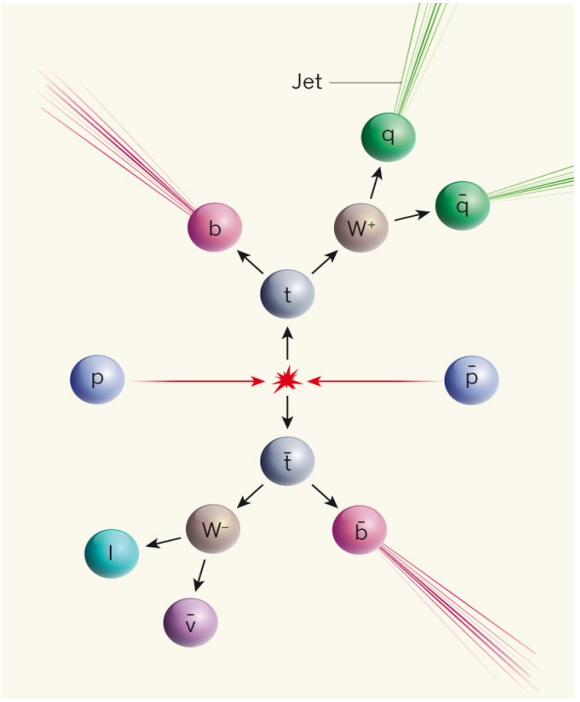

RWTH AACHEN UNIVERSITY

Theory developments in differential distributions for $t\bar{t}$ at NNLO

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TOP2015 Ischia, September 2015

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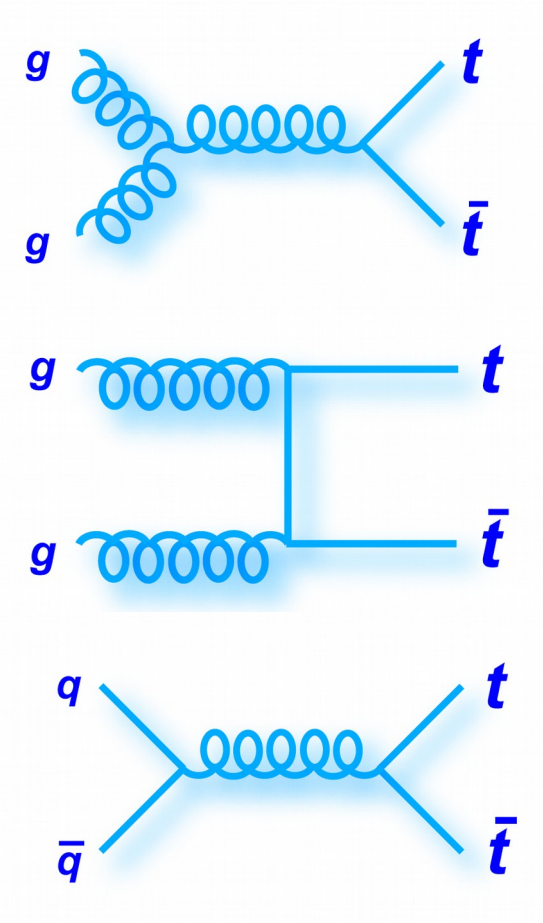
Top pair production at the LHC

- Measured total cross section 8 TeV: ~ 250 pb
- Integrated Luminosity Run I (8 TeV): ~ 25 1/fb
- Produced top pairs
  - 8 TeV $\rightarrow 10^6$ per year
  - 13 TeV $\rightarrow 10^7$ per year
  - TeVatron $\rightarrow 10^4$ per year
- High precision tests of perturbative QCD and the Standard Model are possible
- Important background (for BSM)
- Top pair production could be associated with BSM
- PDF determination

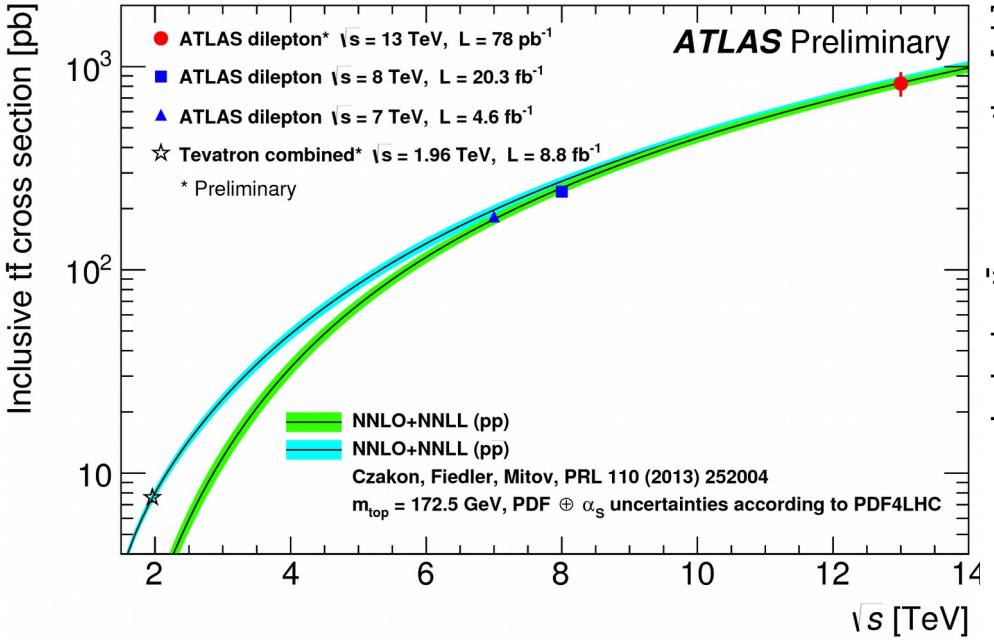


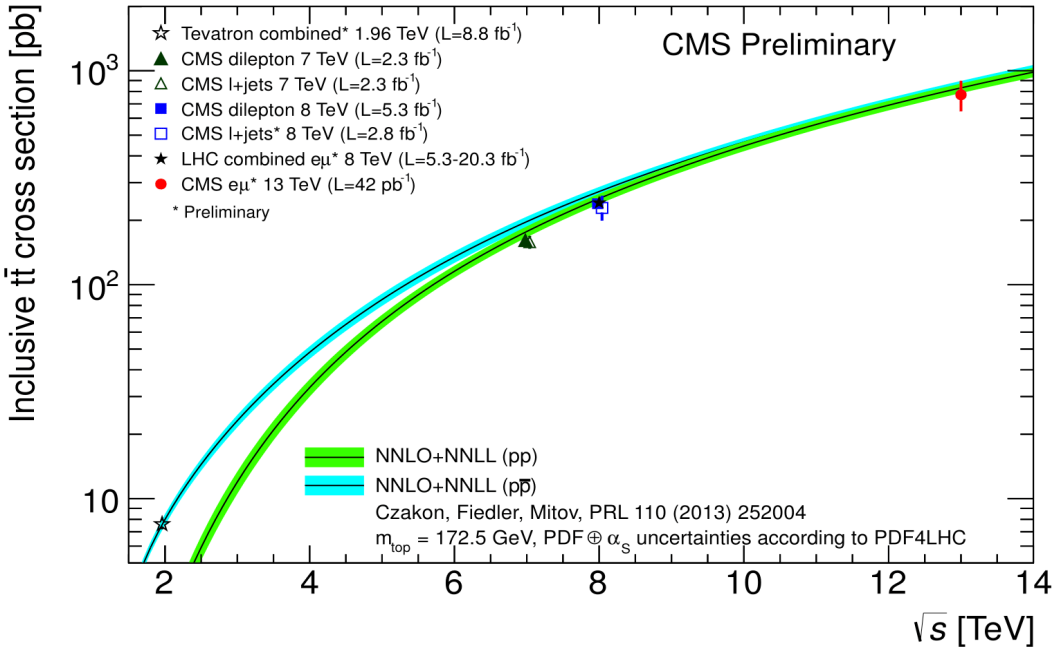
- Dominated by gluon channel (~ 90%)

Total inclusive cross section at NNLO (+NNLL)

[Czakon, Fiedler, Mitov; 2013]

- Measurement vs. prediction (Top ++)



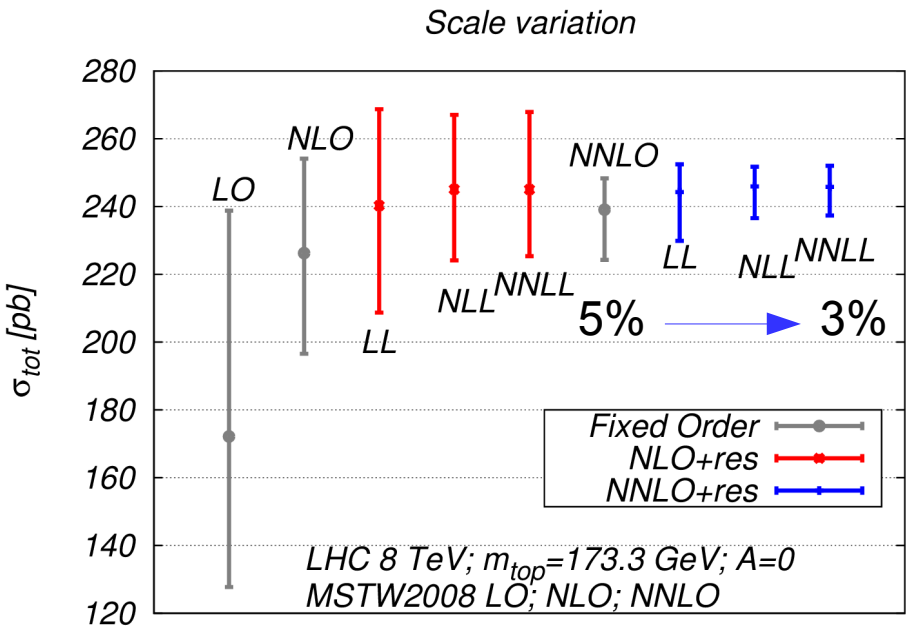


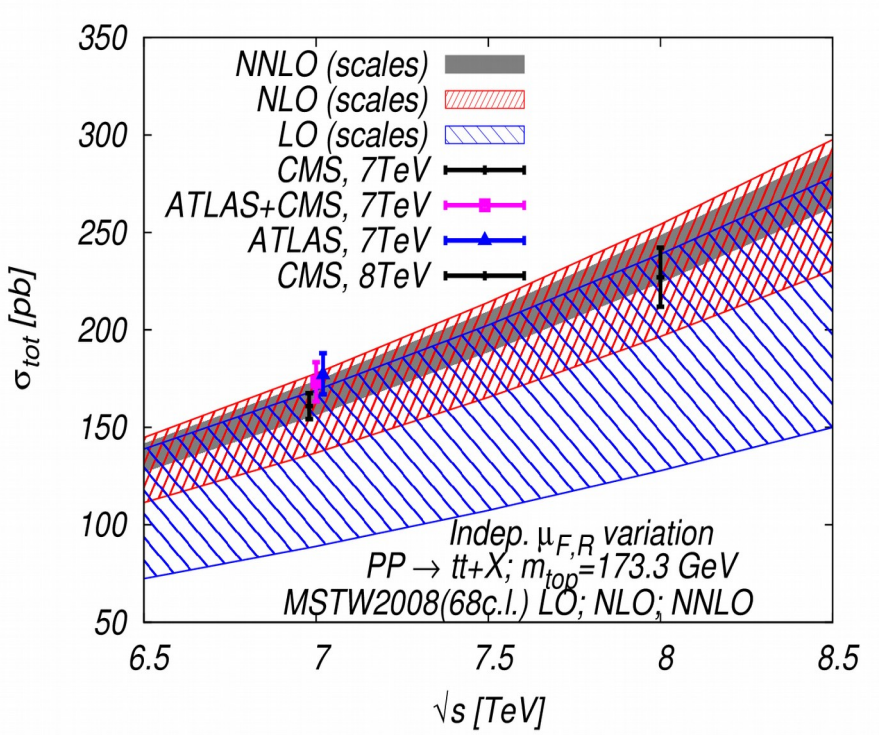
- Agreement at 7 TeV, 8 TeV and 13 TeV (!!!!)
- Theoretical and experimental uncertainty at the same level
- Prediction of the total cross section allows to draw non-trivial conclusions
  - PDF determination [Czakon, Mangano, Mitov, Rojo; 2013]
  - Exclusion of BSM models [Czakon, Fiedler, Mitov, Rojo; 2013]

Total inclusive cross section at NNLO (+NNLL)

[Czakon, Fiedler, Mitov; 2013]

- Do we need NNLO ?



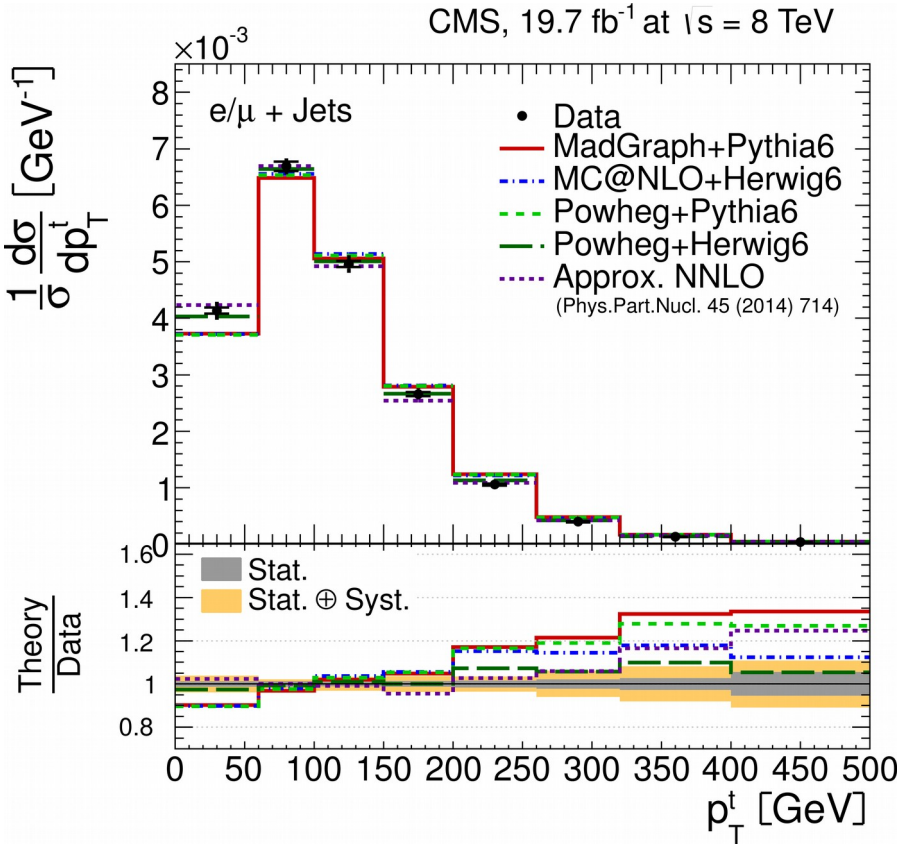


- Uncertainties
  - Scales: ~ 3 %
  - PDF (68% cl): ~ 2 – 3 %
  - Top – mass: ~ 3 %
  - Coupling: ~ 1.5 %

Differential Distributions

Differential measurements and predictions (LHC)

- Transverse momentum of the top



Top Pair Decay Channels

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	$e\bar{e}$	$e\mu$	$e\tau$	electron+jets	
μ^-	$e\mu$	$\mu\bar{\mu}$	$\mu\tau$	muon+jets	
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

dileptons

- Needed: NNLO predictions including decays
- better understanding

Overview of the status: $t\bar{t}$ at NNLO

- Subtraction framework for NNLO computations
  - Consistent cancellation of IR-divergences among different contributions
  - Different approaches

[Abelof, Gehrmann-DeRidder, Maierhofer, Pozzorini; '14, '15]

- Based on **antenna subtraction**
  - Partial results for the quark channel
- Extension of **qt-subtraction** to top pairs [Zhu, Li, Li, Shao, Yang; '13]
  - Proven applicability to top-pairs [Bonciani, Catani, Grazzini, Sargsyan, Torre; '14. '15]
  - Total cross section for qg, flavor off-diagonal $q(\bar{q})\ q'$

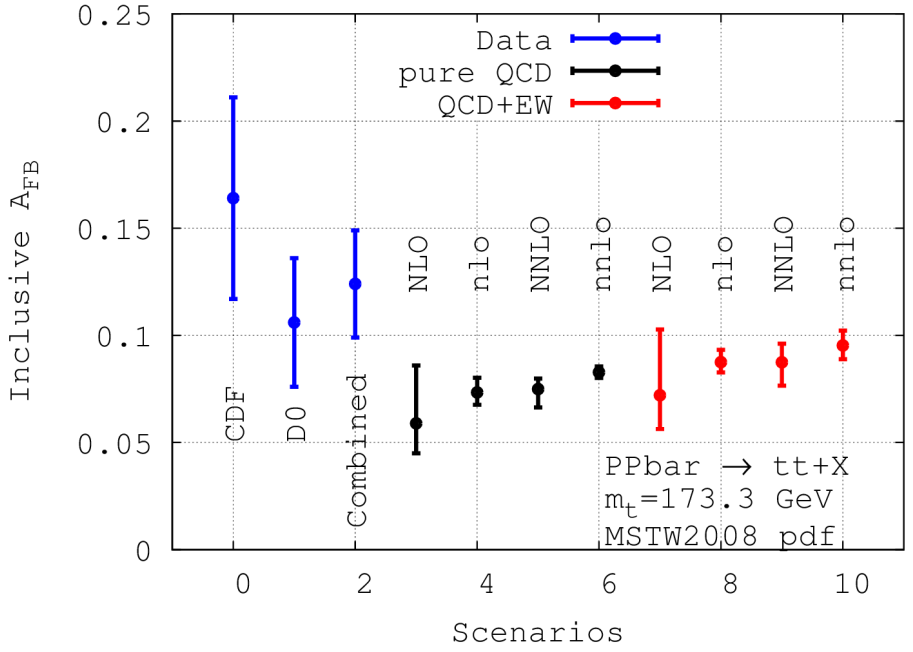
[see talk by: Emanuele Re]

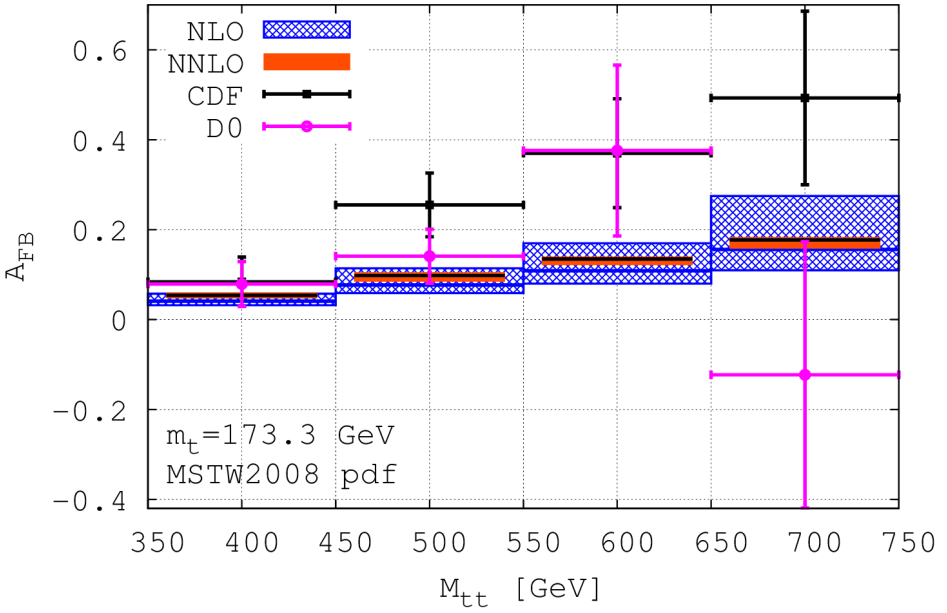
- **STRIPPER** [Czakon; '10, '11]
  - Total cross section (Full, no approximations) [Baernreuther, Czakon, Fiedler, Mitov; 2013]
  - Differential distributions for the TeVatron (no approximations) [Czakon, Fiedler, Mitov; '14]

Application: Differential Distributions at TeVatron

- (Differential) asymmetry at TeVatron

[Czakon, Fiedler, Mitov; 2014]





$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

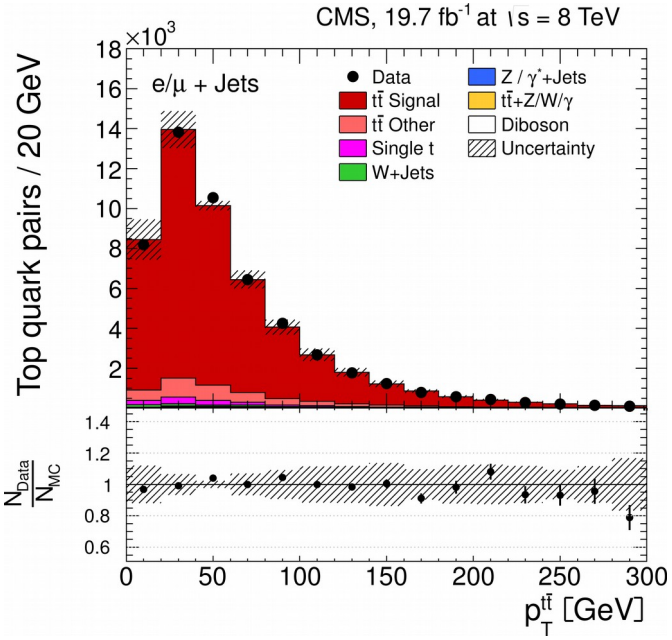
$$\Delta y = y_t - y_{\bar{t}}$$

Fully differential NNLO result for $t\bar{t}$ (exact, all channels included)

Differential Distributions for the LHC

Towards differential distributions → LHC

- Demands are challenging

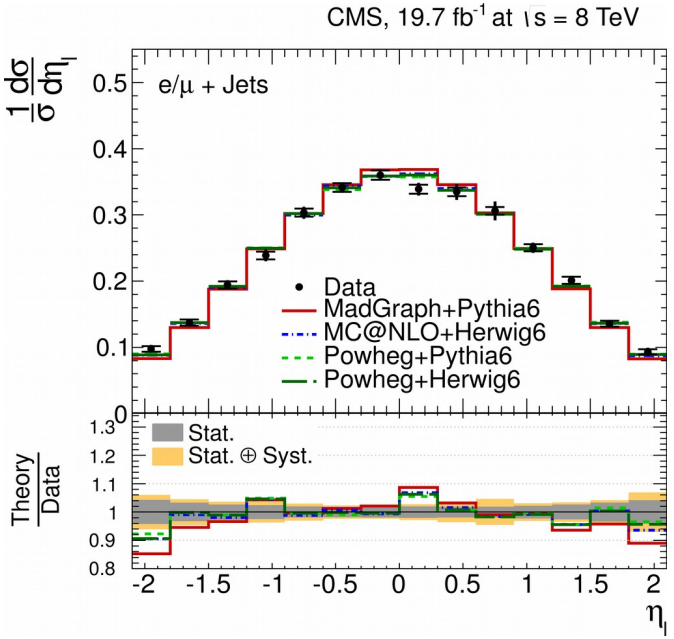


Transverse momentum of the (anti-) top

- Needed
  - Flexible code which can be adapted to experimental setup
  - Large number of bins required → High statistics → Fast implementation is needed
  - Many different observables, flexible cuts
  - Different PDF sets

Towards differential distributions → LHC

- Demands are challenging

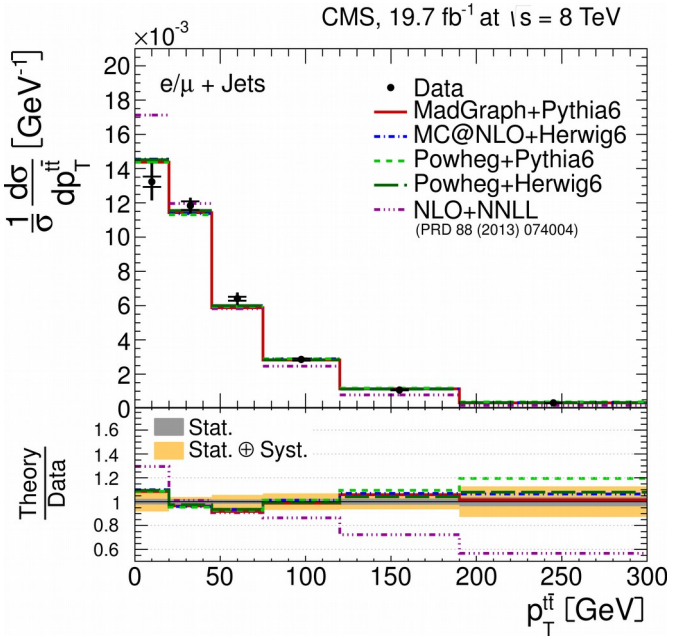


Rapidity of the (anti-) top

- Needed
  - Flexible code which can be adapted to experimental setup
  - Large number of bins required → High statistics → Fast implementation is needed
  - Many different observables, flexible cuts
  - Different PDF sets

Towards differential distributions → LHC

- Demands are challenging

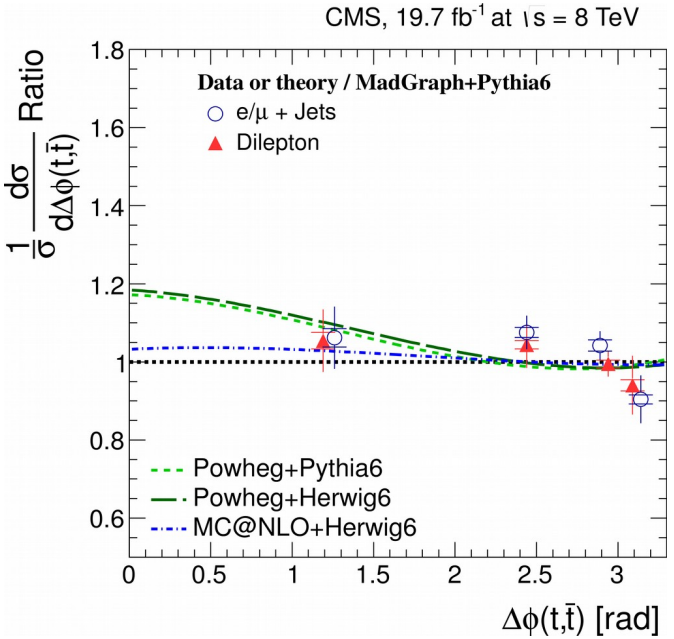


Transverse momentum of the $t\bar{t}$ -pair

- Needed
  - Flexible code which can be adapted to experimental setup
  - Large number of bins required → High statistics → Fast implementation is needed
  - Many different observables, flexible cuts
  - Different PDF sets

Towards differential distributions → LHC

- Demands are challenging

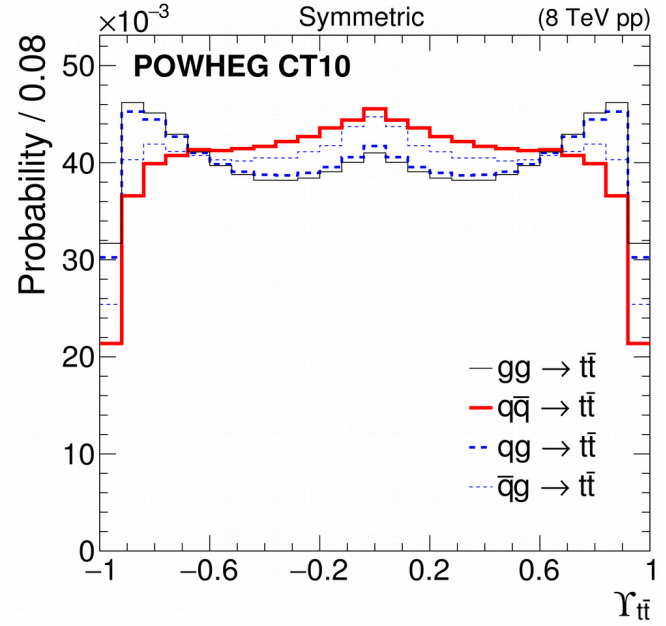


Angle between the $t\bar{t}$ -pair

- Needed
  - Flexible code which can be adapted to experimental setup
  - Large number of bins required → High statistics → Fast implementation is needed
  - Many different observables, flexible cuts
  - Different PDF sets

Towards differential distributions → LHC

- Demands are challenging

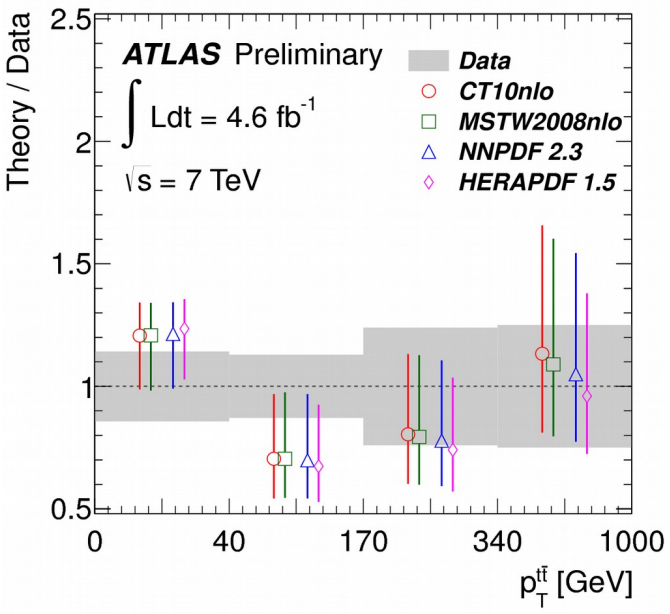


Charge asymmetry

- Needed
  - Flexible code which can be adapted to experimental setup
  - Large number of bins required → High statistics → Fast implementation is needed
  - Many different observables, flexible cuts
  - Different PDF sets

Towards differential distributions → LHC

- Demands are challenging



And many more…

- Needed
  - Flexible code which can be adapted to experimental setup
  - Large number of bins required → High statistics → Fast implementation is needed
  - Many different observables, flexible cuts
  - Different PDF sets

Towards Differential distributions → LHC

- The NNLO event generator: STRIPPER [Czakon, DH]
  - Based on improved formulation of the subtraction scheme [Czakon, DH; '14]
  - Complete independent C++11 implementation
  - Most SM tree-level matrix elements are included [vanHameren]
  - Process independent: User has to interface the one-loop and two-loop **finite** contributions
  - Built in One – Loop ?
    - High requirements on stability (much higher than at NLO)
  - Not limited to 2 → 2 processes !!!
  - Decays, hadron-hadron collider, lepton-hadron collider, lepton collider
  - Speed: Monte Carlo over processes and polarizations
  - Variable bin size histograms (1D, 2D)
  - Simultaneous computation of:
    - Different PDF sets
    - Different renormalization and factorization scales (fixed and dynamical)
    - Different observables

NEW Results !!!

- First Applications to Top-Quark Pair production

Differential Distributions for the LHC (8 TeV)

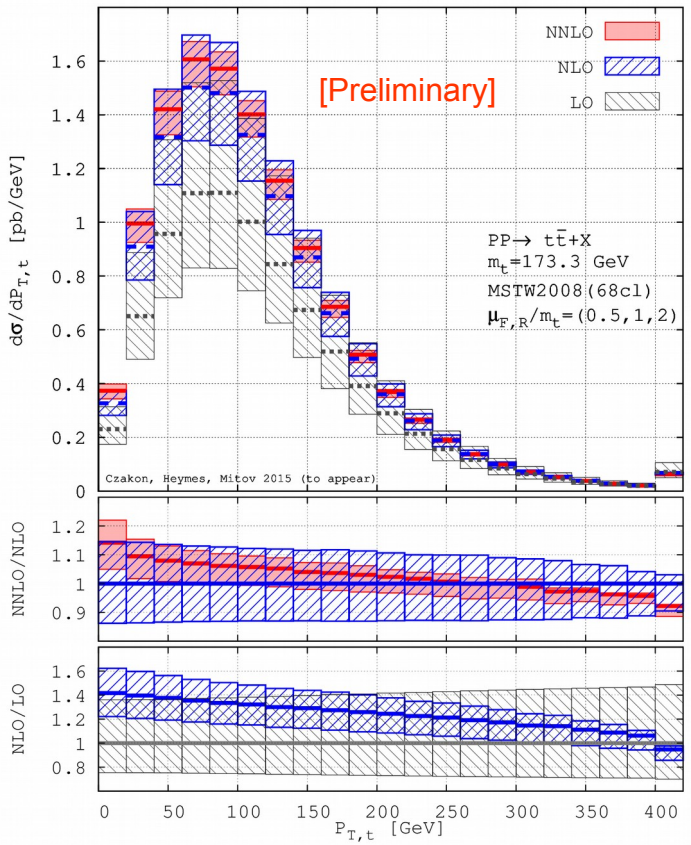
- Full NNLO

  (no further approximations are made)
- Checks of the total cross section
  - Agreement: ~ 0.1 %
  - Highly non-trivial check of the software and the subtraction scheme
- Setup for the presented (preliminary) results using STRIPPER
  - Full LO
  - Full NLO
  - Full NNLO
  - Independent scale variation: 7 different scales (fixed)
    - $\frac{1}{2}\, m_t \leq \mu_R \leq 2\, m_t$, $\frac{1}{2}\, m_t \leq \mu_F \leq 2\, m_t$
  - MSTW2008(nn)lo68cl
  - Top-Mass: 173.3 GeV

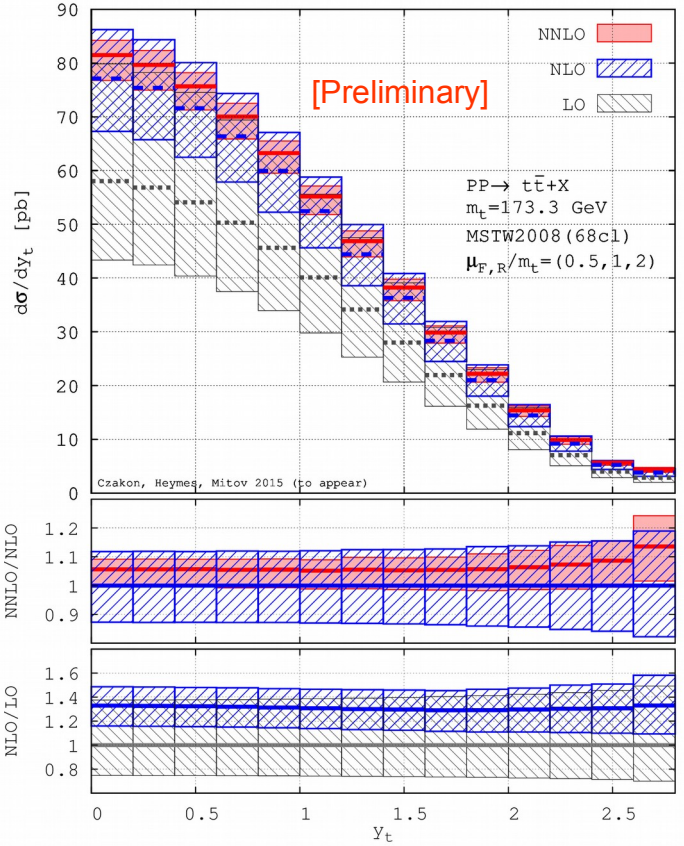
LHC 8TeV (preliminary)

[Czakon, Fiedler, DH, Mitov.; in preperation]

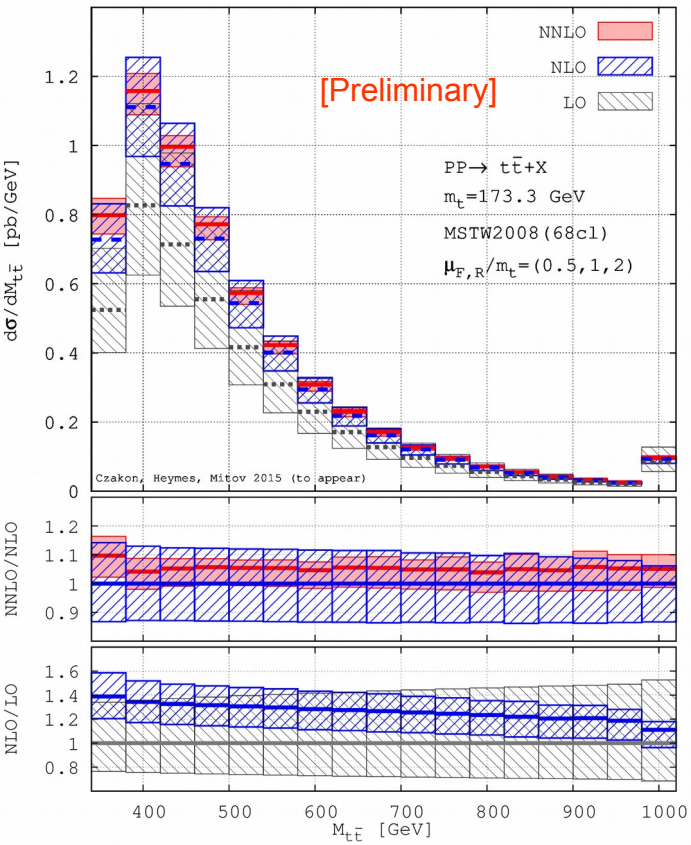
P_T of t



Rapidity of t



Invariant mass

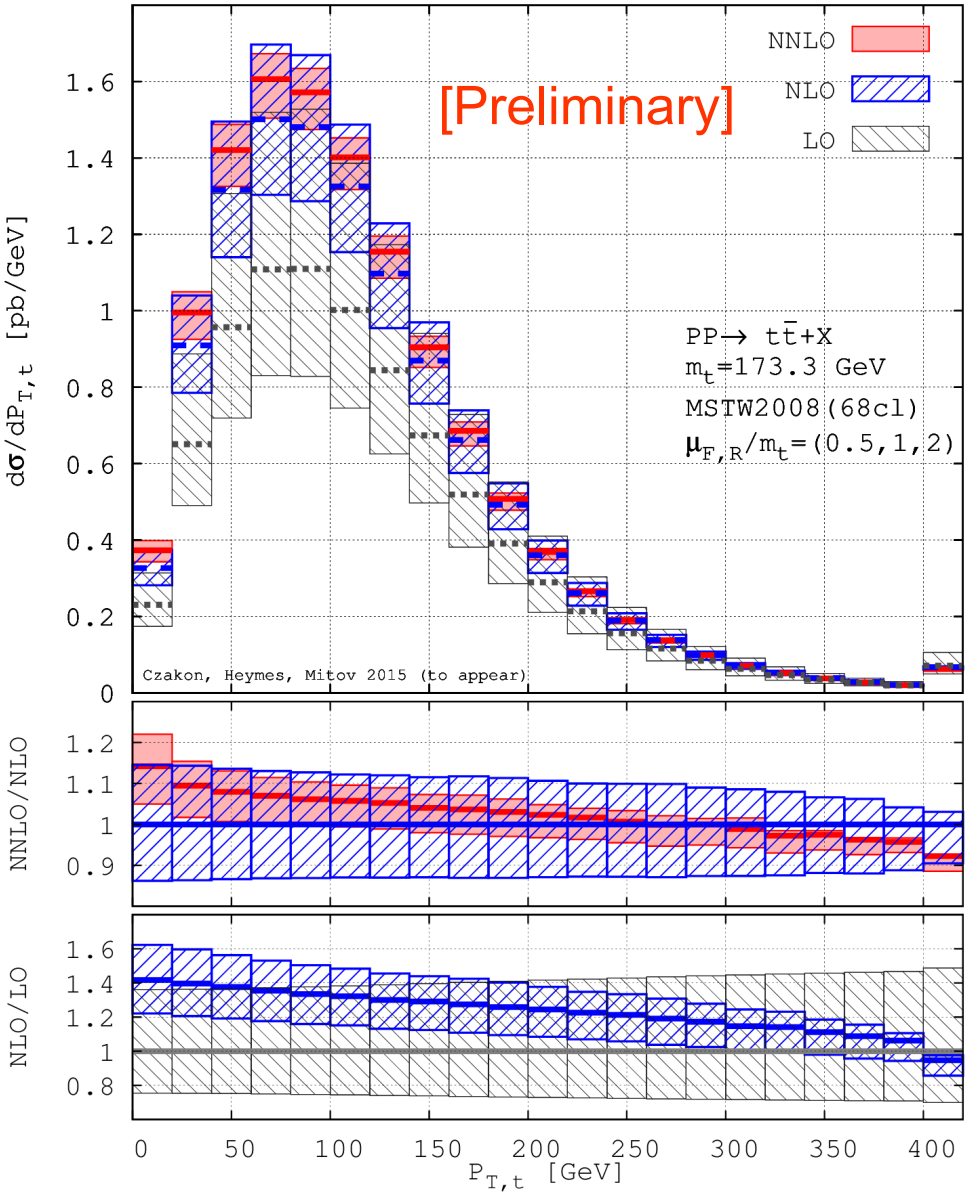


- Absolute normalization
- Last bin is overflow bin
- Fixed scale variation
- Good convergence of the perturbative series in each bin

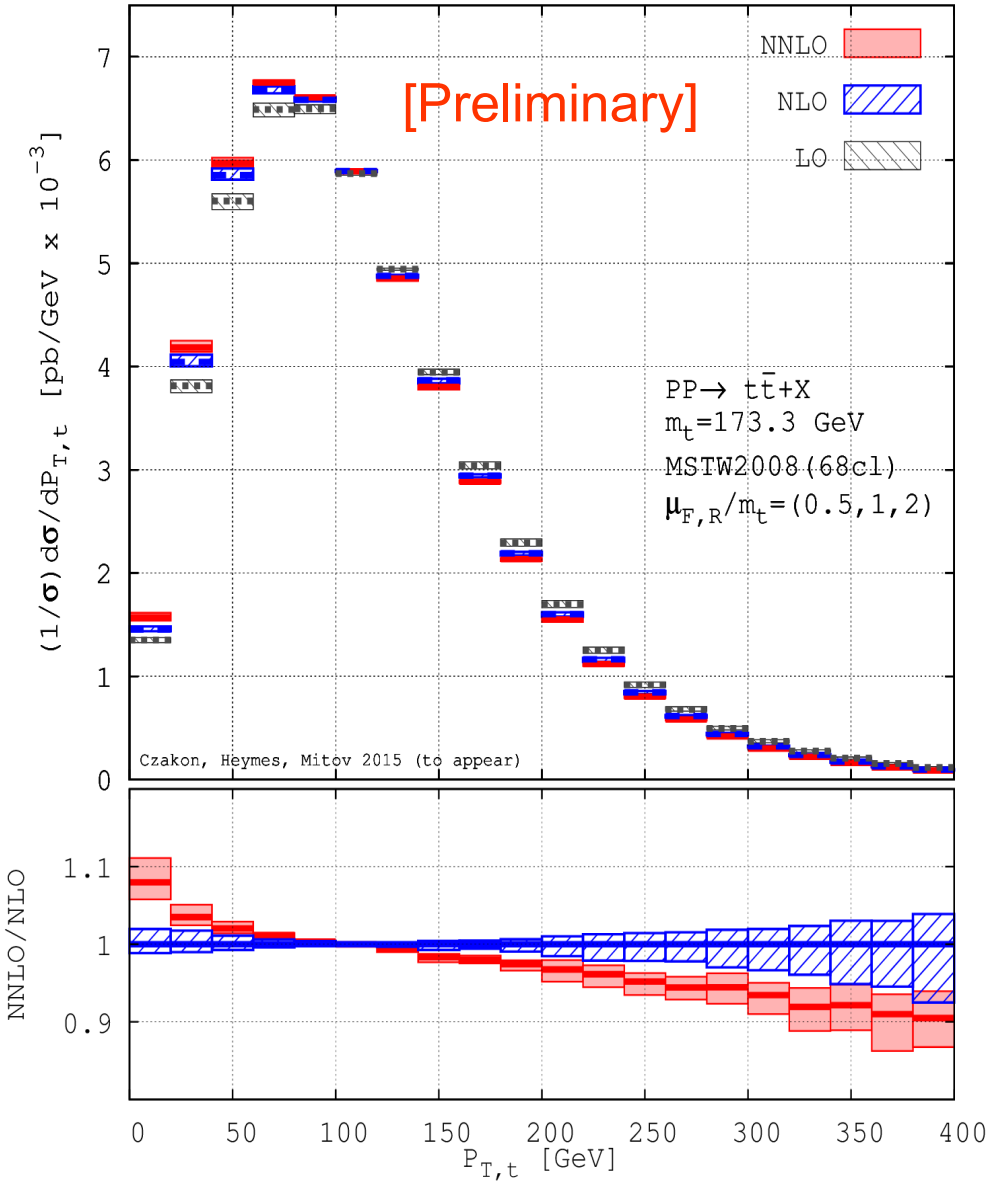
P_T-distribution LHC 8TeV (preliminary)

[Czakon, Fiedler, DH, Mitov.; in preperation]

Absolute normalization



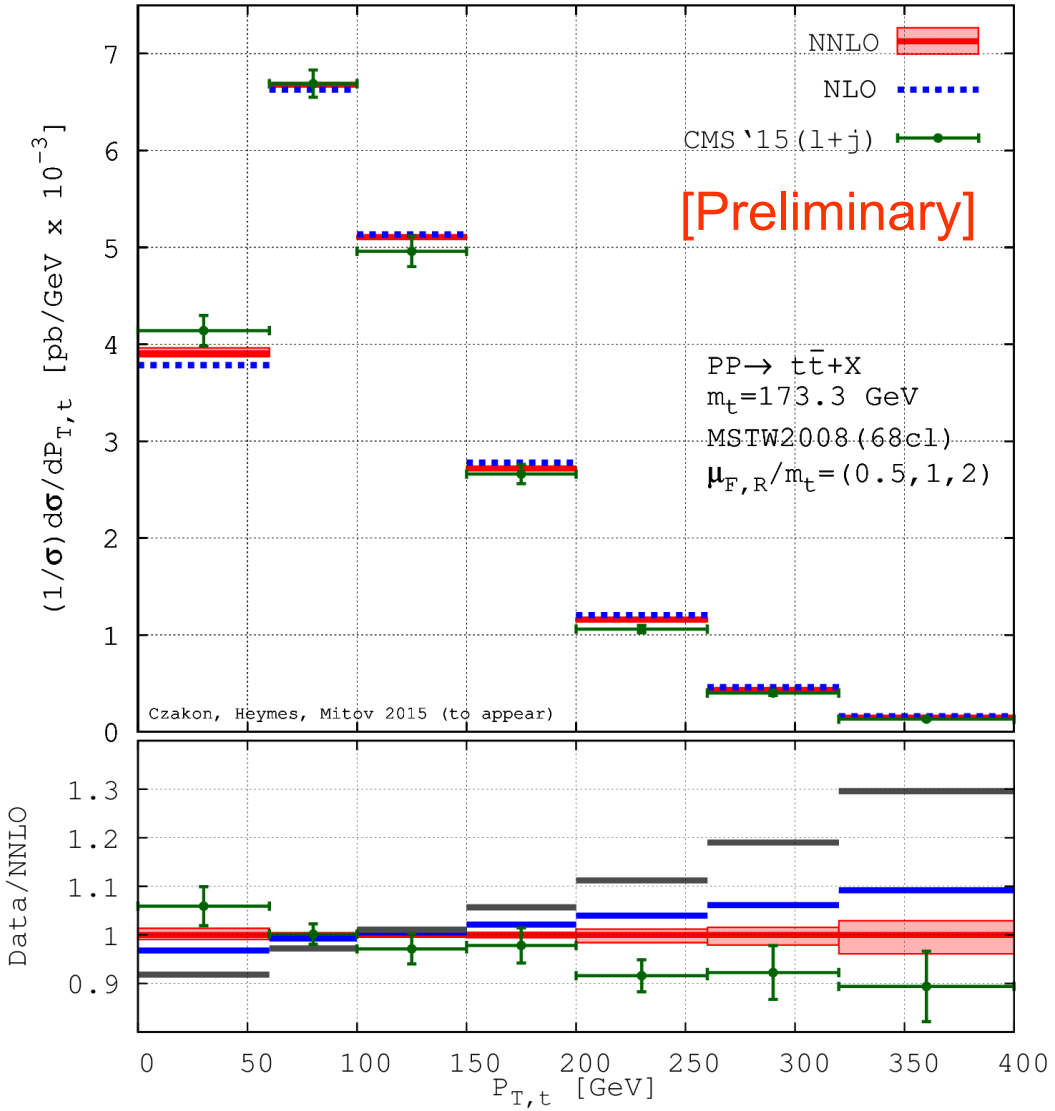
Normalized (no overflow bin)



P_T-distribution LHC 8TeV (preliminary)

[Czakon, Fiedler, DH, Mitov.; in preperation]

- NNLO prediction vs. measurement



- No overflow bin included
- Good convergence of series
- ATLAS data has been shown

  → [see talk by: B. Tannenwald]

  appears to be in perfect agreement with NNLO

Summary and outlook

- New independent software for NNLO computations (STRIPPER)
  - First results for $t\bar{t}$-distributions at LHC 8TeV (preliminary)
  - Framework and software is process independent

- Soon
  - Top Decays (NNLO Decays are available) [Gao, Li, Zhu; '12]
  - Software will be publicly available [Brucherseifer, Caola, Melnikov; '13]
  - Applications to different processes