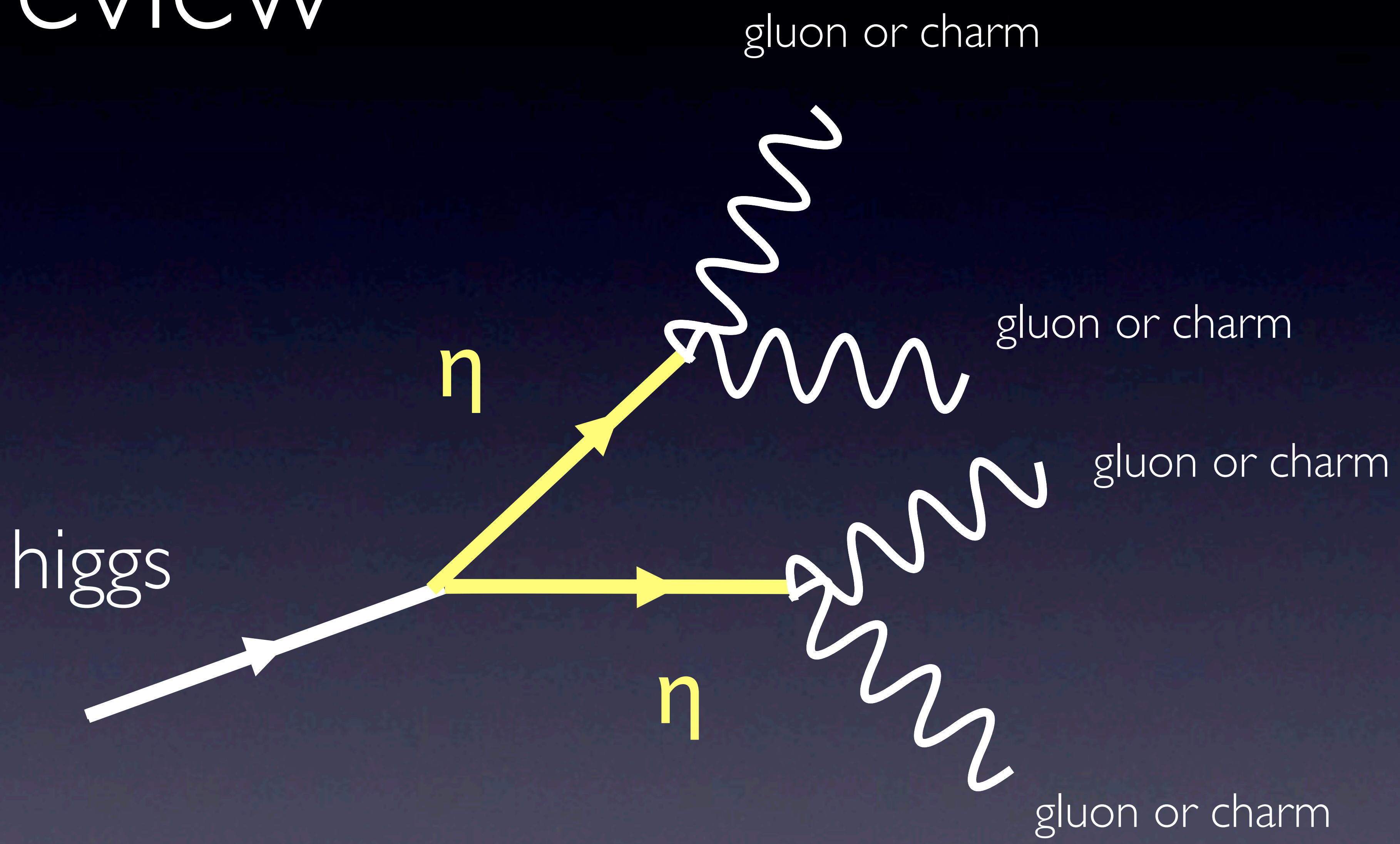
Natural non-standard Higgs boson decays

Andreas Weiler
(CERN)

Physics at the LHC 2010
DESY, Hamburg

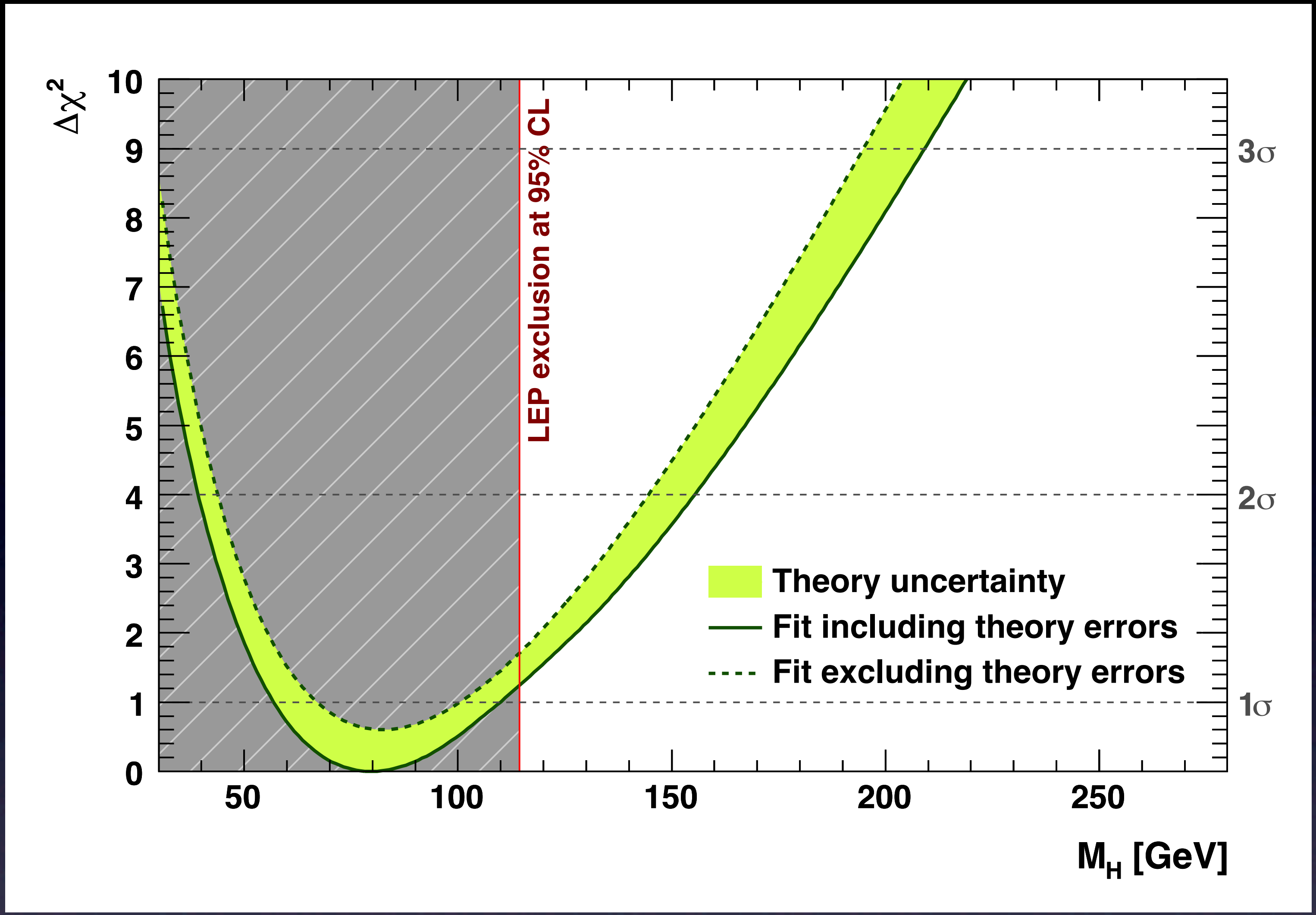
Preview



h → 4 gluon or h → 4 charm

Higgs @ LEP

Gfitter '08



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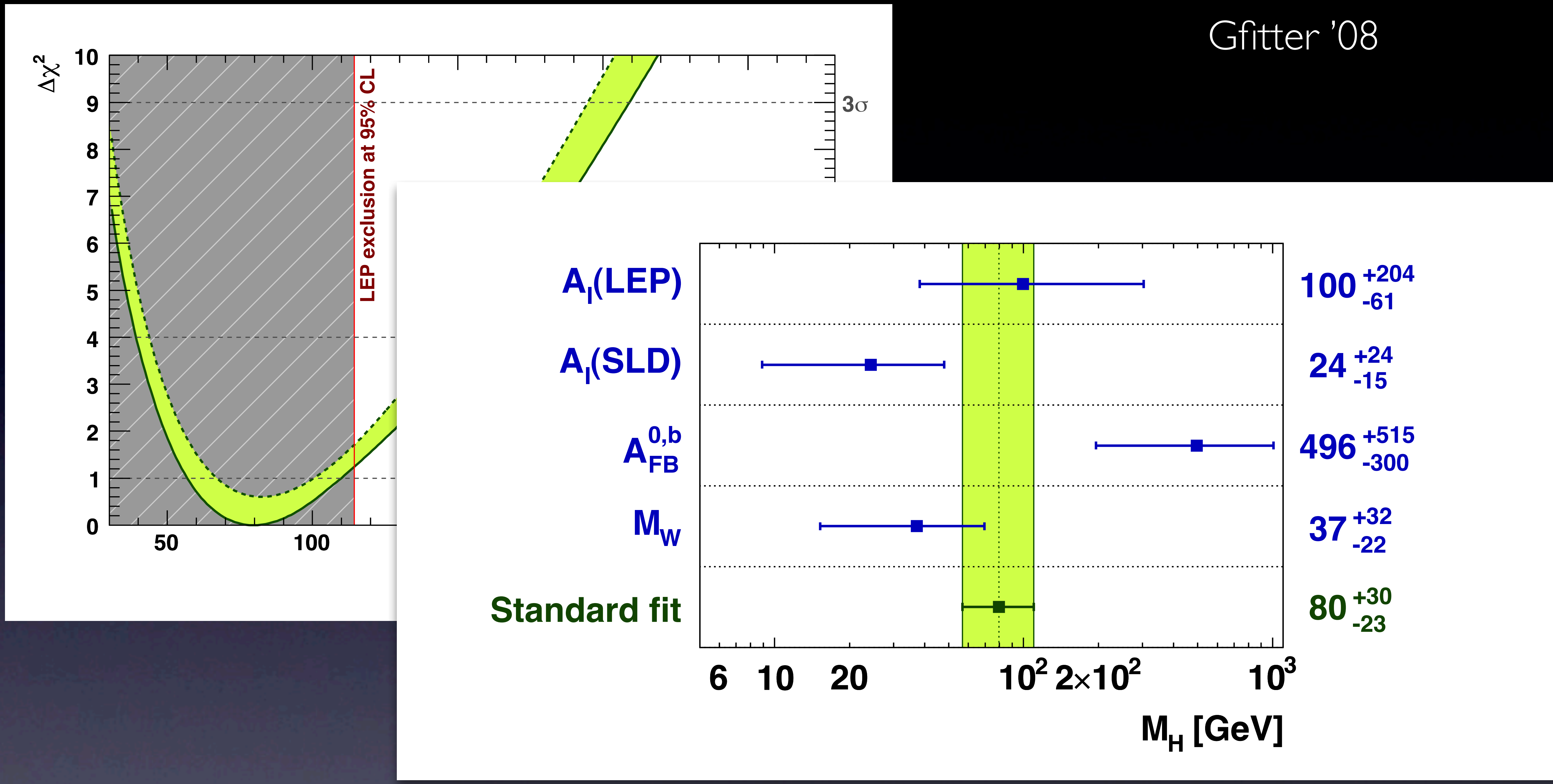

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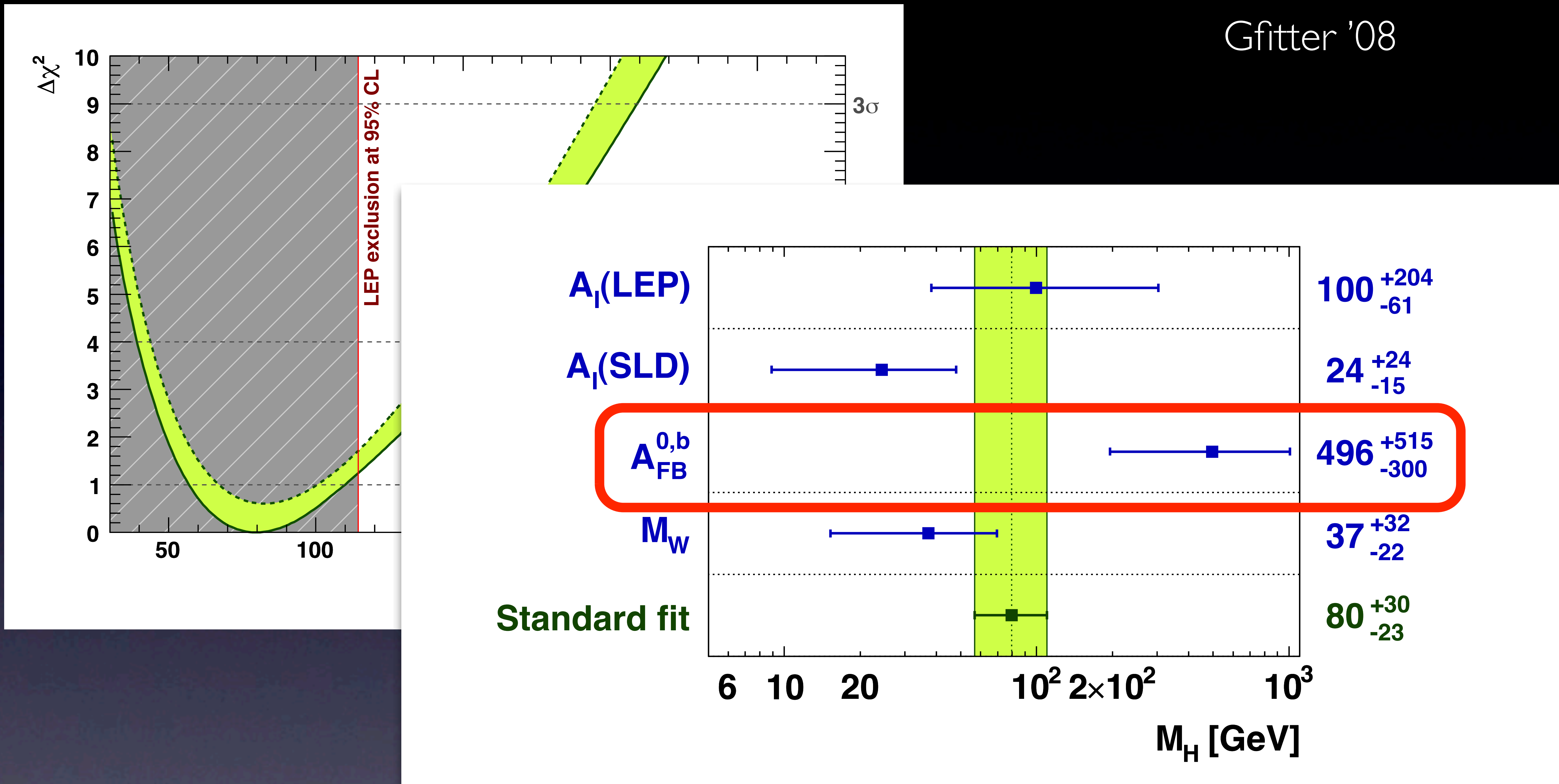
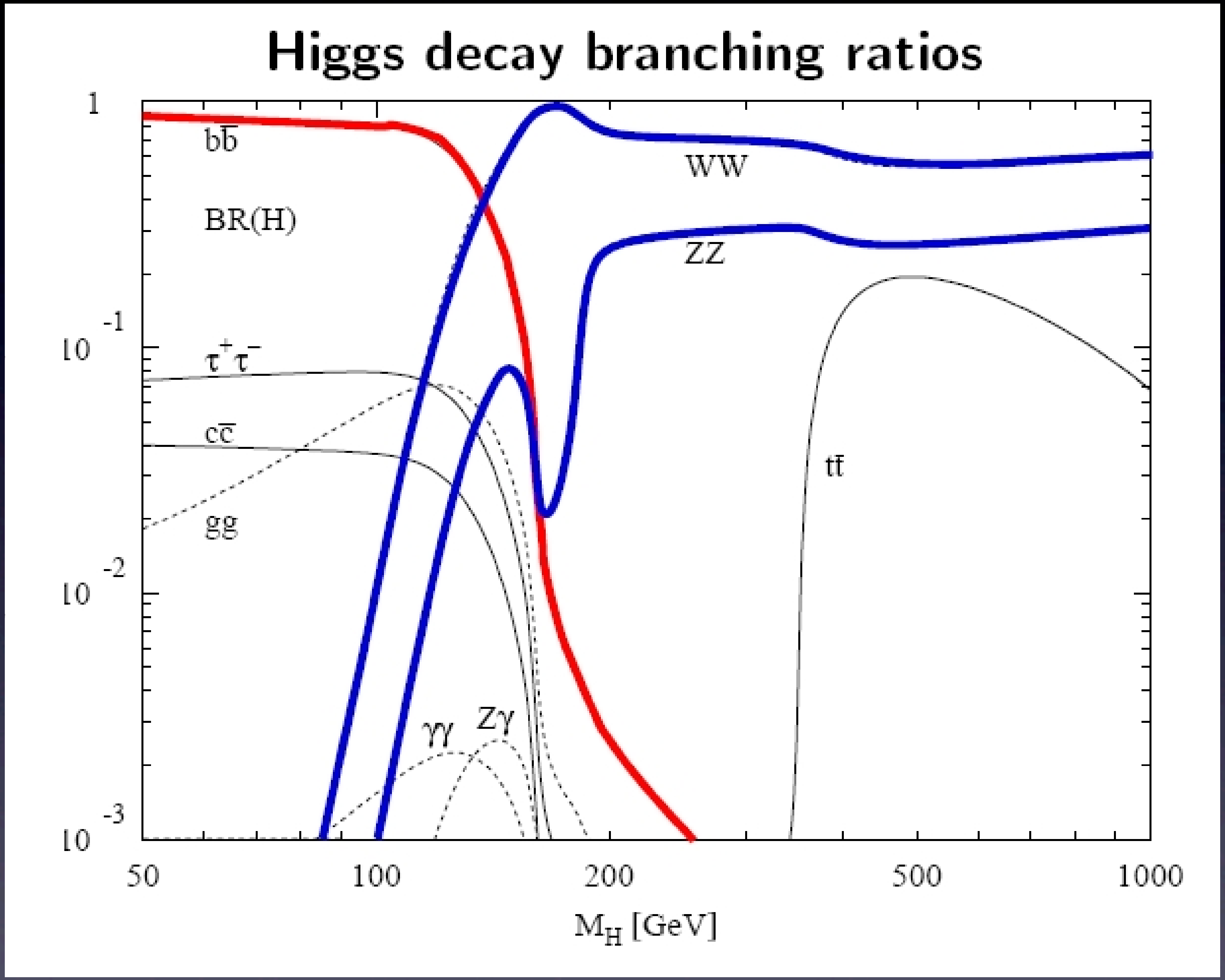


- Indirect tests suggest light scalar < 158 GeV (95%cl)
- without A_{FB}^{b}, $\quad m_H = 55^{+32}_{-21}$ GeV

Chanowitz, 0806.0890

Standard Higgs decays



- Coupling ~ mass, decays into heaviest available
- For light Higgs, dominant decay $h \rightarrow bb$

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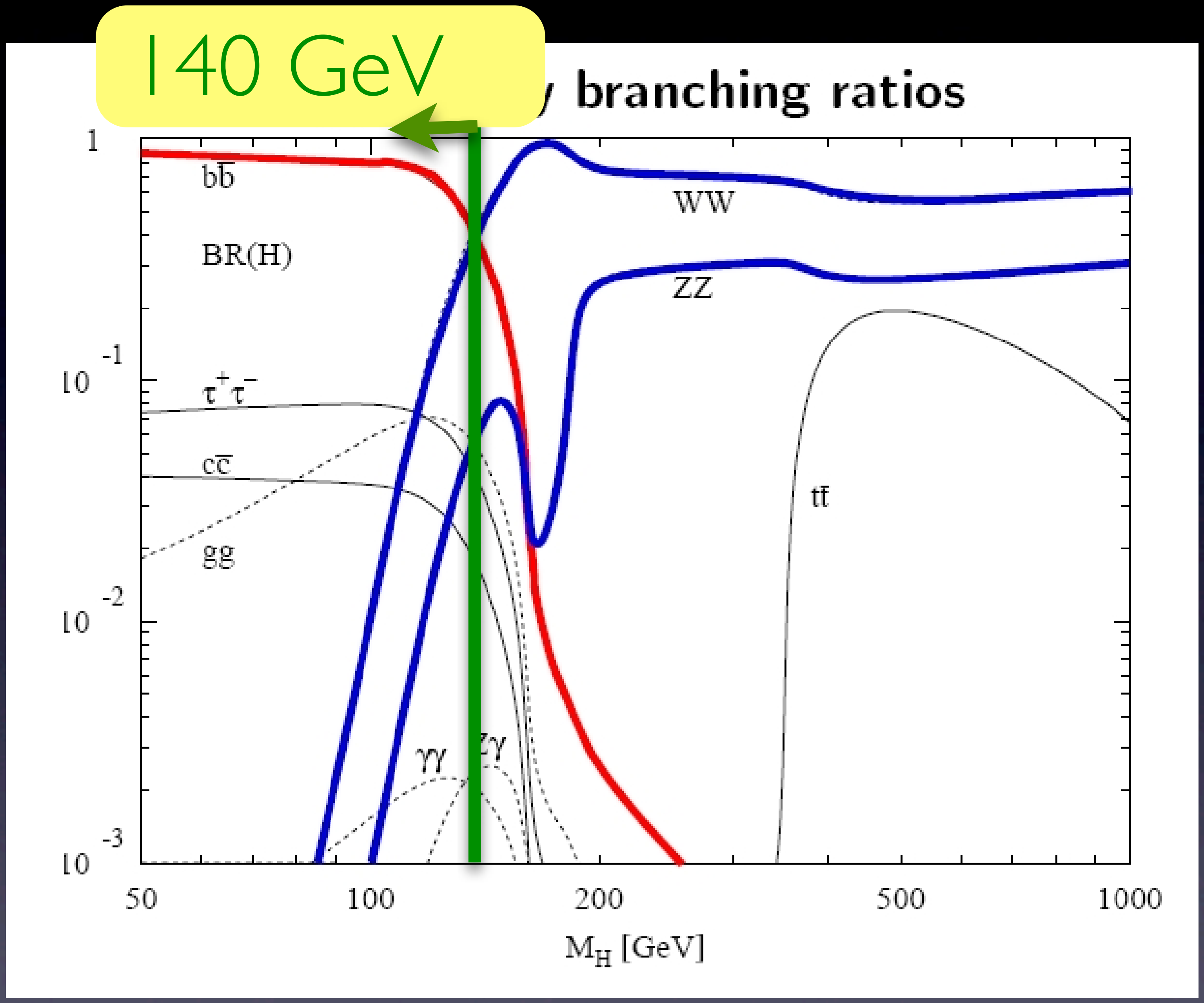

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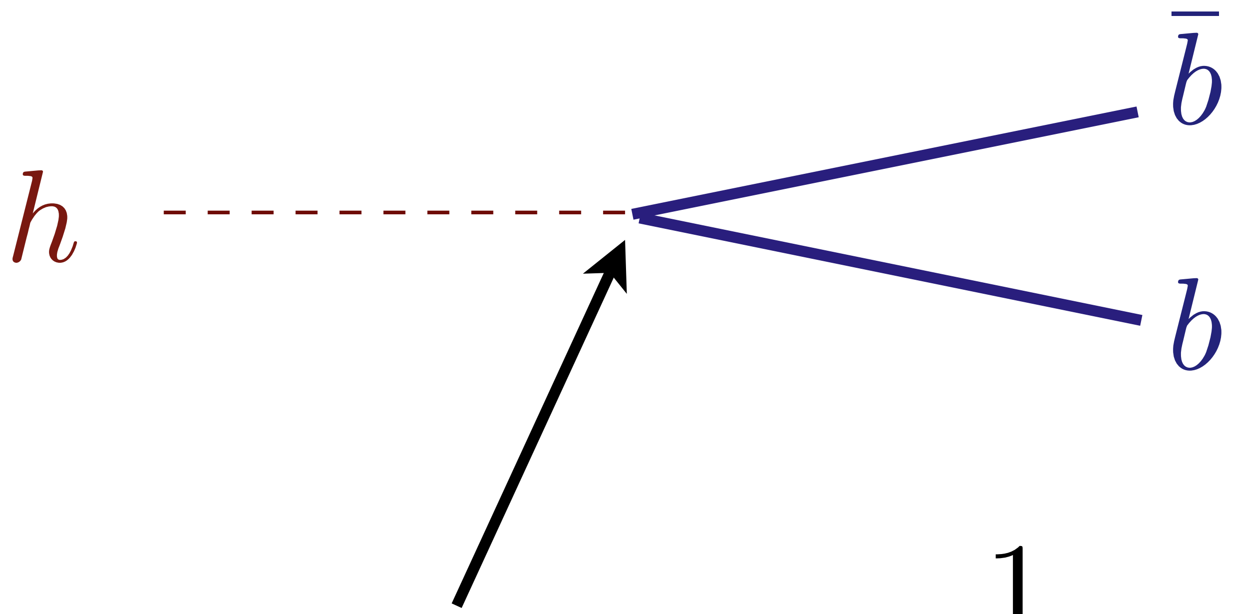
Higgs missed at LEP?

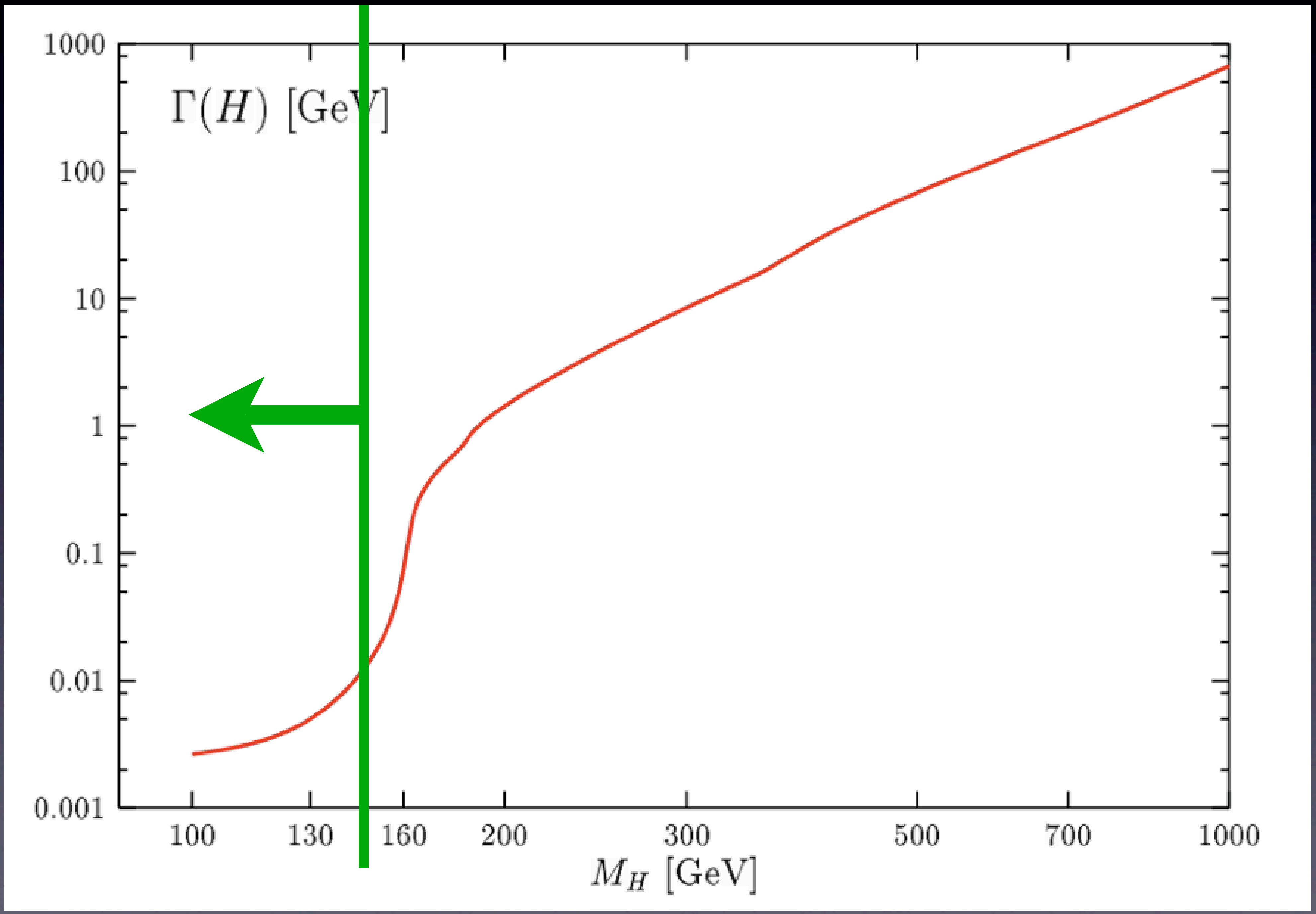
Light Higgs' Small Width



$$y_b(m_h) \sim \frac{1}{60}$$

$$\Gamma_{h \to b\bar{b}} \sim y_b^2$$

The Higgs Width



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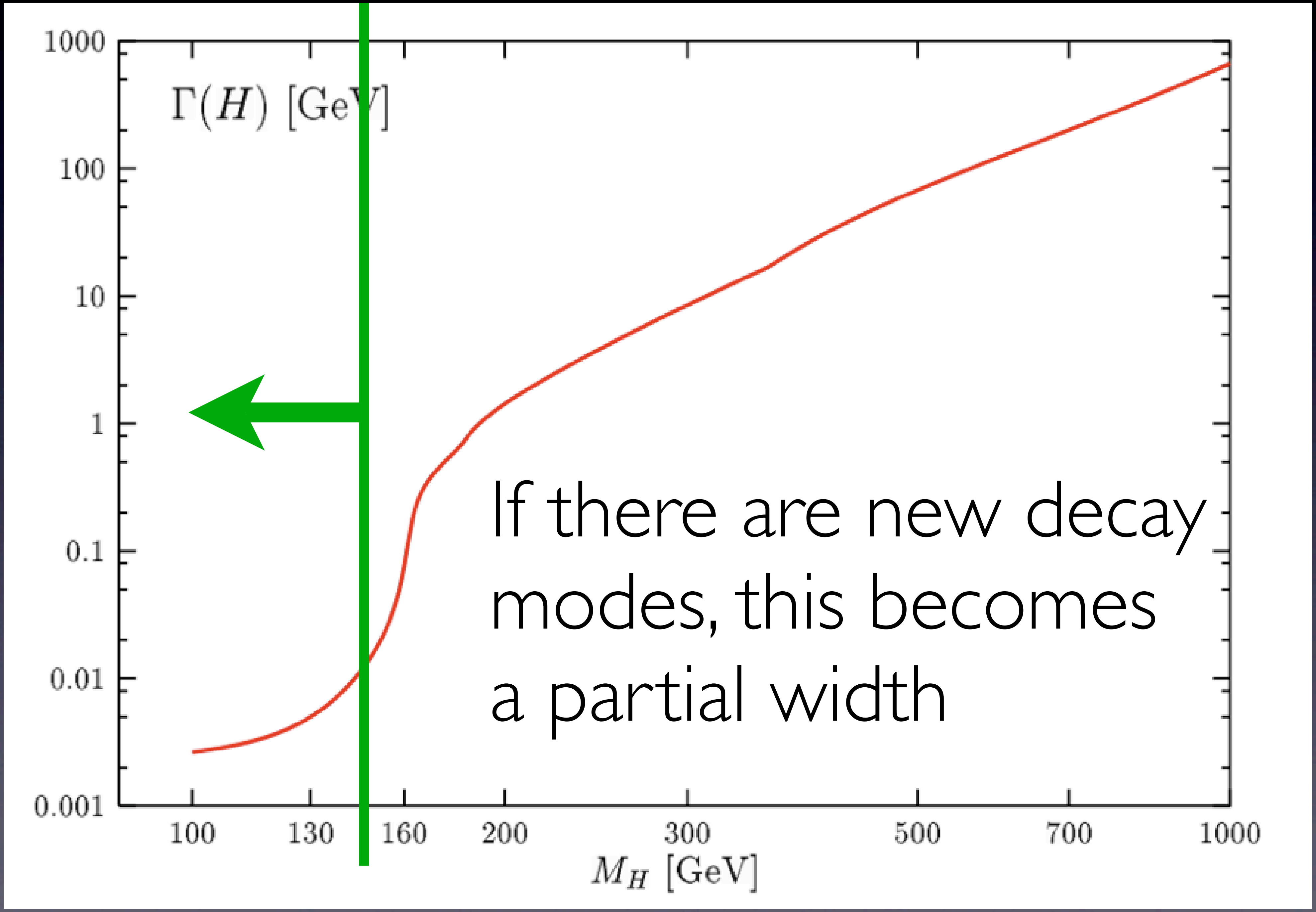
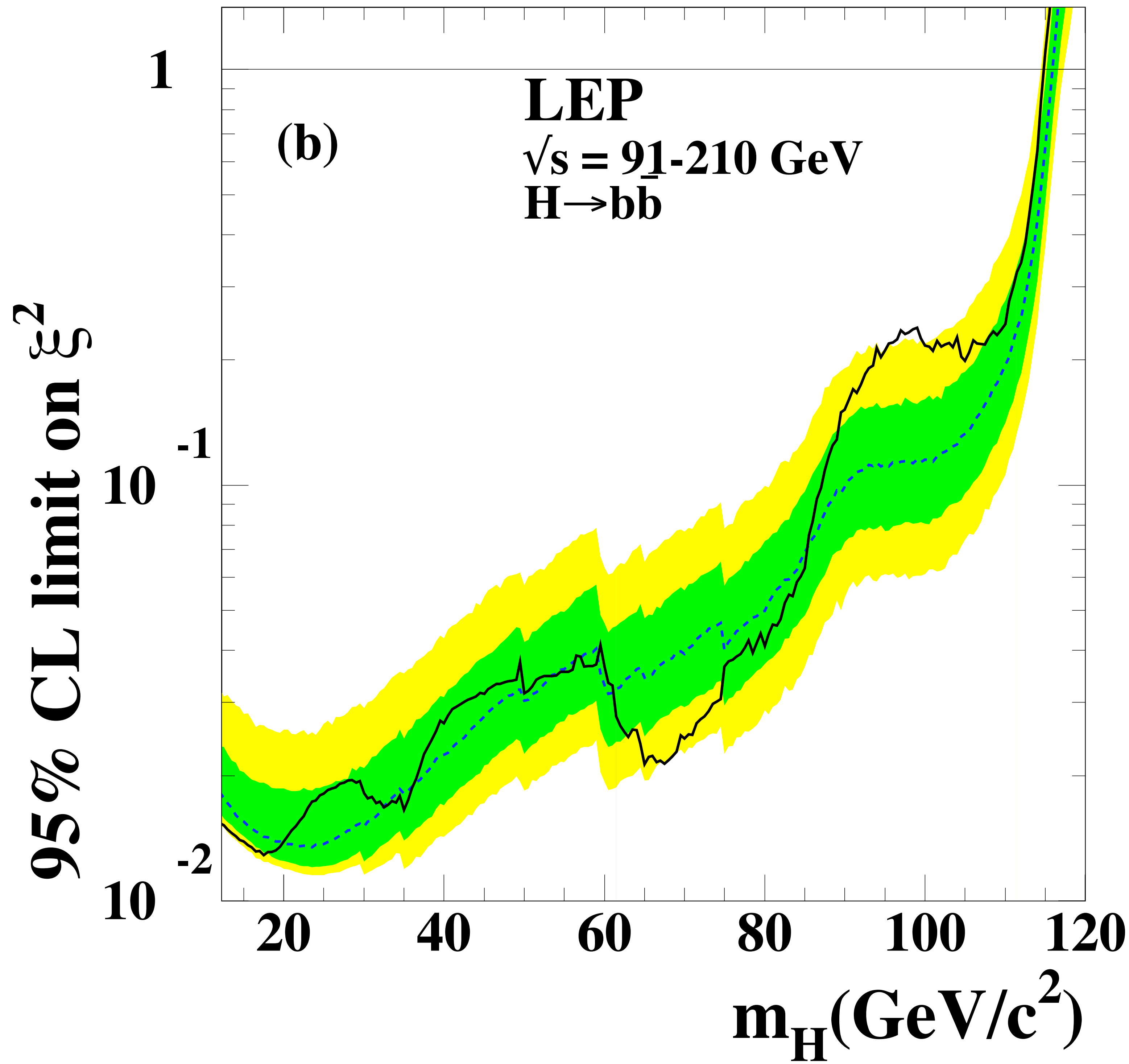
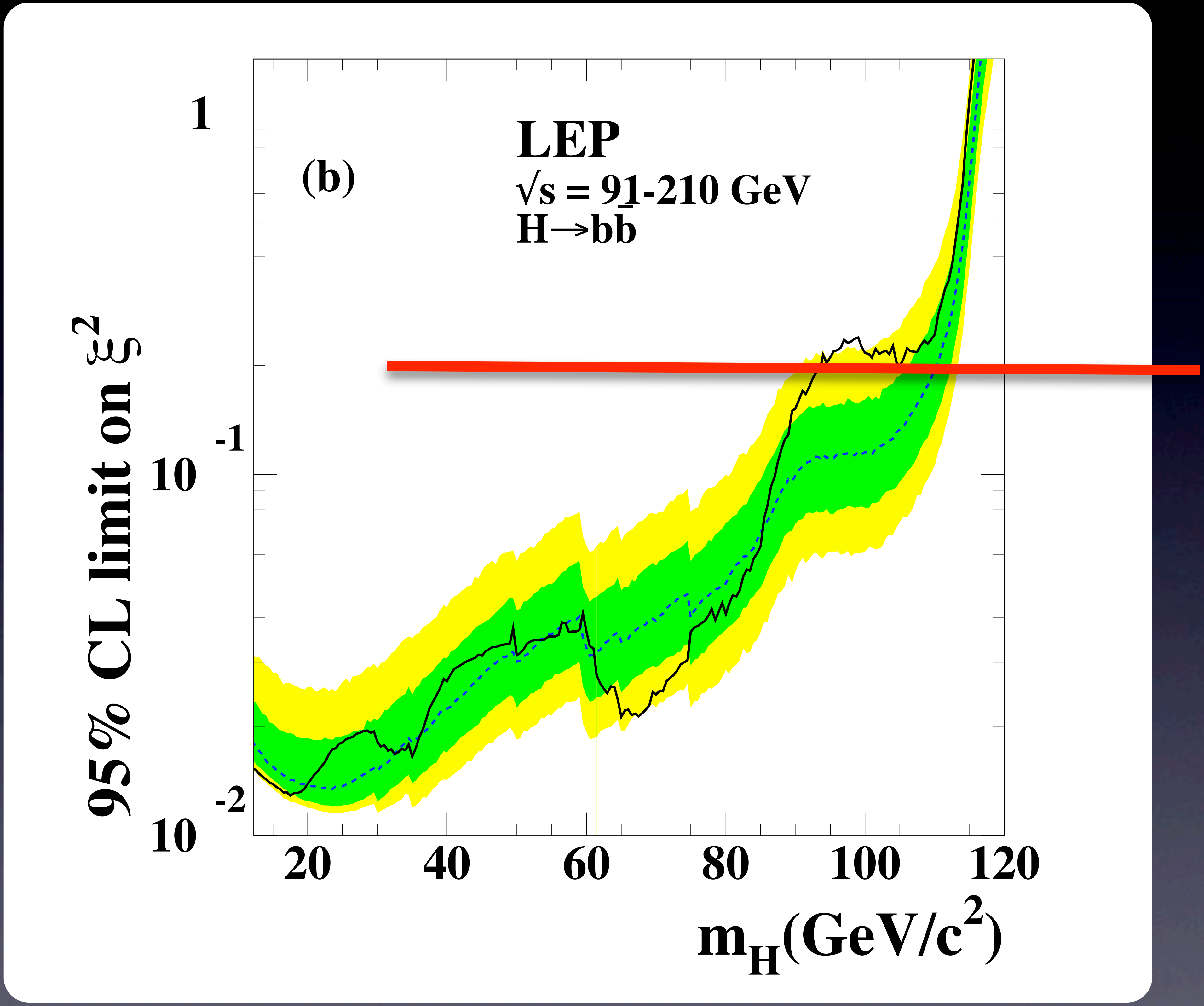




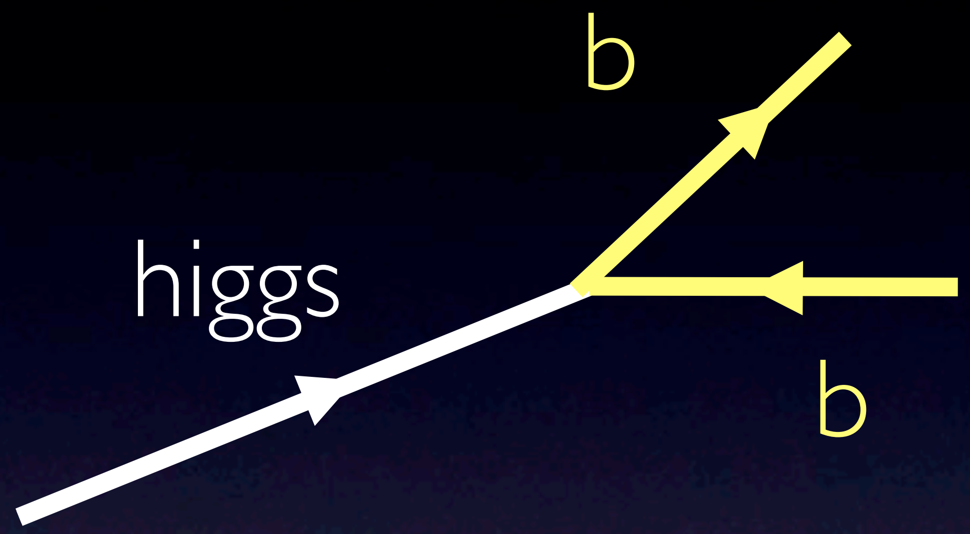
LEP
(b)
√s = 91-210 GeV
H→bb̄
95% CL limit on ξ²
1
10⁻¹
10⁻²
20
40
60
80
100
120
m_H(GeV/c²)



Suppressing SM BR to ~ 20 % is enough

Example: MSSM + singlet η

Dermisek & Gunion '06



VS.

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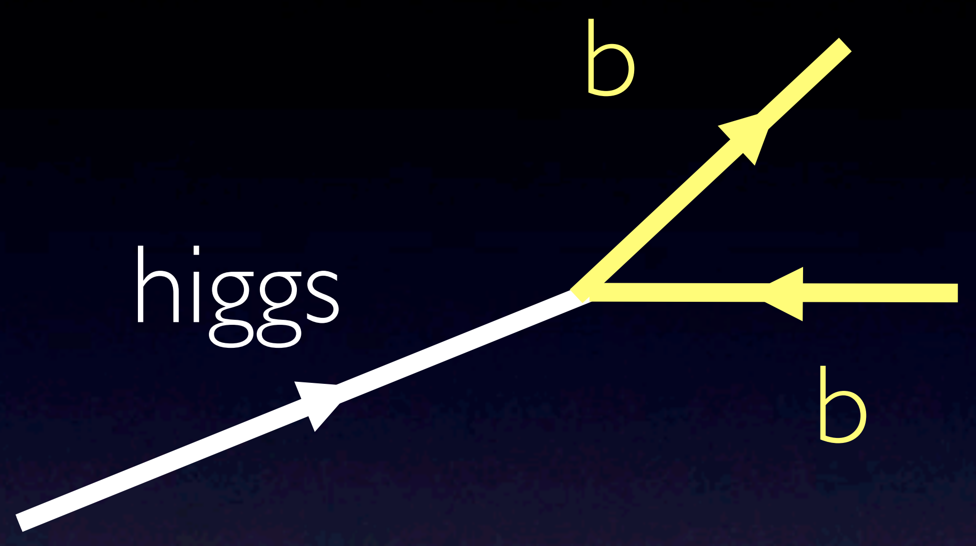

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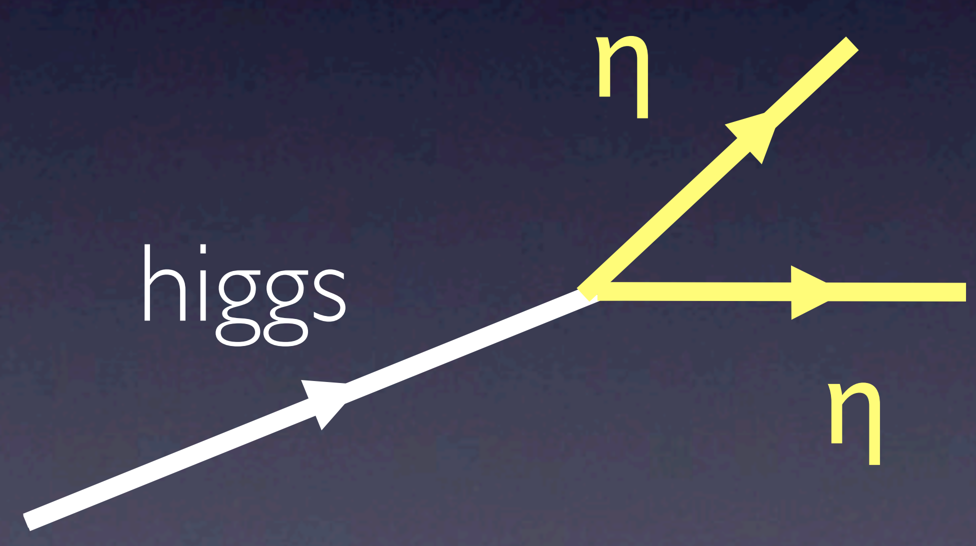

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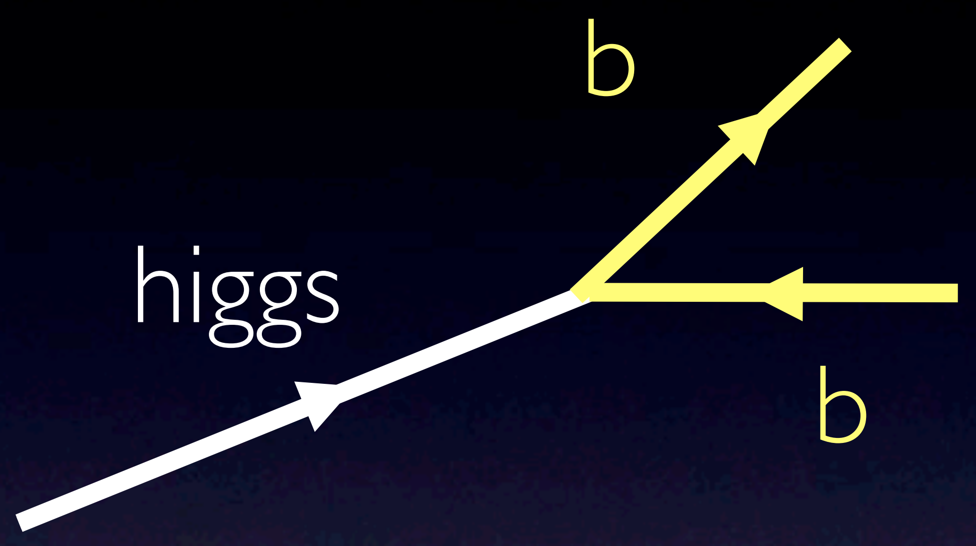

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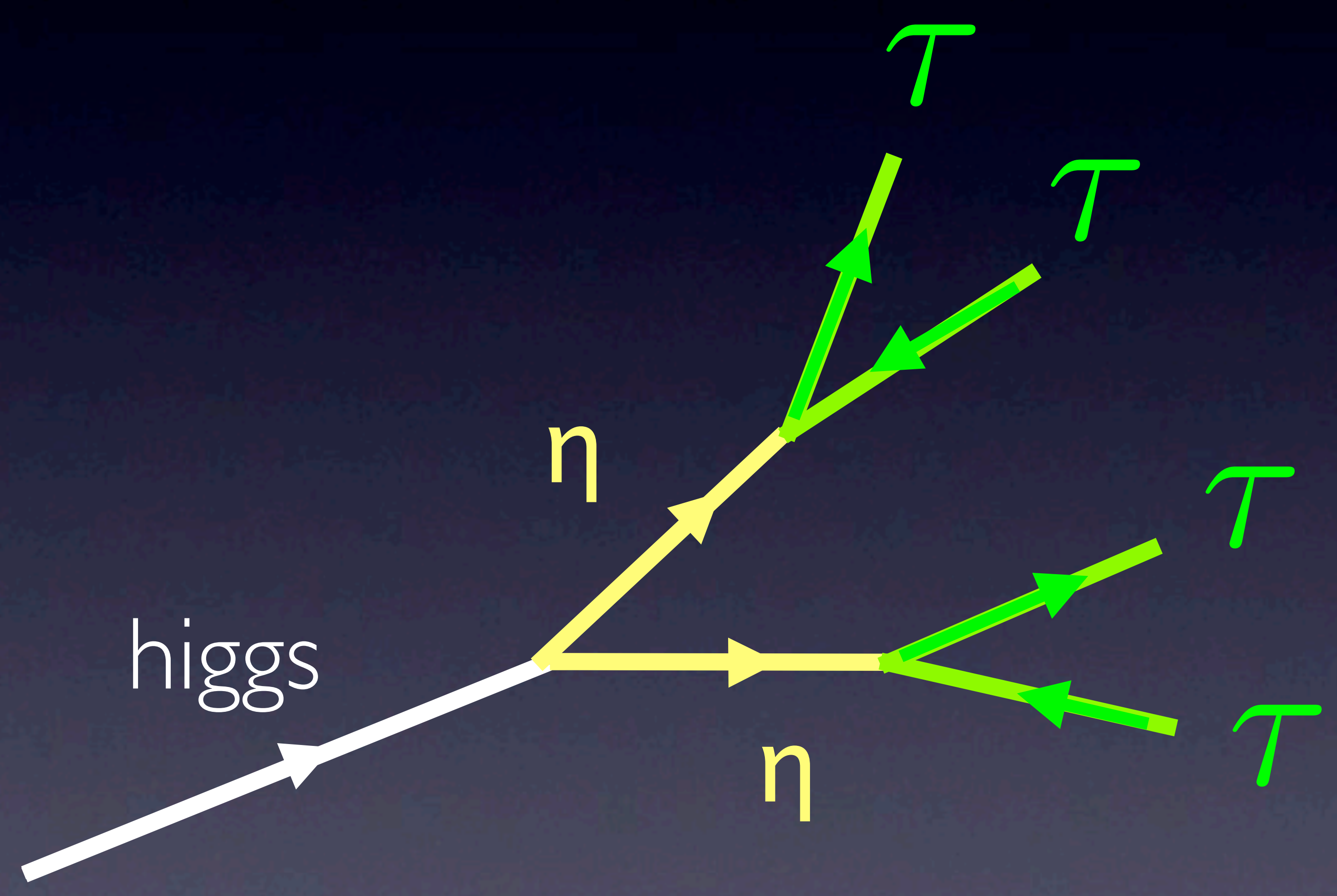

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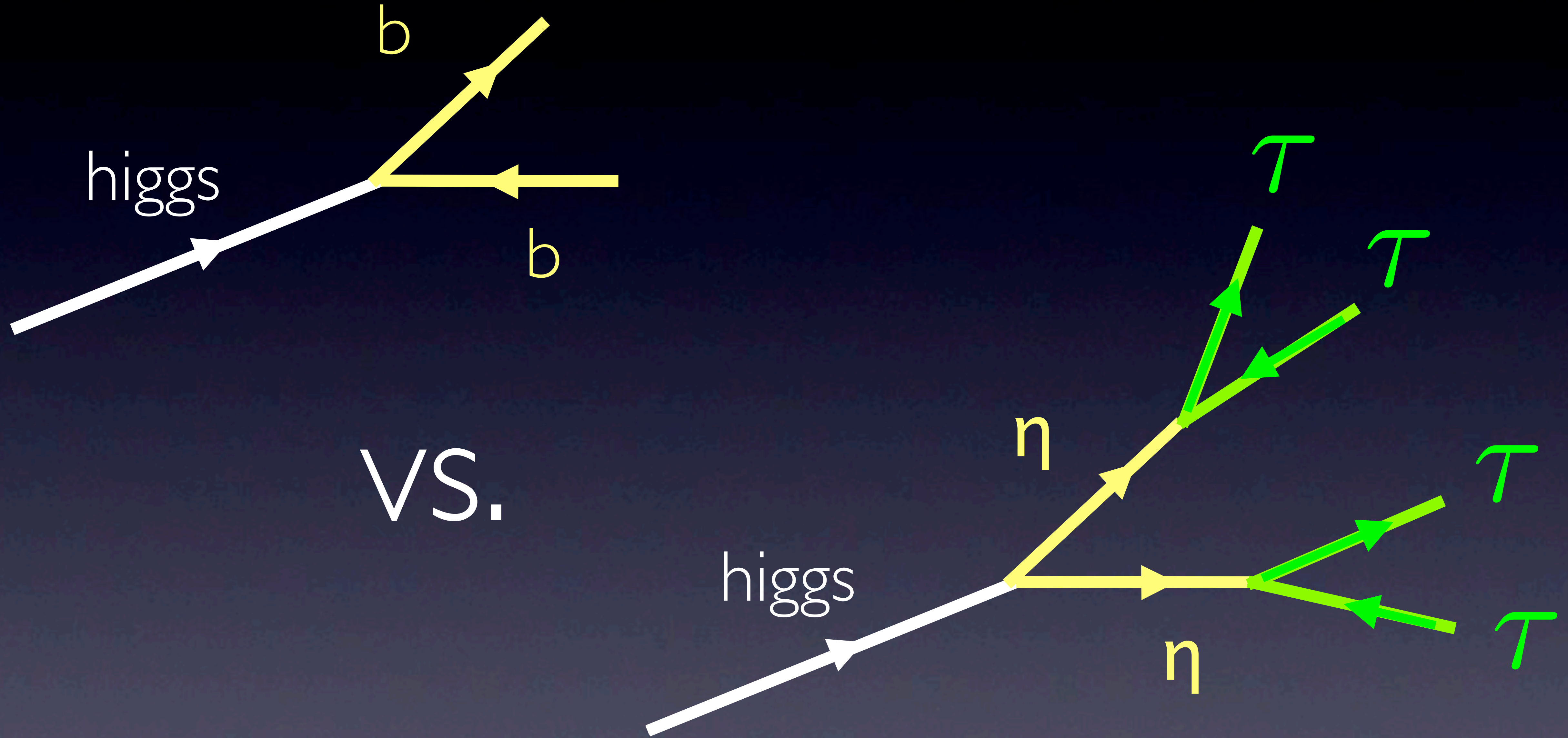

assuming $m_\eta < 2m_b$

Non-standard Higgs decays

Decay Channel	**Limit**
$h \to b\bar{b}$ or $\tau\bar{\tau}$	115 GeV
$h \to jj$	113 GeV
$h \to WW^*$ or ZZ^*	110 GeV
$h \to \gamma\gamma$	117 GeV
$h \to \not{E}$	114 GeV
$h \to AA \to 4b$	110 GeV
$h \to AA \to 4\tau, 4c, 4g$	86 GeV
$h \to$ anything	82 GeV

Constraints on 4 body decays (but 4c and 4g) almost as strong as SM limit.

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arXiv:1003.0705 [hep-ex]

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Why is the η so light?

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Who ordered the η?

Higgs as a pseudo Goldstone Boson

- Higgs as pGB of SU(3)/SU(2) at $f \approx (2-3) \times v$

8 - 3 $=$ **5** broken generators

5 $=$ **4** (Higgs doublet) **+ 1** (singlet)

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The Higgs mass in MSSM

$$V = (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

At tree-level firm upper bound on the lightest of the two CP even Higgs bosons

$$m(h^0) < M_Z$$

Experimentally: $m(h^0) > 114\,\text{GeV}$

Either MSSM is wrong or loop correction large (**75%**).

Tuning in the MSSM

$$m_{h^0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\rm stop}^2}{m_t^2}$$

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$$\delta m_{Hu}^2(\mathrm{loop}) = -\frac{3y_t^2}{8\pi^2} m_{\rm stop}^2 \ln \frac{\Lambda^2}{m_{\rm stop}^2} \approx 600 \cdot \frac{m_Z^2}{2}$$

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Little Hierarchy problem

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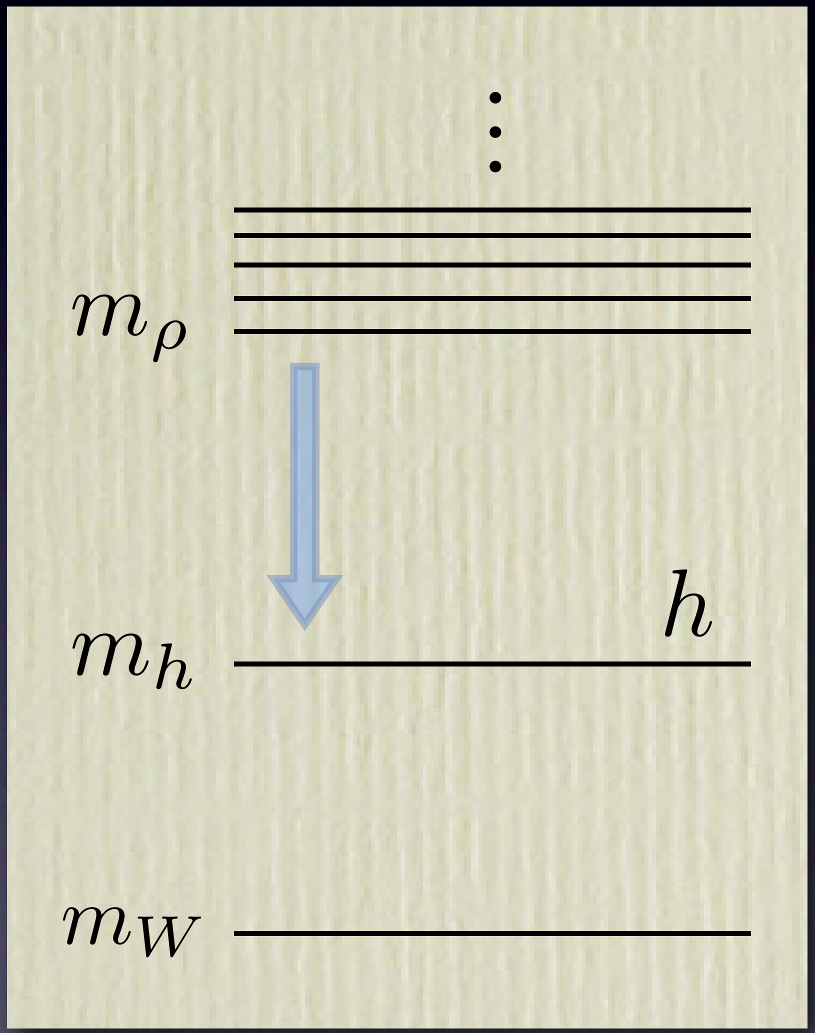
Composite Higgs

Georgi, Kaplan

Light Higgs-like scalar arises as a bound state from a strongly-interacting EWSB sector

- A composite Higgs solves the hierarchy problem
- A light Higgs is preferred by the electroweak fit

A light composite Higgs can naturally arise as a (pseudo) Goldstone boson



Minimal Composite Higgs

Agashe, Contino, Pomarol, → Margarete Mühlleitner's talk

- $m_Z/m_W \cos\theta_W \simeq 1 \Rightarrow T \sim 0$
- Need custodial symmetry
- Replace $U(1)_Y$ by $SU(2)_R$
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$
- Need 'symmetry' for S-parameter: $SO(5) \rightarrow SO(4)$
- GBs: ***4*** $SO(4) = (2,2)$ of $SU(2)_L \times SU(2)_R$ like the Higgs !

Yukawa and gauge interactions break SO(5), Higgs gets small mass from top

NonMCH, eg. SO(6)/SO(5)

→ Alex Pomarol's talk

In non-minimal composite Higgs models where Higgs is in SO(6)/SO(5):

$$SO(6)\ /\ SO(5) = \mathbf{15-10} = (\mathbf{2},\mathbf{2})_{Higgs} + (\mathbf{1},\mathbf{1})_{\eta}$$

Depending on SM fermion embedding, similar phenomenology possible.

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Back to susy pGB pheno...

pGB's: Higgs + singlet

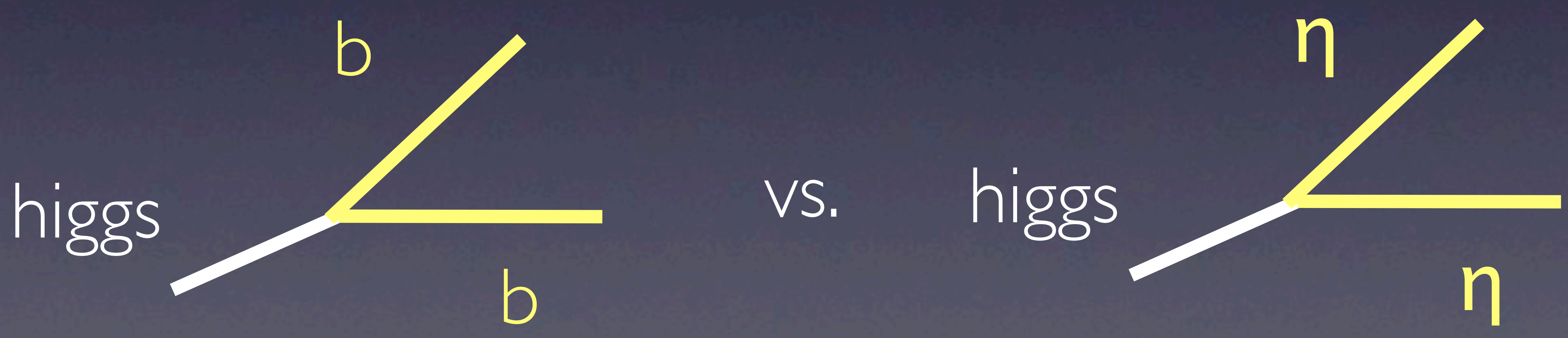
Parameterization of Higgses:
GB of SU(3)→SU(2)

$$\Sigma_{u,d}(\mathbf{3}_{\pm 1/3}) = e^{iT^a G^a} \begin{pmatrix} 0 \\ 0 \\ f_{u,d} \end{pmatrix}, \quad T^a G^a = \frac{1}{f} \begin{pmatrix} 0 & H \\ H^\dagger & \eta \end{pmatrix},$$

$h \to \eta\eta$ vs. $h \to bb$

Goldstone interaction *fixed by symmetry*

$$\mathcal{L}_{h\eta^2} \approx -h(\partial_\mu \eta)^2 \frac{\tan(\tilde{v}/f)}{\sqrt{2}f}$$



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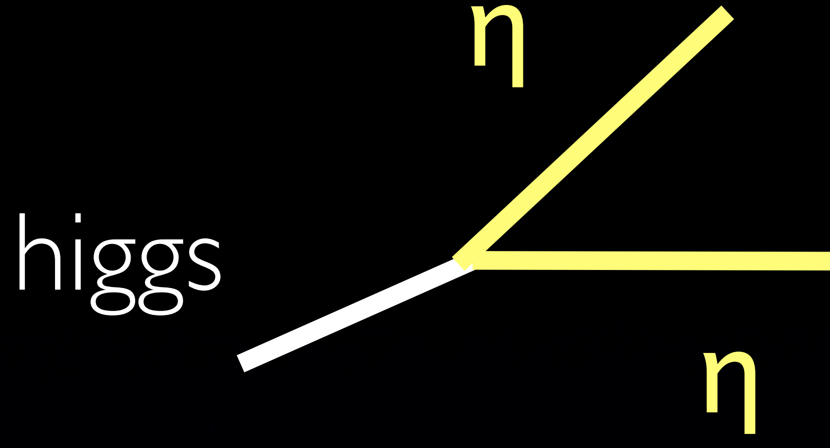

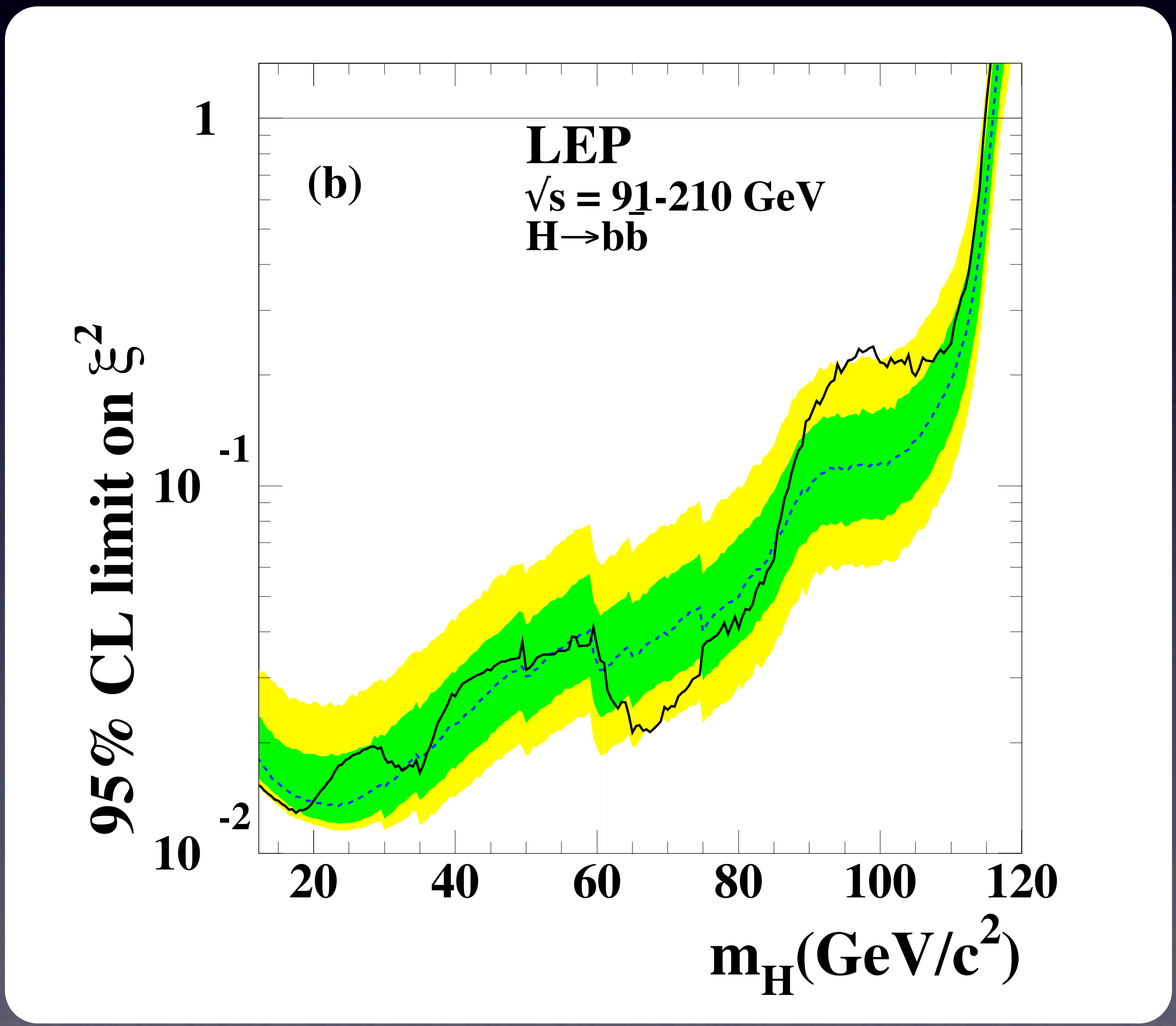

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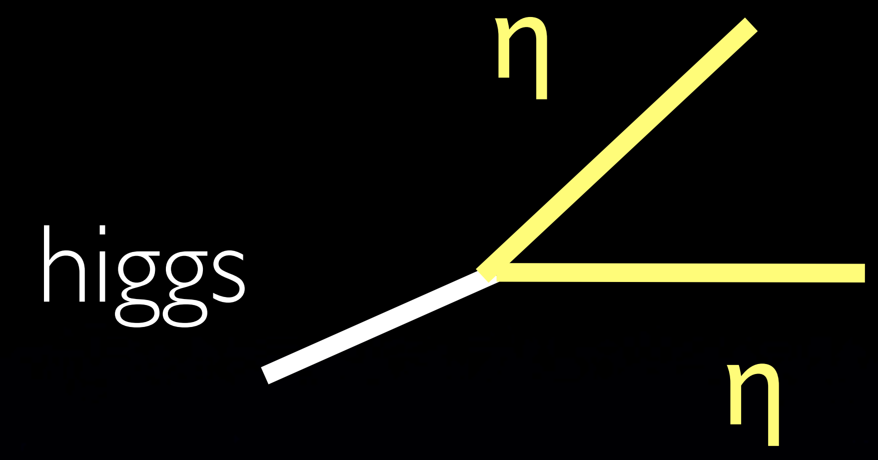

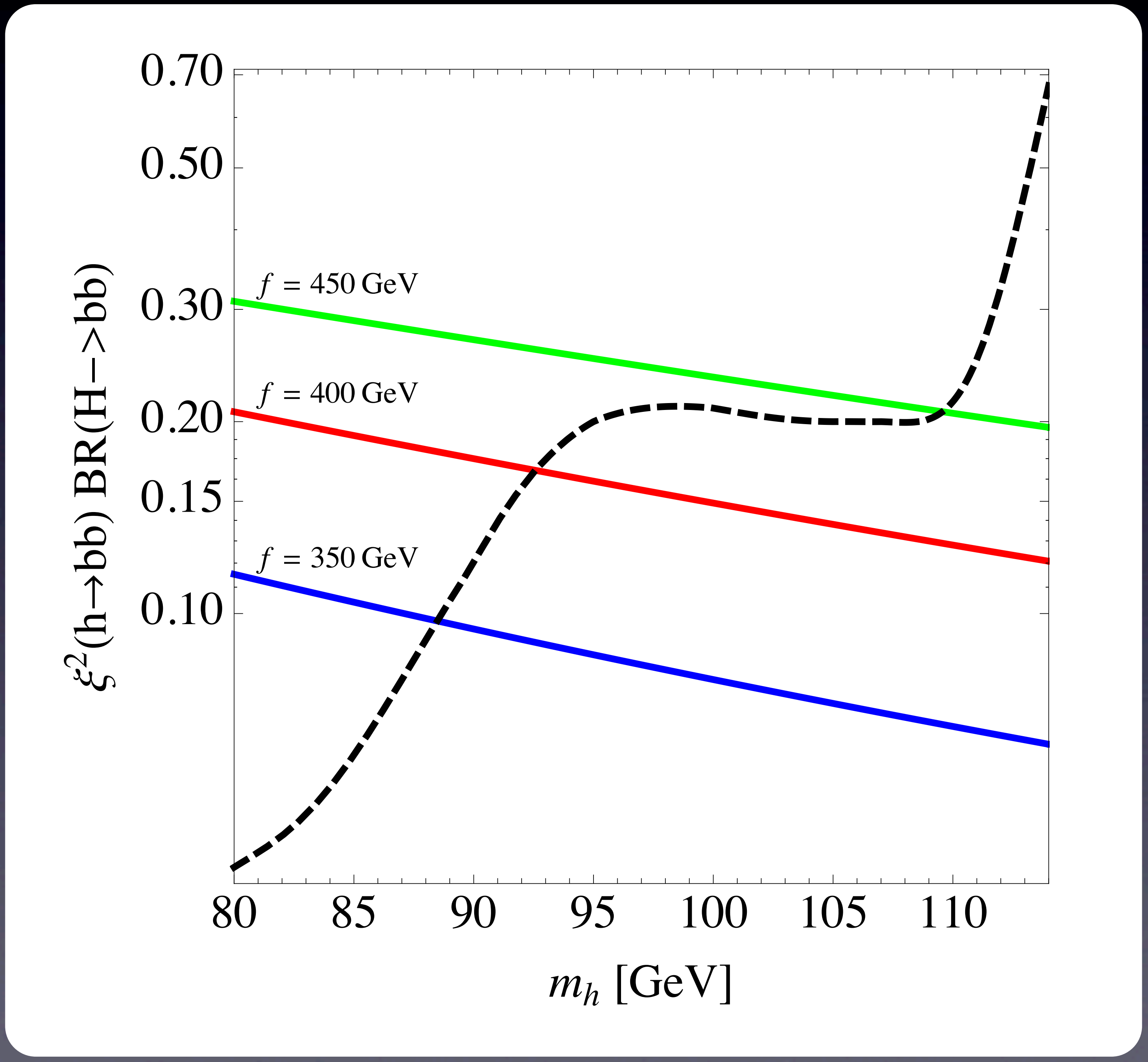

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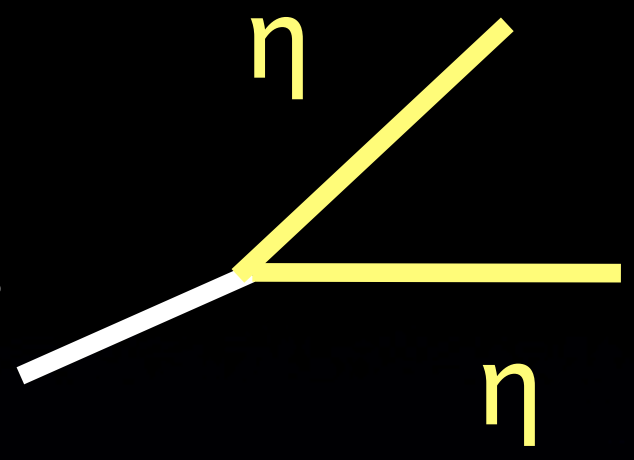
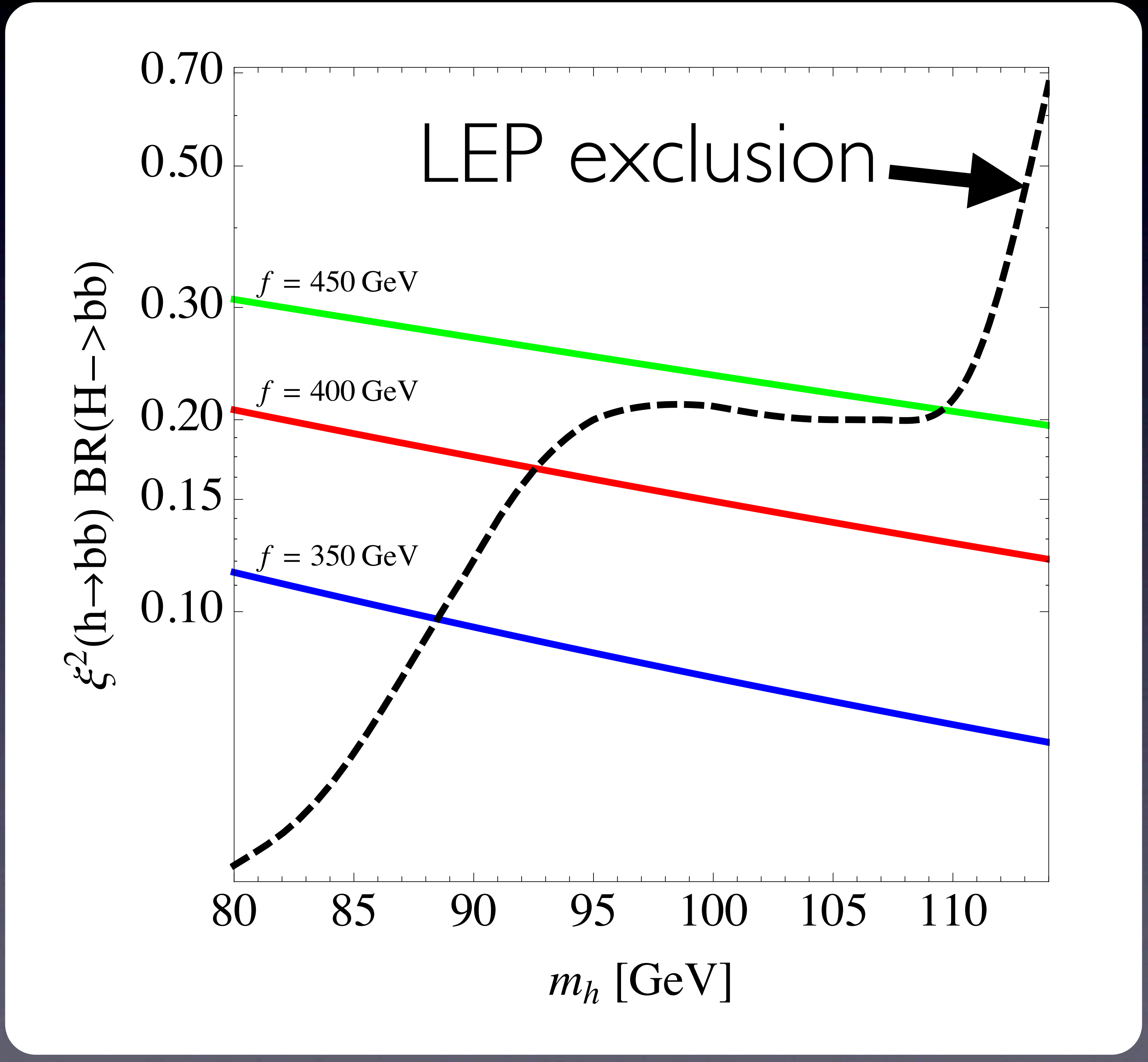
higgs





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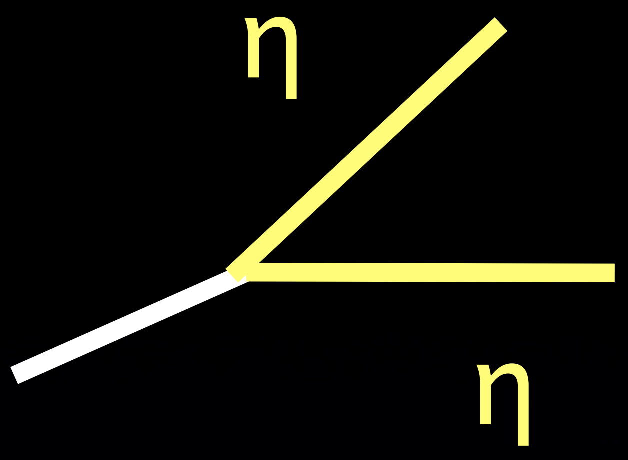

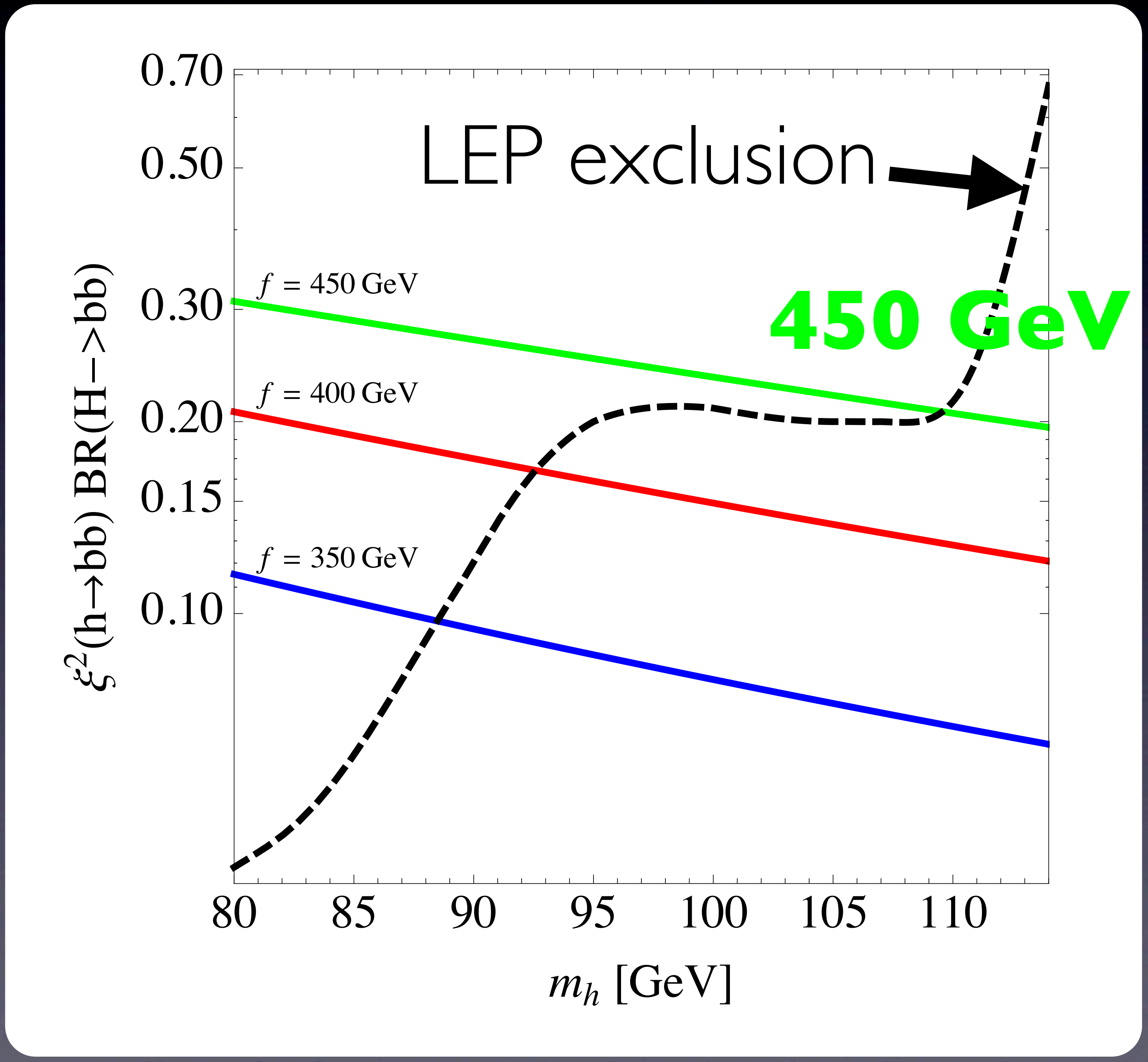

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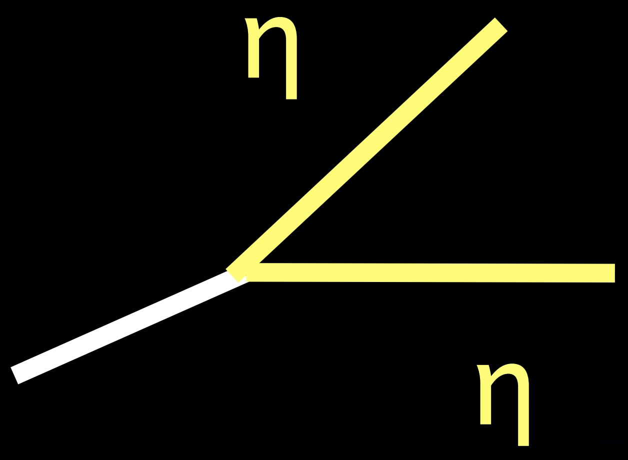

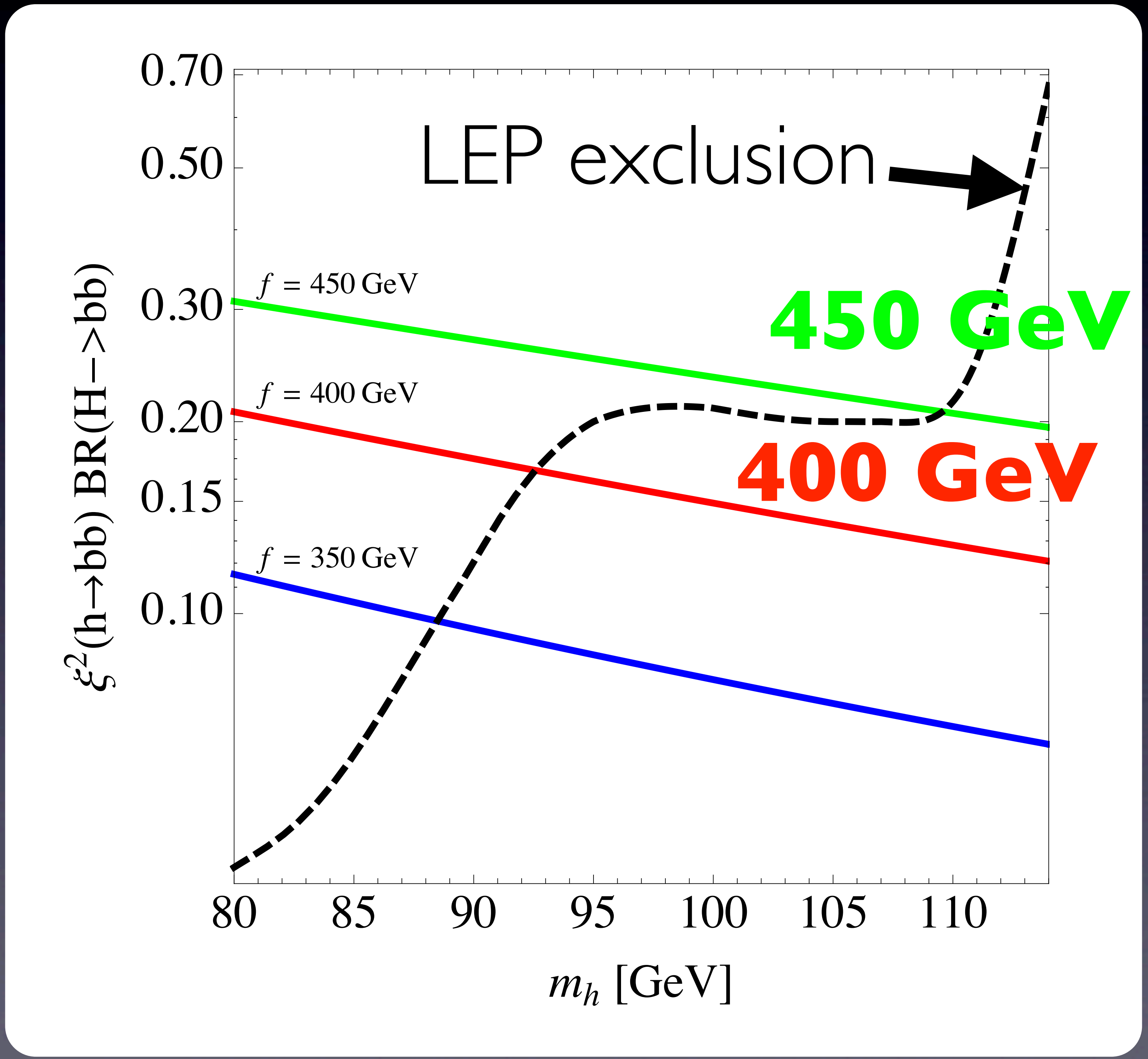

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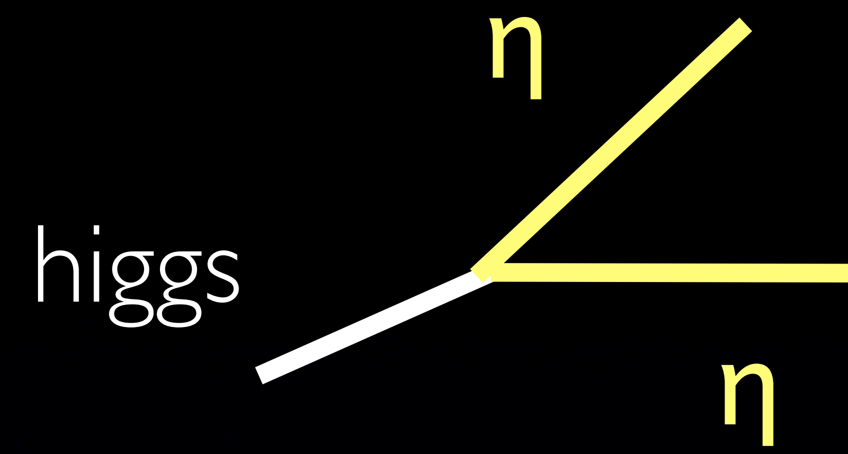

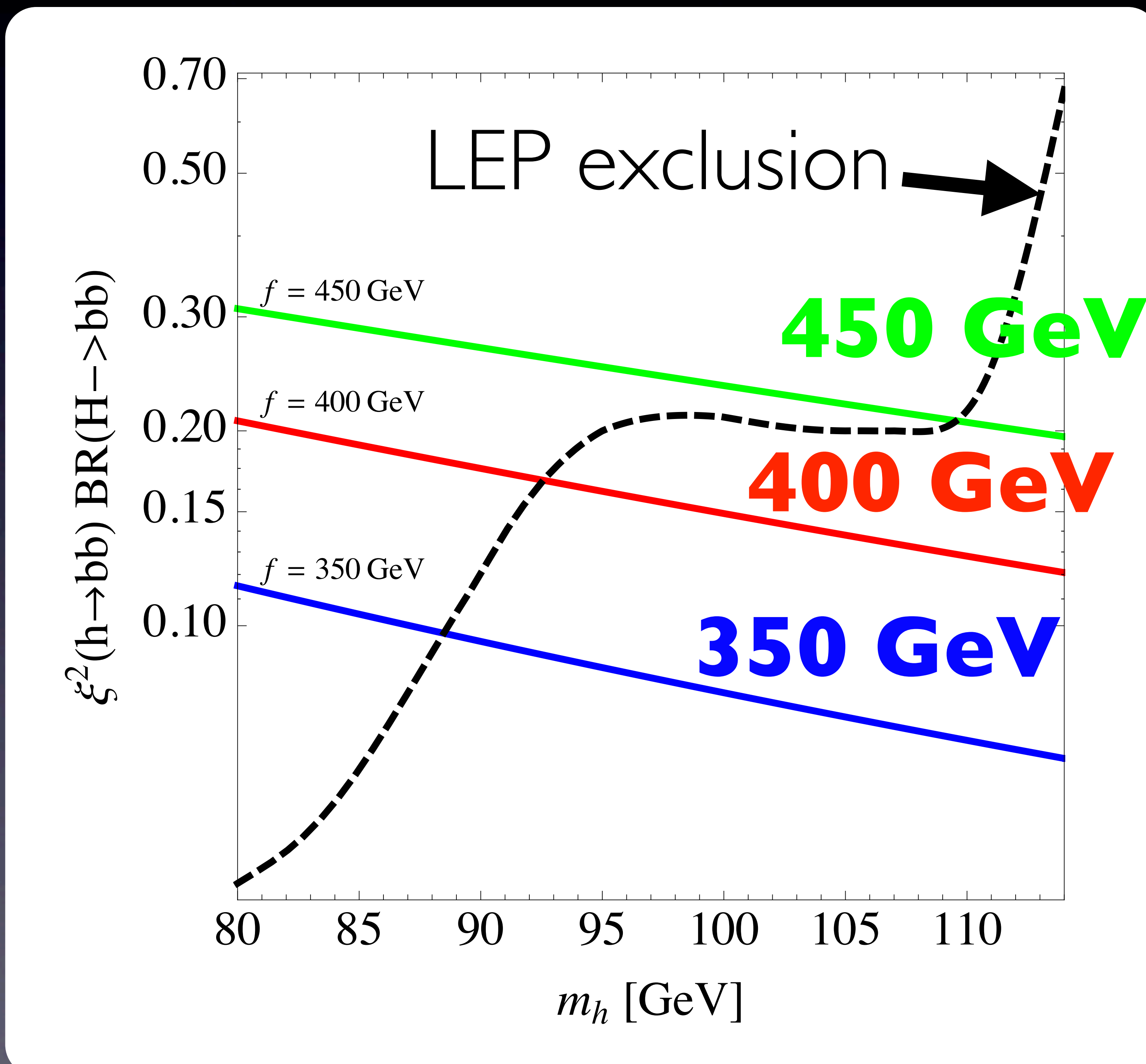

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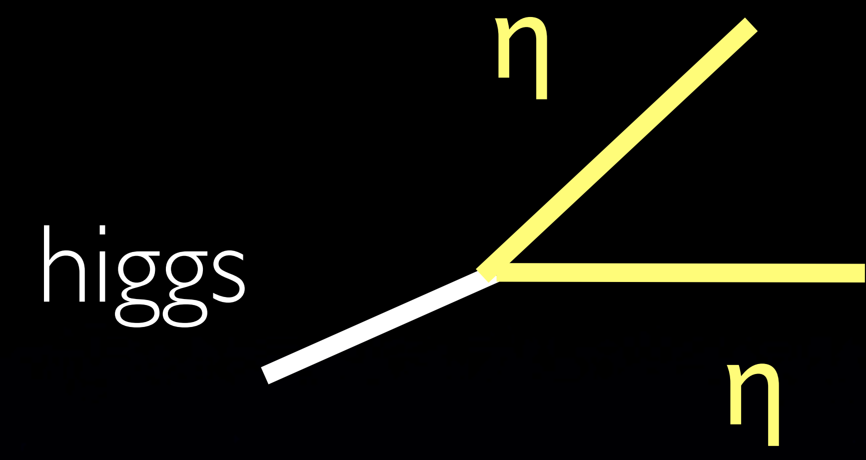
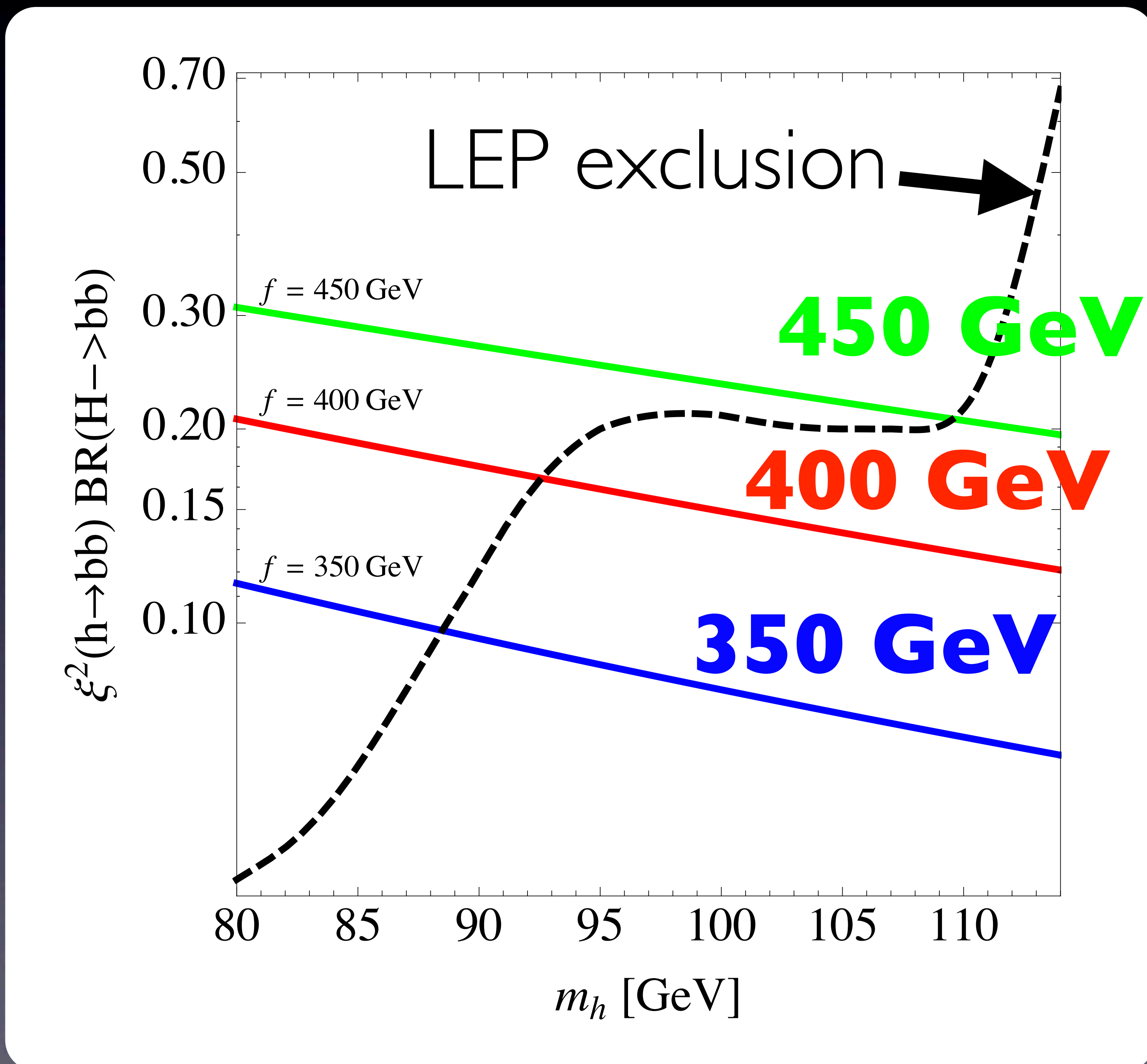




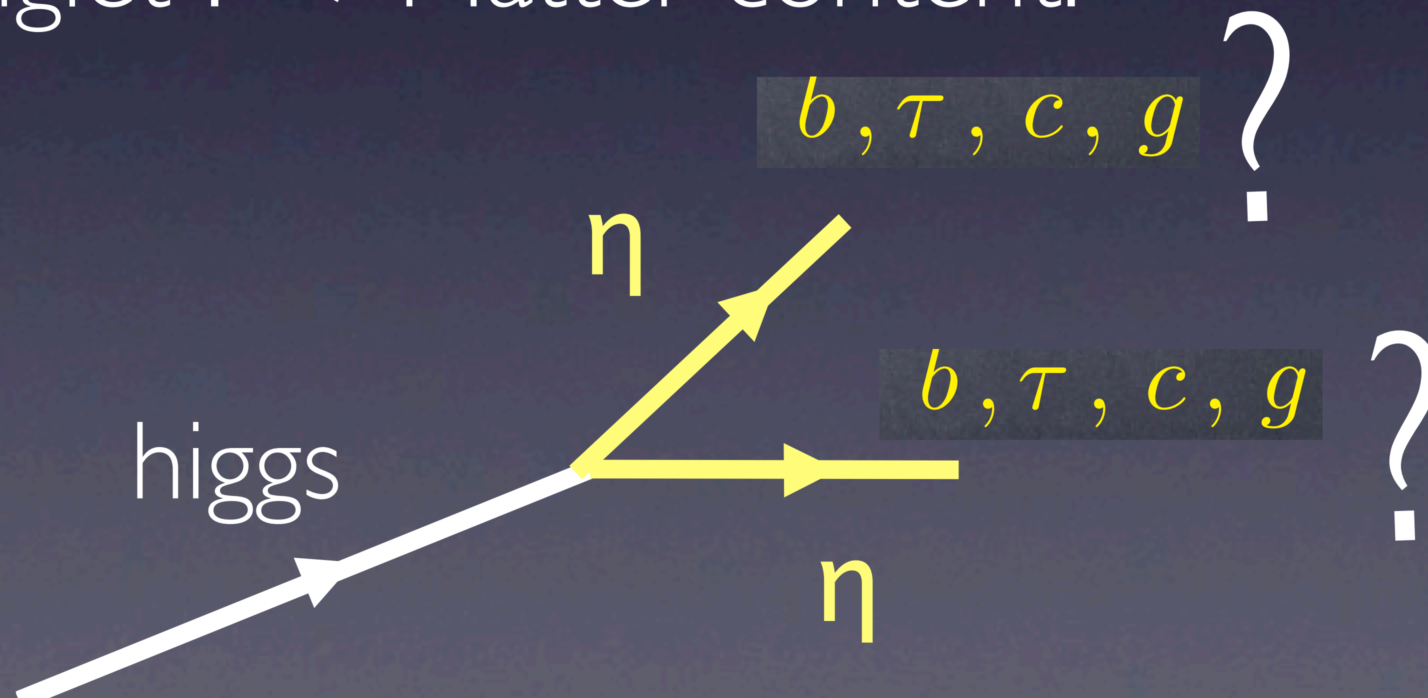
$f < 400$ GeV

So far...

- Found Susy pGB Higgs model, no little hierarchy problem
- Higgs + singlet **η**, Higgs decays mostly into **η**. Higgs and **η** mass? LEP? ⇒ Matter content!
- What happens to singlet ? ⇒ Matter content!

$m_\eta = ?$

$m_h = ?$



Very surprising result:

η decays dominantly into 2 gluons!

Eta fermion coupling

η in 3rd component of Higgs triplet

SM fermions mostly in 1,2 component of Quark triplet

→ Coupling $i(\bar{f}\gamma_5 f)\eta \sim$ to mixing with heavy partner

	non-flipped	flipped
	Buried	Charming
Top	$\tilde{y}_t \sim \frac{m_t^3}{\sqrt{2}v_{EW}^2 f} \sim 0.2$	$\tilde{y}_t \sim \frac{m_t}{\sqrt{2}f} \sim 0.2$
Charm	$\tilde{y}_c \sim \frac{m_c^3}{\sqrt{2}v_{EW}^2 f} \sim 10^{-9}$	$\tilde{y}_c \sim \frac{m_c}{\sqrt{2}f} \sim 10^{-3}$
B	$\tilde{y}_b \sim \frac{m_b m_t^2}{\sqrt{2}v_{EW}^2 f} \sim 10^{-2}$	$\tilde{y}_b \sim \frac{m_b^3}{\mu_V^2 f} \sim 10^{-12}$
Tau	$\tilde{y}_\tau \sim \frac{m_\tau^3 f}{\sqrt{2}f v_{EW}^2} \sim 10^{-8}$	$\tilde{y}_\tau \sim \frac{m_\tau^3 f}{\sqrt{2}f v_{EW}^2} \sim 10^{-8}$

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$m_{eta} < 2m_b$

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→ Coupling $i(\bar{f}\gamma_5 f)\eta \sim$ to mixing with heavy partner

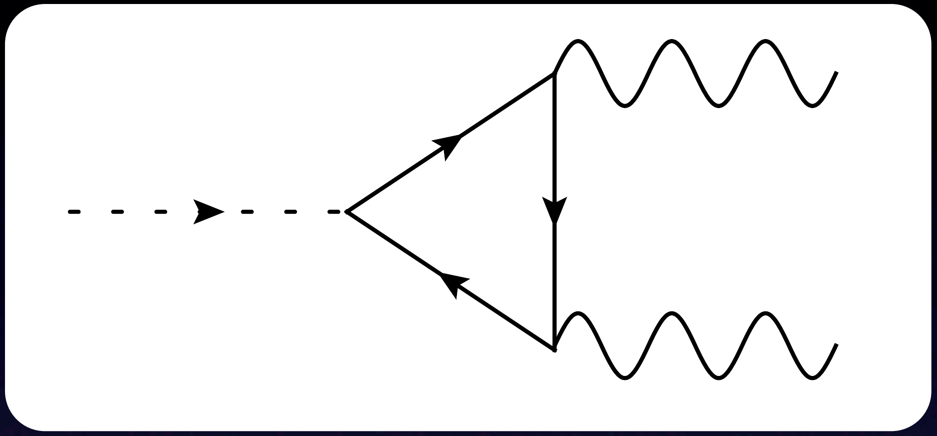
Extra suppression

$$\tilde{y}_b \sim \frac{m_b}{f} \times \frac{m_b^2}{\mu_V^2}$$

	non-flipped	flipped
	Buried	Charming
Top	~~$\tilde{y}_t \sim \frac{m_t^3}{\sqrt{2}v_{EW}^2 f} \sim 0.2$~~	~~$\tilde{y}_t \sim \frac{m_t}{\sqrt{2}f} \sim 0.2$~~
Charm	$\tilde{y}_c \sim \frac{m_c^3}{\sqrt{2}v_{EW}^2 f} \sim 10^{-9}$	$\tilde{y}_c \sim \frac{m_c}{\sqrt{2}f} \sim 10^{-3}$
B	~~$\tilde{y}_b \sim \frac{m_b m_t^2}{\sqrt{2}v_{EW}^2 f} \sim 10^{-2}$~~	$\tilde{y}_b \sim \frac{m_b^3}{\mu_V^2 f} \sim 10^{-12}$
Tau	$\tilde{y}_\tau \sim \frac{m_\tau^3 f}{\sqrt{2}f v_{EW}^2} \sim 10^{-8}$	$\tilde{y}_\tau \sim \frac{m_\tau^3 f}{\sqrt{2}f v_{EW}^2} \sim 10^{-8}$

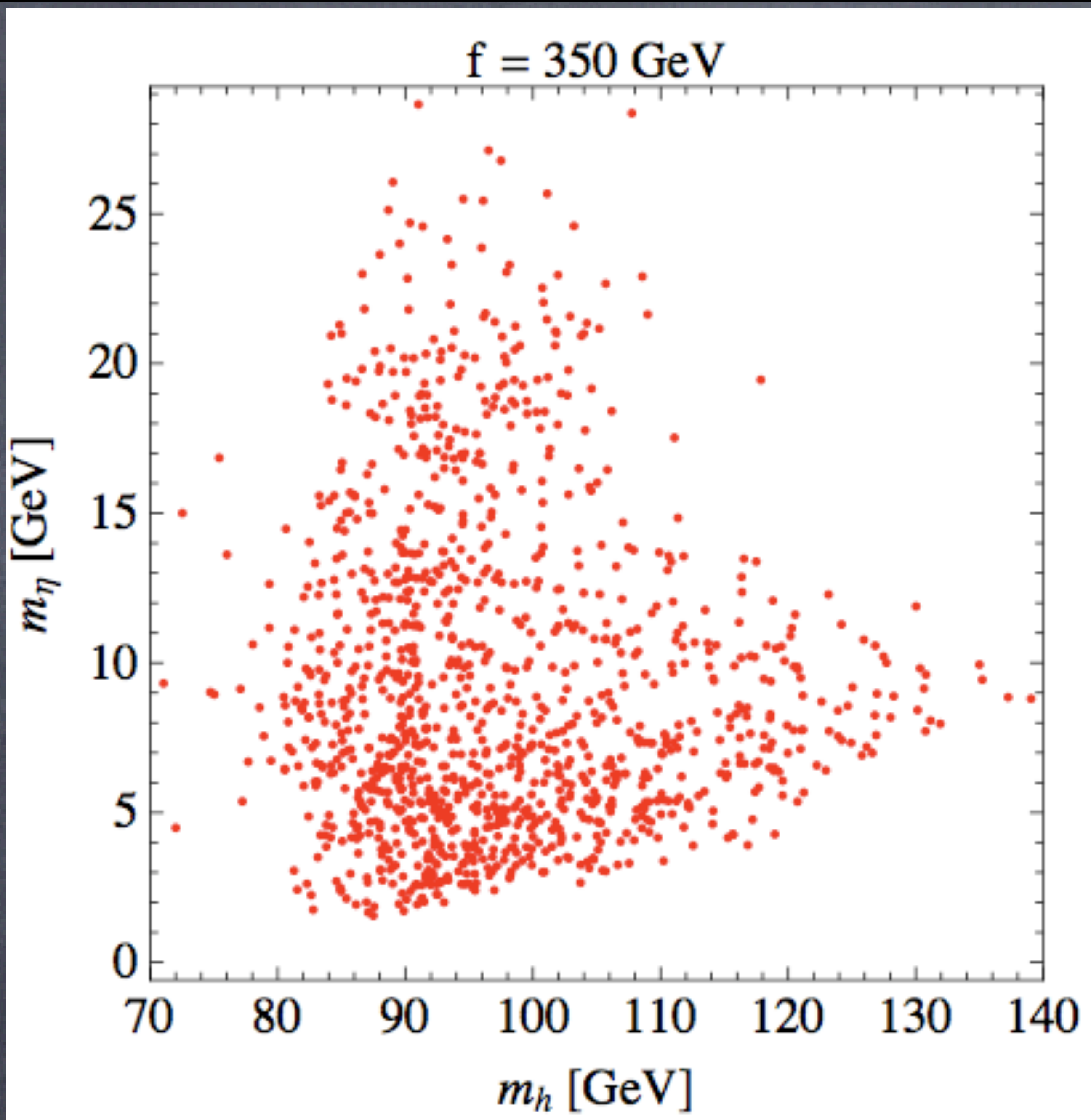
$m_{eta} < 2m_b$

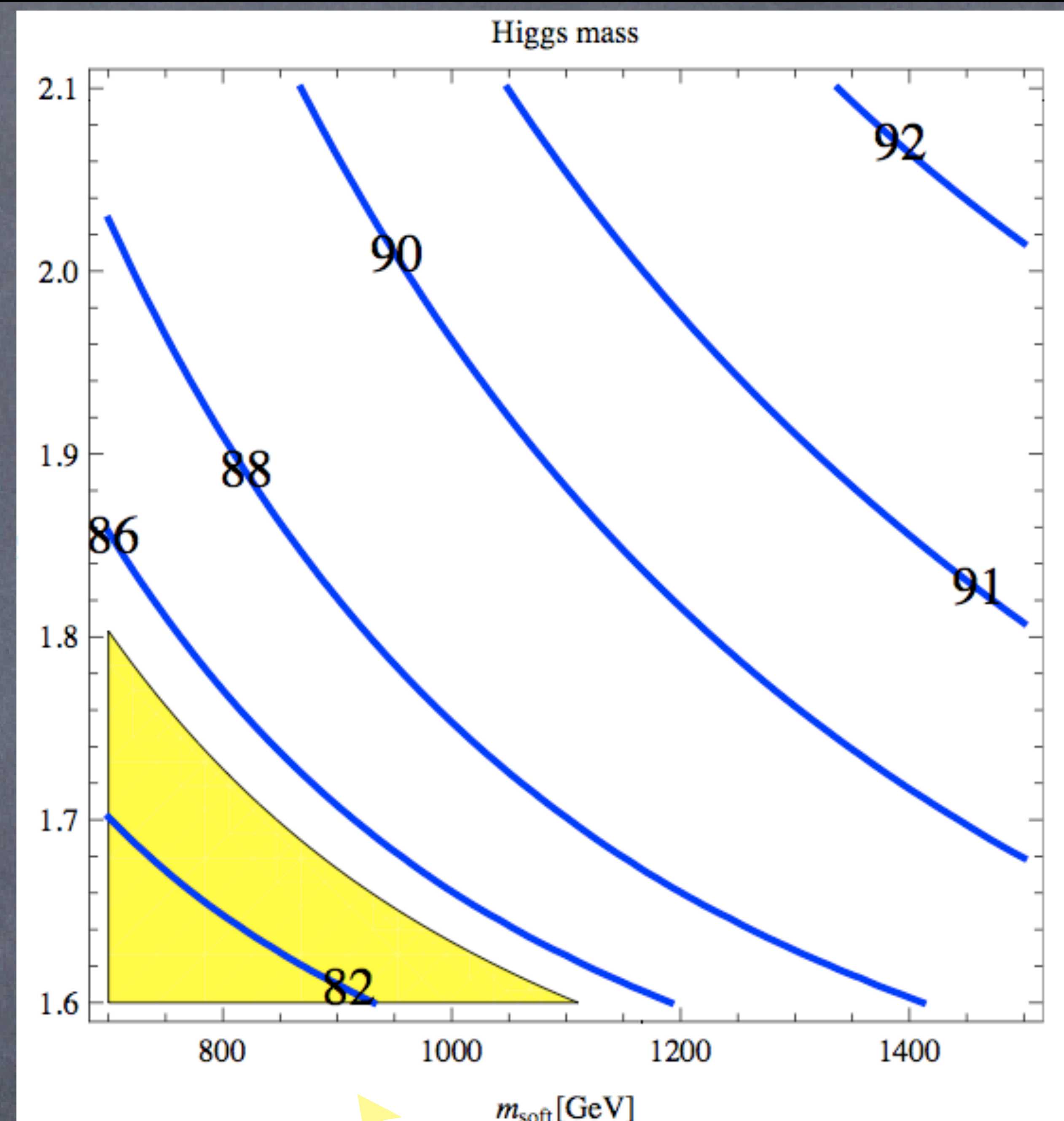
Eta decays - 1 loop



For $m_{eta} < 2\ m_b$ will decay mostly to two gluons

$$\kappa^g \eta \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}\ , \qquad \kappa^g = \frac{g^2}{32\pi^2} \sum_\psi \frac{\tilde{y}_\psi}{m_\psi} c_2(\psi) \tau_\psi f(\tau_\psi)$$


f = 350 GeV
m_η [GeV]
m_h [GeV]
0
5
10
15
20
25
70
80
90
100
110
120
130
140


Higgs mass
m_{soft}[GeV]
1.6
1.7
1.8
1.9
2.0
2.1
800
1000
1200
1400
82
86
88
90
91
92

Higgs decays dominantly

higgs $\rightarrow$ 2 η $\rightarrow$ 4 gluons

Eta is naturally light (7-8 GeV).

Very non-standard Higgs phenomenology!

LHC Signals

1) Higgs Impostor
2) Subjet 'unburying'
3) Rich & light spectrum

Higgs Impostor

$$\mathcal{H}_u \approx (f + r/\sqrt{2}) \begin{pmatrix} 0 \\ \sin((\tilde{v} + h/f)) \\ \cos((\tilde{v} + h/f)) \end{pmatrix}$$

$$m_r^2 \approx 4\lambda_{\mathcal{H}} f^2 \sim 350 \text{ GeV}$$

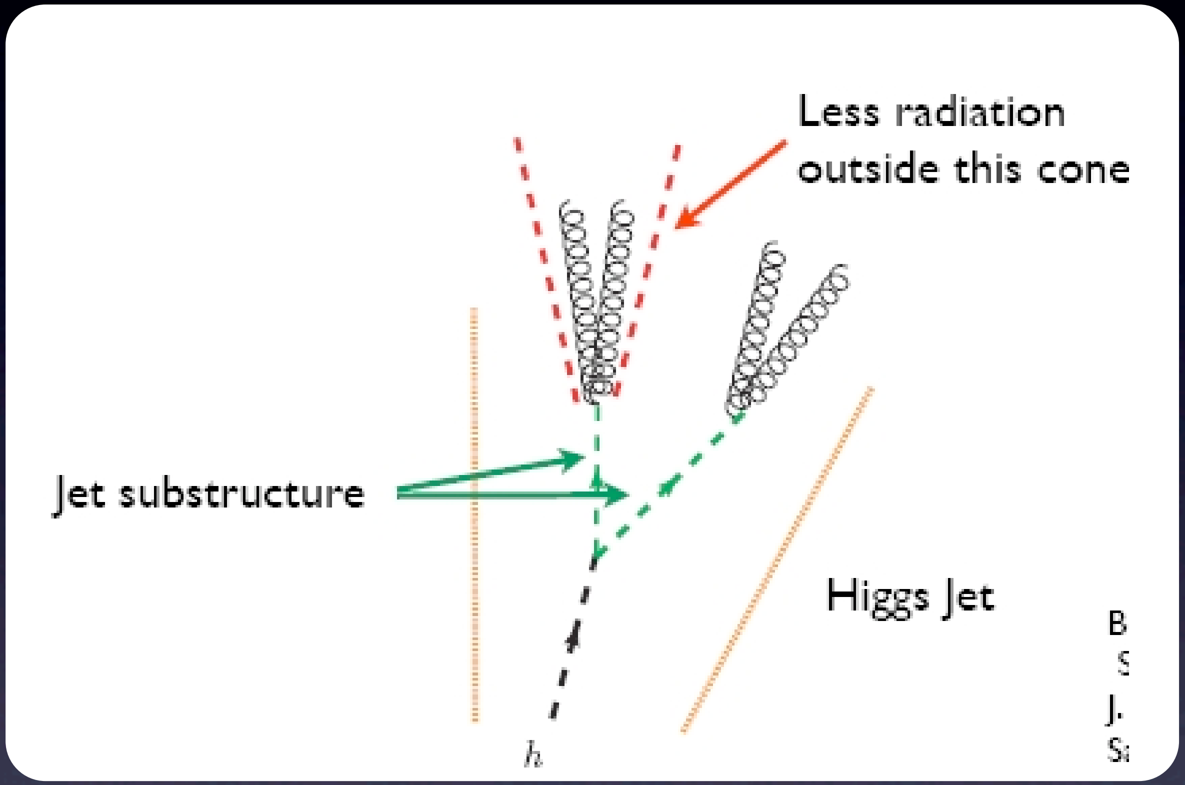
It Couples like the Higgs but suppressed

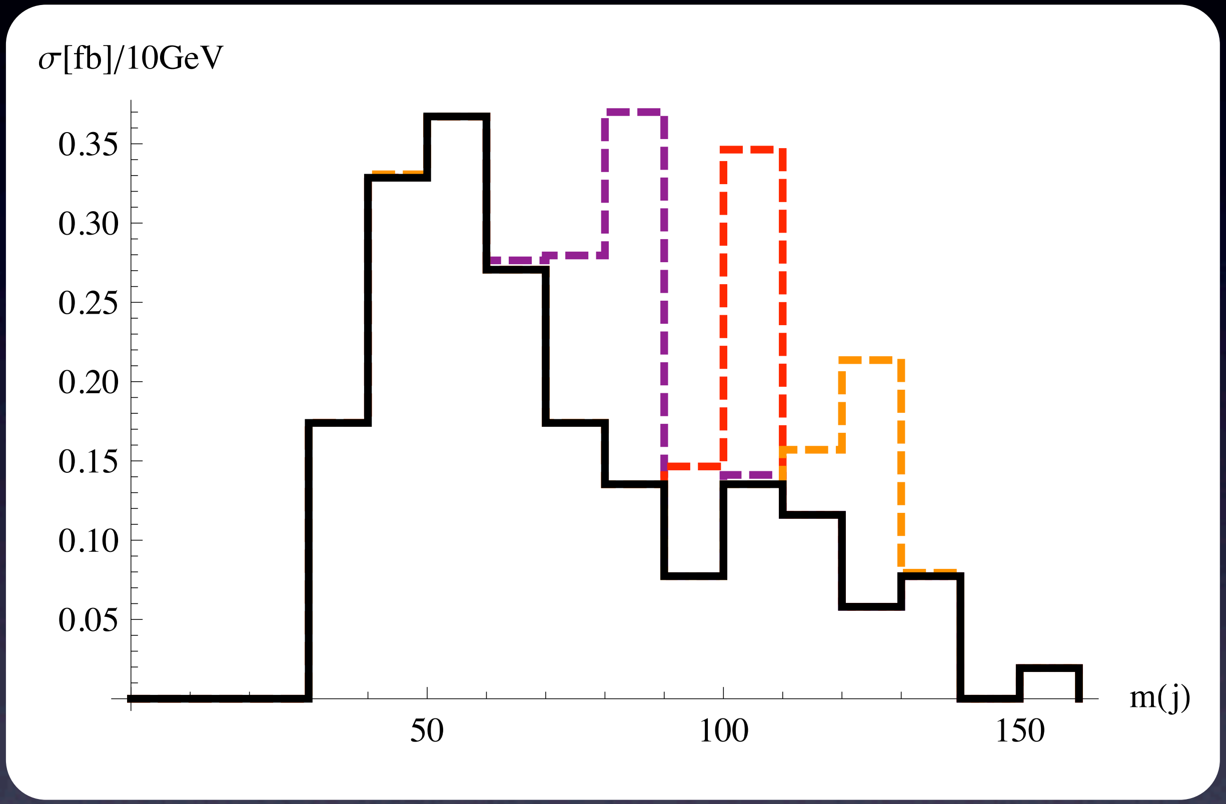
$$g_{rVV} = g_{hVV}^{SM} \times (v_{EW}/f) \approx \frac{1}{2} \times g_{hVV}^{SM}$$

easily visible @ LHC: $gg \to r \to ZZ \to 4l$

Jet substructure in ttH

Falkowski, Krohn, Shelton, Thallapillil, Wang in preparation





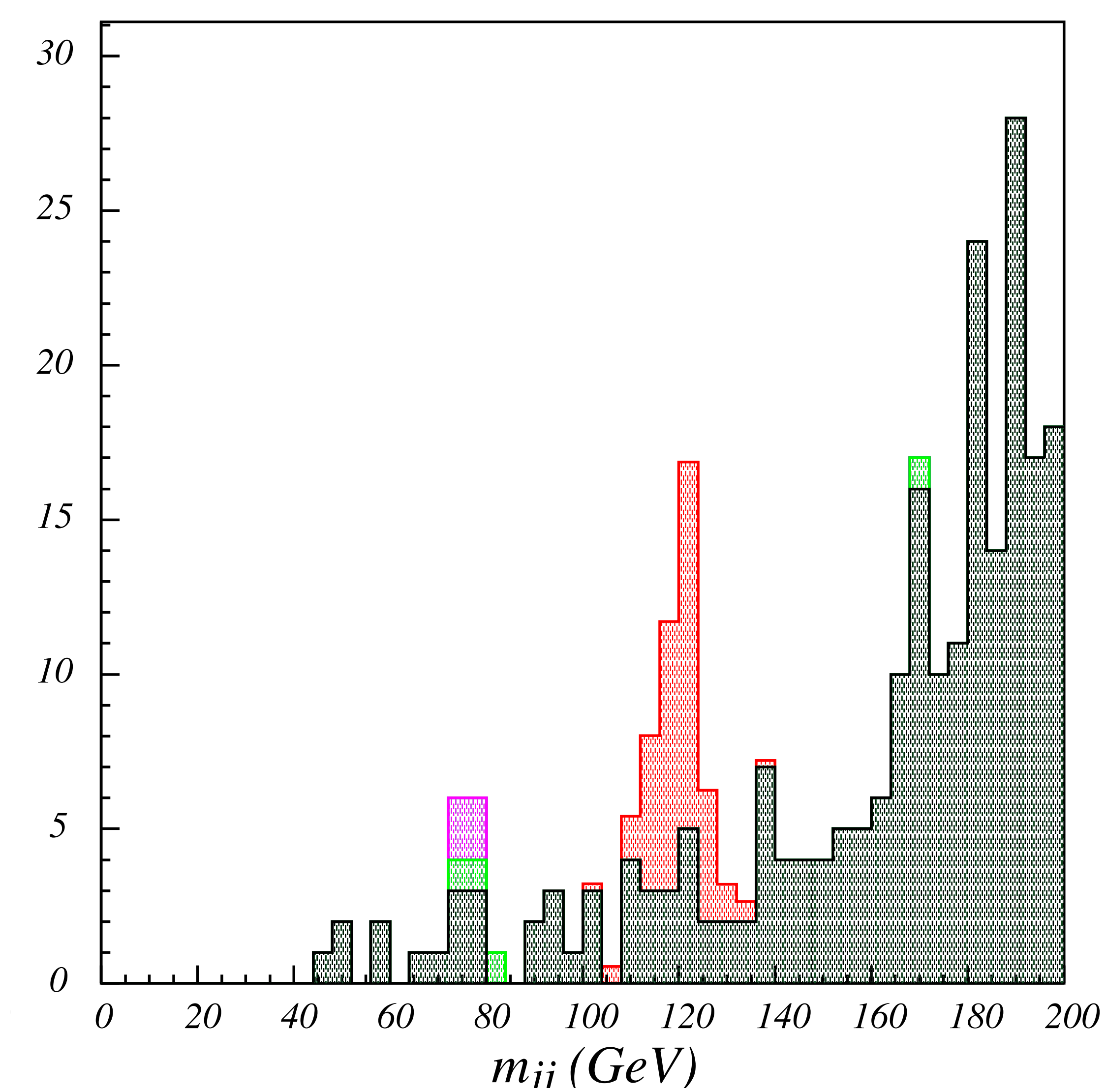
Can unbury the Higgs!

Jet Substructure II: hW→eνjj

Chen, Nojiri, Sreethawong arXiv:1006.1151v1 [hep-ph]

Today on the arxiv

shown here: m_η= 4GeV (m_η = 8GeV slightly harder)



Jet Substructure II: hW→eνjj

Chen, Nojiri, Sreethawong arXiv:1006.1151v1 [hep-ph]

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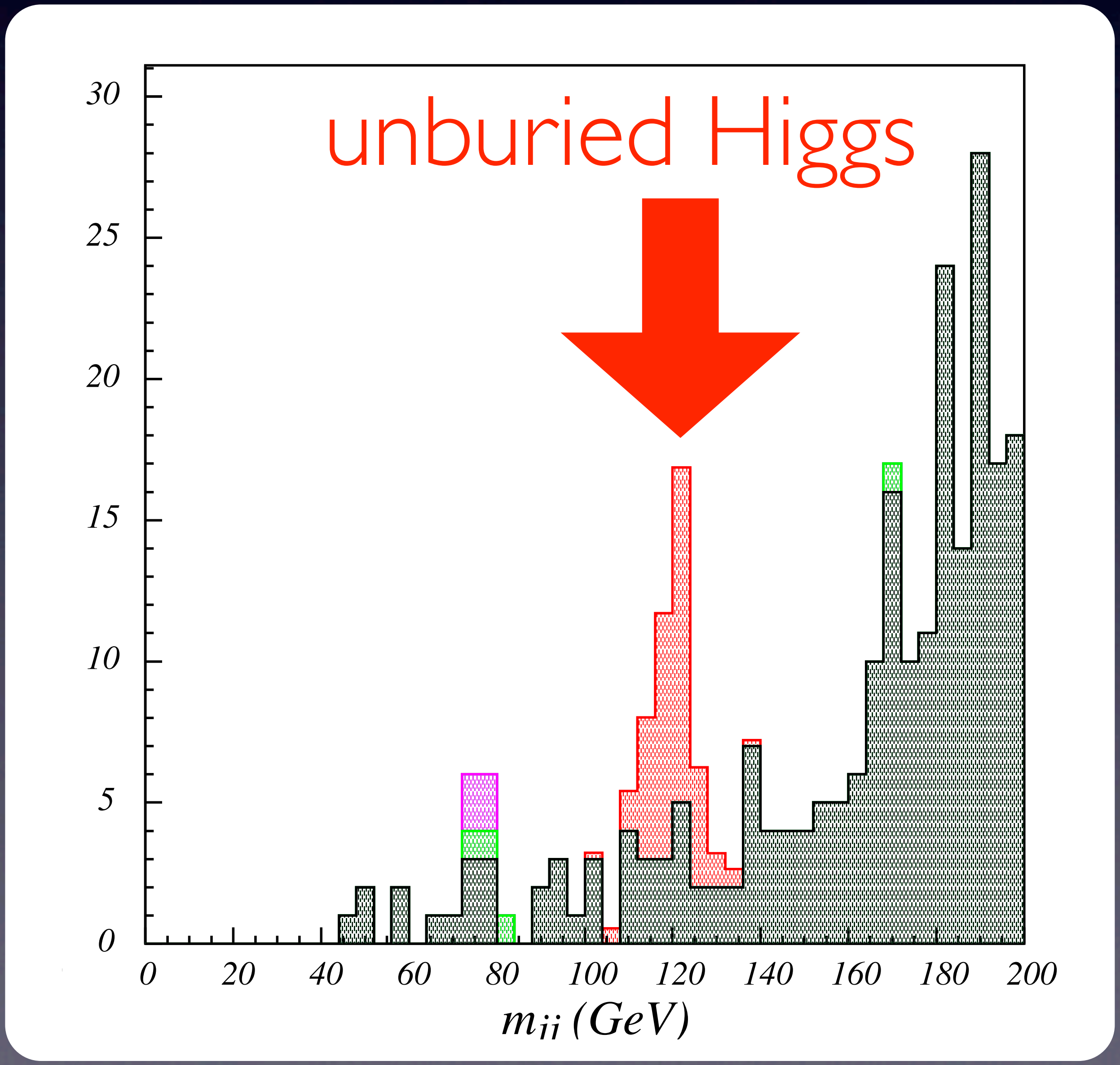


Jet Substructure II: hW→eνjj

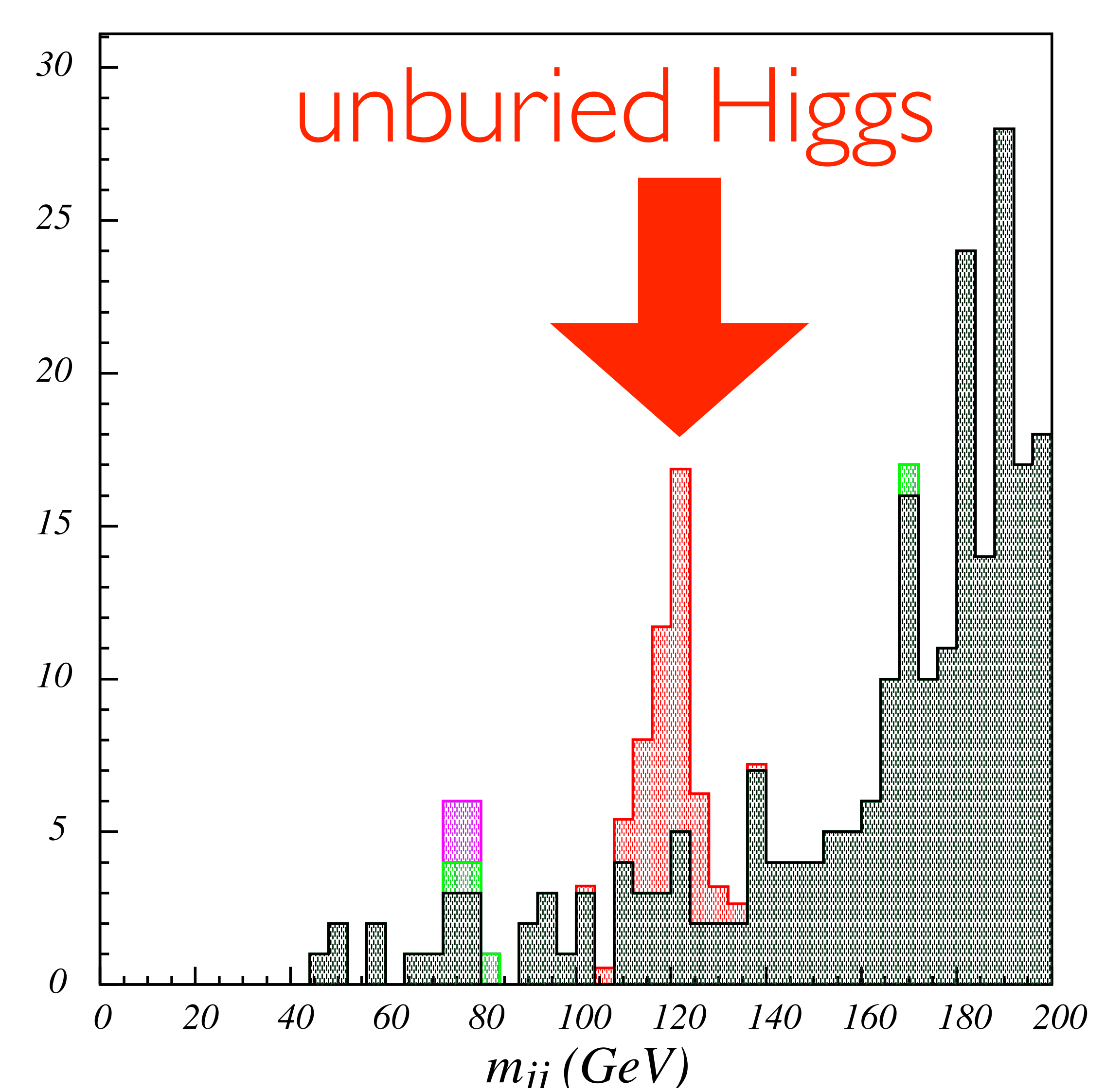
Chen, Nojiri, Sreethawong arXiv:1006.1151v1 [hep-ph]

Today on the arxiv

shown here: m_η= *4GeV* (m_η = *8GeV* slightly harder)

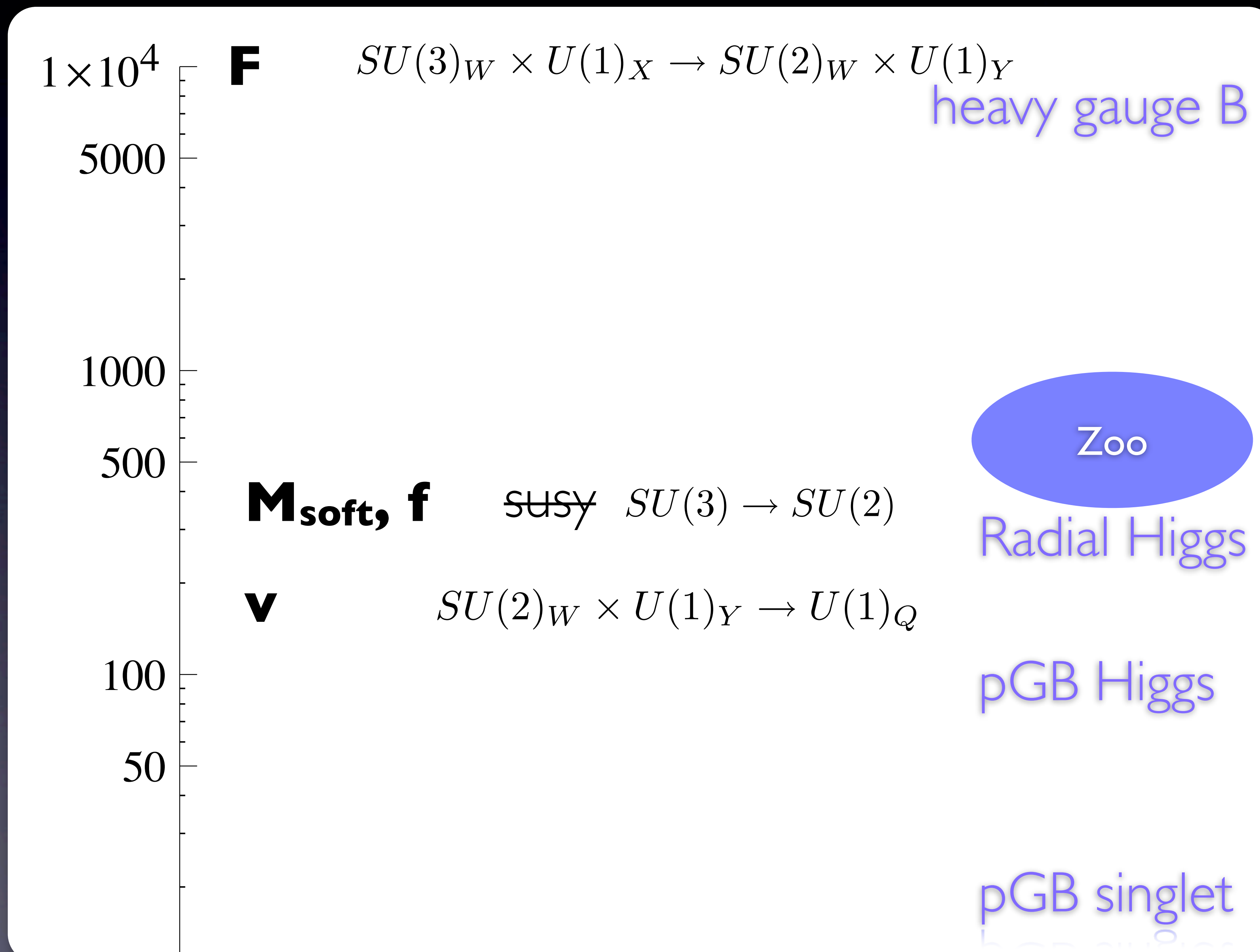
Jet algorithm	σ_S (fb)	$S/\sqrt{B}$
CA	1.13	7.09
KT	0.97	7.03

Table 4: Signal cross section and statistical significance after all cuts in the dijet invariant mass window 110 GeV $\leq m_{jj} \leq$ 130 GeV for $\mathcal{L} = 30$ fb^{-1} at the LHC.



Very rich phenomenology

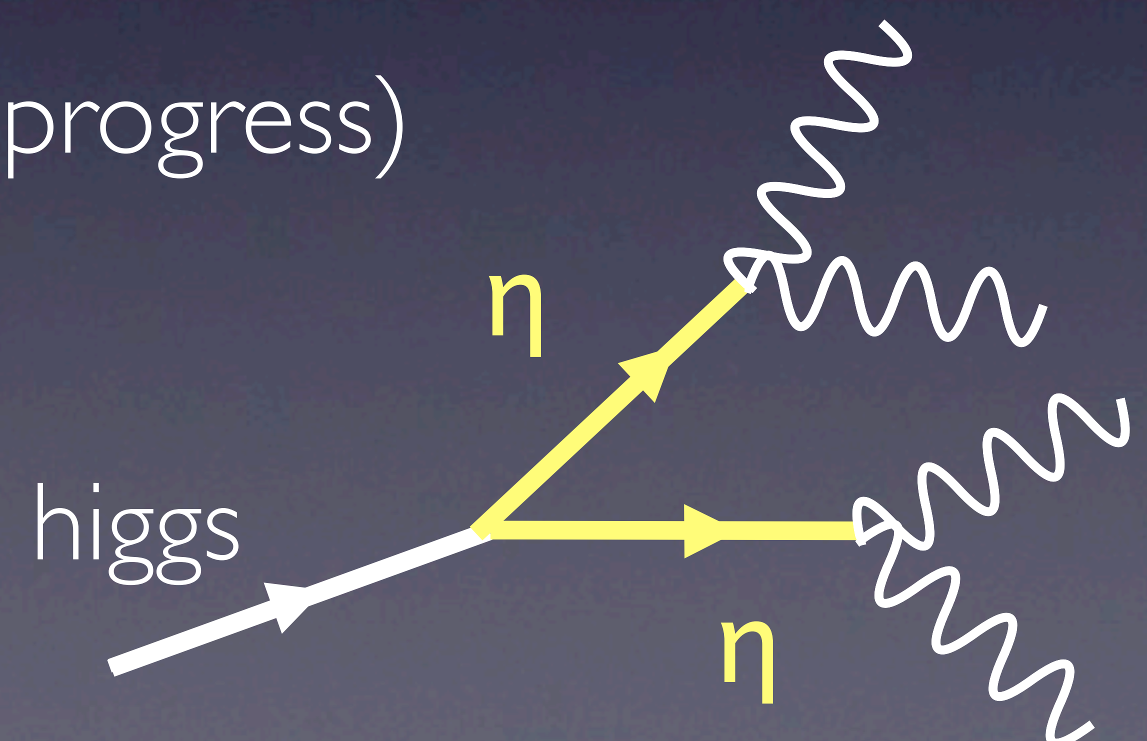
GeV



Summary

- The Higgs search is *'at risk'* because the Higgs width is very sensitive to new light unseen physics.

- Higgs can be below SM LEP bound (90 GeV)
- Higgs buried in QCD background (subjets & detailed LEP analysis in progress)
- Fake Higgs predicted



Fin

Simplest super-Little Higgs

Easiest SUSY embedding of LH is "simplest little Higgs"

Kaplan, Schmaltz '03; Schmaltz '04

Extend $SU(2)_W \times U(1)_Y$ to $SU(3)_W \times U(1)_X$

Higgs doublets become SU(3) triplets

$$H_{u,d} \rightarrow \mathcal{H}_{u,d} = (H_{u,d}, S_{u,d}) = \mathbf{3}, \bar{\mathbf{3}}$$

and receive cloned partners $\Phi_{u,d} = \mathbf{3}, \bar{\mathbf{3}}$

F-Term respects $SU(3)_1 \times SU(3)_2$ symmetry

$$\mathcal{W} = \mathcal{W}_\Phi + \mathcal{W}_\mathcal{H}$$

Symmetry breaking: Step 1

At ~ 10 TeV: $\langle \Phi_{u,d} \rangle = (0, 0, F \sim 10\,\mathrm{TeV})$

Global symmetries

$$\Rightarrow \quad SU(3)_1 \times SU(3)_2 \to SU(2)_1 \times SU(3)_2$$

Gauge symmetry

$$\Rightarrow \quad SU(3)_W \times U(1)_X \to SU(2)_W \times U(1)_Y$$

5 GB eaten by heavy gauge fields.

Step 2: pGBs

At ~ 500 GeV: $\langle \mathcal{H}_{u,d} \rangle = (0, 0, f_{u,d} \sim 500\,\mathrm{GeV})$

Global symmetries

$$\Rightarrow \quad SU(2)_1 \times SU(3)_2 \rightarrow SU(2)_1 \times SU(2)_2$$

4 + 1 Goldstone bosons. Higgs doublet H + singlet **η** :

$$\Sigma_{u,d}(\mathbf{3}_{\pm\mathbf{1/3}}) = e^{iT^a G^a} \begin{pmatrix} 0 \\ 0 \\ f_{u,d} \end{pmatrix}, \quad T^a G^a = \frac{1}{f} \begin{pmatrix} 0 & H \\ H^\dagger & \eta \end{pmatrix},$$

Step 3: SM

Higgs doublet misaligns $SU(2)_2$ and $SU(2)_W$

$$\mathcal{H}_u = (H^T, \sqrt{f^2 - |H|^2}) \sin\beta$$
$$\mathcal{H}_d = (H\ \ , \sqrt{f^2 - |H|^2}) \cos\beta$$

EWSB if $v \neq 0$. $\langle H \rangle = (0, v)$ breaks to SM

$SU(2)_W \times U(1)_Y \rightarrow U(1)_Q$

SB summary

$$\langle \Phi_{u,d} \rangle = (0, 0, F \sim 10\,\mathrm{TeV})$$

$$\Rightarrow \quad SU(3)_W \times U(1)_X \to SU(2)_W \times U(1)_Y$$

$$Y = T^8/\sqrt{3} + X$$

$$\langle \mathcal{H}_{u,d} \rangle = (0, 0, f_{u,d} \sim 500\,\mathrm{GeV})$$

$$\Rightarrow \quad SU(2)_1 \times SU(3)_2 \to SU(2)_1 \times SU(2)_2$$

$$\mathcal{H}_u = (H^T, \sqrt{f^2 - |H|^2}) \sin\beta$$

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$\langle H \rangle = (0, v)$ ⇒ $SU(2)_W \times U(1)_Y \to U(1)_Q$

SB summary

Susy dynamics

$$\langle \Phi_{u,d} \rangle = (0, 0, F \sim 10\,\mathrm{TeV})$$

$$\Rightarrow \quad SU(3)_W \times U(1)_X \to SU(2)_W \times U(1)_Y$$

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$$\langle \mathcal{H}_{u,d} \rangle = (0, 0, f_{u,d} \sim 500\,\mathrm{GeV})$$

$$\Rightarrow \quad SU(2)_1 \times SU(3)_2 \to SU(2)_1 \times SU(2)_2$$

CW 1-loop

$$\mathcal{H}_u = (H^T, \sqrt{f^2 - |H|^2}) \sin\beta$$

$$\mathcal{H}_d = (H \;, \sqrt{f^2 - |H|^2}) \cos\beta$$

$\langle H \rangle = (0, v)$ ⇒ $SU(2)_W \times U(1)_Y \to U(1)_Q$

SB summary

Susy dynamics

$$\langle \Phi_{u,d} \rangle = (0, 0, F \sim 10\,\mathrm{TeV})$$

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$\langle H \rangle = (0, v)$ ⇒ $SU(2)_W \times U(1)_Y \rightarrow U(1)_Q$

CW 1-loop

Higgs potential

Both f/F and v/f radiatively generated through bottom-top loops in Coleman-Weinberg.
Triplet potential

$$m^2_{\mathcal{H}_u} \approx -\frac{3y_2^2\sin^2\beta}{2\pi^2}M^2_{\rm soft}\log(\Lambda/M_T)$$

$$\lambda_{\mathcal{H}_u} \approx \frac{3y_2^4\sin^4\beta}{8\pi^2}\log((M^2_{\rm soft}+M_T^2)/M_T^2)$$

$(m_{Hu})^2$ finite !

$$\Delta m^2 \approx -\frac{3m_t^2}{8\pi^2 v_{EW}^2}\left[M_T^2\log\frac{M^2_{\rm soft}+M_T^2}{M_T^2}+M^2_{\rm soft}\log\frac{M^2_{\rm soft}+M_T^2}{M^2_{\rm soft}}\right]$$

physical $(m_{Higgs})^2$

$$m_h^2 = \left(1-\frac{v_{EW}^2}{f^2}\right)\left\{m_Z^2\cos^2(2\beta)+\frac{3m_t^4}{4\pi^2v_{EW}^2}\left[\log\left(\frac{M^2_{\rm soft}M_T^2}{m_t^2(M^2_{\rm soft}+M_T^2)}\right)\right.\right.$$
$$\left.\left.-2\frac{M^2_{\rm soft}}{M_T^2}\log\left(\frac{M^2_{\rm soft}+M_T^2}{M^2_{\rm soft}}\right)\right]\right\}$$

Higgs potential

Both f/F and v/f radiatively generated through bottom-top loops in Coleman-Weinberg.
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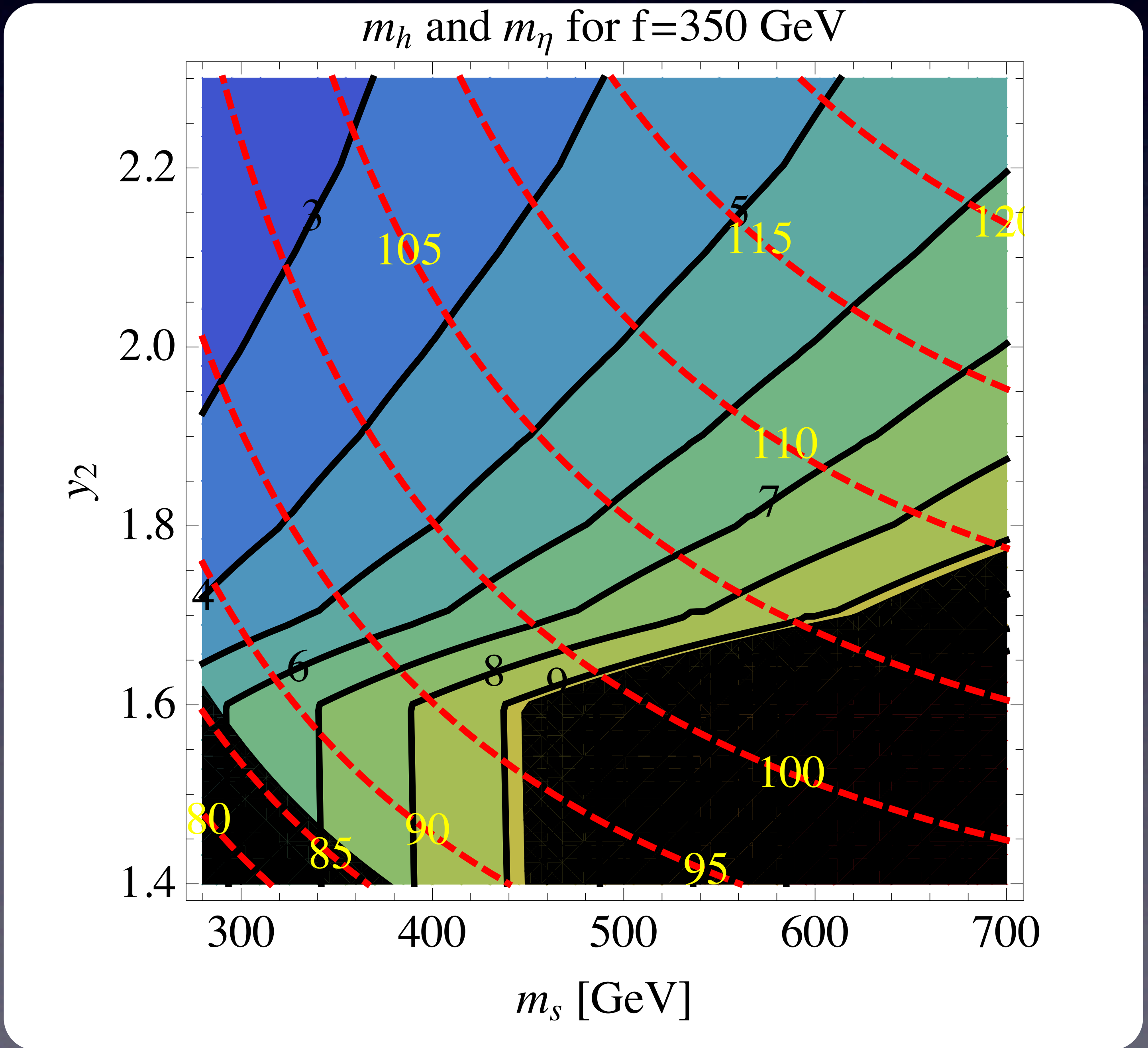
$$\Delta m^2 \approx -\frac{3m_t^2}{8\pi^2 v_{EW}^2}\left[M_T^2 \log \frac{M^2_{\text{soft}} + M_T^2}{M_T^2} + M^2_{\text{soft}} \log \frac{M^2_{\text{soft}} + M_T^2}{M^2_{\text{soft}}}\right]$$

physical $(m_{Higgs})^2$

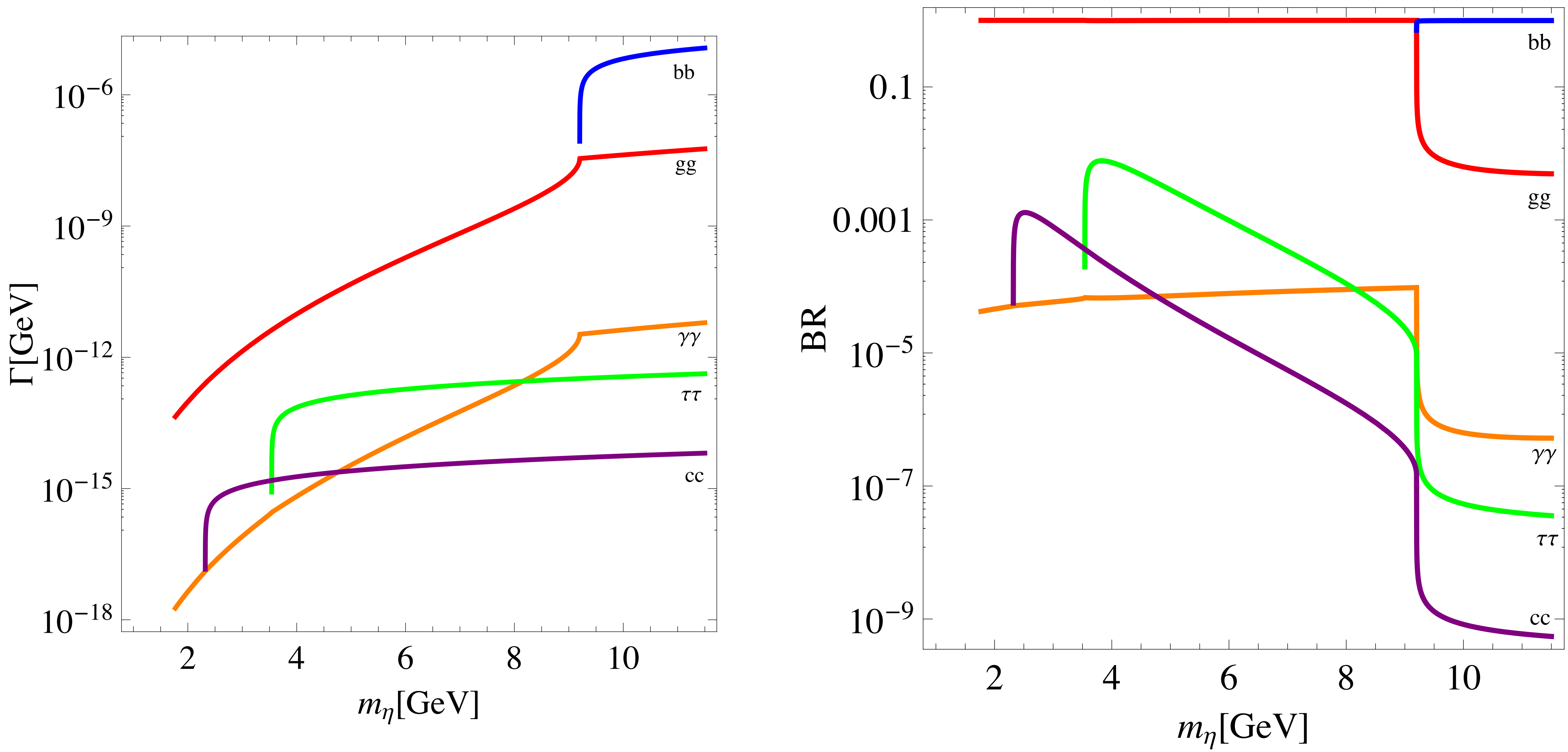
$$m_h^2 = \left(1 - \frac{v_{EW}^2}{f^2}\right)\left\{m_Z^2\cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v_{EW}^2}\left[\log\left(\frac{M^2_{\text{soft}} M_T^2}{m_t^2(M^2_{\text{soft}} + M_T^2)}\right) -2\frac{M^2_{\text{soft}}}{M_T^2}\log\left(\frac{M^2_{\text{soft}} + M_T^2}{M^2_{\text{soft}}}\right)\right]\right\}$$

Higgs potential

Both f/F and v/f radiatively generated through bottom top loops in Coleman-Weinberg, Higgs potential finite



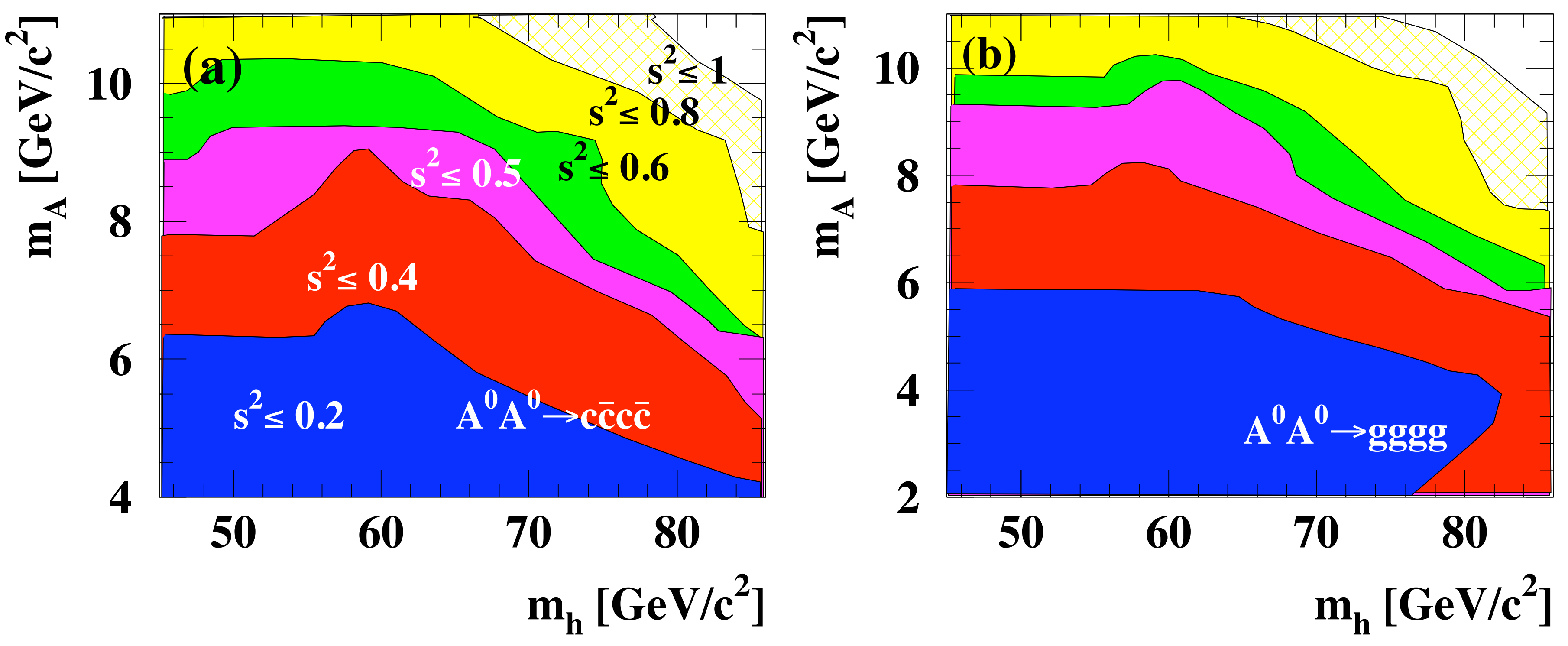
Eta decays - buried Higgs



$$\Gamma_{\eta\to gg} = (N_c^2 - 1)\frac{|\kappa^g|^2}{\pi} m_\eta^3$$

OPAL limits on h→4j

Model independent bound $m_H > 78$ GeV



s = relative Higgs production cross-section,

in our case $s = (1-(v_{ew}/f)^2) \sim 0.7$-$0.8$ and Br ~ 0.8

We need $m_{eta} > 6$ GeV otherwise $\theta_{min} \sim 4\, m_{eta}/m_H$ too small and 2-jet bound would apply.