EWSB Theory on the eve of Higgs boson Exclusion/Discovery

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EPS HEP 2011
Grenoble, 27 July 2011

Plan

1. Basic tenets & Heresies

2. Comments on the models
   - susy
   - strong
   - composite
   - little
   - warped…

1. In Naturalness We Trust

Fundamental scalars are unnatural:

$$\mathscr{L} = (\partial\phi)^2 + m^2\phi^2 + \lambda\phi^4$$

requires finetuning to be valid up to energies $\Lambda \gg m$

Experimentally verified!

Ferromagnets near Curie point $T \sim T_c$ are described by this Lagrangian (in 3D)

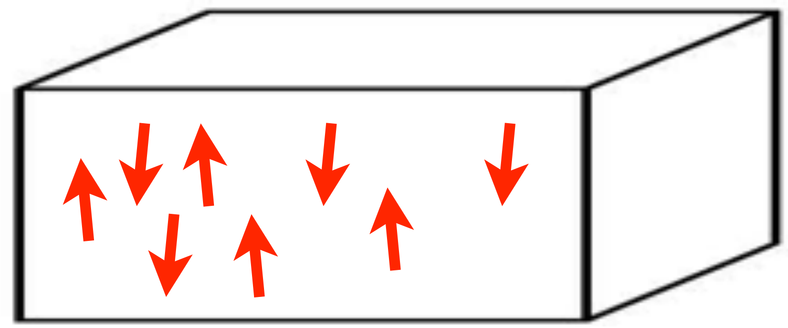
Landau,Ginzburg

$\Lambda^{-1} \longleftrightarrow a$ - atomic spacing

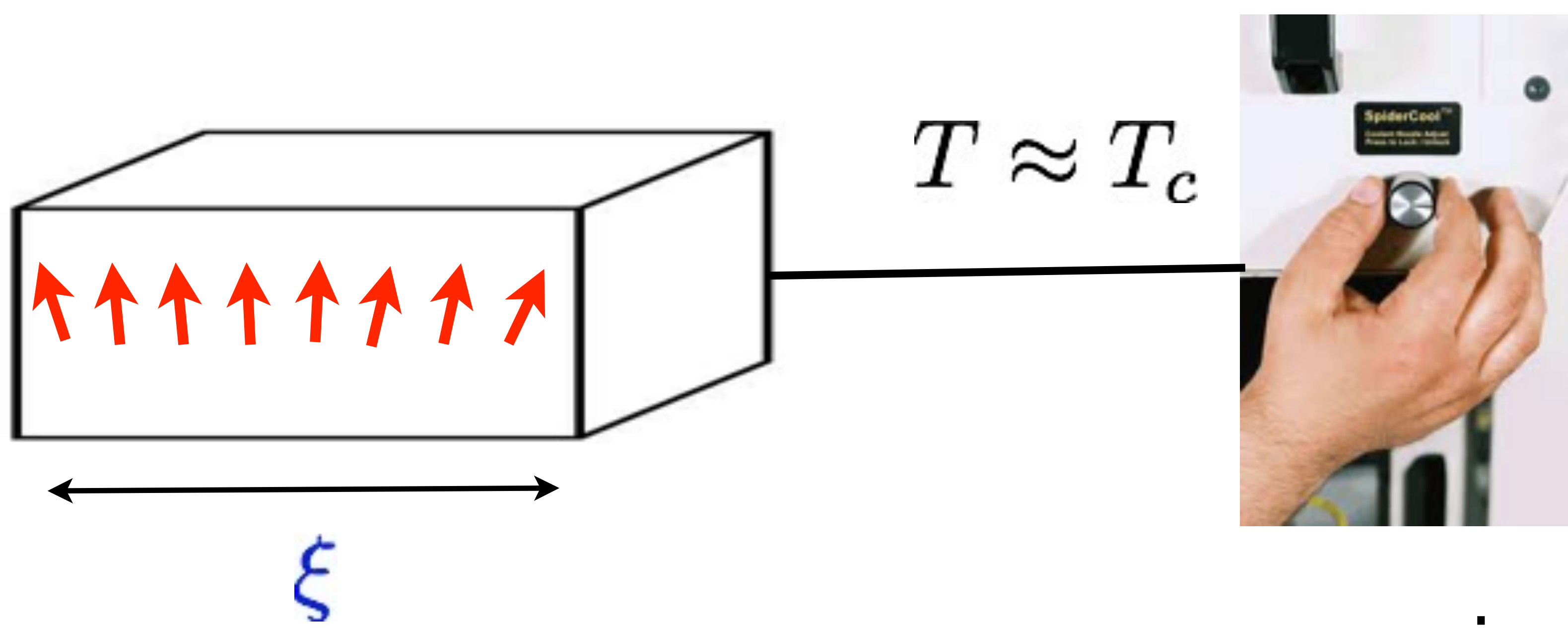
$m^{-1} \longleftrightarrow \xi$ - correlation length

$\Lambda \gg m \iff \xi \gg a$ - critical point

For generic T ferromagnet is not a critical point:



$T \to T_c$ requires to finetune the temperature:



experimenter

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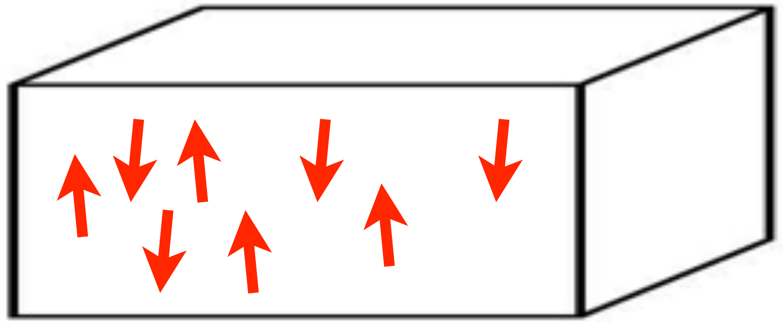

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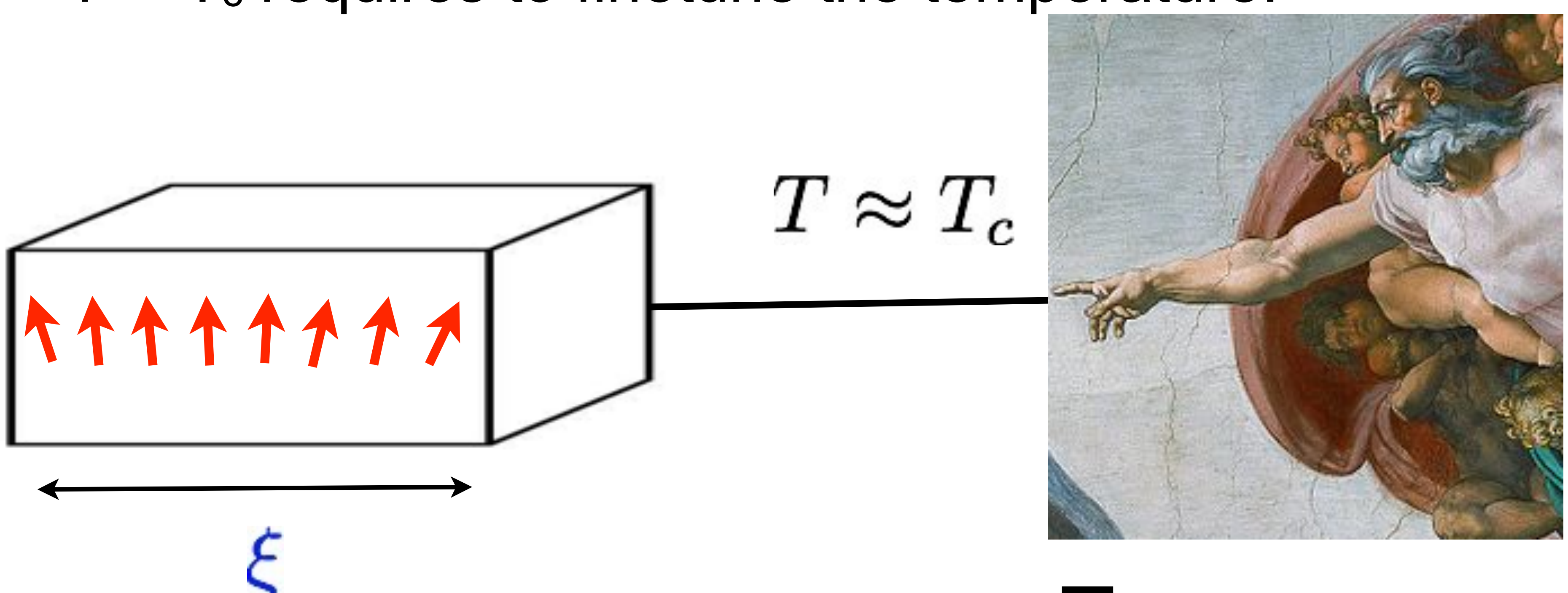


Experimenter

Exit strategies if naturalness fails

Minimality:

SM + 3 ν_R @ keV-MeV

Shaposhnikov et al

- neutrino oscillations
- Dark Matter
- baryogenesis

SM + 5-plet Ψ of *SU(2)* @ 10 TeV

Cirelli, Fornengo, Strumia

- naturally stable Dark Matter

Environmental selection

`A new kind of science'

can make predictions assuming peaked distributions in the Landscape

$m_H = 115 \pm 6$ GeV   Feldstein,Hall,Watari 2006

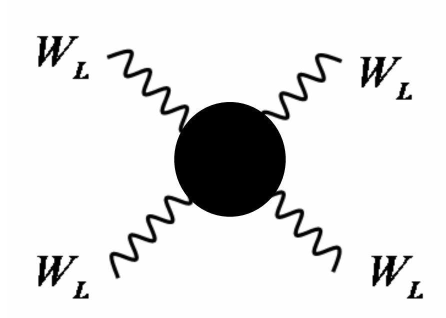
$m_H = 141 \pm 2$ GeV   Hall,Nomura 2009

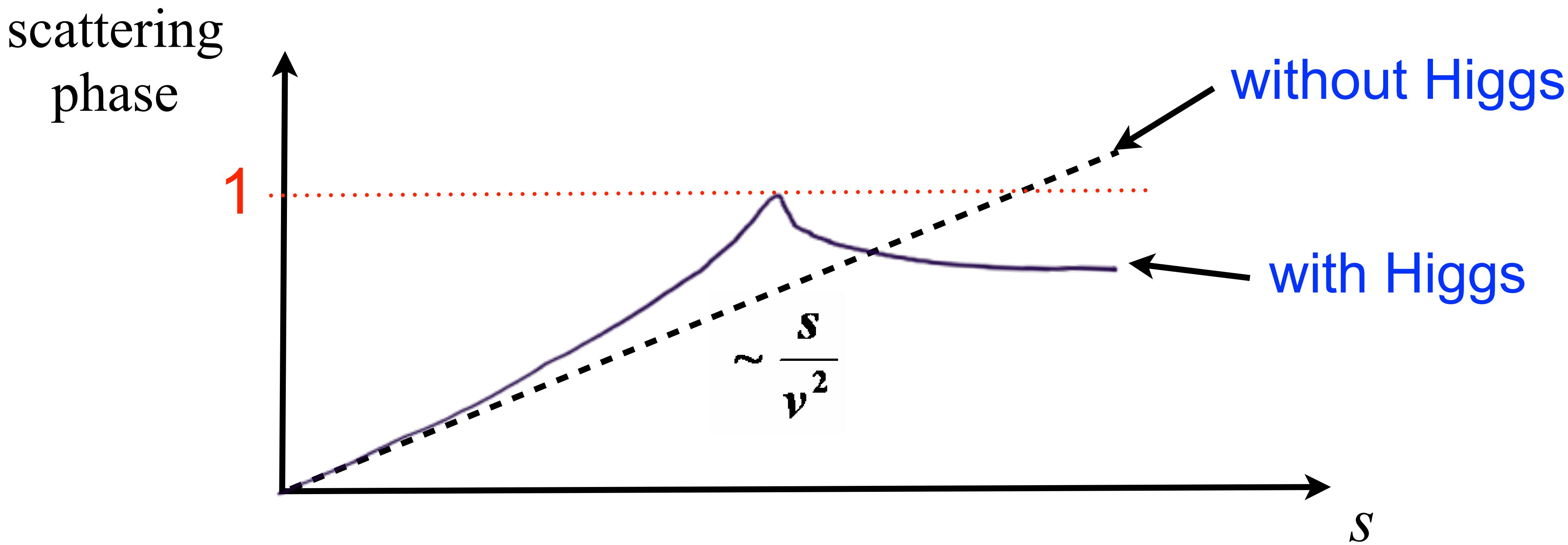
(obviously, different assumptions lead to different predictions)

2. Need for unitarization

Higgsless SM is incomplete, UV cutoff at $\Lambda \sim 4\pi v \sim$2-3 TeV

Just look at $W_L W_L$ scattering:





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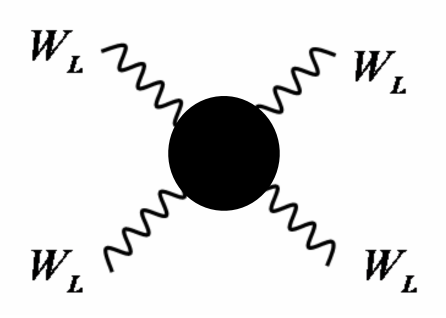
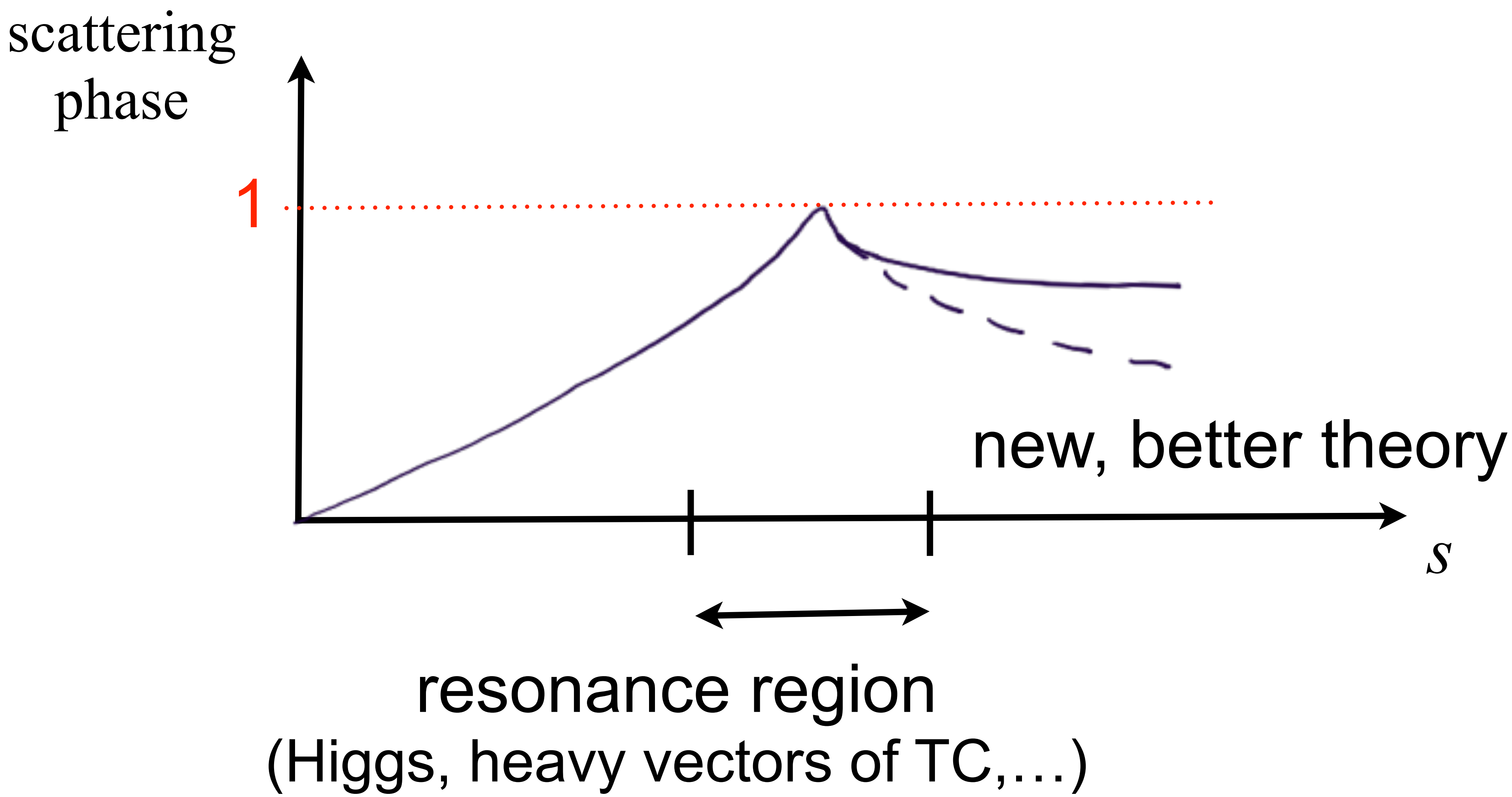


Expect this to be general:



Iconoclasm

Dvali, Giudice, Gomez, Kehagias "UV completion by Classicalization" 1010.1415

Claim:

Higgsless SM may be UV complete *by itself* in a novel sense. Processes at $E \gg \Lambda$ can be computed by solving classical field equations

Weak points:

- What about the resonance region? (Most important for the LHC)
- Argument is rather handwaving. No concrete computation of, say, WW scattering at 10 TeV is given

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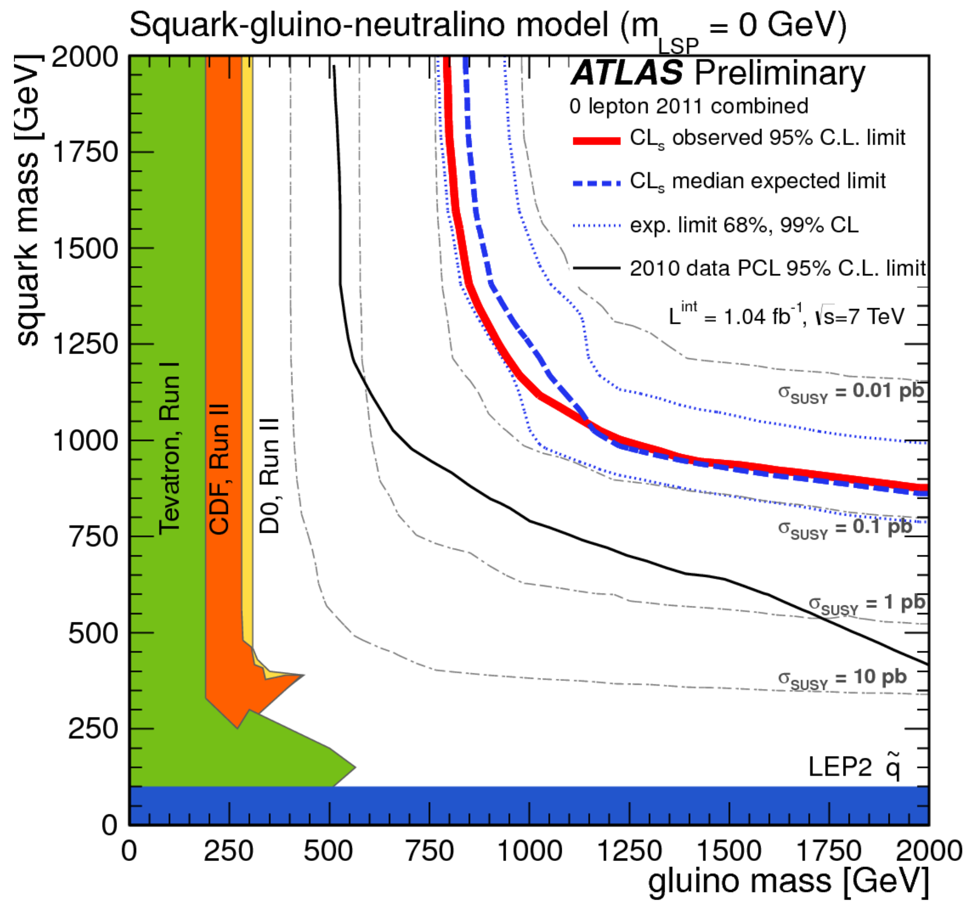
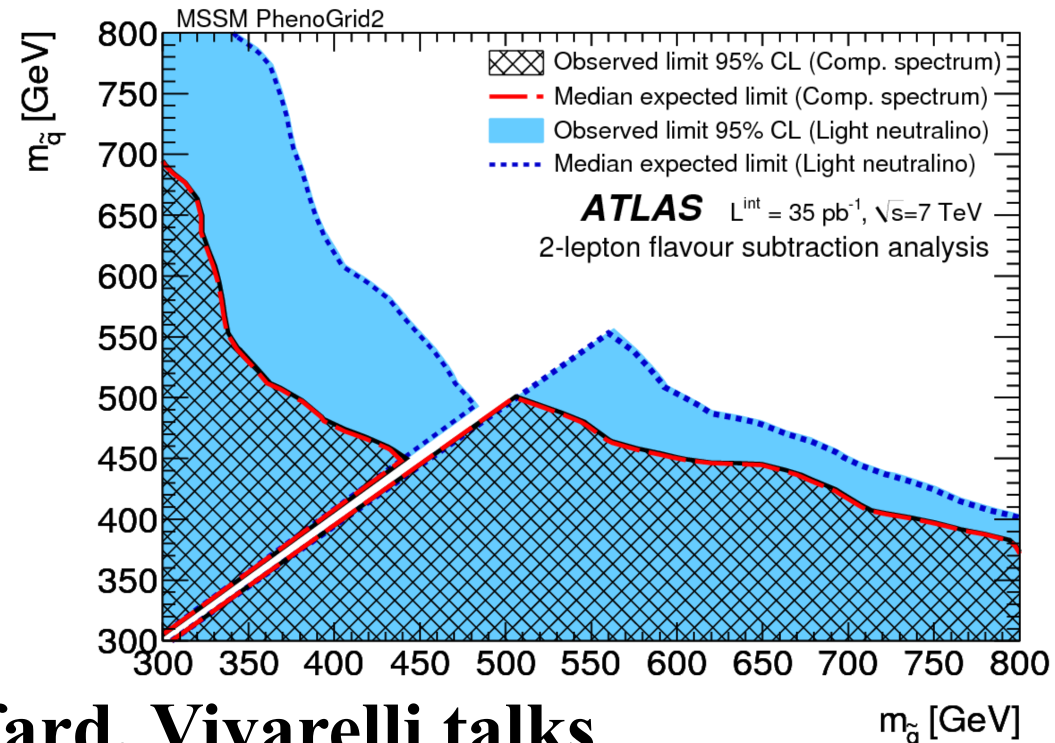
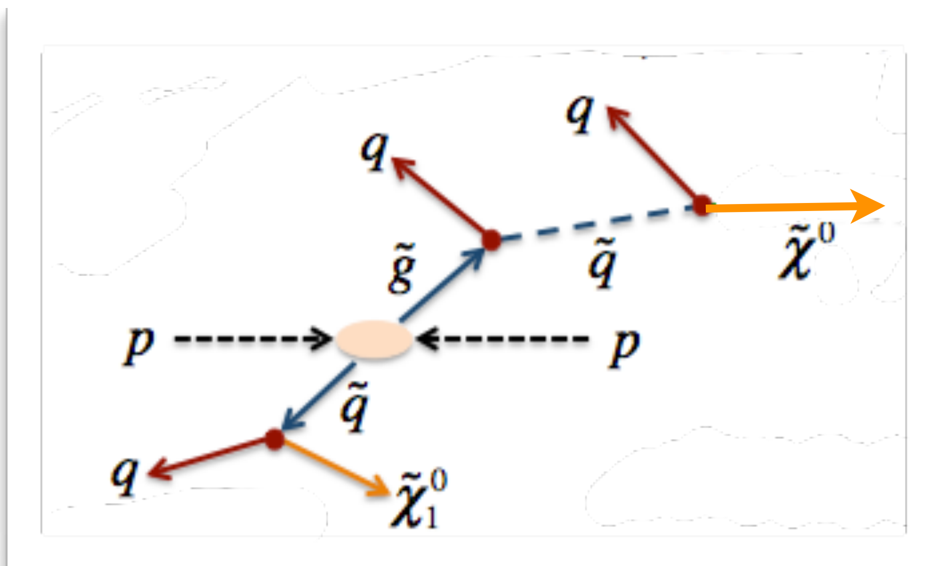
Supersymmetry

Seen many new SUSY limits at this conference:

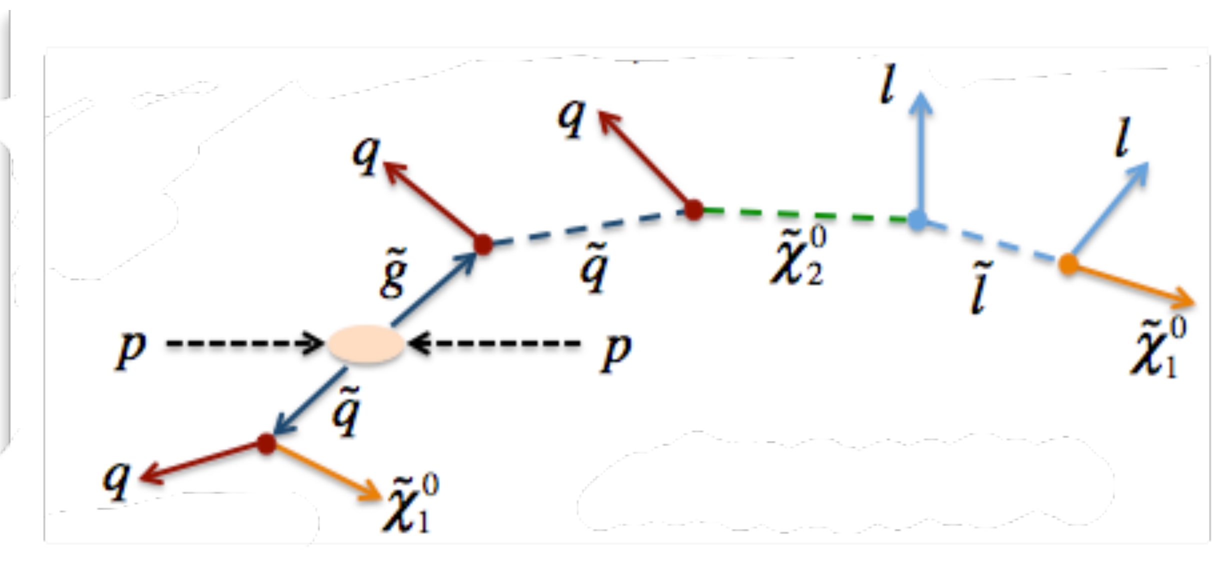




Taffard, Vivarelli talks



$\text{jets} + \not{E}_T$



$\text{jets} + 2l + \not{E}_T$

Impressive bounds on squarks and gluinos, into TeV range...

What do we learn? → **Papucci talk**

1. Plain vanilla SUSY models (like MSSM with flavor-universal soft masses) are being pushed into a corner

but

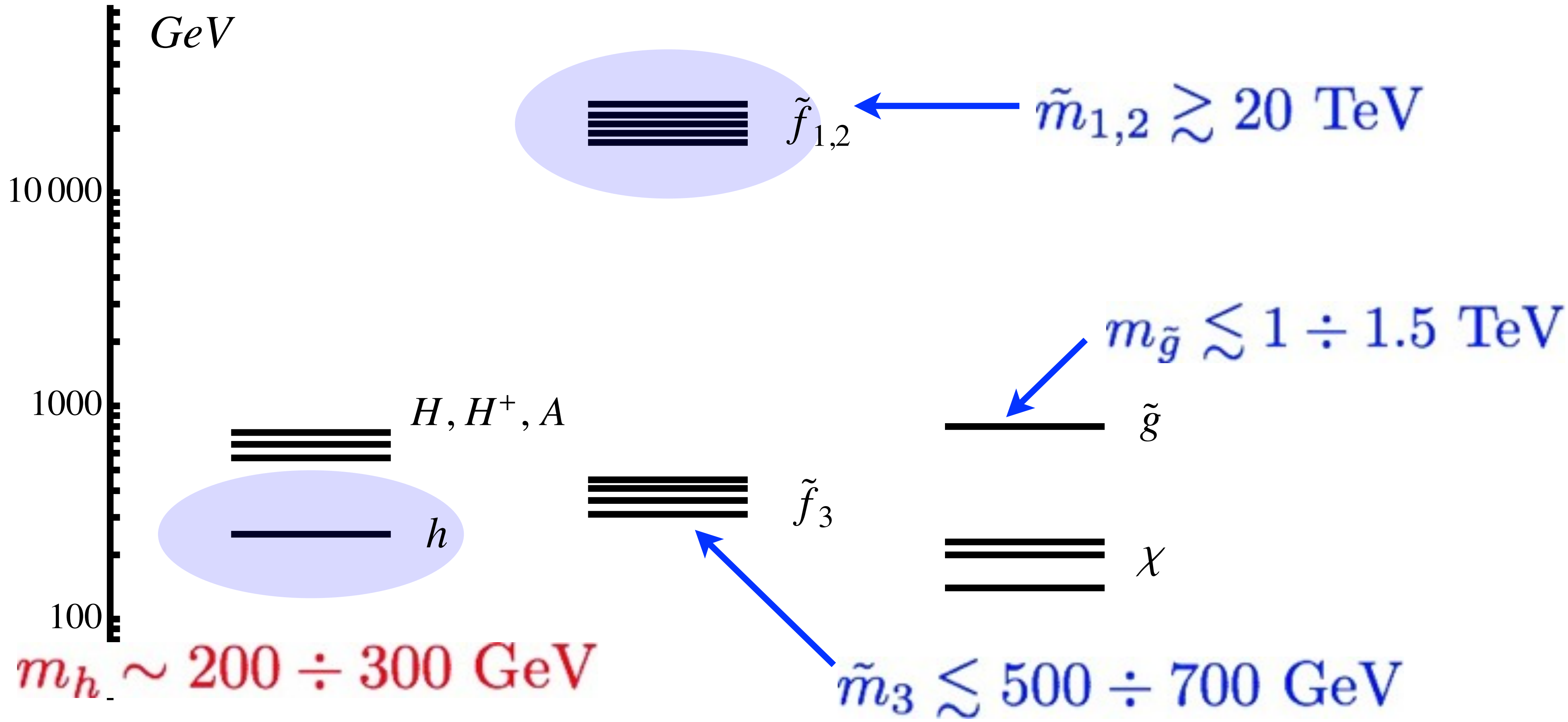
2. Several other, theoretically motivated, scenarios remain very poorly constrained by existing searches

"Flavor-Split" spectra (heavy 1st-2nd gen squarks, gluino below 1-1.5 TeV, light 3rd gen)	"Squashed" spectra (everything below ~500GeV but splittings are small, O(10GeV))	Low MET scenarios (not necessarily RPV)

SUSY with flavor-split spectra

3rd generation "light" vs 1st-2nd generation "heavy"

Cohen et al '96, Barbieri et al '07-11 $\longrightarrow$ **Straub talk**



via `fat Higgs' aka λSUSY mechanism

$$pp \to \tilde{g}\tilde{g} \to q_3 q_3 \bar{q}_3 \bar{q}_3 + \chi\chi \qquad q_3 = t, b$$

SUSY with flavor-split spectra

3rd generation “light” vs 1st-2nd generation “heavy”

Cohen et al ’96, Barbieri et al ’07-11 → **Straub talk**

$_{,2} \gtrsim 20$ TeV

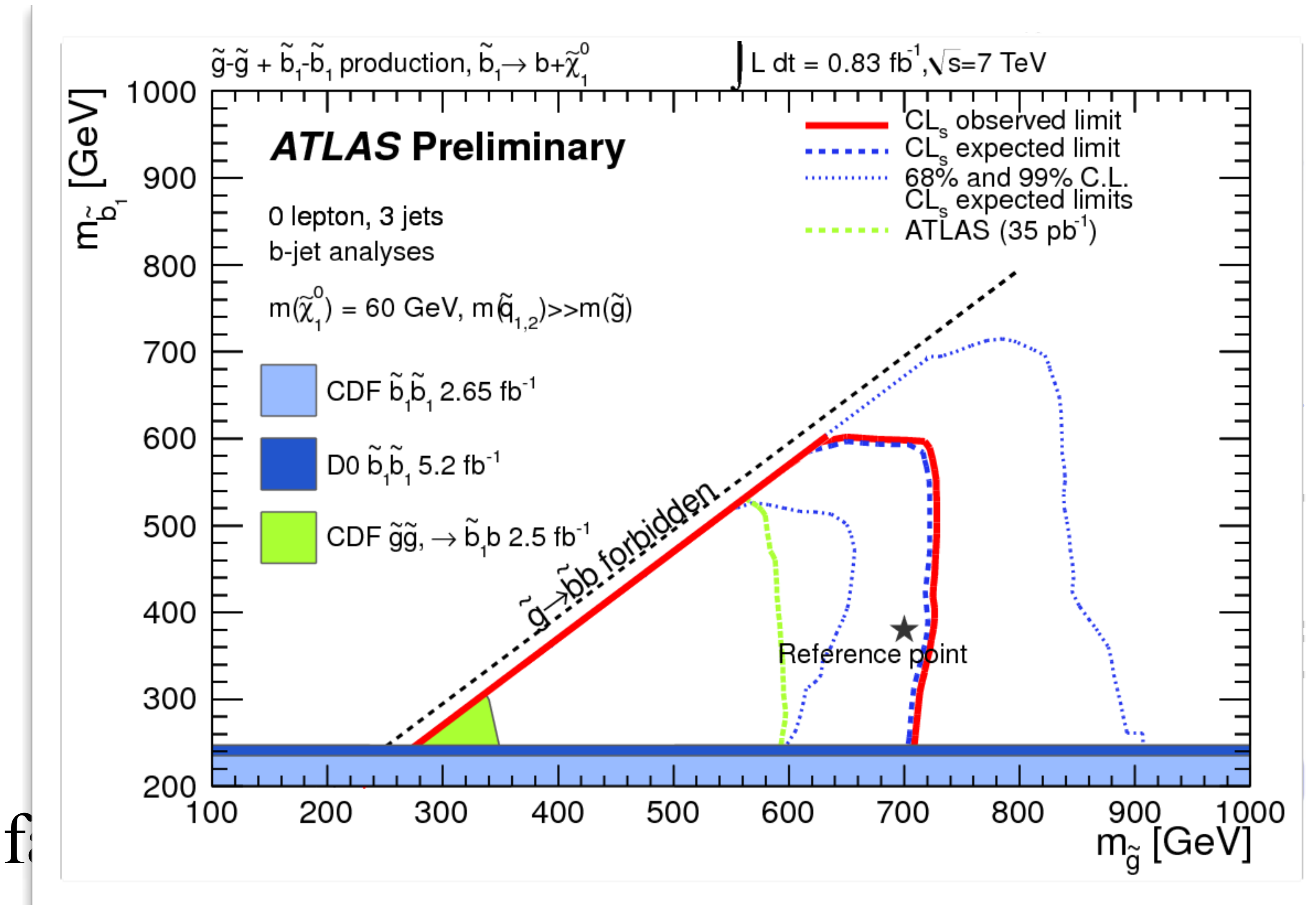
$m_{\tilde g} \lesssim 1 \div 1.5$ TeV

$\tilde g$

χ

$\div$ 700 GeV

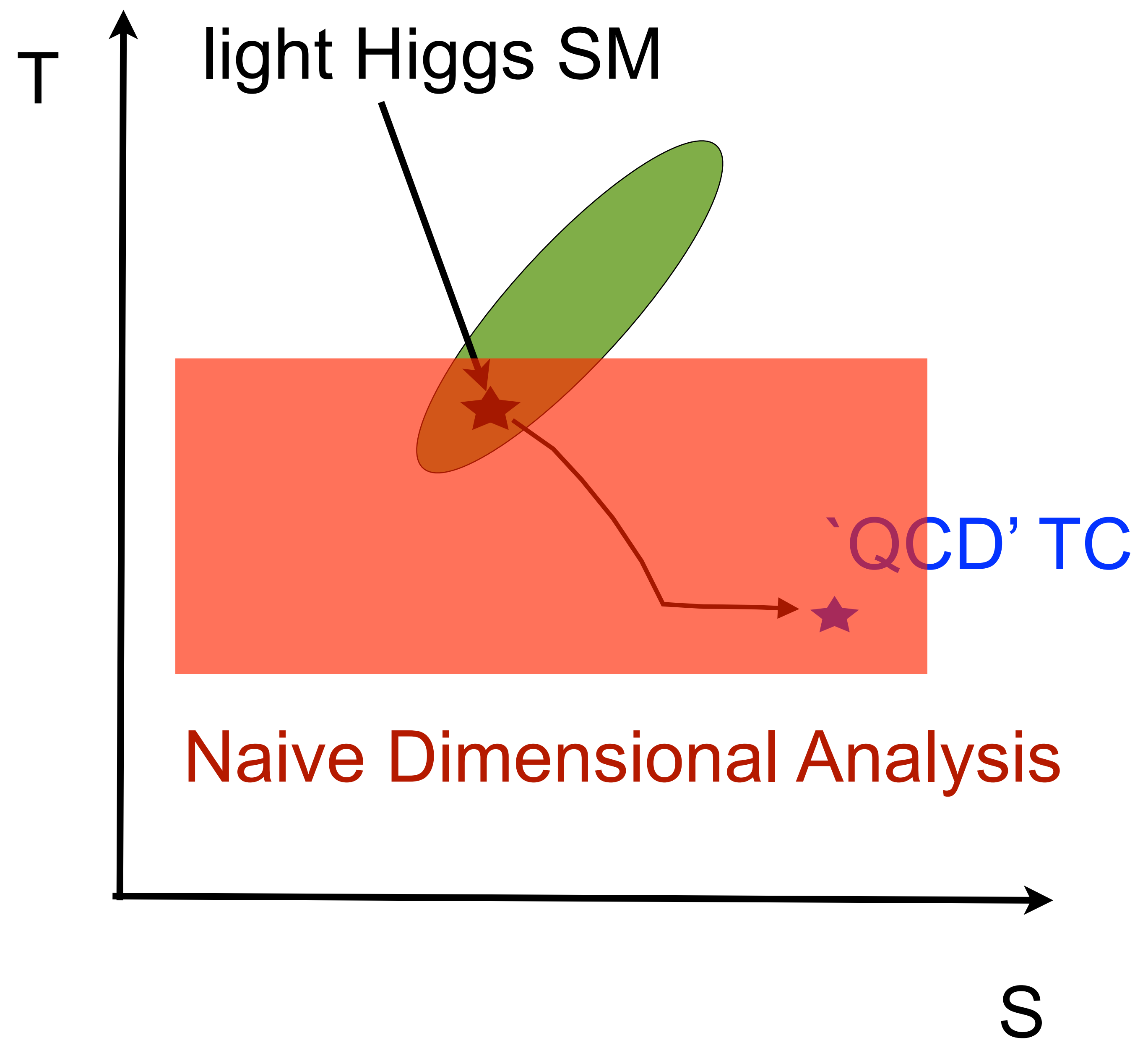
via `f



$$pp \to \tilde g \tilde g \to q_3 q_3 \bar q_3 \bar q_3 + \chi\chi \qquad q_3 = t, b$$

as yet poorly constrained...

Strong EWSB (Technicolor etc)



With 10% accident we may be in business...

It's not going to be QCD-like

flavor physics hints at that

Technicolor Higgs field is a composite operator
⇒ Yukawa couplings are not dimensionless:

$$\frac{y}{\Lambda^{\dim H-1}} H_{TC} (\bar{q}q)_{SM}$$

If TC is QCD-like, then $H_{TC} \sim \bar{\psi}\psi \qquad \dim H = 3 \gg 1$

⇒ strong FCNC

Way out: walking/conformal behavior above 1 TeV

$$1 < \dim H < 3$$

Holdom
Akiba and Yanagida
Yamawaki, Bando, Matumoto
Appelquist, Karabali, Wijewardhana

Much of the old literature focused on **dim$H$ ≈ 2**

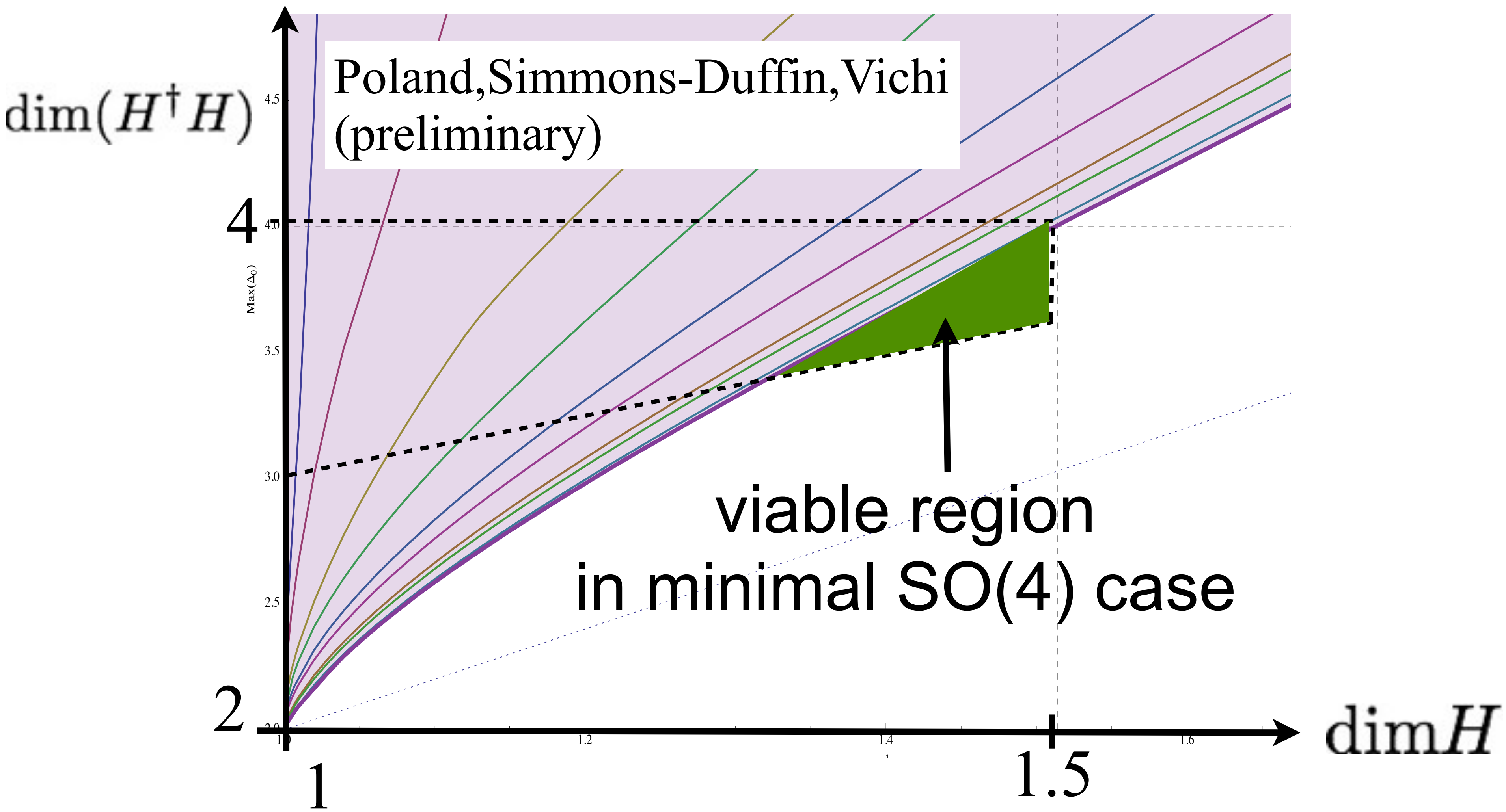
Most economic scenario; to give masses to all SM fermions (**including top**) without flavor problems requires

Luty and Okui ’04

$$\mathrm{dim}H \lesssim 1.5$$

Rigorous inequalities about CFT dimensions allow this.

Rattazzi, Tonni, Rychkov, Vichi

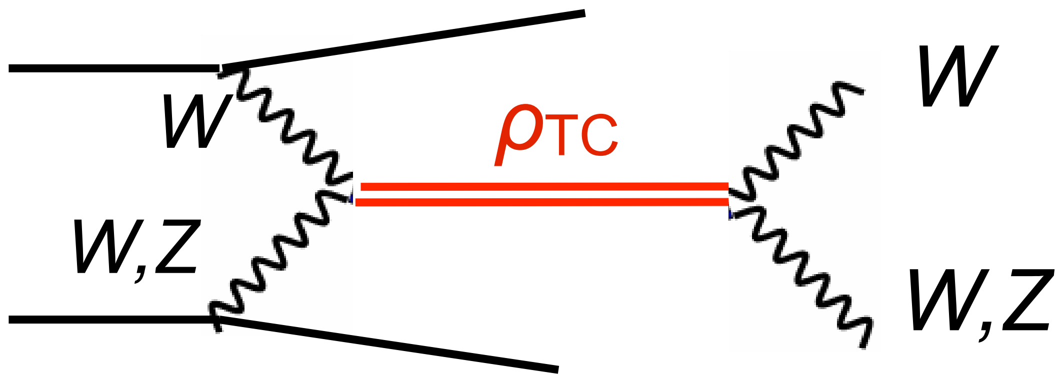


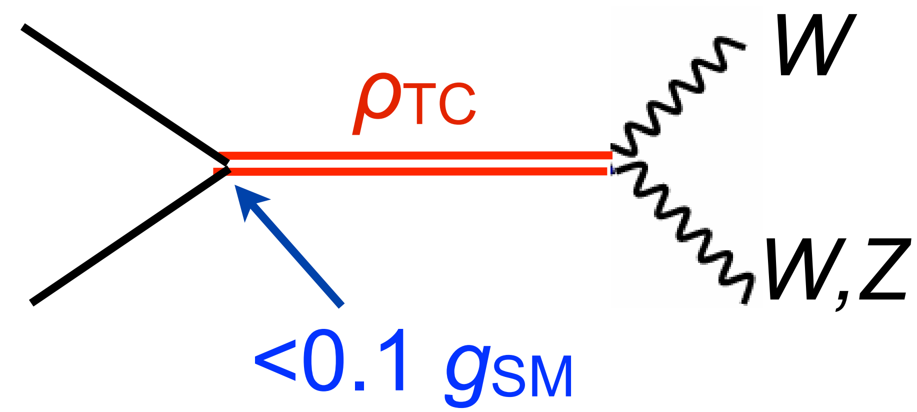
TC signals

1. **Heavy vectors** (techni-ρ), M~1-3 TeV

NB rather narrow: $\Gamma(\rho_{TC} \to WW) \sim 10\% \, \Gamma(H \to WW)$

decay into WW,WZ, produced in WW fusion and Drell-Yan (need ~100 fb^{-1})

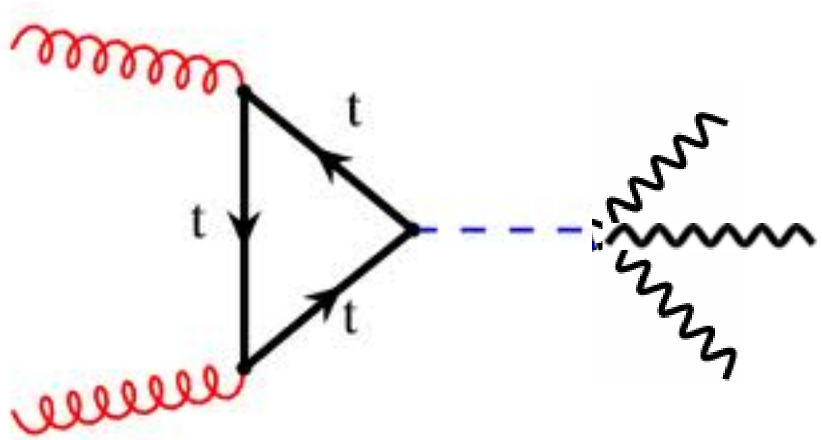




2. **Heavy scalars**

a) Isospin singlets - wide, difficult to see (like σ of QCD)

b) Isospin triplets (or neg. parity isosinglets) - narrow, decay into WWW and t-tbar produced in gluon fusion:



Evans, Luty

Strongish EWSB

Giudice EPS 2007, Grojean EPS 2009

(composite pseudo-NGB Higgs boson)

Postpone onset of truly strong interactions to $\Lambda = (\text{few})4\pi v$

(computable at LHC energies in terms of a few parameters)

One or more Higgs bosons emerge as low-energy remnants
of this, unspecified, strong dynamics

Higgs is light because PNGB

Dynamics of Higgses is largely controlled by symmetry

Higgs potential is controlled by small symmetry breaking terms
(like coupling to the rest of the SM)

We don't know what the symmetry is (experiment will tell).

There is a discrete list of possibilities.

In order of increasing complexity:

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = \underline{(\mathbf{2},\mathbf{2})}$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + \underline{(\mathbf{2},\mathbf{2})}$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}} + \bar{\mathbf{4}}_{-\mathbf{2}} = 2 \times \underline{(\mathbf{2},\mathbf{2})}$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1},\mathbf{1}) + \underline{(\mathbf{2},\mathbf{2})}$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + \underline{(\mathbf{2},\mathbf{2})}$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + \underline{(\mathbf{2},\mathbf{2})}$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3 \times \underline{(\mathbf{2},\mathbf{2})}$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2 \times \underline{(\mathbf{2},\mathbf{2})}, \underline{(\mathbf{2},\mathbf{2})} + 2 \times (\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2 \times \underline{(\mathbf{2},\mathbf{2})}$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + \underline{(\mathbf{2},\mathbf{2})} + (\mathbf{1},\mathbf{1})$

global group

unbroken group

no. of PNGB's

representation content

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$\mathrm{SO}(6)$	$\mathrm{SO}(5)$		
$\mathrm{SO}(6)$	$\mathrm{SO}(4)\times\mathrm{SO}($		
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Minimal Composite Higgs Model
Agashe, Contino, Pomarol

global group

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SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + \underline{(\mathbf{2},\mathbf{2})}$
SO(6)	SO(4) ×		
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Next-to-Minimal Composite Higgs Model

Gripaios, Pomarol,Riva,Serra

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SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	[illegible]	[illegible]	[illegible]
SO(7)	SO([illegible]	[illegible]	[illegible] $(\mathbf{2},\mathbf{2})$
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Composite Two-Higgs-Doublet Models

Mrazek,Pomarol,Rattazzi,Redi,Serra,Wulzer

global group

unbroken group

no. of PNGB's

representation content

Generic predictions for Higgs physics

1. M_H typically below 200 GeV, but can be as high as 300 GeV

2. O(10-20%) deviations in Higgs-boson couplings to all SM particles

Giudice, Grojean,Pomarol,Rattazzi

3. Correlated! In minimal model controlled by just two coefficients

4. The sign of deviations can often be predicted (mostly suppression)

Low,Rattazzi,Vichi

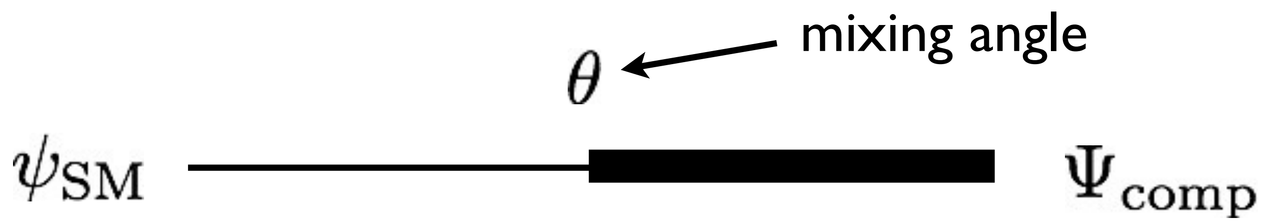
5. New Higgs decay channels in non-minimal models (with predicted BR). E.g. $H \to \eta\eta$ in SO(6)/SO(5) Gripaios, Pomarol,Riva,Serra

ILC would be required to fully explore this phenomenology if LHC sees hints of it

Connections with flavor physics → **Weiler talk**

Composite Higgs models typically use ‘partial compositeness’ mechanism for giving masses to SM fermions

D.B.Kaplan 1991



Fermion mass and CKM hierarchies explained by hierarchies in mixing angles

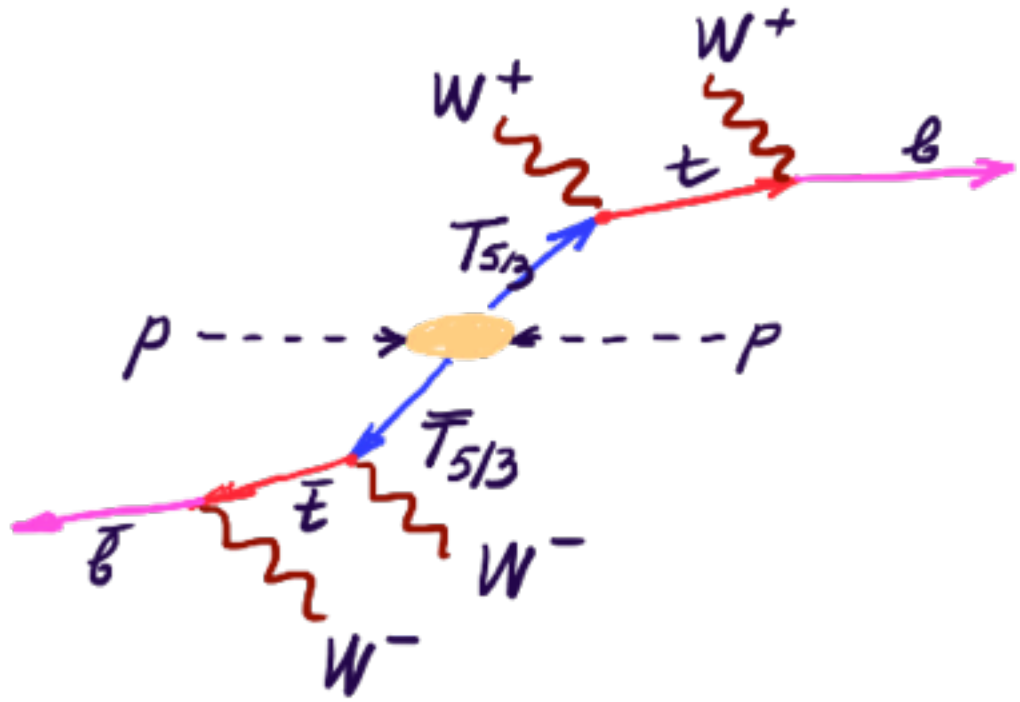
This picture makes a lot of sense theoretically and allows a detailed and honest discussion of flavor effects involving all 3 generations (*unlike in Little Higgs Models which usually do not go beyond top Yukawa*)

Much of early literature was phrased in terms of (warped) extra dimensions. Red herring: this class of models is much more general.

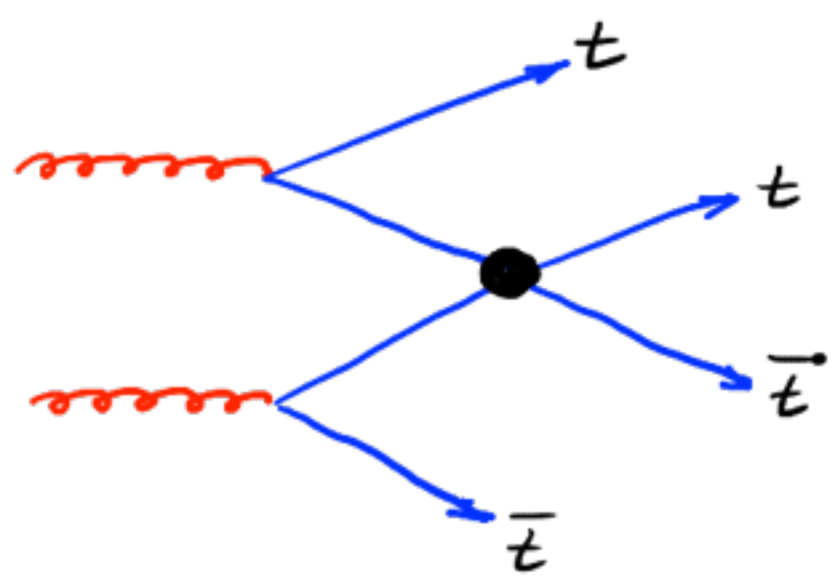
(Some) Non-Higgs signals of Composite Higgs

New non-chiral quarks (**top partners**) with 500 GeV-1 TeV mass, perhaps exotic charge 5/3:

Contino,Servant
Mrazek,Wulzer



Anomalous *tttt* production from top-right compositeness:



Lillie, Shu,Tait
Pomarol,Serra

Final remarks and conclusions

Many impressive new limits set at this conference

On what models???

Z'   CMSSM   split SUSY... (just a few examples)

Did we believe in these models?

Another casualty: Large Extra Dimensions (never a truly bona fide solution to the naturalness problem)

Truly motivated, not ad hoc models are very few:

SUSY / Strong EWSB / Composite Higgs

BACKUP

Kudoz to ATLAS for presenting the limits as a function of the width