

# YR4 Uptakes

Special thanks to colleagues from CMS and ATLAS for inputs.



Reisaburo TANAKA (LAL)  
LHC Higgs XS WG General Meeting  
July 13, 2017, CERN

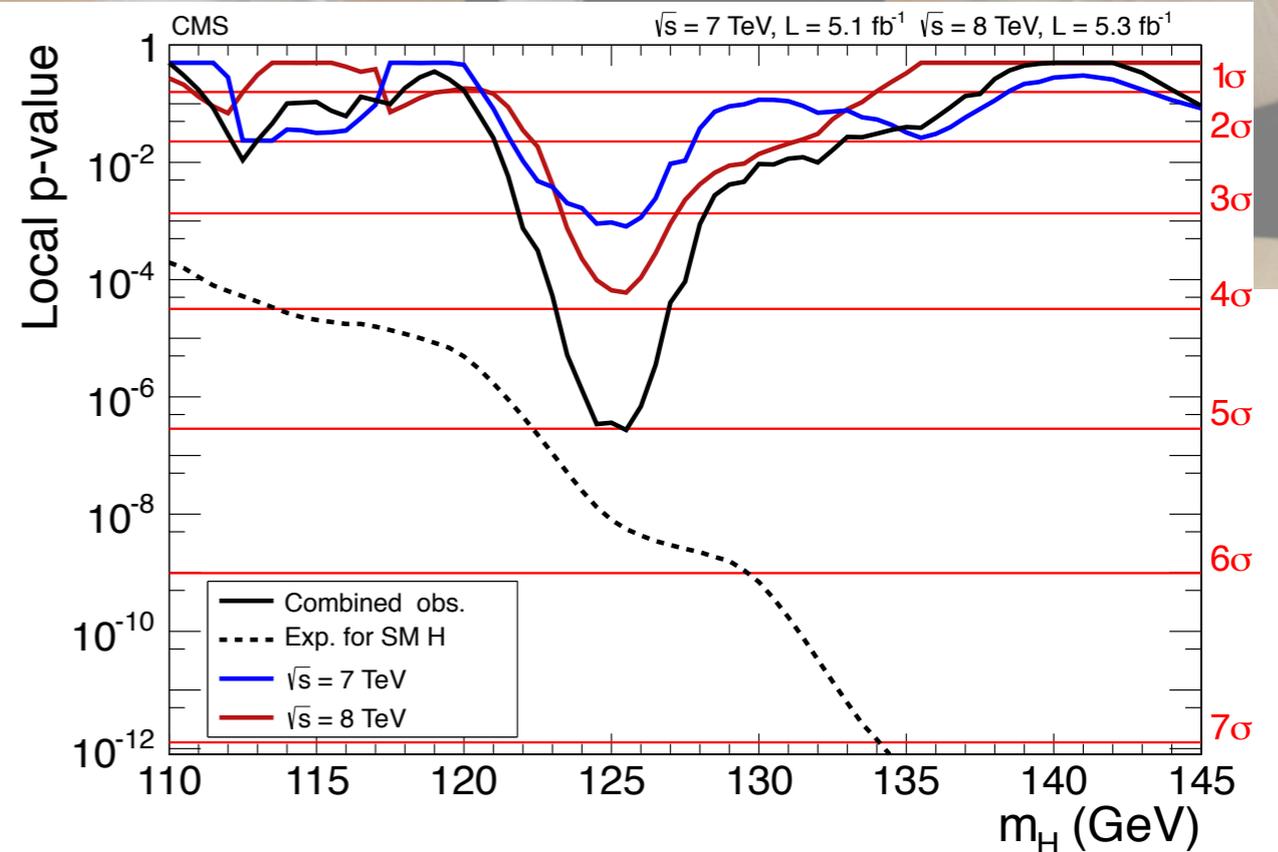
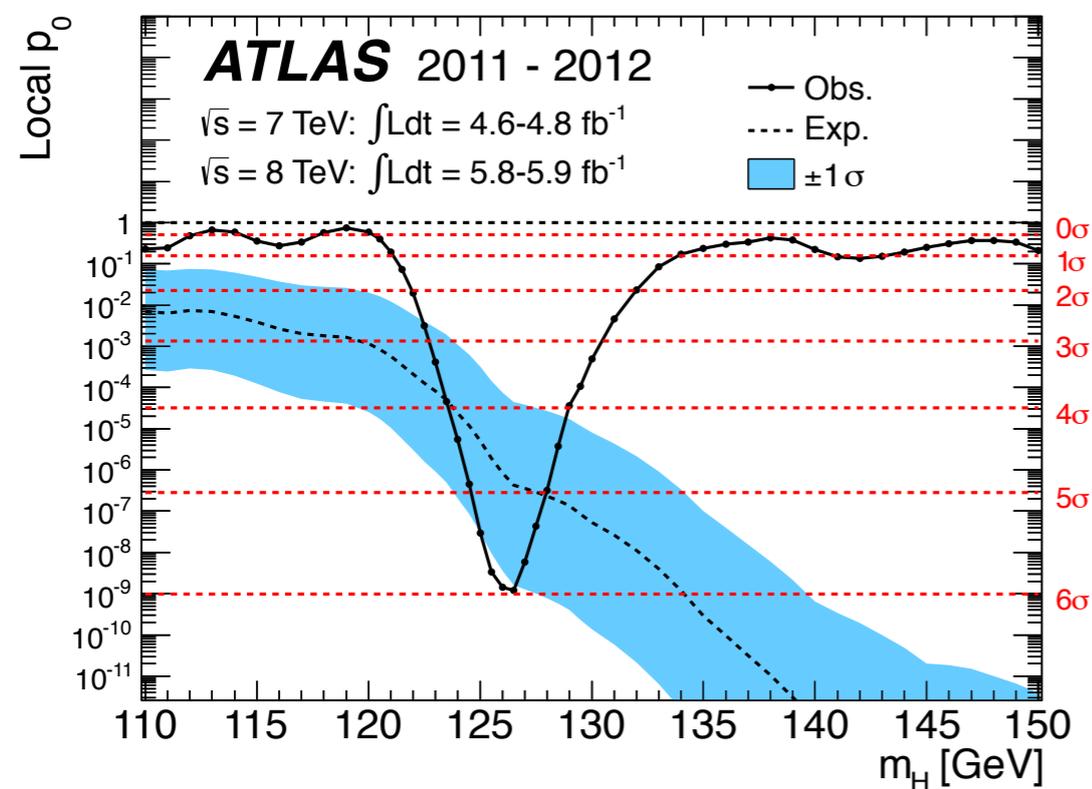


# What EXP's need for the scalar sector research 5 years after July 4<sup>th</sup> 2012?

I was there!

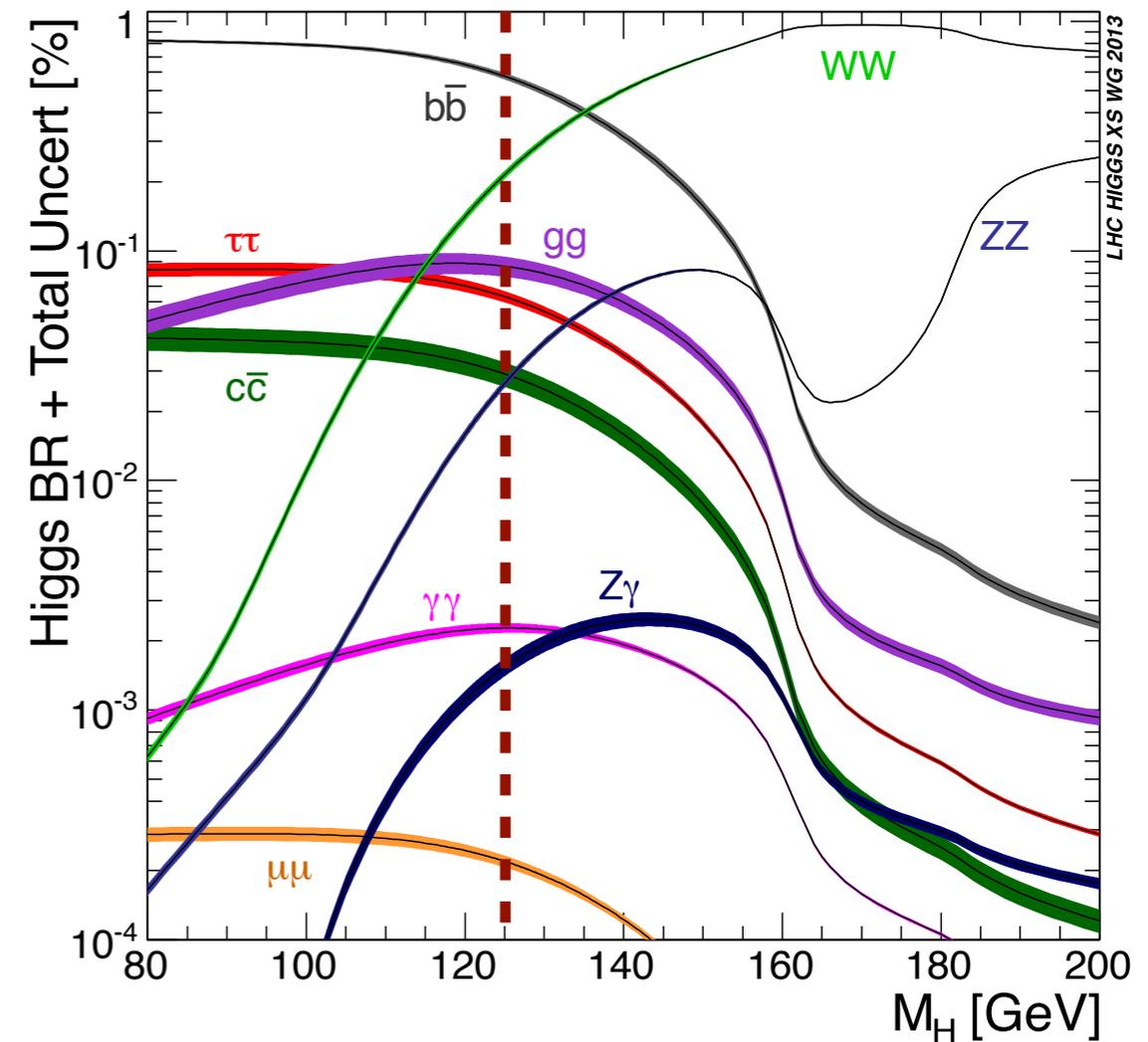
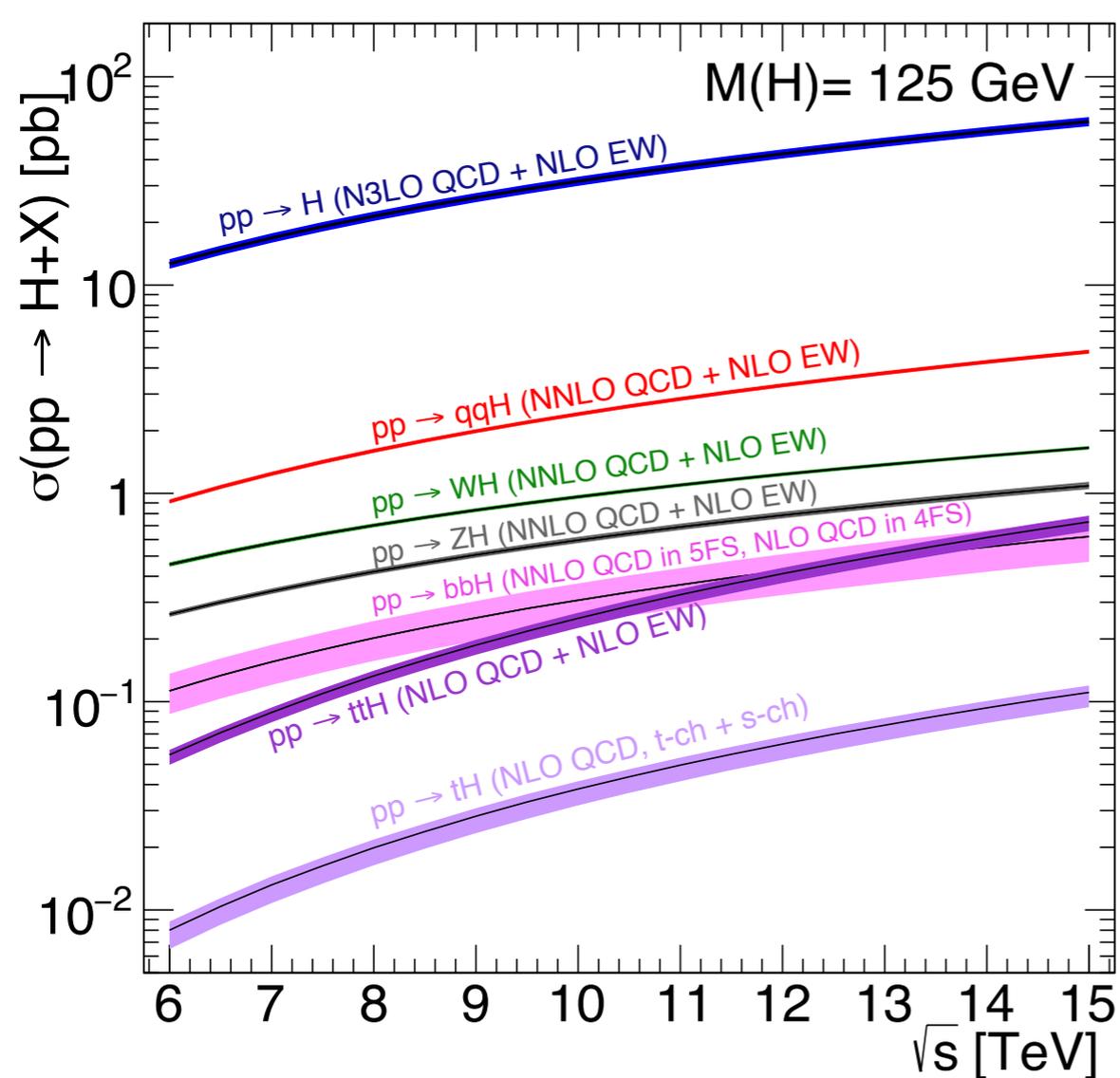
[PLB 716 \(2012\) 1](#)

[PLB 716 \(2012\) 30](#)



# 1. Higgs boson production cross section and decay width&BR

# Higgs Boson Production and Decay



## LHC Higgs XS WG CERN Reports

### Handbook of LHC Higgs Cross Sections:

1. Inclusive Observables (CERN 2011-002, 151 pp)
2. Differential Distributions (CERN 2012-002, 275 pp)
3. Higgs Properties (CERN 2013-004, 392 pp)
4. Deciphering the nature of the Higgs sector (CERN-2017-002-M, 869 pp)

New



# Higgs XS&BR Calculation Instruction

## SM input parameter

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsCalc>

$M_{\text{top}}=172.5\pm 1$  GeV,  $\alpha_s(m_z)=0.118\pm 0.0015$  (not PDG values)

## Cross Section Scan

SM Higgs scan  $M_H=125\pm 5$  GeV

Ecm scan  $\sqrt{s} = [6, 15]$  TeV

Heavy Higgs  $M_H=[10, 3000]$  GeV

## PDF4LHC PDF set

SM Higgs PDF4LHC15\_100 set

BSM Higgs PDF4LHC15\_mc set

## Numerical Results

Separate theory uncertainty (THU), parametric uncertainty (PU), PDF uncertainties.

$XS \pm \text{Scale Uncertainty} [\%] \pm \text{THU} [\%] \pm \text{PU}(\text{quark-mass}) [\%] \pm \text{PU}(\alpha_s) [\%] \pm \text{PDF Uncertainty} [\%]$

$BR \pm \text{THU} [\%] \pm \text{PU}(\text{quark-mass}) [\%] \pm \text{PU}(\alpha_s) [\%]$

Correlate PU(quark-mass,  $\alpha_s$ ) between Higgs production and decay, and PDF for different Higgs production and SM backgrounds.

All results at <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG>

kappa-modifier updates: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG2KAPPA>

### Mass range and step for SM-like Higgs boson:

Higgs Mass range	step size	# of points	addendum
[120,124] GeV	0.5 GeV	9 points	
[124,126] GeV	0.1 GeV	20 points	+ $M_H=125.09$ GeV
[126,130] GeV	0.5 GeV	8 points	

• Total 38 points for  $M_H=[120,130]$  GeV.

### Mass range and step for BSM Higgs boson:

Higgs Mass range	step size	# of points	addendum
[10,150] GeV	5 GeV	29 points	
[150,500] GeV	10 GeV	35 points	+ $M_H=125.09$ GeV
[500,3000] GeV	50 GeV	50 points	

• Total 115 points for  $M_H=[10,3000]$  GeV.

# QCD scale uncertainty correlations in $qq/gg \rightarrow VH, VV$ and $H$

---

	$qq \rightarrow VH$	$gg \rightarrow ZH$	$qq \rightarrow VV$	$gg \rightarrow VV$	$gg \rightarrow H \rightarrow VV$
$qq \rightarrow VH$		0	<b>+50%</b>	0	0
$gg \rightarrow ZH$	0		0	<b>+50%</b>	<b>+50%</b>
$qq \rightarrow VV$	<b>+50%</b>	0		0	0
$gg \rightarrow VV$	0	<b>+50%</b>	0		<b>+100%</b>
$gg \rightarrow H \rightarrow VV$	0	<b>+50%</b>	0	<b>+100%</b>	

- Note 1:  $V=W,Z$ . And assumes +100% correlation between ( $qq \rightarrow WH$  and  $ZH$ ), ( $qq \rightarrow WW$  and  $ZZ$ ), and ( $gg \rightarrow WW$  and  $ZZ$ ).
- Note 2: +50% correlation among different processes should be reasonable estimate.
- Note 3: no correlations between others:  $ggF$ ,  $VBF$ ,  $VH$ ,  $ttH$ ,  $bbH$  and SM  $VV$  ?

# gluon-gluon fusion $gg \rightarrow H$

First complete N3LO calculation at hadron collider ! [Anastasiou:2016cez]

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t, b, c)$	$\delta(1/m_t)$
+0.10 pb -1.15 pb	$\pm 0.18$ pb	$\pm 0.56$ pb	$\pm 0.49$ pb	$\pm 0.40$ pb	$\pm 0.49$ pb
+0.21% -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

↑ missing higher-orders  
↑ uncertainty from the soft expansion  
↑ missing N<sub>3</sub>LO PDFs  
↑ EW corrections  
↑ uncertainty from heavy-quark mass dependence  
↑ uncertainty in the  $1/m_t$  included corrections

13TeV,  $M_H=125\text{GeV}$

$\sigma = 48.58 \text{ pb} \begin{matrix} +2.22 \text{ pb} (+4.56\%) \\ -3.27 \text{ pb} (-6.72\%) \end{matrix} \text{ (theory)} \pm 1.56 \text{ pb} (3.20\%) \text{ (PDF} + \alpha_s)$

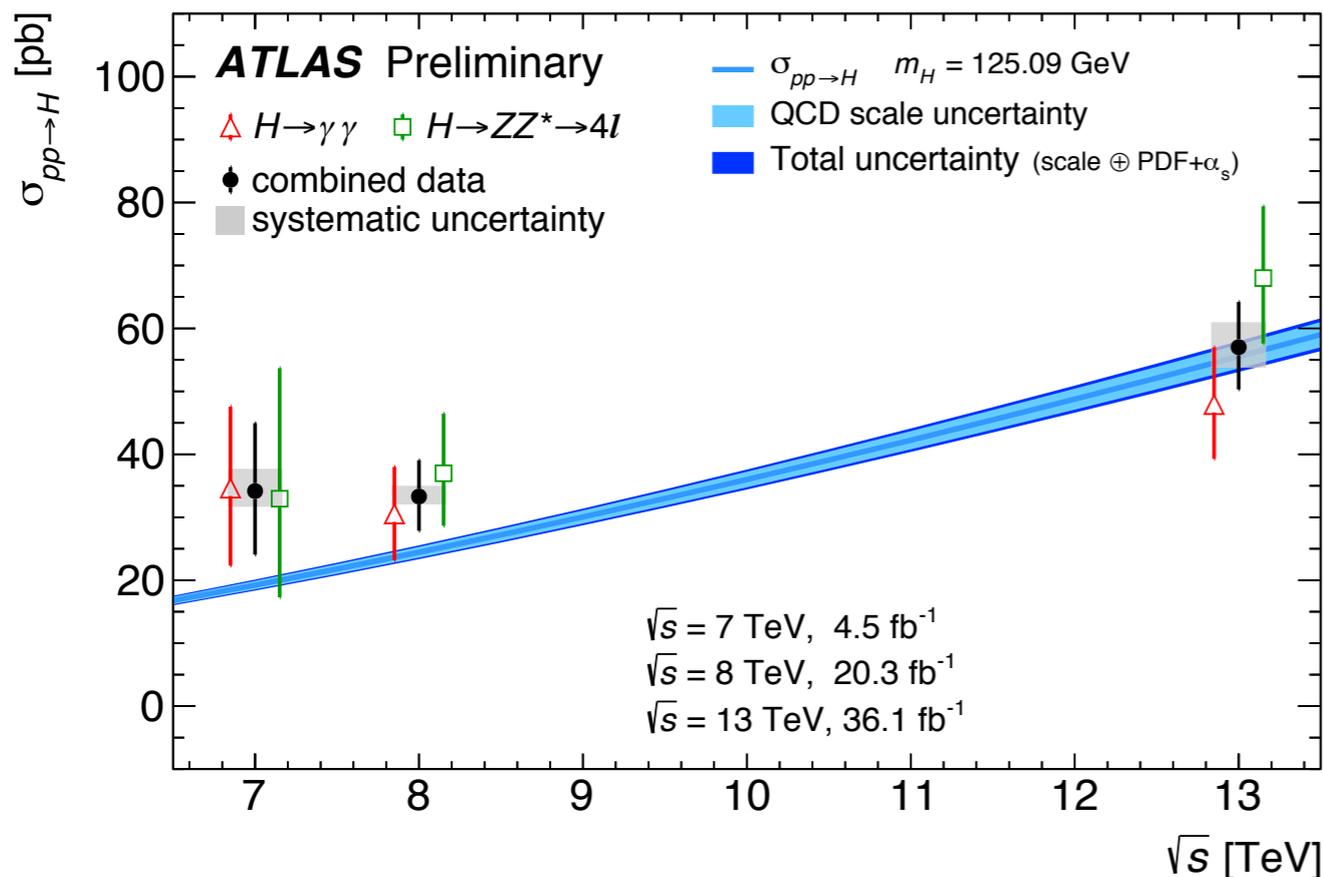
NNLO+NNLL:  $\sigma = 44.14 \text{ pb} \begin{matrix} +7.6 \\ -8.1\% \end{matrix} \text{ (QCD scale)} \pm 3.1\% \text{ (PDF} + \alpha_s)$

- Debates in WG1 on TH uncertainty treatment
  - ETH-Zurich: N3LO, scale  $[M_H/4, M_H]$ , add uncertainties in linear.  $[-6.7, +4.6]\%$
  - Milan: N3LO+N3LL, scale  $[M_H/4, M_H]$ , add uncertainties in quadrature.  $\pm 4.5\%$
- Recommendation: **use ETU-Zürich numbers**
- Flat uncertainty:  $[-6.7, +4.6]\%$  @100% CL**
- Gaussian uncertainty:  $\max\{\text{neg, pos}\}/\sqrt{3} = \pm 3.9\%$  @67% CL**  $\theta = \sigma$  for  $\kappa = 1$
- Use this number for current workspace construction à la [LHC-HCG prescription](#).
- Interest for H+0-jet XS measurement at NNLO QCD (H+0/1 jets@NNLO).

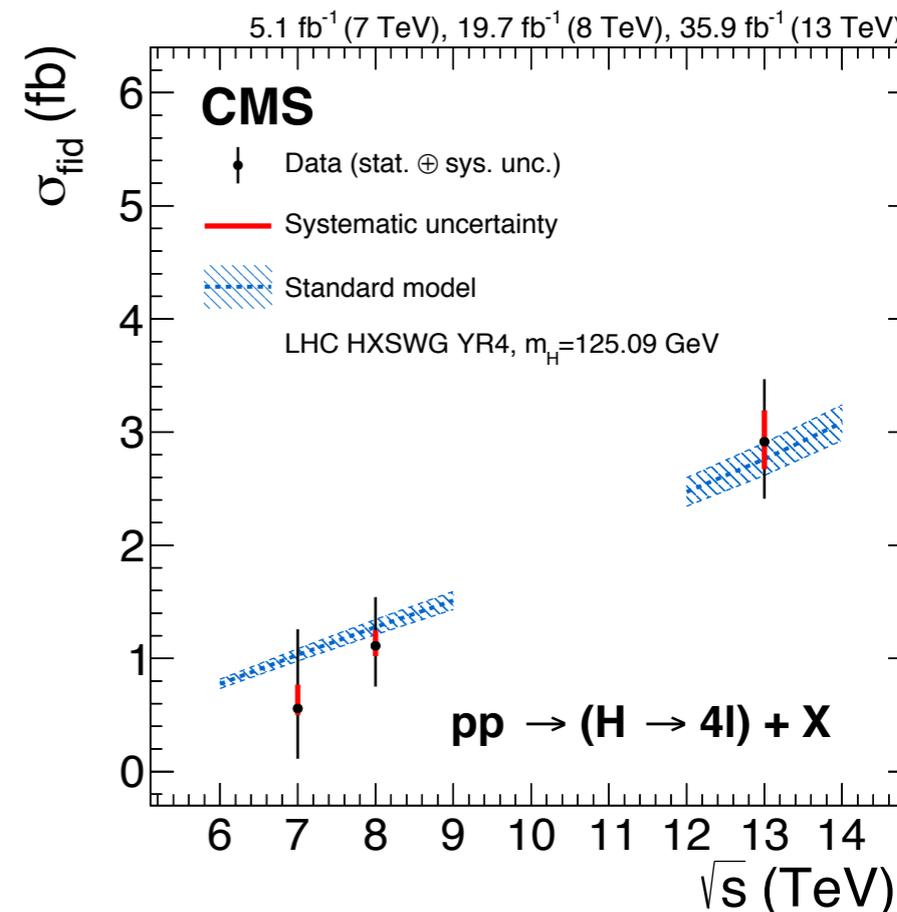
$$\rho(\theta) = \frac{1}{\sqrt{2\pi} \ln(\kappa)} \exp\left(-\frac{(\ln(\theta/\bar{\theta}))^2}{2(\ln \kappa)^2}\right) \frac{1}{\theta}$$

# Total/Fiducial cross sections

ATLAS-CONF-2017-047



CMS-PAS-HIG-16-041



Tremendous progress in QCD and EW theory predictions.  
**ggF prediction in N3LO QCD**

**scale uncertainty  $\pm 8\%$  (NNLO)  $\searrow$   $\pm 4\%$  (N3LO)**

**PDF+ $\alpha_s$  uncertainty  $\pm 7\%$   $\searrow$   $\pm 3\%$  (new PDF4LHC)**

Uncertainties in  $\sigma$  for combined  $\gamma\gamma+ZZ$  (ATLAS)

**stat  $\pm 10\%$ , syst  $\pm 10\%$ , theory  $\pm 5\%$  for  $\int L dt = 36$  fb $^{-1}$**

Needs 150 fb $^{-1}$  when stat. uncertainty reaches theory uncertainty

RUN-2 120 fb $^{-1}$ , RUN-3 300 fb $^{-1}$ , HL-LHC 3 ab $^{-1}$

Perhaps I was exaggerating a bit to ggF conveners but it will take long for EXP to reach TH accuracy !

Giulia Zanderighi

“Precision theory for precise measurements at LHC and future colliders”, Vietnam, 2016.

“... EXP precision is very far away (TH went ahead 15 years of EXP?), but it would be better to have numbers with best precision.”

[email by Reisaburo Tanaka to the ggF conveners]

# Global Signal Strength & Production Cross Section

- ATLAS Combined  $\gamma\gamma+ZZ$  for RUN-2 data

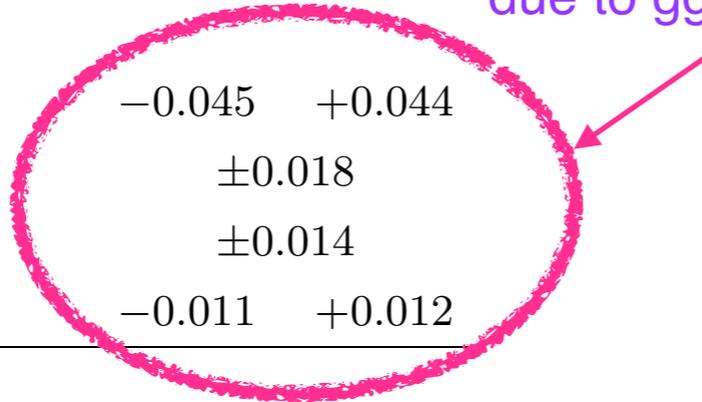
$$\mu = 1.09 \pm 0.12 = 1.09 \pm 0.09 \text{ (stat.) } \begin{matrix} +0.06 \\ -0.05 \end{matrix} \text{ (exp.) } \begin{matrix} +0.06 \\ -0.05 \end{matrix} \text{ (th.)}$$



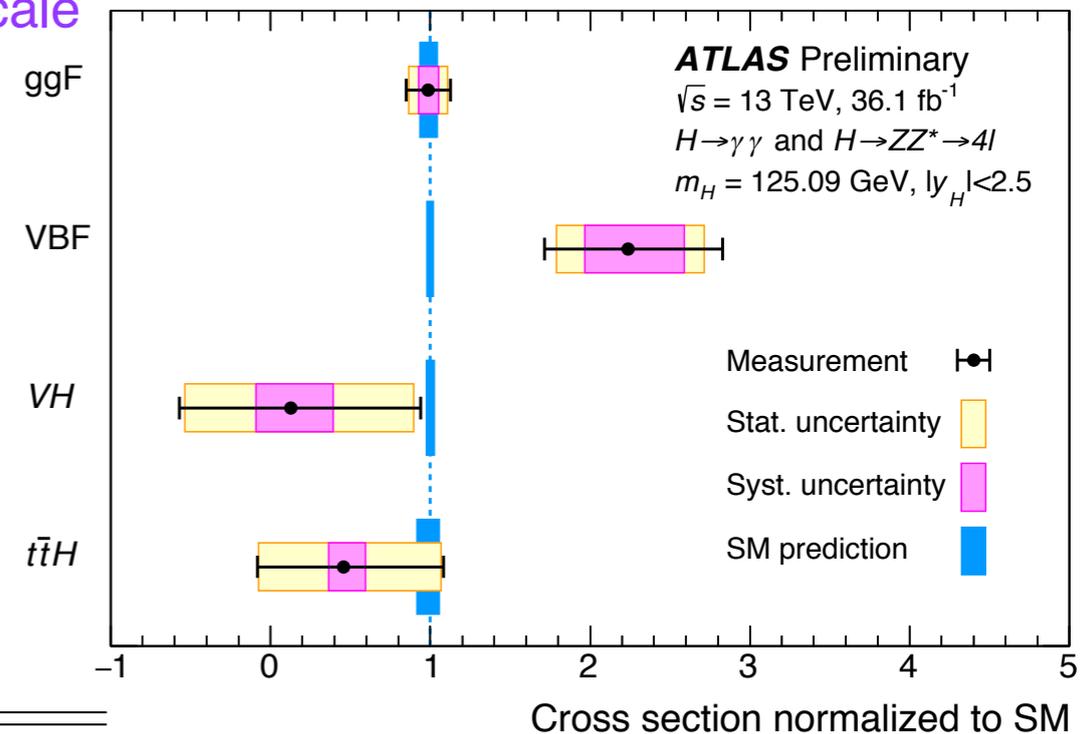
ATLAS-CONF-2017-047

Source	Up	Down
Theoretical		
$\sigma_{\text{ggF}}^{\text{SM}}$ (perturbative)	-0.045	+0.044
PDFs	$\pm 0.018$	
Branching fractions	$\pm 0.014$	
$\alpha_S$	-0.011	+0.012
Experimental		
Luminosity	-0.037	+0.038
Electron and photon resolution	+0.021	-0.019
Pileup	+0.014	-0.015

Major TH uncertainty due to ggF QCD scale



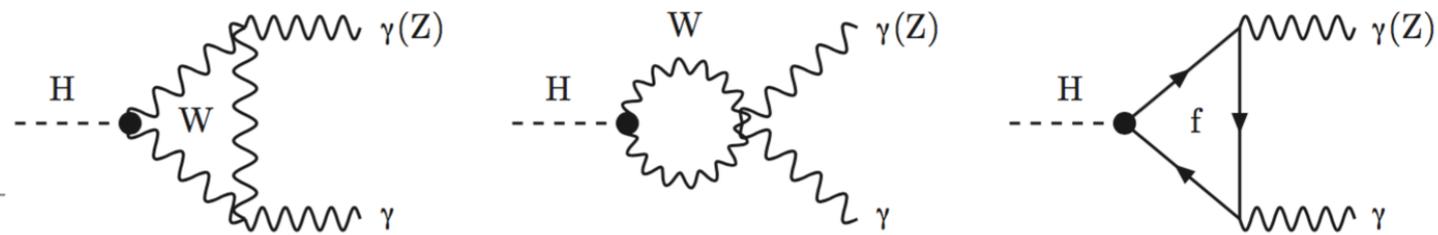
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Process ( $ y_H  < 2.5$ )	Result [pb]	Total	Uncertainty [pb]			SM prediction [pb]
			Stat.	Exp.	Th.	
ggF	43.9	$\begin{matrix} +6.2 \\ -6.0 \end{matrix}$	$\begin{pmatrix} +5.5 \\ -5.4 \end{pmatrix}$	$\begin{pmatrix} +2.7 \\ -2.3 \end{pmatrix}$	$\pm 1.2$	$44.5^{+2.0}_{-3.0}$
VBF	7.9	$\begin{matrix} +2.1 \\ -1.8 \end{matrix}$	$\begin{pmatrix} +1.7 \\ -1.6 \end{pmatrix}$	$\begin{pmatrix} +0.8 \\ -0.6 \end{pmatrix}$	$\begin{pmatrix} +1.0 \\ -0.7 \end{pmatrix}$	$3.52^{+0.08}_{-0.07}$
VH	0.3	$\begin{matrix} +1.6 \\ -1.4 \end{matrix}$	$\begin{pmatrix} +1.5 \\ -1.3 \end{pmatrix}$	$\pm 0.4$	$\begin{pmatrix} +0.3 \\ -0.2 \end{pmatrix}$	$1.99^{+0.06}_{-0.05}$
$t\bar{t}H$	0.27	$\begin{matrix} +0.37 \\ -0.32 \end{matrix}$	$\begin{pmatrix} +0.36 \\ -0.31 \end{pmatrix}$	$\begin{pmatrix} +0.06 \\ -0.05 \end{pmatrix}$	$\begin{pmatrix} +0.05 \\ -0.02 \end{pmatrix}$	$0.59^{+0.03}_{-0.05}$

Large theory uncertainties in VBF, VH and  $t\bar{t}H$  channels due to ggF contamination, UE/PS uncertainty etc.

# H → γγ

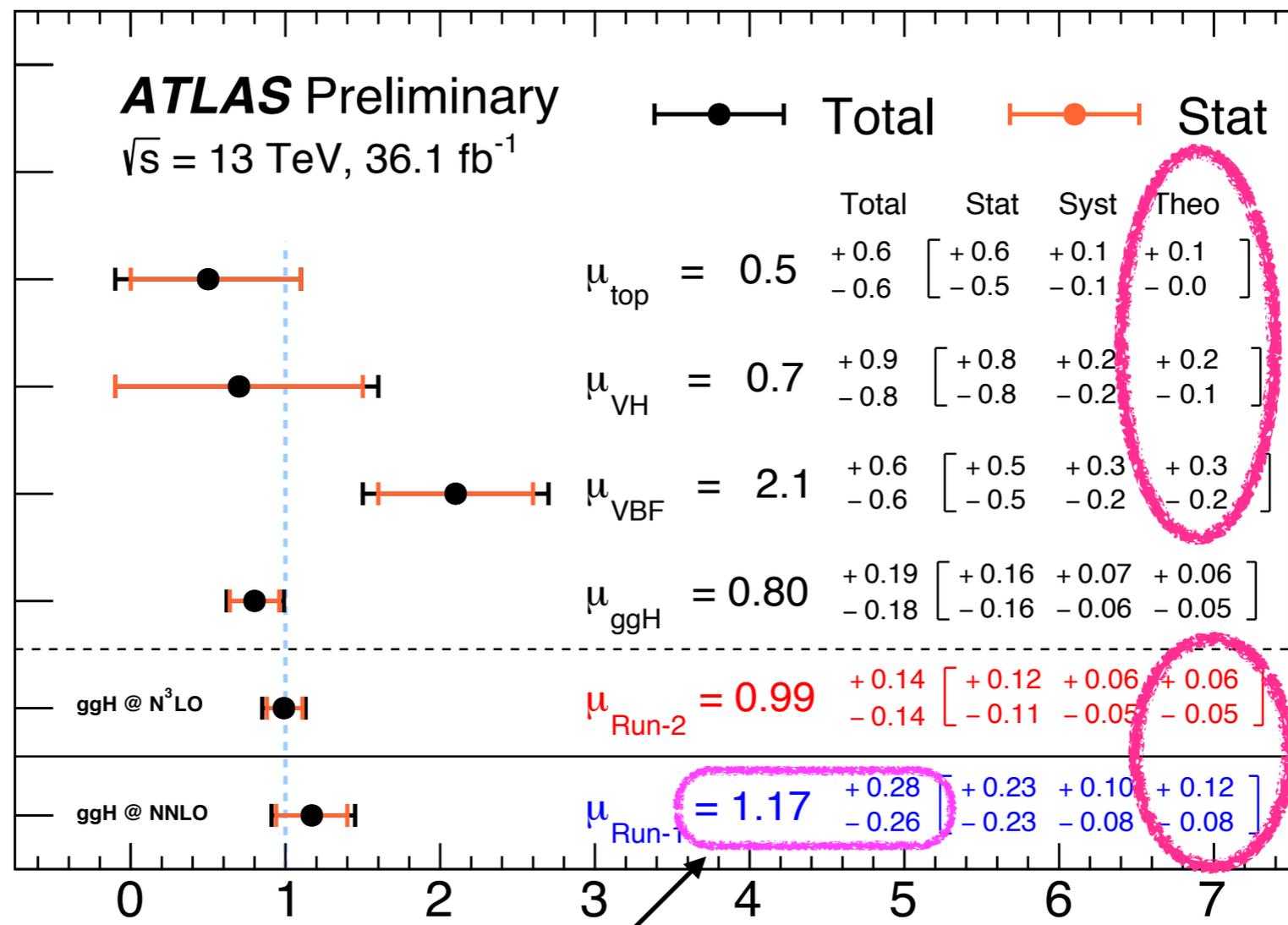


- Signal strength is obtained for each Higgs boson production mode.
- Categorize events by production topology
  - ttH, VH, VBF and ggF (with p<sub>T</sub>)

**RUN-2**

ATLAS-CONF-2017-045

$$\mu = \frac{\sigma \cdot \text{BR}}{(\sigma \cdot \text{BR})_{\text{SM}}}$$



Large Theory uncertainty for ttH/tH, VH and VBF

Theory uncertainty 1/2

Would have been 10% smaller if ggF@N3LO was calculation used.

Signal Strength

# Higgs boson decay width and branching ratio

$$\Gamma_H = \Gamma^{\text{HDECAY}} - \Gamma_{\text{WW}}^{\text{HDECAY}} - \Gamma_{\text{ZZ}}^{\text{HDECAY}} + \Gamma_{4f}^{\text{Prophecy4f}}$$

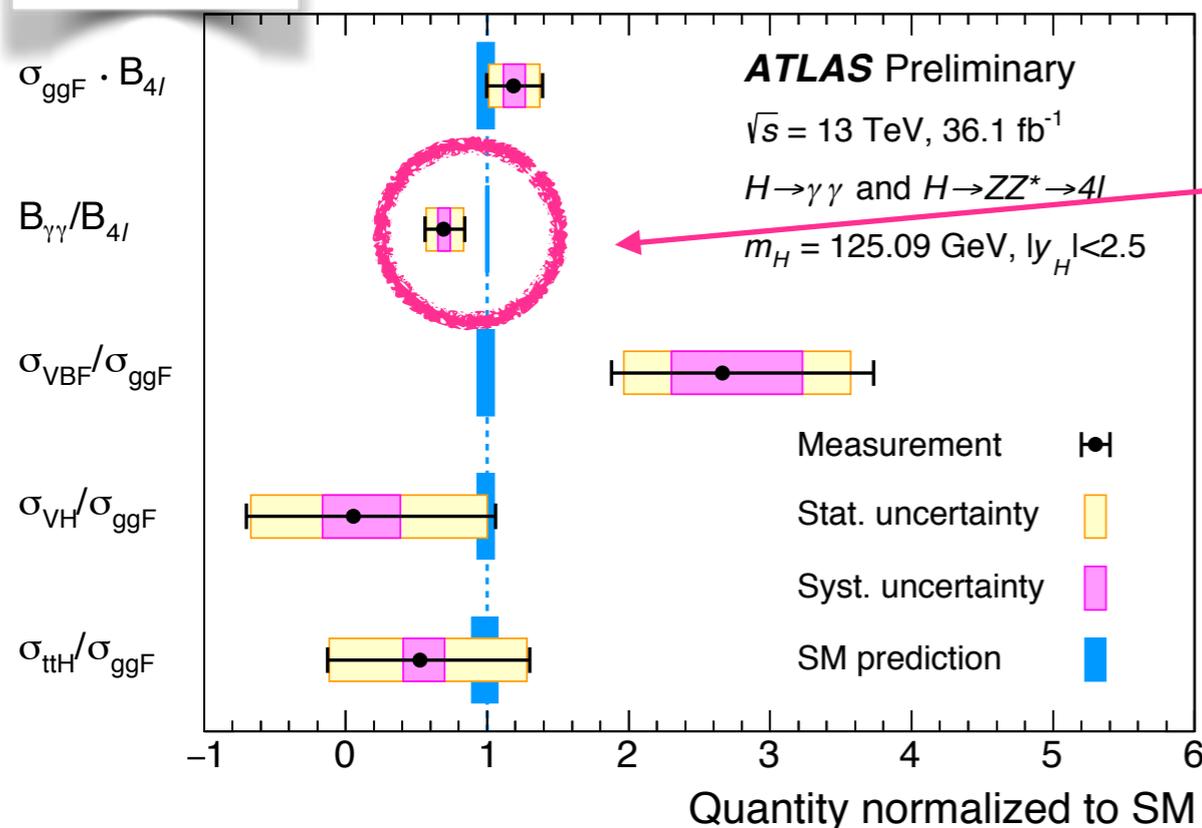
1. Start with Higgs boson decay width
2. Categorize PU( $\alpha_s, m_b, m_c, m_t$ ) and THU  
Separate treatment of PU( $\Delta\alpha_s, \Delta m_q$ ) and THU
3. Convert to BR (correlations are taken into)  
Partial cancellation for  $h \rightarrow bb, cc$  but not for  $gg$  !

$$BR(H \rightarrow VV) = \frac{\Gamma_{VV}}{\Gamma_{\text{tot}}} = \frac{\Gamma_{VV}}{\Gamma_{f\bar{f}} + \Gamma_{VV}}$$

$\Gamma_{f\bar{f}} : \Gamma_{VV} \simeq 3 : 1$  (dominated by  $\Gamma_{b\bar{b}}$ )

**RUN-2**

ATLAS-CONF-2017-047



$M_H=126\text{GeV}$	Decay width uncertainty				
Decay	$\Delta\alpha_s$	$\Delta m_b$	$\Delta m_c$	$\Delta m_t$	THU
$H \rightarrow b\bar{b}$	$\mp 2.3\%$	$\pm 3.3\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 2.0\%$
$H \rightarrow c\bar{c}$	$\mp 7.1\%$	$-0.1\%$	$\pm 6.2\%$	$\pm 0.1\%$	$\pm 2.0\%$
$H \rightarrow \tau\tau$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.1\%$	$\pm 2.0\%$
$H \rightarrow \mu\mu$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 2.0\%$
$H \rightarrow gg$	$\pm 4.2\%$	$-0.1\%$	$\pm 0.0\%$	$\mp 0.2\%$	$\pm 3.0\%$
$H \rightarrow \gamma\gamma$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.1\%$	$\pm 1.0\%$
$H \rightarrow Z\gamma$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 5.0\%$
$H \rightarrow WW$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.5\%$
$H \rightarrow ZZ$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.5\%$

Interesting quantity  $\Gamma_{\gamma\gamma}/\Gamma_{ZZ}$ :  
sensitive to new physics via loop in  $\gamma\gamma$

⇒ theory uncertainty is  $\pm 1.1\%$  !

But current EXP error is  $\pm 20\%$ . Long way to go...

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{ZZ}} = \frac{\left| \begin{array}{c} \text{Loop diagram with Higgs boson and fermion } f \text{ emitting two photons } \gamma \end{array} \right|^2}{\left| \begin{array}{c} \text{Tree-level diagram with Higgs boson decaying into } W, Z \end{array} \right|^2}$$

# Higgs boson decay width and branching ratio

$$\Gamma_H = \Gamma^{\text{HDECAY}} - \Gamma_{\text{WW}}^{\text{HDECAY}} - \Gamma_{\text{ZZ}}^{\text{HDECAY}} + \Gamma_{4f}^{\text{Prophecy4f}}$$

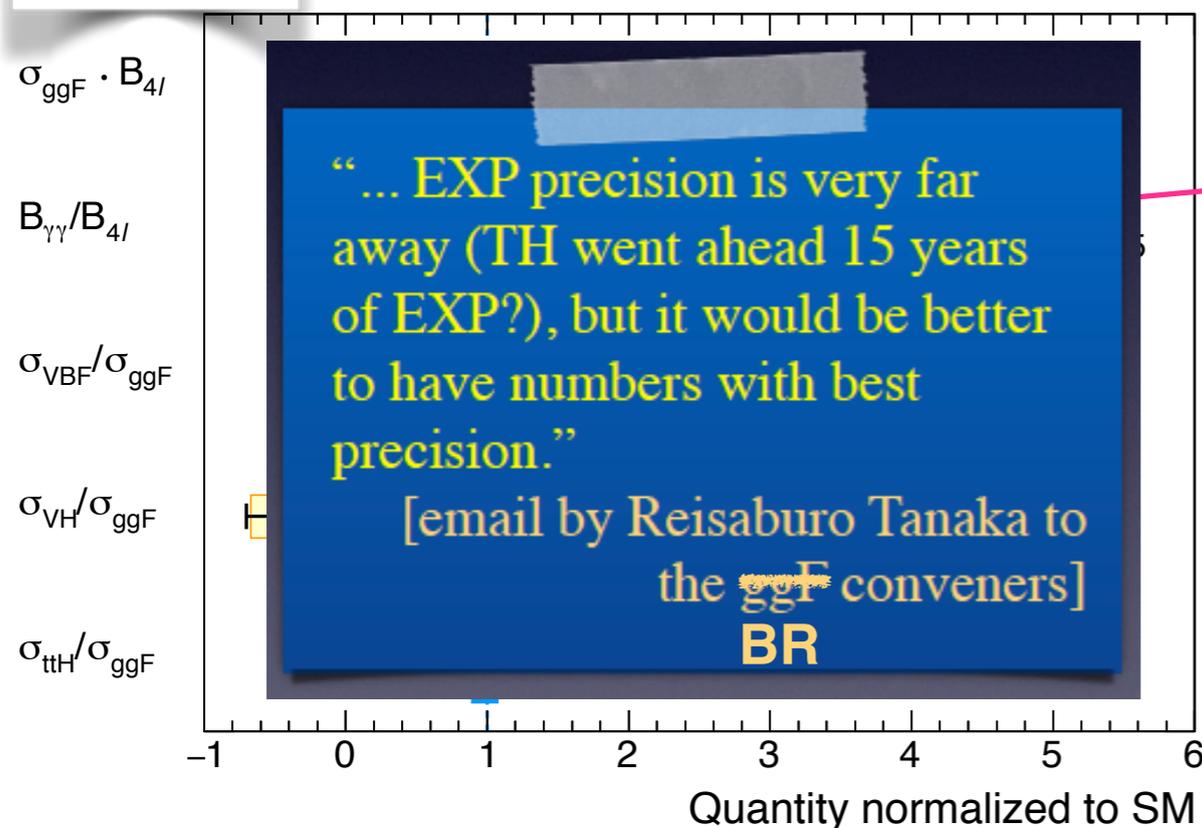
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Partial cancellation for  $h \rightarrow bb, cc$  but not for  $gg$  !

$$BR(H \rightarrow VV) = \frac{\Gamma_{VV}}{\Gamma_{\text{tot}}} = \frac{\Gamma_{VV}}{\Gamma_{f\bar{f}} + \Gamma_{VV}}$$

$\Gamma_{f\bar{f}} : \Gamma_{VV} \simeq 3 : 1$  (dominated by  $\Gamma_{b\bar{b}}$ )

**RUN-2**

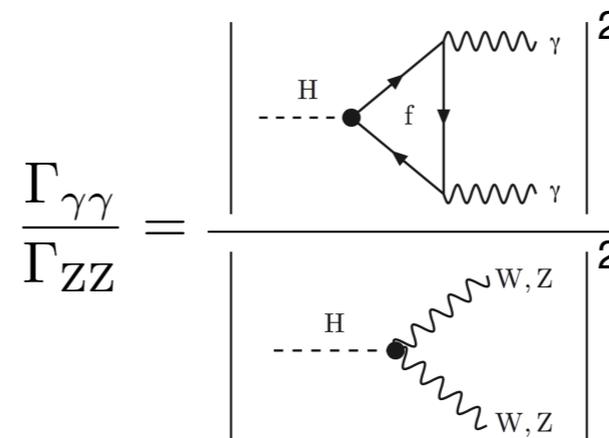
ATLAS-CONF-2017-047



Decay	Decay width uncertainty				THU
	$\Delta\alpha_s$	$\Delta m_b$	$\Delta m_c$	$\Delta m_t$	
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$H \rightarrow Z\gamma$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 5.0\%$
$H \rightarrow WW$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.5\%$
$H \rightarrow ZZ$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.0\%$	$\pm 0.5\%$

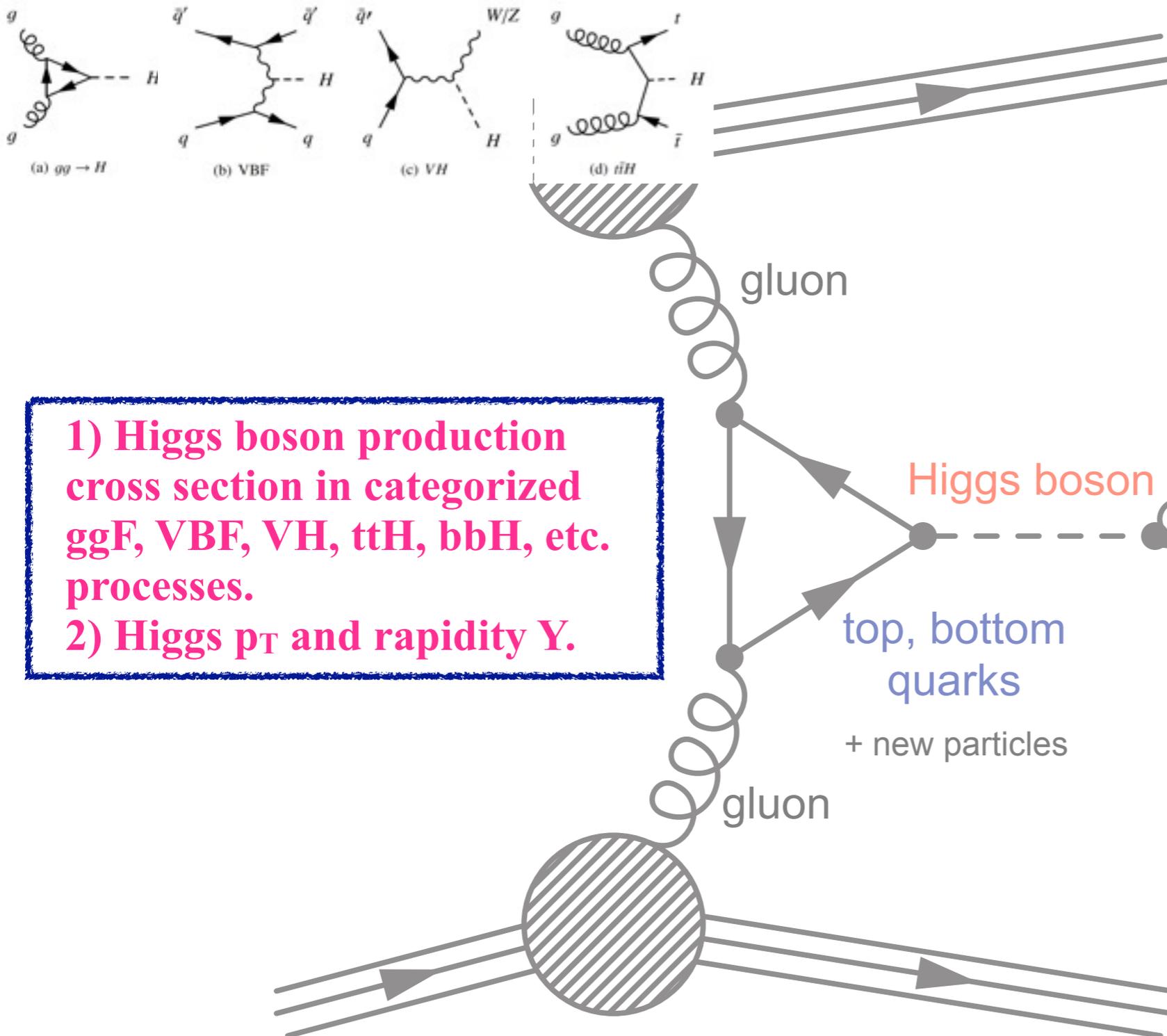
Interesting quantity  $\Gamma_{\gamma\gamma}/\Gamma_{ZZ}$ :  
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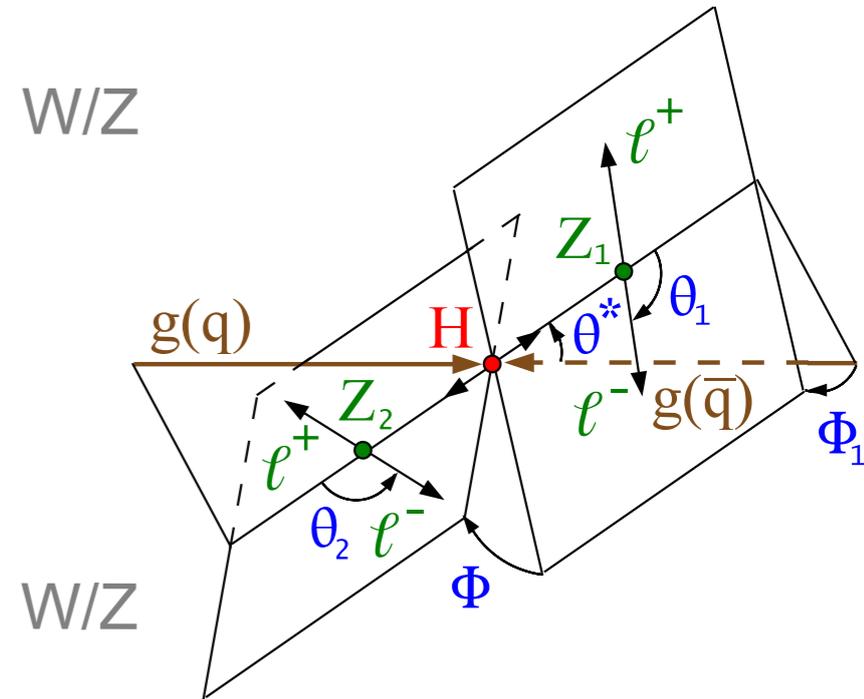
## 2. Higgs boson differential distributions

# Higgs Production and Decay Differential distributions



**1) Higgs boson production cross section in categorized ggF, VBF, VH, ttH, bbH, etc. processes.**  
**2) Higgs  $p_T$  and rapidity  $Y$ .**

**3) Higgs boson decay kinematical variables (8D in  $H \rightarrow 4l$ )**



$$(M_{4l}, M_{Z_1}, M_{Z_2}),$$

$$\vec{\Omega} = (\theta^*, \cos \theta_1, \cos \theta_2, \Phi_1, \Phi)$$

**Use combined information of Higgs production and decay!**

# Differential Distributions

RUN-2

CMS-PAS-HIG-17-015

ATLAS-CONF-2017-045

BSM physics may reveal in high  $p_T$  regime. Very important to treat finite top-quark mass effect.

Dynamical scale reduces cross section but also changes the shape!

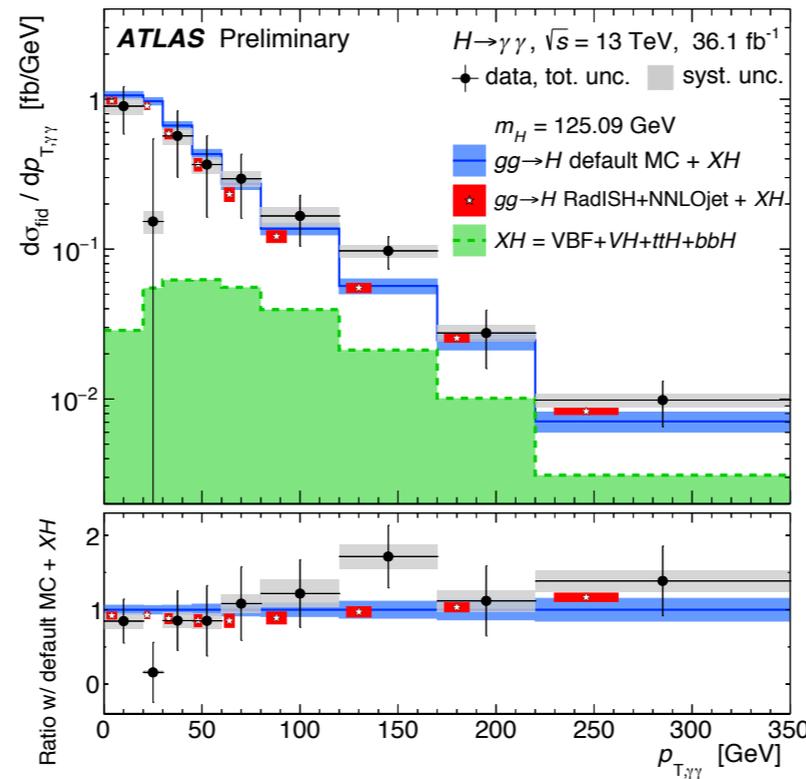
Higgs  $p_T$  was used to reweight MC to take into account NLO EW effect.

Recent progress

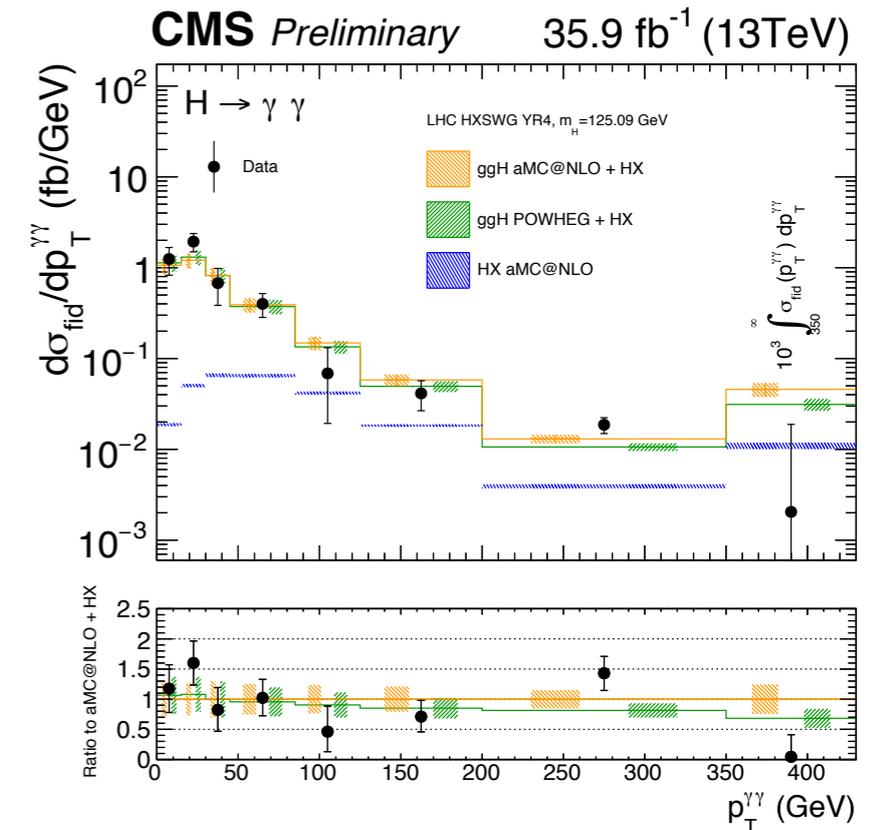
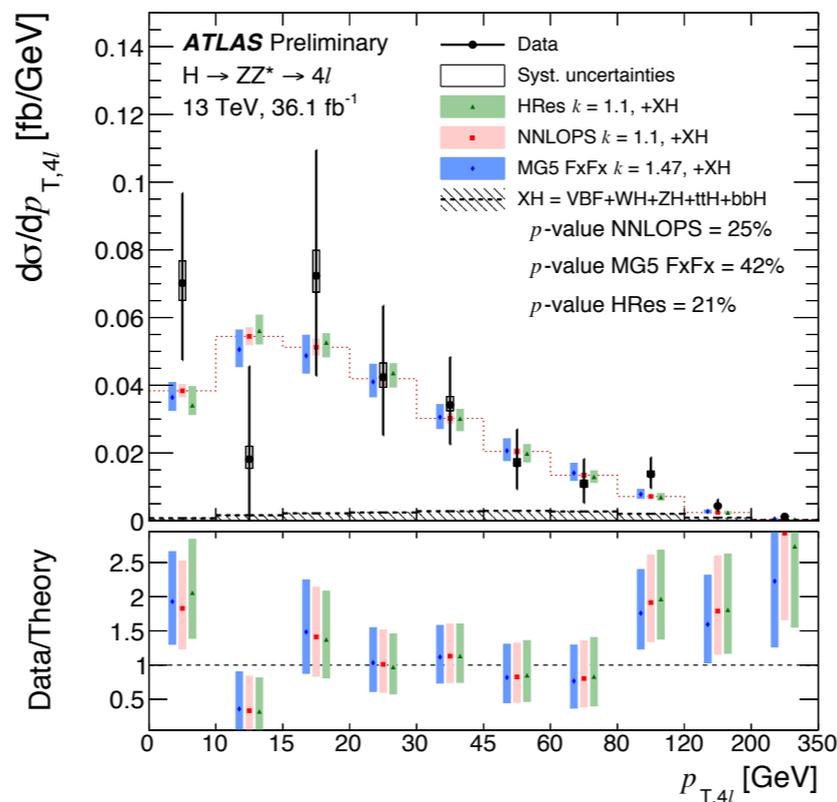
**NNLOPS** Higgs  $p_T$  spectrum agrees well with **HRes**.  $\Rightarrow$  No need to reweight MC.

**RadISH**: inclusion of NNLL resummation and matches to H +1-jet NNLO.

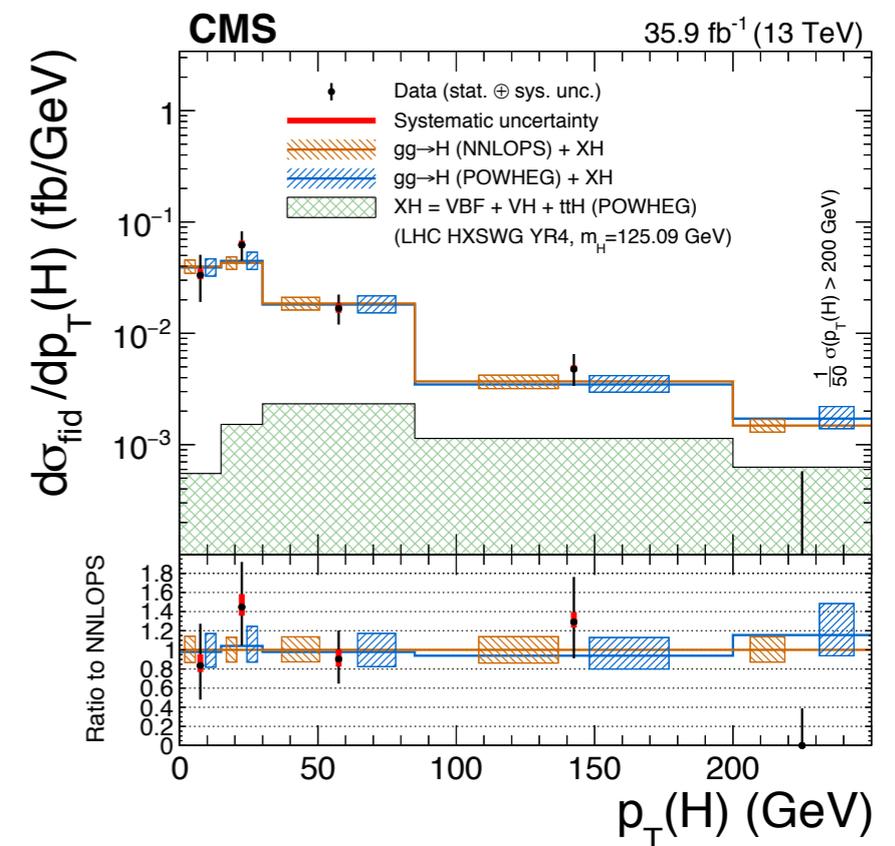
Higgs measurement in exclusive H +0,1, $\geq$ 2-jets bin interesting. Not trivial for  $H \rightarrow \gamma\gamma$  due to continuum background. Clean in  $H \rightarrow ZZ$  but suffers from low statistics.  $H \rightarrow WW$ ?



ATLAS-CONF-2017-032



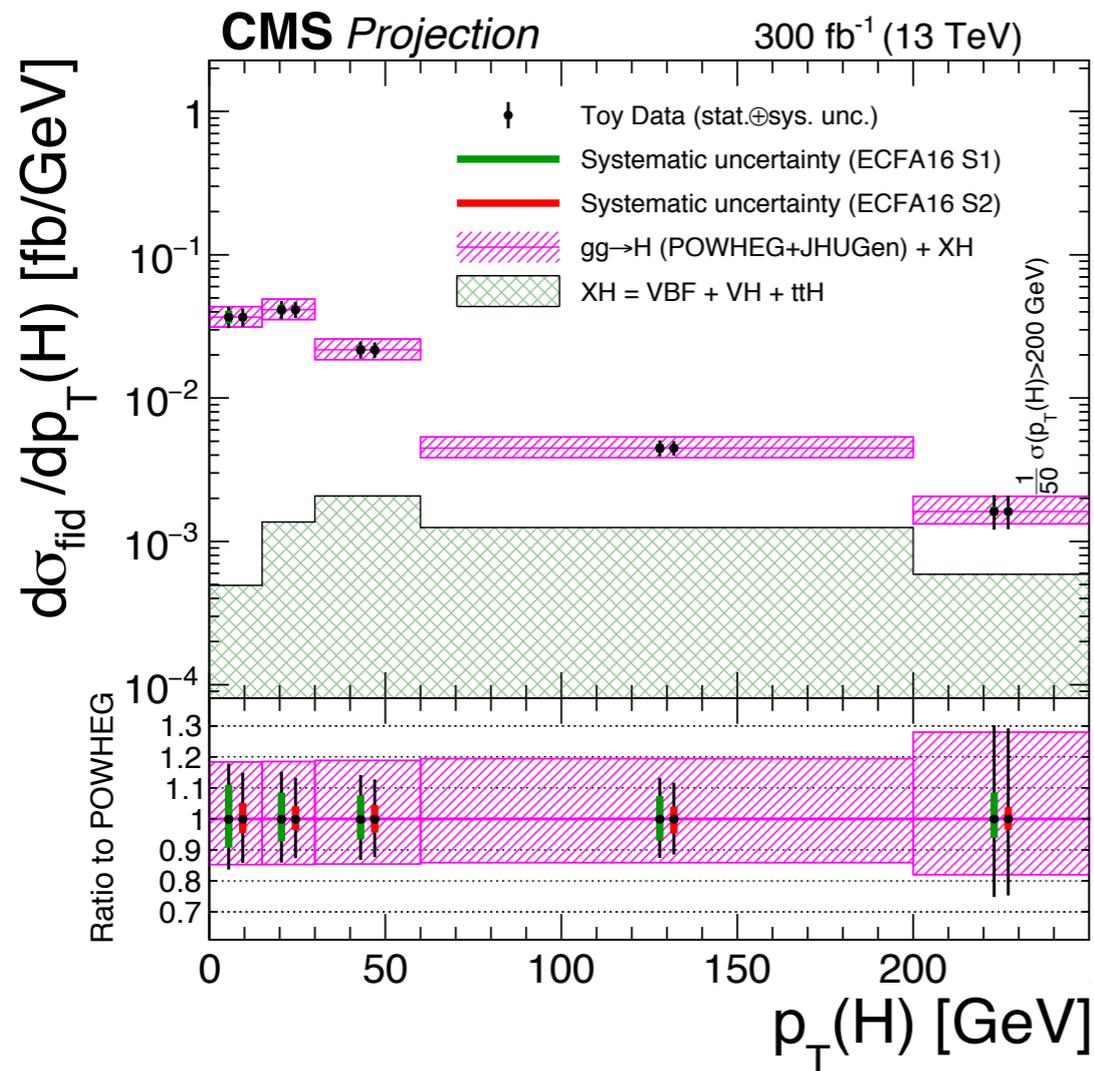
CMS-PAS-HIG-16-041



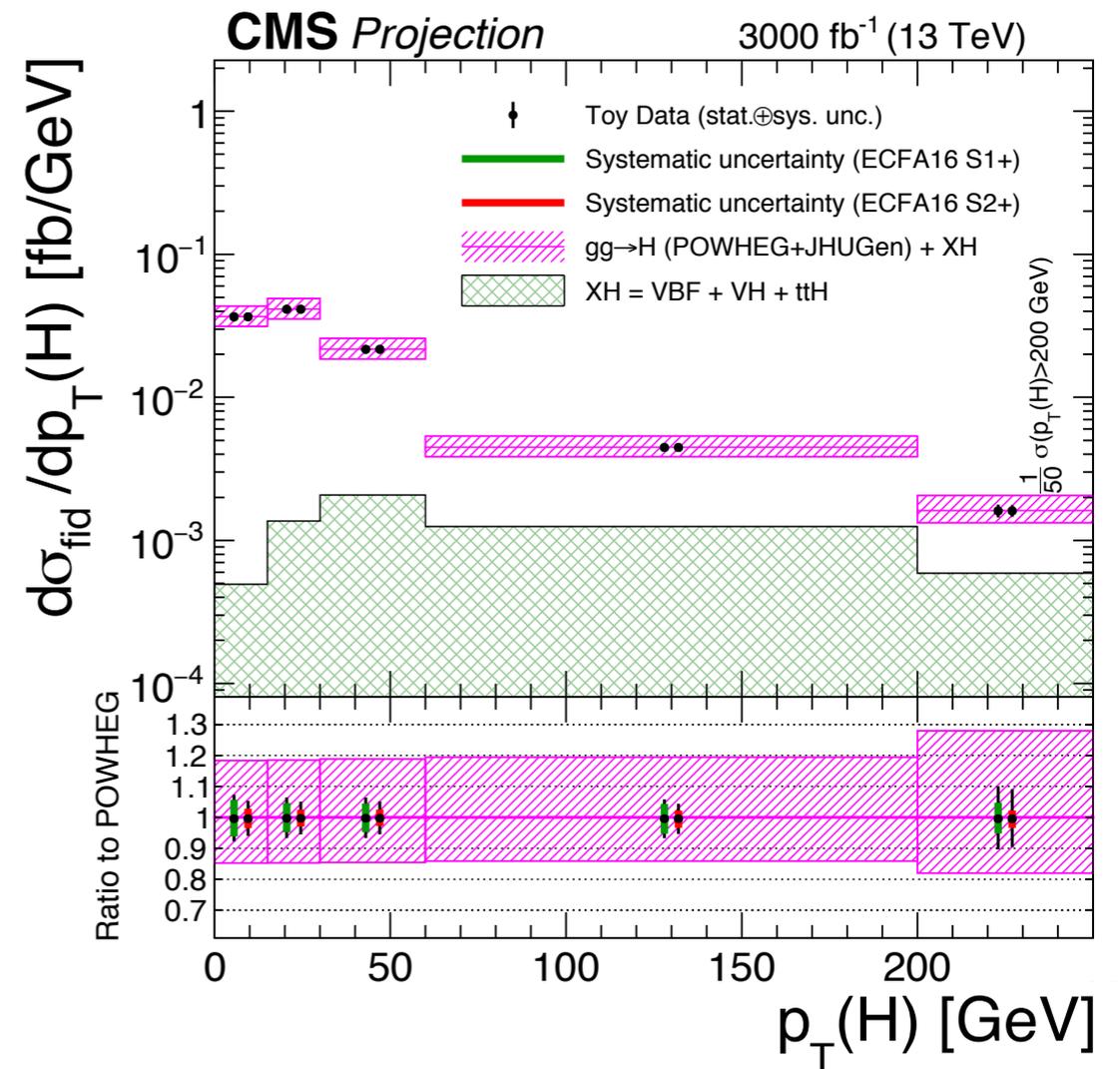
# Higgs $p_T$ projection for RUN-3 and HL-LHC

- Projected Higgs  $p_T$  spectrum uncertainties by CMS
- For Higgs  $p_T > 200 \text{ GeV}$ , the statistical uncertainties:  $\pm 29\%$  (RUN3),  $\pm 9\%$  (HL-LC)

CMS PAS FTR-16-002



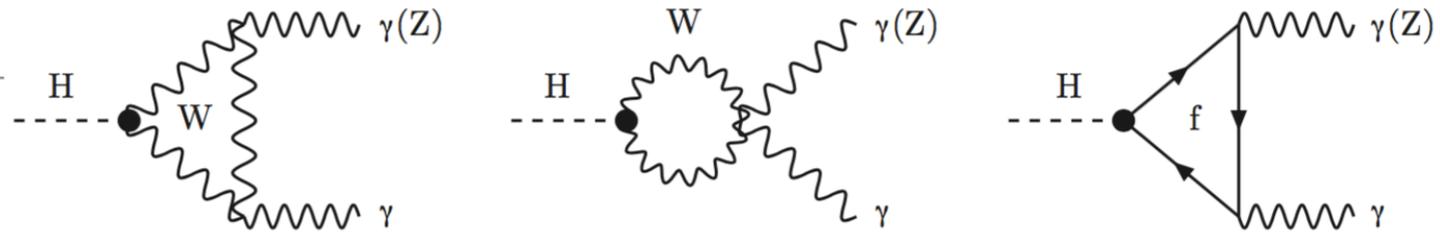
CMS PAS FTR-16-002



# Jet-bin Uncertainty

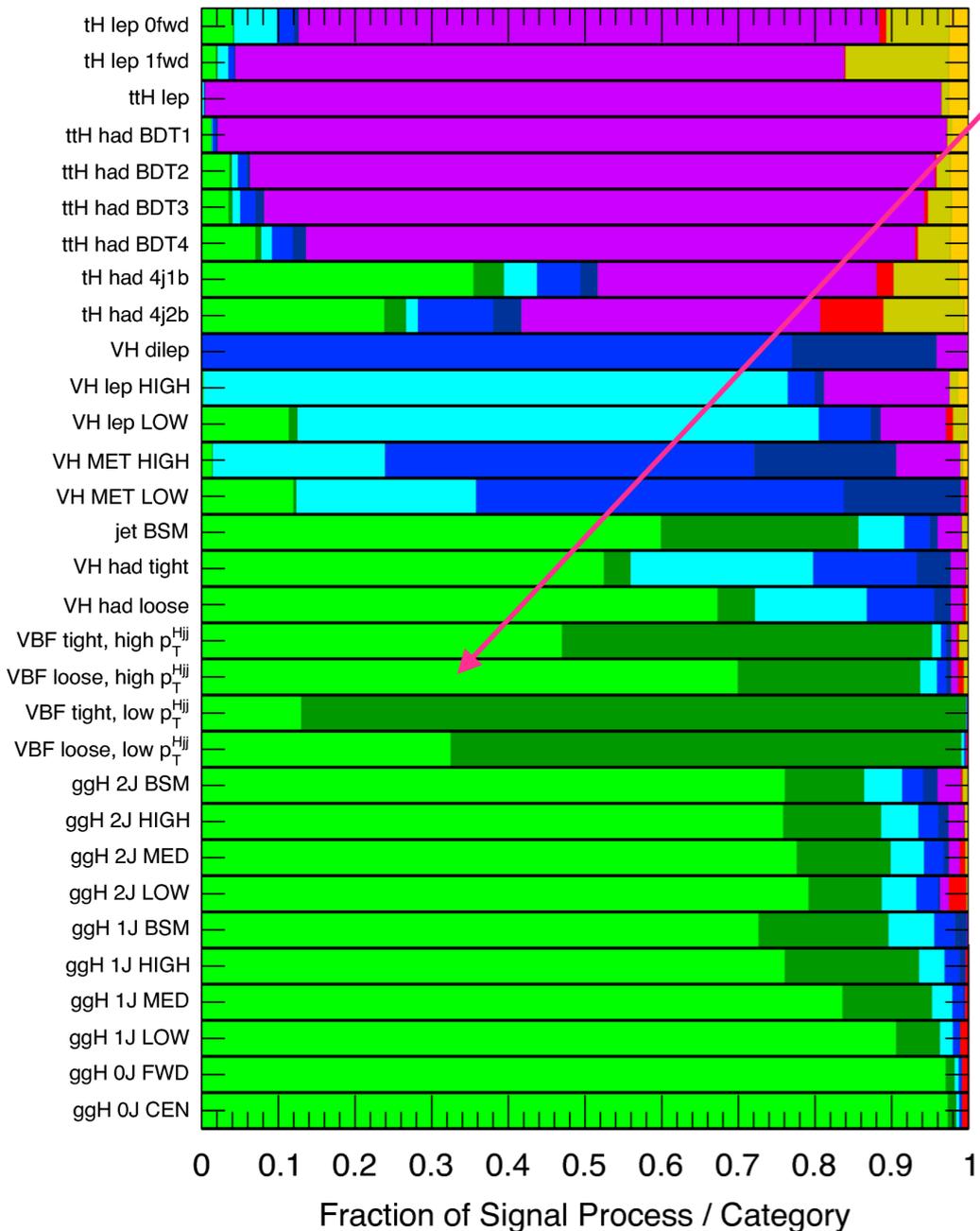
## $H \rightarrow \gamma\gamma$ categorization

ATLAS-CONF-2017-045



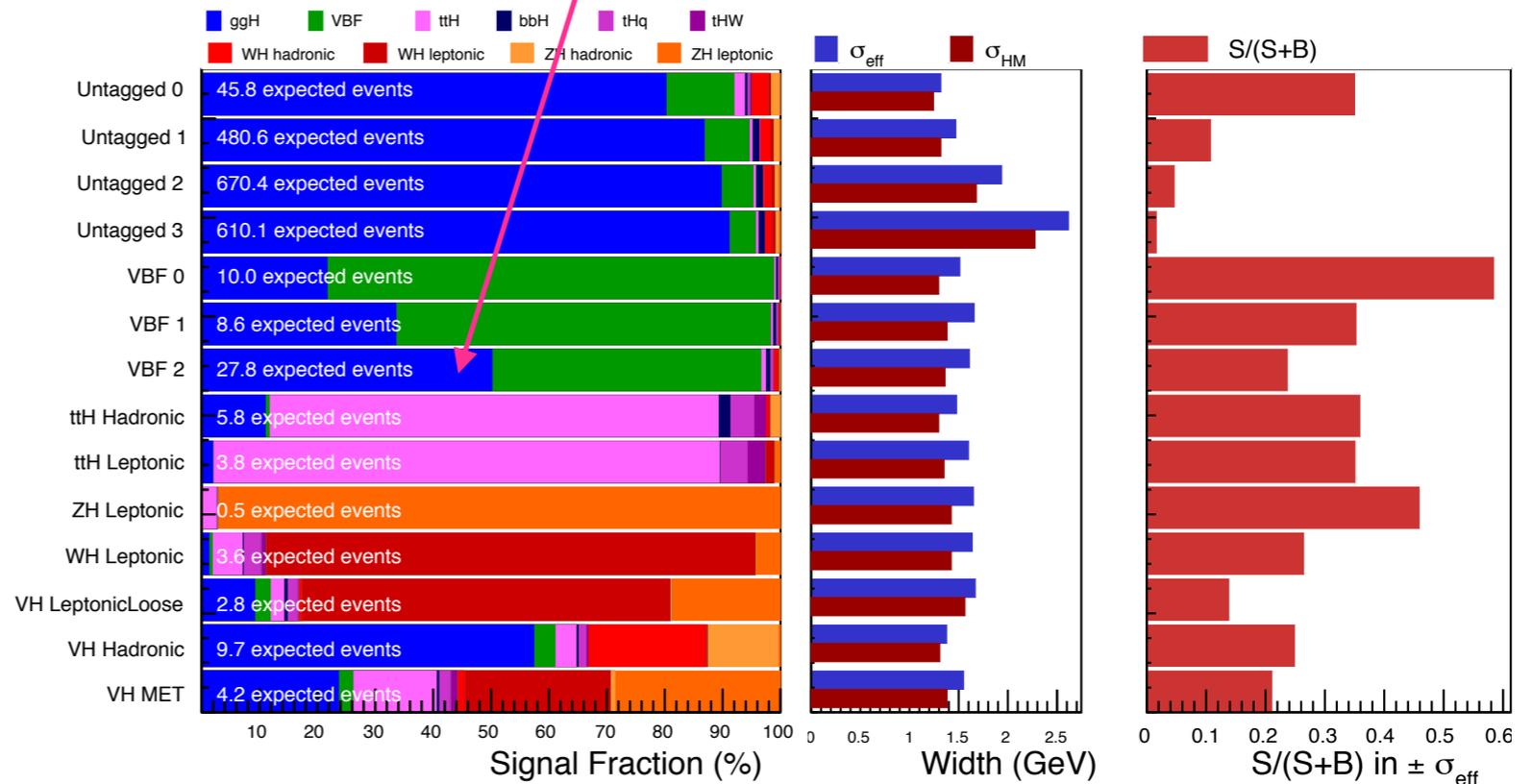
Legend for signal processes: ggH (green), VBF (dark green), WH (cyan), ZH (blue), ggZH (dark blue), ttH (magenta), bbH (red), tHqb (yellow-green), tHW (yellow).

ATLAS Preliminary  $H \rightarrow \gamma\gamma$ ,  $m_H = 125.09$  GeV



Large ggF contamination in VBF category

CMS Preliminary  $H \rightarrow \gamma\gamma$

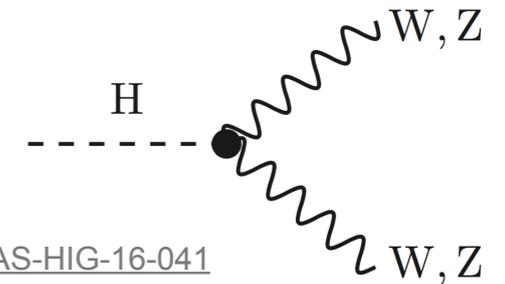


CMS-PAS-HIG-16-040

35.9 fb<sup>-1</sup> (13 TeV)

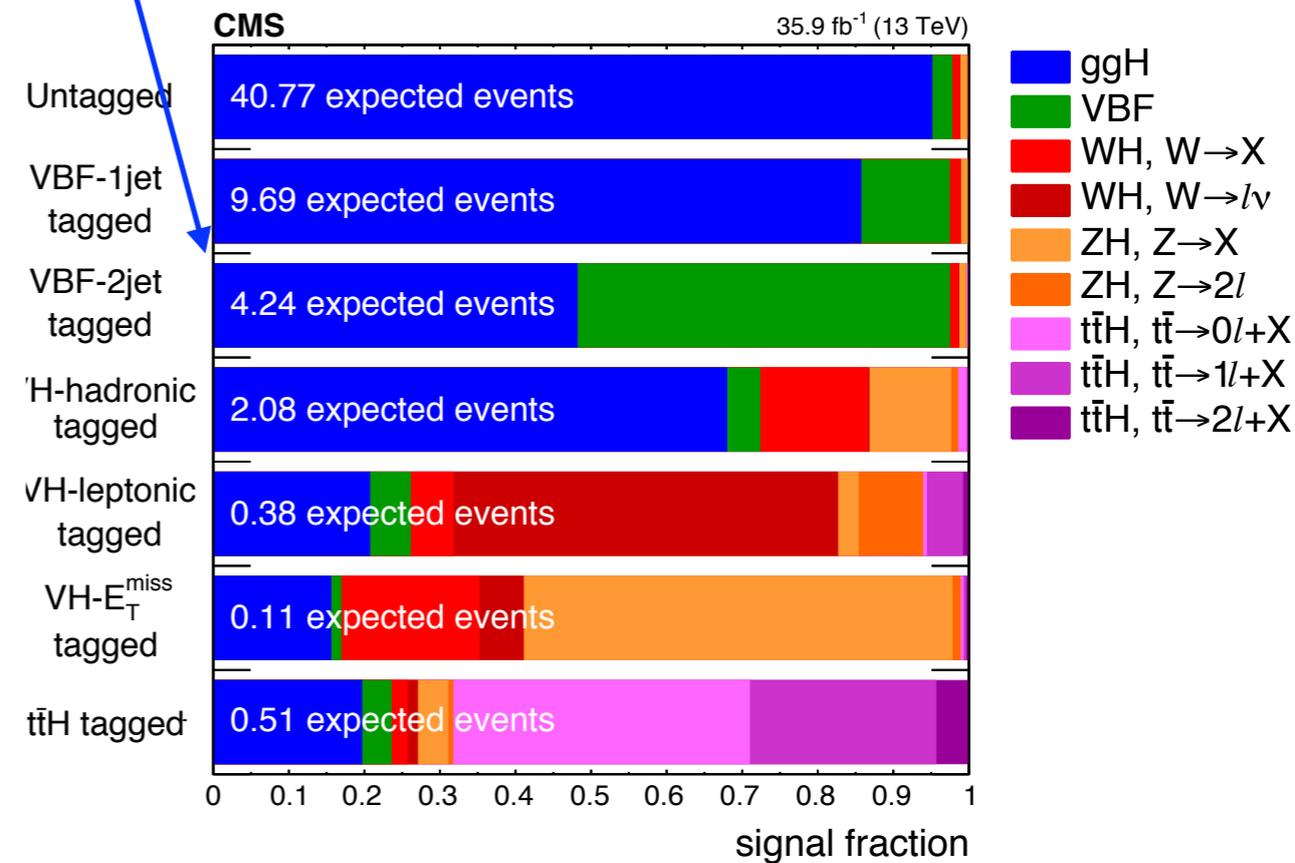
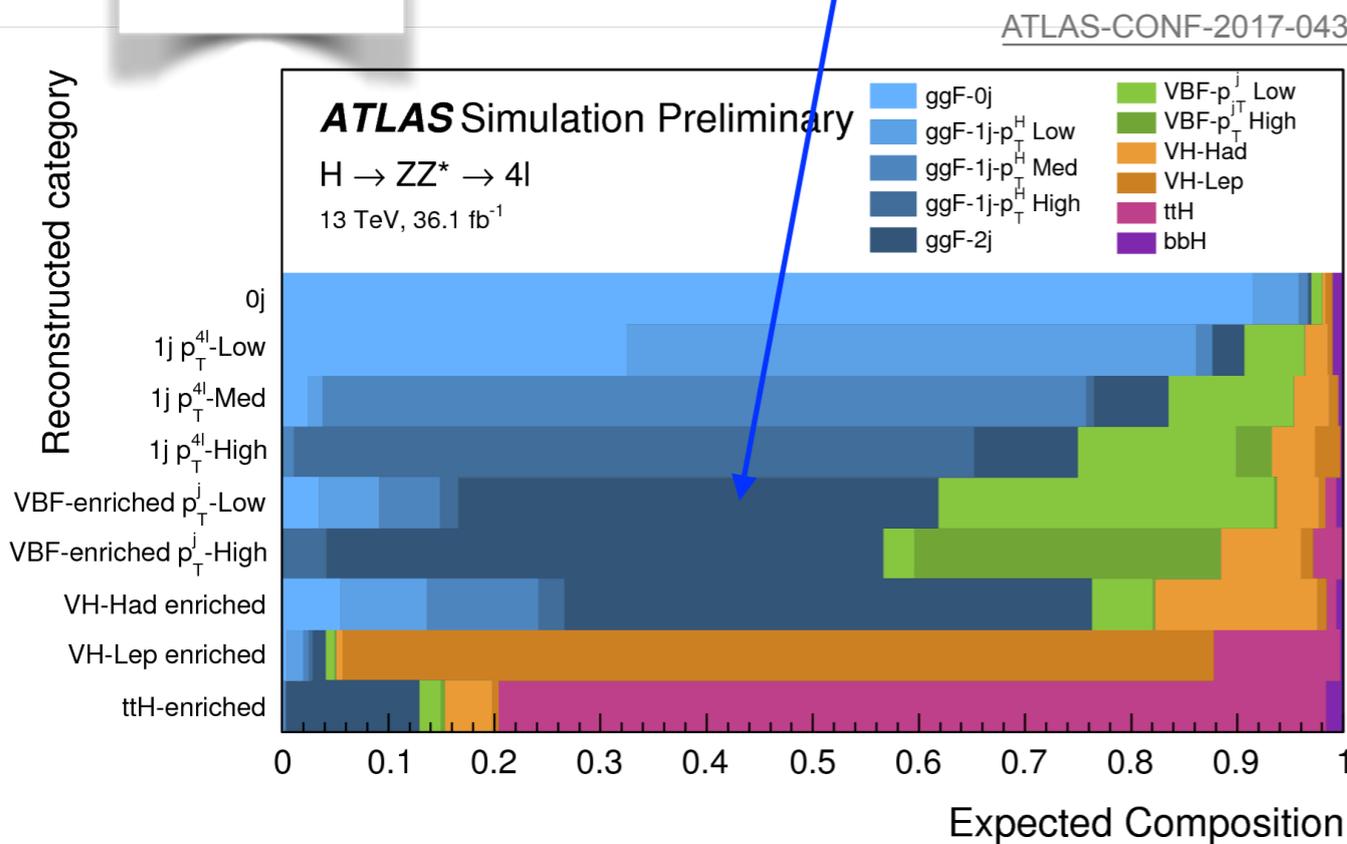
# H → ZZ\* → 4 leptons categorization

- Despite small  $BR(H \rightarrow 4l) = 1.24 \times 10^{-4}$  ( $l=e, \mu$ ) for  $M_H = 125 \text{ GeV}$ , very clean signal  $S/B > 2$ .
- Events are categorized in ggF, VBF, VH and ttH production modes.
- Categorized in # of jets, b-jets and additional leptons.



**RUN-2**

Large ggF contamination in VBF category



- Active discussions in WG1/ggF subgroup for new jet-bin uncertainty prescription including post YR-4.
  - Hot area after arrivals of ggF N3LO inclusive, NNLO H+0/1-jet exclusive calculations.
  - New prescriptions with STWZ, PLPTW, JVE, etc., including for Simplified Template XS.
  - Well documented recommendation for post YR-4 is crucial.

# 3. Higgs boson coupling measurements

# Higgs signal-strength

## LO $\kappa$ -framework

$$\mu = \frac{\sigma \cdot \text{BR}}{(\sigma \cdot \text{BR})_{\text{SM}}}$$

$$\mu = \frac{(\sigma \cdot \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma)}{\{\sigma(gg \rightarrow H) \cdot \text{BR}(H \rightarrow \gamma\gamma)\}_{\text{SM}}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$$\kappa_H^2 = \sum_{jj=WW^*, ZZ^*, b\bar{b}, \tau^-\tau^+, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+} \frac{\kappa_j^2 \Gamma_{jj}^{\text{SM}}}{\Gamma_H^{\text{SM}}}$$

gluon

photon

- Measure with coupling **scale factors**  $\kappa_i$ .
- The coupling of SM particles to Higgs boson scales with particle mass:

$$g_F = \sqrt{2} \frac{m_f}{v}, \quad g_V = 2 \frac{m_V^2}{v}$$

- Holds up to electroweak effects of O(5-10%).

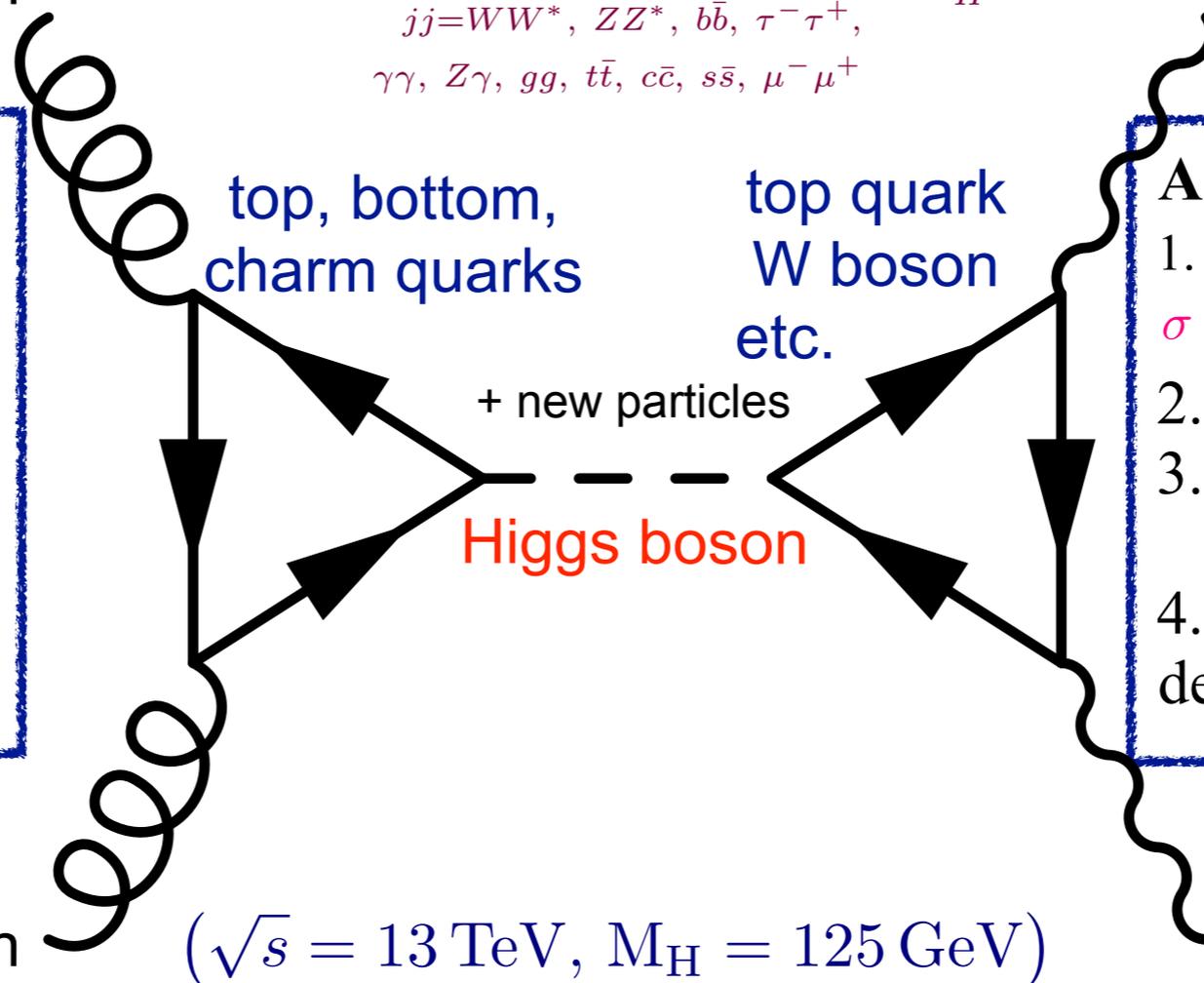
### Assumptions

1. narrow width approx.
2. only 1 SM-like Higgs
3. SM tensor structure (spin 0, CP-even)
4. on-shell production and decay (no-sense for offshell)

gluon

 $(\sqrt{s} = 13 \text{ TeV}, M_H = 125 \text{ GeV})$ 

photon



$$\begin{aligned} \kappa_g^2(\kappa_t, \kappa_b, \kappa_c) &= 1.040\kappa_t^2 + 0.002\kappa_b^2 + 0.00002\kappa_c^2 \\ &- 0.038\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0004\kappa_b\kappa_c \end{aligned}$$

$$\kappa_\gamma^2(\kappa_W, \kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

**Destructive interference in both  $gg \rightarrow H$  (top-bottom) and  $H \rightarrow \gamma\gamma$  (W-top) loops.**

# Note on Coupling versus Mass relation

Post YR-3 activity.

Discussions on quark mass (M. Spira)

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGSMInputParameter>

$$\left\{ \begin{array}{l} y_F = \kappa_F \frac{m_f}{v} \\ y_V = \sqrt{\kappa_V} \frac{m_V}{v} \end{array} \right.$$

Prescription for mass vs coupling plot

[https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWGSMInputParameter/Higgs\\_coupling.pdf](https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWGSMInputParameter/Higgs_coupling.pdf)

1. One can define quark mass for Yukawa coupling,

$$\bar{g}_Q(M_H), \bar{g}_Q(M_Q), g_Q^{\text{pole}}$$

2. Though above are theoretically equivalent, running mass evaluated at Higgs mass scale is better to avoid the offset due to non-universal corrections in quarks and leptons,

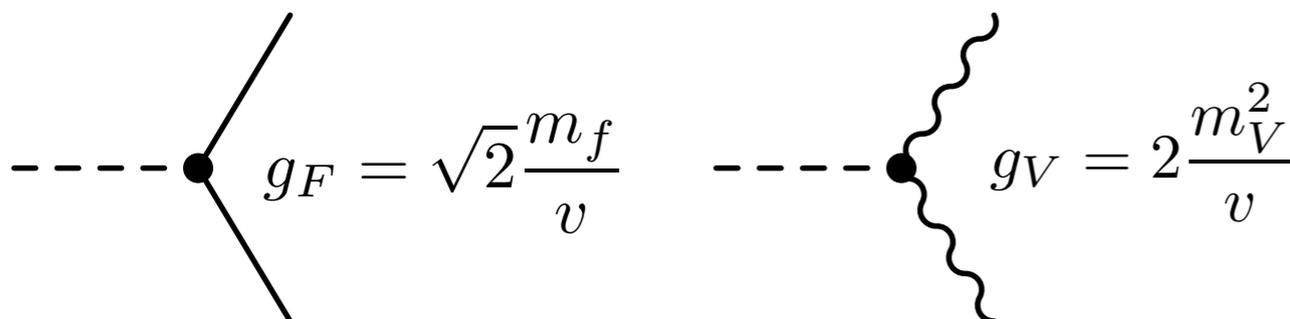
$$\Gamma(H \rightarrow Q\bar{Q}) = \bar{g}_Q^2(M_H) \frac{3M_H}{16\pi} \left\{ 1 + \frac{17}{3} \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2) \right\}$$

$$m_b(m_b) = \cancel{4.16} \text{ GeV}, m_b(M_H) = \cancel{2.76} \text{ GeV}$$

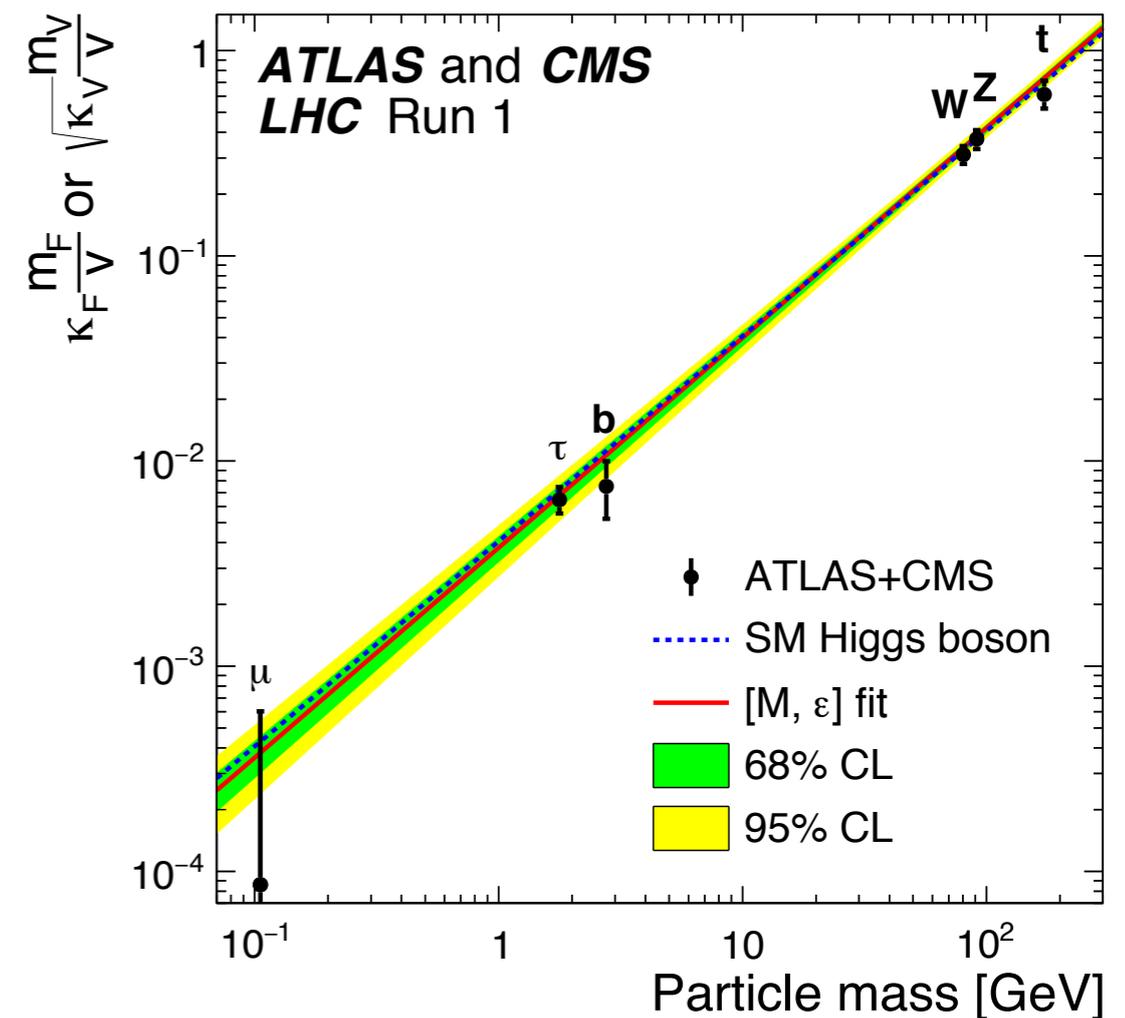
4.18

3. Use pole mass for top quark (172.5 GeV).

4. Use PDG values for leptons and W/Z boson masses.



ATLAS and CMS, JHEP 08 (2016) 045

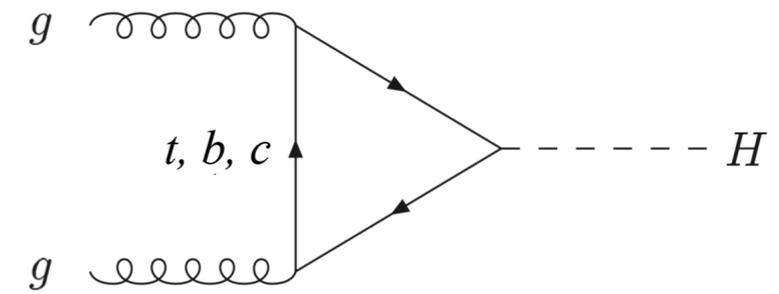


$$m_b(m_b) = \cancel{4.16} \text{ GeV}, m_b(M_H) = \cancel{2.76} \text{ GeV}$$

4.18 needs to update

# Updates of $\kappa$ -framework: ggF

Post YR-4 activity. Other processes in backup slides.



- Cross sections are calculated in N3LO QCD by Zürich group ([Note by Zürich group](#)).
- QCD scales:  $\mu=\mu_F=\mu_R=M_h/2$ , PDF set: PDF4LHC15\_nnlo\_100
- References: [[Anastasiou:2014vaa](#),[Anastasiou:2014lda](#),[Anastasiou:2016cez](#),[Anastasiou:2016hlm](#)]
- Numbers in bottom-quark related cross sections and corresponding  $\kappa$  coupling modifiers have changed with respect to CERN Report 3 (see Eq. (111) and Table 38).

For  $M_h=125$  GeV at  $\sqrt{s}=8$  TeV,

CERN Report 3:  $\kappa_g^2 = 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b$

CERN Report 4:  $\kappa_g^2 = 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2$

- The main origins of these differences are:
  1. Due to change in central QCD scale from  $M_h$  (CERN Report 3) to  $M_h/2$  (CERN Report 4). This affects  $\sigma_{tt}$  but doesn't affect much  $\sigma_{tb}$  or  $\sigma_{bb}$ .
  2. Due to inclusion of charm quark.
  3. Due to change in quark-mass definition from on-shell mass in CERN Report 3 ( $M_t=172.5$  GeV,  $M_b=4.84131$  GeV) to MSbar mass in CERN Report 4 ( $M_t(M_t)=162.7$  GeV,  $M_b(M_b)=4.18$  GeV and  $M_c(3\text{ GeV})=0.986$  GeV)
    - In the MSbar scheme the light quark masses run to a significantly lower value (at scale of  $\mu \sim M_h/2$  or  $M_h$ ) than their pole masses.
    - Hence there is an effect on the top-bottom interference and the bottom-bottom part (also for charm).
    - It has been checked that HIGLU (M. Spira) and Zürich calculations agree perfectly with the same input condition in on-shell mass scheme.
- Some interest in charm-Yukawa coupling measurement via  $J/\psi+\gamma$ ,  $H_j$  [[arXiv:1606.09253](#)],  $VH(H\rightarrow cc)$ , etc.

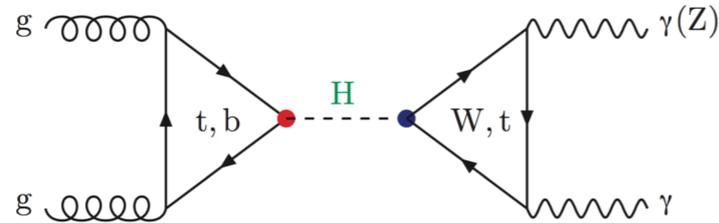
13 TeV															
$M_h$ [GeV]	$\sigma_{EW}$ [pb]	$\sigma_{tt}$ [pb]	$\sigma_{tb}$ [pb]	$\sigma_{bb}$ [pb]	$\sigma_{tc}$ [pb]	$\sigma_{bc}$ [pb]	$\sigma_{cc}$ [pb]	$\sigma_{tot}$ [pb]	$\sigma_{QCD}$ [pb]	$\kappa_t^2$	$\kappa_t\kappa_b$	$\kappa_b^2$	$\kappa_t\kappa_c$	$\kappa_b\kappa_c$	$\kappa_c^2$
124.50	2.40	48.35	-1.76	0.10	-0.22	0.02	0.0009	48.89	46.49	1.040	-0.038	0.002	-0.005	0.0004	0.00002
125.00	2.39	48.00	-1.74	0.10	-0.22	0.02	0.0009	48.55	46.16	1.040	-0.038	0.002	-0.005	0.0004	0.00002
125.09	2.39	47.94	-1.73	0.10	-0.22	0.02	0.0009	48.50	46.11	1.040	-0.038	0.002	-0.005	0.0004	0.00002
125.50	2.39	47.65	-1.72	0.10	-0.22	0.02	0.0009	48.22	45.83	1.040	-0.038	0.002	-0.005	0.0004	0.00002

# Couplings ( $\kappa_V, \kappa_F$ ) in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

- Slope due to negative interference between top and W-boson in  $H \rightarrow \gamma\gamma$  decay

$$\kappa_\gamma^2(\kappa_W, \kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

$$\text{slope : } \frac{d\kappa_F}{d\kappa_V} \simeq 4.7$$



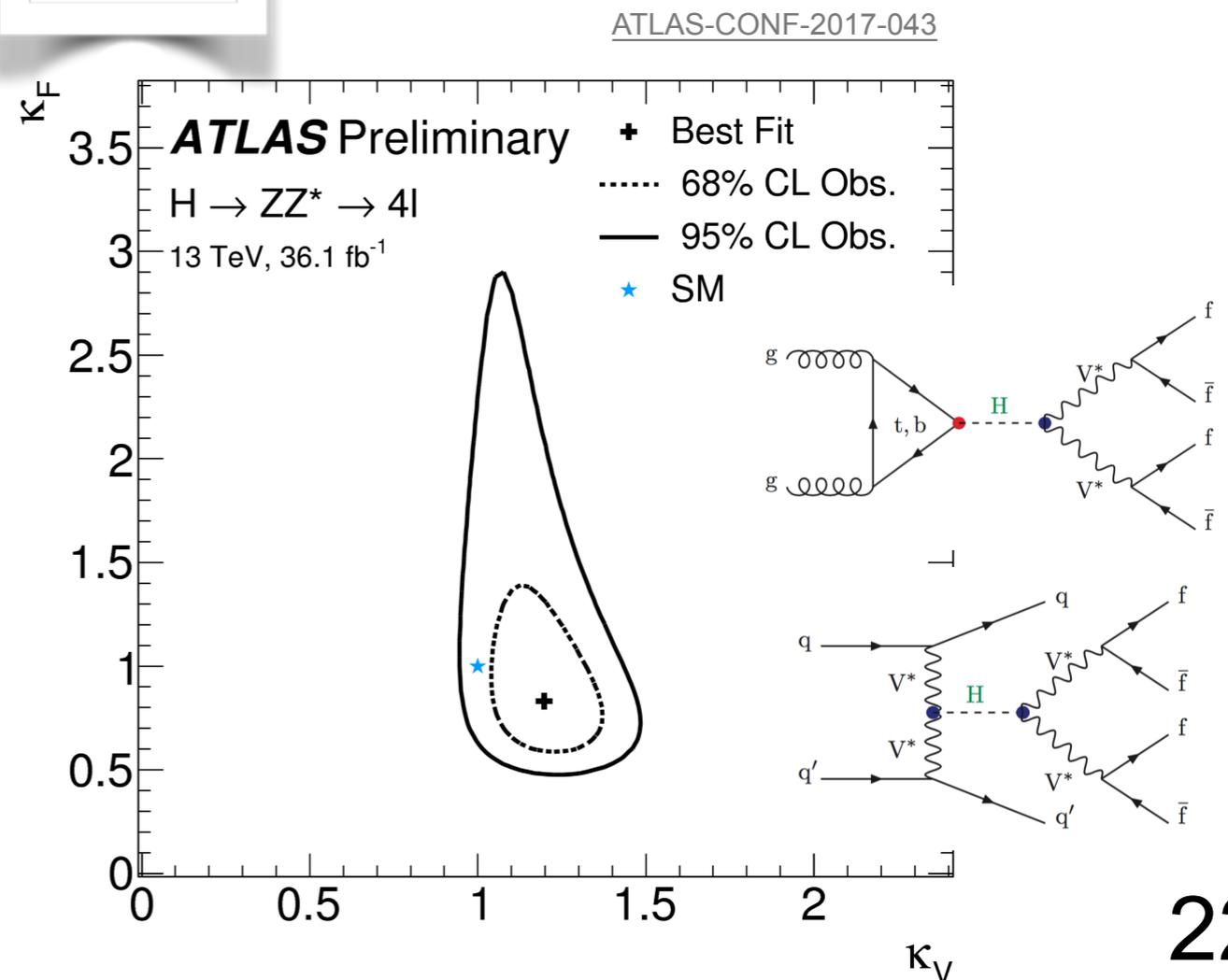
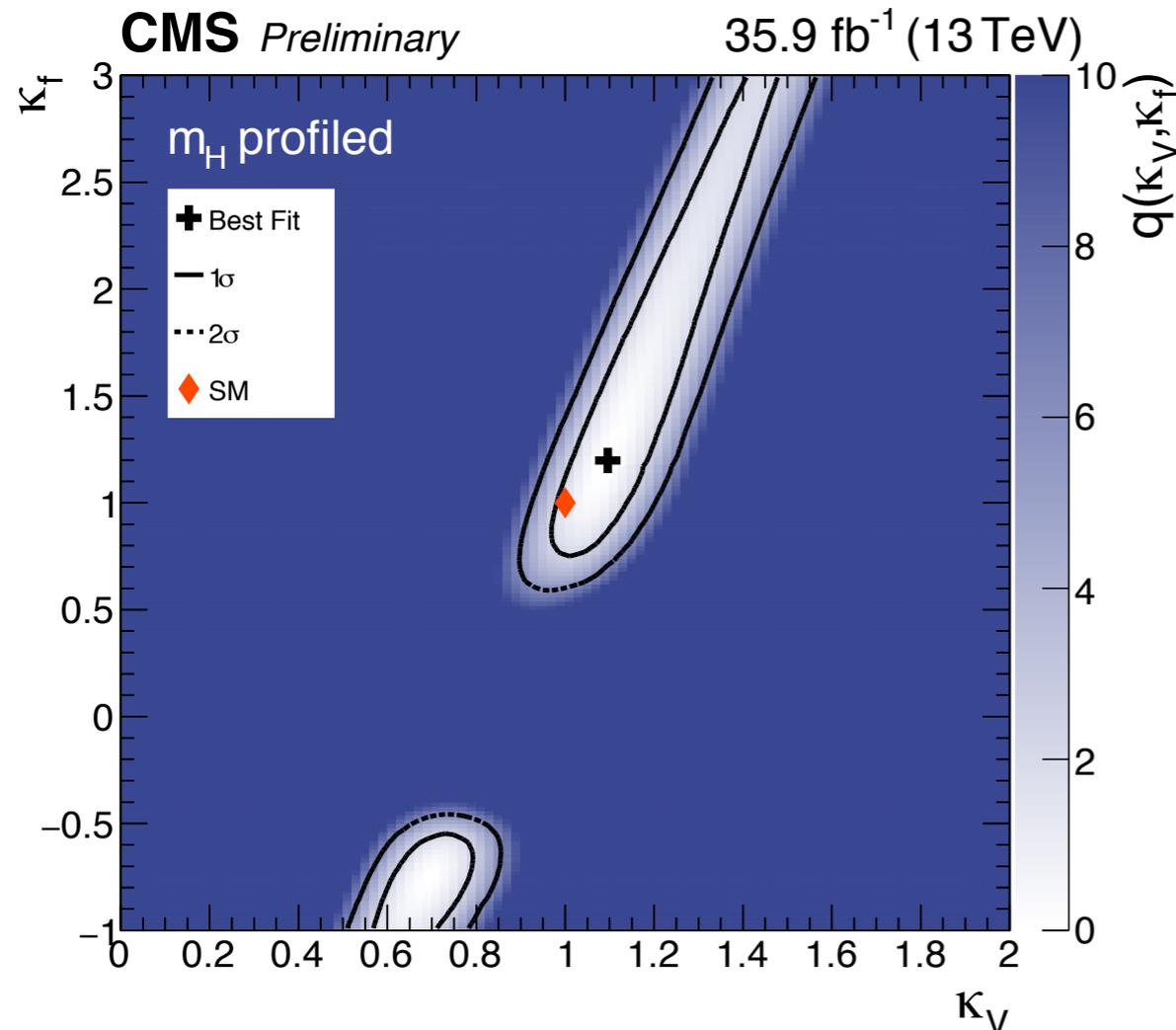
CMS-PAS-HIG-16-040

- Mostly sensitive to  $\kappa_V$ , but can constrain on  $\kappa_F$  with associated productions in VBF and VH. ( $\because$  too large  $\kappa_F$  means small  $\text{BR} = \Gamma_{ZZ} / \Gamma_{\text{tot}}$  where  $\Gamma_{\text{tot}}$  is dominated by  $H \rightarrow b\bar{b}$ ).

$$\text{BR}(H \rightarrow VV) = \frac{\Gamma_{VV}}{\Gamma_{\text{tot}}} = \frac{\Gamma_{VV}}{\Gamma_{f\bar{f}} + \Gamma_{VV}}$$

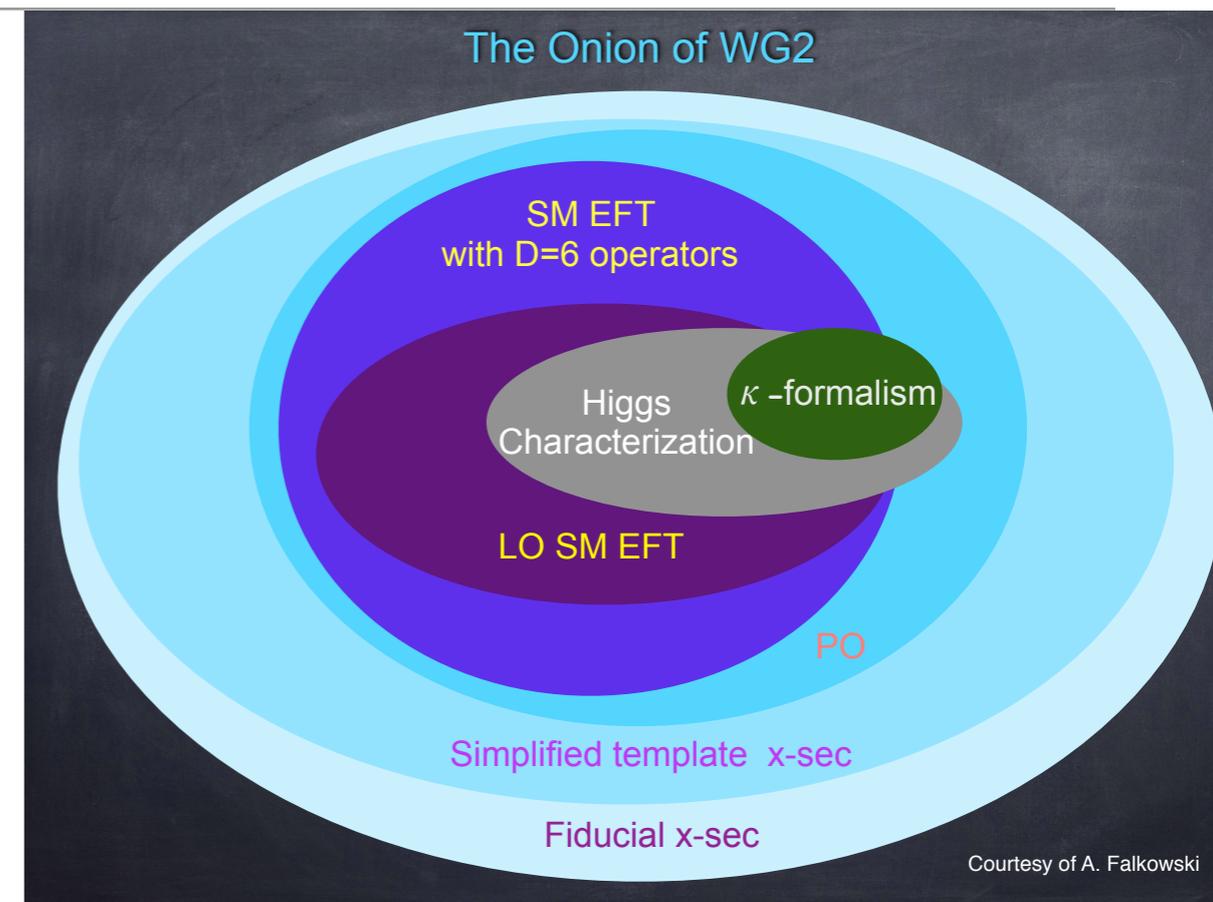
$$\Gamma_{f\bar{f}} : \Gamma_{VV} \simeq 3 : 1 \text{ (dominated by } \Gamma_{b\bar{b}})$$

**RUN-2**



# Go beyond $\kappa$ -framework

- Various frameworks exist:
  1. Fiducial Cross Section
  2. Simplified Template Cross Section
  3. Pseudo-Observables
  4. Higgs Effective Field Theory
  5. Higgs Characterization (did in RUN-1)
  6. kappa-framework (did in RUN-1)

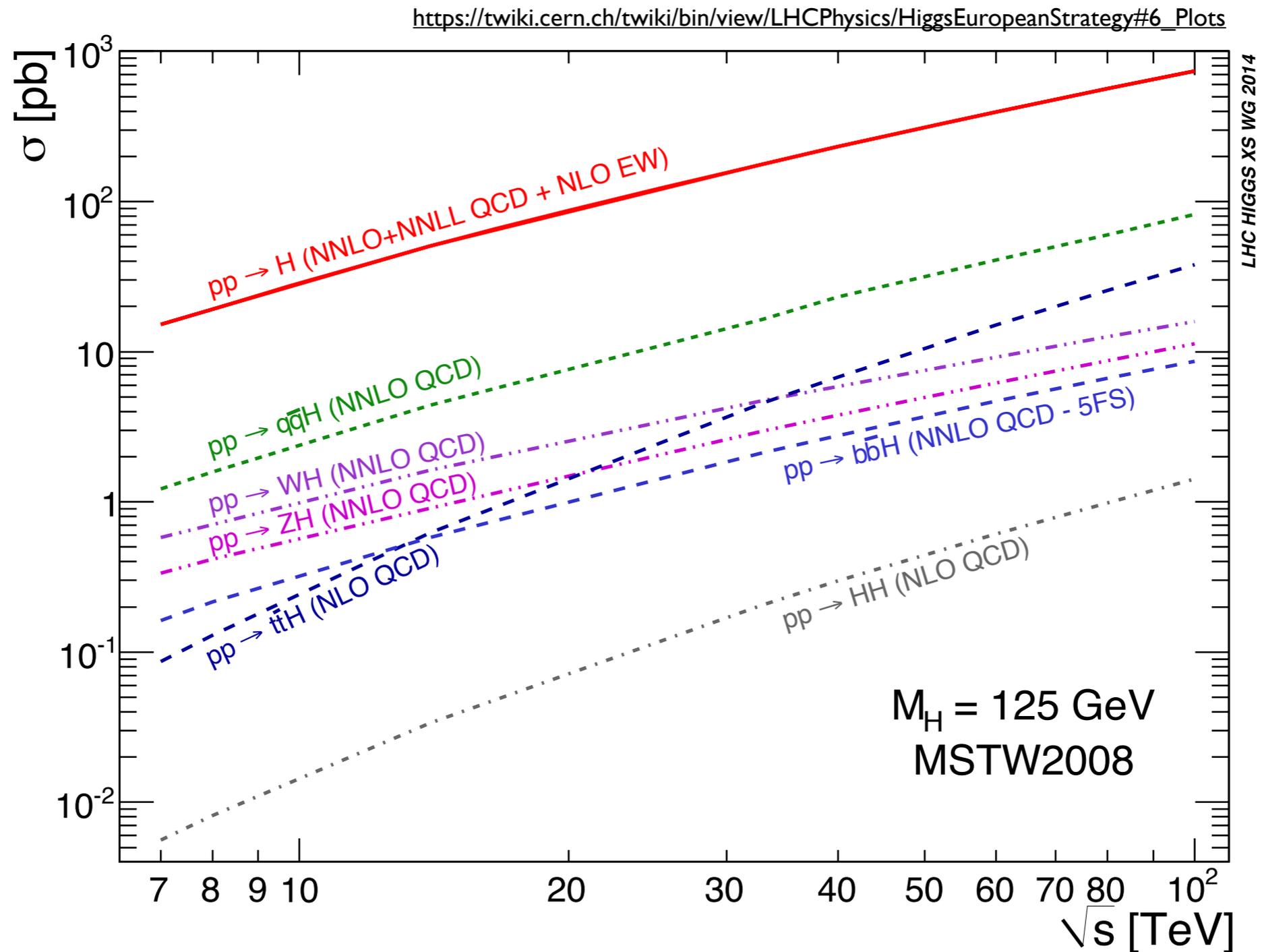


## ⇒ $\kappa$ -framework remains as an option in RUN-2

- References [LHCHXSWG-2012-001] [CERN Yellow Report 3]
- $\kappa$ -framework is aimed to “detect the deviation from the SM”, not “measuring the coupling itself for precision physics”.
- Extensive discussions in WG2 of the LHC Higgs Cross Section Working Group
  - Experiments provide Fiducial XS and Simplified Template XS.
  - Measurements in Pseudo-Observables
  - Interpretation in the Effective Field theory (eventual combination with EWPD, discussion started)
- Recommendations from WG2 are eagerly waited on Higgs EFT in particular.

# FCC-hh

Q) Different theory consideration needed for 100TeV?



# Challenges beyond $\gamma\mathcal{R}$ -4

## ggF

- N3NLO differential  $d\sigma/dY$
- $\alpha_s$  uncertainty reduction
- Reduction of ggF in VBF category

## Differential NNLO

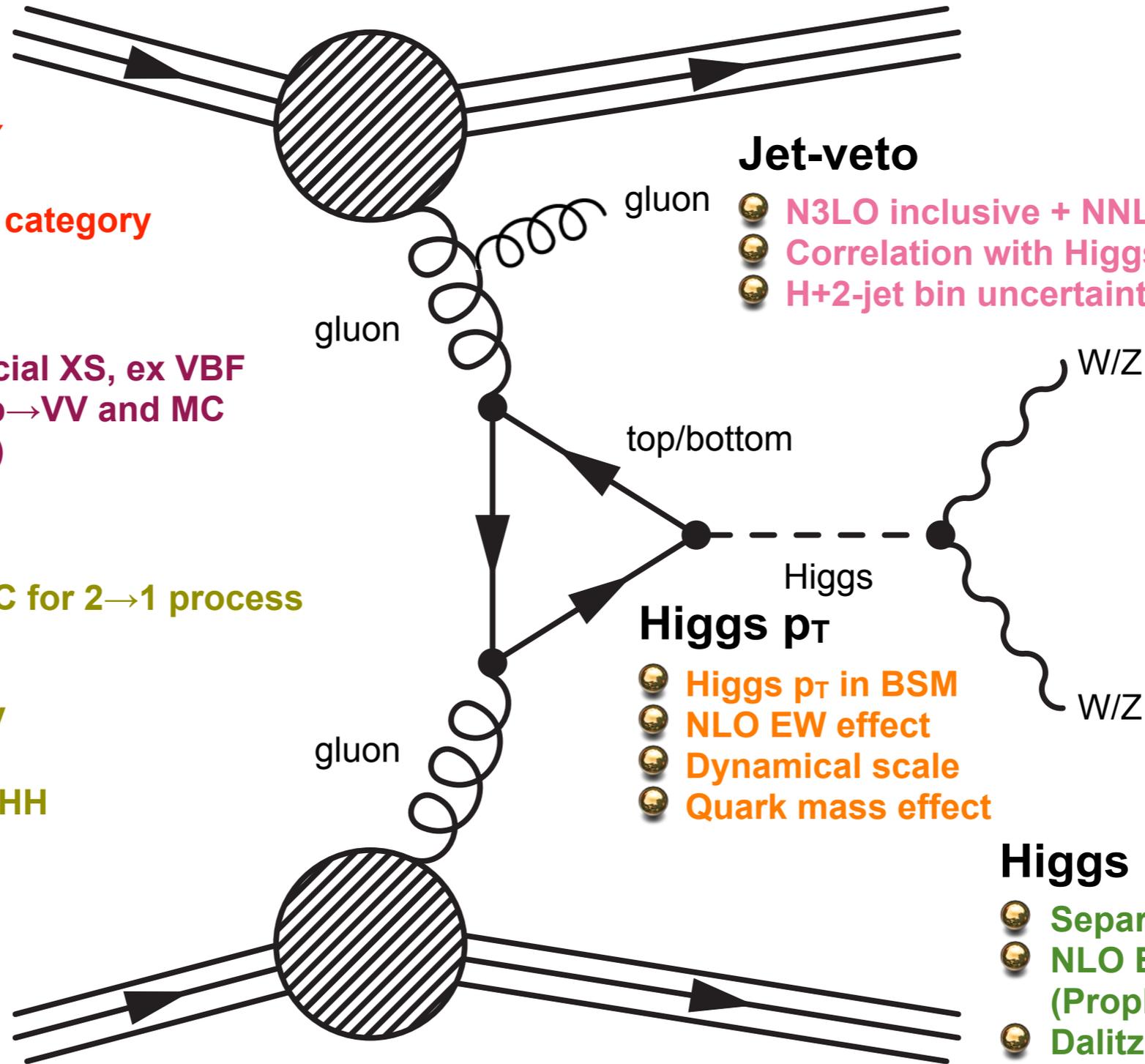
- NNLO QCD effect in fiducial XS, ex VBF
- NNLO QCD + NLO EW  $pp \rightarrow VV$  and MC (include offshell, ex  $Z^*Z^*$ )

## (N)NLO MC

- NNLO QCD + NLO EW MC for  $2 \rightarrow 1$  process
- NLO EW in MC
- H+0/1/2-jets (N)NLO MC
- H+3-jets NLO MC for CJV
- $\Delta\Phi_{jj}$  in H+2-jets MC
- NLO MC for  $gg \rightarrow VV, ZH, HH$

## SM Backgrounds

- $t\bar{t} + V/HF + \text{jets}$



## Jet-veto

- N3LO inclusive + NNLO H+0/1-jet comb.
- Correlation with Higgs  $p_T$
- H+2-jet bin uncertainty beyond NLO

## Higgs $p_T$

- Higgs  $p_T$  in BSM
- NLO EW effect
- Dynamical scale
- Quark mass effect

## Higgs Decay

- Separation of THU and PU
- NLO EW differential (Prophecy4f/Hto4l)
- Dalitz decay common def.

## PDF

- N3LO PDF
- PDF and  $\alpha_s$  correlations between Higgs and SM bkg.

# Tools for Higgs Analysis

## ggF

- [HIGLU](#) (NNLO QCD+NLO EW)
- [iHixs](#) (NNLO QCD+NLO EW)
- [FeHiPro](#) (NNLO QCD+NLO EW)
- [HNNLO, HRes](#) (NNLO+NNLL QCD)
- [RGHiggs](#) (NNLO+NNLL QCD)
- [SusHi](#) (NNNLO QCD)
- [ggHiggs](#) (NNNLO QCD)
- [TROLL](#) (NNNLO+NNLL QCD)

## VBF

- [VV2H](#) (NLO QCD)
- [VBFNLO](#) (NLO QCD)
- [HAWK](#) (NLO QCD+EW)
- [VBF@NNLO](#) (NNLO QCD)

## WH/ZH

- [V2HV](#) (NLO QCD)
- [HAWK](#) (NLO QCD+EW)
- [VH@NNLO](#) (NNLO)

## ttH

- [HQQ](#) (LO QCD)
- [POWHEL](#) (NLO QCD)
- [MG5\\_aMC@NLO](#) (NLO QCD)

## bbH

- [bbh@NNLO](#) (NNLO QCD)
- [MG5\\_aMC@NLO](#) (NLO QCD)
- [bbhFONLL](#) (NLO+NNLL QCD)
- [bbX](#) (NLO+NNLL QCD)

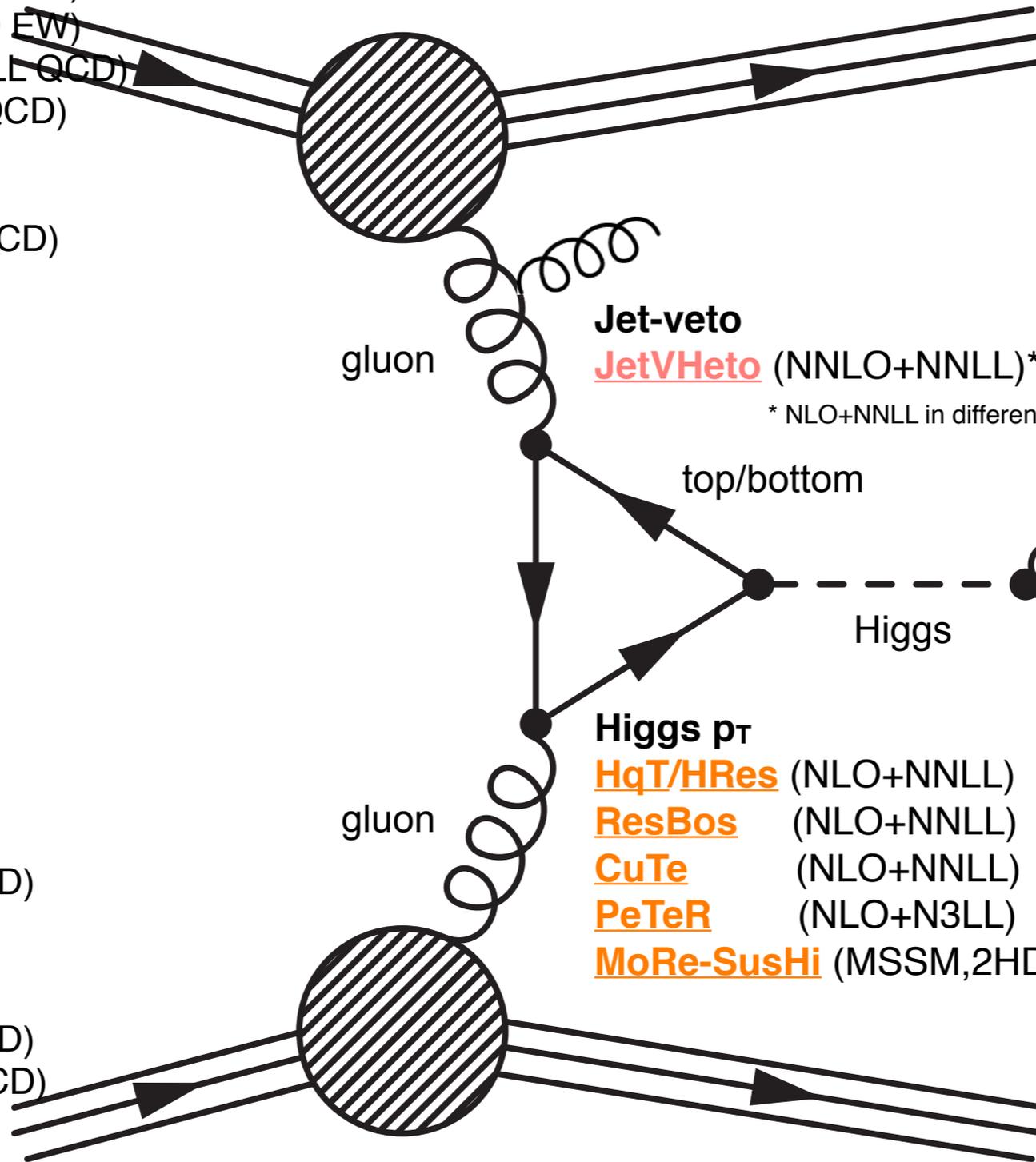
## HH

- [HPAIR](#) (NLO QCD)
- [MG5\\_aMC@NLO](#) (NLO QCD)

PDF: [MSTW/MMHT](#), [CTEQ](#), [NNPDF](#), [xFitter](#), [PDF4LHC](#), ...  
[METAPDF](#), [LHAPDF](#), [HOPPET](#), [APFEL](#)

SM: [MCFM](#), [MG5\\_aMC@NLO](#), [VVamp](#), [gg2VV](#),  
[DiffTop](#)

+ private codes



## NLO MC

- [POWHEG-BOX](#) [MiNLO](#)
- [MadGraph5\\_aMC@NLO](#)
- [SHERPA](#) [MEPS@NLO](#)
- [PYTHIA8](#) [UNLOPS](#)
- [HERWIG++](#) [Matchbox](#)

## NLO ME/Automated NLO

- [MCFM](#), [MG5\\_aMC@NLO](#)
- [BlackHat](#), [GoSam](#), [HELAC](#),  
[OpenLoops](#), etc.

W/Z

## Higgs Decay

- [HDECAY](#) (NLO++)
- [Prophecy4f](#) (NLO QCD+EW)
- [Hto4l](#) (NLO QCD+EW)

W/Z

## Higgs Properties

- [MELA/JHU](#), [MEKD](#), [Lilith](#),  
[HiggsBounds/HiggsSignals](#)

## HEFT

- [MG5\\_aMC@NLO \(SILH,HC\)](#)
- [eHDECAY](#)

## MSSM/2HDM

- [FeynHiggs](#), [CPSuperH](#)
- [SusHi+2HDMC](#)
- [HIGLU+HDECAY](#)

# Tools for Higgs Analysis

Clickable Link

## ggF

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- [FeHiPro](#) (NNLO QCD+NLO EW)
- [HNNLO](#), [HRes](#) (NNLO+NNLL QCD)
- [RGHiggs](#) (NNLO+NNLL QCD)
- [SusHi](#) (NNNLO QCD)
- [ggHiggs](#) (NNNLO QCD)
- [TROLL](#) (NNNLO+NNLL QCD)

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- [VBFNLO](#) (NLO QCD)
- [HAWK](#) (NLO QCD+EW)
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## WH/ZH

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- [HAWK](#) (NLO QCD+EW)
- [VH@NNLO](#) (NNLO)

## ttH

- [HQQ](#) (LO QCD)
- [POWHEL](#) (NLO QCD)
- [MG5\\_aMC@NLO](#) (NLO QCD)

## bbH

- [bbh@NNLO](#) (NNLO QCD)
- [MG5\\_aMC@NLO](#) (NLO QCD)
- [bbhFONLL](#) (NLO+NNLL QCD)
- [bbX](#) (NLO+NNLL QCD)

## HH

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- [MG5\\_aMC@NLO](#) (NLO QCD)

+ private codes

PDF: [MSTW/MMHT](#), [CTEQ](#), [NNPDF](#), [xFitter](#), [PDF4LHC](#), ..., [METAPDF](#), [LHAPDF](#), [HOPPET](#), [APFEL](#)

SM: [MCFM](#), [MG5\\_aMC@NLO](#), [VVamp](#), [gg2VV](#), [DiffTop](#)

## NLO MC

- [POWHEG-BOX](#) [MiNLO](#)
- [MadGraph5\\_aMC@NLO](#)
- [SHERPA](#) [MEPS@NLO](#)
- [PYTHIA8](#) [UNLOPS](#)
- [HERWIG++](#) [Matchbox](#)

## NLO ME/Automated NLO

- [MCFM](#), [MG5\\_aMC@NLO](#)
- [BlackHat](#), [GoSam](#), [HELAC](#), [OpenLoops](#), etc.

## Higgs Decay

- [HDECAY](#) (NLO++)
- [Prophecy4f](#) (NLO QCD+EW)
- [Hto4l](#) (NLO QCD+EW)

## Higgs Properties

- [MELA/JHU](#), [MEKD](#), [Lilith](#), [HiggsBounds/HiggsSignals](#)

## HEFT

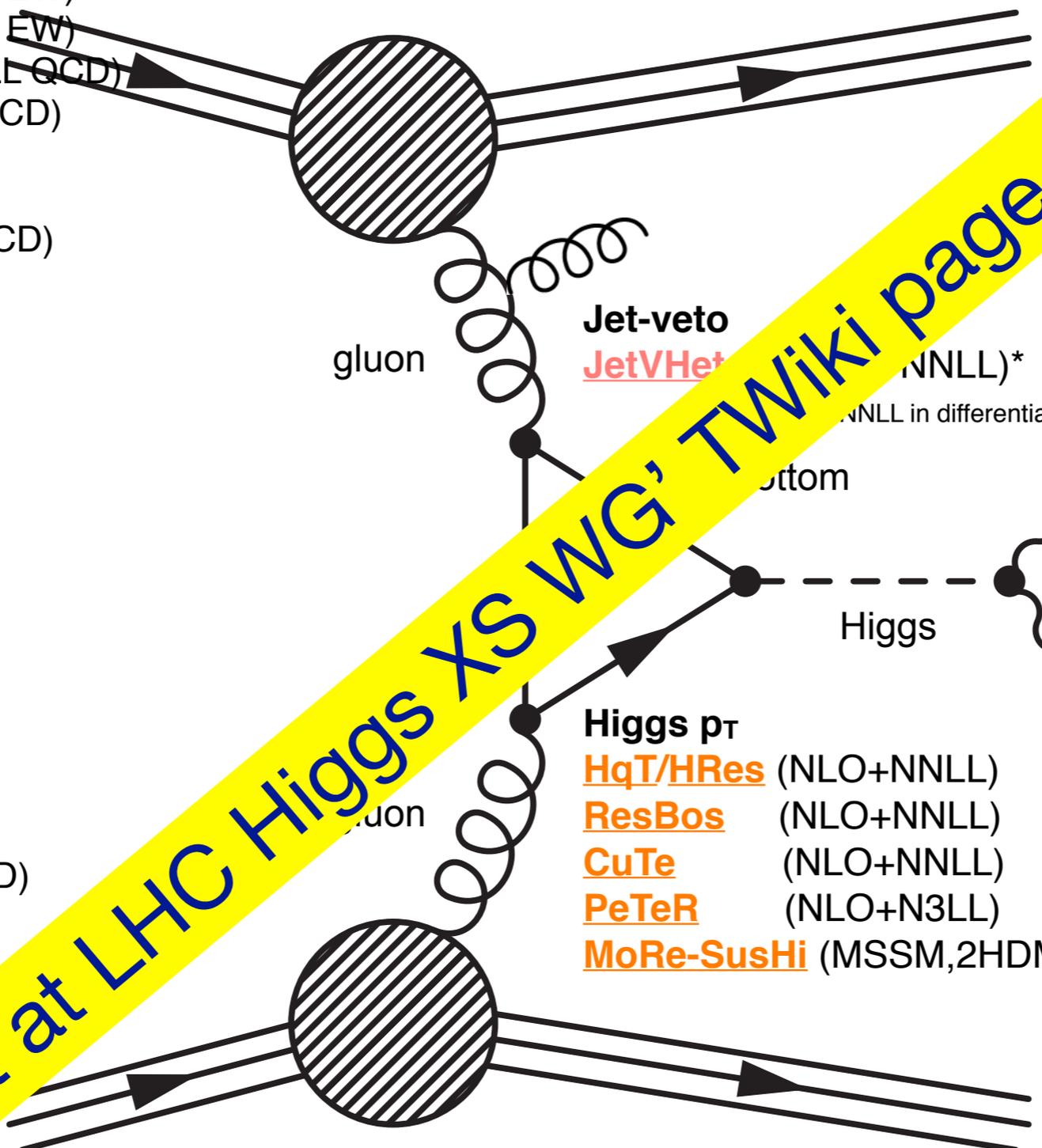
- [MG5\\_aMC@NLO](#) (SILH,HC)
- [eHDECAY](#)

## MSSM/2HDM

- [FeynHiggs](#), [CPSuperH](#)
- [SusHi+2HDMC](#)
- [HIGLU+HDECAY](#)

Compiled by R. Tanaka, May 2017

Put at LHC Higgs XS WG' TWiki page?



gluon

Jet-veto

[JetVHet](#)

(NNLL)\*

NNLL in differential

bottom

Higgs

Higgs p<sub>T</sub>

[HqT/HRes](#) (NLO+NNLL)

[ResBos](#) (NLO+NNLL)

[CuTe](#) (NLO+NNLL)

[PeTeR](#) (NLO+N<sup>3</sup>LL)

[MoRe-SusHi](#) (MSSM,2HDM)

W/Z

W/Z

# Summary

---

- CERN Report 4 completed after many years of works !!!
  - Experiments should be able to survive for a while at least for RUN-2.
- Experimental status as of today
  - We know  $M_H$ ,  $\Gamma_H$ , spin/CP and couplings but not much yet for direct Yukawa, Higgs potential and BSM sector !
  - Experiments are starting the precision measurements in Higgs-gauge sector with  $H \rightarrow \gamma\gamma$ ,  $ZZ$  channels.  $H \rightarrow WW$ , to come.
  - We still know little about Higgs-Yukawa sector. Analyses are very difficult in  $H \rightarrow \tau\tau$ ,  $VH(bb)$ ,  $ttH(bb)$ .
  - Rare decays such as  $H \rightarrow Z\gamma$ ,  $\mu\mu$  are important in view 2nd generation.
- Post YR-4
  - Experimental analyses are more and more differential. Crucial for Higgs  $p_T$  and jet-bin uncertainties, in particular VBF  $H+2$ -jets category.
  - Conversations among ATLAS, CMS and TH community is vital as was in RUN-1 !

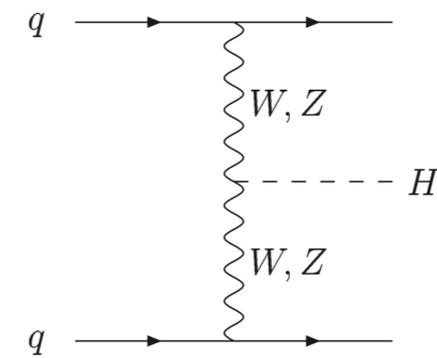
backup

# Discussion items (selected topics)

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- Higgs XS
  - Scale uncertainty (THU), PDF+ $\alpha_s$  correlations among Higgs and SM backgrounds
- Higgs decay
  - BR uncertainty correlation (THU,PU). Decay kinematics, ex.  $h \rightarrow 4l$  with Prophecy4f, H4l
- Higgs pT
  - MC Higgs pT reweighing? Uncertainty in high pT (dynamical scale, mq effect)
- Jet-binning
  - S&T, advanced S&T, JetVHeto, etc. N3LO and NNLO in  $H+0/1$ -jet.  $H+>2$ -jets category?
- Needs improvements in ggF contamination in VBF and VH channels.
- MC
  - NLO EW reweighing? NLO EW implementation ?
- Coupling, Tensor Structure measurements
  - kappa-framework, Higgs EFT vs PO
- MSSM
  - bbh 4FS vs 5FS

# VBF

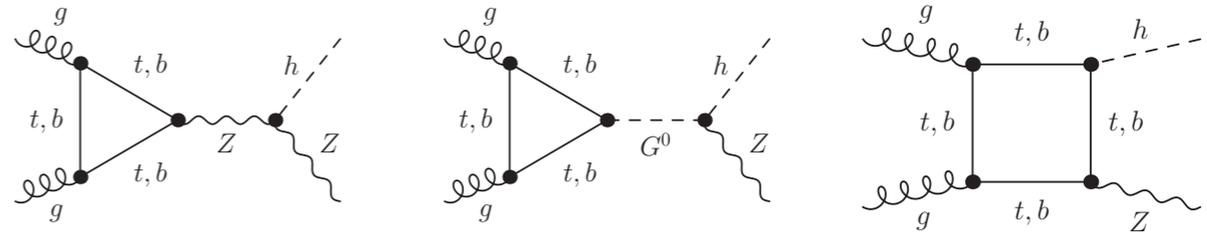


- Cross sections are calculated in NNLO QCD with VBF@NNLO program (CERN Report 4, Appendix).
- QCD scales:  $\mu=\mu_F=\mu_R=M_W$ , PDF set: PDF4LHC15\_nnlo\_30\_pdfas
- References: [[Bolzoni:2010xr](#),[Bolzoni:2011cu](#)]
- $\kappa_W^2 : \kappa_Z^2 \simeq 3:1$  at LHC (largely opposite for VBF in  $e^+e^-$  collider)
- CERN Report 3:  $\sigma_{WW} = 0.938$  (1.210) pb and  $\sigma_{ZZ} = 0.321$  (0.417) pb for  $\sqrt{s} = 7(8)$  TeV  
For  $M_h=125$  GeV at  $\sqrt{s}=7(8)$  TeV,  
CERN Report 3:  $\kappa_W^2 = 0.745$  (0.744) and  $\kappa_Z^2 = 0.255$  (0.256)  
CERN Report 4:  $\kappa_W^2 = 0.740$  (0.738) and  $\kappa_Z^2 = 0.260$  (0.262)

⇒ Consistent results between CERN Report 3 & 4 and  $\kappa_W^2$  and  $\kappa_Z^2$  are constant wrt centre-of-mass energies.

$M_h$ [GeV]	7 TeV				8 TeV				13 TeV				14 TeV			
	$\sigma_{WW}$ [pb]	$\sigma_{ZZ}$ [pb]	$\kappa_W^2$	$\kappa_Z^2$	$\sigma_{WW}$ [pb]	$\sigma_{ZZ}$ [pb]	$\kappa_W^2$	$\kappa_Z^2$	$\sigma_{WW}$	$\sigma_{ZZ}$	$\kappa_W^2$	$\kappa_Z^2$	$\sigma_{WW}$ [pb]	$\sigma_{ZZ}$ [pb]	$\kappa_W^2$	$\kappa_Z^2$
120.0	0.993	0.349	0.740	0.260	1.278	0.452	0.739	0.261	3.001	1.091	0.733	0.267	3.392	1.238	0.733	0.267
125.0	0.946	0.333	0.740	0.260	1.220	0.432	0.738	0.262	2.882	1.049	0.733	0.267	3.260	1.191	0.732	0.268
130.0	0.902	0.318	0.740	0.260	1.166	0.413	0.738	0.262	2.770	1.009	0.733	0.267	3.135	1.146	0.732	0.268

# $gg \rightarrow ZH$



● Cross sections are calculated in LO QCD with VH@NNLO program.

● QCD scales:  $\mu = \mu_F = \mu_R = M_{ZH}$ , PDF set: PDF4LHC15\_nnlo\_mc

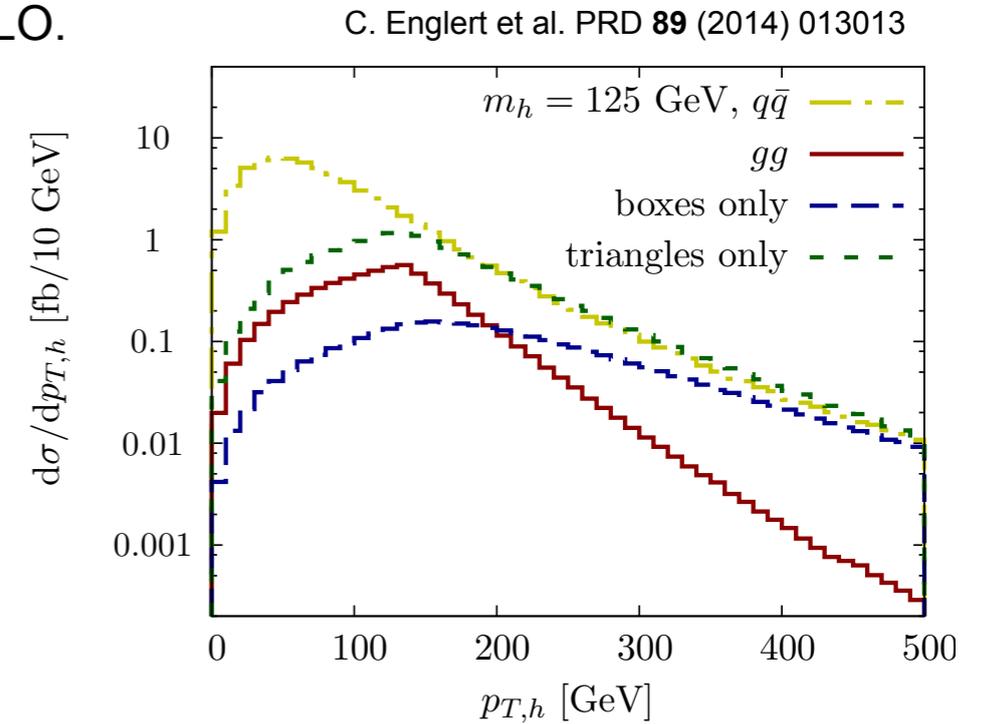
● References: [Brein:2012ne, Harlander:2013mla] for VH@NNLO.

● For  $M_h = 125.09$  GeV at  $\sqrt{s} = 8$  TeV,

CERN-EP-2016-100:  $2.27 \kappa_Z^2 + 0.37 \kappa_t^2 - 1.64 \kappa_t \kappa_Z$

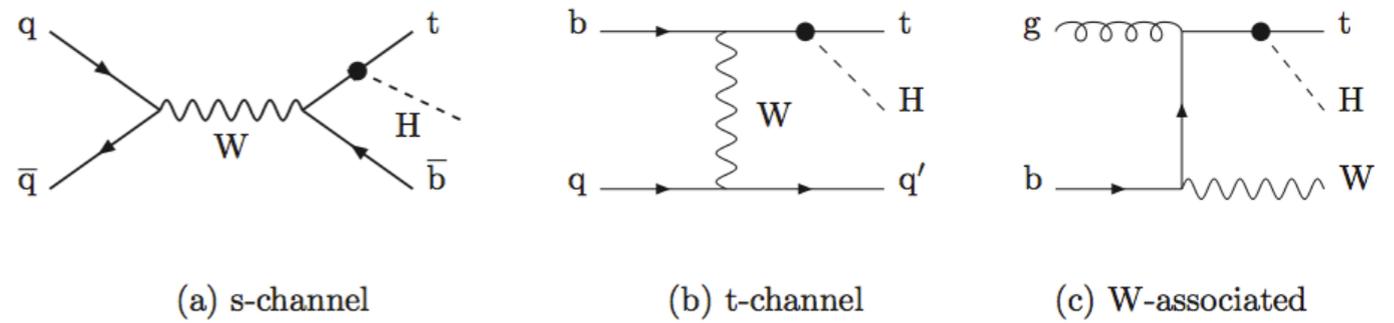
CERN Report 4:  $2.46 \kappa_Z^2 + 0.46 \kappa_t^2 - 1.90 \kappa_t \kappa_Z$

... slight change in coefficients due to inclusion of b ?



13 TeV													
$M_h$ [GeV]	$\sigma_t^2$ [fb]	$\sigma_b^2$ [fb]	$\sigma_Z^2$ [fb]	$\sigma_t \sigma_b$ [fb]	$\sigma_t \sigma_Z$ [fb]	$\sigma_b \sigma_Z$ [fb]	$\sigma(ZZ \rightarrow ZH)$ [fb]	$\kappa_t^2$	$\kappa_b^2$	$\kappa_Z^2$	$\kappa_t \kappa_b$	$\kappa_t \kappa_Z$	$\kappa_b \kappa_Z$
124.50	23.47	0.021	126.80	0.14	-98.07	-0.58	51.75	0.454	0.0004	2.450	0.003	-1.895	-0.011
125.00	23.45	0.021	126.34	0.14	-97.87	-0.58	51.47	0.456	0.0004	2.455	0.003	-1.902	-0.011
125.09	23.44	0.021	126.26	0.14	-97.83	-0.58	51.42	0.456	0.0004	2.456	0.003	-1.903	-0.011
125.50	23.42	0.020	125.88	0.14	-97.66	-0.57	51.19	0.457	0.0004	2.459	0.003	-1.908	-0.011

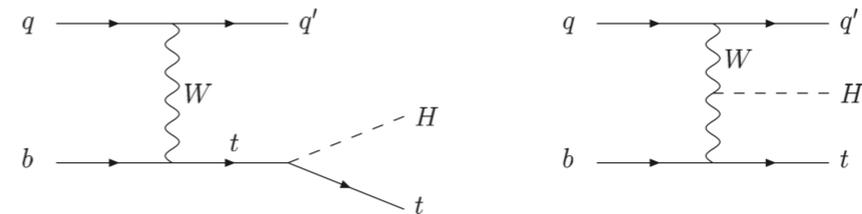
# tH (t-ch)



- s-ch, t-ch and W-associated productions (s-ch cross section is small)

For  $M_h=125.09$  GeV at  $\sqrt{s}=13$  TeV,  $\sigma(\text{s-ch})=2.875$  fb,  $\sigma(\text{t-ch})=74.26$  fb,  $\sigma(\text{tHW})\sim 16$  fb

- Possibility for resolving the degeneracy in  $\kappa_F$  with interference in tH



## t-ch production ( $qb \rightarrow tHq$ )

- Cross sections are calculated in NLO QCD with MG5\_aMC@NLO program.

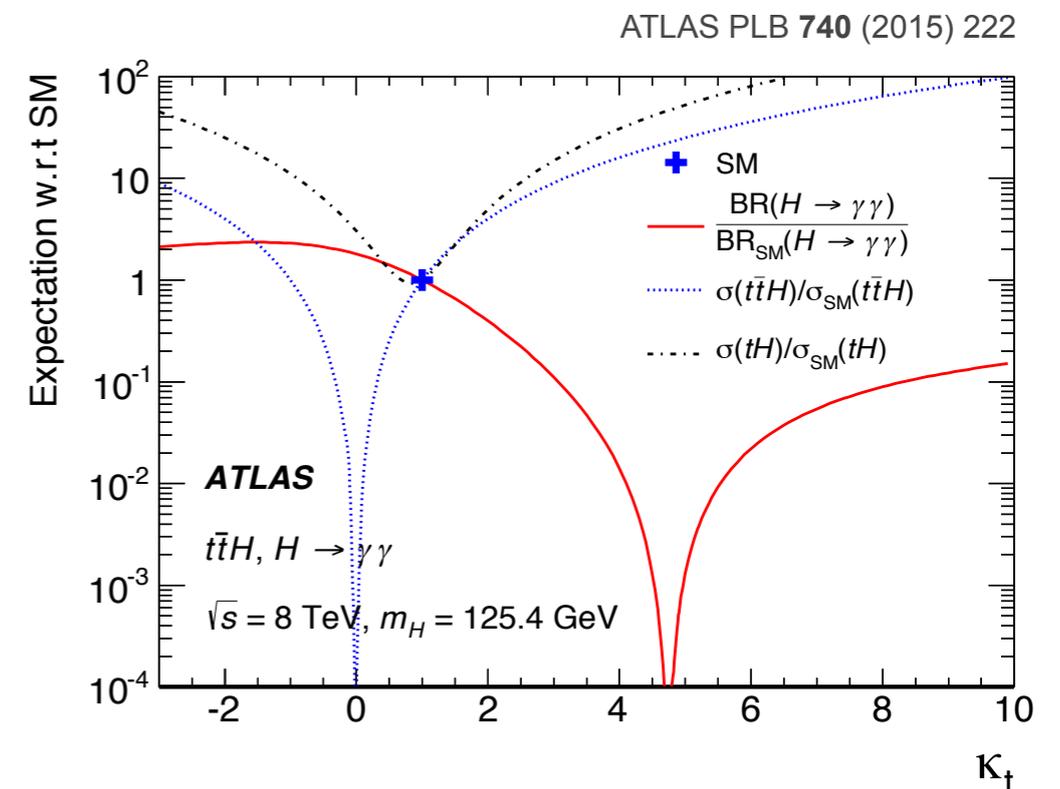
References: [Demartin:2015uha] for tH process

For  $M_h=125.09$  GeV at  $\sqrt{s}=8$  TeV,

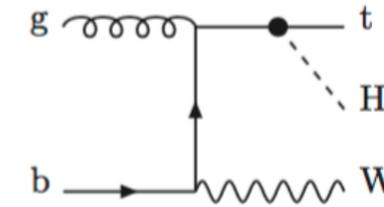
CERN-EP-2016-100:  $3.40\kappa_t^2 + 3.56\kappa_W^2 - 5.96\kappa_t\kappa_W$

CERN Report 4: to be calculated.

13 TeV						
$M_h$ [GeV]	$\sigma_t^2$ [fb]	$\sigma_W^2$ [fb]	$\sigma_t\sigma_W$ [fb]	$\kappa_t^2$	$\kappa_W^2$	$\kappa_t\kappa_W$
125.00	195.5	265.7	-387.0	2.633	3.578	-5.211
14 TeV						
$M_h$ [GeV]	$\sigma_t^2$ [fb]	$\sigma_W^2$ [fb]	$\sigma_t\sigma_W$ [fb]	$\kappa_t^2$	$\kappa_W^2$	$\kappa_t\kappa_W$
125.00	232.6	318.8	-461.3	2.582	3.538	-5.120



# tH (tHW)



## W-associated production (gb→tHW)

- Due to large interference effect between  $t\bar{t}H(WbWbb)$  and  $tWH(WbWbb)$  (also between  $t\bar{t}b$  and  $tW$ ), official XS for tHW has not been provided in Yellow Report 4.
- New calculations presented last summer by F. Maltoni et al. ([arXiv:1607.05862](https://arxiv.org/abs/1607.05862))

### “DR2” (Diagram Removal with interference effect)

- Consider only single-top and interference between single&doubly resonant diagrams.

- Do not touch  $t\bar{t}H$  cross section.

$$|\mathcal{A}_{tWb}|_{\text{DR2}}^2 = |\mathcal{A}_{1t}|^2 + 2\text{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*)$$

- Interference effect is large **DR2(with interf.)/DR1(no interf.):** -25% and kinematics dependent.

### For $M_h=125\text{GeV}$ at $\sqrt{s}=13\text{ TeV}$ in NLO QCD in 5FS

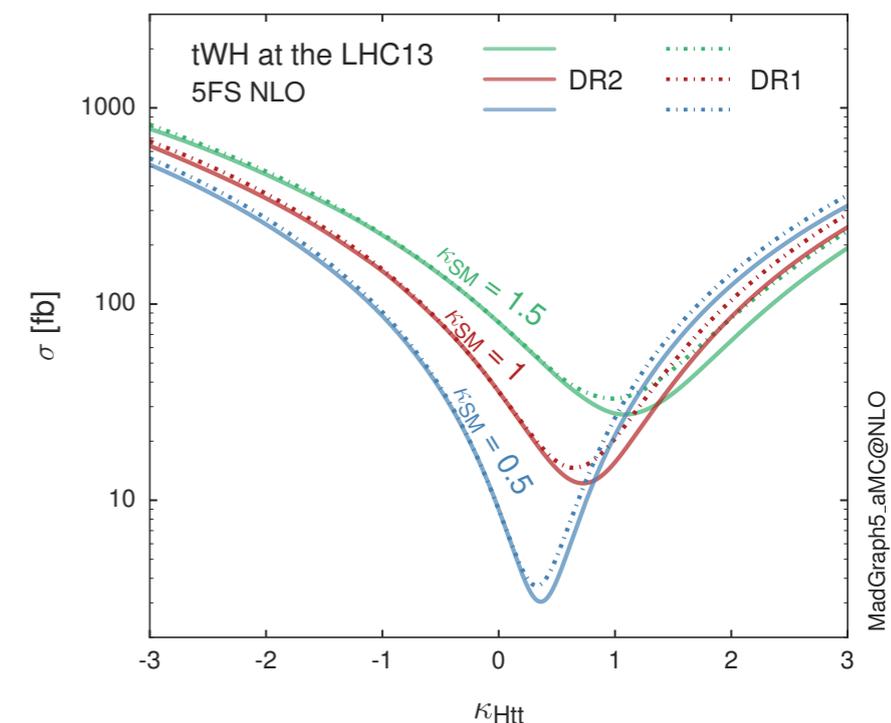
	No cuts	Fiducial cuts		Fiducial cuts + top reco.	
	$\sigma_{\text{NLO}} \pm \delta_{\mu}^{\%} \pm \delta_{\text{PDF}}^{\%}$	$\sigma_{\text{NLO}} \pm \delta_{\mu}^{\%} \pm \delta_{\text{PDF}}^{\%}$	eff.	$\sigma_{\text{NLO}} \pm \delta_{\mu}^{\%} \pm \delta_{\text{PDF}}^{\%}$	eff.
$t\bar{t}H$	485.0(9) $^{+1.3}_{-5.3} \pm 1.8$	21.5(2) $^{+2.0}_{-6.8} \pm 2.7$	0.04	21.5(2) $^{+2.0}_{-6.8} \pm 2.7$	0.04
$tWH$ DR1	20.72(2) $^{+5.0}_{-3.1} \pm 3.0$	12.12(2) $^{+2.7}_{-2.3} \pm 2.5$	0.58	11.18(2) $^{+2.2}_{-2.3} \pm 2.5$	0.54
$tWH$ DR2	15.68(3) $^{+4.5}_{-5.9} \pm 2.7$	11.43(2) $^{+1.6}_{-2.4} \pm 2.4$	0.73	11.04(2) $^{+1.8}_{-2.4} \pm 2.4$	0.70
$tWH$ DS1	19.11(3) $^{+2.3}_{-2.3} \pm 2.9$	11.79(2) $^{+1.8}_{-2.3} \pm 2.5$	0.62	11.02(2) $^{+1.7}_{-2.3} \pm 2.5$	0.58
$tWH$ DS2	15.31(3) $^{+5.1}_{-6.7} \pm 2.5$	11.37(2) $^{+1.6}_{-2.3} \pm 2.4$	0.74	11.05(2) $^{+1.8}_{-2.4} \pm 2.4$	0.72

Interference effect less significant after fiducial cuts.

### For $M_h=125.09\text{ GeV}$ at $\sqrt{s}=8\text{ TeV}$ ,

$$\text{CERN-EP-2016-100: } 1.84\kappa_t^2 + 1.57\kappa_W^2 - 2.41\kappa_t\kappa_W$$

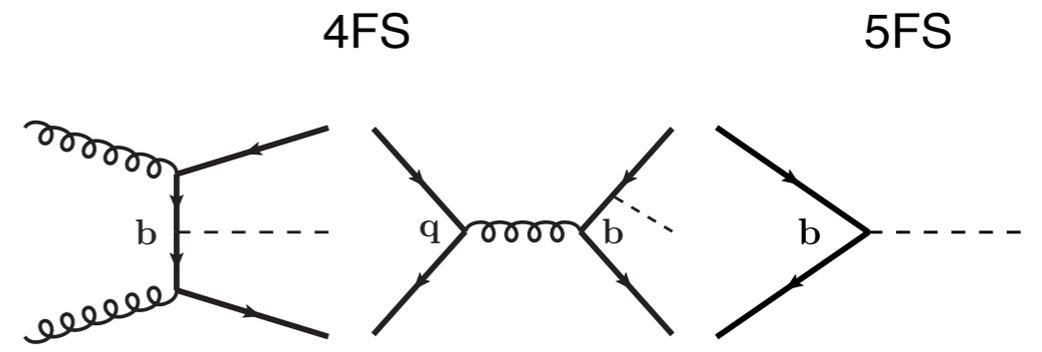
F. Demartin et al., [arXiv:1607.05862](https://arxiv.org/abs/1607.05862)



MadGraph5\_aMC@NLO

# bbH

- Pros and Cons in 4FS vs 5FS
    - 4FS: NLO QCD, massive b, b-tag well defined
    - 5FS: NNLO QCD, massless b, resummed  $\ln(m_b/Q)$
  - Santander matching to combine 4FS+5FS
    - **New Santander matching agreed !**
  - top/bottom Yukawa vs ggF
    - 4FS:  $y_b^2$  and  $y_t y_b$  terms
    - $\sigma(y_t y_b)$  is O(-10%) of  $\sigma(y_b^2)$ ,  $|\sigma(y_t y_b)| < \sigma(\text{cch})$
    - 5FS:  $y_b^2$  term only (interf. bbh and ggF vanishes)
- $$\sigma_{bb\phi}^{4FS} = \underbrace{\alpha_s^2 y_b^2 \Delta_{y_b^2}^{(0)}}_{\equiv \sigma_{y_b^2}} + \underbrace{\alpha_s^3 \left( y_b^2 \Delta_{y_b^2}^{(1)} + y_b y_t \Delta_{y_b y_t}^{(1)} \right)}_{\equiv \sigma_{y_b y_t} / \alpha_s^3} + \alpha_s^4 \left( y_b^2 \Delta_{y_b^2}^{(2)} + y_b y_t \Delta_{y_b y_t}^{(2)} \right) + \mathcal{O}(\alpha_s^5).$$
- $$\sigma_{bb\phi}^{5FS} = y_b^2 \left( \Delta_{y_b^2}^{(0)} + \alpha_s \Delta_{y_b^2}^{(1)} + \alpha_s^2 \Delta_{y_b^2}^{(2)} + \alpha_s^3 \Delta_{y_b^2}^{(3)} + \mathcal{O}(\alpha_s^4) \right).$$
- MC with MadGraph5\_aMC@NLO
    - separate generation for  $y_b^2$  and term  $y_t y_b$  term
    - kinematical distributions very similar [[Wiesemann:2014ioa](#)]
    - **bbh contribution becomes different with b-jet veto (4FS) !**



4FS 1-loop diagram with  $y_t$

