Discovering the Higgs with Low Mass Muon Pairs

Mariangela Lisanti

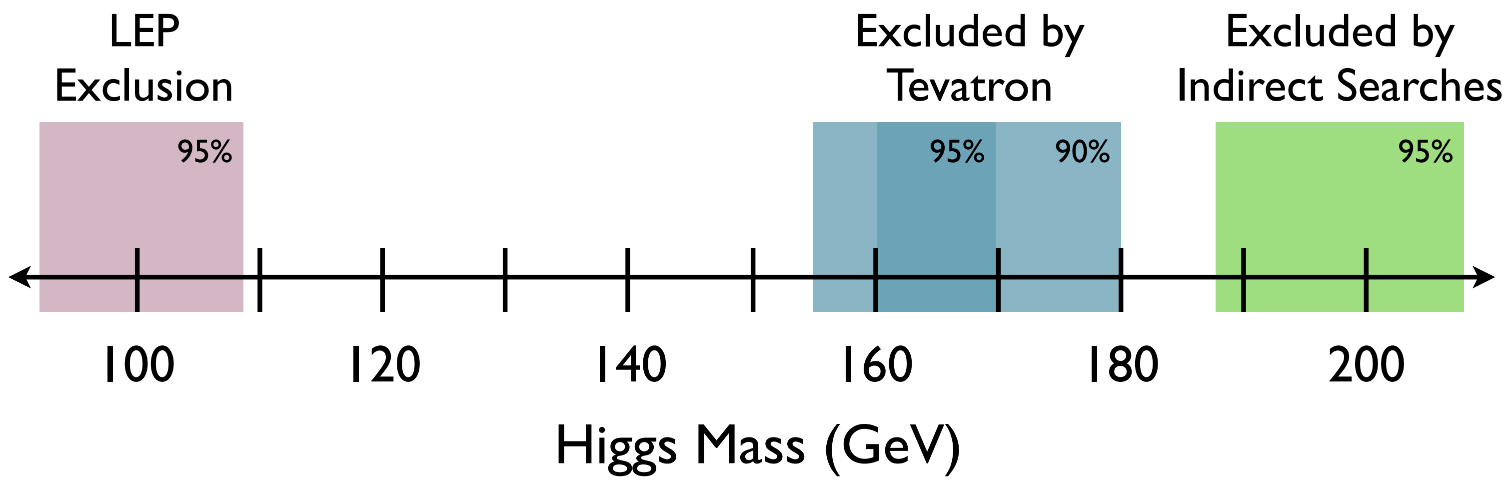
SLAC/Stanford

May 11, 2009

M. L. & Jay G. Wacker, arXiv: 0903.1377
Andy Haas w/DØ Collaboration, Note 5891

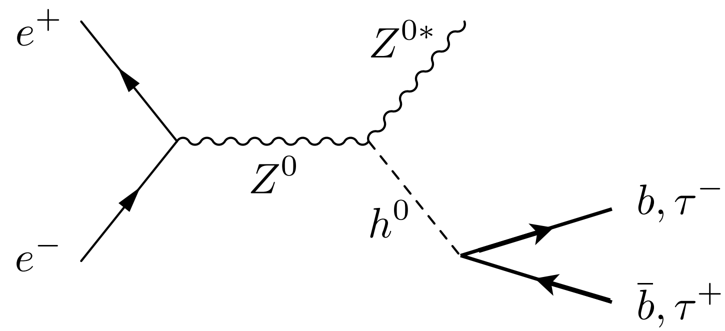
Status of Higgs Searches

[as of March 2009]



LEP Direct Bounds

Mass limit of 114 GeV pertains specifically to Standard Model decay modes



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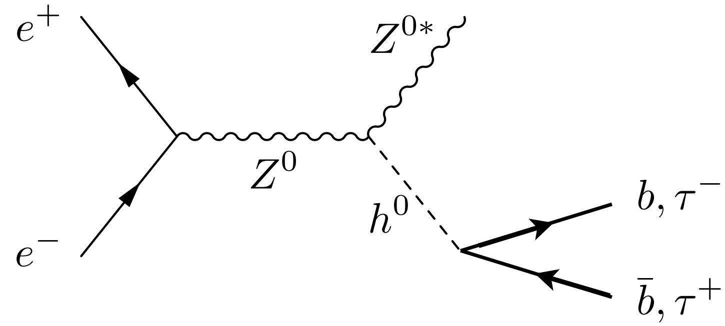
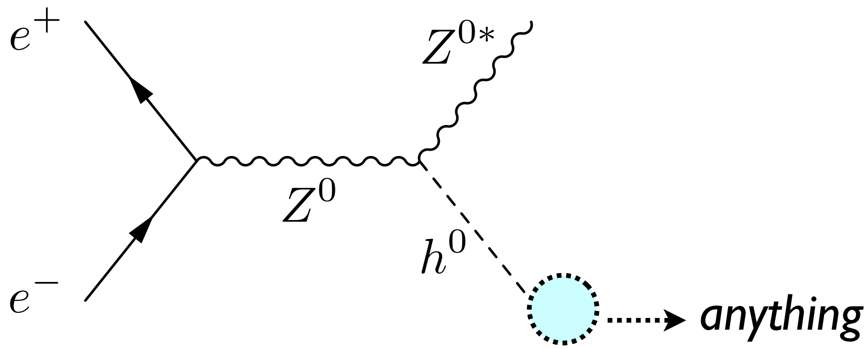


Nonstandard Decays



Model-independent: $m_{h^0} \gtrsim 82\ \mathrm{GeV}$

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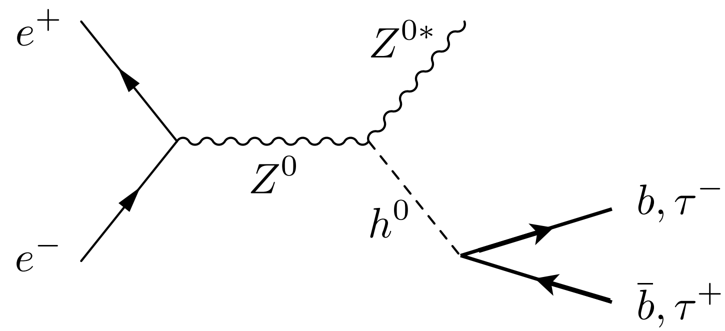

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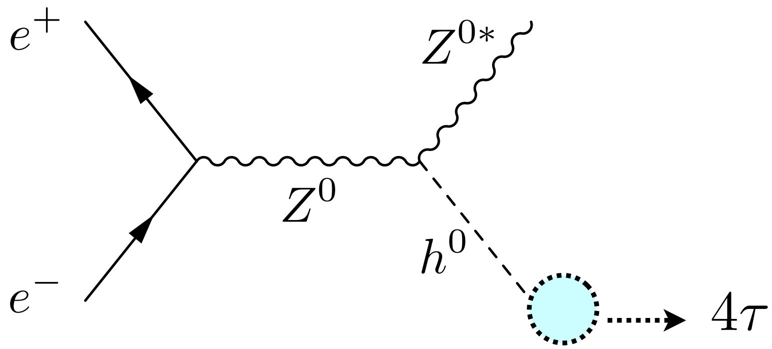

Model-independent: $m_{h^0} \gtrsim 82$ GeV

Cascade-decaying Higgs: $m_{h^0} \gtrsim 86$ GeV

Cascading Higgs

Let Higgs decay dominantly to two new scalars

$$h^0 \to \phi\phi \to (\tau^+\tau^-)(\tau^+\tau^-)$$

Chang, Dermisek, Gunion, Weiner, arXiv: 0801.4554

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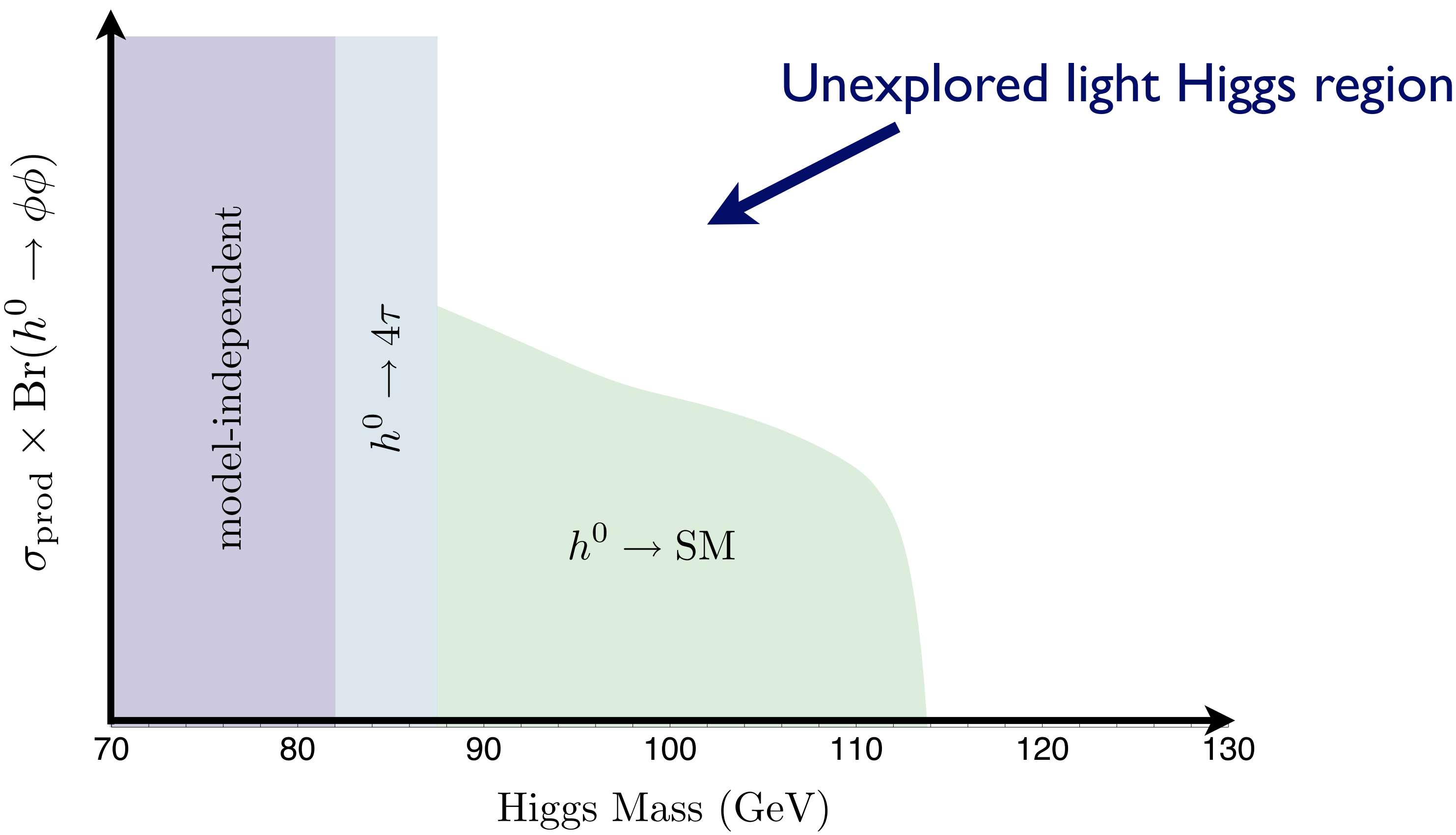

Chang, Dermisek, Gunion, Weiner, arXiv: 0801.4554

Pseudoscalars

Approximate symmetry in Higgs potential explicitly broken

↓

pseudo-Goldstone bosons

↓

pseudoscalars have O(1) coupling to Higgs

↓

Higgs has substantial branching fraction to pseudoscalars

Outline

I. Light pseudoscalar phenomenology

II. Cascade-decaying higgses at colliders

III. Preliminary results from DØ experiment

Model

Two Higgs doublet model with additional singlet

$$H_u = \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v \sin\beta + h_u) \end{pmatrix} e^{ia_u/v\sin\beta} \qquad H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v \cos\beta + h_d) \\ H_d^- \end{pmatrix} e^{ia_d/v\cos\beta}$$

$$S = \frac{1}{\sqrt{2}}(\langle S \rangle + s^0) e^{ia_s/\langle S \rangle}$$

The interactions between the three pseudoscalars a_u, a_d, a_s arise from

(i) derivative couplings in kinetic terms

(ii) symmetry breaking terms in the potential

Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{\rm kin} - \lambda_1 S^2 H_u^\dagger H_d^\dagger - \lambda_2 S^2 H_u H_d + \text{h.c.}$$

①

(Pseudo-) Goldstones

① $\omega_{Z^0} = -a_u \sin\beta + a_d \cos\beta$ Gives mass to the Z^0

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③ $a^0 = \sin\theta_a (a_u \cos\beta + a_d \sin\beta) + a_s \cos\theta_a$ — Light pseudo-Goldstone

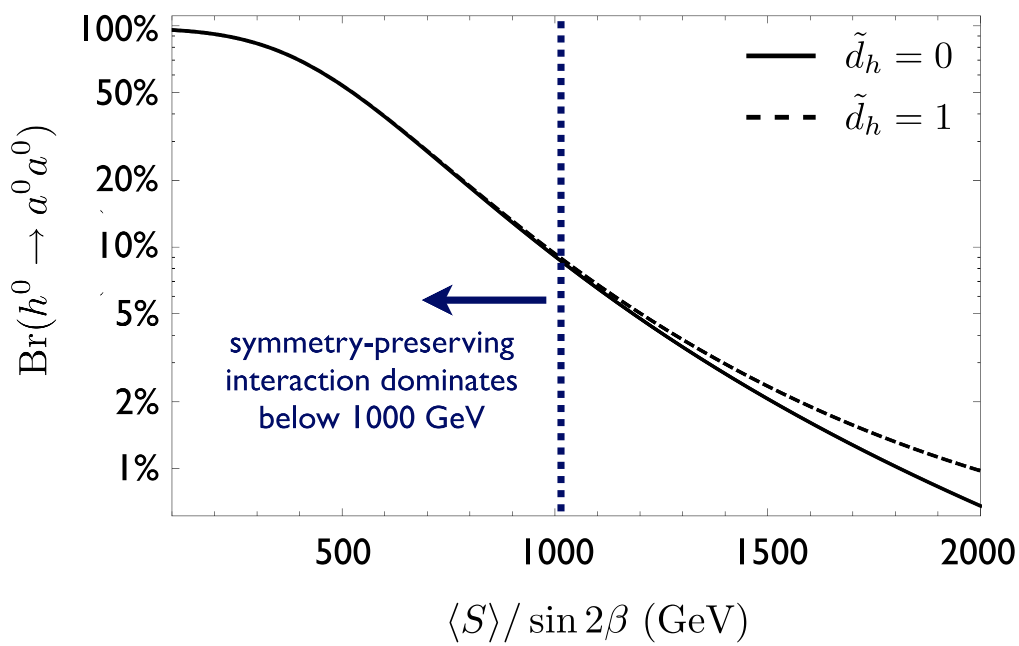
Coupling to Higgs

$$\mathcal{L}_{\text{int}} = \tilde{c}_h \frac{v}{\langle S \rangle^2} h^0 \partial_\mu a^0 \partial^\mu a^0 - \tilde{d}_h \frac{m_{a^0}^2}{v} h^0 a^0 a^0$$

- Kinetic terms in Lagrangian give

$$\tilde{c}_h \frac{v}{\langle S \rangle^2} \sim \frac{1}{1 + \left(\frac{\langle S \rangle}{\sin 2\beta}\right)^2}$$

- Value of $\tilde{d}_h$ depends on symmetry breaking potential



Coupling to Fermions

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

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

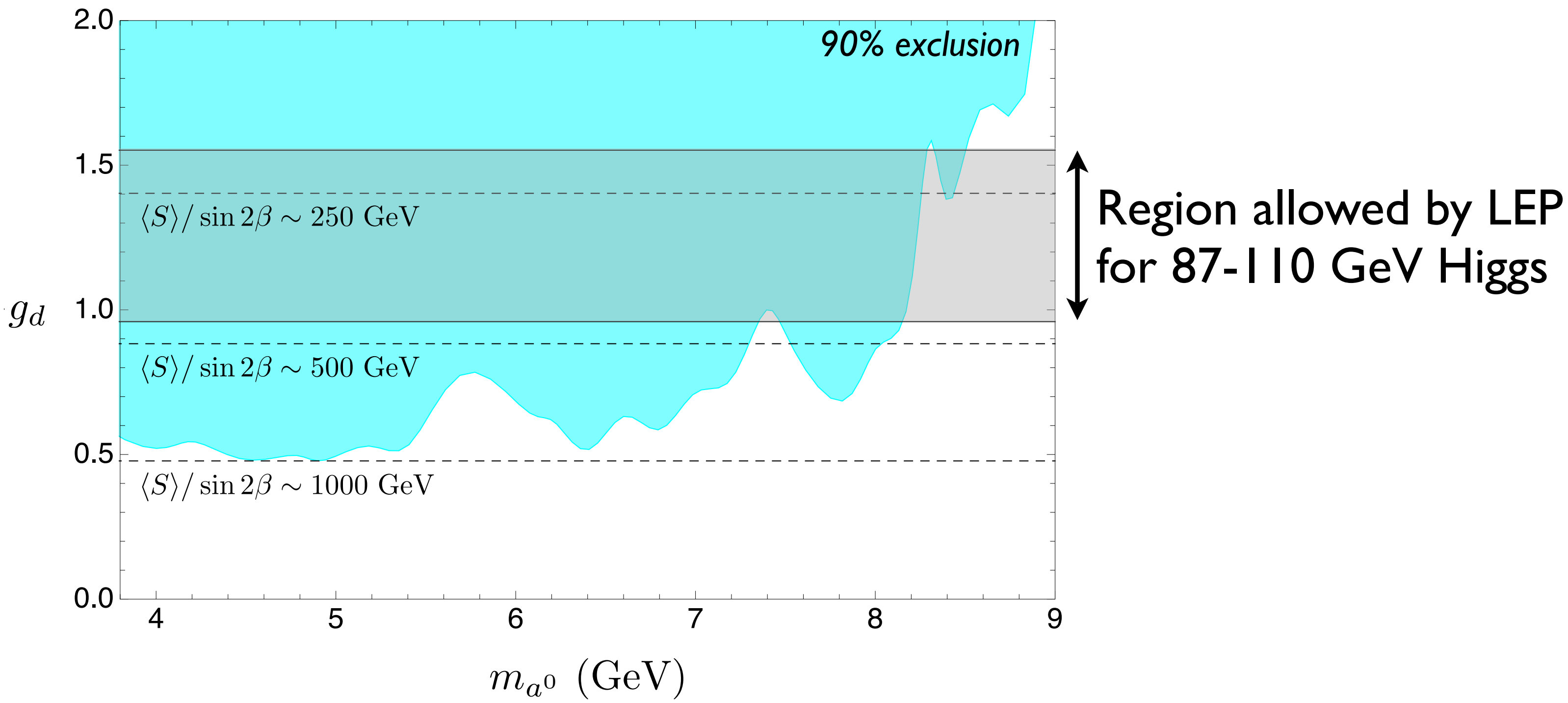
← suppressed by 2 powers of $\tan\beta$

Below the b-quark threshold,
pseudoscalar decays primarily to taus rather than charm quarks

CLEO limits

CLEO sets limits on the coupling of a^0 to fermions

$$\frac{\mathrm{Br}(\Upsilon \to a^0 \gamma)}{\mathrm{Br}(\Upsilon \to \mu^+ \mu^-)} \propto g_d^2 \left(1 - \frac{m_{a^0}^2}{m_\Upsilon^2}\right)$$



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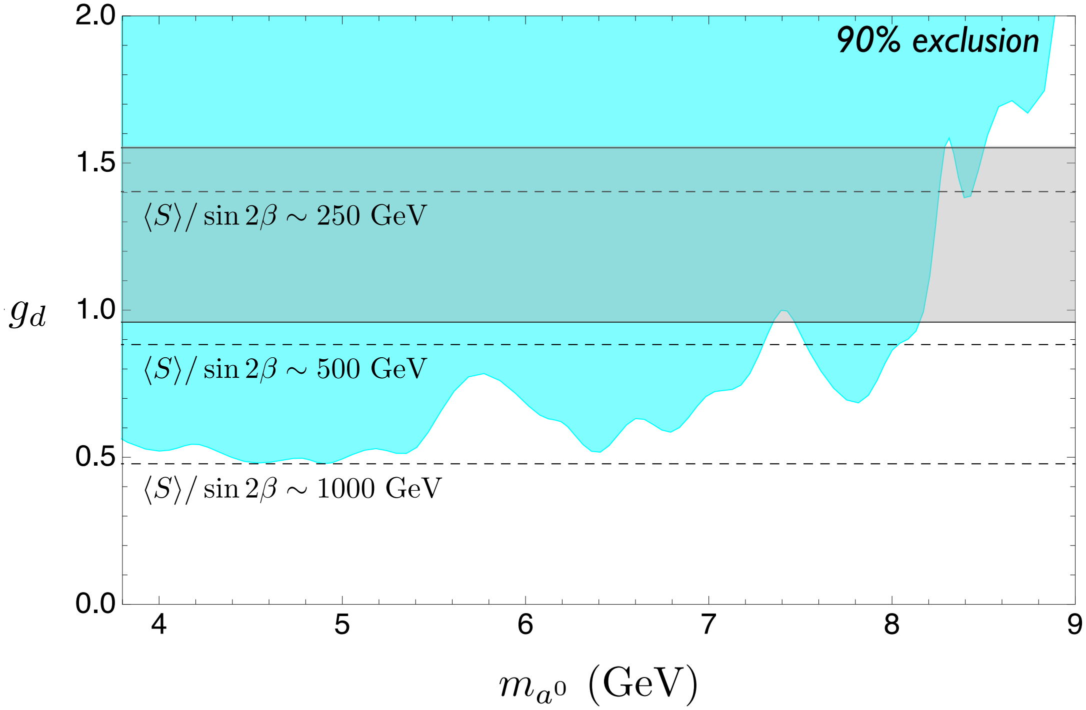

Tension

LEP results prefer strong coupling of pseudoscalar to Higgs...
but CLEO results tightly bound this region

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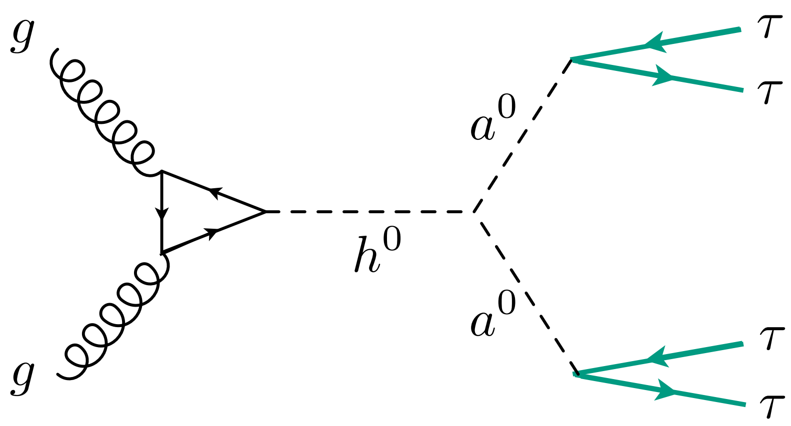
a^0 at Colliders



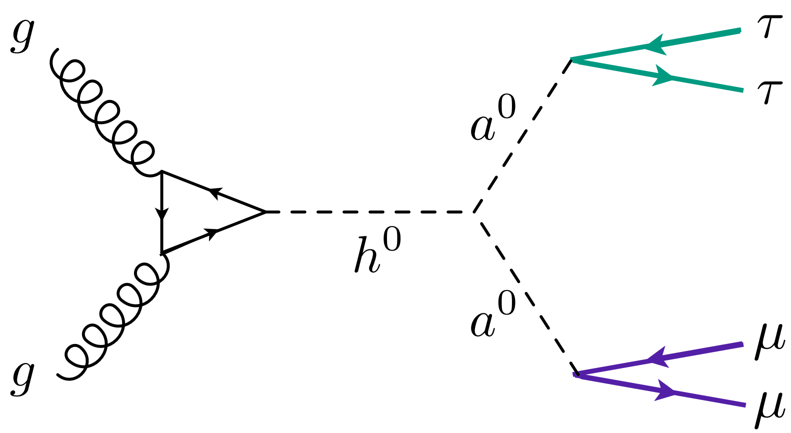
Signal

$$h^0 \to 4\tau \to \text{ leptons} + \not{E}_T$$

Challenges

- Tau decays leptonically 33% of time
- Leptons are soft

a^0 at Colliders



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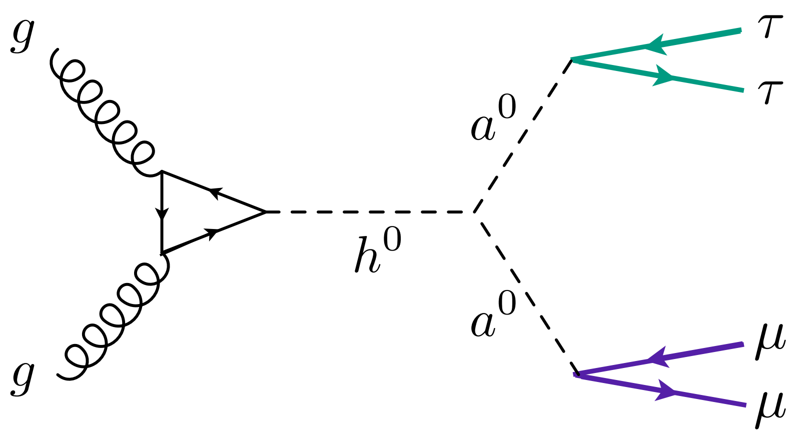
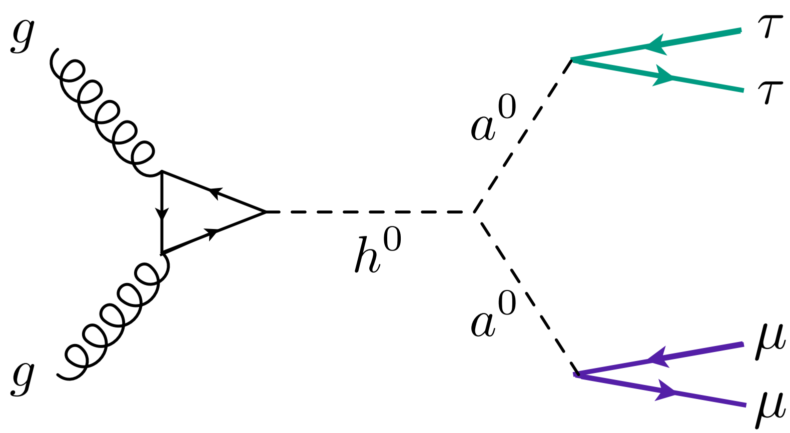


Branching fraction of a^0 to muons is much smaller than that to taus

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

a^0 at Colliders



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For 7 GeV pseudoscalar,

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

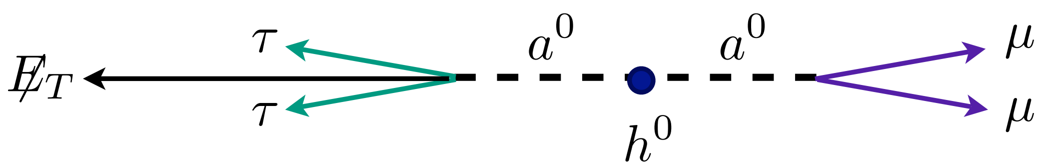
$$\mathrm{Br}(a^0 \to \tau^+\tau^-) = 98\%$$

Despite small branching fraction to muons...

300 events   20 fb^{-1} Tevatron

250 events   0.5 fb^{-1} LHC

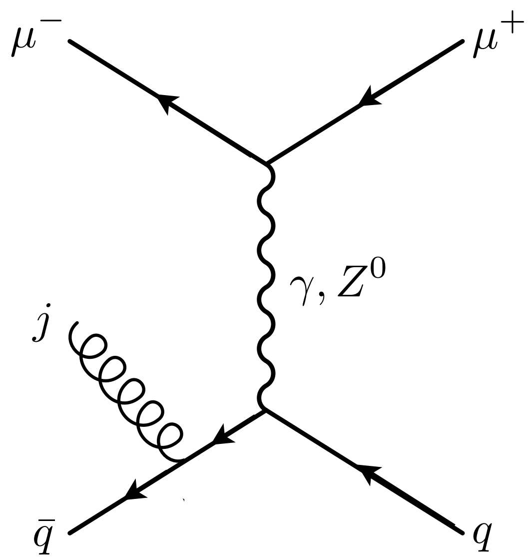
Kinematics



Characteristic Signatures

- collinear, high pT muon pair
- 1 or 2 jets opposite to the muons
- Missing energy acoplanar with muons

Main Backgrounds



Drell-Yan

Most important background

Muons recoil against ISR jet

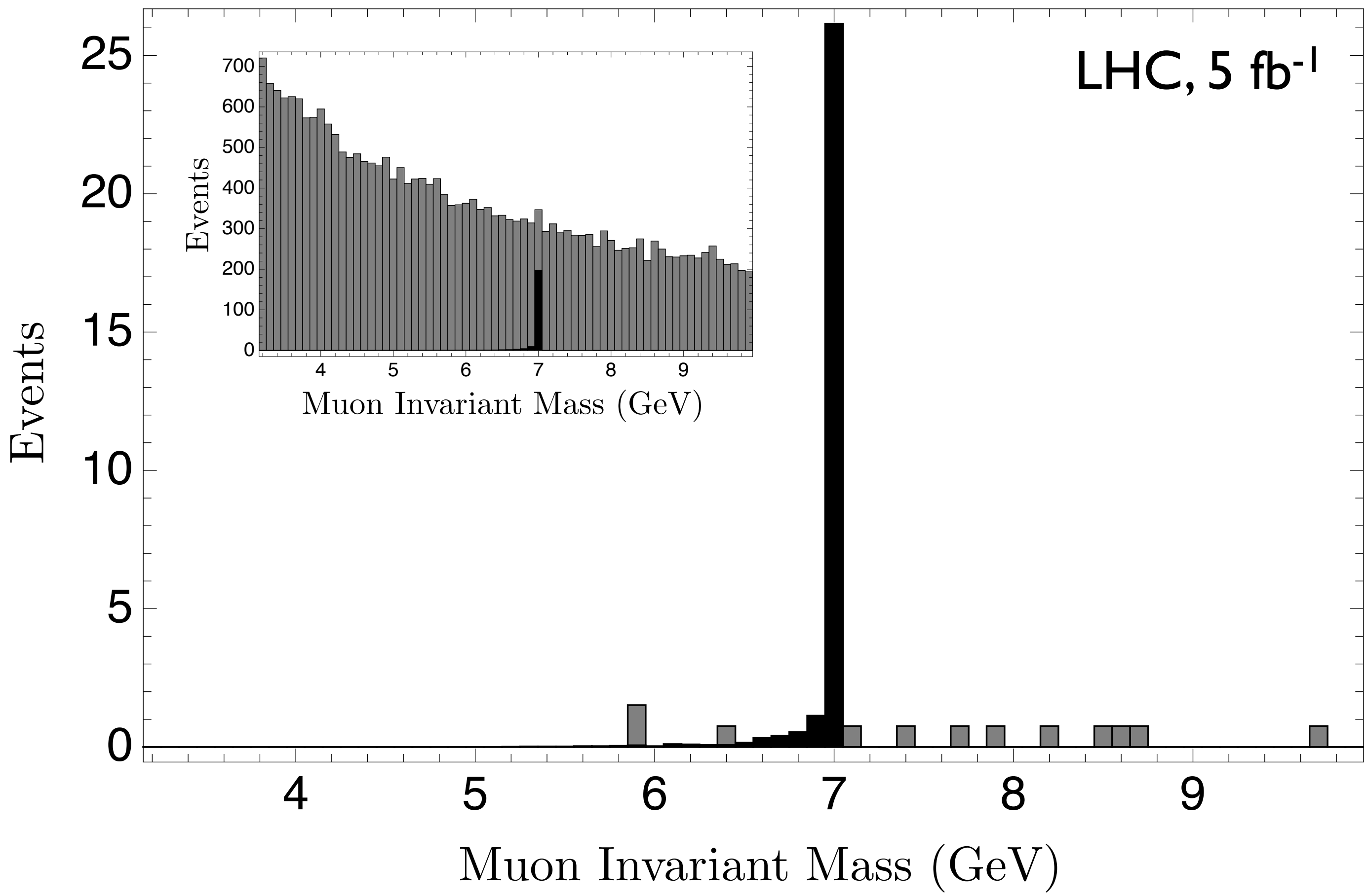
Missing energy from jet energy mismeasurement or neutrinos from heavy semileptonic decays in jet

Summary

$$\frac{d\sigma}{dM_{\mu\mu}} \ (\text{fb/GeV})$$

	DY+j	WW	tt
Tevatron	0.15	0.03	0.02
LHC	0.24	0.08	0.14

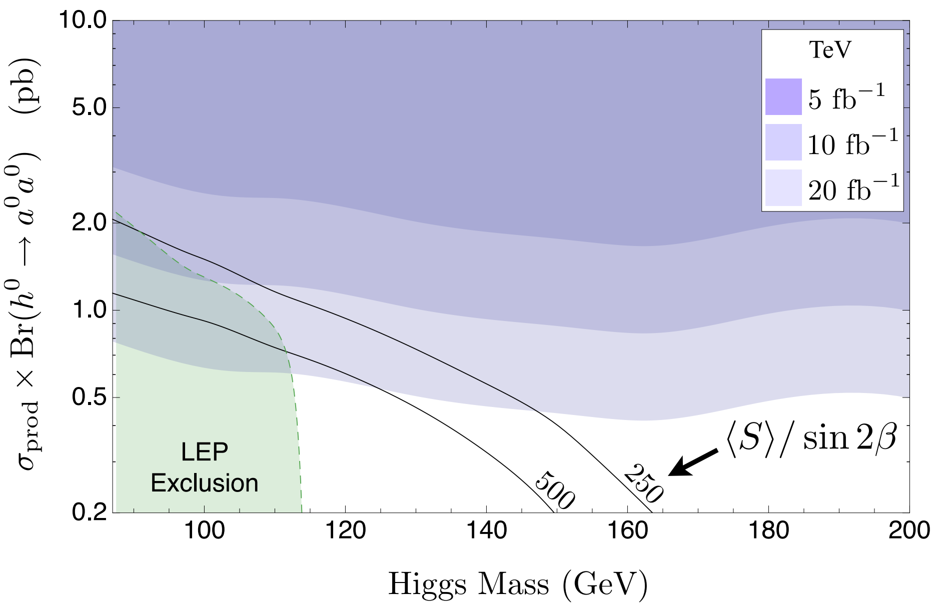
Muon Invariant Mass



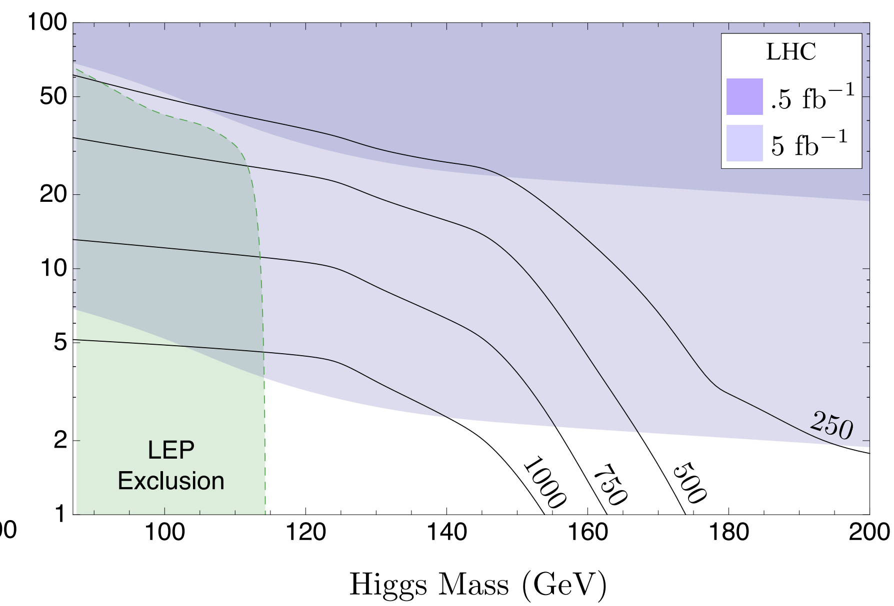
■ : Signal ■ : D-Y Background

Expected Sensitivity

Tevatron



LHC

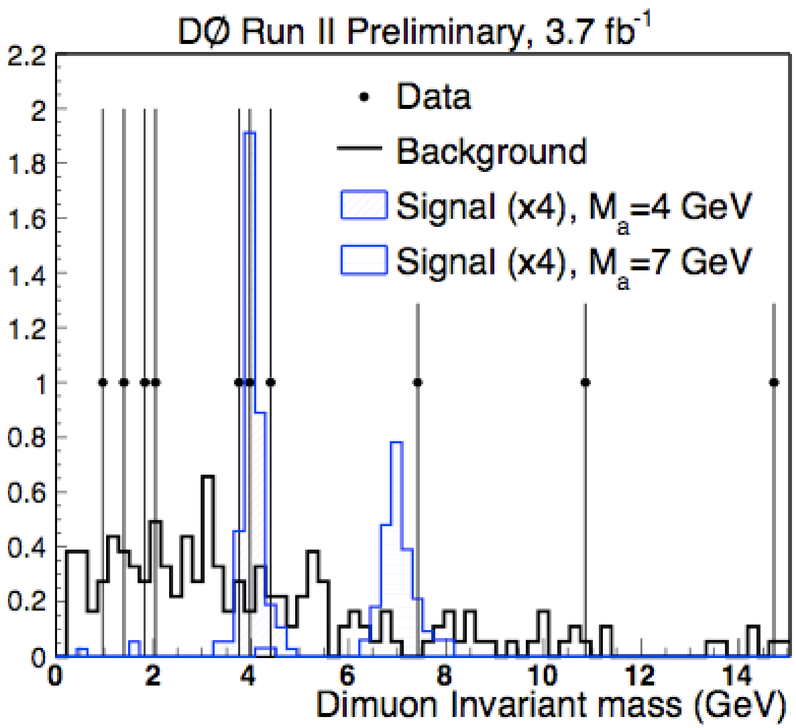


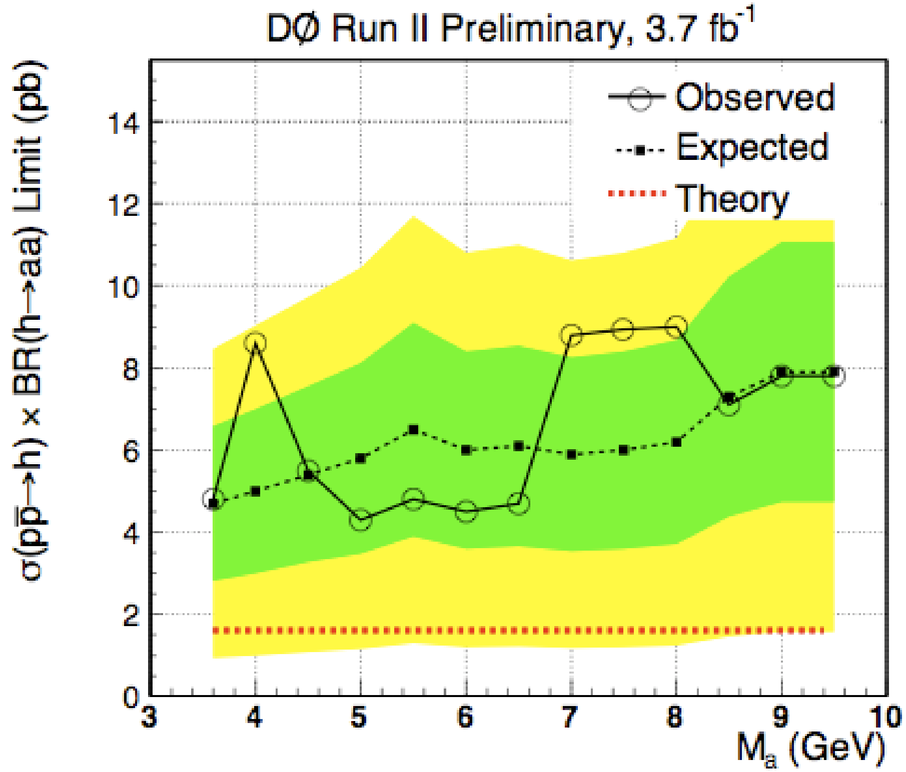
Combined results of DØ and CDF can set lower limit on Higgs mass regardless of admixture to pseudoscalars

Recover LEP limit with ~1 fb^{-1}

Higgs discovery with sub-fb^{-1} data set possible

DØ Results





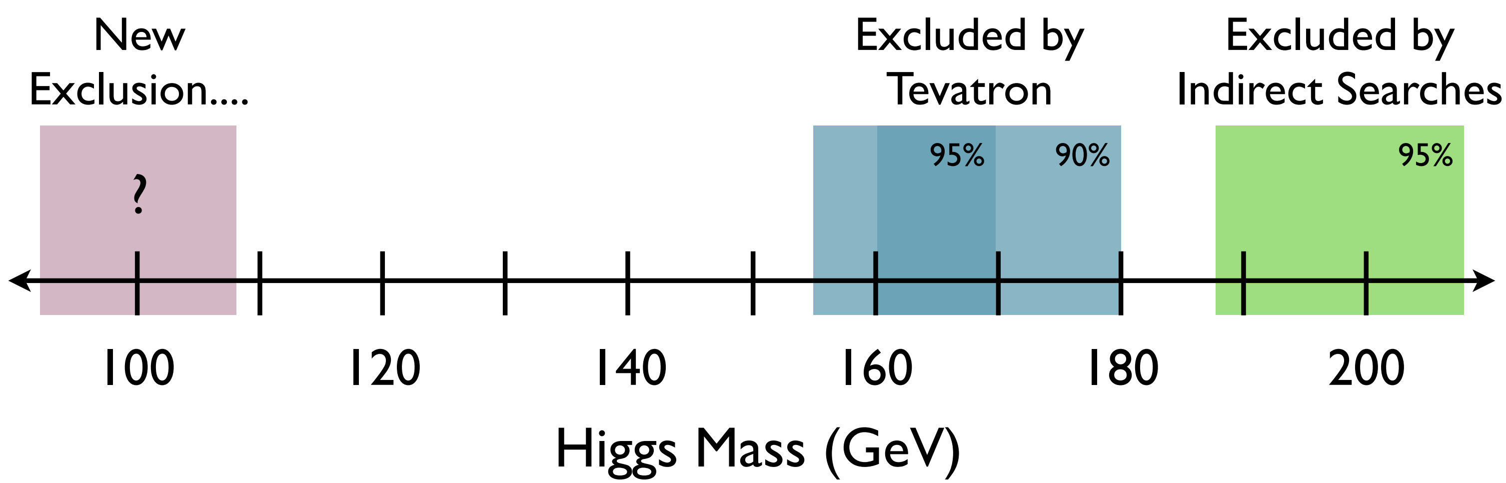
DØ Collaboration, Note 5891 (March 2009).

Conclusions

- Possible to evade LEP bound if Higgs decays primarily to pseudoscalars

- Light pseudoscalars typical when there is an approximate symmetry in Higgs potential that is broken

- Possible to discover cascading Higgs in $2\mu 2\tau$ channel with complete Tevatron data set or early data at LHC



Extras

Light Higgs in Theory

One-loop corrections to Higgs mass in MSSM:

$$m_{h^0}^2 \simeq m_{Z^0}^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + a_t^2\left(1 - \frac{a_t^2}{12}\right)\right)$$

Mass corrections depend on stop mass $m_{\tilde{t}}$ and mixing $a_t \simeq \dfrac{A_t}{m_{\tilde{t}}}$

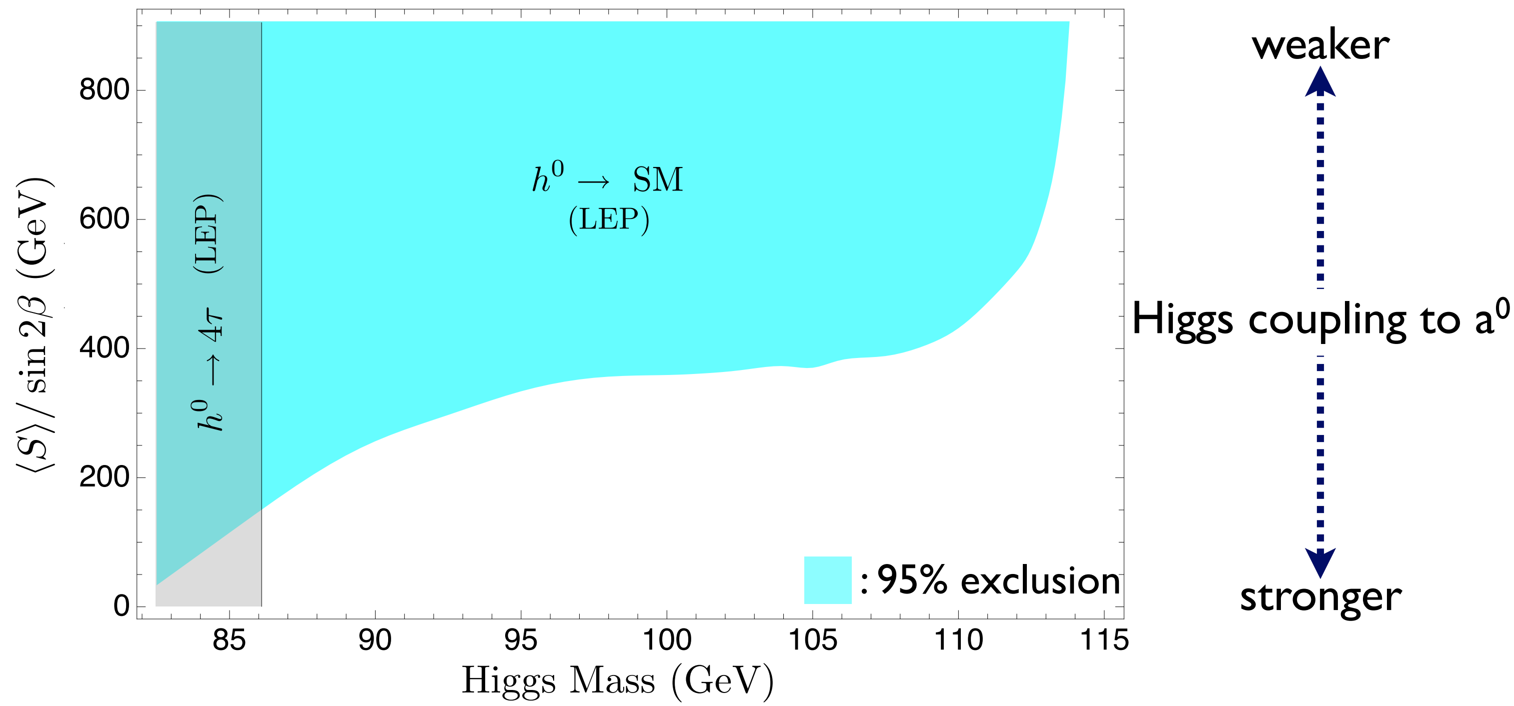
Moderate Mixing	Maximal Mixing	
m_h=120 GeV	m_h=130 GeV	$m_{\tilde{t}} = 1\ \text{TeV}$
	m_h=120 GeV	$m_{\tilde{t}} = 400\ \text{GeV}$

LEP Limits

LEP sets limits on branching fraction of Higgs into Standard Model

$$\xi^2_{h\to X} \equiv \frac{\sigma(e^+e^- \to Zh)}{\sigma(e^+e^- \to Zh)_{\rm SM}} {\rm Br}(h \to X)$$

This translates into a bound on coupling strength of Higgs to a^0



Hadronic Backgrounds

(i) Double semi-leptonic decays

Background: $b \to c \to s/d$

Minimal because: hadronic activity surrounding muons
high pT muons are rare

(ii) Heavy flavor quarkonia

Background: $\Upsilon \to \tau\text{'s} \to \mu\text{'s}$

Minimal because: missing energy in direction of muon pair
pT spectrum of ϒ falls off rapidly

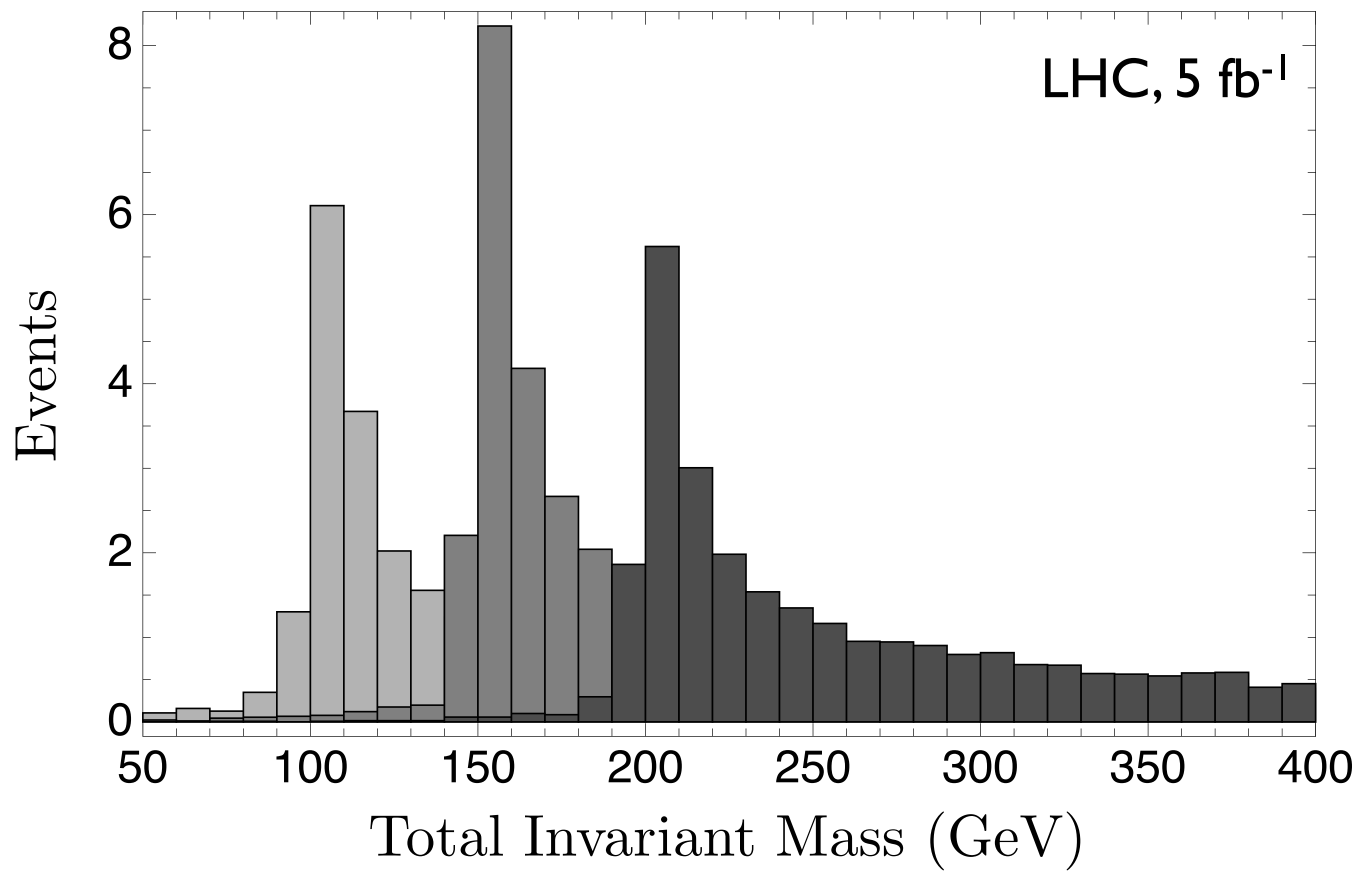
(ii) Leptonic decays of light mesons

Background: J/Ψ muon invariant mass distribution

Minimal because: Lorentzian tail of decay width
Gaussian mismeasurement tail

Hadronic contribution is << 10% Drell-Yan background

Total Invariant Mass



* Project missing energy in direction of hardest jet *