# Four Top Final States At NLO QCD

Malgorzata Worek
Wuppertal Uni.

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# Motivations

- Successful running of collisions at 7 TeV and 8 TeV @ LHC
- November 2012 Delivered: **$\mathcal{L}$ = 21 fb$^{-1}$ at 8 TeV**
- The large statistics have opened a window on entirely new measurements & analysis of novel more complex final states
- Reducing theoretical uncertainties for correct interpretation of the data is needed
- A theoretical accuracy at least at NLO is desirable & demanded for most analyses
  - More reliable theoretical error related to the scale dependence
  - Normalization and shape of distributions
  - Improved description of jets
  - Correct choice of scales for many scale processes: V+ jets, ttH, ttbb, …

***The strongest argument in support of higher order calculations is their success in an accurate description of the LEP and TeVatron data !***

# Four Tops

- LHC energy is sufficient to produce 4 tops at a sensible rate

- Interesting channel to probe several realizations of BSM Physics
  - Models of Higgs and top compositeness
  - Models involving the production of new colored resonances
  - Kaluza-Klein gluons from the Randall-Sudrum warped extra dimensions
  - Many models predict effective four-top quark interactions
  - New processes such as pp $\rightarrow$ GG and pp $\rightarrow$ ttG with G $\rightarrow$ tt
  - Major background for many processes arising from (…)MSSM
  - Heavy Higgs boson production
  - Long cascade decays of colored new particles like squarks or gluinos

***Precise theoretical description of the four-top production rate in the Standard Model may help to constrain new physics scenarios***

# Four Tops

- LO cross section @ LHC with $m_t$ = 173.2 GeV and CTEQ PDF (CT09MC1)
  - $LHC_{7\,TeV} \rightarrow \sigma_{LO} = (0.73 \pm 0.45)$ fb
  - $LHC_{8\,TeV} \rightarrow \sigma_{LO} = (1.3 \pm 0.8)$ fb
- For integrated luminosity of 20 $fb^{-1}$ this correspond to ~20 events
  - $LHC_{14\,TeV} \rightarrow \sigma_{LO} = (13.1 \pm 7.4)$ fb
- For integrated luminosity of 100 $fb^{-1}$ ~1300 events @ 14 TeV

***NLO QCD corrections @ 14 TeV a necessary step towards a correct interpretation of the possible signals of new physics that may arise in this channel***

# Structure of NLO Calculations

$$\sigma^{\mathrm{NLO}} = \int_m d\sigma^{\mathrm{B}} + \int_{m+1} d\sigma^{\mathrm{R}} - \int_{m+1} d\sigma^{\mathrm{A}} + \int_{m+1} d\sigma^{\mathrm{A}} + \int_m d\sigma^{\mathrm{V}}$$

$$= \int_m d\sigma^{\mathrm{B}} + \int_{m+1} \left[d\sigma^{\mathrm{R}} - d\sigma^{\mathrm{D}}\right] + \int_m \left[d\sigma^{\mathrm{V}} + d\sigma^{\mathrm{I}} + d\sigma^{\mathrm{KP}}\right]$$

- Main Building Blocks of **HELAC-NLO** (Virtual Part)
  - Evaluation of one-loop amplitude - **HELAC-1LOOP**
  - Reduction at integrand level - OPP method – **CUTTOOLS**
  - Evaluation of scalar functions - **ONELOOP**


*Ossola, Papadopoulos, Pittau '07, '08*
*Draggiotis, Garzelli, Papadopoulos, Pittau '09*
*Garzelli, Malamos, Pittau '09*
*van Hameren, Papadopoulos, Pittau '09*
*van Hameren, '10*

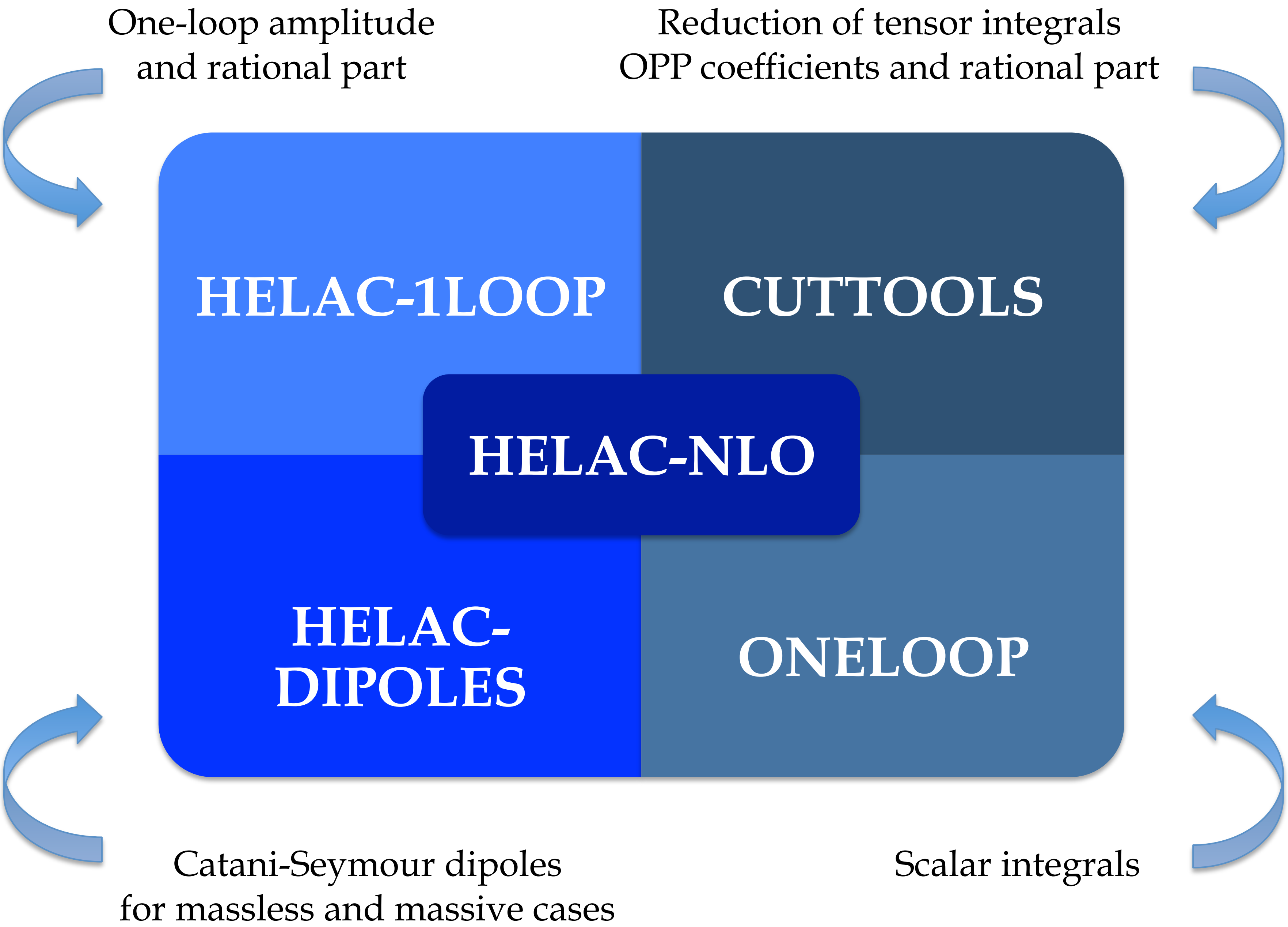
# Structure of NLO Calculations

$$\sigma^{\mathrm{NLO}} = \int_m d\sigma^{\mathrm{B}} + \int_{m+1} d\sigma^{\mathrm{R}} - \int_{m+1} d\sigma^{\mathrm{A}} + \int_{m+1} d\sigma^{\mathrm{A}} + \int_m d\sigma^{\mathrm{V}}$$

$$= \int_m d\sigma^{\mathrm{B}} + \int_{m+1} \left[d\sigma^{\mathrm{R}} - d\sigma^{\mathrm{D}}\right] + \int_m \left[d\sigma^{\mathrm{V}} + d\sigma^{\mathrm{I}} + d\sigma^{\mathrm{KP}}\right]$$

- Main Building Blocks of **HELAC-NLO** (Real Emission Part)
  - Implementation of Catani-Seymour dipoles - **HELAC-DIPOLES**
  - Extended for arbitrary helicity eigenstates of the external partons
  - Phase space restriction on the dipoles phase space

*Czakon, Papadopoulos, Worek '09*


One-loop amplitude
and rational part
Reduction of tensor integrals
OPP coefficients and rational part
HELAC-1LOOP
CUTTOOLS
HELAC-NLO
HELAC-
DIPOLES
ONELOOP
Catani-Seymour dipoles
for massless and massive cases
Scalar integrals

# Fixed Scale: $2m_T$

- Natural scale - the mass of the heavy particle appearing in the process
- Production relatively close to the threshold as defined by particle masses
- 14 TeV and MSTW2008 PDF set

| Process | $\sigma_{\rm LO}$ [fb] | $\sigma_{\rm NLO}^{\alpha_{\rm max}=1}$ [fb] | $\sigma_{\rm NLO}^{\alpha_{\rm max}=0.01}$ [fb] | K-Factor | [%] |
|---|---|---|---|---|---|
| $pp \to t\bar{t}t\bar{t} + X$ | 12.056(6) | 15.33(2) | 15.35(3) | 1.27 | 27 |

$$\sigma^{\rm LO}_{t\bar{t}t\bar{t}}({\rm LHC}_{\rm 14TeV}, m_t = 173.2 \text{ GeV}, {\rm MSTW2008lo}) = 12.056^{+9.364(+78\%)}_{-4.876(-40\%)} \text{ fb}$$

$$\sigma^{\rm NLO}_{t\bar{t}t\bar{t}}({\rm LHC}_{\rm 14TeV}, m_t = 173.2 \text{ GeV}, {\rm MSTW2008nlo}) = 15.33^{+3.95(+26\%)}_{-3.81(-25\%)} \text{ fb.}$$

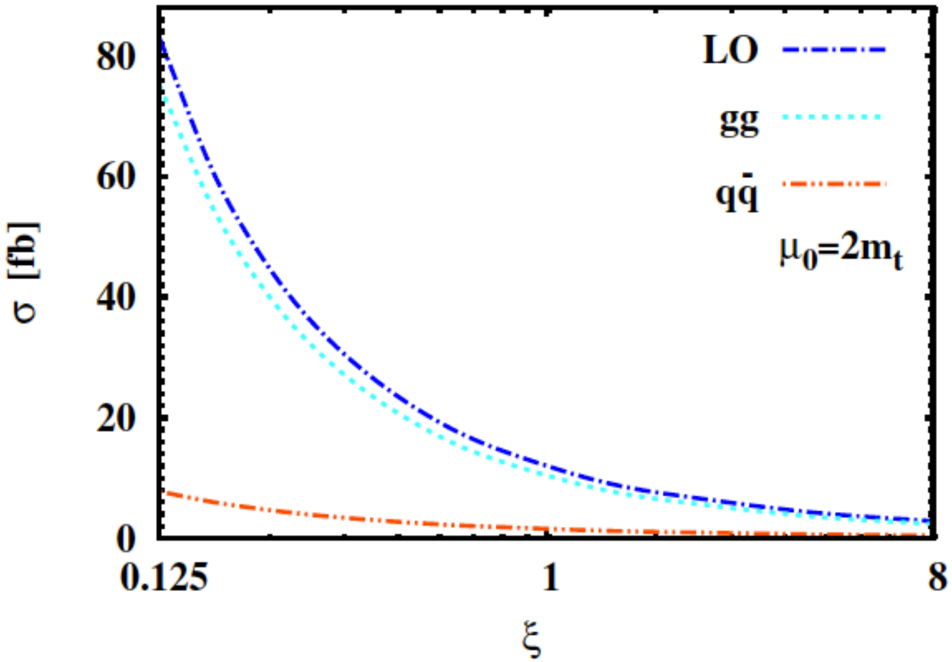
- Scale uncertainty at LO at the level of **78%** (**59%** after symmetrization)
- At NLO the scale uncertainty is reduced down to **26%**

*Bevilacqua, Worek '12*

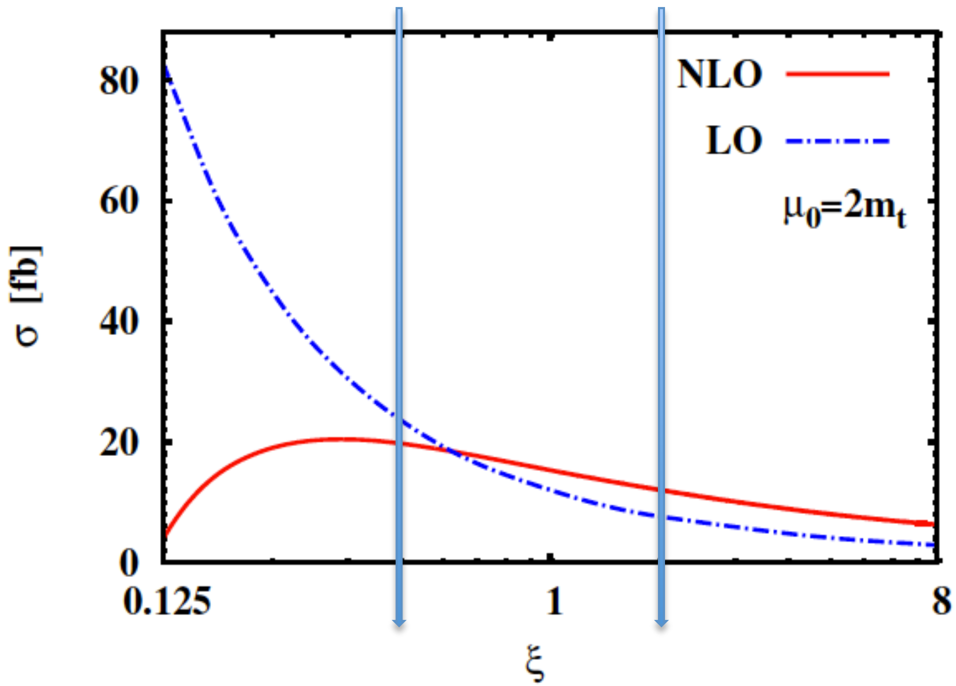
# Theoretical Uncertainty

- Scale dependence of the LO cross section with the individual contributions
- Scale dependence of the LO and NLO cross sections

*Bevilacqua, Worek '12*




gg channel 87%
qq channel 13%




| | | |
|---|---|---|
| LO: | 78% | 40% |
| NLO: | 26% | 25% |

# PDF Uncertainty

- The best fit PDFs and a set of 40 PDF parameterizations inside MSTW2008 set
- Describes $\pm 1\sigma$ variation of all parameters used in the global fit
- Asymmetric PDF uncertainties **+5.7%** and **−4.5%**

- Does not account for the theoretical assumptions that enter into parameterization
- Different PDF set e.g. CTEQ PDF with different theoretical assumptions

$$\sigma^{\rm LO}_{t\bar{t}t\bar{t}}({\rm LHC}_{\rm 14TeV}, m_t = 173.2~{\rm GeV}, {\rm CT09MC1}) = 11.414(8)~{\rm fb}$$

$$\sigma^{\rm NLO}_{t\bar{t}t\bar{t}}({\rm LHC}_{\rm 14TeV}, m_t = 173.2~{\rm GeV}, {\rm CT10}) = 14.37(2)~{\rm fb}\,.$$

- The MSTW2008 results are larger than the CTEQ by **5.6%** at LO and **6.7%** at NLO
- Comparable to the individual estimates of MSTW2008 PDF systematics
- Well below the theoretical uncertainties due to scale dependence

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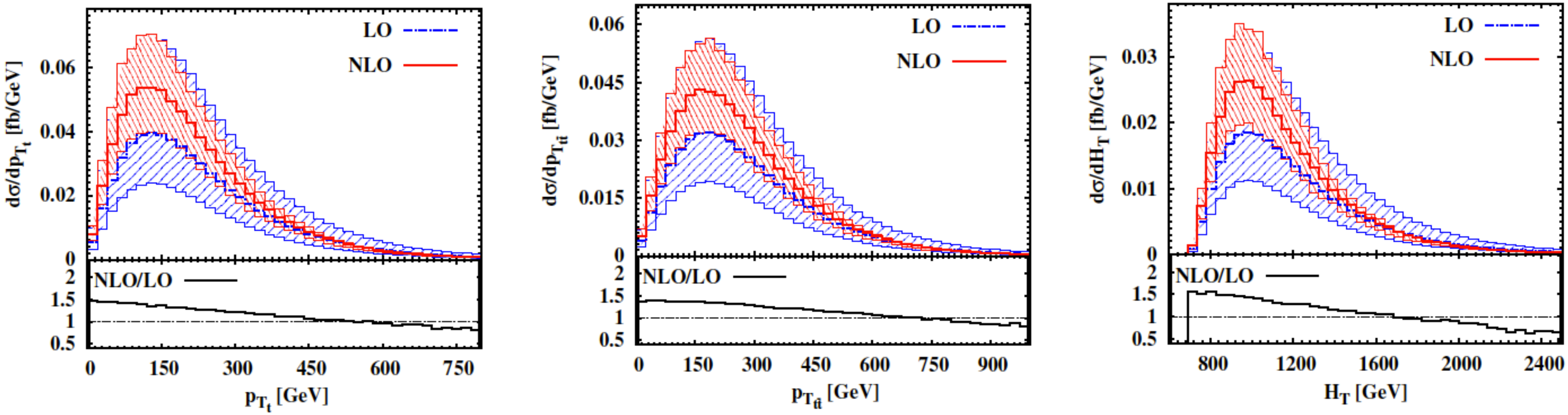
# Differential Distributions




- Differential K factor
- Transverse momentum distribution of tt pair and of the top quark
- Distribution of the total transverse energy of the 4t system
- Distortions at the level of **60% - 80%**
- Large and negative NLO corrections affect the tails
- NLO error bands do not fit within the LO ones

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# Dynamical Scale: $H_T/4$

- 14 TeV and MSTW2008 PDF set and with the dynamical scale

$$\sigma^{LO}_{t\bar{t}t\bar{t}}(\text{LHC}_{14\text{TeV}}, m_t = 173.2 \text{ GeV}, \text{MSTW2008lo}) = 13.891^{+11.074(+80\%)}_{-5.711(-41\%)} \text{ fb}$$

$$\sigma^{NLO}_{t\bar{t}t\bar{t}}(\text{LHC}_{14\text{TeV}}, m_t = 173.2 \text{ GeV}, \text{MSTW2008nlo}) = 16.87^{+4.04(+24\%)}_{-4.26(-25\%)} \text{ fb}$$

| Process | $\sigma_{LO}$ [fb] | $\sigma^{\alpha_{max}=1}_{NLO}$ [fb] | $\sigma^{\alpha_{max}=0.01}_{NLO}$ [fb] | K-Factor | [%] |
|---|---|---|---|---|---|
| $pp \to t\bar{t}t\bar{t} + X$ | 13.891(9) | 16.87(2) | 16.86(3) | 1.21 | 21 |

- Before for the fixed scale $2m_t$
  - Cross section and K-factor $\sigma^{LO}$ = 12.056 fb, $\sigma^{NLO}$ = 15.33 fb, K =1.27
  - Scale dependence LO = +78% & -40%, NLO = +26% & -25%

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# Theoretical Uncertainty

- ❑ Scale dependence of the LO cross section with the individual contributions
- ❑ Scale dependence of the LO and NLO cross sections

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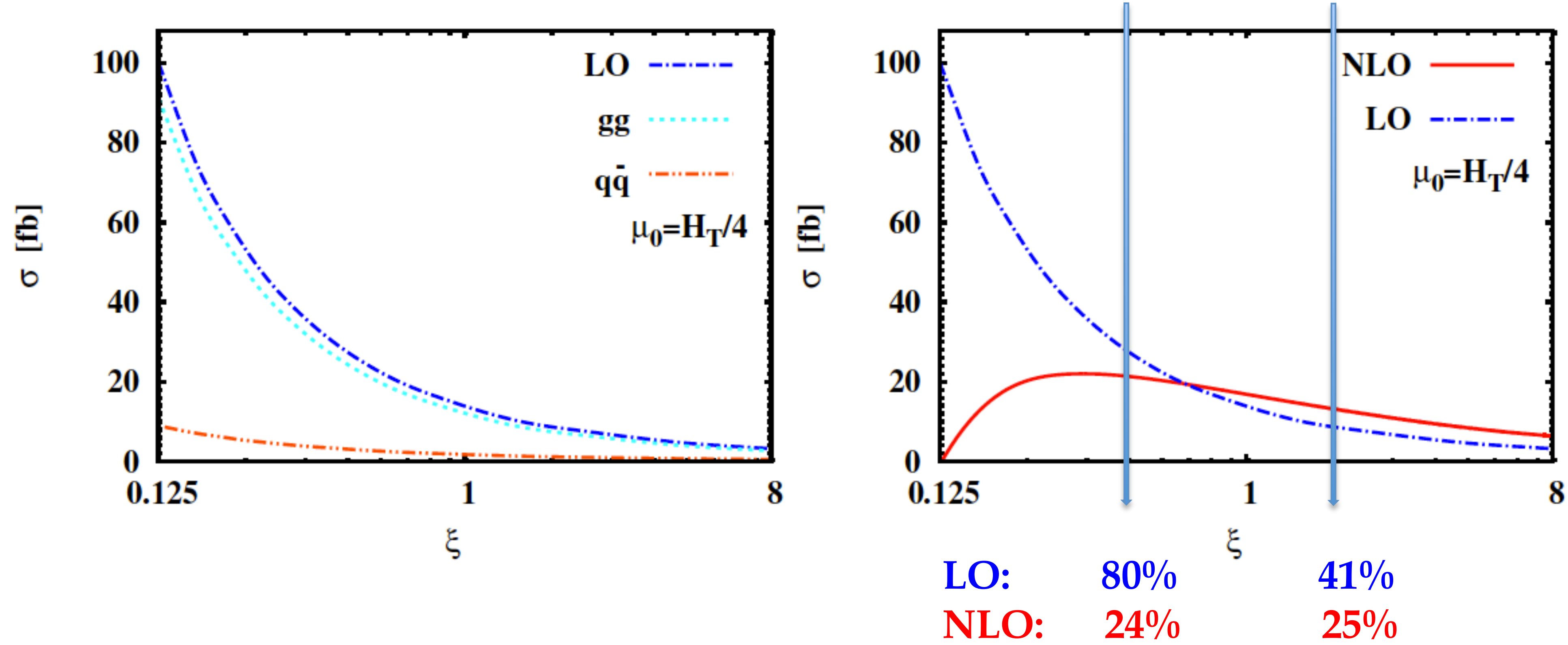
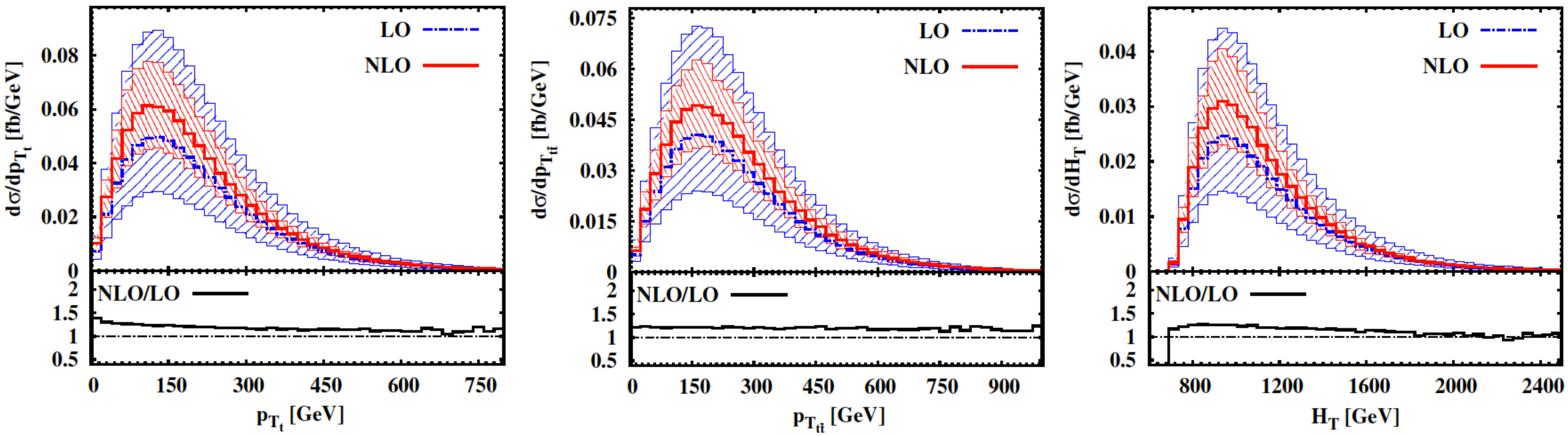


# Differential Distributions




- ❑ Results for the integrated cross sections have only slightly changed
- ❑ Constant(-ish) differential K-factors for the distributions
- ❑ Moderate and positive corrections of the order or **20%** over the whole range
- ❑ NLO error bands fit within LO error bands

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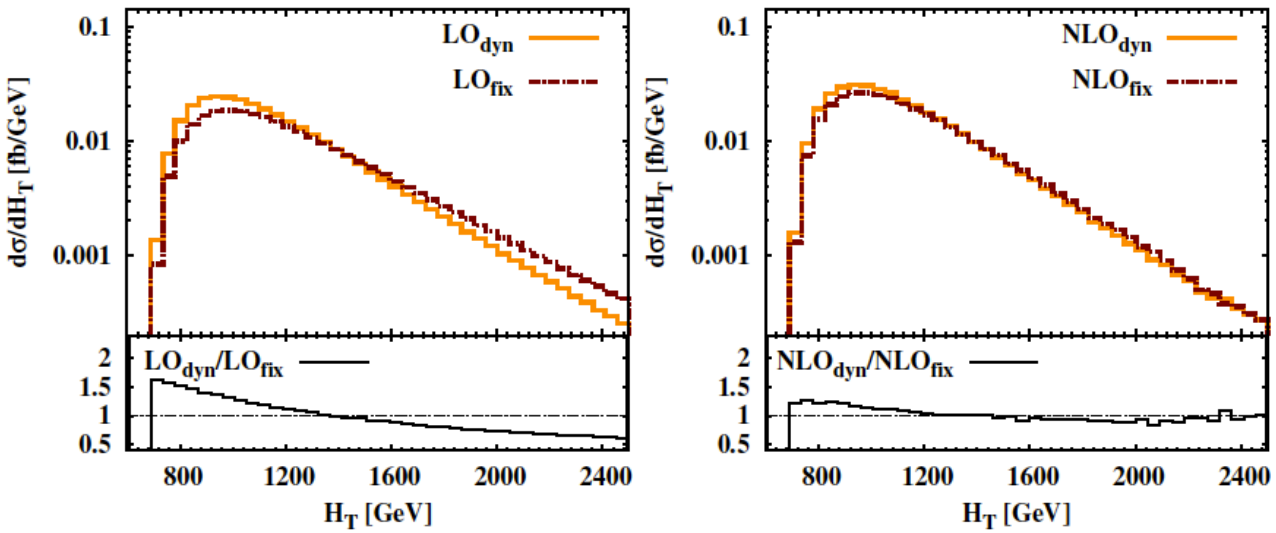
# Differential Distributions




- Improvement obtained with a dynamic scale at NLO is moderate
- The change in the shape of LO distributions is rather strong

***The fixed order approximation is meaningful, when the improved scale choice affects NLO cross sections to a much lower extent than the LO ones***

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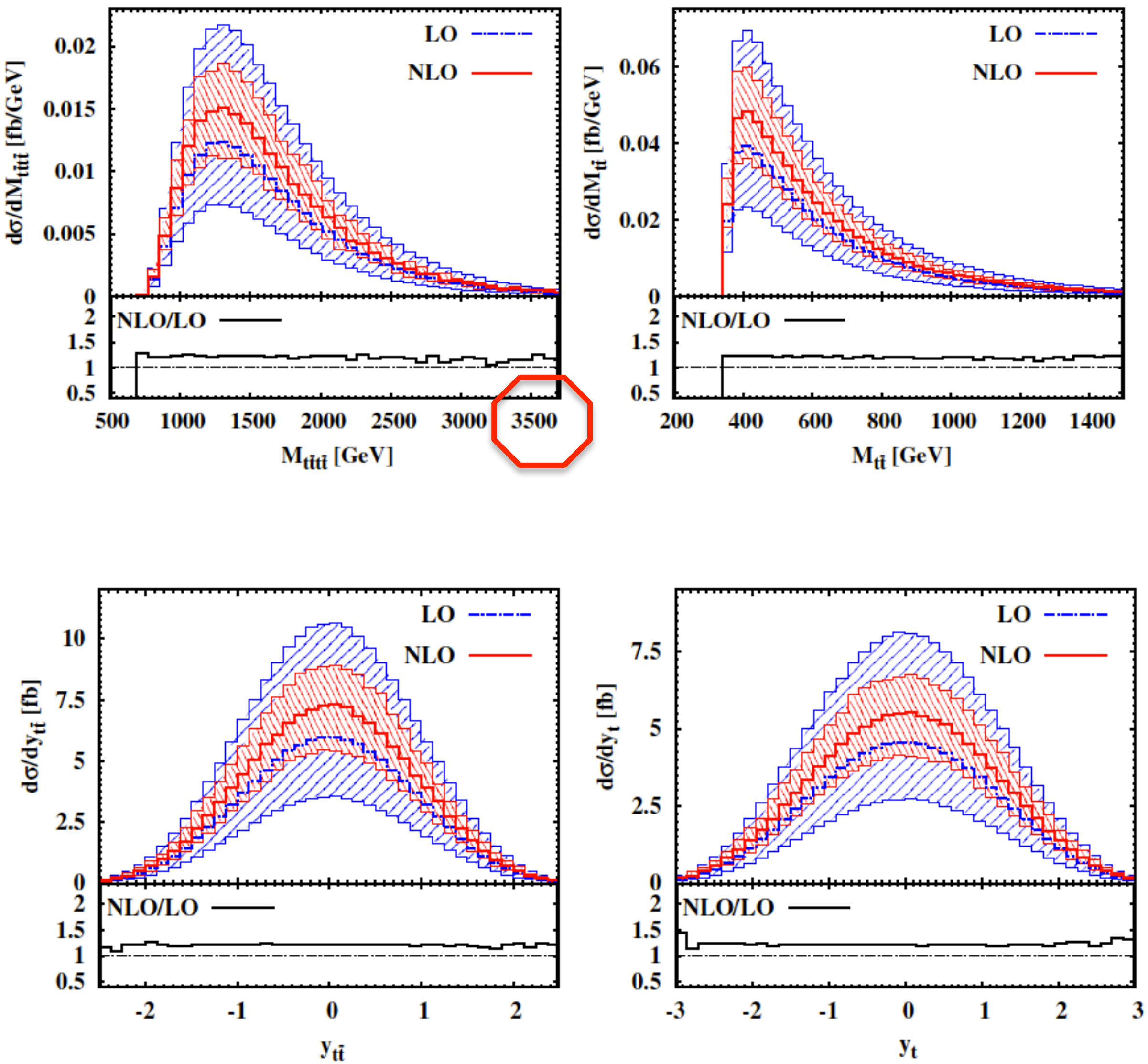
# Differential Distributions




- ❑ Invariant mass of the tttt
- ❑ Invariant mass of the tt pair
- ❑ Rapidity of the tt pair
- ❑ Rapidity of top quark

- ❑ Differential K-factors are constant within the whole range

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# Fixed Scale Vs Dynamical

- Looking only at the total cross section both scale choices are in good shape
- Results agree well within the corresponding theoretical errors

- Differential cross sections show large distortions up to 80% for fixed scale
- Large negative corrections in the tails of several distributions
- Accurate description of the shapes of observables only via full NLO QCD

- Moderate, positive and almost constant corrections of the order of 20% for all investigated observables for dynamical scale
- Efficiently accommodates for the multi-scale kinematics of the process
- Can be used in LO calculation together with some global K−factor
- Well approximate the full NLO QCD calculation
- Easily matched/merged with parton shower programs to obtain realistic events

# Final Remark

- Our NLO QCD predictions for tttt final state @ LHC with 14 TeV

$$\sigma^{NLO} = 17 \pm 4 \text{ [scales]} \pm 1 \text{ [PDF] fb}$$

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- For integrated luminosity of 100 $fb^{-1}$ we can have ~ 1700 events
- For comparison typical predictions of new physics scenarios

  - Effective four top interactions, Kaluza-Klein gluons or top-philic Z′ are set in the range:

    $\sigma = (5 - 100)$ fb for $m_{new} = 1$ TeV

    $\sigma = (1 - 20)$ fb for $m_{new} = 1.5$ TeV

    $\sigma < 1$ fb for masses greater than 2 – 3 TeV

  - $m_{new}$ is the mass of the new heavy particle or the energy scale associated with new physics effects

*G. Brooijmans et al. [New Physics Working Group Collaboration] arXiv:1005.1229 [hep-ph]*

# Summary & Outlook

- The most striking features of LHC → High multiplicity processes !
- Increased energy and luminosity, the immense amount of available phase space → Final states with several hard jets
- These events hide or strongly modify all possible signals of new physics
- Being able to predict their features is therefore essential
- A theoretical accuracy at least at NLO is demanded
- Obstacle → existence of several hard scales
- Better understanding of the scale choice that describes high $p_T$ region correctly
- Dynamic scales that depend on the event structure could help in some cases

- Remarkable development in NLO calculations driven by the LHC needs
- 2 → 4(5) processes are currently scrutinized @ NLO
  - **ttbb, ttjj, WWbb,** WWjj, Wjjj, Zjjj, jjjj, bbbb, **tttt,** … **(HELAC-NLO group)**
  - Wjjjj, Zjjjj

- Four top final states at NLO → Constraining BSM Physics at the LHC