ggF Theory Overview For Highest Precision

Higgs Couplings 2015

Lumley Castle

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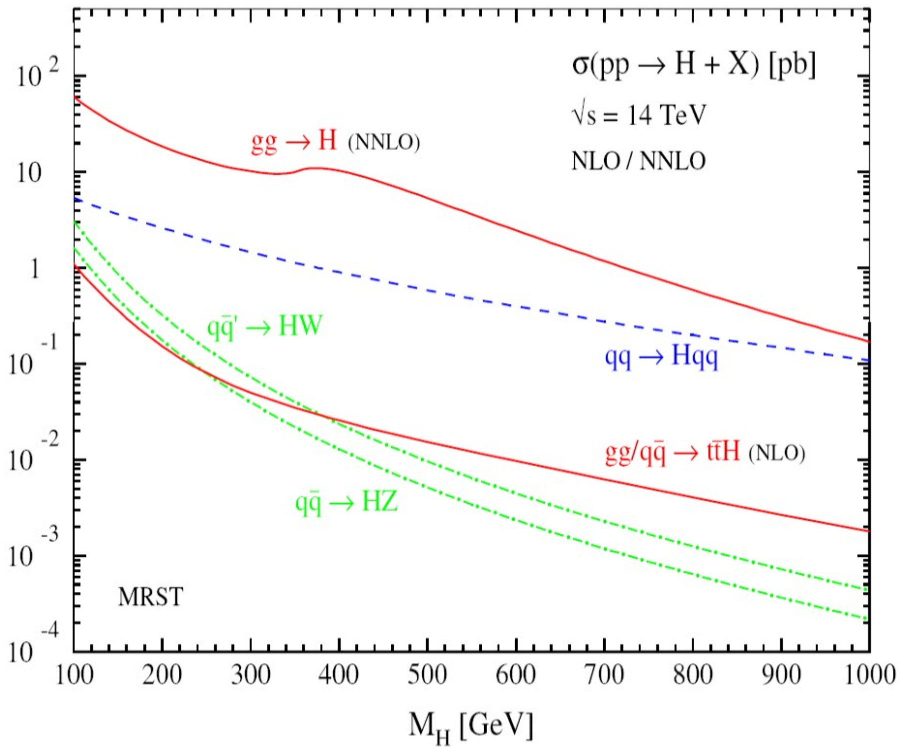
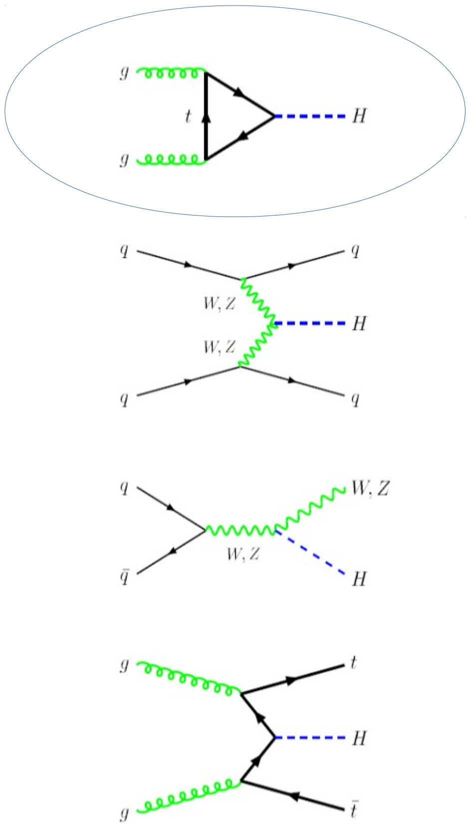
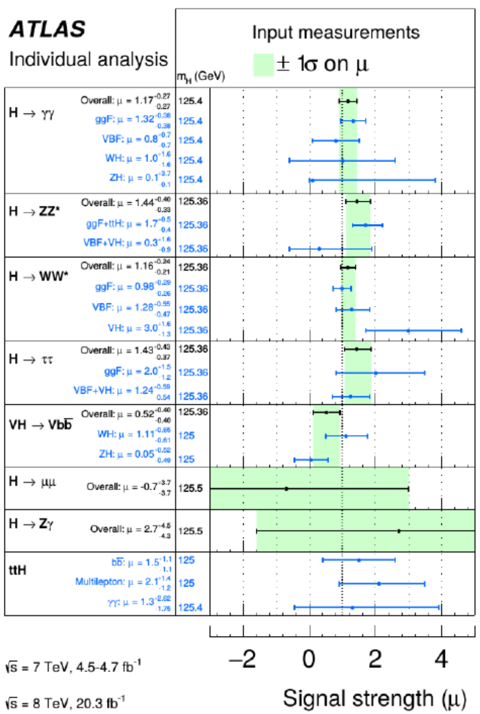
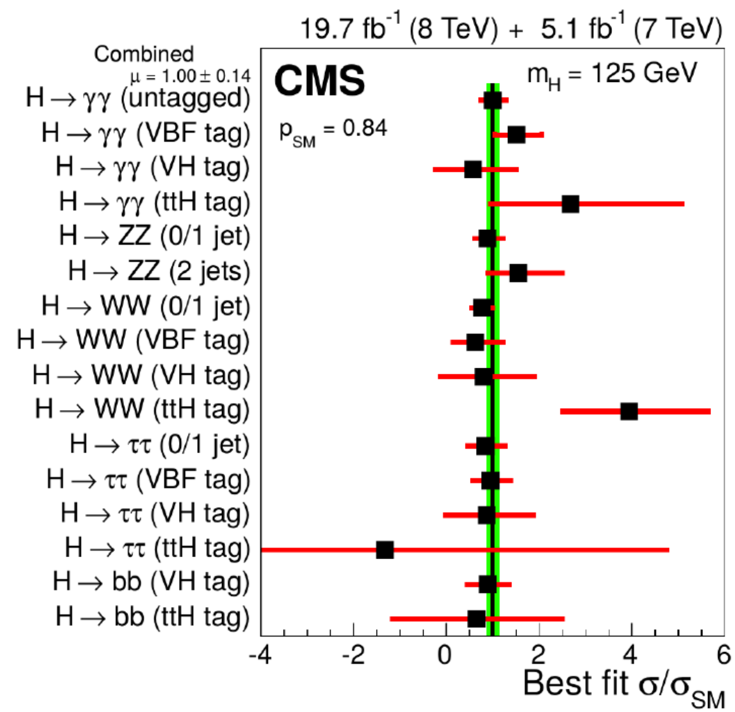
LHC Higgs Production in the Standard Model





LHC Higgs Data





ATLAS Mass: PRL 114, 191803
ATLAS Couplings: arXiv:1507.04548

CMS Mass & Couplings
EPJ 75 (2015) 212

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,{}^{+0.04}_{-0.04}\,(\text{expt})\,{}^{+0.03}_{-0.03}\,(\text{thbgd})\,{}^{+0.07}_{-0.06}\,(\text{thsig})$$

most precise measurement, theoretical error as large as the statistical one !

Theoretical Formalism

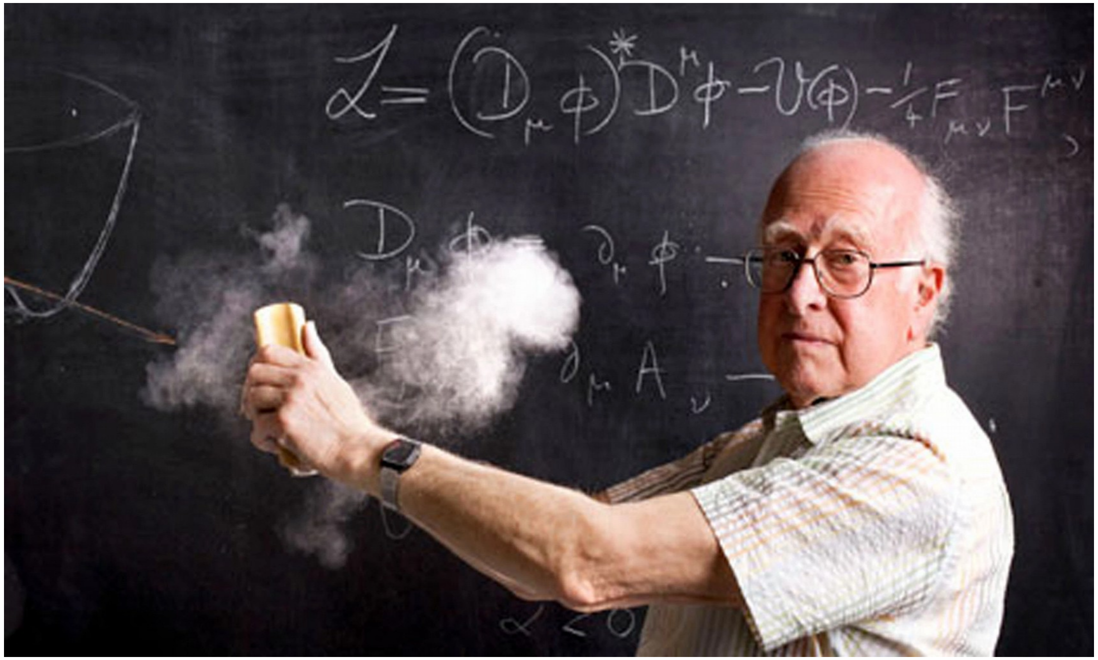
To compute cross sections we use the Factorisation Master Formula:

$$\sigma_{PP\to X}[J] = \sum_{ij} \int dx_1 dx_2\, f_i(x_1,\mu_F) f_j(x_2,\mu_F) \\ \times d\sigma_{ij\to X}(x_1,x_2,\mu_R,\mu_F,\{\alpha\},\{p\}) \\ \times J(\{p\}) \left(1 + \mathcal{O}(\Lambda_{QCD}/Q)\right)$$

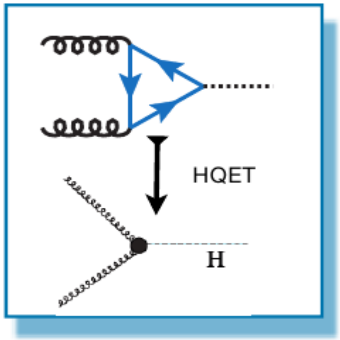
This formula gives rise to several sources of uncertainties:

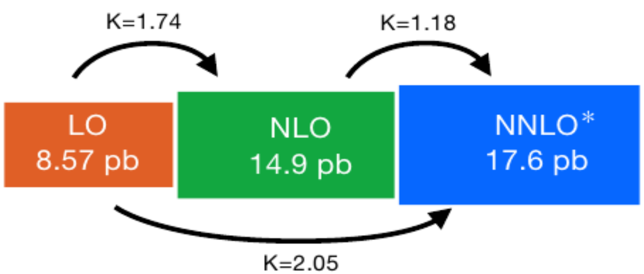
- **PDF Uncertainties:**
  Due to our limited knowledge of the Parton Distributions inside the Proton
- **Couplings and Masses:**
  Due to our limited knowledge of coupling and mass parameters
- **Perturbative Uncertainties:**
  Due to our limited ability to calculate partonic cross sections in perturbative QFT
- **Non-perturbative Uncertainties:**
  Due to factorisation breaking terms. We don't know how to quantify these!

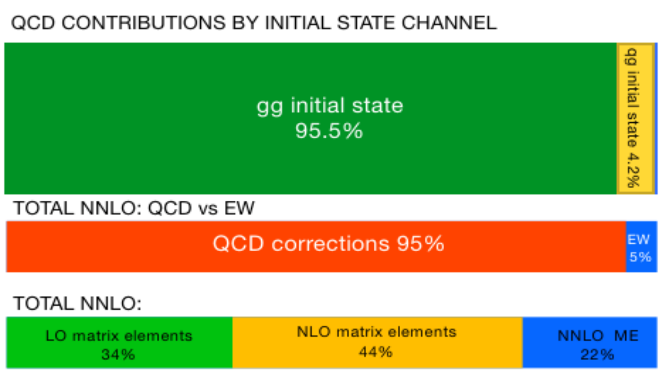
Higgs Production in gluon fusion



Total Higgs Cross section as of 2014







[graphics by A.Lazopoulos]

- NLO QCD corrections known exactly (with top-bottom interference) [Graudenz et al 93, Spira et al 95,Harlander et al 05,Anastasiou 06, Aglietti 06]
- NNLO QCD in HQET [Harlander et al 02, Anastasiou et al 02, Ravindran et al 03]
- Subleading terms in the heavy top expansion [Pak et al 09, Harlander et al 09]
- EW corrections [Actis et al 08+09,Aglietti et al 04,Degrassi et al 04]
- mixed QCD EW corrections [Anastasiou et al 09]
- Soft gluon NNLL [Catani et al 03] SCET NNLL [Ahrens et al 08]
- Approximate N3LO [Moch et al 05, Ball et al 13]
- N3LL resummation of threshold logs [Bonvini et al 14, Catani et al 14]
- Soft Virtual and next to soft Approximation for N3LO [Anastasiou et al 14]

$\%\delta_{PDF}$	$\%\delta_{\mu}$
$^{+7.79}_{-7.53}$	$^{+8.37}_{-9.26}$

To increase Theory Precision one needs N3LO QCD

- In HQET the Higgs boson cross section depends only on a single dimensionless variable:

$$z = \frac{m_H^2}{\hat{s}}$$

- Analytic evaluation likely in terms of multiple polylogarithms.

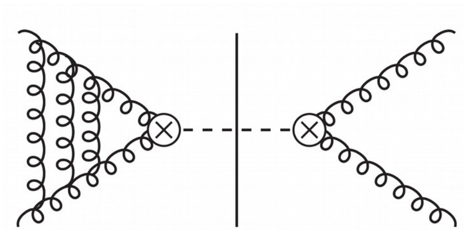
However..

- Number of cut-diagrams to be evaluated is around 100.000
- Infra-red divergences up to

$$\mathcal{O}\left(\frac{1}{\epsilon^6}\right)$$

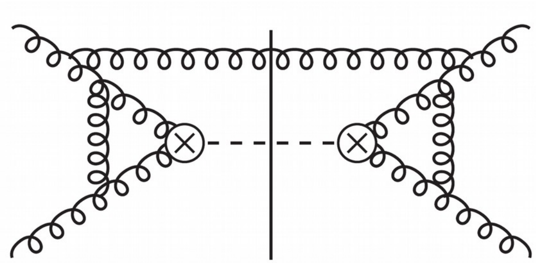
- Phase Space Integrals “were” completely unknown from other processes

2015: The first N3LO Calculation for the LHC



Triple Virtual

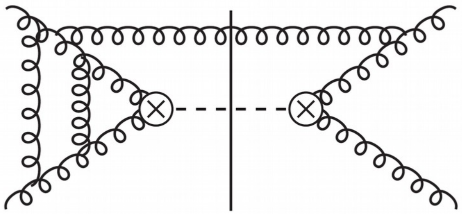
Known from QCD Form Factor
[Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser; Gehrmann, Glover, Huber, Ikizlerli, Studerus]



Real-Virtual Squared

Known [Anastasiou, Duhr, Dulat, FH, Mistlberger; Kilgore]

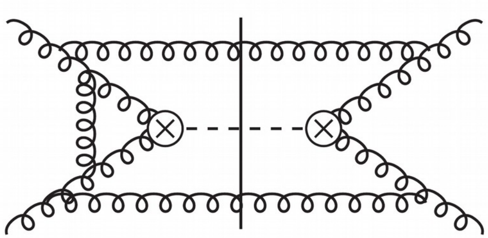
+UV and IR counter terms
Known[Pak, Rogal, Steinhauser; Anastasiou, Buehler, Duhr, FH; Höschele, Hoff, Pak, Steinhauser, Ueda; Buehler, Lazopoulos]



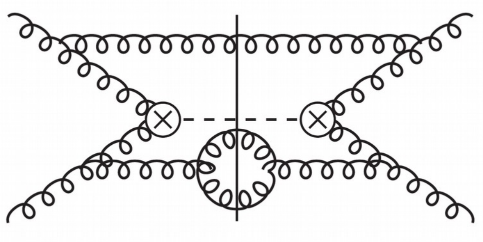
Double Virtual- Real

Known [Dulat, Mistlberger; Duhr, Gehrmann]

N3LO



Double Real - Virtual



Triple Real

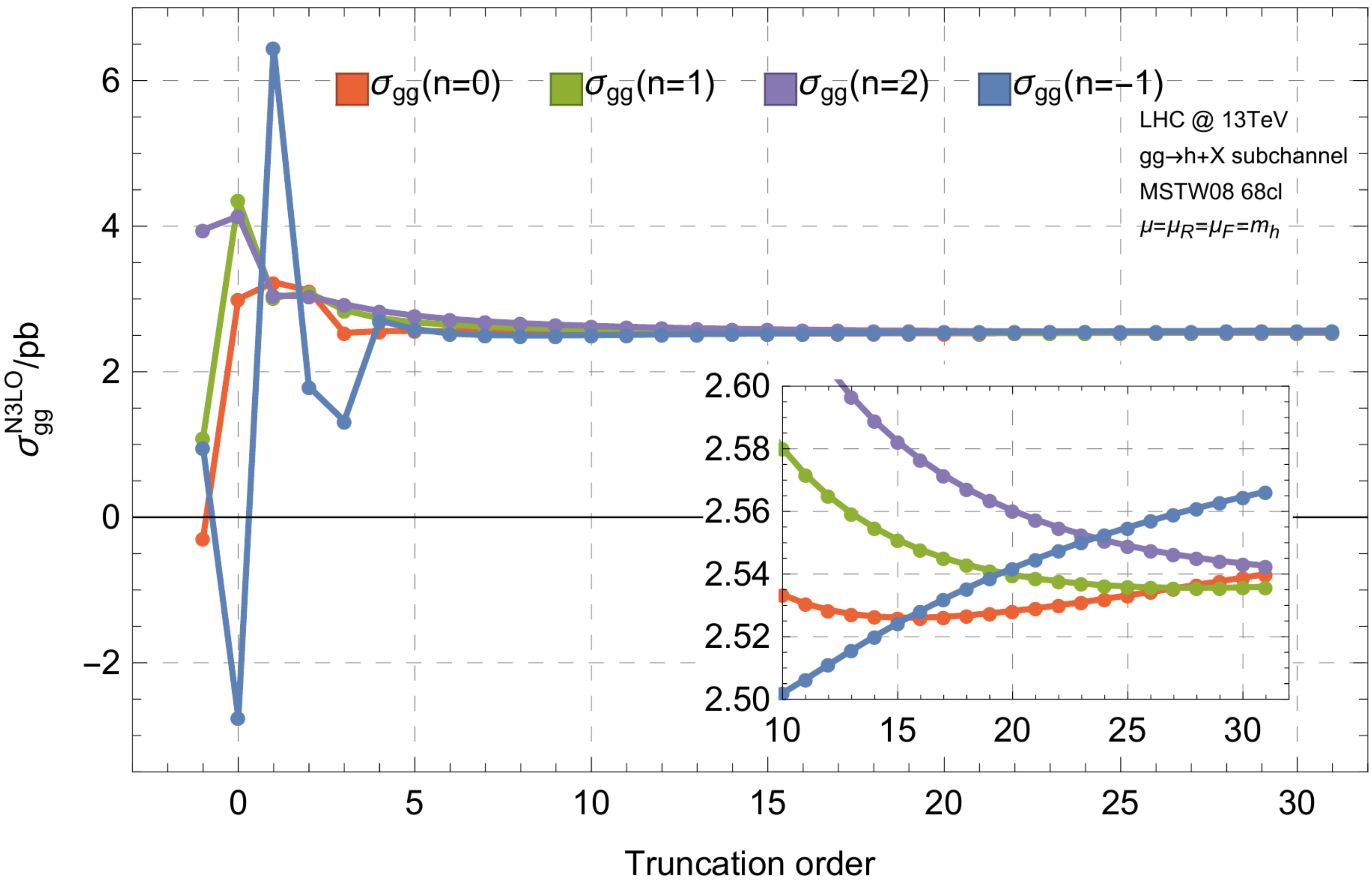
qq` channel known [Chihaya Anzai, Alexander Hasselhuhn, Maik Höschele, Jens Hoff, William Kilgore, Matthias Steinhauser, Takahiro Ueda]

2 terms in soft expansion [Anastasiou, Duhr, Dulat, FH, Mistlberger,Furlan; Li, Mantueffel, Schabinger, Zhu]
30 terms [Anastasiou, Duhr, Dulat, FH, Mistlberger]

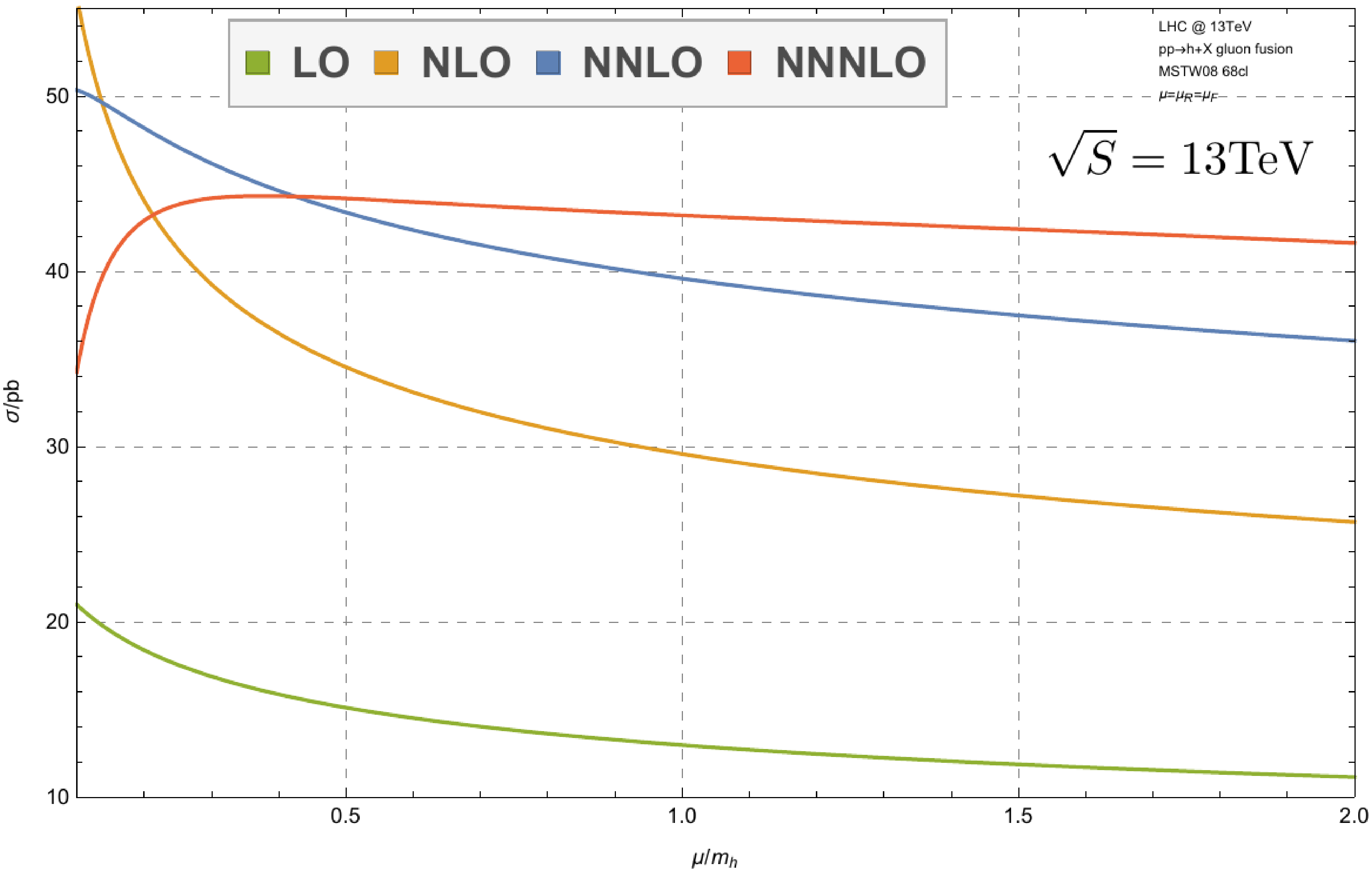
2 terms in soft expansion [Anastasiou, Duhr, Dulat, Mistlberger; Zhu]
30 terms [Anastasiou, Duhr, Dulat, FH, Mistlberger]

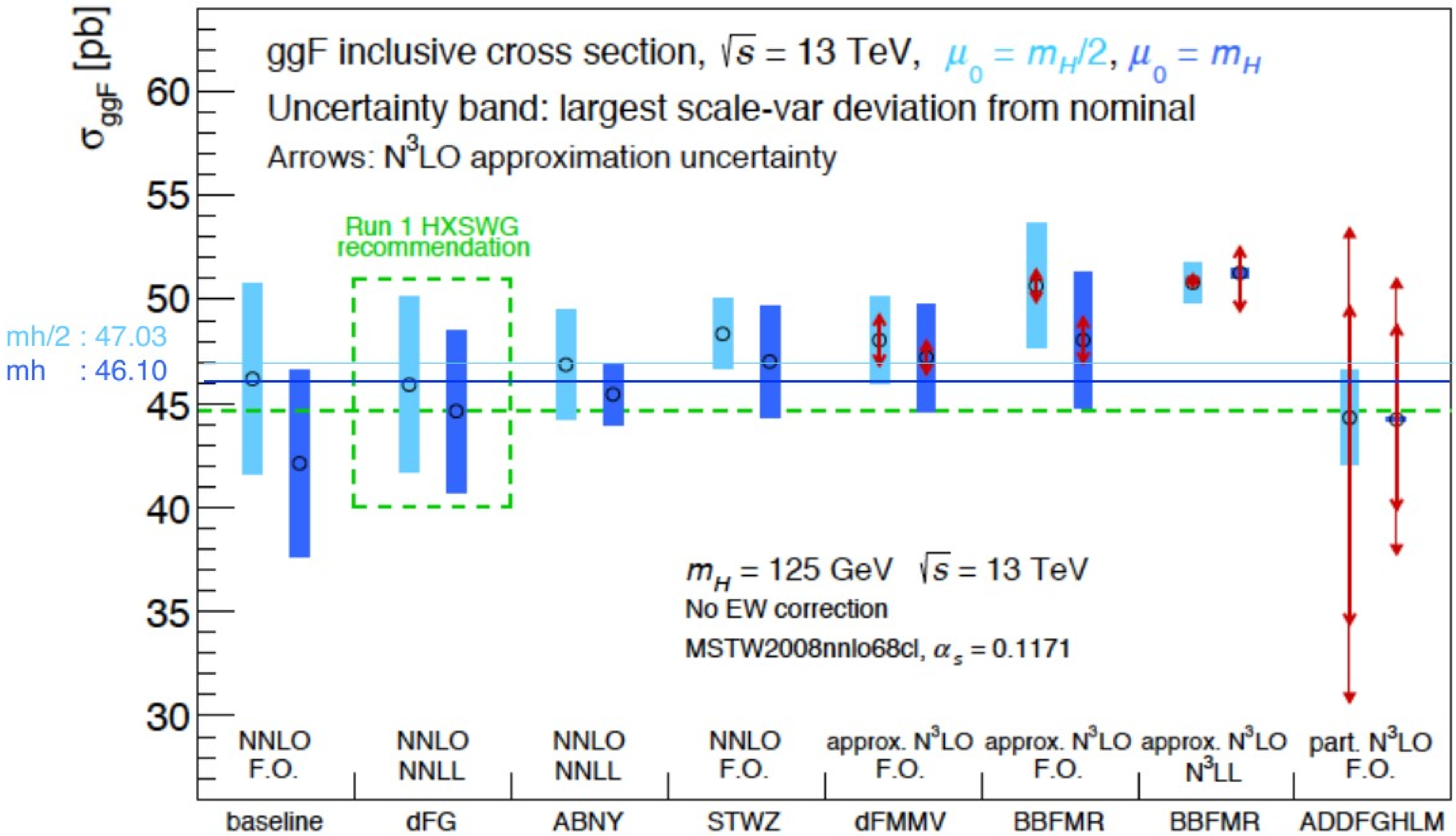
The soft Expansion at N3LO in QCD:

An extremely good approximation for Higgs productions

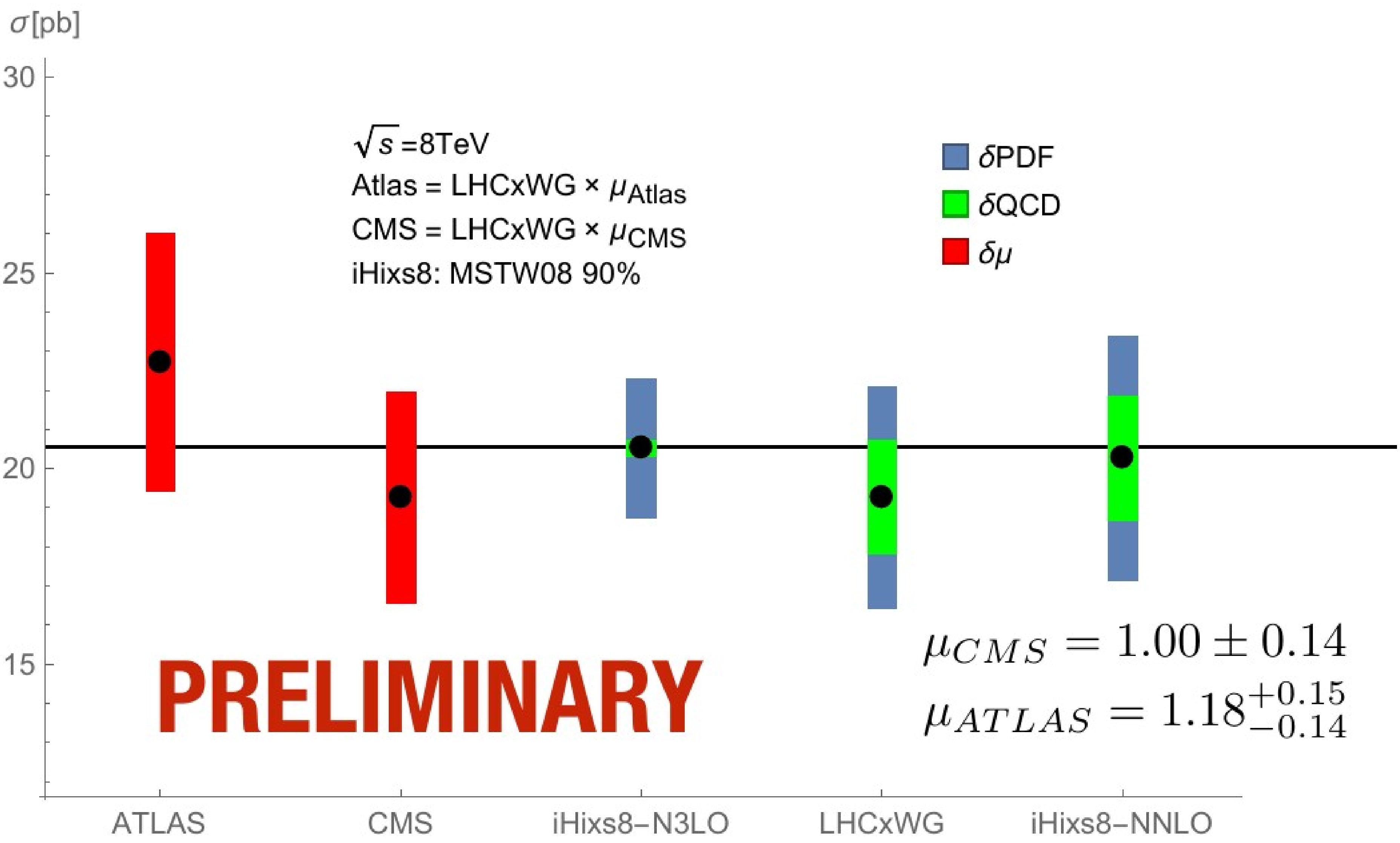


Scale Variation gives Theory uncertainty of 2-3%



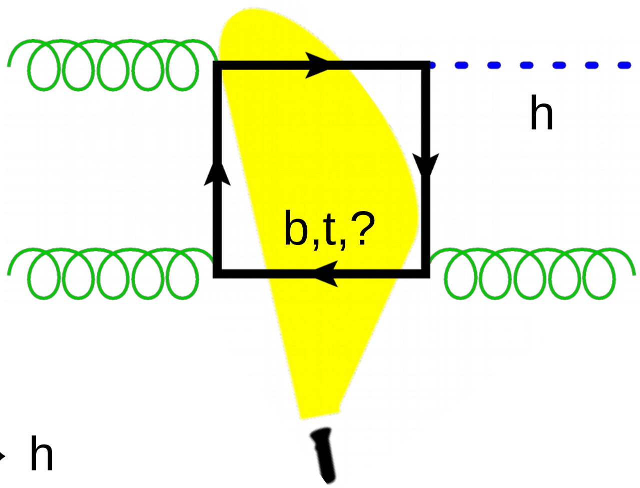


mh/2 : 47.03
mh : 46.10
σ_{ggF} [pb]
ggF inclusive cross section, $\sqrt{s}$ = 13 TeV, $\mu_0 = m_H/2$, $\mu_0 = m_H$
Uncertainty band: largest scale-var deviation from nominal
Arrows: N^3LO approximation uncertainty
Run 1 HXSWG recommendation
m_H = 125 GeV $\sqrt{s}$ = 13 TeV
No EW correction
MSTW2008nnlo68cl, α_s = 0.1171
NNLO F.O.
NNLO NNLL
NNLO NNLL
NNLO F.O.
approx. N^3LO F.O.
approx. N^3LO F.O.
approx. N^3LO N^3LL
part. N^3LO F.O.
baseline
dFG
ABNY
STWZ
dFMMV
BBFMR
BBFMR
ADDFGHLM


σ[pb]
30
25
20
15
$\sqrt{s}$=8TeV
Atlas = LHCxWG × μ_{Atlas}
CMS = LHCxWG × μ_{CMS}
iHixs8: MSTW08 90%
δPDF
δQCD
δμ
PRELIMINARY
$\mu_{CMS} = 1.00 \pm 0.14$
$\mu_{ATLAS} = 1.18^{+0.15}_{-0.14}$
ATLAS
CMS
iHixs8−N3LO
LHCxWG
iHixs8−NNLO

Higgs+Jet

Higgs+Jet



- Is a subprocess of gg → h

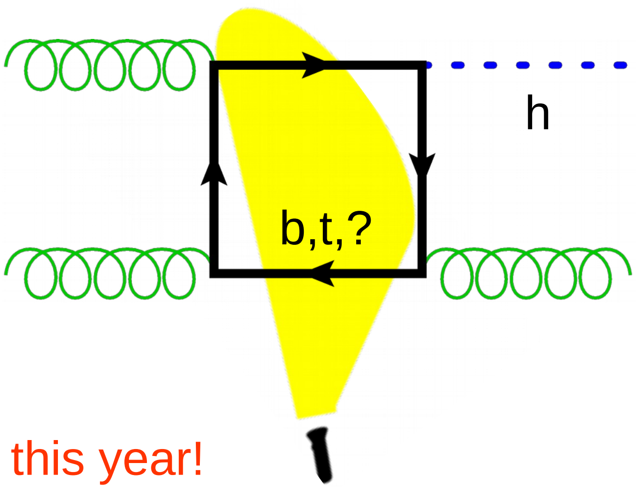
- Higgs transverse momentum is generated from jet recoil!

- By tagging on a jet, major backgrounds can be eliminated in several decay channels, like WW, or γγ

- Independent information about the Higgs coupling to gluons can be extracted from its pt-spectrum

- QCD K-factors are similarly as in gluonfusion → NNLO is mandatory!
- Jet-veto may need resumation

Higgs+Jet

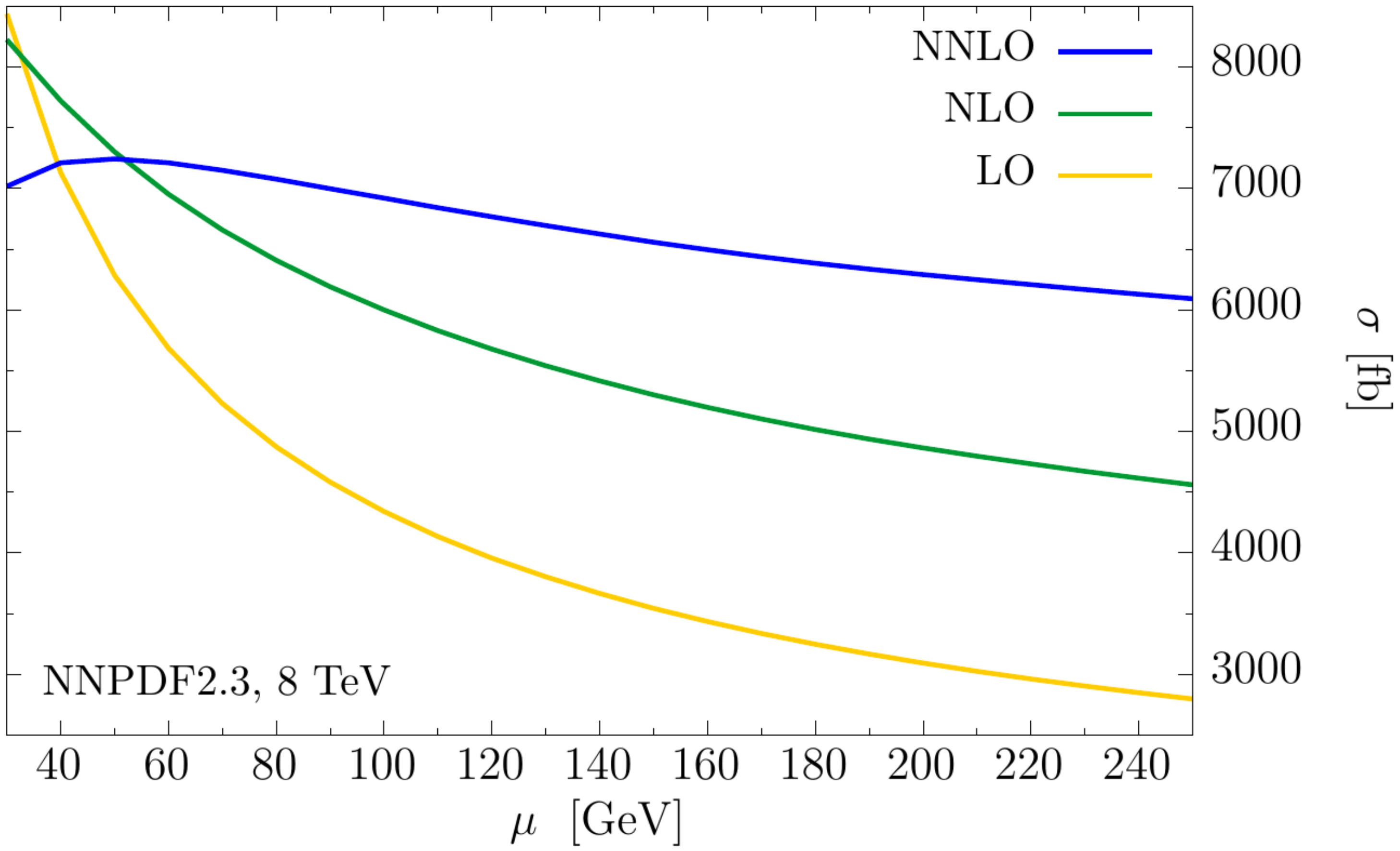


- NNLO QCD in HQET this year!
  - Sector Improved Subtraction
    [Boughezal, Caola, Melnikov, Petriello, Schulze]
    (with decays) [Caola, Melnikov, Schulze]
  - NJettiness improved Slicing
    [Boughezal, Focke, Giele, Liu, Petriello]
  - Antennas (gg channel only)
    [Chen, Gehrmann, Glover, Jaquier]
- NLO EW known

- Resumations:
  - 0-Jet Veto:[Banfi, Salam, Zanderighi; Becher Neubert; Stewart, Tackmann, Zuberi; Tackmann, Walsh]
  - 1-jet veto: [Liu, Petriello]

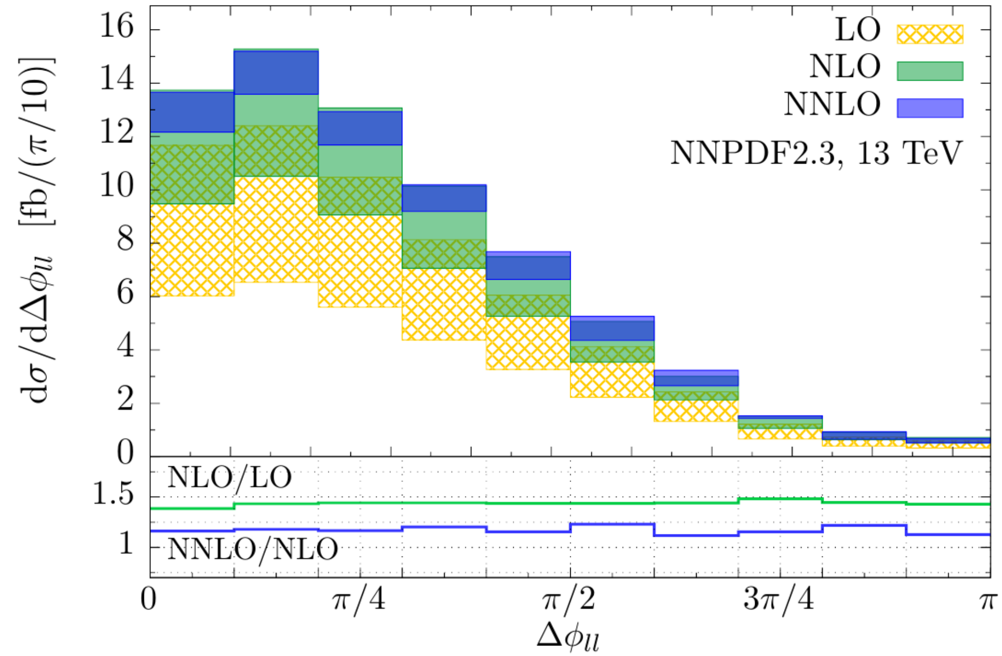
Higgs+Jet

$$\text{Anti} - k_\perp \text{ with } R = 0.5,\ k_\perp > 30\,\text{GeV}$$



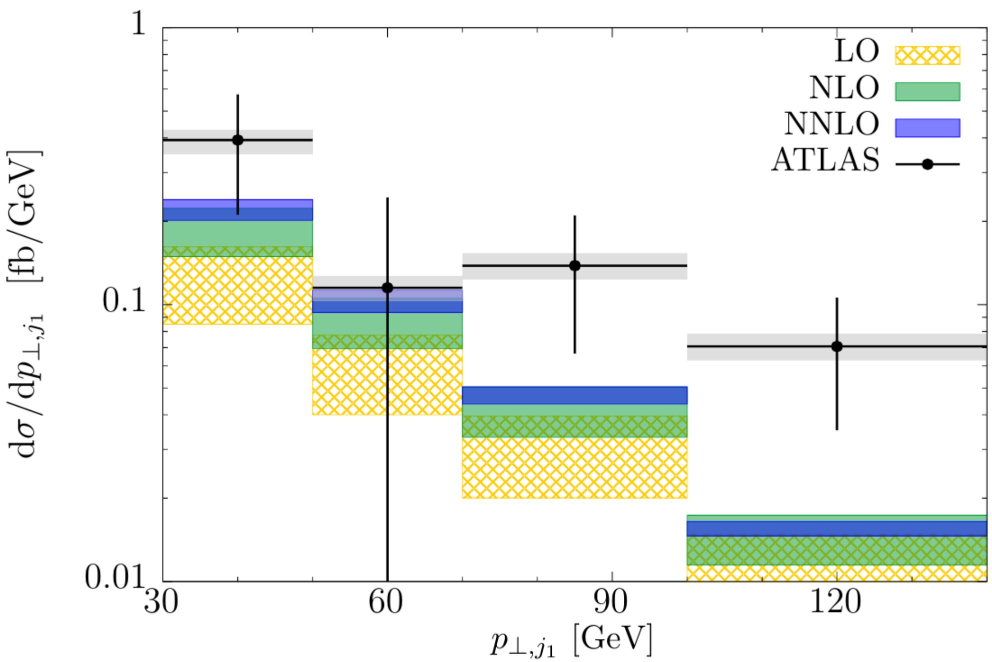
Fiducial Cross Sections arXiv:1508.02684

$$pp \to H(e^+\mu^-\nu\bar{\nu}) + j$$



$$pp \to H(\gamma\gamma) + j$$

NNLO Jet pt confronts ATLAS data



Azimuthal opening angle of two lepton in H→ WW decay

The 0-jet Bin at N3LO

Combining H@N3LO and H+j@NNLO

$$\sigma^{N3LO}_{n_J=0}(p^{cut}_\perp) = \sigma^{N3LO}_{inclusive} - \sigma^{NNLO}_{n_J\geq 1}(p^{cut}_\perp)$$

$$\mathrm{Anti} - k_\perp \text{ with } R = 0.5,\ k_\perp > 30\,\mathrm{GeV}$$

Preliminary

0-jet bin

ord	$\sigma^{\mathrm{f.o.}}_{0-\mathrm{jet}}$ (JVE)	$\sigma^{\mathrm{f.o.+NNLL}}_{0-\mathrm{jet}}$ (JVE)	$\sigma^{\mathrm{f.o.+NNLL}}_{0-\mathrm{jet}}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
$\mathrm{N^3LO}$	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\mathrm{f.o.}}_{\geq 1-\mathrm{jet}}$ (scales)	$\sigma^{\mathrm{f.o.}}_{\geq 1-\mathrm{jet}}$ (JVE)	$\sigma^{\mathrm{f.o.+NNLL}}_{\geq 1-\mathrm{jet}}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

[Caola, Dulat, Monni]

- Good perturbative convergence for these parameters!
- Lower order uncertainties well estimated.
- Re-summation not required.

Conclusions

- A new Era of Higgs Precision Physics has begun at the LHC! Theory is *(almost)* ready.
- N3LO Barrier has fallen! NNLO is becoming the new standard!!
- The theory uncertainties in Higgs Production have decreased dramatically
  Scale ~ 3% ~ PDF (next talk)
- Higgs+jet theory uncertainties are under control:
  Scale ~ 6-8%, PDF ~ 5%???
- In order to start controlling at percent level. Need get solid control on:
  - PDF + α_s Uncertainties
    - N3LO PDFs?
  - Electroweak corrections
  - Top, bottom mass corrections
  - Non-perturbative/factorisation breaking corrections
  - Fully Differential (Rapidity) at N3LO

Jet veto Re-summation