

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

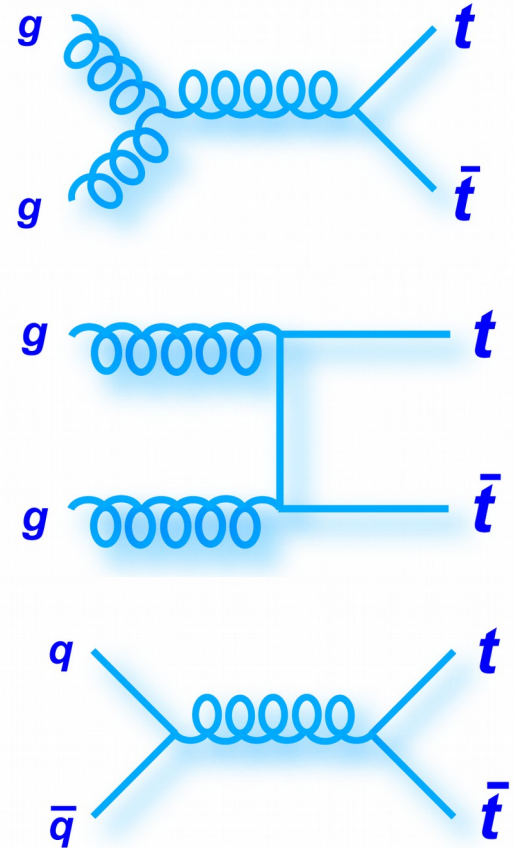
David Heymes

LHCP St. Petersburg, September 2015

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Top pair production at the LHC

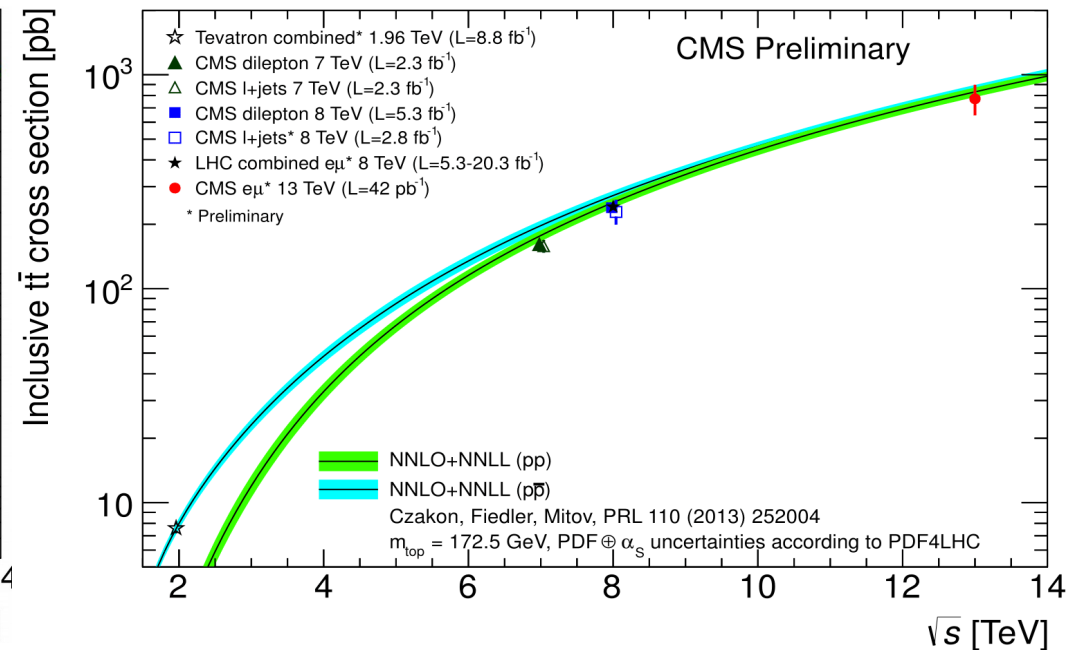
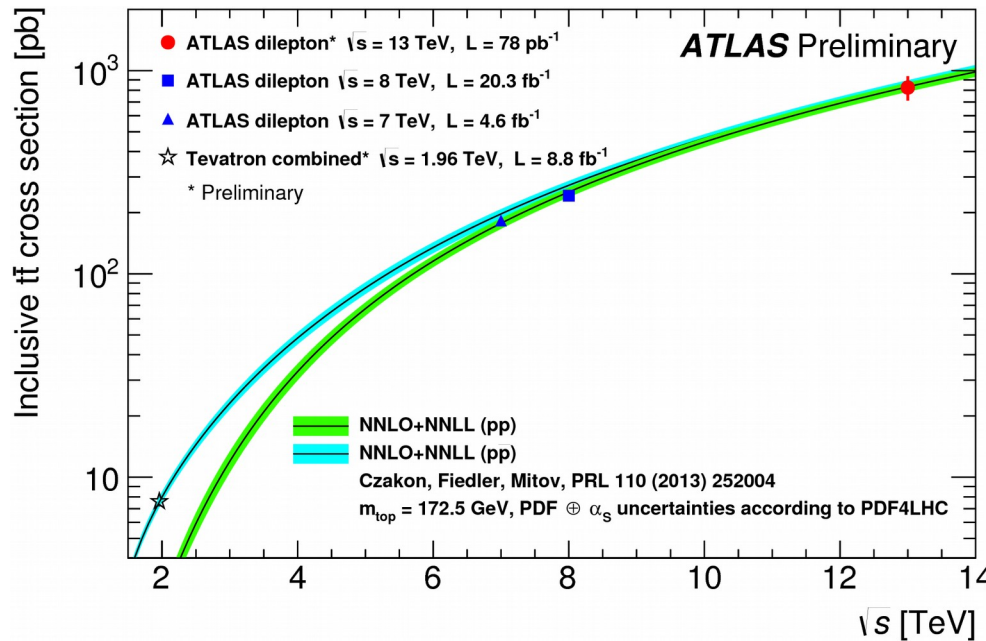
- Measured total cross section 8 TeV: ~ 250 pb
- Integrated Luminosity Run I (8 TeV): ~ 25 1/fb
- Produced top pairs
 - 8 TeV $\rightarrow 10^6$ per year
 - 13 TeV $\rightarrow 10^7$ per year
 - Tevatron $\rightarrow 10^4$ per year
- High precision tests of perturbative QCD and the Standard Model are possible
- Important background (for BSM)
- Top pair production could be associated with BSM
- PDF determination
- Dominated by gluon channel ($\sim 90\%$)



Total inclusive cross section at NNLO (+NNLL)

[Czakon, Fiedler, Mitov; 2013]

■ Measurement vs. prediction (Top ++)

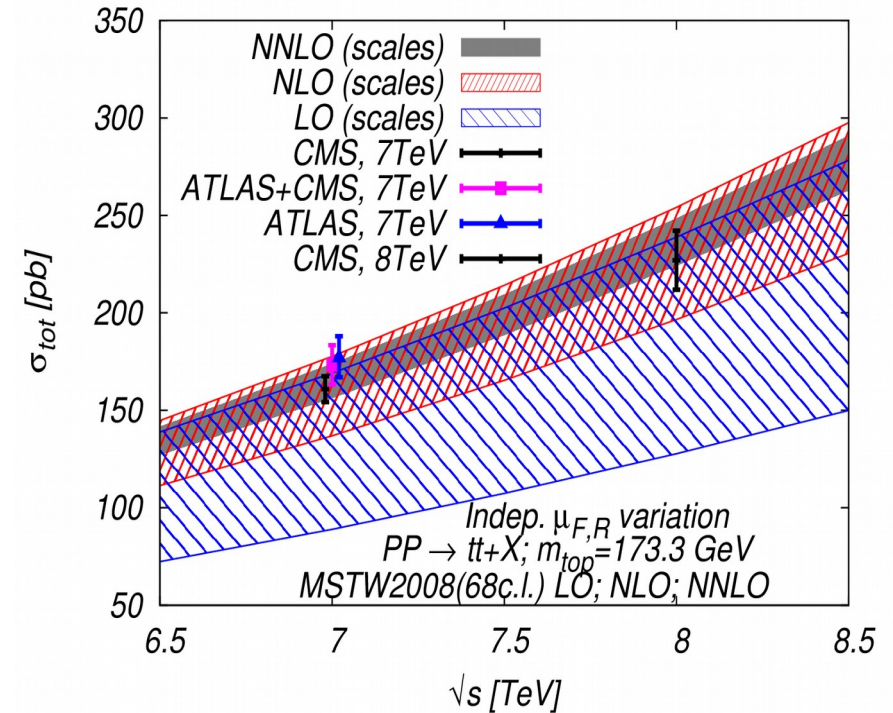
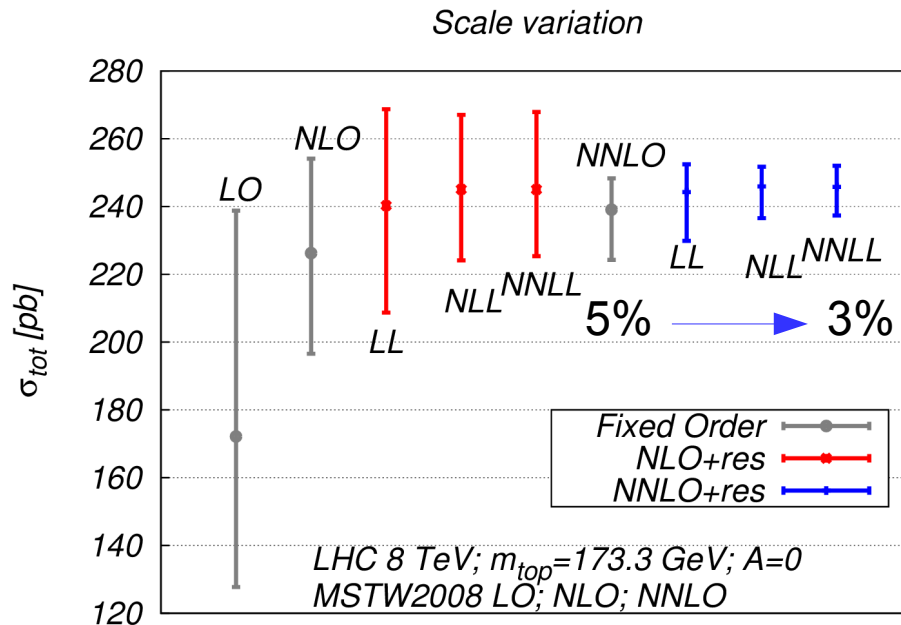


- Agreement at 7 TeV, 8 TeV and 13 TeV (!!!!)
- Theoretical and experimental uncertainty at the same level
- Prediction of the total cross section allows to draw non-trivial conclusions
 - PDF determination [Czakon, Mangano, Mitov, Rojo; 2013]
 - Exclusion of BSM models [Czakon, Fiedler, Mitov, Rojo;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

Total inclusive cross section at NNLO (+NNLL)

[Czakon, Fiedler, Mitov; 2013]

Do we need NNLO ?



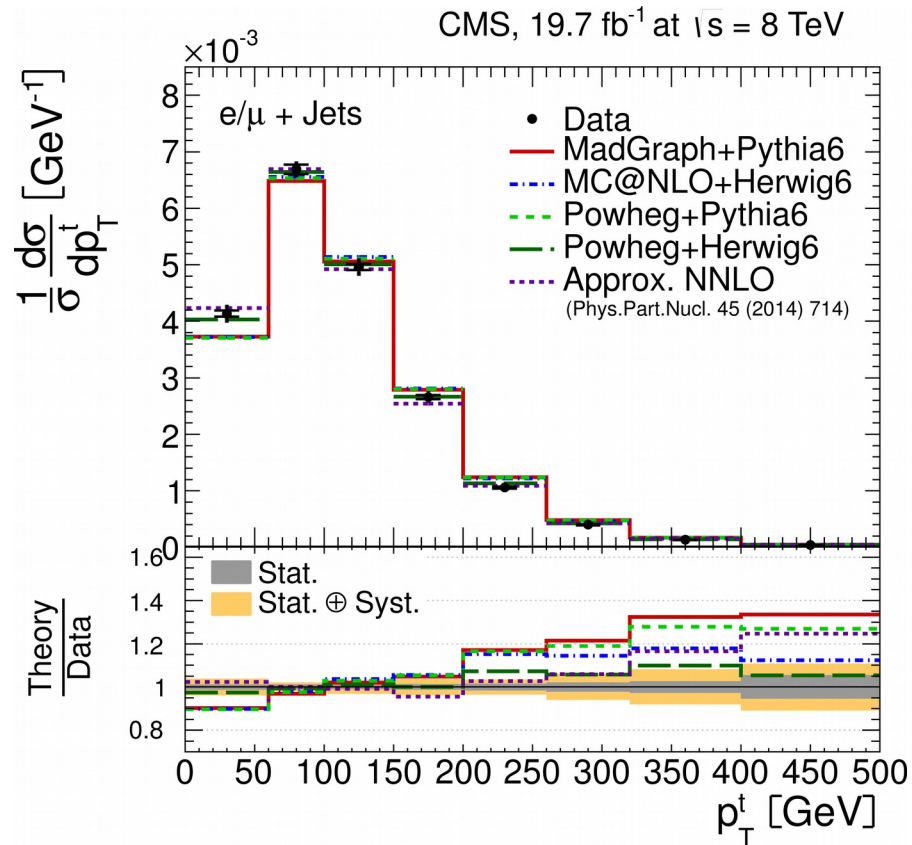
Uncertainties

- Scales: $\sim 3 \%$
- PDF (68% cl): $\sim 2 - 3 \%$
- Top – mass: $\sim 3 \%$
- Coupling: $\sim 1.5 \%$

Differential Distributions

Differential measurements and predictions (LHC)

■ Transverse momentum of the top



- Needed: NNLO predictions including decays
- better understanding

Top Pair Decay Channels

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

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 **antennae 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 $q\bar{q}$, flavor off-diagonal $q(\bar{q})q'$

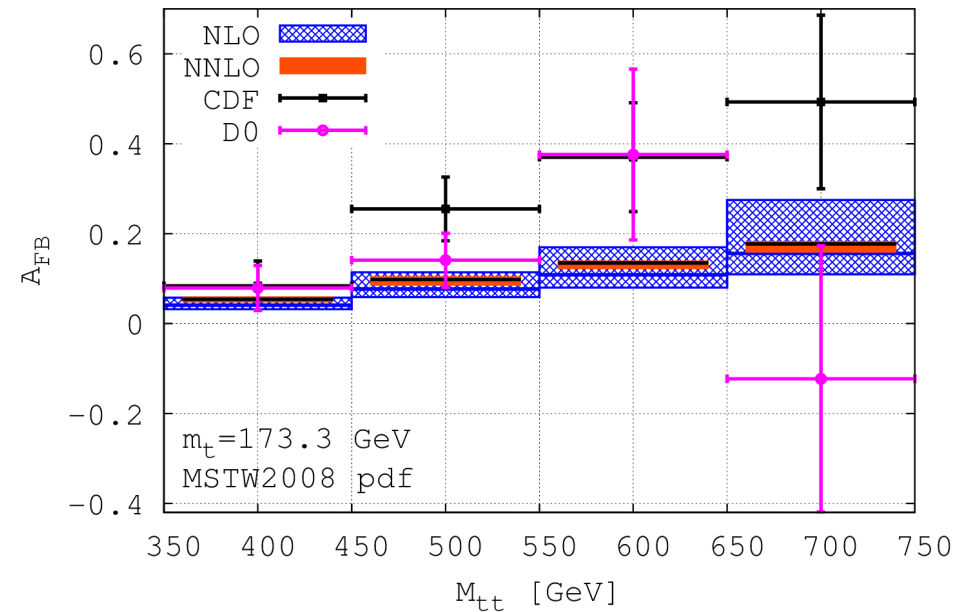
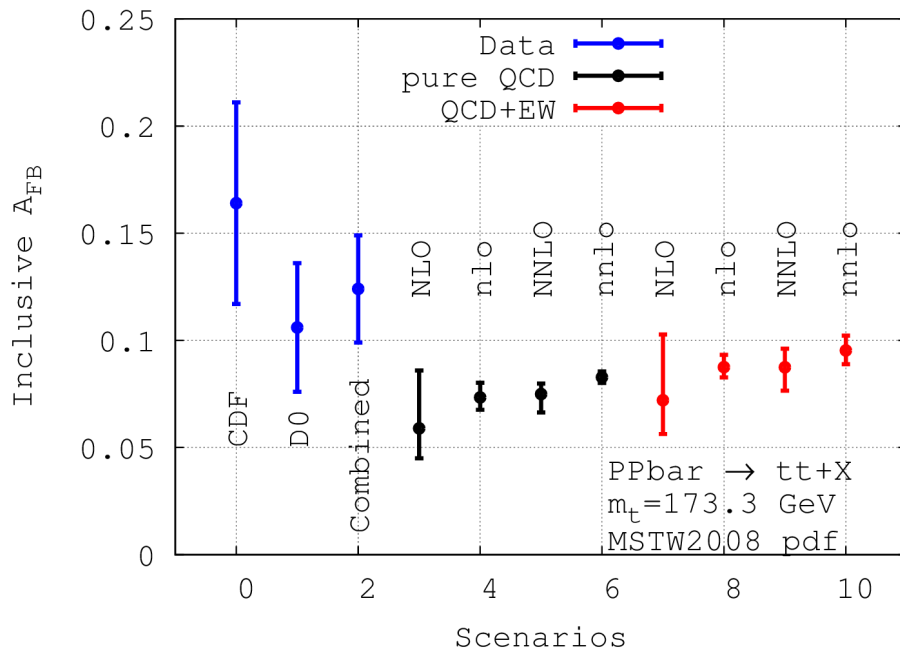
- **STRIPPER** [Czakon; '10, '11]

- 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]



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

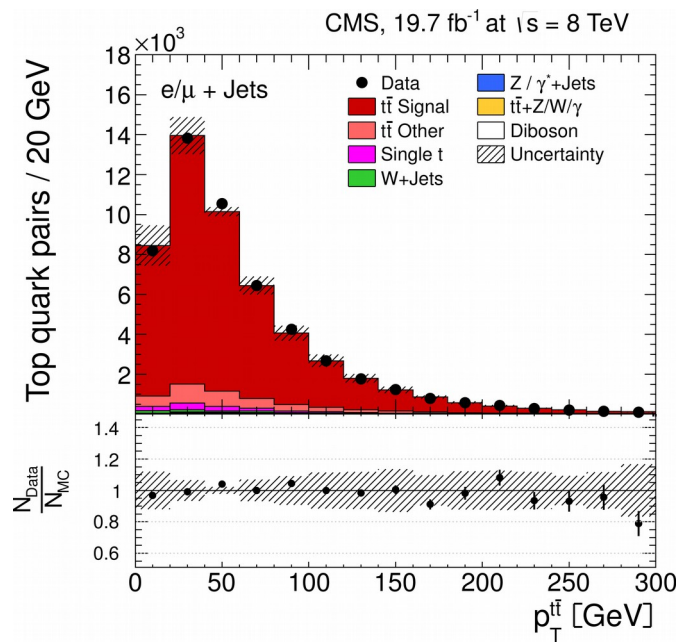
$$\Delta y = y_t - y_{\bar{t}}$$

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

Differential Distributions for the LHC

Towards differential distributions → LHC

■ Demands are challenging



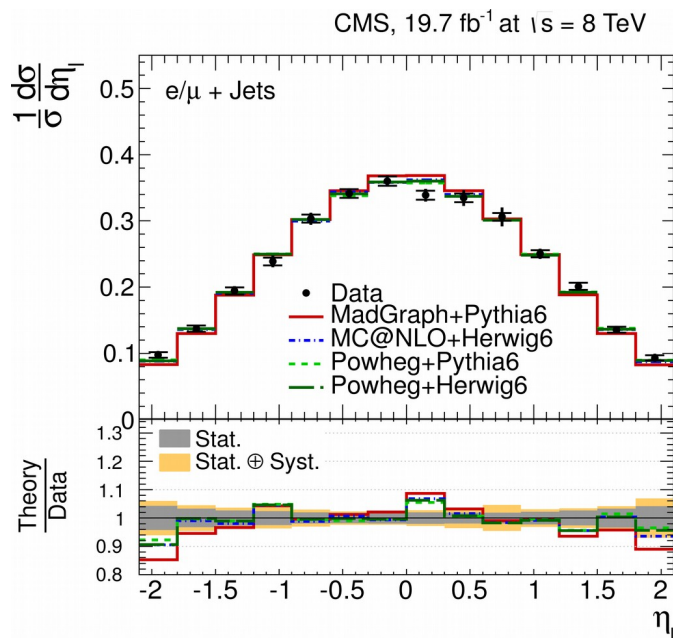
Transverse momentum of the (anti-) top

■ 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



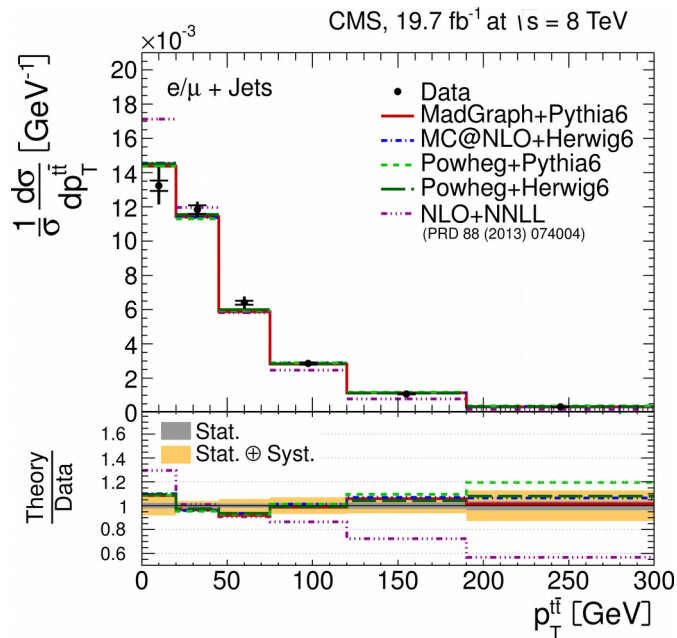
Rapidity of the (anti-) top

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Towards differential distributions \rightarrow LHC

■ Demands are challenging



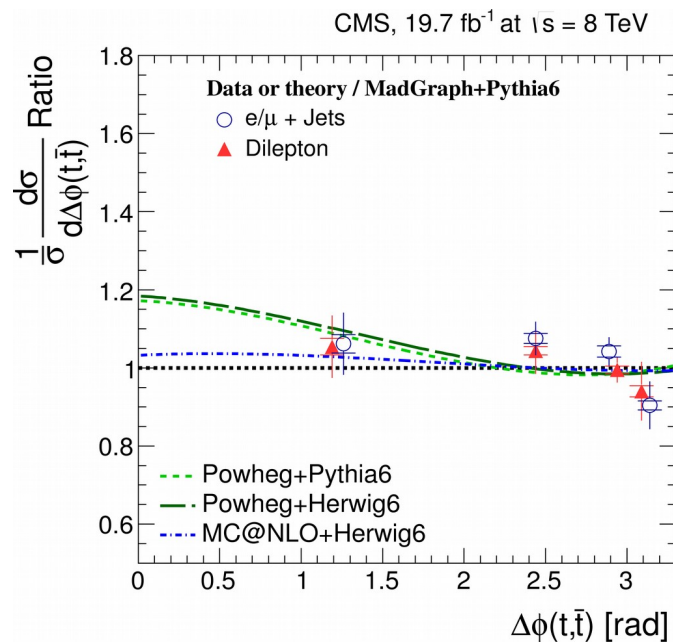
Transverse momentum of the $t\bar{t}$ -pair

■ Needed

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Towards differential distributions \rightarrow LHC

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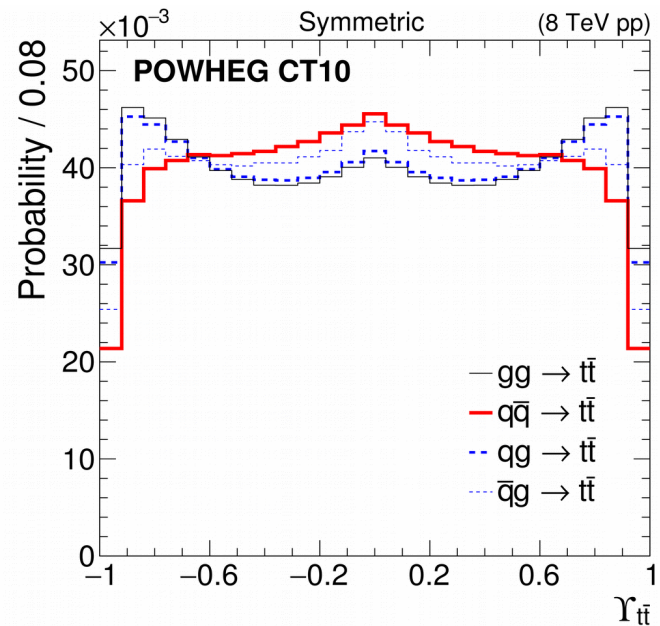
Angle between the $t\bar{t}$ -pair

■ Needed

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Towards differential distributions \rightarrow LHC

■ Demands are challenging



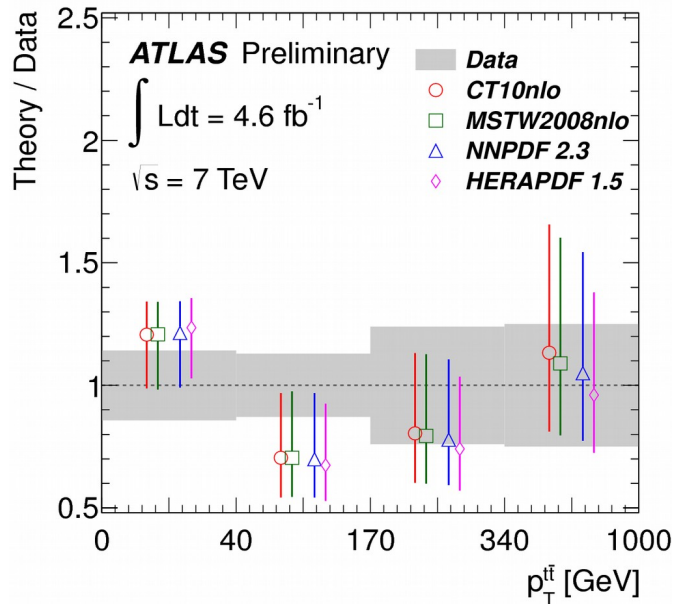
Charge asymmetry

■ Needed

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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
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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
 - Different observables

NEW Results !!!

- First Applications to Top-Quark Pair production

Differential Distributions for the LHC (8 TeV)

- Total cross section (MSTW2008)

$$\sigma = 239.167 \pm 9.233 \text{ [pb]}$$

- Total cross section gluon channel (MSTW2008)

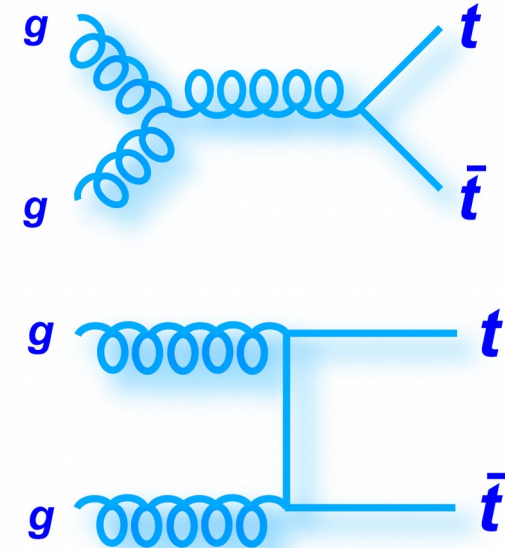
$$\sigma = 205.532 \pm 17.104 \text{ [pb]}$$

- At 8 TeV the gluon channel contributes $\sim 86\%$
 - Including only gluons at α^4 and the full NLO contribution $\sim 100\%$

- STRIPPER results checked against known result (Top++)

- Agreement: $< 0.1\%$
- Highly non-trivial check of the software and the subtraction scheme

- Quark-channels are still in the testing phase (in progress)



Differential Distributions for the LHC (8 TeV)

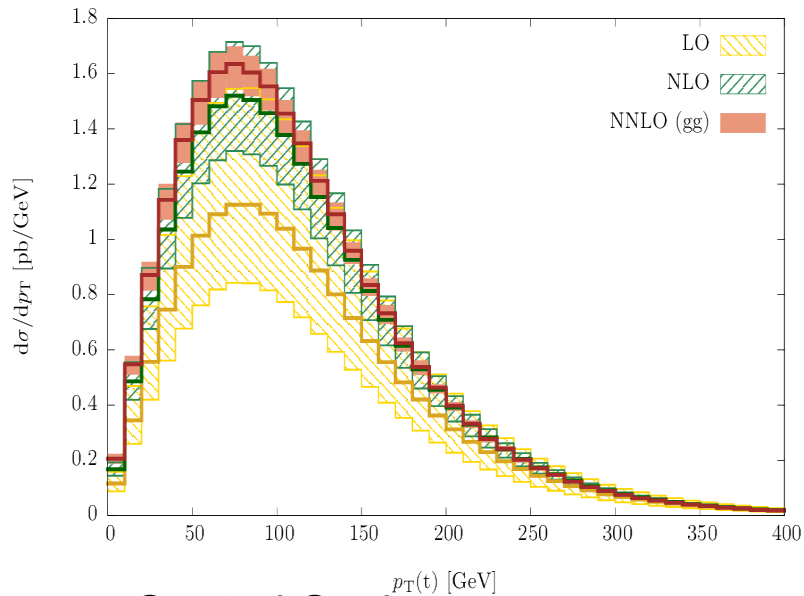
- Full NNLO results for the gluon channel
(no further approximations are made)
- Setup for the presented results
 - Full LO
 - Full NLO
 - NNLO, only gluon channel included → NNLO (gg)

 - Independent scale variation: 7 different scales
 - $\frac{1}{2} m_t \leq \mu_R \leq 2 m_t$, $\frac{1}{2} m_t \leq \mu_F \leq 2 m_t$
 - MSTW2008(nn)lo68cl
 - Top-Mass: 173.3 GeV

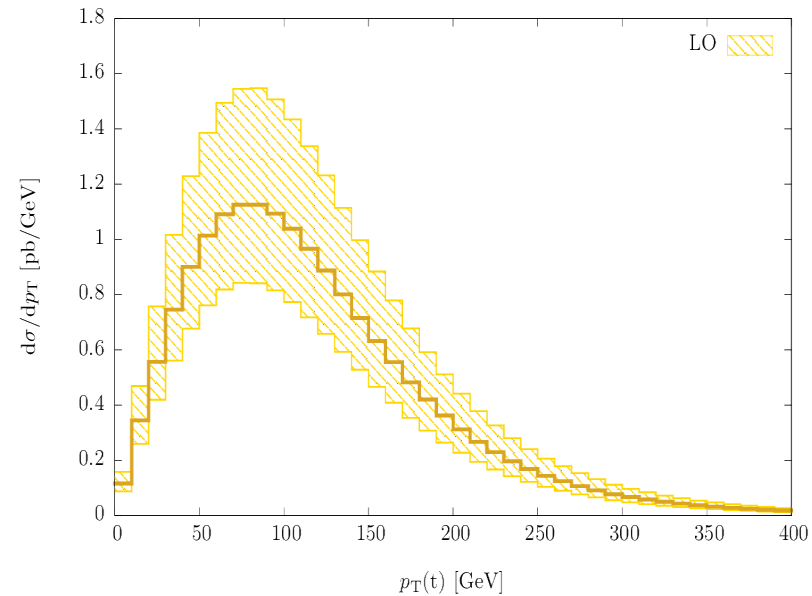
p_T -distribution LHC 8TeV (preliminary)

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

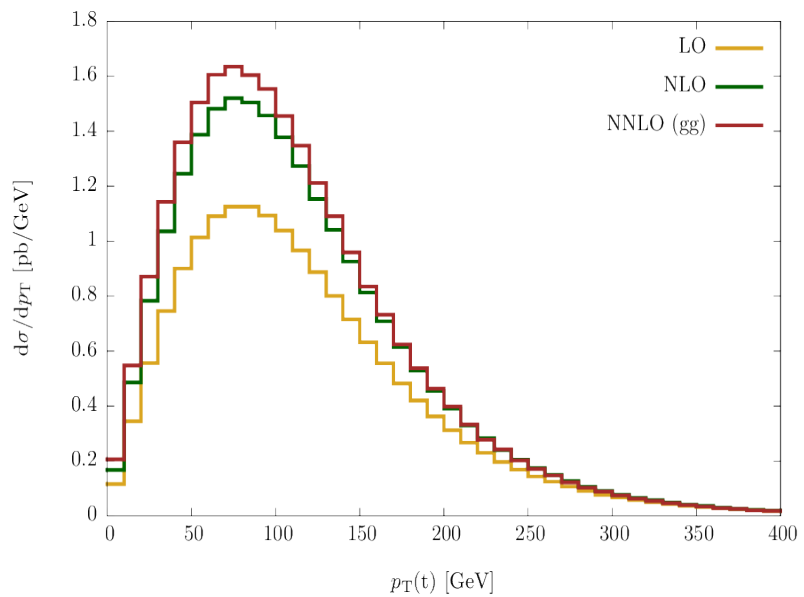
Scale dependence



LO



Central Scale

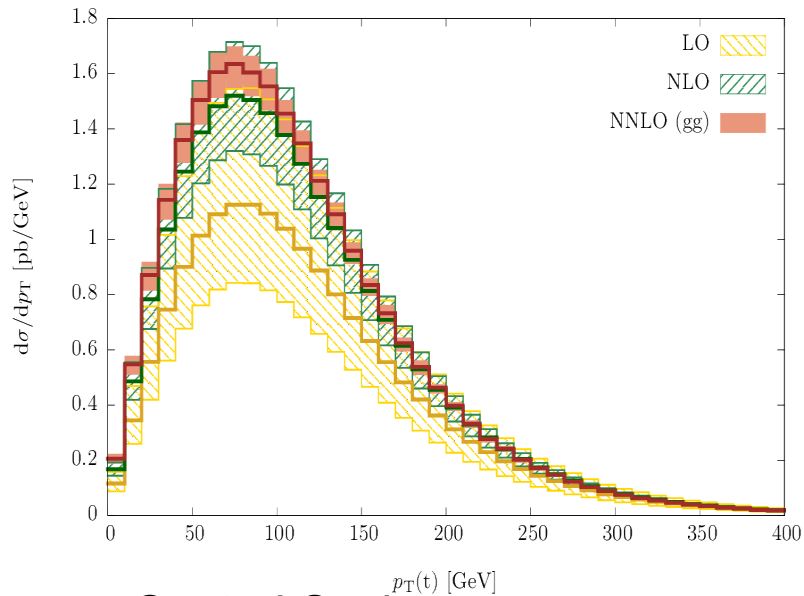


- Significant reduction of scale dependence
- Convergence of the perturbative series per bin

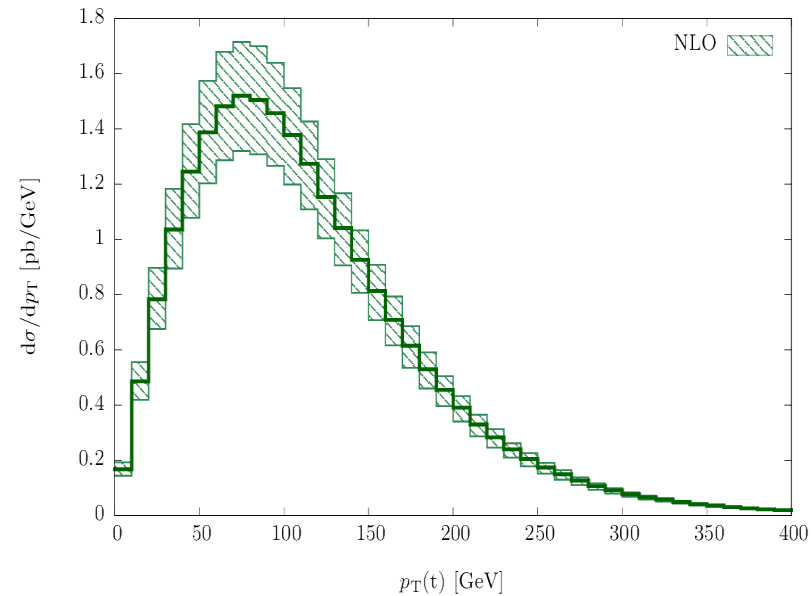
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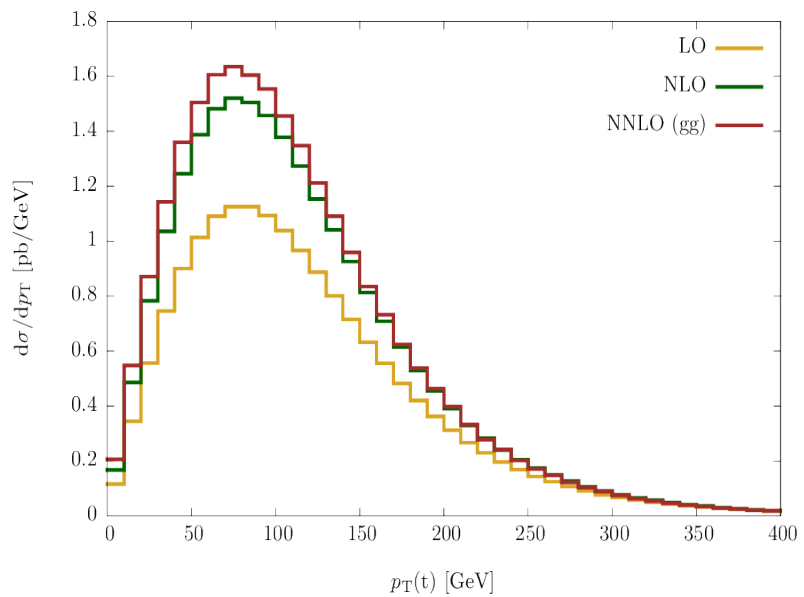
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NLO



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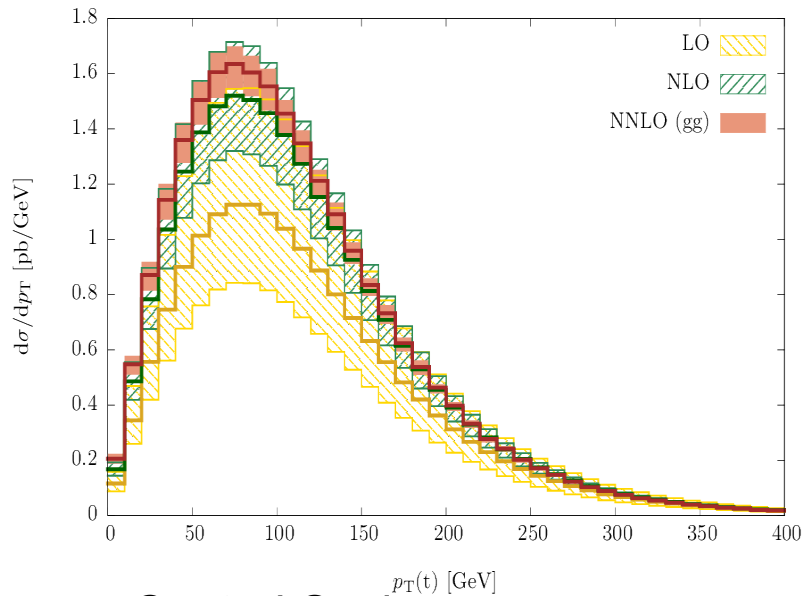


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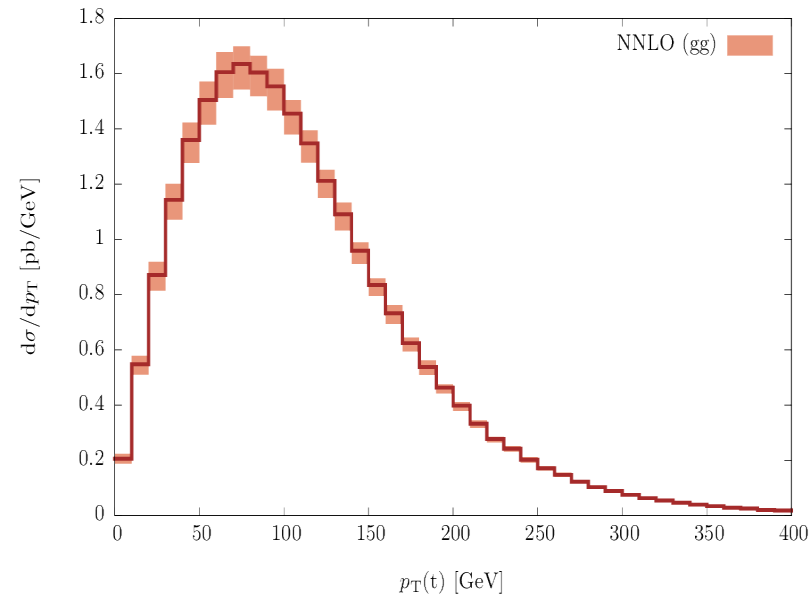
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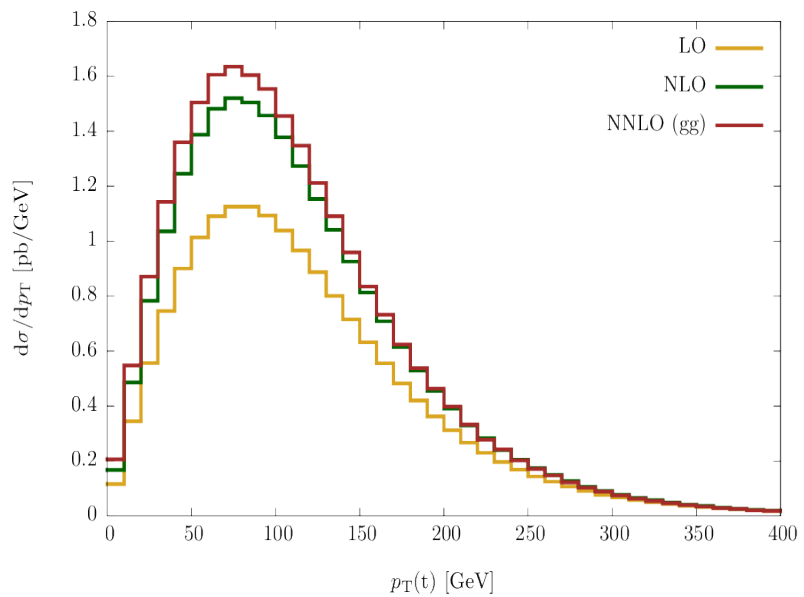
Scale dependence



NNLO (gg)



Central Scale

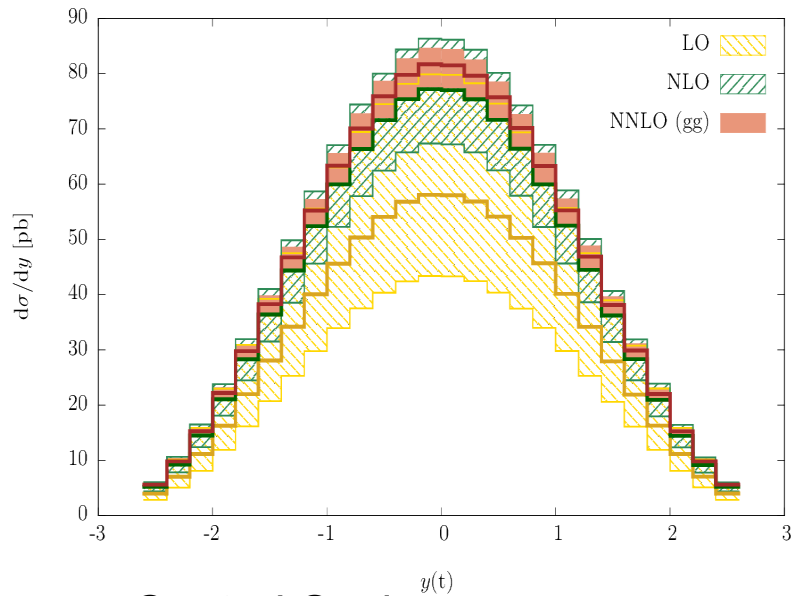


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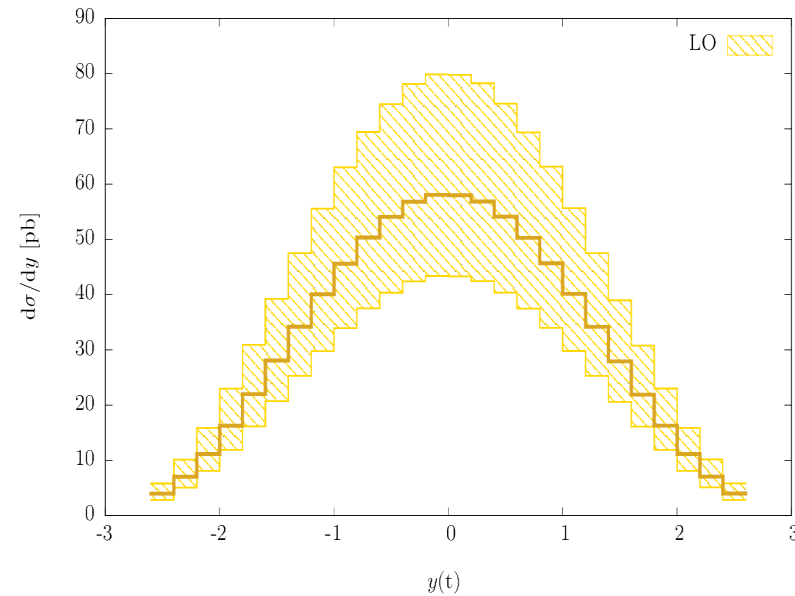
Rapidity-distribution LHC 8TeV (preliminary)

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

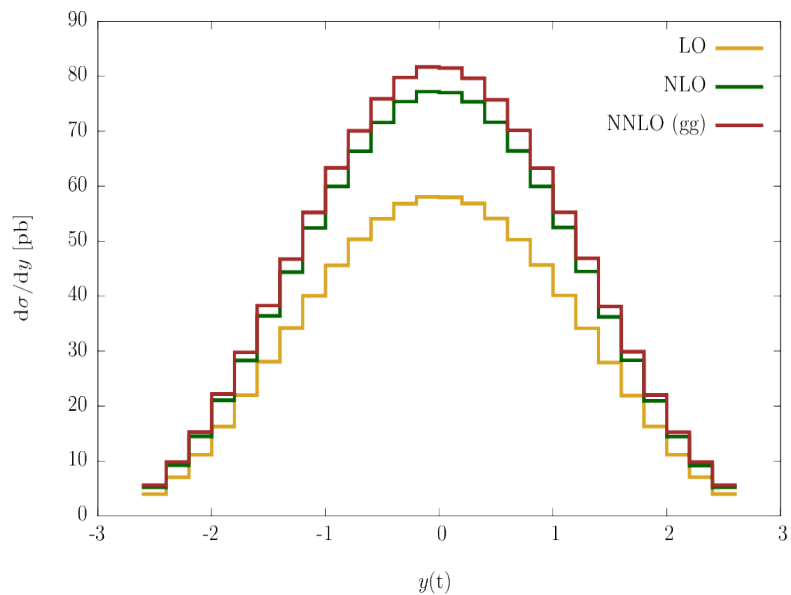
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LO



Central Scale

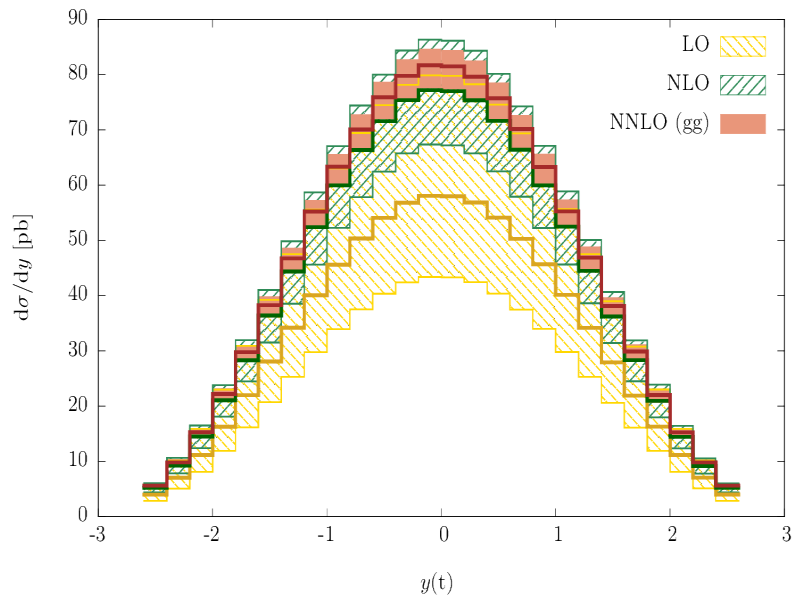


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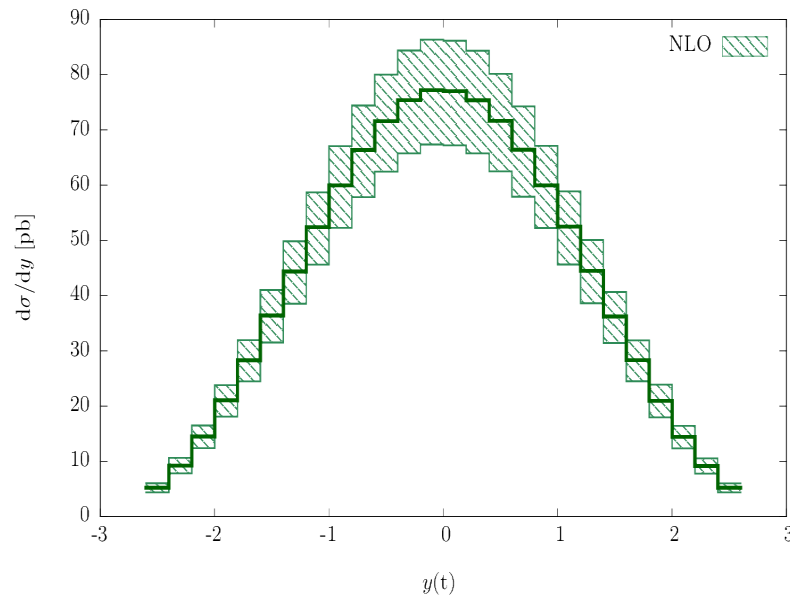
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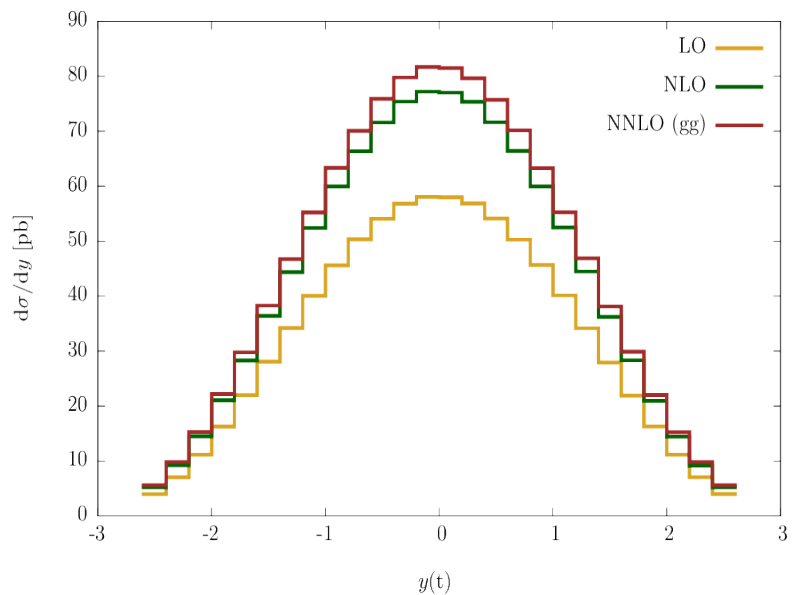
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NLO



Central Scale

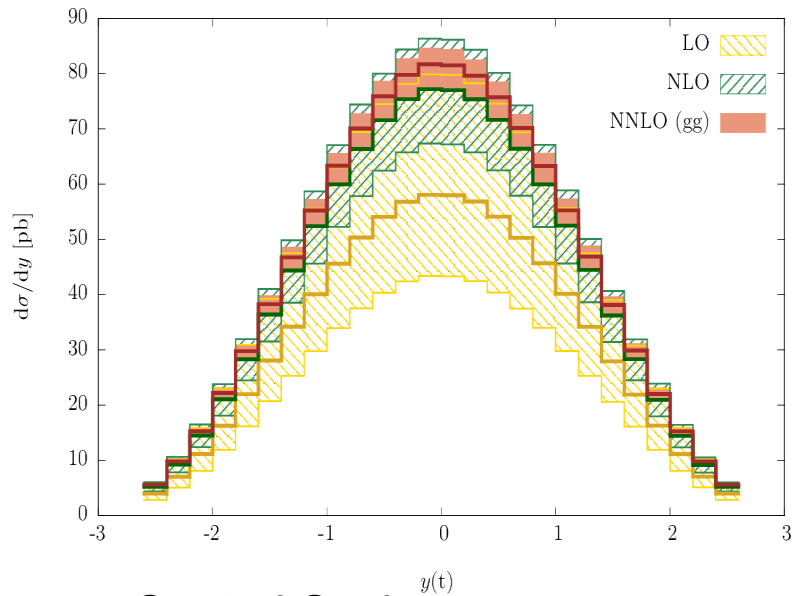


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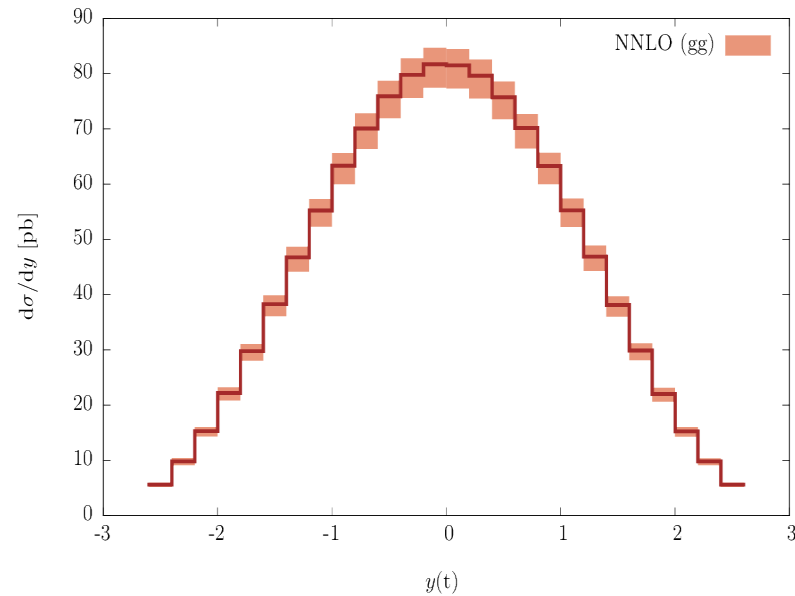
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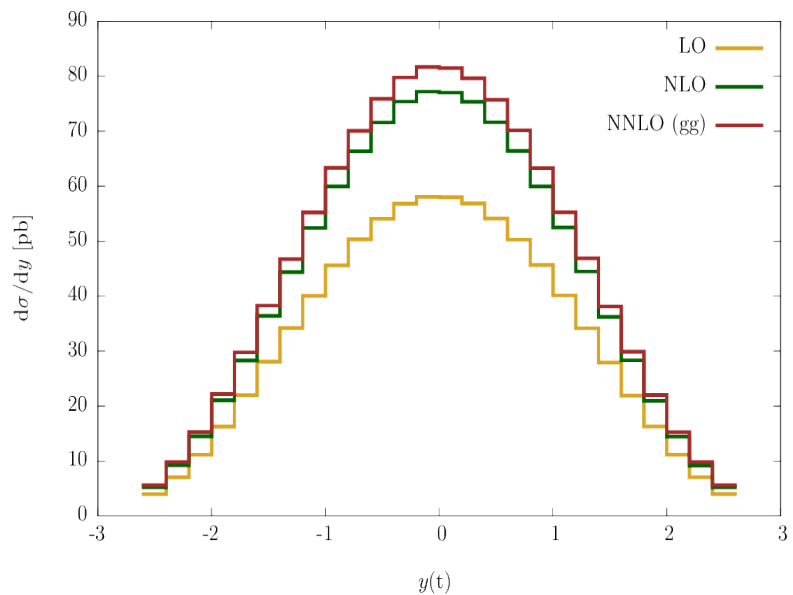
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NNLO (gg)



Central Scale

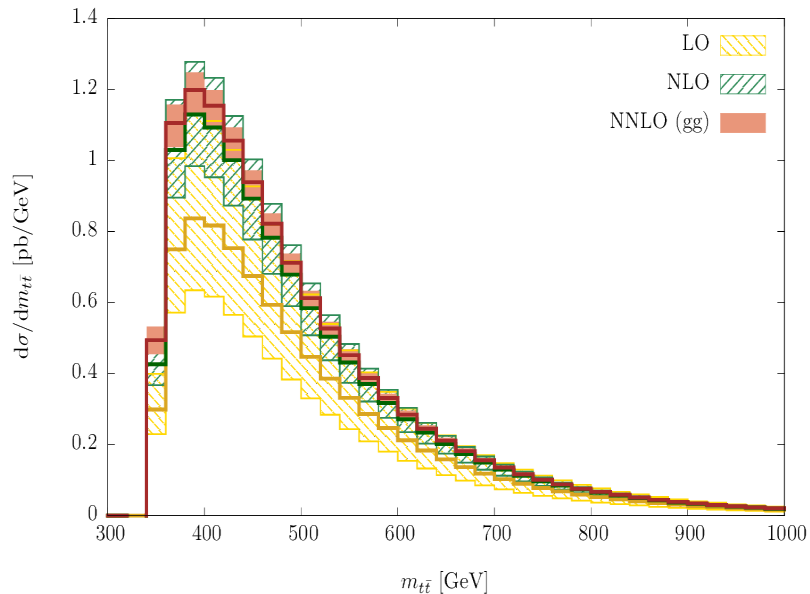


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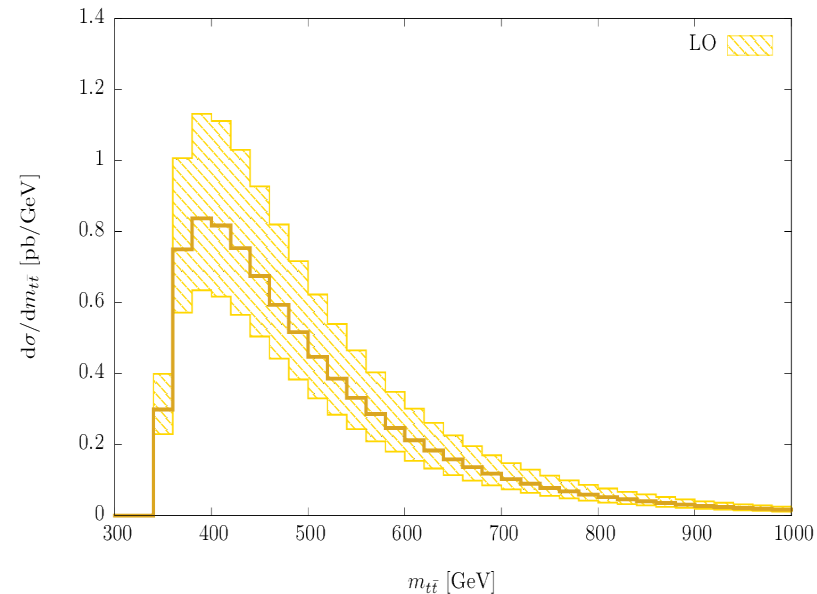
$m_{t\bar{t}}$ -distribution LHC 8TeV (preliminary)

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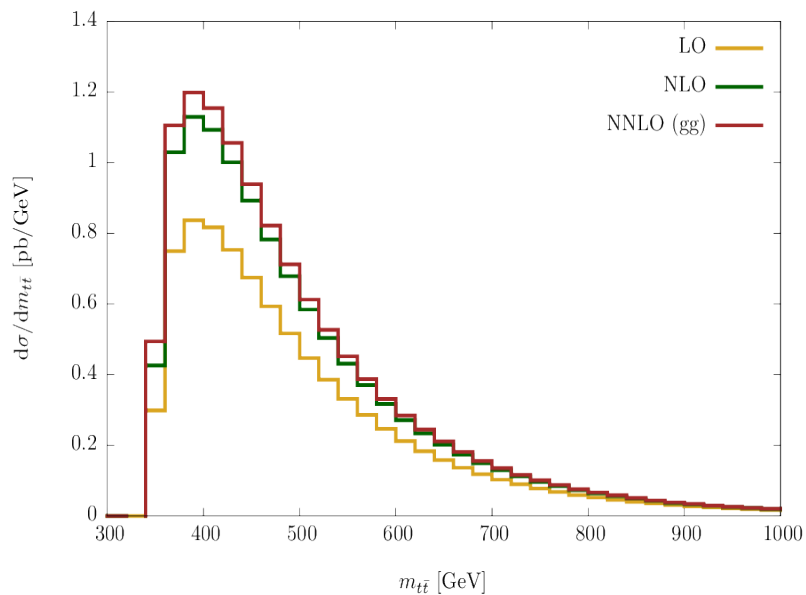
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LO



Central Scale

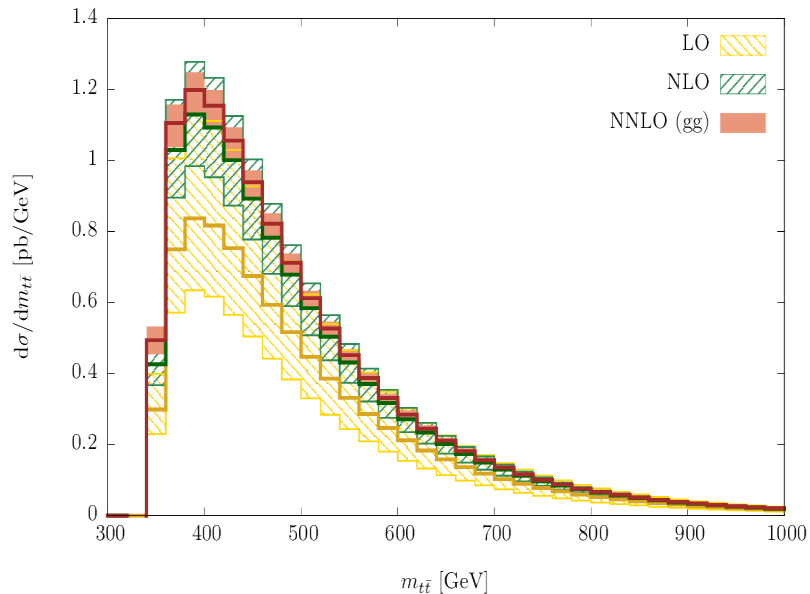


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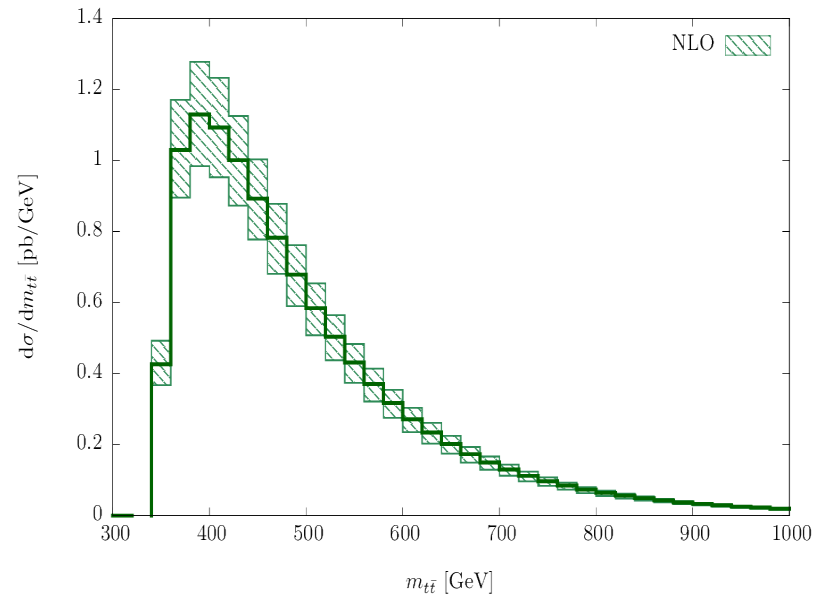
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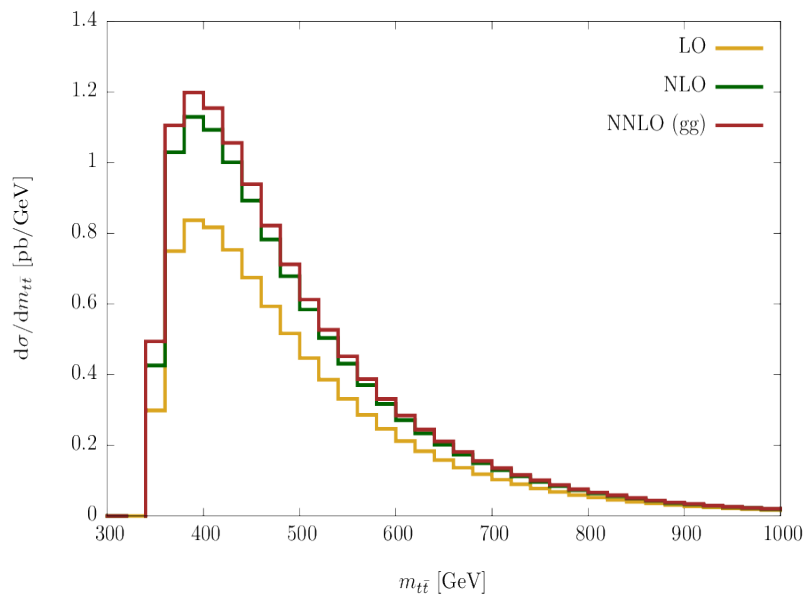
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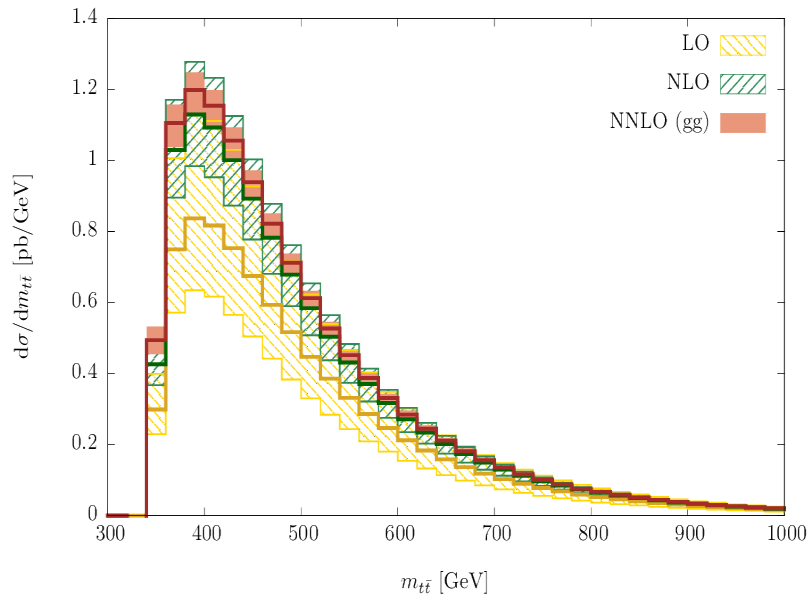


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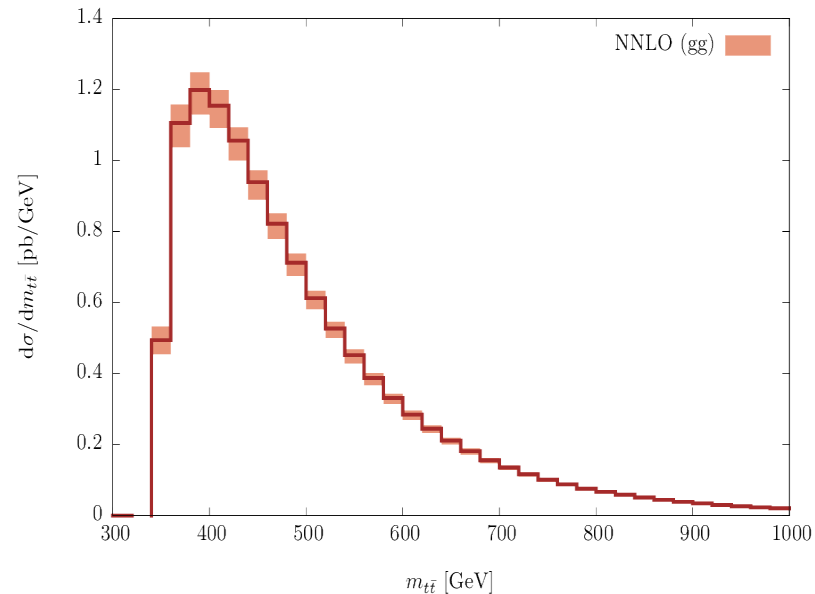
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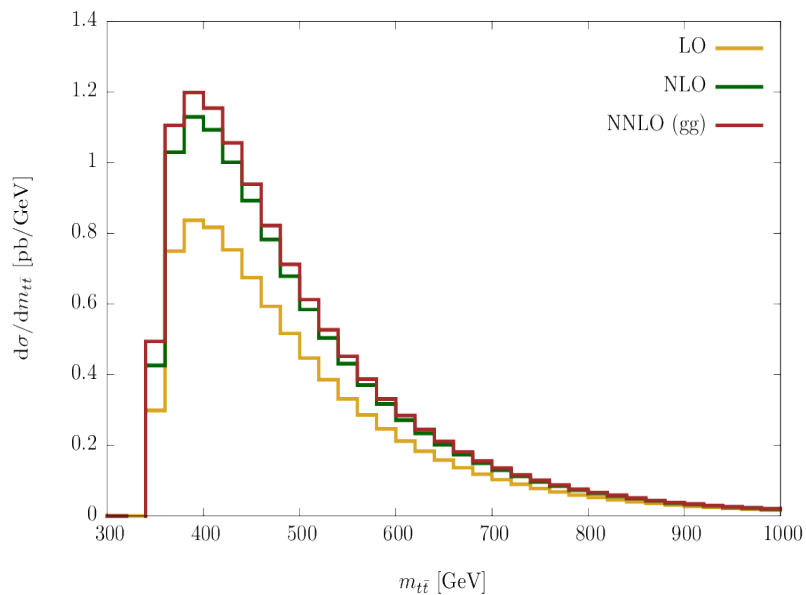
Scale dependence



NNLO (gg)



Central Scale



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Summary and outlook

- New independent software for NNLO computations
 - First partial results (NNLO (gg)) for $t\bar{t}$ -distributions at LHC (preliminary)
 - Quark-Channels are still being tested
 - Framework and software is process independent
- Soon
 - Differential distributions for LHC 8TeV (including quarks) [Brucherseifer, Caola, Melnikov; '13]
 - Top Decays (NNLO Decays are available) [Gao, Li, Zhu; '12]
 - Software will be publicly available
 - Applications to different processes

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- **Thank you for your attention !!!**