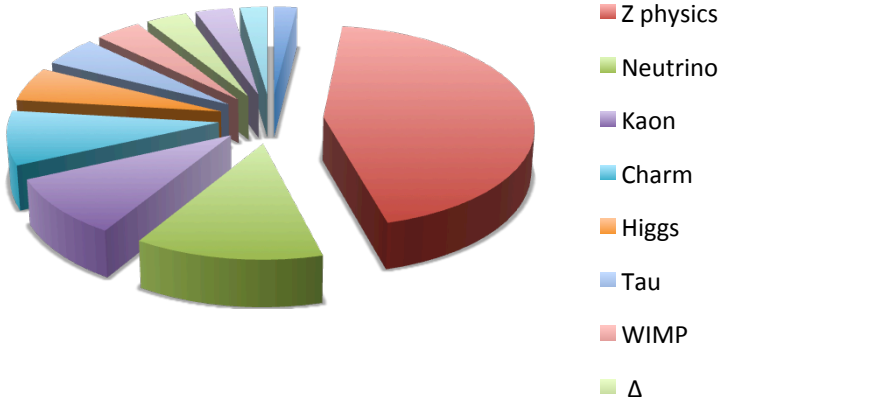
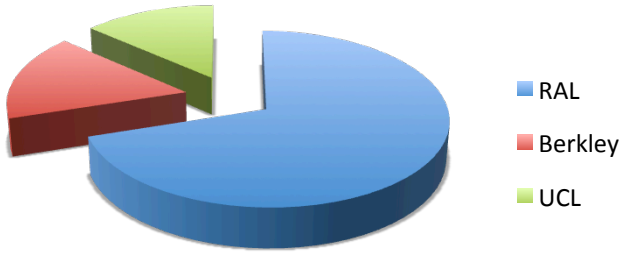
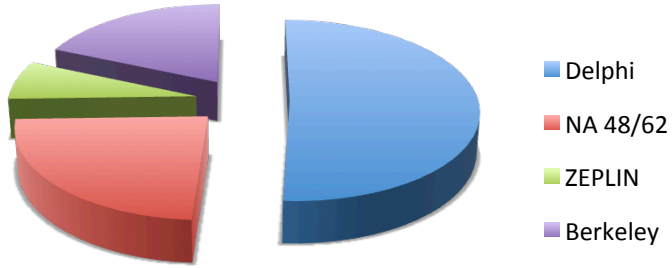
From Regge poles to the Higgs, and beyond

Graham Ross,
Meeting in honour of George@80,
RAL,
April 2015

George @ 80


Bubble chamber 1958->
Z physics
Neutrino
Kaon
Charm
Higgs
Tau
WIMP
Δ


RAL
Berkley
UCL


Delphi
NA 48/62
ZEPLIN
Berkeley

RAL theory 1969-74	**Roger Phillips**	Regge physics,
	Hong Mo Chan	Veneziano model,..
	Richard Roberts	
	Gordon Ringland	
	D.P.Roy	
	Hannu Miettenen	
	Gordy Kane	
	G.V.Dass	
	David Morgan	ππ..
	Mike Pennington	
	A.N.Kamal	
	Pasha Kabir	CP,CPT,C..
	A.Love	Field theory
	GGR	

ParticleTheory ~1969

The analytic S-matrix, ELOP, 1966
…. , S. Mandelstam

Bootstrap model, G. Chew, 1968

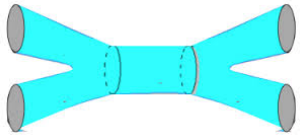
Crossing symmetry + Regge

Finite energy sum rules, R. Dolen, D.Horn, C. Schmidt, 1967

Duality

Construction of a crossing-simmetric, Regge-behaved amplitude for linearly rising trajectories, G.Veneziano, 1968

Quantum dynamics of a massless relativistic string, P.Goddard, J. Goldstone, C. Rebbi and C.B.Thorne, 1973



Field theory ~1969

Harvard,
Oxford (J.C.Taylor),..

Electroweak theory:

A model of leptons, S. Weinberg, 1967

Broken symmetries and the masses of gauge bosons, P.Higgs, 1964

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Broken symmetries and the masses of gauge bosons, P.Higgs, 1964

Alex Love -> S.Weinberg (1970)

(Electromagnetic and weak masses, S. Weinberg, 1972)

Purely hadronic weak interactions in unified field theories of the weak and electromagnetic interactions,
D.Bailin, A.Love, D.Nanopoulos, GGR, 1973

SU(2)XU(1) afterthought

(Just before Gargamelle)

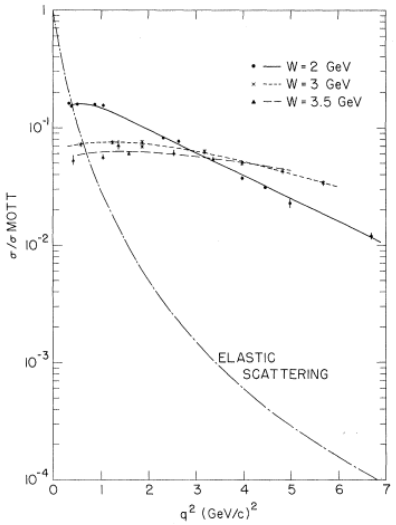
Polarised scattering as test for Z parity violating coupling

Quarks and QCD

Quark model for the elementary particles, R.H.Dalitz, 1965, 1973… (F.E.Close)

QCD, Fritzsch, Gell-Mann, Leutwyler 1972-73

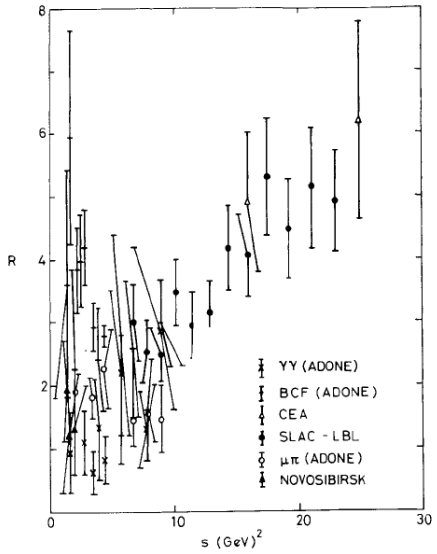
Asymptotic freedom, **H.D. Politzer**; D.J.Gross, F. Wilczek (1973).



Breidenbach et al 1969

Bjorken scaling

$$\frac{\sigma_{e^+e^-\to hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$



1974

Ambiguous

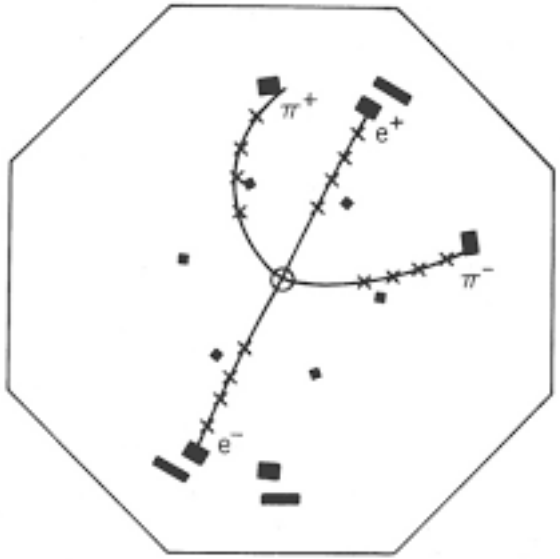
…by 1974 : theoretical elements of Standard Model in place

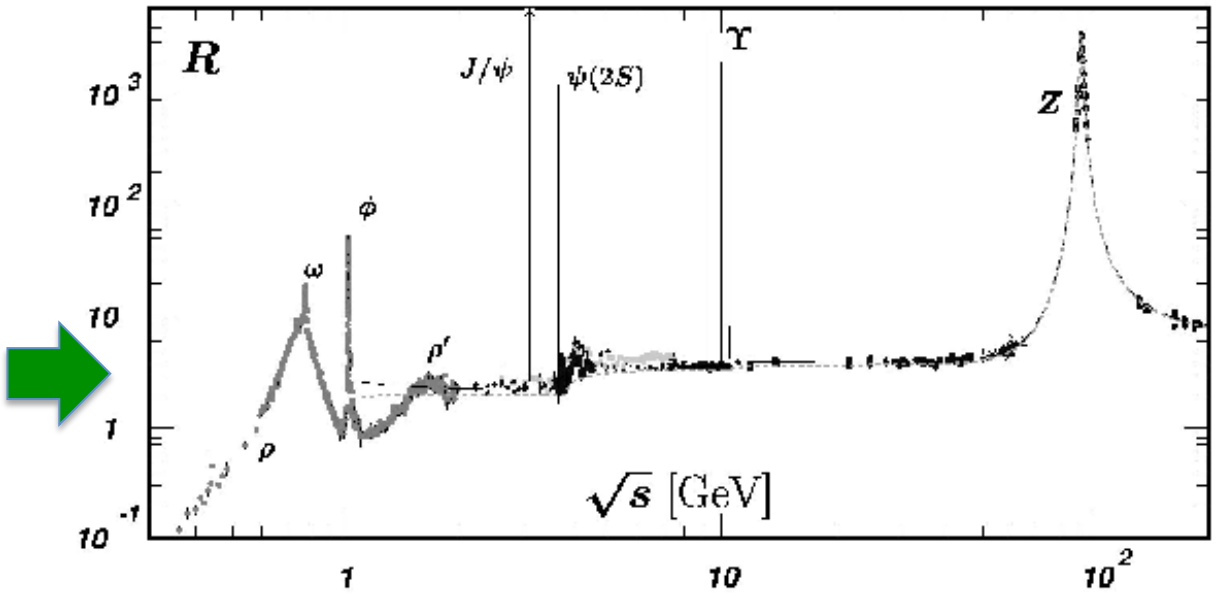
…but community not convinced

J/Ψ discovery

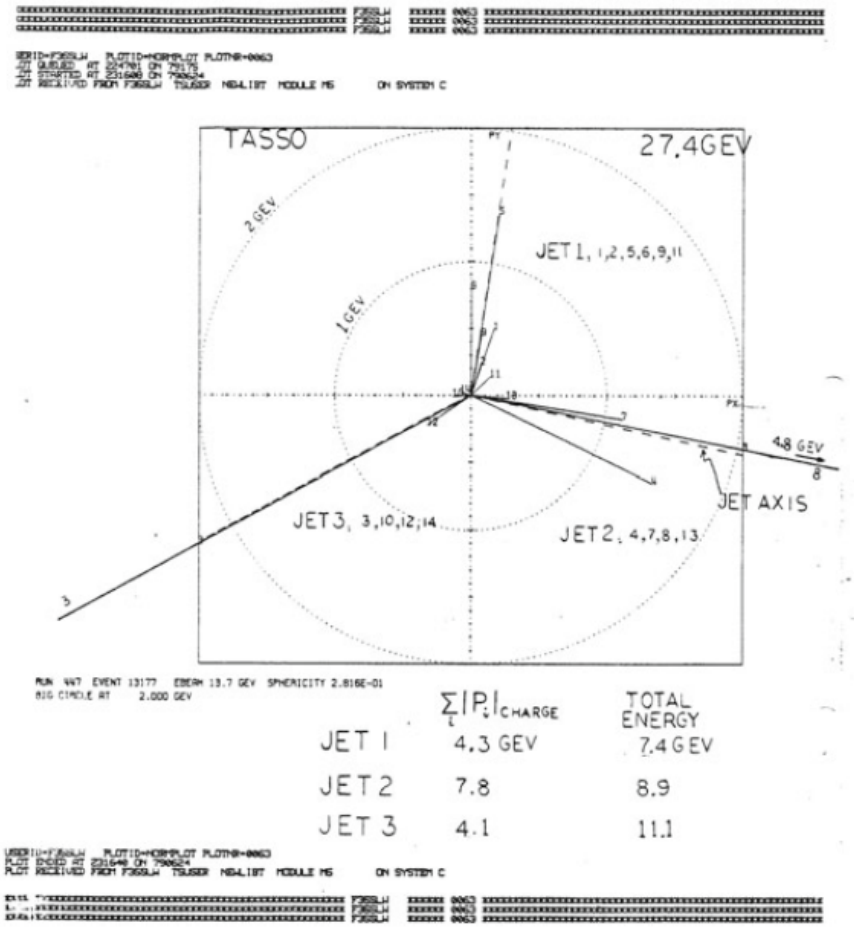
November 1974

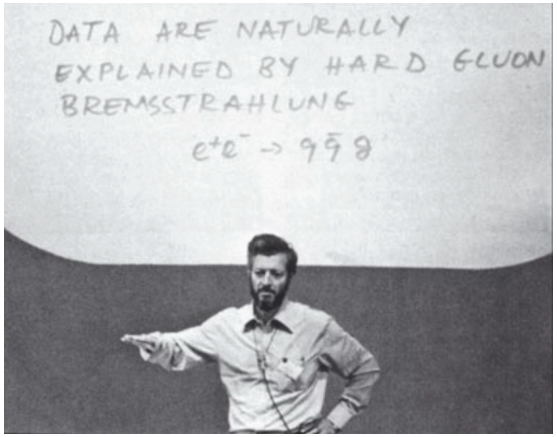
Physics telegrams:
Z?, H?, …





DESY: JADE, Mark-J, PLUTO, TASSO – Lepton-Photon symposium Fermilab, Aug 1979

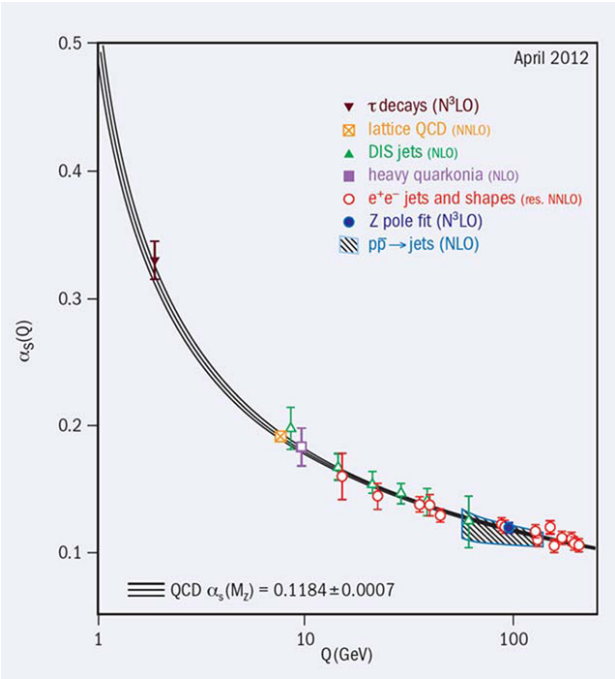


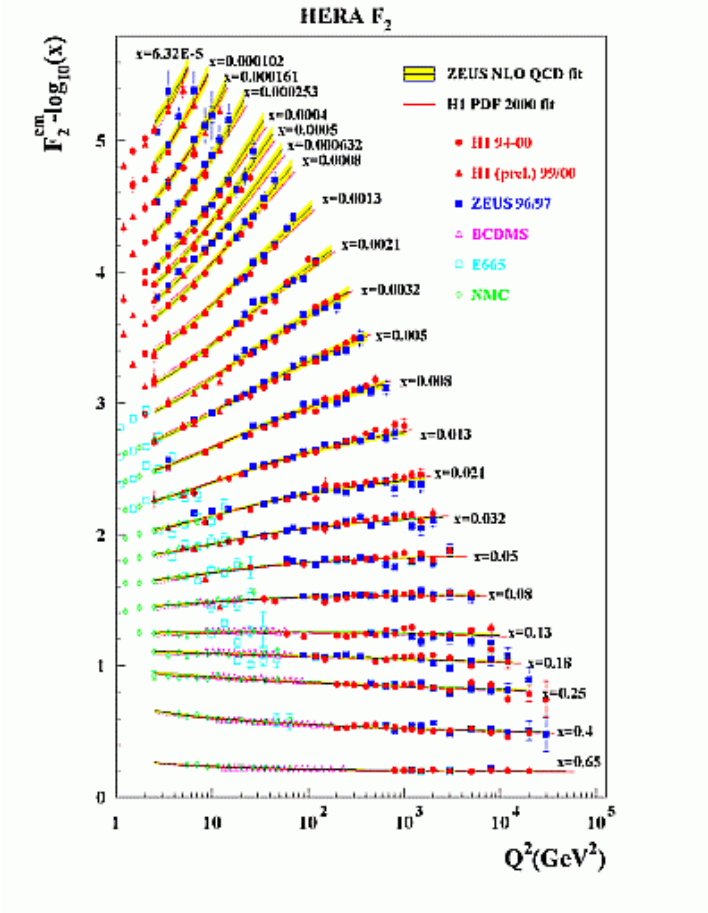


The computer printout of the first three-jet event found in June 1979

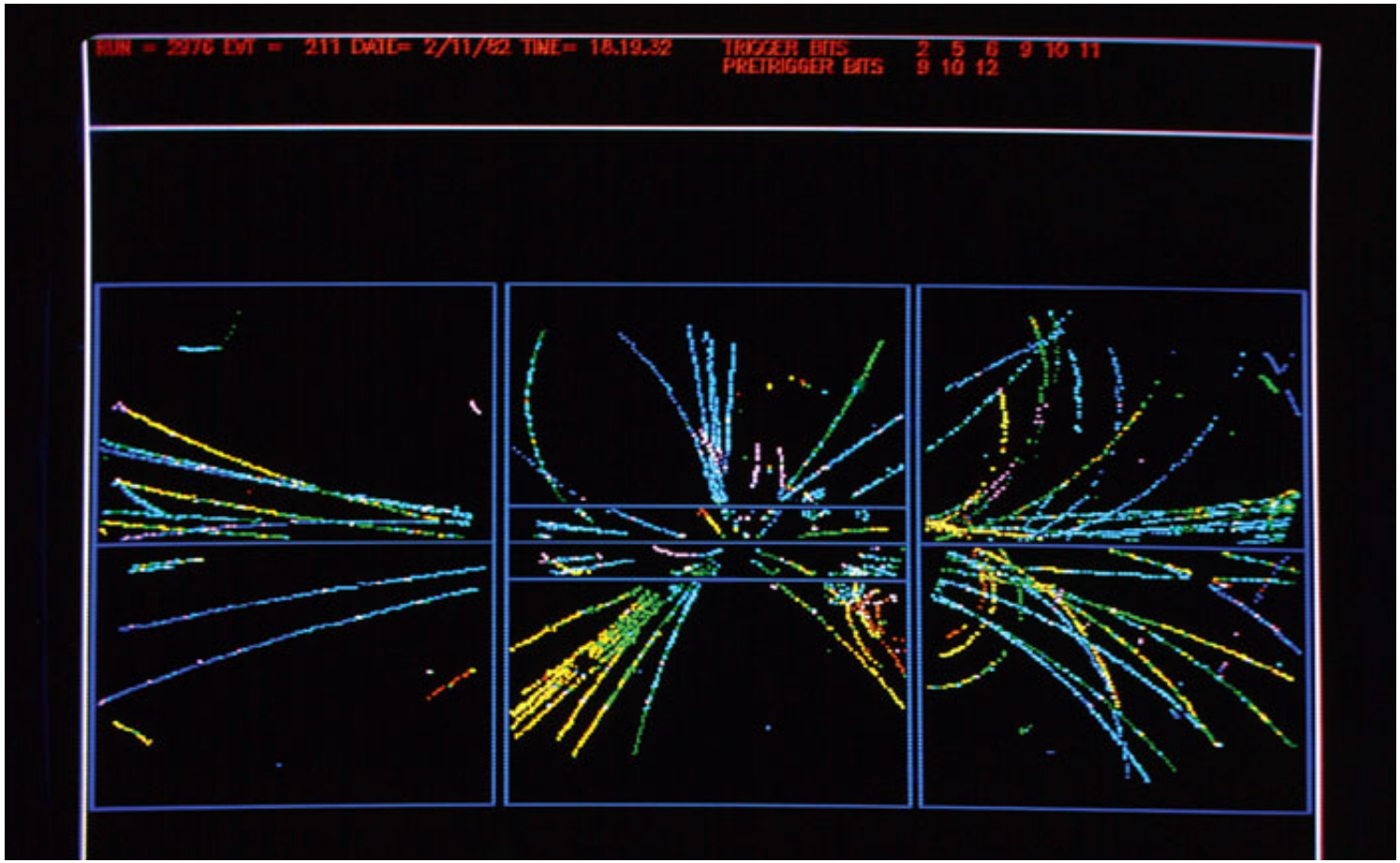
Second force particle(s) discovered !

QCD predictions confirmed





UA1, UA2 W, Z discovery (1983)



$$SU(3)\times SU(2)\times U(1)$$

$\tau(1975), b(1977), t(1995), \nu_\tau(2000)$ discoveries

complete the Standard Model

… apart from the Higgs

$\tau(1975), b(1977), t(1995), \nu_\tau(2000)$ discoveries

complete the Standard Model

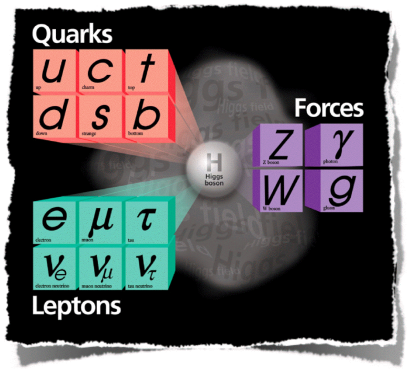
… apart from the Higgs

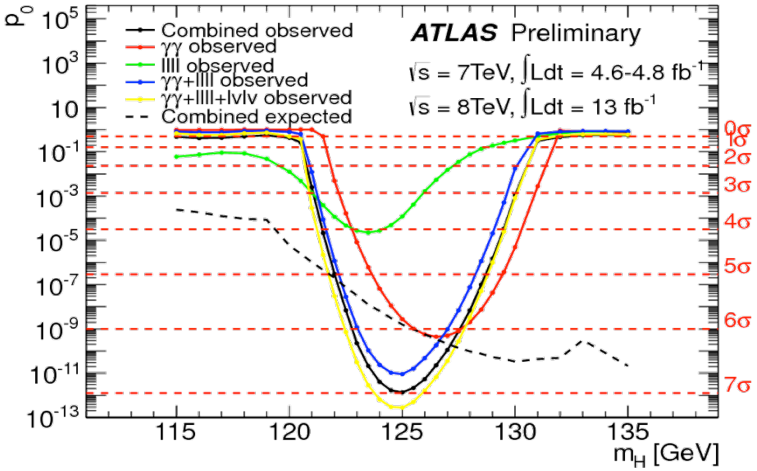
…fast forward

LHC

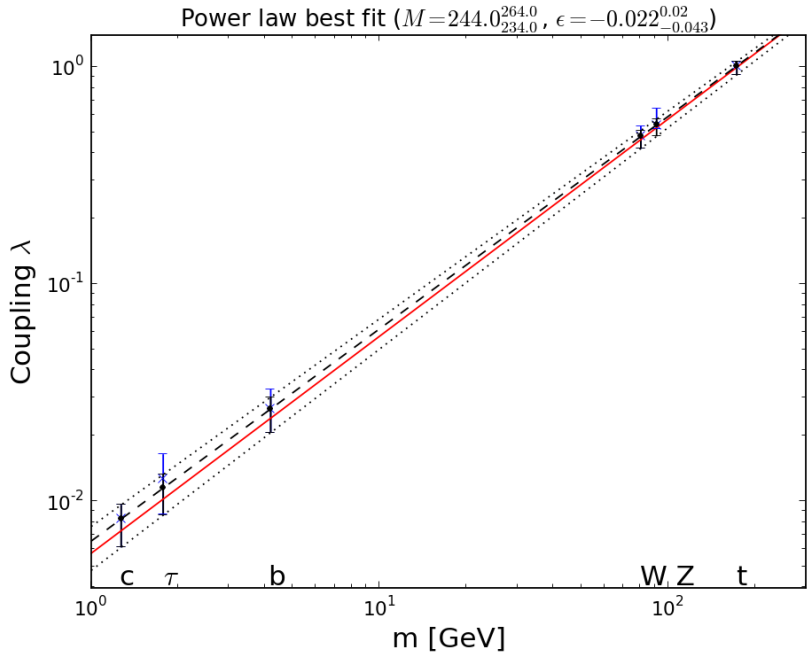
Higgs discovery (2012)!

…completes the Standard Model





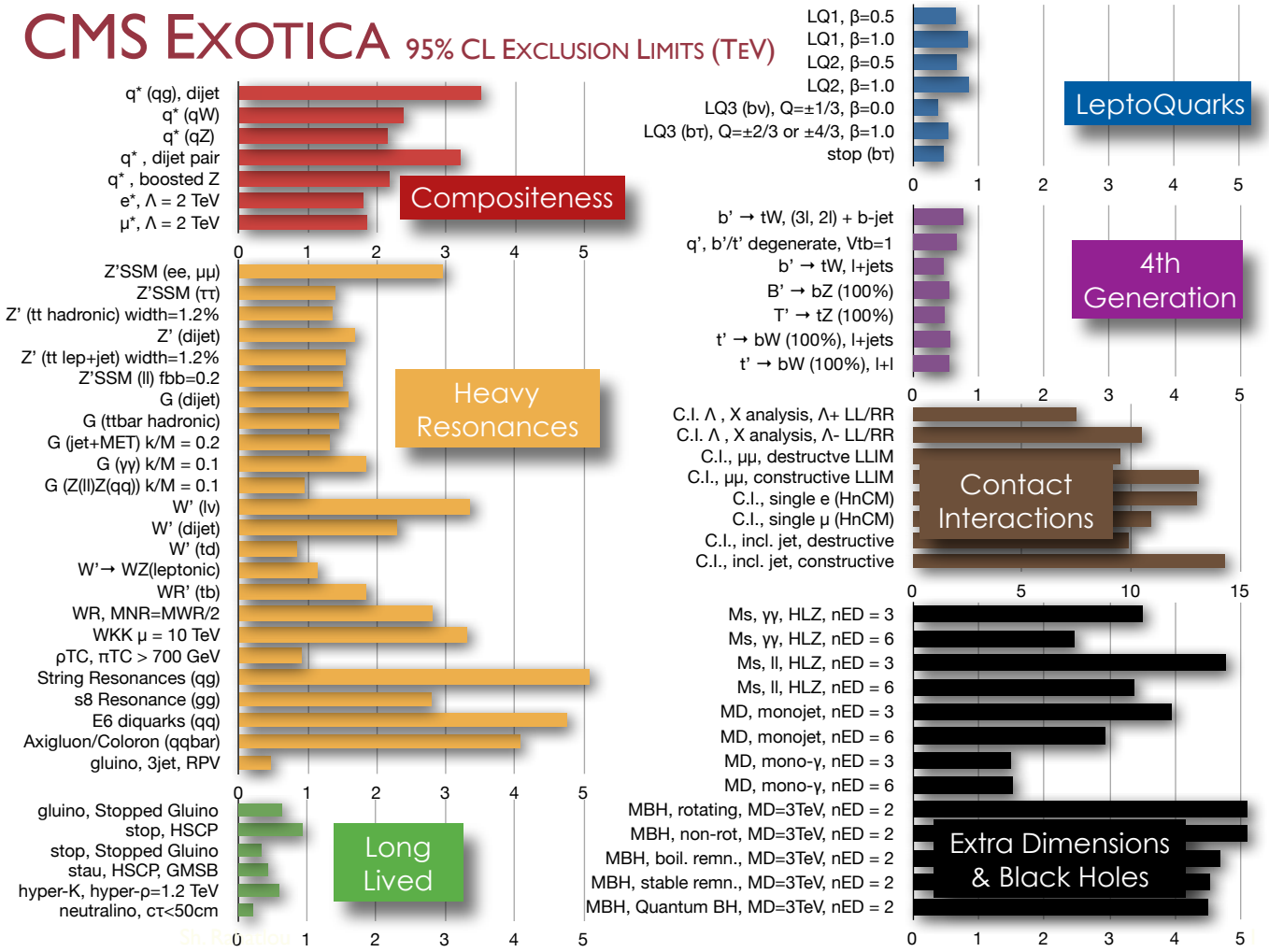
m_H = 125.09 ± 0.24 (0.21 stat. ± 0.11 syst.) GeV



- Strong exclusion of a spin-1 resonance
- 0^- excluded at > 3σ level
- Graviton-like resonances excluded at >3σ

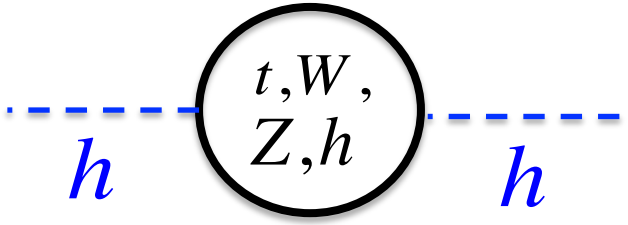
LHC 8

No evidence (yet) for BSM



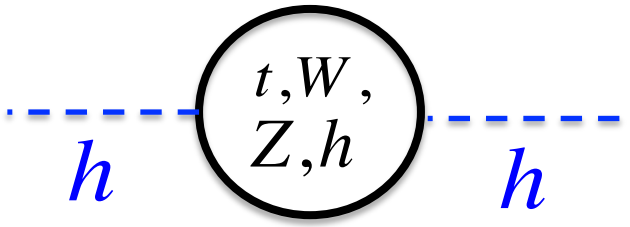
… and beyond

The Hierarchy problem



$$\delta m_h^2 \mid_{SM} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 = \left(\frac{\Lambda}{500GeV}\right)^2 m_h^2$$

The Hierarchy problem



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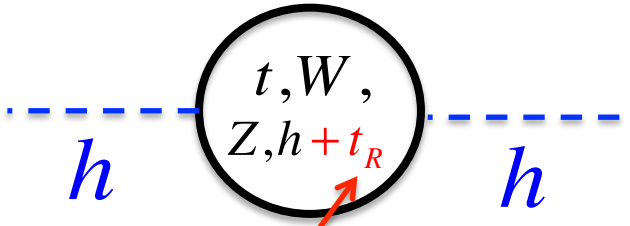
Light Higgs $\Longrightarrow$ Symmetry protection

- Composite models – Higgs as Pseudo-Goldstone boson
- Supersymmetric models – Higgs as chiral superpartner
- Scale invariant models - $m_0^2 + \delta m^2 = 0$

- Composite models – Higgs as Pseudo-Goldstone boson

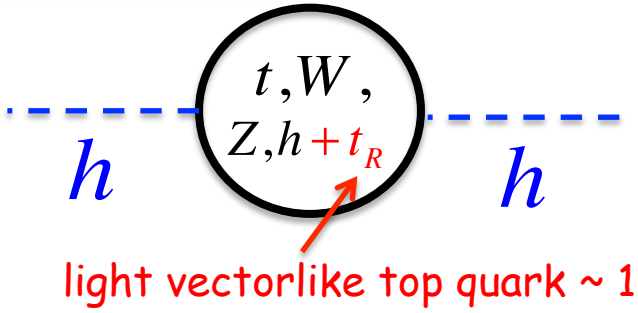


light vectorlike top quark ~ 1TeV

$$\delta m_h^2 \,|_{SM} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 = \left(\frac{\Lambda}{500GeV}\right)^2 m_h^2$$

Partial compositeness $\Longrightarrow$ Technifermion top quark resonance ~ 1TeV

- Composite models – Higgs as Pseudo-Goldstone boson



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Partial compositeness $\Longrightarrow$ Technifermion top quark resonance ~ 1TeV

LHC discovery potential:

$QCD\ pair\ production: \quad \sigma_{m_t=500GeV} = 570\,fb, \quad \sigma_{m_t=1TeV} = 1.3\,fb \quad (8TeV\ CM)$

$$BR\left(Q_{5/3(8/3)} \to l^+l^+..\right) = 5(6)\%, \quad BR\left(Q_{5/3(8/3)} \to lll..\right) = 3(6.5)\%$$

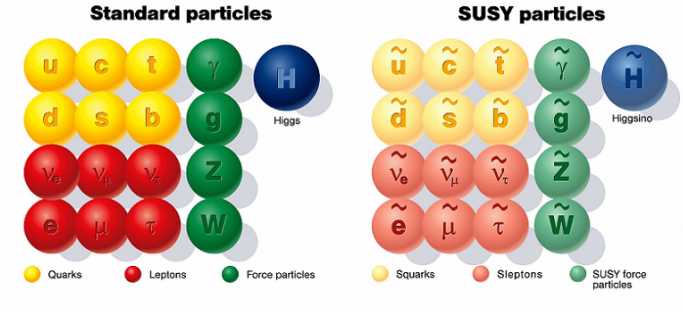
$LHC_8 \qquad m_t > 770GeV\ (95\%)$

Panico et al 1201.7114
Pappadopulo et al 1303.3062

:

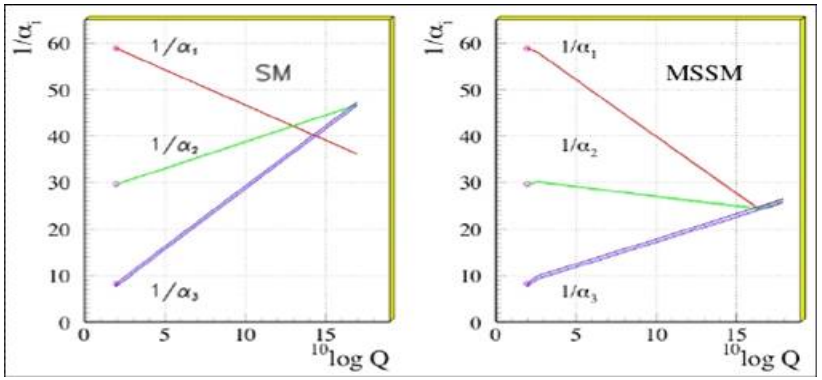
- Supersymmetric models – Higgs as chiral superpartner

e.g. MSSM:



$$\begin{pmatrix} \widetilde{H}_u \\ H_u \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d \\ H_d \end{pmatrix}$$

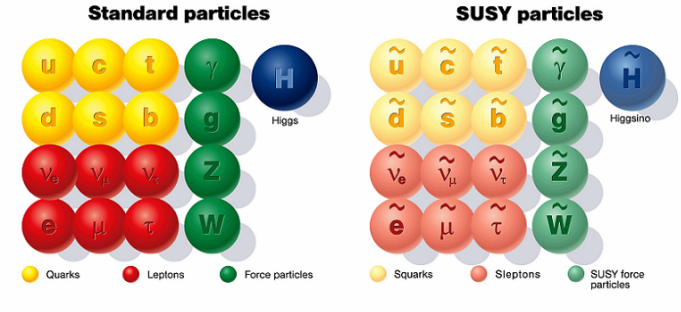
$$\mu \widetilde{H}_u \widetilde{H}_d, \quad \widetilde{H}_u \to e^{i\alpha} \widetilde{H}_u \Rightarrow \mu = 0$$



U. Amaldi, W. deBoer, and H. Furstenau
Ibanez, GGR

- Supersymmetric models – Higgs as chiral superpartner

e.g. MSSM:



$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right) + \delta_t\right) + \ldots \simeq 126\,GeV$$

$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right)$$

LHC Higgs discovery $\Longrightarrow$ $\Delta_{\min}^{MSSM} > 350\,, \quad m_h = 125.6 \pm 3GeV$

Fine tuning measure (Δ<100 acceptable)

- Supersymmetric models – Higgs as chiral superpartner

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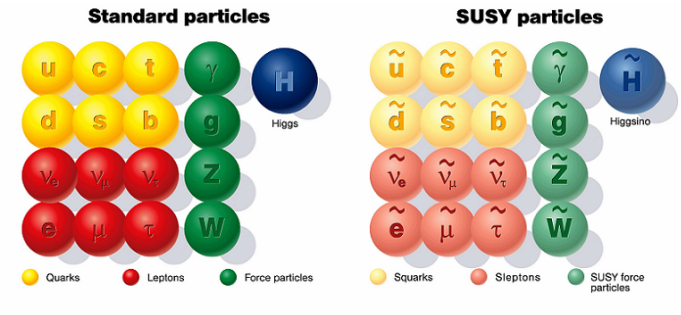

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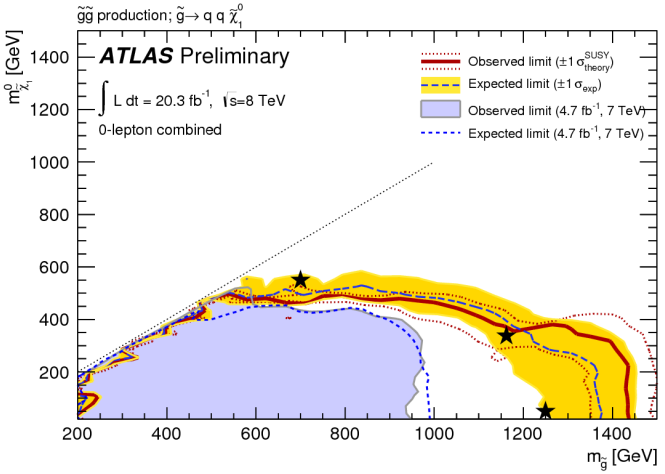
LHC Higgs discovery $\Longrightarrow$ $\Delta_{\min}^{MSSM} > 350\,, \quad m_h = 125.6 \pm 3GeV$

Fine tuning measure (Δ<100 acceptable)

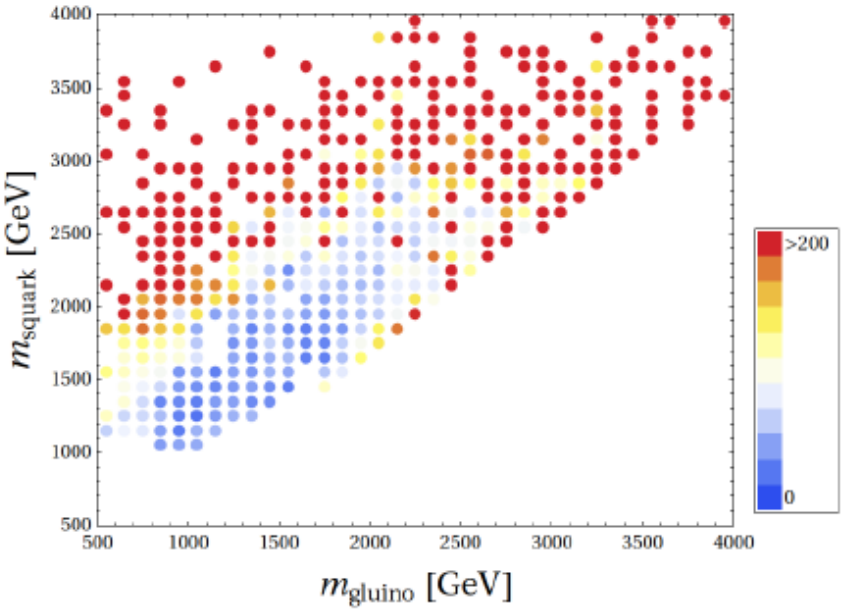
…but generalisations still viable

e.g. NMSSM with non-universal gaugino masses:

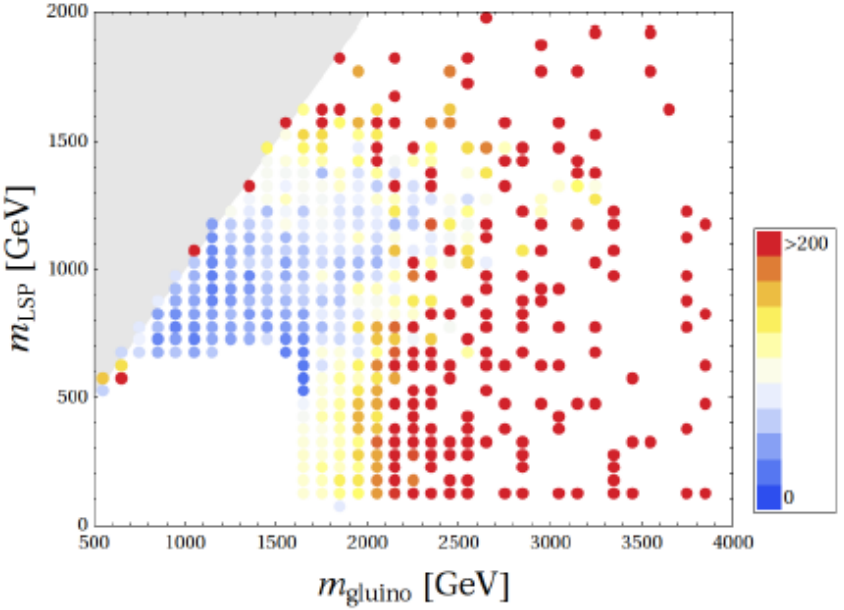
Masses v/s fine tuning



m_{squark}



m_{LSP}



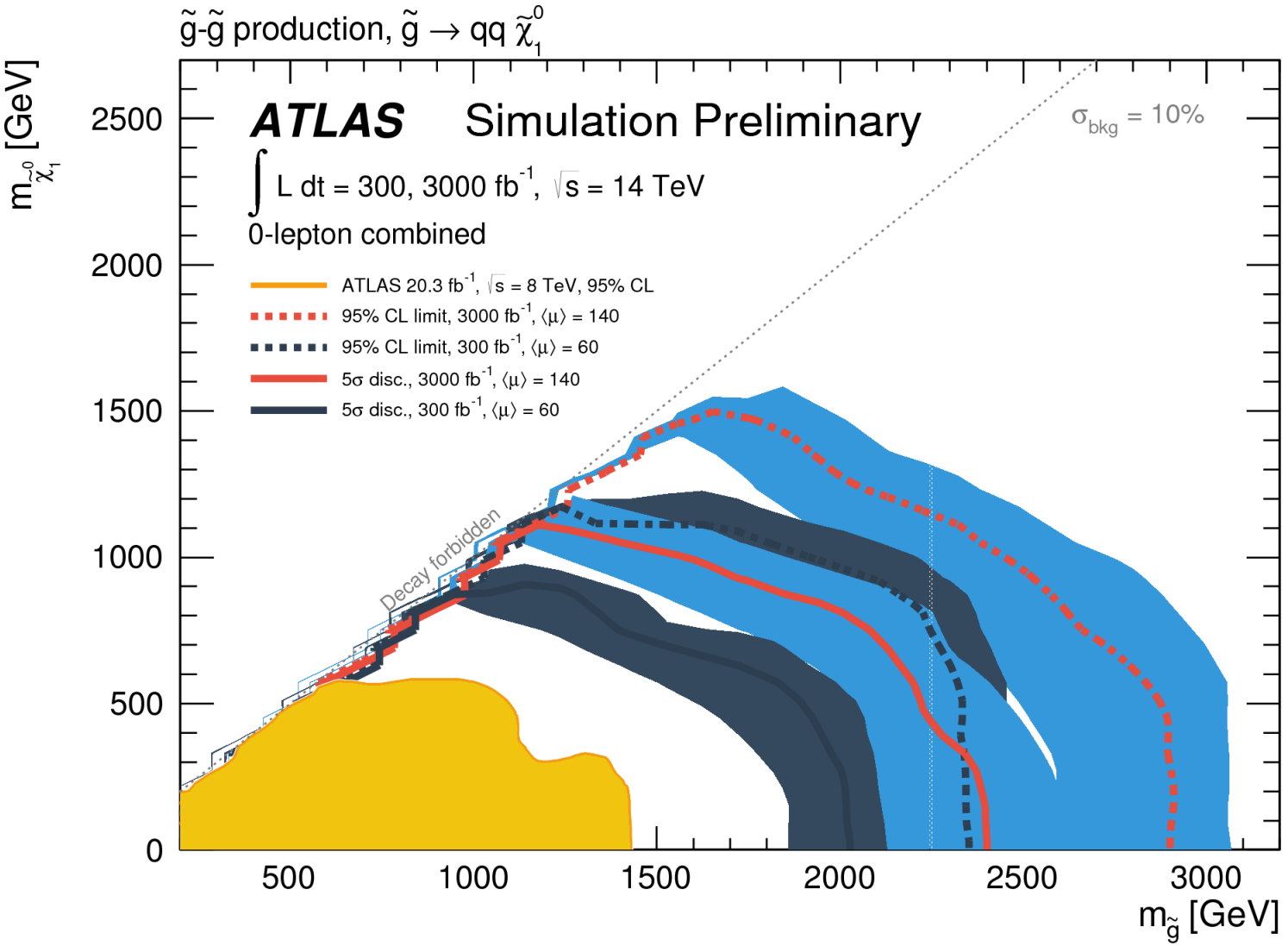
> 200

0

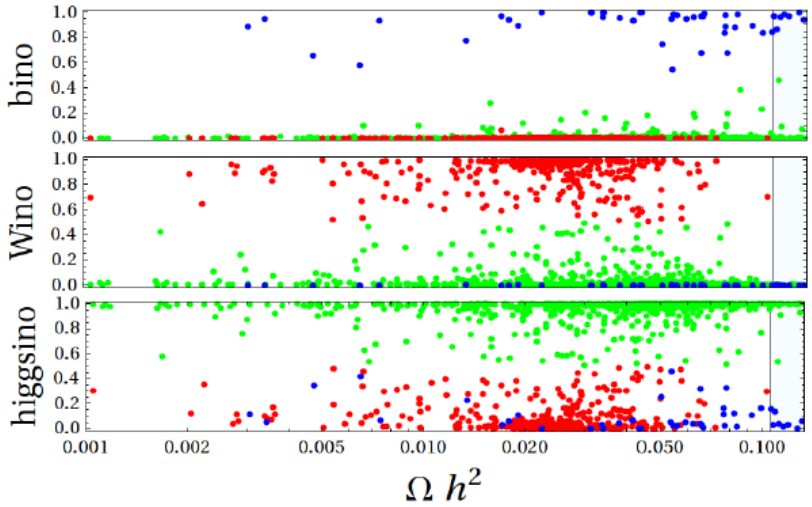
Δ

M_{gluino}

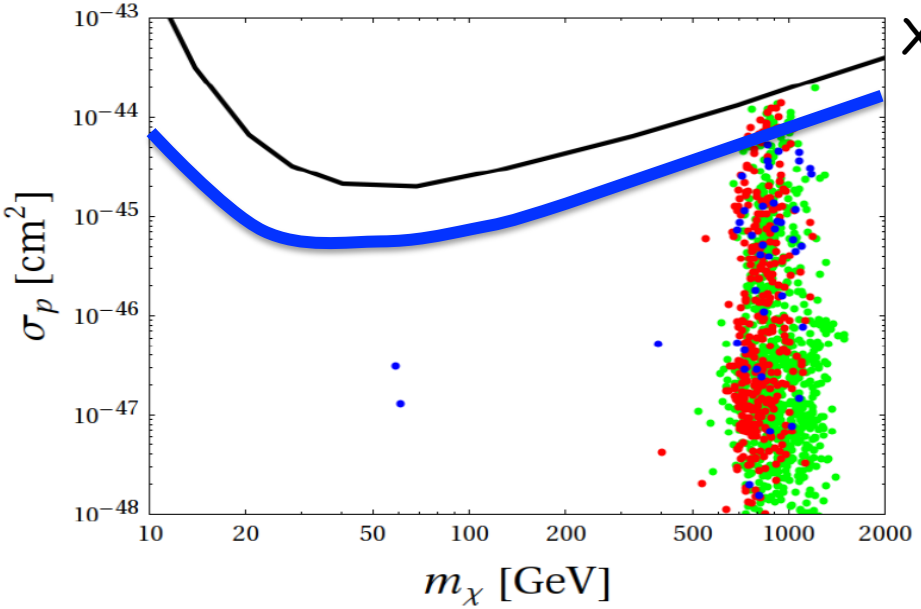
Heavy LSP reach



Dark matter



LSP composition



XENON 100

LUX

Direct DM searches

- Scale invariant models:

(SM in absence of Higgs mass is scale invariant)

Field theory: δm^2 not measureable

...only $m^2 = m_0^2 + \delta m^2$ "physical"

Only $m^2 = 0$ special

$$\Rightarrow \quad \frac{d\, m_H^2}{d\, \ln \mu} = \frac{3 m_H^2}{8\pi^2} \left(2\lambda + y_t^2 - \frac{3 g_2^2}{4} - \frac{3 g_1^2}{20} \right)$$

...no hierarchy problem for SM!

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Only $m^2 = 0$ special ... origin of EW breaking ?

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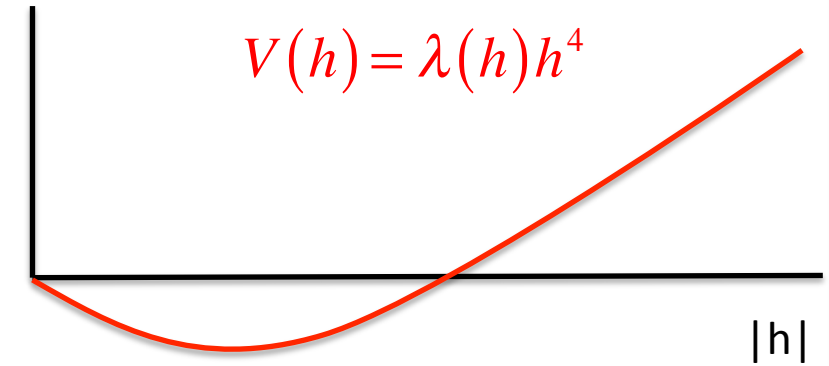
Dimensional transmutation:

Coleman Weinberg



"real" hierarchy problem

..... many models with new light states interacting with the Higgs

No heavy thresholds? (real hierarchy problem)

- Neutrino masses? $L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$

$e.g.\quad h_A^2 = 5.10^{-14}, h_B^2 = 5.10^{-15}, M_a = 20GeV$

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- Baryogenesis?

e.g. ν_{Ra} oscillate

$$\not{CP}, \quad L_{A,B,C} \neq 0, \quad L_A + L_B + L_C = 0$$

$$\Delta_{L\,AB} = L_A + L_B \xrightarrow[Sphalerons]{} \Delta B = \Delta_{L\,AB} / 2$$

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- Strong CP problem?

$$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}, \quad \theta \leq 10^{-10} \; ??$$

$$S = (|S| + f_a) e^{i\frac{a}{f_a}}, \qquad 10^{10} GeV \leq f_a \leq 10^{12} GeV$$

- Strong CP problem: $\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$, $\theta \le 10^{-10}$??

$$S = (|S| + f_a) e^{i\frac{a}{f_a}}, \qquad 10^{10}\,GeV \le f_a \le 10^{12}\,GeV$$

DFSZ axion: 2 Higgs doublets $H_{1,2}$, complex singlet, S

$$V(H_1, H_2) = \frac{\lambda_1}{2}|H_u|^4 + \frac{\lambda_2}{2}|H_d|^4 + \lambda_3 |H_u|^2 |H_d|^2 + \lambda_4 |H_u^\dagger H_d|^2$$
$$+ \zeta_1 |S|^2 |H_u|^2 + \zeta_2 |S|^2 |H_d|^2 + \zeta_3 S^2 H_u H_d + h.c.$$

Requires two Higgs doublets (type II couplings) + light pseudo-dilaton

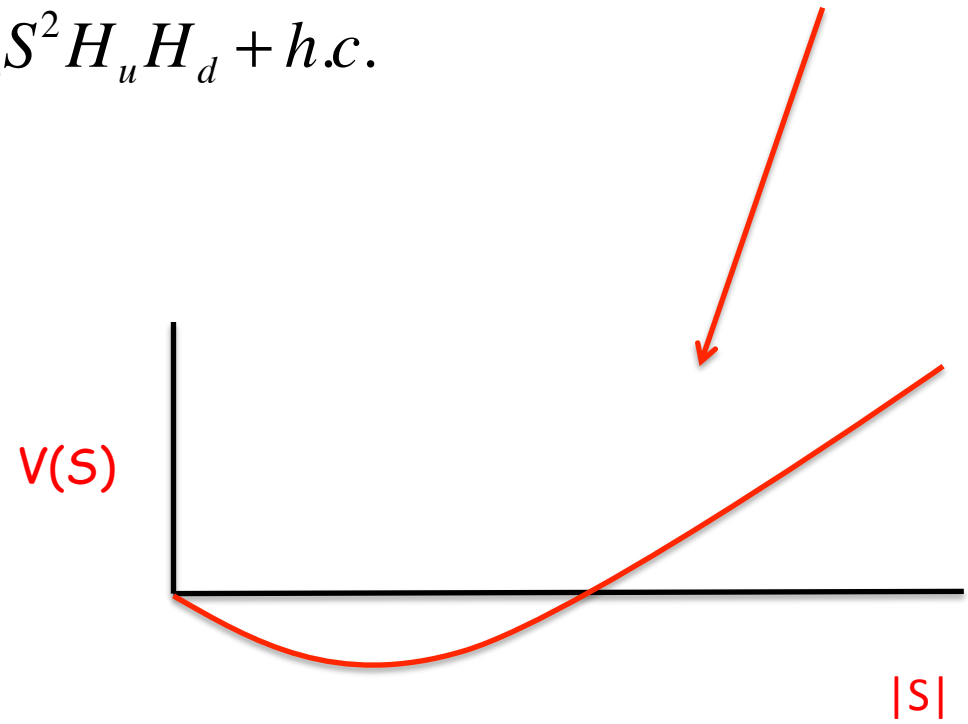
$$m^2_{H^0_2}, m^2_{H^\pm} \le O(TeV)$$

Coleman Weinberg in DFSZ model

$\zeta_2 S^2 |H_d|^2$

$$V_{DFSZ}(H_1, H_2, S) \simeq \frac{\lambda_1}{2}\left(|H_u|^2 + \frac{\zeta_1}{\lambda_1}|S|^2\right)^2 + \frac{1}{64\pi^2}\left(\zeta_2 |S|^2\right)^2\left(-\frac{1}{2} + \ln\frac{|S|^2}{f_a^2}\right)$$

$$+\frac{\lambda_2}{2}|H_d|^4 + \zeta_3 S^2 H_u H_d + h.c.$$



$\left\langle H_u^2 \right\rangle = -\frac{\zeta_1}{\lambda_1}\left\langle S^2 \right\rangle$ triggers EW breaking

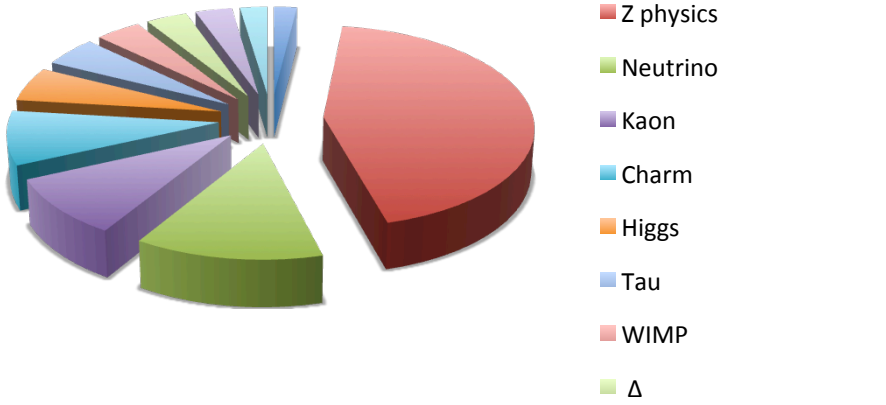
…and beyond

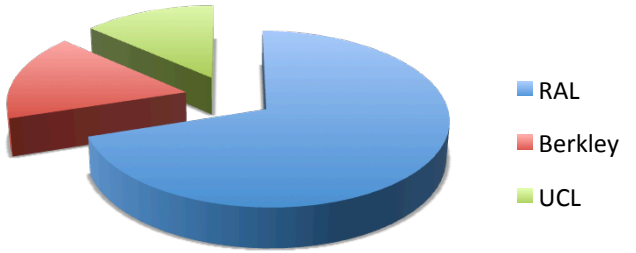
Field theory corrections to Higgs mass inevitable:

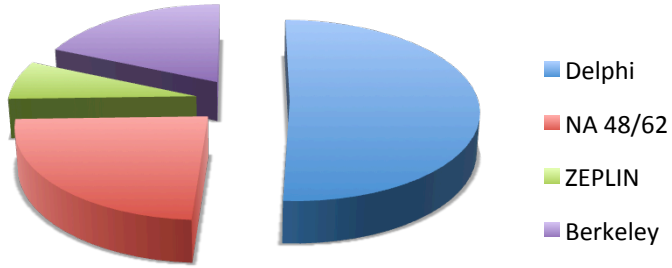
if don't appeal to anthropics need symmetry to keep Higgs light

$\Longrightarrow$ BSM physics visible at LHC 13/14

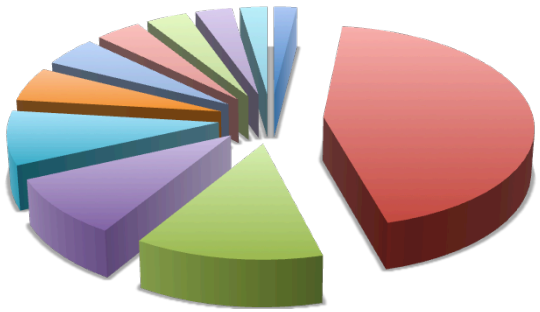
George @ 80

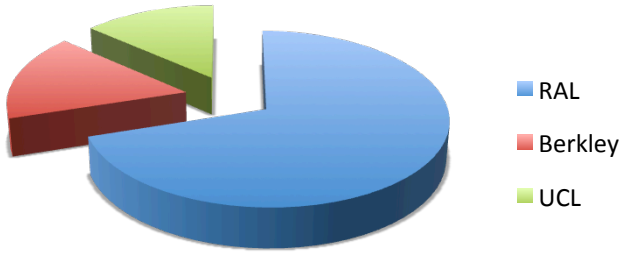

Bubble chamber 1958->
Z physics
Neutrino
Kaon
Charm
Higgs
Tau
WIMP
Δ

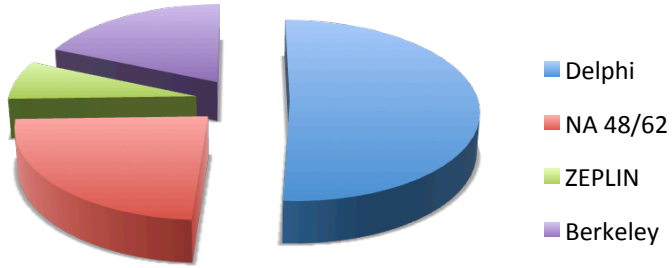

RAL
Berkley
UCL


Delphi
NA 48/62
ZEPLIN
Berkeley

George @ 80, and beyond





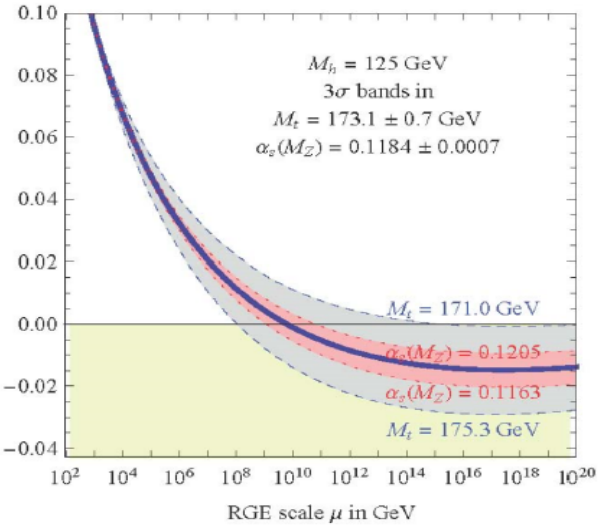


- SUSY discovery?

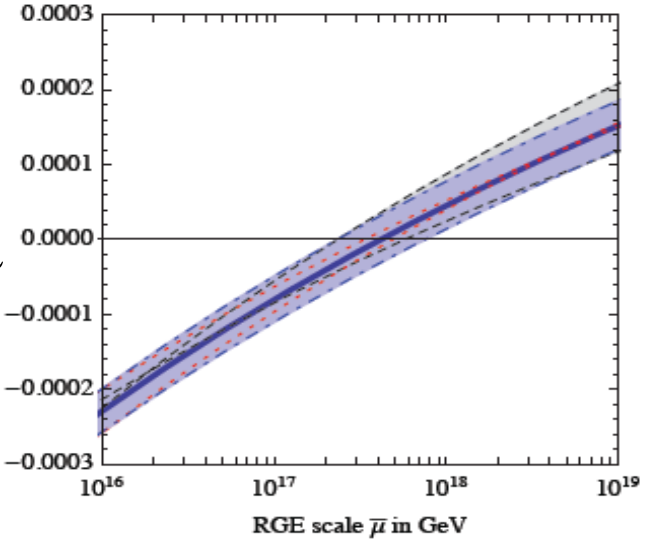
LHC 8

Higgs discovery!

λ



β_λ



DeGrassi et al,...

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

$$m^2 \simeq \left(89 GeV^2\right), \lambda \simeq 0.13$$