NNLO predictions for $t\bar{t}$ spin correlations

LHC TOP WG meeting

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in collaboration with
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Cavendish Laboratory

$t\bar{t}$ Spin Correlation in $\Delta\phi(\ell,\bar{\ell})$ and $|\Delta\eta(\ell,\bar{\ell})|$

Aim of our studies: Quantifying agreement of SM with data

- NNLO QCD predictions for inclusive and fiducial volumes
  - Investigate scale choice and dependence
  - PDF sensitivity
- Dependence on top-quark mass m_t parameter
- Offshell and electroweak effects
- Comparison to measurements of $\Delta\phi(\ell,\bar{\ell})$ (fiducial and inclusive volume)

Theory setup:

- NWA approximation (t-quark, W-boson) $\rightarrow$ factorization of QCD corrections to production and decay
- But: keeping spin information
- Subtraction framework: sector-improved residue subtraction scheme [Czakon, Heymes 1408.2500]
- Treatment of width: systematic expansion of $\frac{1}{\Gamma}$:

$$\frac{1}{\Gamma^{(0)} + \alpha_s \Gamma^{(1)} + \ldots} = \frac{1}{\Gamma^{(0)}} - \alpha_s \frac{\Gamma^{(1)}}{\Gamma^{(0)2}} + \ldots$$

- Similar to [Gao,Papanastasiou 1705.08903] but with full NNLO treatment

Definition of Fiducial Phase Space

Potential differences of fiducial phase space used by experiment and (fixed order) theory $\rightarrow$ is this important?

Definition of 'b-jets' through B-hadrons in experiment

vs.

b-quark flavoured jets in fixed order calculations

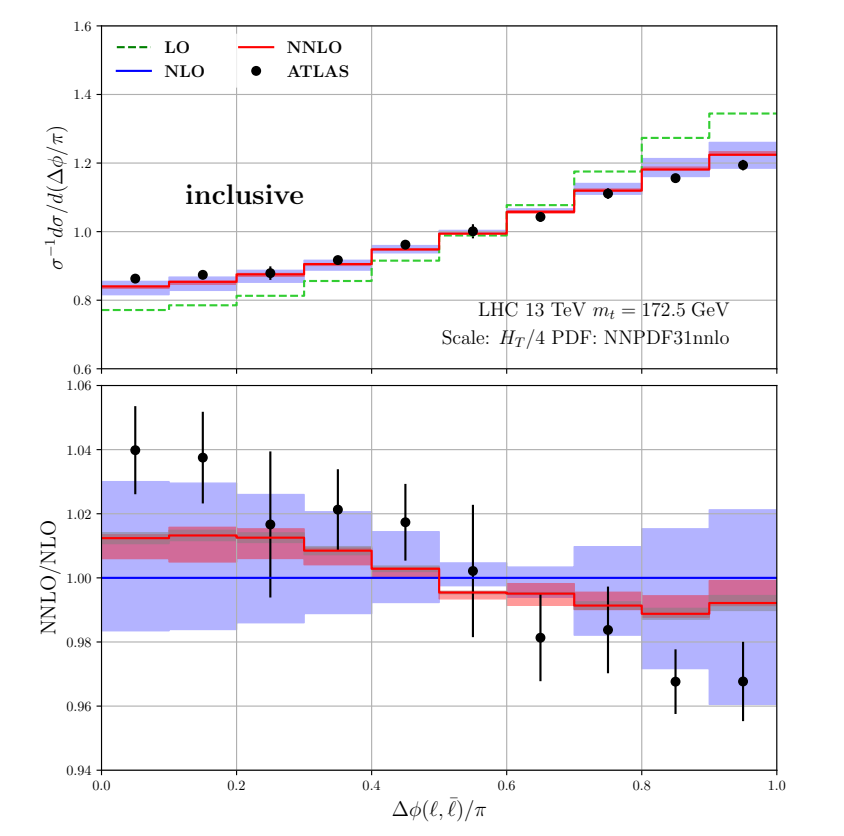
Fiducial volume:

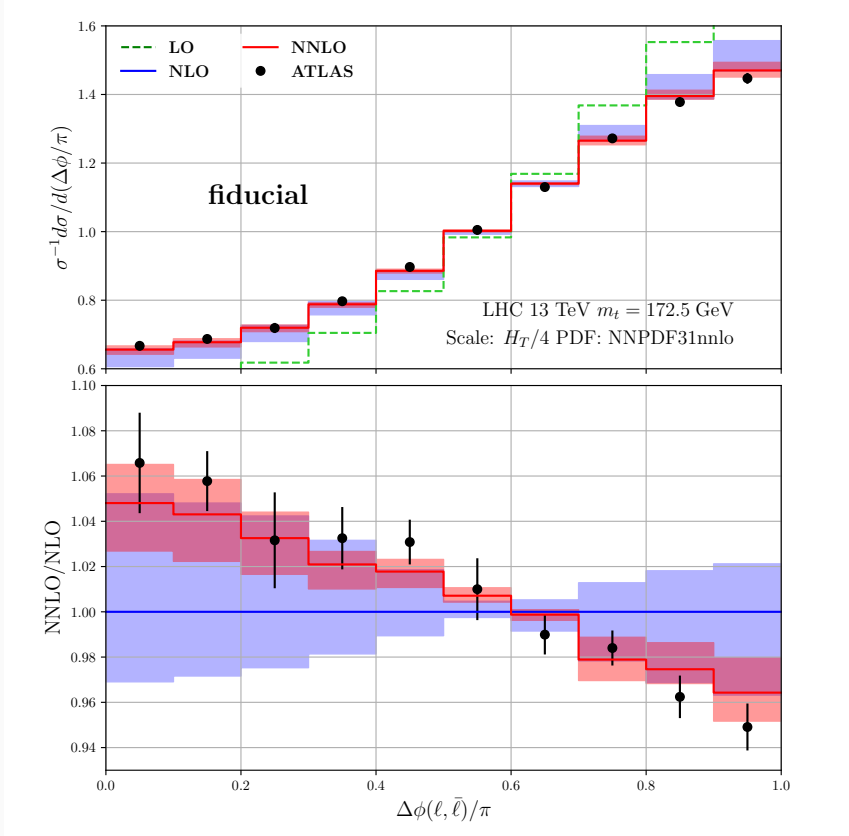
Our implementation of fiducial volume (based on **ATLAS-CONF-2018-027**):

- opposite charged μ and e
  - $p_T > 27(25)$ GeV
  - $|\eta| < 2.5$
- Two jets
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - $1 \leq b$-tags

Results for $\Delta\phi(\ell, \bar{\ell})$

$\Delta\phi(\ell,\bar{\ell})$ Theory vs. data from ATLAS-CONF-2018-027

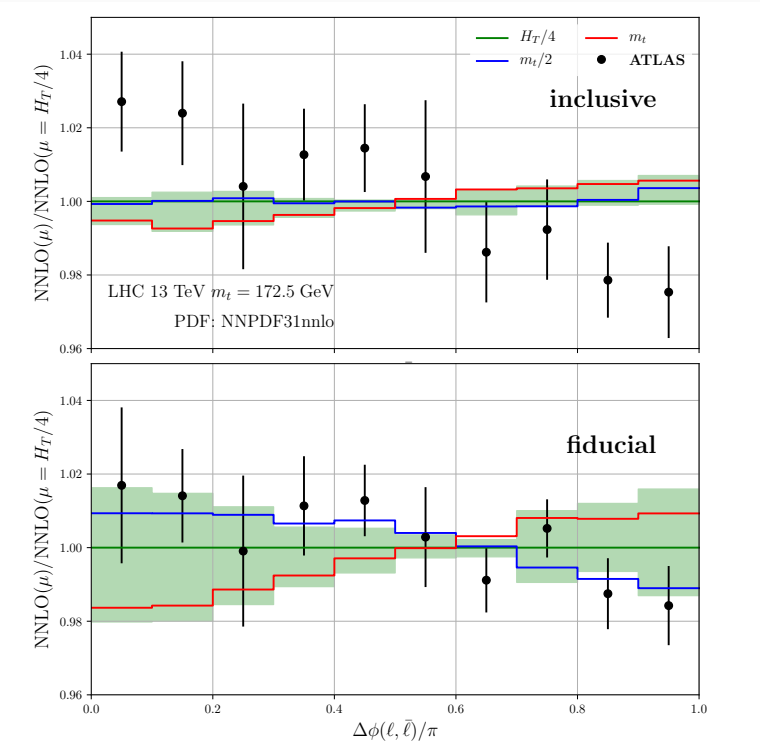




Perfect agreement in fiducial, differences in inclusive phase space $\rightarrow$ possibly hints at differences in the extrapolation to inclusive phase space

How robust are these results?

$\Delta\phi(\ell,\bar{\ell})$ scale dependence and choice

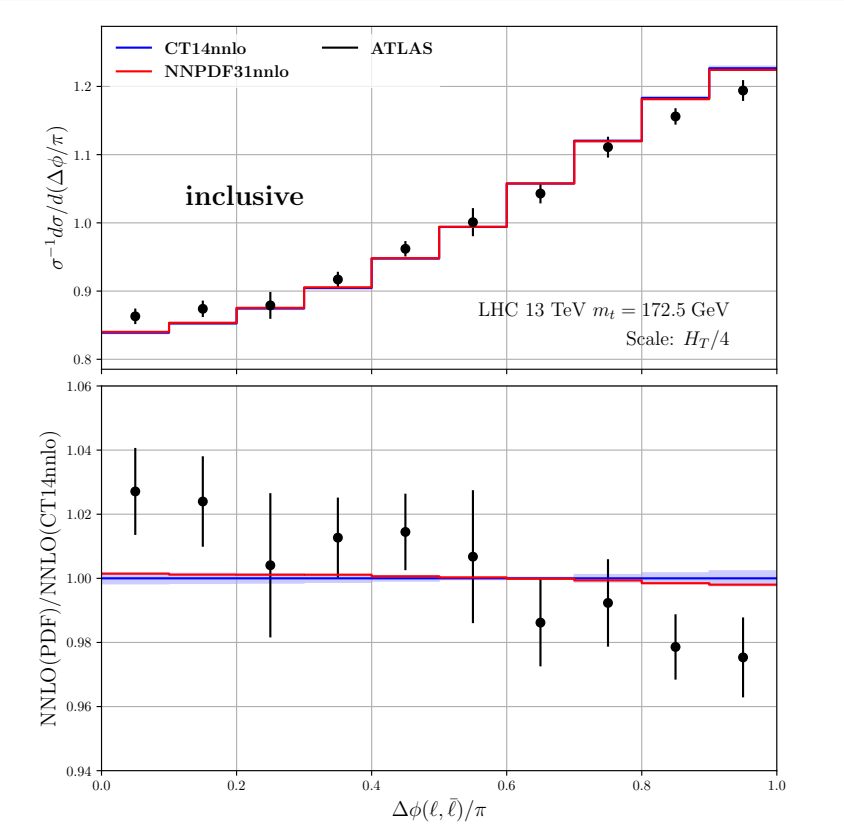


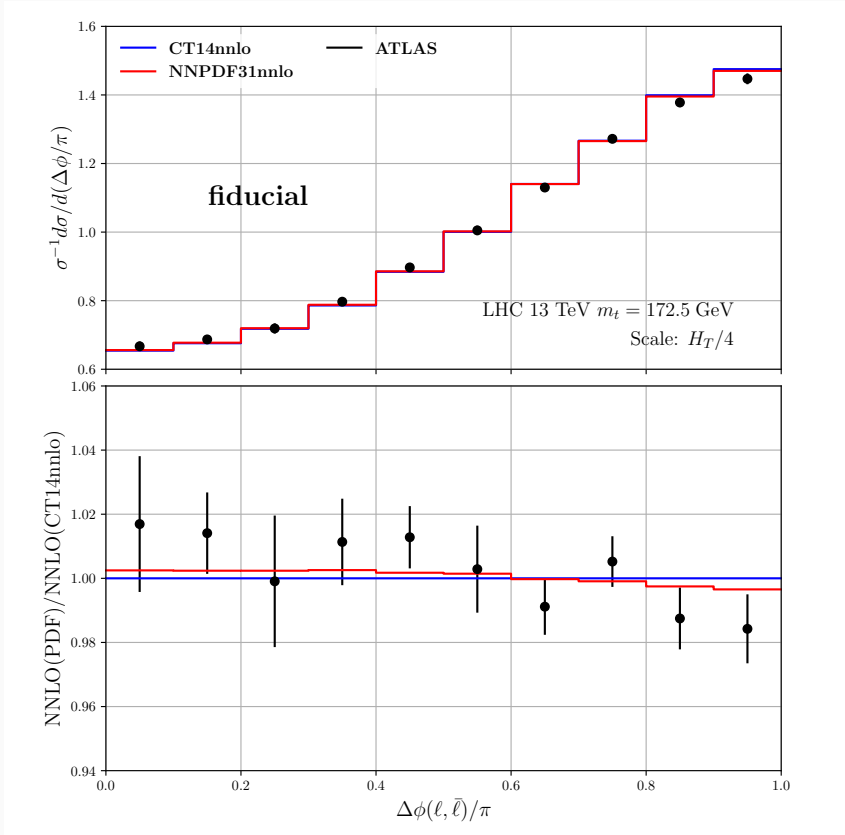
- investigate three different central choices $\mu_0 = H_T/4,\ m_t$ and $m_t/2$
- using the underlying $t, \bar{t}$ momenta for $H_T = \sum_{i\in\{t,\bar{t}\}} \sqrt{m_t^2 + p_{T,i}^2}$
- Standard seven-point scale variation
- *Remark*: In normalised distributions consider correlated variation

$$\sigma(\mu_i)^{-1}\mathrm{d}\sigma(\mu_i)/\mathrm{d}X$$

$H_T/4$ shows fastest convergence,
all scales consistent within scale variations

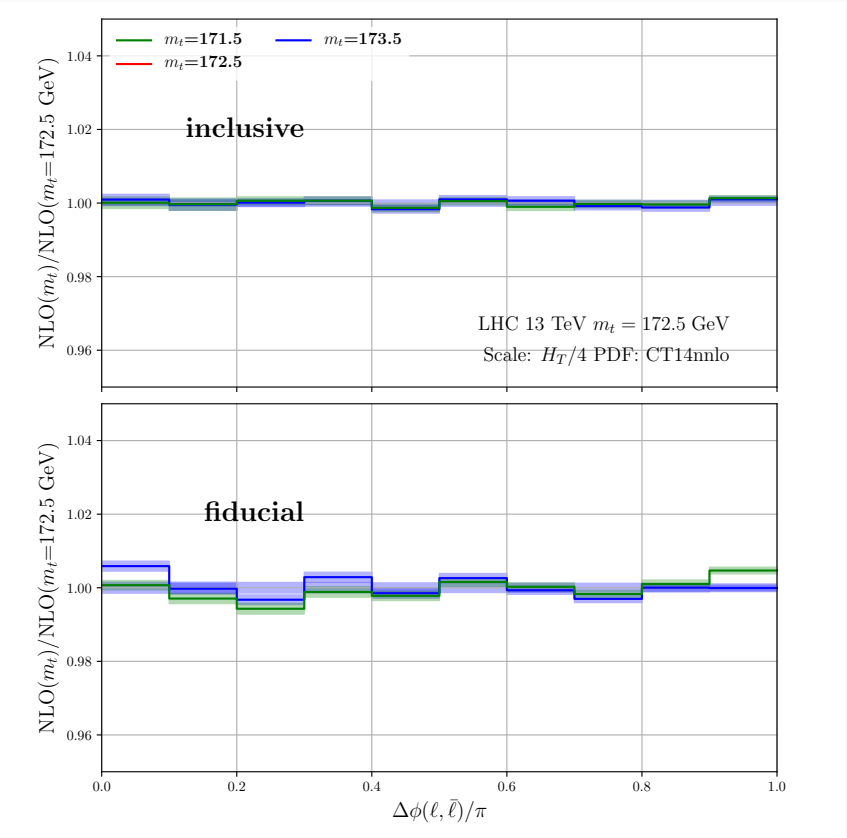
CT14 PDF error compared with NNPDF3.1





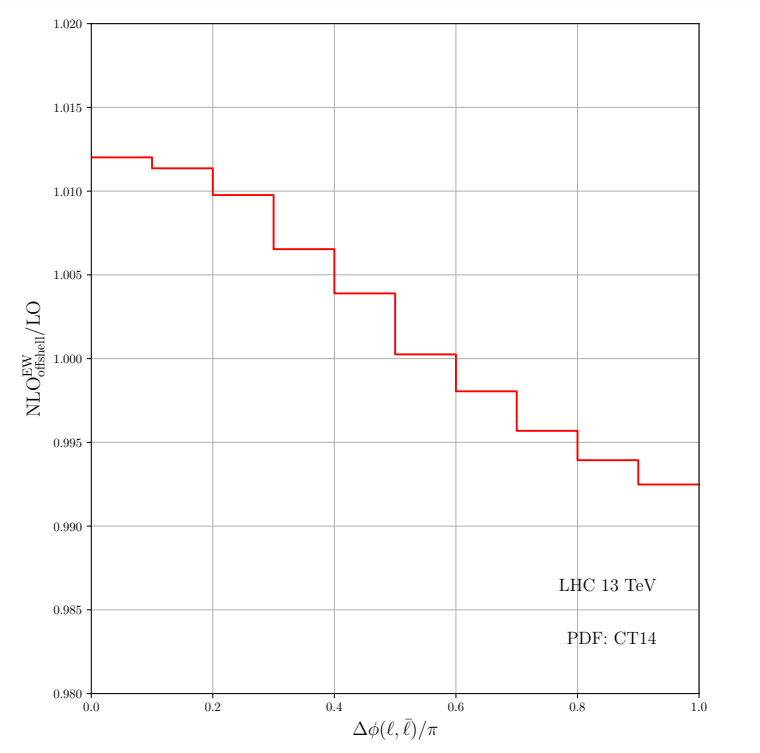
negligible effect in $\Delta\phi$

$\Delta\phi(\ell, \bar{\ell})$ Mass dependence (@NLO)



negligible mass dependence $\mathcal{O}(< 1\%)$

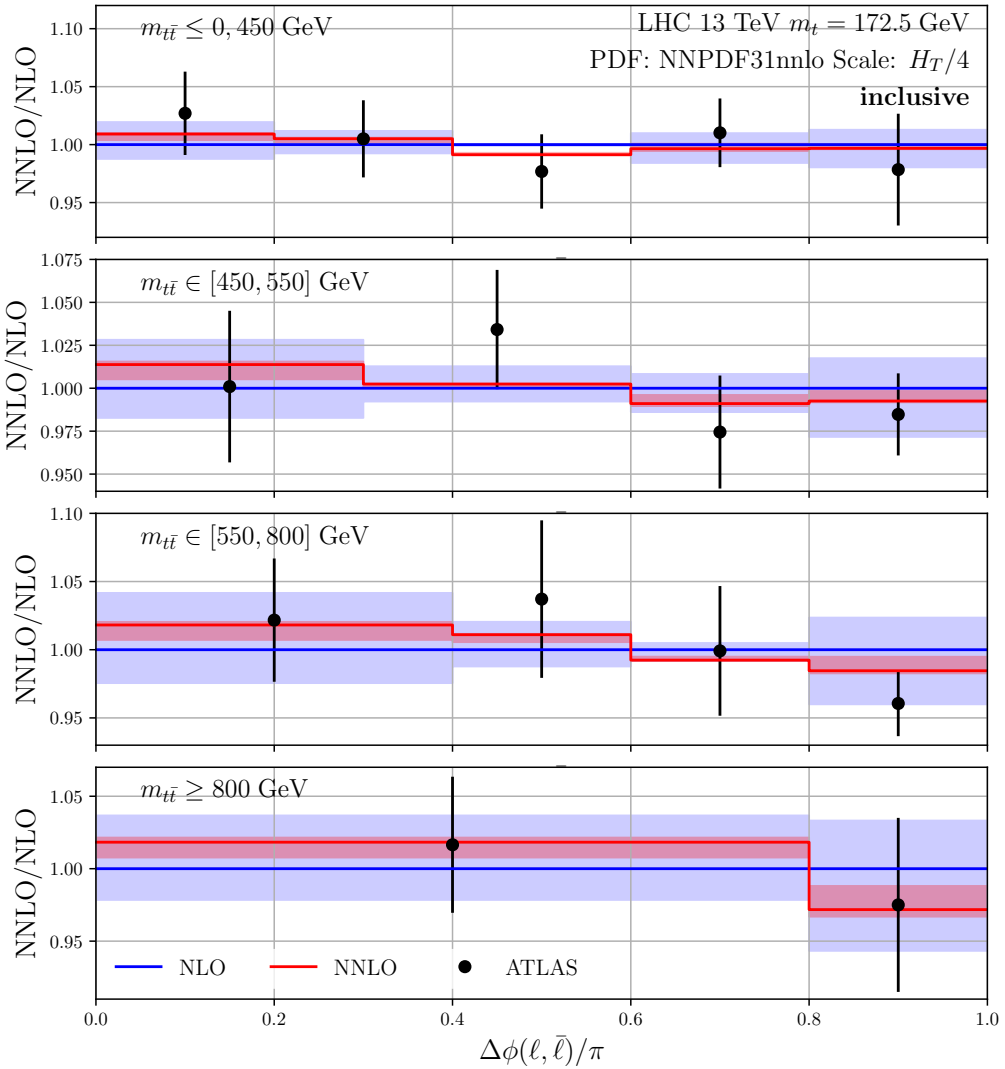
$\Delta\phi(\ell,\bar{\ell})$ Off-shell and EW effects



- Thanks to Mathieu Pellen [Denner, Pellen 1607.05571]
- Rough check only
- Slightly different fiducial volume (2 b-jets)
- LO NWA vs. NLO EW Off-shell

suggests a small effect $\mathcal{O}(1\%)$
which goes in the same direction as NNLO QCD
a rigorous study would be welcomed

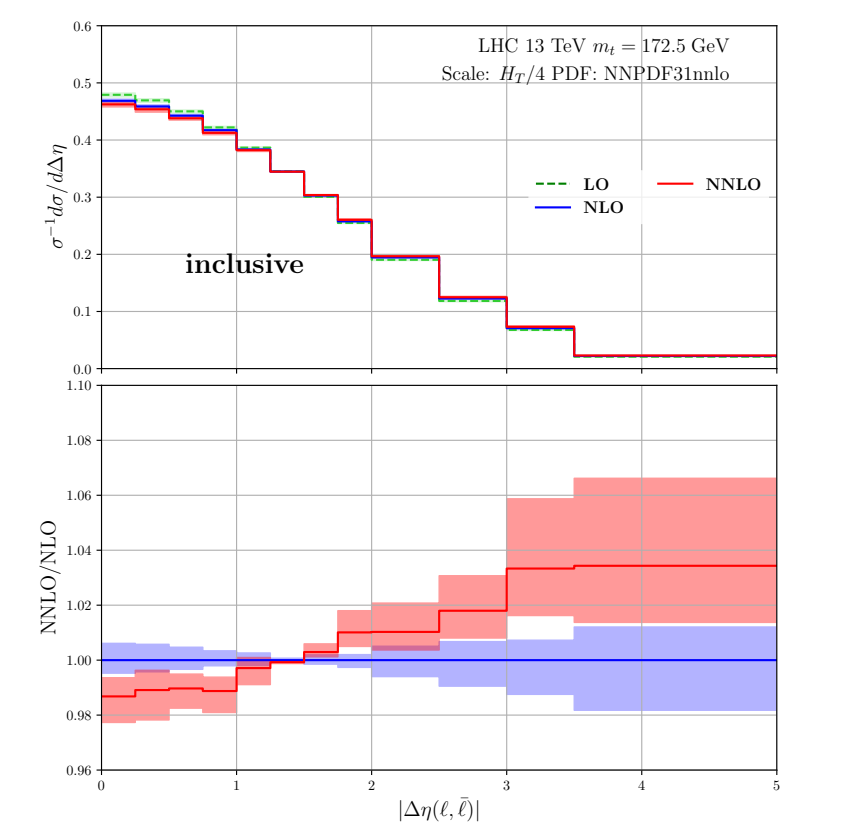
$\Delta\phi(\ell, \bar{\ell})$ Double differential

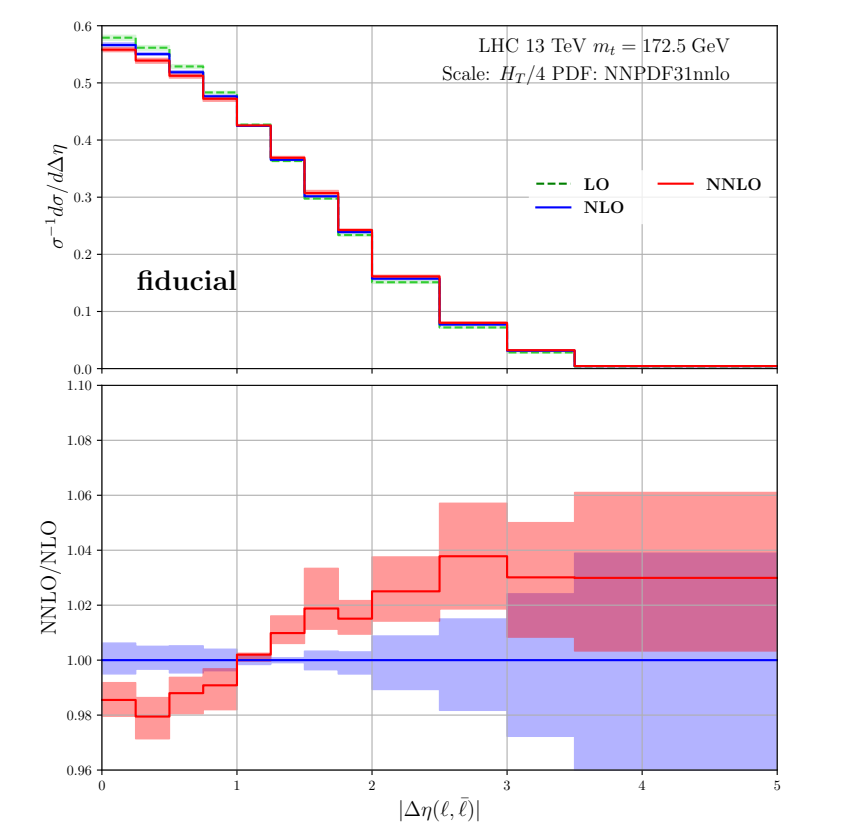


- $m_{t\bar{t}}$ based on true top-momenta
- Large experimental error
- so far good agreement between measurement and theory

Results for $|\Delta\eta(\ell, \bar{\ell})|$

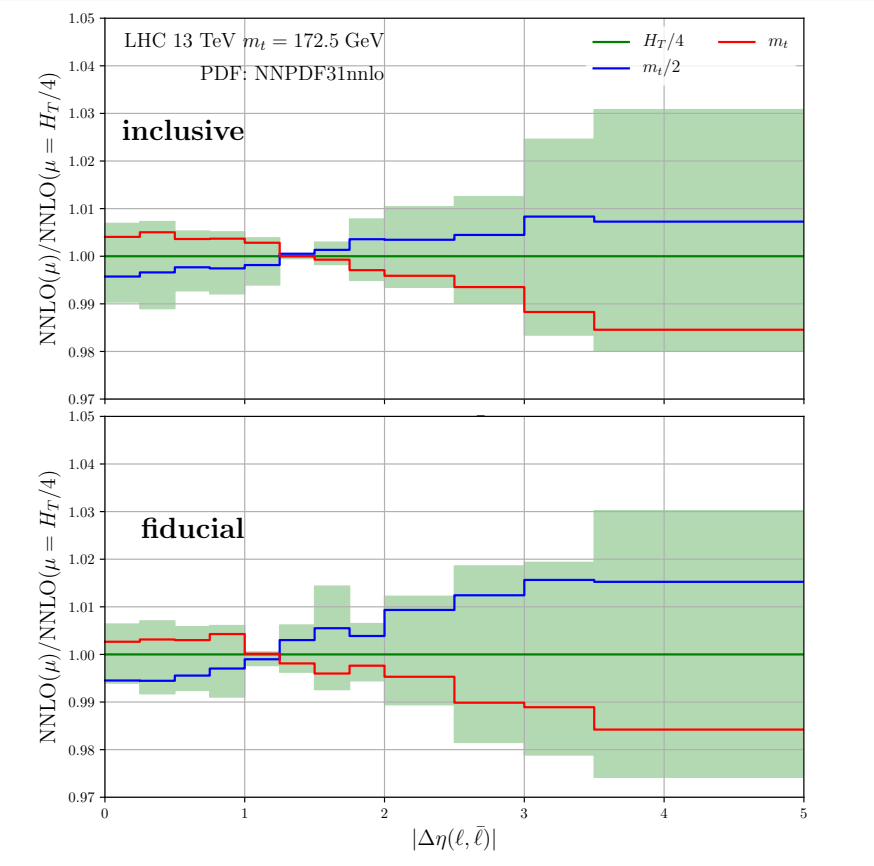
$|\Delta\eta(\ell,\bar{\ell})|$ Inclusive vs fiducial $t\bar{t}$ production





Large NNLO corrections in both cases

$|\Delta\eta(\ell,\bar{\ell})|$ Scale choice and dependence



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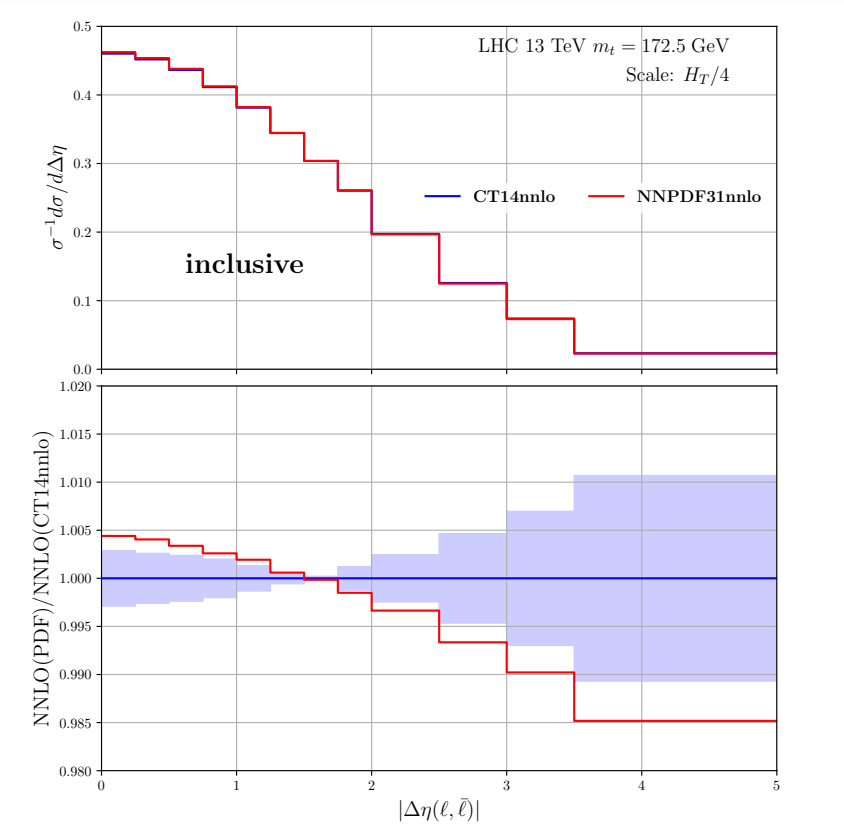
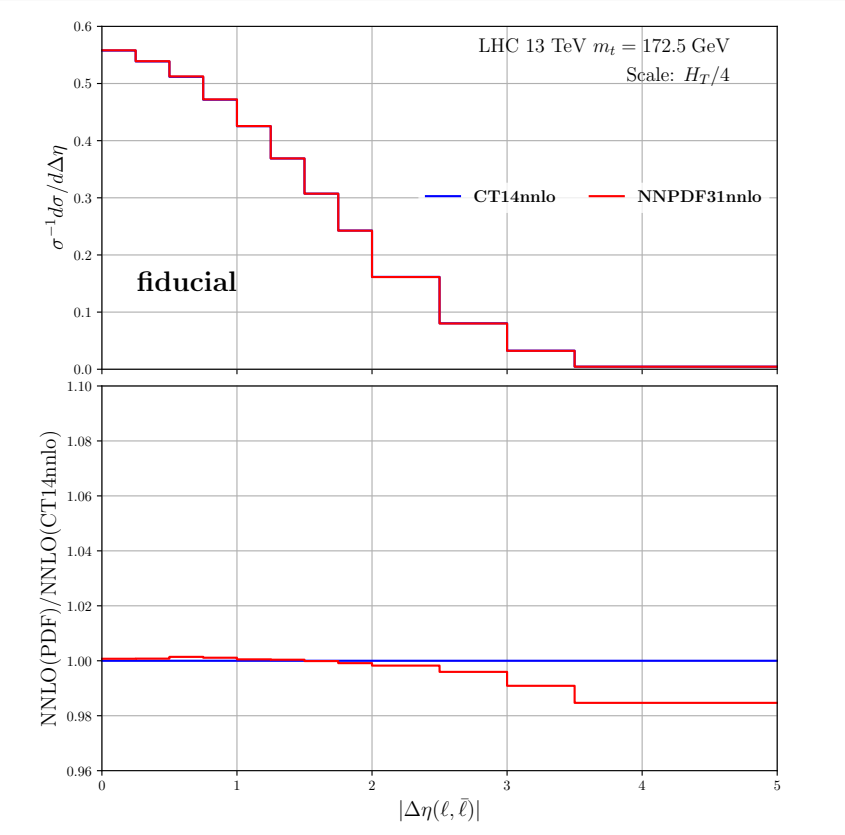
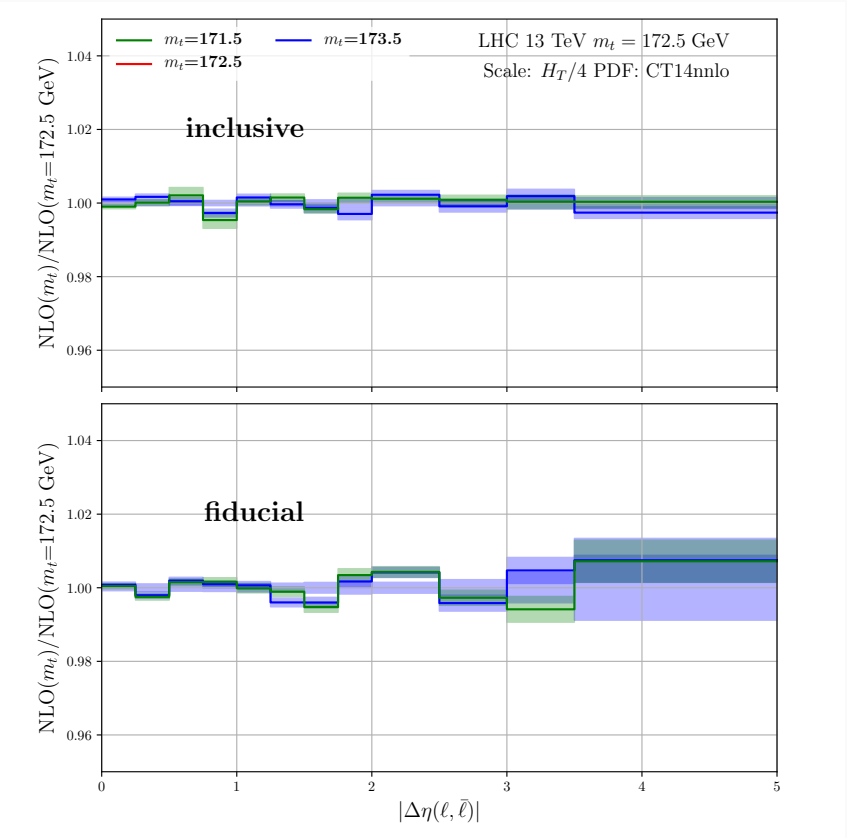




visible but small effect in $\Delta\eta$

$|\Delta\eta(\ell,\bar{\ell})|$ Mass dependence (@NLO)



negligible mass dependence $\mathcal{O}(< 1\%)$

Summary

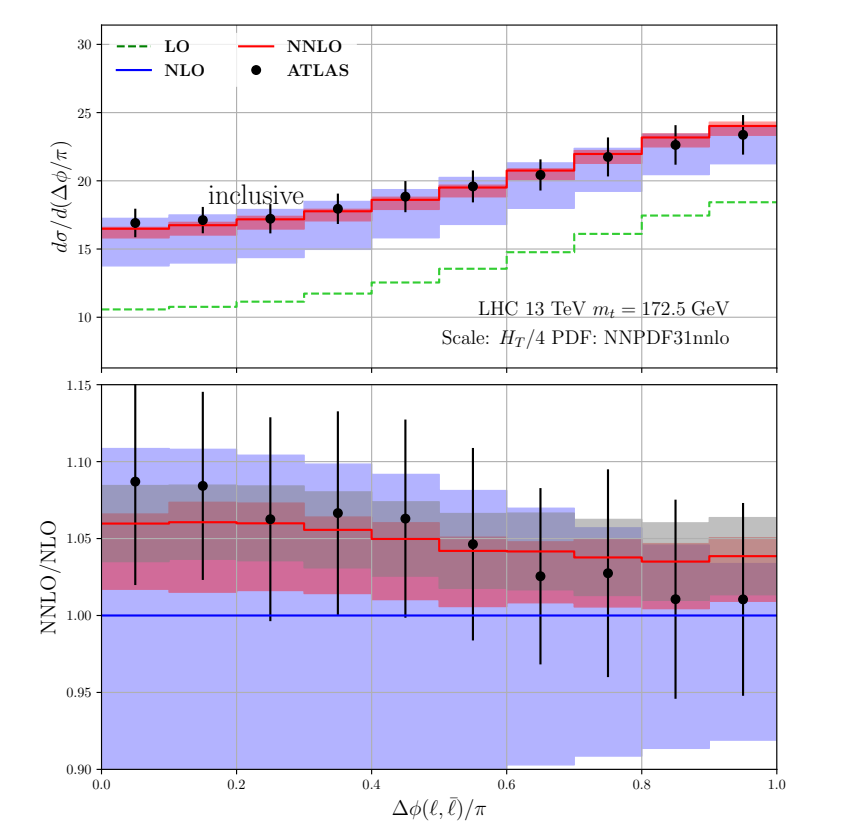
- First ever NNLO production times NNLO decay calculation
  - results for various leptonic observables available
- NNLO QCD corrections to observables sensitive spin correlation
  - PDF dependence has been found to be small
  - Data favors $H_T/4$ and $m_t/2$ over m_t as scale choice, all three choices are consistent within scale variations
  - EW and off-shell effects seem to be small
- Our findings are:
  - Fiducial: Excellent description of $\Delta\phi$ data by NNLO, large corrections to $|\Delta\eta|$ (no data yet)
  - Inclusive: small NNLO corrections, still some discrepancy with data left, large corrections to $|\Delta\eta|$ (no data yet)

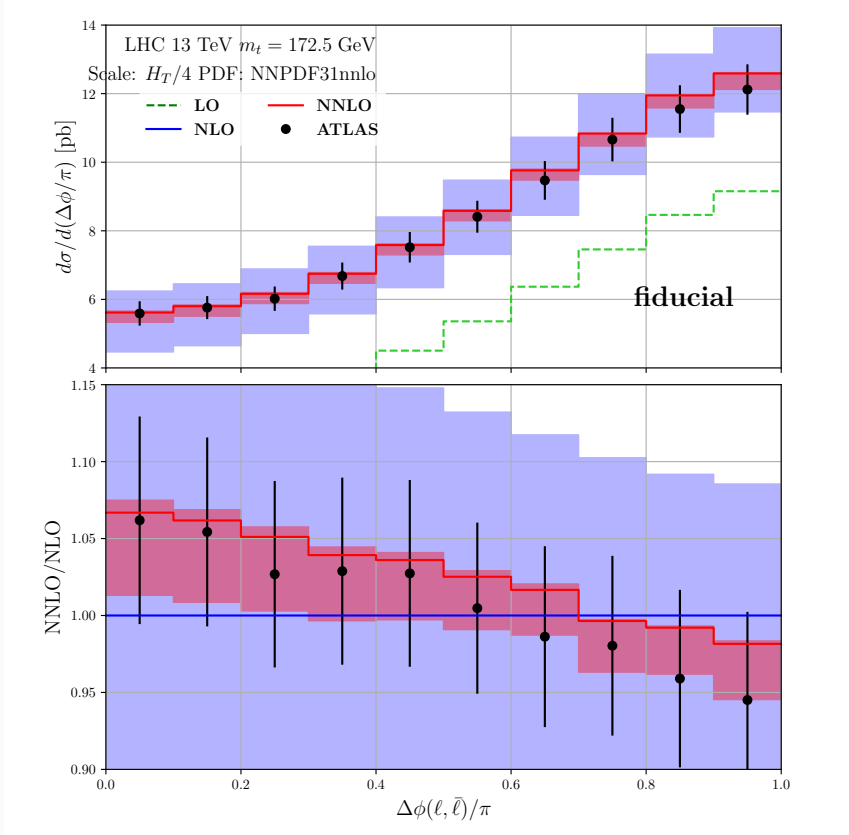
Backup

Theory Input parameter

m_t	172.5 GeV
m_W	80.385 GeV
m_Z	91.1876 GeV
Γ_W	2.0928 GeV
G_F	$1.16379 \cdot 10^{-5}$ Gev^2
$\Gamma_t^{(0)}$	1.4806 GeV
$\alpha_s(m_Z)$	0.118

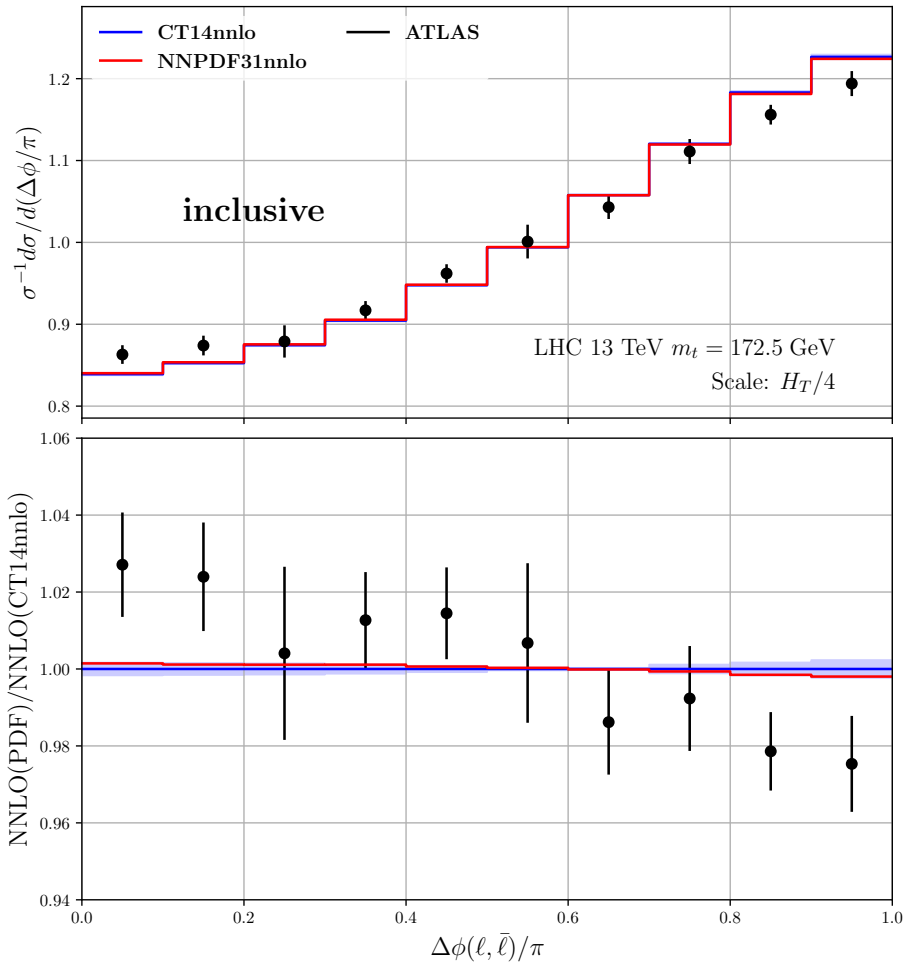
$\Delta\phi(\ell,\bar{\ell})$ Absolute distributions with data





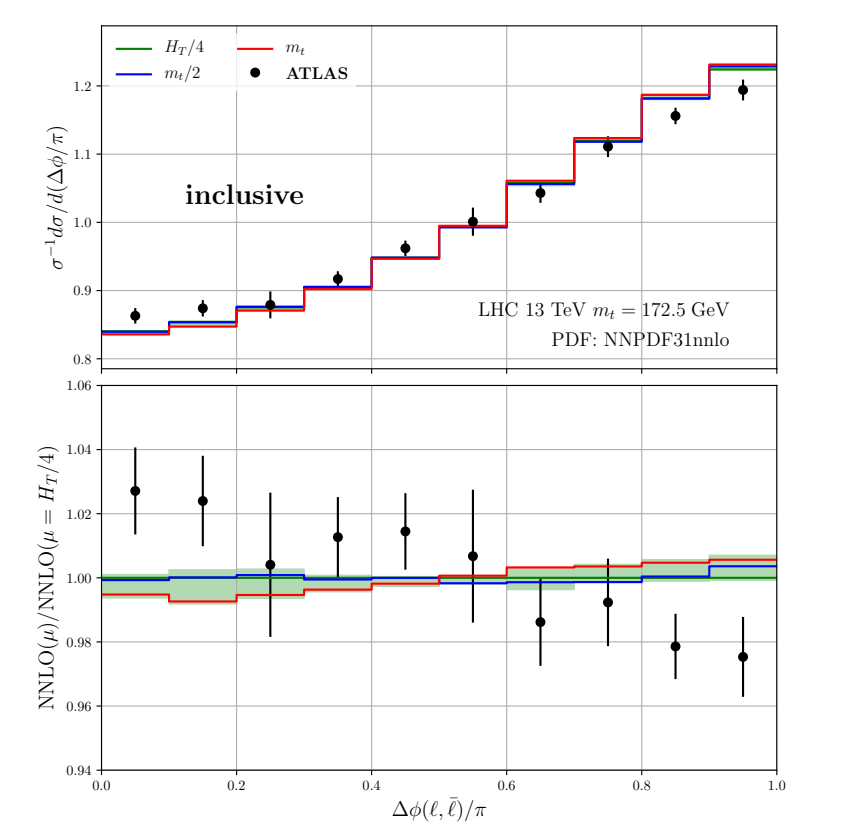
Data from ATLAS-CONF-2018-027, scale and PDF (inclusive only) uncertainty shown

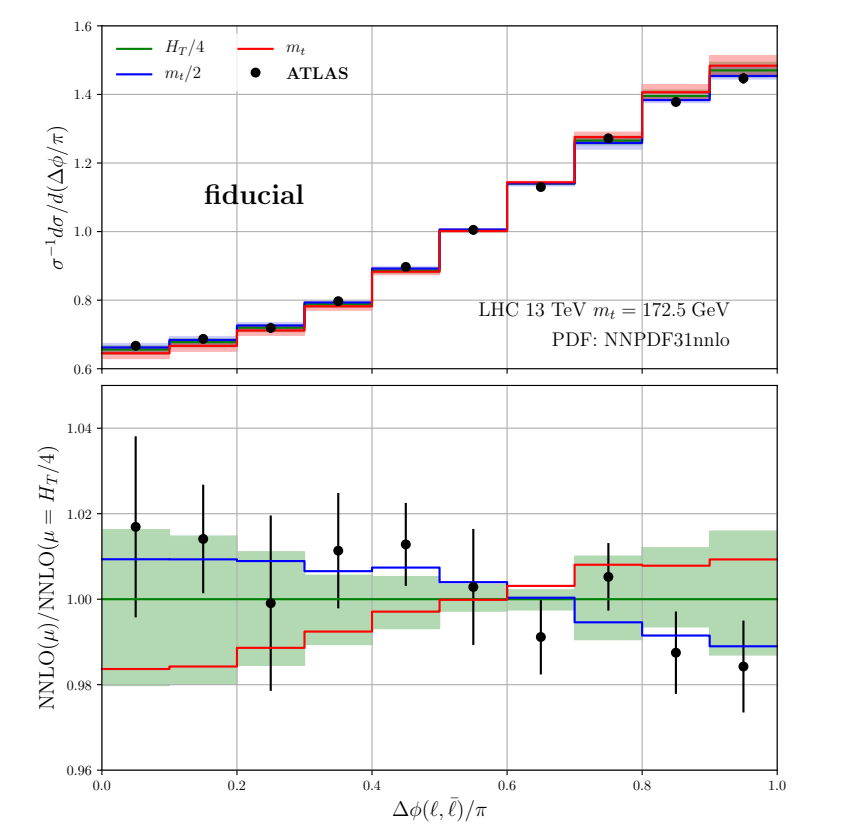
$\Delta\phi(\ell,\bar{\ell})$ PDF uncertainties and data



Data from ATLAS-CONF-2018-027

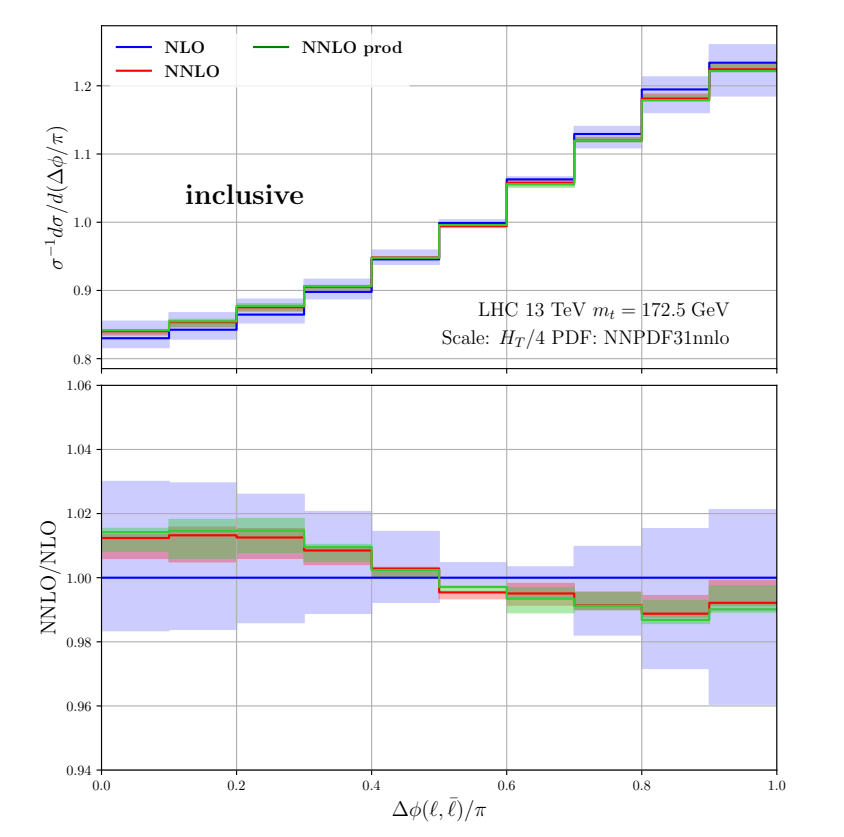
$\Delta\phi(\ell,\bar{\ell})$ Scale uncertainties and data

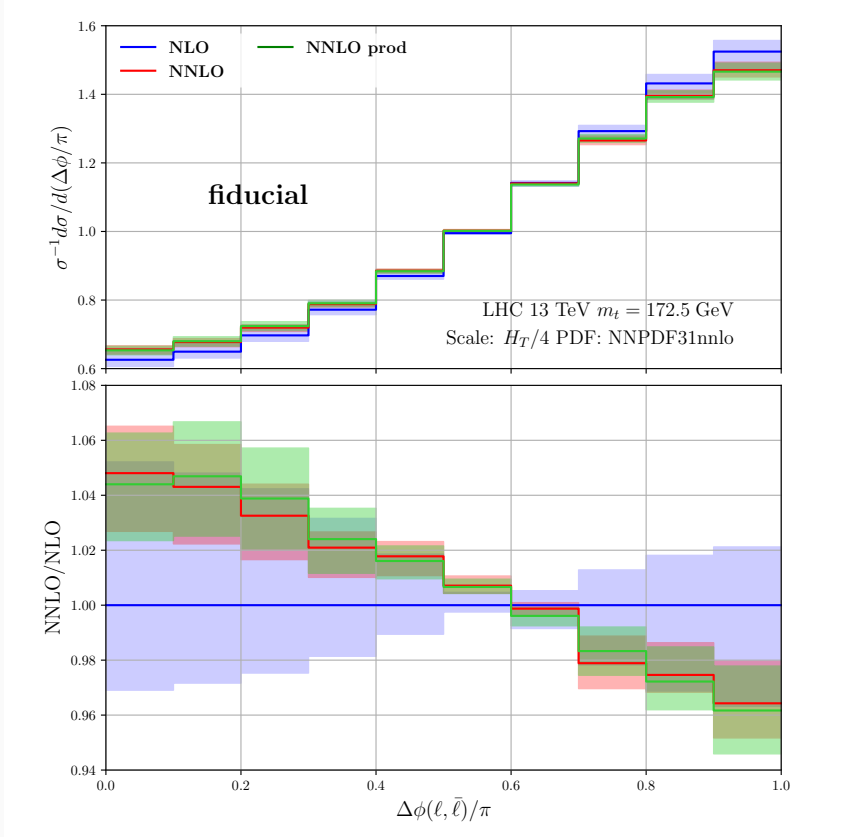




Data from ATLAS-CONF-2018-027

$\Delta\phi(\ell,\bar{\ell})$ Decay corrections





Dominant effect from production corrections