FCC week, Washington DC, March 23-27, 2015

H selfcouplings, vector-boson scattering at high mass, high energy probes of EWSB

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Outline

- Higgs Effective Field Theory
- H self-coupling
- High energy scattering/High energy probe of EWSB
- BSM at high Mass/Energy & Exclusive analysis

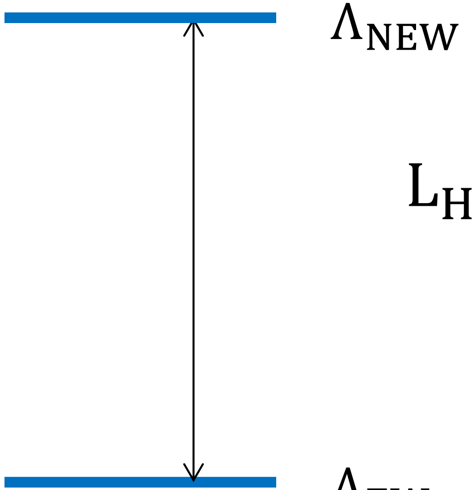
Higgs Effective Field Theory (HEFT)

: Model Independent Approach

We first need to

define a framework to study Higgs properties, BSM etc.

Assumption: Separation of scale



$$\mathrm{L}_{\mathrm{HEFT}} = \mathrm{L}_{\mathrm{pheno.}} + \text{Higgs d.o.f.}$$

: Systematic derivative and h expansions

Basis in the unitary gauge

Adding spin-0, custodial singlet Higgs field in $SU(2) \times U(1)$ invariant way

- Higgs is not necessarily $SU(2)$ doublet (more generic)
- Coefficients in 0H, 1H, 2H etc are not necessarily related
- It can accommodate large deviations of couplings, e.g. HHH
- Derivative expansion

$$L = \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots \right)$$

$$- \mathrm{m_t} \bar{t}_L \mathrm{t_R} \left(1 + c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} + \cdots \right) + h.c. + \text{other fermions}$$

$$- \frac{\alpha_s}{\pi} \left(c_g \frac{h}{v} + \frac{c_{2g}}{2} \frac{h^2}{v^2} \right) G_{\mu\nu}^a \mathrm{G}^{a\mu\nu}$$

$$+ \frac{1}{2} \left(\partial_\mu h \right)^2 - \frac{1}{2} m_h^2 h^2 - c_3 \frac{1}{6} \left(\frac{3\, m_h^2}{v} \right) h^3 - d_4 \frac{1}{24} \left(\frac{3\, m_h^2}{v^2} \right) h^4 + \cdots$$

Higgs doublet basis

- Assume that we are in the vicinity of SM point
  : very special since theory stays weakly-coupled up to very high scales
- Expand in terms of Higgs doublet in addition to derivative expansion

$$H = e^{i\pi/v}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$L = L_{SM} + \Delta L_6 + \Delta L_8 + \cdots$$

$$\Delta L_6 \ni \frac{\bar{c}_H}{2v^2}\,\partial_\mu |H|^2 \partial^\mu |H|^2 + \frac{\bar{c}_u}{v^2} y_u \bar{q}_L H u_R |H|^2 - \frac{\bar{c}_6}{v^2}\frac{m_h^2}{2v^2}|H|^6 + \frac{\bar{c}_g g_s^2}{m_W^2}|H|^2 G_{\mu\nu}G^{\mu\nu}$$

- Matches to ``basis in the unitary gauge'' up to resuming over Higgs powers and expanding in terms of *h*
- Higgs couplings in the previous slide are correlated,
  e.g. at the level of dim-6 ops.

$$c_t = 1 - \frac{1}{2}\bar{c}_H - \bar{c}_u\,, \quad c_{2t} = 0 - \frac{1}{2}\bar{c}_H - \frac{3}{2}\bar{c}_u\,, \quad c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H, \quad c_g = c_{2g} = \bar{c}_g\left(\frac{4\pi}{\alpha_2}\right)$$

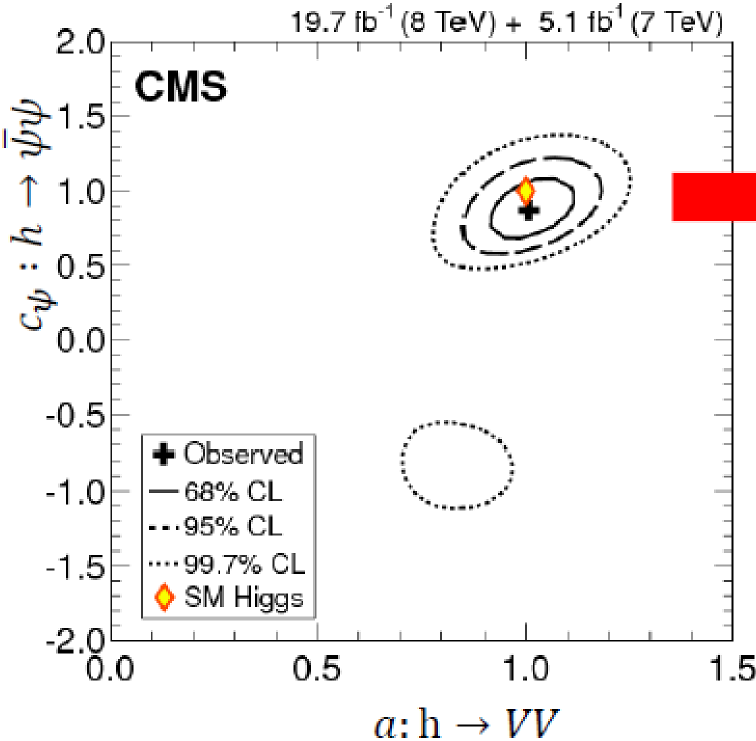
Higgs doublet basis

- Assume th
  : very spec
- Expand in t

$$L = L_{SM} + \Delta$$

$$\Delta L_6 \ni \frac{\bar{c}_H}{2v}$$

[CMS-HIG-14-009](CMS-HIG-14-009)



$\delta c_i \leq O(20 - 30\%)$

Data favor SM point

- Matches to basis in the unitary gauge up to resuming over Higgs powers and expanding in terms of *h*
- Higgs couplings in the previous slide are correlated,
  e.g. at the level of dim-6 ops.

$$c_t = 1 - \frac{1}{2}\bar{c}_H - \bar{c}_u\,, \quad c_{2t} = 0 - \frac{1}{2}\bar{c}_H - \frac{3}{2}\bar{c}_u\,, \quad c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H, \quad c_g = c_{2g} = \bar{c}_g\left(\frac{4\pi}{\alpha_2}\right)$$

Power counting/NDA rules

NDA sizes of coefficients depend on assumptions on the nature of Higgs sector

- SILH Based on strongly coupled dyn.
  with one coupling g_* and one scale m_*
  Higgs is strongly coupled pGB

  Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

$$\frac{\Delta c_{V,\psi}}{c_{SM}} \sim \frac{\Delta\lambda_{HHH}}{\lambda_{HHH}^{SM}} \sim O\left(\frac{g_*^2 v^2}{m_*^2}\right)$$

HHH is not measured by single Higgs data. Is it reasonable to imagine O(1) deviation of HHH without screwing up single Higgs fit ?

→ Modify power counting rules

- Non pGB Higgs
- Higgs portal e.g $\lambda|H|^2 O$

$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}^{SM}} \gg \frac{\Delta c_{V,\psi}}{c_{SM}}$$

can be realized

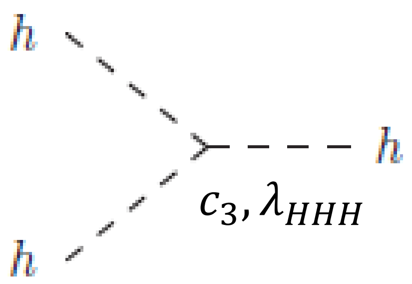
How power counting would go in SUSY?

- SUSY Weakly coupled dyn.
  In a certain decoupling setup

$$\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} \sim O\left(\frac{g_{weak}^2 v^2}{m_s^2}\right) + \text{Non-decoupling effects}$$

Important to keep broad approaches
to cover all possibilities in future searches

H self coupling



$$\frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3\,m_h^2}{v}\right) h^3 - d_4 \frac{1}{24}\left(\frac{3\,m_h^2}{v^2}\right) h^4 + \cdots$$

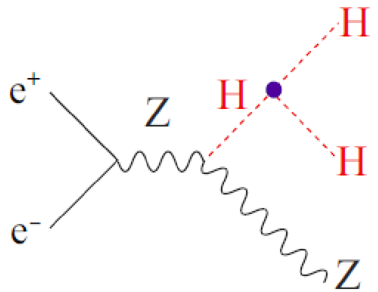
HHH is not accessible yet and it carries crucial information of Higgs/EWSB sector

- ✓ However, measuring HHH is extremely challenging even at HL LHC
- ✓ We will definitely need $\mathrm{FCC}_{@100\mathrm{TeV}}$ or ILC/CLIC to reach O(5-10%)-level precision

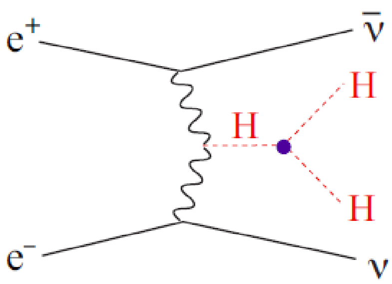
Relevant processes for HHH coupling

e^+e^- colliders

Double Higgs-strahlung

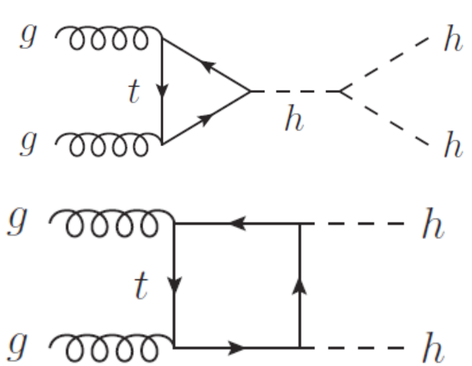


HH via VBF

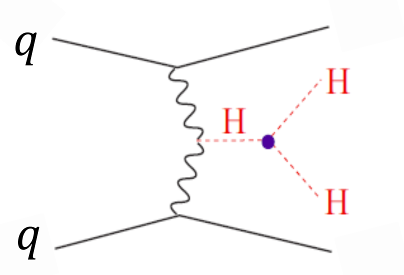


pp colliders

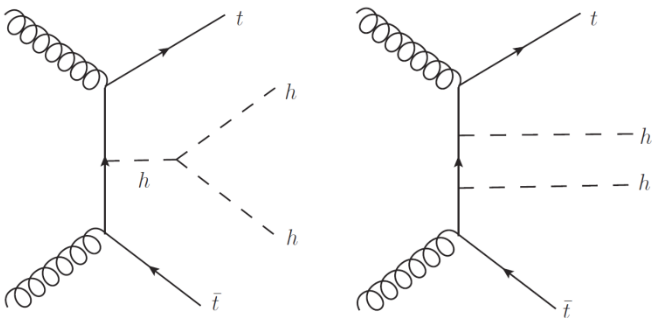
HH via Gluon Fusion



HH via VBF



ttHH



Literatures on HHH coupling at HL LHC

HH via Gluon Fusion

$hh \to b\bar{b}\gamma\gamma$

Baur, Plehn, Rainwater PRD 69 (2004) 053004
Baglio et al. JHEP 1304 (2013) 151
Yao arXiv:1308.6302
Barger et al. PLB 728 (2014) 433
ATLAS ATL-PHYS-PUB-2014-019
Barr et al. arXiv:1412.7154
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Papaefstathiou, Yang, Zurita PRD 87 (2013) 011301

$hh \to b\bar{b}b\bar{b}$

De Lima, Papaefstathiou, Spannowsky arXiv:1404.7139

VBF HH

$hh \to b\bar{b}\tau\tau$

Dolan, Englert, Creiner, Spannowsky PRL 112 (2014)101802

$hh \to b\bar{b}WW$

Les Houches 2013 arXiv:1405.1617

$hh \to b\bar{b}b\bar{b}$

Les Houches 2013 arXiv:1405.1617

ttHH

Englert, Krauss,
Spannowsky, Thompson PLB 743 (2015) 93
Liu, Zhang arXiv:1410.1855

Sorry if I missed your paper

Status on HHH coupling at HL LHC

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ttHH

Englert, Krauss,
Spannowsky, Thompson PLB 743 (2015) 93
Liu, Zhang arXiv:1410.1855

- ✓ More rare process
- ✓ Might be complementary to gluon fusion process
- ✓ Many works in progress

Sorry if I missed your paper

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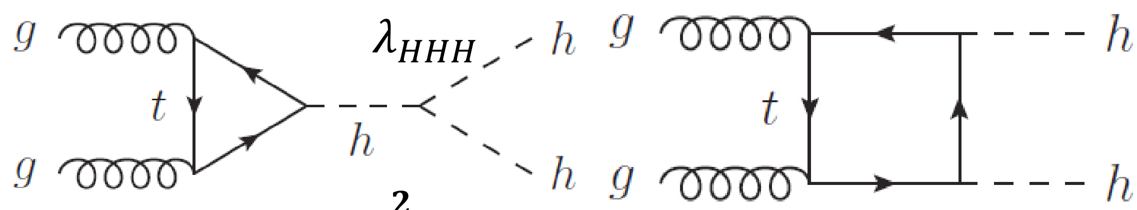

$$\sim \frac{m_h^2}{s}$$

- ✓ HHH is sensitive only to the kinematics around threshold energy where most backgrounds are populated
- ✓ Large negative interference between two diagrams making the situation worse
- ✓ Playing with kinematics at high energy or high invariant mass does not help
- ✓ Resolving finite top loop is important

Status on HHH coupling at HL LHC

Hard to tell which channel is the best…

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$hh \to b\bar{b}\tau\tau$

Higher rate, promising? Requires further detailed study

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Dolan, Englert, Spannowsky JHEP 1210 (2012) 112
Baglio et al. JHEP 1304 (2013) 151
Barr, Dolan, Englert, Spannowsky PLB 728 (2014) 308
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$hh \to b\bar{b}WW$

Looks like ttbar backgrounds

Dolan, Englert, Spannowsky JHEP 1210 (2012) 112
Baglio et al. JHEP 1304 (2013) 151
Papaefstathiou, Yang, Zurita PRD 87 (2013) 011301

$hh \to b\bar{b}b\bar{b}$

Highest rate, but Huge QCD backgrounds

De Lima, Papaefstathiou, Spannowsky arXiv:1404.7139

Status on HHH coupling at HL LHC

HH via Gluon Fusion

$hh \to b\bar{b}\gamma\gamma$ **Cleanest but small rate**

Baur, Plehn, Rainwater PRD 69 (2004) 053004
Baglio et al. JHEP 1304 (2013) 151
Yao arXiv:1308.6302
Barger et al. PLB 728 (2014) 433
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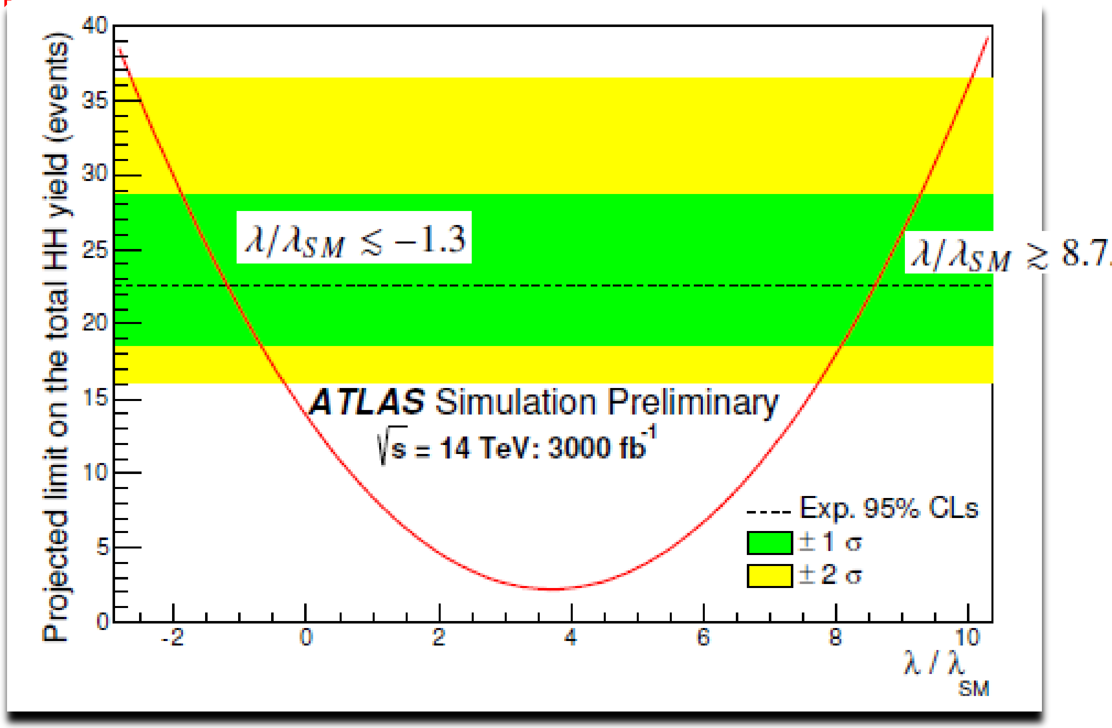
Azatov, Contino, Panico, Son arXiv:1502.00539

So far, the only channel studied by experimentalists



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This channel is the cleanest & significant of progress are done recently, many on-going studies including recent ATLAS study

Most results from old studies were too optimistic for the following reasons

Status on HHH coupling at HL LHC

HL LHC 3/ab

ATL-PHYS-PUB-2014-019

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Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$bbjj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4

✓ Fake rates are big, especially $\epsilon_{c\to b}$ and $\epsilon_{j\to\gamma}$

Status on HHH coupling at HL LHC

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- ✓ Fake rates are big, especially $\epsilon_{c\to b}$ and $\epsilon_{j\to\gamma}$
- ✓ $b\bar{b}\gamma\gamma$ is subject to large NLO k-factor, $k_{b\bar{b}\gamma\gamma} \sim 2$

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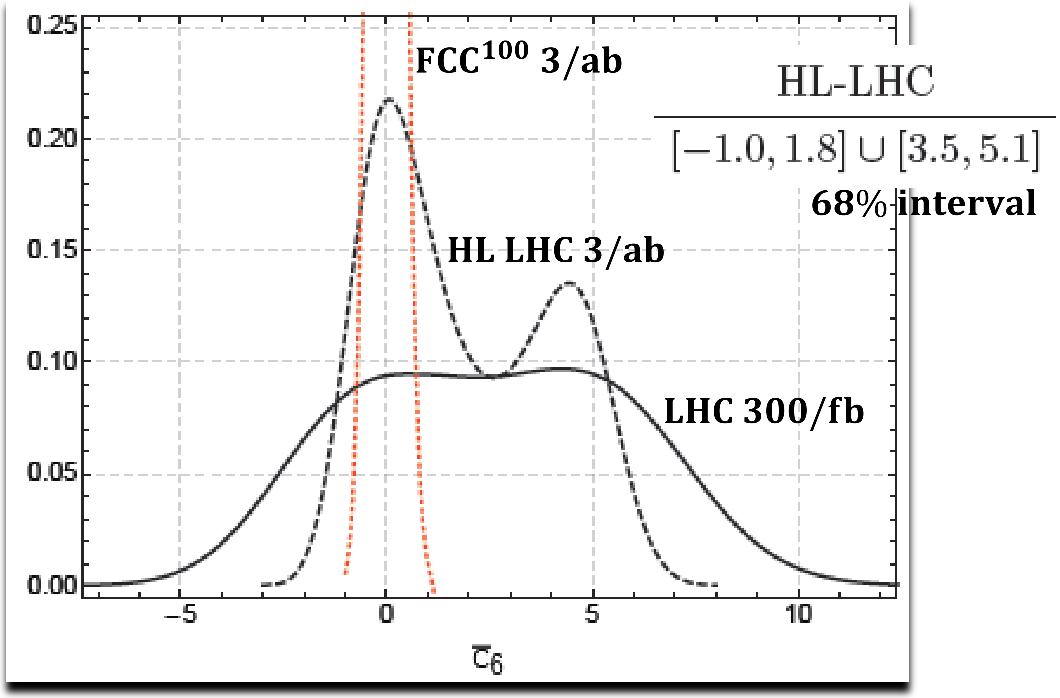

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- ✓ $b\bar{b}\gamma\gamma$ is subject to large NLO k-factor, $k_{b\bar{b}\gamma\gamma} \sim 2$
- ✓ Simple linear parameterization of $\frac{d\sigma}{d\lambda_{HHH}}$ at HL LHC fails due to 2nd solution

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- ✓ Simple linear parameterization of $\frac{d\sigma}{d\lambda_{HHH}}$ at HL LHC fails due to 2nd solution
- ✓ Precision on HHH coupling depends on statistical treatment (uncertainty on top Yukawa is correlated with precision of HHH coupling)

Precision at FCC @100TeV

summary from FCC meeting at CERN (Mar. 11-13)

http://indico.cern.ch/event/352868/

$hh \to b\bar{b}\gamma\gamma$

Barr, Dolan, Englert, Lima, M.Spannowsky JHEP 1502 (2015) 016
R. Contino, A. Azatov, G. Panico, M. Son arXiv:1502.00539
H. He, J. Ren, W. Yao Work in progress

~~Cleanest but small rate~~

Clean & enough statistics

- ✓ Unlike at 14TeV, $b\bar{b}\gamma\gamma$ channel at $\mathrm{FCC}_{@100\mathrm{TeV}}$ has enough statistics due to $\sim 40\times$ enhanced cross section. It might be a golden channel.
- ✓ Other channels (both rare and not-rare) are under study

See talk by A. Papaefstathiou at FCC meeting

Precision at FCC @100TeV

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$HH \to b\bar{b}\gamma\gamma$	Barr, Dolan, Englert, Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren, Yao (follow-up of Snowmass study)
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 3/ab	30~40%	30%	15%
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet $/W_{had}$ veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV
Comments	1. Need correct values of fake-rates. What fake-rates would be acceptable? 2. Need better understanding of $m_{bb}, m_{\gamma\gamma}$ resolutions to optimize mass windows. What would be experimental limit? 3. Precision from single Higgs fit is important for HHH, e.g. Top Yukawa coupling		

Precision at FCC @100TeV

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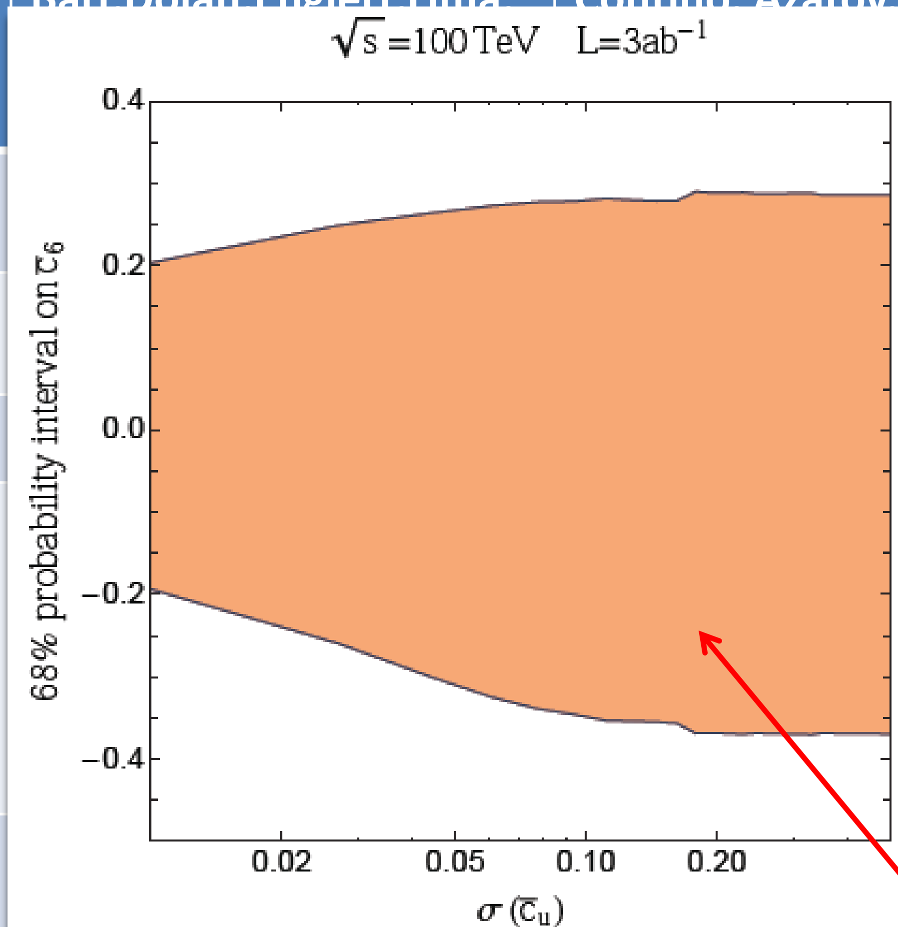
$HH \to b\bar{b}\gamma\gamma$	Barr Dolan Englert Lima	Contino, Azatov ... 9	He, Ren, Yao (follow-up of Snowmass study)
$FCC_{@100TeV}$ 3/ab			15%
$FCC_{@100TeV}$ 30/ab			5%
$S/\sqrt{B}$			16.5
Details		...ch ... γ ... GeV	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV
Comments	...ates would be acceptable? ...tions to optimize mass windows. What would be experimental limit? 3. Precision from single Higgs fit is important for HHH, e.g. Top Yukawa coupling		



Precision at FCC @100TeV

summary from FCC meeting at CERN (Mar. 11-13)

There is a hope to achieve 5%-level precision with 30/ab, but three issues need to be clarified

- Clarifying differences among various analyses
- Quantifying theory uncertainty

  PDF uncertainty
  k-factor with full top loop
  MC for signal and bkg. modeling

- Detector performance/requirement

  Any improvements on
  - Photon/bjet Et resolution (e.g. mass resolution)
  - heavy flavor tagging (b, c-tagging) vs mistag
  - Efficiencies for object reconstruction

  are crucial to achieve our goal

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are crucial to achieve our goal

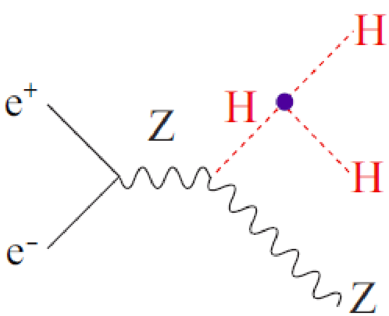
Importance of these items is under study by WG

Precision at e^+e^- colliders

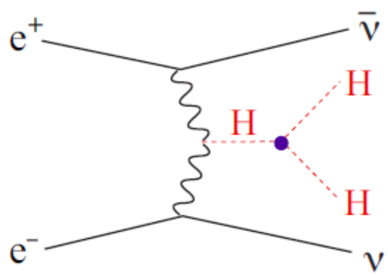
Three important thresholds

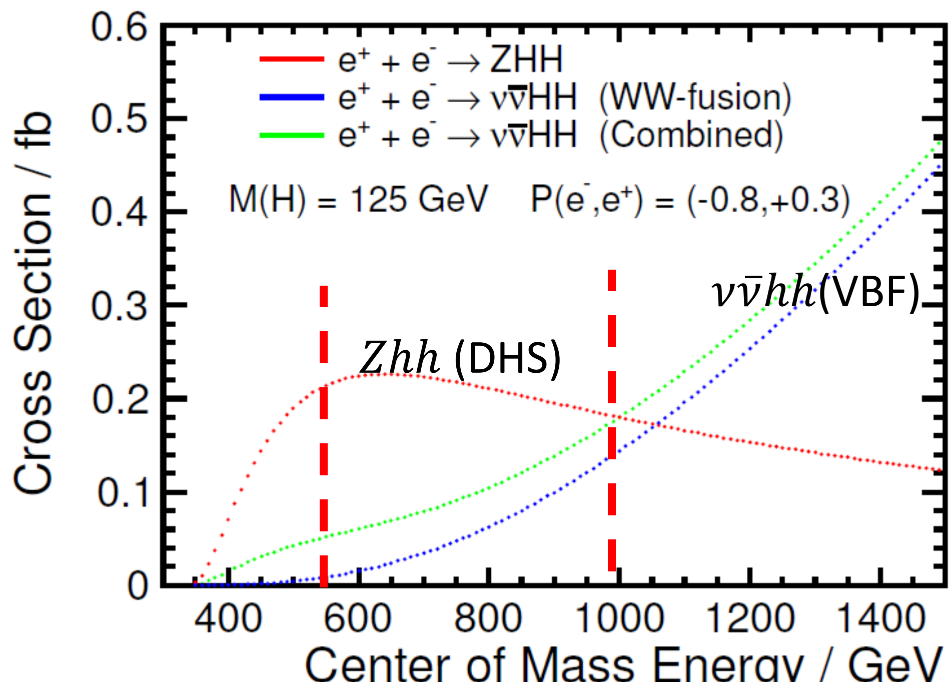
~250 GeV	~350 GeV	~ 500 GeV	~ 1 TeV	**Center of Mass Energy**
Zh	$t\bar{t}$	Zhh(DHS)	VBF at 1 TeV improves HHH coupling by combining with Zhh	
		HHH opens up!		
		Top Yukawa via $t\bar{t}h$		

Double Higgs-strahlung (DHS)



VBF HH production





Tian, Fujii 1311.6528, ILC TDR

Precision at e^+e^- colliders

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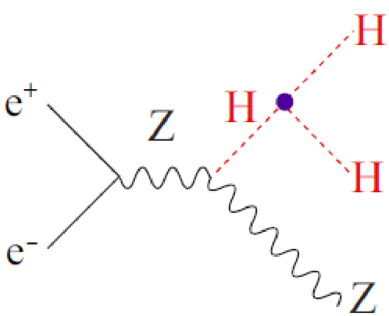


HH via VBF$^{@1\mathrm{TeV}}$ 1/ab can achieve precision of ~ 28%

DHS$^{@\mathrm{threshold}}$ gives ~ O(1) determination of λ_{HHH}

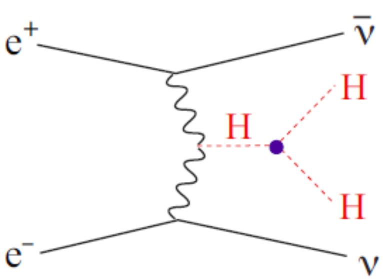
See ILC TDR for details

DHS alone at ILC gives only O(1) determination of HHH

e.g. ~ 70% at 500 GeV/1TeV

Contino, Grojean, Pappadopulo, Rattazzi, Thamm 1309.7038

VBF HH production



Better determination of HHH at CLIC, 3TeV via VBF

e.g. ~ 20% for unpolarized, 12% for polarized with 2/ab

Snowmass 1307.5288

Contino, Grojean, Pappadopulo, Rattazzi, Thamm 1309.7038

High energy scattering & High Energy probe of EWSB

- ✓ Another powerful benefit from FCC lies on the huge enhancement of cross sections at the tail of invariant mass

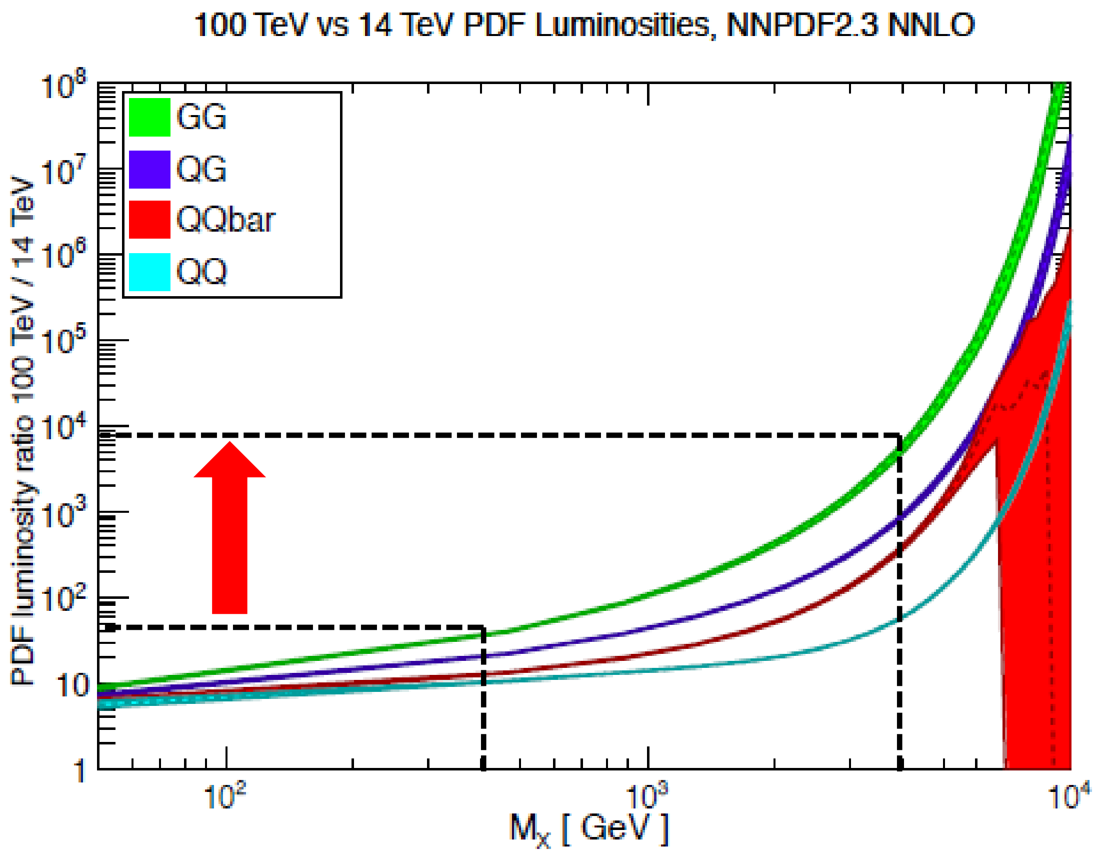
This is where BSM effects are the largest

$$\frac{\delta c}{c_{SM}} \sim \left(\frac{g_*}{g_{SM}}\right)^2 \frac{m_h^2}{m_*^2} \qquad \frac{\delta\sigma_{2\to 2}}{\sigma_{SM}} \sim \left(\frac{g_*}{g_{SM}}\right)^2 \frac{E^2}{m_*^2}$$

From on-shell Higgs process

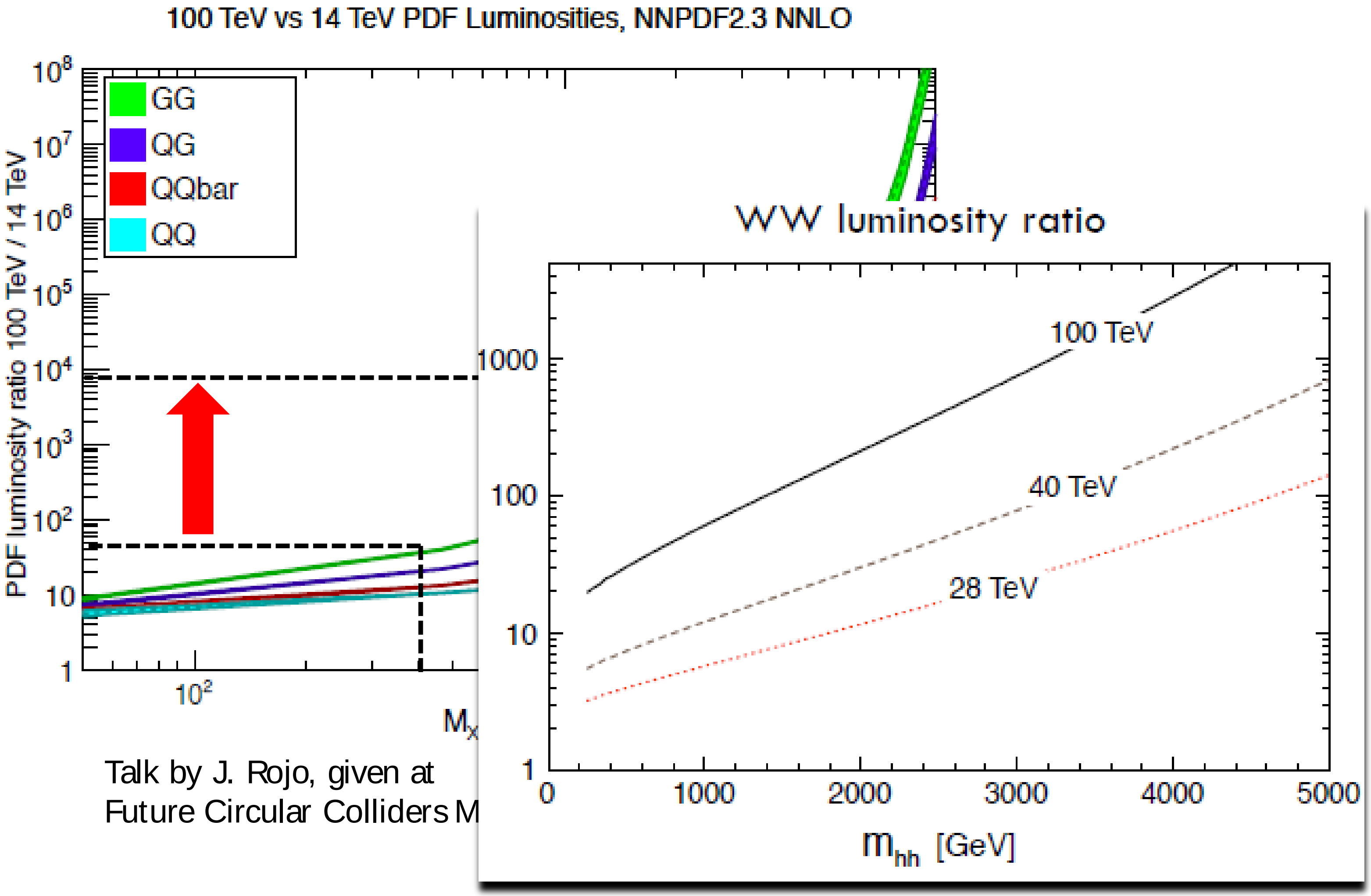
What is the capability of FCC to probe this region?

PDF luminosity ratio grows with the energy



Talk by J. Rojo, given at
Future Circular Colliders Meeting, CERN, 27.01.2014

PDF luminosity ratio grows with the energy



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R. Contino, talk given at
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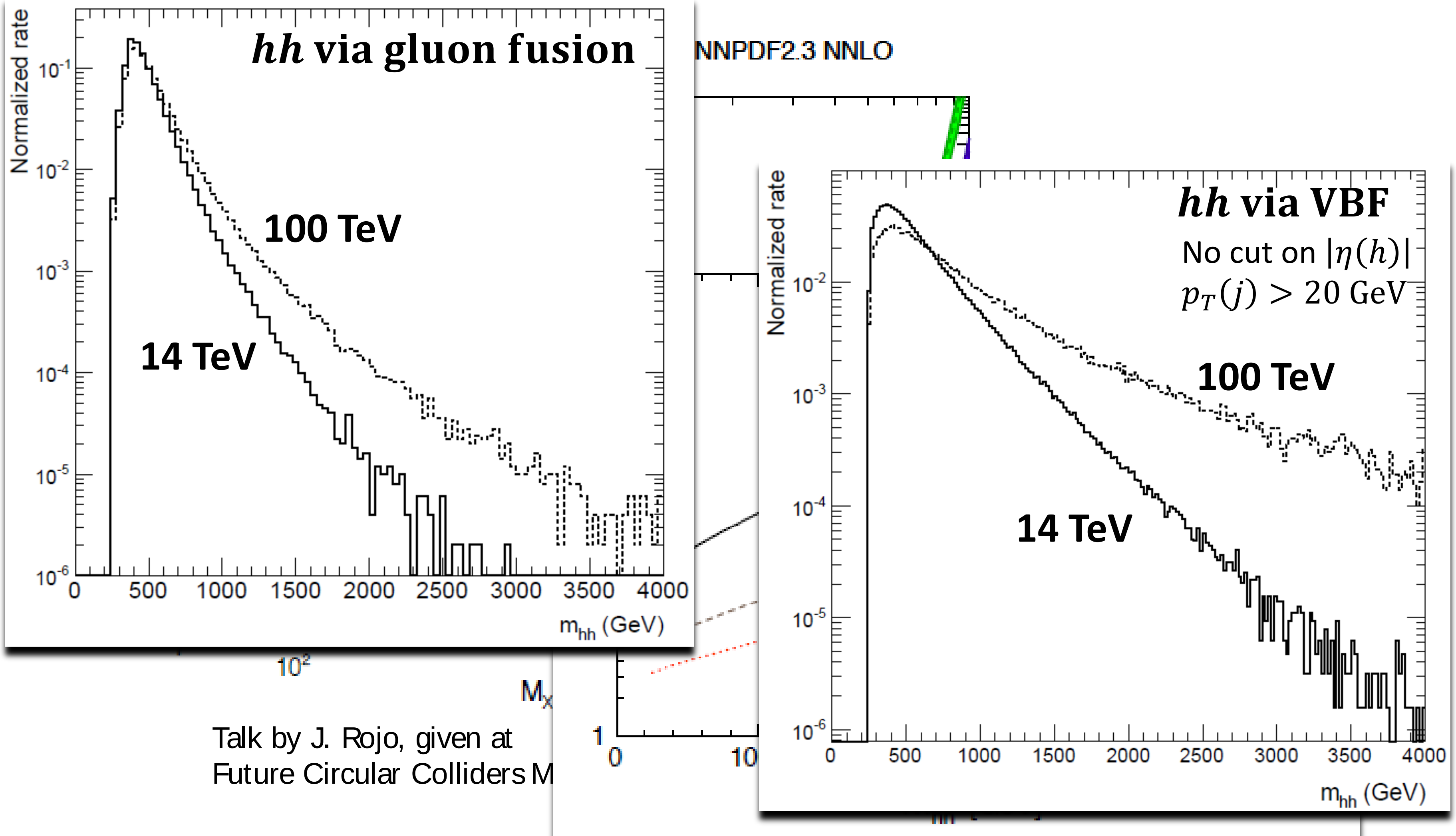

Talk by J. Rojo, given at
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R. Contino, talk given at
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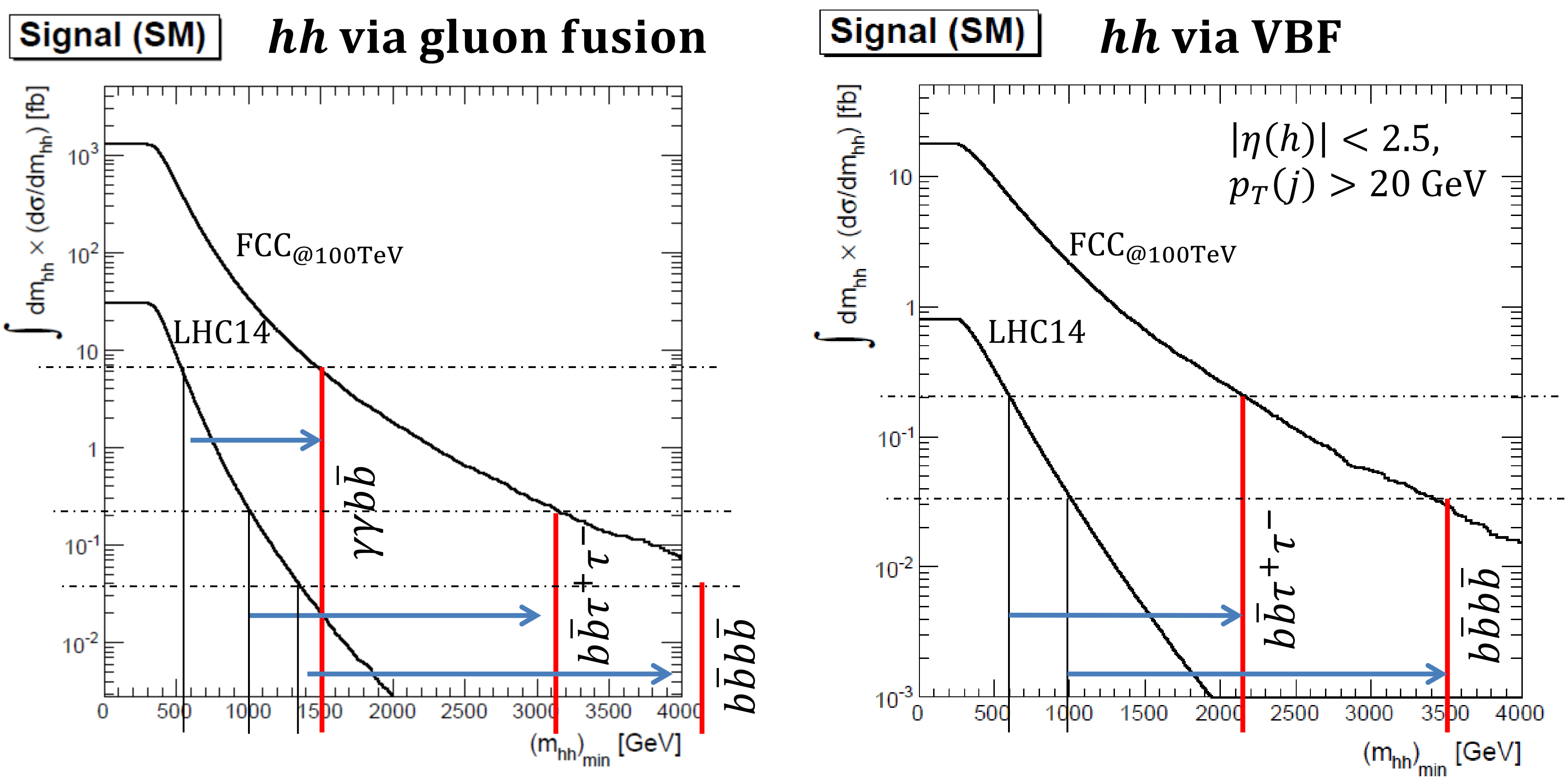
Capability of probing new physics scale



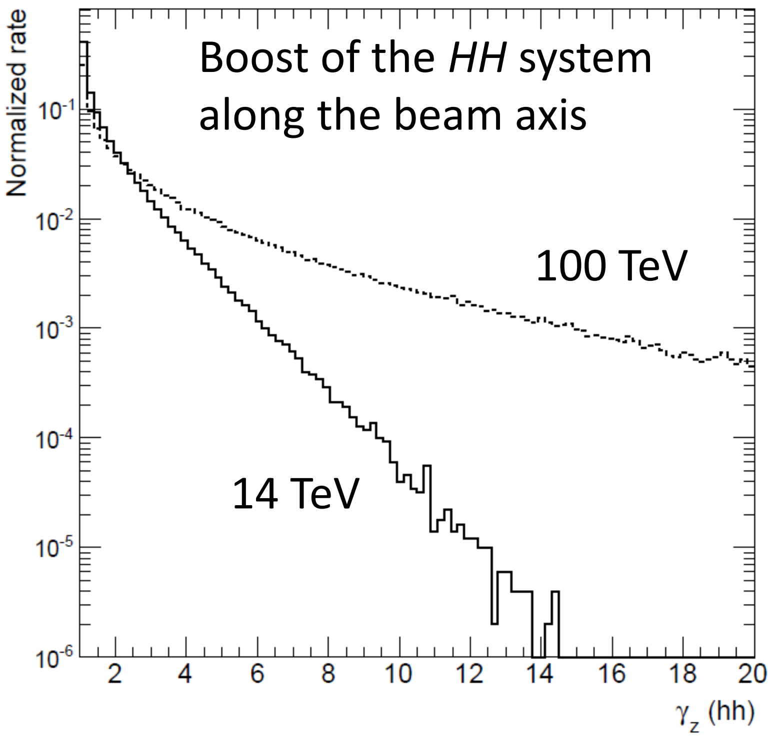
$$\sigma \geq \frac{5 \text{ Events}}{\text{BR}(hh \to X) \times \epsilon_S \times 3000\ \text{fb}^{-1}}$$

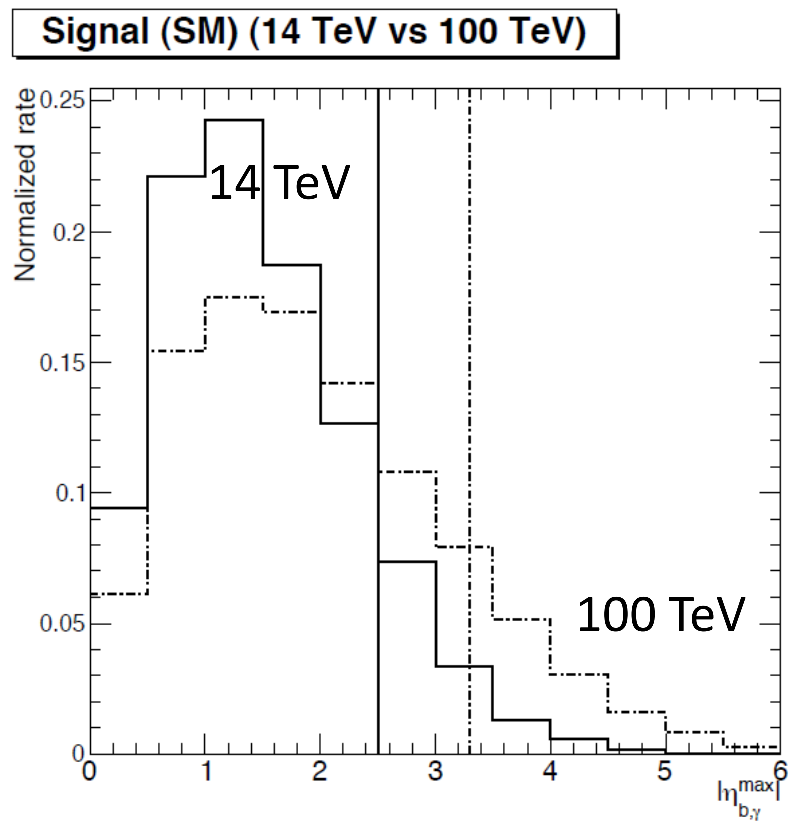
assuming 10 % signal efficiency

Detector requirement at $\mathrm{FCC}_{@100\mathrm{TeV}}$

We need larger coverage in $|\eta|$: gg $\rightarrow HH$

Large imbalance
in x_i, x_j in gluon PDF





~30% of signal events $|\eta| > 2.5$ (v.s. ~13% at the LHC)
Needs to extend to 3.3 to keep same fraction as the LHC

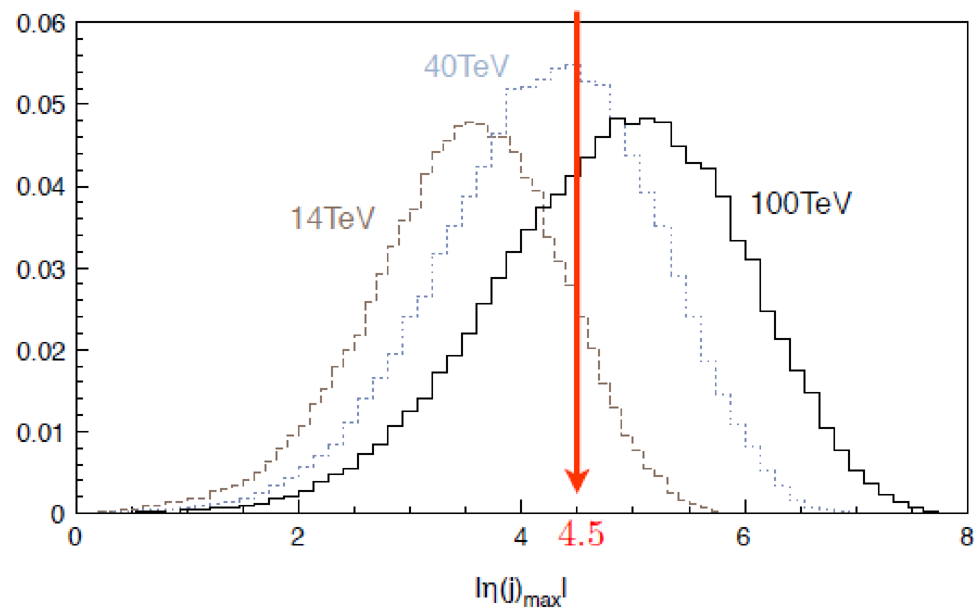
Detector requirement at $\mathrm{FCC}_{@100\mathrm{TeV}}$

We need larger coverage in $|\eta|$: $VV \rightarrow HH$

~67% of signal events at 100TeV has $|\eta(j)_{max}| > 4.5$

Tagging forward jets at 100 TeV

R. Contino, talk given at
1st Future Hadron Collider Workshop CERN,
May 26-28, 2014



Study of VBF at 100TeV requires a dedicated detector in the very forward region ($\eta \gtrsim 6$)

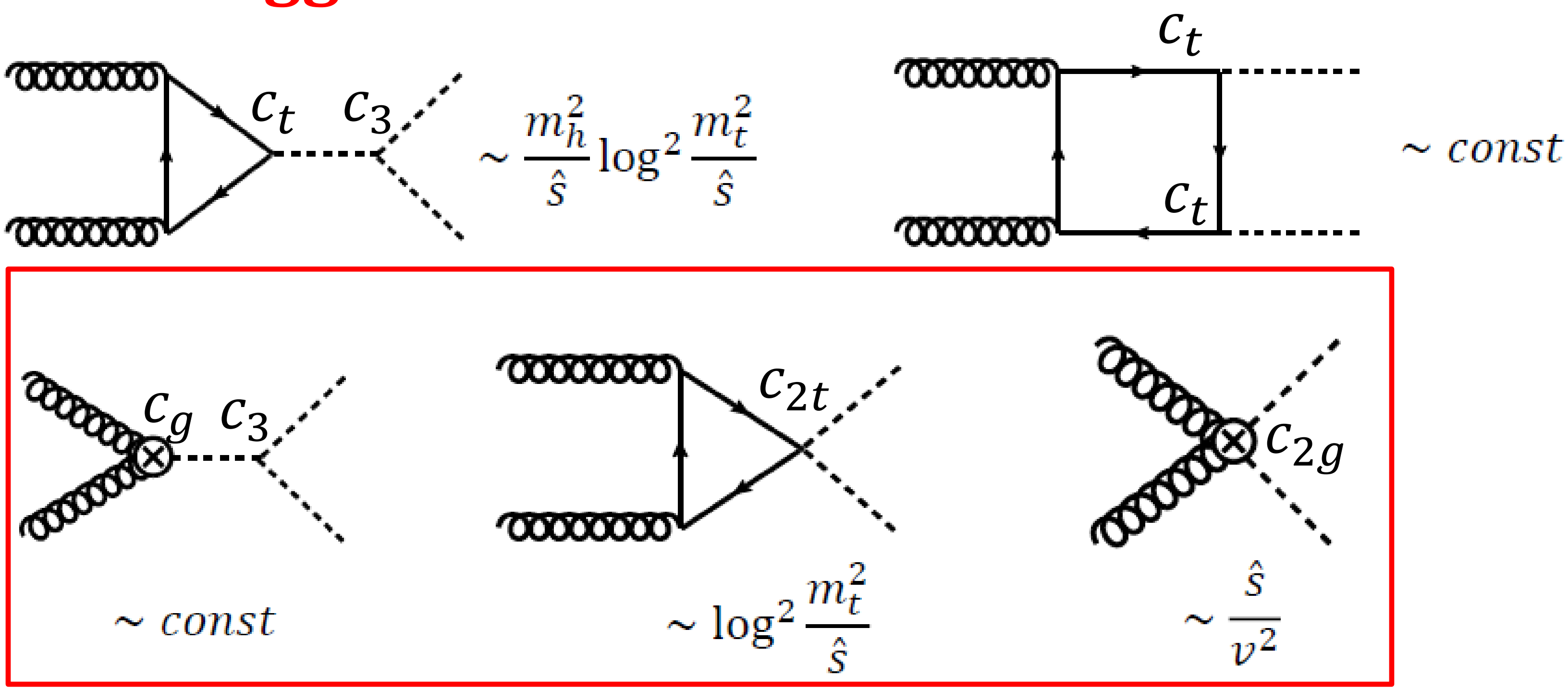
BSM at high Mass/Energy & Exclusive analysis

BSM effects are encoded in terms
with different energy-dependence in scattering amplitudes

➡ Exclusive analysis is required to break degeneracies among various BSM coefficients and to isolate various effects

How exclusive analysis helps us at $\mathrm{FCC}_{@100\mathrm{TeV}}$?

BSM via $\mathbf{gg \to hh}$

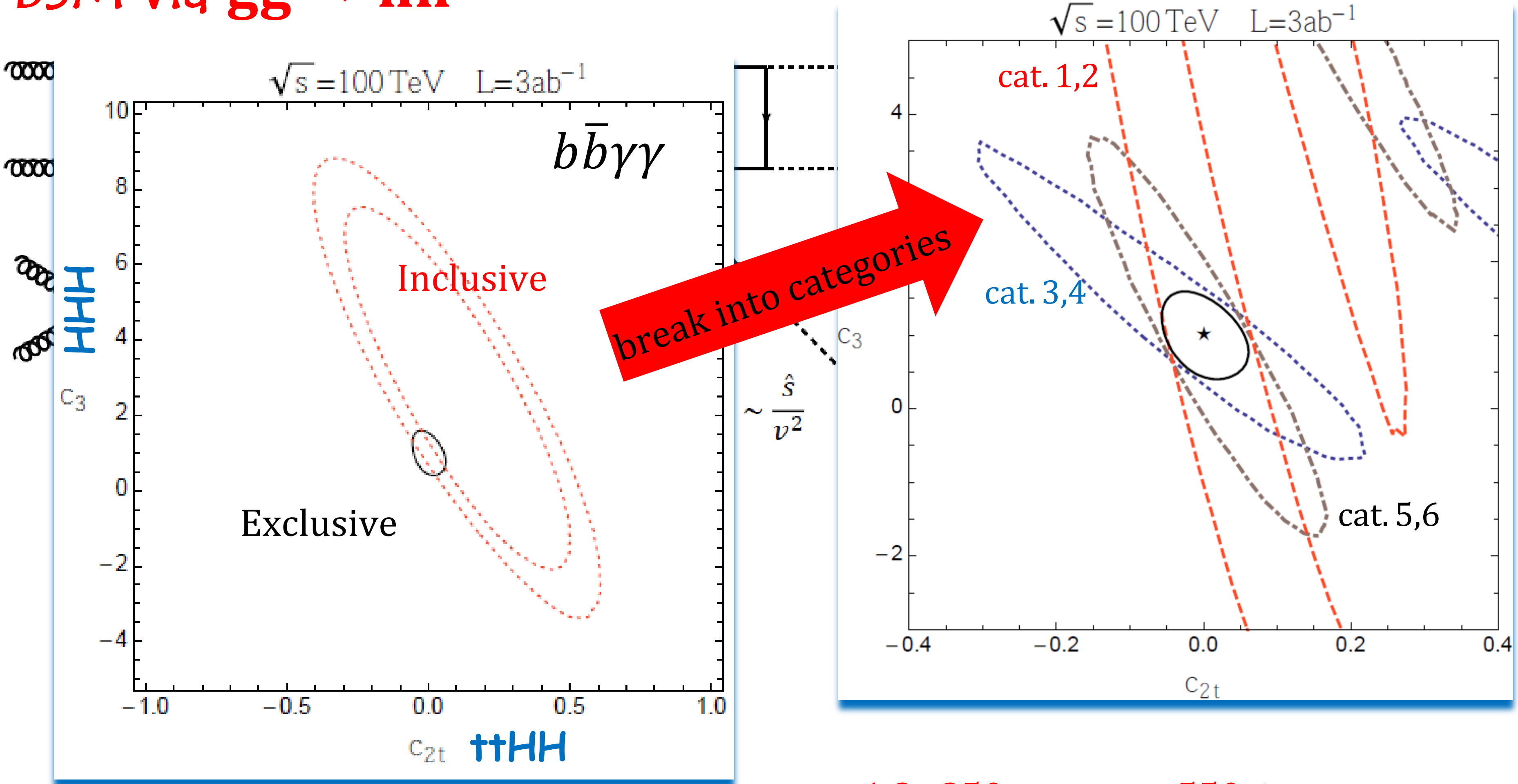


Azatov, Contino, Panico, Son arXiv:1502.00539

- More terms for generic BSM
- All diagrams have different energy-dependences
- m_{hh} is an important shape variable

How exclusive analysis helps us at $\mathrm{FCC}_{@100\mathrm{TeV}}$?

BSM via $gg \to hh$

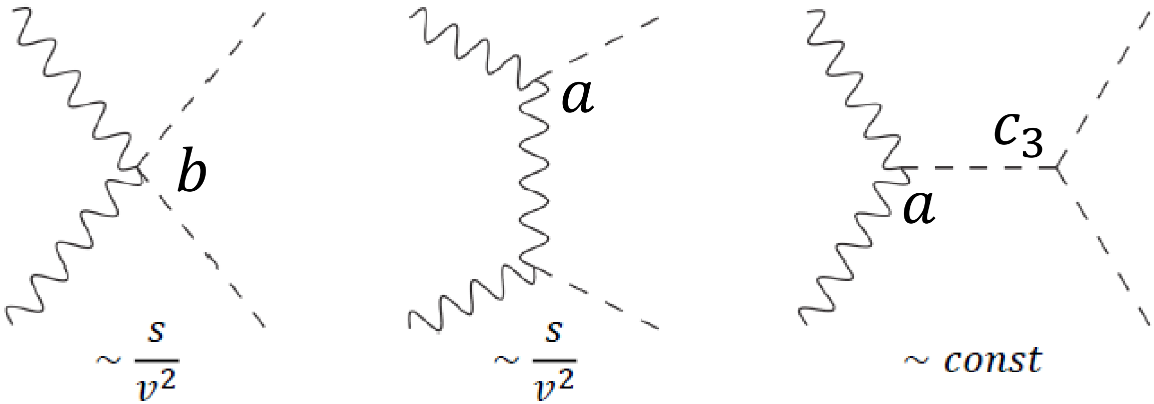


Azatov, Contino, Panico, Son arXiv:1502.00539

cat. 1,2: $250 < m_{hh} < 550$ GeV
cat. 3,4: $550 < m_{hh} < 850$ GeV
cat. 5,6: $850 < m_{hh}$

How exclusive analysis helps us at $\mathrm{FCC}_{@100\mathrm{TeV}}$?

BSM via VV→ **hh**



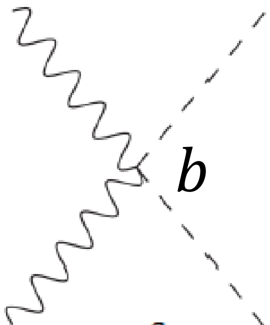
$$A(s) = \frac{s}{v^2}(b - a^2) + g^2 \frac{(4a^2 - 2b)m_W^2 + (3ac_3 - 2a^2)m_h^2}{4m_W^2} + \cdots$$

In BSM case ⟶ $\sim \frac{E^2}{v^2}(b - a^2)$

Contino, Grojean,Moretti,Piccinini,Rattazzi JHEP 1005 (2010) 089

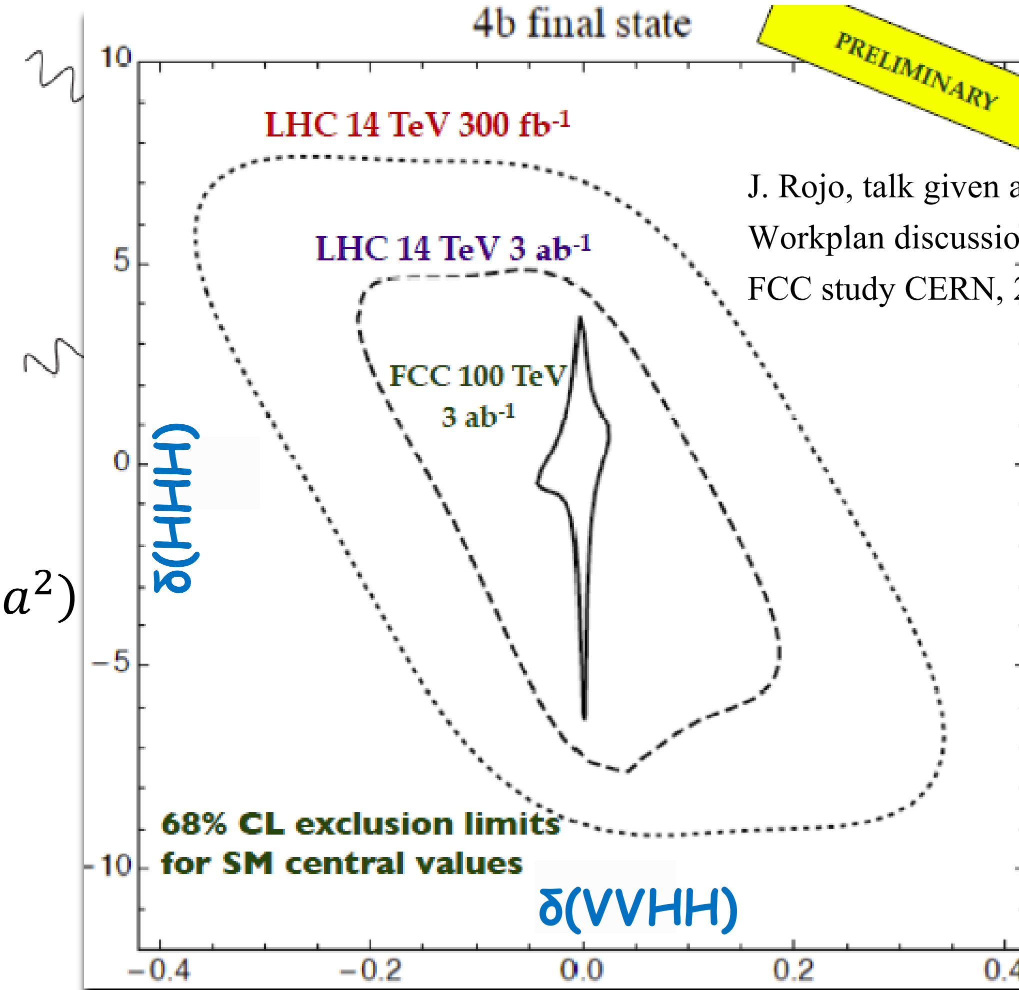
How exclusive analysis helps us at $\text{FCC}_{@100\text{TeV}}$?

BSM via VV→ **hh**



$\sim \frac{s}{v^2}$

$$A(s) = \frac{s}{v^2}(b - a^2)$$



J. Rojo, talk given at
Workplan discussion of Higgs and BSM WG of
FCC study CERN, 24/11/2014

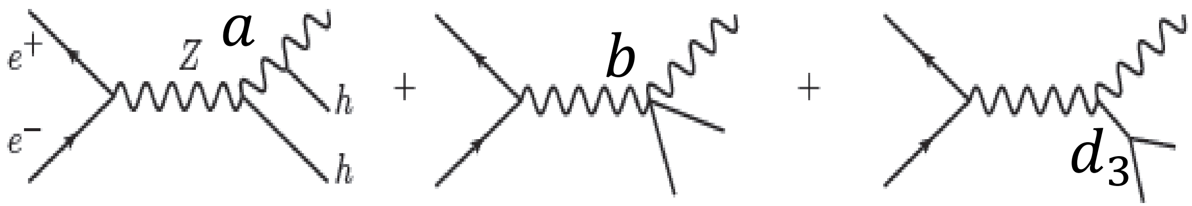
· ···

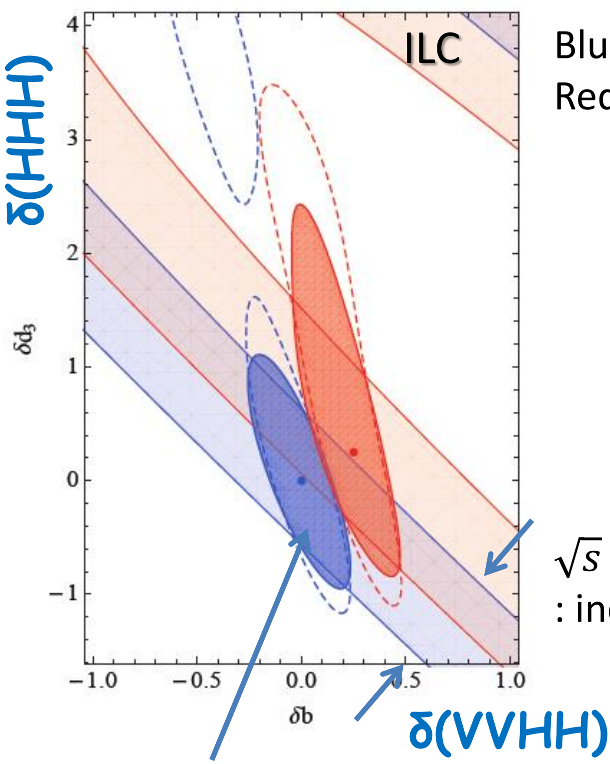
zi JHEP 1005 (2010) 089

How exclusive analysis helps us at ILC/CLIC ?

BSM via HH-strahlung

Contino, Grojean, Pappadopulo, Rattazzi, Thamm 1309.7038





Blue curves/region: Injecting SM
Red curves/region: Injecting BSM point

$\sqrt{s} = 500$ GeV
: inclusive

500 GeV && 1 TeV

How exclusive analysis helps us at ILC/CLIC ?

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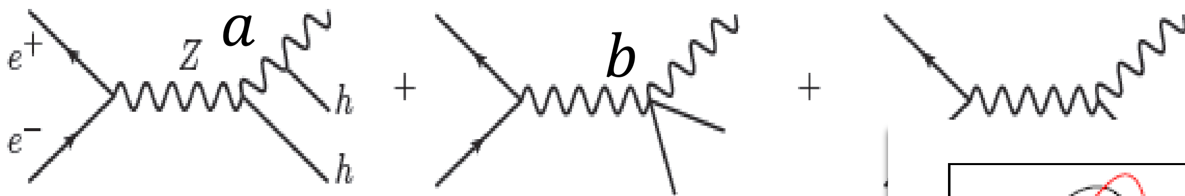
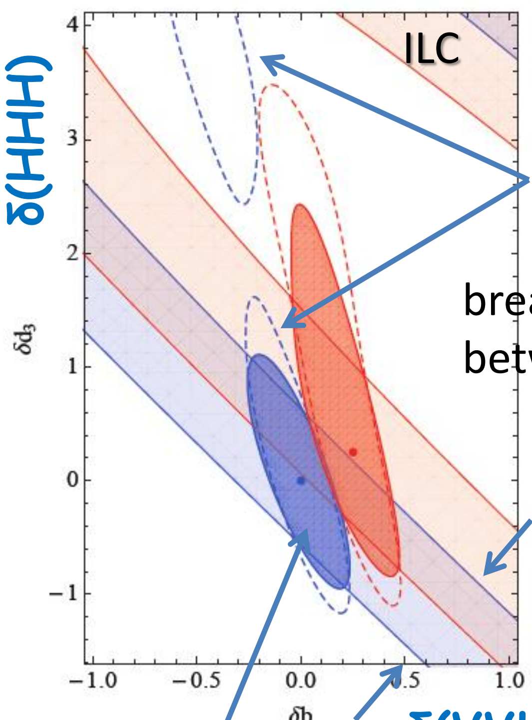




Blue curves/region: In

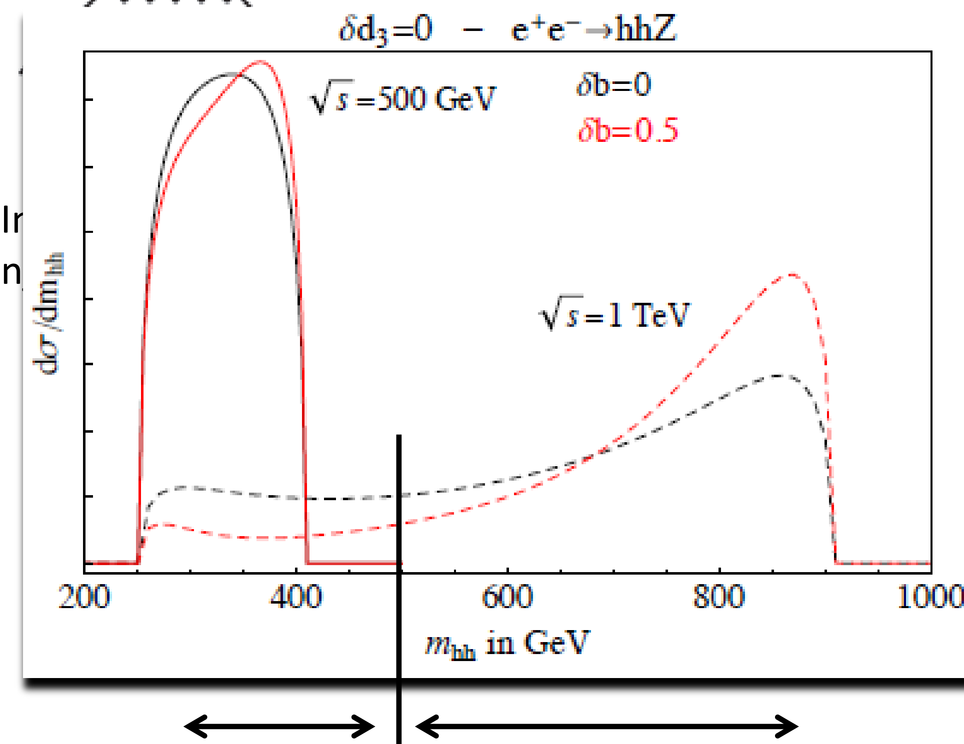
Red curves/region: In

$\sqrt{s} = 1$ TeV
: exclusive

breaks entanglement between δd_3 and δb

$\sqrt{s} = 500$ GeV
: inclusive

500 GeV && 1 TeV



I. $m_{hh} < 500$ GeV

II. $m_{hh} > 500$ GeV

Summary on H self-coupling

	HL LHC 3/ab	ILC/CLIC	FCC 100TeV
Precision on λ_{HHH}	$b\bar{b}\gamma\gamma$: poor, only $\sim O(1)$ determination Other channels: needs more detailed studies	ILC • DHS alone at 500 GeV and 1TeV gives only $\sim O(1)$ determination • ~28% via VBF at 1TeV, 1/ab CLIC at 3TeV, 2/ab • ~12% via VBF	$b\bar{b}\gamma\gamma$: golden channel. 5-10% determination might be possible with 30/ab. ~3x less sensitivity with 3/ab
Comments	Combining various channels might be important	The role of VBF is important High CM energy and high luminosity are crucial	Improvements on heavy flavor tagging, fakes, mass resolution etc are crucial to achieve our goal

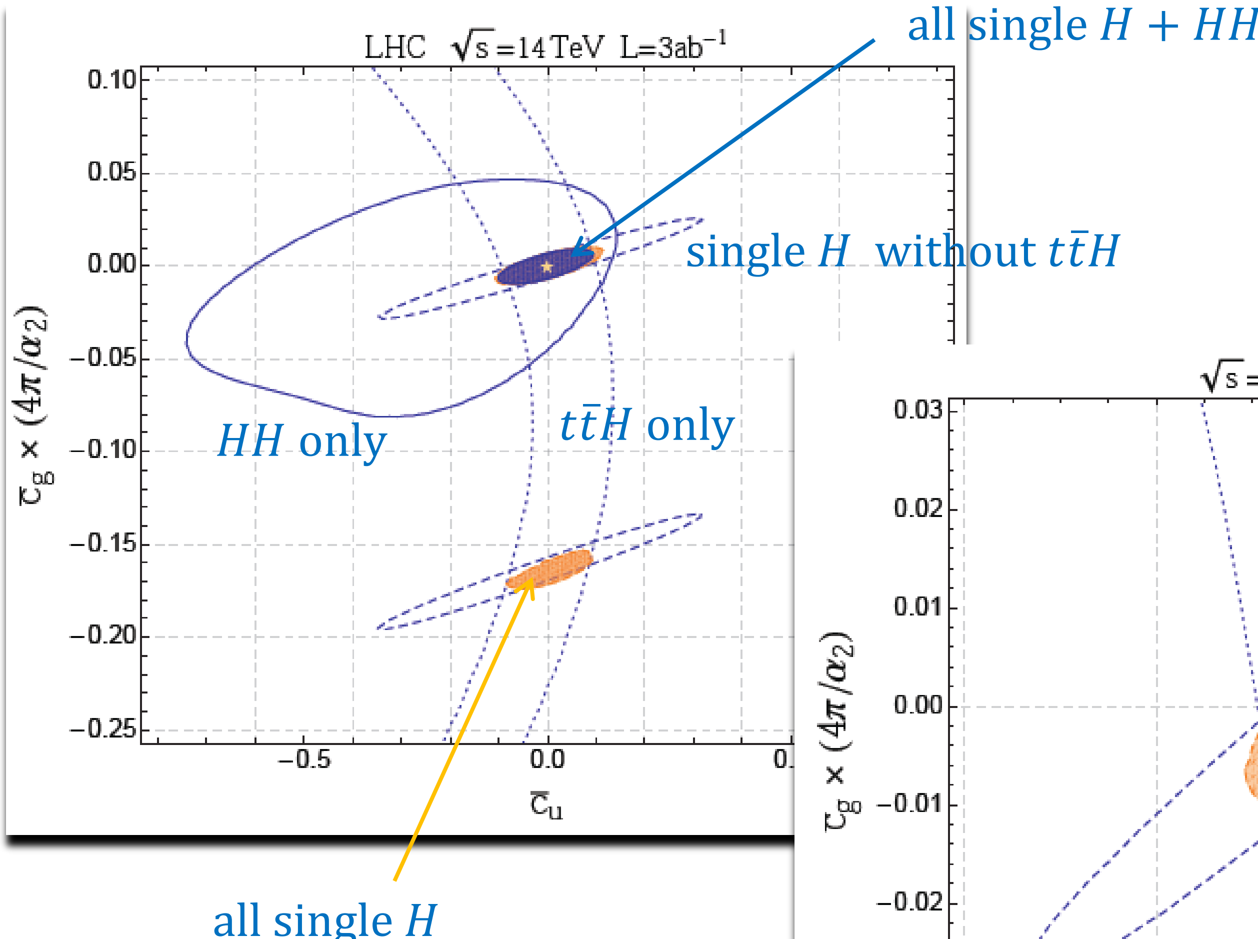
Summary on High energy scattering/probe of EWSB

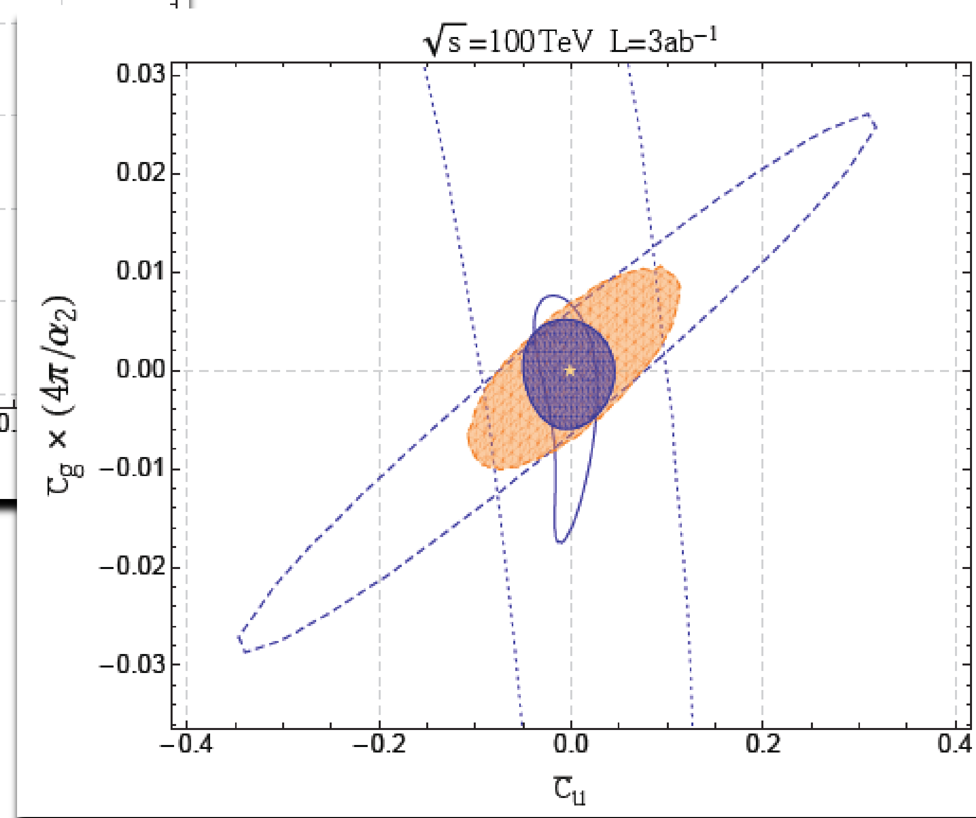
Benefits of FCC & Exclusive analysis	• **PDF luminosity ratio 100TeV/14TeV indicates a large enhancement of cross sections at the tail of invariant mass** • $\frac{\delta\sigma_{2\to 2}}{\sigma_{SM}} \sim \left(\frac{g_*^2}{g_{SM}^2}\right)\frac{E^2}{m_*^2} \quad \left(\text{v. s.} \frac{\delta c}{c_{SM}} \sim \left(\frac{g_*^2}{g_{SM}^2}\right)\frac{m_h^2}{m_*^2} \text{ from onshell process}\right)$ • **BSM effects appear in various E-dependent terms** • **Exclusive analysis is required to break “degeneracy” among various BSM coefficients**
Detector Issue	• More events leak into forward region due to the boost along the beam axis • Forward jets are more forward

Extra slides

More on BSM search via $gg \to hh \to b\bar{b}\gamma\gamma$

Azatov, Contino, Panico, Son arXiv:1502.00539





More work needed for better estimate at HL LHC

$hh \to b\bar{b}\tau\tau$

Baur, Plehn, Rainwater PRD 68 (2003) 033001
Dolan, Englert, Spannowsky JHEP 1210 (2012) 112
Baglio et al. JHEP 1304 (2013) 151
Barr, Dolan, Englert, Spannowsky PLB 728 (2014) 308
Goertz, Papaefstathiou, Yang, Zurita arXiv:1410.3471

- ✓ $bb\tau\tau$ could be promising, but need a better treatment of tau reconstruction and background estimates (including fakes).
  - ➢ Fully hadronic ditau might be very challenging due to large fakes.
  - ➢ Consider semileptonic ditau (there might be a good chance)

- ✓ Further improvement can be made by combining various channels just like single Higgs fit. e.g. $b\bar{b}\gamma\gamma + b\bar{b}\tau\tau +$ ...

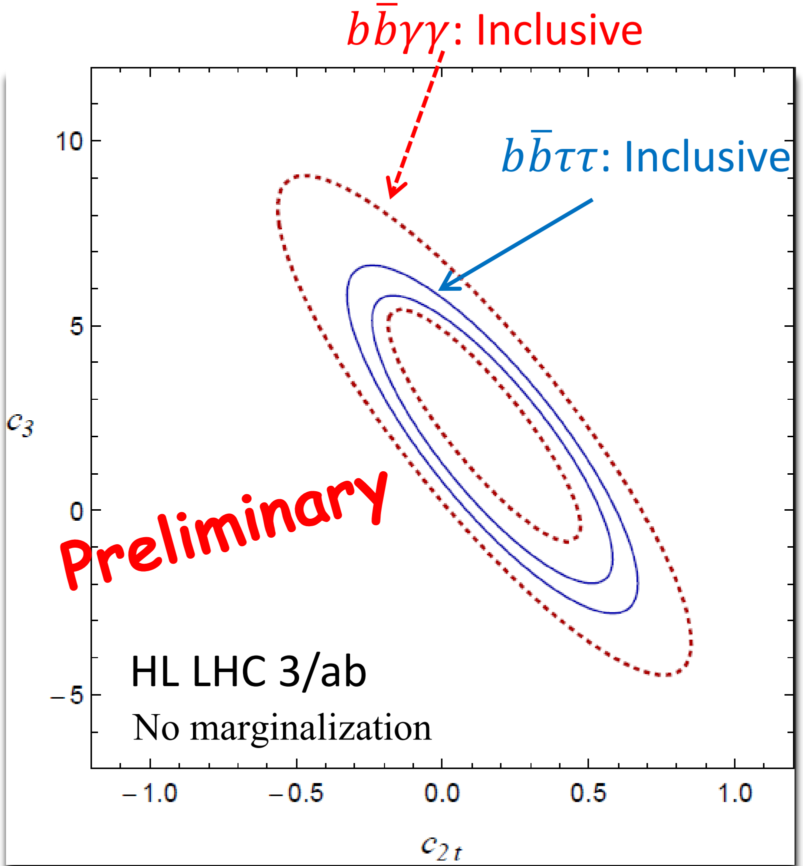
MS Work in progress

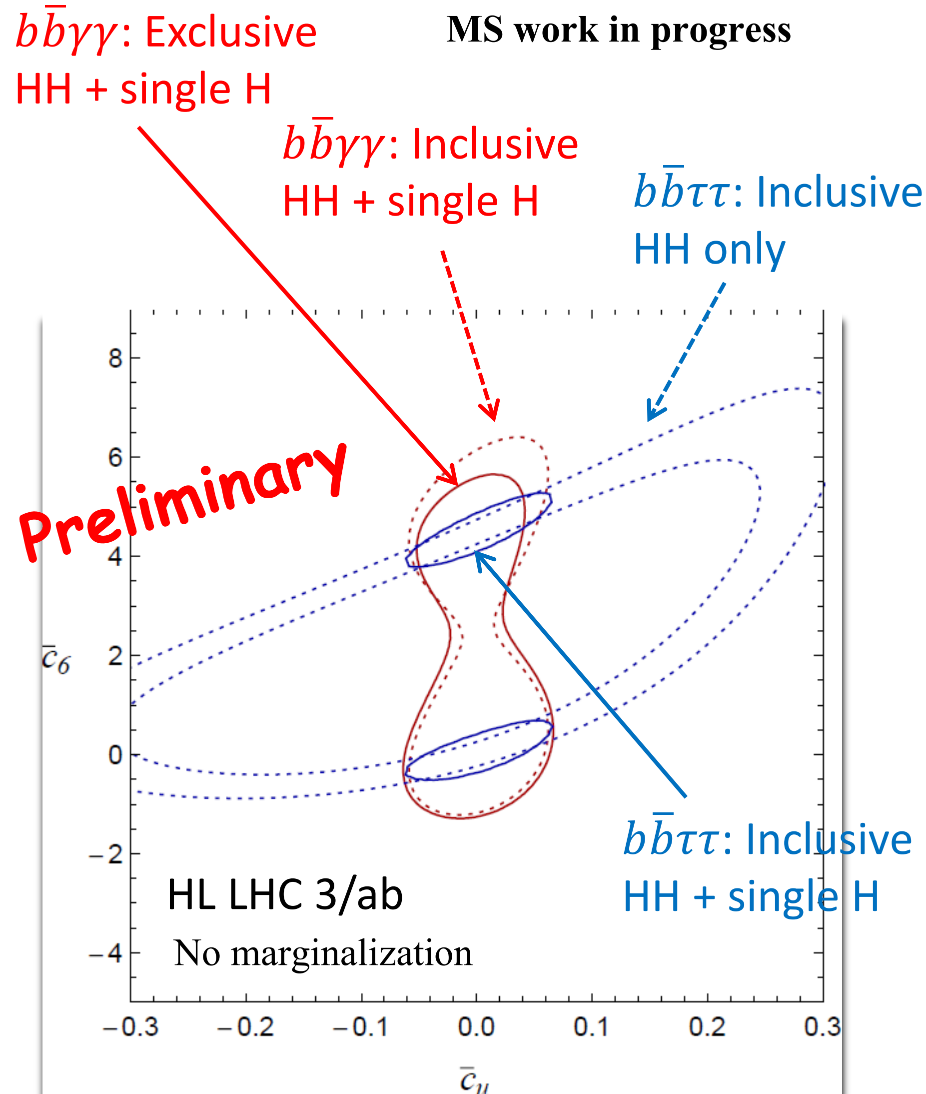
Applied same analysis as "Dolan, Englert, Spannowsky JHEP 1210 (2012) 112" to BSM signal events and used their bkg estimate.

Rescaled signal and backgrounds to include only semileptonic ditau channel

Full analysis via EFT approach with various channels

MS work in progress





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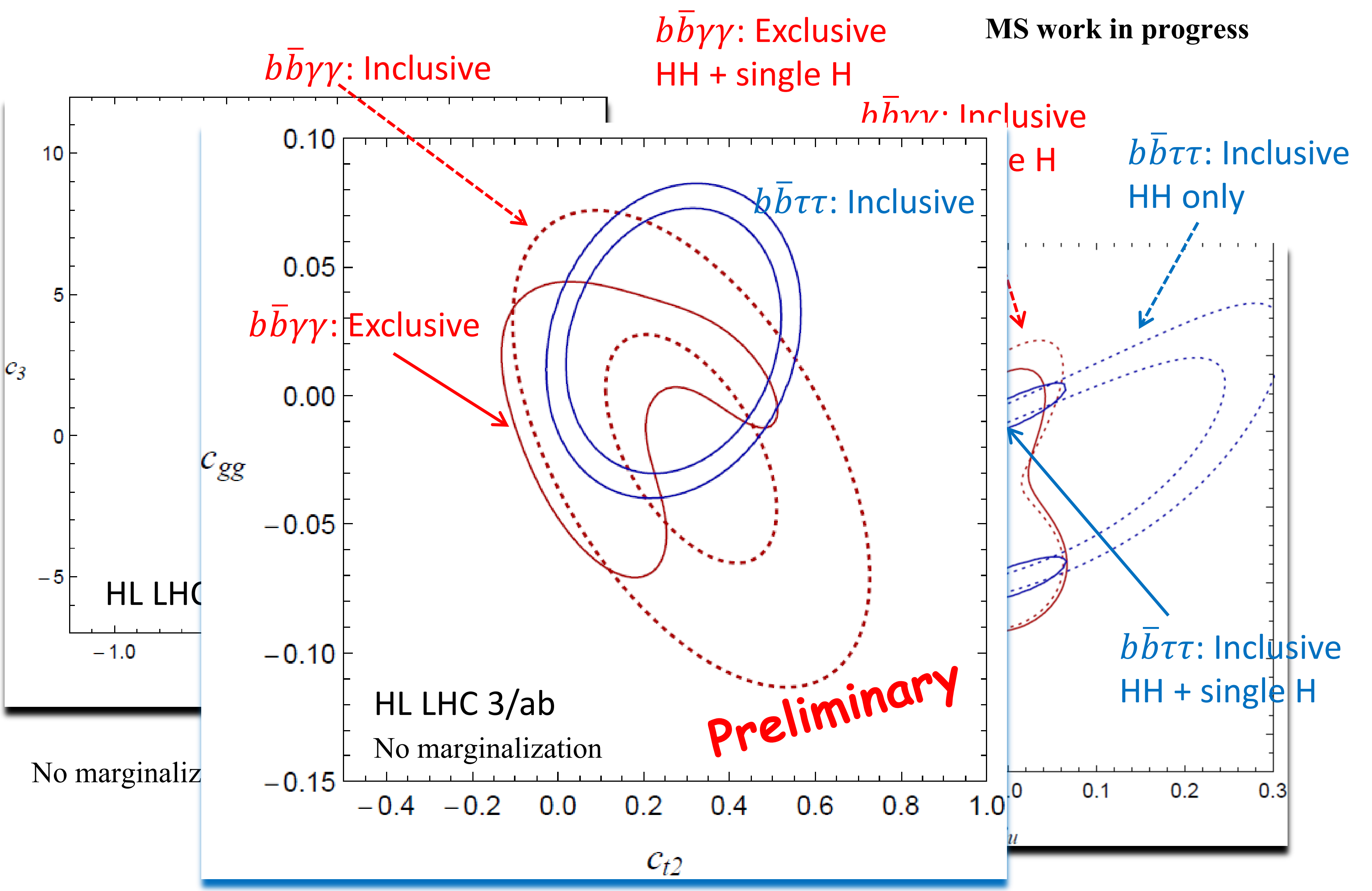
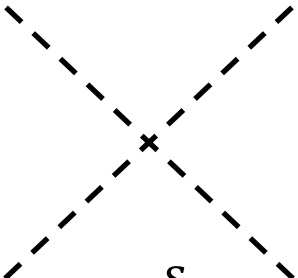
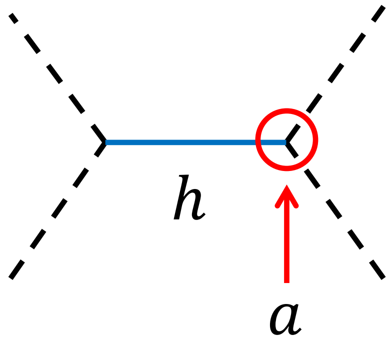


How to measure the strength of EWSB? What is the connection to New Physics?

Adapted from talk by R. Contino at
1st Future Hadron Collider Workshop CERN, May 26-28, 2014



$\sim \frac{s}{v^2}$



$$A(s) = \frac{s}{v^2}(1 - a^2) - a^2 \frac{m_h^2}{v^2} \frac{s}{s - m_h^2 + i\,\Gamma\, m_h}$$

In SM limit $a = 1$ $\longrightarrow$ $\sim \frac{m_h^2}{v^2}$

E-growing parts are perfectly canceled and saturated at weak coupling!

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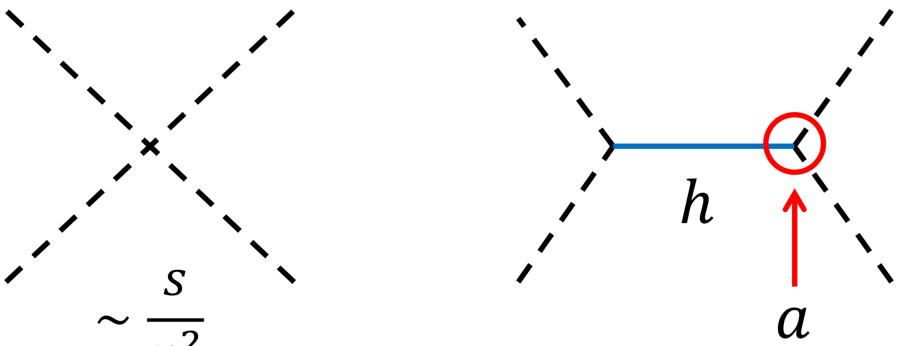

$\sim \frac{s}{v^2}$

$$A(s) = \frac{s}{v^2}(1 - a^2) - a^2 \frac{m_h^2}{v^2} \frac{s}{s - m_h^2 + i\,\Gamma\, m_h}$$

In BSM case $\longrightarrow \sim \frac{m_h^2}{v^2} + \boxed{\frac{E^2}{v^2}\delta}$

$$1 - a^2 = \delta$$

Imperfect cancellation
picks up
E-growing piece!

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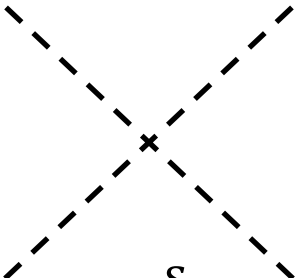

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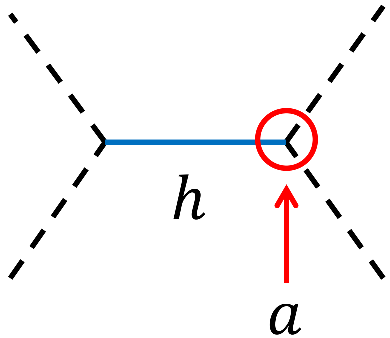

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In BSM case $\longrightarrow \sim \frac{m_h^2}{v^2} + \boxed{\frac{E^2}{v^2}\delta} + \Delta(BSM)$

$$1 - a^2 = \delta$$

HEFT will be invalid at some point and New physics needs to enter before $A(s)$ blows up to saturate its value again

How to measure the strength of EWSB? What is the connection to New Physics?

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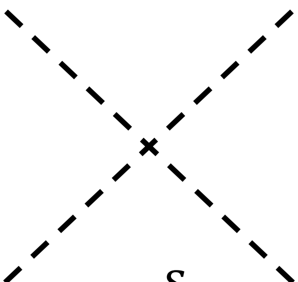
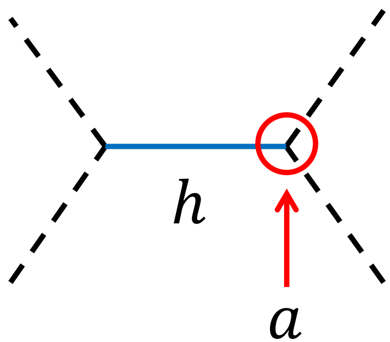


$$\sim \frac{s}{v^2}$$



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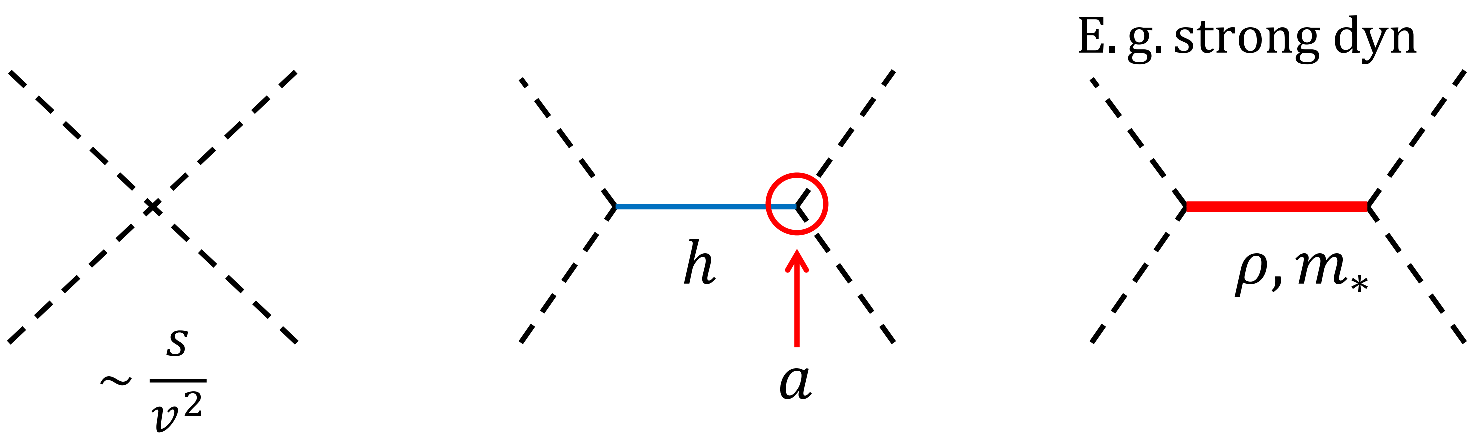
In BSM case $\longrightarrow \sim \frac{m_h^2}{v^2} + \boxed{\frac{E^2}{v^2}\delta} + \Delta(BSM)$

$$1 - a^2 = \delta$$

Measures the strength of EWSB or size of BSM in HEFT

How to measure the strength of EWSB? What is the connection to New Physics?

Adapted from talk by R. Contino at
1st Future Hadron Collider Workshop CERN, May 26-28, 2014



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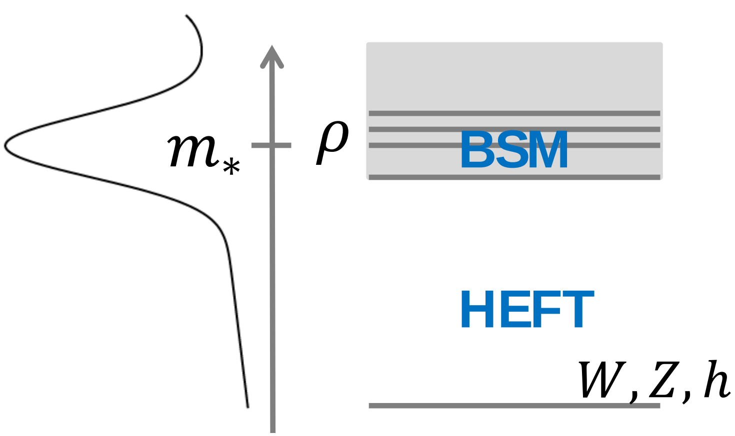

In BSM case

$$\sim \frac{m_h^2}{v^2} + \frac{E^2}{v^2}\delta + \Delta(BSM)$$

$$1 - a^2 = \delta$$

Sees the tail of heavy resonances sitting just beyond the reach of HEFT