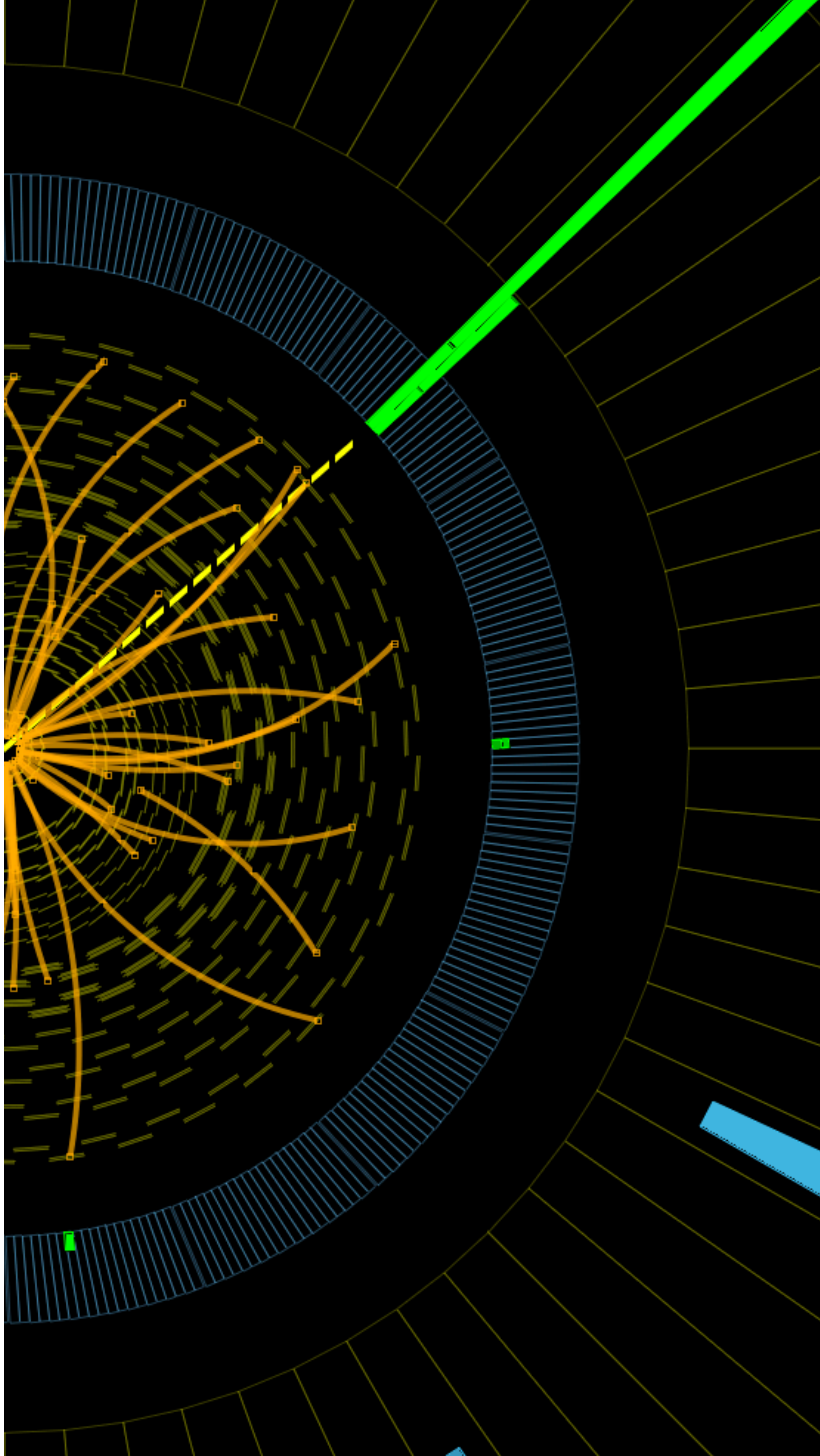
HIGGS PRECISION PHYSICS AT THE LHC



Amplitudes in the LHC era
GGI, Florence Oct. 29th 2018

Lorenzo Tancredi - CERN TH

INTRODUCTION: WHY THE HIGGS?

Higgs discovery has opened a new chapter in particle physics

The SM is far from being understood!

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Higgs discovery has opened a new chapter in particle physics

The SM is far from being understood!

Being able to MODEL something doesn't mean to UNDERSTAND it!

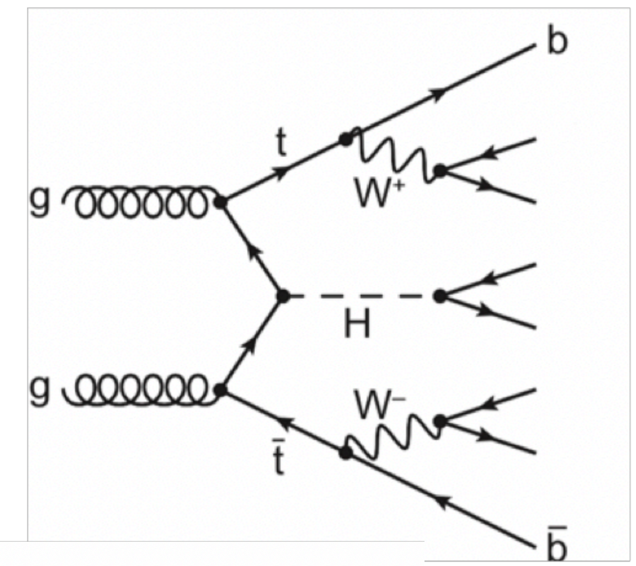
Details of SSB mechanism? **Higgs potential**? Vacuum stability?

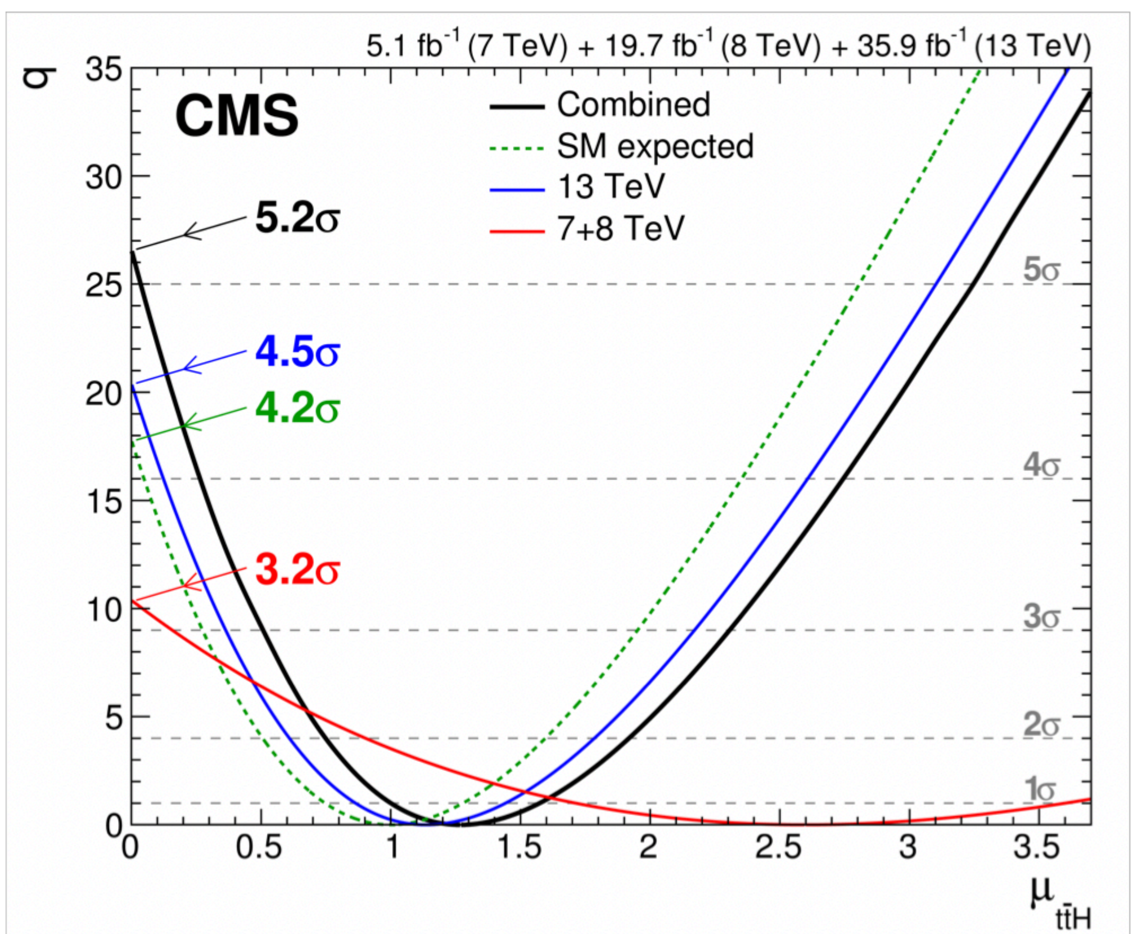
Origin of **masses** and **hierarchy** (why *up quark* lighter than *down quark*?…)

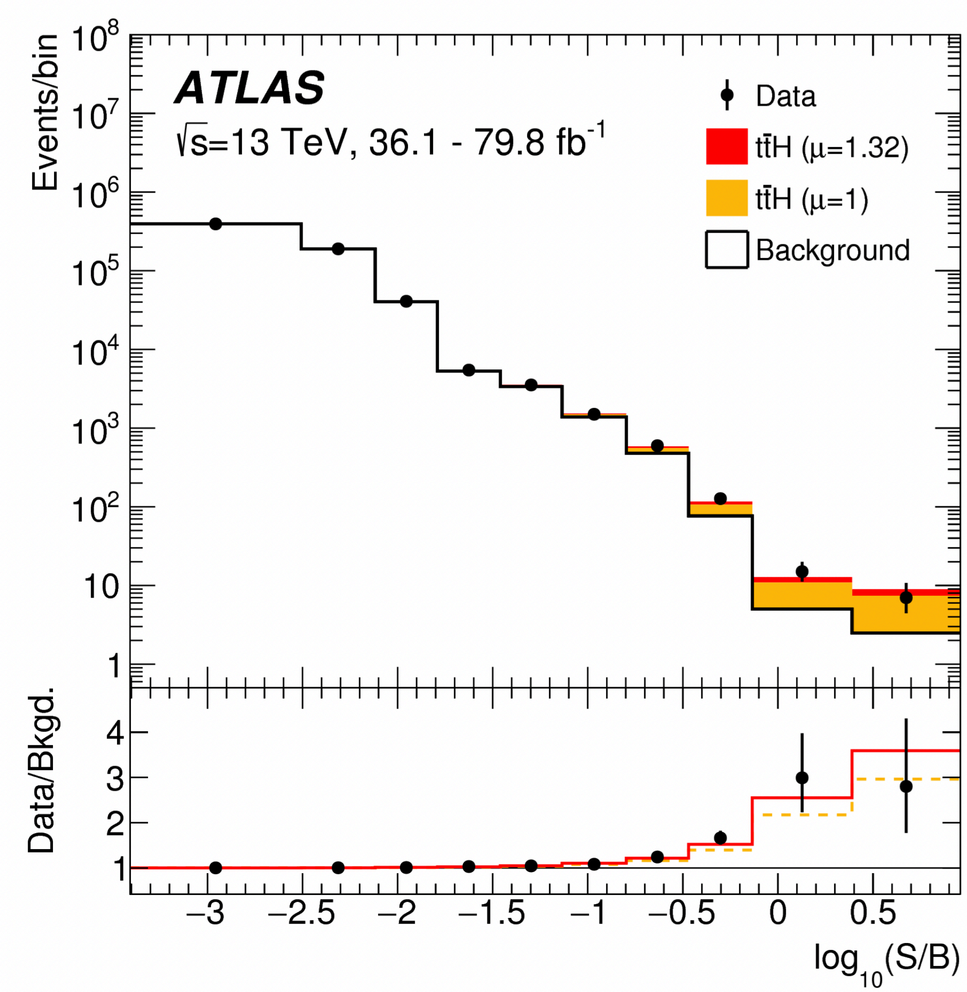
INTRODUCTION: WHY THE LHC?

The LHC is the first machine able to probe this energy scale!

First direct observation of H coupling to quarks, **ttbH @ LHC**

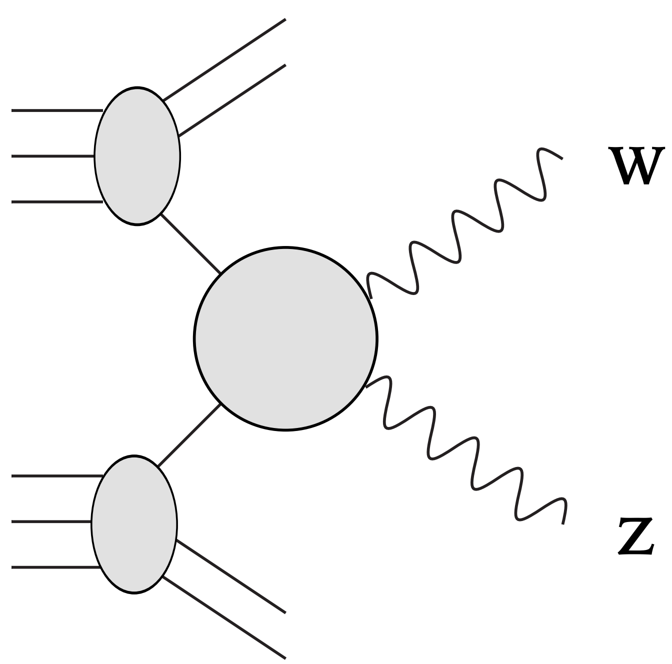




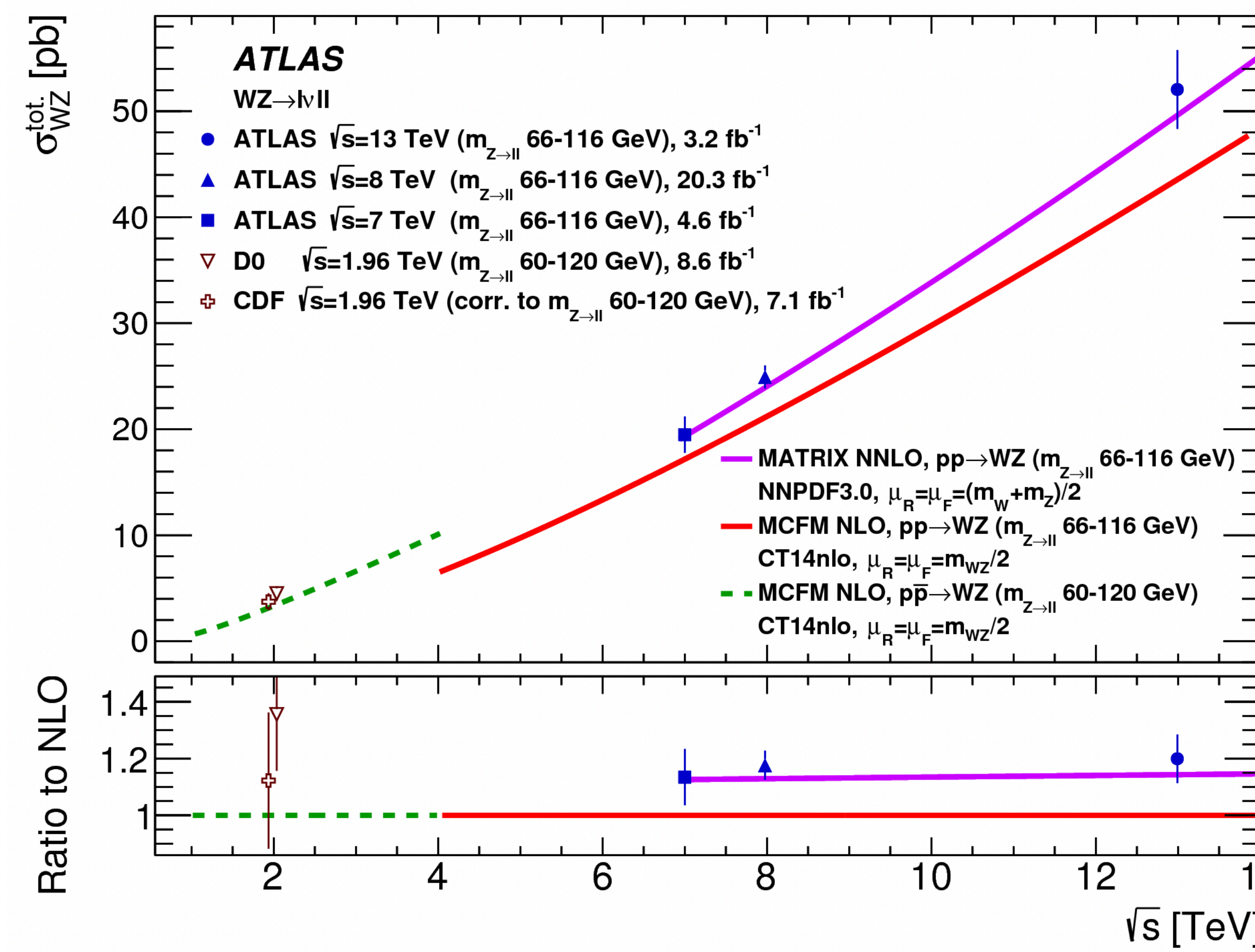


INTRODUCTION: WHY PRECISION?

Without precision, new physics would be everywhere



[ATLAS Phys. Lett. B 762 (2016) 1]



Higher order corrections are essential to describe properly the data!

PRECISION QCD @ LHC: WHAT AND HOW

Precision @ the LHC, means (mainly) **precision in QCD**, in a very **dirty environment!**
How precise can we hope to get?

$$pp \to HX \to l_1\bar{l}_1 + l_2\bar{l}_2 + X$$

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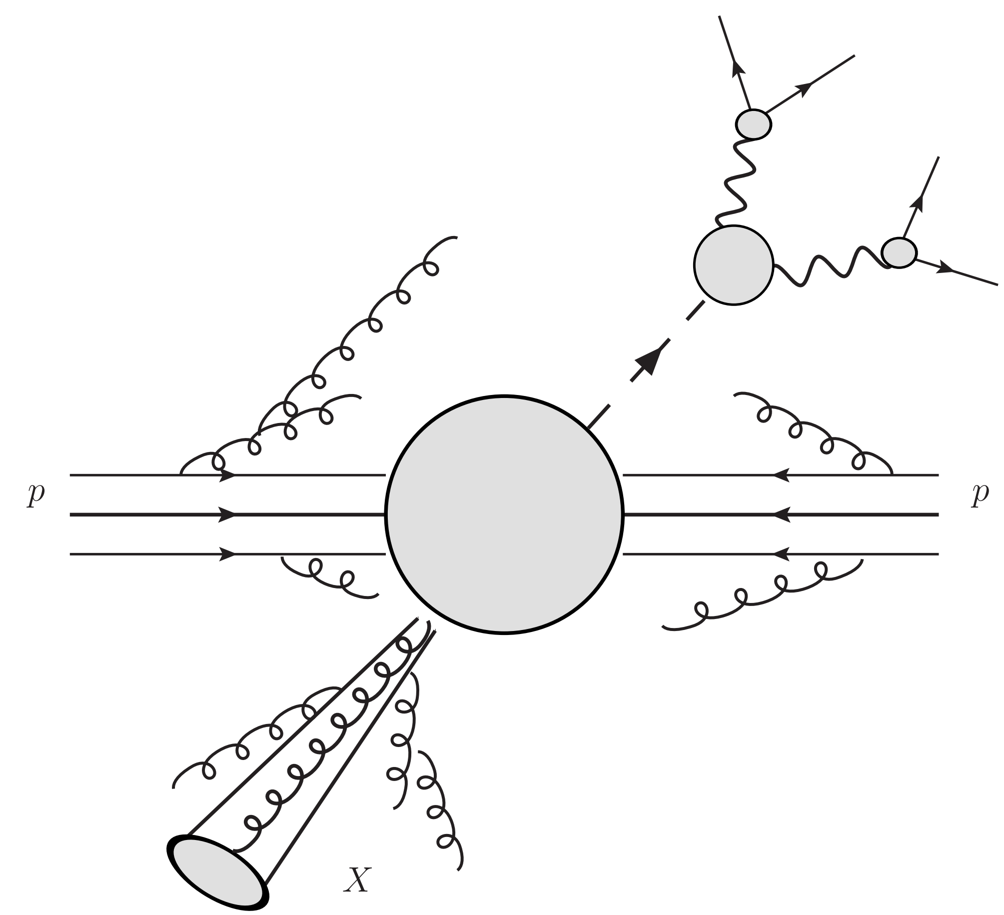

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Non perturbative corrections

$$\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right) \sim \text{few percent?}$$

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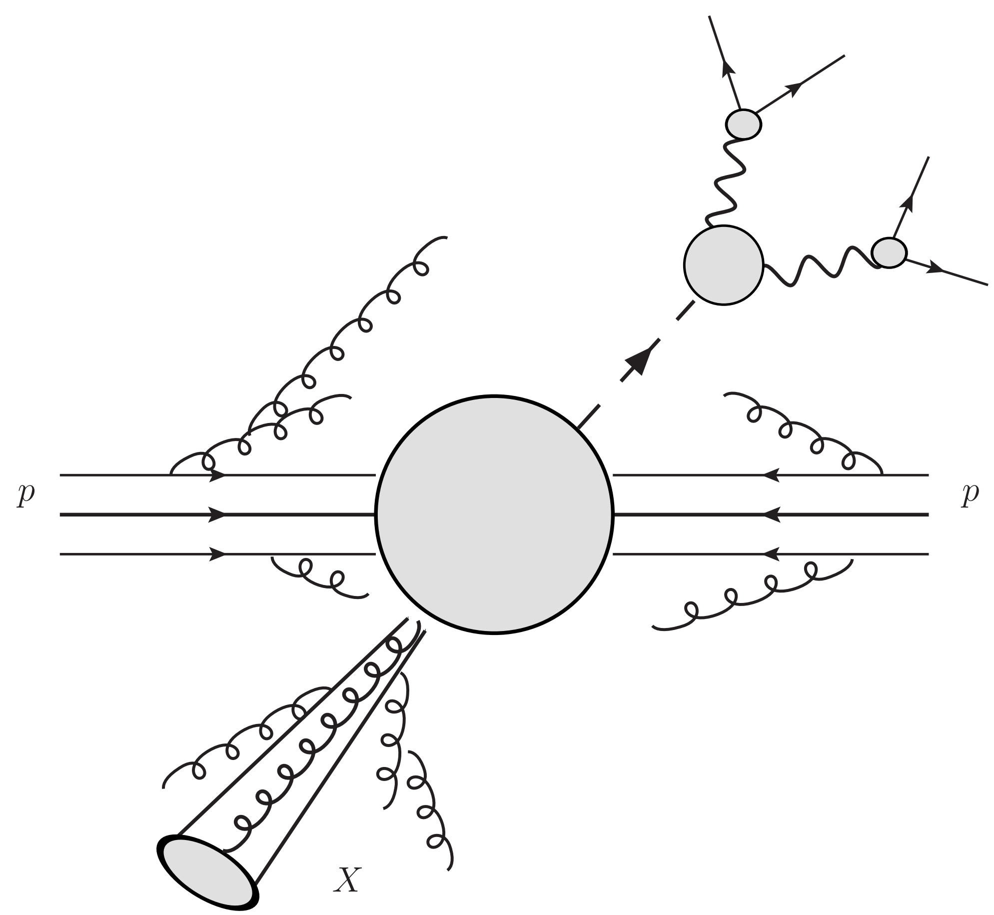

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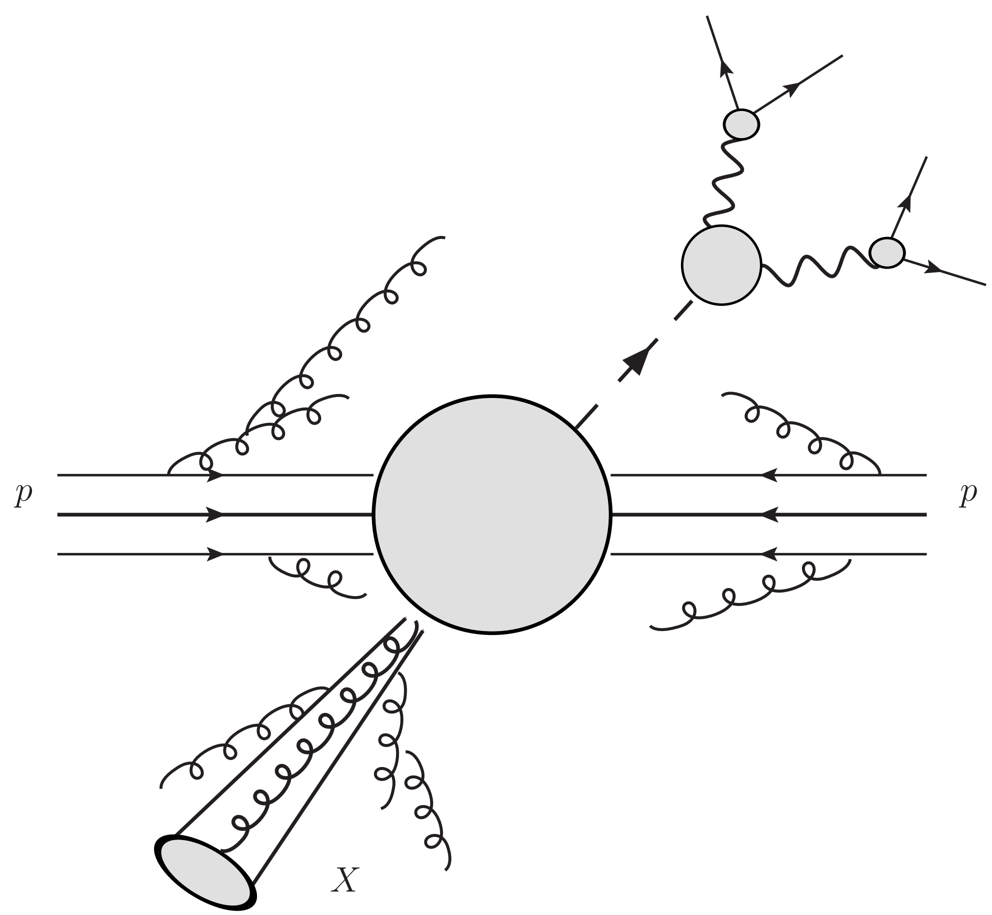

Precise determination of **parton content of proton**

PDFs Currently known at level ~ few % for LHC

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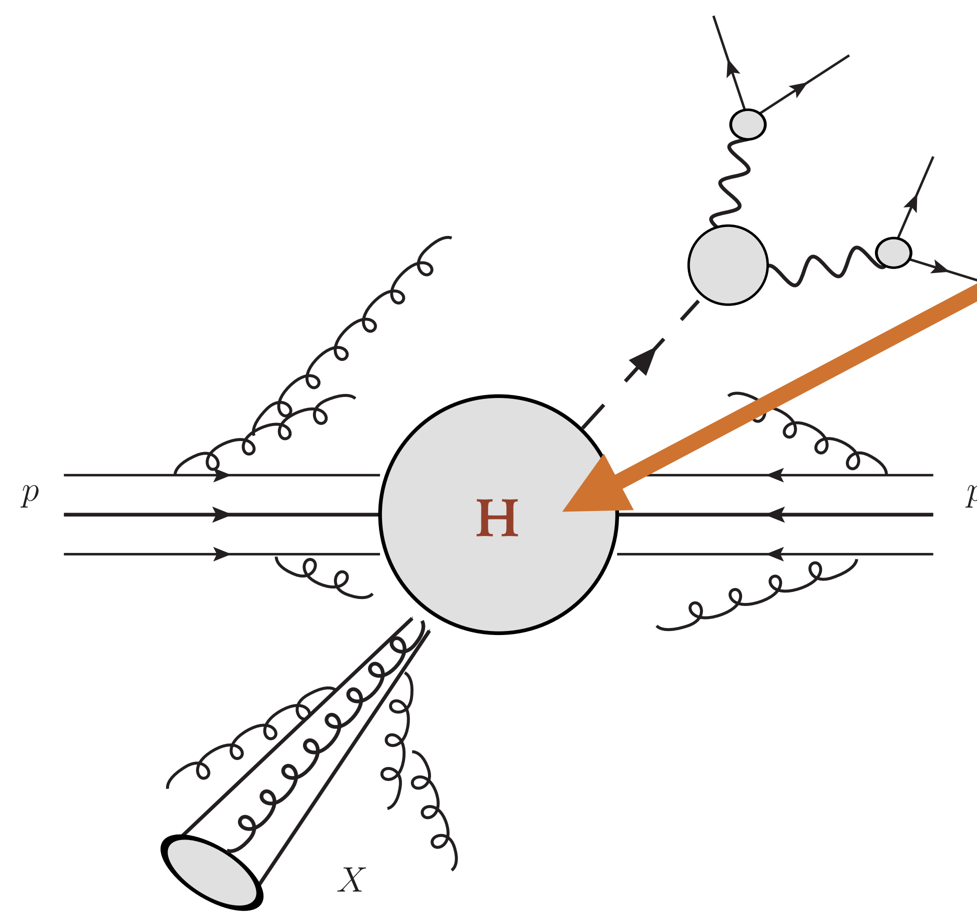


Hard scattering process

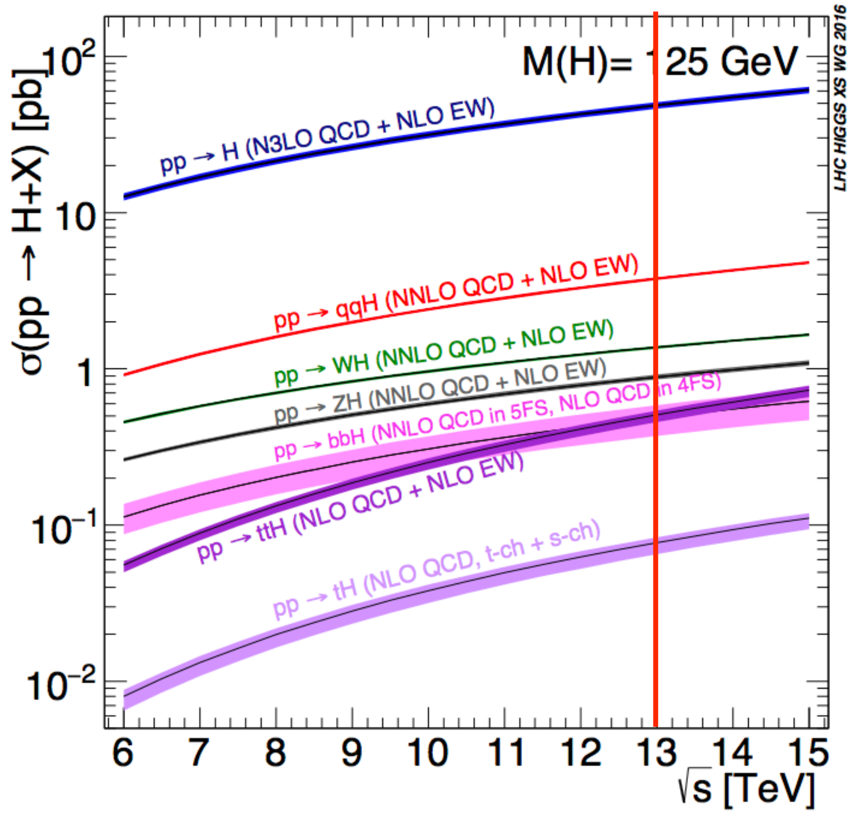
Aim to $\sim$ **few % precision**

Precise determination of **parton content of proton**

PDFs Currently known at level $\sim$ few % for LHC

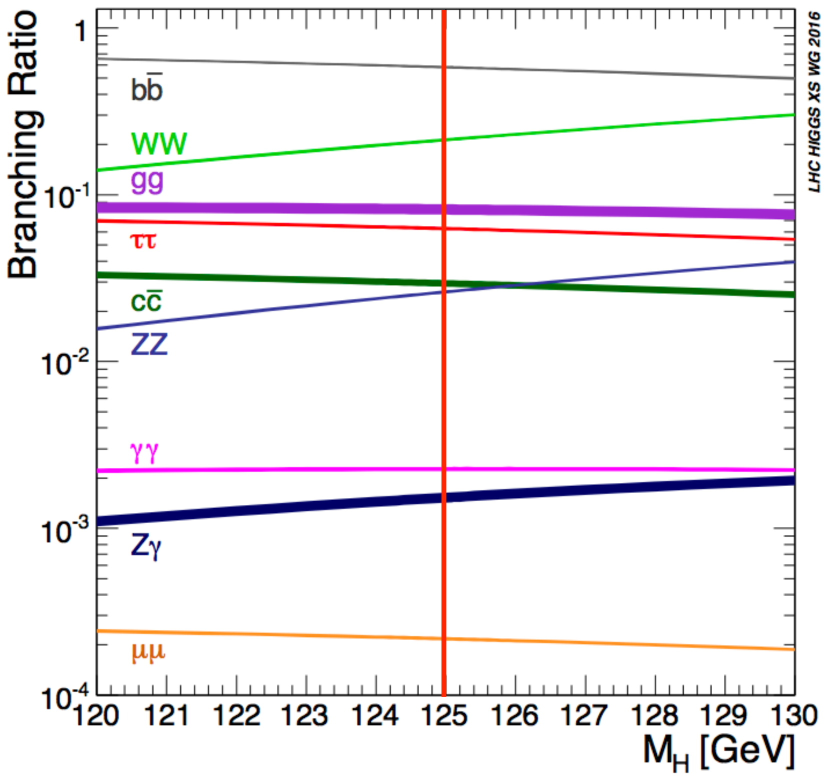
HIGGS PRODUCTION AND DECAYS

Production channels



$\sqrt{s}$ (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 channels



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}	$^{+6.0\%}_{-5.9\%}$

HIGGS PRODUCTION AND DECAYS

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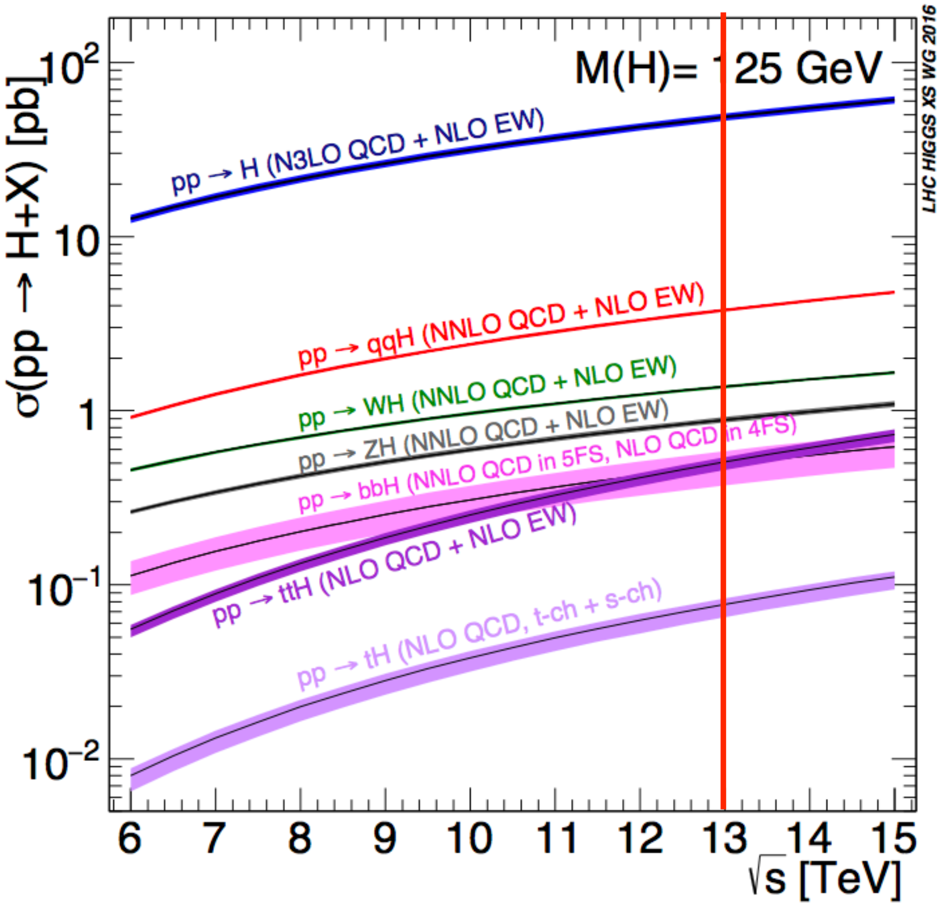

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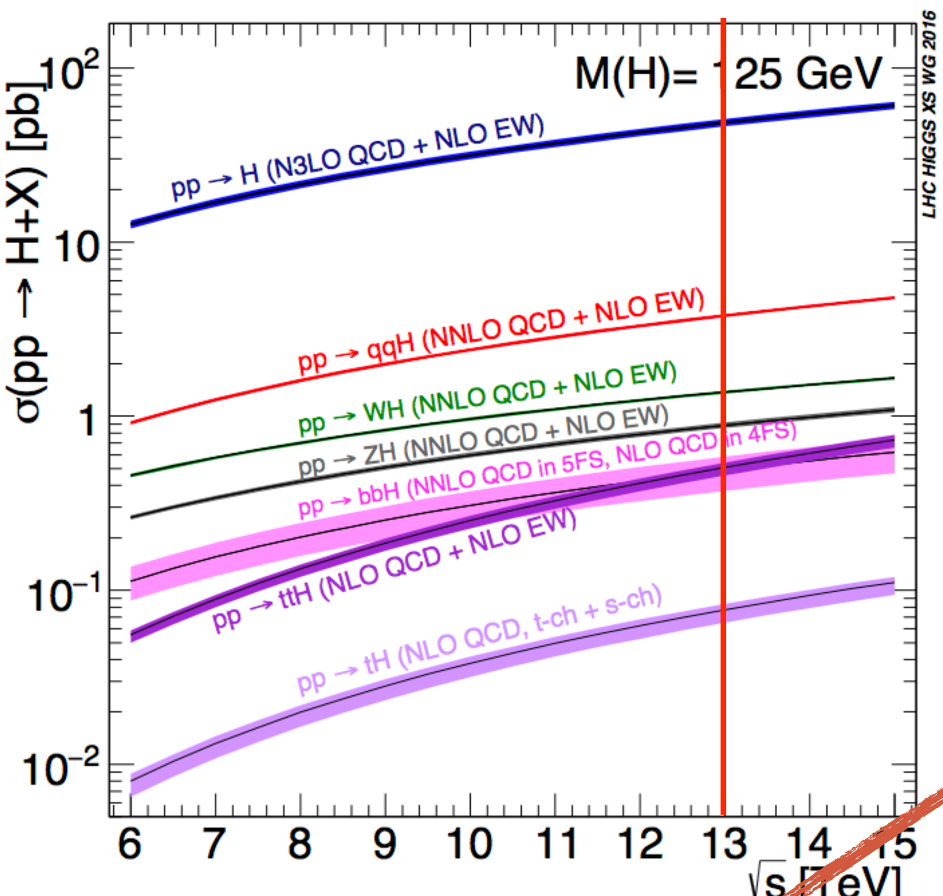

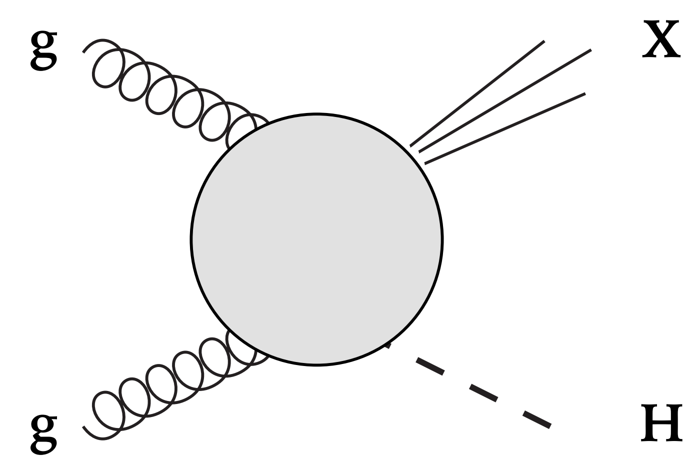

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gg is 90% at 13 TeV

HIGGS INCLUSIVE PRODUCTION

90% given by gluon fusion channel. To be understood with very high precision!

Pure QCD 95%:
see Bernhard's Talk

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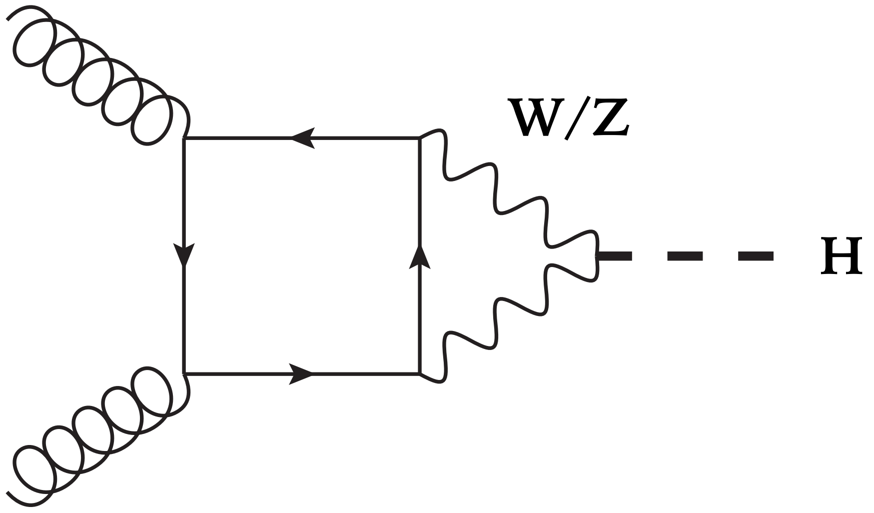
QCD-EW:
5%



Higgs known to suffer of **poor convergence of the perturbative series**. Following pattern of pure QCD corrections, **this 5% could change of up to 100% @ NLO**

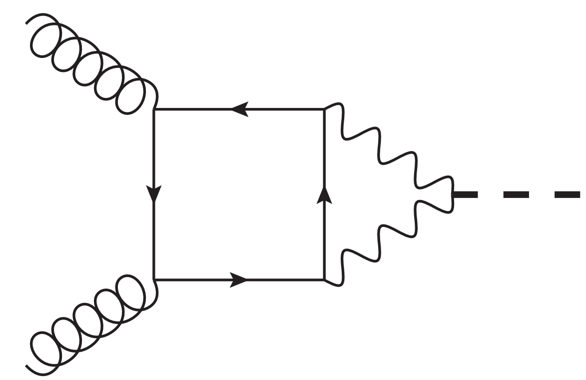
HIGGS INCLUSIVE PRODUCTION

Estimate of radiative corrections in **unphysical limit** $mW >> mH$

[Anastasiou et al 2009]

Theoretical uncertainties

δ_{scale}	$\delta_{\text{PDF-TH}}$	$\delta_{\text{QCD-EW}}$	$\delta_{t,\,b,\,c}$	δ_{1/m_t}
$\sim 2\%$	1.16%	1%	0.83%	1%



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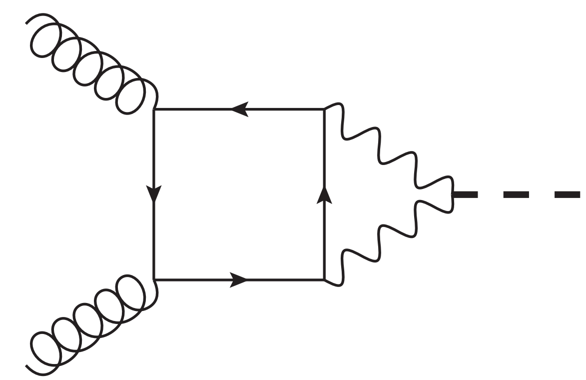
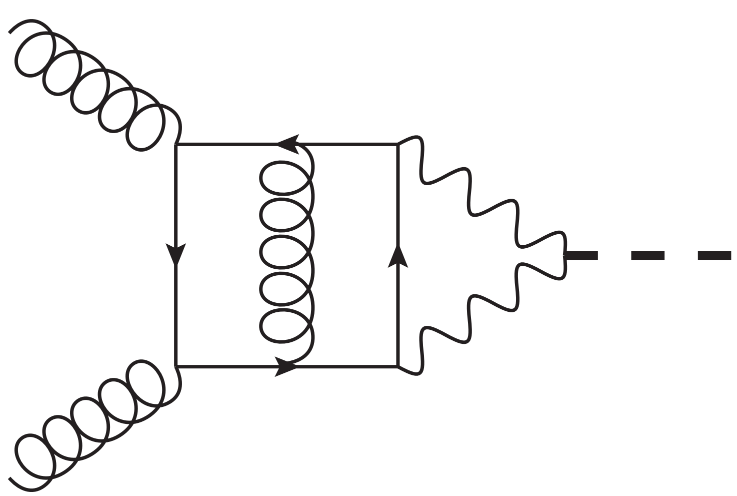
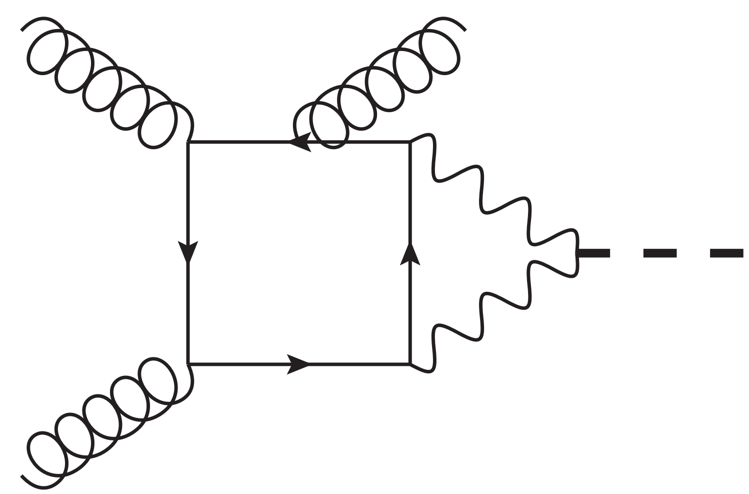


To really claim theory uncertainty at the 1% requires going one order higher (NLO)

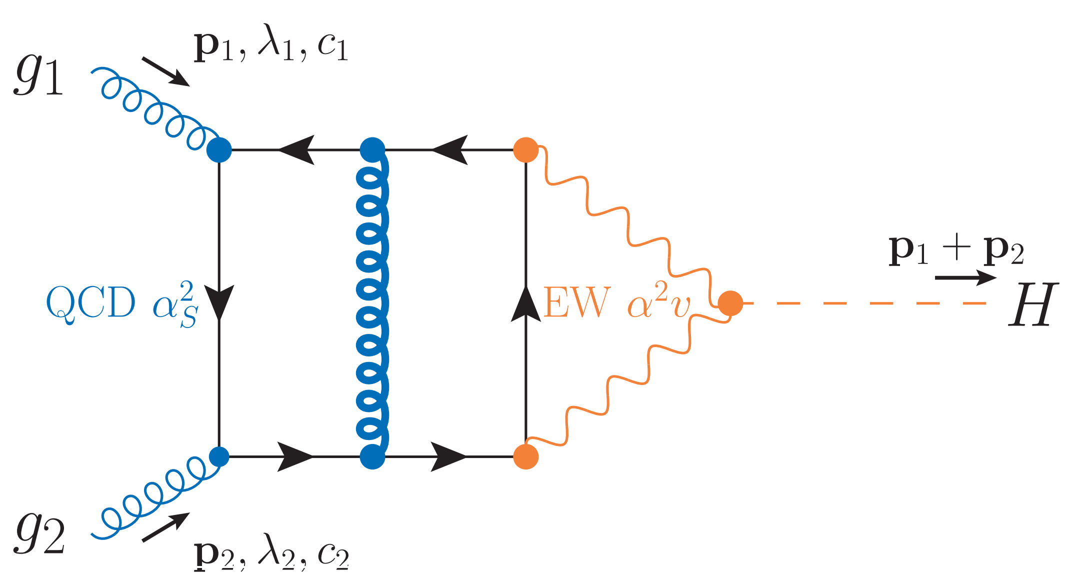


Virtual: 3 loops with masses



Real: 2 loops with masses

THE QCD-EW CORRECTIONS: VIRTUAL



47 3-loop Feynman Integrals, with two internal massive propagators, functions of ***one ratio:***

$$y := \frac{\sqrt{1 - 4m^2/s} - 1}{\sqrt{1 - 4m^2/s} + 1}$$

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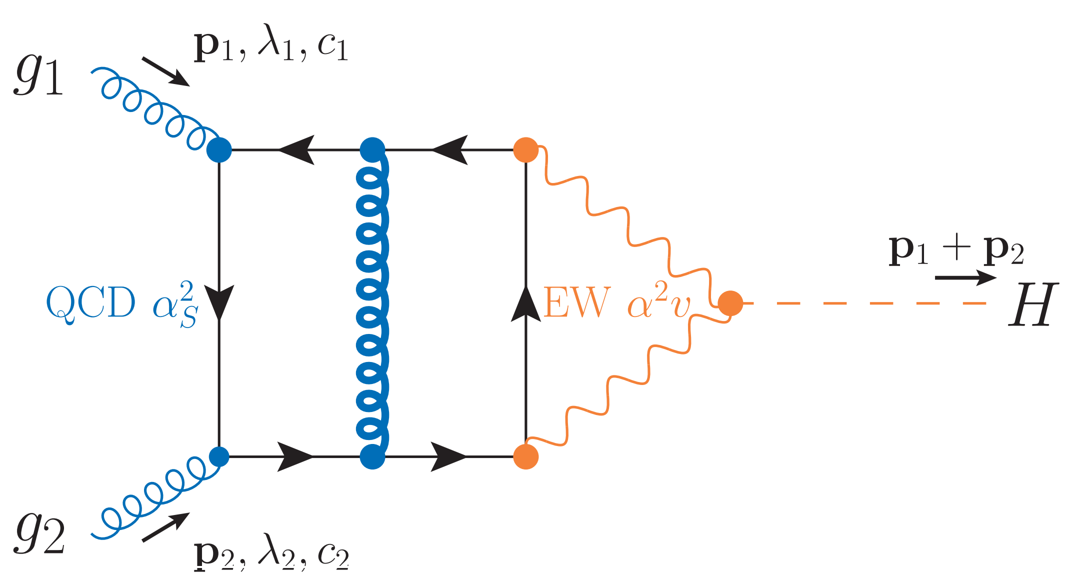

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$$\mathcal{M}^{\,c_1 c_2}_{\,\lambda_1\lambda_2} = \delta^{c_1 c_2} \epsilon_{\lambda_1}(\mathbf{p}_1) \cdot \epsilon_{\lambda_2}(\mathbf{p}_2) \mathcal{F}\,(s, m_W, m_Z)$$

$$\mathcal{F}(s, m_W, m_Z) = -\mathrm{i} \frac{\alpha^2 \alpha_S(\mu) v}{64\pi \sin^4\theta_W} \sum_{V=W,Z} C_V\, A(m_V^2/s, \mu^2/s)$$

$$C_W = 4$$
$$C_Z = \frac{2}{\cos^4\theta_W}\left(\frac{5}{4} - \frac{7}{3}\sin^2\theta_W + \frac{22}{9}\sin^4\theta_W\right)$$

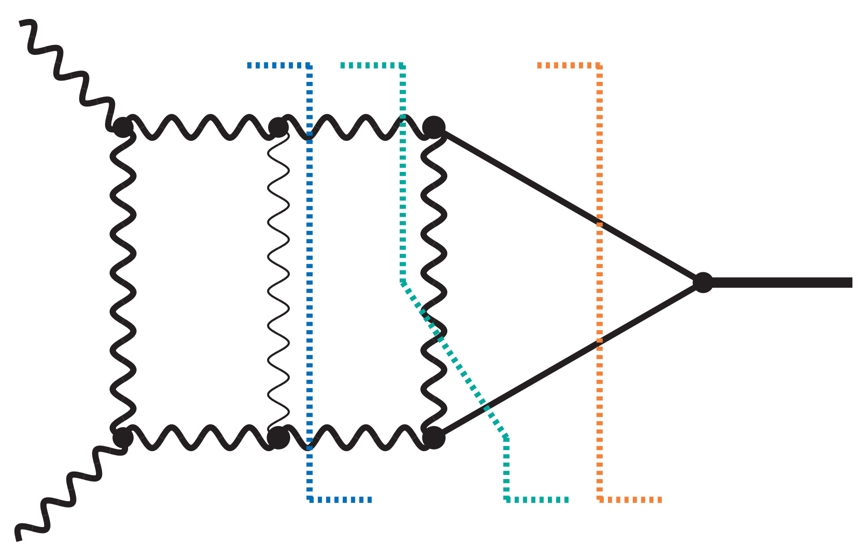
$$A(m^2/s, \mu^2/s) = A_{2\mathrm{L}}(m^2/s) + \frac{\alpha_S(\mu)}{2\pi} A_{3\mathrm{L}}(m^2/s, \mu^2/s) + \mathcal{O}(\alpha_S^2)$$

[Drawings by M. Bonetti]

THE QCD–EW CORRECTIONS: VIRTUAL

Fulfil a system of **differential equations** in **canonical form** **[Henn '13]**

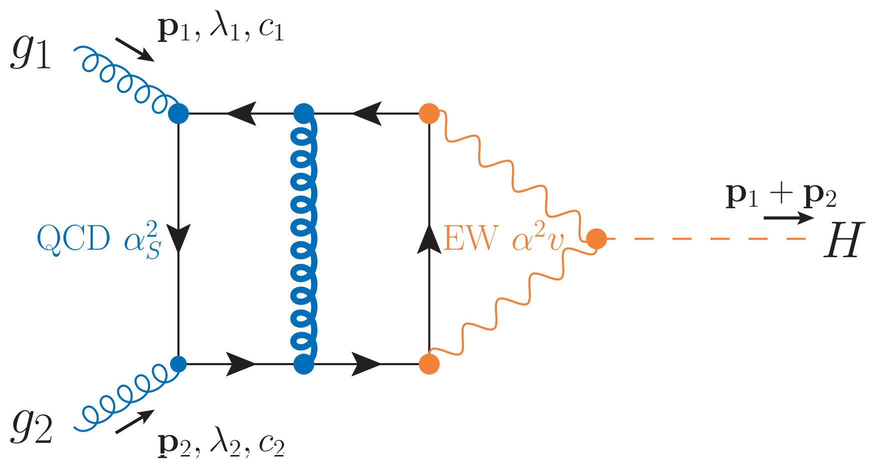
$$\mathrm{d}\mathbf{F}(y,\epsilon) = \epsilon \; \Big[\; B_+ \, \mathrm{d}\log(1-y) \; + B_r \, \mathrm{d}\log(y^2 - y + 1) \; + \; + B_- \, \mathrm{d}\log(y+1) \; + B_0 \, \mathrm{d}\log y \; \Big]\mathbf{F}(y,\epsilon$$



s	0	m^2	$4m^2$	$[\infty]$
y	$+1$	$e^{i\pi/3}$	-1	$[0]$
Kernel	$\frac{1}{\xi-1}$	$\frac{2\xi-1}{\xi^2-\xi+1}$	$\frac{1}{\xi+1}$	$\left[\frac{1}{\xi}\right]$

[Drawings by M. Bonetti]

THE QCD-EW CORRECTIONS: VIRTUAL



$$\mathcal{M}_3{}^{c_1 c_2}_{\lambda_1 \lambda_2} = \delta^{c_1 c_2} \epsilon_{\lambda_1}(\mathbf{p}_1) \cdot \epsilon_{\lambda_2}(\mathbf{p}_2) \mathcal{F}_3(s, m_W, m_Z)$$

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$$s = \mu = m_H = 125.09\,\text{GeV}, \; m_W = 80.385\,\text{GeV}, \; m_Z = 91.1876\,\text{GeV}, \; N_C = 3, \; N_f = 5$$

$$\begin{aligned}
A_{2\text{L}}(m_Z^2/m_H^2, 1) &= -6.880846 \; -\mathrm{i}\, 0.5784119 \\
A_{2\text{L}}(m_W^2/m_H^2, 1) &= -10.71693 \; -\mathrm{i}\, 2.302953 \\
A_{3\text{L}}^{\text{fin}}(m_Z^2/m_H^2, 1) &= -2.975801 \; -\mathrm{i}\, 41.19509 \\
A_{3\text{L}}^{\text{fin}}(m_W^2/m_H^2, 1) &= -11.31557 \; -\mathrm{i}\, 54.02989
\end{aligned}$$

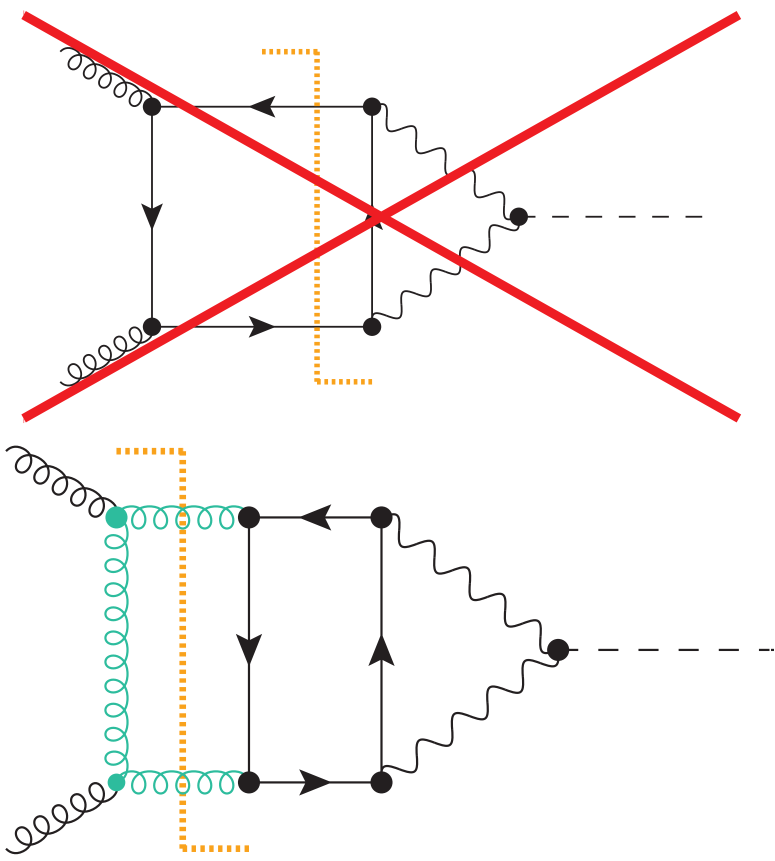
→ **UV renormalized + Catani subtracted**

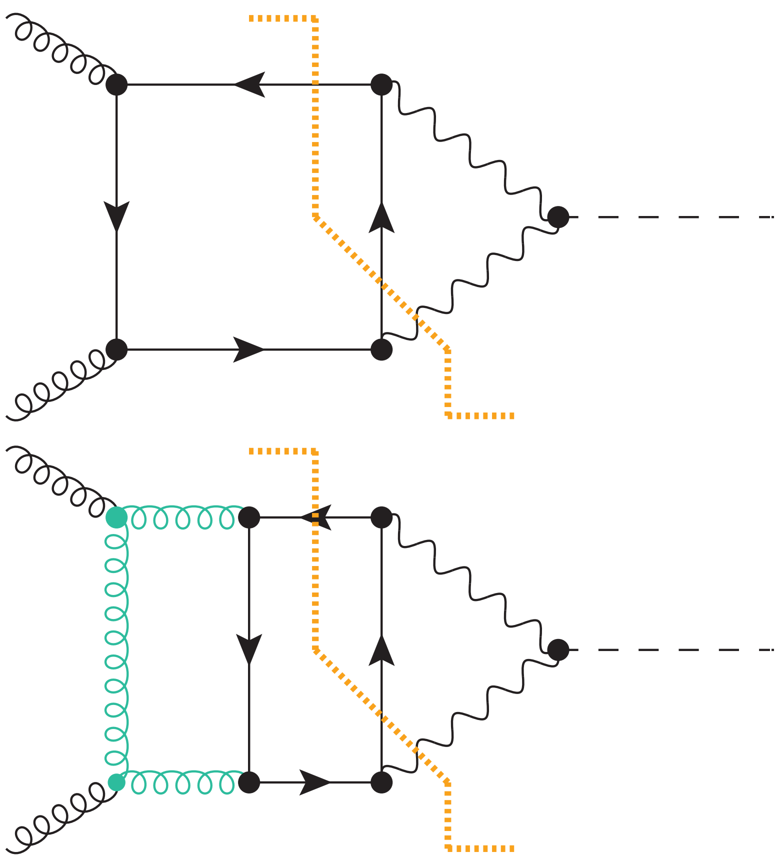
[Drawings by M. Bonetti]

THE QCD–EW CORRECTIONS: VIRTUAL (IMAGINARY PART)

$s = 0$

$s = m^2$





$-\mathrm{i}\, 2.302953$

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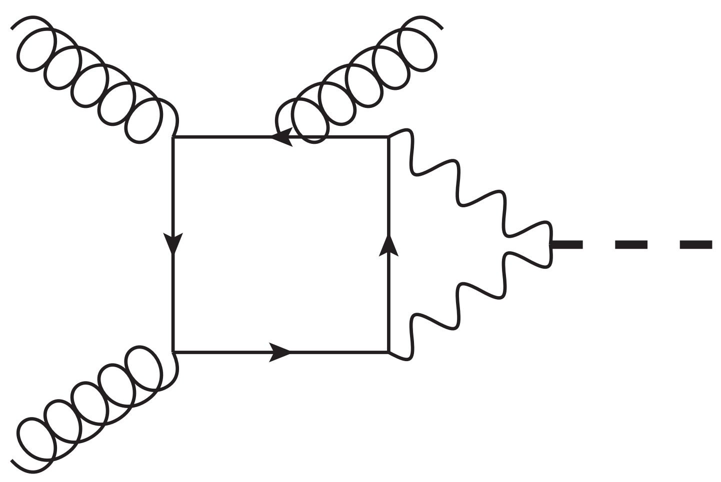
THE QCD-EW CORRECTIONS: THE REALS

What about the **real corrections**? **Non-trivial** using standard methods.

Since small corrections (5% of total cross-section) we can do an approximations:



Most of the cross-section comes from region where **extra gluon is soft** (PDFs suppression, parton xsection evaluated close to threshold!): **Soft gluon approximation**

[de Florian et al 2012, Forte et al 2013]

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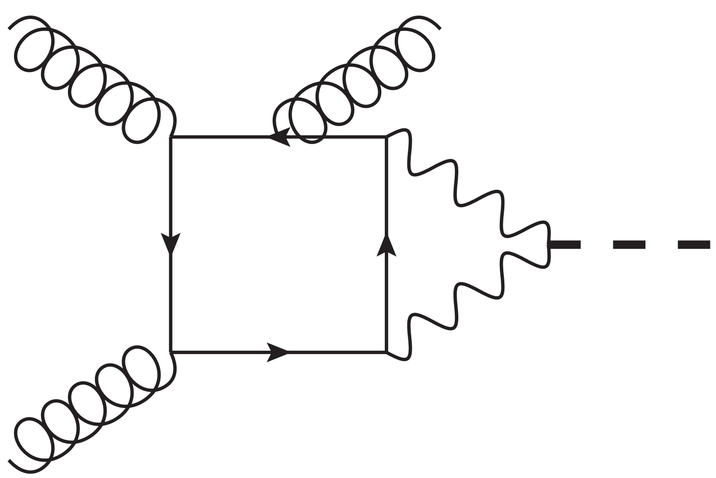

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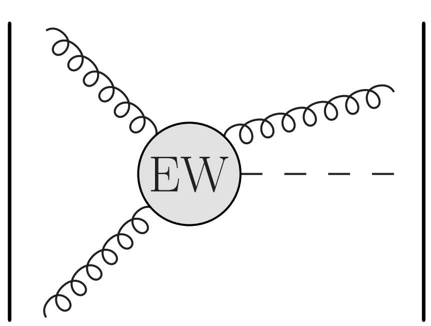
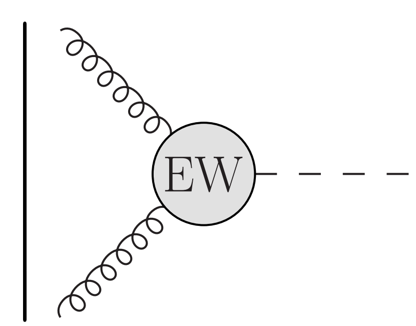


$$\left| \cdots \right|^2 \underbrace{=}_{E_g \to 0} \frac{\alpha_S}{4\pi} C_A \frac{2\, p_1 \cdot p_2}{p_1 \cdot p_4 \; p_2 \cdot p_4} \left| \cdots \right|^2 + O\left(p_4^{-1}\right)$$



Eikonal approximation

THE QCD-EW CORRECTIONS

$$\sigma = \int_0^1 \int_0^1 f(x_1,\mu)\, f(x_2,\mu)\, \sigma_{\mathrm{LO}}\, z\, G(z,\mu,\alpha_S)\, \mathrm{d}x_2 \mathrm{d}x_1$$

$z := m_H^2/(S_h x_1 x_2)$, $\quad gg \to H$ energy

$$G = \delta(1-z) + \frac{\alpha_S}{2\pi}\left[8C_A\left(\mathcal{D}_1 + \frac{\mathcal{D}_0}{2}\log\frac{m_H^2}{\mu^2}\right) + \left(\frac{2\pi^2}{3}C_A + \frac{\sigma_{\mathrm{NLO}}^{\mathrm{fin}}}{\sigma_{\mathrm{LO}}}\right)\delta(1-z)\right]$$

$$\mathcal{D}_0 = \left[\frac{1}{1-z}\right]_+$$

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$\sigma_{\mathrm{LO}}^{\mathrm{QCD}} = 20.6\,\mathrm{pb}$ $\quad \sigma_{\mathrm{LO}}^{\mathrm{QCD\text{-}EW}} = 21.7\,\mathrm{pb}$ $\quad \Rightarrow \quad +5.3\%$ at LO

$\sigma_{\mathrm{NLO}}^{\mathrm{QCD}} = 32.7\,\mathrm{pb}$ $\quad \sigma_{\mathrm{NLO}}^{\mathrm{QCD\text{-}EW}} = 34.4\,\mathrm{pb}$ $\quad \Rightarrow \quad +5.2\%$ at NLO

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Supports complete factorization of QCD-EW corrections!

THE QCD-EW CORRECTIONS

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$$\mathcal{D}_1 = \left[\frac{\log(1-z)}{1-z}\right]_+ + (2-3z+2z^2)\frac{\log[(1-z)/\sqrt{z}]}{1-z} - \frac{\log(1-z)}{1-z}$$

$\sigma_{\rm LO}^{\rm QCD} = 20.6\,{\rm pb} \qquad \sigma_{\rm LO}^{\rm QCD\text{-}EW} = 21.7\,{\rm pb} \quad \Rightarrow \quad +5.3\%$ at LO

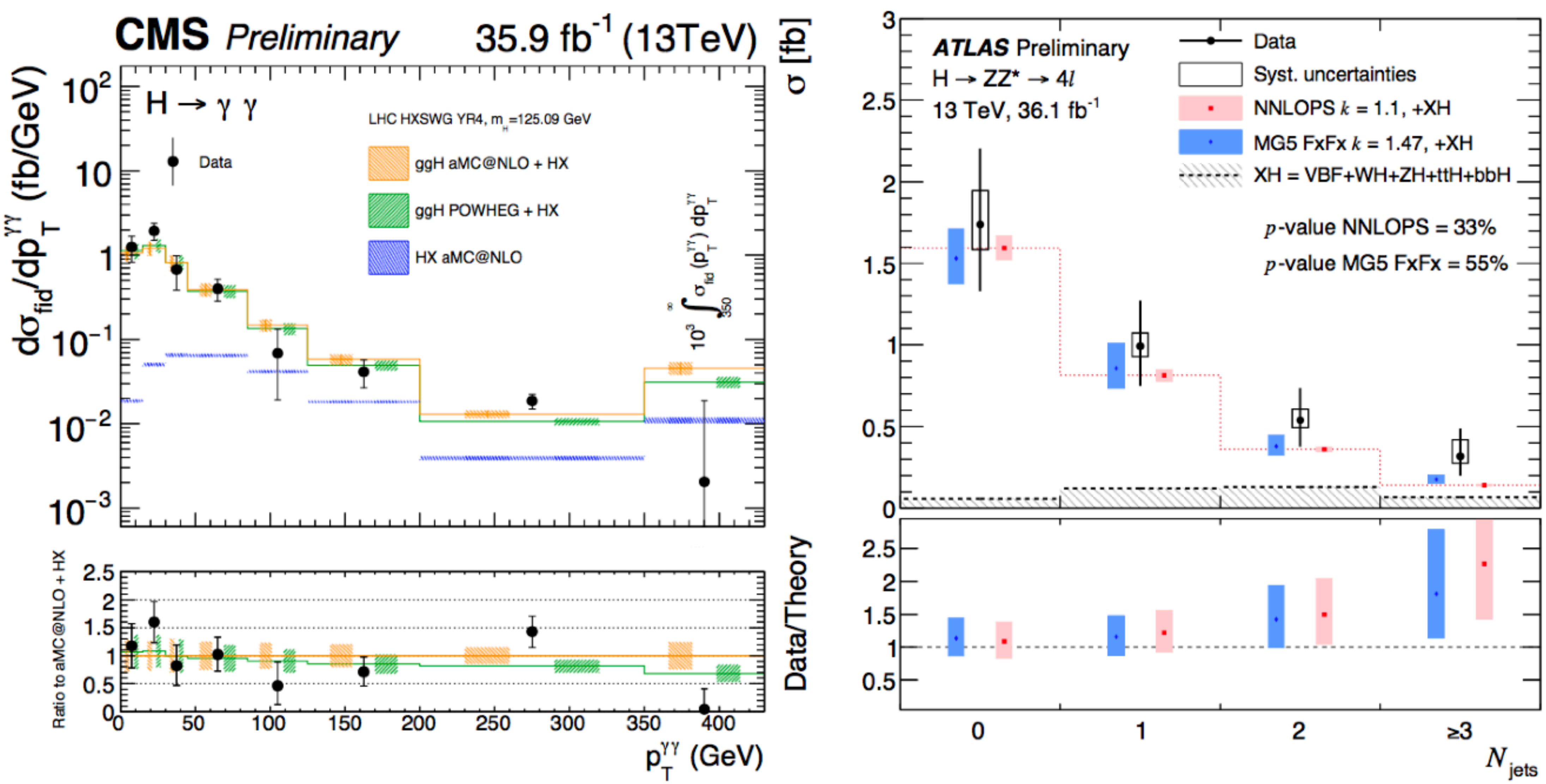
$\sigma_{\rm NLO}^{\rm QCD} = 32.7\,{\rm pb} \qquad \sigma_{\rm NLO}^{\rm QCD\text{-}EW} = 34.4\,{\rm pb} \quad \Rightarrow \quad +5.2\%$ at NLO

Theoretical uncertainties now

$\delta_{\rm scale}$	$\delta_{\rm PDF\text{-}TH}$	$\delta_{\rm QCD\text{-}EW}$		$\delta_{t,\ b,\ c}$	δ_{1/m_t}
$\sim 2\%$	1.16%	0.7%	$\mu \in [m_H/4, m_H]$	0.83%	1%

GOING DIFFERENTIAL

WHY GOING DIFFERENTIAL? (THE DEVIL IS IN THE DISTRIBUTIONS)

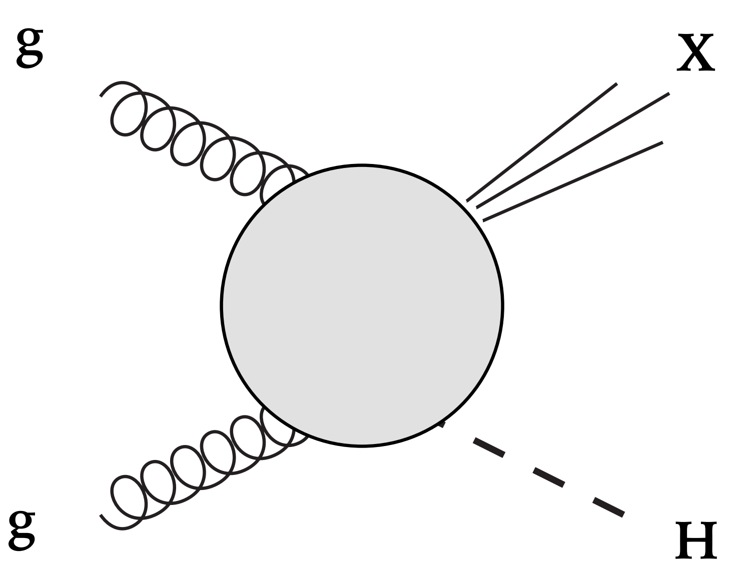


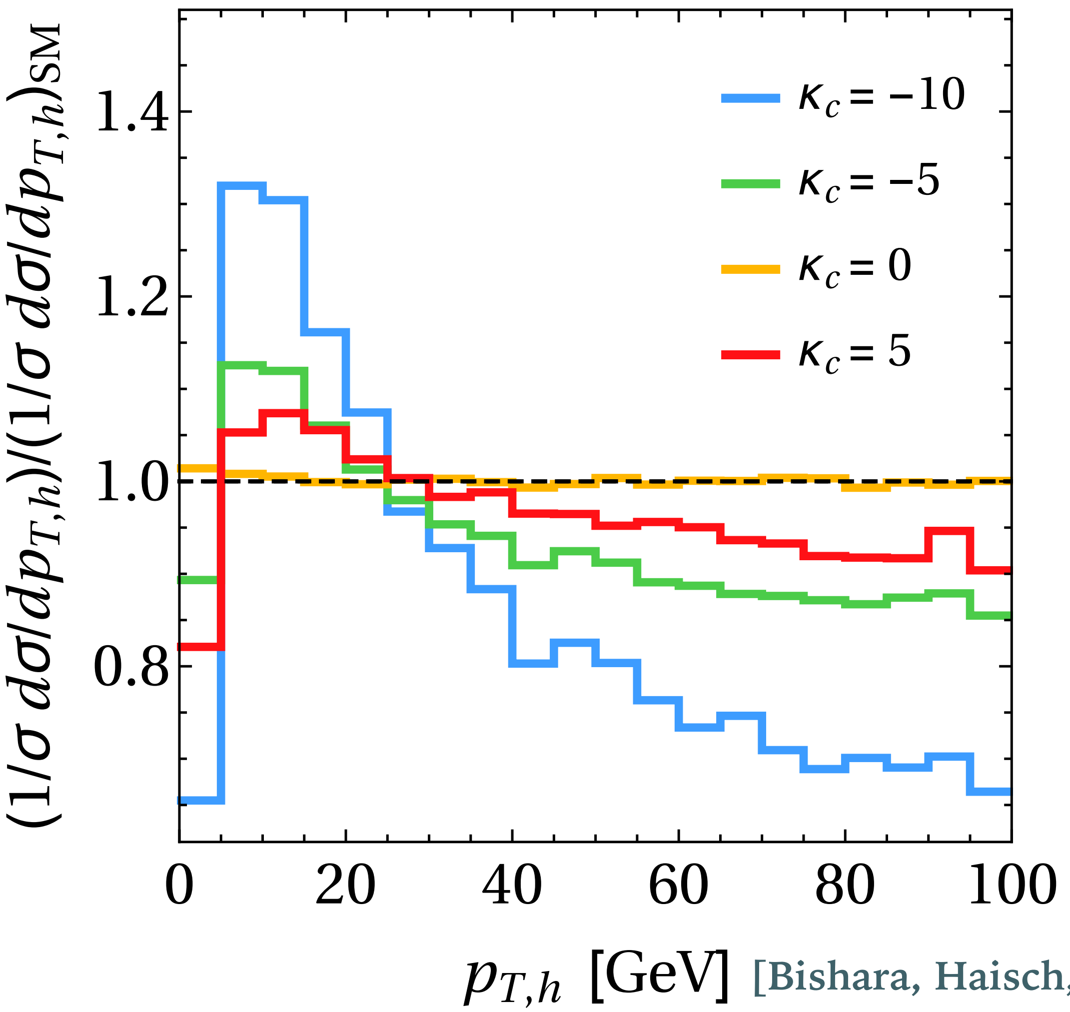
Distributions contain much more information (**shape distortion often very non-trivial**)

Theory errors more often underestimated, exp. error catching up and already competitive.

THE HIGGS TRANSVERSE MOMENTUM

Higgs transverse momentum distribution as a **new physics probe**





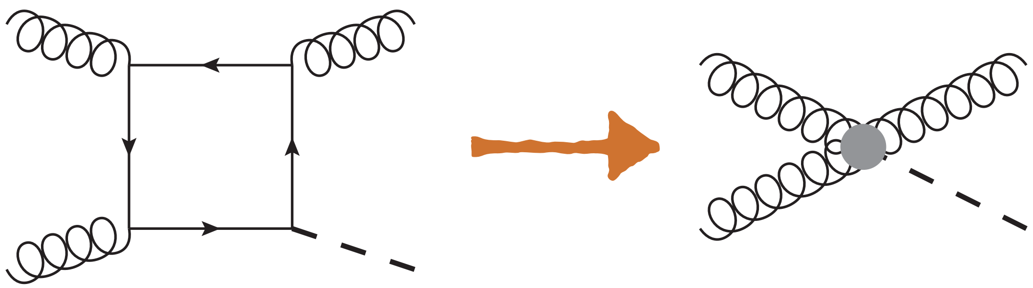
[Bishara, Haisch, Monni, Re, '16]
[Soreq, Zhu, Zupan, '16]

High precision theory determination of Higgs pT, allows to put constraints on **Higgs couplings to light quarks**

HOW WELL DO WE MODEL THE TRANSVERSE MOMENTUM?

The Higgs **transverse momentum distribution** is shaped by:

- **Top-quarks** running in the loops: **HEFT** provides a good description for **small pT**



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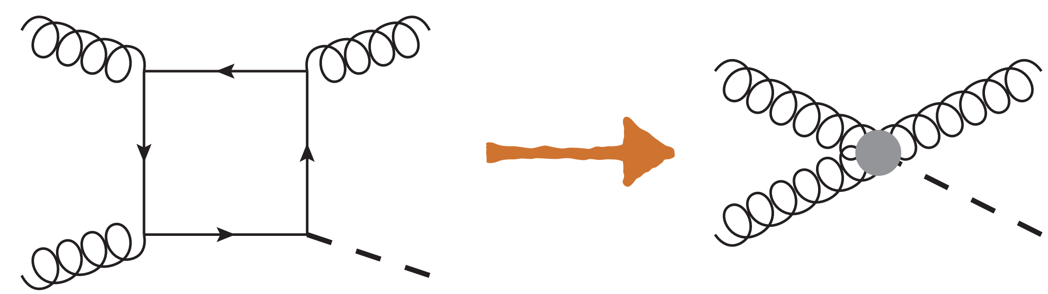
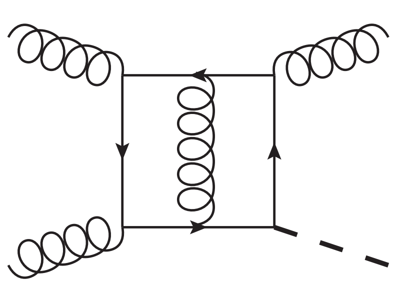
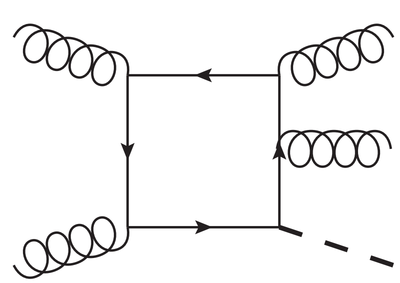


- At high pT, **top-quarks resolved in the loops**. Need full mass dependence (NLO is a 2-loop process already)





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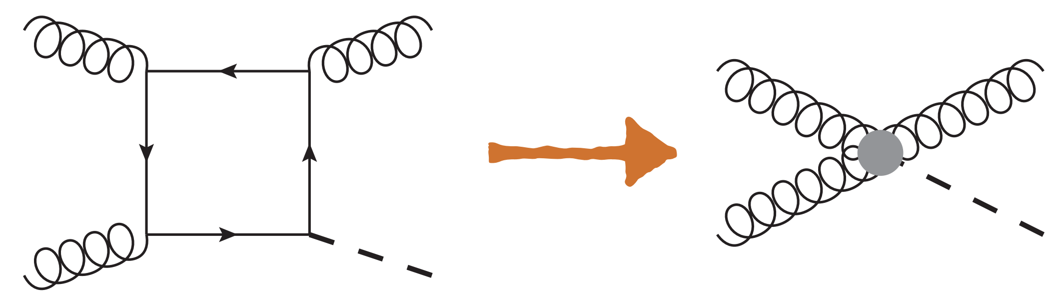
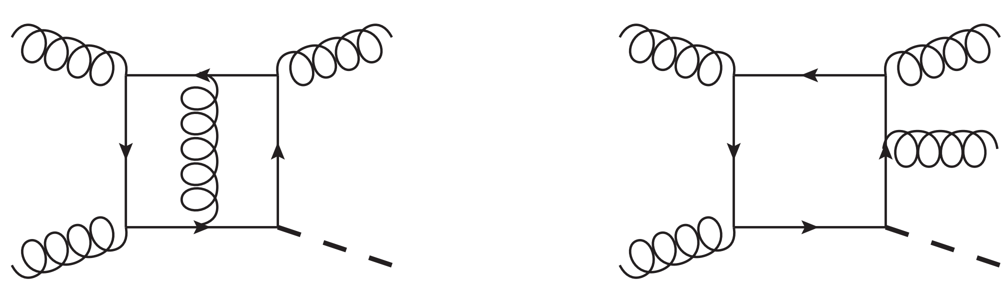


- At high pT, **top-quarks resolved in the loops**. Need full mass dependence (NLO is a 2-loop process already)

- What about **b-quarks**? Amplitude suppressed by **two powers of mb**! Still, **interference top-bottom** contributes **O(5%) to the pT distribution at LO**

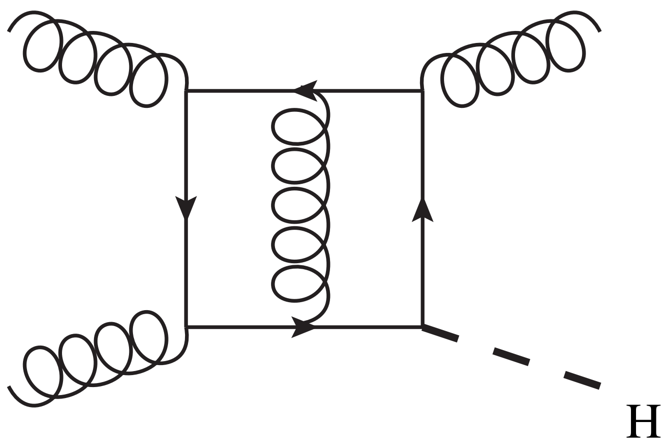


$$A_{gg\to Hg} \sim \left\{ \frac{m_b^2}{m_H^2} \log^2\left(\frac{m_H^2}{m_b^2}\right) , \frac{m_b^2}{m_H^2} \log^2\left(\frac{p_\perp^2}{m_b^2}\right) \right\}$$

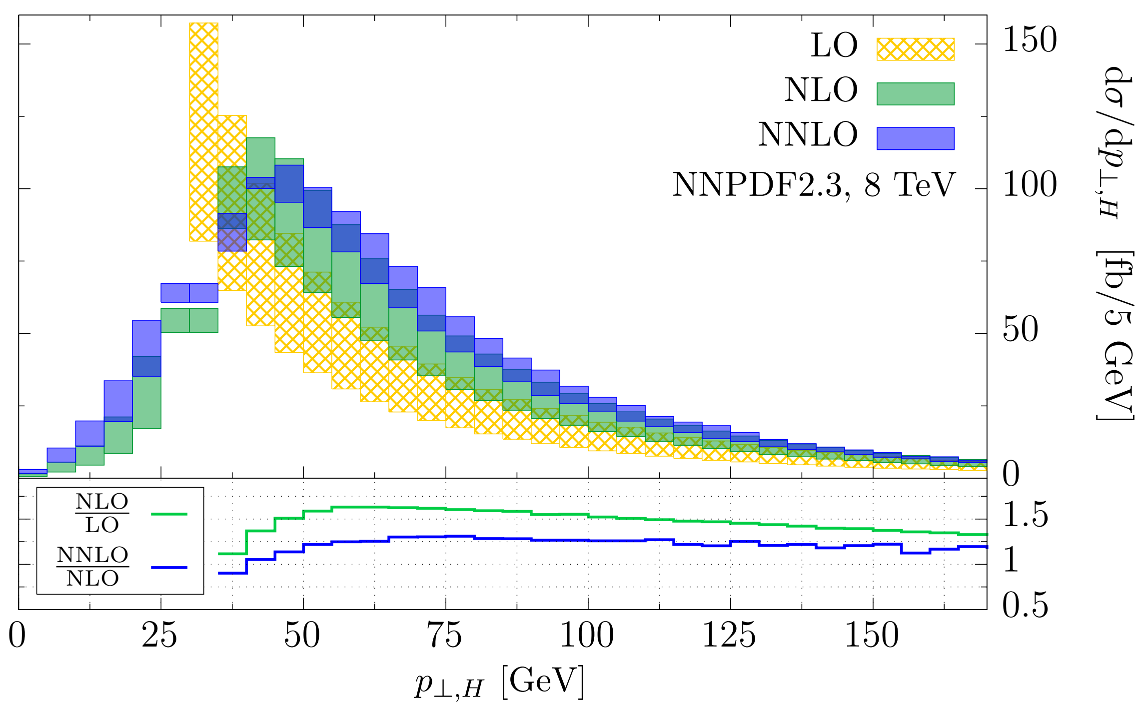
TOP-QUARK CONTRIBUTION

NNLO QCD in HEFT theory known since a couple of years

[Boughezal et al '15, Chen et al '16]

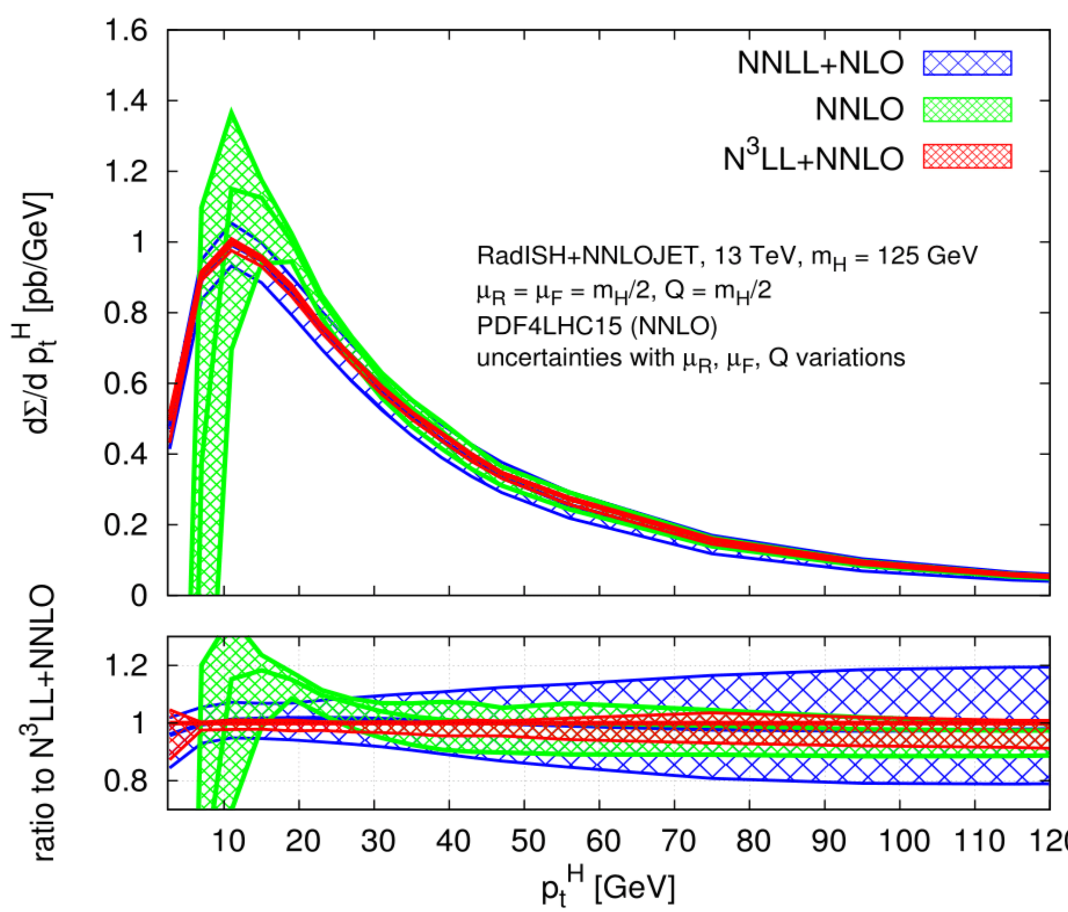


$$\sigma_{pp\to H+j} = 10.2^{+4.0}_{-2.6}\ \text{pb},\ 14.7^{+3.0}_{-2.5}\ \text{pb},\ 17.5^{+1.1}_{-1.4}\ \text{pb}$$



QCD radiative corrections depend on the kinematics. Indeed, the NNLO to NLO cross-sections ratio changes from 1.25 at $p_\perp = 30$ GeV to ~ 1 at $p_\perp \sim 150$ GeV.

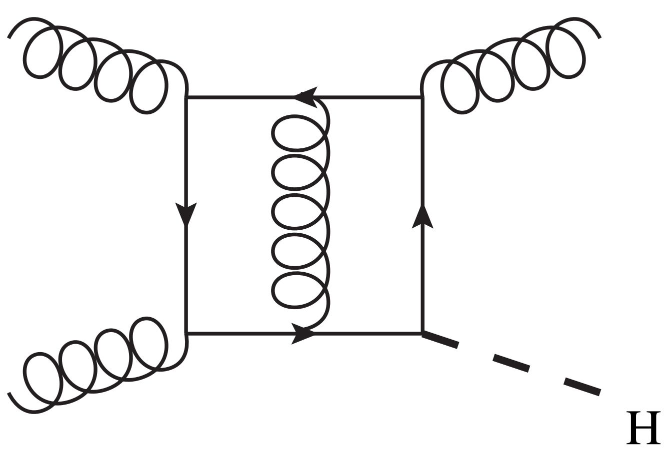
NNLO + N3LL resummation



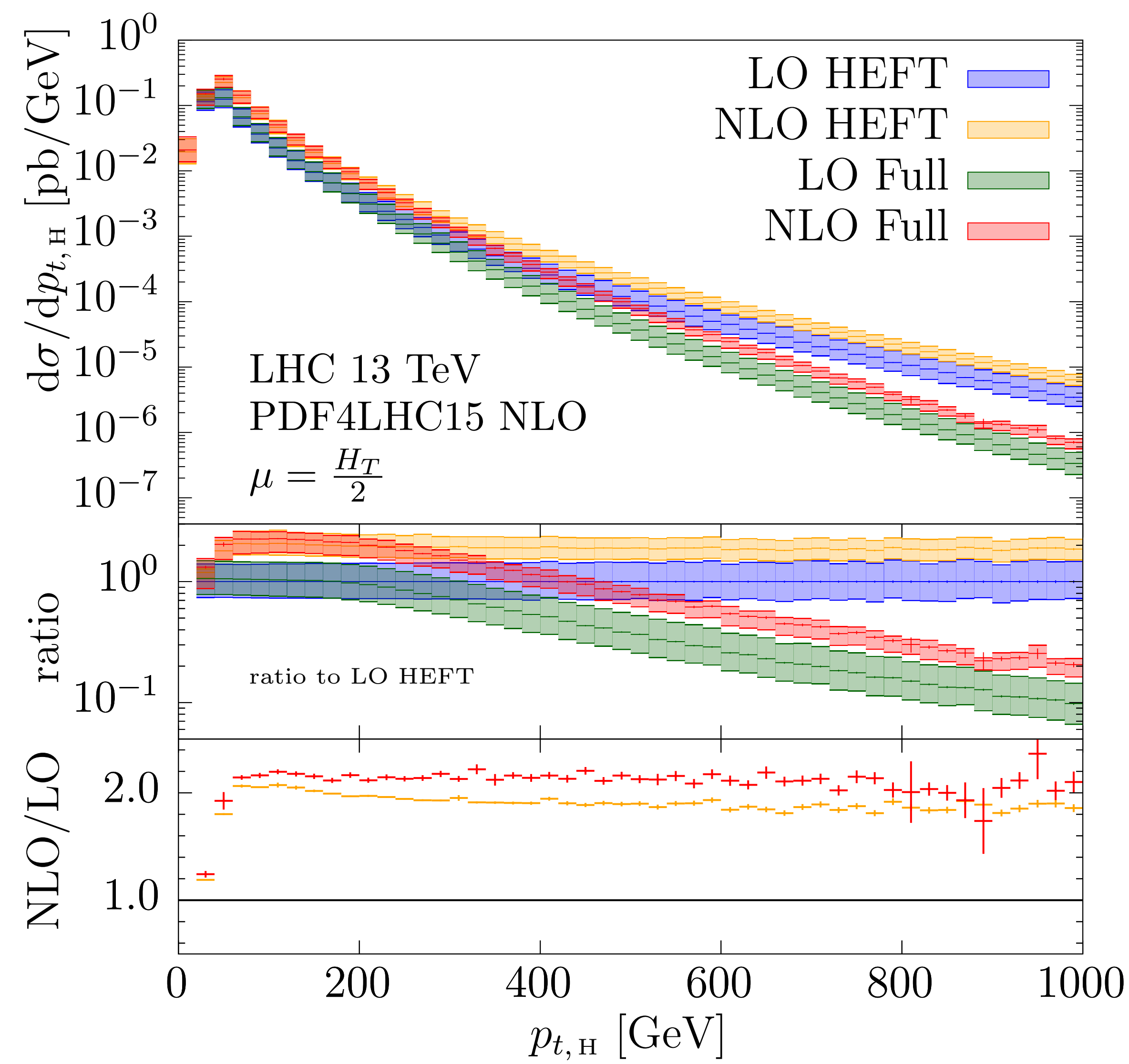
[Bizon et al '18]

TOP-QUARK CONTRIBUTION

Exact dependence on the top-mass [Jones, Kerner, Luisoni '18]



Virtual amplitudes can be computed numerically using **Sector Decomposition.** Using ***Finite basis of master integrals*** [von Manteuffel, Panzer, Schabinger '14]



- Top-mass effects increase NLO of ~9%.
- Different scaling HEFT vs Full Theory

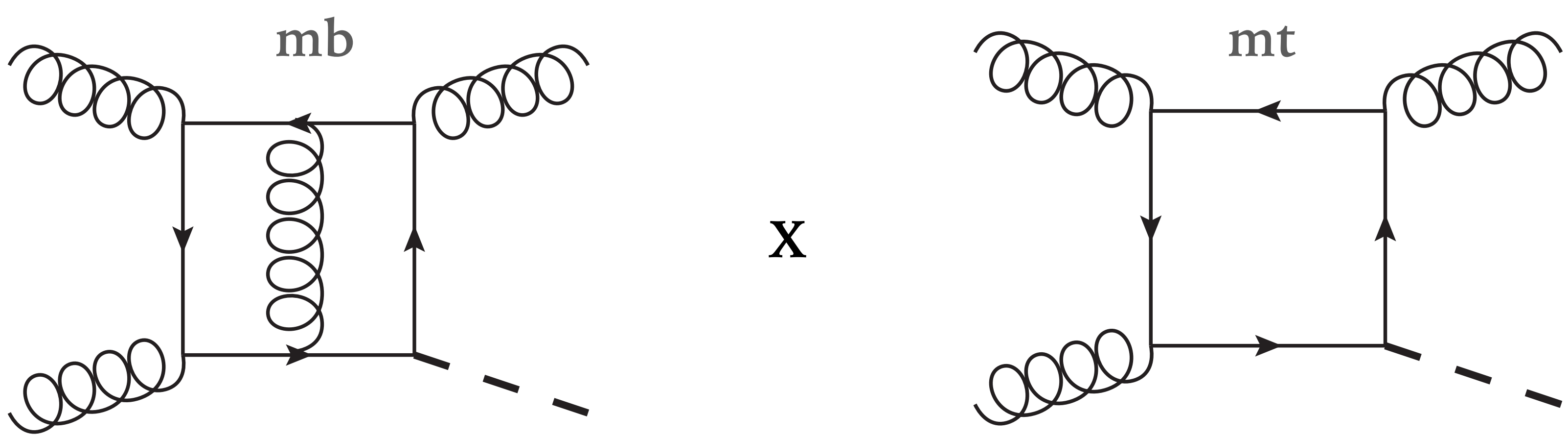
$$\frac{d\sigma}{dp_\perp^2} \sim p_\perp^{-2} \quad \text{HEFT}$$

$$\frac{d\sigma}{dp_\perp^2} \sim p_\perp^{-4} \quad \text{full theory}$$

- Nearly constant K factor @ NLO in full theory

EFFECT OF BOTTOM QUARKS ON THE HIGGS PT

Most important contribution is clearly the **interference with the top-induced** diagrams



$$A_{gg\to Hg} \sim \left\{ \frac{m_b^2}{m_H^2} \log^2\left(\frac{m_H^2}{m_b^2}\right), \frac{m_b^2}{m_H^2} \log^2\left(\frac{p_\perp^2}{m_b^2}\right) \right\}$$

$$m_H = 125\,\mathrm{GeV}$$

$$m_b \sim 4.7\,\mathrm{GeV}$$

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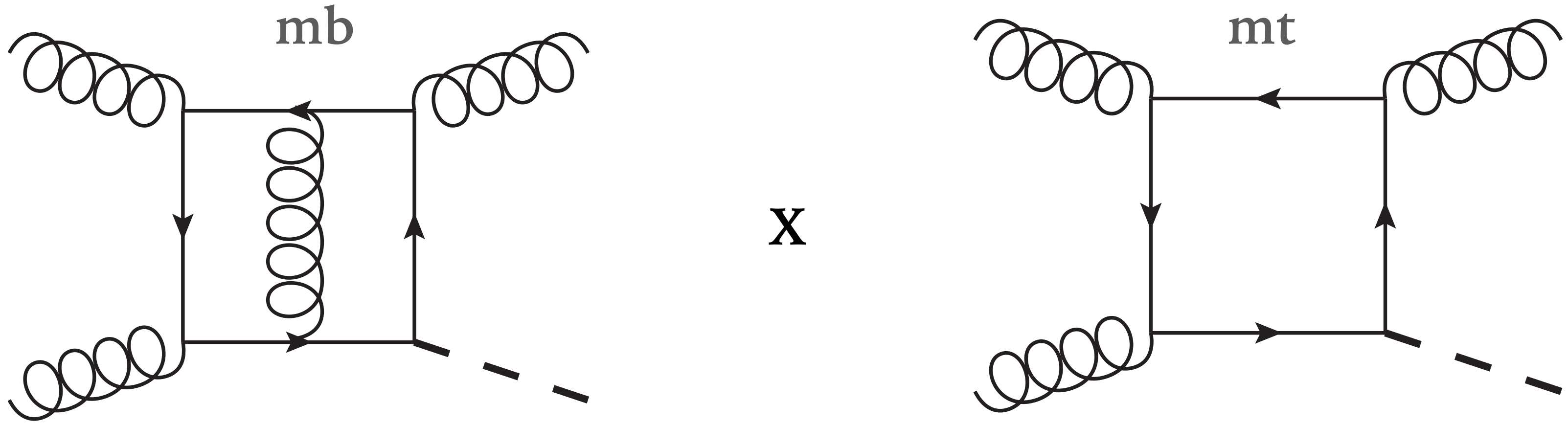

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$$m_H = 125\,\text{GeV}$$
$$m_b \sim 4.7\,\text{GeV}$$
$$p_\perp^{\text{typ}} \sim 30\,\text{GeV}$$

$$10^{-3} \times (\sim 6.5)^2 \sim 10^{-1}$$

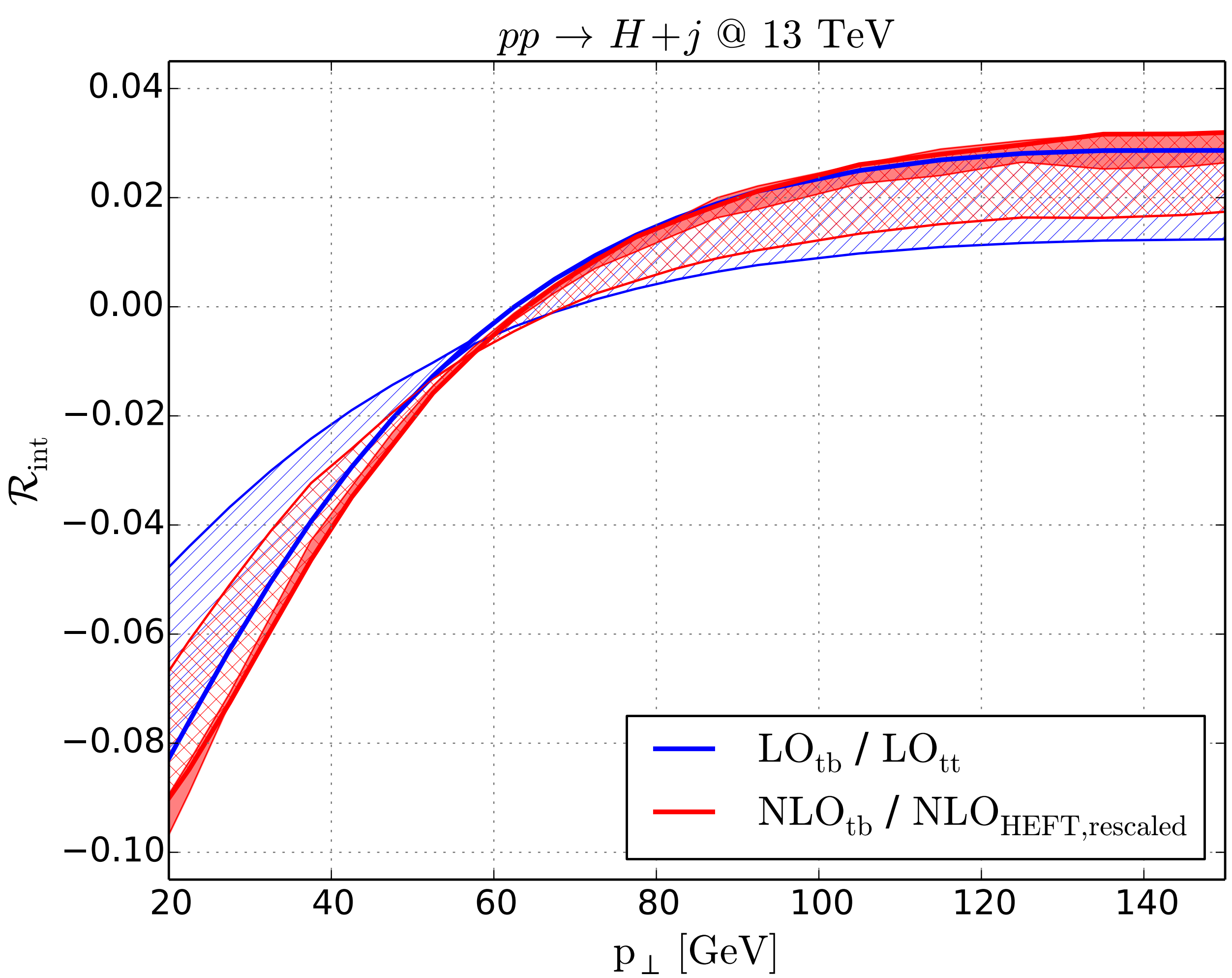
Potentially 10%!

RESULTS @ FIXED ORDER

Handling the **bottom-mass is delicate**. Being so small can also generate numerical instabilities!

$m_b \ll m_H, p_\perp^{\mathrm{typ}}$, where $p_\perp^{\mathrm{typ}} \sim 30$ GeV → Amplitudes can be evaluated by ***expanding in the small bottom mass***!

[Melnikov, Tancredi, Wever '16]



[Lindert, Melnikov, Tancredi, Wever '17]

At LO, **bottom quark affects Higgs** pT by

-8% at $p_\perp \sim 20$ GeV and $+2\%$ at $p_\perp \sim 100$ GeV

$$\mathcal{R}_{\mathrm{int}}\left[\mathcal{O}\right] = \frac{\int \mathrm{d}\sigma_{tb}\, \delta(\mathcal{O} - \mathcal{O}(\vec{x}))}{\int \mathrm{d}\sigma_{tt}\, \delta(\mathcal{O} - \mathcal{O}(\vec{x}))}$$

NLO gives sizable corrections on interference proper $\mathcal{O}(40-50\%)$

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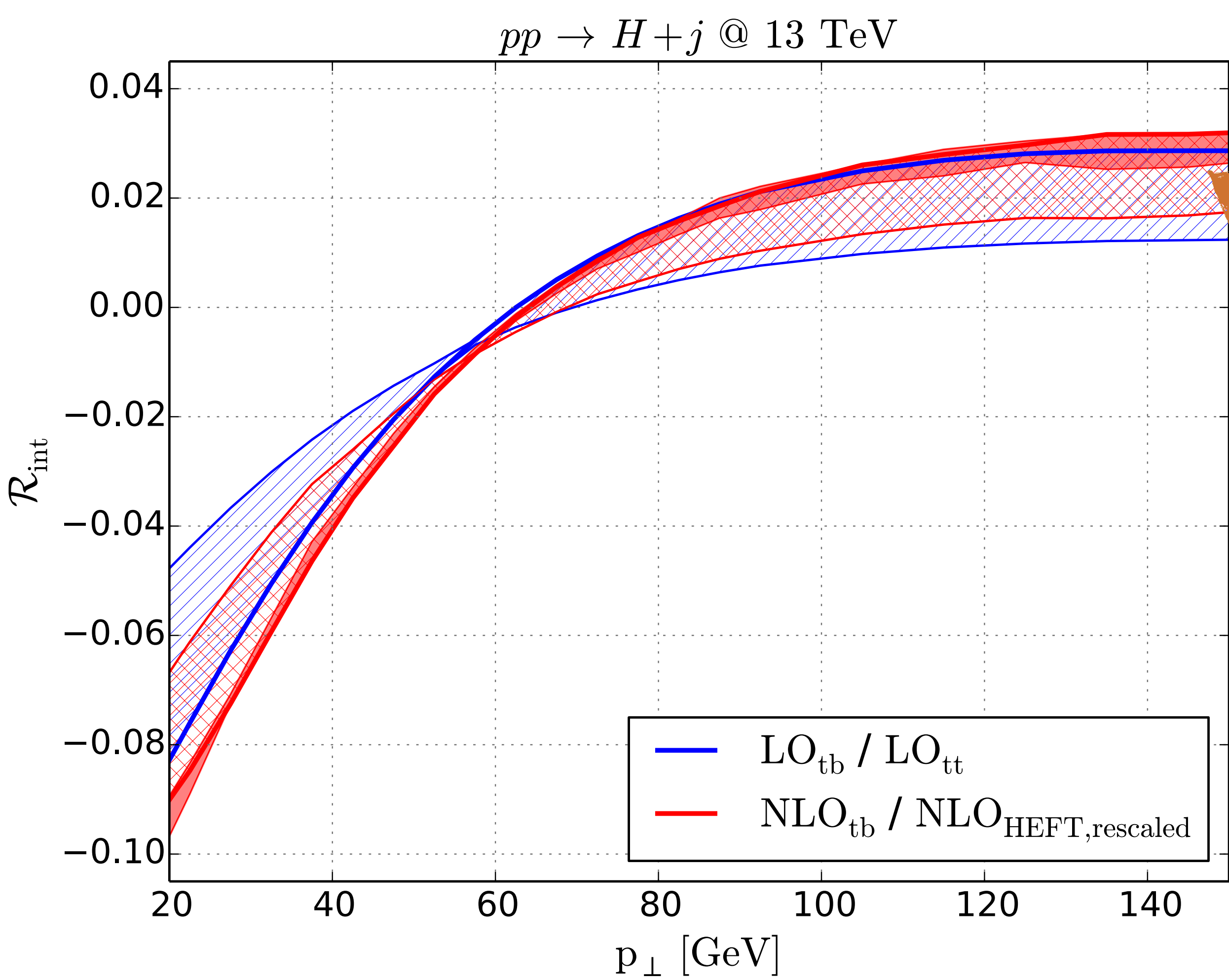

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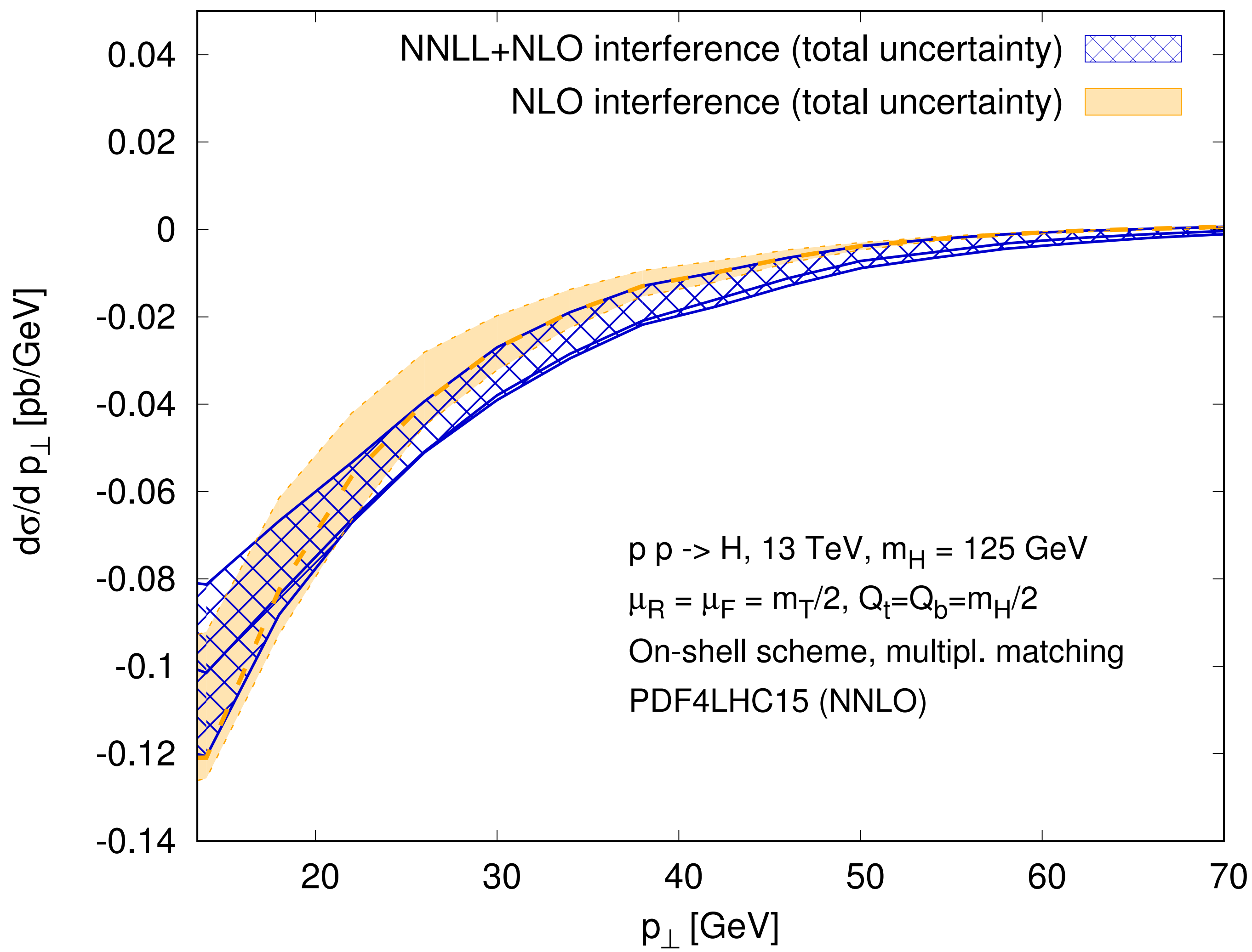
Scale variation
Vs
Mass renormalization ambiguity

$$m_b^{\overline{\text{MS}}}(100\ \text{GeV}) = 3.07\ \text{GeV}$$
$$m_b = 4.75\ \text{GeV}$$

THE HIGGS AT MEDIUM TRANSVERSE MOMENTA

Full control on the region of low/medium pT requires also resummation, at least of those logs that we can resum!



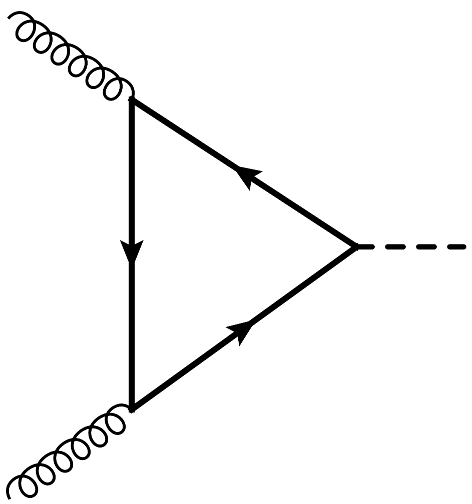
Main residual uncertainty remains due to **bottom mass renormalisation ambiguities:**

~ 10-15% down to pT ~ 10 GeV

[Caola, Lindert, Melnikov, Monni, Tancredi, Wever '18]

WHAT ABOUT THE OTHER LOGS?

Conceptually these new logarithms are troublesome!



$$\propto \ln^2(m_H^2/m_b^2)\frac{m_b^2}{m_H^2}$$

Means that, effectively, the expansion parameter becomes $\alpha_s \ln^2(m_H^2/m_b^2) \sim 40\alpha_s$

Requires LL resummation beyond leading power in QCD

Double logs induced by soft quark exchange! [Penin, '14; Liu, Penin '17, '18]

Used to estimate contribution from bottom quarks at NNLO -> 3 loops ~ -0.6 %!

[Liu, Penin '18]

CONCLUSIONS

- **The Higgs is NEW PHYSICS!**
- We have the chance to study the Higgs at the LHC with % precision, both inclusively and exclusively.
- This requires many contributions: top quarks, bottom quarks, QCD-EW corrections etc..
- Their calculation is very involved and requires going beyond the current machinery for higher order calculations
- Lately a lot of progress, not only in QCD! Still a lot to do from the more formal side.
- Theoretical description of Higgs physics under good control soon!

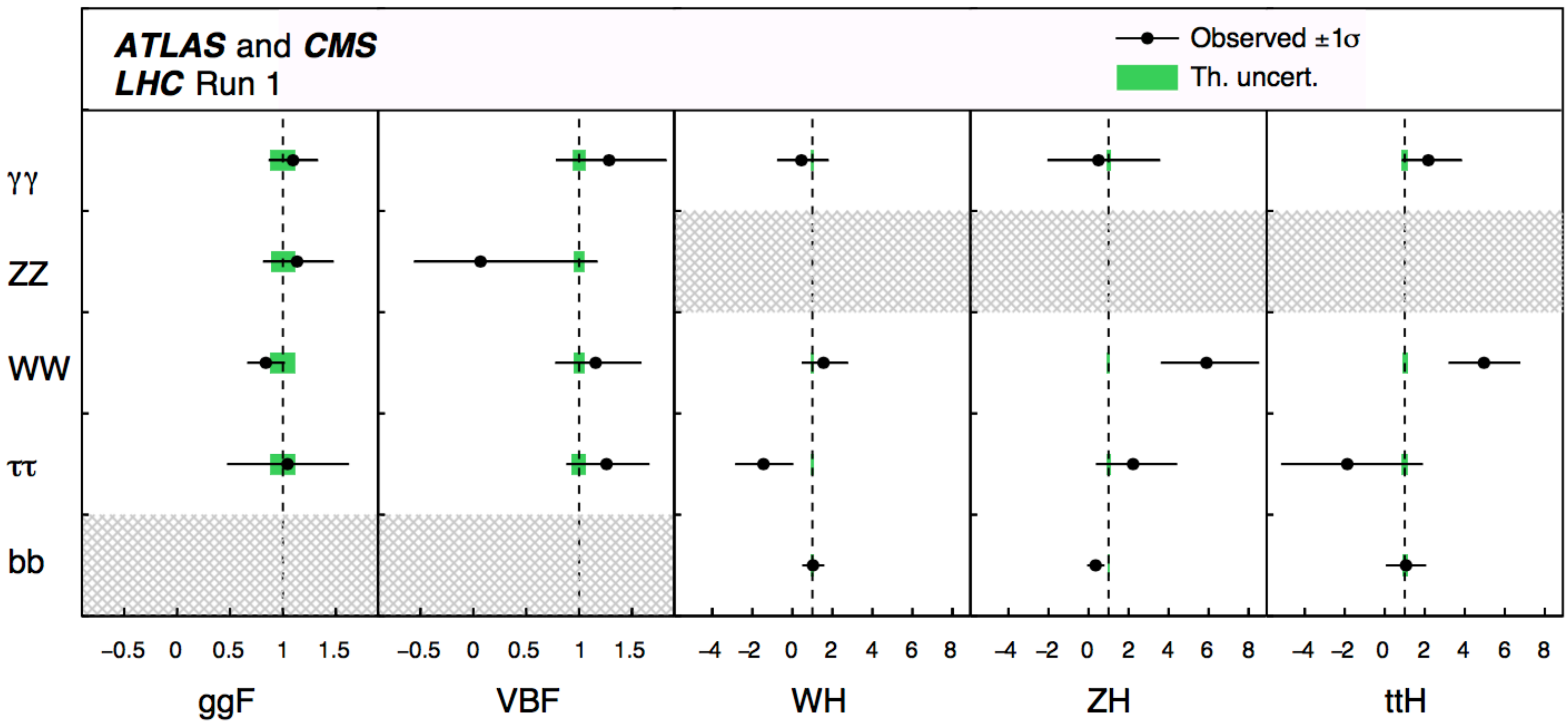
THANK YOU!

BACK UP SLIDES

HIGGS INCLUSIVE PRODUCTION

Can we describe **Higgs with % precision in the Standard Model, consistently with experiments?**

Inclusive Higgs Production



Theory looks pretty good! How did we get to such a good theory precision?