Pseudo Axions in Little-Higgs Models

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in collaboration with: W. Kilian (DESY), D. Rainwater (Rochester)

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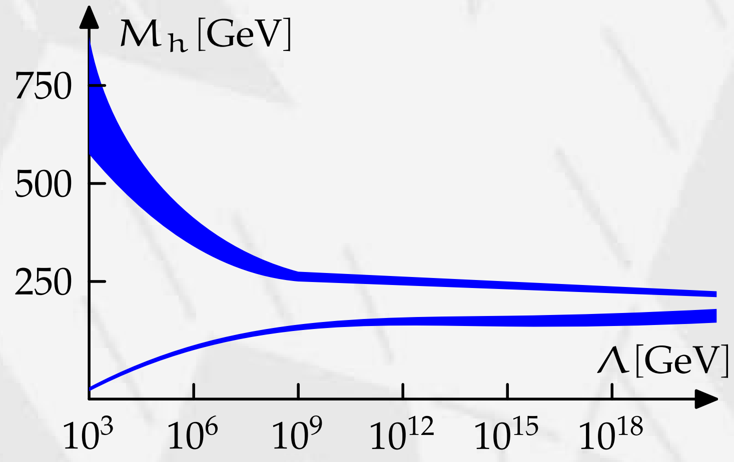
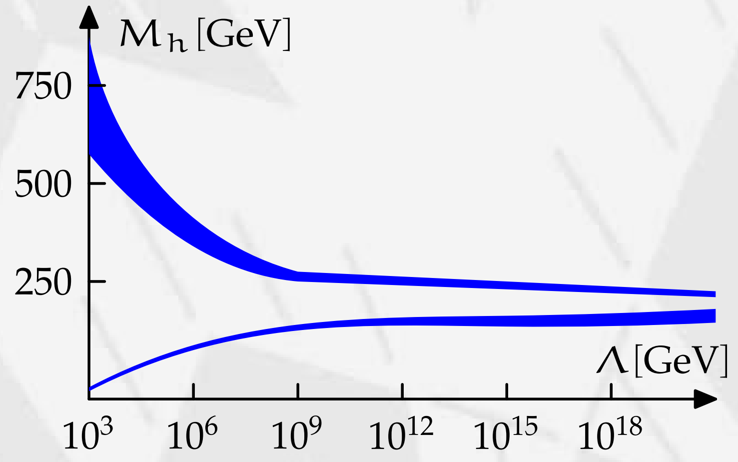


Motivation: Hierarchy Problem

- Effective theories below a scale $\Lambda \quad \Rightarrow$



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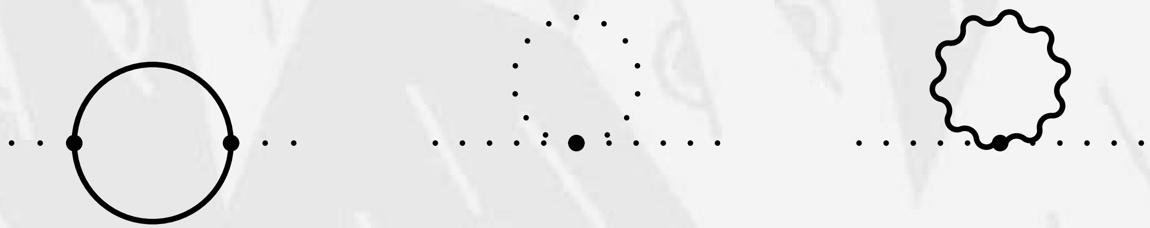
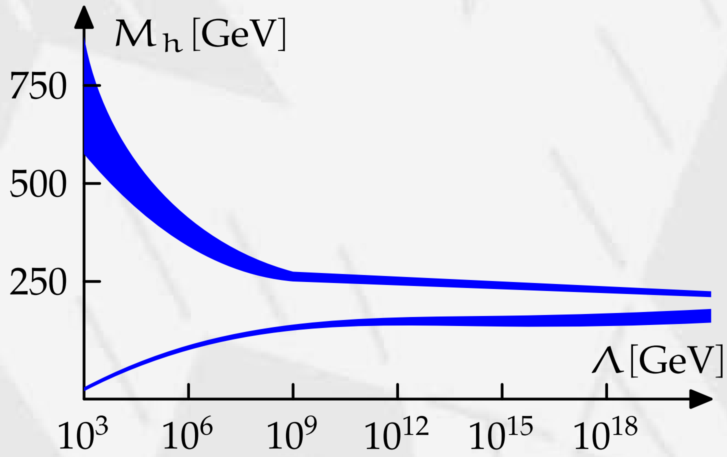


$\sim \Lambda^2$



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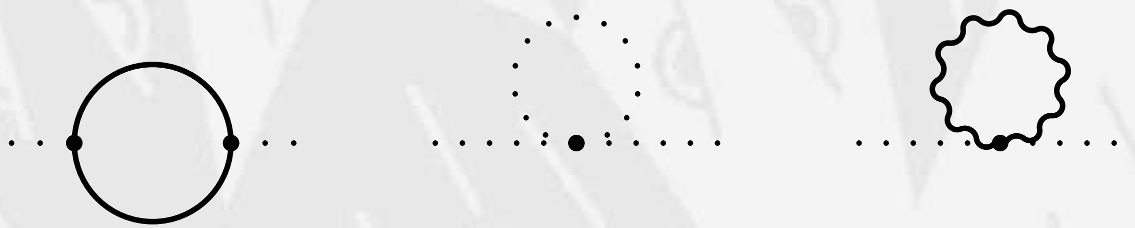

$\sim \Lambda^2$

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

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

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

- $m_h \ll \Lambda \quad \Leftrightarrow \quad$ Fine-Tuning !?
- **Solution:** Mechanism for elimination of loop contributions

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

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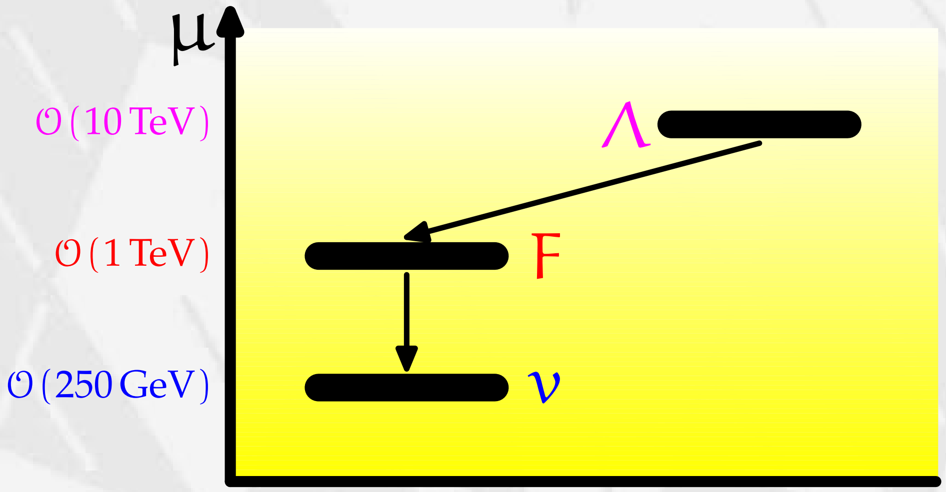
New Ingredience: Arkani-Hamed/Cohen/Georgi/. . . , 2001

Gauge group structure eliminates quadratic divergences 1-loop level $\Longrightarrow$ 3-scale model

Scales and Masses



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- Scale F: Pseudo-Goldstone bosons, new vector bosons and fermions
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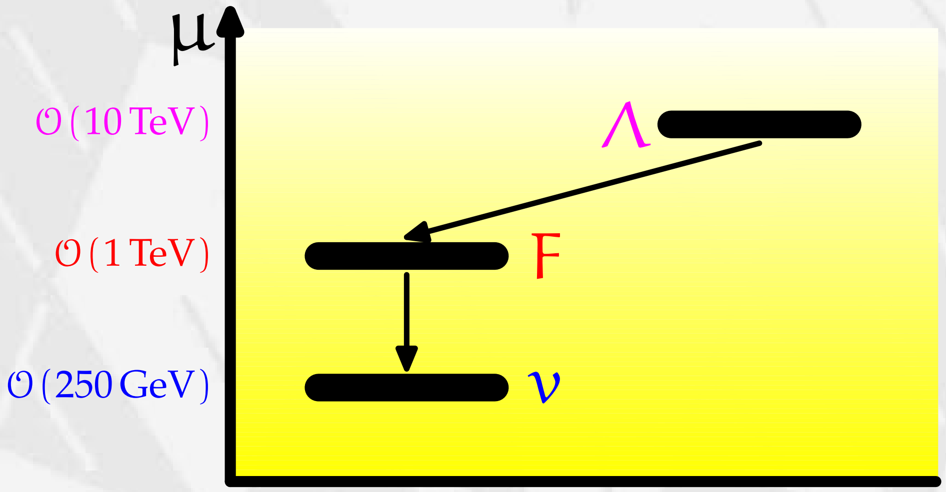

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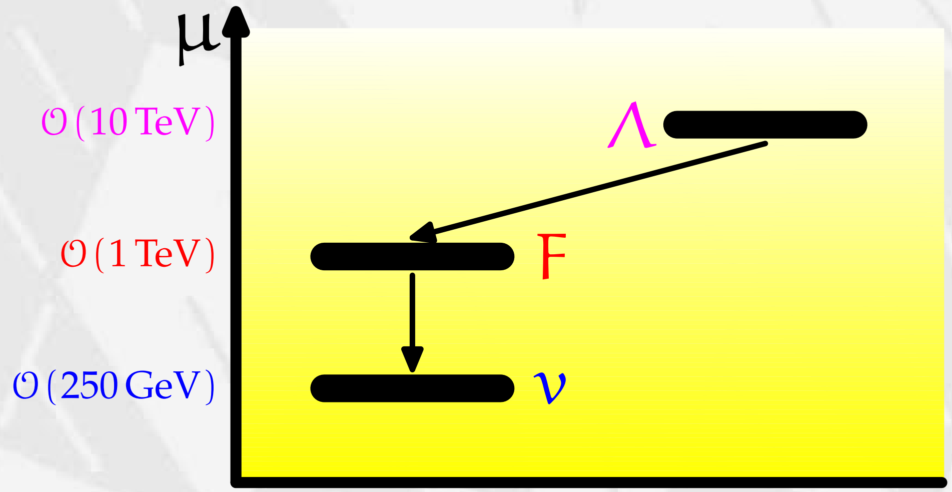

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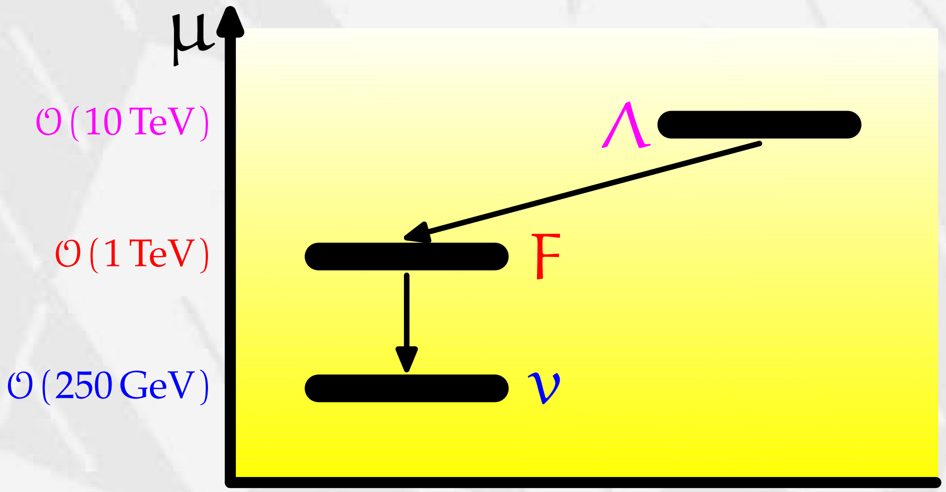

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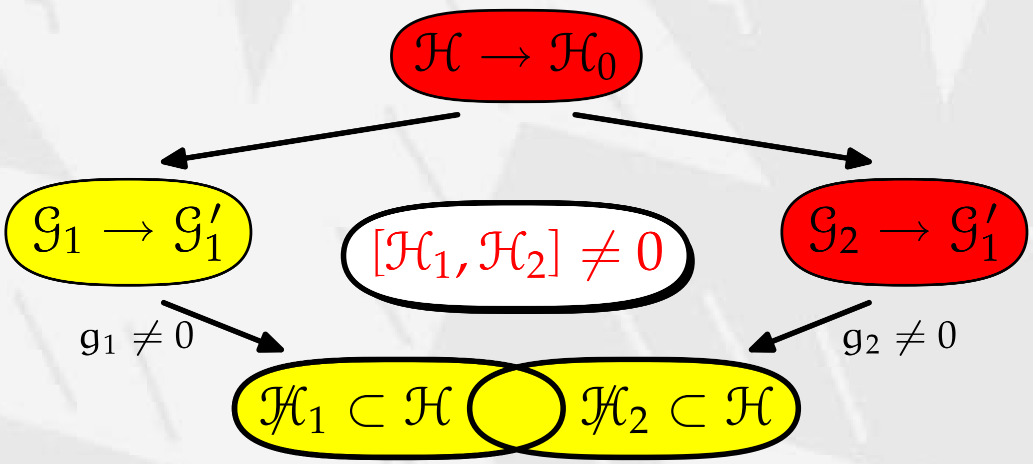

How does Little Higgs actually work?

$$M_H \sim g_1 g_2 \Lambda / 16\pi^2$$

Generic properties

Kilian/JR (2004), . . . , PDG (2004), Schmaltz (2005)

- Extended scalar (Higgs-) sector

Extended global symmetry

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- **Specific form of the potential:**

$$\mathcal{V}(h,\Phi) = C_1 F^2 \left| \Phi + \frac{i}{F} h \otimes h \right|^2 + C_2 F^2 \left| \Phi - \frac{i}{F} h \otimes h \right|^2$$

m_h=0 @ 1-loop-level, $\langle h \rangle$, $m_h \sim v$, $M_\Phi \sim F$, $i \cdot \langle \Phi \rangle \sim v^2/F$, h/Φ mix

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- Extended Top sector: new quarks, t, t' loops $\Rightarrow M_h^2 < 0 \Rightarrow$ EWSB

Symmetry breaking and anomalous $\mathrm{U}(1)$

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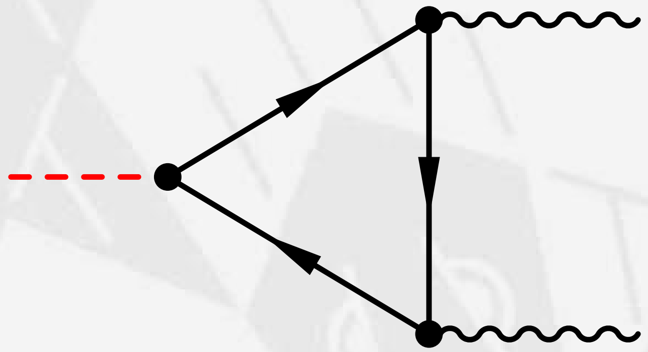
QCD-(PQ) axion: $\mathcal{L}_{\text{Ax.}} = \frac{1}{\Lambda}\frac{\alpha_s}{8\pi^2} A_g \eta G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad \tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$

Anomalous $\mathrm{U}(1)_\eta$:



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- *no new hierarchy problem* $\Rightarrow m_\eta \lesssim v \sim 250\,\text{GeV}$
- η couplings an to SM particles v/F suppressed
- Branching ratios (BRs): dominant $(t\bar{t},)$ $b\bar{b}$, $\tau^+\tau^-$, ...

Chiral Structure of Yukawa couplings in LHM with heavy $SU(2)$ singlet T:

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

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

The μ Model (Simple-Group Model)

- "Moose"-like model Schmaltz (2004), Kilian/Rainwater/JR (2004)
- μ term explicitly breaks global symm. ($\longrightarrow$ MSSM) $\Rightarrow$ EWSB, no Fine-Tuning
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$$\Phi_{1/2} = \exp\left[\pm i \frac{F_{2/1}}{F_{1/2}} \Theta\right] \begin{pmatrix} 0 \\ 0 \\ F_{1/2} \end{pmatrix} \qquad \Theta = \frac{1}{\sqrt{F_1^2 + F_2^2}} \begin{pmatrix} \eta & 0 & h^* \\ 0 & \eta & \\ h^T & & \eta \end{pmatrix}$$

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Scalar Potential ($\kappa \equiv F_1/F_2 + F_2/F_1 \geqslant 2$):

$$-V = -(\delta m^2 + \mu^2 \kappa)(h^\dagger h) - \mu^2 \kappa \frac{\eta^2}{2} + \left(\frac{\mu^2 \kappa^2}{12 F_1 F_2} - \delta\lambda\right)(h^\dagger h)^2 + \ldots$$

δm, $\delta\lambda$ 1-loop contributions (Coleman-Weinberg Potential)

$\boxed{m_\eta = \sqrt{\kappa}\,\mu \geqslant \sqrt{2}\,\mu}$ no Fine-tuning: $\mu \sim v$ $m_H^2 = -2(\delta m^2 + m_\eta^2)$

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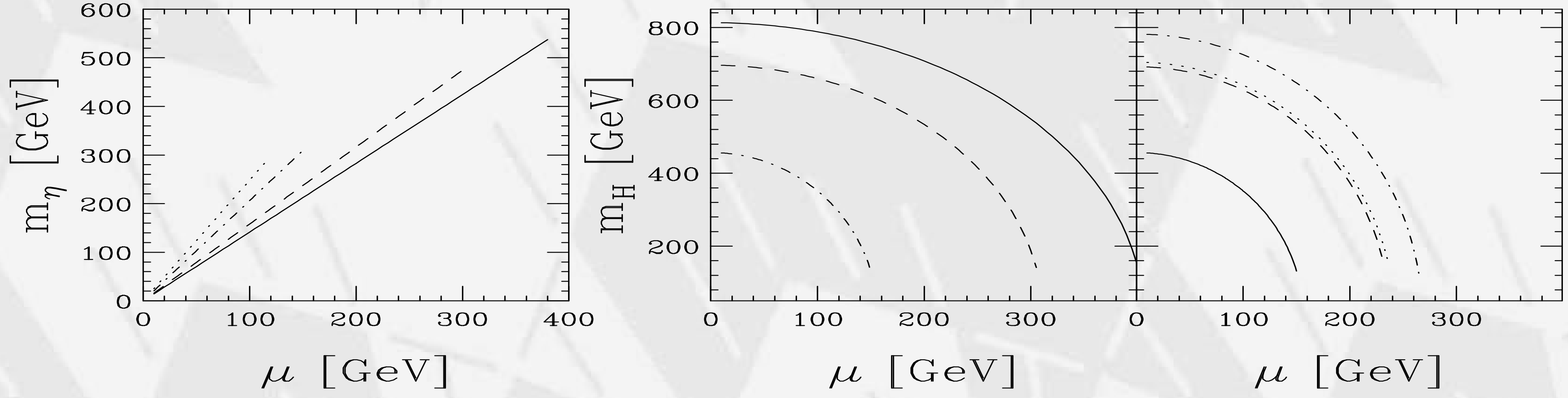

Left: $F_1/F_2 = 1$, 1/2, 1/4, 1/6 Middle: fixed $F_2 = 2.0$ TeV. Right: fixed $F_1/F_2 = 1/4$, various F_1 [TeV]: 0.5, 1.0, 1.5, 2.0 (—, $- - -$, $- \cdot -\cdot$, $\cdots$, resp.)

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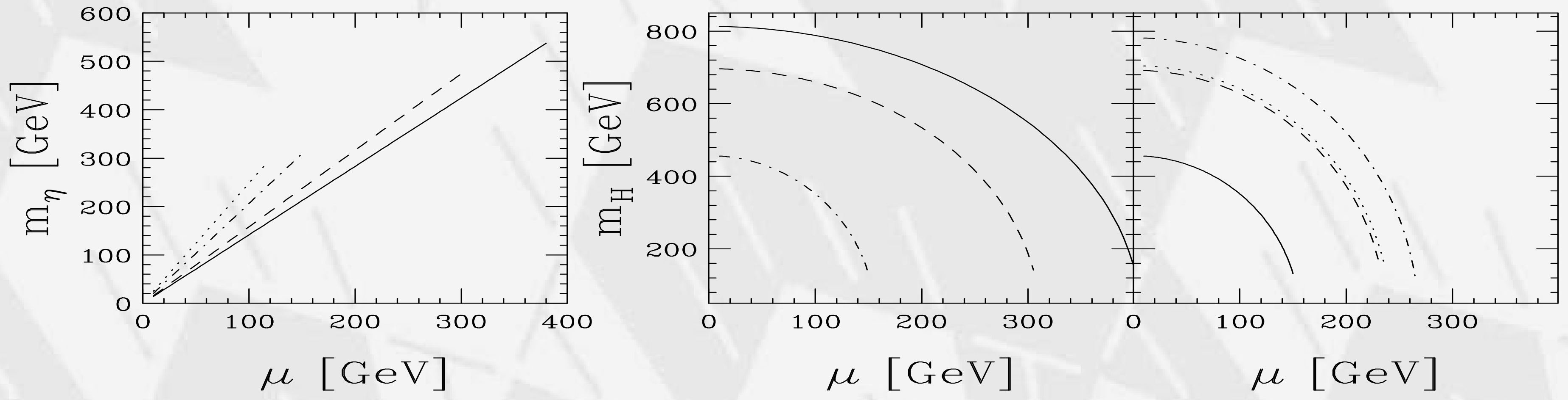

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- heavy partners for SM fermions ($\Psi_L = (t_L, b_L, T_L)^T$)

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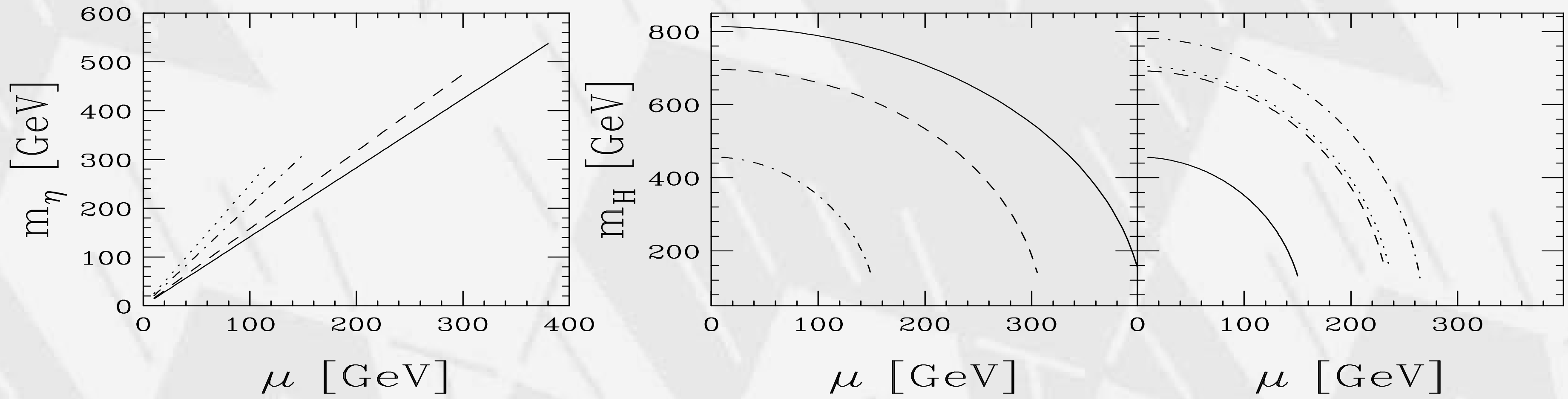

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- Assumptions: *no mixing* between SM and heavy fermions in 1./2. family, minimal M_T (LHC)

- **free parameters:** $F_{1,2}$ and μ with $\sqrt{F_1^2 + F_2^2} \gtrsim 2$ TeV [ΔT, Contact IA]
  $F_1 \gtrsim v$, $F_2 > F_1$ (Fermion mixing/universality)

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"Golden Point" (fulfills EW precision and flavor limits):

F_1	$= 0.5$ TeV	$m_{D,S}$	$= 0.7$ TeV
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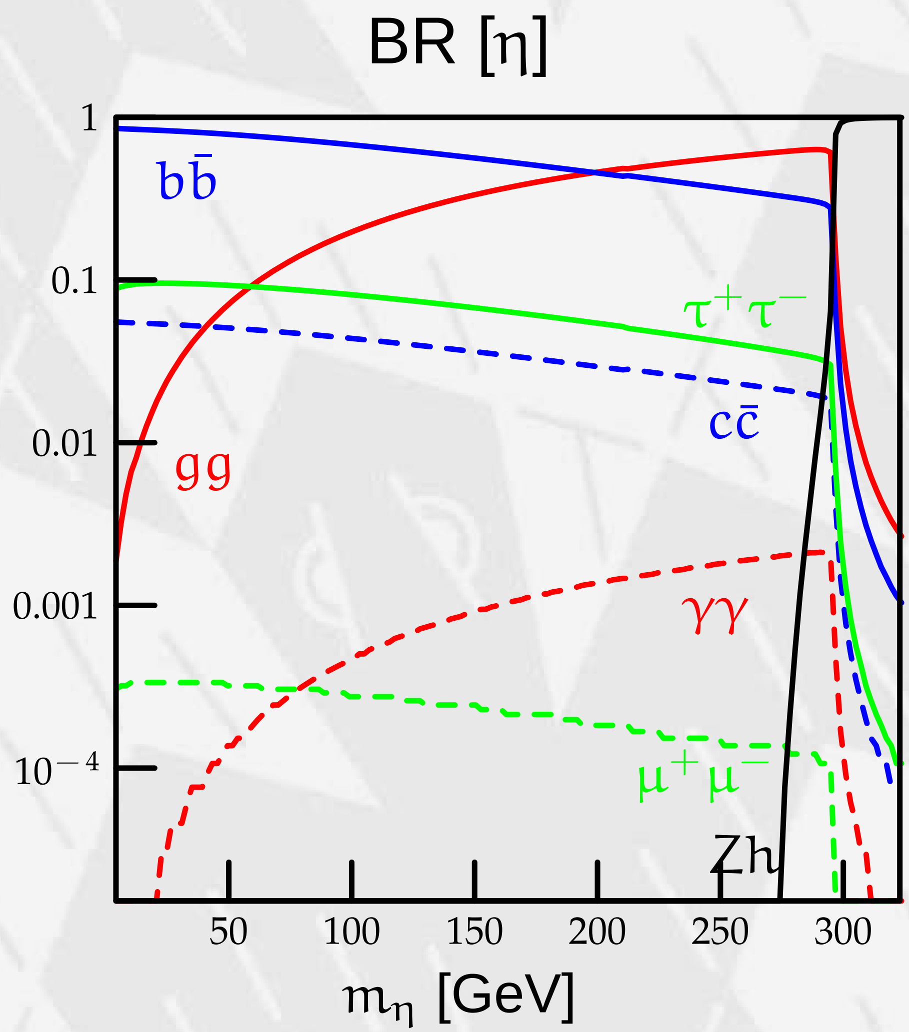
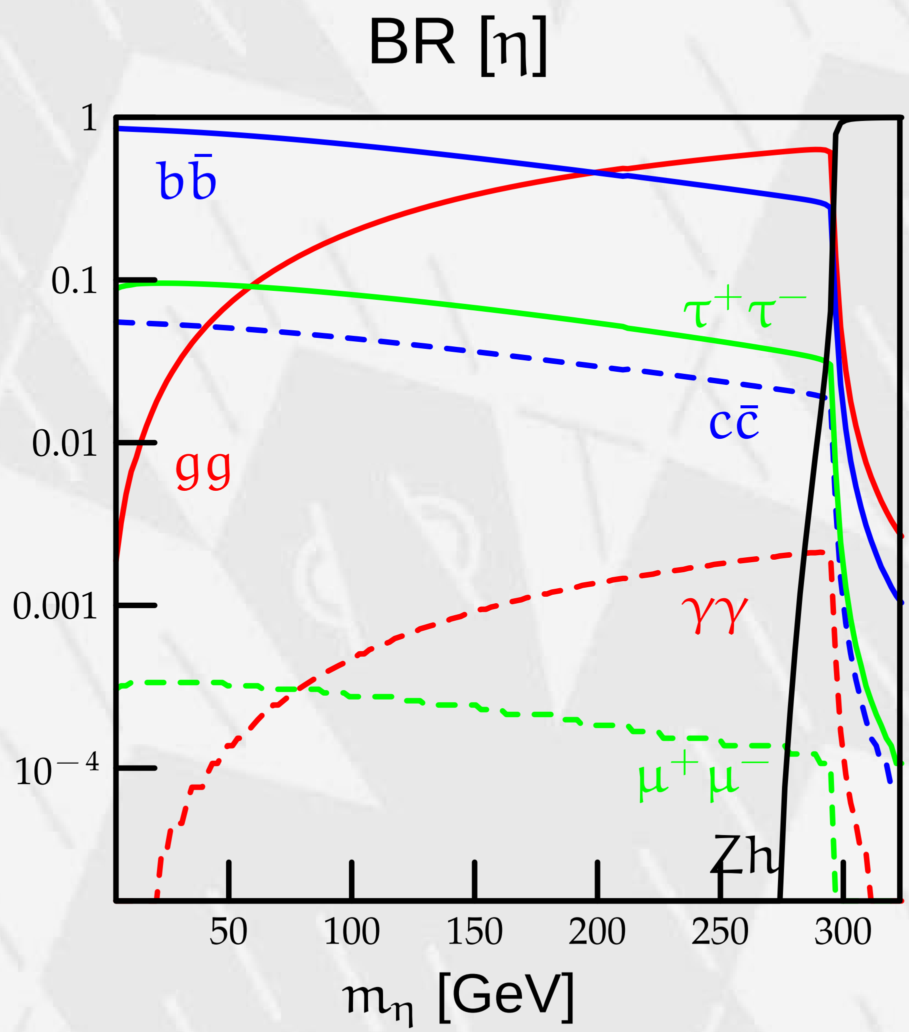
$ZH\eta$ **coupling:** $\mathcal{L}_{ZH\eta} \propto \frac{m_Z}{\sqrt{2}F} Z_\mu (\eta \partial^\mu H - H \partial^\mu \eta)$

N.B.: v/F suppression compensated!

η analogous to A in 2HDM for small $\tan\beta = F_1/F_2 < 1$ (flavor)

η Branching Ratios





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

$\mathrm{BR}(H \to \eta\eta) < 10^{-4}$ [$\sim 5 - 10\%$ 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 %

- **Gluon Fusion** (axial $U(1)_\eta$ anomaly) (analogous to $gg \to H \to \gamma\gamma$ cf. ATLAS/CMS TDR)
- v/F-suppression in the loop compensated!
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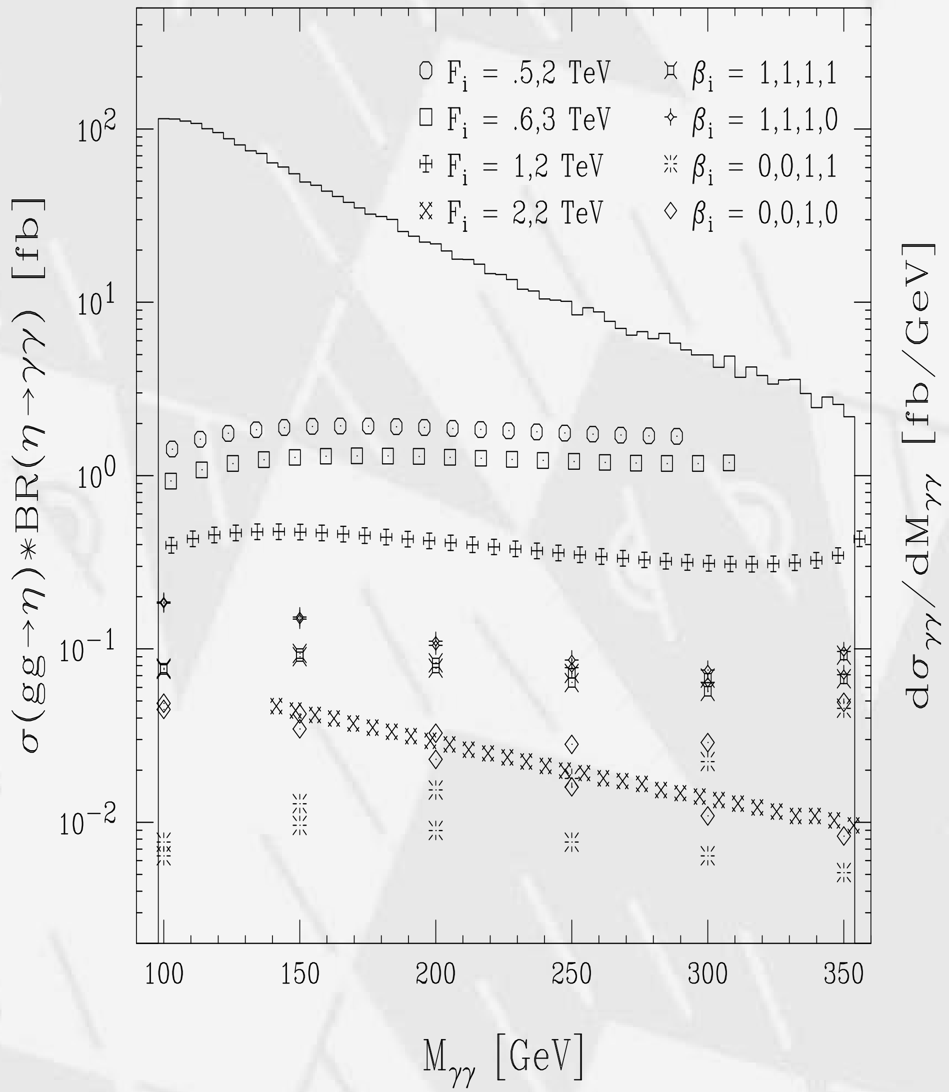
- "Golden Point" LHC(300 fb^{-1}): $m_\eta \sim 320$ GeV 7σ
  5σ for $m_\eta = 240$ GeV
  (SLHC up to $m_\eta = 130$ GeV)
  $S : B \sim 1/10 - 1/50$
- NLO cross sections; diphoton Bkgd. (Diphox Binoth); $p_T(\gamma) > 40$ GeV, $|\eta_\gamma| < 2.5$, $\epsilon_\gamma = 0.8$



$t\bar{t}\eta$ **associated production**

Problem: Cross section vs. bkgd.

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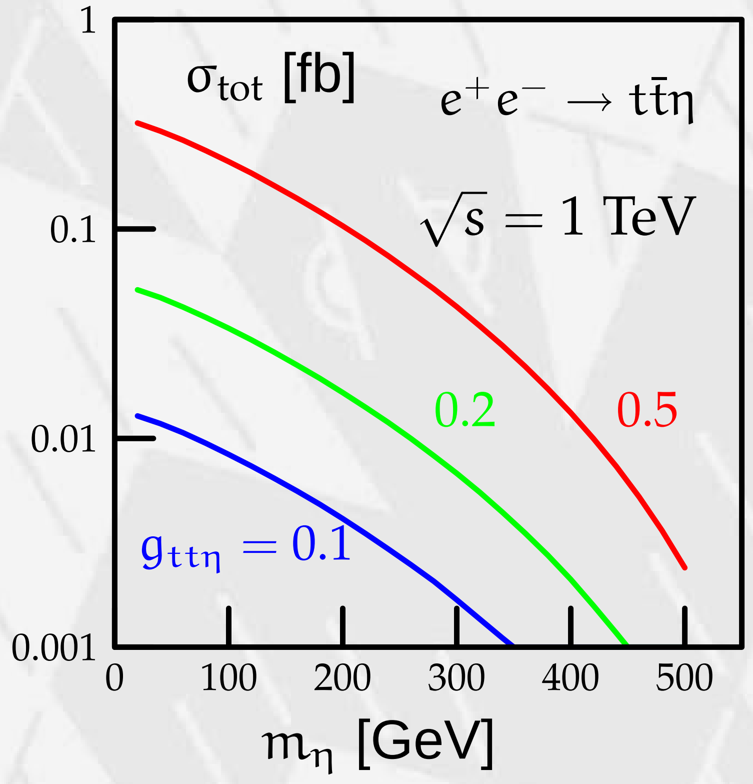

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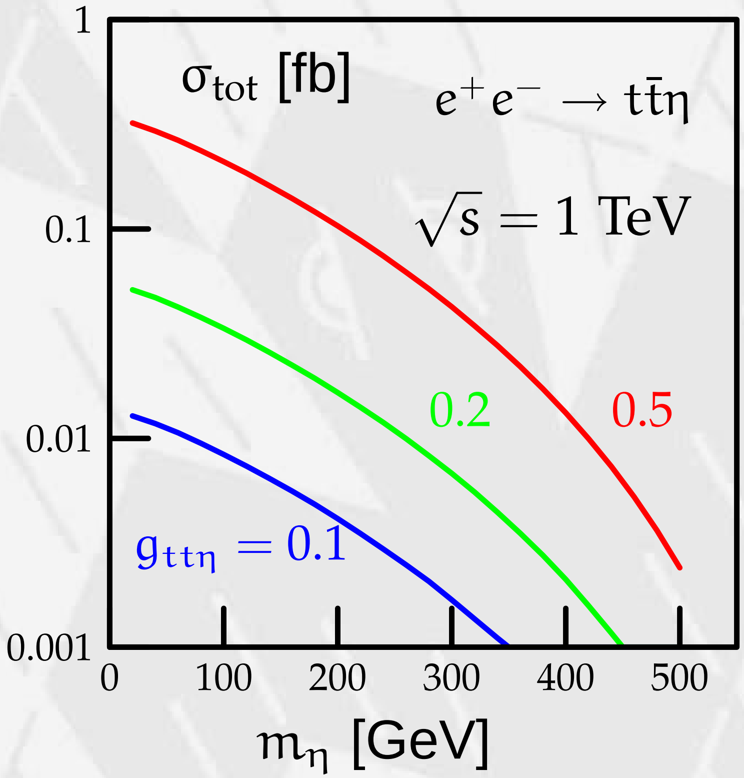

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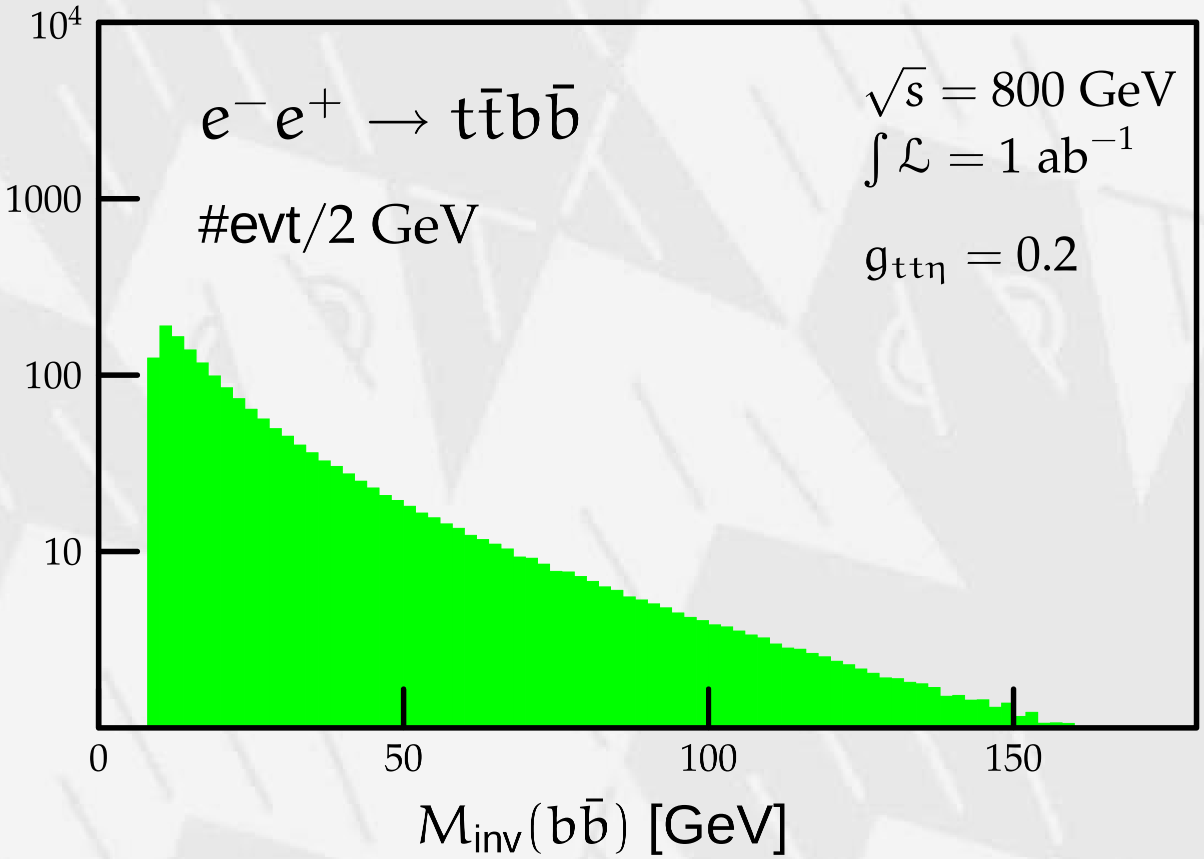

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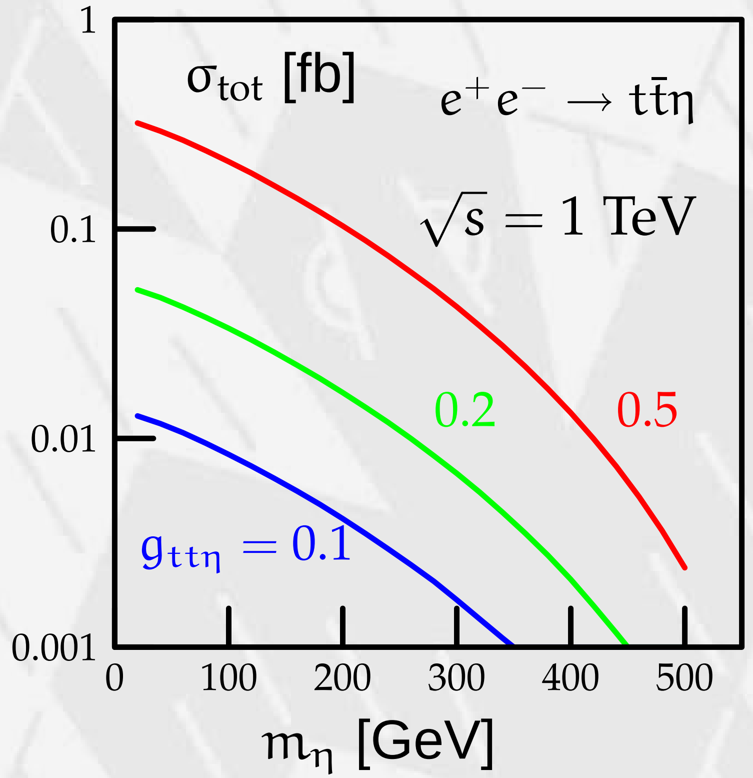

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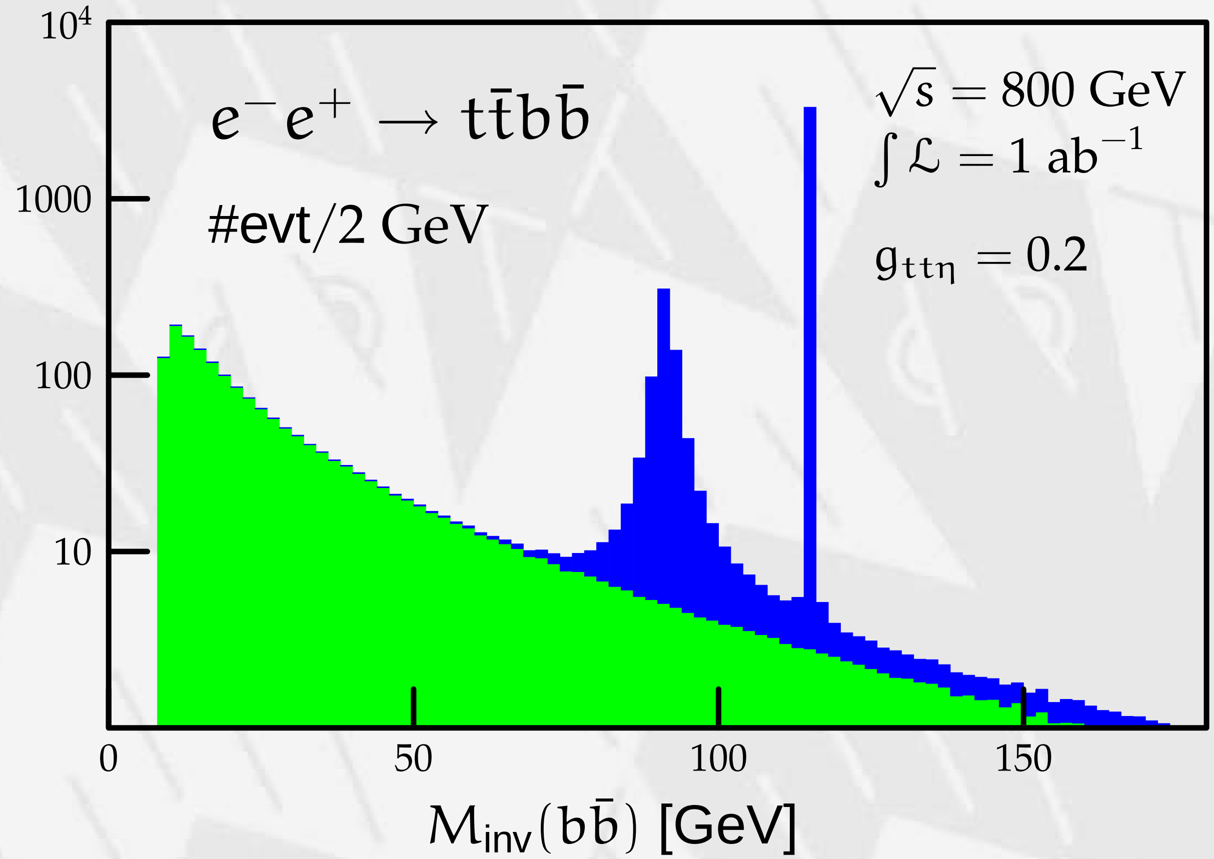

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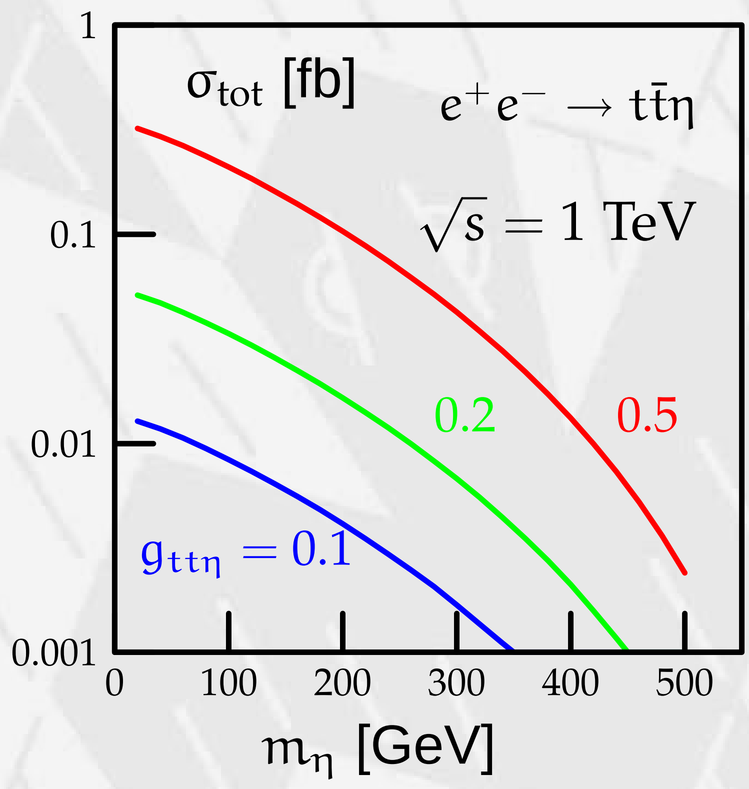
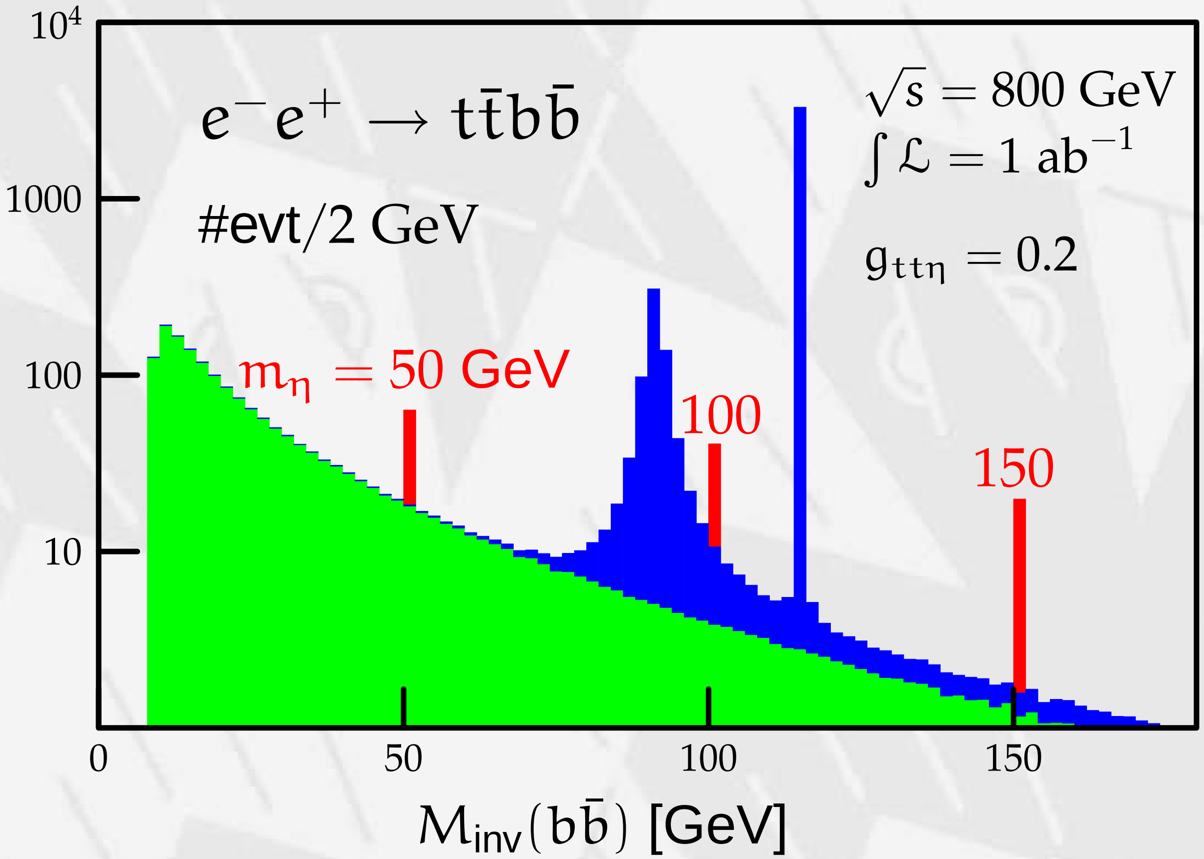
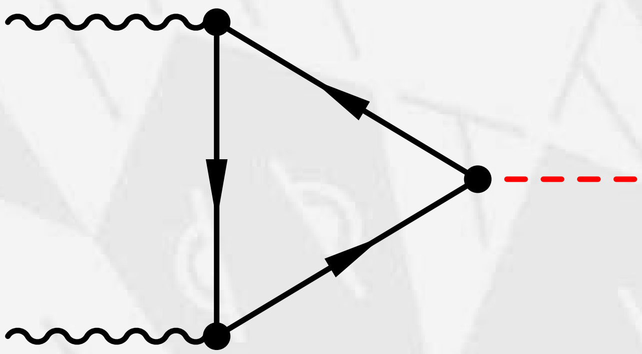




Possibility: $Z^* \to H\eta$ (analogous to A in 2HDM)

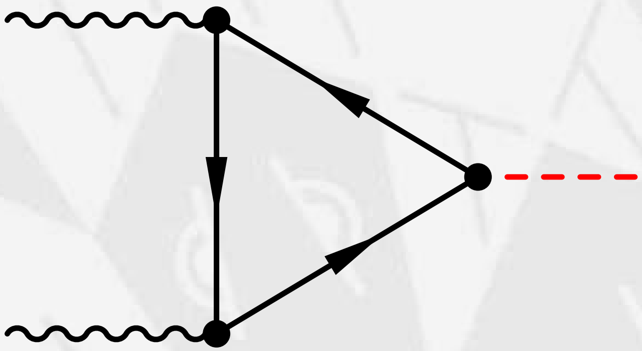
Kilian/JR/Rainwater (in prep.)

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



- S/B analogous to LC
- η in the μ model with (almost) identical parameters as A in MSSM
($\hookrightarrow$ Mühlleitner et al. (2001))

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



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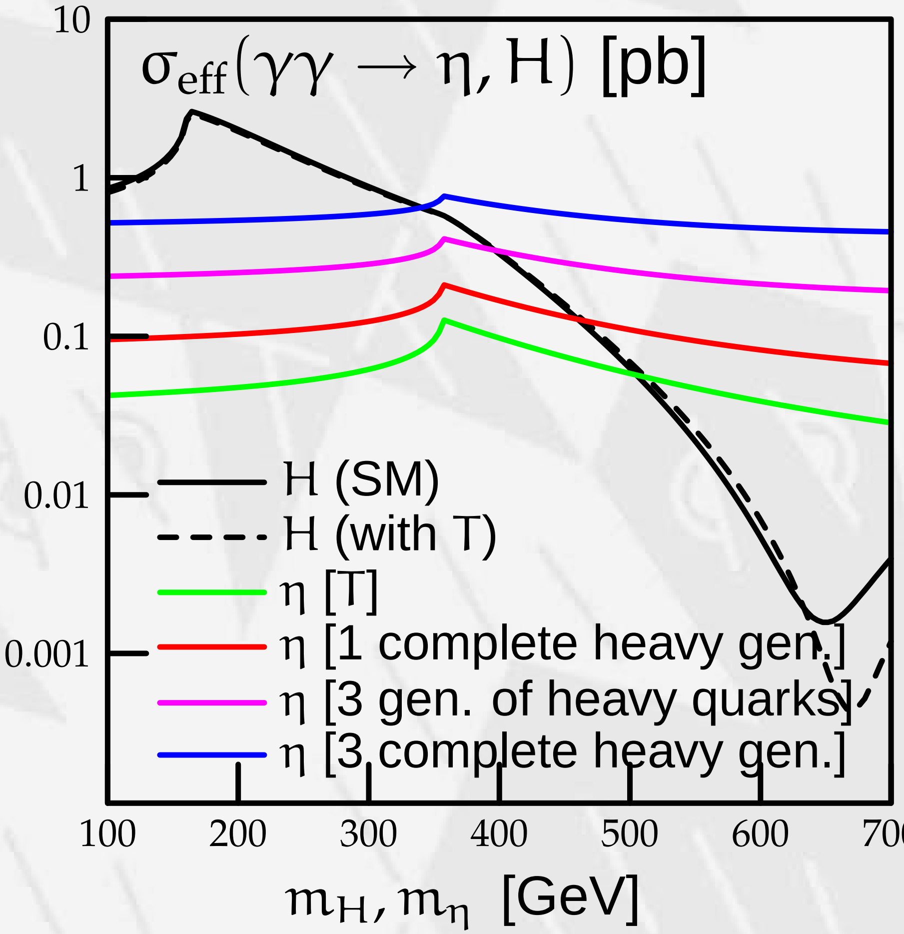

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$\Gamma_{\gamma\gamma}$[keV]	0.15	0.27	1.1	3.6

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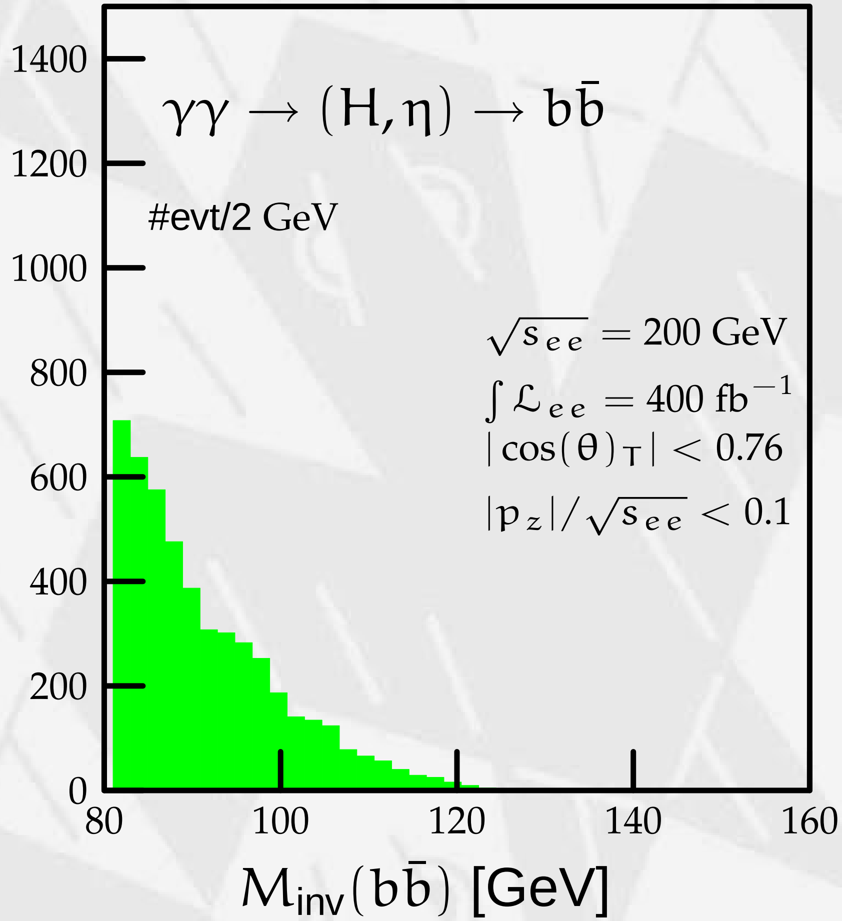

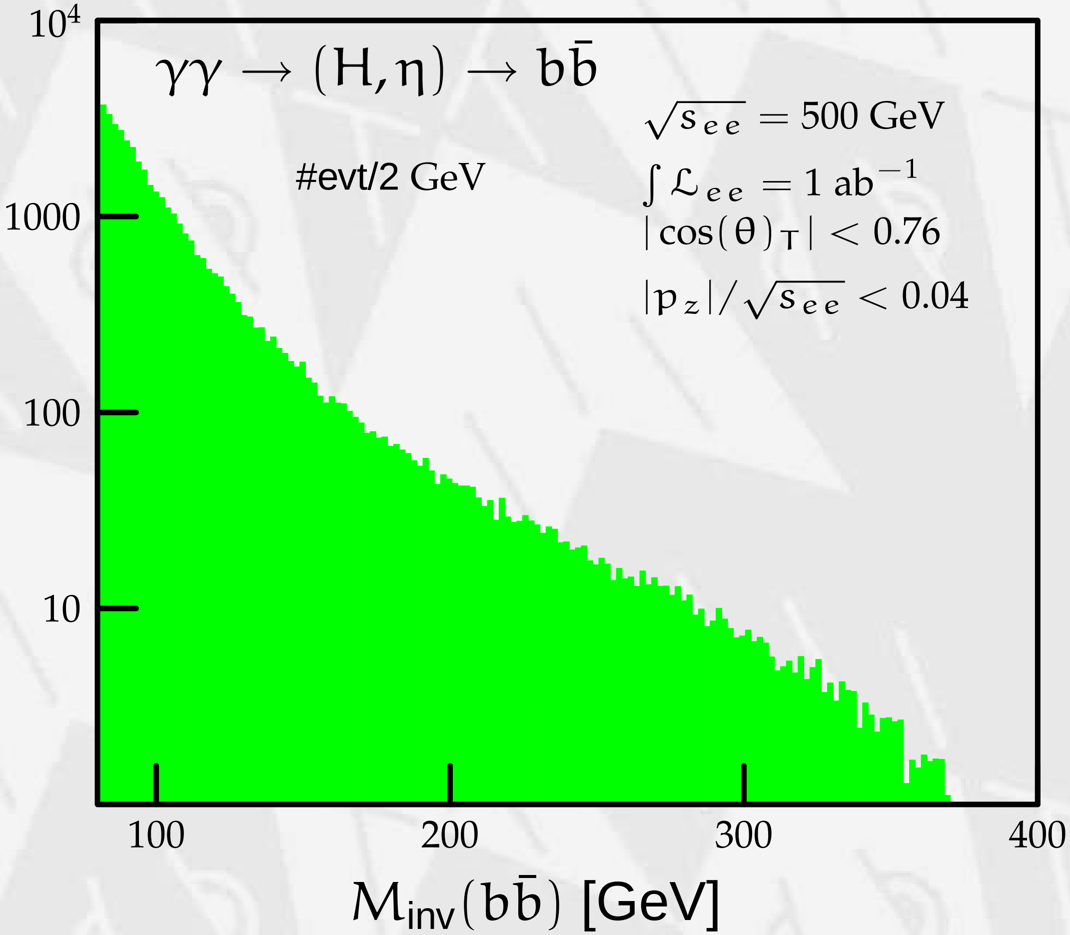

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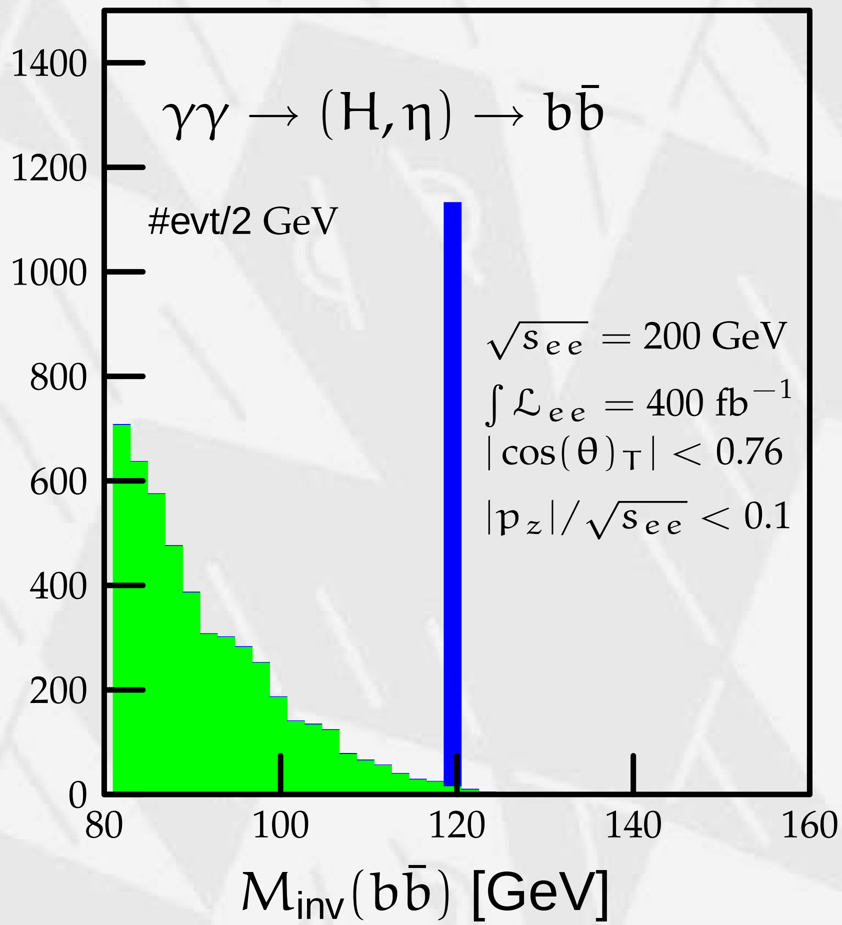

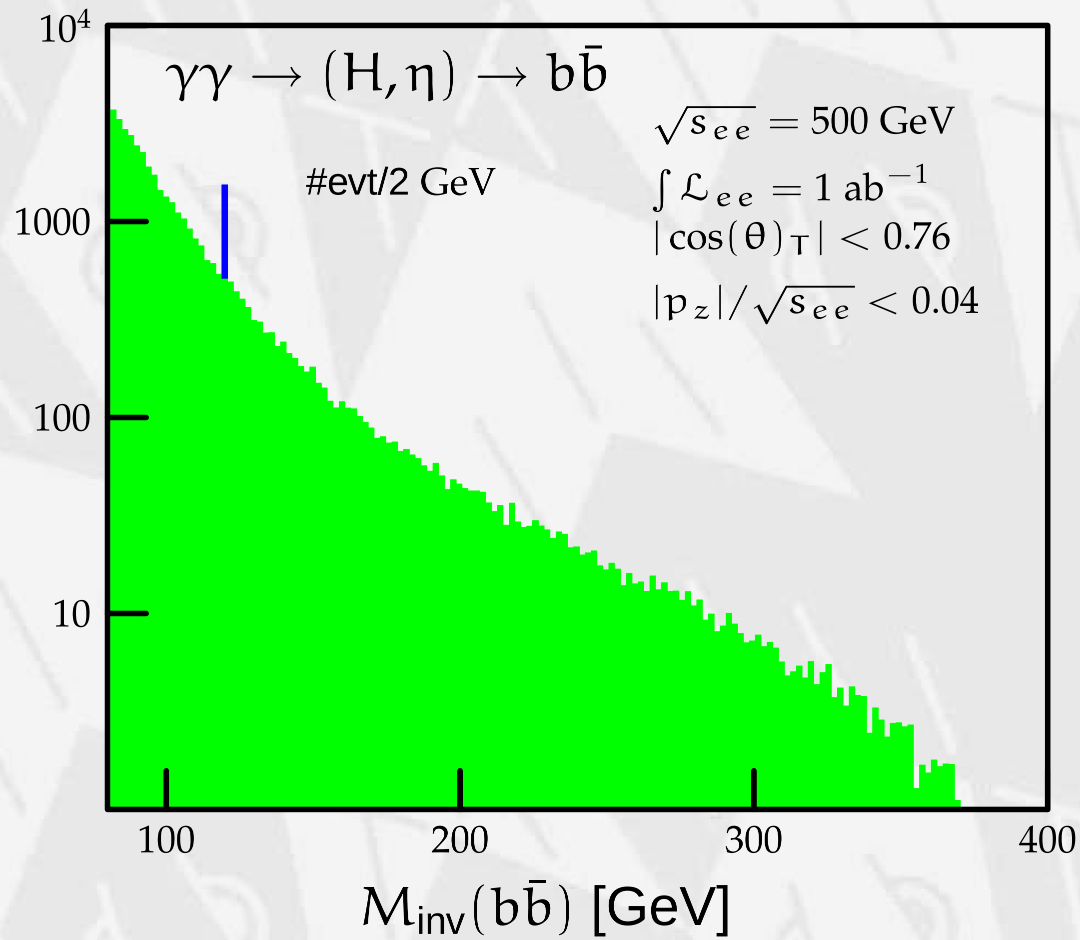

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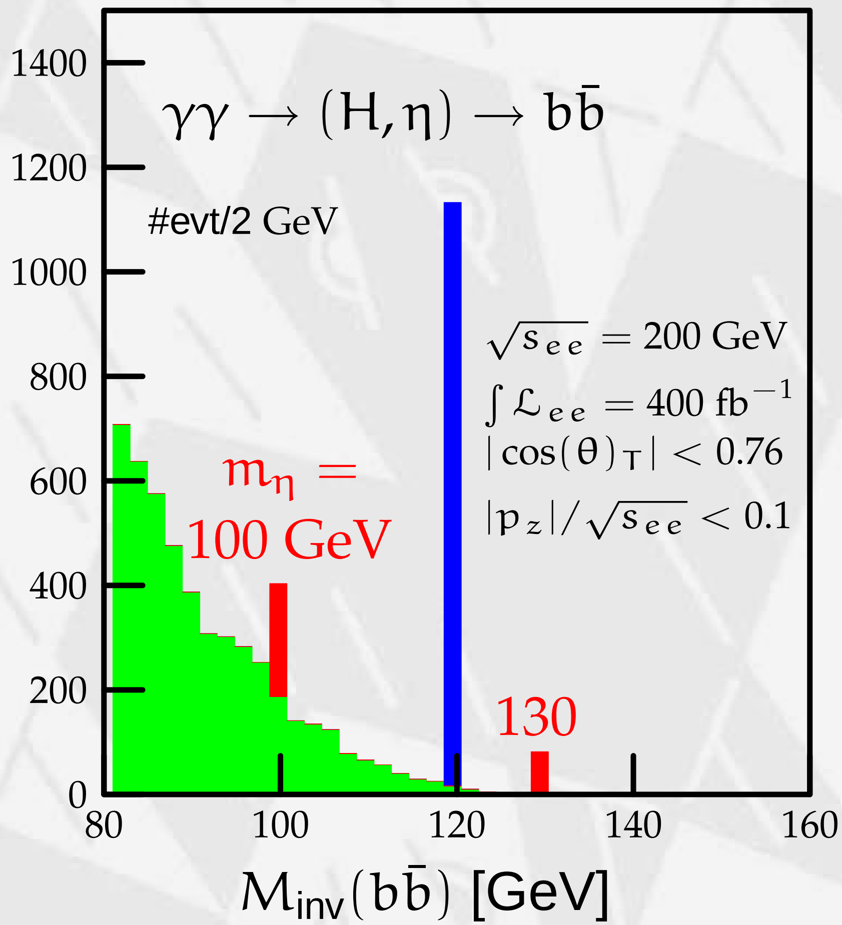

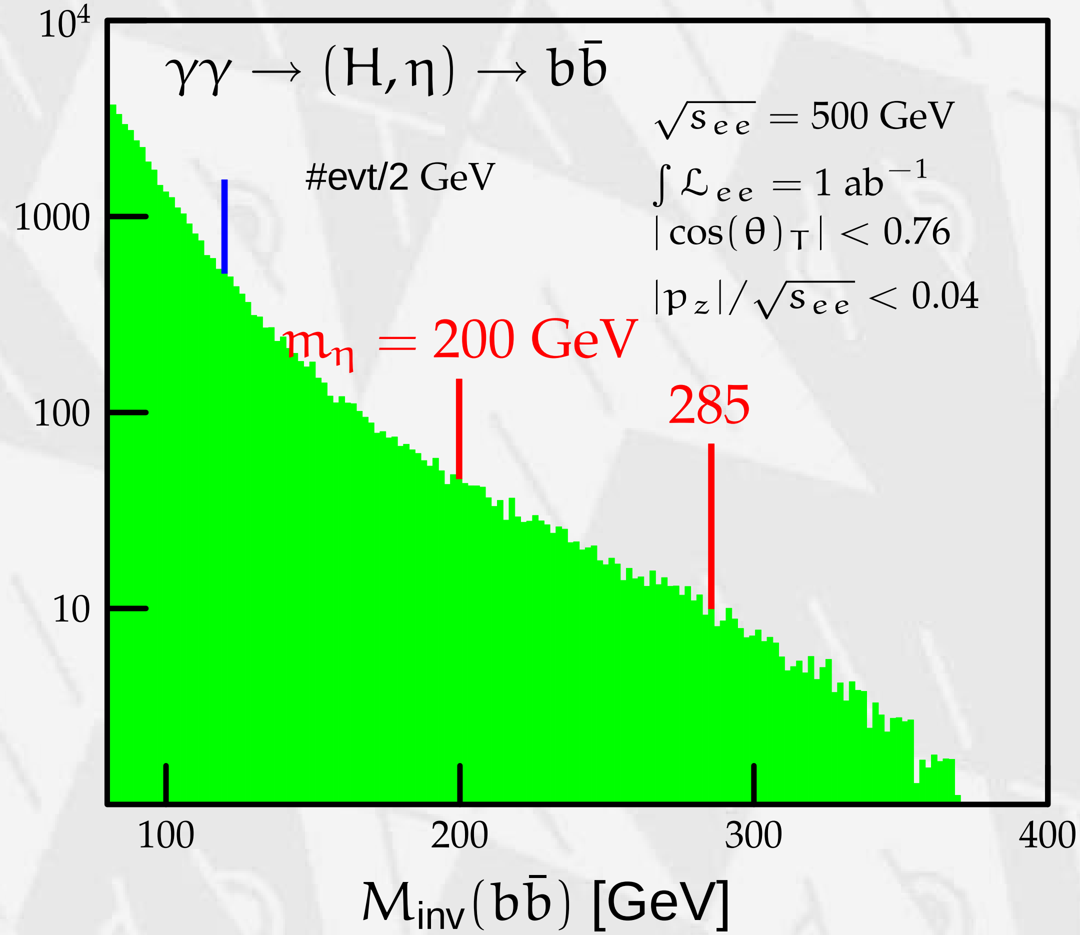

◊ Little Higgs elegant alternative to SUSY

ungauged, anomalous $U(1)_\eta$: new singlet (pseudo-)scalars η

- massive Z' (easily detectable) $\longleftrightarrow$ η physical (difficult)
- Explicit symmetry breaking circumvents axion limits
- **LHC:** η production in gluon fusion, diphoton signal
- Pseudo axions change T phenomenology!
- **ILC:** $t\bar{t}$ associated production (m_η small), $Z^* \to H\eta$
  Photon Collider: all masses, complementary measurement