$\mathbf{H} \to \mathbf{4}\ell$ *at the LHC :*
constraints on Abelian Hidden sector models

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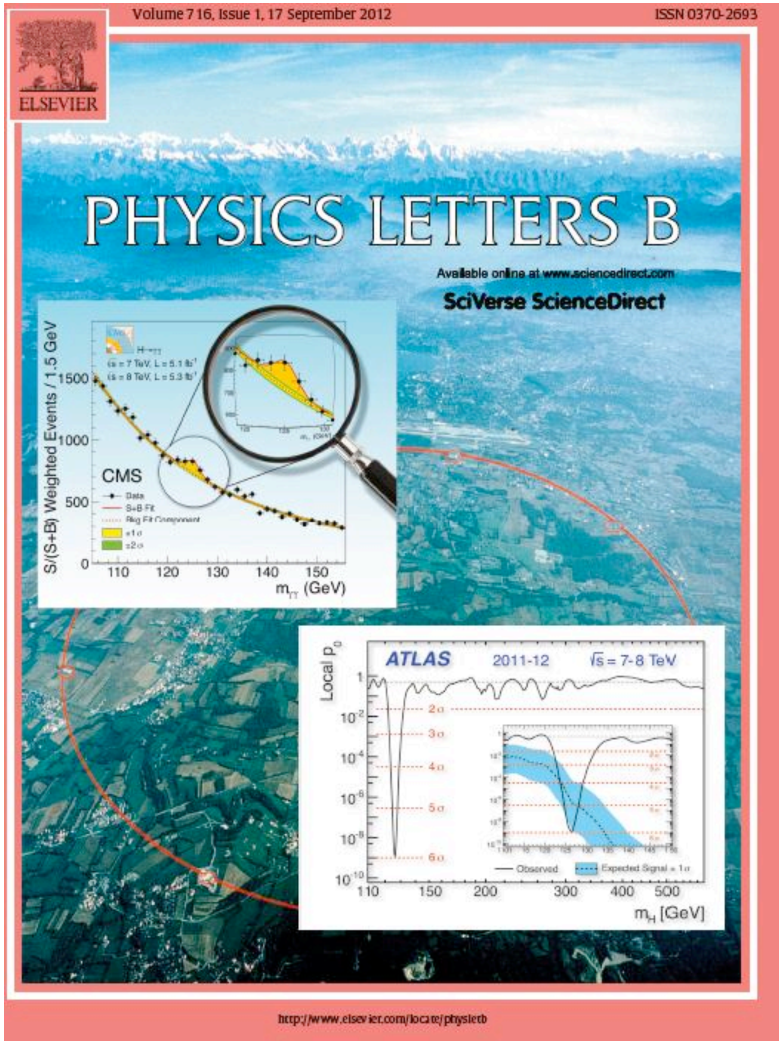
- Introduction and motivations
- Hidden Abelian Higgs model (HAHM) (*Wells et al.*)
  - Higgs and Gauge boson mixings
  - Phenomenology
  - Possible experimental searches
- Reinterpreting ATLAS/CMS results
  - Higgs mixing angle and hidden width
  - Higgs mixing angle and new gauge boson mass
- Conclusion and outlook

References

- Model :
  - J.D. Wells, *How to find a hidden world at the large hadron collider*, **arXiv:0803.1243, 2008**.
  - S. Gopalakrishna, S. Jung, and J.D. Wells, *Higgs boson decays to four fermions through an abelian hidden sector*, **Physical Review D, 78(5): 055002, 2008**.
- Experimental results from ATLAS and CMS :
  - The ATLAS Collaboration, *Observation of a new particle in the search for the standard model higgs boson with the ATLAS detector at the LHC*, **Physics Letters B, 2012**.
    - and updates from HCP
  - The CMS Collaboration, *Observation of a new boson at a mass of 125 gev with the CMS experiment at the LHC*, **Physics Letters B, 2012**.
    - and updates from HCP



- Experimental results
  - Discovery
  - Mass, spin/CP, signal strength, couplings
  - For now, μ is compatible with 1 in the 2 experiments

- Measurement of couplings and signal rate
  - SM Higgs ?
  - Other ?
  - Can the current measured rate provide some insight already ?

Hidden Abelian Higgs Model (HAHM) (1)

- Hidden sector coupled to the SM through kinetic mixing
- Strength of the coupling : parameter $\eta \ll 1$
- Benchmark point is $\eta \sim 10^{-4}$, consistent with EW precision measurements

Lagrangian in the Higgs sector :

$$\mathcal{L}_\Phi = |D_\mu \Phi_{\rm SM}|^2 + m^2_{\Phi_{\rm SM}} |\Phi_{\rm SM}|^2 - \lambda |\Phi_{\rm SM}|^4 \quad \longrightarrow \sim \text{SM}$$

$$+ |D_\mu \Phi_X|^2 + m^2_{\Phi_X} |\Phi_X|^2 - \rho |\Phi_X|^4 \quad \longrightarrow \text{Hidden sector}$$

$$- \kappa |\Phi_{\rm SM}|^2 |\Phi_X|^2 \quad . \quad \longrightarrow \text{Mixing}$$

Higgs mixing :

$$\begin{pmatrix} \Phi_{\rm SM} \\ \Phi_X \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

Mixing angle — Mass eigenstates

- ✓ Fairly general process
- ✓ Exists in other models
- ✓ For small mixing ($s_h^2 \ll 1$), H_1 is SM-like

$$M^2_{H_1,H_2} = (\lambda v^2 + \rho \xi^2) \mp \sqrt{(\lambda v^2 - \rho \xi^2)^2 + \kappa^2 v^2 \xi^2}$$

Hidden Abelian Higgs Model (HAHM) (2)

- We can now specify what is the Hidden sector and its mixing to the SM
- $U(1)_X$ gauge group for the HAHM model proposed by *Wells et al.*

Gauge boson mixing :

$$\begin{pmatrix} B \\ W^3 \\ X \end{pmatrix} = \begin{pmatrix} c_W & -s_W c_\alpha & s_W s_\alpha \\ s_W & c_W c_\alpha & -c_W s_\alpha \\ 0 & c_\alpha & s_\alpha \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix}$$

A, Z: ~ SM

Z': Hidden sector

c_α: function of : η, hidden sector *vev* and coupling constants, Z and Z' boson masses

$$M_{Z,Z'} = \frac{M_{Z_0}^2}{2}\left[(1 + s_W^2\eta^2 + \Delta_Z) \pm \sqrt{(1 - s_W^2\eta^2 - \Delta_Z)^2 + 4s_W^2\eta^2}\right]$$

Hidden Abelian Higgs Model (HAHM) (3)

Type	Notation	Status	Equation/Value	sector (SM/Hidden)
Lagrangian	χ	Internal	Eq. 2	Hidden
	η	Fixed-value	$\eta = 10^{-4}$	Hidden
	ξ	Fixed-value	$\xi = 1$ TeV	Hidden
	κ	Internal	Eq. 7	SM/Hidden
	ρ	Internal	Eq. 8	Hidden
	λ	Internal	Eq. 9	SM/Hidden
Mixing angles	θ_α	Internal	Eq. 12	Hidden
	θ_h †	Free	$s_h^2 \in [0,1]$	Hidden
Masses	M_Z	Fixed-value	$M_Z = 91.18$GeV	SM
	$M_{Z'}$	Free	$M_{Z'} \in [15,80]$GeV	Hidden
	M_{H_1}	Free	$M_{H_1} \in [110,1000]$GeV	SM/Hidden
	M_{H_2}	Free	$M_{H_2} \in [110,1000]$GeV	SM/Hidden

- Higgs sector mixing
  - Additional Higgs boson
  - Masses depend on free parameters

- Gauge boson mixing
  - Additional Gauge boson (*Z'*)
  - Mass depend on free parameters
  - Photon and *Z* boson are mostly unchanged compared to SM

Couplings

Higgs couplings :

$gg \to H$ (effective), suppressed by a factor c_h^2

$$hZZ : 2ic_h \frac{M_{Z_0}^2}{v}(-c_\alpha + \eta s_W s_\alpha)^2 - 2is_h \frac{M_X^2}{\xi} s_\alpha^2$$

$$hZ'Z' : 2ic_h \frac{M_{Z_0}^2}{v}(s_\alpha + \eta s_W c_\alpha)^2 - 2is_h \frac{M_X^2}{\xi} c_\alpha^2$$

$$hZZ' : 2ic_h \frac{M_{Z_0}^2}{v}(-c_\alpha + \eta s_W s_\alpha)(s_\alpha + \eta s_W c_\alpha) - 2is_h \frac{M_X^2}{\xi} s_\alpha c_\alpha$$

$\Big\}\ H \to ZZ, Z'Z', ZZ'$

Coupling to SM fermions :

$$\bar{\psi}\psi Z : \frac{ig}{c_W}[c_\alpha(1 - t_\alpha \eta s_W)]\left[T_L^3 - \frac{1 - t_\alpha \eta / s_W}{1 - t_\alpha \eta s_W} s_W^2 Q\right]$$

$$\bar{\psi}\psi Z' : \frac{-ig}{c_W}[c_\alpha(t_\alpha + \eta s_W)]\left[T_L^3 - \frac{t_\alpha + \eta / s_W}{t_\alpha + \eta s_W} s_W^2 Q\right]$$

$\Big\}\ Z, Z' \to \ell^+\ell^-$

- Calculation of widths and BR
  - "analytical" (private program (HDECAY-like), cross-checked with model authors)
  - in a (m_H, $m_{Z'}$, s_h^2) parameter space
- Event generation
  - Model exists in FeynRules
  - We add another FeynRules notebook more usable by experiments :
    - (m_H, $m_{Z'}$, s_h^2) as free parameters, instead of (κ, ρ, λ)
    - HEFT to have gg->H production

Phenomenology (2)

- Possible searches
  - In a “standard” *H->4l* search to include *H->Z’Z’->4l* decays :
    - event rate changed w.r.t. SM
  - Direct search :
    - direct production (but very suppressed because of low coupling to fermions)
    - search for a resonance in dilepton mass spectrum in a *H->4l* type of search

- But before that …
  - … what do current results tell us about this model ?
  - Isn’t it already excluded by the observation of *H->ZZ->4l* events ?

ATLAS and CMS results

Signal strength (HCP update) in the 4-lepton channel only

ATLAS : μ = 1.4 +/- 0.6

CMS : $\mu = 0.8^{+0.35}_{-0.28}$

ATLAS/CMS : mass ~ 126 GeV

$$\mu \equiv \frac{\sigma}{\sigma_{\rm SM}}$$

- Both results are compatible with 1 (SM), within 1 sigma (still large uncertainties …)
- At this stage, we may not expect very large deviations from SM
- We will assume in the following that the new particle *is a Higgs boson of 126 GeV*

Two approaches to reinterpret these results

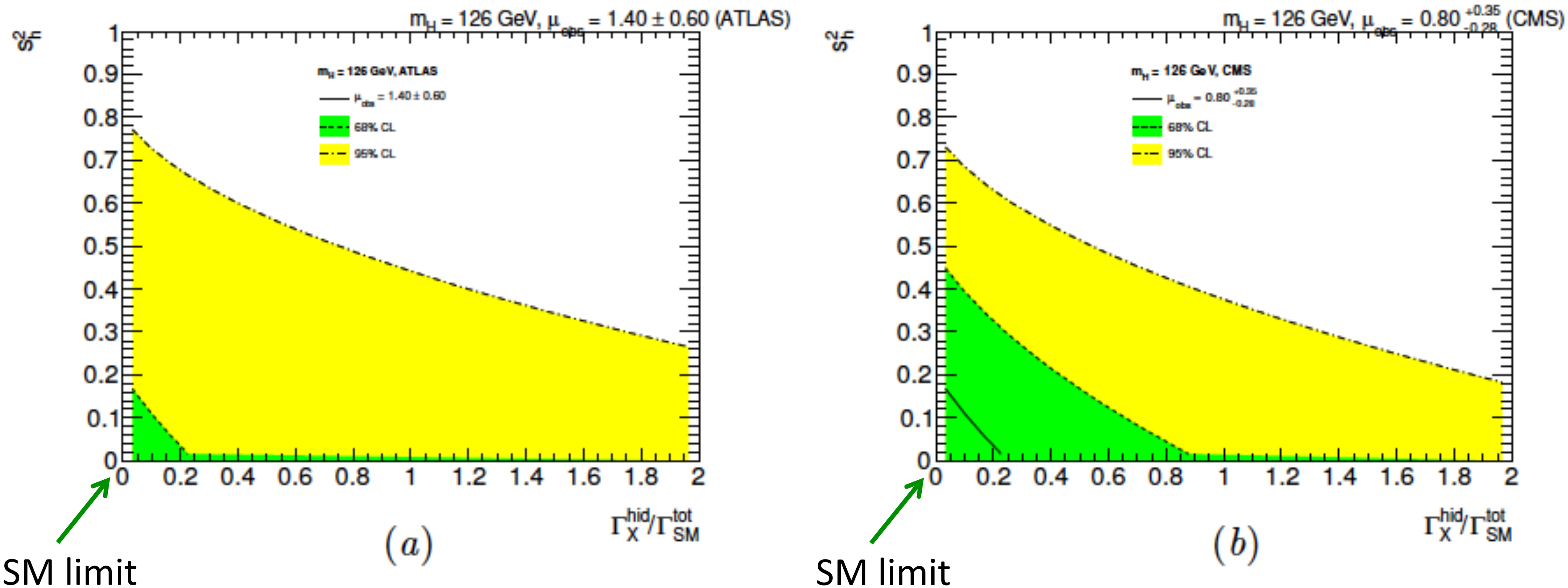
1) Mixing angle and hidden width
2) Mixing angle and *Z'* mass

Assumptions :

- lepton kinematic in H->Z'Z'->4l events in comparable to that of (SM) H->ZZ->4l events for $m_{Z'}$ > 15 GeV (we will assume same acceptance, efficiencies, etc.)
- experimental analyses cut on the dilepton invariant mass :
  - CMS : m_{12} > 40 GeV, m_{34} > 12 GeV
  - ATLAS : m_{12} > 50 GeV, m_{34} > 17.5 GeV (for m_{4l} ~ 126 GeV)

- New Higgs decay
  - change the Higgs partial width to 4 leptons, and total width
  - depends on the Higgs mixing angle
- Decay of "hidden" particles (e.g. Z' in HAHM)
  - non-detectable
    - e.g. very light new boson or some particle that does not decay to SM particles
    - lead to a loss of events or large missing energy
  - detectable
    - e.g. larger mass new boson (few 10 GeV)
    - further decay to SM leptons, can be measured

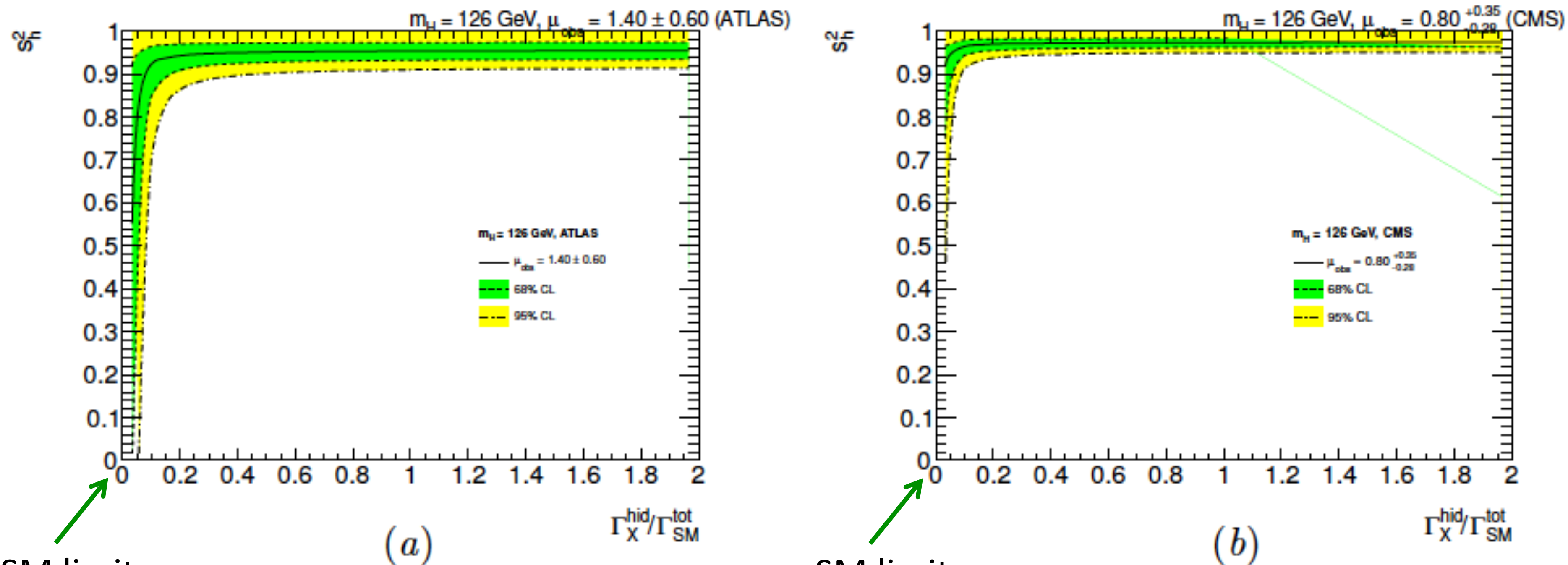
“Invisible” hidden sector



“Invisible” hidden sector (usual approach)

- not very conclusive because of large uncertainties
- expected rate is lower than SM, so “more compatible” with $\mu < 1$ (CMS)

"Visible" hidden sector



SM limit

SM limit

"Visible" hidden sector : here we assume that the hidden particles can be detected

Two regions are compatible with the measurements :

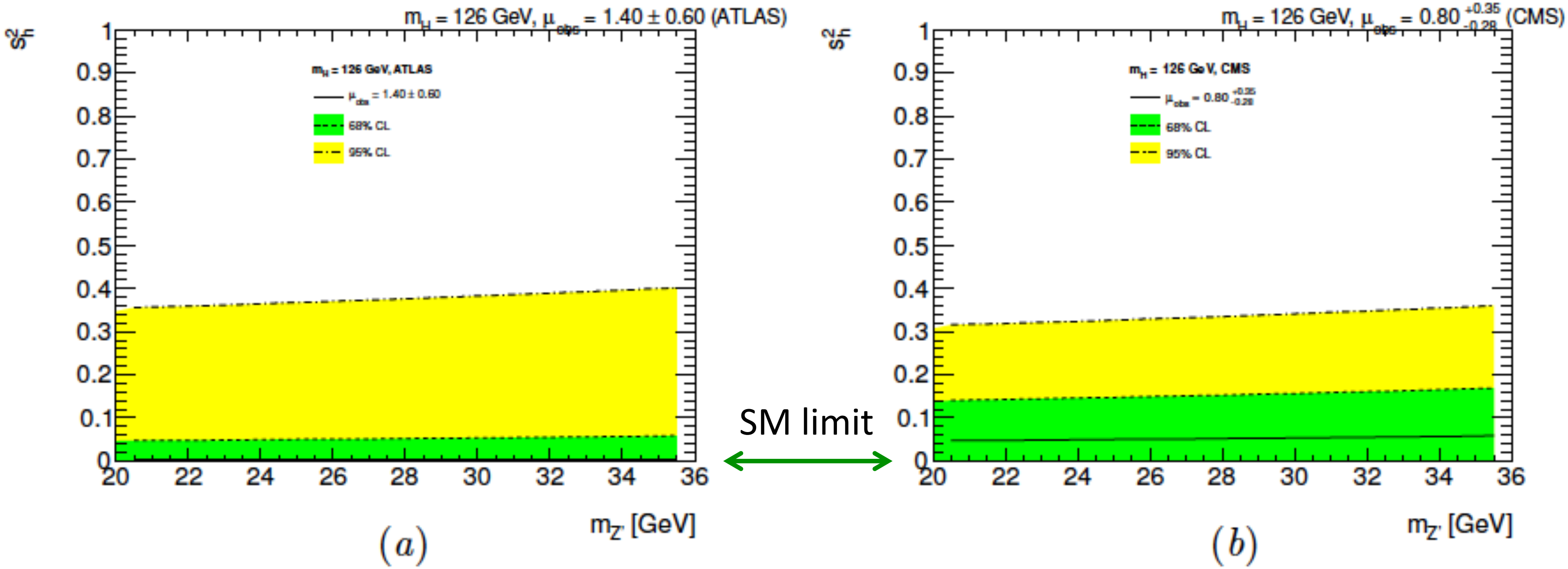
- large mixing (sh2 ~ 1)
- small hidden width

Note: the relationship between the model parameters (Higgs and Z' masses, mixing angle) and the hidden width is not straightforward

- New Higgs decay
  - opens new H->4l events that may be detected as part of SM H->ZZ*->4l search
  - event rate depends on mixing angle and Z' mass
- Decay of "hidden" particles (Z' leptonic decay)
  - non-detectable
    - 20 < mZ' < 35 GeV
  - detectable
    - 55 < mZ' < 80 GeV

Mixing angle and Z' mass approach (2)

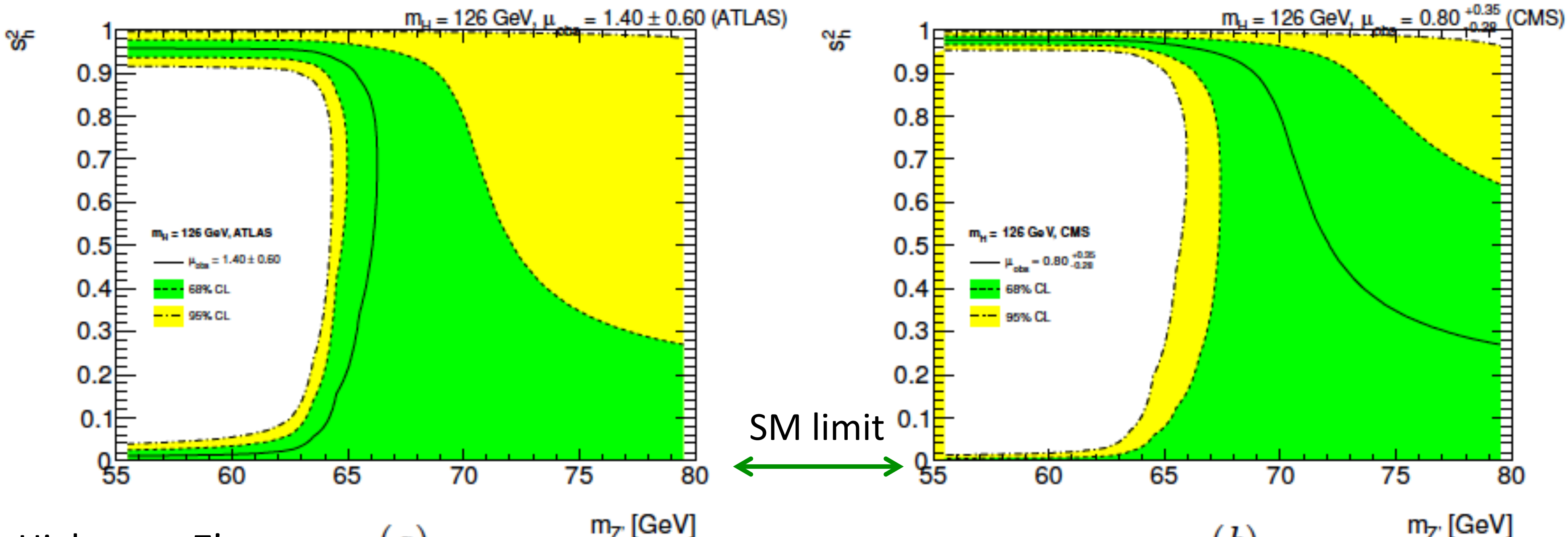
Low mass Z' (< 35 GeV)



Low mass Z'

- H->Z'Z'->4l decay not detected
- event rate simply suppressed, proportional to c_h^2
- exclude most mixing angles, except close to $s_h^2 = 0$ (SM limit)
- large uncertainties

High mass Z’ (> 55 GeV)



(a) (b)

High mass Z’

- H->Z’Z’->4l decay can be detected, we assume same acceptance
- large part of parameter space compatible with experimental result
- transition at mZ’ = 63 GeV (m_H/2) :
  - below: H->Z’Z’ (2-body) is favored compared to H->ZZ* (3-body)
  - above: H->Z’Z’ (3-body) is suppressed compared to H->ZZ* (3-body), more SM-like
- Low mass Z’ are excluded (< m_H/2), except for :
  - low mixing (H->Z’Z’ favored by kinematics but compensated by s_h^2 suppression)
  - large mixing (enhancement of H->Z’Z’ compensated by c_h^2 suppression of ggH)

Conclusion and outlook

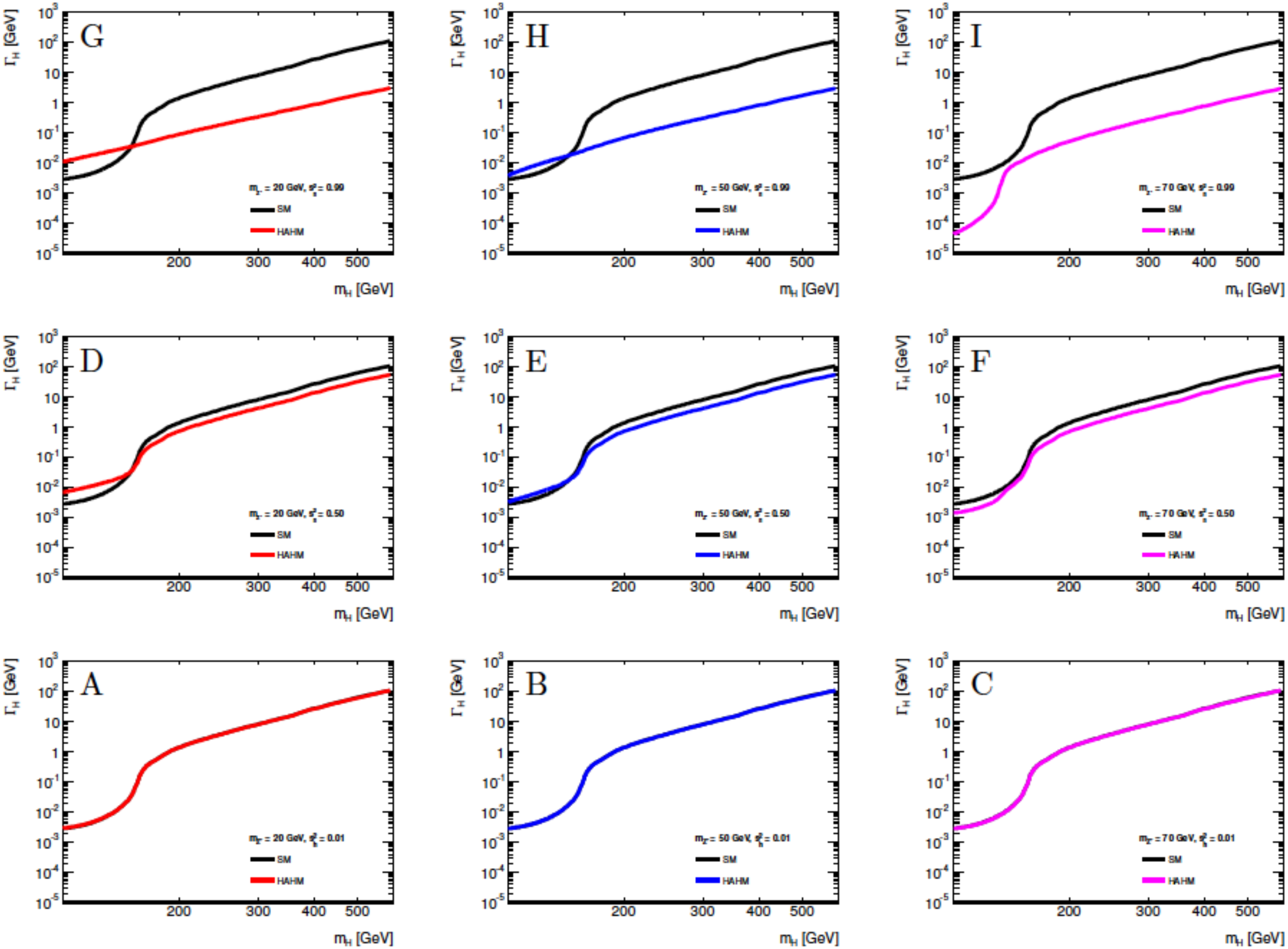
- Conclusion
  - Experimentally accessible search
    - other interesting process involve the heavier Higgs mass eigenstate, cascade decays
  - Model not (yet) excluded by compatibility of experimental results with SM
    - waiting for uncertainties to shrink !

- Other models can use the same approach
  - dark Z (Davoudiasl et al., 2012)
    - lower mass, more difficult experimentally

- Further work
  - update these results when ATLAS/CMS update their measurements
    - I stay tuned !
  - direct searches (or exclusion) by experiments
    - promising complementary search to SM Higgs boson

BACK-UP

Total Higgs width



sh2 = 0.99

sh2 = 0.5

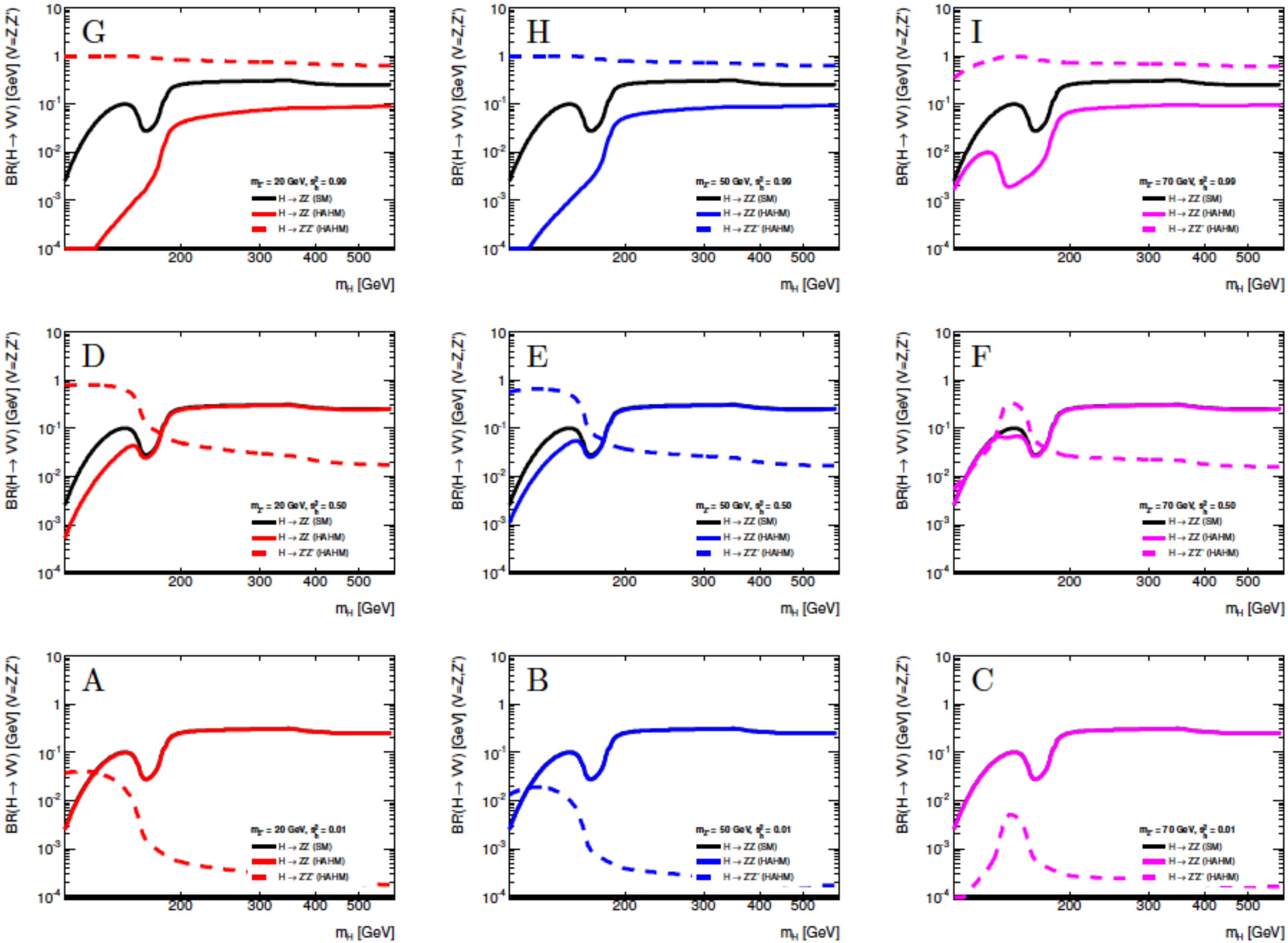
sh2 = 0.01

mZ’ = 20 GeV

mZ’ = 50 GeV

mZ’ = 70 GeV

BR(H->ZZ,Z'Z')



sh2 = 0.99

sh2 = 0.5

sh2 = 0.01

mZ' = 20 GeV

mZ' = 50 GeV

mZ' = 70 GeV