EWSB and CDM from Strongly Interacting Hidden Sector

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SCGT 2012 Mini, Nagoya, Japan
(March 18-20, 2012)

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- Motivations
- Strongly Interacting Hidden Sector
- Singlet fermion CDM with Higgs portal
- Conclusions

Motivations

Current Status of the SM

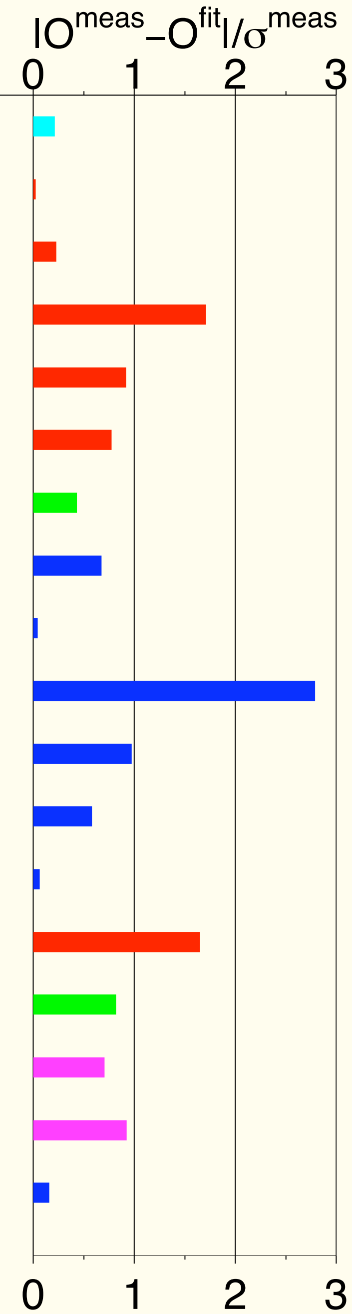
SO GOOD with all the data, EWPT, CKM except for

1. Unseen Higgs so far
2. Neutrino masses and mixings
3. Baryon Number Asymmetry
4. Nature of CDM

- LHC designed to discover SM Higgs (Item 1)
- Seesaw + Leptogenesis (Items 2+3)
- Many models for Item 4

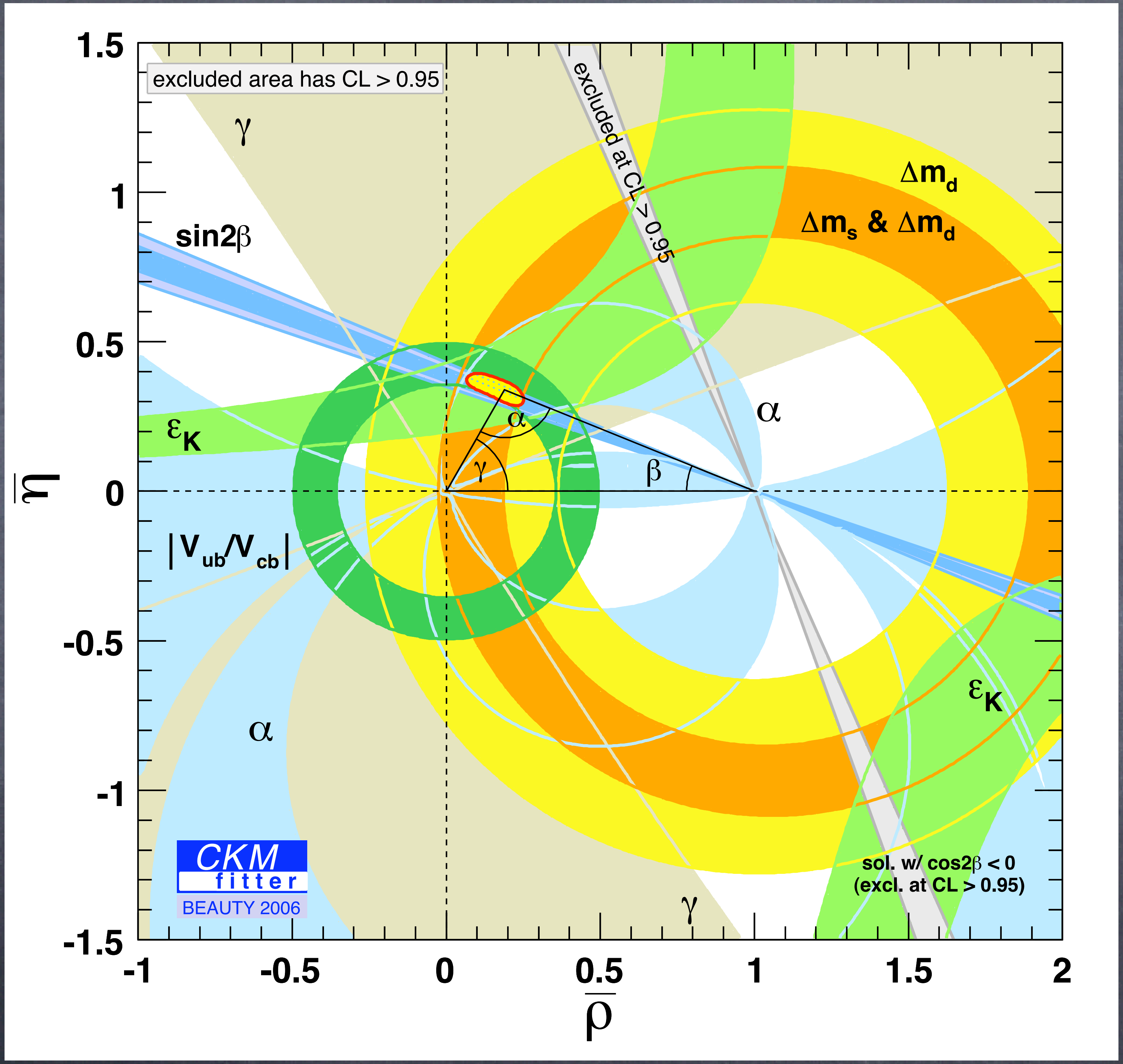
Overall features of EWPT

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



$$\Lambda_{NP} > O(10)\mathrm{TeV}$$

CKM Fit



$$\Lambda_{\rm NP} > O(100)\,\mathrm{TeV}$$

What's next ?

- Understanding of

  - Origin of EWSB
  - Origin of families (Flavors)
  - Many fine tuning problems

I ignore here

- Usual arguments for new physics around TeV scale based on quadratic divergence of (Higgs mass)^2
- Real Fine tuning problem with EWPT & CKM
- New physics better insensitive to the SM interaction, but has something to do with CDM & EWSB

K. Wilson "The origin of lattice gauge theory" hep-lat/0412043

5. BLUNDERS AND A BIZARRE EPISODE

In the early 1970's, I committed several blunders that deserve a brief mention. The blunders all occurred in the same article [27]: a 1971 article about the possibility of applying the renormalization group to strong interactions, published before the discovery of asymptotic freedom. My first blunder was not recognizing the theoretical possibility of asymptotic freedom. In my 1971 article, my intent was to identify all the distinct alternatives for the behavior of the Gell-Mann–Low function $\beta(g)$, which is negative for small g in the case of asymptotic freedom. But I ignored this possibility. The only

exactly at threshhold for binding, and the di-neutron also [28].

The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry [23]. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon. But this claim makes no sense when one becomes familiar with the history of physics. There have been a number of cases where numbers arose that were unexpectedly small or large.

Wise and Manohar, Hep-ph/0606172

Most of the extensions of the standard model with new physics at the TeV scale have been motivated by the hierarchy puzzle, i.e., why is the weak scale so small compared with the Planck or unification scales. However, the measured value of the cosmological constant suggests that a fine tuning that is qualitatively similar to that needed to achieve the smallness of the weak scale is needed for the cosmological constant. Perhaps we are not looking at this issue correctly.

If one does not adopt the hierarchy puzzle as the criteria for motivating extensions of the standard model then one can take a more general point of view. Certainly the

Motivations

- Ignore fine tuning problem of Higgs mass, and consider a hidden sector (neutral under SM gauge group) at EW scale
- Real Fine tuning problem with EWPT & CKM
- New physics better insensitive to the SM interaction, but has something to do with CDM & EWSB
- Introduce new particles neutral under the SM gauge group (Hidden Sector)
- Hidden sector : Generic in many BSM's & Why not ? (e.g. SUSY is broken in a hidden sector)
- Less constrained by EWPT and CKMology, because new particlers are SM singlets, and good CDM

Can we understand

- the stability of DM without ad hoc Z2 symmetry ?
- the generation of mass scales from quantum mechanics ?
- the effects of a hidden sector, if it exists ?
- Answer to these seemingly unrelated questions is YES !

Stability of DM

- Usually guaranteed by ad hoc Z2 symmetry
- Or life time of DM made very long by fine tuning of couplings
- Note that quark flavor is conserved within renormalizable QCD (accidental symmetry)
- Can we find a similar reason for the DM stability ?

Can we understand the origin of all the masses ?

- In massless QCD, all the masses originate from dimensional transmutation
- Proton mass dynamically generated by quarks and gluons, not by the quark masses
- A similar mechanism for elementary particles ?
- Questions by Coleman and Weinberg, F. Wilczek, C. Hill, W. Bardeen, ...

Hidden sector ?

- Usually the hidden sector breaks SUSY spontaneously, and then does nothing else
- Could play an important role in phenomenology at TeV scale, especially in Higgs phenomenology (Invisible Higgs decay into a pair of CDM's)
- Many possibilities for the choice of gauge groups and matter contents of the hidden sector (e.g.# of colors and flavors in the hidden QCD) and mediators between the SM and a hidden sector

Related Works & Talks

(as of 2007)

- Foot, Volkas, et al (Mirror World)
- Berezhiani et al (Mirror World)
- Strassler, Zurek, et al (Hidden Valley)
- Wilczek (Higgs portal & Phantom)
- Cheung, Ng, et al (Shadow)
- Ko et al (Hidden Sector strong interaction)
- Many works after 2007

Weakly Interacting Hidden Sector

- Perturbation applicable & easy to analyze,
- Gauge boson mass is generated by Higgs mechanism
- Origin of mass scale remains unclear (or by ordinary Higgs mechanism), just like in SM
- Leptophilic Dirac Fermion DM (Baek and Ko)

Strongly Interacting Hiddens Sector

- Perturbation not applicable & difficult to analyze
- Construct relevant Effective Field Theory (EFT) depending on the physics problems
- Can address dynamical generation of mass scale, like in massless QCD
- Chiral lagrangian technique for the Nambu-Goldstone boson (the hidden sector pion = CDM)

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Nicety of QCD

- Renormalizable : Valid to very high energy scale
- Asymtotic feedom : No Landau pole below $M_{\rm Planck}$
- QM dimensional transmutation :

$$g_s \rightarrow \Lambda_{\rm QCD} \ll M_{\rm Planck}$$

- Trace anomaly breaks scale sym. of massless QCD
- Chiral symmetry breaking (spontaneous & explicit)
- Light hadron mass dominantly from chiral sym breaking
- Flavor conservation : accidental symmetry of QCD

Can we build a model for EWSB and CDM similar to QCD ?

Can we build a model
for EWSB and CDM
similar to QCD ?

Yes !

Strongly Interacting Hidden Sector

Toy Model

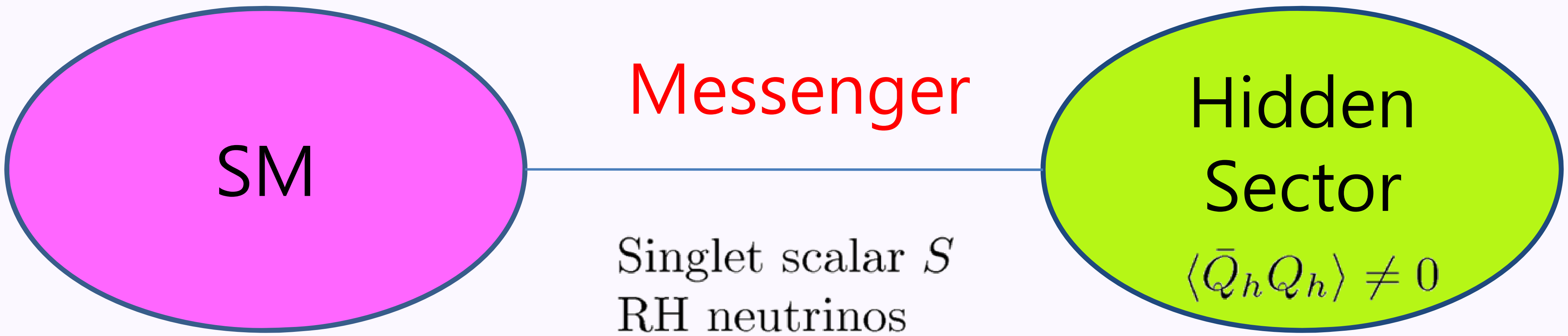
(arXiv:0709.1218, Phys. Lett. B696, 262 (2011)
with T.Hur, D.W.Jung and J.Y.Lee)

Hidden Sector Pion as a CDM

- CDM in most models stable due to ad hoc Z2 symmetry
- In our models I&II, the hidden sector pion is stable due to flavor conservation in hQCD (accidental symmetry of the underlying gauge theory), which is a very nice aspect of our model
- Remember pion is stable under strong interaction in ordinary hadronic world, decays only through em or weak interaction

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture



Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Warming up with a toy model

- Reinterpretation of 2 Higgs doublet model
- Consider a hidden sector with QCD like new strong interaction, with two light flavors
- Approximate SU(2)L X SU(2)R chiral symmetry, which is broken spontaneously
- Lightest meson π_h : Nambu-Goldstone boson -> Chiral lagrangian applicable
- Flavor conservation makes π_h stable -> CDM

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

Not present in the two-Higgs Doublet model

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

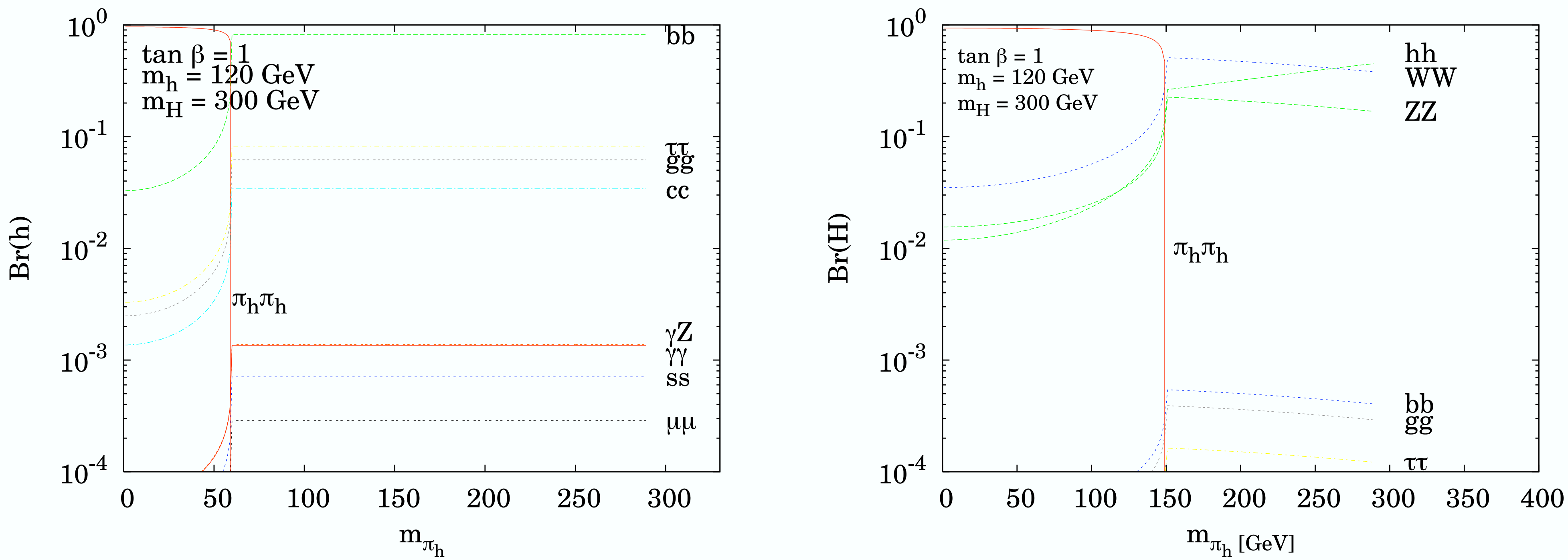
12년 3월 18일 일요일

Similar to the usual two-Higgs doublet model, except that

- H2 : SM singlet, no contribution to W,Z, or fermion masses -> Less problem with EWPT or Higgs mediated CPV
- "a" term gives hidden sector pion mass ->CDM
- Charges of hidden pion : Not electric charge, but the hidden sector isospin (I3)

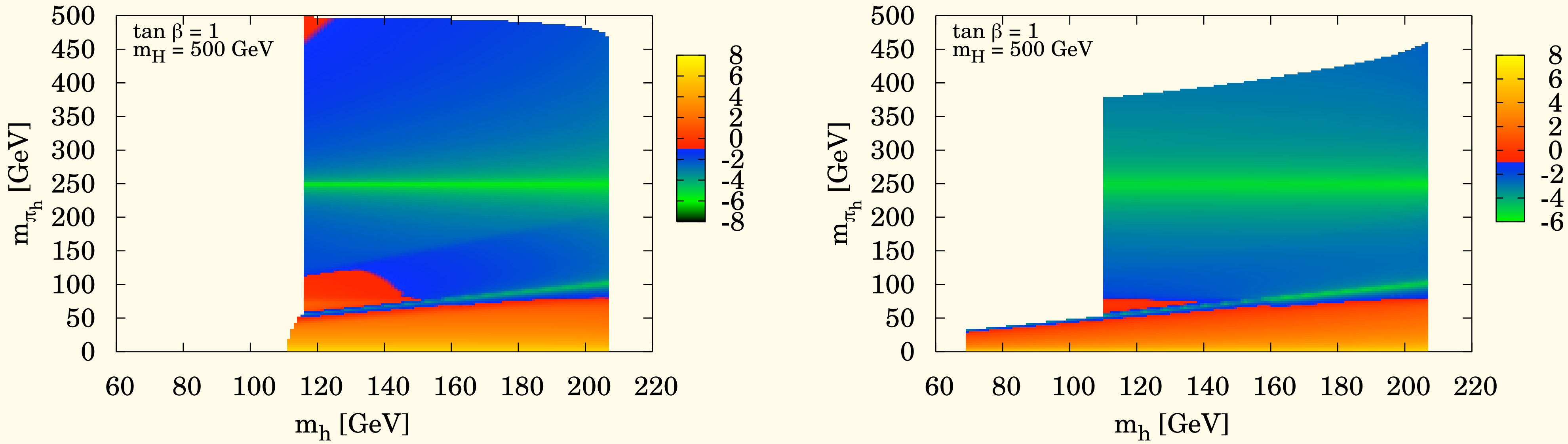
- h and H are mixtures of $h_{\rm SM}$ and σ_h: partially composite
- $h(H) - V - V$ couplings : the same as the $H_{\rm SM} - V - V$ couplings modulo $\cos\alpha$ and $\sin\alpha$
- the same is true for the $h(H) - f - \bar{f}$ with SM fermions f couplings
- Productions of h and H at colliders are suppressed by $\cos^2\alpha$ and $\sin^2\alpha$, relative to the production of the SM Higgs with the same mass
- $h(H) - \pi_h - \pi_h$ couplings contribute to the invisible decays $h(H) \to \pi_h \pi_h$
- 4 parameters for $\mu_1^2 = 0$: $\tan\beta$, m_{π_h}, λ_1 and λ_2 or trade the last two with m_h and m_H

Br of h and H



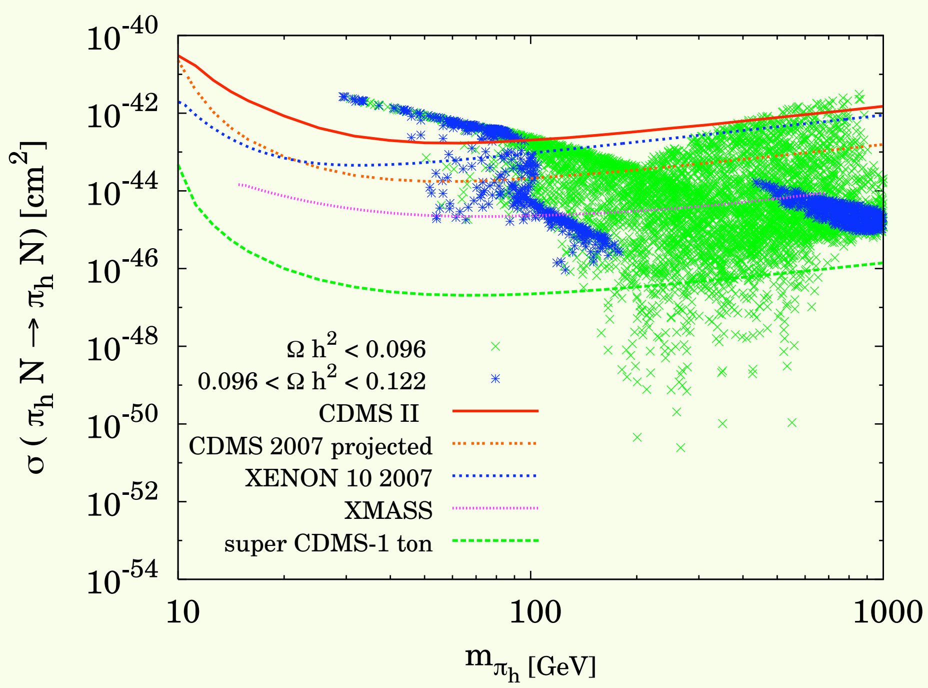
- Branching ratios of h and H as functions of m_{π_h} for $\tan\beta = 1$, $m_h = 120$ GeV and $m_H = 300$ GeV.
- $h, H \to \pi_h \pi_h$: invisible decay branching ratios make difficult to detect them at colliders

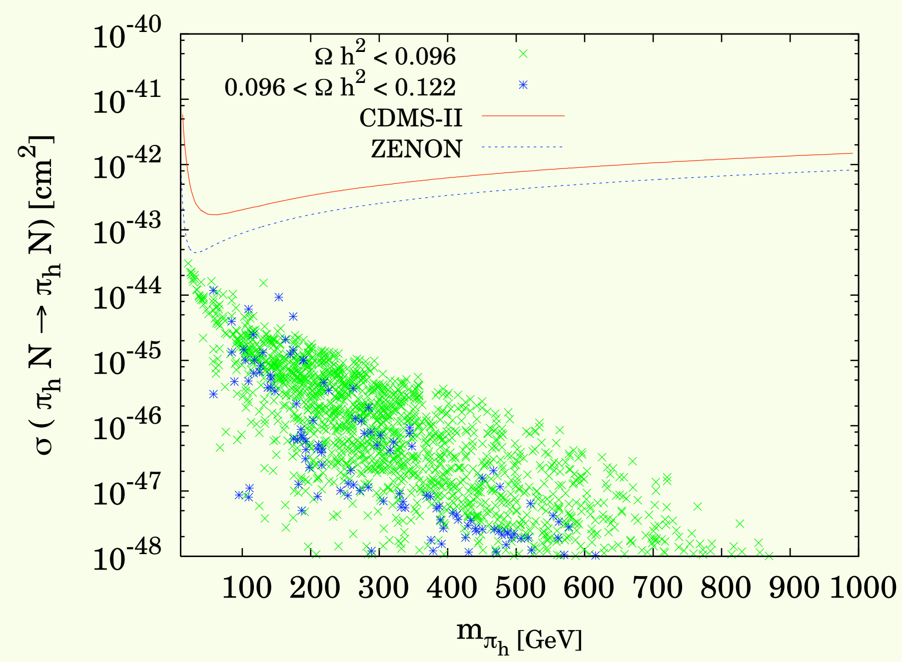
Relic Density



- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate





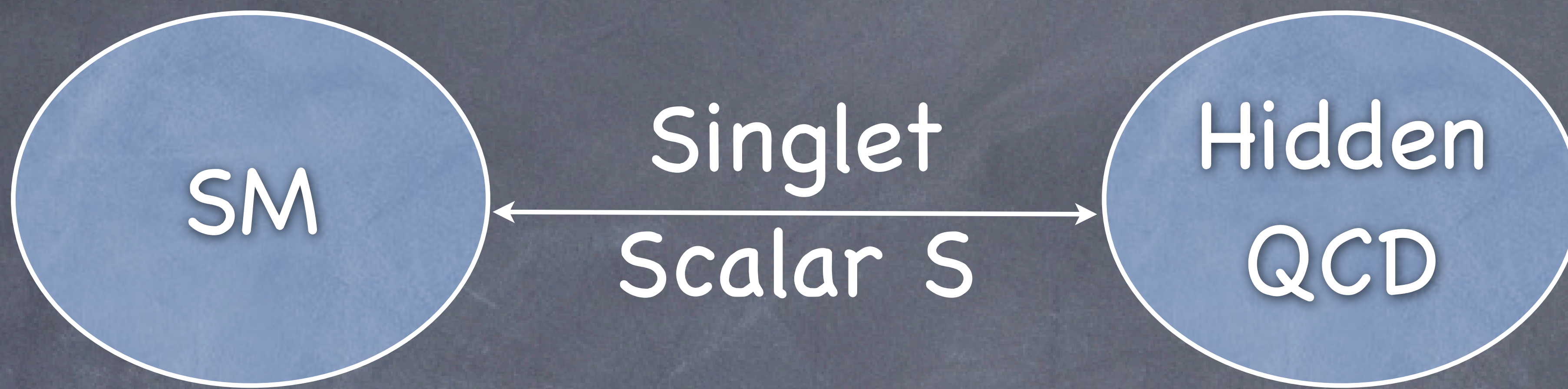
- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Model I : Scalar Messenger
(Scale invariant extension of the SM)

arXiv:1103.2571 [hep-ph] (with Taeil Hur)

PRL 106: 141802 (2011)

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

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

Hidden sector lagrangian with new strong interaction

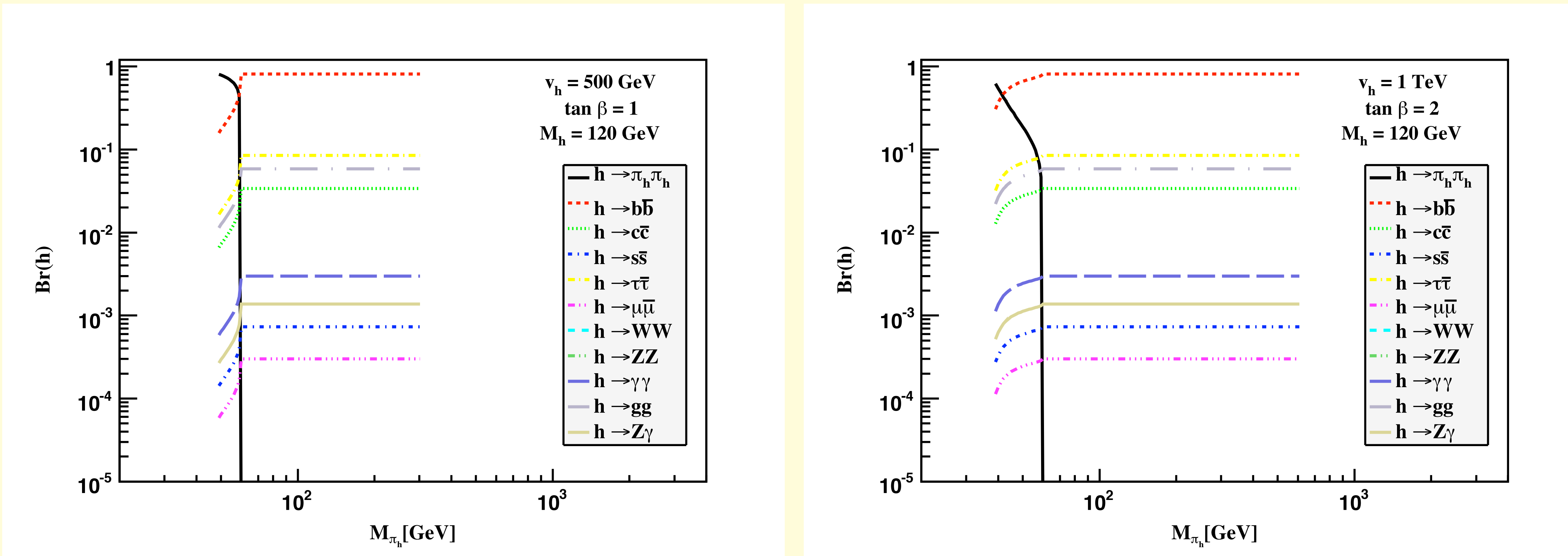
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k(i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

- Hidden sector condensate develops a linear potential for S -> Nonzero VEV for S
- Hidden sector quarks get massive by <S>
- Nonzero Higgs mass parameter form <S>
- EWSB occurs if the sign is correct
- Therefore, all the mass scales from hidden sector quark condensates
- Construct effective chiral lagrangian for the hidden sector pion
- Calculate the relic density, (in)direct detection rate etc.

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

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

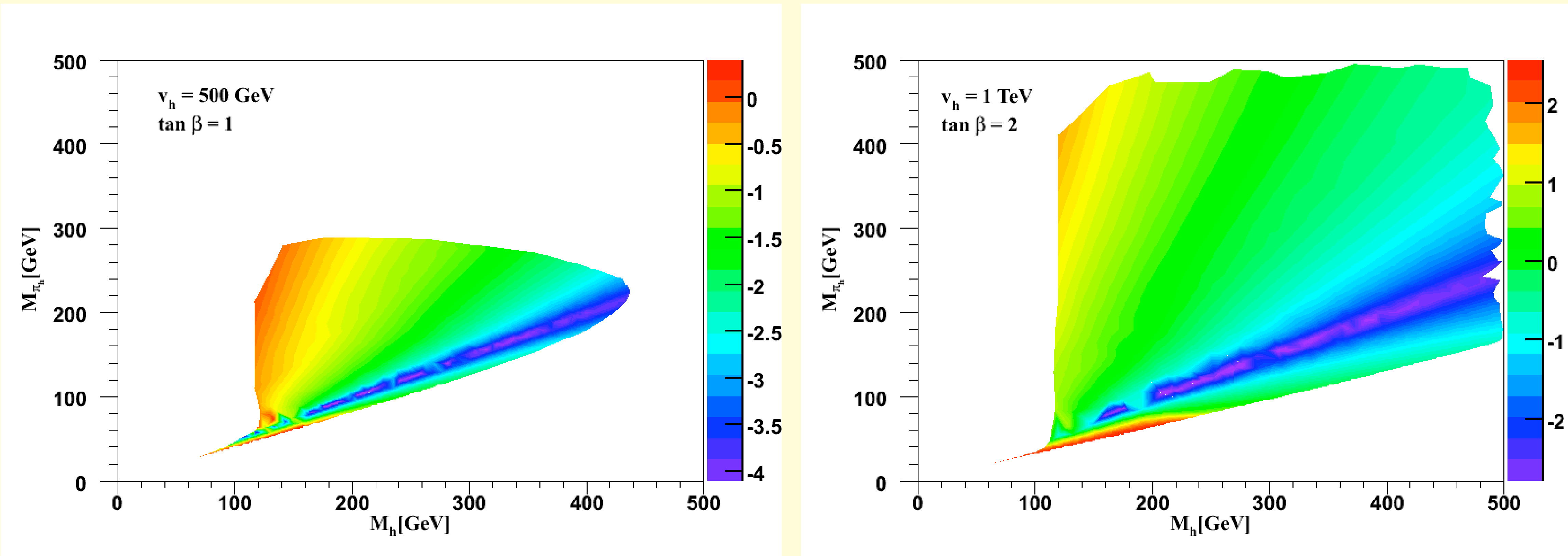
Br for lighter Higgs h



Br's of h owith $m_h = 120$ GeV as functions of m_{π_h} for (a)$v_h = 500$ GeV and $\tan\beta = 1$

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

Relic density

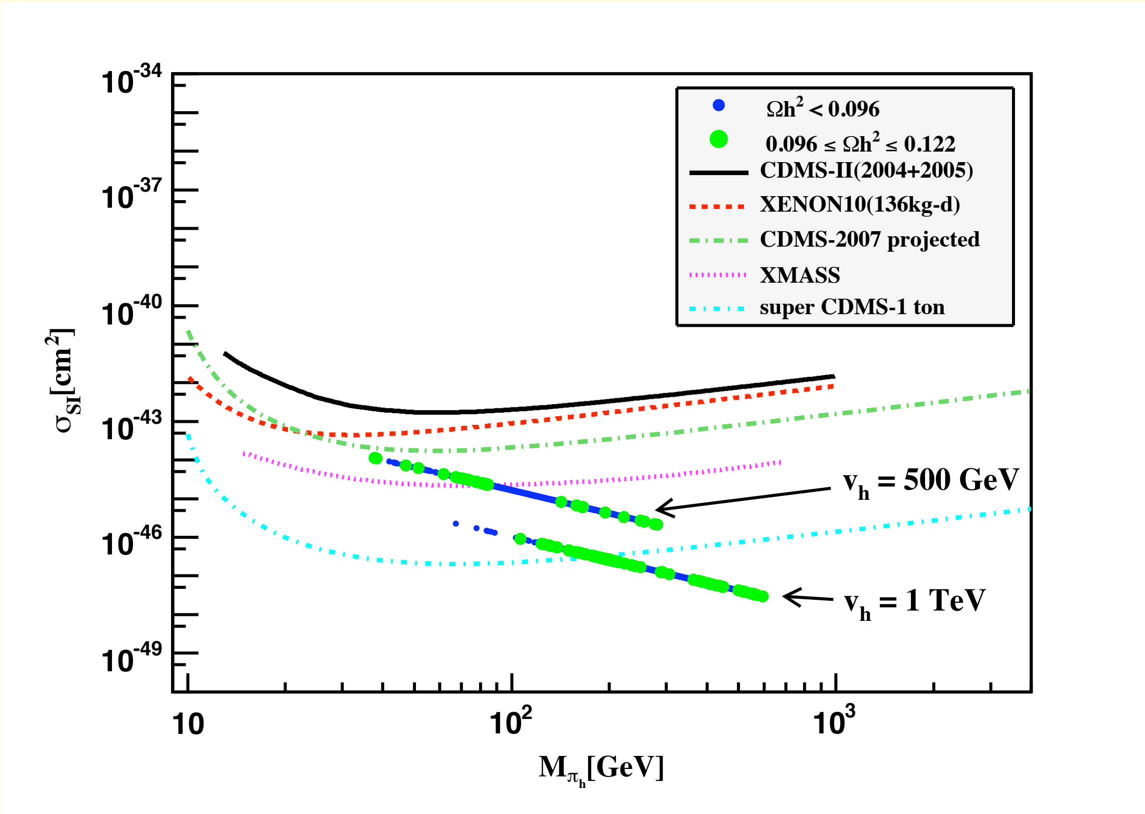


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

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

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

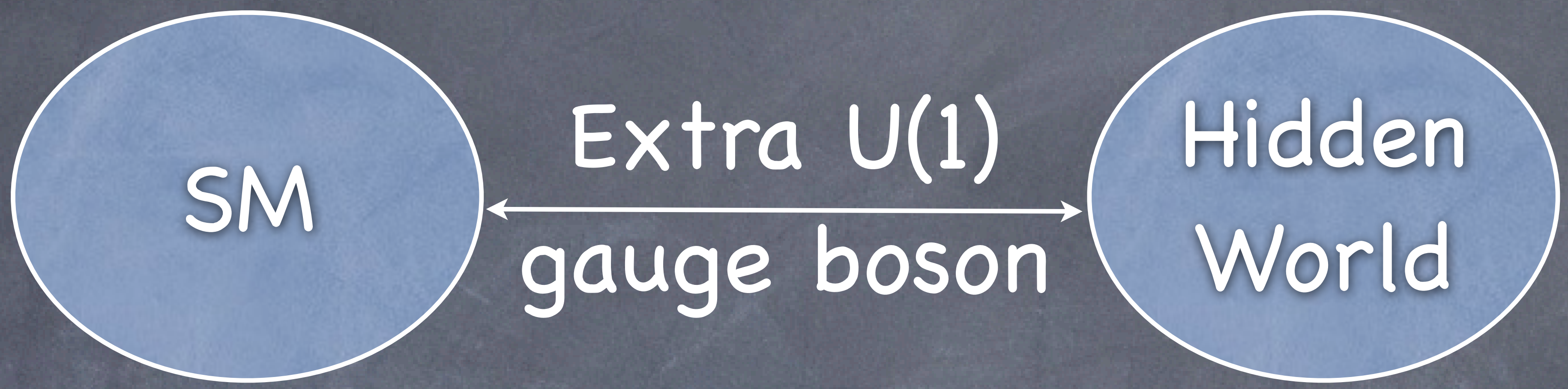
Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ 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 $\tan\beta = 2$.

Model II & III (Extra U(1))



- We consider two models
- U(1) model by Strassler et al. (Hidden valley scenario) : with hidden sector QCD
- Leptophilic U(1) motivated by PAMELA and FERMI data (Baek and Ko) : with hidden sector DM Dirac fermion

Summary of the stongly interacting hidden sector

- Hidden sector could be generic, is less constrained by EWPT and CKMology, and could be important is EWSB and CDM

- All the masses (including CDM mass) can come from dimensional transmutation in the hidden sector QCD

- (In)Direct Detection Exp.t's of CDM may be able to find some signatures

- Higgs phenomenology can be affected a lot (More than one neutral scalar bosons, Invisible Br, Reduced productions at colliders, etc.)

- " No Higgs (observed) at LHC " is not impossible (Another Nightmare ?) ---> Seems to be disfavored by the LHC data

Future Direction

- SUSY version ?
- Weakly interacting nonabelian hidden sector ?
- Connection between Baryon/DM ratio ? --> Natural setting for asymmetric dark matter (work in progress)
- Gauge coupling unification and embedding into GUT or String Model ?

Elusive Higgs bosons at LHC with a singlet fermion dark matter

Based on arXiv:1112.1847, in JHEP;
and work in progress
(with Seungwon Baek, Pyungwon Ko)

Outlines

- Higgs in standard model
- Current status of Higgs search
- Ratiocination
- Constraints
- Discovery possibility
- Conclusions

Higgs in Standard Model

- Lagrangian in SM

$$\mathcal{L}_H = (D_\mu H)^\dagger (D^\mu H) - \underbrace{\lambda \left(|H|^2 - v^2\right)^2}_{m_H = 2\sqrt{\lambda}\, v} + \mathcal{L}_{\text{Yukawa}}$$

λ: unknown

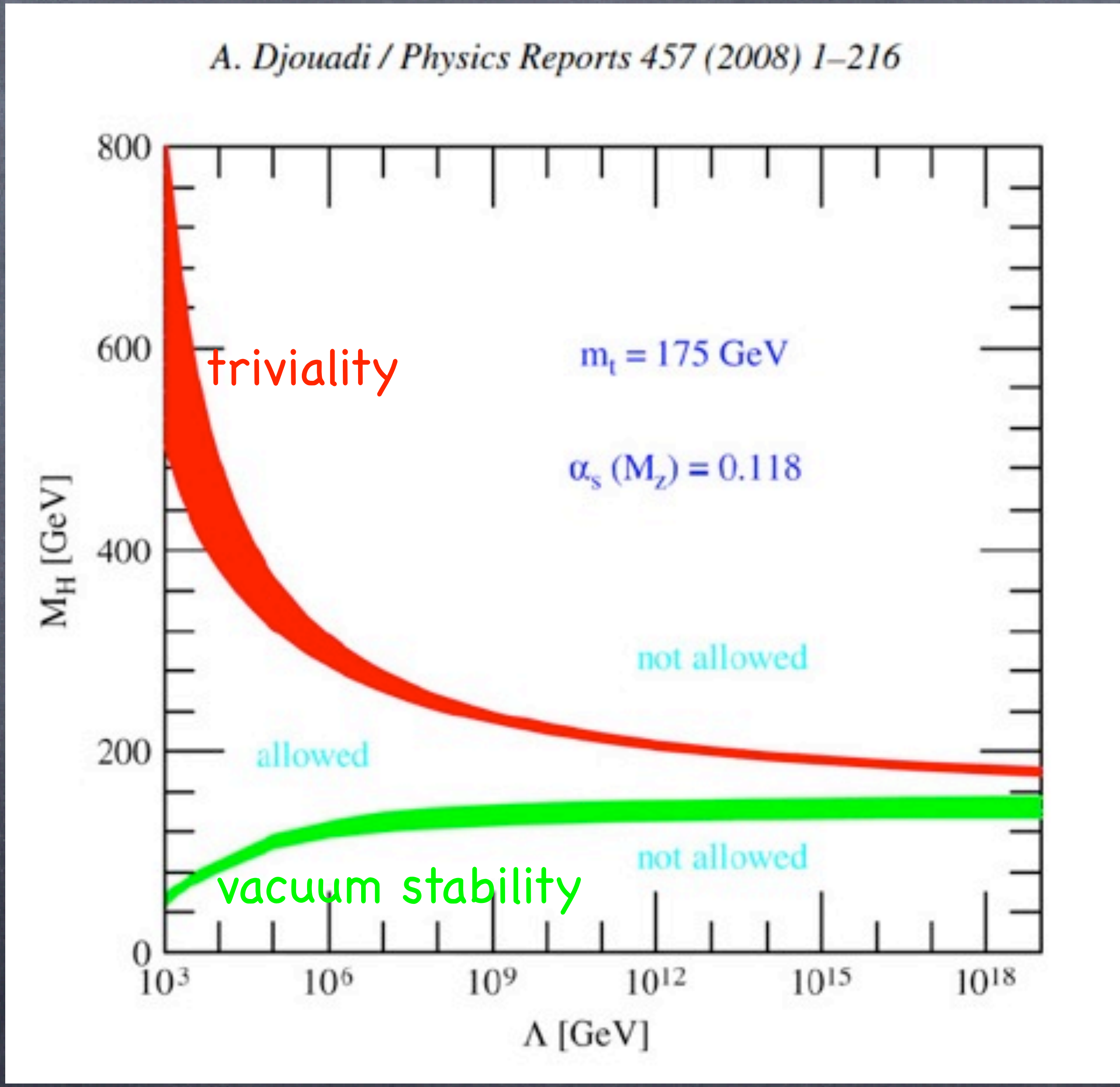
- Theoretical constraint on the Higgs mass

$$\underbrace{50\,\text{GeV}}_{\text{Vacuum stability}} \lesssim m_H \lesssim \underbrace{700\,\text{GeV}}_{\text{unitarity, perturbativity, triviality}}$$

Djouadi, Phys.Rept.457,1 (2008)

Higgs in standard model

- Theoretical band of Higgs mass vs. UV-cutoff



Hidden Sector CDM

Multiple neutral Higgs bosons and their invisible decays into a pair of CDM's in the hidden sector

Our scenario is very different from the more popular real singlet scalar CDM with Z2 symmetry, since there is only one Higgs boson in that case

- Hur, Jung, Ko & Lee, arxiv:0709.1218 [hep-ph], PLB696(2011)
- Ko, arxiv:0801.4284 [hep-ph], and a number of talks
- Hur & Ko, PRL106(2011)

- He & Tandean, arXiv:1109.1277 and many other works in this direction during the past few years

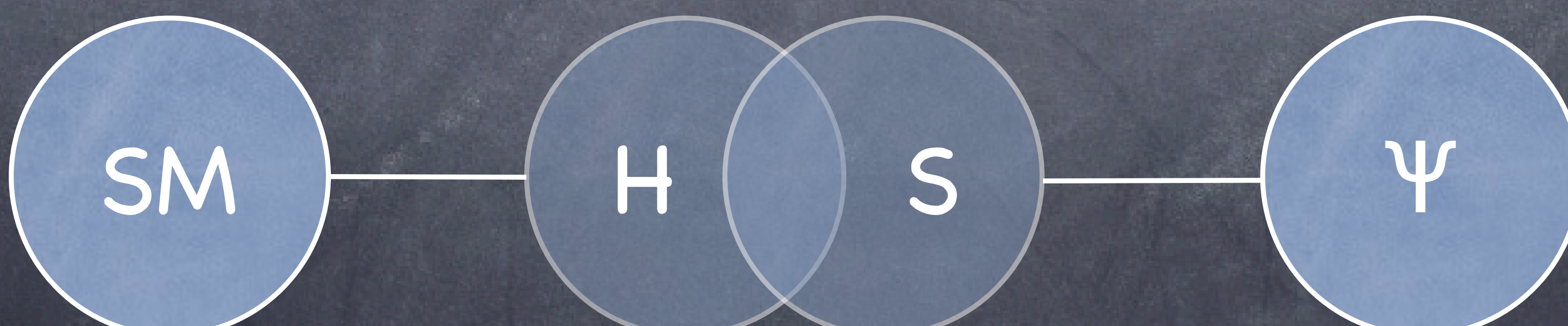
Ratiocination

- A scenario of a singlet fermion dark matter

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

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

Ratiocination

- Mixing and Eigen-states 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!

Constraints

- Unitarity
- LEP bound
- Electroweak precision observables
- DM-nucleon cross-section
- CDM relic density

Constraints

- Perturbative Unitarity

$$m_1^2 \cos^2\alpha + m_2^2 \sin^2\alpha \lesssim (700\,\mathrm{GeV})^2$$

- LEP bound on r_i for m_i < 120 GeV

Constraints

- EW precision observables

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

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

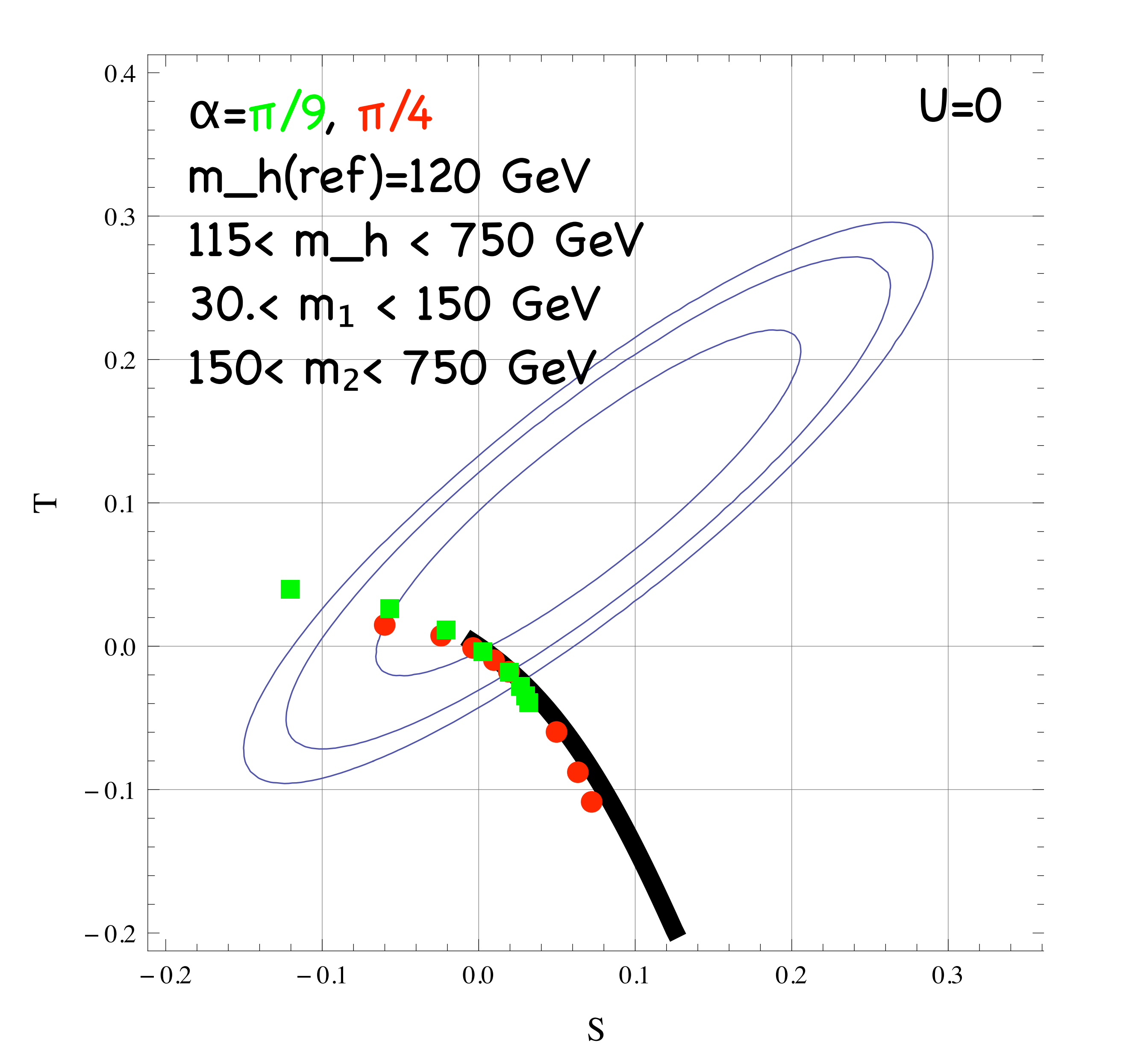
$$\alpha_{\rm em} T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

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

$$\Downarrow$$

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

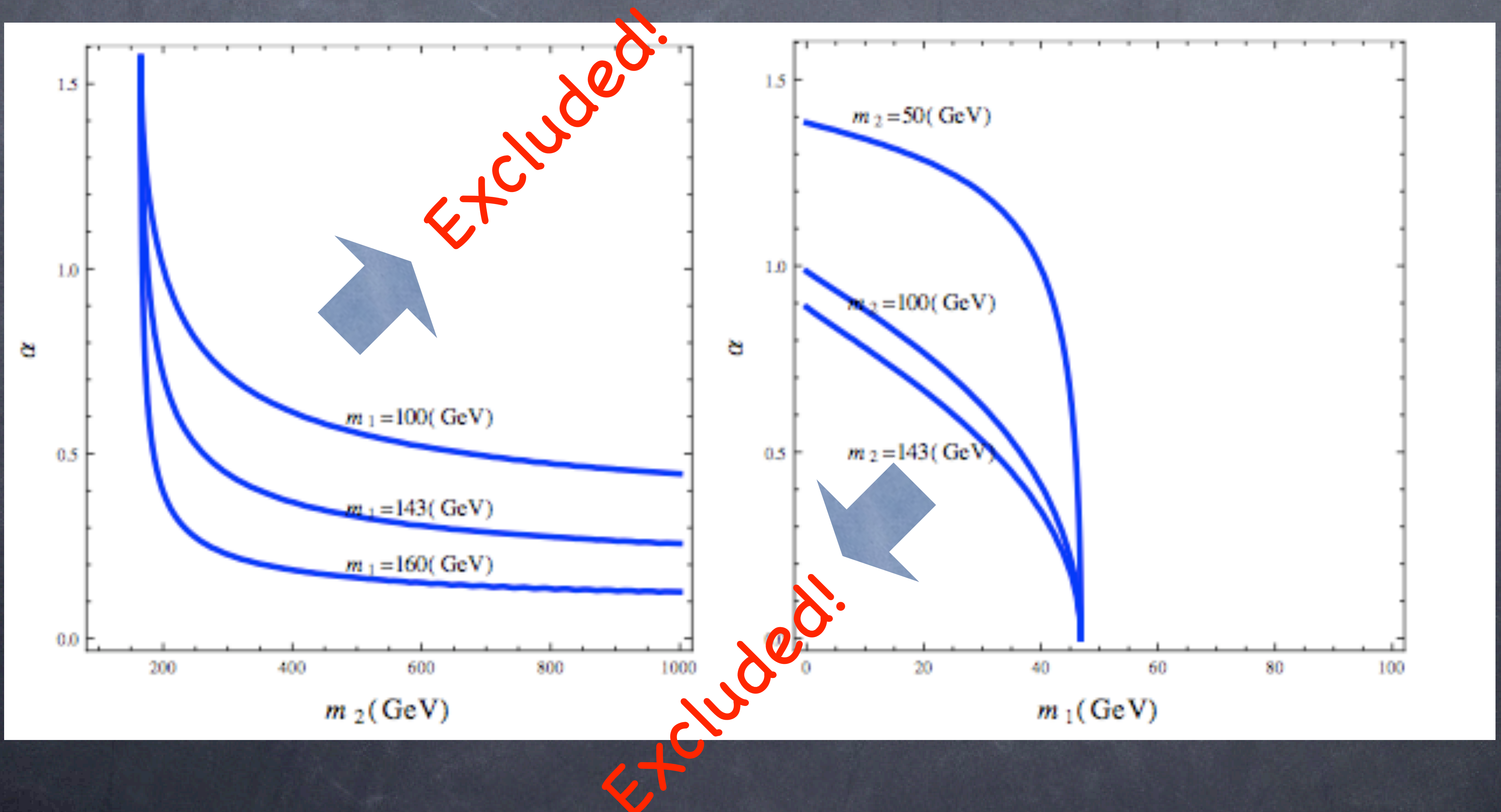
Same for T and U



Constraints

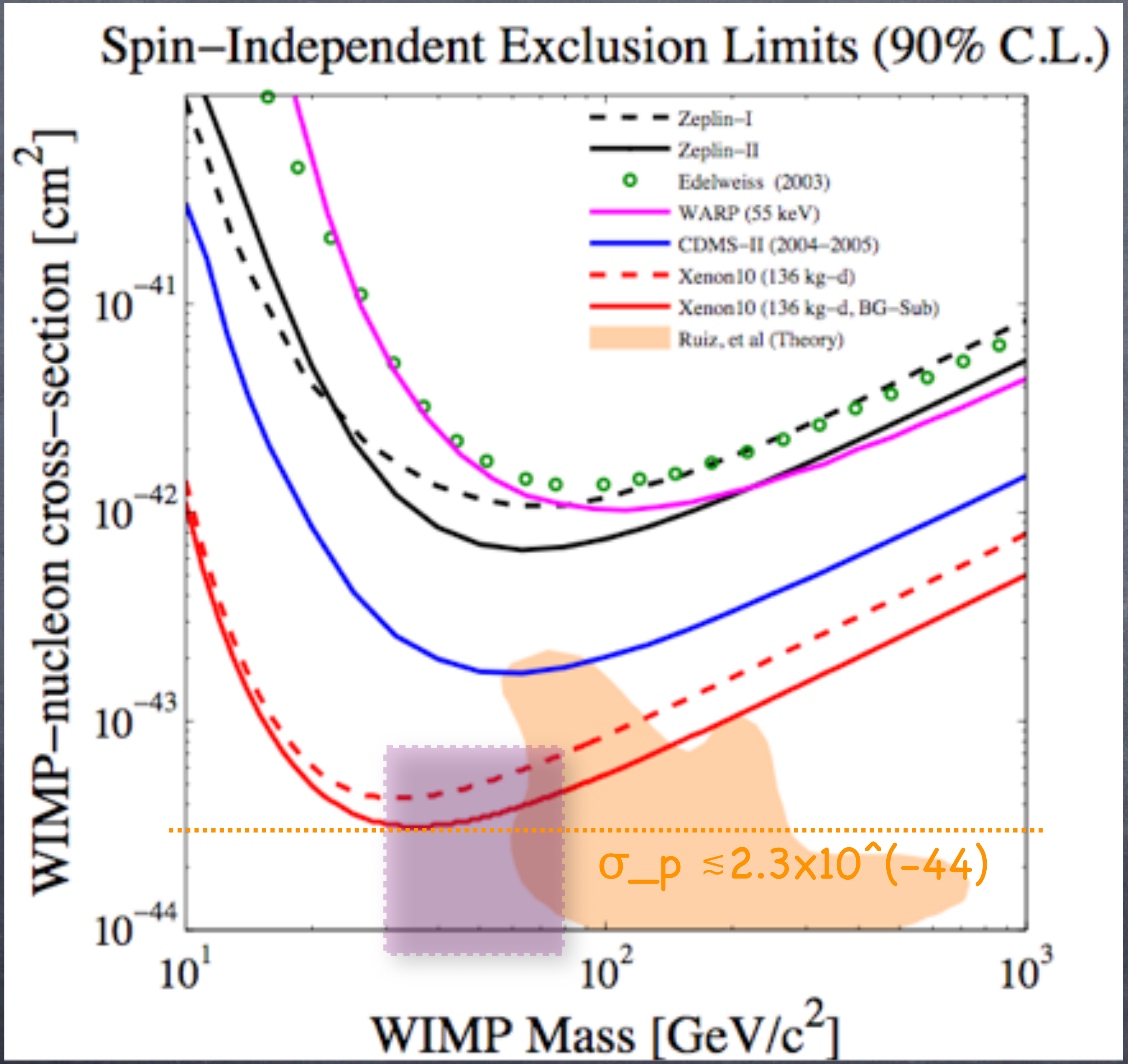
- Electroweak precision observables (constraints)

$\Delta\chi^2 < 7.815$ (2σ)



Constraints

- Dark matter to nucleon cross section (observation)
-



(http://xenon.physics.rice.edu/)

12년 3월 17일 토요일

Constraints

- Dark matter to nucleon cross section (expectation)

$$\mathcal{L} = \lambda_p \bar{\psi}\psi \bar{p}p \Rightarrow \sigma_0^{\rm SI} = \frac{\mu^2}{\pi}|\lambda_p|^2$$

$$\lambda_p \;=\; \left[\sum_{q\le 3} f_q^p \frac{m_p}{m_q} y_q + \frac{2}{27}\left(1 - \sum_{q\le 3} f_q^p\right)\sum_{q>3}\frac{m_p}{m_q} y_q\right]\lambda s_\alpha c_\alpha \left(\frac{1}{m_1^2} - \frac{1}{m_2^2}\right)$$

Quark current coefficients in a nucleon:

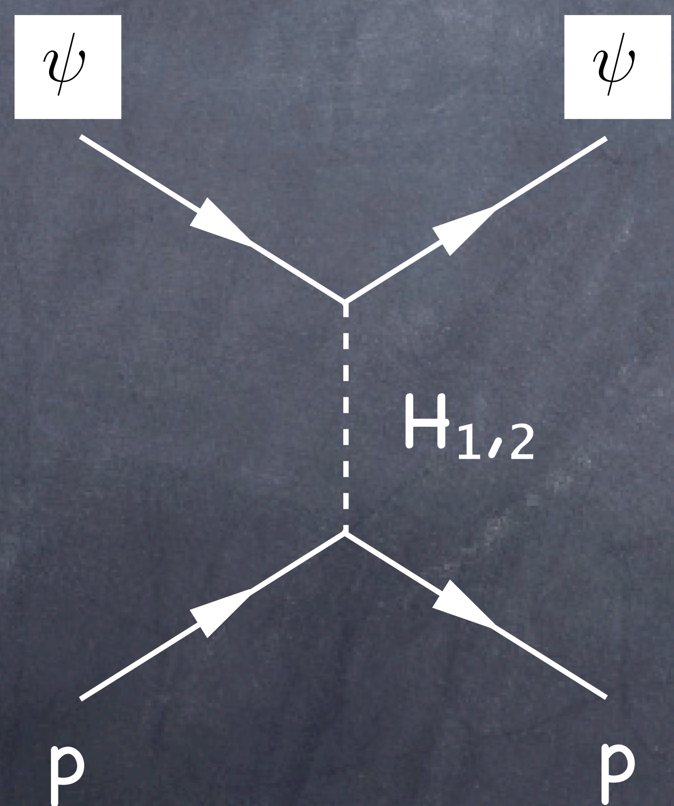
$$f_d^p = 0.033 \quad , \quad f_u^p = 0.023 \quad , \quad f_s^p = 0.26$$

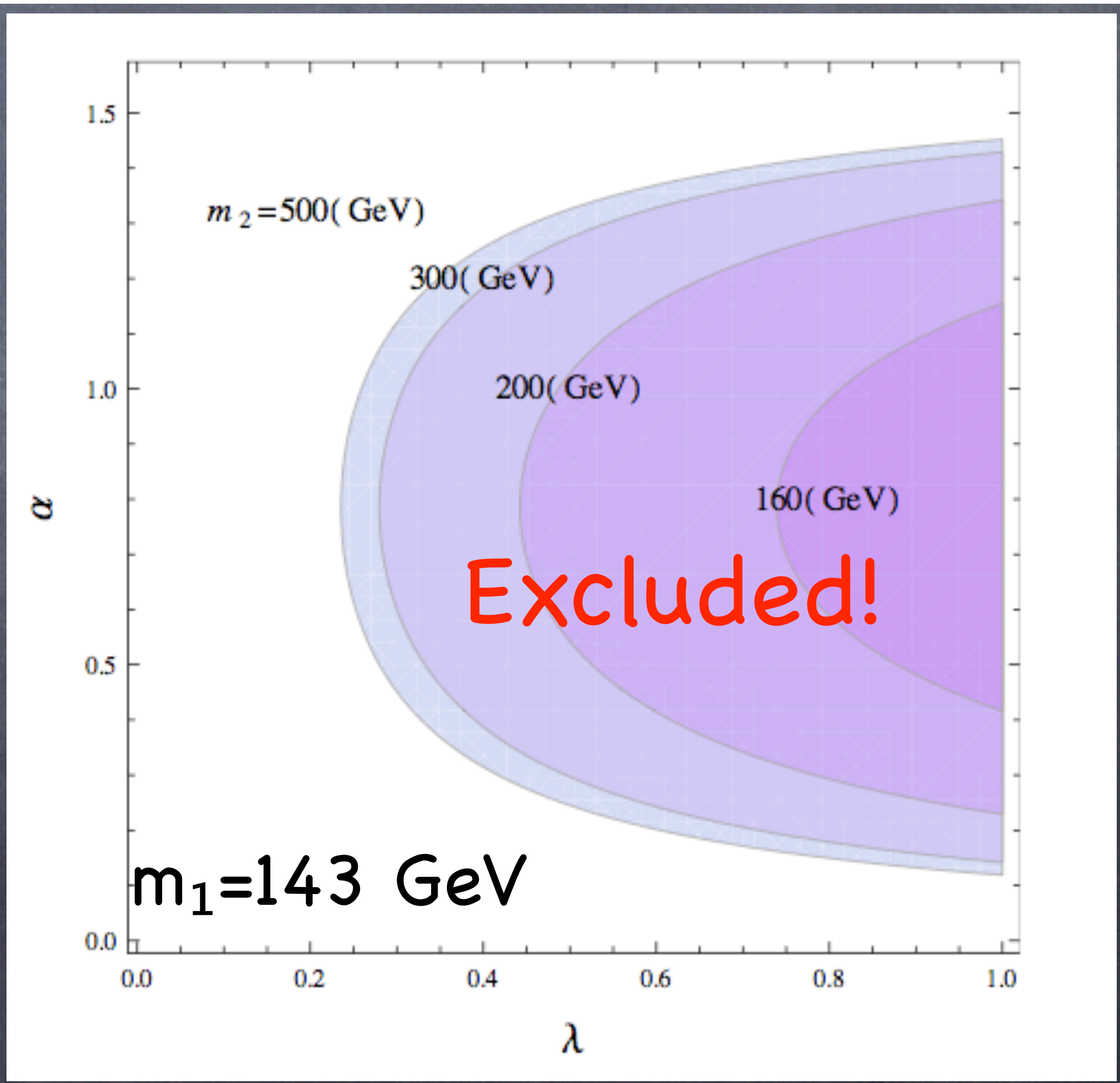
$$\boxed{\sigma_0^{\rm SI} \simeq 2.7 \times 10^{-2} \frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda \sin\alpha\cos\alpha\left(\frac{1}{m_1^2} - \frac{1}{m_2^2}\right)\right|^2}$$

Constraints

- Dark matter to nucleon cross section (constraint)

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



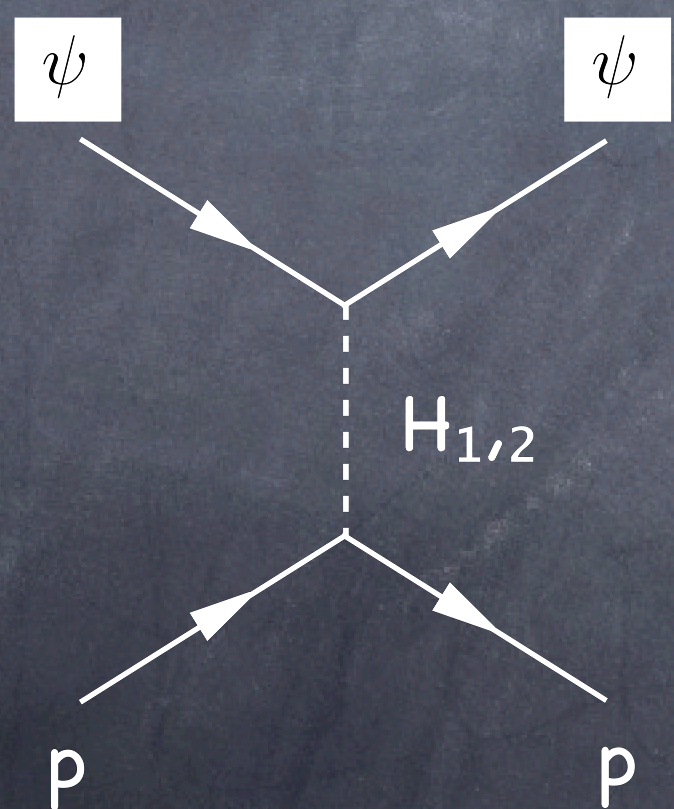


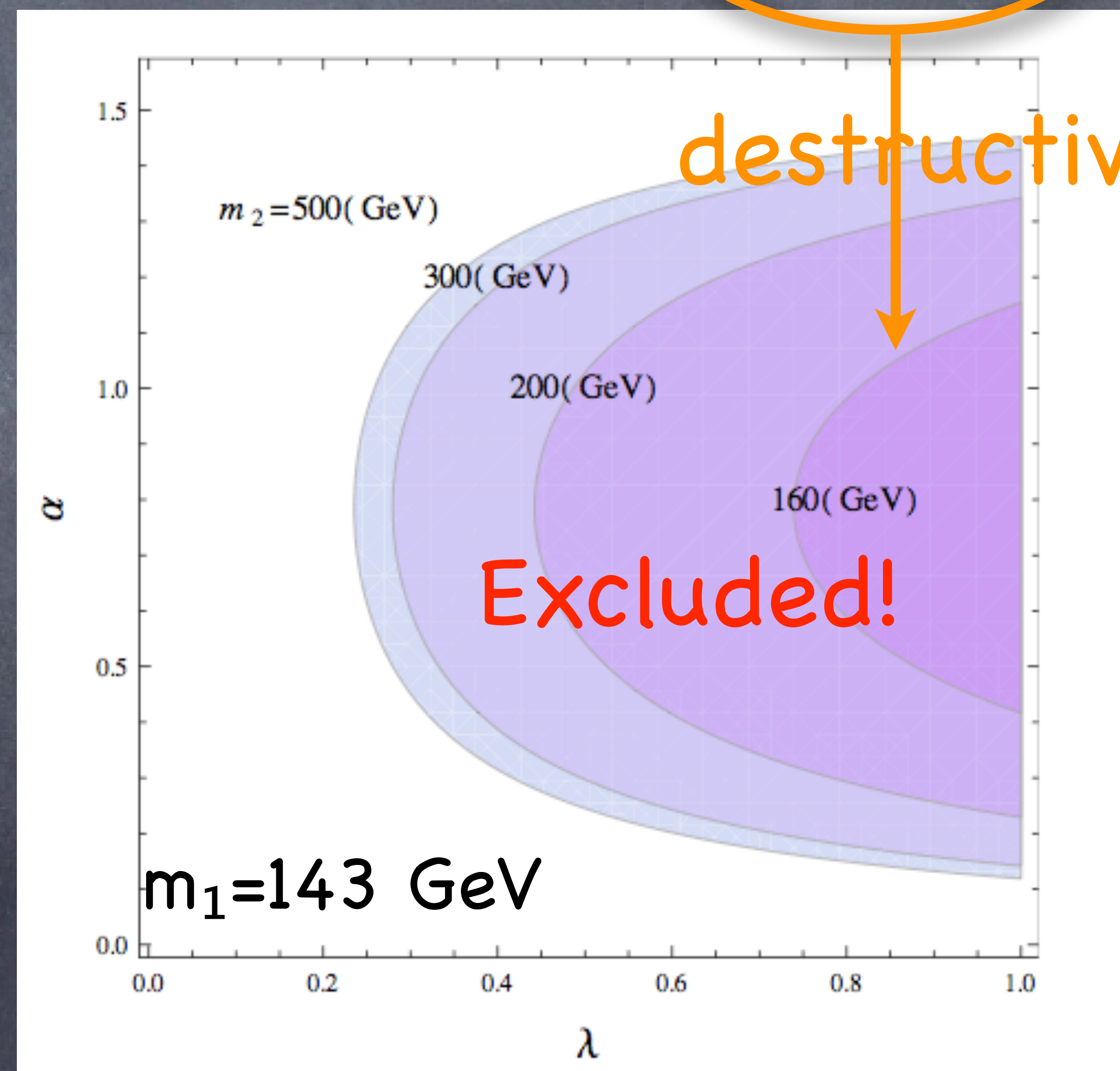
Constraints

- Dark matter to nucleon cross section (constraint)

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

destructive!



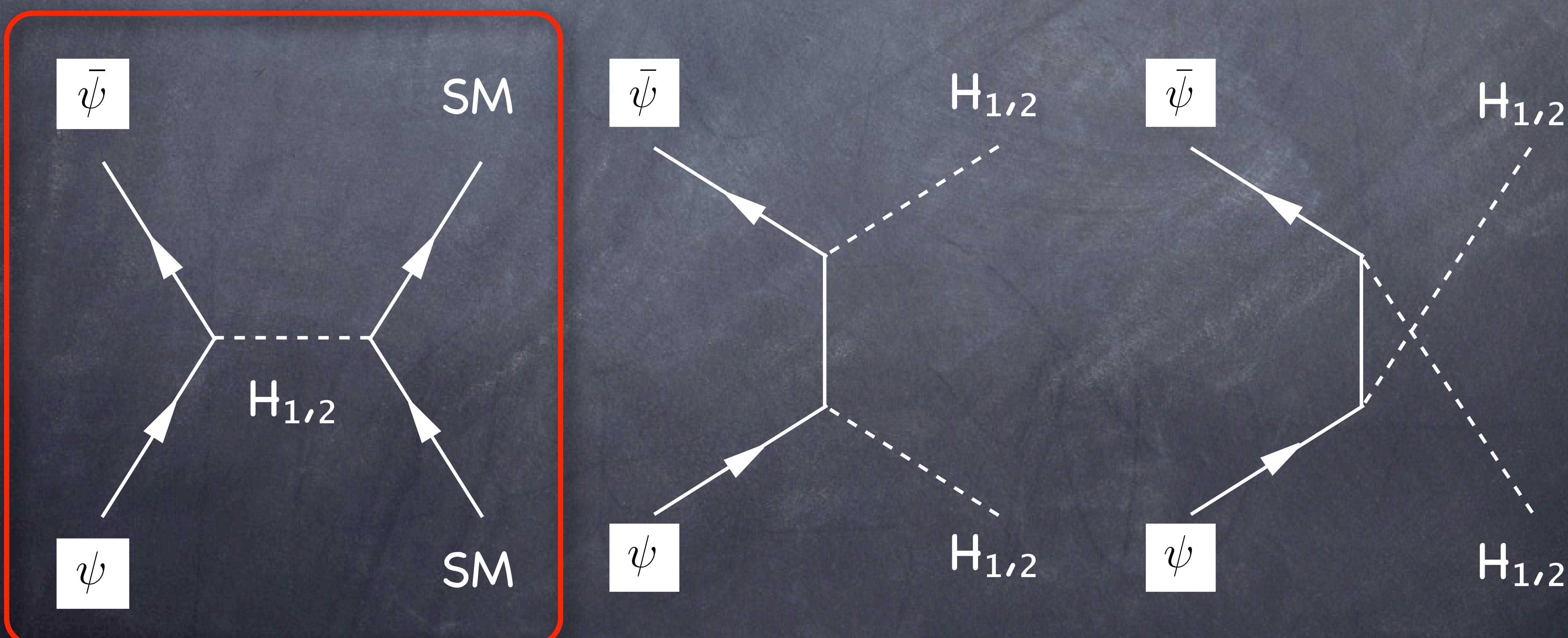


Constraints

- Dark matter relic density (observation)

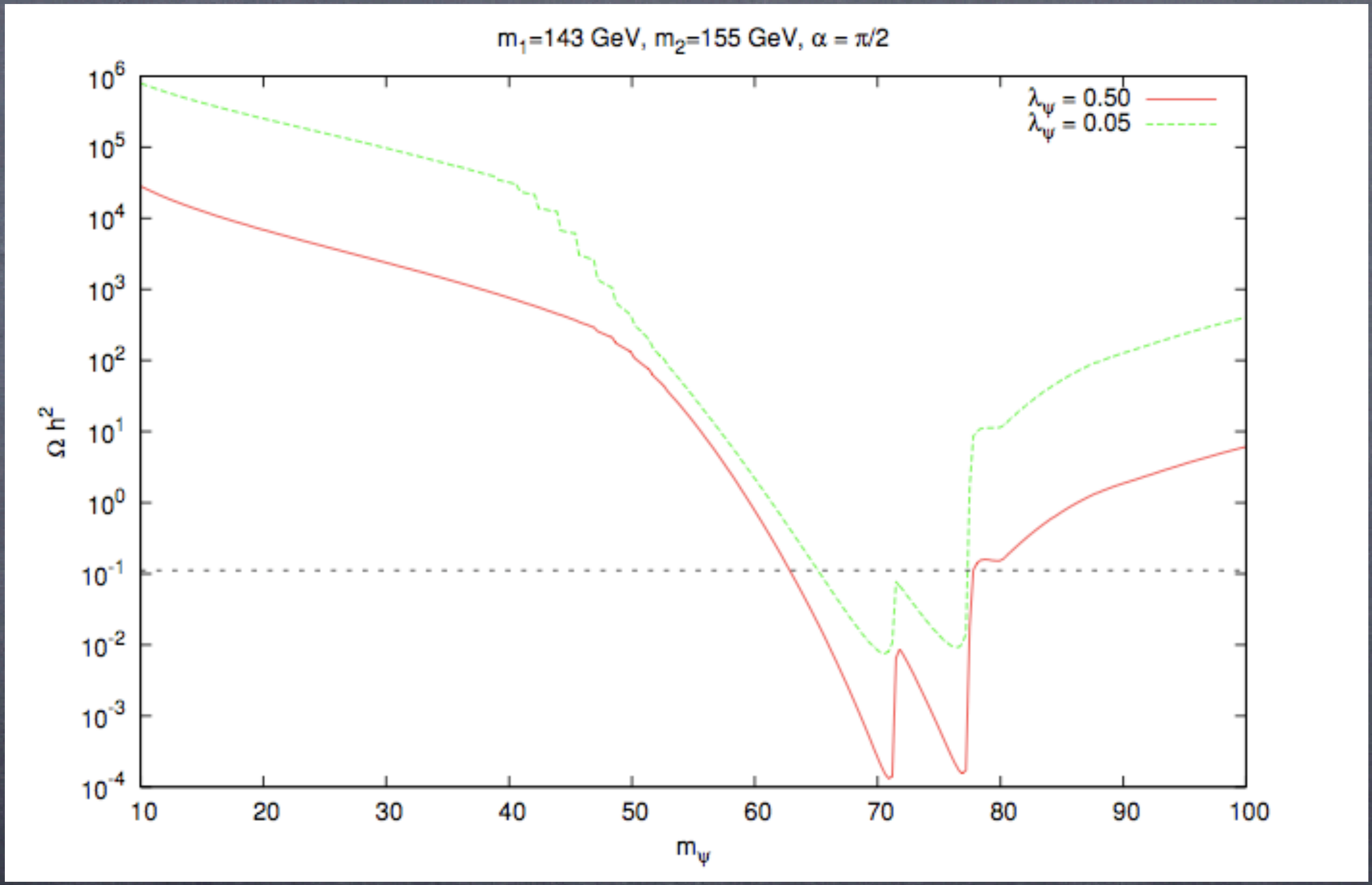
$$\Omega_{\rm CDM}h^2 \sim \underline{0.11}\left(\frac{10^{-36}{\rm cm}^2}{\langle\sigma v\rangle_{\rm fz}}\right)$$

Astrophys.J.Suppl.192:14,2011(WMAP 7-year data)



Constraints

- Dark matter relic density (expectation)

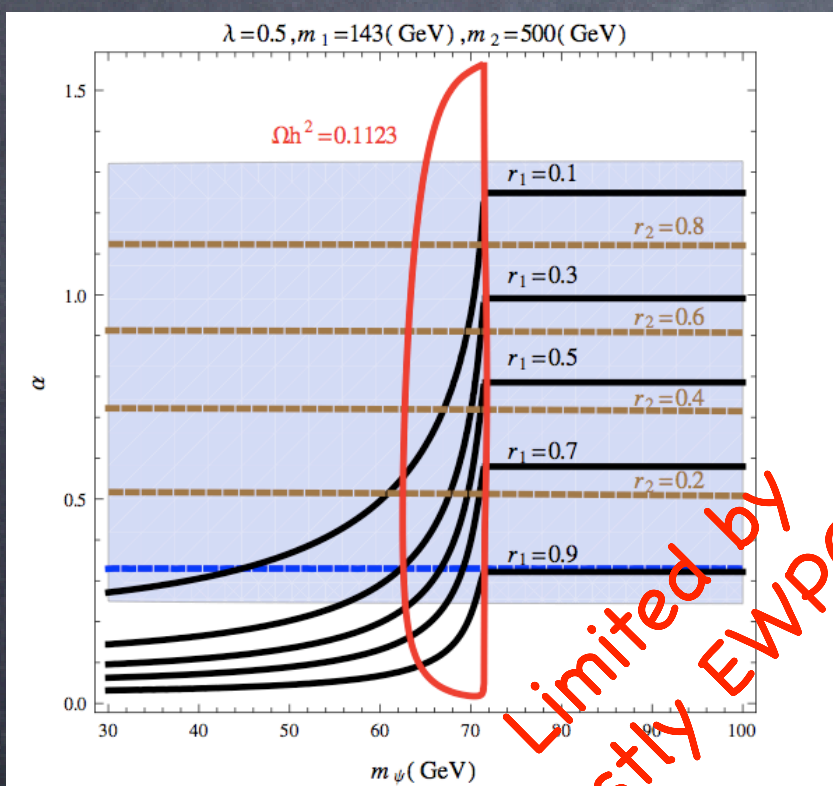


☞ $m\_cdm \lesssim m\_i/2$ can provides a proper relic density.

Constraints

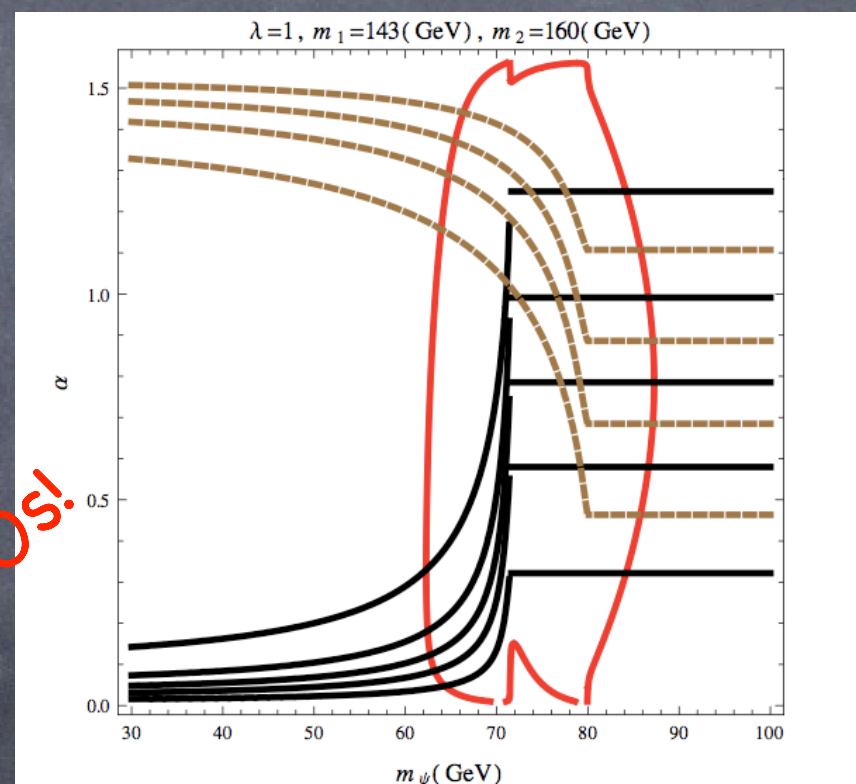
- Observables under all constraints

m_1=143 GeV << m_2

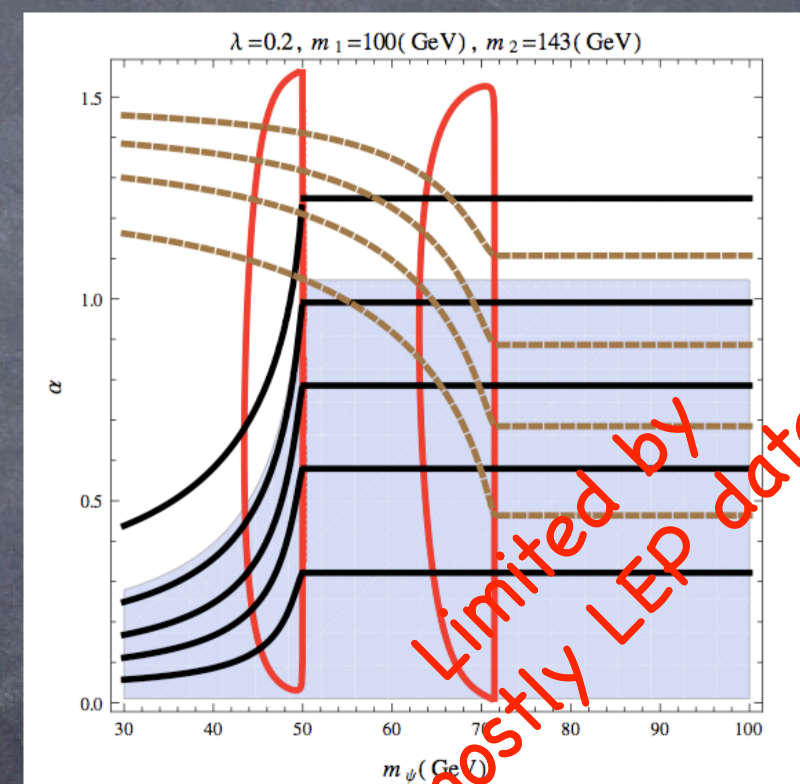


Limited by mostly EWPOs!

m_1=143 GeV ~ m_2



m_1 << m_2=143 GeV



Limited by mostly LEP data!

$\alpha \ll 1$,
$r_1 \gtrsim 0.3$
$r_2 < 0.1$

Thanks to destructive interference!

$\alpha \gtrsim 0.3$,
$r_1 \lesssim 0.3$

12년 3월 17일 토요일

Discovery possibility

- Expected signal strength of SM Higgs at CMS

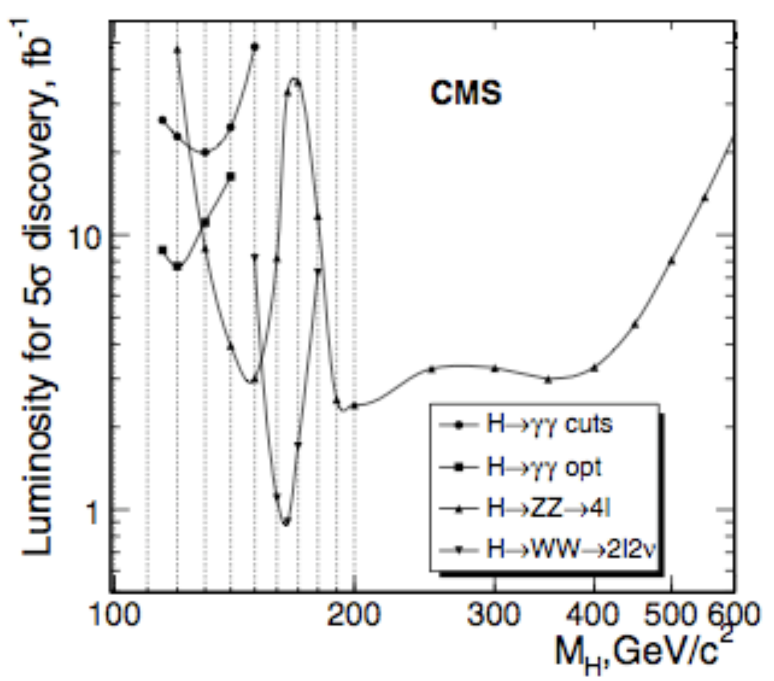


Figure 10.38. The integrated luminosity needed for the 5σ discovery of the inclusive Higgs boson production $pp \to H + X$ with the Higgs boson decay modes $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, and $H \to WW \to 2\ell 2\nu$.

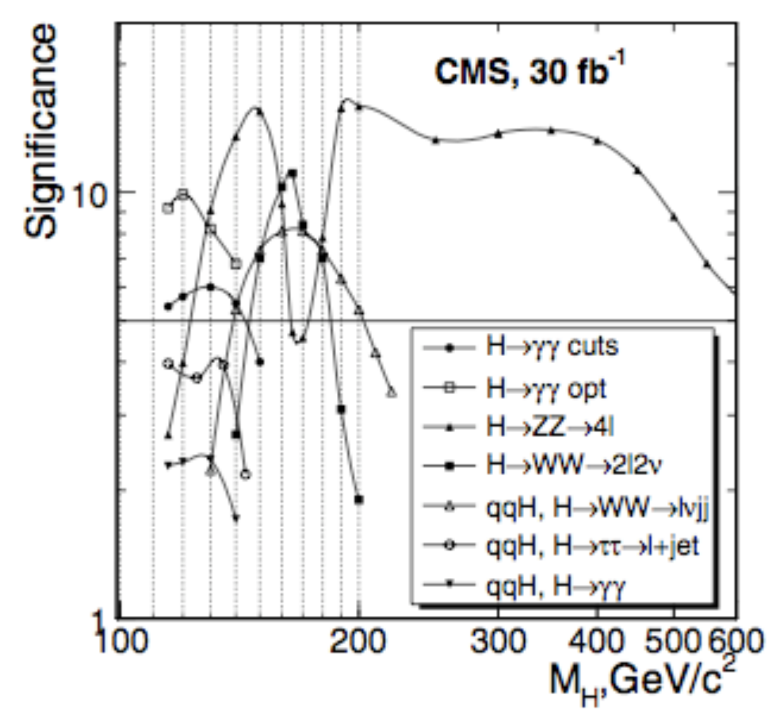


Figure 10.39. The signal significance as a function of the Higgs boson mass for 30 fb^{-1} of the integrated luminosity for the different Higgs boson production and decay channels.

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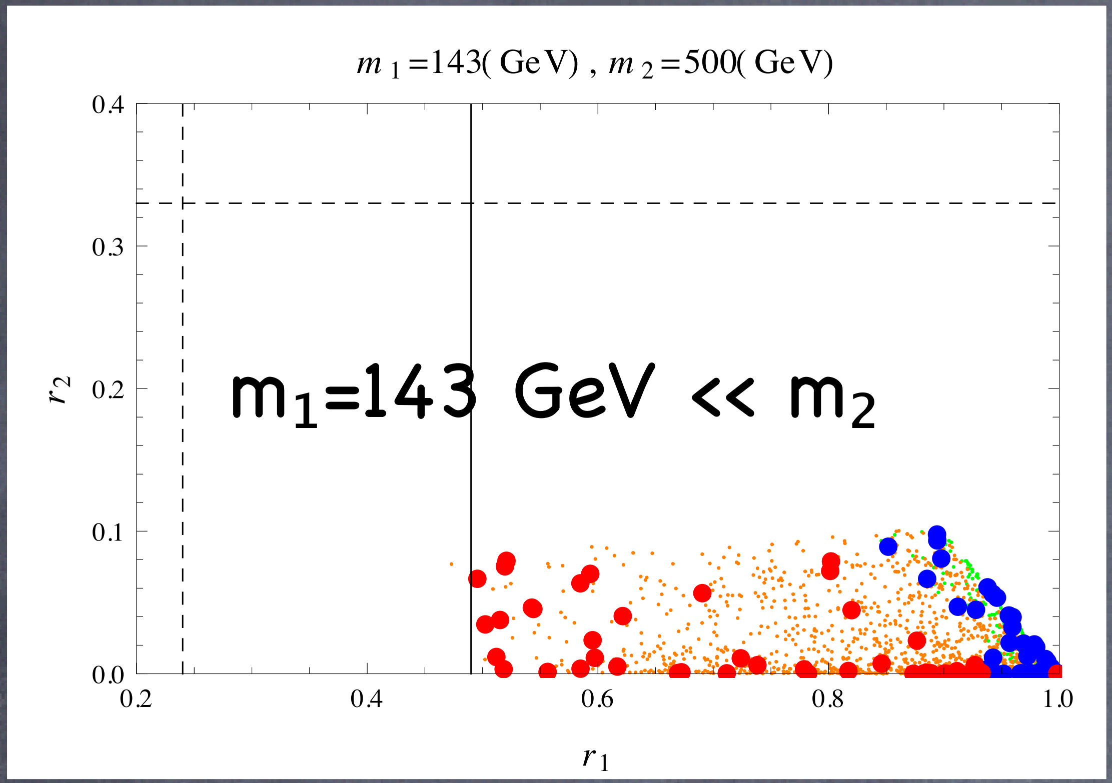
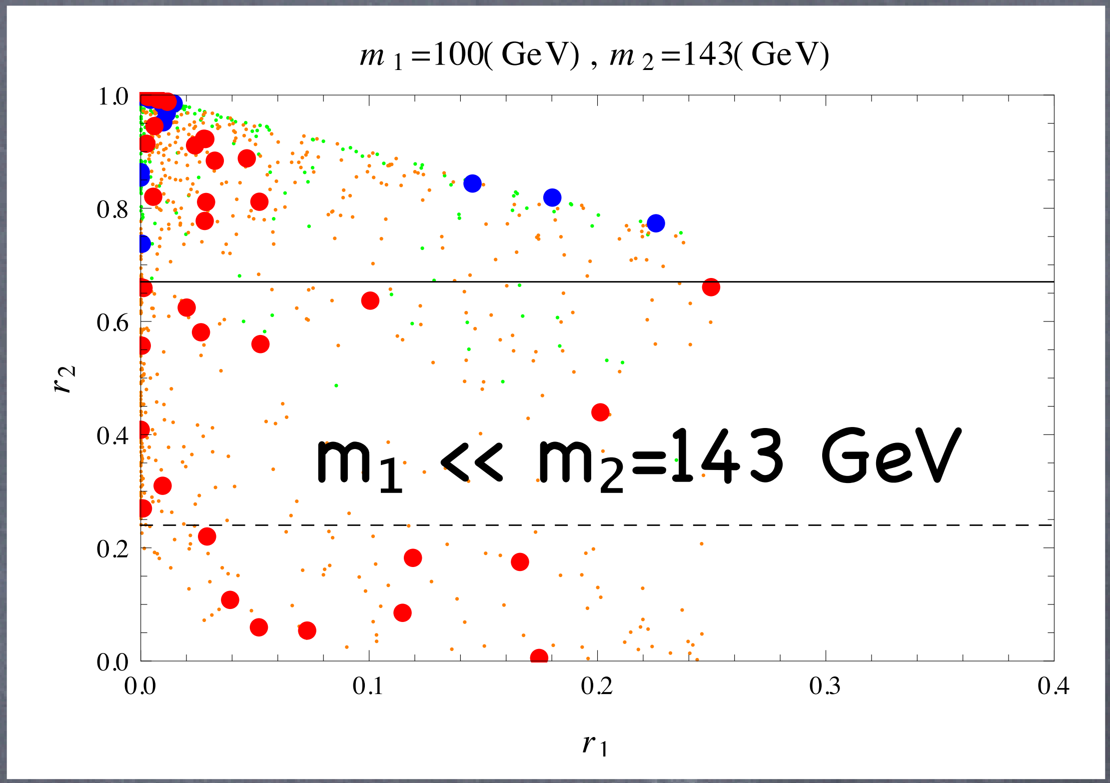
significance > 3σ ⇒ r_i >

$m/$ GeV	143	160	500
$L/\mathrm{fb}^{-1} = 5$	0.49	0.54	0.67
$L/\mathrm{fb}^{-1} = 10$	0.24	0.27	0.33

Discovery possibility

- Signal strength (r_2 vs r_1)

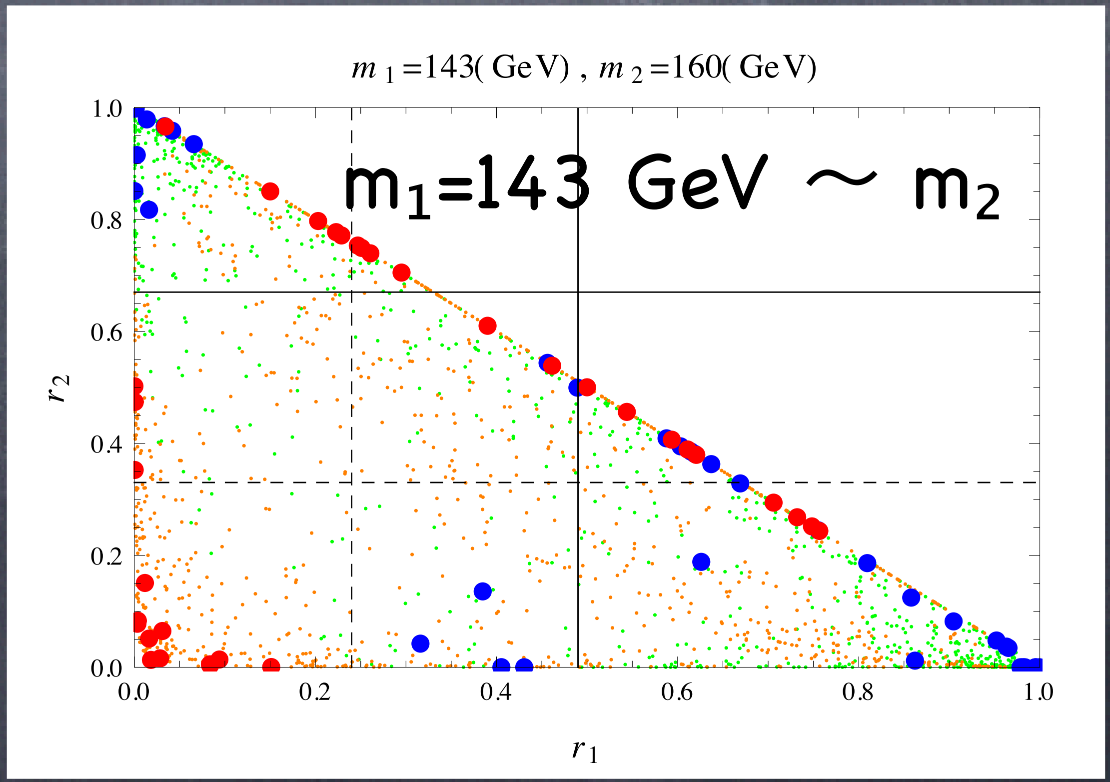




— : L= 5 fb^{-1} for 3σ Sig.

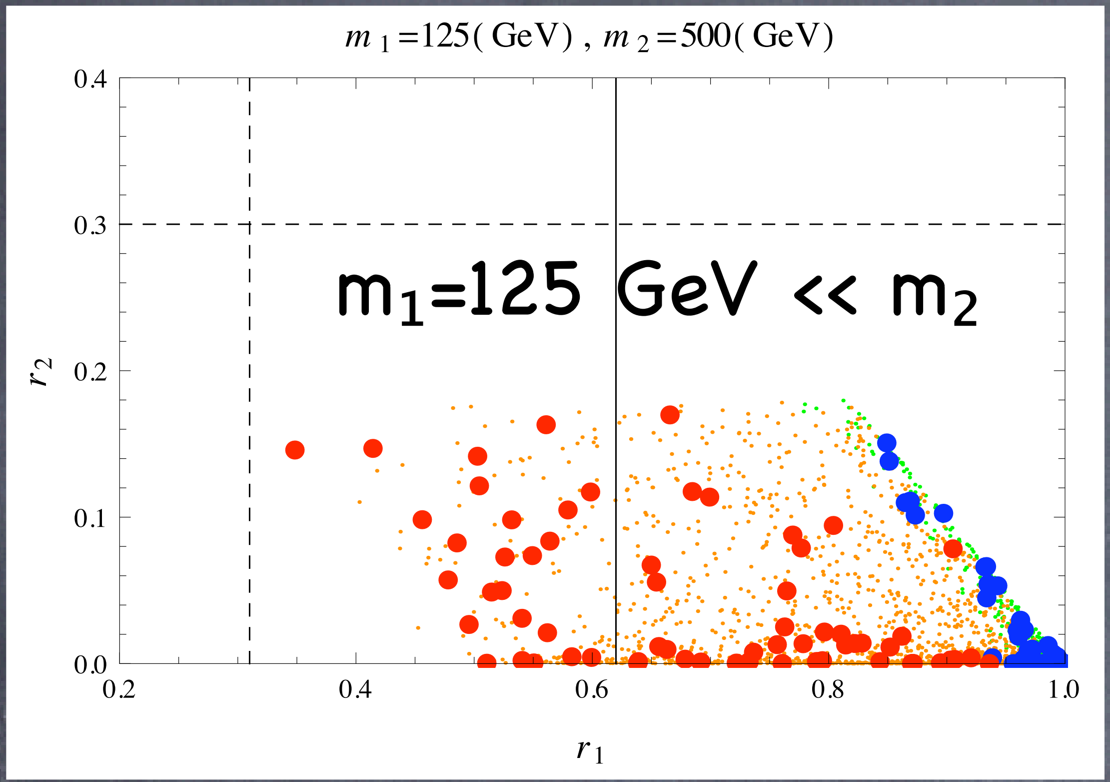
⋯⋯ : L=10 fb^{-1} for 3σ Sig.

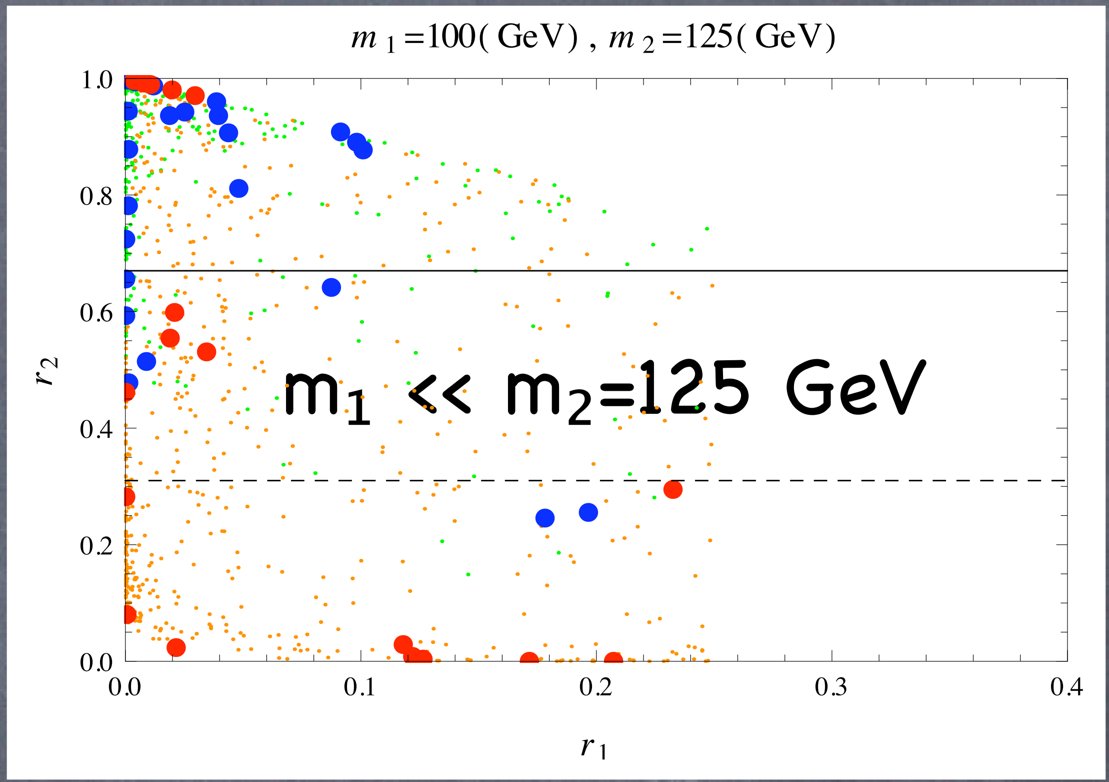
- (green): Ω(x),σ_p(x)
- (orange): Ω(x),σ_p(o)
- (blue): Ω(o),σ_p(x)
- (red): Ω(o),σ_p(o)



Discovery possibility

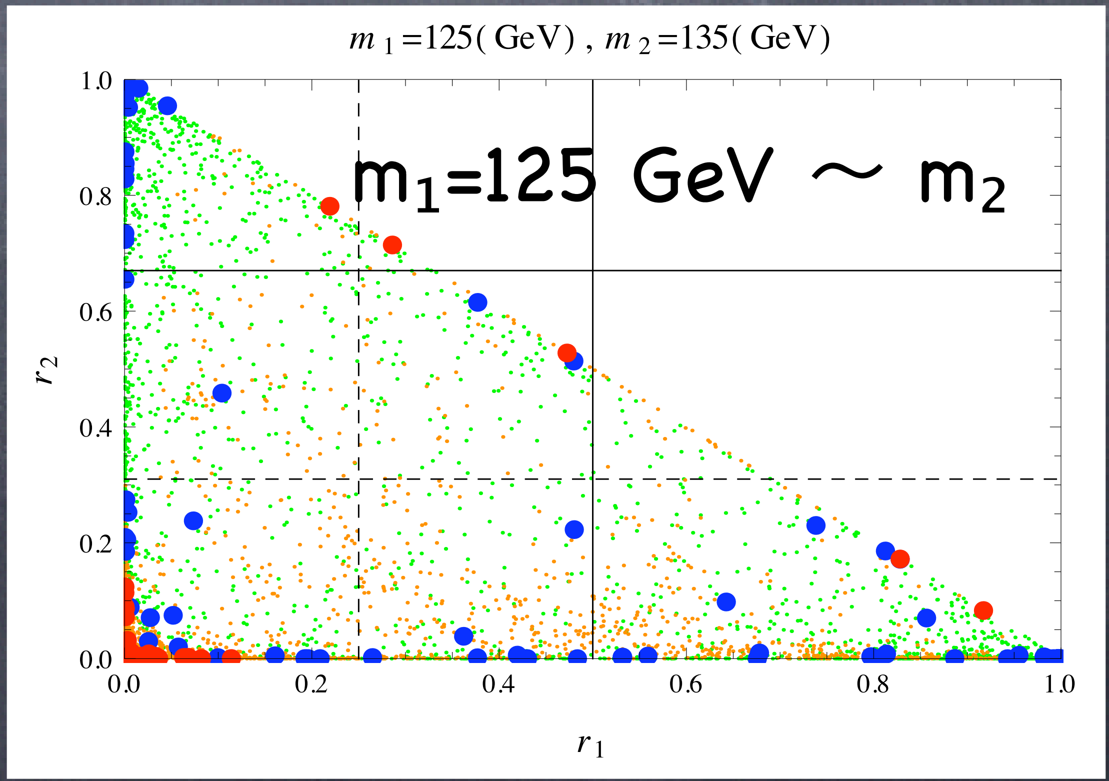
- Signal strength (r_2 vs r_1)





— : 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)

●: Ω(o),σ_p(o)

Conclusions

- Singlet fermion dark matter model is a simple possibility as an extension of SM.
- A singlet scalar mediating hidden to SM sector causes a reduction of the expected SM-like signal strength at LHC via mixing irrespective of invisible decay mode.
- Nearly degenerate Higgses allows a large coupling to dark matter while satisfying the bound from direct detection exp. thanks to destructive interference.
- Some of these features are missed in EFT approach
- Two, or one or none of the two Higgs particles can be probed at LHC, depending on mass spectra and couplings

- Hidden sector is generic in many BSM's, including SUSY models
- Hidden sector can affect the (MS)SM sector, in terms of EWSB and CDM
- Generic features : a number of new scalars, and their invisible decays if kinematically allowed
- Collider signatures could be different from SUSY or Extra dim scenarios, crucially depending on the messengers between the hidden and the SM sector
- Even if a SM like Higgs is discovered at the LHC, it is likely that another Higgs could escape detection very easily ---> Difficult to test