THE 3RD TOYAMA INTERNATIONAL WORKSHOP ON "HIGGS AS A PROBE OF NEW PHYSICS 2017"

Bound State via Higgs Exchanging and resonant di-Higgs

Based on arXiv:1606.01531, Zhaofeng Kang

Zhaofeng Kang(康昭峰),
KIAS(韩国高等研究院), 03/02/2017

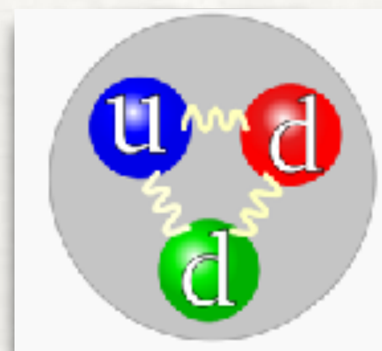
0. OUTLINE

- basics for bound state
- bound state via higgs exchanging
- examples and conclusions

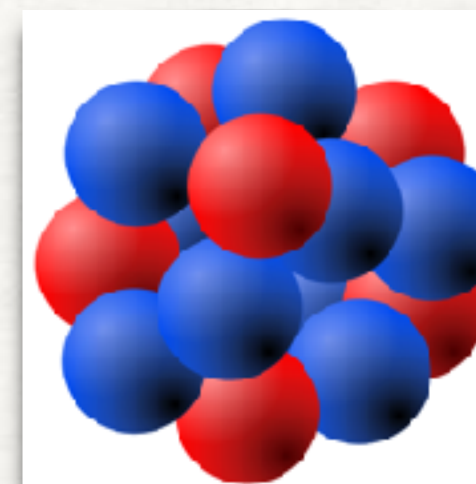
1. BASICS FOR BOUND STATE

- Bound states are everywhere in our known Universe

Proton & neutron due to confinement in QCD

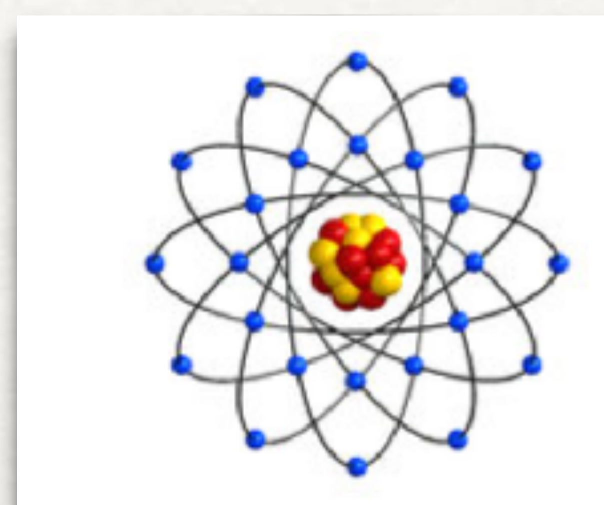


Atomic nucleus due to the residual strong force (nuclear force)



Atoms due to electromagnetic force/QED

what about in the unknown universe? Ex, dark atom dark matter?



1. BASICS FOR BOUND STATE

- A complicated non-perturbative object in QFT

I) it does not appear in the conventional perturbative calculations
II) Bethe-Saltpeter equation furnishes a powerful tool to study bound state in QFT

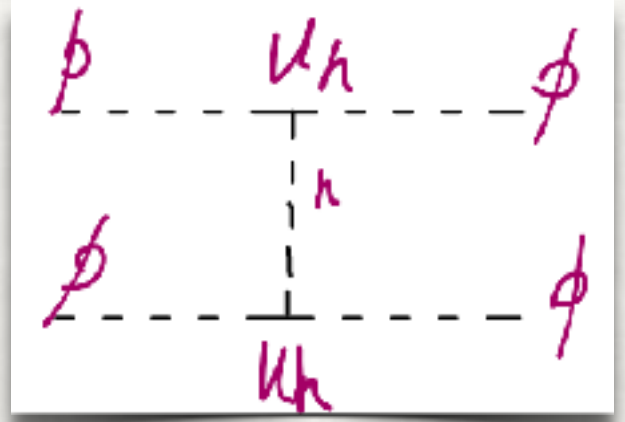
- Nonrelativistic (NR) limit simplification: Schrodinger equation

$$\left[-\frac{\nabla^2}{2\mu}+V(\mathbf{r})\right]\psi_n(\mathbf{r})=\mathcal{E}_n\psi_n(\mathbf{r})$$

1. i.e., we use NR quantum mechanism to describe the dynamics
2. it can be derived from the Bethe-Saltpeter equation

the potential V(r), by exchanging a massive scalar quantum φ, for instance the SM Higgs boson *h*, is the well-known Yukawa potential:

$$-\frac{\alpha_h}{r}e^{-m_h r}\ \text{with}\ \alpha_h = u_h^2/(16\pi m_\phi^2)$$

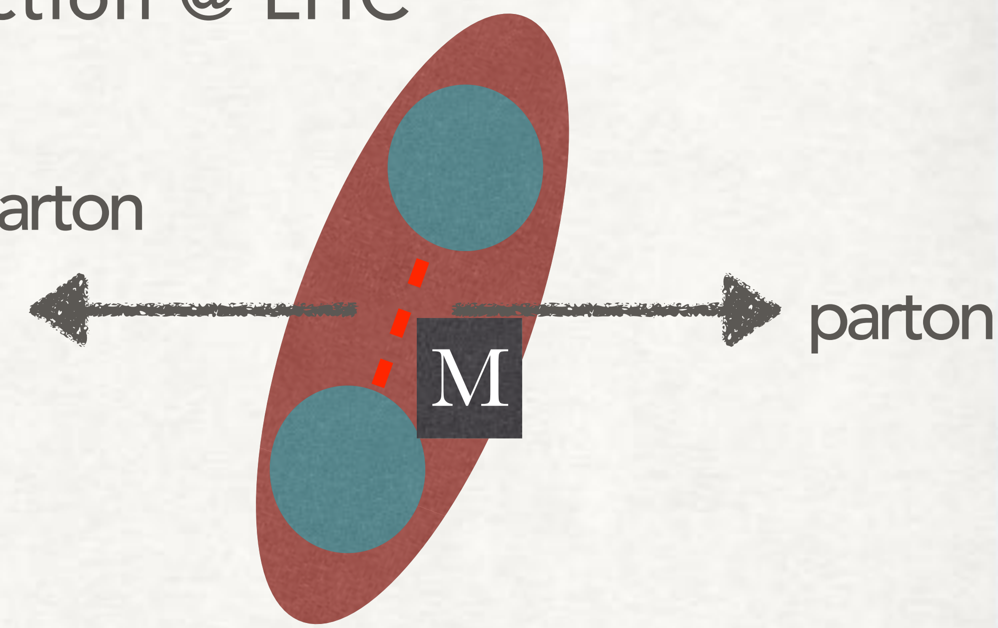


How to solve the equation? later——

1. BASICS FOR BOUND STATE

- Bound state (s-wave ground state) production @ LHC

I. the constitute pairly produced near M
II. under the condition that the constitute is sufficiently long-lived
III. observable for a sufficiently narrow width (assumed hereafter)



$$\hat{\sigma}_{ab\to M}(\hat{s}) \simeq \frac{2\pi\,(2J+1)\,D_M}{D_a D_b}\,\frac{\Gamma_{M\to ab}}{M}\,2\pi\,\delta(\hat{s}-M^2) \qquad [\,\times 2 \quad \text{if} \quad a=b\,]$$

the dimension of SU(3)c representation of x

- Bound state annihilation decay

$$\Gamma_{M\to XY} = \frac{1}{2m_M}\frac{N_c}{1+\delta_{XY}}\int d\Pi_2 \frac{2}{m_M}|\mathcal{M}_{\phi\phi^*\to XY}|^2|\Psi(0)|^2,$$

amplitude of constitute pair annihilation into XY

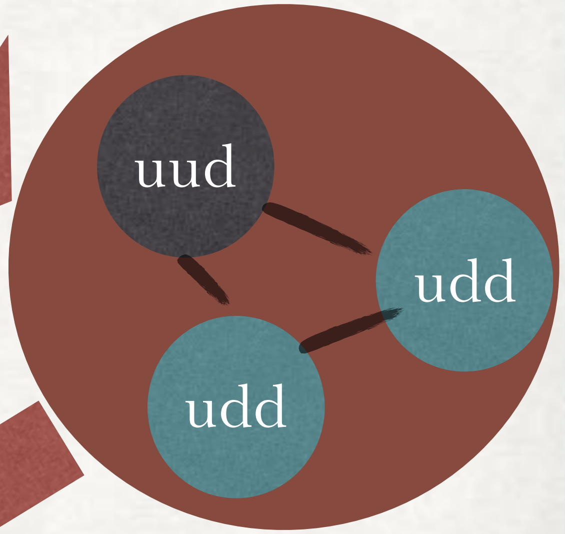
2. B_h: BOUND STATE VIA HIGGS EXCHANGING

- An illustrating conjecture: Higgs force & bound state B_h

Higgs is just around the weak scale ~ m_Z, m_W, relatively light compared to the TeV scale, the hypothetic scale for new physics

In addition, it has spin-0, potential to be a force carrier

it is reminiscent of the π meson of Yukawa, to bound nucleons inside a nucleus



This is exactly the picture in the framework of composite Higgs where the Higgs is a PGSB, and the SM fermions (or other exotic) may be composite at least partially

2. B_h: BOUND STATE VIA HIGGS EXCHANGING

- An illustrating conjecture: Higgs force & bound state B_h

A general study on B_h in new physics, based on the simplified model

$$-\mathcal{L}_h = u_{h\phi\phi} h|\phi|^2 + m_\phi|\phi|^2$$

I) a scalar field ϕ for simplicity
II) discussions can be generalized to constitute with other spins

$$-\frac{\alpha_h}{r}e^{-m_h r} \text{ with } \alpha_h = u_h^2/(16\pi m_\phi^2)$$

The existence of bound state $D_h=(1/m_h)/a_0>0.84$ with $a_0=1/(\alpha_h\, m_\phi/2)$ requires a heavy constitute field ϕ & large α_h,

$$m_\phi \gtrsim 0.84 \times \frac{2}{\alpha_h} m_h \approx 0.7 \times \left(\frac{0.3}{\alpha_h}\right) \text{TeV}$$

For D_h>>1, one recovers the well-known Coulomb limit

2. B_h: BOUND STATE VIA HIGGS EXCHANGING

- B_h close to the critical point D_h~1

  Far from the Column limit, so the previous approximation may be invalid

  A new approximation: Yukawa potential ~ scaled Hulthen potential； the later admits analytical solution

$$V_{SH}(r) = -\alpha_h \frac{R_s m_h e^{-R_s m_h r}}{1 - e^{-R_s m_h r}}, \quad R_s \approx 1.75$$

$$|\Psi_n(0)|^2 \approx \frac{\epsilon(R_s/D_h)}{n^3} \frac{1}{\pi a_0^3} = \frac{\left(1 - \frac{R_s^2}{4D_h^2}\right)^{\frac{3}{2}}}{n^3} \frac{\alpha_h^3 m_B^3}{64\pi}$$

R. Dutt, K. Chowdhury, and Y. P. Varshni, Journal of Physics A 18.9 (1985).

I) For D_h>>1, one recovers the well-known Coulomb limit

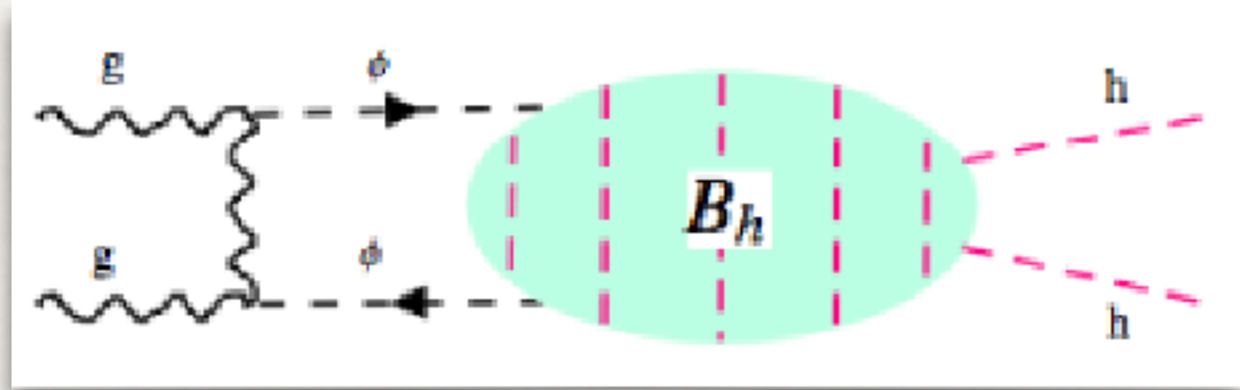
II) as D_h~1, there is a sizable reduction of wave function at the origin

2. B_h: BOUND STATE VIA HIGGS EXCHANGING

- B_h and resonant di-Higgs signature

  B_h can be produced at LHC via GGF if ϕ carries color or ϕ mixes with h

  Due to the strong coupling between h and ϕ, B_h dominantly annihilation decays into a pair of Higgs boson



$$\Gamma_{B\to hh} \approx \frac{N_c}{16\pi}\frac{|\Psi(0)|^2}{m_B^2}\left[\frac{4u_h^4}{\left(\frac{1}{2}m_B^2 - m_h^2\right)^2}\right]$$

- B_h and Higgs signature shifts

$$\delta r_\gamma \approx r_{\mathrm{SM},\gamma} + \mathrm{sign}(u_h)\frac{d(\phi)Q_\phi^2}{12}\sqrt{2\pi\alpha_h}\frac{v}{m_\phi},$$

$$\delta r_g \approx r_{\mathrm{SM},g} + \mathrm{sign}(u_h)C(\phi)\sqrt{2\pi\alpha_h}\frac{v}{m_\phi},$$

3. STOPONIUM: BOUND STATE OF STOP

- A large soft trilinear term and a large stop mixing angle….

$$m^2_{stop} \approx \begin{pmatrix} m^2_{RR} & m_t X_t \\ m_t X_t & m^2_{LL} \end{pmatrix}$$

$$X_t = A_t - \mu \cot\beta \approx A_t$$

$$-\mathcal{L}_{soft} \supset y_t A_t \tilde{t}_L \left(v_u + \frac{h}{\sqrt{2}} \right) \tilde{t}^*_R + h.c.,$$

I. large At term is good for radiatively lifting mh
II. also good for large left-right stop mixing

$$-\mathcal{L}_{h\tilde{t}_1\tilde{t}_1} = u_{h\tilde{t}^*_1\tilde{t}_1} h |\tilde{t}_1|^2 \text{ with } u_{h\tilde{t}_1\tilde{t}_1} \approx \frac{m_t A_t}{\sqrt{2} v} \sin 2\theta_t$$

- The lighter stop two-body decay can be suppressed either by the degenerate with LSP or gravitino being the LSP (says in GMSB)

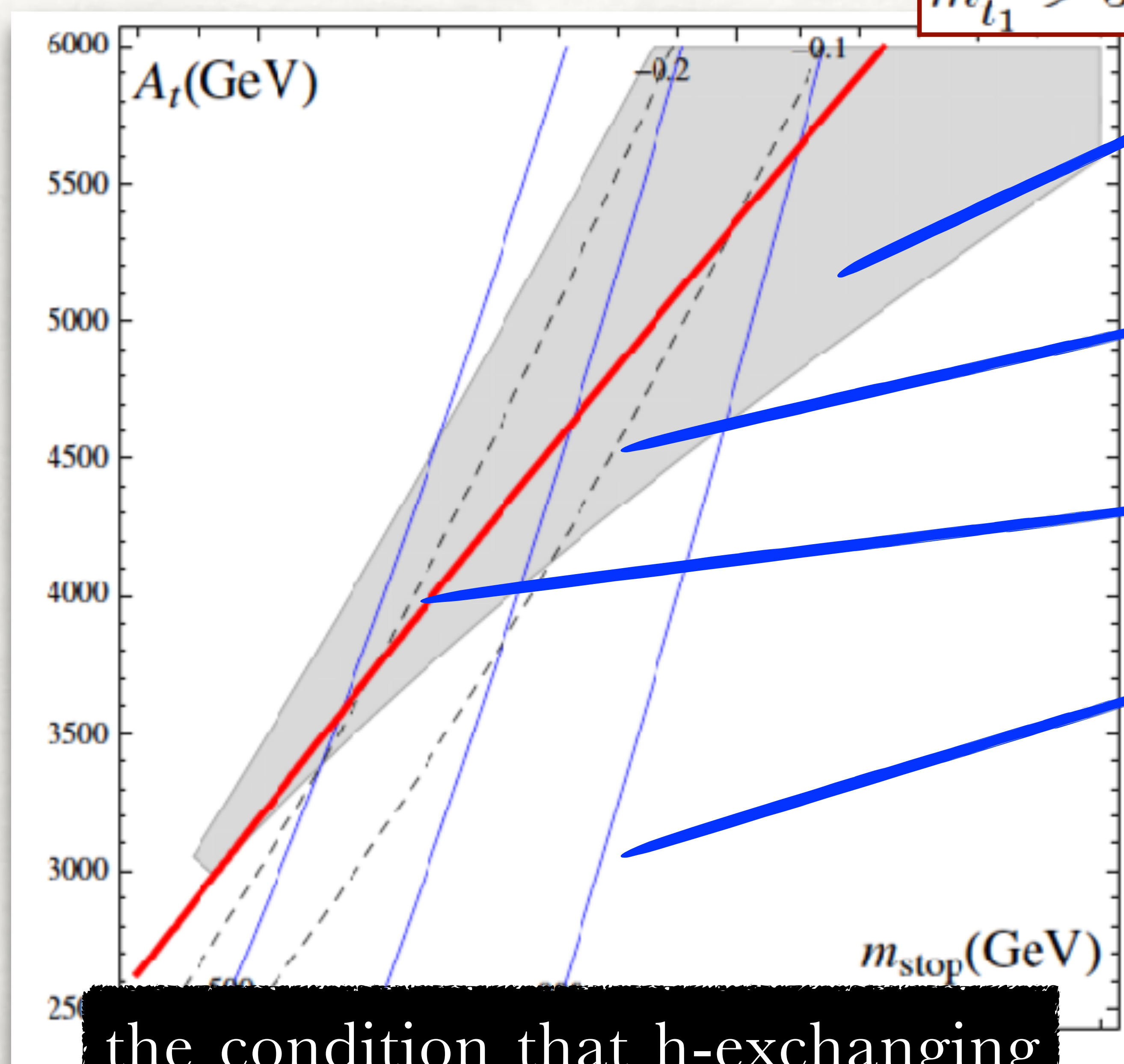
- Sbottom sector with a large μ-term from unnatural SUSY

$$\mu H_u H_d + y_b Q_3 H_d U^c_3 \Rightarrow \frac{m_b \tan\beta}{\sqrt{2} v} \mu \sin 2\theta_b h |\tilde{b}_1|^2.$$

3. STOPONIUM: BOUND STATE OF STOP

- Is stoponium still possible?

$m_{\tilde{t}_1} > 300$ GeV, $|\sin\theta| < 0.2$ and $D_h > 0.84$



Higgs-to-diphoton reduction rate

mh=125 GeV, adjustable

the lighter stop mass

the condition that h-exchanging is dominant over QCD

the region with multi-TeV At & TeV stop mass parameter still allows stoponium near TeV scale or above

3. INERT HIGGS DOUBLET FROM RADIATIVE SEESAW

- Higgs portal term with a large dimensionless coupling $\lambda|X|^2|\Phi_2|^2$

Can X be dark matter? No! direct detection rules it out!

$$\sigma_{\rm SI}^n \approx \frac{4\alpha_h}{v^2}\frac{m_n^4}{m_h^4}\left(\Sigma_q f_{T_q}^{(n)}\right)^2 = 3.6\times 10^{-6}\times\left(\frac{\alpha_h}{0.3}\right)\,{\rm pb},$$

- But scalar X with λ>>1 are well motivated for triggering strong first order phase transition (SFOPT) or classical scale symmetry breaking

- Consider a celebrated model with X=quasi inert Higgs doublet Φ_1,

$$-\mathcal{L}_{\rm Ma} = \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] + \left(y_N\bar{l}\Phi_1 P_R N + c.c.\right)$$

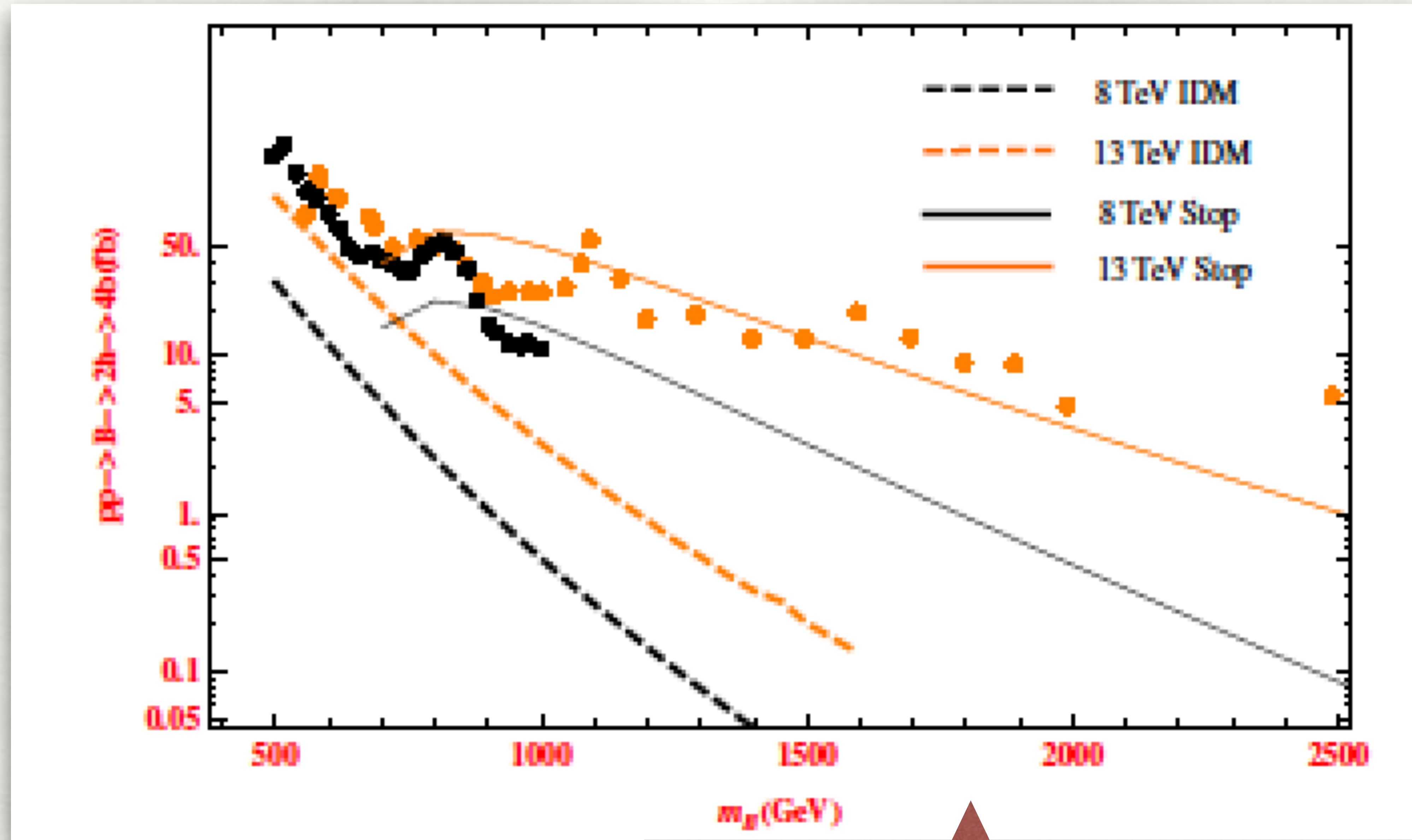
Ma's model for radiative neutrino masses

$$-\mathcal{L}_h \supset \sqrt{2}\lambda_3 v\, hC^+C^- + \frac{v}{\sqrt{2}}\left(\lambda_3 - \frac{m_C^2-m_S^2}{v^2}\right)hS^2 + \frac{v}{\sqrt{2}}\left(\lambda_3 - \frac{m_C^2-m_A^2}{v^2}\right)hA^2.$$

$$\lambda_3 = 8.5\times\left(\frac{D_h}{0.84}\right)\left(\frac{0.5}{\alpha_h}\right)^{\frac{1}{2}}.$$

4. CURRENT B_h AT LHC VIA RESONANT DI-HIGGS

- The best sensitivity comes from the 4b channel @ 13 TeV



For IDM the production is via the bound state mixing with SM-Higgs boson

5. SUMMARY PART III

- Higgs boson may mediate a relatively strong new force, leading to bound state B_h
- A characteristic feature of B_h is producing resonant di-Higgs (~TeV) signature at LHC
- Stop/sbottom/inert Higgs doublet can be good candidates

Thank you!!!