Higher order corrections to spin correlations in top quark pair production at the LHC

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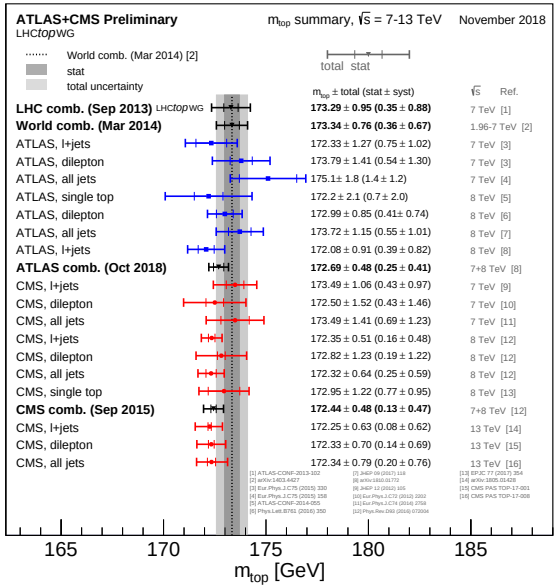
Outline

The top quark

- Heaviest known elementary particle
- Discovered in 1995 at the Tevatron
- Abundantly produced at the LHC
- Very active field of research (theory & experiment)
- Interesting in its own right, but also as a probe of BSM physics
- Both aspects require precise understanding of its properties (mass, width, spin, couplings, . . .)



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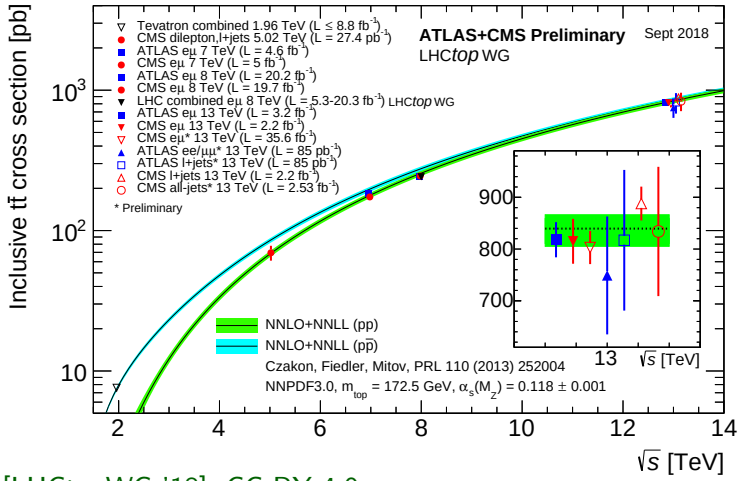
Top pair production



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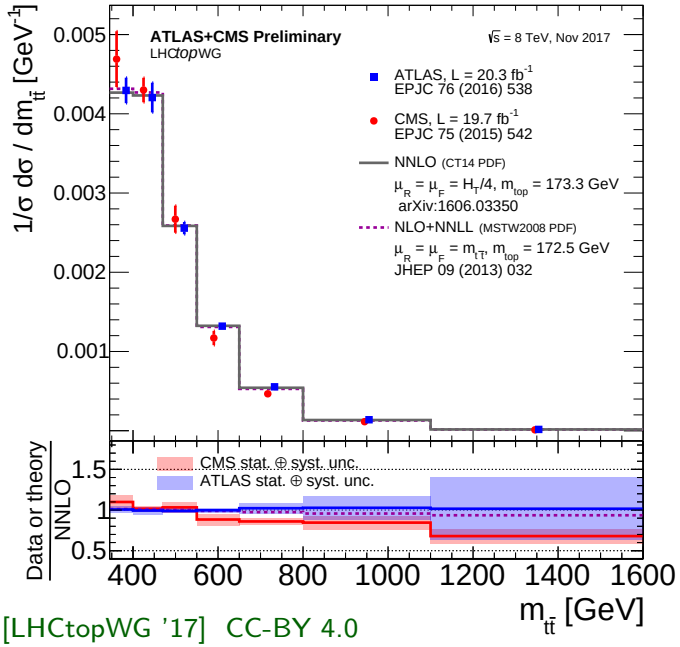

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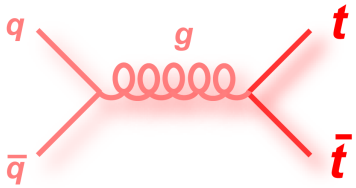
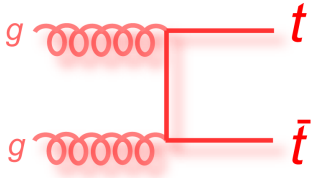
- $t\bar{t}$ production at hadron colliders: mostly QCD
  Tevatron: $q\bar{q}$ dominates LHC: gg dominates



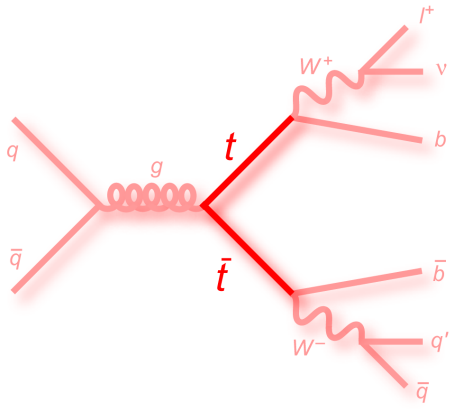


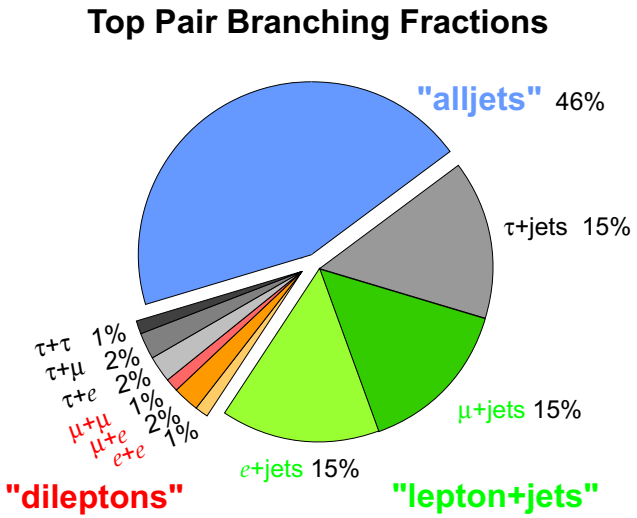
- Known to NNLO QCD, NLO EW and with NNLL resummation for stable top quarks
- SM predictions for differential distribution agree well with data

Top pair production with decays

Top quarks decay almost exclusively via $t \to Wb$, i.e. $pp \to t\bar{t} \to W^+W^-b\bar{b}$

- Classify reactions according to W decays
  - all jets: $t\bar{t} \to b\bar{b} + 4j$
  - lepton+jets: $t\bar{t} \to b\bar{b} + \ell\nu + 2j$
  - dilepton: $t\bar{t} \to b\bar{b} + \ell\nu + \ell'\nu'$
- This talk: dilepton channel with $e^{\pm}\mu^{\mp}$
  - Cleanest signature, but also smallest rate
  - Incomplete kinematic information due to invisible neutrinos
  - e^+e^- and $\mu^+\mu^-$ have larger Drell-Yan backgrounds





Top quark spin

Spin properties of top quarks

- Top quark is a fermion $\Rightarrow$ Couplings are spin-dependent
- Direct measurement of top quark spin not possible
  $\Rightarrow$ measurement through decay products
- Unique situation: Top quarks decay before decorrelation

Spin-dependence of top pair production

- Individual top quarks from $pp \to t\bar{t}$ are not polarised
- But: Spin correlation between t and $\bar{t}$
- Can be measured in differential distributions

Spin correlations: Strategies and observables

Dilepton channel is very well suited for measuring spin correlations:

- Very clean signal
- Lepton momenta can be measured well

Direct measurement

- Decompose cross section into basis in spin space
- Use lepton momenta to probe coefficients

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i\, d\cos\theta_2^i} = \frac{1}{4}\left(1 + B_1^i \cos\theta_1^i + B_2^j \cos\theta_2^j - C_{ij}\cos\theta_1^i \cos\theta_2^j\right)$$

  where $\theta_{1(2)}^{i(j)}$ are lepton angles of $t(\bar{t})$ wrt. axis $i(j)$ in $t(\bar{t})$ rest frames
- Measure differential distributions in angles and extract coefficients
- Pro: Full spin information
- Contra: Requires reconstruction of t & $\bar{t}$ rest frames
- Has actually been pursued, e.g., by CMS [CMS-PAS-TOP-18-006]

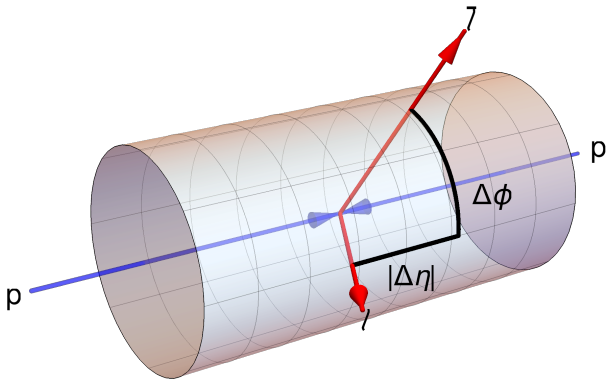
Spin correlations: Strategies and observables

Dilepton channel is very well suited for measuring spin correlations:

- Very clean signal
- Lepton momenta can be measured well

Indirect measurement

- Measure differential distributions of lepton geometry in *lab frame*
  - Lepton azimuthal opening angle $\Delta\phi(\ell, \bar{\ell})$
  - Lepton rapidity difference $|\Delta\eta(\ell, \bar{\ell})|$



- Boost of top quarks enhances anti-parallel leptons
- Spin correlations counteract and enhance parallel leptons

Spin correlations: Experimental situation

- Compare measurement to predictions with and without spin correlations
- Bin-wise linear fit

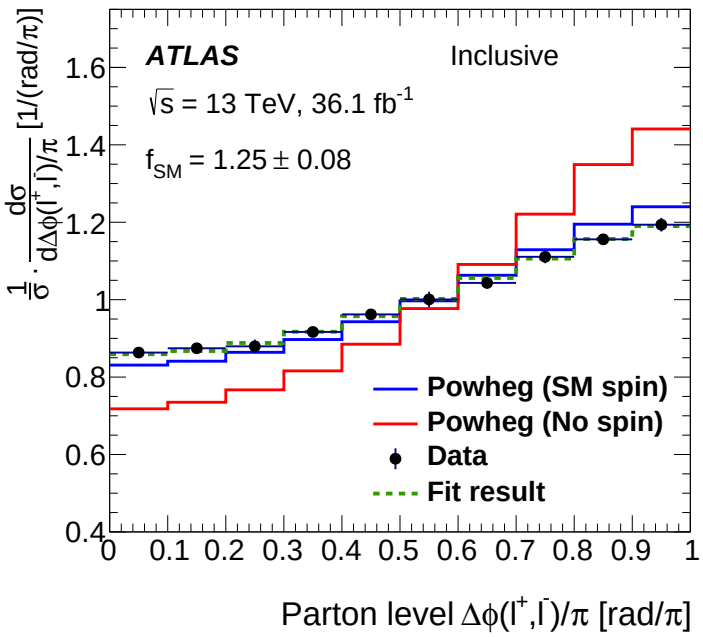
$$x_i = f_{\mathrm{SM}} x_{\mathrm{spin},i} + (1 - f_{\mathrm{SM}}) x_{\mathrm{nospin},i}$$

- SM expectation: $f_{\mathrm{SM}} = 1$
- At ICHEP2018 ATLAS reported measurement of $\Delta\phi(\ell, \bar{\ell})$ distributions and

$$f_{\mathrm{SM}} = 1.25 \pm 0.08$$

$\Rightarrow$ 3.2σ deviation from SM

Largest deviation from the SM in the top sector at that time

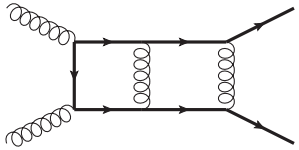


[ATLAS '19] CC-BY 4.0

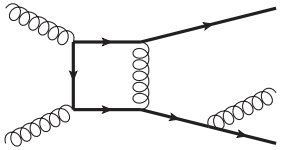
Question: Could this be due to missing NNLO corrections?

Ingredients of a NNLO fixed-order calculation

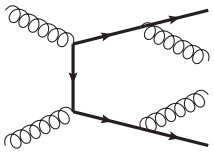
Matrix elements



2-loop



1-loop + 1 real

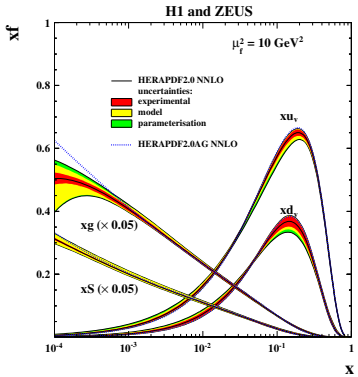


tree-level + 2 real

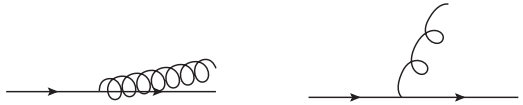
Collinear factorisation

UV renormalisation

PDFs & parameters



Scheme to deal with IR divergences



Narrow width approximation

$pp \to t\bar{t} \to b\bar{b}\ell^+\ell'^-\nu\bar{\nu}'$ at NNLO

- In general needs 2-loop 8-point amplitudes $\Rightarrow$ too difficult
- However: $\Gamma_t \ll m_t \Rightarrow$ Use narrow width approximation

Narrow width approximation (NWA)

$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \xrightarrow{\Gamma_t/m_t \to 0} \frac{\pi\delta(p^2 - m_t^2)}{m_t\Gamma_t}$$

- On-shell tops $\Rightarrow$ Revert spin sum for propagator numerators

$$\not{p} + m_t = \sum_\lambda u_\lambda(p)\bar{u}_\lambda(p)$$

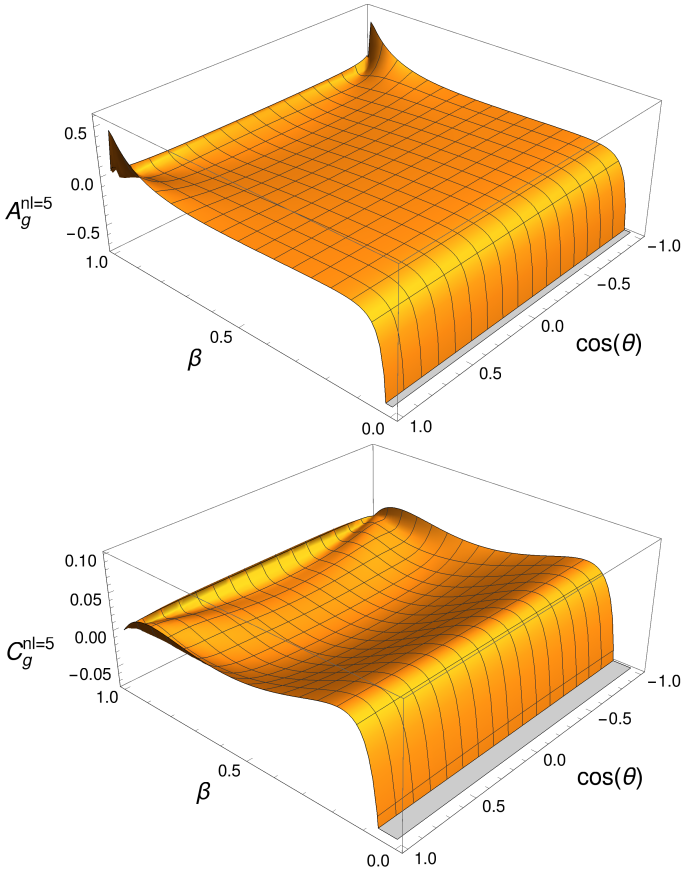
- Factorizes production and decay
- Requires polarised matrix elements for production and decay

Matrix elements

$pp \to t\bar{t}$ with polarised top quarks

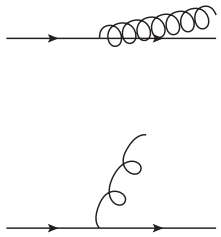
[Chen,Czakon,Poncelet '17]

- Projection onto spin- and colour structures
- IBP reduction onto master integrals
  - 422 master integrals
  - Involve also elliptic structures
  - Not yet completely known analytically
- Numerical calculation of master integrals
  - Solve differential equations numerically from boundary conditions in high-energy limit
  - New: Partially canonicalised DEQ system $\to$ CANONICA [Meyer '18]



Infrared divergences

- Real and virtual corrections contain IR divergences
- IR safe observables: Divergences cancel between real and virtual contributions
- Dimensional regularisation ($d = 4 - 2\epsilon$):
  Real and virtual contain poles in $1/\epsilon$
- Arise from integration over massless degrees of freedom



$$\frac{1}{(p+k)^2} = \frac{1}{2p \cdot k} = \frac{1}{2E_p E_k (1 - \cos\theta)}$$

  - Requires performing the loop and phase space integrals first
  - Phase space integrals are usually done numerically
  - Can't naively expand integrand in ϵ before integration
- Devise scheme to extract and cancel divergences
  - Slicing methods
  - Subtraction methods

Sector-improved residue subtraction scheme

Problem: Many singular limits; overlapping singularities

Idea:

- Subdivide phase space into sectors (similar to FKS scheme)
- Use sector decomposition to extract the singularities
  - Parametrise phasespace such that soft and collinear singularities are mapped to integration boundary of just one variable
  - Use plus distributions to generate subtraction terms
  - Express subtraction terms through QCD factorisation formulae
- Regulated terms can be expanded in ϵ at integrand level
- Integrate coefficients of truncated Laurent series numerically

Sector-improved residue subtraction scheme

Problem: Many singular limits; overlapping singularities

Idea:

- Subdivide phase space into sectors (similar to FKS scheme)

$$1 = \sum_{i,j} \left[\sum_{k} \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right]$$

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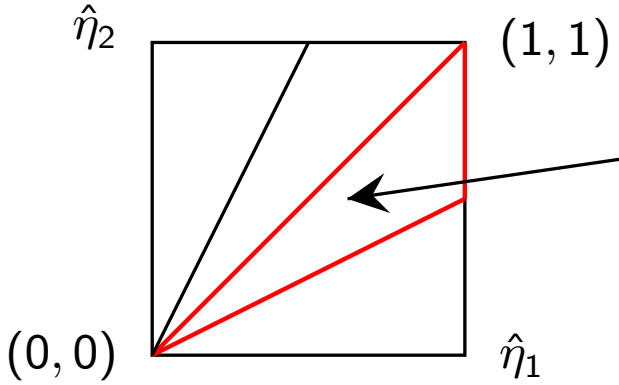

$$\hat{\eta}_i = \tfrac{1}{2}(1 - \cos\theta_i)$$
$$\hat{\eta}_1 = \eta_1$$
$$\hat{\eta}_2 = \eta_1\left(1 - \tfrac{\eta_2}{2}\right)$$

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$$\int_0^1 dx \frac{f(x)}{x^{1+b\epsilon}} = -\frac{f(0)}{b\epsilon} + \int_0^1 dx \frac{f(x) - f(0)}{x^{1+b\epsilon}}$$

  - Express subtraction terms through QCD factorisation formulae
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Sector-improved residue subtraction scheme

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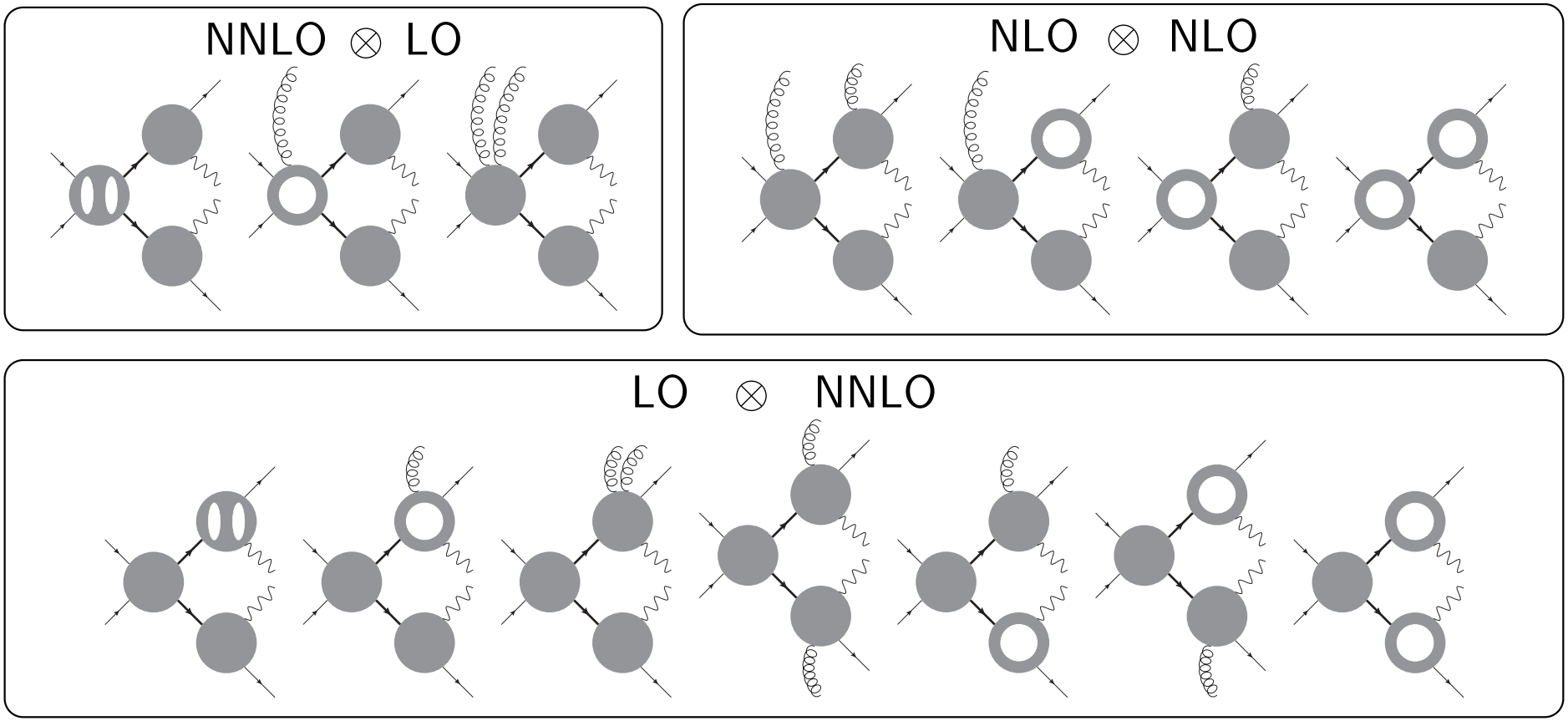
$$\langle \mathcal{M}_{n+1}^{(0)} \mid \mathcal{M}_{n+1}^{(0)} \rangle \overset{q\to 0}{\simeq} -g_s^2 \sum_{i,j} S_{ij}(q) \langle \mathcal{M}_n^{(0)} \mid \mathbf{T}_i \cdot \mathbf{T}_j \mid \mathcal{M}_n^{(0)} \rangle$$

- Regulated terms can be expanded in ϵ at integrand level
- Integrate coefficients of truncated Laurent series numerically

Sector-improved residue subtraction: New developments

- New phasespace construction
  - Minimises the number of resolved kinematics for subtraction terms
  - Reduces the problem of mis-binning
  - Improved stability of invariant mass distribution
- Rederivation of the four-dimensional formulation of the scheme
  - Treat resolved momenta and spins as four-dimensional
  - Non-trivial since poles are calculated numerically
  - Crucial for high-multiplicity final states
  - New phasespace construction works in lab frame
    $\Rightarrow$ rederivation of four-dimensional formulation necessary
  - Allows to check numerical pole cancellation for individual phase space points

Subtraction for top pair production and decay



- Extended implementation of subtraction scheme to include decays
- NNLO $\otimes$ LO and LO $\otimes$ NNLO done with sector-improved residue subtraction
- NLO $\otimes$ NLO used Catani-Seymour for NLO decays

Setup of the calculation

ATLAS published data for two selection cuts, which we try to reproduce: Fiducial and inclusive

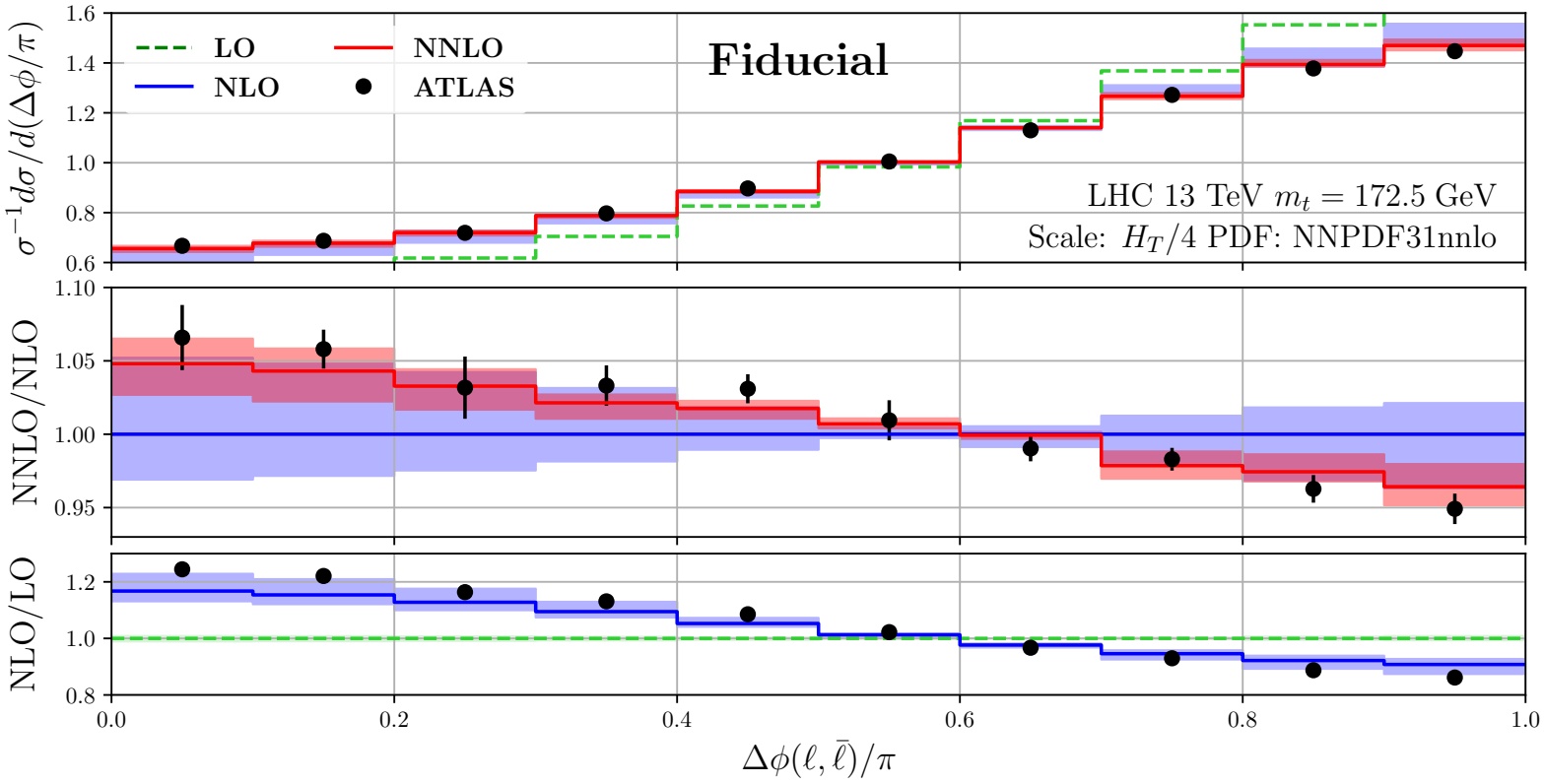
Fiducial setup

- Exactly 2 opposite sign leptons with $p_T > 27(25)$ GeV for the harder (softer) lepton and $|\eta| < 2.5$
- At least 2 jets with $p_T > 25$ GeV and $|\eta| < 2.5$ at least one of them b-flavoured
- Jets defined with anti-k_T algorithm with $R = 0.4$

Inclusive setup

- No selection cuts
- ATLAS extrapolates via Monte Carlo simulation

Differential distributions for $\Delta\phi_{\ell\bar{\ell}}$ at NNLO



- Agreement between data and theory improves at NNLO
- NNLO corrections are larger in fiducial than in inclusive phasespace
- Inclusive: NNLO predictions still somewhat disagree with data
  $\Rightarrow$ Issue with extrapolation due to NLO Monte Carlo?

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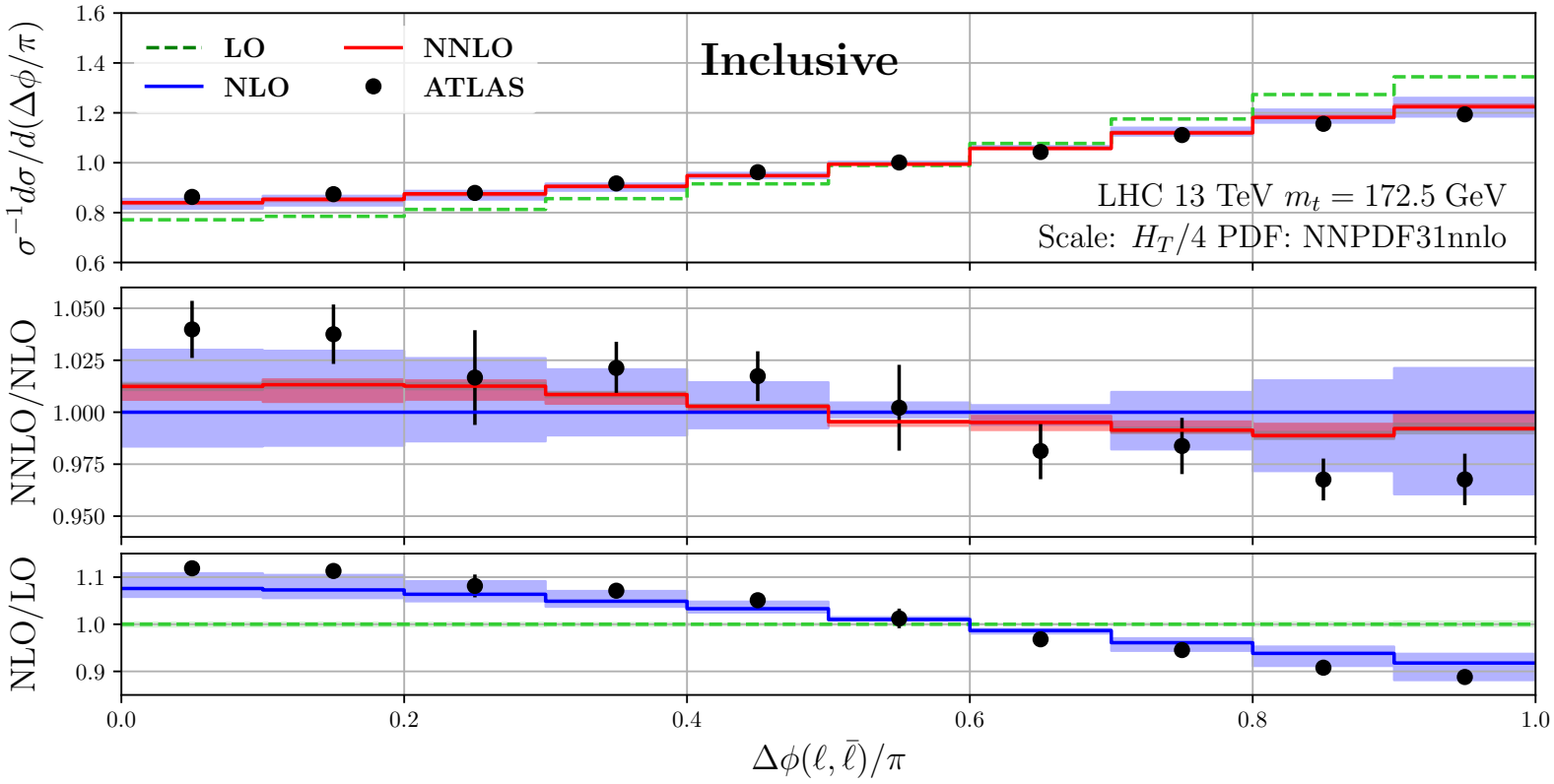

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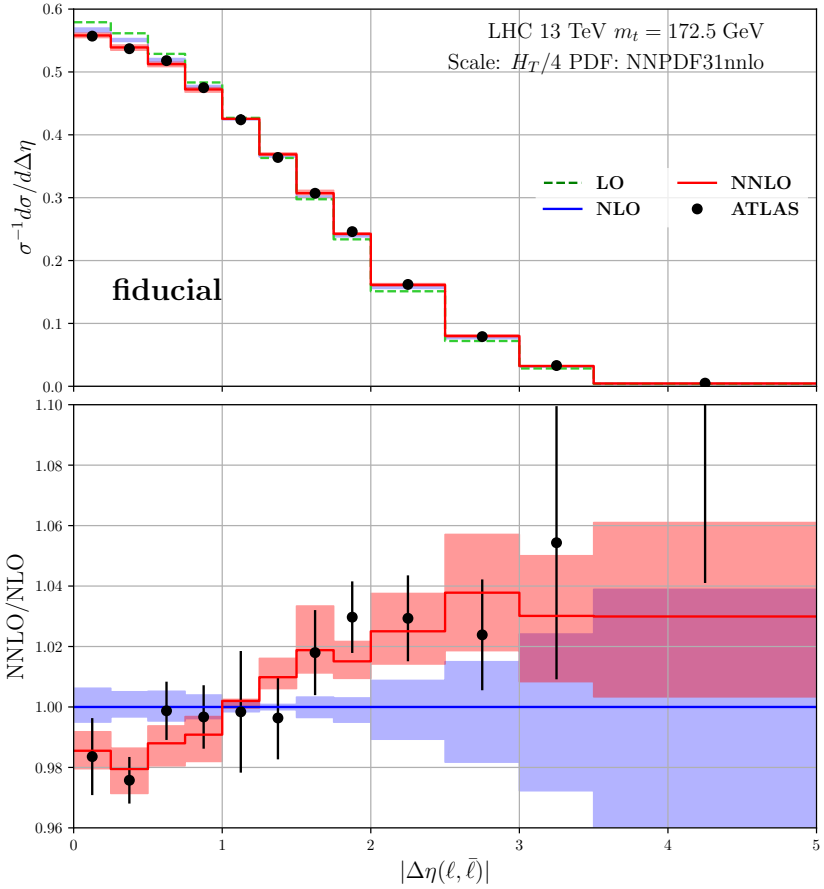
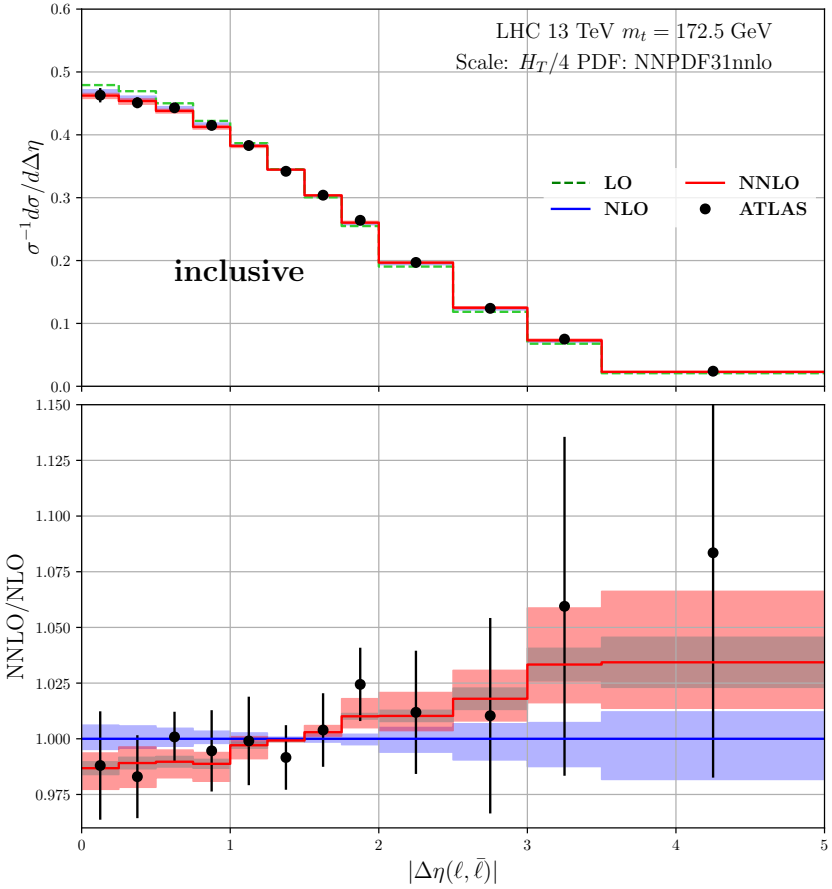
Differential distributions for $\Delta\eta_{\ell\bar{\ell}}$ at NNLO



- NNLO corrections improve agreement with data
- Slightly larger corrections in inclusive case
- Overall good agreement with available data

Differential distributions for $\Delta\eta_{\ell\bar{\ell}}$ at NNLO



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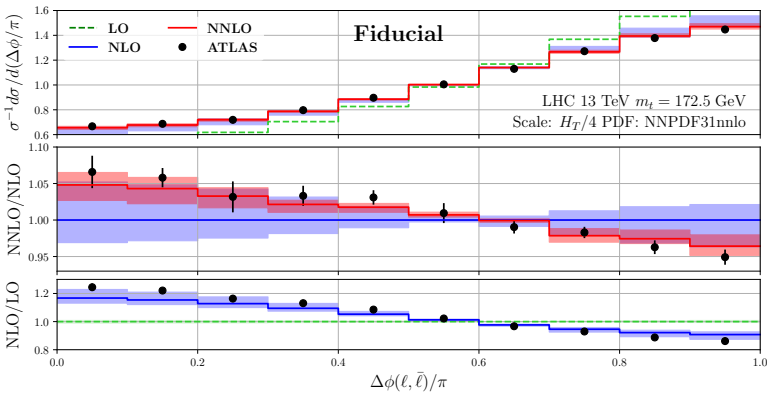
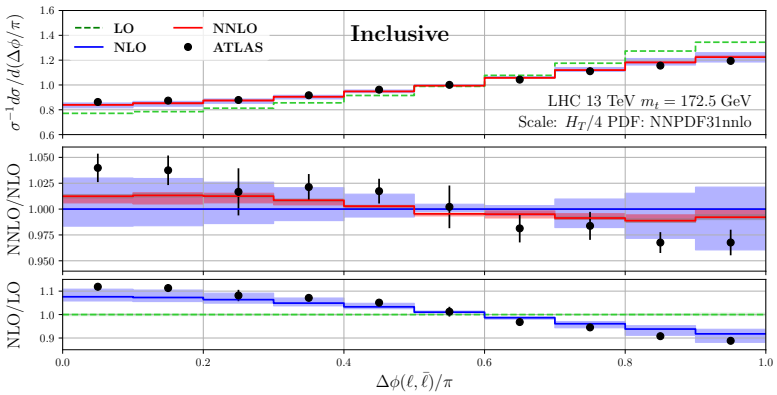
Anatomy of the higher-order $\Delta\phi_{\ell\bar{\ell}}$ corrections

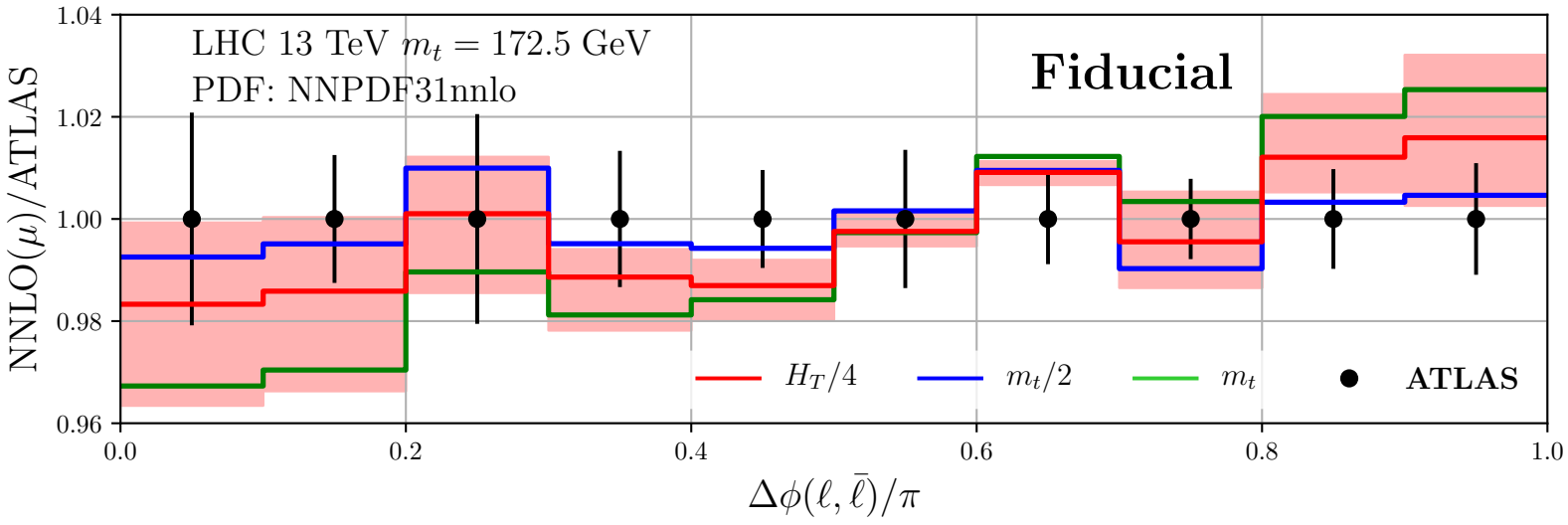




Size of the NNLO correction

- Fiducial: For $\mu_{F,R} = H_T/4$ NNLO corrections are at most $\sim 5\%$
  - Consistent with NLO scale uncertainty
  - NLO/LO K-factor up to $\sim 15\%$
- Inclusive: Smaller K-factor and less scale variation
- Consistent with good perturbative convergence
- NNLO corrections are important
  - Reduce scale uncertainty by more than factor 2
  - Modify shape of distribution in same direction as spin correlations
  - Improve agreement with data

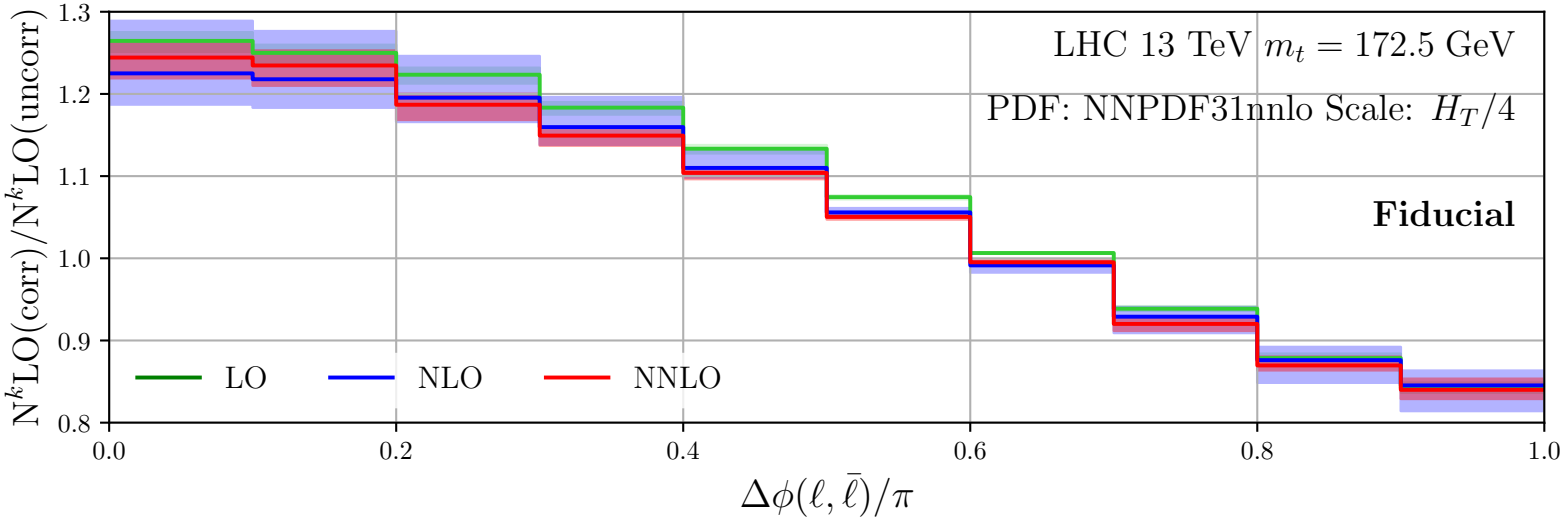
Anatomy of the higher-order $\Delta\phi_{\ell\bar{\ell}}$ corrections



Scale choices

- We tried three scale choices: $\mu_{F,R} = H_T/4$, $m_t/2$ and m_t with $H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2}$
- $H_T/4$ and $m_t/2$ show similar behaviour
- m_t shows slower perturbative convergence
  $\rightarrow$ non-negligible corrections beyond NNLO?

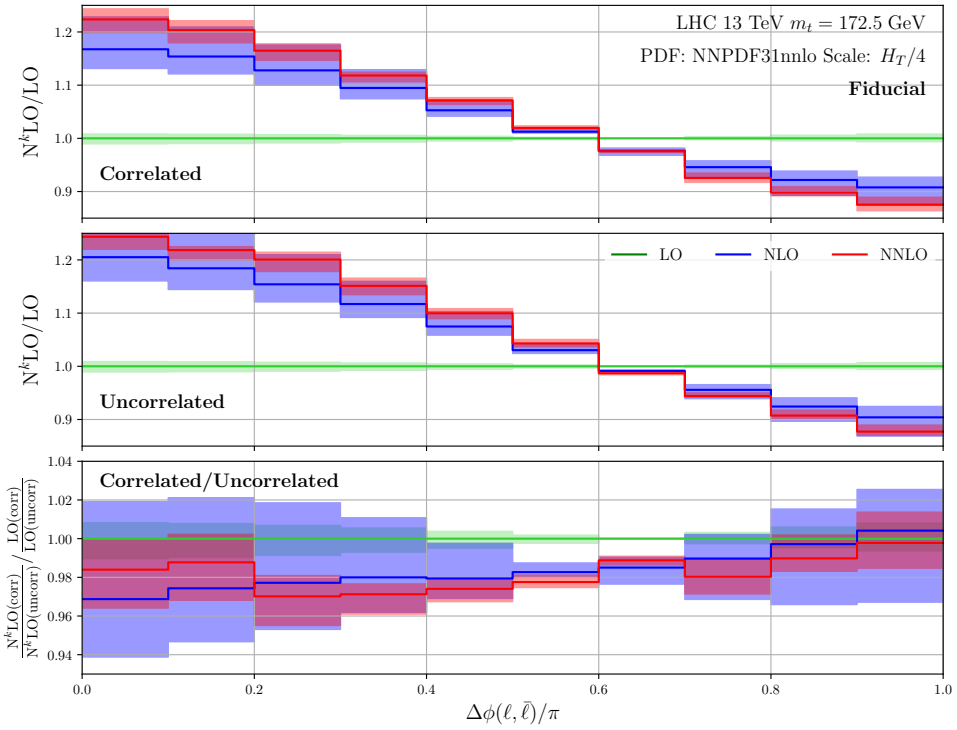
Anatomy of the higher-order $\Delta\phi_{\ell\bar{\ell}}$ corrections



Quantifying spin correlations

- Compare correlated and uncorrelated results at each order
- Correlations are an important effect (up to $\sim 25\%$)
- Change little at higher orders

Anatomy of the higher-order $\Delta\phi_{\ell\bar{\ell}}$ corrections



Quantifying spin correlations

- Disentangle kinematics and spin effects
- Higher order corrections are mostly a kinematic effect

Conclusions

Summary

- Calculated NNLO QCD corrections to top pair production with decays at the LHC in the NWA
- Allows for consistent treatment of production and decay
- Fiducial cross sections become available at NNLO
- Reduced scale uncertainty
- NNLO corrections to $\Delta\phi(\ell, \bar{\ell})$ and $\Delta\eta(\ell, \bar{\ell})$ distributions improve agreement with data from ATLAS collaboration

Outlook

- m_t dependence of differential distributions
  $\Rightarrow$ extraction of m_t from fiducial cross sections
- Predictions for lepton charge asymmetry