Discovering the Higgs with Low Mass Muon Pairs

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in collaboration with

Andy Haas

Plan of the Talk

- Motivation for New Higgs Decay Modes

  Analysis of Higgs Decaying into PNGBs

  Searching for the Higgs at Hadron Colliders

  Discussion

Origin of EWSB

Major open questions:

What unitarizes WW scattering?

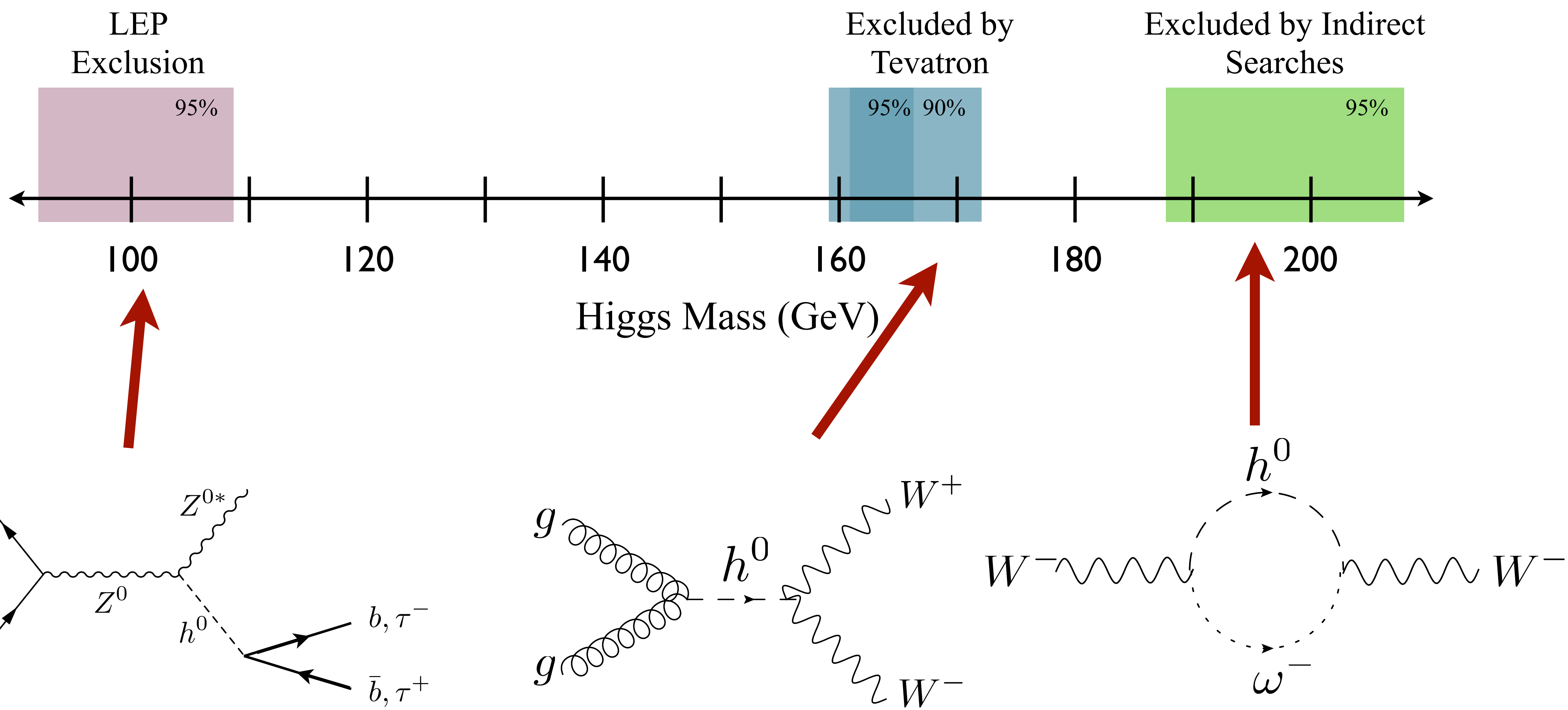
Is there only one Higgs Boson?

Is it described by the SM Higgs sector?

What stabilizes the Higgs boson mass?

Where is the Higgs Boson?

The shrinking parameter space



Tension between BSM theories and null results

Most BSM predicts light Higgs

Higgs mass < 120 GeV

LEP Limit usually leads to Little Hierarchy Problem (1 - 10% fine tuning)

Radiative corrections to Higgs mass parameter 10 - 100 times actual size

Tension is between solving the Hierarchy Problem & Higgs Mass

$$\Lambda \sim M_{\rm GUT}$$

Higgs is

A.) An elementary scalar (i.e. susy)

quartic coupling is IR free and runs weak

B.) A Goldstone Boson (i.e. Little Higgs or A_5)

quartic generated radiatively off SM couplings

C.) A strongly interacting composite (RS, fat Higgs)

quartic is large, but usually Flavor/Precision EW problems

$$M_{\rm composite} \sim 10 - 30 \text{ TeV}$$

The Susy Higgs Mass Problem

$$m_{h^0}^2 = 2\lambda v^2 = -2\mu^2$$

$$V_{\rm Higgs} = \lambda |H|^4 + \mu^2 |H|^2$$

The Susy Higgs Mass Problem

$$m_{h^0}^2 = 2\lambda v^2 = -2\mu^2$$

$$\lambda_{\rm susy} = \frac{1}{8}\left(g^2 + g'^2\right)\cos^2 2\beta$$

$$m_{h^0} \leq M_{Z^0}$$

The Susy Higgs Mass Problem

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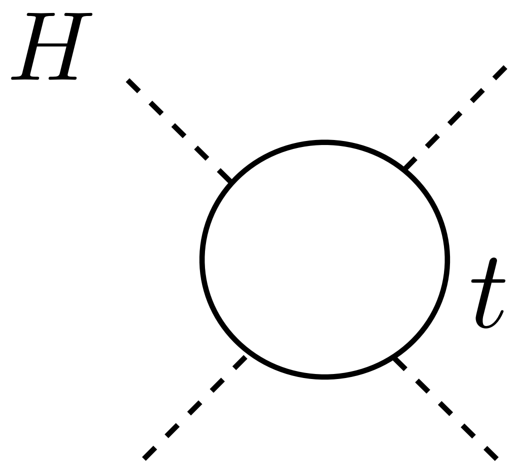
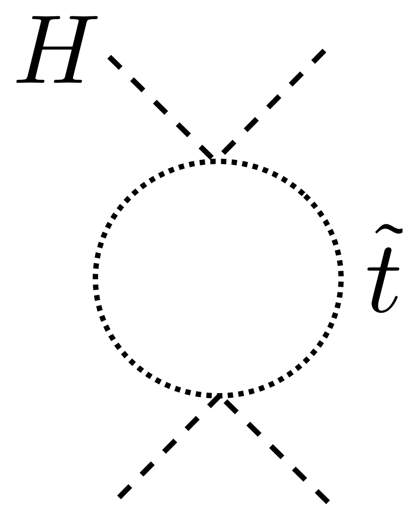
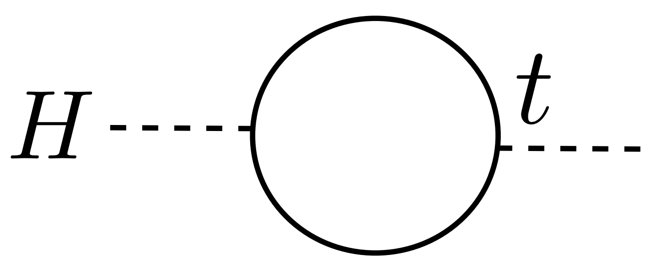
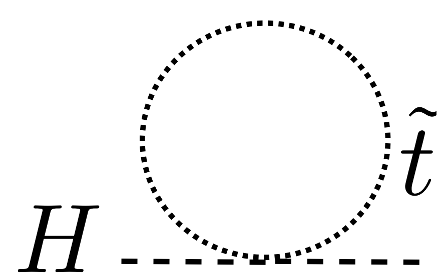




$$\delta\lambda = \frac{3y_{\rm top}^4}{8\pi^2}\log\frac{m_{\rm stop}}{m_{\rm top}}$$





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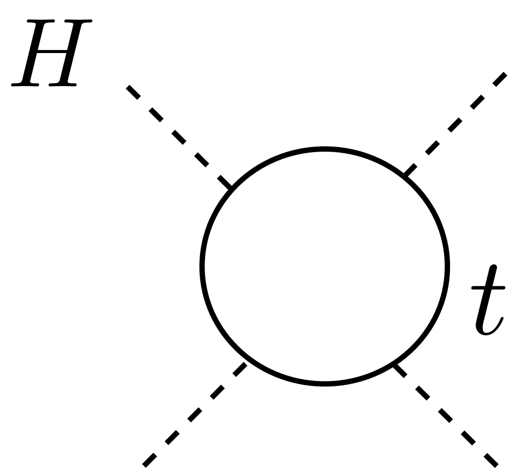

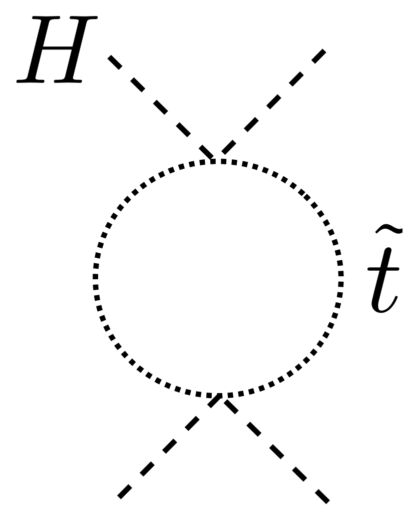

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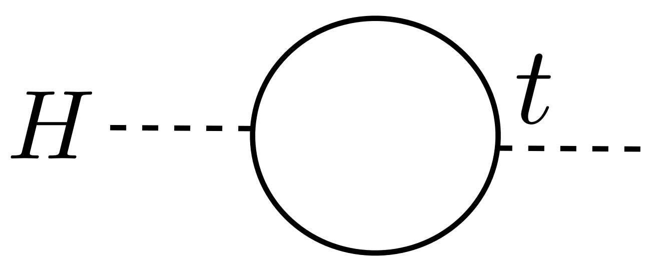
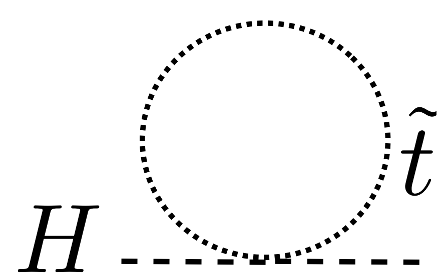




$$\delta\mu^2 = -\frac{3y_{\text{top}}^2}{8\pi^2}m_{\text{stop}}^2$$

Higgs mass gain is only log

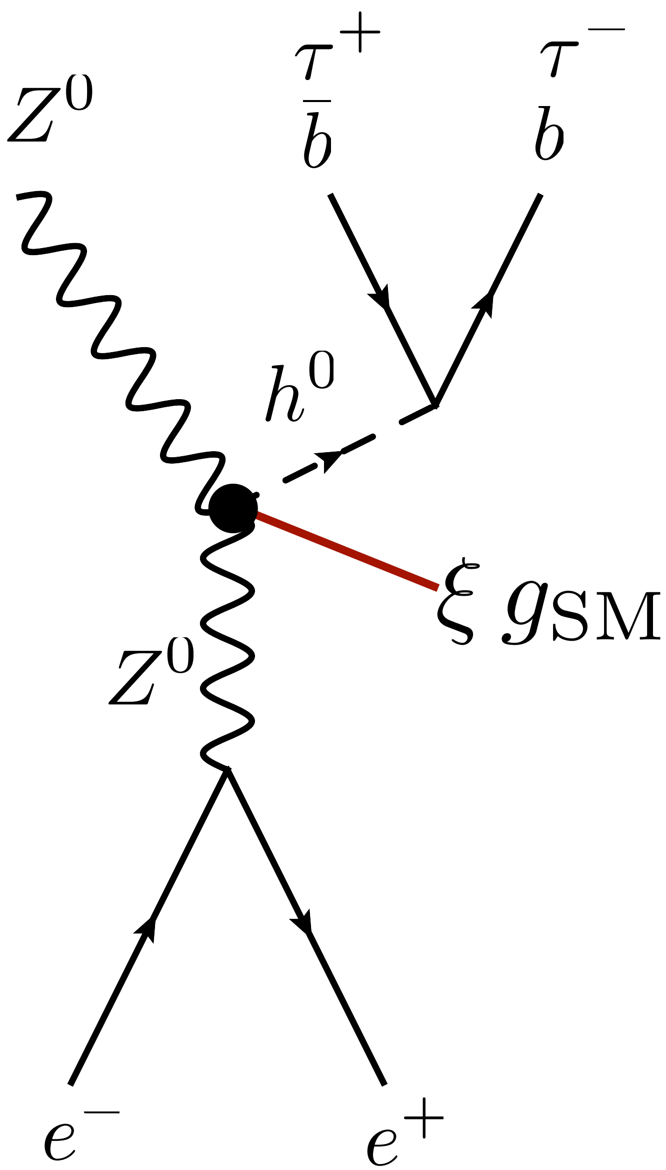
Fine tuning loss is quadratic

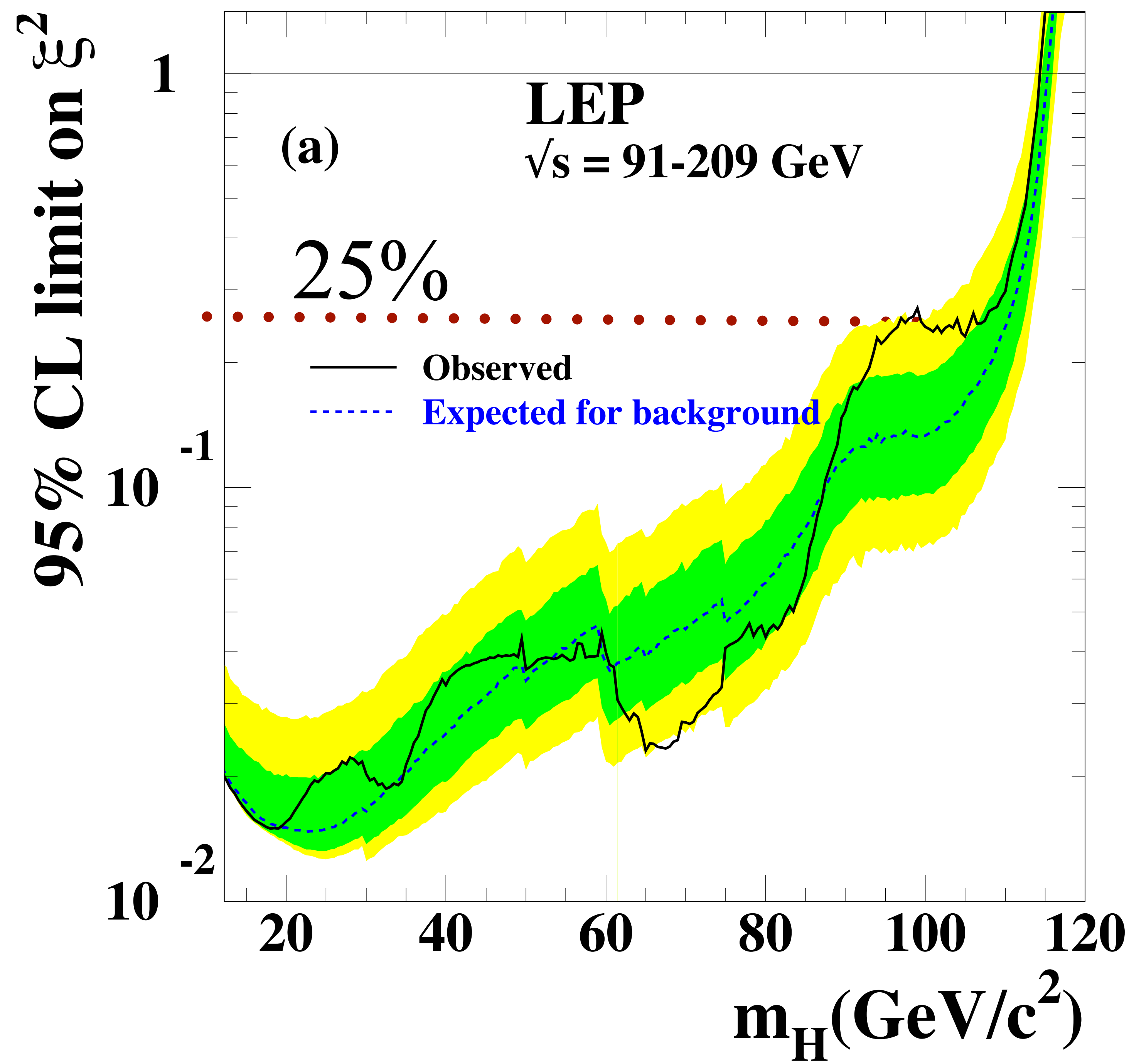
$$\text{FT} \sim \frac{m_{h^0}^2}{\delta\mu^2}$$

Every 5 GeV in Higgs mass needs a doubling of stop mass

Could the Higgs be lighter than LEP Limit?

Examine SM Higgs Limit

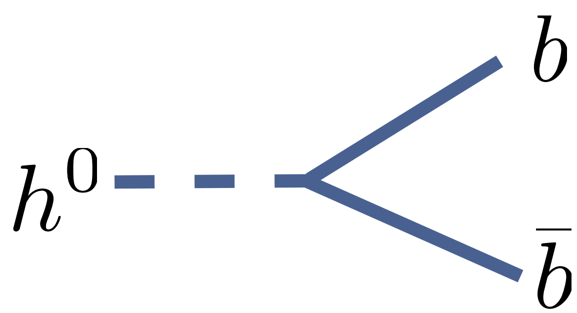




Could dilute SM decay modes

If there is BSM Physics, Higgs discovery can be easily altered

ξ interpreted as a limit on SM BR of Higgs



$$\frac{\Gamma_{h^0\ \mathrm{SM}}}{m_{h^0}} = \frac{3m_b^2}{4\pi v^2} \sim 10^{-4}$$

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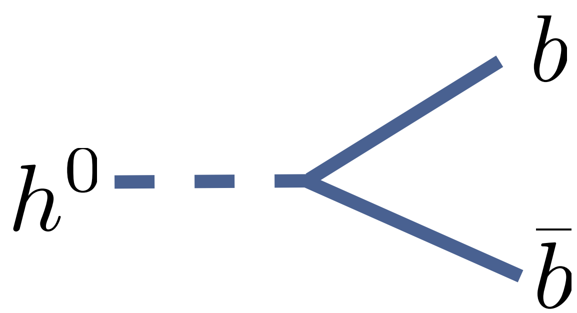

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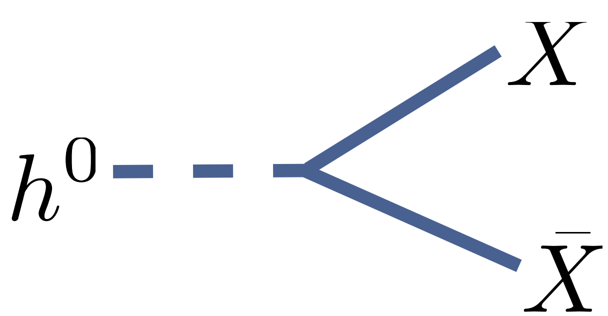
New physics could open up unsuppressed decay channels



$$\frac{\Gamma_{h^0\ \mathrm{BSM}}}{m_{h^0}} = \frac{g^2_{hX\bar{X}}}{4\pi} \sim 10^{-2}$$

$$\mathrm{Br}(h^0 \to \mathrm{SM}) \sim 10^{-2}$$

Existing search strategies could be ineffective

A concern up to *WW* threshold

New Decay Mode Caveat

LEP2 performed extensive searches for new decay modes

$h^0 \to \gamma\gamma$		$m_h > 110$ GeV
$h^0 \to$ Invisible		$m_h > 110$ GeV
$h^0 \to jj$		$m_h > 110$ GeV
$h^0 \to s^0 s^0$	$s^0 \to b\bar{b}$	$m_h > 110$ GeV
	$s^0 \to \tau^+\tau^-$	$m_h > 86$ GeV
$h^0 \to$ Anything		$m_h > 82$ GeV

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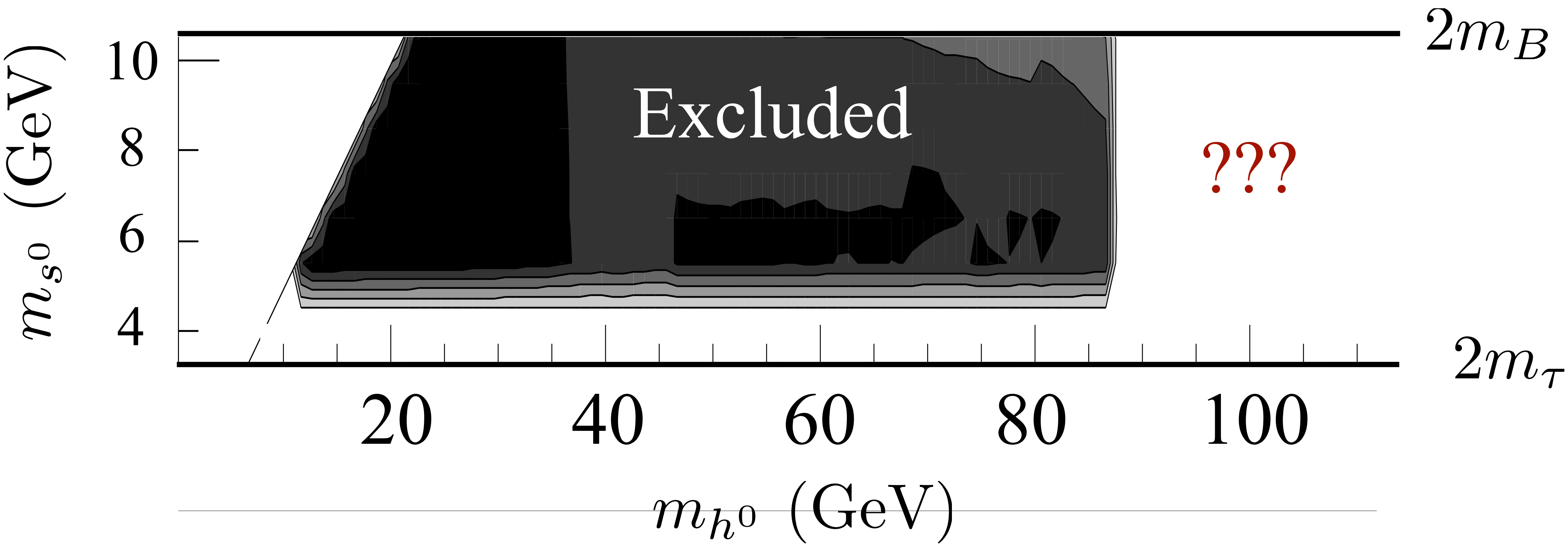
4τ Hole

$$h^0 \to s^0 s^0 \to (\tau\tau)(\tau\tau)$$

LEP2 stopped looking above 86 GeV

Until recently (Kyle Kramner)



Difficult to discover at Hadron colliders

But how likely is this scenario?

Plan of the Talk

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NMSSM

Singlet extension of the MSSM

$$\int d^2\theta \;\; \lambda S H_u H_d - \kappa S^3$$

$$V_{\rm Susy} = \lambda^\dagger \kappa \; s^2 h_u^\dagger h_d^\dagger + |\lambda|^2 |h_u|^2 |h_d|^2 \cdots$$

Can make Higgs heavier $\delta\lambda_{\rm eff} = \frac{|\lambda|^2}{4} \sin^2 2\beta$

Solves the μ & B_μ problems

$$\mu = \lambda \langle s \rangle \qquad B_\mu = \lambda^\dagger \kappa \langle s \rangle^2$$

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Solves the μ & B_μ problems

$$\mu = \lambda \langle s \rangle \qquad B_\mu = \lambda^\dagger \kappa \langle s \rangle^2$$

If Soft Susy breaking A-terms vanish

$$V_{\rm Soft} = a_\lambda \; s h_u h_d + a_\kappa \; s^3 + \cdots$$

U(1)$_{\rm R}$ symmetry appears $\;\phi \to e^{i\alpha}\phi$

(all scalars fields have same charge)

vevs spontaneously break symmetry: a Goldstone boson

NMSSM Gauge Mediation

small A-terms (generated from gaugino masses)

$$a_\lambda \simeq \frac{g^2}{16\pi^2}\lambda\, m_{\tilde{w}} \lesssim 1 \text{ GeV}$$

Approximate Goldstone Bosons

$$m^2_{a^0} \simeq a_\lambda \frac{v^2}{\langle s \rangle} \simeq \text{few GeV}$$

Interacts like A^0 in MSSM -- Higgs can decay into a^0

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Interacts like A^0 in MSSM -- Higgs can decay into a^0

Decays to heaviest fermions available

$$\text{Br}(a^0 \to \bar{f} f) \propto N_c m_f^2 \begin{cases} 1 & \text{down quarks and leptons} \\ \frac{1}{\tan^4\beta} & \text{up quarks} \end{cases}$$

Primarily to taus if beneath bottom threshold

Opens up Higgs to 4 Tau as dominant Higgs decay mode

EWSB/Higgs sector is extended

↓

Additional approximate symmetries

↓

Light PNGBs

↓

New Higgs decay modes

Not a complicated story!

Can make this story tighter

1 Higgs Doublet: No Go

Need at least one more complex scalar

Simplest example is a singlet

$$V = V(|H|^2, S)$$

Can't have Higgs and singlet charged under same global symmetry

e.g. $$V = (\mu^2 + \lambda |H|^2)|S|^2 \to (\mu^2 + \lambda v^2 + v h^0)|S|^2$$

Width and mass are related unless mass is fine tuned

$$\Gamma(h^0 \to SS) \sim \frac{m_S^4}{4\pi v^3}$$

Can't make into dominant decay mode if *S* is light

Minimal Model: 2 HDM + Singlet

(Has pure 2HDM as a limit)

3 U(1) Symmetries   Hypercharge + 2 Global

H_u H_d S

3 Pseudoscalars

Eaten Z^0 Goldstone   Active A^0 Inert a^0

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Use Exponential basis for pseudoscalars

$$H_u \sim v \sin\beta \, e^{ia_u/vs_\beta} \qquad H_d \sim v \cos\beta \, e^{ia_d/vc_\beta} \qquad S \sim s \, e^{ia_s/s}$$

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Symmetric terms are independent of pseudoscalars

Globally invariant terms

$V_0 \sim |\phi|^2, |\phi|^4$ Gives mass to non-PNGBs and EWSB

Higgs Potential

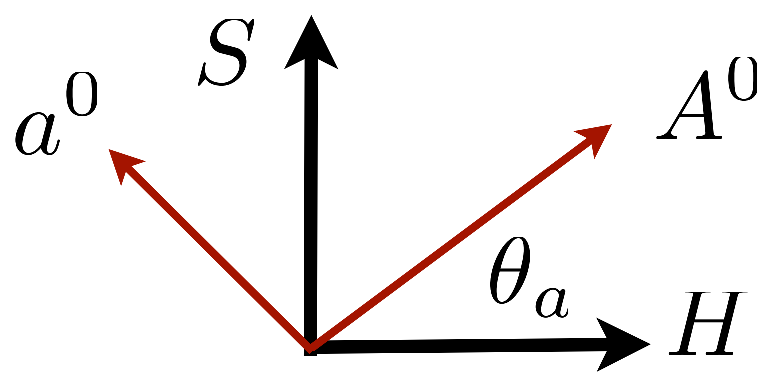
Explicit breaking of 1st U(1)

$$V_1 = \lambda_1 S^2 H_u^\dagger H_d^\dagger + \text{ h.c.}$$

Gives mass to A^0

Mixes singlet and Higgs eigenstates

Defines mixing angle between active and inert pseudoscalars



$$\tan\theta_a = \frac{v}{\langle S\rangle}\sin 2\beta$$

$\theta_a \to 0$ A^0 active, a^0 inert

Leaves a^0 massless

Determines all coupling not suppressed by m_{a^0}

Higgs Potential

Need explicit breaking of 2nd U(1)

Lots of choices

$$V_2 = \lambda_2 S^2 H_u H_d + \text{ h.c.} \qquad V_{2'} = \lambda_{2'} S^4 + \text{ h.c.}$$

Gives mass to a^0

$$m_{a^0}^2 \sim \lambda_2 s^2 \sin^2\theta_a \qquad m_{a^0}^2 \sim \lambda_{2'} s^2 \cos^2\theta_a$$

Need a hierarchy between

$$\lambda_1 \gg \lambda_2, \lambda_{2'}$$

Determines symmetry breaking couplings

If a^0 is naturally light, these couplings are small!

Higgs Decaying Into PNGBs

Exists for exact Goldstones

$$\mathcal{L}_{\rm int} = \frac{c_h}{v}\, h^0 \partial_\mu a^0 \partial^\mu a^0$$

Symmetry preserving $\quad a^0 \to a^0 + \epsilon$

$$c_h = \sin^2\theta_a \qquad \sin\theta_a = \frac{v \sin 2\beta}{\sqrt{s^2 + v^2 \sin^2 2\beta}}$$

Max size at $\sin\theta_a = 1 \quad \frac{h^0}{v}(\partial a^0)^2$

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Max size at $\sin\theta_a = 1 \quad \frac{h^0}{v}(\partial a^0)^2$

$\frac{v}{\sin\theta_a}$ acts as Goldstone decay constant

$$f_{a^0} \to \begin{cases} s/\sin 2\beta & s \gg v \\ v & v \gg s \end{cases}$$

Higgs Decaying Into PNGBs

Symmetry violating decay terms

$$\mathcal{L}_{\rm int} = \frac{c_h}{v}\ h^0\partial_\mu a^0\partial^\mu a^0 + \frac{d_h}{v}m_{a^0}^2\ h^0a^0a^0$$

Acts like any other field acquiring mass from Higgs boson

$$d_h = 1 \qquad \lambda_2 \gg \lambda_{2'}$$

Previous works conflated c_h & d_h

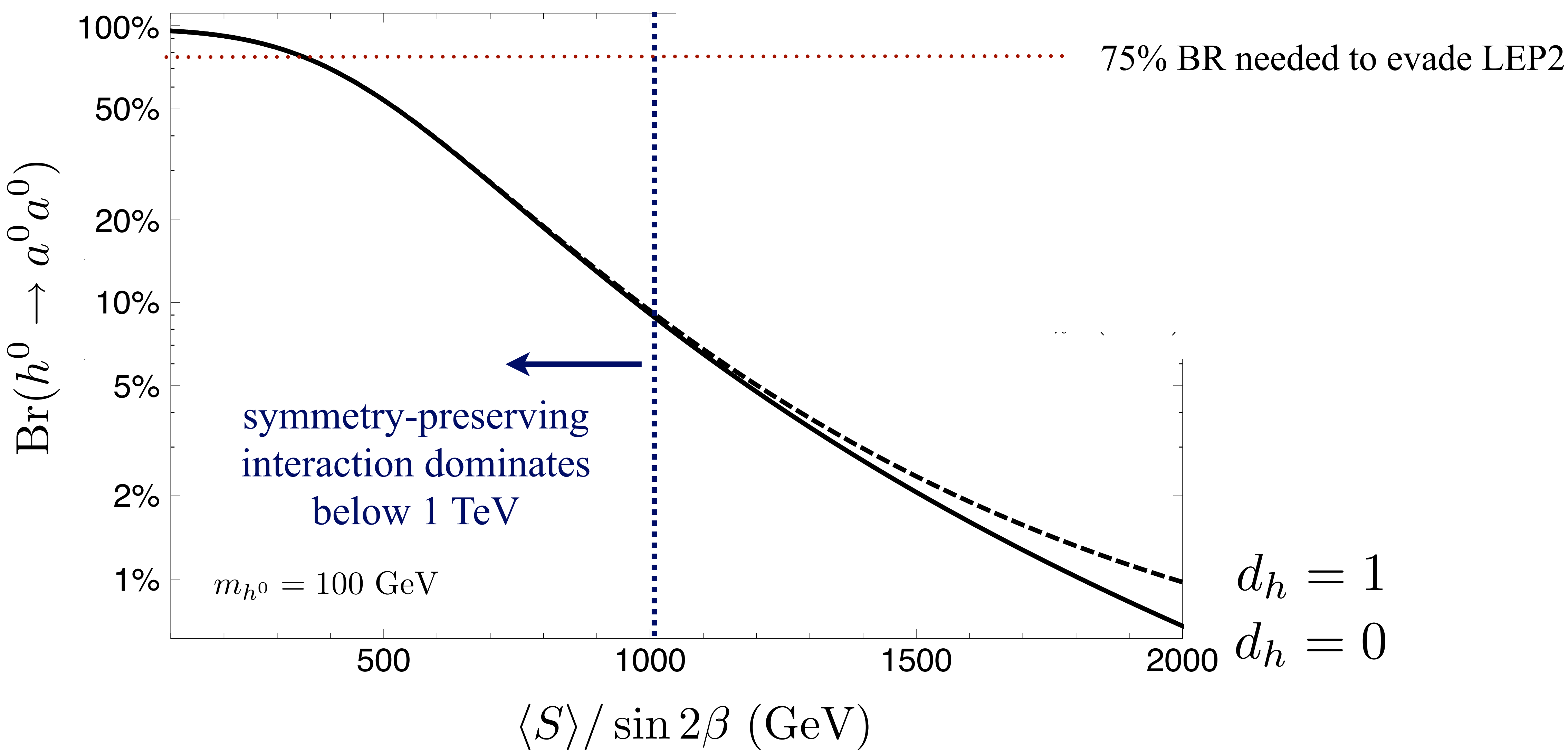
Scans often found fine-tuned regions where $d_h >> 1$

Replacing one 1% tuning with another 1% tuning

Branching Fraction to a^0

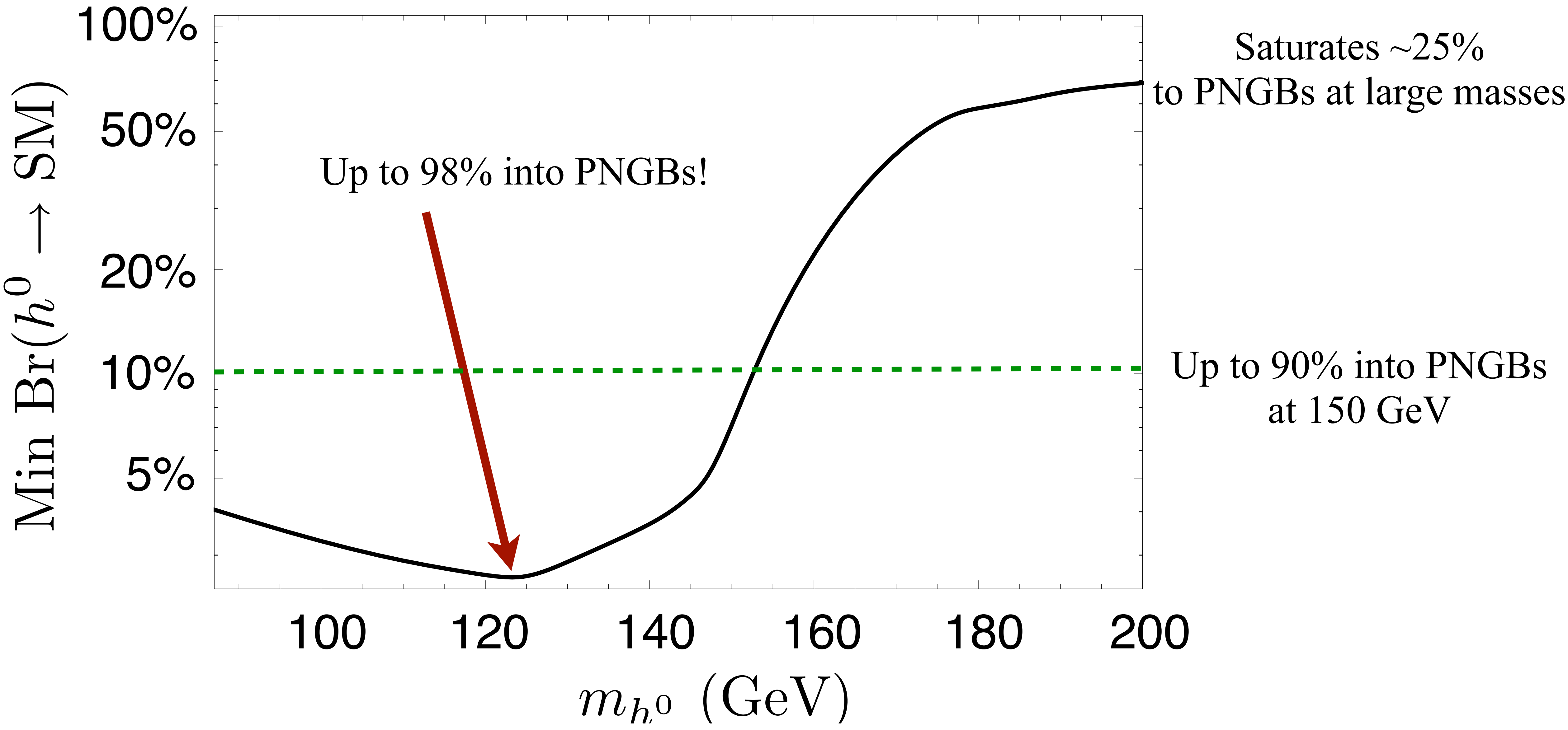
$$\frac{\Gamma_{h^0 \to a^0 a^0}}{m_{h^0}} \sim \frac{c_h^2 m_{h^0}^4}{v^4} + \frac{d_h^2 m_{a^0}^4}{v^2 m_{h^0}^2}$$

Symmetry preserving decays dominate moderate $\langle S \rangle$ unless a^0 fine tuned light



Swamping of SM Decay Modes

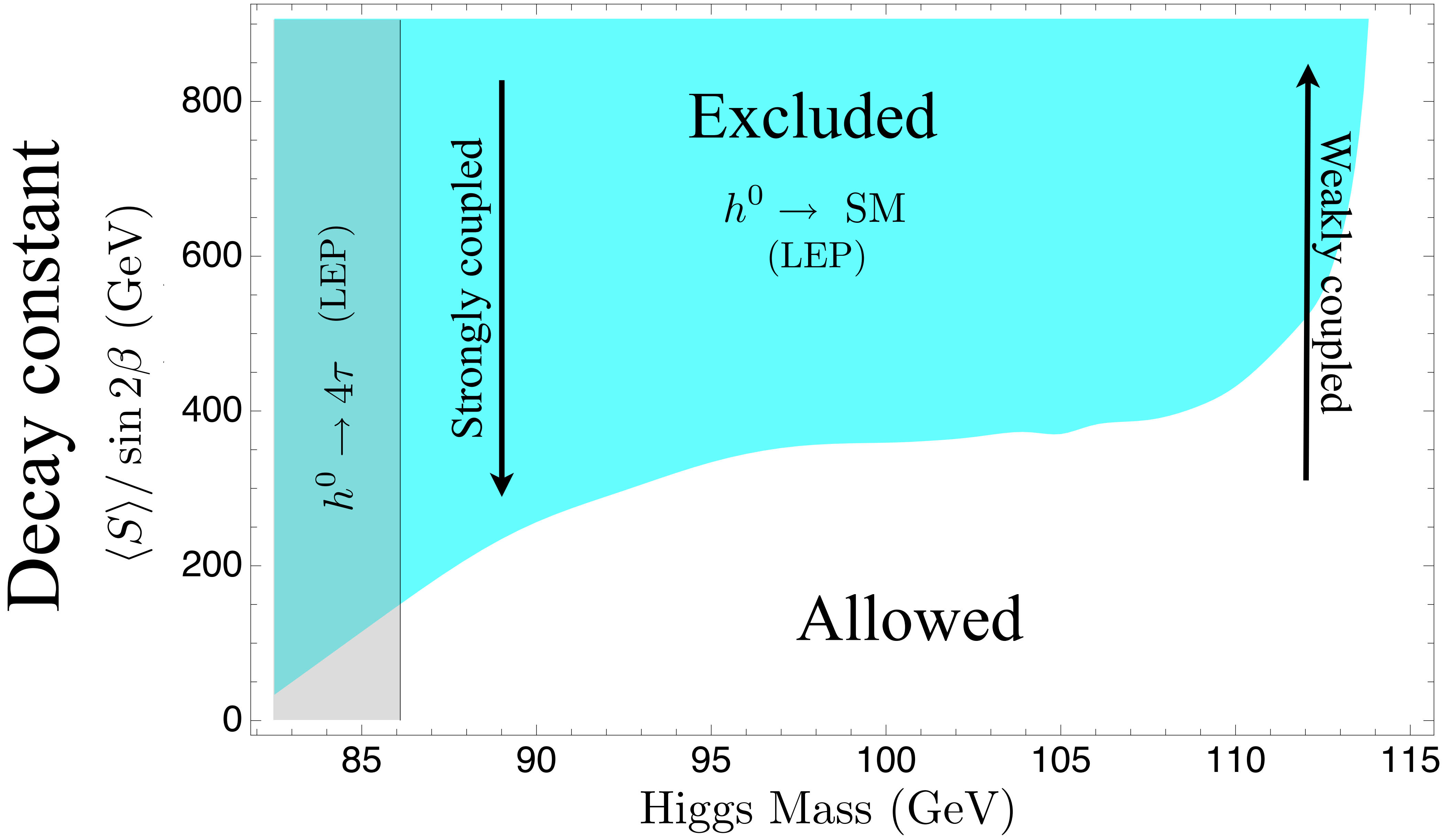
Not only a problem for a light Higgs boson



Living Beneath 114 GeV...

Need a large BR into a^0s and $3.5 \text{ GeV} \leq m_{a^0} \leq 9.5 \text{ GeV}$

$m_{h^0} \leq 114 \text{ GeV}$ and may be less fine tuning



Coupling to SM Fermions

$$\mathcal{L}_{\text{int}} = i g_f \frac{m_f}{v} \bar{f} \gamma_5 f a^0$$

$$g_f = \sin\theta_a \begin{cases} \cot\beta & \text{(up-type quarks)} \\ \tan\beta & \text{(down-type quarks/leptons)} \end{cases}$$

← suppressed by 2 powers of $\tan\beta$

$$\sin\theta_a \sim \frac{v}{\langle S \rangle \tan\beta}$$

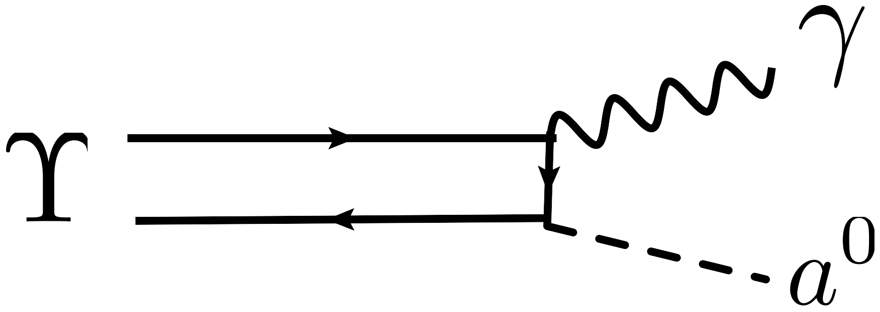
Need strong coupling to Higgs to get large decay width

Small $\langle S \rangle \rightarrow$ strong coupling of a^0 to fermions

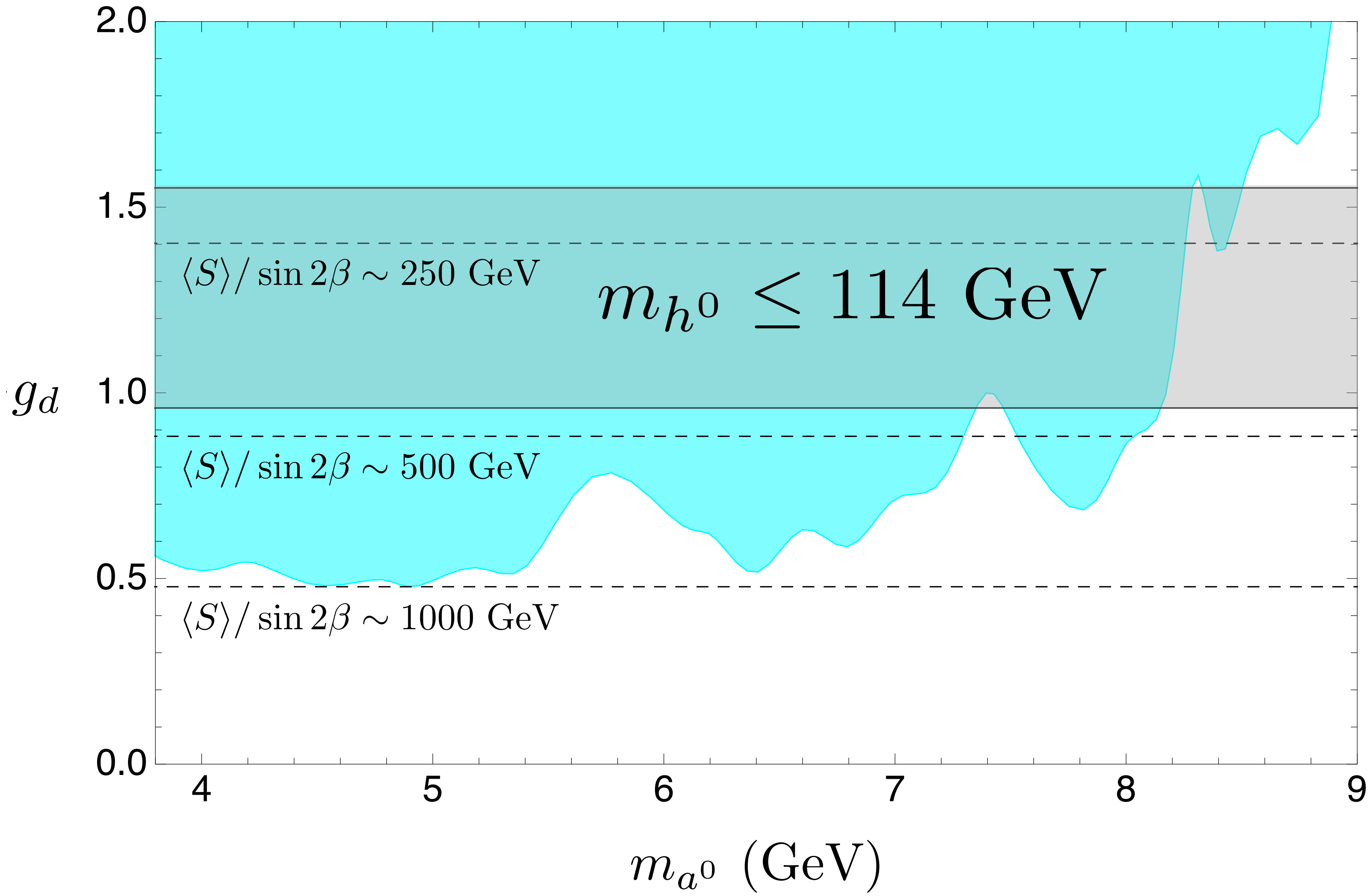
Possible constraints from heavy flavor physics

Direct a^0 searches

CLEO places bounds on a^0 coupling



$$\frac{\mathrm{Br}(\Upsilon \to a^0\gamma)}{\mathrm{Br}(\Upsilon \to \mu^+\mu^-)} = \frac{G_F m_\Upsilon^2}{4\sqrt{2}\pi\alpha} g_d^2$$



Becoming constrained

unless explicit symmetry breaking decays

1% tuning of a^0 mass

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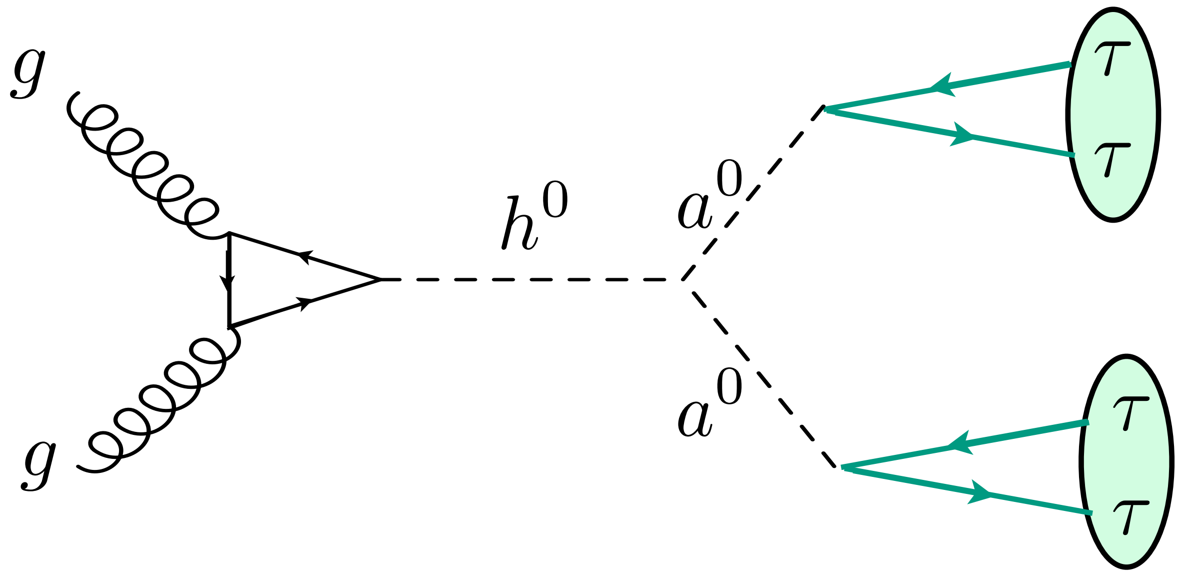
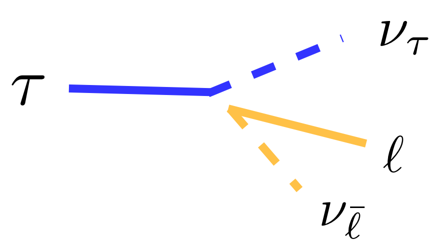
Finding the Higgs if $2m_\tau \leq m_{a^0} \leq 2m_b$

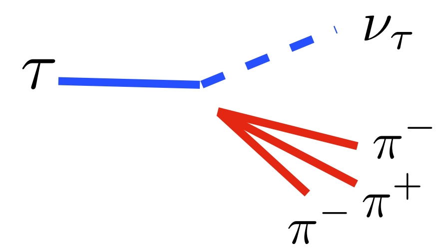
Hadron machines: make a lot of Higgs bosons, but difficult to see

Dominant decay mode is $h^0 \to (\tau^+\tau^-)(\tau^+\tau^-)$





35%



65%

A heterogenous decay mode!

$\mathrm{Br}(\tau\tau)$	$\tau_h\tau_h$	$\tau_h\ell$	$\ell\ell$
$\tau_h\tau_h$	17.6%	38.0%	10.4%
$\tau_h\ell$		20.4%	11.2%
$\ell\ell$			1.5%

4τ at the Tevatron

w/ A. Pierce & P. Graham (2006)

Associated Higgs production is rate starved up to 10/fb

Gluon production has challenging backgrounds

Focus on opposite flavor dileptons

	$\tau_h\tau_h$	$\tau_h\ell$	$\ell\ell$
$e\mu$	5.2%	5.6%	0.8%

.

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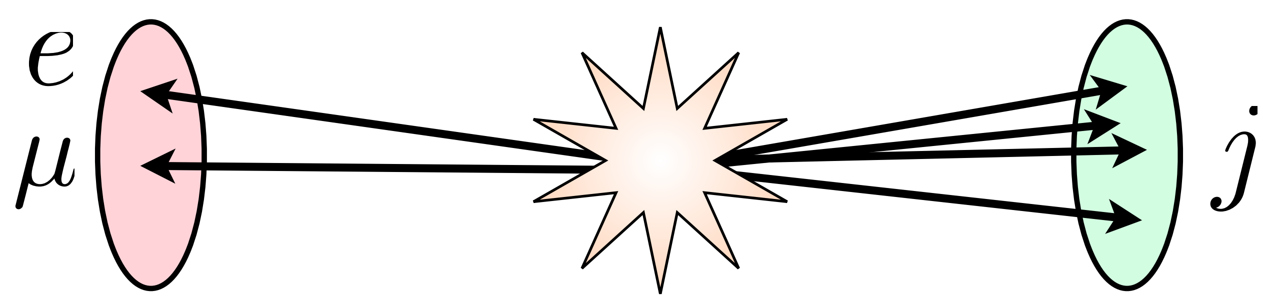
	$\tau_h\tau_h$	$\tau_h\ell$	$\ell\ell$
$e\mu$	5.2%	5.6%	0.8%

$$E_\ell \leq \frac{1}{12} m_{h^0} \qquad 3 \text{ GeV} \lesssim p_{T\ell} \lesssim 10 \text{ GeV}$$



Isolated opposite flavor pair

low track multiplicity jet

Similar to b-jets - might be able to pull out

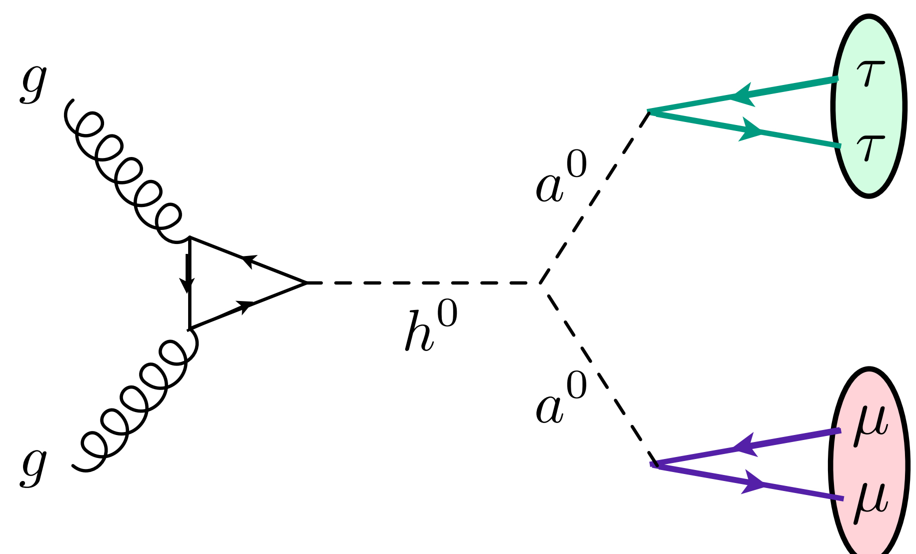
Using a Subdominant Decay Mode

Always have coupling to muons

$$\frac{\Gamma(a^0 \to \mu^+\mu^-)}{\Gamma(a^0 \to \tau^+\tau^-)} = \frac{m_\mu^2}{m_\tau^2 \sqrt{1-(2m_\tau/m_{a^0})^2}}$$

For 7 GeV a^0:

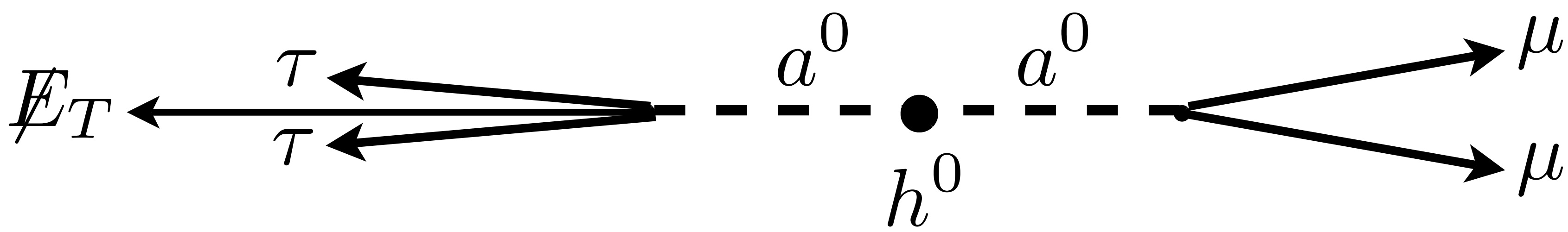
$$\mathrm{Br}(a^0 \to \mu^+\mu^-) = 0.4\%$$
$$\mathrm{Br}(a^0 \to \tau^+\tau^-) = 98\%$$



$$\mathrm{Br}(h^0 \to (\mu\mu)(\tau\tau)) \sim 0.8\%$$

Large gluon fusion production cross section overcomes small branching fraction to muons

Geometry of Decays



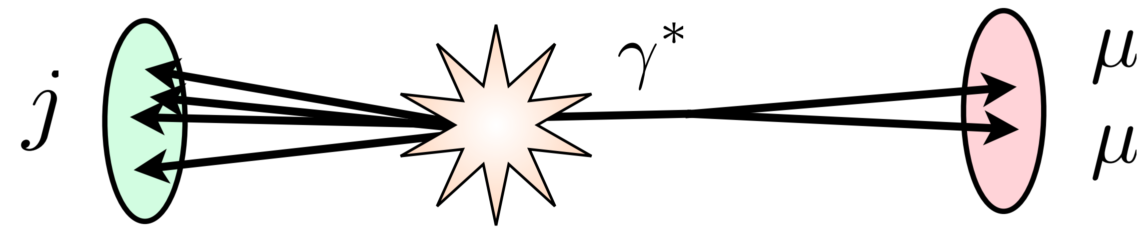
MET pointing away from muons

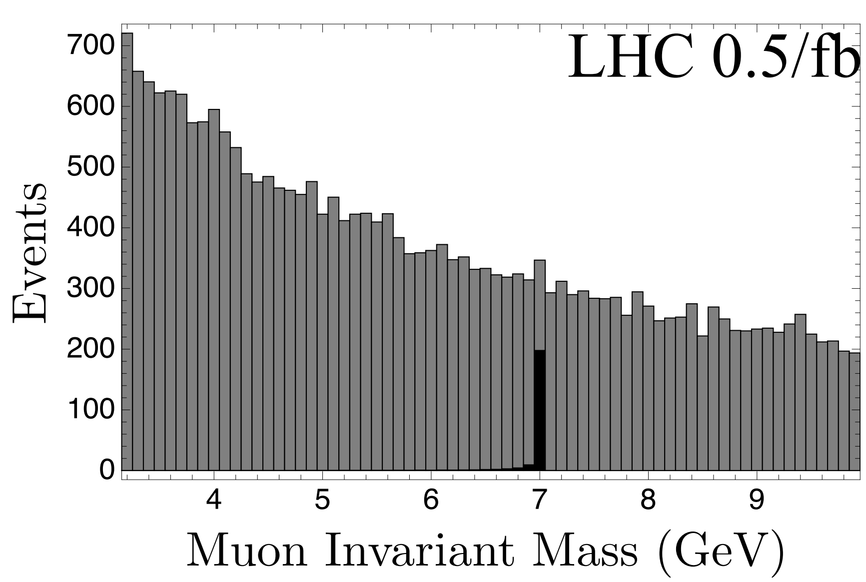
Higgs mass reconstructable

Mass of a^0 reconstructed

High p_T muons $p_T \gtrsim 15$ GeV

Dominant Background in Drell-Yan + Jet





Continuum background: S/B ~ 1/few

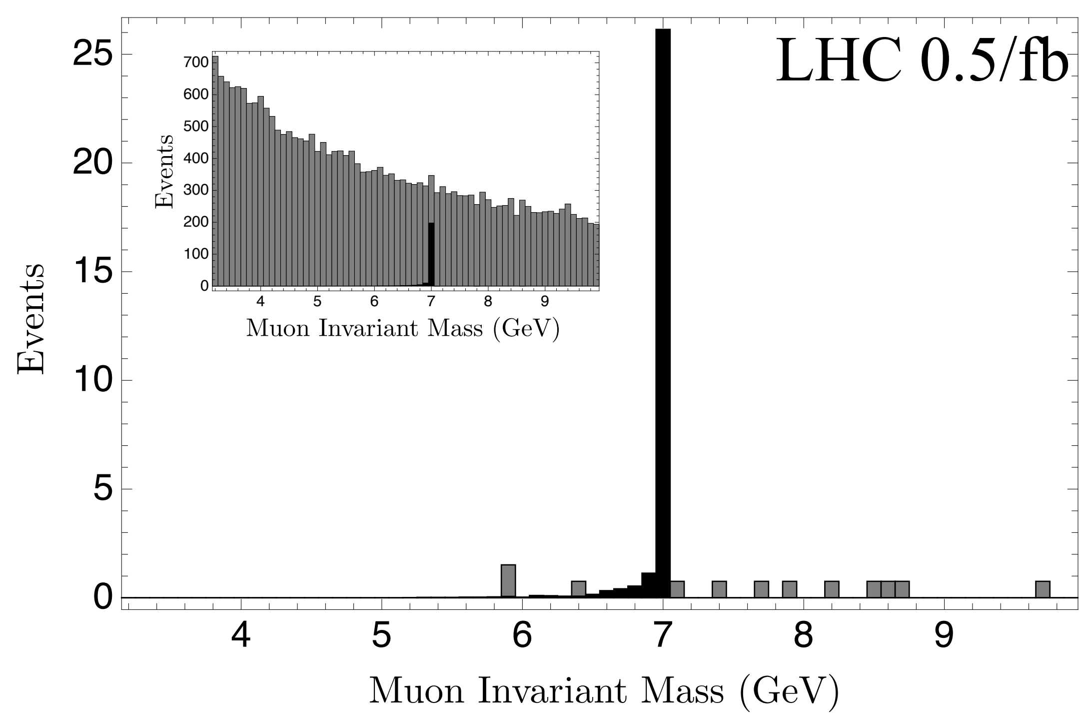
Modest MET cut reduces to S/B ~ few

Clean up Cuts

	Signal Efficiency	
Selection Criteria	Relative	Cumulative
Pre-Selection Criteria	26%	26%
Jet veto	99%	26%
Muon iso & tracking	$\sim$ 50%	13%
$M_{\mu\mu} < 10$ GeV	98%	13%
$p_T^{\mu\mu} > 40$ GeV	76%	9.8%
$\not{E}_T > 30$ GeV	29%	2.8%
$\Delta\phi(\mu, \not{E}_T) > 140°$	73%	2.1%
$\Delta R(\mu, \mu) > 0.26$	63%	1.8%

Efficiencies from PGS

Enough striking characteristics to be very clean channel



Continuum Backgrounds after cuts

$$\frac{d\sigma}{dM_{\mu\mu}}$$

fb/GeV	TeV	LHC
DY+j	0.15	0.24
W^+W^-	0.03	0.08
$t\bar{t}$	0.02	0.14
$b\bar{b}$	$\lesssim 0.001$	~ 0.03
$\Upsilon + j$	0.001	0.002
$\mu\mu+\tau\tau$	$\ll 0.001$	$\lesssim 0.001$
$J/\psi + j$	$\ll 0.001$	$\ll 0.001$
Total	0.20	0.49

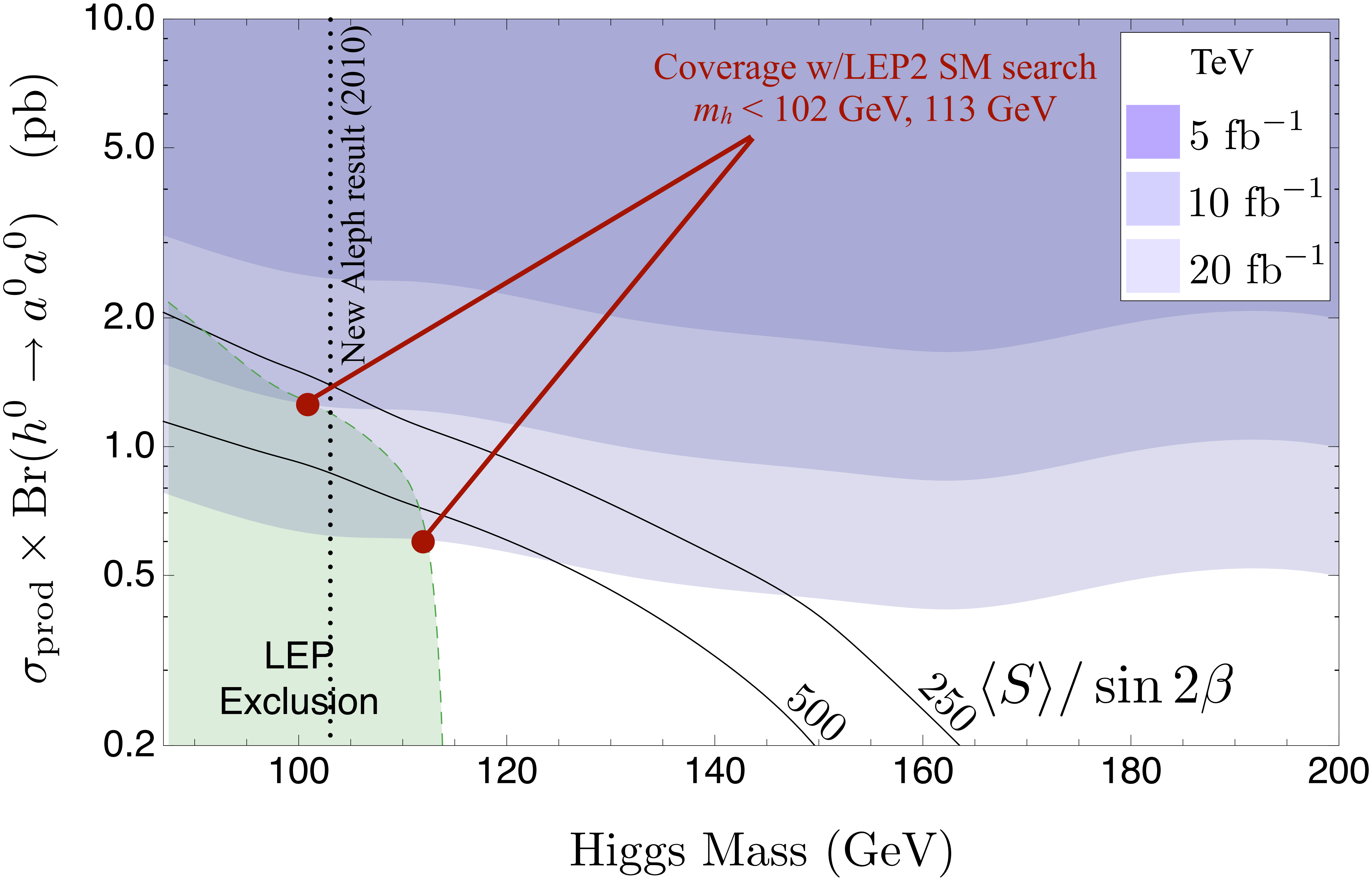
Backgrounds uniformly distributed in invariant mass

Resolution is 1 GeV for D0 and 0.3 GeV for CDF & LHC

Nearly background free

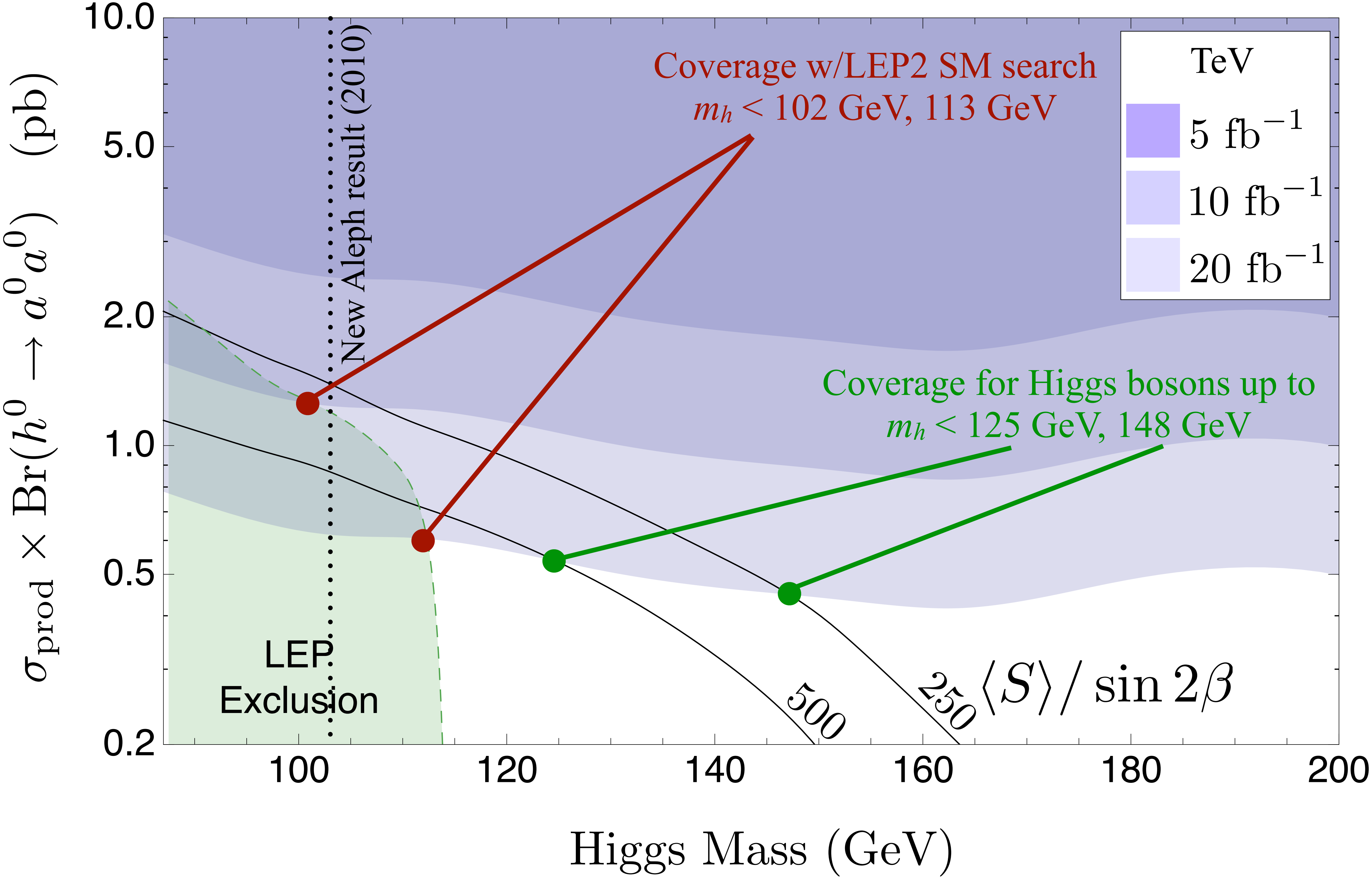
Tevatron Sensitivity

Getting close to the necessary sensitivity



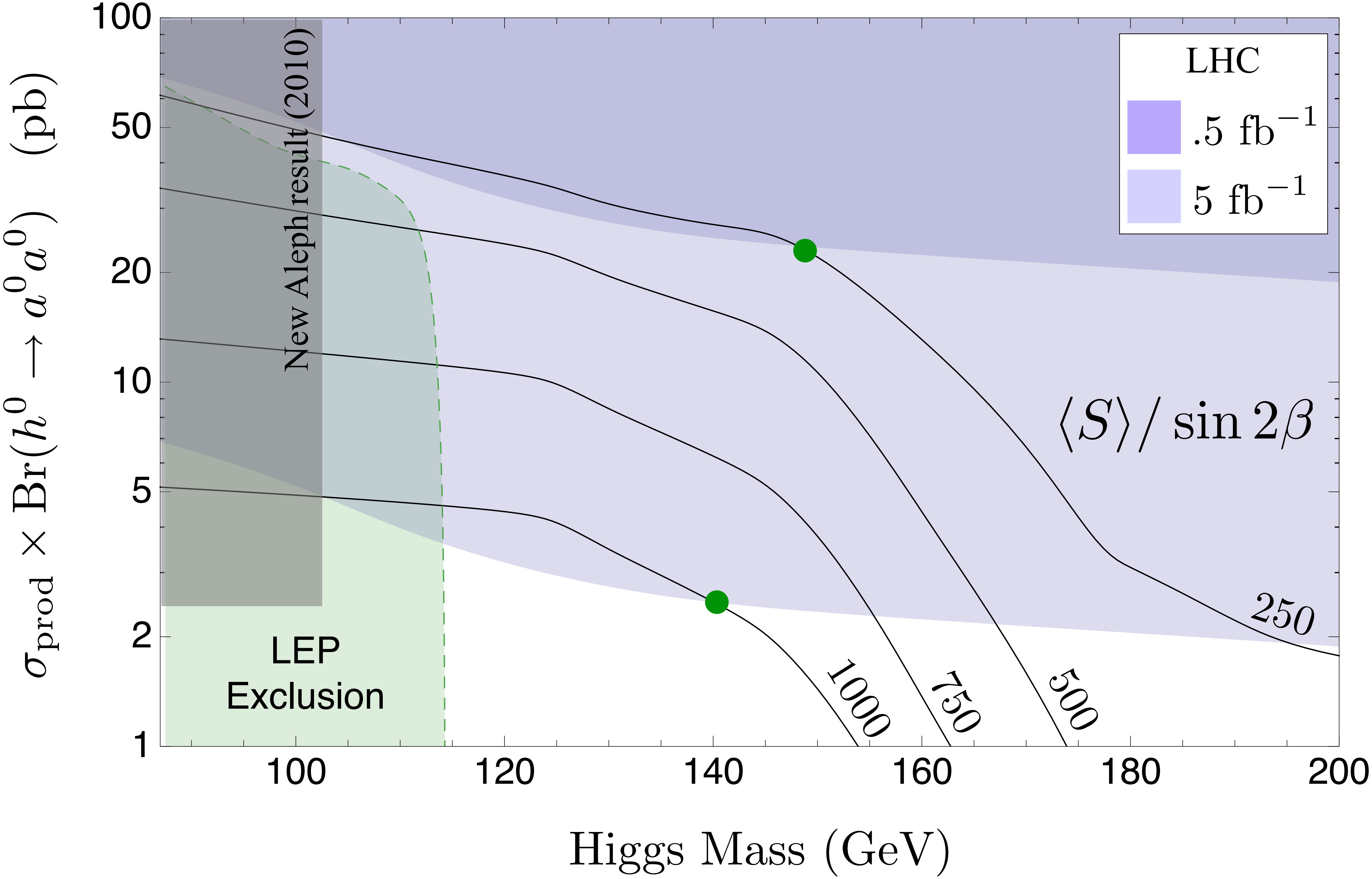
Tevatron Sensitivity

Getting close to the necessary sensitivity

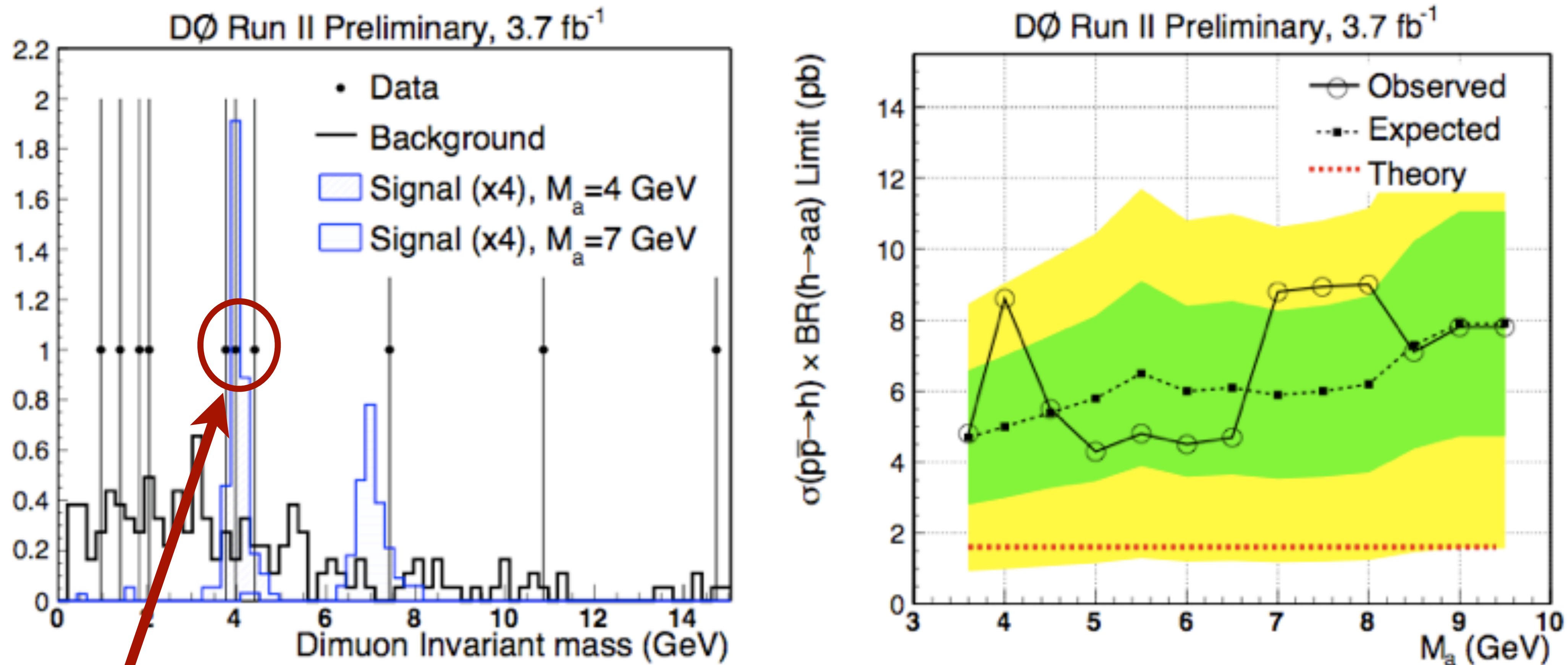


LHC Projected Sensitivity

An early LHC Higgs search
Will probe 1% BRs



D0 Results



4 events in relevant mass window

$$\frac{0.2\ \text{fb}}{\text{GeV}} \times 6.5\ \text{GeV} \times 3.7\ \text{fb}^{-1} = 4.4\ \text{Events}$$

Drell-Yan + Jet peaked at lower invariant mass

CDF performing analysis (Chris Hays)

Plan of the Talk

Motivation for New Higgs Decay Modes

Analysis of Higgs Decaying into PNGBs

- Searching for the Higgs at Hadron Colliders

Discussion

Other Higgs Decay modes

Altering the Higgs decay modes for $m_h > 114$ GeV possible

$$h^0 \to a^0 a^0 \to (bb)(bb)$$

Above the τ threshold

$$h^0 \to a^0 a^0 \to (\mu\mu)(\mu\mu)$$

Under the τ threshold

$$h^0 \to a^0 a^0 \to (gg)(gg) \qquad h^0 \to a^0 a^0 \to (gg)(\gamma\gamma)$$

Leptophobic decays

$$h^0 \to \chi\chi \to (qqq)(\bar{q}\bar{q}\bar{q}) \qquad h^0 \to \chi\chi \to (qqq)(qqq)$$

Baryon number violating R-parity violation

$$h^0 \to s^0 s^0 \to (a^0 a^0)(a^0 a^0) \to \cdots$$

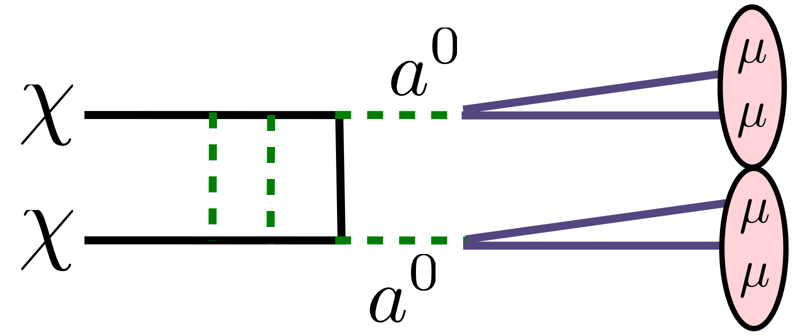
Two step cascades

Prototype for Lepton-jet Searches

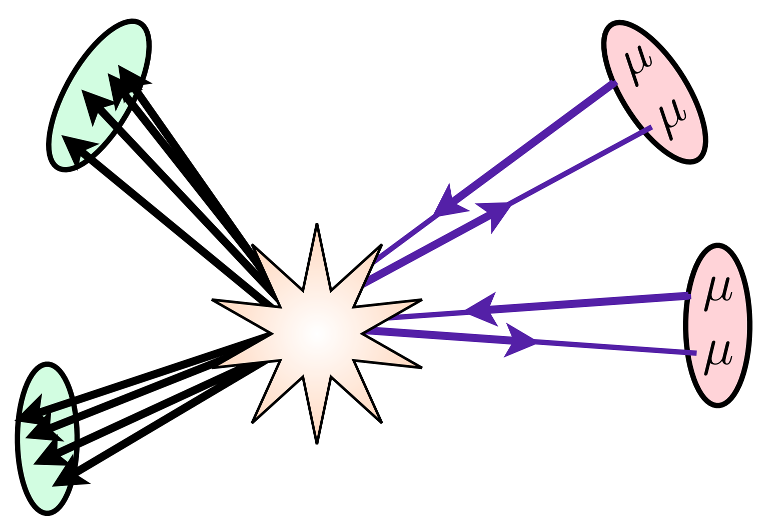
Astrophysical anomalies point towards
leptophilic, low mass particles

PAMELA, FERMI, ATIC (electron/positron excesses)

New light bosons leading to Sommerfeld enhanced annihilation



These particles can appear in cascade decays of new particles



Summary

Having additional Higgs decay modes is "generic"

Could alter Higgs discovery even if $m_{h^0} \gtrsim 114~\mathrm{GeV}$

Some tension with "hiding the Higgs" with 4τ decay mode

$2\mu 2\tau$ decay mode is better than 4τ

Could lead to early discovery at LHC,
even if mode is not the dominant decay mode