Research Training Group Physics of the Heaviest Particles at the LHC

RWTH AACHEN UNIVERSITY

Collaborative Research Center TRR 257

P H

Particle Physics Phenomenology after the Higgs Discovery

$pp \to t\bar{t}j$ @ NLO in QCD
Off-Shell Calculations & Mass Extraction

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RWTH AACHEN UNIVERSITY

Workshop on top-quark mass measurements, 21-23 May 2024, Valencia

Instead of Introduction

NLO corrections for stable top quarks

- General idea about size of NLO QCD corrections
- Can not provide reliable description of top quark decay products & radiation pattern

S. Dittmaier, P. Uwer, S. Weinzierl, Phys. Rev. Lett. 98 (2007) 262002
S. Dittmaier, P. Uwer, S. Weinzierl, Eur. Phys. J. C 59 (2009) 625
M. Czakon, H. B. Hartanto, M. Kraus, M. Worek, JHEP 06 (2015) 033

For more realistic studies decays are needed

- *NLO QCD for $pp \to ttj$ + PS* $\Rightarrow$ Corrections to production & Top decays in parton shower approximation & omitting (even LO) *tt* spin correlations

  A. Kardos, C. G. Papadopoulos, Z. Trocsanyi, Phys. Lett. B 705 (2011) 76

- *NLO QCD for $pp \to ttj$ + LO decays + PS* $\Rightarrow$ Top decays @ LO before matched to parton shower programs & LO *tt* spin correlations

  S. Alioli, S.Moch, P. Uwer, JHEP 01 (2012) 137

- *NLO QCD for $pp \to ttj$ + LO decays* $\Rightarrow$ Top decays @ LO & LO *tt* spin correlations

  K. Melnikov, M. Schulze, Nucl. Phys. B 840 (2010) 129

- *NLO QCD in NWA for $pp \to ttj$* $\Rightarrow$ NLO QCD corrections to top production & decays & NLO *tt* spin correlations

  K. Melnikov, M. Schulze, Phys. Rev. D 85 (2012) 054002

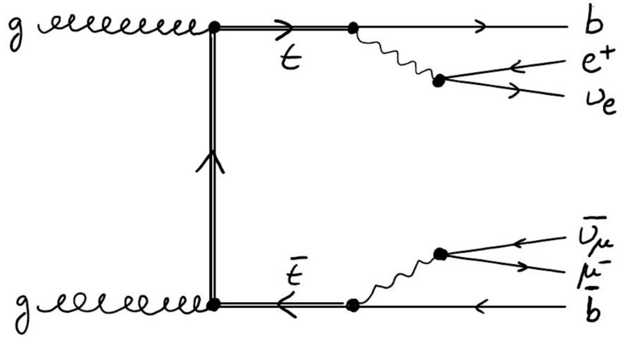
- *NLO QCD with complete off-shell effects of top quarks for $pp \to ttj$* $\Rightarrow$ Additionally to previous effects $\Rightarrow$ Resonant & non-resonant diagrams & Interference effects & Off-shell *t & W* described by Breit-Wigner propagators

  G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, JHEP 11 (2016) 098
  G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

Full Off-Shell Predictions

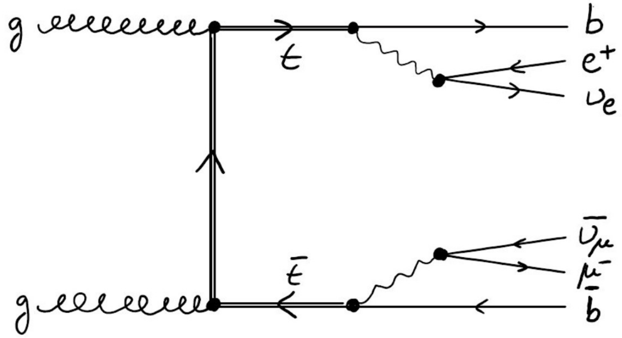
- Modelling of unstable particles based on *tt*

$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$

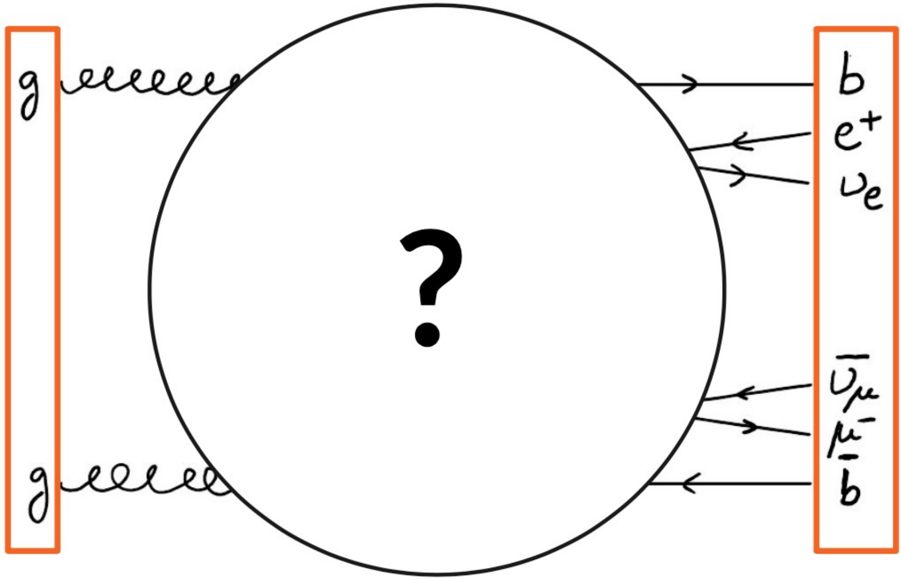


Full Off-Shell Predictions

- Modelling of unstable particles based on tt

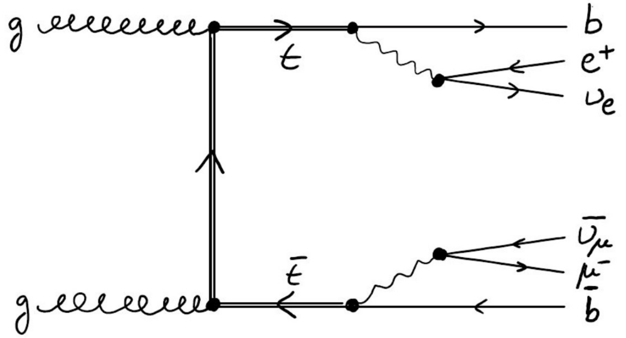


$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$



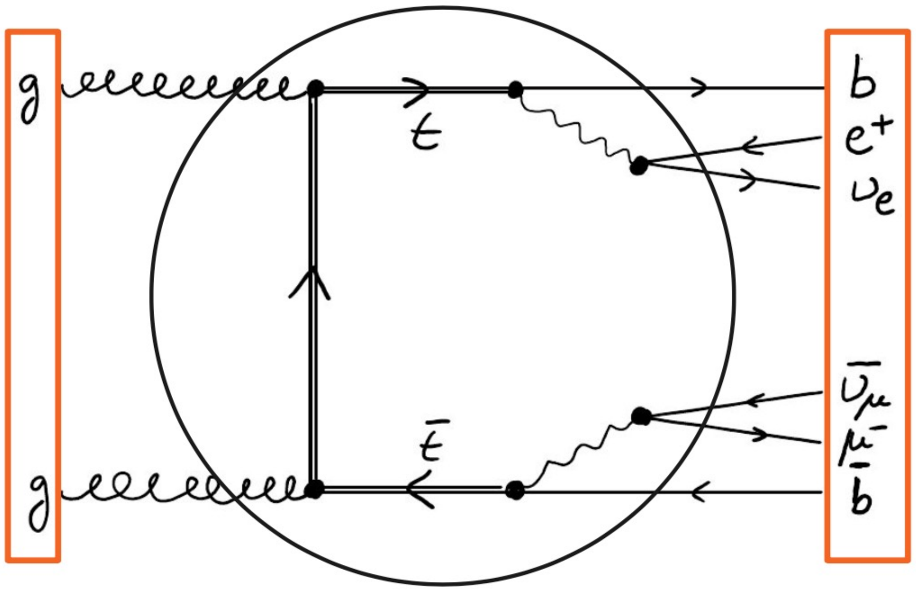
Full Off-Shell Predictions

- Modelling of unstable particles based on tt



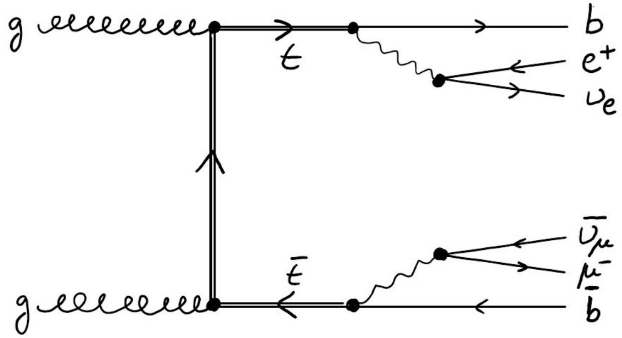
$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$

Double-resonant diagram



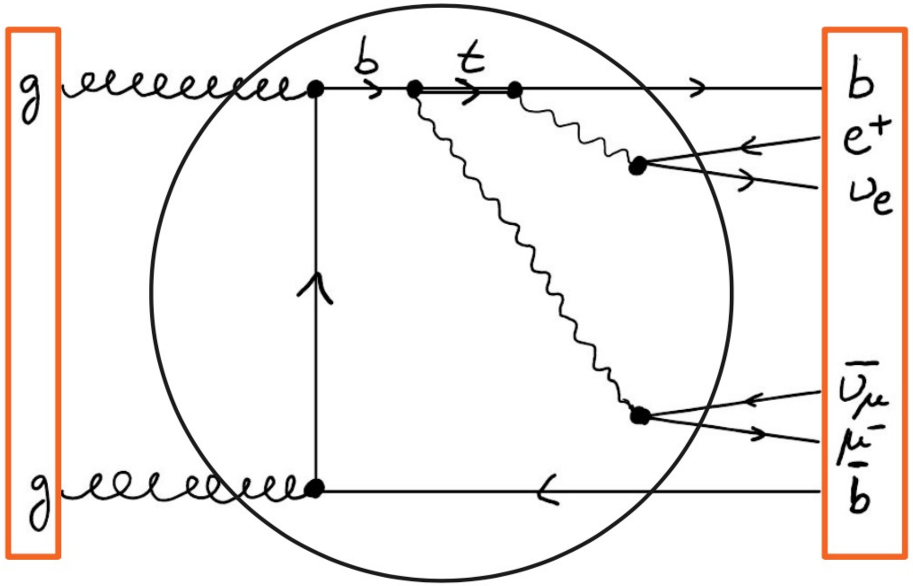
Full Off-Shell Predictions

- Modelling of unstable particles based on *tt*



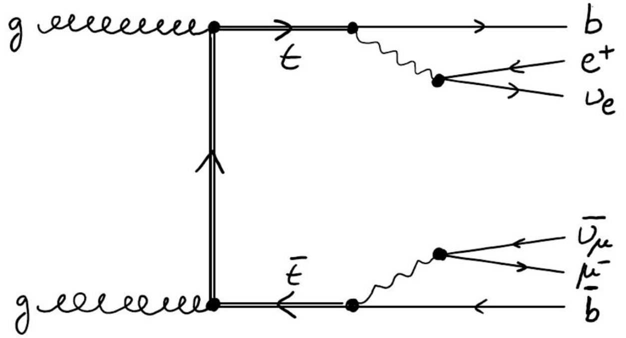
$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$

Single-resonant diagram



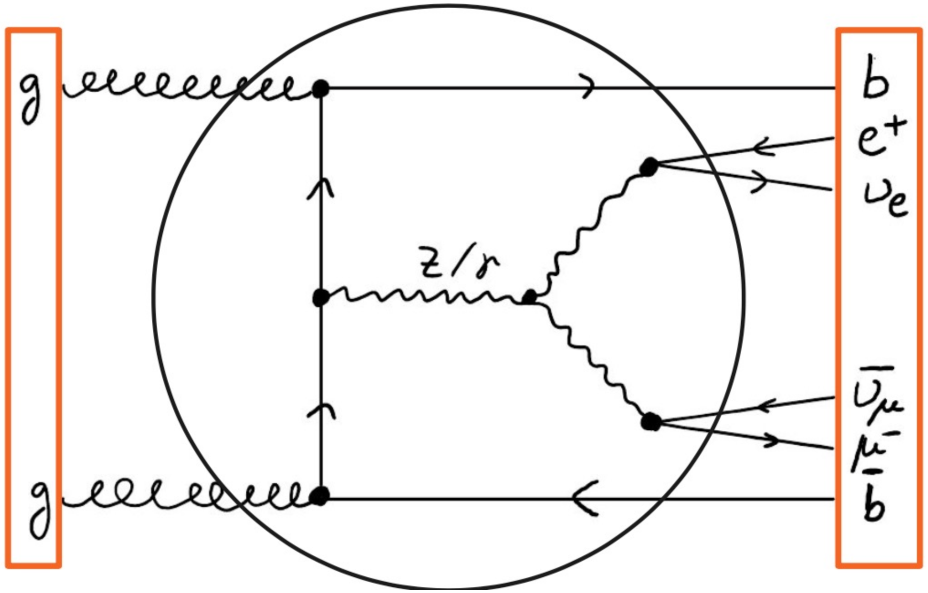
Full Off-Shell Predictions

- Modelling of unstable particles based on *tt*



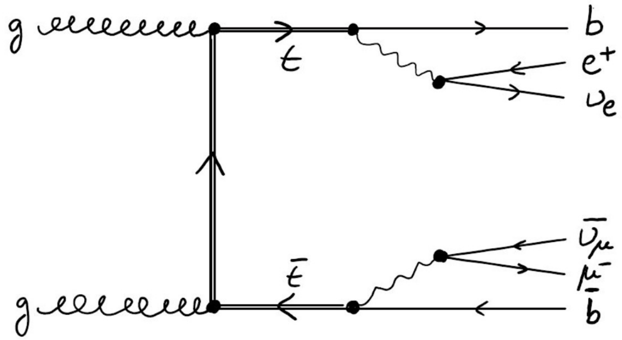
$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$

Non-resonant diagram



On-Shell Predictions

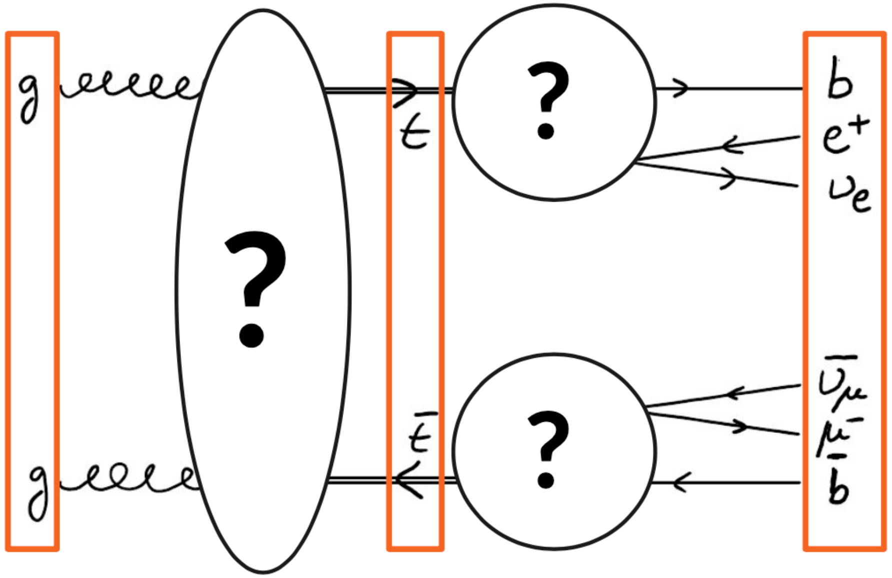
- Modelling of unstable particles based on tt



$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$

Narrow-width approximation (NWA)
→ Fix intermediate state to be on-shell

$$\frac{\Gamma}{m} \to 0$$



$$\frac{\Gamma_W}{m_W} > \frac{\Gamma_t}{m_t} \gg \frac{\Gamma_H}{m_H},$$

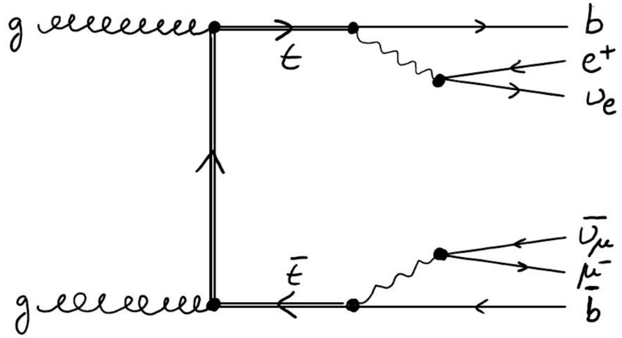
$$2.6\% > 0.8\% \gg 0.003\%$$

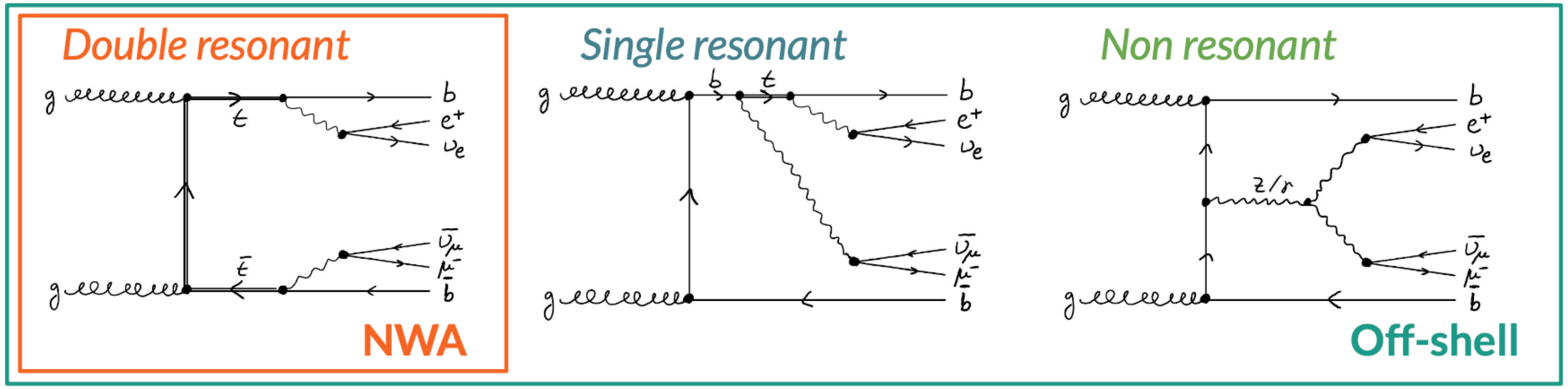
- Good approximation for very inclusive observables
  - Integrated cross sections
  - Angular distributions

Off-Shell versus On-Shell Predictions

- Modelling of unstable particles based on $pp \to tt$

$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$





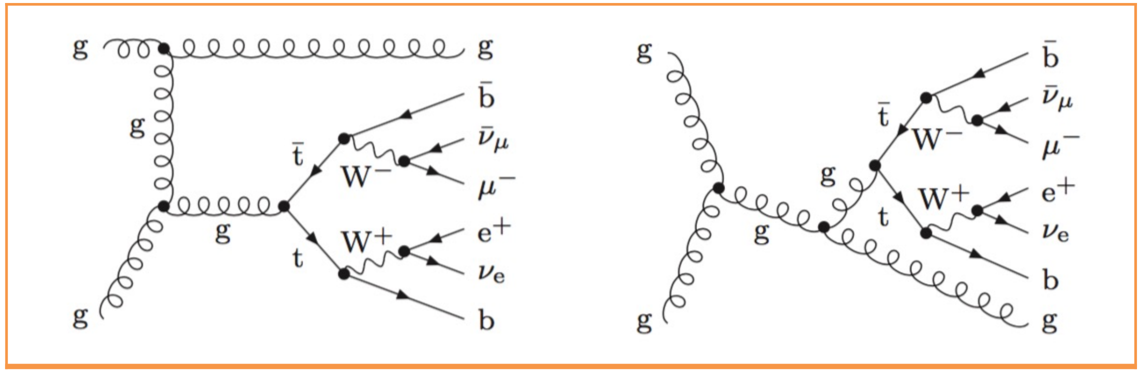
✓ Full off-shell = DR + SR + NR + interferences + Breit-Wigner propagators ⇛ @ NLO QCD

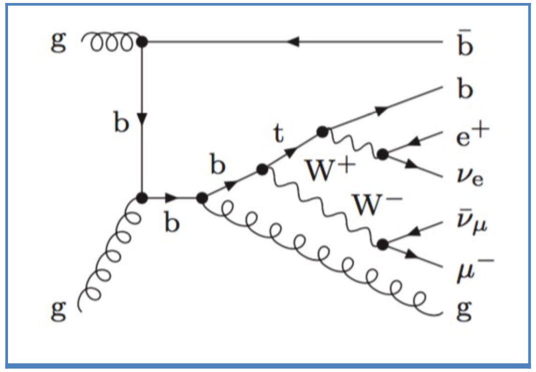
✓ NWA = DR restricts unstable t & W to on-shell states ⇛ @ NLO QCD

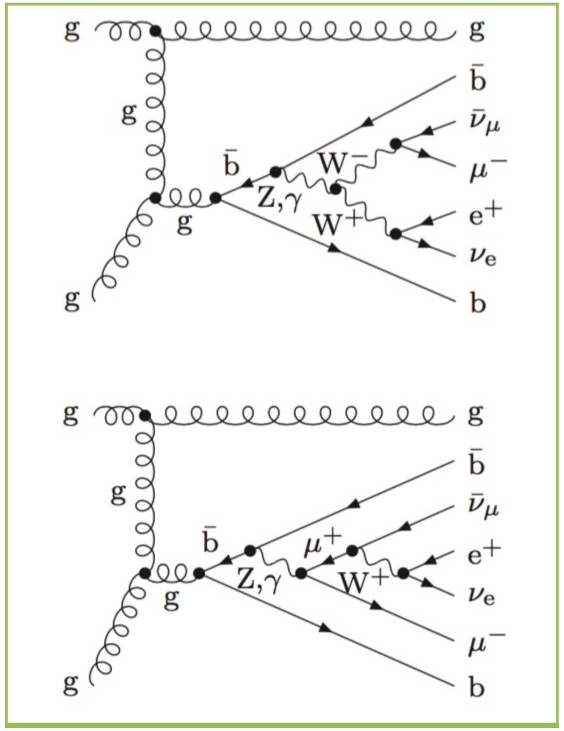
✓ NWA_{LO} = NLO QCD corrections to ttj production only

Off-Shell Predictions for TTJ

- Why do we not make such calculations for all processes?







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

- $pp \to ttj$ with leptonic decays @ $\mathcal{O}(\alpha_s^4\alpha^4)$
- $2 \to 5$ process from QCD point of view $\Rightarrow$ $pp \to WWbbj$
- Diagrams with complete off-shell effects for t & W for gg initial state:
  - *LO: 508*
  - *Real emission: 4447*

Off-Shell Predictions for TTJ

- gg channel comprises *39 180 one-loop diagrams* $\Rightarrow$ According to **QGRAF**

P. Nogueira, J. Comput. Phys. 105 (1993) 279

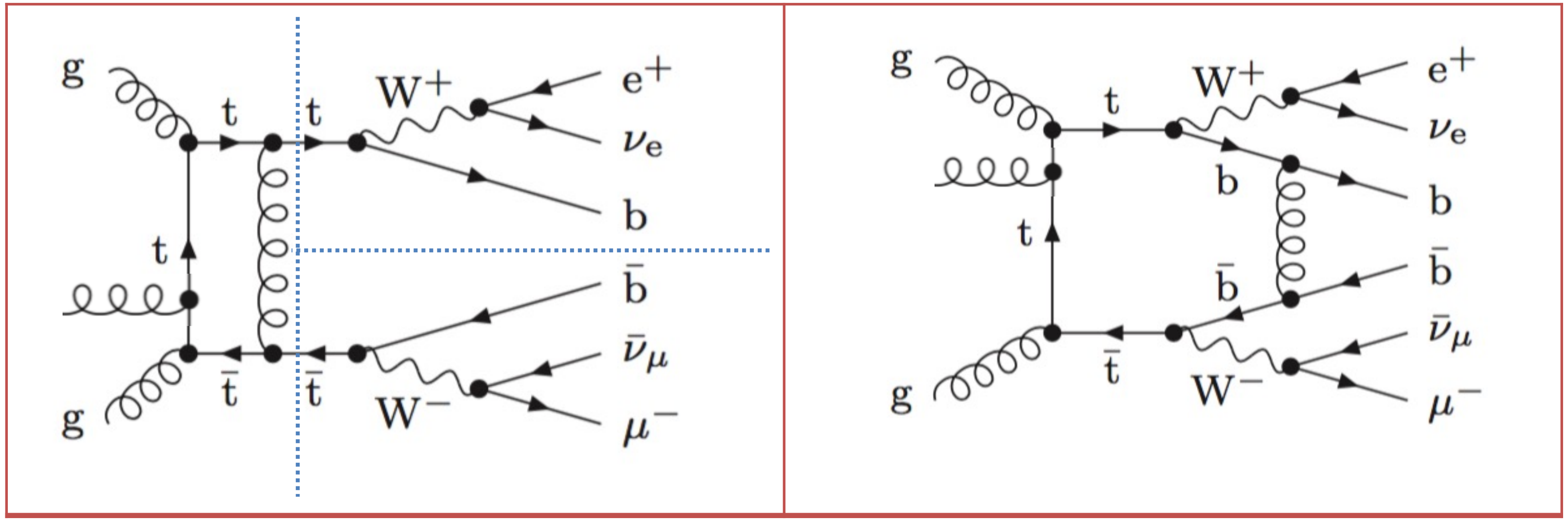
- Most complicated ones are *1155 hexagons & 120 heptagons*
- Tensor integrals up to rank six

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

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

Full calculations for ttj – up to heptagons !

No cross-talk between ttj production & top-quark decays



factorizable & non-factorizable QCD corrections included

Off-Shell Versus On-Shell Predictions

- Modelling of unstable particles in di-lepton channel for $t\bar{t}j$ @ LHC

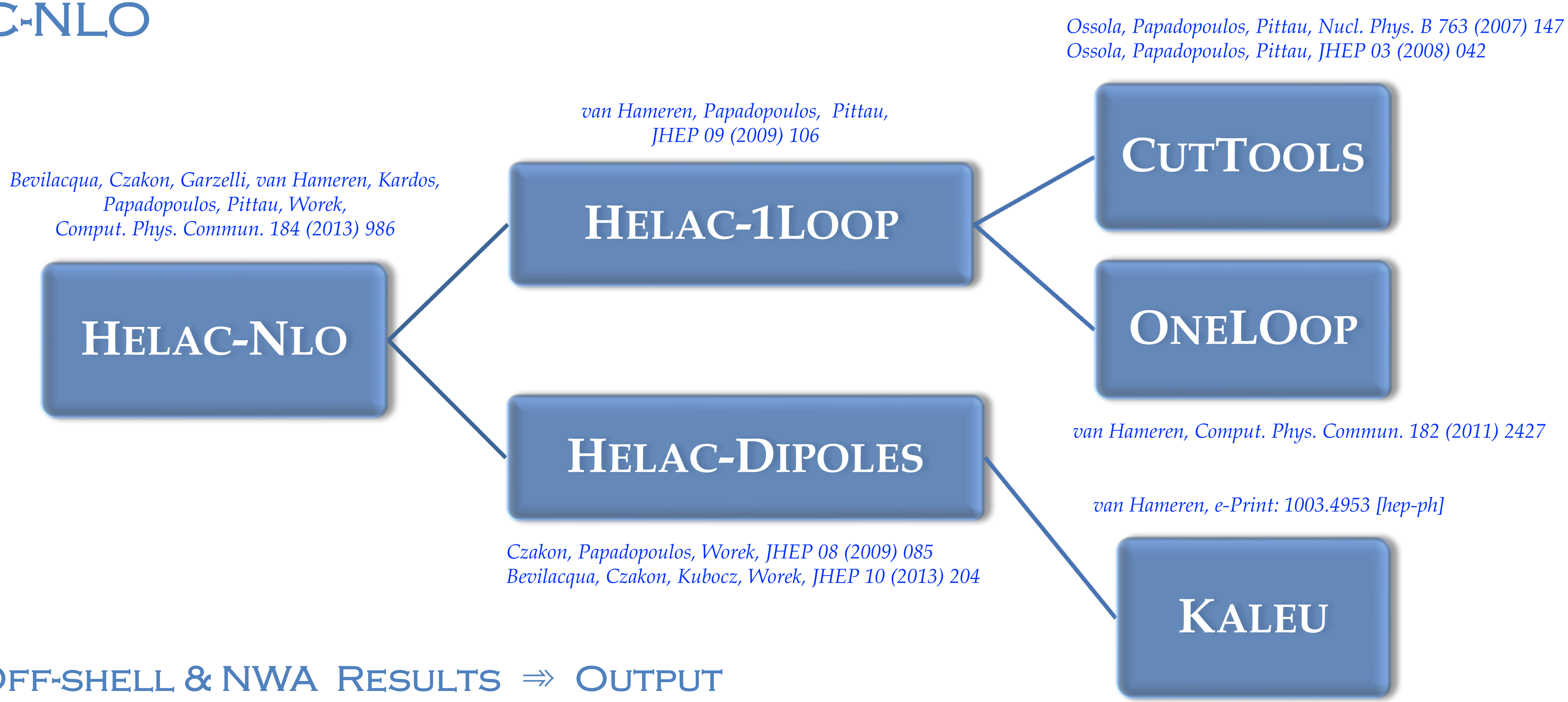
  - Full off-shell = DR + SR + NR + interferences + Breit-Wigner propagators
  - NWA = DR restricts unstable t & W to on-shell states

- Understand two approaches & compare them

- Generally full off-shell predictions impact:

  - IR-safe (integrated) cross sections $\Rightarrow$ Normalisation in BSM $\Rightarrow$ $pp \to t\bar{t} + A$ pseudoscalar Higgs boson
  - IR-safe (differential) observables $\Rightarrow$ Shape of dimensionful distributions $\Rightarrow$ high p_T & kinematical edges
  - SM parameter extraction $\Rightarrow$ m_t
  - BSM exclusion limits $\Rightarrow$ $pp \to t\bar{t} + DM$ @ LHC with SM background processes $pp \to t\bar{t}$ & $pp \to t\bar{t}Z$
  - New Physics signal modelling $\Rightarrow$ $pp \to t\bar{t}H$ with anomalous couplings $\Rightarrow$ $pp \to t\bar{t}H$ in SMEFT
  - Definition of $pp \to tW$ & $pp \to t\bar{t}$ $\Rightarrow$ Diagram removal versus Diagram subtraction
  - Final systematic uncertainties
  - Matching to parton shower programs $\Rightarrow$ Resonant aware matching is required

HELAC-NLO



- FULL OFF-SHELL & NWA RESULTS ⇒ OUTPUT
  - Predictions stored as partially unweighted "events" ⇒ *ROOT-Ntuples Files & Les Houches Files*
  - Each "event" provided with supplementary matrix element & PDF information
  - Results for different scale settings & PDF choices by can be obtained by reweighting
  - Different observables and/or binning can be provided + more exclusive cuts ⇒ With caveat

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Comput. Phys. Commun. 185 (2014) 1443

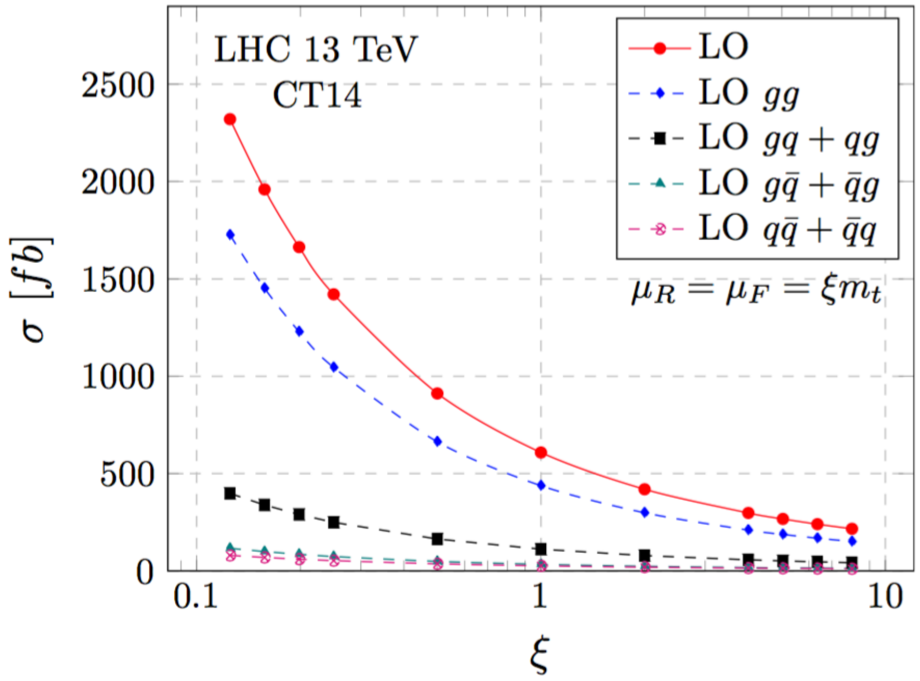
Scale Dependence

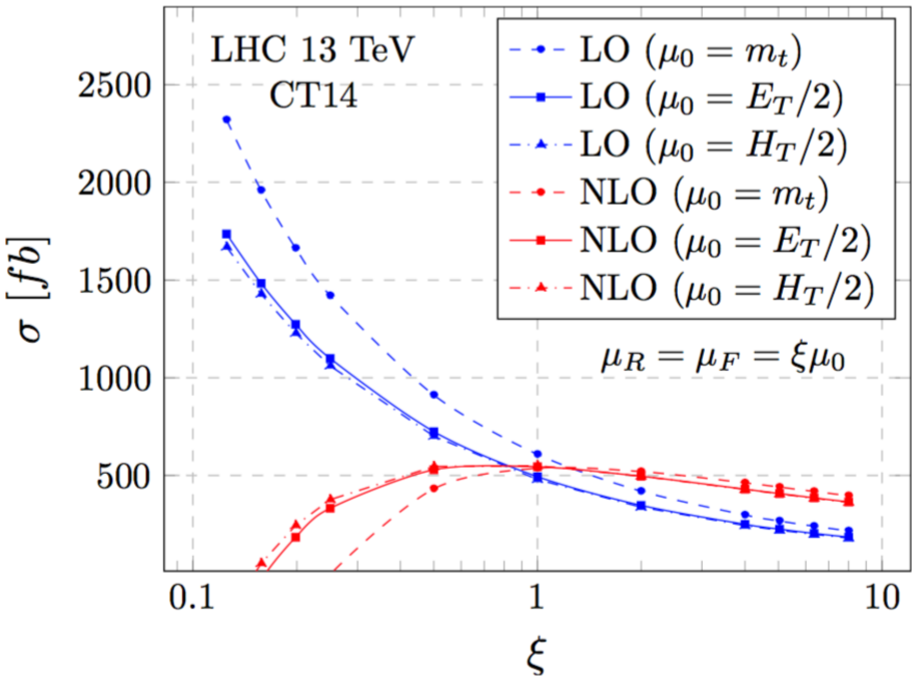
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, JHEP 11 (2016) 098
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

- Integrated cross section @ LHC 13 TeV
- Scales: $\mu_R = \mu_F = \mu_0 = m_t,\ E_T/2,\ H_T/2$

$H_T = \sum_i p_{T,i} + p_T^{\text{miss}}$	$E_T = m_{T,t} + m_{T,\bar{t}}$





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

Scale Dependence

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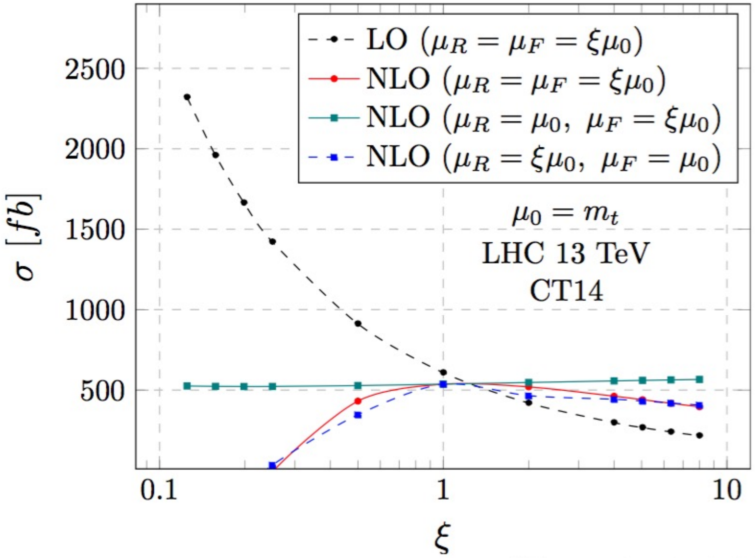
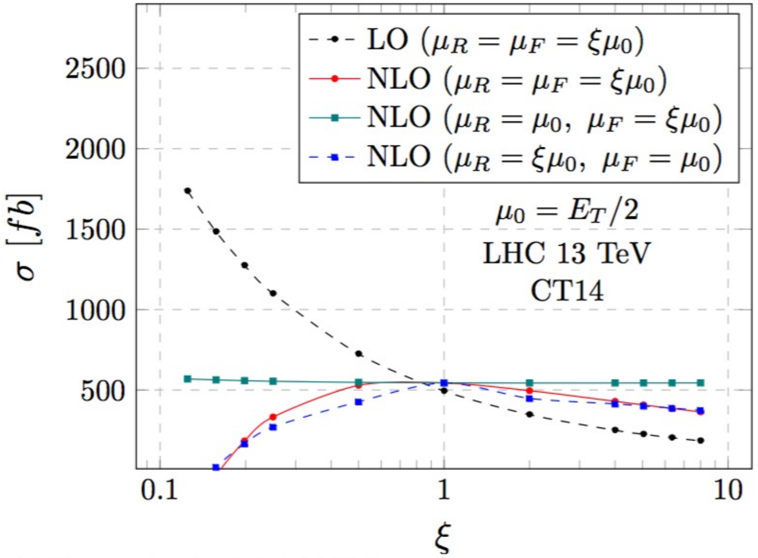
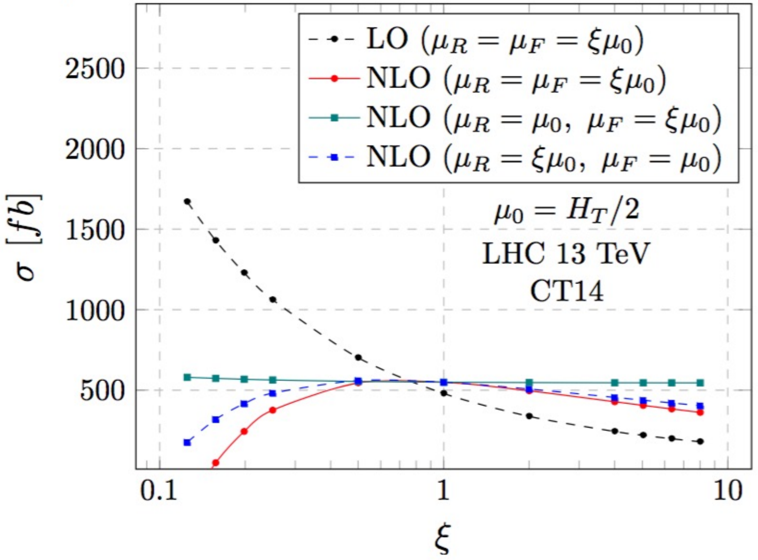
- Integrated cross section *@ LHC $_{13\ TeV}$*







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

- scale variation fully driven by changes in μ_R independently of scale choice
- 7-point scale variation and 3-point scale variation would give similar results

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

$$H_T = p_T(e^+) + p_T(\mu^-) + p_T(j_{b_1}) + p_T(j_{b_2}) + p_T(j_1) + p_T^{\text{miss}}$$

Scale & PDF Uncertainties

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

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, JHEP 11 (2016) 098
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

- Size of NLO corrections for CT14 NLO

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

7-point scale variation

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

$$1/2 \leq \mu_R/\mu_F \leq 2$$

- PDFs: *CT14, MMHT14, NNPDF3.0*

- Integrated fiducial cross sections for $\mu_0 = H_T/2$

68% C.L.

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

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

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

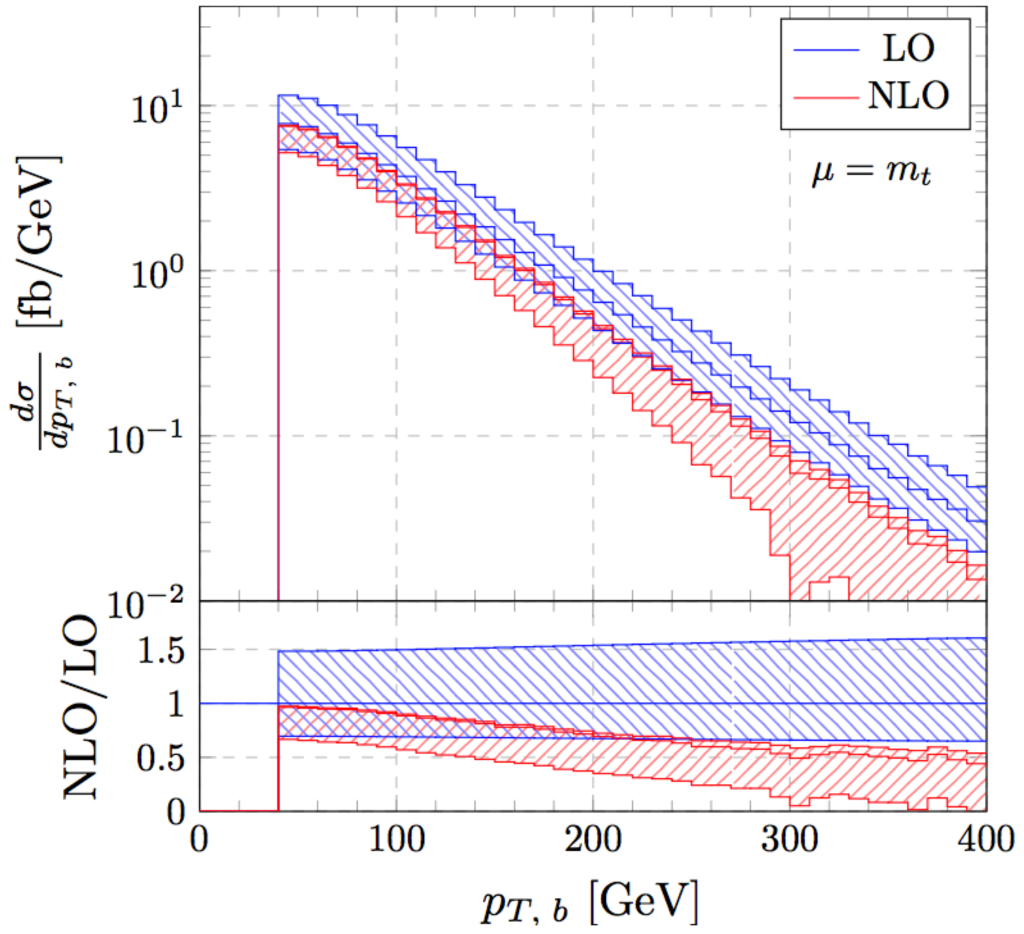
Differential Distributions

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

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, JHEP 11 (2016) 098
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

- 16 differential cross section distributions have been examined, here are just few examples…

- *Dimensionful observable: $p_T(b)$ with $\mu_0 = m_t$*



- NLO do not simply rescale shape of LO $p_T(b)$
- NLO corrections up to -55%
- $p_T(b)$ properly described only via NLO
- Negative NLO results in high p_T tails
- LO higher than NLO in p_T tails

- Dynamic scale should depend on p_T of hardest jet & top-quark decay products ↑
- *Asymptotic freedom ⇒ α_s ↓ in tails*
- *Dependence on α_s @ LO ≫ @ NLO*
- Would drive positive NLO/LO ratio in this region

Differential Distributions

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

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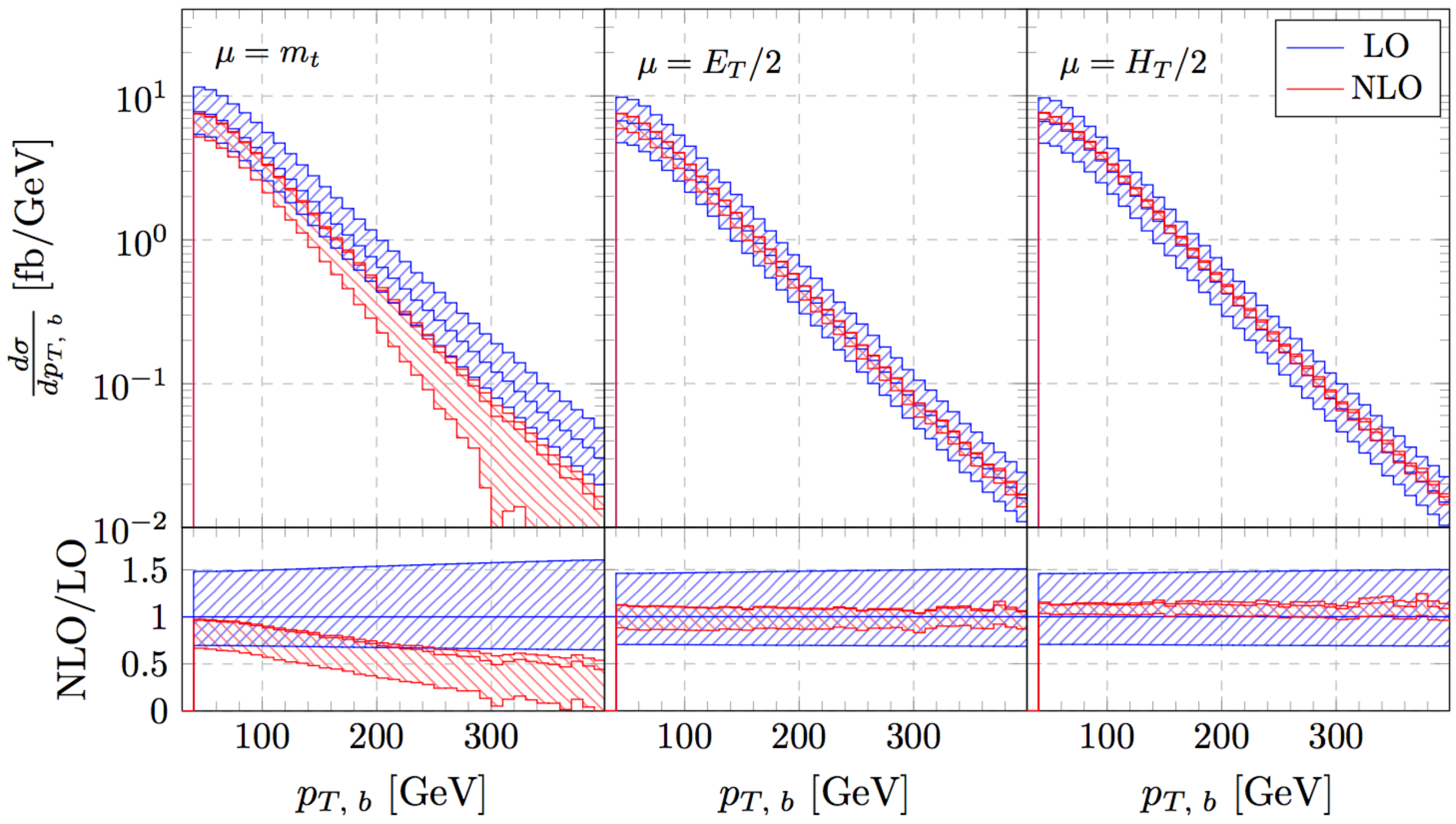
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

- *Dimensionful observable: $p_T(b)$ with all 3 scale settings*

- Positive corrections below *20%* when $\mu_F = \mu_R = \mu_0 = ½\, E_T$ *or* $\mu_F = \mu_R = \mu_0 = ½\, H_T$ used instead



Differential Distributions

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

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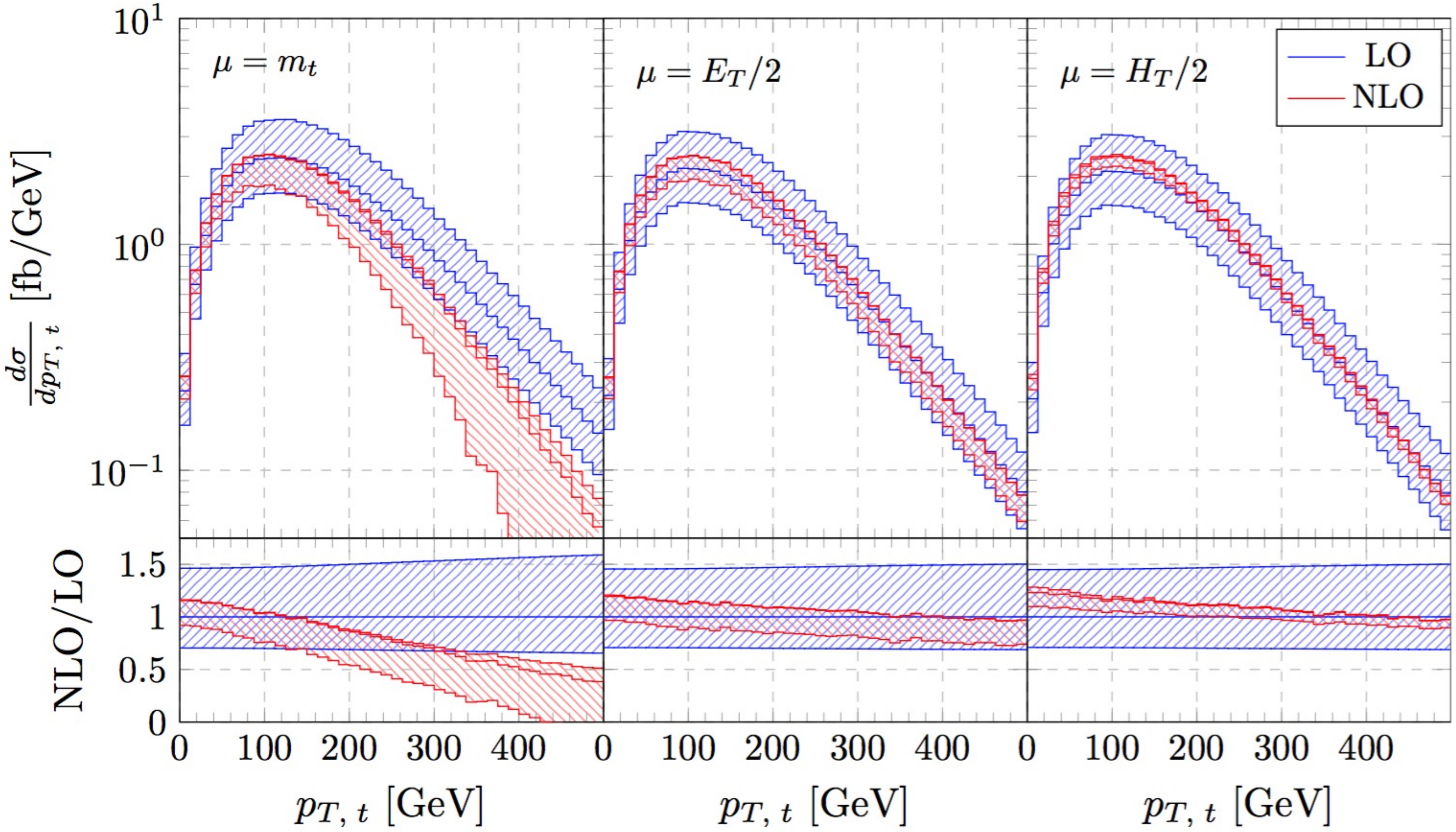
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

- *Dimensionful observable: $p_T(t)$ with all 3 scale settings*

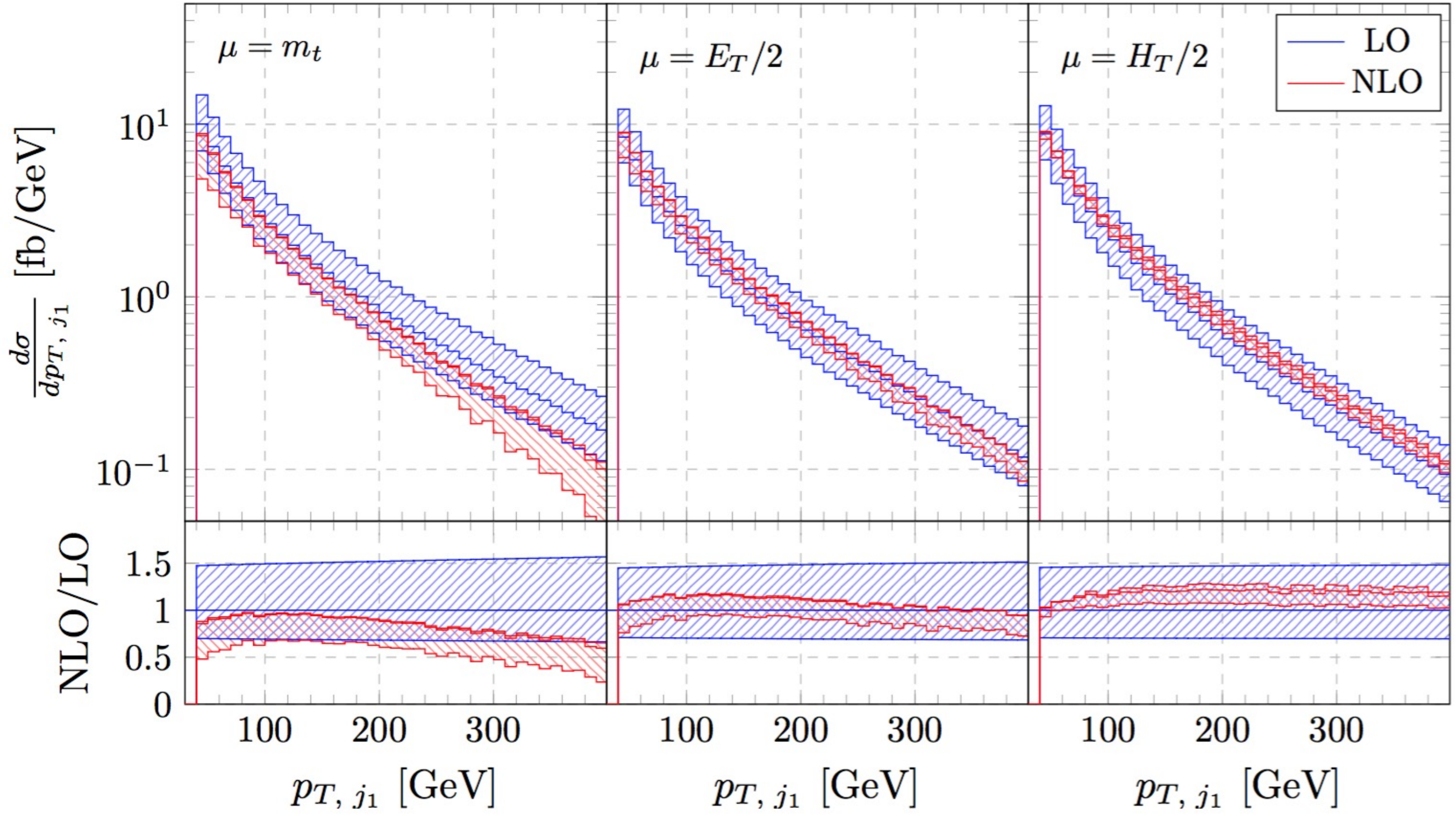


Differential Distributions

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

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, JHEP 11 (2016) 098
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, Phys. Rev. Lett. 116 (2016) 5, 052003

- *Dimensionful observable: $p_T(j_1)$ with all 3 scale settings*



Differential Distributions

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

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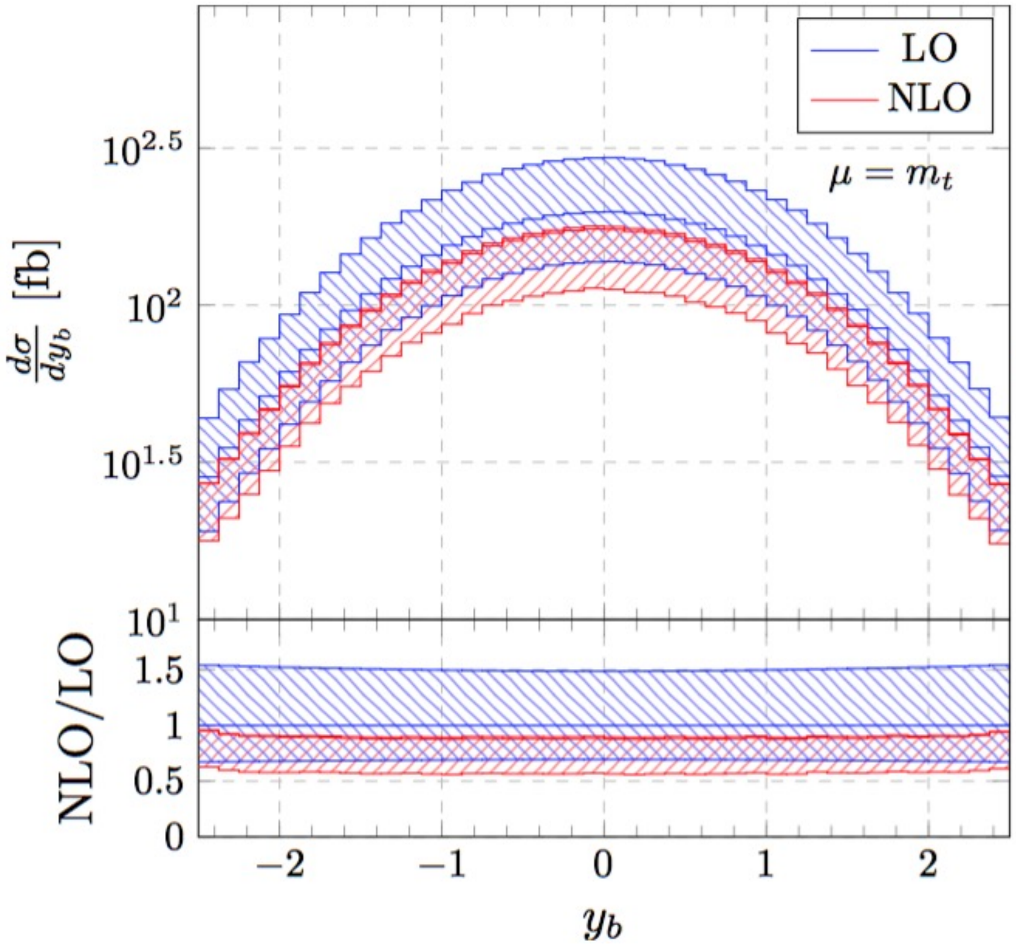
- *Dimensionless observable: y(b) with $\mu_0 = m_t$*



- Negative, moderate *10%* ⇒ But quite stable NLO corrections
- Receives contributions from various scale settings ⇒ Also from these sensitive to threshold for *tt* production
- For $\mu_F = \mu_R = \mu_0 = m_t$ effects of phase-space regions close to *ttj* threshold dominate

Differential Distributions

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

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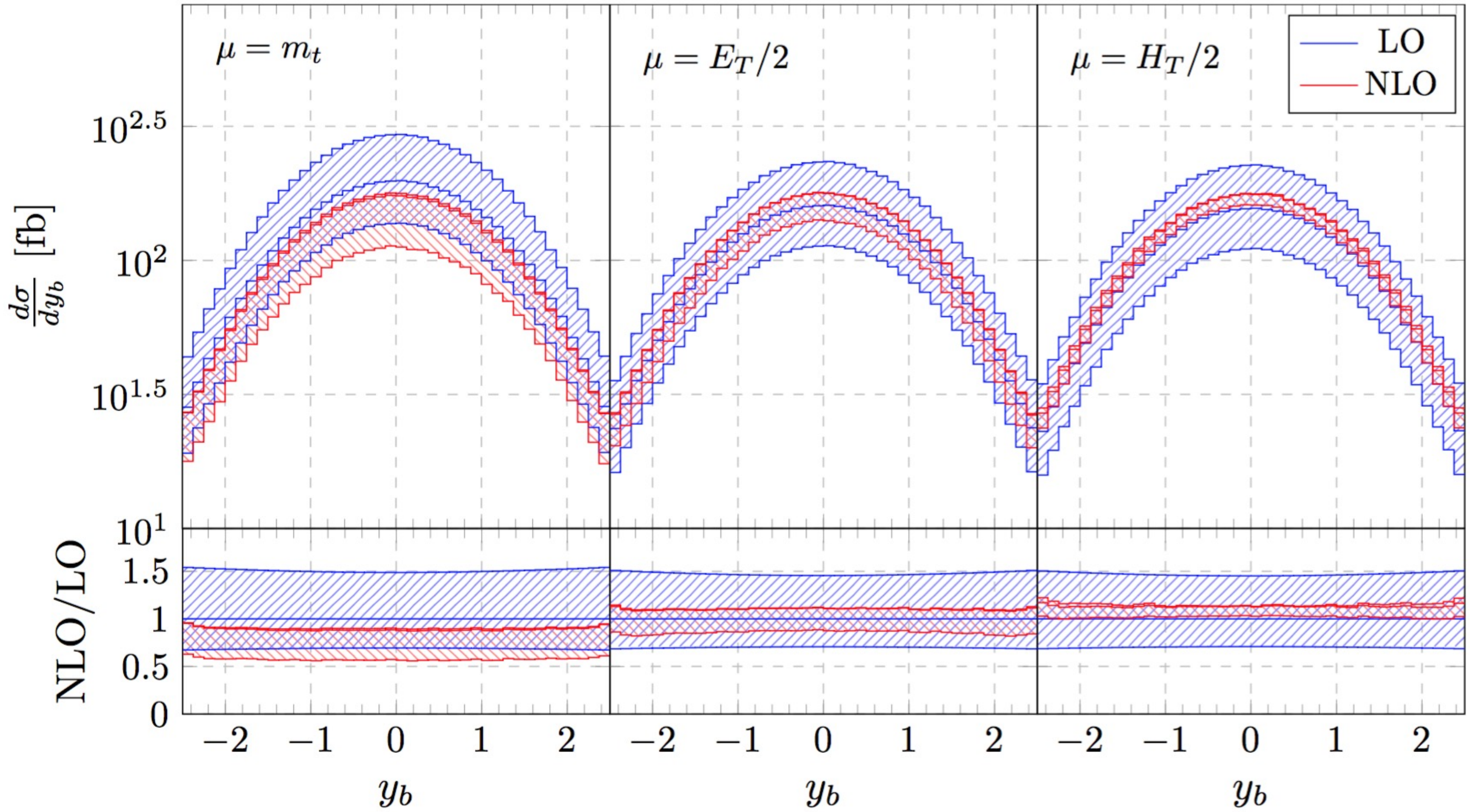
- *Dimensionless observable: y(b) with all 3 scale settings*

- Replaced by positive moderate NLO corrections for dynamical scale settings



Scale & PDF Uncertainties

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

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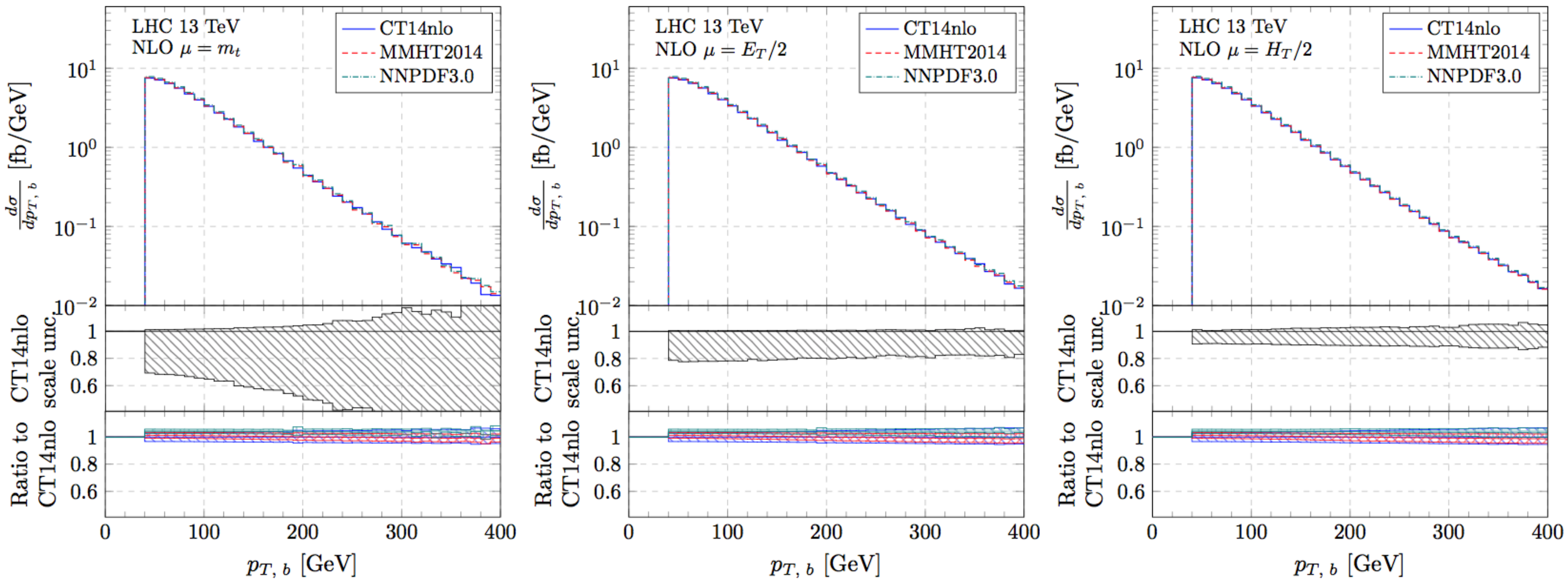
- *Upper panel*
  - NLO prediction for three different PDF sets at $\mu_F = \mu_R = \mu_0$
- *Middle panel*
  - NLO scale-dependence band normalized to central CT14 NLO prediction
- *Lower panel*
  - PDF uncertainties obtained for each PDF set separately $\Rightarrow$ Normalized to central NLO prediction with CT14 PDF set



Scale & PDF Uncertainties

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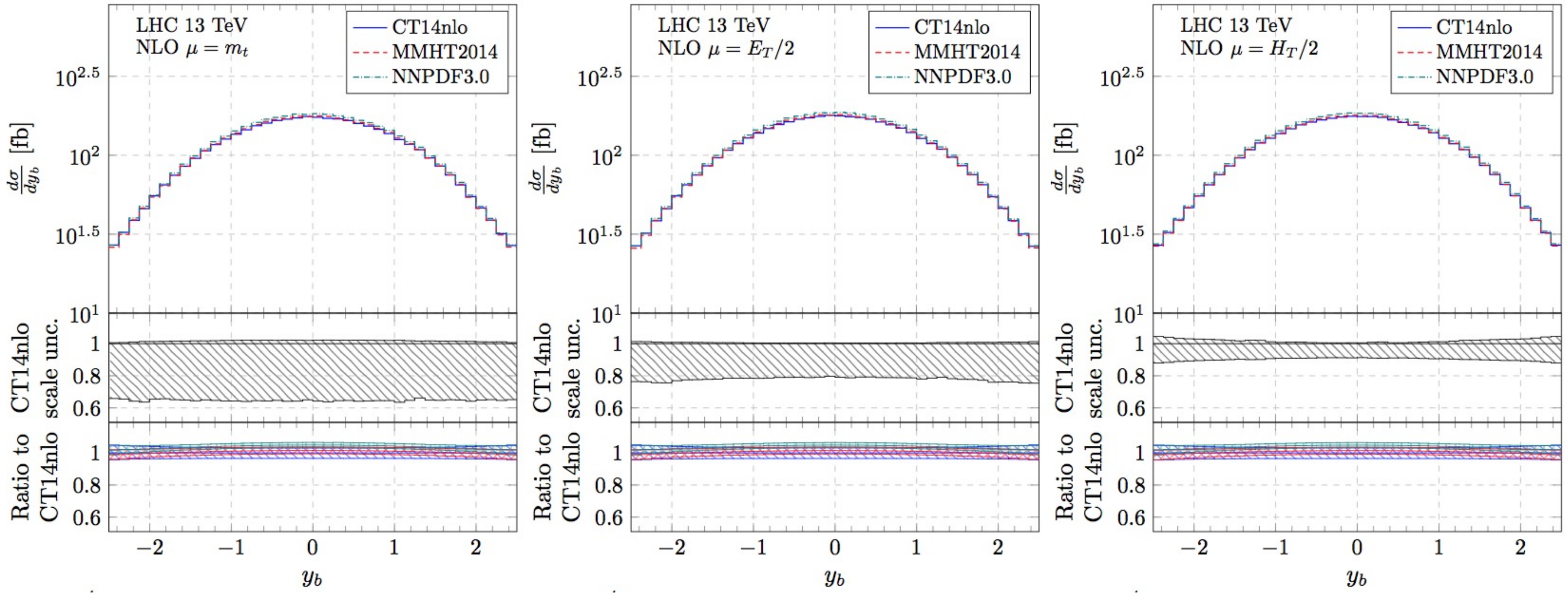
- $p_T(b)$ $\Rightarrow$ For $\mu_0 = ½\, H_T$ scale uncertainties have reached almost *10%* $\Rightarrow$ PDF uncertainties stayed below *6%*
- $y(b)$ $\Rightarrow$ For $\mu_0 = ½\, H_T$ scale uncertainties are below *8%* $\Rightarrow$ PDF uncertainties are below *5%*
- Scale uncertainties dominant source of theoretical uncertainties

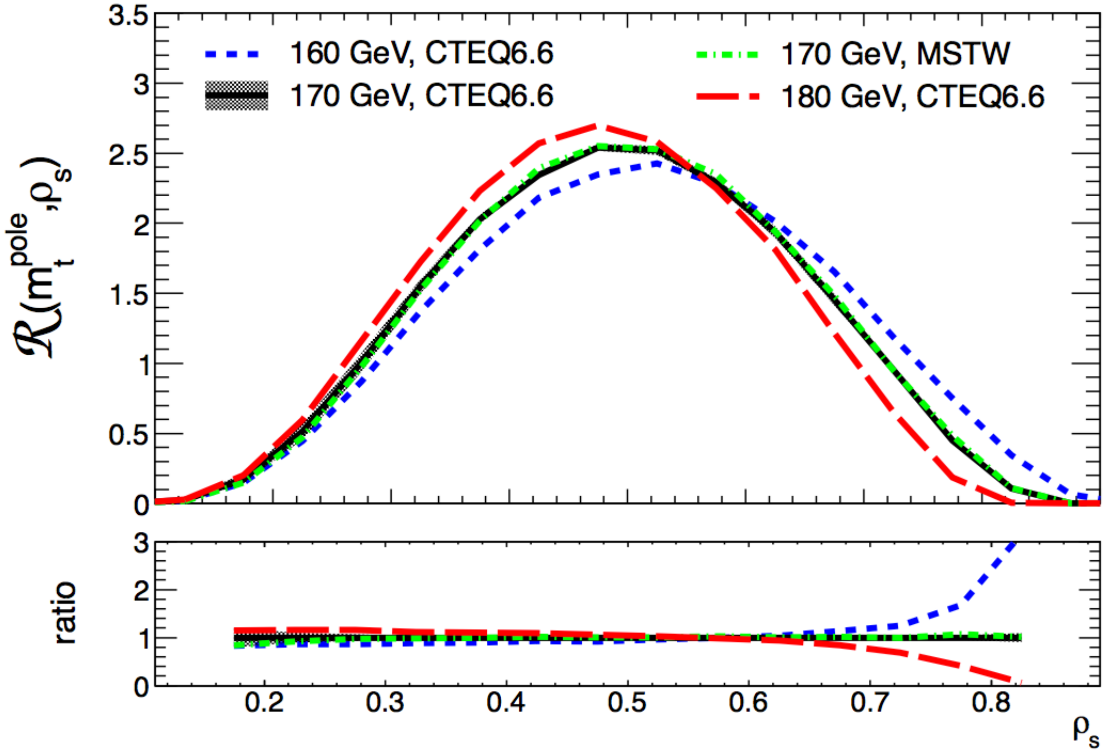


Applications

- Alternative method for m_t
- m_t from normalized differential cross section for $pp \to ttj$
- $\mathcal{R}$ has been calculated using $pp \to ttj$ @ NLO in QCD + **POWHEG** matched with **PYTHIA**
- Theoretical uncertainties & PDF uncertainties affect m_t extraction $< 1\ GeV$
- Worth looking at …

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

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

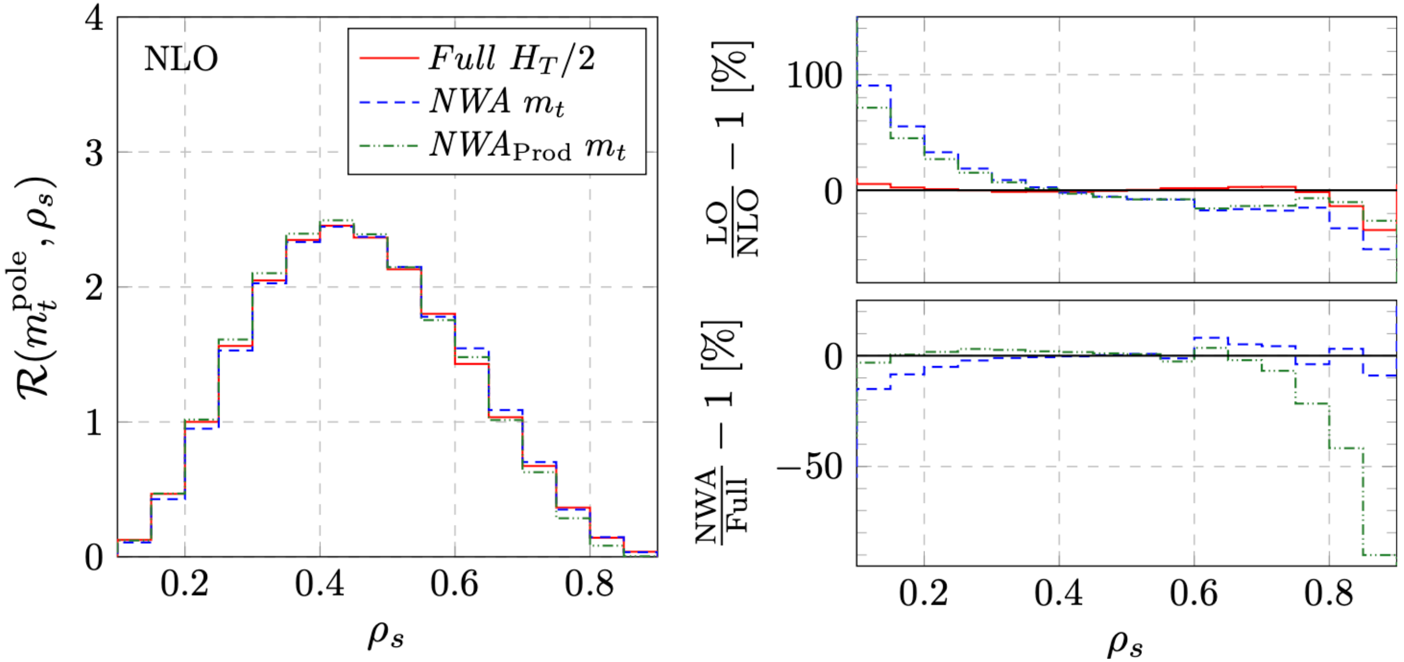


S. Alioli, P. Fernandez, J. Fuster, A. Irles, S. O. Moch, P. Uwer, M. Vos, Eur. Phys. J. C 73 (2013) 2438

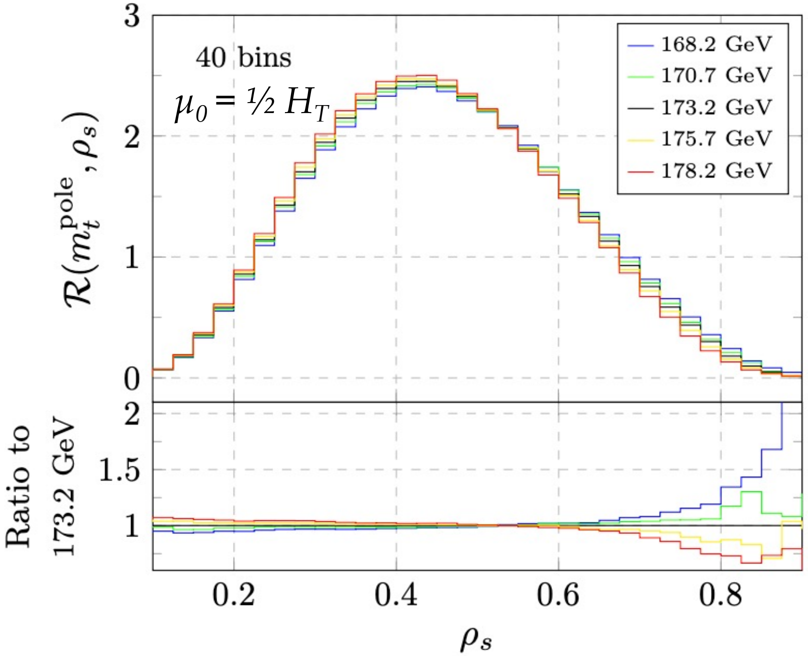
Off-Shell Versus On-Shell Predictions

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

Shape differences @ differential level



Full case for five different top quark masses



- Normalised ρ_s differential distribution
- Three different theoretical descriptions
  - Relative size of NLO QCD corrections
  - Relative size of full off-shell *t & W* effects
  - Relative size of corrections to top-quark decays

Normalisation differences @ integrated level

	Full $[m_t]$	*Full* $[\frac{1}{2}H_T]$	*NWA* $[m_t]$	$NWA_{\text{Prod.}}$ $[m_t]$	$\frac{NWA}{Full} - 1$ $[m_t/m_t]$	$\frac{NWA}{Full} - 1$ $[m_t/\frac{1}{2}H_T]$
$\sigma^{\text{NLO}}_{t\bar{t}j}$ [fb]	537.2	538.6	527.1	656.1	−1.9%	−2.1%

- Full off-shell effects change NLO cross section by 2%
- Consistent with uncertainty of NWA $\Rightarrow$ $\mathcal{O}(\Gamma_t/m_t)$

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Off-Shell Versus On-Shell Predictions

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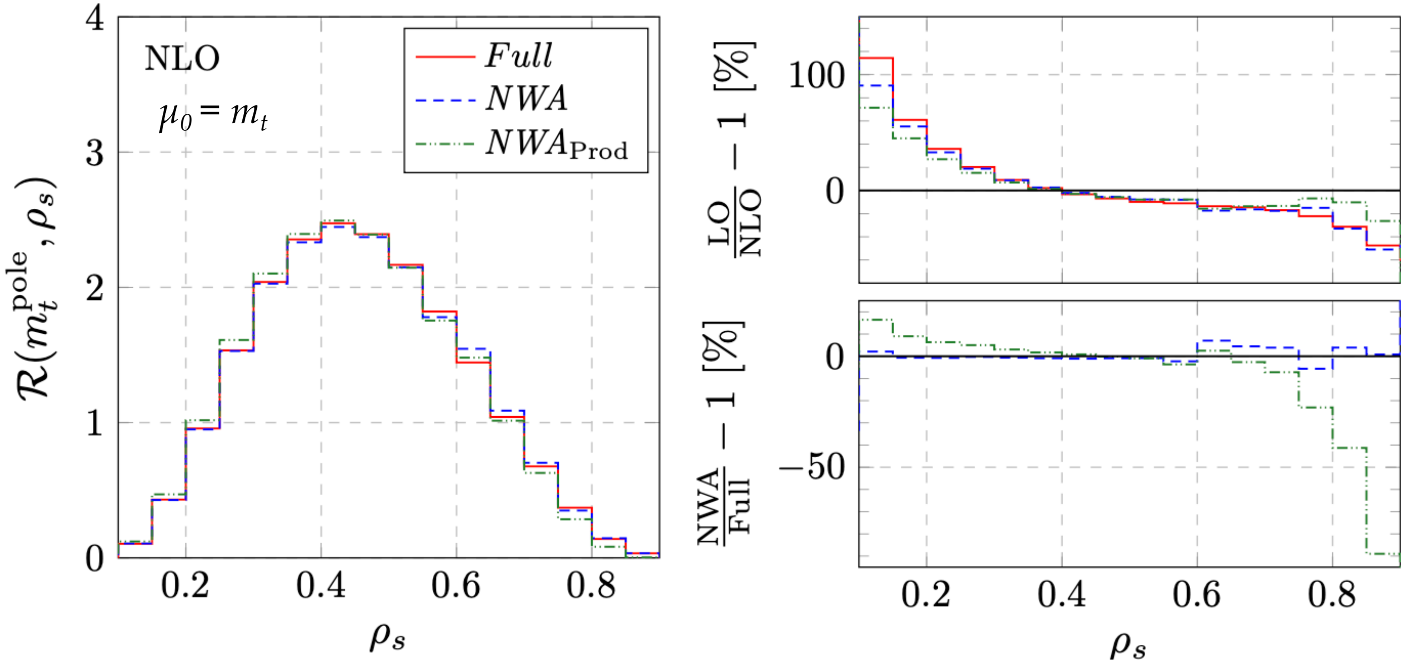
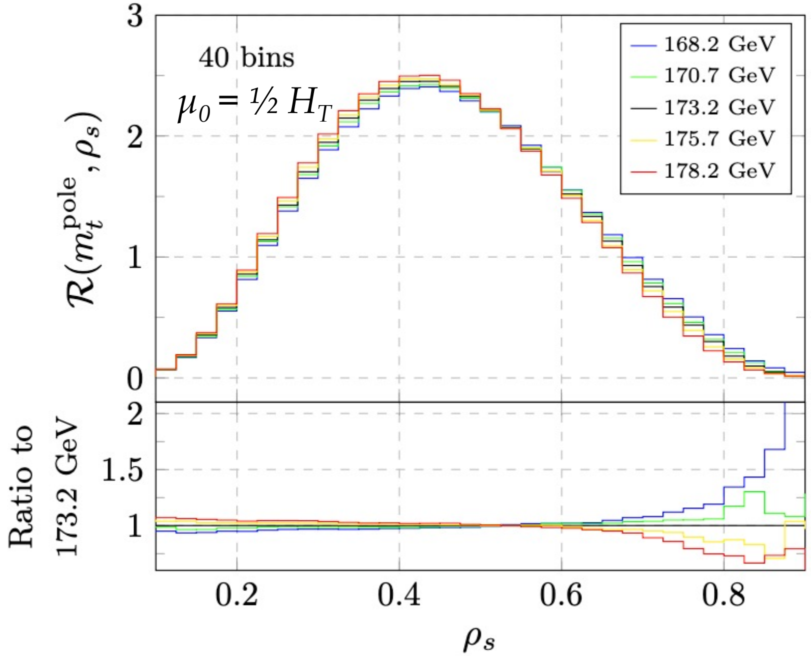
Shape differences @ differential level



Full case for five different top quark masses



- Normalised ρ_s differential distribution
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Off-Shell Versus On-Shell Predictions

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

Luminosity of 2.5 fb^{-1} & m_t^{in} = 173.2 GeV

Same bin size

Different bin size

Theory, NLO QCD CT14 PDF	$m_t^{\rm out} \pm \delta m_t^{\rm out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\rm in} - m_t^{\rm out}$ [GeV]
31 bins				
Full, $\mu_0 = H_T/2$	173.38 ± 1.34	1.04	0.40 (0.8σ)	−0.18
Full, $\mu_0 = E_T/2$	172.84 ± 1.33	1.05	0.39 (0.9σ)	+0.36
Full, $\mu_0 = m_t$	174.11 ± 1.39	1.07	0.37 (0.9σ)	−0.91
NWA, $\mu_0 = m_t$	175.70 ± 0.96	1.17	0.24 (1.2σ)	−2.50
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.93 ± 0.98	1.20	0.20 (1.3σ)	+3.27
5 bins				
Full, $\mu_0 = H_T/2$	173.15 ± 1.32	0.93	0.44 (0.8σ)	+0.05
Full, $\mu_0 = E_T/2$	172.55 ± 1.18	1.07	0.37 (0.9σ)	+0.65
Full, $\mu_0 = m_t$	173.92 ± 1.38	1.48	0.20 (1.3σ)	−0.72
NWA, $\mu_0 = m_t$	175.54 ± 0.97	1.38	0.24 (1.2σ)	−2.34
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.37 ± 1.43	1.16	0.33 (1.0σ)	+3.83
ATLAS binning				
Full, $\mu_0 = H_T/2$	173.05 ± 1.31	0.99	0.42 (0.8σ)	+0.15
Full, $\mu_0 = E_T/2$	172.19 ± 1.34	1.05	0.39 (0.9σ)	+1.01
Full, $\mu_0 = m_t$	173.86 ± 1.39	1.42	0.21 (1.2σ)	−0.66
NWA, $\mu_0 = m_t$	175.22 ± 1.15	1.38	0.23 (1.2σ)	−2.02
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.39 ± 1.46	1.12	0.35 (0.9σ)	+3.81
CMS binning				
Full, $\mu_0 = H_T/2$	173.09 ± 1.53	0.94	0.44 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.20 ± 1.54	0.96	0.43 (0.8σ)	+1.00
Full, $\mu_0 = m_t$	173.94 ± 1.49	1.42	0.22 (1.2σ)	−0.74
NWA, $\mu_0 = m_t$	175.66 ± 1.10	1.42	0.22 (1.2σ)	−2.46
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.96 ± 1.80	1.00	0.41 (0.8σ)	+3.24

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- Agreement within *$0.8\sigma - 1.3\sigma$* between various theoretical descriptions & pseudo-data
- *68 % C.L. (1σ)* statistical error ⇒ Still large ⇒ *0.96 – 1.80*
- Averaged minimal *χ^2/d.o.f* is of order of *1*
- Number of standard deviations for each *p-value*
- Top quark mass shift ⇒ Depending on theory used various mass shifts are observed
  - *2.0 – 2.5 GeV* mass shift is visible for NWA with $\mu_0 = m_t$ if pseudo data obtained from full off-shell case with $\mu_0 = ½\, H_T$
  - *1.2 – 2.0 GeV* mass shift is visible for NWA with $\mu_0 = m_t$ if pseudo data obtained from full off-shell case with $\mu_0 = m_t$
  - For $\mathrm{NWA}_{\rm Prod.}$ substantial deviation ⇒ *3.2 – 3.8 GeV*

Off-Shell Versus On-Shell Predictions

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

- For higher luminosity despite diminished quality of $\chi^2/d.o.f$ fit mass shifts persist
  - Up to *2.5 GeV* for NWA with $\mu_0 = m_t$ when pseudo-data are generated from full off-shell case with $\mu_0 = ½\, H_T$
  - Up to *2.0 GeV* for NWA with $\mu_0 = m_t$ when pseudo-data are generated from full off-shell case with $\mu_0 = m_t$
- Statistical error $\Rightarrow$ *0.3 – 0.4 GeV* only
- NWA case is disfavoured at *4σ – 5σ level*
- $\mathrm{NWA_{Prod.}}$ at *2σ – 5σ level*
- Full off-shell case with $\mu_0 = m_t$ at *3σ – 4σ level*
- *Off-shell effects and non-resonant contributions of t & W are not negligible for top-quark mass extraction*
- *Scale setting plays important role*

Luminosity of 25 fb^{-1} & m_t^{in} = 173.2 GeV

Theory, NLO QCD CT14 PDF	$m_t^{\rm out} \pm \delta m_t^{\rm out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\rm in} - m_t^{\rm out}$ [GeV]
		31 bins		
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$	173.76 ± 0.40	1.87	0.003 (3.0σ)	−0.56
NWA, $\mu_0 = m_t$	175.65 ± 0.31	2.99	$7 \cdot 10^{-8}$ (5.4σ)	−2.45
NWA$_{\rm Prod.}$, $\mu_0 = m_t$	169.59 ± 0.30	3.10	$2 \cdot 10^{-8}$ (5.6σ)	+3.61
		5 bins		
Full, $\mu_0 = H_T/2$	173.08 ± 0.40	0.94	0.44 (0.8σ)	+0.12
Full, $\mu_0 = E_T/2$	172.48 ± 0.38	1.58	0.18 (1.3σ)	+0.72
Full, $\mu_0 = m_t$	173.75 ± 0.40	6.76	$2 \cdot 10^{-5}$ (4.3σ)	−0.55
NWA, $\mu_0 = m_t$	175.49 ± 0.30	5.31	$2 \cdot 10^{-4}$ (3.7σ)	−2.29
NWA$_{\rm Prod.}$, $\mu_0 = m_t$	169.39 ± 0.47	3.42	$8 \cdot 10^{-3}$ (2.6σ)	+3.81
		ATLAS binning		
Full, $\mu_0 = H_T/2$	173.06 ± 0.44	0.97	0.44 (0.8σ)	+0.14
Full, $\mu_0 = E_T/2$	172.36 ± 0.44	1.38	0.23 (1.2σ)	+0.84
Full, $\mu_0 = m_t$	173.84 ± 0.42	5.12	$1 \cdot 10^{-4}$ (3.9σ)	−0.64
NWA, $\mu_0 = m_t$	175.23 ± 0.37	5.28	$7 \cdot 10^{-5}$ (4.0σ)	−2.03
NWA$_{\rm Prod.}$, $\mu_0 = m_t$	169.43 ± 0.50	2.61	0.02 (2.3σ)	+3.77
		CMS binning		
Full, $\mu_0 = H_T/2$	173.09 ± 0.50	0.96	0.43 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.22 ± 0.48	1.32	0.26 (1.1σ)	+0.98
Full, $\mu_0 = m_t$	174.02 ± 0.46	6.57	$3 \cdot 10^{-5}$ (4.2σ)	−0.82
NWA, $\mu_0 = m_t$	175.74 ± 0.34	6.00	$8 \cdot 10^{-5}$ (3.9σ)	−2.54
NWA$_{\rm Prod.}$, $\mu_0 = m_t$	170.22 ± 0.53	2.19	0.07 (1.8σ)	+2.98

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Scale & PDF Uncertainties

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

$$\left(\Delta m_t^{\rm out}\right)_\mu = \pm \max\left\{ \left| m_t^{\rm out}\left(\frac{\mu_0}{2}, {\rm CT14}\right) - m_t^{\rm out}(\mu_0, {\rm CT14}) \right| \right.$$
$$\left. \left| m_t^{\rm out}(2\mu_0, {\rm CT14}) - m_t^{\rm out}(\mu_0, {\rm CT14}) \right| \right\}$$

$$\left(\Delta m_t^{\rm out}\right)_{\rm PDF} = \pm \max\left\{ \left| m_t^{\rm out}(\mu_0, {\rm MMHT14}) - m_t^{\rm out}(\mu_0, {\rm CT14}) \right| \right.$$
$$\left. \left| m_t^{\rm out}(\mu_0, {\rm NNPDF3}) - m_t^{\rm out}(\mu_0, {\rm CT14}) \right| \right\}$$

Default setup with $\mu_0 = ½\, H_T$

- Simultaneous variation of renormalisation & factorisation scales up & down by factor of 2 around central value μ_0
- For $\mu_0 = ½\, H_T$ & $\mu_0 = ½\, E_T$ theoretical uncertainties stemming from scale variation ⇒ *0.6 GeV – 1.2 GeV*
- For $\mu_0 = m_t$ they are larger ⇒ *2.1 GeV – 2.8 GeV*
- PDF uncertainties ⇒ *0.4 GeV – 0.7 GeV*
- **Comparison with ATLAS** ⇒ *New setup* ⇒ Full 7-point scale variation & internal PDF uncertainties for NNPDF3.0 with α_s variations, CT18, PDF4LHC21 for 7 different top-quark masses

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Summary

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

- Complete description for $pp \to ttj$ process with **HELAC-NLO** for di-lepton channel
  - "resonant" and "non-resonant" contributions at NLO QCD

- Various scale settings: $\mu_0 = ½\, H_T$ & $\mu_0 = ½\, E_T$ & $\mu_0 = m_t$
- $\mu_0 = ½\, H_T$ "better" than $\mu_0 = ½\, E_T$ ⇛ Booth stabilizes *high* p_T *tails* but $\mu_0 = ½\, H_T$ gives smaller error

- Scale & PDF uncertainties for σ & various $d\sigma/dX$

- Further studies are needed:
  - Bottom-mass effects ⇛ Comparisons between Five- & Four-Flavor schemes

- Phenomenological applications ⇛ Alternative method for m_t extraction
  - Shape-based m_t measurement (e.g. end point of M_{e+b} and/or ρ_s)
  - Relies on precise modeling of top-quark decays
  - *Off-shell effects and non-resonant contributions of t & W are not negligible for top-quark mass extraction*
  - *Scale setting plays important role*
  - Predictions for $pp \to ttj$ should go beyond simple approximation of factorizing top quark production & decays

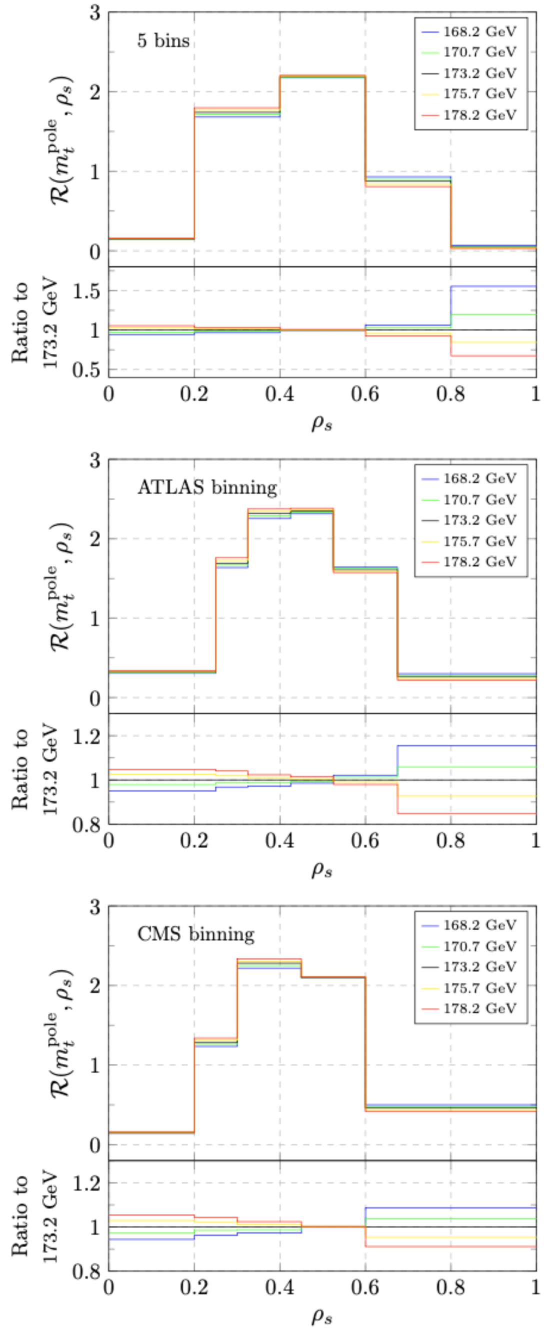
Backup

Normalised ρ_s distribution

5 equal size bins	ATLAS binning	CMS binning
0.00–0.20	0.000–0.250	0.00–0.20
0.20–0.40	0.250–0.325	0.20–0.30
0.40–0.60	0.325–0.425	0.30–0.45
0.60–0.80	0.425–0.525	0.45–0.60
0.80–1.00	0.525–0.675	0.60–1.00
–	0.675–1.000	–

- Various binnings used in m_t extraction from normalised ρ_s distribution
- Three cases are shown:
  - 5 equal size intervals
  - ATLAS intervals
  - CMS intervals
- The latter two optimised for *l+jets & di-lepton* channels @ *7 TeV & 8 TeV*

$$R_i(m_t^{\rm pole}) = \int_{\rho_{i-1}}^{\rho_i} d\rho_s \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t^{\rm pole}, \rho_s)\,, \qquad i = 1, \ldots\,,$$



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Off-shell $t\bar{t}j$

Results are provided for 7 input mass parameters m_t:

- 169 GeV, 170 GeV, 171 GeV, 172 GeV, 172.5 GeV, 173 GeV, 174 GeV

Scale choice:

- $\mu = H_T/2$, where $H_T = p_T^{l_1} + p_T^{l_2} + p_T^{b_1} + p_T^{b_2} + p_T^{miss} + p_T^{j_1}$

Uncertainties:

- 7-point scale variations
- Internal PDF uncertainties for $m_t = 172.5$ GeV for all PDF sets
- Results are provided for multiple PDF sets
- Variations + bands provided for both PDF and scale uncertainties
- All uncertainties are calculated after summing all channels and normalizing

PDF sets:

- NNPDF30_nlo_as_0118_hessian (303000)
    - In addition: α_S variations (265000, 266000)
- CT18NLO (14400)
- PDF4LHC21_40_pdfas (93300)

Off-shell $t\bar{t}j$

- exactly two b-jets, at least one light jet, two charged leptons and missing transverse momentum, denoted as p_T^{miss}
- Cuts:

$$
\begin{array}{lll}
p_{T\,\ell_1}(p_{T\,\ell_2}) > 28\,(20)\ \mathrm{GeV}\,, & p_{T\,b} > 30\ \mathrm{GeV}\,, & p_{T\,j} > 60\ \mathrm{GeV}\,, \\
|y_\ell| < 2.5\,, & |y_b| < 2.5\,, & |y_j| < 2.5\,, \\
\Delta R_{\ell\ell} > 0.4\,, & \Delta R_{bb} > 0.4\,, & \Delta R_{jj} > 0.4\,, \\
\Delta R_{\ell b} > 0.4\,, & \Delta R_{\ell j} > 0.4\,, & \Delta R_{bj} > 0.4
\end{array}
$$

- In the same flavor channels e^+e^- and $\mu^+\mu^-$, we apply $p_T^{miss} > 30\,\mathrm{GeV}$.
- anti-k_T jet clustering algorithm with $R = 0.4$

Normalised ρ_s distribution & TTJ @ NLO QCD

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

$p_{T,\ell} > 30~\mathrm{GeV}\,,$	$p_{T,j} > 40~\mathrm{GeV}\,,$
$\not{p}_T > 40~\mathrm{GeV}\,,$	$\Delta R_{jj} > 0.5\,,$
$\Delta R_{\ell\ell} > 0.4\,,$	$\Delta R_{\ell j} > 0.4\,,$
$\lvert y_\ell\rvert < 2.5\,,$	$\lvert y_j\rvert < 2.5\,,$

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

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

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

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 & missing p_T* $\Rightarrow$ Fairly inclusive cuts

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Normalised ρ_s distribution & TTJ @ NLO QCD

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

$G_\mu = 1.16637 \cdot 10^{-5}\ \mathrm{GeV}^{-2}\,,$ $m_W = 80.399\ \mathrm{GeV}\,,$ $m_Z = 91.1876\ \mathrm{GeV}\,,$	$m_t = 173.2\ \mathrm{GeV}$ $\Gamma_W = 2.09875\ \mathrm{GeV}\,,$ $\Gamma_Z = 2.50848\ \mathrm{GeV}\,.$
$\alpha = \frac{\sqrt{2}}{\pi} G_\mu m_W^2 \sin^2\theta_W$	$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$
$\Gamma_t^{\mathrm{LO}} = 1.47834\ \mathrm{GeV}\,,$	$\Gamma_t^{\mathrm{NLO}} = 1.35146\ \mathrm{GeV}\,.$

- Different lepton generations
- Same lepton interference effects neglected $\Rightarrow$ per-mille level @ LO
- Top width for unstable W bosons, neglecting bottom quark mass
- All light quarks including b-quarks & leptons are massless
- Contribution from b quarks in initial state neglected $\Rightarrow$ Effect $< 1\%$ @ LO

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek, JHEP 11 (2016) 098