Where Do We Come From
What Are We
Where Are We Going

John March-Russell
Oxford University

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What Are We
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(not Tahiti, Abingdon UK HEP!)

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The Situation…

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Recent experiments have confirmed the earlier indirect indications of a fundamental propagating Bose field to better than 5 sigma

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And have triumphantly verified our standard model (with yet no "new" physics, though mass scales are heavier than expected)

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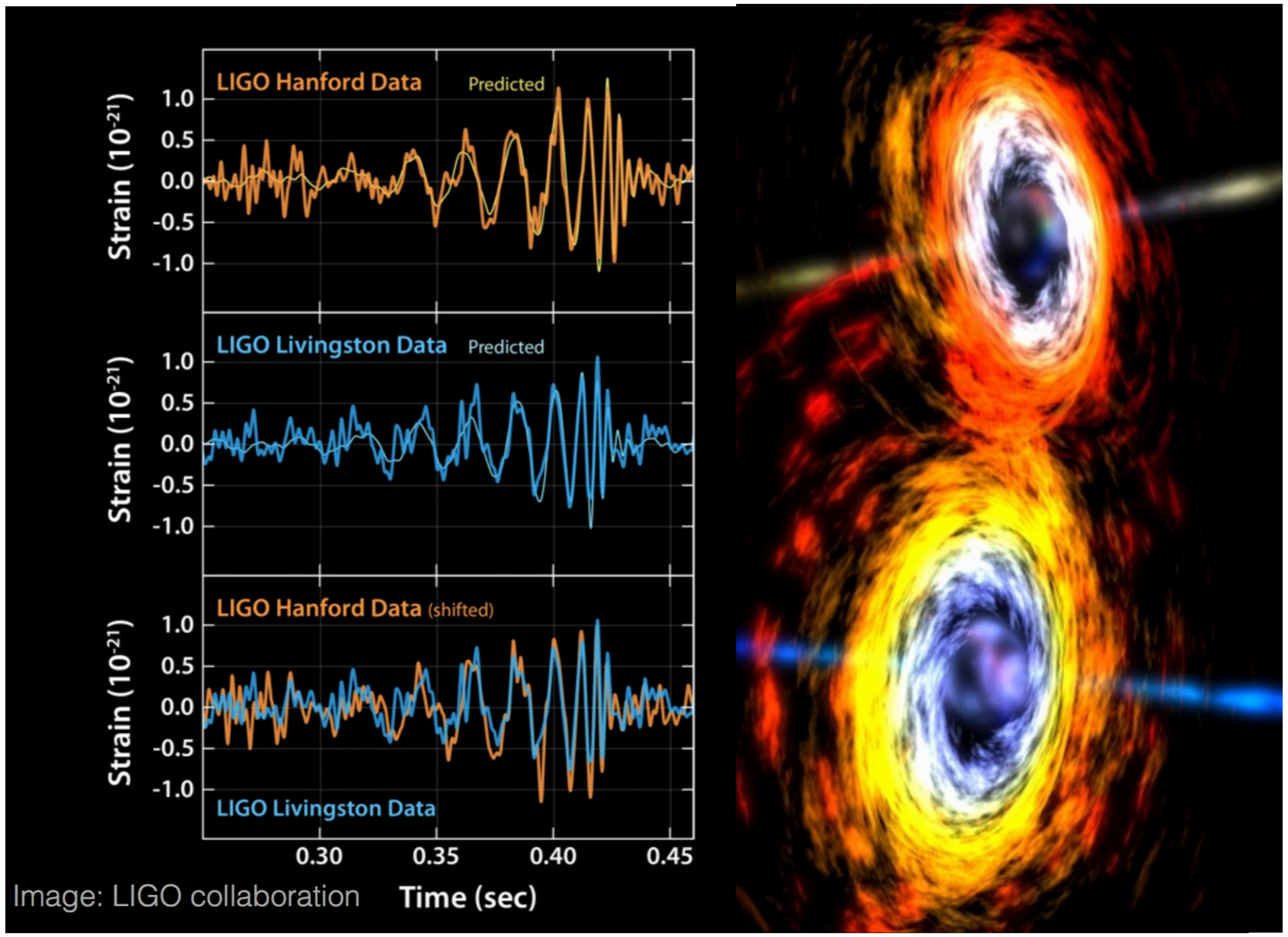
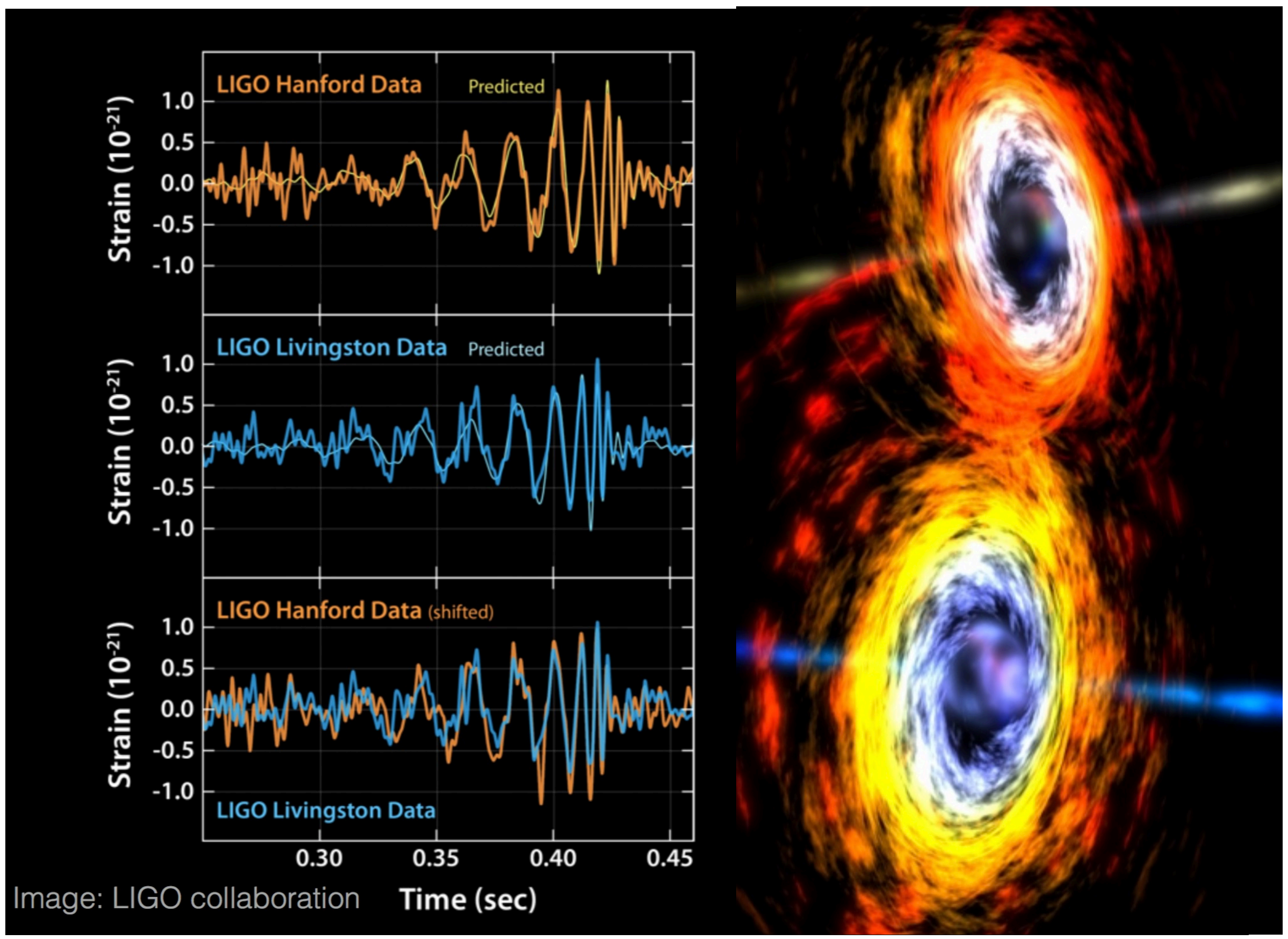
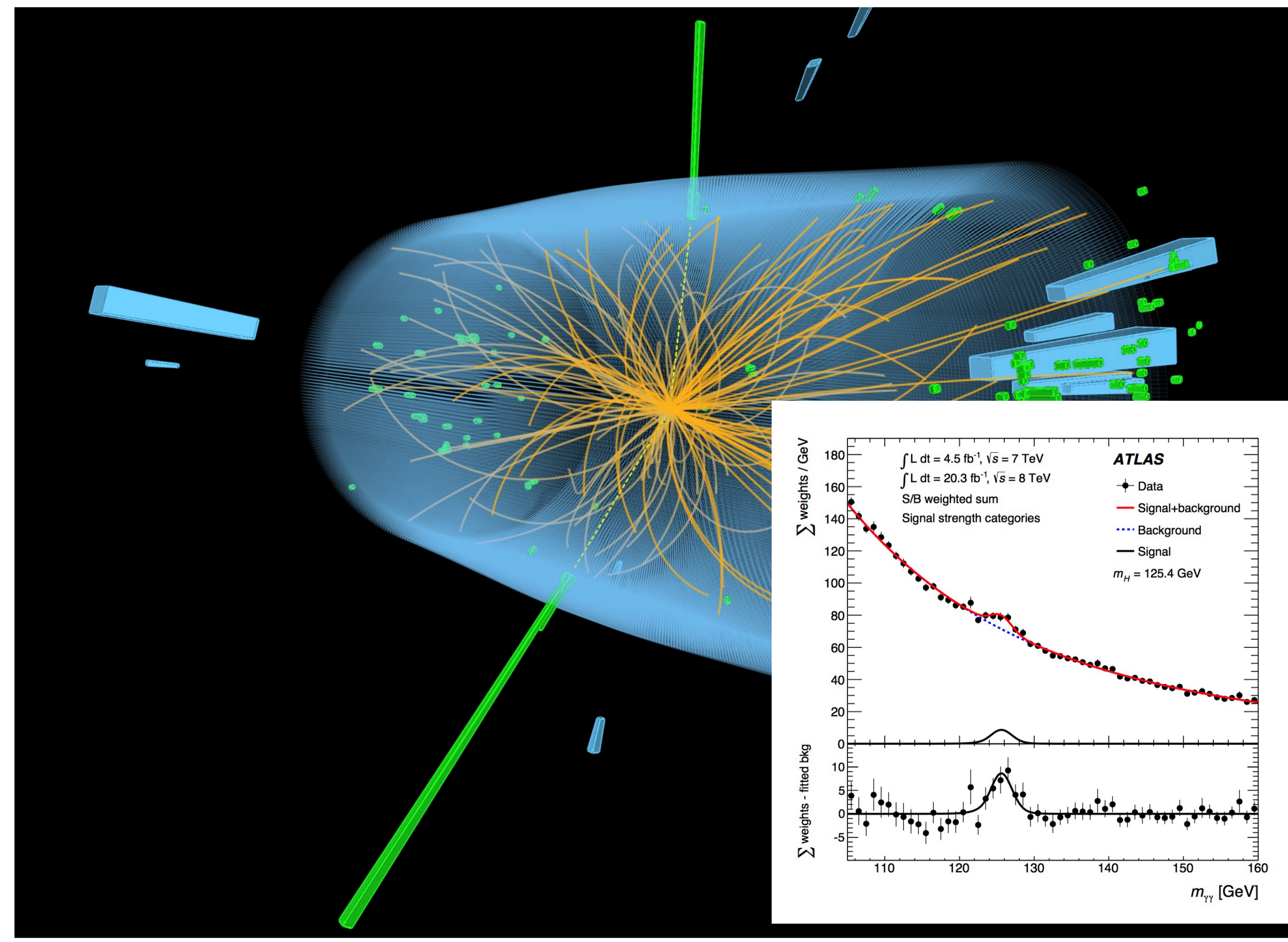


Image: LIGO collaboration

The Situation…





Nature + beautiful experiments have provided us with *two* new dof/probes with special status

- Gravity waves are unique probes of extreme conditions *and* the *very* Early Universe
- Among all SM particles the Higgs is uniquely sensitive to *very* high scales *and* hidden physics
- Both gravity and EWSB are deeply mysterious (and have been getting more so…)

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we are in process of learning fundamental lessons

No lack of major questions...

- Origin of the Weak Scale
- Flavour-physics
- CP-violation
- Dark matter
- Strong CP problem
- Gauge unification
- Neutrino masses
- Family replication
- Baryogenesis
- Inflation
- Almost zero vacuum energy

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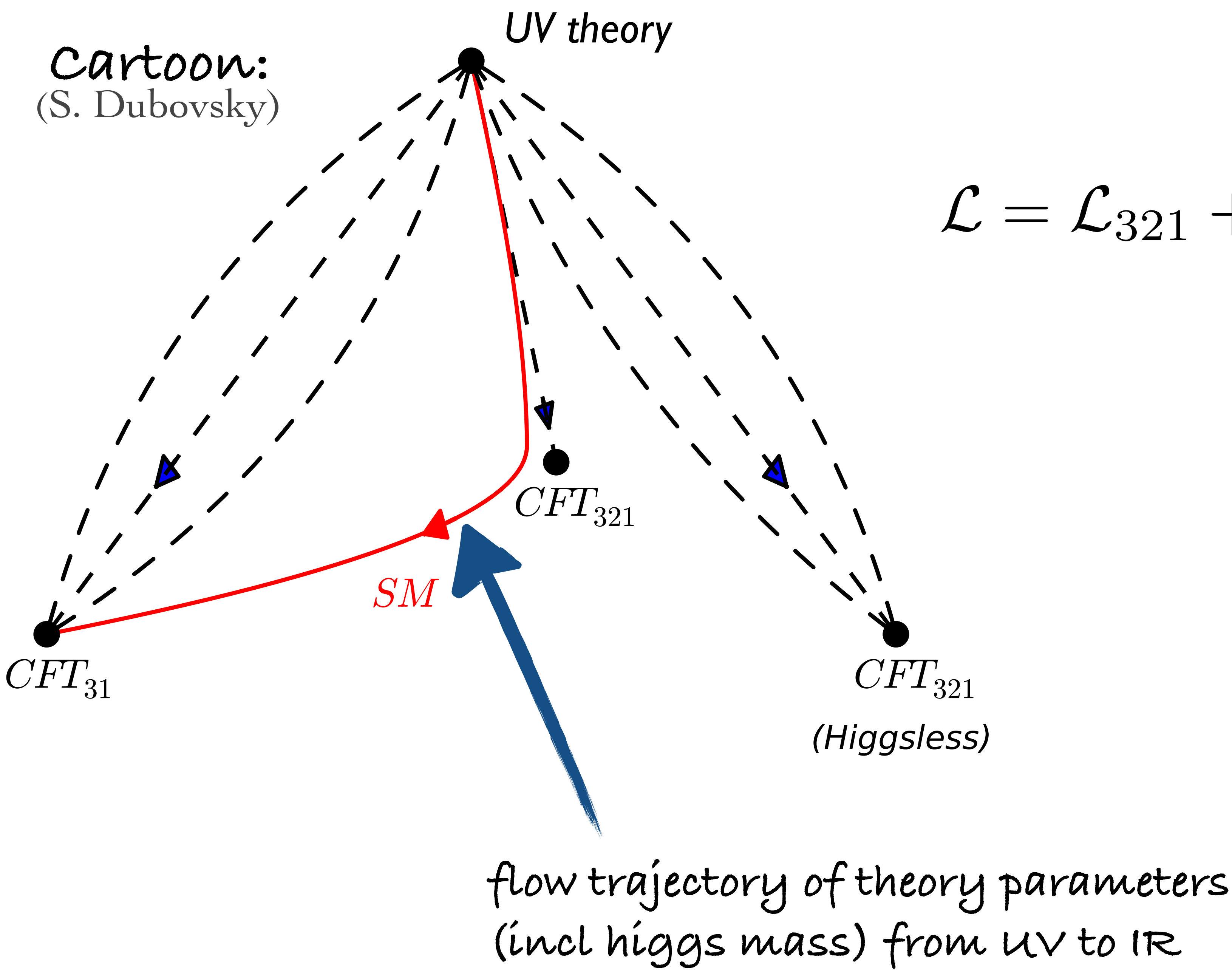
most strongly affected by answer to first

Hierarchy Problem

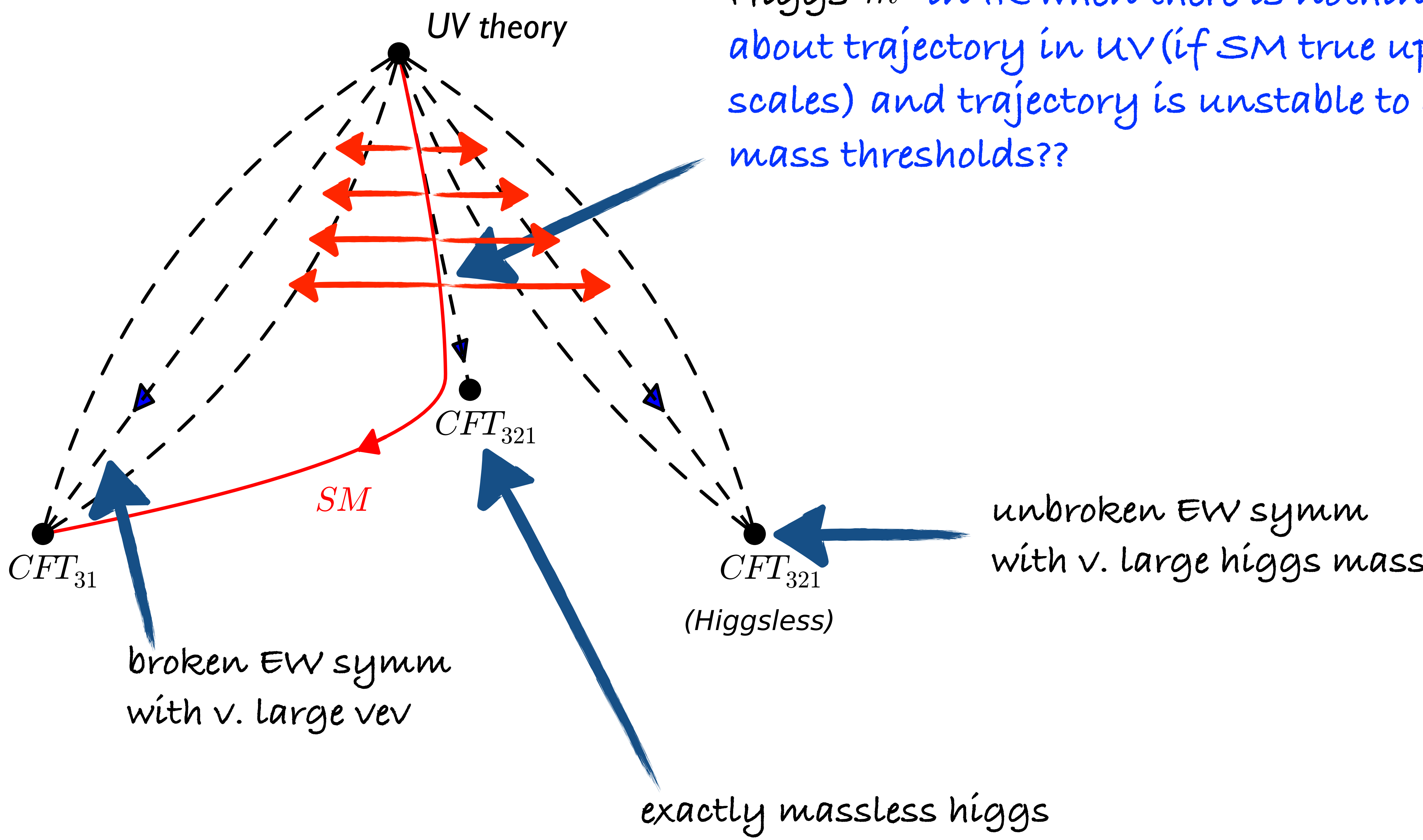
Can discuss hierarchy problem directly in terms of the Wilsonian RG flow of finite quantities (no quadratic divergencies here…!)



$$\mathcal{L} = \mathcal{L}_{321} + m^2 H^\dagger H + \sum_i \frac{\mathcal{O}^{\Delta_i}}{\Lambda_{UV}^{(\Delta_i - 4)}}$$

strongly relevant operator not forbidden by symm if SM correct

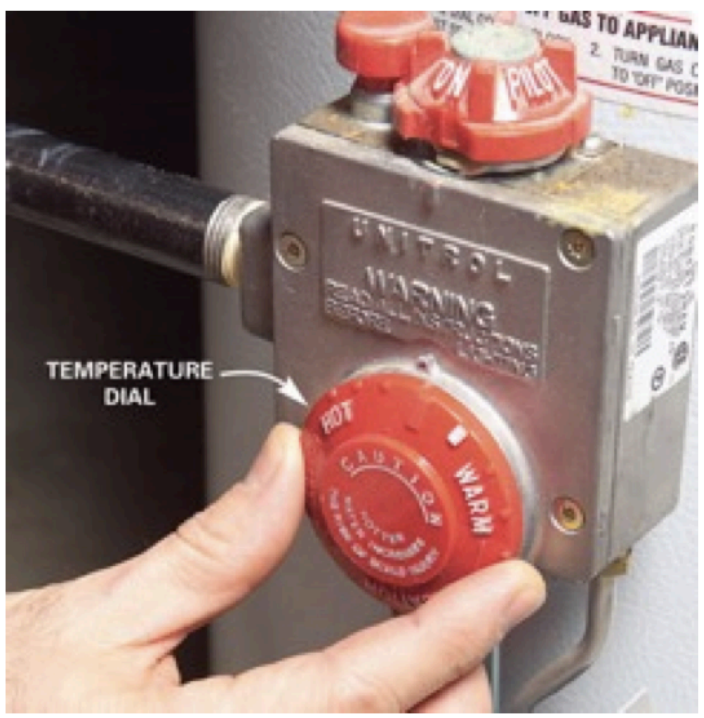
Hierarchy Problem

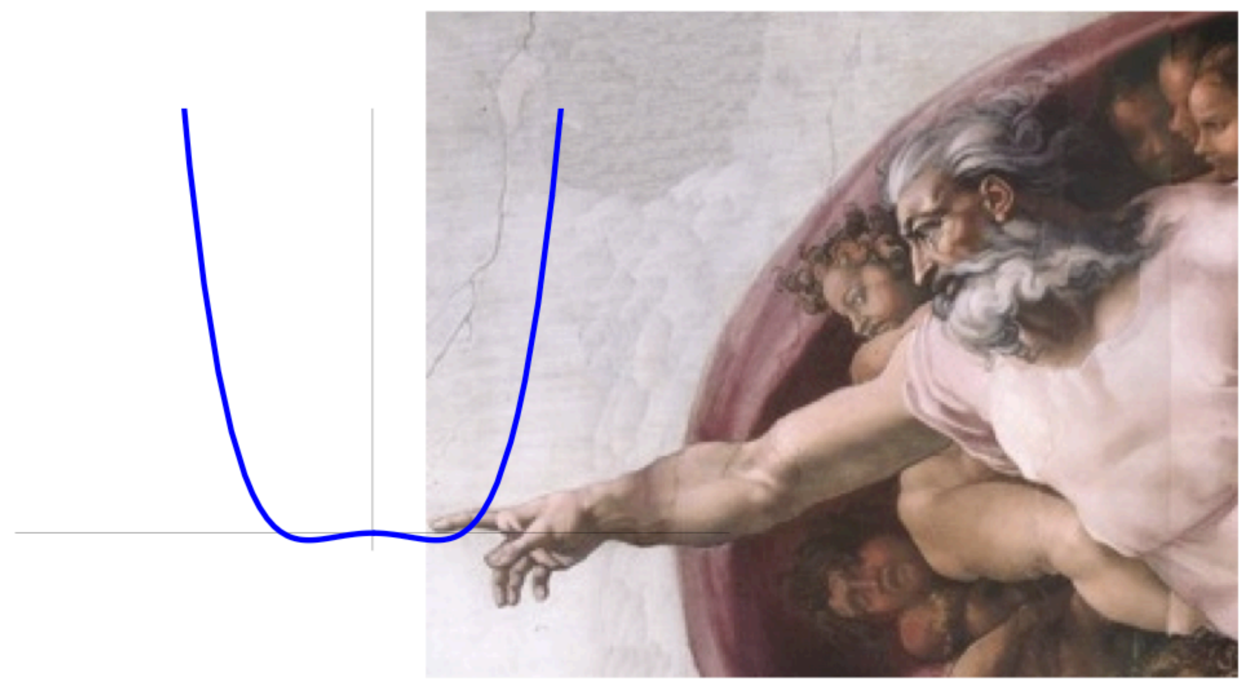


Why does trajectory of SM so closely approach zero, -0.00000000000000000000000000001Λ^2_{UV}, Higgs m^2 in IR when there is nothing special about trajectory in UV (if SM true up to high scales) and trajectory is unstable to effects of mass thresholds??

Hierarchy Problem

Like tuning of a phase transition to 2nd-order point — nothing *a-priori* special about 374.4 C and 217.7 atm for water — an experimentalist has to very carefully *tune* the knobs!





$$|T - T_c| \ll T$$

pictures courtesy R. Rattazzi & V. Rychkov
who stole them anyway

Hierarchy Problem

Hierarchy problem is sharp for theories where Higgs properties (EWSB condensate, and higgs mass) are calculable

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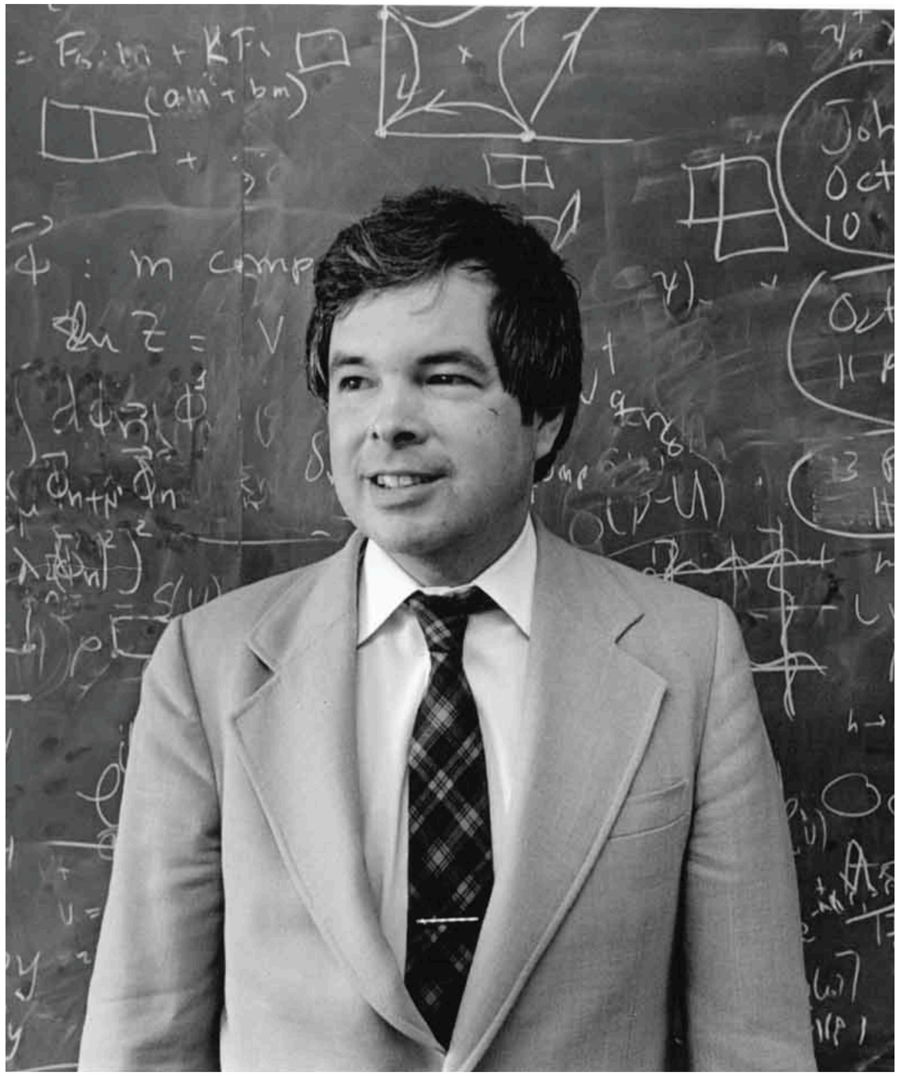
Unless there is a solution to the HP at < (few TeV) energies we almost certainly violate the Wilsonian understanding of QFT



Naturalness aka Dynamics

Past successes of Wilsonian reasoning

Problem	Solution	
Hydrogen binding energy	QM $E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2}m_e$	✓
Electron mass	Chiral Symmetry	✓
π^+ - π^0 mass difference	Symmetry/Dynamics	✓
Kaon mixing	Flavour Symmetry	✓
QCD scale	Dimensional Transmutation	✓

(each step v. non-trivial, ~20+yrs, with qualitatively new dynamics/symmetry)

Multiverse??

Useful to recall some more history...

Problem	Solution
Earth-Sun Distance	Anthropic Selection 10^{22} suns ✓
Cosmological Constant	Anthropic Selection 10^{500} universes ???
7 eV line of ^{229}Th nucleus	Many possible lines…
Solar Eclipse & moon's size	Plain luck!

Major flaws:

How many vacua? Distribution of stable vacua? Which parameters scan and how? With what correlations? What properties should we select on and how detailed? ("existence of atoms" "existence of life"??)

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No one will/should believe a fully (or partially) tuned multiverse 'solution' until every possibility of novel symmetry & dynamics is exhausted

Hierarchy Problem

Dynamics/Naturalness at scale now being explored by LHC is *by far* best bet

so where is the new physics?! —
didn't theorists say that it should
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yes, certainly the most minimal natural
theories of the weak scale should have
shown up (at LEP....)

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we need to ask if exist unusual natural theories still to be explored

(non-QCD-like) Composite EWSB?

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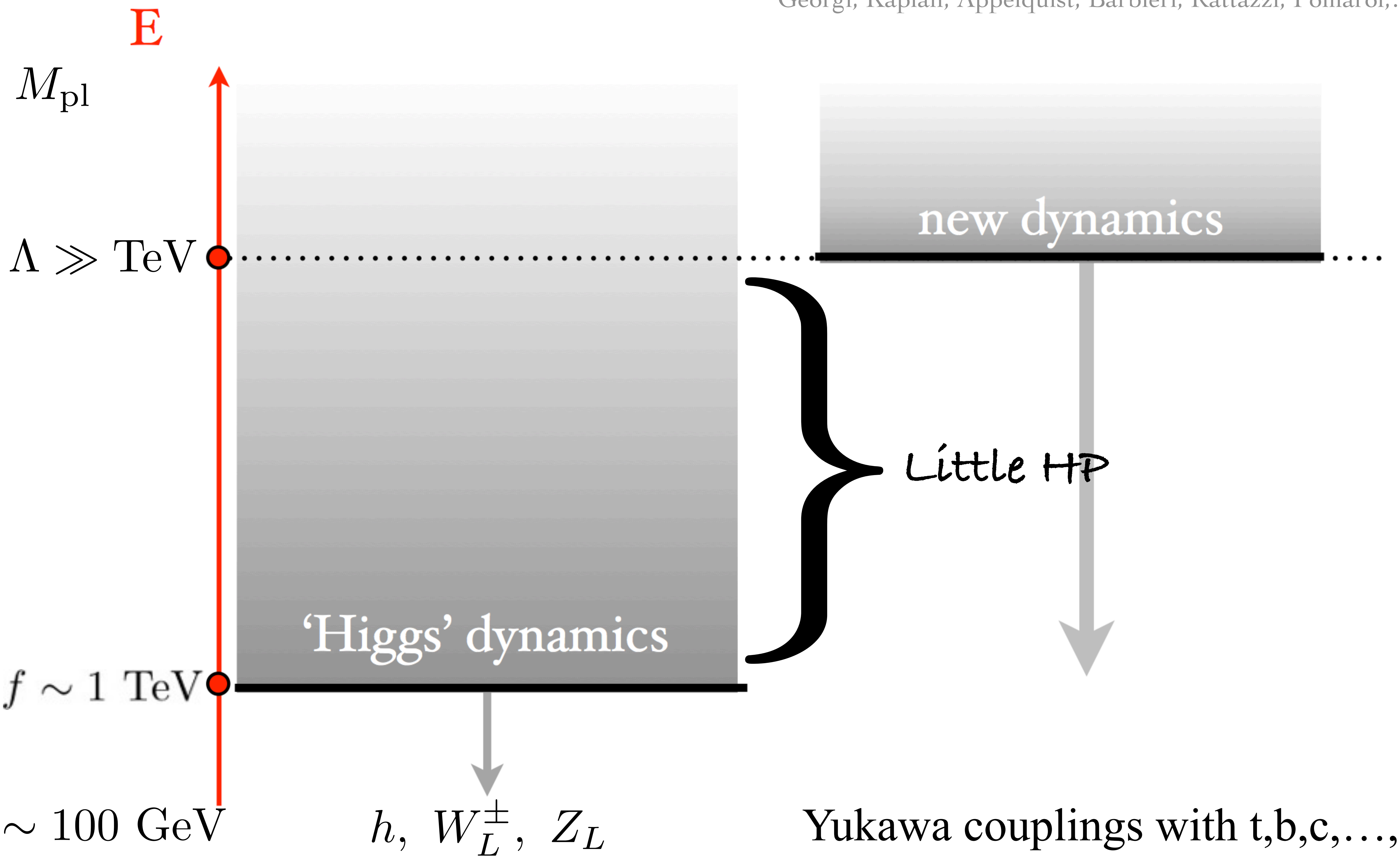
Georgi, Kaplan, Appelquist, Barbieri, Rattazzi, Pomarol,....



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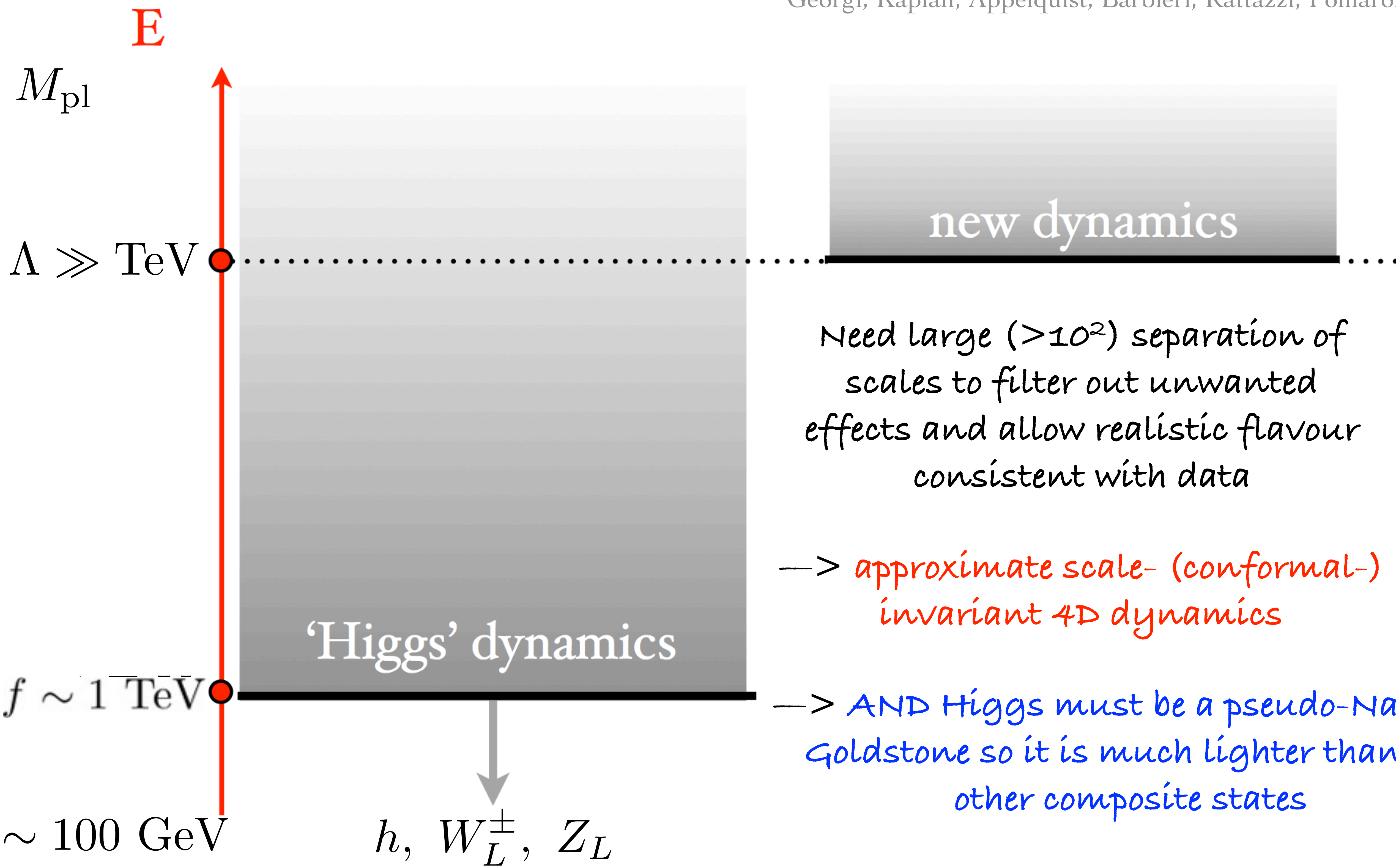


Need large ($>10^2$) separation of scales to filter out unwanted effects and allow realistic flavour consistent with data

—> approximate scale- (conformal-) invariant 4D dynamics

—> AND Higgs must be a pseudo-Nambu-Goldstone so it is much lighter than all other composite states

(non-QCD-like) Composite EWSB?

Higgs if it is to be so light compared to other scales must be a pseudo-Nambu-Goldstone

Georgi, Kaplan

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ h + i\phi_3 \end{pmatrix}$$

all 4 components must be pNGBs

QCD-like-compositeness had global symm structure SO(4)/SO(3) → 3 NGB and higgs was massive

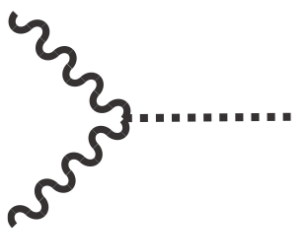
Generalise to SO(5)/SO(4) → 4 NGBs and higgs is automatically light

(non-QCD-like) Composite EWSB?

Effective Lagrangian for a composite light pseudo-NG Higgs boson: 2 leading operators

$$\# \frac{1}{2f^2} \partial_\mu |H|^2 \partial^\mu |H|^2$$

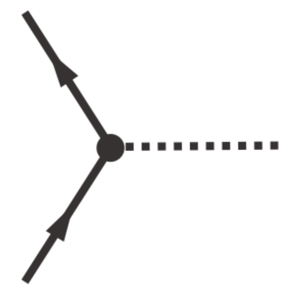
$$\# \frac{y_i}{f^2} (\bar{f}_i f_i H) |H|^2$$



$$a \times \frac{2m_V^2}{v}$$

$$a \simeq 1 - \frac{1}{2}\frac{v^2}{f^2} < 1$$

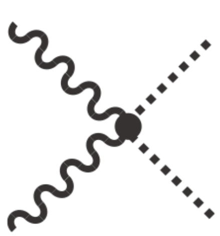
robust consequence
of coset structure



$$c_i \times \frac{m_i}{v}$$

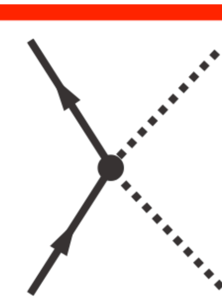
$$c_i \simeq 1 + O(\frac{v^2}{f^2}) < 1$$

generic but not a theorem



$$b \times \frac{m_V^2}{v^2}$$

$$b \simeq 1 - 2\frac{v^2}{f^2}$$

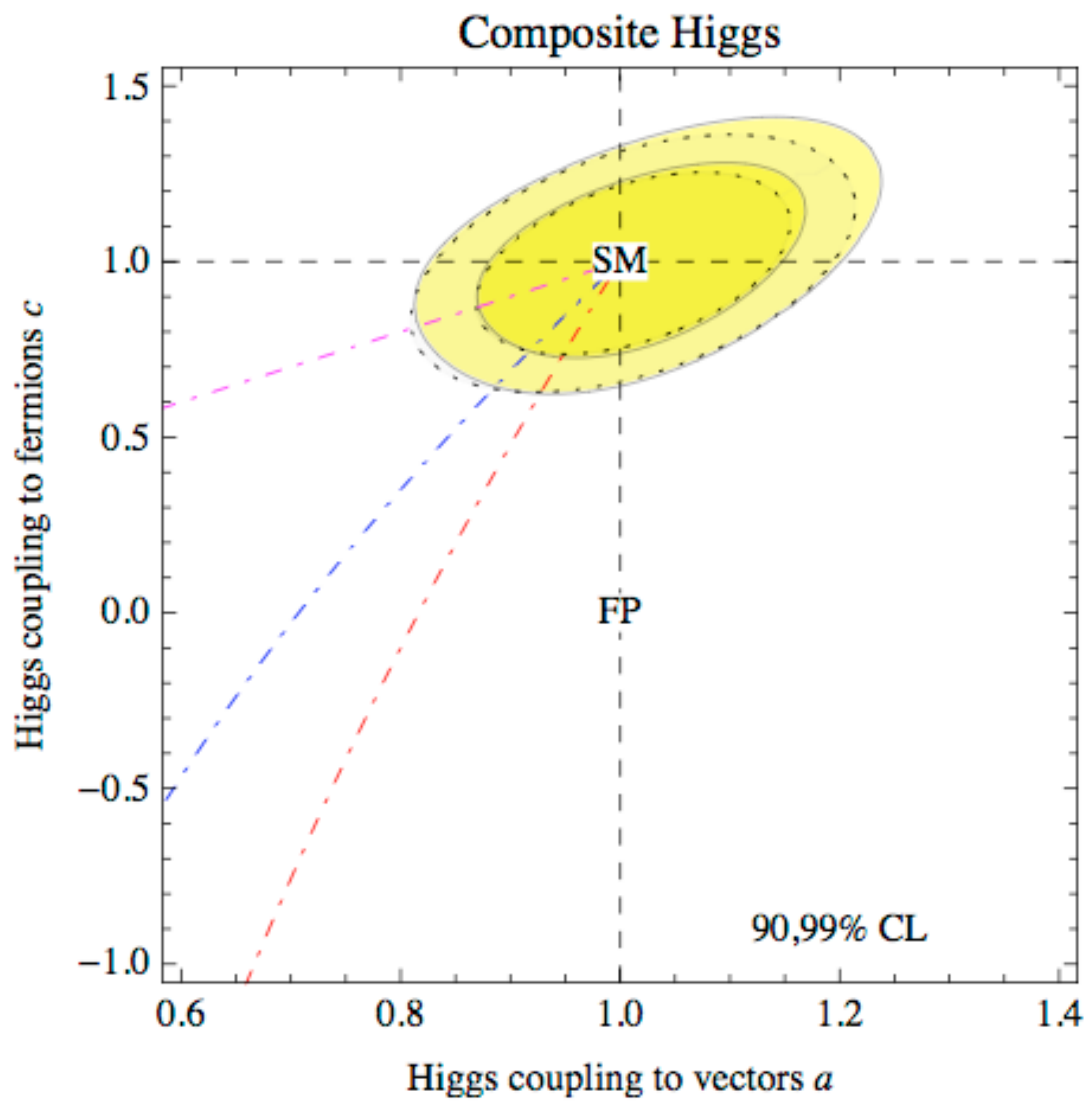


$$\propto \frac{m_i}{f^2}$$

New!

courtesy of R. Rattazzi

(non-QCD-like) Composite EWSB?



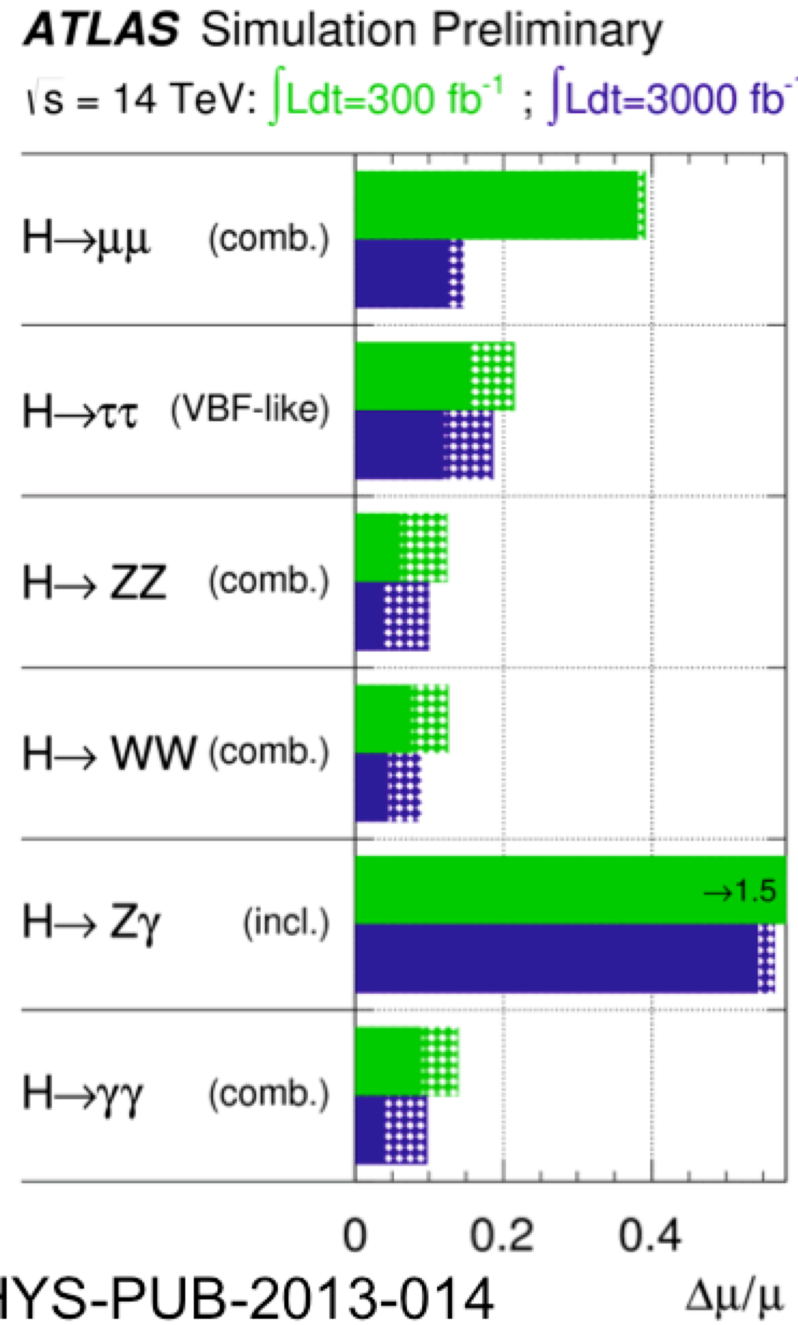
Prospects for H(125) measurements

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Future LHC data: measure H couplings at 2-8% level (cf 20-50% today), and to access rare decays such as H→μμ



ATL-PHYS-PUB-2013-014

CMS projections for coupling precision (arXiv:1307.7135)

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

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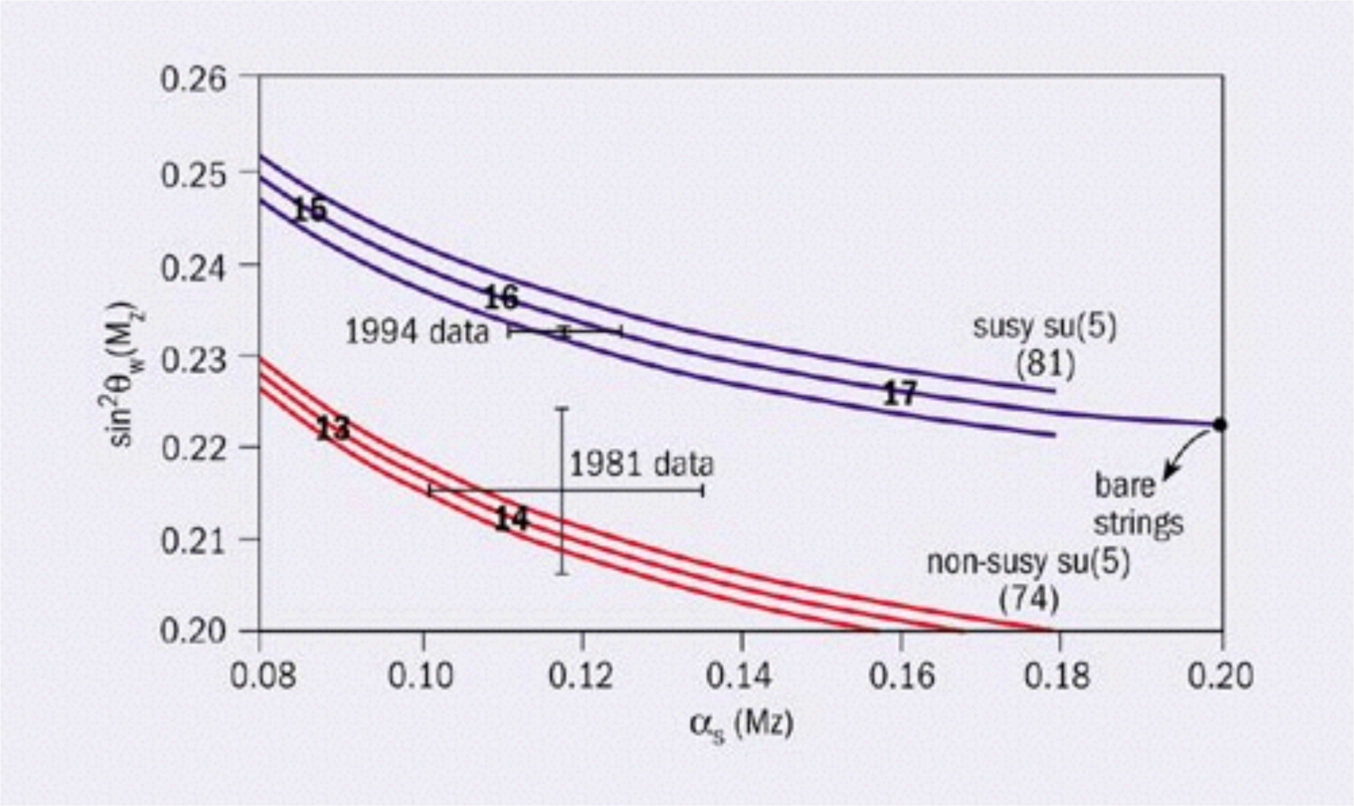

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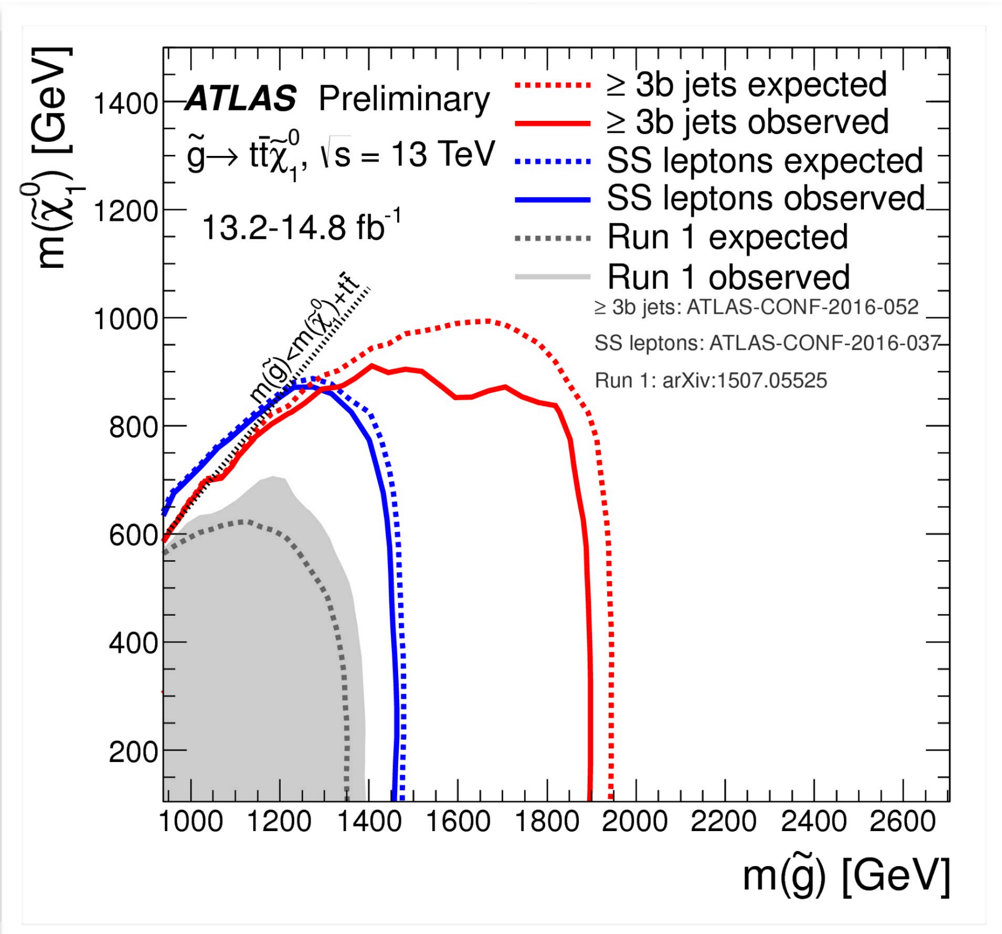
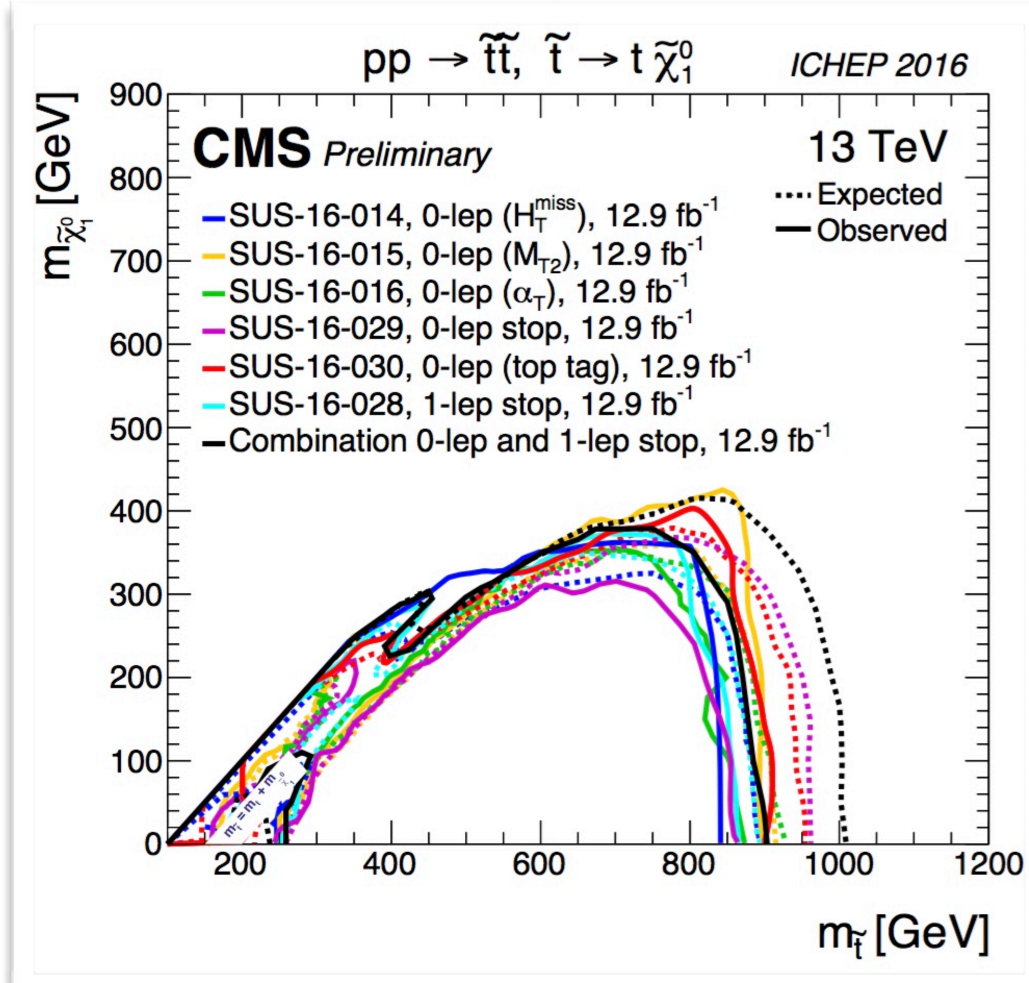
BUT we have seen nothing so far!!??

Supersymmetry





SUSY tuning still much,
much better than SM but…

a fully natural theory
requires some extra
structure/dynamics
beyond vanilla MSSM

MSSM Fine-Tuning Problem

Successful EWSB requires
$$\frac{m_Z^2}{2} \simeq -m_{H_u}^2 - |\mu|^2 \qquad (\tan\beta >> 1)$$

Sole source of higgsino mass
$\Longrightarrow$ some tree level tuning

At 1-loop Higgs soft mass gets large corrections

$$\Delta m_{H_u}^2 \sim -\frac{3|y_t|^2}{4\pi^2}(m_{\tilde{t}}^2 + |A_t|^2/2)\log\left(\frac{\Lambda}{\tilde{m}}\right)$$

$\Longrightarrow$ large loop-level tuning if stop mass & A-term not small

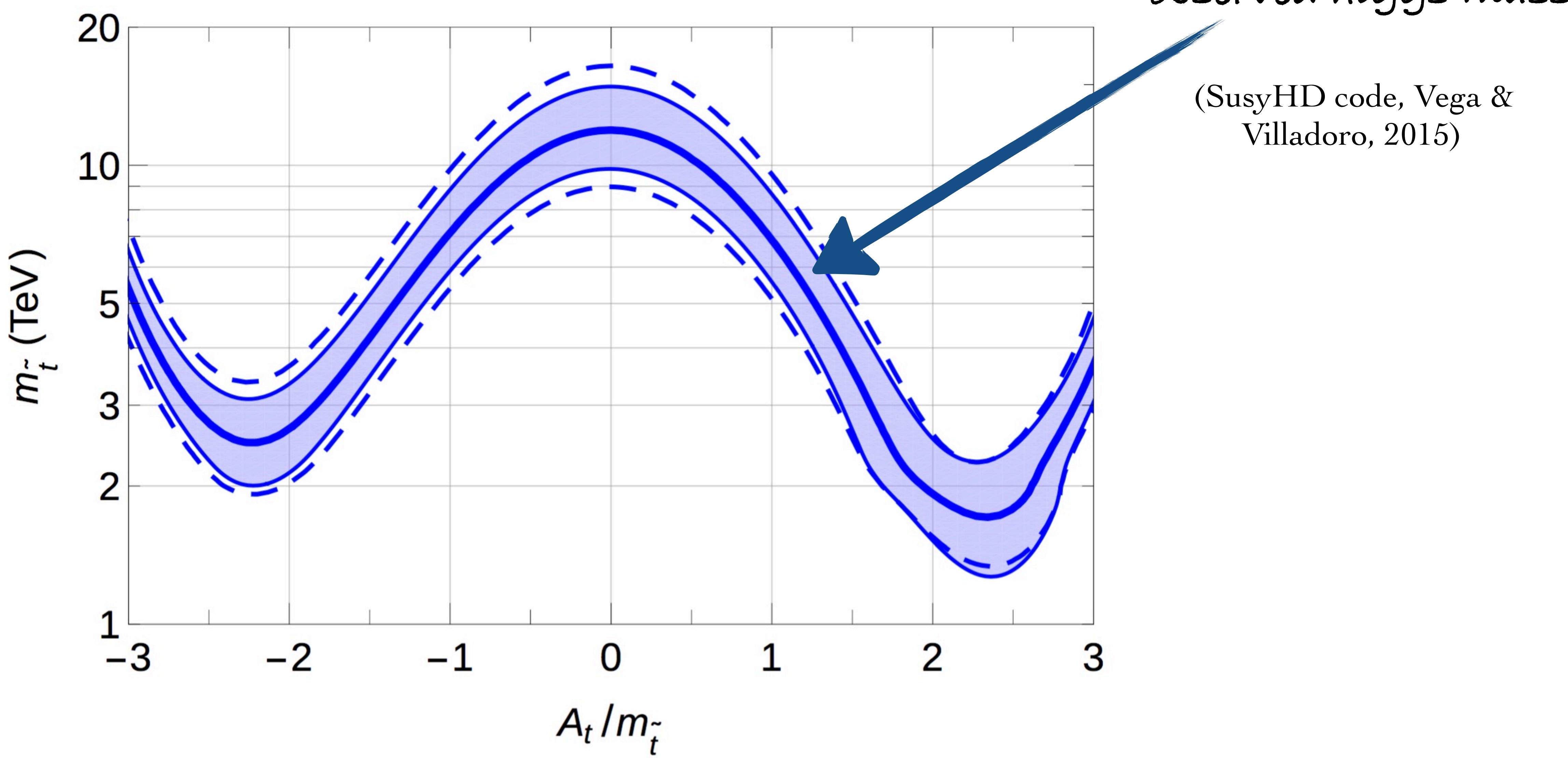
mediation scale of SUSY breaking

$\log \sim 35$ gravity

$\log \sim 6$ gauge

Naturalness in MSSM SUSY

In the MSSM: Tuning dominated by achieving the Higgs Mass



(SusyHD code, Vega & Villadoro, 2015)

$$\Delta m_{H_u}^2 \sim -\frac{3|y_t|^2}{4\pi^2}(m_{\tilde{t}}^2 + |A_t|^2/2)\log\left(\frac{\Lambda}{\tilde{m}}\right) \implies$$

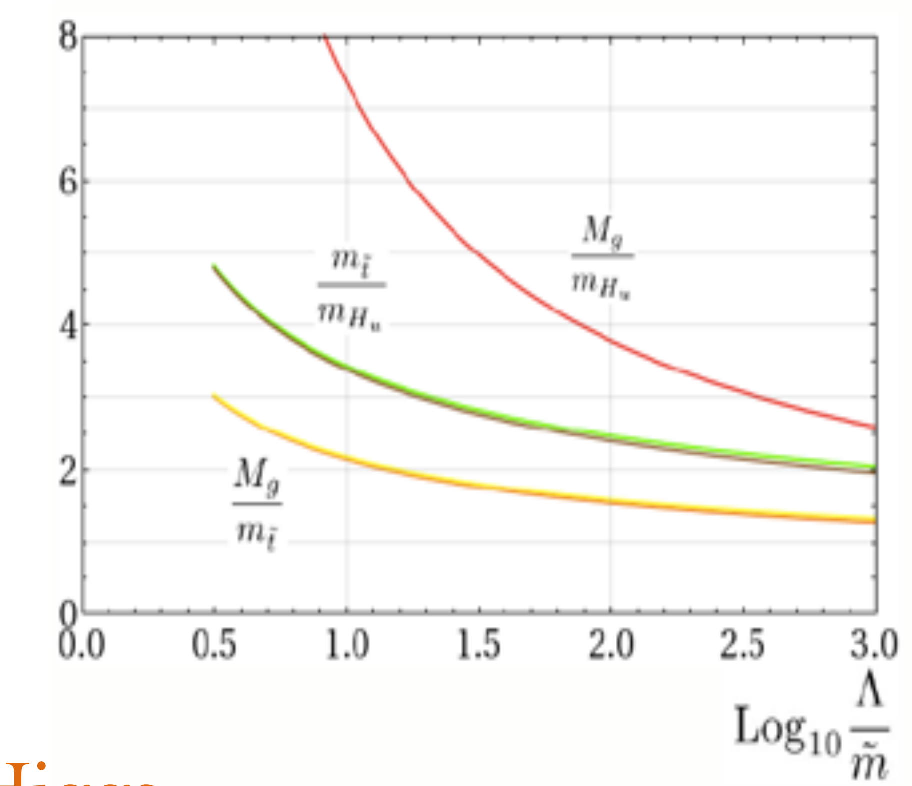
0.5% tuning or worse

The Gluino Sucks Problem

WORSE: RG evolution quickly pulls up stop mass, and so EW scale, to gluino mass

$$\Delta m_{\tilde{t}}^2 \sim \frac{8\alpha_s}{3\pi} M_3^2 \log\left(\frac{\Lambda}{\tilde{m}}\right)$$

$$\Delta m_{H_u}^2 \sim -\frac{3|y_t|^2}{4\pi^2}(m_{\tilde{t}}^2 + |A_t|^2/2)\log\left(\frac{\Lambda}{\tilde{m}}\right)$$



this is problem independent of getting 125 GeV Higgs

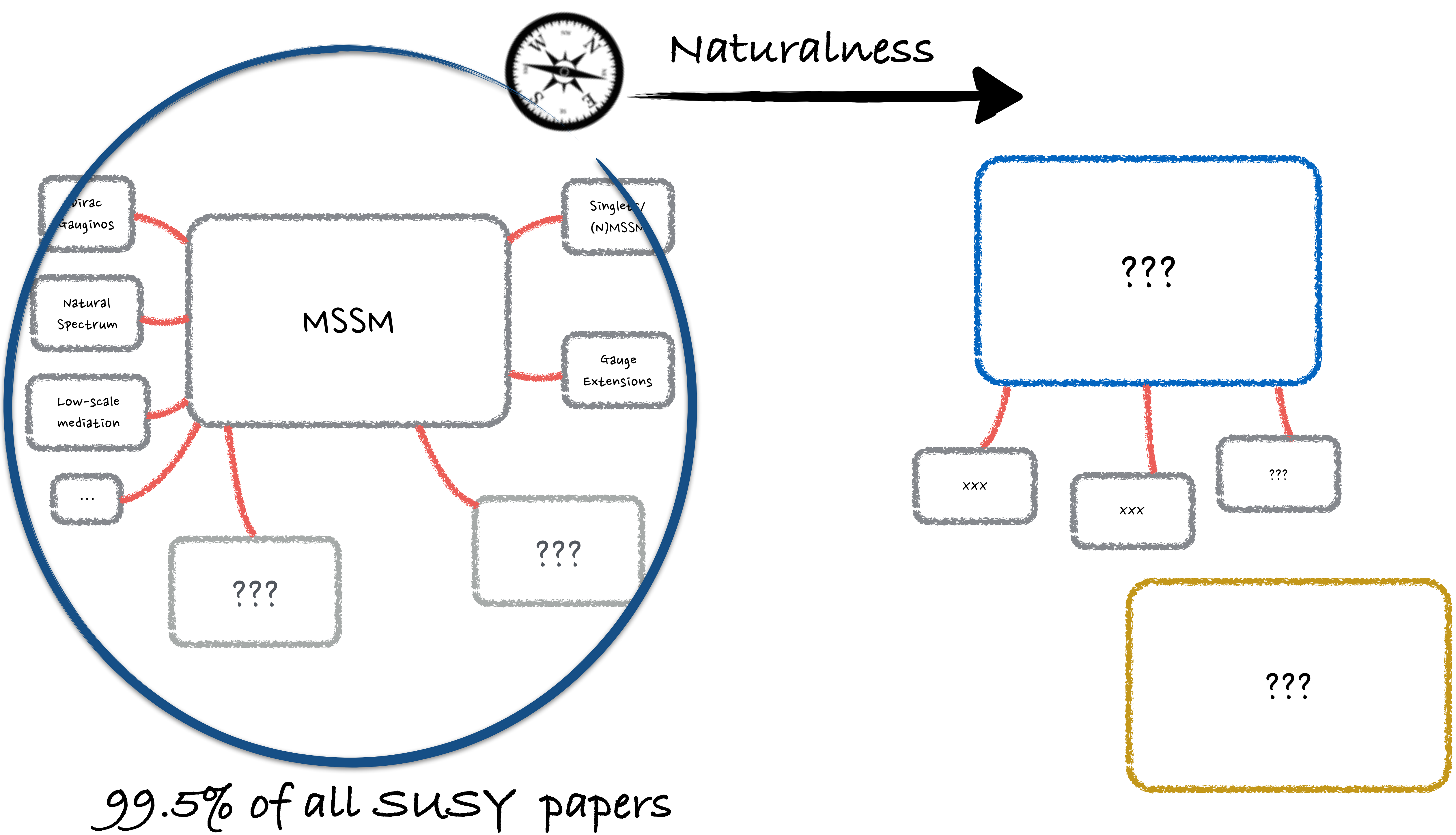
Gluino bounds constrain all MSSM-like scenarios to ~1% tuning..

(Arvanitaki, etal, 2013)

(CMSSM more severely tuned still+high-scale mediation bad)

Supersymmetric Theory Space

There exist qualitatively different ways of implementing SUSY than MSSM



Fully Natural Supersymmetry?

We need to find symmetry-enhanced broken SUSY theories where new cancellations occur

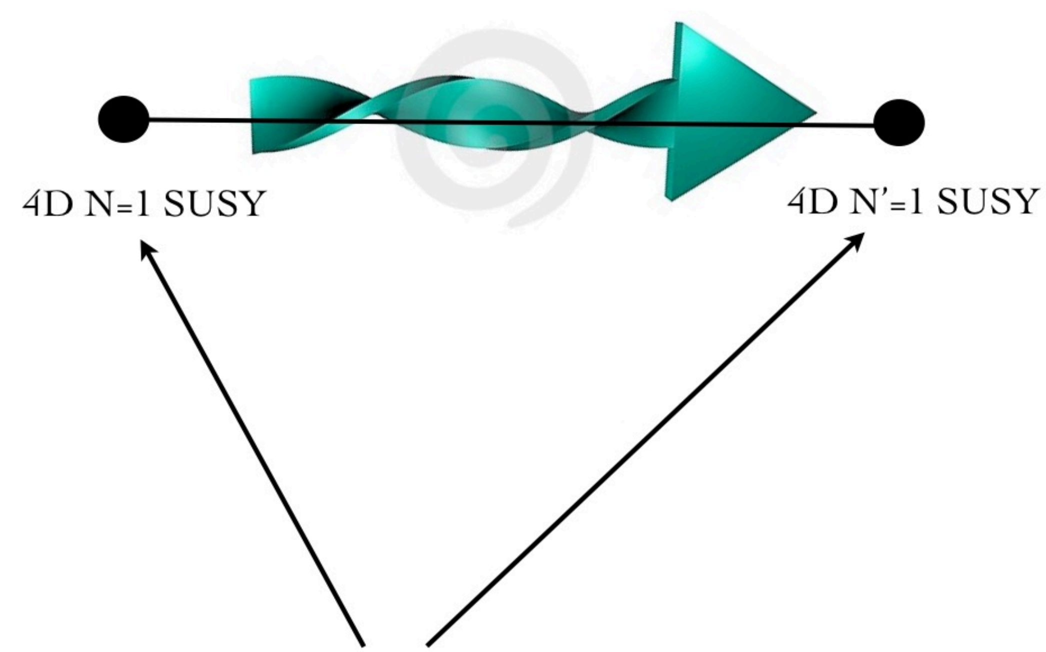
At least two types of new structures that much reduce tuning:

- Enhanced symmetry structure involving N=2 SUSY structure in gauge/Higgs sector (and/or locality in extra dim versions of SUSY)
- Enhanced discrete symmetry of "Twin Higgs" type

Highlights of Max Natural SUSY

Savas Dimopoulos, Kiel Howe, JMR; *Maximally Natural Supersymmetry,* arXiv:1404.7554
Isabel Garcia Garcia, JMR; *Rare Flavor Processes in Maximally Natural Supersymmetry,* arXiv:1409.5669
Isabel Garcia Garcia, Kiel Howe, JMR; *Natural Scherk-Schwarz Theories of the Weak Scale,* arXiv:1510.07045
Junwu Huang, JMR; *Unified Maximally Natural Supersymmetry,* arXiv:1607.08622

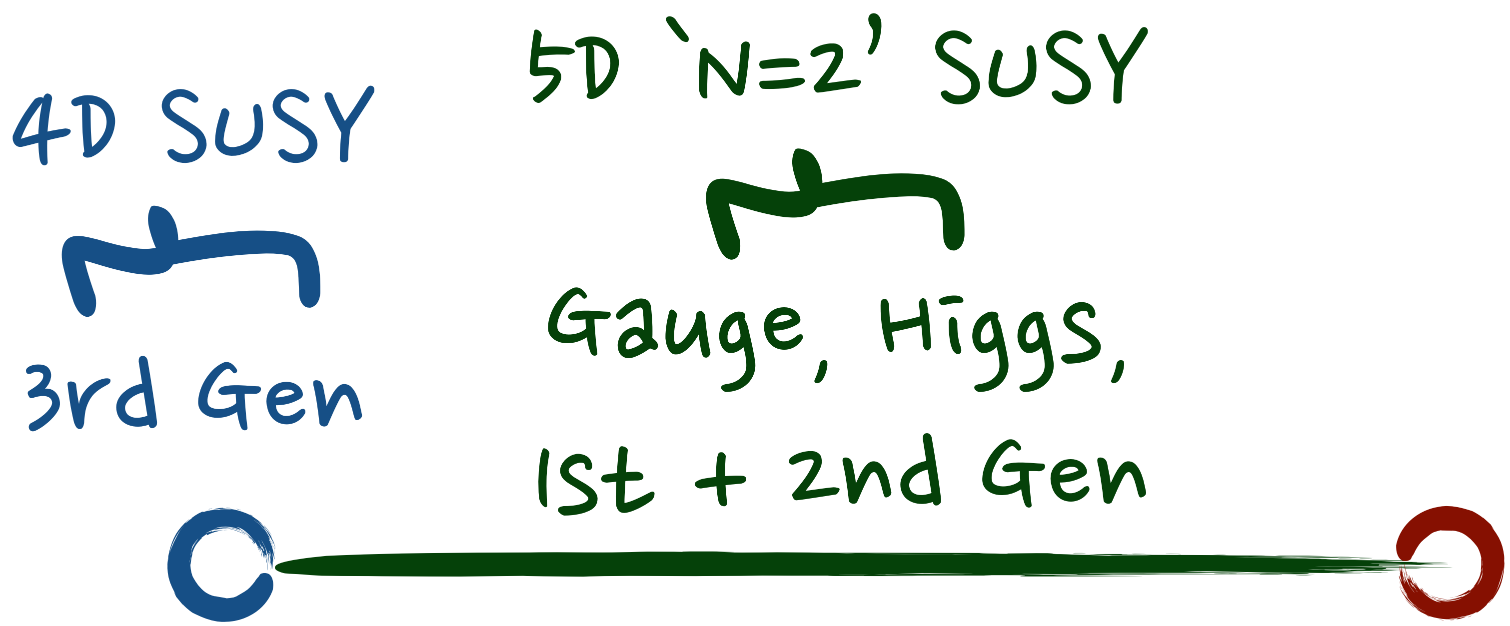
Scherk-Schwarz ~~SUSY~~ is *non-local breaking in 5D* using R-symmetry twist - *finite*



Different incompatible supersymmetries so overall 4D SUSY broken

But locally in 5D SUSY is everywhere preserved — leads to remarkable properties

geographical set-up



$R \sim 1/(\text{few} \times \text{TeV}) \sim 1/m_{soft}$

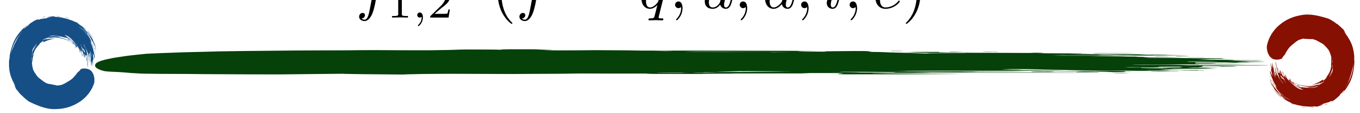
Tree-level Scherk-Schwarz Spectrum

(maximal twist)

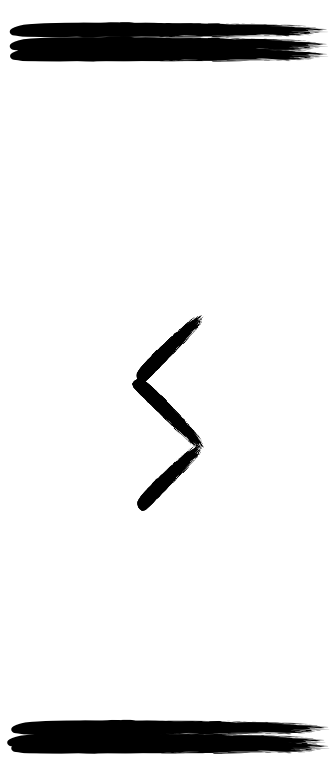
$SU(3) \times SU(2) \times U(1)$ $\quad H_u, H_d$

$f_{1,2}$ $\;(f = q, u, d, l, e)$

f_3



$y = 0$ $\qquad y = \pi R$



$$m_{\tilde{f}}^2 = m_{\tilde{\lambda}}^2 = m_{\tilde{H}}^2 = \frac{1}{2R}$$

Direct & universal bulk soft masses

No tree-level tuning!!

Almost exact $U(1)_R$ Dirac Masses

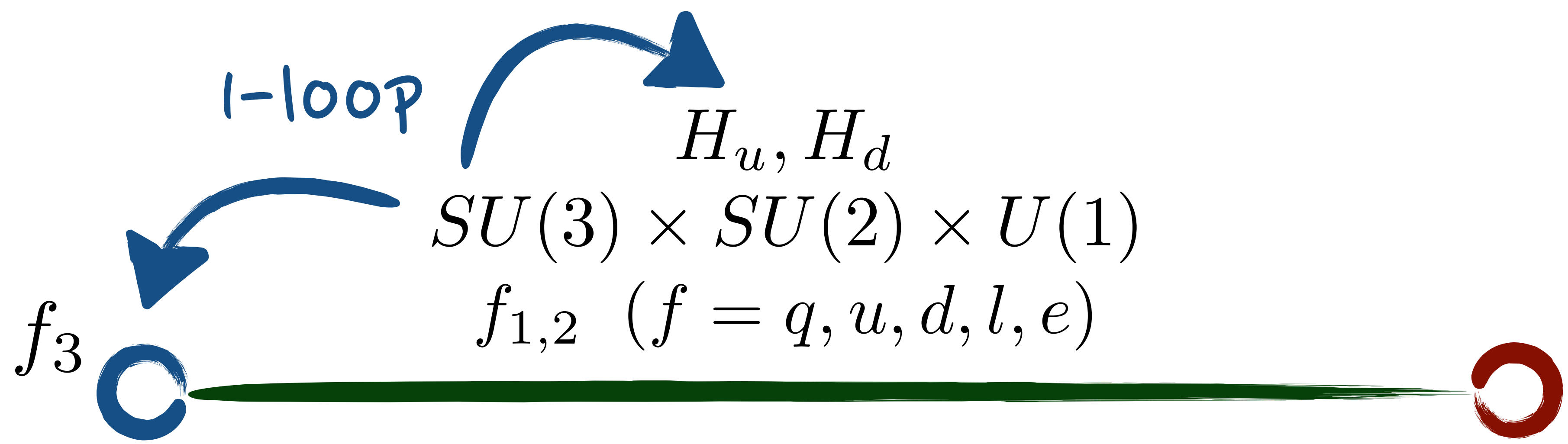
$$m_{\tilde{H}} \tilde{H} \tilde{H}^c \qquad m_{\tilde{\lambda}} \tilde{\lambda} \tilde{\lambda}^c$$

$$m_{\tilde{f}_3}^2 = m_{h_{u,d}}^2 = 0$$

No mu-term necessary for higgsino masses

locality $\qquad$ zero mode

Loop-level Scherk-Schwarz Spectrum



$$\delta \tilde{m}_i^2 \simeq \frac{7\zeta(3)}{16\pi^4 R^2}\left(\sum_{I=1,2,3} C_I(i) g_I^2 + C_t(i) y_t^2\right)$$

SUSY loops finite (NO LOGS!)

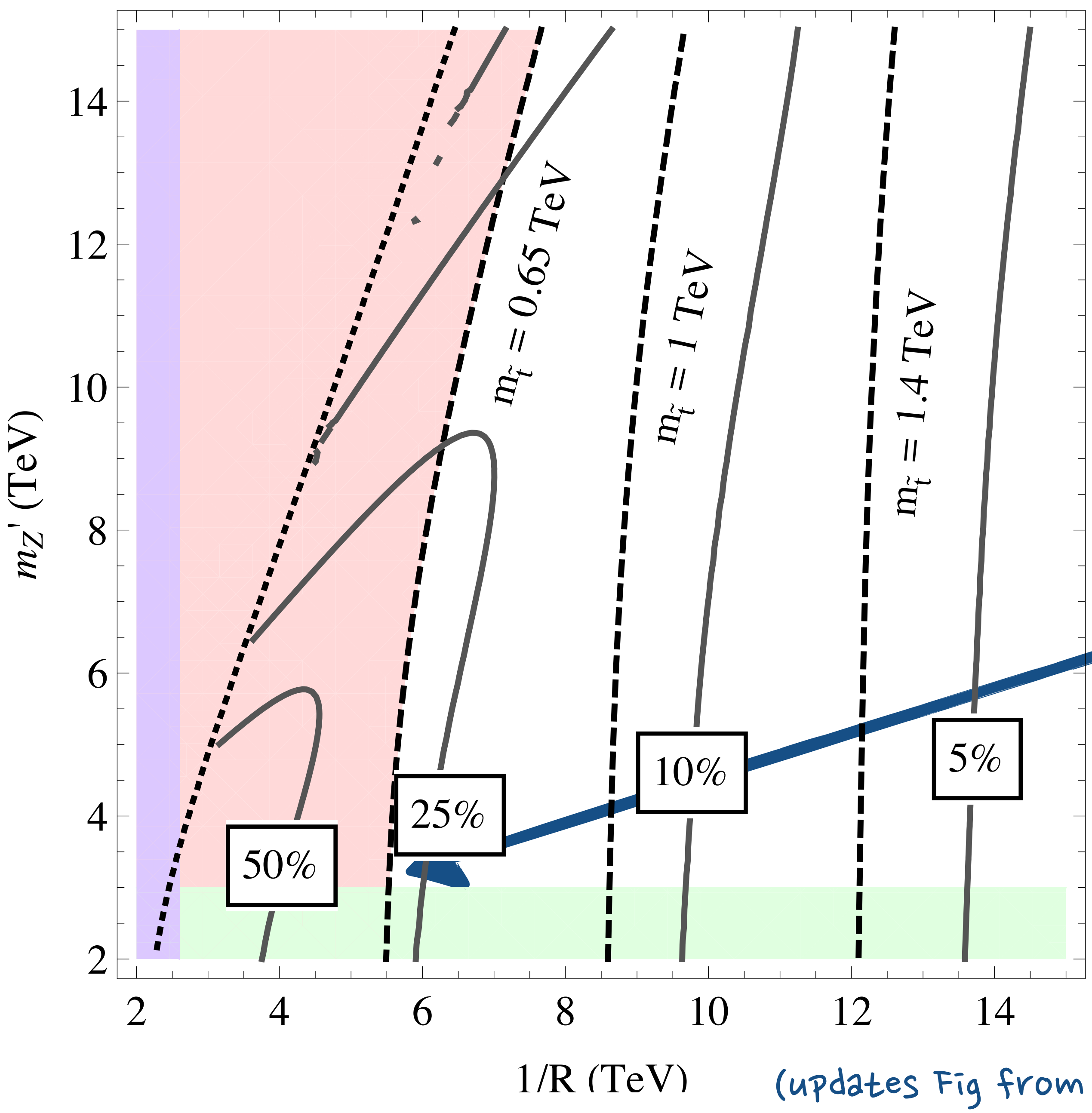
$$m_{\tilde{t}}^2 \approx \left(\frac{1}{10} \times \frac{1}{R}\right)^2 \approx \left(\frac{1}{5} \times M_3\right)^2$$

→ Large stop-gluino hierarchy (gluino doesn't suck)

How EWSB works: magnitude of EW scale² 1-EW-loop effect from EW-ino masses + HDOs

Need a bit more for Higgs mass

U(1)' Variation



(updates Fig from orig paper)

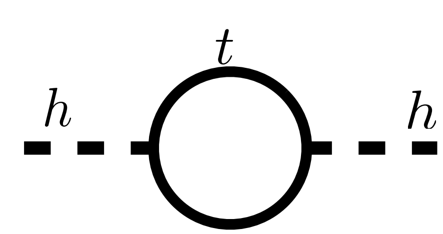
$$\Delta = \sqrt{\left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{t}}^2}\right)^2 + \left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{Z}'}^2}\right)^2}$$

LOW TUNING(!)

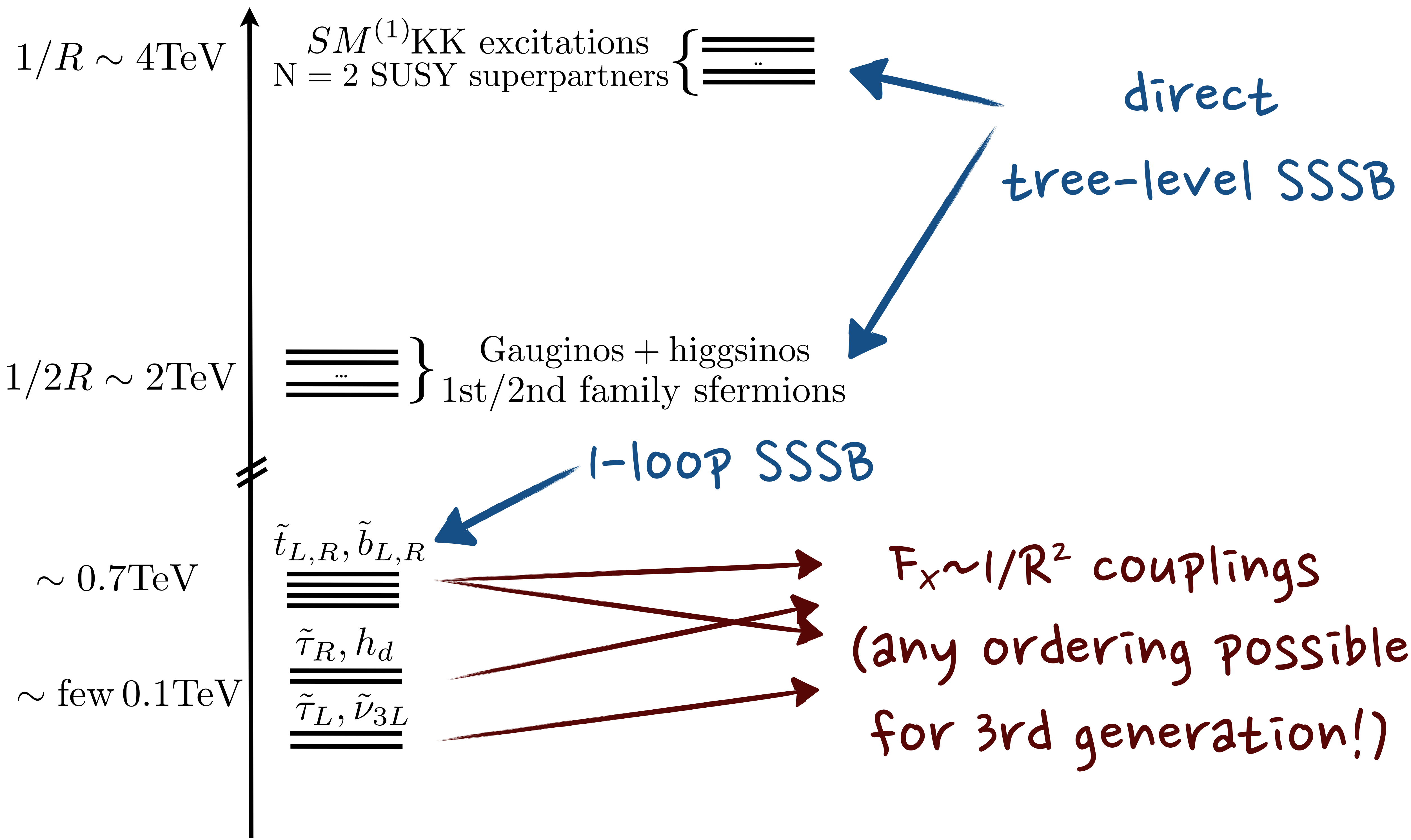
For ~700 GeV Stop & 2 TeV Gluinos/Squarks

<10% tuned within LHC13 Reach

"Maximal" ~ saturates one-loop tuning $\Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2} M^2$



Overall Spectrum



Max Natural SUSY advantages

Why so much less tuned than usual?

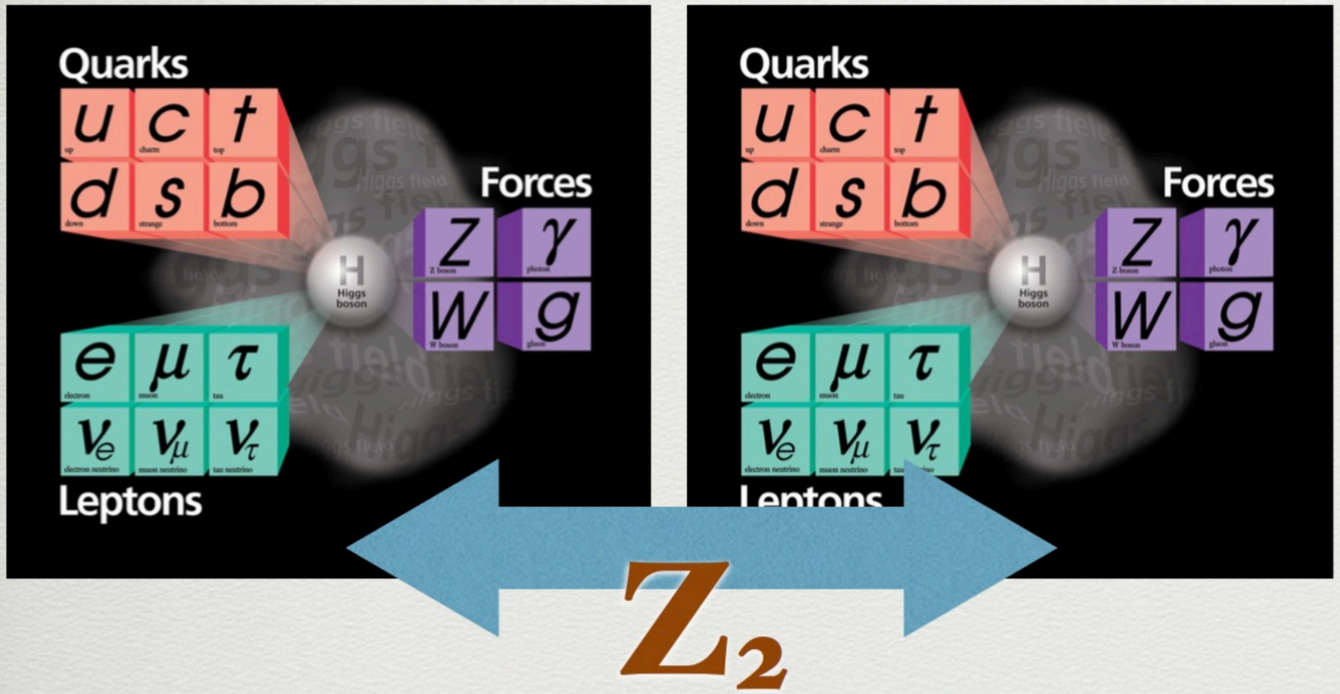
- No tree-level tuning as no mu-term
- SUSY breaking directly communicated to Higgsinos, gauginos, and 1st/2nd family sfermions. 3rd family protected from tree SUSY breaking
- SSSB is super-soft as it is a non-local (in 5d) breaking of SUSY. No logs, so suppresses the gluino sucks problem
- A natural SUSY spectrum is trivial to obtain via localization of the 3rd family on a 4D brane (also vital for successful EWSB)
- There is an approximate $U(1)_R$ symmetry

from A. Katz, "SUSY Alive?"

The Twin Higgs

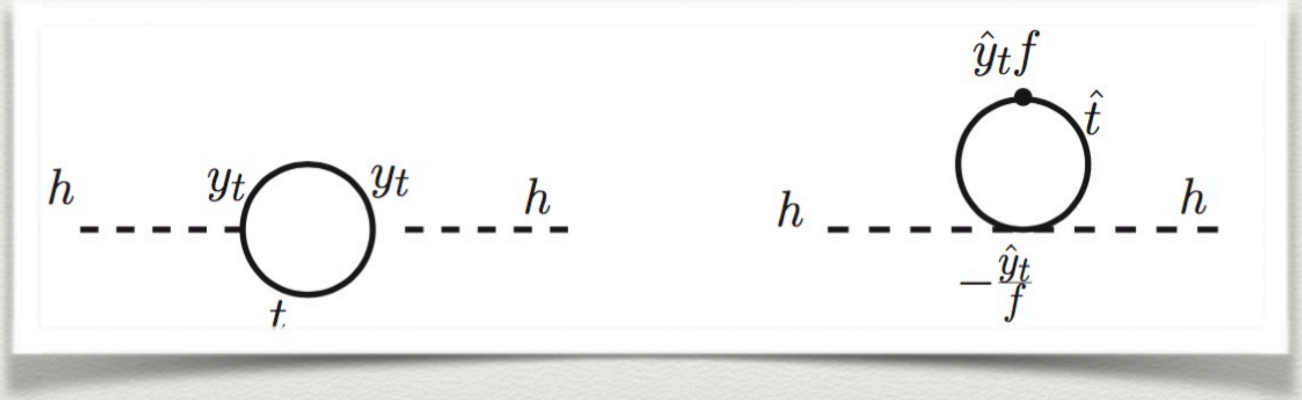
Chacko, Goh, Harnik; 2005

In the Twin Higgs the lightness of the EW scale is explained by the fact, that the SM like higgs is a pGB of an approximate SU(4) [enhanced to SO(8)] symmetry of the Lagrangian. This symmetry is not exact, but holds up to good approximation due to a mirror symmetry of the Lagrangian



At the leading order only Z_2 is needed

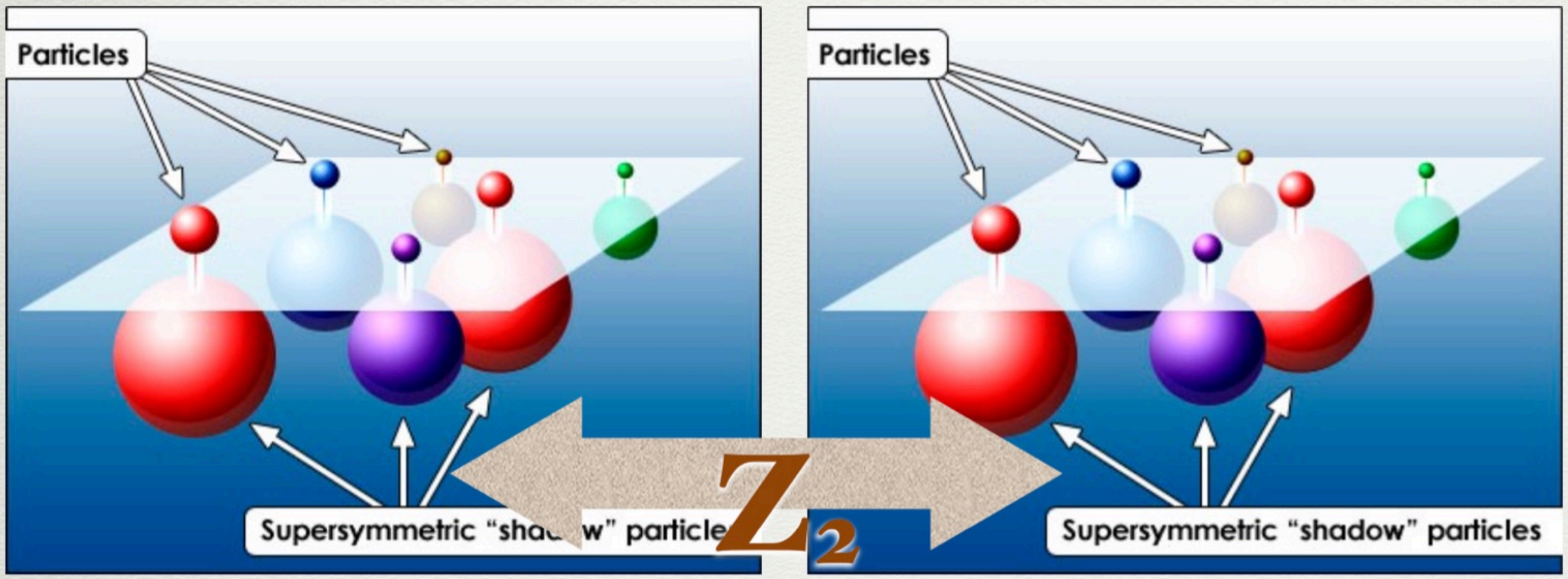
Cancellation of the leading divergencies:



from A. Katz, "SUSY Alive?"

SUSY Meets Its Twin

Falkowski, Pokorski, Schmaltz; 2006;; Chang, Hall, Weiner; 2006



How do we get the necessary couplings?

Getting SU(4) conserving quartic: **NMSSM** (well, almost)

$$W = \lambda S \mathcal{H}_u \mathcal{H}_d$$

$\mathcal{H}_u \mathcal{H}_d$ → *full multiplets of the approximate SU(4)*

λ → assume to be order-1

The singlet should be integrated out non-supersymmetrically (soft mass ≫ SUSY mass)

from A. Katz, "SUSY Alive?"

The Bi-Doublets

Desiderata: negative mirror symmetry preserving quartic, hard mirror symmetry breaking terms. Any way to get this?

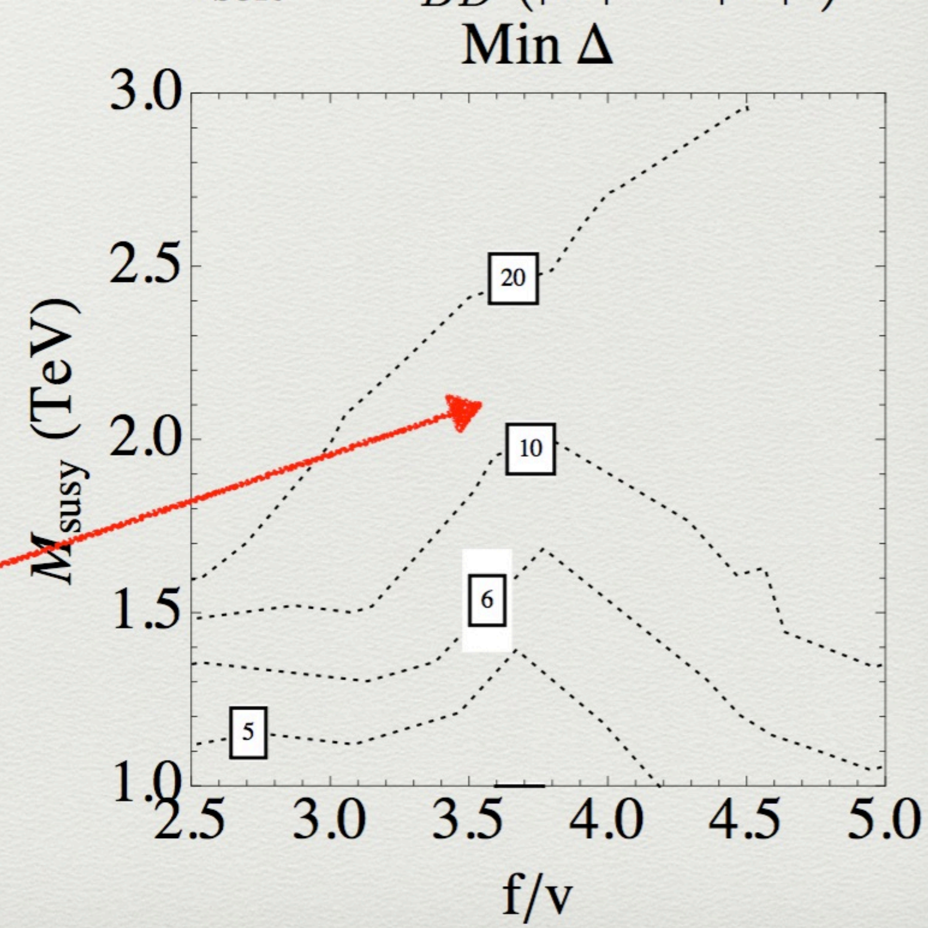
Trick: introduce vectorlike bidoublets:

$$\Delta W = \lambda_B B h_u^A h_u^B + M_{BD} \overline{B} B \,, \qquad V_{\rm soft} = m_{BD}^2 \left(|B|^2 + |\overline{B}|^2 \right) \,.$$

Automatically get negative quartic which can outweigh the D-terms

Contours of the FT (scan!!)

We can improve the situation qualitatively



HP & "Physical Naturalness"?

Bardeen, Foot, Shaposhnikov, Lykken,…

Some say another way of addressing HP — "it doesn't exist"

Basically claim that there might be no higher mass scales feeding into H:

In principle gravity might be UV completed with no new particles so not affecting the Higgs mass (we know of no such construction)

AND suppose there are no other mass scales (eg, from origin of flavour; unification; dark matter;…) coupling to H either

Is this a "no-tuning" solution to hierarchy problem with
no low-energy consequences??

Consequences of “Physical Naturalness”

All BSM states carrying SM gauge quantum number must be below a few TeV
(so no high scale gauge unification)

Yukawa coupled particles can be heavier, $M_{\nu R} < 10^7$ GeV

Gravitationally coupled particles less than 10^{12} GeV? (requires a 3 loop calculation not yet performed)

Problems of "Physical Naturalness"

Must do all physics with previous constraints:

Still must explain why $M_{pl} >> v$

Family quantum numbers

Dark matter

Neutrino masses

Baryogenesis

Inflation

Flavour

$\sin^2\theta_W$...

and avoid all Landau Poles in a controllable way

looks very tough!

Problems of "Physical Naturalness"

Arvanitaki, Dimopoulos, Dubovsky, Strumia, Giudice, Villadoro…

Need to expand gauge group at the TeV scale, eg, to SU(4)xSU(2)xSU(2), or $SU(3)^3$ to solve U(1) Landau pole

Add further states to avoid Higgs quartic Landau pole

And do all the rest of physics at low scales or with mysterious quantum gravity effects...

attempts so far failed even at first stages

(& even if this program worked there is generically new physics accessible by LHC/other experiments)

Some comments on Experiments

1) Is the LHC exploration mostly done? Not at all!

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unexplored resonance searches

TABLE I. Existing two-body exclusive final state resonance searches at $\sqrt{s} = 8$ TeV. The $\varnothing$ symbol indicates no existing search at the LHC.

	e	μ	τ	γ	j	b	t	W	Z	h
e	$\pm\mp$[4], $\pm\pm$[5]	$\pm\pm$[5, 6] $\pm\mp$[6, 7]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
μ		$\pm\mp$[4], $\pm\pm$[5]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
τ			[8]	$\varnothing$	$\varnothing$	$\varnothing$	[9]	$\varnothing$	$\varnothing$	$\varnothing$
γ				[10]	[11–13]	$\varnothing$	$\varnothing$	[14]	[14]	$\varnothing$
j					[15]	[16]	[17]	[18]	[18]	$\varnothing$
b						[16]	[19]	$\varnothing$	$\varnothing$	$\varnothing$
t							[20]	[21]	$\varnothing$	$\varnothing$
W								[22–25]	[23, 24, 26, 27]	[28–30]
Z									[23, 25, 31]	[28, 30, 32, 33]
h										[34–37]

Craig, etal, arXiv:1610.09392

Some comments on Experiments

2) Precision/flavour physics is vitally important and could (should!) give us first hints

Some comments on Experiments

2) Precision/flavour physics is vitally important and could (should!) give us first hints

let's not forget the long-standing (g-2)-muon anomaly, and the recent LHCb, R_K, and B-meson decay anomalies, eg,

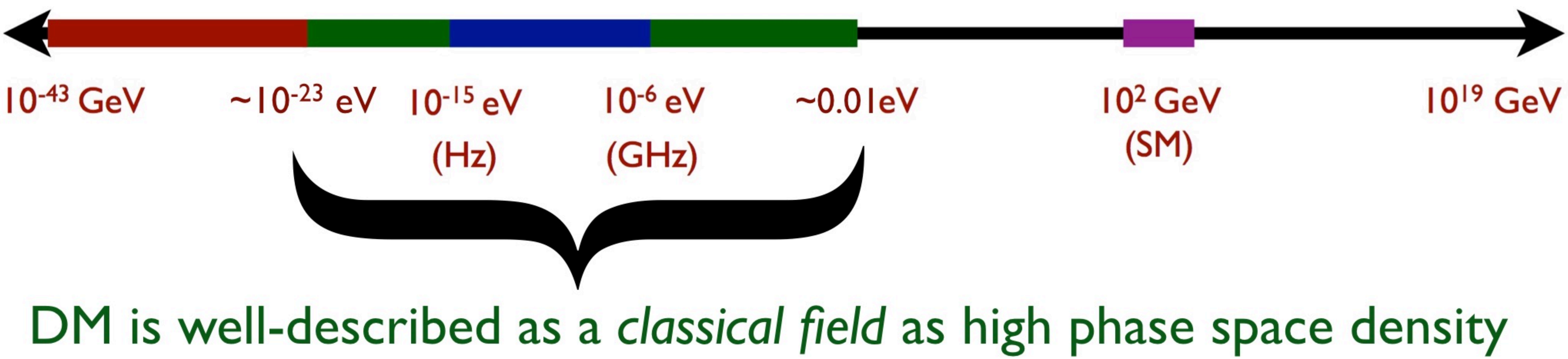
$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

Some comments on Experiments

3) There are great opportunities in ultra-high-precision experiments, eg, looking for very light (<< 1eV) dark matter or axions

The Dark Matter Landscape

(bosonic)



Some comments on Experiments

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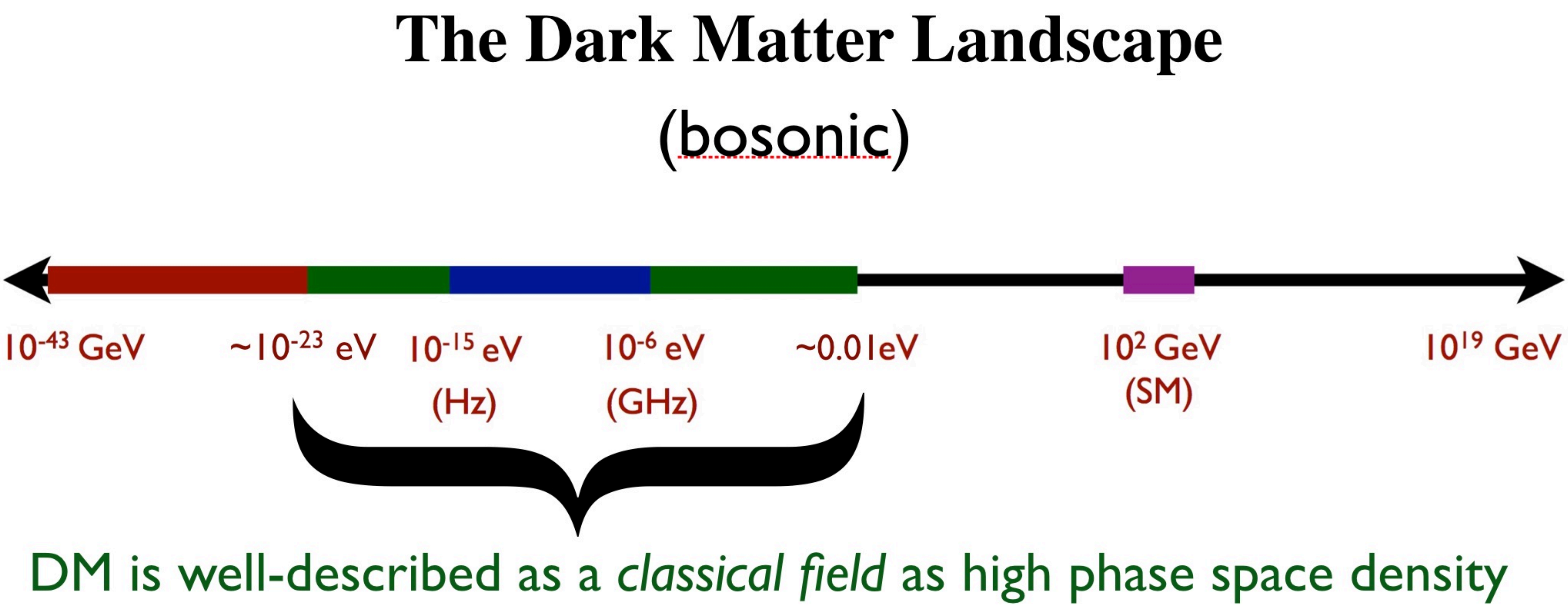


to hear about these possibilities come to Durham DM meeting in 2 weeks!

Some comments on Experiments

3) There are great opportunities in ultra-high-precision experiments, eg, looking for very light (<< 1eV) dark matter or axions

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

Electromagnetism

$\left(\frac{a}{f_a} F\tilde{F}\right)$

$\left(\sim \frac{a}{f_a}\vec{E}.\vec{B}\right)$

Nuclear Force

$\left(\frac{a}{f_a} G\tilde{G}\right)$

QCD Axion

Nuclear Spin

$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$

General Axions

Spin 1

Anomaly free Standard Model couplings

Nuclear Spin

$\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}N\right)$

Dipole moment

Electro-magnetism

$\left(\epsilon F' F\right)$

Kinetic Mixing

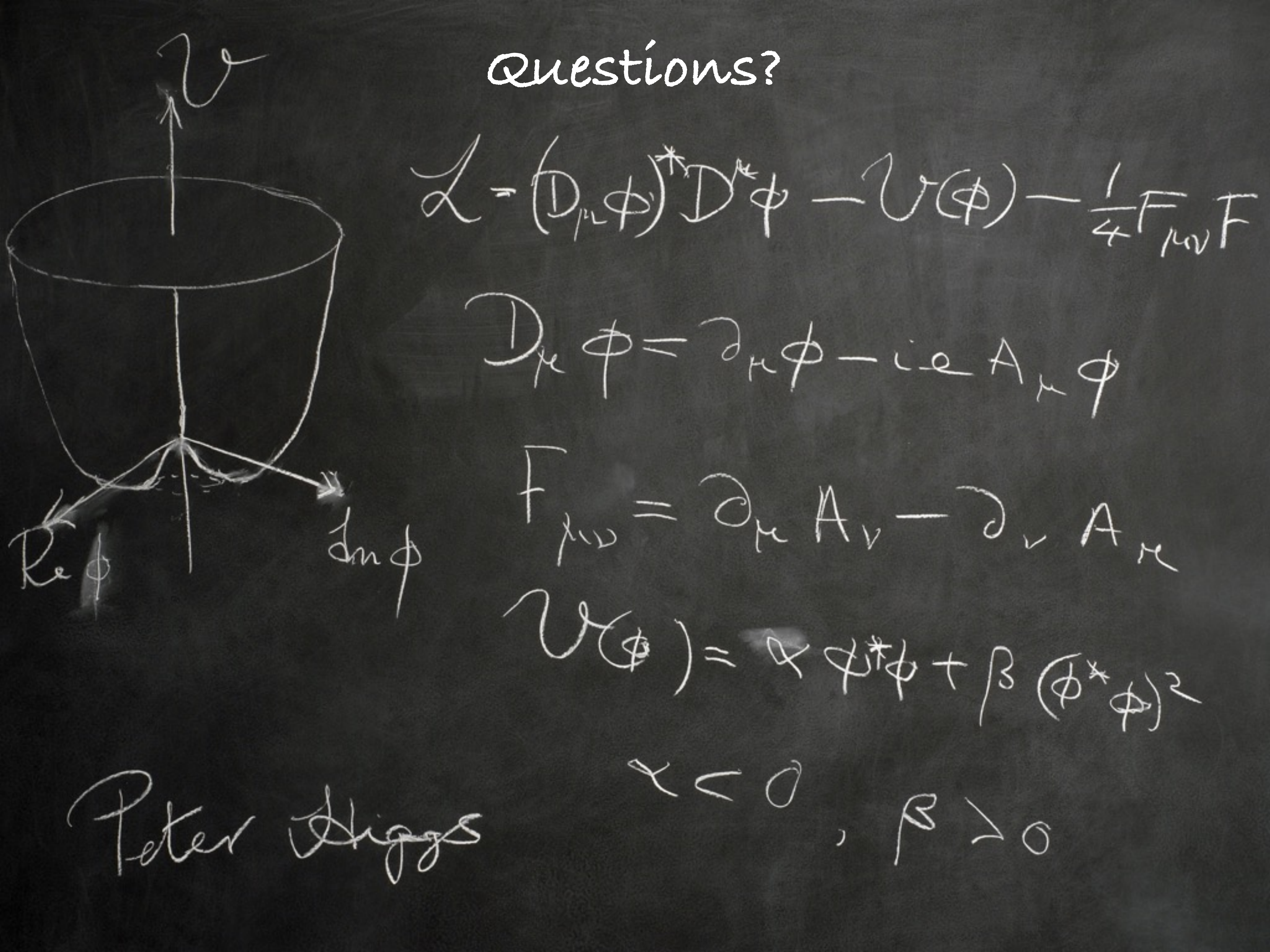
Nucleon Current

$\left(g A'_\mu J^\mu_{B-L}\right)$

B-L

if bosons (part of) DM then oscillating $\omega \simeq m_a + \delta\omega$

Questions?



V
Re φ
Im φ
$\mathcal{L} = (D_\mu\phi)^* D^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F$
$D_\mu\phi = \partial_\mu\phi - ieA_\mu\phi$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \alpha\phi^*\phi + \beta(\phi^*\phi)^2$
$\alpha < 0, \beta > 0$
Peter Higgs

back-up slides

Naturalness aka Dynamics

Partially tuned dynamics??

Deuteron Binding Energy!?

$$2 \text{ MeV} \ll \Lambda_{QCD} \simeq 200 \text{ MeV}$$

Often stated that involves <1% tune compared to natural nuclear scales (so justifying similar state of affairs for Weak Scale?)

Naturalness aka Dynamics

~~Partially tuned~~ dynamics??

Deuteron Binding Energy!?

$$2\ \mathrm{MeV} \ll \Lambda_{QCD} \simeq 200\ \mathrm{MeV}$$

cf. saturated nuclear binding energy of 8 MeV per nucleon in whole range of larger nuclei

~~Often stated that involves <1% tune compared to natural nuclear scales (so justifying similar state of affairs for Weak Scale?)~~

$$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$$

$$\approx 2\ \mathrm{MeV}$$

fully natural

(full argument developed by Arvanitaki, Dimopoulos, & Villadoro)

Higgs Enigma

have rest of usual SM terms

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

$$- \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.} \right]$$

$$\widetilde{H}_j = \epsilon_{jk} H^{\dagger\, k}$$

LHC now measuring these Yukawa couplings for the first time

(this will be important)

Higgs Enigma

In addition now measuring or constraining the couplings of these 11 further terms in Lagrangian

$2: H^6$		$3: H^4 D^2$		$4: X^2 H^2$	
Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
		Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
				Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
				$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
				Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
				$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
				Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
				$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

Higgs Enigma

Not done yet as also have these further 19 terms involving leptons or quarks

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Higgs Enigma

Also have strong constraints on couplings of many of these non-Higgs terms

(this will also be important...)

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

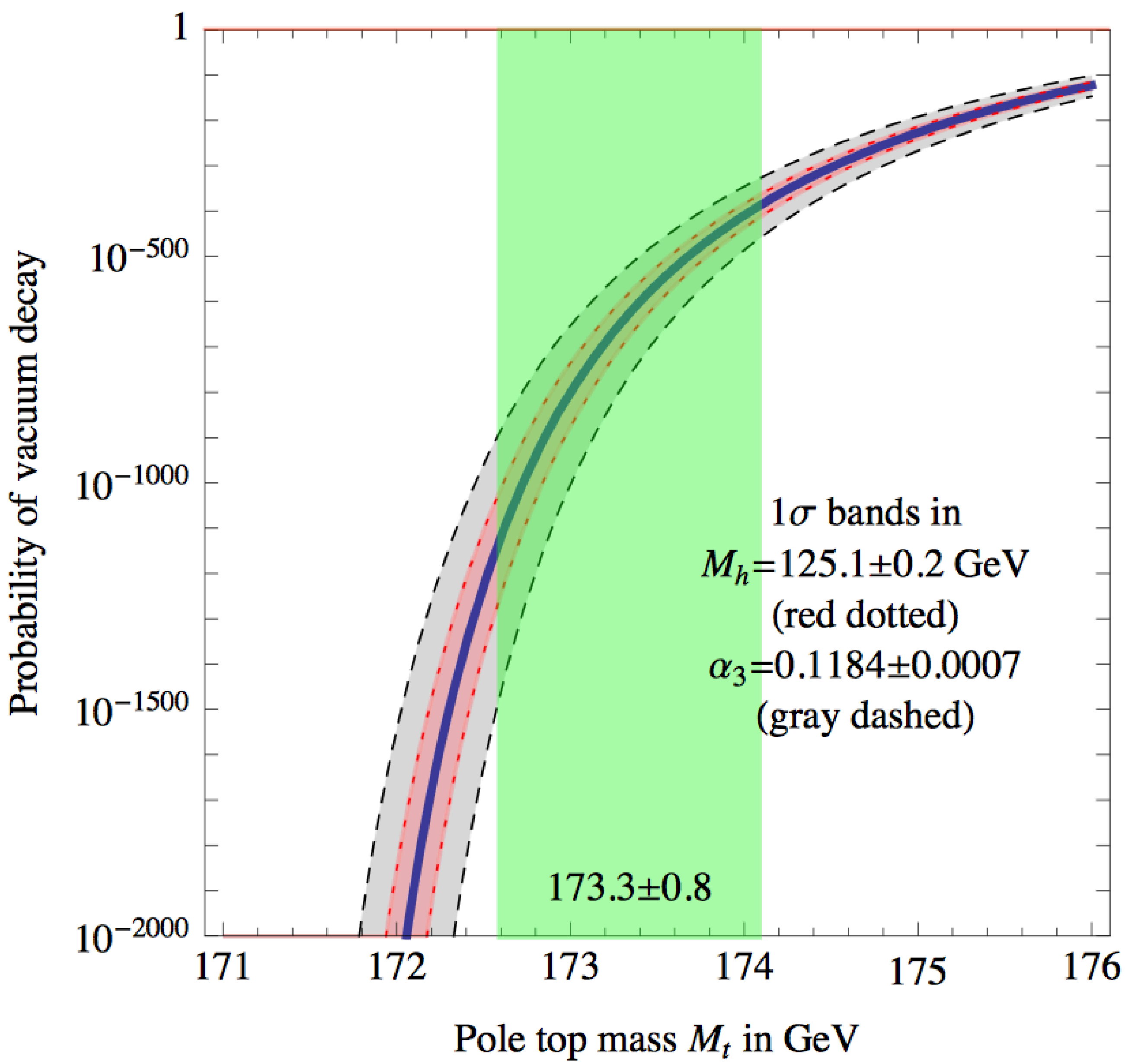
$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

Stability of SM all the way up?

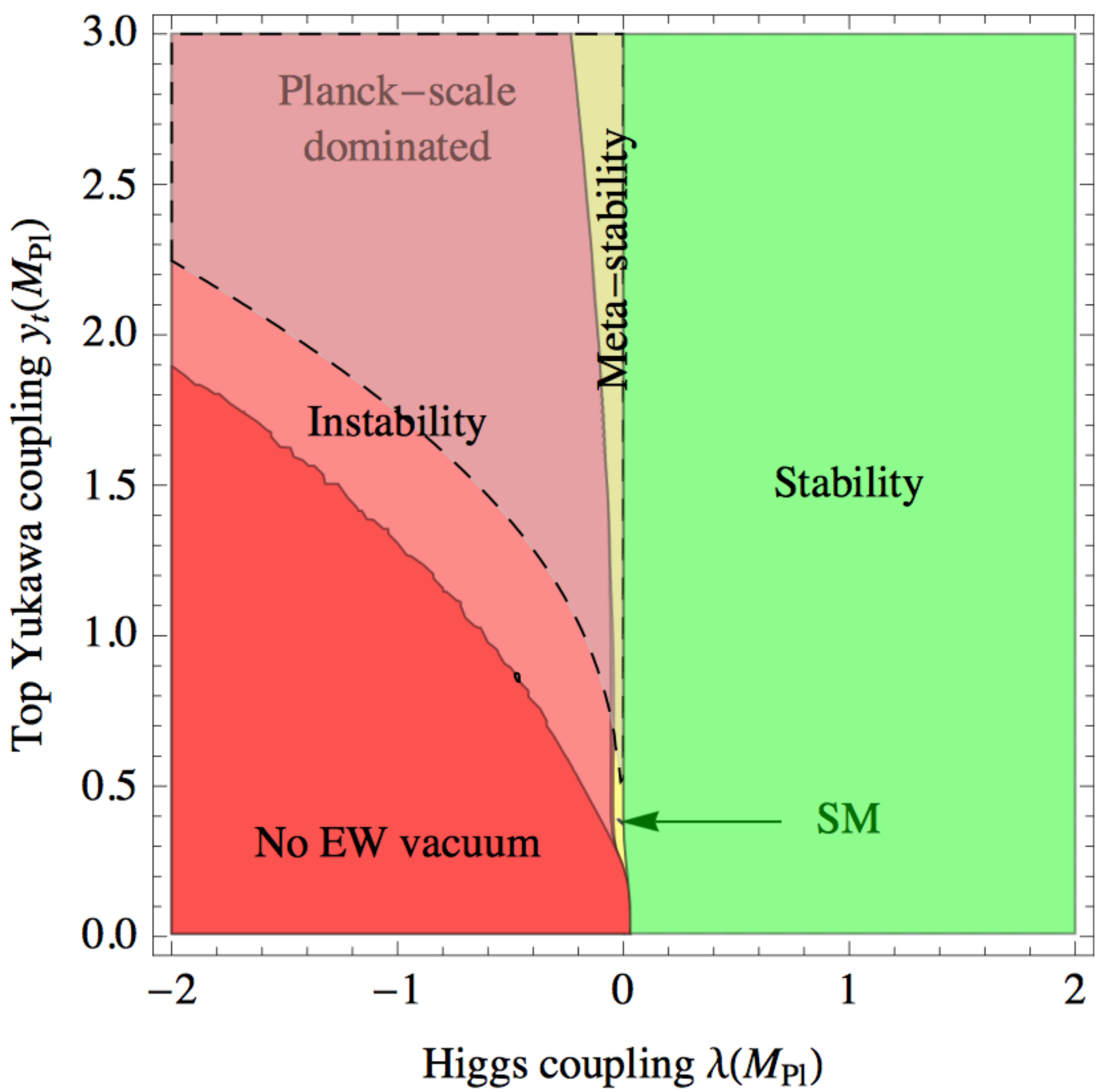
How metastable?

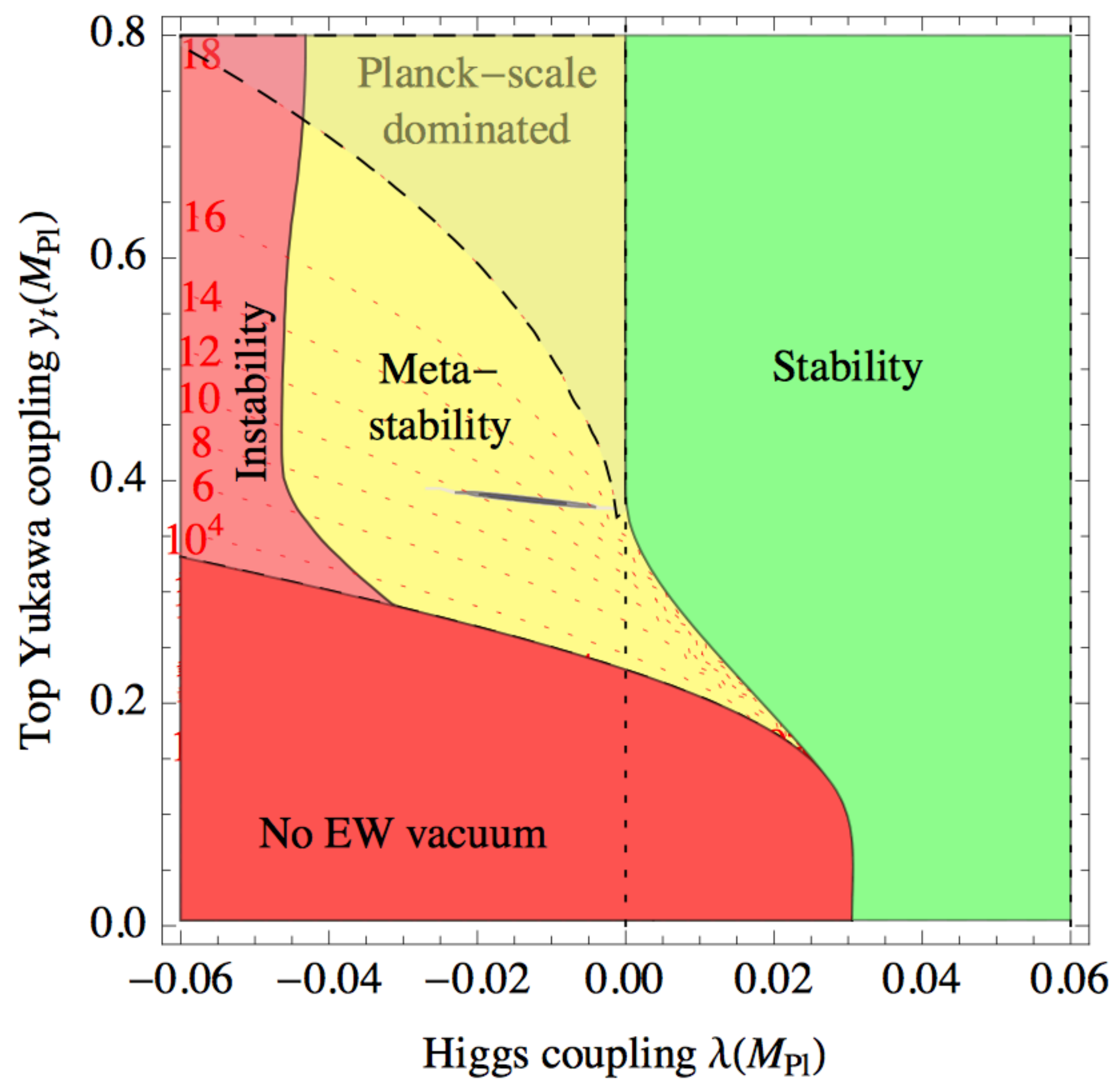


Stability of SM all the way up?

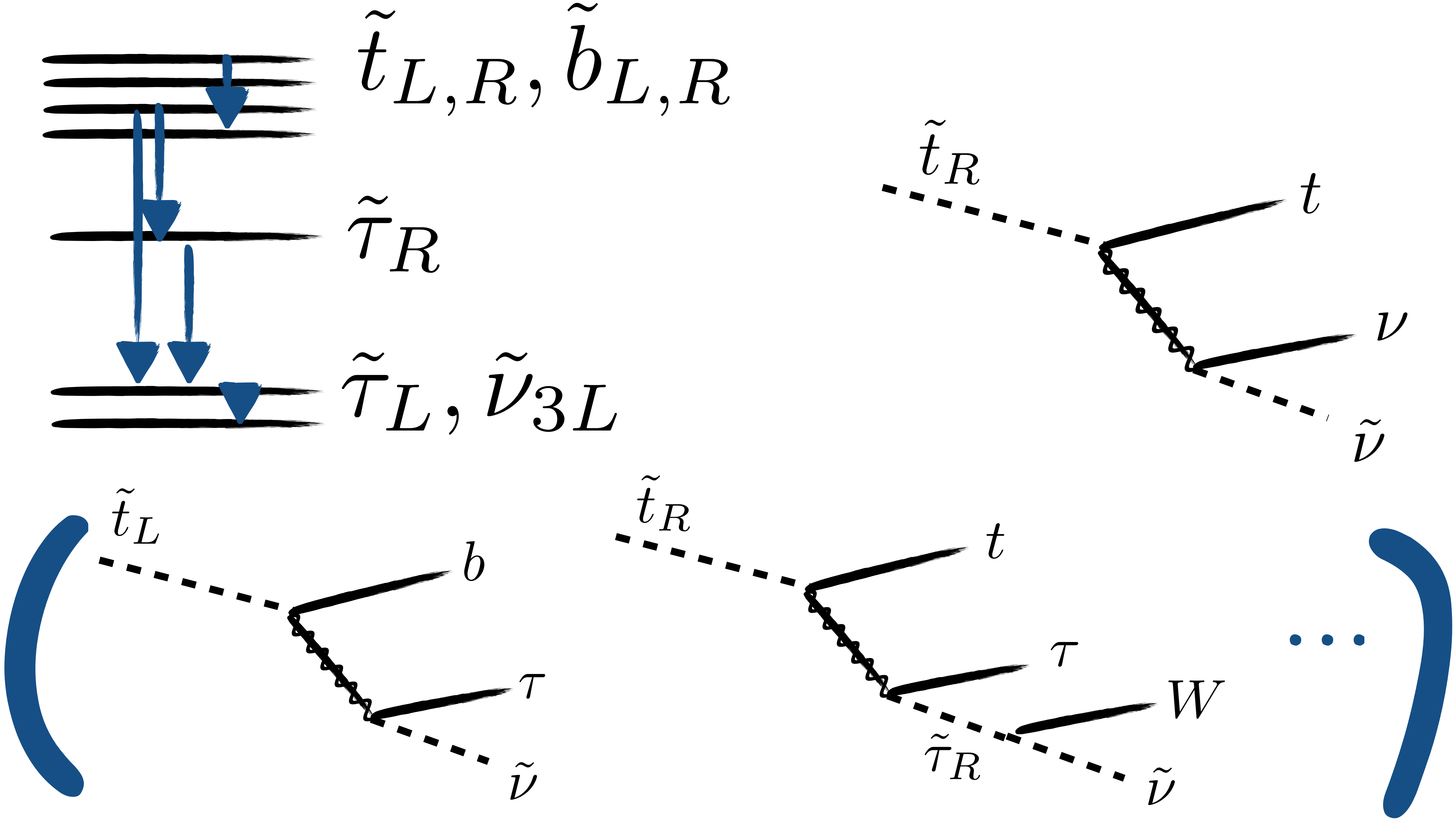
Sher, Giudice, Strumia,…

An intriguing feature of measured values of Higgs coupling and top Yukawa extrapolated to M_{pl} assuming SM all the way up:

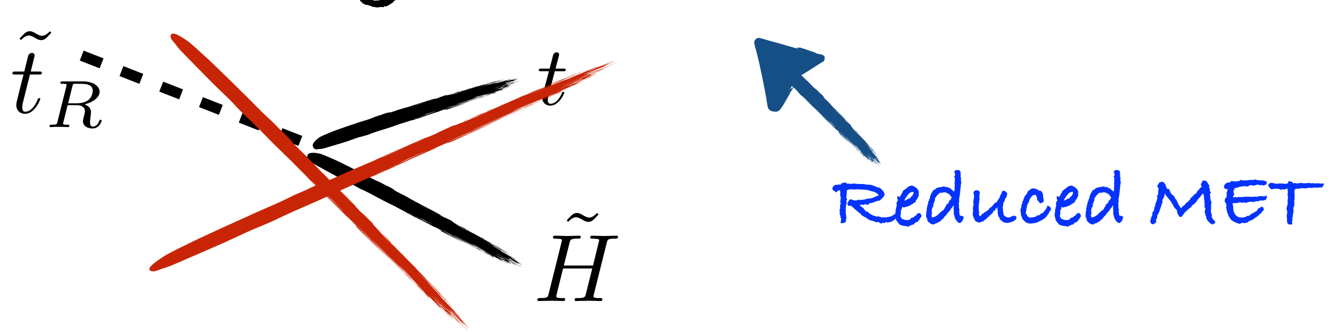




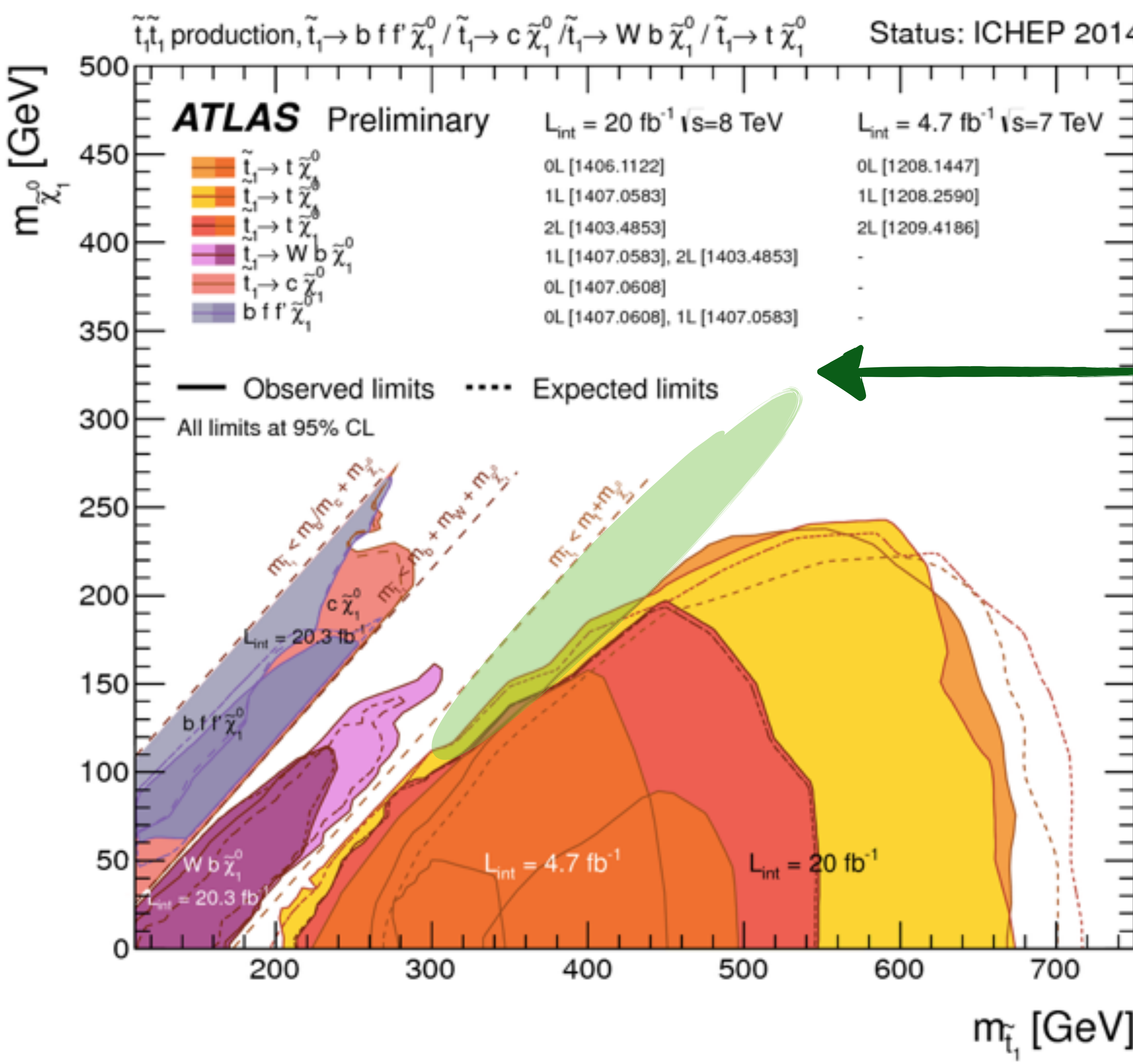
$\tilde{\nu}_3$ LSP: New Signatures of Naturalness?



3-body Kinematics, taus + b's final states, ...



Auto-Concealment of SUSY ?



susy theories can dynamically sit in this region

need precision understanding of SM to pull signal from background