New Physics at the Electroweak Scale

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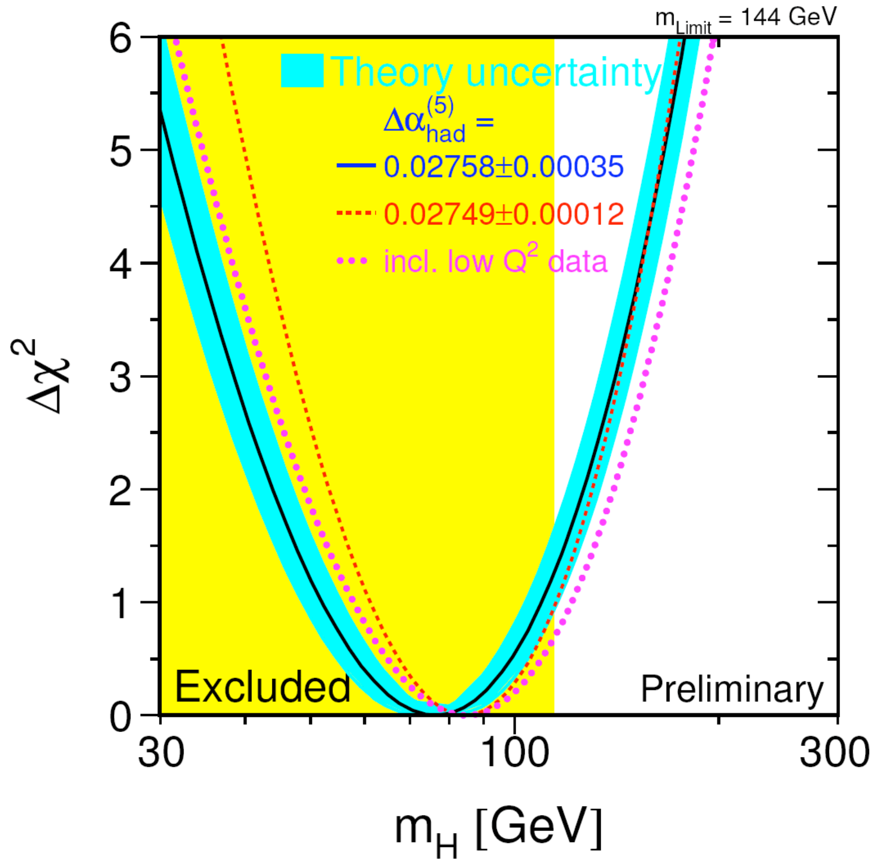
Is there a Higgs?

$$A\left(W_L^+W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}\left(1 - \frac{E^2}{E^2 - m_H^2}\right)$$

Without Higgs ⇨ E < 1.2 TeV

With Higgs ⇨ m_H < 780 GeV



- Most economical solution for EW breaking
- LEP gives indications for a light Higgs

Preferred value $m_H = 76^{+33}_{-24}\,\mathrm{GeV}$

Upper limit $m_H < 144\,\mathrm{GeV}$ (95% CL)

including direct limit of $114\,\mathrm{GeV}$:

$m_H < 182\,\mathrm{GeV}$ (95% CL)

LEPEWWG 07

The decrease in m_t has worsened the SM fit

LEP/SLD/m_W/Γ_W : $m_t = 178.9^{+11.7}_{-8.6}$ GeV

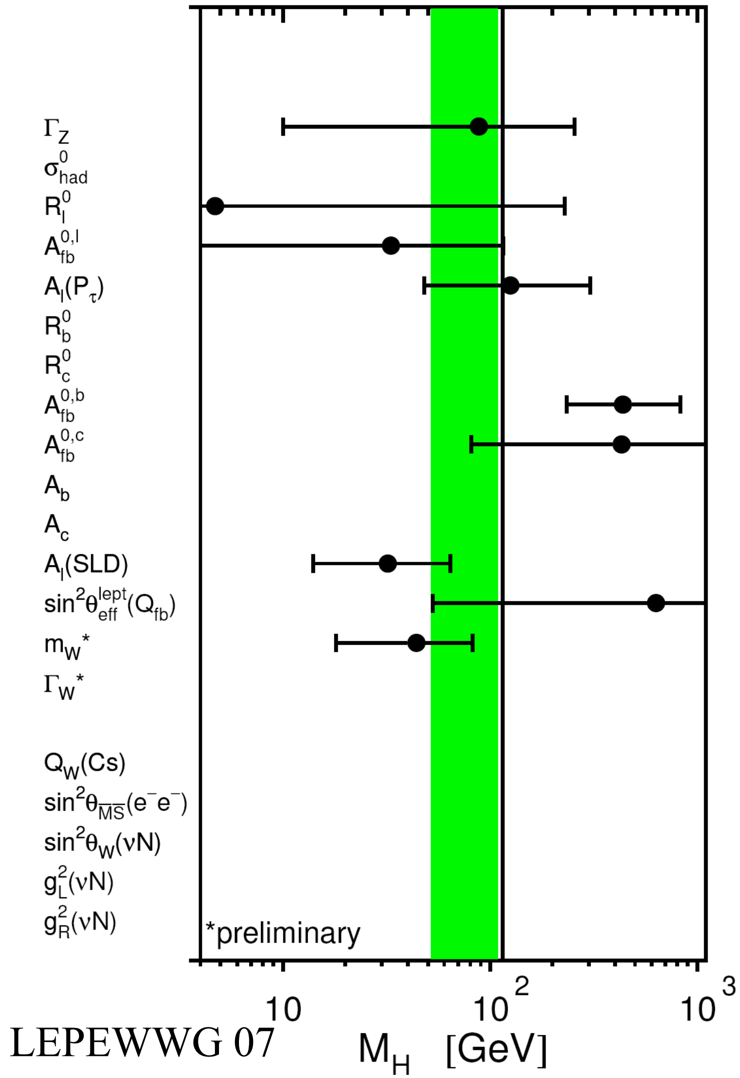
CDF/D∅ : $m_t = 170.9 \pm 1.8$ GeV

The two best measurements of $sin^2\theta_W$ do not agree

$$A_{fb}^{0,b} \Rightarrow m_H = (230 - 800)\,\text{GeV}$$

$$A_\ell(\text{SLD}) \Rightarrow m_H = (13 - 65)\,\text{GeV}$$

This makes the argument for a light Higgs less compelling



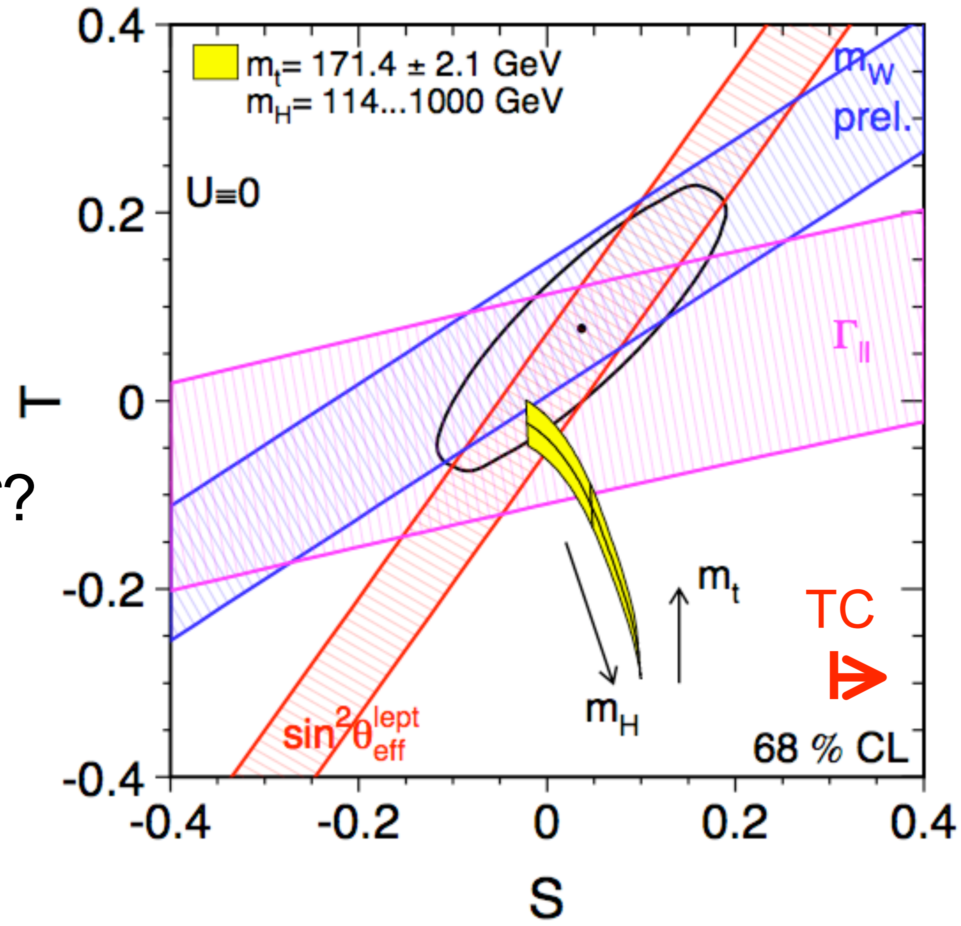
Still open is the possibility of no Higgs, and new strong dynamics

- flavour?
- EW precision data?

$$\Delta S \approx \frac{1}{6\pi}\left(n_{TF}N_{TC} + \ln\frac{\Lambda_{TC}}{m_Z}\right)$$

Negative contributions to *S*?

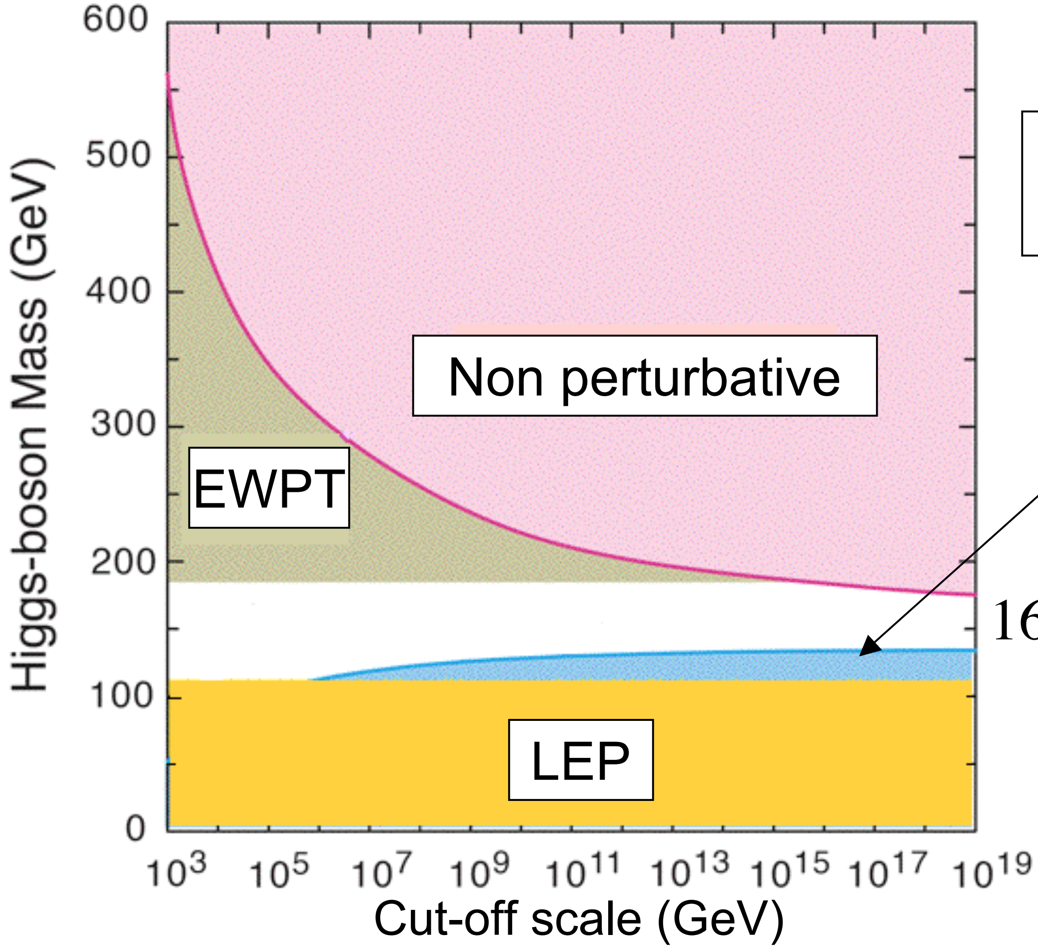
Walking at small N_{TC}?



Higgsless? EW broken by boundary conditions with KK gauge bosons curing unitarity up to about 10 TeV (or less)

What is the Higgs mass?

Important indirect information from Higgs mass measurement



EW vacuum is metastable for
115 GeV < m_H < 125 GeV

$$16\pi^2 \frac{d\lambda}{d\ln\mu} = 6\left(4\lambda^2 + 2\lambda y_t^2 - y_t^4\right) + \ldots$$

Higgs mass is a good discriminator for BSM theories

$$m_H^2 = M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{\tilde{m}_t^2}{m_t^2} + \ldots$$

$$M_Z^2 = \frac{3h_t^2}{2\pi^2} \tilde{m}_t^2 \log \frac{\Lambda}{\tilde{m}_t} + \ldots$$

no mixing ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 112\,\mathrm{GeV}$

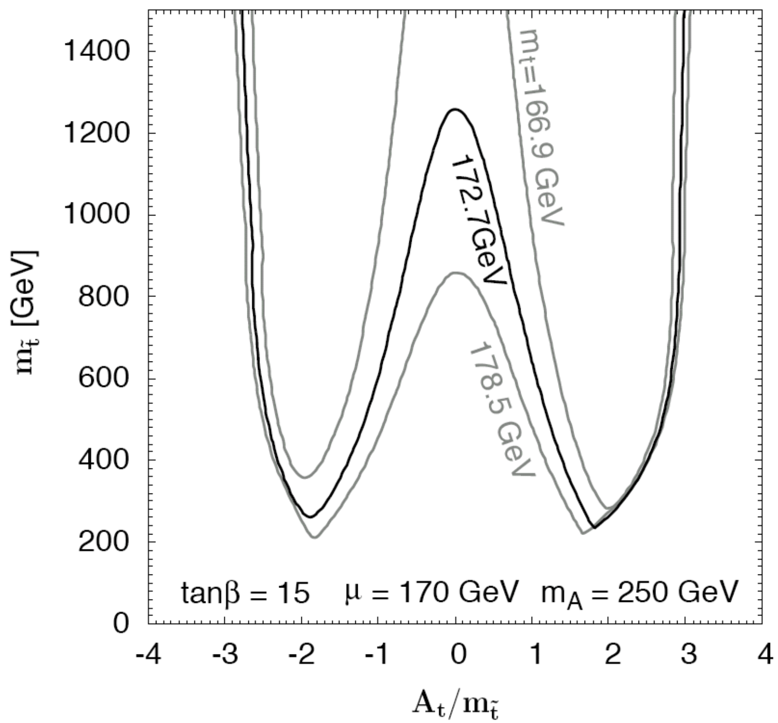
gauge med ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 115\,\mathrm{GeV}$

max mixing ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 128\,\mathrm{GeV}$

split susy ($\tilde{m} = 10^7\,\mathrm{GeV}$): $m_H < 145\,\mathrm{GeV}$

λ perturb. up to $10^7\,\mathrm{GeV}$: $m_H < 150\,\mathrm{GeV}$

Smaller m_t reduces loop correction to m_H



Is the Higgs a SM-like weak doublet?

The choice of a single SU_2 doublet is dictated by simplicity
More Higgs doublets (susy) or new Higgs singlets

Recent activity in studying extensions

Link to mirror worlds?

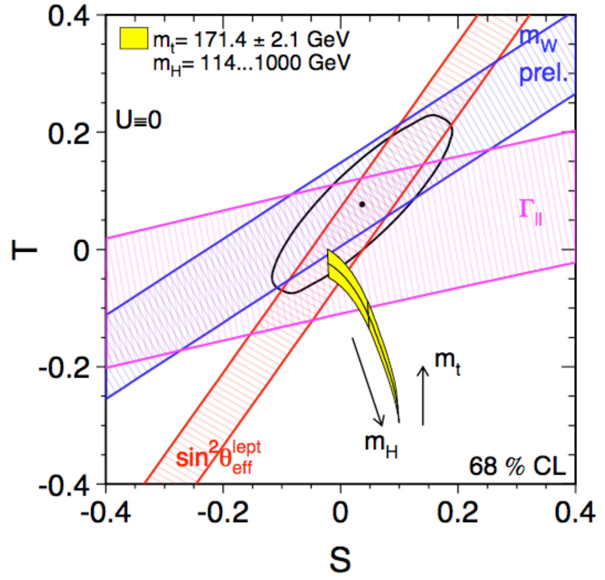
Higgs mass is only allowed super-renormalizable term

$$L = c|H|^2 O$$

Hidden-sector operator

- Evading m_H upper bound from EWPT?

Requires new physics with
ΔT=0.2–0.3 and ΔS small

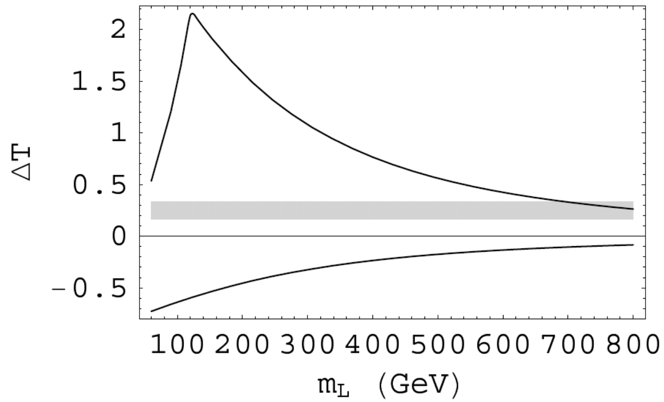


- Inert Doublet Model:

parity $H_2 \to - H_2$ and $\langle H_2 \rangle$=0

Lightest parity-odd Higgs can be DM

No significant improvement in naturalness



- Susy with large $\lambda N H_1 H_2$

ΔT from Higgs-higgsino system

Heavy Higgs, but validity only up to about 10 TeV

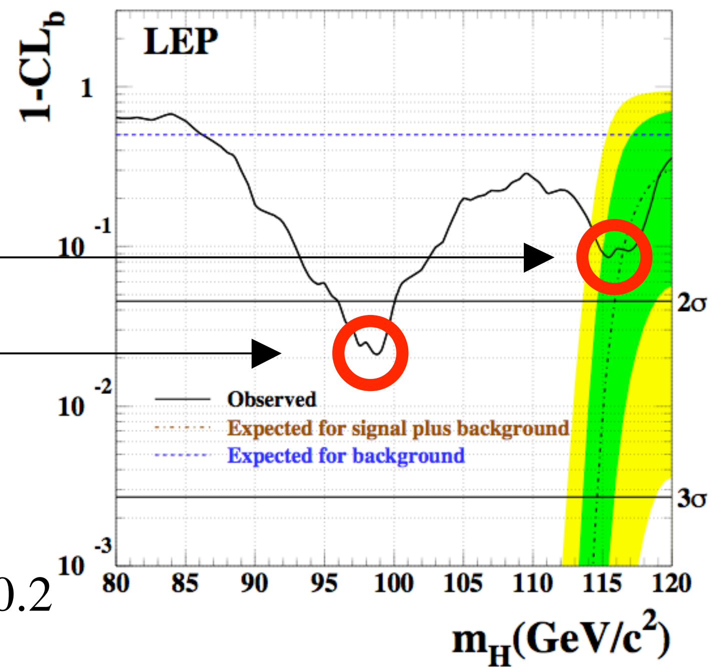
- New EW fermions

DM candidate

- Evading m_H lower bound from LEP?

Controversial signal at 115 GeV

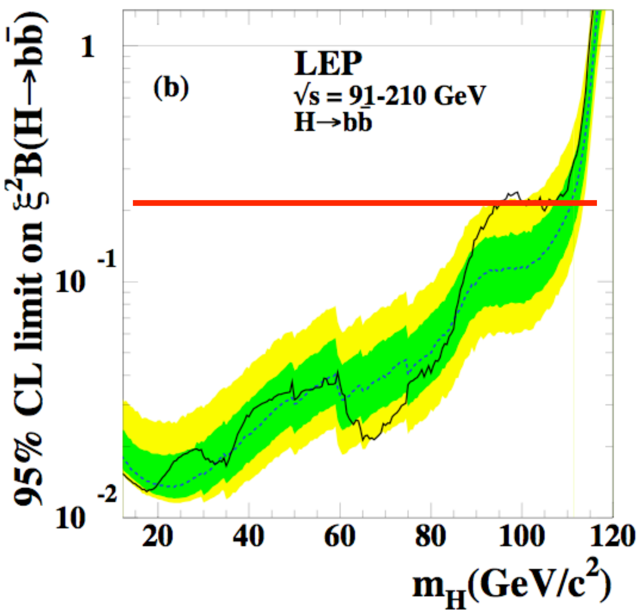
2.3σ excess at 98 GeV



Excess at 100 GeV requires $\left(\frac{g_{hZZ}}{g_{hZZ}^{(SM)}}\right)^2 B(h \to b\bar{b}) \approx 0.2$

New decay modes (new particles)

Change Higgs nature (mixing with other states)



Limits on unconventional decay modes

$h \to \gamma\gamma$	$m_h > 117\,\mathrm{GeV}$	
$h \to b\bar{b}b\bar{b}$	$m_h > 110\,\mathrm{GeV}$	
$h \to \tau^+\tau^-\tau^+\tau^-$	$m_h > 87\,\mathrm{GeV}$	
$h \to$ anything	$m_h > 82\,\mathrm{GeV}$	OPAL

Possible explanations in supersymmetry

• Reduced *hZZ* coupling for the lightest Higgs with m_H=98 GeV (and SM coupling for a Higgs with m_H=115 GeV)

• SM Higgs couplings, but new decay channel into a light pseudoscalar ($m_A < 2m_b$)

$$h \to a\,a \to \tau^+\tau^-(c\bar{c})\,\tau^+\tau^-(c\bar{c})$$

Reanalysis of LEP data?

• Light neutralino with *R*-parity breaking decay

$$h \to \chi\chi \to 6q$$

Displaced vertices at LHCb?

Is the Higgs elementary or composite?

Determine the nature of the force that breaks EW

Elementary
- SM (with $m_H < 190$ GeV)
- SUSY (H,Q,L are all chiral superfields; no new quartic interaction)

Composite: Higgs is a light remnant of a strong force
- pseudoGoldstone
- Little Higgs
- Gauge-Higgs unification
- Holographic Higgs
- ….

HIGGS AS PSEUDOGOLDSTONE BOSON

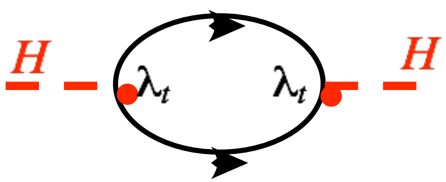
$$\Phi = \frac{\rho + f}{\sqrt{2}} e^{i\theta/f} \qquad \langle \Phi \rangle = f \qquad \Phi \to e^{ia}\Phi : \quad \begin{cases} \rho \to \rho \\ \theta \to \theta + a \end{cases}$$

Non-linearly realized symmetry $h \to h + a$ forbids $m^2 h^2$

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

⇨Violate global symmetry and introduce quadratic divergences

Top sector



$$\delta m_H^2 \sim -\frac{3}{4\pi^2}\lambda_t^2 \Lambda_{NP}^2$$

No fine-tuning $|\delta m_H^2| < (200\,\mathrm{GeV})^2 \;\Rightarrow\; \Lambda_{NP} < 600\,\mathrm{GeV}$

If the scale of New Physics is so low,
why do LEP data work so well?

LITTLE HIGGS

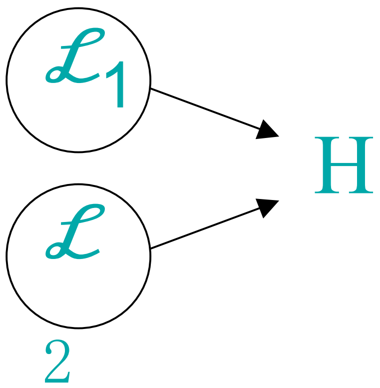
Explain only little hierarchy

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

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

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

“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

Turning off gauge coupling to Φ_1 ⇨

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

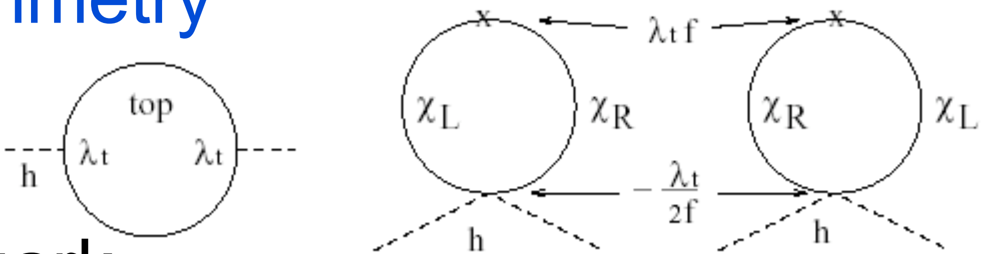
$$\delta m_H^2 \approx \frac{g^4}{(4\pi)^4}\Lambda^2 \qquad \text{two loops}$$

Realistic models are rather elaborate

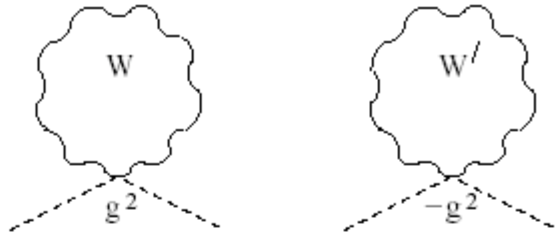
Effectively, new particles at the scale f cancel (same-spin) SM one-loop divergences with couplings related by symmetry

Typical spectrum:

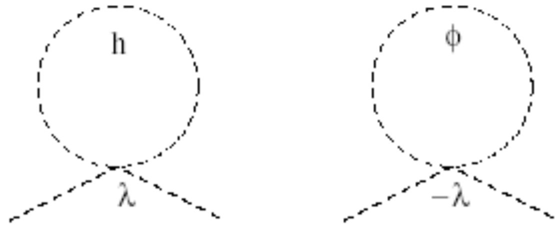
Vectorlike charge 2/3 quark



Gauge bosons EW triplet + singlet



Scalars (triplets ?)

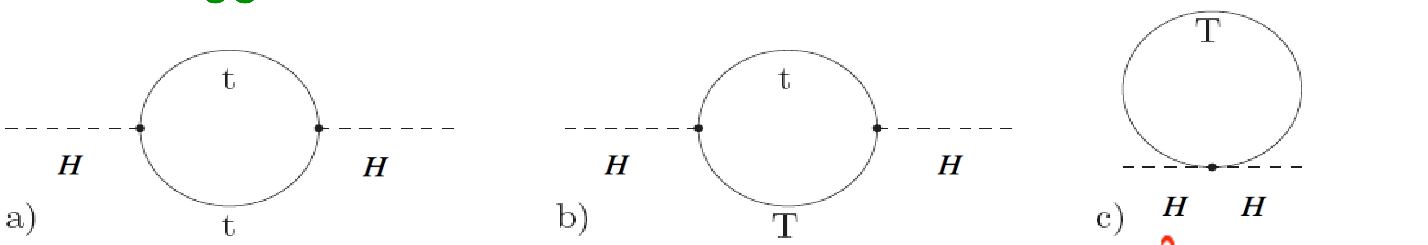


New states have naturally mass $\sim \frac{\alpha}{4\pi}\Lambda_{NP}^2 \equiv e^2 f^2$ $\sim 1\,\mathrm{TeV}$

$$f \equiv \frac{\Lambda_{NP}}{4\pi}$$

New states cut-off quadratically divergent contributions to m_H

Ex.: littlest Higgs model $H \in SU(5)/SO(5)$



$$\frac{\Lambda^2}{16\pi^2}\left(+\lambda_t^2 + \lambda_T^2 - 2\frac{\lambda_T m_T}{f}\right) = 0$$

Log term: $\delta m_H^2 = -\frac{3}{8\pi^2}\lambda_t^2 m_T^2 \ln\left(\frac{\Lambda}{m_T}\right) < 0$ analogous to effect of stop loops in supersymmetry

Severe bounds from LEP data

NEW INGREDIENTS FROM EXTRA DIMENSIONS

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 KK

Correct Higgs quantum numbers by projecting out unwanted states with orbifold

The difficulty is to generate Yukawa and quartic couplings without reintroducing quadratic divergences

Light Higgs

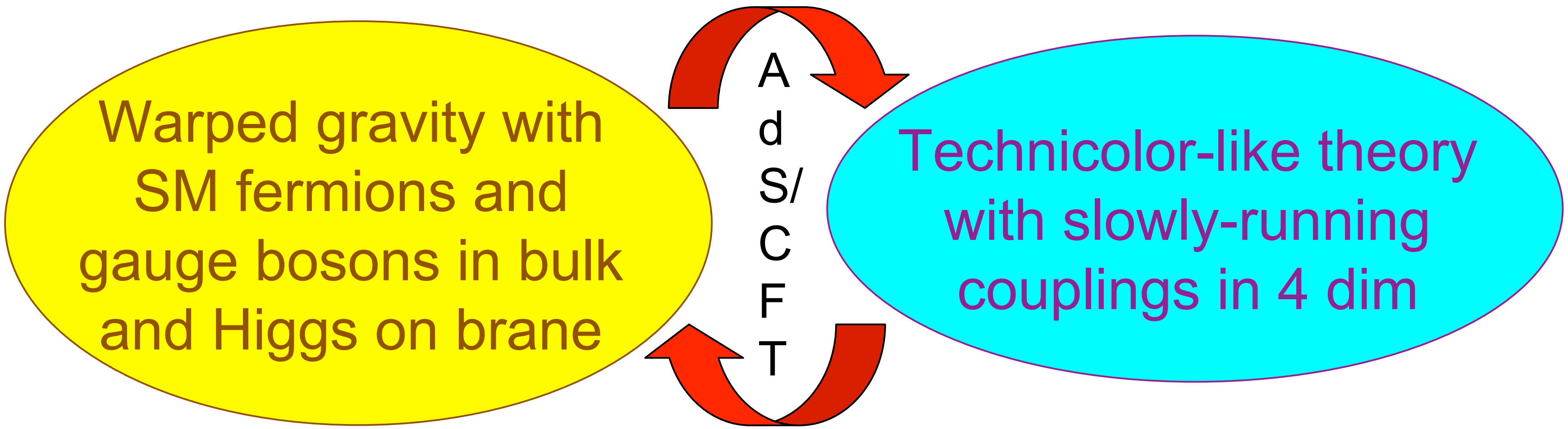
$m_h = 0$

- pseudoGoldstone of a strong force $h \to h + a$
- Belong to higher-dim gauge multiplet $A_5 \to A_5 + \partial_5 \Lambda$

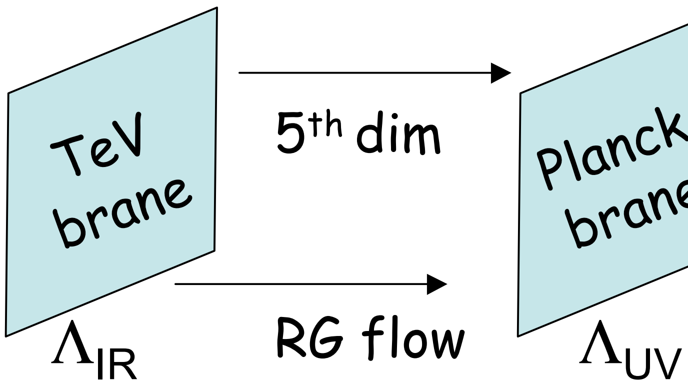
Same thing? (duality)

Relation between models of strong dynamics and extra dimensions

New extra dimensions or new strong forces?



As particle & wave are different aspects of the same reality, familiar concepts of dimension & force may not be distinct



Duality position & energy (typical of a gravitational field)

Signatures at LHC? New resonances, *W',Z',t'*, KK excitations

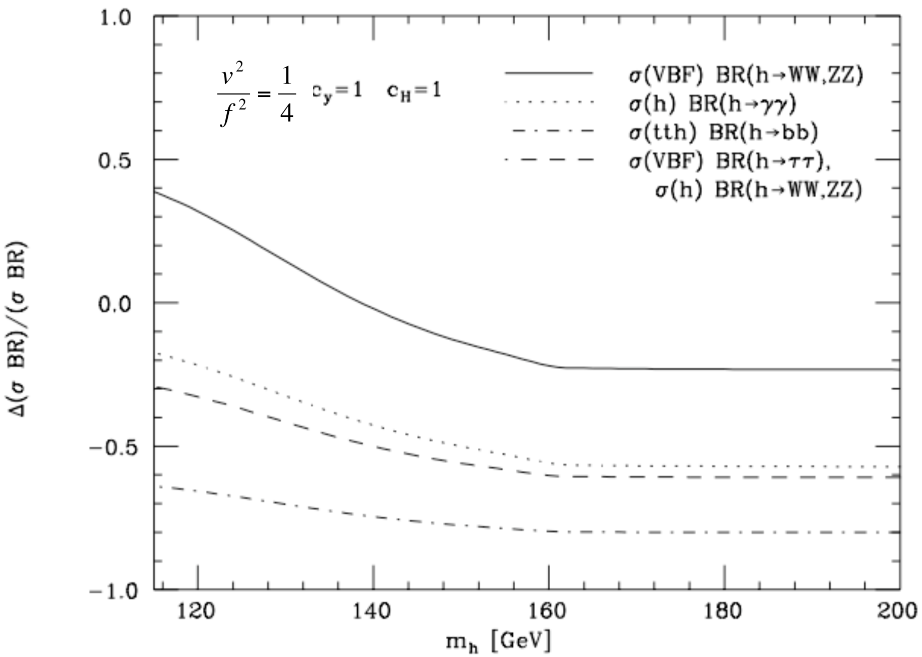
Common low-energy theory of Higgs interactions

What are the distinctive features of compositeness at the LHC?

Recent progress on effective-theory description of a composite Higgs

Describe Higgs with a σ-model deformed by gauge and Yukawa interactions

Specific patterns of modified Higgs couplings



Deviations from SM Higgs couplings can test v^2 / f^2 up to

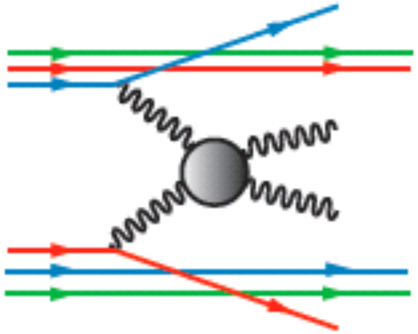
LHC 20–40 %

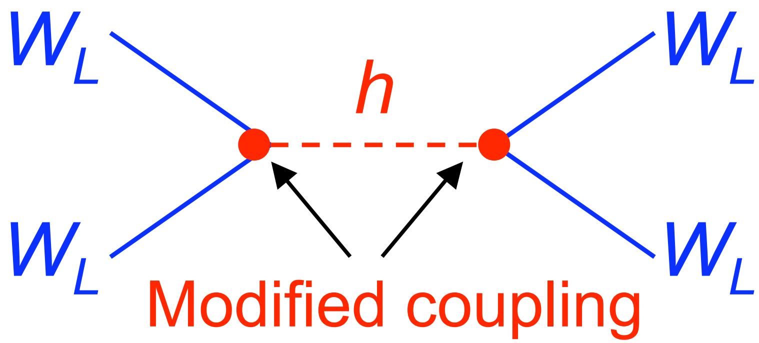
SLHC 10 %

ILC 1 % $\Rightarrow$ $4\pi f$ = 30 TeV

Genuine signal of Higgs compositeness at high energies

In spite of light Higgs, longitudinal gauge-boson scattering amplitude violates unitarity at high energies





$$\sigma\left(pp \to V_L V_L' X\right) = \frac{v^4}{f^4}\,\sigma\left(pp \to V_L V_L' X\right)_{\not H}$$ Identify hadronically-decaying W

$V_L V_L$ scattering is an important channel, even for light Higgs

Higgs is viewed as pseudoGoldstone boson: its properties are related to those of the exact (eaten) Goldstones

Strong gauge-boson scattering ⇒ strong Higgs production

Is the stability of M_W / M_P explained by a symmetry or dynamical principle?

BSM constructions have focused on the hierarchy problem

Good examples of naturalness at work

	Cancellation of	Existence of
	electron self-energy	positron
	π^+-π^0 mass difference	ρ
	K_L-K_S mass difference	charm
	gauge anomaly	top

Observations

- $\Lambda_{CC} \leq 10^{-3}$ eV
- LEP constraints on BSM

Theory

- No good symmetry explanation for Λ_{CC}
- Landscape of vacua in string theory

Different views on naturalness & hierarchy

Anthropic selection principle at work

Complexity

$\longleftarrow$

life ← biochemistry ← atomic physics ← SM ← "final theory"

$\longrightarrow$

Microscopic probes

Breaking of naturalness would require new principles

- the "final theory" is a complex phenomenon with IR/UV interplay
- some of the particle-physics parameters are "environmental"

Can we get experimental indications from LHC? Are there observable predictions?

Evidence for “unnaturalness” at work

- Split Supersymmetry

Heavy squarks and sleptons

Keep	Discard
• DM	• flavor problem
• gauge unif.	• very light Higgs
	• fast *p*-decay

• Long-lived gluino at LHC (time delay & anomalous ionization energy loss; measuring long lifetimes of stopped gluinos)

• Modified gaugino couplings at the ILC

• Measurable effects in EDM

- Little hierarchy in Supersymmetry

If distribution of vacua grows with M_{susy} and
we require the prior of EW breaking

$$\left\langle \frac{M_Z^2}{M_{susy}^2} \right\rangle \approx \text{loop factor}$$

- Value of the Higgs (and top) mass

If distribution of vacua grows at small λ and
we require metastability of Higgs vacuum

$$m_H = 115 \pm 6 \text{ GeV}$$

(better discover the Higgs quickly, because the end of the world is near)

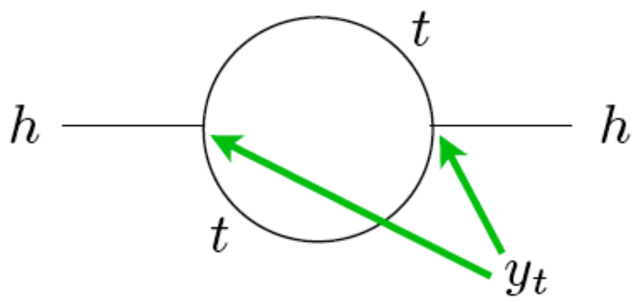
If also λ_{top} scans: $m_t = 172.4 - 176.9$ GeV

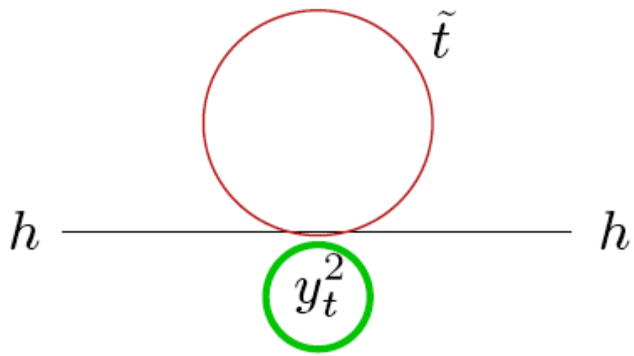
SUPERSYMMETRY

Best solution to the hierarchy problem with valid extrapolation up to very high scales

Its main problem is why neither the Higgs nor sparticles have been observed at LEP

Break susy, but keep UV behavior $\Rightarrow$ soft breaking



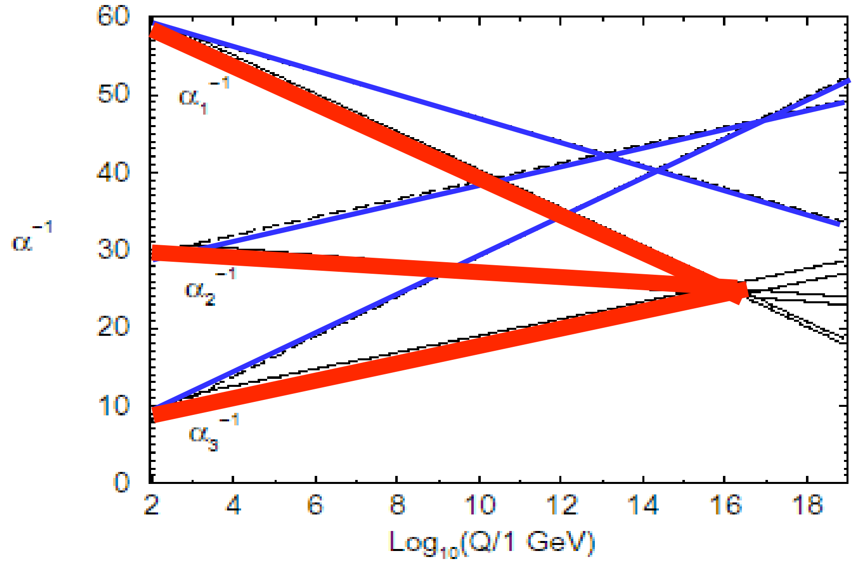


$$m_{\tilde{t}}^2 \neq m_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (m_{\tilde{t}}^2 - m_t^2) \ln \Lambda \qquad \text{Soft breaking}$$

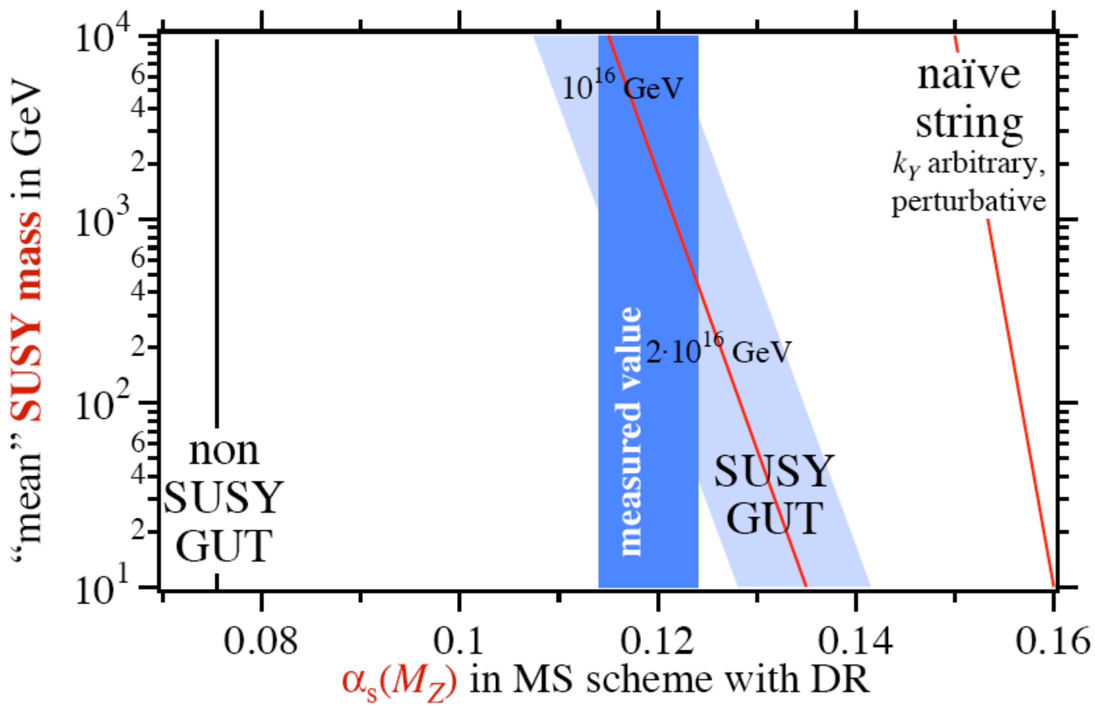
$$y_{\tilde{t}}^2 \neq y_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (y_{\tilde{t}}^2 - y_t^2) \Lambda^2 \qquad \text{Hard breaking}$$

Some properties are "robust"

Gauge-coupling unification



α_s^{exp} =0.1176±0.0020



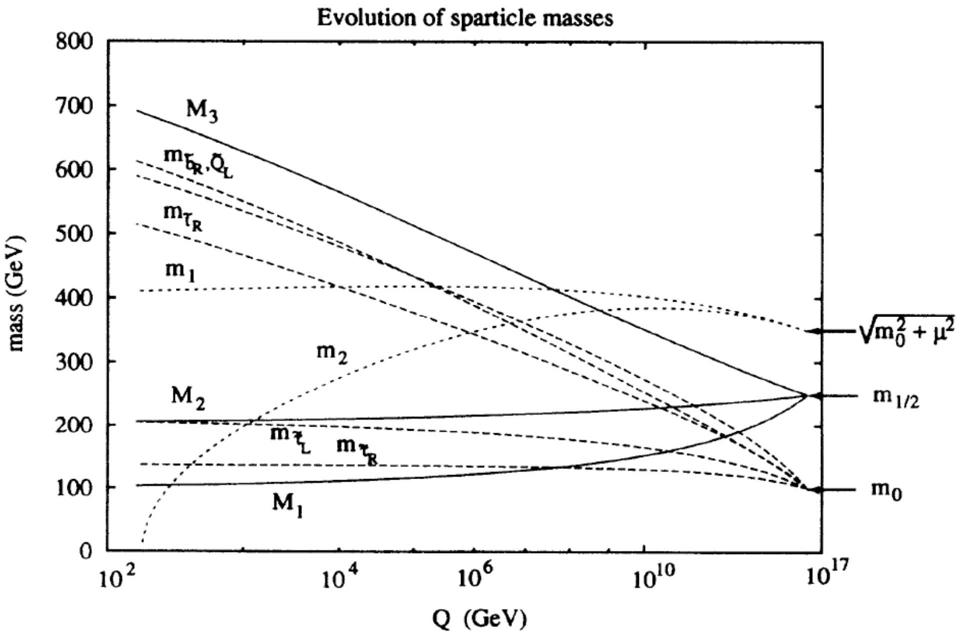
- success of susy
- does not strongly depend on details of soft terms
- remarkable that M_{GUT} is predicted below M_P and above p-decay limit

EW breaking induced by quantum corrections

RG running:

gauge effects

Yukawa effects



$$-8\pi^2 \frac{dM_3}{d\ln Q} = +3g_3^2 M_3$$

$$-8\pi^2 \frac{dm^2_{\tilde{t}_L}}{d\ln Q} = +\frac{16}{3} g_3^2 M_3^2 - \lambda_t^2 (m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + |A_t|^2 + m_2^2 - \mu^2) + (\text{EW effects})$$

$$-8\pi^2 \frac{dm_2^2}{d\ln Q} = -3\lambda_t^2 (m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + |A_t|^2 + m_2^2) + (\text{EW effects})$$

- If λ_t large enough $\Rightarrow$ *SU(2)×U(1)* spontaneously broken
- If α_s large enough $\Rightarrow$ *SU(3)* unbroken
- Mass spectrum separation m_2^2 < weak susy < strong susy

m_S IS THE SEED OF EW BREAKING

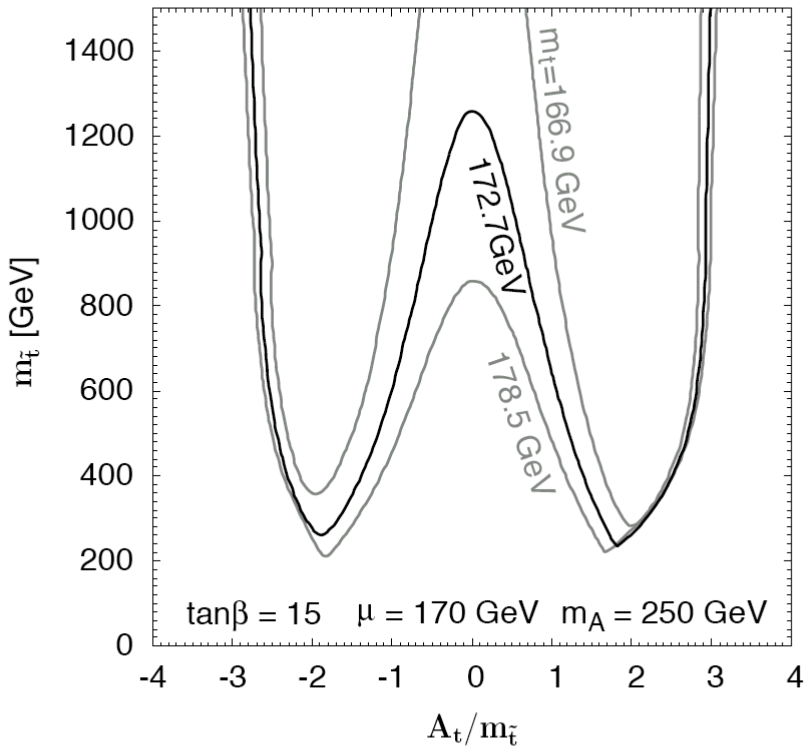
EW breaking is related to susy breaking, $m_S \Rightarrow m_Z$

$$\delta m_2^2 = -\frac{3\lambda_t^2}{8\pi^2}\int^{\Lambda^2}\frac{k^2 dk^2}{k^2+m_t^2} + \frac{3\lambda_t^2}{8\pi^2}\int^{\Lambda^2}\frac{k^2 dk^2}{k^2+m_t^2+m_S^2} = -\frac{3\lambda_t^2}{4\pi^2} m_S^2 \ln\frac{\Lambda}{m_S}$$

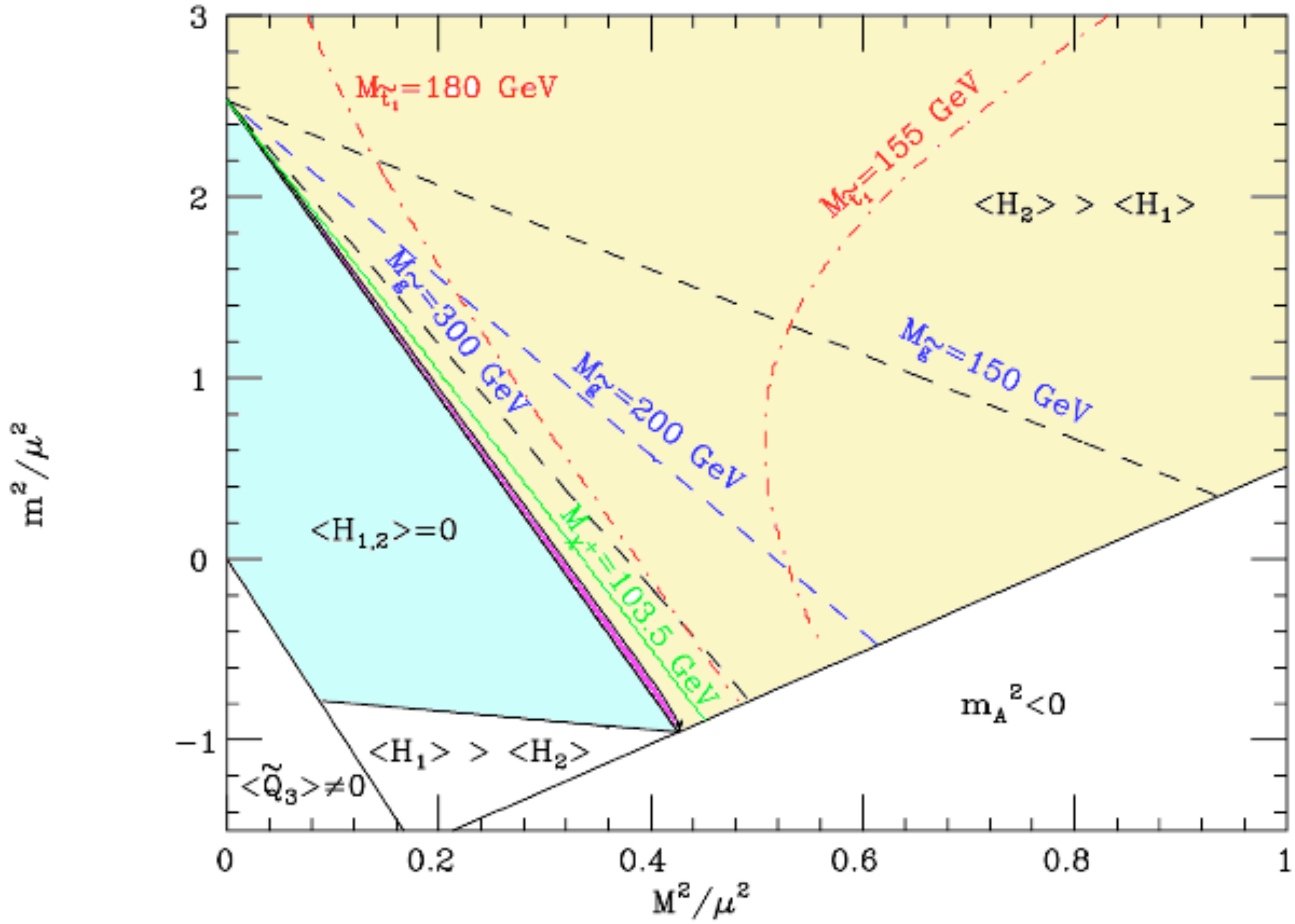
- m_S plays the role of Λ^2 cutoff
- The quantum correction is negative and drives EW breaking

$$m_H^2 = M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\log\frac{\tilde{m}_t^2}{m_t^2} + \ldots$$

$$M_Z^2 = \frac{3h_t^2}{2\pi^2}\tilde{m}_t^2 \log\frac{\Lambda}{\tilde{m}_t} + \ldots$$

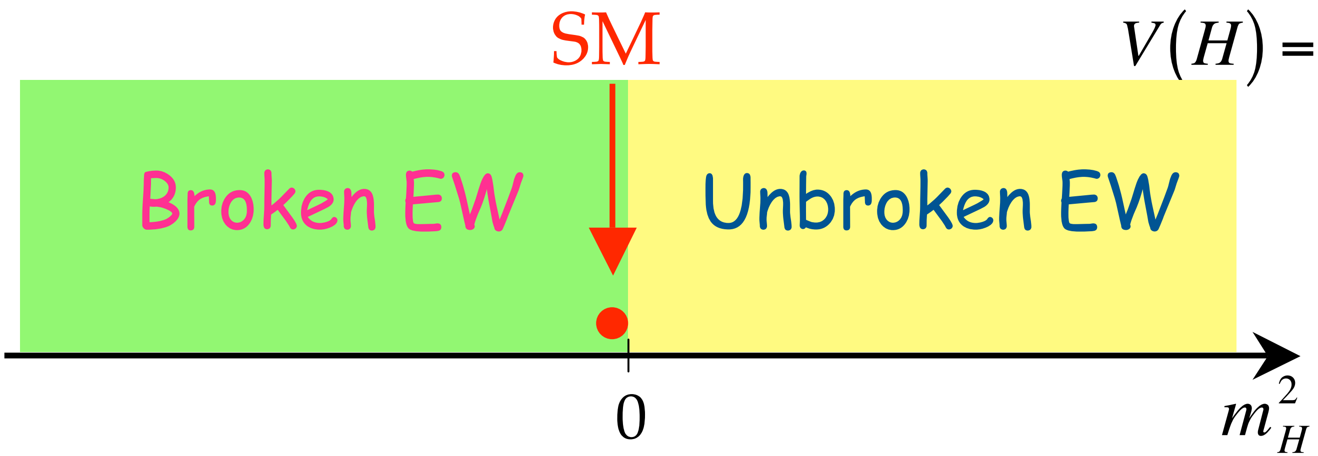


“Natural” supersymmetry has already been ruled out



Characterizing the tuning as a "criticality" condition

$$V(H) = -m_H^2 |H|^2 + \lambda |H|^4$$



Why is nature so close to the critical line?

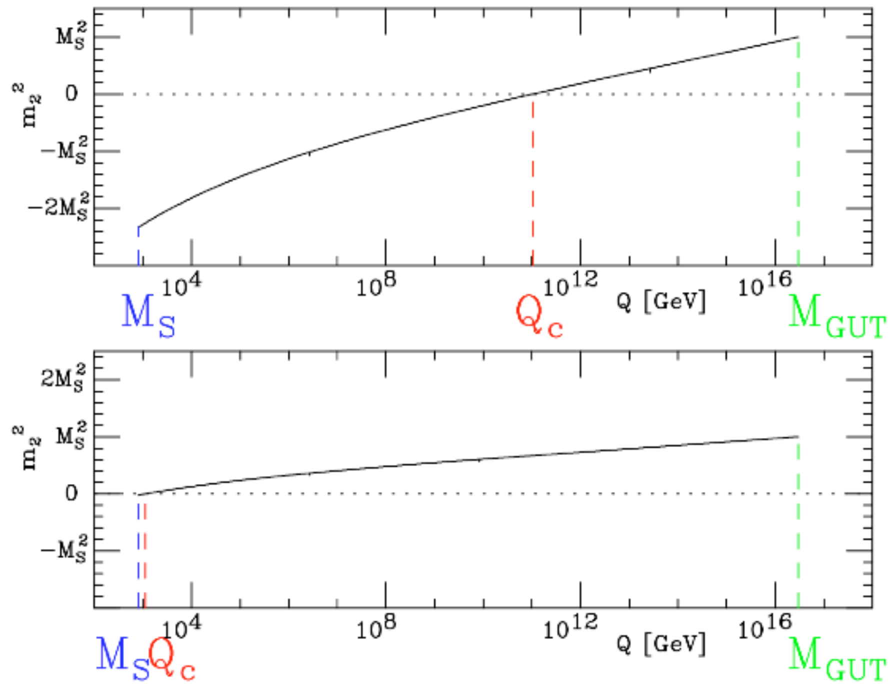
- Exact susy (and μ=0) $\Rightarrow$ critical line
- Dynamical susy breaking $M_S \sim M_P\, e^{-1/\alpha}$ $\Rightarrow$

  - small departure from critical line
  - stabilization of flat direction $|H_1| = |H_2|$

$\Rightarrow$ "natural" supersymmetry with $M_S \sim M_Z$

“natural” supersymmetry: $M_S << Q_C << M_P$

$Q_C \sim e^{-1/\alpha} M_P$
- unrelated to M_S (depends on ratios of soft terms and α_a)
- much smaller than UV scale



M_S and Q_C equal to few %

“tuned” supersymmetry: $M_S \sim Q_C << M_P$

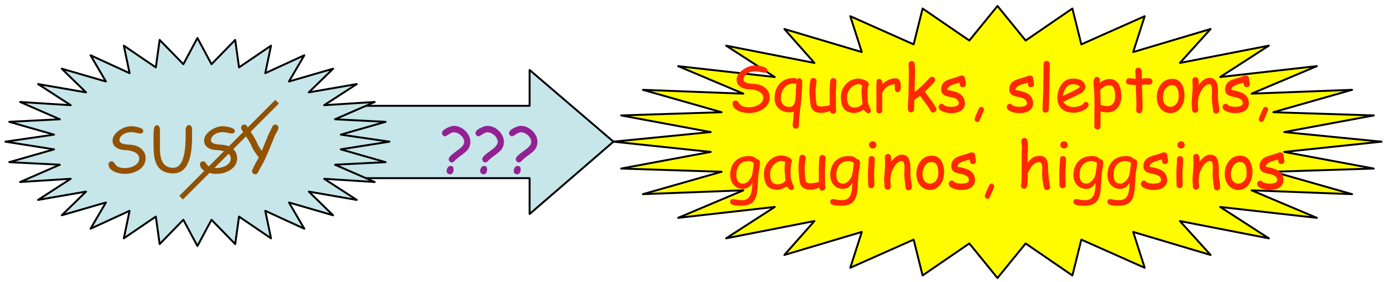
$M_S < Q_C$ broken EW; $M_S > Q_C$ unbroken EW

Why supersymmetry should prefer to be near critical?

Collider signatures of supersymmetry crucially depend on the structure of the soft terms

THEORY OF SOFT TERMS

- Explain origin of supersymmetry breaking
- Compute soft terms
- Derive phenomenological properties



What force mediates susy-breaking effects?

GRAVITY AS MEDIATOR

Gravity couples to all forms of energy

Assume no force stronger than gravity couples the two sectors

Susy breaking in hidden sector parametrized by X with $<F_X> \neq 0$

$$\frac{1}{M_P}\int d^2\theta\, X W_\alpha W^\alpha \quad \rightarrow \quad m_S \lambda\lambda \qquad \text{gaugino mass}$$

$$\frac{1}{M_P^2}\int d^4\theta\, X^+ X\, \Phi^+ e^V \Phi \quad \rightarrow \quad m_S^2 \varphi^+ \varphi \qquad \text{scalar mass}$$

$$\frac{1}{M_P}\int d^4\theta\, X^+ \Phi^+ e^V \Phi \quad \rightarrow \quad m_S\, \varphi F_\varphi^* = -m_S\, \varphi \frac{\partial f}{\partial \varphi} \qquad A\text{ - term}$$

$$\frac{1}{M_P}\int d^2\theta\, X f(\Phi) \quad \rightarrow \quad m_S f(\varphi) \qquad A\text{ - term}$$

$$\frac{1}{M_P}\int d^4\theta\, X^+ H_1 H_2 \quad \rightarrow \quad m_S \int d^2\theta\, H_1 H_2 \qquad \mu \text{ term}$$

$$\frac{1}{M_P^2}\int d^4\theta\, X X^+ H_1 H_2 \quad \rightarrow \quad m_S^2 H_1 H_2 \qquad B_\mu \text{ - term}$$

$m_S = F_X / M_P$

$m_S = \text{TeV} \Rightarrow$
$F_X^{1/2} = 10^{11}$ GeV

ATTRACTIVE SCENARIO

- Gravity a feature of local supersymmetry
- Gravity plays a role in EW physics
- No need to introduce *ad hoc* interactions
- Justification for $\mu \approx m_S$

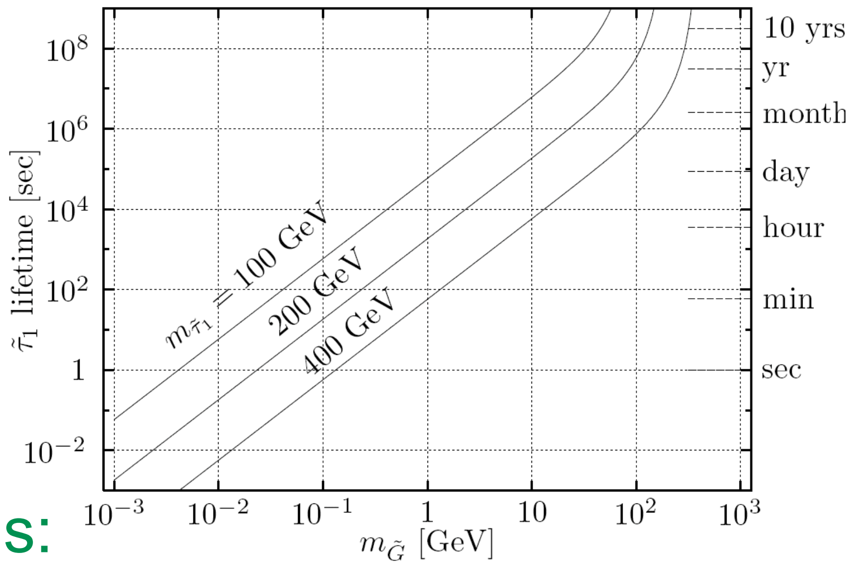
BUT

- Lack of predictivity (10^2 parameters)
- Flavour problem

χ^0 LSP: most studied case

$\tilde{G}$ LSP: It can be DM with stau as NLSP

Long-lived charged particle at the LHC ($\tilde{\tau} \rightarrow \tau \tilde{G}$)



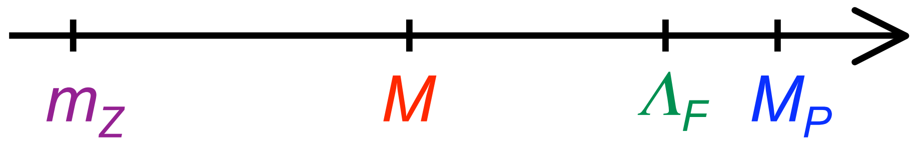
Distinctive ToF and energy loss signatures

"Stoppers" in ATLAS/CMS caverns:

- Measure position and time of stopped $\tilde{\tau}$; time and energy of τ
- Reconstruct susy scale and gravitational coupling
- With large statistics, the gravitino spin can be measured from $\tilde{\tau} \rightarrow \tau \gamma \tilde{G}$ distributions

GAUGE MEDIATION

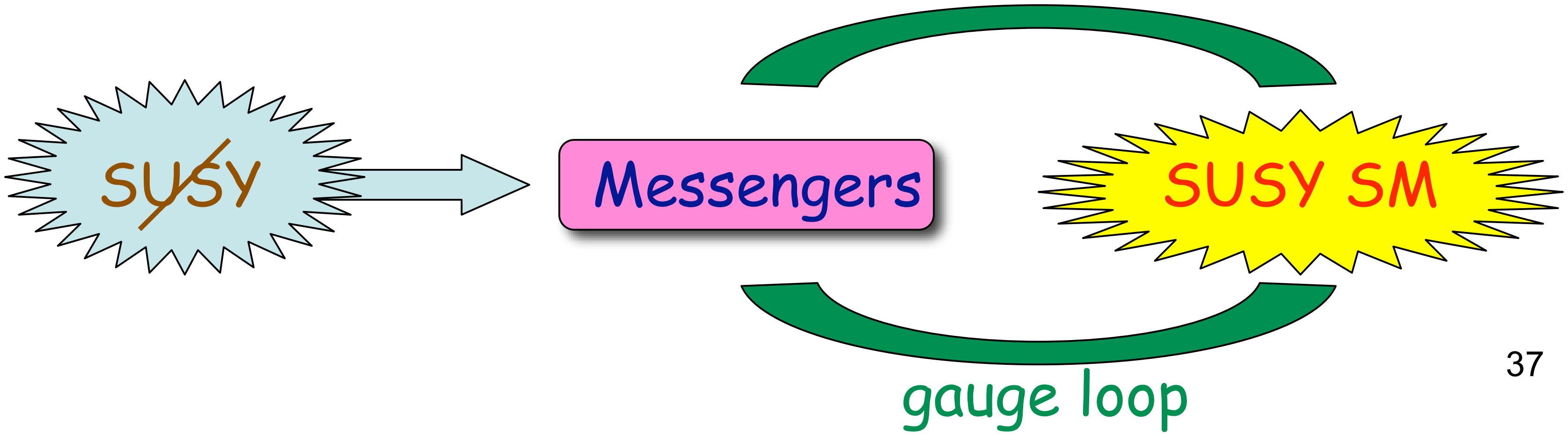
Soft terms are generated by quantum effects at a scale $M \ll M_P$

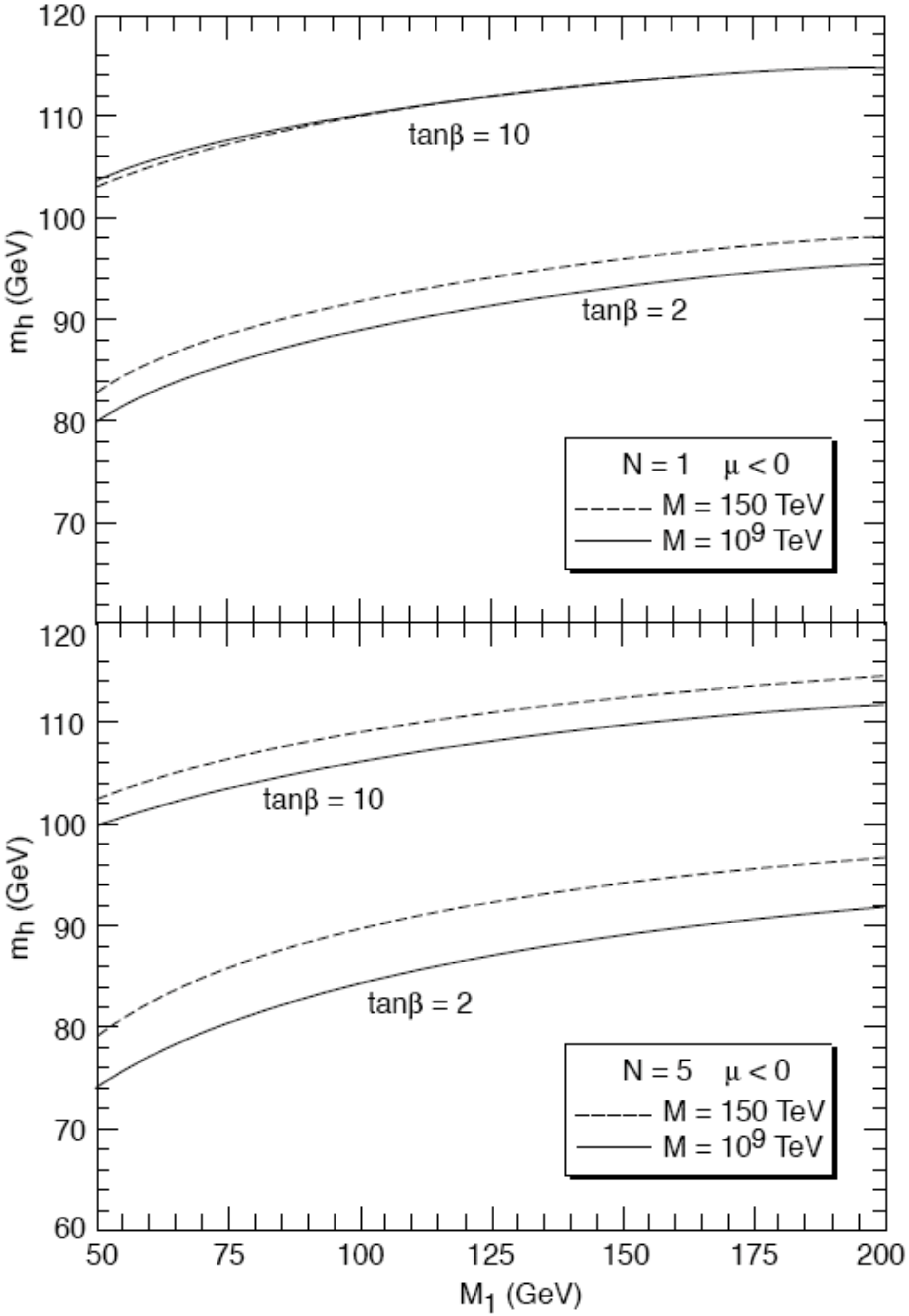


• If $M \ll \Lambda_F$, Yukawa is the only effective source of flavour breaking (MFV); flavour physics is decoupled (unlike sugra or technicolour)

• Soft terms are computable and theory is highly predictive

• Free from unknowns related to quantum gravity





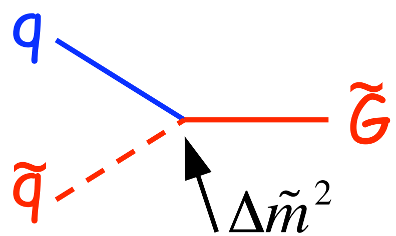
Higgs mass is the strongest constraint: stop masses at several TeV

Large squark/slepton mass ratio and small *A* do not help with tuning

Crucial difference between gauge and gravity mediation

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} \Rightarrow \text{ in gravity } m_{3/2} \approx m_S, \text{ in gauge } m_{3/2} \approx \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^2 2 \text{ eV}$$

In gauge mediation, the gravitino is *always* the LSP



$$L = -\frac{1}{F} J_Q^\mu \partial_\mu \tilde{G} = -\frac{1}{F}\left(\tilde{m}_\varphi^2 \overline{\psi}_L \varphi + \frac{M_{\tilde{g}}}{4\sqrt{2}} \overline{\lambda}^a \sigma^{\mu\nu} F_{\mu\nu}^a\right)\tilde{G} + \text{h.c.}$$

$\frac{\Delta\tilde{m}^2}{F}$ on mass shell

Goldberger-Treiman*ino* relation

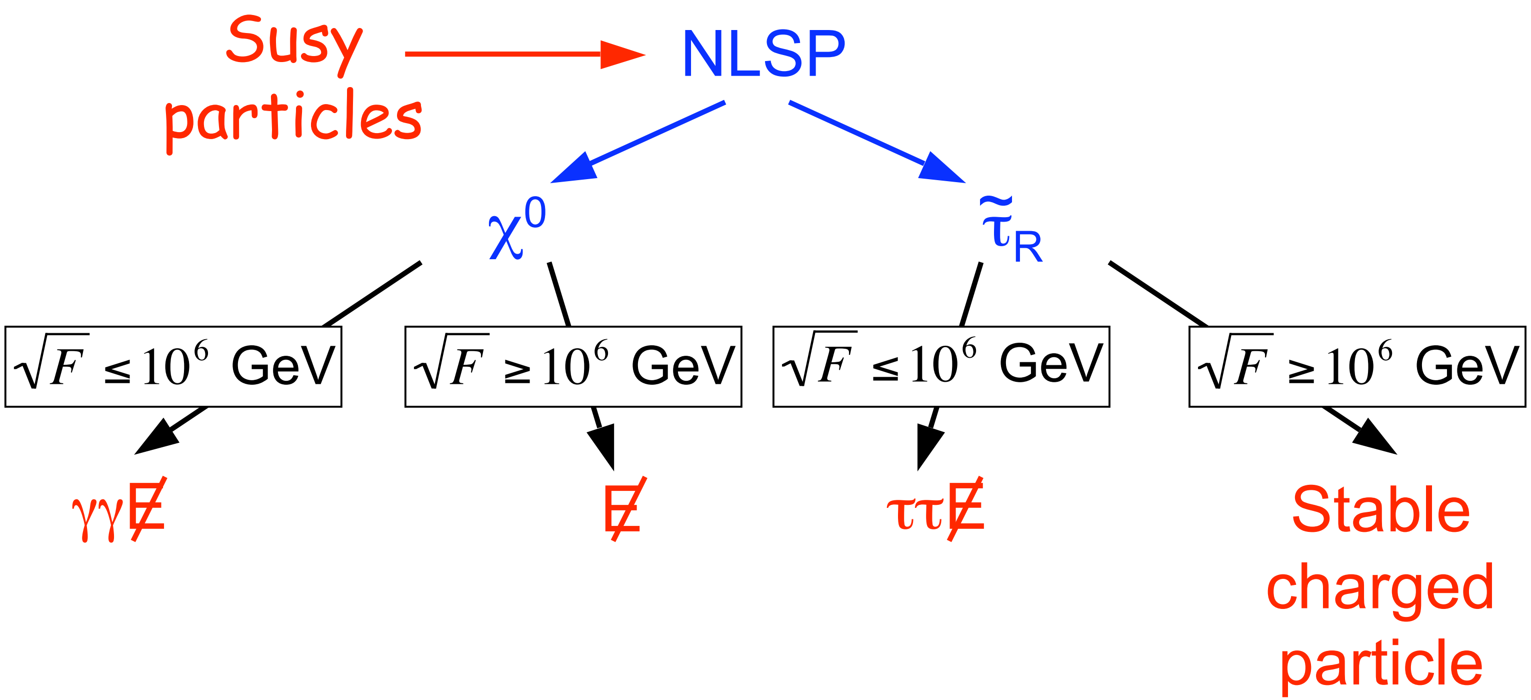
NLSP decays travelling an average distance

$$\ell \approx \left(\frac{100 \text{ GeV}}{m_{NLSP}}\right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4 \sqrt{\frac{E^2}{m_{NLSP}^2} - 1} \quad 0.1 \text{ mm}$$

From microscopic to astronomical distances

χ^0 or $\tilde{\tau}_R$ are the NLSP (NLSP can be charged)

In gravity-mediation, "missing energy" is the signature



Intermediate region very interesting

(vertex displacement; direct measurement of *F*)

ANOMALY MEDIATION

- Supergravity mediation effects depend on higher-dimensional couplings of hidden-visible sector
- There is an “unavoidable” effect ⇒ anomaly mediation
- In many cases it is subleading. In some cases it can become the dominant effect

Consider coupling to gravity in superconformal formalism with the conformal compensator chiral superfield

$$\Phi = 1 - m_{3/2}\theta^2$$

Its couplings are dictated by conformal invariance

$$L = \int d^4\theta \Phi^+ \Phi Q^+ e^V Q + \int d^2\theta \left(\Phi^3 f(Q) + \frac{1}{g^2} W^\alpha W_\alpha + \text{h.c.} \right)$$

- One can construct allowed couplings by considering all visible fields with $d = R = 0$ and Φ with $d_\Phi = 1$, $R_\Phi = 2/3$

- By rescaling $Q \to Q/\Phi$, we can eliminate Φ, if $f(Q) \sim Q^3$ has no dimensionful couplings (it is the case of interest because μ has to come from susy breaking)

- Classically, but not quantum mechanically! (Scale anomaly)

$$L = \int d^4\theta Z\left(\frac{\mu}{|\Phi|}\right) Q^+ e^V Q + \int d^2\theta \left[f(Q) + S\left(\frac{\mu}{\Phi}\right) W^\alpha W_\alpha \right] + \text{h.c.}$$

Can depend on both Φ and Φ^+, but R-symmetry implies dependence only on $\Phi\Phi^+$

Holography implies dependence only on Φ

$$M_\lambda = -\frac{1}{2}\frac{\partial \ln S}{\partial \ln \Phi}\bigg|_0 F_\Phi$$

$$m^2_{\tilde{Q}} = -\frac{\partial^2 \ln Z_Q}{\partial \ln \Phi \partial \ln \Phi^\dagger}\bigg|_0 F^\dagger_\Phi F_\Phi$$

$$A_{Q_i} = \frac{\partial \ln Z_{Q_i}}{\partial \ln \Phi}\bigg|_0 F_\Phi.$$

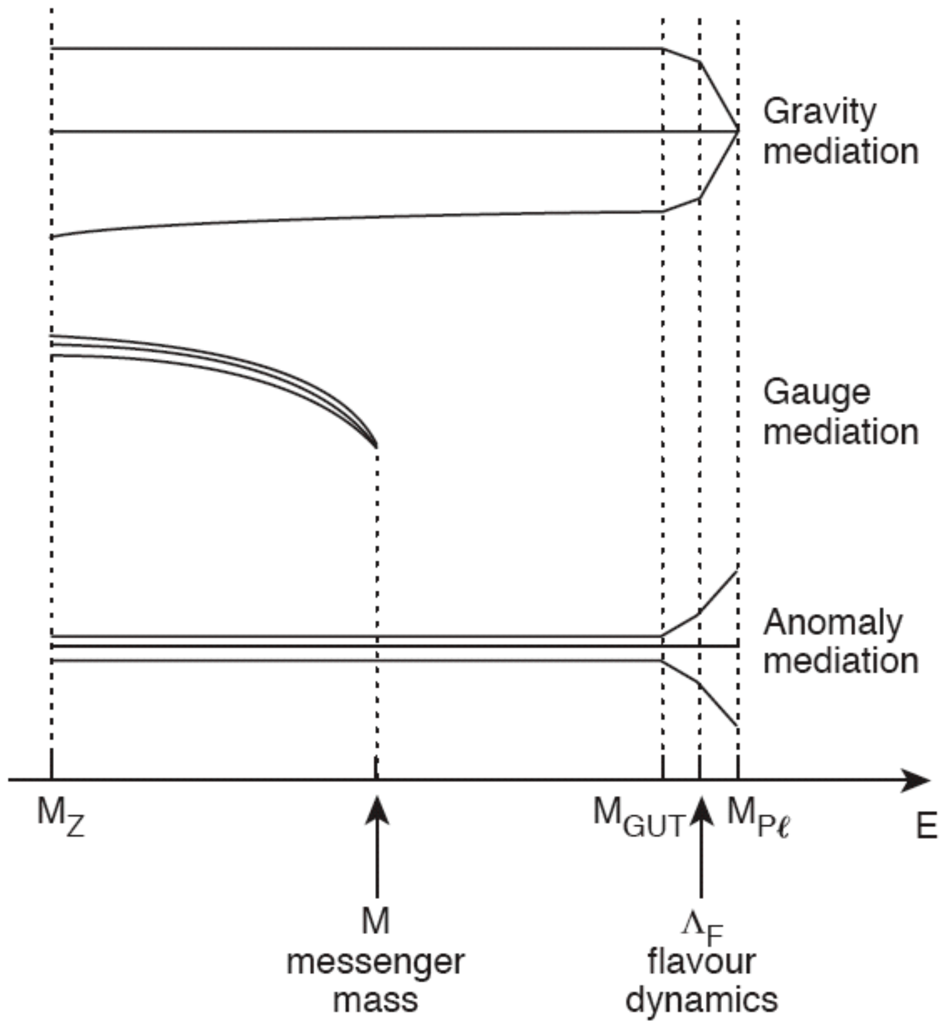
$$M_\lambda = -\frac{g^2}{2}\frac{dg^{-2}}{d\ln\mu} m_{3/2} = \frac{\beta_g}{g} m_{3/2}$$

$$m^2_{\tilde{Q}} = -\frac{1}{4}\frac{d^2 \ln Z_Q}{d(\ln\mu)^2} m^2_{3/2} = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) m^2_{3/2}$$

$$A_y = \frac{1}{2}\sum_i \frac{d\ln Z_{Q_i}}{d\ln\mu} m_{3/2} = -\frac{\beta_y}{y} m_{3/2}.$$

- Gravitino is heavy, $m_{3/2}$ ~ 10-100 TeV
- Form of soft terms invariant under RG transformations
- β function and threshold effects of heavy states exactly compensate
- Negative slepton square masses

- Predictive power: all soft terms determined by low-energy parameters (up to overall scale $m_{3/2}$)
- UV insensitivity: solution to the flavour problem



Characteristic features of anomaly mediation

With gaugino unification $\frac{M_2}{M_1} \approx 2 \quad \frac{M_3}{M_1} \approx 7$

In anomaly mediation $\frac{M_1}{M_2} \approx 3 \quad \frac{M_3}{M_2} \approx 7$

LSP nearly degenerate *W*-ino

$$m_{\chi^\pm} - m_{\chi^0} \approx \frac{\alpha M_W}{2(1+\cos\theta_W)} \approx 165 \text{ MeV (tree level is typically smaller)}$$

This allows the fast decay $\tilde{W}^\pm \to \pi^\pm \tilde{W}^0$

The pions are soft, making their detection difficult

MIRAGE UNIFICATION

It is possible to have a mixed modulus and anomaly mediation such that

$$\frac{F_T}{T} = M_0 \approx \frac{m_{3/2}}{\ln\left(M_P / m_{3/2}\right)}$$

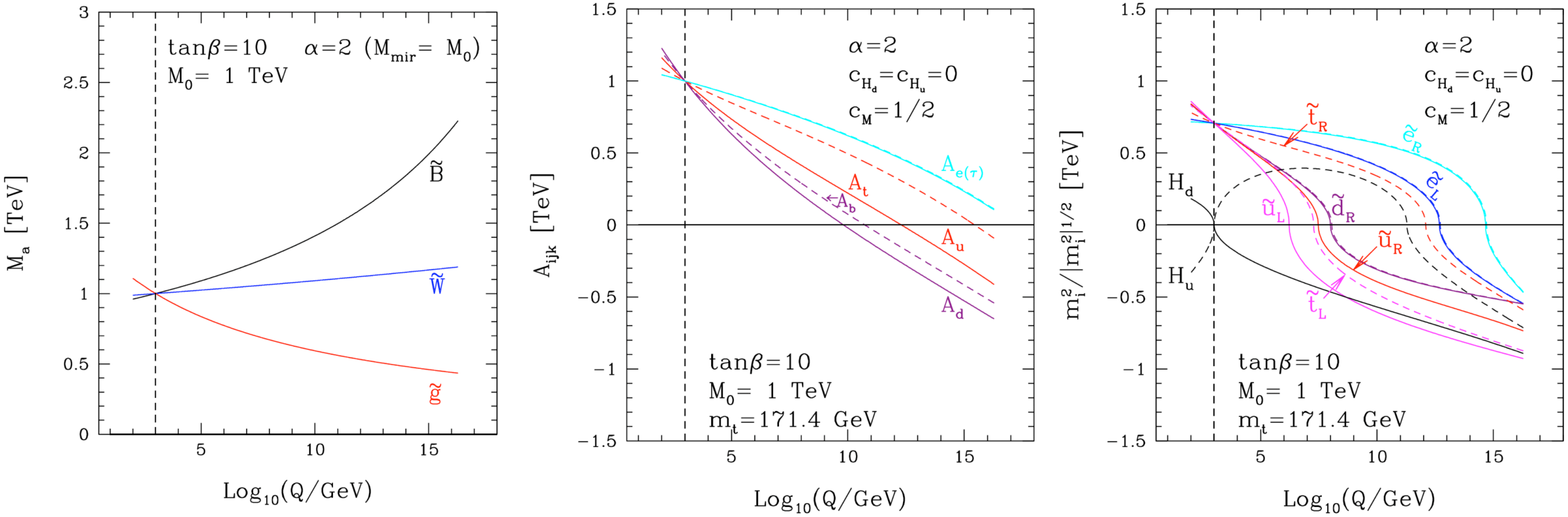
For $m_{3/2} \approx 10$ TeV, this is comparable to anomaly contribution

Although uplift potential not consistent with extra dim, one finds

$$M_{\tilde{g}} = A = \sqrt{2}\,\tilde{m} \quad \text{at} \quad M_{mir} = \frac{M_{GUT}}{\left(M_P / m_{3/2}\right)^{\alpha/2}}$$

α is the ratio of anomaly/modulus contributions

No physical threshold at M_{mir}



• small log

• large A

• compressed spectrum

is best to reduce tuning

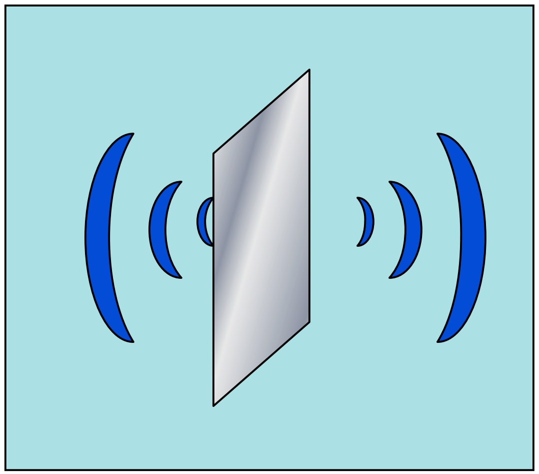
EXTRA DIMENSIONS AND THE WEAK SCALE

Usual approach: fundamental theory at M_{Pl}, while Λ_W is a derived quantity

Alternative: Λ_W is fundamental scale, while M_{Pl} is a derived effect

New approach requires
- extra spatial dimensions
- confinement of matter on subspaces

Natural setting in string theory $\Rightarrow$ Localization of gauge theories on defects (D-branes: end points of open strings)



We are confined in a 4-dim world, which is embedded in a higher-dim space where gravity can propagate

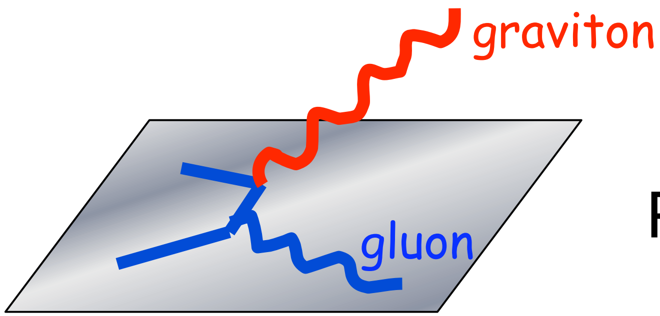
Suppose fundamental mass scale $M_D \sim \text{TeV}$

$$M_{Pl} = M_D \left(RM_D\right)^{\frac{D-4}{2}}$$ very large if R is large (in units of M_D^{-1})

Radius of compactified space

$$R = \begin{cases} \left(5\times10^{-4}\ \text{eV}\right)^{-1} \approx 0.4\ \text{mm} & D-4=2 \\ \left(20\ \text{keV}\right)^{-1} \approx 10^{-5}\ \mu\text{m} & D-4=4 \\ \left(7\ \text{MeV}\right)^{-1} \approx 30\ \text{fm} & D-4=6 \end{cases}$$

- Smallness of G_N/G_F related to largeness of RM_D
- Gravity is weak because it is diluted in a large space (small overlap with branes)
- Need dynamical explanation for $RM_D >> 1$



Probe gravity at colliders

Probability of producing a KK graviton $\approx \dfrac{E^2}{M_{Pl}^2}$

$$\sigma\left(pp \to G^{(n)}\,\mathrm{jet}\right) = \frac{\alpha_s}{\pi} G_N = 10^{-28}\ \mathrm{fb} \qquad 1\ \mathrm{event}\ \Rightarrow\ \mathrm{run\ LHC\ for}\ 10^{16}\ t_U$$

Number of KK modes with mass less than *E* (use *m*=*n*/*R*)

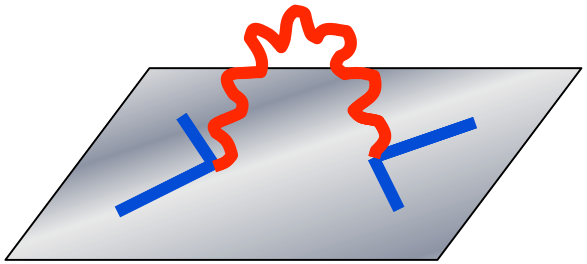
$$\propto n^{D-4} \approx (ER)^{D-4} \approx \frac{E^{D-4} M_{Pl}^2}{M_D^{D-2}}$$

Inclusive cross section $\displaystyle\sum_n \sigma\left(pp \to G^{(n)}\,\mathrm{jet}\right) \approx \frac{\alpha_s E^{D-4}}{\pi\, M_D^{D-2}}$

It does not depend on V_D (*i.e.* on the Planck mass)

Missing energy and jet with characteristic spectrum

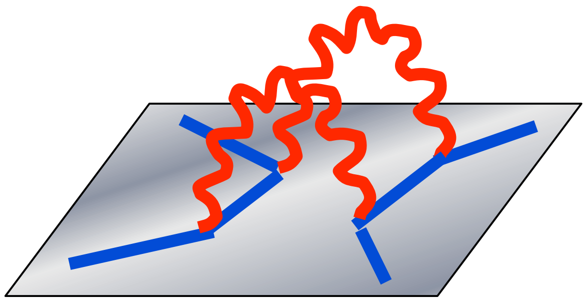
Contact interactions from graviton exchange



$$L = \pm \frac{4\pi}{\Lambda_T^4} T$$

$$T = \frac{1}{2}\left(T_{\mu\nu} T^{\mu\nu} - \frac{1}{D-2} T_\mu^\mu T_\nu^\nu \right)$$

- Sensitive to UV physics
- d-wave contribution to scattering processes
- predictions for related processes
- Limits from Bhabha/di-γ at LEP and Drell-Yan/ di-γ at Tevatron: Λ_T > 1.2 - 1.4 TeV



$$L = \pm \frac{4\pi}{\Lambda_\Upsilon^2} \Upsilon$$

$$\Upsilon = \frac{1}{2}\left(\sum_{f=q,l} \bar{f} \gamma_\mu \gamma_5 f \right)^2$$

- Loop effect, but dim-6 vs. dim-8
- Υ only dim-6 generated by pure gravity
- Λ_Υ > 15 - 17 TeV from LEP

G-emission is based on linearized gravity, valid at $s \ll M_D^2$

TRANSPLANCKIAN REGIME

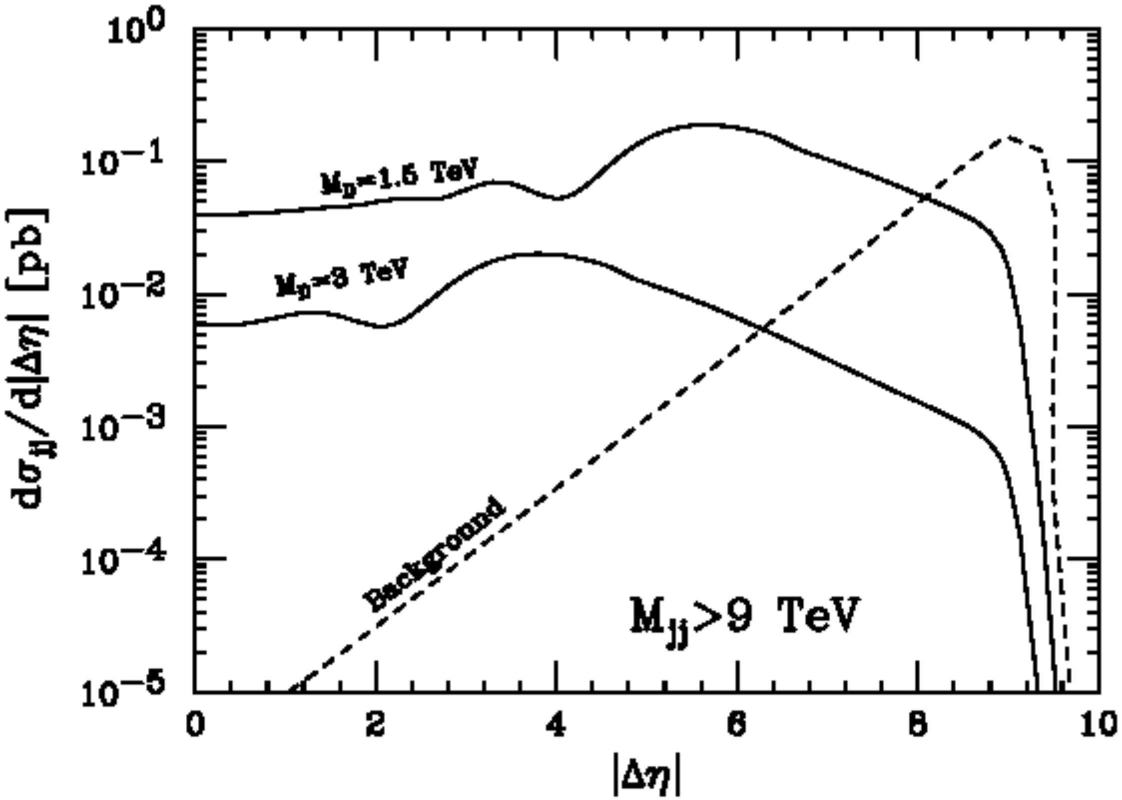
Planck length $\lambda_P = \left(\frac{G_D \hbar}{c^3} \right)^{\frac{1}{\delta+2}}$ quantum-gravity scale

Schwarzschild radius $R_S = \frac{1}{\sqrt{\pi}} \left[\frac{8}{\delta+2} \Gamma\left(\frac{\delta+3}{2} \right) \right]^{\frac{1}{\delta+1}} \left(\frac{G_D \sqrt{s}}{c^3} \right)^{\frac{1}{\delta+1}}$ classical gravity

$$\left.\begin{array}{lll} \text{classical limit} & (\hbar \to 0) : & R_S >> \lambda_P \\ \text{transplanckian limit} & (\sqrt{s} >> M_D) : & R_S >> \lambda_P \end{array}\right\} \text{same regime}$$

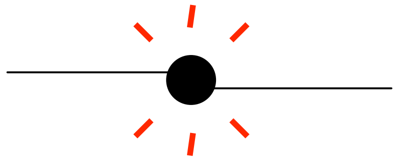
The transplanckian regime is described by classical physics (general relativity) ⇨ independent test, crucial to verify gravitational nature of new physics

Gravitational scattering in extra dimensions: two-jet signal at the LHC



Diffractive pattern characterized by

$$b_c \approx \left(\frac{G_D s}{\hbar} \right)^{\frac{1}{\delta}}$$



$b < R_S$ At $b<R_S$, no longer calculable

Strong indications for black-hole formation

BH with angular momentum, gauge quantum numbers, hairs
(multiple moments of the asymmetric distribution of gauge charges and energy-momentum)

Gravitational and gauge radiation during collapse
$\Rightarrow$ spinning Kerr BH

$\sigma \sim \pi R_S^2$ 10 pb (for M_{BH}=6 TeV and M_D=1.5 TeV)

Hawking radiation until Planck phase is reached
$T_H \sim R_S^{-1} \sim M_D\,(M_D / M_{BH})^{1/(\delta+1)}$

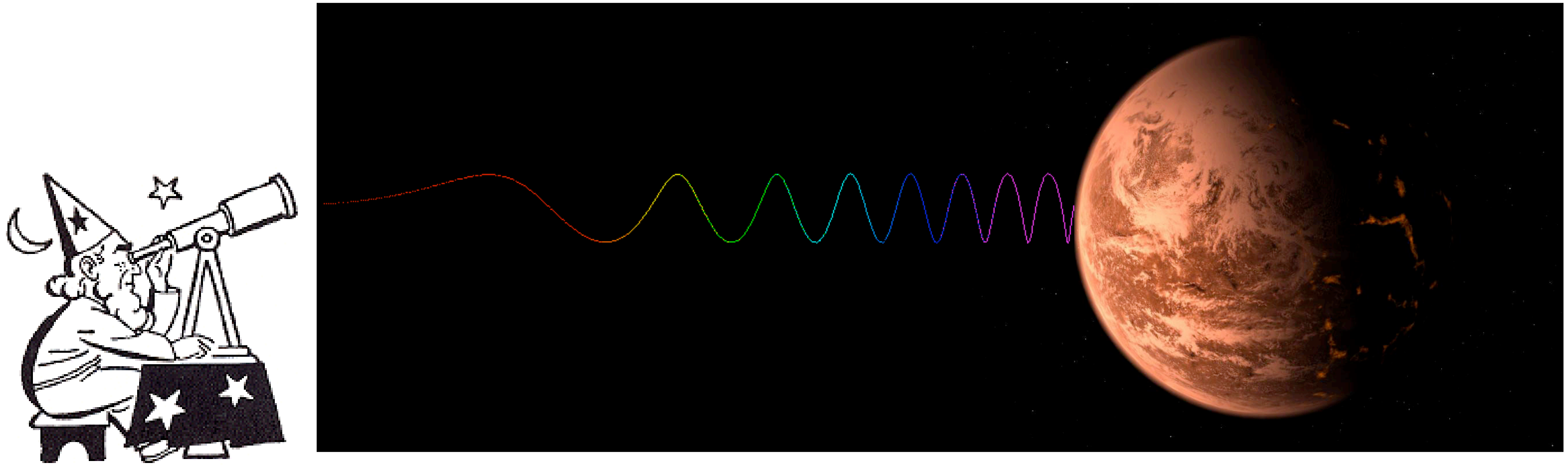
Evaporation with $\tau \sim M_{BH}^{(\delta+3)/(\delta+1)} / M_D^{2(\delta+2)/(\delta+1)}$ (10^{-26} s for M_D=1 TeV)

Characteristic events with large multiplicity ($\langle N \rangle \sim M_{BH} / \langle E \rangle \sim (M_{BH} / M_D)^{(\delta+2)/(\delta+1)}$) and typical energy $\langle E \rangle \sim T_H$

Transplanckian condition $M_{BH} \gg M_D$?

WARPED GRAVITY

A classical mechanism to make quanta softer



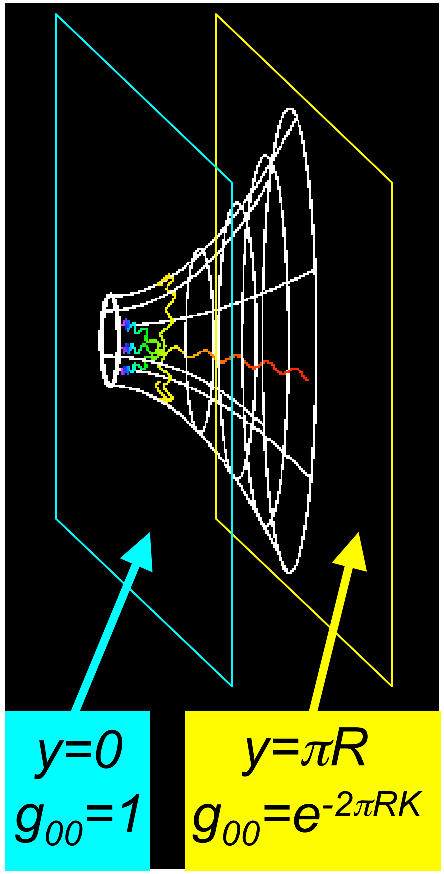
For time-indep. metrics with $g_{0\mu}=0 \Rightarrow E\,|g_{00}|^{1/2}$ conserved

. (proper time $d\tau^2 = g_{00}\, dt^2$)

Schwarzschild metric $g_{00} = 1 - \frac{2G_N M}{r} \quad \Rightarrow \quad \frac{E_{obs} - E_{em}}{E_{em}} = \sqrt{|g_{00}|} - 1 = -\frac{G_N M}{r_{em}}$

On non-trivial metrics, we see far-away objects as red-shifted

GRAVITATIONAL RED-SHIFT



$$ds^2 = e^{-2K|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

Masses on two branes related by

$$\frac{m_{\pi R}}{m_0} = e^{-\pi RK}$$

Same result can be obtained by integrating S_E over y

$$R \approx 10\, K^{-1} \quad \Rightarrow \quad \frac{m_{\pi R}}{m_0} \approx \frac{M_Z}{M_{GUT}}$$

PHYSICAL INTERPRETATION

- Gravitational field configuration is non-trivial
- Gravity concentrated at $y=0$, while our world confined at $y=\pi R$
- Small overlap $\Rightarrow$ weakness of gravity

WARPED GRAVITY AT COLLIDERS

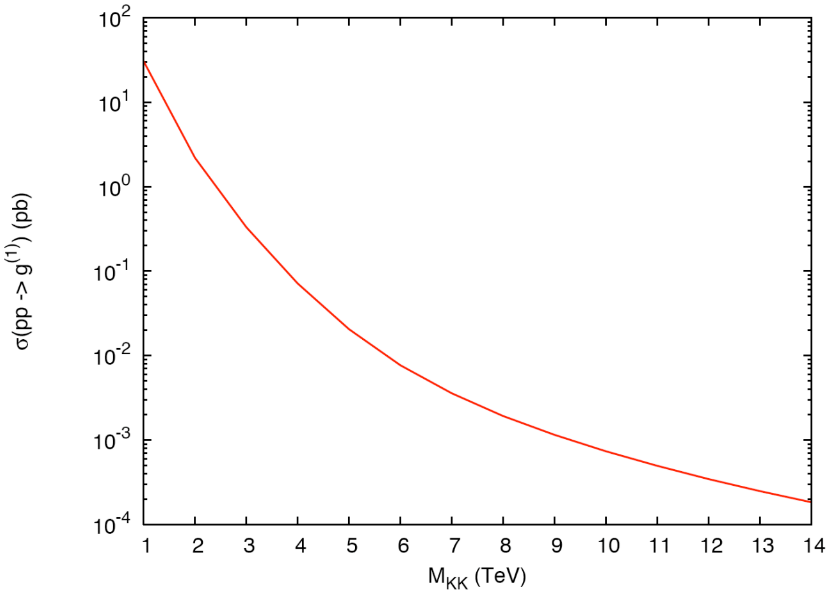
- KK masses $m_n = Kx_n e^{-\pi RK}$ [x_n roots of $J_1(x)$] not equally spaced
- Characteristic mass $Ke^{-\pi RK} \sim$ TeV
- KK couplings

$$L = -T^{\mu\nu}\left(\frac{G^{(0)}_{\mu\nu}}{M_{Pl}} + \sum_{n=1}^{\infty}\frac{G^{(n)}_{\mu\nu}}{\Lambda_\pi}\right) \qquad \Lambda_\pi \equiv e^{-\pi RK} M_{Pl} \approx \text{TeV}$$

- KK gravitons have large mass gap and are "strongly" coupled

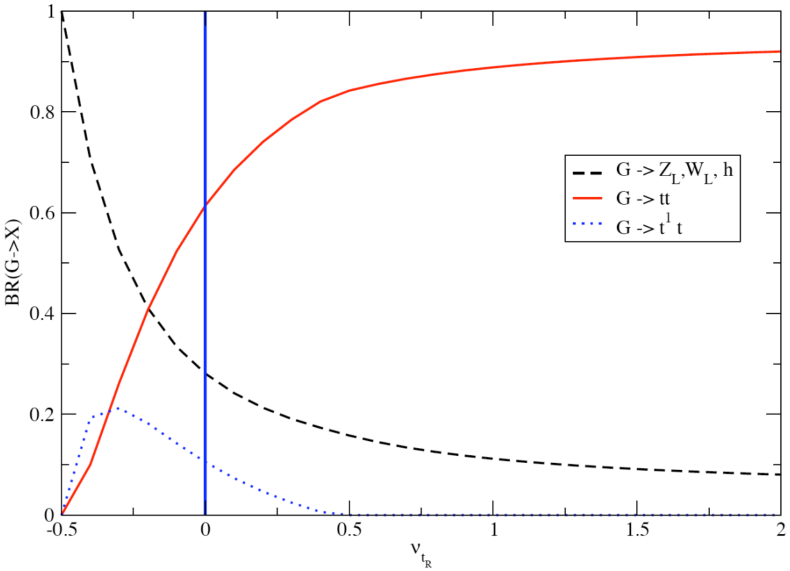
RS with gauge bosons & fermions in the bulk is emerging as one of the most interesting model with extra dimensions

Discovery through KK-gluon production $q\bar{q} \to g^{(1)} \to t\bar{t}$

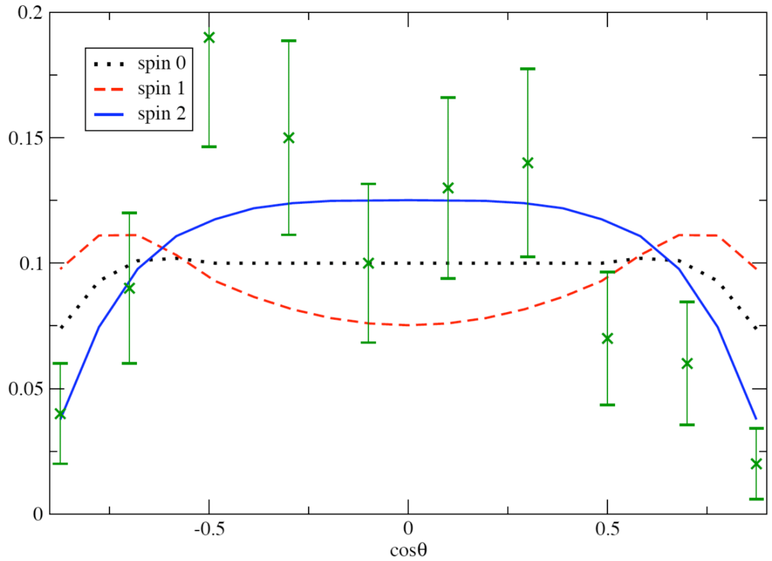


It can be identified up to M_{KK} = 5 TeV

Test of gravitational nature from KK-graviton production



Using *tt* and *ZZ* final states, LHC can test up to M_{KK} = 2 TeV



Possible to identify the spin-2 structure