Vector pair cross sections at 100 TeV

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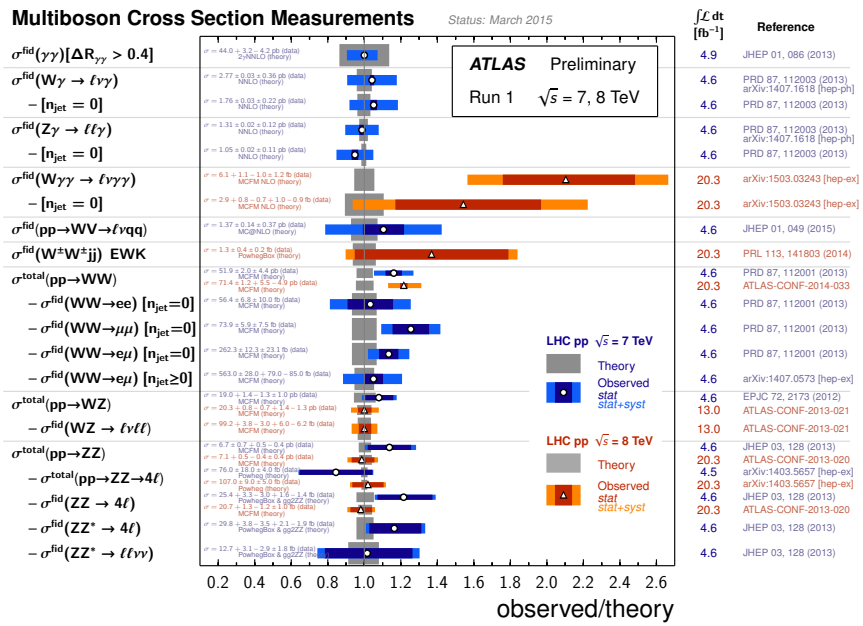
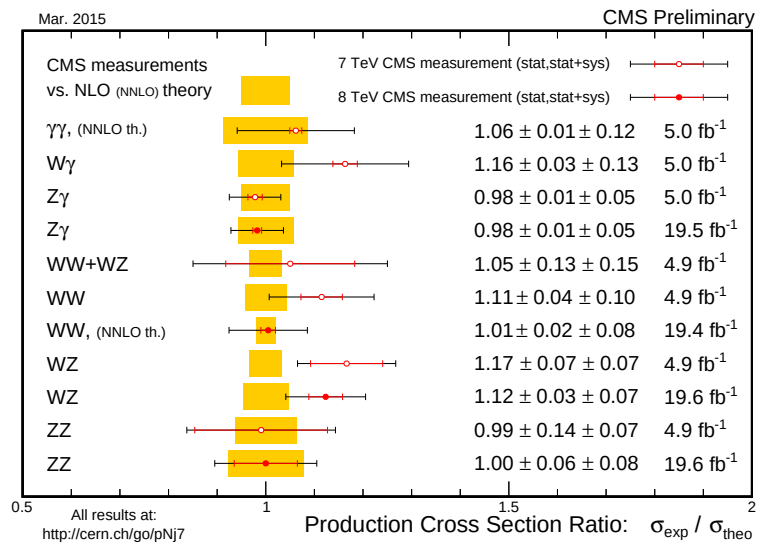
Vector boson pair production

- vector boson pair production $pp \to VV'$ is a crucial part of the LHC physics programme
  - important standard model test, directly probes non-Abelian interactions
    $\Rightarrow$ gives access to anomalous couplings
  - background for Higgs analyses and BSM searches



[ATLAS collaboration (2015)]



[CMS collaboration (2015)]

QCD corrections: ingredients

- NLO QCD corrections available for all diboson processes, including correlations and off-shell effects, for example in MCFM

  [Campbell, Ellis, Williams (2011)]

- NNLO subtraction well understood, e.g. q_T subtraction [Catani, Grazzini (2007)]
- up to now: bottleneck were the two-loop amplitudes, but now the list is finally complete:
  - $\gamma\gamma$: [Anastasiou, Glover, Tejeda-Yeomans (2002)]
  - $Z\gamma$ and $W\gamma$: [Gehrmann, Tancredi (2012)]
  - VV on-shell: [Gehrmann, von Manteuffel, Tancredi, Weihs (2014)]
  - VV': [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); Gehrmann, von Manteuffel, Tancredi (2015)]
- [Gehrmann, von Manteuffel, Tancredi (2015)] provide a stable and sufficiently fast numerical implementation of the helicity amplitudes
- in the not so far future: perturbative accuracy of all diboson processes at full NNLO in QCD!

QCD corrections: gluon fusion contributions

- for $\gamma\gamma$, $Z\gamma$, ZZ and W^+W^- there is loop-induced gluon fusion contribution:

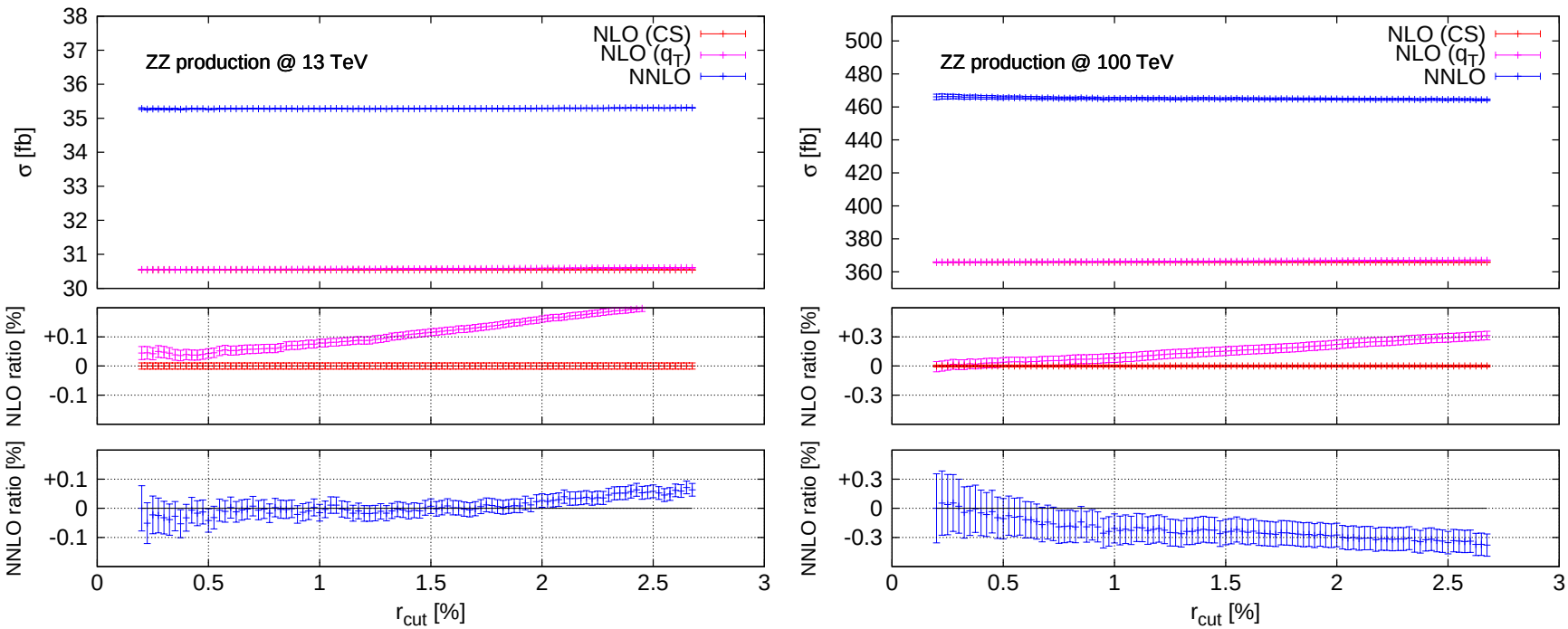
$$gg \to VV'$$

- formally starts to contribute at $\mathcal{O}\left(\alpha_S^2\right)$, i.e. at NNLO
- known to leading order (NLO requires two-loop amplitudes)
- contribution between the $\lesssim 1\%$ ($Z\gamma$) and the 5% level (ZZ and W^+W^-)
- for ZZ and W^+W^- this is the largest source of theoretical uncertainty after inclusion of NNLO corrections
- now the dominant part of the two-loop amplitudes is known

  [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); von Manteuffel, Tancredi (2015)]
- first results for $gg \to ZZ$ have appeared [Caola, Melnikov, Röntsch, Tancredi (2015)]

q_{T} subtraction at 100 TeV

- need small technical cut on q_{T}
- cross section has to become independent of $r_{\mathrm{cut}} \equiv q_{\mathrm{T}}^{\mathrm{cut}}/M_F$
  $\Rightarrow$ strong check on correctness
- need to integrate into the deep infrared, numerically very challenging



$pp \to ZZ$

- **all results preliminary!**
- 4 lepton production with $66\,\text{GeV} < m_{\ell\ell} < 116\,\text{GeV}$ cuts

		LO	NLO	NLO+gg	NNLO
13 TeV	σ [fb]	24.7	30.5	33.4	35.3
	rel. correction		23%	10%	16%
100 TeV	σ [fb]	303	366	437	466
	rel. correction		21%	19%	26%

- corrections to $q\bar{q}$ channel grow slightly
- gg fusion contribution significantly enhanced at 100 TeV

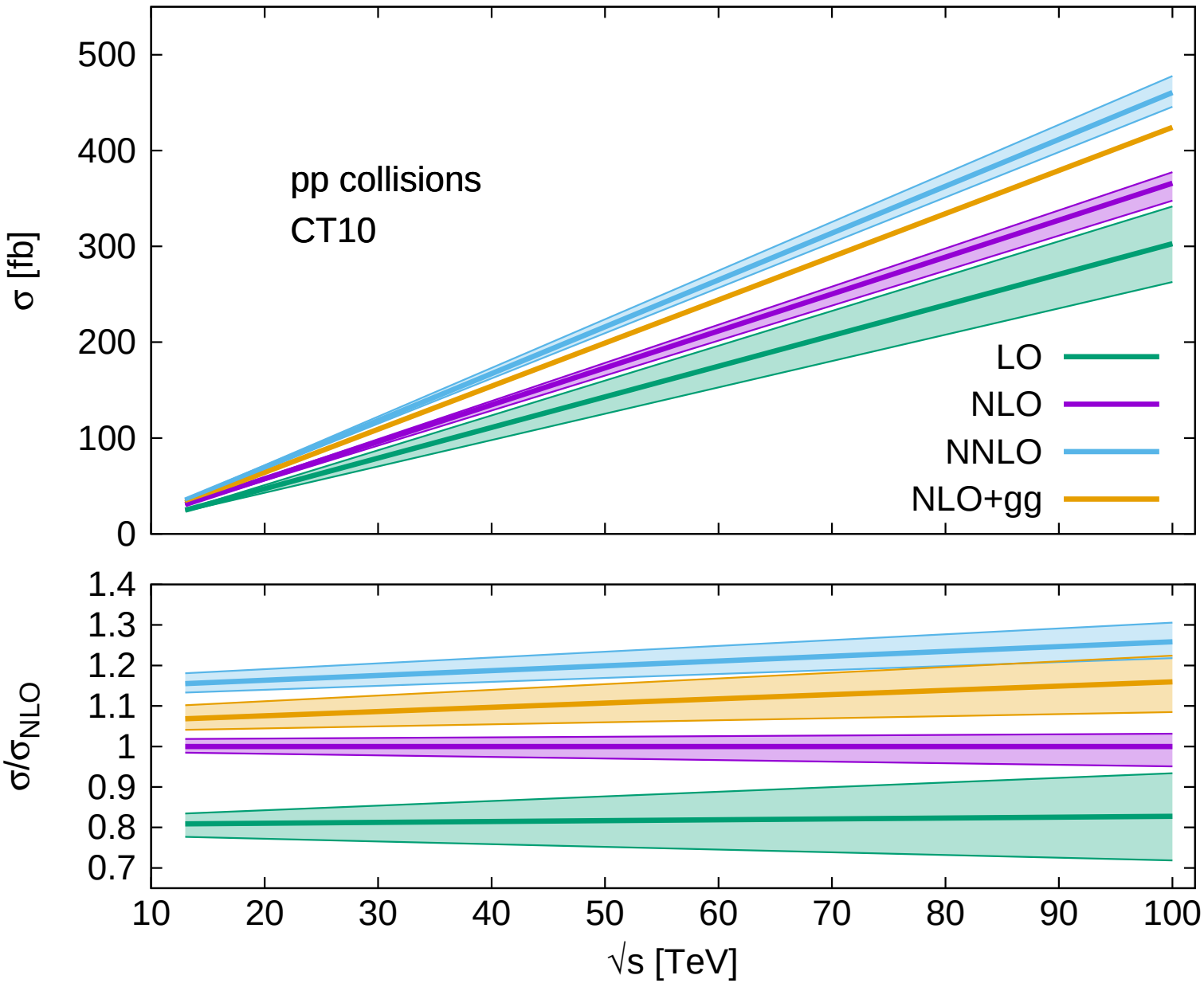
$pp \to ZZ$: scale and PDF uncertainties

- 7-point-variation of μ_F and μ_R
- CT10 and MMHT2014 PDF sets

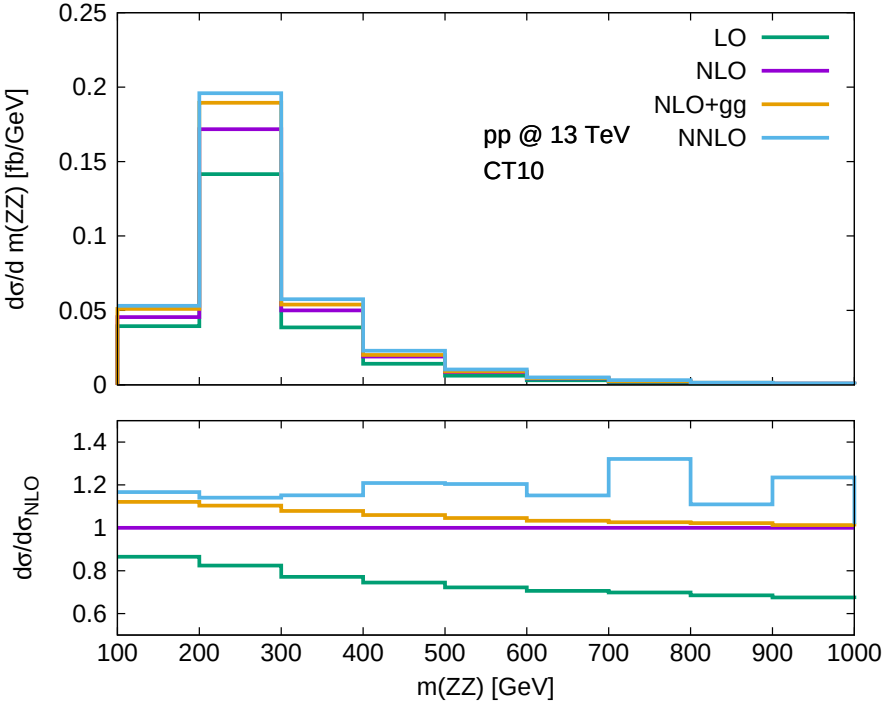
		LO	NLO	NLO+gg	NNLO
13 TeV	scales	$\pm 4\%$	$\pm 2\%$	$\pm 3\%$	$\pm 2\%$
	PDFs (CT10)	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$	$\pm 2\%$
	PDFs (MMHT2014)	$\pm 1\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
100 TeV	scales	$\pm 13\%$	$\pm 4\%$	$\pm 5\%$	$\pm 4\%$
	PDFs (CT10)	$\pm 6\%$	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$
	PDFs (MMHT2014)	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$

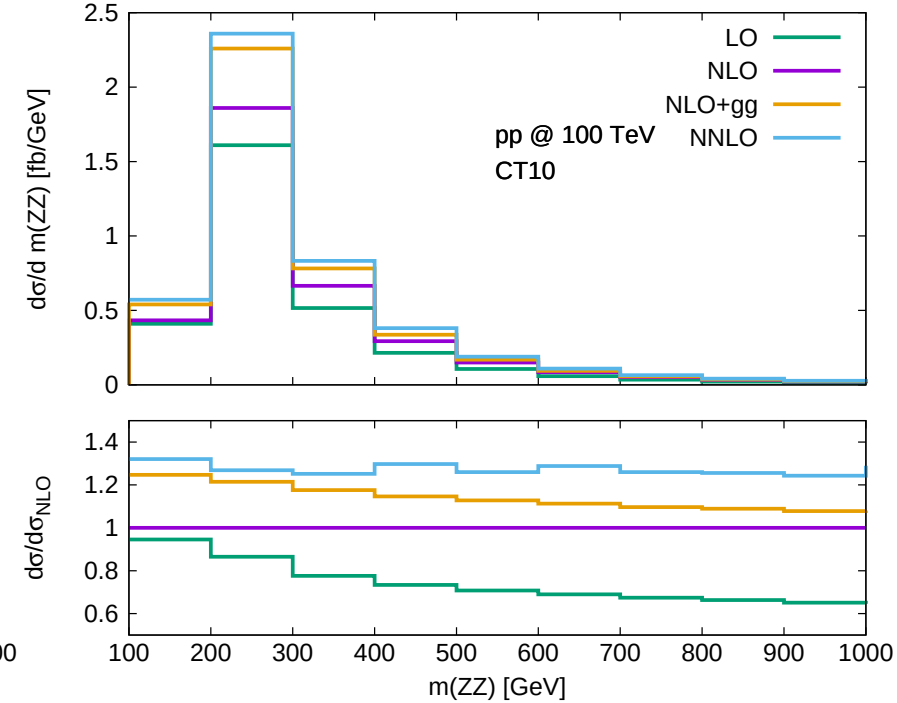
- cross sections with different PDF sets compatible within uncertainties ($< 1\%$ differences)
- smaller uncertainties with newer PDF sets?
- theoretical uncertainty dominated by scale uncertainty

$pp \to ZZ$


pp collisions
CT10
LO
NLO
NNLO
NLO+gg
σ [fb]
σ/σNLO
√s [TeV]
0
100
200
300
400
500
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
10
20
30
40
50
60
70
80
90
100

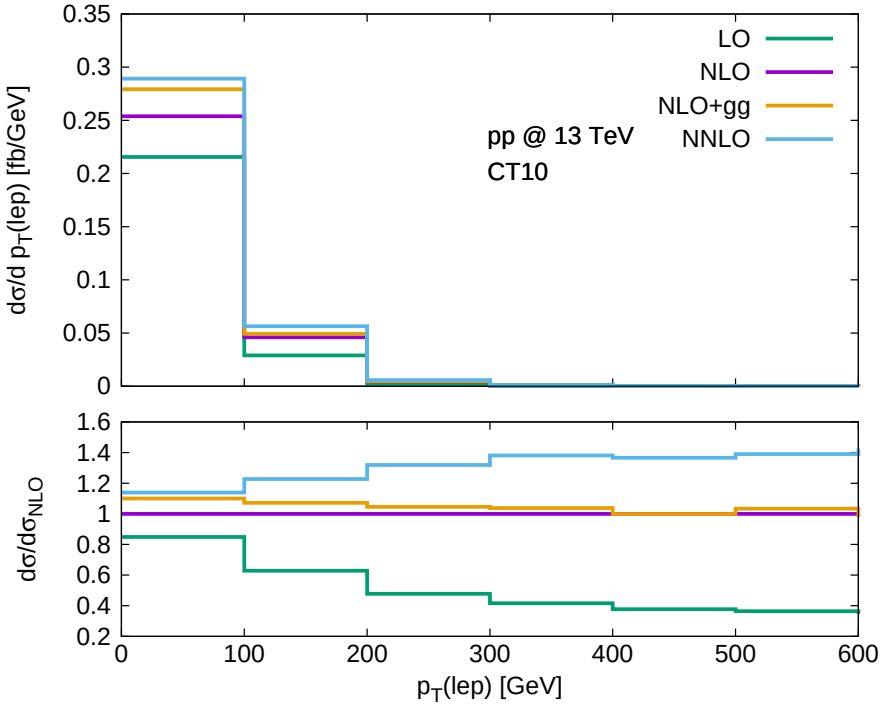
$pp \to ZZ$: invariant mass spectrum

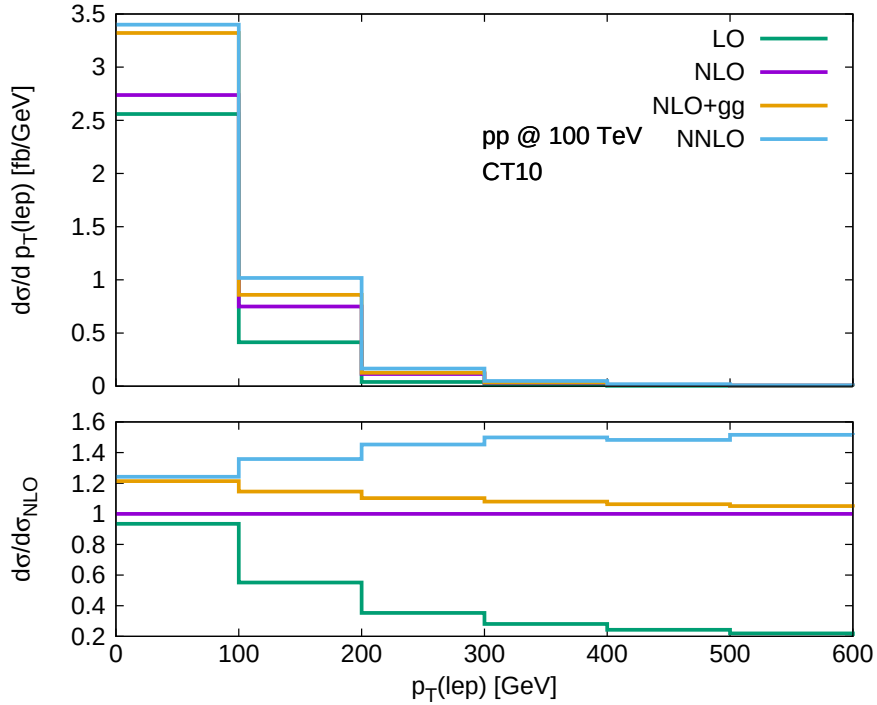




- gg fusion drops much more slowly
- large NNLO corrections in the tail

$pp \to ZZ$: transverse momentum spectrum

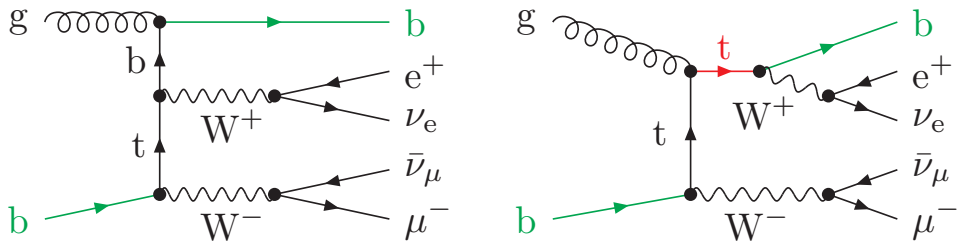




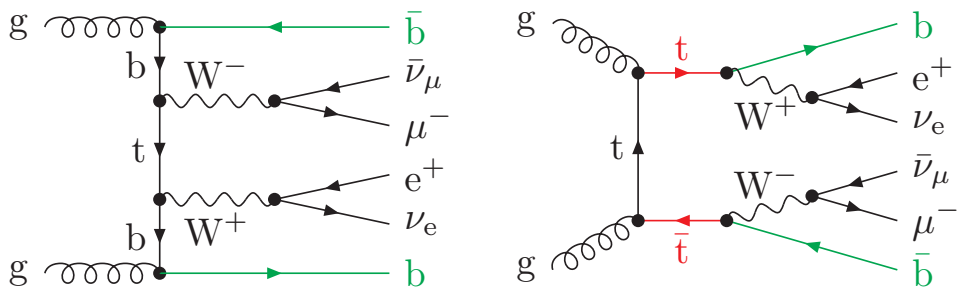
- slightly larger corrections
- gg drops quickly

$pp \to W^+W^-$

- $\sigma\,(pp \to W^+W^-)$ is not well-defined in naive PT
  - at NLO: contribution from $gb \to Wt \to WWb$



  - at NNLO: contribution from $q\bar{q}/gg \to t\bar{t} \to WWb\bar{b}$



  - large "higher-order corrections" corrections (30%/400% at NLO/NNLO)
  - cannot consistently be removed in 5FS, due to collinear singularities

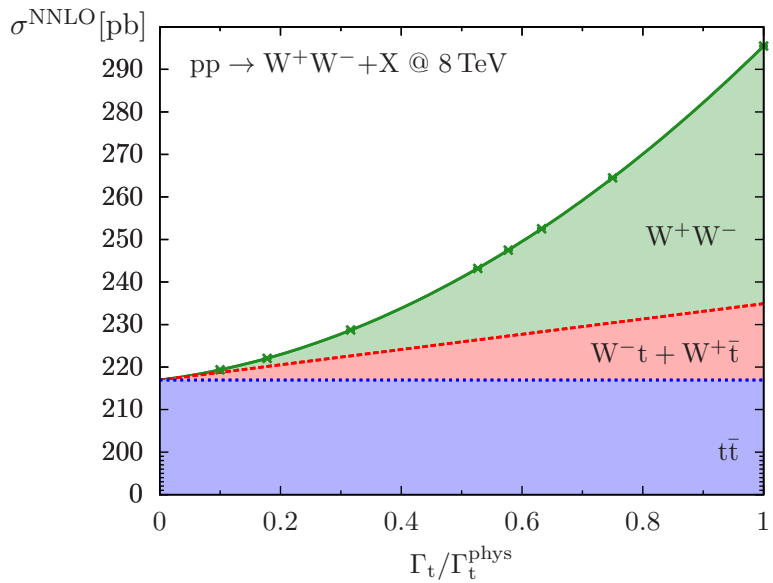
$pp \to W^+W^-$

- WW cross section is well-defined in 4FS (due to massive b's), but how to quantify the inherent uncertainty?
- can exploit different scaling behaviour of genuine WW, single top and top pair production w.r.t. Γ_t

$$\sigma_{\mathrm{WW}} \propto 1, \quad \sigma_{\mathrm{Wt}} \propto \Gamma_t^{-1}, \quad \sigma_{\mathrm{tt}} \propto \Gamma_t^{-2}$$

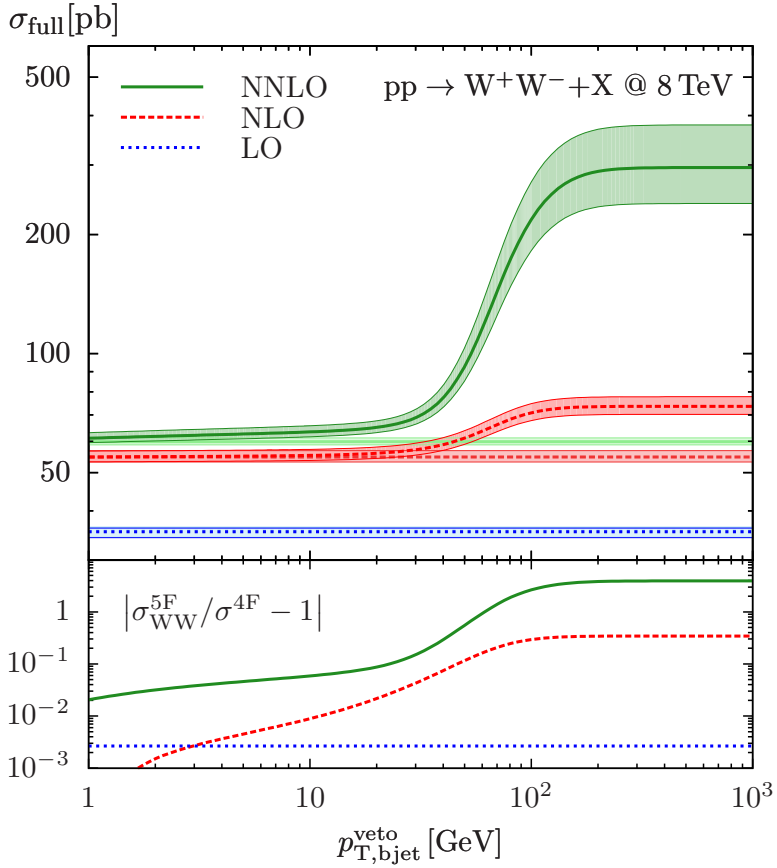
- fit quadratic polynomial to $\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)^2 \sigma_{5FS}\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)$

$$\sigma_{5\mathrm{FS}} = \sigma_{\mathrm{WW}} + \sigma_{\mathrm{Wt}} + \sigma_{\mathrm{tt}}$$



$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

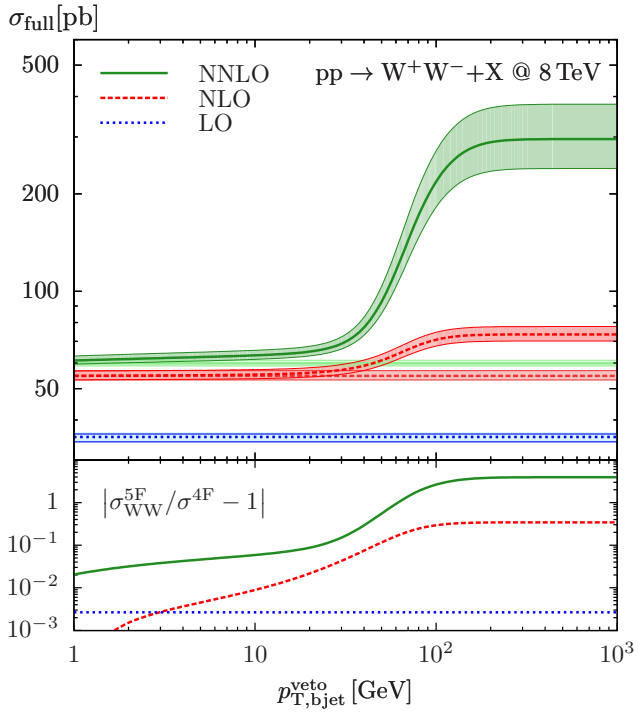
- expect b-jet-veto to suppress the top contamination

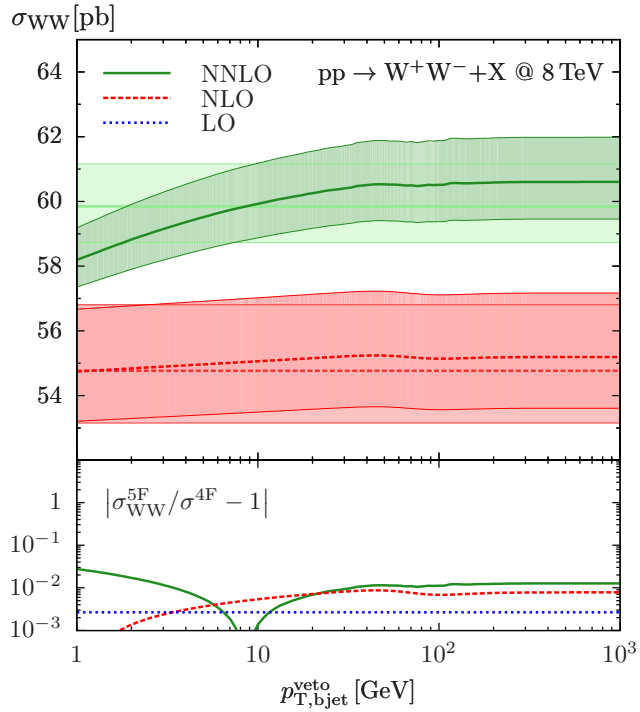


- at "typical" $p^{\rm veto}_{T,\rm bjet} \sim 30\,\text{GeV}$, about 15% enhancement remains
- $p^{\rm veto}_{T,\rm bjet} \to 0$ limit cannot be taken (infrared divergence)

$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

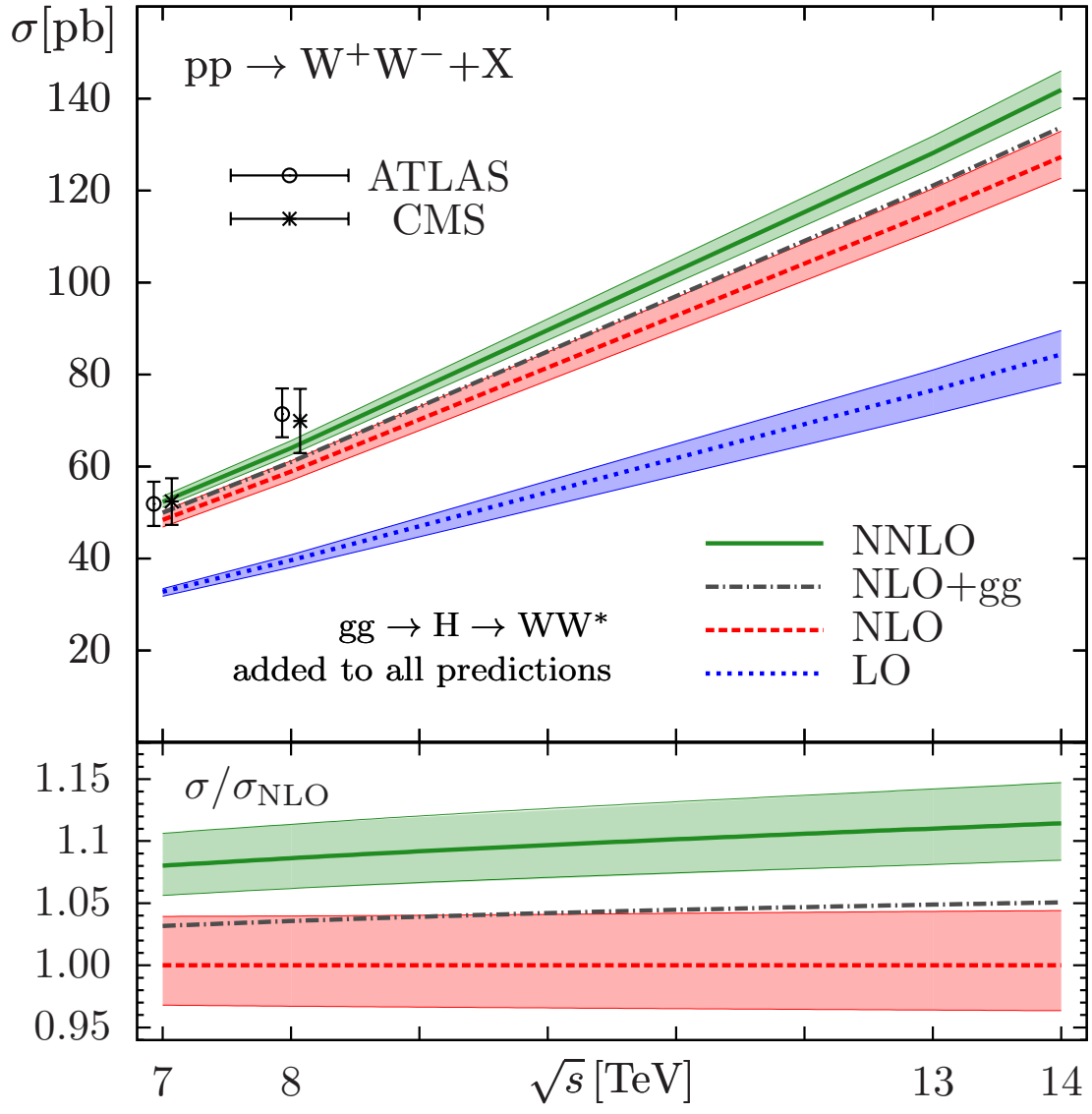
- $\sigma_{\rm WW}$ should not change when applying a b-jet veto if properly defined





- σ_{WW} is stable above $p^{veto}_{T,bjet} \approx 30\,\text{GeV}$, coincides with 4FS result (within $\sim 2\%$)
- logarithmic singularity at small $p^{\rm veto}_{T,\rm bjet}$

$pp \to W^+W^-$


σ[pb]
pp → W+W−+X
ATLAS
CMS
gg → H → WW*
added to all predictions
NNLO
NLO+gg
NLO
LO
σ/σNLO
√s [TeV]

$pp \to W^+W^-$

- study $pp \to \ell\ell\nu\nu$
- NNPDF3.0 $N_f = 4$
- $\mu_R = \mu_F = \frac{1}{2}\left(E_T^{W_1} + E_T^{W_2}\right)$

		LO	NLO	NLO+gg
13 TeV	σ [pb] rel. correction	0.775	1.17 52%	1.21 3%
100 TeV	σ [pb] rel. correction	6.88	12.3 79%	13.3 8%

- PDF uncertainties on the the $6-8\%$ level
- with NNPDF3.0 $N_f = 5$ at LO: $\pm 0\%$ at 13 TeV, -5% at 100 TeV

Summary

- recently significant progress on the NNLO QCD corrections to diboson production
- standard theory precision for all diboson processes will soon be NNLO QCD + NLO EW + NLO gg
- very few NNLO results at 100 TeV at the moment, but more will come
  - corrections significantly larger than at the LHC
  - gg fusion contribution (even) more important
    $\Rightarrow$ NLO corrections crucial
- so far considered only inclusive results
  $\rightarrow$ what about cuts?
- definition of W^+W^- cross section?