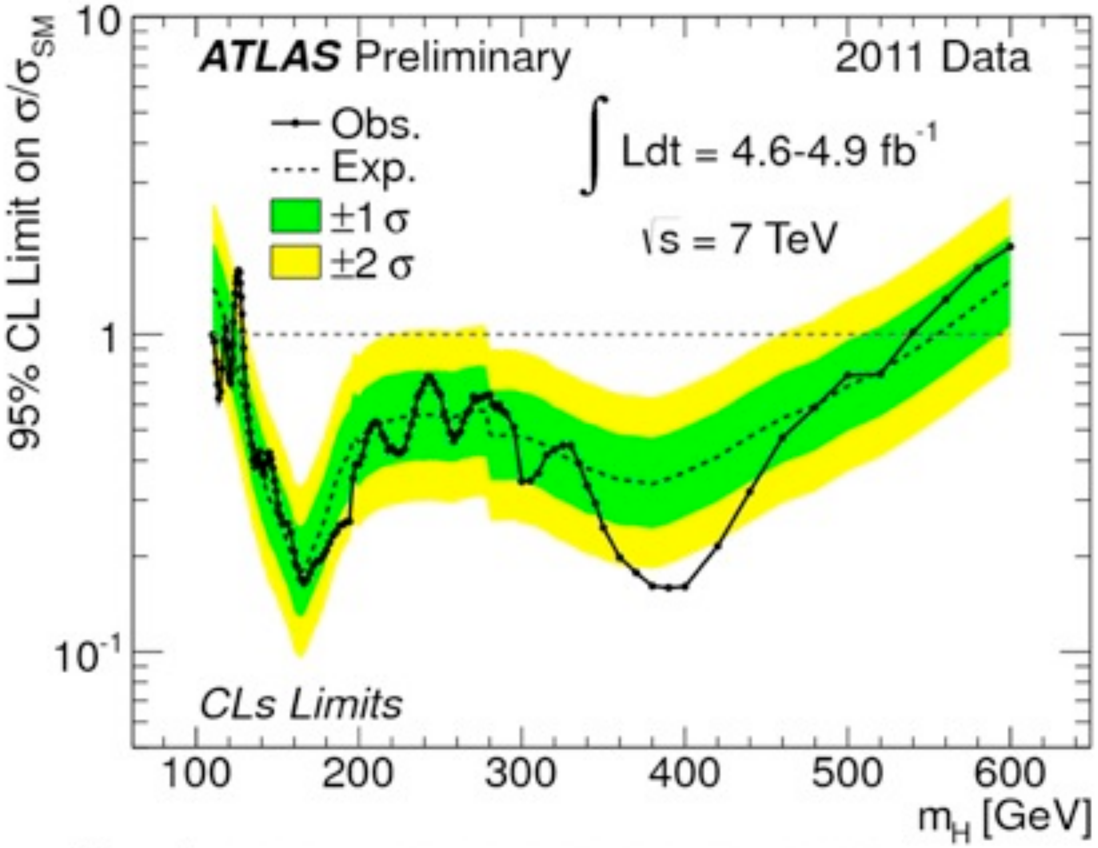
THE **DARK** SIDE OF THE HIGGS BOSON

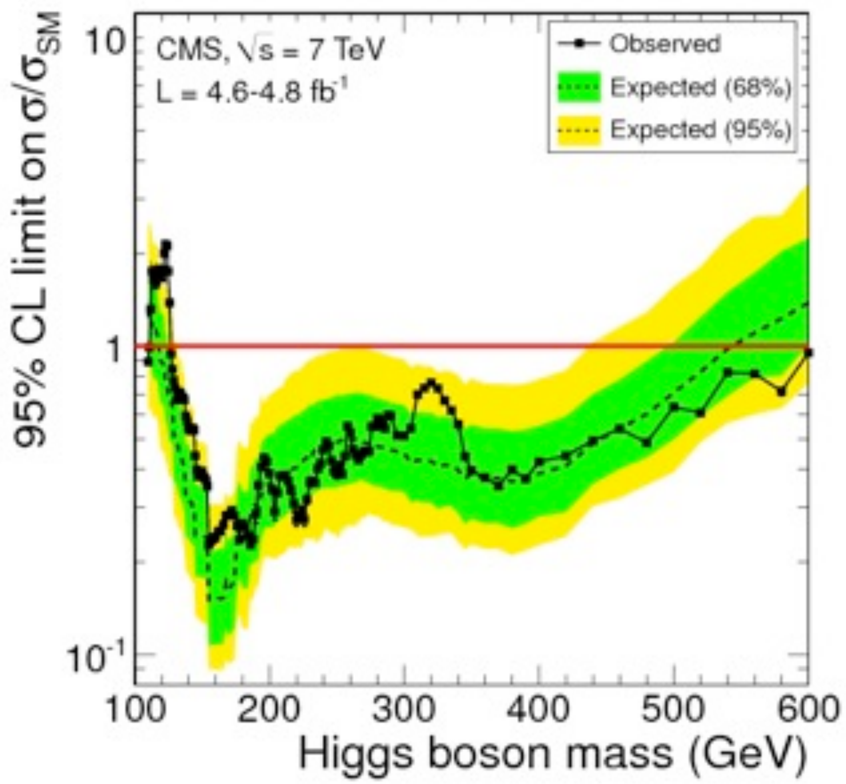
Pedro Schwaller

Argonne/UIC

Planck 2012

LHC: NO HIGGS (YET)





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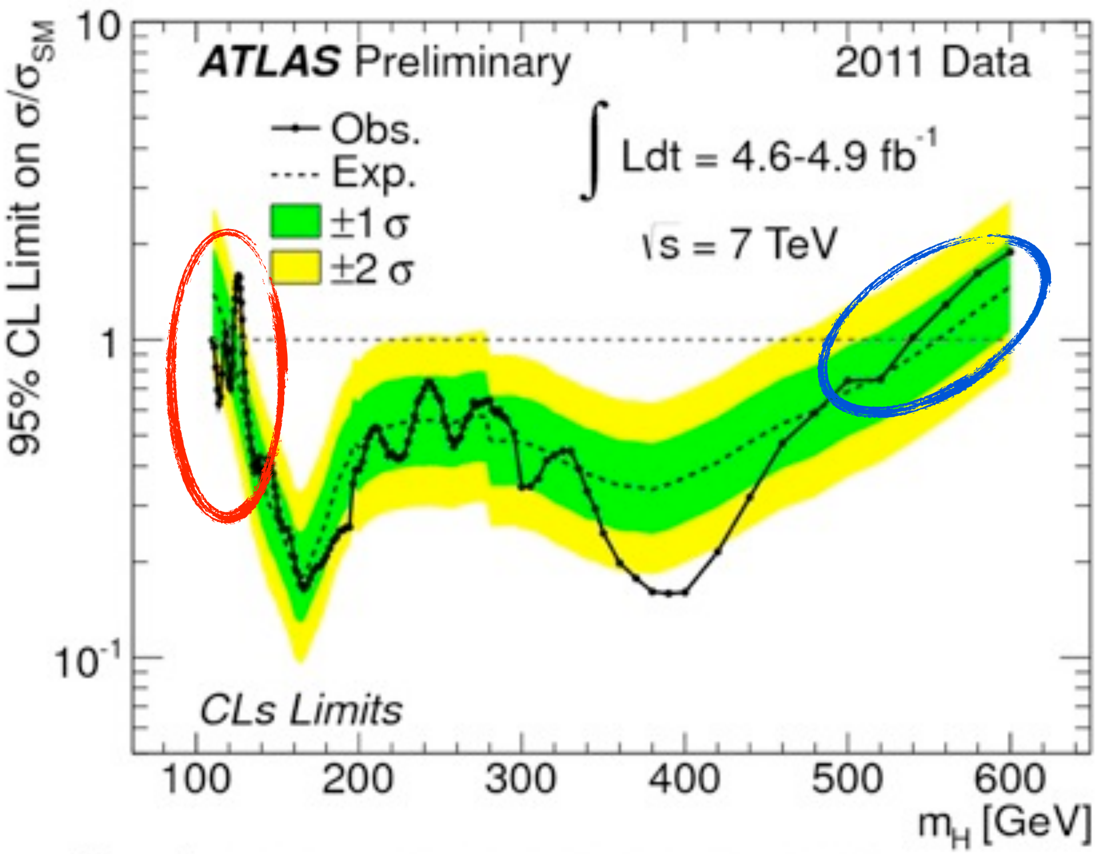
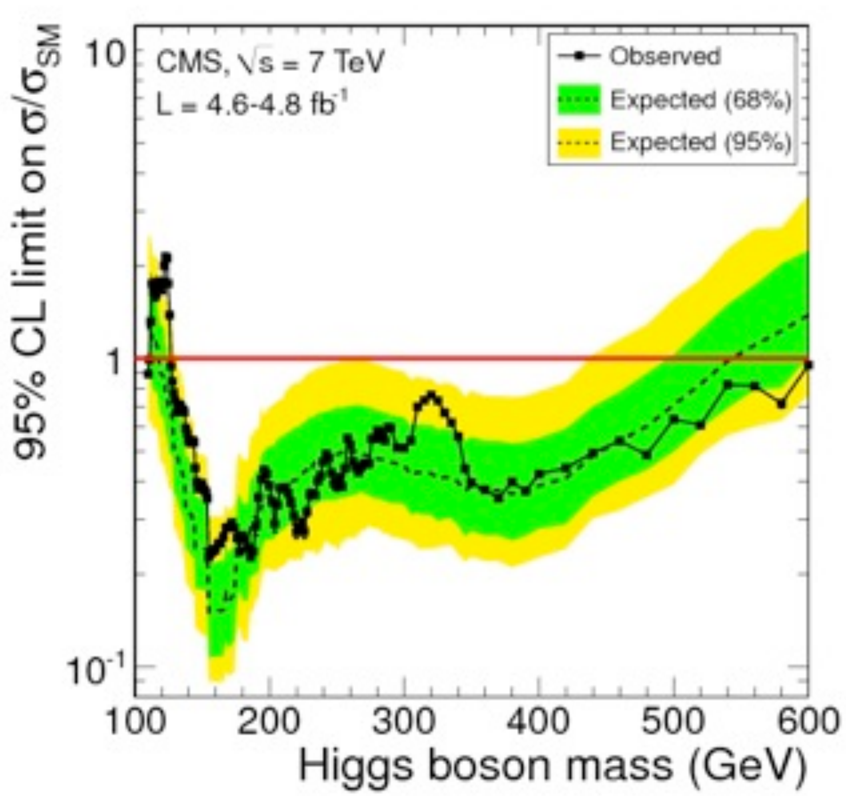
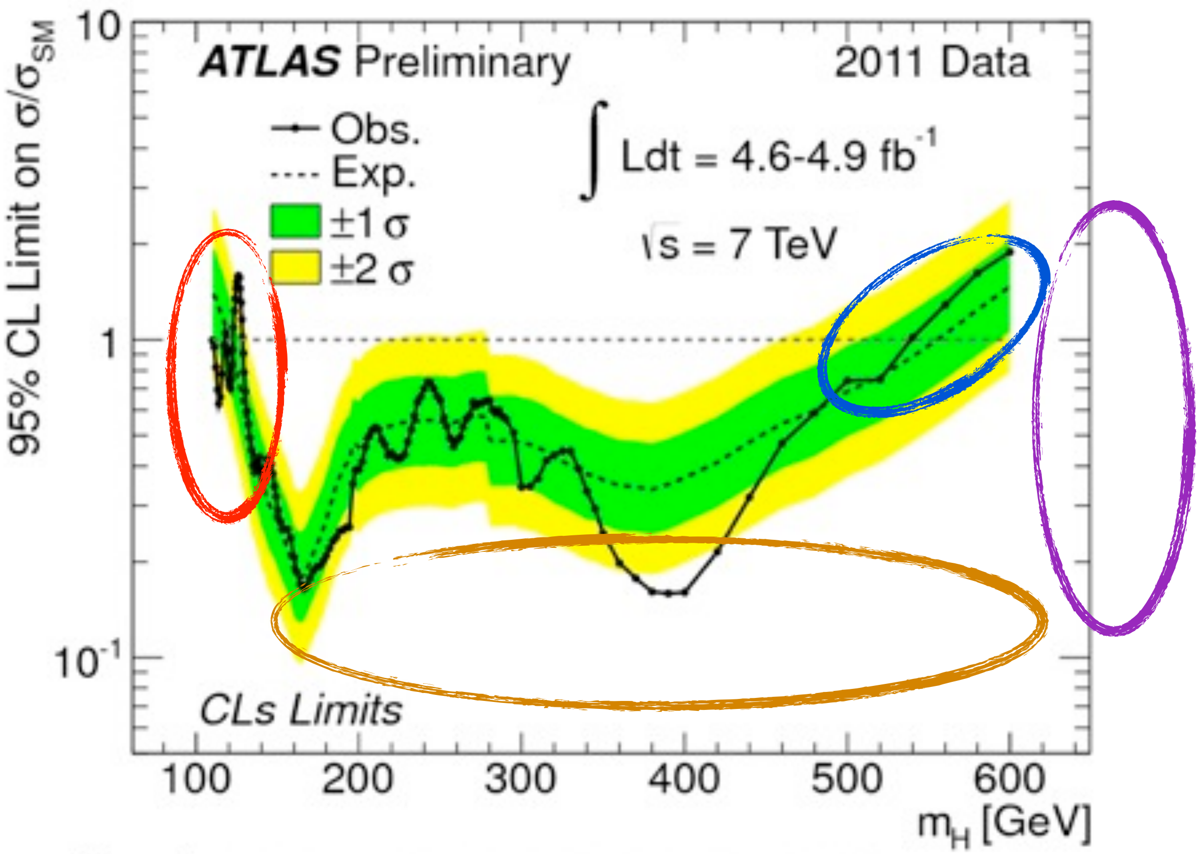


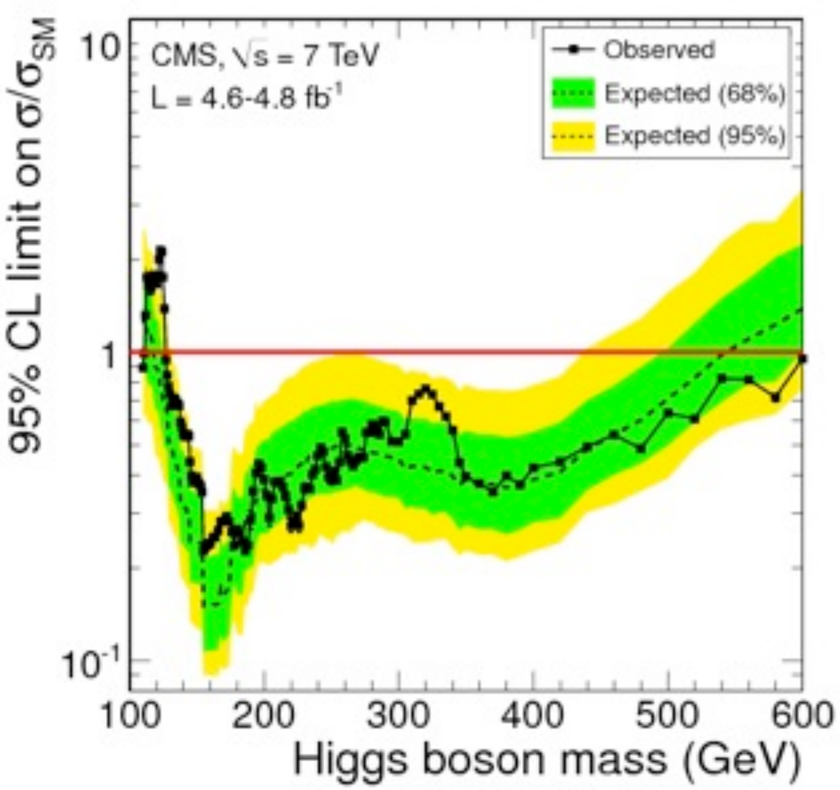


very light Higgs (~3 sigma)

heavy Higgs (Problem: EWPT)

LHC: NO HIGGS (YET)





very light Higgs (MSSM?)

heavy Higgs (Problem: EWPT)

no Higgs?

invisible Higgs (this talk!)

in Collaboration with
I. Low, G. Shaughnessy, C. Wagner
Phys.Rev. D85 (2012) 015009

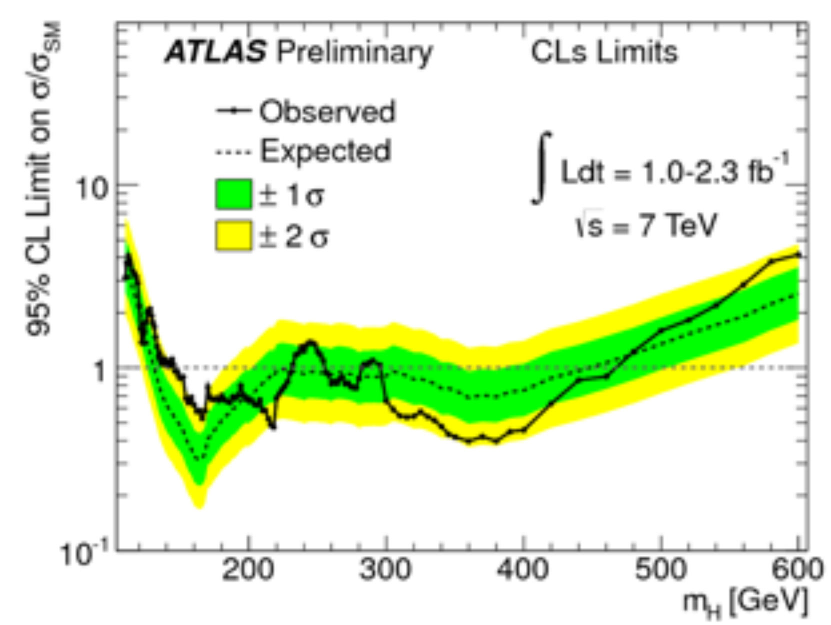
OUTLINE

★Invisible Higgs & Higgs Portal Dark Matter

★Constraining the invisible Higgs width (after discovery!)

INVISIBLE HIGGS DECAYS

- Interpret the current exclusion as a lower bound on the invisible Higgs width



$$\sigma(pp \to h \to X_{\rm SM}) = \frac{\Gamma_{\rm SM}}{\Gamma_{\rm SM}+\Gamma_{\rm inv}}\sigma_{\rm SM}$$

- Requirement:

$$150 - 220 \text{ GeV}: \quad \Gamma_{\rm inv} \sim 0.5\Gamma_{\rm SM}$$
$$300 - 450 \text{ GeV}: \quad \Gamma_{\rm inv} \sim \Gamma_{\rm SM}$$

Summer 2011

INVISIBLE HIGGS DECAYS

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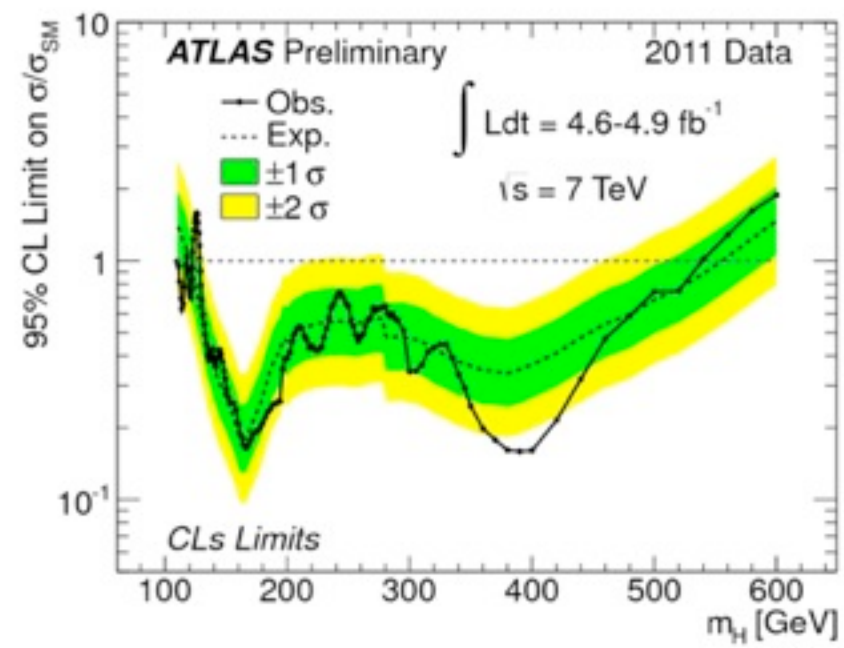


$$\sigma(pp \to h \to X_{\rm SM}) = \frac{\Gamma_{\rm SM}}{\Gamma_{\rm SM} + \Gamma_{\rm inv}} \sigma_{\rm SM}$$

- Requirement:

~~$150 - 220\ \text{GeV}: \quad \Gamma_{\rm inv} \sim 0.5\Gamma_{\rm SM}$~~

~~$300 - 450\ \text{GeV}: \quad \Gamma_{\rm inv} \sim \Gamma_{\rm SM}$~~

Summer 2011

$140 - 500\ \text{GeV}: \Gamma_{\rm inv} \gtrsim \Gamma_{SM}$

Full 2011

MODELS?

- Below WW threshold: very easy, just need to compete with $b\bar{b}$ channel (insert favorite model)
- For $m_h > 2m_W$: Need (relatively) light state with sizable coupling to Higgs boson
- Models: Fat Higgs, λSUSY, Higgs Portal,...
- expect other modifications of Higgs production/decay

MINIMALISTIC APPROACH

- Effective Higgs coupling to (Majorana) fermion

$$\mathcal{L} \supset m\bar{\psi}\psi + \frac{y_f}{\Lambda}\left(v + h/\sqrt{2}\right)^2 \bar{\psi}\psi$$

- Singlet scalar

$$\mathcal{L} \supset \frac{1}{2}m^2 S^\dagger S + \frac{1}{2}\lambda H^\dagger H S^\dagger S + \mathcal{L}_H + \mathcal{L}_S$$

- Not worry about UV completion etc. right now, only require that couplings are perturbative

DM CANDIDATE?

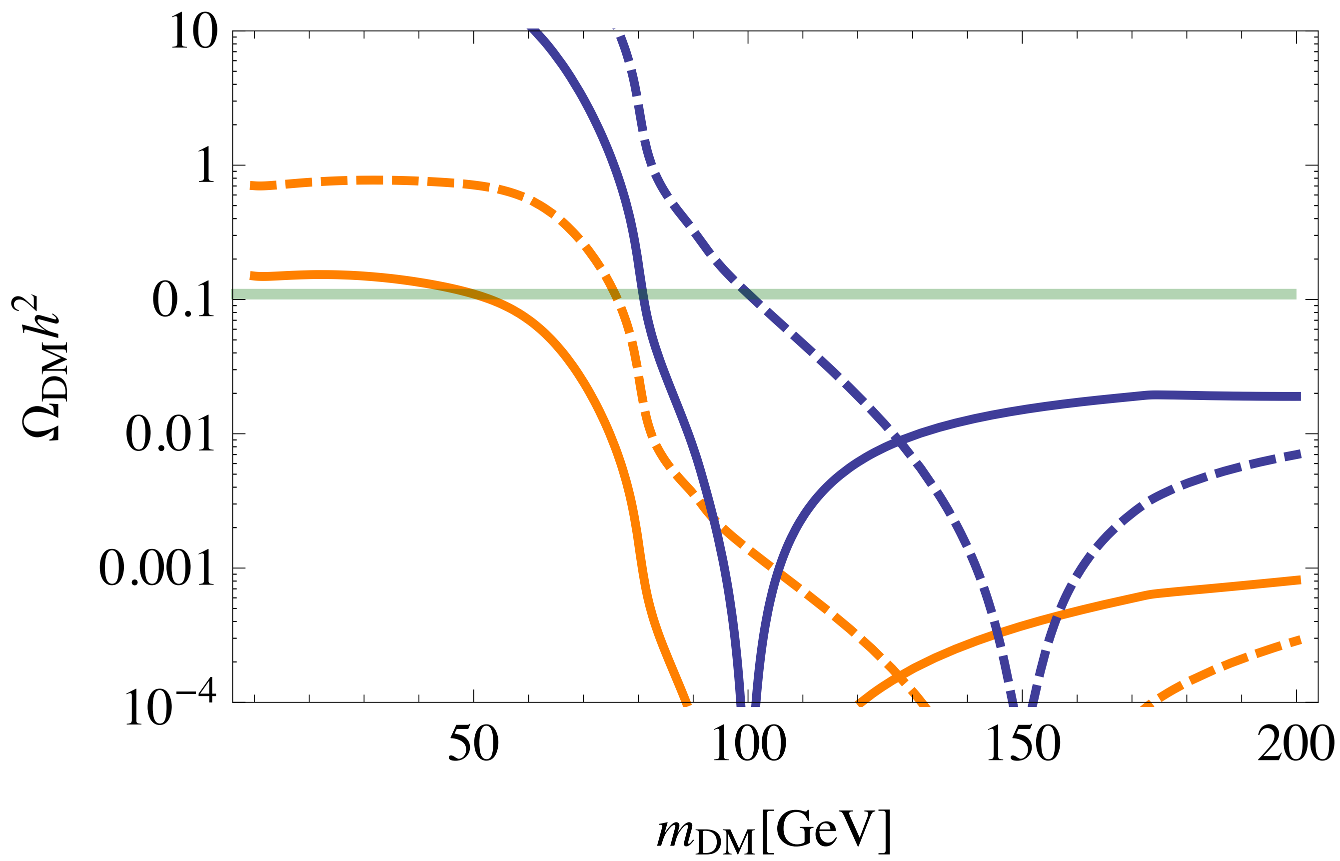
- "Higgs portal" DM
- E.g. scalar: McDonald, 1994; many others or fermion: Cirelli, Fornengo, Strumia, 2005 Lee, Kim, 2006
- Annihilation purely through Higgs:

$$(\sigma v)_{SS \to X_{\rm SM}} = \frac{2\lambda_s^2 v^2}{(4m_s^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} \, \frac{\Gamma_{h\to {\rm SM}}(m_h = 2m_s)}{2m_s} \,,$$

$$(\sigma v)_{\psi\psi \to X_{\rm SM}} = v_{\rm rel}^2 \frac{\tilde{\lambda}_f^2 m_f^2}{(4m_f^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} \, \frac{\Gamma_{h\to {\rm SM}}(m_h = 2m_f)}{2m_f} \,,$$

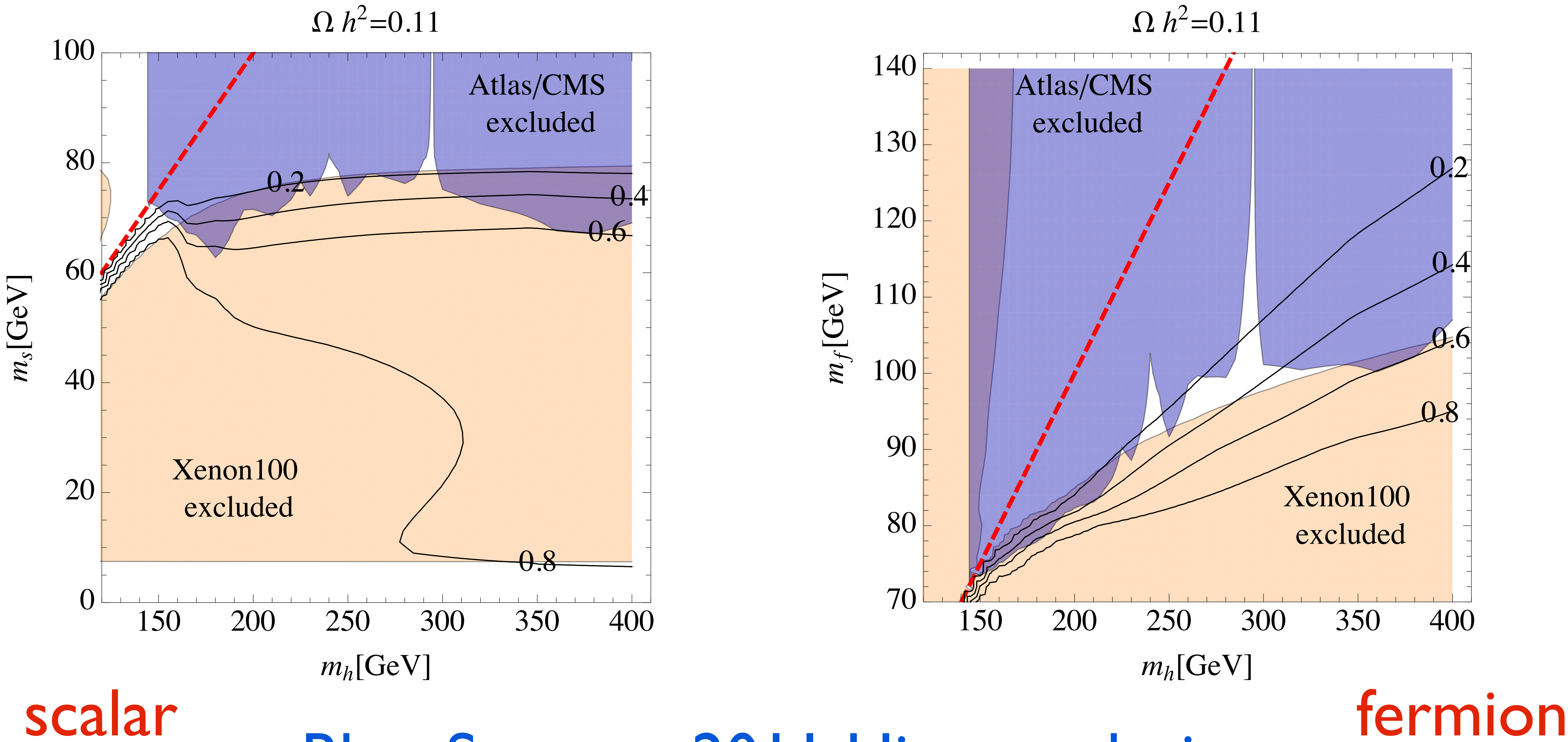
CONSTRAINTS

- Relic density: $\lambda, \tilde{\lambda} = 1$
  - scalar (red): better below WW treshold
  - fermion (blue): better above WW threshold



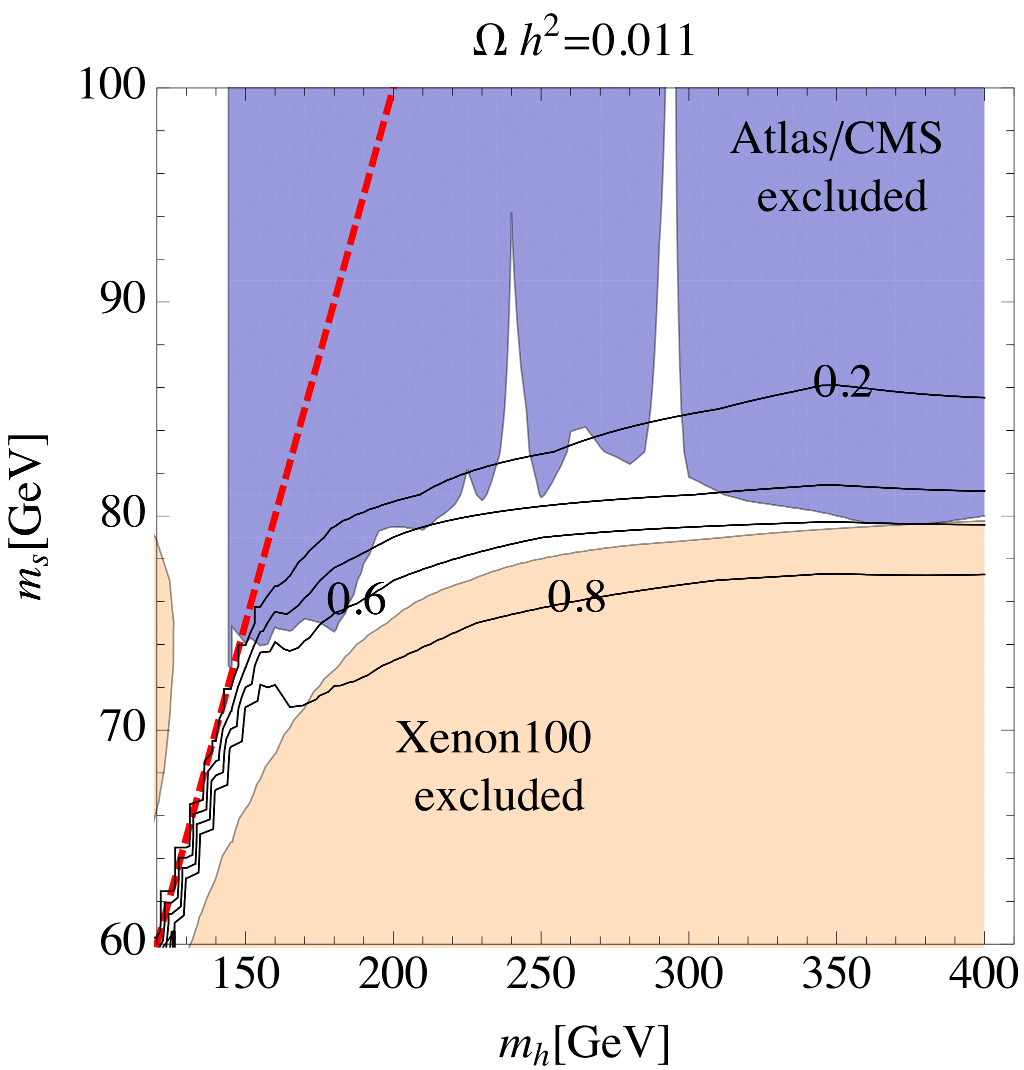
- Strategy:
  - pick Higgs mass m_h and dark matter mass $m_{\rm DM}$
  - determine coupling through relic density, then impose LHC, Xenon100 constraints

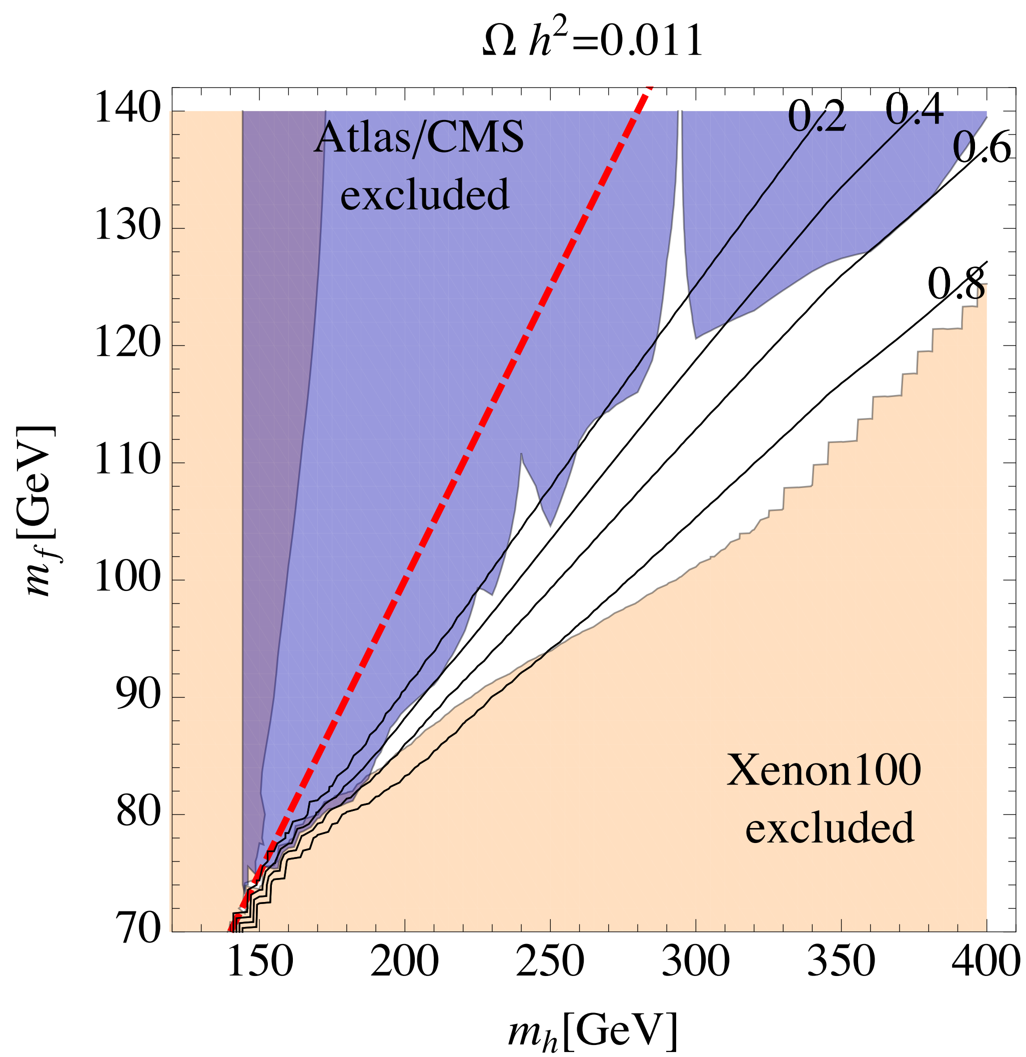
HIGGS + DM SEARCH LIMITS



Blue: Summer 2011 Higgs exclusion
Full 2011 data excludes this scenario, except for 125 GeV Higgs region

HIGGS + DM SEARCH LIMITS





scalar

fermion

Heavy Higgs allowed if relic density constraint is relaxed: large invisible width!

NOW WHAT?

- For $m_h > 200\ \mathrm{GeV}$, hard to fully suppress all modes
- Eventually, we will see it in $h \to ZZ \to 4\ell$
- Reduced rate, might be due to
  - increased total width, i.e. smaller ZZ, WW branchings
  - reduced production cross section

→ **measure/constrain the width**

HIGGS LINESHAPE

Low, PS, Shaughnessy, Wagner, 2011

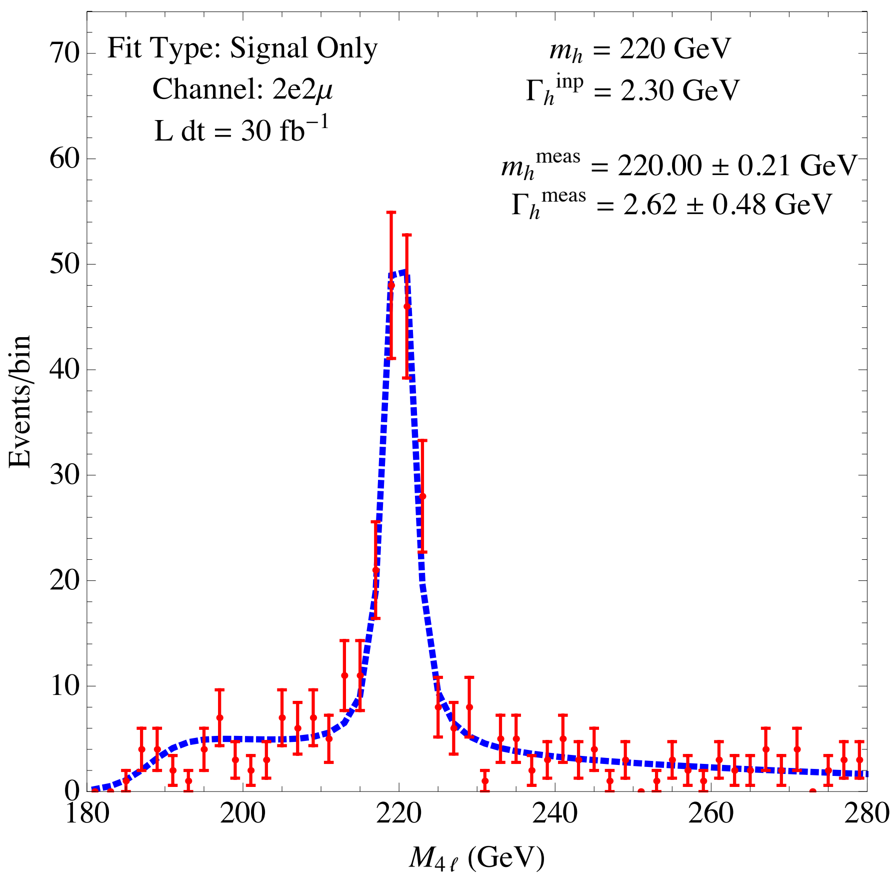
- Can be measured in

$$h \to ZZ \to 4\ell$$

- Modified Breit-Wigner shape:

$$\frac{d\sigma_l}{d\sqrt{\hat{s}}} \sim A\sqrt{\hat{s}}^3 \frac{\sqrt{1-4x_Z}(1-4x_Z+12x_Z^2)}{((\hat{s}-M_h^2)^2+M_h^2\Gamma_h^2)}$$

$$x_Z = m_Z^2/\hat{s}$$



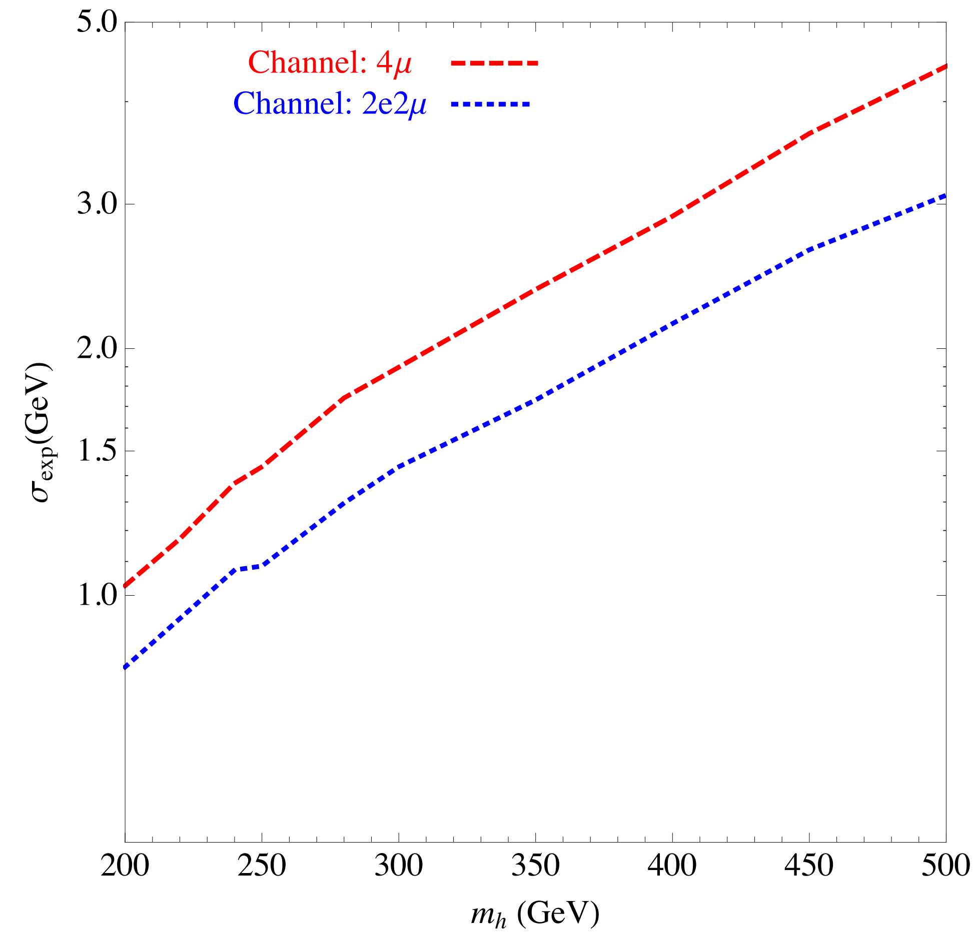
- Need to understand exp. resolution

RESOLUTION

- Electron/muon momentum uncertainty (CMS):

$$\left(\frac{\Delta p}{p}\right)_\mu = 0.84\% \oplus 1\% \left(\frac{p_T}{100\ \text{GeV}}\right) \qquad \left(\frac{\Delta p}{p}\right)_E = 0.26\% \oplus \frac{2.8\%}{\sqrt{p/\text{GeV}}} \oplus \frac{12.4\%}{p/\text{GeV}}$$

  - Generate zero width events, smear, fit to gaussian
  - Determine detector "lineshape"
  - Exp. width grows with Higgs mass, $ee\mu\mu$ more accurate



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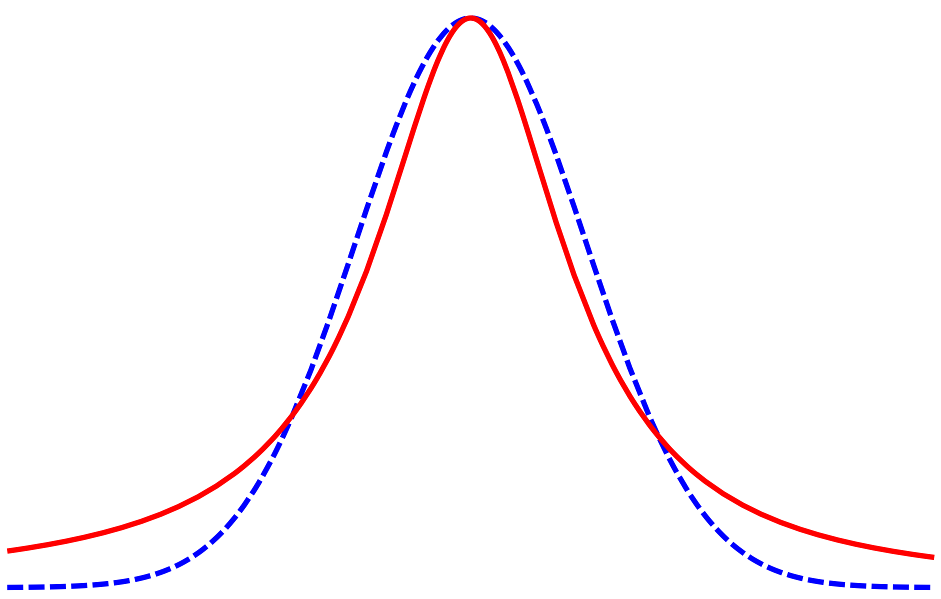
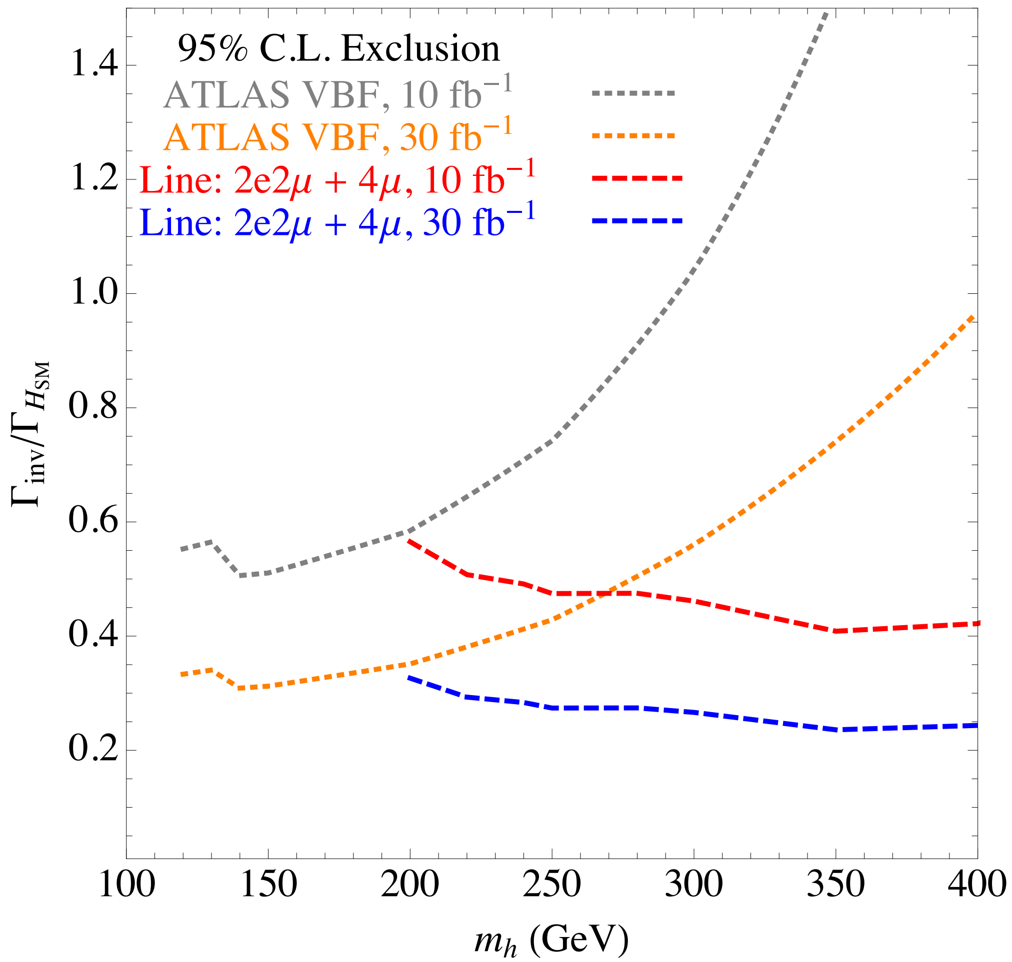
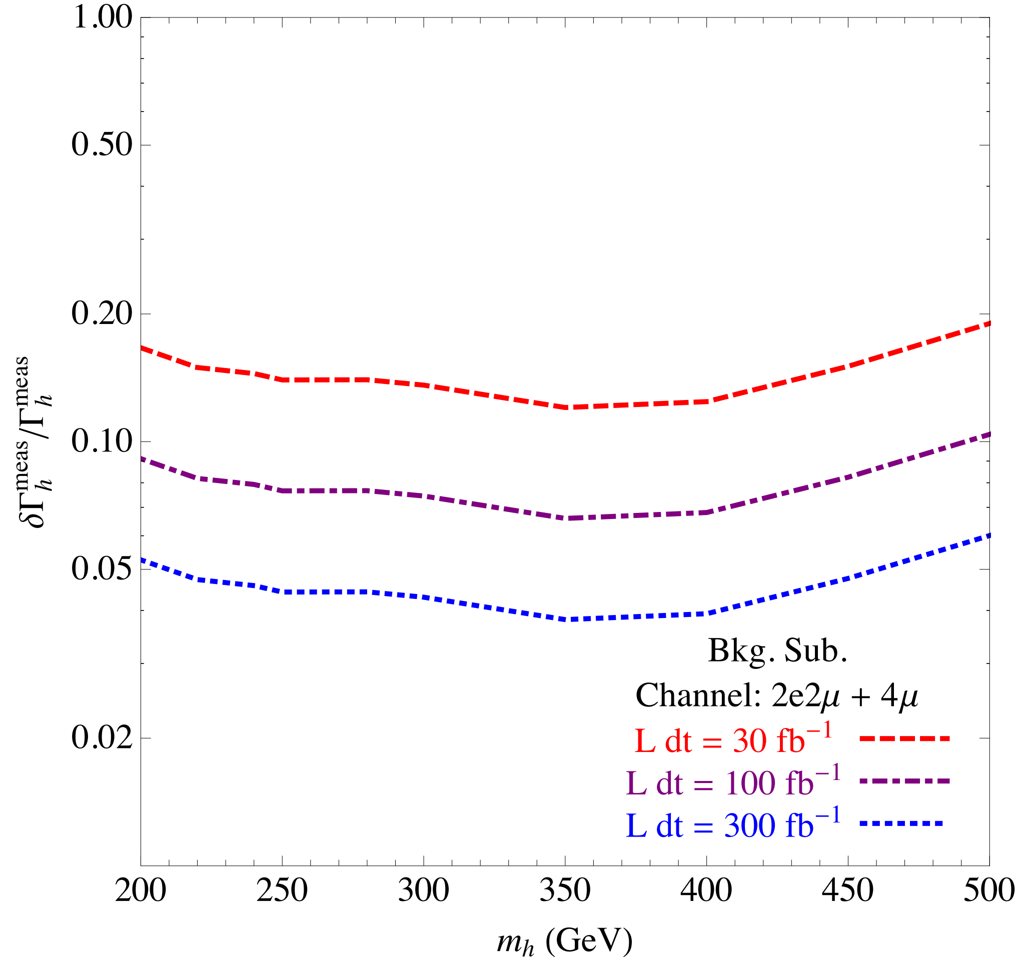
- Gaussian vs. Breit Wigner:
  - quite similar
  - fit convolution of Breit-Wigner and Gaussian
  - width measurement possible down to $\Gamma \sim \sigma_{\mathrm{exp}}$, if we trust the detector simulation



RESULTS

$\sqrt{s} = 14\ \mathrm{TeV}$





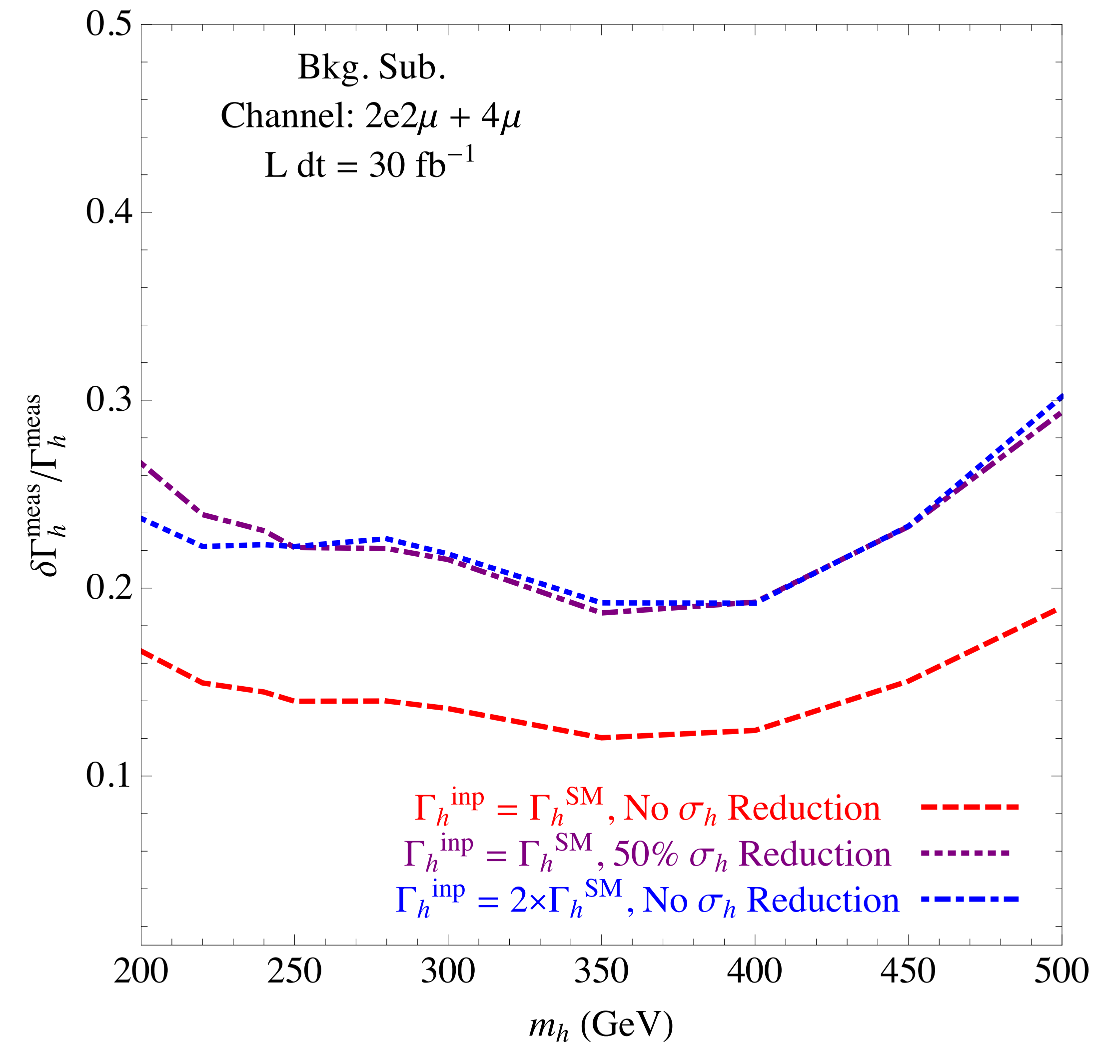
- Comparable or better than VBF reach for Γ_{inv}

VBF studied e.g. in Davoudiasl, Han, Logan 2005; ZH, WH in Eboli, Zeppenfeld, 2000

- Accurate probe of Higgs width with 300 fb^{-1}

WITH 50% REDUCED RATE

- Either reduced production cross section (purple) or
- Invisible decay, increased total width (blue)
- Small difference for $m_h < 250$ GeV otherwise just statistical effect and decreased S/B



CONCLUSIONS

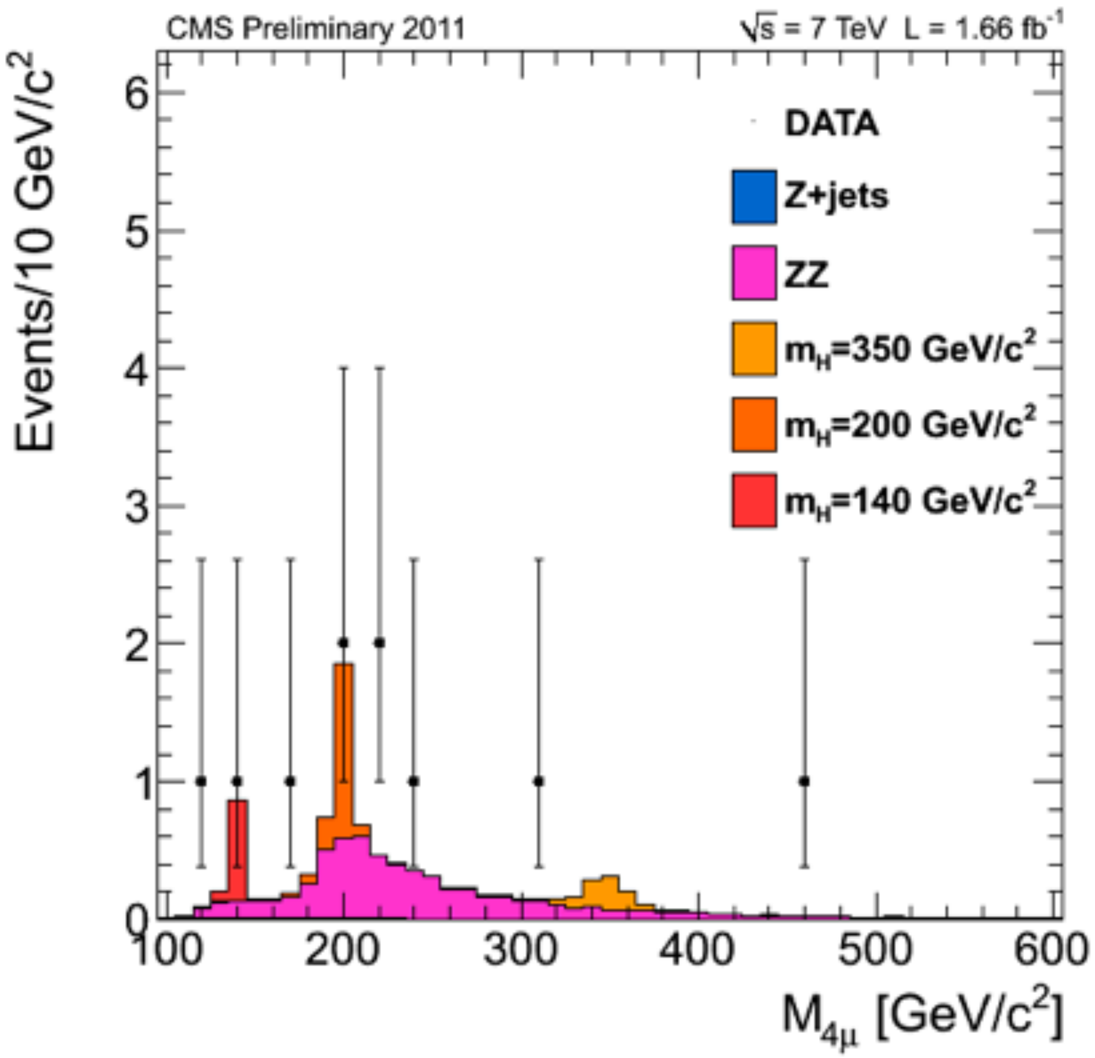
- Intermediate mass Higgs bosons viable if they have a sizable invisible width
- Simple models compatible with Higgs portal dark matter strongly constrained now
- Width can be probed using the $h \to ZZ \to 4\ell$ lineshape, more sensitive than VBF for large of Higgs masses

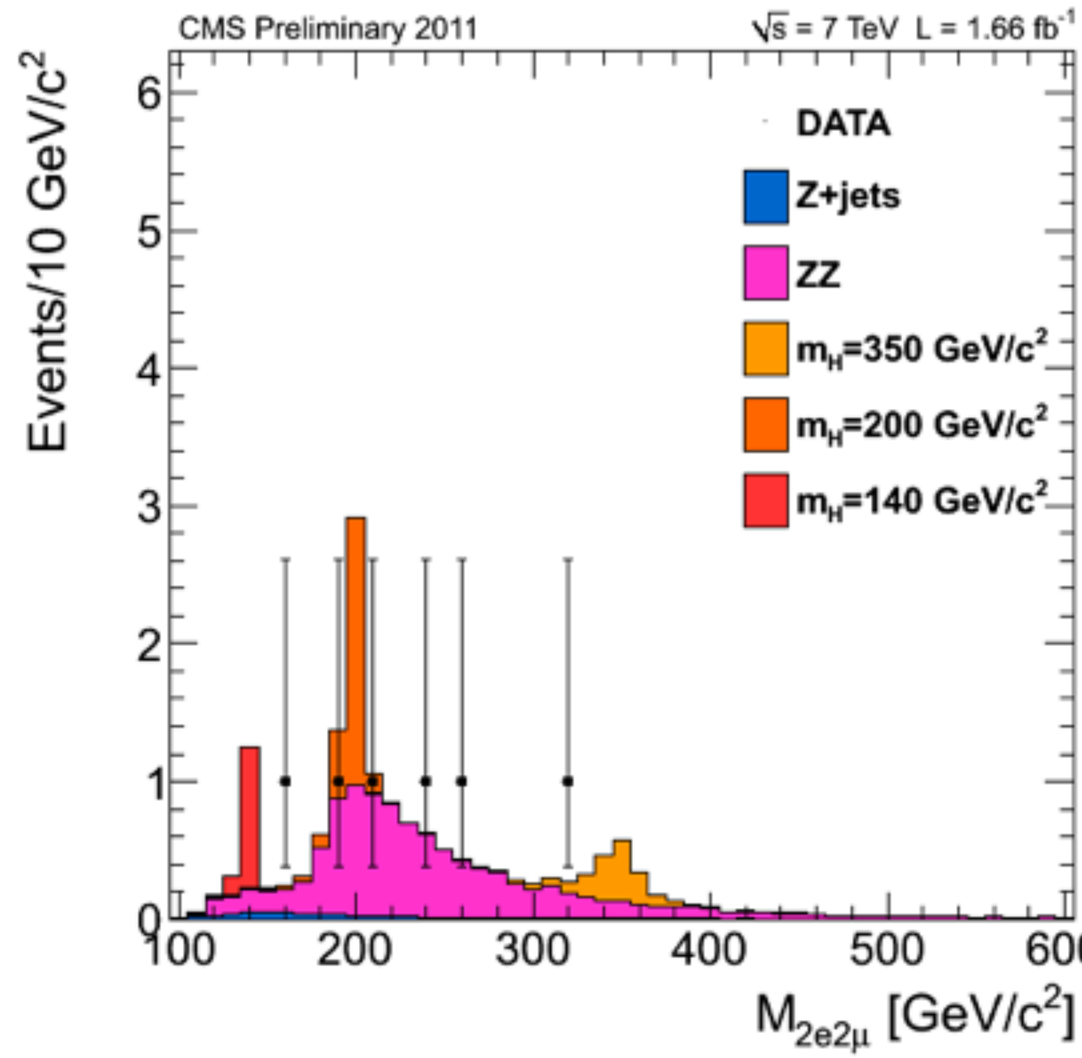
if we find it...

Thanks for your attention!

Backup

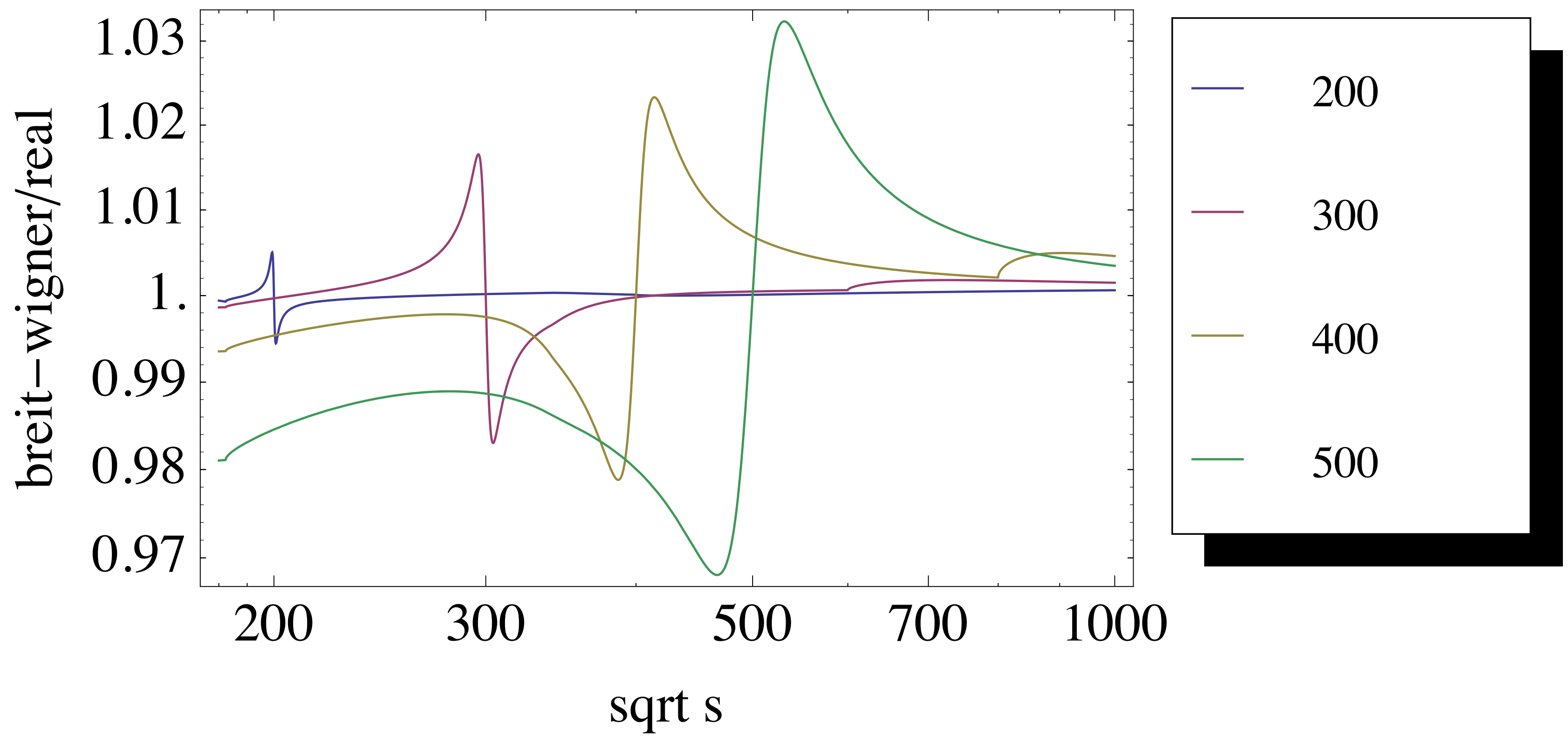
CMS, HIGGS TO 4 LEPTON





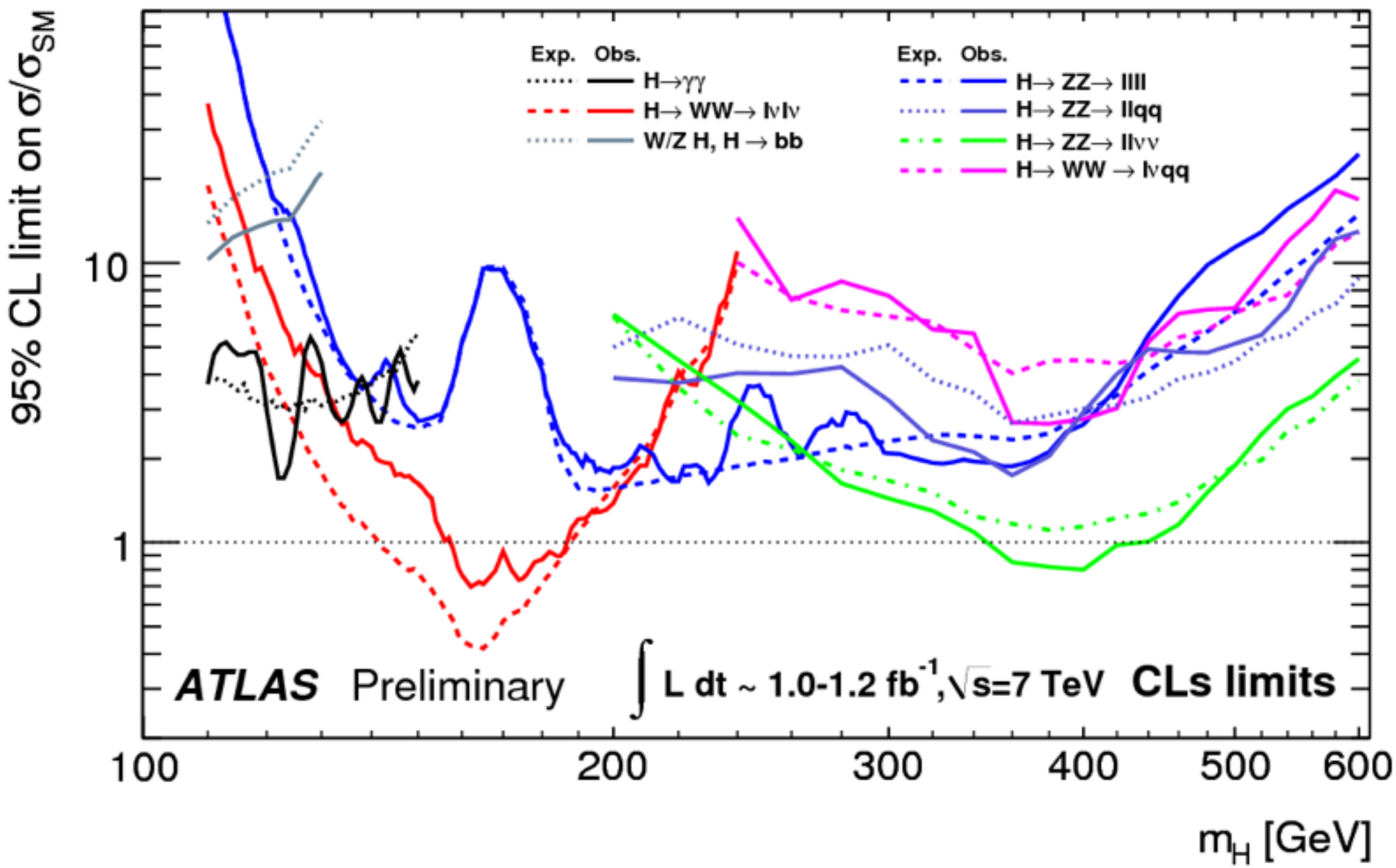
LINESHAPE AT NLO

- using results of Papavassiliou & Pilaftsis



  - Deviation small as long as width < 0.2 mass
  - Sensitivity only at linear (muon) collider

ATLAS COMBINATION



MEASURING HIGGS PROPERTIES

- Understanding of modified Higgs cross section requires measurement of couplings to gauge bosons, fermions

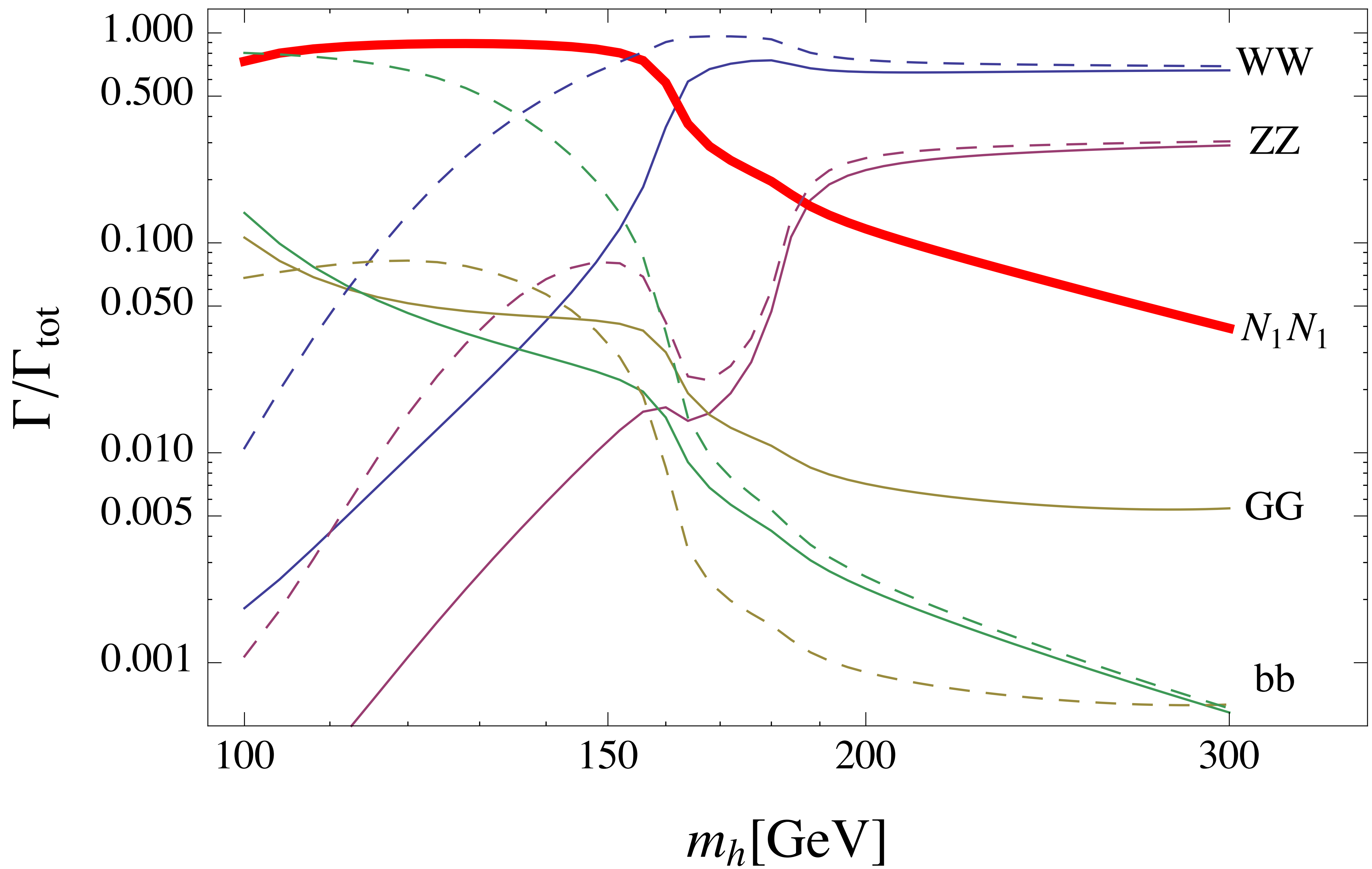
- Combination of many channels, in particular also need VBF and associated Higgs production

- For us, a bit easier: What can we learn from the $h \to ZZ \to 4\ell$ lineshape?

Low, PS, Shaughnessy, Wagner, 2011

HIGGS DECAYS (DIRAC N1)

Keung, PS, 2011

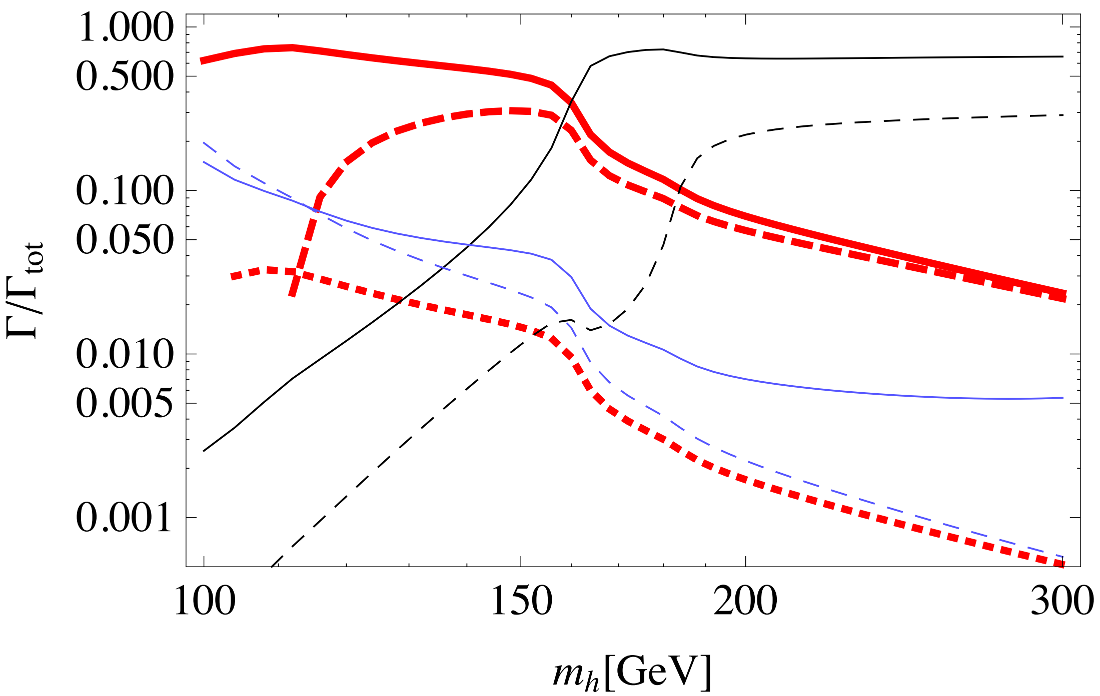


$$M_1 = M_2 = 45 \text{ GeV}$$

HIGGS DECAY (MAJORANA N1)

Keung, PS, 2011

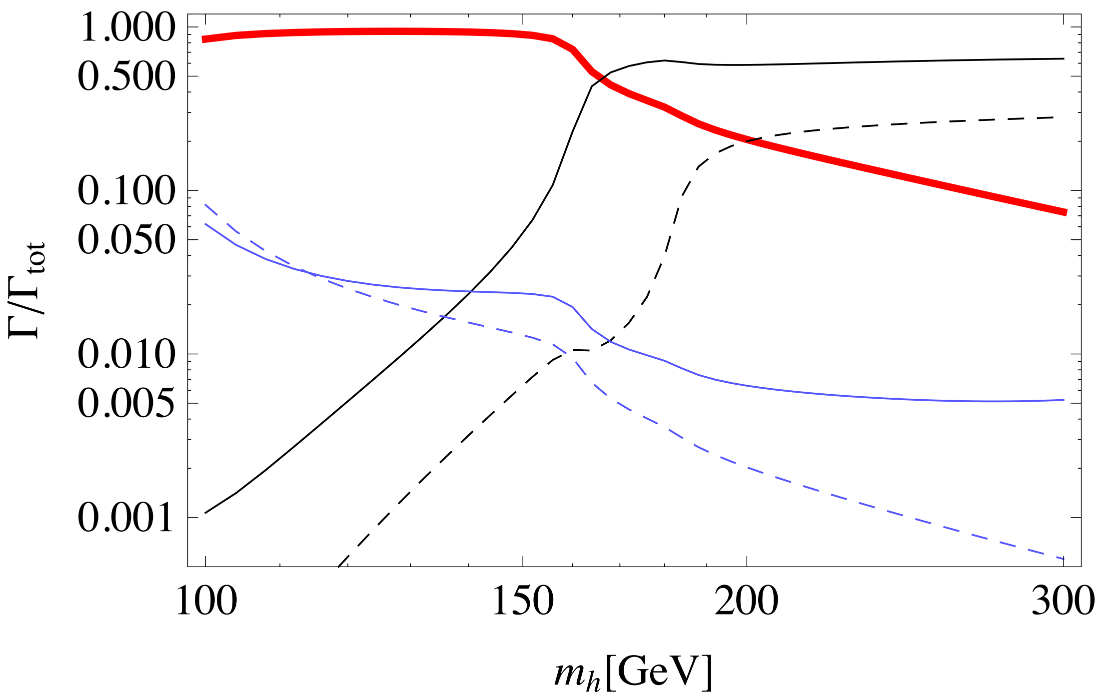
mixed Dirac/Majorana



$$M_1 = 45 \text{ GeV}$$

$$\Delta M = 20 \text{ GeV}$$

pure Majorana

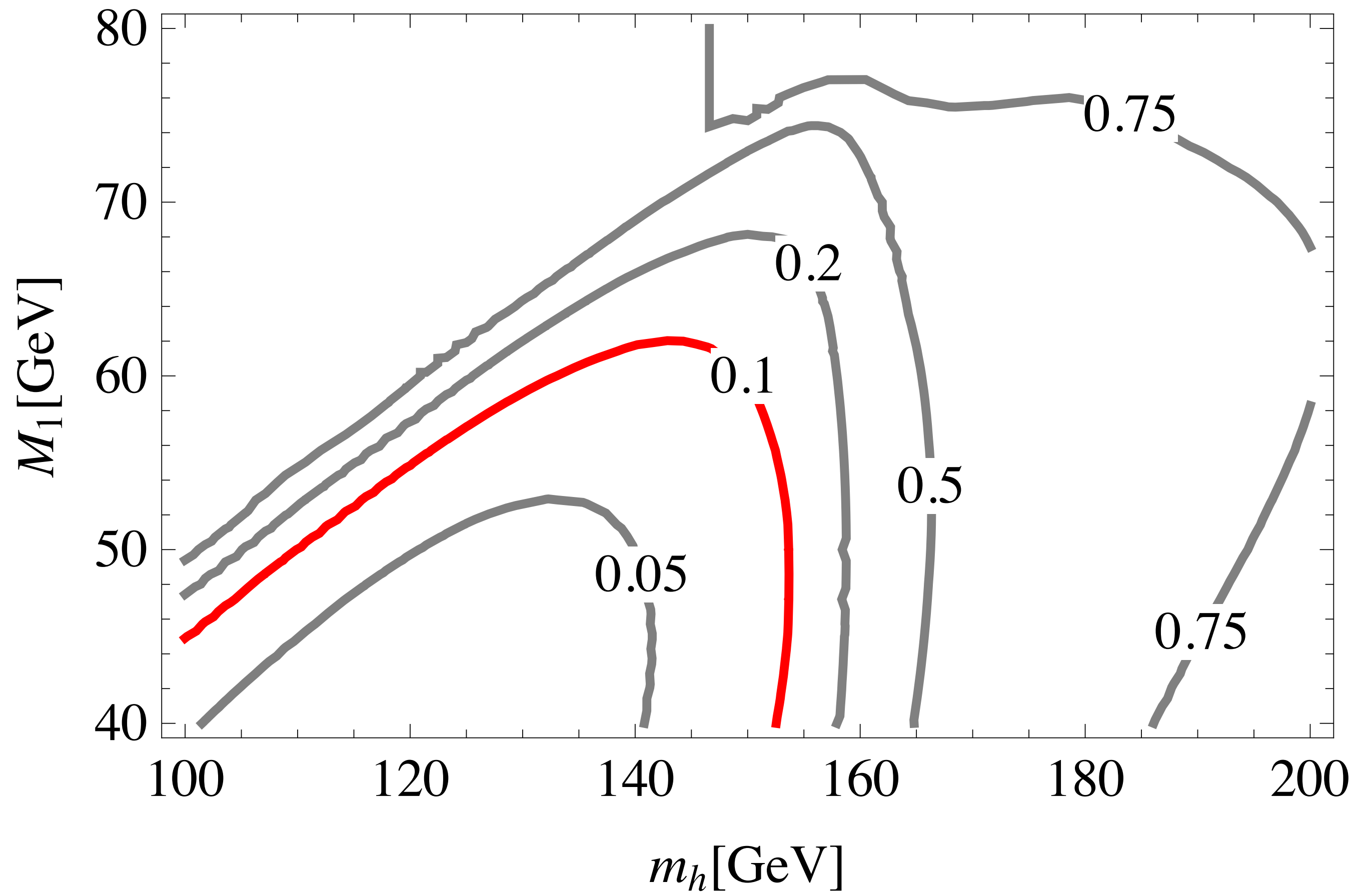


$$M_1 = 45 \text{ GeV}$$

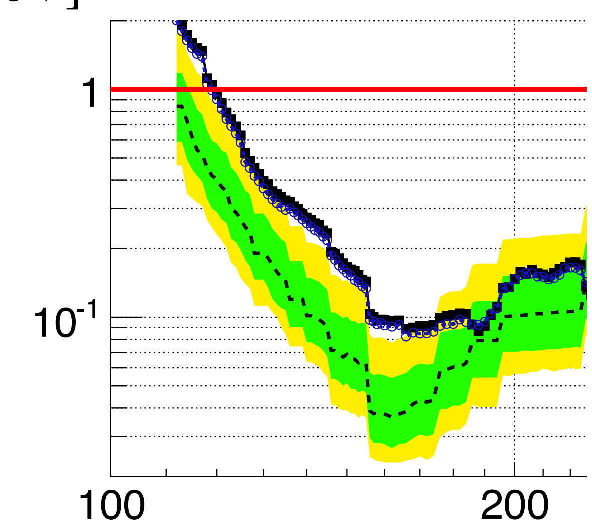
$$M_2 \gg M_1$$

THE ACTUAL 4G-HIGGS EXCLUSION

- Reduction of $h \to WW^*$ branching fraction



- Includes enhanced $h \to gg$



- With $M_1 \sim 50$ GeV, resurrect 4G Higgs masses below 150 GeV