Deutsche Forschungsgemeinschaft

Off-shell ttj Production

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XXIII Cracow Epiphany Conference,
Particle Theory Meets the First Data from LHC Run 2, 9-12 January 2017

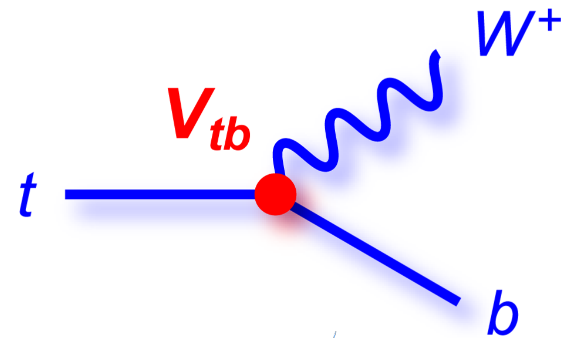
Plan

1. Motivation
2. Top-quark off-shell effects
3. Status of theoretical predictions for ttj
4. Top-quark off-shell effects with **HELAC–NLO**
5. Results for ttj in dilepton channel @ LHC Run 2
6. Summary & Outlook

Collaborators:

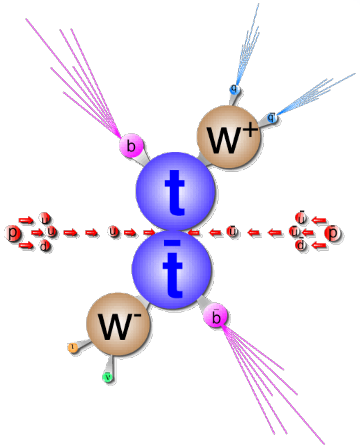
G. Bevilacqua (University of Debrecen)
H. B. Hartanto (University of Durham)
M. Kraus (Humboldt-Universität zu Berlin)

Top-Quark Physics



- Top-quark pair production at the LHC
  - NNLO+NNLL for **σ (tt) with on-shell top-quarks**
  - NNLO for differential cross sections **dσ (tt) /dX**

Czakon, Fiedler, Mitov '13
Czakon, Heymes, Mitov '16



- Infrared structure of QCD
- Extract parameters of the SM: α_s & m_t
- Constraints on the large-x gluon PDF

Czakon, Mangano, Mitov, Rojo '13
Czakon, Hartland, Mitov, Nocera, Rojo '16

- Background process to various SM & BSM physics

Motivation For ttj

- @ LHC tops are produced with large energies & high transverse momenta
- Increase probability for additional (hard) radiation of gluons → ttj final state
- How big is the contribution of ttj in the inclusive tt sample ?

- NLO on-shell **tt & ttj** productions for **m_t = 173.2 GeV @ $\mathrm{LHC}_{13\ \mathrm{TeV}}$** with **CT14**

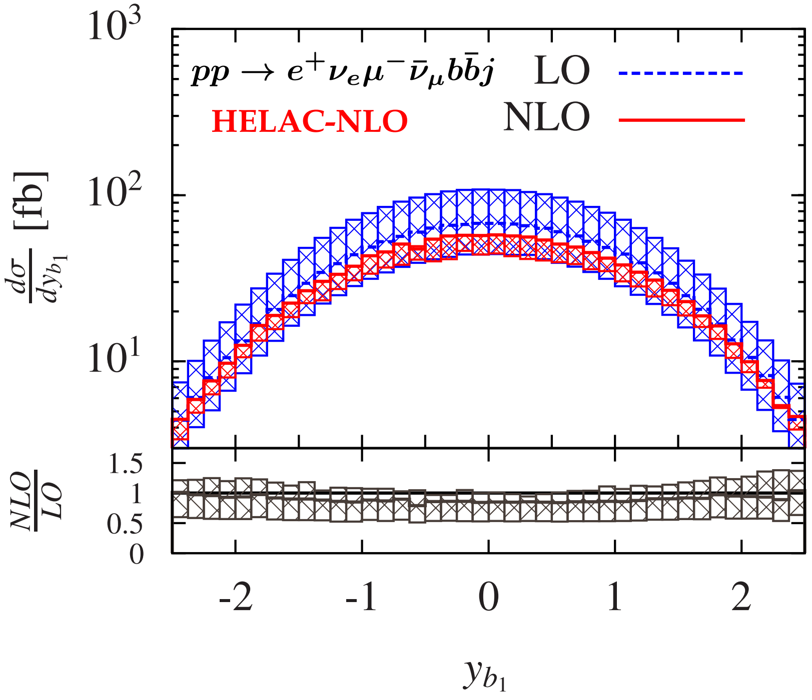
σ (tt) = 715.58 pb

Jet p_T cut [GeV]	σ (ttj) [pb]	σ (ttj)/σ (tt) [%]
40	296.97 ± 0.29	41
60	207.88 ± 0.19	29
80	152.89 ± 0.13	21
100	115.60 ± 0.14	16
120	89.05 ± 0.10	12

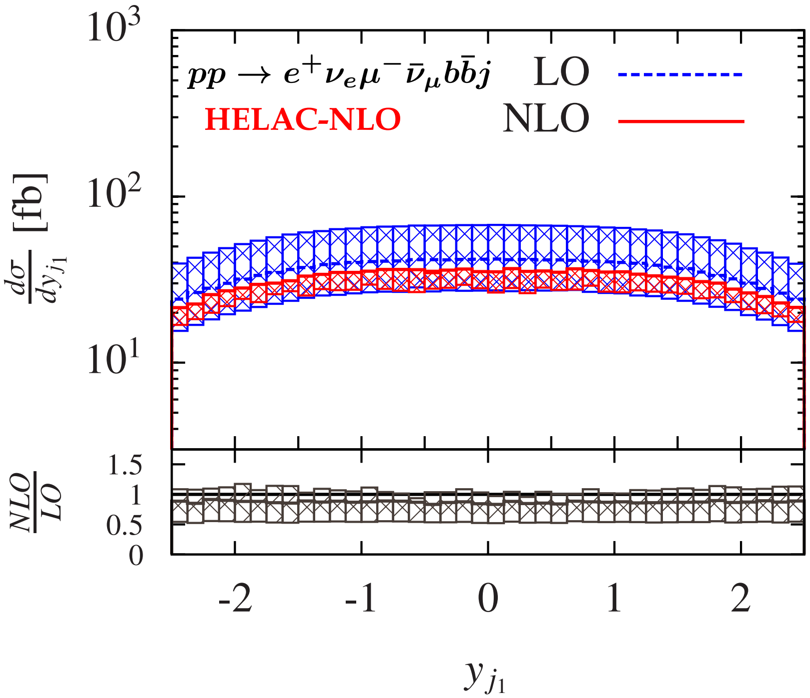
HELAC-NLO, G. Bevilacqua et al. '13

Motivation For ttj

- Background to SM Higgs production in VBF: $qq \rightarrow Hqq \rightarrow W^+W^-qq$
- 2 tagging jets: $\Delta y_{j_1 j_2} = |y_{j_1} - y_{j_2}| > 4 \;\; \& \;\; y_{j_1} \times y_{j_2} < 0$
- ⬇ **tt background:** tt → WWbb & ⬆ **ttj background:** ttj → WWbbj



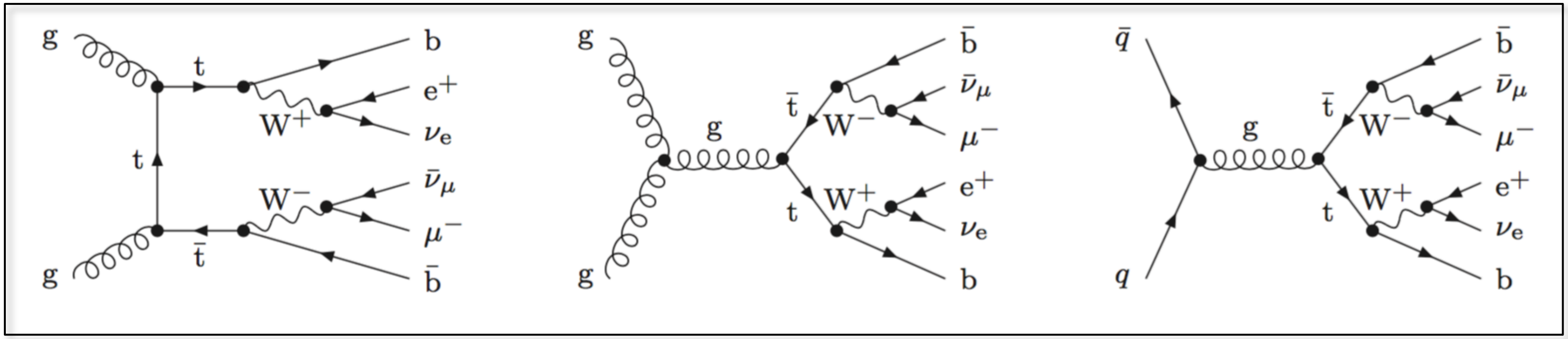
b-jets distributed centrally



light-jet spans a broader range

NWA & Off-Shell Effects

- NWA for $pp \to t\bar{t}$ → Tops are restricted to on-shell states
- Approximation is controlled by the ratio: $\Gamma_t/m_t \approx 10^{-2}$
- Contributions from diagrams involving two top-quark resonances

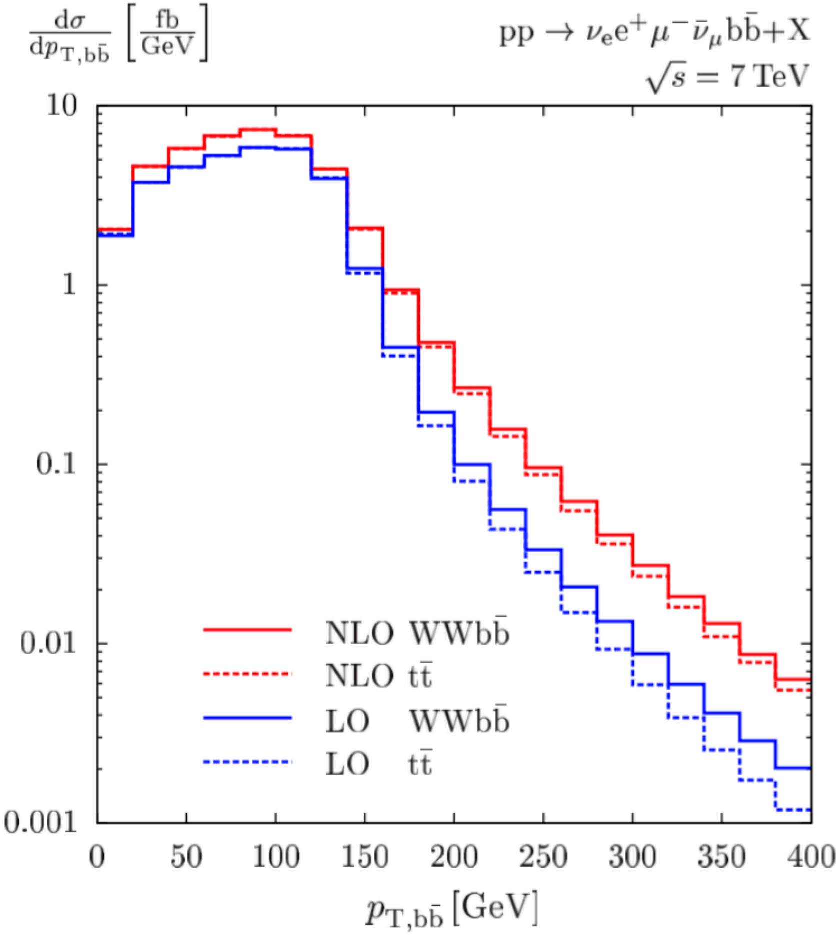


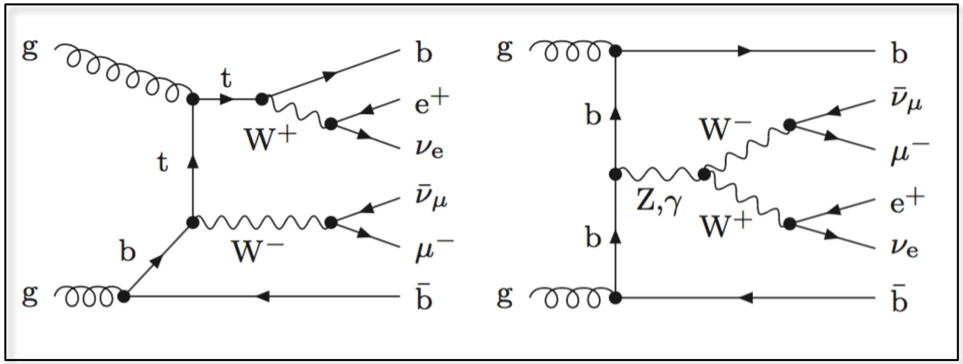
- Should be ccurate for sufficiently inclusive observables
- Indeed → **top-quark off-shell effects for σ at few % level**

✧ **pp → tt**	*A. Denner et al. ’11, G. Bevilacqua et al. ’11, A. Denner et al. ‘12* *R. Frederix ’14, F. Cascioli et al. ’14, G. Heinrich et al ‘14 , A. Denner et al. ‘16*
✧ **pp → ttH**	*A. Denner, R. Feger ’15*
✧ **pp → ttj**	*G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek ’16*

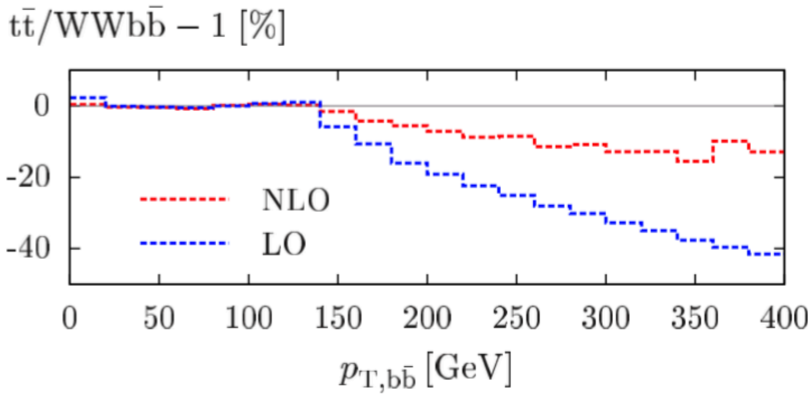
NWA & Off-Shell Effects

- Not the case for differential cross sections even for inclusive setup
- **Full NWA (tt)** versus **full calculation (WWbb)** for **p_T(bb)**





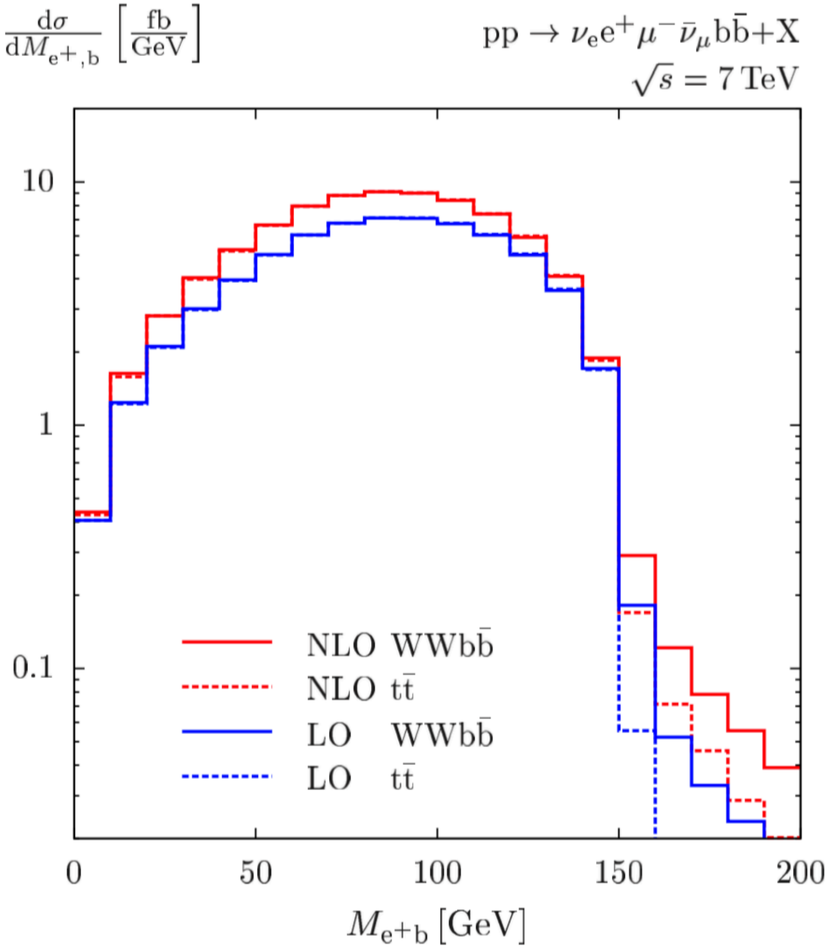
…also diagrams with one or no top-quark resonances



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

NWA & Off-Shell Effects

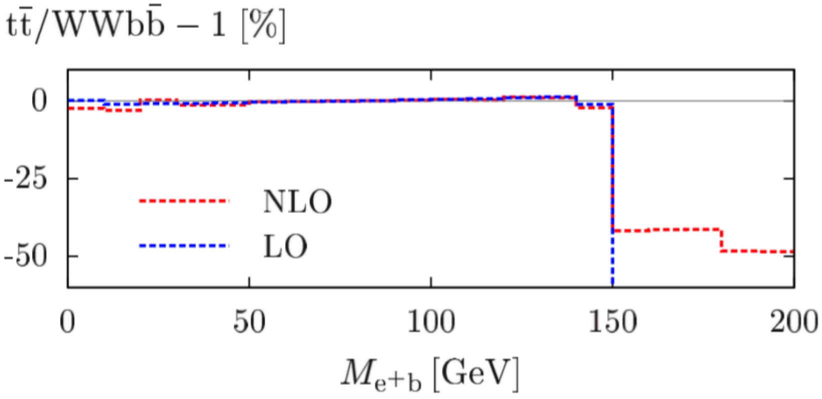
- Not the case for differential cross sections even for inclusive setup
- **Full NWA (tt)** versus **full calculation (WWbb)** for M_{e+b}



- If top and W decay on-shell @ LO
  → end-point given by sharp cut

$$M_{e+b} = \sqrt{m_t^2 - m_W^2} \approx 152\ \mathrm{GeV}$$

- Additional radiation & off-shell effects introduce smearing



A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze ‘12

Theoretical Predictions For ttj

- NLO QCD corrections to on-shell ttj production

  S. Dittmaier, P. Uwer, S. Weinzierl '07 '09

- NLO QCD correction to on-shell ttj production with LO decays

  K. Melnikov, M. Schulze '10

- NLO QCD corrections to ttj in NWA (with jet radiation in top-quark decays)

  K. Melnikov, M. Schulze '12

- NLO QCD corrections to ttj with full top-quark and W off-shell effects

  G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

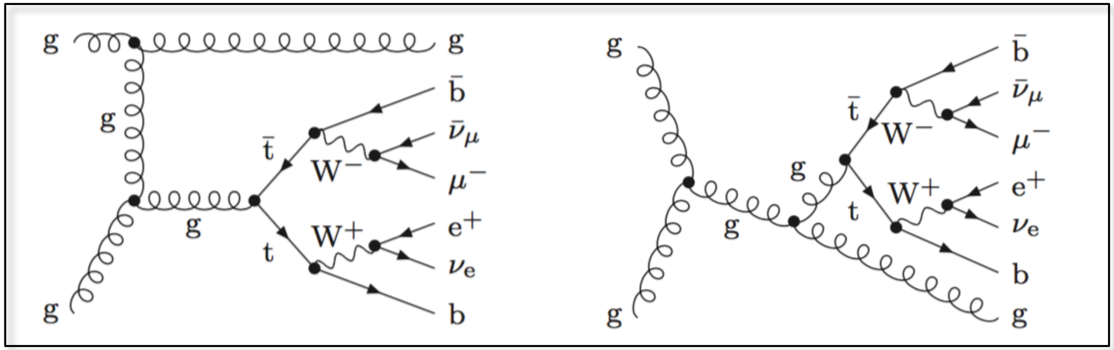
- NLO QCD correction to on-shell ttj production + PS
  - ✧ **POWHEG + PYTHIA** → no spin correlations

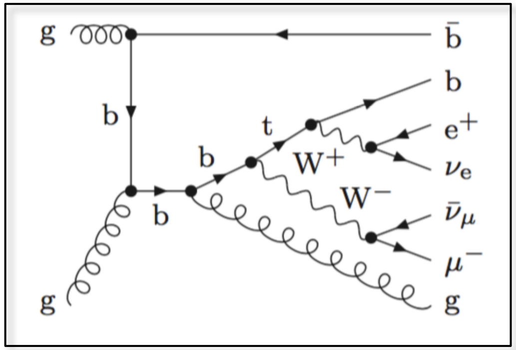
    A. Kardos, C. G. Papadopoulosa, Z. Trocsanyi '11
  - ✧ **POWHEG + PYTHIA/HERWIG** → with spin-correlations @ LO

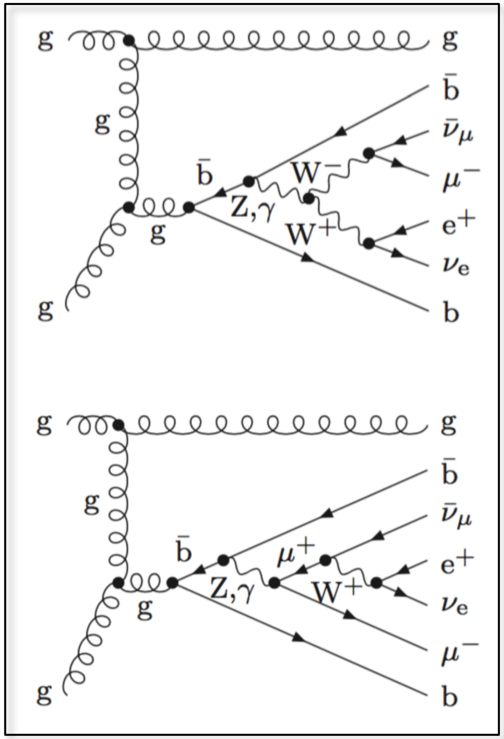
    S. Alioli, S.Moch, P. Uwer '12
  - ✧ **MC@NLO + DEDUCTOR** → without top-quark decays

    M. Czakon, H. B. Hartanto, M. Kraus, M. Worek '15

Off-Shell Effects For ttj







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

- ttj with leptonic decays at $\mathcal{O}(\alpha_s^4\alpha^4)$
- 2 → 5 process from the QCD point of view (WWbbj)
- Diagrams with complete off-shell effects for top quarks & W gauge boson for **gg initial state**:
  - ✧ **LO: 508**
  - ✧ **Real emission: 4447**

Off-Shell Effects For ttj

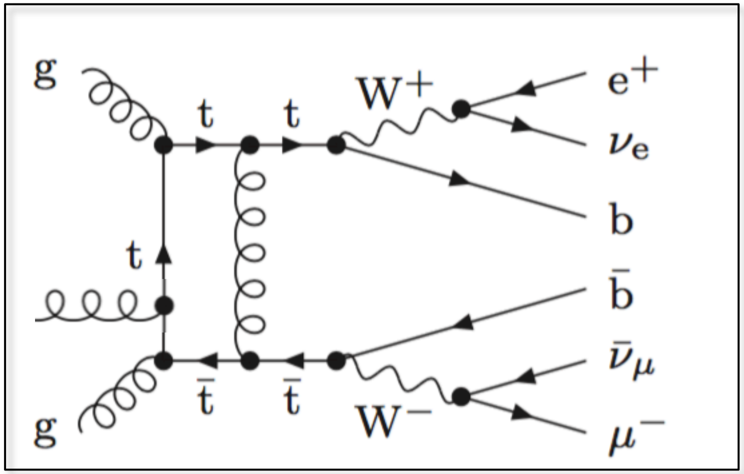
- **gg channel comprises 39 180 one-loop diagrams** → according to **QGRAF**

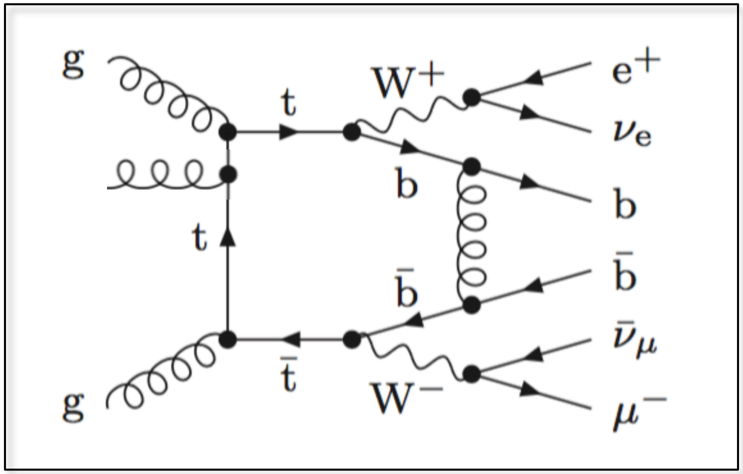
P. Nogueira '93

- The most complicated ones are **1155 hexagons & 120 heptagons**
- Tensor integrals up to rank six

NWA for ttj (on-shell top-quark production) – up to pentagons !

Full calculations for ttj – up to heptagons !





Intermediate Top Resonances

- Putting simply $\Gamma_t \neq 0$ violates gauge invariance
- **Gauge-invariant treatment → complex-mass scheme**
- Γ_t → incorporated into top mass via:

$$\mu_t^2 = m_t^2 - i\, m_t \Gamma_t$$

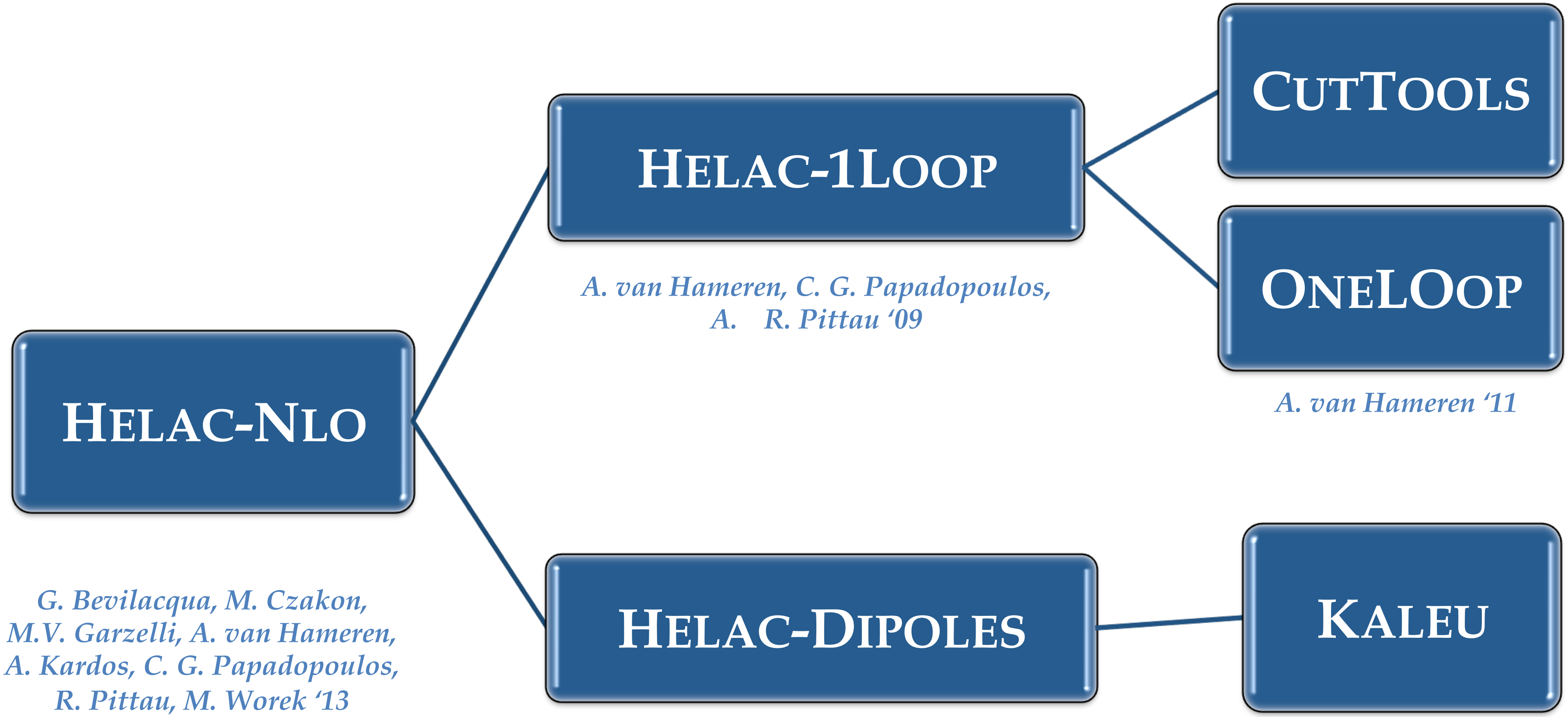
A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99
A. Denner, S. Dittmaier, M. Roth, L. H. Wieders '05

- All matrix elements evaluated using complex masses
- μ_t^2 → identified with the position of pole of top-quark propagator
- Top-mass counter-term $\delta\mu_t$ related to top-quark self-energy at: $p_t^2 = \mu_t^2$

- **Another non trivial aspect**: evaluation of one-loop scalar integrals !
- Scalar integrals with complex masses → supported e.g. by **ONELOOP**

A. van Hameren '11

HELAC-NLO



HELAC-NLO

G. Bevilacqua, M. Czakon,
M.V. Garzelli, A. van Hameren,
A. Kardos, C. G. Papadopoulos,
R. Pittau, M. Worek ‘13

HELAC-1LOOP

A. van Hameren, C. G. Papadopoulos,
A. R. Pittau ‘09

CUTTOOLS

G. Ossola, C. G. Papadopoulos,
R. Pittau ‘08

ONELOOP

A. van Hameren ‘11

HELAC-DIPOLES

M. Czakon, C. G. Papadopoulos, M. Worek ’09
G. Bevilacqua, M. Czakon, M. Kubocz, M. Worek ‘13

KALEU

A. van Hameren ‘10

Setup

- Different lepton generations: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$
  - ✧ $\gamma^* \to \ell^\pm\ell^\mp$ **interference effects neglected → per-mille level @ LO**
  - ✧ Feynman Diagrams for gg initial state @ LO:

    $$\text{508 for } e^+\mu^- \longrightarrow \text{1240 for } e^+e^-$$

- **Top width for unstable W bosons, neglecting bottom quark mass**

- All light quarks including **b-quarks** and leptons **are massless**
- **Contribution from b quarks** in the initial state **neglected → effect < 1% @ LO**

- **Jets:** Final-state quarks and gluons with pseudo-rapidity **|y| < 5** recombined into jets using **anti-k_T jet** algorithm with **R = 0.5**

- **Requirement:** exactly 2 b-jets, at least one light-jet, 2 charged leptons, and missing p_T → fairly inclusive cuts with $p_T(j) > 40$ GeV

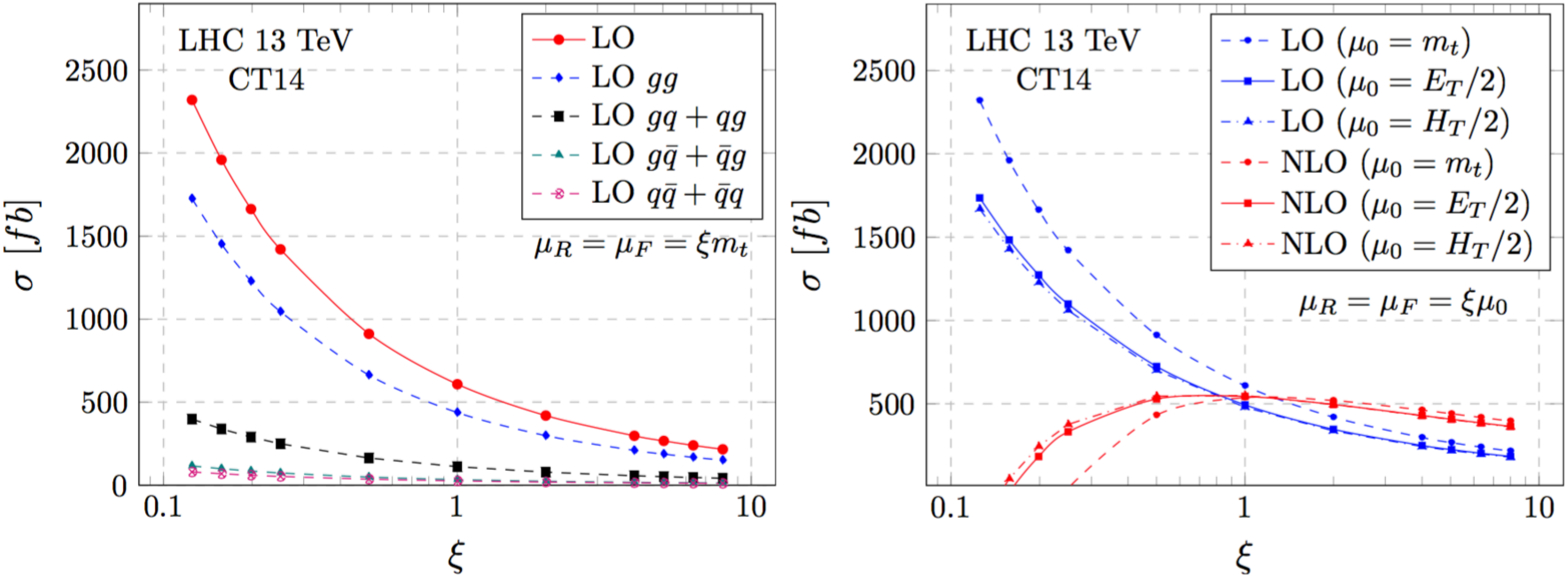
Scale Dependence

- Total cross section **@ LHC $_{\mathbf{13\ TeV}}$**
- Scales:

$$\boldsymbol{\mu_R = \mu_F = \mu_0 = m_t,\ E_T/2,\ H_T/2}$$

$$\boldsymbol{H_T = \sum_i p_{T,\,i} + p_T^{\text{miss}}}$$

$$\boldsymbol{E_T = m_{T,\,t} + m_{T,\,\bar{t}}}$$



- LO contributions: $\boldsymbol{gg : 72\%,\ gq : 18\%,\ g\bar{q} : 6\%,\ q\bar{q} : 4\%}$

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

Theoretical Uncertainties

- Size of NLO corrections for CT14 NLO

$\mu_0 = m_t$	$\mathcal{K} = 0.88$	$-\ 12\%$
$\mu_0 = E_T/2$	$\mathcal{K} = 1.10$	$+\ 10\%$
$\mu_0 = H_T/2$	$\mathcal{K} = 1.12$	$+\ 12\%$

$$1/2\mu_0 \le \mu_R,\ \mu_F \le 2\mu_0$$

$$1/2 \le \mu_R/\mu_F \le 2$$

- PDFs: **CT14, MMHT14, NNPDF3.0**
- Total cross sections for $\mu_0 = H_T/2$

68% C.L.

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14}, \mu_0 = H_T/2) = 549.65^{+10.25\ (+2\%)}_{-53.42\ (-10\%)}\ [\text{scales}]\ {}^{+18.00\ (+3\%)}_{-19.15\ (-3\%)}\ [\text{PDF}]\ \text{fb}$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm MMHT14}, \mu_0 = H_T/2) = 554.61^{+10.85\ (+2\%)}_{-54.51\ (-10\%)}\ [\text{scales}]\ {}^{+12.06\ (+2\%)}_{-12.22\ (-2\%)}\ [\text{PDF}]\ \text{fb}$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm NNPDF3.0}, \mu_0 = H_T/2) = 572.18^{+11.14\ (+2\%)}_{-56.23\ (-10\%)}\ [\text{scales}]\ {}^{+11.31\ (+2\%)}_{-11.31\ (-2\%)}\ [\text{PDF}]\ \text{fb}$$

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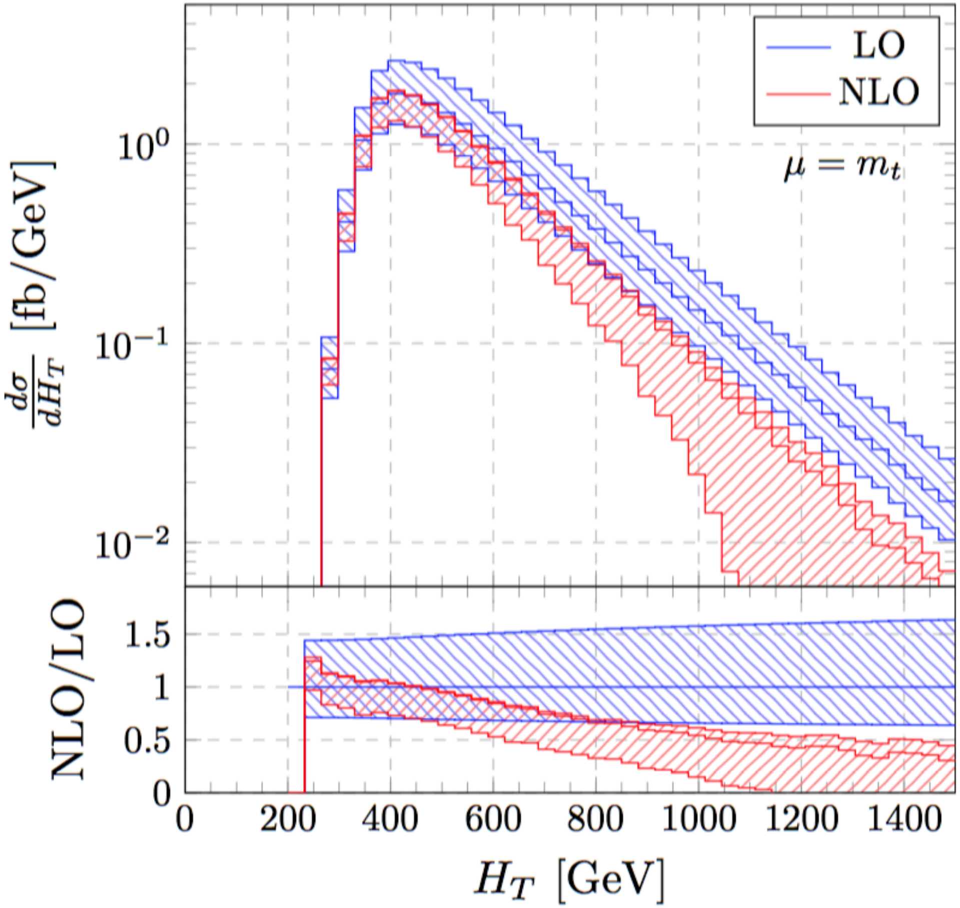
Total Transverse Energy

- 16 differential cross sections have been examined, here are just two examples…
- **Dimensionful observable: H_T with $\mu_0 = m_t$**



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

- NLO do not rescale shape of LO
- NLO corrections up to **-70%**
- Properly described only via NLO
- Negative NLO in p_T tails
  → LO higher than NLO

- The dynamic scale should depend on p_T of hardest jet and/or top decay products ↑
- Asymptotic freedom → α_s ↓ in tails
- Dependence on α_s @ LO >> @ NLO
- Would drive positive NLO/LO ratio in this region

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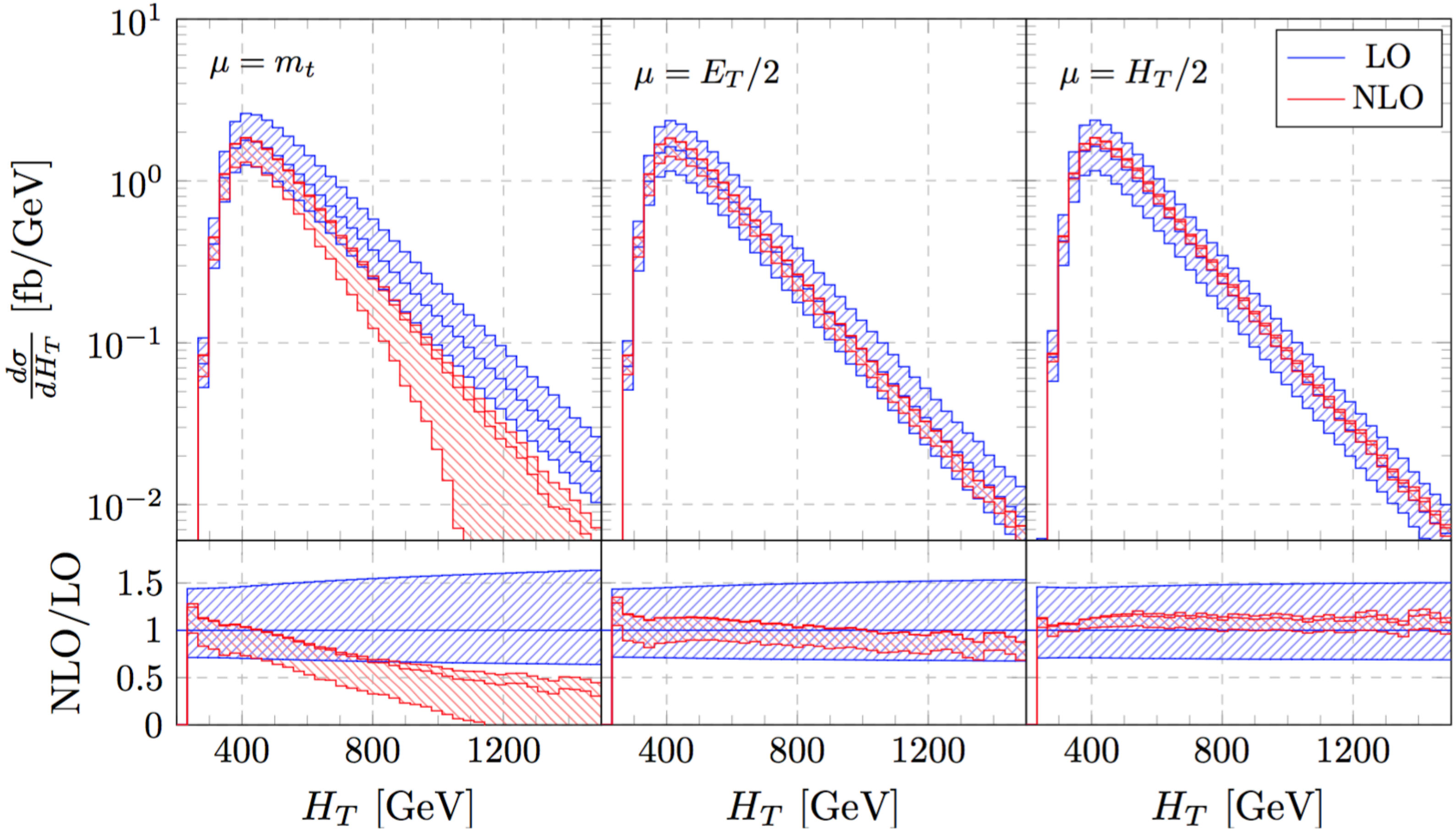
Total Transverse Energy

- 16 differential cross sections have been examined, here are just some examples…
- Dimensionful observable: H_T with all 3 scales

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



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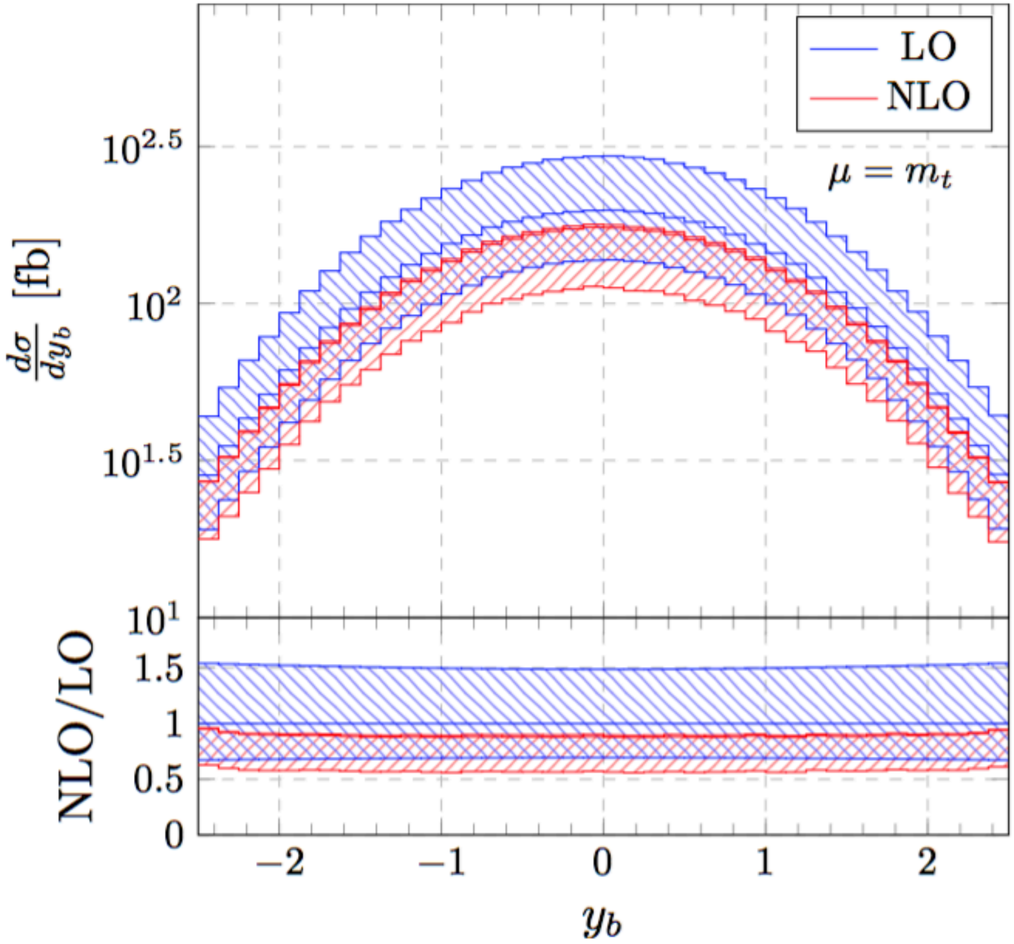
b-Jet Rapidity

- **Dimensionless observable: y_b with $\mu_0 = m_t$**

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



- Negative, moderate but … quite stable NLO corrections
- Receives contributions from various scales → also from these sensitive to threshold for tt production
- For $\mu_0 = m_t$ effects of phase-space regions close to ttj threshold dominate

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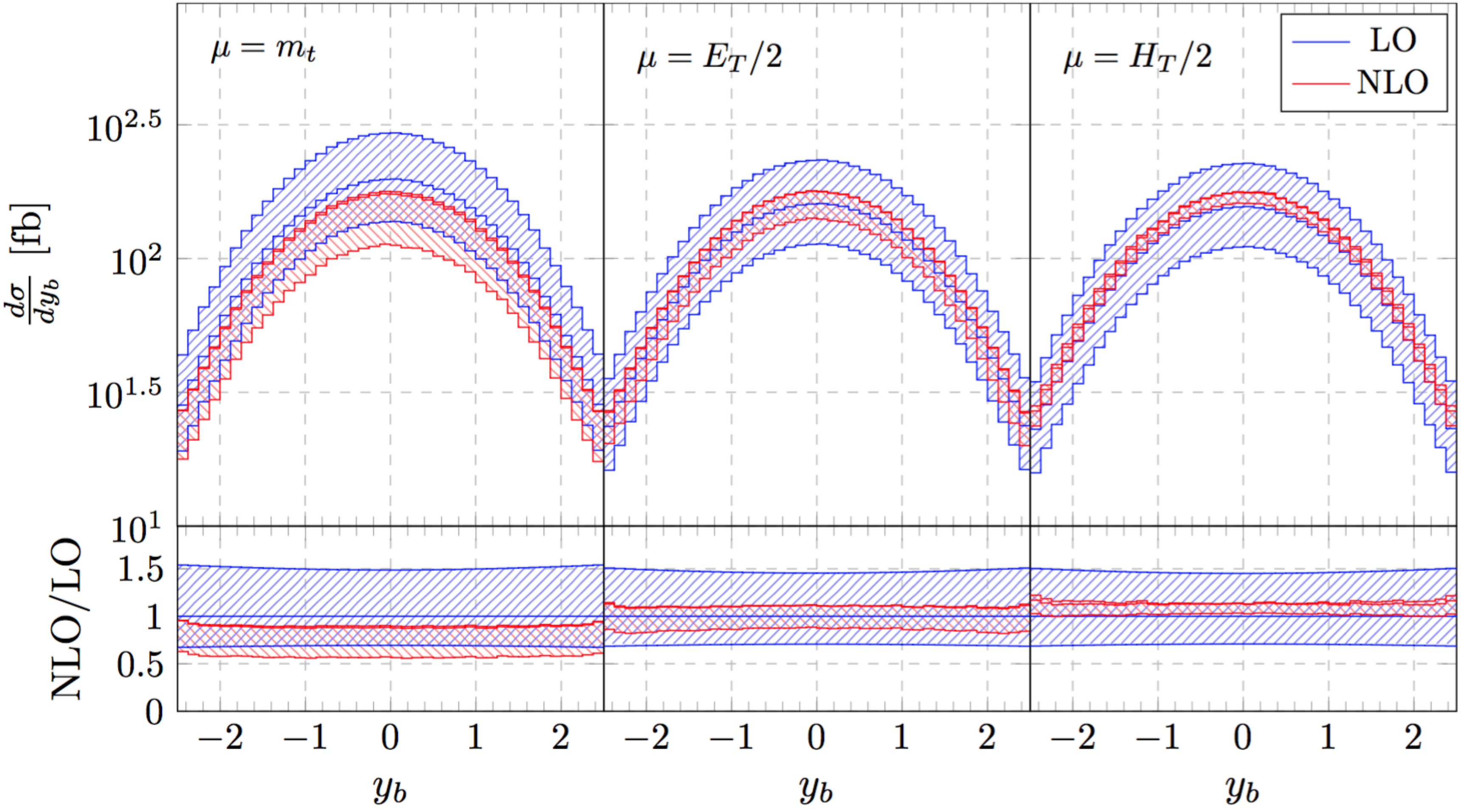
b-Jet Rapidity

- Dimensionless observable: y_b

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



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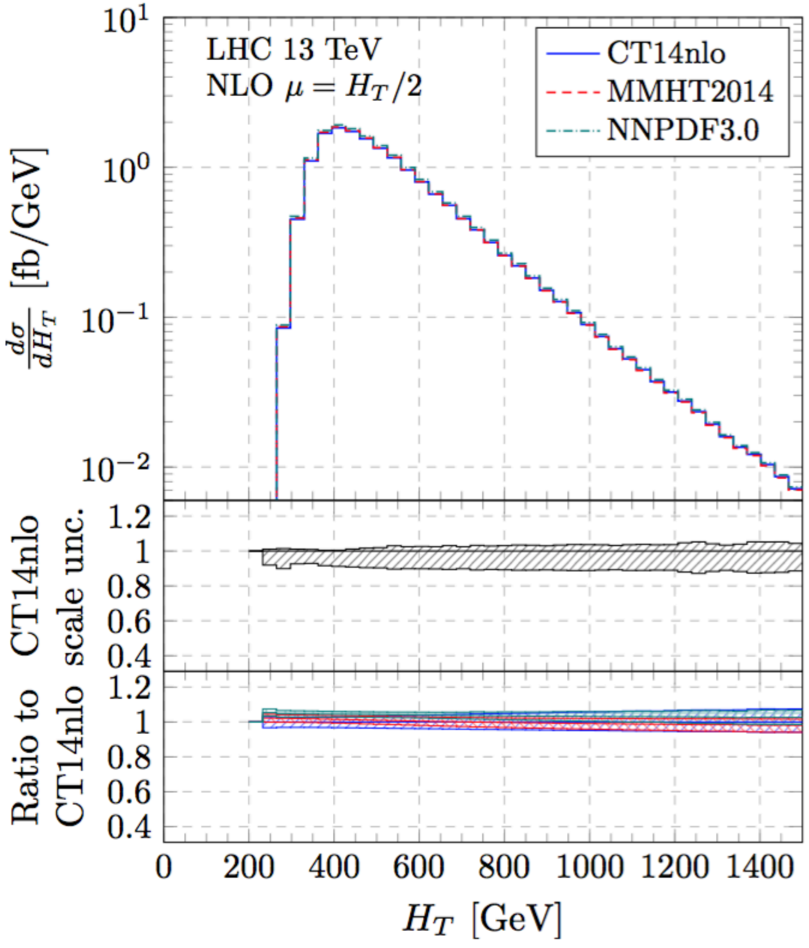
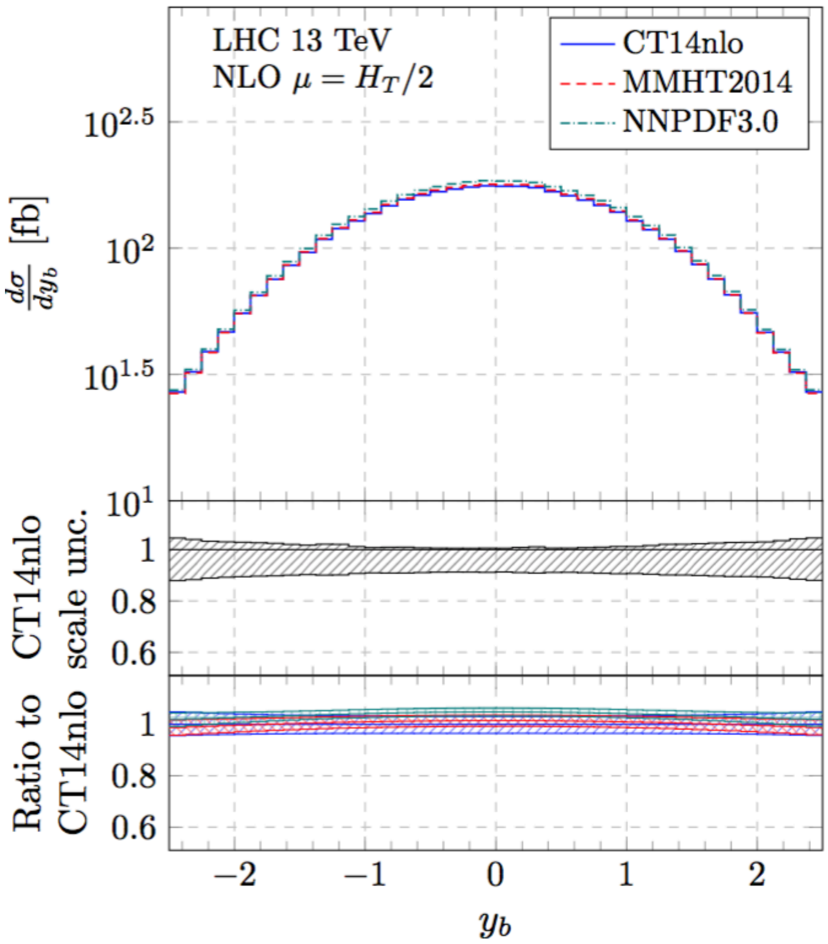
Uncertainties



Scales < 10% & PDF CT14 ~ 7%



Scales < 10% & PDF CT14 ~ 5%

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Applications

- Alternative method for m_t
- m_t from normalized differential cross section for ttj

S. Alioli, et al. '13

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s),$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}},$$

- $\mathcal{R}$ has been calculated using ttj @ NLO + **POWHEG** matched with **PYTHIA**

- Theoretical uncertainties & PDF uncertainties affect m_t extraction ~ 1 GeV

- **For now:**
  - ✧ **ATLAS @ 7 TeV: $m_t = 173.7 \pm 2.3$ GeV** *ATLAS, arXiv:1507.01769 (July 2015)*
  - ✧ **CMS @ 8 TeV: $m_t = 169.9 \pm 3.9$ GeV** *CMS-PAS-TOP-13-006 (May 2016)*

- Worth looking at with complete off-shell effects…

Summary

- Complete description for ttj process with **HELAC-NLO**
  - ✧ "resonant" and "non-resonant" contributions at NLO QCD

- Various scales: **m_t & $E_T/2$ & $H_T/2$**
- **$H_T/2$** "better" than $E_T/2$ → both stabilizes tails but **$H_T/2$** gives the smallest error

- Scale and PDF uncertainties for σ & and various dσ/dX

- Further studies are needed:
  - ✧ Bottom-mass effects → comparisons between Five- & Four-Flavour schemes
  - ✧ Off-shell versus NWA effects for differential distributions

- Phenomenological applications → Alternative method for m_t extraction
  - ✧ Shape-based m_t measurement (M_{e+b} and/or ρ_s) relies on precise modeling of top-quark decays
  - ✧ Goal: m_t extraction ~ 1 GeV
  - ✧ Predictions should go beyond simple approximation of factorizing top quark production & decays

Backup Slides

Inclusive Selection Cuts

$$p_{T,\ell} > 30 \text{ GeV}\,, \qquad p_{T,j} > 40 \text{ GeV}\,,$$

$$\not\!p_T > 40 \text{ GeV}\,, \qquad \Delta R_{jj} > 0.5\,,$$

$$\Delta R_{\ell\ell} > 0.4\,, \qquad \Delta R_{\ell j} > 0.4\,,$$

$$|y_\ell| < 2.5\,, \qquad |y_j| < 2.5\,,$$

$$p_{T,i} = \sqrt{p_{x,i}^2 + p_{y,i}^2}\,,$$

$$y_i = \frac{1}{2}\ln\left(\frac{E_i + p_{z,i}}{E_i - p_{z,i}}\right)\,,$$

$$\Delta R_{ik} = \sqrt{\Delta\phi_{ik}^2 + \Delta y_{ik}^2}\,.$$

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Scale & PDF Uncertainties

$$\sigma^{\rm LO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}(\mathrm{CT14}, \mu_0 = m_t) = 608.09^{+303.52\ (+50\%)}_{-188.85\ (-31\%)}\ [\mathrm{scales}]\ \mathrm{fb}\,,$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}(\mathrm{CT14}, \mu_0 = m_t) = 537.24^{+10.12\ (+2\%)}_{-190.35\ (-35\%)}\ [\mathrm{scales}]\ ^{+17.32\ (+3\%)}_{-18.34\ (-3\%)}\ [\mathrm{PDF}]\ \mathrm{fb}\,.$$

$$\sigma^{\rm LO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}(\mathrm{CT14}, \mu_0 = E_T/2) = 493.54^{+230.40\ (+47\%)}_{-147.02\ (-30\%)}\ [\mathrm{scales}]\ \mathrm{fb}\,,$$

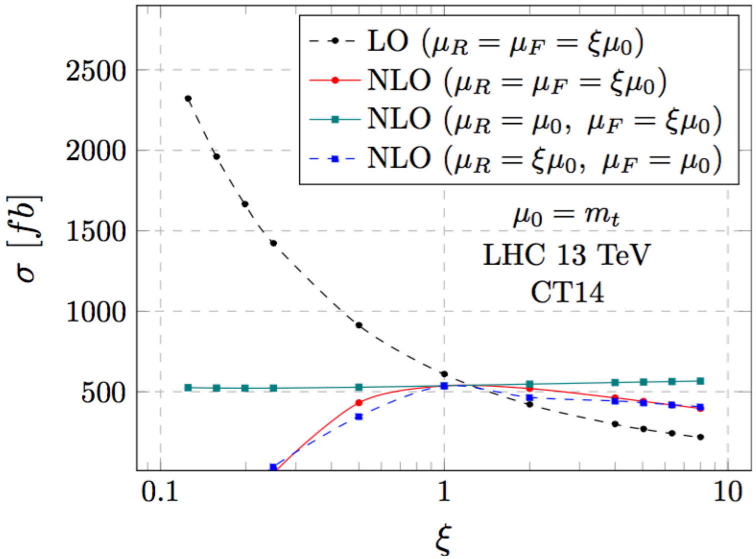
$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}(\mathrm{CT14}, \mu_0 = E_T/2) = 544.64^{+2.95\ (+1\%)}_{-117.47\ (-22\%)}\ [\mathrm{scales}]\ ^{+18.10\ (+3\%)}_{-18.92\ (-3\%)}\ [\mathrm{PDF}]\ \mathrm{fb}\,.$$

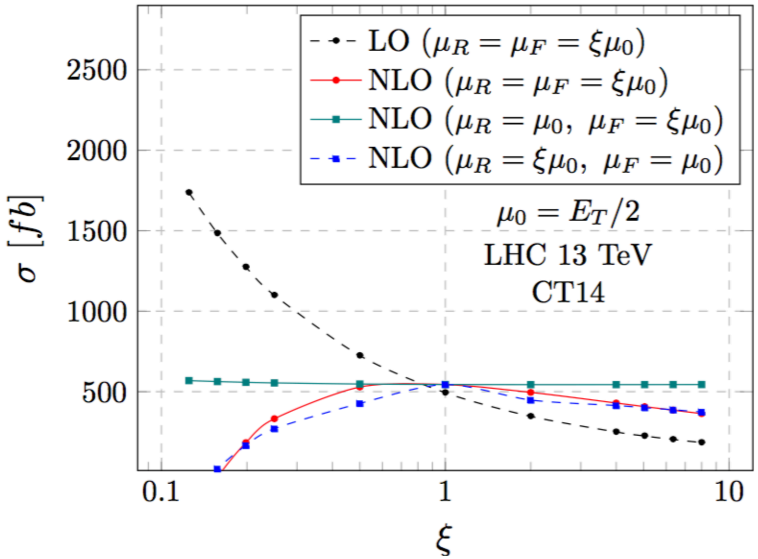
$$\sigma^{\rm LO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}(\mathrm{CT14}, \mu_0 = H_T/2) = 479.38^{+221.91\ (+46\%)}_{-142.05\ (-30\%)}\ [\mathrm{scales}]\ \mathrm{fb}\,,$$

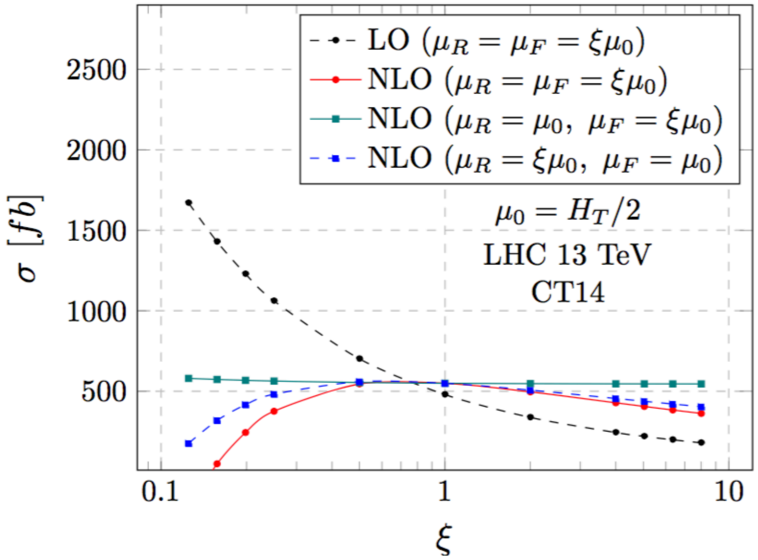
$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}(\mathrm{CT14}, \mu_0 = H_T/2) = 549.65^{+10.25\ (+2\%)}_{-53.42\ (-10\%)}\ [\mathrm{scales}]\ ^{+18.00\ (+3\%)}_{-19.15\ (-3\%)}\ [\mathrm{PDF}]\ \mathrm{fb}$$

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek ‘16

Scale Dependence







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Ntuple

- Number of events, number of files, averaged number of events per file & total size per contribution for the different Ntuple samples

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

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

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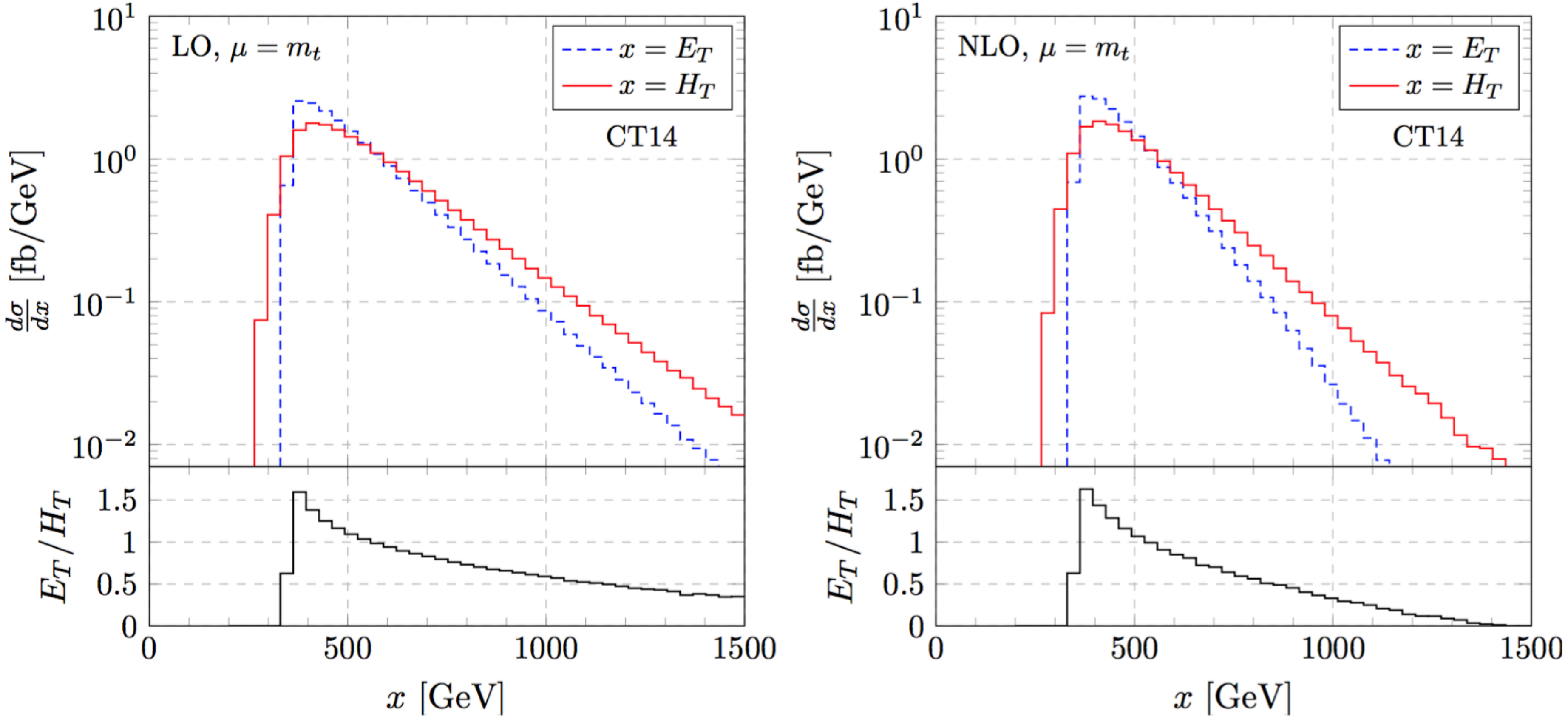
E_T Versus H_T

- E_T and H_T @ LO & @ NLO as well as E_T / H_T ratio for $\mu_0 = m_t$

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



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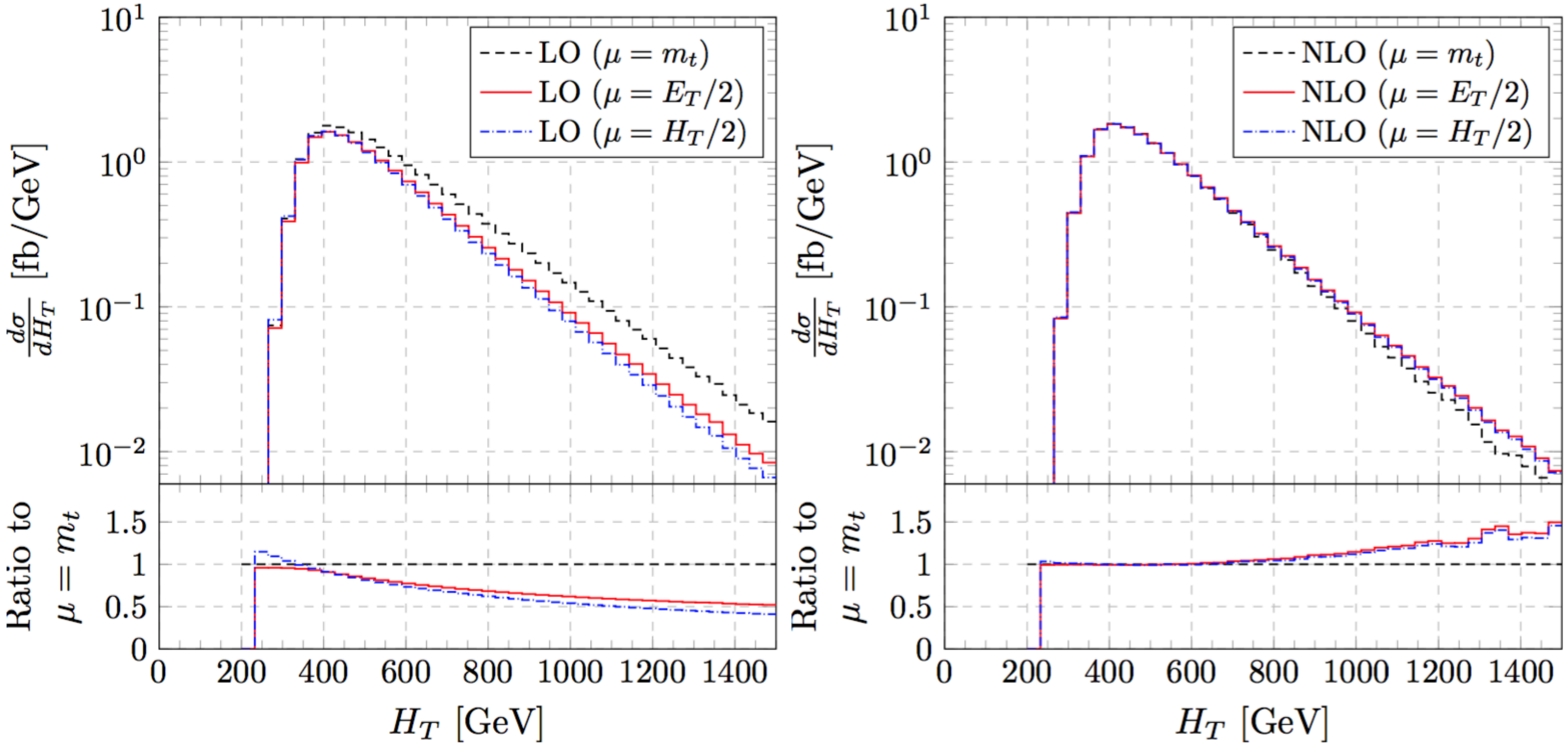
Total Transverse Energy

- Central values & ratios to the fixed scale @ LO & @ NLO

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



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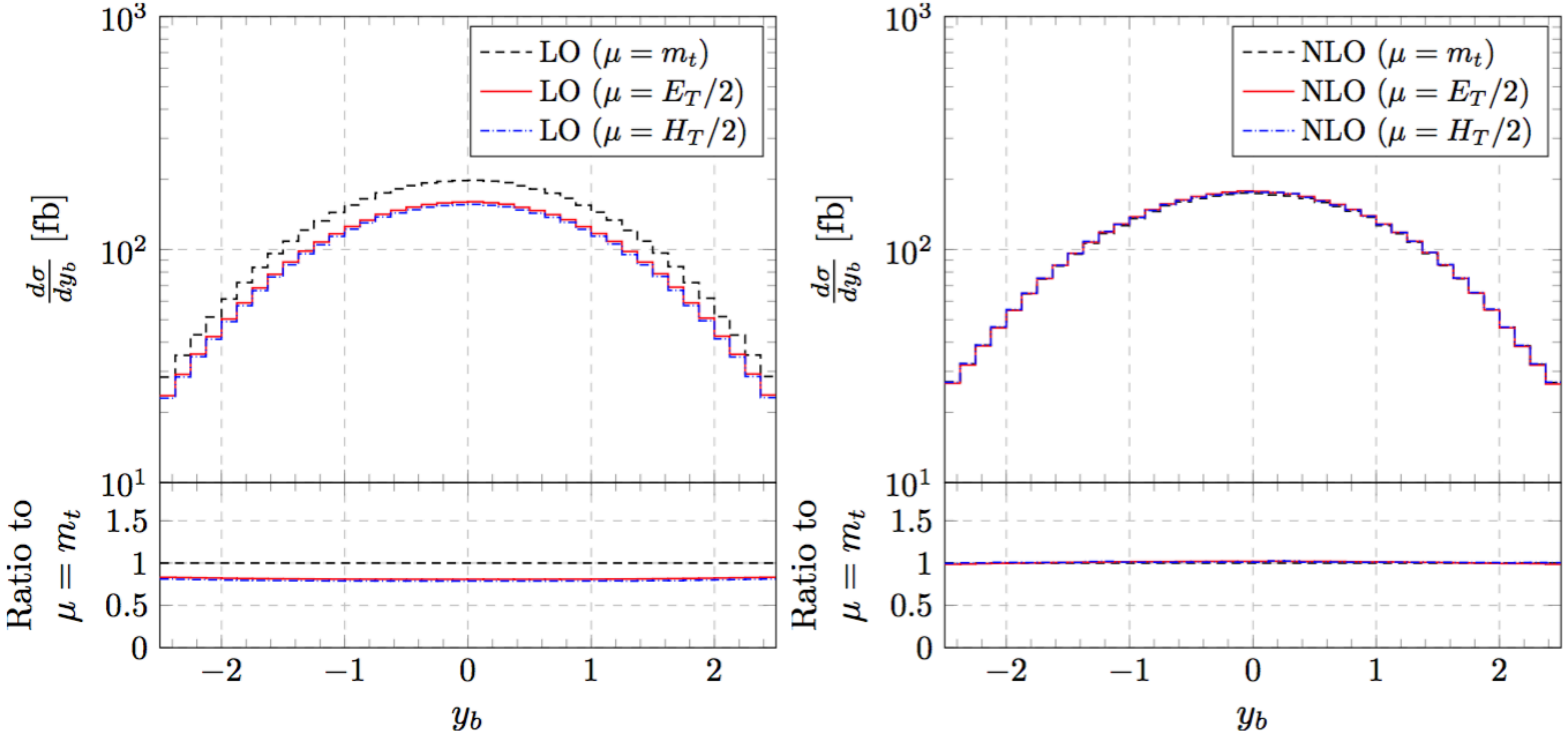
b-Jet Rapidity

- Central values & ratios to the fixed scale @ LO & @ NLO

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



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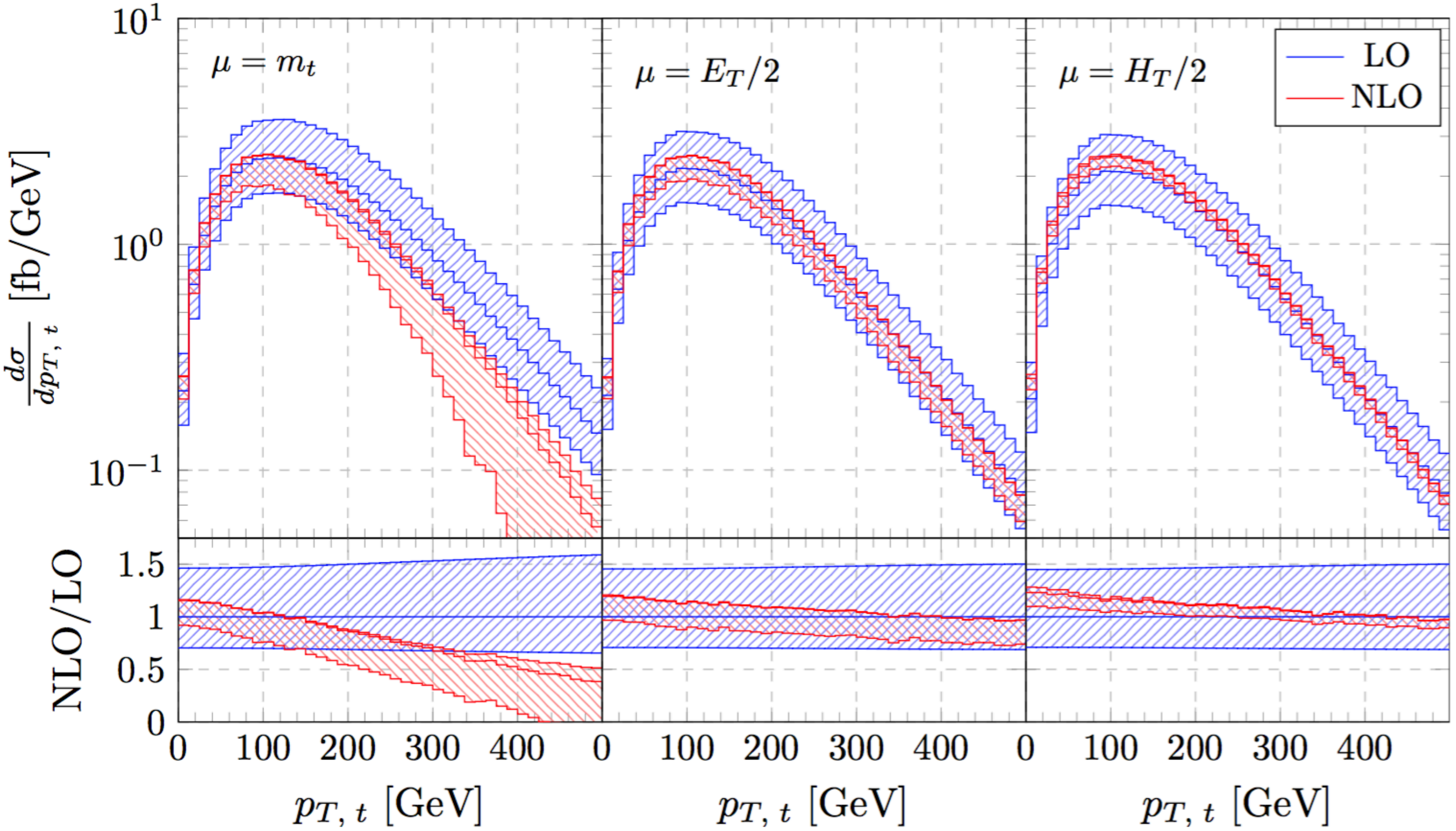
Top Quark



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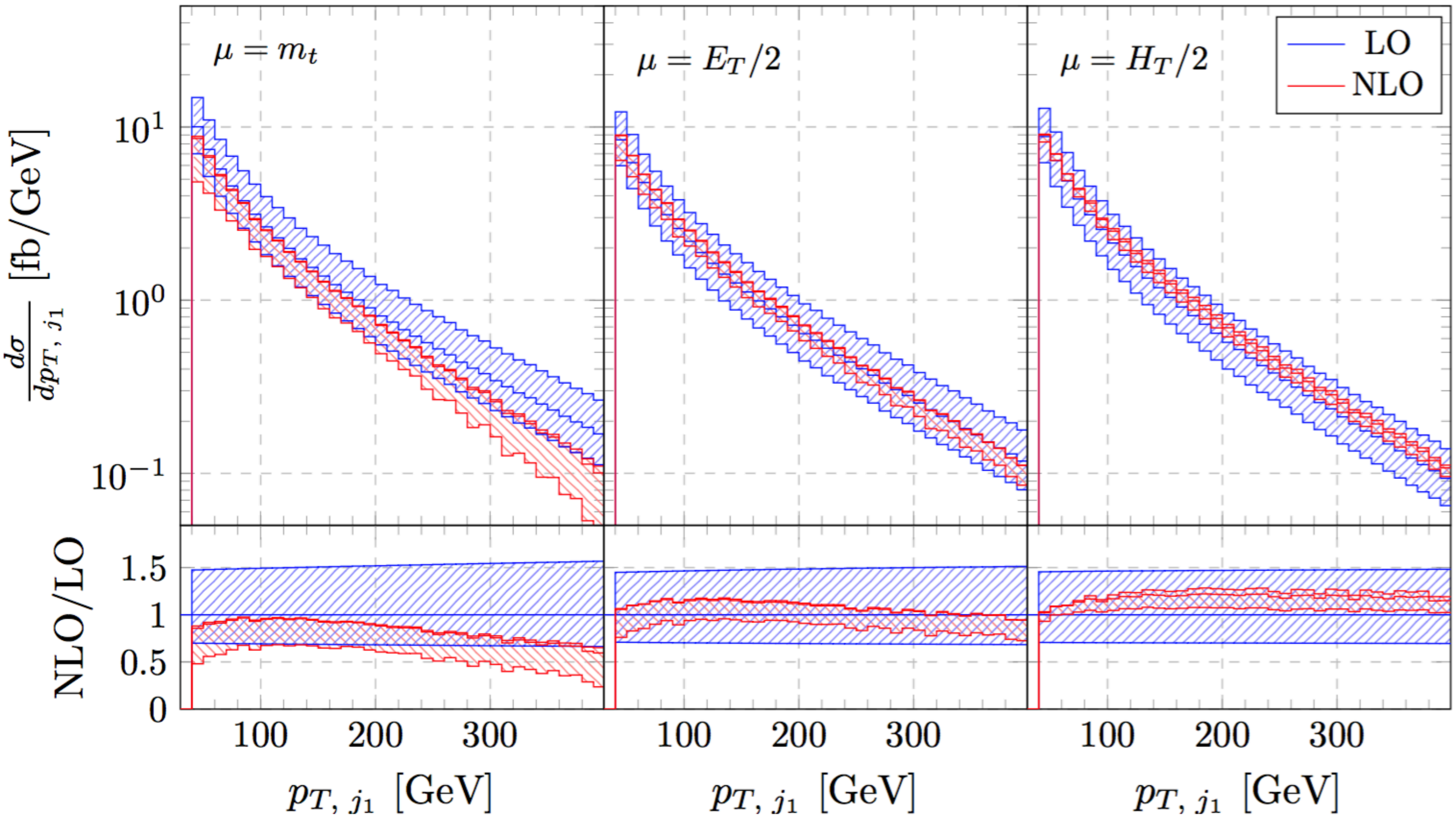
Hardest Light Jet



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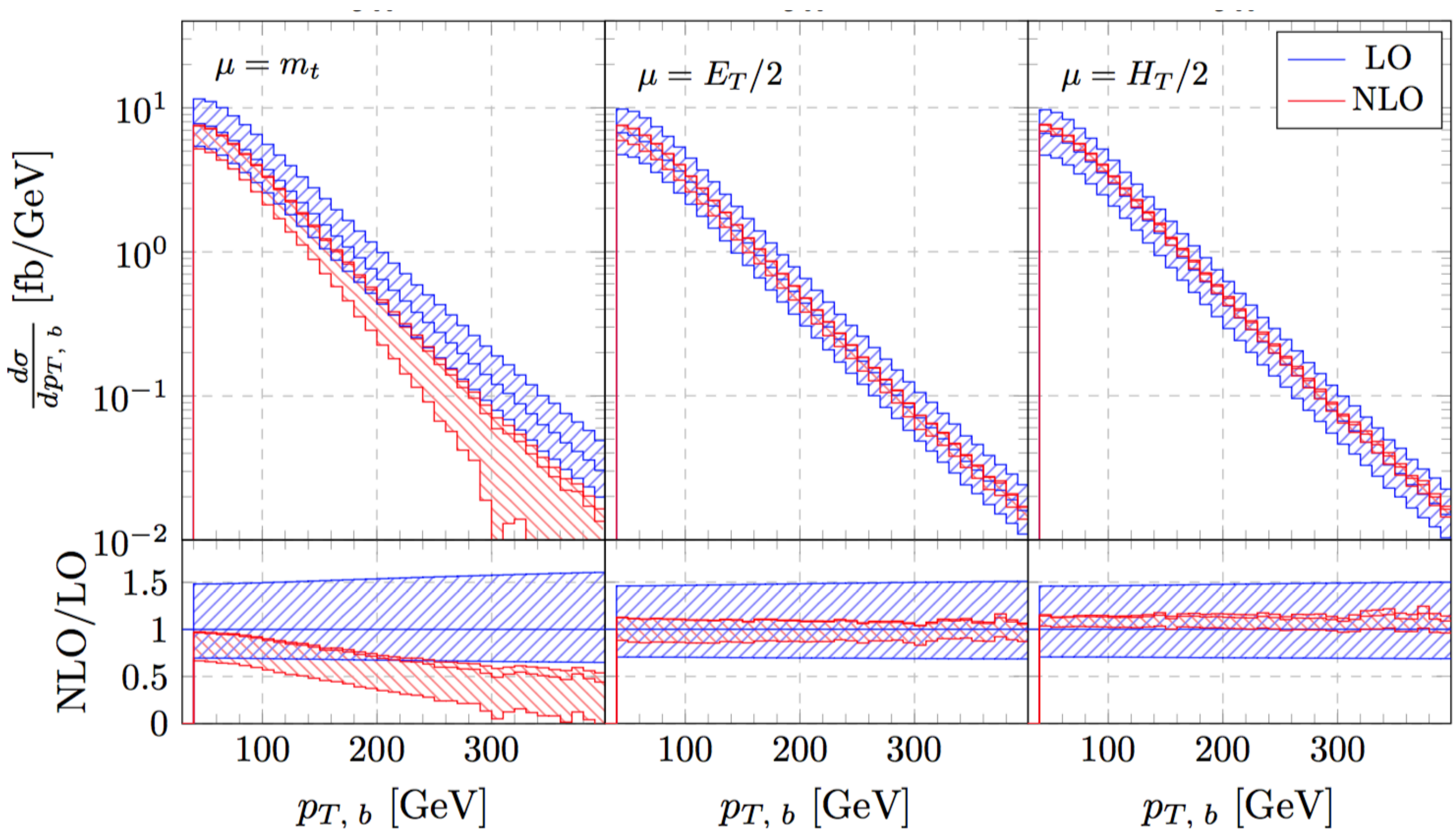
b-Jet



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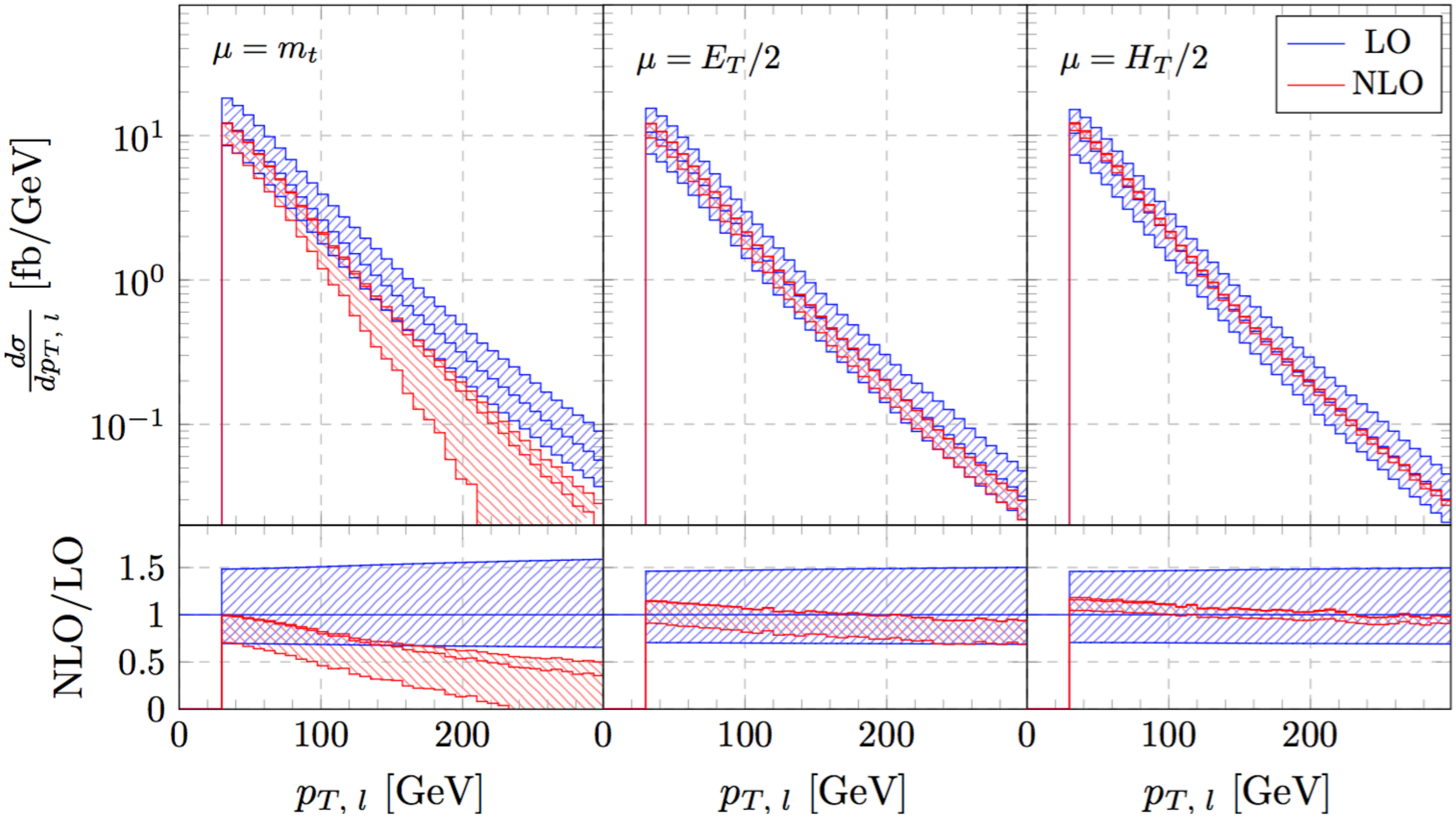
Lepton



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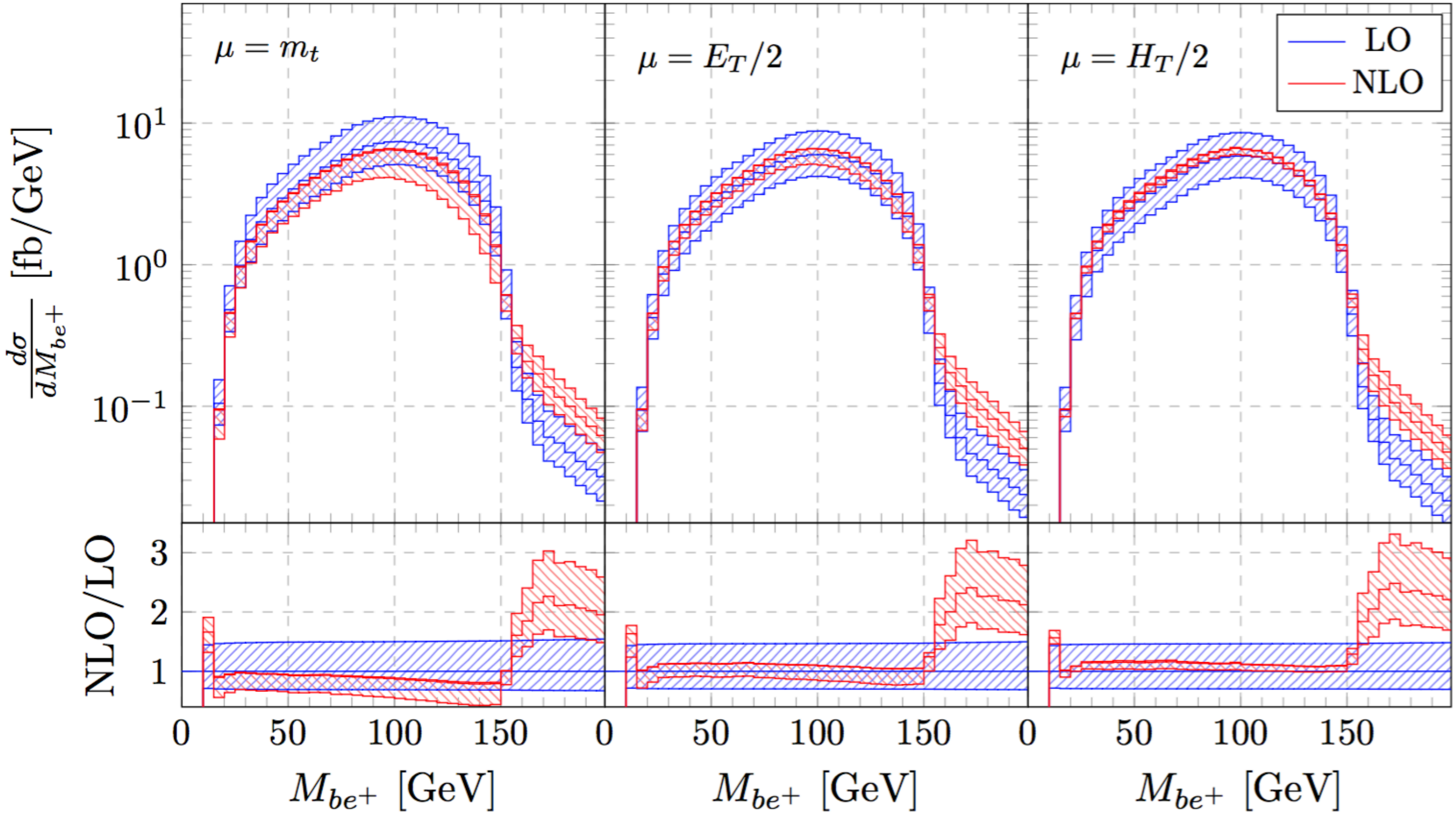
Lepton b-Jet System



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