HIGGS CROSS SECTION AND BRANCHING RATIO CALCULATIONS

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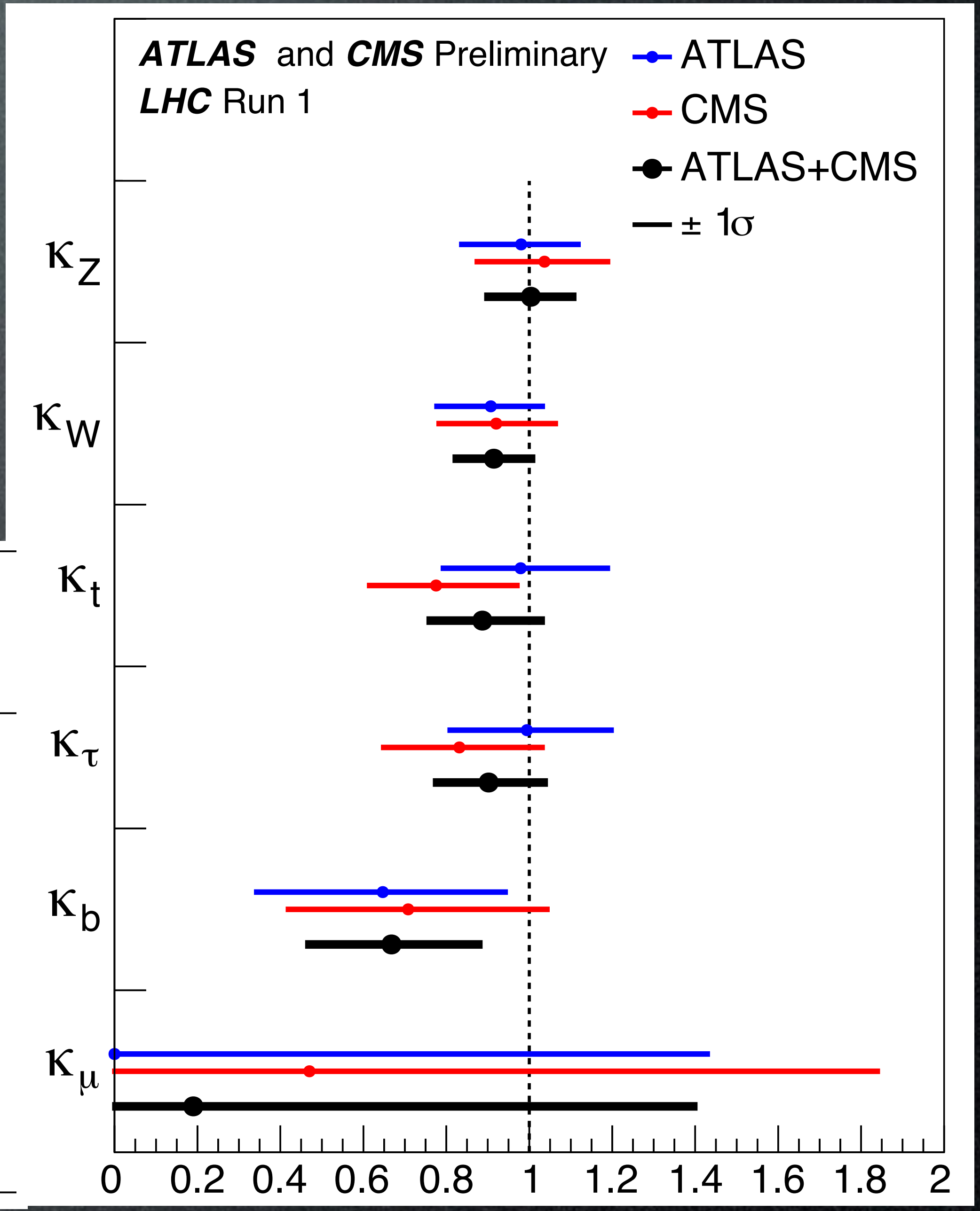
Standard Model at LHC 2016

Pittsburgh, May 3 - 6 2016

"Standard Model at the LHC"

- The next aim of the LHC is to test the Higgs sector
- but do we have "only" a Standard Model Higgs sector?
- so far, it looks pretty much like it..

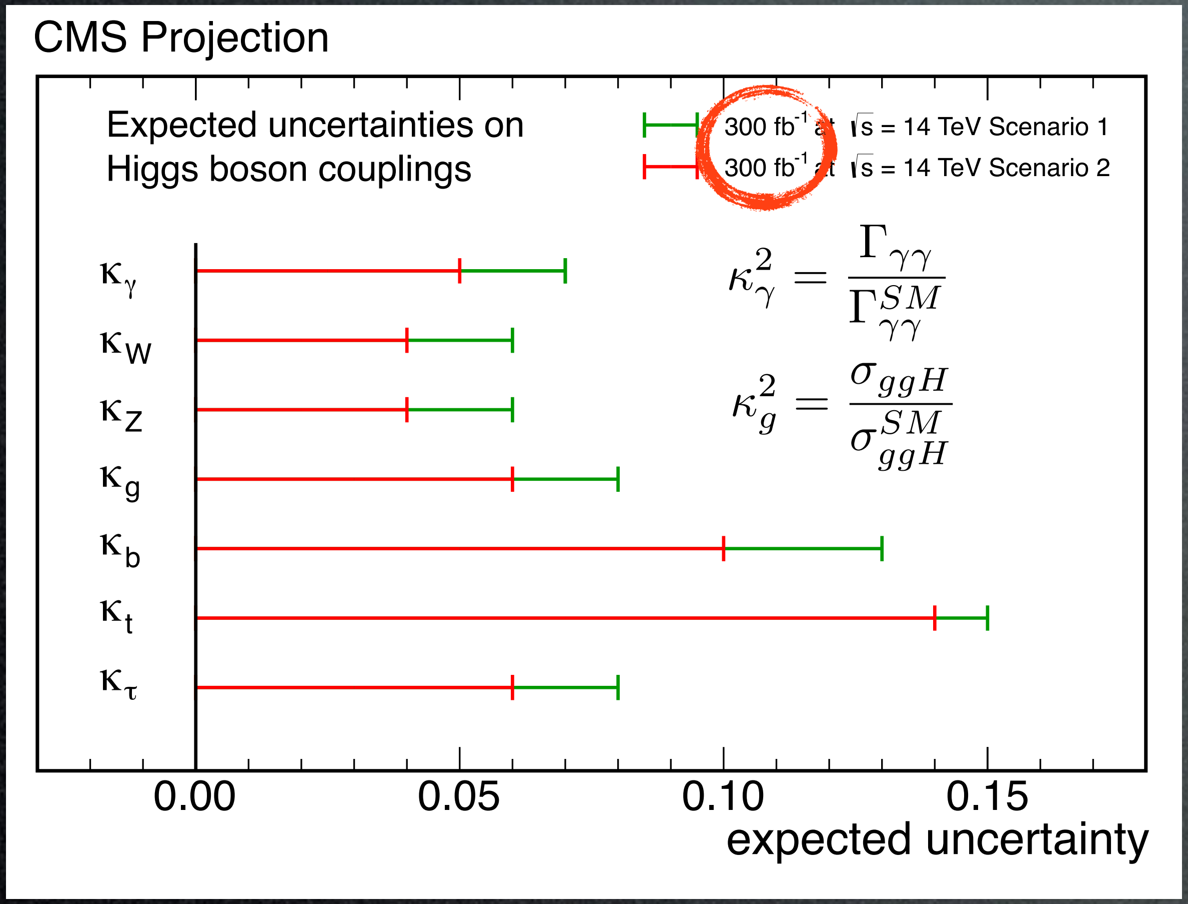
Parameter $\kappa_j \geq 0$	ATLAS+CMS Measured
κ_Z	$1.00^{+0.10}_{-0.11}$
κ_W	$0.91^{+0.09}_{-0.09}$
κ_t	$0.89^{+0.15}_{-0.13}$
κ_τ	$0.90^{+0.14}_{-0.13}$
κ_b	$0.67^{+0.22}_{-0.20}$
κ_μ	$0.2^{+1.2}_{-0.2}$

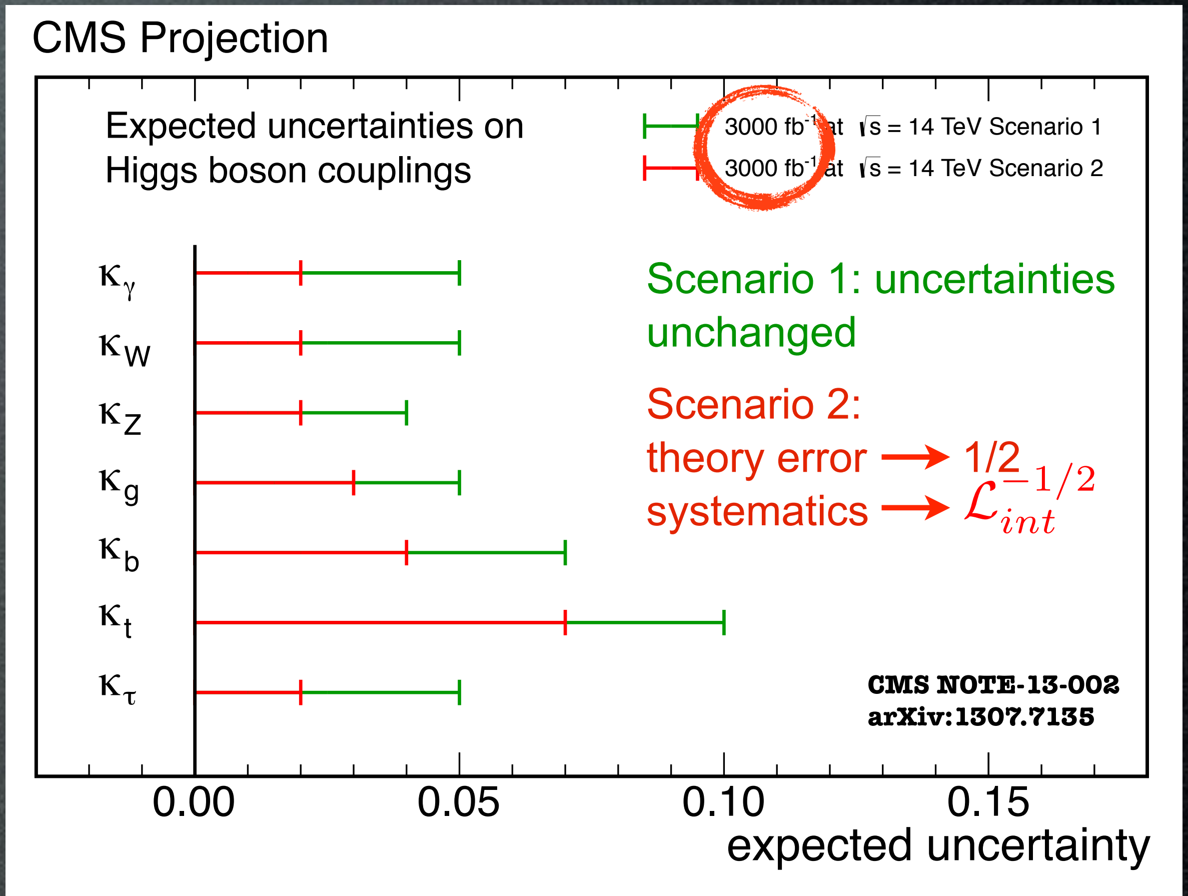


ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Precision Higgs physics

- uncertainties are still large ($\mathcal{O}$ (10%) or more)
- lot of room for improvement





Precision Higgs physics

- uncertainties are still large ($\mathcal{O}$ (10%) or more)
- lot of room for improvement
- precise measurements and (more) precise theory predictions are fundamental!

The theory error: decays

Situation in general well under control:

- theory error typically at the percent level

$H \to \gamma\gamma$	NLO QCD, NLO electroweak
$H \to \tau\tau, H \to b\bar{b}$	NLO electroweak

or lower

$H \to VV \to 4f$	NLO QCD and electroweak corrections, including final-state interference
$H \to b\bar{b}$	N^4LO QCD corrections (theory error $\mathcal{O}(0.1\%)$)

The theory error: decays

Exception:

$H \to Z\gamma$ electroweak corrections unknown, yielding a ~ 5% error

The theory error: decays

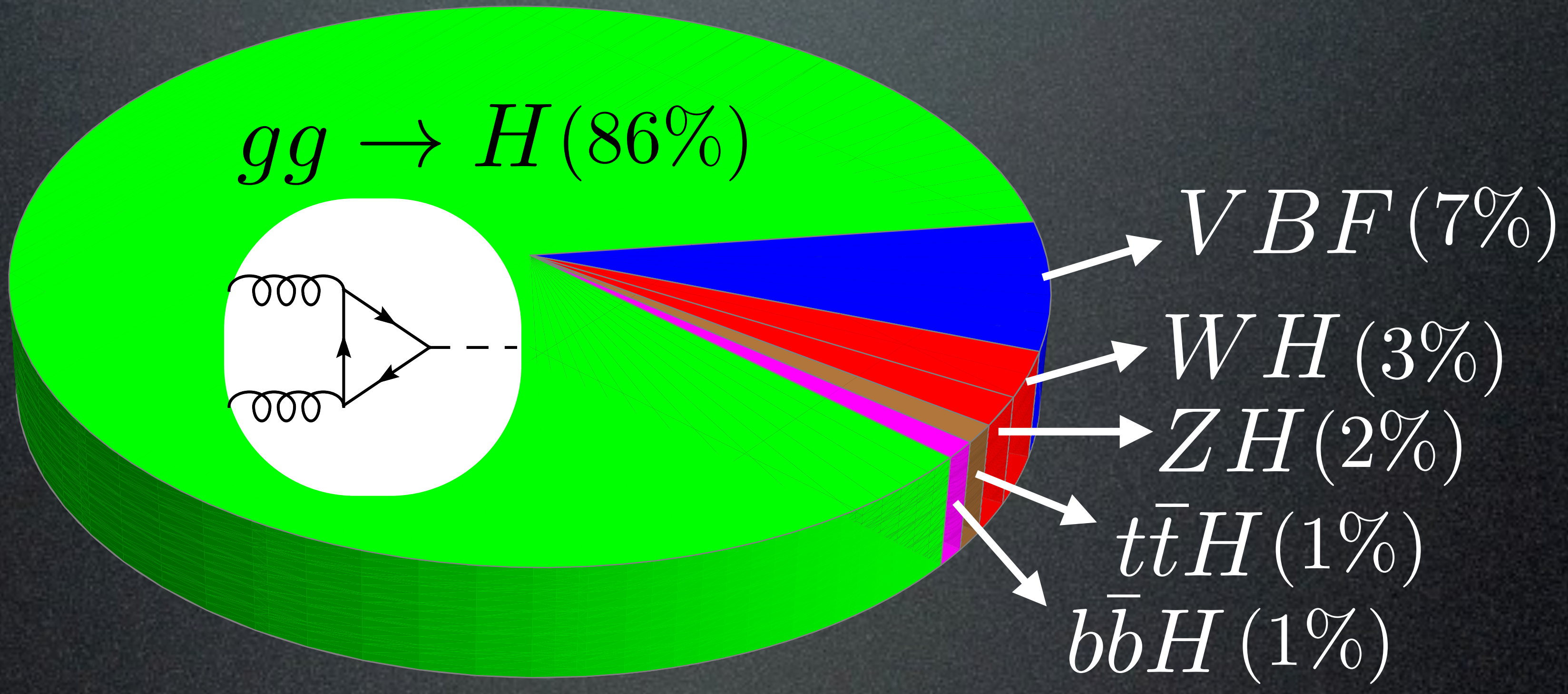
➡ uncertainty on the branching ratios well under control

Decay channel	BR	Theory uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	+1.73% -1.72%
$H \to ZZ$	2.62×10^{-2}	+0.99% -0.99%
$H \to WW$	2.14×10^{-1}	+0.99% -0.99%
$H \to \tau\tau$	6.27×10^{-2}	+1.17% -1.16%
$H \to b\bar{b}$	5.82×10^{-1}	+0.65% -0.65%
$H \to Z\gamma$	1.53×10^{-3}	+5.71% -5.71%
$H \to \mu\mu$	2.18×10^{-4}	+1.23% -1.23%

HXSWG, Update for CERN YR4, 2016

The theory error: production

- gluon fusion is the main Higgs production mechanism...



The theory error: production

- ... and therefore drives the current uncertainty in the extraction of the Higgs couplings

$\sqrt{s} = 13$ TeV	σ [pb]	$\delta\sigma^{theo}/\sigma$
ggH	44	+7.4% -7.9%
VBF	3.7	+0.7% -0.7%
WH	1.4	+0.7% -1.5%
ZH	0.87	+3.8% -3.8%
⋮	⋮	⋮

LHC Higgs cross section WG recommendations, 2014

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NNLO+NNLL QCD
NLO EW

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gluon channel: NLO QCD
others: NNLO QCD
NLO EW

LHC Higgs cross section WG recommendations, 2014

The theory error: production

- Very similar numbers in the preliminary Higgs cross section WG recommendations for 2016

- Difference: inclusion of partial NNLO QCD results and of NLL QCD resummation for the gluon-initiated ZH channel

Ferrera, Grazzini and Tramontano, PLB740 (2015) 51-55
Dawson, Han, Lai, Leibovich and Lewis, PRD86 (2012) 074007

➡ full NNLO available now

Campbell, Ellis and Williams, 1601.00658

- To be included: N^3LO QCD corrections to ggH!

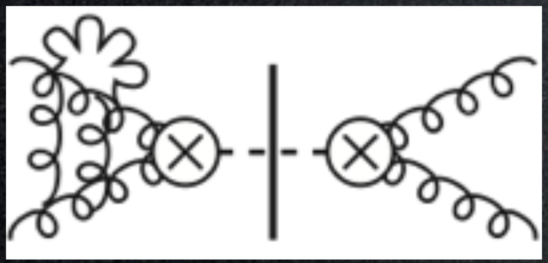
Anastasiou, Duhr, Dulat, EF, Gehrmann, Herzog, Lazopoulos and Mistlberger, arXiv:1602.00695

Higgs Production at N^3LO

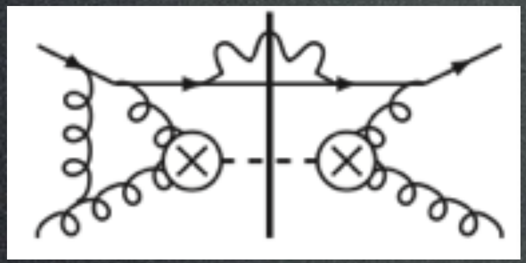
- At LO, gluon-fusion Higgs production is mediated by *one* loop of heavy quarks

    ➡ N^3LO ⟶ four loops! (~ 15000 diagrams)

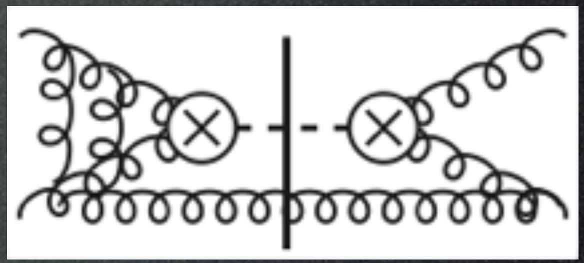
- huge number of contributions from "real" radiation (~100000 interference diagrams)



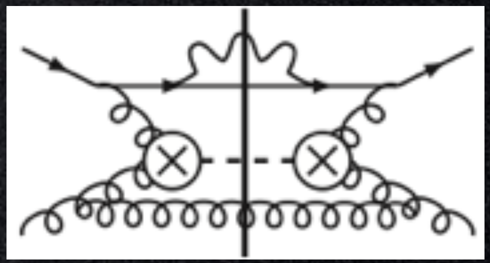
Baikov et al., Phys. Rev. Lett. 102, 212002 (2009); Gehrmann et al., JHEP 1006, 094 (2010)



Gehrmann et al., JHEP 1201, 056 (2012); Duhr et al., Phys. Lett. B 727, 452 (2013); Li et al., JHEP 1311, 080 (2013)



Anastasiou et al., JHEP 1312, 088 (2013); Kilgore, Phys. Rev. D 89 073008 (2014)



Anastasiou et al., JHEP 1307, 003 (2013)

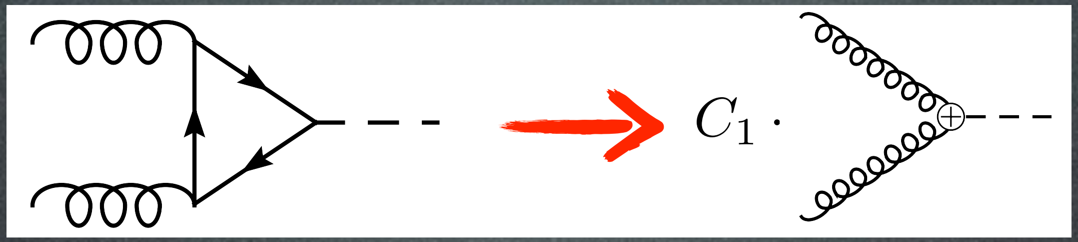
Higgs Production at N^3LO

"Ingredients"

- (rescaled) heavy-quark effective field theory

Heavy quark effective theory

- for a light Higgs boson, the top quark can be integrated out

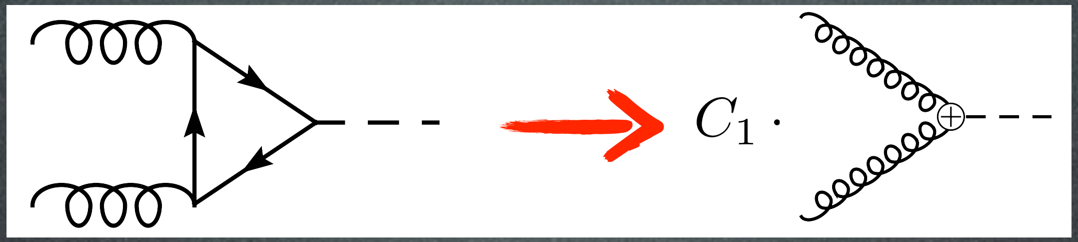


➡ construct an heavy quark effective theory

$$\mathcal{L} \to \mathcal{L}_{\text{light}} - \frac{\alpha_S}{4v} C_1\, H G^a_{\mu\nu} G^{a\mu\nu}$$

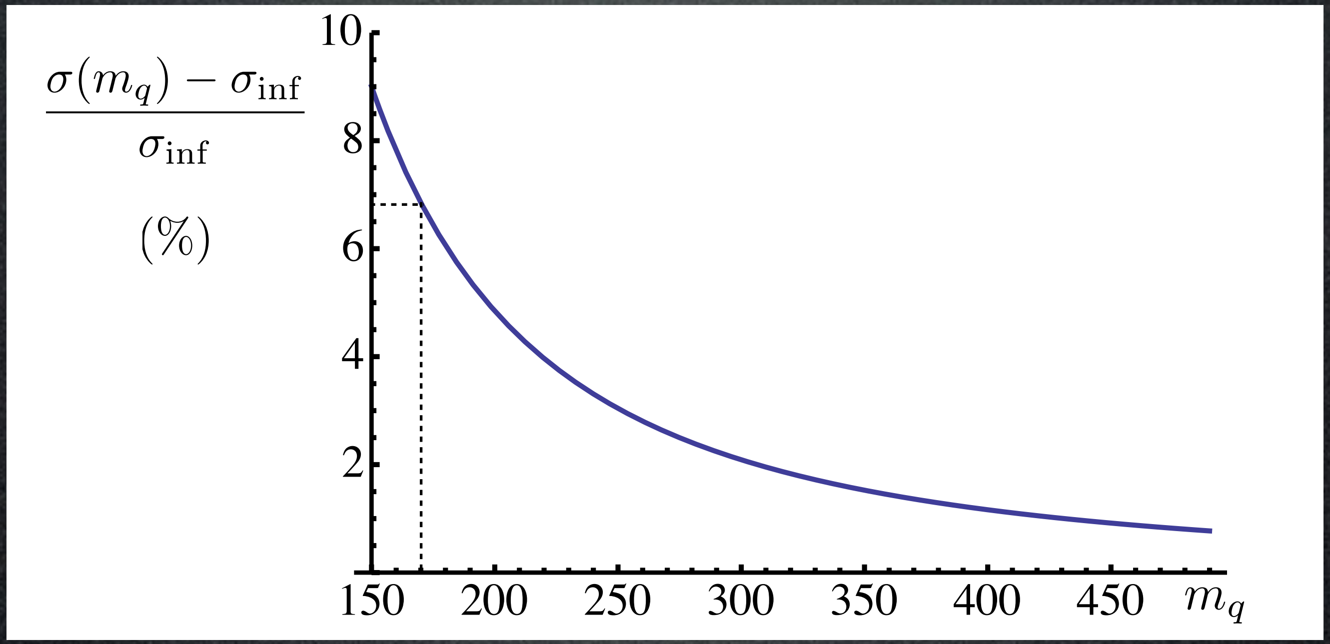
Heavy quark effective theory

- for a light Higgs boson, the top quark can be integrated out



➡ construct an heavy quark effective theory

➡ "pretty good" approximation



“Refinement”

- “rescale” heavy-quark effective theory by the correct LO through N^3LO

$$\sigma_{rEFT}^{N^xLO} = R_{LO} \times \sigma_{EFT}^{N^xLO}$$
$$R_{LO} = \frac{\sigma_{exact}^{LO}}{\sigma_{EFT}^{LO}}$$

- at NLO reduces the discrepancy from the exact result from 5% to 0.7% !

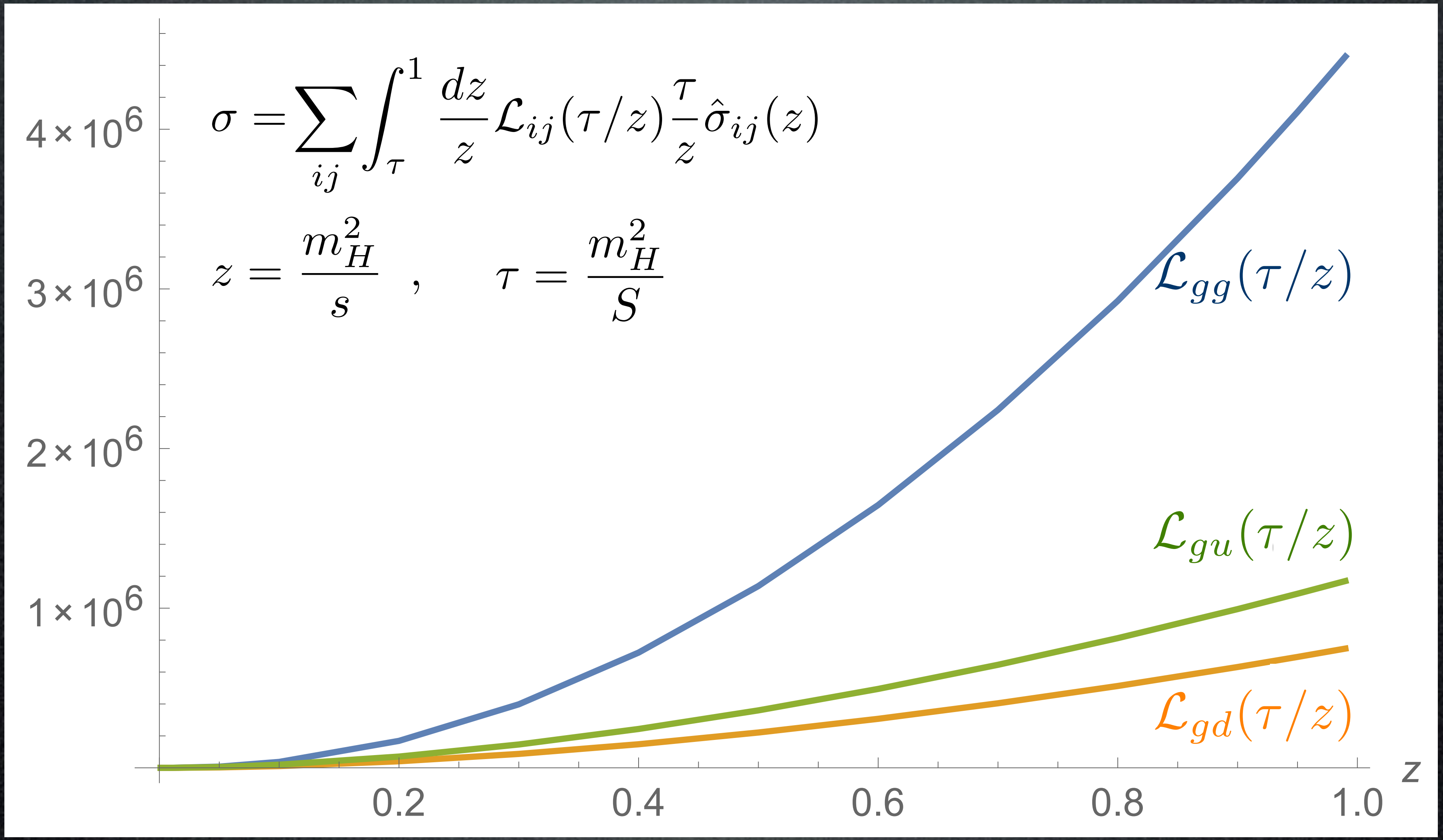
Higgs Production at N^3LO

"Ingredients"

- (rescaled) heavy-quark effective field theory
- Higgs threshold expansion

Threshold expansion

- The largest contribution comes from the Higgs threshold region



Threshold expansion

- The largest contribution comes from the Higgs threshold region

➡ compute the cross section as an expansion around threshold

$$\hat{\sigma}^{N^3LO}(z) = \hat{\sigma}_{SV} + \sum_{n=0}^{N_{trunc}} \sigma^{(n)}(1-z)^n$$

$(N_{trunc} = 37)$

C. Anastasiou et al., PRL 114 (2015) 212001

Higgs Production at N^3LO

"Ingredients"

- (rescaled) heavy-quark effective field theory
- Higgs threshold expansion
- full quark-mass effects (from top, bottom, charm) through NLO
- 2-loop EW, 3-loop mixed QCD-EW corrections
- convolution with parton distribution functions
- uncertainties (scale, pdf, α_s, missing contributions, approximations)

Uncertainties

- due to the approximations introduced, missing contributions, PDFs, uncertainties on the input parameters

$\delta(\text{PDF})$	$\delta(\alpha_s)$	$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(tbc)$	$\delta(1/m_t)$	
± 0.90	$^{+1.27}_{-1.25}$	$^{+0.10}_{-1.15}$	± 0.18	± 0.56	± 0.49	± 0.40	± 0.49	pb
± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.83	± 1	%

in quadrature

linearly

Uncertainties

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± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.85	$\pm$ [illegible]	%

"traditionally neglected"

in quadrature

linearly

(the scale variation error at NNLO is so large that they are not relevant)

Uncertainties

- due to the approximations introduced, missing contributions, PDFs, uncertainties on the input parameters

$\delta(\text{PDF})$	$\delta(\alpha_s)$	$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(tbc)$	$\delta(1/m_t)$	
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± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.83	± 1	%

can be improved/eliminated

The N^3LO cross section

The N^3LO Higgs boson production cross section and the associated errors are

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

or, with the "traditional" errors,

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+1.73\%)}_{-3.27\,\text{pb}\,(-3.90\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

New HXSWG recommendations*

$\sqrt{s} = 13$ TeV	σ [pb]	$\delta\sigma^{theo}/\sigma$
ggH	44	+7.6% -8.1%
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WH	1.4	+0.5% -0.7%
ZH	0.88	+3.8% -3.1%
⋮	⋮	⋮

+4.7%
-6.7%

* the N^3LO gluon-fusion result is currently under discussion

Summary

- The theory error on the Higgs branching ratios is well under control, typically at the level of a few percent

- On the production, there has been a reduction on the gluon-fusion uncertainty by a 60-80% due to the inclusion of the N^3LO corrections

  ➡ could be reduced to 20-50% of the current (preliminary) HXSWG recommendations!

- Other production channels well under control

Higgs decay calculations

Available results:

$H \to \gamma\gamma$

- full NLO QCD corrections (theory error ~ 1%)

Zheng and Wu, PRD42, 3760 (1990); Djouadi et al., PLB257, 187 (1991); Dawson and Kauffman, PRD47, 1264 (1993); Djouadi, Spira, and Zerwas, PLB311, 255 (1993); Melnikov and Yakovlev, PLB312, 179 (1993); Inoue et al., Mod. Phys. Lett. A9, 1189 (1994), Spira et al., Nucl. Phys. B453, 17 (1995)

- NLO electroweak corrections (theory error ~ 1%)

Aglietti et al., PLB595, 432 (2004); Degrassi and Maltoni, PLB600, 255 (2004); Actis et al., PLB670, 12 (2008), PLB600, 57 (2004); Degrassi and Maltoni, Nucl. Phys. B724, 183 (2005); Aglietti et al., arXiv:hep-ph/0612172 (2006)

Higgs decay calculations

Available results:

$H \to VV \to 4f$

- full NLO QCD and electroweak corrections, including final-state interference (theory error below percent level)

Bredenstein, Denner, Dittmaier and Weber, PRD 74 (2006) 013004 and JHEP 0702 (2007) 080

Higgs decay calculations

Available results:

$H \to b\bar{b}$

- N^{4}LO QCD corrections (theory error ~ 0.1%!)

Gorishnii, Kataev, Larin, and Surguladze, Mod. Phys. Lett. A5 (1990) and PRD43 (1991) 1633-1640; Kataev and Kim, Mod. Phys. Lett. A9 (1994) 1309-1326; Surguladze, PLB341 (1994) 60-72, arXiv:hep-ph/9405325; Larin, van Ritbergen, and Vermaseren, PLB362 (1995) 134-140; Chetyrkin and Kwiatkowski, NPB461 (1996) 3-18; Chetyrkin, PLB390 (1997) 309-317; Baikov, Chetyrkin, and Kuhn, PRL 96 (2006).

$H \to \tau\tau, H \to b\bar{b}$

- NLO electroweak corrections (theory error around 1%)

Fleischer and Jegerlehner, PRD23 (1981) 2001-2026; Bardin, Vilensky, and Khristova, Sov. J. Nucl. Phys. 53 (1991) 152-158; Dabelstein and Hollik, Z. Phys. C53 (1992) 507-516; Kniehl, NPB376 (1992) 3-28.