Theories for the Fermi Scale

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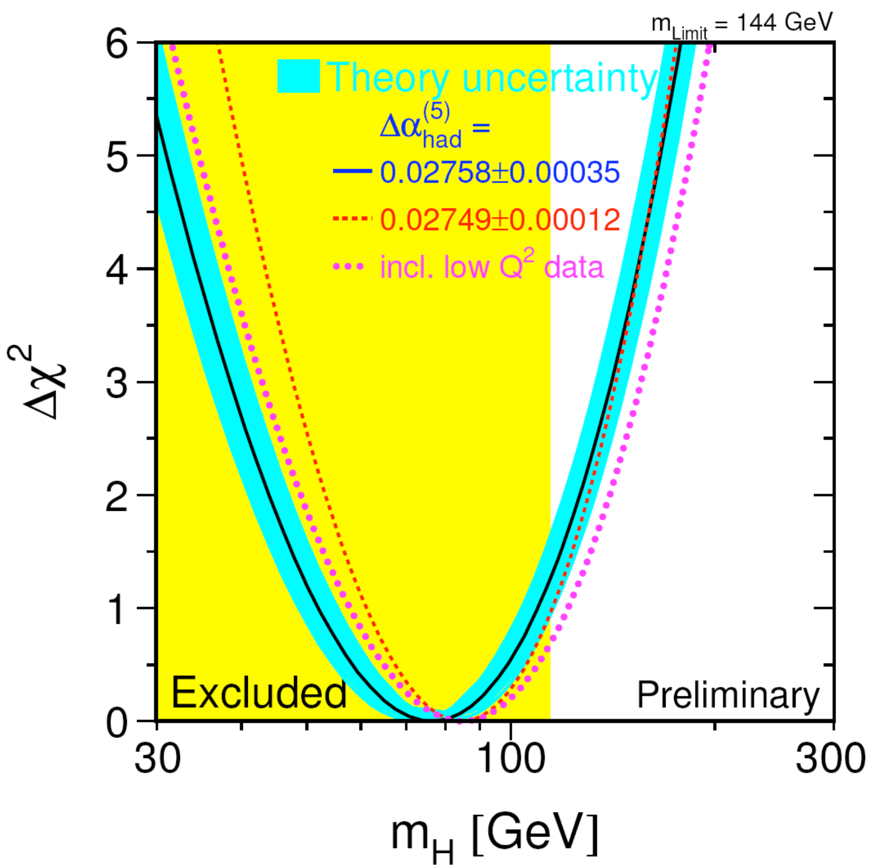
Ten questions to be answered by the LHC

1) Is there a Higgs?

- 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

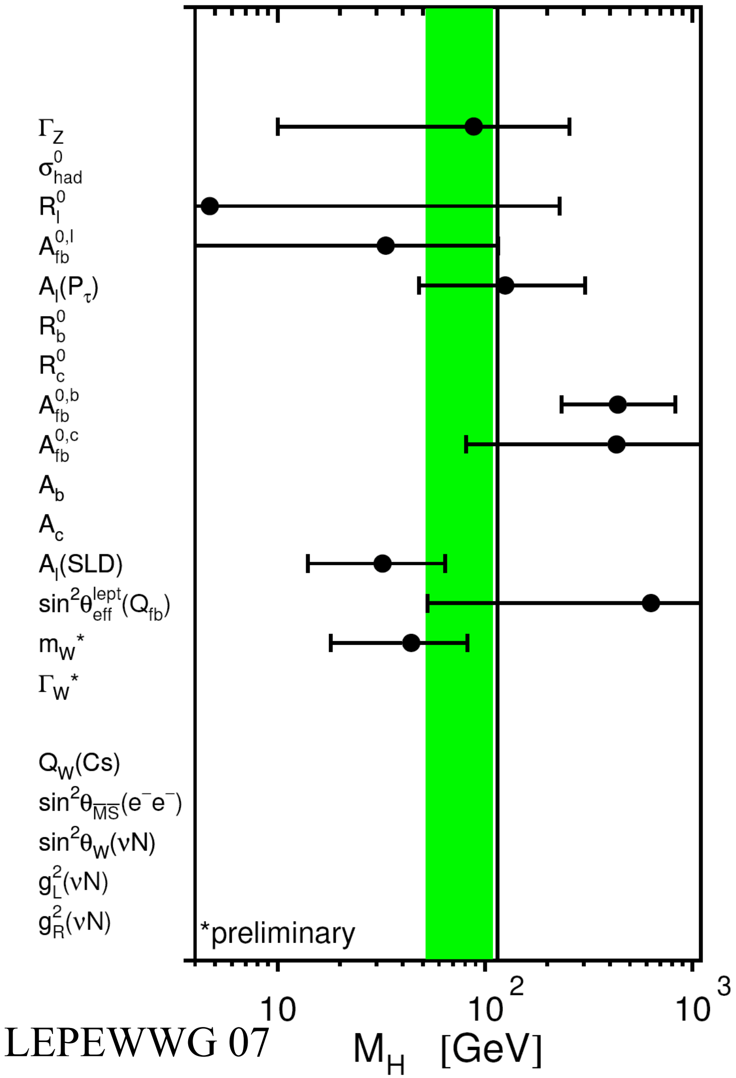
CDF/D∅: $m_t = 170.9 \pm 1.8$ GeV

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

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

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

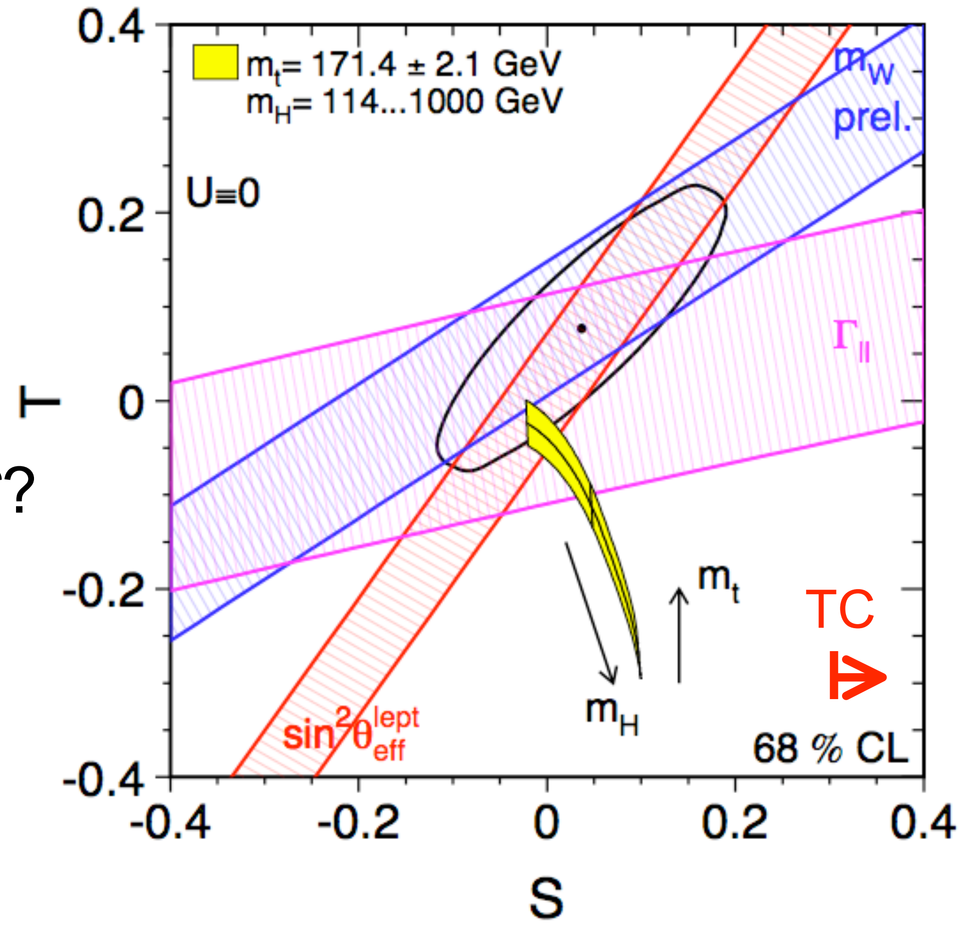
This makes the argument for a light Higgs less compelling



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?

Hirn-Sanz; Delgado-Falkowski; Agashe-Csaki-Grojean-Reece

Walking at small N_{TC}?

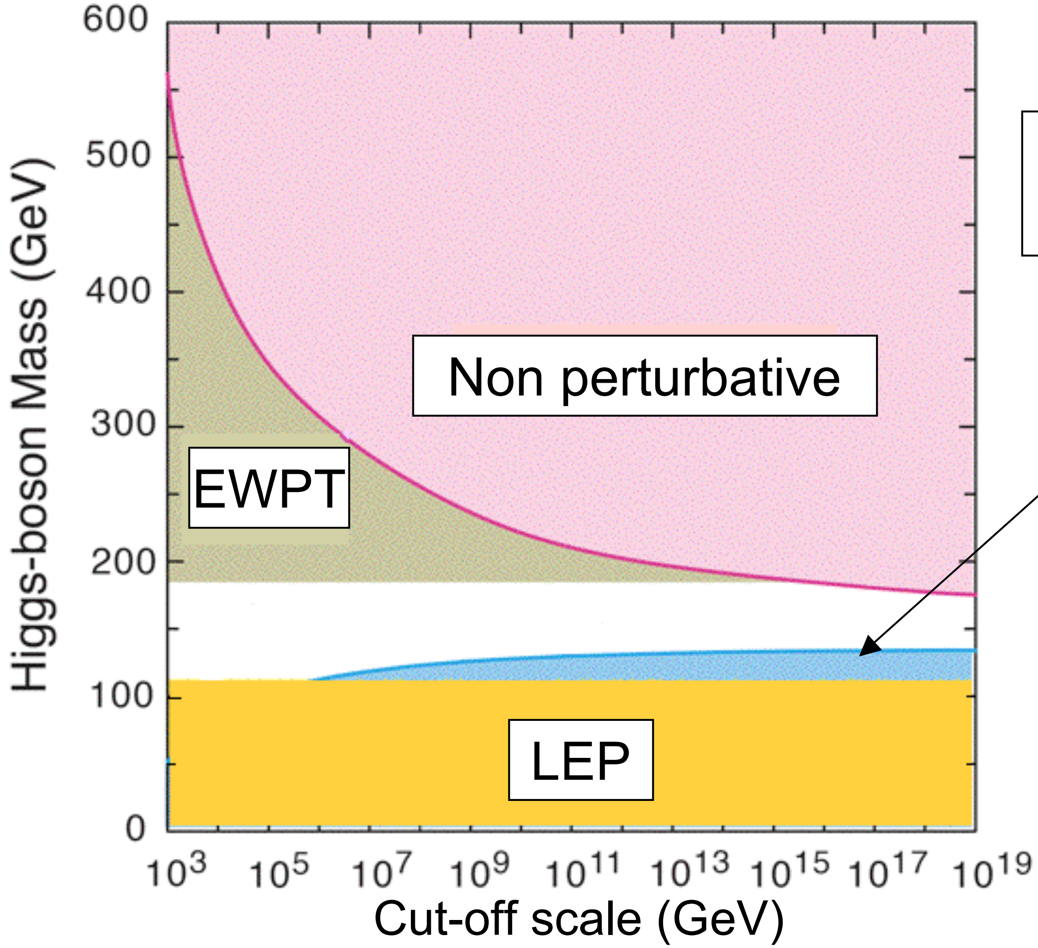
Foadi-Frandsen-Ryttov-Sannino; Piai

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

Csaki-Grojean-Pilo-Terning

2) What is the Higgs mass?

Important indirect information from Higgs mass measurement



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

Higgs mass provides one of the strongest constraints to supersymmetry

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

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

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

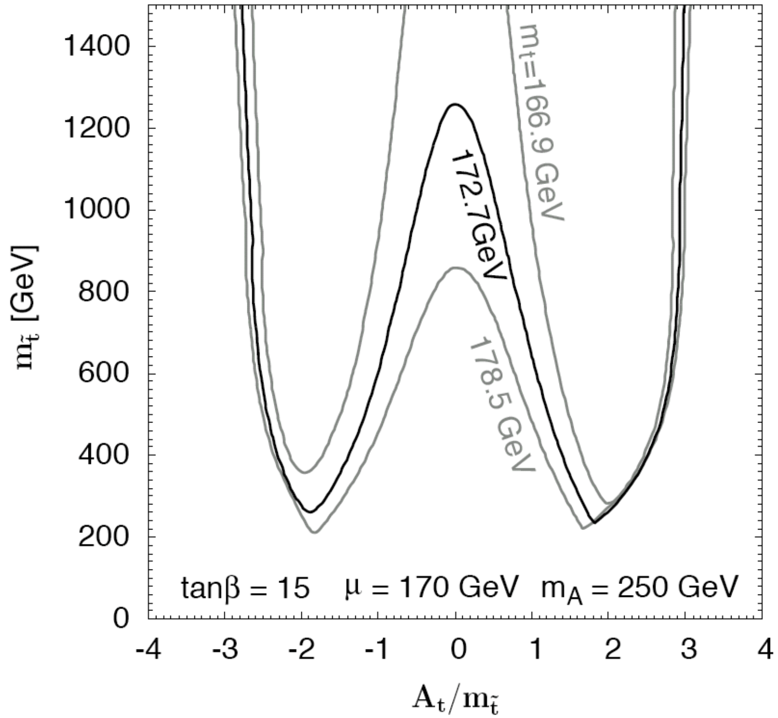
gauge med ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 115\,\mathrm{GeV}$

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



Extensions with new states and new interactions at (multi)TeV scale to generate new quartic couplings

- New singlet $W = \lambda N H_u H_d + k N^3$
- New gauge interactions

Using an effective-theory approach

Brignole-Casas-Espinosa-Navarro;
Dine-Seiberg-Thomas

$$L = \int d^2\theta \, \mu H_u H_d + \frac{1}{M}(H_u H_d)^2$$

$$V = B_\mu H_u H_d + \frac{\tilde{m}}{M}(H_u H_d)^2$$

Sub-TeV stop and heavy Higgs (m_H >130 GeV) will be evidence for additional structure

3) 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

- New singlets? O'Connell-Ramsey-Musolf-Wise; Chang-Fox-Weiner
- Link to mirror worlds? Chacko-Goh-Harnik; Strassler; Patt-Wilczek

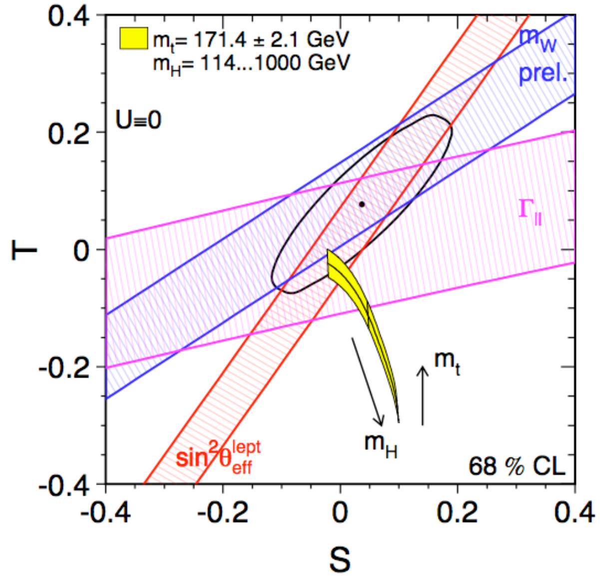
Higgs mass is only allowed super-renormalizable term

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

↑ Hidden-sector operator

- Evading m_H upper bound from EWPT?

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



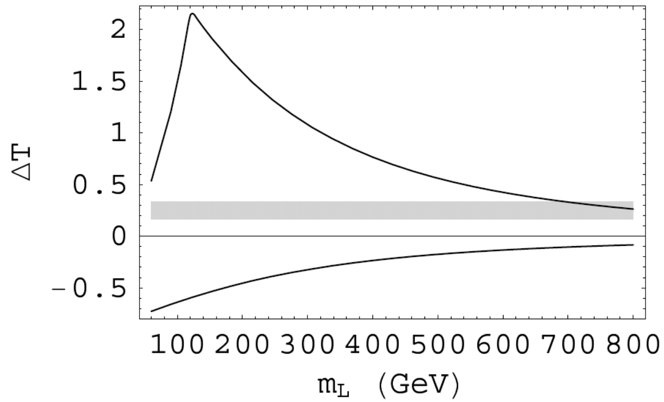
- Inert Doublet Model: Barbieri-Hall-Rychkov

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

Lightest parity-odd Higgs can be DM

Casas-Espinosa-Hidalgo

No significant improvement in naturalness



- Susy with large $\lambda N H_1 H_2$

Barbieri-Hall-Nomura-Rychkov

ΔT from Higgs-higgsino system

Heavy Higgs, but validity only up to about 10 TeV

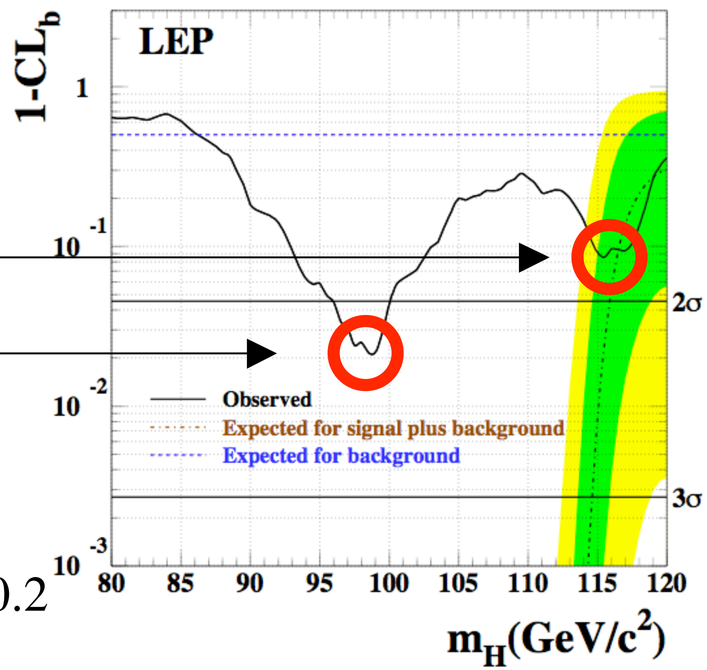
- New EW fermions Enberg-Fox-Hall-Papaioannou-Papucci

DM candidate

- Evading m_H lower bound from LEP?

Controversial signal at 115 GeV

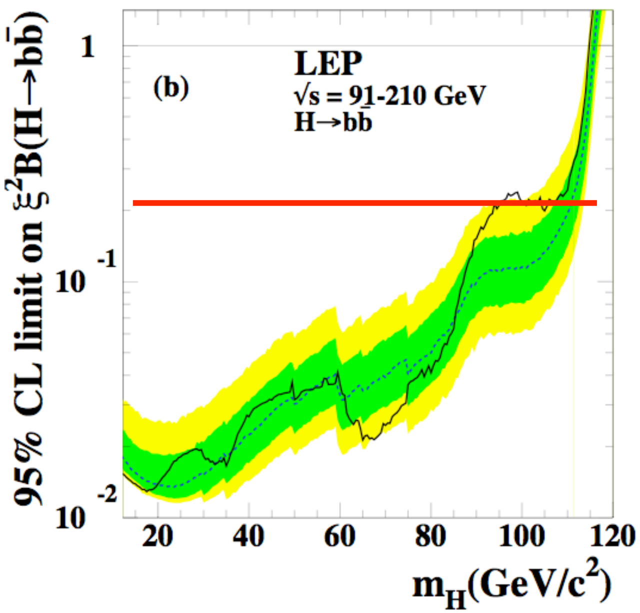
2.3σ excess at 98 GeV



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

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)

Drees; Kim-Maekawa-Matsuzaki-Sakurai-Sanda-Yoshikawa; Belyaev-Cao-Nomura-Tobe-Yuan

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

Dermisek-Gunion

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

Reanalysis of LEP data?

- Light neutralino with R-parity breaking decay

Carpenter-Kaplan-Rhee

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

Displaced vertices at LHCb?

4) 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)

Composite: Higgs is a light remnant of a strong force
- pseudoGoldstone — Georgi-Kaplan
- Little Higgs — Arkani-Hamed-Cohen-Georgi
- Gauge-Higgs unification — Manton; Hosotani
- Holographic Higgs — Agashe-Contino-Pomarol
- ….

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

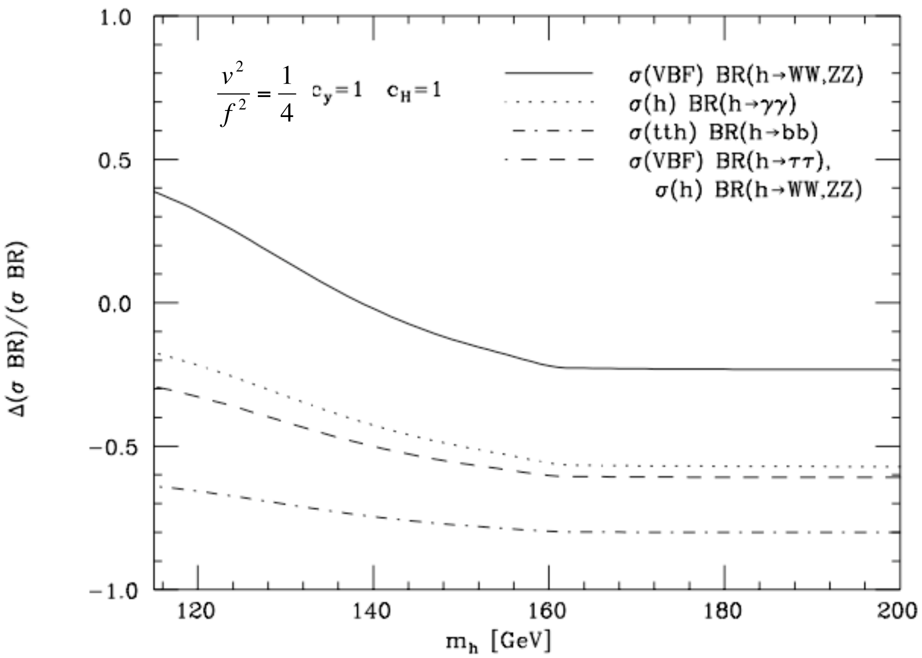
What are the distinctive features of compositeness at the LHC?

Recent progress on effective-theory description of a composite Higgs

Contino-Kramer-Son-Sundrum;
Giudice-Grojean-Pomarol-Rattazzi;
Barbieri-Bellazzini-Rychkov-Varagnolo

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

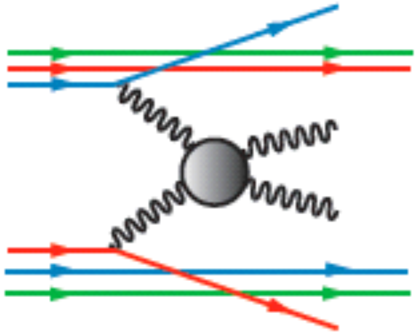
LHC 20–40 %

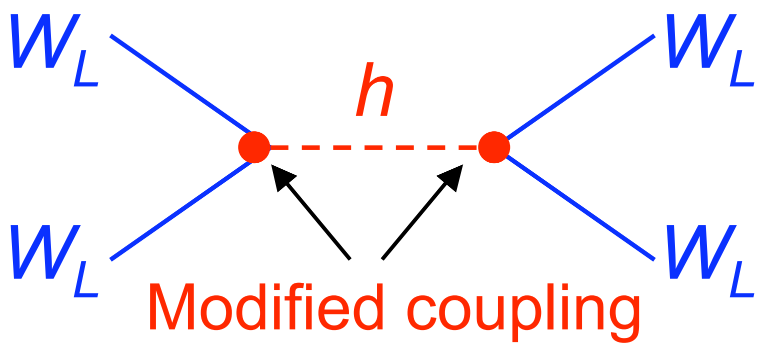
SLHC 10 %

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
Butterworth-Cox-Forshaw

$V_L V_L$ 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 $\Rightarrow$ strong Higgs production

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

BSM constructions have focused on the hierarchy problem

	Cancellation of	Existence of
Good examples of naturalness at work	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

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

Evidence for “unnaturalness” at work

- Split Supersymmetry   Arkani-Hamed-Dimopoulos; Giudice-Romanino

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   Giudice-Rattazzi

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   Hall-Watari

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

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

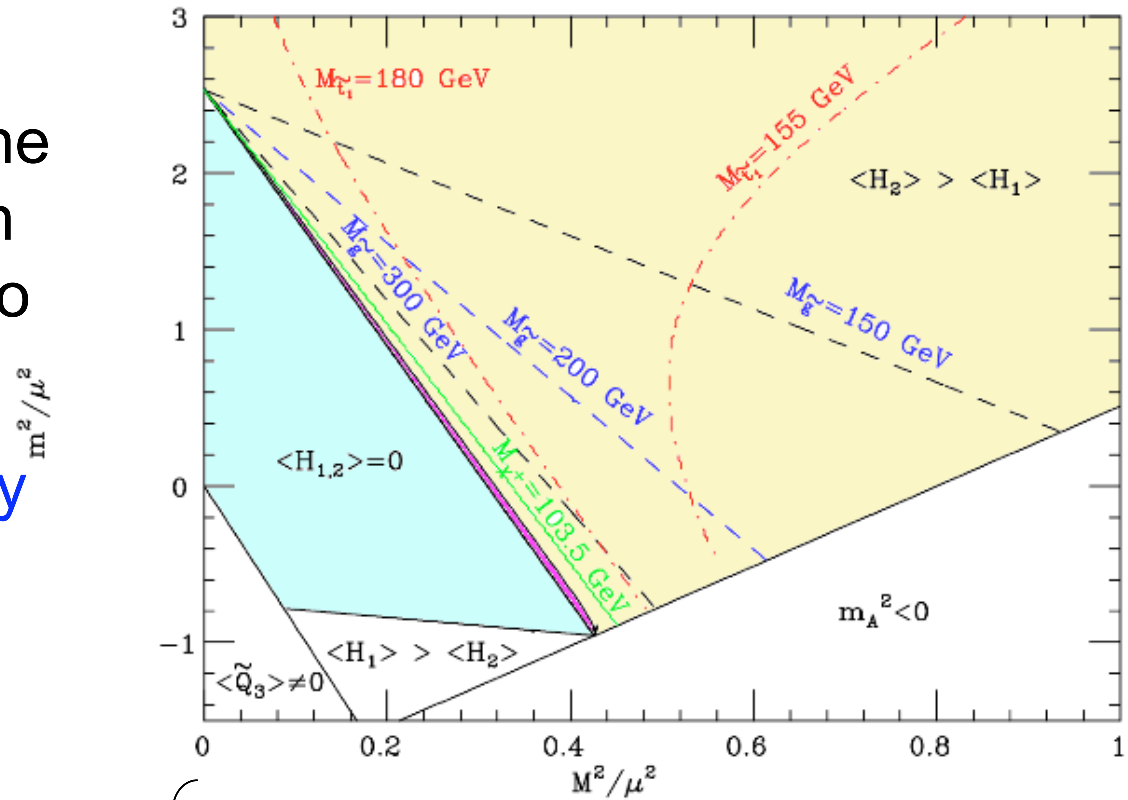
(better discover the Higgs quickly, because the end of the world is near)

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

6) Is supersymmetry effective at the weak scale?

Susy: 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



Why is susy "near-critical"?

- Bad luck
- Dynamical explanation
- Statistical explanation
- Wrong track

Supersymmetry can be realized in many different ways with totally different signatures at the LHC

Each scheme has pros and cons and none has emerged as theoretically preferred

Quick overview with emphasis on recent results

- SUPERGRAVITY

Interesting connection EW/gravity, but arbitrariness in susy-breaking terms (excessive FCNC & CP violation)

χ^0 LSP: most studied case (although in specific points)

Attempts to go beyond theoretically unjustified constrained versions or benchmark points and explore the wide parameter space

Arkani-Hamed-Kane-Thaler-Wang

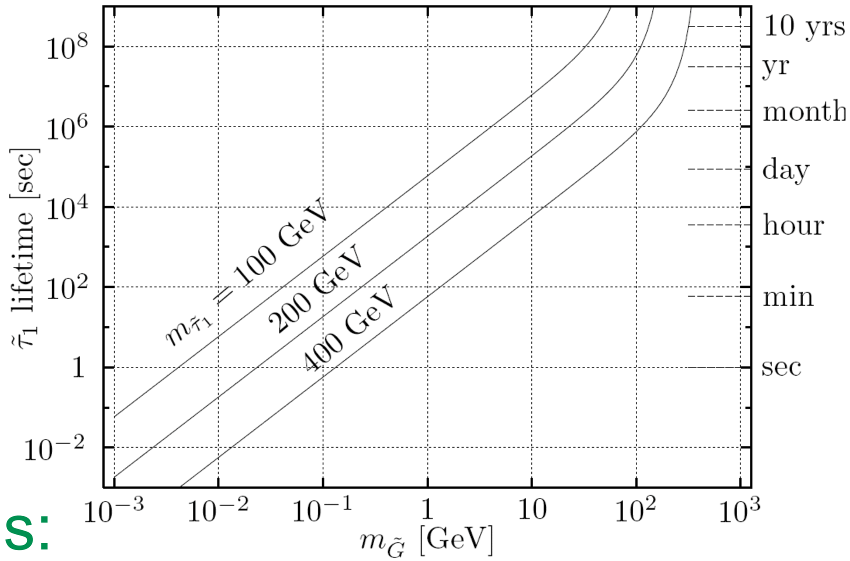
$\tilde{G}$ LSP:

It can be DM with stau as NLSP

Feng-Rajaraman-Takayama; Ellis-Olive-Santoso-Spanos; Roszkowski-Ruiz-Choi

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

Hamaguchi-Kuno-Nakaya-Nojiri; Feng-Smith; Ellis-Raklev-Øye; Hamaguchi-Nojiri-de Roeck



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

Buchmuller-Hamaguchi-Ratz-Yanagida

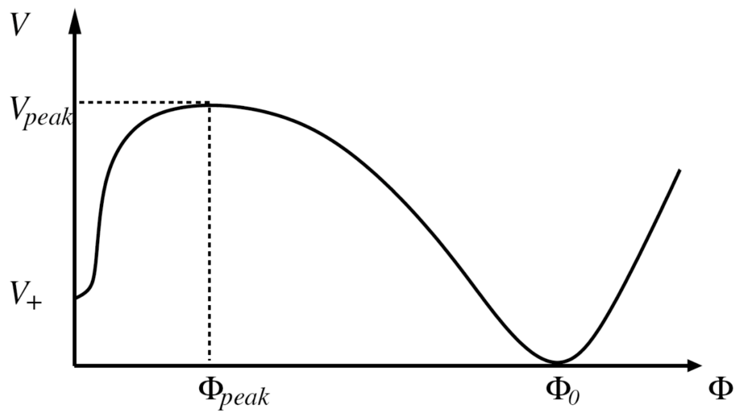
GAUGE MEDIATION

Theoretically attractive
- Soft terms computable
- No flavour problem (but μ problem)

Experimentally very constrained
- Small stop mixing: large tuning to have m_H above LEP limit

Living in a metastable susy-breaking vacuum with exact susy in global minimum

Dimopoulos-Dvali-Rattazzi-Giudice; Luty



Generic feature of supersymmetric QCD with massive flavours

Intriligator-Seiberg-Shih

Recent burst of activity in model building

ANOMALY MEDIATION

- Unavoidable effect in visible sector, once susy is broken

Leading effect: extra-dimensional separation — Randall-Sundrum

no singlets in hidden sector — Giudice-Luty-Murayama-Rattazzi

conformal sequestering — Schmaltz-Sundrum

- Soft terms computable and UV insensitive
- Requires another source of ~~susy~~ to cure slepton masses

Recent result: anomaly + modulus = mirage

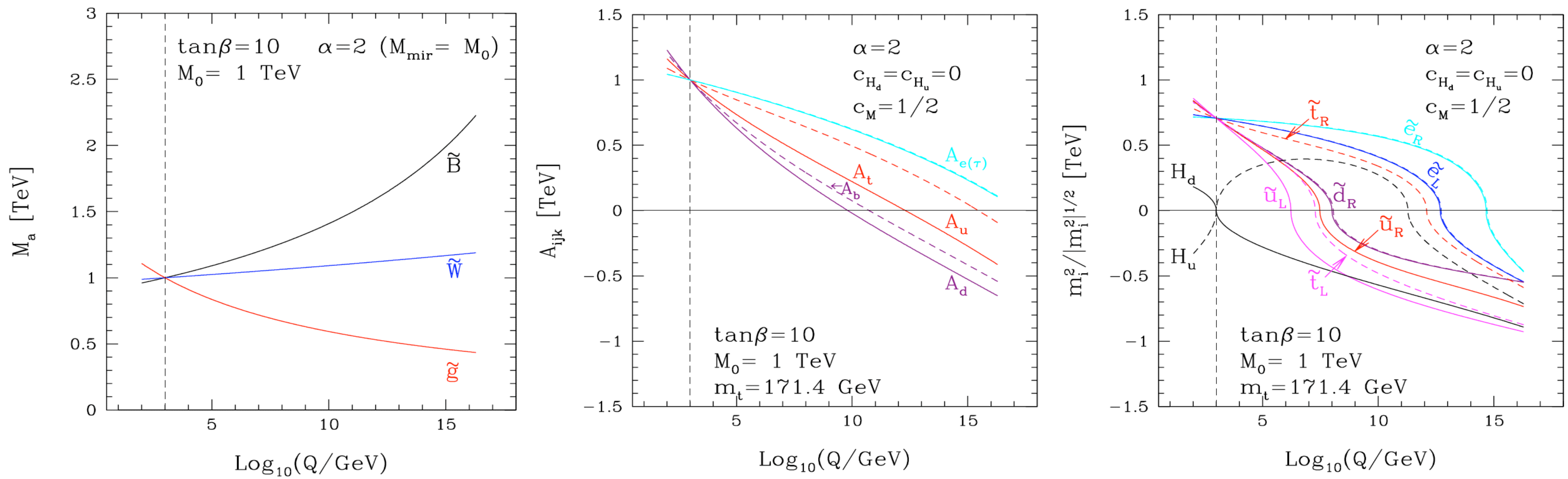
Choi-Jeong-Kobayashi-Okumura; Choi-Falkowski-Nilles-Olechowski-Pokorski

Problem to justify the theory structure, — Pierce-Thaler

but interesting spectrum

Kitano-Nomura; Choi-Jeong-Kobayashi-Okumura

Mirage mediation



Under certain assumptions

$$M_{\tilde{g}} = A = \tilde{m}\sqrt{2} \quad \text{at } M_{mir} = \frac{M_{GUT} m_{3/2}}{M_{Pl}} \approx \text{TeV}$$

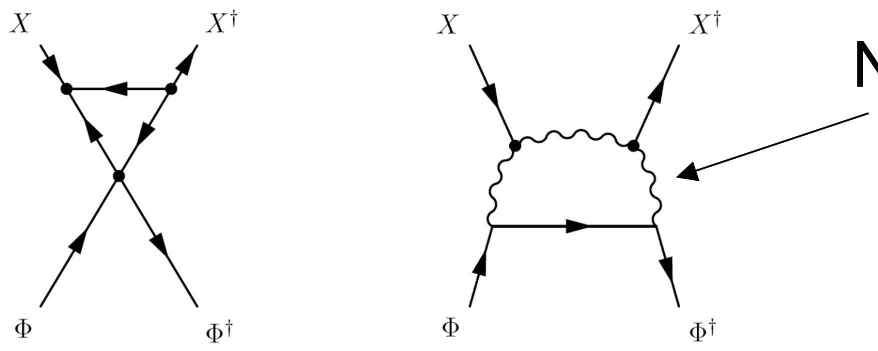
No physical threshold at M_{mir}

- small color/weak mass ratio
- small *log* M_{mir} / M_S
- large A

Best way to make Higgs sufficiently heavy with least apparent tuning

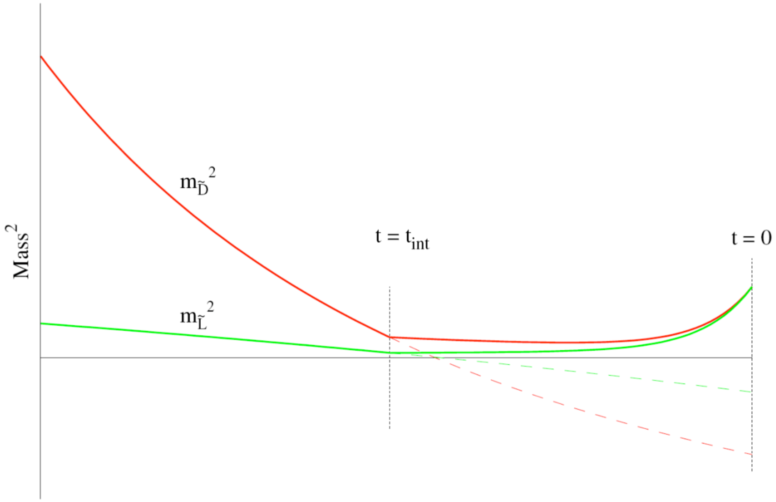
If supersymmetry is discovered, the role of experiments will be to disentangle the various possibilities

The problem not only is experimentally challenging, but also theoretically intricate



Non-universal effect on scalar masses from hidden-sector couplings

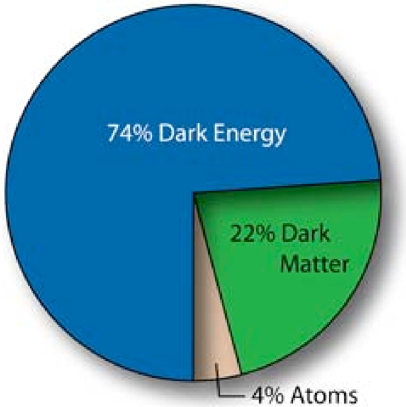
Cohen-Schmaltz-Roy



Scalar mass unification can occur in simple theories, but it could be disguised by strong hidden-sector dynamics

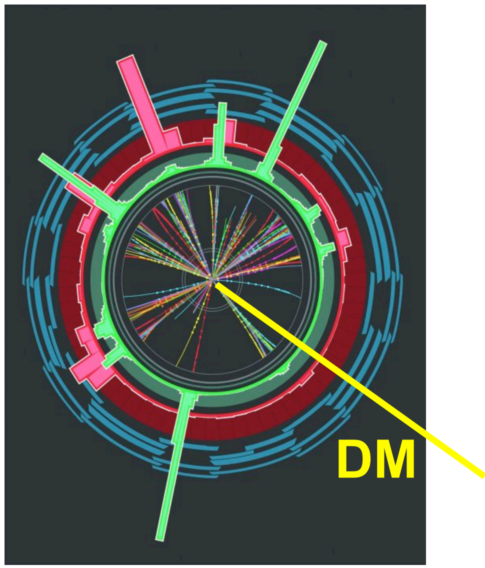
7) Will we discover DM at the LHC?

Impossible to overestimate the importance of discovering DM at the LHC



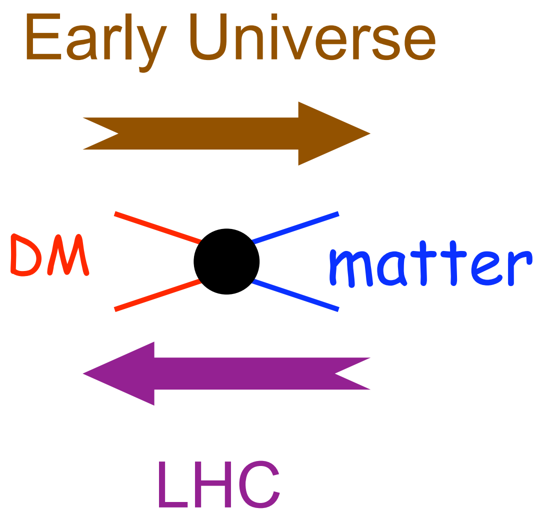
$$\Omega_{DM} = \frac{(4\pi)^2}{3}\sqrt{\frac{\pi}{45}}\frac{x_f g_S(\gamma)}{g_*^{1/2}}\frac{T_\gamma^3}{H_0^2 M_P^3 \sigma} = 0.22\,\frac{\text{pb}}{\sigma}$$

How can LHC establish that a new discovery is the DM of the Universe?



1) If excess of $\not{E}_T$ is observed, DM is the prime suspect

2) Reconstructing relic abundance



DM interactions ⇒ DM — matter ⇒ Ω_{DM}

Learn about the history of the universe up to $T_f = m_{DM} / 20$

Requires high precision and knowledge of the mass spectrum (LHC +ILC?)

Possible only for thermal relics

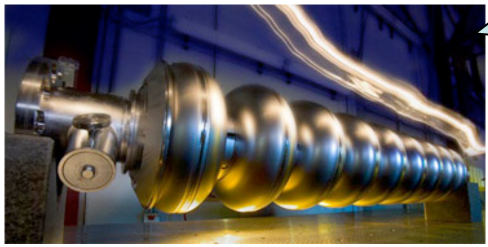
3) Combining collider with DM searches

Complementarity of information

LHC
Mass
Interactions

Direct detection
Mass
Rate (depends on local halo density)

DM

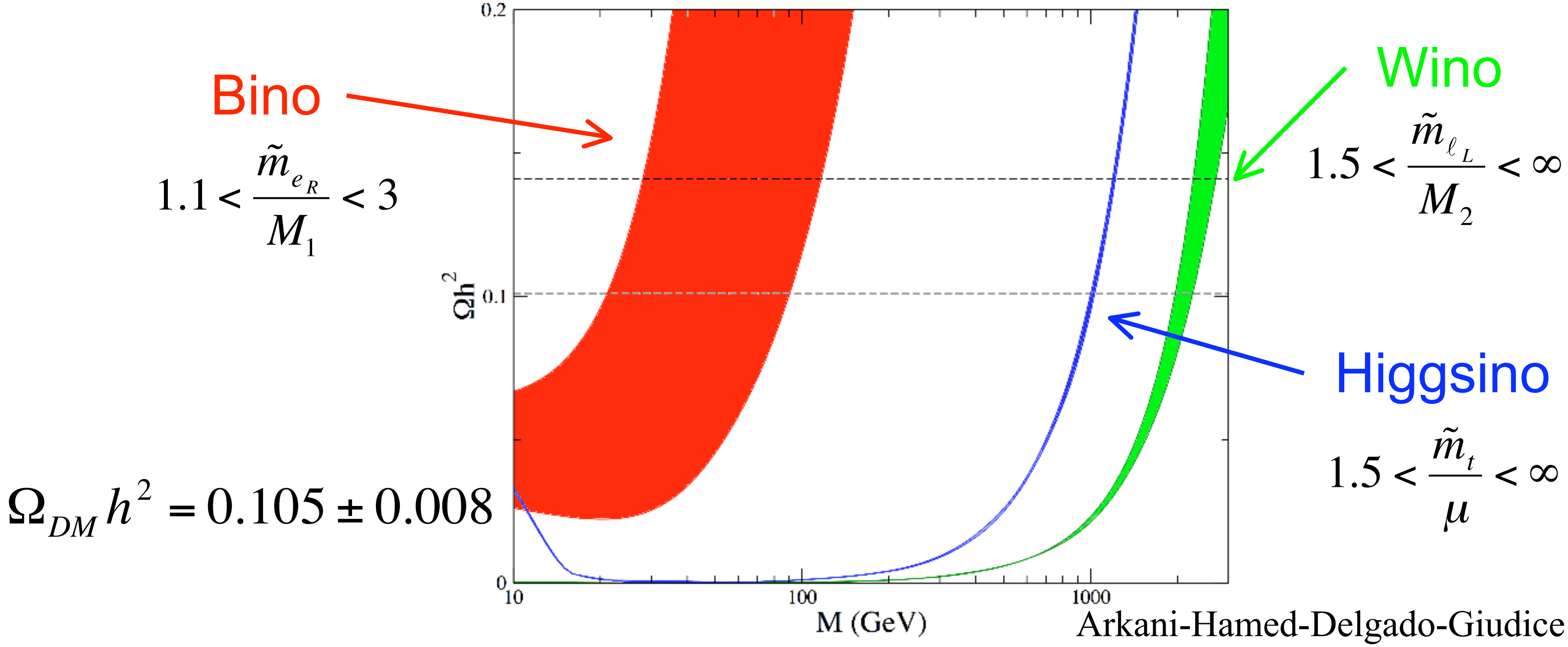


ILC
Precision measurements

Indirect detection
Halo profile

4) Identify model-dependent features

DM neutralino in supersymmetry



Arkani-Hamed-Delgado-Giudice

Neutralino: natural DM candidate for light supersymmetry

Quantitative difference after LEP & WMAP

Both M_Z and Ω_{DM} can be reproduced by low-energy supersymmetry, but at the price of some tuning.

Correct relic abundance under special conditions:

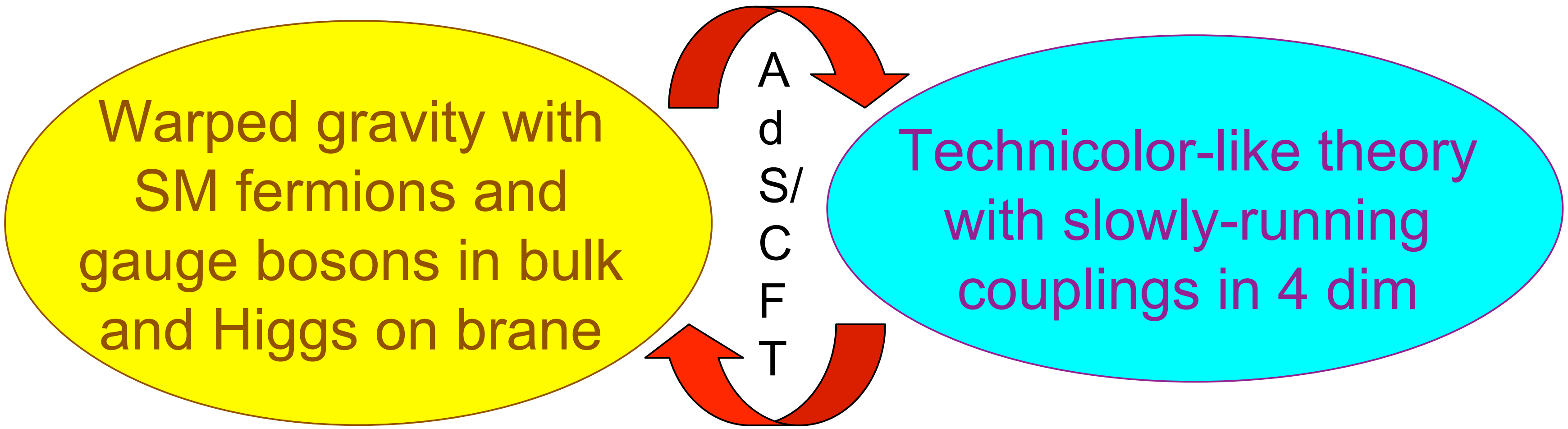
- Heavy susy spectrum: Higgsino (1 TeV) or Wino (2.5 TeV)
- Coannihilation Bino-stau (or light stop?)
- Nearly degenerate Bino-Higgsino or Bino-Wino
- S-channel resonance (heavy Higgs with mass $2m_\chi$)
- Slepton masses close to the LEP bound
- T_{RH} close to T_f
- Decay into a lighter particle (*e.g.* gravitino)

All these possibilities have a very critical behavior with underlying parameters

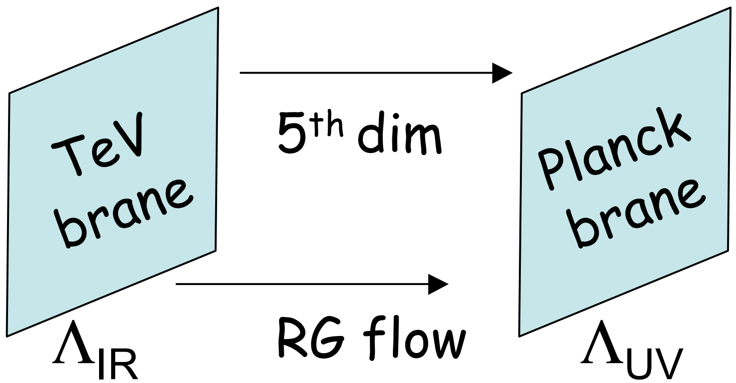
Identifying one of these features at the LHC will be in indication in favor of DM

8) Are there extra dimensions? Are there new strong forces?

Apparently unrelated questions, but



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



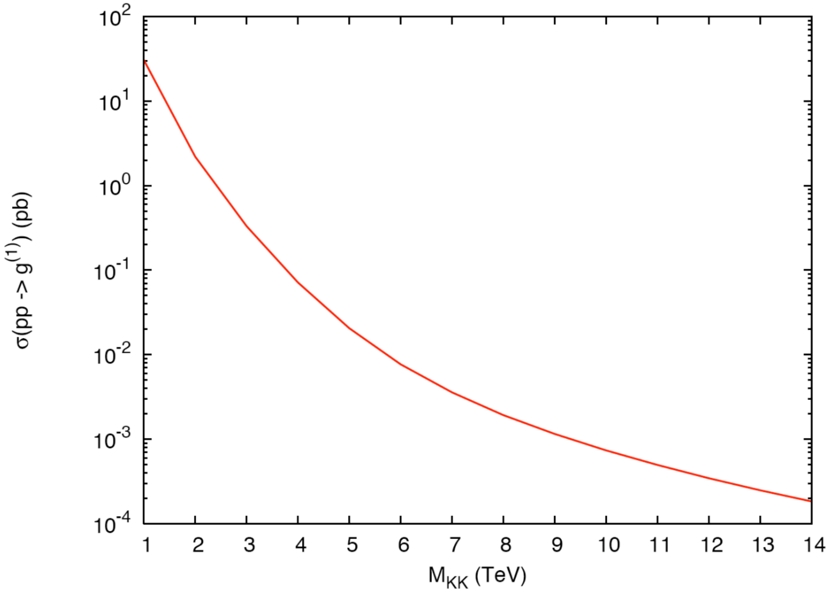
Duality position & energy (typical of a gravitational field)

RS with gauge bosons & fermions in the bulk is emerging as one of the most interesting model with extra dimensions (or new forces?)

It can address:

- hierarchy problem
- gauge-coupling unification
- suppression of flavour violations
- fermion mass structure

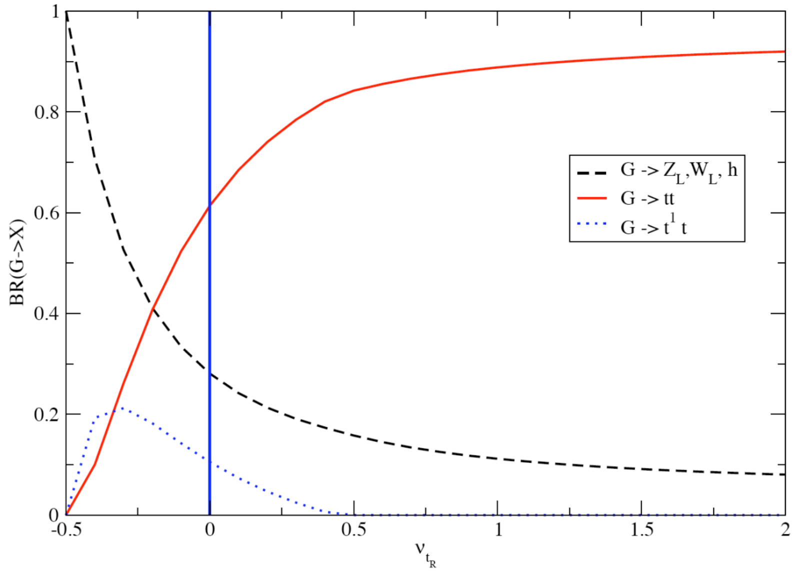
Discovery through KK-gluon production $q\bar{q} \longrightarrow g^{(1)} \longrightarrow t\bar{t}$



Agashe-Belyaev-Krupovnickas-Perez-Virzi; Lillie-Randall-Wang

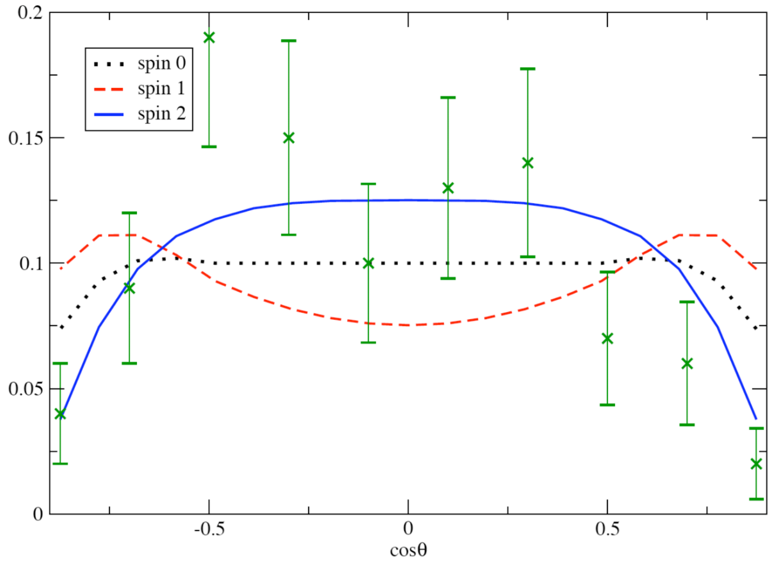
It can be identified up to M_{KK} = 5 TeV

Test of gravitational nature from KK-graviton production



Fitzpatrick-Kaplan-Randall-Wang;
Agashe-Davoudiasl-Perez-Soni

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



Possible to identify the spin-2 structure

9) Are there totally unexpected phenomena?

One of the most appealing outcomes of LHC

Theorists have done their best to predict the possible and the impossible…

… from Lee-Wick theory — Grinstein-O'Connell-Wise

to unparticles — Georgi

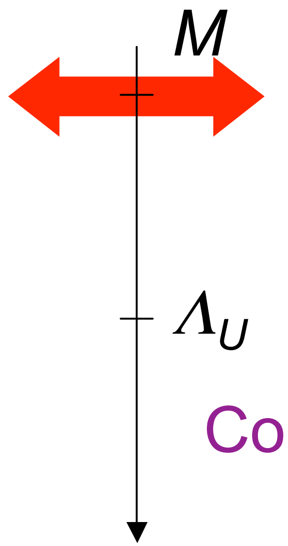
UNPARTICLES

Georgi

Hypothetical matter from scale-invariant sector of the theory

SM sector

Hidden sector



$$\frac{1}{M^{d+n-4}} O_{SM}^{(n)} O_{UV}^{(d)}$$

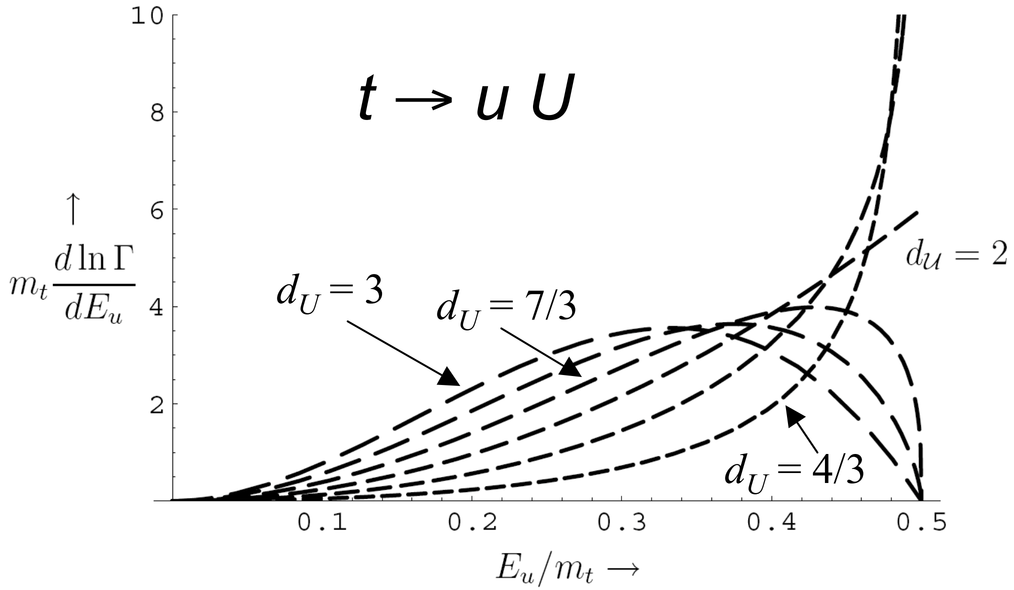
$$\downarrow$$

Conformal theory

$$\frac{\Lambda_U^{d-d_U}}{M^{d+n-4}} O_{SM}^{(n)} O_U^{(d_U)}$$

It cannot be described by particles but, in an effective theory, as operators coupled to the SM sector

Production in decay of SM particles $P \to P'\ U$



Looks like decay rate into a non-integer number d_U (scaling dim of associated operator) of invisible particles

Virtual exchange of unparticles gives amplitude with imaginary part for all $q^2 > 0$

Modifications of SM couplings and new effective contact interactions

Analogy with extra dimensions using AdS/CFT

CONCLUSIONS: 10) What is the mechanism of EW breaking?

This question summarizes all of them
and the LHC will give us the answer

- Discovery of the Higgs will unveil the phenomenon giving rise to the Fermi scale
- Measuring the properties of the Higgs can give insight to the underlying structure of the theory
- Alternatives to the Higgs mechanism are possible
- Discovery of new physics associated with the hierarchy will be a new success of the concept of symmetry
- Discovery of DM will be a new triumph of the particle/cosmo connection