Top Quark Mass Studies with $pp \to ttj$ @ LHC

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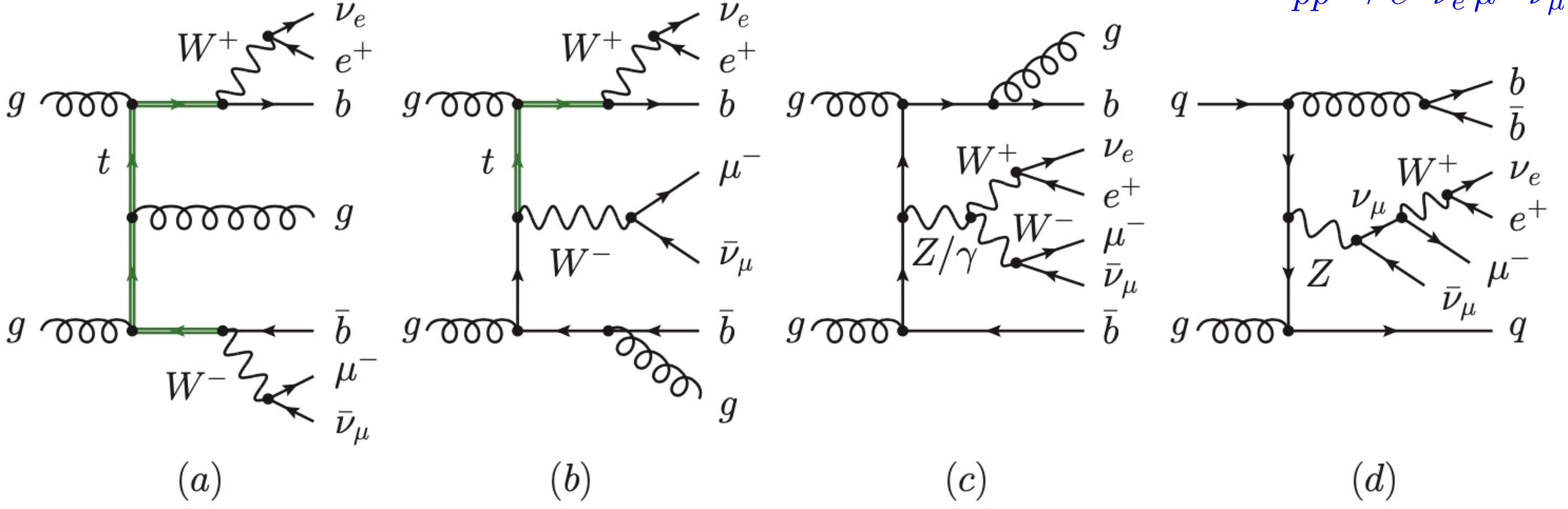
Theory-Experimental Top Quark Mass Workshop, 27-28 June 2022

Plan

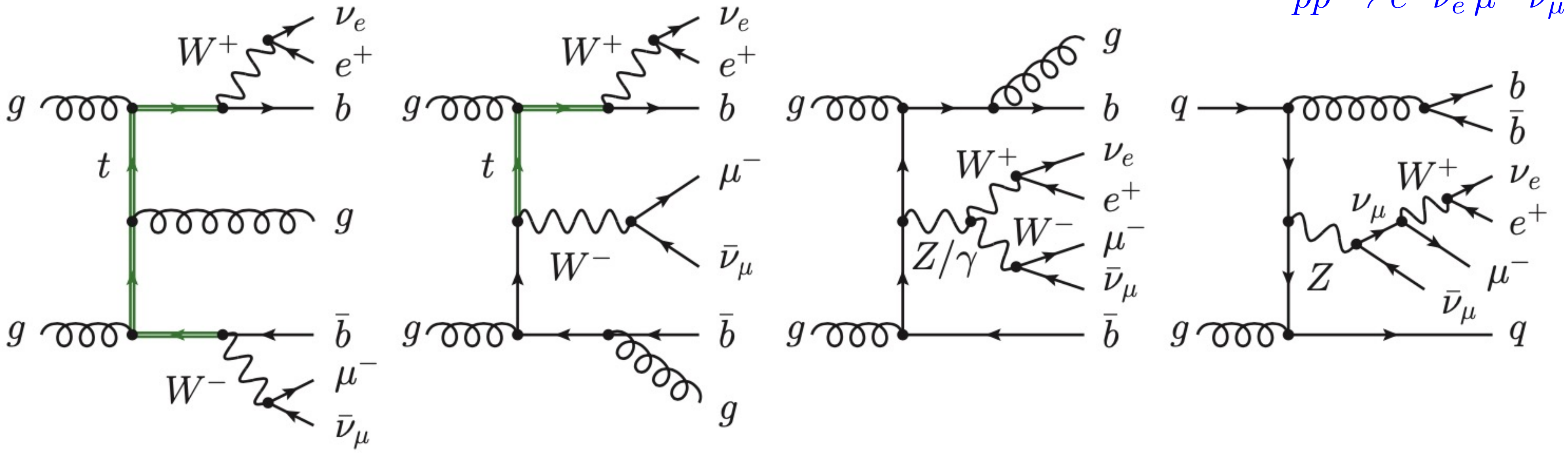
$pp \to e^+ \nu_e \, \mu^- \, \bar{\nu}_\mu \, b\bar{b} \, j + X$



On/Offshell effects in top-quark mass extraction

Full/Complete off-shell effects

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

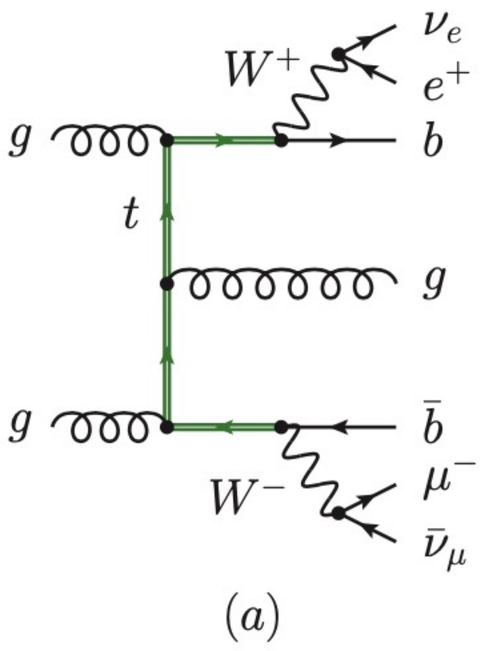


(a) (b) (c) (d)

- Off-shell *t & W* described by Breit-Wigner propagators
- Double-, single- & non-resonant top-quark contributions included
- All interference effects incorporated at matrix element level

- NLO QCD corrections to production & decays
- Nonfactorizable NLO QCD corrections included ⇨ Cross-talk between production & decays
- NLO spin correlations

NWA



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

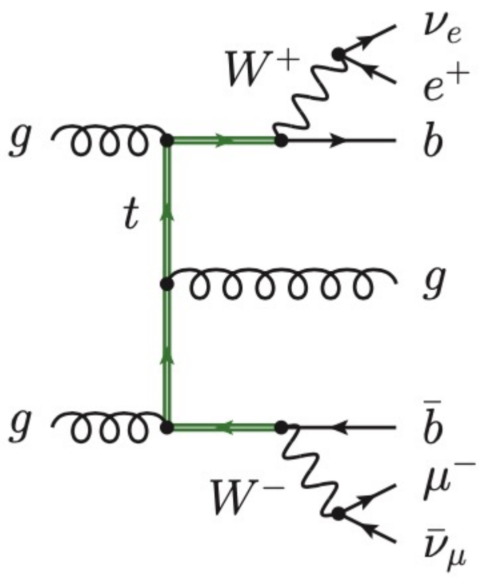
- NWA with LO Decays (NWA$_{\text{LODEC}}$)
  - Without NLO QCD corrections to top-quark decays
  - Hard jet only in production stage
  - LO spin correlations

$$\Gamma_t = 1.35146 \text{ GeV},\ m_t = 173.2\,\text{GeV},\ \Gamma_t/m_t \approx 0.008$$

- Works in the limit ⇨ $\Gamma_t/m_t \to 0$
- Incorporates only double resonant contributions
- Restricts unstable t & W to on-shell states

- NLO QCD corrections separately to production & separately to decays
- Hard jet also emitted in top-quark decay stage
- NLO QCD nonfactorizable corrections missing ⇨ No cross-talk between production & decays
- NLO spin correlations

NLO + PS



(a)

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

POWHEG-BOX MG5_AMC@NLO
POWHEG-BOX + LO DECAYS MG5_AMC@NLO + MADSPIN

- NLO QCD corrections to stable *t & W* matched to parton shower programs: *ttj @ NLO+PS*

- Decays via parton shower ⇨ Without spin correlations
- Decays using LO matrix element
  - Double resonant contributions only
  - Breit-Wigner propagators for *t & W* with some cut-off
  - LO spin correlations
  - Single & non-resonant contributions for *t & W* are still missing as well as their interference effects

Process

- $t\bar{t}j$ @ $\mathcal{O}(\alpha_s^4\alpha^4)$ in fiducial phase space region @ LHC with $\sqrt{s} = 13\ TeV$
- Jets: IR-safe *anti*$-k_T$ jet algorithm with separation parameter set to $R = 0.5$
- We require:

  exactly 2 b-jets, at least one light-jet, two charged leptons & non-zero missing transverse momentum

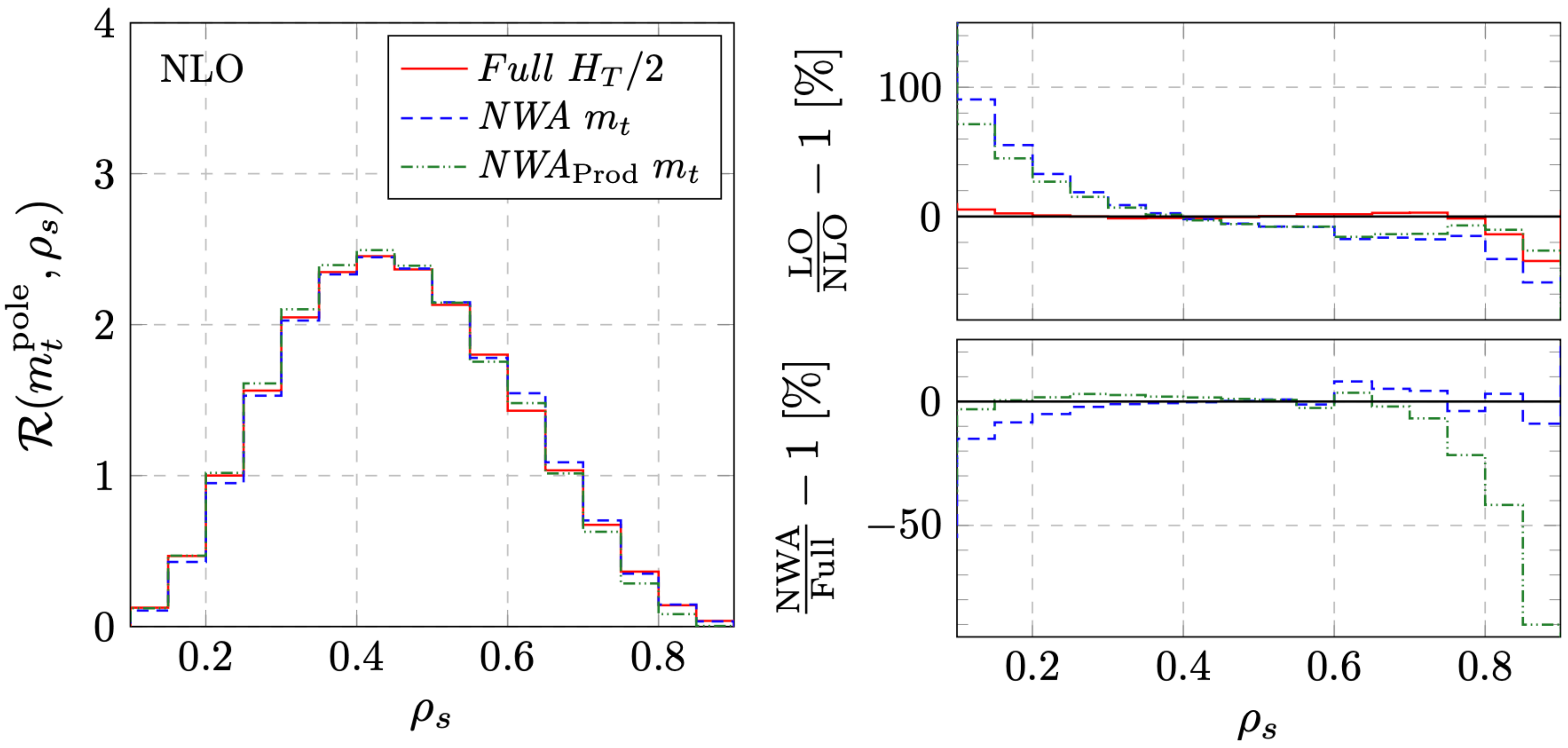
- These final states have to fulfil inclusive selection cuts

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

Observable

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

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t^{pole}, \rho_s)\,, \qquad \text{with} \qquad \rho_s = \frac{2m_0}{M_{t\bar{t}j}}$$



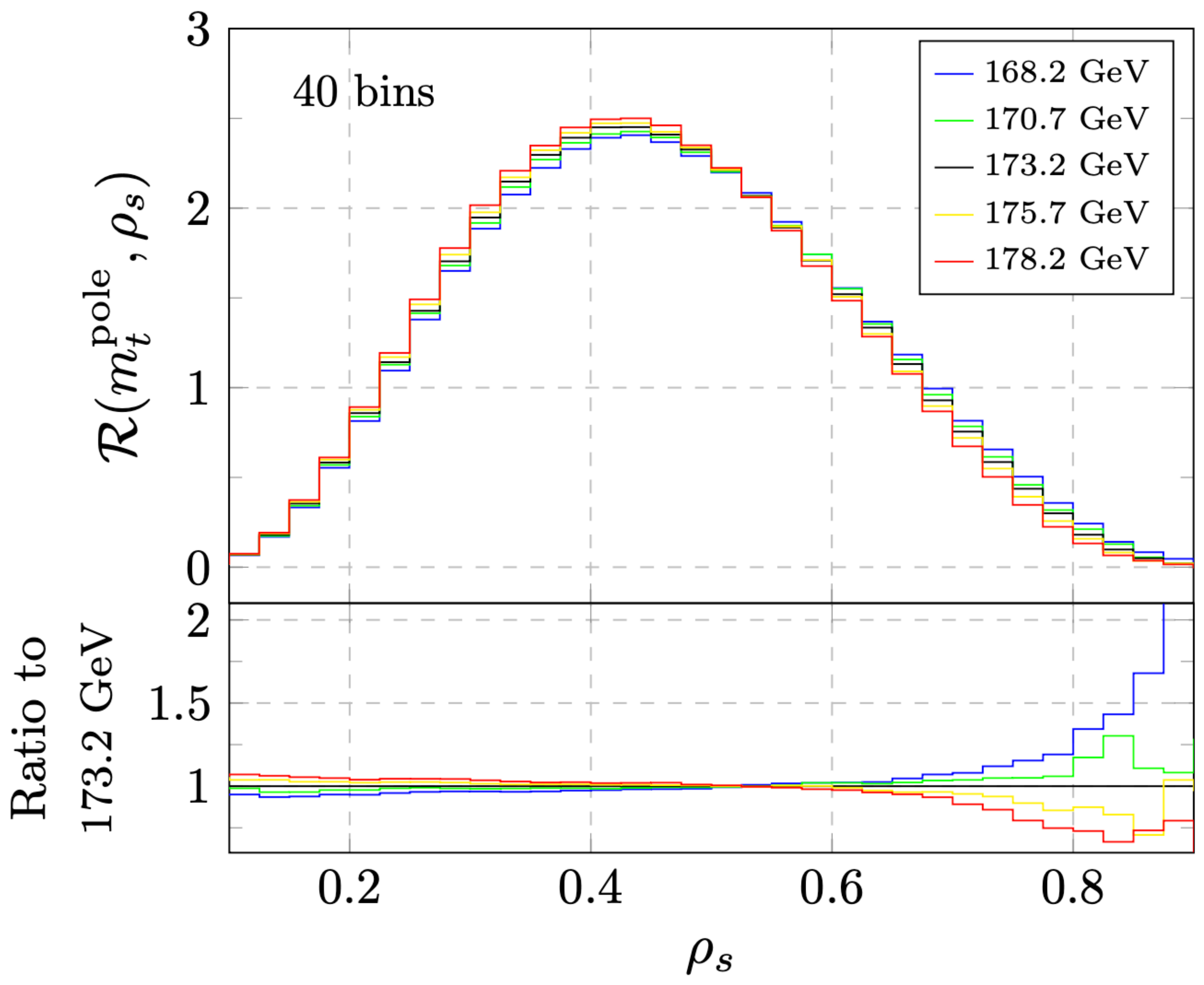
$m_t = 173.2$ GeV

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

Observable

- Normalised ρ_s differential distribution
- Full case for 5 different top quark masses
- Default value m_t = 173.2 GeV
- Renormalisation & factorisation scales set to $\mu_R = \mu_F = \mu_0 = H_T/2$
- CT14 PDF set employed
- Mass dependence observed for regions $\rho_s < 0.4$ & $\rho_s > 0.6$
- Regions most sensitive to top-quark mass extraction above $\rho_s > 0.7$

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



Observable

- Pseudo-data generated from full off-shell NLO QCD calculations for $pp \to e^+\nu_e\mu^-\nu_\mu b\bar{b}j + X$ production
  - m_t = 173.2 GeV & $\mu_0 = H_T/2$
- Predictions @ NLO in QCD: *Full off-shell & NWA & NWA$_{Prod}$* with LO top-quark decays with CT14 PDF set
- Various scales choices: $\mu_0 = H_T/2$ & $\mu_0 = E_T/2$ & $\mu_0 = m_t$

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

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

- Five different top-quark masses ⇨ $m_t \in \{168.2, 170.7, 173.2, 175.7, 178.2\}$ GeV
- High statistics Monte Carlo errors in each bin ⇨ Negligible compared to errors of pseudo-data samples

Observable

- Theoretical uncertainties from scale variation and from PDFs not included in χ^2 distribution

- They are treated as external variations

- Scale variation ⇨ Increases as number of bins decreases

  - Dynamical scale setting: *(0.6 − 1.2) GeV*
  - Fixed scale setting: *(2.1 − 2.8) GeV*

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

- PDFs
  - *(0.4 − 0.7) GeV*

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

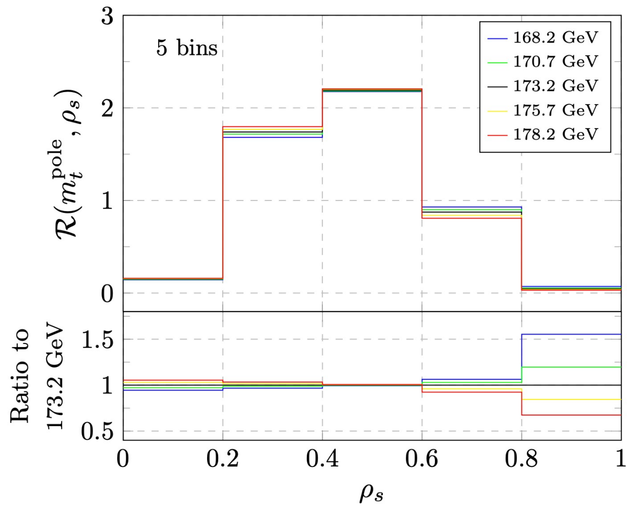
- Highest value from two obtained results chosen and symmetrisation not utilised

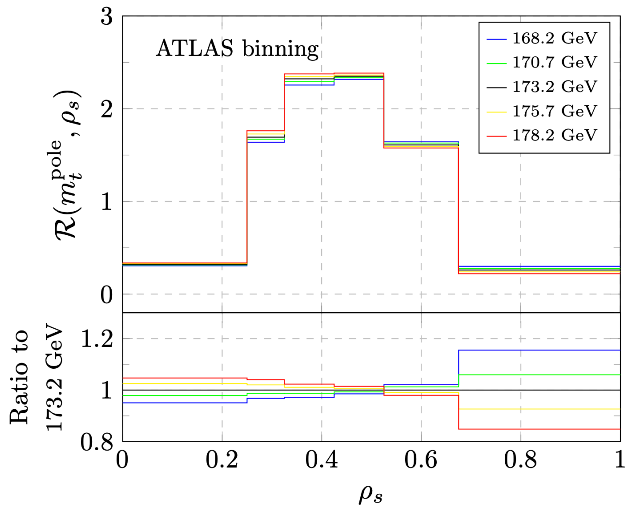
Observable

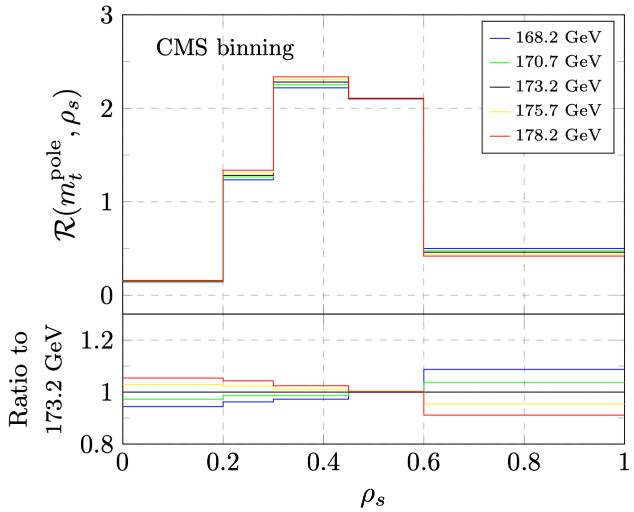
$$pp \to e^+ \nu_e \, \mu^- \, \bar{\nu}_\mu \, b\bar{b} \, j + X$$

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

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
- 5 equal size intervals, ATLAS and CMS intervals

Results

- Mean value of top-quark mass m_t^{out} from 1000 pseudo-experiments
- 68% C.L. (1σ) statistical error of top-quark mass δm_t^{out}
- Averaged minimal $\chi^2/d.o.f$ and *p-value*
- Top-quark mass shift $m_t^{in} - m_t^{out}$ with $m_t^{in} = 173.2\ GeV$
- **Findings:**
  - Mass shifts of $(2.0 - 2.5)\ GeV$ for NWA
  - Mass shifts of $(3.2 - 3.8)\ GeV$ for NWA_{Prod}
  - If full case with $\mu_0 = m_t$ used for generation of pseudo-data mass shifts of $(1.2 - 2.0)\ GeV$ for NWA
  - Statistical uncertainty δm_t^{out} still quite high

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [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
$NWA_{Prod.}$, $\mu_0 = m_t$	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
$NWA_{Prod.}$, $\mu_0 = m_t$	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
$NWA_{Prod.}$, $\mu_0 = m_t$	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
$NWA_{Prod.}$, $\mu_0 = m_t$	169.96 ± 1.80	1.00	0.41 (0.8σ)	+3.24

Luminosity of $2.5\ fb^{-1}$

Results

- Mean value of top-quark mass m_t^{out} from 1000 pseudo-experiments
- 68% C.L. (1σ) statistical error of top-quark mass δm_t^{out}
- Averaged minimal $\chi^2/d.o.f$ and *p-value*
- Top-quark mass shift $m_t^{in} - m_t^{out}$ with $m_t^{in} = 173.2$ *GeV*
- **Findings:**
  - Mass shifts again up to 2.5 *GeV* for NWA
  - Mass shifts up to 2.0 *GeV* for NWA with $\mu_0 = m_t$ when pseudo-data generated from full case with $\mu_0 = m_t$
  - Mass shifts of (3.0 − 3.8) *GeV* for NWA_{Prod}
  - $\delta m_t^{out} = (0.3 - 0.5)$ *GeV* only
- Not only full off-shell effects, non-resonant background and interreference effects of *t & W* but also scale choices play important role

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [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
$NWA_{Prod.}$, $\mu_0 = m_t$	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
$NWA_{Prod.}$, $\mu_0 = m_t$	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
$NWA_{Prod.}$, $\mu_0 = m_t$	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
$NWA_{Prod.}$, $\mu_0 = m_t$	170.22 ± 0.53	2.19	0.07 (1.8σ)	+2.98

Luminosity of 25 fb^{-1}

Summary

- Three different theoretical descriptions of top-quark decay chain investigated

- In first approach all interferences, off-shell effects and non-resonant backgrounds included

- In second approach top-quark decays in NWA considered:

  - NWA ⇨ QCD corrections and jet radiation present also in top-quark decays
  - NWA_{Prod} ⇨ Corrections to production process with leading order top-quark decays

- Pseudo-data sets generated from best theoretical description
  - Full prediction at NLO in QCD as generated with $m_t = 173.2\ GeV$ & $\mu_R = \mu_F = \mu_0 = H_T/2$
  - Full prediction at NLO in QCD with $\mu_0 = m_t$ also checked

- $L = 2.5\ fb^{-1}$ & $L = 25\ fb^{-1}$
  - *5400 & 54000* events assuming perfect detector efficiency
  - Mass shifts up to $2.5\ GeV$ for NWA
  - Mass shifts up to $3.8\ GeV$ for NWA_{Prod}
  - Statistical uncertainty on top-quark mass $\delta m_t^{out} = (1 - 1.5)\ GeV$ & $\delta m_t^{out} = (0.3 - 0.5)\ GeV$

Summary

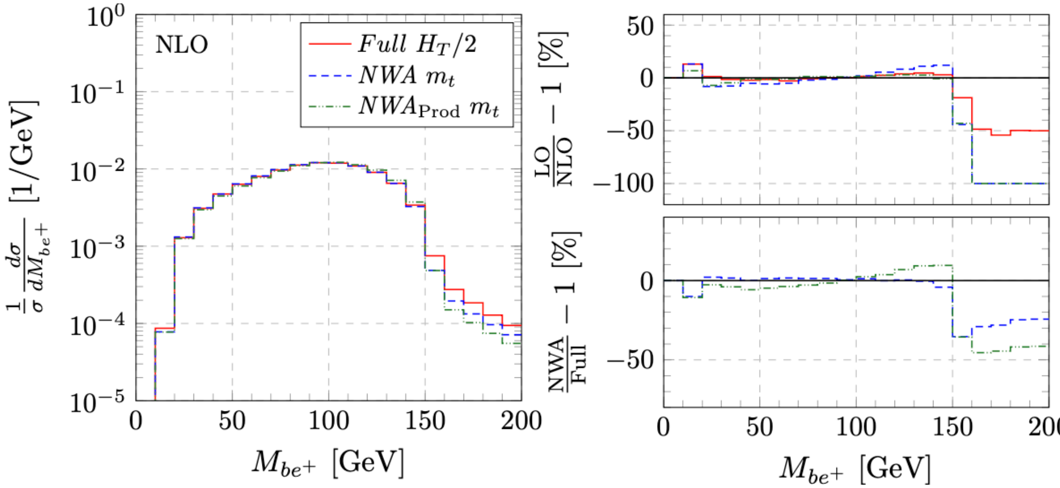
- Theoretical study ⇨ Additional systematic uncertainties need to be addressed
- Among others impact of parton shower on shape of ρ_s should be examined
- Non-perturbative effects together with *b-jet* tagging and neutrino reconstruction efficiencies should be estimated
- We can make following general statements

  - **Small luminosity:**
    - Large mass shifts
    - Various theoretical descriptions at NLO in QCD can be employed as long as one compensates for these mass shifts
    - We do not have sufficient sensitivity to see differences in various descriptions of top-quark decays
  - **Larger Luminosity:**
    - Large mass shifts
    - Full theoretical description with dynamical scale choice, either $\mu_0 = H_T/2$ or $\mu_0 = E_T/2$, should be used to simulate ttj production @ LHC to extract top-quark mass

- Higher number of bins corresponds to increased sensitivity to m_t
- Helps to clearly distinguish between case where theory (still) agrees with pseudo-data and case where theory is disfavoured by such pseudo-data

Outlook

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



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