Z-H-η COUPLINGS IN LITTLE HIGGS MODELS

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– Litte Higgs pseudo-axions
– Product Group v. Simple Group
– ILC pheno

Little Higgs psuedo-axions

Little Higgs models have pseudo-axions!

[Kilian, DR, Reuter, PRD(71) 015008]

$\rightarrow$ corresponds to broken diagonal generator

In general, extra $U(1)$s appear, but don't gauge:

A' tends to conflicts w/ EW data

Examples:

1. Minimal moose $[SU(3)]^4 \rightarrow SU(3)$: rank $8 \rightarrow 2 \;\therefore 6\,\eta$;
   gauged $SU(3) \times SU(2) \times U(1)$, rank 2 higher than EW,
   $\therefore 2\,\eta$ eaten by heavy VBs, 4 pseudo-axions remain
2. Simple group $[SU(4)]^3 \rightarrow [SU(3)]^2 \times SU(2)$: rank $9 \rightarrow 5 \;\therefore 4\,\eta$;
   gauged $SU(4) \times U(1)$, rank 2 higher than EW,
   $\therefore 2\,\eta$ eaten, 2 remain
3. Schmaltz μ-model: $SU(3) \rightarrow SU(2)$: rank $2 \rightarrow 1 \;\therefore 1\,\eta$;
   gauged $SU(2)$ is EW sector $\therefore$ no η eaten, 1 remains

Littlest Higgs ($SU(5) \to SO(5)$) model pseudo-axion

NGBs parameterized by 5×5 matrix $\Sigma = \left(\exp \frac{2i}{F}\Pi\right)\Sigma_0$

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 1_{2\times 2} \\ 0 & 1 & 0 \\ 1_{2\times 2} & 0 & 0 \end{pmatrix}, \quad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{10} & h & \phi \\ h^\dagger & -4\eta/\sqrt{10} & h^T \\ \phi^\dagger & h^* & \eta/\sqrt{10} \end{pmatrix}$$

Yukawa interactions also have η-dependent factors $\xi = \exp \frac{i}{\sqrt{5}F}\eta$

$$\chi_L = \begin{pmatrix} i\tau^2 \xi^{\beta_0} T_L & iq_L & 0 \\ -iq_L^T & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad iT_2^2 = \text{diag}(0,0,-i\tau^{2*})/2$$

$$\begin{aligned} \mathcal{L}_Y^t &= \lambda_1 F \xi^{\beta_1} \bar{t}_R \text{Tr}\left[\Sigma^*(iT_2^2)\Sigma^*\chi_L\right] - \lambda_2 F \xi^{\beta_2} \bar{T}_R T_L + \text{h.c.} \\ \mathcal{L}_Y^b &= -\frac{\lambda_b}{\sqrt{2}} F \xi^{\beta_3} \bar{b}_R \text{Tr}\left[\Sigma Y_1 \chi_L\right] + \text{h.c.} \end{aligned}$$

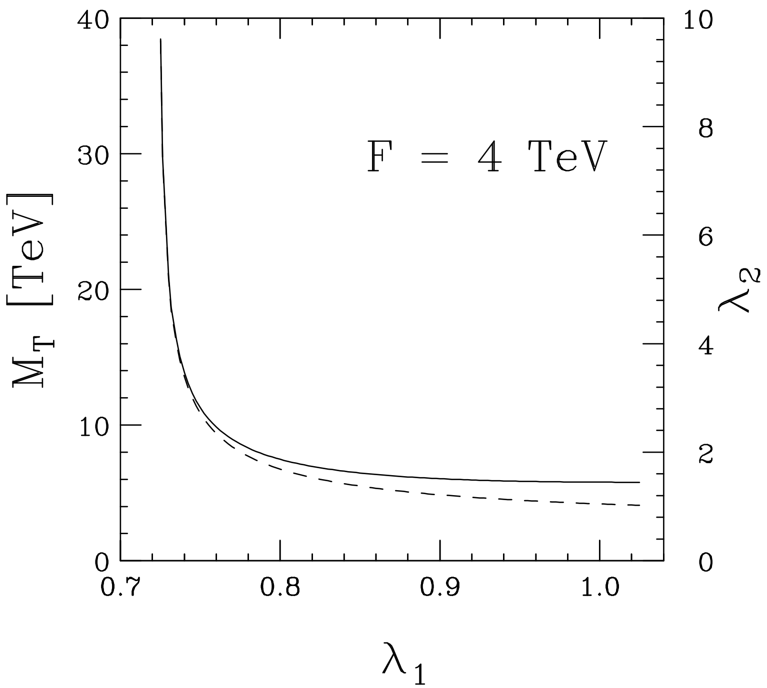
β_i are real #s, diff.'s of $U(1)_\eta$ fermion hypercharges

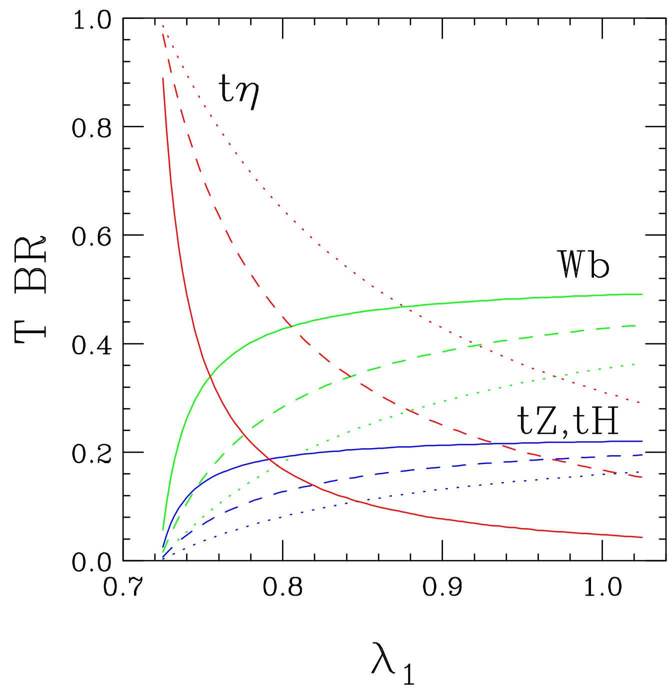
Littlest Higgs pseudo-axion – what do we know?

- mass is free parameter (> few GeV to avoid P.-Q. axion limits)
- β_i are free parameters
- no tree-level gauge boson couplings; loop-induced gg, $\gamma\gamma$ decays
- t, T couplings to H, η complementary & alters T decays!

$\bar{T}TH$	$O(\frac{v}{F})$
$\bar{T}tH$	$O(1)\,\mathcal{P}_L + O(\frac{v}{F})\,\mathcal{P}_R$
$\bar{t}tH$	$O(1)$

$\bar{T}T\eta$	$O(1)\,\gamma_5$
$\bar{T}t\eta$	$O(1)\,\mathcal{P}_R + O(\frac{v}{F})\,\mathcal{P}_L$
$\bar{t}t\eta$	$O(\frac{v}{F})\,\gamma_5$





The μ-model pseudo-axion

$SU(3)\times U(1)_Y \longrightarrow SU(2)_L \times U(1)_Y$ via 2 non-linear sigma fields:

$$\Phi_1 = \exp\left[i\frac{F_2}{F_1}\Theta\right]\begin{pmatrix}0\\0\\F_1\end{pmatrix}, \qquad \Phi_2 = \exp\left[-i\frac{F_1}{F_2}\Theta\right]\begin{pmatrix}0\\0\\F_2\end{pmatrix},$$

$$\Theta = \frac{1}{F}\left\{\frac{\eta}{\sqrt{2}} + \begin{pmatrix}0 & 0 & h\\ 0 & 0 & \\ & h^\dagger & 0\end{pmatrix}\right\}, \qquad F^2 = F_1^2 + F_2^2$$

· Little Higgs sym. broken radiatively (Yukawas)

$\longrightarrow$ global $U(1)_\eta$ symmetry left intact

· $U(1)_\eta$ breaking via μ-term: $V = -\mu^2\Phi_1^\dagger\Phi_2 + \text{h.c.}$

· m_η predicted! $\Rightarrow m_\eta = \sqrt{\kappa}\mu$, $\kappa = \frac{F1}{F2} + \frac{F2}{F1} \geq 2$

· Higgs mass related: $m_H^2 = -2(\delta m^2 + m_\eta^2)$

$\longrightarrow \delta m^2$ from 1-loop Coleman-Weinberg potential

μ-model has additional coupling: $ZH\eta$

Arises from kinetic terms for fields $\Phi_{1,2}$:

$$\mathcal{L} = (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2)$$

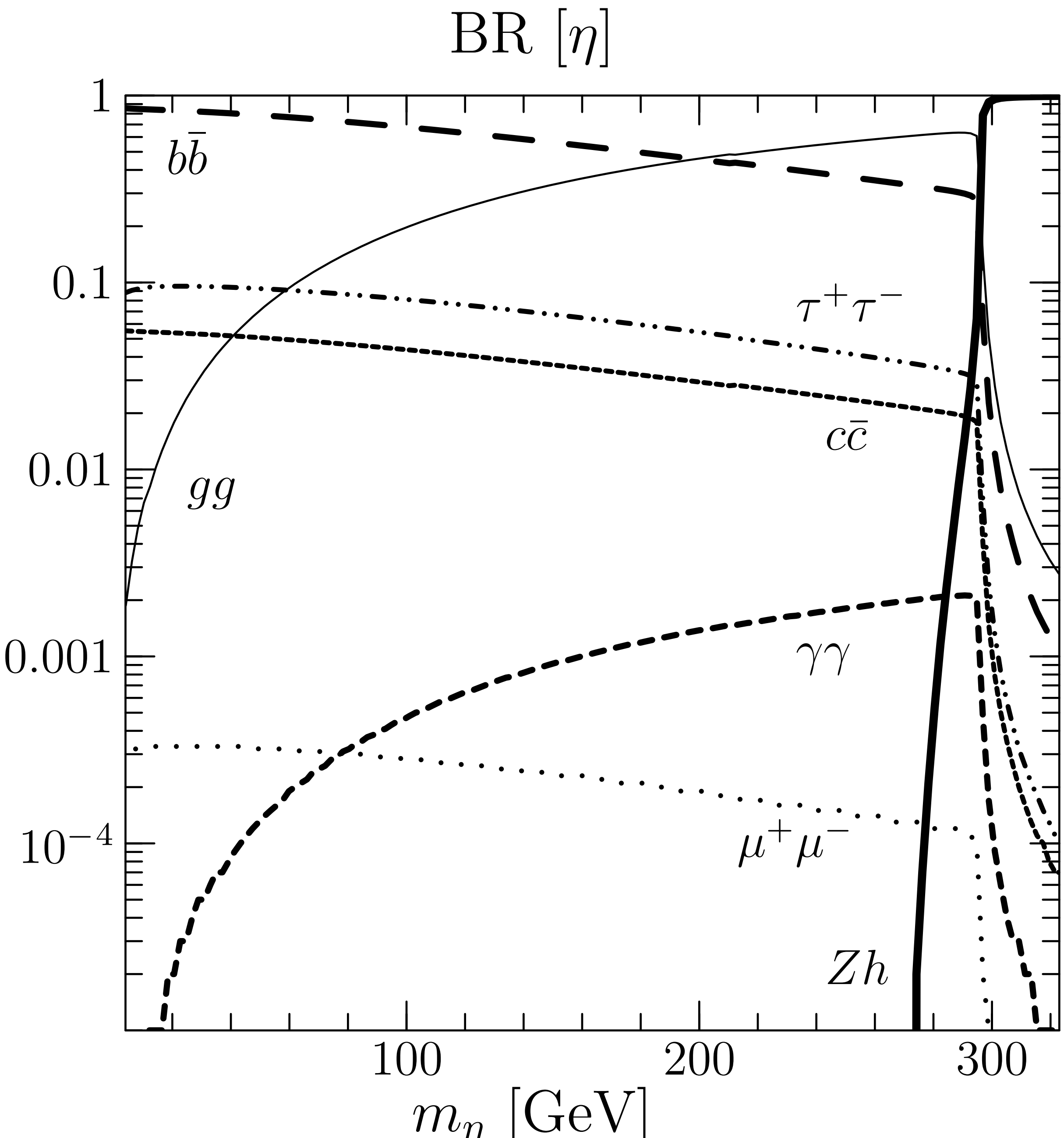
Leads to $ZH\eta$ derivative coupling:

$$\mathcal{L}_{ZH\eta} = \frac{m_Z}{\sqrt{2}F} N_2 Z_\mu (\eta \partial^\mu H - H \partial^\mu \eta), \qquad N_2 = \frac{F_2^2 - F_1^2}{F_1 F_2}$$

- coupling forbidden for unbroken EW symmetry (here, $SU(3)$), so must be proportional to v/F, but N_2 can be large!
- drastically changes pheno if kinem. accessible

μ-model η decay patterns

"Golden Point", varying μ $(10 \lesssim \mu \lesssim 150\ \mathrm{GeV})$



PRODUCT GROUP MODELS
V.
SIMPLE GROUP MODELS

Are these two models general observations? If so,

► existence of Z-H-η coupling distinguishes models!

Obvious collider tests:

· Drell-Yan $H\eta$ production

· inclusive $H \to Z\eta$ or $\eta \to ZH$ (depending on masses)

· $T \to t\eta \to tZH$ or $T \to tH \to tZ\eta$ (“)

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Theorem 1:

Product Group models cannot have a Z-H-η coupling

Theorem 2:

Simple Group models must have a Z-H-η coupling if $F_1 \neq F_2$

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3. Write kinetic term:

$$\begin{aligned}
\mathcal{L}_{\text{kin.}} &= \sim f^2(\partial_\mu\xi)\xi^\dagger \operatorname{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] + \text{h.c.} \sim (\partial_\mu\eta)\operatorname{Im}\operatorname{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] \\
D_\mu\Sigma &= \partial_\mu\Sigma + W^a_{1,\mu}\left(T^a_1\Sigma + \Sigma(T^a_1)^T\right) + W^a_{2,\mu}\left(T^a_2\Sigma + \Sigma(T^a_2)^T\right)
\end{aligned}$$

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\operatorname{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] &\simeq W^a_\mu \operatorname{Tr}\left[(\Sigma^\dagger(T^a_1+T^a_2)\Sigma + (T^a_1+T^a_2)^*\right] \\
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5. B fields: $U(1)$ generators in global group also be traceless

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$$\Pi = \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix}, \quad \mathbb{V}_\mu = \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \text{heavy fields (ignore)}, \quad D_\mu = \partial_\mu + ig\mathbb{V}_\mu$$

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4. Two Φ fields: coupling $\propto \frac{F_2}{F_1} - \frac{F_1}{F_2}$ $\quad (\to 0$ if $F_1 = F_2$, e.g. T-parity$)$

ILC PHENOMENOLOGY

(VERY PRELIMINARY)

$e^+e^- \rightarrow Z^* \rightarrow \eta H$

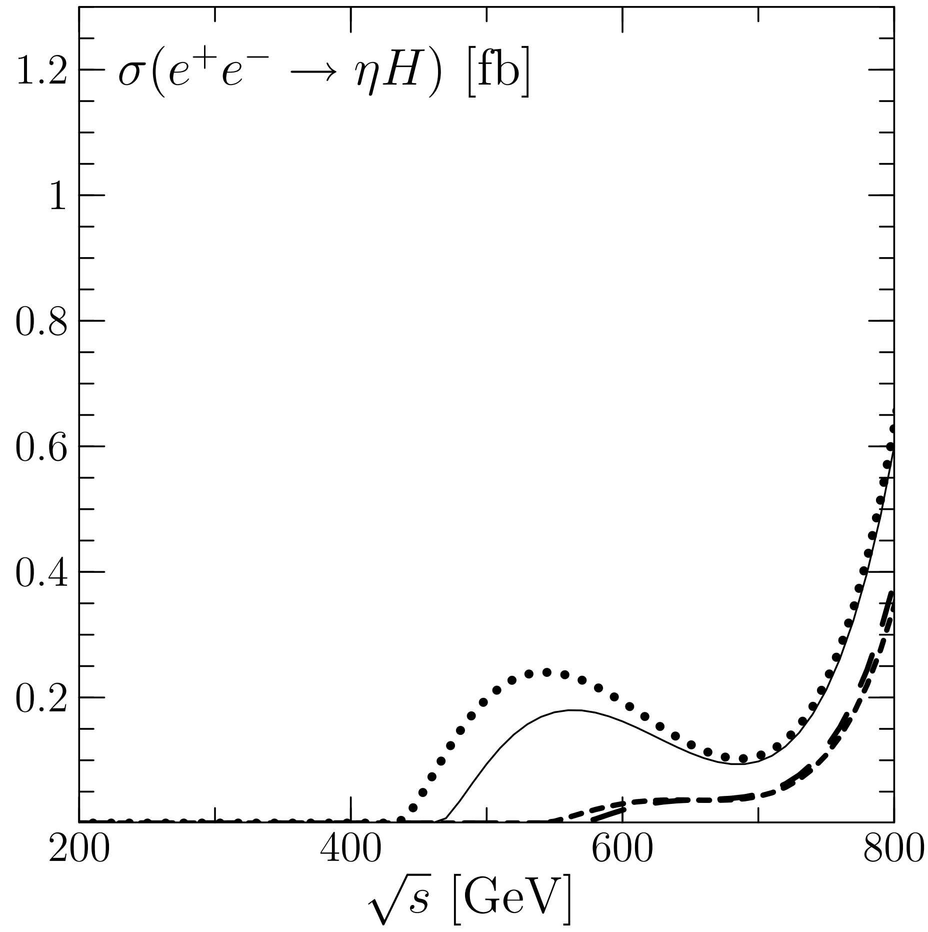
Foreword: Z'-H-η coupling also exists,
but assume the resonance is well above ILC energy

Lots of parameter space, so choose some representative points:

μ [GeV]	m_H [GeV]	m_η [GeV]
154	119	318
150	156	310
97	368	200
49	442	100

$\rightarrow$ very small rates!

▶ strong destructive interference with Z'



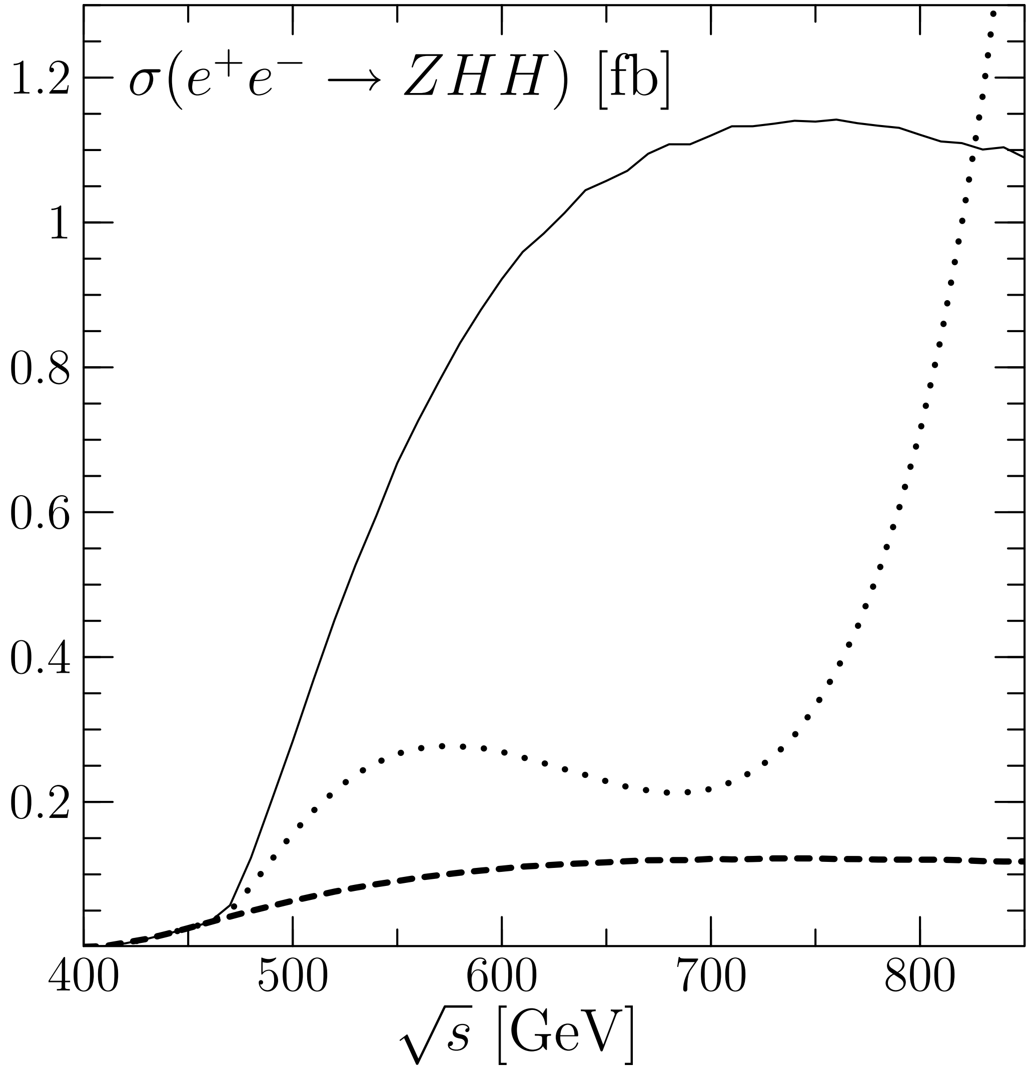
$e^+e^- \to Z^* \to \eta H \to ZHH$ (η decays)

- "Golden Point" of Schmaltz model: $F_{1,2} = 0.5, 2$ TeV:
  $m_T = 1$ TeV, $m_{Z'} = 1.11$ TeV

- for $m_\eta > 290$ GeV,
  $\eta \to ZH$ dominates

  dashed = SM
  dotted = LH
  solid = no Z' interf.

- SM ZHH marginal, but LH has η resonance, so would be observable



$e^+e^- \to Z^* \to \eta H \to Hjj$ (η decays to gg)

- "Golden Point" again
- for $m_\eta < 290$ GeV, $\eta \to gg$ dominates

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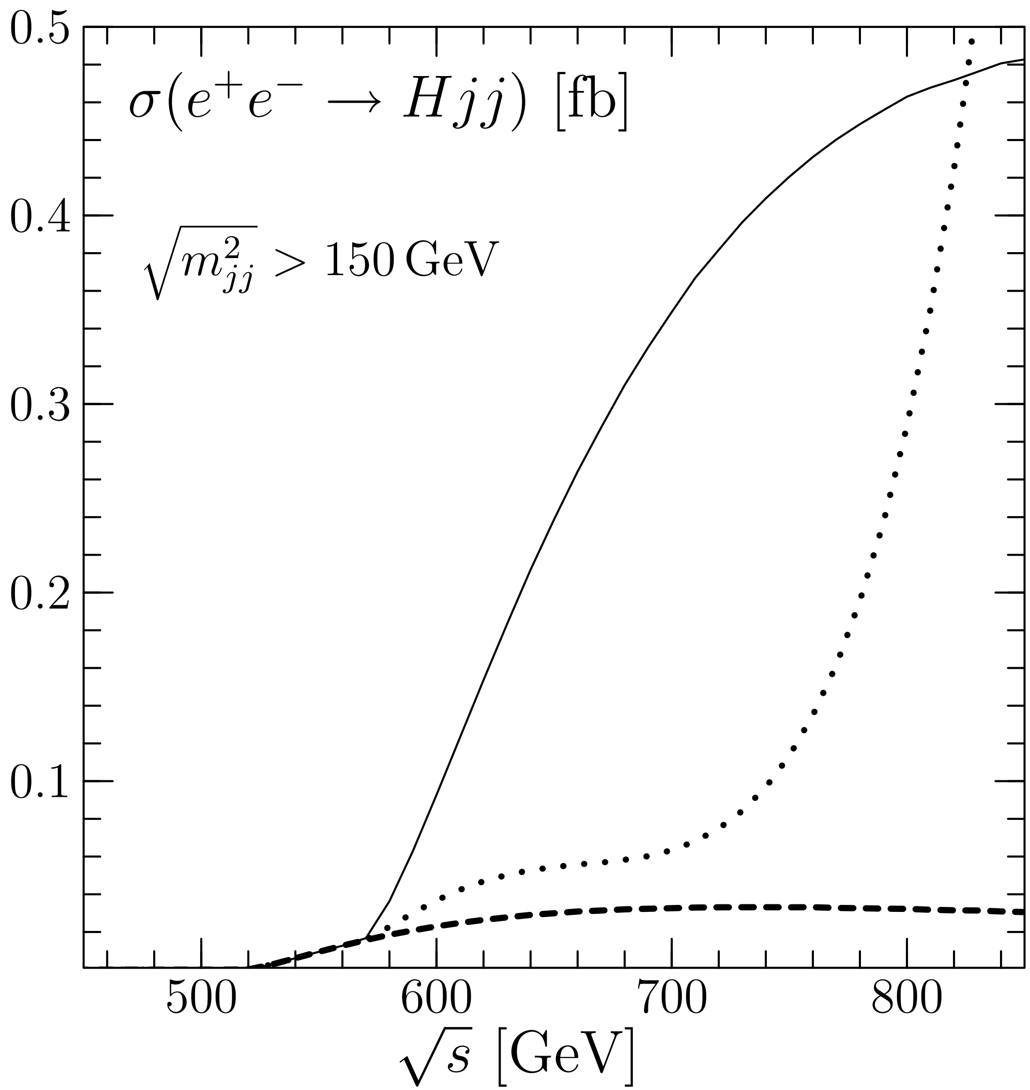
- *MUCH* tougher case, but perhaps possible



SUMMARY

- Little Higgs models generally have extra pseudoscalars
- these pseudo-axions *are not* ruled out by astro
- Product Group and Simple Group models differ:
  the latter have Z-H-η, Z'-H-η couplings
  (unless T-parity or other reason for $F_1 = F_2$)
- low rates at ILC, but clean environment promising
- LHC phenomenology on the way! (many more options)
  - $gg \to H \to Z\eta$
  - $gg \to \eta \to ZH$
  - $Z' \to Z\eta$
  - $T \to t\eta$