

Higgs Microscope (Higgs Precision)

Po-Yan Tseng (Kavli IPMU)

Collaborators:

Kingman Cheung(NTHU, NCTS)

Jae Sik Lee(Chonnam National U.)

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Higgcision

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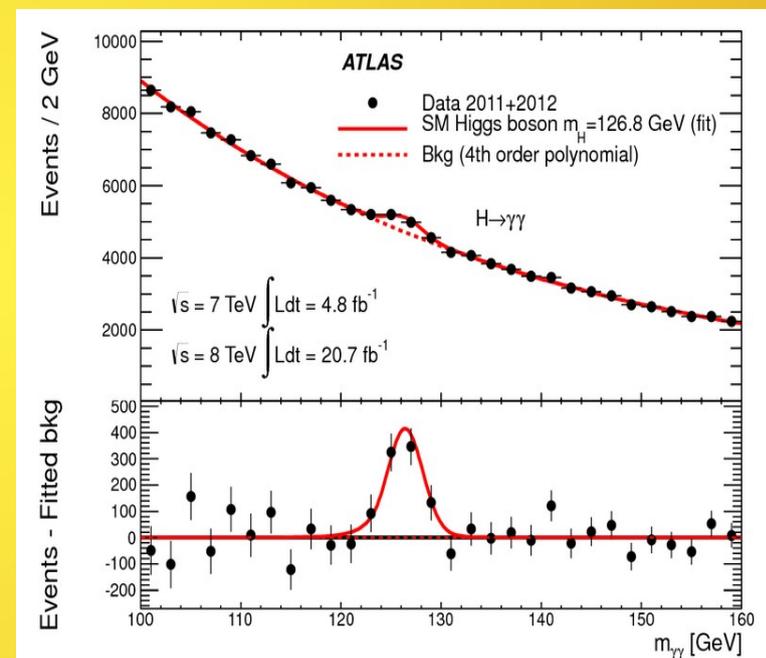
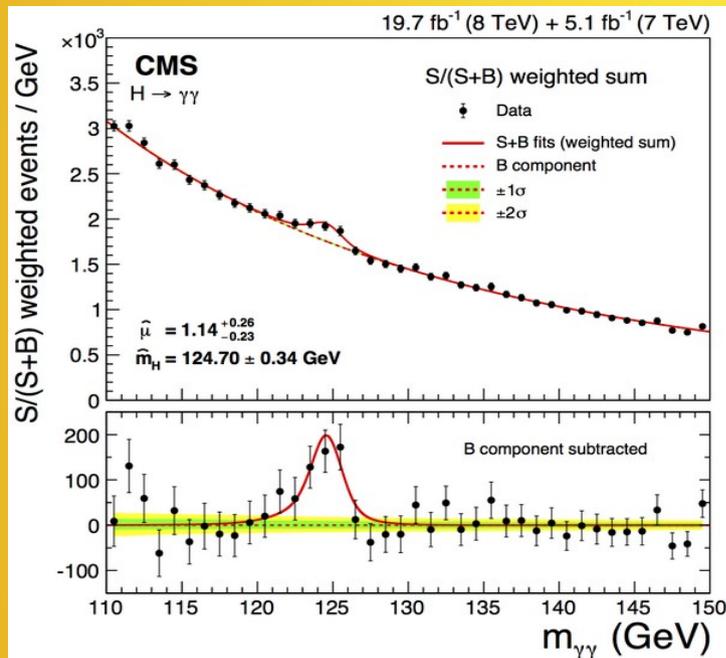
Jae Sik Lee(Chonnam National U.)

KAVLI
IPMU



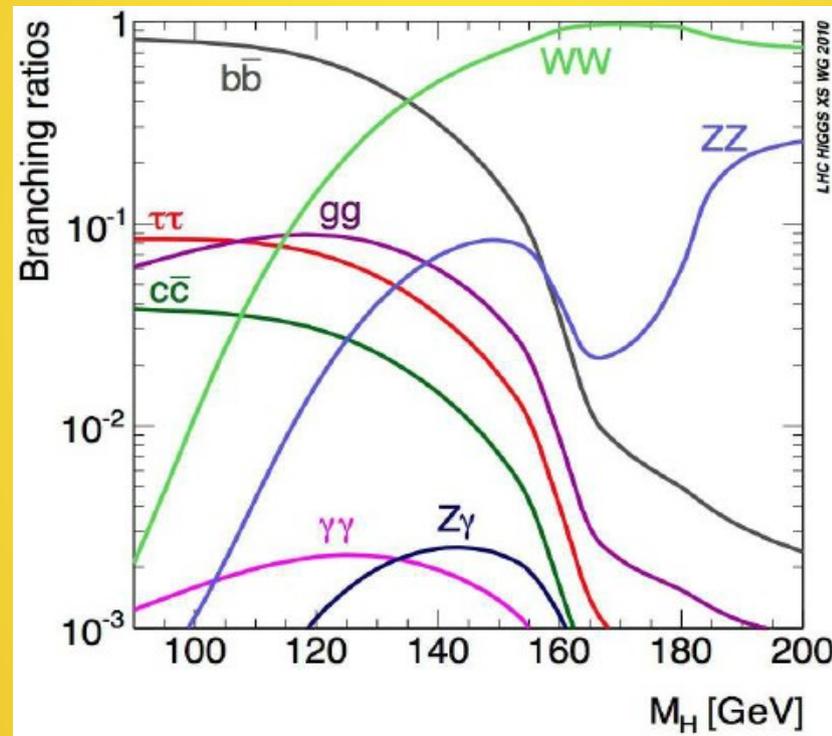
Introduction

- ◆ 125 GeV Higgs is discovered at CERN LHC on 2012.



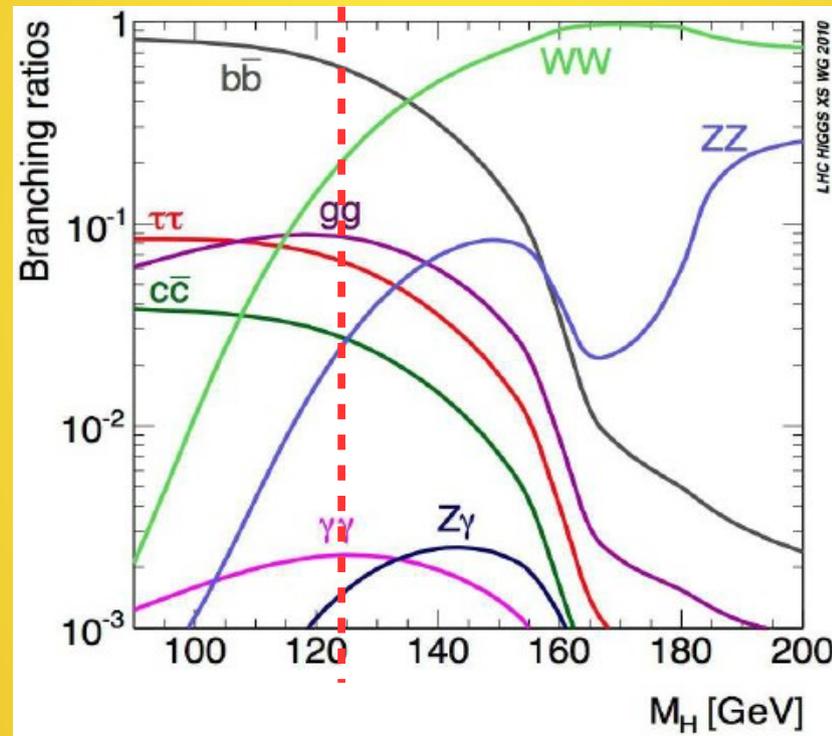
Introduction

- 125 GeV Higgs decay. First, we saw the diphoton signal.



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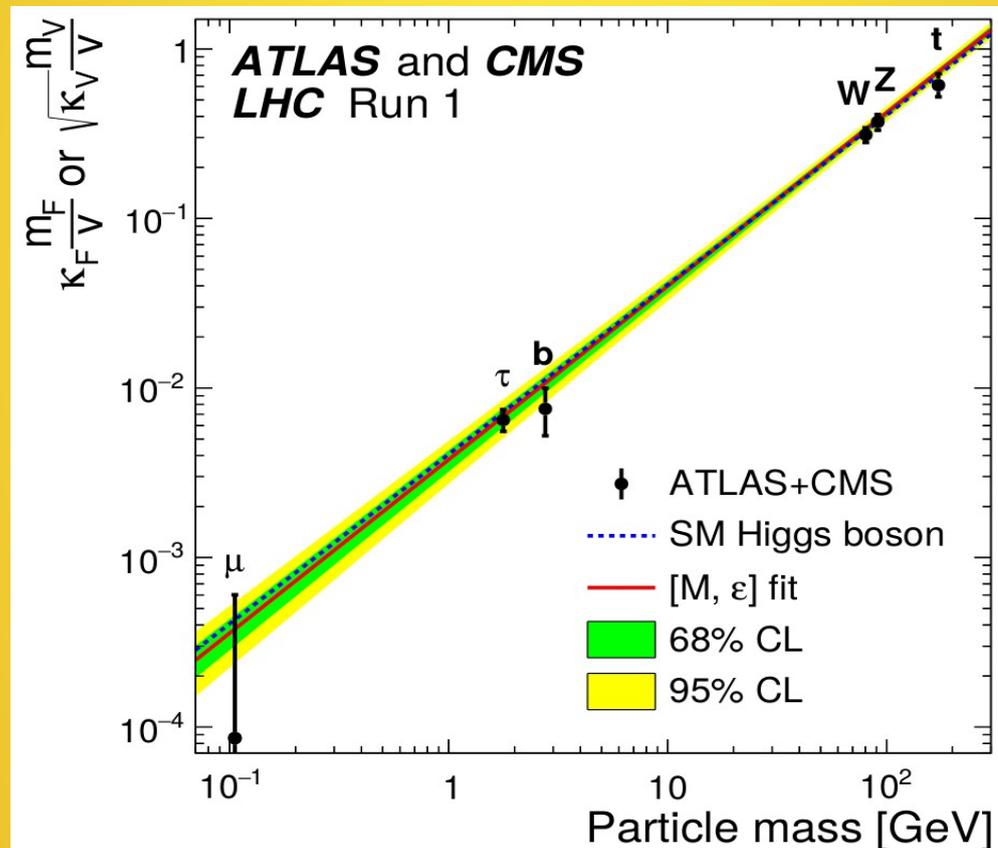


Outline

- ◆ Introduction
- ◆ Higgs production. LHC & ILC.
- ◆ Recoil Higgs at ILC, Higgs invisible & non-standard decay.
- ◆ Model independent analysis.
- ◆ Apply to BSM, 2HDM, Higgs portal, MSSM.
- ◆ What can do at ILC?

Introduction

- ◆ 125 GeV Higgs decay. Determine the Yukawa couplings.



Introduction

- ◆ The **coupling scale factors**: To describe the deviation from SM Higgs.

$$\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, \dots$$

- ◆ For SM:

$$\kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z = 1$$

Introduction

- ◆ The coupling scale factors are model-dependent.

$$\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, \dots$$

- ◆ Effective Field Theory Formalism:

K.Fujii, S.Jung, T.Ogawa, M.E.Peskin, J.Tian et.al: 1708.08912,
Peskin's and Junping's talks.

- ◆ 84 SM gauge invariant dim-6 operators relate to Higgs couplings.
- ◆ Reduced to 10 CP conserving operators, and 4 CP violating operators.

Introduction

- ◆ SM Higgs invisible decay:

$$\text{BR}(h_{\text{SM}} \rightarrow ZZ \rightarrow \nu\nu\nu\nu) \simeq 1 \times 10^{-3}$$

- ◆ 125 GeV Higgs non-standard decay.

$$\text{BR}(h_{125} \rightarrow \text{non - standard})$$

- ◆ BSM, Higgs decay into

1. DM through Higgs portal model

2. light neutralino from MSSM

3. neutrinos

Introduction

- ◆ SM Higgs invisible decay:

$$\text{BR}(h_{\text{SM}} \rightarrow ZZ \rightarrow \nu\nu\nu\nu) \simeq 1 \times 10^{-3}$$

- ◆ 125 GeV Higgs non-standard decay.

$$\text{BR}(h_{125} \rightarrow \text{non - standard})$$

- ◆ At LHC, in order to give upper limit for it, Further assumptions are needed:

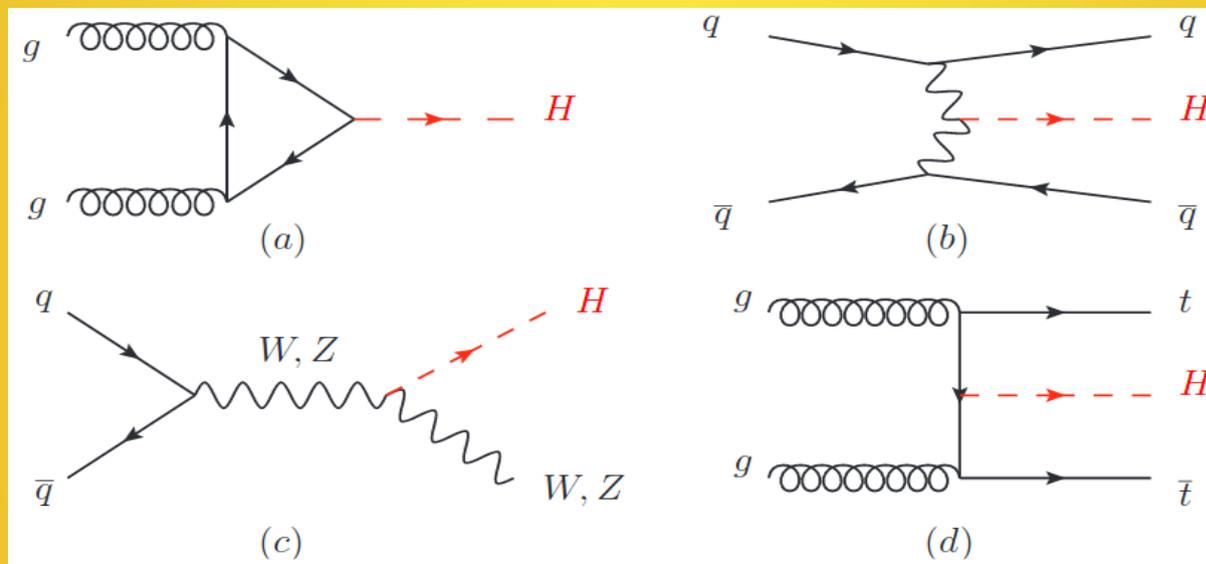
$$i). \text{BR}(h_{125} \rightarrow \text{Non - S.}) = \text{BR}(h_{125} \rightarrow \text{inv.})$$

$$ii). \text{BR}(h_{125} \rightarrow \text{Non - S.}) = \text{BR}(h_{125} \rightarrow gg, cc, \dots)$$

$$\kappa_V \leq 1$$

Higgs Production at LHC

- ◆ The production mechanism: ggF, VBF, Vh, tth.



C.Grojean: 1708.00794

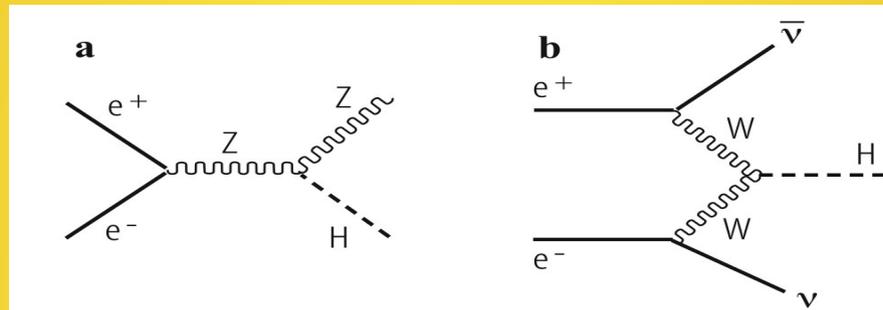
ProductionRate :

ggF = 80%, VBF = 15%, Vh = 4.5%, tth = 0.5%

K.Cheung, J.S.Lee, P.Y.Tseng: 1302.3794

Higgs Production at Lepton collider

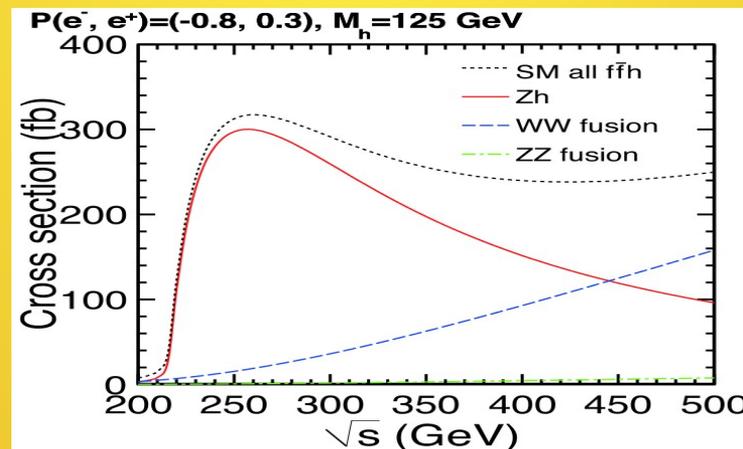
- ◆ The production mechanism: Zh, vvh.



The theory of Electroweak interaction

- ◆ At ILC(250GeV): Zh, ILC(500GeV):Zh+vvh.

T.Mawatari's talk, K.Fujii,A.Ishigawa,D.Jeans,,J.Tian,H.Yamamoto:1604.07524



Higgs Production at Lepton collider

- ◆ At 250 GeV center of mass energy: production rate is 230fb.
- ◆ LHC 13 TeV, production rate is 44pb.

ILC(250GeV) : luminosity : 2 ab^{-1} , # of h : 6×10^5

CEPC : luminosity : 5 ab^{-1} , # of h : 1.2×10^6

FCC — ee : luminosity : 30 ab^{-1} , # of h : 6.9×10^6

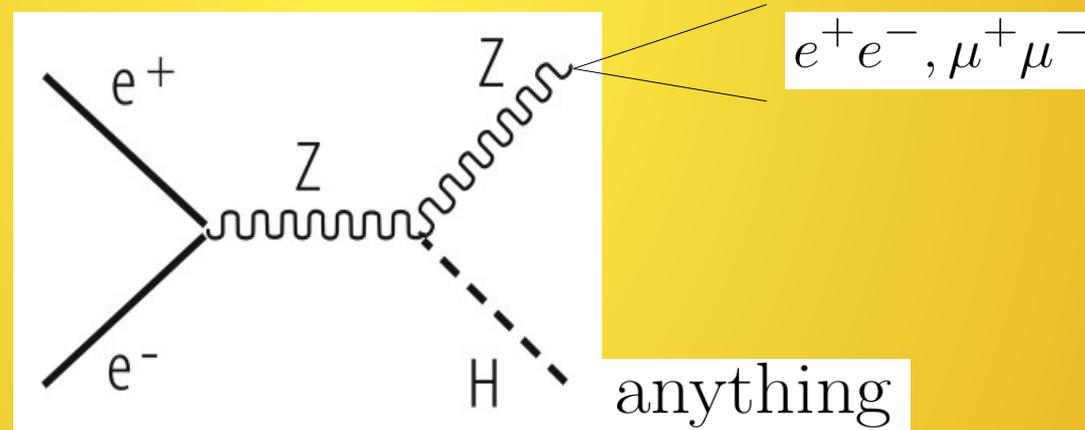
HL — LHC : luminosity : 3 ab^{-1} , # of h : 1.3×10^8

Z.Liu, L.T.Wang, H.Zhang: 1612.09284

Higgsstrahlung process

- ◆ The production production at ILC(250GeV): Zh.
- ◆ Higgs tagging: recoil mass technique.

Z.Liu, L.T.Wang, H.Zhang: 1612.09284



Higgsstrahlung process

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- ◆ Higgs tagging: recoil mass technique.

J.Tian, K. Fujii: Nuc. & Par. Phys. Proc. 273-275 (2016) 826-833
Z.Liu, L.T.Wang, H.Zhang: 1612.09284

- ◆ 4-momentums of final states can be fully reconstructed.

$$m_{\text{recoil}} \equiv \sqrt{s - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-}) + m_{\ell\ell}^2}$$
$$|m_{\text{recoil}} - 125\text{GeV}| < 5\text{GeV}$$

- ◆ The hZZ coupling(1.3%) and Higgs mass(+/-30MeV) can be measured model-independently.

Higgsstrahlung process

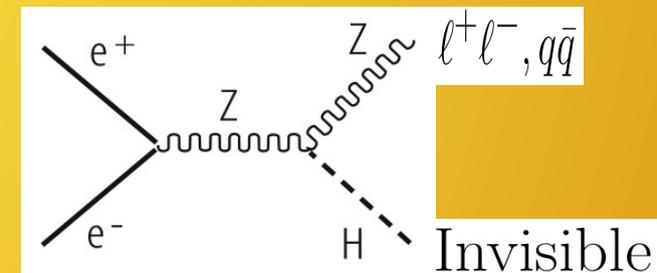
- Once know the hZZ coupling, the Higgs total width obtained from:

$$\Gamma_h^{\text{tot}} = \frac{\Gamma_{h \rightarrow ZZ^*}}{\text{BR}(h \rightarrow ZZ^*)}$$

J.Tian, K. Fujii: Nuc. & Par. Phys. Proc. 273-275 (2016) 826-833

- For invisible Higgs decay, use the recoil mass technique, this time $Z \rightarrow qq$ mode also used.

$$\Delta\text{BR}(h_{125} \rightarrow \text{invisible}) \lesssim 0.44\%$$



Higgs non-standard decay

- ◆ Fix the coupling scales to their SM value 1.

$$i).BR(h_{125} \rightarrow \text{inv.}) \leq 17\%$$

$$ii).BR(h_{125} \rightarrow \text{N.S.}) \leq 20\%$$

P. Bechtle et. al.: 1403.1582, K.Cheung, J.S.Lee, P.Y.Tseng: 1302.3794

For the invisible case, it include the hZ searches from ATLAS and CMS.

- ◆ The total width can be determined by the off-shell Higgs production.

$$\Gamma_{h_{125}} \lesssim 3 \times \Gamma_h^{\text{SM}}$$

Hideki Okawa's talk

F. Caola, K. Melnikov: 1307.4935

J.M.Campbell, R.K. Ellis, C.Williams:1311.3589

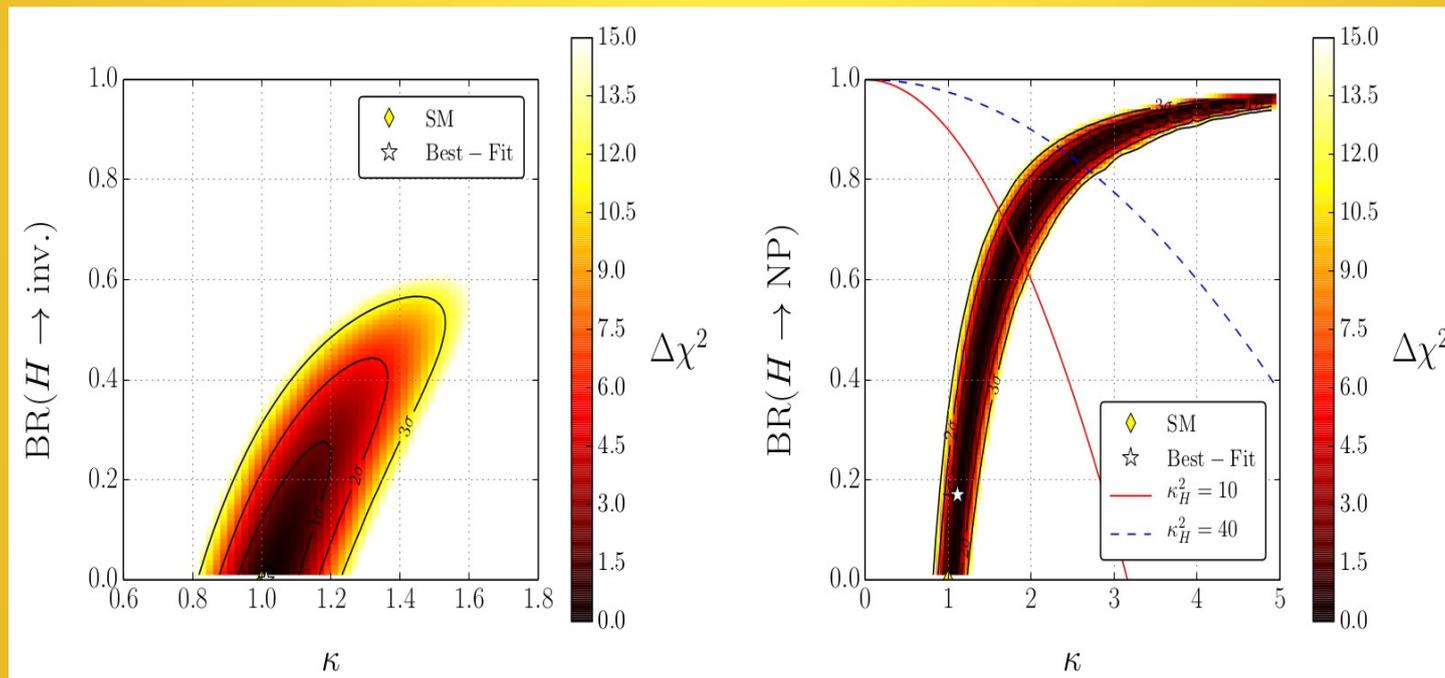
Model-Independent

Model independent

- ◆ Universal coupling scales case:

$$\kappa \equiv \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z$$

$$\text{BR}(h \rightarrow \text{N.S.})$$



$$\text{BR}(h_{125} \rightarrow \text{N.S.}) = \text{BR}(h_{125} \rightarrow \text{inv.})$$

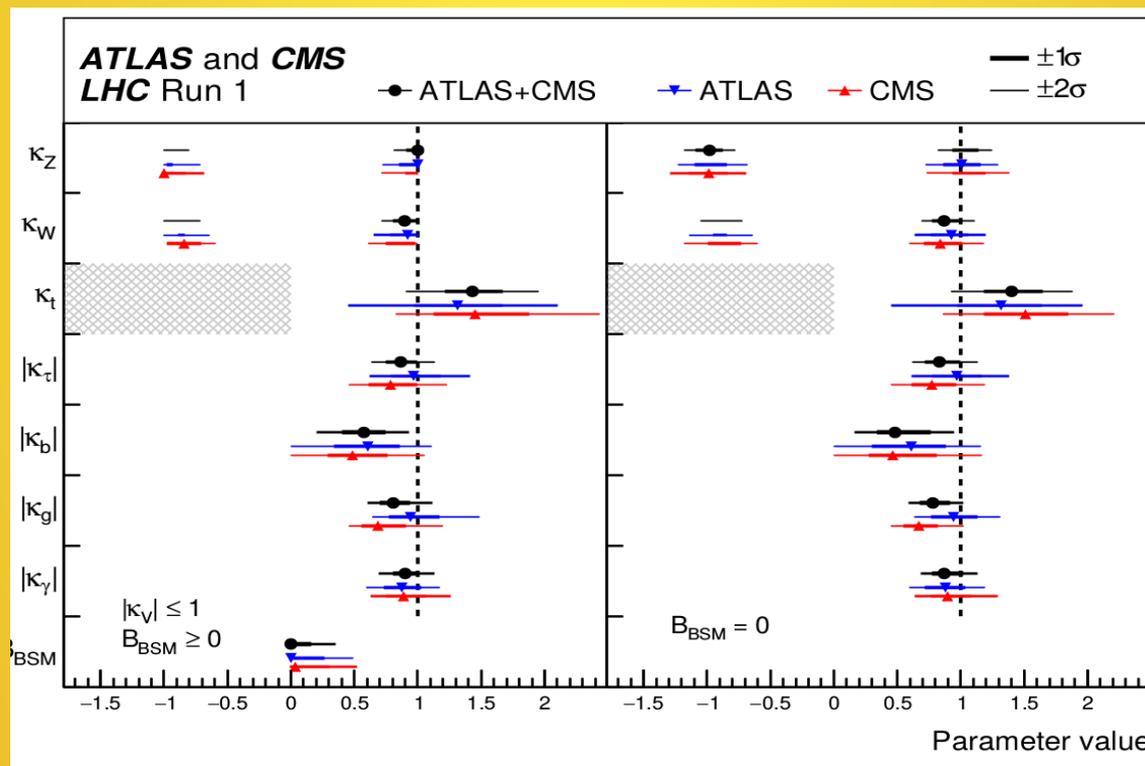
P. Bechtle et. al.: 1403.1582

Model independent

- Model independent coupling scales case:

$$\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z$$

$$\text{BR}(h \rightarrow \text{N.S.})$$



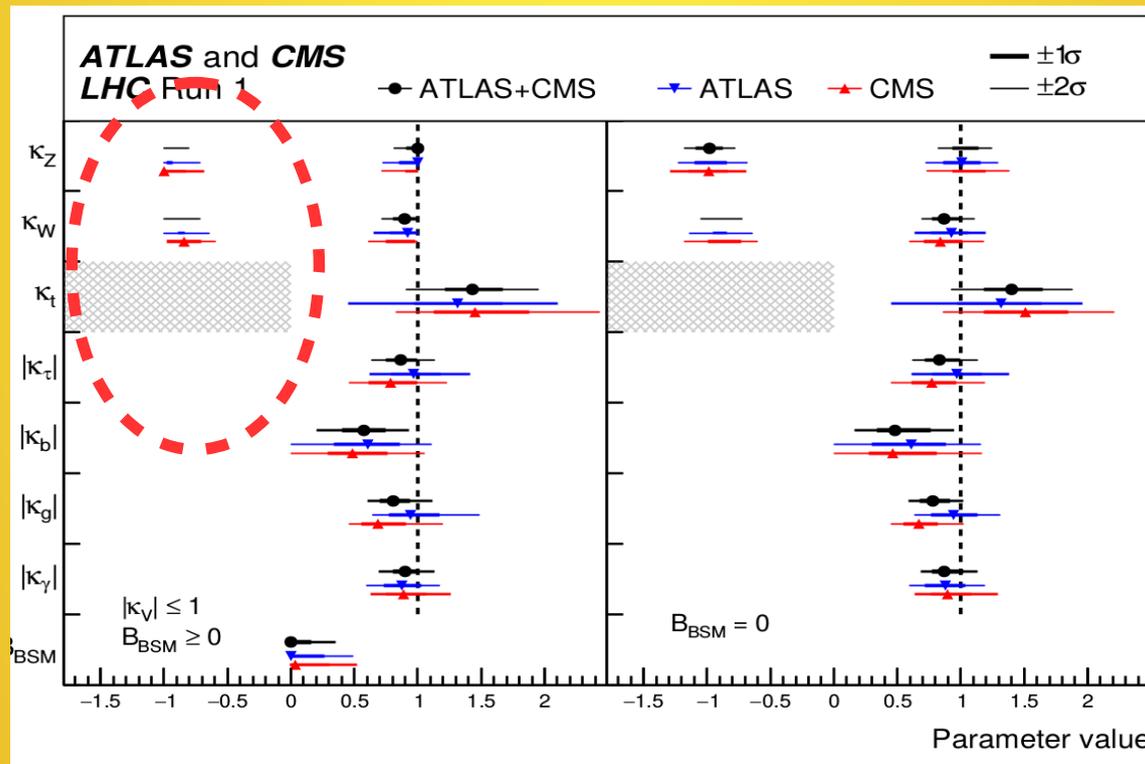
ATLAS,CMS collaborations: 1606.02266

Model independent

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$$\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z$$

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Beyond SM

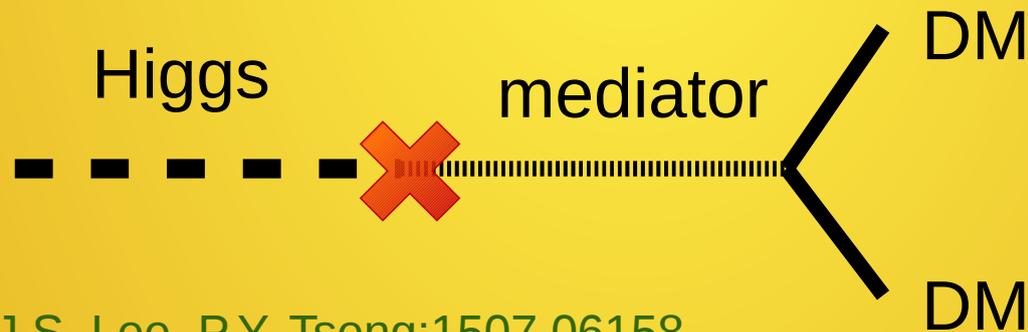
Higgs Portal DM

- The $A_{\Phi H} \Phi H^\dagger H$ allowed the mixing between Higgs doublet and scalar singlet

- Higgs precision measurement at LHC:

$$\Delta\text{BR}(h_{125} \rightarrow ZZ) \lesssim 10\% \Rightarrow |\sin \theta| \lesssim 0.32$$

- The invisible Higgs decay mode:



K.Cheung, P.Ko, J.S. Lee, P.Y. Tseng:1507.06158,
T.Kamom, P.Ko, J.Li: 1705.02149,

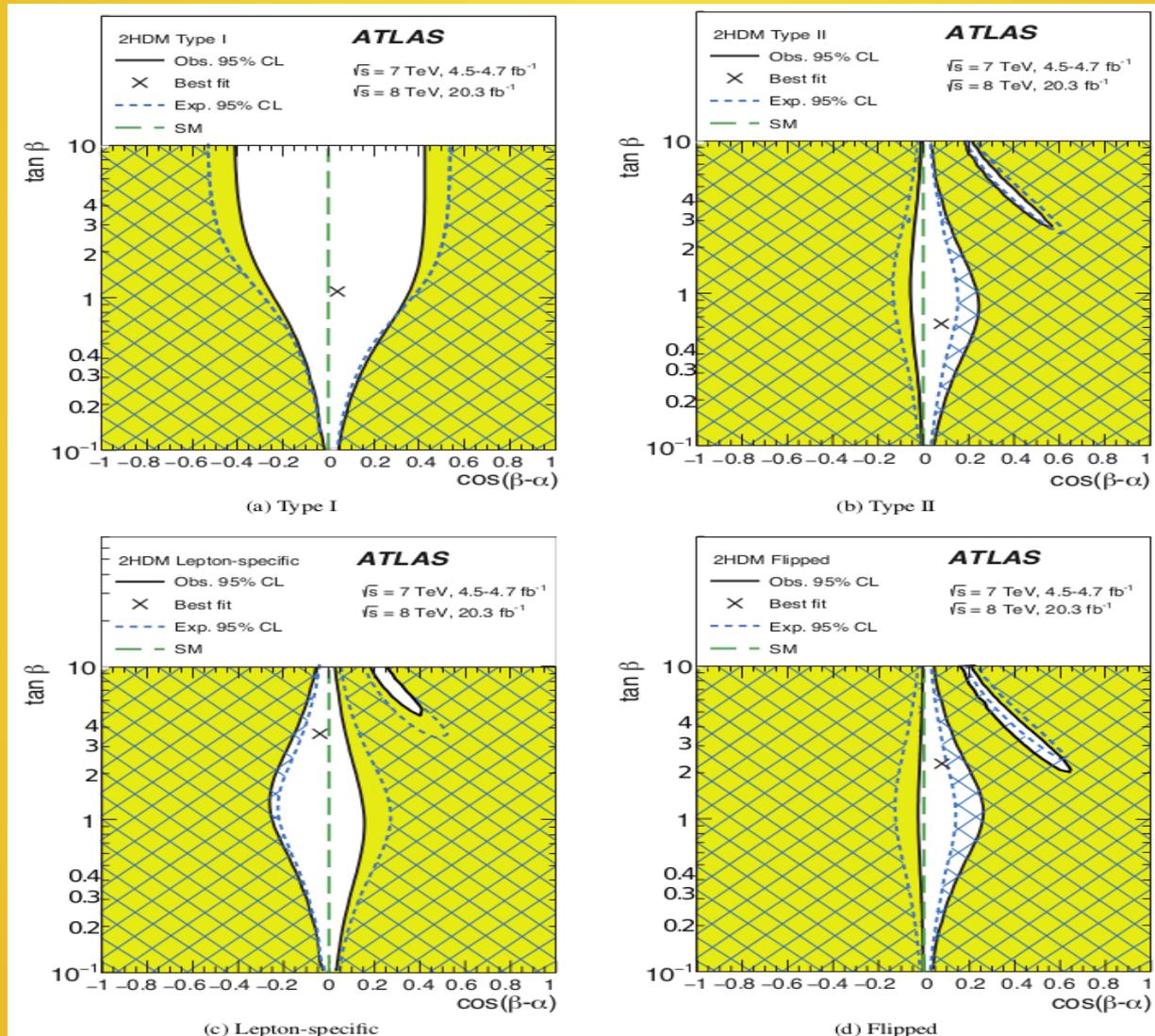
Two-Higgs-Doublet Model

- ◆ The coupling scales are correlated:

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta - \alpha)$			
κ_u	$\cos(\alpha) / \sin(\beta)$			
κ_d	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$
κ_ℓ	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$

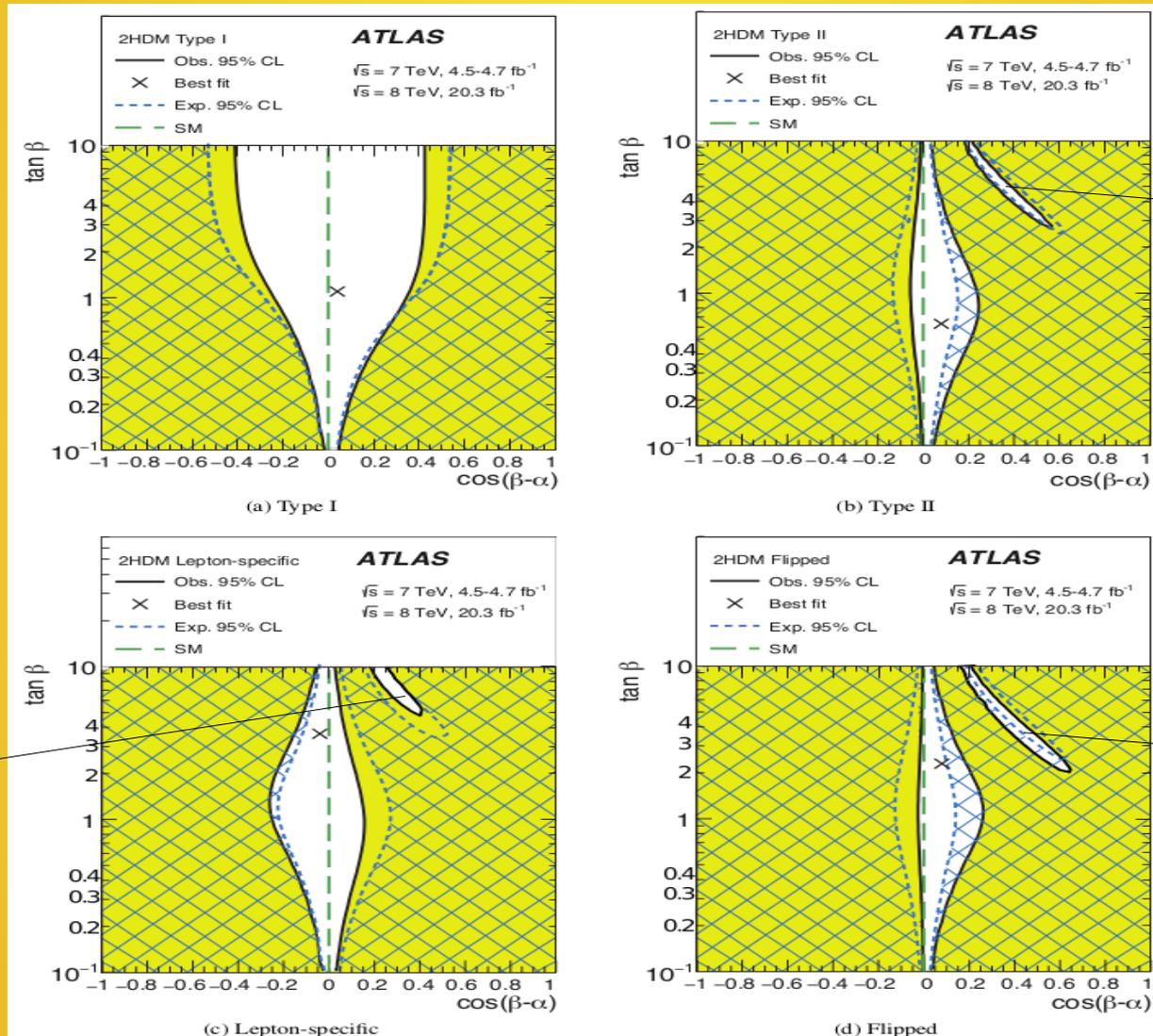
ATLAS collaborations: 1509.00672

Two-Higgs-Doublet Model



ATLAS collaborations: 1509.00672

Two-Higgs-Doublet Model



$$\kappa_b \sim -1$$

$$\kappa_T \sim -1$$

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$$\kappa_b \sim -1$$

Minimal SUSY

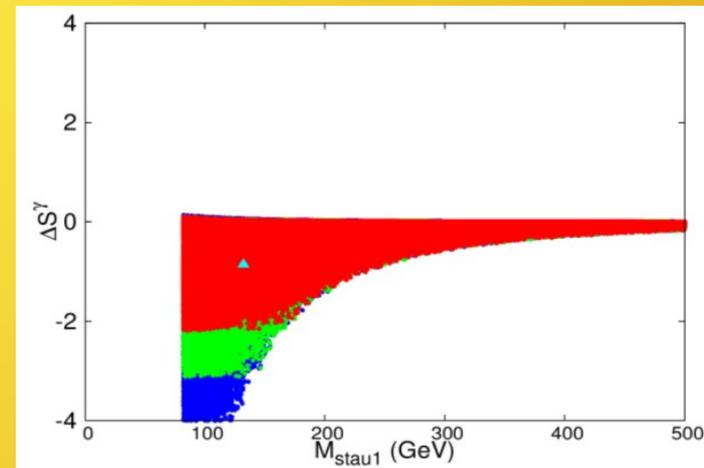
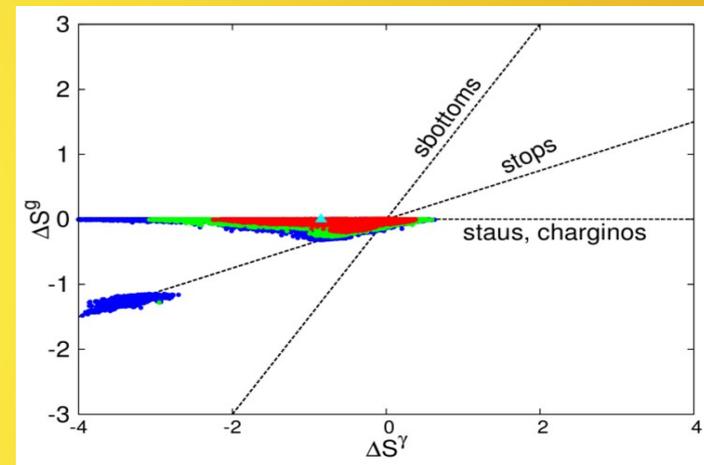
- ◆ The coupling scales of h-digluon and h-diphoton will be modified by the squarks and sleptons.

The form factors are given by

$$S^\gamma(M_{H_i}) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H_i \bar{f} f}^S F_{sf}(\tau_f) - g_{H_i V V} F_1(\tau_W) + \Delta S_i^\gamma,$$

$$P^\gamma(M_{H_i}) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H_i \bar{f} f}^P F_{pf}(\tau_f) + \Delta P_i^\gamma,$$

K.Cheung, J.S.Lee, P.Y.Tseng: 1501.03552



What can do at ILC?

Higgs Precision at HL-LHC & ILC

- ◆ The uncertainties of coupling scales can be improved:

Scenario	HL-LHC	ILC only			
	S2, csv.	250	500	1000	1000 (LumiUp)
BR($H \rightarrow \text{inv.}$)	≤ 5.1	≤ 2.9	≤ 2.2	≤ 2.1	≤ 1.1
κ_V	+3.8 -2.8	+4.6 -4.4	+1.2 -0.7	+1.2 -0.6	+0.7 -0.4
κ_u	+7.5 -6.5	+1.3 -0.7	+1.0 -0.6	+0.9 -0.6	+0.5 -0.4
κ_d	+6.5 -5.5	+6.8 -6.3	+3.8 -3.3	+2.3 -2.3	+1.6 -1.6
κ_ℓ	+4.3 -3.3	+5.3 -4.3	+2.3 -1.8	+1.8 -1.3	+1.4 -1.1
κ_g	+5.5 -4.5	+6.3 -5.3	+2.8 -2.3	+2.3 -1.8	+1.9 -1.6
κ_γ	+3.8 -2.8	+15.8 -17.8	+8.3 -8.3	+3.8 -3.8	+2.6 -2.6

P. Bechtle et. al.: 1403.1582

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P. Bechtle et. al.: 1403.1582

Higgs Precision at HL-LHC & ILC

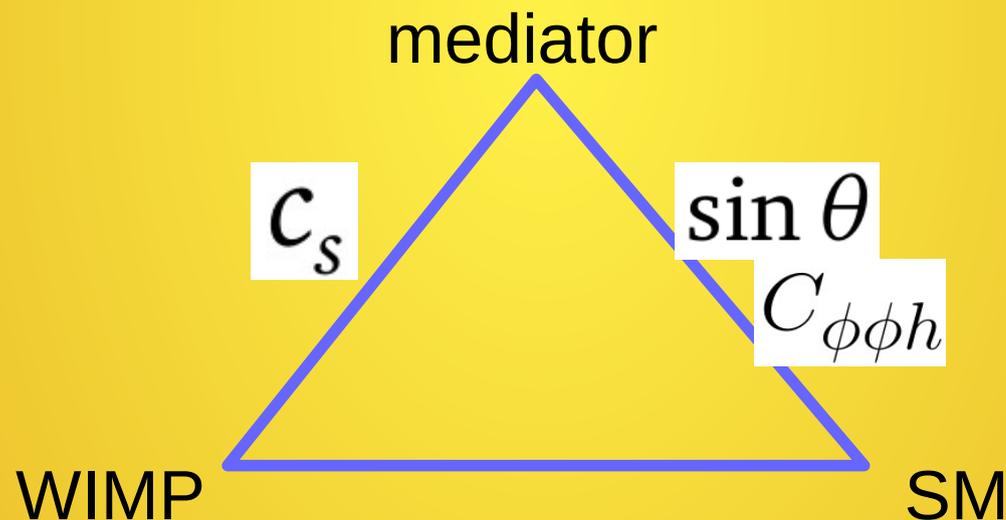
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P. Bechtle et. al.: 1403.1582

ILC v.s Light WIMP with scalar mediator

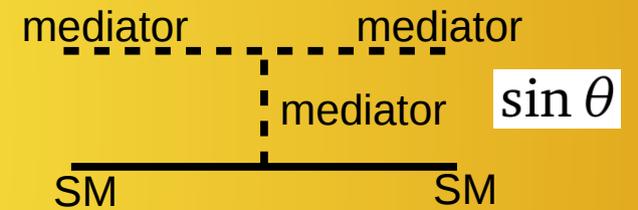
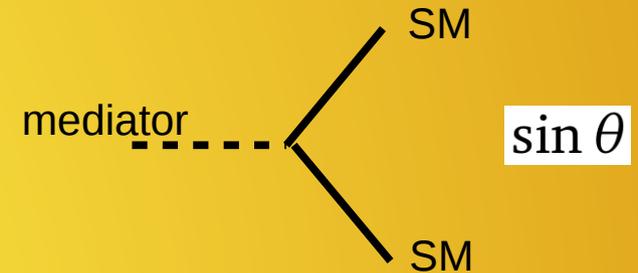
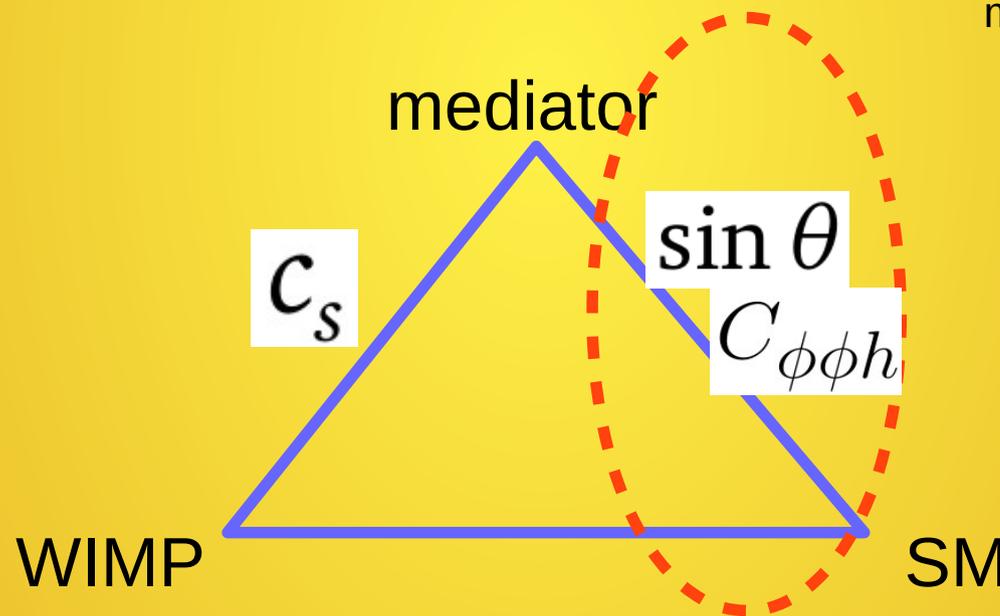
- ◆ Sub-GeV WIMP with scalar mediator.
- ◆ Thermal equilibrium: $WIMP \leftrightarrow \text{mediator} \leftrightarrow SM$.



S.Matsumoto, Y.L Sming Tsai, P.Y. Tseng

ILC v.s Light WIMP with scalar mediator

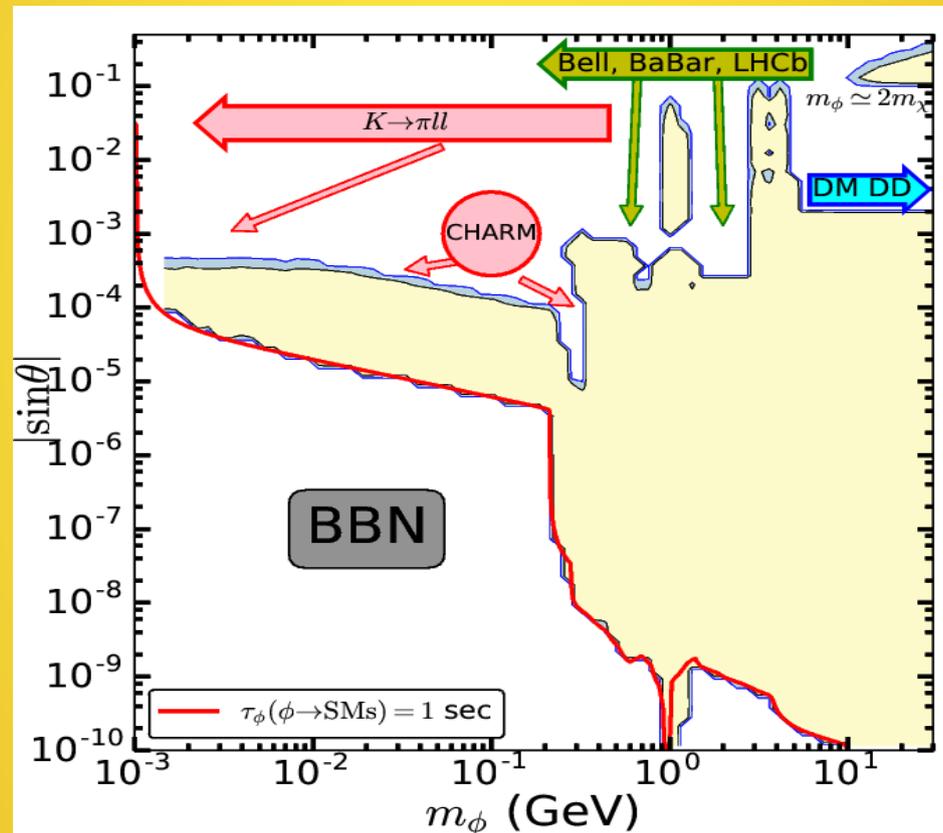
- ◆ Maintain thermal equilibrium.
- ◆ $WIMP \leftrightarrow \text{mediator} \leftrightarrow \text{SM}$.



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ILC v.s Light WIMP with scalar mediator

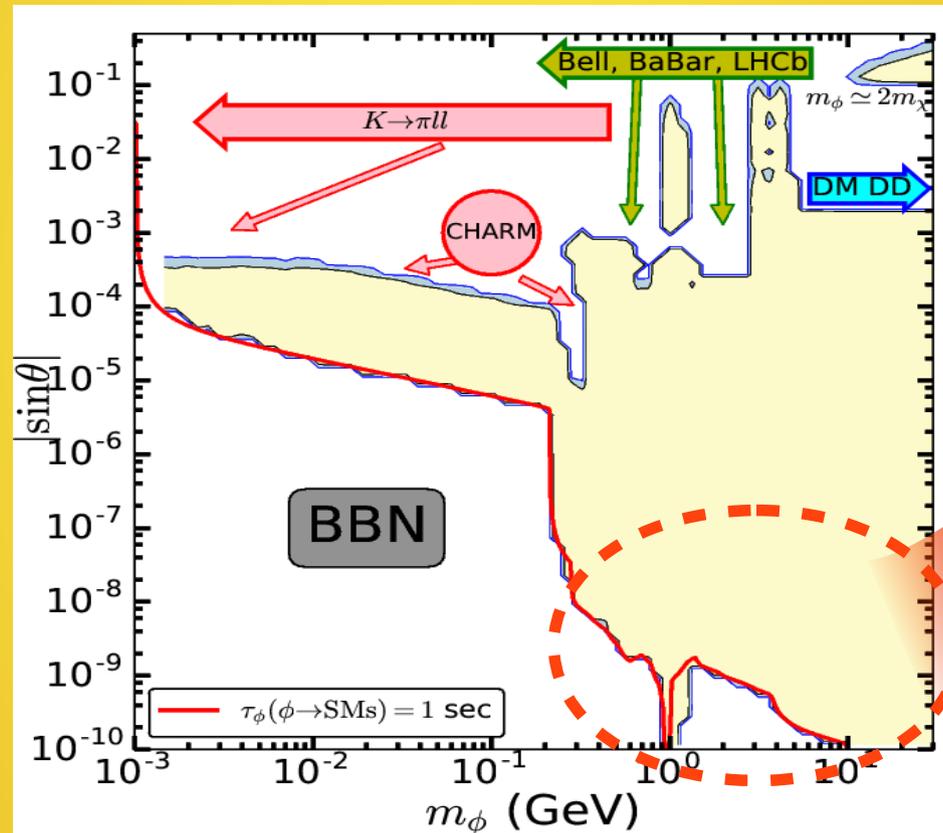
- ◆ Current experimental constraints for light mediator



S.Matsumoto, Y.L Sming Tsai, P.Y. Tseng

ILC v.s Light WIMP with scalar mediator

- Current experimental constraints for light mediator

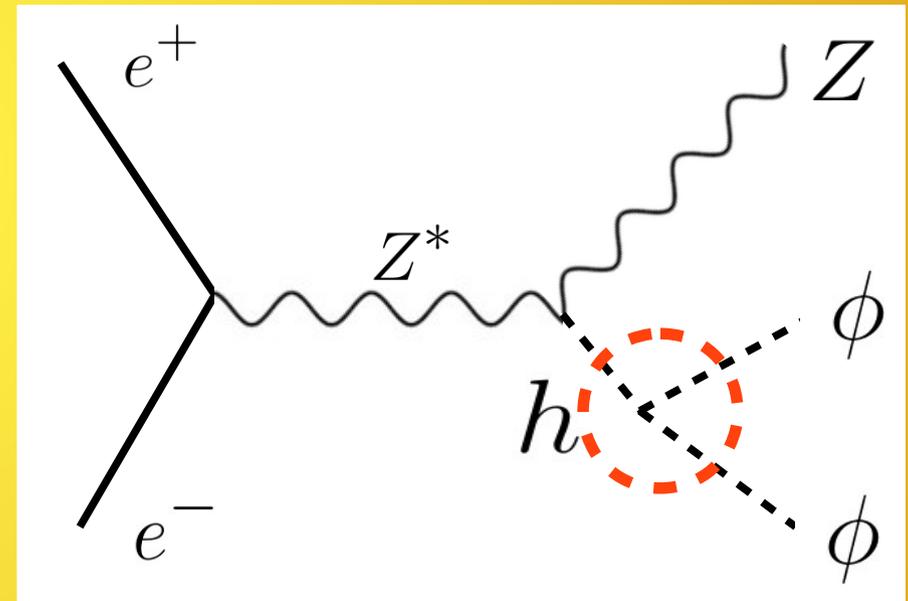
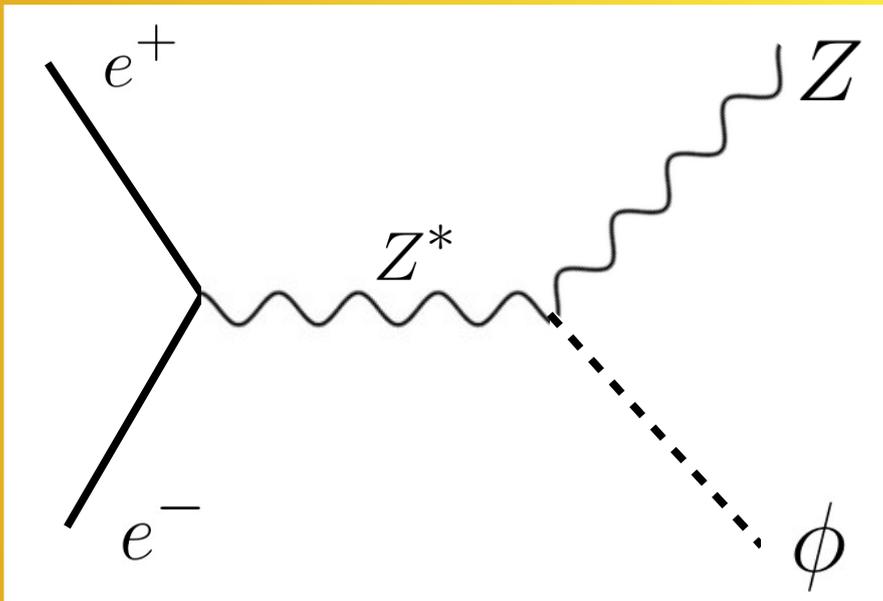


The $\sin \theta$ too small,
but $C_{h\phi\phi}$ need to be large
to maintain thermal equilibrium.

S. Matsumoto, Y.L. Sming Tsai, P.Y. Tseng

ILC v.s Light WIMP with scalar mediator

- ◆ Mediator produced at ILC

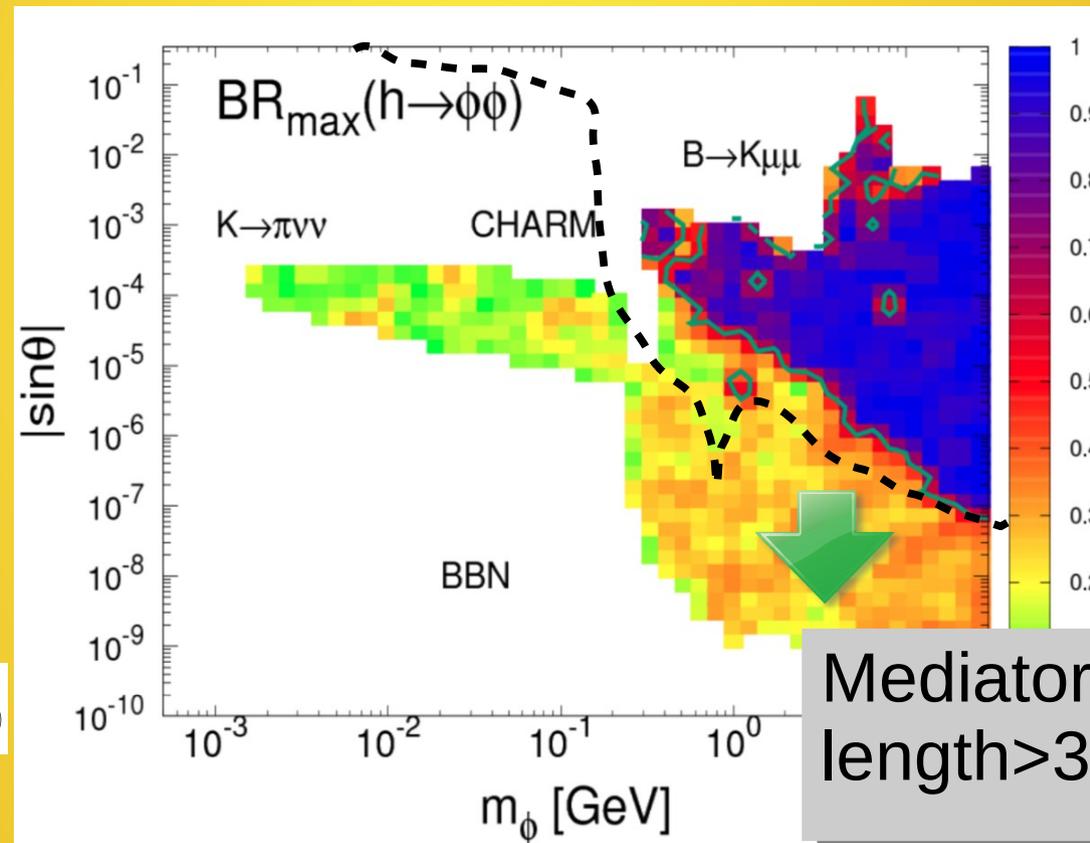


ILC v.s Light WIMP with scalar mediator

- Current experimental constraints for light mediator

$$C_{\phi\phi h} \simeq \frac{2(m_\phi^2 - \mu_\phi^2)}{v_H}$$

$$\Gamma(h \rightarrow \phi\phi) \simeq \frac{C_{\phi\phi h}^2}{32\pi m_h}$$



Mediator decay length > 30m

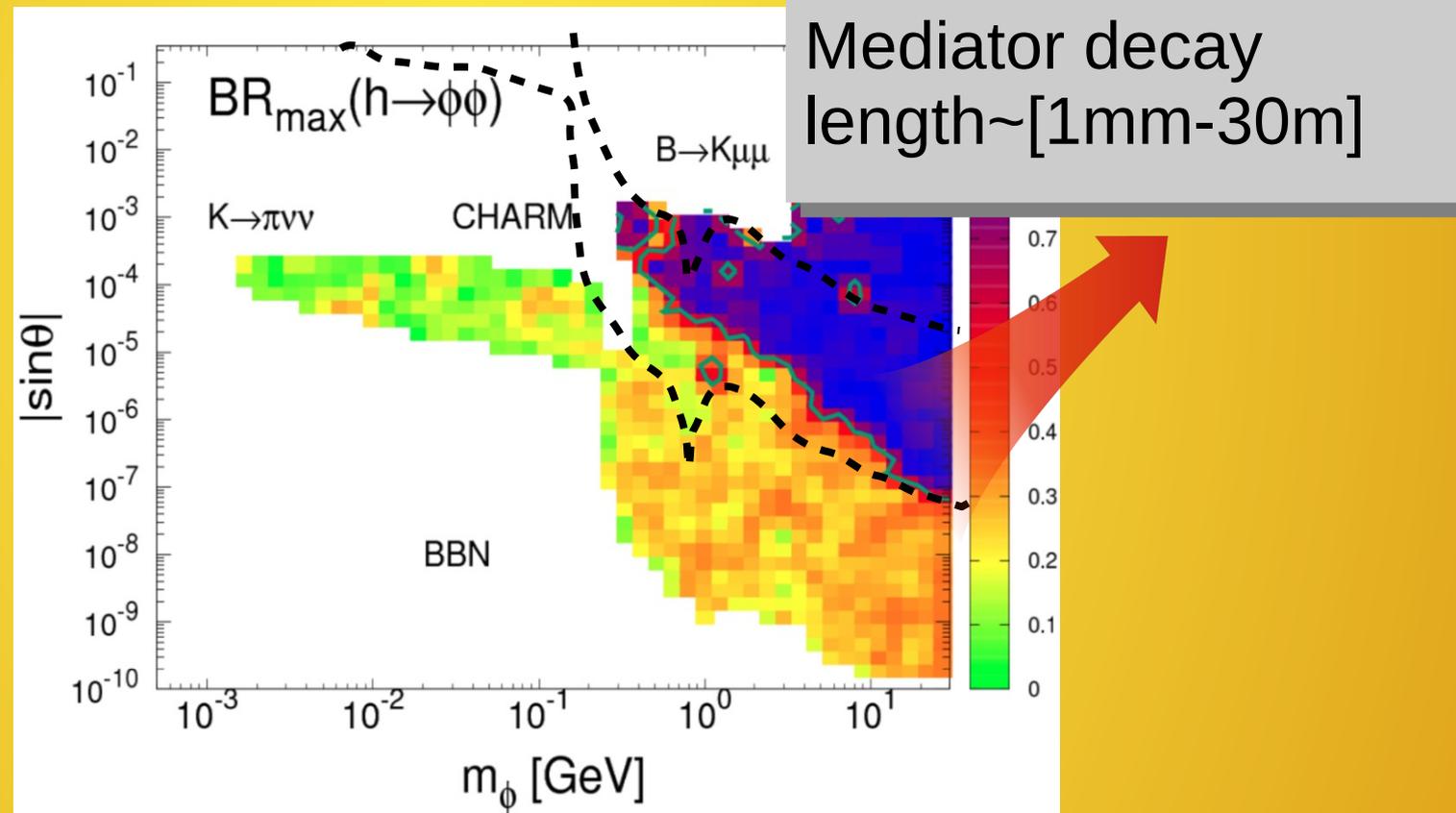
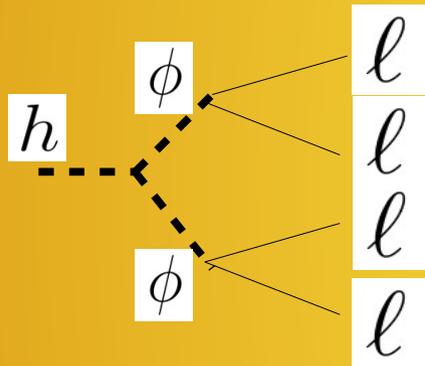
$$\Delta\text{BR}(h_{125} \rightarrow \text{invisible}) \lesssim 0.44\%$$

H. Baer et. al., ILC:
1306.6352

S. Matsumoto, Y.L. Sming Tsai, P.Y. Tseng

ILC v.s Light WIMP with scalar mediator

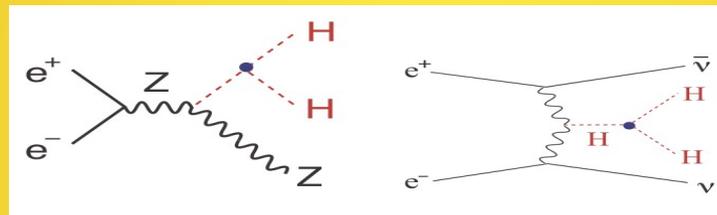
- Current experimental constraints for light mediator



S.Matsumoto, Y.L Sming Tsai, P.Y. Tseng

Triple Higgs coupling

- At ILC(500GeV), the triple Higgs coupling can be measured from



J.Tian, K. Fujii: Nuc. & Par. Phys. Proc. 273-275 (2016) 826-833

$\Delta g/g$	Baseline			LumiUP		
	250 GeV	+500 GeV	+1 TeV	250 GeV	+500 GeV	+1 TeV
$\int Ldt/\text{fb}$	250	500	1000	1150	1600	2500
Γ_H	11%	5.0%	4.6%	5.4%	2.5%	2.3%
Inv.	0.95%	0.95%	0.95%	0.44%	0.44%	0.44%
λ_{HHH}	-	83%	21%	-	46%	13%

Triple Higgs coupling

- ◆ However, triple Higgs coupling receives many contributions and uncertainties from BSM effects.

K.Fujii, S.Jung, M.E.Peskin, J.Tian et.al: 1708.09079
Sunghoon's talk.

- ◆ Using effective field theory formalism, they shown only 5% systemic uncertainty in the determination of the triple Higgs coupling.

It is sub-dominant to the statistical and experiment systematic errors.

- ◆ Model independent limit for operator $-\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$ can be obtained.

Summary

- ◆ Higgs precision as powerful tool to probe BSM.
- ◆ New physics modified 125 GeV Higgs couplings via:
 - I) mixing, ii) heavy fermion running in hgg, h-diphoton loops,
 - iii) decay into DM or mediator pair.
- ◆ At ILC, the total Higgs width will be nail down to few percent by recoil mass technique. This can be used to probe **light WIMP** scenario.

Thank You !

Back Up

Higgsstrahlung process

- ◆ ATLAS and CMS, Z boson recoiling against missing transverse energy for Zh production.
- ◆ The assumption for non-standard decay mode:

$$i). \text{BR}(h_{125} \rightarrow \text{Non - S.}) = \text{BR}(h_{125} \rightarrow \text{inv.})$$

O.J. Eboli, D. Zeppenfeld: hep-ph/0009158

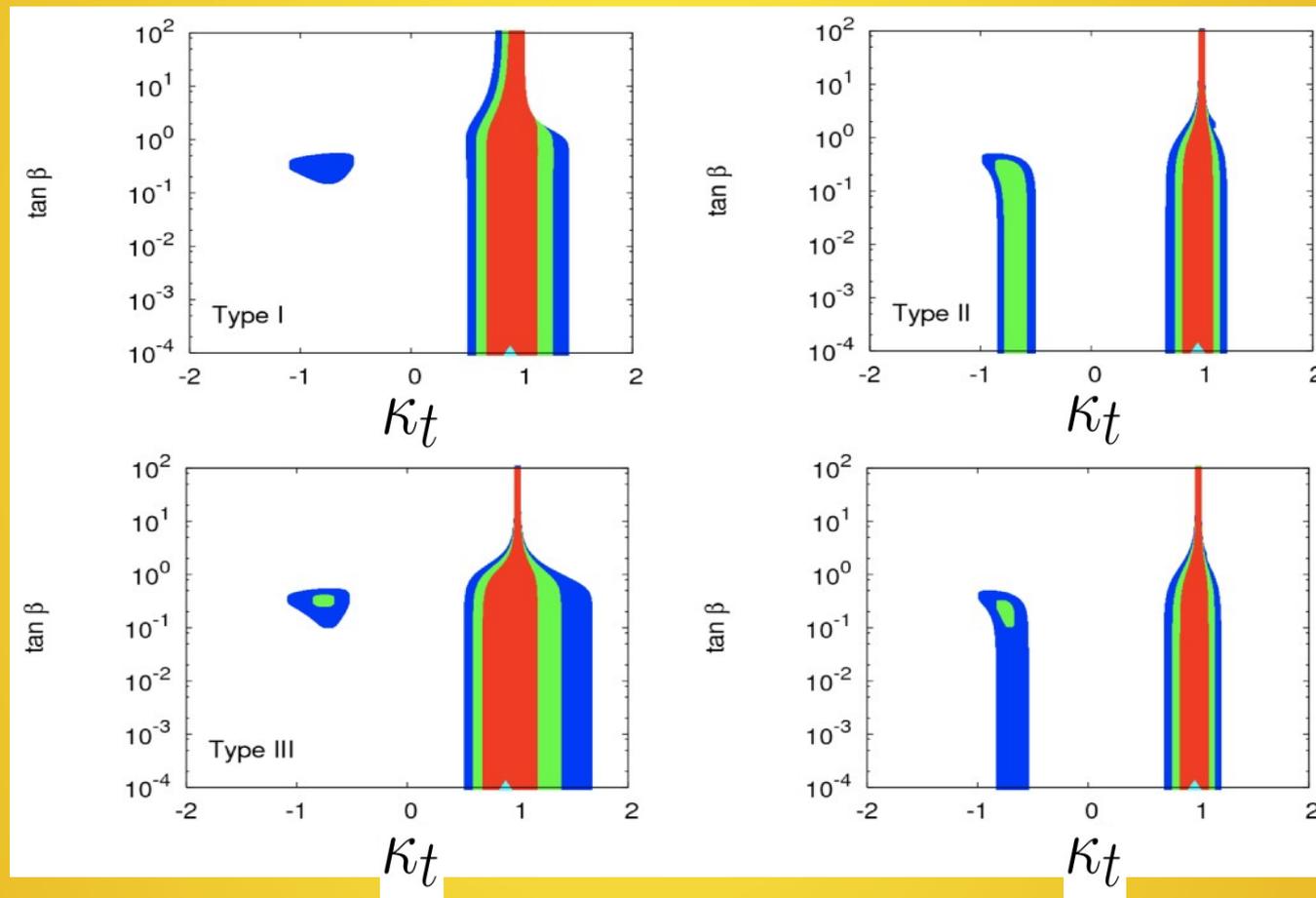
- ◆ They obtained upper limit for

$$\kappa_Z^2 \times \text{BR}(h_{125} \rightarrow \text{invisible}) \lesssim 0.75$$

ATLAS-CONF-2013-011, ATLAS-CONF-2013-013
, CMS-PAS-HIG-13-018, CMS-PAS-HIG-13-028
, ATLAS 1708.09624, CMS 1610.09218.

Two-Higgs-Doublet Model

- ◆ The wrong sign coupling corresponds to small $\tan\beta$:



K.Cheung, J.S.Lee, P.Y.Tseng: 1310.3937

Minimal SUSY

- The coupling scales in simplified Higgs sector hMSSM:

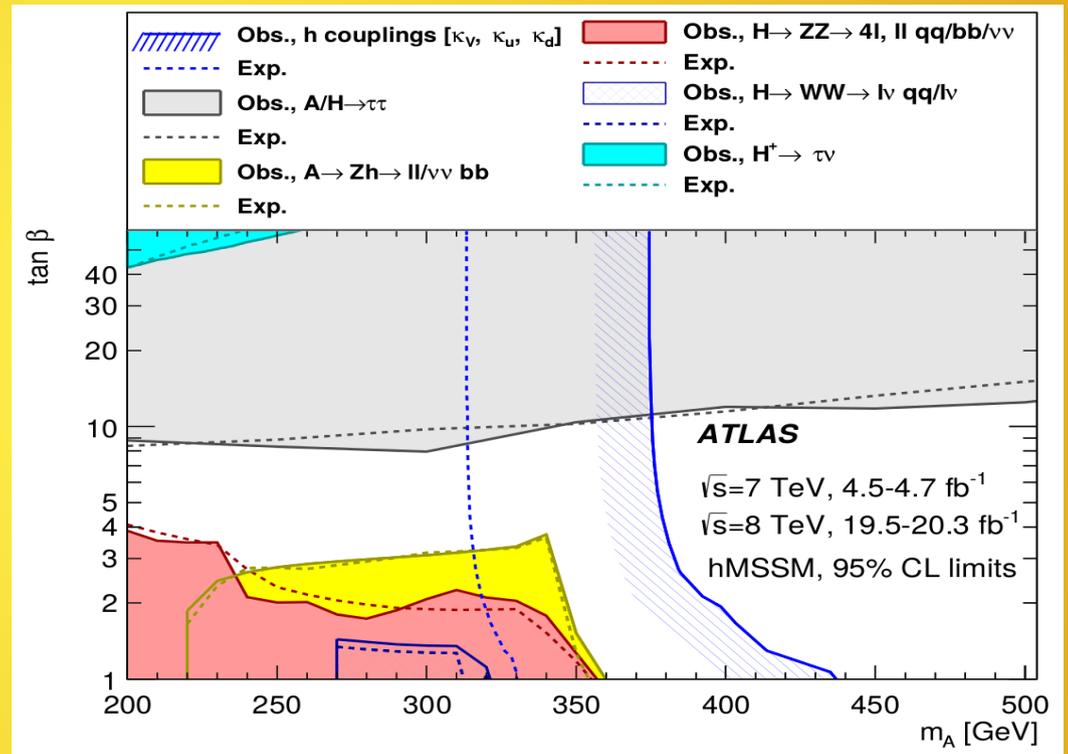
$$\kappa_V = \frac{s_d(m_A, \tan \beta) + \tan \beta s_u(m_A, \tan \beta)}{\sqrt{1 + \tan^2 \beta}}$$

$$\kappa_u = s_u(m_A, \tan \beta) \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta}$$

$$\kappa_d = s_d(m_A, \tan \beta) \sqrt{1 + \tan^2 \beta} \quad ,$$

$$s_u = \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2 \beta}{(m_Z^2 + m_A^2 \tan^2 \beta - m_h^2(1 + \tan^2 \beta))^2}}}$$

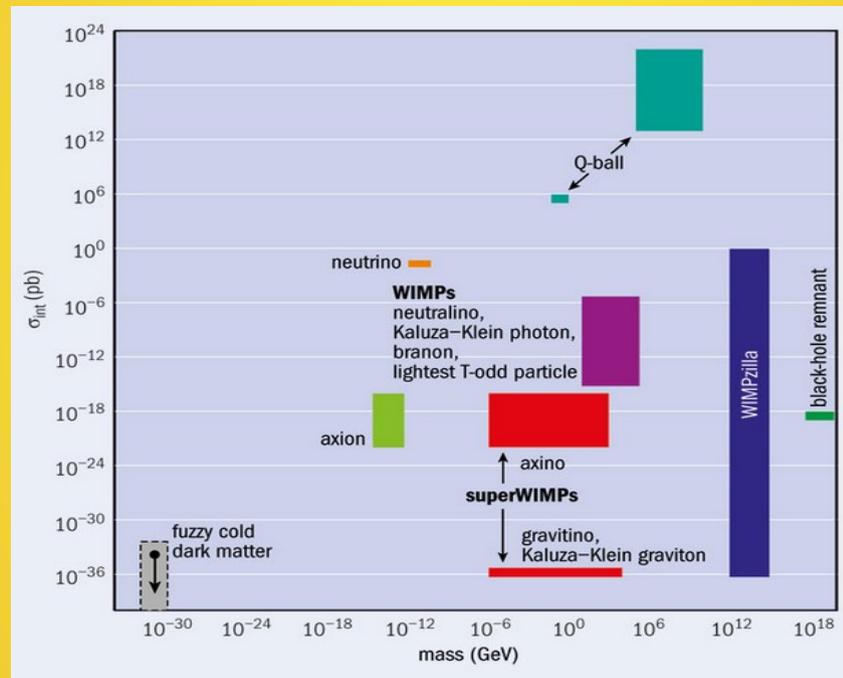
$$s_d = \frac{(m_A^2 + m_Z^2) \tan \beta}{m_Z^2 + m_A^2 \tan^2 \beta - m_h^2(1 + \tan^2 \beta)} s_u$$



ATLAS collaborations: 1509.00672

ILC v.s Light WIMP with scalar mediator

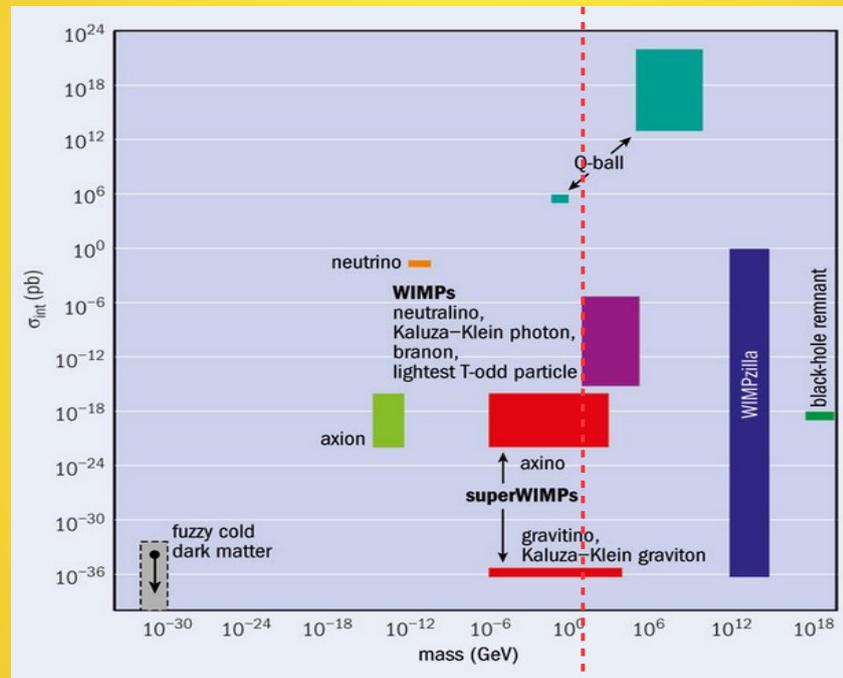
- ◆ The mass of WIMP from GeV to O(100) TeV.



Towards Dark Matter Discovery 2018

ILC v.s Light WIMP with scalar mediator

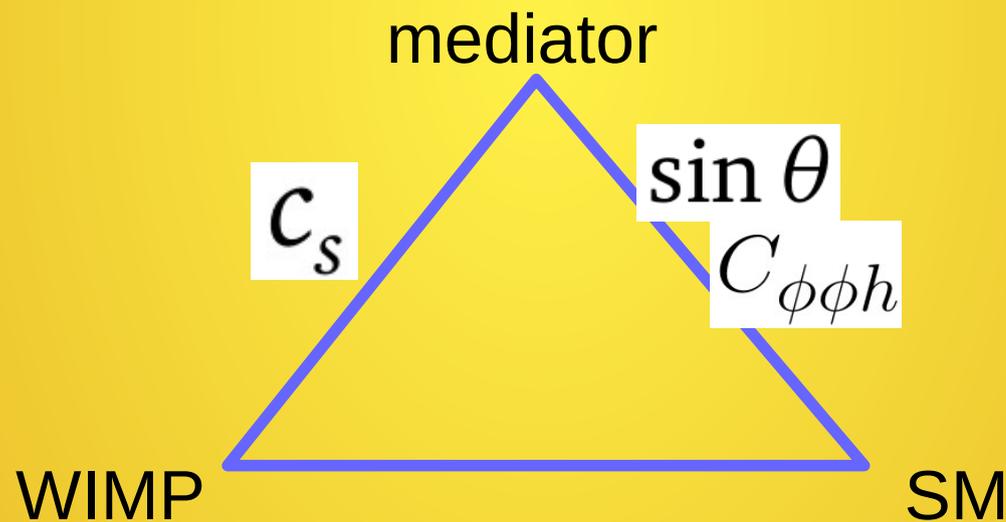
- ◆ The mass of WIMP from GeV to O(100) TeV.



Towards Dark Matter Discovery 2018

Introduction

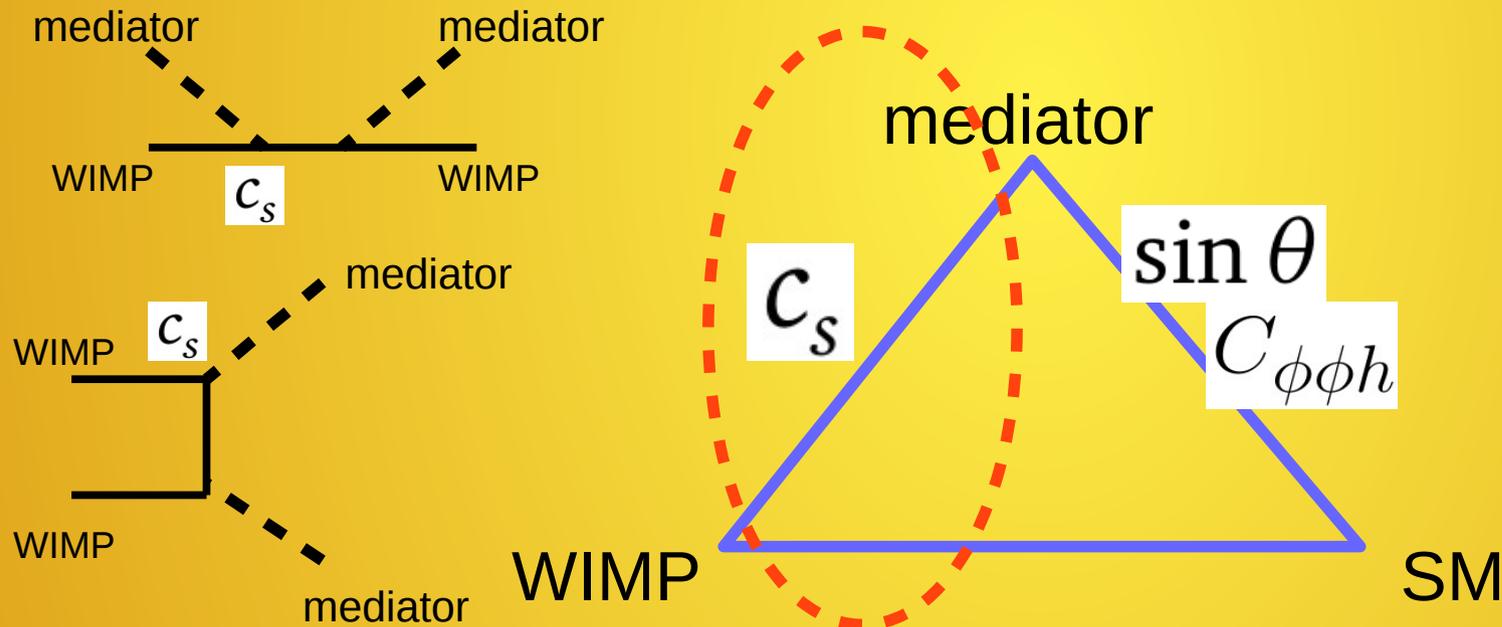
- Thermal equilibrium.
- $WIMP \leftrightarrow \text{mediator} \leftrightarrow SM$.



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Introduction

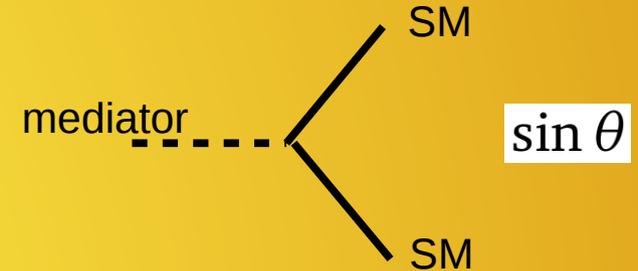
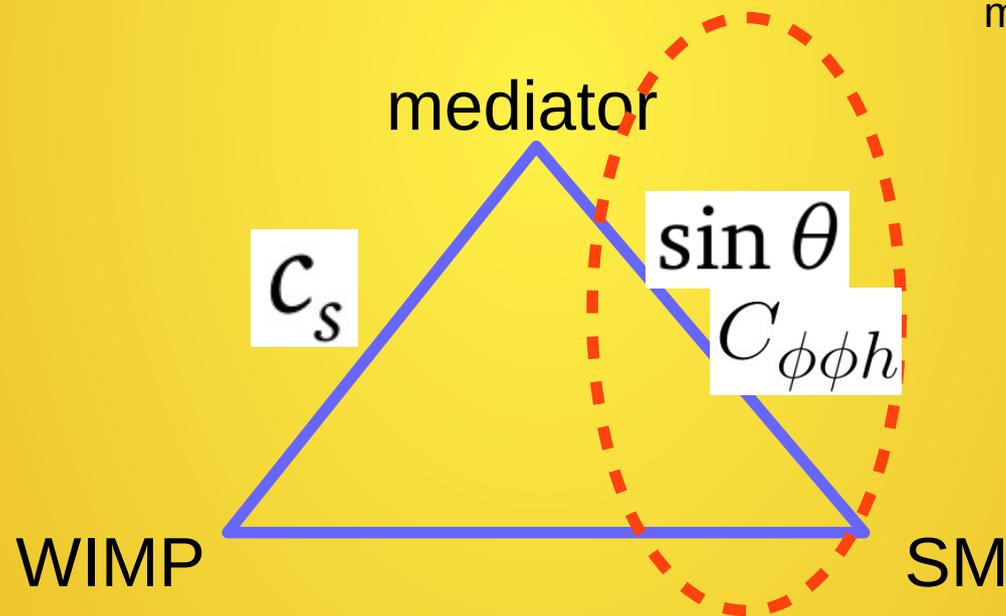
- ◆ Thermal equilibrium.
- ◆ $WIMP \leftrightarrow \text{mediator} \leftrightarrow SM$.



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Introduction

- Thermal equilibrium.
- $WIMP \leftrightarrow \text{mediator} \leftrightarrow SM$.



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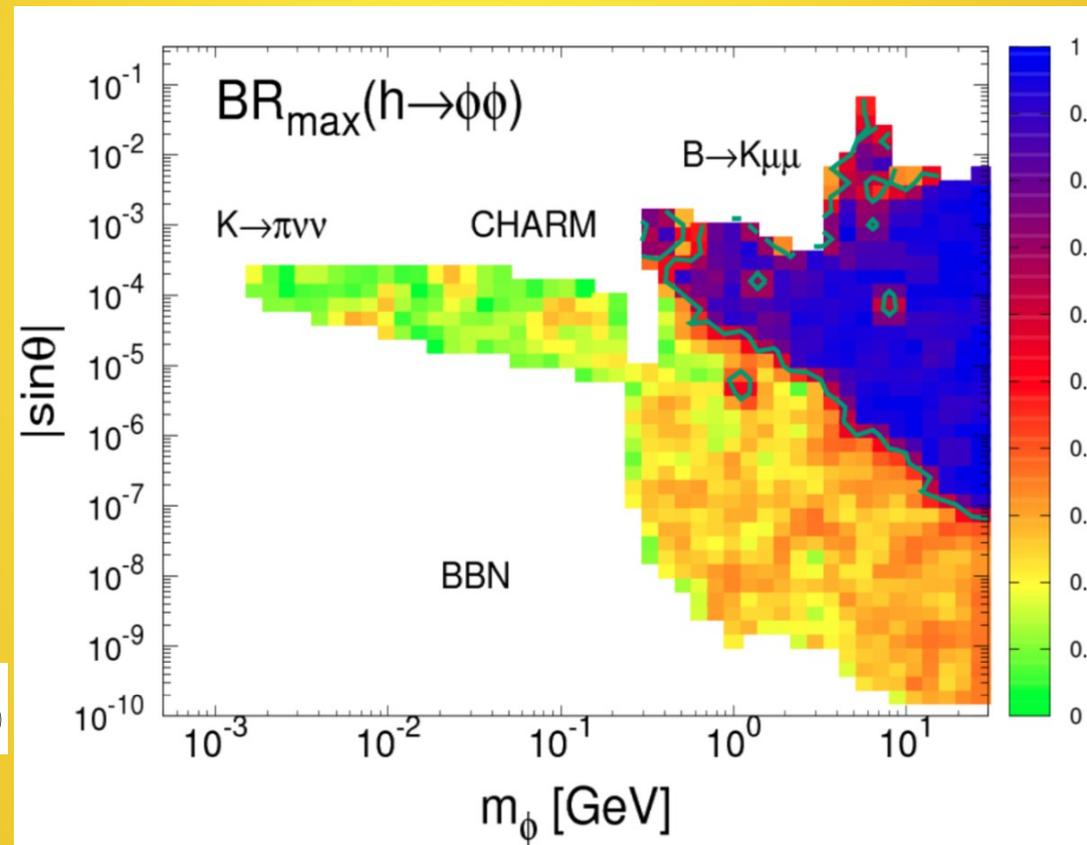
ILC v.s Light WIMP with scalar mediator

- Current experimental constraints for light mediator

$$C_{\phi\phi h} \simeq \frac{2(m_\phi^2 - \mu_\phi^2)}{v_H}$$

$$\Gamma(h \rightarrow \phi\phi) \simeq \frac{C_{\phi\phi h}^2}{32\pi m_h}$$

$$\Delta\text{BR}(h_{125} \rightarrow \text{invisible}) \lesssim 0.44\%$$



H. Baer et. al., ILC:
1306.6352

S. Matsumoto, Y.L. Sming Tsai, P.Y. Tseng