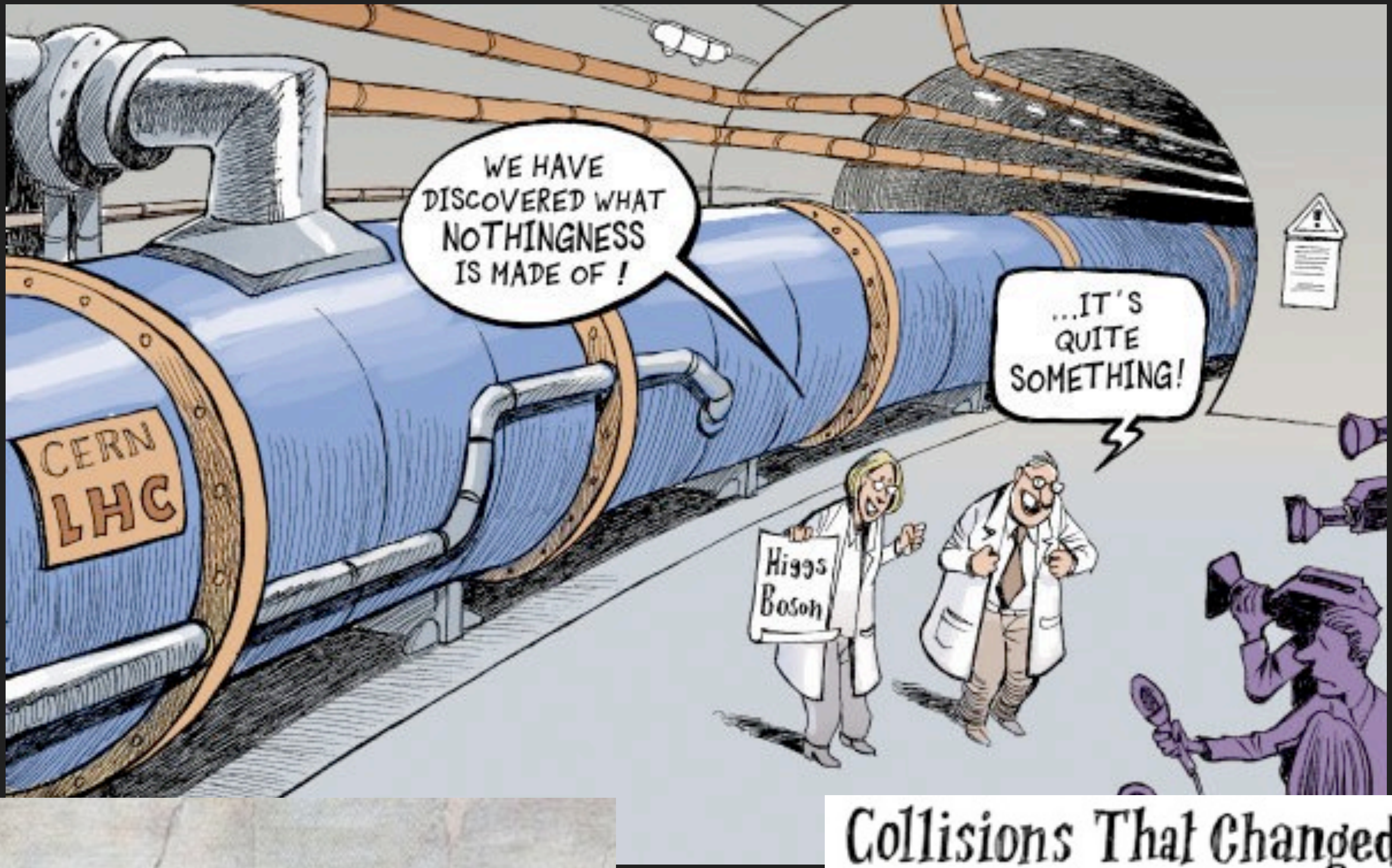
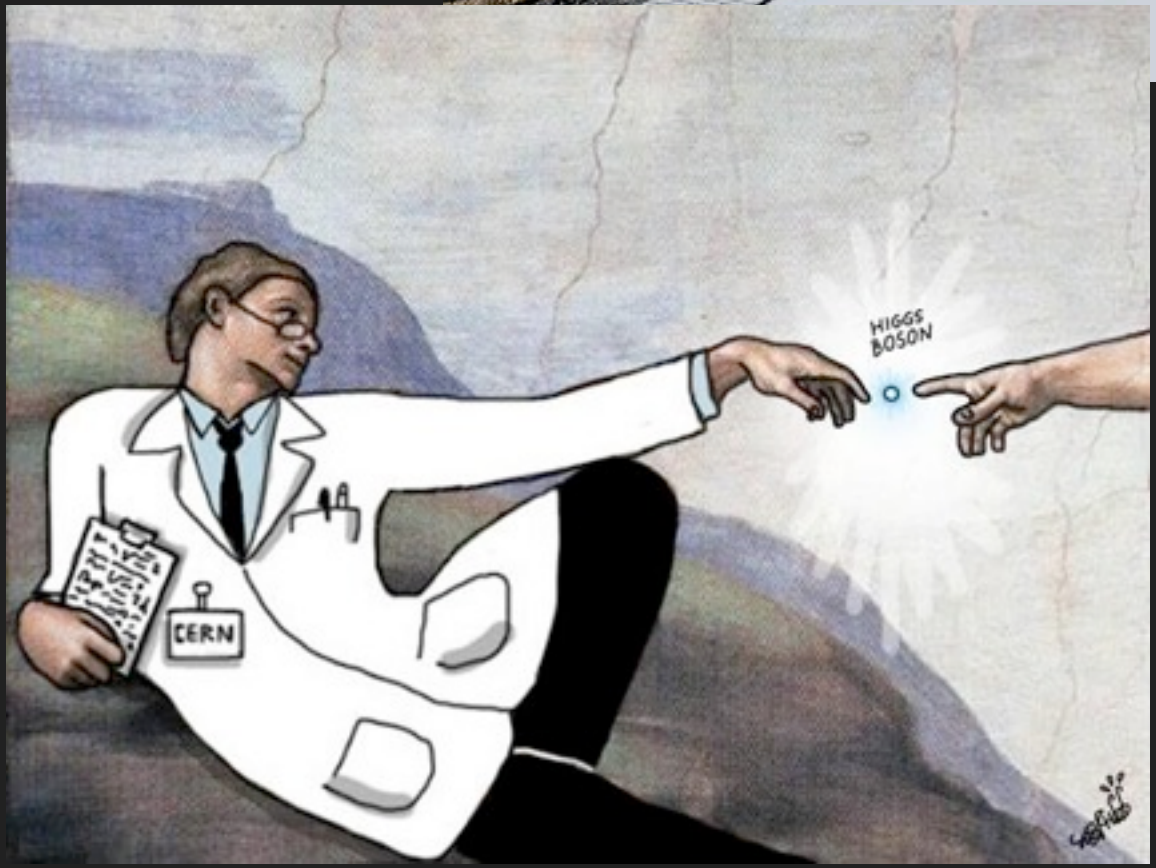
So a Higgs Boson has Been Discovered ... Now What?

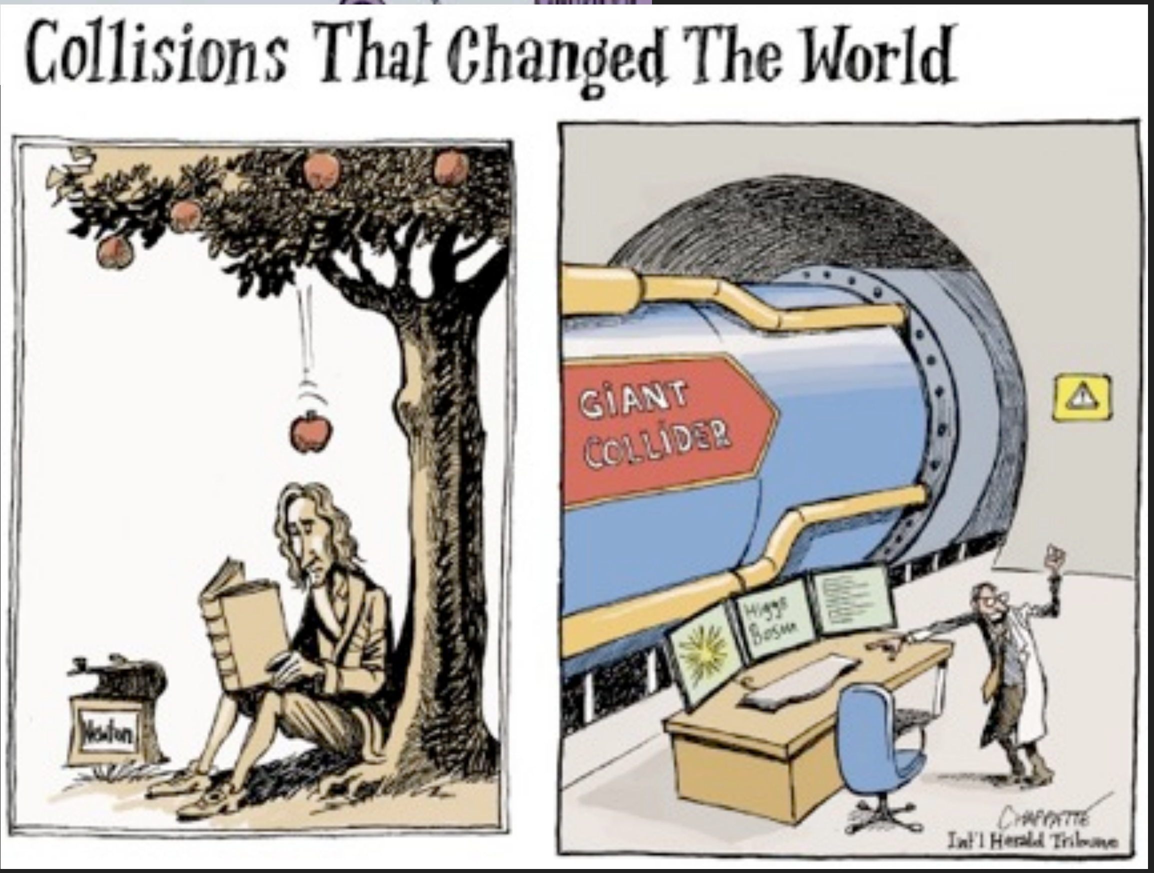
R. Sekhar Chivukula
Michigan State University
July 16, 2013

CTEQ

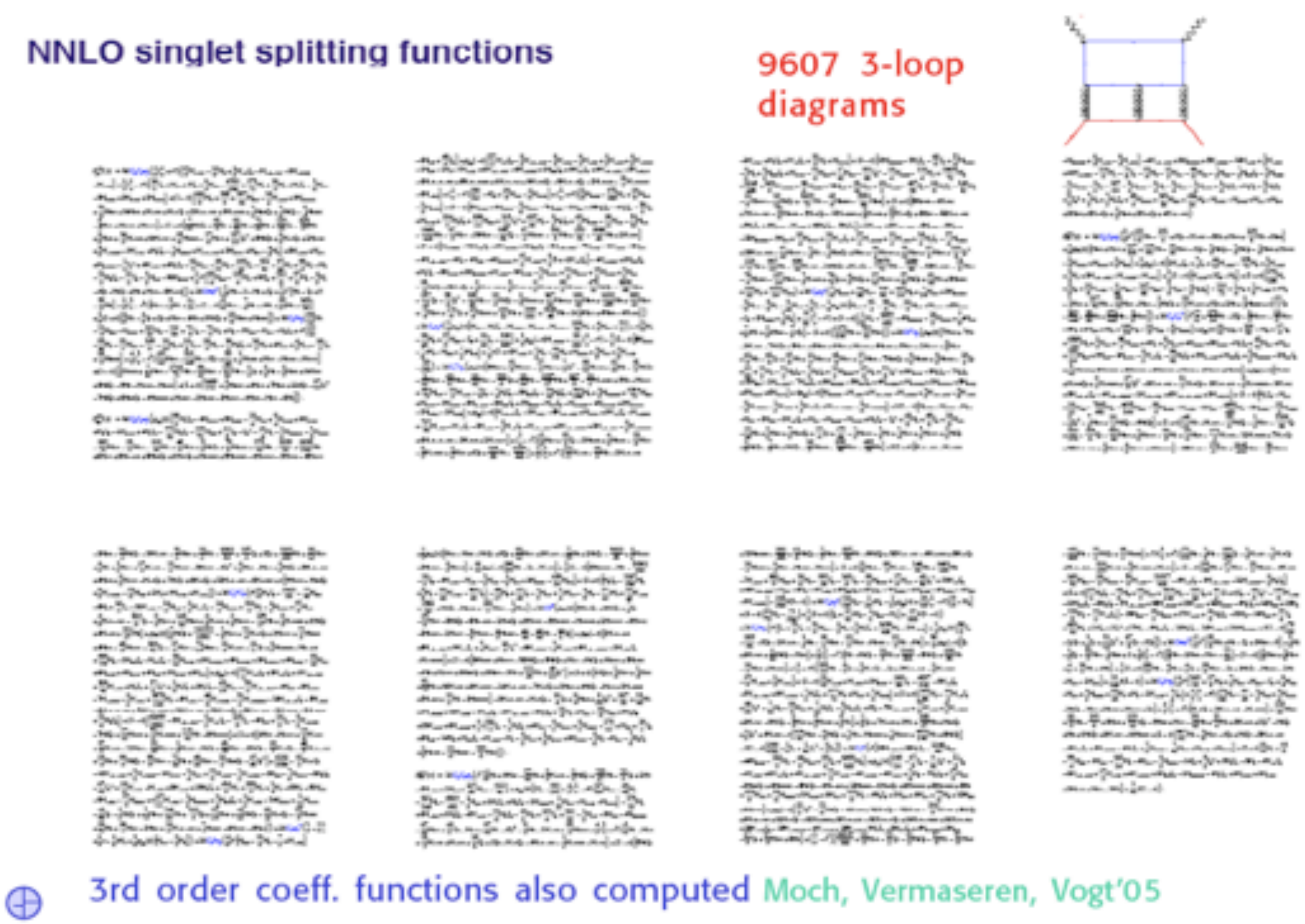
In Cartoons


WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN LHC
Higgs Boson


HIGGS BOSON
CERN


Collisions That Changed The World
Newton
GIANT COLLIDER
CHAPPATTE
Int'l Herald Tribune

What I will try to avoid:



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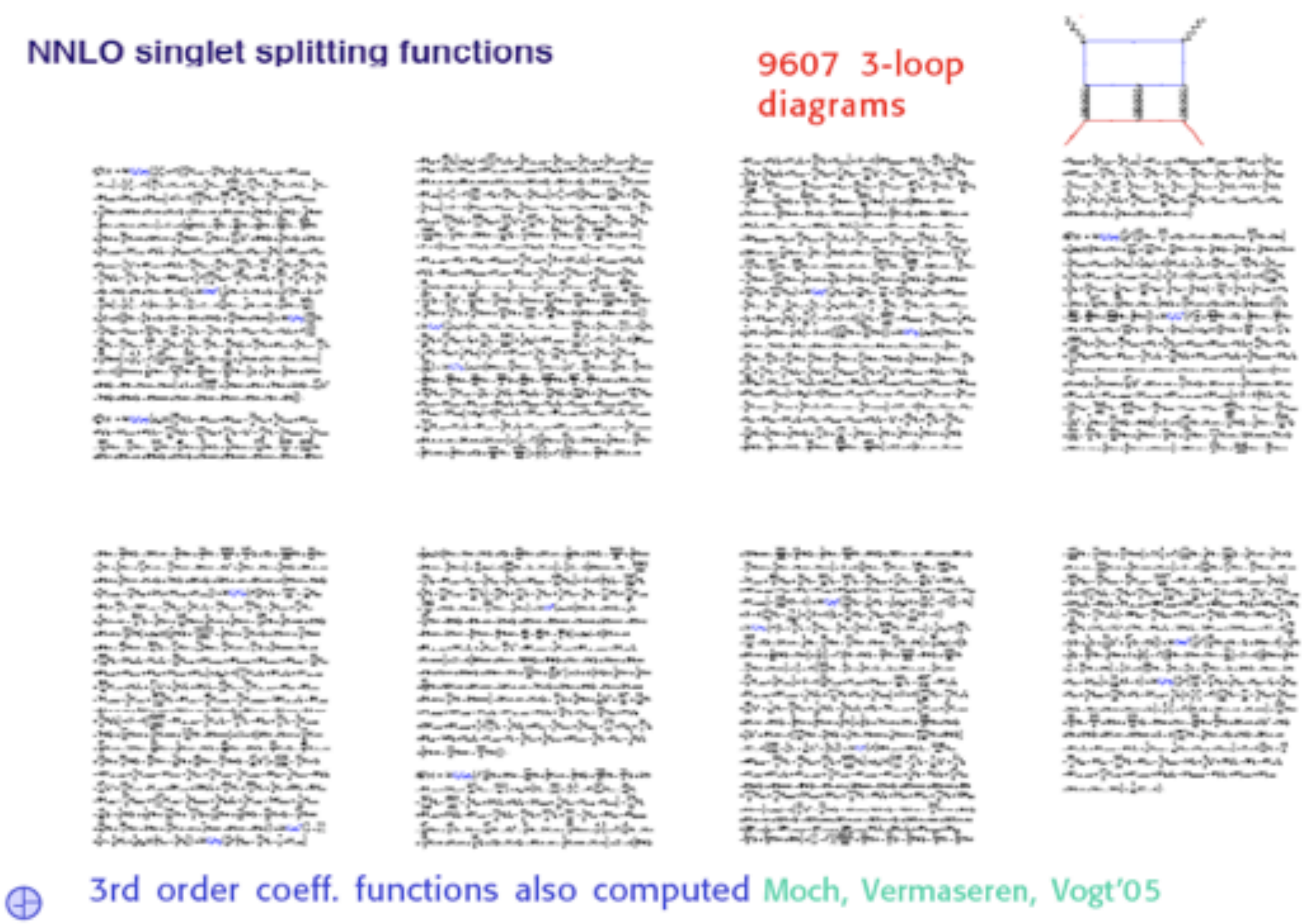
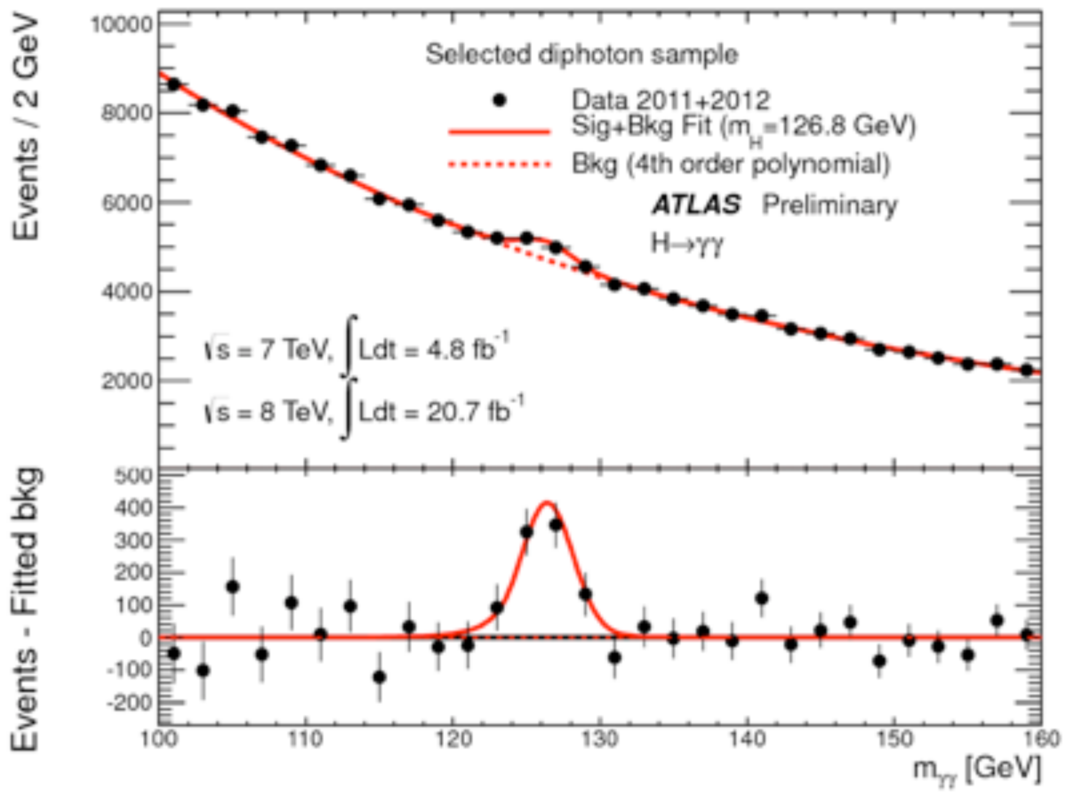
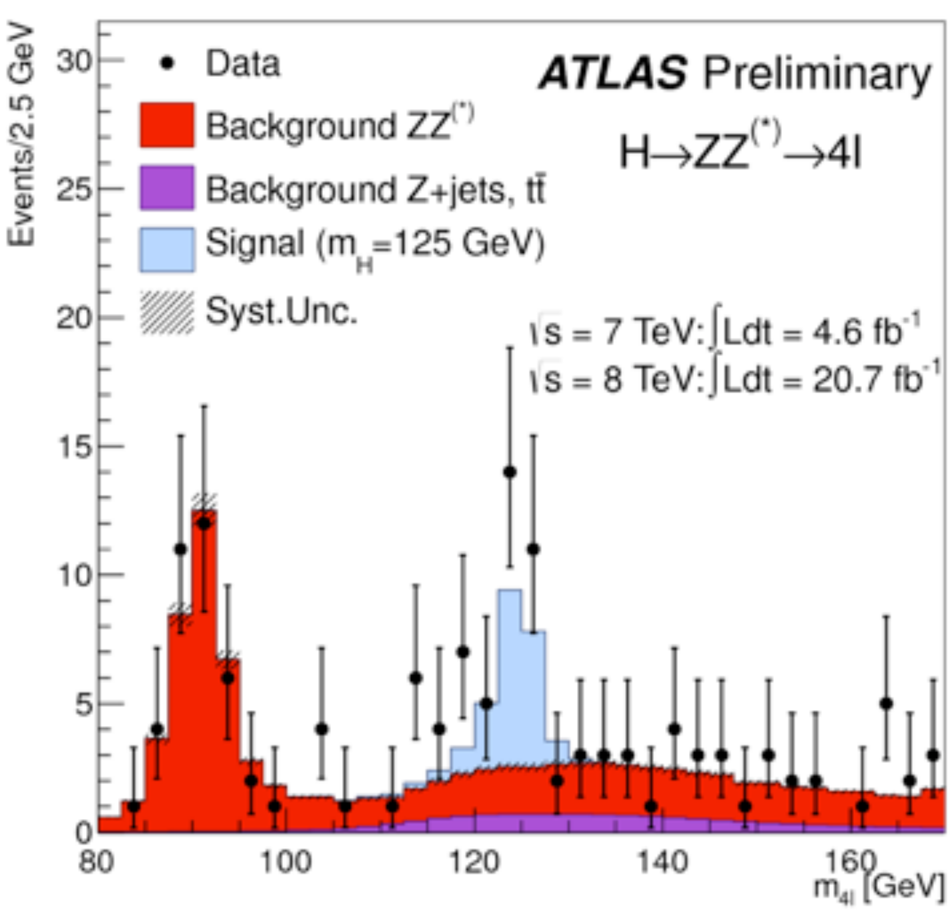


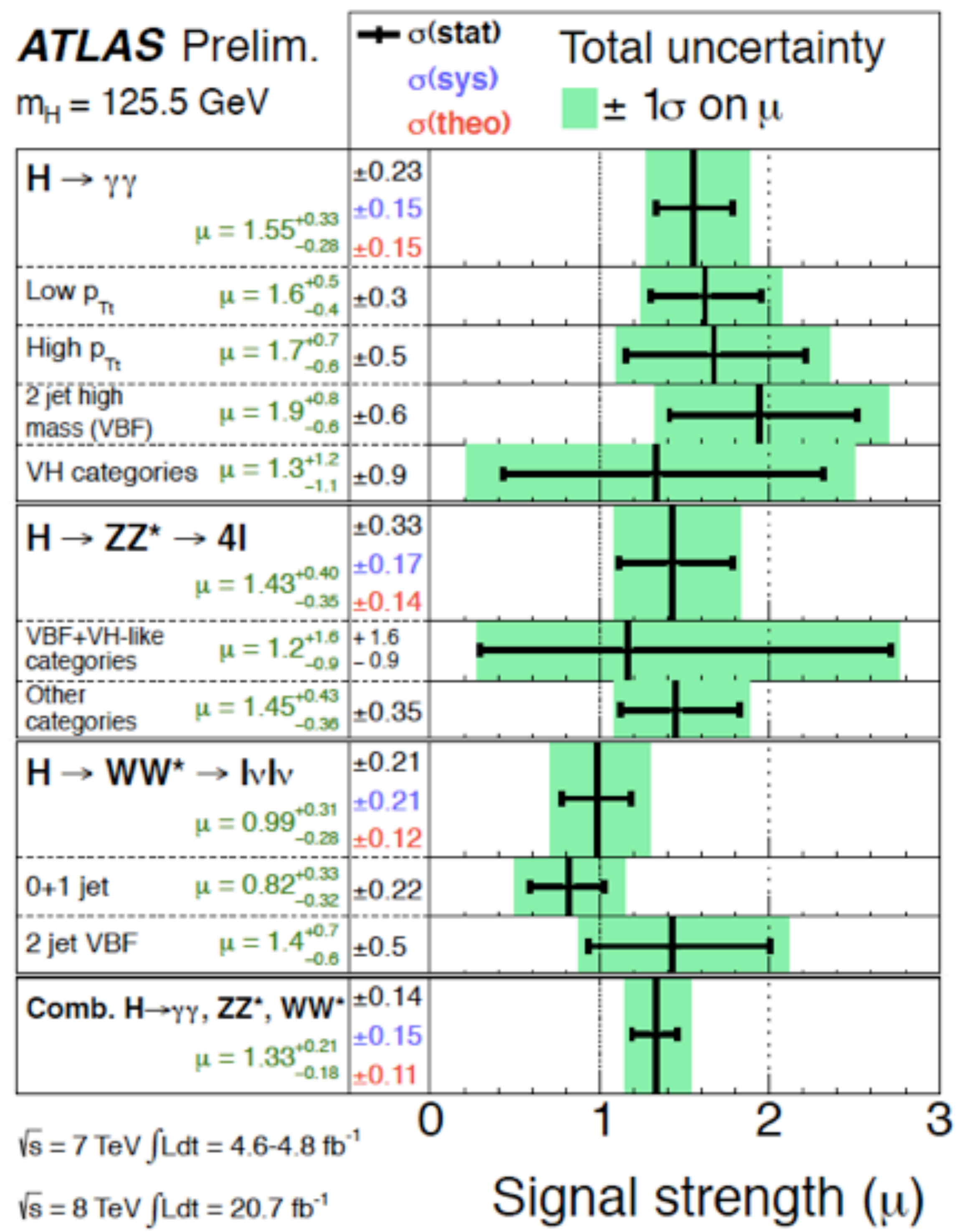
Your questions are welcome and encouraged at any time!!

A Higgs Boson

ATLAS

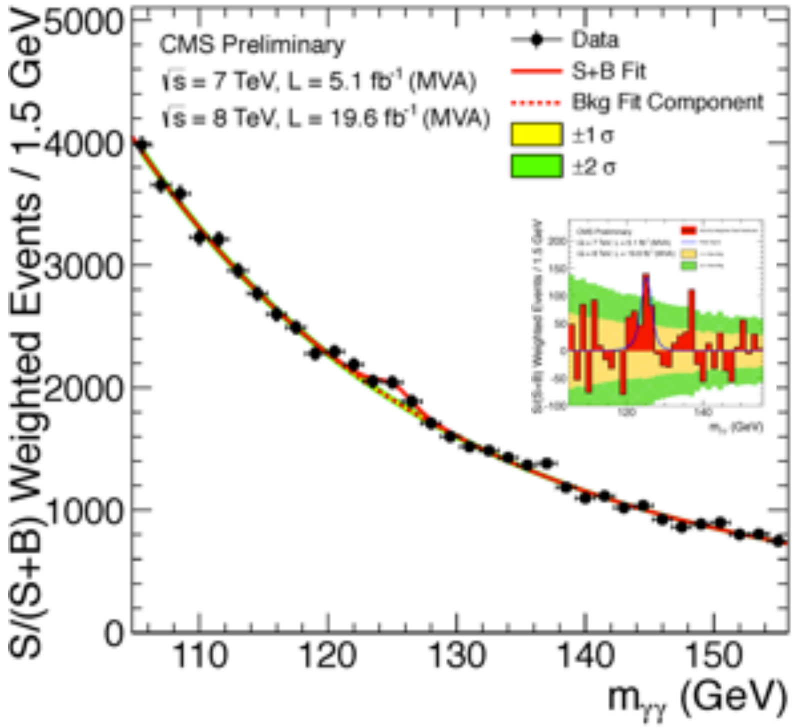


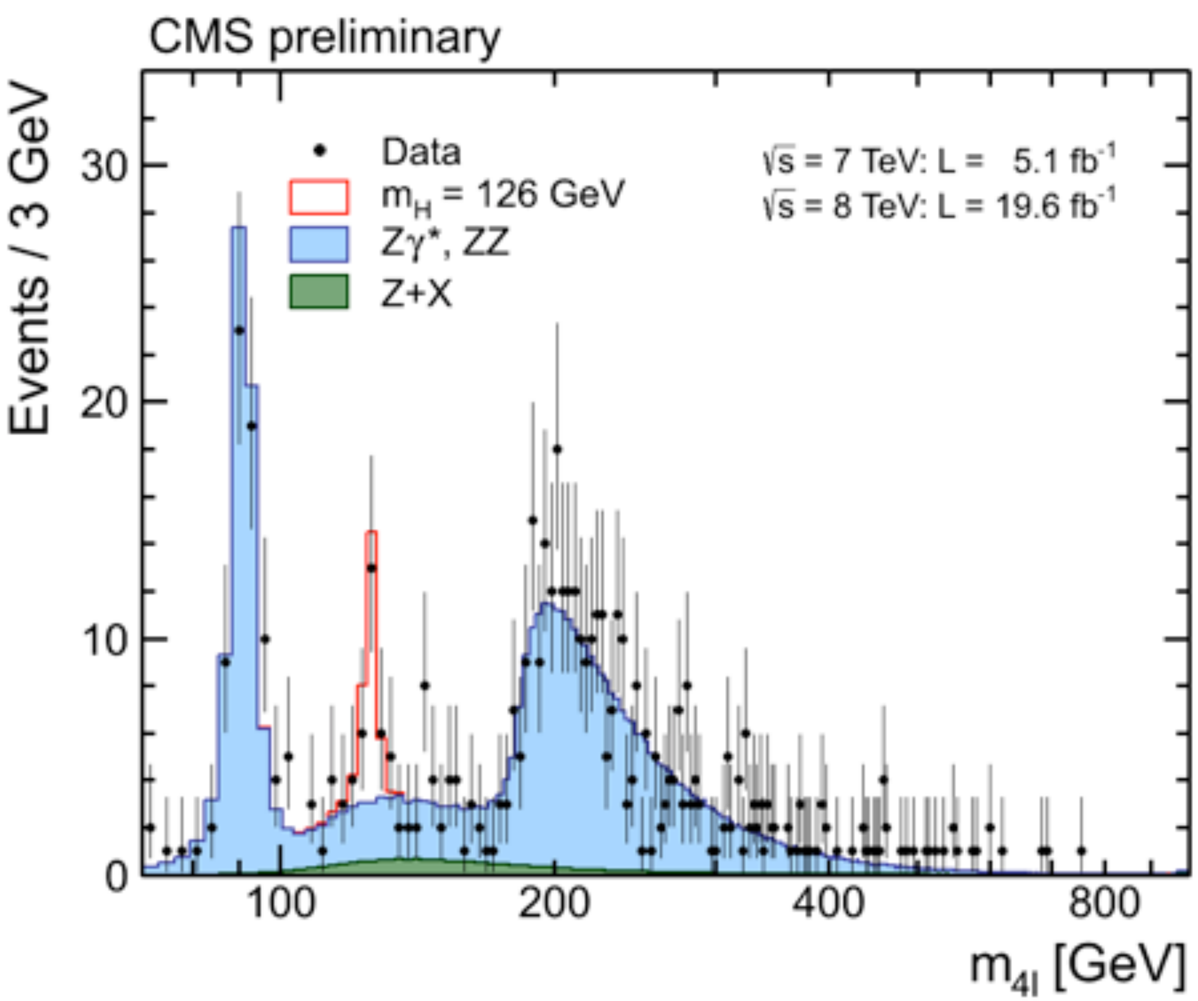


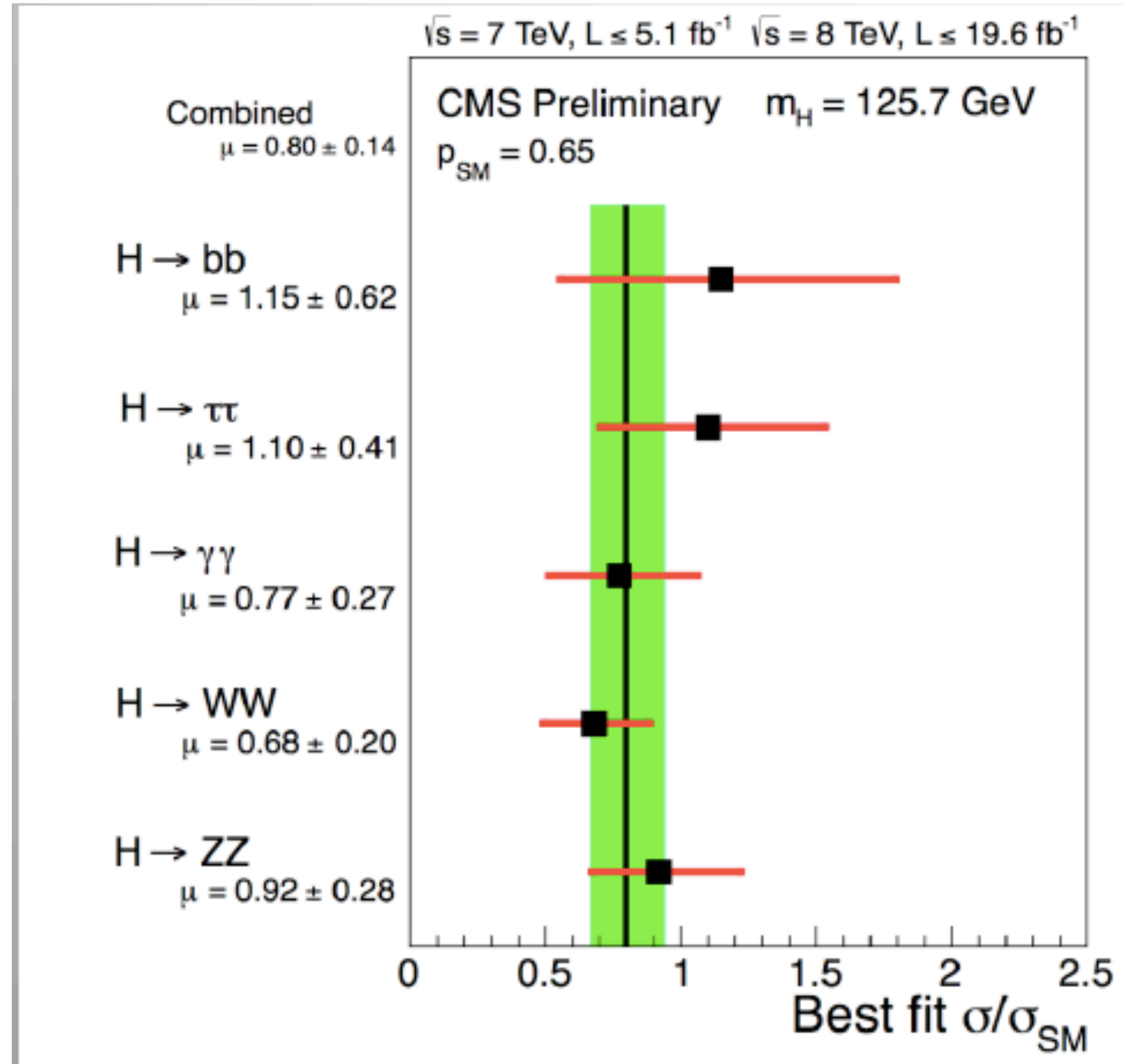


Moriond EW 2013, LP2013
ATLAS-CONF-2013-034,012,013

CMS







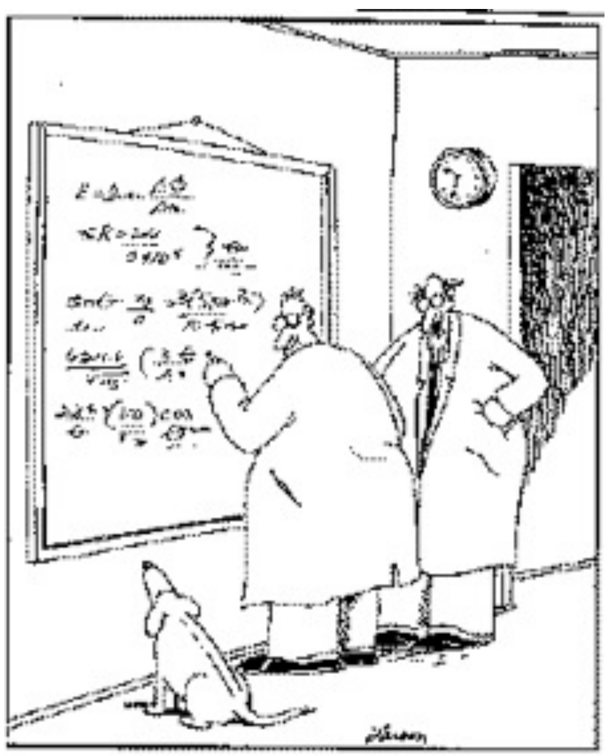
p-value= 0.65 w.r.t. $\mu=1$

Moriond EW 2013, LP2013
CMS-PAS-HIG-13-001,2
CMS-PAS-HIG-12-045

What is Our Theoretical Framework?

Effective Field Theory

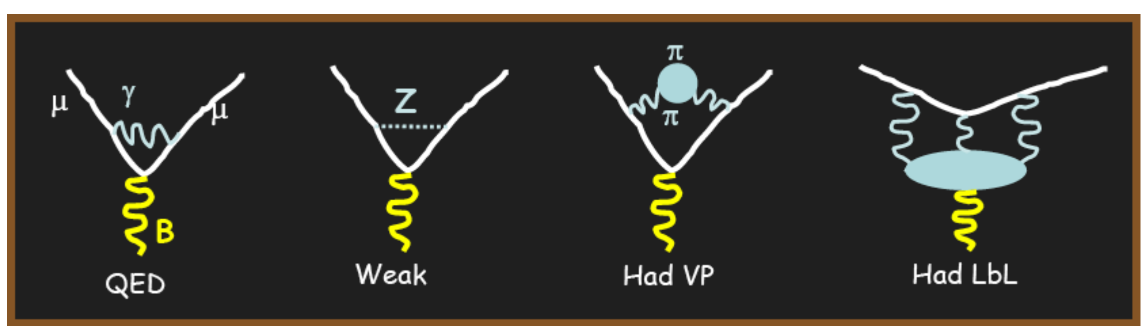
Why do we believe in (effective) field theory?



"They act so cute when they try to understand Quantum Field Theory"

QFT Reconciles QM with Relativity

A local, Lorentz-invariant, Hermitian, QFT with a finite number of fields yields a unitary, CPT-invariant, S-matrix satisfying cluster decomposition



à la Landau (e.g. superconductivity): the converse is also true!

"Any" S-matrix is derivable from a QFT

Example:
A Scalar Doublet...

Consider theory valid below UV cutoff Λ:

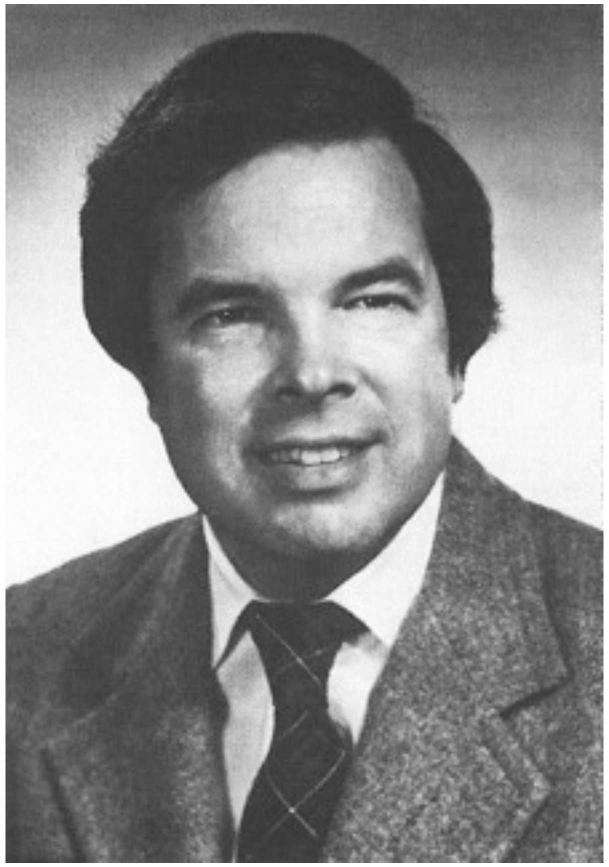
$$\mathcal{L}_\Lambda = \quad D^\mu \phi^\dagger D_\mu \phi + m^2(\Lambda)\phi^\dagger\phi + \frac{\lambda(\Lambda)}{4}(\phi^\dagger\phi)^2 + \frac{\kappa(\Lambda)}{36\Lambda^2}(\phi^\dagger\phi)^3 + \ldots$$

(Note "scaling dimension" of operators)

- **That which is not forbidden is required**: includes all interactions consistent with **space-time, global, and gauge symmetries**.

Wilsonian Renormalization Group

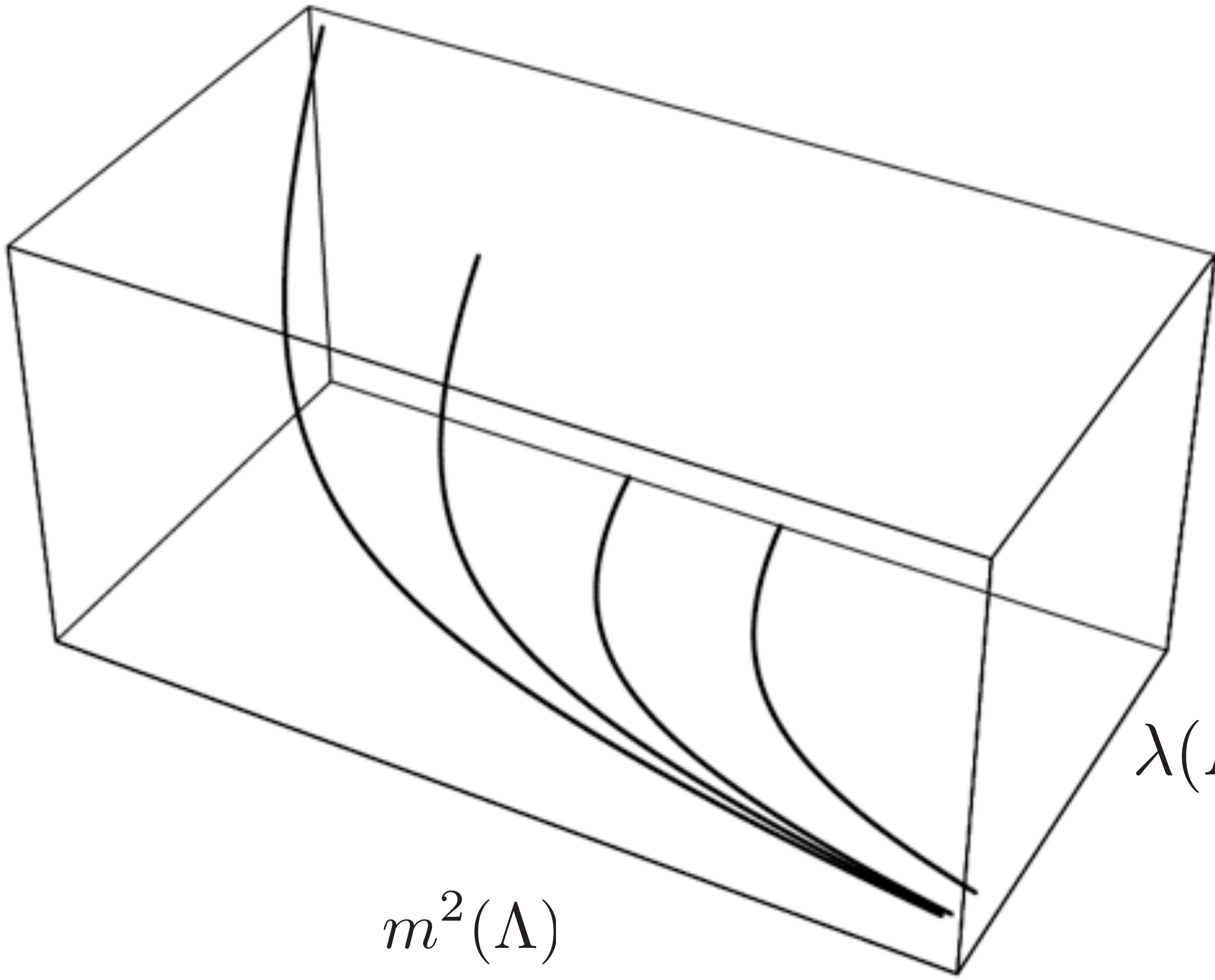
Integrate out states with $\Lambda' < k < \Lambda$:

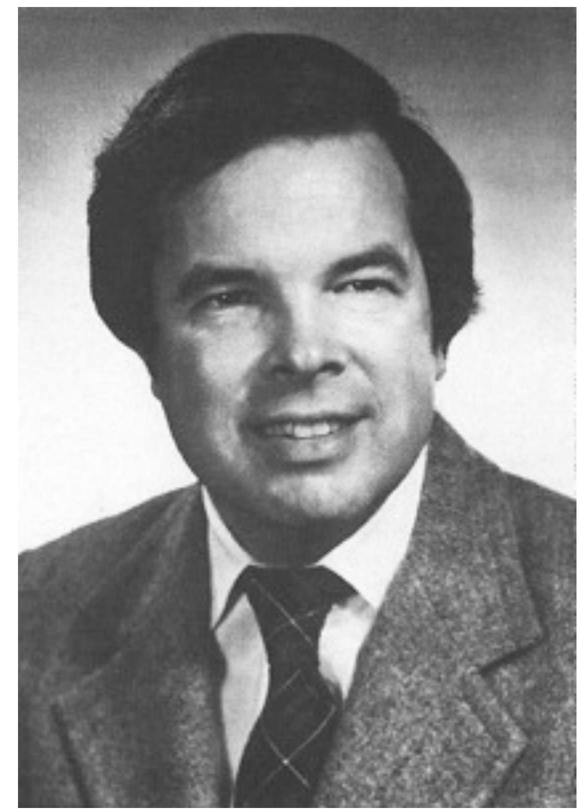


$$\begin{aligned} \mathcal{L}_\Lambda &\Rightarrow \mathcal{L}_{\Lambda'} \\ m^2(\Lambda) &\rightarrow m^2(\Lambda') \\ \lambda(\Lambda) &\rightarrow \lambda(\Lambda') \\ \kappa(\Lambda) &\rightarrow \kappa(\Lambda') \end{aligned}$$

Consider evolution of couplings in the IR-limit....

Wilsonian Renormalization Group



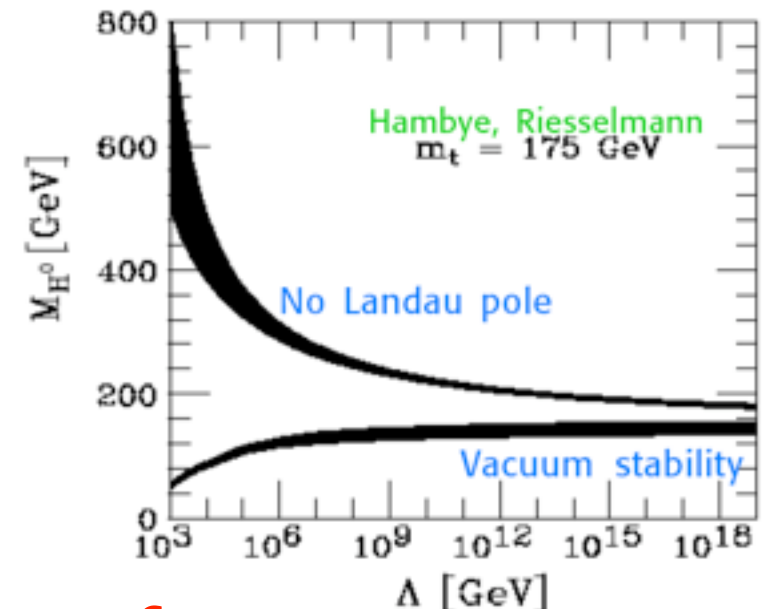


$$D^\mu\phi^\dagger D_\mu\phi + m^2(\Lambda)\phi^\dagger\phi + \frac{\lambda(\Lambda)}{4}(\phi^\dagger\phi)^2$$
$$+\frac{\kappa(\Lambda)}{36\Lambda^2}(\phi^\dagger\phi)^3 + \ldots$$

- $\kappa \to 0$ — "Renormalizability", if $m_H \ll \Lambda$.
- $m^2 \to \infty$ — Naturalness/Hierarchy Problem:
$$\frac{\Delta m^2(\Lambda)}{m^2(\Lambda)} \propto \frac{v^2}{\Lambda^2}$$
- $\lambda \to 0$ — Triviality ...

QFT *Reinterpreted*

- Lagrangian and S-matrix are expansions in p^2/Λ^2 - at any order, only a finite number of operators contribute.
- “Renormalizable” theories are a special case, with $\Lambda \to \infty$: S-matrix “exactly” calculable in terms of a few parameters.



- The Hierarchy problem is not a problem of principle, it is matter of (good) taste.
- Triviality and vacuum stability, on the other hand...

Elastic (2-body) Unitarity

$$S^\dagger S = \mathcal{I} \quad \Rightarrow \quad |s_l|^2 = 1$$

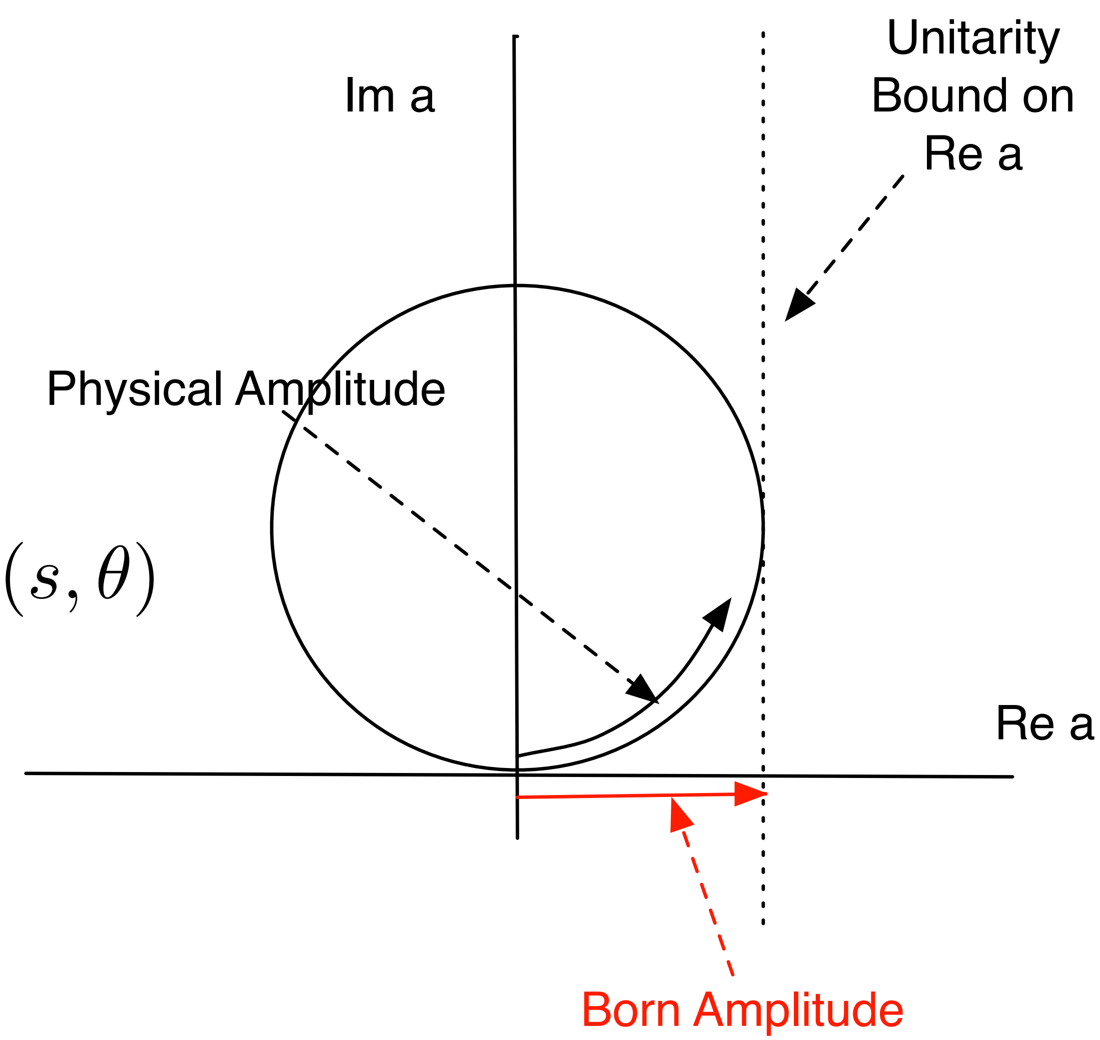
$$s_l = 1 + 2ia_l \quad \Rightarrow \quad \mathrm{Im}(a_l) = |a_l|^2$$

$$a_l = e^{i\delta_l} \sin\delta_l$$

$$a_l = \frac{1}{32(2)\pi}\left[\frac{4k^2}{s}\right]^{1/2} \int_{-1}^{+1} d\cos\theta \, P_l(\theta) \mathcal{M}(s,\theta)$$

Identical Particle Factor

Feynman Amplitude



These formulae apply to the elastic scattering of pairs of particles of fixed helicity

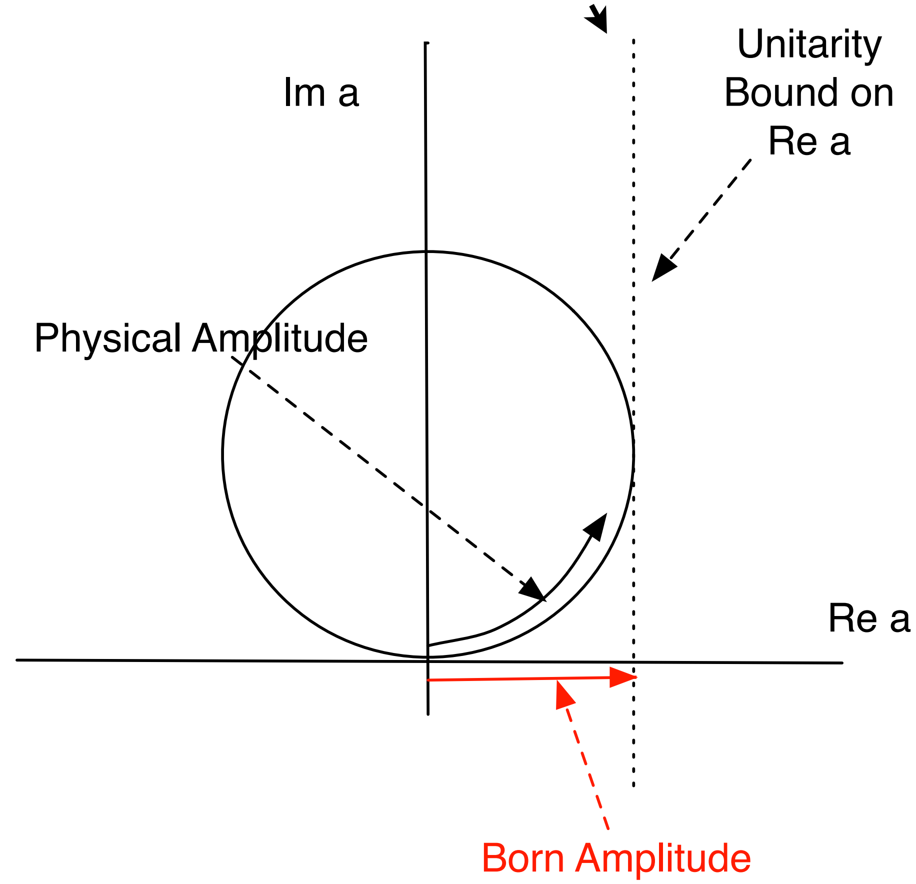
Jacob and Wick, 1959

Limits of an Effective Theory

$$\mathcal{L} = \sum_i \frac{\kappa_i(\Lambda)\mathcal{O}_i}{\Lambda^{d_i-4}}$$ with $d_i>4$ leads to $$\mathcal{M} \propto \frac{\kappa_i(\Lambda)p^{d_i-4}}{\Lambda^{d_i-4}}$$

Amplitude "violates" unitarity at scale M, and the (perturbative) effective theory breaks down

M is the scale at which the description of the theory changes, e.g. the W instead of Fermi Theory



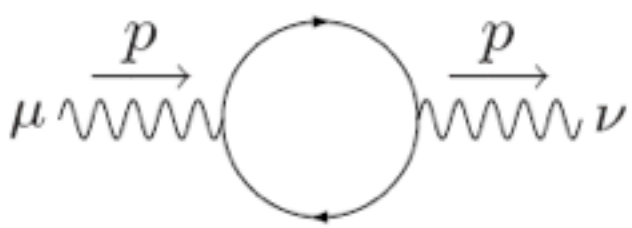
Gauge Invariance?

- The only consistent S-matrix for a spin-1 *massless* particle arises when it couples to a conserved current - e.g., like a gauge-boson! (Weinberg's theorem)
- Corollary: Given a spin-1 boson of mass m, the only theory consistent up to scale M *is*, in the limit m/M→0, a gauge theory.
- LEP I/II and Tevatron: SU(2) x U(1) gauge-invariance good to ~ few TeV! e.g.

$$\frac{(\varphi^\dagger D^\mu \varphi)^2}{M^2} \to \alpha T \text{ or } \Delta\rho$$

The Higgs *Mechanism*

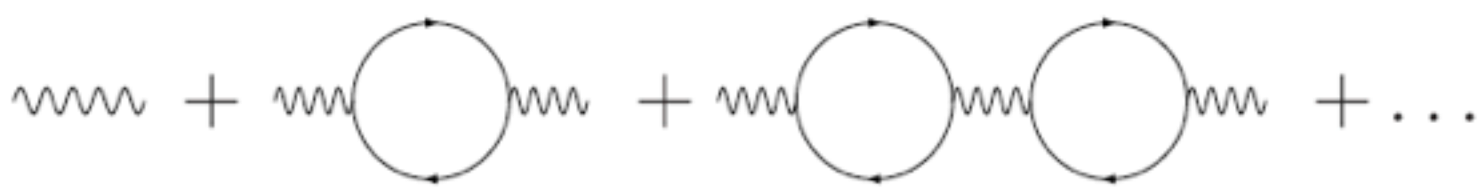
The polarization tensor $\Pi_{\mu\nu}(p)$ is defined as:



$$i\,\Pi_{\mu\nu}(p) \equiv i(p_\mu p_\nu - p^2 g_{\mu\nu})\Pi(p^2)$$

where the form of $\Pi_{\mu\nu}(p)$ is governed by gauge invariance, i.e. it satisfies $p^\mu \Pi_{\mu\nu}(p) = p^\nu \Pi_{\mu\nu}(p) = 0$.

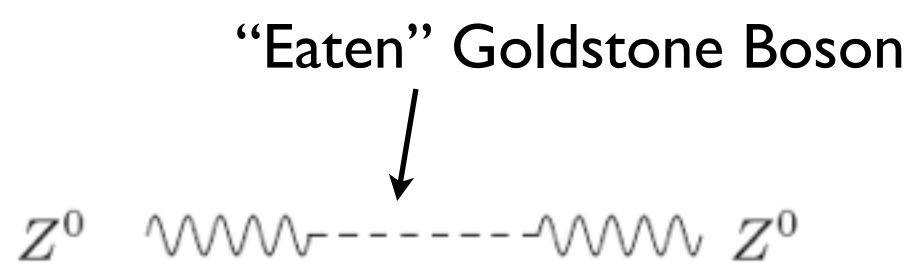
The renormalized propagator is the sum of a geometric series



$$= \frac{-i(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2})}{p^2[1+\Pi(p^2)]}$$

The pole at $p^2 = 0$ is shifted to a non-zero value if:

$$\Pi(p^2) \underset{p^2 \to 0}{\simeq} \frac{-g^2 v^2}{p^2}\,.$$



Then $p^2[1 + \Pi(p^2)] = p^2 - g^2 v^2$, yielding a gauge boson mass of gv.

Haber

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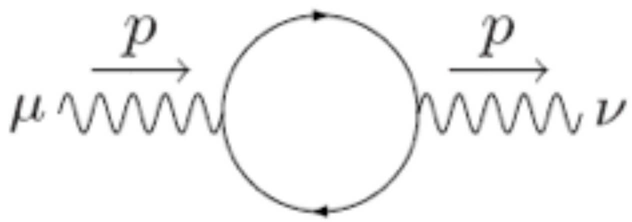

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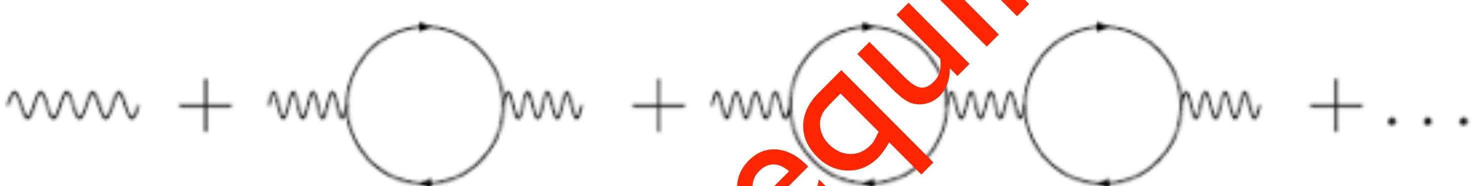

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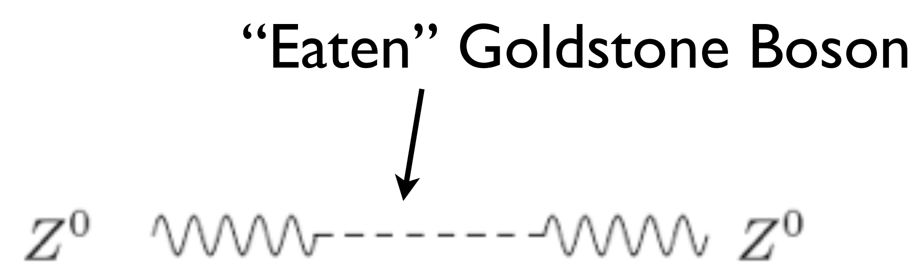

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Doesn't require a Higgs Boson

Haber

Warnings*

- The QFT description of an S-matrix need *not* be unique, e.g. QCD and the χLagrangian, ADS/CFT.
- "Gauge Symmetries" are not symmetries: they are redundancies in our description.
- "Coupling constants" are not observables.
- "Fundamental" and "Composite" are in the eye of the *calculator* ... more important: strong or weak

* Things you should know about QFT, but were afraid to ask.

When is A Higgs The Higgs?

Then:

WHEN IS A HIGGS THE HIGGS?

OR

THE PHENOMENOLOGY OF A NON-STANDARD HIGGS BOSON

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and

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ABSTRACT

The one-Higgs-doublet standard model is necessarily incomplete because of the triviality of the scalar symmetry-breaking sector. If the Higgs mass is approximately 600 GeV or higher, there must be additional dynamics at a scale Λ which is less than a few TeV. In this case the properties of the Higgs resonance can differ substantially from those predicted by the standard model. In this talk we construct an effective Lagrangian description of a theory with a non-standard Higgs boson and analyze the features of a theory with such a resonance coupled to the Goldstone Bosons of the breaking of $SU(2) \times U(1)$.

Talk presented by R. S. Chivukula at the conference on "Continuous Advances in QCD", Minneapolis, Feb. 18-20, 1994.

BUHEP-94-9
hep-ph/9405275

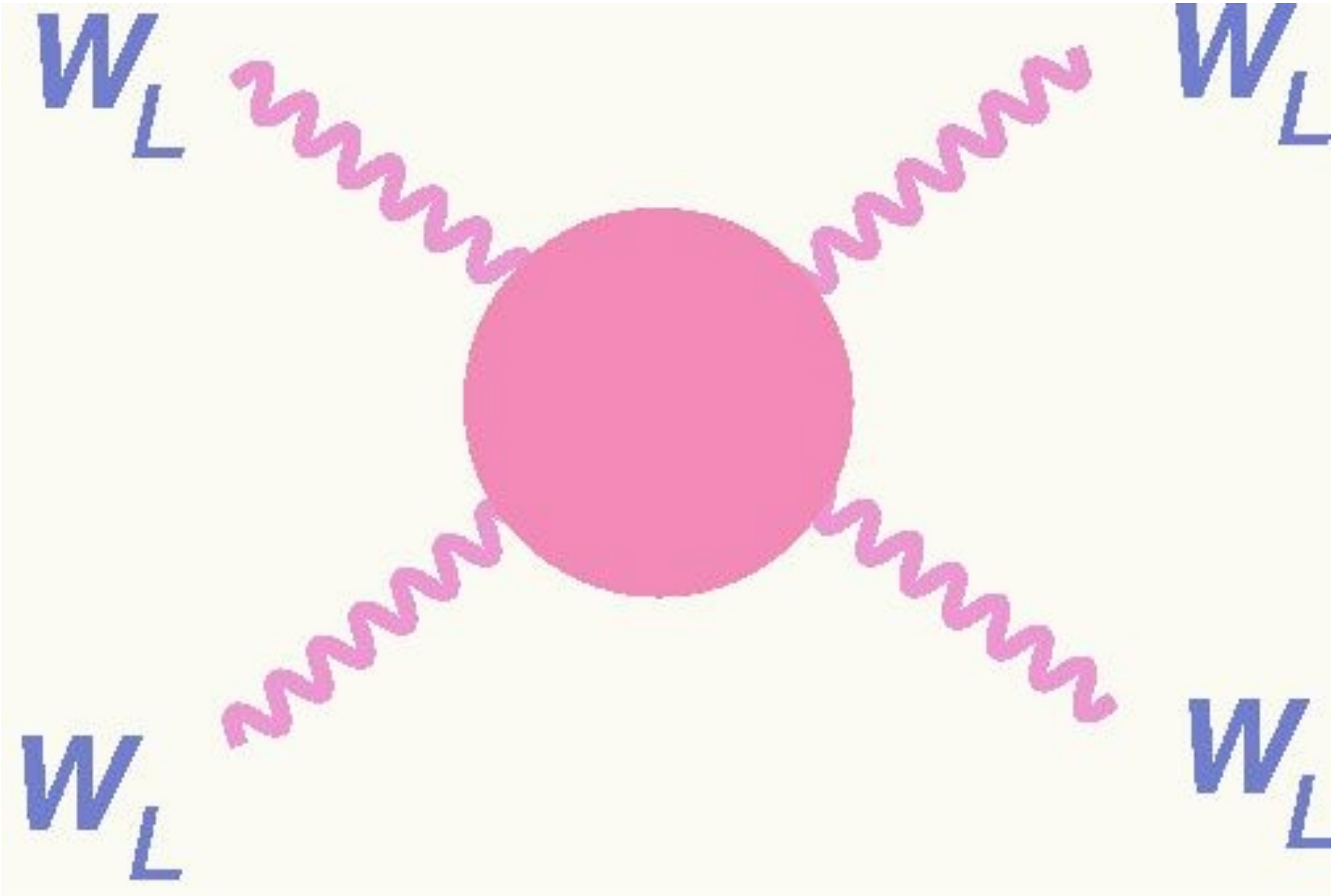
Now:

For other analyses of the X particle couplings, see: D. Carmi, A. Falkowski, E. Kuflik and T. Volanski, arXiv:1202.3144 [hep-ph]; A. Azatov, R. Contino and J. Galloway, JHEP **1204** (2012) 127 [hep-ph/1202.3415]. J.R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1202.3697 [hep-ph]; P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, arXiv:1203.4254 [hep-ph]; T. Li, X. Wan, Y. Wang and S. Zhu, arXiv:1203.5083 [hep-ph]; M. Rauch, arXiv:1203.6826 [hep-ph]; J. Ellis and T. You, JHEP **1206** (2012) 140, [arXiv:1204.0464 [hep-ph]]; A. Azatov, R. Contino, D. Del Re, J. Galloway, M. Grassi and S. Rahatlou, arXiv:1204.4817 [hep-ph]; M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, arXiv:1205.2699 [hep-ph]; D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, arXiv:1206.4201 [hep-ph]; M. J. Dolan, C. Englert and M. Spannowsky, arXiv:1206.5001 [hep-ph]; J. Chang, K. Cheung, P. Tseng and T. Yuan, arXiv:1206.5853 [hep-ph]; S. Chang, C. A. Newby, N. Raj and C. Wanotayaroj, arXiv:1207.0493 [hep-ph]; I. Low, J. Lykken and G. Shaughnessy, arXiv:1207.1093 [hep-ph]; T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, arXiv:1207.1344 [hep-ph]; P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, arXiv:1207.1347 [hep-ph]; M. Montull and F. Riva, arXiv:1207.1716 [hep-ph]; J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1207.1717 [hep-ph]; D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, arXiv:1207.1718 [hep-ph]; S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya, JHEP bf 10 (2012) 062, [arXiv:1207.3588 [hep-ph]]; F. Bonner, T. Ota, M. Rauch and W. Winter, arXiv:1207.4599 [hep-ph]; T. Plehn and M. Rauch, arXiv:1207.6108 [hep-ph]; A. Djouadi, arXiv:1208.3436 [hep-ph]; B. Batell, S. Gori and L. T. Wang, arXiv:1209.6832 [hep-ph]; G. Cacciapaglia, A. Deandrea, G. D. La Rochelle and J-B. Flament, arXiv:1210.8120 [hep-ph]; E. Masso and V. Sanz, arXiv:1211.1320 [hep-ph]; T. Corbett, O. J. P. Ebol, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, arXiv:1211.4580 [hep-ph]; R. Tito D'Agnolo, E. Kuflik and M. Zanetti, arXiv:1212.1165 [hep-ph]; A. Azatov and J. Galloway, arXiv:1212.1380 [hep-ph]; D. Choudhury, R. Islam, A. Kundu and B. Mukhopadhyaya, arXiv:1212.4652 [hep-ph]; R. S. Gupta, M. Montull and F. Riva, arXiv:1212.5240 [hep-ph]; G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, arXiv:1212.5244 [hep-ph]; K. Cheung, J. S. Lee and P-Y. Tseng, arXiv:1302.3794 [hep-ph].

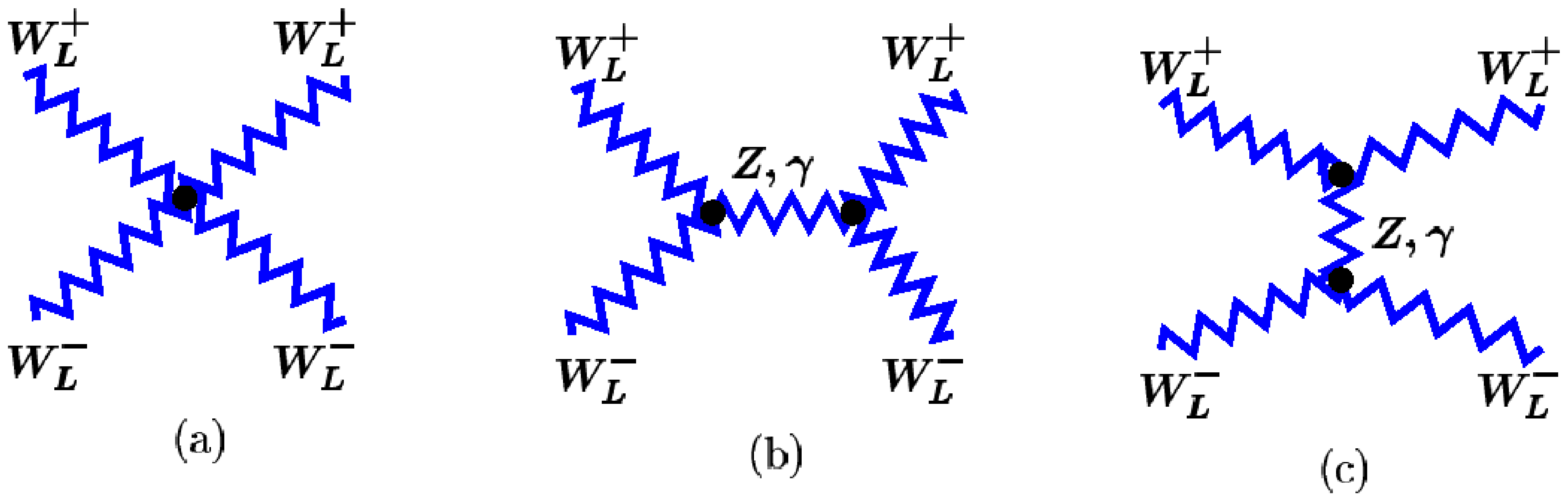
Post Moriond 2013 Fits:

Falkowski, et. al., arXiv: 13031812
Giardino, et. al., arXiv: 1303.3570
Ellis, et. al., arXiv: 1303.3879
(ATLAS and CMS)

Loss of Unitarity in



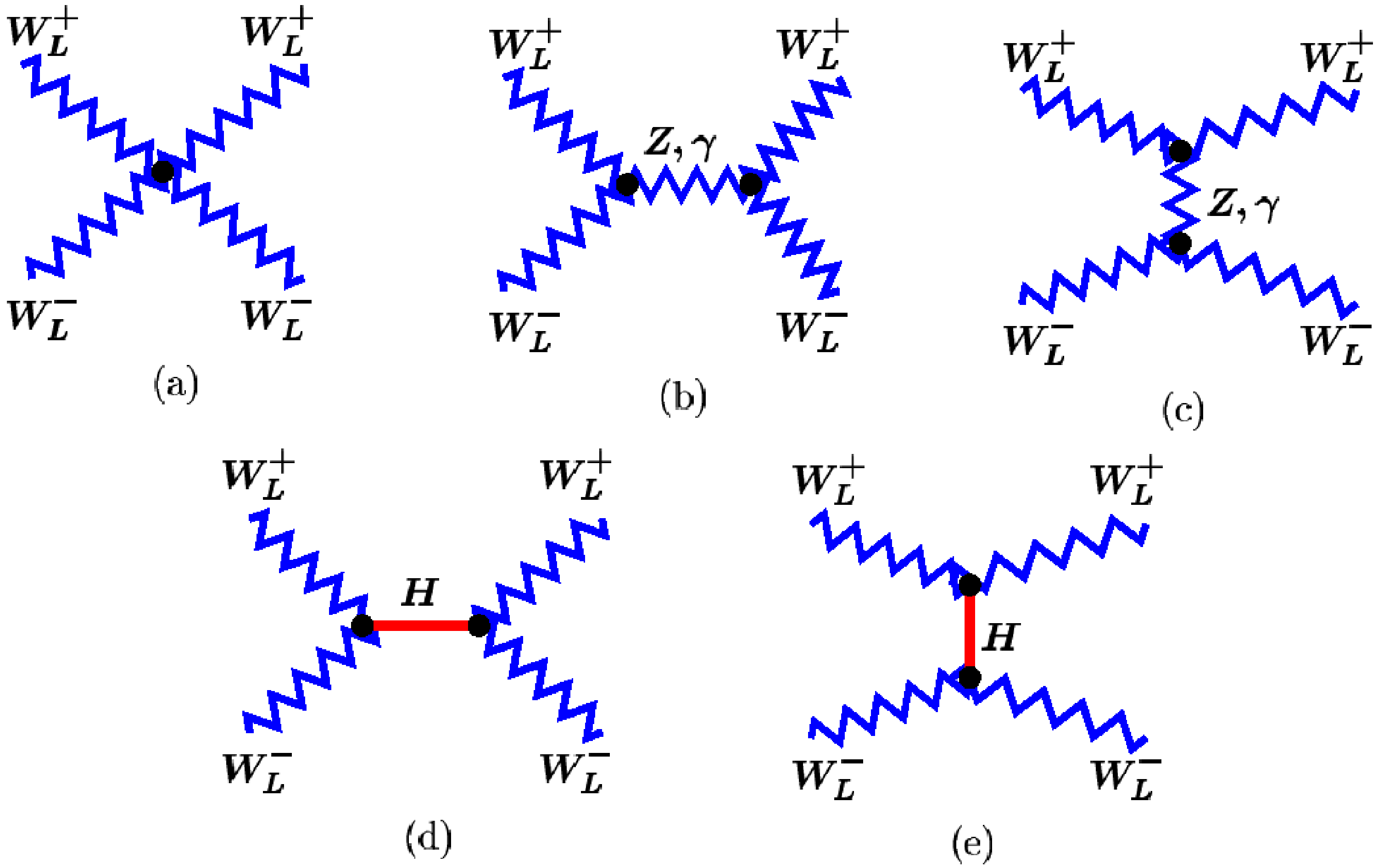
SU(2) x U(1) @ E^4



Graphs	$g^2 \frac{E^4}{m_w^4}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$
Sum	0

$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

SU(2) x U(1) @ E^2 & The Higgs

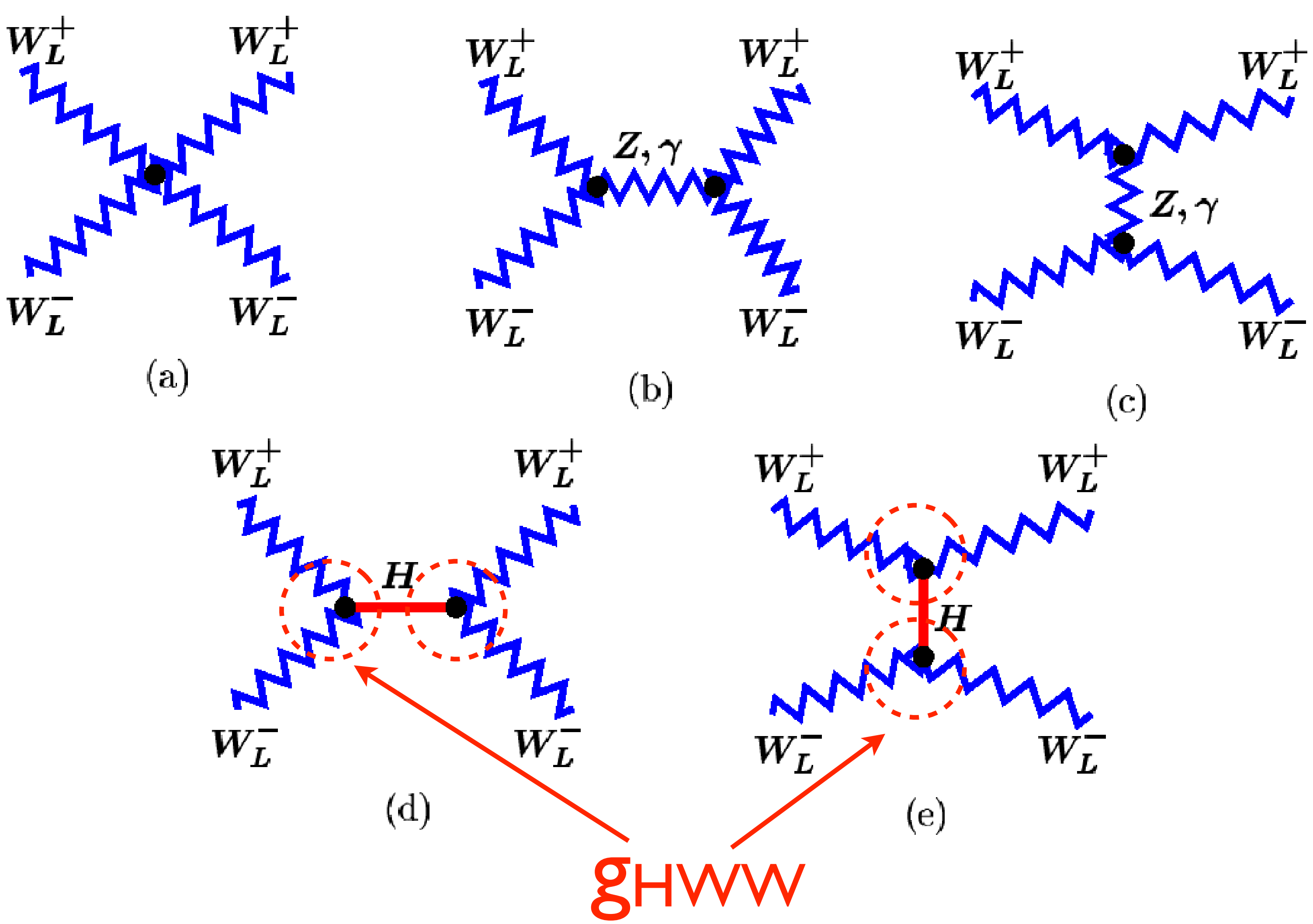


Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow$ $E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

Lee, Quigg, Thacker

SU(2) x U(1) @ E² & The Higgs



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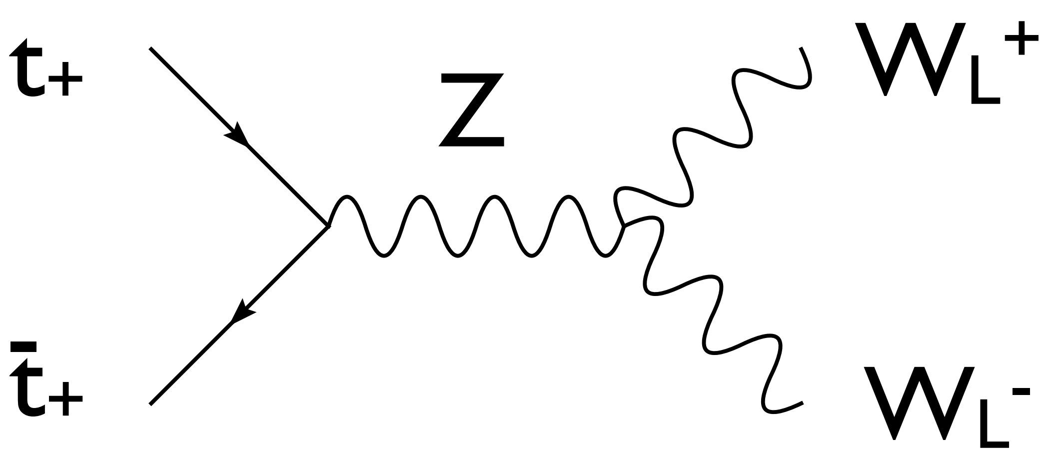
Lee, Quigg, Thacker

SU(2) x U(1) @ E & The Higgs



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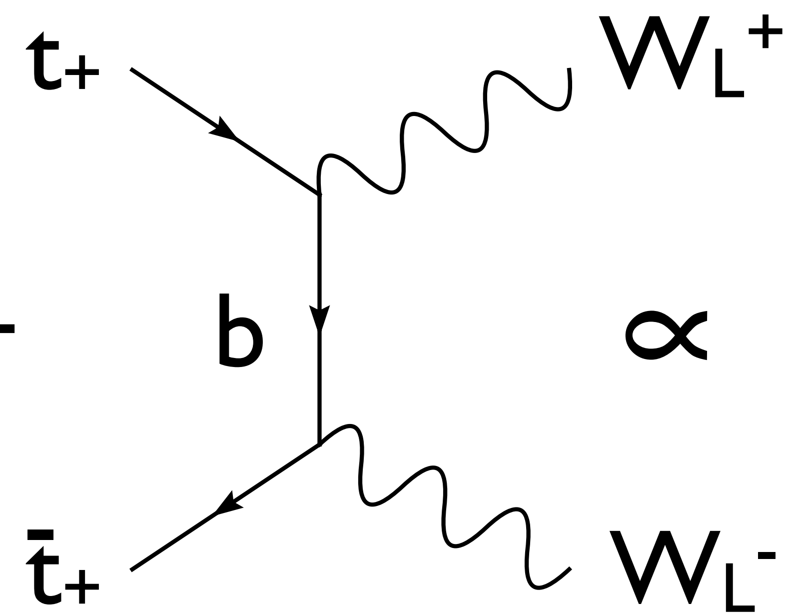
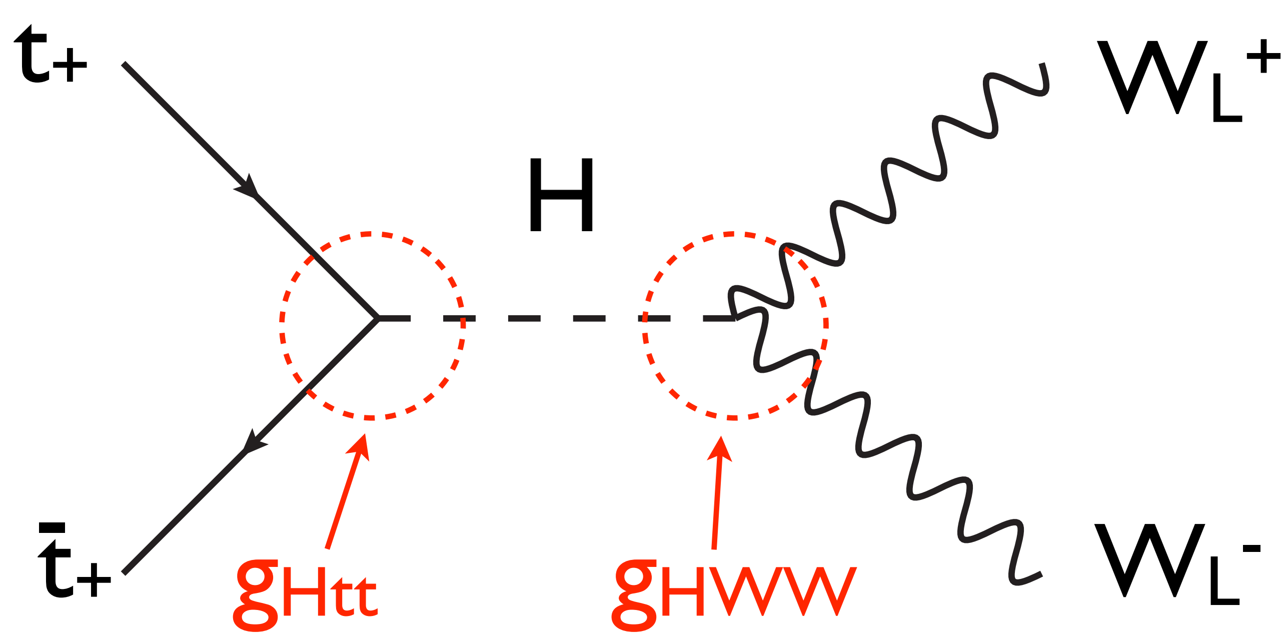


$$\propto \frac{m_t E}{v^2}$$

Bad high-energy behavior cancelled by:



Chanowitz, Furman, Hinchliffe

What do we know about these couplings?

Assuming No BSM Decays

Test Consistency of SM

Properties of the Higgs Boson

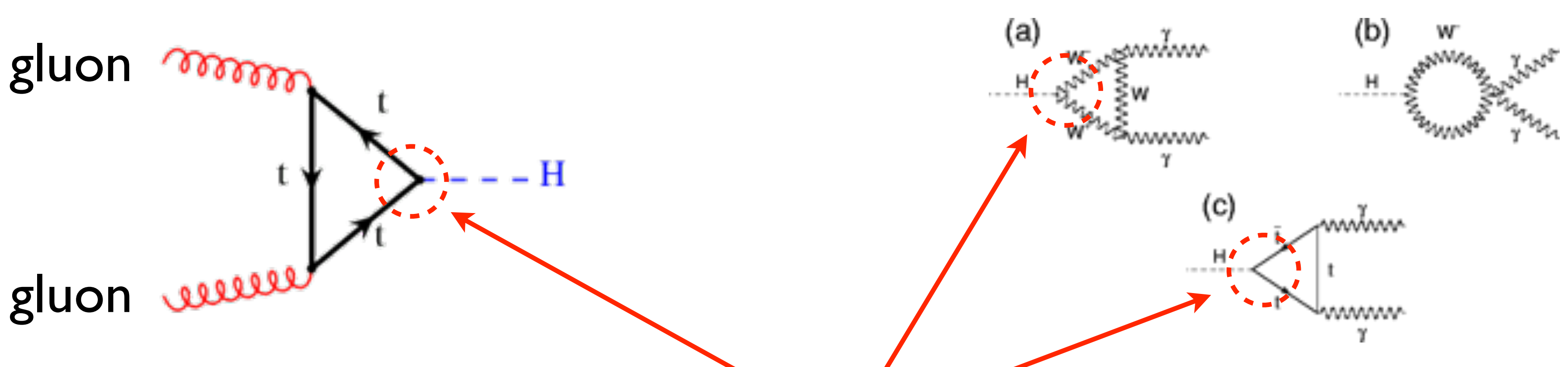
- All masses proportional to ⟨H⟩=v, hence

$$\mathcal{L}_{SM} \supset M_W^2 \left(1+\frac{H}{v}\right)^2 W^{+\mu}W^-_\mu + \frac{M_Z^2}{2}\left(1+\frac{H}{v}\right)^2 Z^\mu Z_\mu$$

- and

$$\mathcal{L}_{SM} \supset -\sum_f m_f \left(1+\frac{H}{v}\right)\bar{\psi}_{Lf}\psi_{Rf} + h.c.$$

- Important <u>loop</u> effects

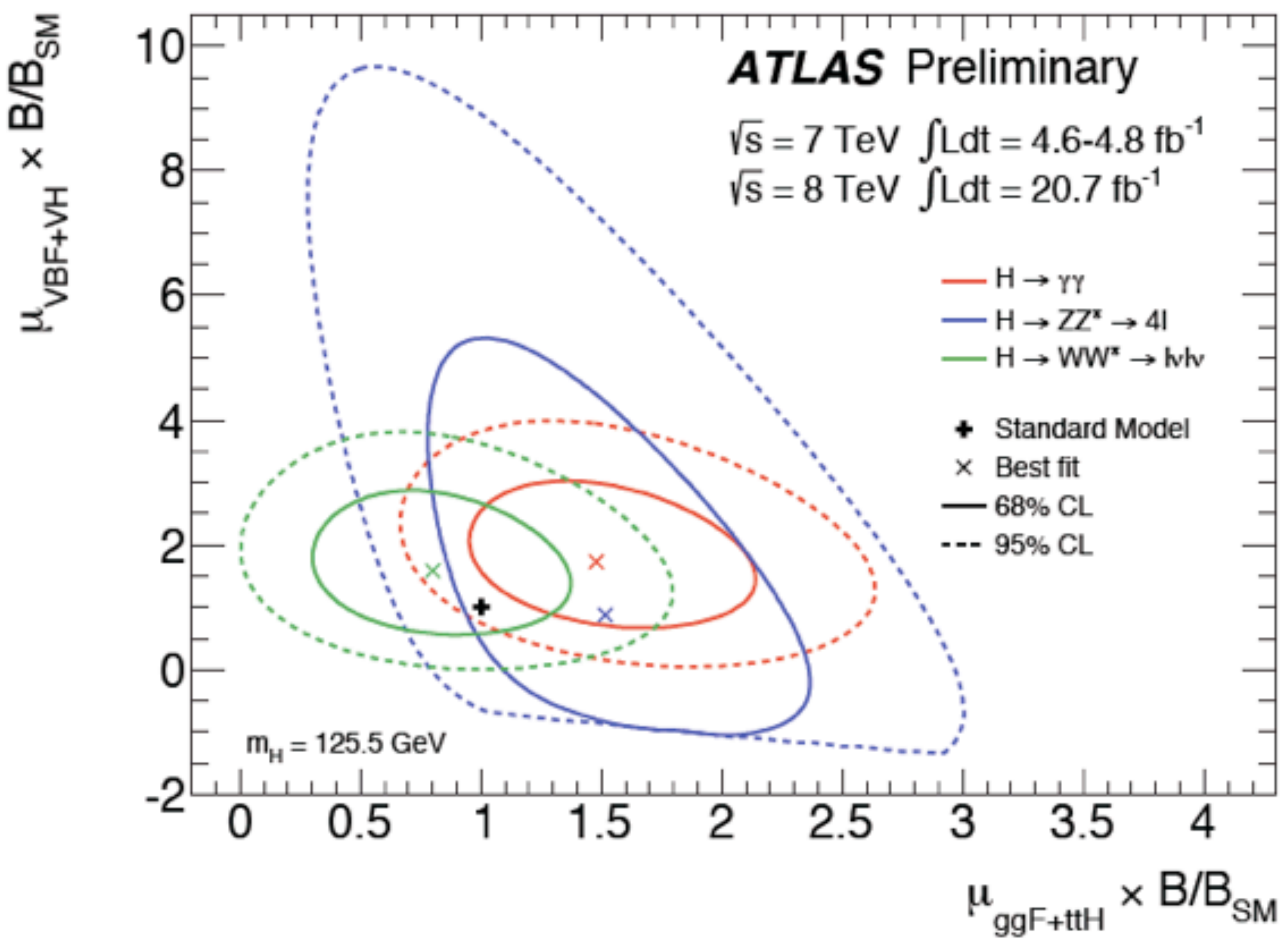


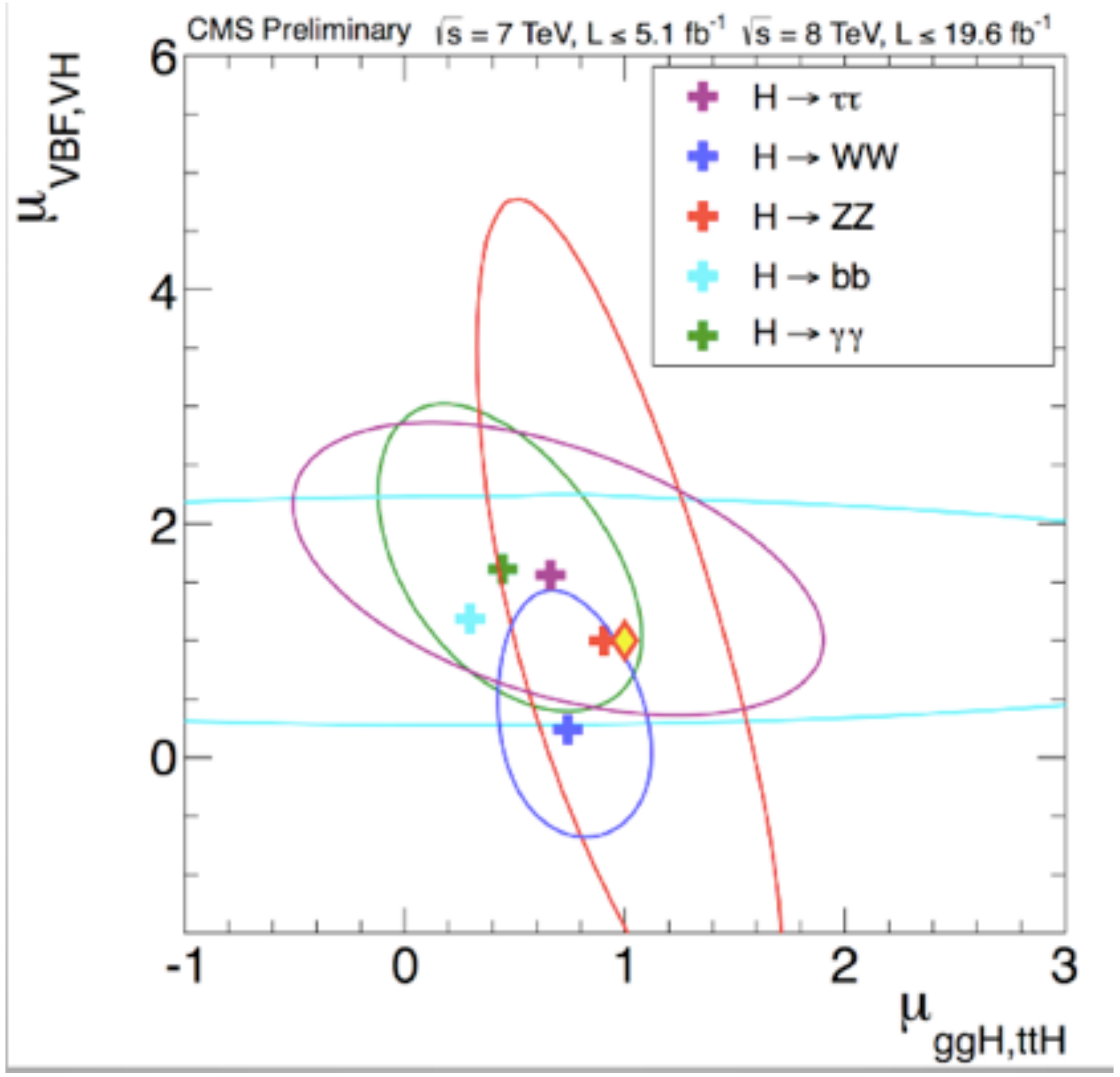
$\sigma(pp \to H)$

$\Gamma(H \to \gamma\gamma)$

non-decoupling!

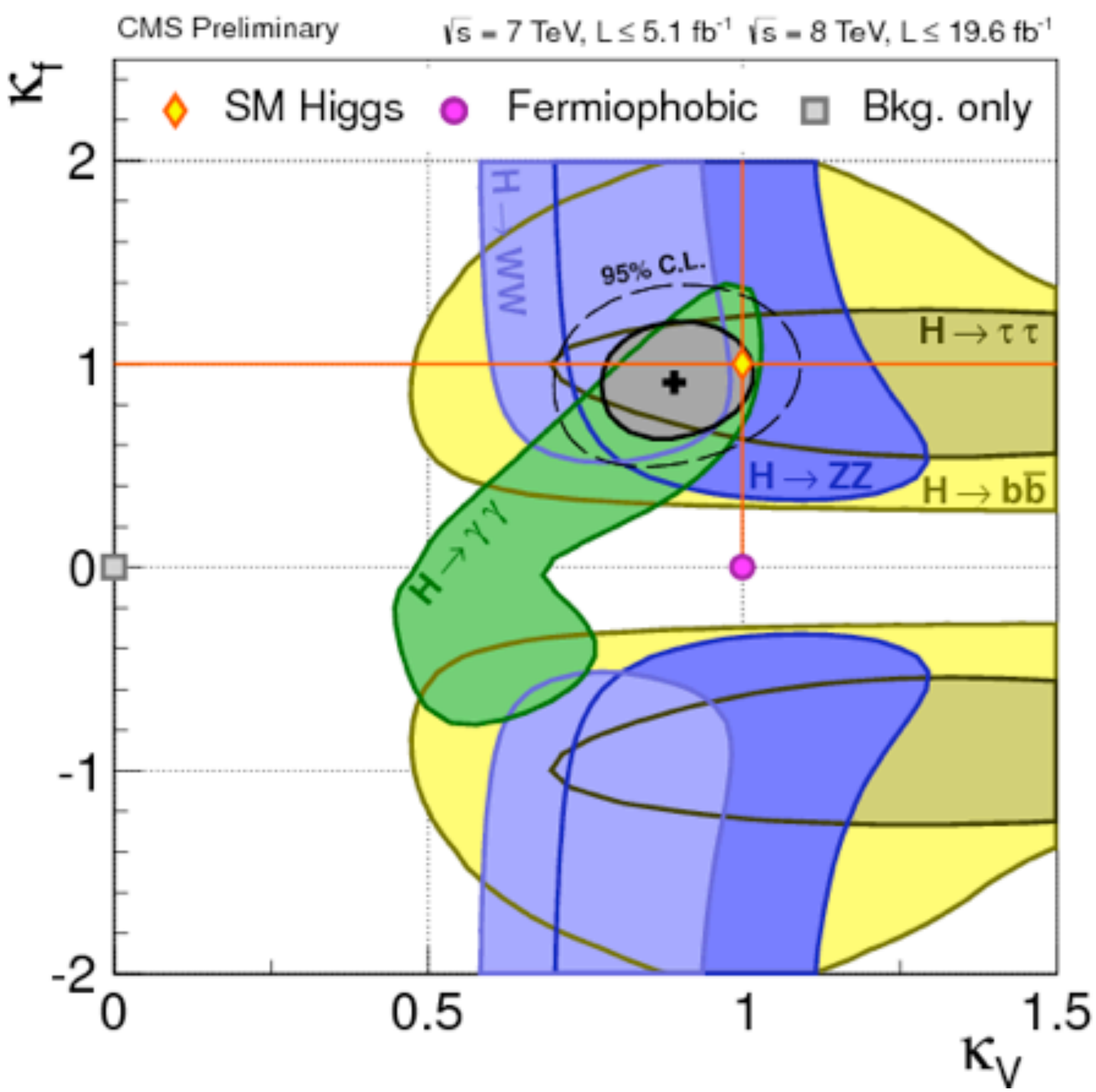
Consistency: VBF vs. Gluon Fusion

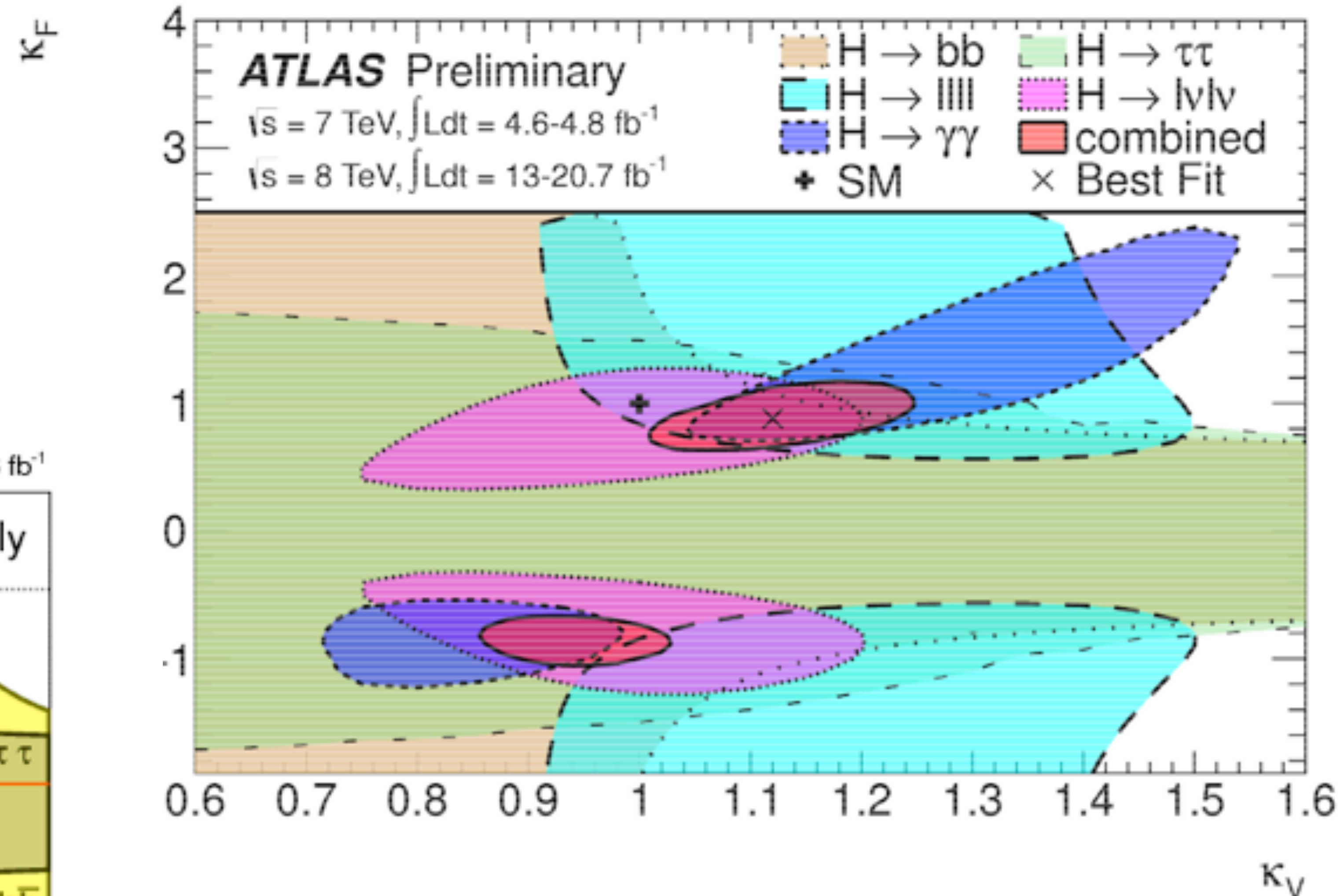




Moriond EW 2013, LP2013

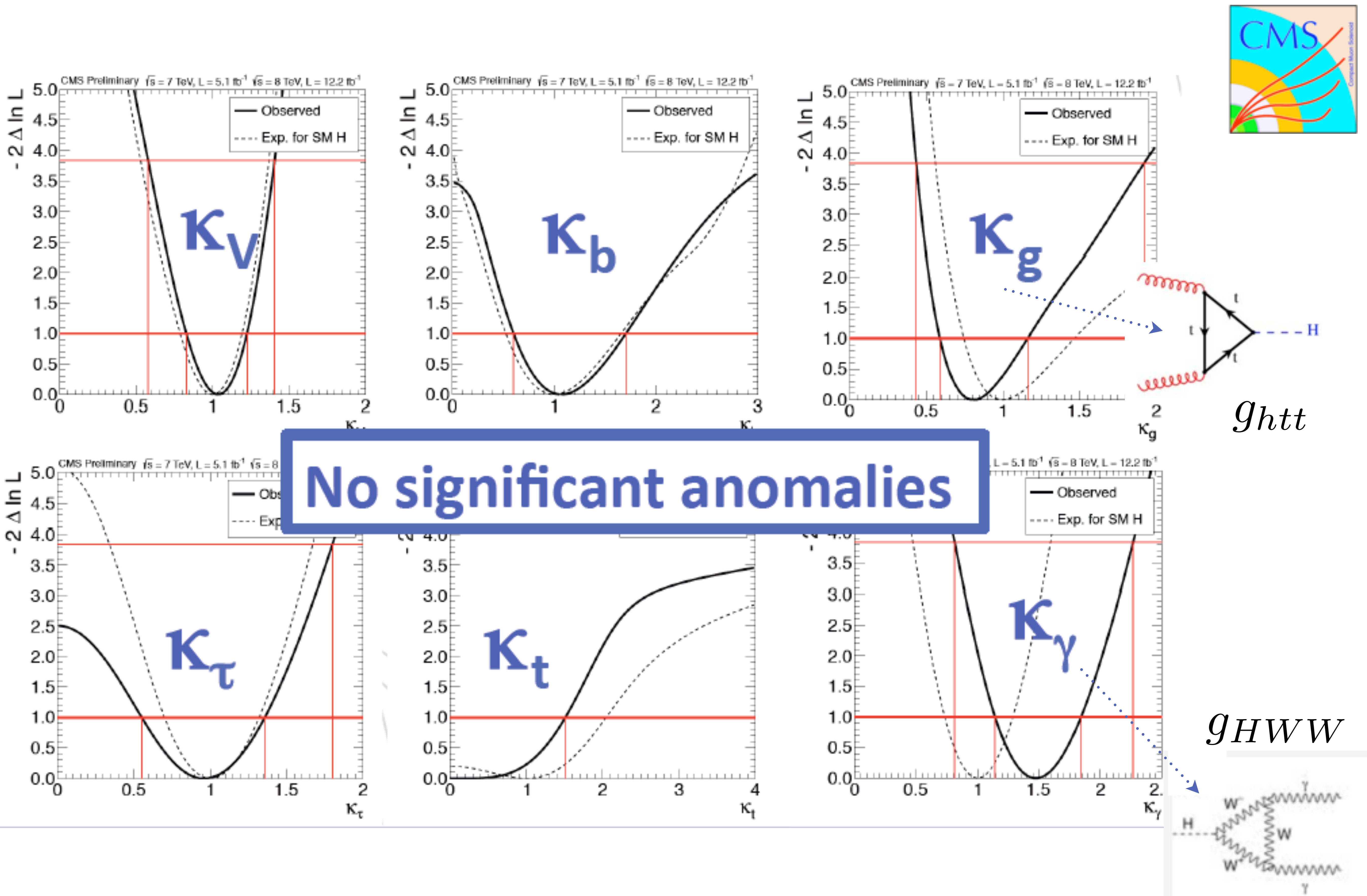
Allow Couplings to "Float" within SM



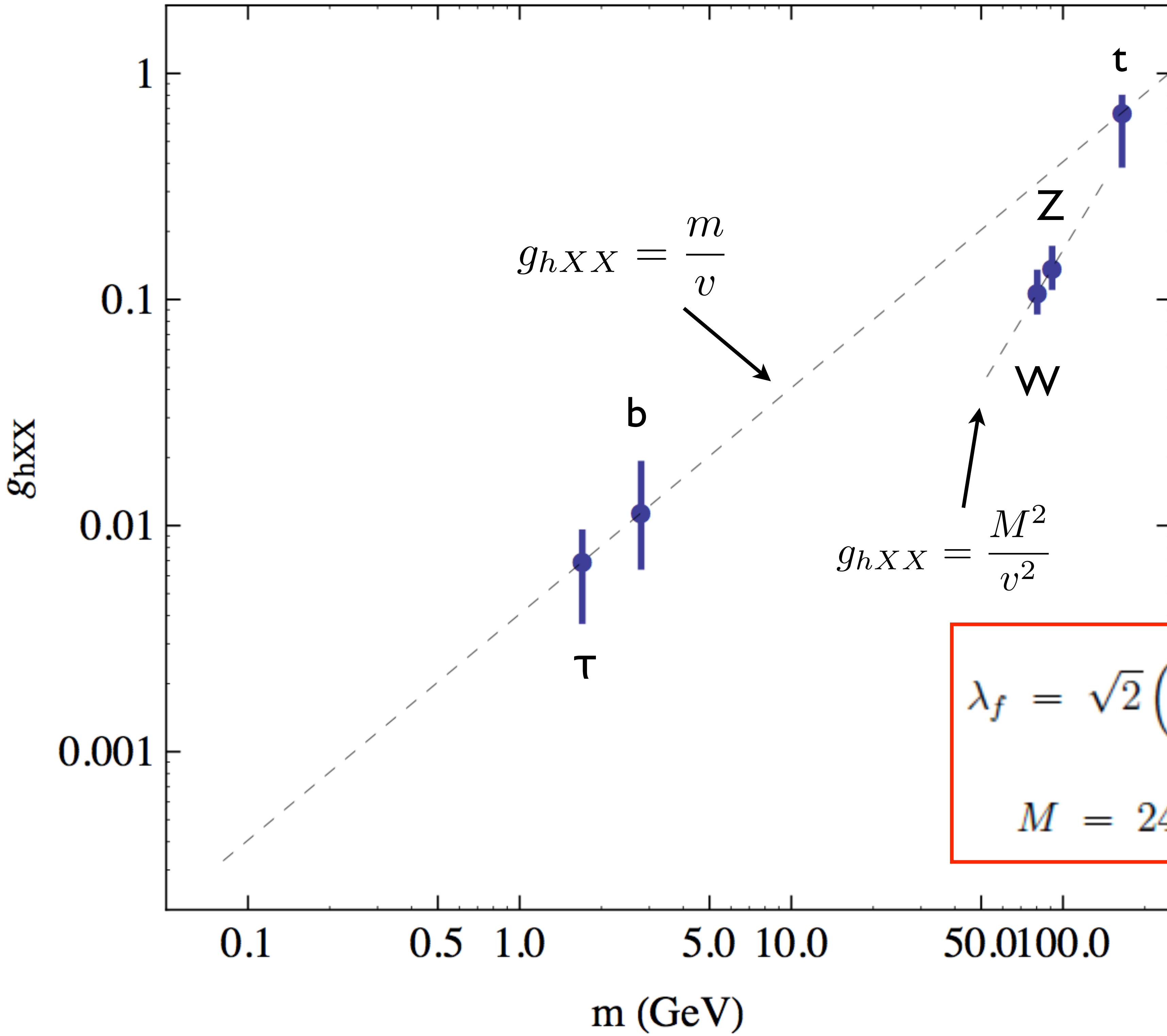


ATLAS-CONF-2013-34
CMS-PAS-HIG-13-005

Allow Couplings to "Float" within SM



"Textbook" Plot of Higgs Couplings

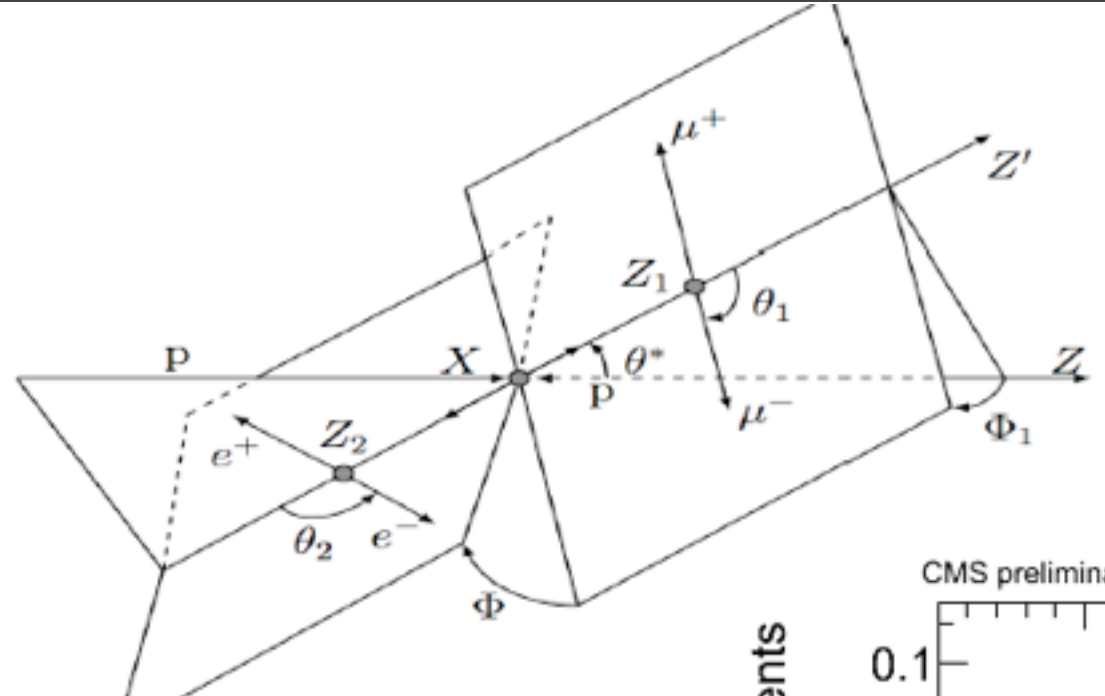


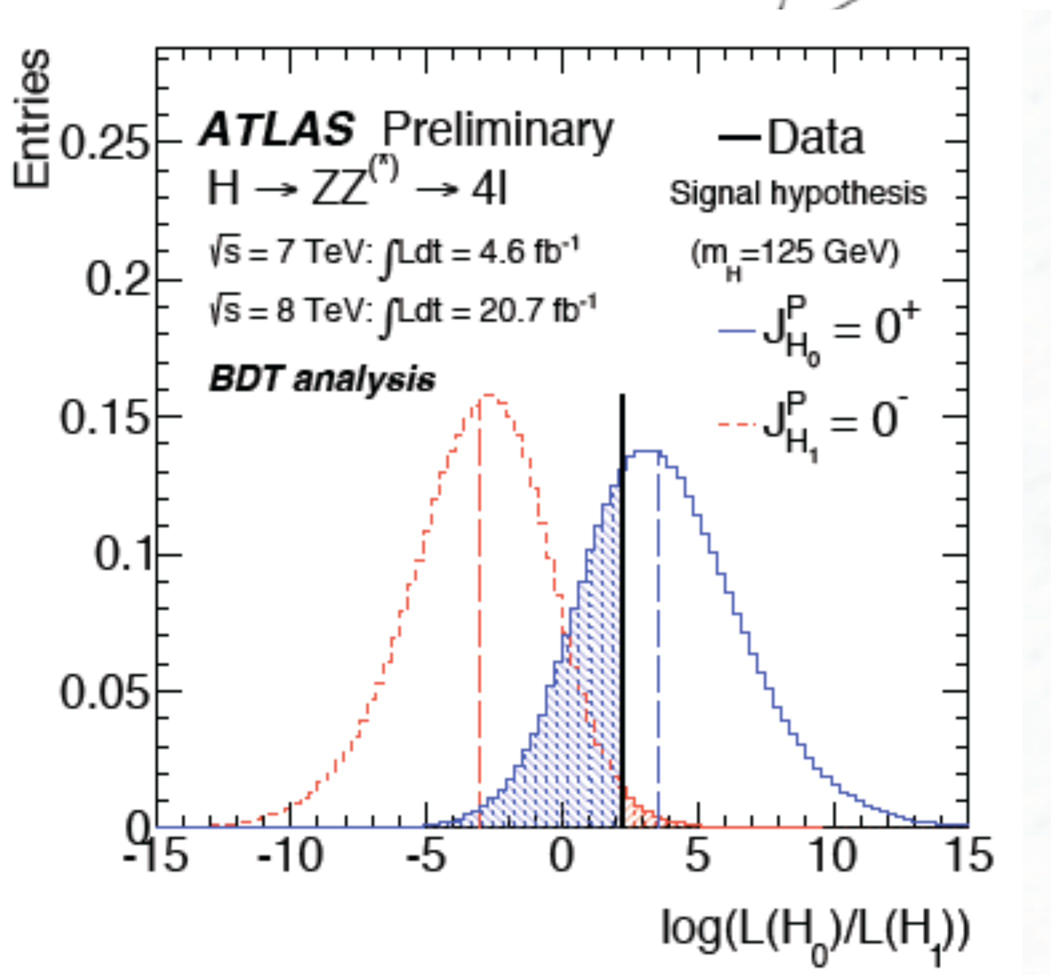
$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right),$$

$$M = 244^{+20}_{-10}\text{ GeV}, \; \epsilon = -0.022^{+0.042}_{-0.021};$$

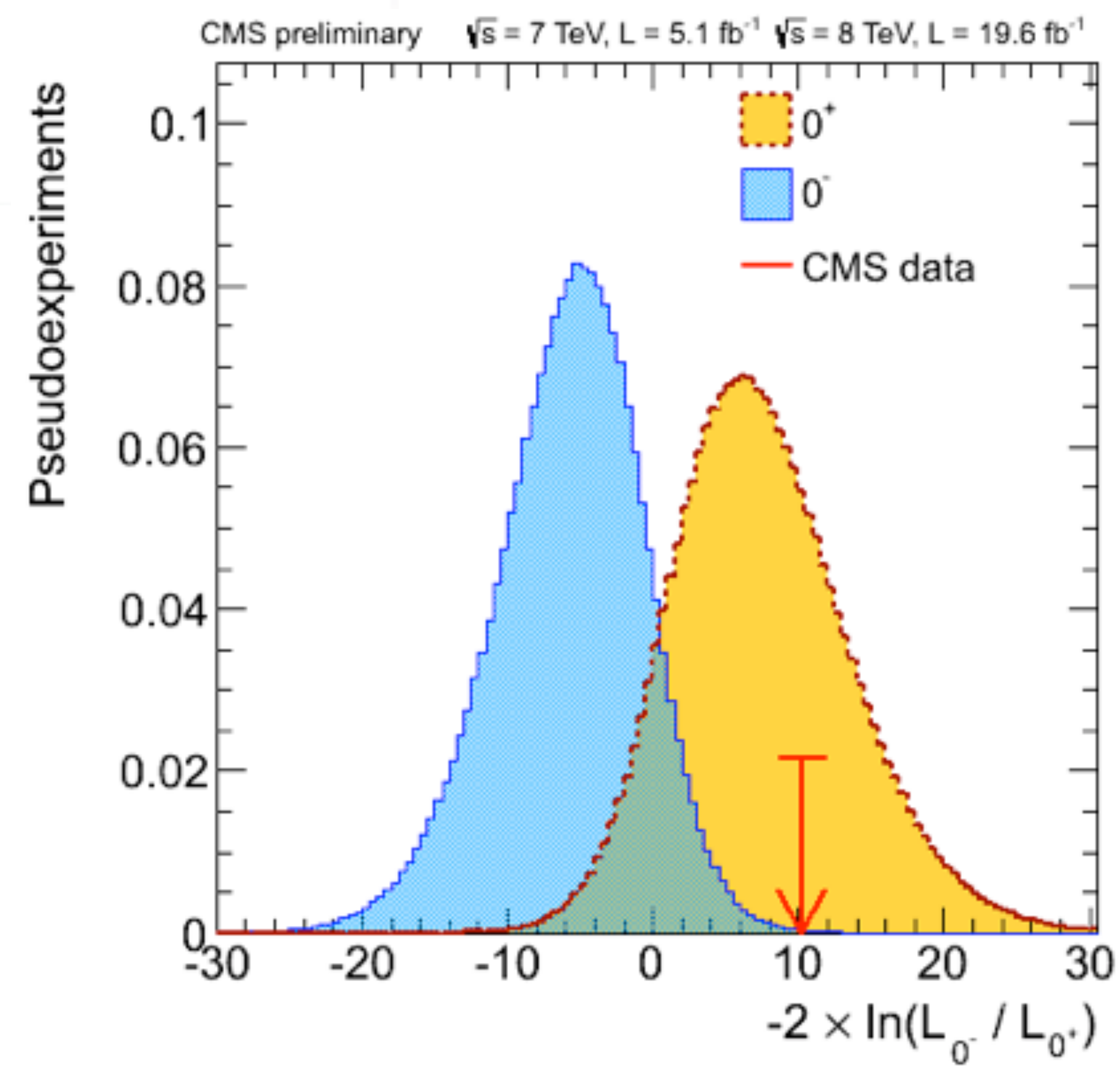
Particle couples to mass in the correct way!

$H \rightarrow ZZ^*$ Spin/Parity: 0^+ vs. 0^-





Exclude 0^- at 97.8% CL



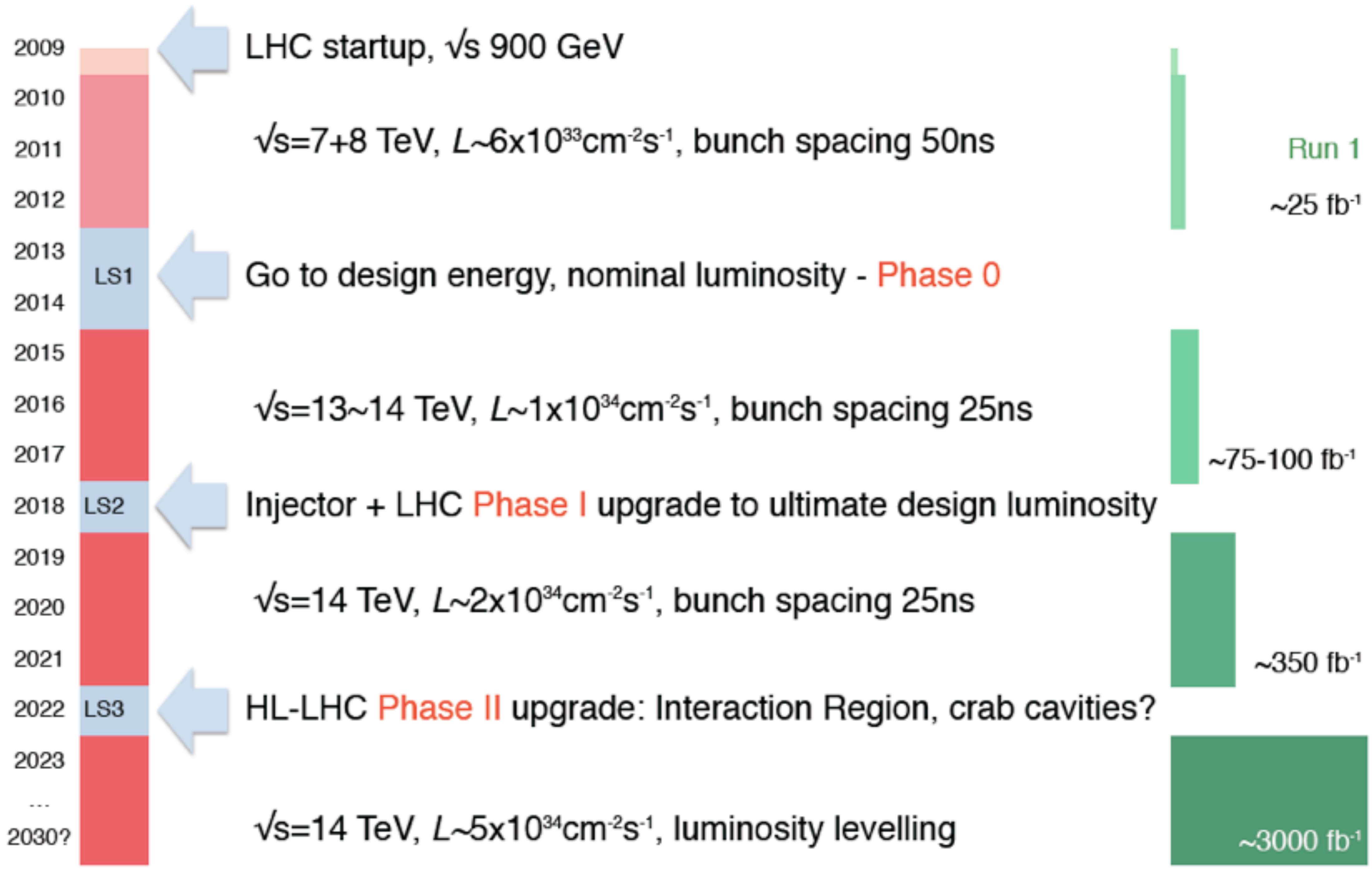
$CL_{0^-} = 0.16\%$

Future Prospects

Slides from P. Wells, LP2013

LHC Roadmap

LHC roadmap to achieve full potential



CTEQ Can Lead the Way!

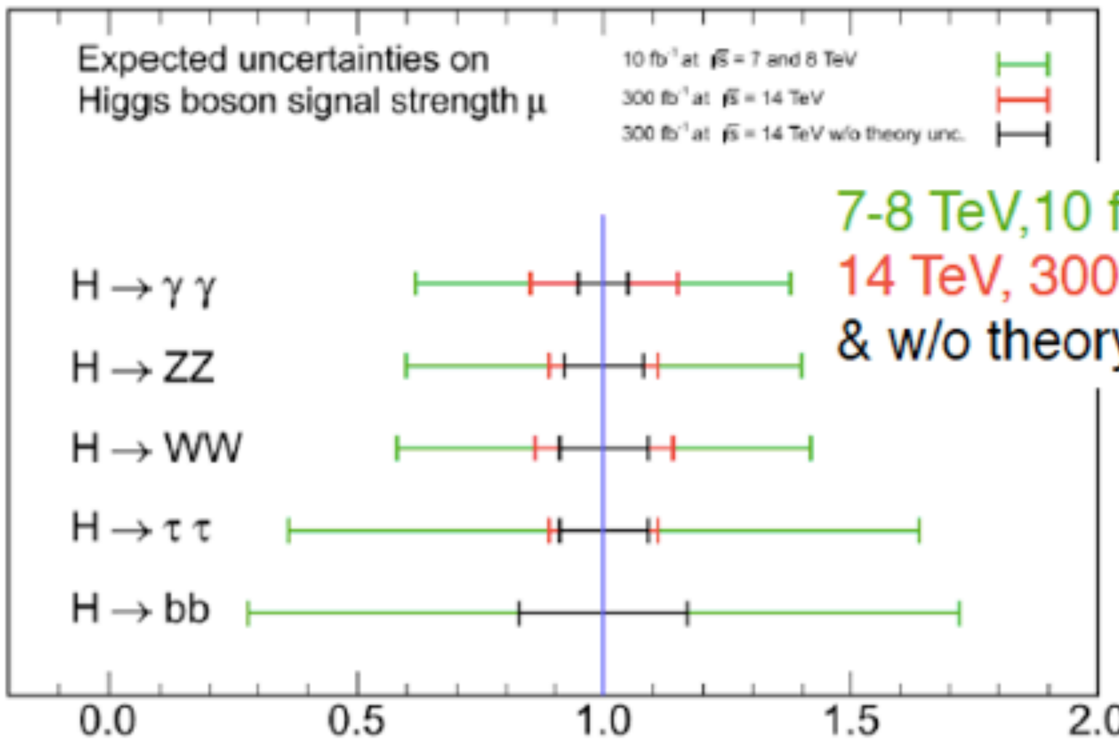
Theoretical uncertainties

- Theoretical predictions for known and new processes are critical
  - Missing higher order (QCD) radiative corrections are estimated by varying factorisation and renormalisation scales (0.5 ~ 2.0)
  - Electroweak corrections
  - Treatment of heavy quarks
  - PDF uncertainties (which also depend on the order of calculation available)
  - m_H=125 GeV @ 14 TeV: $\sigma(pp(gg)\rightarrow H+X)$ scale $^{+9}_{-12}$%, PDF ±8.5%
- PDF uncertainties can be reduced by future precise experimental measurements at LHC, including
  - W, Z σ and differential distributions for lower x quarks
  - High mass Drell-Yan measurements for higher x quarks
  - Inclusive jets, dijets for high x quarks and gluons
  - Top pair differential distributions for medium/large x gluons
  - Single top for gluon and b-quark
  - Direct photons for small/medium x gluons

Higgs boson μ values

- CMS results from 7-8 TeV 10 fb^{-1} and extrapolated to 300 fb^{-1} with fixed systematic uncertainties with or w/o theory uncertainties

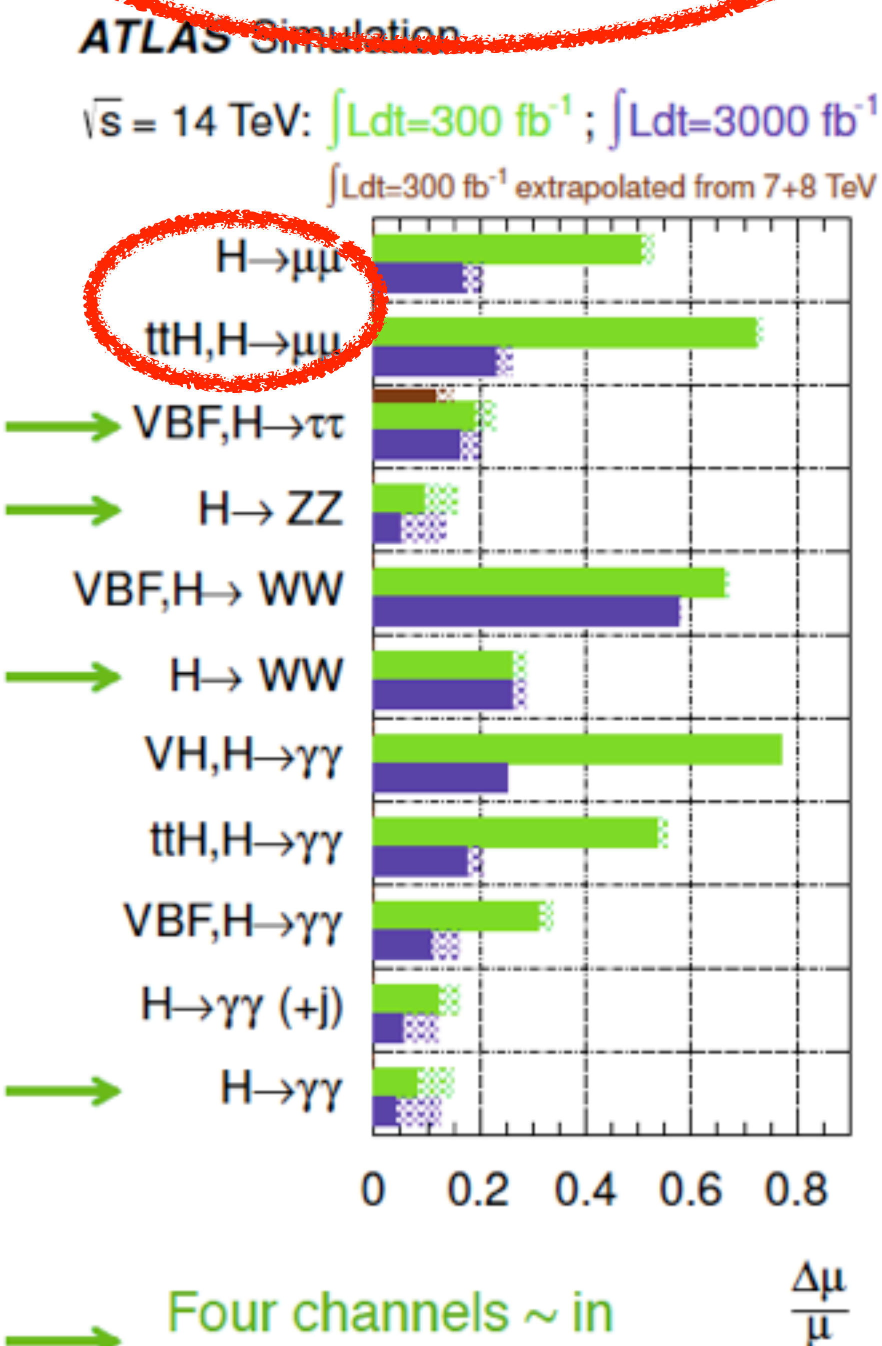
CMS Projection



7-8 TeV,10 fb^{-1}
14 TeV, 300 fb^{-1}
& w/o theory unc.

- Achieve 10-15% precision with 300 fb^{-1} for these main channels

Note sensitivity to μμ, and ttH with 3000 fb^{-1}



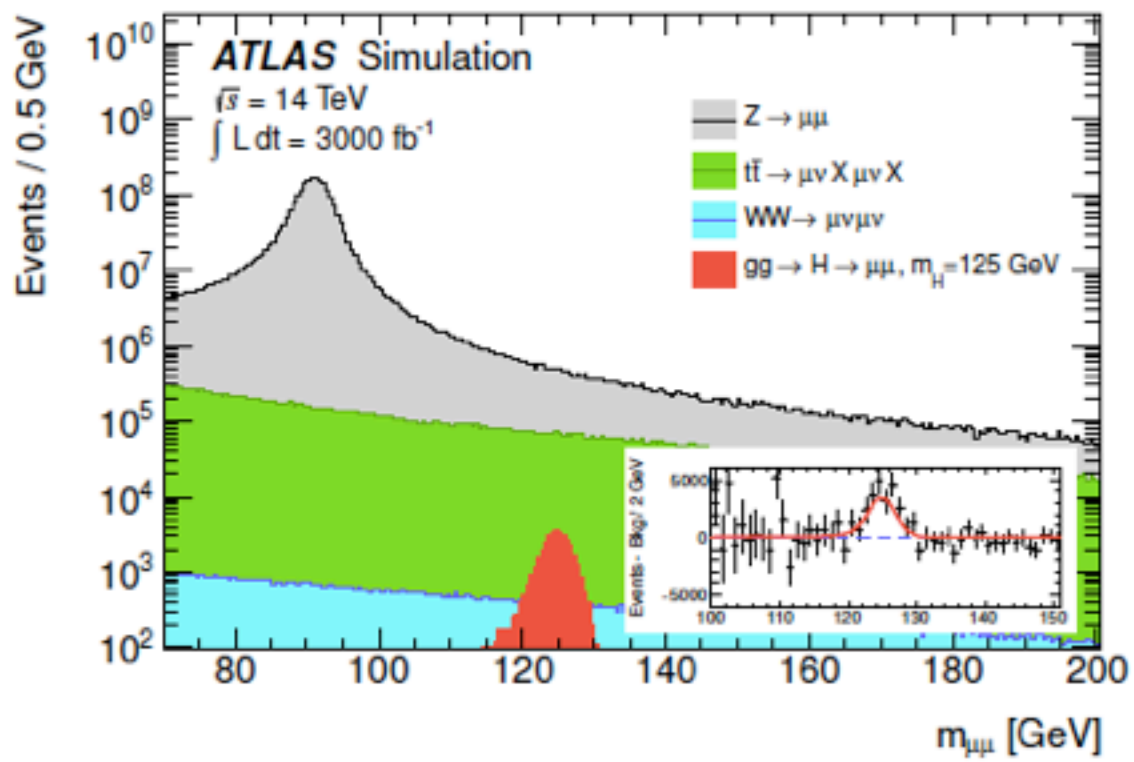
Four channels ~ in common with CMS study

Rare H processes

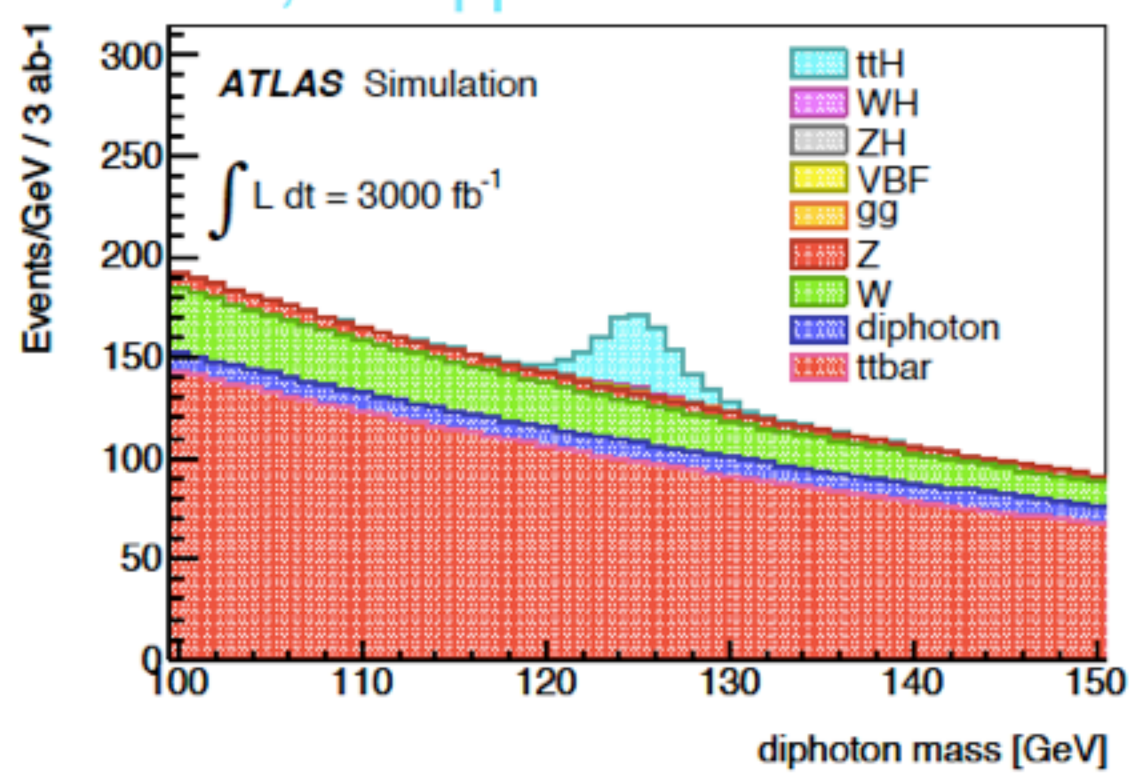
- H→μμ
  - ATLAS expect >6σ significance with 3000 fb^{-1}
  - CMS also expect >5σ significance
  - → coupling measured to 10~20%

- ttH, H→γγ (ATLAS)
  - >100 signal events
  - Signal/background 20%
- ttH, H→μμ (ATLAS)
  - Only ~30 signal events with 3000 fb^{-1} but S/B~1.

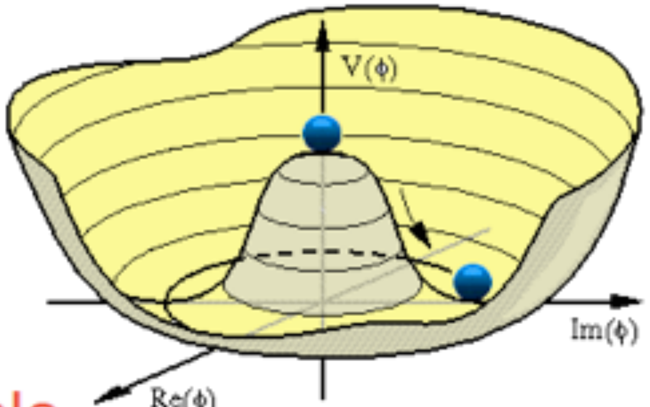
H→μμ



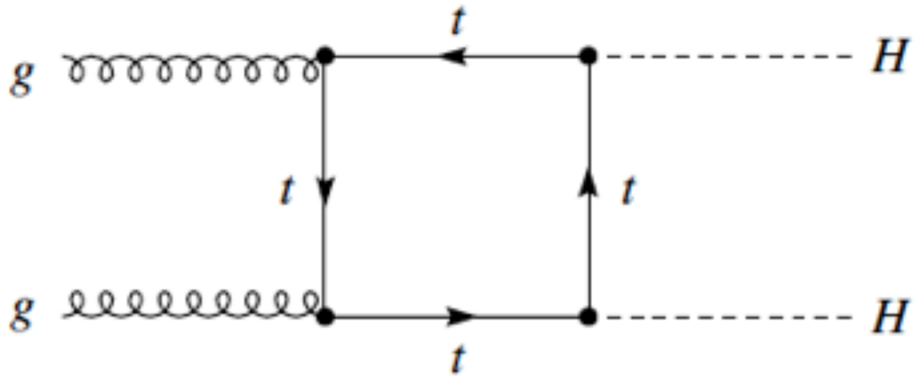
ttH, H→γγ

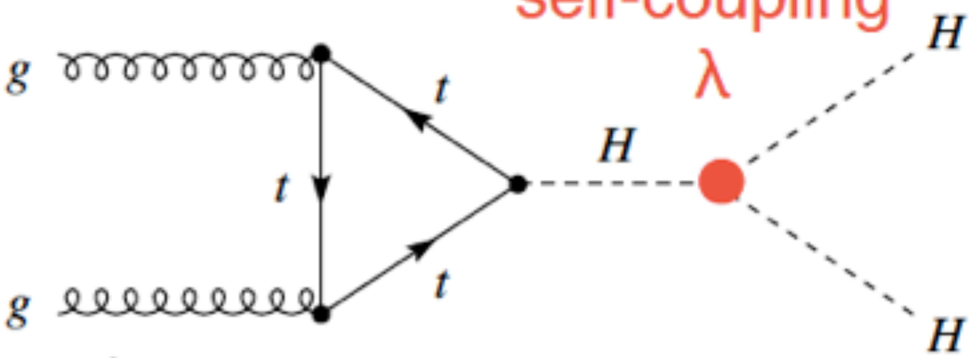


Higgs Self coupling



- Higgs pair production includes destructive interference between processes:

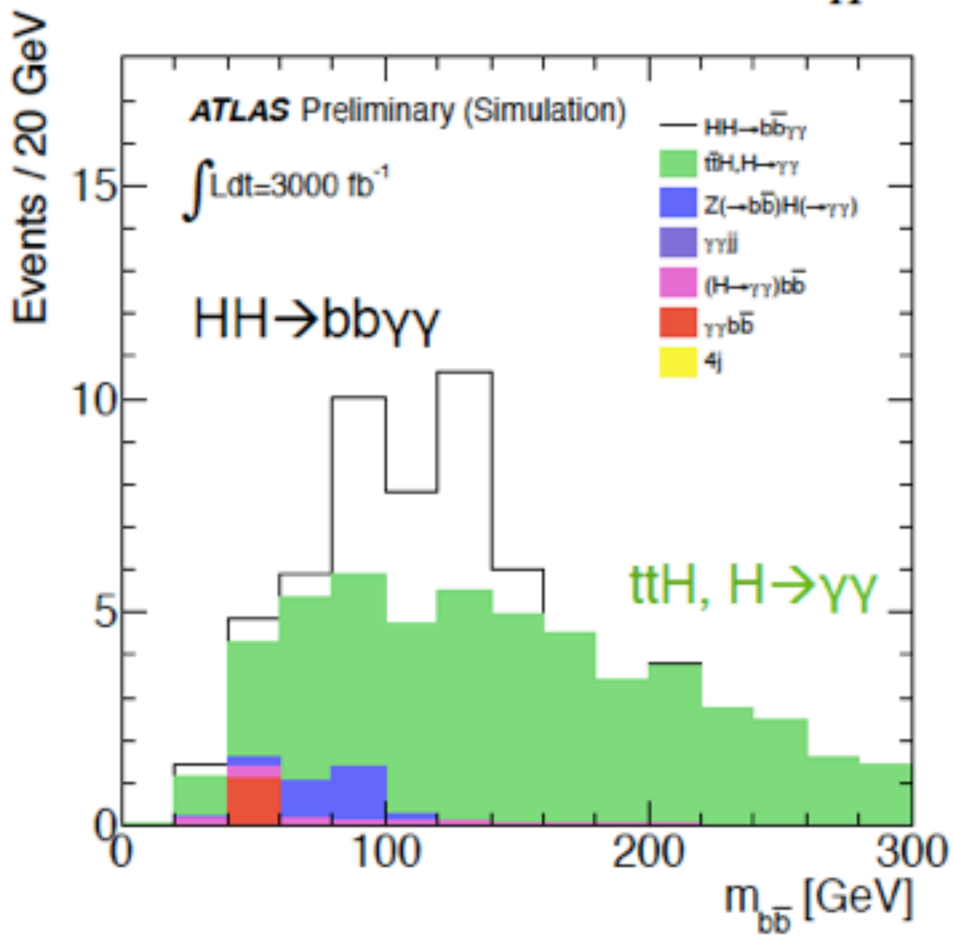


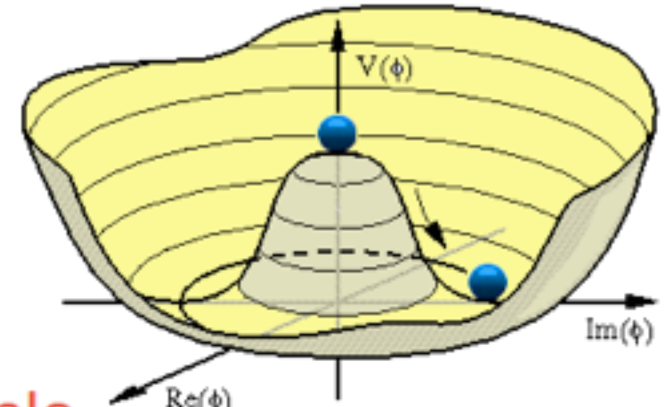


Test Higgs Potential

- λ=SM, σ=34 fb
  λ=0, σ=71 fb
  λ=2xSM, σ=16 fb

- ATLAS HH→bbγγ yields 3σ significance with 3000fb^{-1}
- Combining with HH→bbττ, & with two experiments, hope to reach 30% precision on λ





Test Higgs Potential

Higgs Self coupling

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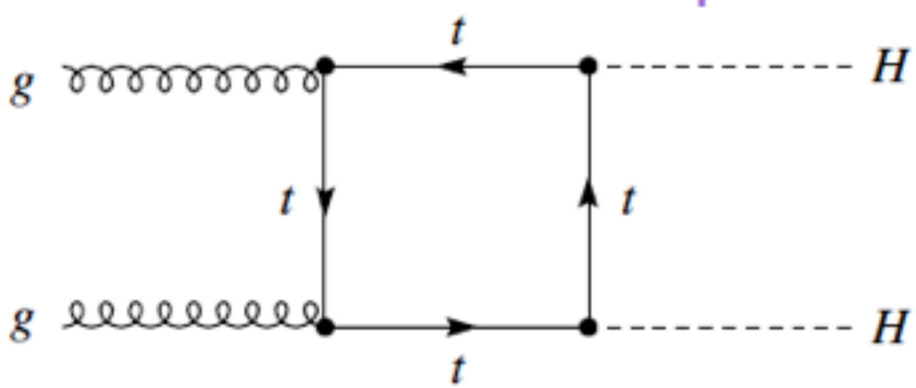

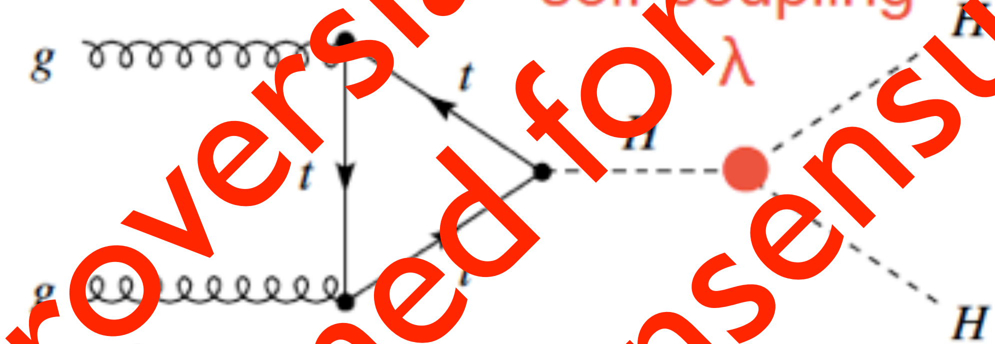

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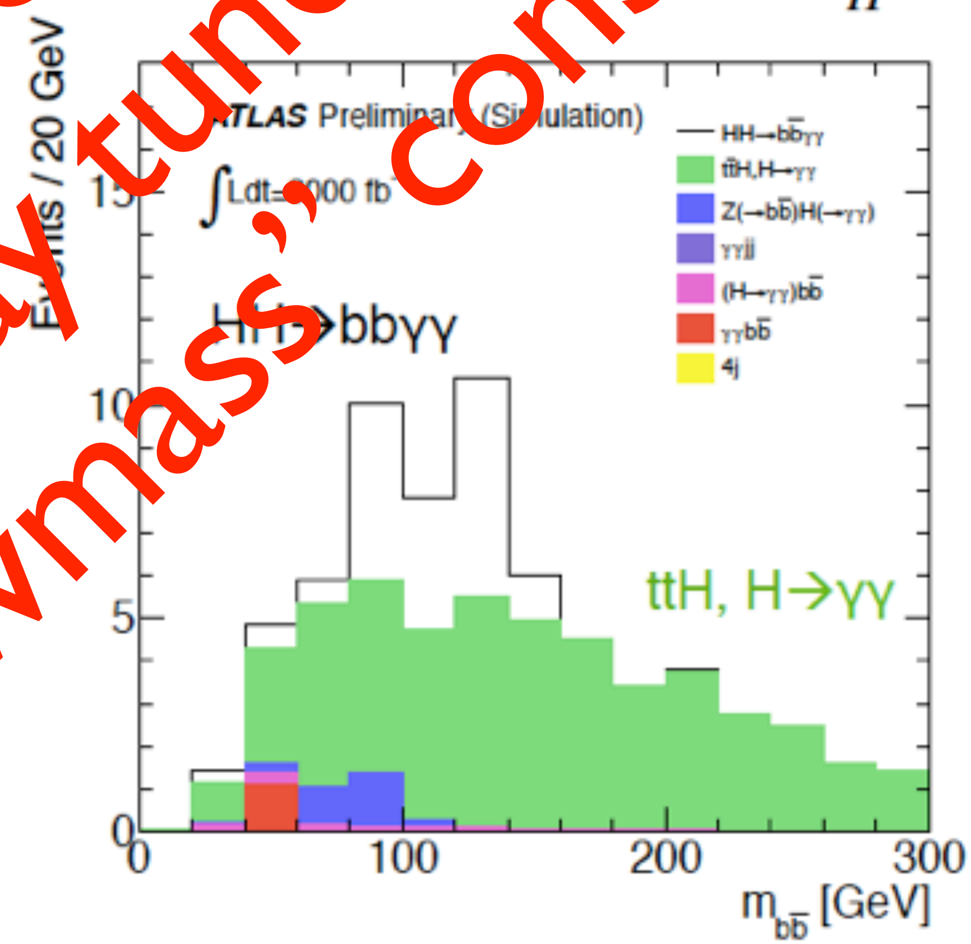
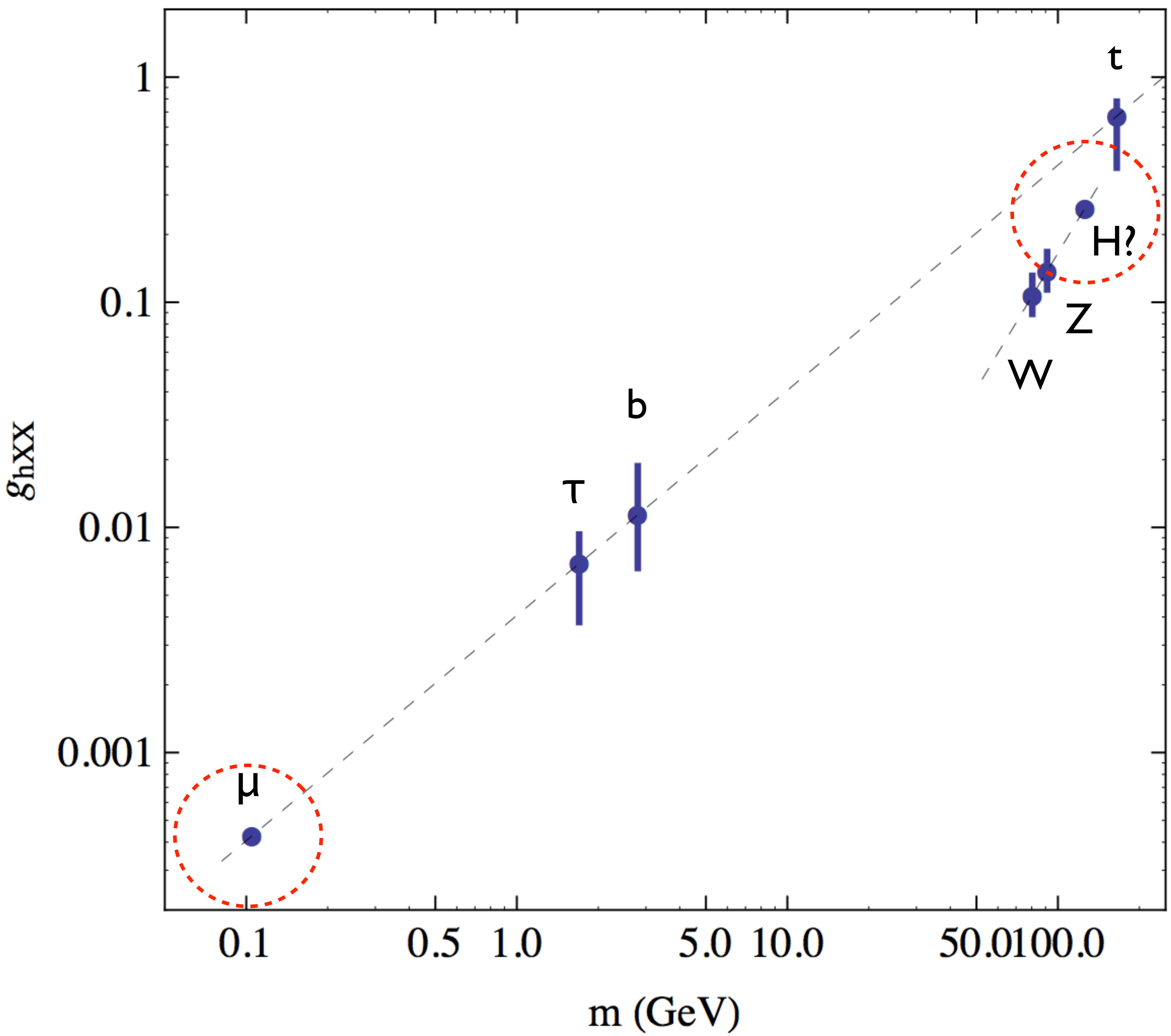


Controversial!!
Stay tuned for
"Snowmass" consensus…

The Future?



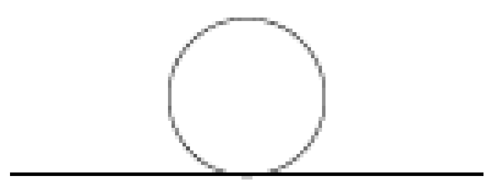
Scott Thomas

Problems with the Higgs Model

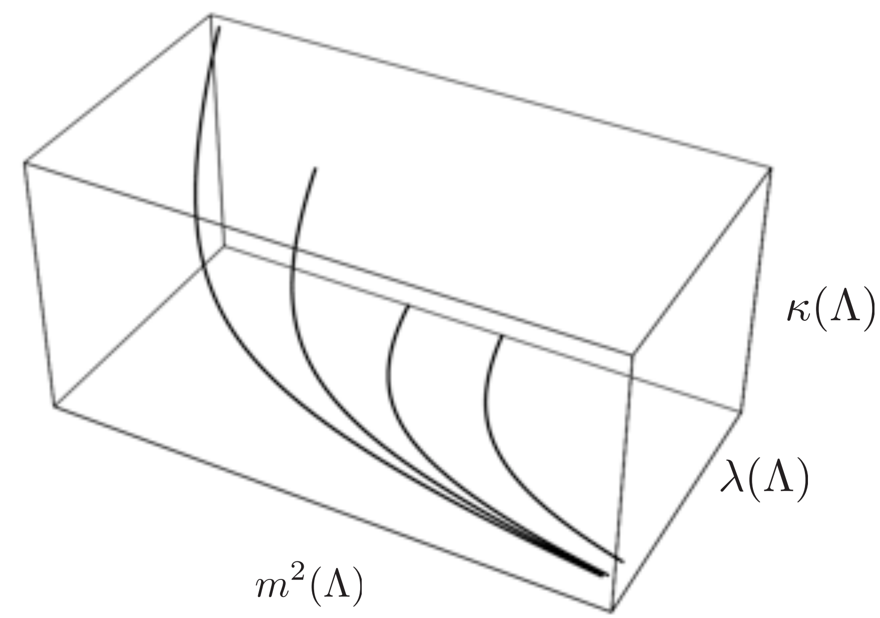
- No (other?) fundamental scalars observed in nature

- No explanation of dynamics responsible for Electroweak Symmetry Breaking

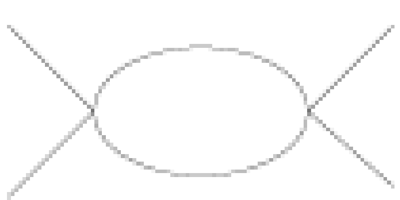
- Hierarchy or Naturalness Problem



$$\Rightarrow \quad m_H^2 \propto \Lambda^2$$

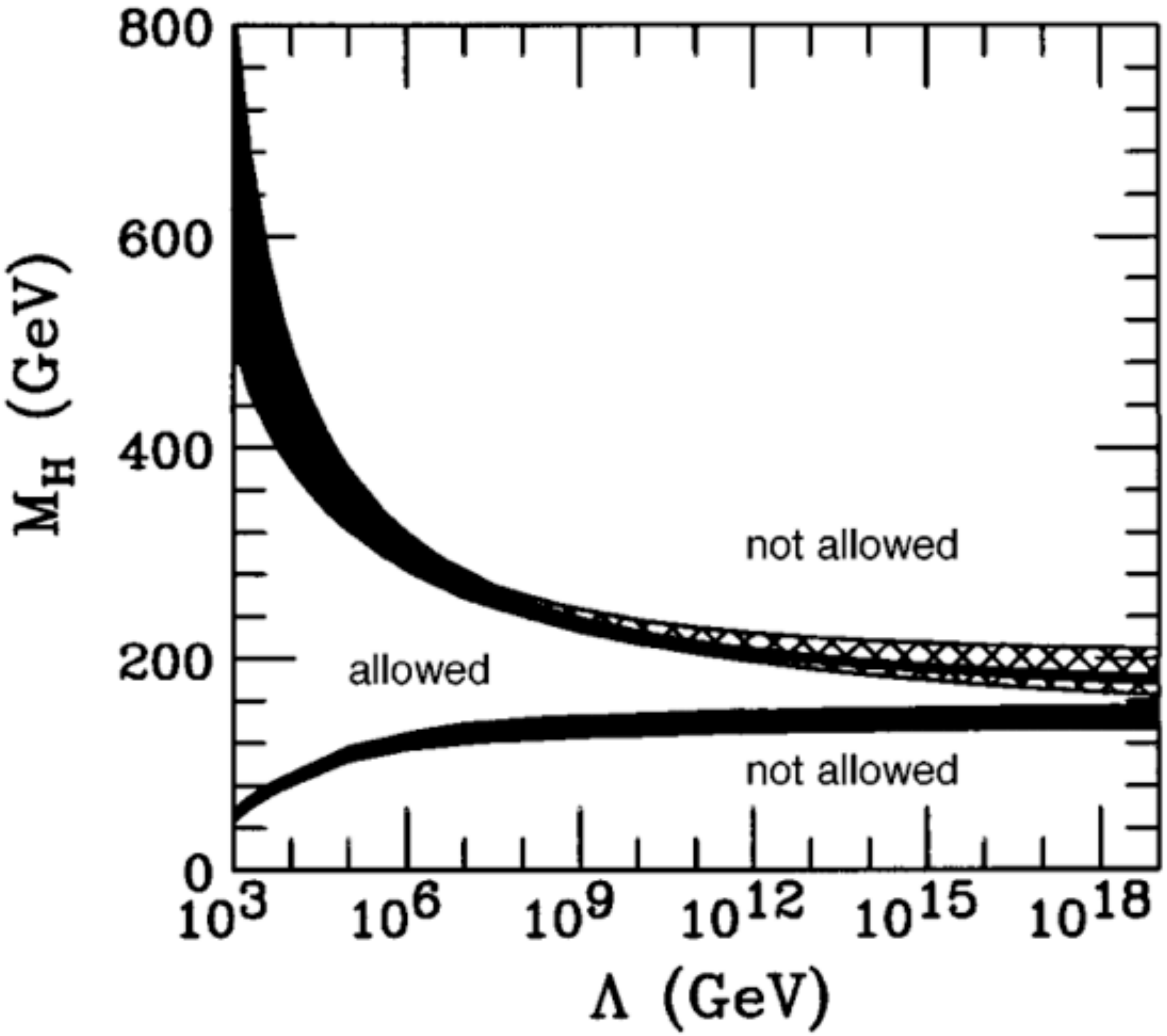


- Triviality and Vacuum Stability Problems...



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \qquad \lambda(\mu) < \frac{3}{2\pi^2 \log\frac{\Lambda}{\mu}}$$

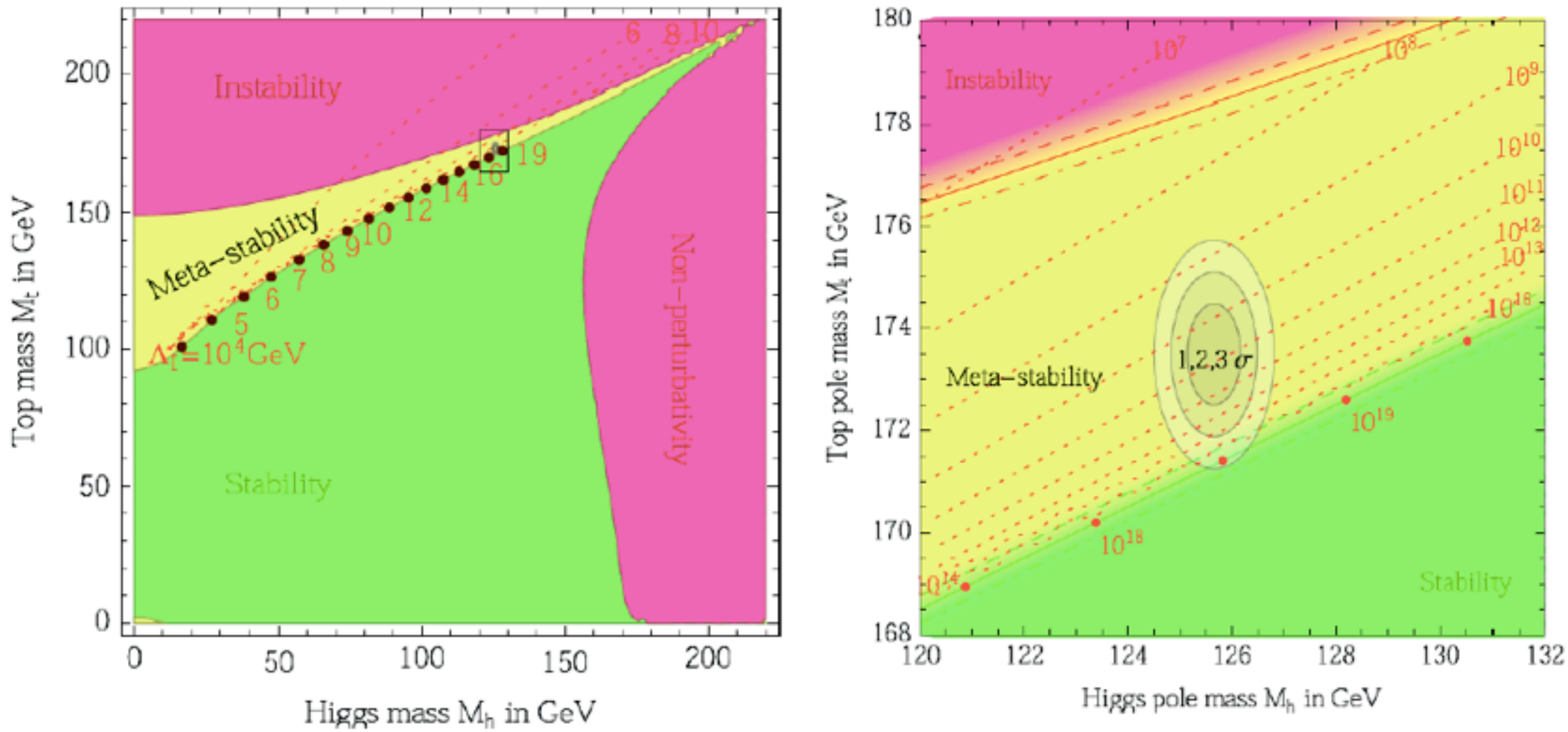
Triviality and Stability



$$\frac{d\lambda}{d\log\mu} = \frac{3}{8\pi^2}\left[4\lambda^2 + 2\lambda g_t^2 - g_t^4\right]$$

T. Hambye and K. Riesselmann, Phys. Rev. D55, 7255 (1997), [hep-ph/9610272].

Updated



We live in a metastable universe close to the border with the stability region.

Stability condition:

$$\frac{M_h}{\text{GeV}} > 129.6 + 1.3\left(\frac{M_t - 173.35\,\text{GeV}}{0.65\,\text{GeV}}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{\text{pert.}} \pm 0.6_{\text{non-pert.}}$$

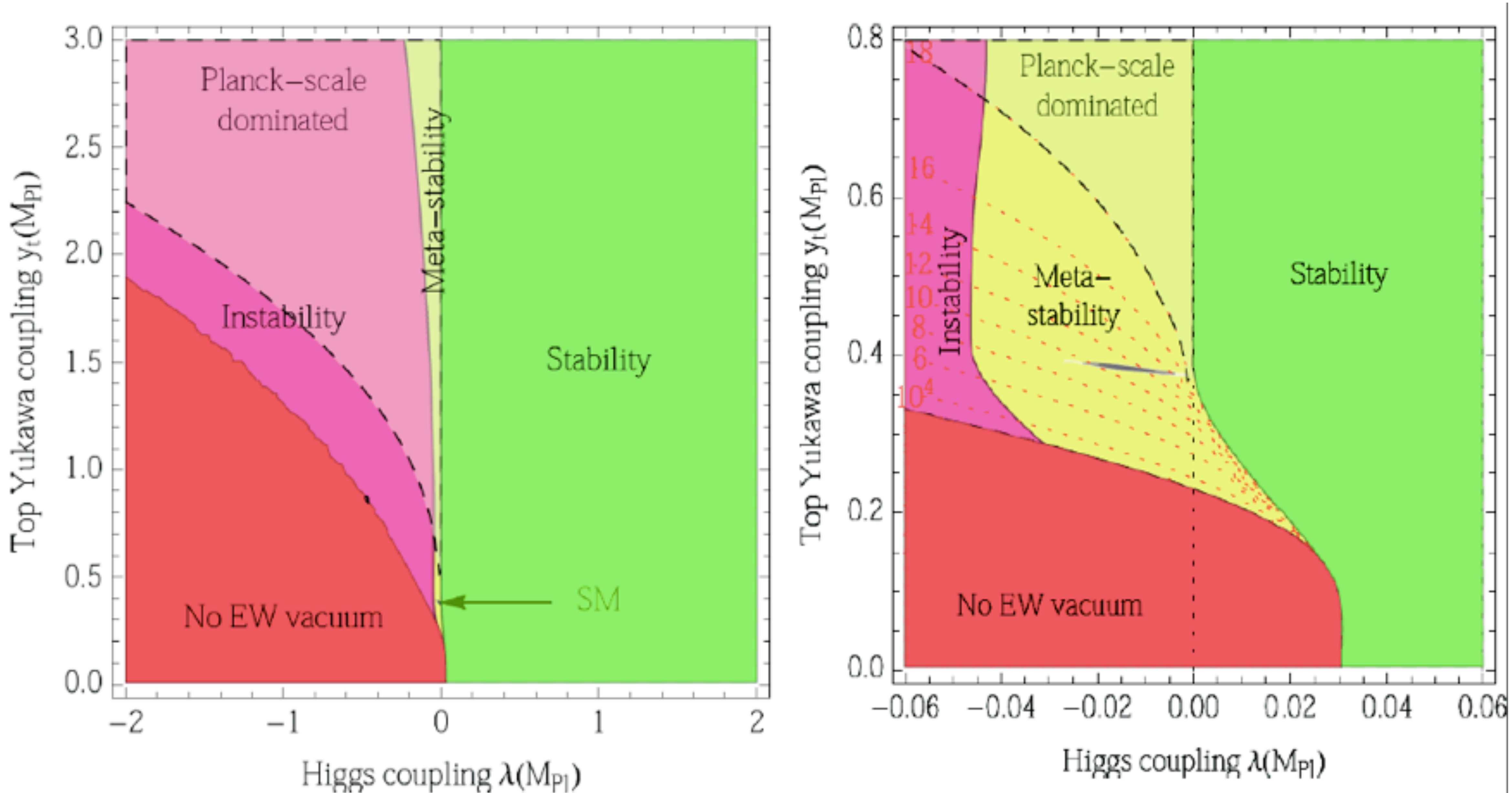
$$M_t < (171.36 \pm 0.15_{\text{pert.}} \pm 0.30_{\text{non-pert.}} \pm 0.25_{\alpha_s} \pm 0.17_{M_h})\,\text{GeV}$$

reduced

Or: other particles (e.g. superpartners) could stablize the potential...

DeGrassi, KITP 2013

Updated



$\lambda(M_{Pl})$ and $y_t(M_{Pl})$ almost at the minimum of the funnel

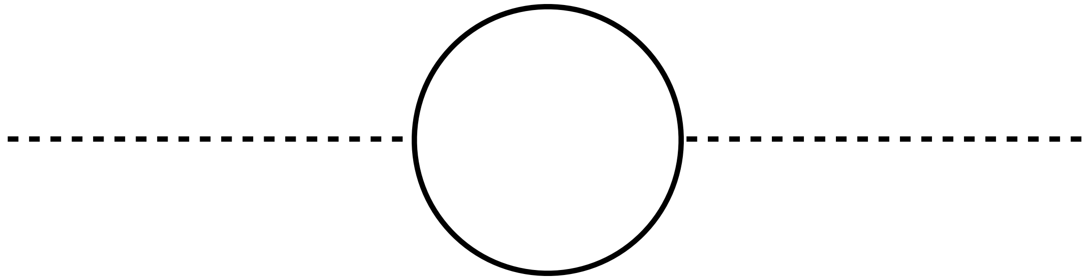
An accident or deep meaning?

DeGrassi, KITP 2013

Symmetry Magazine,
Oct 30, 2012

The Little Hierarchy Problem

The top-quark is not a small perturbation to the EWSB sector!



$$\delta m_H^2 \propto \frac{2\lambda_t^2 \Lambda^2}{16\pi^2}$$

$$\delta m_H^2 < m_H^2 \Rightarrow \Lambda \leq 1 - 2\,\mathrm{TeV}$$

Where is the new physics?
(Is there something wrong with this argument?)

“No Higgs” Theories

Technicolor:
Higgsless since 1976!

Technicolor

This line of reasoning inspired **Technicolor:**

introduce new gauge force with symmetry $SU(N)_{TC}$

force carriers are **techni**gluons, inspired by QCD gluons

add **techni**quarks carrying $SU(N)_{TC}$ charge:

matter particles inspired by QCD quarks

- e.g. $T_L = (U_L, D_L)$ forms a weak doublet

  U_R, D_R are weak singlets

- Lagrangian has familiar global (chiral) symmetry $SU(2)_L \times SU(2)_R$

Susskind, Weinberg

Technicolor

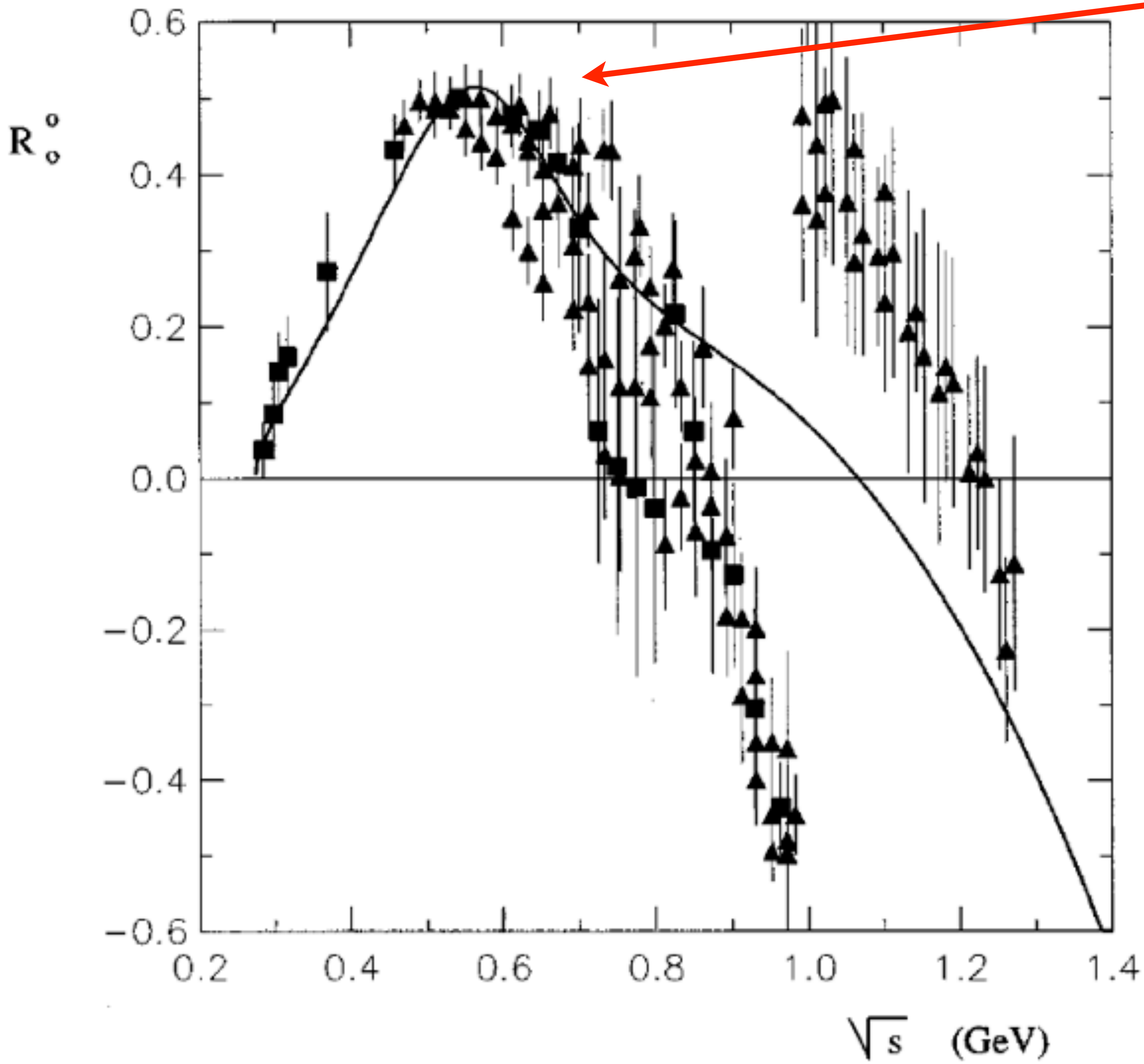
If SU(N)$_{TC}$ force were stronger than QCD ... then spontaneous symmetry breaking and pion formation would happen at a higher energy scale... e.g.

- gauge coupling becomes large at $\Lambda_{TC} \approx 1000\,\mathrm{GeV}$
- $\langle T_L T_R \rangle \approx 250\,\mathrm{GeV}$ breaks electroweak symmetry
- \`**techni**pions' Π_{TC} become the W_L, Z_L
- W and Z boson masses are the size seen in experiment!

(What about fermion masses?)

Is there a Higgs in Technicolor?

Look at ππ scattering in QCD:



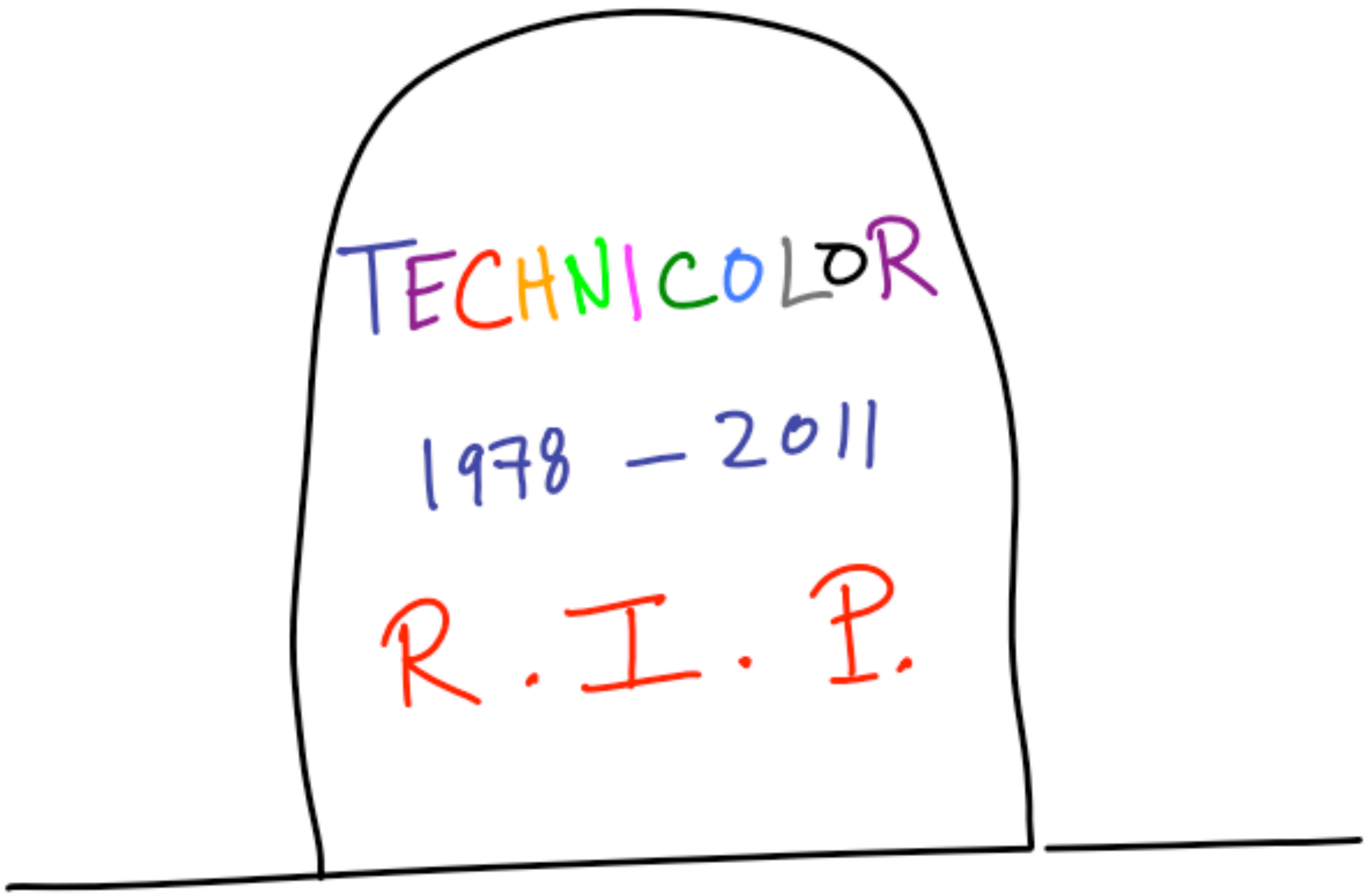
σ-meson:
M_σ= 560 MeV ≅ 6 f_π
Γ_σ=400 MeV ≅ 4 f_π

Natural expectation in Technicolor ($f_\pi \to v$):
Heavy meson (1.5 TeV) that is very broad (1 TeV)

(Mixing?)

Discussion Question

Obvious Implications of $m_H \sim 125$ GeV ?



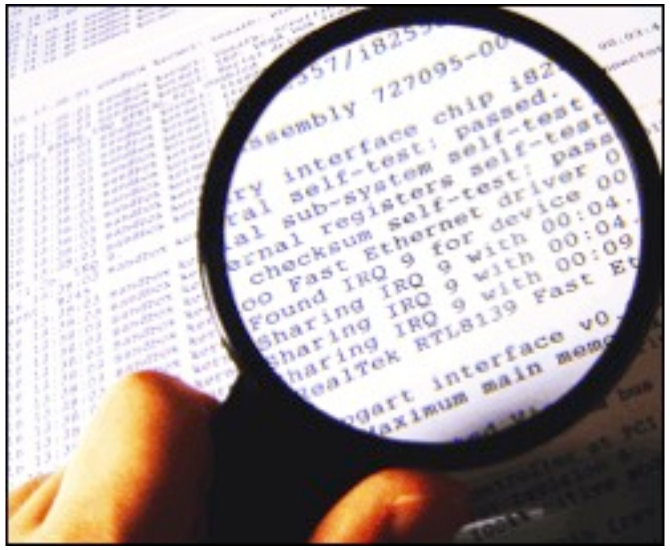
N.Arkani-Hamed, SavasFest 2012

Dilaton?

Space-time Symmetries of Field Theory

- Poincare Invariance
- C, P, and T (as written...)
- (Approximate) Scale Invariance*

A scale transformation:



$$x^\mu \to \lambda \cdot x^\mu$$

$$\psi_q(x) \to \lambda^{3/2}\psi_q(\lambda x) \qquad A^a_\mu(x) \to \lambda\, A^a_\mu(\lambda x)$$

NB: Broken by all mass terms...

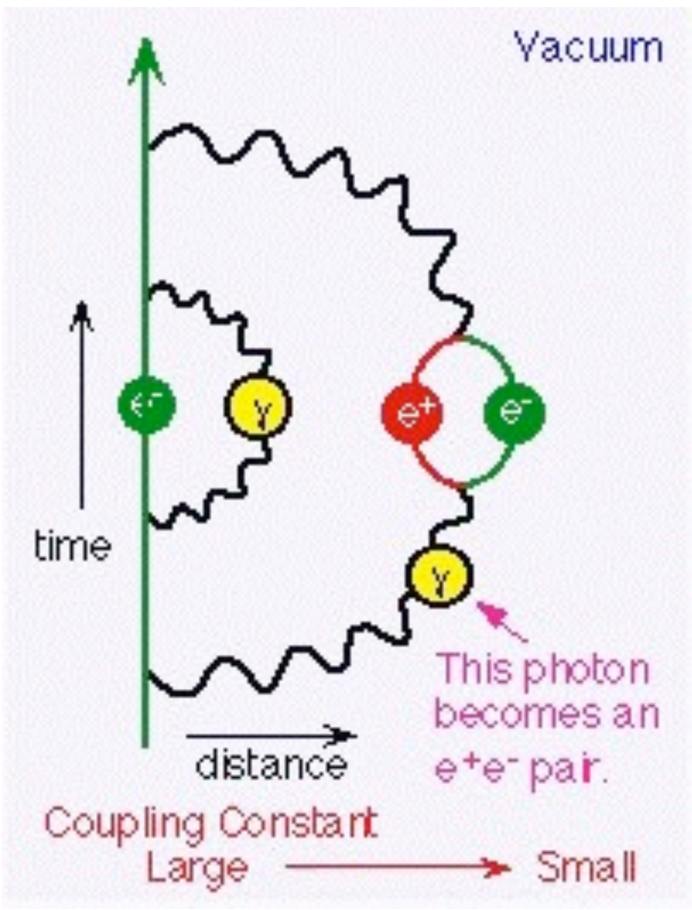
*(& Proper conformal trans.)

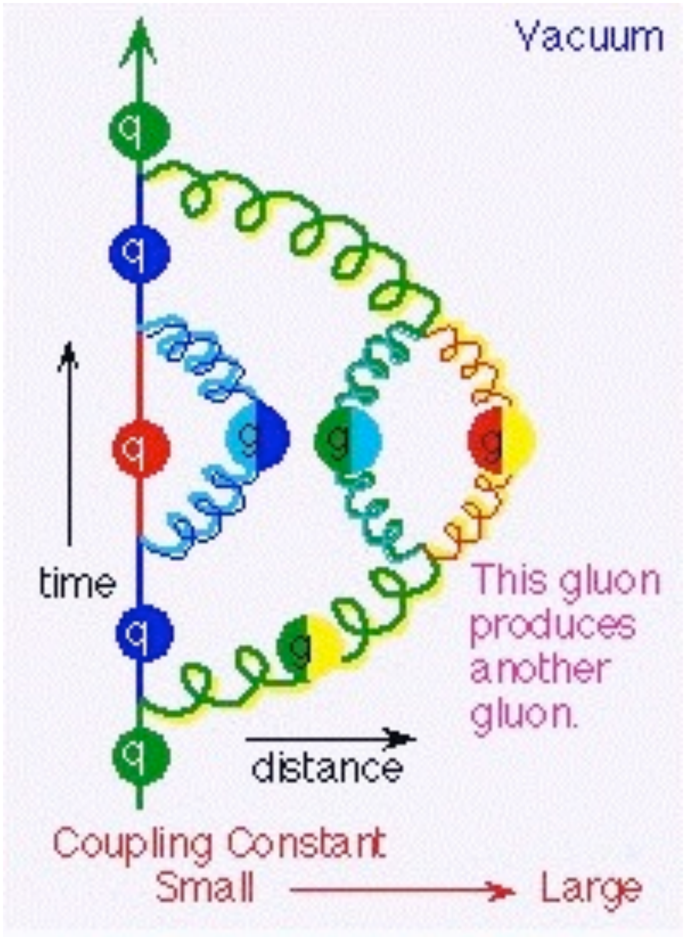
NB: Local scale invariance the reason for the name "gauge transformation" (Weyl)

No Quantum Scale-Invariance

- Quantum vacuum is a polarizable medium

QED





QCD

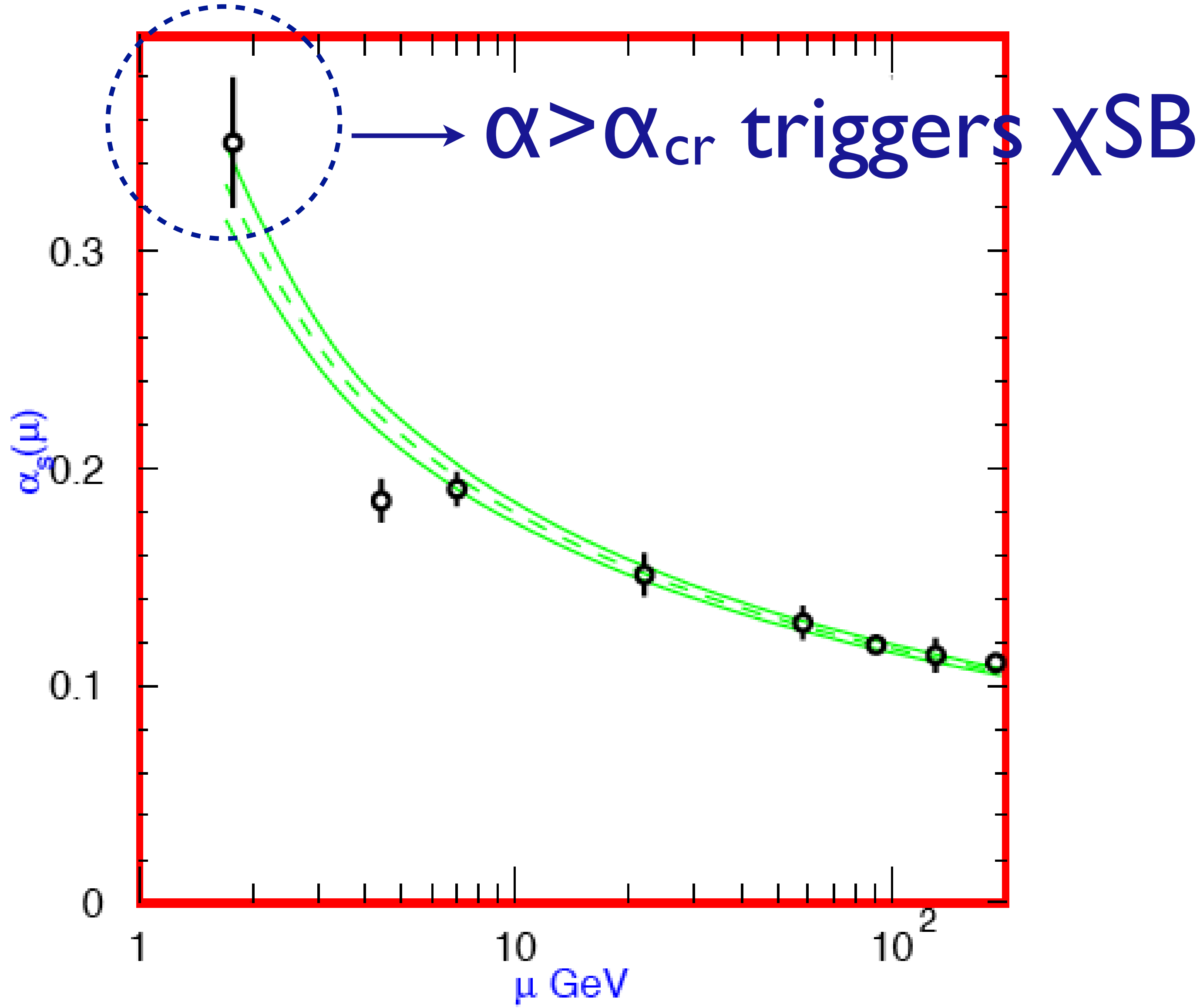
Fermions and Gluons make opposite contributions!

QCD Beta Function

$$\mu\frac{\partial\alpha_s}{\partial\mu} = 2\beta(\alpha_s) = -\frac{\beta_0}{2\pi}\alpha_s^2 - \frac{\beta_1}{4\pi^2}\alpha_s^3$$

$$\beta_0 = 11 - \frac{2}{3}n_f\ ,$$

$$\beta_1 = 51 - \frac{19}{3}n_f\ ,$$



Asymptotic Freedom

vs.

Infrared Slavery

RPP2004

2004 Nobel Prize:

Gross, Politzer, Wilczek

A Model Builder's Dream

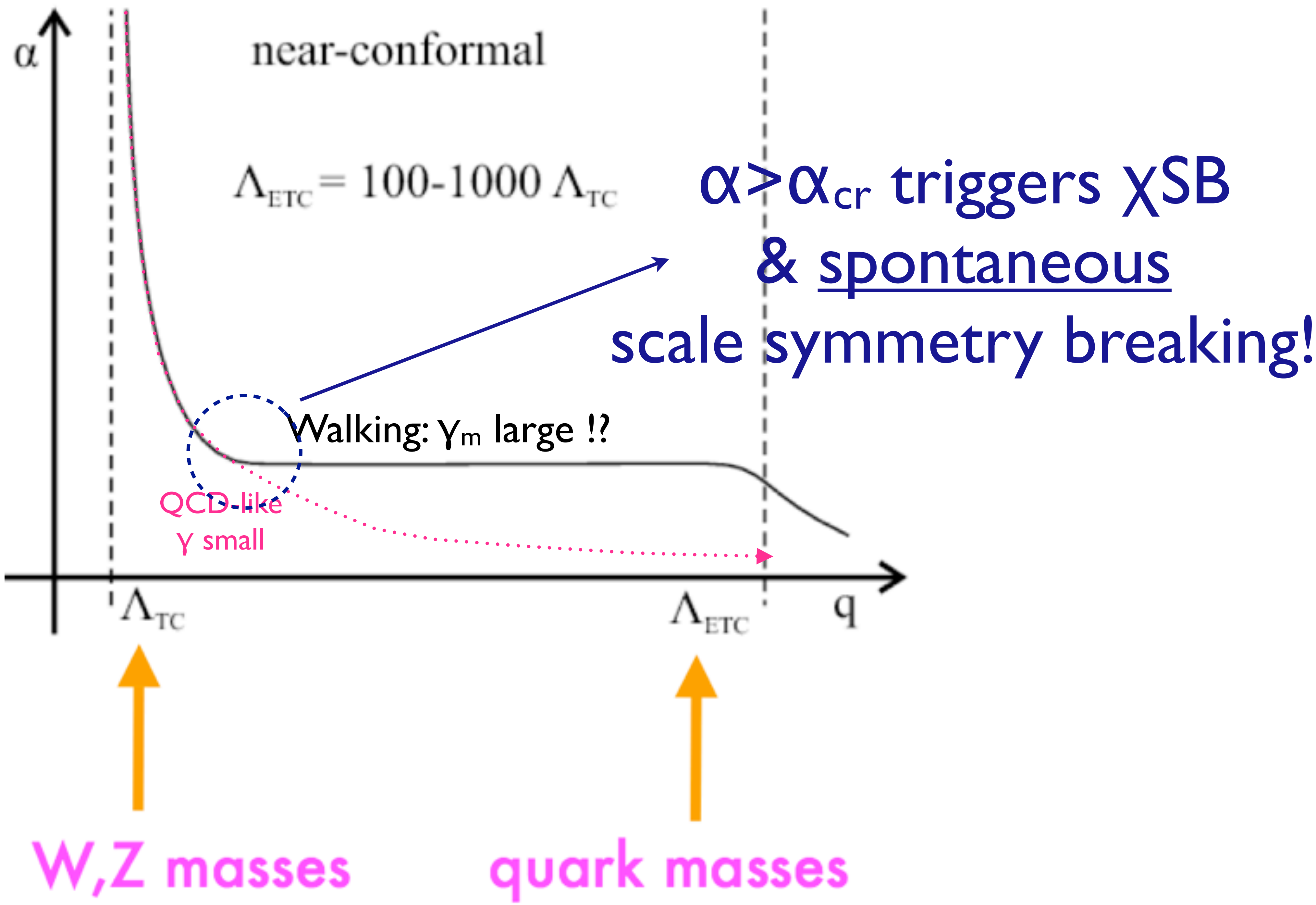


Figure: K. Holland XQCD 2008

Dilaton Couples to Scale Current

- A continuous symmetry has a conserved current, but scale symmetry is anomalous.

$$\partial_\mu s^\mu = T^\lambda_\lambda = -\sum_i \frac{\beta_i}{2g_i} F^2_{i\mu\nu} - \sum_q m_q \bar{\psi}_q \psi_q + M_Z^2 Z_\mu^2 + 2M^2 W^+_\mu W^{-\mu}$$

Quantum Effect!

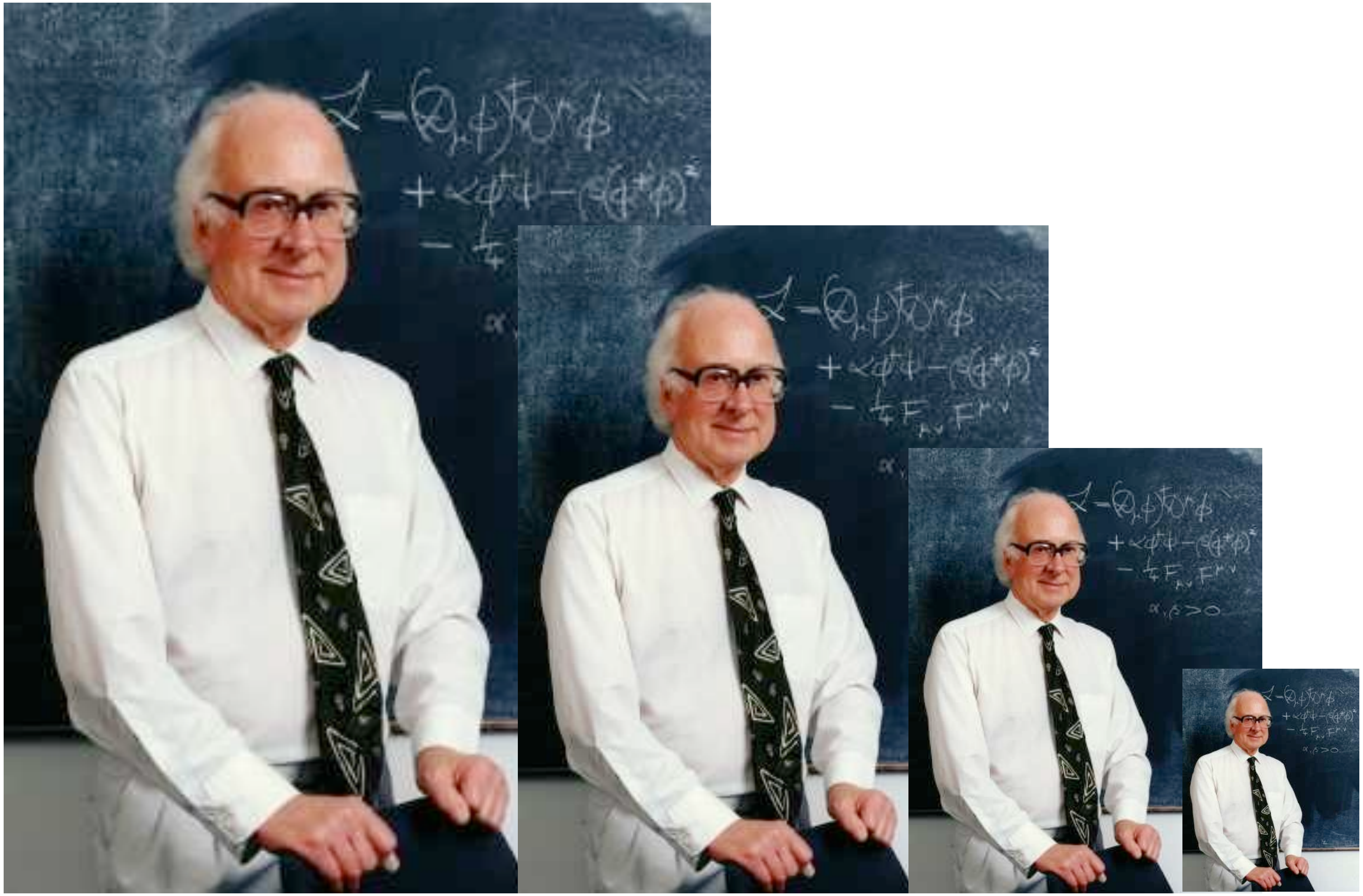
- A dilaton-“Higgs” couples via

$$\frac{H}{f_\sigma} T^\lambda_\lambda$$

- Higgs-like, but
  - But $f_\pi \neq f_\sigma$, hence $\delta g_H / g_H = O(100\%)$
  - Even assuming $f_\pi = f_\sigma$, wrong gg and $\gamma\gamma$ couplings?

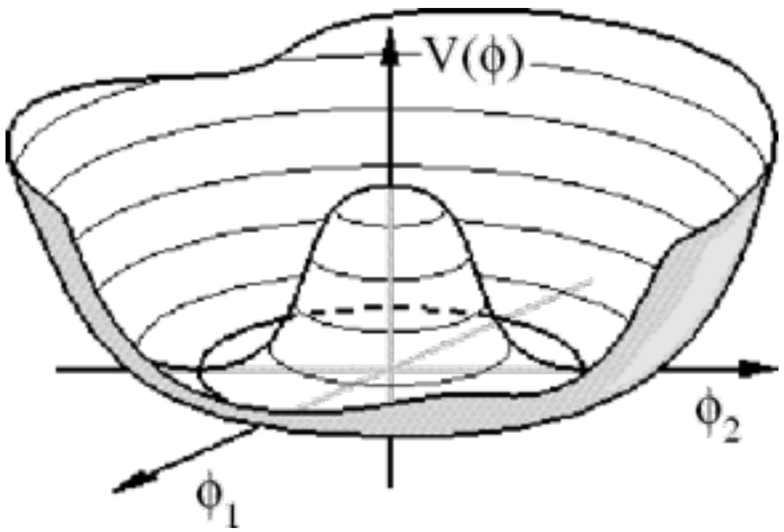
“Composite Higgs”

Composite Higgs



Composite Higgs

Higgs as (Pseudo-)Goldstone Boson:



Hard to do!

$$V(h) = \frac{Cg^2}{16\pi^2}\left(-\eta_2 f^2|h|^2 + \eta_4\frac{|h|^4}{2} + \ldots\right)$$

$g \ll 1$ — Decay Constant

Yields: $\langle h\rangle^2 \simeq \frac{\eta_2}{\eta_4} f^2$ (But, EWPT: $f >$ few TeV)

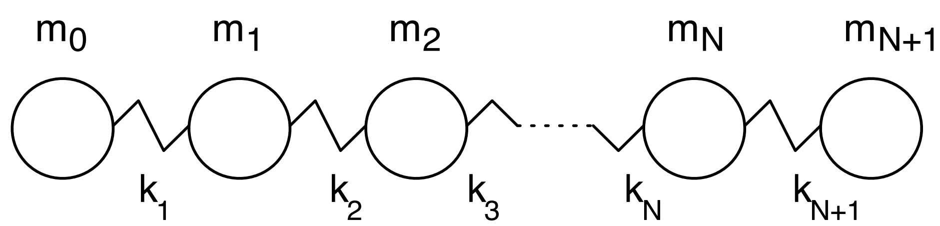
Must suppress η_2 without suppressing η_4

Georgi & Kaplan; Banks

Chacko et. al., hep-ph/0510273

Little Higgs Theories

Collective Symmetry Breaking:



For weak springs, masses at end very weakly coupled!

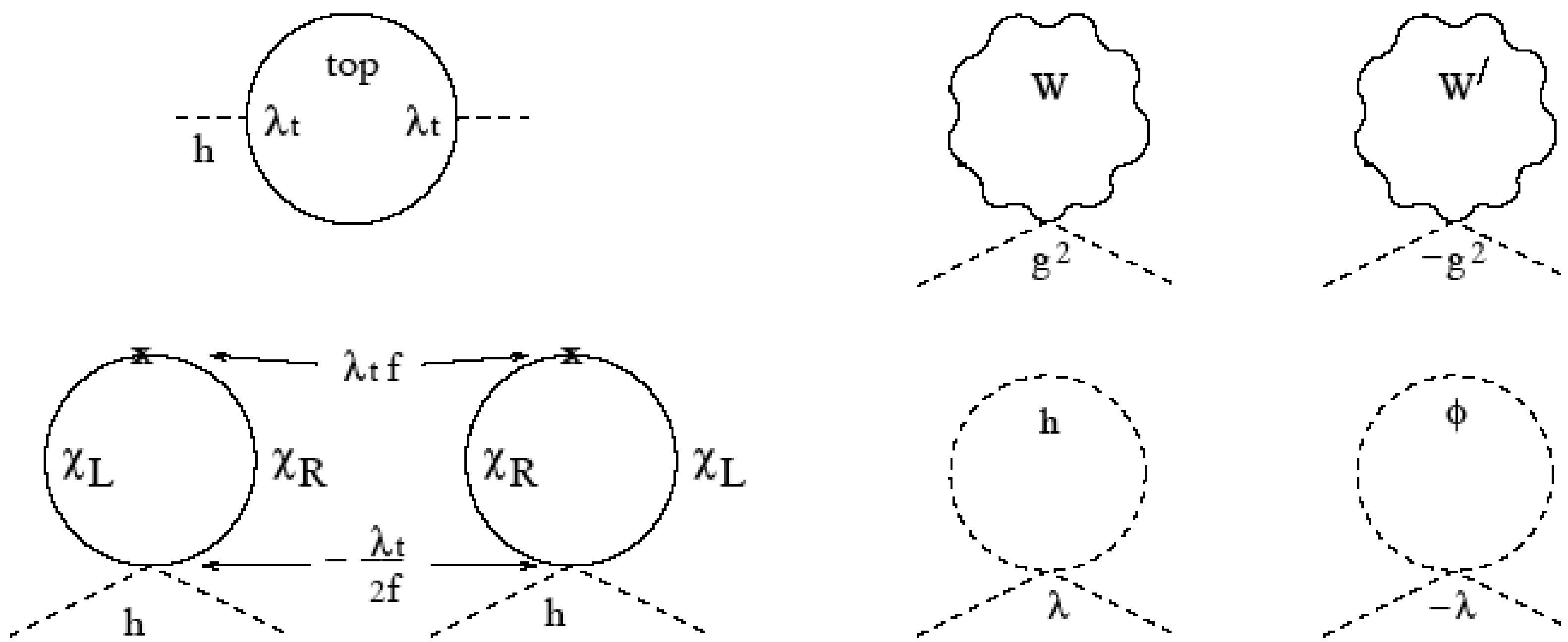
In practice: $$\frac{\eta_2}{\eta_4} \simeq \frac{g^2}{16\pi^2} \qquad m_h^2 \simeq \frac{g^2}{16\pi^2} f^2$$

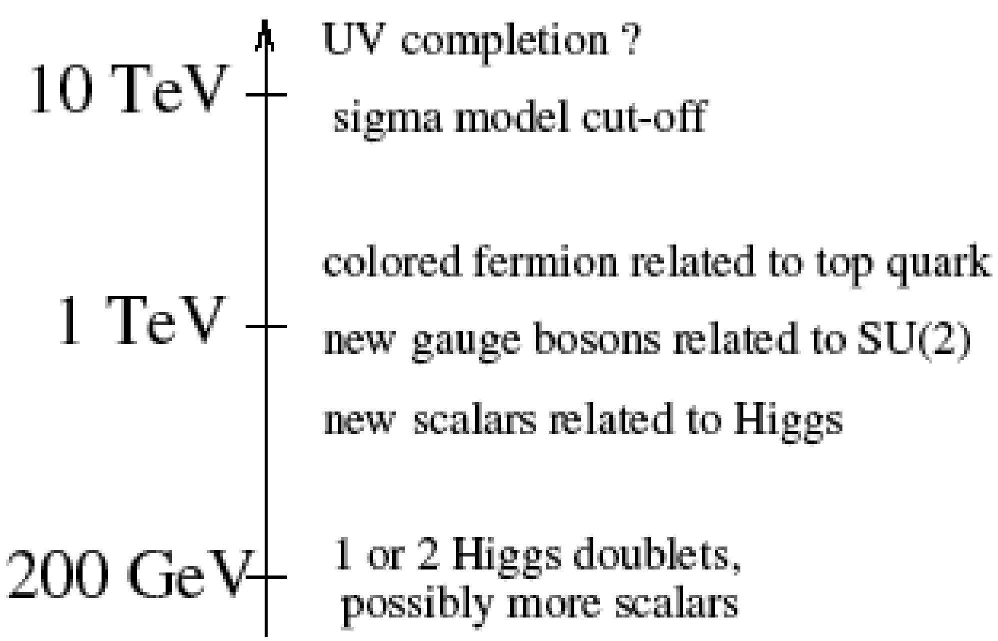
Global Symmetries	Gauge Symmetries	triplet	# Higgs
$SU(5)/SO(5)$	$[SU(2)\times U(1)]^2$	Yes	1
$SU(3)^8/SU(3)^4$	$SU(3)\times SU(2)\times U(1)$	Yes	2
$SU(6)/Sp(6)$	$[SU(2)\times U(1)]^2$	No	2
$SU(4)^4/SU(3)^4$	$SU(4)\times U(1)$	No	2
$SO(5)^8/SO(5)^4$	$SO(5)\times SU(2)\times U(1)$	Yes	2
$SU(9)/SU(8)$	$SU(3)\times U(1)$	No	2
$SO(9)/[SO(5)\times SO(4)]$	$SU(2)^3\times U(1)$	Yes	1

Arkani-Hamed, Cohen, Georgi

Meade, hep-ph/0402036

Little Higgs: The Hierarchy





Cancellation of divergences by particles of same spin!

T-Parity: minimize Z-pole effects & DM

Schmaltz hep-ph/0210415

Constraints On Composite Higgs

D ≤ 4 interactions same as standard model!

Higher dimension operators:

$$\frac{(\phi^\dagger D^\mu \phi)^2}{f^2} \quad \Rightarrow \quad \Delta T \neq 0,\ f > \text{few TeV}$$

$$\frac{(\phi^\dagger \phi) D^\mu \phi^\dagger D_\mu \phi}{f^2}$$

$$\frac{\phi^\dagger \phi}{f^2} \sum_q m_q \bar{\psi}_q \psi_q$$

$$\frac{\alpha_s}{4\pi}\left(\frac{\phi^\dagger \phi}{f^2}\right) G^{a\mu\nu} G^a_{\mu\nu}$$

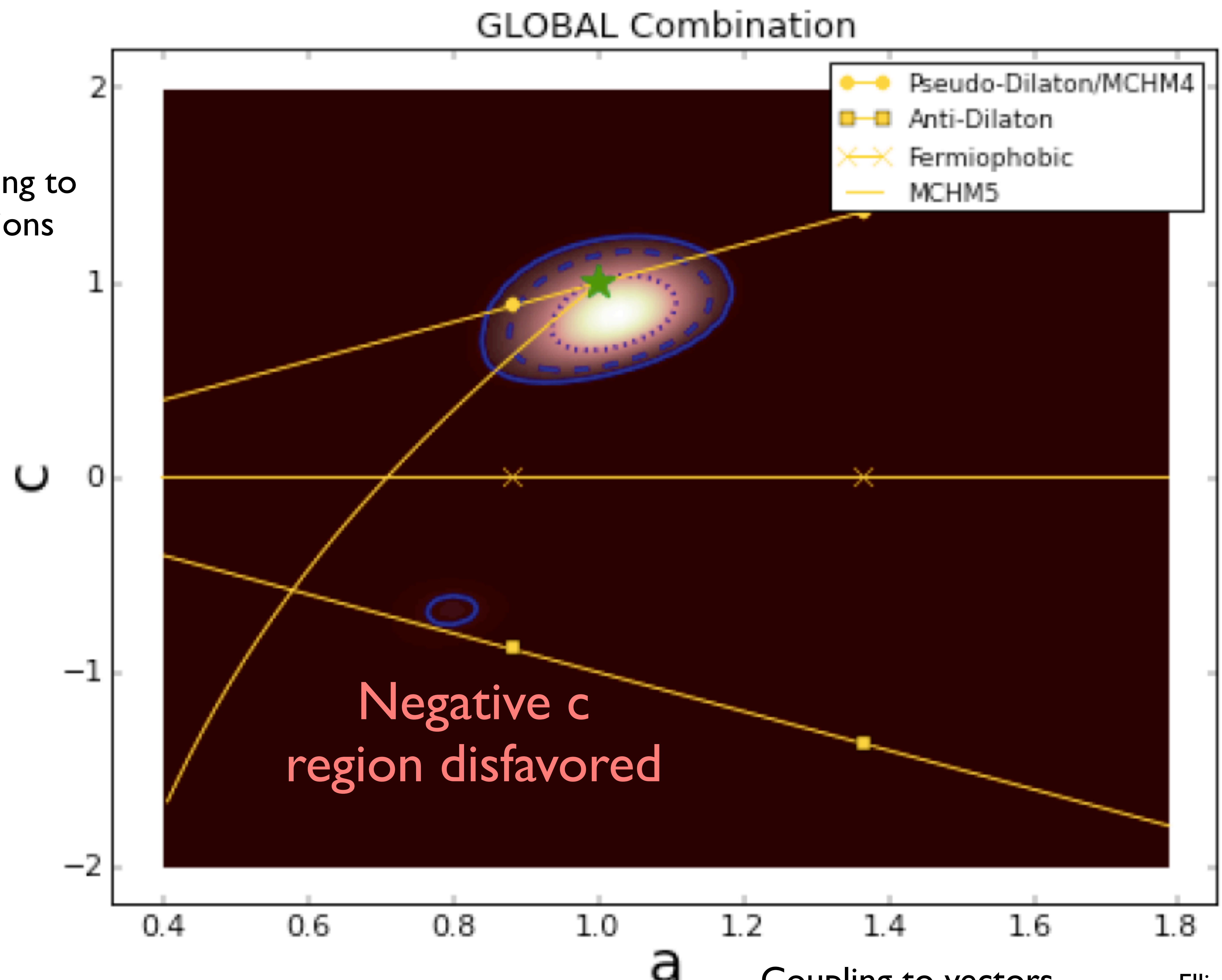
$$\frac{\alpha_Y}{4\pi}\left(\frac{\phi^\dagger \phi}{f^2}\right) B^{\mu\nu} B_{\mu\nu}$$

$$\delta g_H = \mathcal{O}\left(\frac{v^2}{f^2}\right) = \mathcal{O}(10\%)$$

Ignored on next page

Flavor-Universal Deviations

Coupling to fermions



Coupling to vectors

Ellis and You

Multiple Higgs,
SUSY & Decoupling

Two-Higgs Model

$$\phi_{1,2} = \begin{pmatrix} \phi_{1,2}^{+} \\ \phi_{1,2}^{0} \end{pmatrix} \quad ,$$

With softly broken $\phi_1 \to -\phi_1$ symmetry,

$$\begin{aligned} V(\phi_1, \phi_2) &= \lambda_1(\phi_1^\dagger \phi_1 - v_1^2/2)^2 + \lambda_2(\phi_2^\dagger \phi_2 - v_2^2/2)^2 \\ &+ \lambda_3 \left[(\phi_1^\dagger \phi_1 - v_1^2/2) + (\phi_2^\dagger \phi_2 - v_2^2/2)\right]^2 \\ &+ \lambda_4 \left[(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) - (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)\right] \\ &+ \lambda_5 \left[\mathrm{Re}(\phi_1^\dagger \phi_2) - v_1 v_2 \cos\xi/2\right]^2 \\ &+ \lambda_6 \left[\mathrm{Im}(\phi_1^\dagger \phi_2) - v_1 v_2 \sin\xi/2\right]^2 \quad . \end{aligned}$$

Two-Higgs Model

For a range of λ_i & for $v_1^2,\, v_2^2 > 0 \Rightarrow$

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} \quad , \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v_2 e^{i\xi}/\sqrt{2} \end{pmatrix} .$$

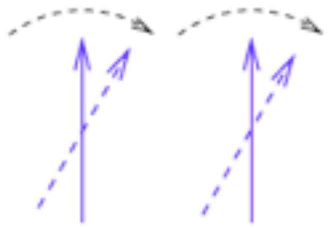
$$M_W^2 = \frac{g^2}{2}(v_1^2 + v_2^2)\ ,\ \rho = \frac{M_W}{M_Z \cos\theta_W} \equiv 1$$

$v_1^2 + v_2^2 = v^2 \approx (246\,\mathrm{GeV})^2$.

Simplify: $\sin\xi = 0$ (avoid CP-violation)

Define $\cos\beta = v_1/v$ & $\sin\beta = v_2/v$.

- Three "eaten" Goldstone Bosons:



$$G^{\pm,0} = (\phi_1^{\pm}, \sqrt{2}\,\mathrm{Im}\,\phi_1^0)\cos\beta + (\phi_2^{\pm}, \sqrt{2}\,\mathrm{Im}\,\phi_2^0)\sin\beta$$

Two-Higgs Model

- Three pseudo-scalar bosons: 

$$(H^{\pm}, A^0) = -(\phi_1^{\pm}, \sqrt{2}\,\mathrm{Im}\phi_1^0)\sin\beta + (\phi_2^{\pm}, \sqrt{2}\,\mathrm{Im}\phi_2^0)\cos\beta$$

$$m_{H^{\pm}}^2 = \lambda_4(v_1^2 + v_2^2)/2 \quad \neq \quad m_{A^0}^2 = \lambda_6(v_1^2 + v_2^2)/2$$

- Two neutral scalars:

$$(H_1, H_2) = (\sqrt{2}\,\mathrm{Re}\,\phi_{1,2}^0 - v_{1,2}).$$

$$\begin{pmatrix} 2v_1^2(\lambda_1 + \lambda_3) + v_2^2\lambda_5/2 & (4\lambda_3 + \lambda_5)v_1 v_2/2 \\ (4\lambda_3 + \lambda_5)v_1 v_2/2 & 2v_1^2(\lambda_2 + \lambda_3) + v_2^2\lambda_5/2 \end{pmatrix}$$

Mass Eigenstates $\Rightarrow$ Mixing-angle α

$$\begin{aligned} H^0 &= H_1\cos\alpha + H_2\sin\alpha \\ h^0 &= -H_1\sin\alpha + H_2\cos\alpha \end{aligned}$$

Couplings to Fermions

Most general quark couplings:

$$\sum_{ij}\left[\lambda^u_{1ij}\bar{q}^i_L\tilde{\phi}_1 u_j + \lambda^u_{2ij}\bar{q}^i_L\tilde{\phi}_2 u_j + \lambda^d_{1ij}\bar{q}^i_L\phi_1 d_j + \lambda^d_{2ij}\bar{q}^i_L\phi_2 d_j\right] + h.c.$$

Fermion masses and Higgs couplings not diagonalized at same time!

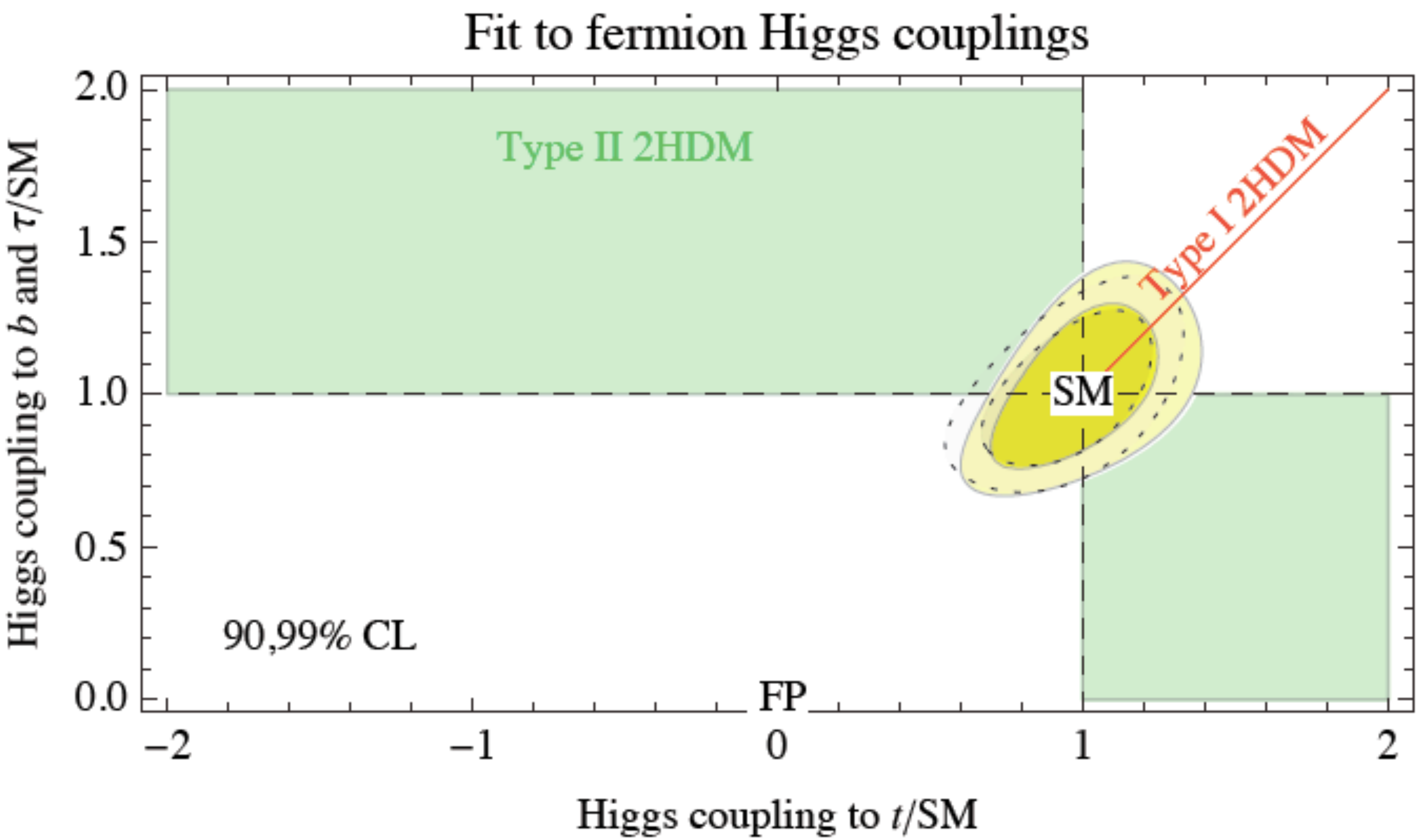
Model-building solutions:

- "Type-I": $\lambda_{2u,d}$=0
  One Higgs gives mass only to W and Z

- "Type-II": λ_{2u}=0 & λ_{1d}=0
  Each Higgs gives mass to only ups or downs
  $m_d \propto 1/\sin\beta$, could have $\lambda_t = \lambda_b$

Glashow and Weinberg, 1977

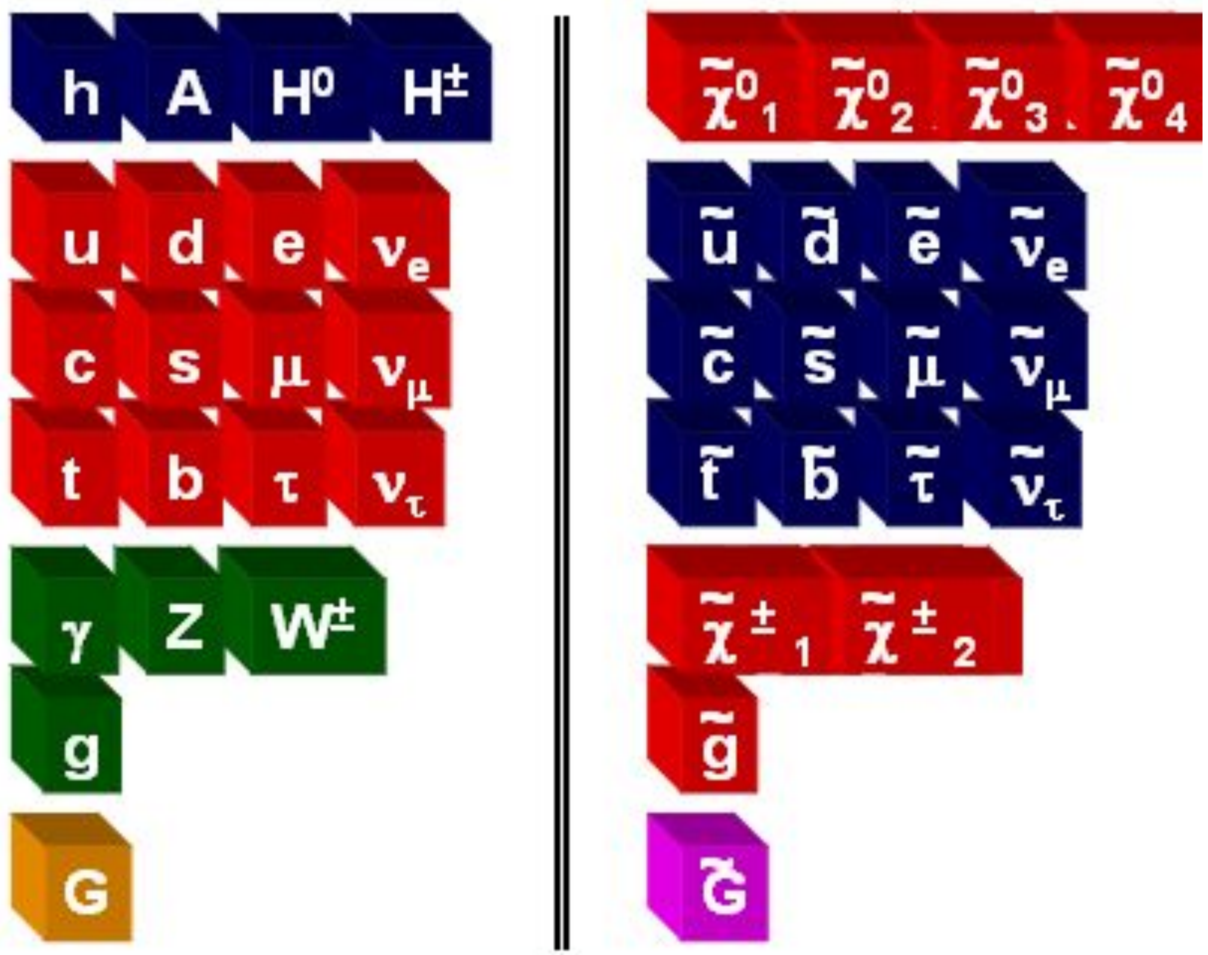
Limits on Two-Higgs Models

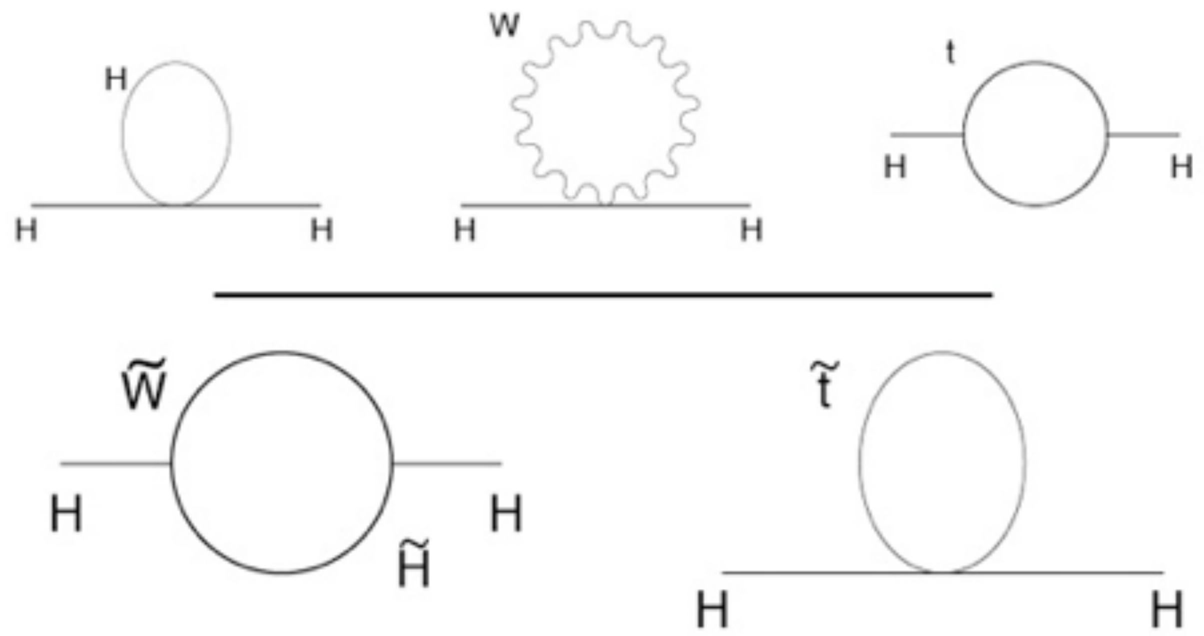


Giardino, et. al.

SuperSymmetry

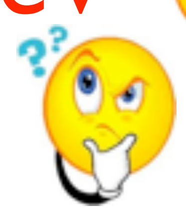
Make the Higgs Boson natural!





- Higgs mass protected by chiral symmetry of partner
  - $\Delta m^2_H \propto \log(M^2_{SUSY})$
  - $\lambda \propto g^2, g'^2$, m_H bounded by ~130 GeV

  - Why is μ of order a TeV?



the canonical BSM paradigm

- Natural + ~MFV SUSY at the weak scale
- Neutralino dark matter
- A grand desert populated at the high end by a hidden sector for dynamical SUSY breaking, some heavy Majorana neutrinos, maybe PQ axions, inflatons
- Gauge coupling unification circa 10^{16} GeV accompanied by GUT or stringy unification of matter and gauge forces
- Planck scale stringiness with lots of extra structure to explain flavor etc.

lots of good arguments for this picture

Talks by Gordy Kane, Carlos Wagner and Paul Langacker

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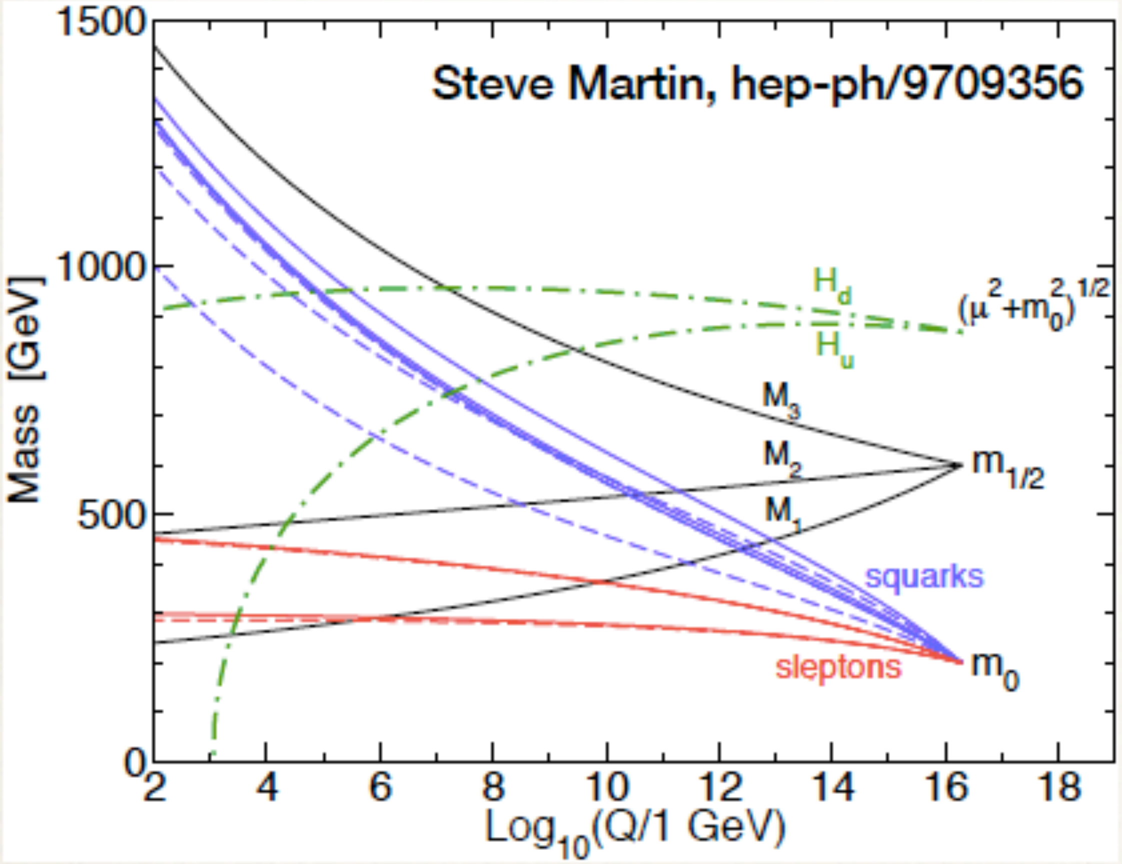
the canonical BSM paradigm

the experimental program that goes with this paradigm is pretty clear:

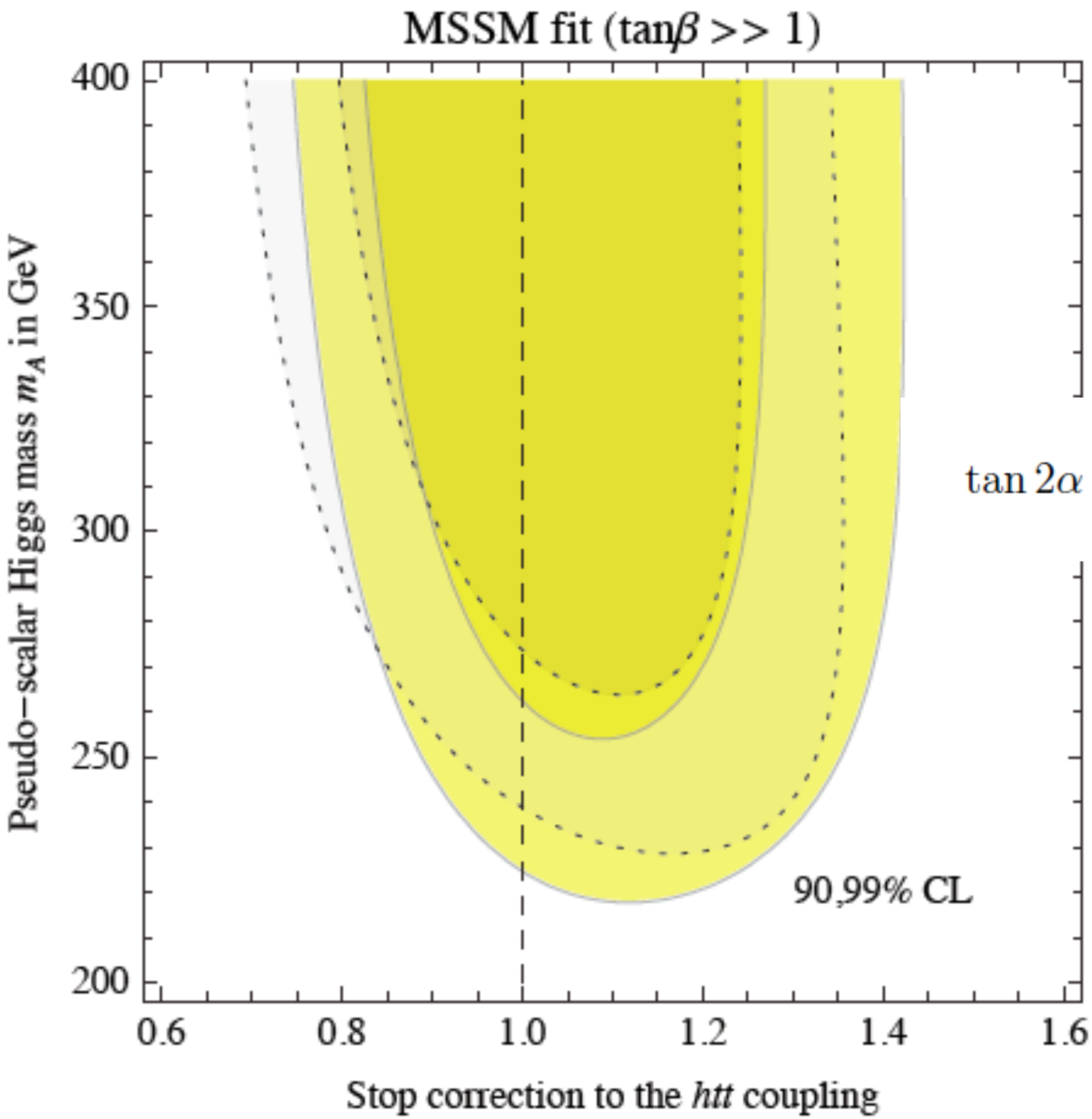
- ✔ Find a light fundamental Higgs boson
- Find superpartners, nail down masses, flavor, CP
- Nail down the extended Higgs sector
- Close the circle on dark matter between colliders, DD, ID, and large scale structure
- Nail down the neutrino sector, proton decay, CLFV
- Extrapolate everything to high scales, deduce features of the UV theory (compactification, unification, etc)
- Apply insights to cosmology, dark energy, black holes



SuperSymmetry & Decoupling

- SUSY requires two Higgs bosons to give u- and d-masses ("type-II")
- In limit all soft SUSY breaking masses get large, $\sin(\beta-\alpha)\rightarrow 1$
  - Lightest Higgs standard model-like! 
    - Decoupling regime? 
  - But where are superpartners? 

SUSY Higgs Sector Limits



$$\tan 2\alpha = \frac{m_A^2 + M_Z^2}{m_A^2 - M_Z^2} \tan 2\beta.$$

Giardino, et. al.

SUSY Higgs Sector Limits

How easy is to get M_H ~ 125 GeV in the MSSM ?

$$M_h^2 \simeq M_z c_{2\beta}^2 + \frac{3\, m_t^4}{4\,\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right] + \ldots$$

SUSY breaking parameters

$$X_t = A_t - \mu \cot\beta,\;\; M_S = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}})$$

To get M_H ~ 125 GeV:

- Large tan β, tan β > 10 (increase the tree-level)
- Heavy stops, i.e. large M_S (increase the ln)
- Large stop mixing, i.e. large X_t

The more assumptions we take on the mechanism of SUSY-breaking, the more difficult becomes to get M_H ~ 125 GeV

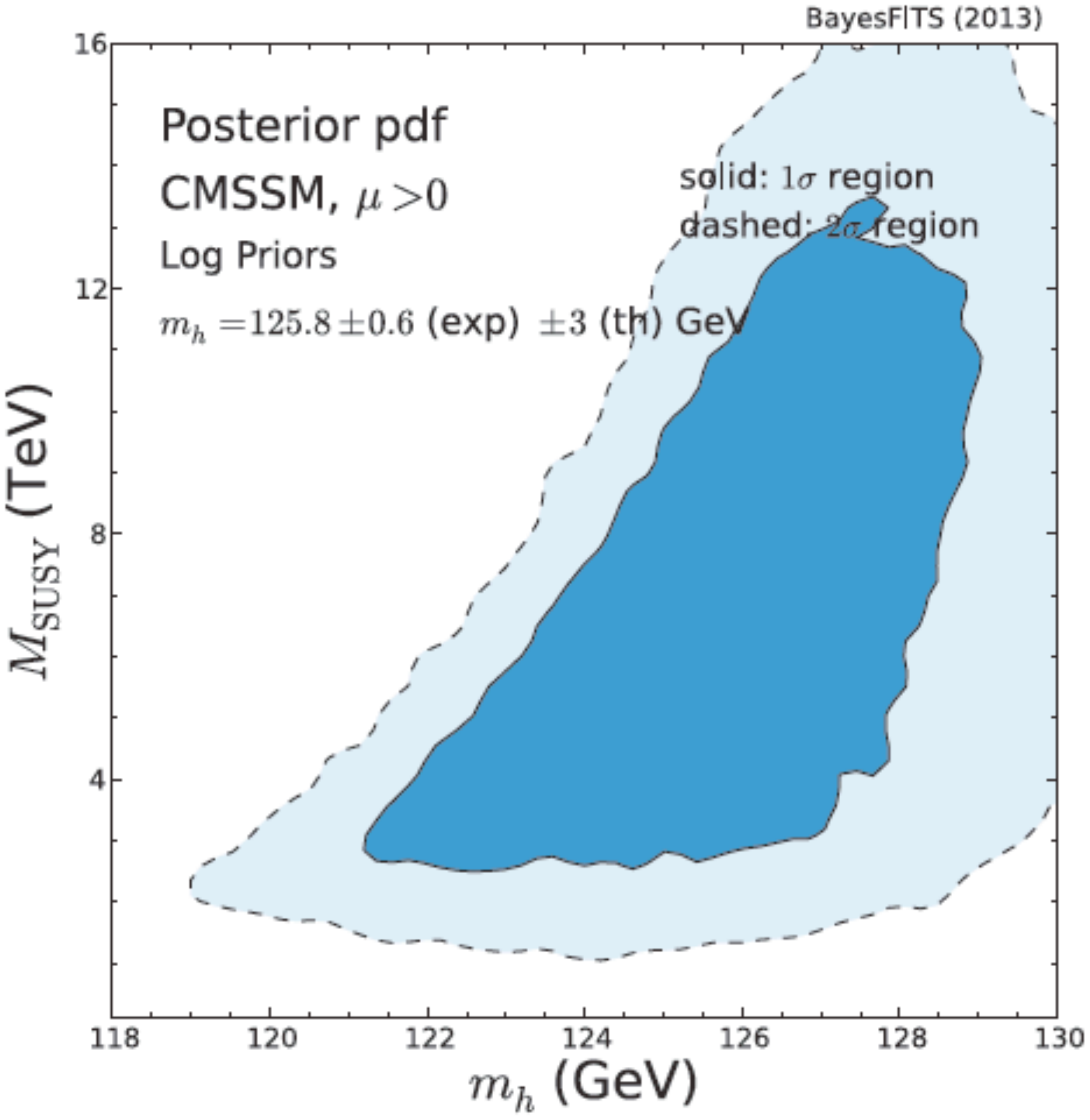
DeGrassi, KITP 2013

The 126 GeV Higgs Boson and SUSY

A curse…

-> Multi-TeV scale of SUSY

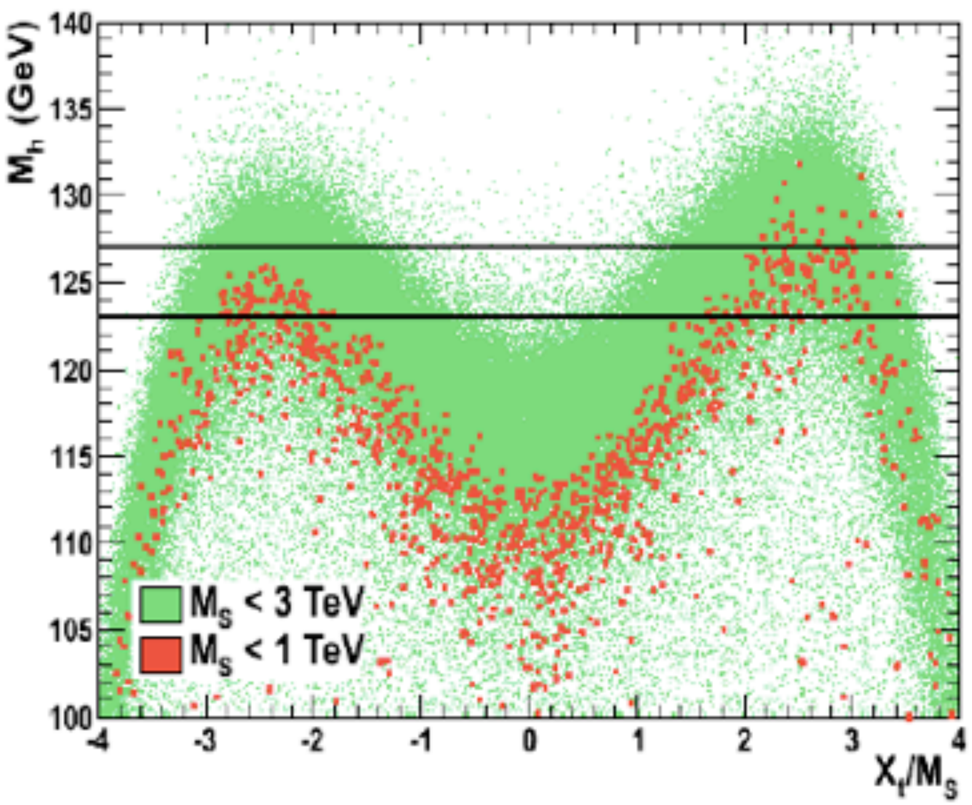
Only m_h~126 GeV and CMS lower bounds on SUSY applied.

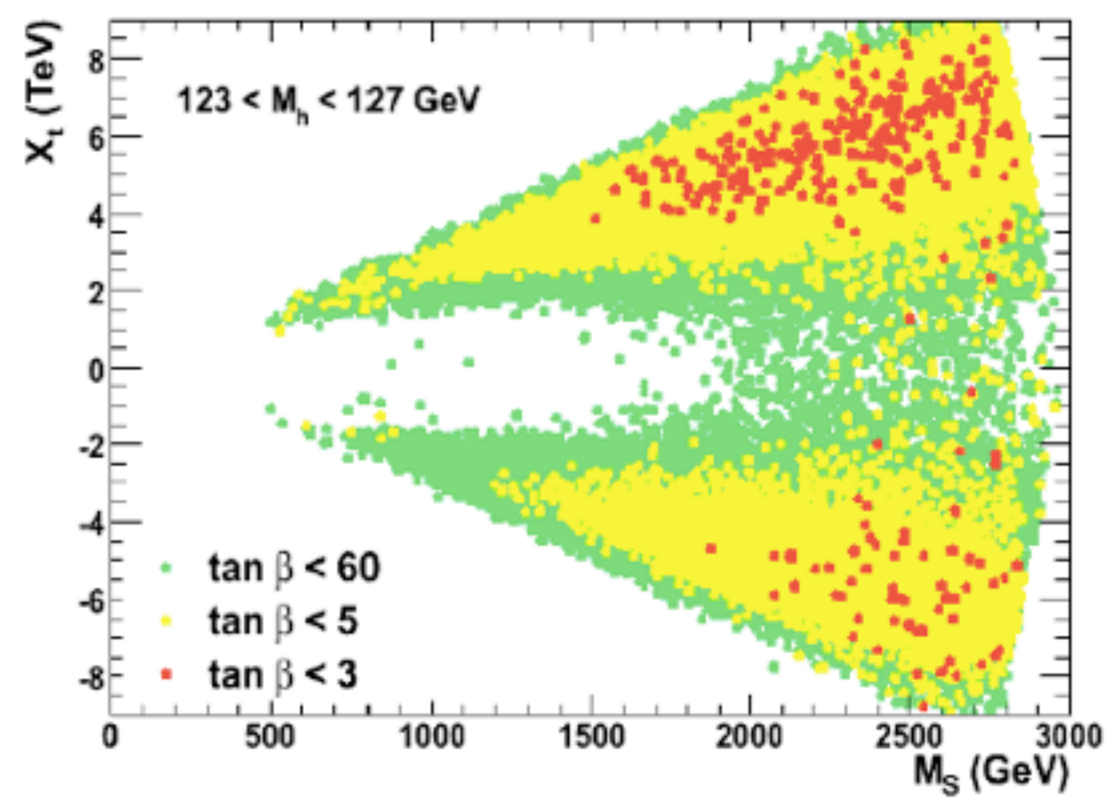


$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

SUSY Higgs Sector Limits

pMSSM: minimal assumptions on SUSY-breaking parameters





Arbey et al., 2011

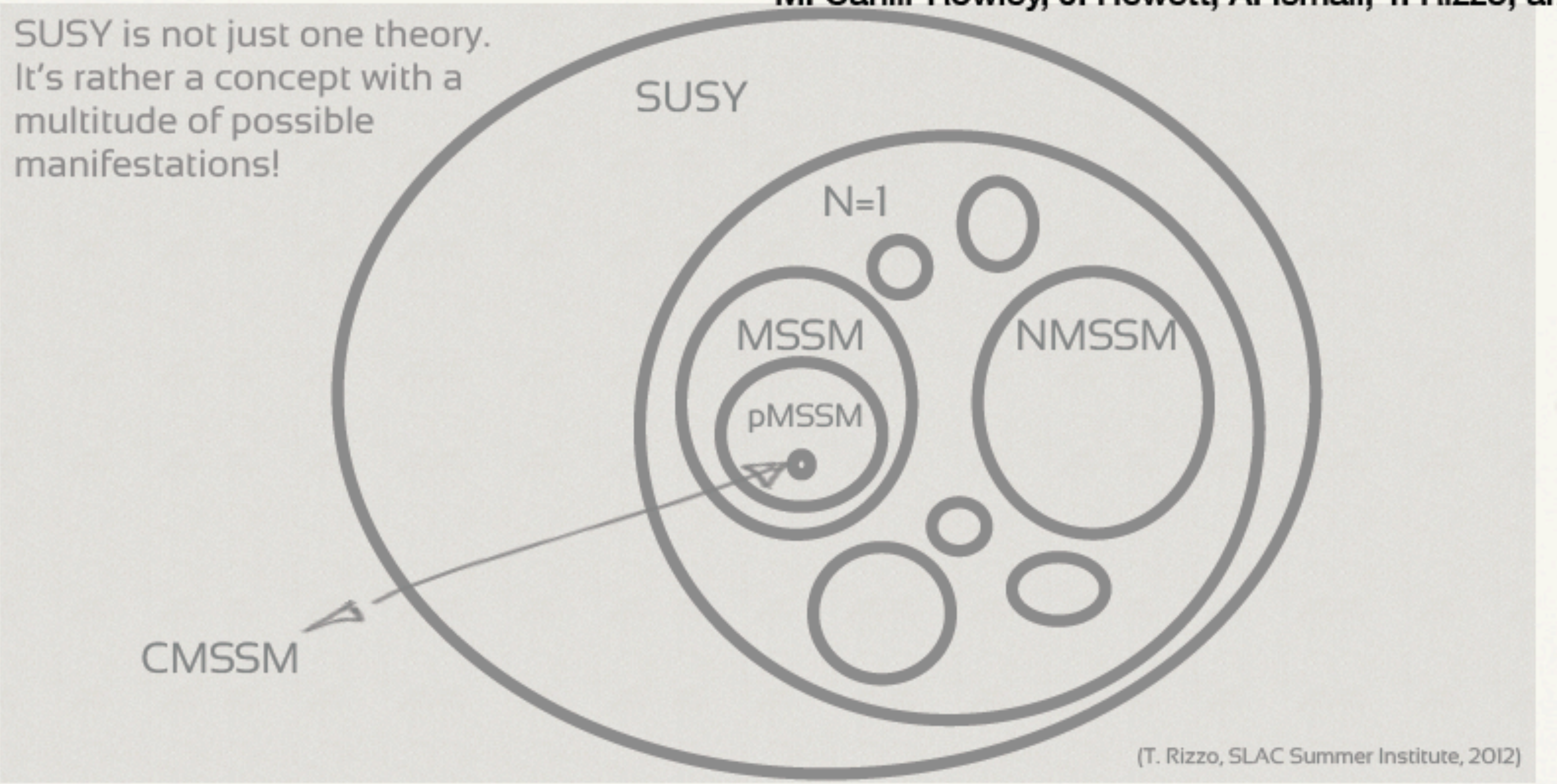
22 input parameters varying in the domains:

$$1 \leq \tan\beta \leq 60\,, \;\; 50 \text{ GeV} \leq M_A \leq 3 \text{ TeV}\,, \;\; -9 \text{ TeV} \leq A_f \leq 9 \text{ TeV}\,,$$
$$50 \text{ GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3 \text{ TeV}\,, \;\; 50 \text{ GeV} \leq M_1, M_2, |\mu| \leq 1.5 \text{ TeV}.$$

DeGrassi, KITP 2013

Weak Scale SUSY? : too soon to tell

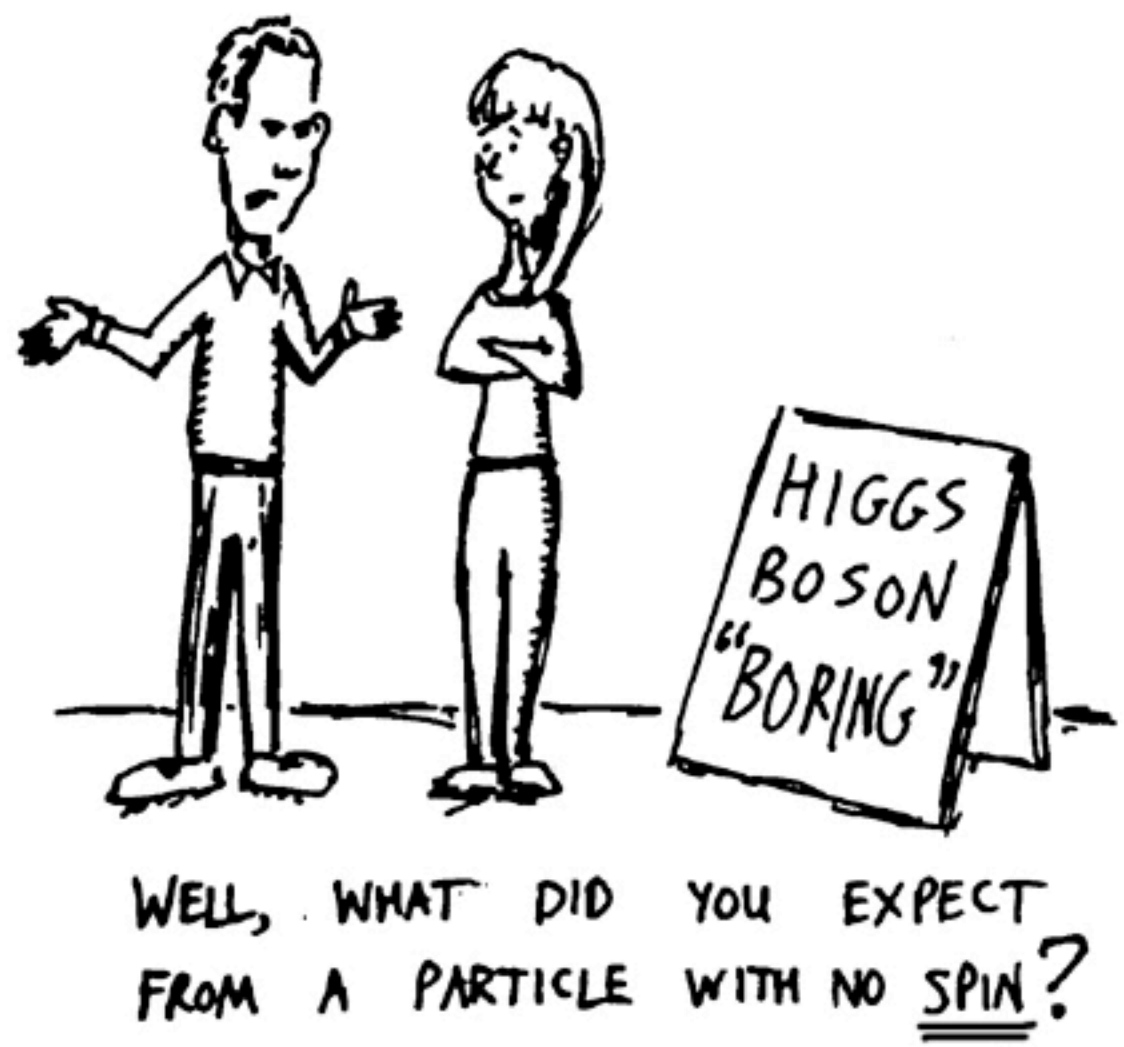
M. Cahill-Rowley, J. Hewett, A. Ismail, T. Rizzo, arXiv:1211.1981



LHC searches at 7 and 8 TeV have so far excluded about 1/3 of the parameter space of the pMSSM; the full parameter space of relevant SUSY models is not even defined

Conclusions

Implications of $M_h \sim 125$ GeV



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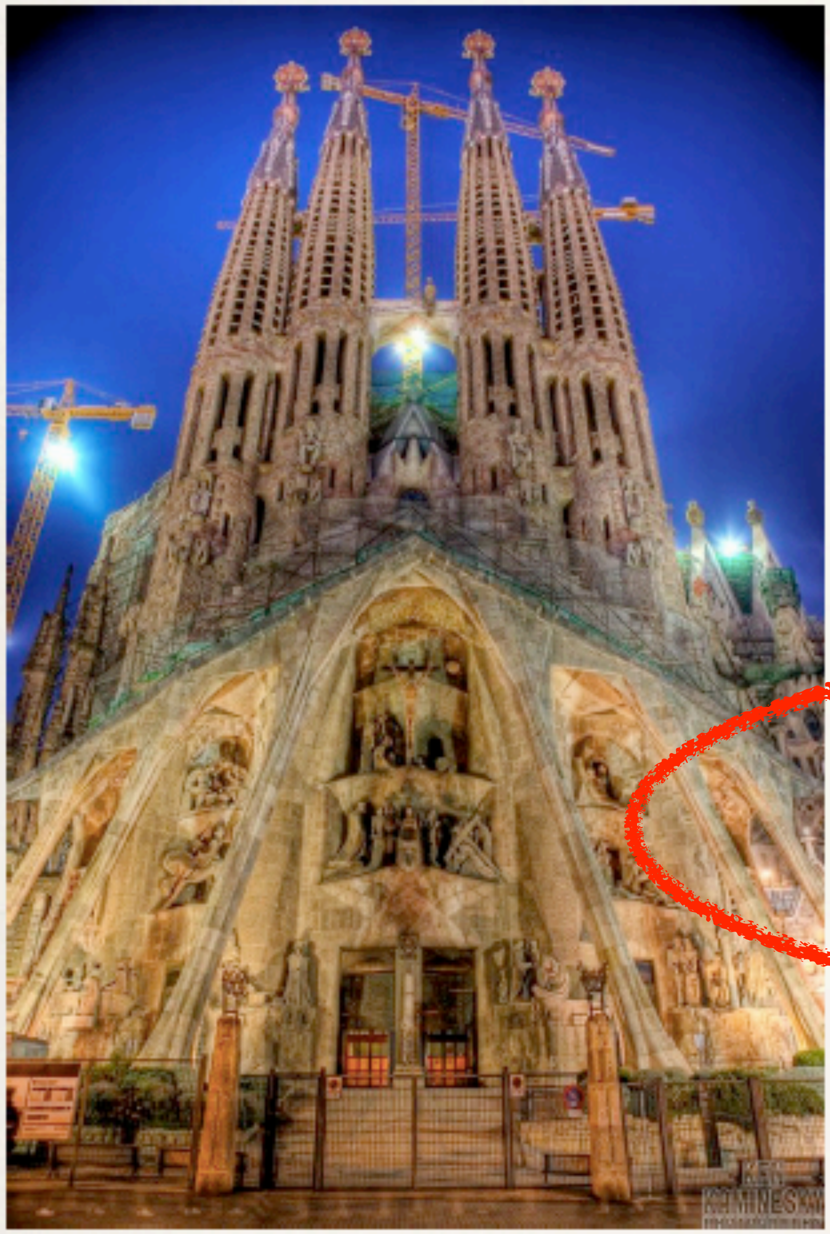
Theory Summary

Theory	Hierarchy Problem	Precision EW	Λ_{UV}	$\delta g_H/g_H$	LHC
Fundamental Higgs	YES!	✔	$< M_{Planck}$	0%	
SUSY	No	✔	M_{GUT}?	< few %	
Composite Higgs	No	f > few TeV	< 50 TeV	O(few-10%)	
Dilaton	No	✔?	1-10 TeV	O(100%)	
Higgsless/ TC	No	Ideal fermions	1-10 TeV	no narrow scalar?	

- What is the Higgs trying to tell us?

The Naturalness Dogma:

quem deus vult perdere, dementat prius



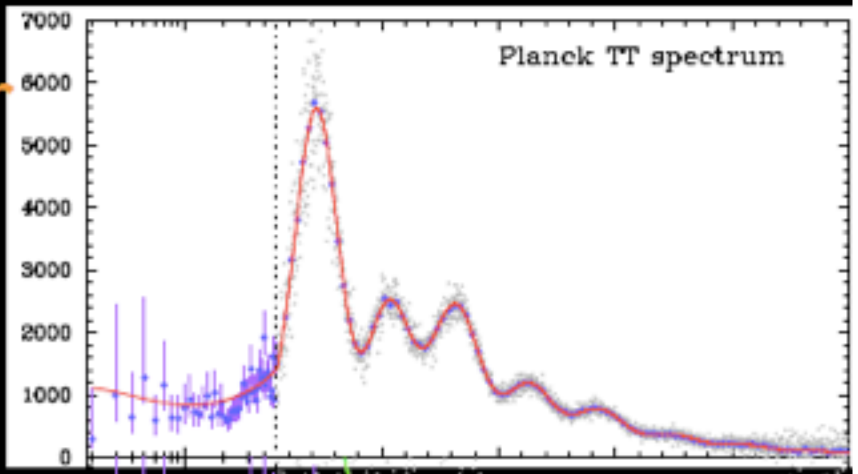
- If superpartners are discovered at LHC, we will figure out what kind of SUSY model we actually have, and shed light on the "small" tuning issues
- Ditto if we find Higgs compositeness etc
- But it is interesting already to question whether the mighty cathedral of BSM built up over 30 years may rest on shaky foundations...

Whither Particle Physics?

KAVLI IPMU

Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry



We don't really know their energy scales...

H. Murayama, LP2013