Singlet Portal Extensions of the Standard Seesaw Models to a Dark Sector with Local Dark Gauge Symmetry

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[from "Seungwon Baek, P.Ko and Wan-IlPark, arXiv: 1303.4280 (accepted for JHEP)"]

MITP Workshop on "Cosmic Rays and positrons..."
Schloss Waldhausen, June 24-28 (2013)

Why BSM?

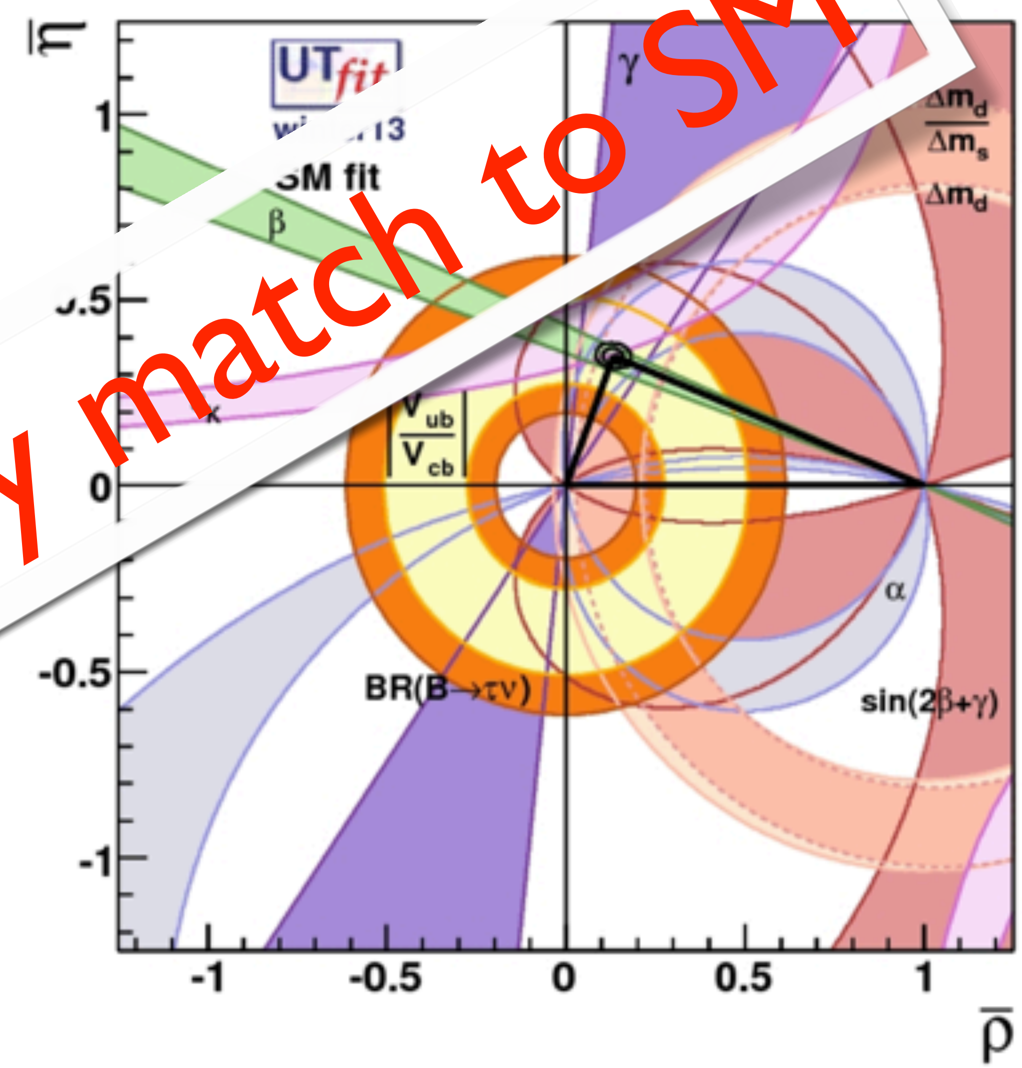
For subatomic world

- SM has been so successful.

EWPT

[LEPEWWG, Mar 2012]

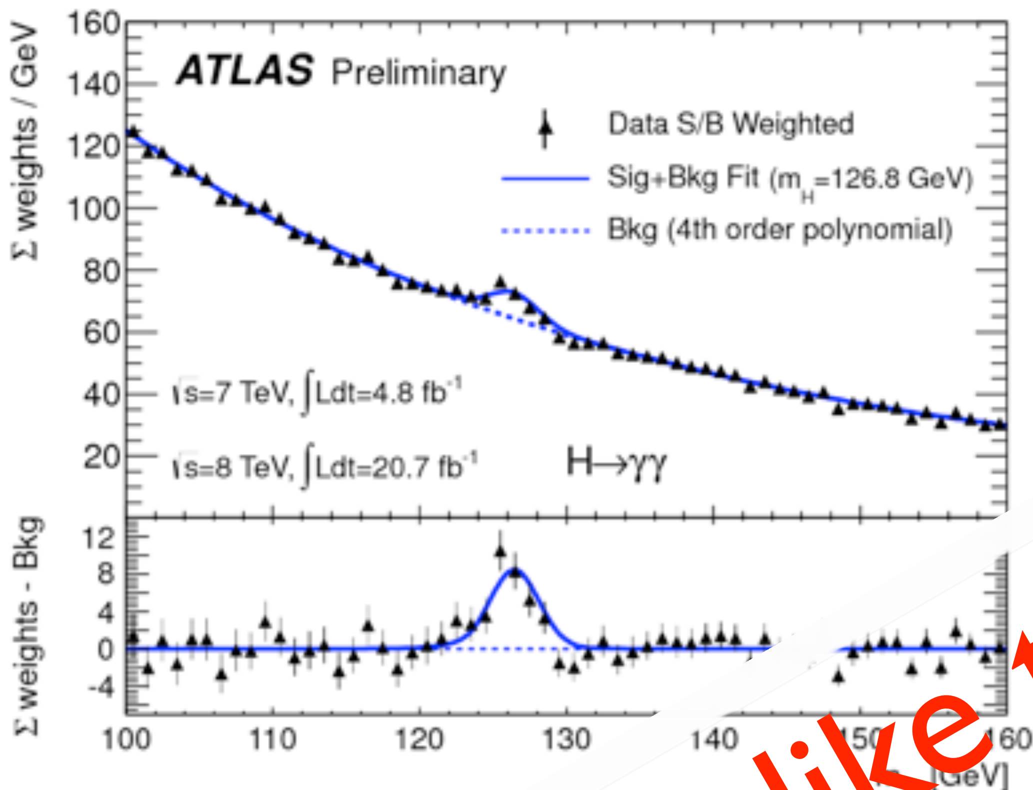
CKM

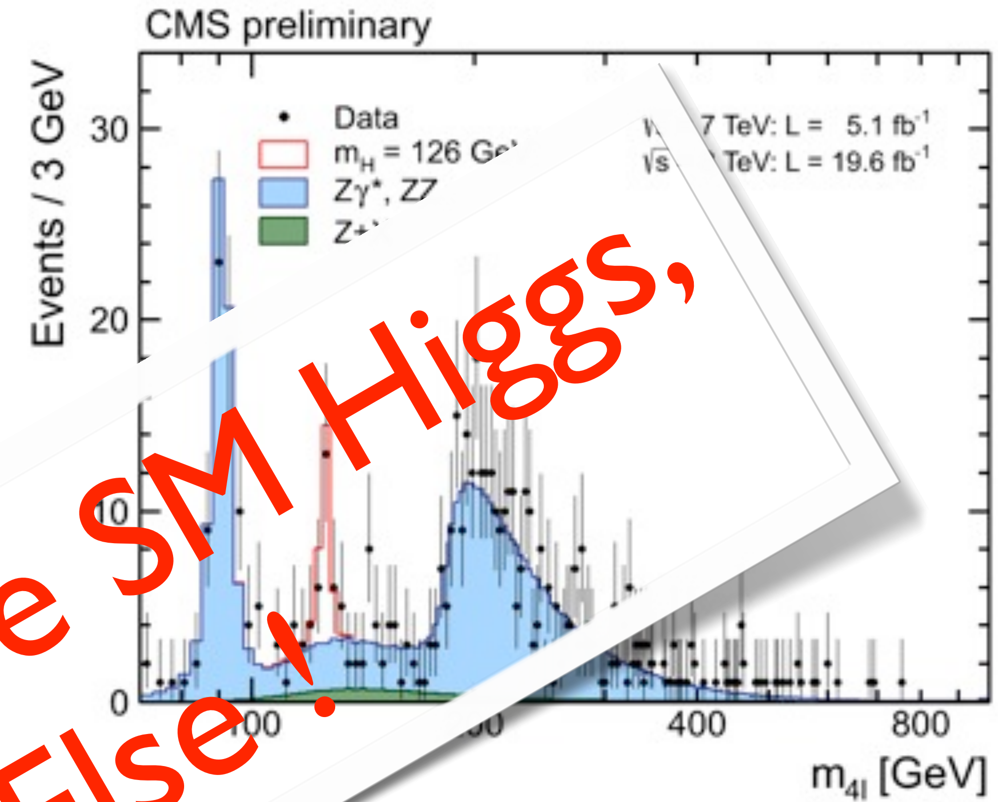


[Unitary Triangle fit]

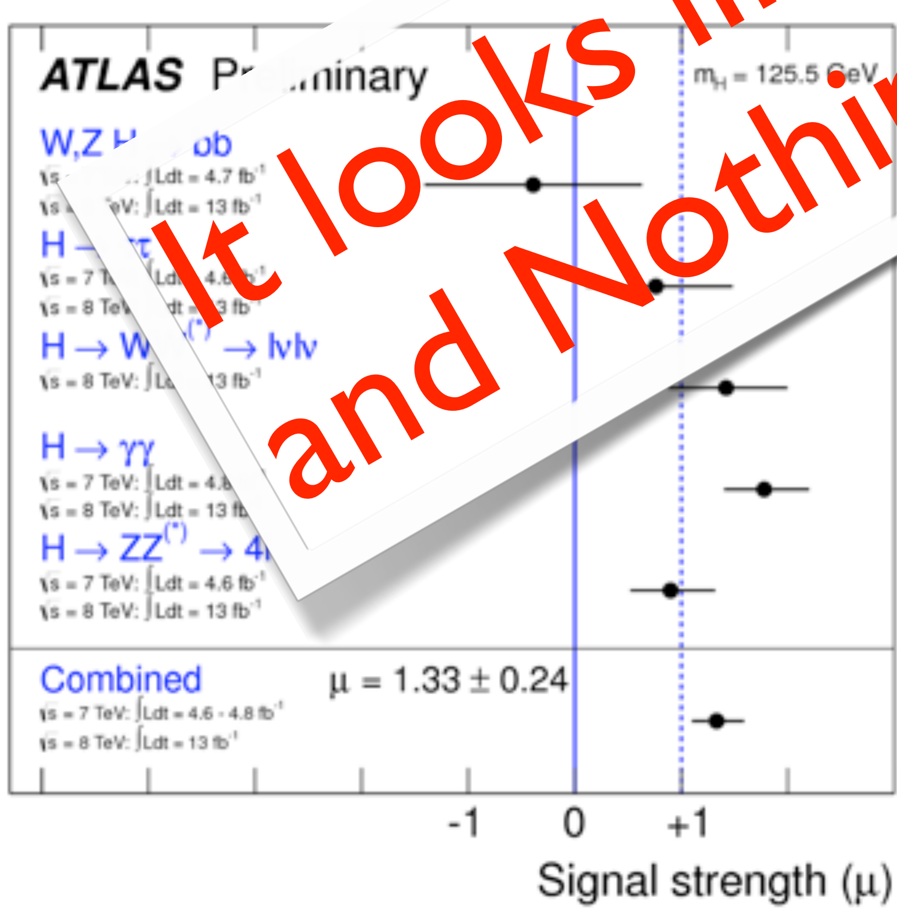
Almost perfectly match to SM

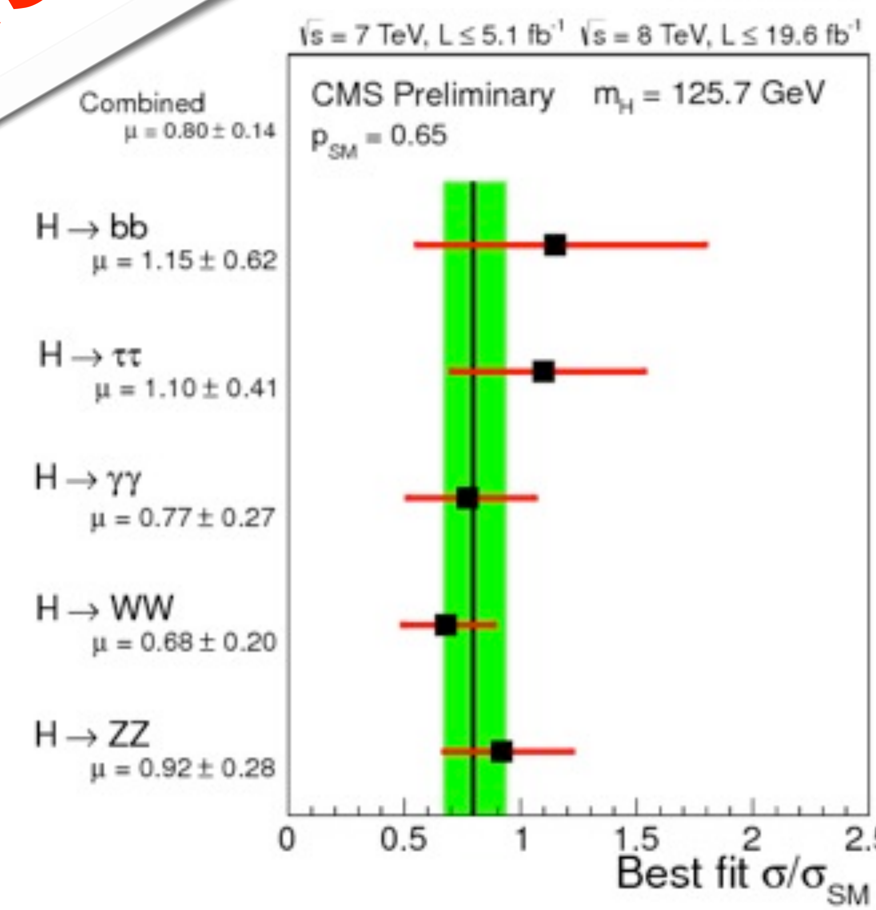
- The last SM chapter also looks correct.





It looks like the SM Higgs,
and Nothing Else!

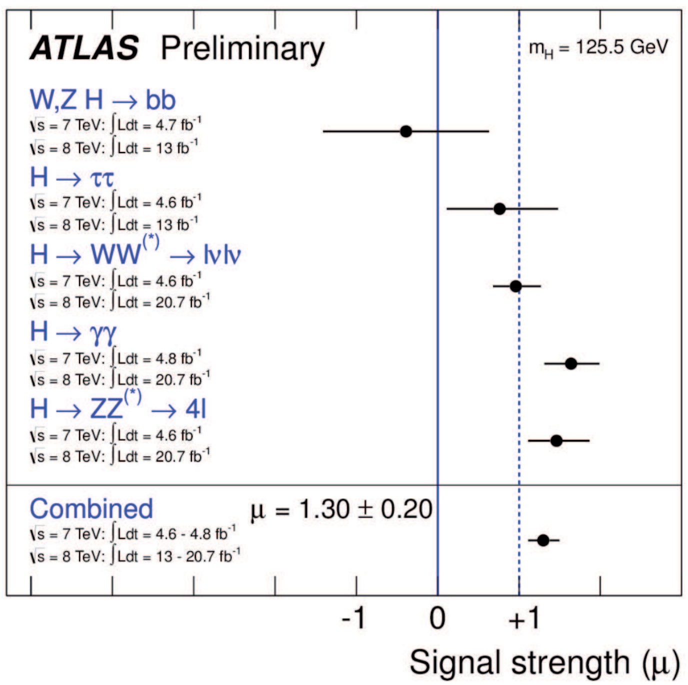


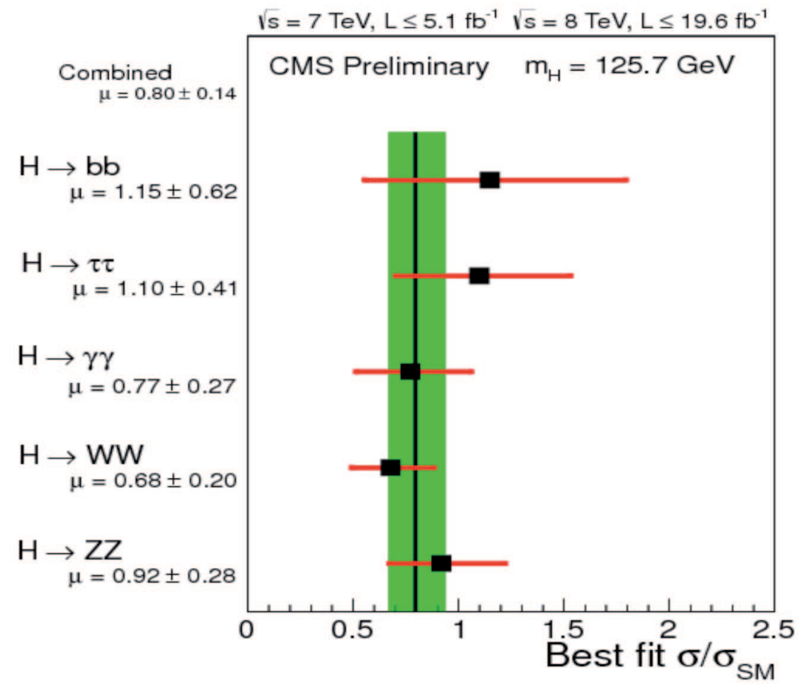


Updates@LHCP

Signal Strengths

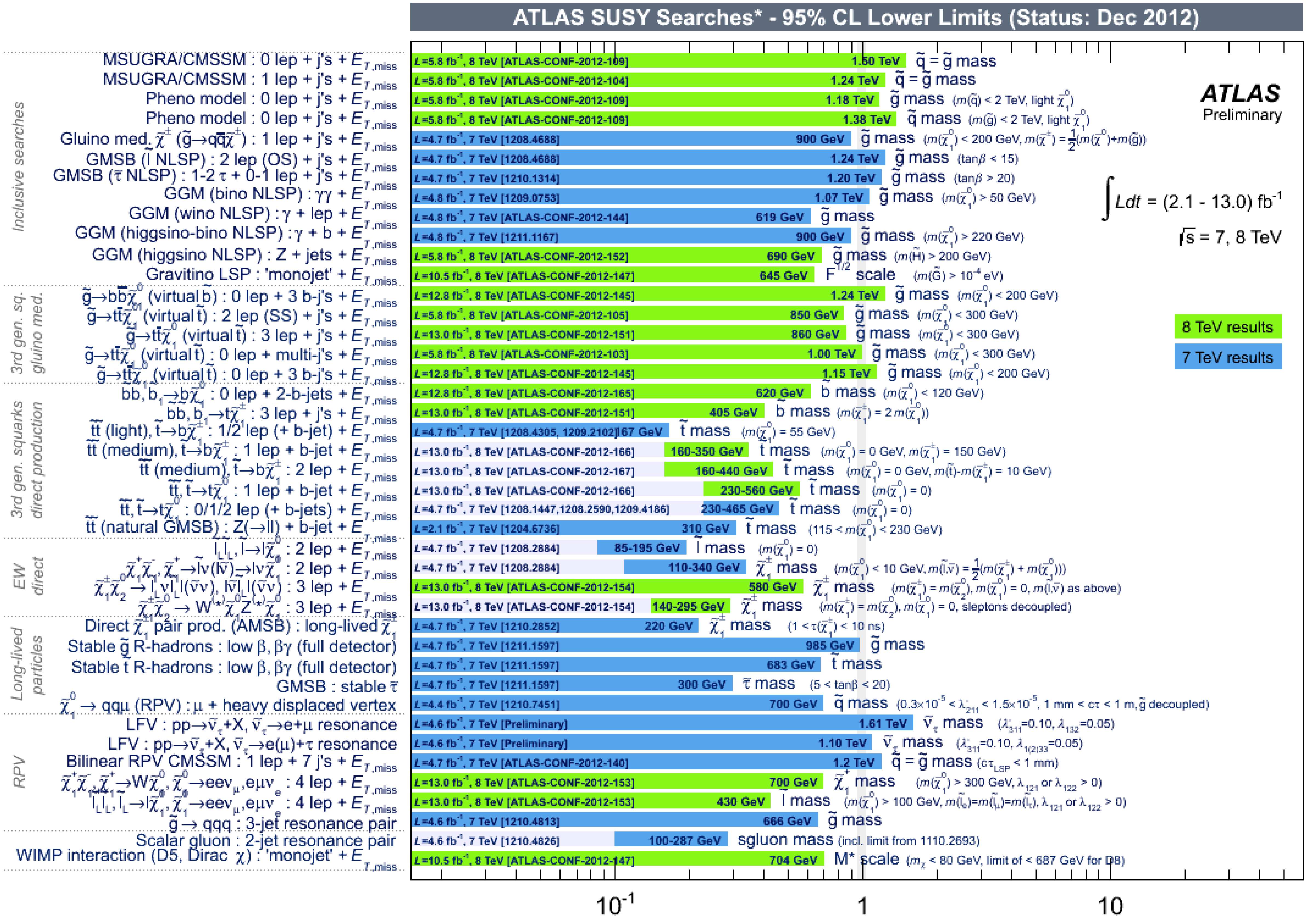
$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$





Decay Mode	ATLAS (M_H = 125.5 GeV)	CMS (M_H = 125.7 GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = \mathbf{0.96 \pm 0.12}$$

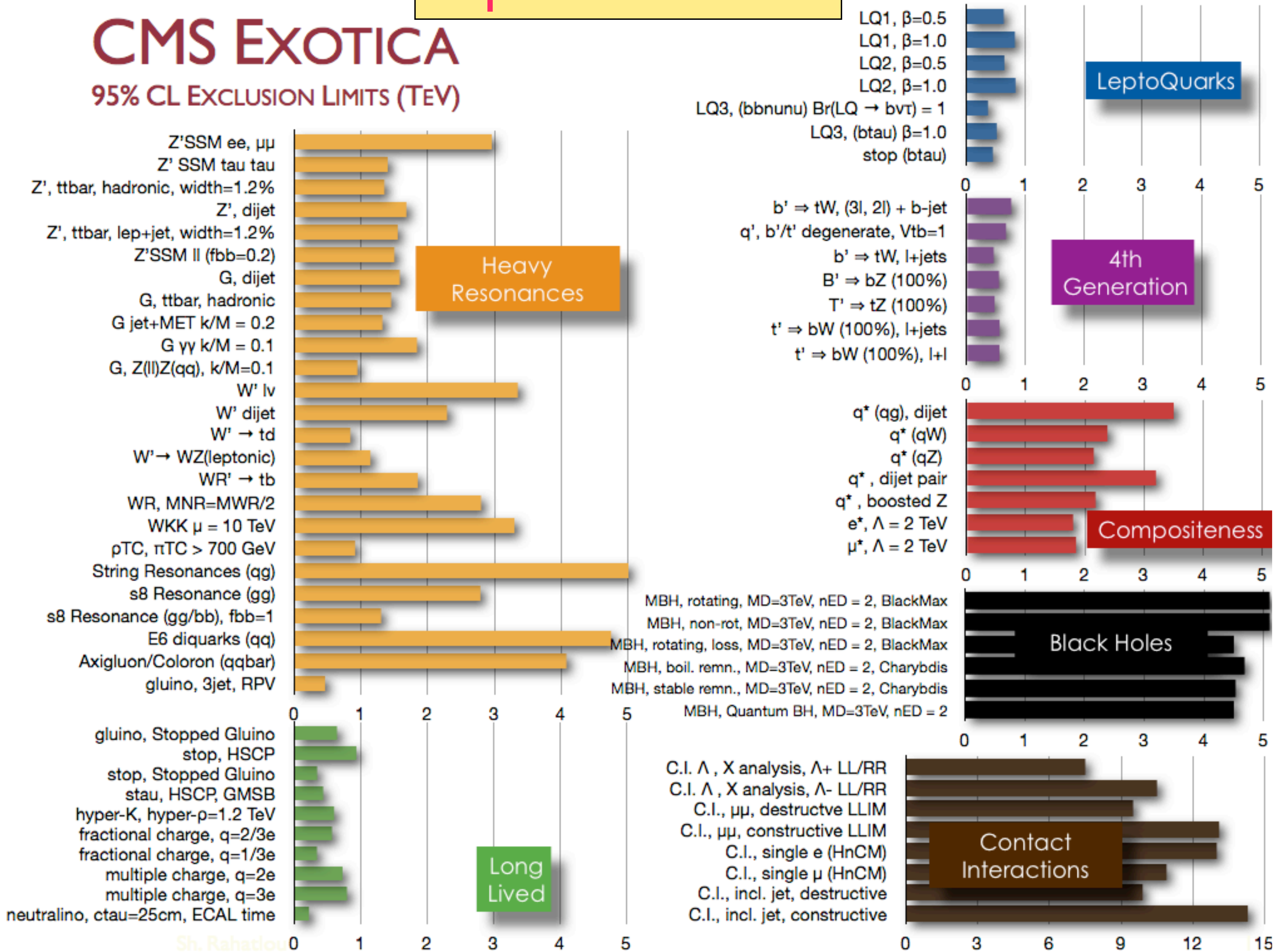


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

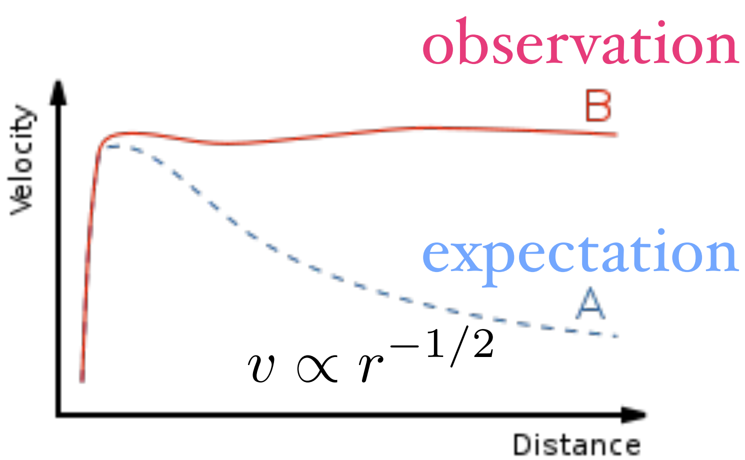
Aspen this March

CMS Exotica

95% CL Exclusion Limits (TeV)



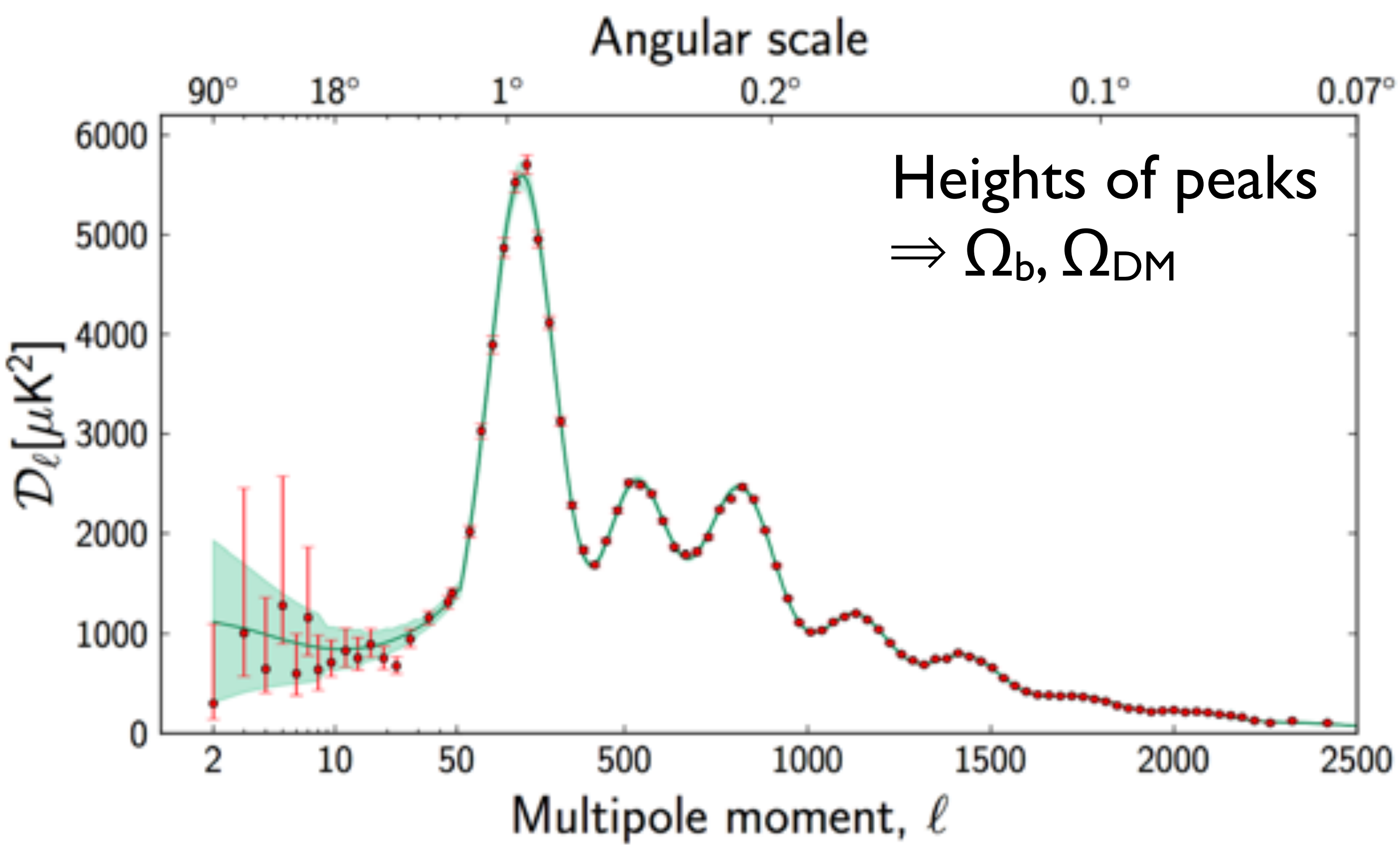
- Dark & visible matter and dark energy



Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster

Strong gravitational lensing in Abell 1689

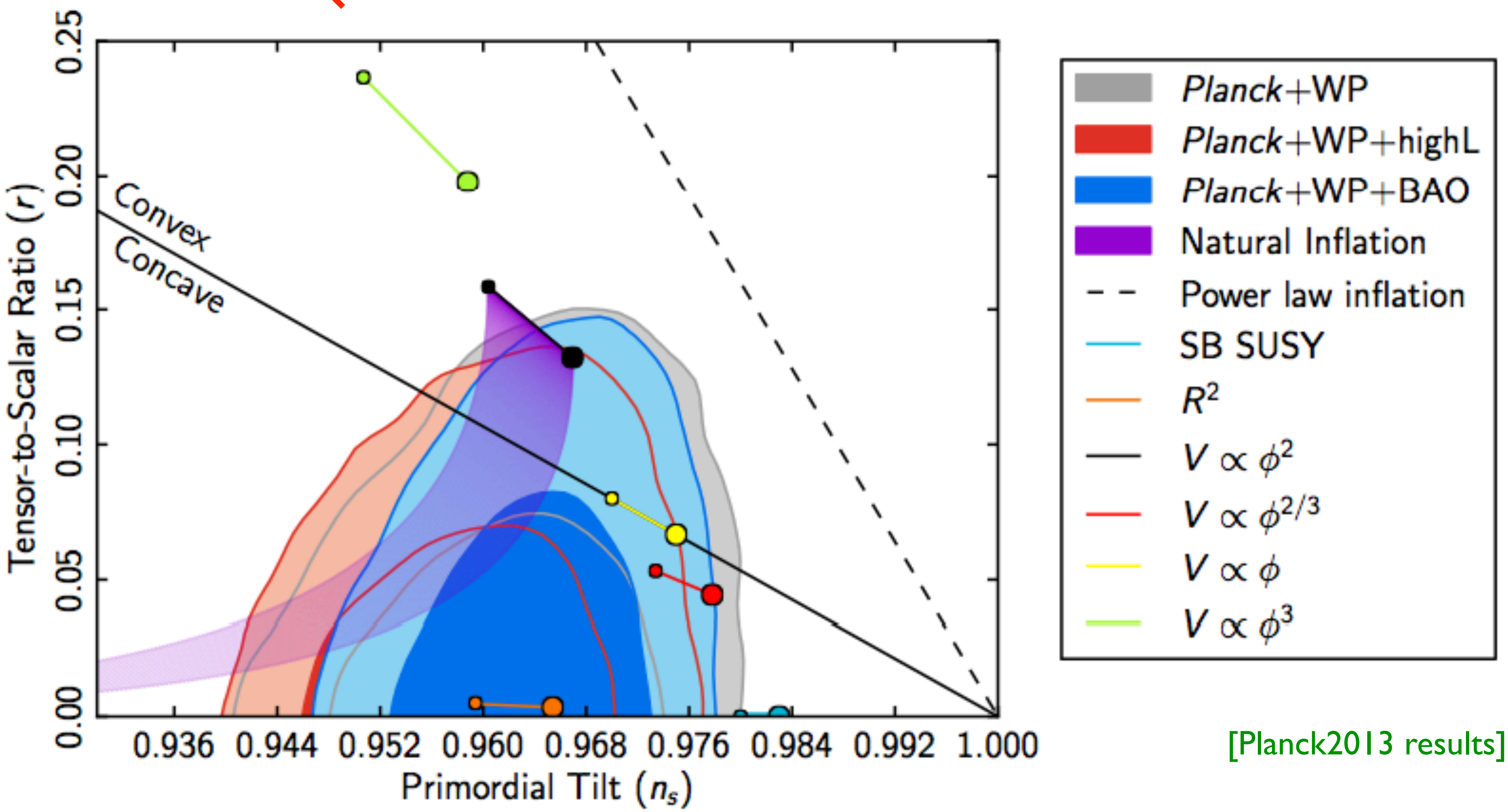


$$\Omega_b \simeq 0.048$$
$$\Omega_{DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

Inflation models in light of Planck2013 data

$\Rightarrow V \propto \phi^4$



[Planck2013 results]

Maybe it is right time to think about what LHC data tells us about New Physics@EW scale

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

How to do Model Building

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- You may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

(3,2,1) or SU(3)cXU(1)em ?

- Well below the EW sym breaking scale, it may be fine to impose SU(3)c X U(1)em
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different resultsSinglet mixing with SM Higgs

Shortcomings of SM

- Density perturbations
- Baryon number asymmetry
- Dark matter
- Dark energy
- Neutrino masses and mixing

No explanations to most of astrophysical and cosmological observations.

Contents

- Hidden Sector DM
- Higgs Portal : EFT vs. Renormalizable Model
- Local vs. Global Dark Symmetry
- Singlet Portal Seesaw Models
- Implications for Higgs phenomenology

Based on the works

(with S.Baek, Suyong Choi, T. Hur, D.W.Jung, Sunghoon Jung, J.Y.Lee, W.I.Park, E.Senaha in various combinations)

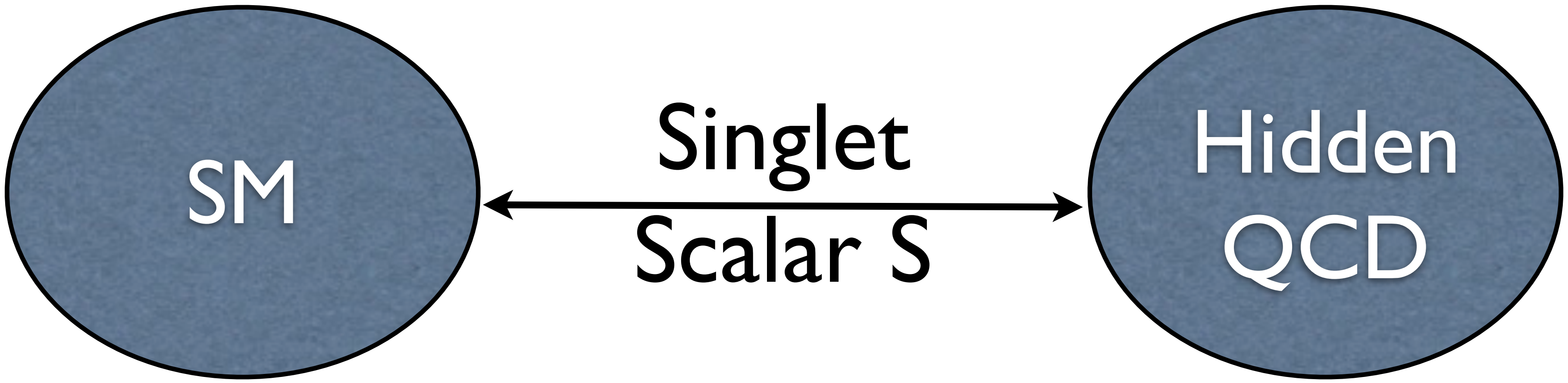
- Strongly interacting hidden sector (0709.1218 PLB, 1103.2571 PRL)
- Singlet fermion dark matter (1112.1847 JHEP)
- Higgs portal vector dark matter (1212.2131 JHEP)
- Vacuum structure and stability issues (1209.4163 JHEP)
- Singlet portal extensions of the standard seesaw models with unbroken dark symmetry (1303.4280 JHEP)

(And a few works in preparation)

Hidden Sector

- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could make CDM
- Hidden gauge sym can stabilize CDM
- Generic in many BSM's including SUSY models
- Can address "QM generation of all the mass scales from strong dynamics in the hidden sector" (orthogonal to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

Model I (Scalar Messenger)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by “S”

Modified SM with classical scale symmetry

$$
\begin{aligned}
\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\
&+ \left(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \right. \\
&+ \left. \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c.\right)
\end{aligned}
$$

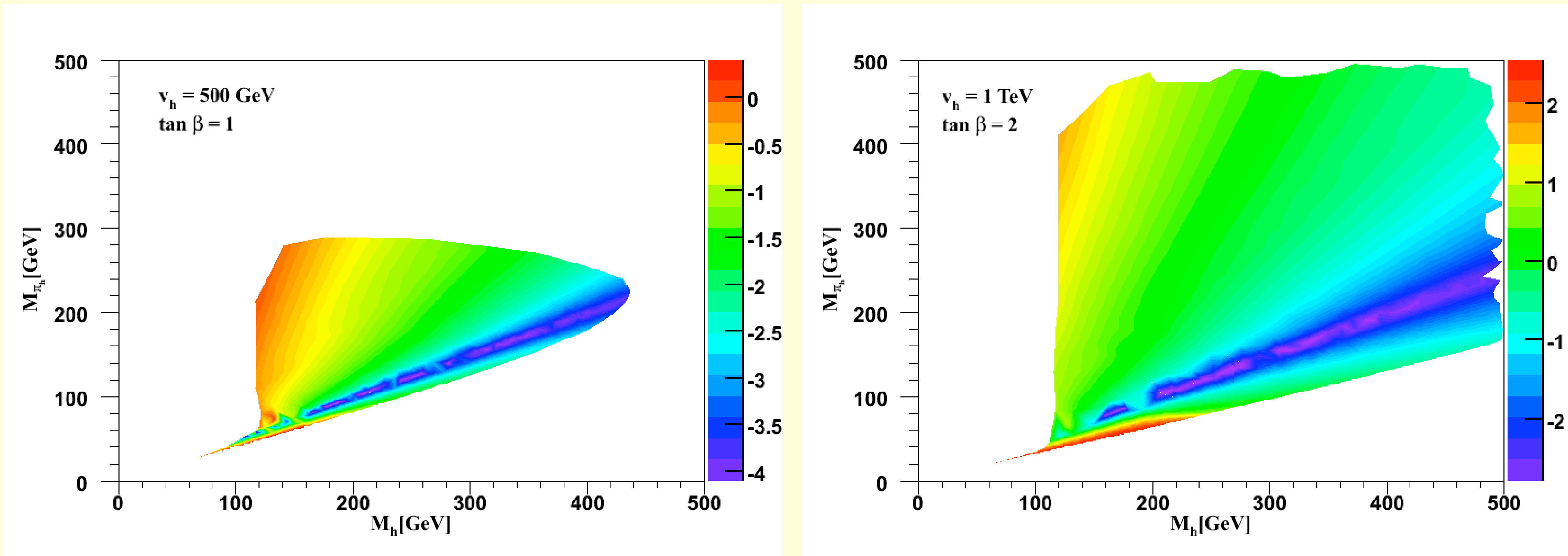
Hidden sector lagrangian with new strong interaction

$$
\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k
$$

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}$$

Relic density

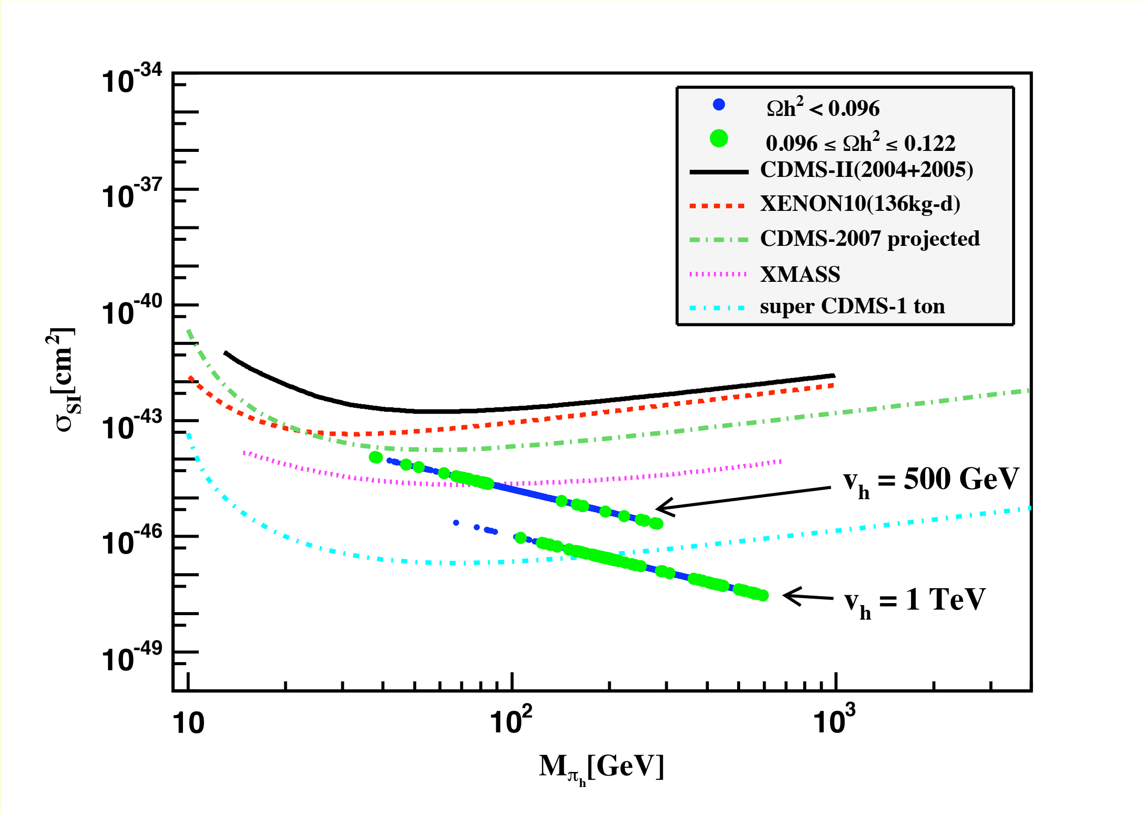


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

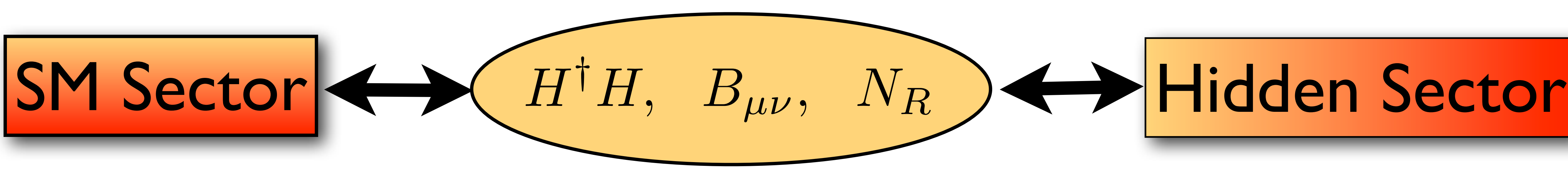
the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

How to specify hidden sector ?

- Gauge group (G_h) : Abelian or Nonabelian
- Strength of gauge coupling : strong or weak
- Matter contents : singlet, fundamental or higher dim representations of G_h
- All of these can be freely chosen at the moment : Any predictions possible ?
- But there are some generic testable features in Higgs phenomenology

Singlet Portal

- If there is a hidden sector, then we need a portal to it in order not to overclose the universe
- There are only three unique gauge singlets in the SM + RH neutrinos



$$\boxed{N_R \leftrightarrow \widetilde{H} l_L}$$

General Comments

- Many studies on DM physics using EFT
- However we don't know the mass scales of DM and the force mediator
- Sometimes one can get misleading results
- Better to work in a minimal renormalizable and anomaly-free models
- Explicit examples : singlet fermion Higgs portal DM, vector DM, Z2 scalar CDM

Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H\ \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

A. Djouadi, et.al. 2011

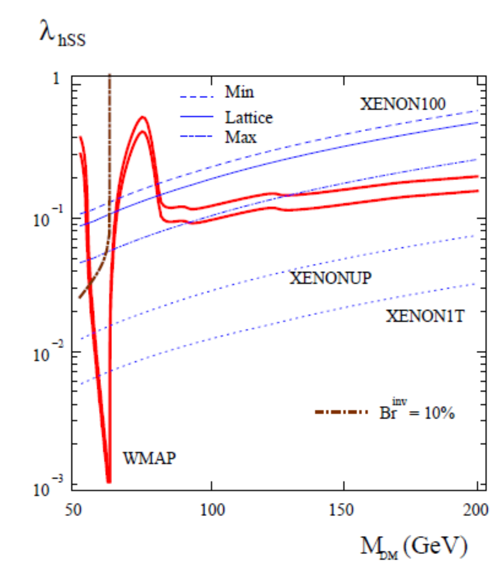


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

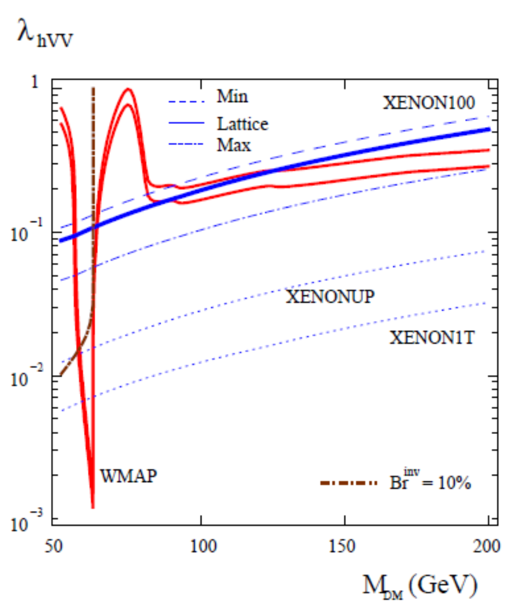


FIG. 2. Same as Fig. 1 for vector DM particles.

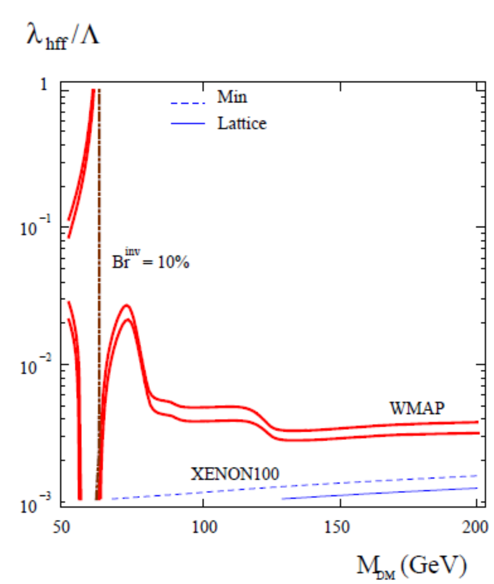


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i \gamma \cdot \partial - m_\psi \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \ \overline{\psi} \psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{2} \lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

- Scalar CDM : looks OK, renorm. .. BUT .....
- Fermion CDM : nonrenormalizable
- Vector CDM : looks OK, but it has a number of problems (in fact, it is not renormalizable)

Usual story within EFT

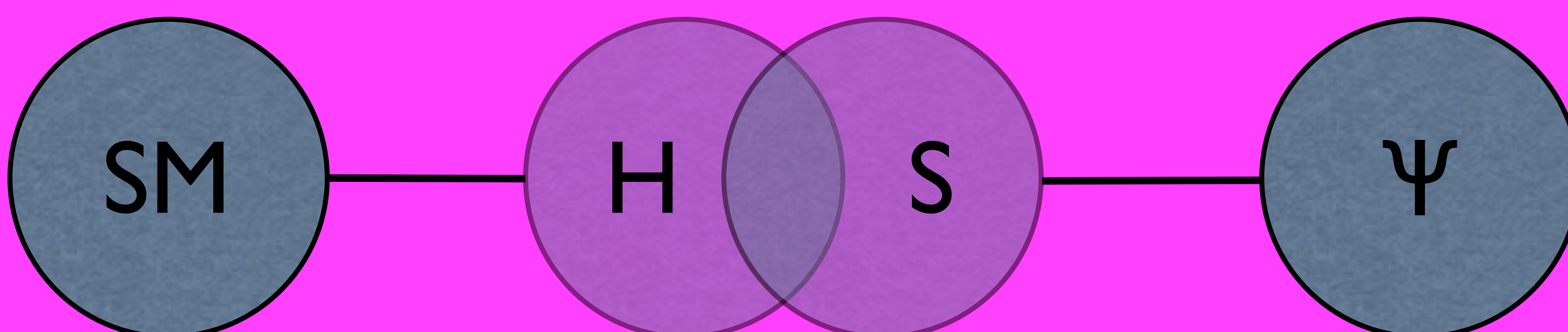
- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in the full theories (renormalizable) however

Singlet fermion CDM

$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\
& + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4 \\
& + \overline{\psi}(i \not{\partial} - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi
\end{aligned}
$$

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Ratiocination

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2}\lambda_{HS} v_S^2,$$
$$m_S^2 = -\frac{\mu_S^3}{v_S} - \mu_S' v_S - \lambda_S v_S^2 - \frac{\mu_{HS} v_H^2}{2 v_S} - \frac{1}{2}\lambda_{HS} v_H^2,$$

at vacuum

$$M_{\text{Higgs}}^2 \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$
$$H_2 = h\sin\alpha + s\cos\alpha.$$

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$
\begin{aligned}
r_i &= \frac{\sigma_i \, \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \, \mathrm{Br}(h \to \mathrm{SM})} \\
r_1 &= \frac{\cos^4\alpha \, \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \, \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \, \Gamma^{\mathrm{hid}}_{H_1}} \\
r_2 &= \frac{\sin^4\alpha \, \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \, \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \, \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}
\end{aligned}
$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$

Invisible decay mode is not necessary!

If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

EW precision observables

Peskin & Takeuchi, Phys.Rev.Lett.65,964(1990)

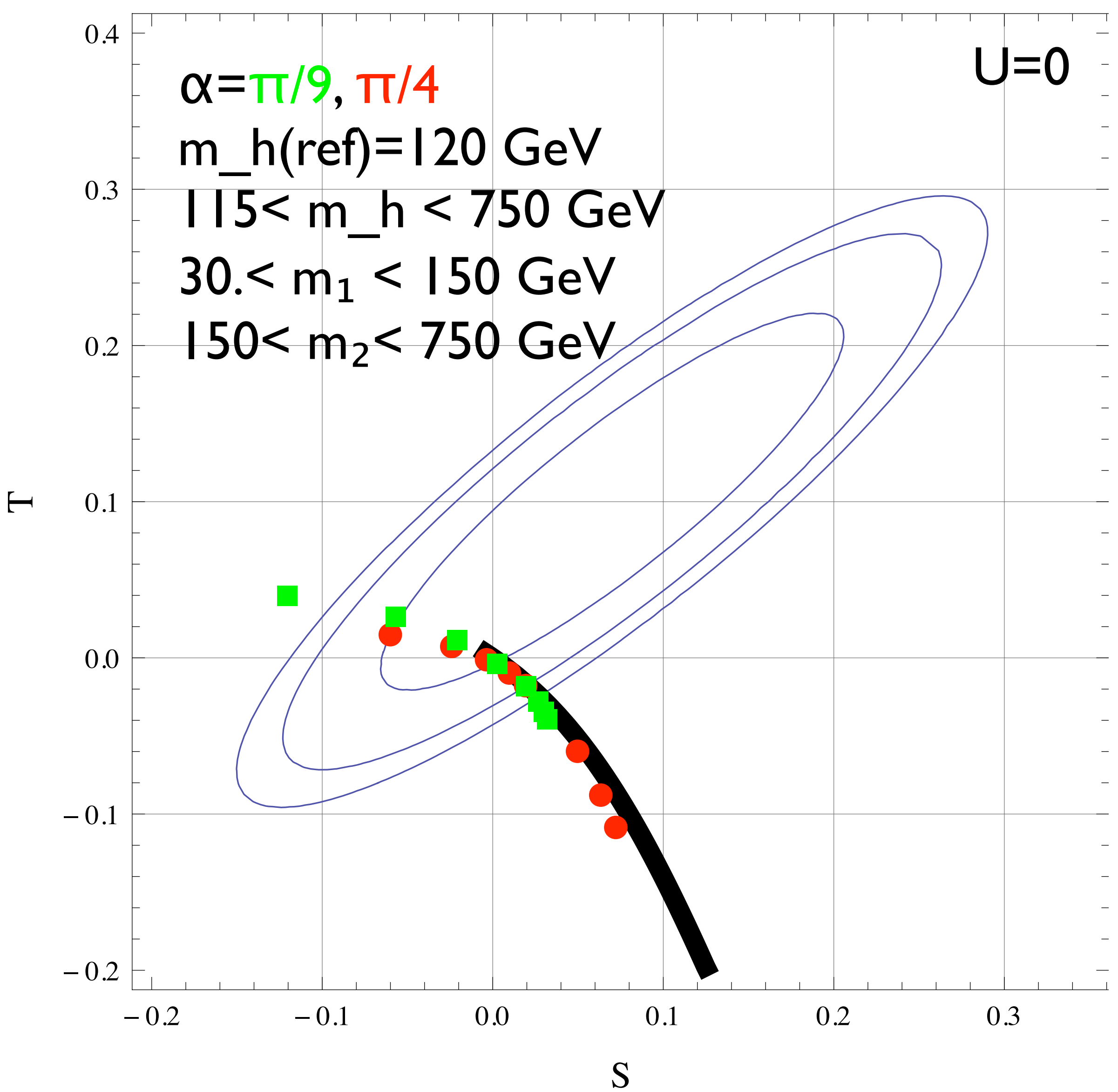
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

$$\alpha_{\rm em} T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha_{\rm em} U = 4 s_W^2 \left[\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2} \right]$$

$$S = \cos^2\alpha \; S(m_1) + \sin^2\alpha \; S(m_2)$$

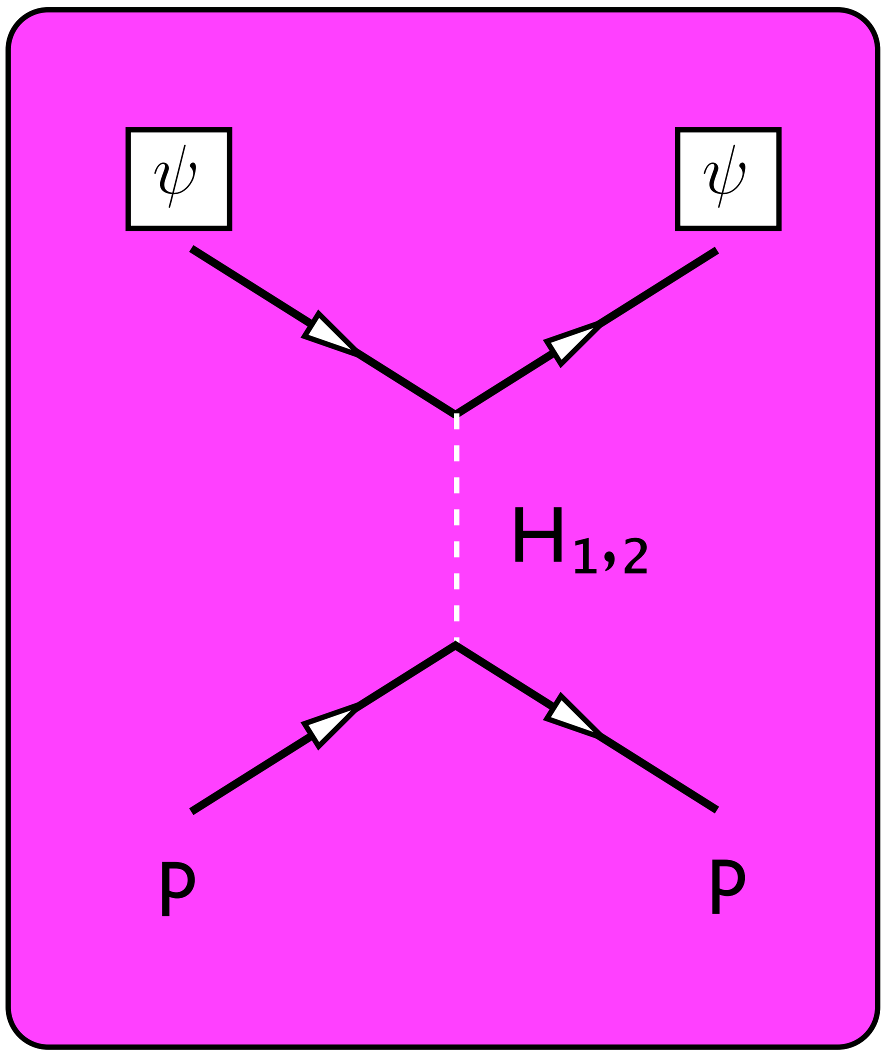
Same for T and U

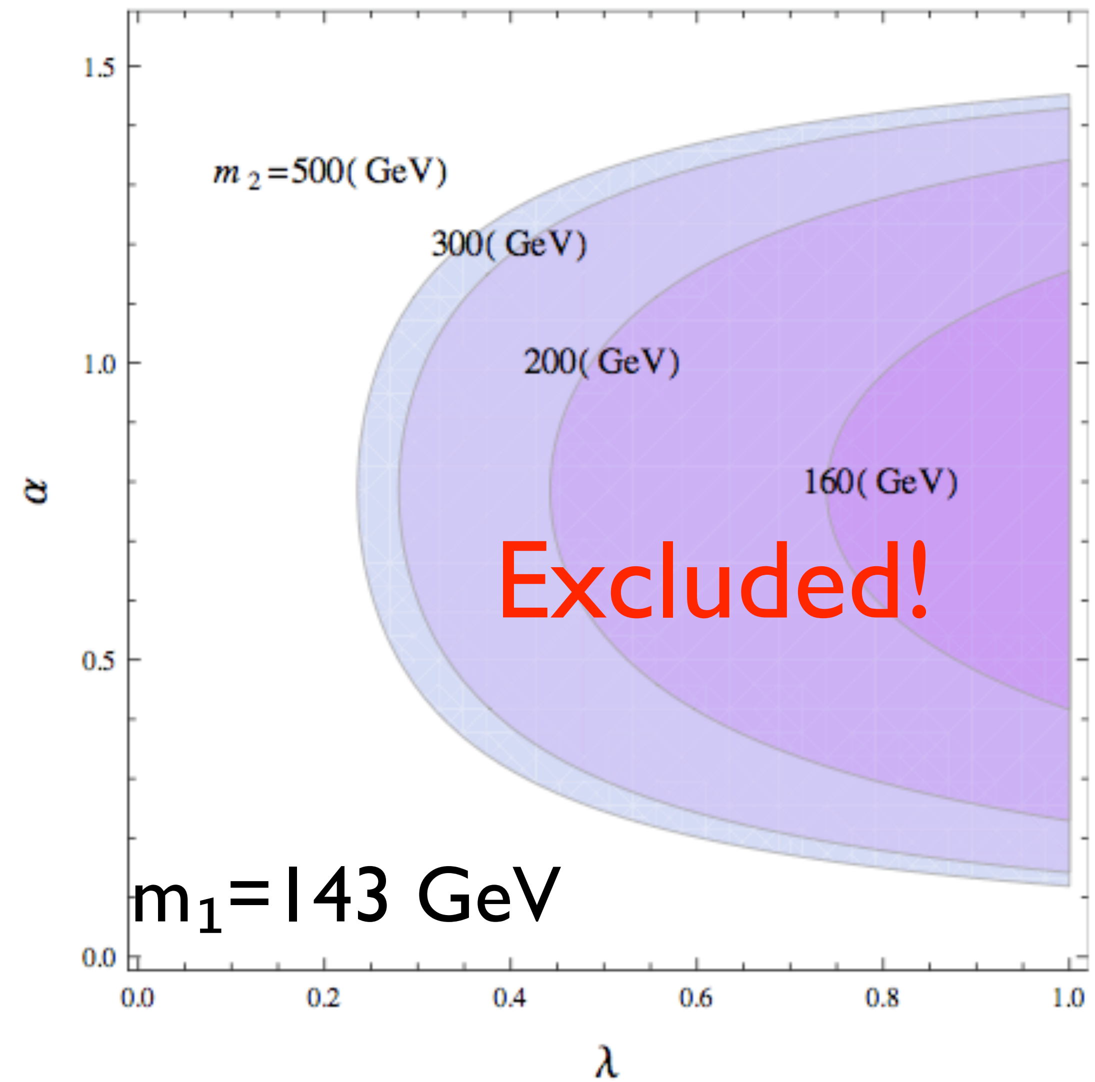


Constraints

- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda\sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$





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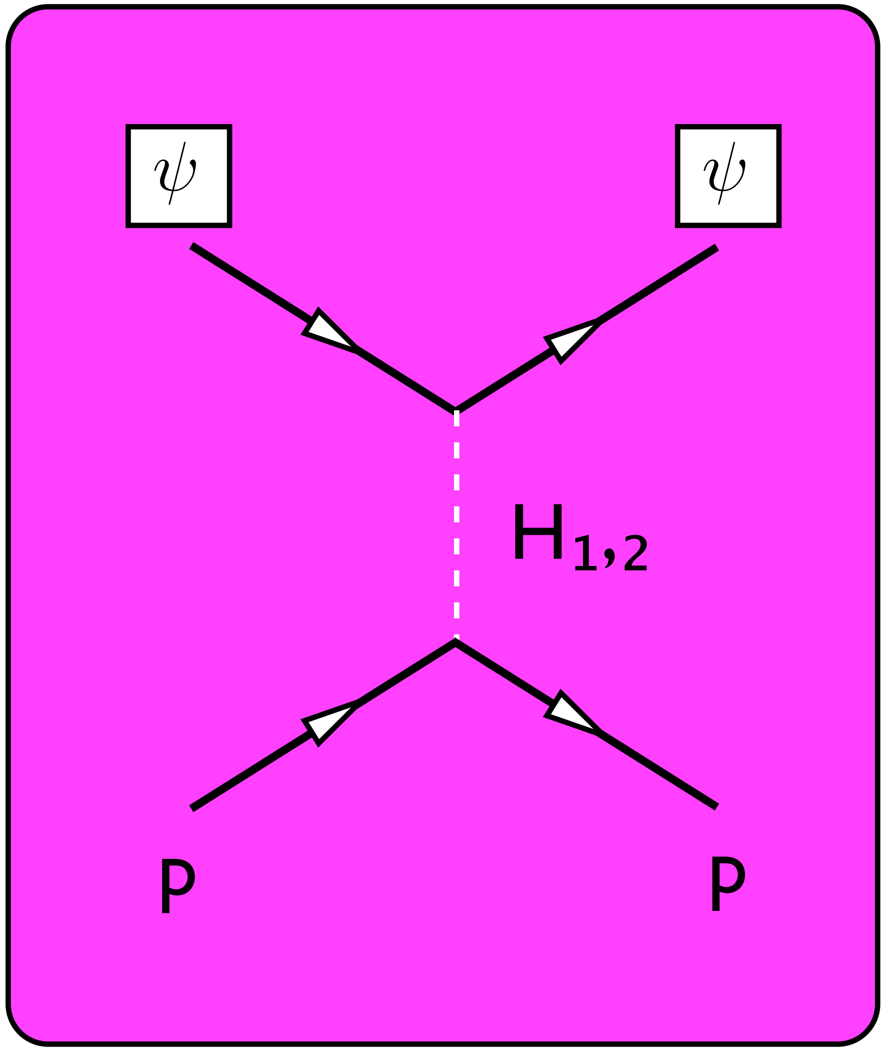
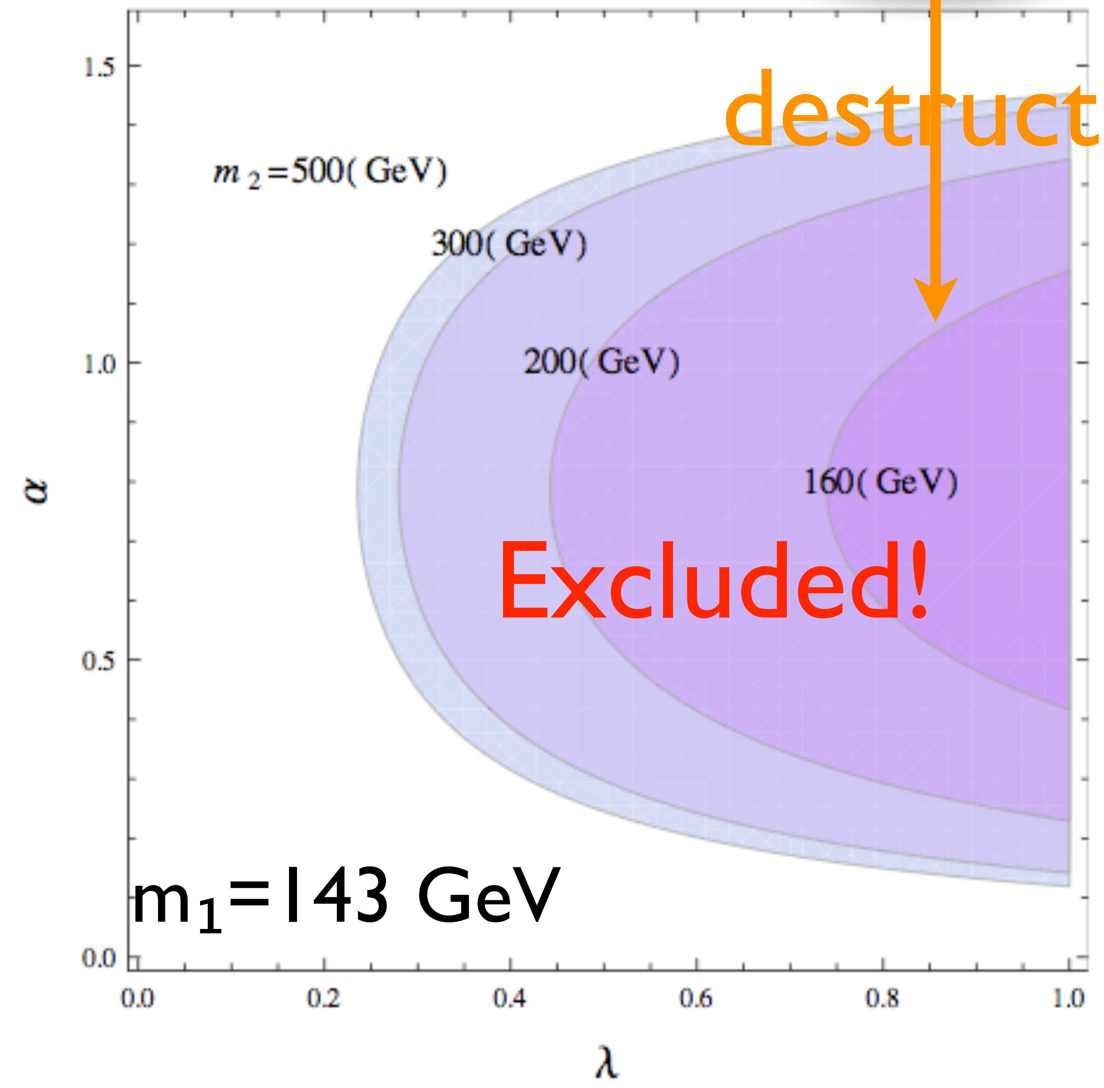


destructive!



- We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

$$\mathcal{L}_{\rm eff} = \overline{\psi}\left(m_0 + \frac{H^\dagger H}{\Lambda}\right)\psi.$$

- Only one Higgs boson (alpha = 0)

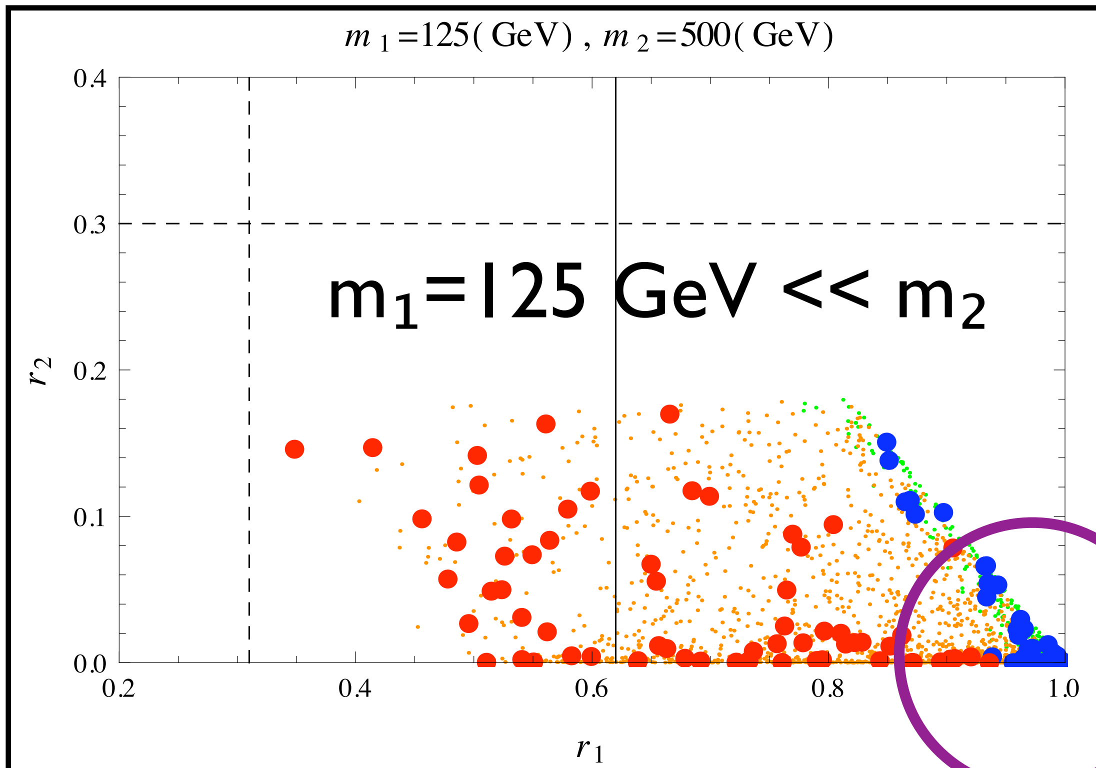
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

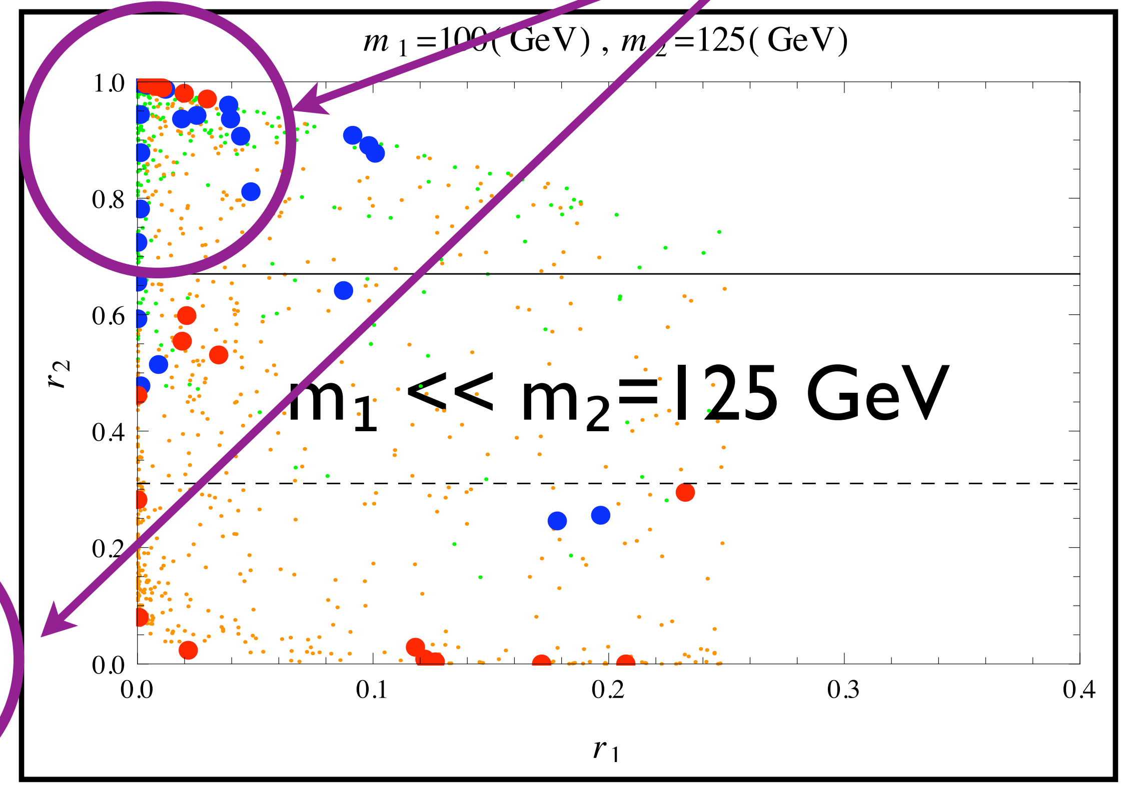
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

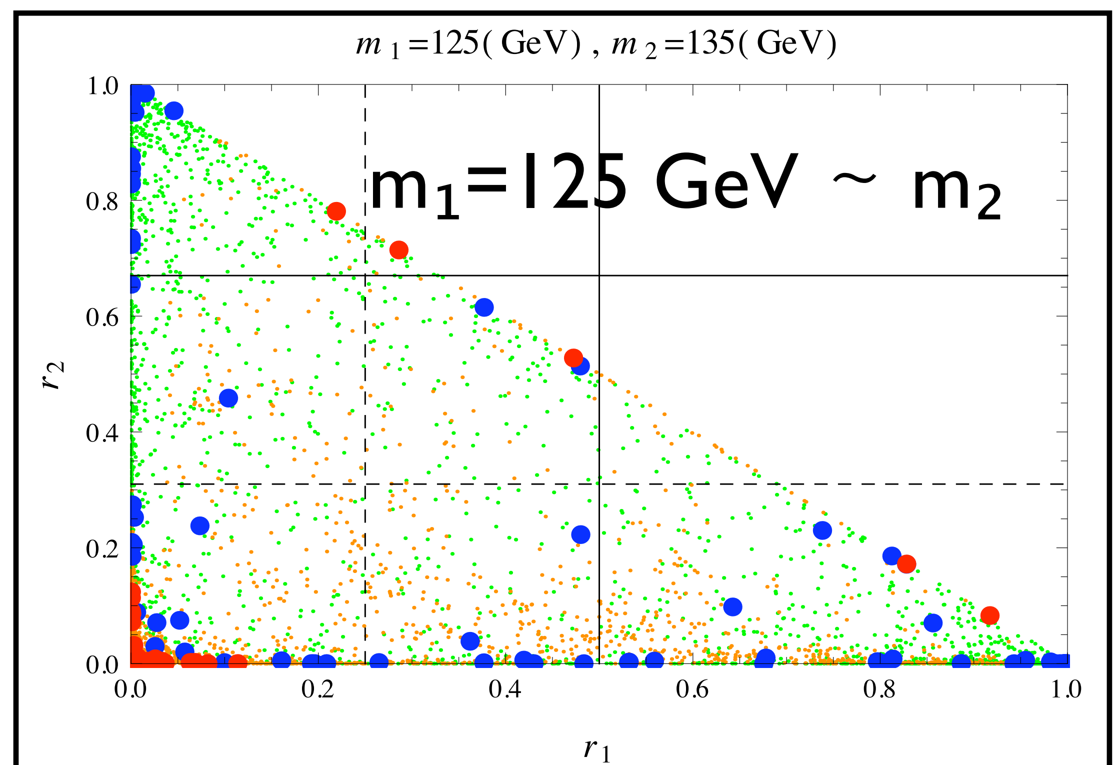
LHC data for 125 GeV resonance

- Signal strength (r_2 vs r_1)





: L= 5 fb^{-1} for 3σ Sig.
: L=10 fb^{-1} for 3σ Sig.



- : Ω(x),σ_p(x)
- : Ω(x),σ_p(o)
- : Ω(o),σ_p(x)
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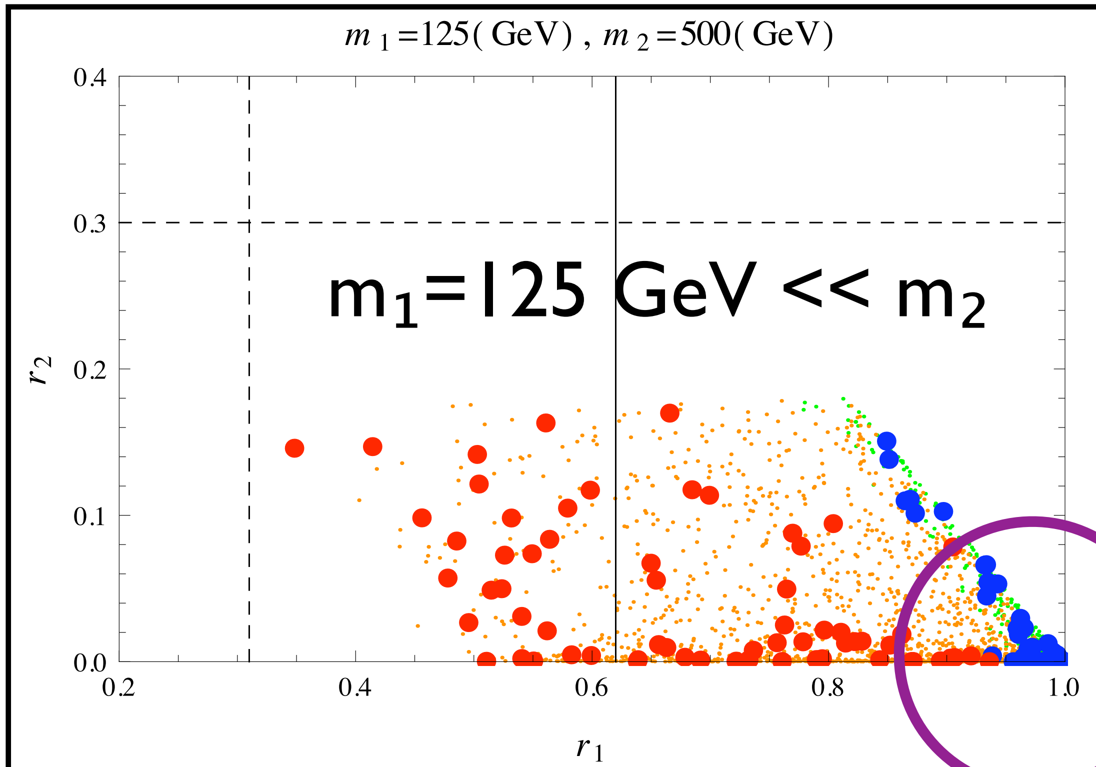

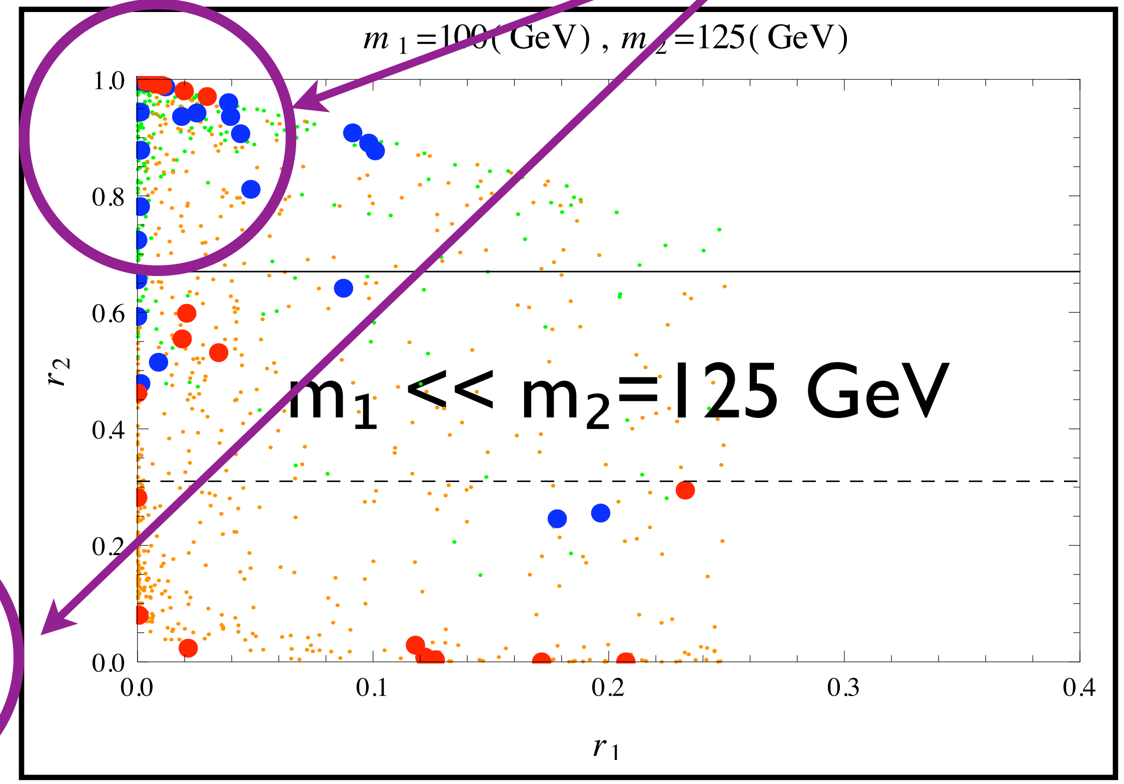

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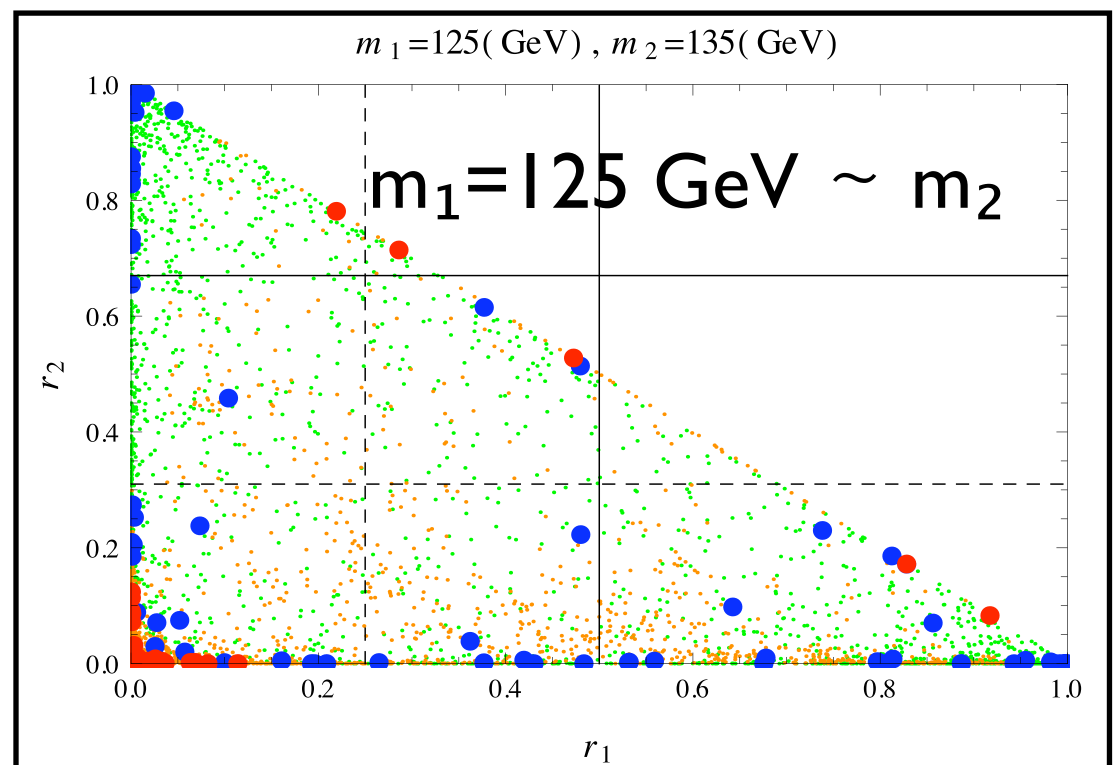

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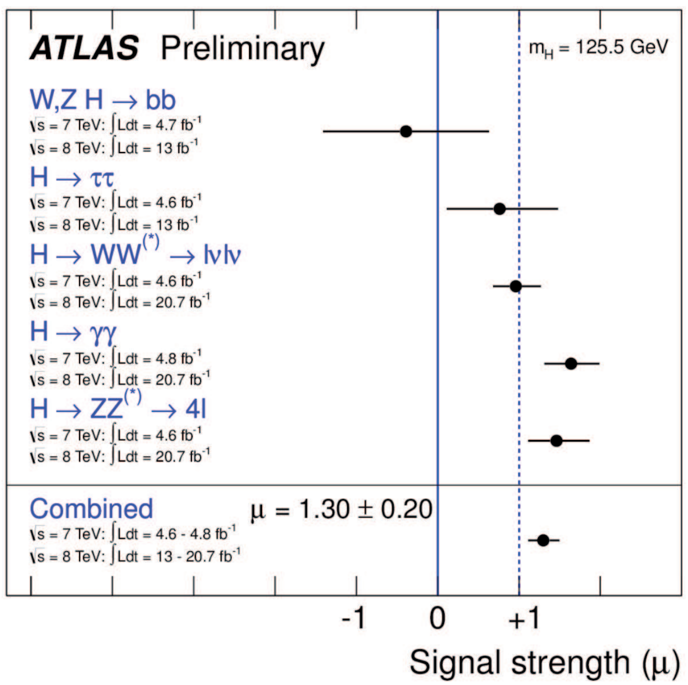
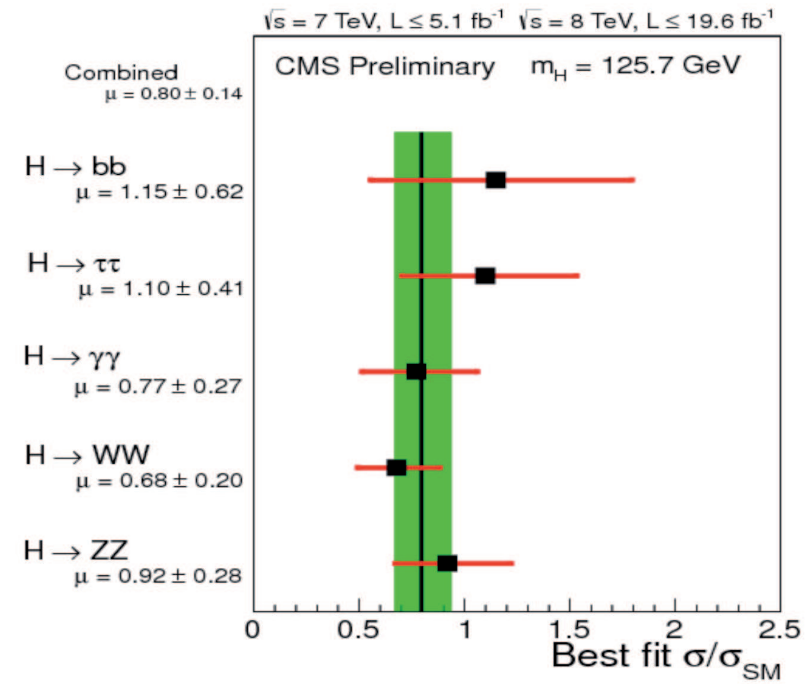
Updates@LHCP

Signal Strengths

$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\rm SM} \cdot \mathrm{Br}_{\rm SM}}$$



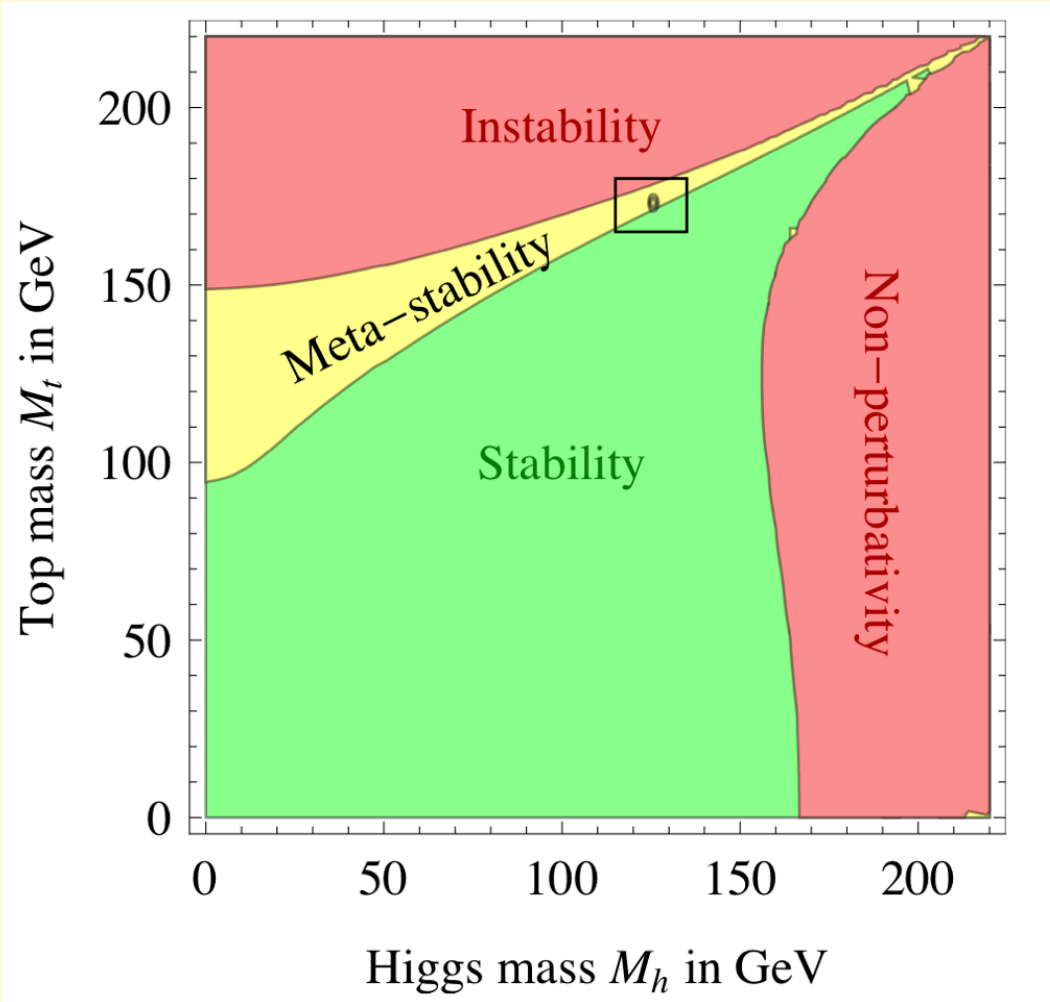


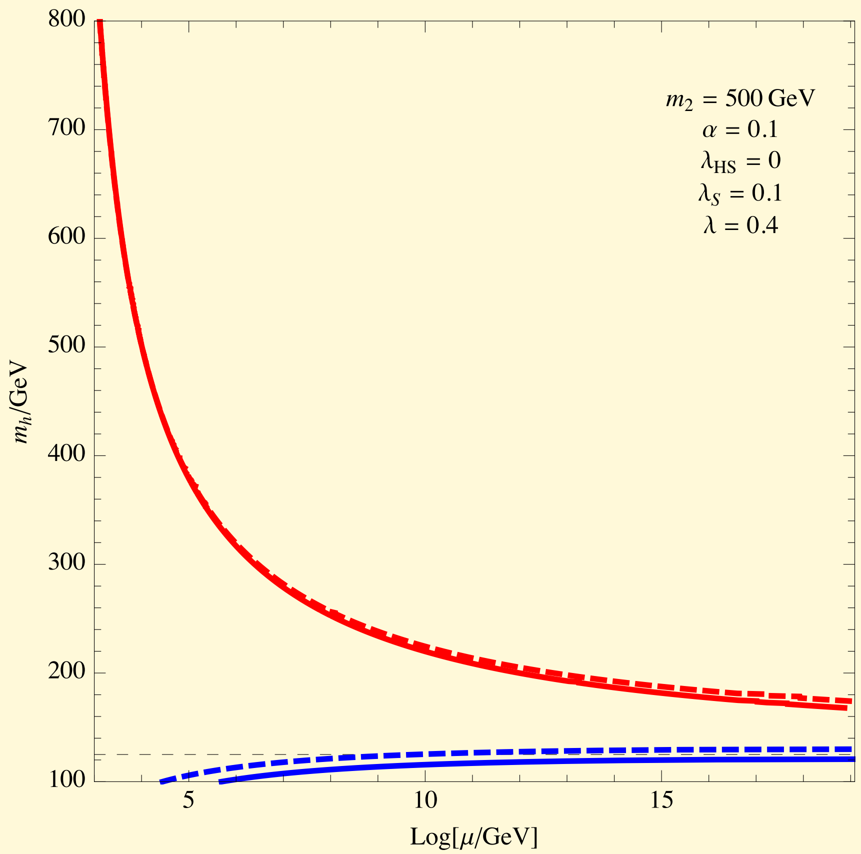
Decay Mode	ATLAS (M_H = 125.5 GeV)	CMS (M_H = 125.7 GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = \mathbf{0.96 \pm 0.12}$$

Getting smaller

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Similar for Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- A complete model should be something like this:

$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \frac{\lambda_\Phi}{4}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2$$
$$-\lambda_{H\Phi}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right) ,$$

$$\langle 0|\phi_X|0\rangle = v_X + h_X(x)$$

- There appear a new singlet scalar h_X from phi_X , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model
- Important to consider a minimal renormalizable model to discuss physics correctly
- Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)

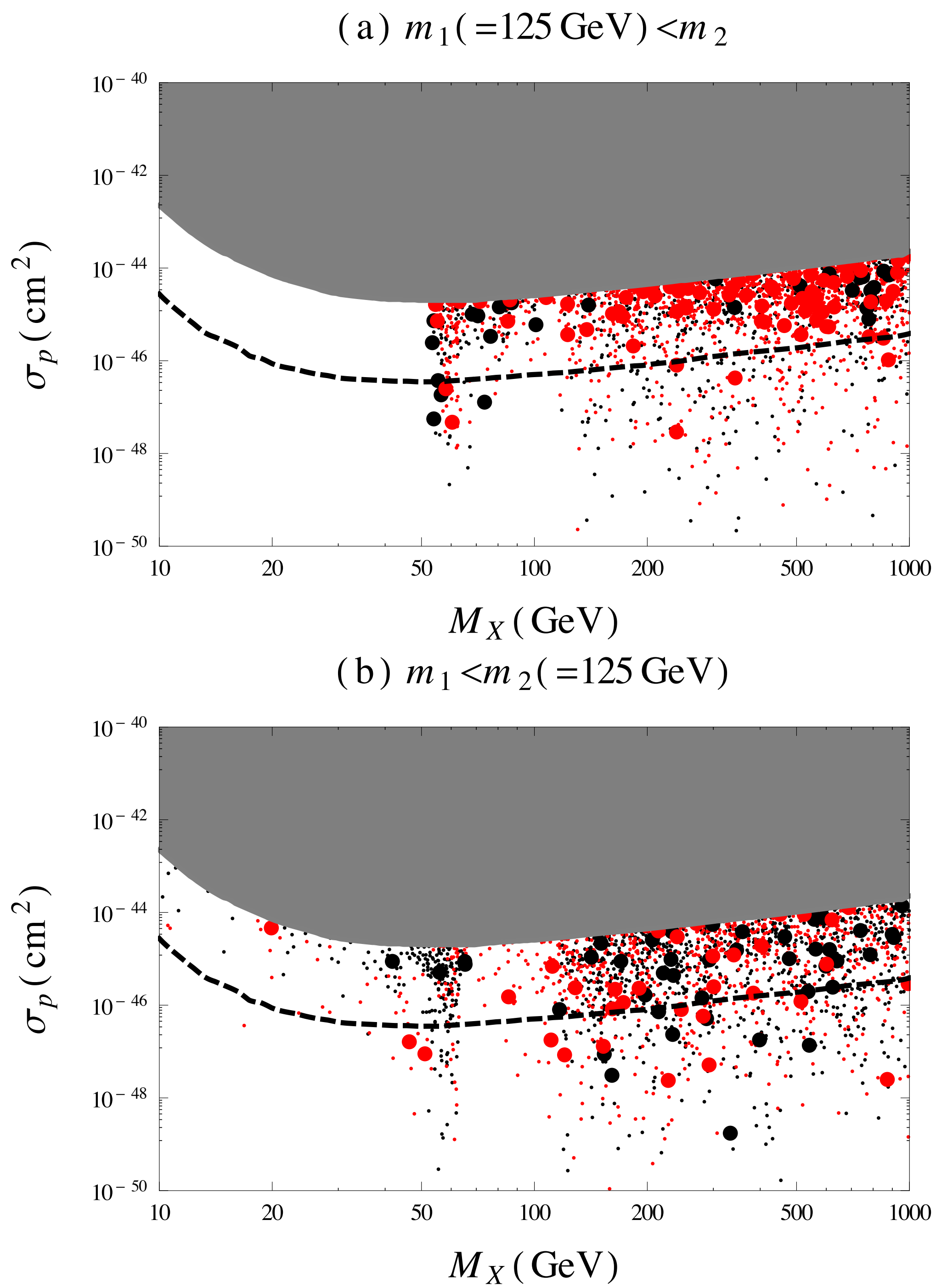


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

New scalar improves EW vacuum stability

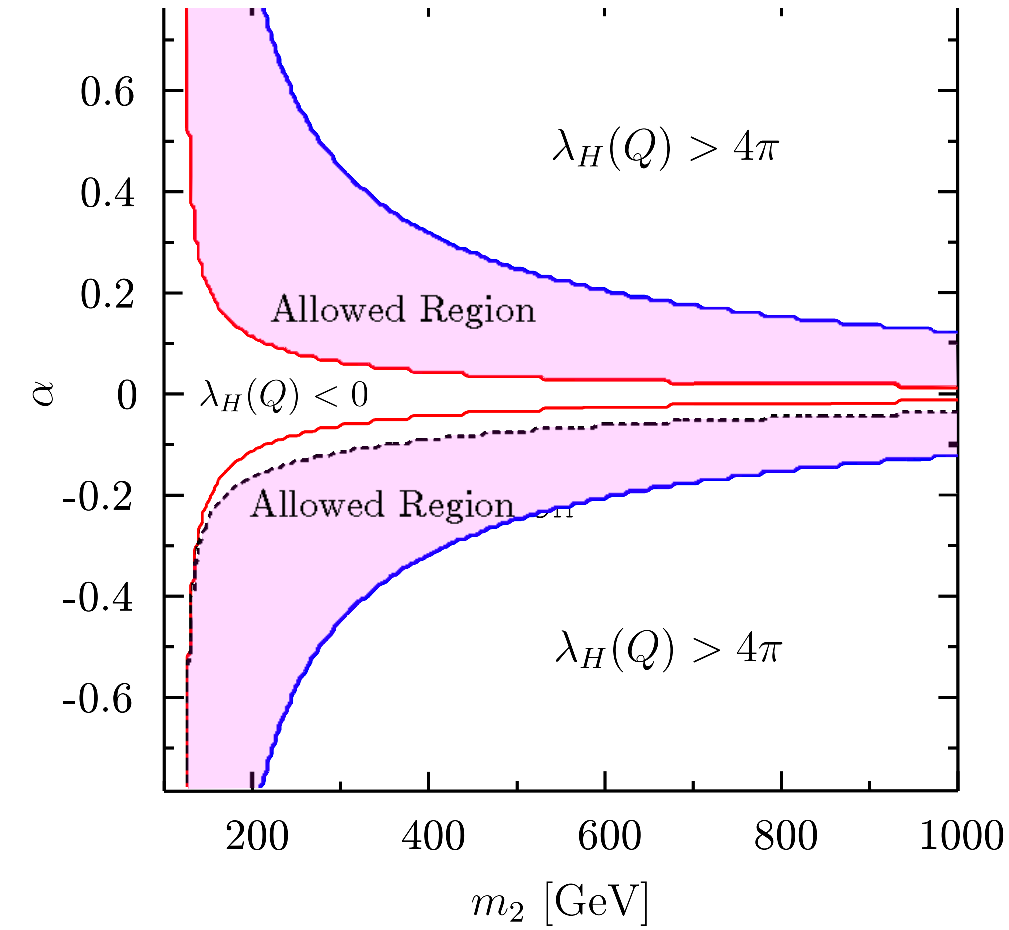


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Comparison with the EFT approach

- SFDM scenario is ruled out in the EFT
- We may lose imformation in DM pheno.

A. Djouadi, et.al. 2011

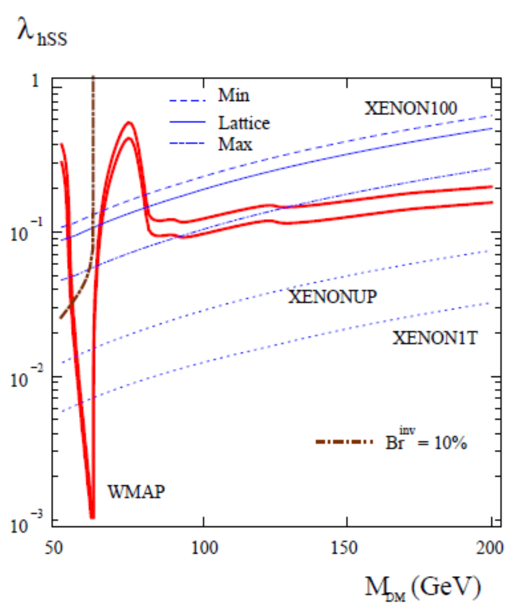


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

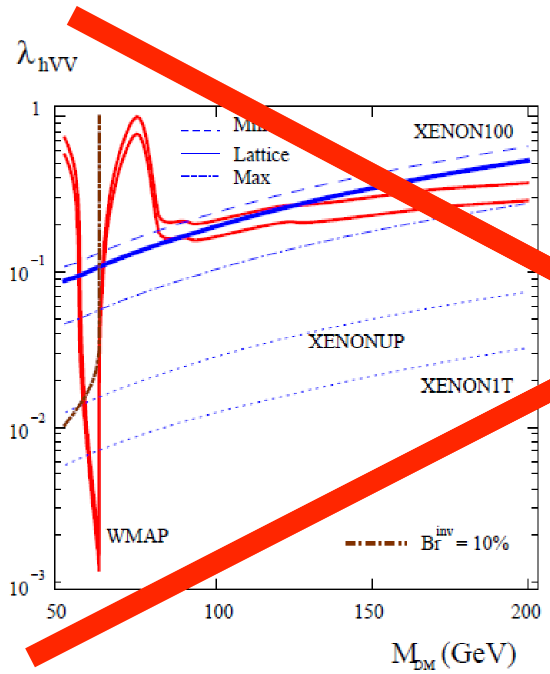


FIG. 2. Same as Fig. 1 for vector DM particles.

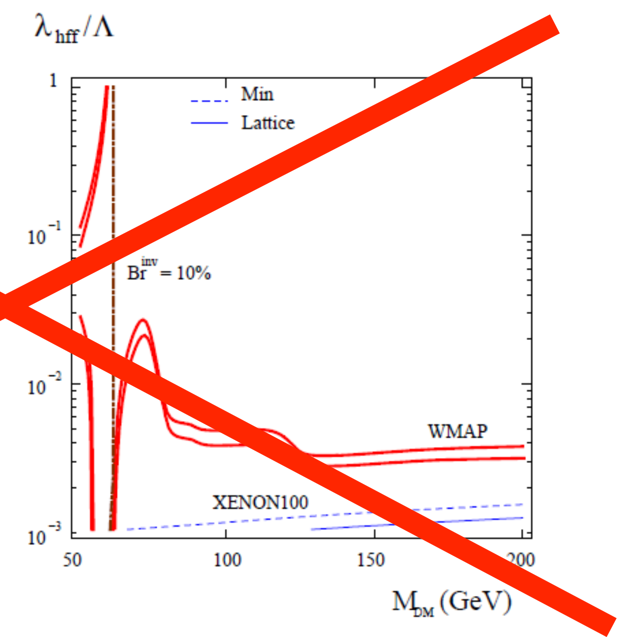


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian,
we get different results !

Why Dark Symmetry ?

- Is DM absolutely stable or very long lived ?
- If DM is absolutely stable, one can assume it carries a new conserved dark charge, associated with unbroken dark gauge sym
- DM can be long lived (lower bound on DM lifetime is much weaker than that on proton lifetime) if dark sym is spontaneously broken

Higgs is harmful to DM stability

Z2 sym scalar DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H.$$

- Very popular alternative to SUSY LSP
- Simplest in terms of the # of new dof's
- But, where does this Z2 symmetry come from ?
- Is it Global or Local ?

Fate of CDM with Z2 sym

- Global Z2 cannot save DM from decay with long enough lifetime

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\rm Planck}} S O_{\rm SM}$$

keeping dim-4 SM operators only

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S{}^3}{M_{\rm Planck}^2} \sim \left(\frac{m_S}{100{\rm GeV}}\right)^3 10^{-37} GeV$$

The lifetime is too short for 100 GeV DM

Fate of CDM with Z2 sym

- Spontaneously broken local U(1)x can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$$\phi_X^\dagger X H^\dagger H, \quad \text{and} \quad \phi_X^\dagger X O_{\rm SM}^{(dim-4)}$$

Problematic !

Perfectly fine !

- These arguments will apply to all the CDM models based on ad hoc global Z2 symmetry

- One way out is to implement Z2 symmetry as local U(1) symmetry (In preparation with Seungwon Baek and Wan-Il Park@ KIAS)

$$Q_X(\phi) = 2, \quad Q_X(X) = 1$$

In preparation w/ WIPark and SBaek

$$\mathcal{L} = \mathcal{L}_{\rm SM} + -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon X_{\mu\nu}B^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X - \frac{\lambda_X}{4}\left(\phi_X^\dagger\phi_X - v_\phi^2\right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X$$
$$- \frac{\lambda_X}{4}\left(X^\dagger X\right)^2 - \left(\mu X^2\phi^\dagger + H.c.\right) - \frac{\lambda_{XH}}{4}X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4}\phi_X^\dagger\phi_X H^\dagger H - \frac{\lambda_{XH}}{4}X^\dagger X\phi_X^\dagger\phi_X$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

$$X_R \to X_I\gamma_h^* \quad \text{followed by} \quad \gamma_h^* \to \gamma \to e^+e^-$$ etc.

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Unbroken Local Dark Sym

- Dark charge is conserved if dark symmetry is unbroken (E. Noether's theorem)
- In this case, the Higgs sector needs not be extended
- Higgs phenomenology should be the same as the SM sector in the minimal version (modulo invisible H decay)
- Still the model could be OK until Planck scale for 125 GeV Higgs, since there could be other scalar fields (scalar CDM, for example)

Unbroken Local Dark Sym

- Local dark symmetry can be either confining (like QCD) or not
- For confining dark symmetry, gauge fields will confine and there is no long range dark force, and DM will be composite baryons/mesons in the hidden sector
- Otherwise, there could be a long range dark force that is constrained by large/small structures, and contributes to dark radiation

Spon. Broken local dark sym

- If dark sym is spont. broken, DM will decay in general, if there is no remaining (discrete) unbroken gauge symmetry
- There will be a singlet scalar after spontaneous breaking of dark gauge symmetry, which mixes with the SM Higgs boson
- There will be at least two neutral scalars (and no charged scalars)
- Vacuum stability is improved by the new scalar
- Higgs Signal strengths universally reduced from "ONE"