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Fully Differential predictions for top-quark pair production at NNLO using STRIPPER

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NNLO – Cross section

$$\sigma_{h_1 h_2}(P_1, P_2) = \sum_{ab} \iint_0^1 \mathrm{d}x_1 \mathrm{d}x_2\, f_{a/h_1}(x_1, \mu_\mathrm{F}^2)\, f_{b/h_2}(x_2, \mu_\mathrm{F}^2)\, \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2;\, \alpha_s(\mu_\mathrm{R}^2),\, \mu_\mathrm{R}^2,\, \mu_\mathrm{F}^2)$$

- Partonic cross section expansion in α_s at NNLO

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \hat{\sigma}_{ab}^{(1)} + \hat{\sigma}_{ab}^{(2)}$$

R: Real radiation
V: Virtual
C: Collinear Factorization

- NNLO contribution

$$\hat{\sigma}_{ab}^{(2)} = \hat{\sigma}_{ab}^{\mathrm{RR}} + \hat{\sigma}_{ab}^{\mathrm{RV}} + \hat{\sigma}_{ab}^{\mathrm{VV}} + \hat{\sigma}_{ab}^{\mathrm{C1}} + \hat{\sigma}_{ab}^{\mathrm{C2}}$$

Sum is Finite

Real IR - poles (RR, RV)

Virtual IR - poles (RV, VV)

- STRIPPER
  - Subtraction scheme to consistently cancel IR - singularities

Subtraction/slicing schemes at NNLO

- Antenna subtraction
  - e+e- → 3 jets, pp → 2 jets, qq → tt, H + jet

[Gehrmann, GehrmannDeRidder, Glover, Heinrich '05 - '08]
[Weinzierl '08, '09]
[Currie, Gehrmann, GehrmannDeRidder, Glover, Pires, '13 -'14]
[Bernreuther, Bogner, Dekkers, '11,'14]
[Abelof, (Dekkers), GermannDeRidder, '11-'15]
[Abelof, GehrmannDeRidder, Maierhofer, Pozzorini, '14]
[Chen, Gehrmann, Glover, Jaquier, '15]

- Colorful subtraction
  - H → bb, e+e- → 3 jets

[DelDuca, Somogyi, Troscsanyi, '05 - '13]
[DelDuca, Duhr, Somogyi, Tramontano, Trocsanyi, '15]
[DelDuca et al. , '16]

- qT – slicing
  - pp → H, pp → V, pp → H + V, pp → VV, qq → tt (flavour off-diagonal)

[Catani, Grazzini, '07]
[Ferrera, Grazzini, Tramontano, '11]
[Catani, Cieri, DeFlorian, Ferrera, Grazzini, '12]
[Gehrmann, Grazzini, Kallweit, Maierhofer, Manteuffel, Rathlev, Torre, '14 -'15]
[Bonciani, Catani, Grazzini, Sargsyan, Torre; '14. '15]

- N-jettiness slicing
  - pp → H + jet, pp → W + jet, pp → Z + jet, pp → H + V, pp → γγ

[Gaunt, Stahlhofen, Tackmann, Walsh, '15]
[Boughezal, Focke, Giele, Liu, Petriello, '15-'16]
[Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, '15]
[Campbell, Ellis, Williams, '16]

Sector improved residue subtraction (STRIPPER)

SecToR Improved Phase sPacE for real Radiation

- Local subtraction scheme for NNLO (no approximations)
- First formulation [Czakon, '10, '11]
    - pp → tt (total cross section, A_{FB} at Tevatron, distributions at Tevatron) [Czakon, Fiedler, Mitov; '13, '15] [Czakon, Fiedler, DH, Mitov; '16]
    - pp → H + jet , Z → e+ e-, Muon – decay, b – decay, top – decay, single top production [Boughezal, Caola, Melnikov, Petriello, Schulze, '13 '14] [Boughezal, Melnikov, Petriello, '11] [Caola, Czernecki, Liang, Melnikov, Szafron, '14] [Brucherseifer, Caola, Melnikov, '13, '13, '14]
- Generalization to 4 dimensions [Czakon, DH, '14]

STRIPPER – Main Idea

- Numerical cancellation of IR – poles between NNLO contributions
- Example: Double real radiation (most complicated)

$$\hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \frac{1}{N_{ab}} \int \mathrm{d}\boldsymbol{\Phi}_{n+2} \, \langle \mathcal{M}_{n+2}^{(0)} | \mathcal{M}_{n+2}^{(0)} \rangle \, \mathrm{F}_{n+2}$$

1) Use selector functions to split phase space into triple and double collinear sectors

2) Use physical parametrization (angles, energies) [Frixione, Kunszt, Signer (FKS); '95]

3) Physical sector decomposition: Factorization of non-commuting singularities [Binoth, Heinrich; '00]

4) Generate subtraction terms

5) Laurent series in ϵ ($\rightarrow$ numerical integration of all coefficients)

STRIPPER – General formulation

[Czakon, DH; '14]

$$\hat{\sigma}^{(2)}_{ab} = \hat{\sigma}^{\rm RR}_{ab} + \hat{\sigma}^{\rm RV}_{ab} + \hat{\sigma}^{\rm VV}_{ab} + \hat{\sigma}^{\rm C1}_{ab} + \hat{\sigma}^{\rm C2}_{ab}$$

- Each contribution is a Laurent series in ϵ
- Separation of independently finite contributions (check number of unresolved particles)
  - Finite contribution (all particles resolved)
  - Single unresolved $|\mathcal{M}^{(0)}_{n+1}\rangle$
  - Double unresolved $|\mathcal{M}^{(0)}_{n}\rangle$
  - Finite Remainder $|\mathcal{F}^{(1)}_n\rangle = |\mathcal{M}^{(1)}_n\rangle - \mathbf{Z}^{(1)}|\mathcal{M}^{(0)}_n\rangle$

$$\hat{\sigma}^{\rm RR}_{\rm F}\,, \quad \hat{\sigma}^{\rm RV}_{\rm F}\,, \quad \hat{\sigma}^{\rm VV}_{\rm F}\,, \quad \hat{\sigma}_{\rm FR} = \hat{\sigma}^{\rm RV}_{\rm FR} + \hat{\sigma}^{\rm VV}_{\rm FR} + \hat{\sigma}^{\rm C2}_{\rm FR}\,,$$

$$\hat{\sigma}_{\rm SU} = \hat{\sigma}^{\rm RR}_{\rm SU} + \hat{\sigma}^{\rm RV}_{\rm SU} + \hat{\sigma}^{\rm C1}_{\rm SU}\,, \quad \hat{\sigma}_{\rm DU} = \hat{\sigma}^{\rm RR}_{\rm DU} + \hat{\sigma}^{\rm RV}_{\rm DU} + \hat{\sigma}^{\rm VV}_{\rm DU} + \hat{\sigma}^{\rm C1}_{\rm DU} + \hat{\sigma}^{\rm C2}_{\rm DU}$$

- Make sure that SU and DU cancel independently ($\rightarrow$ resolved particles in 4 dimensions)

Differential top-quark pair production at NNLO

[Czakon, DH, Mitov; 2015, 2016]

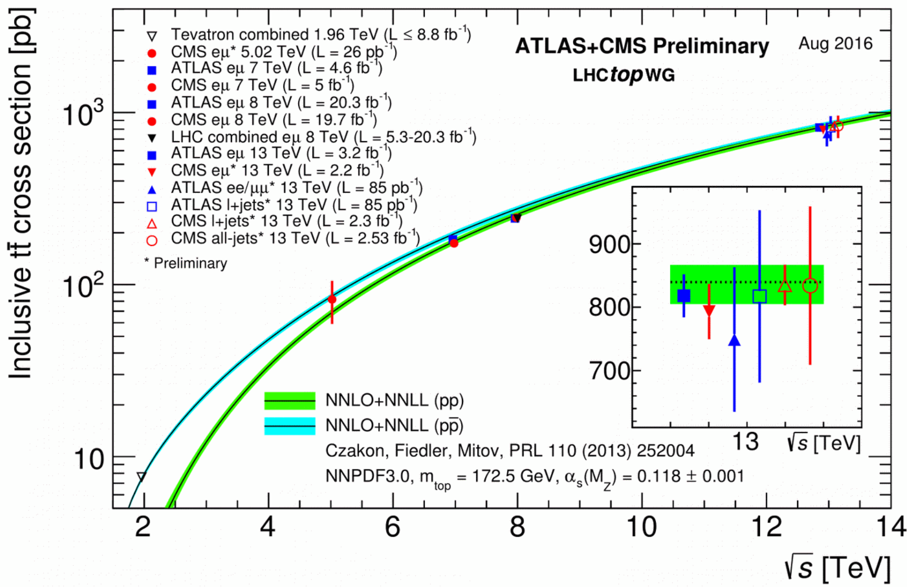
Top-quark pairs at the LHC

- Total cross section measured (~ 7 %)

$$\sigma_{t\bar{t}}(13\,\mathrm{TeV}) \approx (800 \pm 50)\mathrm{pb}$$

- Uncertainty of the prediction
  - LO (30 %) → NLO (15%) → NNLO + NNLL (5%)

→ Percent - level precision required



- Precision tests of the Standard Model
- Background for many searches and processes (Higgs, New Physics,...)
- Constrain gluon PDF at high x
- ...

Scale dependence and best scale choice

[Czakon, DH, Mitov; 2016]

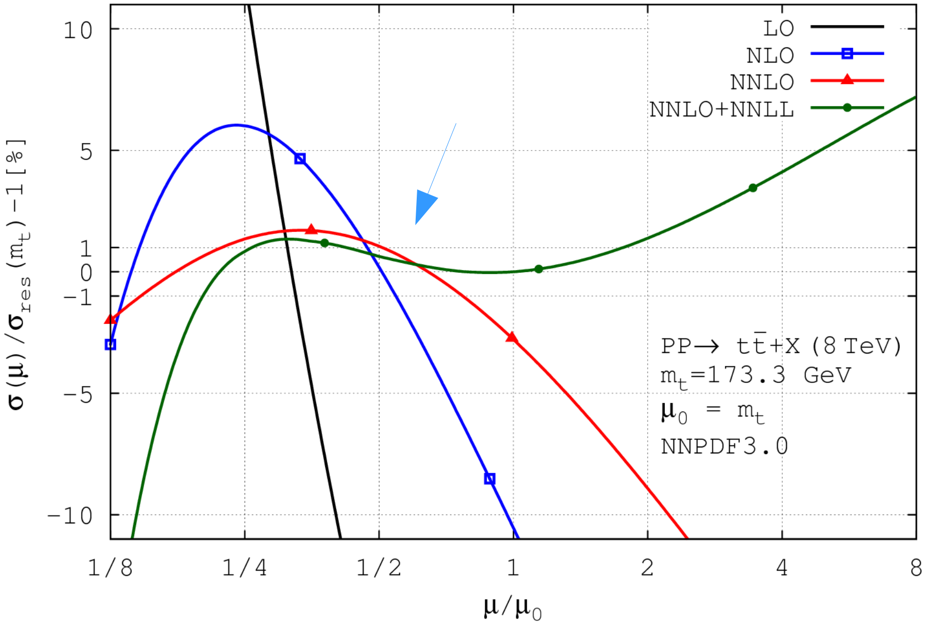
$$\sigma_{h_1 h_2}(P_1, P_2) = \sum_{ab} \iint_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \, f_{a/h_1}(x_1, \mu_\mathrm{F}^2) \, f_{b/h_2}(x_2, \mu_\mathrm{F}^2) \, \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2; \, \alpha_s(\mu_\mathrm{R}^2), \, \mu_\mathrm{R}^2, \, \mu_\mathrm{F}^2)$$

- What is the "best" (dynamical) scale?
  - Difference between different dynamical scales could be as large as difference between dynamical scale and fixed scale
  - Precision predictions only possible for deliberately chosen scale
- Comparative study of perturbative convergence based on different scales

- Selection of the "correct" scale is based on the following criteria:
  - Perturbative convergence for both total and differential cross section
  - Limiting behavior: Low p_T (m_{tt}): ~ m_{top} ↔ High p_T (m_{tt}): ~ p_T
  - Restriction to simple functional forms studied in the past (H_T, m_{tt}, ...)

Scale dependence – Total cross section

[Czakon, DH, Mitov; 2016]



- Look for convergence
  - Scale value which minimizes difference
    - NLO → NNLO → (NNLO + NNLL)
  - Best convergence: $\mu_0 < m_{top}$
  - Little dependence on PDFset at NNLO

  - Value of NNLO cross section at point of best convergence equals the NNLO+NNLL at the usual canonical scale $\mu_0 = m_{top}$

    → Therefore: Resummation has negligible impact on the total cross section at the point of fastest convergence

Scale dependence – Differential Distributions

[Czakon, DH, Mitov; 2016]

- Main guidance is perturbative convergence to discriminate between scales
  - Invariant mass distribution

$$\mu_0 = H_T/4$$ ✓

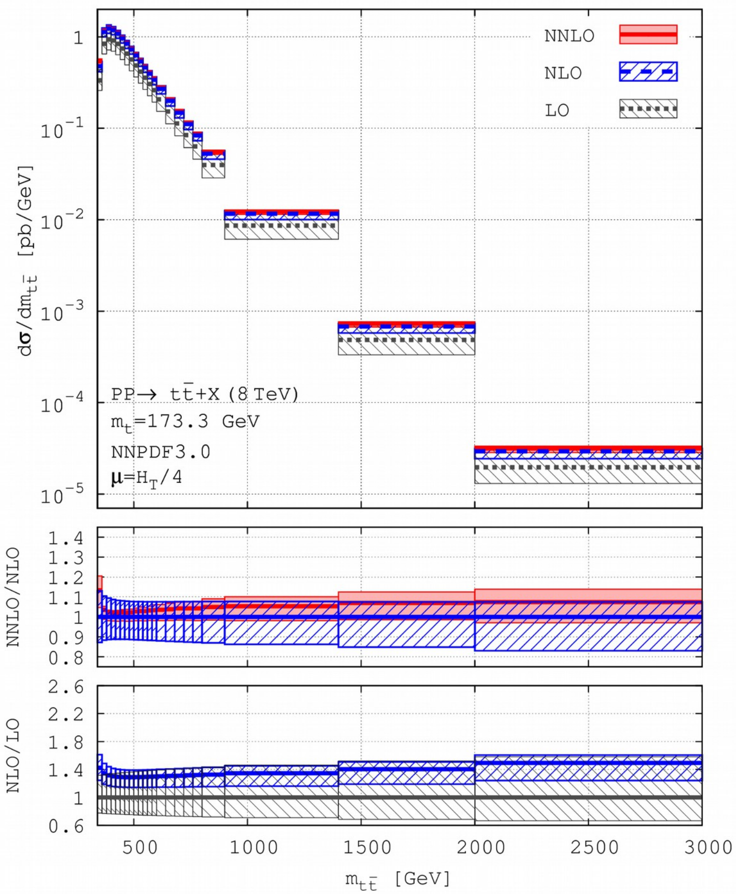
$$H_T = \sqrt{m_t^2 + p_{\mathrm{T}t}^2} + \sqrt{m_t^2 + p_{\mathrm{T}\bar{t}}^2}$$

  - Limiting behaviour

$$\mu_0(p_\mathrm{T} \to 0) \quad \to \quad m_t/2$$
$$\mu_0(p_\mathrm{T} \to \infty) \quad \to \quad (p_{\mathrm{T},t} + p_{\mathrm{T},\bar{t}})/4$$

  - Scales based on the invariant mass itself

$$\mu \propto m_{t\bar{t}}$$ ✗



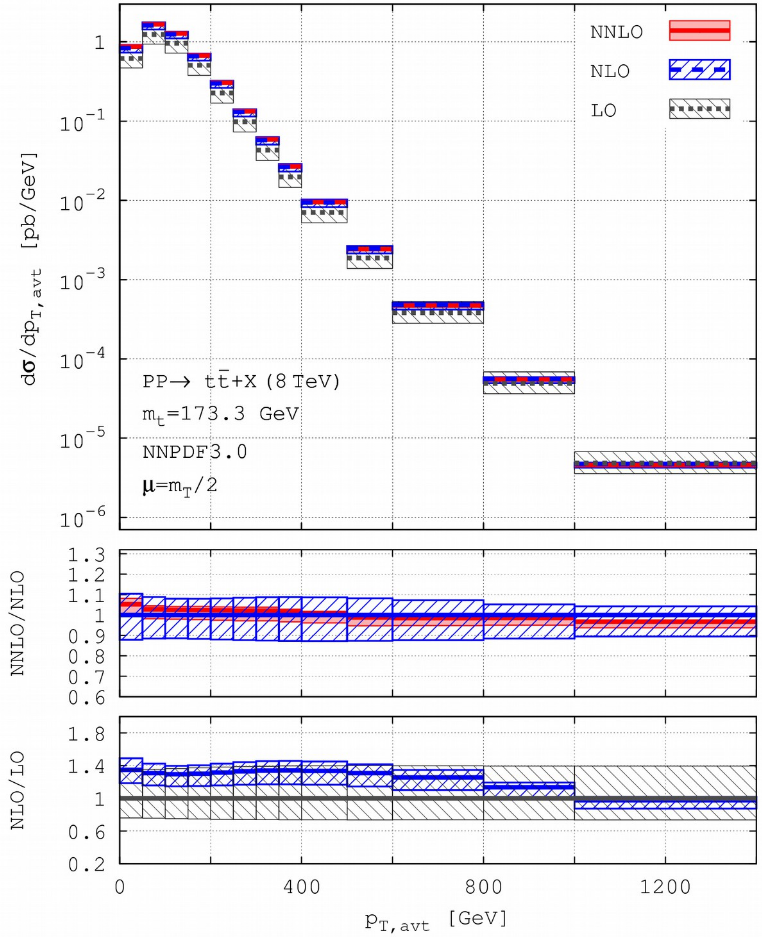
Scale dependence – Differential Distributions

[Czakon, DH, Mitov; 2016]

- Main guidance is perturbative convergence to discriminate between scales
  - Choose individual scales for top and antitop p_T
  - Transverse mass scale

$$\mu_0 = \frac{1}{2} m_{\mathrm{T}}(t/\bar{t}) = \frac{1}{2}\sqrt{m_t^2 + p_{\mathrm{T},t/\bar{t}}^2}$$

  - Average distributions afterwards

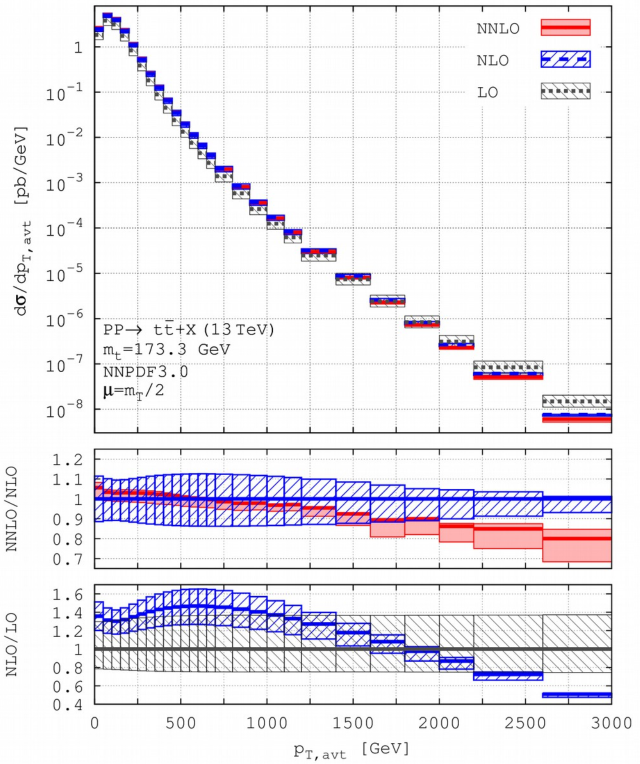


Different scale choices for different observables

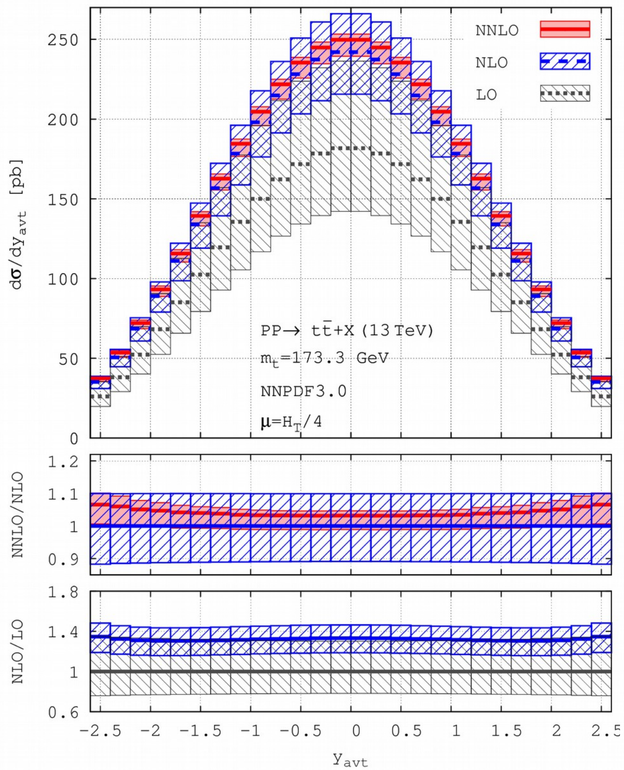
Differential Distributions @ 13 TeV

[Czakon, DH, Mitov; 2016]

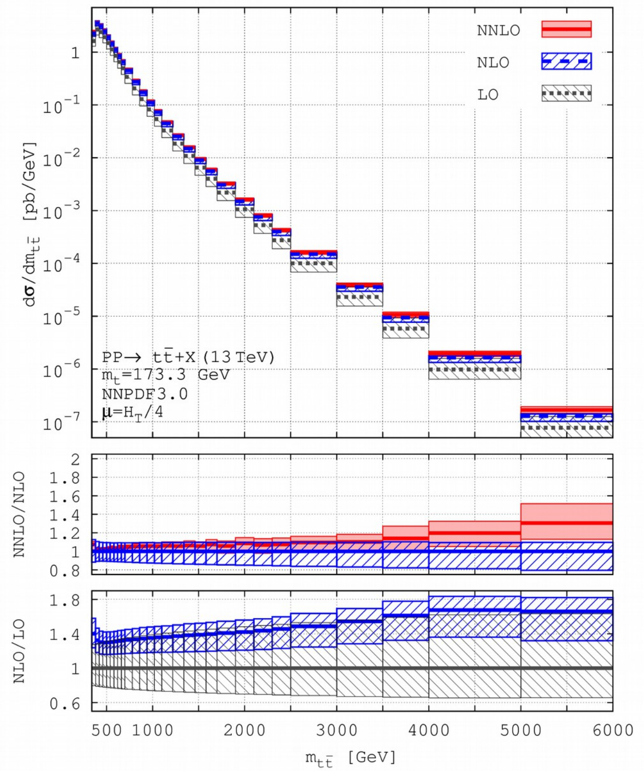
PT ot the top



Rapidity of the top



Invariant mass



Dynamical scales → extended kinematical regime

- Comparison with data → Good agreement

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Bump hunting in top-pair events

(Example: 750 GeV)

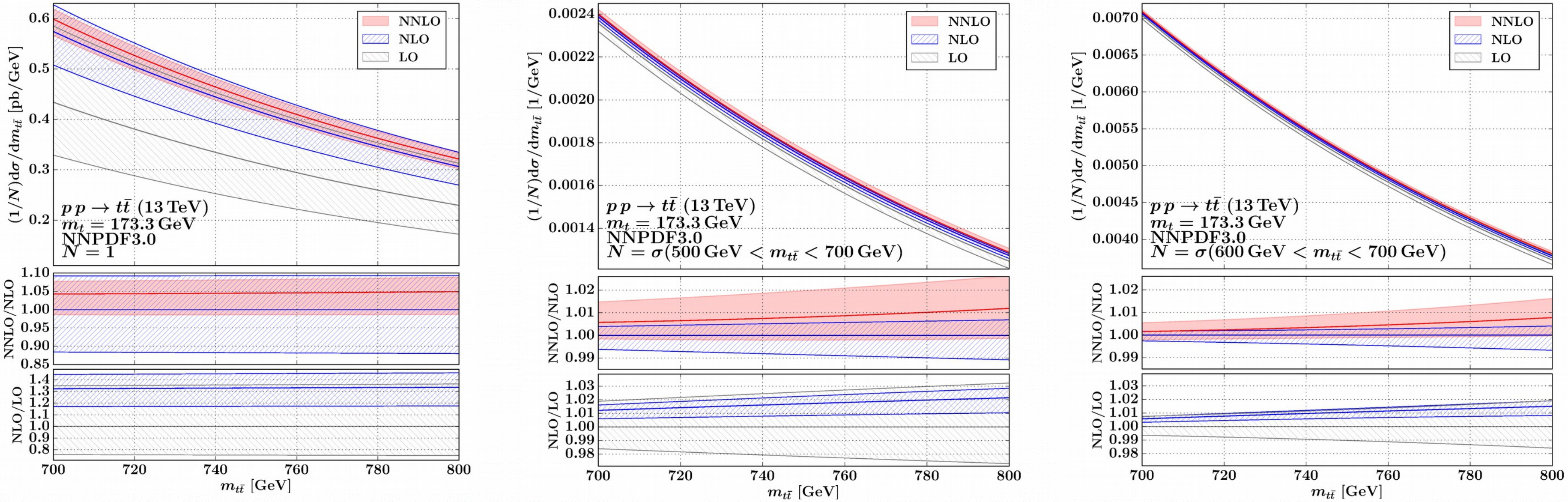
[Czakon,DH, Mitov; 2016]

Bumps in top-pair invariant mass distribution

[Czakon, DH, Mitov; 2016]

- Minimize theory uncertainty → choose appropriate normalization

NNLO scale + (approx.) PDF uncertainty added in quadrature

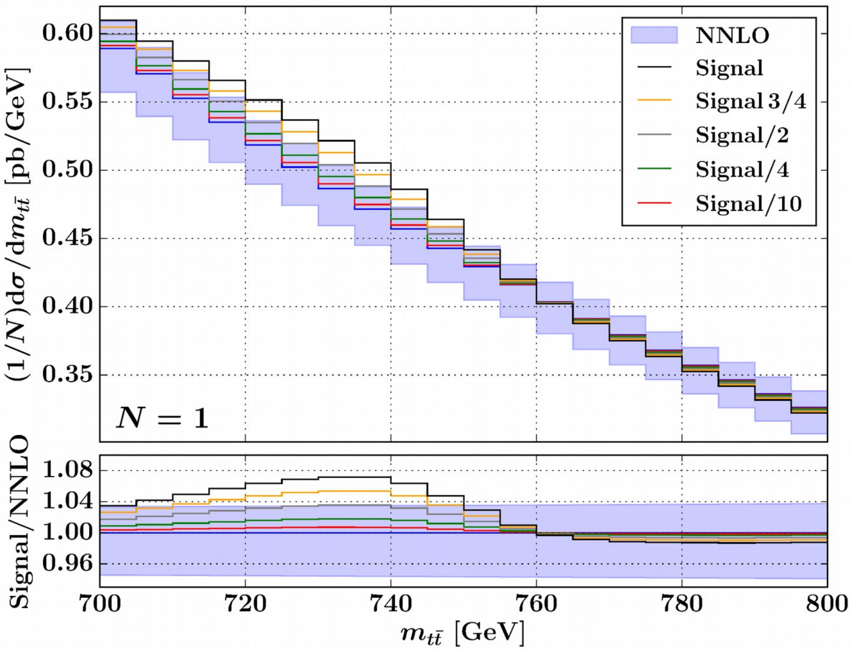


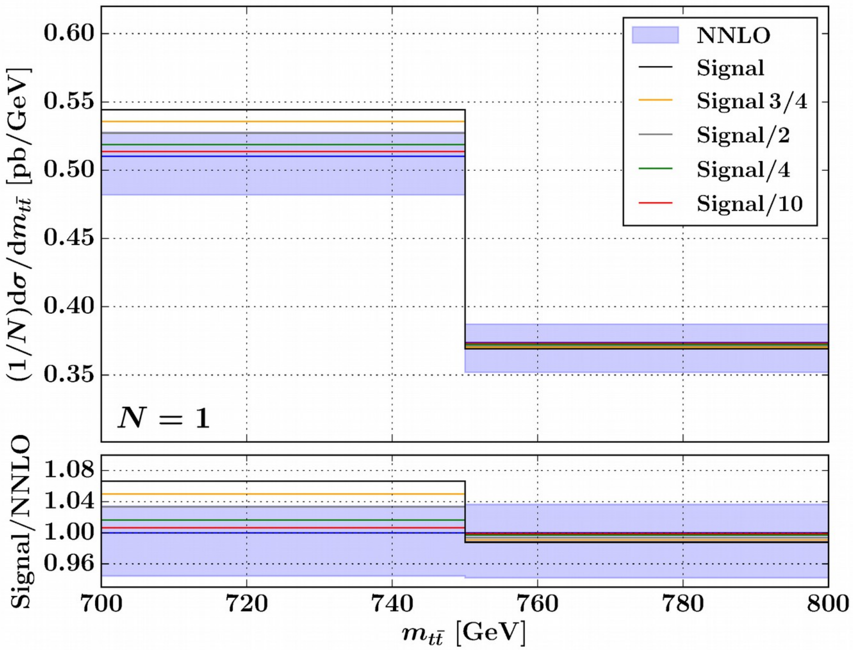
- Trade off between experimental uncertainty and theory uncertainty to choose N
  - Minimize dependence on the top-mass << 1%, checked at NLO
- Analytic fit of the distribution allows flexible rebinning

Bumps in top-pair invariant mass distribution

[Czakon, DH, Mitov; 2016]

- Discriminate Signal from Background





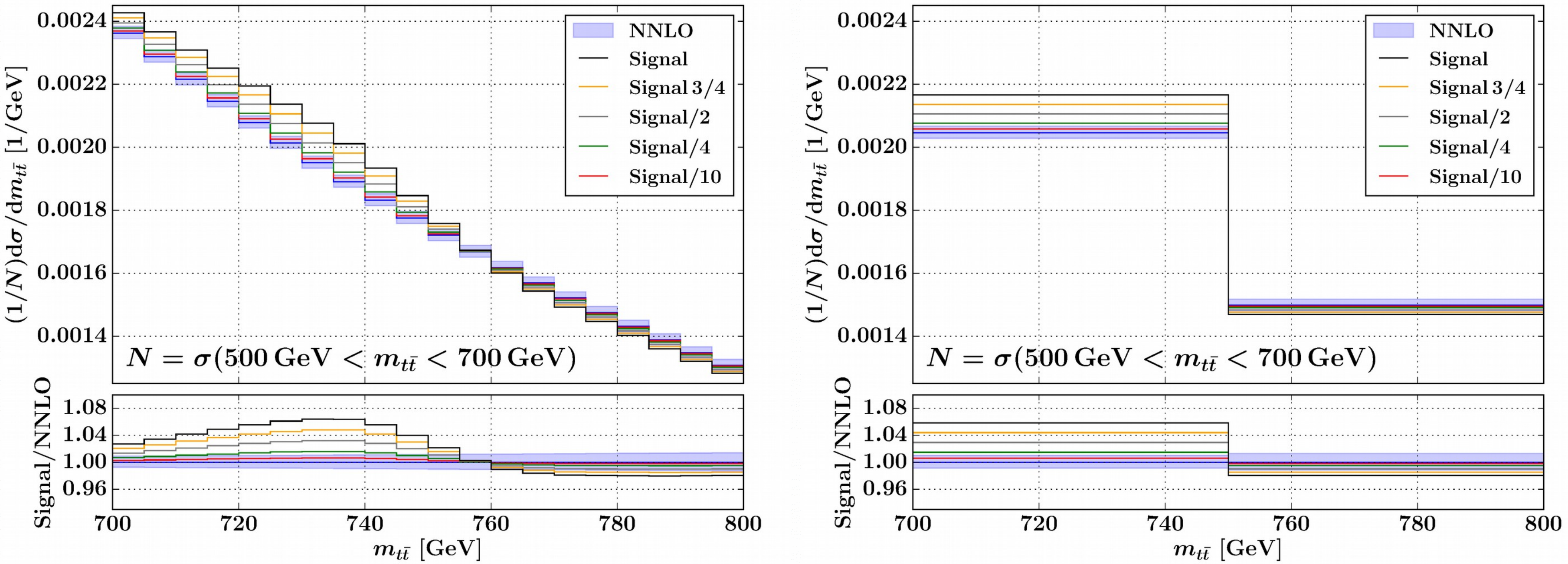
  - Signal Model (BSM) from [Hespel, Maltoni, Vryonidou 2016] → 1.1 pb

  - Significance depends on the bin-width

Bumps in top-pair invariant mass distribution

[Czakon, DH, Mitov; 2016]

- Discriminate Signal from Background



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Bumps in top-pair invariant mass distribution

[Czakon, DH, Mitov; 2016]

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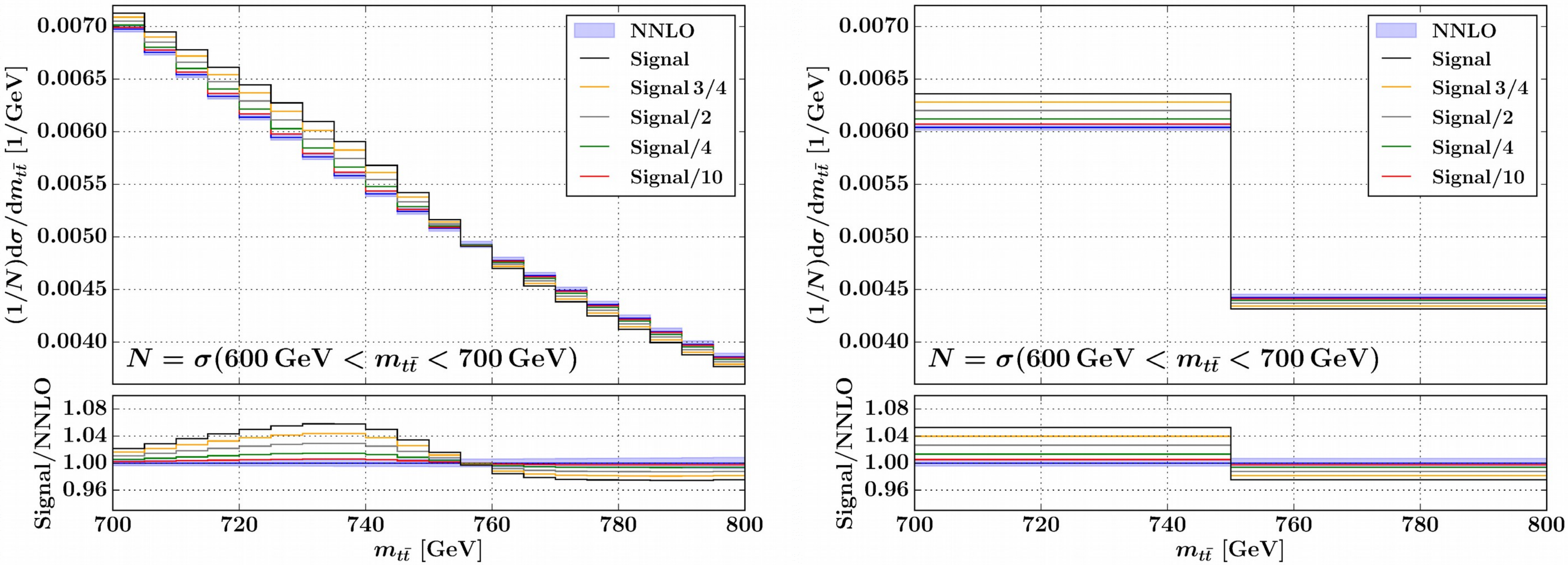


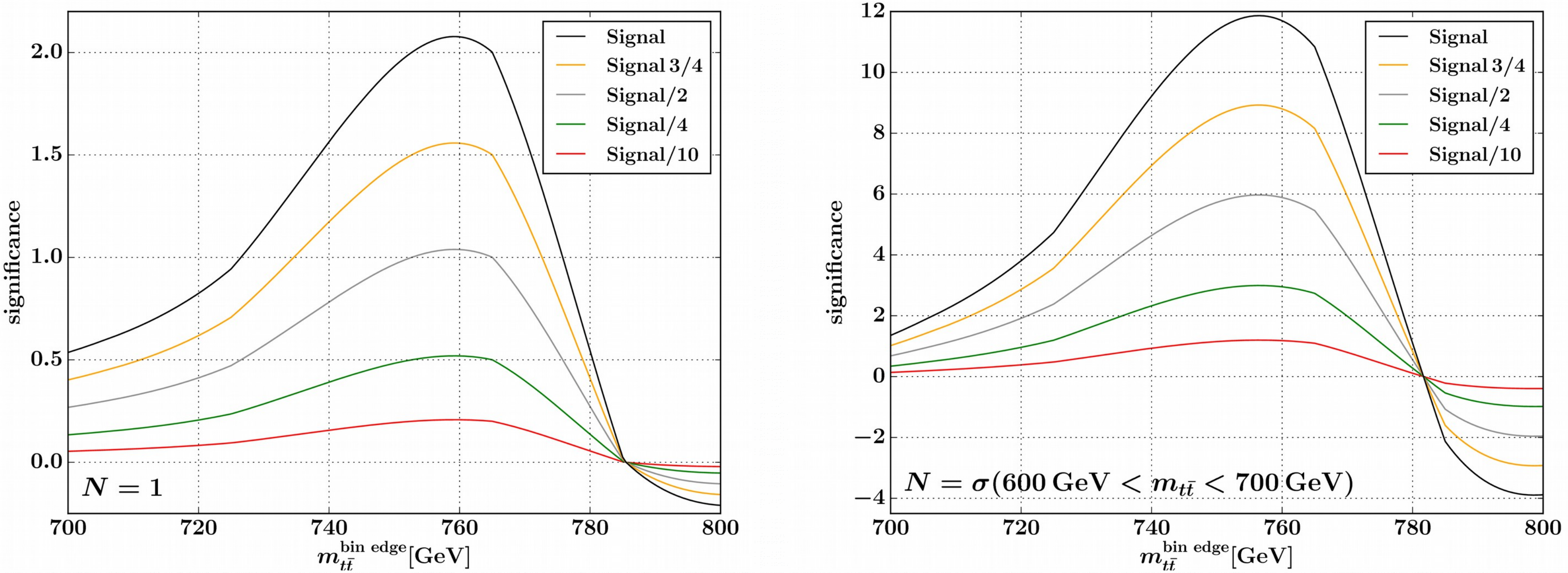
  - Signal Model (BSM) from [Hespel, Maltoni, Vryonidou 2016] → 1.1 pb
  - Significance depends on the bin-width

Bumps in top-pair invariant mass

[Czakon, DH, Mitov; 2016]

- Discriminate Signal from Background
  - Significance depends on the position of the bin as well

$$\text{significance} = \frac{(\text{SM} + \text{BSM})_{\text{central}} - (\text{pure SM})_{\text{central}}}{(\text{pure SM})_{\text{error}}}$$



Summary and Outlook

- Implementation of the Sector improved residue subtraction (STRIPPER)
- Applied to differential top-quark pair productions
  - High quality predictions for LHC at 8 TeV and 13 TeV
  - Precision could be used for new physics searches (Example at 750 GeV)
- Outlook
  - Combine NNLO-QCD with NLO-EW (published soon, in collaboration with Pagani, Tsinikos and Zaro)
  - Include top-quark decays at NNLO

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Back Up Slides

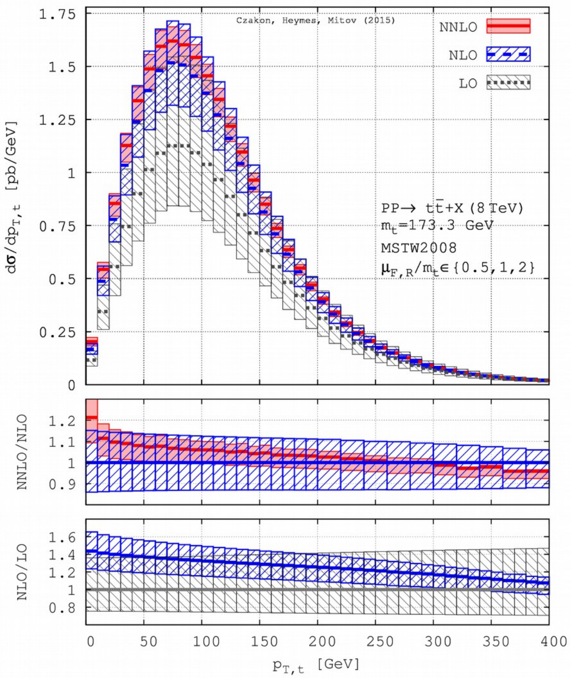
STRIPPER - Implementation

- General purpose event generator for NNLO computation
- Based on four-dimensional formulation of the subtraction scheme
- Complete independent implementation
- SM tree-level matrix elements are included [vanHameren, Bury; '09, '15]
- **Process independent:** User has to interface the one-loop and two-loop **finite** contributions
- **Speed:** Monte Carlo over processes and polarizations
- Simultaneous computation of:
  - Different PDF sets (LHAPDF interface)
  - Different renormalization and factorizations scales
  - Different observables

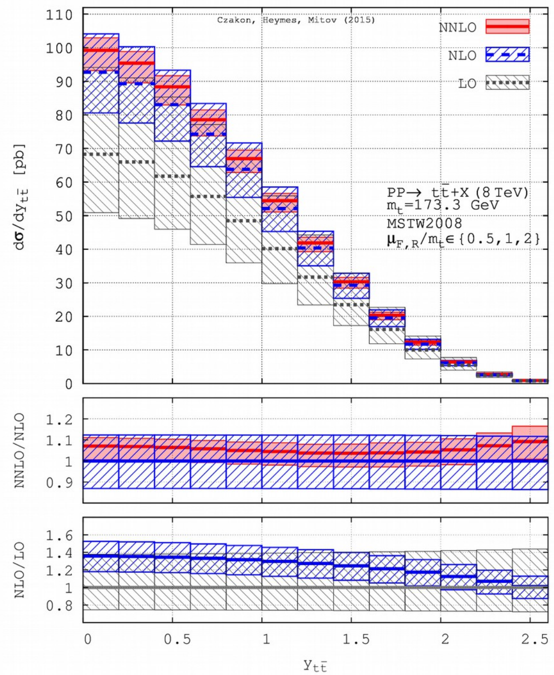
Differential Distributions @ 8 TeV

[Czakon, DH, Mitov; published 2015]

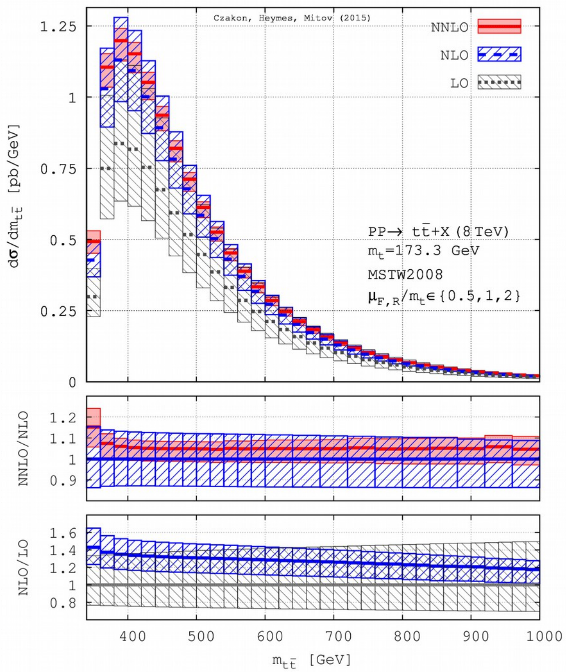
P_T ot the top



Rapidity of the top-pair



Invariant mass

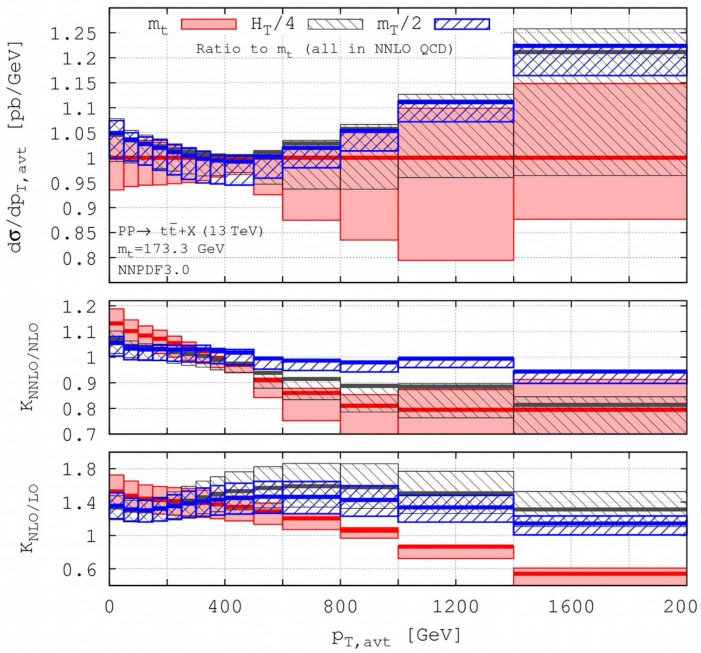


- NNLO has important impact (Good perturbative convergence)
- Good agreement with data → [CMS 2015, ATLAS 2015]
- **However: Results with fixed scales applicable only to limited kinematical range**

Scale dependence – Differential Distributions

[Czakon, DH, Mitov; 2016]

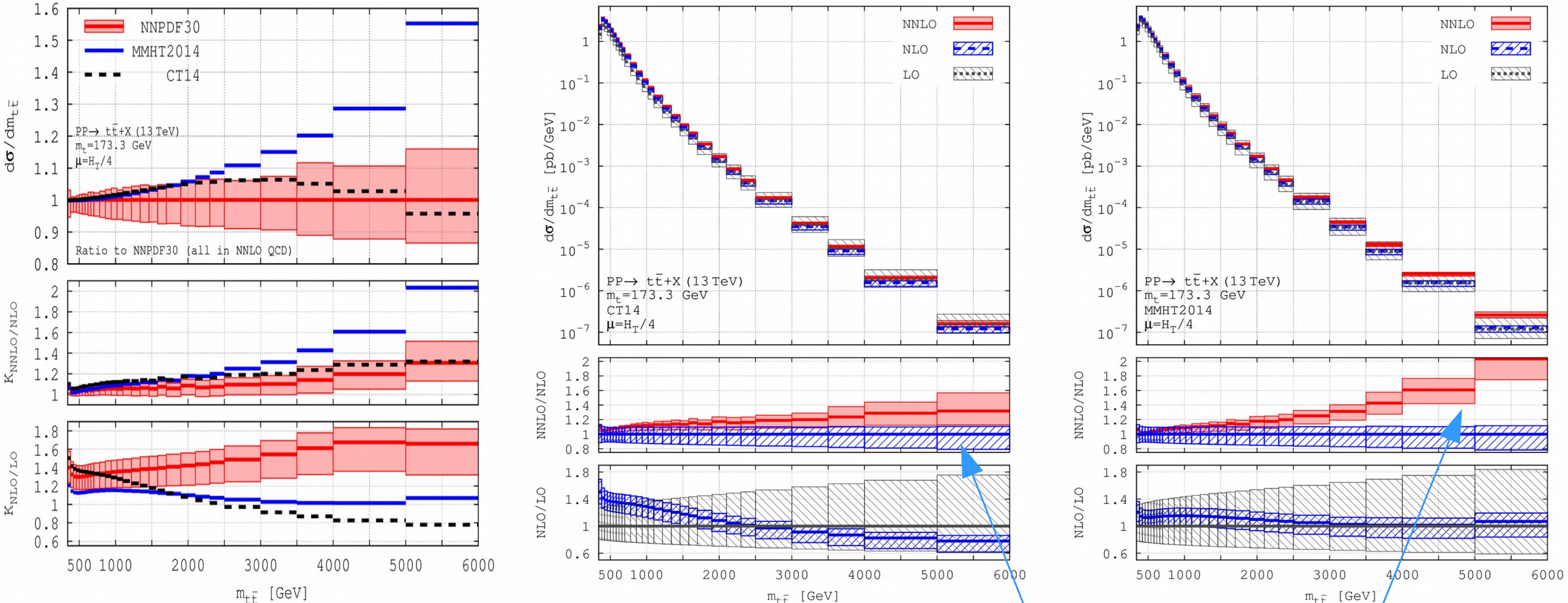
- Comparison between different scale choices
  - Difference within uncertainty
  - Main impact on scale dependence at high values and the K-factor
- Independence of PDF sets has been checked



Differential Distributions @ 13 TeV

[Czakon, DH, Mitov; 2016]

- PDF - dependence



Large PDF error in the multi TeV region

- Useful to constrain PDF sets