Z' at CLIC (Z' at CLIC)
3:30		Coffee
4:00	V.A. Ilyin	Potentials of LC in Stoponium Searches ($\tilde{t}$ resonnance)
4:20	Tao Han	Higgs-Gauge boson Coupling with CP-violation at Linear Colliders (CP Higgs coupling)
4:40	Clemens Heusch	Linear Collider Prospects for Finding Heavy Majorana Neutrino Signals in the Absence of Neutrinoless Double Beta Decay (Majorana Neutrino)
5:00-6:00		Plenary Talk: SUSY and the SUSY Breaking Scale
6:00		Dinner

Agenda V1.1

Last update : October 3, 2000

Pat Kalyniak
LC WS 2000
Fermilab
Oct. 26, 2000

Detection and Identification of W′ Bosons at High Energy e^+e^- Colliders

S. Godfrey, P. Kalyniak, B. Kamal
Carleton U., Ottawa
A. Leike
LMU, München
M. Donchesk̀i
Pennsylvania State, Mont Alto

1. Introduction

2. Models

3. Processes at e^+e^- Colliders

   i) $e^+e^- \longrightarrow \nu\bar{\nu}\gamma$

   ii) $e\gamma \longrightarrow \nu q X$

4. Summary

Discovery and ID of extra gauge bosons in $e^+e^- \to \nu\bar{\nu}\gamma$, PRD61, 113009 [hep-ph/0001074]

Discovery and ID of W′ bosons in $e\gamma \to \nu q X$ [hep-ph/0008157]

1. Introduction

- Many models are based on extensions of the SM gauge group, including in the context of GUTS
- Hence they include extra gauge bosons
- Extra Z's have been well studied in the literature →
- W's have been less studied
- Here, we look at indirect evidence for W's at high energy Linear Colliders
- Indirect limits from low energy precision electroweak data
  - highly model dependent

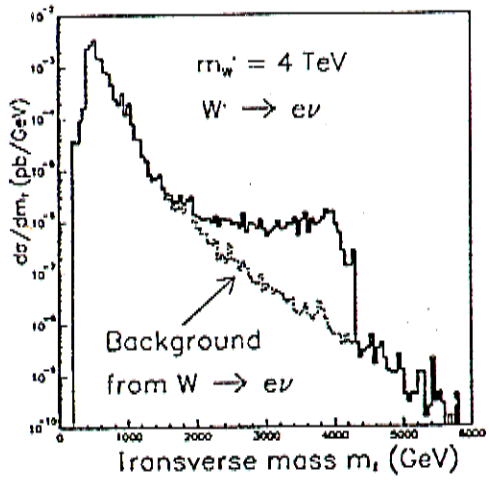
e.g. $m_{W_R} \gtrsim 1.6$ TeV — $K_L - K_S$ mass difference in LR model with $g_L = g_R$ (Beall, Bender, Soni, PRL 48, 848 (1982))

$m_{W_R} > 715$ GeV — Simultaneous fit to charged neutral sectors (Czakon et al PL B458, 355 (1999))

Direct Searches in Hadron Colliders

$pp \to W + X$

Present Limits (PDB '2000)



$m_{W_R'} > 720$ GeV

- W' with SM couplings decaying to $e\nu$, $\mu\nu$

Future Limits from LHC

$m_{W'} \gtrsim 6$ TeV

- model dependent (g_R/g_L, right-handed CKM, GUT)

(T. Rizzo, PR D50, 325 (1994); J. Collet, A. Ferrari – ATLAS)

Future Direct Limits from Linear Collider

$$\left.\begin{array}{l} e^+e^- \to W'^+ W'^- \\ e^\pm\gamma \to W'^\pm N \end{array}\right\} m_{W'} \text{ up to Kinematic limit}$$

2. Models with Extra Gauge Bosons

2.1 Sequential Standard Model (SSM)

- Benchmark rather than a model
- Extra gauge bosons with SM couplings
- SSM (W') $\longleftarrow$ W' only, totally artificial
- SSM ($W'+Z'$) $\longleftarrow$ Assume $M_{W'} = M_{Z'}$

2.2 General Left-Right Model (LRM)

- Extended gauge group is

$$\underset{\substack{\uparrow \\ g_L}}{SU(2)_L} \times \underset{\substack{\uparrow \\ g_R}}{SU(2)_R} \times U(1)_{B-L}$$

- f_L transform as doublets under $SU(2)_L$ and singlets under $SU(2)_R$
- $f_R \longrightarrow$ vice versa
- ν_R is included in the fermion content

2.3 "Un-unified" Model (UUM)

- Extended electroweak group is

$$SU(2)_q \times SU(2)_\ell \times U(1)_Y$$

- Left-handed quarks and leptons each transform under their respective $SU(2)$

- q_R, ℓ_R singlets under both $SU(2)_q$, $SU(2)_\ell$

- Parameter φ - angle which represents the mixing of the charged gauge bosons of the $SU(2)$'s.

$$0.24 \lesssim \varphi \lesssim 0.99$$

$$M_{W'} \sim M_{Z'}$$

$$\mathcal{L}_{UU} = \frac{-e}{2 s_W} \frac{s_\varphi}{c_\varphi} \left[\sqrt{2}\, W'^{+}_\mu \bar{\nu} \gamma^\mu \ell_L + Z'_\mu \left(\bar{\nu} \gamma^\mu \nu_L - \bar{\ell} \gamma^\mu \ell_L \right) \right] + h.c.$$

- left-handed couplings

(Georgi, Jenkins, Simmons, PRL 62, 27 (1989), N.P. B 331, 541 (1990)
Barger + Rizzo, PR D41, 946 (1990).)

2.4 Kaluza-Klein excitations in models with large extra dimensions (KK)

- As minimal example consider 5DSM *
- Extra dimension of size $R \sim \mathrm{TeV}^{-1}$ may imply infinite tower of KK excitations of standard model gauge bosons
- Mass associated with compactification scale $\sim n M_c$ $\quad n \to 1, \ldots, \infty$ $\quad M_c \to M_c \sim R^{-1}$
- Consider W', Z' corresponding to first KK excitation $\quad M_{W'} = M_{Z'}$
- Global analyses constrain W, Z masses and couplings to be $\sim$SM
- W', Z' couplings to fermions enhanced over SM by factor $\sqrt{2}$.

* (Masip + Pomeral, PR D60, 096005 (1999);
Rizzo + Wells, ibid. 61, 016007 (2000);
Giudice, Rattazzi, Wells, N. P. B544, 3 (1999);
Han, Lykken, Zhang, P. R. D59, 105006 (1999).)

2.5 "3rd Family" Model (3FM)

- Third — heavy — family transforms according to its own $SU(2)$

$$\underset{\text{heavy}}{SU(2)_h} \xrightarrow{g_h} \times \underset{\text{light}}{SU(2)_\ell} \xrightarrow{g_\ell} \times U(1)_Y$$

$$\downarrow$$

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

$$\downarrow$$

$$U(1)_{em}$$

via $\langle \sigma \rangle \sim (2,2,0)$ (h, ℓ)

via $\langle \varphi \rangle \sim (1,2,1/2)$ or $(2,1,1/2)$

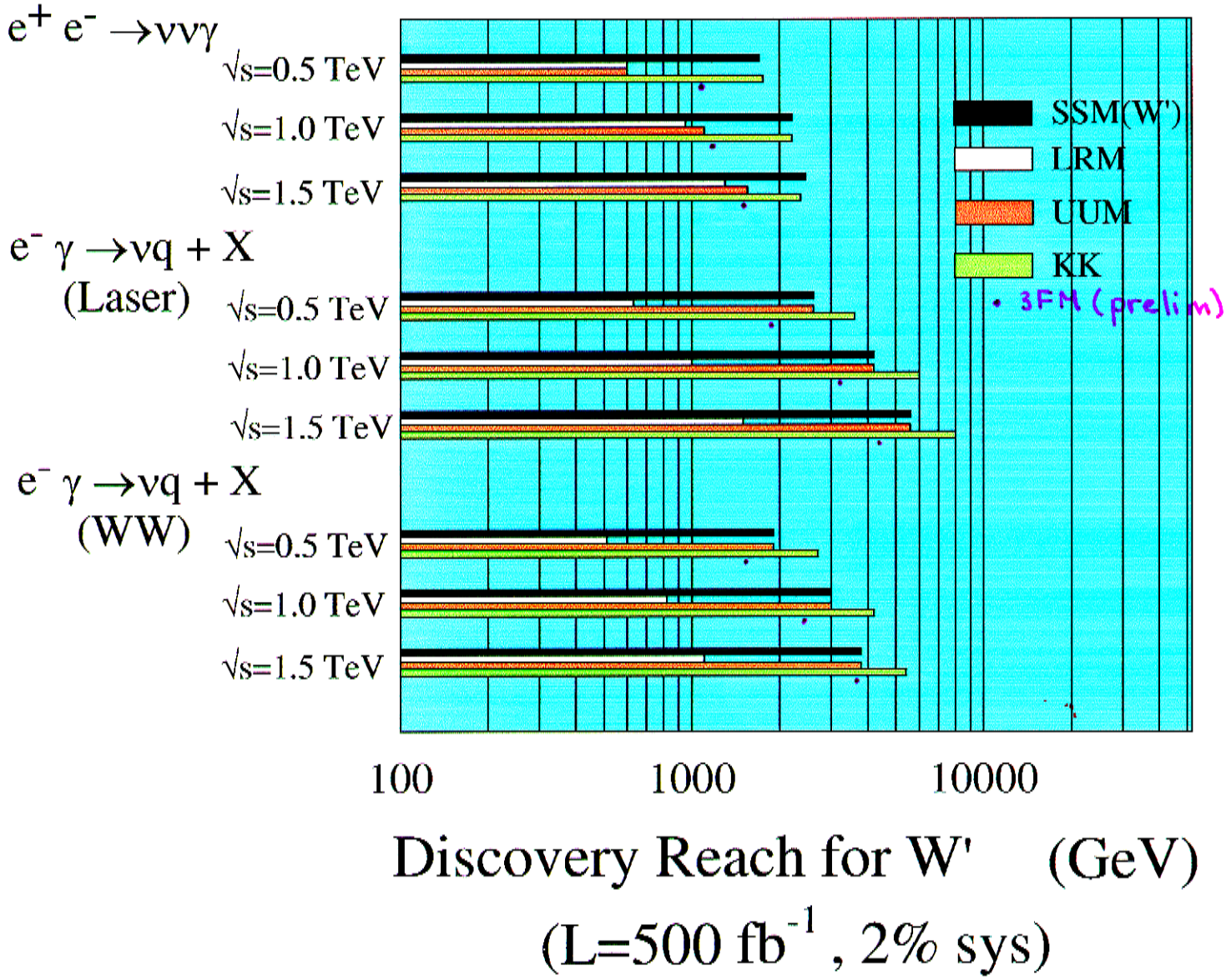
"Light breaking" scheme allows Z', W' as light as ~ 400 GeV

Parametrize via a mixing angle arising from the two $SU(2)$'s, φ.

$$\mathcal{L} \sim \frac{1}{\sqrt{2}}\left[g \frac{c_\varphi}{s_\varphi} \bar{u} \gamma_\mu L d W'^{+} - g \frac{s_\varphi}{c_\varphi} \bar{t} \gamma_\mu L b W'^{+} \right] + h.c.$$

+ neutral sector

(Chivukula, Simmons, + Terning, PL B331, 383 (1994), PR D53, 5258 (1996)
Lynch, Mrenna, Narain, Simmons, hep-ph/0007286


e+ e- →ννγ
√s=0.5 TeV
√s=1.0 TeV
√s=1.5 TeV
e- γ →νq + X
(Laser)
√s=0.5 TeV
√s=1.0 TeV
√s=1.5 TeV
e- γ →νq + X
(WW)
√s=0.5 TeV
√s=1.0 TeV
√s=1.5 TeV
SSM(W')
LRM
UUM
KK
• 3FM (prelim)
100
1000
10000
Discovery Reach for W' (GeV)
(L=500 fb-1 , 2% sys)

Indications of New physics in Fermion Pair Production

Sabine Riemann (DESY Zeuthen)

LCWS200
Fermilab
October 24 - 28, 2000

Outline:

- Sensitivity w/o e^+ polarization
- New Physics:
  - Contact interaction, extra dimensions
  - Z'
  - Exchange of leptoquarks/squarks
  - Comparison LC and LHC

$e^+e^- \to f\bar{f}$ at LC:

interference of virtual γ and Z exchange with NP

$$\frac{d\sigma}{d\cos\theta} \sim \frac{d\sigma(\mathrm{SM})}{d\cos\theta} + \frac{d\sigma(\gamma \otimes NP, Z \otimes NP)}{d\cos\theta} + \frac{d\sigma(NP)}{d\cos\theta}$$

$\sigma(\gamma \otimes NP, Z \otimes NP)$: main contribution to potential deviations from SM expectations

Already studied:

- Z′: sensitivity, resolution power
- CI, Extra Dimensions
- LQ, $\tilde{q}$: sensitivity above kin. limit
- details see DESY 123/A...E, Talks & proceeedings at workshops and conferences and ref. therein

HERE:

- gain with polarization of positrons
- 'realistic' error scenarios
- Comparison with LHC

Four-fermion contact interaction

general framework to describe interactions beyond the SM

$$\mathcal{L}_{eff} \sim \sum_{i,k=L,R} \eta_{ik} \frac{g^2}{\Lambda_{ik}^2} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_k \gamma^\mu f_k)$$

C.I. models

Model	η_{LL}	η_{RR}	η_{LR}	η_{RL}
LL	± 1	0	0	0
RR	0	± 1	0	0
LR	0	0	± 1	0
RL	0	0	0	± 1
VV	± 1	± 1	± 1	± 1
AA	± 1	± 1	∓ 1	∓ 1
V0	± 1	± 1	0	0
A0	0	0	± 1	± 1

$\Lambda \approx \lambda / m_X$

LEP2:

- errors of σ, A_{FB} statistically dominated
- $ee \to \mu\mu$: $\Lambda > 7.2...20$ TeV
  $ee \to uu$: $\Lambda > 2.2...16$ TeV
  $ee \to dd$: $\Lambda > 2.2...16$ TeV
  $ee \to qq$: $\Lambda > 3.4....8$ TeV

Extrapolation to higher energies:

$$\Lambda \sim \frac{m_X}{g} \sim (\mathcal{L}_{int} \times s)^{1/4}$$

Expect at LC improvement at least by factor $\approx 7-8$!

BUT:

Limitation by syst. errors

$$\Lambda \sim (\mathcal{L}_{int} \times s)^{1/4} \times \left[1 + (\Delta sys/\Delta stat)^2\right]^{-1/4}$$

With e^+ polarization: P_{e^-}, $P_{e^+} \Rightarrow P$;

$$P = \frac{-P_{e^-} + P_{e^+}}{1 - P_{e^-} P_{e^+}}$$

$P_{e^+} = 0.8$, $P_{e^+} = 0.6$: P=0.95
$P_{e^+} = 0.8$, $P_{e^+} = 0.4$: P=0.91

- Assume: ΔP is the dominating syst. error in A_{LR} measurement;

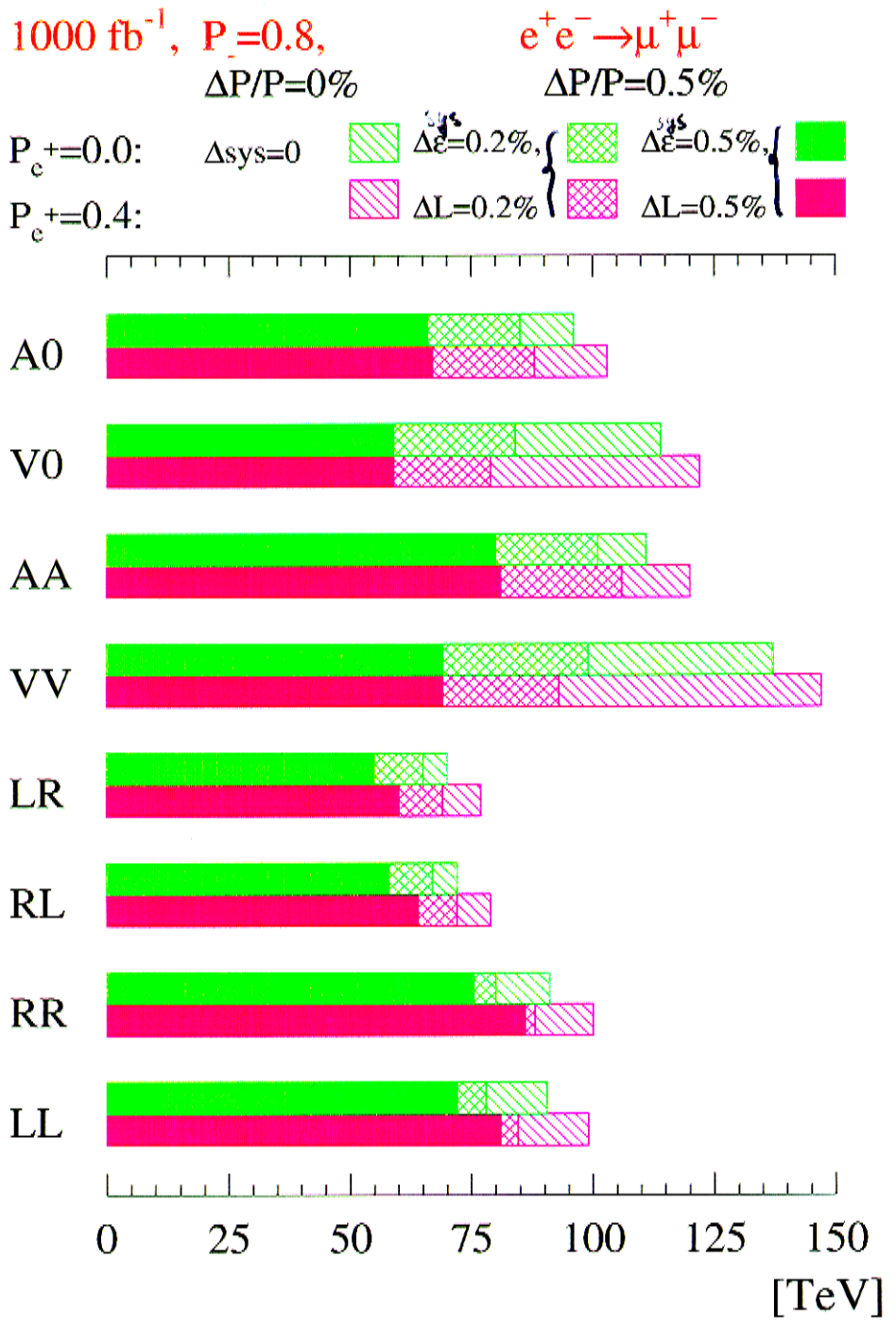
$$\Delta A_{LR} = \sqrt{(\Delta_{stat} A_{LR})^2 + (\Delta_{syst} A_{LR})^2}$$

$$= \sqrt{\frac{1 - P^2 A_{LR}^2}{N P^2} + A_{LR}^2 (\frac{\Delta P}{P})^2}$$

- $A_{LR}^{\mu\mu} \approx$ 6%, $\Delta_{stat} A^{\mu\mu} \approx$0.2%
  $A_{LR}^{q\bar{q}} \approx$ 45%, $\Delta_{stat} A_{LR}^{q\bar{q}} \approx$0.1%

- ΔP_{e^-}, ΔP_{e^+} should be smaller than 1% !!

Expected Sensitivity from $ee \to \mu\mu$



LHC is not sensitive to $ee\mu\mu$ contact interction
$\Delta P/P = 1\%$ or 0.5% is not important

CP-violating ZZh Coupling at Linear Colliders*

Tao Han, UW - Madison

(The 5th Linear Collider Workshop, FNAL, Oct. 26, 2000)

I. General parameterization
   ZZh coupling

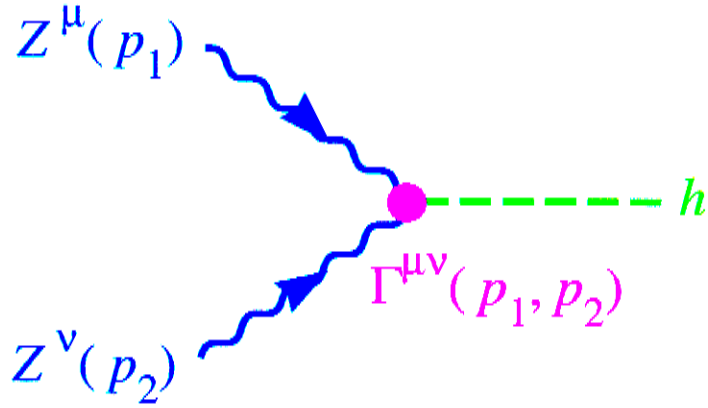
II. $e^+e^- \to e^+e^-h$
   Zh versus ZZ fusion

III. CP-odd observables

*T. Han and J. Jiang, in preparation.

I. General parameterization

The most general vertex function for ZZh



$$\Gamma^{\mu\nu}(p_1, p_2) = i\frac{2}{v}\, h[a\ M_Z^2 g^{\mu\nu} + b\ (p_1^{\mu} p_2^{\nu} - p_1 \cdot p_2 g^{\mu\nu}) + \tilde{b}\ \epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}]$$

$a = 1,\ b = \tilde{b} = 0$ for SM.

In general, $a,\ b,\ \tilde{b}$ complex form factors, describing new physics at a higher scale.

$a,\ b$ terms: CP-even;

$\tilde{b}$ term: CP-odd $\Leftarrow$ goal for this study.

III. CP-odd observables

With longitudinally polarized beams, under CP:

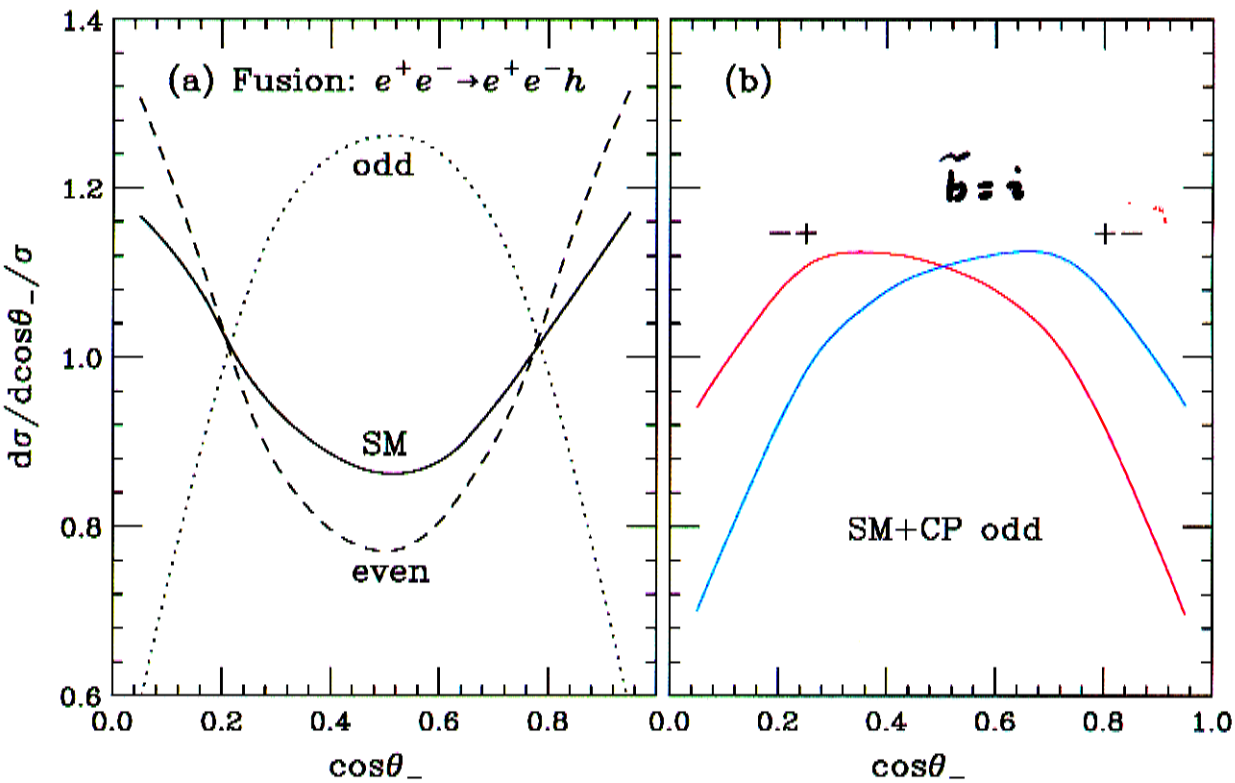
$$\mathcal{M}_{--}(\vec{q}_1, \vec{q}_2) \Rightarrow \mathcal{M}_{++}(-\vec{q}_2, -\vec{q}_1); \quad (1)$$

$$\mathcal{M}_{-+}(\vec{q}_1, \vec{q}_2) \Rightarrow \mathcal{M}_{-+}(-\vec{q}_2, -\vec{q}_1). \quad (2)$$

Define CP-odd angle:

$$\cos\theta_- \sim (\vec{p}_1 \times \vec{q}_0) \cdot (\vec{q}_1 \times \vec{q}_2),$$

with $\vec{q}_0 = \vec{q}_1 - \vec{q}_2$.

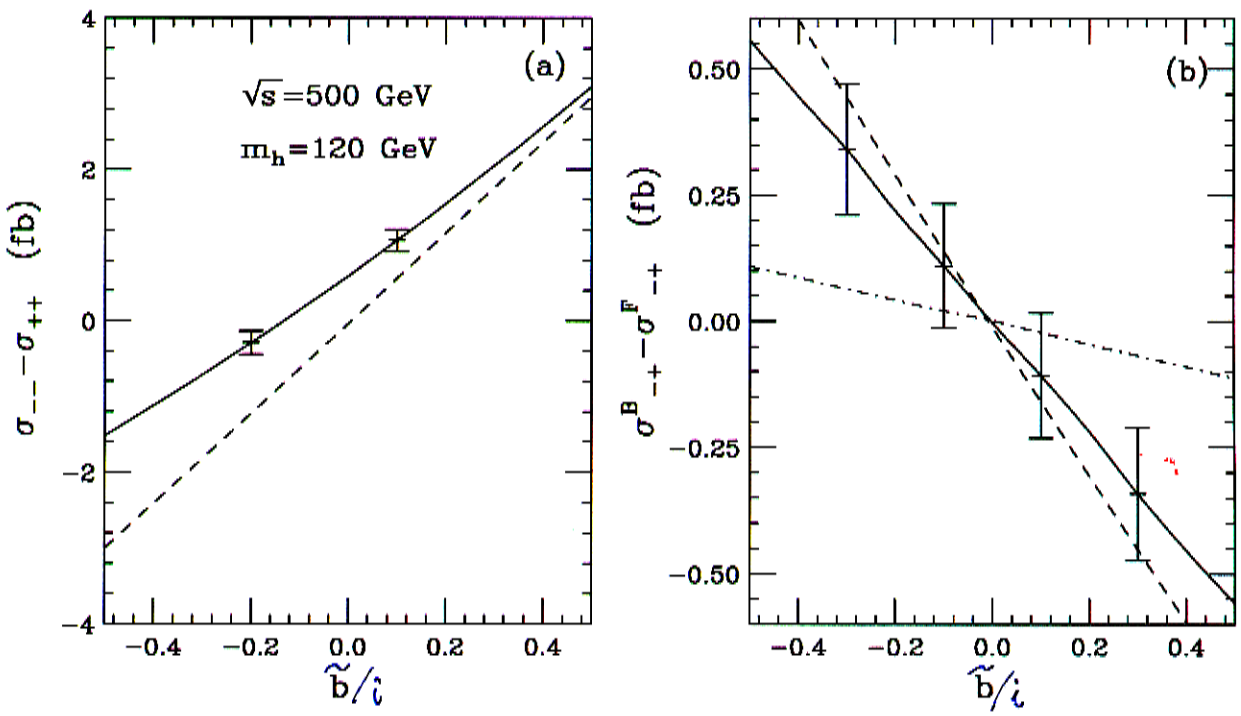


Based on Eq. (1), construct:

$$\mathcal{A}_{hel} = \sigma_{--} - \sigma_{++}$$

Based on Eq. (2), construct:

$$\mathcal{A}_{FB} = \sigma^F_{-+} - \sigma^B_{-+}.$$



dash: assuming 100% e^+e^- polarization;
solid: realistic pol. e^-e^+ : (90%, 65%).

error bars for 500 fb^{-1}.

LCWS2000, 26 Oct, Fermilab

Potentials of Linear Colliders in Stoponium Searchs

D.S. Gorbunov (INR, Moscow)
and
V.A. Ilyin (SINP MSU, Moscow)

- Stoponiums could exist. Two scenaria in MSSM with stoponium.
- Stoponium search at PLC. Stoponium factory in case of 2nd scenario.
- Some prospects to observe stoponium at e^+e^- collider.
- Stoponium at muon collider: excelent possibilities to study couplings.

Stop could be light:

- RG $\searrow$ A_t
- large $\tilde{t}_L - \tilde{t}_R$ mixing

could be in SUGRA, GMSB, ...

ALEPH (Moriond '2000) $m_{\tilde{t}_1} > 90$ GeV if $m_{\tilde{\nu}} > 45$ GeV or $m_{\tilde{\chi}} > 50$ GeV

CDF (Moriond '2000) $m_{\tilde{t}_1} > 130$ GeV if $m_{\tilde{\nu}} < 45$ GeV

If $m_{\tilde{t}} \sim m_{\tilde{\chi}} \Rightarrow m_{\tilde{t}_1} > 60$ GeV (ALEPH)

Like a quarkonium $(\tilde{t}\bar{\tilde{t}})$ system can be treated as a quasistationary system with masses

$$M_n = 2m_{\tilde{t}} + E_n \qquad (E_n < 0)$$

for $m_{\tilde{t}} = 100 - 300$ GeV $\quad E_n \sim 1$ GeV

Hagiwara et al 90'

(S)

Stoponium exists if the formation process (time scale $\sim \frac{1}{|E_n|}$) is faster than destroying processes

LC: $\mathcal{L}^{year}_{e^+e^-} = 300\ fb^{-1}$

PLC: $E^{max}_{\gamma\gamma} \sim 0.8\ E_{e^+e^-}$

for 15% $\sqrt{s_{\gamma\gamma}}$ interval below $E^{max}_{\gamma\gamma}$

$\mathcal{L}^{year}_{\gamma\gamma} \simeq \frac{1}{5}\mathcal{L}^{year}_{e^+e^-} \sim 60\ fb^{-1}$ "canonical"

proposals to decrease of horizontal beam emittance at damping ring and increase of repetition rate at low beam energies

$\Downarrow$

$\mathcal{L}^{year}_{\gamma\gamma} \simeq 3.2 \cdot \mathcal{L}^{year}_{e^+e^-} \sim 1000\ fb^{-1}$ "optimistic"

Signals of new vector resonances at future colliders

Daniele Dominici

Fermilab, 26 October 2000

Outline

- Motivations
- A model with vector and axial vector particles degenerate in mass
- Signals and bounds from LHC
- Indirect effects at TESLA
- Studying the properties of the resonances at a multi-Tev collider
- Conclusions

A model with vector and axial-vector resonances was formulated several years ago

Casalbuoni,De Curtis,D.,Feruglio,Gatto (1989)

The symmetry group is $G' = G \otimes H'_{local} \to H_D$ where

$G = SU(2)_L \otimes SU(2)_R$ $\qquad$ $H_D = SU(2)_V$

$H'_{local} = SU(2)_L \otimes SU(2)_R$ with gauge fields $\mathbf{L}_\mu, \mathbf{R}_\mu$ (triplets)

SSB of $G' \to H_D$ gives $3 \times 4 - 3 = 9$ GB

- 6 are absorbed by $\mathbf{L}_\mu, \mathbf{R}_\mu$ which get mass
- 3 give mass to W and Z when part of G is promoted to local EW gauge symmetry

Taking the same gauge coupling constant g'' for $\mathbf{L}_\mu, \mathbf{R}_\mu$, we end with two more parameters

$$\boxed{M_V,\ M_A,\ g'', z}$$

with the vector and axial-vector resonances defined as $\mathbf{V}_\mu = (\mathbf{L}_\mu + \mathbf{R}_\mu)/2$, $\mathbf{A}_\mu = (\mathbf{R}_\mu - \mathbf{L}_\mu)/2$ and $z = g_V/g_A$.

Degenerate BESS model

Casalbuoni,Deandrea,De Curtis,D.,
Feruglio,Gatto,Grazzini (1995)

Choose the parameters in the BESS model Lagrangian in such a way that

$$M_V = M_A \qquad z = 1$$

the symmetry is enhanced to

$$[SU(2)_L \otimes SU(2)_R]^2_{\text{global}} \otimes [SU(2)_L \otimes SU(2)_R]_{\text{local}}$$

So this special case is protected by an additional custodial symmetry $SU(2)_{\text{cust}} \to SU(2)_{\text{cust}} \otimes [SU(2)_L \otimes SU(2)_R]$.
See also the parity doubling in Appelquist,Da Silva,Sannino (1999)

Features of the model

- $M_L = M_R = M$ (apart from EW corrections)
- DECOUPLING
  In the limit $M \to \infty$ one recovers the SM Lagrangian (for $M_H \to \infty$)
- $\mathbf{L}_\mu, \mathbf{R}_\mu$ are NOT coupled to $w^\pm, z$ (the GB eaten up by $W^\pm, Z$), in QCD dictionary $g_{\rho\pi\pi} = g_{\rho A\pi} = 0 \to$
  the $\mathbf{L}_\mu, \mathbf{R}_\mu$ decays in $W_L W_L$ are suppressed
  Unlike other schemes of SEWSB, the $W_L W_L$ final state is not enhanced

Is it possible to avoid the stringent bounds from LEP?

Deviations with respect to SM can be encoded in the S, T, U $(\epsilon_1, \epsilon_2, \epsilon_3)$ parameters. Peskin, Takeuchi (1990), Altarelli, Barbieri (1991)

Dispersive representation for ϵ_3:

$$\epsilon_3 = -\frac{g^2}{4\pi}\int_0^\infty \frac{ds}{s^2}\Big[\mathrm{Im}\Pi_{VV} - \mathrm{Im}\Pi_{AA}\Big]$$

Peskin, Takeuchi (1990)

where $\Pi_{VV(AA)} = \langle J_{V(A)} J_{V(A)} \rangle$

Assume vector meson dominance:

$$\mathrm{Im}\Pi_{VV(AA)}(s) = -\pi g^2_{V(A)}\delta(s - M^2_{V(A)})$$

$g_{V(A)}$ is the coupling of $V(A)$ to $J_{V(A)}$

$$\epsilon_3 = \frac{g^2}{4}\Big[\frac{g_V^2}{M_V^4} - \frac{g_A^2}{M_A^4}\Big]$$

In QCD-scaled TC models, using Weinberg sum rules $g_V = g_A$, $M_A^2 = 2M_V^2$ and KSFR $g_V^2 = 2v^2 M_V^2$, we get $\epsilon_3 \simeq 0.0008 N_{TC} N_d$ which is ruled out by the experiments.

$$\Downarrow$$

A possibility for $\epsilon_3 \to 0$ is $g_A = g_V$ $M_A = M_V$ that is vector and axial-vector resonances $\boxed{\text{degenerate}}$ in mass and couplings.

Meaningful ONLY if a further symmetry protects the degeneracy.

Bounds from the ϵ-parameters fit

The D-BESS has very loose bounds from the existing experimental data: $\epsilon_i \Rightarrow 0$ for $M \Rightarrow \infty$

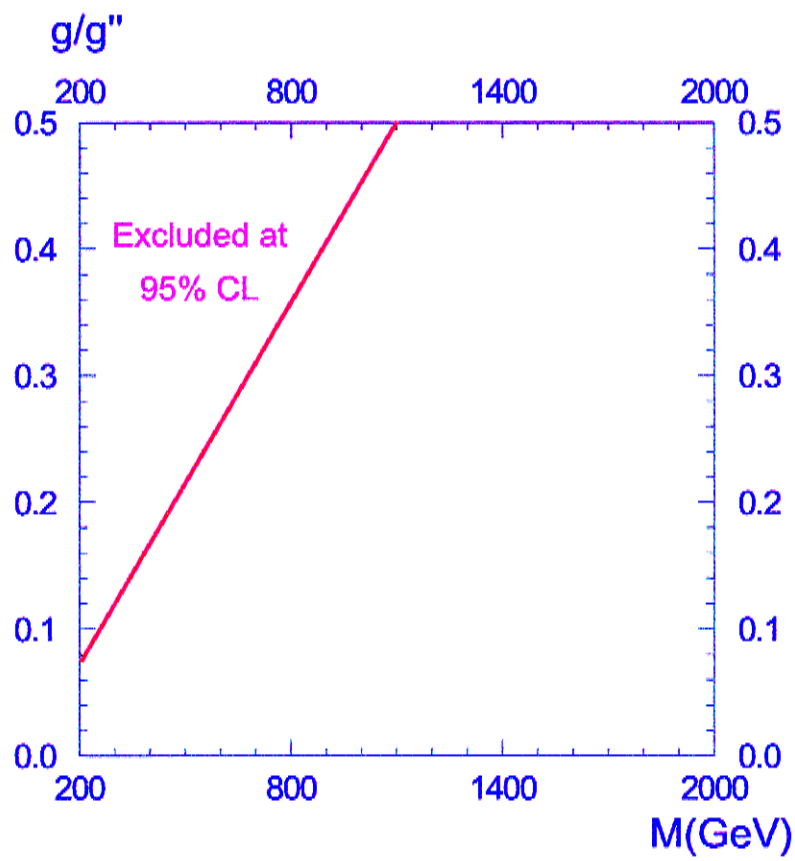
Calculation to the next-to-leading order:

$$\epsilon_1 = -\frac{c_\theta^4 + s_\theta^4}{c_\theta^2} X \qquad \epsilon_2 = -c_\theta^2 X \qquad \epsilon_3 = -X$$

$$X = 2\,(g/g'')^2 (M_Z/M)^2$$

double suppression factor

To compare to the experimental data consider for D-BESS the same radiative corrections of the SM with $m_H = \Lambda = 1\,TeV$ (neglect new physics loop corrections)



Experimental values from all High-Energy data fit:
$\epsilon_1 = (3.92 \pm 1.14) \times 10^{-3}$, $\epsilon_2 = (-9.27 \pm 1.49) \times 10^{-3}$, $\epsilon_3 = (4.19 \pm 1.00) \times 10^{-3}$ (Altarelli (1999))

- The Degenerate BESS is a non renormalizable model, described by an effective lagrangian.
  It is a non linear realization of the spontaneous symmetry breaking. Scalar particles are absent.

- A renormalizable realization The model contains in addition to the vector states scalar fields and it is renormalizable. This allows to discuss the decoupling also at the radiative corrections level.

Casalbuoni,De Curtis,D.,Grazzini (1997)

Gauge symmetry

$$SU(2)_L \otimes U(1) \otimes SU(2)'_L \otimes SU(2)'_R$$
$$\downarrow u$$
$$SU(2)_{weak} \otimes U(1)_Y$$
$$\downarrow v$$
$$U(1)_{em}$$

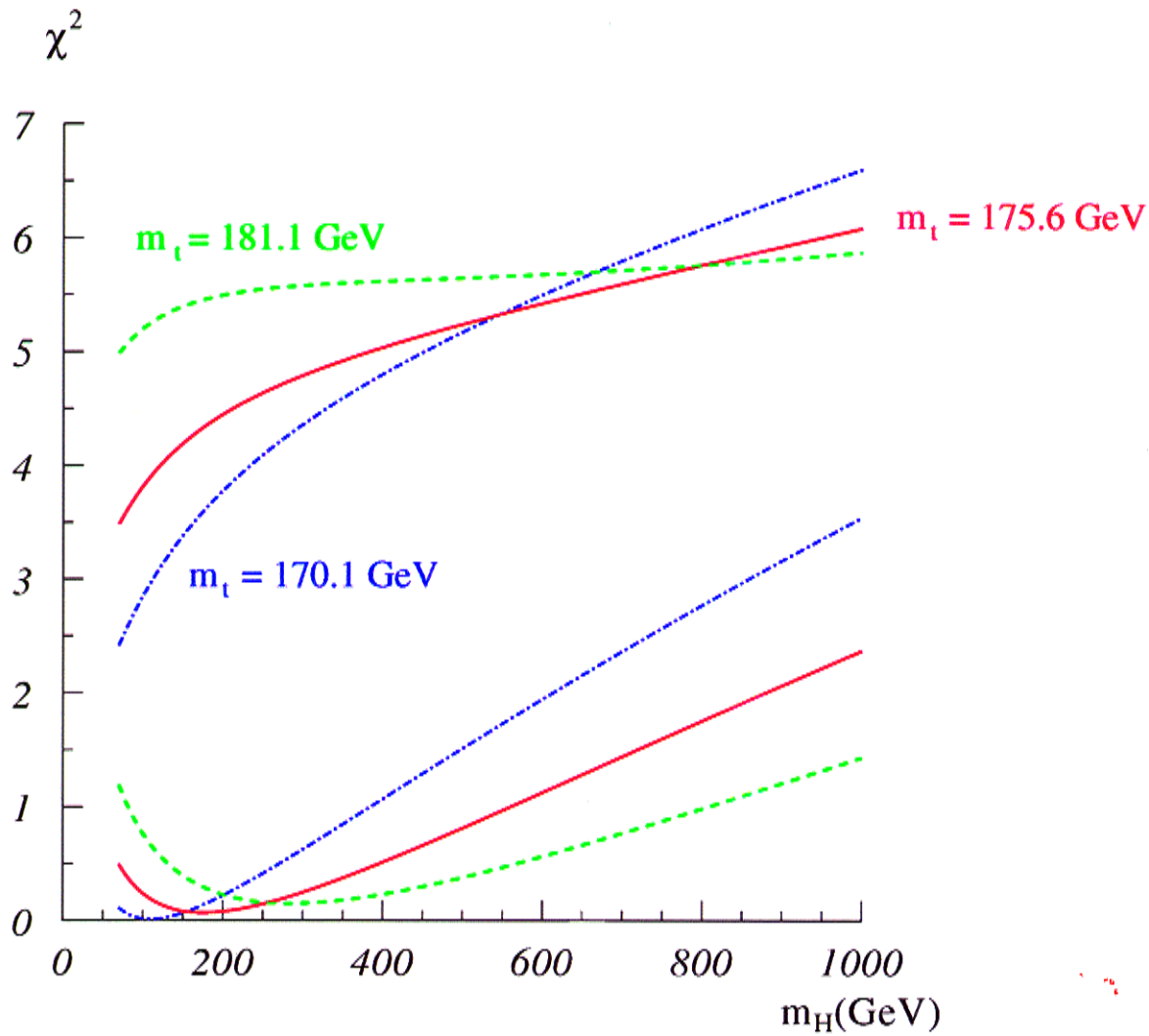
The scale $u = < \tilde{L} > = < \tilde{R} > = 2\sqrt{2}M/g''$.
For $u \Rightarrow \infty$ one recover the SM.
ϵ parameters $\sim X \sim \mathcal{O}(v^2/u^2)$.

A best fit to the ϵ parameters gives

$$1.3 \times 10^{-3} \leq X \leq 2 \times 10^{-3}$$

for $170.1 \leq m_t(GeV) \leq 181.1$, $70 \leq m_H(GeV) \leq 1000$.
Remember

$$X = 2\frac{m_Z^2}{M^2}(\frac{g}{g''})^2$$



Casalbuoni,De Curtis,D.,Gatto,Grazzini (1998)

- Upper part: the SM χ^2.
  Lower part: the decoupling model χ^2 with X corresponding to the best fit.

- Correspondingly the 95% CL bound on m_H goes from $\sim 200\ GeV$ to $\sim 1\ TeV$

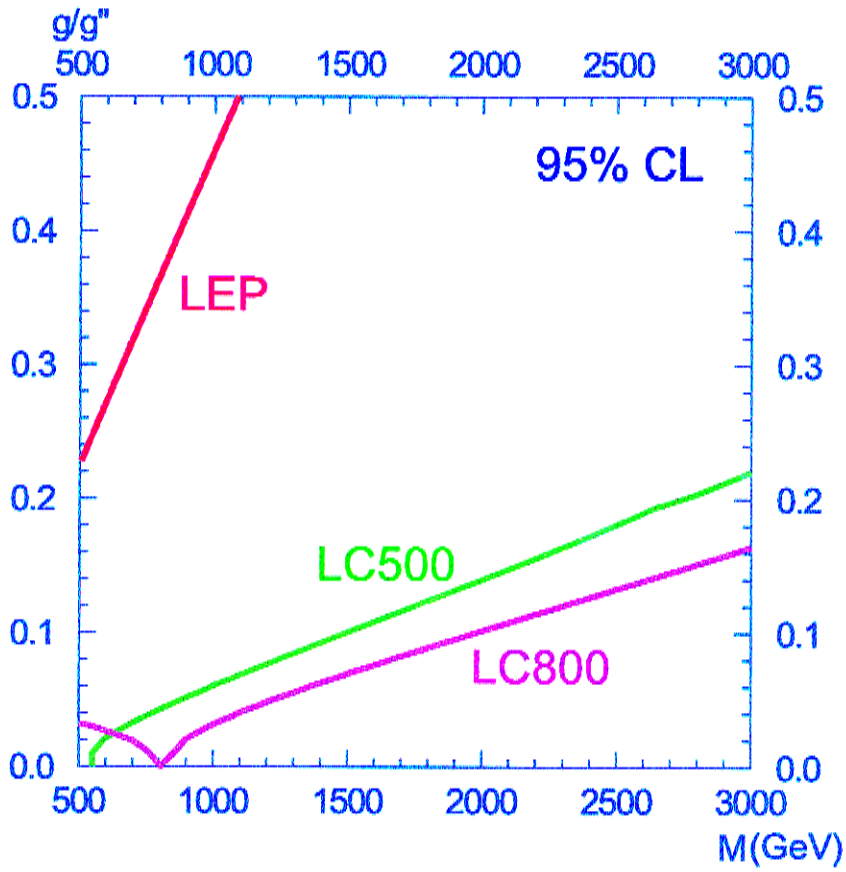
We have considered the following LC configurations:

LC500 : $\sqrt{s}(GeV) = 500$, $L(fb^{-1}) = 1000$

LC800 : $\sqrt{s}(GeV) = 800$, $L(fb^{-1}) = 1000$

with $P(e^-) = 80\%$

IF NO DEVIATIONS are seen within the statistical and systematic errors, a combined χ^2 analysis gives bounds on the parameter space of D-BESS



Compare with the bounds from LHC (only studied for $M \leq 2\ TeV$):

optimistic scenario $\Rightarrow$ LHC is superior for any g/g'', a LC with higher c.o.m. energy is needed to compete

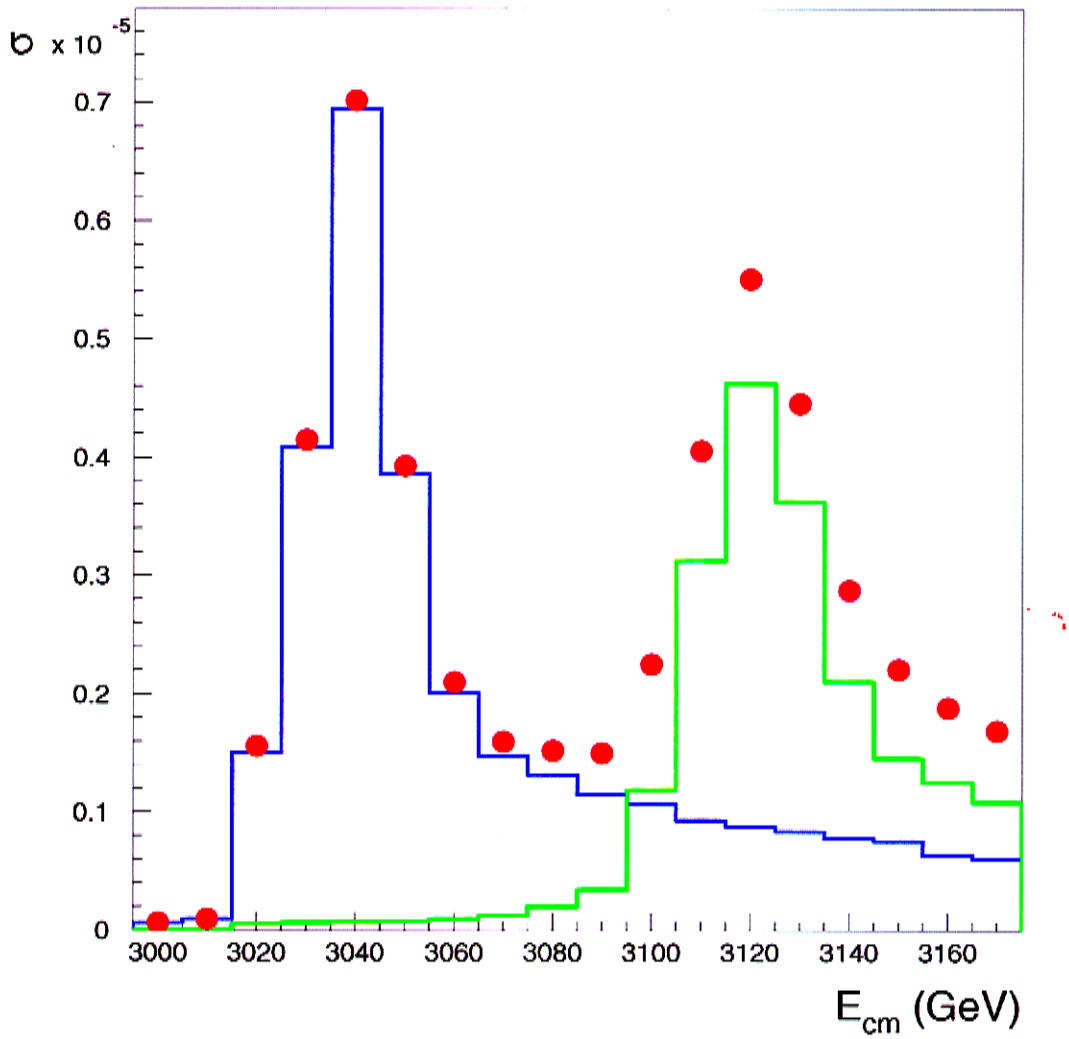
conservative scenario $\Rightarrow$ LHC and LC800 are comparable

worst scenario $\Rightarrow$ LC500 is superior to LHC for any g/g''

D-BESS at CLIC

Physics generator (PYTHIA 6) + CLIC Beam Energy Spectrum (ISR, Beam energy spread, beamstrahlung)

M.Battaglia



$M = 3\ TeV,\ g/g'' = 0.2,\ \Delta M = 84\ GeV$

$\Gamma_{R_3} = 1.2\ GeV,\ \Gamma_{L_3} = 8.2\ GeV$

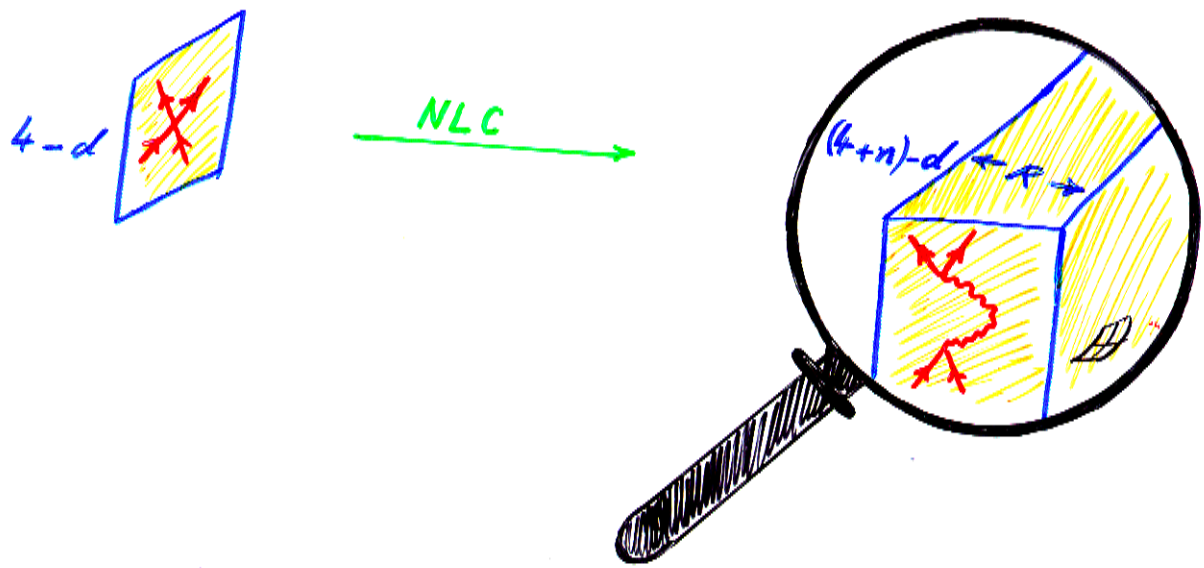
$M_{R_3} = 3035\ GeV,\ M_{L_3} = 3118\ GeV$

II

New Class of Ideas:

Approach hierarchy from a geometric point of view

Instead of adding extra fields (SUSY, ...), add extra dimensions to the universe.



(I) Large Extra Dimensions:

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429, 263 (1998)

Fundamental scale: M_F in $(4+n)$-d.

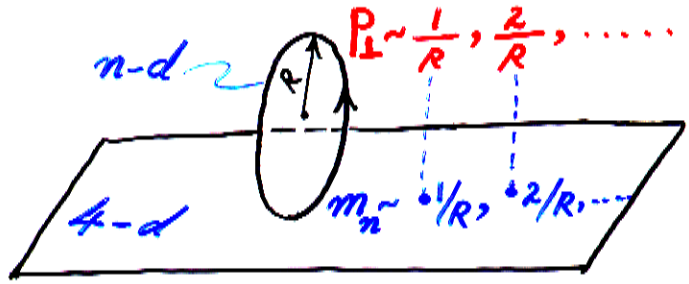
n extra dimensions of size R. $M_F \sim m_W$, no scale hierarchy.

Gauss' law: $V(r) \sim -\dfrac{m_s}{(M_F^{2+n} R^n) r}$, $r \gg R$

$\Rightarrow \bar{M}_P^2 \sim M_F^{2+n} R^n$; $1\,fm \lesssim R \lesssim 1\,mm$ $(2 \leq n \leq 6) \Rightarrow M_F \sim 1\,TeV$.

ADD:

1) Kaluza-Klein (KK) tower of gravitons with mass $m_n \sim n/R$, equal spacing.



2) Each KK mode couples in 4-d $\sim 1/\bar{M}_P$.

3) The KK tower at $\sqrt{s} \sim M_F \sim 1\,\text{TeV}$ gives strong gravitational interactions suppressed by $1/M_F$, due to KK multiplicity $\sim 10^{16}$: $\sum_{n=1}^{10^{16}} \left(G^{(n)} \right) \sim s/M_F^2$; $\bar{M}_P \sim 10^{16}$

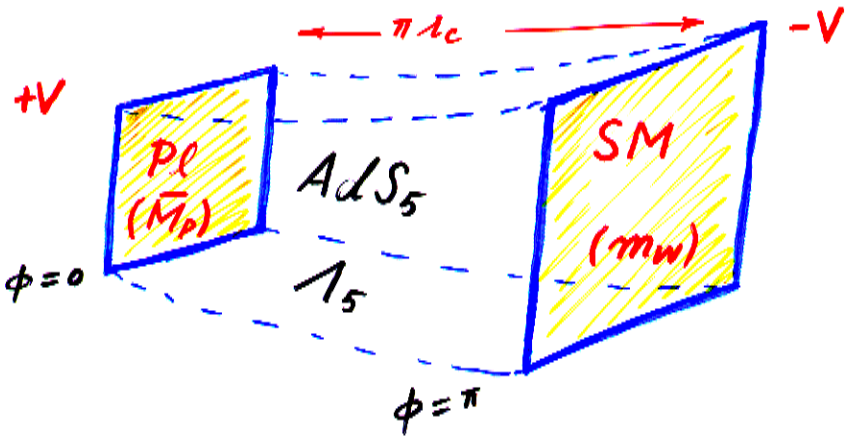
4) SM stuck on a 4-d wall (at least up to $E \sim 1\,\text{TeV}$

5) Factorizable geometry, n flat extra dimensions:

$$ds^2 = \underbrace{\eta_{\mu\nu}\, dx^\mu dx^\nu}_{4\text{-}d} + \underbrace{\sum_{i=1}^{n} dx_i^2}_{n \text{ extra dimensions}}$$

(II) Randall-Sundrum (RS) Localized Gravity:

5-d universe, AdS_5 (constant negative curvature) truncated by two 4-d Minkowski walls, separated by a fixed distance $L = \pi r_c$.



L. Randall, R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999).

$\phi \in [-\pi, \pi]$

Z_2 orbifold: $\phi \to -\phi$

Fundamental scale in 5-d: M_5.

$M_5 \sim \bar{M}_P$, $V \sim M_5^3 k$, $k \sim \bar{M}_P$, $\Lambda_5 \sim M_5^3 k^2$, $r_c^{-1} \sim k$.

No hierarchic parameters.

Geometry warped and non-factorizable:

$$ds^2 = \underbrace{e^{-2\sigma(\phi)}}_{\text{Warp Factor}} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 \quad ; \quad \sigma = k r_c |\phi| .$$

Relation to Hierarchy:

$$S = \frac{1}{2}\int d^5x \sqrt{-G}\left[G^{MN}\partial_\mu \Phi\, \partial_\nu \Phi - m_5^2 \Phi^2\right] \delta^\mu_M \delta^\nu_N \frac{\delta(\phi-\pi)}{r_c} \qquad \left(G_{\mu\nu} = e^{-2\sigma}\eta_{\mu\nu}\right)$$

$$e^{-4kr_c\pi} \qquad e^{2kr_c\pi}\eta^{\mu\nu}$$

$$= \frac{1}{2}\int d^4x\, e^{-4kr_c\pi}\left[e^{2kr_c\pi}\eta^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi - m_5^2\Phi^2\right]$$

$$\Phi \to e^{kr_c\pi}\Phi \qquad \text{(To get canonical kinetic term)}$$

$$\Rightarrow \quad S = \frac{1}{2}\int d^4x\left(\eta^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi - e^{-2kr_c\pi} m_5^2 \Phi^2\right)$$

$\Rightarrow$ At $\phi = \pi$ (SM wall): $\boxed{m_4 = e^{-kr_c\pi} m_5}$

$kr_c \sim 10$, $m_5 \sim M_5 \sim \bar{M}_P \Rightarrow m_4 \sim m_W$.

Weak scale generated from Planck scale exponentially via warp factor.

$kr_c \sim 10$ can be generic.

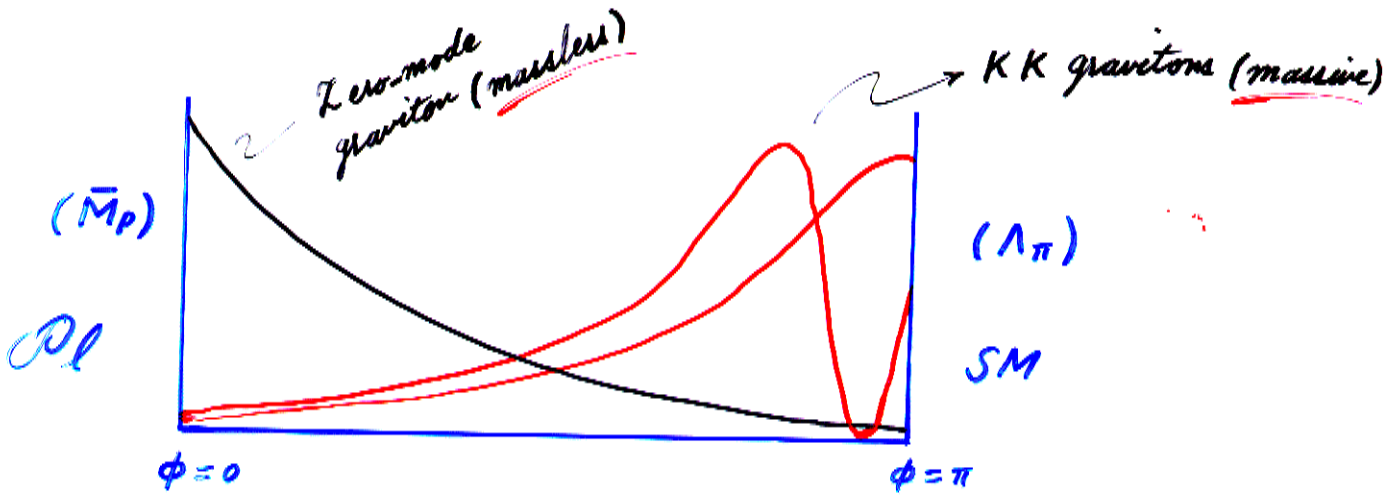
W. Goldberger, M. Wise, Phys. Rev. Lett. 83, 4922 (1999).

RS model:

(1) KK tower of gravitons starts at $m \sim 1\,\text{TeV}$;

$\Delta m \sim 1\,\text{TeV}$, unequal spacing given by Bessel functions.

(2) The zero-mode (massless 4-d) graviton couples $\sim \frac{1}{\bar{M}_P}$ and the massive KK tower gravitons couple $\sim \frac{1}{\Lambda_\pi} \sim 1\,\text{TeV}^{-1}$.



Localized Gravity

(1) $\oplus$ (2) $\Rightarrow$ Colliders with $\sqrt{s} \sim 1\,\text{TeV}$ can produce massive KK graviton resonances.

SM scale $\Lambda_{SM} \sim 1\,\text{TeV}$

RS scale (at $\phi = \pi$) $\Lambda_\pi \sim 1\,\text{TeV}$

Can we place the SM in the 5-d bulk?

W. Goldberger, M. Wise, Phys. Rev. D 60, 107505 (1999).

Try bulk gauge fields, SM fermions on the wall.

$\Rightarrow$ All KK gauge fields couple $\sqrt{2k r_c \pi} \sim 10$ times more strongly to fermions than the zero-mode $(\gamma, g, W^\pm, Z)$.

H.D., J. Hewett, T. Rizzo, Phys. Lett. B 473, 43 (2000).
A. Pomarol, hep-ph/9911294.

Expect strong constraints.

Precision EW data $\Rightarrow m_1^{(A)} \gtrsim 23\,\text{TeV}$.

Regenerating a hierarchy.

All of SM in the Bulk (5-d):

Fermions and gauge fields.

Keep the Higgs on the wall to avoid phenomenological problems.

5-d fermion mass m_Ψ.

$\nu \equiv m_\Psi / k \sim 1$ (Naturalness).

Zero-mode (4-d, SM) fermion wavefunction

$f^{(0)}$ localized: $f^{(0)} \sim e^{\nu \sigma(\phi)}$.

$\nu \ll 0 \rightarrow$ Planck wall ($\sigma = 0$).

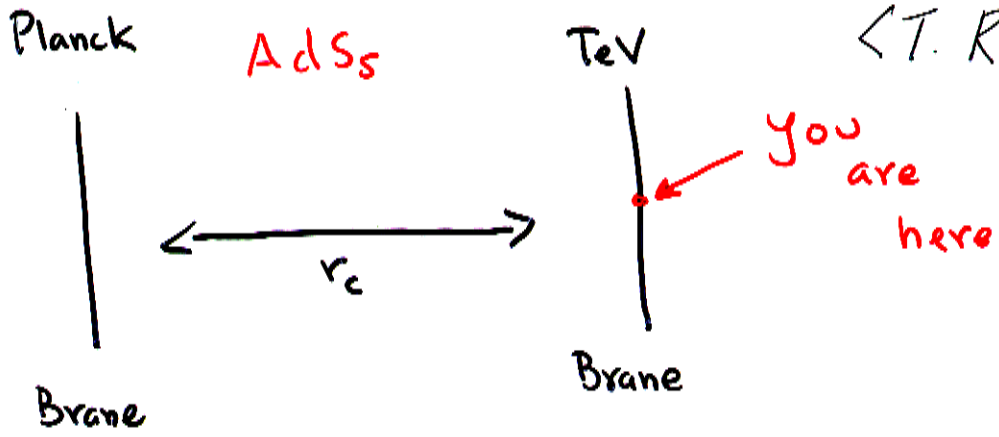
$\nu > 0 \rightarrow$ SM wall ($\sigma = + k r_c \pi$).

Rich phenomenology.

H. D., J. Hewett, T. Rizzo, hep-ph/0006041 (PRD).

<T. Rizzo>

Basics:
(on the wall)



- $\bar{M}_{Pl}^2 = M_{5d}^3 / k$

✱ $kr_c \simeq 11-12$ to solve hierarchy problem (k controls 5-d curvature)

- $\Lambda_\pi = \bar{M}_{Pl}\, e^{-\pi k r_c}$
- $m_n[G^{(n)}] = x_n k e^{-\pi k r_c}$ w/ $J_1(x_n) = 0$

$$\mathcal{L} = -\left\{ \frac{1}{\bar{M}_{Pl}} h_{\mu\nu}^{(0)} + \frac{1}{\Lambda_\pi} \sum_n h_{\mu\nu}^{(n)} \right\} T^{\mu\nu}$$

$\Rightarrow$ fix $\boxed{m_1}$ and $\boxed{c \equiv k/\bar{M}_{Pl}}$ †† + all other parameters known

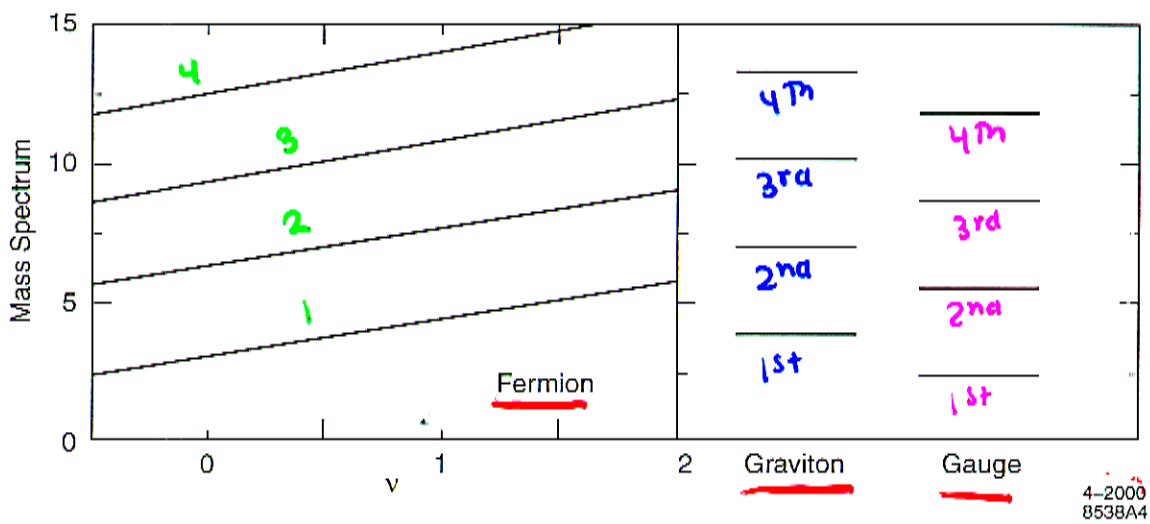
Off the wall: $\boxed{!}$ more parameter $\nu = m_f^{5d}/k$: $\sim O(1)$

<u>Common</u> fermion mass parameter (F/NC)

$\Rightarrow$ everything fixed - not bad!

†† c cannot be too small $\rightarrow$ hierarchy again $\gtrsim 10^{-2}$ $\boxed{\text{BUT}}$ c cannot be too large Curvature constraint [?] $c \lesssim 1$?

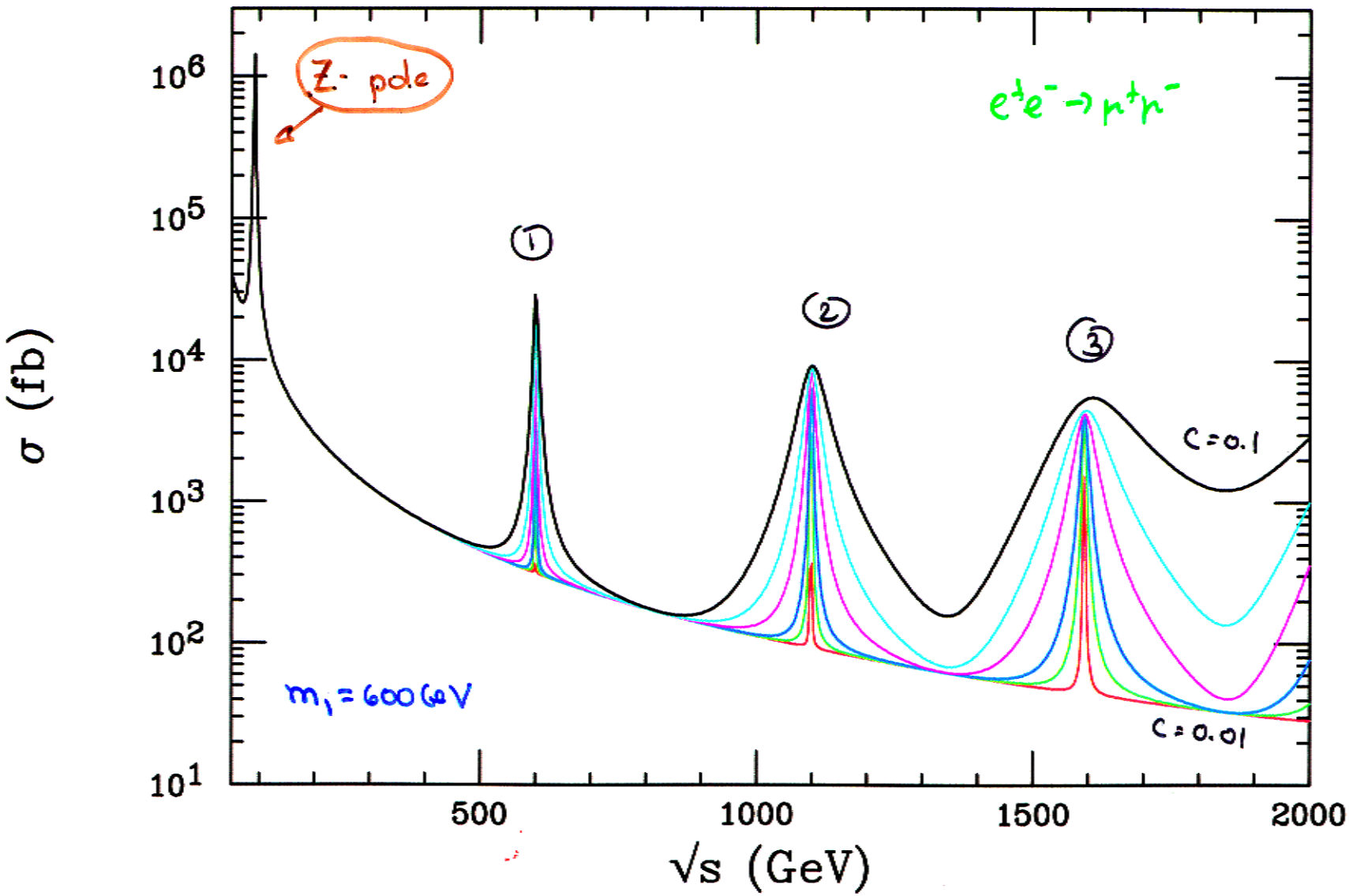
KK Fermion Masses, relative to gravitons + gauges are ν dependent....



$$m_n^\delta \simeq A_n |\nu + 1/2| + B_n$$

For a fixed ν, specifying any <u>one</u> <u>mass</u> gives all others !!

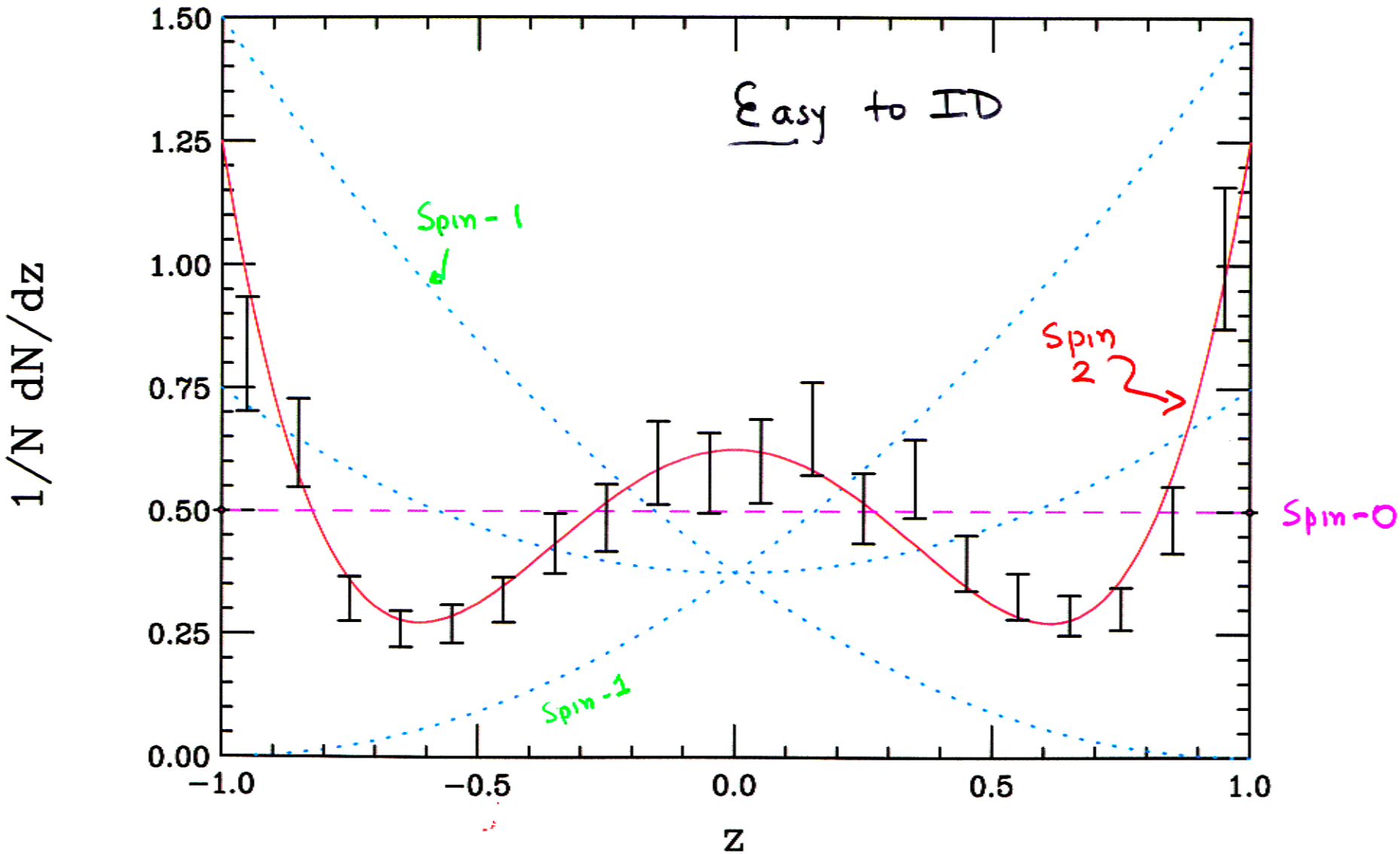
Graviton resonances at LC



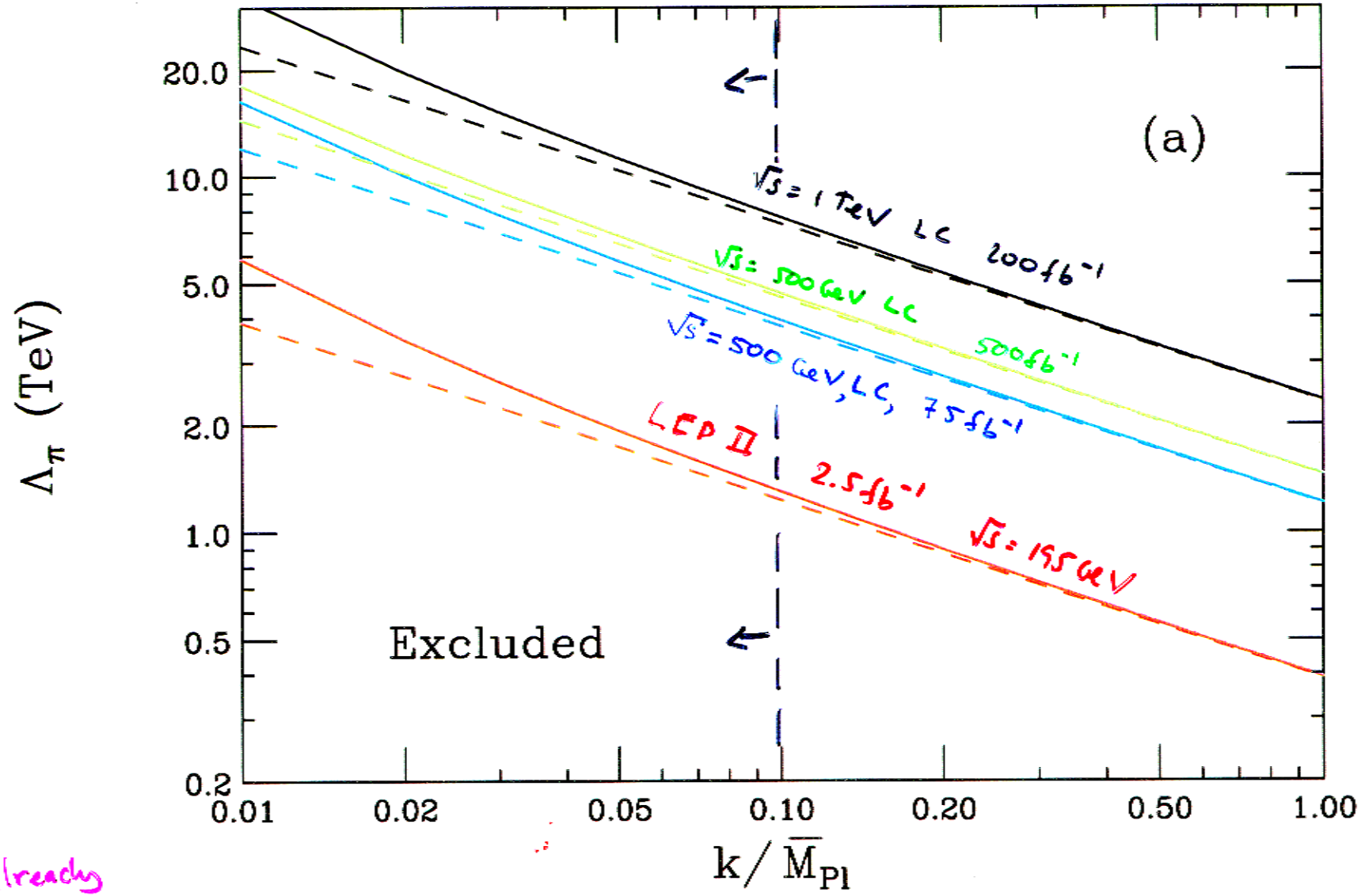
Not Equally Spaced

↑ increases with both c and m_n

$f\bar{f} \to \bar{f}'f'$ on a graviton resonance



CI Constraints on Randall-Sundrum Model



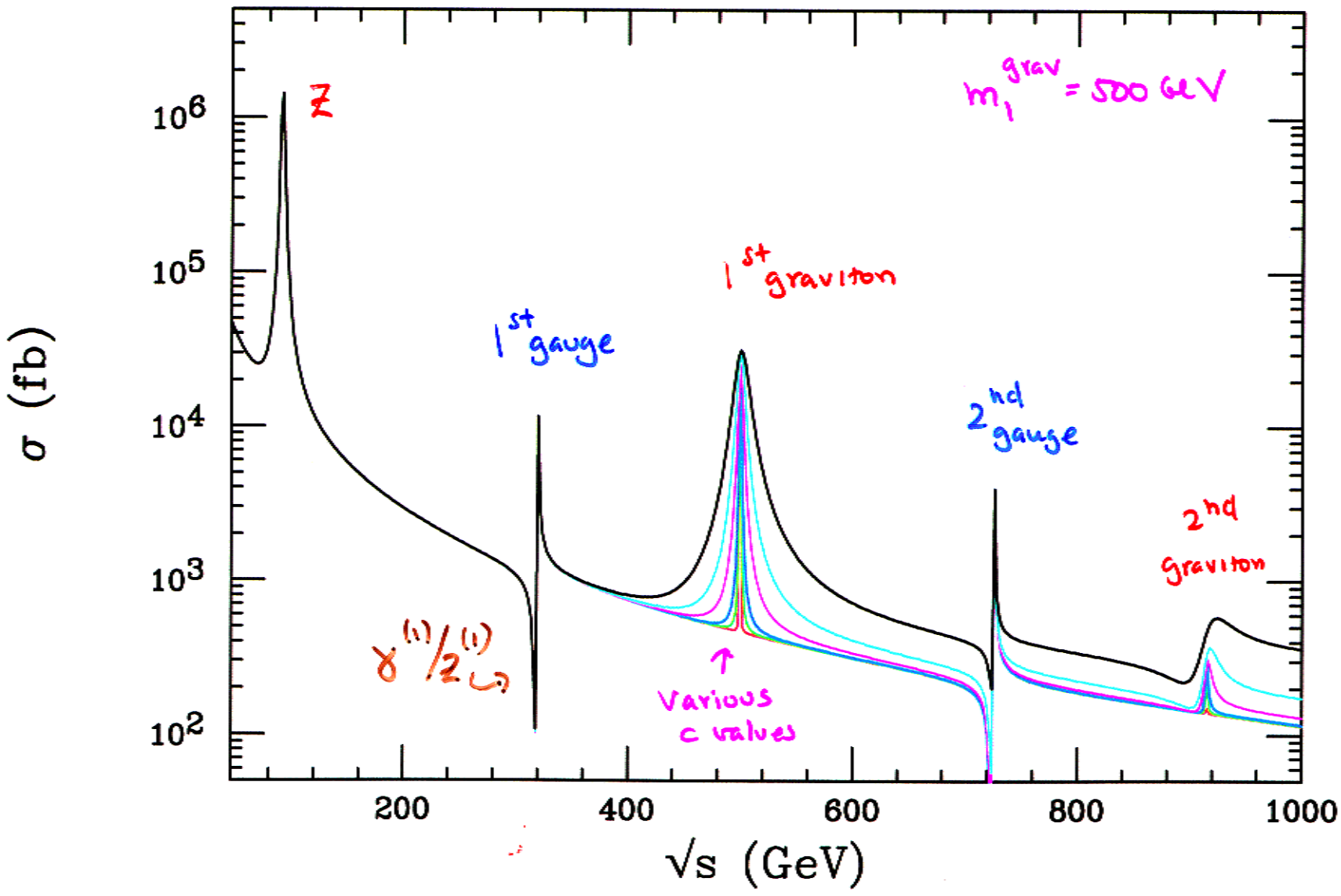
Already

$k/\bar{M}_{Pl}$ much smaller than 10^{-2}

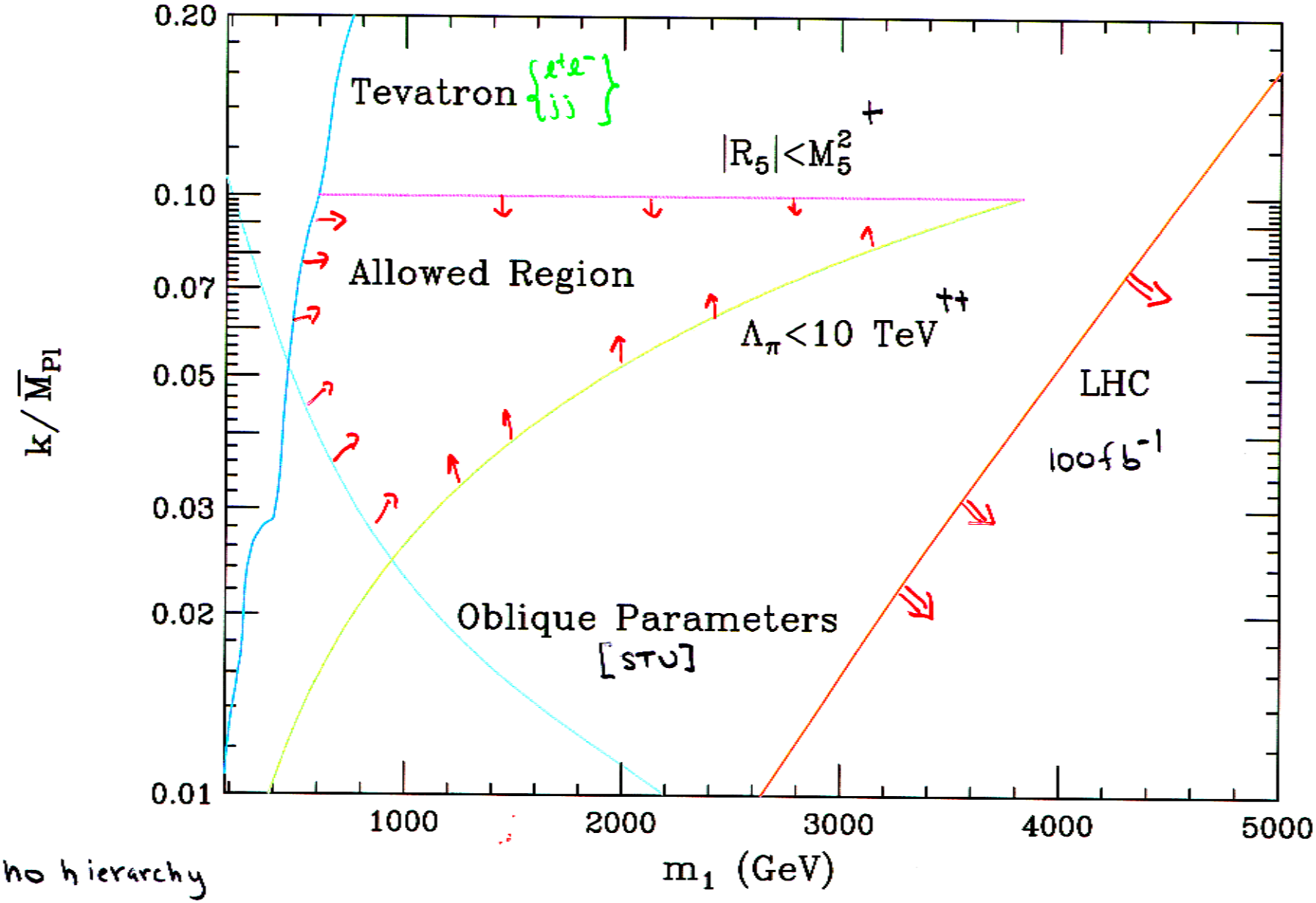
looks bad for hierarchy problem solution...

$e^+e^- \to \mu^+\mu^-$ @ LC

$\nu \approx -0.45$



Regions II + III



++ no hierarchy

+ no higher order curvature terms { unless Gauss-Bonnet } (Kim, Kyae + Long)

Universal Torsion Induced Interaction from Large Extra Dimensions

Tatsu Takeuchi
Virginia Tech

with

Lay Nam Chang
Oleg Lebedev
Will Loinaz

hep-ph/0005236 (to appear in P.R.L.)

What is Torsion?

$$T^{\alpha}{}_{\beta\gamma} = \tilde{\Gamma}^{\alpha}{}_{\beta\gamma} - \tilde{\Gamma}^{\alpha}{}_{\gamma\beta}$$

Usually set to zero in General Relativity since it cannot be removed by a change of coordinates. However:

Metric $\Longleftrightarrow$ Energy-Momentum

Torsion $\Longleftrightarrow$ Spin

Natural to include torsion in the presence of fermions.

The Model:

1. All Standard Model particles are confined to 4 dimensions.

2. Gravity, with torsion, exists in $4+n$ dimensions.

Action:

$$S = -\frac{1}{\hat{\kappa}^2}\int d^{4+n}x \sqrt{|\hat{g}_{4+n}|}\,\tilde{R}$$

$$+\int d^4x \sqrt{|\hat{g}_4|}\,\frac{i}{2}\left[\bar{\psi}\gamma^\mu \tilde{\nabla}_\mu \psi - (\tilde{\nabla}_\mu \bar{\psi})\gamma^\mu \psi + 2iM\bar{\psi}\psi\right]$$

$$\hat{\kappa}^2 = 16\pi G_N^{(4+n)}$$

Eliminate torsion from action:

$$S = -\frac{1}{\hat{\kappa}^2}\int d^{4+n}x\,\sqrt{|\hat{g}_{4+n}|}\,R$$

$$+\int d^4x\,\sqrt{|\hat{g}_4|}$$

$$\times\Big[\bar{\psi}(i\gamma^\mu\nabla_\mu - M)\psi + \underbrace{\frac{3}{32}\frac{\sqrt{|\hat{g}_4|}}{\sqrt{|\hat{g}_{4+n}|}}\hat{\kappa}^2(\bar{\psi}\gamma_\mu\gamma_5\psi)^2\delta^{(n)}(0)}_{\text{Torsion Induced Four Fermion Interaction!!}}\Big]$$

Regularize δ-function

brane width $\approx$ planck mass in $4+n$

$$\delta^{(n)}(x) \to \frac{1}{(2\pi)^n}\int_0^{M_s} d^nk = \frac{M_s^n}{2^{n-1}\pi^{n/2}\,n\,\Gamma(n/2)}$$

$$\hat{\kappa}^2 = 16\pi(4\pi)^{n/2}\Gamma(n/2)\,M_s^{-(n+2)}$$

$$\Delta S = \int d^4x\,\frac{3\pi}{nM_s^2}\Big[\sum_j \bar{\psi}_j\gamma_\mu\gamma_5\psi_j\Big]^2$$

sum over all flavors

$$\frac{3\pi}{n M_s^2}\left[\sum_j \bar{\psi}_j \gamma_\mu \gamma_5 \psi_j\right]^2$$

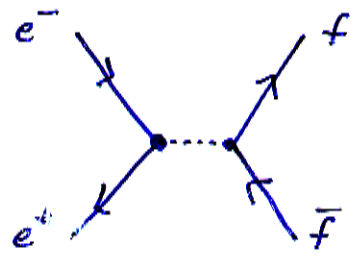
NO SUPPRESSION DUE TO ENERGY OR BRANE RECOIL

Universal !!

U(45) invariant

Can we constrain the size of this interaction ?

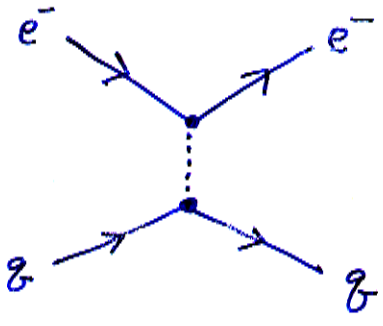
OPAL



$\sqrt{n} M_s \geq 10.3$ TeV

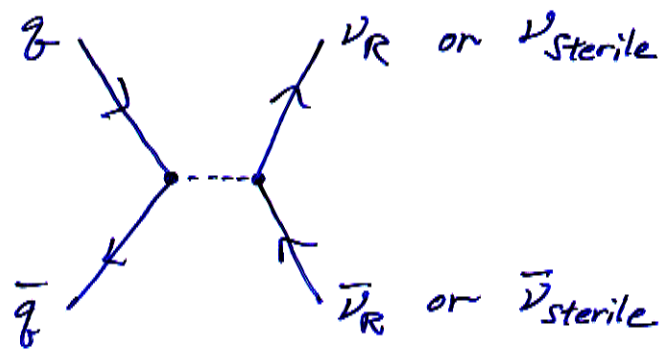
HERA

etc.



$\sqrt{n} M_s \geq 5.3$ TeV

SN 1987A



$$\sqrt{n}\, M_s \geq 210 \text{ TeV}$$

Electroweak symmetry breaking and extra dimensions

Talk by Hsin-Chia Cheng (Univ. of Chicago)

N. Arkani-Hamed, H.-C. Cheng, B. Dobrescu, L. Hall, hep-ph/0006238

Observed fermions and gauge bosons in extra dimensions:

$SU(3)_C \times SU(2)_W \times U(1)_Y$ are attractive strongly-coupled interactions in certain fermion–anti-fermion channels.

Standard Model quantum numbers $\Rightarrow$ most attractive channel is a composite up-type Higgs doublet!

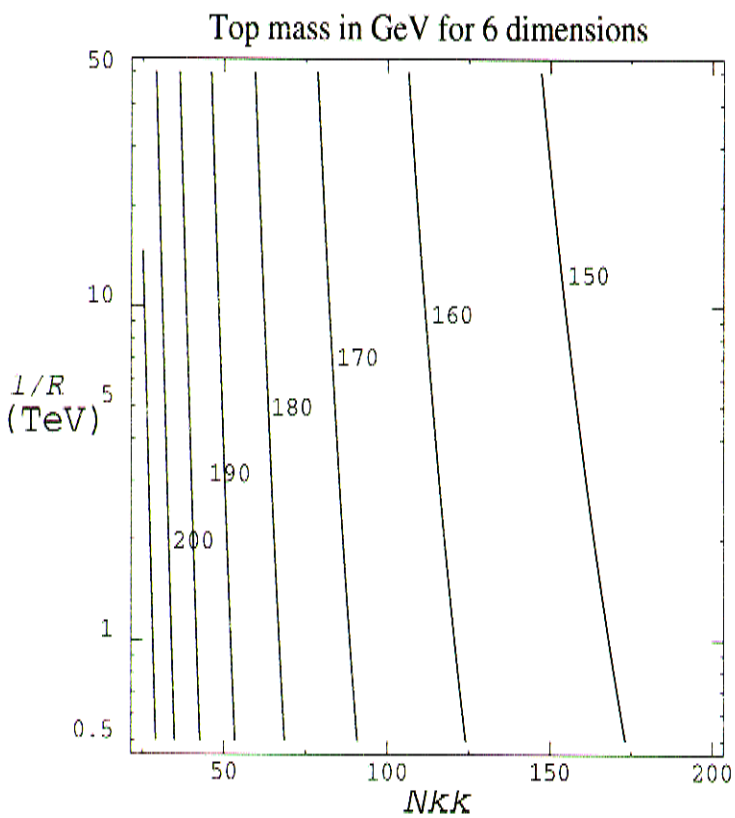
With 2 extra dimensions:

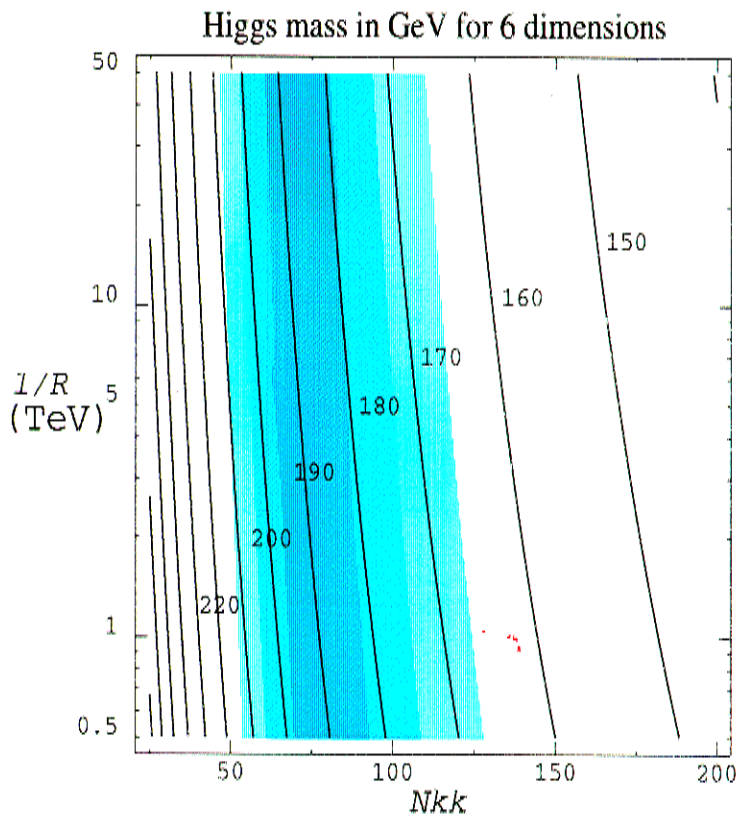
scalar	made of	$SU(3)\times SU(2)\times U(1)$ representation	binding strength	relative binding for $\hat{g}_1 = \hat{g}_2 = \hat{g}_3$
$H_{\mathcal{U}}$	$\overline{\mathcal{Q}}_+\mathcal{U}_-$	$(1, 2, +1/2)$	$\frac{4}{3}\hat{g}_3^2 + \frac{1}{15}\hat{g}_1^2$	1
$H_{\mathcal{D}}$	$\overline{\mathcal{Q}}_+\mathcal{D}_-$	$(1, 2, -1/2)$	$\frac{4}{3}\hat{g}_3^2 - \frac{1}{30}\hat{g}_1^2$	0.93
$\tilde{q}$	$\overline{\mathcal{Q}}_+\mathcal{D}_-^c$	$(3, 2, +1/6)$	$\frac{2}{3}\hat{g}_3^2 + \frac{1}{30}\hat{g}_1^2$	0.5
X	$\overline{\mathcal{Q}}_+\mathcal{U}_-^c$	$(3, 2, -5/6)$	$\frac{2}{3}\hat{g}_3^2 - \frac{1}{15}\hat{g}_1^2$	0.43
$H_{\mathcal{E}}$	$\overline{\mathcal{L}}_+\mathcal{E}_-$	$(1, 2, -1/2)$	$\frac{3}{10}\hat{g}_1^2$	0.21
$\tilde{q}'$	$\overline{\mathcal{L}}_+^c\mathcal{U}_-$	$(3, 2, +1/6)$	$\frac{1}{5}\hat{g}_1^2$	0.14
$\tilde{q}''$	$\overline{\mathcal{L}}_+\mathcal{D}_-$	$(3, 2, +1/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07
X'	$\overline{\mathcal{Q}}_+^c\mathcal{E}_-$	$(3, 2, -5/6)$	$\frac{1}{10}\hat{g}_1^2$	0.07

Predictions of the minimal model in extra dimensions

N. Arkani-Hamed, H.-C. Cheng, B. Dobrescu, L. Hall, hep-ph/0006238

Infrared fixed points: m_t and M_h predictions from the RGE are rather insensitive to the unknown effects of the strongly coupled theory at the ultraviolet scale.





140 GeV $< m_t <$ 220 GeV, **165 GeV $< M_h <$ 210 GeV**

Experimental signals:

Kaluza-Klein modes of all Standard Model particles, and other possible bound states (in addition to the Higgs boson).

2 extra dimensions: two Higgs doublet model below $1/R$

4 extra dimensions: two Higgs doublet model, and a bound state $\tilde{b}$ having the quantum numbers of a bottom-squark!

Look for $e^+e^- \to t\bar{b}\tilde{b}$ or $\tilde{b}\bar{\tilde{b}}$, with $\tilde{b} \to \bar{t}b$.

Collider Signals for Non-Commutative Field Theories

F. Petriello, JLH, T. Rizzo

Motivation for NCQFT:

- Why not? It's interesting!
- String Theory: NCQFT arises through quantization of strings by describing the low-energy excitations of D-branes in background EM fields

Non-Commutative Quantum Field Theories

Generalization of n-dimensional space R^n

Coordinates $x_\mu \Rightarrow$ Operators $\hat{X}_\mu$

$$[\hat{X}_\mu, \hat{X}_\nu] = i\,\theta_{\mu\nu} = \frac{i}{\Lambda_{NC}^2}\, c_{\mu\nu}$$

Space-time "uncertainty" relation $\Delta\hat{X}_\mu \Delta\hat{X}_\nu \geq \frac{1}{2}|\theta^{\mu\nu}|$

Similar to $\Delta x \Delta p \geq \frac{i}{2}\hbar$

Λ_{NC} = Scale where NC becomes relevant

Most likely value for Λ_{NC} ???

- Probably Planck scale, but which one?

$m_{Pl} \sim 10^{19}$ GeV vs $m_* \sim$ TeV

$c_{\mu\nu}$ = anti-symmetric matrix w/ elements $\mathcal{O}(1)$

components are identical in all frames

$\Rightarrow$ breaks Lorentz invariance at Λ_{NC}

Formulation of NC Quantum Field Theory

Fields $\phi(x) \Rightarrow$ Operators $\hat{\phi}(\hat{x})$ via Weyl-Moyal Correspondence

Must be careful to preserve ordering in FT!

Introduce Fourier transform pair:

$$\hat{\phi}(\hat{x}) = \int \frac{d^4k}{(2\pi)^4}\, \phi(k)\, e^{ik\hat{x}}$$

$$\phi(k) = \int d^4x\, \phi(x)\, e^{-ikx}$$

Product of 2 Fields $\Rightarrow$ Star Product

$$\hat{\phi}(\hat{x})\,\hat{\phi}(\hat{x}) = \phi(x) * \phi(x)$$

$$= \int \frac{d^4k}{(2\pi)^4} \frac{d^4p}{(2\pi)^4}\, \phi(k)\,\phi(p)\, e^{ik\hat{x}}\, e^{ip\hat{x}}$$

$$= \phi(x)\, \exp\left\{ \tfrac{i}{2}\, \theta^{\mu\nu} \overleftarrow{\partial}_\mu \overrightarrow{\partial}_\nu \right\} \phi(x)$$

$$= \phi(x)\,\phi(x) + \frac{i}{2}\, \theta^{\mu\nu} \partial_\mu \phi\, \partial_\nu \phi + \mathcal{O}(\theta^2) + \cdots$$

NCQFT = QFT with products $\Rightarrow$ Star Products

+ Moyal brackets

$$[A, B]_{MB} = A * B - B * A$$

with $\int d^4x \, [A(x), B(x)]_{MB} = 0$

NCQFT General Properties

1) Only $U(n)$ Lie algebras are closed under Moyal brackets — Matsubara

$\Rightarrow$ NC gauge theories only based on $U(n)$

2) Renormalizable, gauge invariant FT remain so — Martin, Sanchez-Ruiz ⋮

(But SSB? Campbell, Kaminsky)

3) Covariant derivatives constructed only for fields w/ $Q = 0, \pm 1$

4) NCQFT w/ space-space NC is $\not{CP}$ — Sheikh-Jabbari

NC QED

Hayakawa
Ardolan, Sadooghi
Riad, Sheikh-Jabbari
Martin, Sanchez-Ruiz

$$S_{NCQED} = -\frac{1}{4}\int d^4x\, F_{\mu\nu} * F^{\mu\nu}$$

Gauge invariant under local trans w/

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu]_{MB}$$

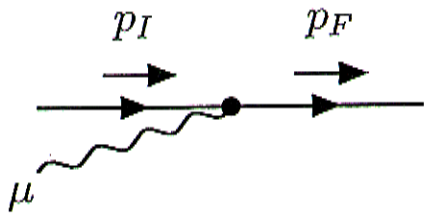
$\Rightarrow$ Induces non-abelian terms!

$\Rightarrow$ 3 + 4-pt functions for γ self-coupling

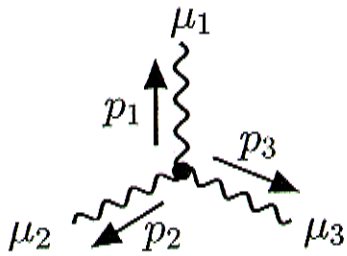
+ interaction vertices pick up momenta dependent phase factors from Fourier transforms

Important for collider tests!

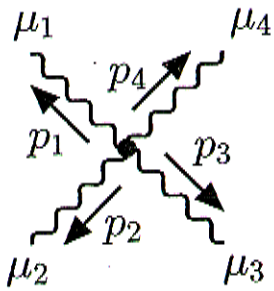
Non-commutative Feynman Rules



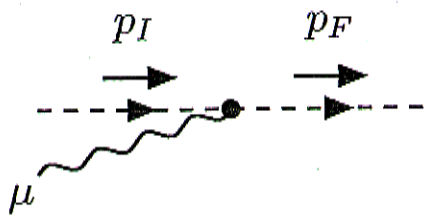
$$= ig\gamma^\mu \exp\left(\tfrac{i}{2} p_I \not{C} p_F\right)$$



$$\begin{aligned} &= +2g \sin\left(\tfrac{1}{2} p_1 \not{C} p_2\right) \\ &\quad \times [(p_1 - p_2)^{\mu_3} g^{\mu_1\mu_2} \\ &\quad + (p_2 - p_3)^{\mu_1} g^{\mu_2\mu_3} \\ &\quad + (p_3 - p_1)^{\mu_2} g^{\mu_3\mu_1}] \end{aligned}$$



$$\begin{aligned} = +4ig^2[&(g^{\mu_1\mu_3} g^{\mu_2\mu_4} - g^{\mu_1\mu_4} g^{\mu_2\mu_3}) \\ &\times \sin\left(\tfrac{1}{2} p_1 C p_2\right) \sin\left(\tfrac{1}{2} p_3 C p_4\right) \\ &+ (g^{\mu_1\mu_4} g^{\mu_2\mu_3} - g^{\mu_1\mu_2} g^{\mu_3\mu_4}) \\ &\times \sin\left(\tfrac{1}{2} p_3 C p_1\right) \sin\left(\tfrac{1}{2} p_2 C p_4\right) \\ &+ (g^{\mu_1\mu_2} g^{\mu_3\mu_4} - g^{\mu_1\mu_3} g^{\mu_2\mu_4}) \\ &\times \sin\left(\tfrac{1}{2} p_1 C p_4\right) \sin\left(\tfrac{1}{2} p_2 C p_3\right)] \end{aligned}$$

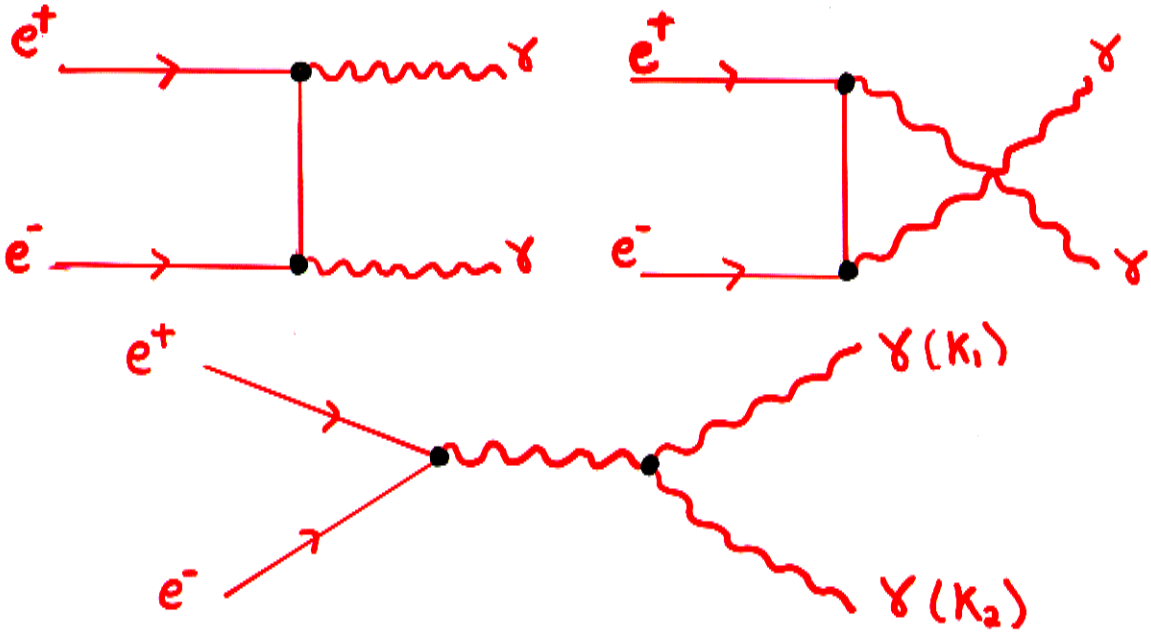


$$= 2igp_F^\mu \sin\left(\tfrac{1}{2} p_I C p_F\right)$$

Propagators are unchanged

$$\int d^4x\, \hat{\phi}(\hat{x}) * \hat{\phi}(\hat{x}) = \int d^4x\, \phi(x)\, \phi(x)$$

Pair Annihilation



$$\frac{d\sigma}{d\cos\theta\, d\phi} = \frac{\alpha^2}{4s}\left[\frac{u}{t} + \frac{t}{u} - 4\,\frac{t^2+u^2}{s^2}\sin^2\left(\tfrac{1}{2}K_1 \wedge K_2\right)\right]$$

$$\Delta_{NC} \equiv K_1 \wedge K_2 = K_1^\mu K_2^\nu C_{\mu\nu}$$

$$= \frac{-s}{2\Lambda_{NC}^2}\left[C_{01}\sin\theta\cos\phi + C_{02}\sin\theta\sin\phi + C_{03}\cos\theta\right]$$

$\Rightarrow$ only probes space-time NC! [in cm frame]

$$= \frac{-s}{2\Lambda_{NC}^2}\left[\cos\theta\cos\alpha + \sin\theta\sin\alpha\cos(\phi-\beta)\right]$$

$$= \frac{-s}{2\Lambda_{NC}^2}\cos\theta_{NC}$$

$\longrightarrow$ $\measuredangle$ between $\vec{E}$ + outgoing γ

Bin integrated distributions - $e^+e^- \to \gamma\gamma$

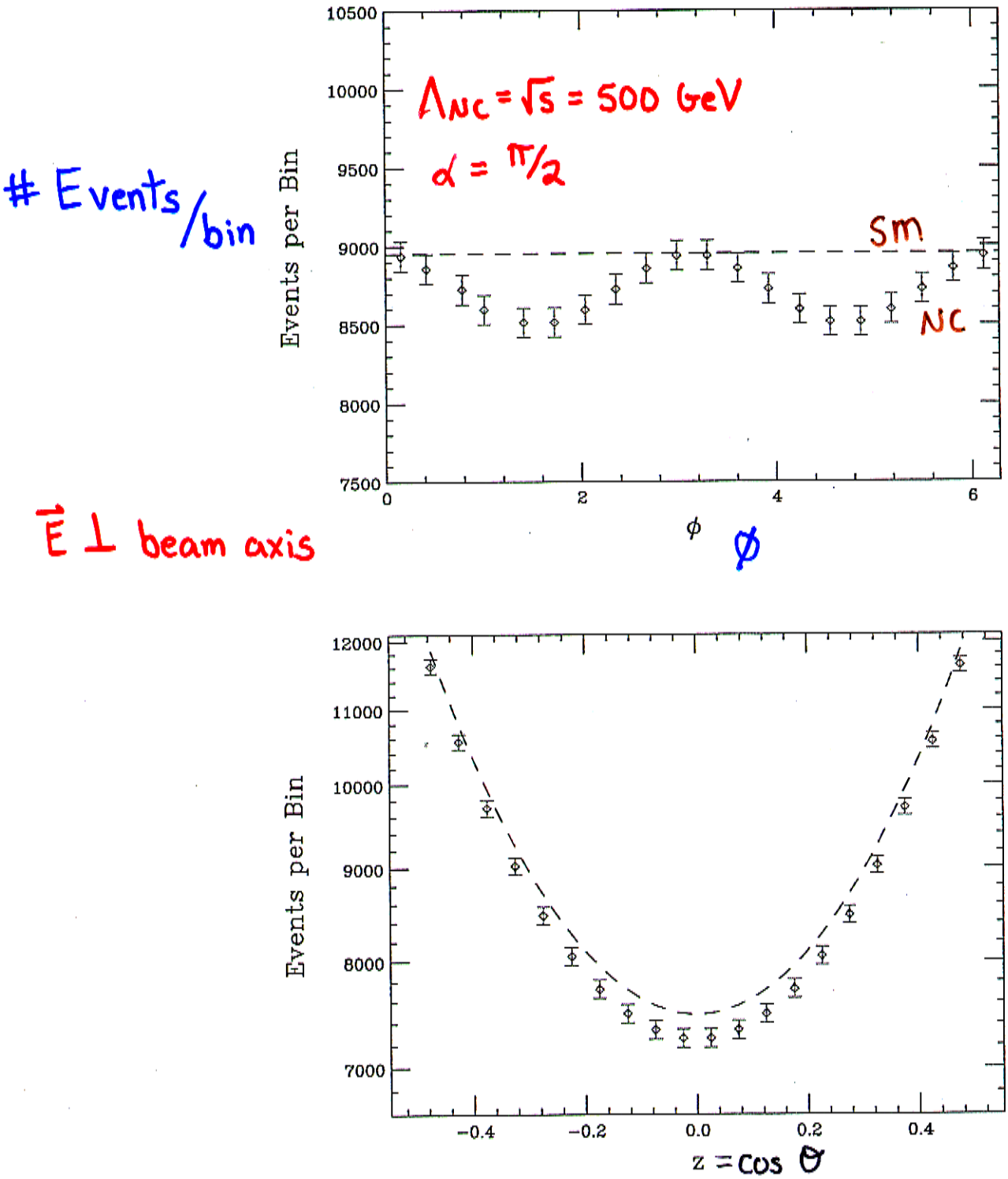


Figure 3: ϕ dependence (top) and θ dependence (bottom) of the $e^+e^- \to \gamma\gamma$ cross section for the case $\alpha = \pi/2$. We use $\Lambda = \sqrt{s} = 500$ GeV, luminosity $500\,\mathrm{fb}^{-1}$, parameters relevant for the NLC. In the top panel a cut $|z| < 0.5$ has been employed. The dashed line is the SM expectation.

III

C.S. Kim

How precisely is Gravity probed (microscopically)

Consider ν - oscillation :

ν-production	ν-propagation	ν-detection
$\hat{H}_{weak}$, $\nu_{e,\mu}$	$\hat{H}_p$, $\nu_{1,2}$	$\hat{H}_{weak}$, $\nu_{e,\mu}$

$\Rightarrow$ If $[\hat{H}_p, \hat{H}_{weak}] \neq 0$,

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$\Rightarrow |\nu_e(t)\rangle = e^{-i\hat{H}_p t} |\nu_e\rangle$$
$$= e^{-iE_1 t} \cos\theta |\nu_1\rangle + e^{-iE_2 t} \sin\theta |\nu_2\rangle$$

$\Rightarrow$ If $E_1 \neq E_2$ (non-degenerate) $\rightarrow$ ν- oscillation.

ν- osc. due to m_ν :

$$\hat{H}_p = E_i = \sqrt{p^2 + m_i^2} \approx p + \frac{m_i^2}{2p}$$ (propagation in Vacuum)

$$A(\nu_e \to \nu_\mu) = \langle \nu_\mu(p) | \nu_e(p) ; t \rangle$$ $\Delta m^2 = m_2^2 - m_1^2$

$$= e^{-ipt - i\frac{m_1^2}{2p}t} \left(\cos^2\theta + e^{-i\frac{\Delta m^2}{2p}t} \sin^2\theta\right)$$

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2}{4p} t\right)$$

$$= \sin^2(2\theta) \cdot \sin^2\left(\frac{\pi L}{\lambda_m}\right)$$ $L \sim t$, $E \sim p$

$$\lambda_m \equiv \frac{4\pi E}{\Delta m^2} = (2.5\,m)\left[\frac{E/MeV}{\Delta m^2/eV^2}\right] \propto E$$

ν-osc. due to E-P violation

[Gasperini; Halpern
Leung, ...]

$$\hat{H}_p = \hat{H}_{Grav} \; ; \; \nu_1^G, \nu_2^G$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_G & -\sin\theta_G \\ \sin\theta_G & \cos\theta_G \end{pmatrix} \begin{pmatrix} \nu_1^G \\ \nu_2^G \end{pmatrix} ;$$

$$|\nu_e(t)\rangle = e^{-i\phi_1 t}\cos\theta_G |\nu_1^G\rangle + e^{-i\phi_2 t}\sin\theta_G |\nu_2^G\rangle$$

If $\phi_1 \neq \phi_2 \rightarrow$ ν-oscillation (even w/ $m_1 = m_2 = 0$)

Treat gravity as a static background
Weak gravitational field $\rightarrow$ linearized:

$$\mathcal{L}_{int} = \frac{if}{4} G^{\alpha\beta}[\bar{\psi}\gamma_\alpha\partial_\beta\psi - \partial_\alpha\bar{\psi}\gamma_\beta\psi] \quad , \; f \equiv \sqrt{8\pi G_N}$$

Eq. of motion for massless ν:

$$[(\eta^{\alpha\beta} + \frac{f_j}{2}G^{\alpha\beta})\gamma_\alpha\partial_\beta + \frac{f_j}{4}(\partial_\alpha G^{\alpha\beta})\gamma_\beta]\nu_j^G = 0 \qquad \eta_{\alpha\beta} = (1,-1,-1,-1)$$

$\rightarrow 0$ (slowly varying G. field)

$$\Rightarrow \quad (\eta^{\alpha\beta} + f_j G^{\alpha\beta})\gamma_\alpha\partial_\beta\nu_j^G = 0 \qquad \text{(to 1st order in } G^{\alpha\beta}\text{)}$$

$f_1 \neq f_2 \rightarrow$ Equivalence-Principle is violated

For a static, spherically symmetric G. source,

$$G^{\alpha\beta} = \frac{2}{f}\phi(r)\delta^{\alpha\beta}, \quad \phi(r) = \text{newtonian G. potential}$$

Energy-momentum relation:

$$E_j^2(1 + 2\phi\frac{f_j}{f}) = P_j^2(1 - 2\phi\frac{f_j}{f})$$

$$\Rightarrow \quad E_j^2 = P_j^2 - 4E_j^2\phi\cdot\frac{f_j}{f} = P_j^2 - \text{"}m_j^2\text{"}$$

$$\text{"}\Delta m_{eff}^2\text{"} = 4E^2|\phi|\cdot\left(\frac{f_2 - f_1}{f}\right) = 4E^2|\phi|\cdot\Delta\gamma$$

$f_1 \neq f_2 \rightarrow (m_1 \neq m_2)_{eff} \rightarrow$ ν-oscillation

$\nu_e \to \nu_\mu$ probability:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_G) \cdot \sin^2\left(\frac{\pi L}{\lambda_G}\right)$$

oscillation length (for constant (slowly varying) ϕ):

$$\lambda_G = \frac{4\pi E}{\Delta m^2_{eff}} = \frac{\pi}{E \cdot |\phi| \cdot \Delta\gamma} \qquad \left(\lambda_m = \frac{4\pi E}{\Delta m^2} \right)$$

$$= 6.2\,\text{km} \left(\frac{10^{-20}}{|\phi| \cdot \Delta\gamma}\right) \cdot \left(\frac{10\,\text{GeV}}{E}\right) \sim \frac{1}{E} \qquad \Delta\gamma \equiv \frac{f_2 - f_1}{f}$$

* at Earth surface $|\phi| \sim 10^{-9}$
" Sun " $\sim 10^{-8}$
" Sun core $\sim 10^{-6}$

Assuming maximal mixing: $\left(\frac{\pi L}{\lambda_G} \sim O(1) \Rightarrow |\phi| \cdot \Delta\gamma \sim \frac{1}{E \cdot L} \right)$

Sensitivity estimation:

Solar ν (just-so)	$\lvert\phi\rvert \cdot \Delta\gamma$
$E \sim 1\,\text{MeV}$	$\sim 10^{-24}$
$L \sim 10^8\,\text{km}$	
Solar ν (MSW)	
$E \sim 1\,\text{MeV}$	$\sim 10^{-22}$
$L \sim 7 \times 10^{-5}\,\text{km}$	
Atmospheric ν	
$E \sim (1 \sim 10^3)\,\text{GeV}$	$\sim 10^{-20} \sim 10^{-26}$
$L \sim (20 \sim 10^4)\,\text{km}$	
Fogli et al. [Best-fit]	$\lvert\phi\rvert \cdot \Delta\gamma < 10^{-24} \sim 10^{-26}$
	(w/ $\sin^2 2\theta_G = 0 \leftrightarrow 1$)

<Cf : Test of E-P>

1890 Eötvös	10^{-8}
⋮	⋮
1971 Braginsky and Panov	10^{-12}

The Search for Maximal Weirdness

Joseph Lykken

Theoretical Physics Dept.
Fermilab

LCWS 2000, 24-28 Oct, Fermilab

String Theory Unbound

To what extent can we use string theory as a guide/prognosticator of Beyond-the-SM phenomenology?

- Problem: string theory has a huge number of stable consistent vacuum states, giving wildly different low energy physics.
- Some day string theory will indeed correlate in deep ways the parameters of the effective theory that we have measured in experiments.
- This requires understanding string theory at a more fundamental level, as well as mapping out the moduli space of its possible vacuum states.

- Meanwhile, string theory is already affecting our thinking about Beyond the Standard Model physics. This influence is of two types:

  - Suggesting new physics possibilities or scenarios which would seem unmotivated (i.e. wacko) otherwise.

  - Making connections between new physics ideas which seem unrelated from a conventional field theory perspective.

- In the bottom up approach, we isolate certain aspects, ideas, and degrees of freedom of string theory and ignore the rest.

- This is certainly much easier than doing real string theory, although this game can also be played in string theory by taking advantage of special decoupling and/or simplifying limits.

- At any rate this is a productive and probably not too misguided strategy.

- Of course a prime example of this strategy are the braneworld extra dimensions scenarios.
- These scenarios involve at least two new kinds of Beyond-the-SM degrees of freedom:
  - Kaluza-Klein (KK) modes for particles in the bulk, and
  - Brane fluctuation modes.
- Experiments measure an effective KK mode spectral density $\rho(m^2)$, where the KK mass m^2 is just the total of the squared momentum components transverse to the brane. This density $\rho(m^2)$ depends both on the geometry of the extra dimensions, and on wave function suppression of the couplings.

Compositeness and nonlocality

- Indeed this network of ideas seems to be telling us something important about the role of compositeness and of nonlocality:
- Interesting new versions of compositeness are popping up in various new strong coupling regimes (B. Dobrescu; A. Nelson and M. Strassler, N. Arkani-Hamed,...).
- Nonlocal effects on potentially observable scales are also popping up all over (see e.g. J. Hewett's talk).

- I will discuss one unusually weird manifestation of both these concepts...

Elementary particles as black holes

- Our understanding of black hole physics has greatly advanced by considering branes as microscopic (extremal, extra-dimensional) limits of black holes. So black holes $\Leftrightarrow$ branes.

- D-branes appear as special BPS solitons in certain limits of string theory. They include DØ branes, particle-like objects. Because they are BPS, the spectrum of n bound DØ branes looks like a tower of evenly spaced massive modes - in fact they are the KK modes of the 11th dimension of M-theory. So particles $\Leftrightarrow$ solitons $\Leftrightarrow$ KK modes.

- Are all elementary particles in some sense black holes?

L. Susskind, ...

- Suppose we consider particle collisions at superPlanckian energies. Here "Planck" is the effective Planck scale M_*, which could be just a few TeV.
- Roughly speaking, if the impact parameter b is smaller than or of the order of

$$b \sim \sqrt{s}/M_*^2$$

then a black hole will form. Thus a high energy point particle becomes an object with finite transverse "size" b.

- The Compton wavelength *decreases* with increasing energy, while the transverse "size" *increases* with increasing energy.
- Energy growing with size sounds like strings or branes.

Maximal Weirdness

- It now appears in string theory that there are examples where "particles" acquire a transverse size at high energies:
- E.g. "Attack of the giant gravitons from Anti de Sitter space" (J. McGreevy, L. Susskind, N. Toumbas).
- E.g. Wrapped branes in warped compactifications of M theory or string theory (E. Silverstein).

In the second case, we compactify 11 dim Horava-Witten theory on a K3 surface, and wrap a 2-brane on a cycle of the K3 with some area A_0. The geometry is warped along the 11th dimension (call this coordinate y).

- In fact, this object is neither a point particle nor a brane, rather it is something in between.

- You can see this by counting states. Compute the KK modes (with respect to the warped direction y) of the wrapped 2-brane. The scalar KK modes are the solutions of a 1 dim Schrodinger eqn with a potential which is approximately quadratic. The KK modes are discrete with

$$E^4 \propto (n + 1/2)$$

- The number of these KK states increases like E^4, compared to $n \propto E$ for a point particle! On the other hand, for a brane (or any extended object), the number of states increase exponentially with energy.

- These new objects are called elastic states (nylons).

Phenomenology

- Could there be accessible regimes where what you thought were point particles turn into nylons?
- Linear colliders are a good way to look for this!
- Note this is not like the usual quark/lepton compositeness, since there (presumably) aren't any bound pointlike constituents. You don't necessarily generate the 4-fermion terms of Eichten-Lane-Peskin, just form factors:

$$\frac{d\sigma}{dQ^2} = \left(\frac{d\sigma}{dQ^2}\right)_{SM} \cdot F_e^2(Q^2) \cdot F_f^2(Q^2),$$

where

$$F(Q^2) = 1 + \frac{1}{6}Q^2 R^2$$

The current best limits on this "electron radius" appear to be from LEP (D. Bourilkov):

$$R_e < 2.8 \cdot 10^{-17}\text{cm}$$