

off-shell $t\bar{t}j$ production

Top quark mass studies at the LHC

Manfred Kraus

G. Bevilacqua, H. B. Hartanto, M. Schulze, M. Worek

RADCOR 2017

St. Gilgen

25. September 2017



LHC is a top quark factory: $t\bar{t}$ pairs are abundantly produced enabling high precision measurements of top quark properties

The study of (associated) $t\bar{t}$ production has a wide range of applications...

- SM benchmarks (e.g. $t\bar{t}$ cross section)
- precision measurements of SM parameters (e.g. m_t)
- probing Higgs-Yukawa sector (e.g. $t\bar{t}H$)
- constraining PDFs (especially gluon at large x)
- searches for BSM physics (e.g. heavy resonances decaying to tops)

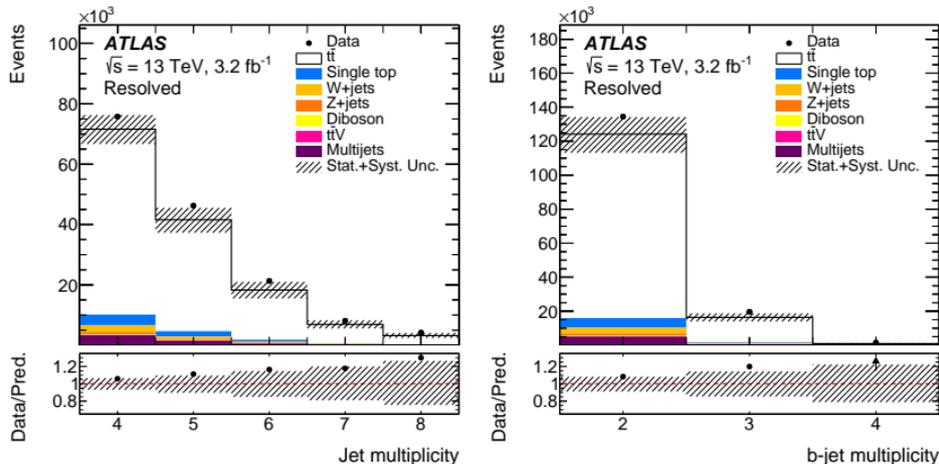
... and many more

We study the associated $t\bar{t}$ production with one additional hard jet ($pp \rightarrow t\bar{t}j$) and its impact on the precise determination of m_t at the LHC

Why study $pp \rightarrow t\bar{t}j$?

- Large fraction of $t\bar{t}$ events accompanied by **hard jets**

[ATLAS, arXiv:1708.00727]



- Compare NLO $t\bar{t}j$ to inclusive $t\bar{t}$ cross section

[Dittmaier et al.]

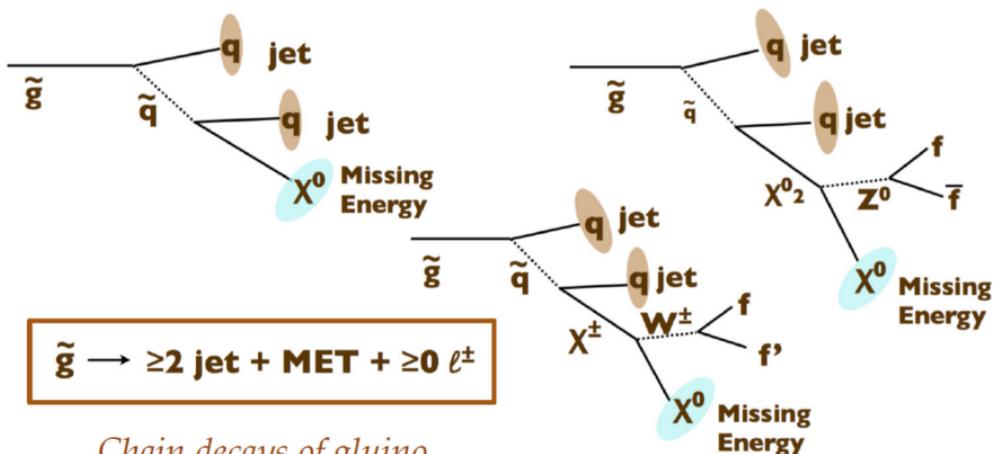
p_T^{cut} [GeV]	$\sigma_{t\bar{t}j}$ [pb]	$\sigma_{t\bar{t}j}/\sigma_{t\bar{t}}$ [%]
40	296.97 ± 0.29	41
60	207.88 ± 0.19	29
80	152.89 ± 0.13	21
100	115.60 ± 0.14	16
120	89.05 ± 0.10	12

Why study $pp \rightarrow t\bar{t}j$?

- Background for SM Higgs production in VBF: $qq \rightarrow Hqq \rightarrow W^+W^-qq$

[Englert et. al]

- Background for SUSY searches



Typical signatures of SUSY cascade decays:

M. L. Mangano '09

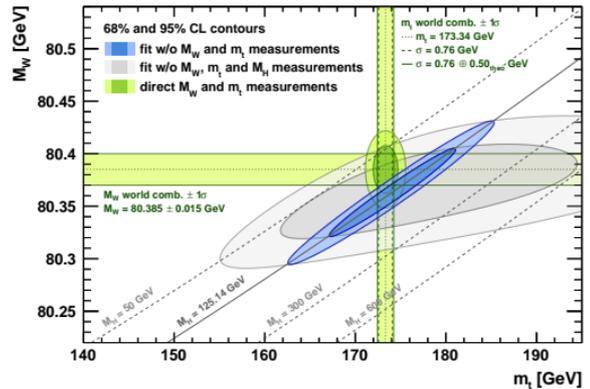
hadronic jets + charged leptons + missing p_T

Top quark mass: precision matters

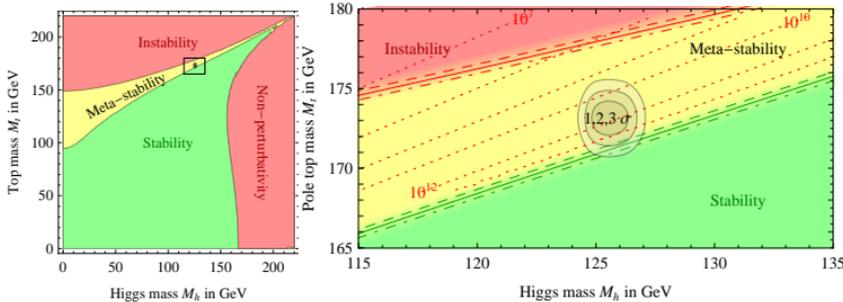
Precision tests of the Standard Model:

global EW fit: [Riemann et al., Baak et al., ...]

→ check self-consistency through
 m_t, m_W, m_H correlations



[Gfitter, Eur. Phys. J C74 (2014) 3046]



Stability of EW vacuum:
 stable or meta-stable?

[Degrassi et al., JHEP 1208 (2012) 098]

Top quark mass dependence of $pp \rightarrow t\bar{t}j$

Case 1: min. invariant mass distribution of lepton and b-jets ($M_{b\ell}$)

- Assuming on-shell top and W decays, $M_{b\ell}$ has a sharp kinematical endpoint:

$$M_{b\ell}^{max} \approx \sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}$$

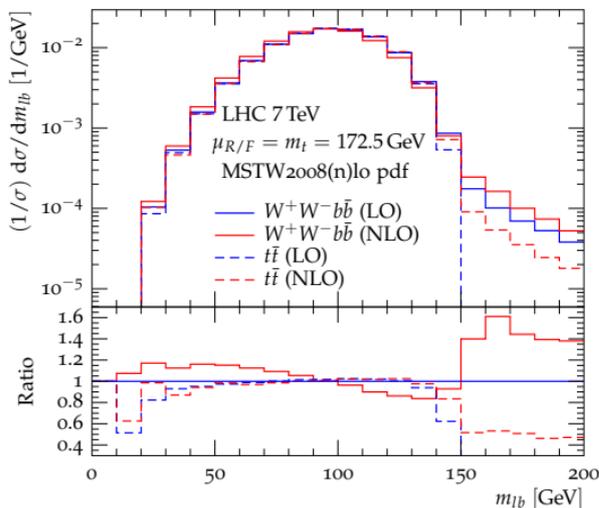
- Off-shell and radiative effects smear the kinematical endpoint.

Studied in detail for $t\bar{t}$

[Denner et al. '12, Heinrich et al. '13,...]

- First study on impact of off-shell effects on m_t measurement by

[Heinrich et al, arXiv:1212.6659]



Top quark mass dependence of $pp \rightarrow t\bar{t}j$

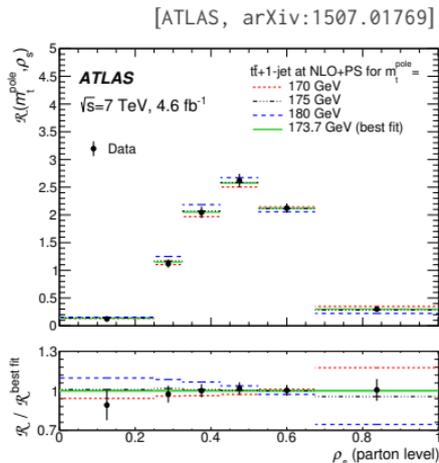
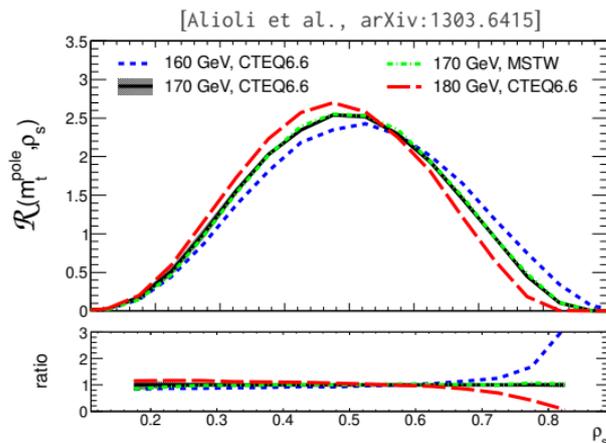
Case 2: normalized inverse $t\bar{t}j$ mass ($\mathcal{R}(m_t, \rho_s)$)

[Alioli, Fernandez, Fuster, Irles, Moch, Uwer and Vos '13]

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

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

- ρ_s shape is sensitive to m_t
- $\rho_s \approx 1 \rightarrow t\bar{t}$ threshold
- $t\bar{t}j$ has higher sensitivity than $t\bar{t}$



What is the impact of off-shell effects on ρ_s distribution?

NLO QCD Fixed-order

- on-shell $t\bar{t}j$ production

[Dittmaier, Uwer, Weinzierl '07'09]

- on-shell $t\bar{t}j$ production with LO decays

[Melnikov, Schulze '10]

- on-shell $t\bar{t}j$ production with NLO decays

[Melnikov, Scharf, Schulze '12]

- off-shell $t\bar{t}j$ production with leptonic decays

[Bevilacqua, Hartanto, MK, Worek '15'16]

Matched to parton shower

- Powheg + Pythia → no spin correlations

[Kardos, Papadopoulos, Trocsanyi '11]

- Powheg + Pythia/Herwig → spin correlations at LO

[Alioli, Moch, Uwer '12]

- MC@NLO + Deductor → without decays

[Czakon, Hartanto, MK, Worek '15]

Narrow Width Approximation

$$\lim_{\Gamma_t/m_t \rightarrow 0} \frac{1}{(p_t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} = \frac{\pi}{m_t \Gamma_t} \delta(p_t^2 - m_t^2)$$

NWA allows to factorize complicated matrix elements

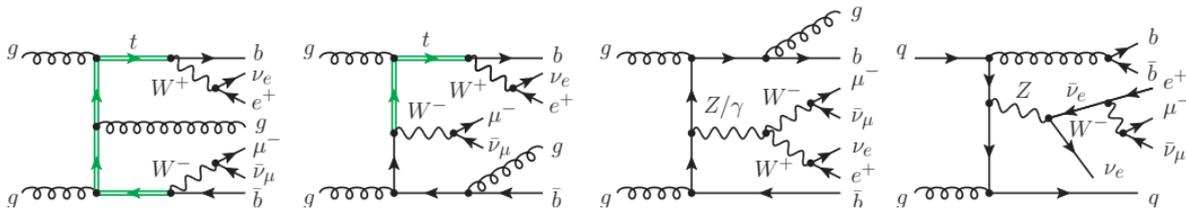
$$\begin{aligned} \lim_{\Gamma_t/m_t \rightarrow 0} \left| M^{WWb\bar{b}j} \right|^2 &= \left| M^{t\bar{t}j} \right|^2 \otimes \mathcal{B}r(t \rightarrow Wb) \otimes \mathcal{B}r(\bar{t} \rightarrow W\bar{b}) \\ &+ \left| M^{t\bar{t}j} \right|^2 \otimes \mathcal{B}r(t \rightarrow Wb\mathbf{j}) \otimes \mathcal{B}r(\bar{t} \rightarrow W\bar{b}) \\ &+ \left| M^{t\bar{t}j} \right|^2 \otimes \mathcal{B}r(t \rightarrow Wb) \otimes \mathcal{B}r(\bar{t} \rightarrow W\bar{b}\mathbf{j}) + \underbrace{\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)}_{\approx 1\%} \end{aligned}$$

- on-shell tops and W
- **hard jet** radiation in decay
- Calculation provided by M. Schulze

[Melnikov, Scharf, Schulze '12]

NWA is best suited for inclusive observables. At the differential level, off-shell effects can reach tens of percent.

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



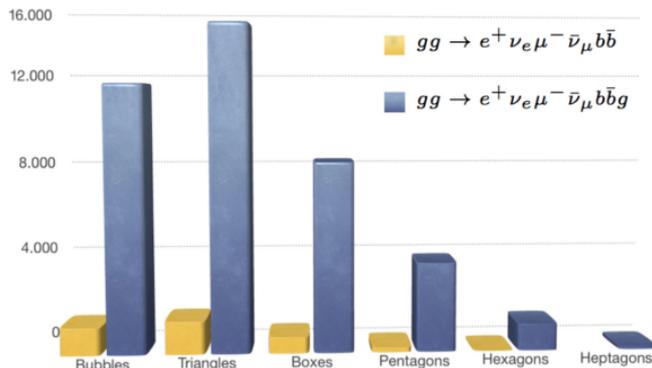
- Double-, single- and Non-resonant contributions

$$|M^{WWb\bar{b}j}|^2 = |M^{t\bar{t}j} + M^B|^2 = \underbrace{|M^{t\bar{t}j}|^2}_{2 \times \text{Resonant}} + \underbrace{|M^B|^2}_{0,1 \times \text{Resonant}} + \underbrace{2\text{Re}[M^{t\bar{t}j}M^{B\dagger}]}_{\text{Interference}}$$

- QCD corrections to $2 \rightarrow 5$ process ($WWb\bar{b}j$)
- $t\bar{t}j$ production at $\mathcal{O}(\alpha_s^4 \alpha^4)$ in the dilepton decay channel

One-Loop corrections

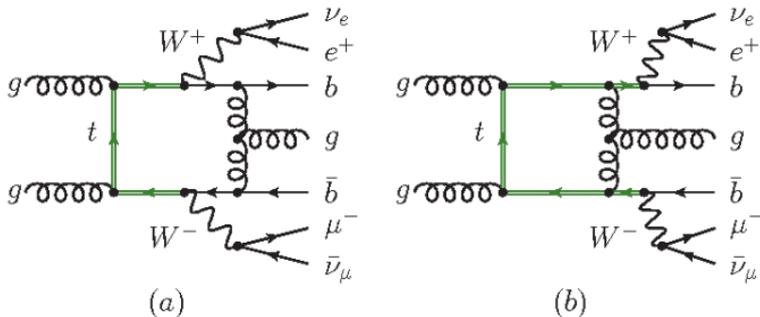
Number of 1-Loop Feynman diagram split by topology: $t\bar{t}$ vs. $t\bar{t}j$



- up to 1155 hexagons and 120 heptagons
- Scalar integrals with complex masses: $m_t^2 \rightarrow m_t^2 - im_t \Gamma_t$

[source: QGRAF (Nogueira '13). Special thanks to A. Kardos]

- NWA for $t\bar{t}j$ only up to pentagons!

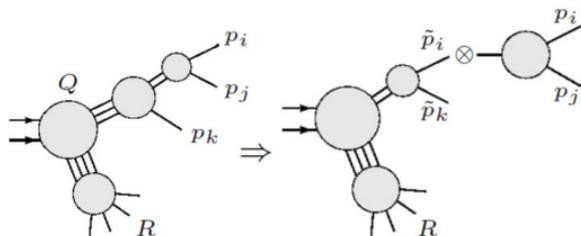


Real corrections

Number of subtracted terms for representative subprocesses

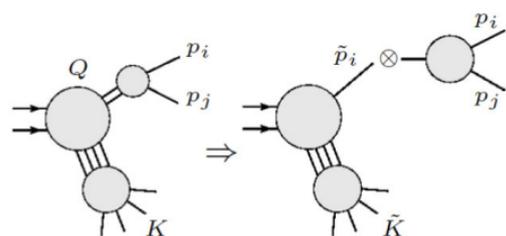
Subprocess	# Diags	# CS dipoles	# NS dipoles
$gg \rightarrow e^+v_e\mu^-\bar{\nu}_\mu b\bar{b}gg$	4447	56	14
$gg \rightarrow e^+v_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$	3904	48	12
$gg \rightarrow e^+v_e\mu^-\bar{\nu}_\mu b\bar{b}q\bar{q}$	1952	40	10
$qq \rightarrow e^+v_e\mu^-\bar{\nu}_\mu b\bar{b}qq$	930	20	5
$qq' \rightarrow e^+v_e\mu^-\bar{\nu}_\mu b\bar{b}qq'$	501	12	3

Catani-Seymour



$$\{p\}_{m+1} \rightarrow \{\tilde{p}\}_m^{(ijk)}$$

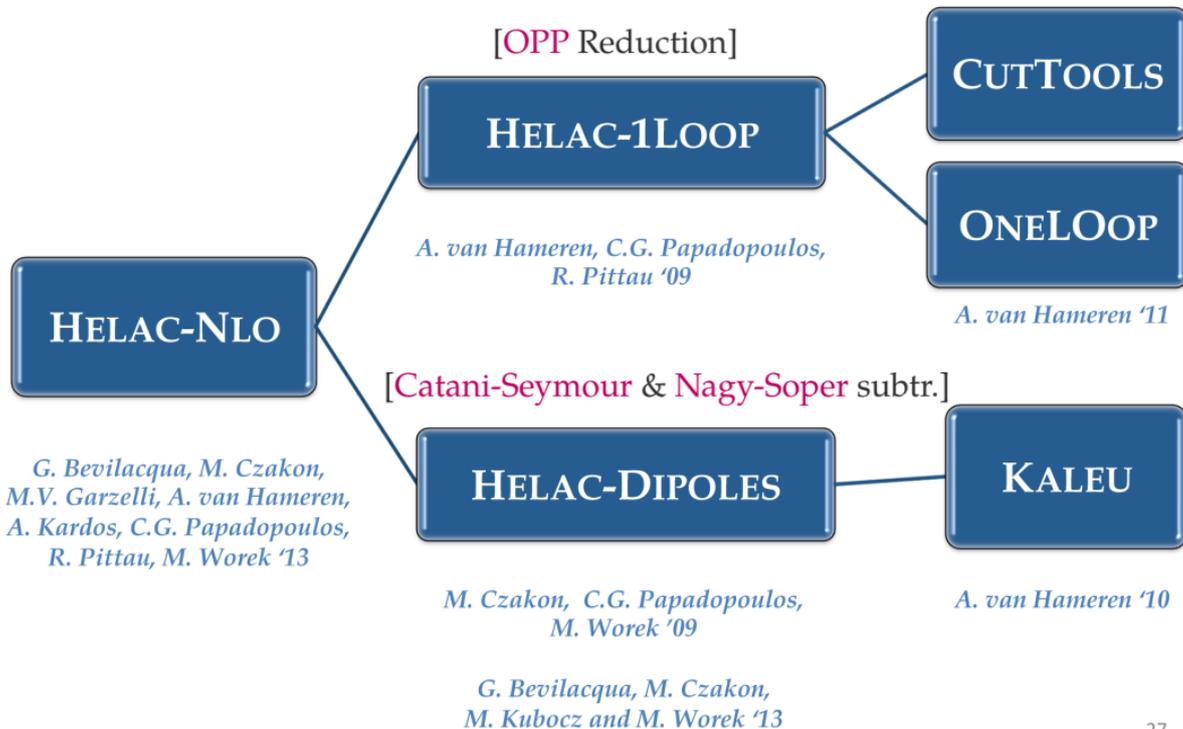
Nagy-Soper



$$\{p\}_{m+1} \rightarrow \{\tilde{p}\}_m^{(ij)}$$

HELAC-NLO

*G. Ossola, C.G. Papadopoulos,
R. Pittau '08*



27

- **NEW:** Ntuple generation + re-weighting for different $\mu_{R,F}$ and PDFs

Numerical results for $t\bar{t}j$ at the LHC

Final state and parameters

- Fully leptonic decays: $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X$
- Light quarks (also bottom) and leptons are massless \rightarrow 5 FS
- Top quark mass: $m_t = 173.2 \text{ GeV}$
- Top quark width with off-shell W : [Jesabek, Kühn, '99, Denner et al. '12]
 $\Gamma_t^{\text{LO}} = 1.47834 \text{ GeV} \quad \Gamma_t^{\text{NLO}} = 1.35146 \text{ GeV}$
- Complex Mass Scheme: $m_t^2 \rightarrow m_t^2 - i m_t \Gamma_t$ [Denner et al. '99, '05]

Kinematics

- exactly 2 b-jets, ≥ 1 light jet, 2 charged leptons, missing p_T
- partons with $|\eta| < 5$, anti- k_T , $\Delta R = 0.5$
- cuts:

$$\begin{aligned} p_{T\ell} &> 30 \text{ GeV}, & p_{Tj} &> 40 \text{ GeV}, & \cancel{p}_T &> 40 \text{ GeV}, \\ \Delta R_{jj} &> 0.5, & \Delta R_{\ell\ell} &> 0.4, & \Delta R_{\ell j} &> 0.4, \\ |y_\ell| &< 2.5, & |y_j| &< 2.5, & & \end{aligned}$$

Inclusive cross sections

PDF: CT14

Fixed scale: $\mu_0 = m_t$

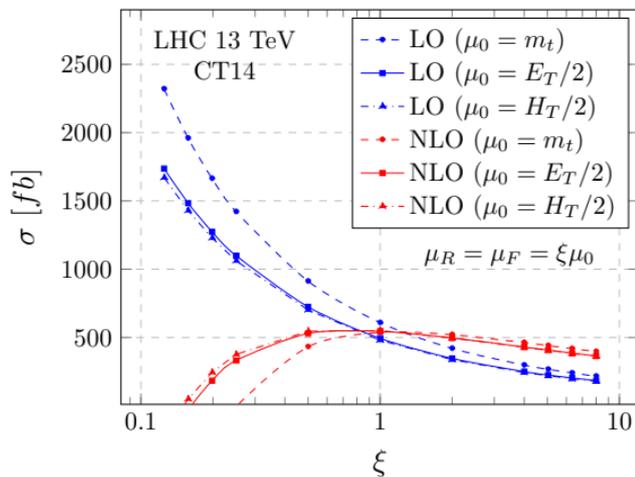
Dynamical scale: $\mu_0 = E_T/2$ and $H_T/2$

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

$$H_T = \sum_i p_{T,i} + \cancel{p}_T$$

Scale uncertainties:

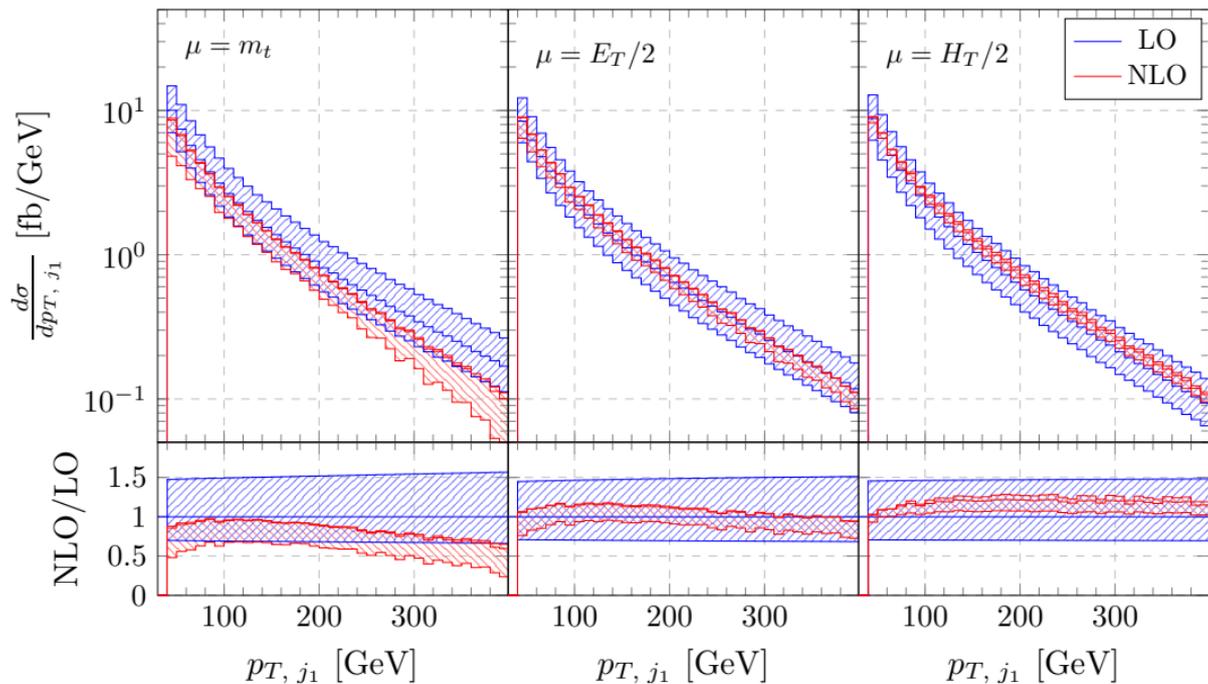
$$\frac{1}{2} \leq \left(\frac{\mu_R}{\mu_F} \right) \leq 2, \quad \frac{1}{2} \leq \mu_R, \mu_F \leq 2$$



μ_0	$\sigma_{LO}[fb]$	$\sigma_{NLO}[fb]$	K
m_t	608.09 $^{+50\%}$ $_{-31\%}$ (scale)	537.24 $^{+2\%}$ $_{-35\%}$ (scale) $^{+3\%}$ $_{-3\%}$ (pdf)	0.88
$E_T/2$	493.54 $^{+47\%}$ $_{-30\%}$ (scale)	544.64 $^{+1\%}$ $_{-22\%}$ (scale) $^{+3\%}$ $_{-3\%}$ (pdf)	1.10
$H_T/2$	479.38 $^{+46\%}$ $_{-30\%}$ (scale)	549.65 $^{+2\%}$ $_{-10\%}$ (scale) $^{+3\%}$ $_{-3\%}$ (pdf)	1.15

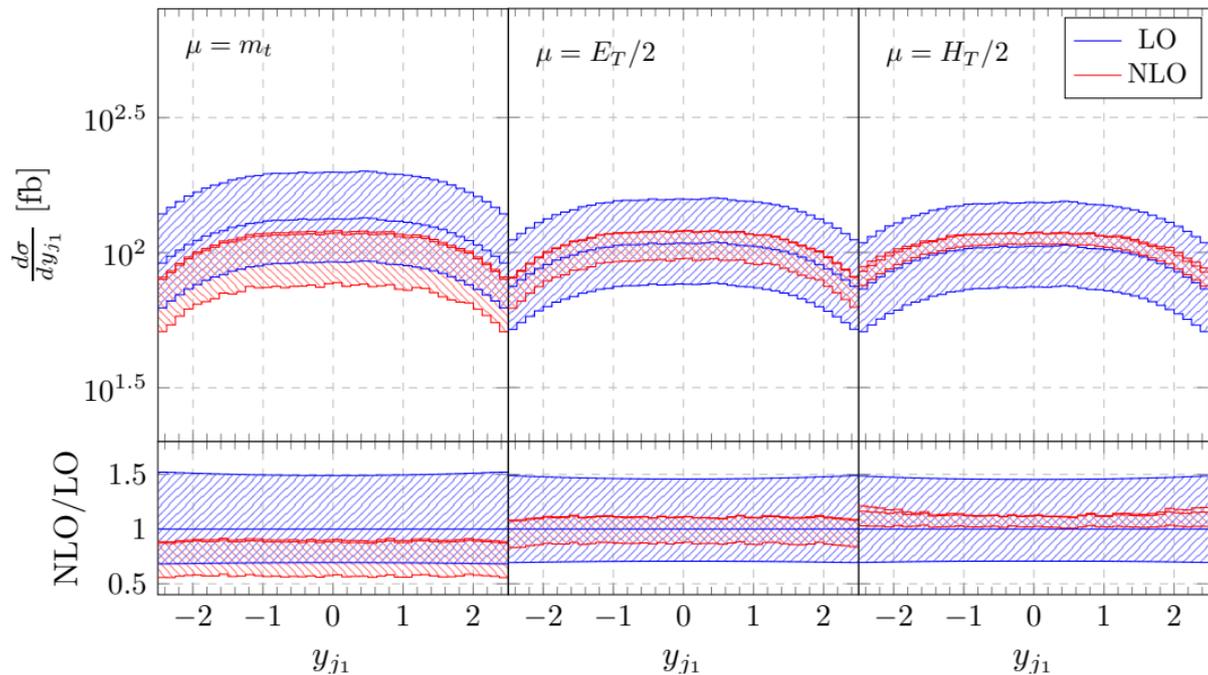
[Bevilacqua, Hartanto, MK, Worek, JHEP 1611 (2016) 098]

Transverse momentum of the hardest jet



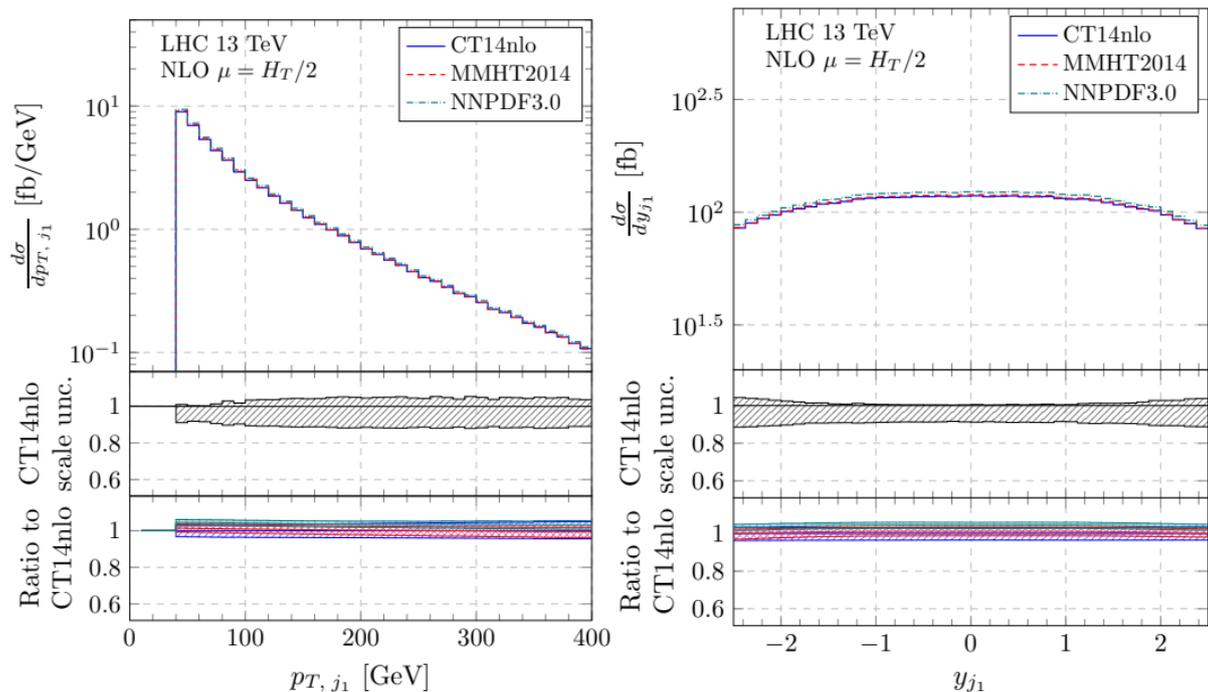
[Bevilacqua, Hartanto, MK, Worek, JHEP 1611 (2016) 098]

Rapidity of the hardest jet



[Bevilacqua, Hartanto, MK, Worek, JHEP 1611 (2016) 098]

PDF vs. Scale uncertainties



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

PRELIMINARY

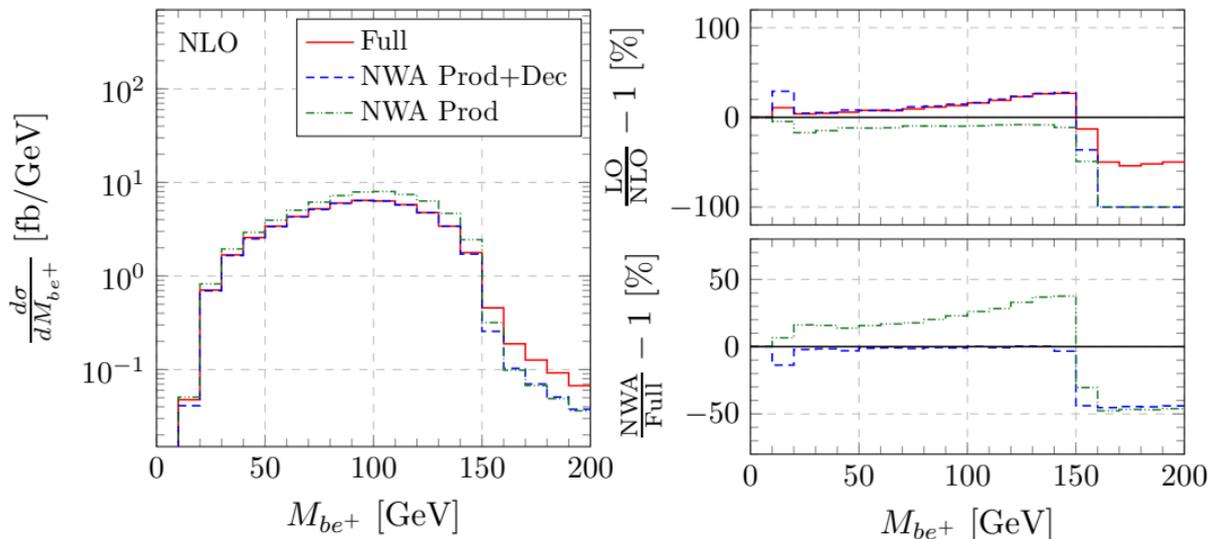
[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]

Comparison to NWA

PDF: CT14

Scale: $\mu_R = \mu_F = m_t$

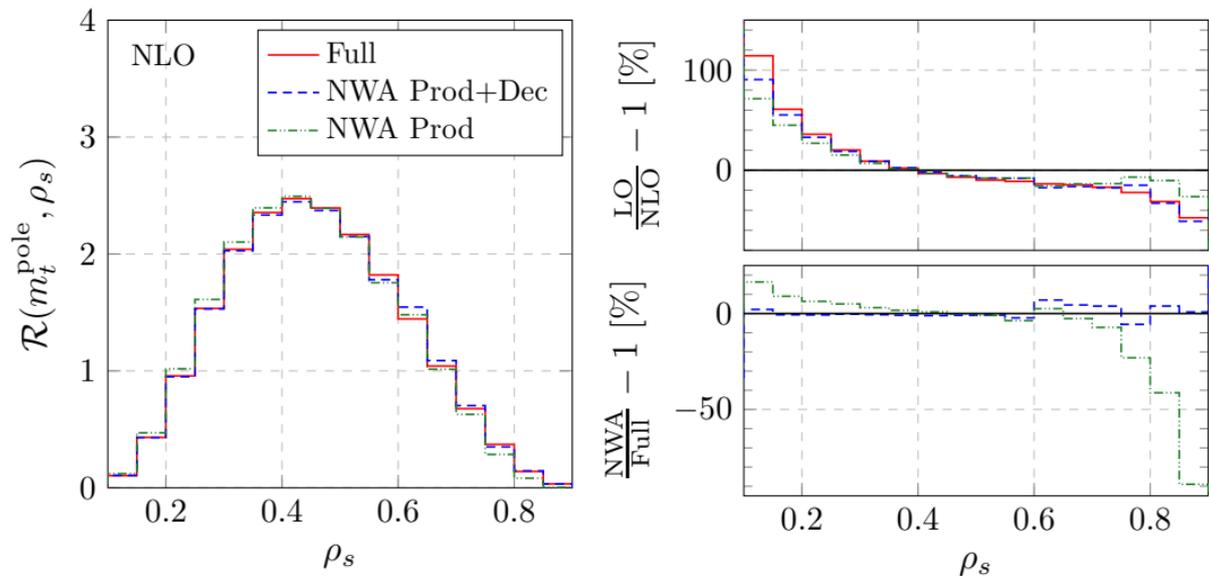
$$\sigma_{\text{NLO}}^{\text{Full}} = 537 \text{ fb} , \quad \sigma_{\text{NLO}}^{\text{NWA}} = 527 \text{ fb} , \quad \sigma_{\text{NLO}}^{\text{NWA(Prod)}} = 656 \text{ fb} .$$



PRELIMINARY

[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]

Comparison to NWA

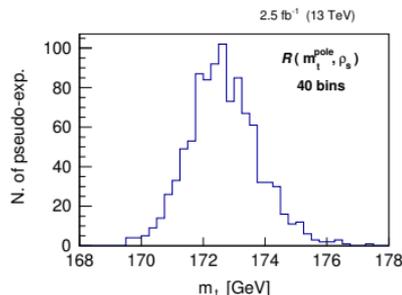
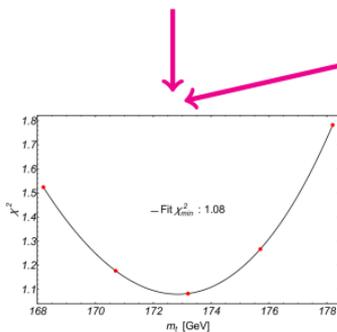
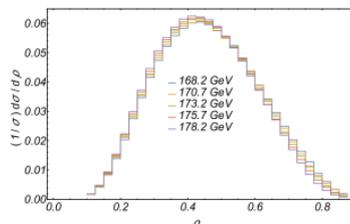
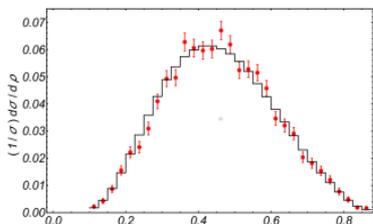


Top quark mass studies with $t\bar{t}j$

Fitting the top quark mass

Basic idea

- generate pseudo-data for a given luminosity, distributed according to the best prediction (\rightarrow NLO with off-shell effects)
- fit pseudo-data with templates for different m_t
- compare results obtained with templates of different accuracy (NWA vs full)



PRELIMINARY

[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged $\chi^2/d.o.f.$	Probability <i>p-value</i>	$m_t^{in} - m_t^{out}$ [GeV]
2.5 fb ⁻¹				
<i>Full</i> , $\mu_0 = H_T/2$	173.09 ± 0.48	1.05	0.38 (0.9σ)	+0.11
<i>Full</i> , $\mu_0 = E_T/2$	173.01 ± 0.50	1.06	0.37 (0.9σ)	+0.19
<i>Full</i> , $\mu_0 = m_t$	173.07 ± 0.49	1.22	0.18 (1.3σ)	+0.13
<i>NWA</i> , $\mu_0 = m_t$	173.90 ± 0.50	1.11	0.30 (1.0σ)	-0.70
<i>NWA</i> _{Prod.} , $\mu_0 = m_t$	172.56 ± 0.54	1.64	0.01 (2.6σ)	+0.64
25 fb ⁻¹				
<i>Full</i> , $\mu_0 = H_T/2$	173.18 ± 0.15	1.02	0.42 (0.8σ)	+0.02
<i>Full</i> , $\mu_0 = E_T/2$	173.23 ± 0.15	1.03	0.41 (0.8σ)	-0.03
<i>Full</i> , $\mu_0 = m_t$	173.22 ± 0.16	1.78	0.005 (2.8σ)	-0.02
<i>NWA</i> , $\mu_0 = m_t$	173.98 ± 0.16	2.56	5 · 10 ⁻⁶ (4.6σ)	-0.78
<i>NWA</i> _{Prod.} , $\mu_0 = m_t$	172.62 ± 0.17	8.23	0 (≥ 5σ)	+0.58

- **NWA vs off-shell**: shift of $\mathcal{O}(800)$ MeV
- Scale uncertainties: dyn. → $\mathcal{O}(50)$ MeV, fix. → $\mathcal{O}(1)$ GeV
- PDF uncertainties: $\mathcal{O}(30)$ MeV

PRELIMINARY

[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged $\chi^2/d.o.f.$	Probability <i>p-value</i>	$m_t^{in} - m_t^{out}$ [GeV]
2.5 fb ⁻¹				
<i>Full</i> , $\mu_0 = H_T/2$	173.05 ± 1.31	0.99	0.42 (0.8σ)	+0.15
<i>Full</i> , $\mu_0 = E_T/2$	172.19 ± 1.34	1.05	0.39 (0.9σ)	+1.01
<i>Full</i> , $\mu_0 = m_t$	173.86 ± 1.39	1.42	0.21 (1.2σ)	-0.66
<i>NWA</i> , $\mu_0 = m_t$	175.22 ± 1.15	1.38	0.23 (1.2σ)	-2.02
<i>NWA</i> _{Prod.} , $\mu_0 = m_t$	169.39 ± 1.46	1.12	0.35 (0.9σ)	+3.81
25 fb ⁻¹				
<i>Full</i> , $\mu_0 = H_T/2$	173.06 ± 0.44	0.97	0.44 (0.8σ)	+0.14
<i>Full</i> , $\mu_0 = E_T/2$	172.36 ± 0.44	1.38	0.23 (1.2σ)	+0.84
<i>Full</i> , $\mu_0 = m_t$	173.84 ± 0.42	5.12	1 · 10 ⁻⁴ (3.9σ)	-0.64
<i>NWA</i> , $\mu_0 = m_t$	175.23 ± 0.37	5.28	7 · 10 ⁻⁵ (4.0σ)	-2.03
<i>NWA</i> _{Prod.} , $\mu_0 = m_t$	169.43 ± 0.50	2.61	0.02 (2.3σ)	+3.77

- **NWA vs off-shell**: shift of $\mathcal{O}(1.4)$ GeV
- Scale uncertainties: dyn. → 0.6 – 1.2 GeV, fix. → 2.1 – 2.8 GeV
- PDF uncertainties: 0.4 – 0.7 GeV

Conclusions



Full calculation of $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X$ at NLO QCD

[JHEP 1611 (2016) 098]

- Full description of $t\bar{t}j$ with all resonant and non-resonant contributions
- Comparison of fixed and dynamic scales: m_t , $E_T/2$, $H_T/2$
- Scale and PDF uncertainties for σ and various $d\sigma/dX$

Comparison with NWA

- off-shell effects on inclusive cross section $\sim 2\%$, non negligible on $d\sigma/dX$ far away from the threshold
- NLO corrections to top decays are important!

First application: top quark mass extraction

- Preliminary analysis for M_{be^+} and $\mathcal{R}(m_t, \rho)$
- fixed scale \rightarrow larger uncertainties, better: dynamical scales
- Complete study soon: M_{be^+} , $\mathcal{R}(m_t, \rho)$, $M_{t\bar{t}}$, H_T

m_t shift: $\mathcal{O}(1)$ GeV

- NWA: needs calibration which comes with uncertainties
- Full off-shell: no/less calibration \rightarrow reduction of uncertainties

Backup

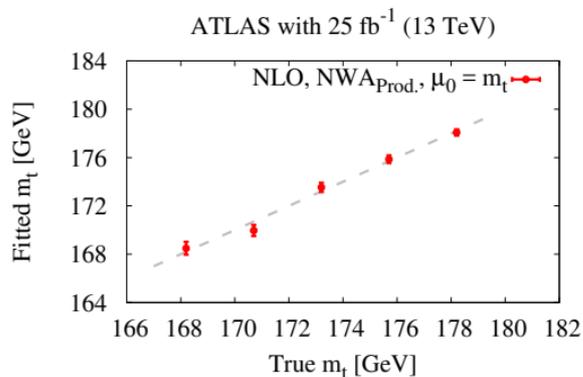
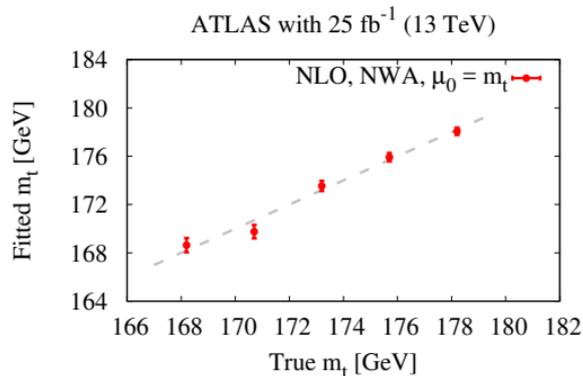
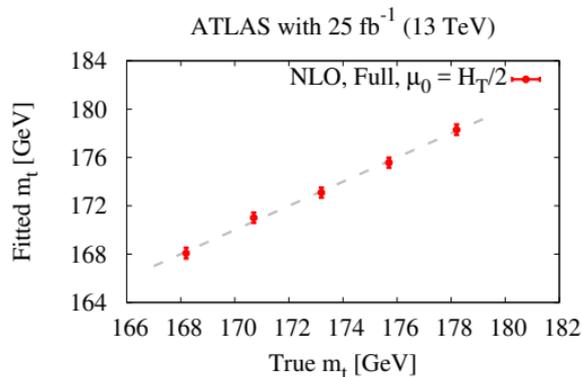
Event samples for $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X$ for $m_t = 173.2$ GeV used for reweighting

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

Consistency check

PRELIMINARY

[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]



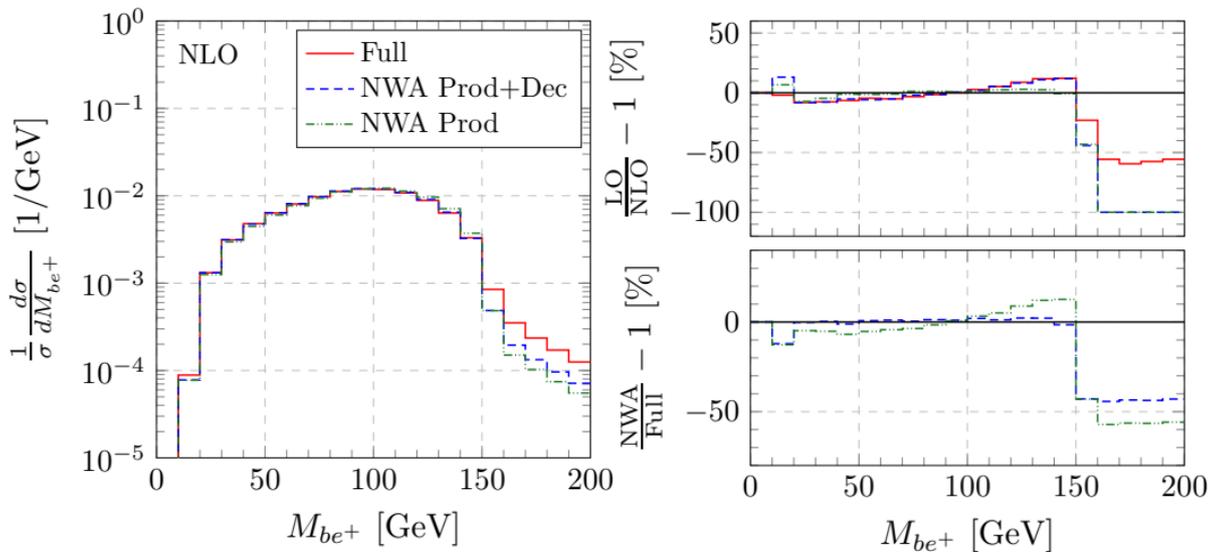
Consider $\mathcal{R}(m_t, \rho_s)$ (using ATLAS binning)

Same theoretical prediction for templates and pseudo-data

True and fitted m_t agree within errors
→ no bias observed

PRELIMINARY

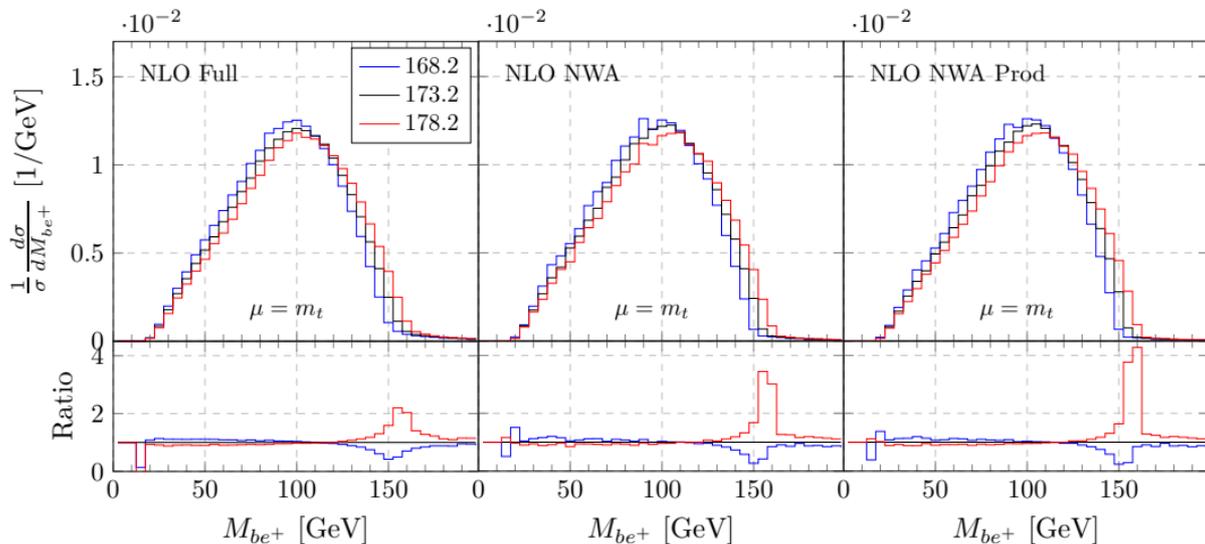
[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]



Top quark mass dependence in M_{be^+}

PRELIMINARY

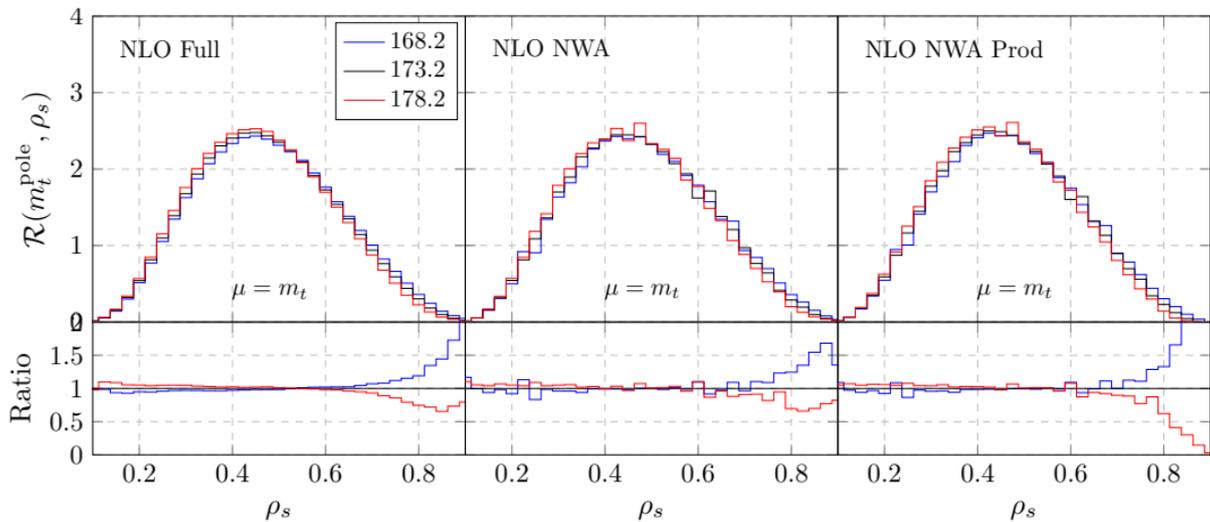
[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]



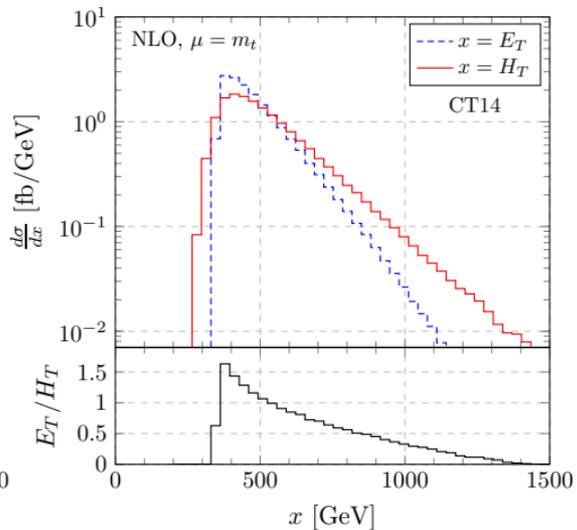
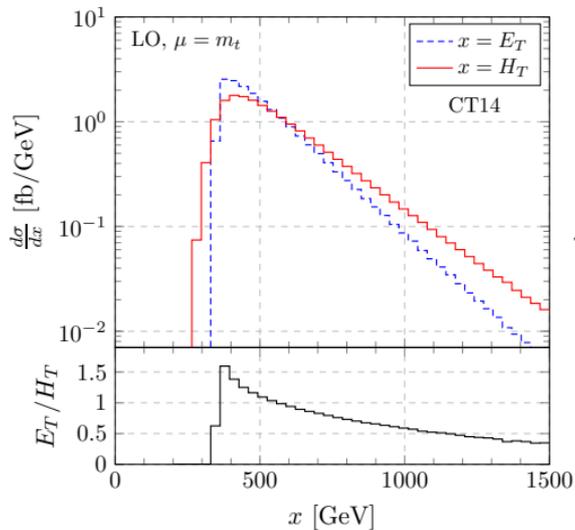
Top quark mass dependence in $\mathcal{R}(m_t, \rho_s)$

PRELIMINARY

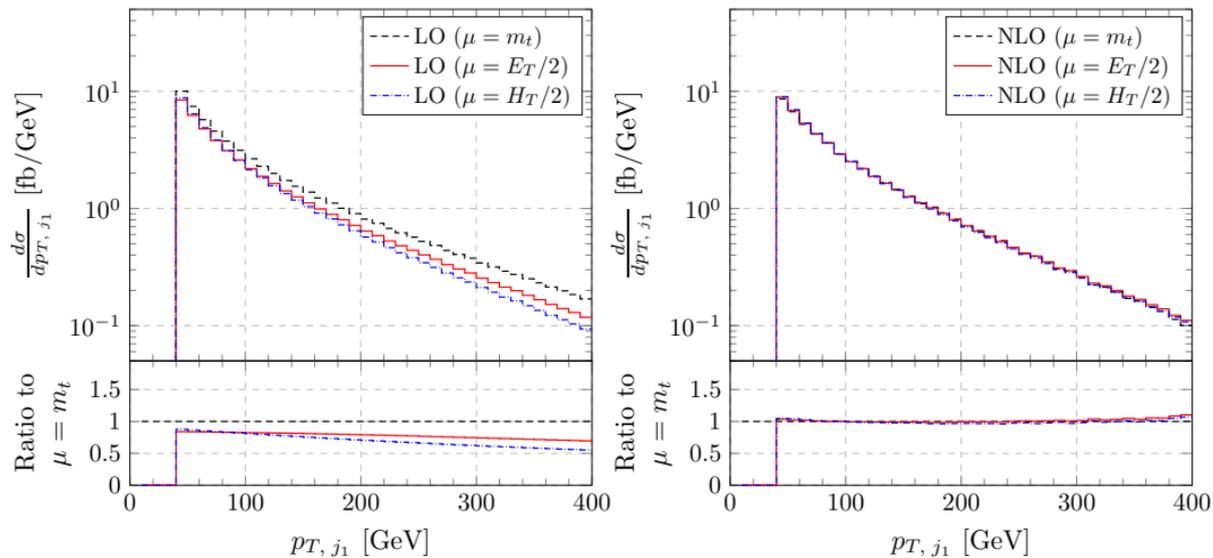
[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]



Comparison of the dynamical scales



Transverse momentum of hardest light jet



Large scale uncertainty in ρ

PRELIMINARY

[Bevilacqua, Hartanto, MK, Schulze, Worek, in preparation]

