t-channel Single-top with complex-mass scheme matched to parton showers

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TOP LHC WG meeting

22nd May 2014, CERN

*Work in progress with:

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Thanks to Rikkert Frederix and Pierre Artoisenet for discussions and help

Purpose of this study

Progress in pQCD and automation have lead an improvement of the description of top quark final states

- in narrow-width approximation (NWA) [Bernreuther,Brandenberg,Si,Uwer,Campbell, Ellis,Tramontano,Melnikov,Schulze,Biswas,Scharf,...] ,
- and when top treated as offshell [Denner,Dittmaier,Kallweit,Pozzorini,Bevilacqua,Czakon,van Hameren,Papadopoulos,Worek,Falgari,Mellor,Signer,Gianuzzi,AP,Frederix, Frixione,Hirschi,Maltoni,Cascioli, Maierhoefer,Heinrich,Maier,Nisius,Schlenk,Winter,...] → see J. Winter's talk

Next step: match this improved fixed-order to parton shower (PS).

→ NWA: see P. Nason's talk

→ less work for the PS to do

→ top decay, finite-width effects all contained in hard event

Focus/study: (all in framework of `mg5-aMC@NLO`)

1. matching *t*-channel single top complex-mass scheme computation to PS
2. differences with other available approximations

Complex-mass scheme [Denner et al]

Complex-mass scheme: a renormalization scheme that introduces Γ_t at the level of the Lagrangian:

$$m_{t,0} = \mu_t + \delta\mu_t, \quad \text{with} \quad \mu_t^2 = m_t^2 - i m_t \Gamma_t$$

μ_t: complex pole of top quark propagator $\Rightarrow m_t = m_t^{\text{pole}}$

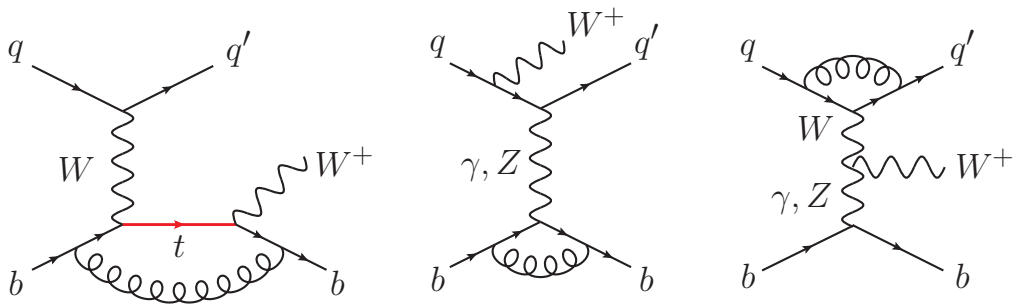
✓ allows for LO and NLO gauge-invariant calculations with finite-width effects

✓ automatable (see `GoSam`, `mg5_aMC@NLO`, `OpenLoops`)

This gives us increased perturbative control of the hard process at fixed-order.

t-channel Single-top with off-shell & non-resonant effects

(mg5-aMCNLO)



[AP, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni '13]

$$p\ p \to W^+\ J_b\ J_{\text{light}}\ +\ X$$

resonant diagrams, non-resonant diagrams + interferences

1. t-channel process in 5-flavour scheme (massless bs)
2. final state must contain a tagged b-jet, J_b:
   - J_b contains at least a b quark
   - J_b has non-zero p_T (here choose $p_T(J_b) > 25$ GeV)
3. CKM matrix diagonal in 3rd generation

Fixed order t-channel $W^+ J_b J_{\text{light}}$: setup

Note: chosen analysis cuts enhance resonant contributions

$\Rightarrow$ allow for a comparison between various approximations ✓

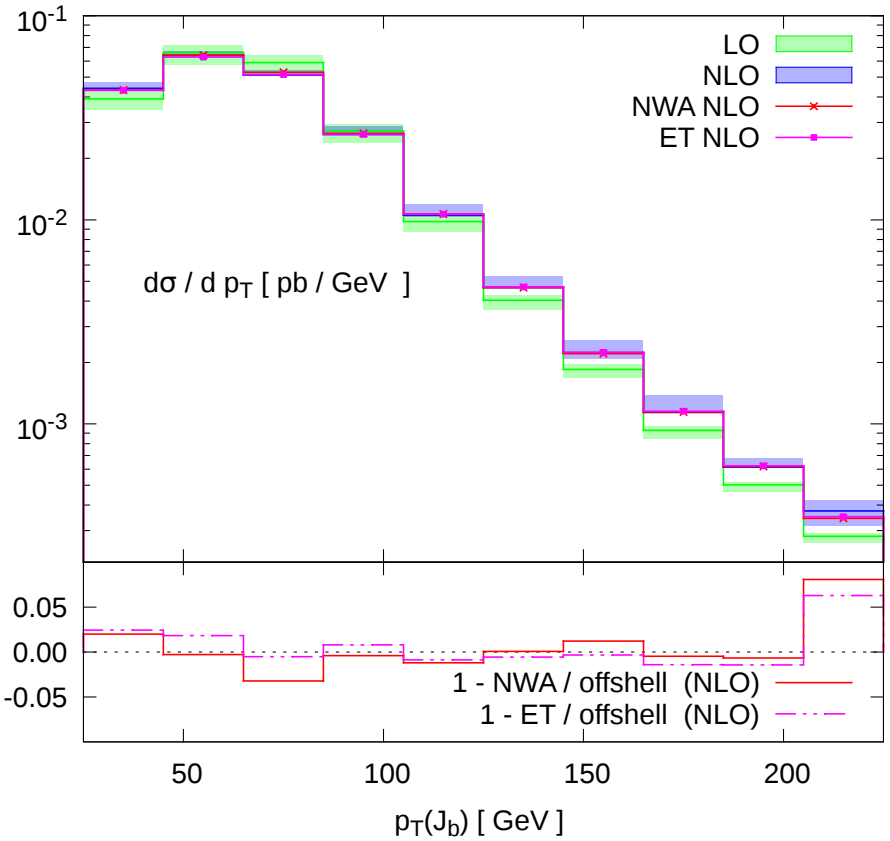
Compare:

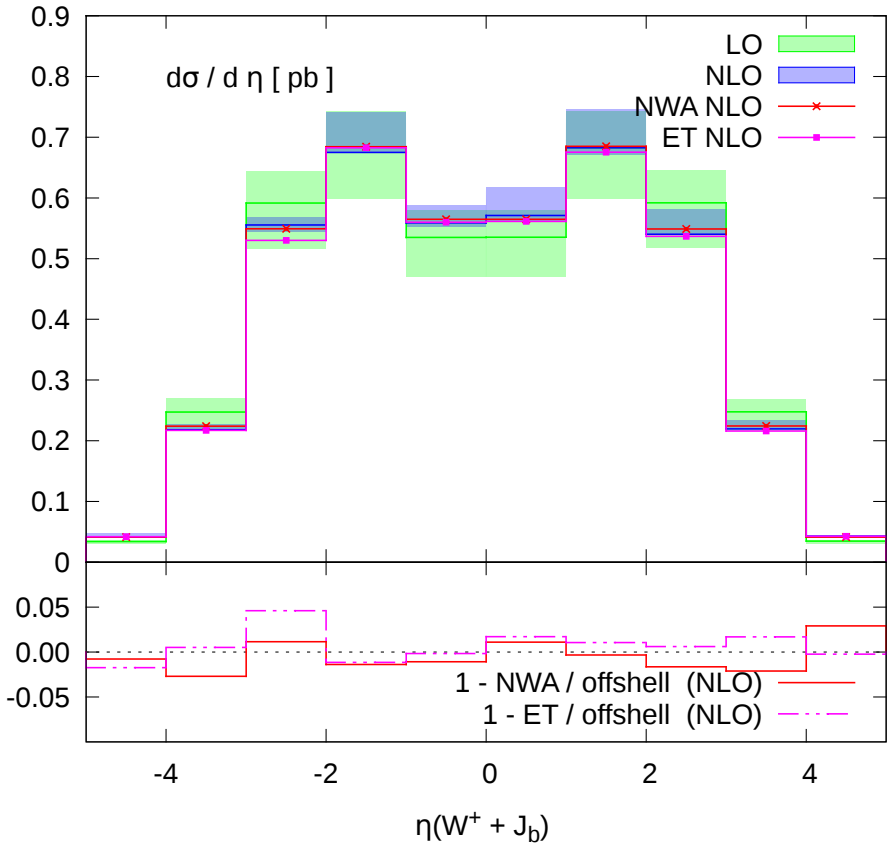
- full off-shell result (complex-mass scheme): $p_t^2 \neq m_t^2$
- NWA, as implemented in MCFM: $p_t^2 = m_t^2$

  [Campbell,Ellis,Tramontano '04, Heim,Cao,Schwienhorst,Yuan,Mueller '09,'11]
- Effective theory (ET) approach $\sim$ pole-expansion: $p_t^2 \sim m_t^2$

  [Falgari,Mellor,Signer '10]

Fixed order t-channel $W^+ J_b J_{\text{light}}$: results1



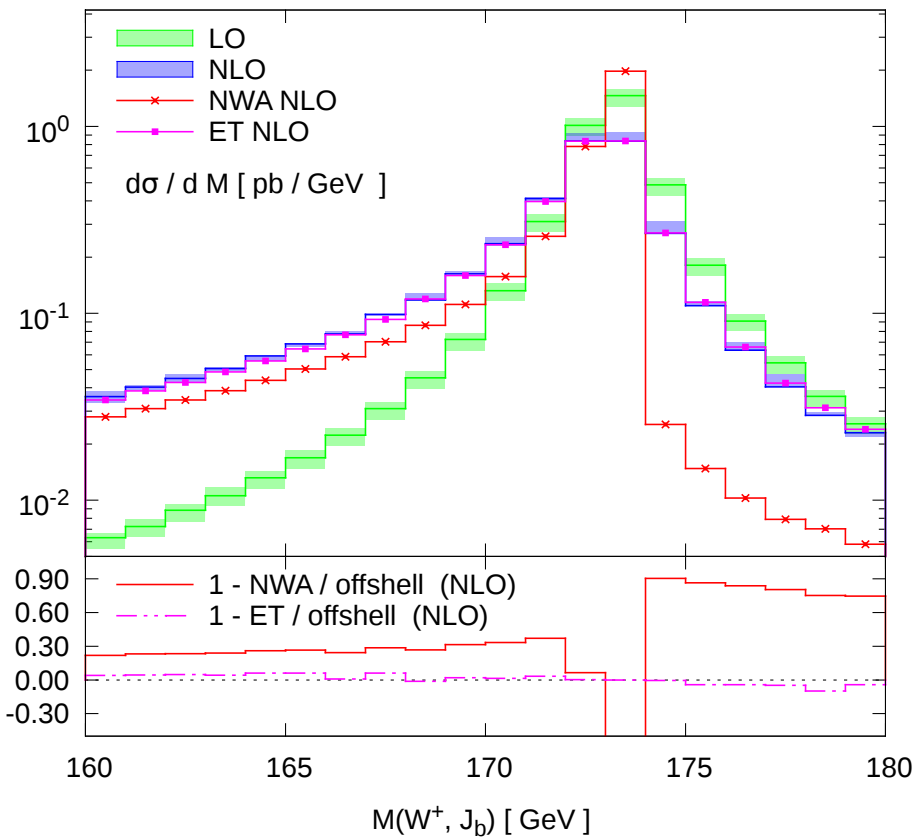


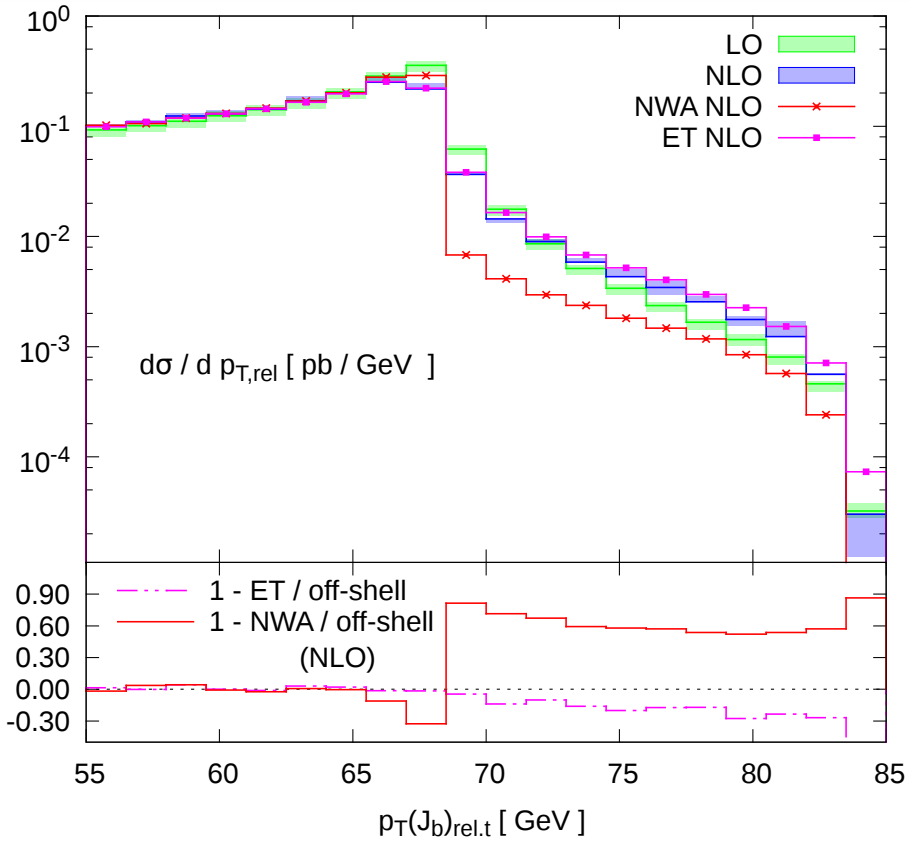
→ difference between NWA and off-shell approaches small $\sim \mathcal{O}(\Gamma_t/m_t) \sim$ 1-2%

→ NWA curves lie within scale uncertainty bands of off-shell result ✓

→ no visible differences in shape ✓

Fixed order t-channel $W^+ J_b J_{\text{light}}$: results2





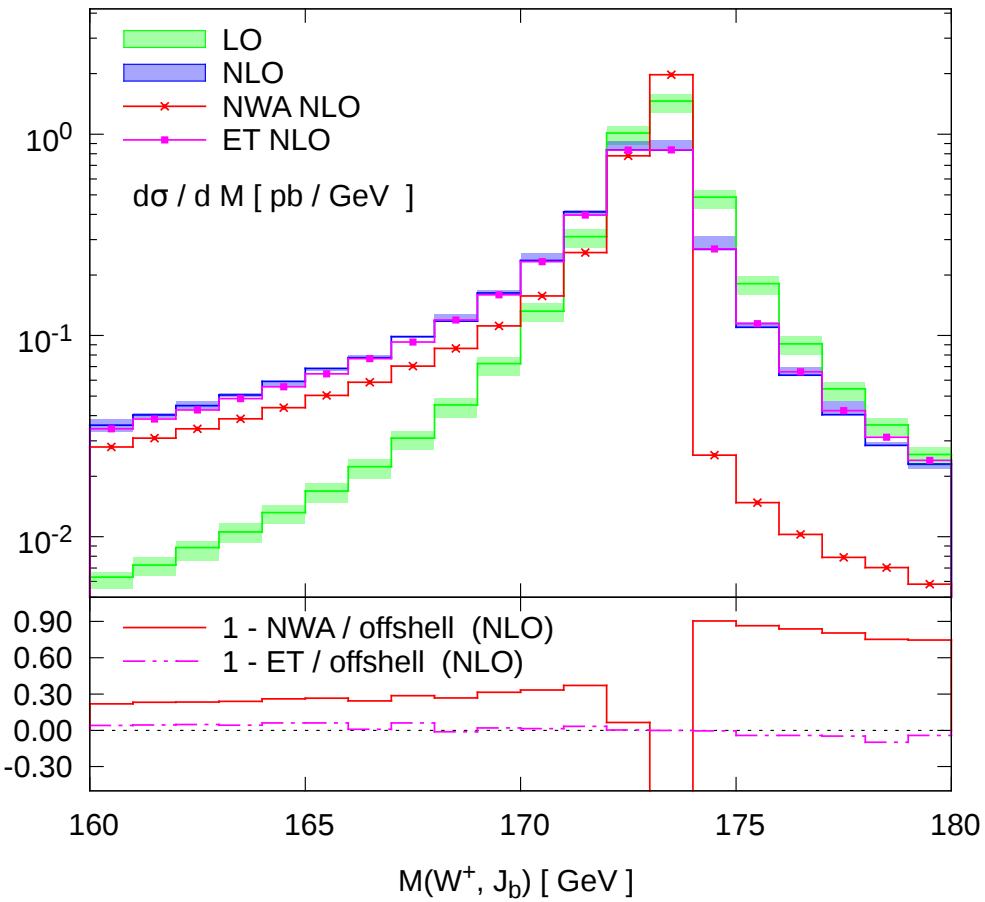
→ difference between NWA and off-shell approaches sizeable (expected)

→ finite-width effects important for shapes near and beyond peaks

Similar studies/conclusions (single top & $t\bar{t}$): [Falgari et al. '10,'11,'13, Bevilacqua et al. '11, Denner et al. '11,'12, Frederix '13, Cascioli et al. '13, Heinrich et al. '13]

Fixed order t-channel $W^+ J_b J_{\text{light}}$: $M(W^+, J_b)$

NWA, though not designed to describe this, gives us an understanding of the structure behind the offshell distribution (which can be clouded in full offshell result):



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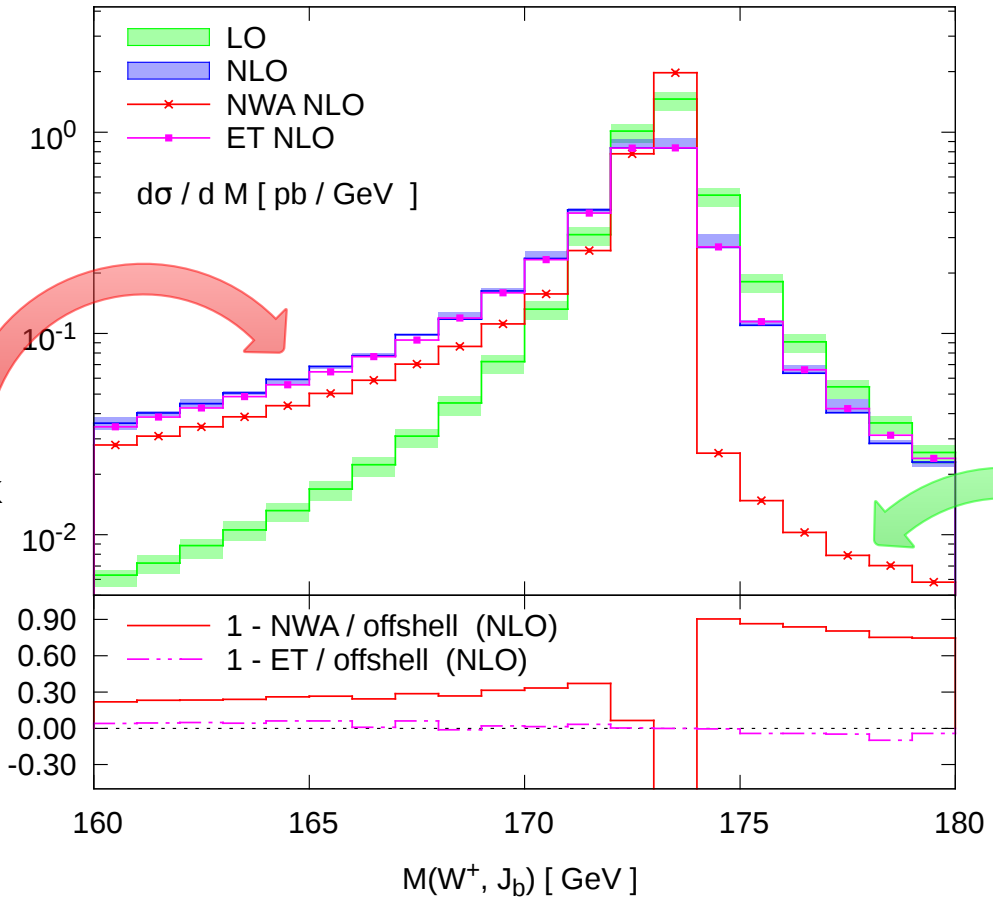
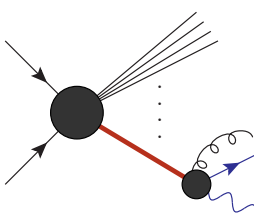
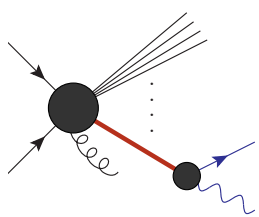


emission from top-decay vertex leaked out of J_b



emissions from 'production' clustered into J_b



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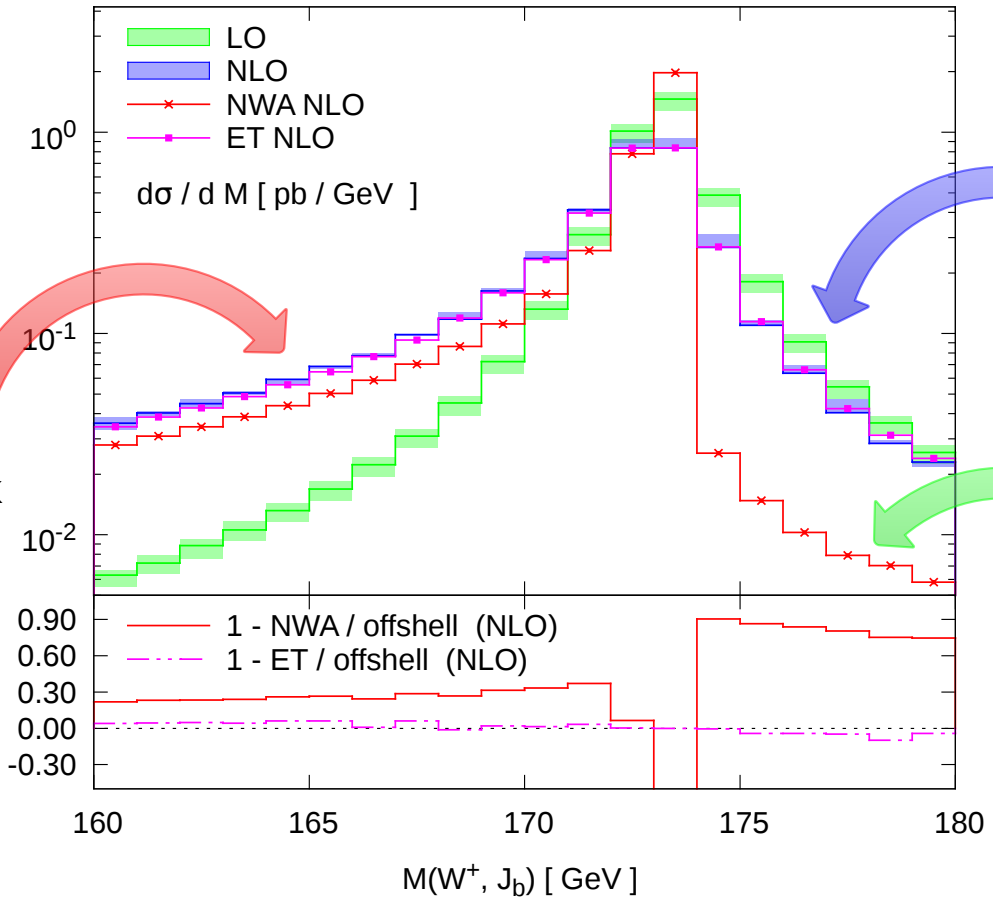

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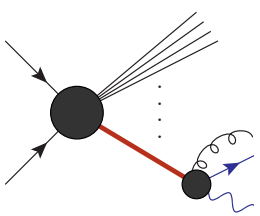
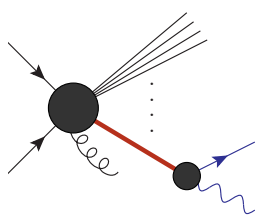


high tail dominated by offshellness of top

emissions from 'production' clustered into J_b



Matching to shower: studies

Aim to stay as close as possible to previous parton-level (fixed-order) study, in order to compare to features found there.

$$p_T(J_b) > 25 \text{ GeV} \qquad p_T(J_{\text{light}}) > 25 \text{ GeV}$$

$$140 < M(W^+, J_b) < 200 \text{ GeV}$$

Study W^+bj matched to PS:

- with two different PSMCs: `Herwig6` and `Pythia8`.
- at hadron level (stable B-hadrons), but no underlying event
- use MC-truth to ensure fulfillment of key requirement: b-jet definition
  - $\rightarrow$ locate B-hadron from outgoing b-parton from hard process
  - $\rightarrow$ thus correctly identify b-jet
    (multiple b-jets possible due to $g \rightarrow b\bar{b}$ splittings in shower phase)

Matching to shower: onshell tops

Stable top events: easy to deal with

hard process: $pp \to t\, j + X$

- top always written into LesHouches event, as a final state particle

  1. hard event showered (with showering off top quark included)
  2. top decay, $t \to W^+ b$ attached
  3. further showering off b-parton, hadronization, etc ...

One wants to understand, since the PS preserves invariant mass of top in event,

- effect of onshell assumption on observables?

Also easy: including decay including spin-correlations (MadSpin) - but also get LO finite-width effects

Matching to shower: offshell tops, ambiguities, worries

Given that the final state is W^+bj, should a 'top' ever be written in the event??

hard process: $pp \to W^+ J_b J_{\text{light}} + X$

NO

- does this even make sense: every event will contain some non-resonant contribution??
- deciding whether or not there is an intermediate top is, formally, a gauge-dependent procedure, based on (W^+, b)-virtuality

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YES

- potential to spoil resonance structure/pattern if top never written (hard emissions off b-parton by shower, not captured in b-jet)
- writing the top in the event results in the parton shower preserving $M(W^+, b)$ (or $M(W^+, b, g)$), which is something that, at the hard event level is NLO correct (via use of the complex-mass scheme).
- want hadron-level result to reflect the fact that the dominant contributions are resonant ones

Matching to shower: offshell tops: event-structure

Writing top in events done via the procedure:

- define a 'top' momentum: $p_t^\mu = p_W^\mu + p_b^\mu \;\; (+p_g^\mu)$
- if: $\sqrt{p_t^2 - m_t^2} < x_{\text{cut}}\Gamma_t \;\; \rightarrow$ write intermediate top in event
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$x_{\text{cut}} = 0 \Rightarrow 0\%$ intermediate tops, $x_{\text{cut}} = \infty \Rightarrow 100\%$ intermediate tops

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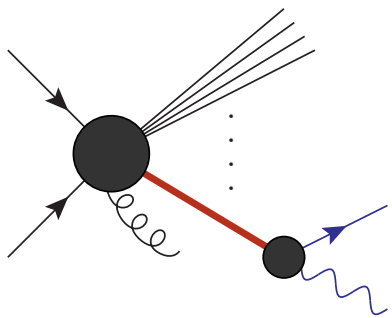
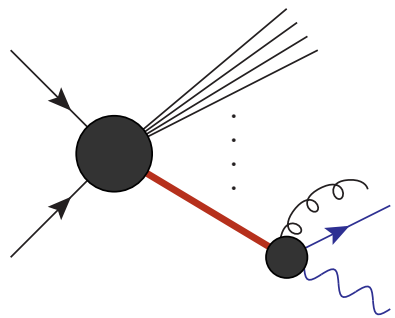
Care with definition of intermediate top



$p_t = p_W + p_b$



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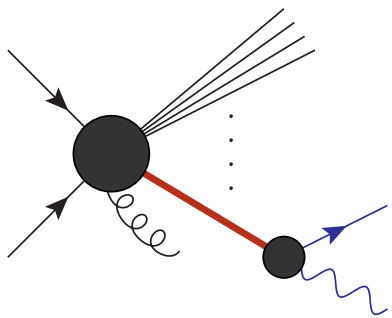

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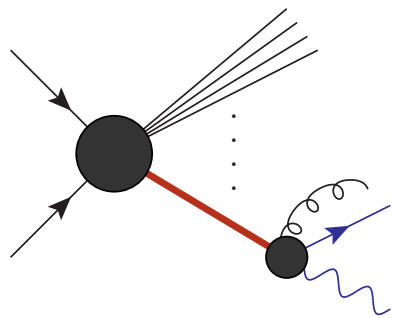
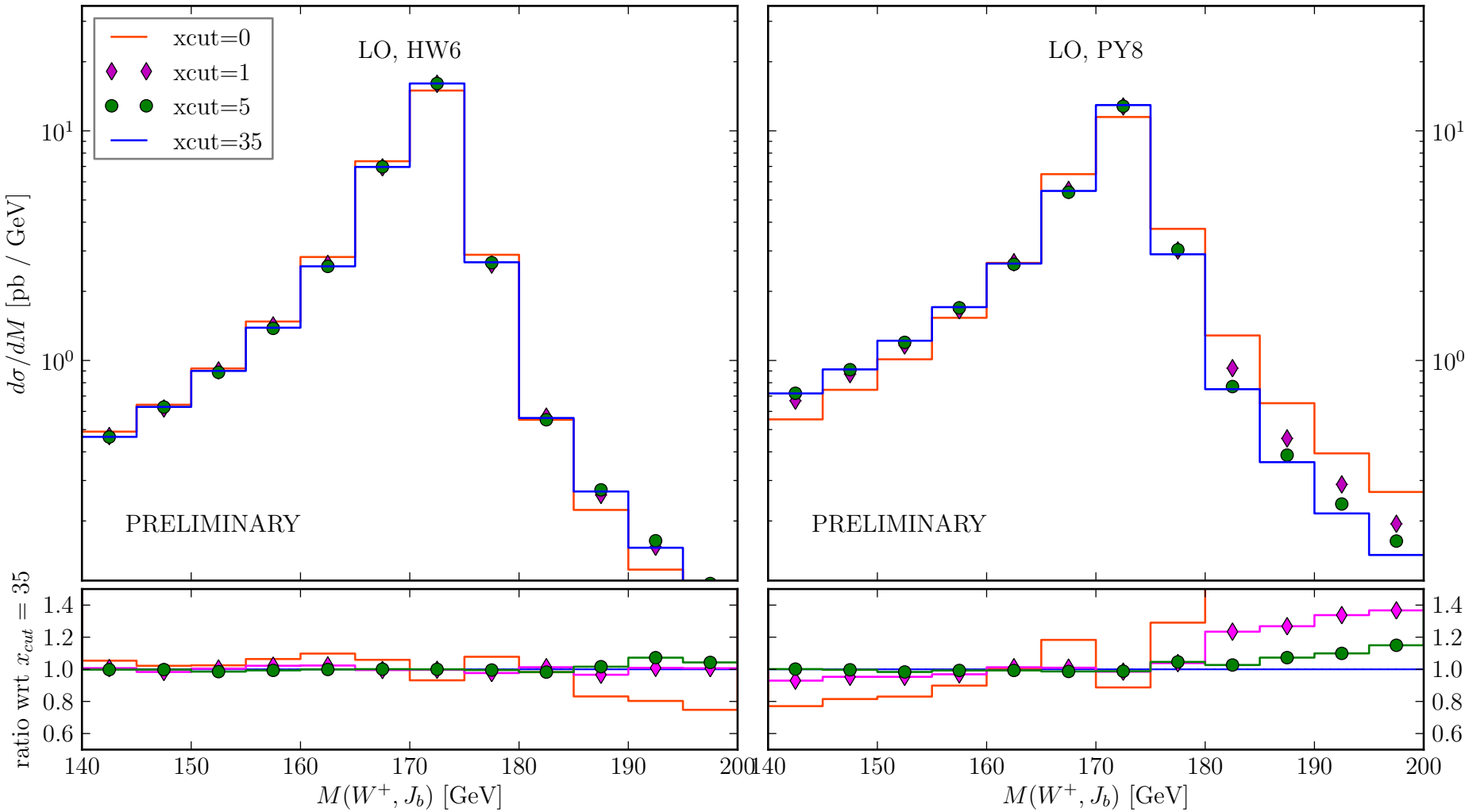


$p_t = p_W + p_b + p_g$

✓ done consistently in `mg5-aMC@NLO`

(for NLO, veto shower emissions off intermediate tops, to prevent double counting)
(HW6: thanks to B. Webber)

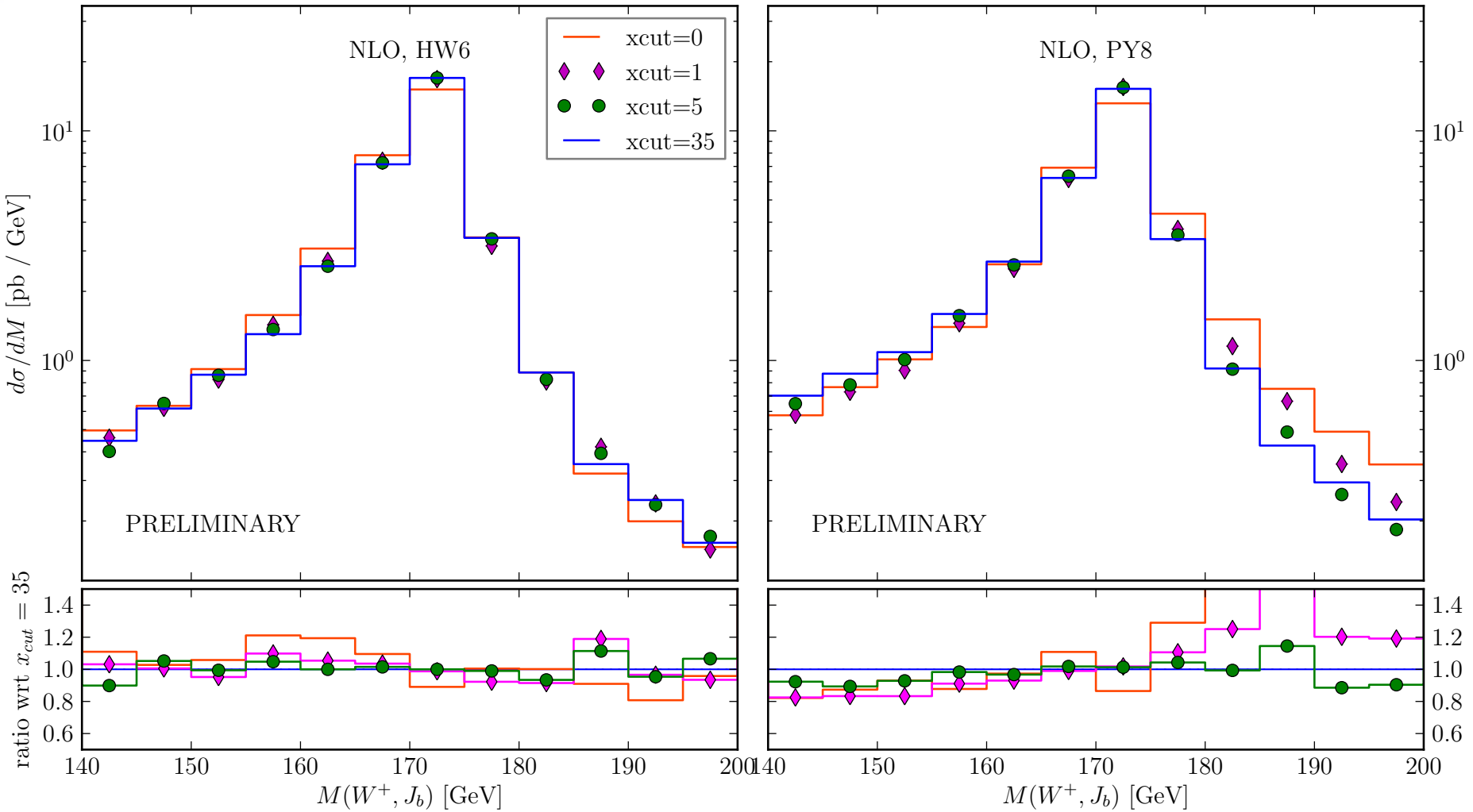
Variation of top in event: effect on resonance



$x_{\text{cut}} = \{0,\ 1,\ 5,\ 35\} \Rightarrow \{0,\ 65,\ 90,\ 98\}\%$ events contain intermediate tops

→`Herwig6`: stable, `Pythia8`: larger effects in high tail

Variation of top in event: effect on resonance



→ near peak, only $x_{\text{cut}} = 0$ shows large deviations from $x_{\text{cut}} = 35$

→ large deviations for `Pythia8` in high tail seem to improve

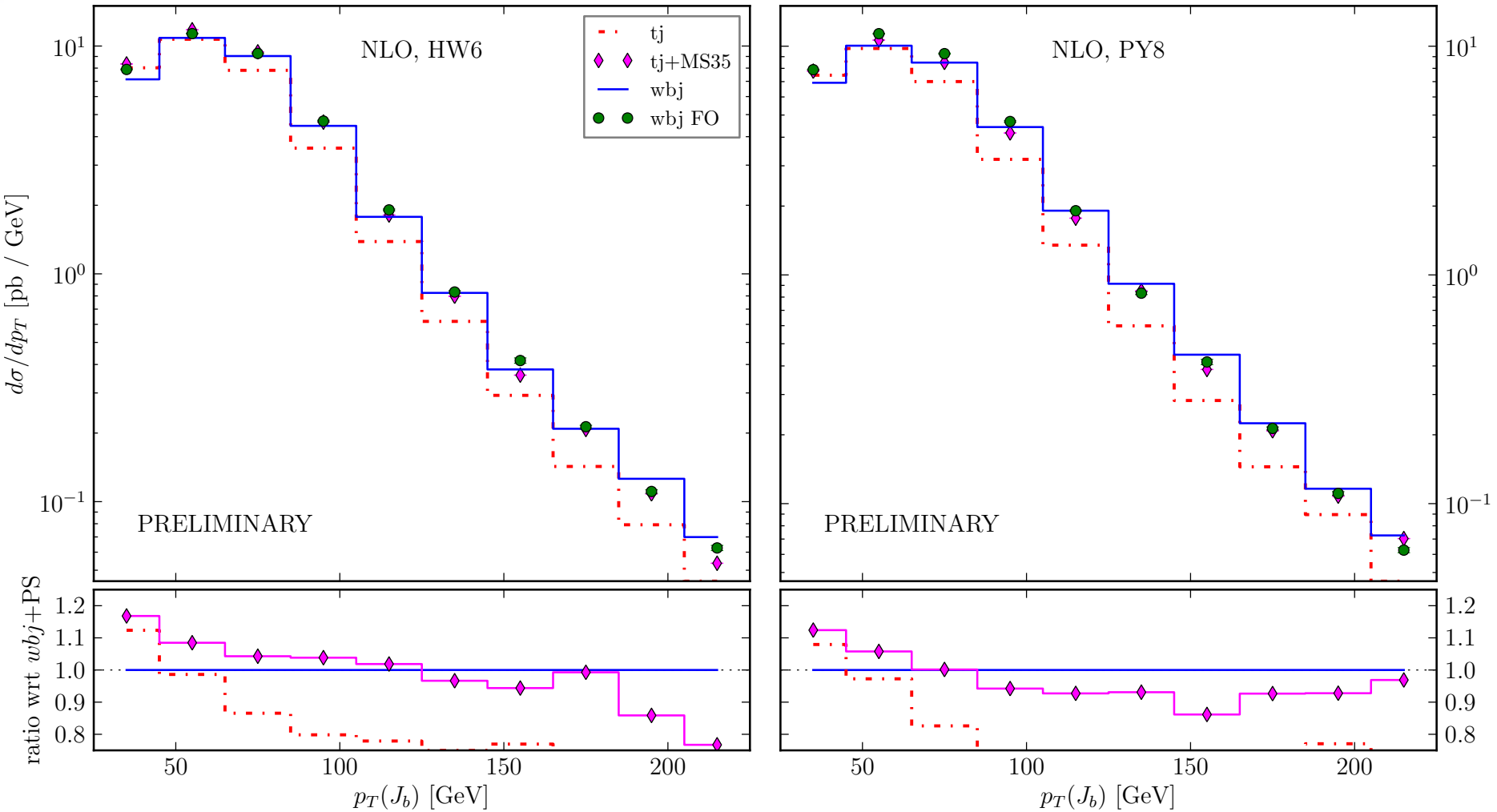
How well do approximations to full W^+bj fair?

Armed with full W^+bj + shower: important to compare to various approximations available and that have been used so far ...

- tj + shower
  - $\rightarrow$ NLO single top with onshell, stable top events
  - $\rightarrow$ top decays performed internally by PS
- tj + spin-correlations + shower
  - $\rightarrow$ NLO single top with onshell, stable top events
  - $\rightarrow$ events decayed with MadSpin*
    (✓ production-decay spin-correlations, ✓ LO offshell effects)

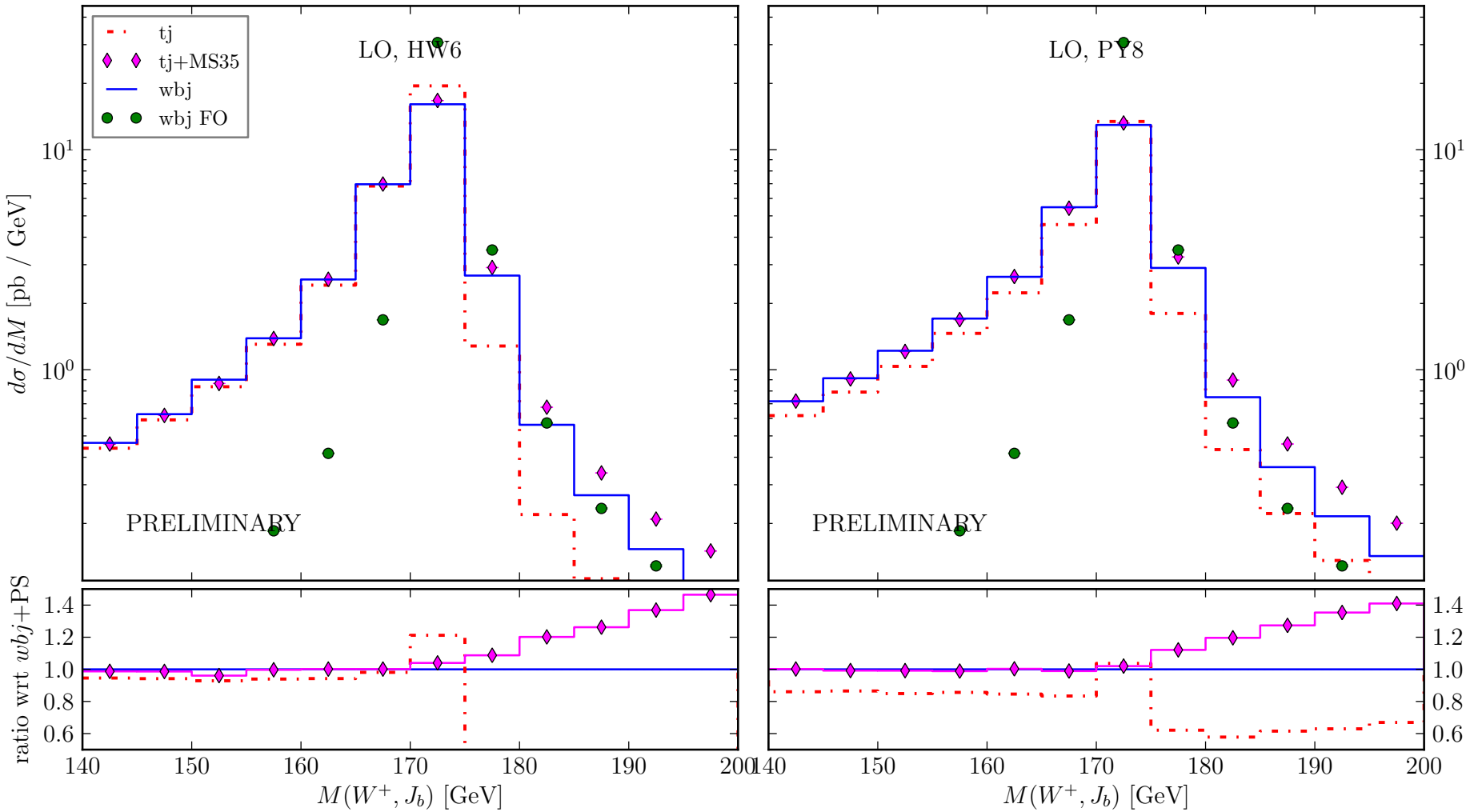
* [MadSpin: Artoisenet, Frederix, Mattelaer, Rietkerk '12]
[Frixione, Laenen, Motylinski, Webber '06]

Comparison of available approximations



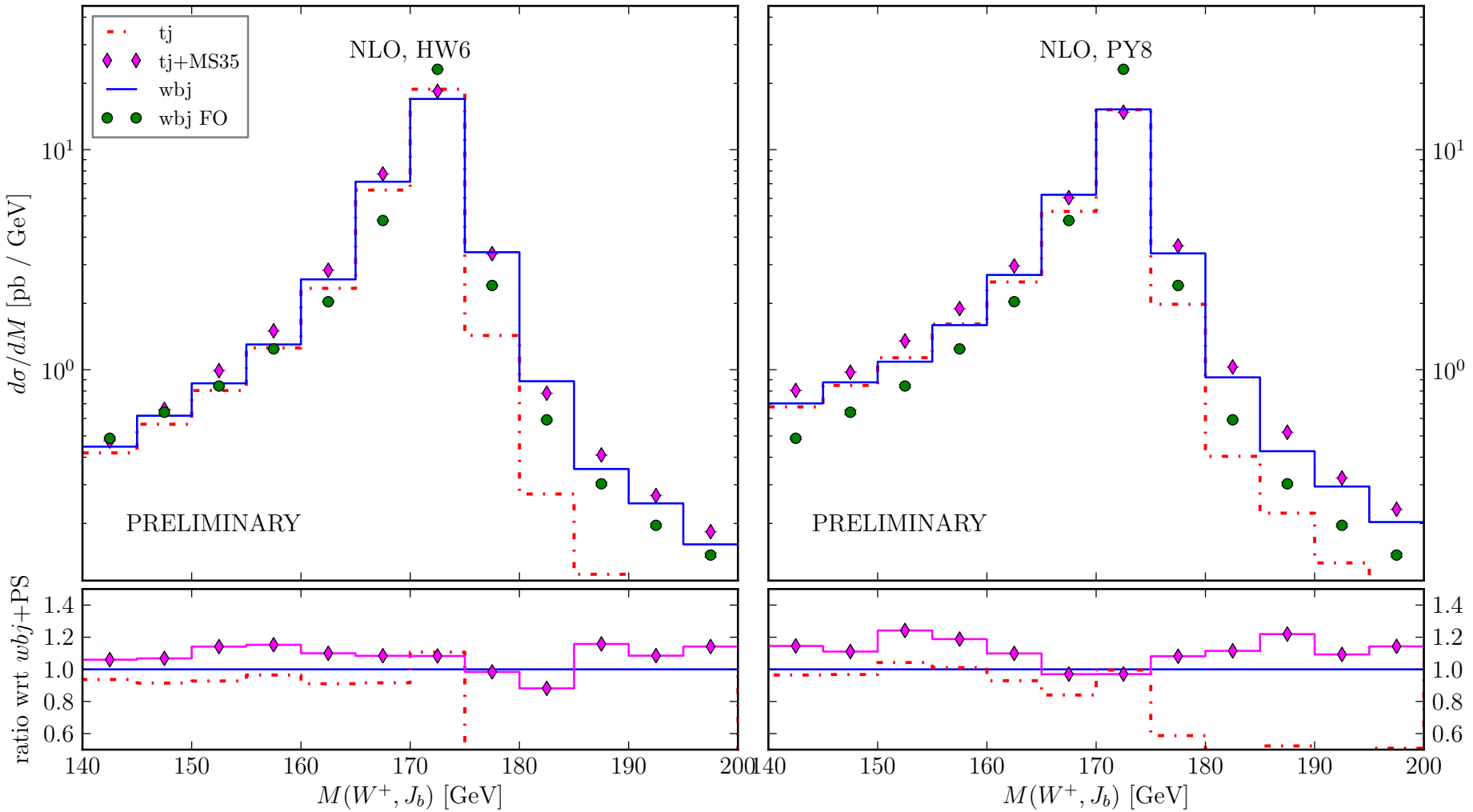
For observables sensitive to top decay, start seeing differences in shape

Comparison of available approximations



Importance of offshellness for shape shows up already at LO, at and beyond peak (note similar pattern to fixed-order $M(W^+, J_b)$)

Comparison of available approximations



→ similar pattern as LO for *tj*

→ MadSpin performs better at NLO, improvement of high tail shape

Comparison of showers: Herwig6 vs Pythia8

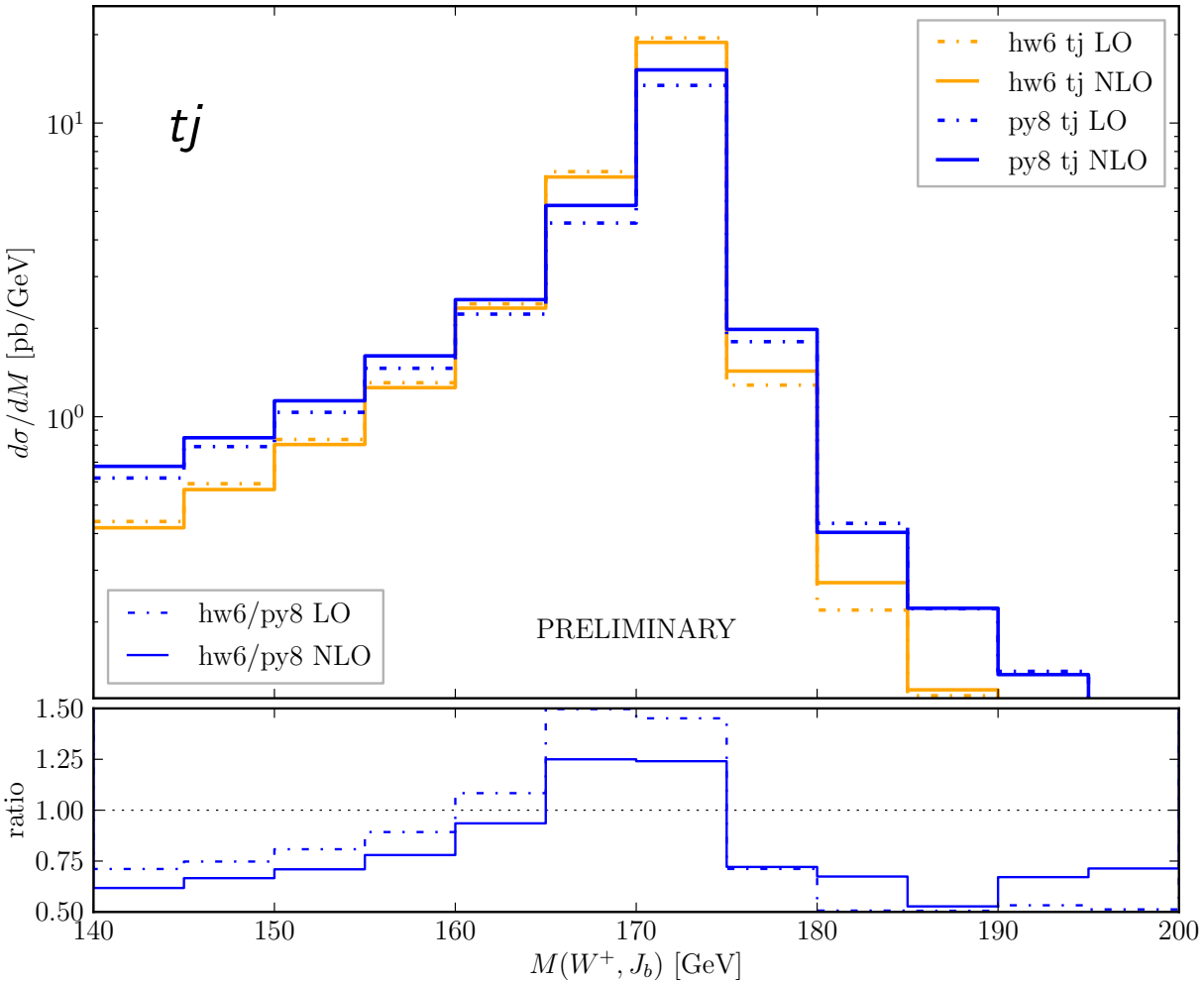
Also important to compare PSMCs against eachother directly.

- highlights intrinsic differences between parton showers, hadronization models
- agreement between showers *should* get better going LO $\rightarrow$ NLO
- the more information goes into hard event, the closer the results after showering with different MCs *should* get

  (less freedom for PS to add decays, 1st emission from b-parton,...)

  $\Rightarrow$ the better the approximation, the better the agreement between showers *should* be

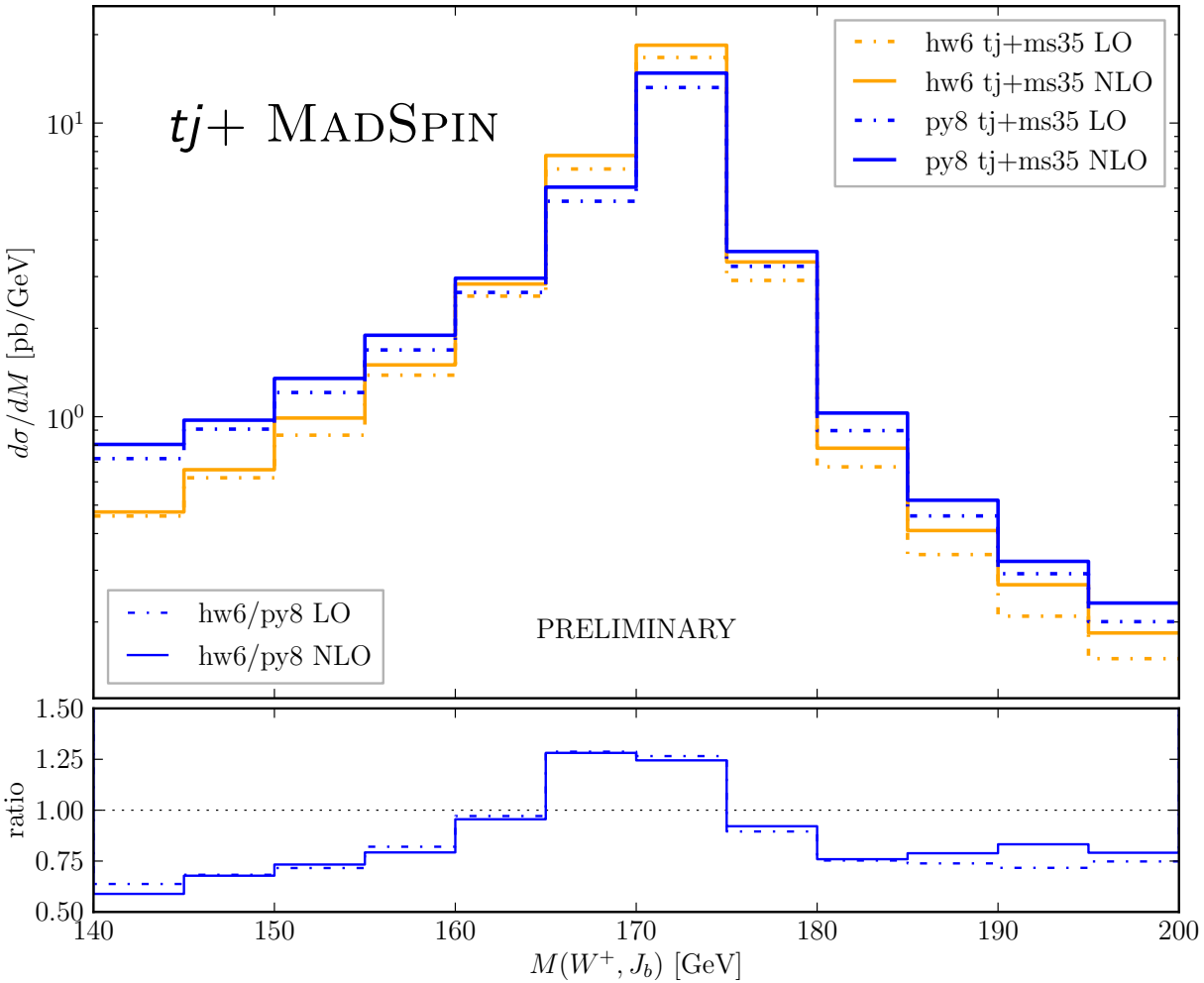
Herwig6 vs Pythia8



→ distribution almost completely shaped by shower

(with exception of high tail, where real emission from production contributes)

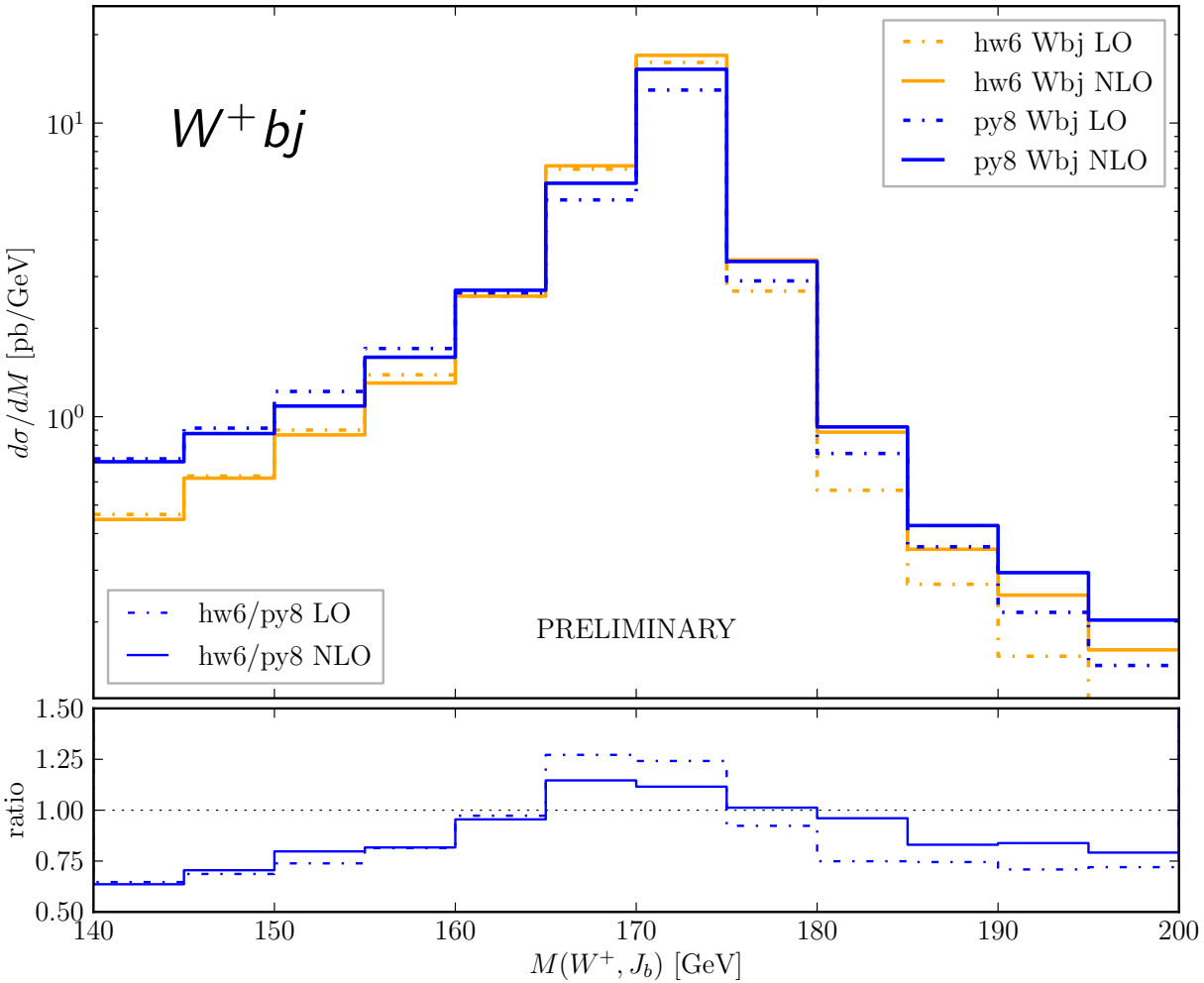
Herwig6 vs Pythia8



→ addition of LO top decay & LO offshellness improves agreement in high tail wrt *tj*+PS

→ no real improvement for LO → NLO

Herwig6 vs Pythia8



→ sizeable differences between showers remain at tails

✓ significant improvement though at resonance and in high tail going $tj \to tj + \text{MadSpin} \to W^+bj$ and NLO

Conclusions & Outlook

Studied:

- t-channel single top, with full offshell effects matched to PS
- ambiguities involved when matching complex-mass scheme to PS
- how various approximations and showers compare

Outcomes:

- writing intermediate top in event: reasonable, despite procedure being formally gauge-dependent
- shower effects can be large in tails of distributions e.g. $M(W^+, J_b)$
- m_t-sensitive distributions can show large differences between approximations (expected)

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By no means a closed topic of study. Comparison to data would be both extremely interesting and useful for MC development.

$\rightarrow$ all this will feed into $W^+W^-b\bar{b}$ ($t\bar{t}$), main m_t-measurement process

Backup slides

Setup: fixed-order & for matching to PS

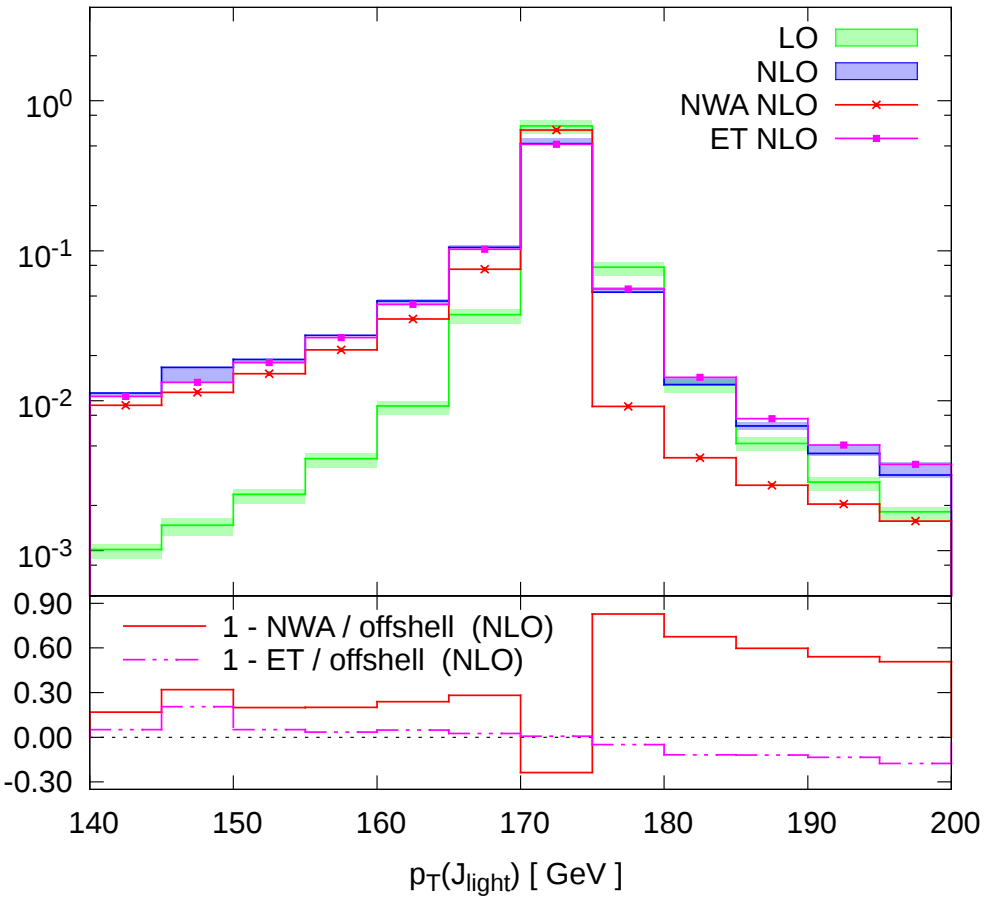
Parameter setup:

$m_t = 173.2$ GeV	$\Gamma_t^{\text{nlo}}(\mu = m_t/2) = 1.3569$GeV
$m_Z = 91.1876$ GeV	$m_W = 80.3980$ GeV
`MSTW2008NLO` PDF set	$V_{tb} = 1$

Analysis setup:

$p_T(J_b) > 25$ GeV	$p_T(J_{\text{light}}) > 25$ GeV
$\lvert\eta(J_b)\rvert < 4.5$	$\lvert\eta(J_{\text{light}})\rvert < 4.5$
$140 < M(W^+, J_b) < 200$ GeV	

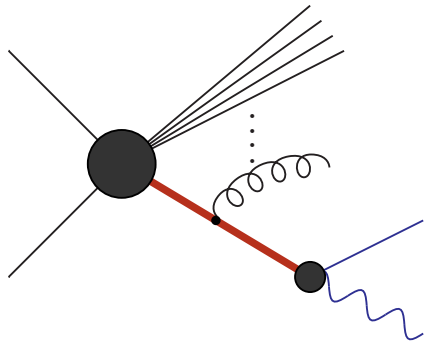
Fixed-order $M(W^+, J_b)$, wider range



$\rightarrow$ ET slowly diverges from full complex-mass scheme result for higher $M(W^+, J_b)$

$\Rightarrow$ indicates resonant/non-resonant interferences & fully non-resonant contributions grow in importance

Radiating off intermediate tops



- NLO complex-mass scheme computation contains non-divergent real emissions off intermediate top propagators

  (potential soft singularity screened by Γ_t)

- IF top written in event, danger of double-counting emissions when shower radiates off top!

  (MC subtraction terms only cure divergent real emissions)

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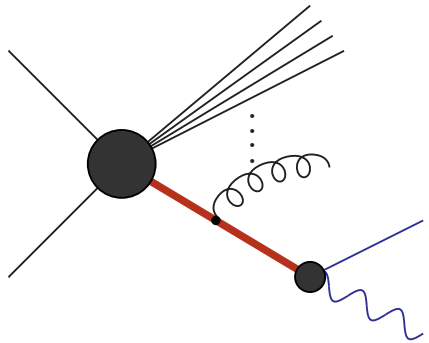

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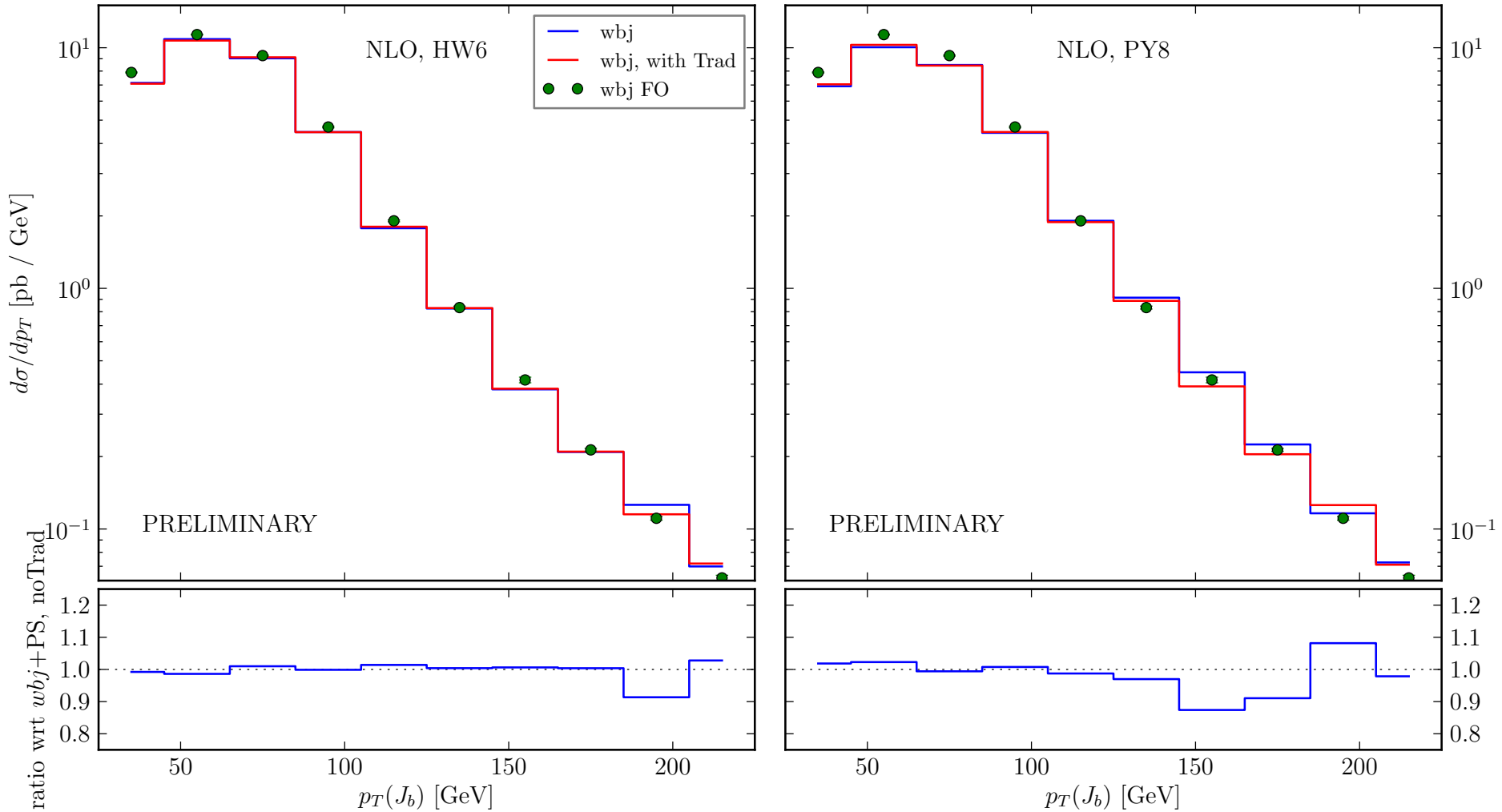
- W^+bj NLO: forbid radiation from intermediate tops [HW6: thanks to B. Webber]

- crude - but effect of radiation off intermediate top is generically small

Effect of radiation from top



$\rightarrow$ no / small effect on p_T spectrum of b-jet

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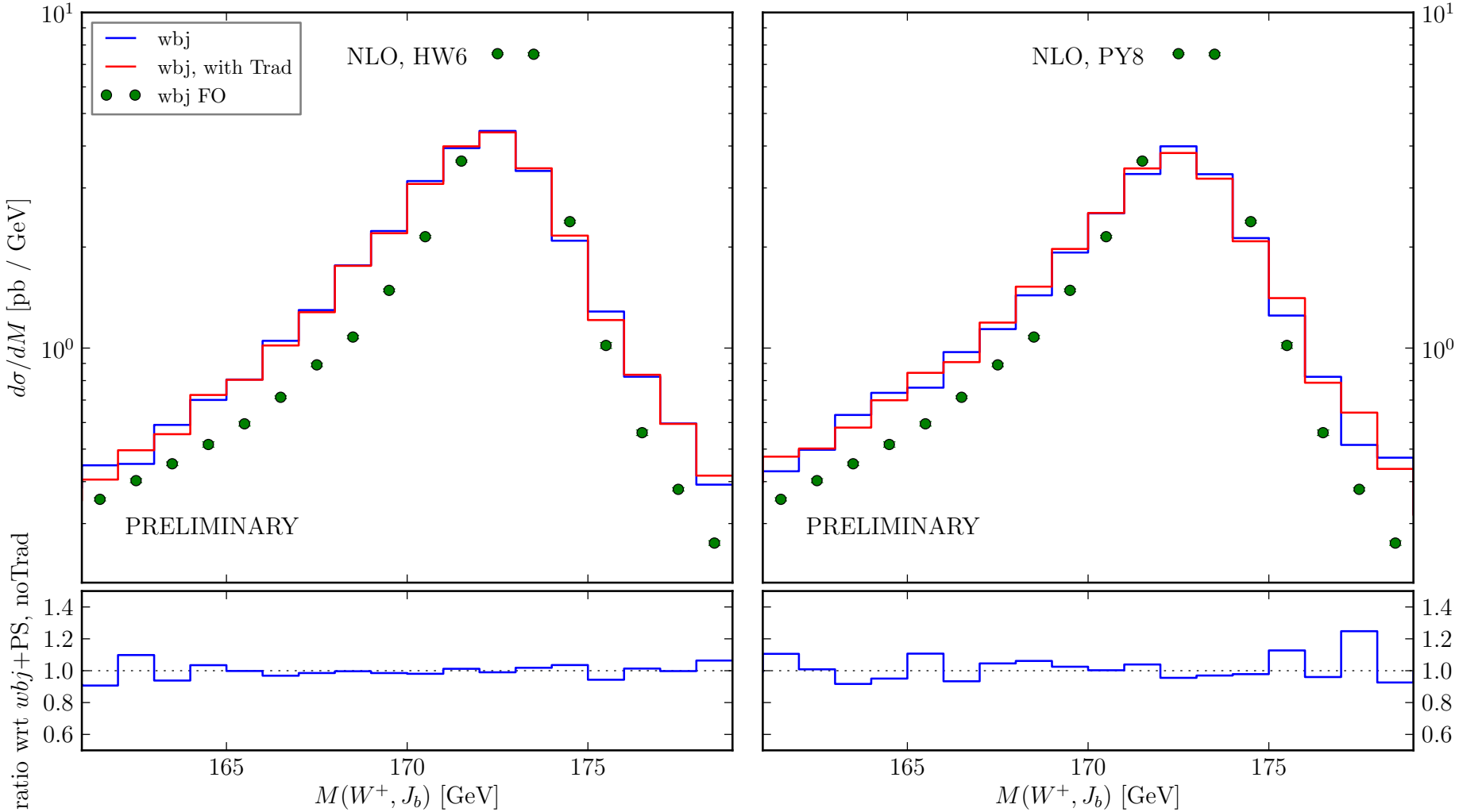
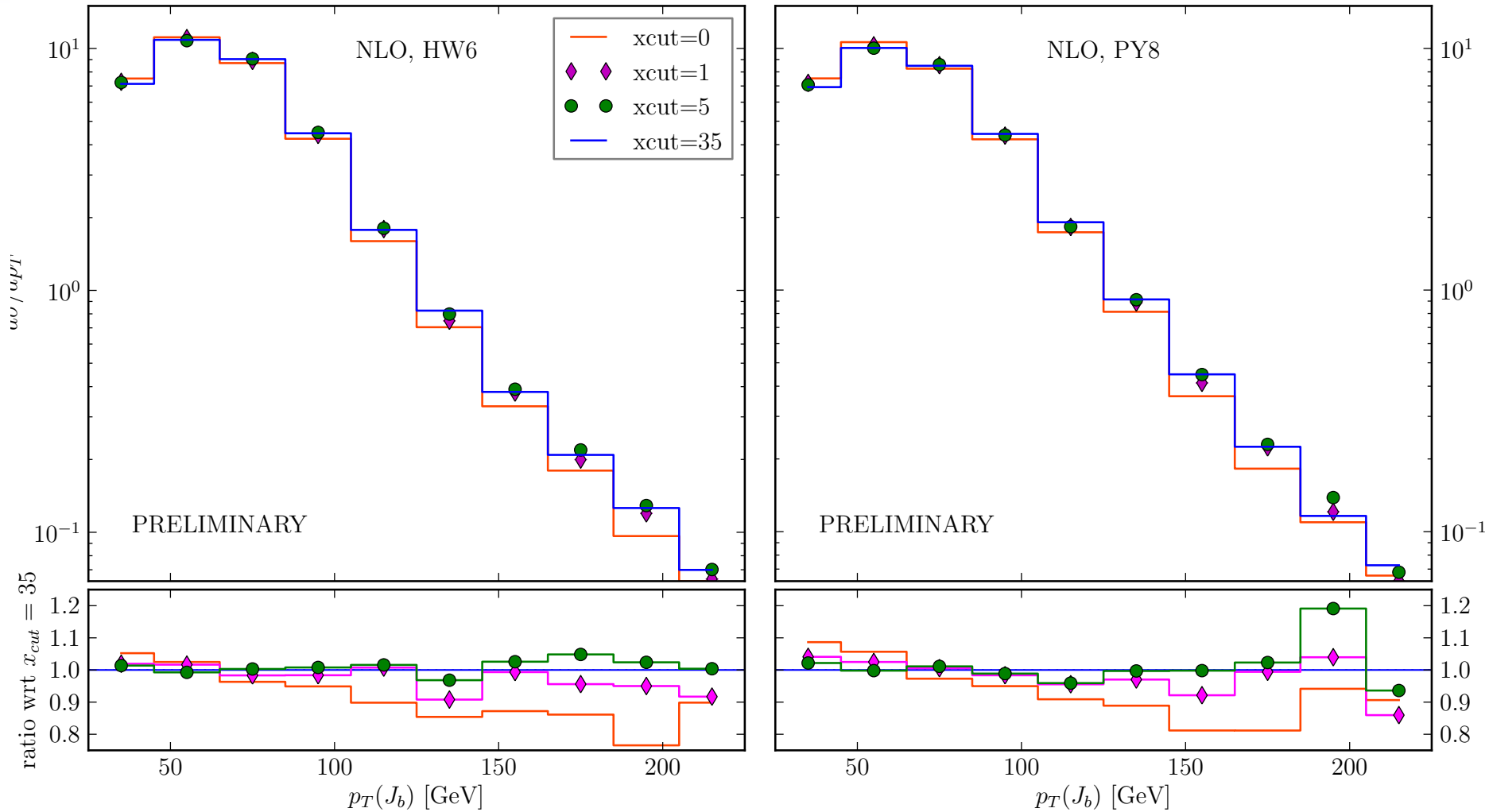
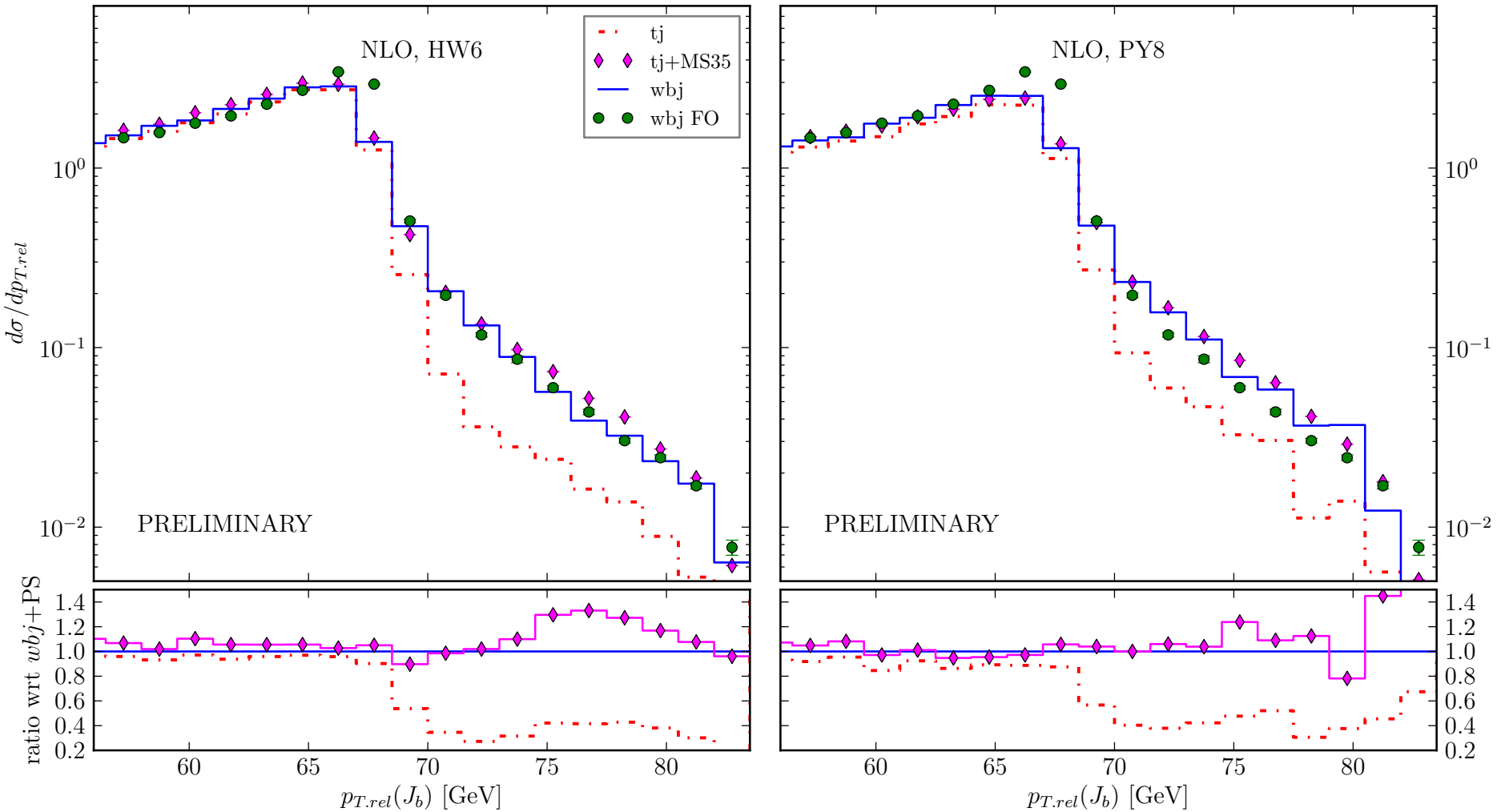


$\rightarrow$ e.g. no effect on invariant mass of reconstructed top

Varying x_{cut}: $p_T(J_b)$



Comparing approximations: $p_{T,rel.}(J_b)$



$\rightarrow$ large distortions of shape of edge tj

$\rightarrow$ expect same for other distributions with sharp edges: $M(J_b, l^+)$, $M_T(J_b, l^+, \nu_e)$