Recent results in precision Higgs calculations

Giulia Zanderighi, CERN, University of Oxford & ERC

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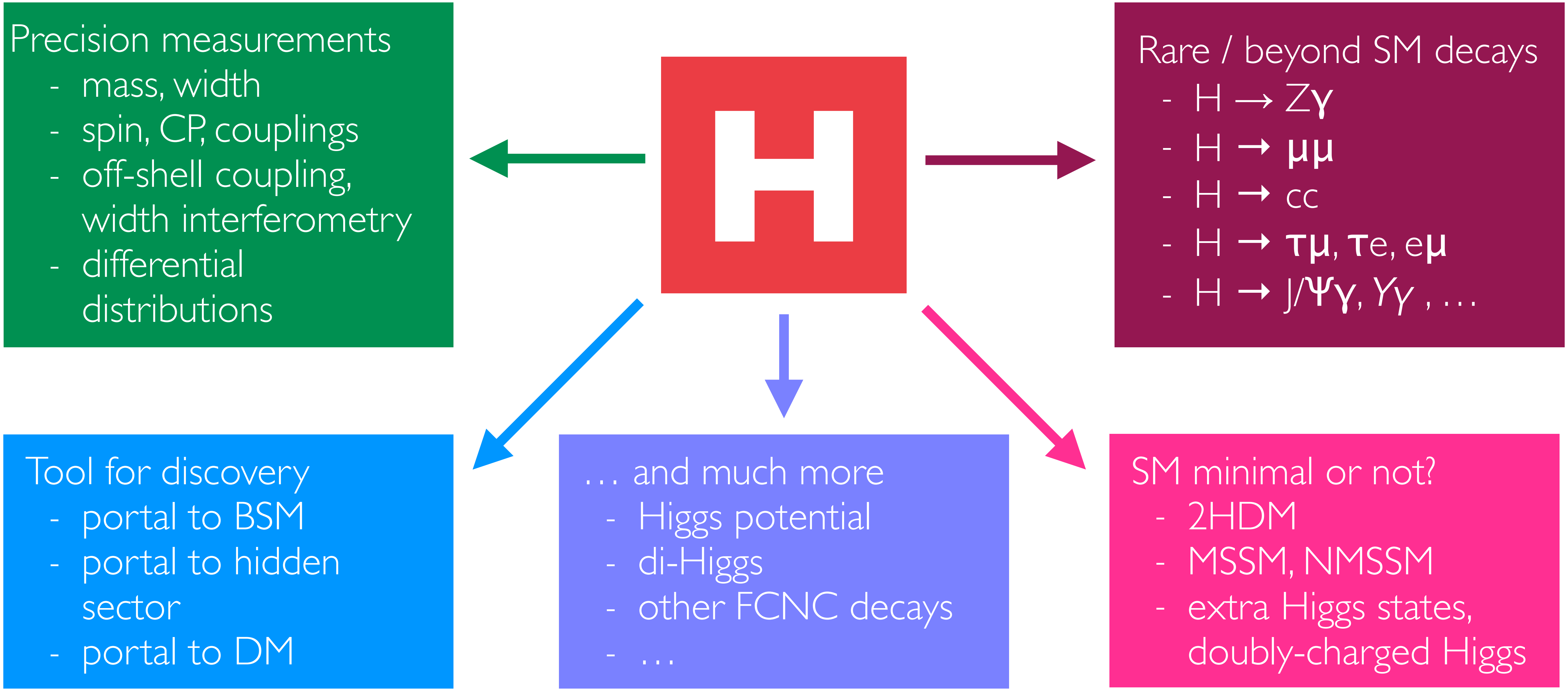
Higgs studies at the LHC

- The discovery of the Higgs boson at the LHC was a milestone in particle physics
- Higgs boson is the only fundamental scalar particle ever discovered. Its study at the LHC is new territory
- It is clear that this will be a long research program at the LHC [in comparison the b-quark was discovered forty years ago and, Belle II at SuperKEK, will now further study hadrons containing b-quarks]

An extremely rich program



Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width interferometry
- differential distributions

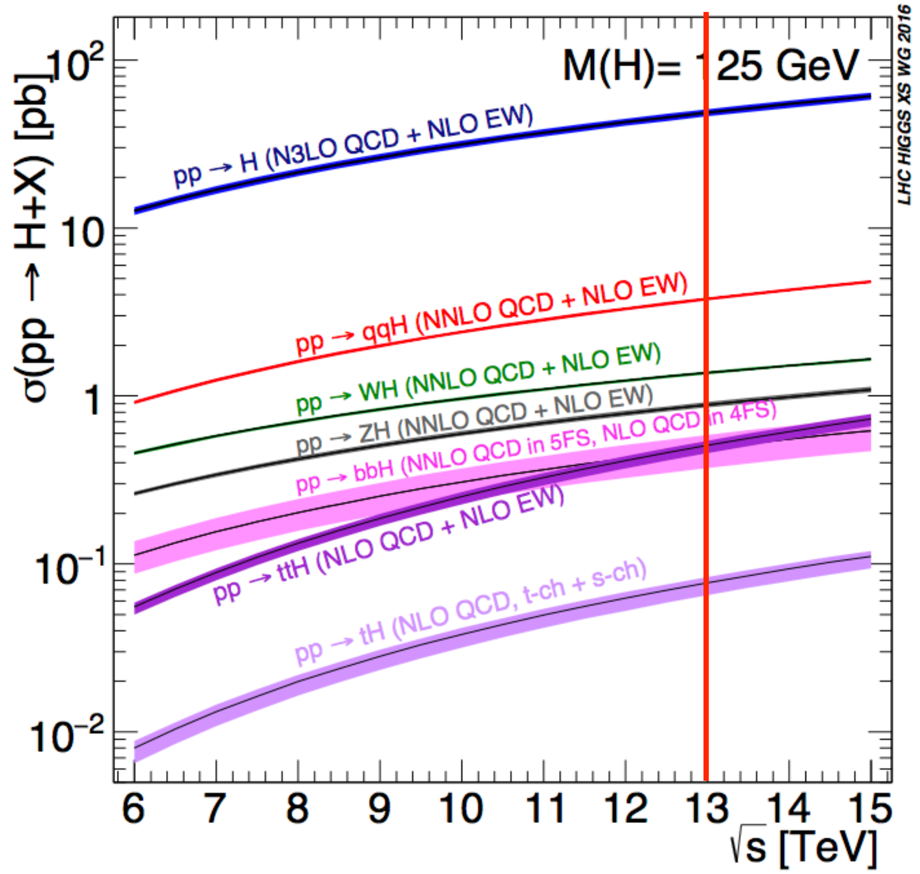
Rare / beyond SM decays
- $H \to Z\gamma$
- $H \to \mu\mu$
- $H \to cc$
- $H \to \tau\mu, \tau e, e\mu$
- $H \to J/\Psi\gamma, \Upsilon\gamma$, …

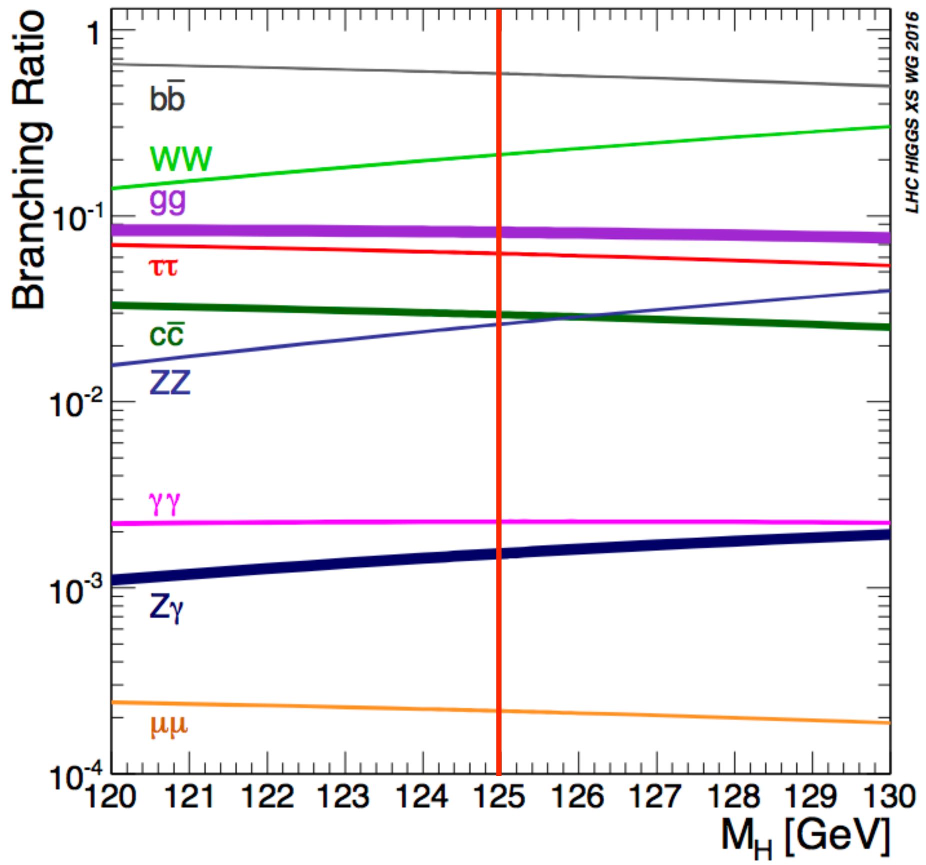
Tool for discovery
- portal to BSM
- portal to hidden sector
- portal to DM

… and much more
- Higgs potential
- di-Higgs
- other FCNC decays
- …

SM minimal or not?
- 2HDM
- MSSM, NMSSM
- extra Higgs states, doubly-charged Higgs

Production and decay

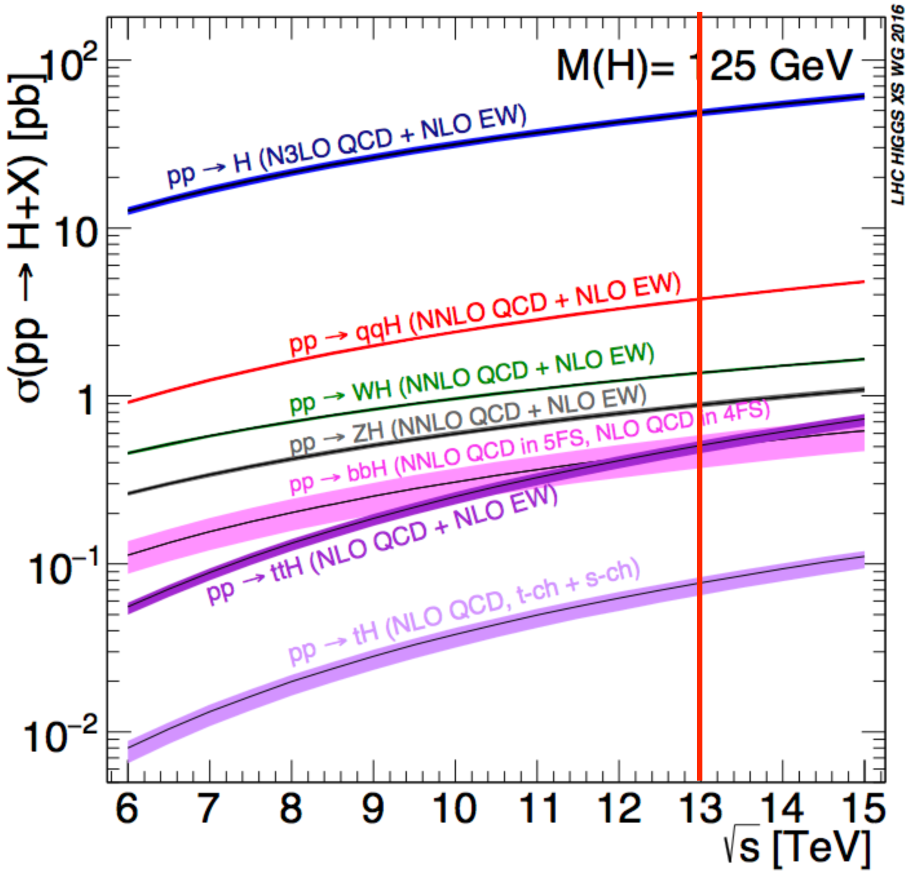


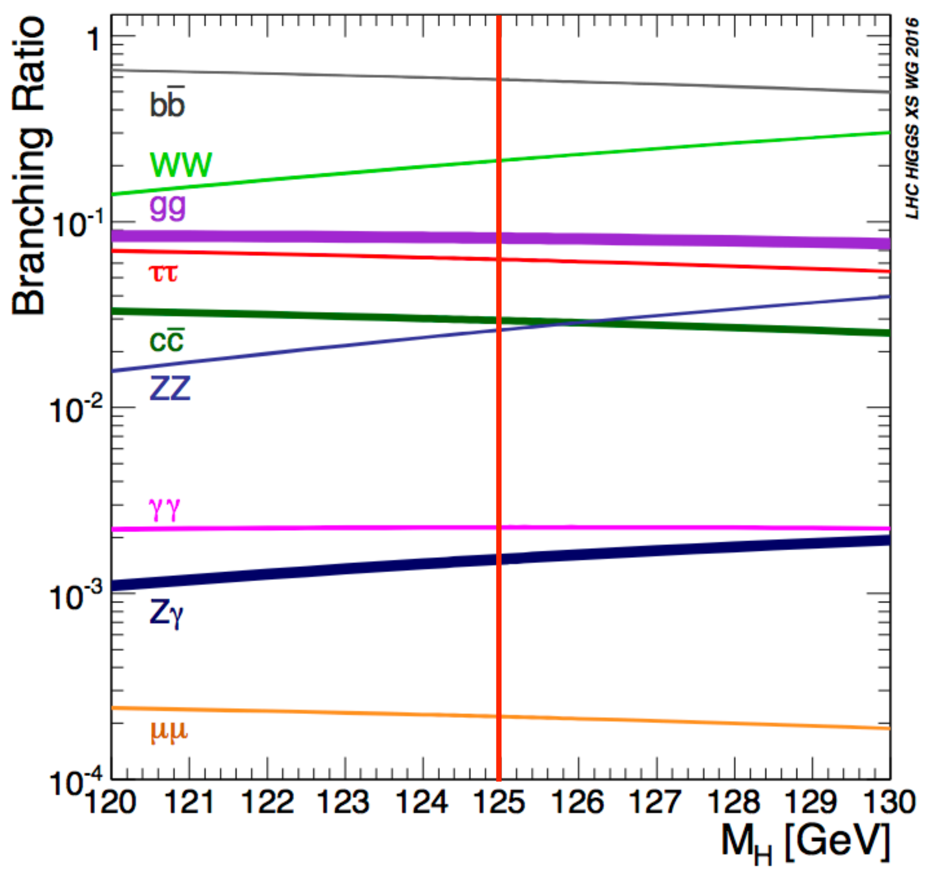


$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\mathrm{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

Production and decay





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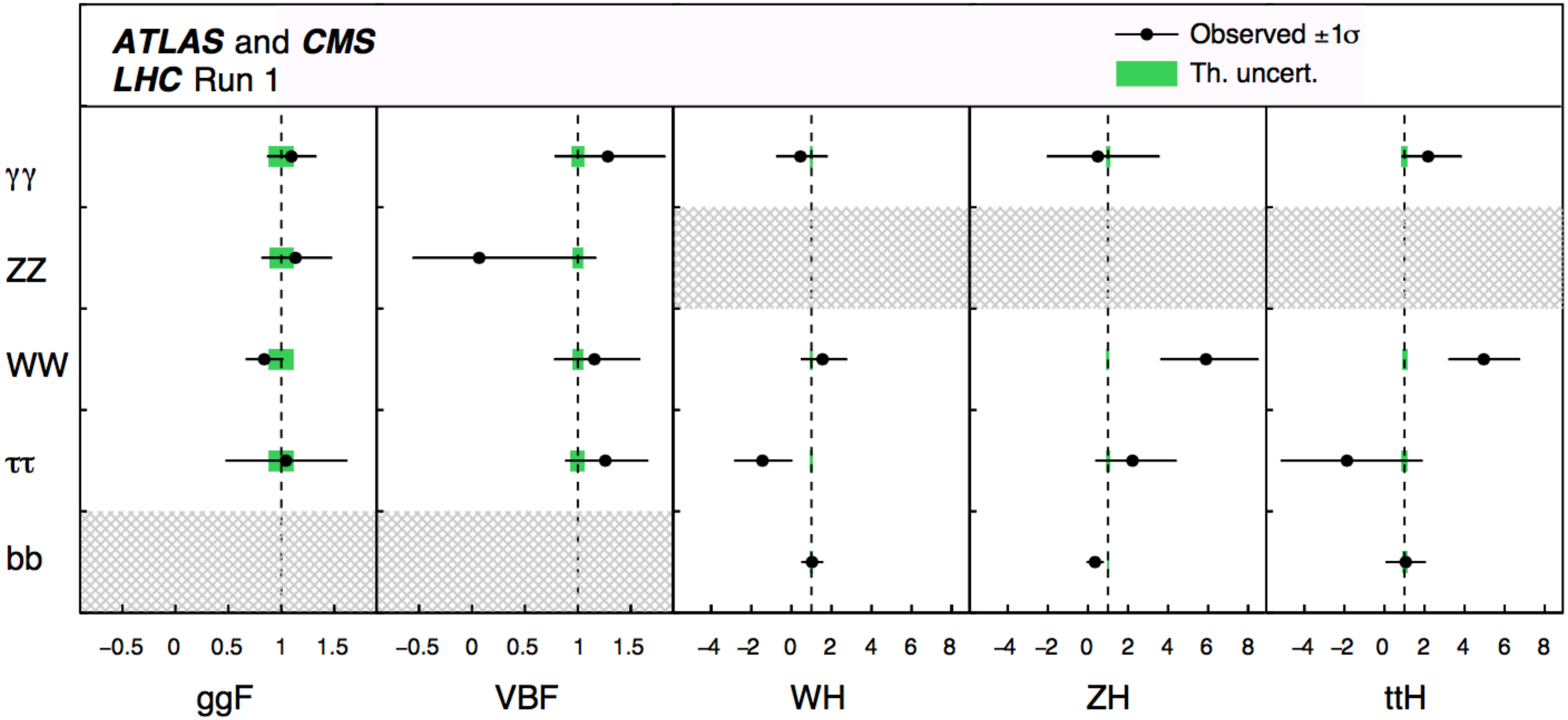
$H \to \mu^+\mu^-$	2.18×10 [illegible]	[illegible] -5.9%

⇒ accordingly 90% of the talk on ggF!

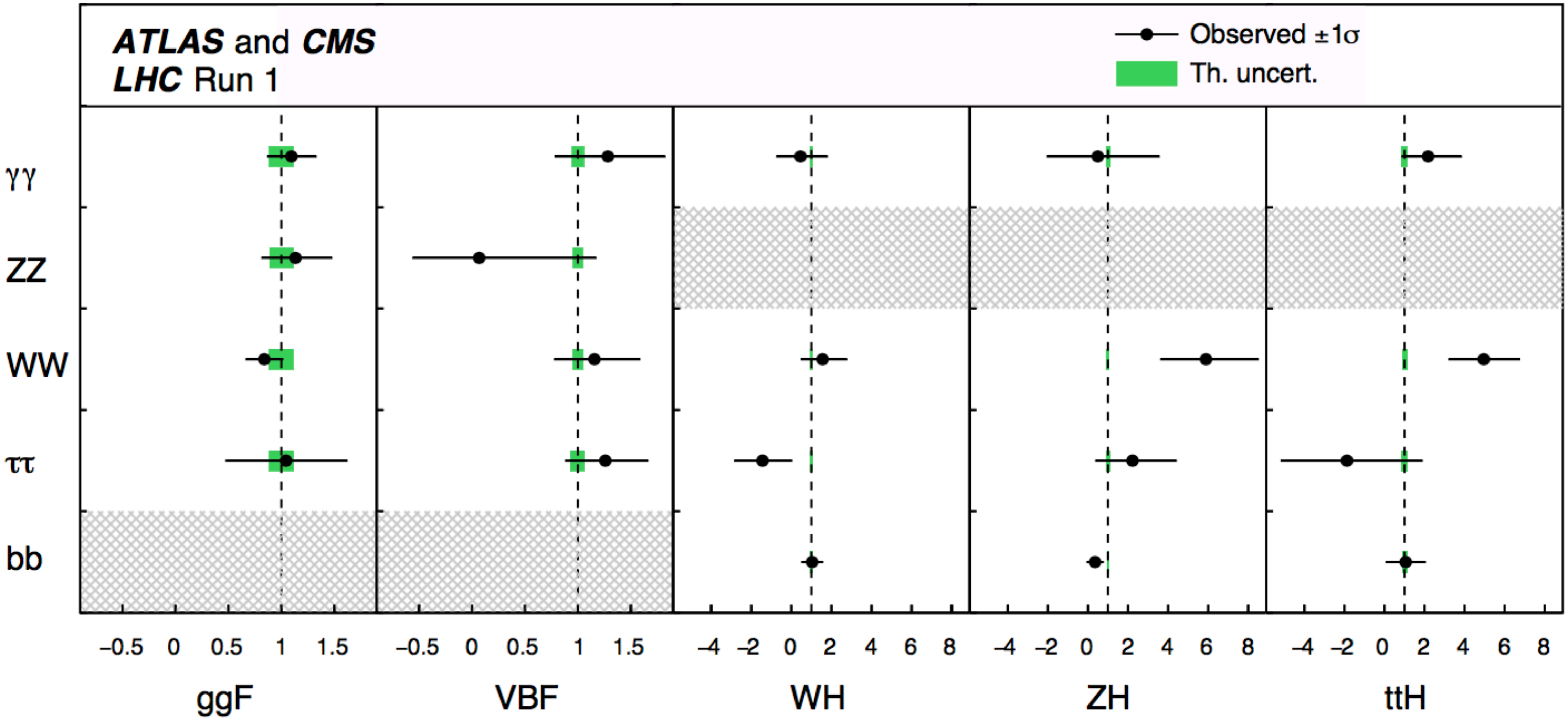
Theory vs data



Conclusion 1: a coherent picture emerges, with good consistency between data and theory

$$\mu = 1.09 \pm 0.07\ (\mathrm{stat})\ \pm 0.04\ (\mathrm{expt})\ \pm 0.03\ (\mathrm{th.\,bkg})\ \pm 0.07\ (\mathrm{th.\,sig})$$

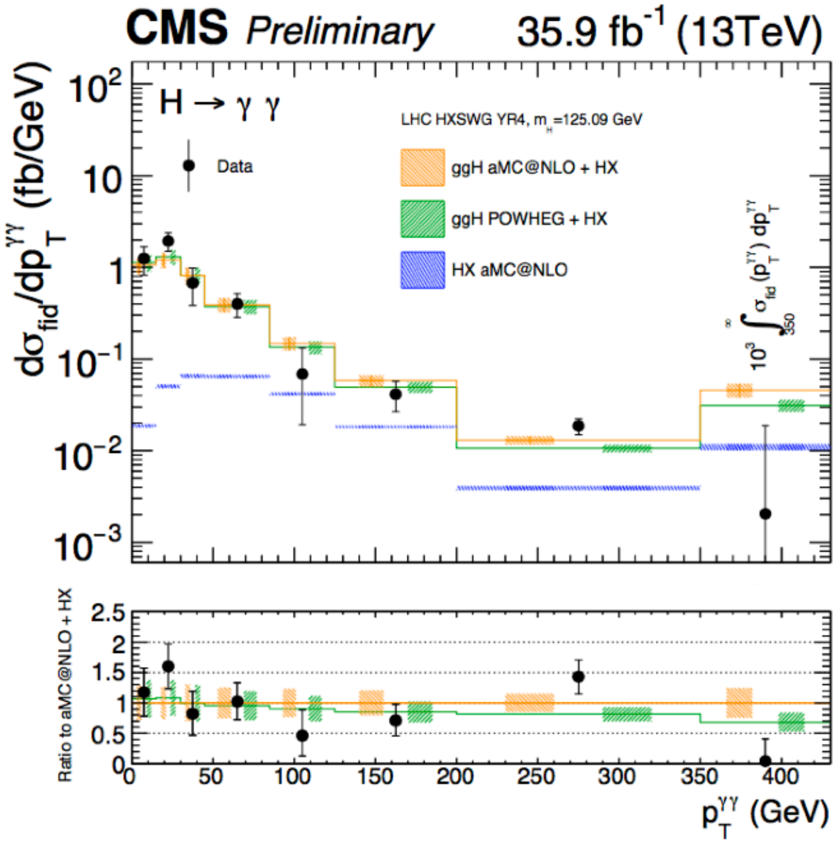
Theory vs data

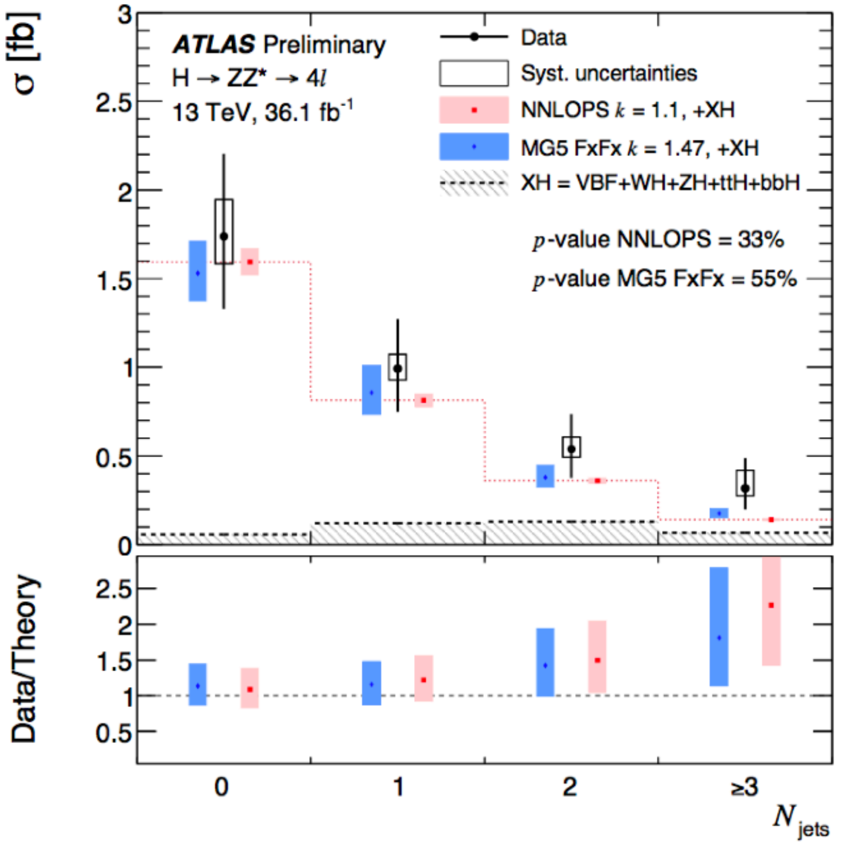


Conclusion 2: theory is good enough ($\mathrm{err_{TH}} \ll \mathrm{err_{EXP.}}$), any further improvement does not bring in much …

Why theory needs to improve

Take more exclusive measurements ($p_{t,H}$, jet-binned cross sections, ...):





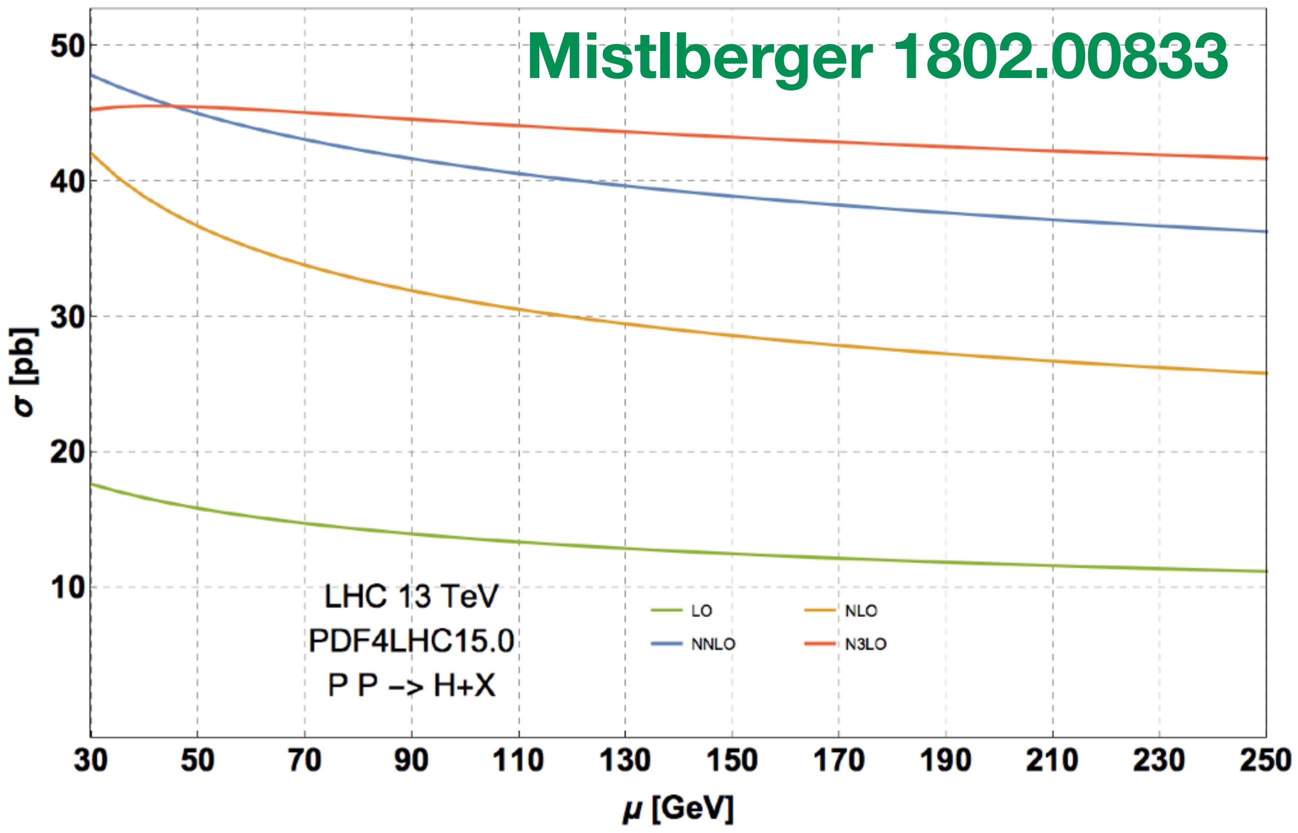
- err_{TH} already closer to err_{EXP}
- experimental error will be reduced considerably, systematic error will decrease too
- often total theory uncertainty was underestimated in the past

Since the Higgs mechanisms was proposed in the 60s’, the Higgs boson production and decay has been at the center of theorists attention. Accordingly, the literature on the subject is immensely vaste. In this talk I will concentrate on presenting just

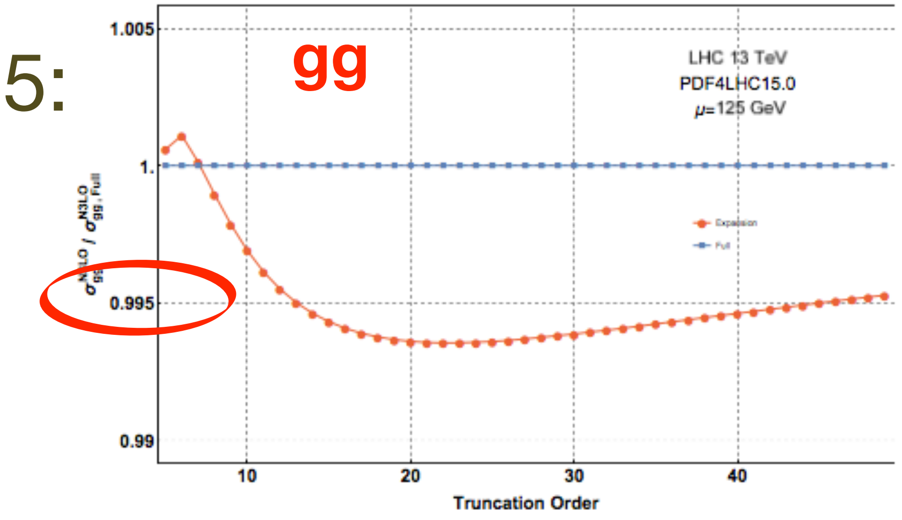
A few very recent (2018) highlights

N^3LO Higgs

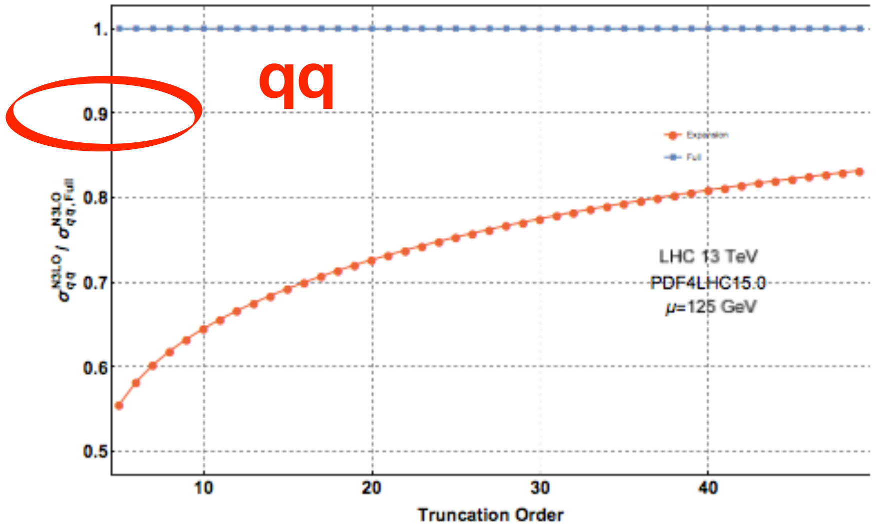
HEFT *beyond* the threshold expansion of 2015:



Mistlberger 1802.00833



(a)



- threshold expansion works very well for gluon-initiated channels, less so for quark-initiated ones
- the estimate of the missing higher-order terms in the threshold approximation covers the difference to the exact result well (3% of the corrections)

NLO QCD to QCD-EW gg → H

NLO QCD corrections to mixed QCD-EW contributions to gluon fusion production in the soft-gluon approximation

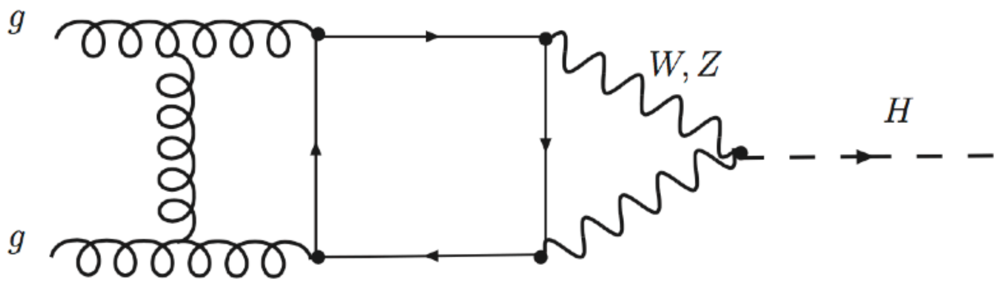
Bonetti, Melnikov, Tancredi 1801.10403

+5%

$$\sigma^{\mathrm{LO}}_{\mathrm{QCD}} = 20.6 \text{ pb}, \qquad \sigma^{\mathrm{LO}}_{\mathrm{QCD/EW}} = 21.7 \text{ pb},$$

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} = 32.66 \text{ pb},$$

+??%



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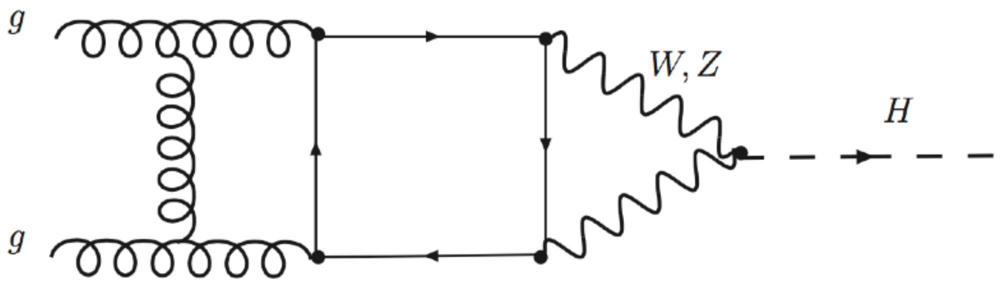
$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} = 32.66 \text{ pb}, \qquad \boxed{\sigma^{\mathrm{NLO}}_{\mathrm{QCD/EW}} = 34.41 \text{ pb.}}$$

+5%



Findings consistent with estimation in Anastasiou et al 0811.3458 (relied on unphysical approximation $M_W >> M_H$)

Result further supports the factorisation of QCD and EW corrections

Further improvements require exact calculation of real corrections

Higgs p_t

Beyond inclusive cross-sections, accurate predictions for differential distributions crucial for Run II

- ➡ signal significance optimized by categorizing events according to kinematic properties (e.g. jet bins, Higgs p_t ...)
- ➡ a large fraction (30-40%) of Higgs events come with at least one jet
- ➡ kinematical distributions used to extract/constraint couplings and quantum numbers

The most basic distribution: transverse momentum of the Higgs boson

It is inclusive on radiation, not sensitive to definition of jets, relatively insensitive to hadronization effects

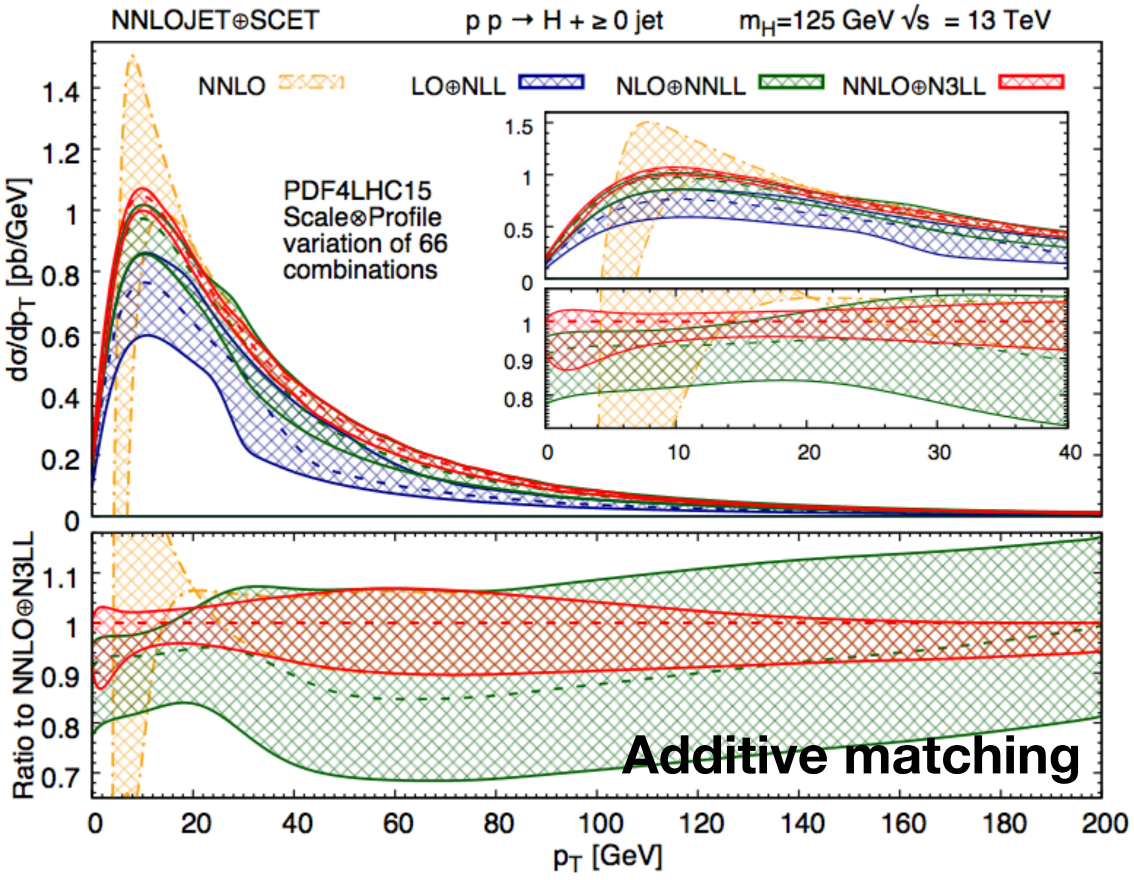
Why is Higgs p_t so diffucult

Higgs pt is shaped by many different and competing effects

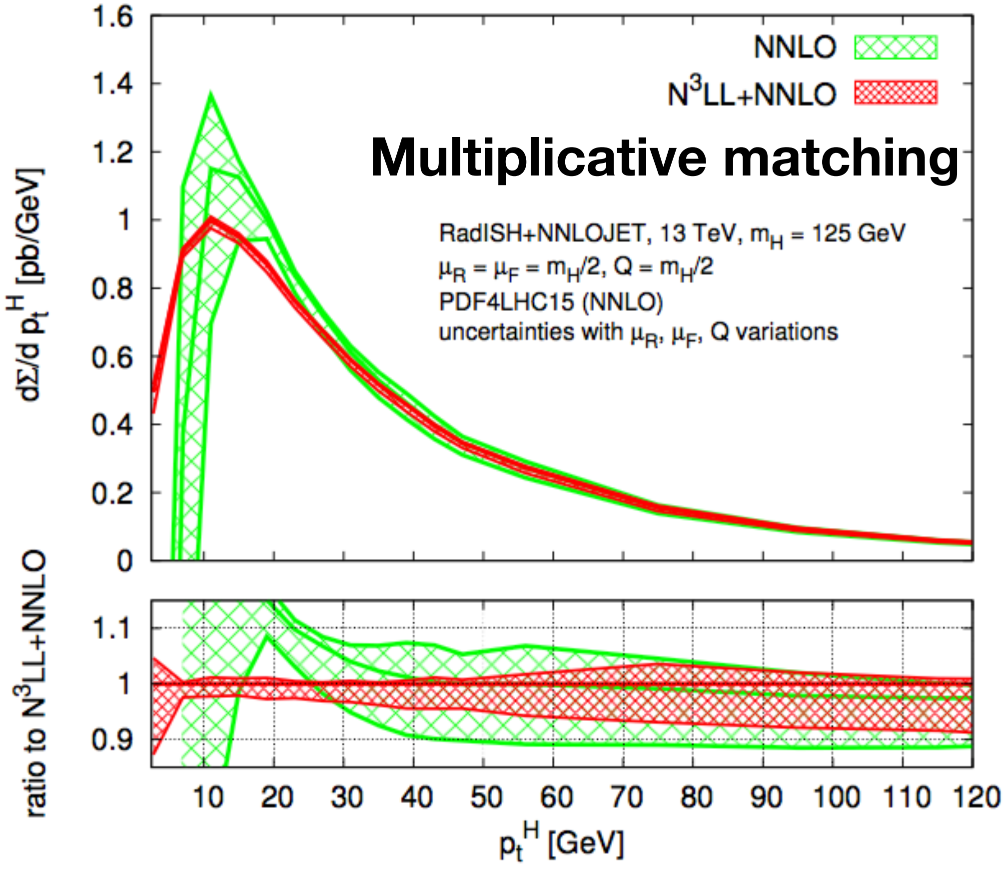
- ➡ dominant contribution due to top-quark loops. HEFT employed at small $p_{t,H}$, but top-loop must be resolved at high $p_{t,H}$ *(leading order description of high-$p_{t,H}$ involves already a one-loop 2 to 2 process)*
- ➡ non-negligible shape-distortions due to interference effects of amplitudes with top and bottom or charm quarks
- ➡ new types of logarithms when light quarks are present
- ➡ resummation of soft logarithms at small $p_{t,H}$ and combination of resummation with bottom-quark effects

Higgs at N^{3}LL+ NNLO

Chen et al 1805.00736



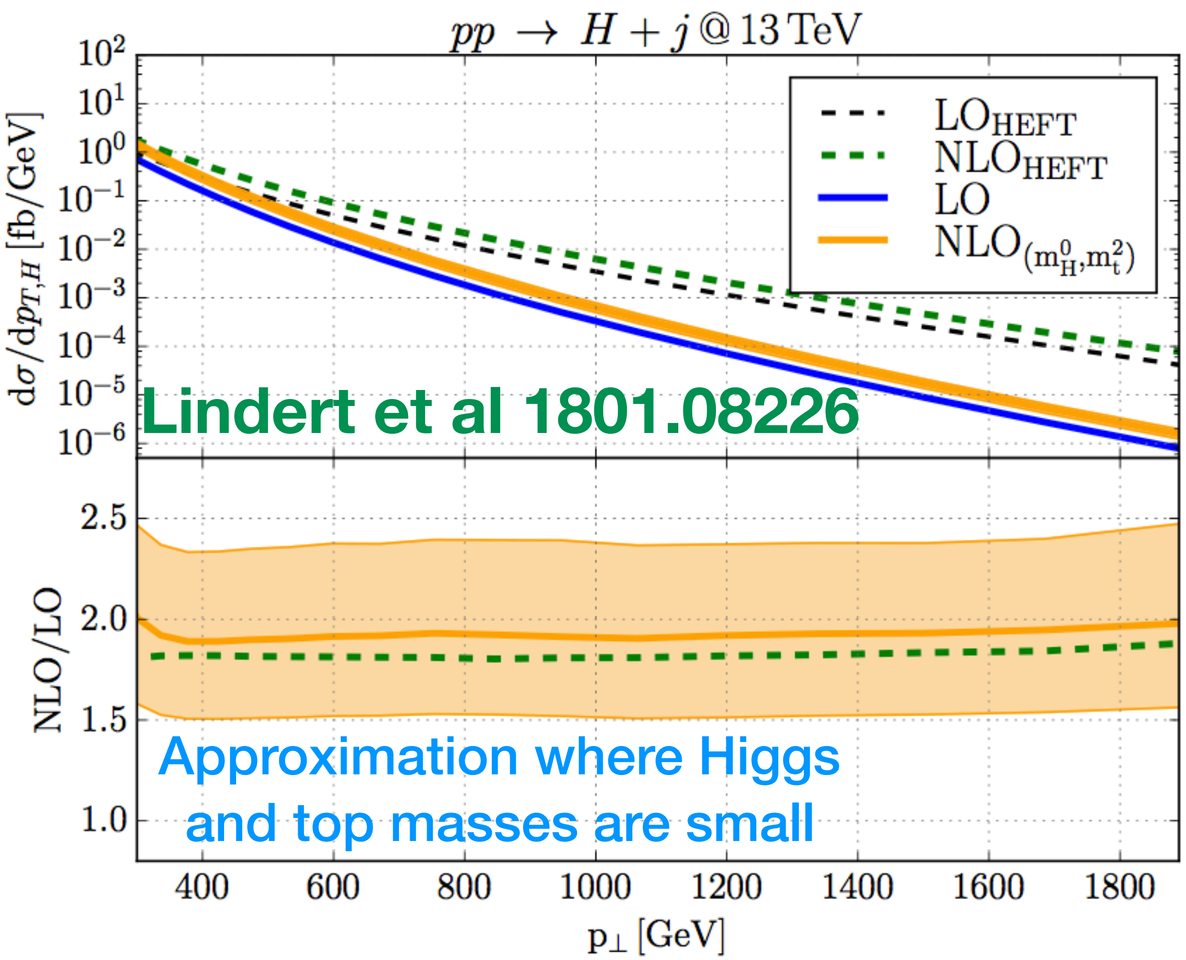
Bizon et al 1805.05916



NEW: includes decay to photons and fiducial cuts

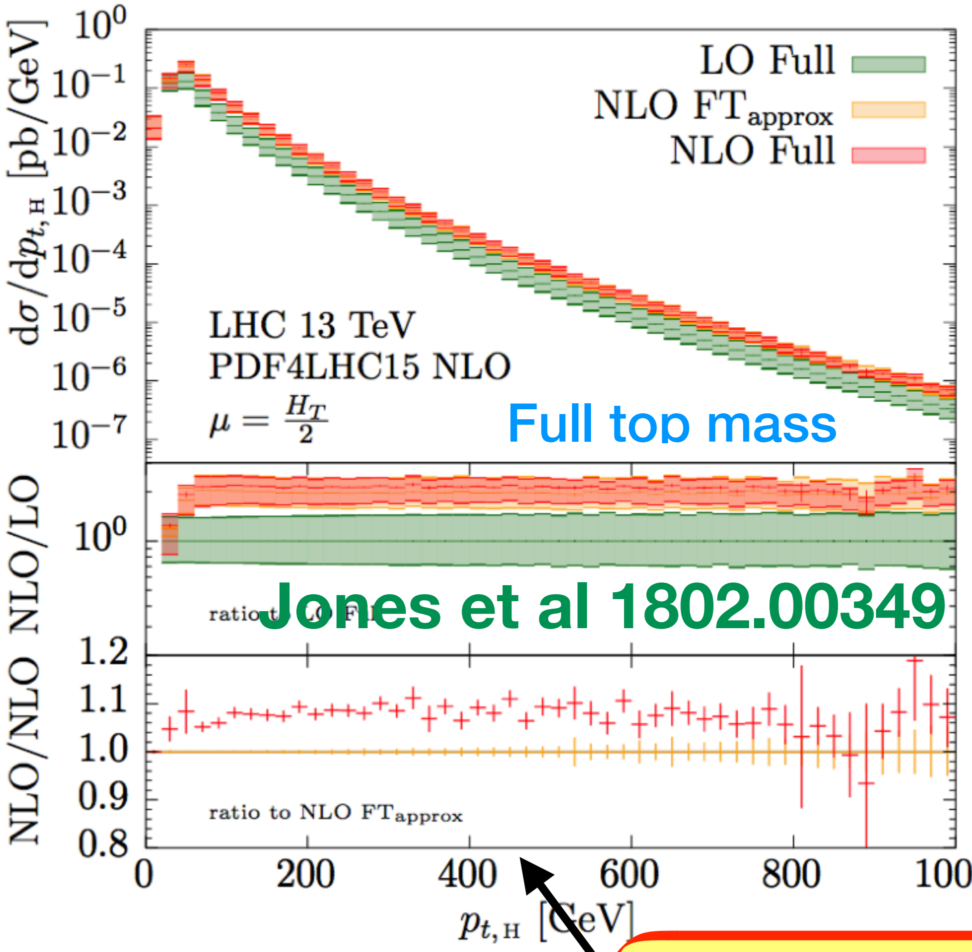
- Calculations in HEFT
- Resummation important below about 40 GeV
- At this level of precision results with scales m_H or $m_H/2$ are very similar (but $m_H/2$ might suffer from unphysical cancelations)

Boosted Higgs: full NLO



Lindert et al 1801.08226

Approximation where Higgs and top masses are small



Full top mass

Jones et al 1802.00349

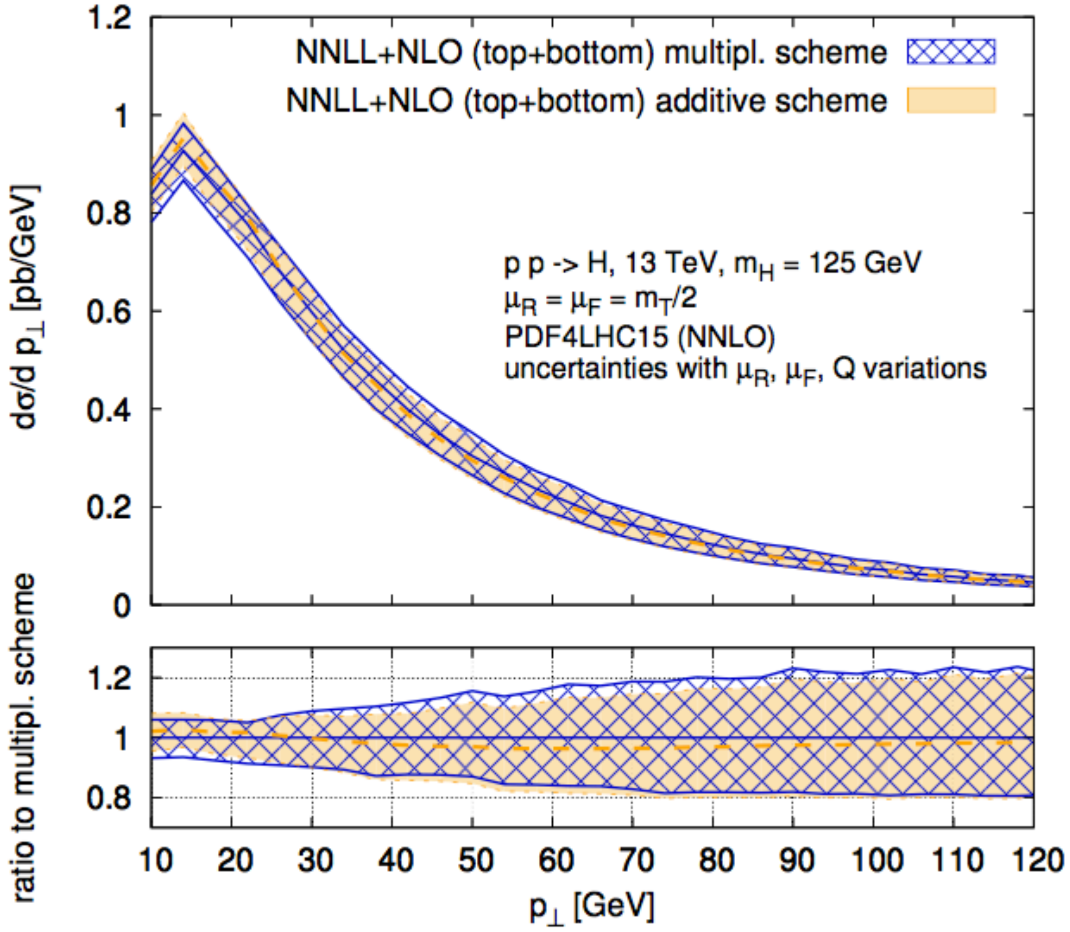
Current CMS data up to here

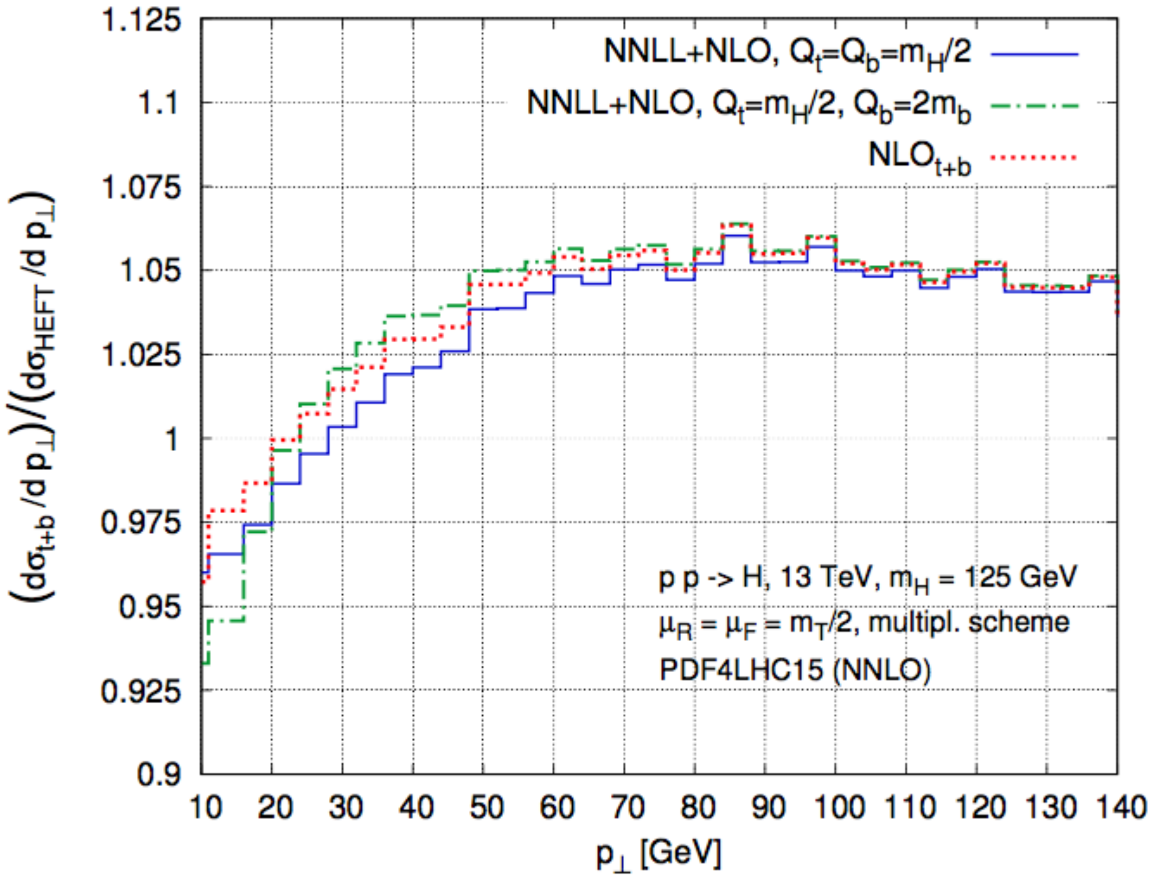
- NLO-approx OK in describing the shape (to within 5%)
- residual 10% normalisation effect
- one of the largest sources of uncertainties in the description of the high-pt region finally removed. Opens up the possibility to use high-pt region to search for BSM (e.g. disentangle point-like to top-induced ggH coupling)

Banfi, Martin, Sanz 1308.4771

Bottom mass effects (intermediate p_t)

Caola et al 1804.07632 (see also Lindert et al 1703.03886)

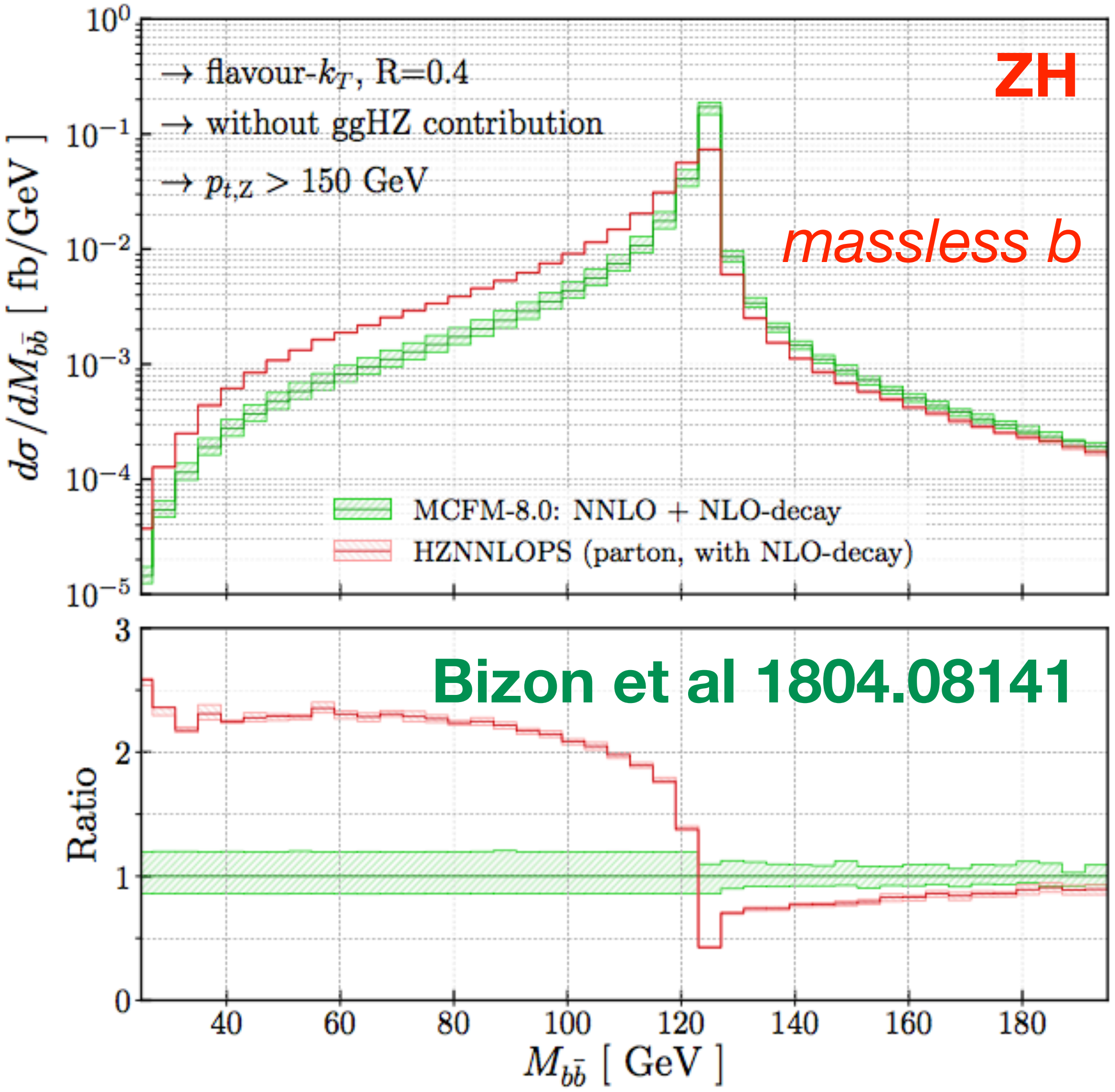




- top-bottom interference effects known to NNLL+NLO can lead to distortions up to 5%
- about 20% residual uncertainty

Improvements in VH (→ bb)

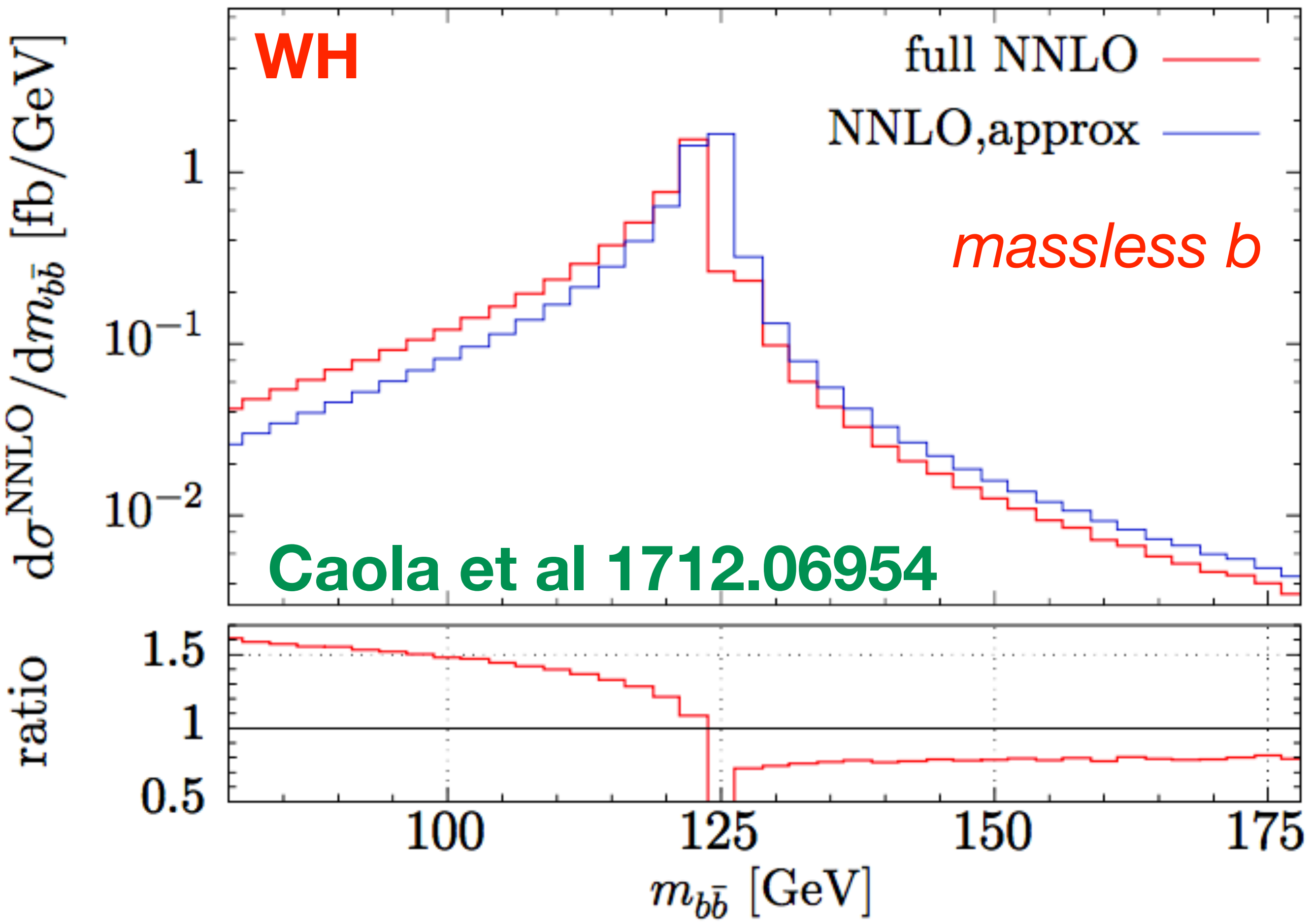
New: NNLOPS for VH + NLO H → bb



Bizon et al 1804.08141

NNLO$_{,\text{approx}}$ = NNLO prod.+NLO decay

New: NNLO production + NNLO decay



Caola et al 1712.06954

Large higher-order corrections in H → bb decay in m_{bb} and other observables

Theory issue in H → bb@ NNLO

Caola et al 1712.06954

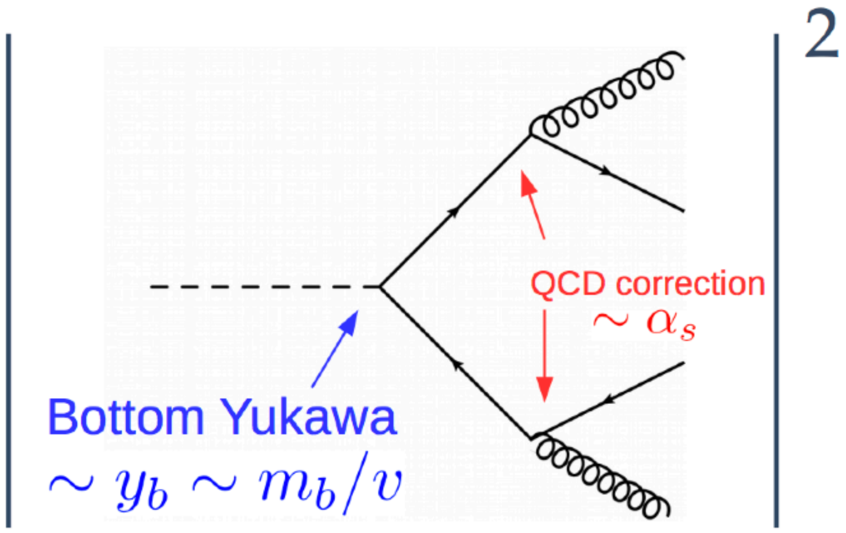
Decay in the massless approximation: extract Yukawa and then set $m_b = 0$

$$\Gamma_{H\to bb} = y_b^2 \left(\Gamma_{m_b=0} + \mathcal{O}\left(\frac{m_b^2}{m_H^2} \right) \right)$$

Above is OK at LO and NLO, but fails at NNLO as it neglects contributions that are of the same order, i.e. $y_b^2 \alpha_s^2$, that arise in diagrams with a helicity flip (and hence a mass insertion)

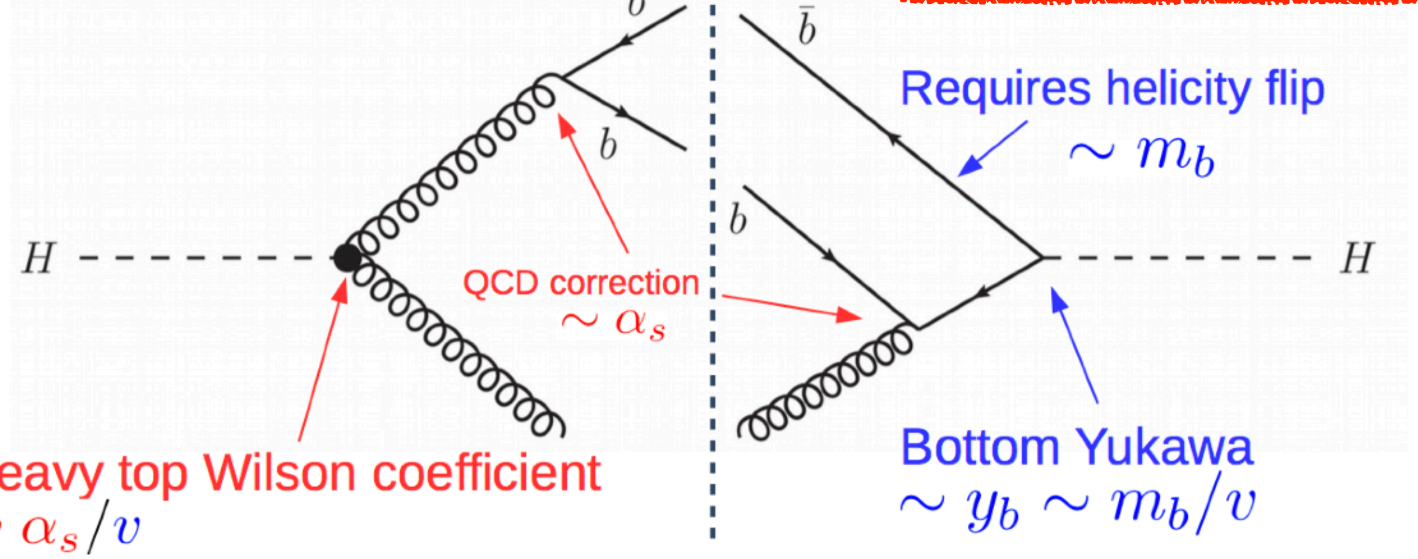
Standard NNLO correction: $\mathcal{O}(y_b^2 \alpha_s^2)$

New NNLO contribution: $\mathcal{O}\left(y_b^2 \alpha_s^2 \ln\left(\frac{m_b^2}{m_H^2} \right) \right)$



QCD correction $\sim \alpha_s$

Bottom Yukawa $\sim y_b \sim m_b/v$



Requires helicity flip $\sim m_b$

QCD correction $\sim \alpha_s$

Heavy top Wilson coefficient $\sim \alpha_s/v$

Bottom Yukawa $\sim y_b \sim m_b/v$

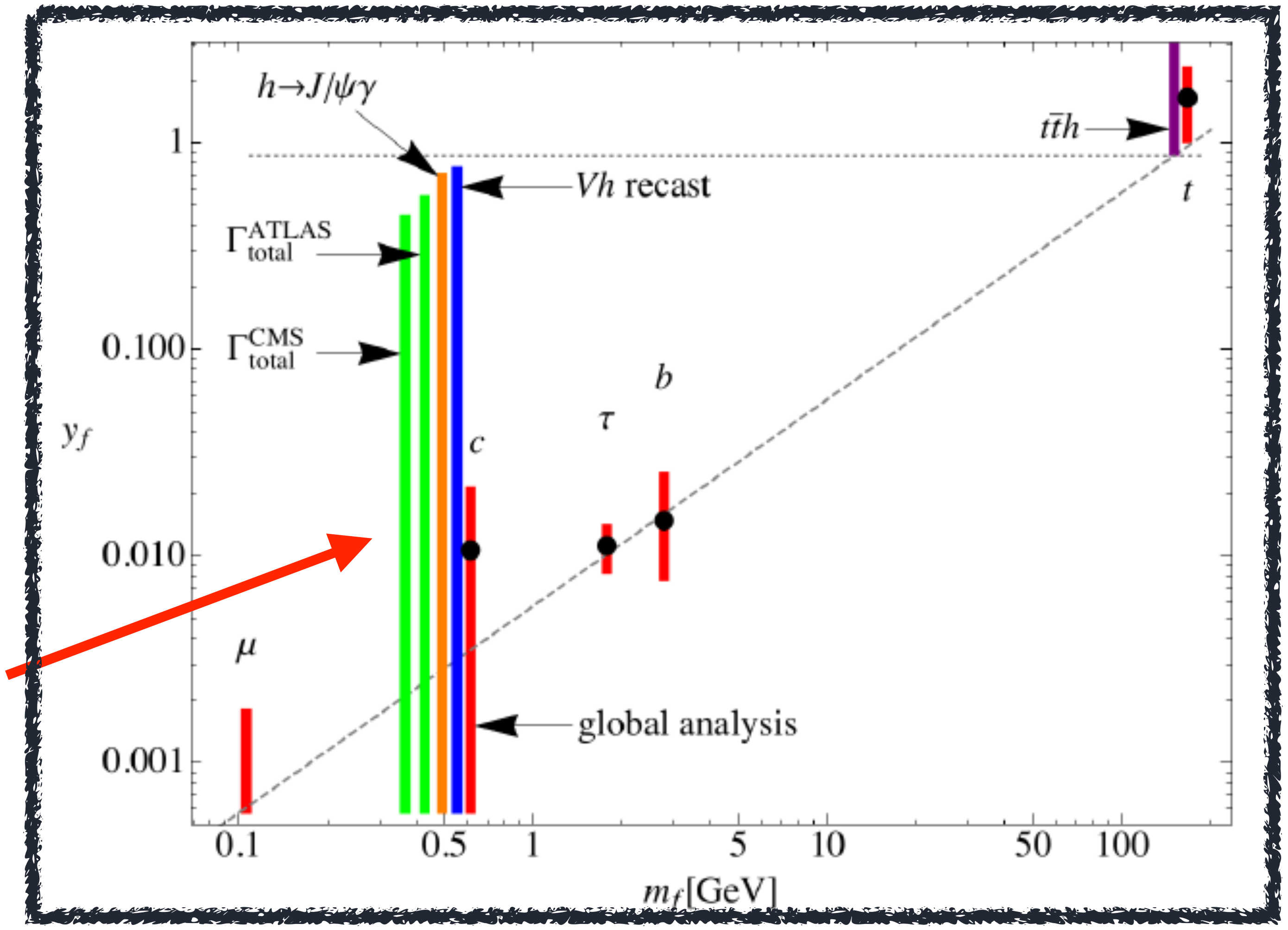
(See Caola's QCD Moriond talk)

Two examples, out of many, where theoretical precision brings new opportunities in the Higgs sector

1. H coupling to light quarks

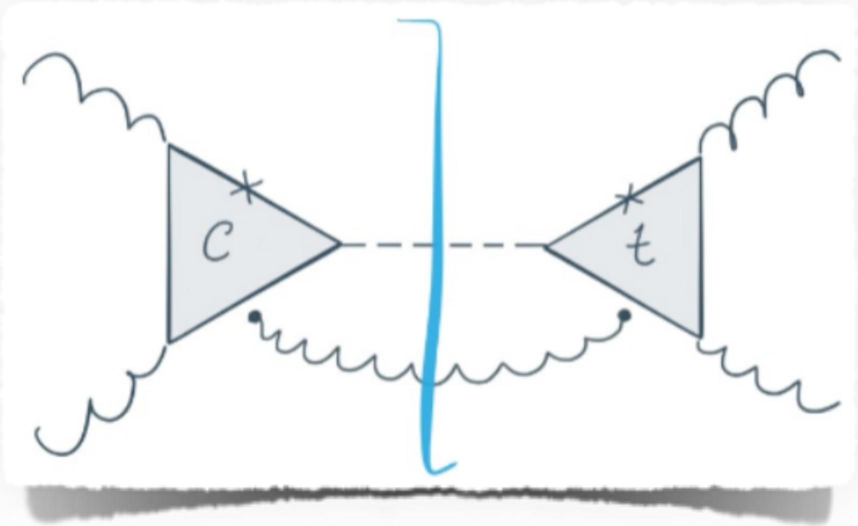
- couplings to 2nd (and 1st) generation notoriously very difficult because they are very small
- a number of ways to constraint the coupling of Higgs to charm:
  - rare exclusive Higgs decays
  - Higgs + charm production
  - constraint from VH (H →bb) including charm mis-tagging
  - constraint from Higgs width

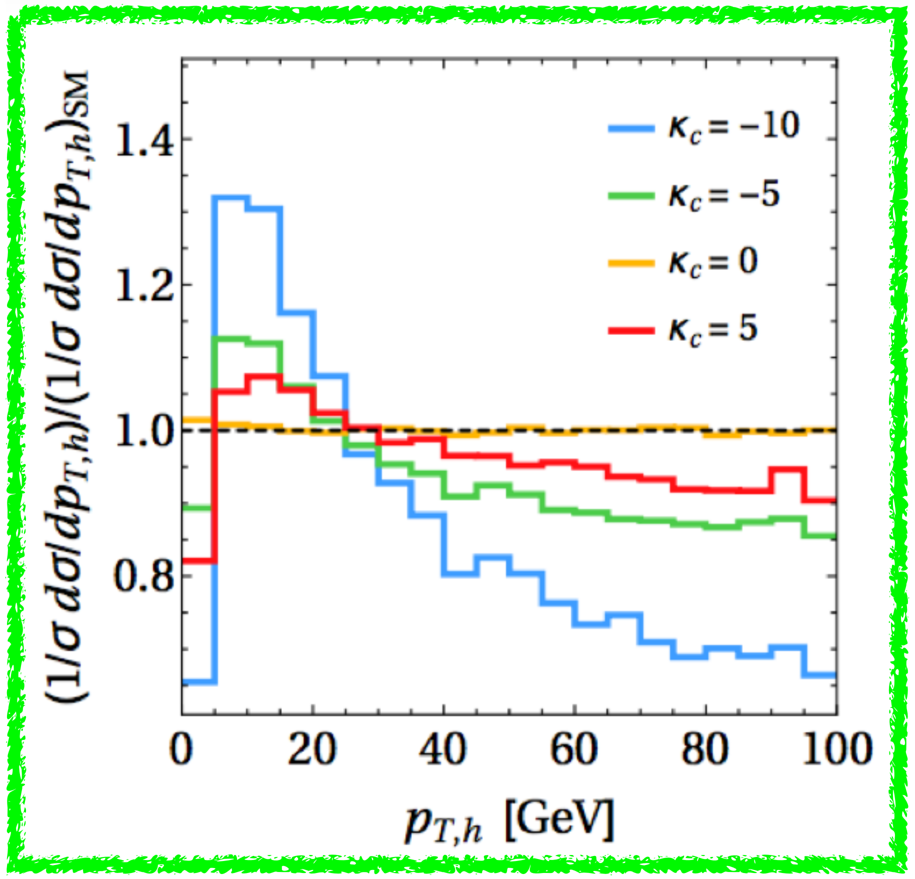
still largely unconstraint



1. H coupling to light quarks

- Higgs produced dominantly via top-quark loop (largest coupling)
- but interference effects with light quarks are not negligible
- provided theoretical predictions are accurate enough (few%?), constraint on charm (and possible strange) Yukawa can be significantly improved





Bishara et al '16

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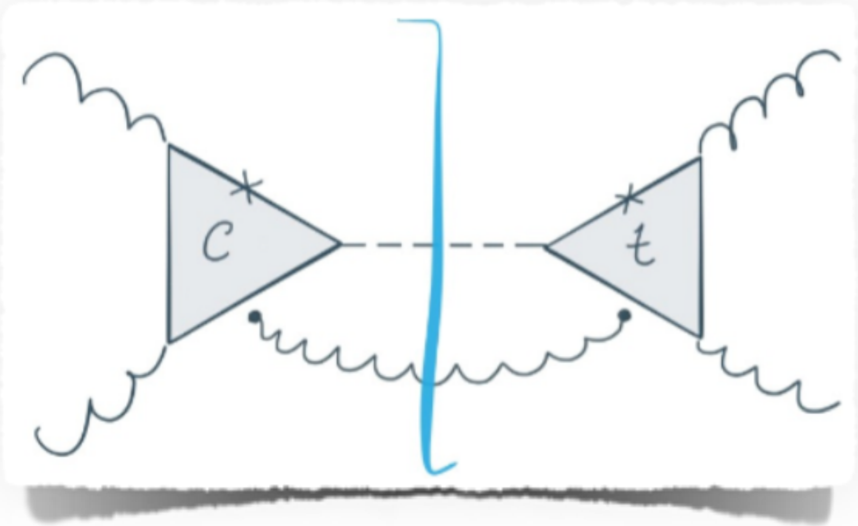
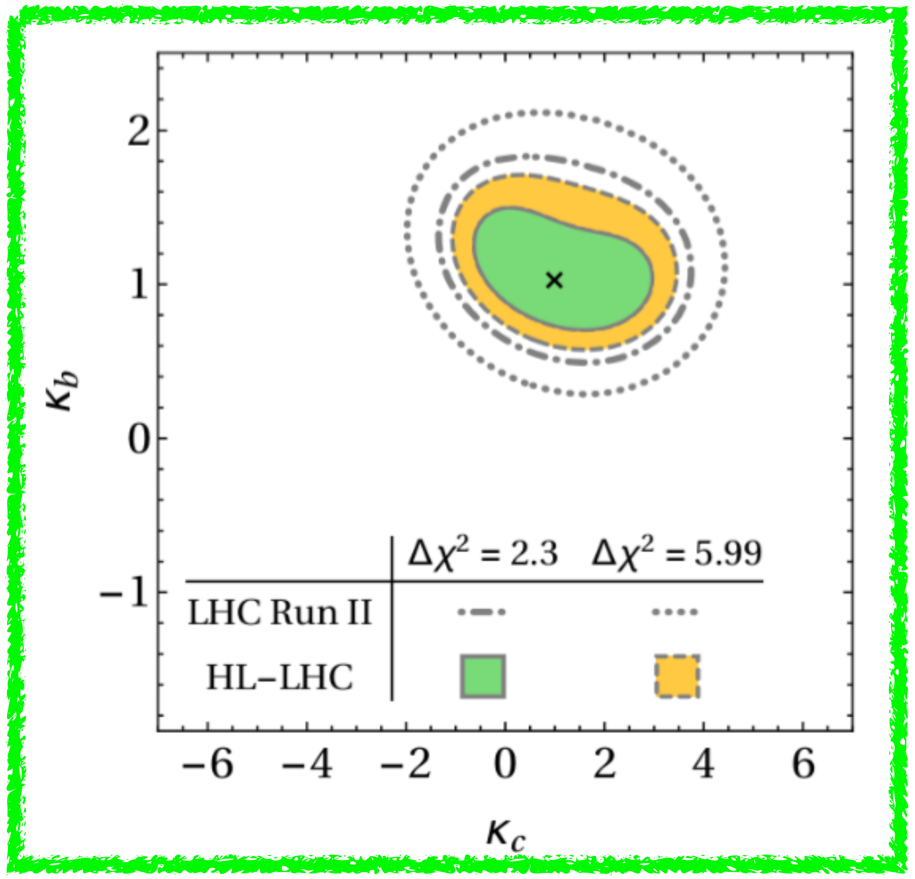
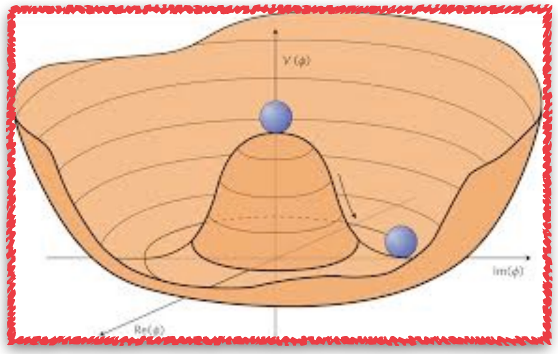




2. The Higgs potential

The Higgs boson is responsible for the masses of all particles we know of. Its potential, linked to the Higgs self coupling, is predicted in the SM, but we have not tested it so far

$$V_{\mathrm{SM}} = \frac{m_h}{2}h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$



☑ Single Higgs
done O(45pb)

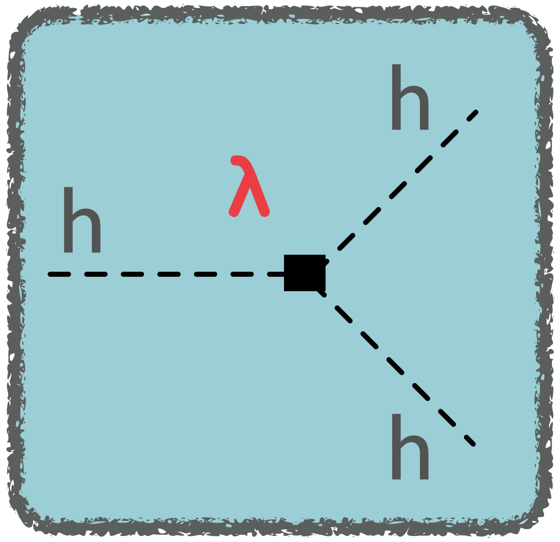
☐ Double Higgs
very hard
O(45fb)

☐ Triple Higgs
out of reach
O(0.1fb)

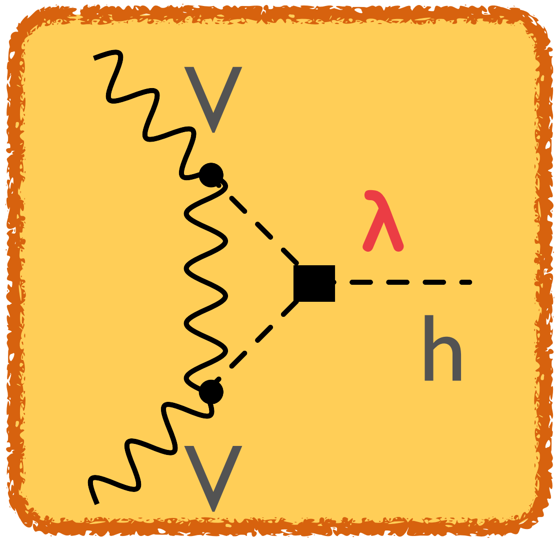
Bounds on λ today from LHC data still very loose (about a factor 10)

2. The Higgs potential

Traditionally: suggested to measure it through the production of two Higgs bosons (but difficult because of very small production rates)



Double Higgs



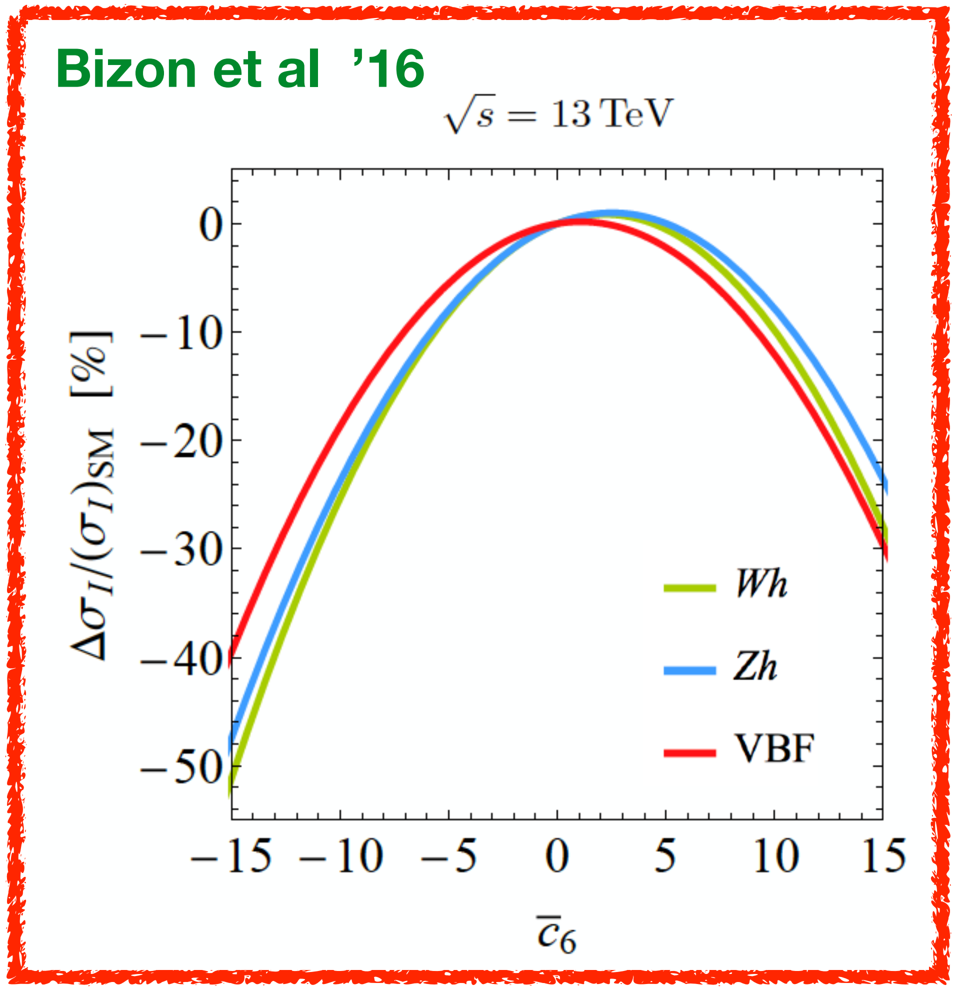
Single Higgs

New idea: **exploit indirect sensitivity to λ of single Higgs production**
Provides a wealth of new measurements (many production processes, many kinematic distributions), but theory and measurements must be accurate enough

2. The Higgs potential

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\bar{c}_6}{2v^2}\mathcal{O}_6$$

$$\mathcal{O}_6 = -\lambda_{\rm SM}(H^\dagger H)^3$$


Bizon et al '16

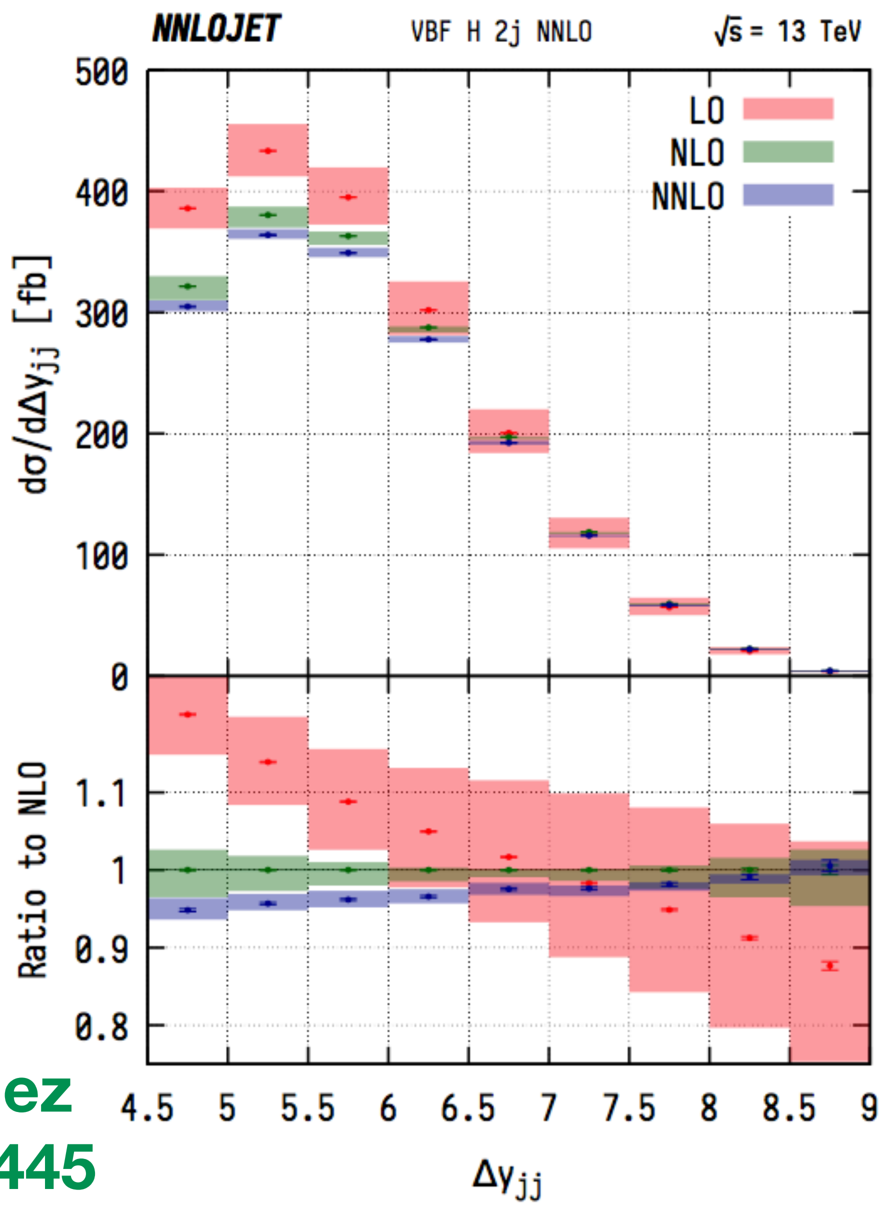
See also
De Grassi et al 1702.01737
Di Vita et al 1704.01953
Maltoni et al 1709.08649
Di Vita et al 1711.03978
[…]

New idea: exploit indirect sensitivity to λ of single Higgs production
Provides a wealth of new measurements (many production processes, many kinematic distributions) to be used in a global fit (but theory must be accurate enough)

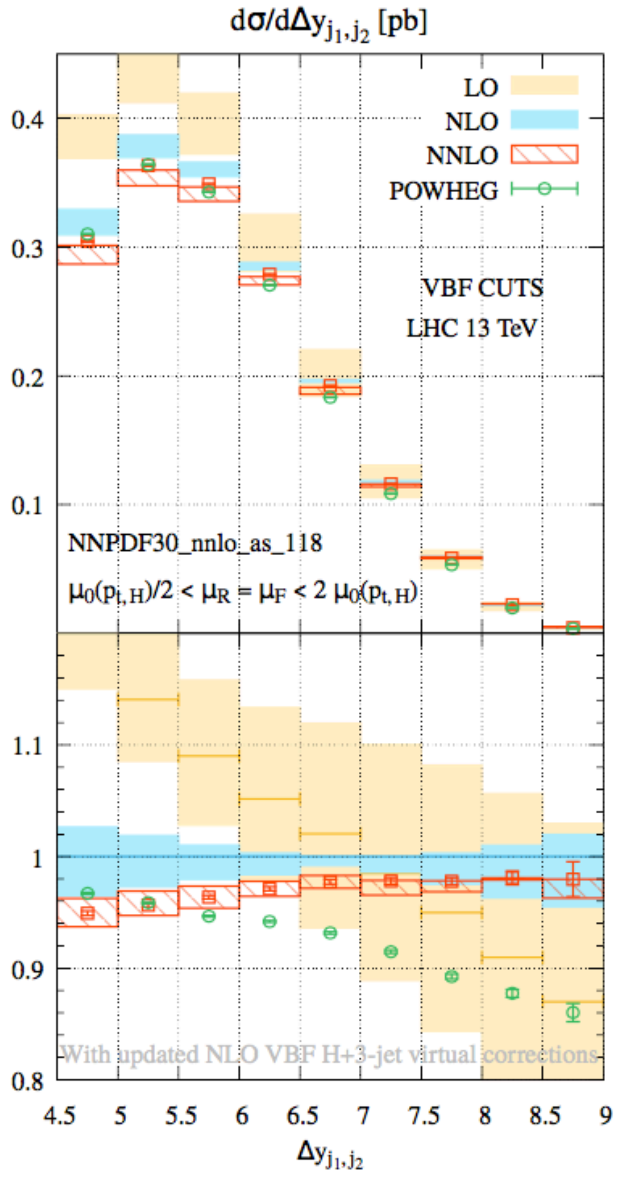
Conclusions

- Precision physics at hadron colliders is already there
- Precision Higgs studies in their infancy, much more to come
- Not just precision measurements of couplings but possibility to address key outstanding questions (Higgs potential, minimal Higgs, fine-tuning, portal to hidden sectors, DM…)
- Fervid theoretical activity. *This talk focused on selected results of the last few months, many other results that I did not have time to cover …*

NNLO VBF



Cruz-Martinez et al 1802.02445

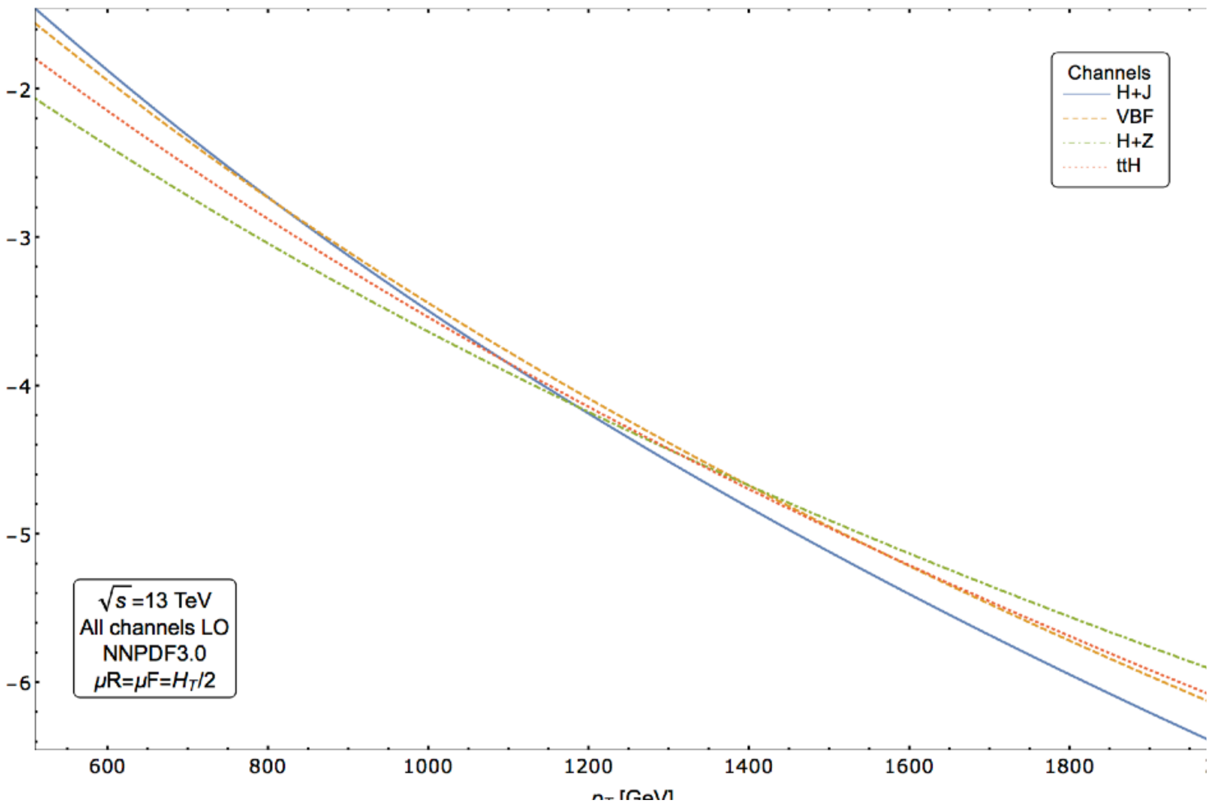


Dryer et al 1506.02660

- validation of previous calculation using P2B method
- NNLO important (large, shape distortions) in fiducial regions

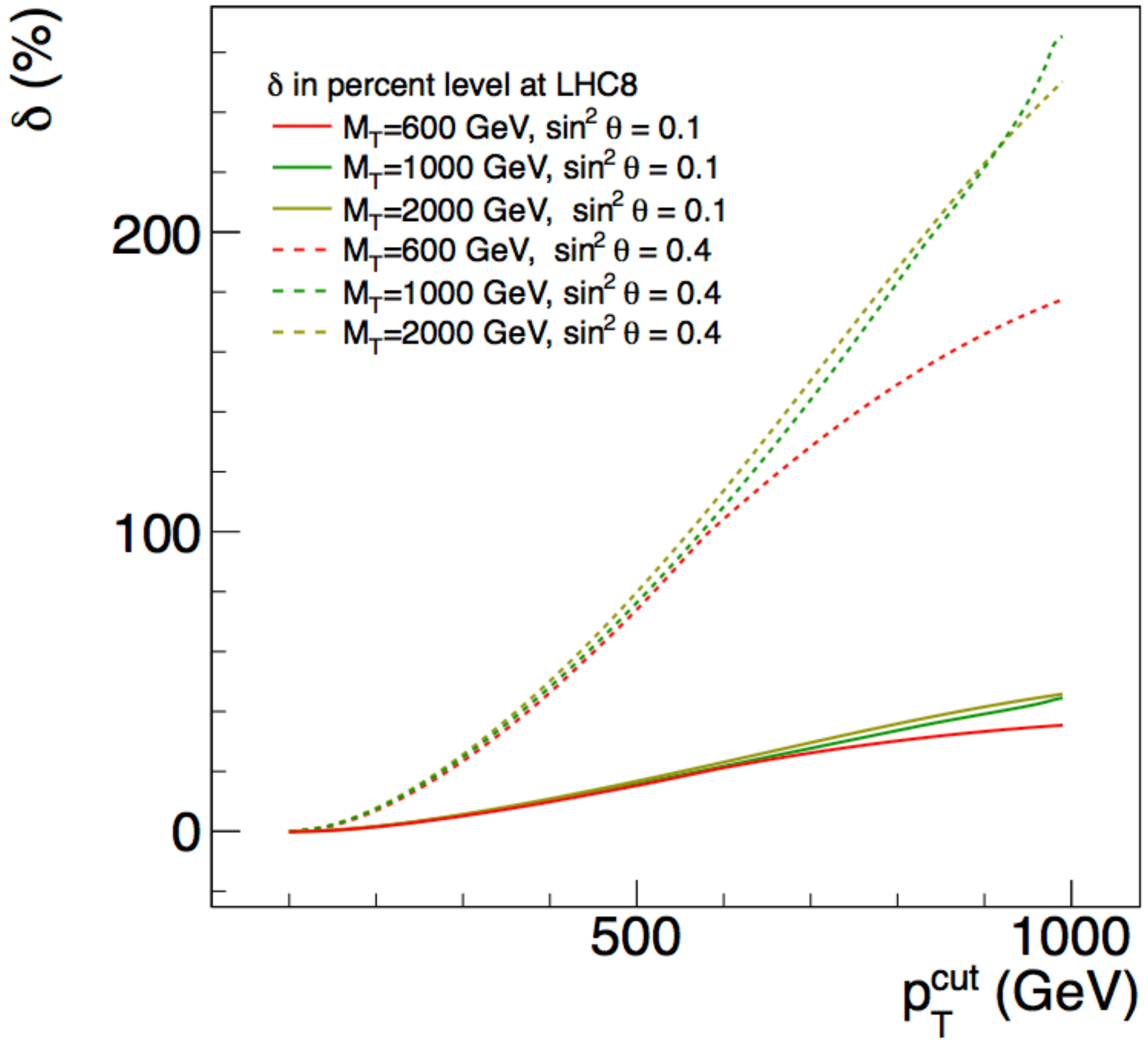
Boosted Higgs

- At high pt hierarchy of modes changes but ggH remains dominant up to about 1 TeV



$$\frac{\sigma_H}{\mathrm{d}p_\perp^2} \sim \frac{\sigma_0}{p_\perp^2} \times \begin{cases} (\kappa_g + \kappa_t)^2, & p_\perp^2 < 4m_t^2, \\ \left(\kappa_g + \kappa_t \frac{4m_t^2}{p_\perp^2}\right)^2, & p_\perp^2 > 4m_t^2. \end{cases}$$

Banfi, Martin, Sanz 1308.4771



- High pt interesting as it allows to disentangle a point like and a top induced ggH coupling