Mainz, April 16-19, 2018

Combined Analysis of double Higgs production via gluon fusion at the HL-LHC in the effective field theory approach

Minho Son
Korea Advanced Institute of Science and Technology (KAIST)

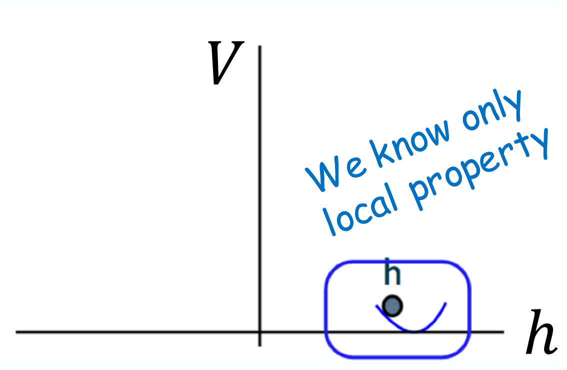
Based on

Azatov, Contino, SON, Panico 1512.00539

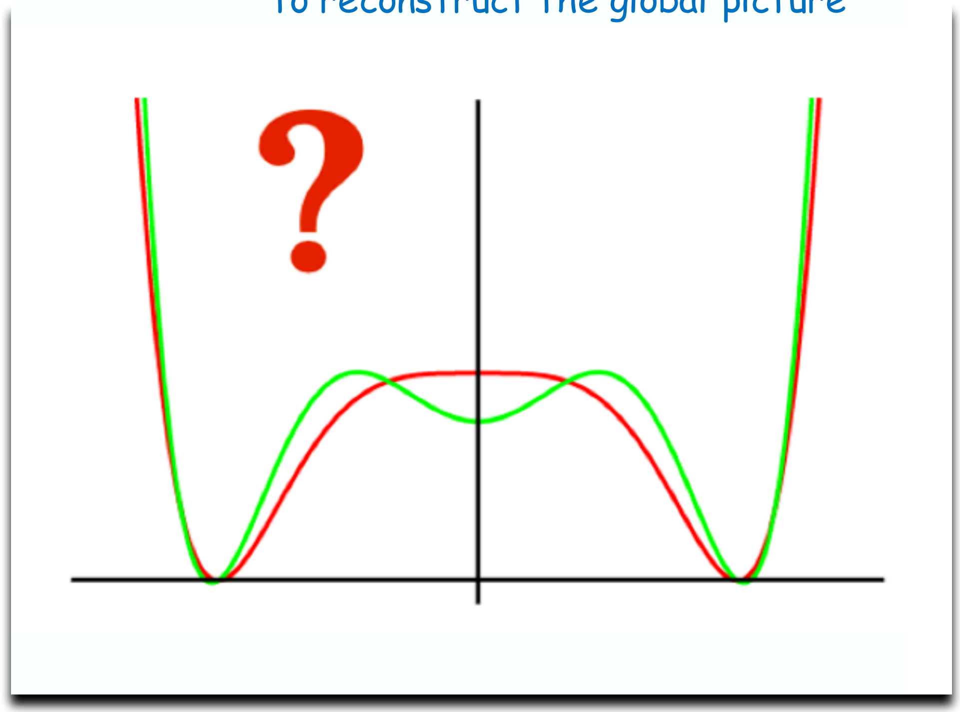
& Kim, SON, Sakaki 1801.06093

We know little about Higgs potential
in Bottom-up approach

Higgs self coupling measurement is crucial
to reconstruct the global picture



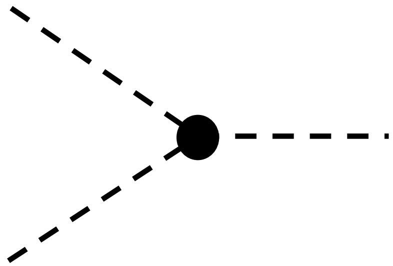
m_h = 125 GeV
v = 246 GeV



Cartoon stolen
from the talk by Liantao Wang

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

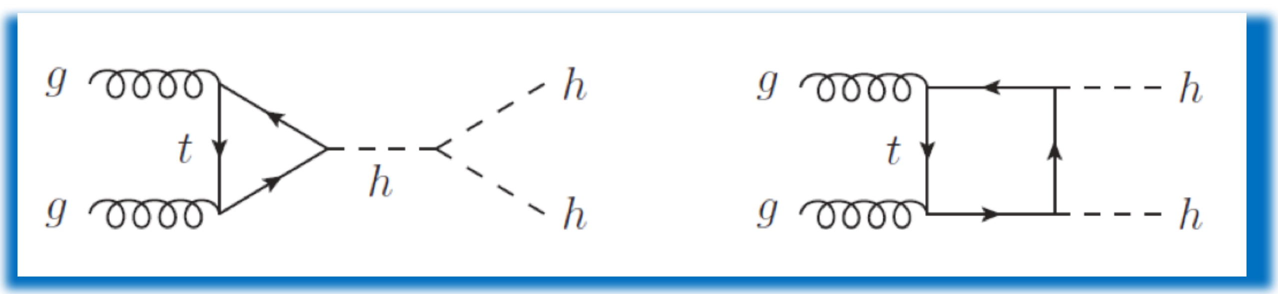
Cubic coupling



HH production via gluon fusion is known to be the best channel

Negatively Interfere

σ [



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

$\times$ BR

Very small signal rate

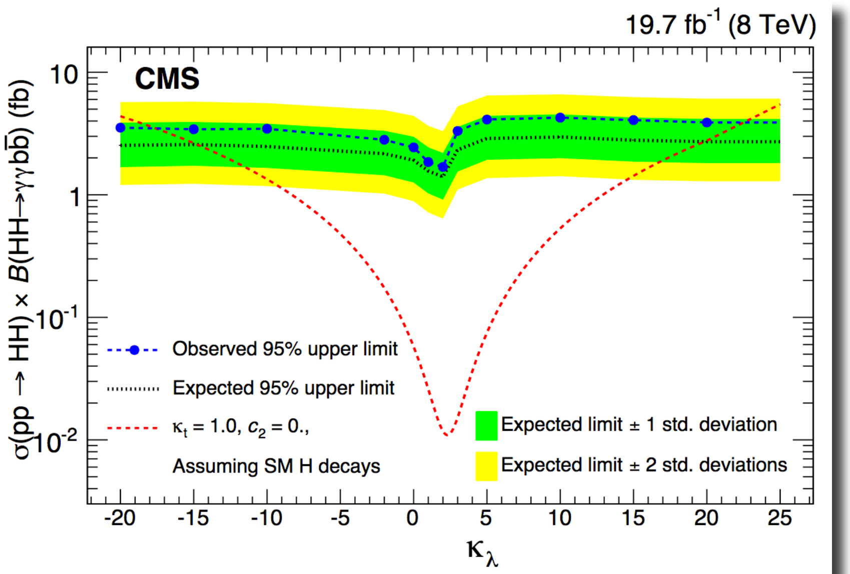
e.g. $b\bar{b}\gamma\gamma$ (0.264%)

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

Threshold region = big backgrounds

Cubic coupling using real data @ LHC, 8 TeV, 13 TeV

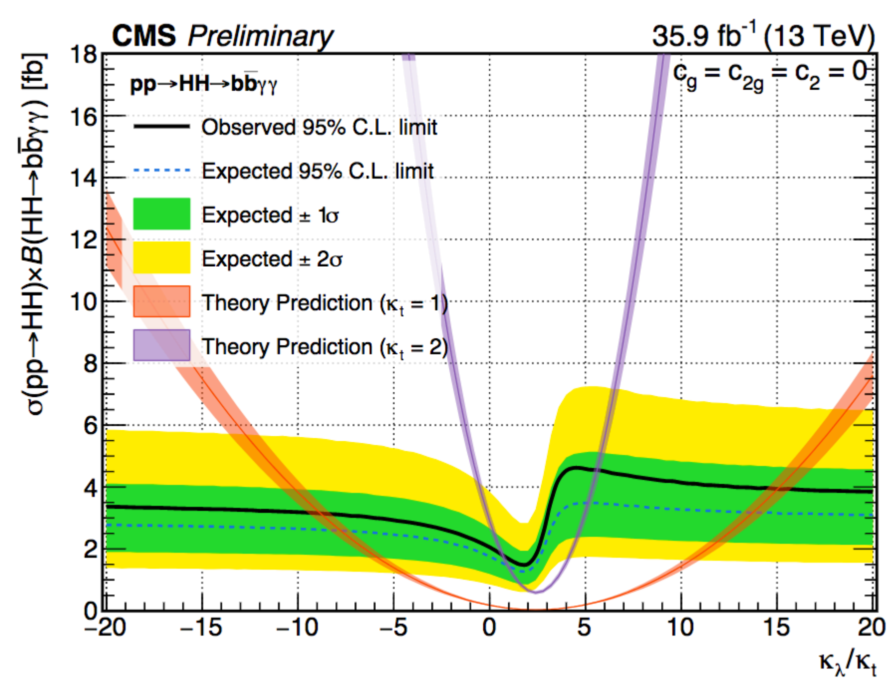
CMS-HIG-13-032 (1603.06896)



$$\Delta\mathcal{L} = \kappa_\lambda\, \lambda^{\rm SM} v\, H^3 - \frac{m_{\rm t}}{v}(v + \kappa_{\rm t} H + \frac{c_2}{v} HH)\,(\bar{t}_{\rm L} t_{\rm R} + {\rm h.c.}),$$

$$\kappa_\lambda < -17 \;\&\; \kappa_\lambda > 22.5$$

CMS PAS HIG-17-008



$$\Delta\mathcal{L} = \kappa_\lambda\, \lambda_{SM} v\, {\rm H}^3 - \frac{m_{\rm t}}{v}(v + \kappa_t {\rm H} + \frac{c_2}{v}{\rm H}^2)\,(\bar{\rm t}_{\rm L}{\rm t}_{\rm R} + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}(c_g {\rm H} - \frac{c_{2g}}{2v}{\rm H}^2)\, G^{\mu\nu}G_{\mu\nu}$$

$$\kappa_\lambda < -8.82 \;\&\; \kappa_\lambda > 15.04$$

- ✓ Constraint by current data is not meaningful!
- ✓ Situation at LHC with 300/fb will be similarly bad

Where do we head for after LHC era?

After LHC-era

HL-LHC

Lepton colliders

CEPC,FCC-ee, ILC,CLIC

Hadron Colliders

HE-LHC, FCC-hh (@ 100 TeV)

Good enough to achieve
a few - 10’s % precision

...
ILC TDR
Barklow, Fujii, Jung, Peskin, Tian 18’
Durieux, Grojean, Gu, Wang 17’
Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon 17’

Where do we head for after LHC era?

After LHC-era

- HL-LHC
- Lepton colliders
  CEPC,FCC-ee, ILC,CLIC
- Hadron Colliders
  HE-LHC, FCC-hh (@ 100 TeV)

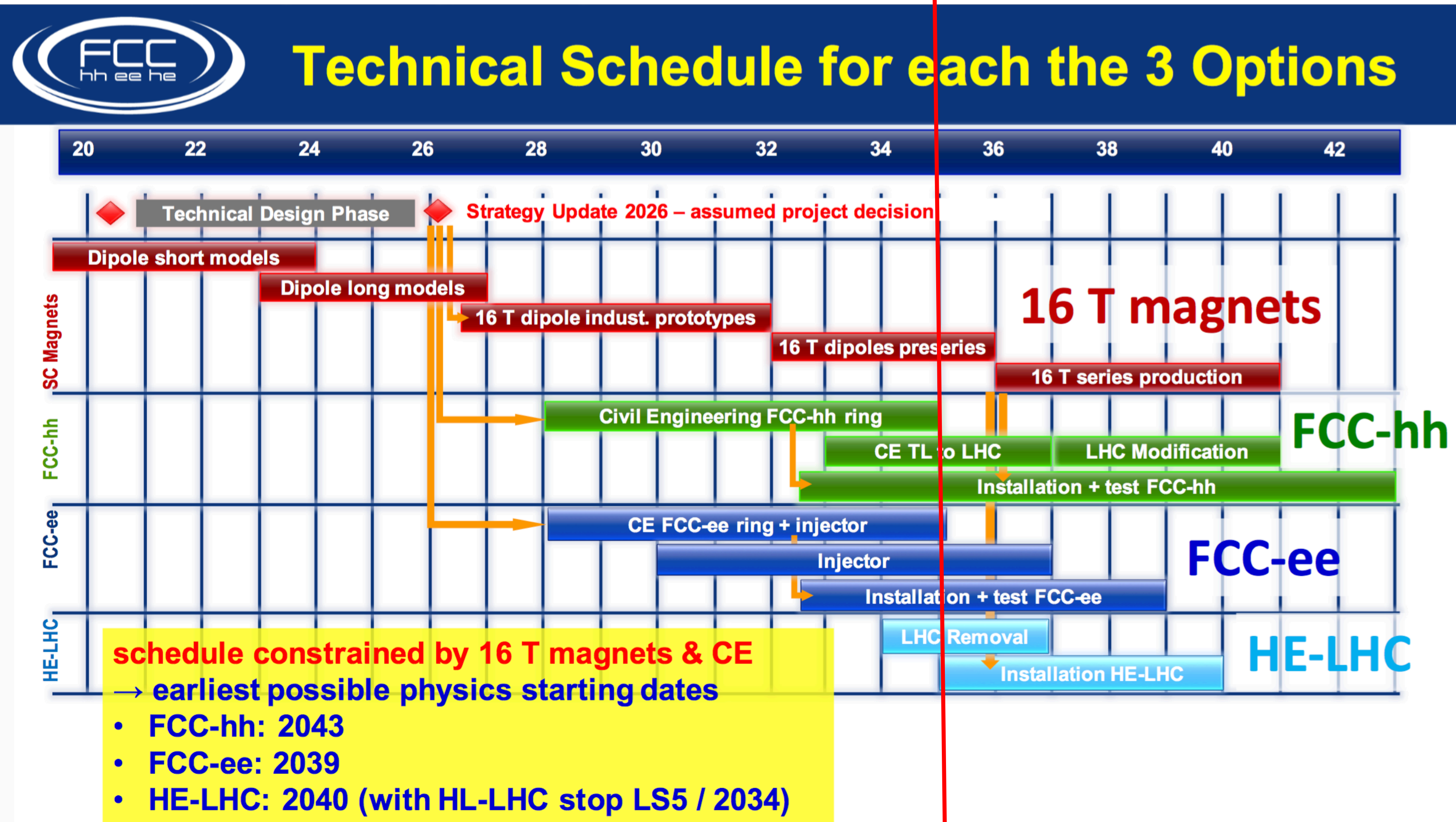
Seems need 100 TeV to achieve
a few - % precision

E.g. $40\times$ enhanced xsec due to PDF, 30/ab

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

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

Taken from
M. Benedikt, FCC Physics workshop, 11 January 2018



HL-LHC (~2025 - 2035)

✓ Obviously HL-LHC is the earliest future collider

High-Luminosity LHC

As the earliest future collider,
Let us do our best to improve HHH @ HL LHC instead of waiting for uncertain future colliders

ATLAS/CMS projection @ HL-LHC, 3000/fb

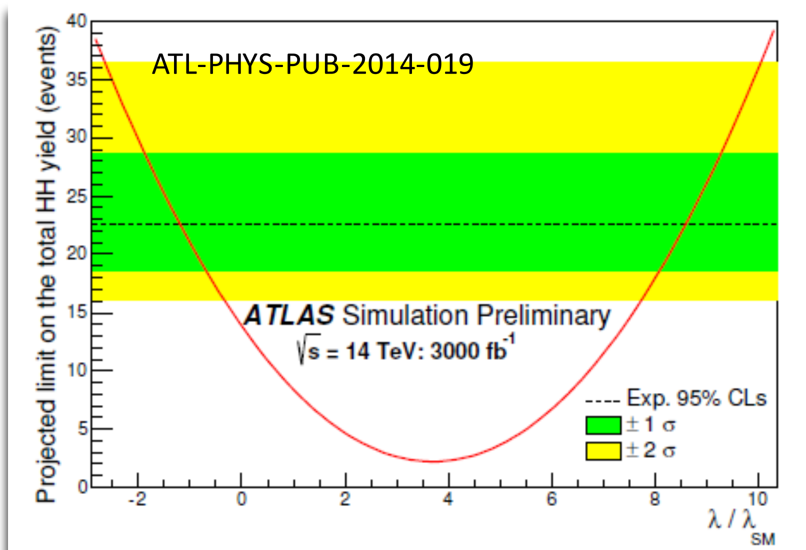
✓ Still very tough process

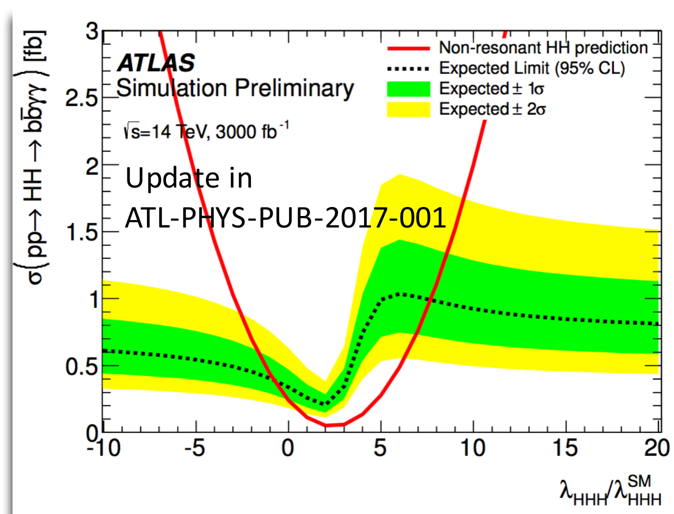
Seems to be the best channel so far

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

ATL-PHYS-PUB-2014-019

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

ATLAS/CMS projection of Cubic coupling @ HL-LHC, 3000/fb

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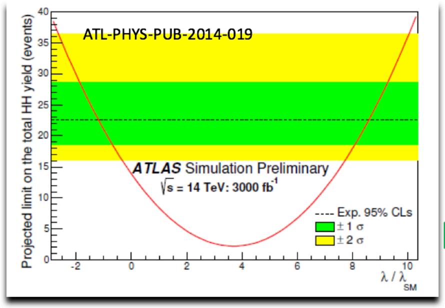
  Seems to be the best channel so far

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



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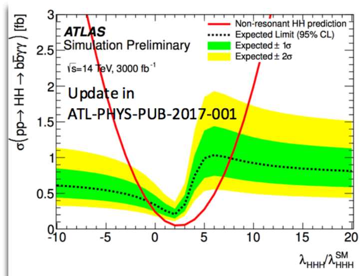

Similarly for $b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-$ by CMS &

CMS FTR-15-002-pas

Above ATLAS/CMS projections are our baseline analysis from which we try to improve further

1. Combined Analysis of various channels

See also CMS PAS FTR-15-002

$b\bar{b}\gamma\gamma$ 0.264% $\xrightarrow{28\times}$ $b\bar{b}\tau^+\tau^-$ 7.35%

- BKG simulation of $b\bar{b}\gamma\gamma$ channel is extremely difficult

1. Fakes, $j, c \to b, j \to \tau, \gamma$
2. Matching (double counting, part of k-factor)

Our treatment is same as ATLAS

- $b\bar{b}\tau^+\tau^-$ in most early theory literature was severely overestimated

E.g. no τ-decay, optimistic τ reconstruction eff., negligible fake rates

1. $\tau_h\tau_h$: fully hadronic (44.4%), $\tau_h\tau_l$: semileptonic (39.8%)
2. $\tau^+\tau^-$ reconstruction is tough (e.g. against Z+jets)
3. Fakes are big

- In reality, $b\bar{b}\tau^+\tau^-$ can be at best comparable with $b\bar{b}\gamma\gamma$ due to a series of penalties

: combining makes sense

We include all these factors in our analysis
(see backup slides for the detail)

1. Combined Analysis of various channels

2. Parametrize the precision of HHH as a function of any \`improvable' parameter

ATL-PHYS-PUB-2014-019

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Fakes are big!

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

Currently used tag, mis-tag rates of heavy-flavor, tau-leptons, photons which are not good will not be final!

- b, c, τ-taggings against QCD-jets will be improved, e.g. machine learning
- Prompt b, c-tagging vs merged b, c-jets ,e.g. from $g \to b\bar{b}, c\bar{c}$ splitting
- Machine learning/multivariate analysis applied to the analysis itself
- ….

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

1. Combined Analysis of various channels

2. Parametrize the precision of HHH as a function of any \`improvable' parameter

Optimistic HL-LHC (OPT-HL-LHC)

Assume a set of improved parameters
: or make your goal for parameters
to achieve the desired precision of HHH

$\epsilon_{b\to b} = 0.8, \epsilon_{c\to b} = 0.1, \epsilon_{j\to b} = 0.01$

$\epsilon_{\tau\to\tau} = 0.7, \epsilon_{j\to\tau} = 0.001$

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

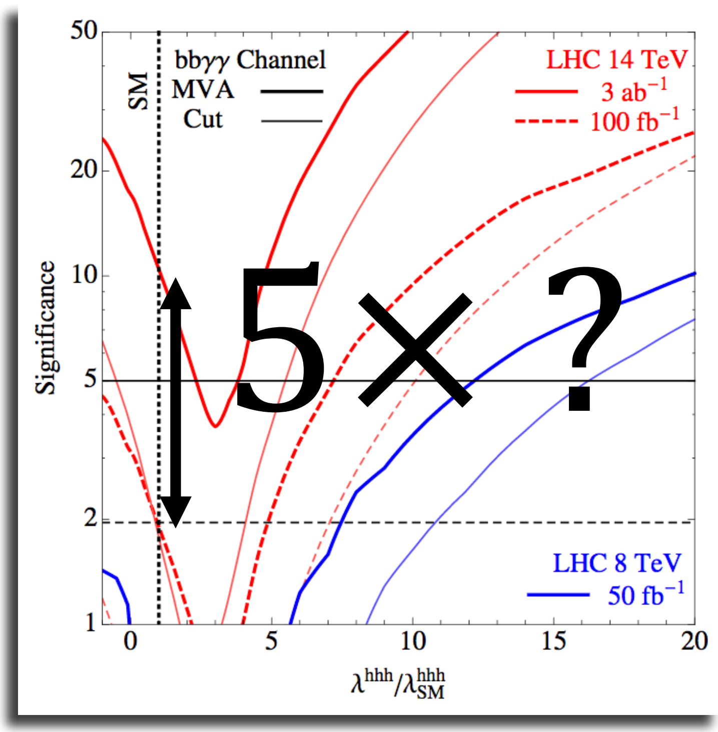
20% improvement of Jet E resolution

Currently used tag, mis-tag rates of heavy flavor, tau-leptons, photons are not good & they will not be final!

1. Combined Analysis of various channels

2. Parametrize the precision of HHH as a function of any \`improvable' parameter

3. Exploit Multivariate Analysis (Boost Decision Tree)



Barger, Everett, Jackson, Shaughnessy 13'

- when variables are not correlated

e.g. signal region has a rectangular shape

Cut-and-count analysis might reach the maximal performance via optimization

- when variables are correlated

e.g. signal region has a complicated boundary

Cut-and-count analysis may not be the best option.

1. Combined Analysis of various channels

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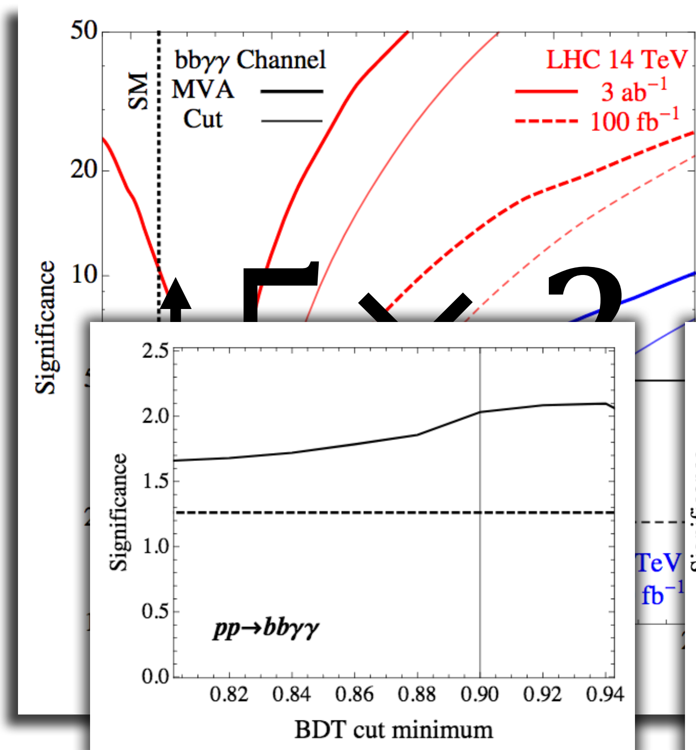

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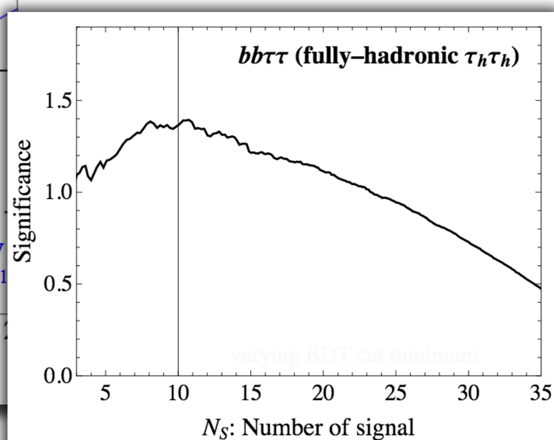
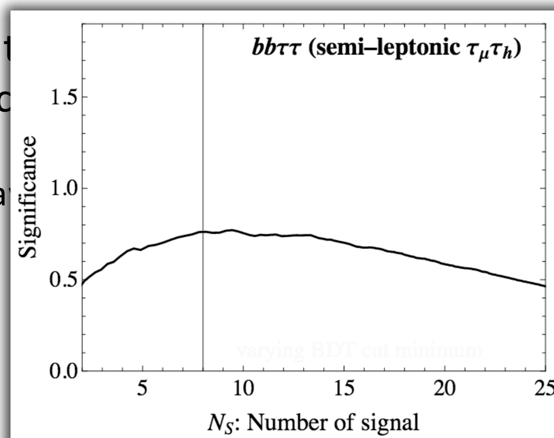




Barger, Everett, Jackson, Shaughnessy 13'

We have used BDT method. Improvement is up to factor of 2 (not ~ 5x !)

1. Combined Analysis of various channels

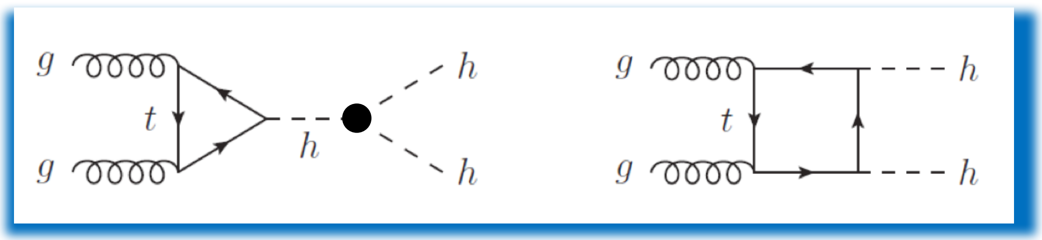
2. Parametrize the precision of HHH as a function of any \`improvable' parameter

3. Exploit Multivariate Analysis (Boost Decision Tree)

4. Marginalization (global fit within HH & some H)

From the Effective Field Theory point of view, varying only HHH is not well-motivated unless a selection of HHH is associated with a symmetry, specific UV completion, or a hidden fine-tuning is involved

Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer 12'
Goertz, Papaefstathiou, Yang, Zurita 14'
Chen, Low 14'
Azatov, Contino, Panico, SON, 15'



1. Combined Analysis of various channels

2. Parametrize the precision of HHH as a function of any \`improvable' parameter

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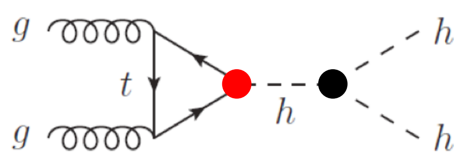
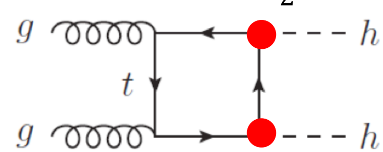
4. Marginalization (global fit within HH & some H)

We take the Effective Field Theory approach keeping all EFT coefficients

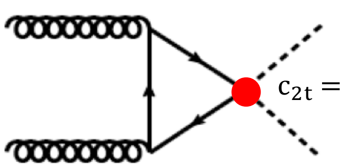
$$\Delta\mathcal{L}_6 \ni \frac{\bar{c}_H}{2v^2}\,\partial_\mu|H|^2\partial^\mu|H|^2 + \frac{\bar{c}_u}{v^2}\,y_u\bar{q}_L H u_R|H|^2 - \frac{\bar{c}_6}{v^2}\frac{m_h^2}{2v^2}|H|^6 + \frac{\bar{c}_g g_s^2}{m_W^2}|H|^2 G_{\mu\nu}G^{\mu\nu}$$

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

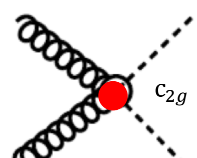




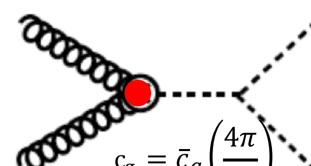
✓ EFT coefficients are correlated. E.g. precision of Yukawa coupling affects the precision of the HHH.



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



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

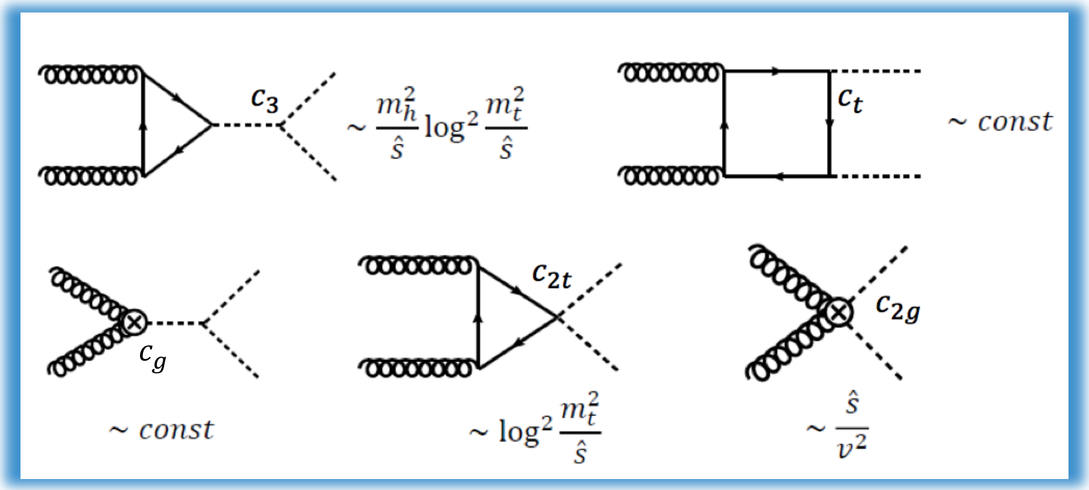


$$c_g = \bar{c}_g\left(\frac{4\pi}{\alpha_2}\right)$$

Non-linear tthh interaction

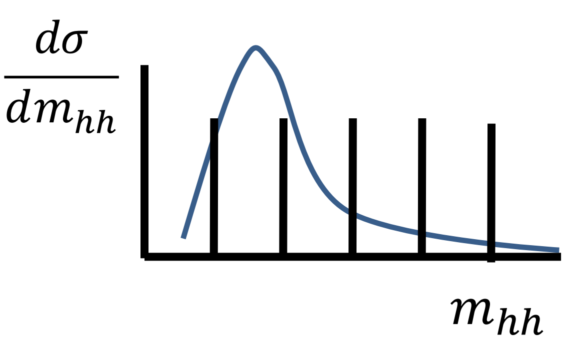
Anomalous Higgs Couplings in EFT approach

E-dependence vs Shape analysis



- All diagrams have different energy-dependences.
- Different E-dependence breaks degeneracy among BSM effects
- $m_{hh} = \sqrt{\hat{s}}$ is an important shape variable

Exclusive analysis



$b\bar{b}\gamma\gamma$: 6 m_{HH} bins

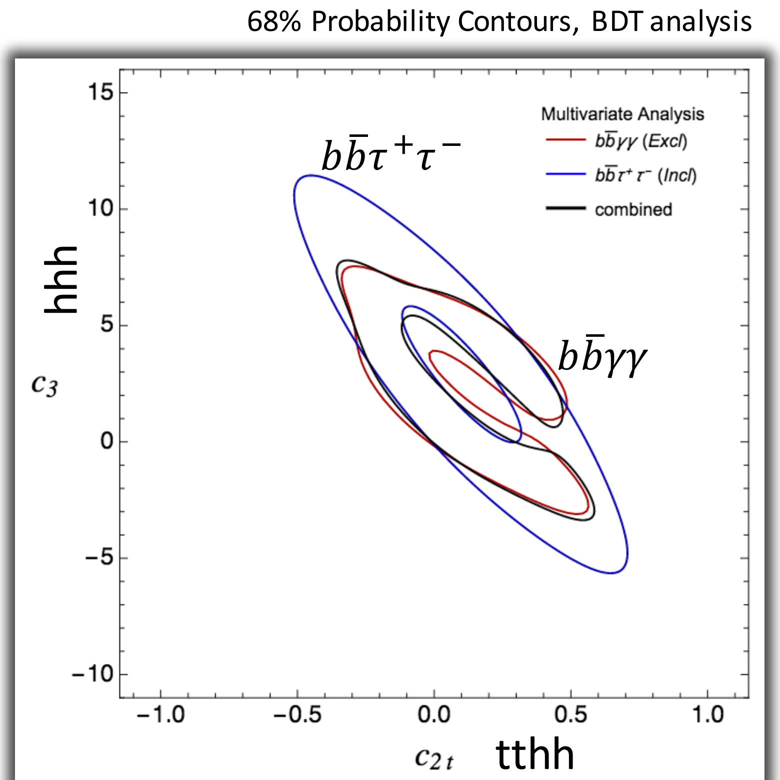
\+ Recycled from Azatov et al 15'

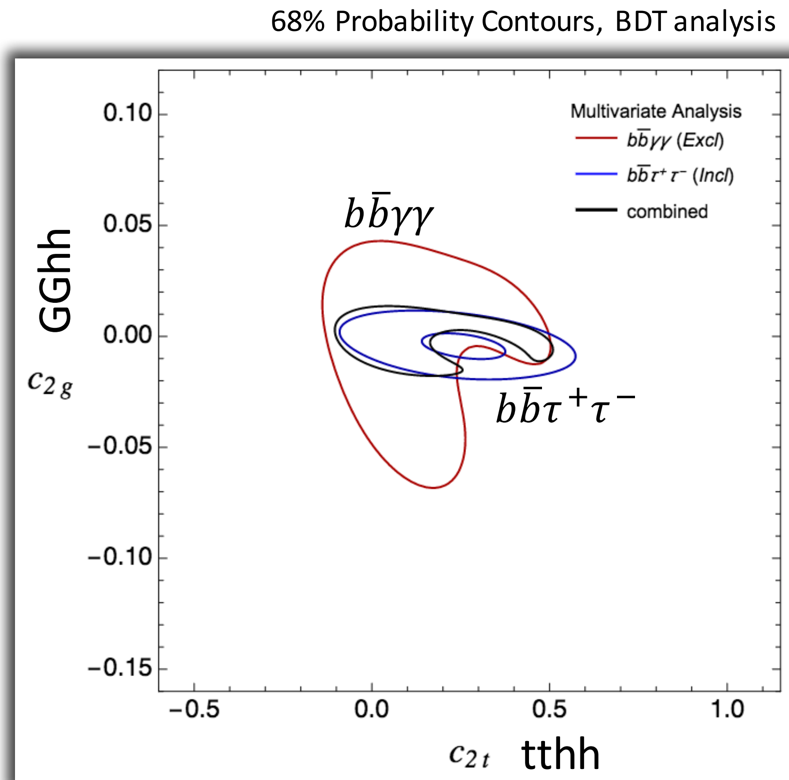
$b\bar{b}\tau^+\tau^-$: no shape analysis

due to technical reason ($\sqrt{\hat{s}} \neq m_{hh}^T$)

On the sensitivity of EFT coefficients

In the non-linear basis

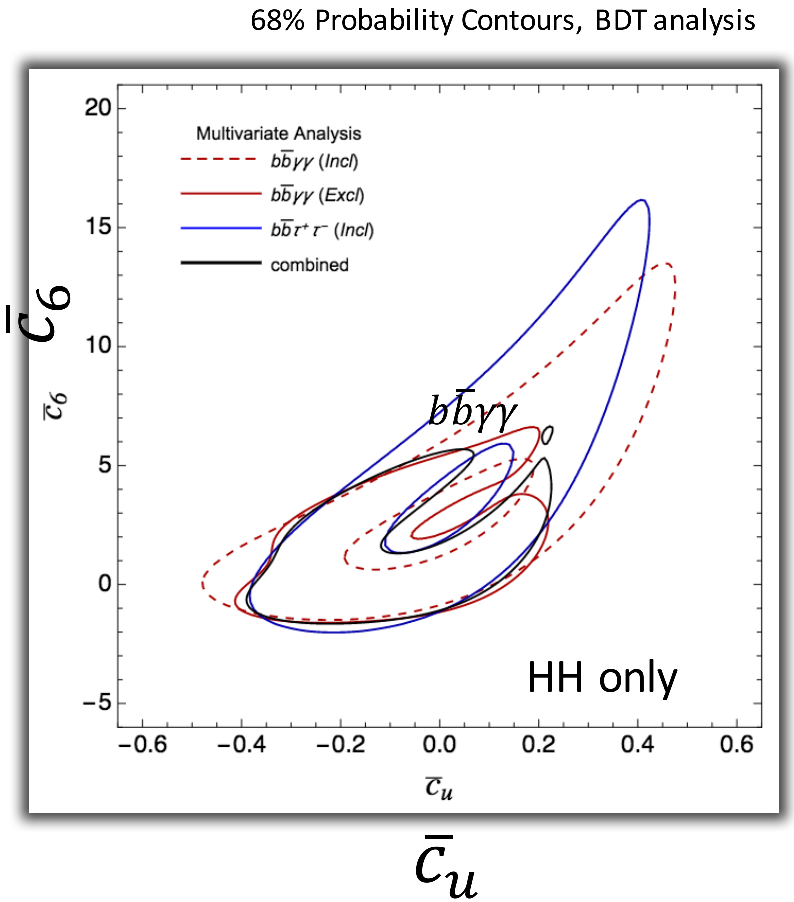


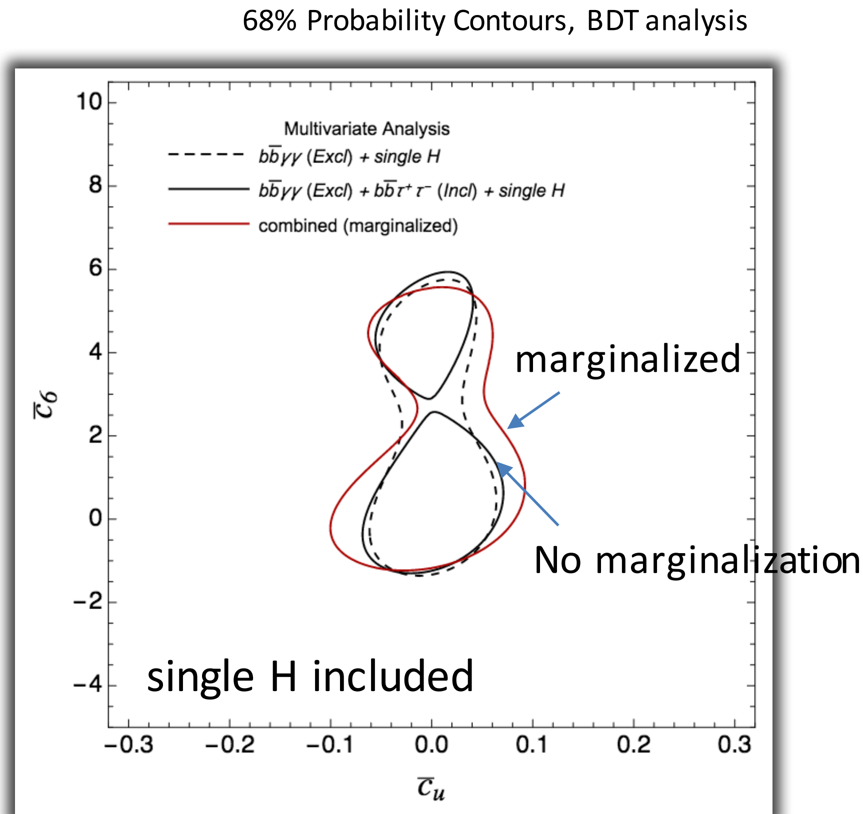


Anti-correlation between c_3 and c_{2t}
: marginalization has a non-negligible impact

$b\bar{b}\tau^+\tau^-$ outperforms $b\bar{b}\gamma\gamma$ on c_{2g}

In the linear basis





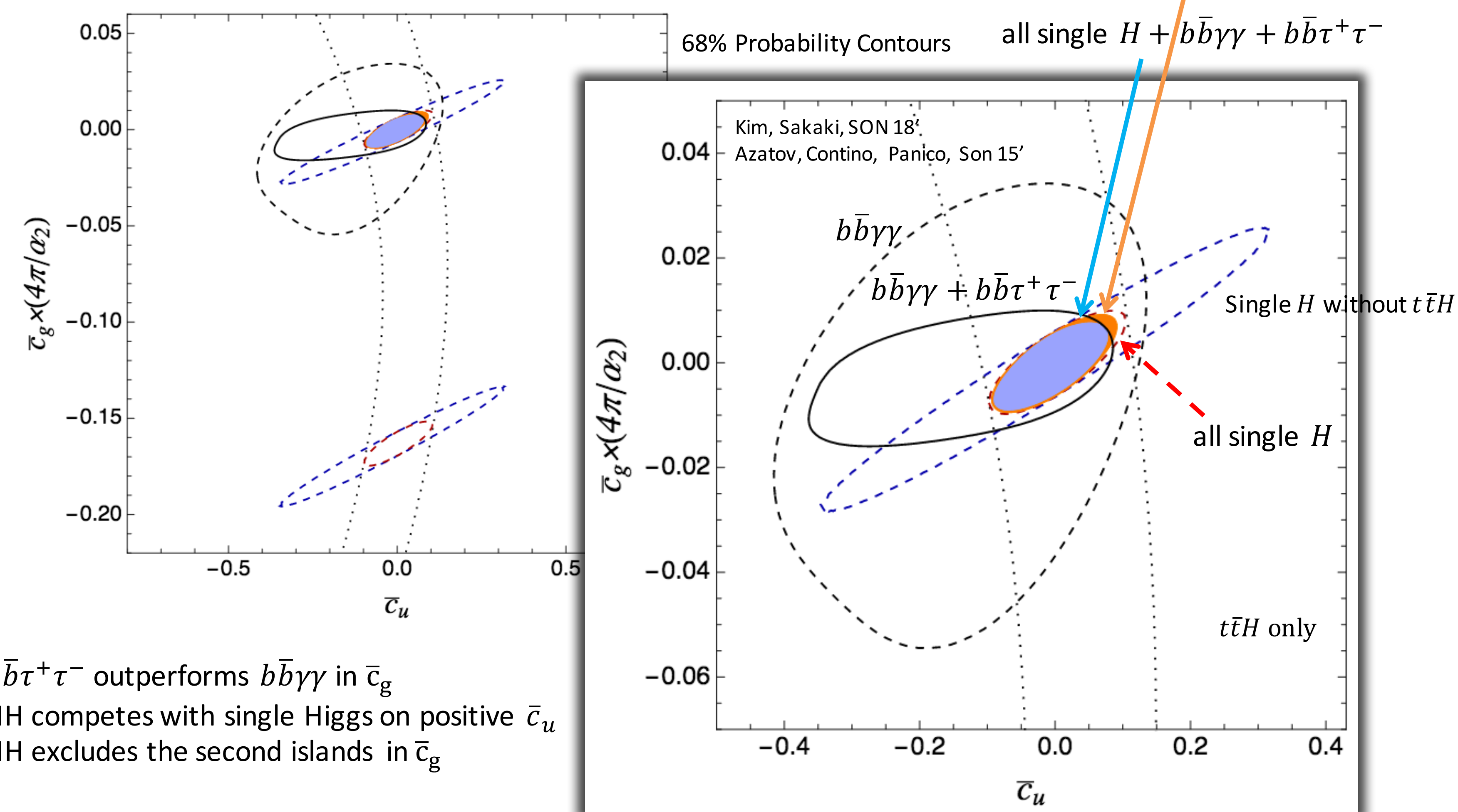
1. Little improvement of HHH by $b\bar{b}\tau^+\tau^-$
2. Single Higgs data is important, especially for $\bar{c}_u$
3. Marginalization over $\bar{c}_g$ is significant

Double H vs single H

In the linear basis

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

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



1. $b\bar{b}\tau^+\tau^-$ outperforms $b\bar{b}\gamma\gamma$ in $\bar{c}_g$
2. HH competes with single Higgs on positive $\bar{c}_u$
3. HH excludes the second islands in $\bar{c}_g$

Focus on

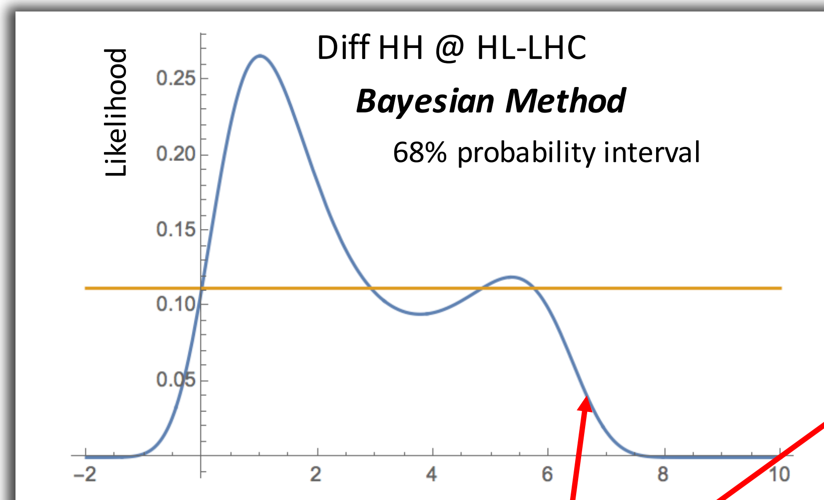
Higgs self coupling

We will investigate 1D likelihood for HHH

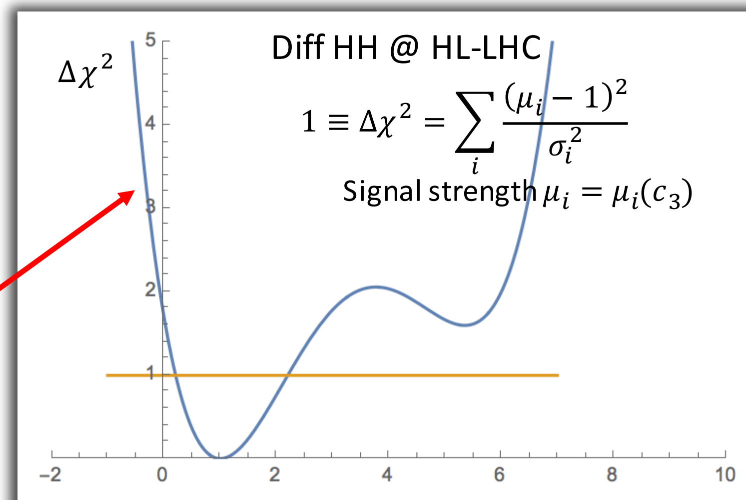
We choose ``Bayesian" Method

Comparing literature needs to be done within the same statistical treatment especially for highly `non-Gaussian' likelihood

What could possibly happen to same likelihood due to different statistical treatment



VS

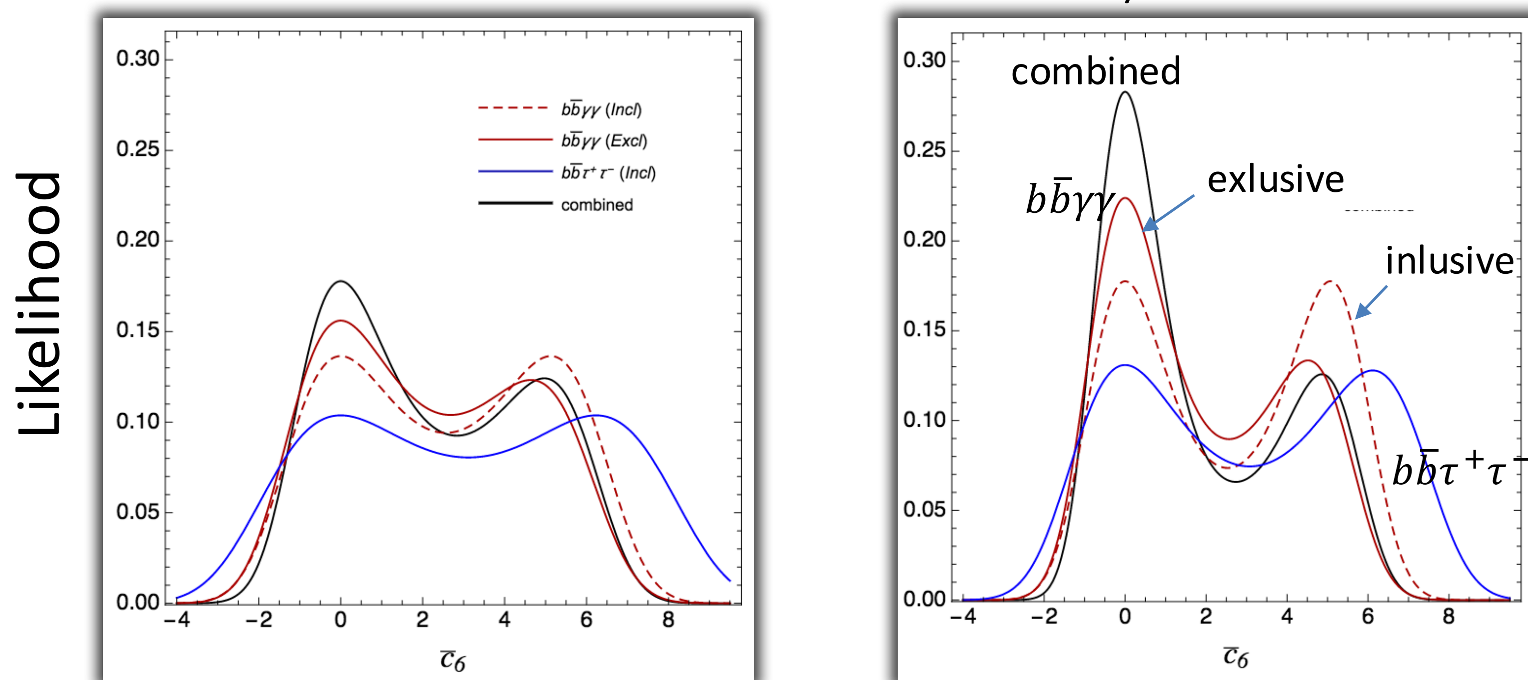


Same Likelihood

✓ You may get artificially better sensitivity. Pay attention to the statistical treatment!

Cut-and-count with ATLAS cuts

BDT analysis



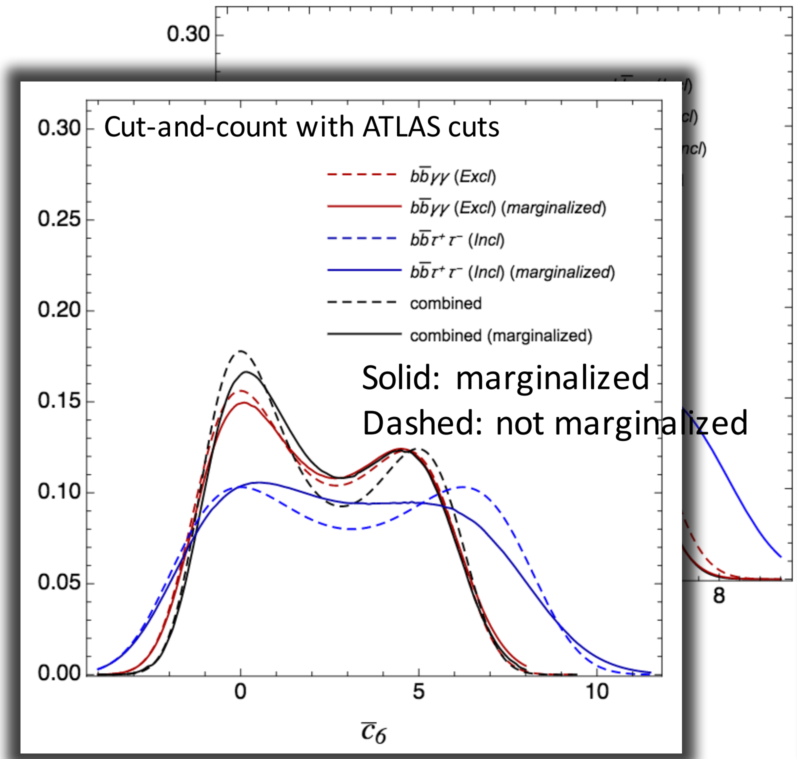
Inclusive vs Exclusive

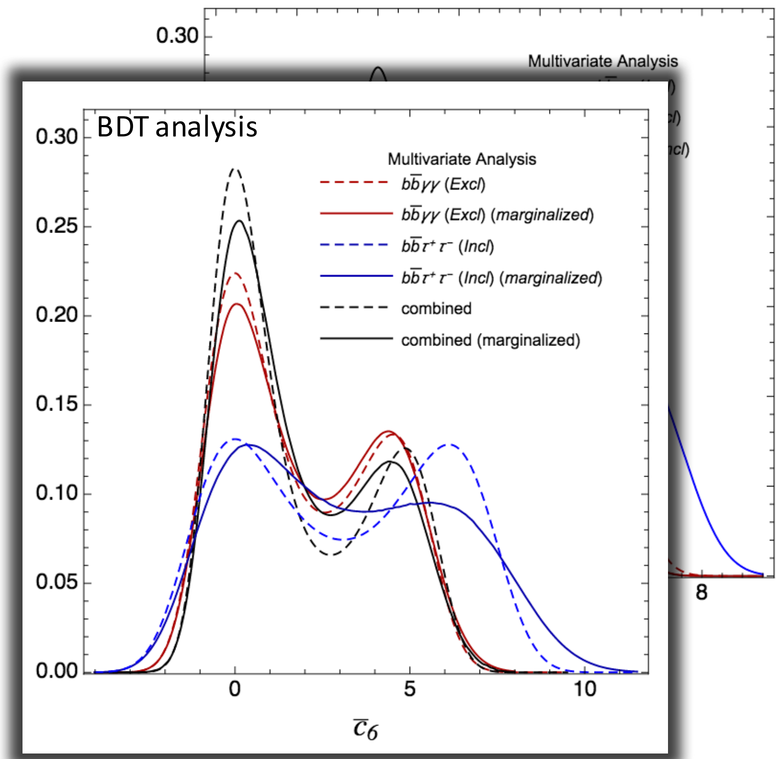
- Exclusive analysis breaks degeneracy of two peaks

Cut-and-count vs Multivariate

- Benefit of multivariate analysis is pronounced in the second peak. Improvement of the 68% prob. interval around SM is weak (characteristic of highly non-Gaussian likelihood at the HL-LHC)

No marginalization vs Marginalization





HL-LHC (3 ab^{-1})	Allowed region on $\bar{c}_6$ 68% probability	95% probability
Cut-based analysis		
$b\bar{b}\gamma\gamma$ (exclusive)	$[-0.98, 2.2] \cup [3.1, 5.3]$	$[-1.8, 6.6]$
$b\bar{b}\tau^+\tau^-$	$[-0.87, 6.1]$	$[-2.5, 8.8]$
Combined	$[-0.91, 2.3] \cup [3.4, 5.3]$	$[-1.6, 6.5]$
Multivariate analysis		
$b\bar{b}\gamma\gamma$ (exclusive)	$[-0.99, 1.8] \cup [3.4, 5.1]$	$[-1.4, 5.9]$
$b\bar{b}\tau^+\tau^-$	$[-0.89, 3.3] \cup [4.1, 6.4]$	$[-1.8, 8.5]$
Combined	$[-0.96, 1.9] \cup [3.8, 5.0]$	$[-1.3, 5.8]$

68% Probability Interval

$$\bar{c}_6 = [-0.96, 1.9] \cup [3.8, 5.0]$$

$$\bar{c}_6^{1=\Delta\chi^2} = [-0.7, 1.3]$$

On the effect of

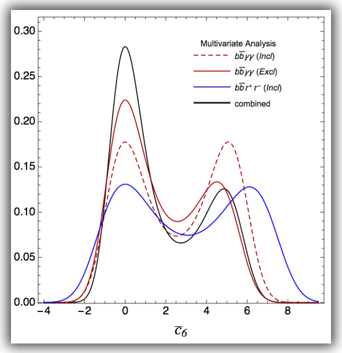
Future Phenomenological Studies

So far we used the same tag, mis-tag rates and so on as ATLAS analysis

ATLAS-PHYS-PUB-0214-019

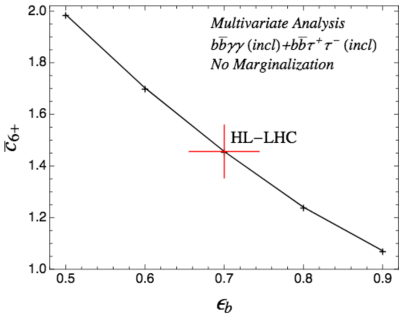
List of improvable parameters

$\bar{c}_{6+}$: positive deviation of the first interval around SM, E.g.

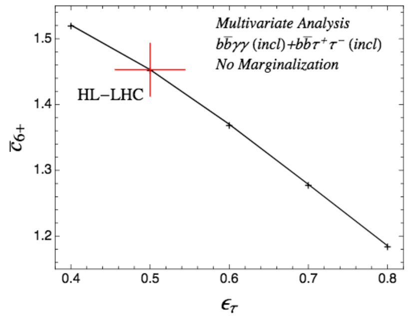


$\bar{c}_{6+}$

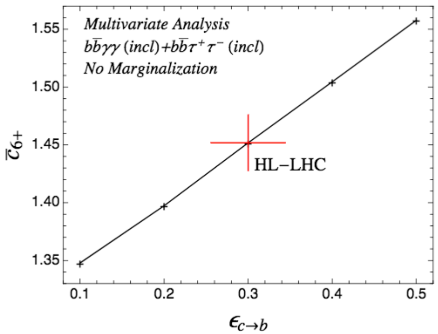
b-tag



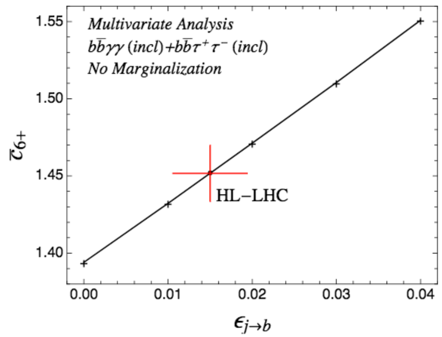
τ-tag



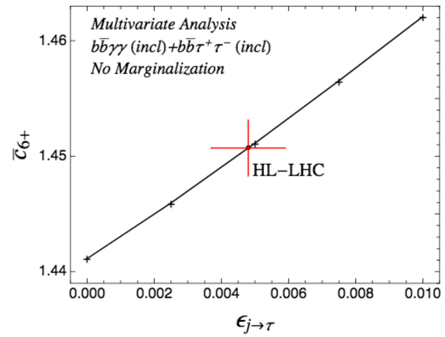
$c \to b$ mis-tag



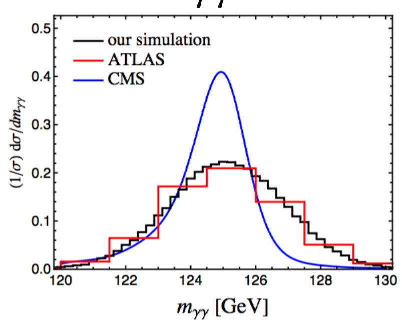
$j \to b$ mis-tag



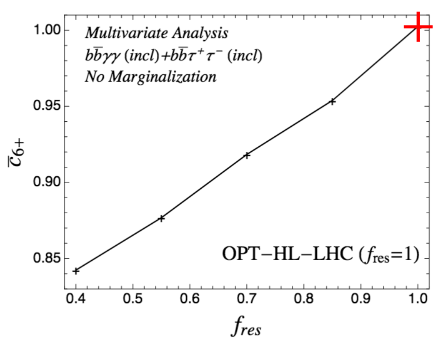
$j \to \tau$ mis-tag



$m_{\gamma\gamma}$ resolution



Jet E resolution



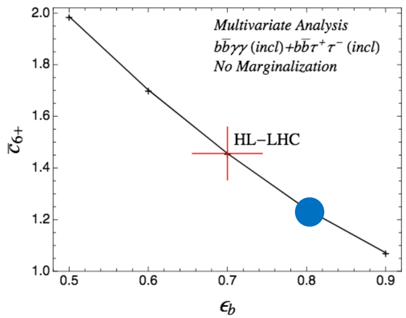
$$\frac{\sigma_{\rm res}}{p_T} = f_{\rm res}\sqrt{\frac{N(\langle\mu\rangle)^2}{p_T^2} + \frac{S^2}{p_T} + C^2}$$

To see accumulated effect of individual improvements

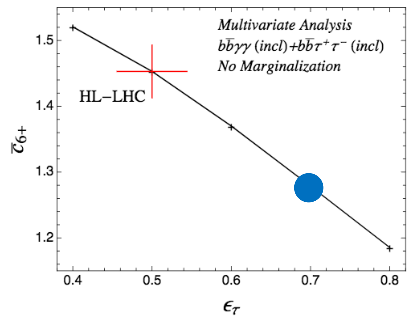
Let us make a benchmark scenario:

$\bar{c}_{6+}$

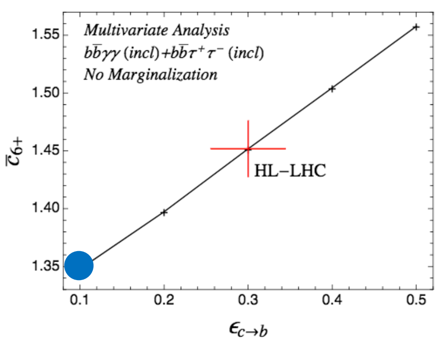
b-tag



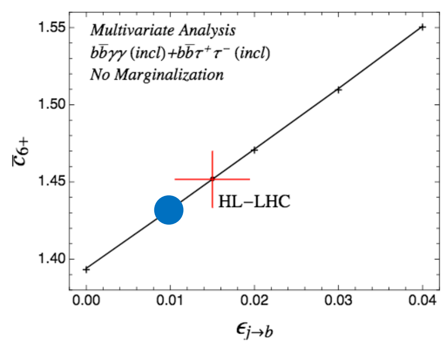
τ-tag



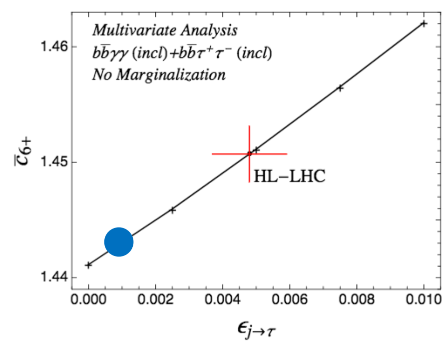
$c \to b$ mis-tag



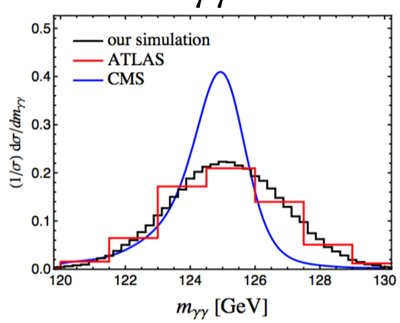
$j \to b$ mis-tag



$j \to \tau$ mis-tag

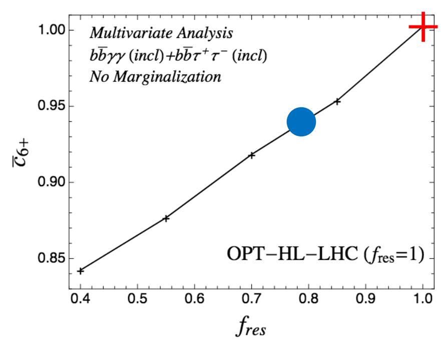


$m_{\gamma\gamma}$ resolution



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

Jet E resolution



$$\frac{\sigma_{\rm res}}{p_T} = f_{\rm res}\sqrt{\frac{N(\langle\mu\rangle)^2}{p_T^2} + \frac{S^2}{p_T} + C^2}$$

** this is better choice than what appeared in Kim et al 1801.06093

Optimistic HL-LHC (OPT-HL-LHC)

Assume a set of improved parameters
: or make your goal for parameters
to achieve the desired precision of HHH

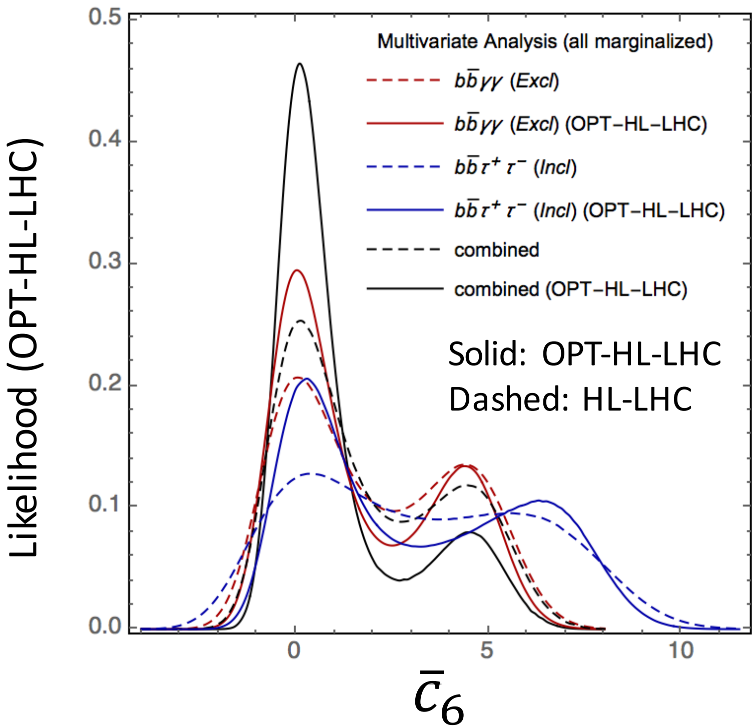
$\epsilon_{b\to b} = 0.8, \epsilon_{c\to b} = 0.1, \epsilon_{j\to b} = 0.01$

$\epsilon_{\tau\to\tau} = 0.7, \epsilon_{j\to\tau} = 0.001$

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

20% improvement of Jet E resolution

* Still includes only muons



OPT-HL-LHC (3 ab^{-1})	Allowed region on $\bar{c}_6$	
	68% probability	95% probability
$b\bar{b}\gamma\gamma$ (exclusive)	$[-0.97, 1.5] \cup [3.7, 5.0]$	$[-1.3, 5.6]$
$b\bar{b}\tau^+\tau^-$	$[-0.80, 2.1] \cup [4.9, 7.3]$	$[-1.1, 8.0]$
Combined	$[-0.8, 1.3]$	$[-1.1, 2.5] \cup [3.0, 5.5]$

68% Probability Interval

$[-0.8, 1.3]$

* $[-0.96, 1.9]$ U $[3.8, 5.0]$ $^{@\,\mathrm{HL-LHC}}$

* $\bar{c}_6^{1=\Delta\chi^2} = [-0.7, 1.3]^{@\,\mathrm{HL-LHC}}$

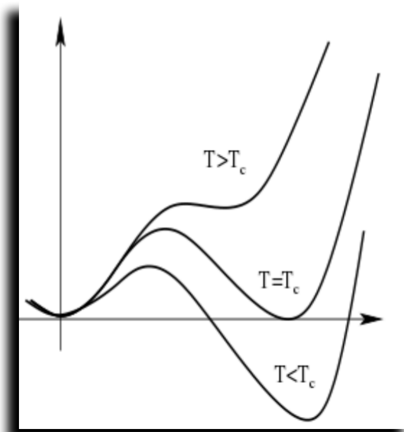
1. Second interval is gone
2. Two intervals even at 95% probability

(: non-Gaussianity matters at 95% CL)

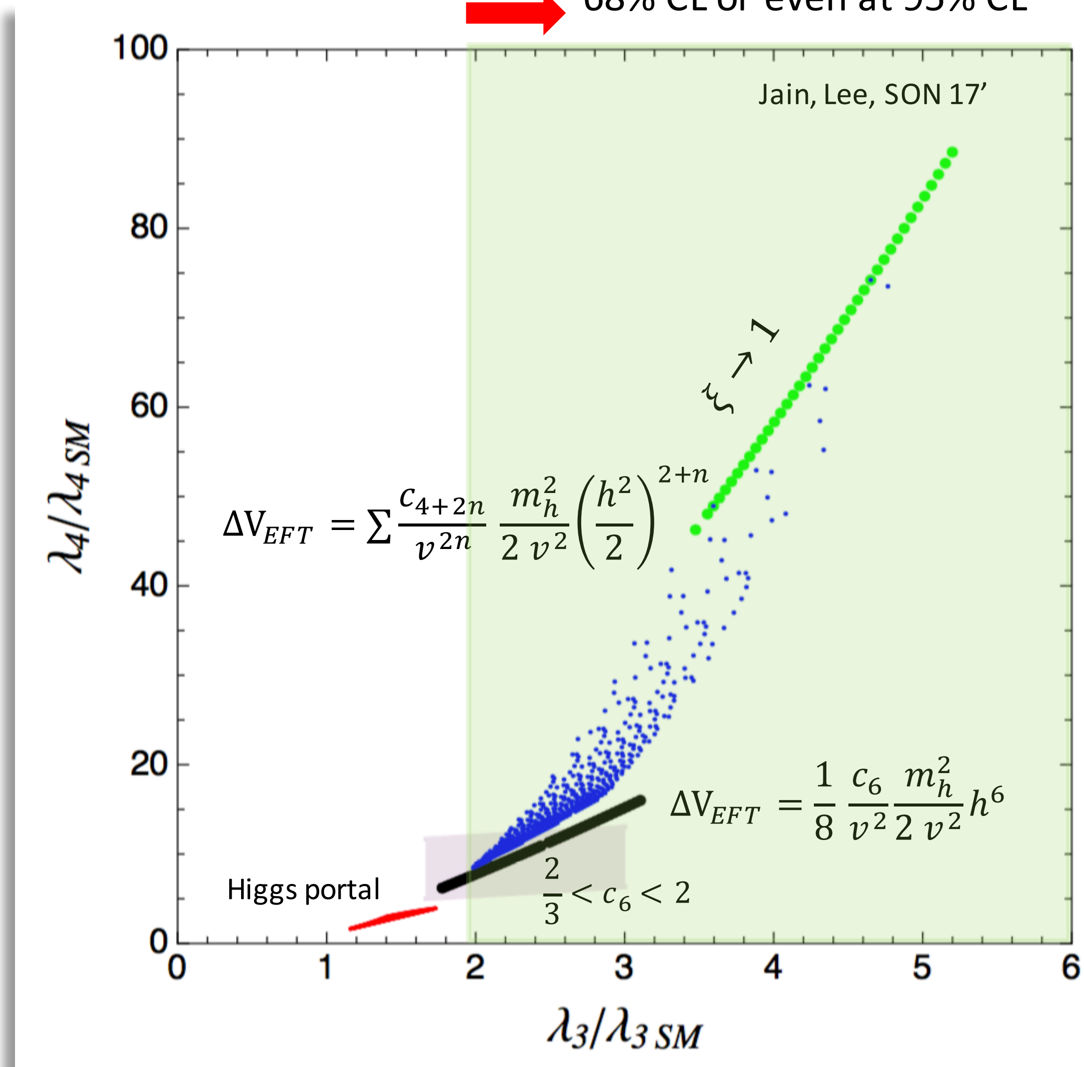
More tailored analysis, improved pars will improve precision further

Improvement at the level of $\mathcal{O}(1)$ determination is physically meaningful !!!

E.g. baryogenesis based on strong 1[st] order EWPT



Can be tested @ HL LHC with 68% CL or even at 95% CL



Constructing EFT model with $\lambda_3/\lambda_{3\,SM} \sim \mathcal{O}(1)$, while achieving parametric hierarchy $\mathcal{O}_H \ll \mathcal{O}_6$, would be very interesting

No summary

Thanks

Backup Slides

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

Our validation

ATLAS-PHYS-PUB-0214-019

Expected yields (3 ab^{-1})	ATLAS [32]	With ATLAS cuts	With cuts in [11]	MVA
$h(b\bar{b})h(\gamma\gamma)$	8.4	8.0	8.1	8.7
$b\bar{b}\gamma\gamma$	9.7	12.3	23	6.4
$c\bar{c}\gamma\gamma$	7.0	7.4	14	2.4
$b\bar{b}\gamma j$	8.4	7.5	16	1.2
$jj\gamma\gamma$	7.4	4.1	8.7	1.7
$t\bar{t}\gamma$	3.2	1.5	4.4	1.5
$t\bar{t}h(\gamma\gamma)$	6.1	5.5	6.8	3.7
$Z(b\bar{b})h(\gamma\gamma)$	2.7	1.2	0.86	1.0
$b\bar{b}h(\gamma\gamma)$	1.2	0.24	0.25	0.2
Total backgrounds	45.7	39.8	73.4	18.0

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

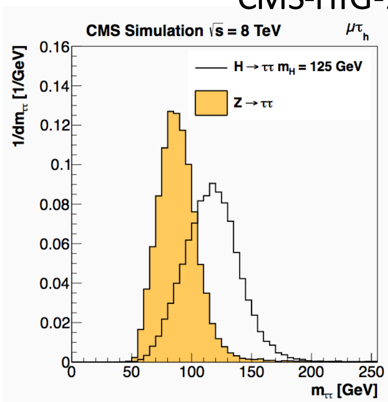
Expected yields (3 ab^{-1})	Fully-hadronic $\tau_h\tau_h$		Semi-leptonic $\tau_\mu\tau_h$	
	Cut-based Analysis	MVA	Cut-based Analysis	MVA
$h(b\bar{b})h(\tau^+\tau^-)$	5.71	10.	5.7	7.9
$t\bar{t}$	2.31	4.46	44.8	28.8
$t\bar{t}h$	7.63	7.37	13.1	12.9
$t\bar{t}V$	3.14	2.74	5.12	7.87
tW	5.37	7.52	28.3	12.6
$Z(\tau^+\tau^-)+\text{jets}$	18.4	25.0	10.1	32.7
hZ	1.72	2.22	1.16	3.8
VV	0.38	0.98	3.41	2.43
Total backgrounds	40.	50.3	106	101

Similar result to
CMS-PAS-FTR-15-002

$\tau^+\tau^-$ reconstruction

CMS uses Maximum Likelihood fit method : SVFIT

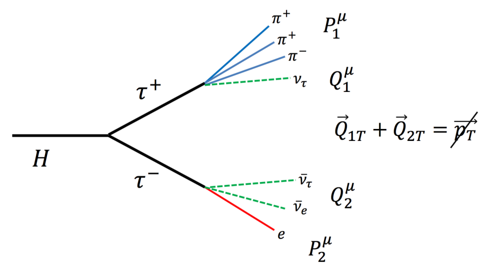
CMS-HIG-13-004

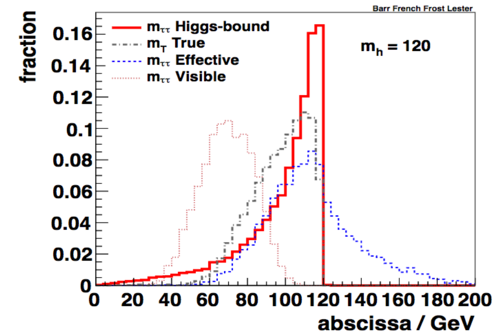


VS

We have used transverse-type mass

Barr, French, Frost, Lester 11'





$$m_{\tau\tau}^{\rm reco}(=m_{\tau\tau}^{\rm Higgs-bound}) \equiv \min_{\{q_1,q_2:\chi\}} \sqrt{H^\mu H_\mu}$$

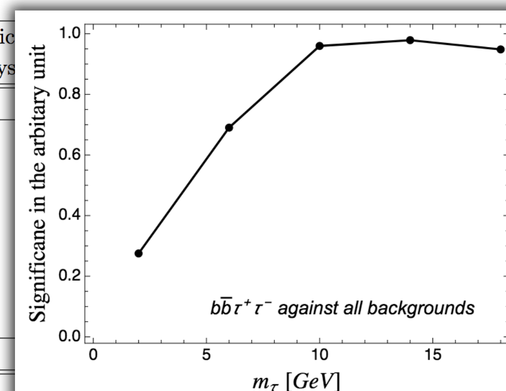
$$H^\mu = p_1^\mu + q_1^\mu + p_2^\mu + q_2^\mu$$

** Low efficiency at hadron-level is overcome by relaxing m_τ mass value

$$M_{T2}(p_1,\, p_2,\, \not{\vec{p}}_T, m_{inv}=0) < m_\tau$$

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

Expected yields (3 ab^{-1})	Fully-hadronic $\tau_h\tau_h$ Cut-based Analysis	Fully-hadronic $\tau_h\tau_h$ MVA	Semi-leptonic Cut-based Analys
$h(b\bar{b})h(\tau^+\tau^-)$	5.71	10.	5.7
$t\bar{t}$	2.31	4.46	44.8
$t\bar{t}h$	7.63	7.37	13.1
$t\bar{t}V$	3.14	2.74	5.12
tW	5.37	7.52	28.3
$Z(\tau^+\tau^-)+\text{jets}$	18.4	25.0	10.1
hZ	1.72	2.22	1.16
VV	0.38	0.98	3.41
Total backgrounds	40.	50.3	106



Similar result to CMS-PAS-FTR-15-002

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

Azatov, Contino, Panico, Son 15'

E.g.

Higgs : p~~G~~B

Generic composite state: tuned …
→ no supurion suppression.

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

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

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

Higgs portal (to strongly coupled sector)

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

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

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

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

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

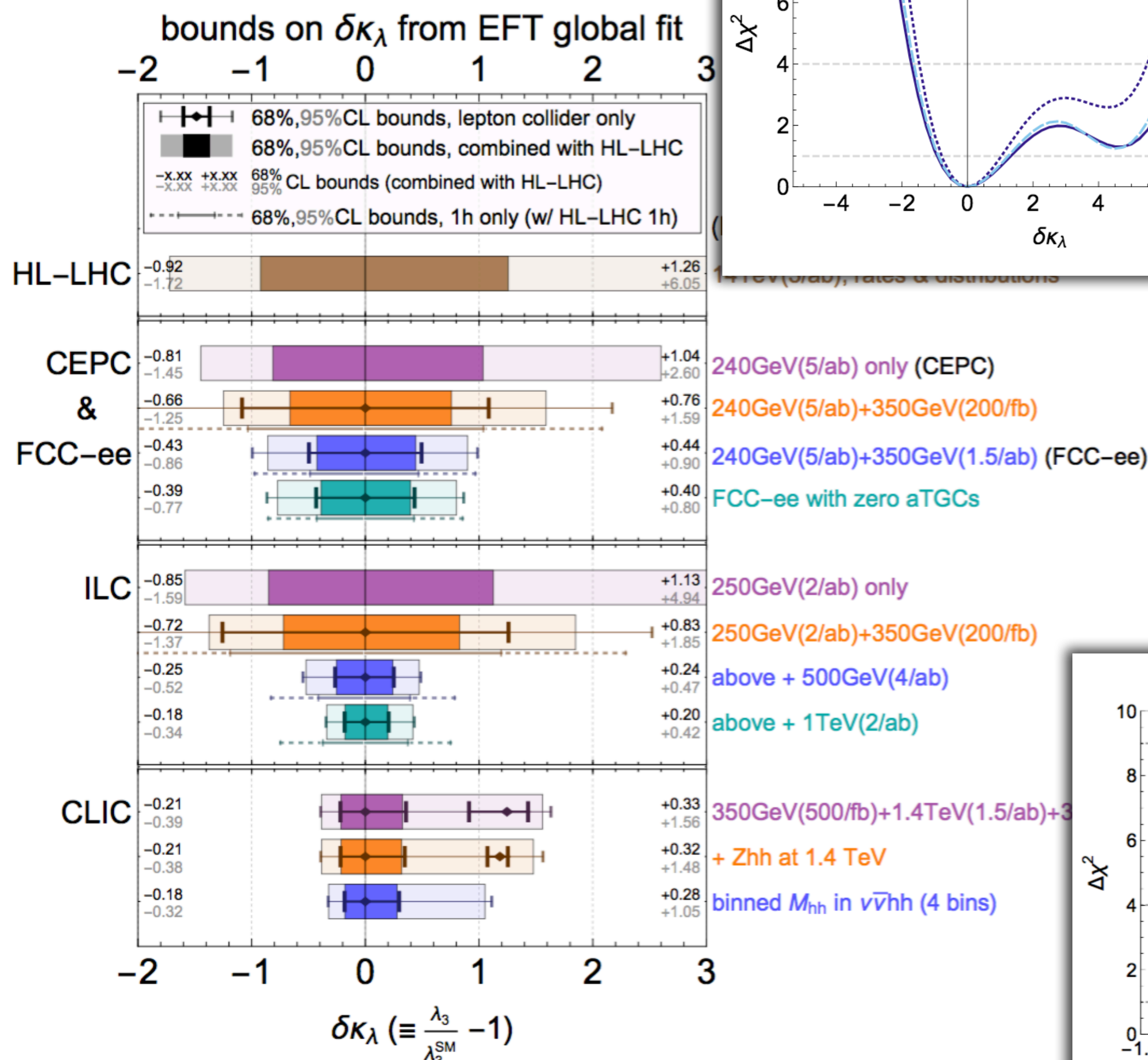
Up to some fine-tuning

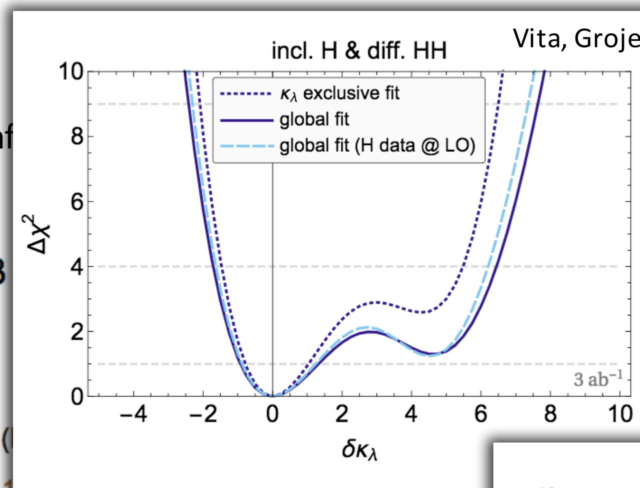
Higgs : pGB (SILH basis)

$$\mathcal{O}_H \sim \left(\partial_\mu |H|^2\right)^2, \quad \mathcal{O}_6 \sim \frac{g_{\cancel{GB}}}{g_*^2} \times |H|^6$$

→ $\bar{c}_H \sim \bar{c}_6 \sim \left(\frac{v}{f}\right)^2$

Taken from
Jiayin Gu, IAS Program on High Energy Physics Conf





Vita, Grojean, Panico, Riembau, Vantalon 17’

$$\delta\kappa_\lambda^{\Delta\chi^2=1} = [-0.9, 1.3]\ @1\sigma$$