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The Dark Side of the Higgs Boson

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May 7, 2012

Pheno 2012

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Phys. Rev. D85 15009

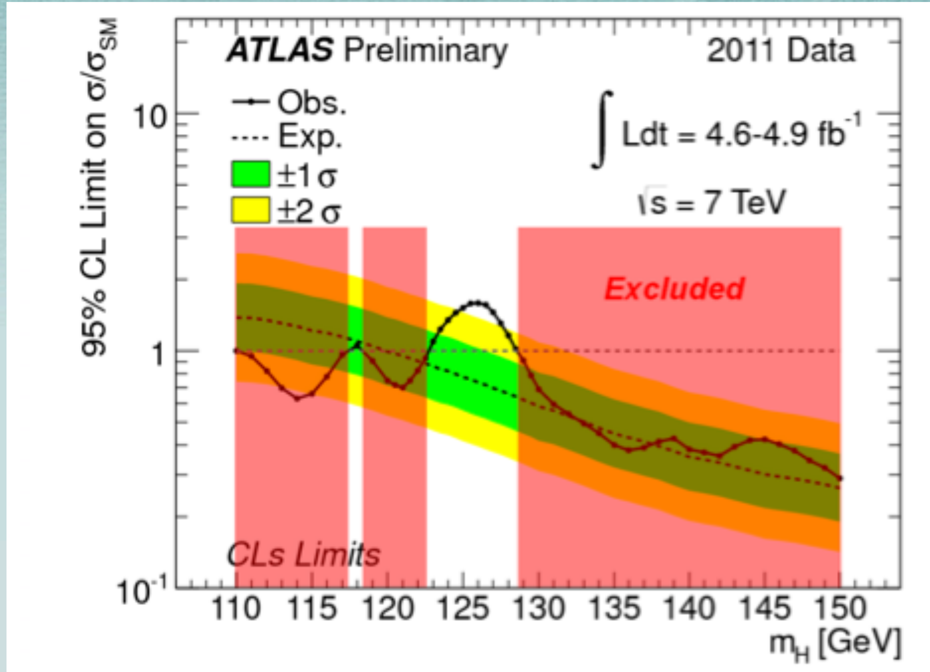
Recent Higgs boson searches

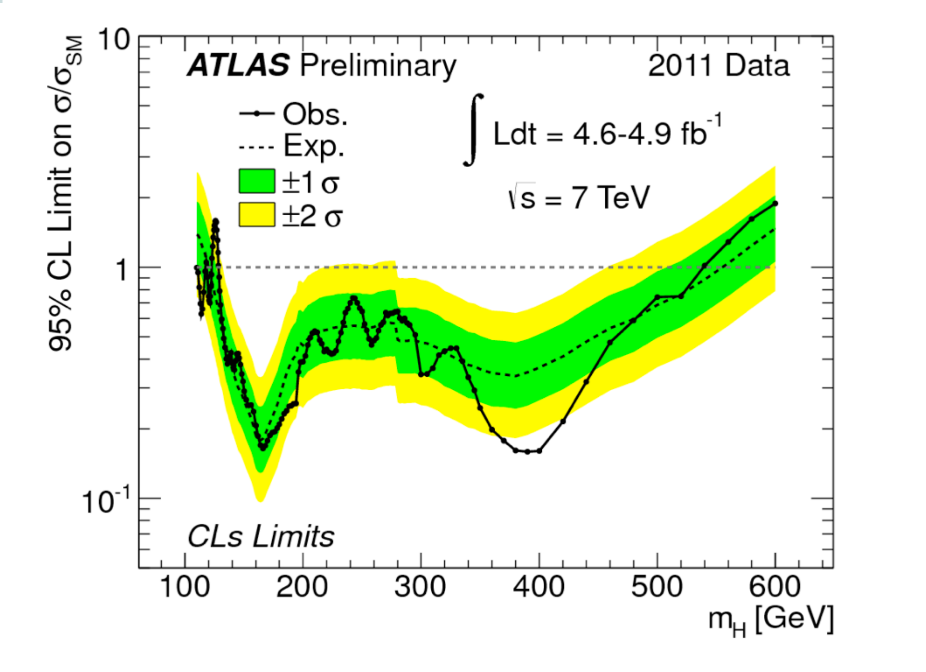
- The Higgs appears evasive
  - Could be in the last place we look!

- Curious $> 2\sigma$ excess seen around 125-126 GeV in both ATLAS and CMS

- What is it? 3 choices:
  - The Higgs!
  - Nothing - just statistics
  - Some other resonance

- Huge 'desert' above 130 GeV up to >500 GeV excludes a SM Higgs





Can a SM Higgs still exist in this mass range?

- SM Higgs signature is modified by two possible effects:
  - Change in production rate (i.e. through mixing)
  - Change in BF to final state signature*

$$B\sigma(pp \to h \to X_{SM}) = \sigma(pp \to h) \times BF(h \to X_{SM})$$

- Coupling strength to decay modes assumed unchanged:

$$\Gamma^{SM}_{h \to X_{SM}} = \Gamma_{h \to X_{SM}}$$

- Modifications to production of signature distilled to changes in the Briet-Wigner lineshape of the Higgs Boson

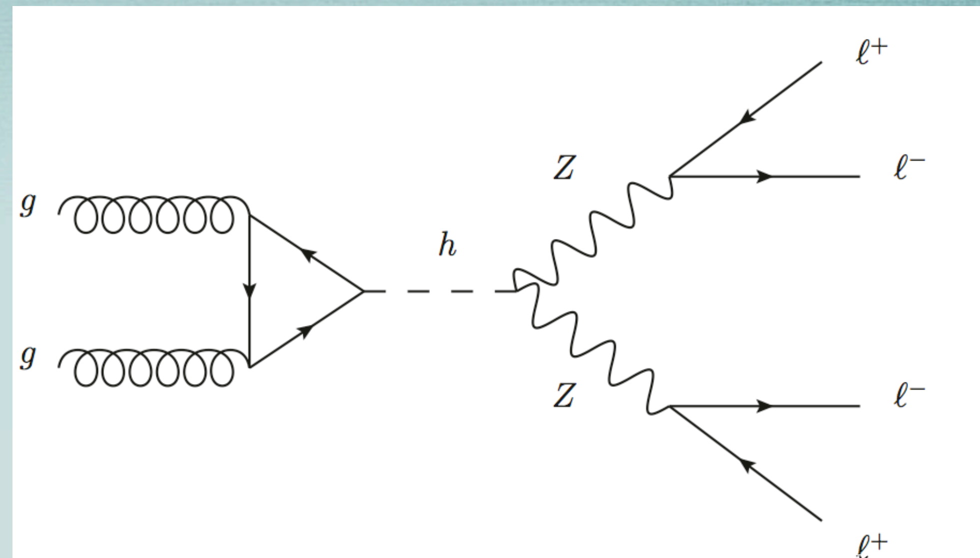
$$B\sigma(pp \to h \to X_{SM}) = B\sigma^{(SM)}(pp \to h \to X_{SM}) \times \frac{\Gamma_{h_{SM}}}{\Gamma_{h_{SM}} + \Gamma(h \to X_{NP})}$$

- Present searches push the new physics (NP) contribution for intermediate masses to be: $\Gamma(h \to X_{NP}) \gtrsim \Gamma(h \to X_{SM})$

- Measuring the Higgs BW line offers insight to the Higgs coupling to new physics!

Measuring the golden channel line

- Best possible route to measure line is via the golden channel



- Key is excellent momentum resolution of leptons:

$$\left(\frac{\Delta p}{p}\right)_\mu = 0.84\% \oplus 1\% \left(\frac{p_T}{100\ \text{GeV}}\right)$$

$$\left(\frac{\Delta p}{p}\right)_e = \frac{2.8\%}{\sqrt{p/\text{GeV}}} \oplus 12.4\% \frac{\text{GeV}}{p} \oplus 0.26\%$$

- We apply separate cuts for $\mu^+\mu^-\mu^+\mu^-$ and $e^+e^-\mu^+\mu^-$ channels

- Best performer is the $e^+e^-\mu^+\mu^-$ channel:

$$\begin{aligned} n_{e^\pm}^{\text{tagged}} &= 2, \quad n_{\mu^\pm}^{\text{tagged}} = 2, \\ p_T(\ell_1) &> 50\ \text{GeV}, \quad p_T(\ell_2) > 35\ \text{GeV}, \\ p_T(\ell_3) &> 25\ \text{GeV}, \quad p_T(\ell_4) > 10\ \text{GeV}, \\ 55\ \text{GeV} &< M_{e^+e^-,\mu^+\mu^-} < 107\ \text{GeV}, \end{aligned}$$

Prominent backgrounds

$Z + Z^*/\gamma^*, Zb\bar{b},$ and $t\bar{t}$

Cuts offer good background rejection

Events simulated for Signal (Madgraph) and Background (Alpgen)

ZZ K-factor = 1.6 for background (MCFM)

Fitting the Higgs Lineshape

- Lineshape at its core is a Briet-Wigner expression

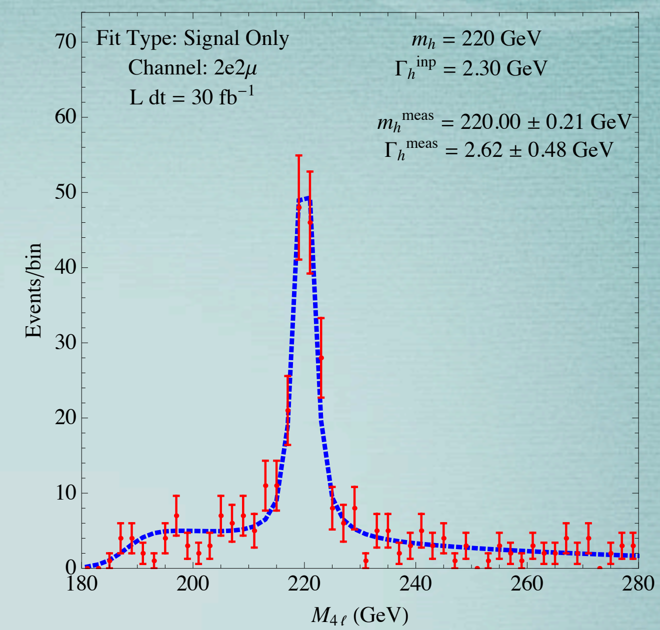
$$\frac{d\sigma_{\rm BW}(\sqrt{\hat{s}})}{dM_{4\ell}} = \frac{\hat{s}^{3/2}\sqrt{1-4x_Z}(1-4x_Z+12x_Z^2)}{((\hat{s}-M_h^2)^2+M_h^2\Gamma_h^2)},$$

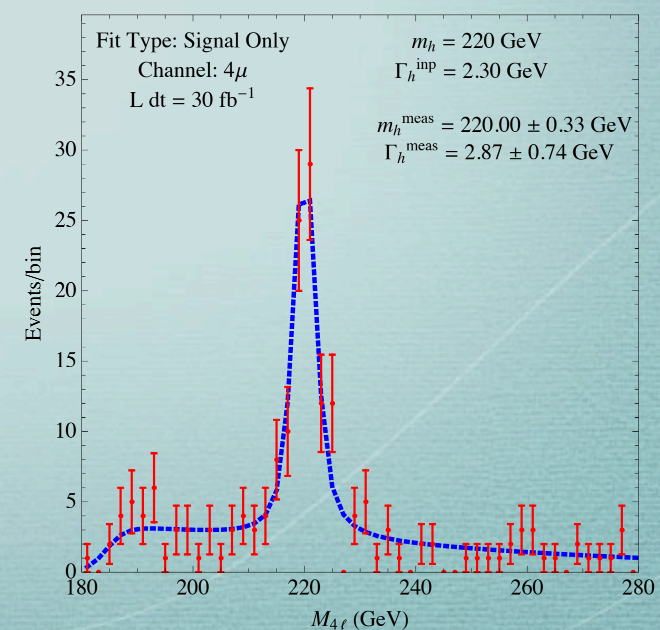
- Experimental measurement is broadened by detector effects. We assume a broadening consistent with

$$\frac{d\sigma_{\rm Gauss}(M')}{dM_{4\ell}} = \frac{1}{\sqrt{2\pi}\sigma_{\rm exp}} e^{-\frac{M'^2}{2\sigma_{\rm exp}^2}},$$

- We fit the simulated lineshape to the convolution of the intrinsic lineshape and the experimental broadening:

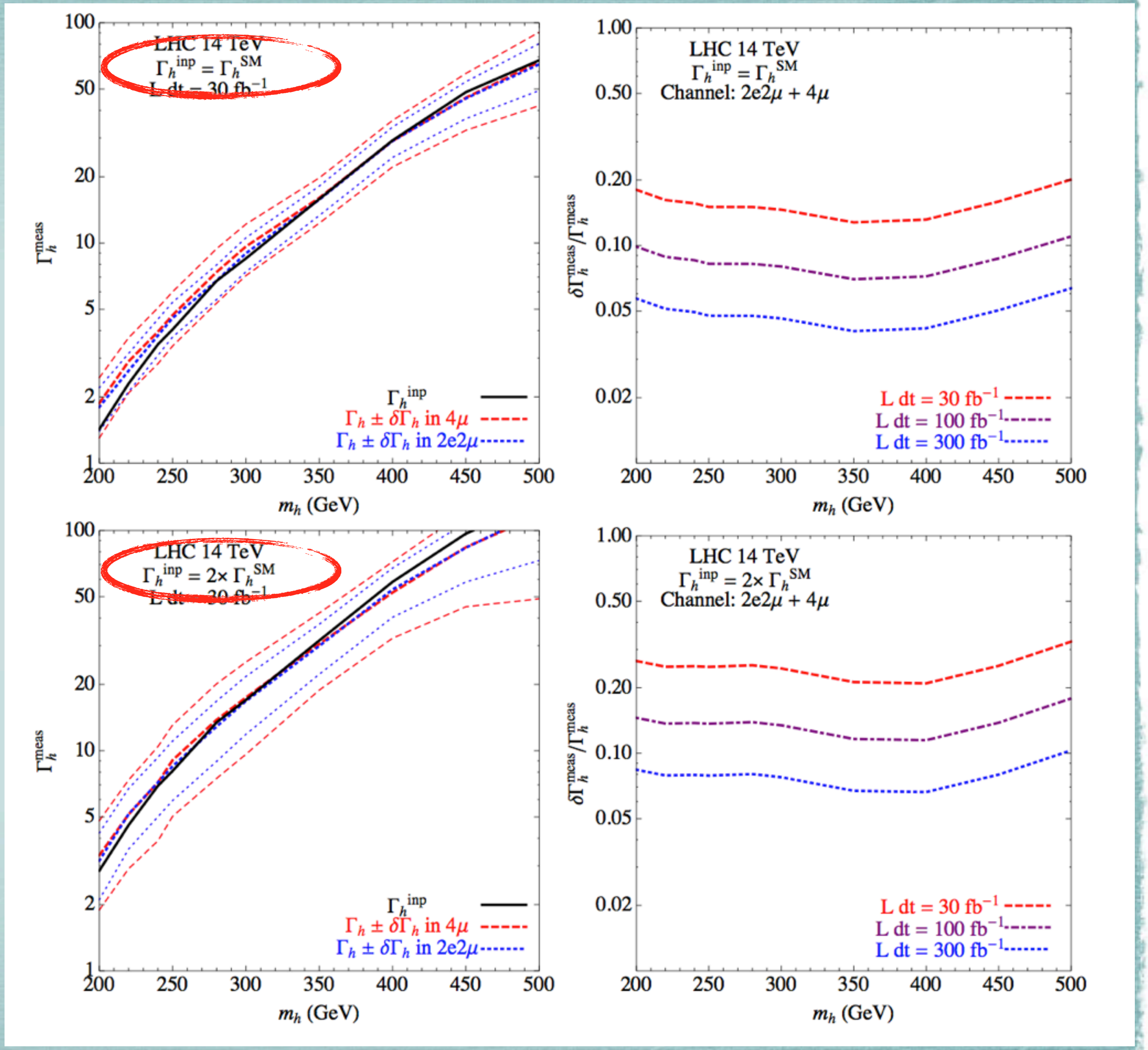
$$\frac{d\sigma}{dM_{4\ell}} = \int dM' \frac{d\sigma_{\rm BW}(\sqrt{\hat{s}}-M')}{dM_{4\ell}} \frac{d\sigma_{\rm Gauss}(M')}{dM_{4\ell}}$$





Higgs line measurements

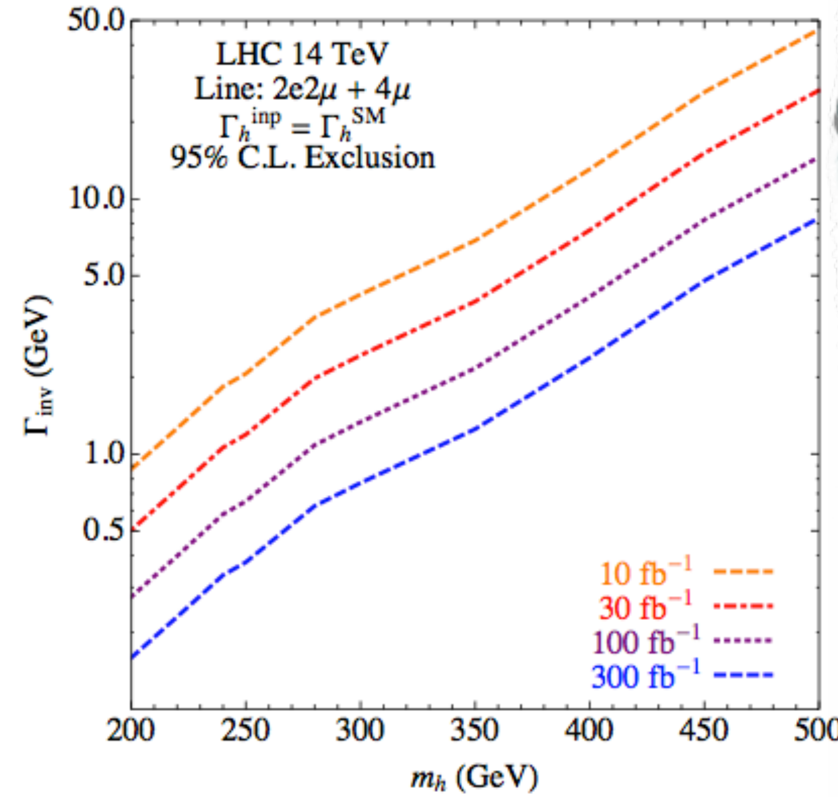
- $\mu^+\mu^-\mu^+\mu^-$ less sensitive than $e^+e^-\mu^+\mu^-$ due to event rate, ID and momentum resolution
- Combining channels gives O(20%) sensitivity for SM-like width
- Doubling width decreases sensitivity due to decreased event rate



Invisible Higgs decay searches

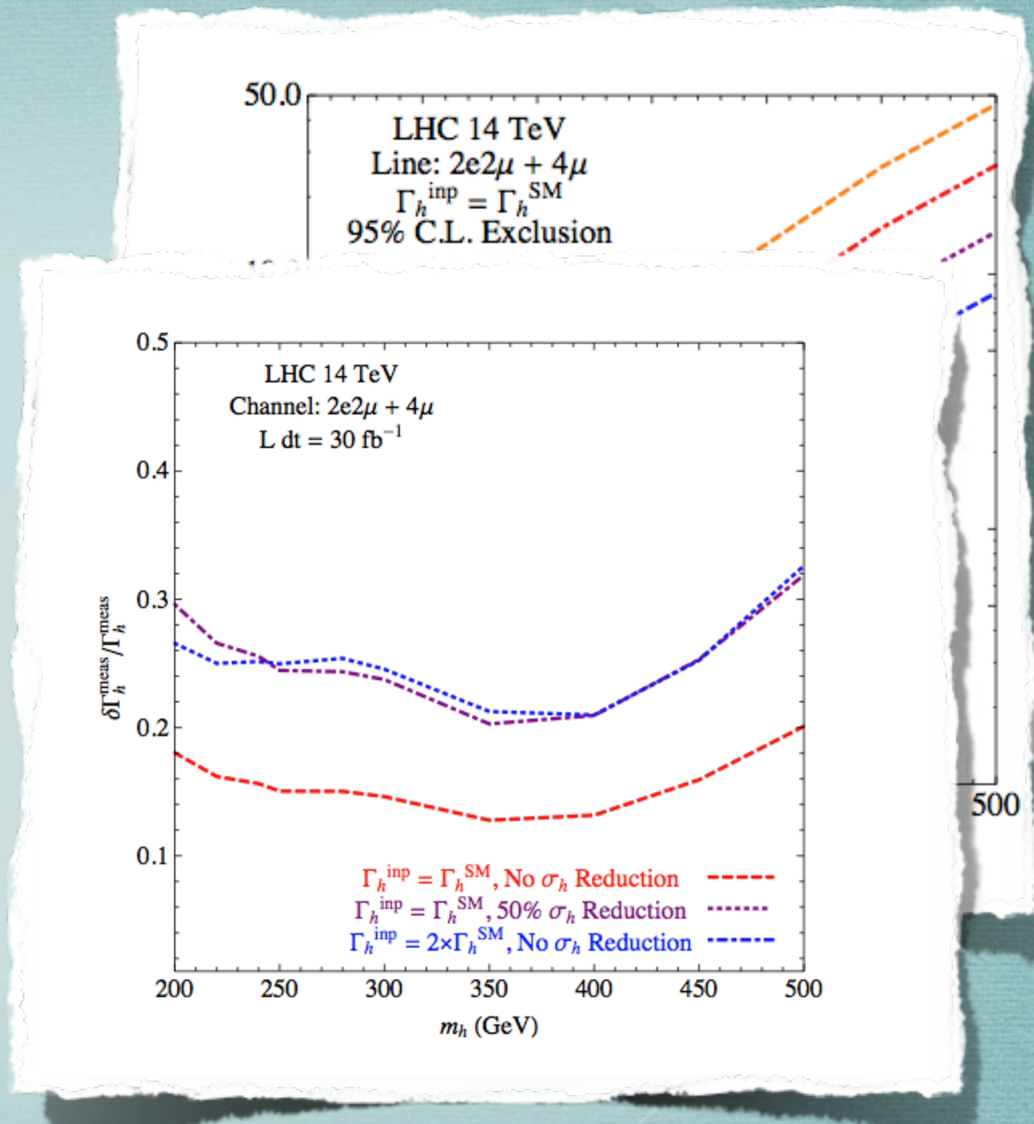
Invisible Higgs decay searches

- If the only new physics decay is invisible, connection to dark matter sector may be possible
- Excess in total width compared with SM prediction seen as the invisible decay width



Invisible Higgs decay searches

- If the only new physics decay is invisible, connection to dark matter sector may be possible
- Excess in total width compared with SM prediction seen as the invisible decay width
- Similar scenarios:
  - Doubling of total width (invisible decay)
  - Reduction of production cross section (Higgs-singlet mixing, NP in $gg \to h$
- Degeneracy broken with coupling measurements + Γ_h measurement

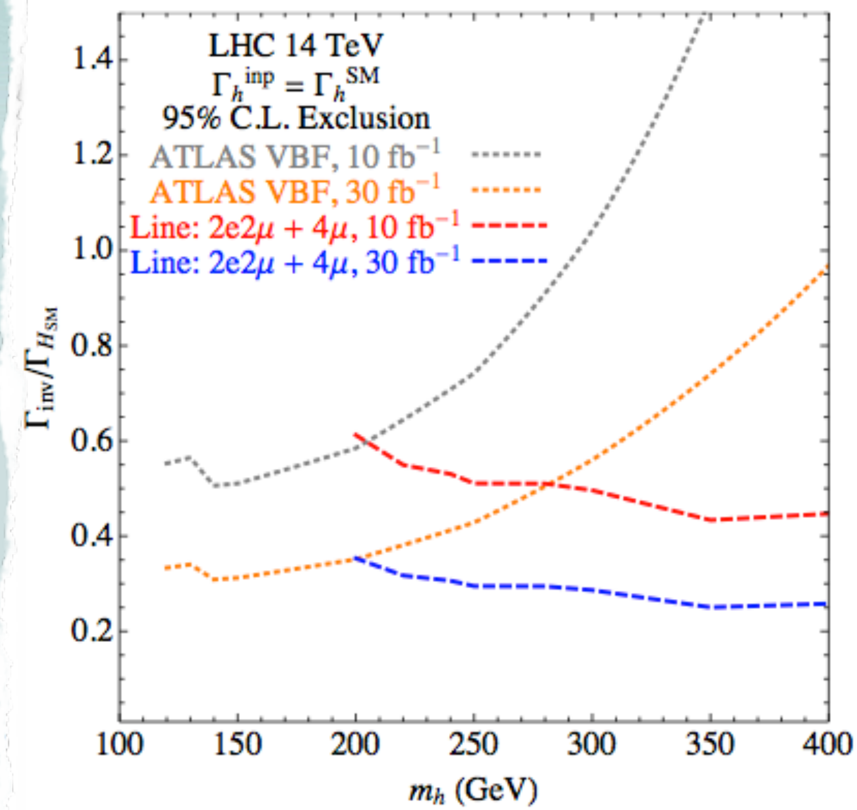


Comparison with other methods

- Direct invisible decay searches involve Vector Boson Fusion
  - Relies heavily on correlated forward jets
  - Best sensitivity to low mass Higgs

Eboli, Zeppenfeld (2000)

- Line measurement offers complementary probe if new physics decay mode is invisible
- Relatively constant sensitivity to larger masses
  - Balance between lower production cross section and larger total SM Higgs width



Connection to Dark Matter

- Higgs connection to DM can be written as

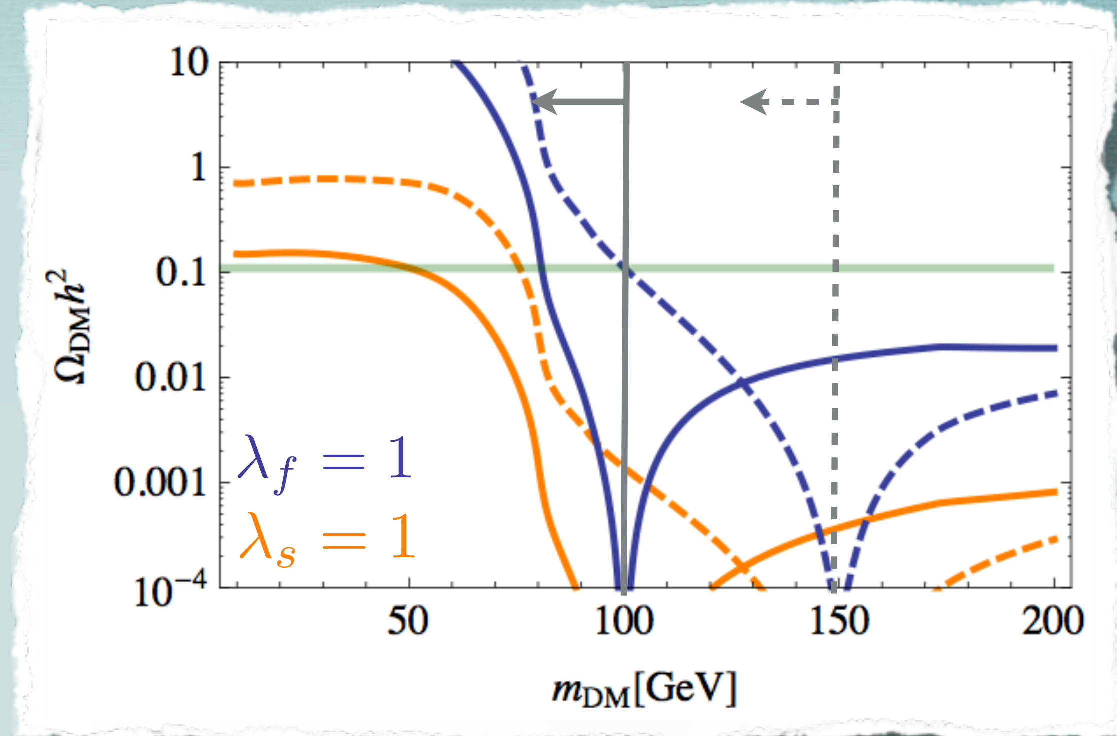
$$\mathcal{L} = \delta_c\, m_s^2 |S|^2 + \delta_c\, \lambda_s H^\dagger H |S|^2$$

$$\mathcal{L} = \delta_c\, m_f \bar{\psi}\psi + \delta_c\, \frac{\lambda_f}{\Lambda} H^\dagger H \bar{\psi}\psi$$

- Decay widths to fermionic/scalar DM

$$\Gamma_{ff} = \delta_c\, \frac{1}{8\pi} \tilde{\lambda}_f^2\, m_h \left(1 - \frac{4m_f^2}{m_h^2}\right)^{3/2}$$

$$\Gamma_{ss} = \delta_c\, \frac{\lambda_s^2 v^2}{16\pi m_h} \sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

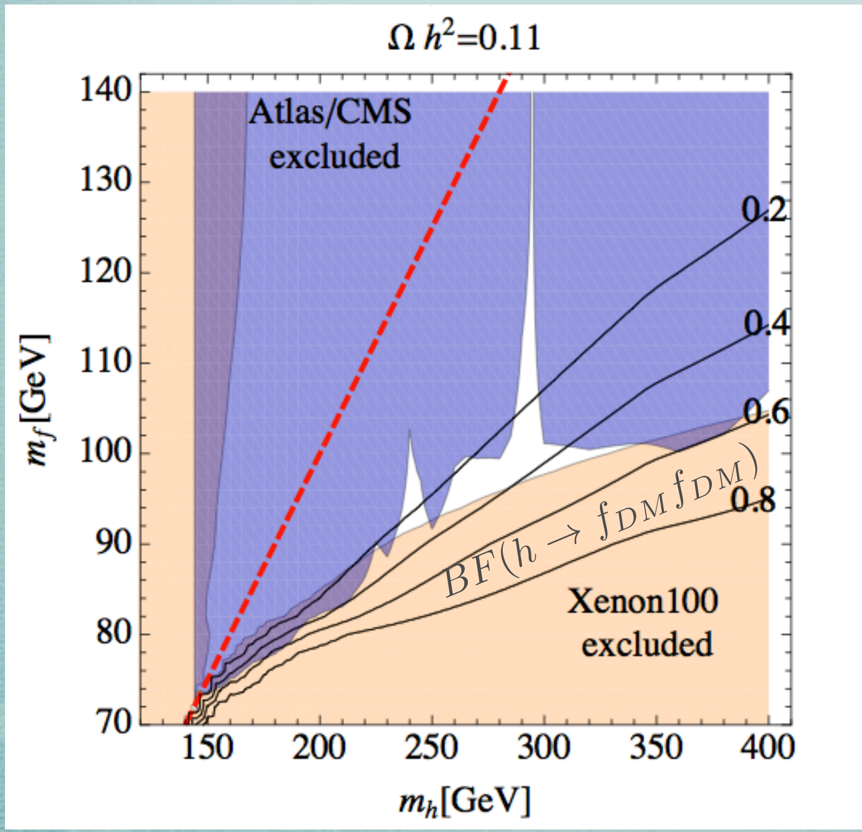


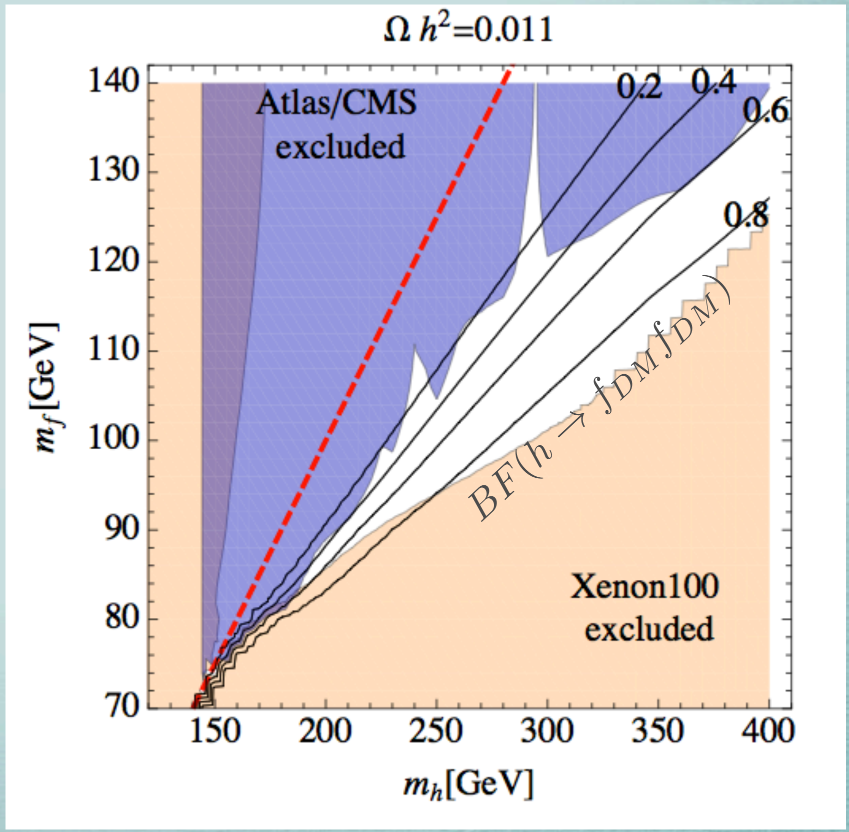
- Threshold for decay to DM requires $m_h > 2m_{DM}$

Dark Matter Consistency

- If DM saturates relic density, tension between direct detection limits from Xenon-100 and the ATLAS/CMS Higgs exclusion

- Tension lessened if invisible state assumed not to be the sole contributor to DM relic density





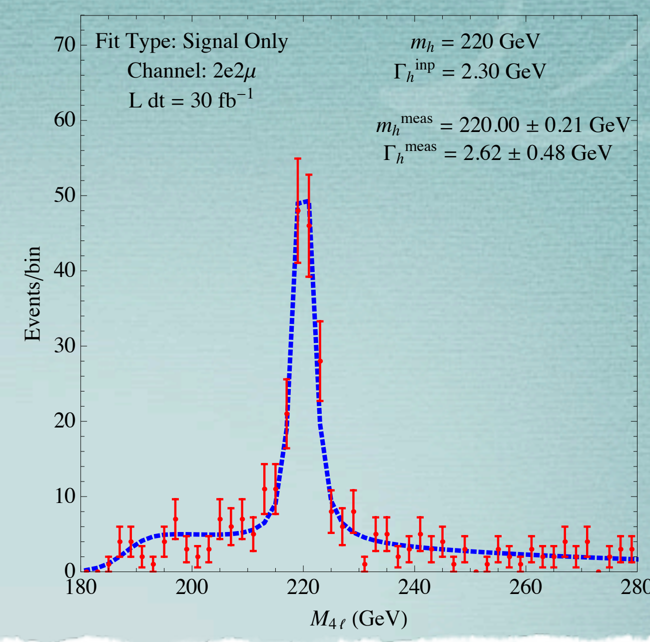
Summary

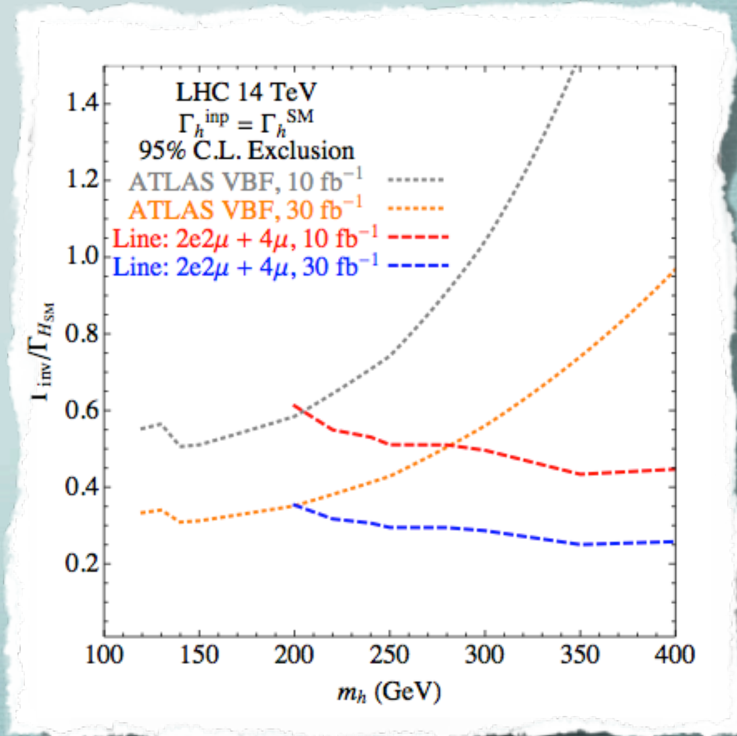
- A moderate to heavy Higgs can be accommodated w/in the ATLAS and CMS results by allowing the Higgs to decay to new physics

- The Higgs decay lineshape can offer insight to new physics and its connection with the EWSB sector

- In context of invisible states like DM, the reach is complementary to the direct searches via Vector Boson Fusion

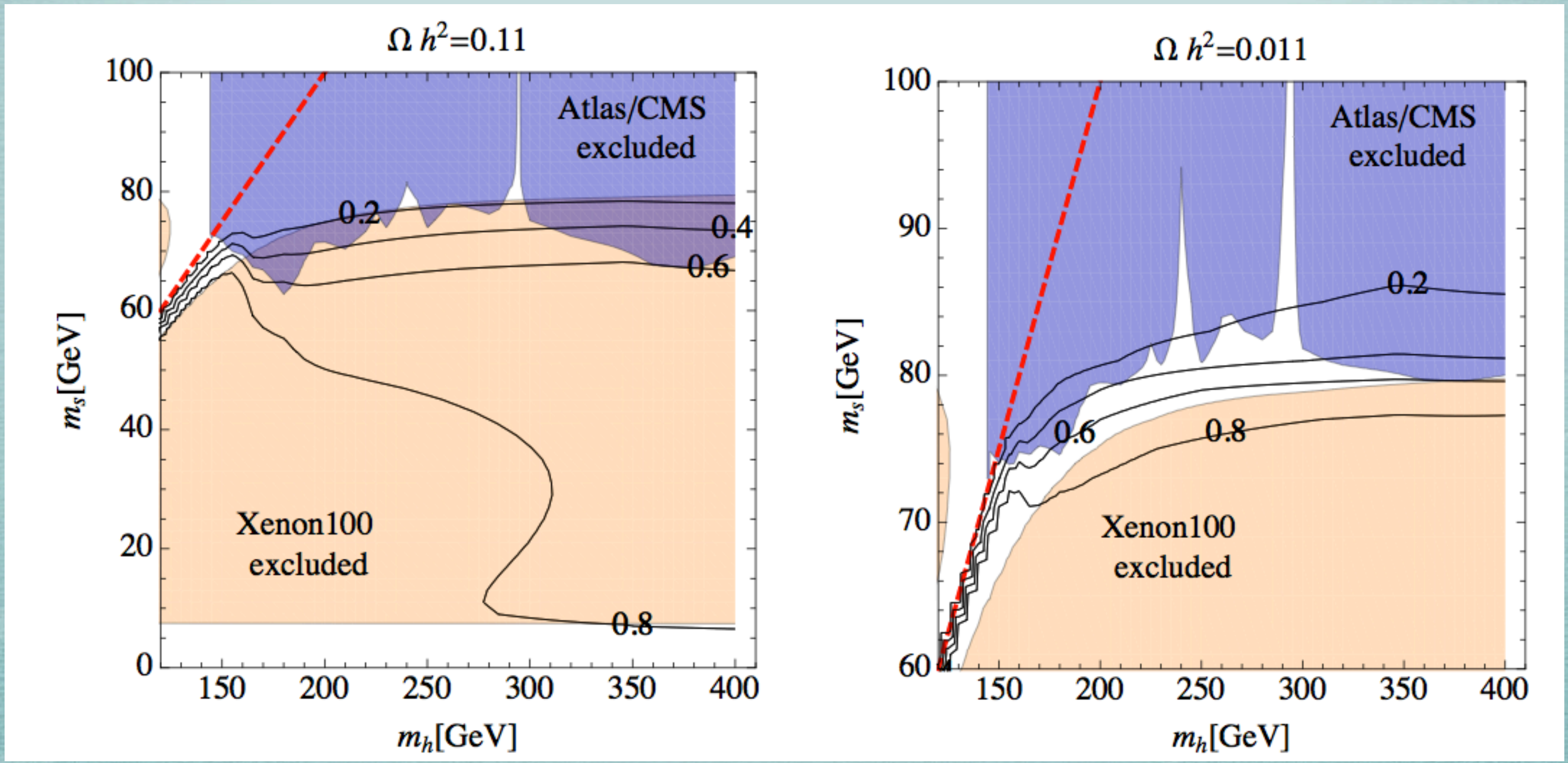
- One shouldn't prematurely dismiss the heavy Higgs scenario!





Backup Slides

Scalar Dark Matter



Partial width Reach

- Luminosity required to exclude enhanced width
  - By increasing width, smaller production of signal is compensated for by wider lineshape