Diboson Physics at LHC, Sept 14-16, 2017

HH production at the LHC and future colliders

Minho Son

KAIST (Korea Advanced Institute of Science and Technology)

Azatov, Contino, SON, Panico 1512.

J. Kim, SON, Y. Sakaki to appear soon

Higgs Self Coupling

Brief Summary of current status at various future colliders & on-going effort for the improvement

@ HL LHC

Anomalous Higgs Couplings

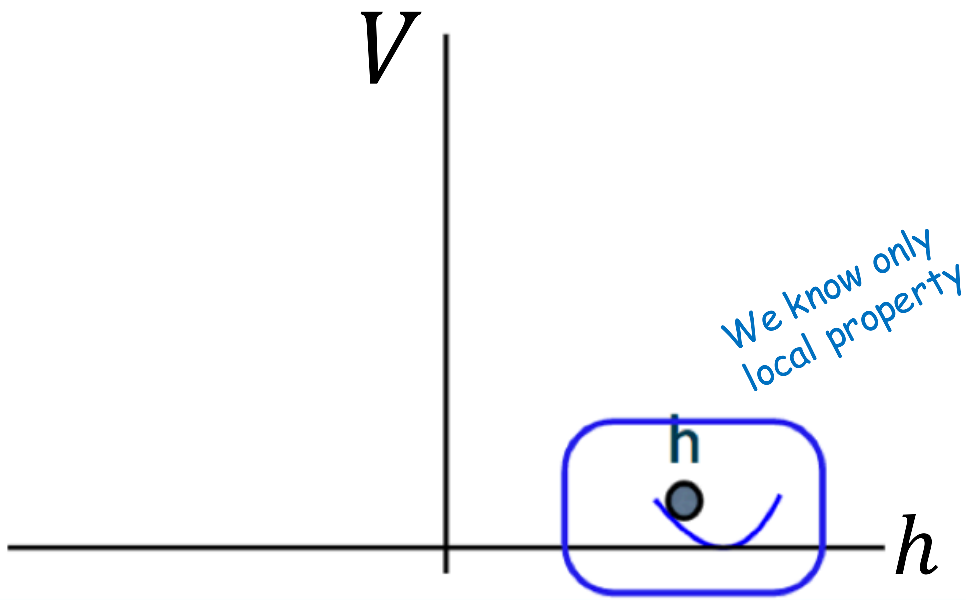
in Effective Field Theory Approach

Higgs Self Coupling

Brief Summary of current status at various future colliders & on-going effort for the improvement

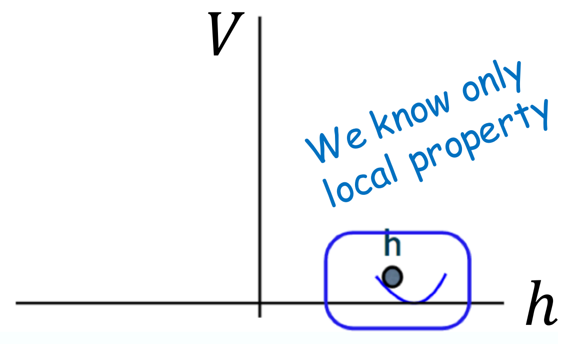
@ HL LHC

What do we know about Higgs potential
in Bottom-up approach?

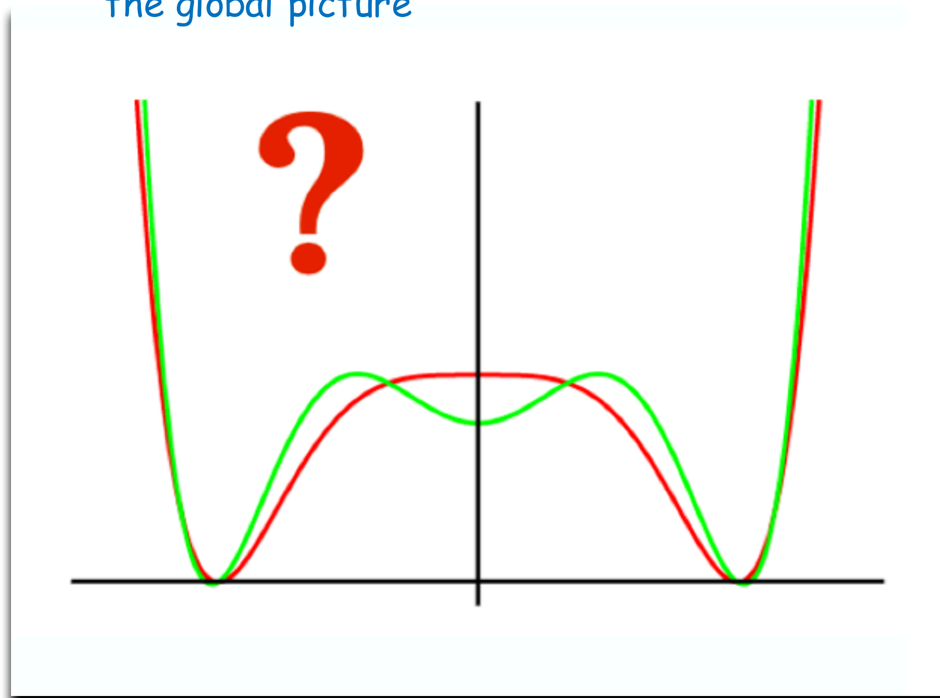


$m_h = 125$ GeV
$v = 246$ GeV

Cartoon stolen
from the talk by Liantao Wang



We want to reconstruct
the global picture



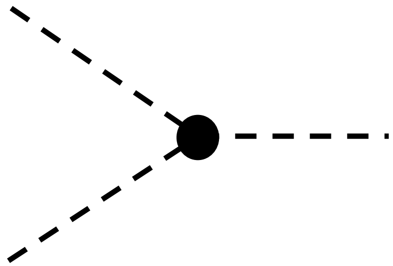
Cartoon stolen
from the talk by Liantao Wang

$$V_h = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6}\left(\frac{3\, m_h^2}{v}\right) h^3 + c_4 \frac{1}{24}\left(\frac{3\, m_h^2}{v^2}\right) h^4$$

An interesting physics still allowed is baryogenesis based on

e.g. 1st order EW-phase transition

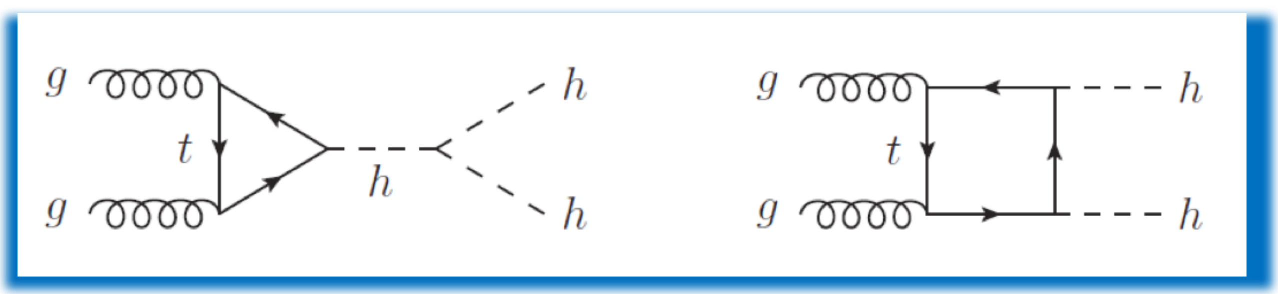
Cubic coupling



HH production via gluon fusion is the best channel

Negatively Interfere

σ [



] $\sim 40\ \mathrm{fb}^{@14\ \mathrm{TeV}}$

$\times$ BR

Very small signal rate

e.g. $b\bar{b}\gamma\gamma$ (0.264%)

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

Threshold region = big backgrounds

Nothing to discuss about Higgs self coupling using current data

ATL-PHYS-PUB-2014-019

$b\bar{b}\gamma\gamma$ by ATLAS

Cubic coupling @ HL LHC using 3000/fb

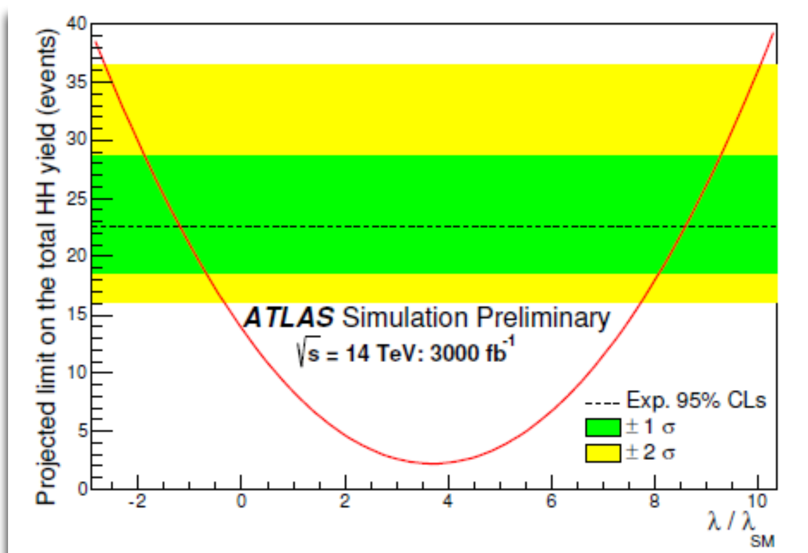
✓ Very tough process

$b\bar{b}\gamma\gamma$ (0.264%)

Seems to be the best channel so far

We would see only ~ 10 events by the end of HL LHC

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
$b\bar{b}jj$	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



Similarly for $b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-$ by CMS

CMS FTR-15-002-pas

Nothing to discuss about Higgs self coupling using current data

Cubic coupling @ HL LHC using 3000/fb

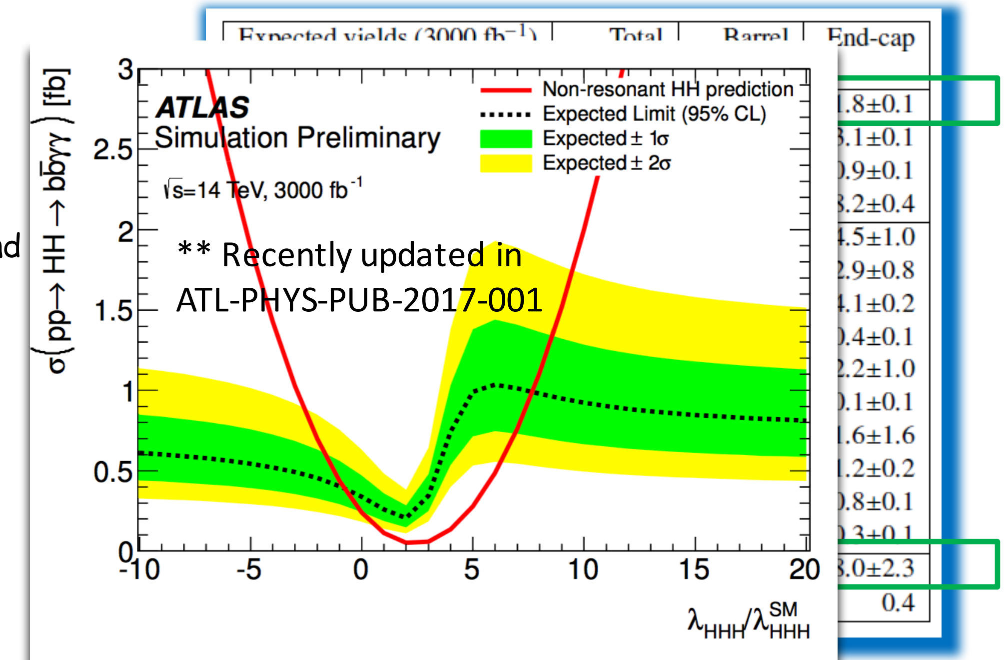
$b\bar{b}\gamma\gamma$ by ATLAS

- ✓ Very tough process

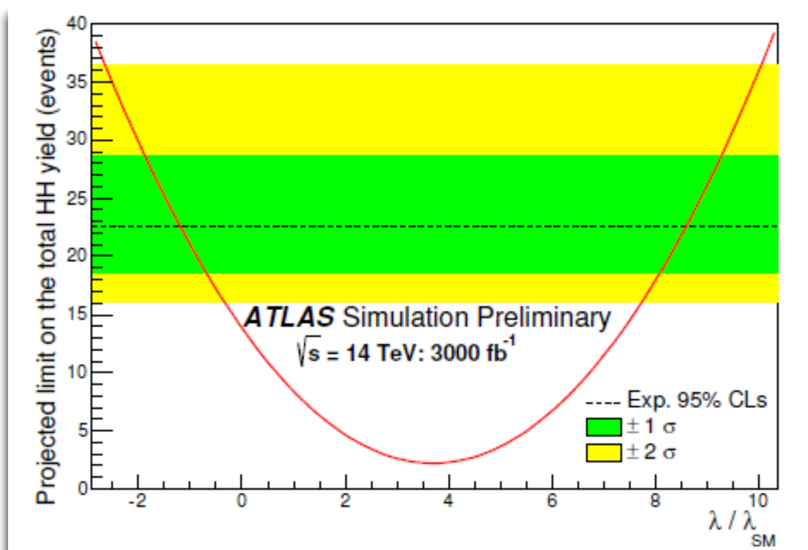
  $b\bar{b}\gamma\gamma$ (0.264%)

  Seems to be the best channel so far

  We would see only ~ 10 events by the end



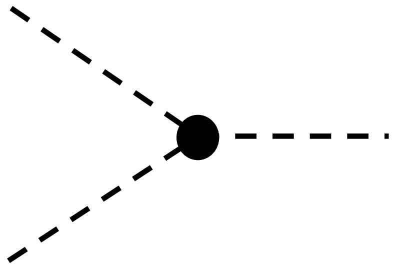
** Recently updated in ATL-PHYS-PUB-2017-001



Similarly for $b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-$ by CMS

CMS FTR-15-002-pas

Cubic coupling @ 100 TeV pp collider using 30/ab



✓ $b\bar{b}\gamma\gamma$ becomes Golden channel at 100 TeV pp collider

$40\times$ enhanced xsec due to PDF

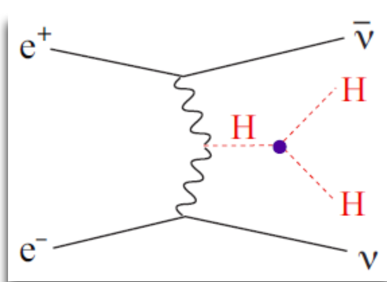
Barr, Dolan, Englert, Lima, M.Spannowsky 15'
Contino, Azatov, Panico, SON 15'
H. He, J. Ren, W. Yao 16'
Physics at 100 TeV

Contino, Panico, Papaefstathiou, Selvaggi, SON
in progress

$\sim$ 3.4 % is possible with 30 ab^{-1}

Physics at 100 TeV, arXiv:1606.09408

✓ ILC via VBF at 1 TeV 5 ab^{-1} $\sim$ 10 %



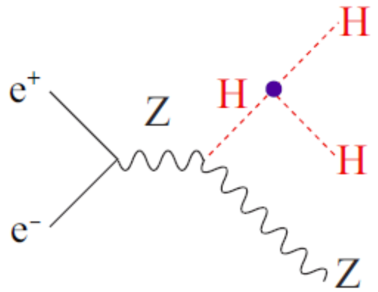
ILC TDR

✓ 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

Other “complementary” processes for Higgs self coupling

Double Higgsstrahlung



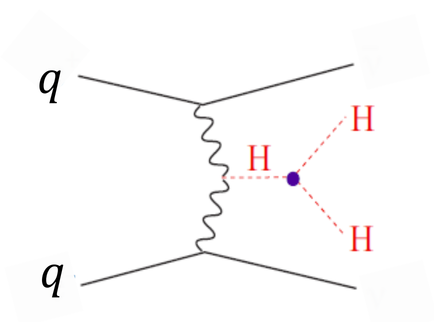
DHS$^{@\text{threshold}}$ gives ~ O(1) determination of λ_{HHH}

ILC TDR

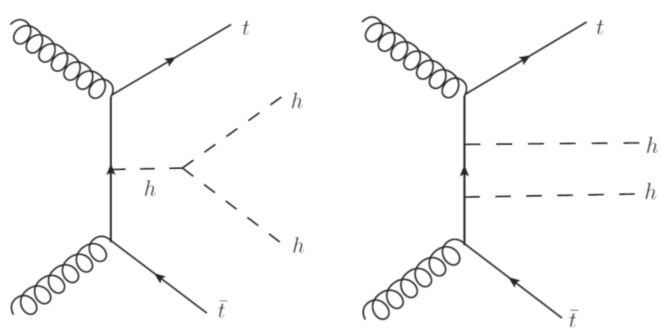
DHS alone at ILC gives only O(1) determination of HHH
e.g. ~ 70% at 500 GeV/1TeV

Contino, Grojean, Pappadopulo, Rattazzi, Thamm 1309.7038

HH via VBF



ttHH



+ many other loop-induced process/theoretical bounds/EWPM for Higgs self coupling

How much can we improve further @ HL LHC?

Combined Analysis of various channels

CMS PAS FTR-15-002

Kim, Sakaki, SON to appear soon

$b\bar{b}\gamma\gamma$ $\quad$ $b\bar{b}\tau^+\tau^-$

0.264% $\quad$ 7.35%

$\xrightarrow[28\,\times]{}$

$\tau_h\tau_h$: Full hadronic (44.4%)

$\tau_h\tau_l$: Semi leptonic $(39.8\ \%)$

- $b\bar{b}\tau^+\tau^-$ in most theory literature was significantly overestimated
- $b\bar{b}\tau^+\tau^-$ can be at best comparable with $b\bar{b}\gamma\gamma$ (combining makes sense)

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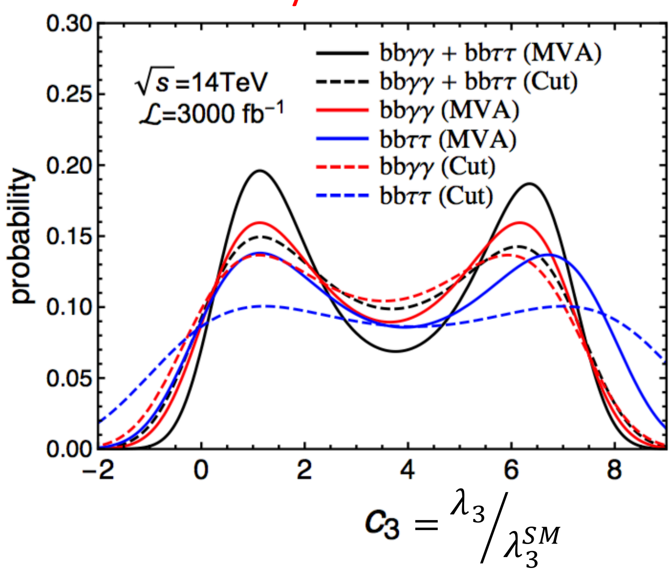
Preliminary



Degeneracy can be broken by differential m_{hh} analysis

Vita, Grojean, Panico, Riembau, Vantalon 1704.01953

analysis	significance $\delta_{sys}=0$	significance $\delta_{sys}=0.1$	allowed region on c_3 68% CL	allowed region on c_3 95% CL
$bb\gamma\gamma$ (cut-based)	1.3	1.1	$[0.2, 2.9] \cup [4.2, 6.9]$	$[-0.7, 7.7]$
$bb\tau\tau$ (cut-based)	1.0	0.8	$[0.0, 3.6] \cup [4.6, 8.2]$	$[-1.4, 9.7]$
$bb\gamma\gamma$ (MVA)	2.0	1.9	$[0.2, 2.6] \cup [4.7, 7.1]$	$[-0.3, 7.6]$
$bb\tau\tau$ (MVA)	1.7	1.4	$[0.1, 2.9] \cup [5.0, 7.8]$	$[-0.5, 8.3]$
combined (MVA)	2.6	2.4	$[0.2, 2.4] \cup [5.1, 7.2]$	$[0.0, 7.5]$

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$28\times$

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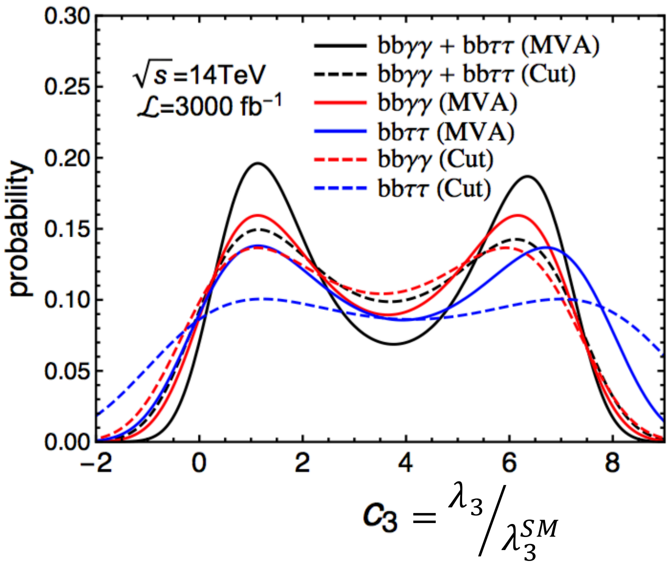
Preliminary



Has a good sensitivity on the negative deviation

: Any interesting New Physics scenario?

analysis	significance $\delta_{sys}=0$	significance $\delta_{sys}=0.1$	allowed region on c_3 68% CL	allowed region on c_3 95% CL
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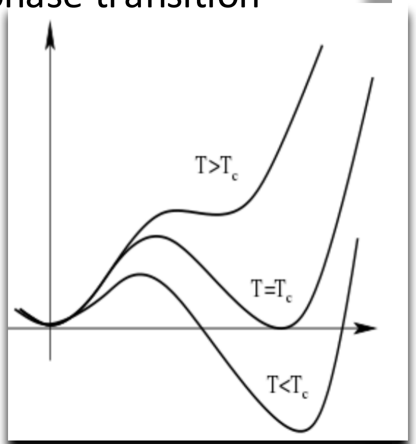
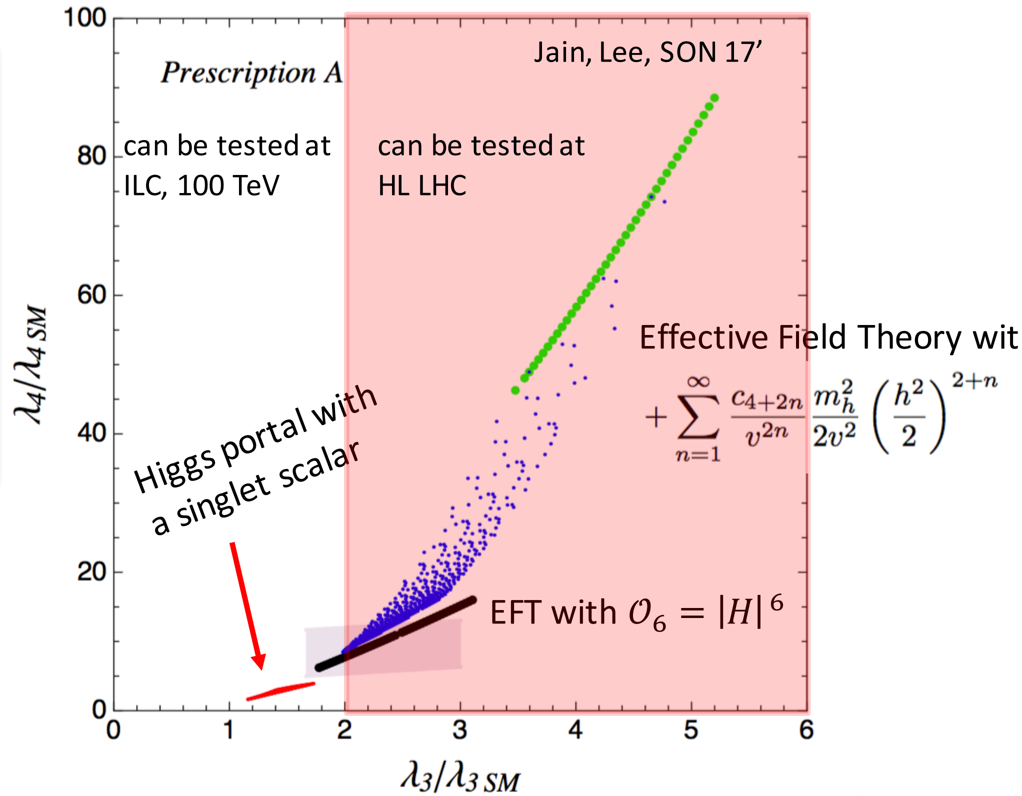
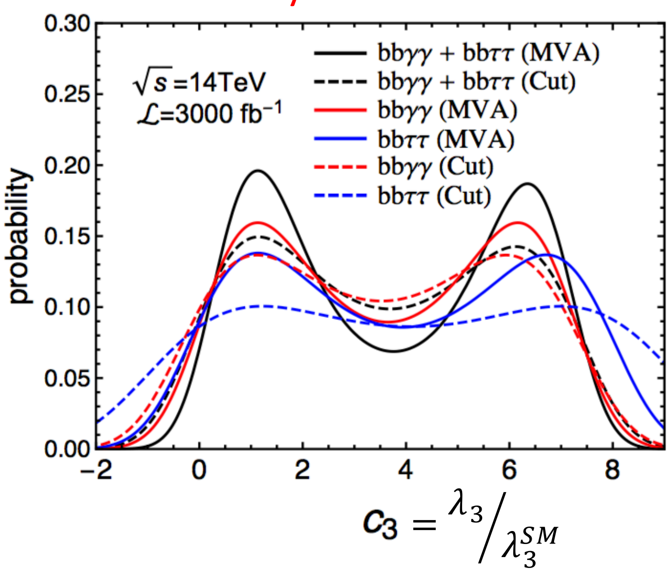
Baryon asymmetry via
Strong 1st order phase transition





Preliminary



analysis	significance		allowed region on c_3	
	$\delta_{sys} = 0$	$\delta_{sys} = 0.1$	68% CL	95% CL
$bb\gamma\gamma$ (cut-based)	1.3	1.1	$[0.2, 2.9] \cup [4.2, 6.9]$	$[-0.7, 7.7]$
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How much can we improve further @ HL LHC?

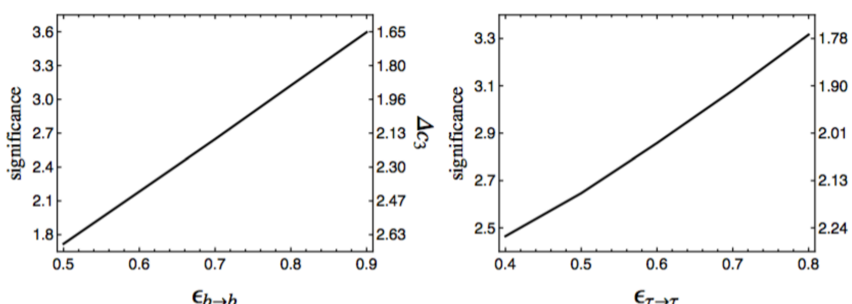
Combined Analysis of various channels

1. Machine learning seems to improve b, c, τ-taggings against QCD-jets
2. Prompt b, c-tagging vs merged b, c-jets (from $g \to b\bar{b}, c\bar{c}$ splitting)
3. Machine learning applied to the analysis itself
4. ....

Parametrize precision of c_3 as a function of any "improvable" parameters
$\to$ future perspective

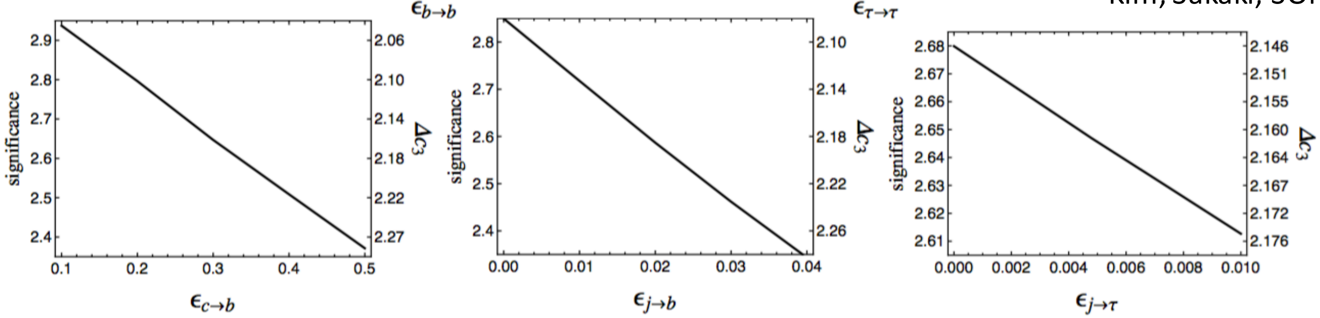
Similar strategy to Physics at 100 TeV, arXiv:1606.09408

Preliminary



$\Delta c_3 = \lambda_3 / \lambda_3^{SM} - 1$

Kim, Sakaki, SON to appear soon



Varied one at a time

What if multiple components gets improved?

We take an optimistic scenario

$$\epsilon_{b\to b} = 0.8, \epsilon_{c\to b} = 0.2, \epsilon_{j\to b} = 0.015$$

$$\epsilon_{\tau\to\tau} = 0.7, \epsilon_{j\to\tau} = 0.01$$

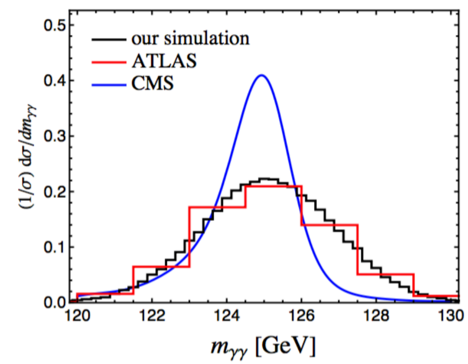
25% of reduced width of $m_{\gamma\gamma}$

For recent improvements on b, τ-tagging
CMS PAS TAU-16-002
ATL-PHYS-PUB-2017-013

previously

$$\epsilon_{b\to b} = 0.7, \epsilon_{c\to b} = 0.3, \epsilon_{j\to b} = 0.015$$

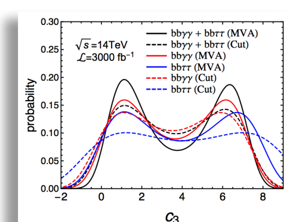
$$\epsilon_{\tau\to\tau} = 0.5, \epsilon_{j\to\tau} = 0.048$$



Preliminary

analysis	significance $\delta_{\rm sys} = 0$	significance $\delta_{\rm sys} = 0.1$	allowed region on c_3 68% CL	allowed region on c_3 95% CL
combined (MVA) bench mark	4.0	3.4	$[0.4, 2.0] \cup [5.7, 7.2]$	$[-0.1, 3.2] \cup [4.4, 7.7]$

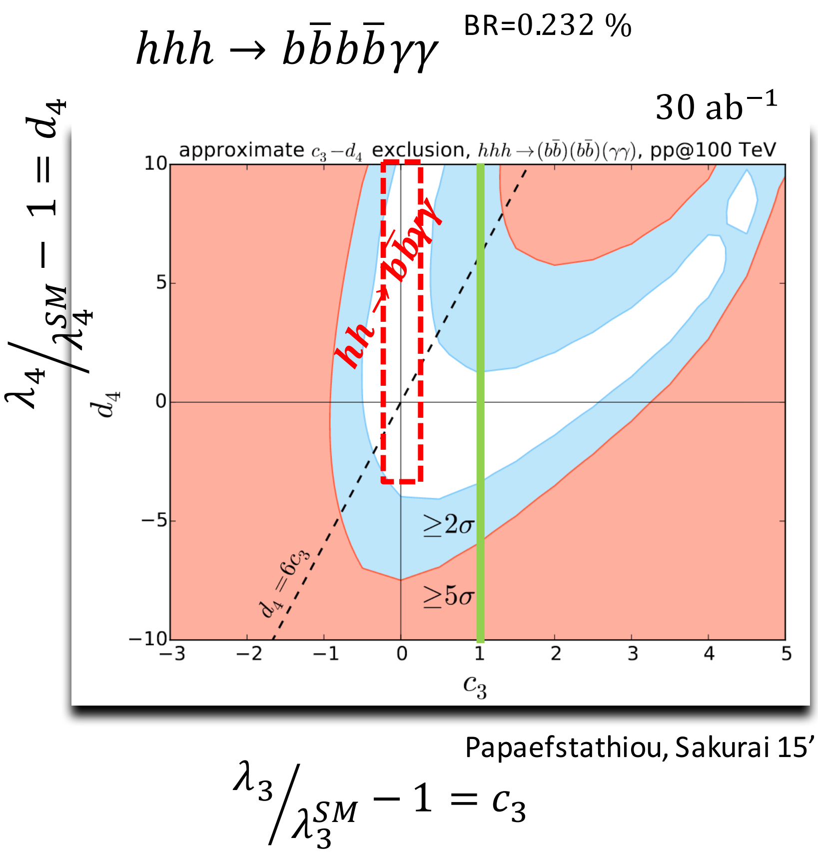
Kim, Sakaki, SON to appear soon

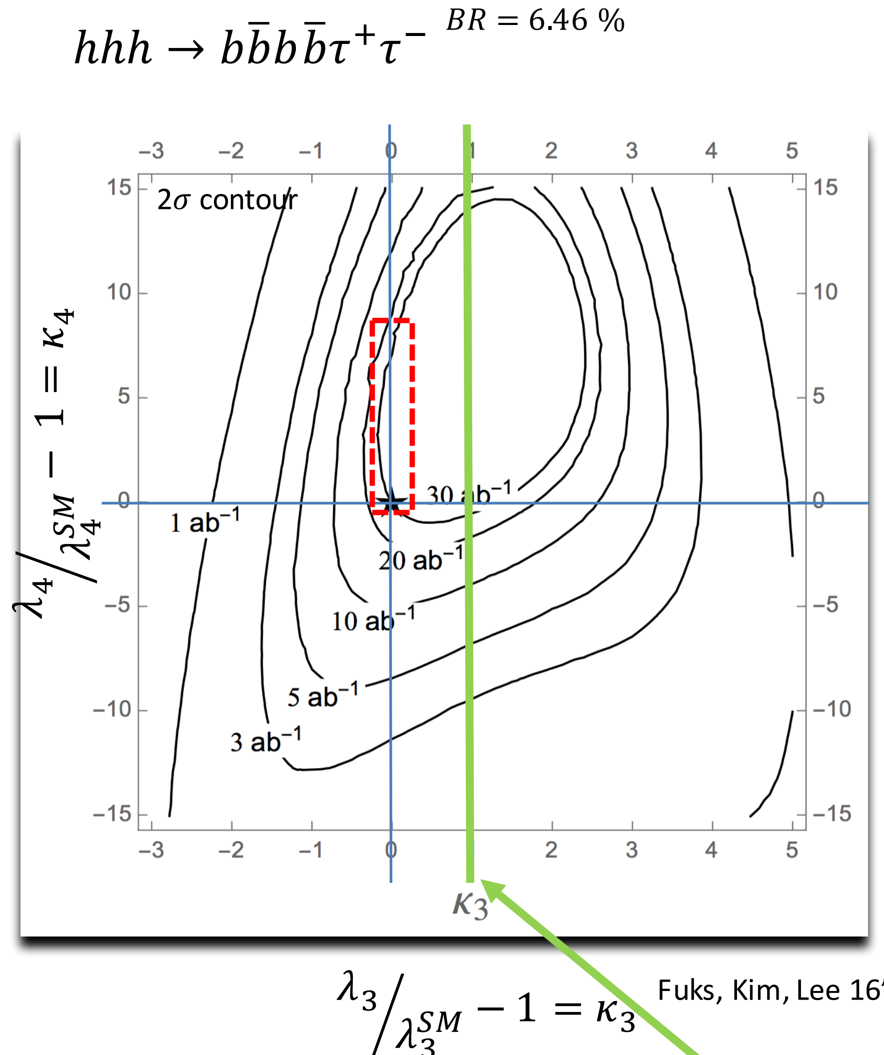


Compare with the sensitivity with the previous tagging effs.

combined (MVA)	2.6	2.4	$[0.2, 2.4] \cup [5.1, 7.2]$	$[0.0, 7.5]$

Quartic coupling λ_4 @ 100 TeV



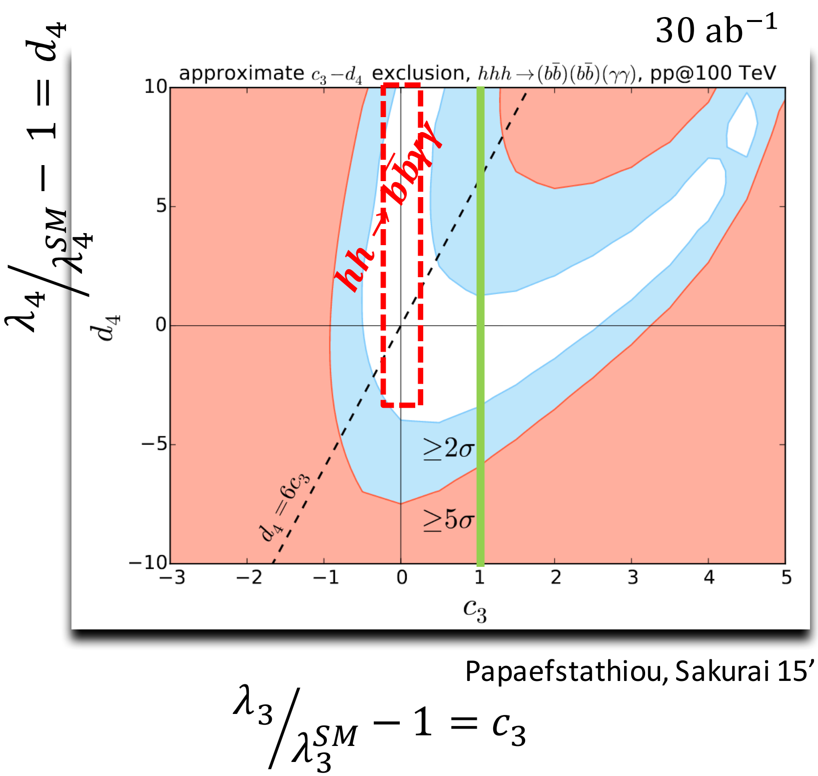


✓ If we observe cubic $\sim \mathcal{O}(1)$ @ HL LHC or 100 TeV, then quartic from 100 TeV is very useful

What if we observe a large κ_3 at HL LHC?

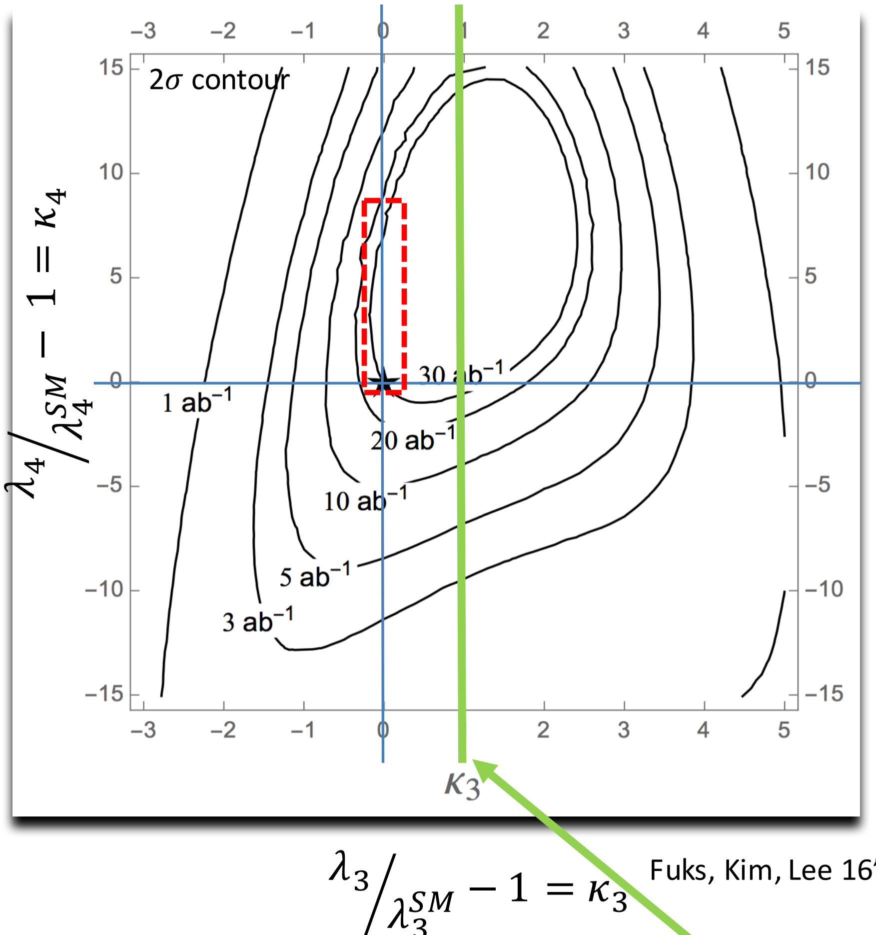
Quartic coupling λ_4 @ 100 TeV

$hhh \to b\bar{b}b\bar{b}\gamma\gamma$ BR=0.232 %



Papaefstathiou, Sakurai 15'

$hhh \to b\bar{b}b\bar{b}\tau^+\tau^-$ $BR = 6.46\ \%$



Fuks, Kim, Lee 16'

✓ If these plots are true, these illustrate the power of combining channels in EFT approach

: Different channel is sensitive to different region

What if we observe a large κ_3 at HL LHC?

Anomalous Higgs Coupling

In the Effective Field Theory Approach

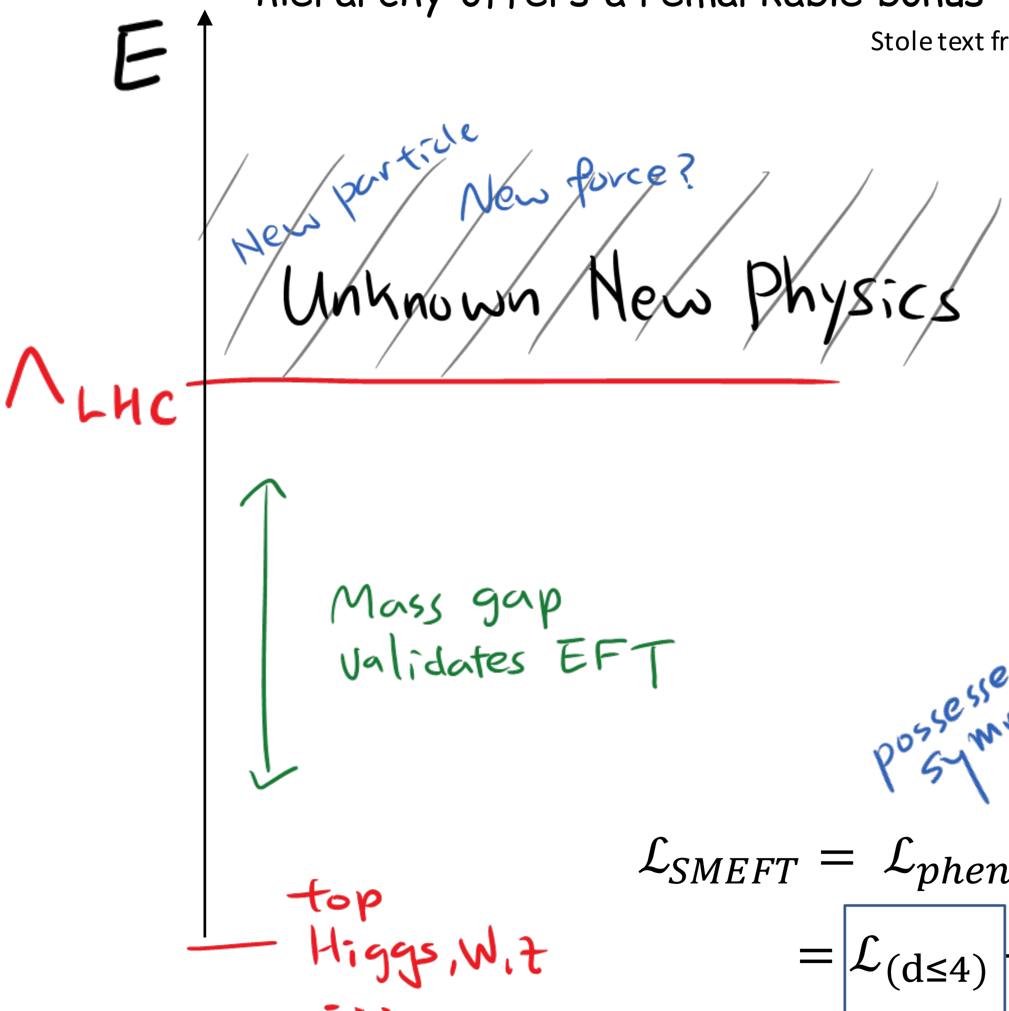
Azatov, Contino, Panico, SON, 1502.00539

Also see
Goertz, Papaefstathiou, Yang, Zurita 1410.3471
Vita, Grojean, Panico, Riembau, Vantalon 1704.01953

SM Effective Field Theory

Widely separated two scales, or seemingly un-natural hierarchy offers a remarkable bonus

Stole text from the talk by Rattazzi



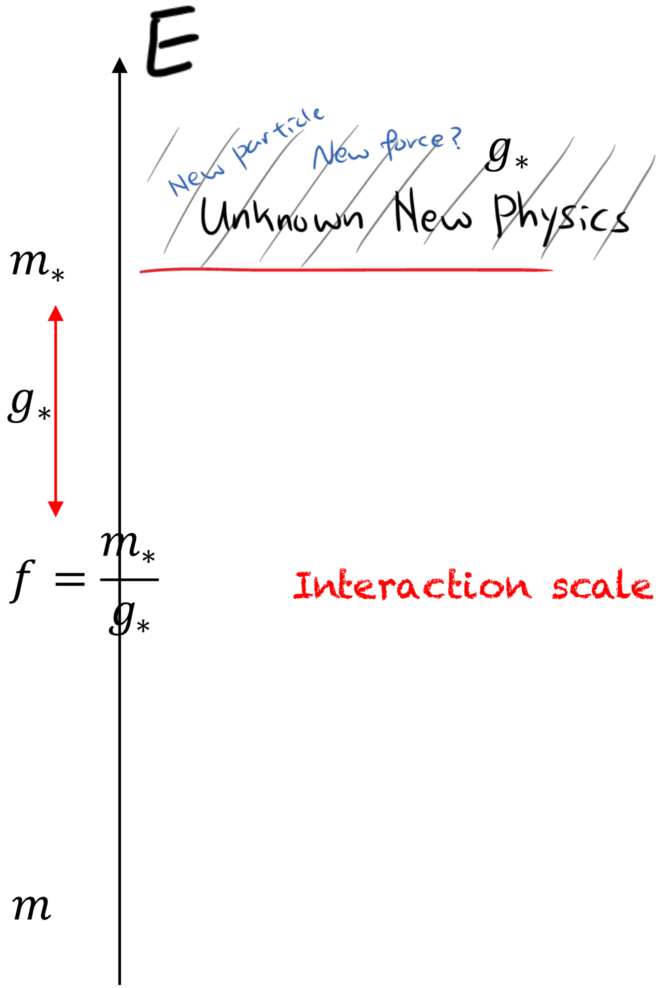
possesses all the accidental symmetries we observe in Nature

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{pheno.} + Higgs$$

$$= \boxed{\mathcal{L}_{(\mathrm{d}\leq 4)}} + \frac{1}{\Lambda_{\mathrm{LHC}}}\mathcal{L}_{(5)} + \frac{1}{\Lambda^2_{\mathrm{LHC}}}\mathcal{L}_{(6)} + \cdots$$

Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'



Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

E

New particle
New force?

g_*

Unknown New Physics

m_*

g_*

$f = \frac{m_*}{g_*}$

Interaction scale

: the only scale accessible to
a low-E observer

m

Typical interaction in EFT is
controlled by the effective coupling,

$$g(E) = \frac{E}{f} \leq \frac{m_*}{f} = g_*$$

Structural picture of EFT

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'

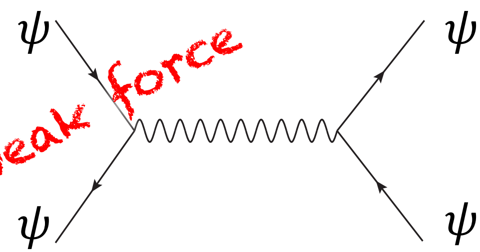
E

New particle

New force? g_*

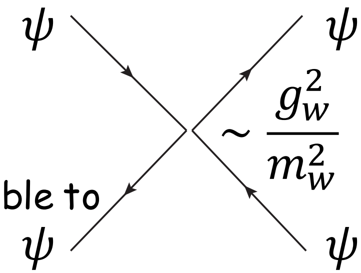
Unknown New Physics

= Weak force



m_* $\rightarrow m_W$

g_* g_W



$\sim \dfrac{g_W^2}{m_W^2}$

$f = \dfrac{m_*}{g_*}$

Interaction scale

: the only scale accessible to a low-E observer

$\rightarrow \dfrac{m_W}{g_W} = \dfrac{1}{\sqrt{G_F}}$

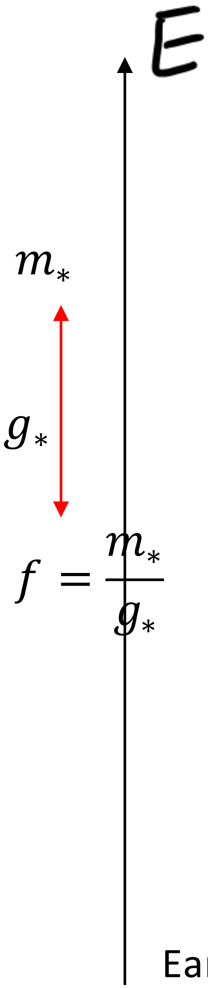
Typical interaction in EFT is controlled by the effective coupling,

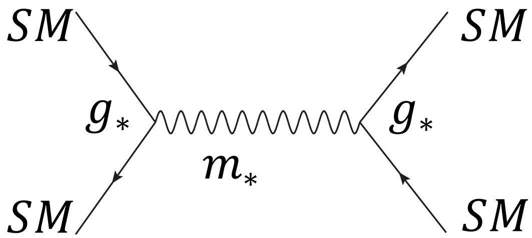
m $\rightarrow m_\psi$

$$g(E) = \frac{E}{f} \leq \frac{m_*}{f} = g_*$$

$$g(E) = \frac{g_W}{m_W} E$$

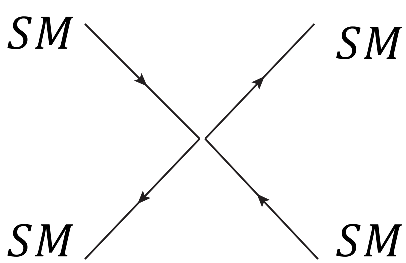
Unitarity violation in EFT





$$\mathcal{A}_{UV} \propto \frac{g_*^2 s}{s - m_*^2} \qquad \to \text{const. as } s \to \infty$$

$$= \frac{g_*^2 s}{m_*^2} + O\left(\frac{s^2}{m_*^4}\right)$$



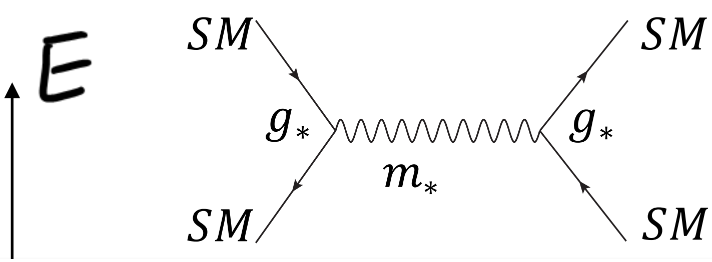
What if our collider was not strong enough to produce $\boldsymbol{m_*}$?

$$\mathcal{A}_{EFT} \sim \frac{s}{f^2} \qquad \to \infty \text{ as } s \to \infty$$

E-growing vs. Validity of EFT

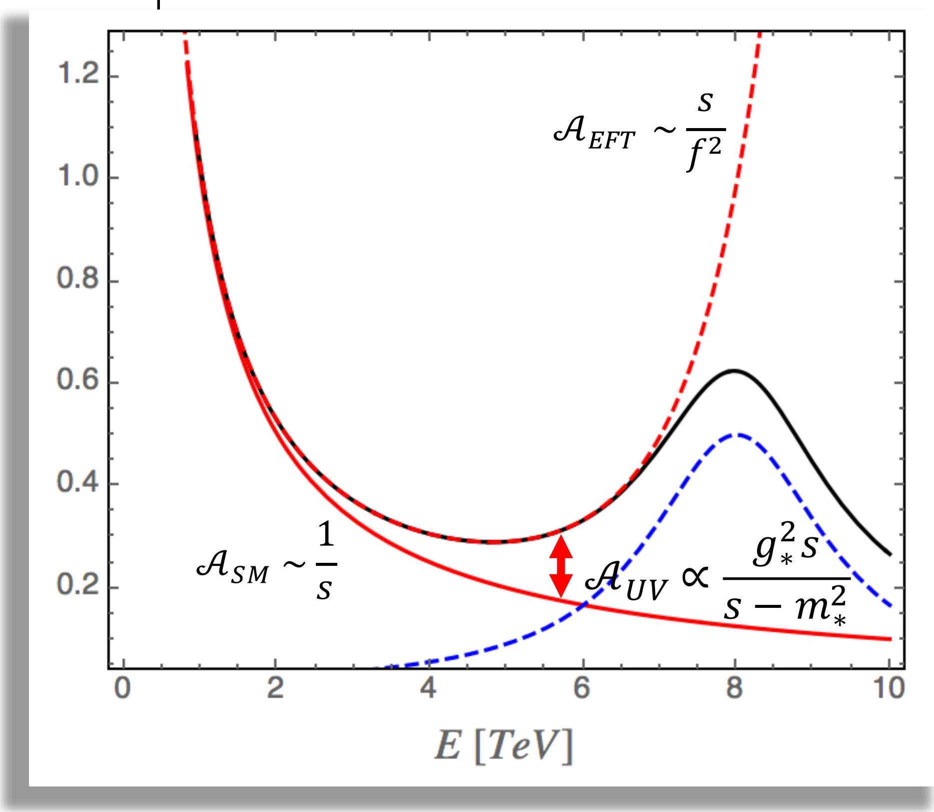
Early new physics hint in EFT approach relies on the E-growing feature due to decent $S/\sqrt{B}$.
However, this benefit should cut off at a certain energy scale, $E < m_*$

Unitarity violation in EFT



$$\mathcal{A}_{UV} \propto \frac{g_*^2 s}{s - m_*^2} \qquad \to \text{const. as } s \to \infty$$

$$= \frac{g_*^2 s}{m_*^2} + O\left(\frac{s^2}{m_*^4}\right)$$



at if our collider was not strong
ough to produce m_* ?

$$\mathcal{A}_{EFT} \sim \frac{s}{f^2} \qquad \to \infty \text{ as } s \to \infty$$

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

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

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

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

$$+\boxed{\frac{1}{2}\left(\partial_\mu h\right)^2 - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{3!}\left(\frac{3\,m_h^2}{v}\right)h^3 - c_4\,\frac{1}{4!}\left(\frac{3\,m_h^2}{v^2}\right)h^4 + \cdots}$$

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

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

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_6 + \Delta\mathcal{L}_8 + \cdots$$

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

- Matches to ``basis in the unitary basis'' 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 estimate

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

New Physics is broadly characterized by one coupling g_* and one scale m_* associated with new states. Higgs as pGB

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

: known as SILH

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

An $\mathcal{O}(1)$ deviation of HHH coupling while being consistent with the single Higgs data ?

→ Modify power counting rules

Non-pGB Higgs

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

Higgs Portal e.g $\lambda |H|^2 O$

- Similar power counting for weakly coupled BSM scenarios

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

$\mathcal{O}_H \ll \mathcal{O}_6$ possible

Azatov, Contino, Panico, Son 15'

E.g.

Higgs : p~~G~~B

Generic composite state: tuned …
→ no supurion suppression.

→ Enhancement by $\dfrac{g_*^2}{g_{\cancel{GB}}} = \dfrac{g_*^2}{\lambda_4}$

e.g. $\mathcal{O}_6 = \dfrac{\bar{c}_6}{v^2}\lambda_4 |H|^6$

$$\bar{c}_H \sim \left(\frac{v}{f}\right)^2 \sim 0.05$$

$$\bar{c}_6 \sim \left(\frac{v}{f}\right)^2 \frac{g_*^2}{\lambda_4} \sim 3.5\ \left(\frac{g_*}{3}\right)^2$$

Higgs portal (to strongly coupled sector)

$$\mathcal{L} = \lambda |H|^2 \mathcal{O}$$

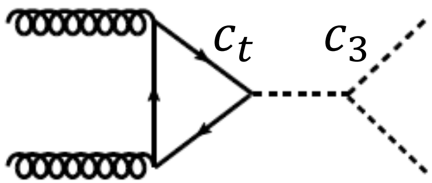
$\mathcal{O}$ characterized by $\{m_*, g_*\}$

$$\bar{c}_H \sim \left(\frac{v}{f}\right)^2 \times \frac{\lambda^2}{g_*^4}$$

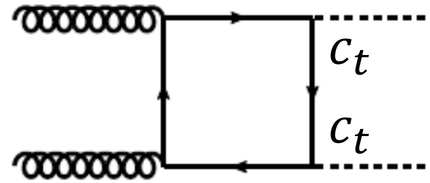
$$\bar{c}_6 \sim \left(\frac{v}{f}\right)^2 \times \frac{\lambda^3}{g_*^4 \lambda_4}$$

$$\bar{c}_H / \bar{c}_6 = \lambda_4 / \lambda$$

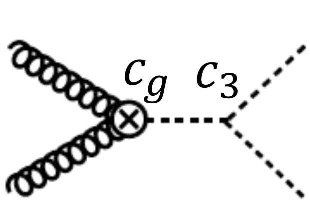
Anomalous couplings of HH in the EFT approach via gg-HH



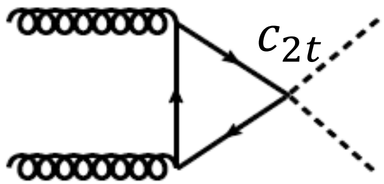
$\sim \frac{m_h^2}{\hat{s}} \log^2 \frac{m_t^2}{\hat{s}}$



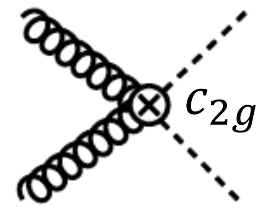
$\sim const$



$\sim const$



$\sim \log^2 \frac{m_t^2}{\hat{s}}$



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

Azatov, Contino, Panico, Son arXiv:1502.00539

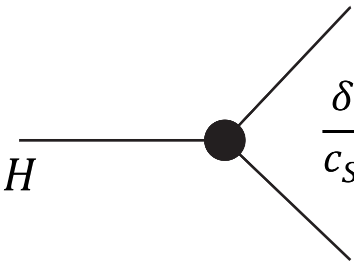
In terms of Higgs doublet basis

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

- ✓ All diagrams have different energy-dependences
- ✓ $m_{hh} = \sqrt{\hat{s}}$ is an important shape variable
- ✓ Better sensitivity on $\bar{c}_u$ from c_{2t} (not from c_t)

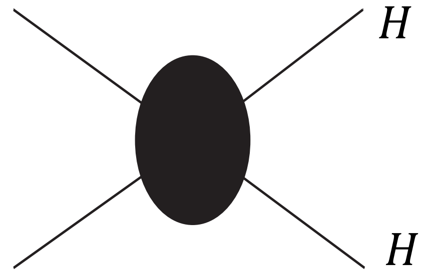
Decay vs 2-to-2 scattering

Kinematics is characterized by θ and $\sqrt{\hat{s}}$



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

Main focus of Run 1



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

Important item of Run 2

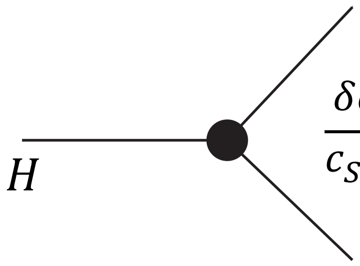
1. Anomalous couplings in SMEFT are $\theta, \sqrt{\hat{s}}$ -dependent

$$\frac{d\sigma}{d\sqrt{\hat{s}}}, \qquad \frac{d\sigma}{dcos\theta},$$

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

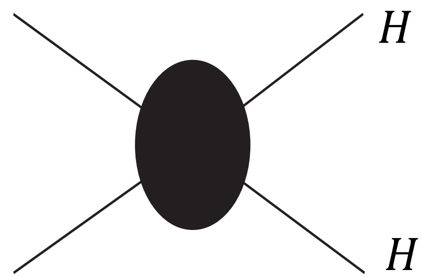
Decay vs 2-to-2 scattering

Kinematics is characterized by θ and $\sqrt{\hat{s}}$



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

Main focus of Run 1



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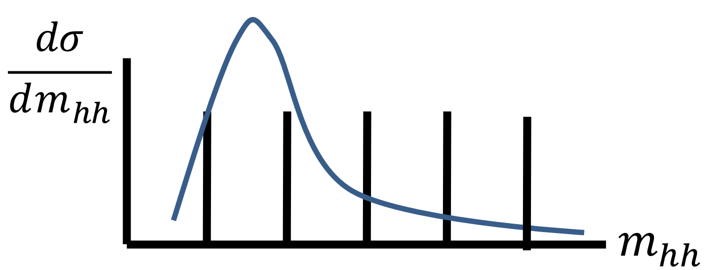
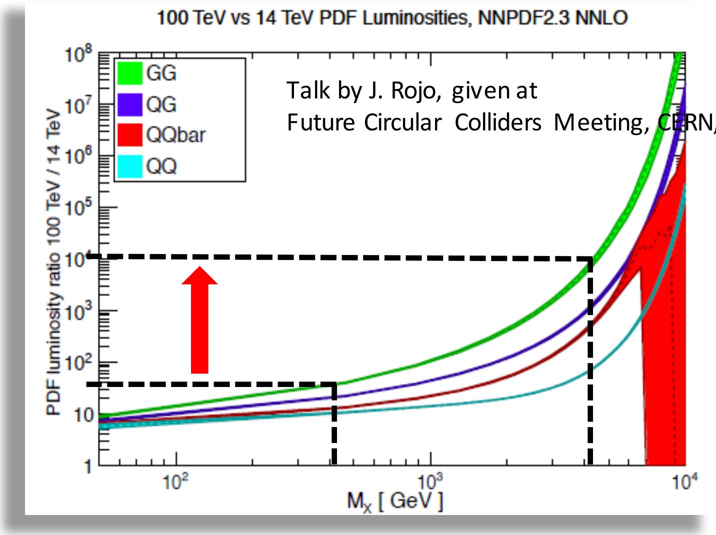
✓ BSM effects are encoded in terms with different E-dependence in scattering amplitudes

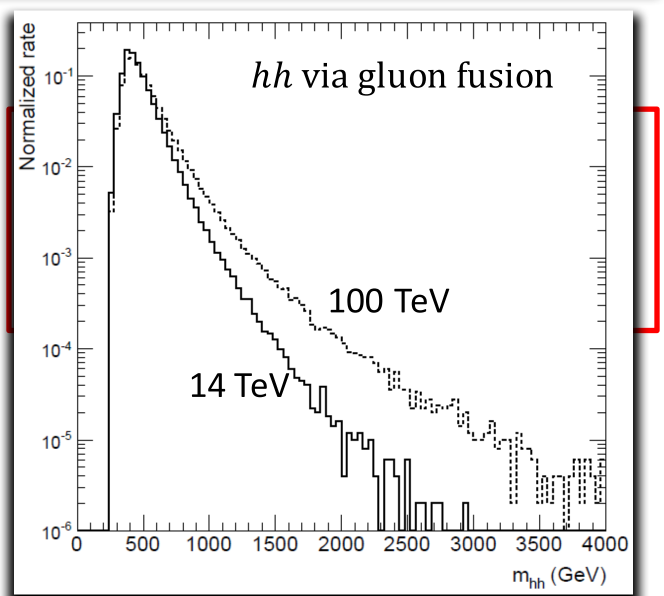
Exclusive analysis

Exclusive analysis, e.g. binning m_{hh}, is required to break degeneracies among various BSM coefficients and to isolate various effects

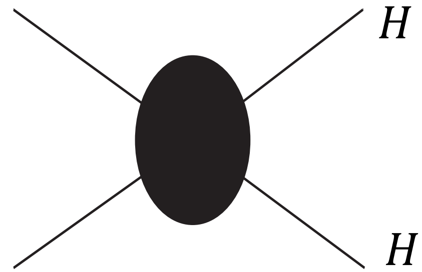


BSM at high Mass/Energy





Kinematics is characterized by θ and $\sqrt{\hat{s}}$



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

Important item of Run 2

1. Anomalous couplings in SMEFT are $\theta, \sqrt{\hat{s}}$ -dependent

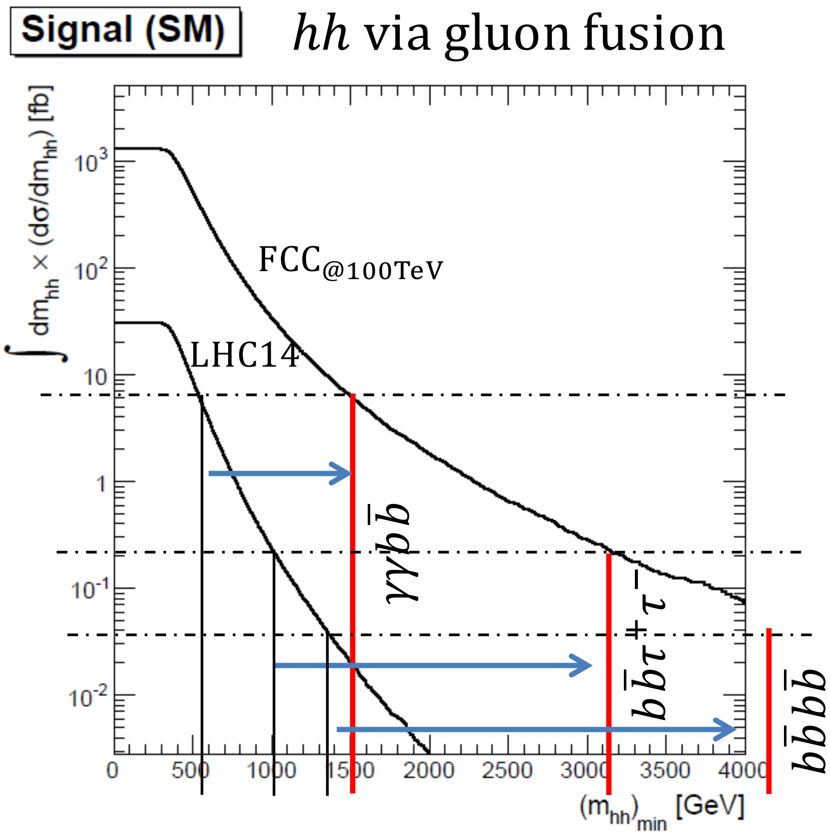
$$\frac{d\sigma}{d\sqrt{\hat{s}}}, \qquad \frac{d\sigma}{dcos\theta},$$

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

2. The higher E we reach (as long as $E < M_{\mathrm{cut}}$), the better sensitivity

✓ A powerful benefit from 100 TeV pp collider lies on the huge enhancement of cross sections at the higher invariant mass

Capability of probing new physics scale



$b\bar{b}\gamma\gamma$

Scale of process can be well constructed. Imposing EFT cut is easy, e.g. includes only events with $E < M_{cut}$

$b\bar{b}\tau^+\tau^-$

Scale of process is NOT easily obtained due to the neutrinos. Only conservative bound might be possible

$b\bar{b}b\bar{b}$

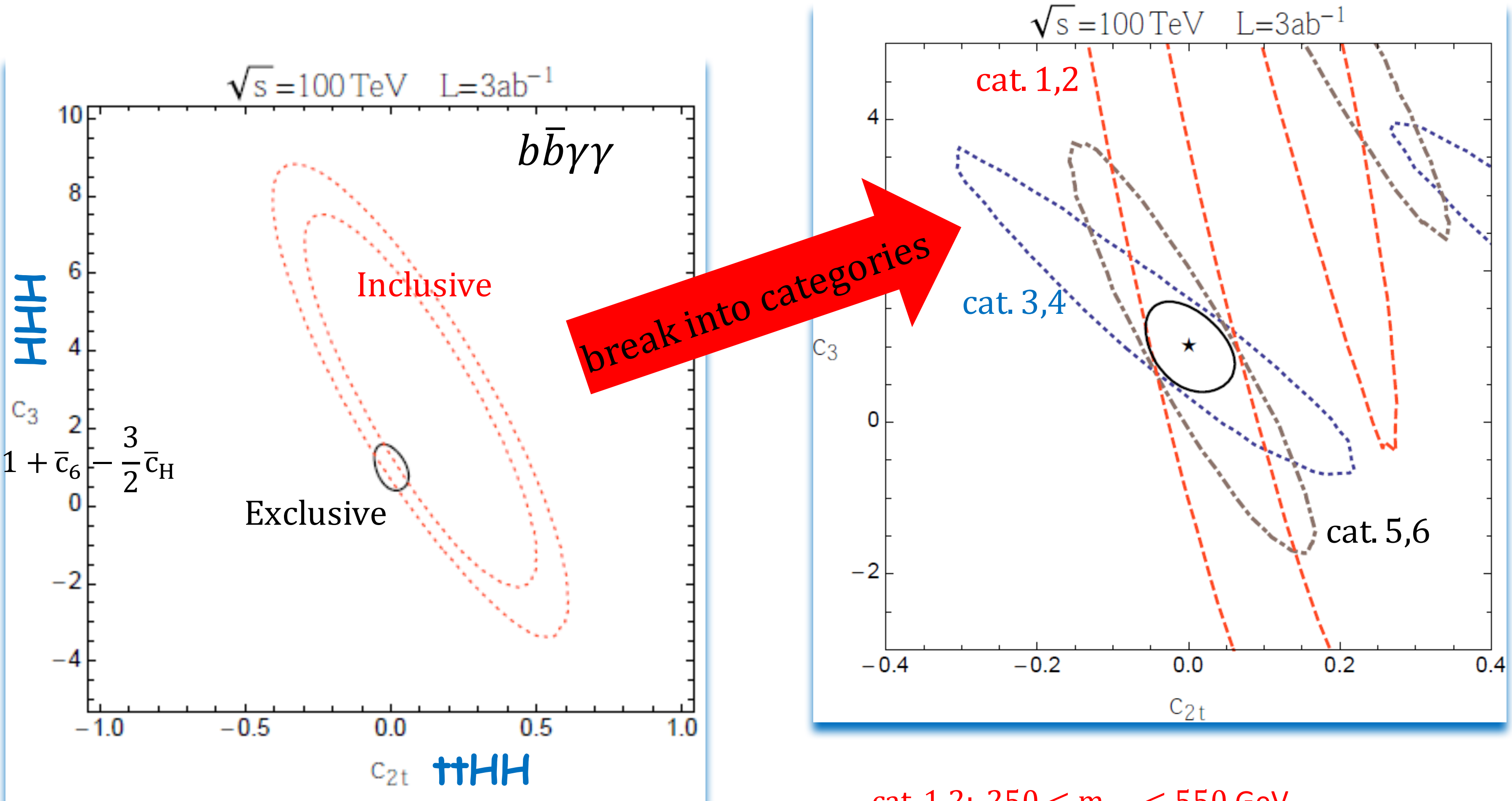
Scale of process can be extracted. Can reach the highest new physics scale where QCD background might be manageable.
Only beneficial to E-growing operator. Not Higgs self coupling.
Jet substructure technique becomes useful

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

assuming 10 % signal efficiency

Anomalous couplings in the unitary basis

Exclusive analysis at 100TeV pp collider



$$c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

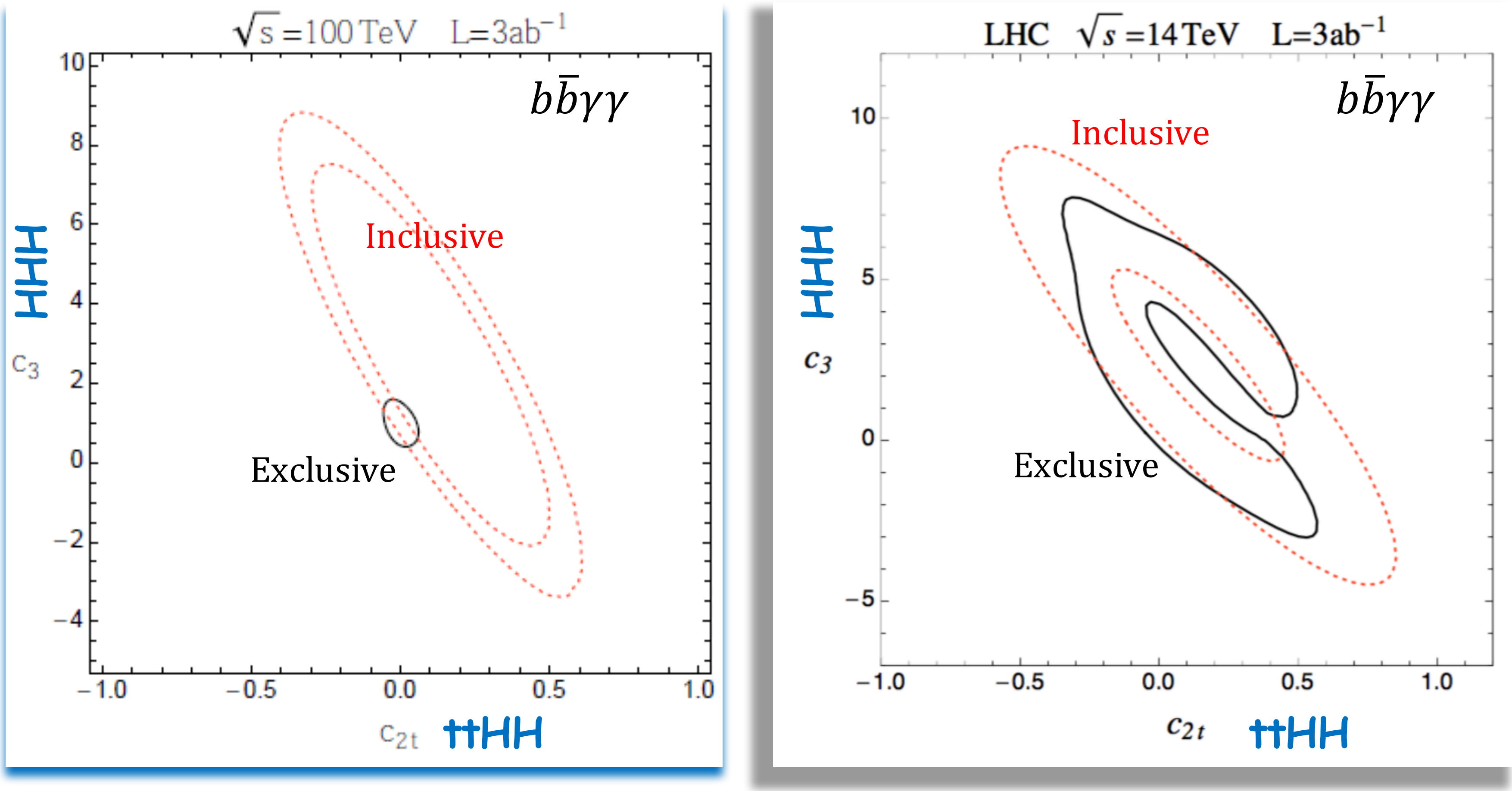
Azatov, Contino, Panico, Son arXiv:1502.00539

$$c_{2t} = 0 - \frac{1}{2}\bar{c}_H - \frac{3}{2}\bar{c}_u \,,$$

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

✓ Exclusive analysis is more beneficial at 100 TeV

: due to more statistics



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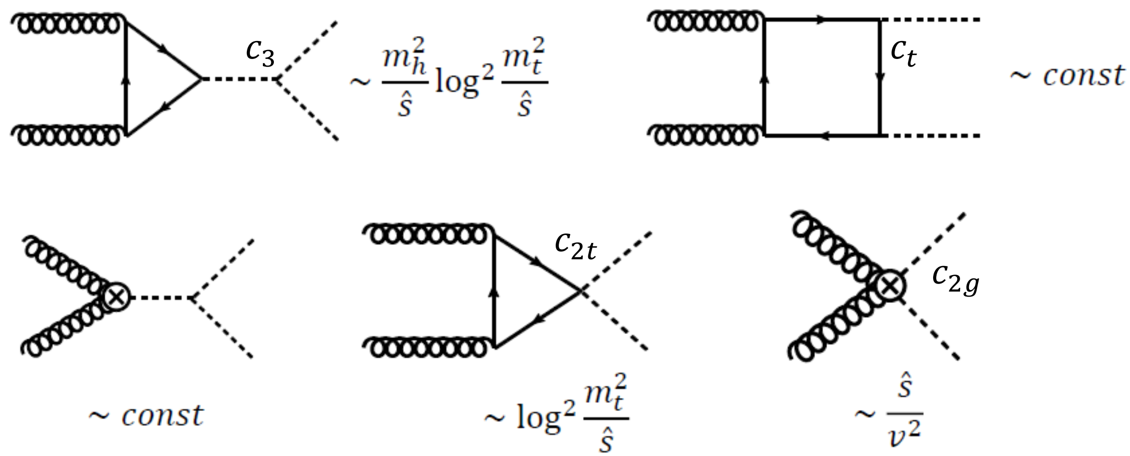
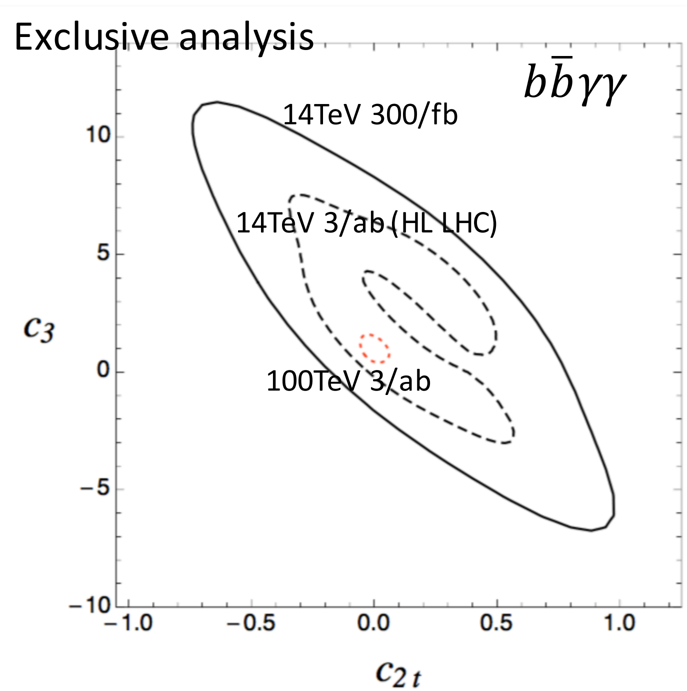
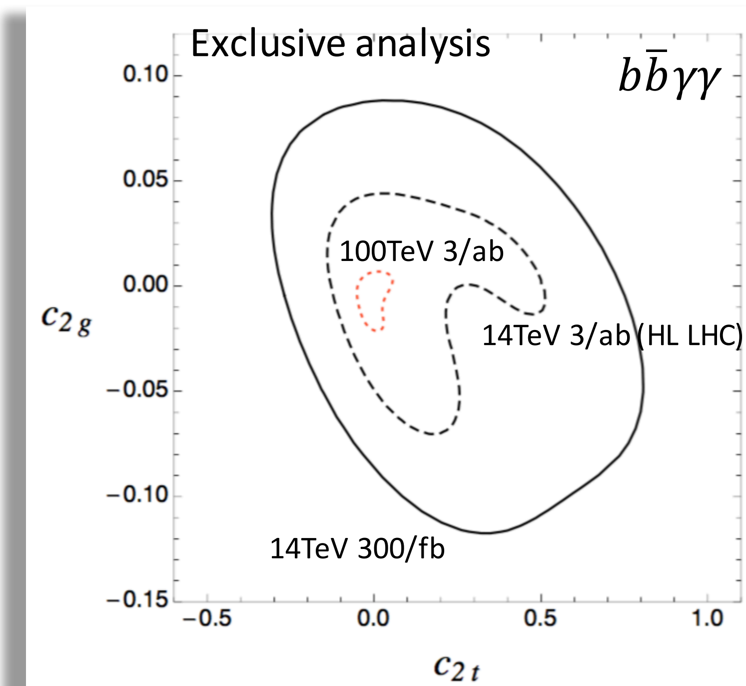
Anomalous couplings in the unitary basis







HH process vs single H data

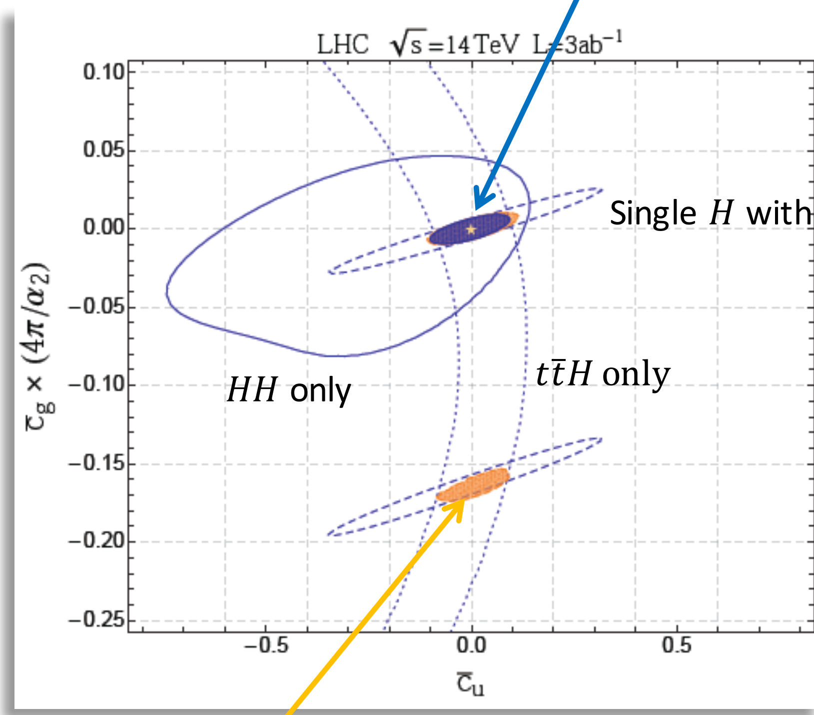
in Higgs doublet basis

$$c_g = c_{2g} = \bar{c}_g \left(\frac{4\pi}{\alpha_2}\right)$$

$$c_{2t} = 0 - \frac{1}{2}\bar{c}_H - \frac{3}{2}\bar{c}_u\,,$$

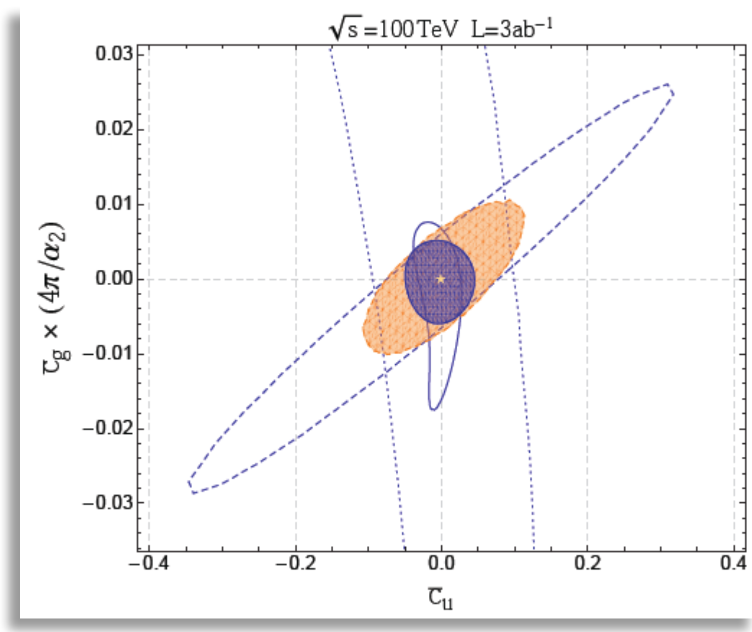
$$c_t = 1 - \frac{1}{2}\bar{c}_H - \bar{c}_u\,,$$

All single $H + HH$



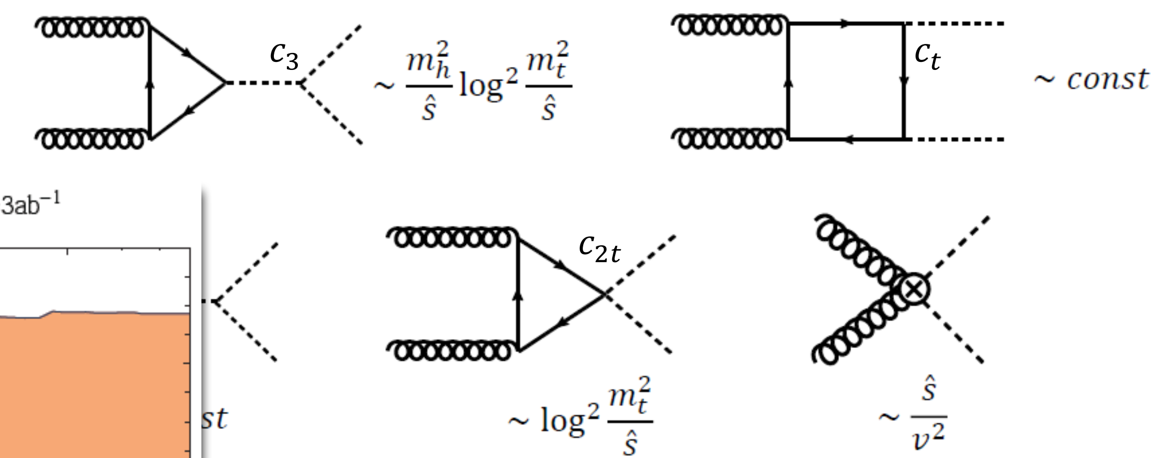
All single H

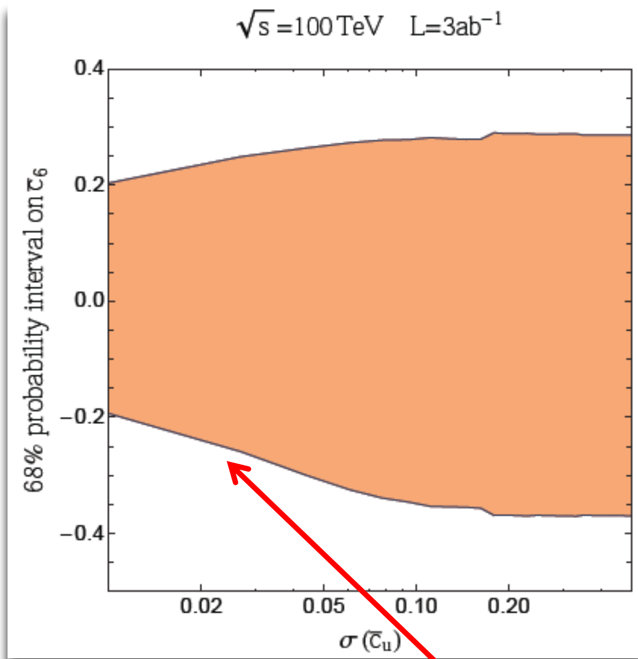
Azatov, Contino, Panico, Son arXiv:1502.00539



- ✓ Double Higgs can compete with single Higgs data on $\bar{c}_u$
- ✓ Double Higgs excludes one of islands in $\bar{c}_g$

✓ Uncertainty on Yukawa coupling affects the precision of HHH coupling



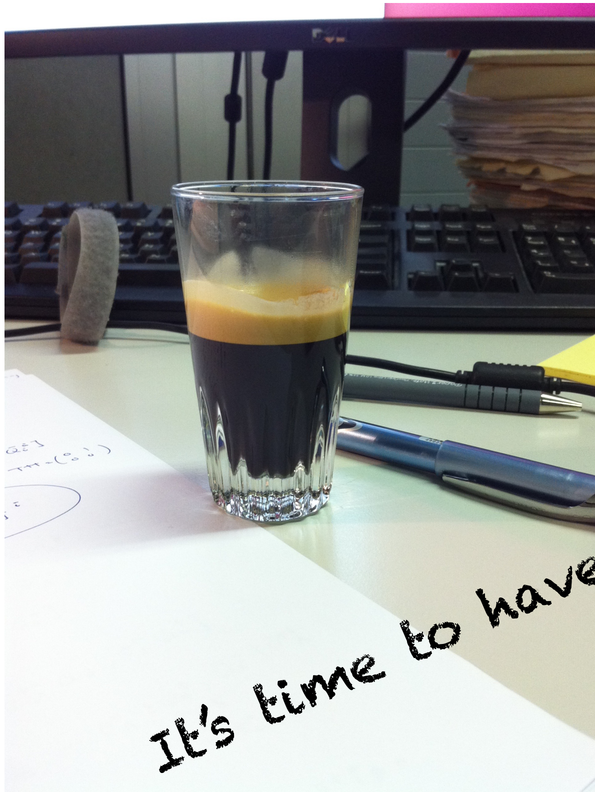


$$c_t = 1 - \frac{1}{2}\bar{c}_H - \bar{c}_u\,, \qquad c_{2t} = 0 - \frac{1}{2}\bar{c}_H - \frac{3}{2}\bar{c}_u\,,$$

Azatov, Contino, Panico, Son arXiv:1502.00539

✓ Precision on HHH coupling depends on statistical treatment (uncertainty on top Yukawa is correlated with precision of HHH coupling)

OK! Let me stop bullshitting ...



It's time to have caffeine injection