Current status of the theory predictions for the Higgs inclusive cross section

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Instituto de Física Teórica UAM-CSIC

IFT Seminar Series

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Why the Higgs?

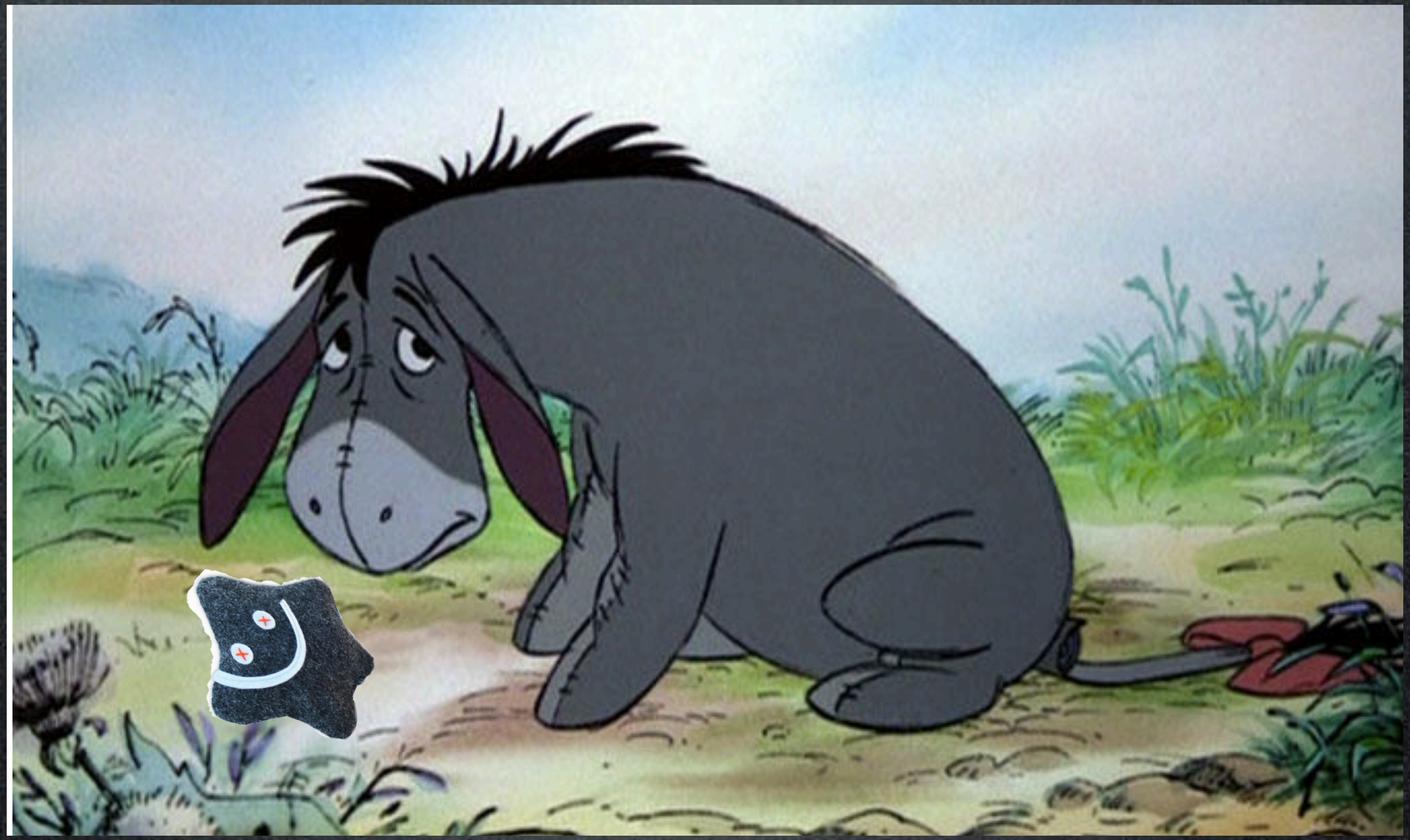
- The Standard Model describes the properties and interactions of the fundamental constituents of all visible matter
- It is an highly predictive theory that has been validated by a huge number of collider experiments
- The Higgs boson is essential for the self-consistency of the Standard Model!

Why (still) the Higgs?

- Its discovery, after decades of searches, brought great excitement…

Why (still) the Higgs?

- Its discovery, after decades of searches, brought great excitement...
  ... followed by a bit of blues..

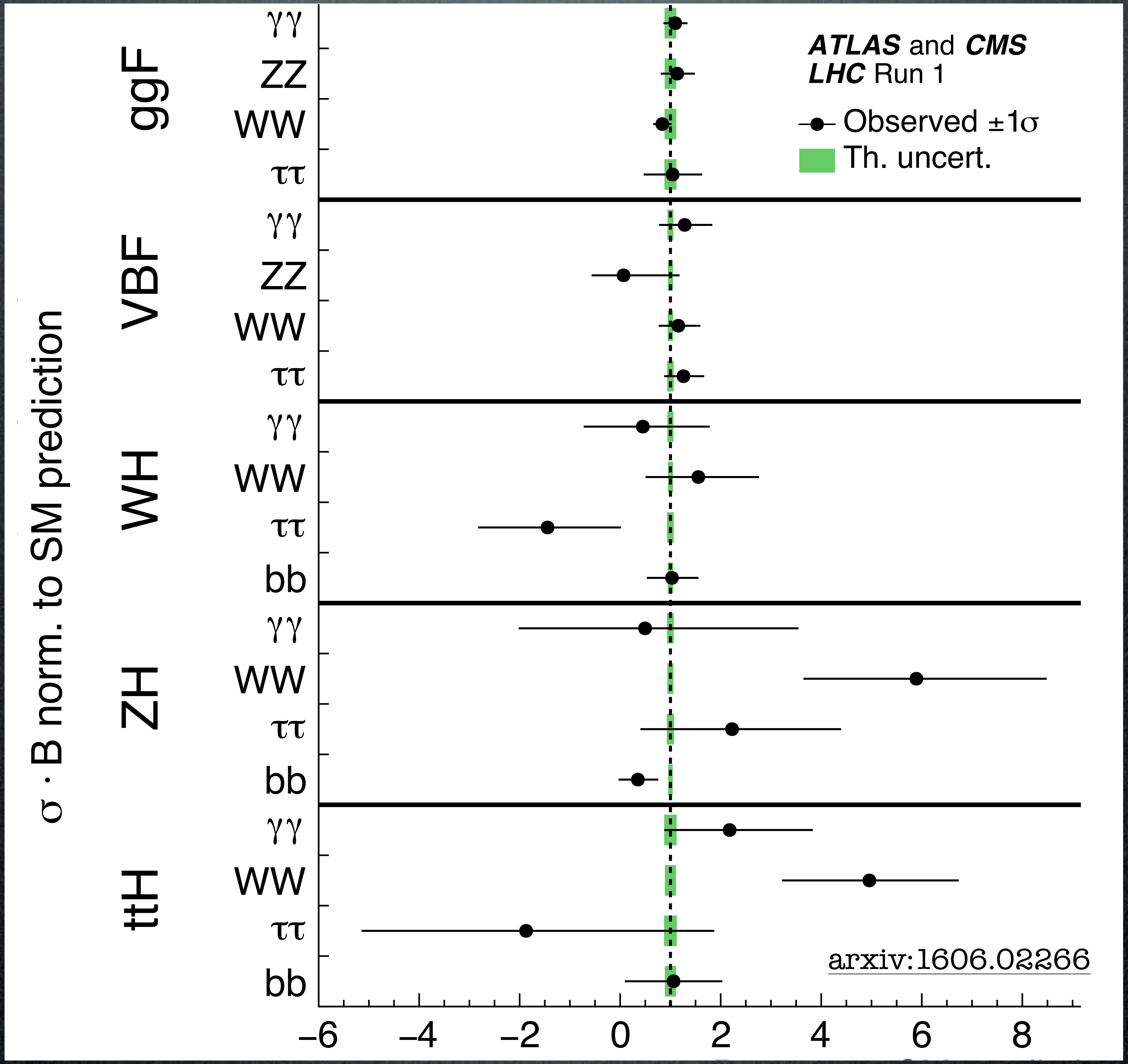


Too predictable?!?

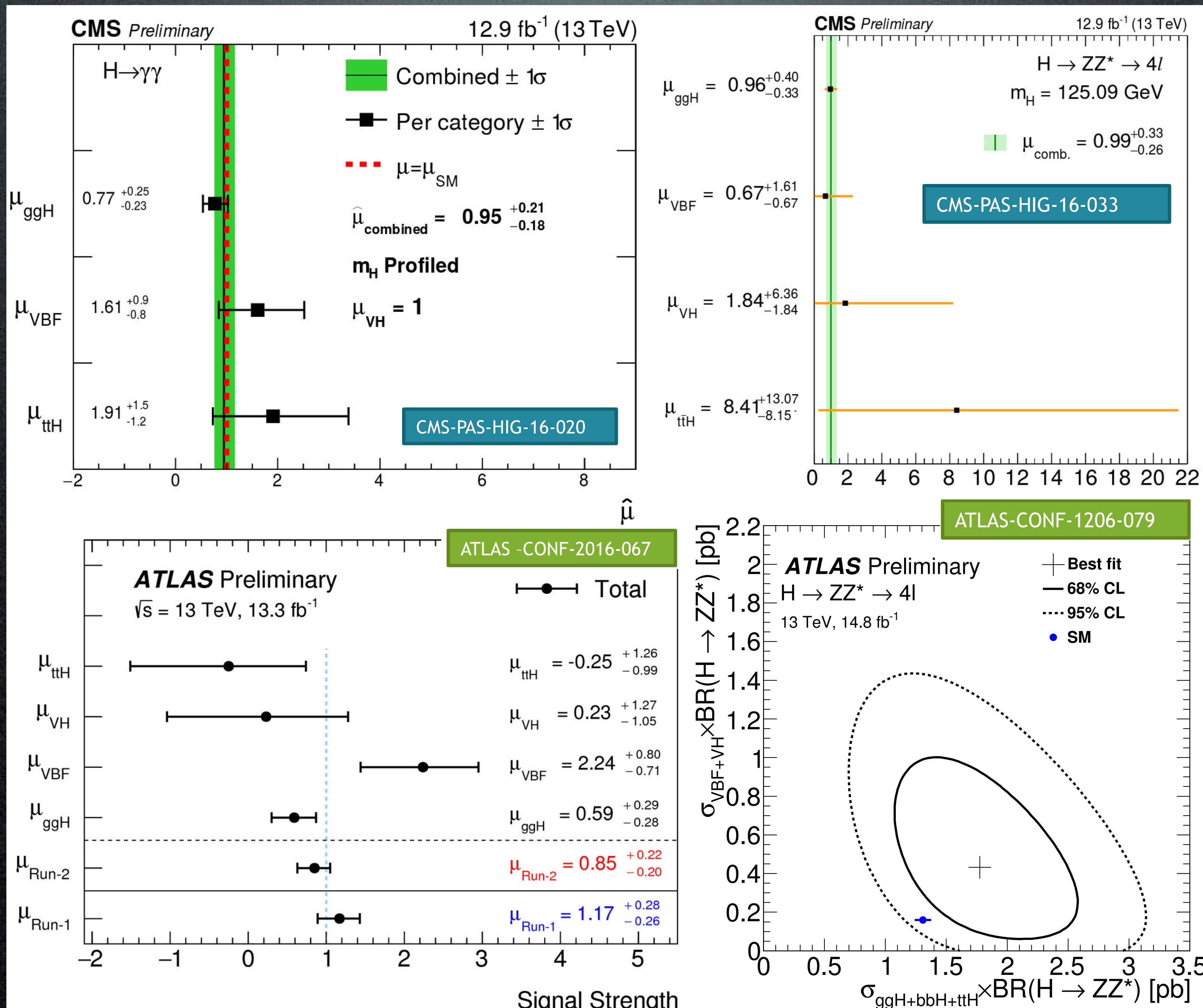
... this Higgs boson looks too “simple”!

- In the “minimal” description of electroweak symmetry breaking, all the couplings of the Higgs are strictly fixed
    - ➡ once its mass is known, all the properties of the Higgs boson (production cross sections, decay rates,..) can be predicted

Too predictable?!?



Too predictable?!?



(see also [summary talk](#) of F. Canelli at ICHEP 2016)

So, what is the problem?

- Many observed phenomena (neutrino mass, dark matter, fermion mass hierarchy, inflation, ..) are not described by the Standard Model
  - can they be related to the origin of electroweak symmetry breaking? Can they affect Higgs physics?
- The Higgs boson is “unnaturally” light
  - how does the electroweak scale emerge? Is the Higgs sector more complicated than in the Standard Model (new particles/interactions)?

Precision Higgs physics

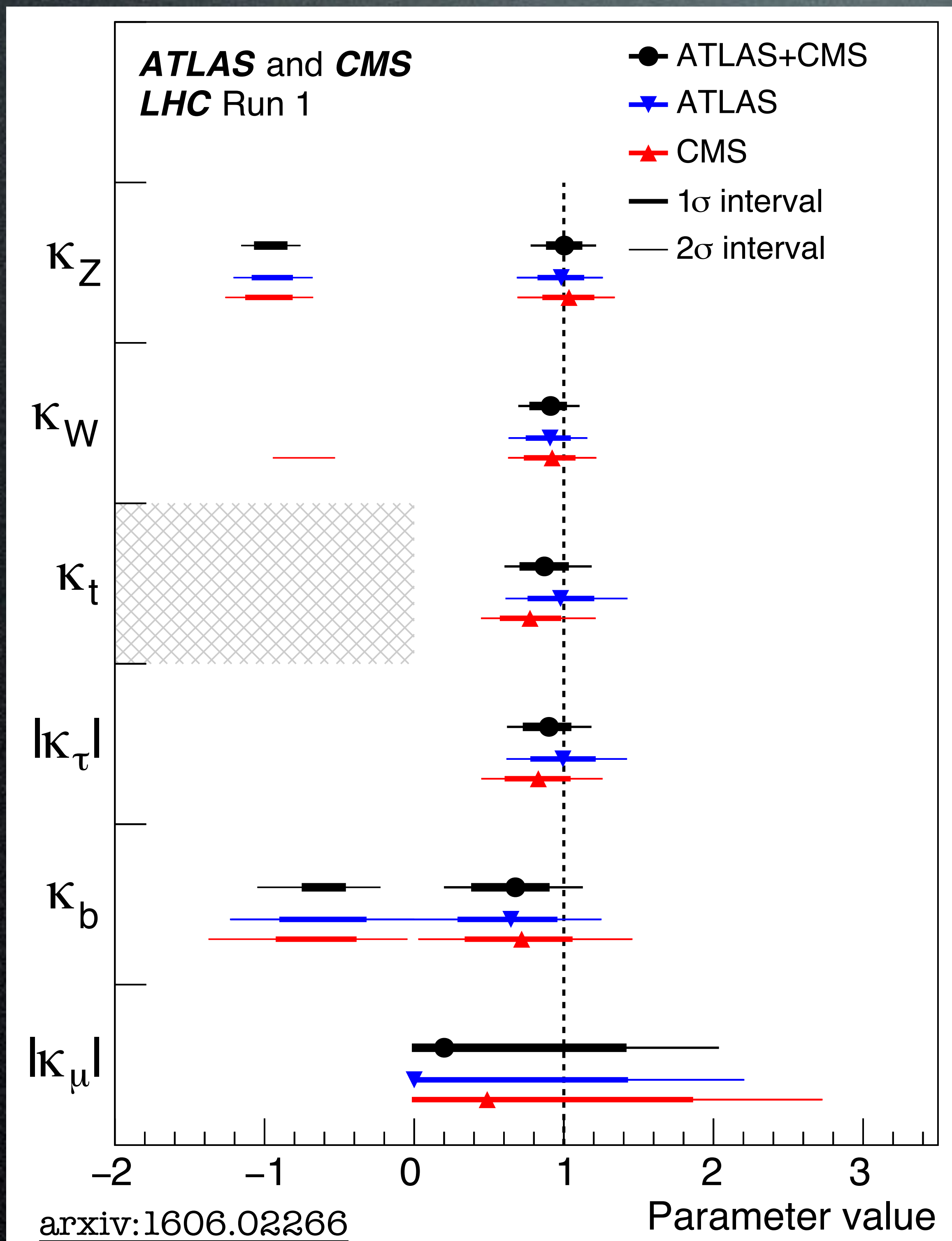
- Several scenarios of “physics beyond the Standard Model” try to address these questions
- They typically predict modifications in the Higgs phenomenology (new decay modes, modification of the couplings,..)
- These effects can be rather small ($\mathcal{O}(\mathrm{few}\%)$)

Precision Higgs physics

➡ to validate the Standard Model (or see hints of new physics) we need

- very accurate measurements of the properties of the Higgs boson ..

Precision Higgs physics



Parameter	ATLAS+CMS Measured
κ_Z	$[-1.08, -0.88] \cup [0.94, 1.13]$
κ_W	0.87 [0.78, 1.00]
κ_t	$1.40^{+0.24}_{-0.21}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$

Precision Higgs physics

➡ to validate the Standard Model (or see hints of new physics) we need

- very accurate measurements of the properties of the Higgs boson ..
- .. and equally accurate theoretical predictions of these properties:
  the precision in the extraction of the Higgs couplings will soon be limited by the uncertainty in the theory predictions!

Precision Higgs physics

- How can we improve our theory predictions?
  - ➡ which are the largest sources of error in the theory result?
  - ➡ what are the status and the prospects for improving it?

The theory error

- on the branching ratios: under control

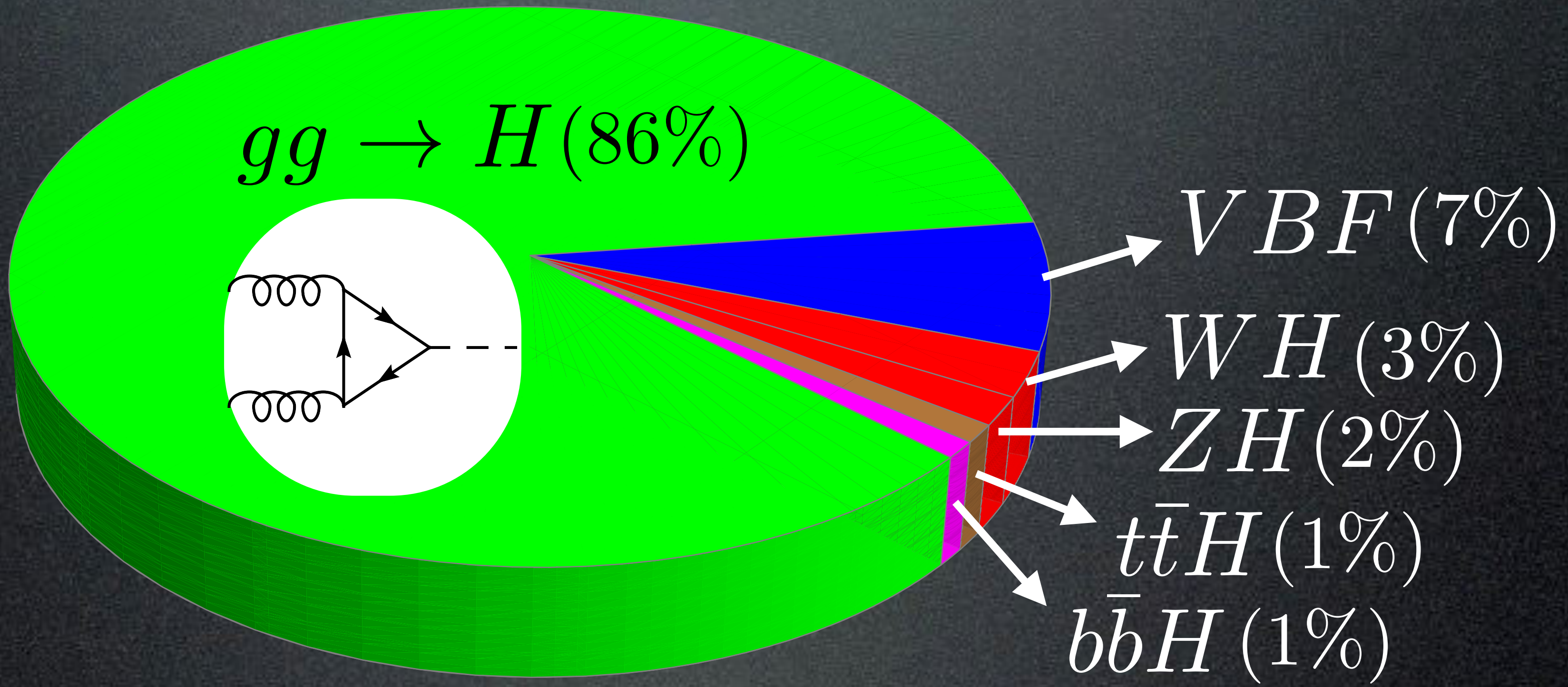
Decay channel	Branching ratio	TU [%]	PU(m_q) [%]	PU(α_s) [%]
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+1.73}_{-1.72}$	$^{+0.93}_{-0.99}$	$^{+0.61}_{-0.62}$
$H \to ZZ$	2.62×10^{-2}	$^{+0.99}_{-0.99}$	$^{+0.99}_{-0.98}$	$^{+0.66}_{-0.63}$
$H \to WW$	2.14×10^{-1}	$^{+0.99}_{-0.99}$	$^{+0.99}_{-0.98}$	$^{+0.66}_{-0.63}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+1.17}_{-1.16}$	$^{+0.98}_{-0.99}$	$^{+0.62}_{-0.62}$
$H \to b\bar{b}$	5.82×10^{-1}	$^{+0.65}_{-0.65}$	$^{+0.72}_{-0.74}$	$^{+0.78}_{-0.80}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+5.71}_{-5.71}$	$^{+0.98}_{-1.01}$	$^{+0.58}_{-0.65}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+1.23}_{-1.23}$	$^{+0.97}_{-0.99}$	$^{+0.59}_{-0.64}$

$m_H = 125$ GeV

De Florian et al., Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, arXiv:1610.07922

The theory error

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



The theory error

- on the production:
  ... and is the channel with the largest theory uncertainty (as of at the end of Run I)

$\sqrt{s}=13$ 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%
$\vdots$	$\vdots$	$\vdots$

LHC Higgs cross section
WG recommendations, 2014

The theory error

- the error on the gluon-fusion cross section dominates the theory uncertainty
- but achieving this level of precision was already extremely hard!

The theory error

➡ the error on the gluon-fusion cross section dominates the theory uncertainty

➡ but achieving this level of precision was already extremely hard!

1978 **LO** $\hat{\sigma}^{8TeV} = 9.6pb \pm 25\%$

Georgi et al, Higgs bosons from two gluon annihilation in proton proton collisions,

1991 **NLO** $\hat{\sigma}^{8TeV} = 16.7pb \pm 20\%$

Dawson; Djouadi, Spira, Zerwas; Graudenz, Spira, Zerwas; Spira, Djouadi, Graudenz, Zerwas

2002 **NNLO** $\hat{\sigma}^{8TeV} = 19.6pb \pm 9\%$

Harlander, Kilgore; Anastasiou, Melnikov

The theory error

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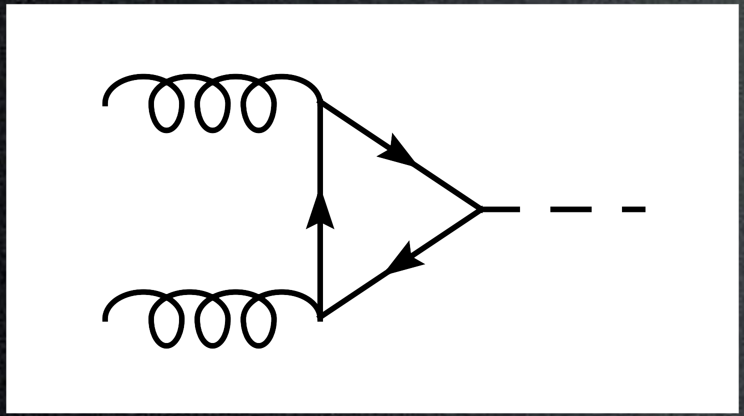


leading (lowest) order, “LO”
➜ already one loop
➜ largest contribution from top quark → massive particle
➜ two external momenta

The theory error

- for Run II, it is necessary to know the gluon-fusion Higgs cross section at N^3LO in QCD..
- .. and to include all other contributions beyond pure QCD that change the result by an $\mathcal{O}(5\%)$

Higgs Production at N^3LO

Tools

- heavy-quark effective field theory (EFT)
- threshold expansion
- inverse unitarity
- integration by part identities (IBPs)
- expansion by regions
- differential equation methods
- ...

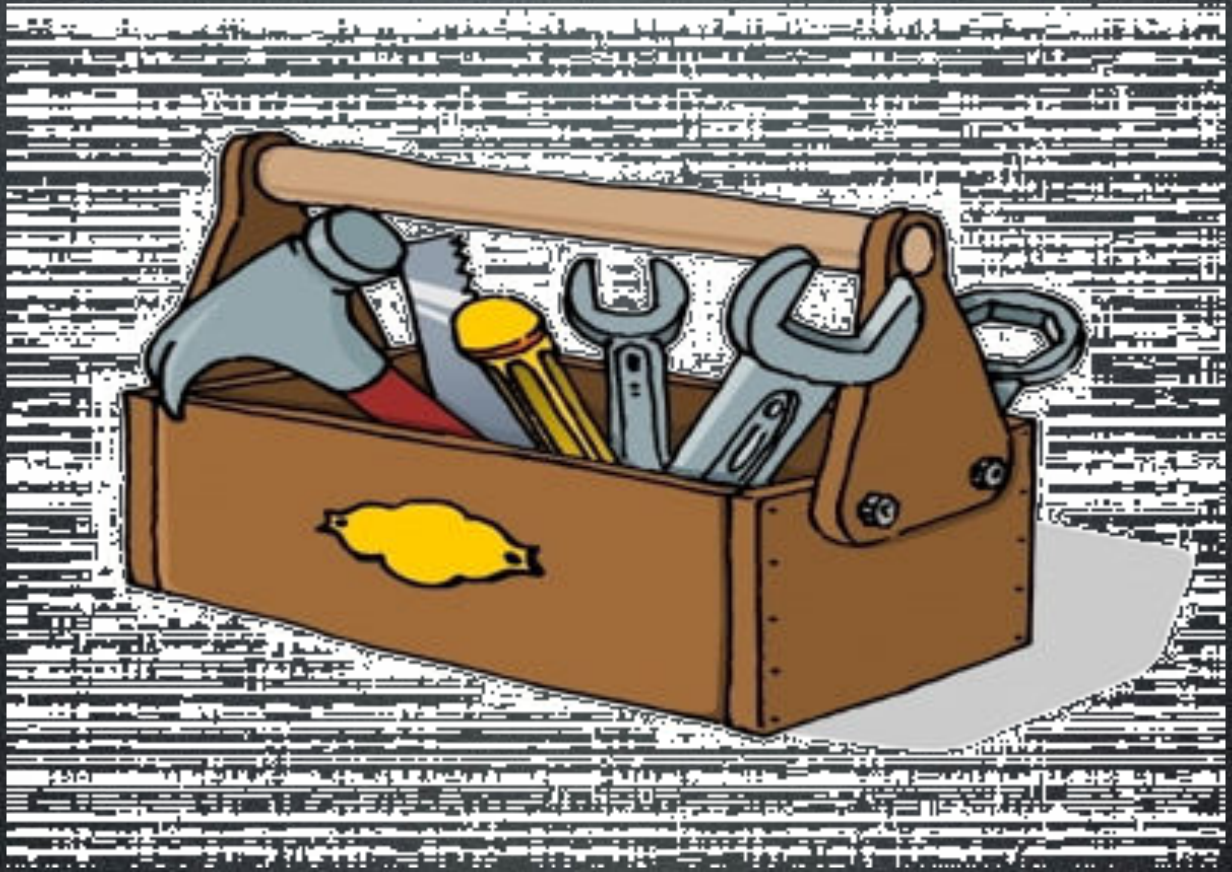
Higgs Production at N^3LO

"Additional ingredients"

- full quark-mass effects (from top, bottom, charm) through NLO ➜ go beyond the EFT!
- electroweak (EW) two-loop corrections
  three-loop QCD/EW corrections
- convolution with parton distribution functions
- assessment of remaining uncertainties (scale, pdf, α_s, missing contributions, approximations)

Tools

(just a few of them..)



Heavy quark effective theory

- at LO, gluon-fusion Higgs production is mediated by *one* loop of heavy quarks
  - ➡ N^{3}LO ➜ four loops! (~15000 diagrams)

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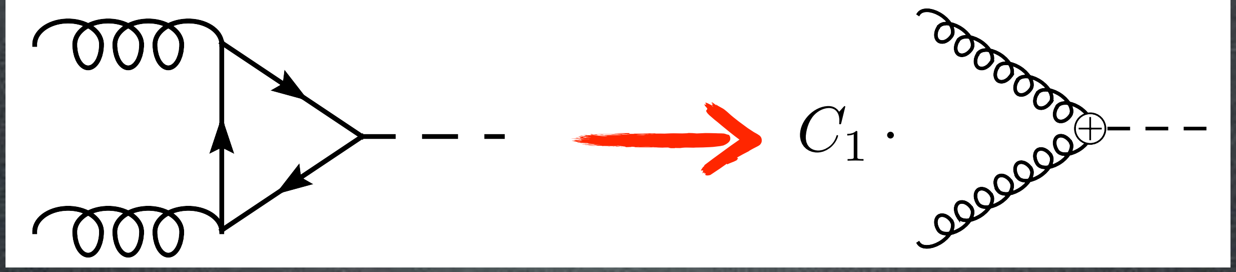
Heavy quark effective theory

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



➡ construct an effective theory than only contains the light (massless) Stand

where the top-quark loop is replaced by an effective gluon-Higgs vertex and only the light dof of the SM are present

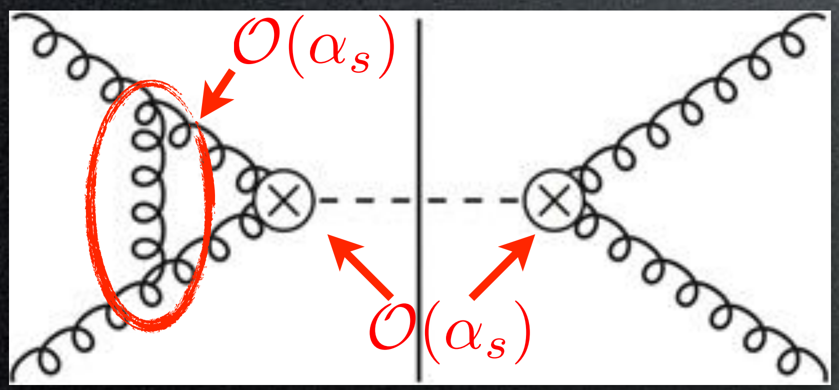
particles

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

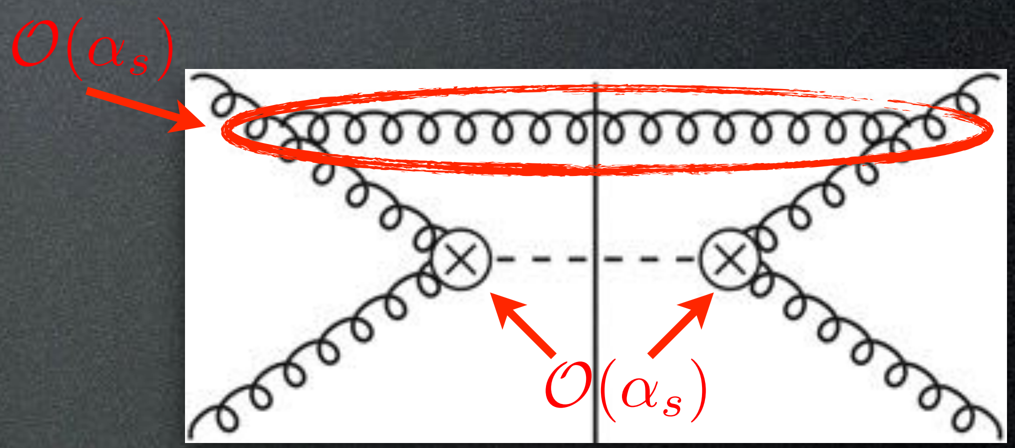
Real radiation

- huge number of contributions from "real" radiation
- at NLO $\left(\mathcal{O}(\alpha_s^3)\right)$, there are two kind of contribution (in addition to the two loop gluon-Higgs vertex)

Dawson, Nucl. Phys. B 359 (1991) 283;
Djouadi et al., Phys. Lett. B 264 (1991)



Virtual corrections

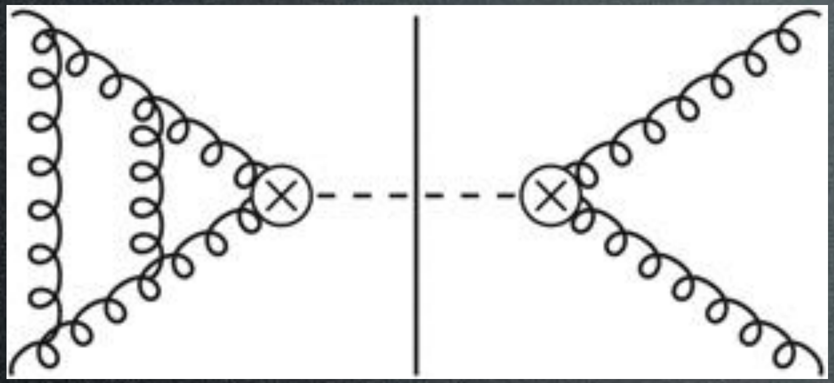


Real radiation

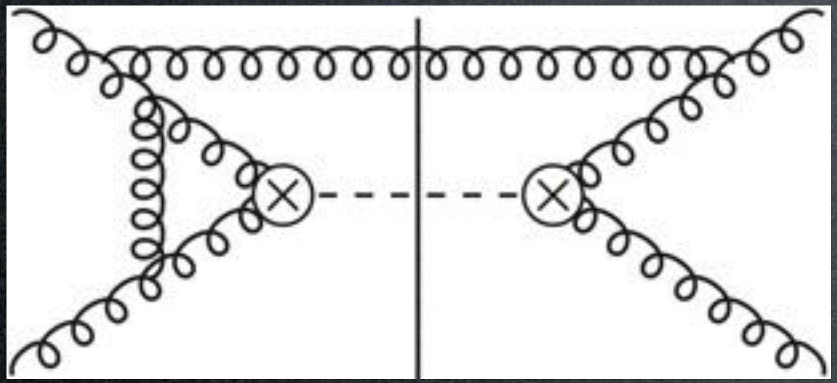
➡ ~ 10 diagrams

Real radiation

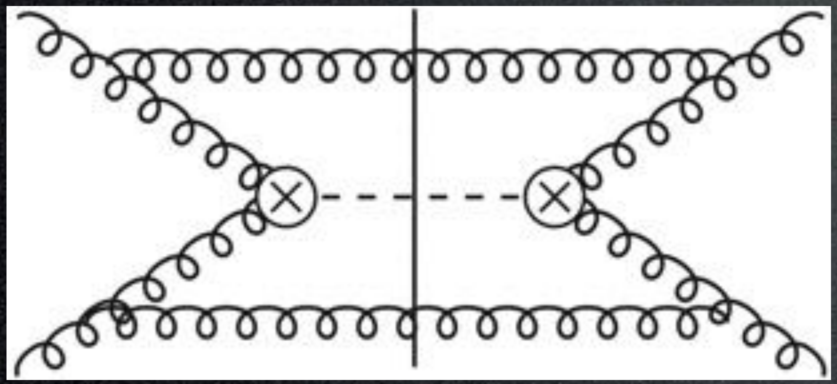
- at NNLO ...



Double-virtual corrections



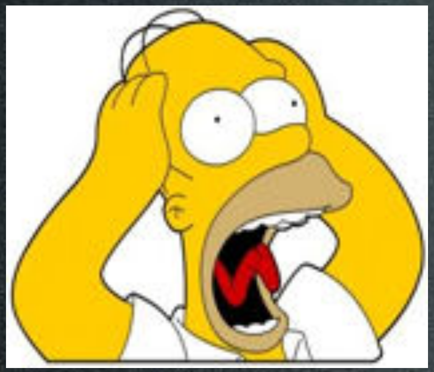
Real-virtual corrections



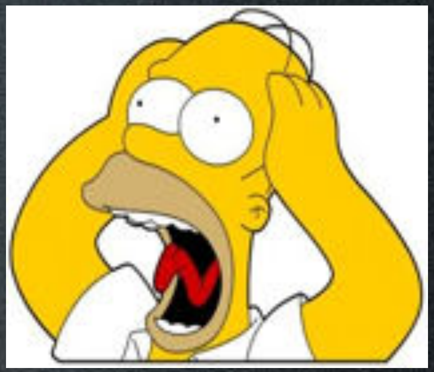
Double-real corrections

➡ ~ 1000 diagrams

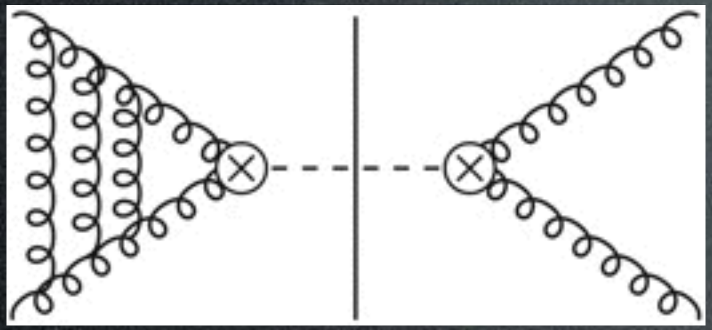
Harlander and Kilgore, PRL 88, 201801 (2002);
Anastasiou and Melnikov, NP B 646 (2002) 220;
Ravindran et al., NP B 665, 325 (2003)



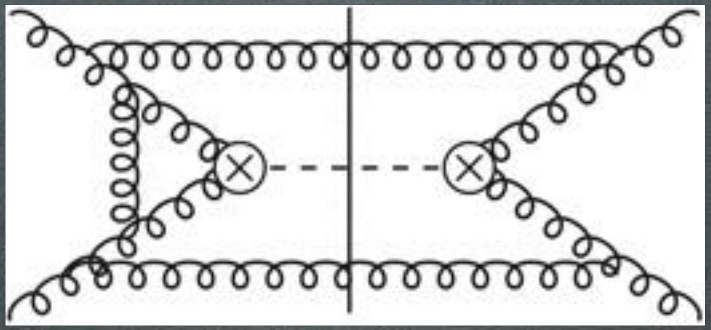
Real radiation



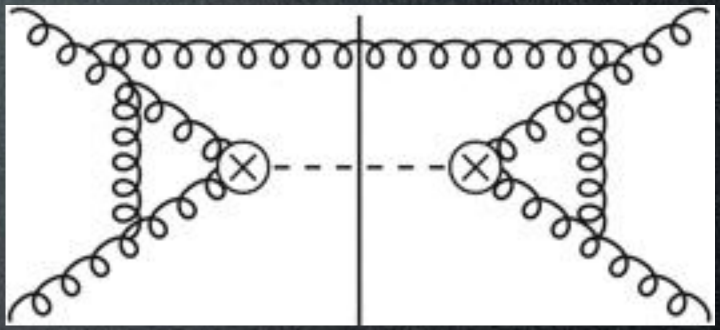
- at N^{3}LO ...



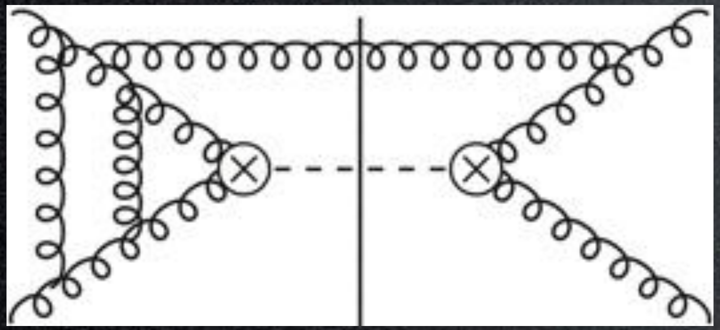
triple-virtual
corrections



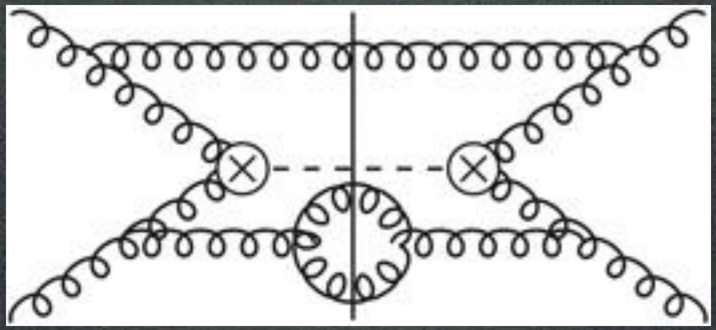
double-real
virtual corrections



real-virtual squared
corrections



double-virtual
real corrections



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Real radiation

- ➡ the number of interference diagrams increases by a factor of 100 from NNLO to N^3LO
- ➡ the number of integrals increases by 10.000!

NNLO	N^3LO
~ 50.000	~ 500.000.000

Real radiation

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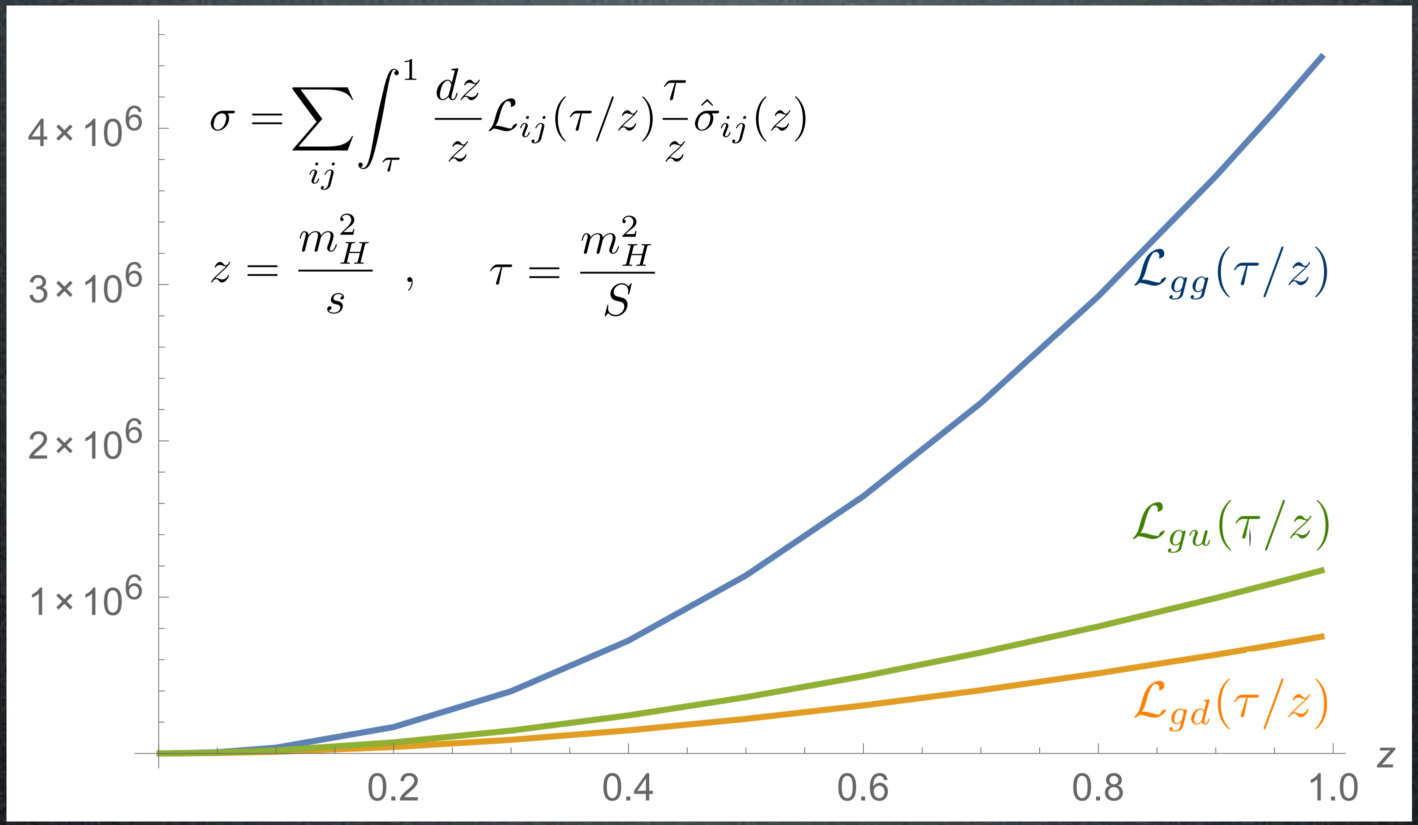
How can we tackle this problem?

Threshold expansion

- As a first approximation, we can consider the production of the Higgs boson at threshold…



Threshold expansion

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- ... and then add subleading terms in the threshold expansion

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

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(still, some 20-30.000 integrals to compute)

Anastasiou, Duhr, Dulat, EF, Gehrmann, Herzog, Mistlberger, PLB 737, 325 (2014); Li, von Manteuffel, Schabinger, Zhu, PRD 90, 053006 (2014)

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Anastasiou, Duhr, Dulat, EF, Gehrmann, Herzog, Mistlberger, JHEP 1503, 091 (2015) (next-to-soft); PRL 114 (2015) 212001 (up to N_{trunc} = 37)

Integration by part identities

- They allow to handle the huge number of integrals to compute
- They are relations among the integrals that we need to compute
- Solving these equations, we can rewrite all the integrals as linear combinations of a small set of "master integrals"

Tkachov, PLB100, 65 (1981); Chetyrkin, Tkachov, NPB192, 159 (1981); Gehrmann, Remiddi, NPB 580 (2000) 485

Integration by part identities

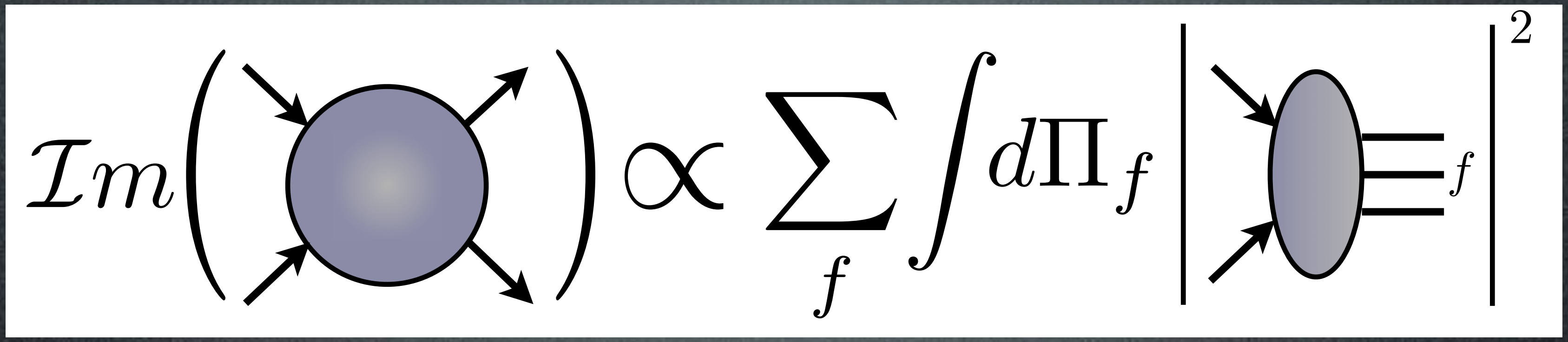
- The system of equation generated is huge itself, but it can be solved in an automated way implementing the Laporta algorithm

Laporta, Int. J. Mod. Phys. A 15, 5087 (2000)

➡ in house software

➡ benefit: reduce to the calculation of ~50 soft master integrals!

Reverse unitarity



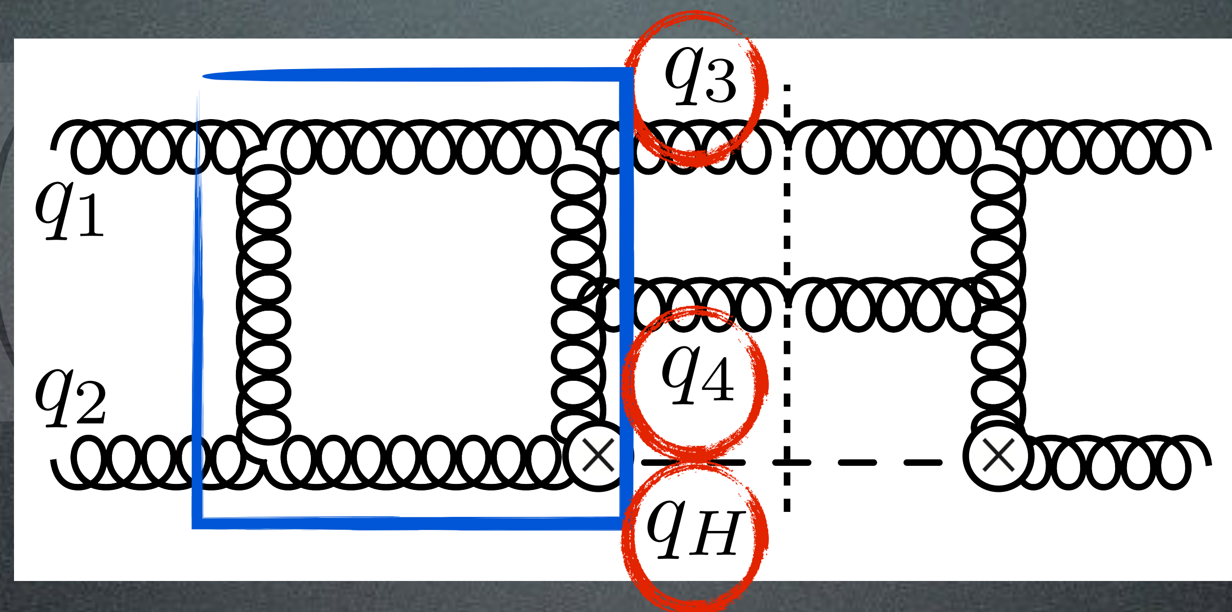
unitarity methods

Bern, Dixon, Kosower, NPB 513, 3 (1998)
Britto, Cachazo, Feng, NPB 725, 275 (2005)
Ossola, Papadopoulos, Pittau, NPB 763, 147 (2007)

reverse unitarity

Anastasiou, Melnikov, NPB 646 (2002) 220;
Anastasiou, Dixon, Melnikov, Petriello, PRL 91 (2003) 182002

Expansion be regions



soft ➡ scalings

$$q_1, q_2 \to p_1, p_2$$

$$q_3, q_4 \to \bar{z}p_3, \bar{z}p_4$$

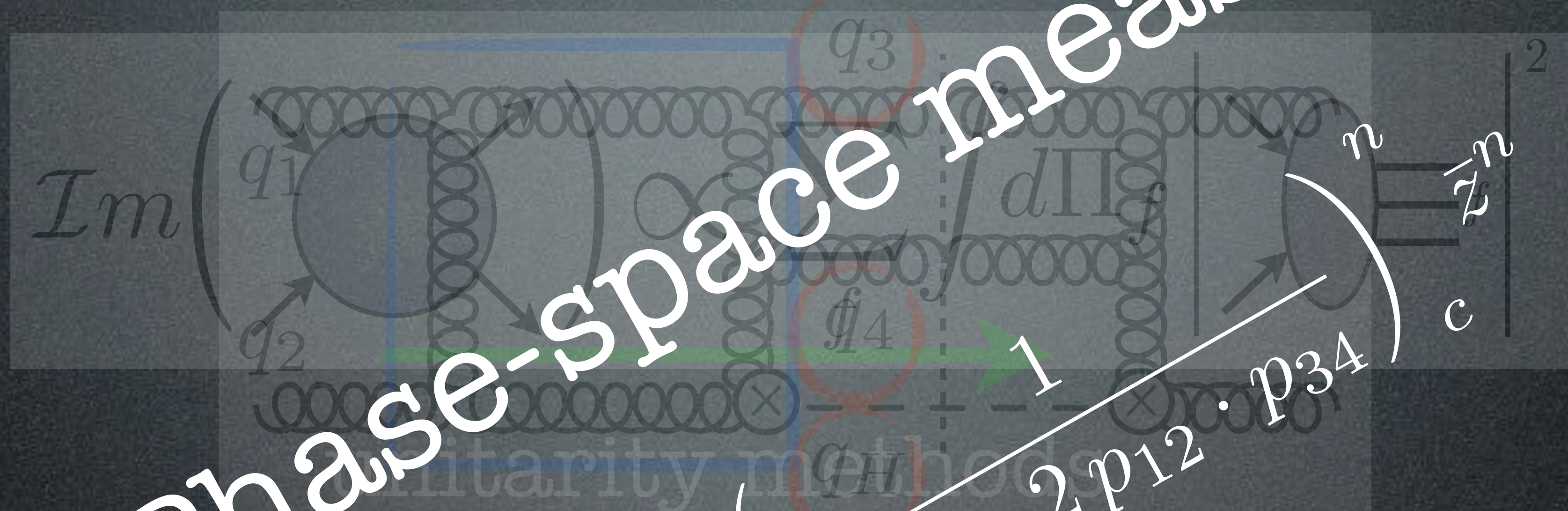
$$\bar{z} = 1 - z$$

Expansion by regions

Reverse unitarity

Phase-space measure

$$\delta_+(s_{12} - 2p_{12}\cdot p_{34})\left(\frac{1}{s_{12} - 2p_{12}\cdot p_{34}}\right)^n$$



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q_3, q_4 soft $\Rightarrow$ scalings

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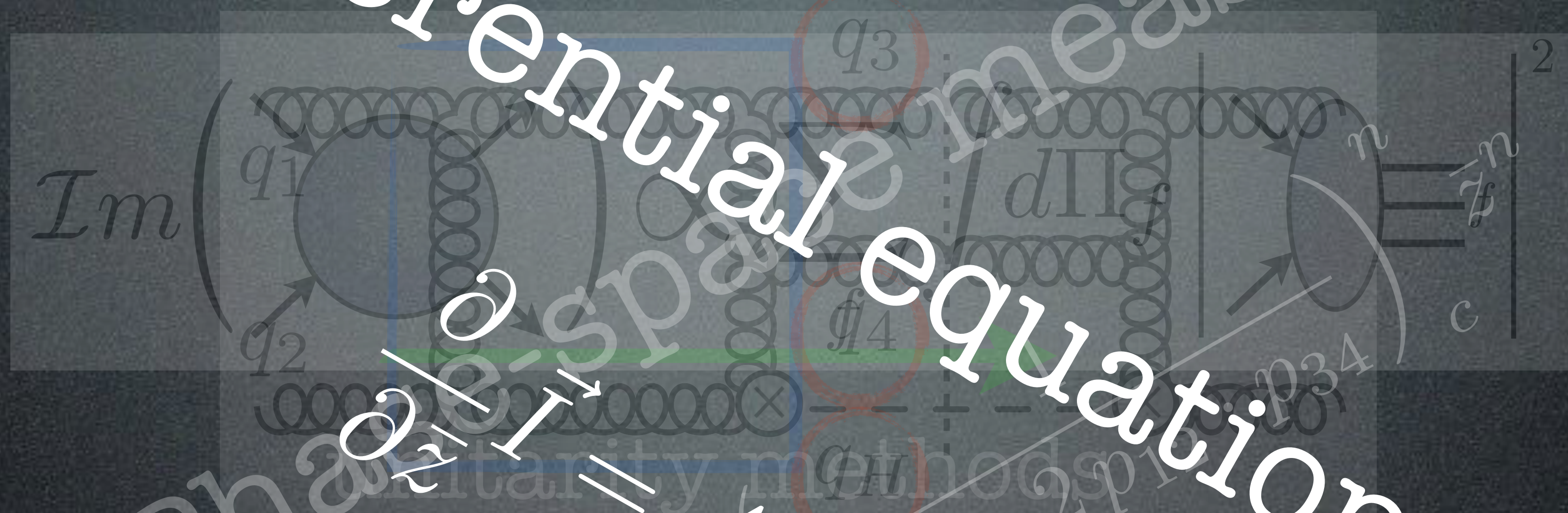
Differential equations

$$\frac{\partial}{\partial \bar{z}}\vec{I} = A(\bar{z},\epsilon)\vec{I}$$

Expansion by regions

Reverse unitarity

Phase-space measure



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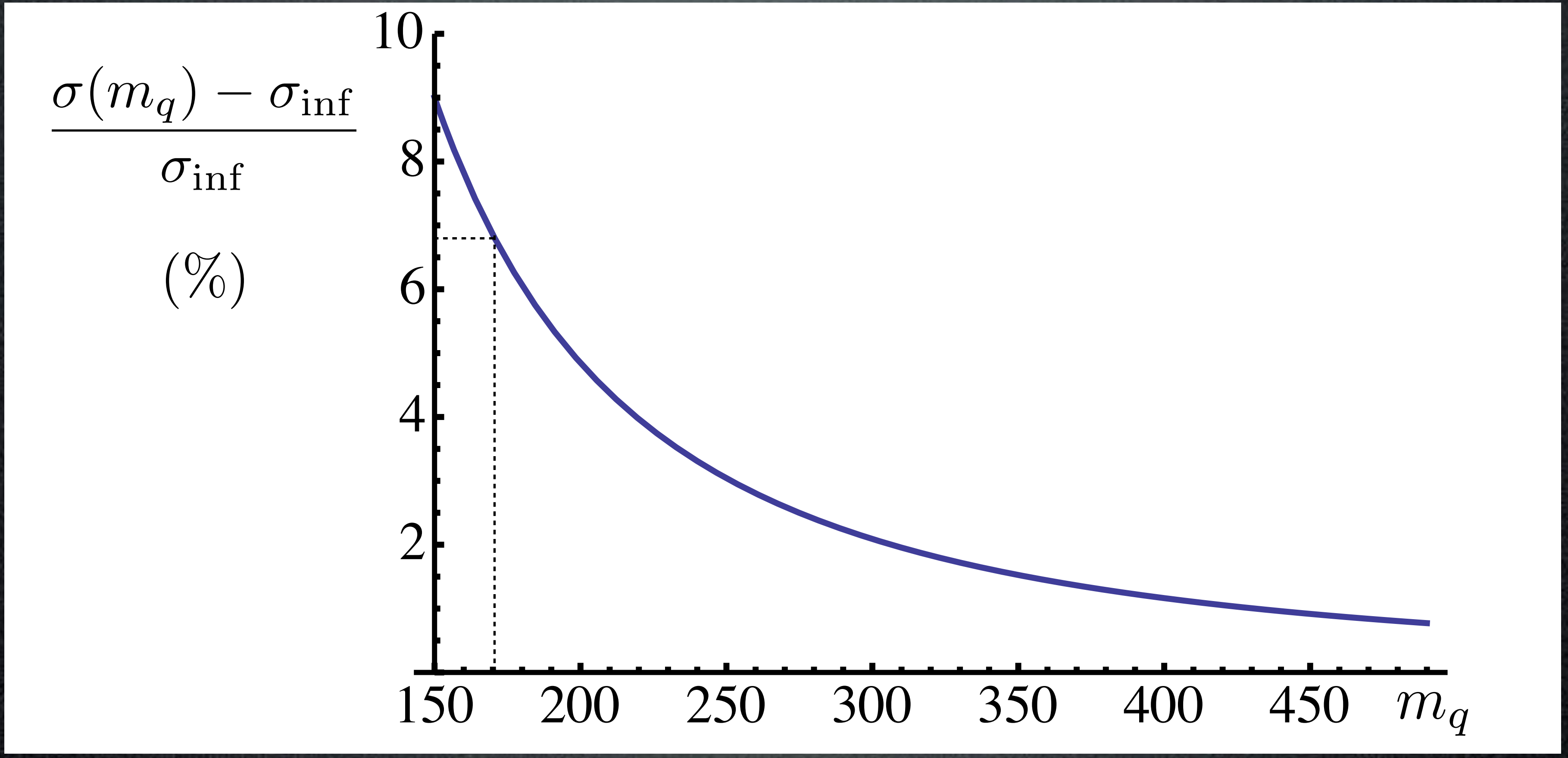
(Intermediate) Results


To the juice...

Finite mass effects

(top quark)

- How good is the heavy-top approximation?
  - at LO



Finite mass effects

(top quark)

- the exact top-mass dependance is known through NLO

Graudenz et al., PRL 70, 1372 (1993); Spira et al., NP B 453, 17 (1995)

- finite top-mass corrections have been computed at NNLO, confirming the accuracy of the effective theory at the per-mille level

Harlander and Ozeren, JHEP 0911, 088 (2009); Pak et al., JHEP 1002, 025 (2010)

➡ include the N^3LO cross section in the "rescaled" heavy-quark effective theory

Finite mass effects

(top quark)

More in detail..

- at NLO, “improve” the EFT result by rescaling it with the exact LO cross section:

$$\begin{aligned}\sigma_{EFT}^{NLO} &= 34.66 \text{ pb} \\ \sigma_{ex}^{NLO} &= 36.60 \text{ pb} \\ \sigma_{EFT,r}^{NLO} &= R_{LO} \times \sigma_{EFT}^{NLO} = 36.84 \text{ pb}\end{aligned}$$

0.65%

$$R_{LO} = \frac{\sigma_{exact}^{LO}}{\sigma_{EFT}^{LO}} \simeq 1.06$$

$\sqrt{S}$	13TeV
m_h	125GeV
PDF	PDF4LHC15_nnlo_100
$a_s(m_Z)$	0.118
$m_t(m_t)$	162.7 ($\overline{MS}$)
$m_b(4.18GeV)$	4.18 ($\overline{MS}$)
$m_c(3GeV)$	0.986 ($\overline{MS}$)
$\mu = \mu_R = \mu_F$	62.5 ($= m_h/2$)

Finite mass effects

(top quark)

- rescale NNLO and N^{3}LO cross sections, computed in the EFT, by R_{LO}

which have also been computed factorizing the exact LO XS

- at NNLO, include known m_H/m_t correction

$$gg \sim +0.8\%$$

$$qg \sim -0.1\%$$

Harlander, Ozeren; Pak, Rogal, Steinhauser; Mantler, Marzani

  - tiny effect ➜ confirms the validity of the rescaled EFT
  - the error due to unknown top-mass effects at NNLO is estimated as

$$\delta(1/m_t) \sim \pm 1\%$$

Harlander, Ozeren; Pak, Rogal, Steinhauser; Mantler, Marzani

Full NLO mass effects

(top, bottom, charm quark)

- The full dependance of the Higgs production cross section on the quark mass is known exactly through NLO

Spira, Djouadi, Graudenz, Zerwas ; Harlander, Kant; Aglietti, Bonciani, Degrassi, Vicini.

- include it for top, bottom and charm quarks

$\sigma^{NLO}_{ex;t}$ $\sigma^{NLO}_{ex;t+b}$ $\sigma^{NLO}_{ex;t+b+c}$

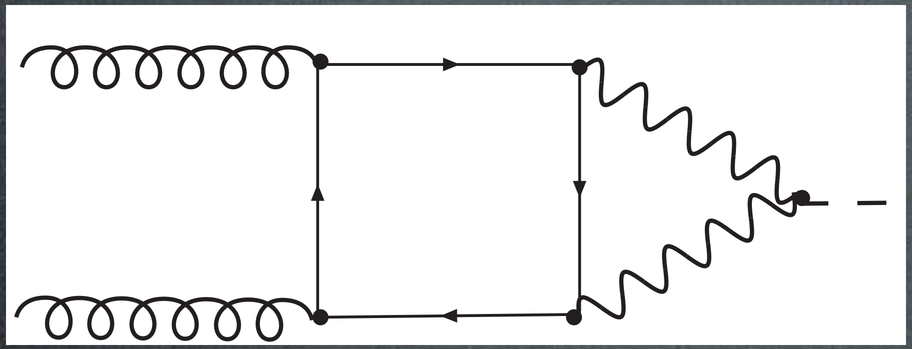
0.65% 5.1% 5.6% on $\sigma^{NLO}_{EFT,r}$

- estimate an error from unknown light-quark effects at NNLO of $\pm 0.6\%$

Electroweak corrections

- Known exactly at LO in α_s $(\mathcal{O}(\alpha\alpha_s))$

Aglietti, Bonciani, Degrassi, Vicini;
Actis, Passarino, Sturm, Uccirati



$\longrightarrow +5.2\%$

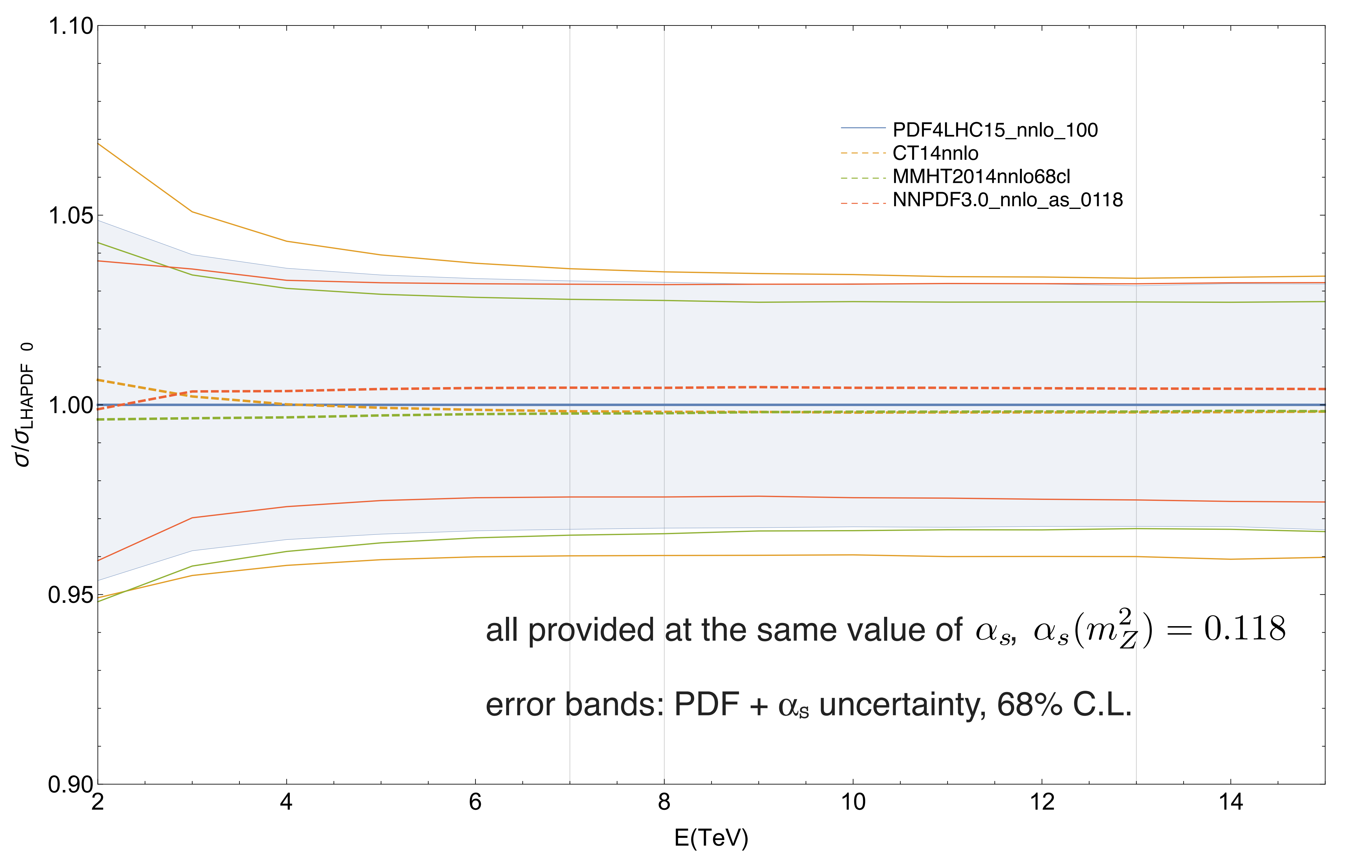
- At NLO, effects from light quarks are known in an effective theory (heavy *t, W, Z*) $\longrightarrow +5.1\%$

- Estimate the error from missing QCD/EW contributions by varying the Wilson coefficient of the QCD/EW effective theory $\longrightarrow \delta(EW) \sim \pm 1\%$

Convolution with PDFs

- Various PDF fits are available at NNLO (ABM12, CT14, MMHT2014, NNPDF3.0, PDF4LHC15, HERAPDF2.0)
- (How) does our cross section prediction change when using these different sets?

Convolution with PDFs

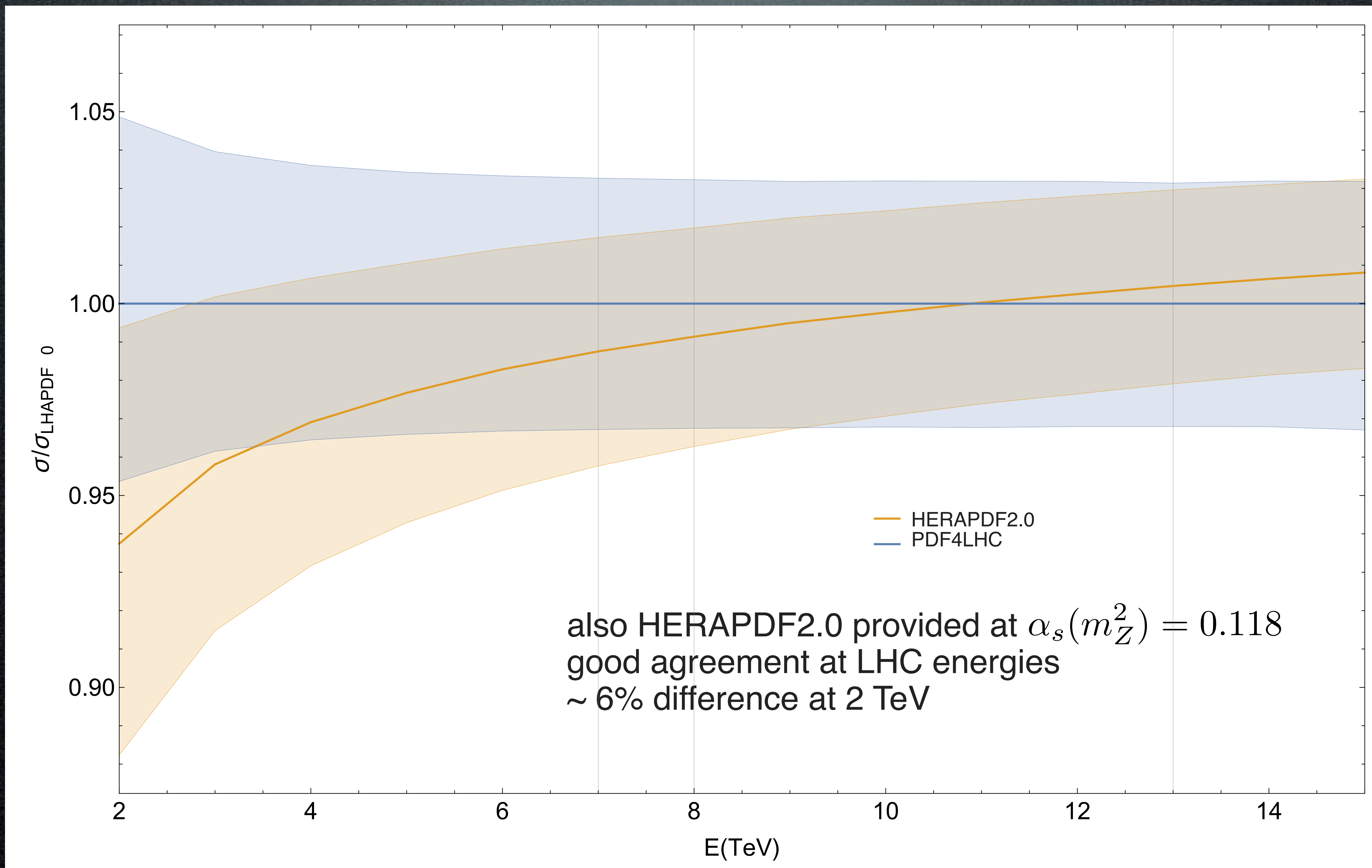


Convolution with PDFs

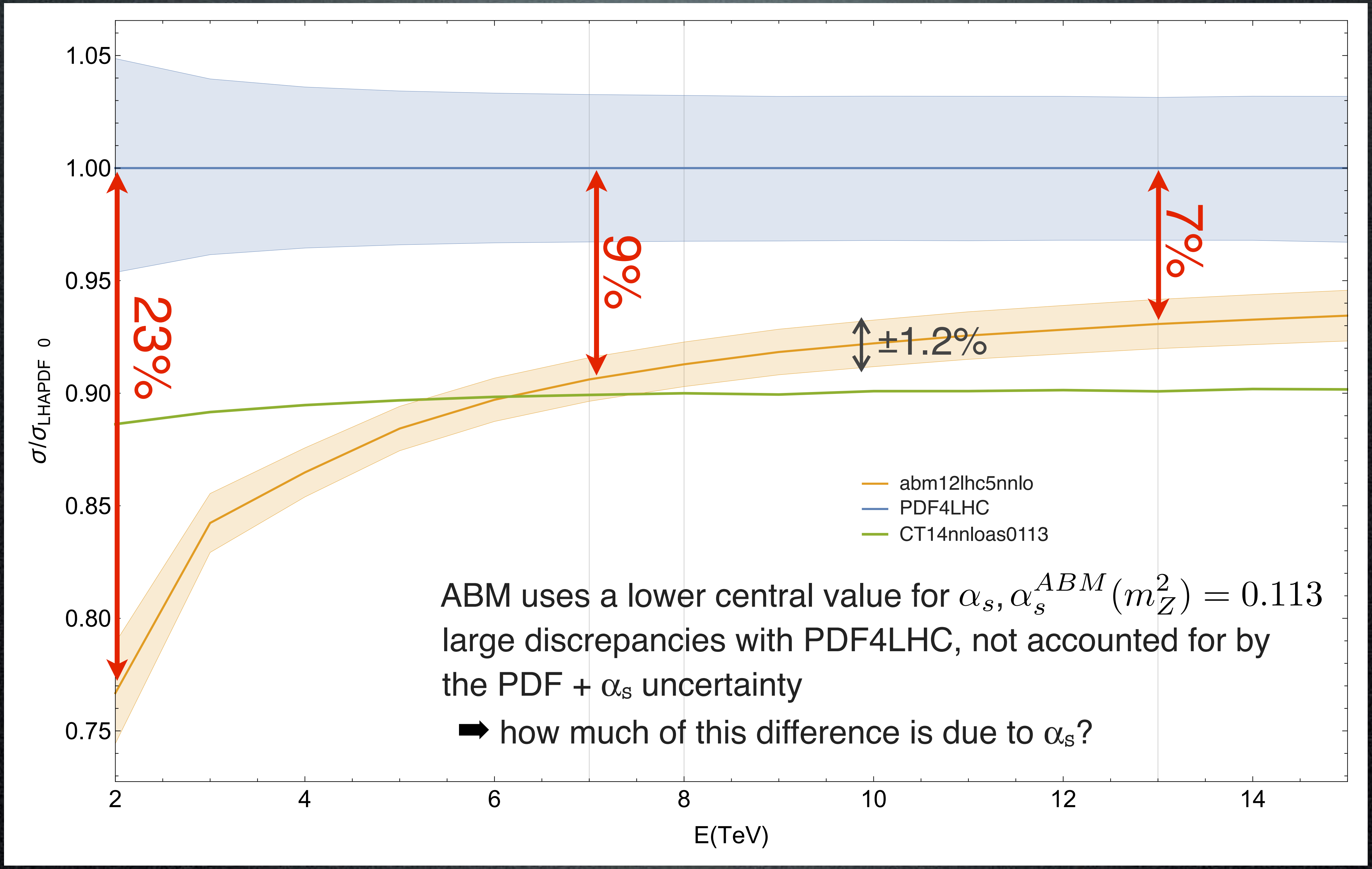
- The central values lie within 1% of each other (with MMHT2014 and NNPDF3.0 agreeing at the permille level)

- The combined PDF + α_s uncertainty is $\sim$ 3-4% at LHC energies and captures well the small difference among the sets

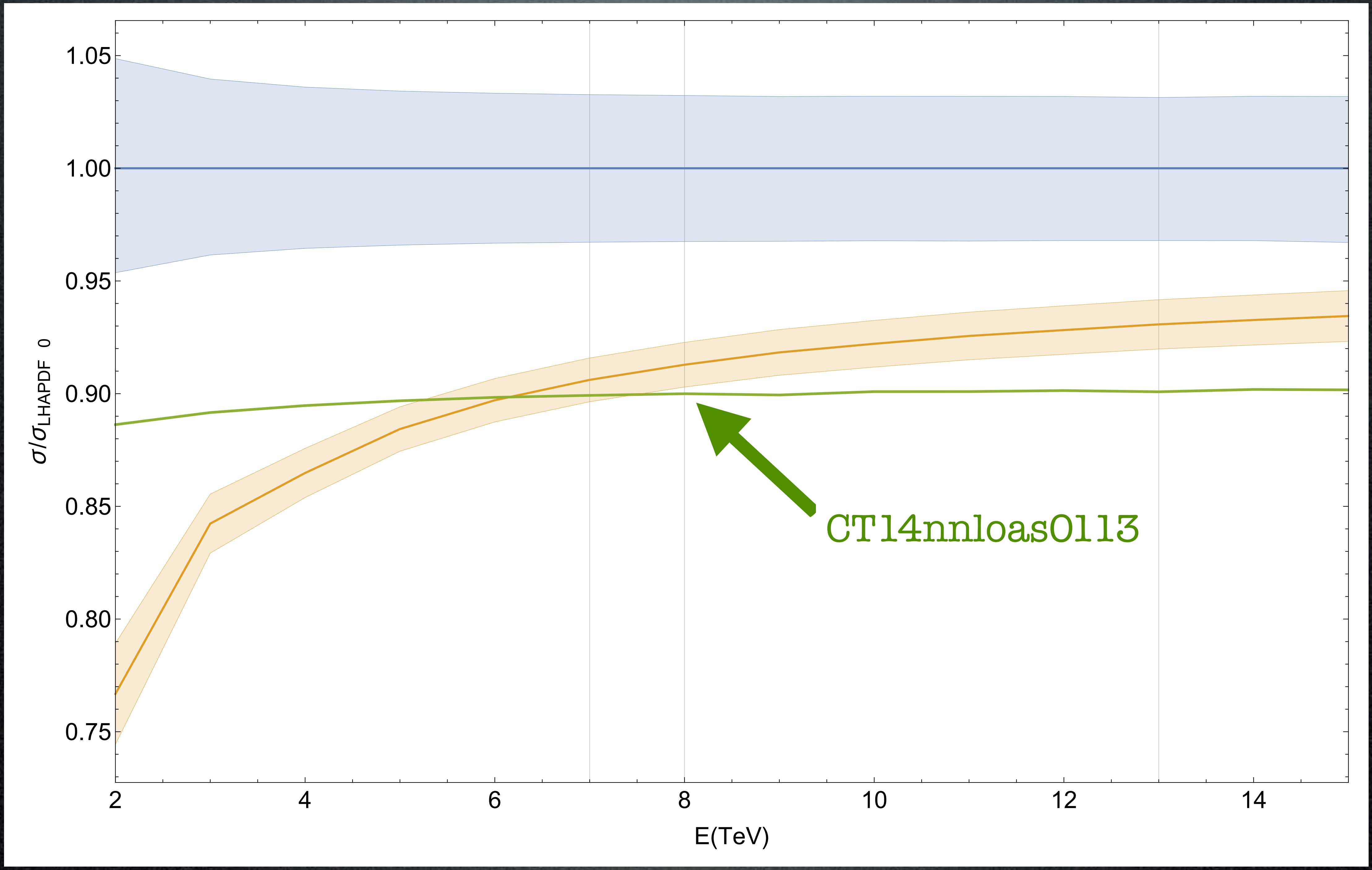
Convolution with PDFs



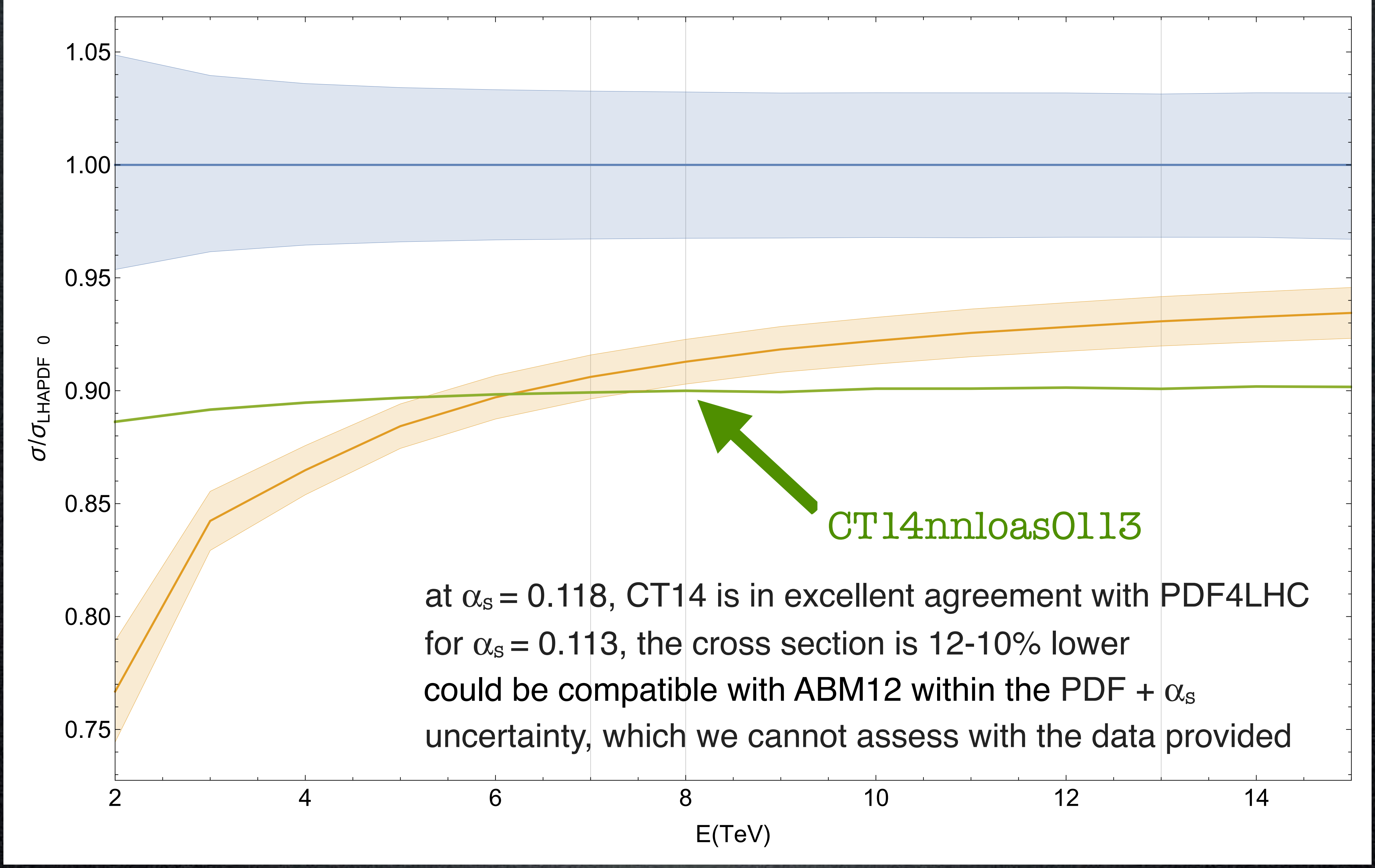
Convolution with PDFs



Convolution with PDFs



Convolution with PDFs



Convolution with PDFs

- Given the good agreement among the various sets that use $\alpha_s = 0.118$ (consistent with the PDG world average), we will use the combined PDF4LHC fit for our final results

- Caveat: we are computing the N^3LO Higgs cross section using NNLO PDFs.
  Is it legitimate to do so?

  - look at what happens to the NNLO cross section using NNLO or NLO PDFs

N^{3}LO PDF uncertainty

- For the uncertainty from missing N^{3}LO PDFs, we adopt a conservative estimate

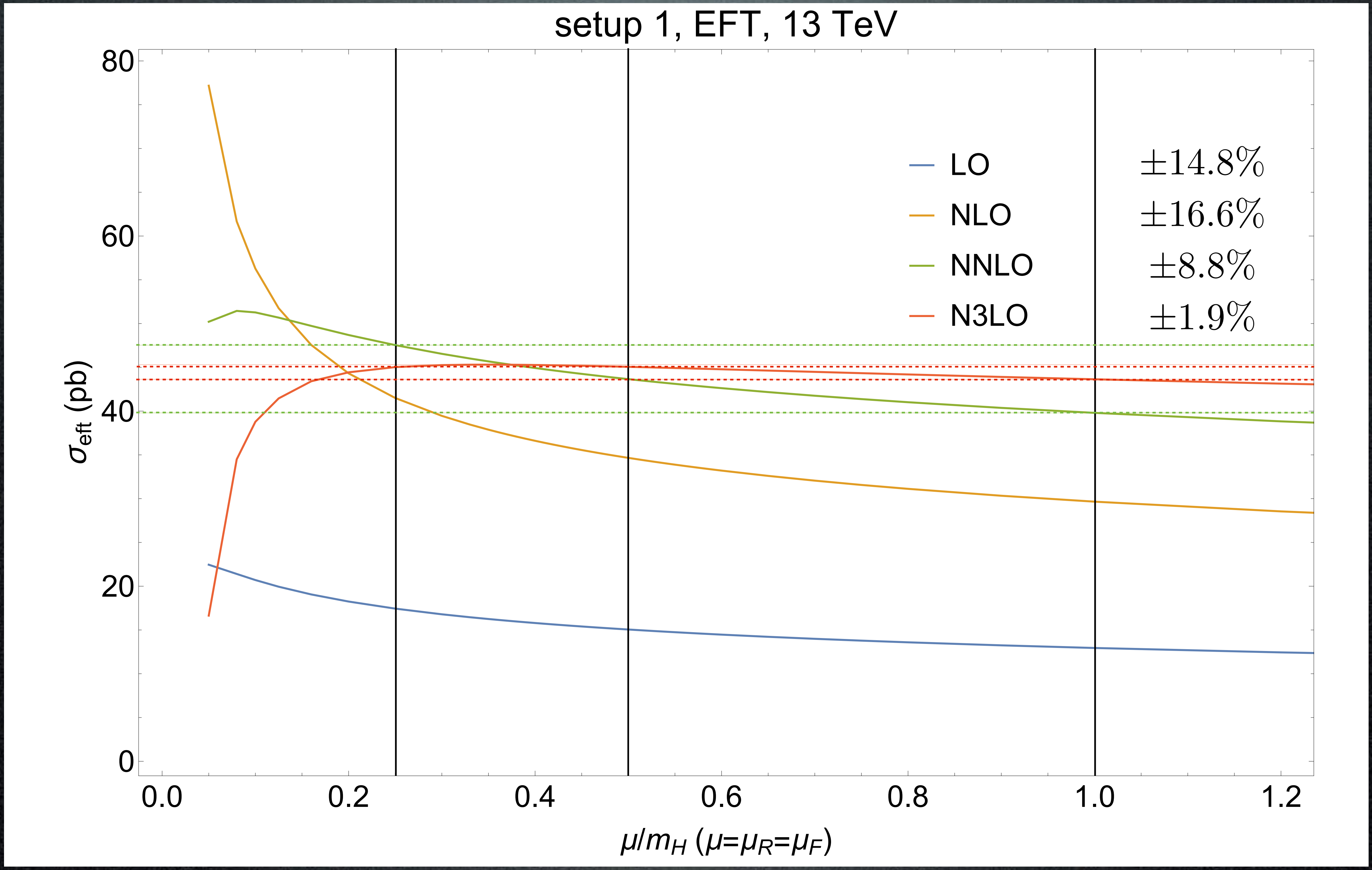
$$\delta(\mathrm{PDF-TH}) = \frac{1}{2}\left|\frac{\sigma^{(2),NNLO}_{EFT} - \sigma^{(2),NLO}_{EFT}}{\sigma^{(2),NNLO}_{EFT}}\right| = 1.16\%$$

from comparison
with other processes
computed at N^{3}LO

Uncertainties

- We already discussed the uncertainties due to missing finite-mass effects at NNLO ($\delta(1/m_t)$, $\delta(tbc)$), unknown electroweak corrections ($\delta(EW)$) and the lack of N^3LO PDFs
- What are the errors associated to missing higher order terms in the α_s expansion and soft approximation?

Effects beyond N^3LO

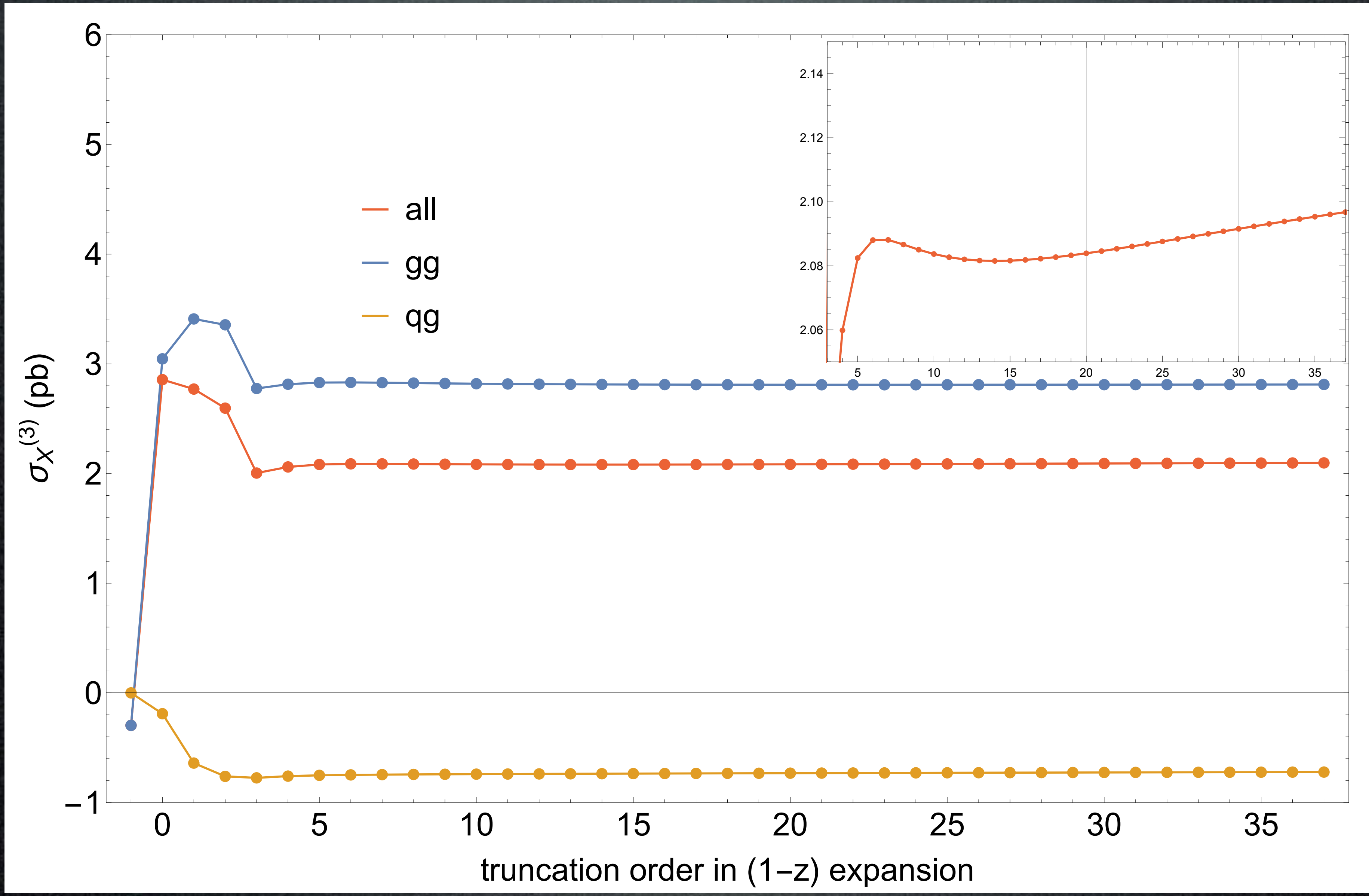


Effects beyond N^3LO

- At N^3LO, one starts to observe a convergence of the α_s expansion
  - the cross section in the EFT increases by about 3%, i.e., within the NNLO scale variation error
  - the scale variation error decreases
  - seems to indicate the validity of scale variation studies as estimates of missing higher order corrections

Soft approximation

- What is the error associated to the truncation of the expansion in $(1-z)$?



Soft approximation

- the cross section increases by 3.7 per mille over the last ten terms in the expansion

- assume (conservatively) that it will take another 100 terms to converge, and it will converge at the same speed

$$\delta(\mathrm{trunc}) = 10 \times \frac{\sigma^{(3)}_{EFT}(37) - \sigma^{(3)}_{EFT}(27)}{\sigma^{\mathrm{N^3LO}}_{EFT}} = 0.37\%$$

(consistent with other estimates of the truncation error)

The N^{3}LO cross section

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

σ	$\delta(\text{PDF})$	$\delta(\alpha_s)$	$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(tbc)$	$\delta(1/m_t)$	
48.58	± 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	$\pm$ 1	± 0.83	$\pm$ 1	%

in quadrature

linearly

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

The N^{3}LO cross section

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	± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.83	$\pm$ [illegible]	%

"traditionally" neglected

in quadrature

linearly

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

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

$$\sigma = 48.58\,\mathrm{pb}^{+0.84\,\mathrm{pb}\,(+1.73\%)}_{-1.89\,\mathrm{pb}\,(-3.90\%)}\ (\text{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

Room for improvement

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

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

in quadrature

linearly

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

Conclusions

- We computed the N^3LO gluon-fusion production cross section in an EFT
- Added all known effects beyond the EFT (finite top mass, light quarks, EW corrections)
- Studied the dependance on the choice of PDFs
- Provided an accurate estimate of the uncertainties, including errors from missing information and from approximations

Conclusions

- Room for improvement
  - going beyond the threshold expansion (full kinematics)
  - exact NNLO cross section/approximate NNLO results for light quarks/exact three-loop mixed QCD/EW corrections