THEORETICAL PREDICTIONS FOR COLLIDER SEARCHES

G.F. Giudice CERN

- “Big” and “little” hierarchy problems
- Supersymmetry
- Little Higgs
- Extra dimensions

Lepton Photon 2003
XXI International Symposium on Lepton and Photon Interactions at High Energies • Fermilab

HIERARCHY PROBLEM

$$\delta m_H^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda_{SM}^2\left(6m_W^2 + 3m_Z^2 + m_H^2 - 12m_t^2\right)$$

$$= -\left(\frac{\Lambda_{SM}}{0.7\ \mathrm{TeV}}\,200\ \mathrm{GeV}\right)^2$$

no fine-tuning ⇨ Λ_{SM} < TeV

"Big" hierarchy between Λ_{SM} and M_{Pl}

Cosmological constant ⇨

Cut off of quartic divergences at $\Lambda < 10^{-3}$ eV

LITTLE HIERARCHY

		−	+
LEP1	$H^+\tau^a H W^a_{\mu\nu} B_{\mu\nu}$	10	9.7
	$\left\|H^+ D_\mu H\right\|^2$	5.6	4.6
	$iH^+ D_\mu H \bar{L}\gamma_\mu L$	9.2	7.3
LEP2	$\bar{e}\gamma_\mu e \bar{\ell}\gamma^\mu \ell$	6.1	4.5
	$\bar{e}\gamma_\mu\gamma_5 e \bar{b}\gamma^\mu\gamma_5 b$	4.3	3.2
MFV	$\frac{1}{2}\left(\bar{q}_L \lambda_u \lambda_u^+ \gamma_\mu q\right)^2$	6.4	5.0
	$H^+ \bar{d}_R \lambda_d \lambda_u \lambda_u^+ \sigma_{\mu\nu} q_L F^{\mu\nu}$	9.3	12.4

Bounds on Λ_{LH}

$$\mathrm{L} = \pm \frac{1}{\Lambda_{\mathrm{LH}}^2} O$$

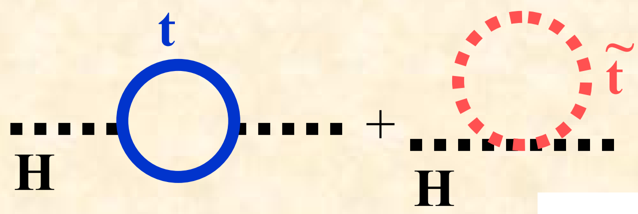
Λ_{LH} > 5-10 TeV

Λ_{SM}<1 TeV, Λ_{LH}>5-10 TeV

“Little” hierarchy between Λ_{SM} and Λ_{LH} ⇨

- New physics at Λ_{SM} is weakly interacting
- No (sizable) tree-level contributions from new physics at Λ_{SM}
- Strongly-interacting physics can only occur at scales larger than Λ_{LH}
- Successful new physics at Λ_{SM} has to pass non-trivial tests

SUPERSYMMETRY

$\delta m_H^2 =$ 

Λ can be extended to M_{Pl}

-Link with quantum gravity

-Successful scenario for GUT

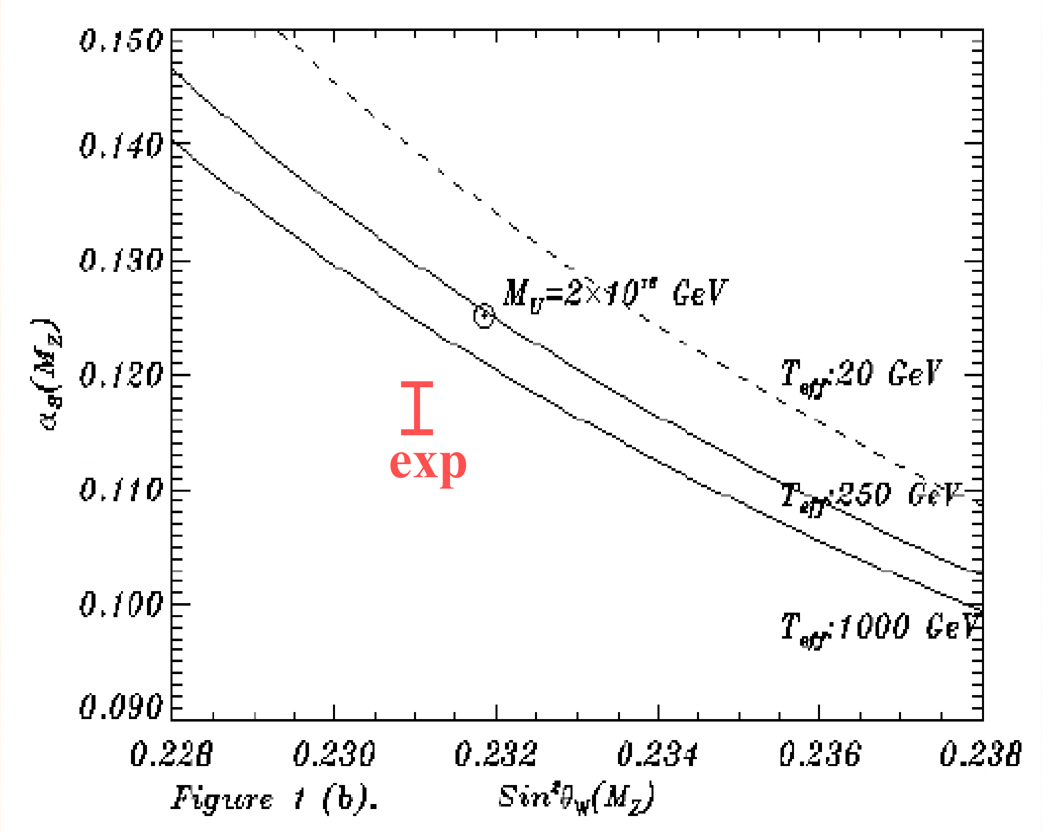


Figure 1 (b).

Ghilencea-Ross

UNIFICATION WITHOUT DESERT

Dienes-Dudas-Gherghetta

- Accelerated running from extra dimensions
- or from gauge group replication Arkani Hamed-Cohen-Georgi
- Different tree-level expression for $\sin^2\theta_W$

GUT: $\sin^2\theta_W = \frac{\mathrm{Tr}\, I_3^2}{\mathrm{Tr}\ \mathrm{Q}^2} = \frac{3}{8}$ trace over GUT irrep

$$SU_3 \times SU_2 \times U_1 \to SU_2 \times U_1$$

$$\text{for } \tilde{g}_2, \tilde{g}_1 >> \tilde{g}_3 \Rightarrow \sin^2\theta_W = \frac{1}{4}$$

Dimopoulos-Kaplan

Little running needed

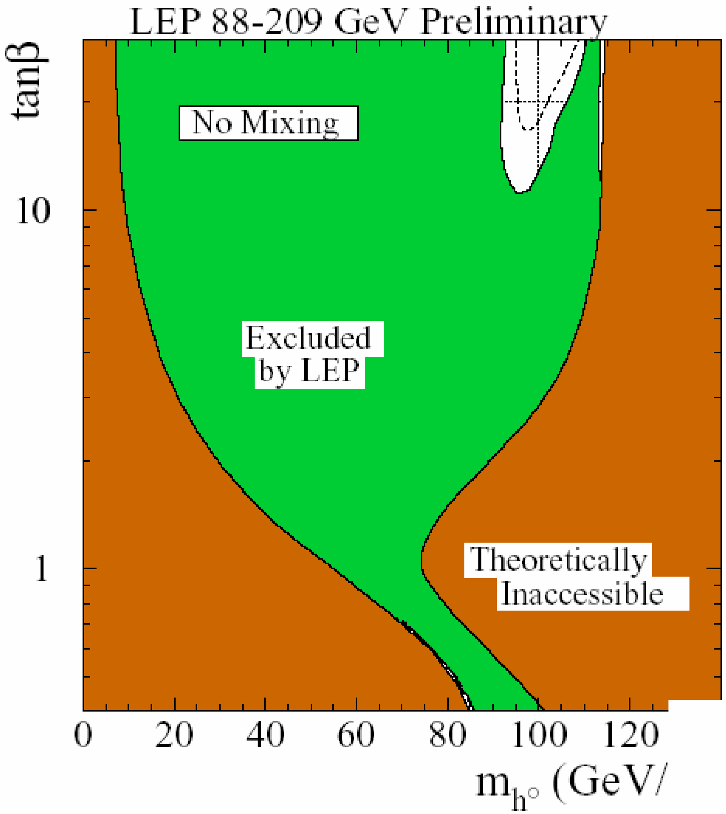
SUPERSYMMETRY

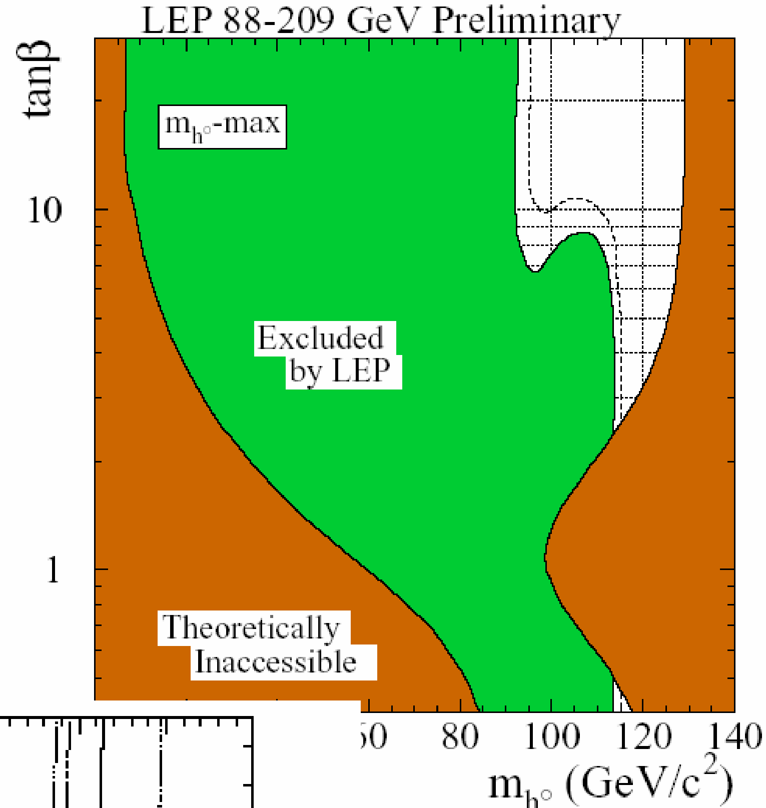
☺

- Gauge-coupling unification
- Radiative EW breaking
- Light Higgs
- Satisfies “little” hierarchy $\Lambda_{LH} \sim 4\pi\Lambda_{SM}$
- Dark matter

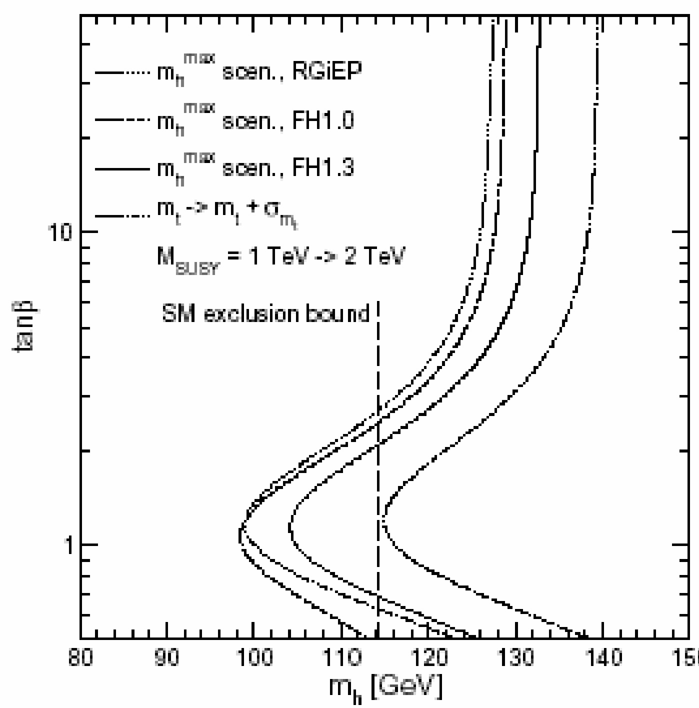
☹

- Sparticles have not been observed
- Susy-breaking sector unspecified

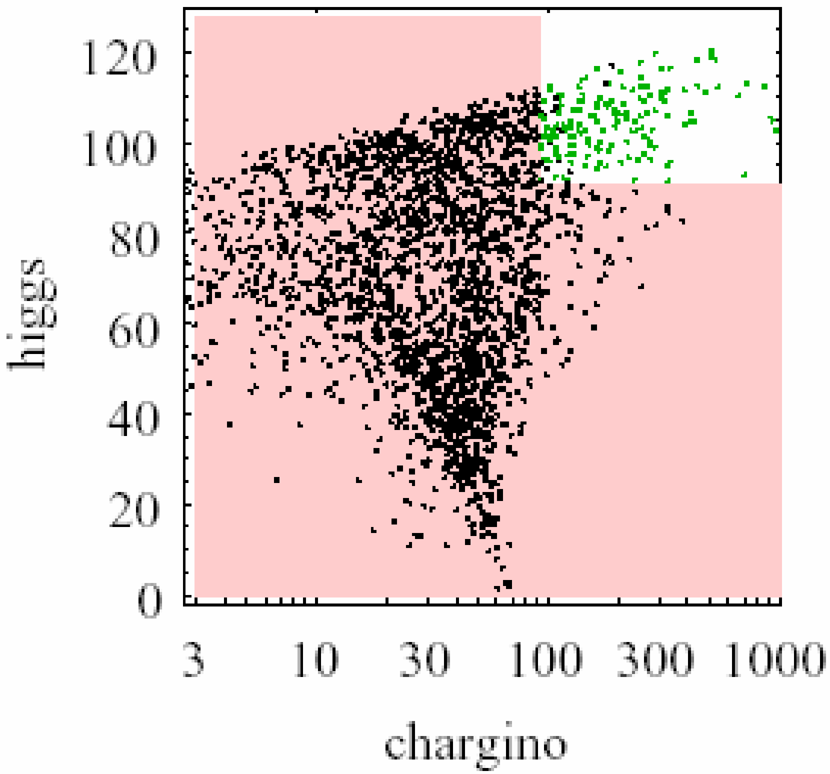




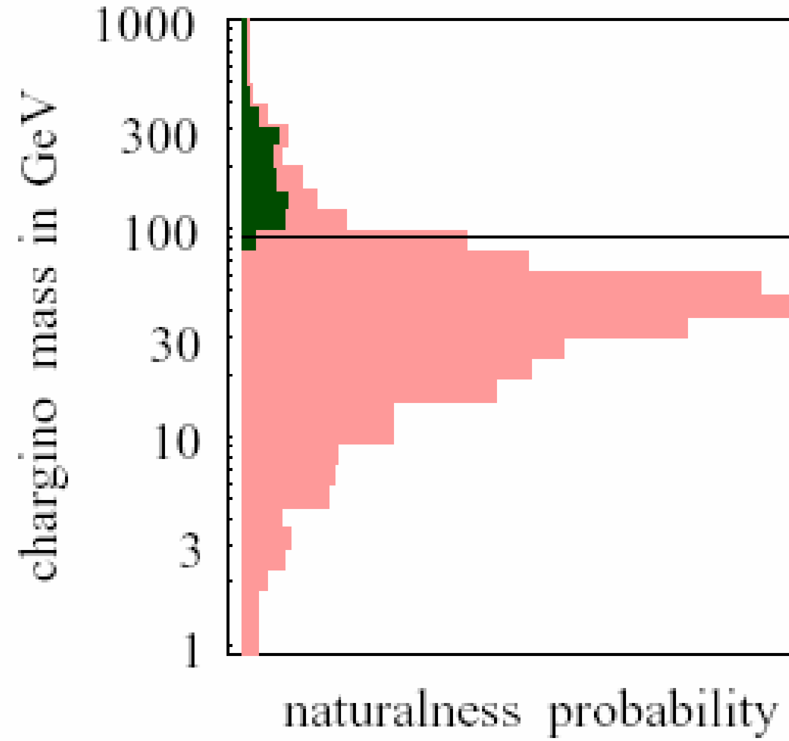
$M\chi+ > 103.5$ GeV



Degrassi-Heinemeyer-Hollik-Slavich-Weiglein



Giusti-Romanino-Strumia



$$\frac{\theta_{\text{sun}} - \theta_{\text{moon}}}{\theta_{\text{sun}}} = 3\%$$

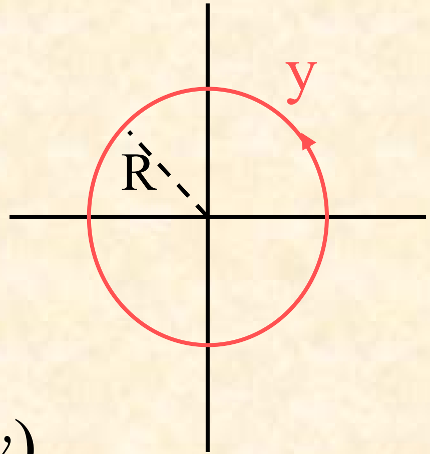
Supersymmetry-breaking sector unspecified

Susy flavour violations	⇨	gauge, gaugino mediation
Connection with gravity	⇨	supergravity, anomaly mediation
μ problem	⇨	supergravity
Predictivity	⇨	gauge, gaugino, anomaly med.

Scenarios with different spectra and different experimental signals

NEW INGREDIENTS FROM EXTRA DIMENSIONS

Scherk-Schwarz breaking



$$\Phi(x, y + 2\pi R) = e^{2\pi i Q_\Phi} \Phi(x, y)$$

KK expansion with boundary conditions

$$\Phi(x, y) = e^{iQ_\Phi y/R} \sum_{n=-\infty}^{+\infty} e^{iny/R} \Phi_n(x) \quad \Rightarrow \quad m_n^2 = \frac{(n + Q_\Phi)^2}{R^2}$$

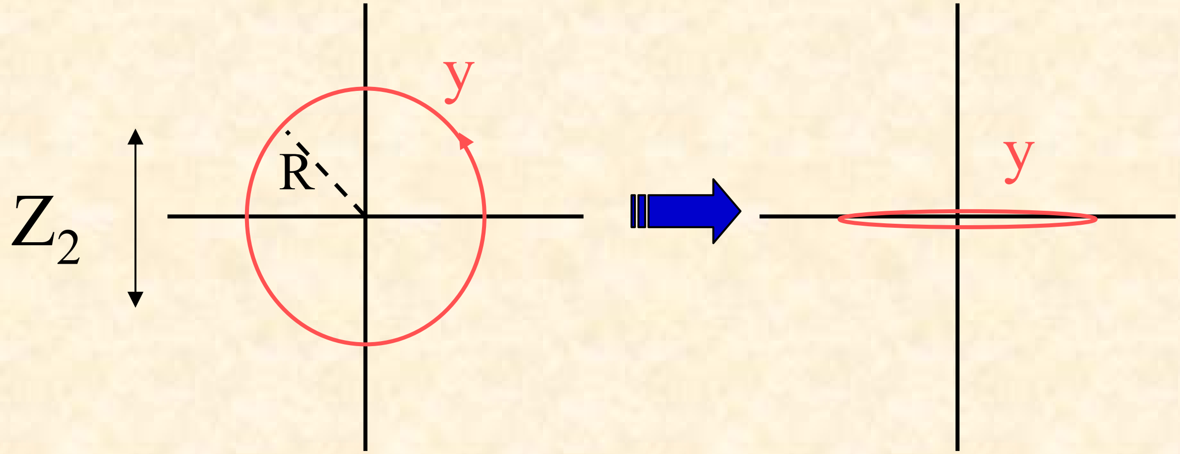
If Q is R-symmetry $\Rightarrow$ **Supersymmetry is broken**

Non-local susy breaking ⇨ involves global structure

At short distances (<R), susy-breaking effects are suppressed

NEW INGREDIENTS FROM EXTRA DIMENSIONS

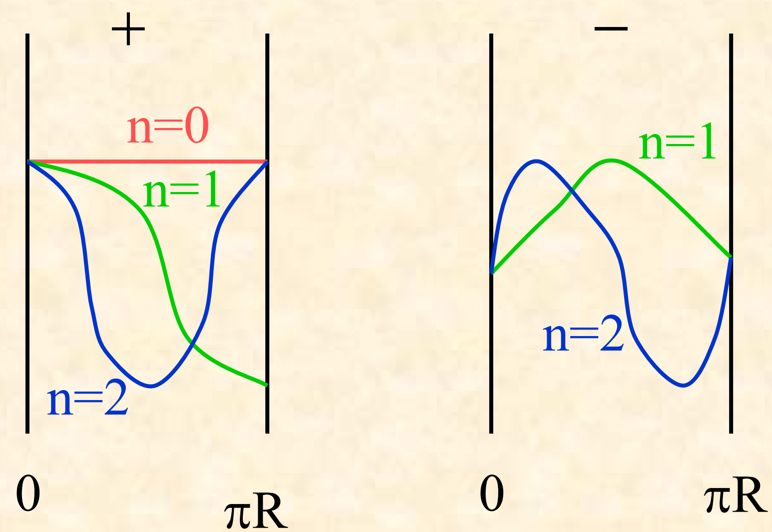
Orbifold projection



Z_2 : y → −y

cos(ny/R)   sin(ny/R)

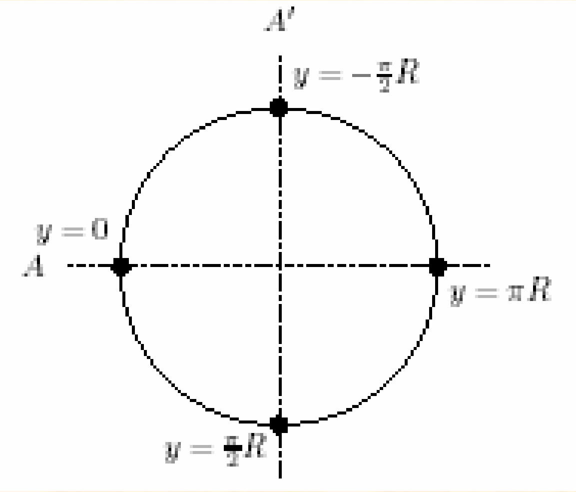
Chiral theories



AN INTERESTING EXAMPLE

Barbieri-Hall-Nomura

5D SUSY SM compactified on $S^1/(Z_2 \times Z_2)$



- Different susy breaking at each boundary

→effective theory non-susy

(susy recovered at d<R)

- Higgs boson mass (rather) insensitive to UV

$m_H = 127 \pm 10$ GeV

Large corrections to $\Delta\rho$?

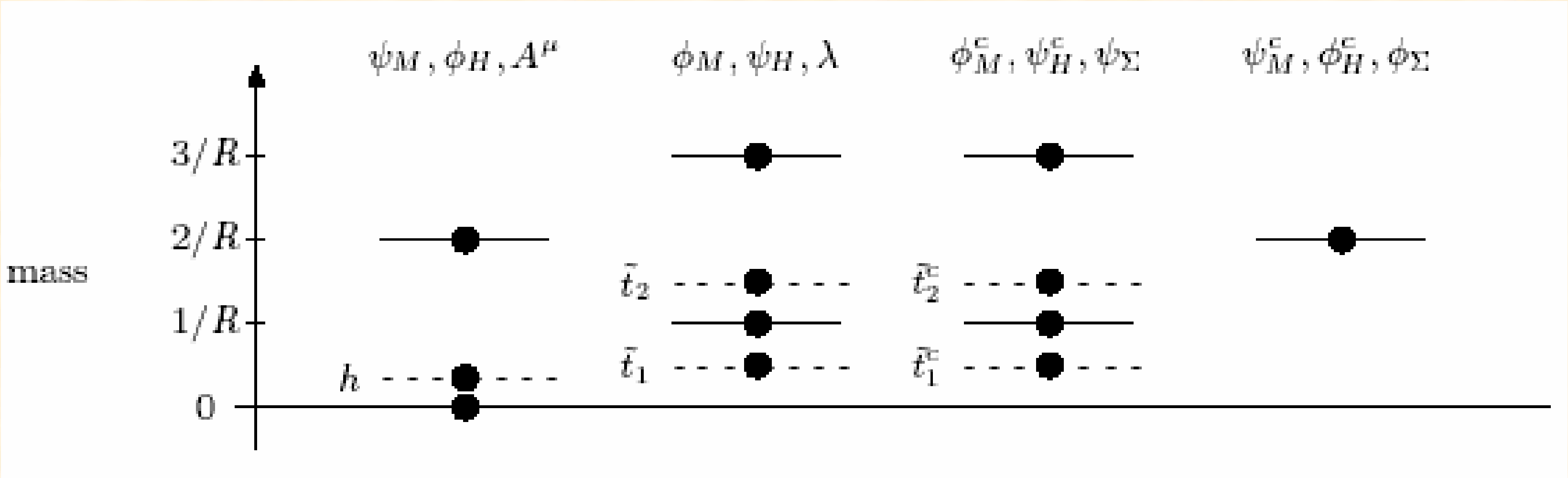
UV completion at $\Lambda \sim 5$ TeV ?

Barbieri-Hall-Marandella-Nomura-Okui-Oliver-Papucci

Mass spectrum is non-supersymmetric

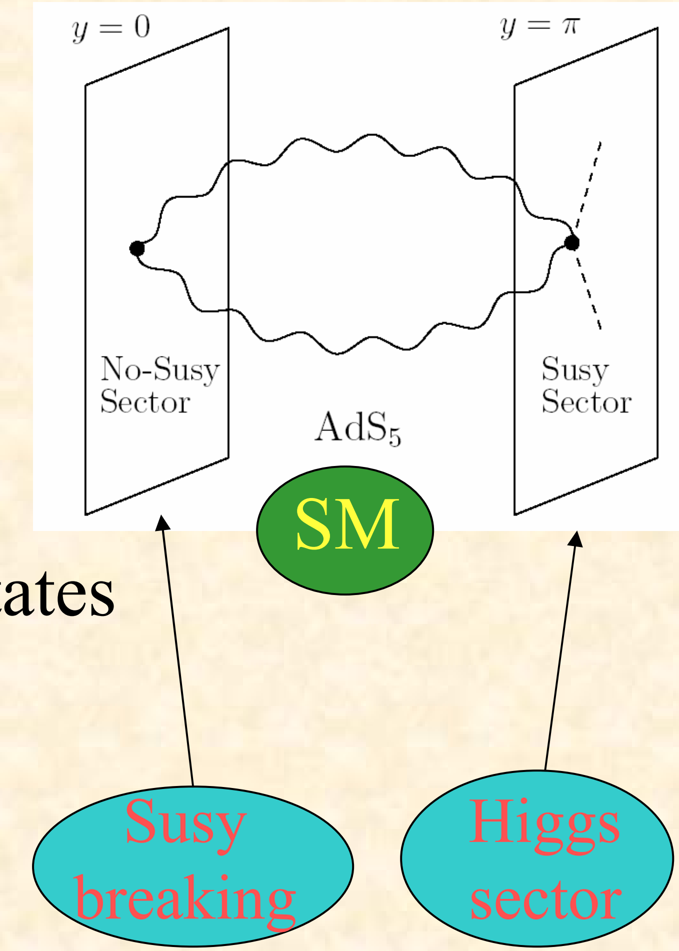
• one Higgs and two sparticles for each SM particle

• LSP stable stop with mass 210 GeV



USING WARPED DIMENSIONS

Gherghetta-Pomarol



- Susy-breaking in Higgs sector is non-local ⇨ finite effects

- AdS/CFT ⇨ SM non-susy

Higgs sector: susy bound states of spontaneously broken CFT

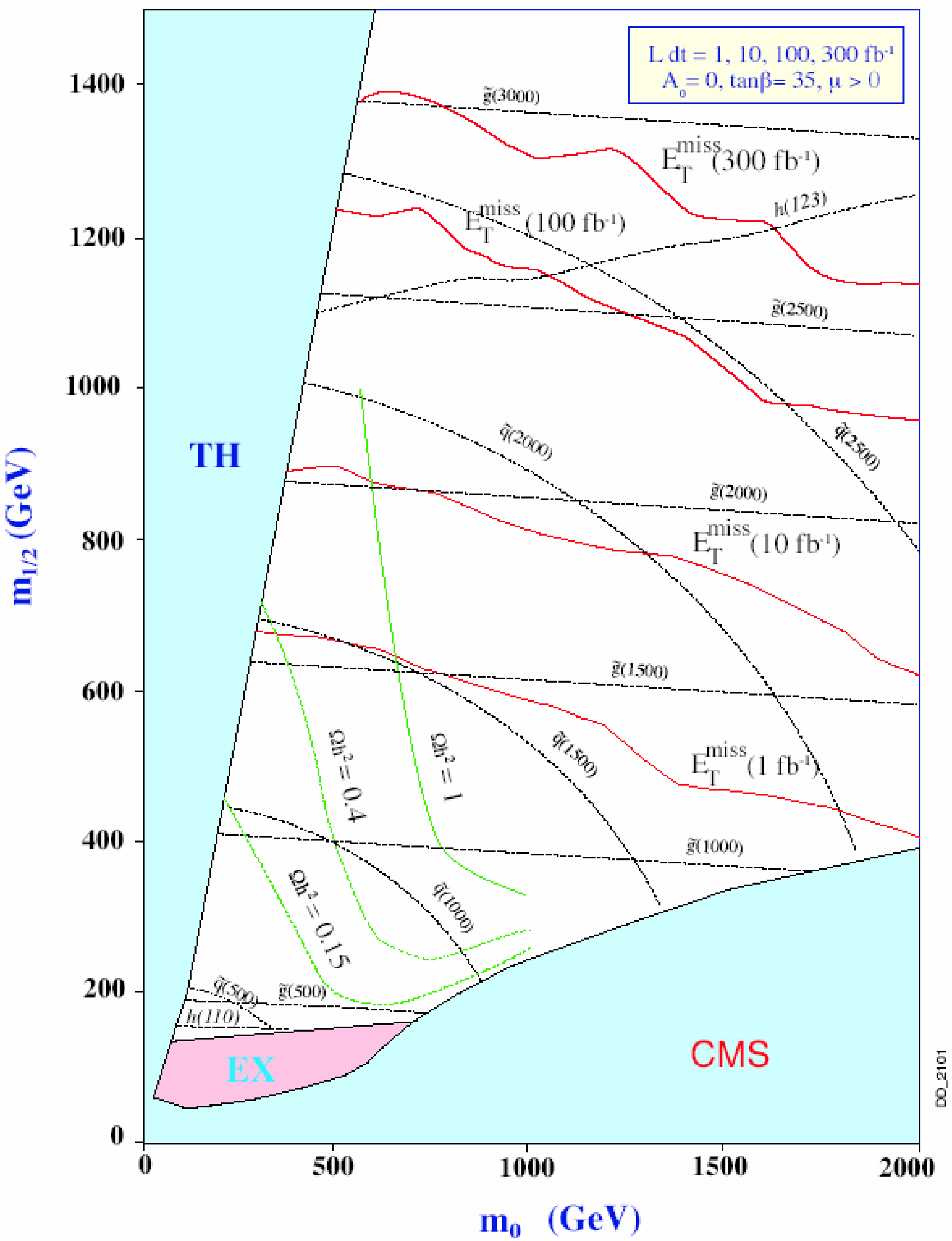
$$m_{EW} = \frac{1}{4\pi} L^{-1} \qquad L^{-1} \text{ size of bound states}$$

- Light Higgs & higgsino

- New CFT states at L^{-1} ~ TeV

- Considerable fine tuning

The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss} + jets inclusive channel for various integrated luminosities



SUPERSYMMETRY: CONCLUSIONS

Susy at EW scale can be realized in very different ways:

- E_T^{miss}
- E_T^{miss} + γ
- E_T^{miss} + ℓ
- Stable charged particle
- Nearly-degenerate $\widetilde{W}^{\pm 0}$
- Stable stop
- Partial susy spectrum

HIGGS AS PSEUDOGOLDSTONE BOSON

$$\Phi = \frac{\rho + f}{\sqrt{2}} e^{i\theta / f} \qquad \langle \Phi \rangle = f$$

$$\Phi \to e^{ia}\Phi : \qquad \begin{cases} \rho \to \rho \\ \theta \to \theta + a \end{cases}$$

Non - linearly realized symmetry

$h \to h + a$ forbids $m^2 h^2$

Gauge, Yukawa and self-interaction are large non-derivative couplings ⇨

Violate global symmetry and introduce quadratic div.

Arkani Hamed-Cohen-Georgi

A less ambitious programme: **LITTLE HIGGS**

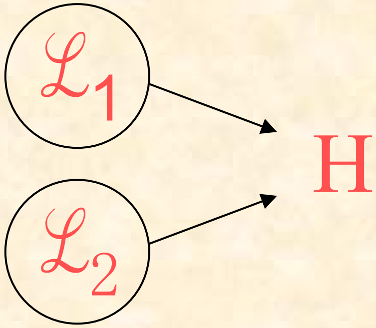
Explain only little hierarchy

$$\text{One loop}\quad \delta m_H^2 = \frac{G_F}{\pi^2} m_{SM}^2 \Lambda_{SM}^2 \Rightarrow \Lambda_{SM} < \frac{\pi}{\sqrt{G_F}} \approx \text{TeV}$$

At Λ_{SM} new physics cancels one-loop power divergences

$$\text{Two loops}\quad \delta m_H^2 = \frac{G_F^2}{\pi^4} m_{SM}^4 \Lambda^2 \Rightarrow \Lambda \approx \frac{\pi^2}{G_F m_{SM}} \approx 10\,\text{TeV} \approx \Lambda_{\text{LH}}$$

"Collective breaking": many (approximate) global symmetries preserve massless Goldstone boson



$$\delta m_H^2 = \frac{\mathcal{L}_1}{4\pi^2} \frac{\mathcal{L}_2}{4\pi^2} \Lambda^2$$

It can be achieved with gauge-group replication

- Goldstone bosons in G/H
- $G \supset G_1 \times G_2$ gauged subgroups, each preserving a non-linear global symmetry
- $\mathrm{SM} \subset G_1 \times G_2$ which breaks all symmetries

Field replication Ex. SU_2 gauge with $\Phi_{1,2}$ doublets such that $V(\Phi_1^+\Phi_1, \Phi_2^+\Phi_2)$ and $\Phi_{1,2}$ spontaneously break SU_2

Kaplan-Schmaltz

Turning off gauge coupling to Φ_1 ⇨

Local $SU_2(\Phi_2)$ × global $SU_2(\Phi_1)$ both spont. broken

$$\delta m_H^2 \approx \frac{g^4}{(4\pi)^4}\Lambda^2 \quad \text{two loops}$$

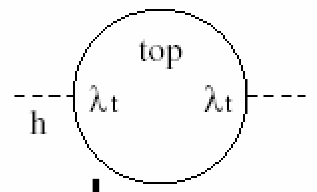
Realistic models are rather elaborate

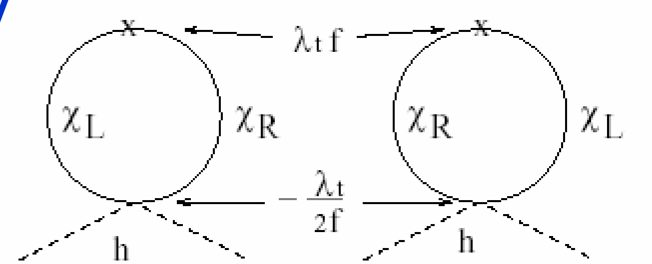
Arkani Hamed-Cohen-Georgi-Katz-Nelson-Gregoire-Wacker-Low-Skiba-Smith-Kaplan-Schmaltz-Terning…

Effectively, new particles at the scale f ~ Λ_{SM} canceling (same-spin) SM one-loop divergences with couplings related by symmetry

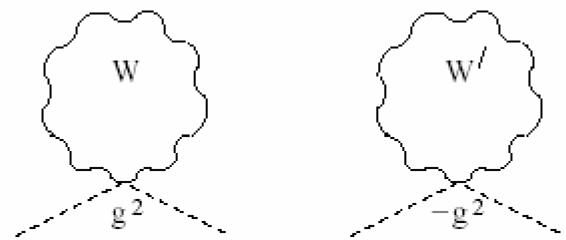
Typical spectrum:

Vectorlike charge 2/3 quark

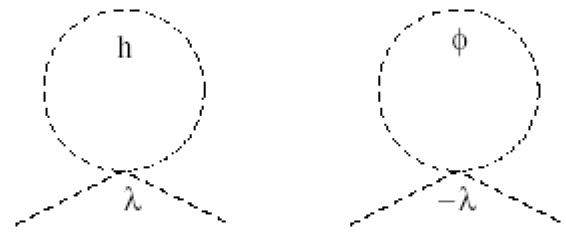




Gauge bosons EW triplet + singlet

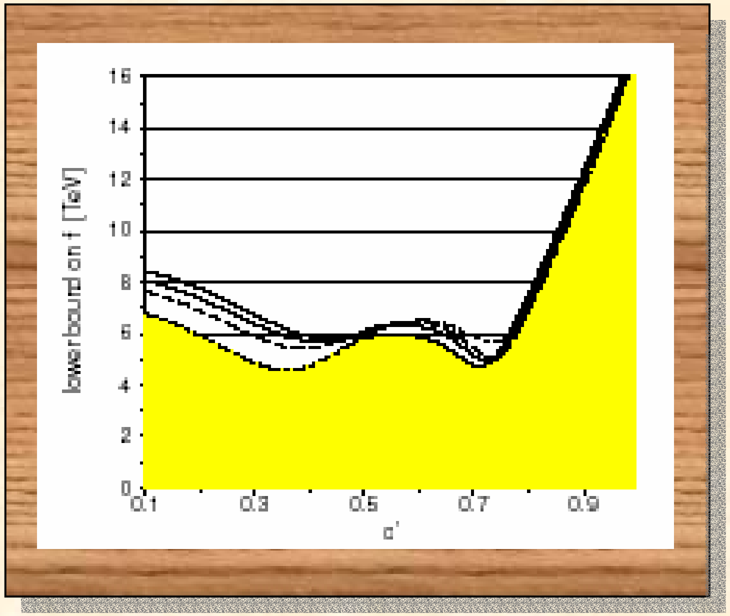


Scalars (triplets ?)



Bounds from: Tevatron limits on new gauge bosons

EW data ($\Delta\rho$ from new gauge and top)



Csaki-Hubisz-Kribs-Meade-Terning

In minimal model:

$$m_{t'} > 2\sqrt{2}\frac{m_t}{v} f = 14\ \text{TeV}\left(\frac{f}{5\ \text{TeV}}\right) \Rightarrow 0.1\%\ \text{fine-tuning}$$

Variations significantly reduce the fine tuning

HIGGS AS EXTRA-DIM COMPONENT OF GAUGE FIELD

$A_M = (A_\mu, A_5)$, $\quad A_5 \to A_5 + \partial_5 \Lambda$ forbids $m^2 A_5^2$

gauge (A_μ) Higgs (A_5)

Higgs/gauge unification as graviton/photon unification in Kaluza-Klein

Correct Higgs quantum numbers by projecting out unwanted states with orbifold

- Yukawa couplings
- Quartic couplings
- Do not reintroduce quadratic divergences

Csaki-Grojean-Murayama

Burdman-Nomura

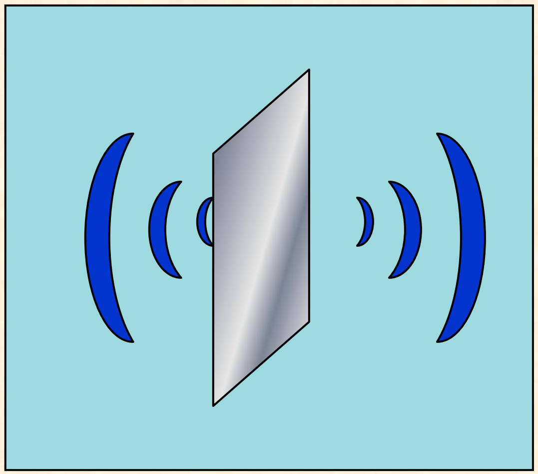
Scrucca-Serone-Silvestrini

EXTRA DIMENSIONS

Forget about symmetries, about little hierarchy

⇨ cut off at Λ_{SM}

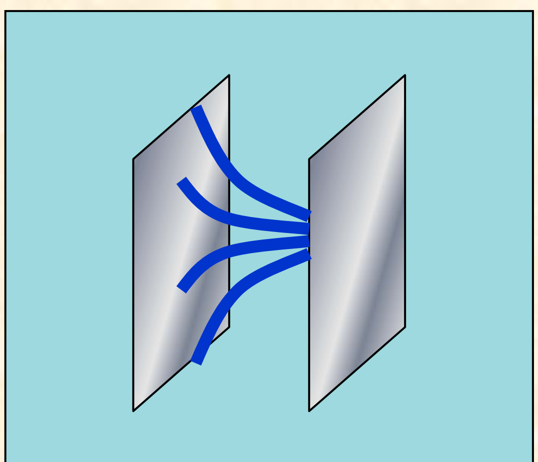
Any short-distance scale < Λ_{SM}^{-1} explained by geometry



FLAT

$$M_{Pl} \approx R^{\delta/2} M_D^{1+\delta/2} \qquad D = 4 + \delta$$

Arkani Hamed-Dimopoulos-Dvali

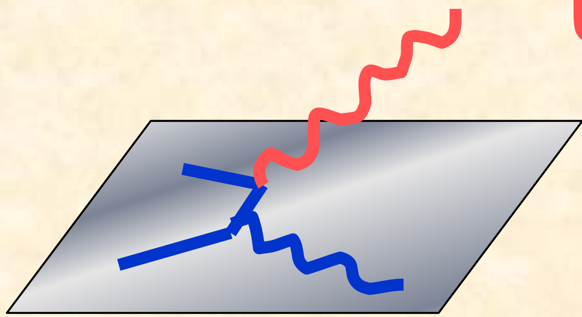


WARPED

$$M_{Pl} \approx M_5 e^{-KR\pi}$$

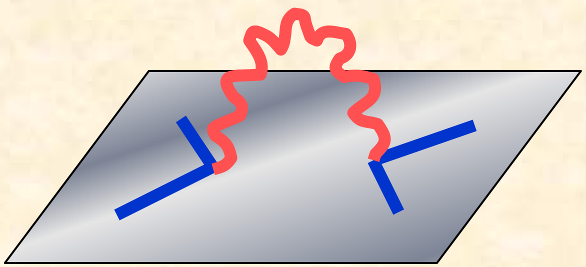
Randall-Sundrum

QUANTUM GRAVITY AT LHC

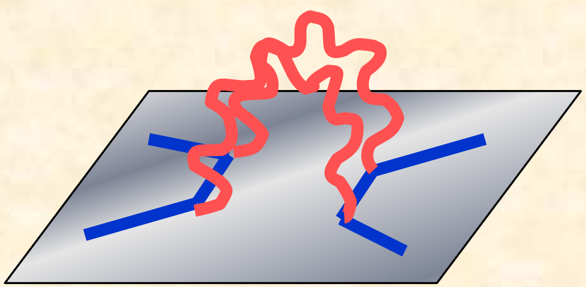


Graviton emission

- Missing energy (flat)
- Resonances (warped)

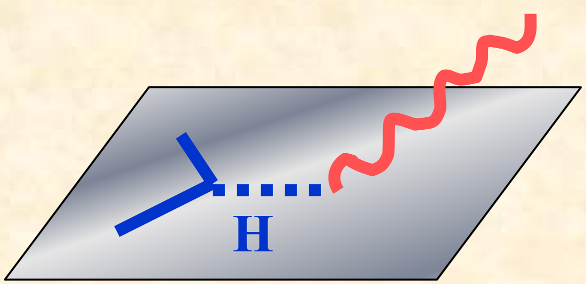


$$\frac{1}{\Lambda^4} T_{\mu\nu} T^{\mu\nu}$$

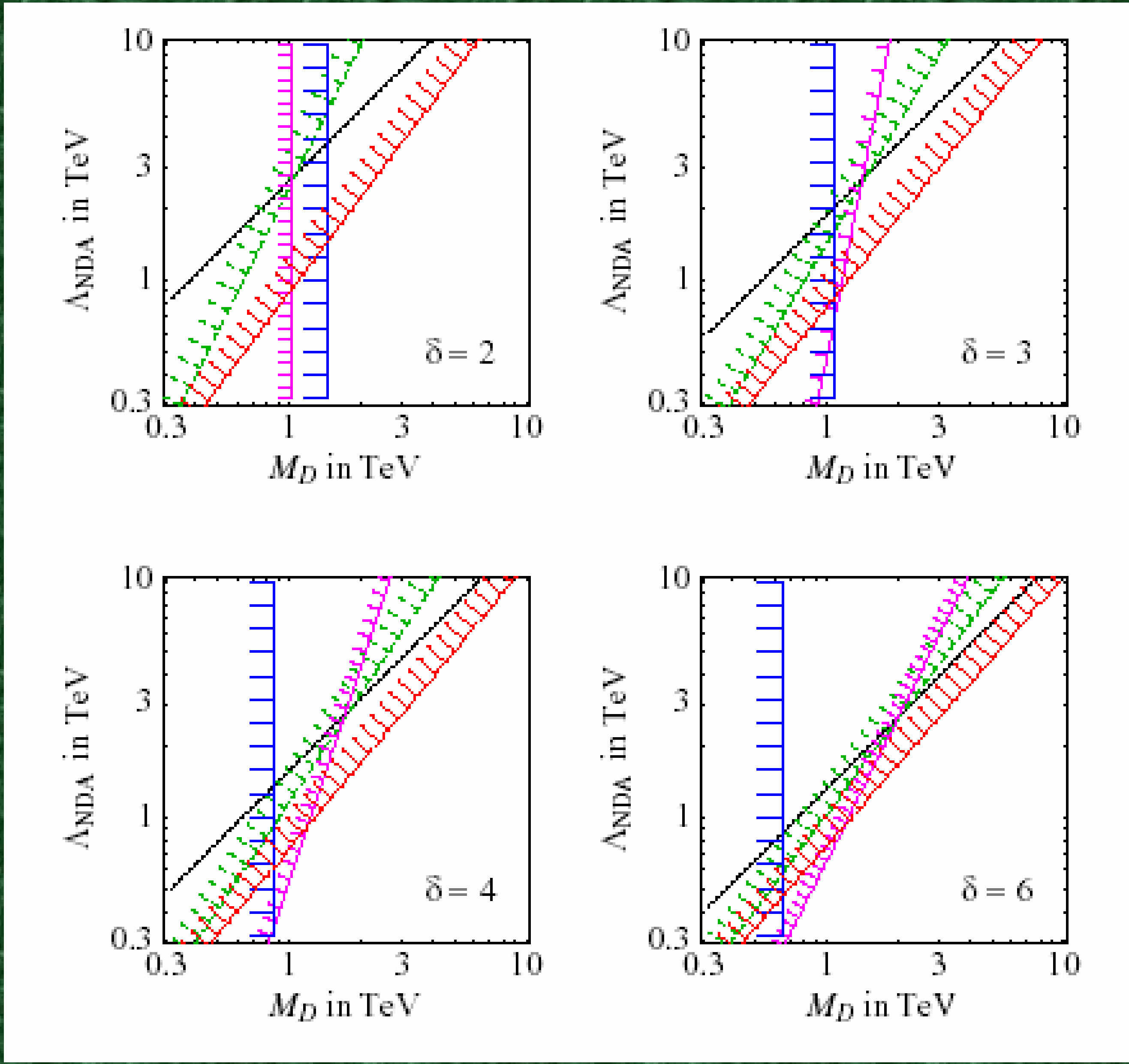


$$\frac{1}{\Lambda^2} \left(\bar{f} \gamma_\mu \gamma_5 f \right)^2$$

Contact interactions
(loop dominates over tree if gravity is strong)



Higgs-radion mixing



Graviton emission

Tree-level graviton exchange

Graviton loops

Gauge/graviton loop

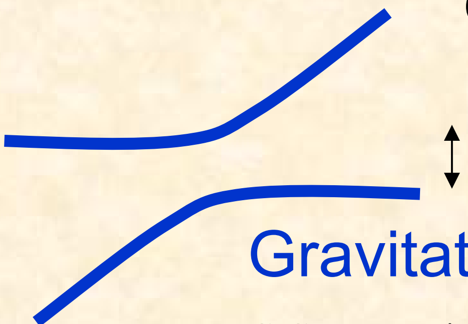
G.G.-Strumia

As $\sqrt{s}$ approaches M_D, linearized gravity breaks down

⇨ underlying quantum gravity (strings?)

TRANSPLANCKIAN REGIME

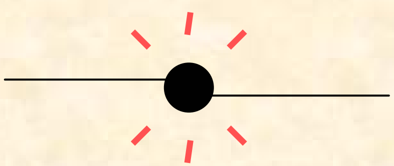
$\sqrt{S} >> M_D$ ⇨ $R_S >> \lambda_{Pl}$ and (semi)classical effects dominate over quantum-gravity effects



$b > R_S$

Gravitational scattering

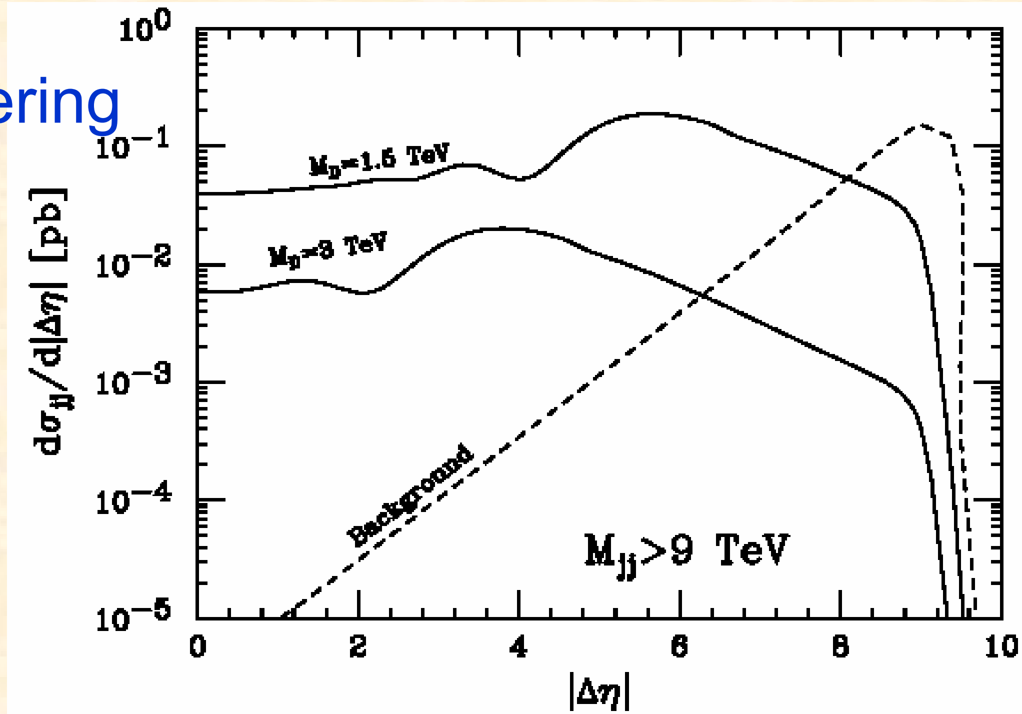
G.G.-Rattazzi-Wells



$b < R_S$

Black-hole production

Giddings-Thomas, Dimopoulos-Landsberg



SM PARTICLES IN EXTRA DIMENSIONS

Gauge bosons in 5D:

Direct + indirect limits $M_c > 6.8$ TeV — Cheung-Landsberg

At LHC up to 13-15 TeV

Weaker bounds in universal extra dimensions

After compactification, momentum conservation in 5th dim ⇨ KK number conserved

KK particles pair produced; no tree-level exchange

$M_c > 0.3$ TeV — Appelquist-Cheng-Dobrescu

CONCLUSIONS

- Many open theoretical options for new physics at EW scale
- Direct searches + precision measurements ⇨ no existing theory is completely free of fine-tuning

Connection with M_{Pl}

Gauge coupling unification

$\Lambda \sim \Lambda_{LH}$ or Λ_{SM} ⇨ **Need for UV completion at Λ**