

# NNLO QCD Corrections for $t\bar{t}$ observables

David Heymes

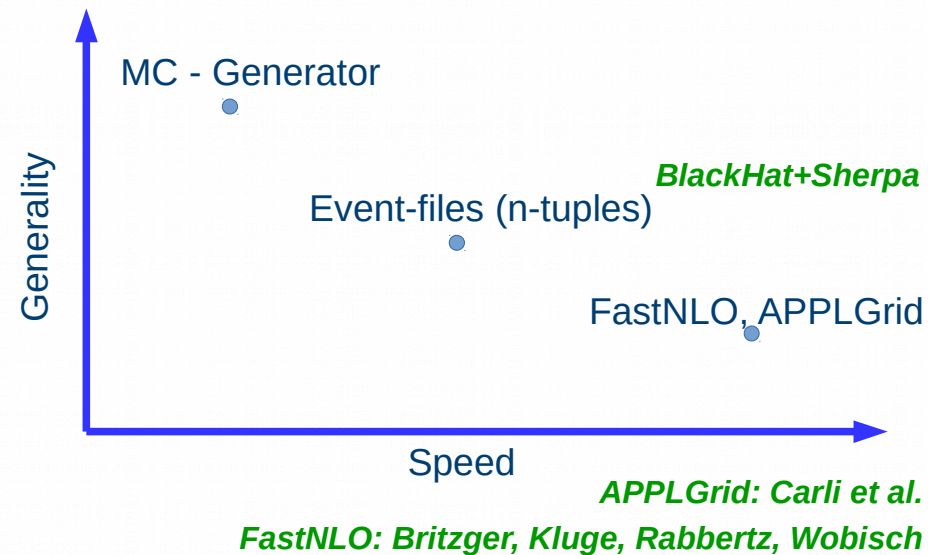
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HF@LHC 2017, Durham

# FastNLO tables for top-quark pairs at NNLO

# How to store/distribute (N)NLO calculations?

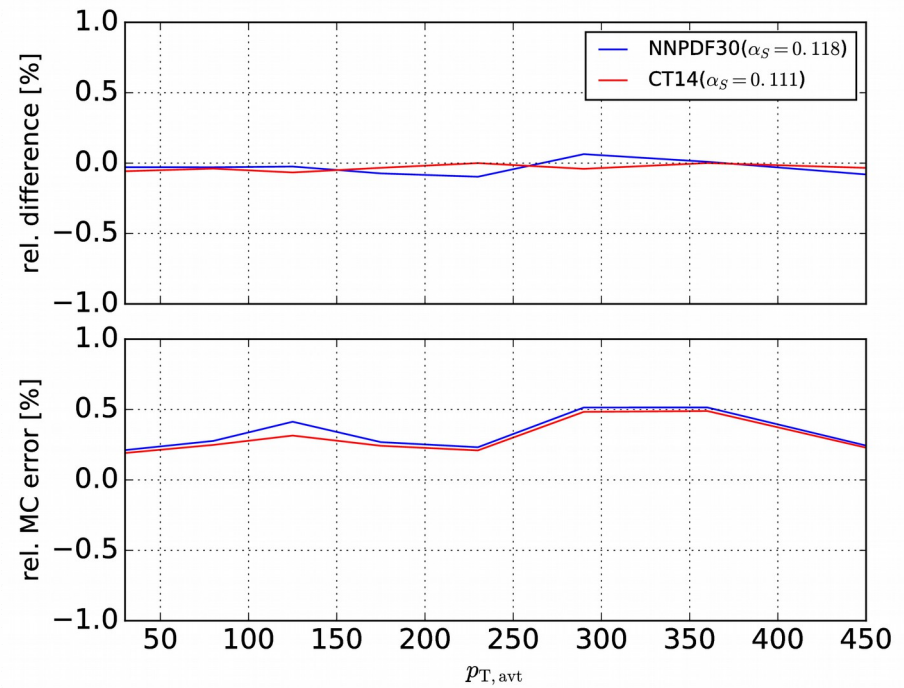
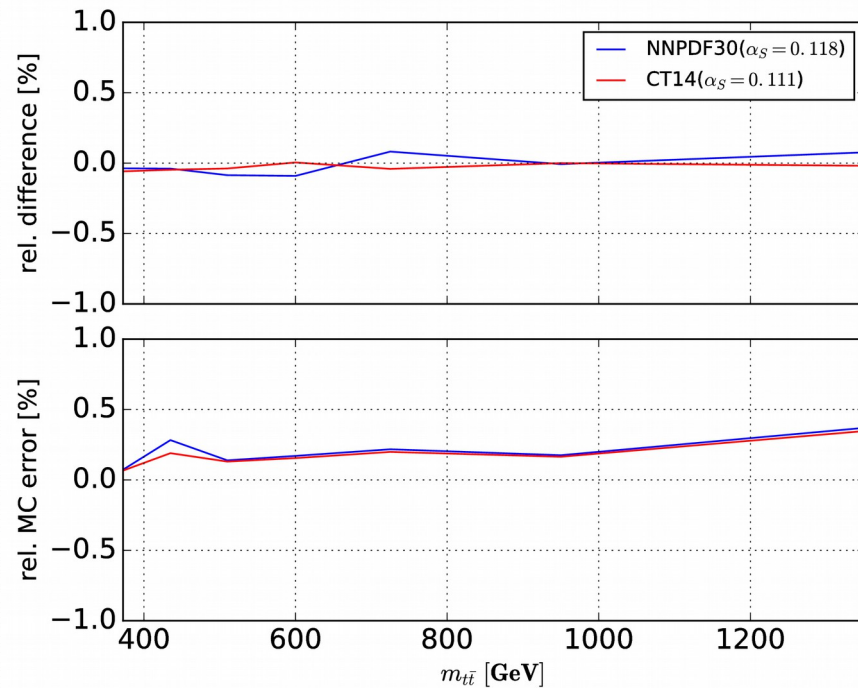
- $O(10000)$  CPU hours for single NNLO calculation
- Observables, scales, masses,  $E_{\text{cms}}$ , PDFs are fixed once calculation is done  
→ More flexible storage format required



- FastNLO interface to NNLO event generator STRIPPER *Czakon, Heymes, Mitov 2017*
- PDF and  $\alpha_s$  independent storage → fast recalculation of distributions
- Useful for pdf extractions,  $\alpha_s$  variation, etc. *Czakon, Hartland, Mitov, Nocera, Rojo 2016.*
- Example: NNLO predictions for LHC at 8TeV, differential measurement in the lepton+jets channel
  - Tables for the central (dynamical) scale choice and main distributions:  $m_{\text{tt}}$ ,  $p_{\text{Tavt}}$ ,  $y_{\text{tt}}$ ,  $y_{\text{avt}}$

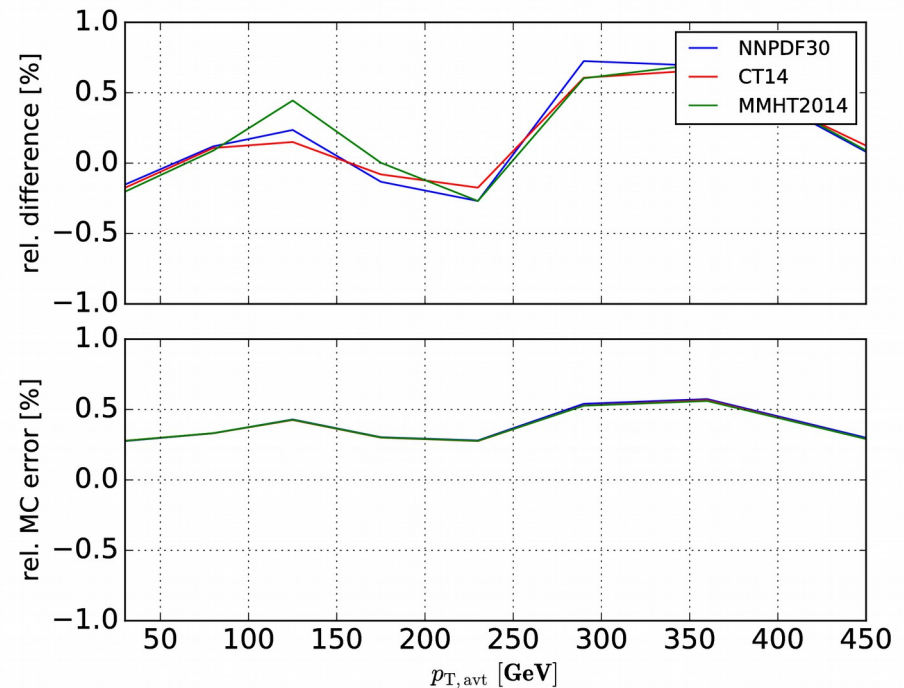
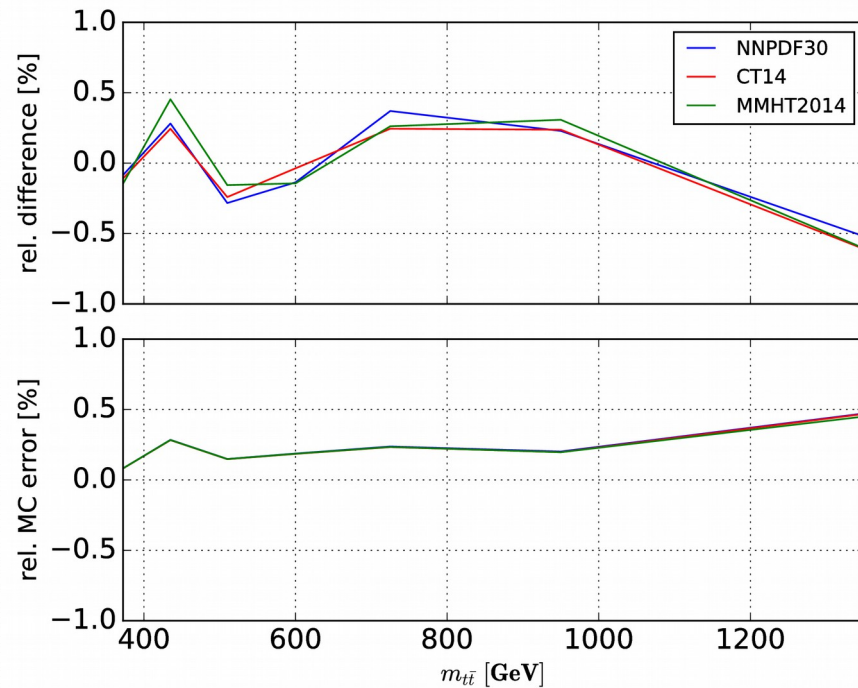
# FastNLO interface to Stripper at NNLO – Validation 1

- Accuracy of the fastNLO Interpolation at NNLO
  - Same sample of MC points for direct calculation and filling of the table is used
  - Interpolation error  $< 0.1\%$ , much smaller than MC error of NNLO calculation  $< 0.5\%$



# FastNLO interface to Stripper – Validation 2

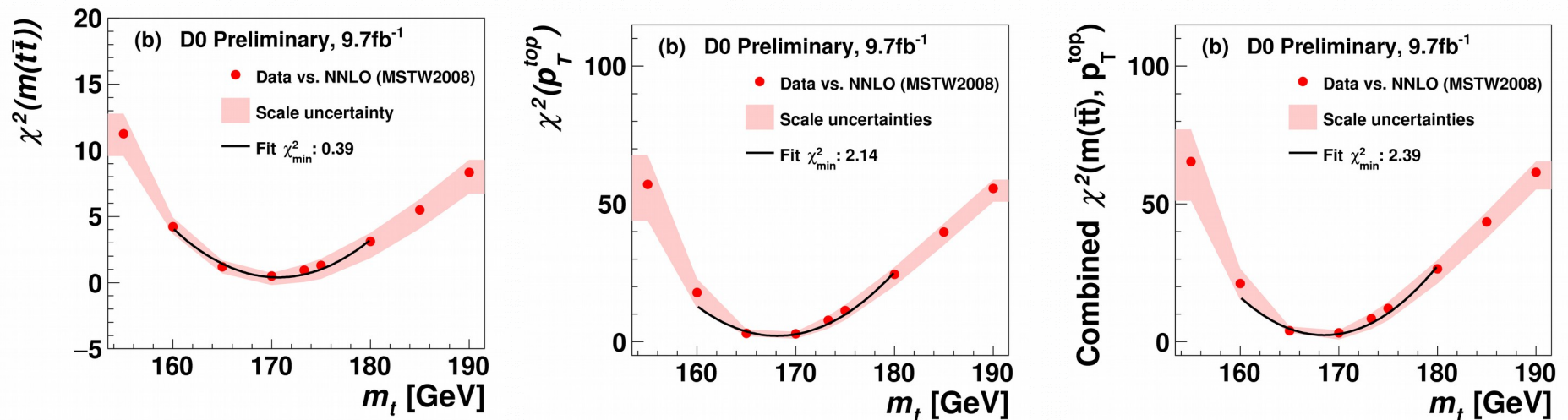
- Numerical precision of the fastNLO table at NNLO
  - Comparison of an independent direct calculation and results obtained from fastNLO table
  - Statistical uncertainty of NNLO prediction < 0.5 %





# FastNLO tables → Applications ?

- Extraction of Parameters and PDF determination → *Talk by Emanuele Nocera*
- Top mass extraction using NNLO predictions and measurements for differential distributions: *D0, Czakon, Fiedler, Heymes, Mitov 2016*

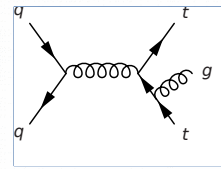
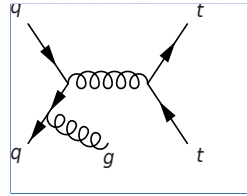
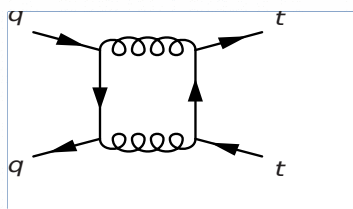


- Provide tables for different masses  
→ extraction of different parameters simultaneously
- All result: <http://www.precision.hep.phy.cam.ac.uk/>

Charge Asymmetry  $A_c$  at 8 TeV (NNLO and EW)

# Asymmetries at Tevatron and LHC

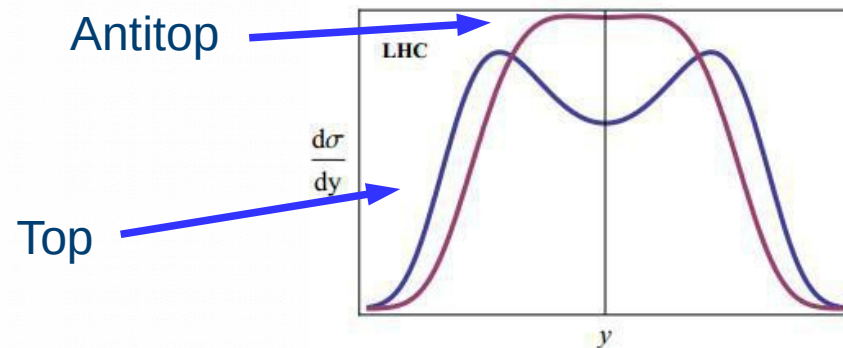
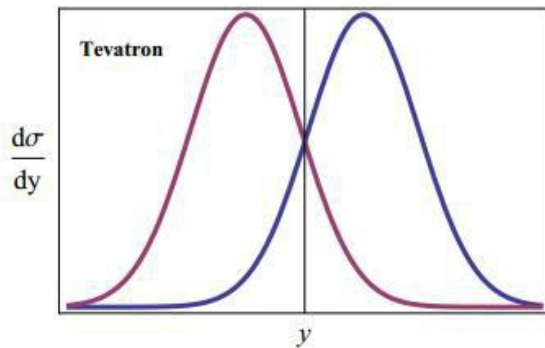
- Non-zero charge asymmetry in the SM starting at NLO



*Kühn, Rodrigo '98, '99*

- Tevatron (Forward-Backward)

- LHC (Charge)



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

with  $\Delta y = y_{\text{top}} - y_{\text{anti-top}}$

$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

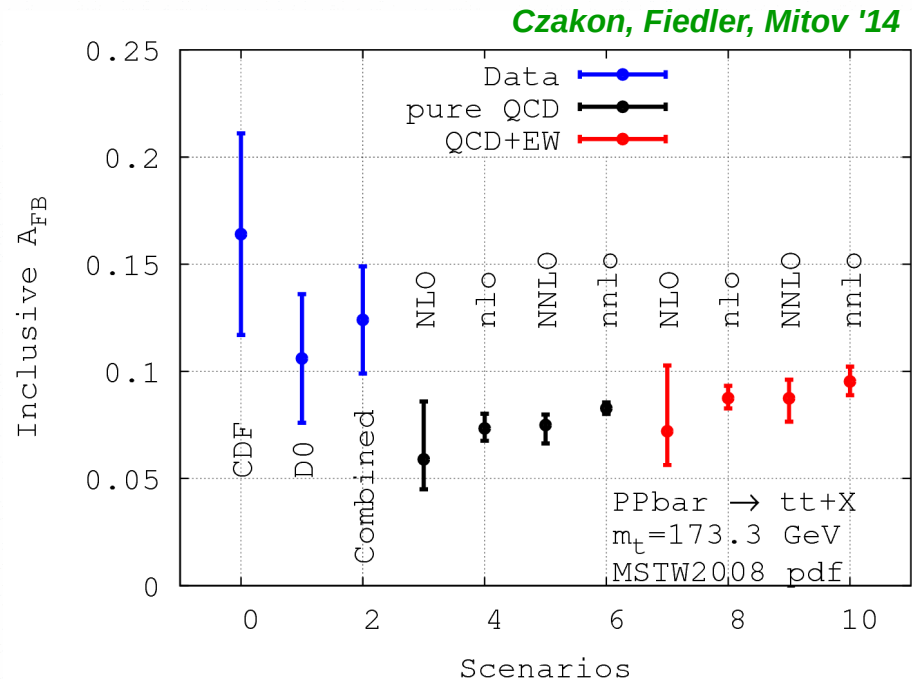
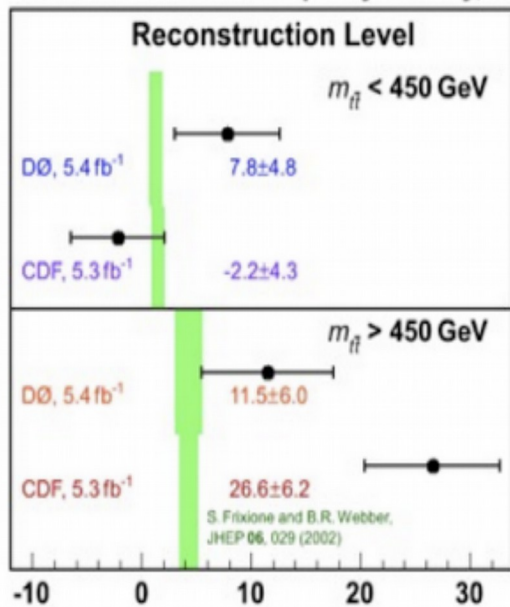
with  $\Delta |y| = |y_{\text{top}}| - |y_{\text{antitop}}|$



# Asymmetry $A_{FB}$ at the Tevatron

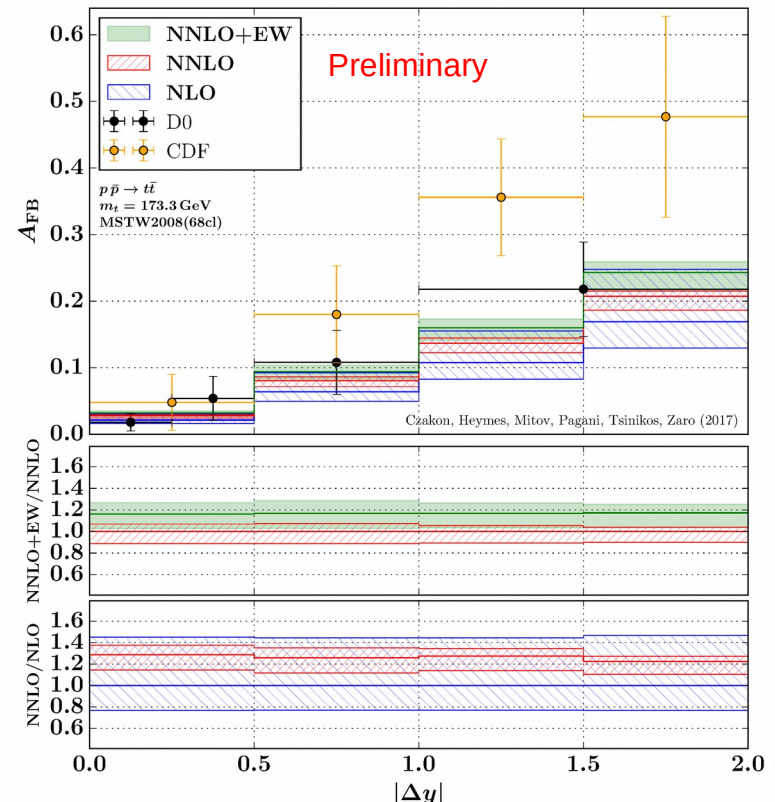
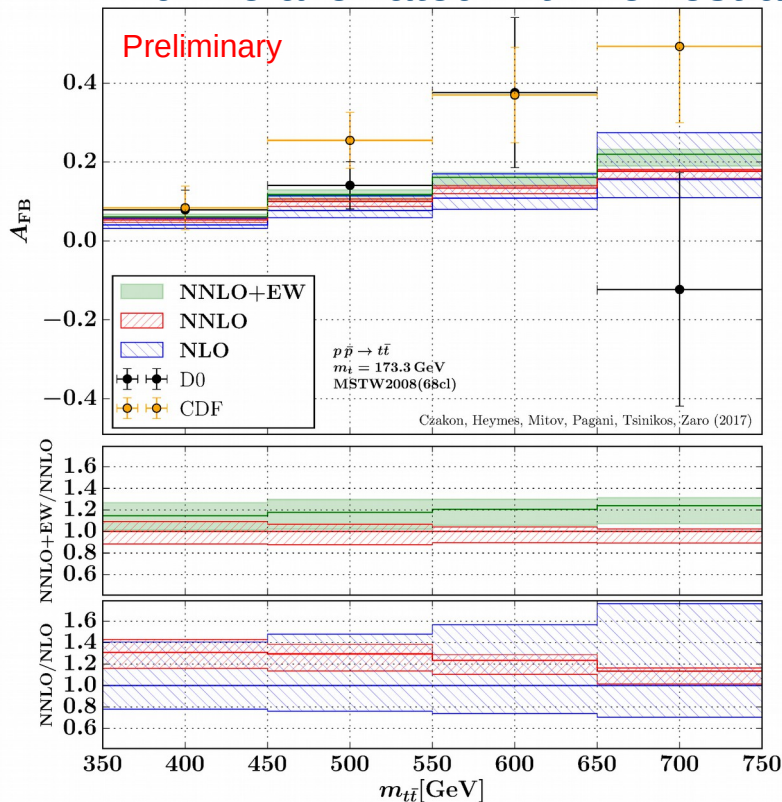
- Asymmetry puzzle → Measurement stated larger asymmetry than NLO prediction (Differential, inclusive)
- Sizeable EW corrections (~ 25% of NLO) and NNLO corrections (~27 % of NLO)
- Approximations to NNLO couldn't capture this effect (soft gluon resummation)

Forward-Backward Top Asymmetry, %



# Asymmetry $A_{FB}$ at the Tevatron (differential)

- NNLO predictions for  $A_{FB}$  published already *Czakon, Fiedler, Mitov '14; Czakon, Fiedler, Heymes, Mitov '17*
- Combination with EW was missing so far *Czakon, Heymes, Mitov, Pagani, Tsiniikos, Zaro (to appear)*
- → Puzzle alleviated with newest analysis of D0 and CDF and NNLO inclusion



# Asymmetry $A_c$ at the LHC

- Predicted charge asymmetry at LHC  $\sim 1\%$  , (Tevatron  $A_{FB} \sim 10\%$ )
- $\rightarrow$  Challenging for experiment, but also numerically challenging for NNLO predictions
- Theoretical question: Expand denominator?
  - Here: No expansion of denominator

$$A_c = \frac{N(\Delta | y > 0) - N(\Delta | y < 0)}{N(\Delta | y > 0) + N(\Delta | y < 0)}$$

- Published measurements from ATLAS and CMS at 8 TeV (combination appears soon) *ATLAS '16, CMS '16*
- Predictions include NNLO QCD and NLO EW (PDF4LHC - LUX)  
*Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (to appear)*



# Asymmetry $A_c$ at the LHC (inclusive)

- Predicted asymmetry at NNLO QCD + EW

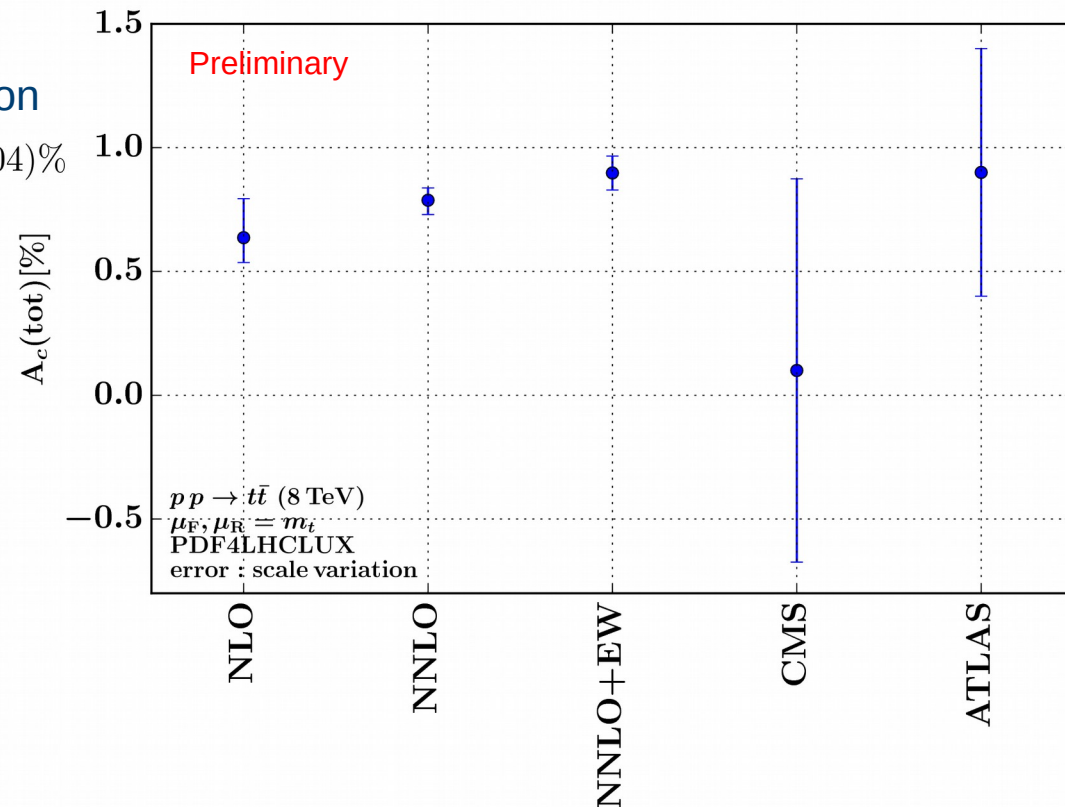
$$A_c = 0.90^{+0.07}_{-0.07}\% \quad \text{Preliminary}$$

- Differences to previous NLO prediction

**Bernreuther, Si, (Kühn, Rodrigo):**  $A_c = (1.11 \pm 0.04)\%$

- No expansion of denominator
- 7-point scale variation
- PDF set
- Agreement for the same setup

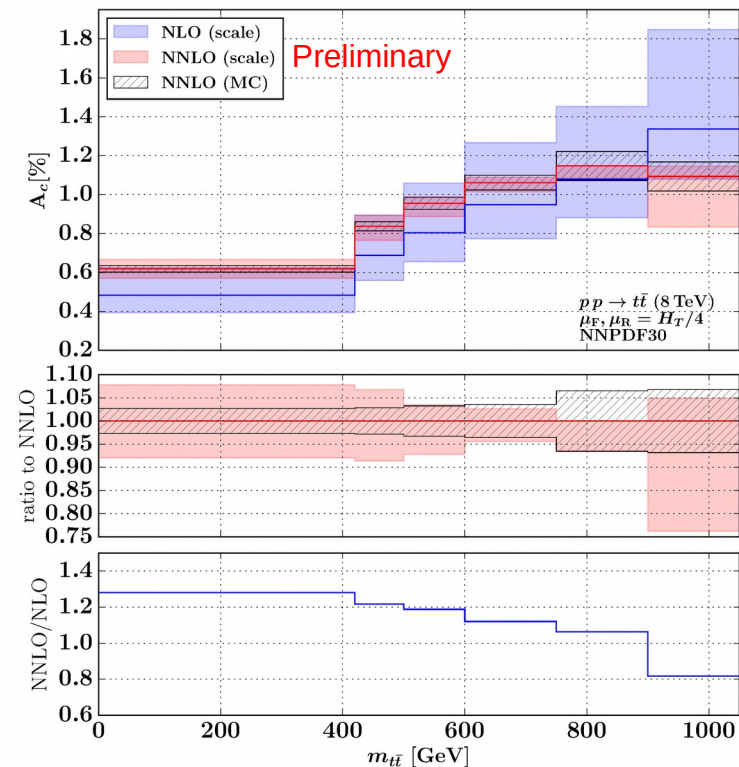
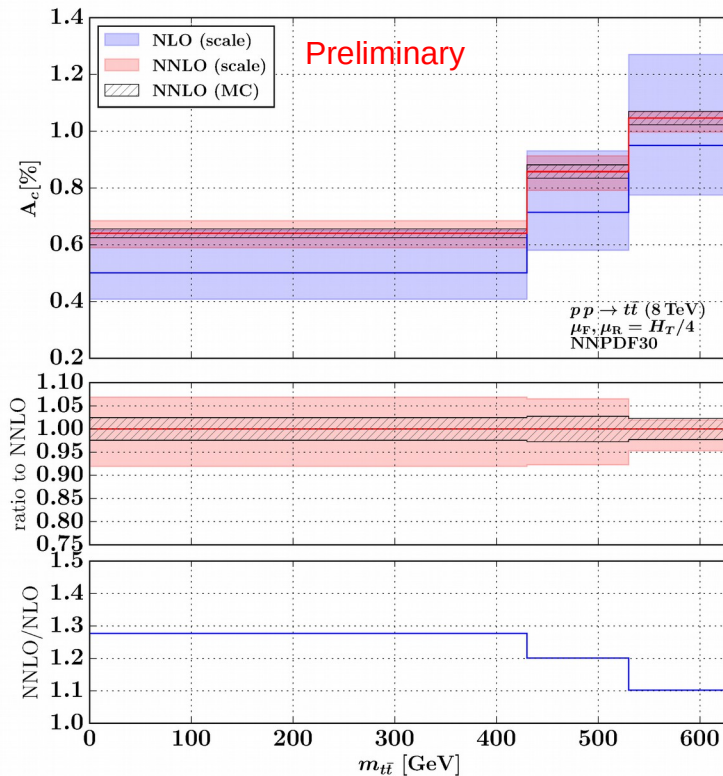
*Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (to appear)*



# Asymmetry $A_c$ at the LHC (differential QCD)

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (to appear)

- Asymmetry can be enhanced in certain phase space regions → differential
- Numerically challenging, due large cancellations in the numerator
- Aim at 1% relative MC uncertainty for NNLO predictions → not feasible (currently) in few bins  
→ Aim: MC uncertainty < Scale uncertainty, add uncertainties in quadrature, if necessary



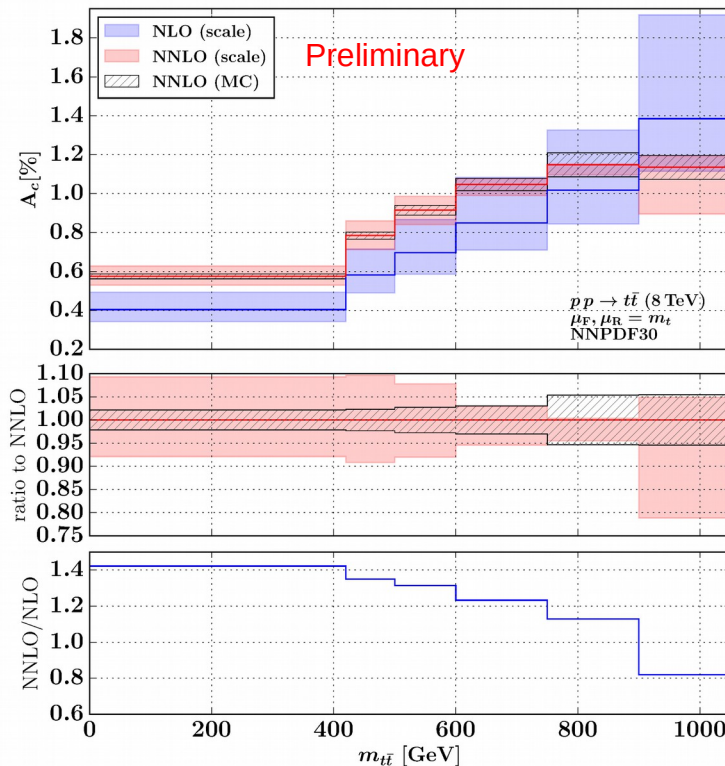


# Asymmetry $A_c$ at the LHC (differential QCD)

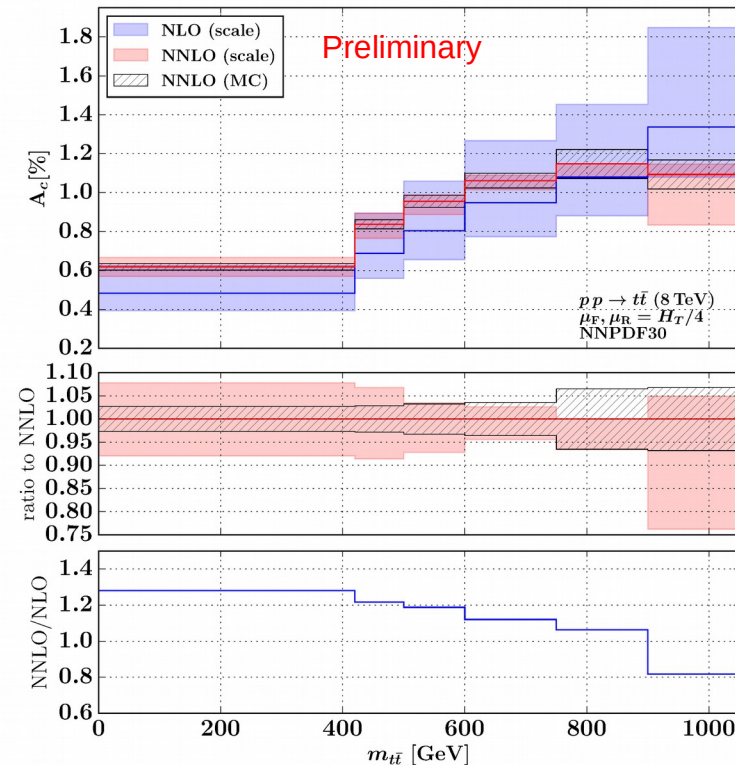
*Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (to appear)*

- Dynamical scales? → Low dependence on scale choice at NNLO (but not at NLO)
- Choose:  $\mu_0 = H_T/4$  *Czakon, Heymes, Mitov '16*

## Fixed Scale



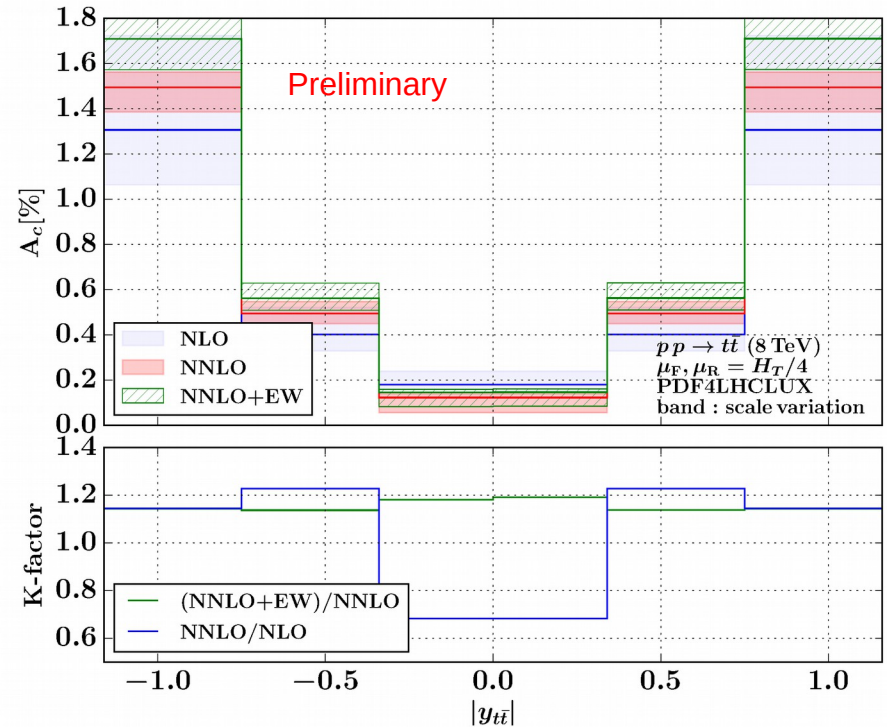
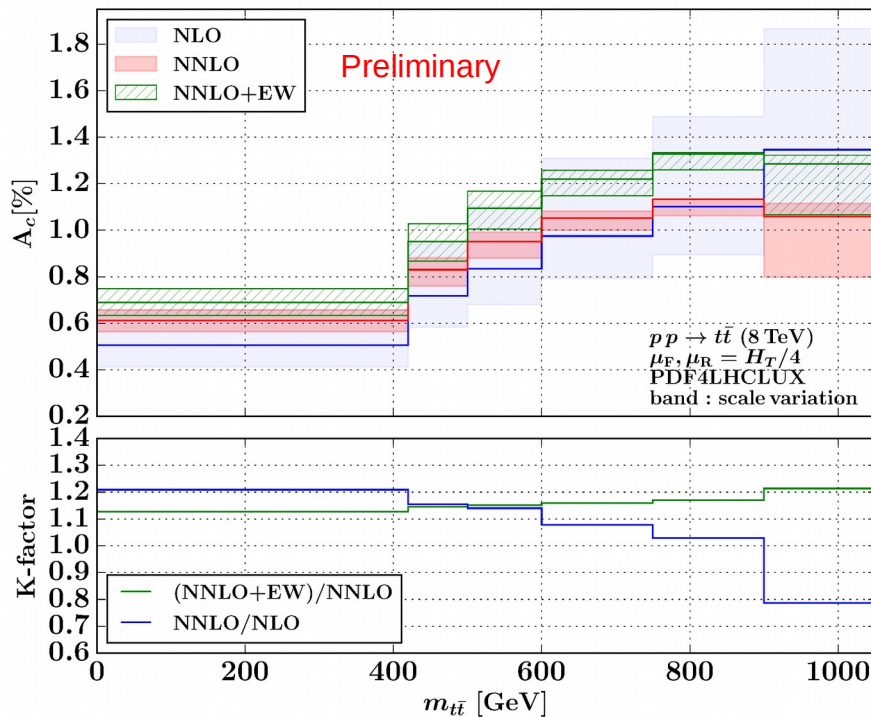
## Dynamical Scale



# Asymmetry $A_c$ at the LHC (differential QCD + EW)

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (to appear)

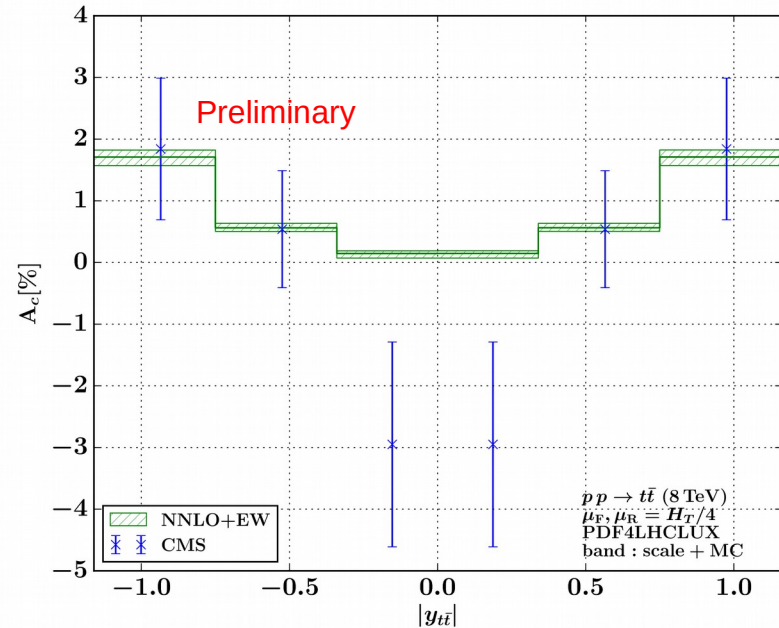
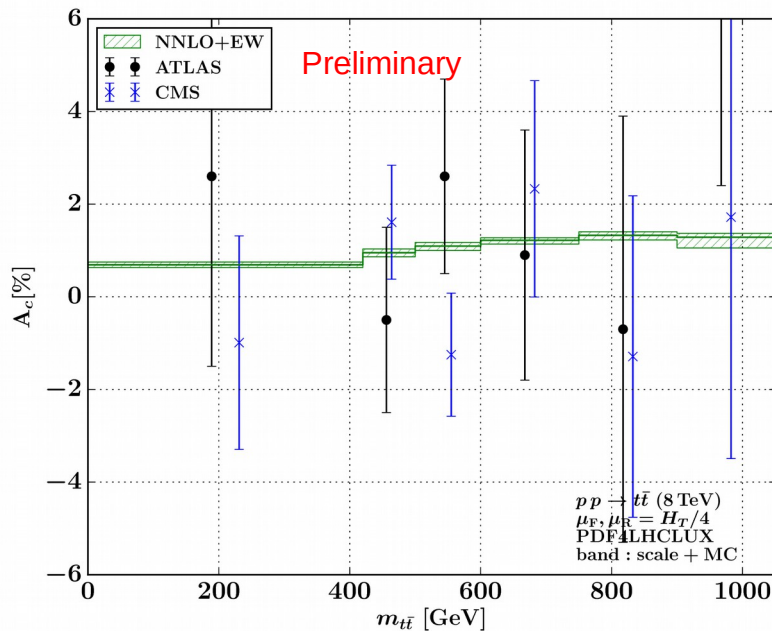
- NNLO QCD + NLO EW predictions for observables measured by ATLAS and CMS
- EW corrections up to 20% of the NNLO



# Asymmetry $A_c$ at the LHC (differential QCD + EW)

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (to appear)

- NNLO QCD + NLO EW predictions for observables measured by ATLAS and CMS
- Measurements limited by statistics
- Best prediction compared to measurement: **ATLAS '16 , CMS '16**



- Can we find new physics in the Asymmetry at the LHC? 13 TeV? HL?



# Summary and Outlook

- FastNLO interfaced to NNLO event generator STRIPPER
  - Pdf independent way of storing NNLO results
  - FastNLO tables for LHC 8TeV top-pair measurements are available
  - More tables are in the pipeline (1D and 2D distributions, 13 TeV,  $m_{\text{top}}$  variation) → *Top 2017*
- Charge Asymmetry at the LHC at 8 TeV at NNLO
  - Interesting and challenging (new physics)
- Future
  - Parameter extraction at the LHC
  - Improvement to the NNLO Event Generator (NWA, different Observables, many technical improvements) → *RadCor 2017*