Precision phenomenology with MCFM

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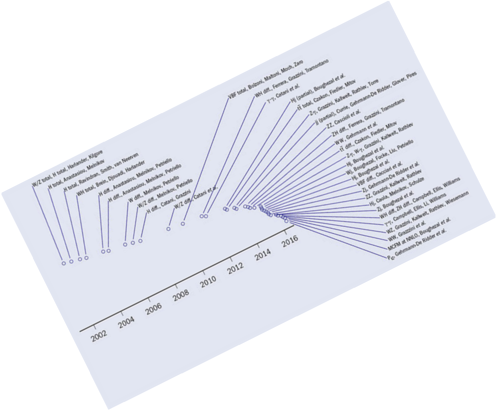
July 15th, 2019

"Explosion" of NNLO calculations

- Only few fully differential codes are public:
  - $\boldsymbol{W/Z}$: DYNNLO (NNLL small q_T in DYres), FEWZ (NLO EW effects), GENEVA (Z, NNLL q_T and thrust)
  - **Higgs**: HNNLO (NNLL small q_T in HRes), SusHi (BSM, mass effects), FehiPro (mass effects)
  - $\boldsymbol{\gamma\gamma}$: 2$\gamma$NNLO



- MATRIX: $Z, W, H, \gamma\gamma, ZZ, WW, WZ, Z\gamma$
- MCFM: $Z, W, H, \gamma\gamma, WH, ZH, Z\gamma$

Some motivation: W and Z production

1612.03016: Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector

- Data together with HERA combined into NNLO PDF set/analysis: ATLAS-epWZ16
  - Fiducial cross sections: FEWZ-DYNNLO difference of up to 1.2%!
  - Experimental uncertainties: 0.6%

- Measurement of $|V_{cs}|$

Measurement of $|V_{cs}|$

1612.03016

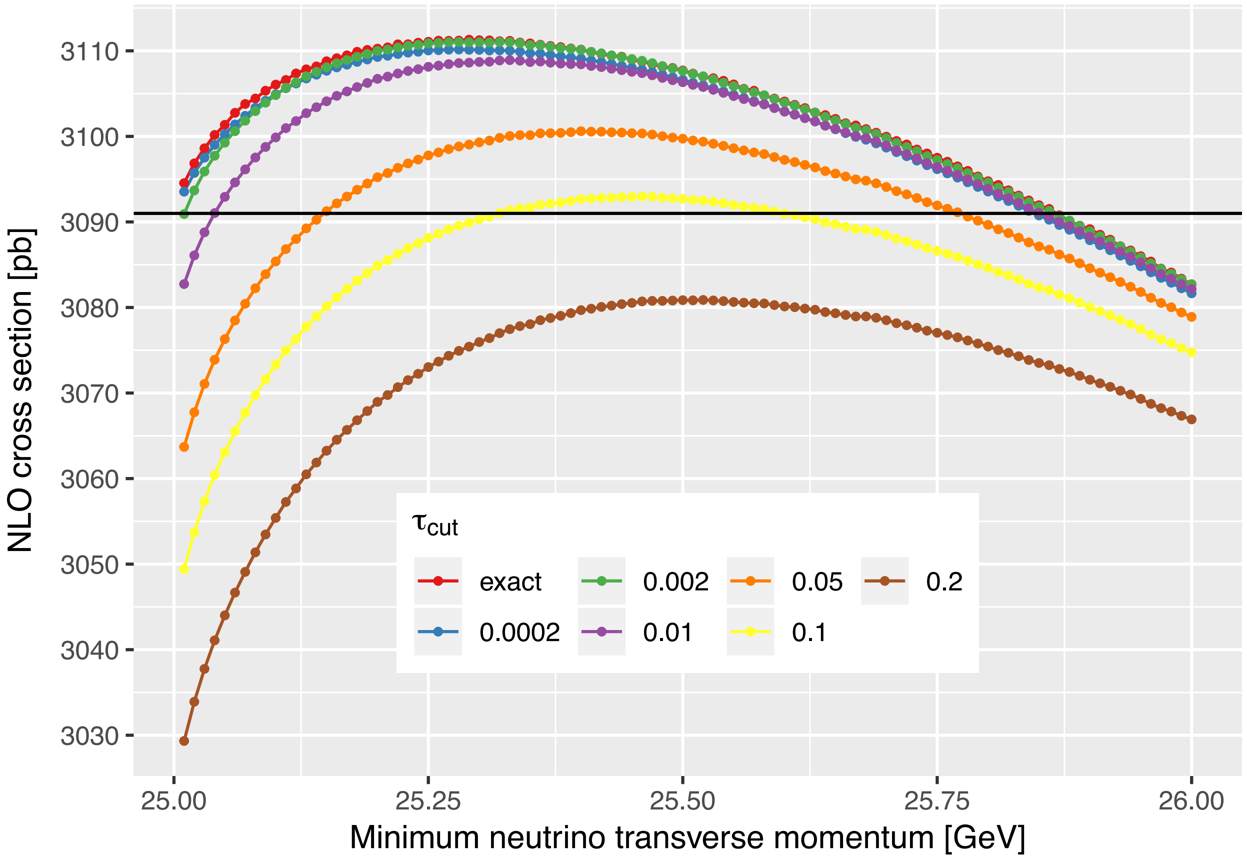
	$\|V_{cs}\|$
Central value	0.969
Experimental data	± 0.013
Model (m_b, Q^2_{min}, Q^2_0 & m_c)	$^{+0.006}_{-0.003}$
Parameterization	$^{+0.003}_{-0.027}$
α_S	± 0.000
EW corrections	± 0.004
QCD scales	$^{+0.000}_{-0.003}$
FEWZ 3.1b2	$+0.011$
Total uncertainty	$^{+0.018}_{-0.031}$

Table 22: Summary of the central value and all uncertainties in the CKM matrix element $|V_{cs}|$.

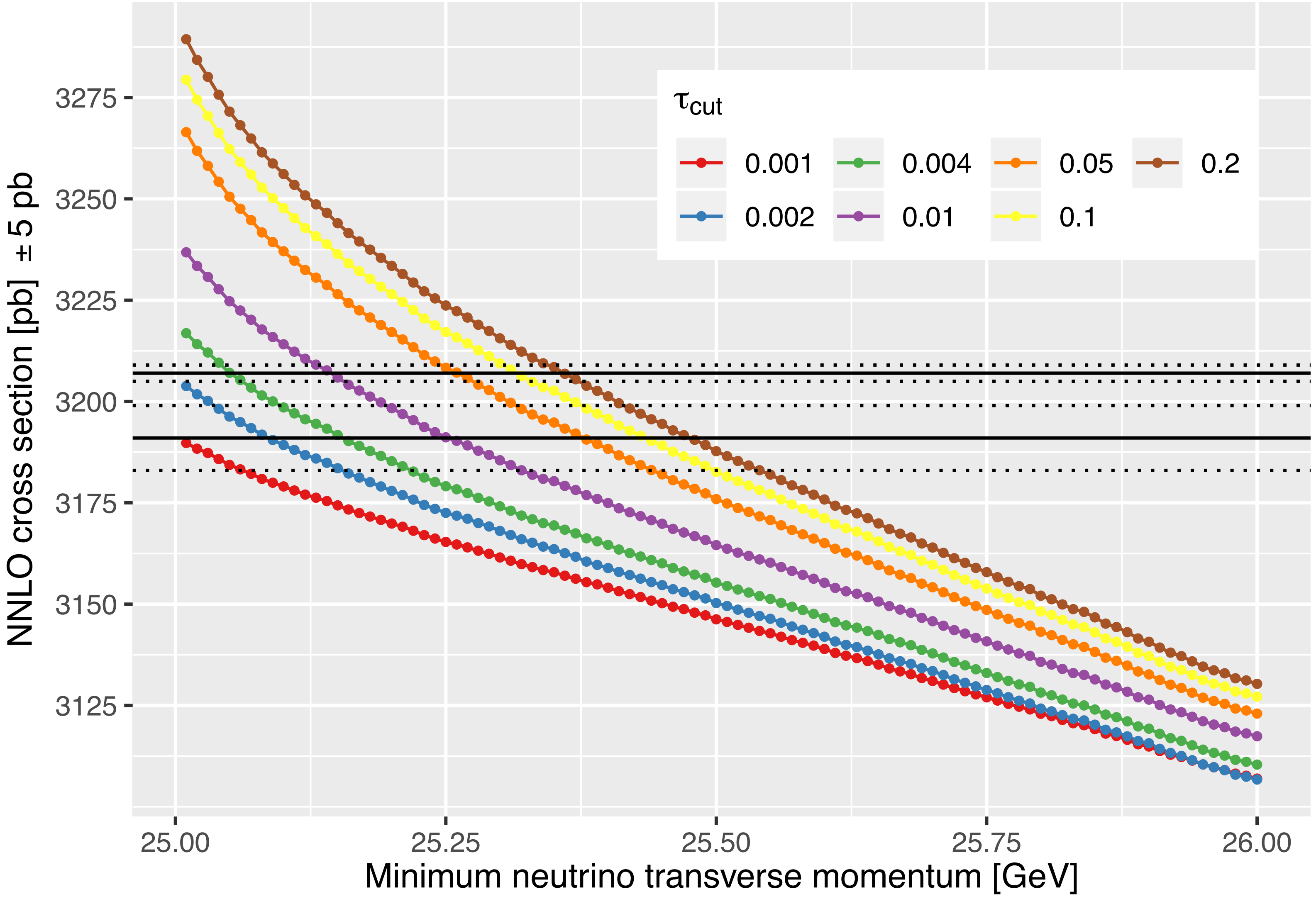
"FEWZ DYNNLO" uncertainty **purely numerical**

Symmetric p_T cuts

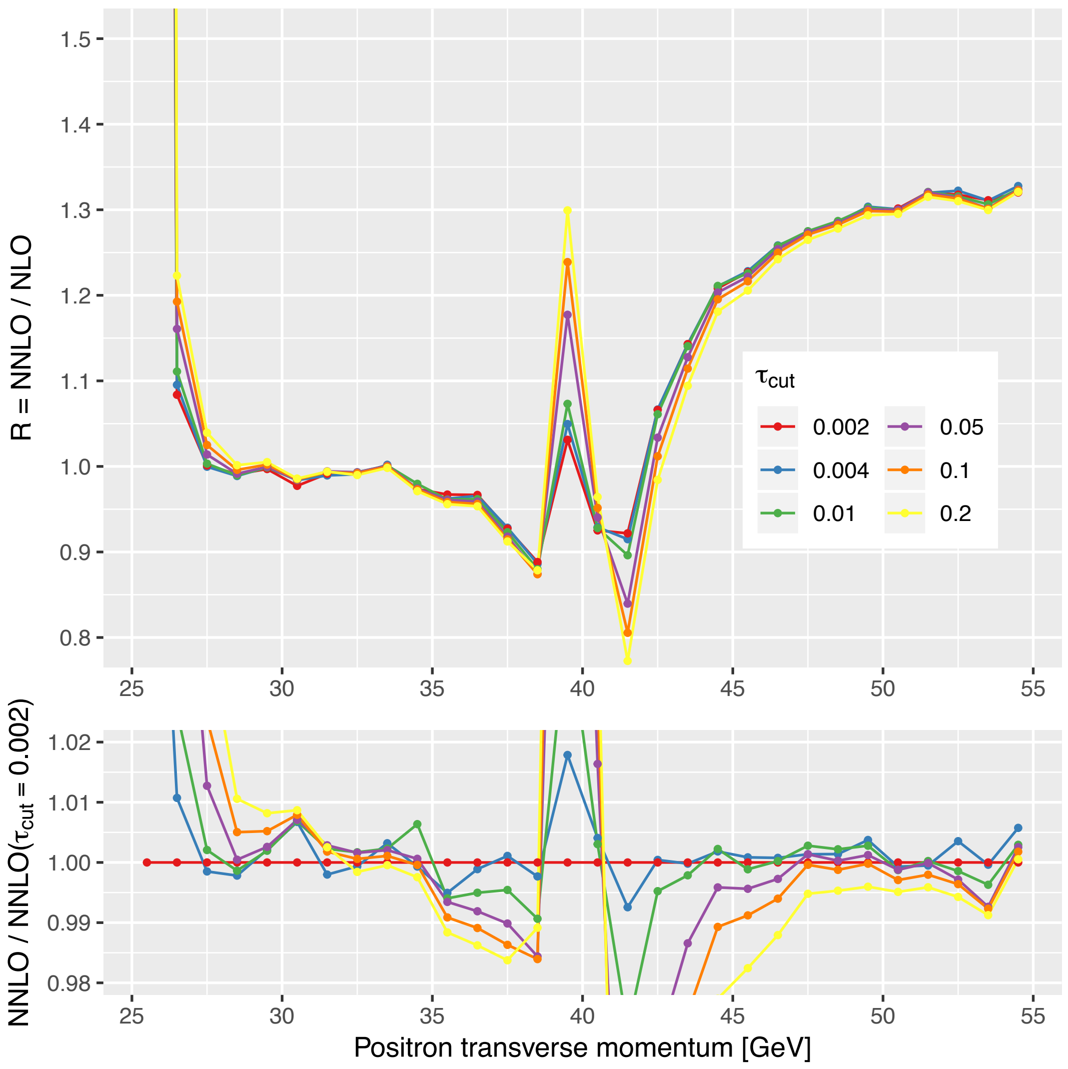
- Exposed to collinear singularity with a cutoff $\sim \delta \cdot \log(\delta)$ *(Frixione, Ridolfi '97)*
- Used in experimental studies and theory benchmark papers
  1606.02330: FEWZ, DYNNLO, SHERPA authors comparison



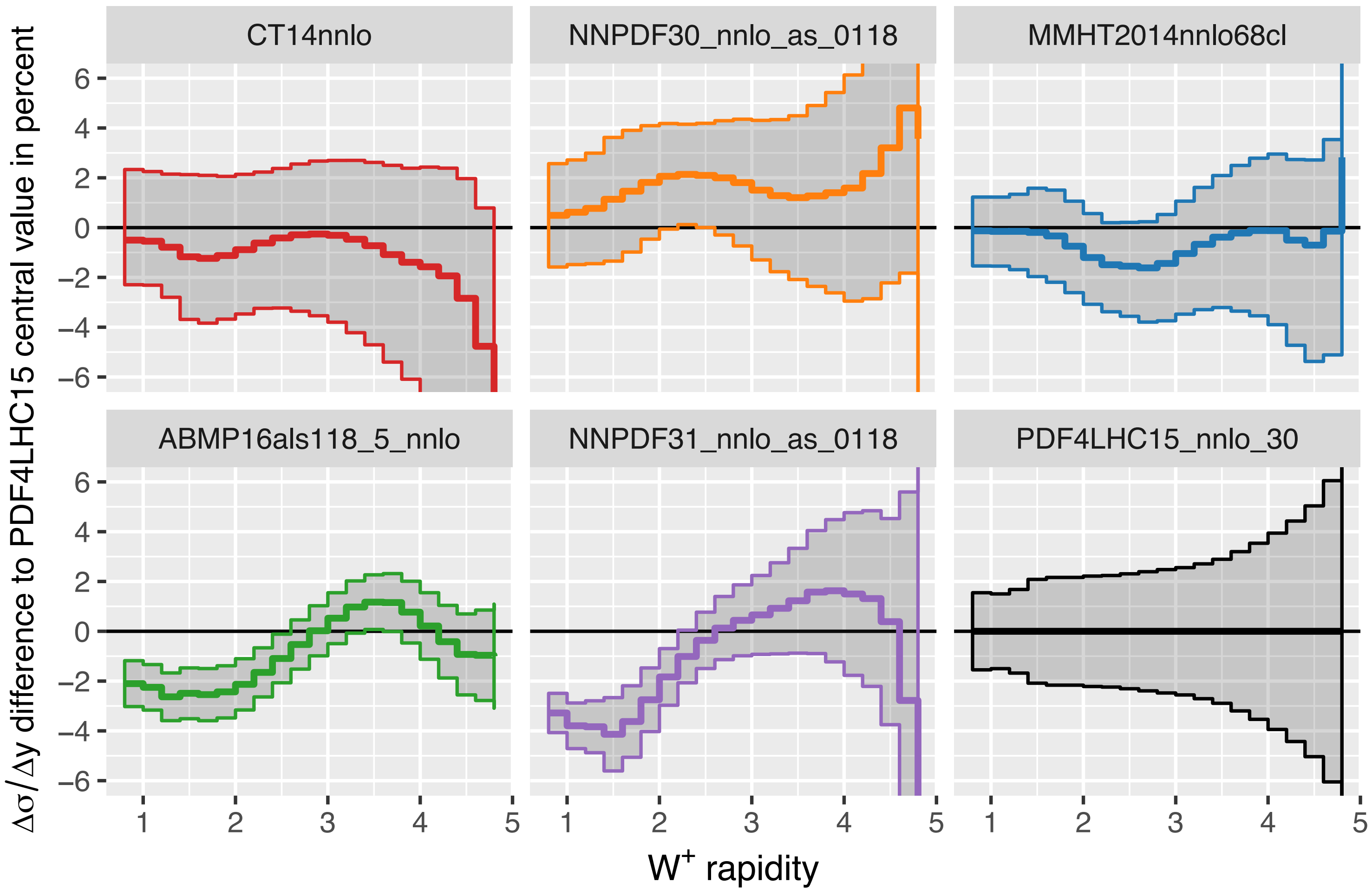
NNLO W^+ cross section with varied missing energy



W^+ benchmark plot as in 1606.02330



NNLO PDF uncertainties



Six PDF sets with 371 members in total

MCFM at a glance

MCFM well established parton level Monte Carlo code

(since '99 Campbell; Ellis; Campbell, Ellis, Williams '11)
2015: MCFM-7.0 with OpenMP (Campbell, Ellis, Giele)
2016: MCFM-8.0 with NNLO, MPI (Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams)

- NLO cross sections: Catani-Seymour dipoles

  Hundreds of processes/decays
  Recently added: EW one-loop corrections; Higgs+jet w/ top-mass effects, off-shell single-top SMEFT
- NNLO cross sections: N-jettiness subtractions

  Most single and diboson processes
- Extensively tested on Linux, Mac, BSD's
- No further external dependency requirements
  - Helicity amplitudes contained in "analytical" form
  - QCDLoop2 included as 1-loop provider
- Optional: LHAPDF, MPI implementation library

NNLO processes in MCFM: Color singlets

	public in MCFM
H	1605.08011: Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams
Z (w. NLO EW)	
$W^{\pm}$	
ZH	
$W^{\pm}H$	1601.00658: Campbell, Ellis, Williams
γ	1612.04333: Campbell, Ellis, Williams
$\gamma\gamma$	1603.02663: Campbell, Ellis, Li, Williams
$Z\gamma$	1708.02925: Campbell, Neumann, Williams

NNLO processes in MCFM: Jet processes

	reference
$W^\pm + \mathrm{jet}$	*1504.02131: Boughezal, Focke, Liu, Petriello*
$H + \mathrm{jet}$	*1505.03893: Boughezal, Focke, Giele, Liu, Petriello* *1906.01020: Campbell, Ellis, Seth*
$Z + \mathrm{jet}$	*1512.01291: Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello*
$\gamma + \mathrm{jet}$	*1703.10109: Campbell, Ellis, Williams*

None of these public yet

CPU budget for +jet processes: $\mathcal{O}(1000)$ hours

MCFM-9.0

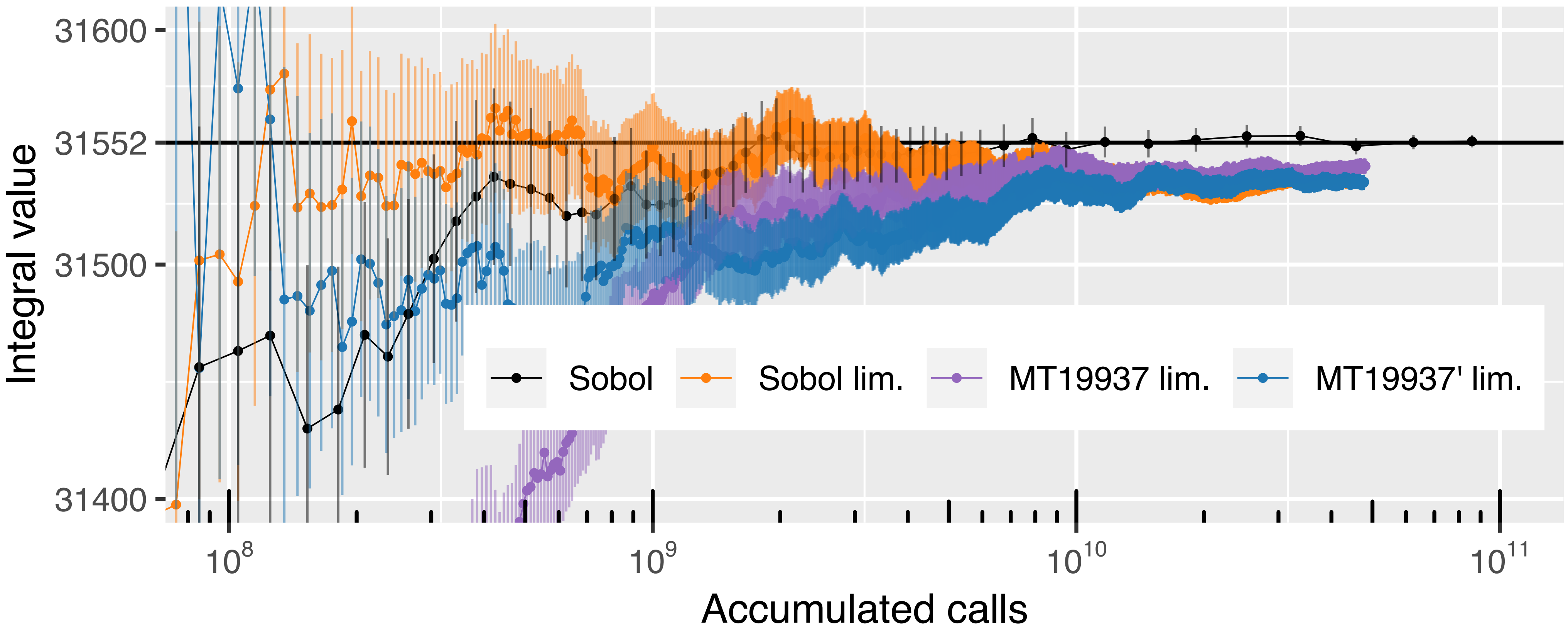
- Completely new core components:
  - Intel compiler compatibility: 10-15% performance benefit
  - Integration: part adaptive, low-discrepancy sequence
  - Histogramming
  - Automatic scale and PDF+α_s uncertainties at NNLO, fully differential
  - NNLO: Multiple τ_{cut} at once with asymptotic fitting

- Major code cleanup, increase hackability & maintainability

  Previous MCFM forks: DYNNLO, HNNLO, DYRes, HRes, MFCM-RE; many more codes make use of MCFM amplitudes and routines

```
./Install && make
```

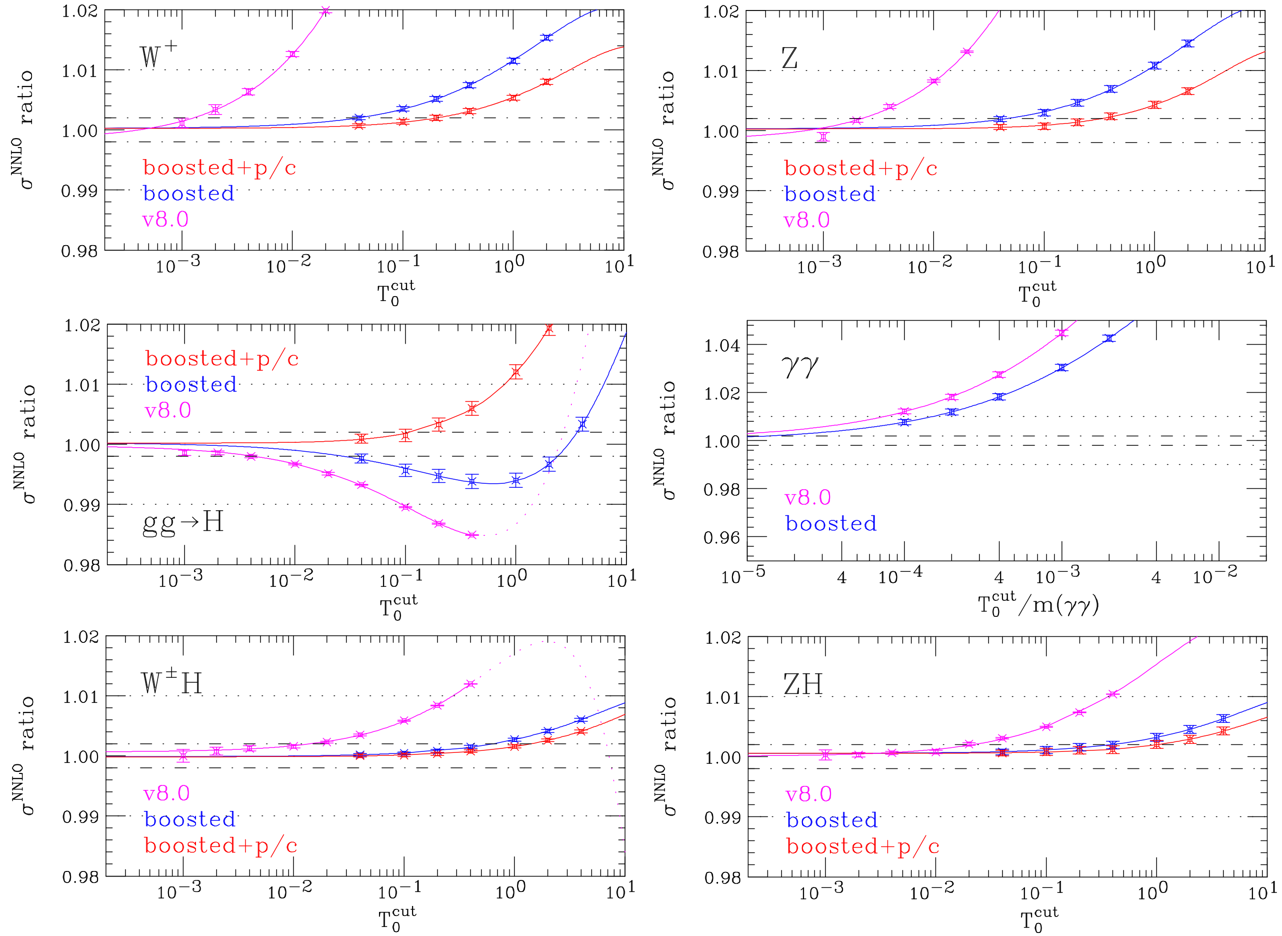
Numerical control matters



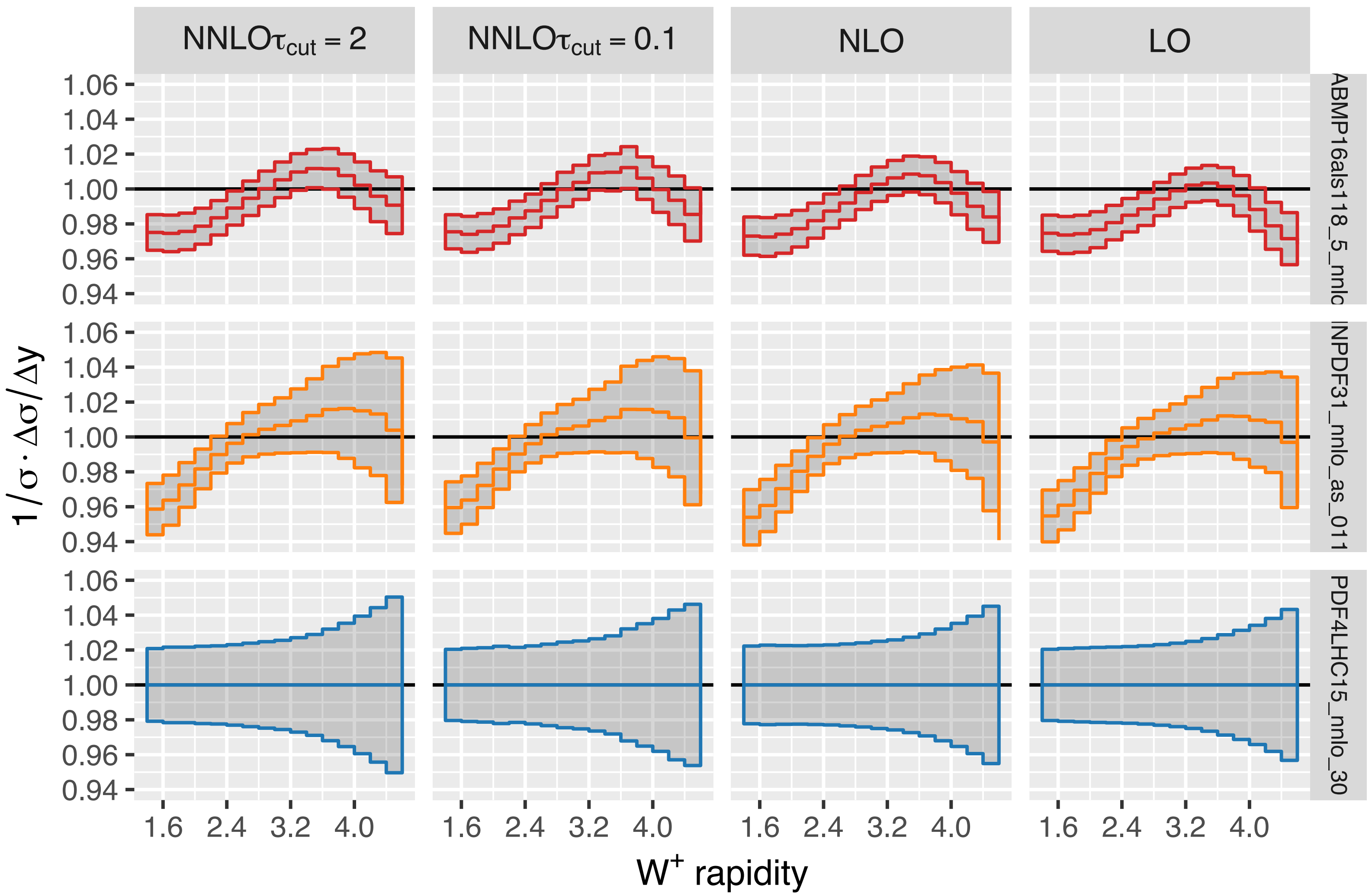
NNLO Higgs production double real emission
precision goal for total cross section 0.2%

Performance matters

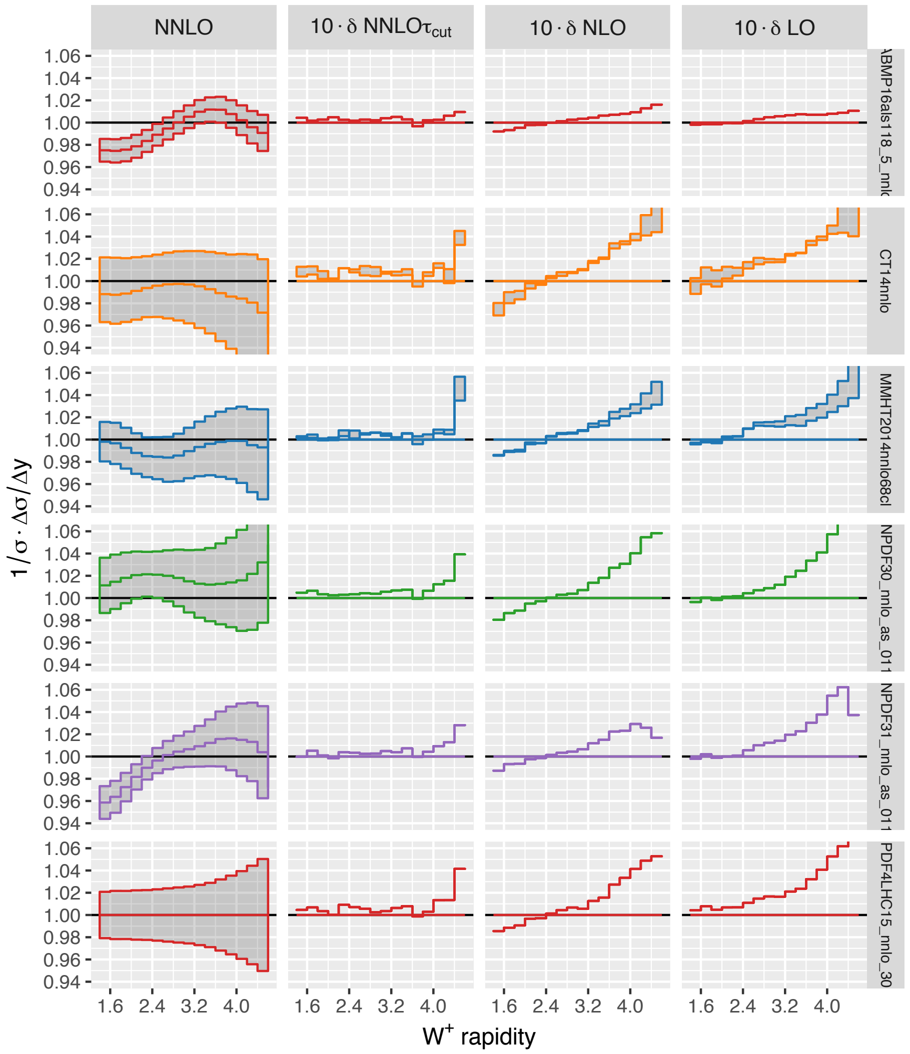
Per-mille NNLO cross sections on your desktop ✔



Go, spot the differences!



371 PDF set members, 1 day, 16 computers (from 2010)



High precision determination of the gluon fusion Higgs boson cross-section at the LHC

Charalampos Anastasiou[a], Claude Duhr[b,c*], Falko Dulat[a], Elisabetta Furlan[a], Thomas Gehrmann[e], Franz Herzog[f], Achilleas Lazopoulos[a], Bernhard Mistlberger[b]

For a Higgs mass of $m_H = 125$ GeV and an LHC center-of-mass energy of 13 TeV, our best prediction for the gluon fusion cross-section is

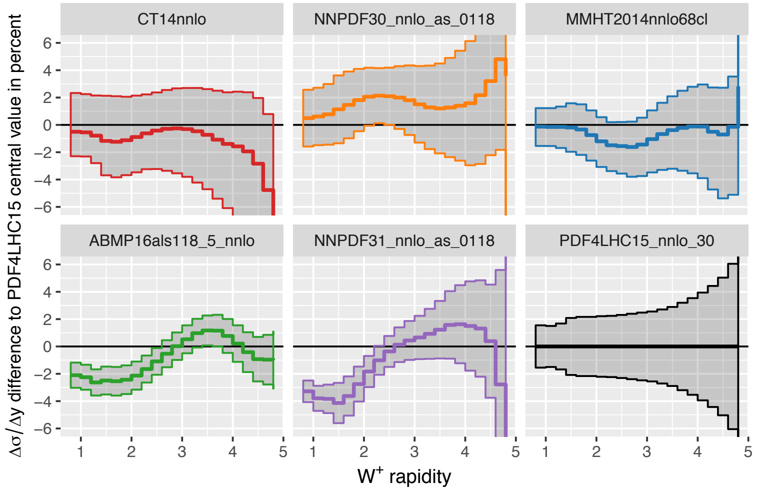
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

vs. 1603.08906: "A critical appraisal and evaluation of modern PDFs"

authors find PDF+α_s of 13%

MCFM-9.0 Summary

- Several orders of magnitude performance improvements
- Easier to use and hack than ever (framework with analytical amplitudes for further applications)
- Automatic PDF+α_s uncertainties at NNLO, fully differentially
- NNLO: multiple τ_{cut} with **asymptotic fitting**, fully differentially



Available in August at
https://mcfm.fnal.gov/