Off-shell top quarks with a jet: A comprehensive study at NLO QCD

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in collaboration with G. Bevilacqua, H. B. Hartanto, M. Worek

DESY Hamburg, 29 September 2016

based on

[*PRL 116 (2016) 052003*]
[*arXiv:1609.01659*]

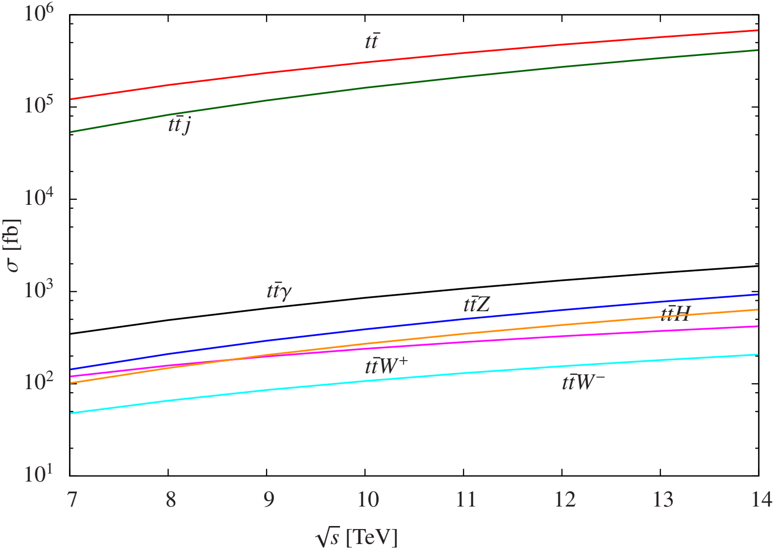
Outline

Next-to-Leading Order QCD predictions for

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$$

1. Motivation for $t\bar{t}j$ process
2. Off-shell effects in top-quark pair production
3. Complete off-shell effects with Helac-Nlo for $t\bar{t}j$
4. Conclusions

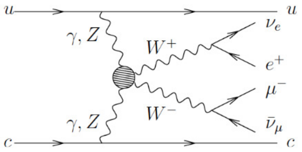
Associated $t\bar{t}$ production



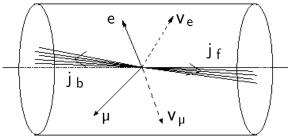
$t\bar{t}j$ AS A BACKGROUND

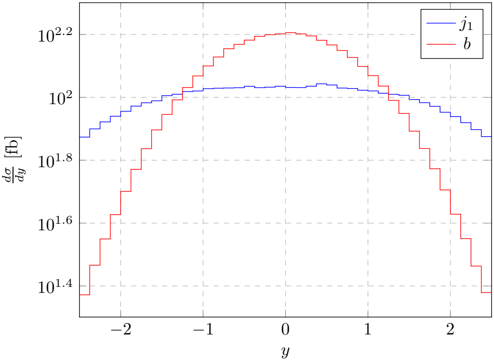
- Background for SM Higgs production in VBF: $qq \to Hqq \to W^+W^-qq$
- VBF requires two tagged jets: $\Delta y_{ij} = |y_i - y_j| > 4$ and $y_i \times y_j < 0$

signal:



signature:





also background for BSM searches with $\ell_1^+\ell_2^- + MET + jets$ signature

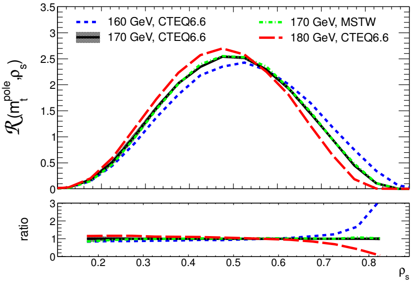
$t\bar{t}j$ AS A SIGNAL

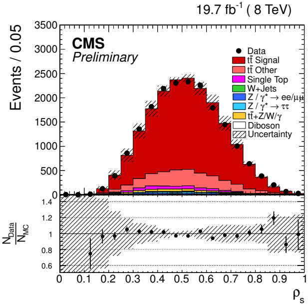
An alternative method for the top-quark mass extraction [Alioli et al '13]

$$\mathcal{R}(m_t, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s(m_t, \rho_s)}$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

- $\mathcal{R}(m_t, \rho_s)$ shape is sensitive to m_t
- $t\bar{t}j$ has higher sensitivity than $t\bar{t}$
- 7 TeV: $m_t = (173.7 \pm 2.2)$ GeV [ATLAS '15]
- 8 TeV: $m_t = (169.9 \pm 3.9)$ GeV [CMS '16]



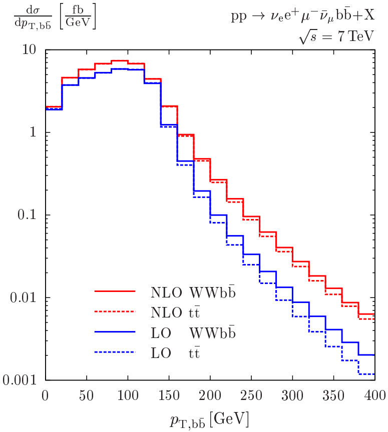


Theoretical and PDF uncertainties affect the m_t extraction

Top-quark off-shell effects - I

Contributions dropped in the NWA are suppressed by $\Gamma_t/m_t \sim 1\%$.

- True for sufficiently inclusive observables
- Larger impact on differential distributions



For σ_{tot} at the % level ($t\bar{t}$,$t\bar{t}j$,$t\bar{t}H$)

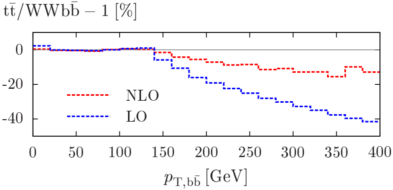
[A. Denner et al '11, '12, '15]

[G. Bevilacqua et al '11, '16]

[R. Frederix '14]

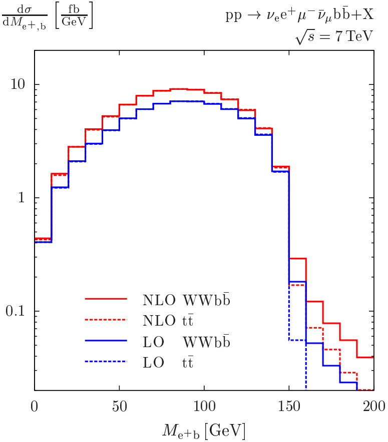
[F. Cascioli et al '14]

[G. Heinrich et al '14]



[A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12]

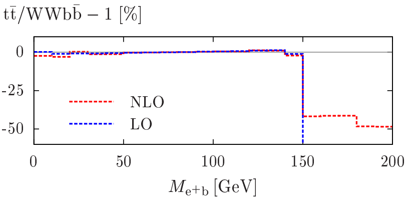
Top-quark off-shell effects - II



- If both top and W decay on-shell $\rightarrow$ end-point given by sharp cut

$$M_{\ell b} = \sqrt{m_t^2 - m_W^2} \approx 152\ \text{GeV}$$

- Additional radiation & off-shell effects introduce smearing



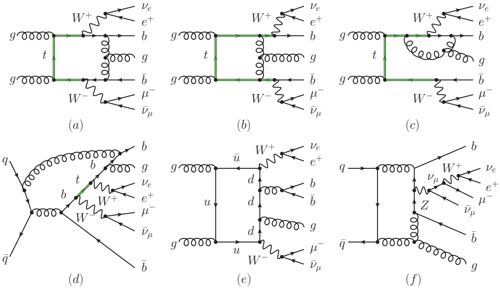
[*A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12*]

m_t measurement based on $M_{\ell b}$ $\rightarrow$ m_t extraction is very sensitive to template (LO/NLO and Full/NWA). [*Heinrich, Maier, Nisius, Schlenk, Winter '14*]

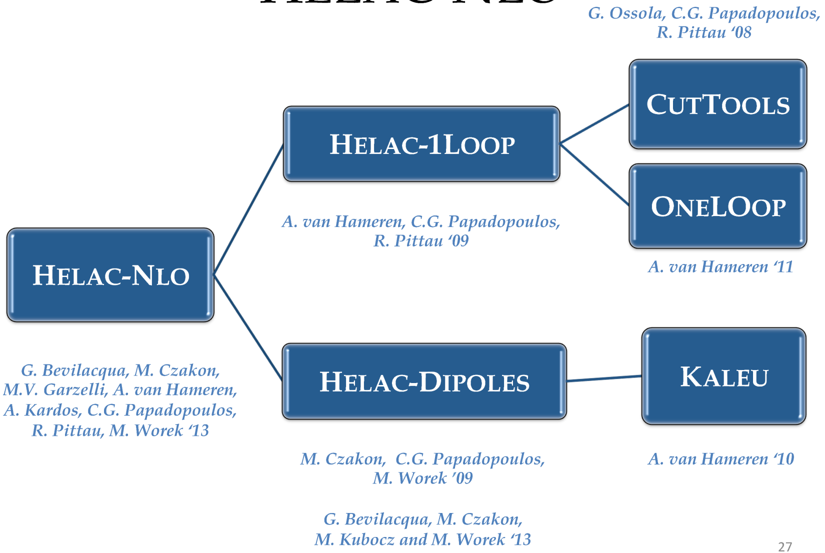
Top-quark off-shell effects in $t\bar{t}j$

$$pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}j + X$$

- $t\bar{t}j$ production at $\mathcal{O}(\alpha_s^4 \alpha^4)$ in the di-lepton decay channel
- $2 \to 5$ QCD process ($W^+W^- b\bar{b}j$)
- gg initial state is the most complicated production channel
  - LO: 508
  - Real: 4447
  - Virtual: 39180 $\to$ 1155 hexagons and 120 heptagons



HELAC-NLO


G. Ossola, C.G. Papadopoulos, R. Pittau '08
CUTTOOLS
HELAC-1LOOP
ONELOOP
A. van Hameren, C.G. Papadopoulos, R. Pittau '09
A. van Hameren '11
HELAC-NLO
G. Bevilacqua, M. Czakon, M.V. Garzelli, A. van Hameren, A. Kardos, C.G. Papadopoulos, R. Pittau, M. Worek '13
HELAC-DIPOLES
KALEU
M. Czakon, C.G. Papadopoulos, M. Worek '09
G. Bevilacqua, M. Czakon, M. Kubocz and M. Worek '13
A. van Hameren '10

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Setup for LHC 13 TeV - I

A comprehensive study for off-shell $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$ production:

- fixed vs. dynamical scale, independent μ_R and μ_F variations
- PDF uncertainties (different PDFs, internal PDF uncertainty)

$\Rightarrow$ very time consuming and CPU intensive

$\Rightarrow$ Extend Helac-Nlo functionality to produce NTuple

Fixed scale: $\mu_0 = m_t$

Dynamical scale: $\mu_0 = E_T/2$ and $\mu_0 = H_T/2$, with

$$E_T = \sqrt{p_T^2(t) + m_t^2} + \sqrt{p_T^2(\bar{t}) + m_t^2}$$

$$H_T = \sum_i p_T(i) + \not{p}_T \,, \qquad i = \{e^+, \mu^-, J_b, J_{\bar{b}}, j_1\}$$

PDF sets: CT14nlo, MMHT14, NNPDF3.0

Scale uncertainty from envelopes obtained from the following grid

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \{(0.5,0.5),(0.5,1),(1,0.5),(1,1),(1,2),(2,1),(2,2)\}$$

Setup for LHC 13 TeV - II

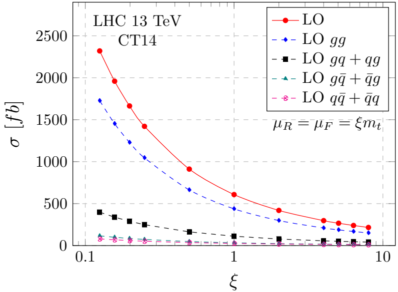
- SM parameters:

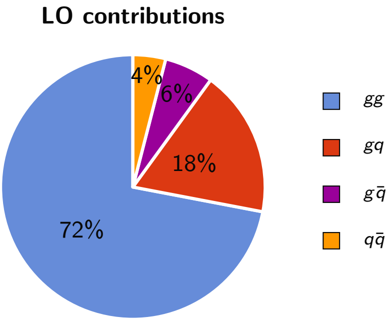
$$G_F = 1.16637 \cdot 10^{-5}\ \text{GeV}^{-2}\,, \qquad m_t = 173.2\ \text{GeV}\,,$$
$$m_W = 80.399\ \text{GeV}\,, \qquad \Gamma_W = 2.09875\ \text{GeV}\,,$$
$$m_Z = 91.1876\ \text{GeV}\,, \qquad \Gamma_Z = 2.50848\ \text{GeV}\,,$$
$$\Gamma_t^{LO} = 1.47834\ \text{GeV}\,, \qquad \Gamma_t^{NLO} = 1.35146\ \text{GeV}\,,$$

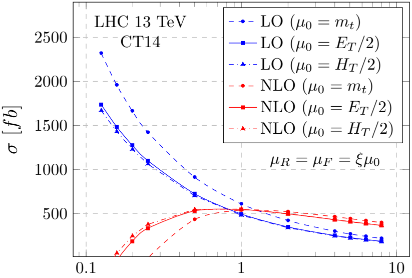
- Light quarks (also bottom) and leptons are massless
- Bottom induced channels are neglected (0.1% at LO)
- Final state: exactly 2 b-jets, at least 1 light jet,
  2 charged leptons, missing p_T
- Jets: partons with $|\eta| < 5$, anti-k_T, $\Delta R = 0.5$
- Cuts:

$$p_{T\,l} > 30\ \text{GeV}\,, \qquad p_{T\,j} > 40\ \text{GeV}\,, \qquad \not{p}_T > 40\ \text{GeV}\,,$$
$$\Delta R_{jj} > 0.5\,, \qquad \Delta R_{ll} > 0.4\,, \qquad \Delta R_{lj} > 0.4\,,$$
$$|y_l| < 2.5\,, \qquad |y_j| < 2.5\,,$$

Scale dependence







$\mu_0 = m_t$	$K = 0.88$	-12%
$\mu_0 = E_T/2$	$K = 1.10$	$+10\%$
$\mu_0 = H_T/2$	$K = 1.15$	$+15\%$

Theoretical uncertainties

- Same PDF, different scales

$$\sigma^{NLO}(CT14, \mu_0 = m_t) = 537.24^{+10.12\ (+2\%)}_{-190.35\ (-35\%)}\ [scales]\ fb$$

$$\sigma^{NLO}(CT14, \mu_0 = E_T/2) = 544.64^{+2.95\ (+1\%)}_{-117.47\ (-22\%)}\ [scales]\ fb$$

$$\sigma^{NLO}(CT14, \mu_0 = H_T/2) = 549.65^{+10.25\ (+2\%)}_{-53.42\ (-10\%)}\ [scales]\ fb$$

$\Rightarrow$ $\mu_0 = H_T/2$ yields smallest uncertainty $\sim 6\%$ (sym)

- Same scale, different PDFs

$$\sigma^{NLO}(CT14, \mu_0 = H_T/2) = 549.65^{+10.25\ (+2\%)}_{-53.42\ (-10\%)}\ [scales]^{+18.00\ (+3\%)}_{-19.15\ (-3\%)}\ [PDF]\ fb$$

$$\sigma^{NLO}(MMHT14, \mu_0 = H_T/2) = 554.61^{+10.85\ (+2\%)}_{-54.51\ (-10\%)}\ [scales]^{+12.06\ (+2\%)}_{-12.22\ (-2\%)}\ [PDF]\ fb$$

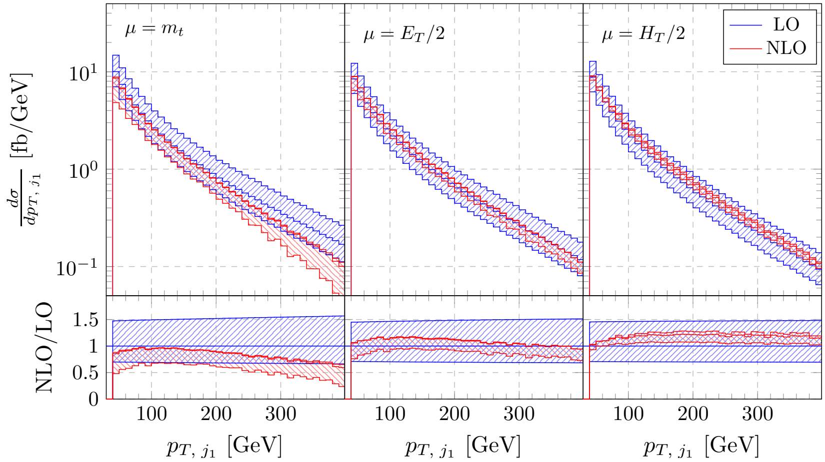
$$\sigma^{NLO}(NNPDF3.0, \mu_0 = H_T/2) = 572.18^{+11.14\ (+2\%)}_{-56.23\ (-10\%)}\ [scales]^{+11.31\ (+2\%)}_{-11.31\ (-2\%)}\ [PDF]\ fb$$

$\Rightarrow$ Scale uncertainty unaffected by PDFs

$\Rightarrow$ PDF uncertainty small $\sim 2 - 3\%$

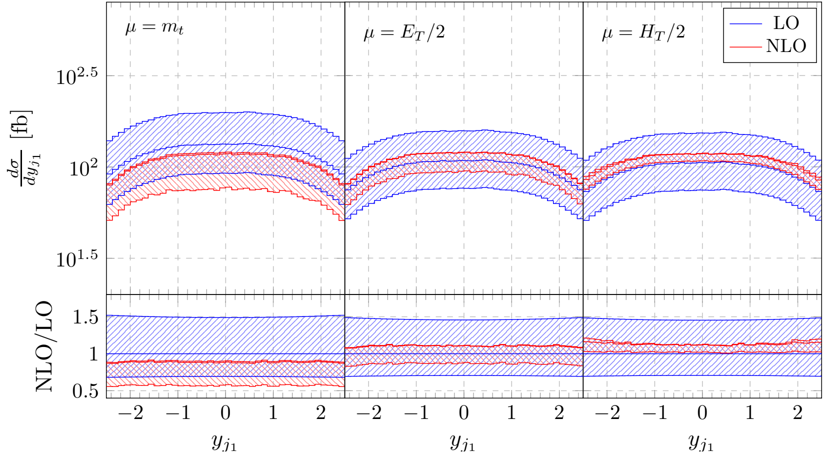
Fixed vs dynamical scale - I

Transverse momentum of hardest light jet

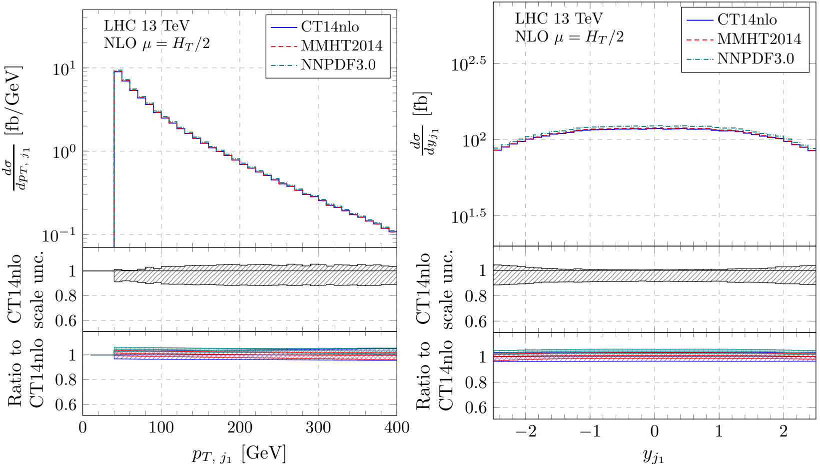


Fixed vs dynamical scale - II

Rapidity of hardest light jet



PDF Uncertainties



Scales $\sim$ 10%, PDF CT14 $\sim$ 5%

Conclusions

Summary:

✓ First description of $t\bar{t}j$ with all resonant and non-resonant contributions

✓ Comparison of fixed and dynamic scales: $m_t,\ E_T/2,\ H_T/2$
$\Rightarrow$ $H_T/2$ gives smaller uncertainty than $E_T/2$

✓ Scale and PDF uncertainties for σ and various $d\sigma/dX$

Work in Progess:

- Comparison of NWA vs full off-shell calculation
- Off-shell effects on the top mass extraction (m_t extraction from M_{be^+}, ρ)

Future studies:

✗ Impact of bottom-quark masses – 4 FS vs. 5 FS

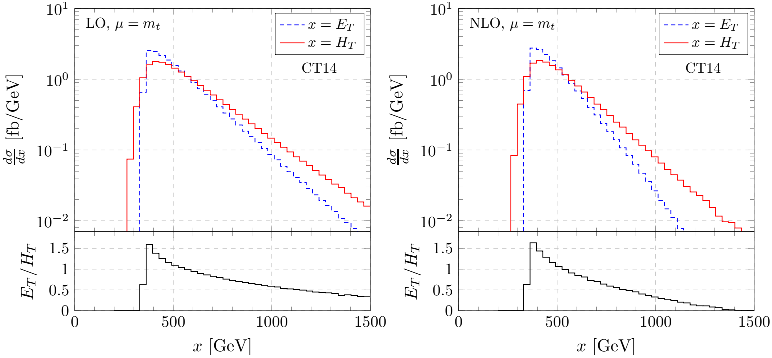
Backup

HelacNLO - Ntuples

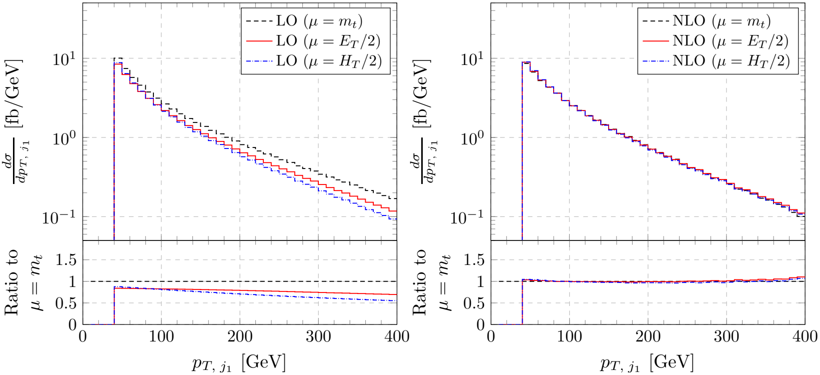
Generated Event samples for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}j + X$ used for reweighting

Contribution	Nr. of Events	Nr. of files	(avg) events/file	Size
Born	$21 \cdot 10^6$	60	$350 \cdot 10^3$	38 GB
Born + Virtual	$33 \cdot 10^6$	380	$87 \cdot 10^3$	72 GB
Int. dipoles	$80 \cdot 10^6$	450	$178 \cdot 10^3$	160 GB
Real subtracted	$626 \cdot 10^6$	18000	$35 \cdot 10^3$	1250 GB
Total:	$760 \cdot 10^6$	18890	$40 \cdot 10^3$	1520 GB

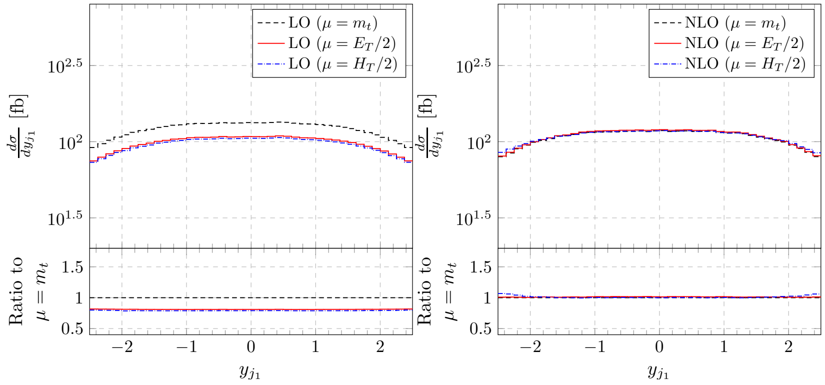
Comparison of the dynamical scales



Transverse momentum of hardest light jet



Rapidity of hardest light jet



Scale dependence