The Big Deal with the Little Higgs

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Outline

Hierarchy Problem

- Higgs as Pseudo-Nambu-Goldstone Boson (PNGB)
- The Little Higgs mechanism

Generic properties

Examples of Models

Phenomenology

- Effective Field Theories
- Electroweak Precision Observables
- Neutrino masses
- Heavy Quark States
- Heavy Vectors
- Heavy Scalars
- Reconstruction of Little Higgs Models
- Pseudo Axions in LHM
- T parity and Dark Matter

Conclusions

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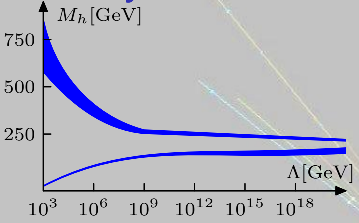

Motivation: Hierarchy Problem

- Effective theories below a scale $\Lambda \quad \Rightarrow$
- Loop integration cut off at order $\sim \Lambda$:

$\sim \Lambda^2$

Problem: Naturally, $m_h \sim \mathcal{O}(\Lambda^2)$:

$$m_h^2 = m_0^2 + \Lambda^2 \times (\text{loop factors})$$

◊ *Light* Higgs favoured by EW precision observables ($m_h < 0.5$ TeV)

- $m_h \ll \Lambda \quad \Leftrightarrow$ **Fine-Tuning !?**
- **Solutions:** Large number of ideas since 1970s

Overview of Solutions

(1) Light Scalar as Pseudo-Goldstone Boson

a) Higgs as massless Goldstone Boson, Higgs mass connected to explicit symmetry breaking

b) No fundamental scalars in Nature: Technicolor (Repetition of QCD); EW Precision Data problematic

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a) Supersymmetry: **Spin-Statistics** $\Longrightarrow$ Loops of bosons and fermions cancel

(b) Little Higgs mechanism: **Global symmetries** $\Rightarrow$ Loops of particles of like statistics cancel

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(3) Removal of Hierarchy:

a) Large Extra Dimensions: Gravity looks only weak; no fundamental scalars, but components of (higher-dem.) gauge fields

b) Warped Extra Dimensions (Randall-Sundrum): Gravity only weak in our world

(4) Numbers chosen by Providence

- Anthropic principle: Values are because we can observe them

Higgs as Pseudo-Nambu-Goldstone Boson (PNGB)

Old Idea: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

Light Higgs as Pseudo-Goldstone boson $\Leftrightarrow$ spontaneously broken (approximate) *global* symmetry; non-linear sigma model

- w/o Fine-Tuning: $v \sim \Lambda/4\pi$

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$$\pi_i \to i\theta^a T^a_{ik}\pi_k \quad \Rightarrow \quad \frac{\partial \mathcal{V}}{\partial \pi_i} T^a_{ij}\pi_j = 0 \quad \Rightarrow \quad \underbrace{\frac{\partial^2 \mathcal{V}}{\partial \pi_i \partial \pi_j}\bigg|_f}_{=(m^2)_{ij}} T^a_{jk} f_k + \underbrace{\frac{\partial \mathcal{V}}{\partial \pi_j}\bigg|_v}_{=0} T^a_{ji} = 0$$

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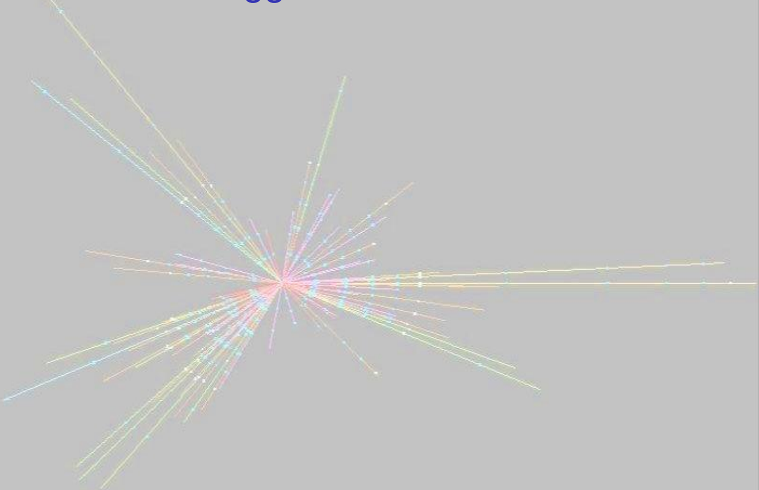
Nonlinear Realization (Example $SU(3) \to SU(2)$):

$$\mathcal{V}(\Phi) = \left(f^2 - (\Phi^\dagger \Phi)\right)^2 \Rightarrow \Phi = \exp\left[\frac{i}{f}\left(\begin{array}{c|c} 0 & \vec{\pi} \\ \hline \vec{\pi}^\dagger & \pi_0 \end{array}\right)\right]\begin{pmatrix} 0 \\ f+\sigma \end{pmatrix} \equiv e^{i\pi}\Phi_0$$

$\vec{\pi} \in$ fundamental $SU(2)$ rep., π_0 singlet

Construction of a Little Higgs model

- $\vec{\pi} \equiv h$??



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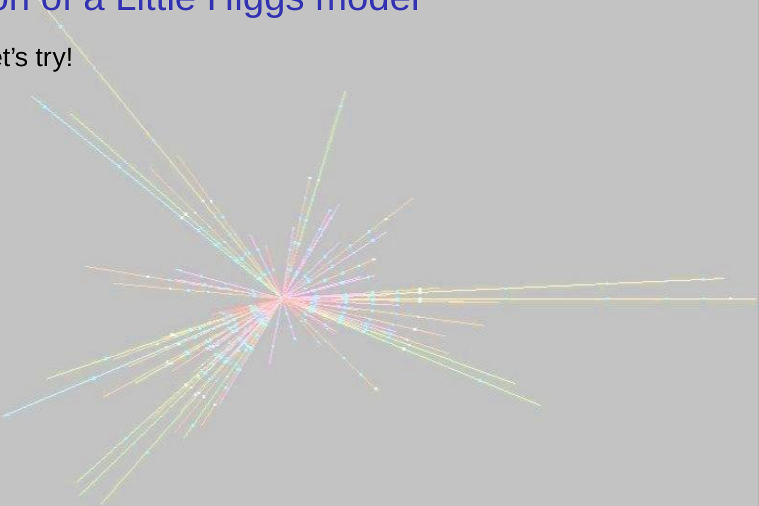

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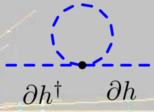
- Gauge and Yukawa interactions?
- Expanding the kinetic term:

$$f^2|\partial\Phi|^2 = |\partial h|^2 + \frac{1}{f^2}(h^\dagger h)|\partial h|^2 + \ldots$$



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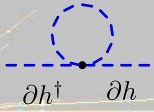

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$\to$ Theory becomes stronlgy interacting at $\Lambda = 4\pi f$.

- <u>Bad news</u> Easy attempts: no potential or quadratic divergences again
- **Collective Symmetry breaking:** Two ways of model building:

   1. simple Higgs representation , doubled gauge group
   2. simple gauge group, doubled Higgs representation

Prime Example: Simple Group Model

- enlarged gauge group: $SU(3) \times U(1)$; globally $U(3) \to U(2)$
- **Two** nonlinear Φ representations $\boxed{\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2}$

$$\Phi_{1/2} = \exp\left[\pm i \frac{f_{2/1}}{f_{1/2}} \Theta\right] \begin{pmatrix} 0 \\ 0 \\ f_{1/2} \end{pmatrix} \qquad \Theta = \frac{1}{\sqrt{f_1^2 + f_2^2}} \begin{pmatrix} \eta & 0 & \\ 0 & \eta & h^* \\ & h^T & \eta \end{pmatrix}$$

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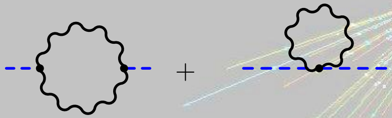
Coleman-Weinberg mechanism: Radiative generation of potential



$$= \frac{g^2}{16\pi^2} \Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2\right) \sim \frac{g^2}{16\pi^2} f^2$$

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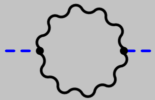
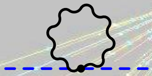
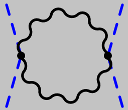
 $+$ 

$$= \frac{g^2}{16\pi^2} \Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2 \right) \sim \frac{g^2}{16\pi^2} f^2$$

but: $\Phi_1^\dagger$, Φ_1  $\Phi_2^\dagger$, Φ_2

$$= \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2 \Rightarrow \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) f^2 (h^\dagger h)$$

Yukawa interactions and heavy Top

Simplest Little Higgs (“μ Model”) Schmaltz (2004), Kilian/Rainwater/JR (2004)

Field content ($SU(3)_c \times SU(3)_w \times U(1)_X$ quantum numbers)

$$\Phi_{1,2} \; : \; (1,3)_{-\frac{1}{3}} \qquad \Psi_\ell \; : \; (1,3)_{-\frac{1}{3}} \qquad {u_{1,2}}^c \; : \; (\bar{3},1)_{-\frac{2}{3}}$$

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Lagrangian $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{\text{Yuk.}} + \mathcal{L}_{\text{pot.}}$ $\Psi_{Q,L} = (u,d,U)_L, \Psi_\ell = (\nu,\ell,N)_L$:

$$\mathcal{L}_{\text{Yuk.}} = -\lambda_1^u \overline{u}_{1,R} \Phi_1^\dagger \Psi_{T,L} - \lambda_2^u \overline{u}_{2,R} \Phi_2^\dagger \Psi_{T,L} - \frac{\lambda^d}{\Lambda} \epsilon^{ijk} \overline{d}_R^b \Phi_1^i \Phi_2^j \Psi_{T,L}^k$$
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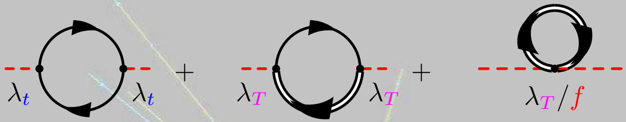
Hypercharge embedding (remember: $\mathrm{diag}(1,1,-2)/(2\sqrt{3})$):

$$Y = X - T^8/\sqrt{3} \qquad D_\mu \Phi = (\partial_\mu - \frac{1}{3} g_X B_\mu^X \Phi + i g W_\mu^w)\Phi$$

Cancellations of Divergencies in Yukawa sector



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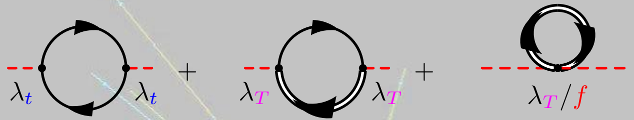

$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2 - m_T^2)} \left\{ \lambda_t^2 (k^2 - m_T^2) + k^2 \lambda_T^2 - \frac{m_T}{F} \lambda_T k^2 \right\}$$

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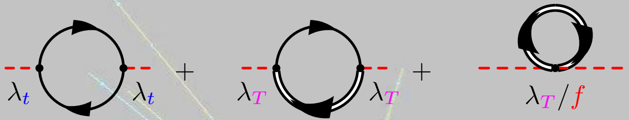

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Little Higgs global symmetry imposes relation

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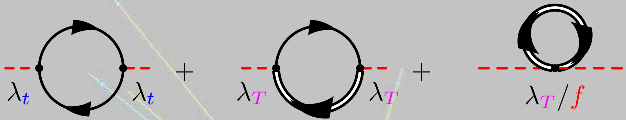

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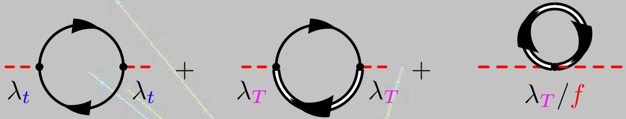

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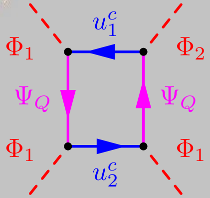
Collective Symm. breaking: $\lambda_t \propto \lambda_1\lambda_2$, $\lambda_1 = 0$ *or* $\lambda_2 = 0 \Rightarrow SU(3) \to [SU(3)]^2$



$$\sim \frac{\lambda_1^2\lambda_2^2}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger\Phi_2|^2$$

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Generic properties — Scales and Masses

- Extended scalar (Higgs-) sector **Extended global symmetry**
- **Specific form of scalar potential**
- **Extended Gauge Sector:** $B', Z', W'^{\pm}$
- **Extended top sector:** new heavy quarks, t, t' loops $\Rightarrow$ $M_h^2 < 0$
  $\Rightarrow$ EWSB

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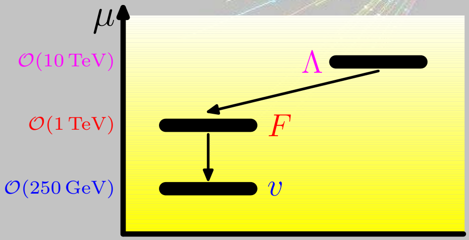


- ◇ Scale Λ: global SB, new dynamics, UV embedding
- ◇ Scale F: Pseudo-Goldstone bosons, new vector bosons and fermions
- ◇ Scale v: Higgs, $W^{\pm}$, Z, $\ell^{\pm}$, ...

Outline

Little Higgs Models

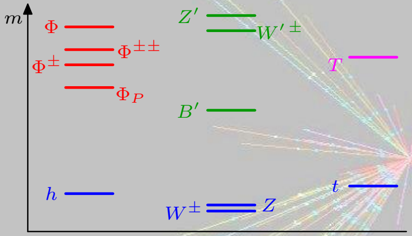
Plethora of "Little Higgs Models" in 3 categories:

- **Moose Models**
  - Orig. Moose (Arkani-Hamed/Cohen/Georgi, 0105239)
  - Simple Moose (Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker, 0206020)
  - Linear Moose (Casalbuoni/De Curtis/Dominici, 0405188)
- **Simple (Goldstone) Representation Models**
  - Littlest Higgs (Arkani-Hamed/Cohen/Katz/Nelson, 0206021)
  - Antisymmetric Little Higgs (Low/Skiba/Smith, 0207243)
  - Custodial $SU(2)$ Little Higgs (Chang/Wacker, 0303001)
  - Littlest Custodial Higgs (Chang, 0306034)
  - Little SUSY (Birkedal/Chacko/Gaillard, 0404197)
- **Simple (Gauge) Group Models**
  - Orig. Simple Group Model (Kaplan/Schmaltz, 0302049)
  - Holographic Little Higgs (Contino/Nomura/Pomarol, 0306259)
  - Simplest Little Higgs (Schmaltz, 0407143)
  - Simplest Little SUSY (Roy/Schmaltz, 0509357)
  - Simplest T parity (Kilian/Rainwater/JR/Schmaltz,...)

Varieties of Particle spectra

- $\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$

  Arkani-Hamed/Cohen/Katz/Nelson, 2002



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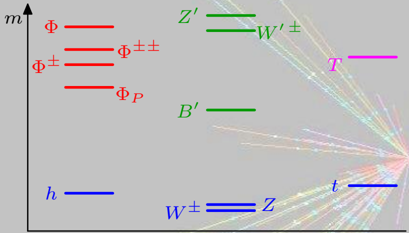
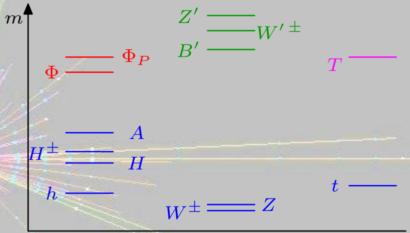


- $\mathcal{H} = \frac{SO(6)}{Sp(6)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$

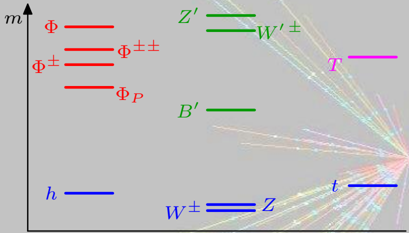
  Low/Skiba/Smith, 2002



Varieties of Particle spectra

- $\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$

  Arkani-Hamed/Cohen/Katz/Nelson, 2002



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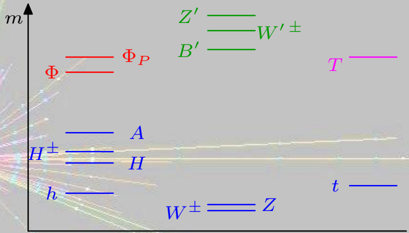
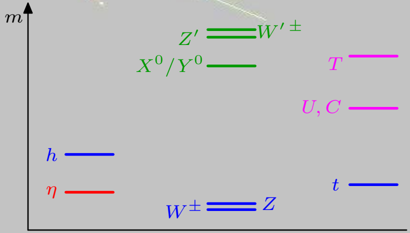


- $\mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2}, \mathcal{G} = \frac{SU(3) \times U(1)}{SU(2) \times U(1)}$ $\Longrightarrow$

  Schmaltz, 2004



- $[SU(4)]^4 \to [SU(3)]^4$

  Kaplan/Schmaltz, 2003

  2HDM, $h_{1/2}$, $\Phi'_{1,2,3}$, $\Phi'_{P\ 1,2,3}$, $Z'_{1,\ldots,8}$, $W'^{\pm}_{1,2}$, q', ℓ'

DESY

Outline

Hierarchy Problem

- Higgs as Pseudo-Nambu-Goldstone Boson (PNGB)
- The Little Higgs mechanism

Generic properties

Examples of Models

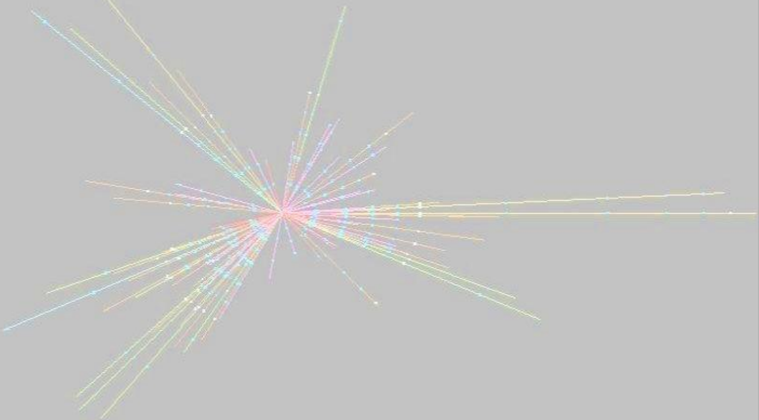
Phenomenology

- Effective Field Theories
- Electroweak Precision Observables
- Neutrino masses
- Heavy Quark States
- Heavy Vectors
- Heavy Scalars
- Reconstruction of Little Higgs Models
- Pseudo Axions in LHM
- T parity and Dark Matter

Conclusions

Effective Field Theories

- How to *clearly* separate effects of heavy degrees of freedom?



Effective Field Theories

How to *clearly* separate effects of heavy degrees of freedom?

Toy model: Two interacting scalar fields φ, Φ

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

Low-energy effective theory $\Rightarrow$ integrating out heavy degrees of freedom (DOF) in path integrals, set up Power Counting Kilian/JR, 2003

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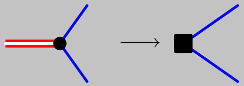
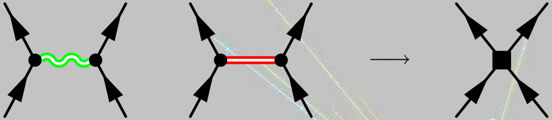
Completing the square:

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \Rightarrow$$

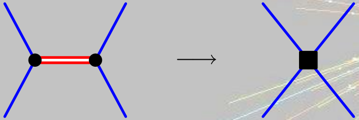


$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi = -\frac{1}{2}\Phi'(M^2 + \partial^2)\Phi' + \frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2.$$

Effective Dim. 6 Operators

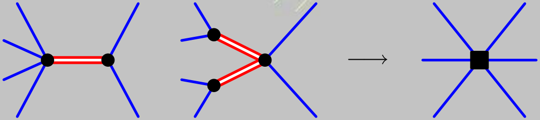


$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{F^2}\,\mathrm{tr}[J^{(I)} \cdot J^{(I)}]$$

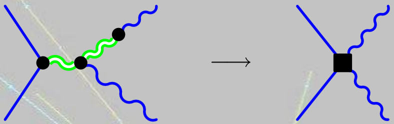


$$\mathcal{O}'_{h,1} = \frac{1}{F^2}\left((Dh)^\dagger h\right) \cdot \left(h^\dagger (D^h)\right) - \frac{v^2}{2}|Dh|^2$$

$$\mathcal{O}'_{hh} = \frac{1}{F^2}(h^\dagger h - v^2/2)\,(Dh)^\dagger \cdot (Dh)$$



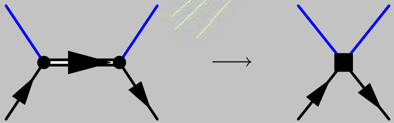
$$\mathcal{O}'_{h,3} = \frac{1}{F^2}\frac{1}{3}(h^\dagger h - v^2/2)^3$$



$$\mathcal{O}'_{WW} = -\frac{1}{F^2}\frac{1}{2}(h^\dagger h - v^2/2)\,\mathrm{tr}\,W_{\mu\nu}W^{\mu\nu}$$

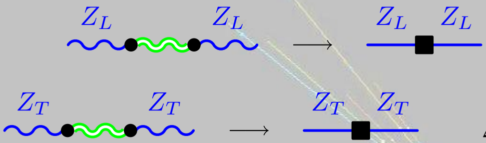
$$\mathcal{O}_B = \frac{1}{F^2}\frac{i}{2}(D_\mu h)^\dagger(D_\nu h)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(h^\dagger h - v^2/2)B_{\mu\nu}B^{\mu\nu}$$



$$\mathcal{O}_{Vq} = \frac{1}{F^2}\overline{q}h(\not{D}h)q$$

Oblique Corrections: S, T, U



$$\Delta T \sim \Delta\rho \sim \Delta M_Z^2 Z \cdot Z$$

$$\Delta S \sim {W^0}_{\mu\nu} B^{\mu\nu}, \Delta U \sim {W^0}_{\mu\nu} W^{0\,\mu\nu}$$

- ◇ All low-energy effects order v^2/F^2 (Wilson coefficients)
- ◇ Low-energy observables with low-energy input G_F, α, M_Z affected by **non-oblique** contributions:

$$G_F = \frac{1}{v} \longrightarrow \frac{1}{v}\left(1 - \alpha\Delta T + \delta\right),$$

$$\boxed{\delta \equiv= -\frac{v^2}{4} f_{JJ}^{(3)} \overset{\text{LHM}}{\longrightarrow} -\frac{c^4 v^2}{F^2}}$$

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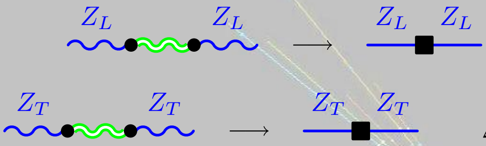

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$$S_{\text{eff}} = \Delta S$$

$$T_{\text{eff}} = \Delta T - \frac{1}{\alpha}\delta$$

$$U_{\text{eff}} = [\Delta U = 0] + \frac{4s_w^2}{\alpha}\delta$$

- Little Higgs Models: S_{eff}, T_{eff}, c, c'
- non-oblique flavour-dependent corrections $\Rightarrow$ enforce flavour-dependent EW fit

Constraints on LHM

Constraints from contact IA: ($f_{JJ}^{(3)}, f_{JJ}^{(1)}$) $4.5\,\text{TeV} \lesssim F/c^2 \quad 10\,\text{TeV} \lesssim F/c'^{\,2}$

- **Constraints evaded** $\quad \Longleftrightarrow \quad c, c' \ll 1$
  $B', Z', W'^{\pm}$ superheavy ($\mathcal{O}(\Lambda)$) *decouple from fermions*

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ΔS, ΔT **in the Littlest Higgs model, violation of Custodial SU(2):** Csáki et al., 2002; Hewett et al., 2002; Han et al., 2003; Kilian/JR, 2003

$$\frac{\Delta S}{8\pi} = -\left[\frac{c^2(c^2-s^2)}{g^2} + 5\frac{c'^2(c'^2-s'^2)}{g'^2}\right]\frac{v^2}{F^2} \to 0 \qquad \alpha\Delta T \to \frac{5}{4}\frac{v^2}{F^2} - \frac{2v^2\lambda_{2\phi}^2}{M_\phi^4} \gtrsim \frac{v^2}{F^2}$$

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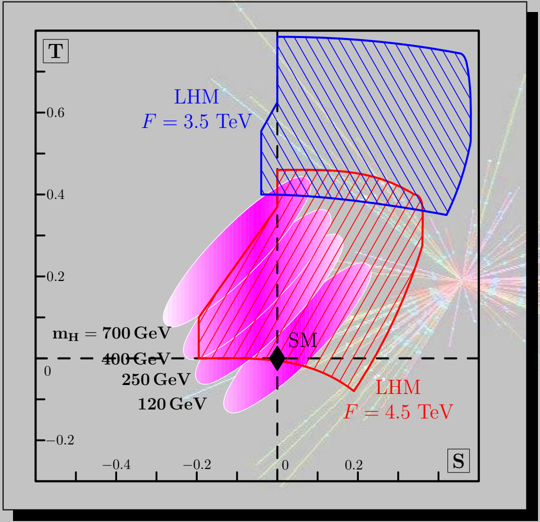
General models

- Triplet sector: (almost) identical to Littlest Higgs (ΔS only)
- More freedom in $U(1)$ sector: (ΔT)

EW Precision Observables



Higgs mass *variable* (Coleman-Weinberg, UV completion)

$$\Delta S = \frac{1}{12\pi} \ln \frac{m_H^2}{m_0^2}$$

$$\Delta T = -\frac{3}{16\pi c_w^2} \ln \frac{m_H^2}{m_0^2}$$

Peskin/Takeuchi, 1992; Hagiwara et al., 1992

Making the Higgs heavier reduces amount of fine-tuning

Neutrino masses

Kilian/JR, 2003; del Aguila et al., 2004; Han/Logan/Wang, 2005

⋆ *Naturalness does not require cancellation mechanism for light fermions*

Lepton-number violating interactions can generate **neutrino masses** (due to presence of triplet scalars)

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Lagrangian invariant under **full gauge symmetry**

$$\boxed{\mathcal{L}_N = -g_N F (\bar{L}^c)^T \Xi L} \quad \text{with} \quad L = (\mathrm{i}\tau^2 \ell_L, 0, 0)^T$$

EWSB: Generation of neutrino masses $\boxed{m_\nu \sim g_N v^2 / F}$

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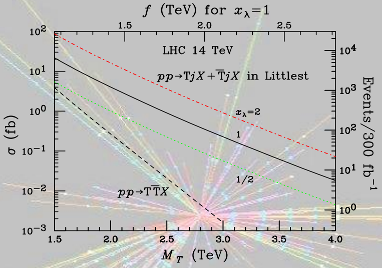
Caveat: m_ν too large compared to observations

$\Rightarrow g_N$ small, e.g. F/Λ', where Λ' : scale of lepton number breaking

Heavy Quark States

- EW single dominates QCD pair production: Perelstein/Peskin/Pierce, ’03



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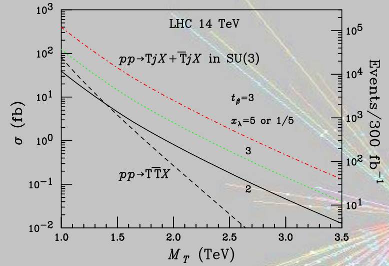
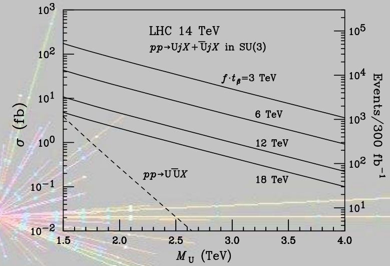




- Characteristic branching ratios :

$$\Gamma(T \to th) \approx \Gamma(T \to tZ) \approx \frac{1}{2}\Gamma(T \to bW^+) \approx \frac{M_T \lambda_T^2}{64\pi}, \qquad \Gamma_T \sim 10\text{--}50\,\text{GeV}$$

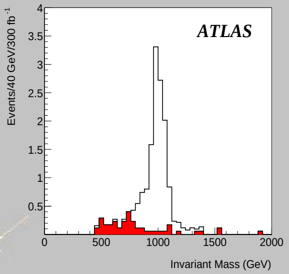
- Proof of T as EW singlet; but: $T \to Z'T, W'b, t\eta$!

AIM: *Determination of* $M_T, \lambda_T, \lambda_{T'}$

$\lambda_{T'}$ indirect ($T\bar{T}h$ impossible)

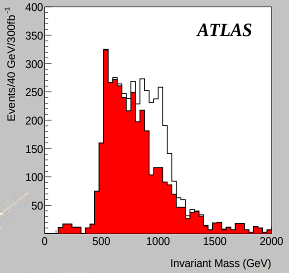
$T \to Zt \to \ell^+\ell^-\ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ GeV, $\ell\ell\ell, p_T > 100/30$ GeV, $b, p_T > 30$ GeV
- Bkgd.: WZ, ZZ, btZ
- Observation for $M_T \lesssim 1.4$ TeV



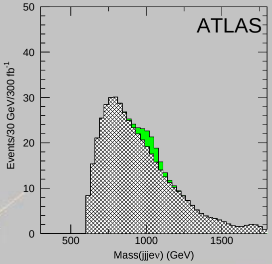
$T \to Wb \to \ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ GeV, $\ell, p_T > 100$ GeV, $b, p_T > 200$ GeV, max. $jj, p_T > 30$ GeV
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single t
- Observation for $M_T \lesssim 2.5$ TeV



$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038

- $\ell, p_T > 100$ GeV, $jjj, p_T > 130$ GeV, at least 1 b-tag
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single t
- Observation for $M_T \lesssim 2.5$ TeV



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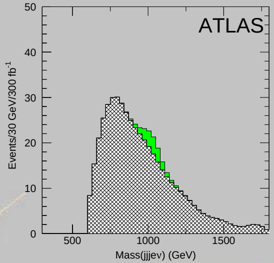
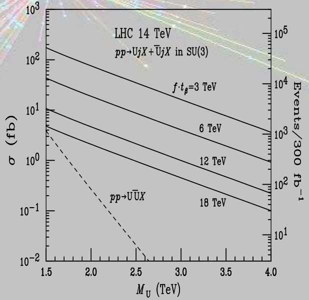


Additional heavy quarks (Simple Group Models): U, C or D, S Han et al., 05

- Large cross section: u or d PDF
- Huge final state ℓ charge asymmetry
- Good mass reconstruction



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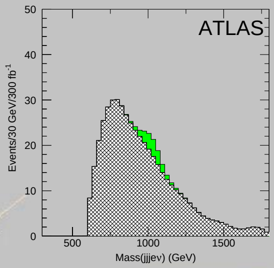

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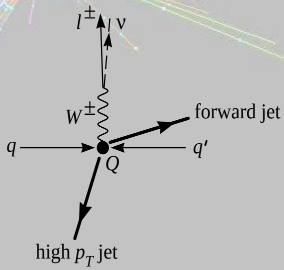

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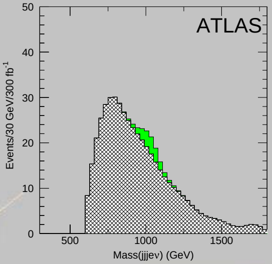

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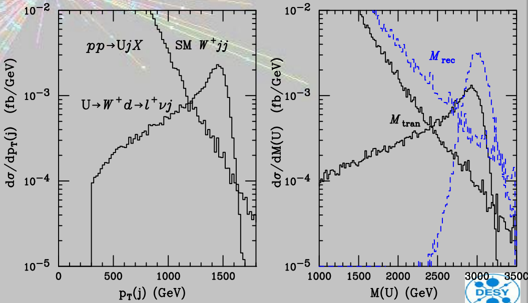
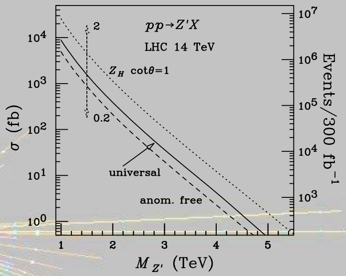


Heavy Vectors

Drell-Yan Production: Tevatron Limits $\sim 500 - 600$ GeV

- Dominant decays:
  Product group: $Z' \to Zh, WW$,
  $W' \to Wh, WZ$
  Simple group: $Z' \to qq$, $X \to fF$



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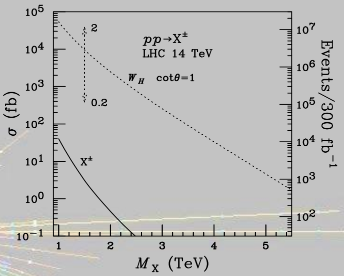

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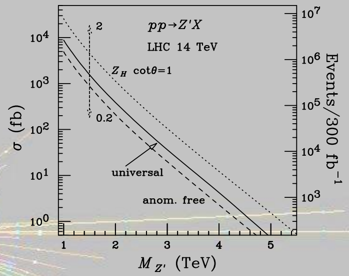
- Discovery channel: $Z' \to \ell\ell$, $W' \to \ell\nu$
- $\Gamma_{Z'} \sim 10 - 50\,$GeV, $\Gamma_X \sim 0.1 - 10\,$GeV



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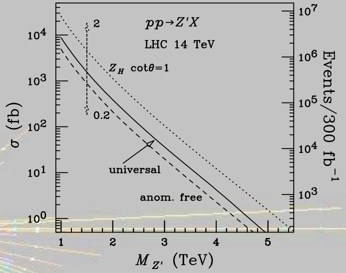

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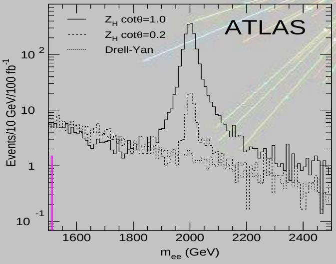
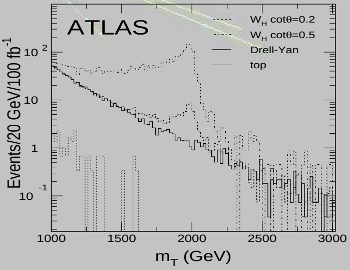
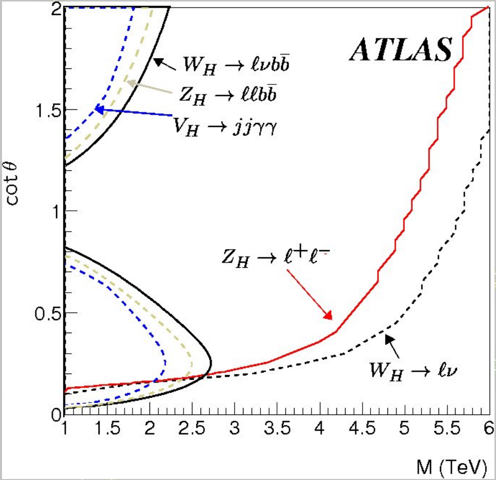






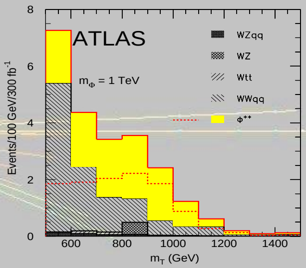
Proof: Sum rule for cancellation of divergences: $g_{HHVV} + g_{HHV'V'} = 0$, associated production $pp \to V'h$

Heavy Scalars

Generally: **Large model dependence**

no states complex singlet complex triplet

- Littlest Higgs, complex triplet: $\Phi^0, \Phi_P, \Phi^{\pm}, \Phi^{\pm\pm}$
- Cleanest channel: $q\bar{q} \to \Phi^{++}\Phi^{--} \to \ell\ell\ell\ell$: Killer: PS
- WW-Fusion: $dd \to uu\Phi^{++} \to uuW^+W^+$
- 2 hard forward jets, hard close $\ell^+\ell^+$ p_T-unbalanced



Alternative: Model-Independent search in WW fusion:

ILC: Beyer/Kilian/Krstonosic/Mönig/JR/Schmidt/Schröder, 2006

LHC: ATLAS-note, Kilian/Mertens/JR/Schumacher

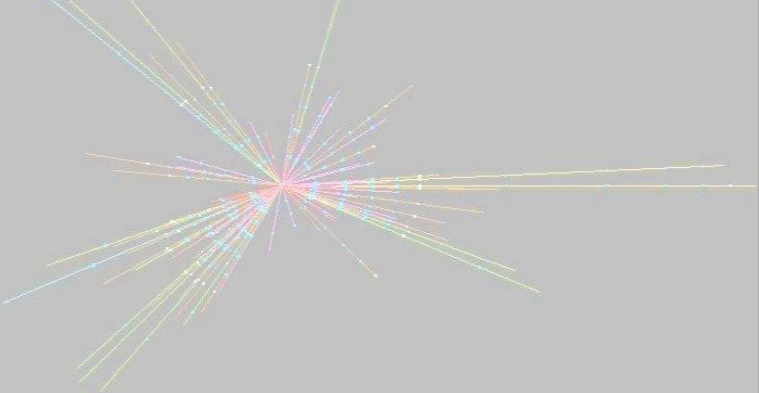
Reconstruction of LHM

How to unravel the structure of LHM @ colliders?

Kilian/JR, 2003; Han et al., 2005

◇ Symmetry structure
$\Rightarrow$ Quadr. Div. Cancell.

◇ Nonlinear Goldstone boson structure



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SIGNALS:

- *Anom.* Triple Gauge Couplings: WWZ, $WW\gamma$
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Vectors:

- Direct Search (LHC) M_V, F, c, c'
- ILC: Contact Terms $e^+e^- \to \ell^+\ell^-, [\nu\bar{\nu}\gamma] \Rightarrow M_{B'} \lesssim 10[5]$ TeV
- Higgsstr., WW fusion: $HZff$, $HWff$ angular distr./energy dependence $\Rightarrow f_{VJ}^{(1/3)}$
- Check from TGC (ILC: per mil precision), GigaZ $\Rightarrow f_{JJ}^{(3)}$

Combining $\Rightarrow$ Determination of *all* coefficients in the gauge sector

Scalars:
Affected by scalars and vectors

- ΔT, $f^{(1)}_{VV}$, B' known $\Rightarrow$ $(\lambda_{2\phi}/M^2_\phi)^2$
- Higgsstr., WW fusion $\Rightarrow$ Higgs coupl., $f^{(3)}_{VV}$
- Higgs BRs $\Rightarrow$ $f^{(1)}_{VV}$, $f^{(3)}_{VV}$; (take care of t)
  $f^{(3)}_{VV}$ **Goldstone contr.** $\Rightarrow$ **Evidence for nonlinear nature**
- HH production $\Rightarrow$ $f_{h,3}$ (difficult!)

LHC $\bowtie$ ILC $\Rightarrow$ 1-2 % accuracy @ Higgs measurements **Reconstruction of scalar sector** up to $F \sim 2$ TeV

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Top:

- Direct production @ LHC
- $t\bar{t}$ production $\Rightarrow f_{Vq}, v_t, a_t$; accuracy 1-2 %
- tbW from t decays, single t production $g_{ttH}/g_{bbH} \Rightarrow$ *anom. Yukawa coupl.* $\Rightarrow f_{hq}$, nonlin. structure w. $\sim 2.5\%$ accuracy

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Include all observables in a combined fit if Little Higgs signals are found (sufficient data from LHC and ILC)

Pseudo Axions in LHM

Kilian/Rainwater/JR, 2004

- broken diagonal generator: η in QCD; *couples to fermions as a pseudoscalar*, behaves as a axion
- analogous particles: techni-axion, topcolor-axion, (N)MSSM-axion

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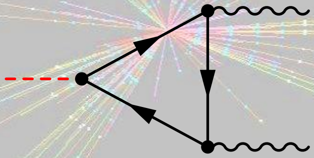
QCD-(PQ) axion: $\mathcal{L}_{\text{Ax.}} = \frac{1}{\Lambda}\frac{\alpha_s}{8\pi^2} A_g \eta G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad \tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}G_{\rho\sigma}$

Anomalous $U(1)_\eta$:



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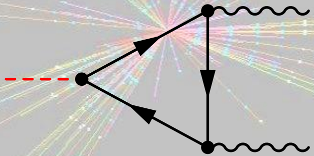

- **explicit symmetry breaking** $\Rightarrow m_\eta$ and $g_{\eta\gamma\gamma}$ independent $\Rightarrow$ axion bounds *not applicable*
- *no new hierarchy problem* $\Rightarrow m_\eta \lesssim v \sim 250$ GeV
- η EW singlet, couplings an to SM particles v/F suppressed

Example: Simple Group Model

Scalar Potential: $\mu \Phi_1^\dagger \Phi_2 + \text{h.c.}$ + Coleman-Weinberg pot.:

$$\boxed{m_\eta \;=\; \sqrt{\kappa}\,\mu \;\geq\; \sqrt{2}\,\mu} \qquad m_H^2 = -2(\delta m^2 + m_\eta^2)$$

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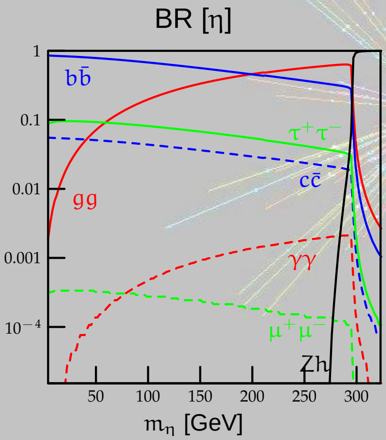


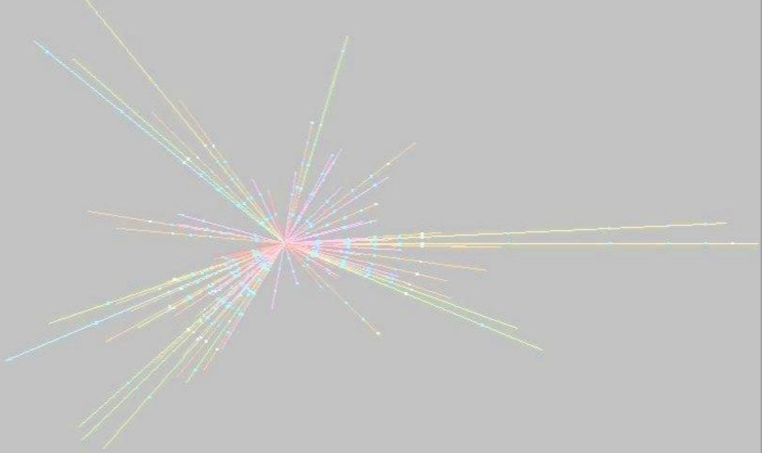
new Higgs decays ($H \to Z\eta$, $H \to \eta\eta$)

BR$(H \to \eta\eta) < 10^{-4}$ [~ 5–10% OSG]

m_H[GeV]	m_η[GeV]	BR$(Z\eta)$
341	223	0.1 %
375	193	0.5 %
400	167	0.8 %
422	137	1.0 %
444	96	1.2 %
464	14	1.4 %

Pseudo Axions at LHC and ILC

- LHC: **Gluon Fusion** ($U(1)_\eta$ anomaly), Peak in diphoton spectrum



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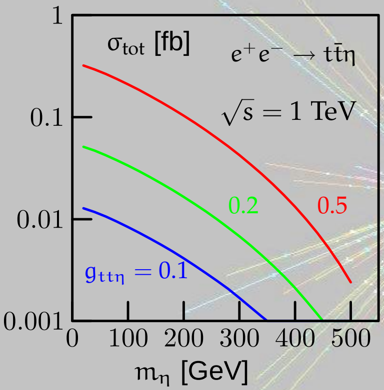
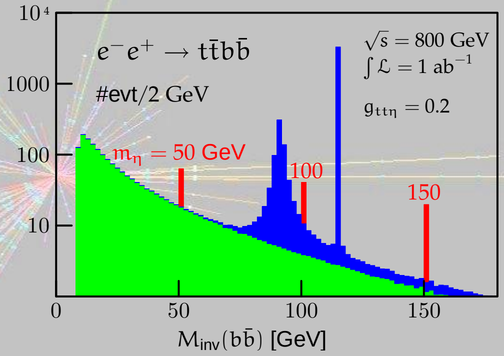
- LHC: **Gluon Fusion** ($U(1)_\eta$ anomaly), Peak in diphoton spectrum
- ILC: **associated production** Problem: Cross section vs. bkgd.





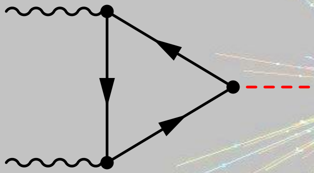
Possibility: $Z^* \to H\eta$ (analogous to A in 2HDM)

Distinction between Simple and Product Group Models

Kilian/JR/Rainwater (in prep.)

Pseudo Axions at the Photon Collider

- Photon Collider as precision machine for Higgs physics (s channel resonance, anomaly coupling)



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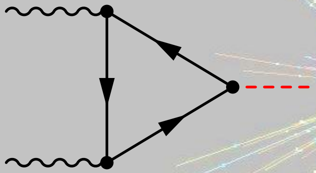

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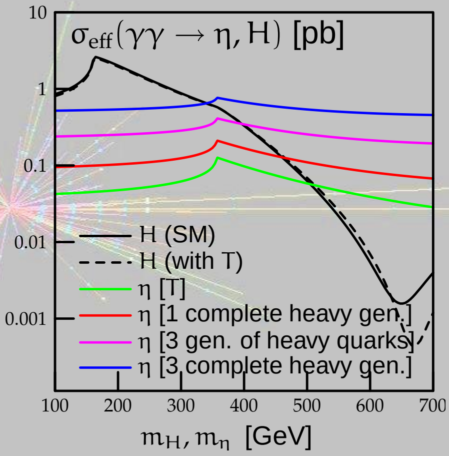
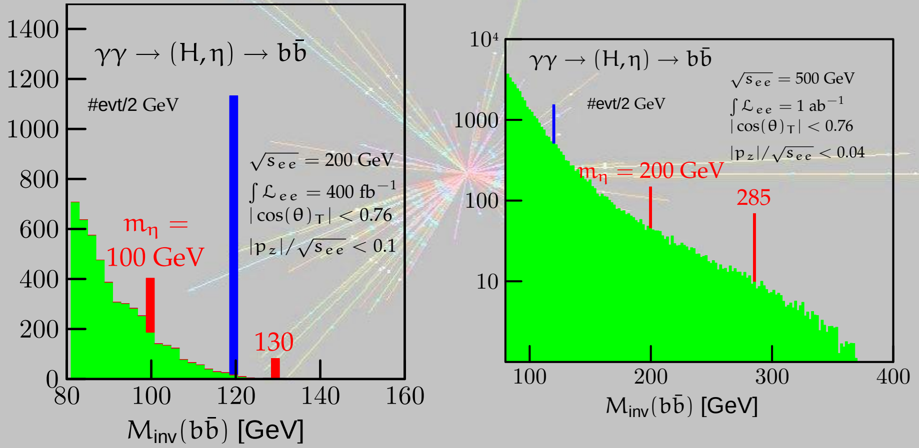


$g_{bb\eta} = 0.4 \cdot g_{bbh}$

m_η	100	130	200	285
$\Gamma_{\gamma\gamma}$[keV]	0.15	0.27	1.1	3.6



T parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005

- T parity: $T^a \to T^a, \quad X^a \to -X^a$, automorphism of coset space
- analogous to R parity in SUSY, KK parity in extra dimensions
- Bounds on f MUCH relaxed,
- *but:* Pair production!, typical cascade decays
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

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Littlest Higgs: A' LTP

$W', Z' \sim$ 650 GeV

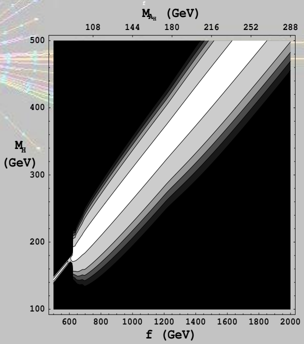
$\Phi \sim$ 1 TeV

$T, T' \sim$ 0.7-1 TeV

Annihilation:

$A'A' \to h \to WW, ZZ, hh$

0/10/50/70/100



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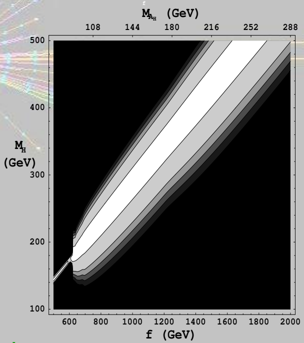

- T parity Simple Group model: Pseudo-Axion η LTP

Kilian/Rainwater/JR/Schmaltz

Outline

Conclusions

Little Higgs elegant alternative to SUSY Gauge/Global Symmetry structure stabilizes EW scale

- Generics: new heavy gauge bosons, scalars, quarks

Little Higgs *in accord w EW precision observ.* **w/o Fine Tuning** (M_H!)

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UV embedding, GUT, Flavor ?

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Clear **experimental signatures:**
direct search [Gauge & Top sector, LHC (ILC)] $\longleftrightarrow$
precision observables [Gauge, Scalar, Top sector ILC (LHC)]

Strategy for Reconstruction by *Complementarity* of ILC & LHC

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