A POWHEG generator for $t\bar{t}$ production including radiation in top decays

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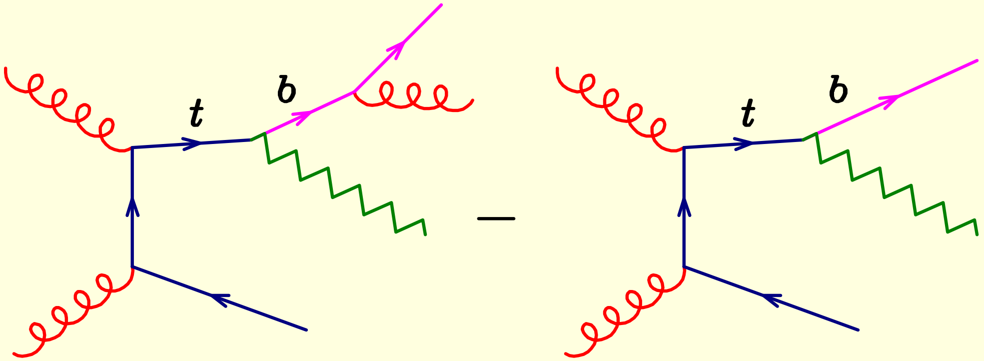
Problems with resonances: NLO calculations

Standard schemes for NLO calculation fail in the narrow resonance limit.
Example: FKS in $t\bar{t}$ production



FKS subtraction term kinematics does not preserve the bgW mass.
(b direction preserved; $W\bar{b}$ recoiling system boosted along b direction and b momentum set to conserve 4-momentum)
Thus: when bgW is on shell, the counterterm is off-shell, spoiling IR cancellation in the narrow width approximation. The same happens with CS dipoles (W four momentum preserved.)

Message #1:

Current NLO subtraction schemes fail in the narrow width limit

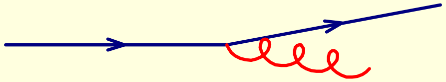
As long as we have finite width, current schemes converge given an unlimited amount of CPU time, i.e. brute force solutions are sometimes possible.
NLO calculations of $W^+W^-b\bar{b}$ have been performed by Bevilacqua etal, 2011, and Denner etal, 2012, in the 5-flavour scheme, and Frederix, 2014, massive b.

If only resonant graphs are included: radiative corrections for production and decays are distinct, and can be separated.
One can use the different subtraction schemes in production and decays;

If non resonant contributions, and interference between non-resonant and resonant graphs are included, more work is needed.

Problems with resonances: PS

Key problem: momentum reshuffling.



Collinear splitting conservers momentum only in the strict collinear limit. Shower Monte Carlo enforce exact momentum conservation by "Momentum reshuffling" (i.e. adjust the momenta by subleading corrections to enforce momentum conservation).

For example (Herwig): If a Final State particle undergoes splitting, and its 3-momentum is kept fixed to balance the 3-momenta of all other FS particles, its energy becomes larger. In order to restore energy conservation, all 3-momenta are rescaled down by a common factor.

If we have a radiating resonance decay, this procedure does not conserve the resonance mass. Hence: in this case, Herwig does momentum reshuffling maintaining the resonance 4-momentum fixed, by rescaling the momenta of the resonance decay products in the resonance rest frame.

Problems with resonances: NLO+PS

POWHEG example:

$$\bar{B}\exp\left[-\int\frac{R}{B}\,\mathrm{d}\Phi_{\mathrm{rad}}\right]\frac{R}{B}\,\mathrm{d}\Phi_{\mathrm{rad}}$$

Here R contains the radiation, and B is the underlying Born kinematics. The standard POWHEG underlying Born mapping does not preserve resonance virtuality: if R is on shell, B is off shell, R/B LARGE!

More quantitatively: consider for example $t\rightarrow bW$; b splits into a bg with mass m^2. The bW mass in the counterterm differs from the original top virtuality by an amount m^2/E_b. So, we expect that

The b jet mass profile is distorted when $m^2_{\mathrm{jet}}/E_b\approx\Gamma_{\mathrm{top}}$.

Message #2:

Current NLO+PS schemes fail in the narrow width limit

Brute force solution: Full $W^+W^-b\bar{b}$ production in `POWHEL` has been implemented (Kardos,Garzelli,Trocsanyi 2014), using the standard `POWHEG BOX` mapping. The euristic argument given above would imply unphysical features of jet structure when $m_{\rm jet}\approx\sqrt{\Gamma E}\approx 8\,{\rm GeV}$. Studies in this direction are being pursued.

NLO+PS with radiating resonances in `narrow width limit`

`POWHEG-BOX-V2` can deal with radiation in resonance decays in the zero-width limit in a fully general way. In order to implement a process one must:

- Specify the resonance and its decay products in the user provided subprocess list. For example:
  ```
  realfl:[ 0, 0,  6, -6, 24,-24,-11, 12, 13,-14,  5, -5, 0]
  realrs:[ 0, 0,  0,  0,  3,  4,  5,  5,  6,  6,  3,  4, 3]
  ```
  represents a real graph for $gg \to (t \to (W \to \bar{e}\nu)\, b\, g)(\bar{t} \to (W^- \to \mu\bar{\nu}))$.
- Virtual corrections should include virtual corrections to resonance decays.
- Real correction should yield separately the radiation from the hard interaction (if the radiated parton does not belong to a resonance), and the radiation from each decaying resonance, depending upon `realrs[n]`

Implementation in $t\bar{t}$ production

(Campbell,Ellis,Re,P.N. 2014, **arXiv:1412.1828**, code to be made public soon)

Matrix elements from Campbell,Ellis,2012.

Narrow resonance decay machinery from `POWHEG BOX V2`.

Further problems:

- Finite width effects
- Multiplicative vs. additive corrections to resonance decays.

Finite width effects

In certain applications (for example, t mass measurement from end-points) the finite width of the top may have an effect. We implement it in the following way:

- We generate the Born phase space with finite width for the t and $\bar{t}$
- We project the Born finite width phase space onto a zero width phase space with a top mass equal to the average top virtuality. The projection conserves the total CM partonic momentum.
- Matrix elements are computed with the projected phase space.
- Real emission events are projected backward into real emission events initiated by the original (off-shell top) kinematics.
- The final cross section is reweighted either with
  - → The exact Born matrix elements for the production of the given final state after decay (from MadGraph), (including interference effects) divided by the projected on-shell matrix element ("full")
  - → The Born matrix elements for the production of the given final state after decay (from MadGraph), including only doublre resonant graphs, divided by the projected on-shell matrix element ("DR")
  - → The Breit Wigner shapes of the t and $\bar{t}$ ("BW")

Comparison with fixed order NLO results

Full NLO calculation of $t\bar{t}$ production and decay, including finite width and reesonance effects, from Denner,Dittmaier,Kallweit,Pozzorini 2012.

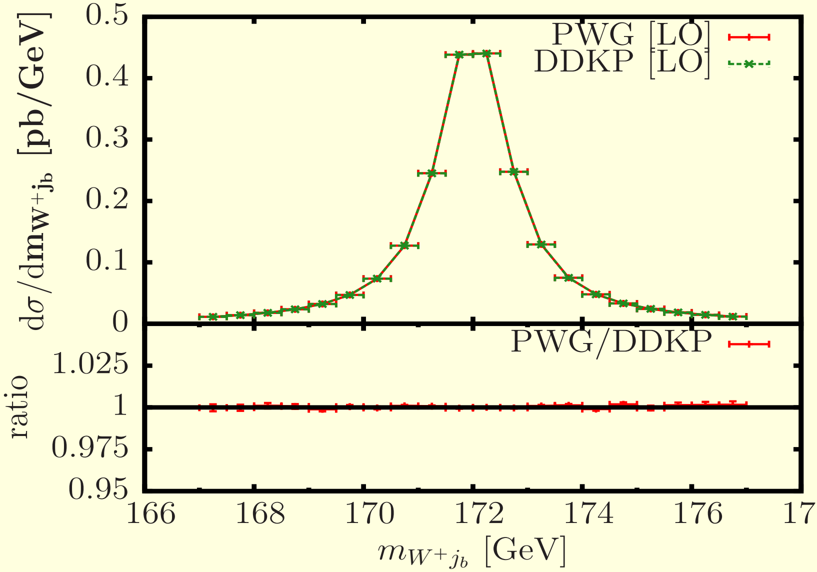
Cuts:

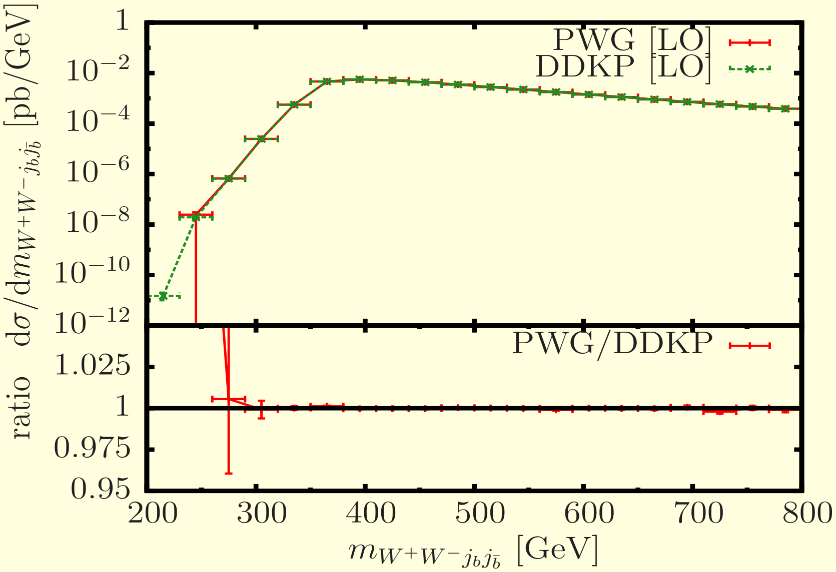
$$p_{T,j_b} > 30\,\mathrm{GeV}, \quad |\eta_{j_b}| < 2.5, \quad p_{T,\mathrm{miss}} > 20\,\mathrm{GeV},$$

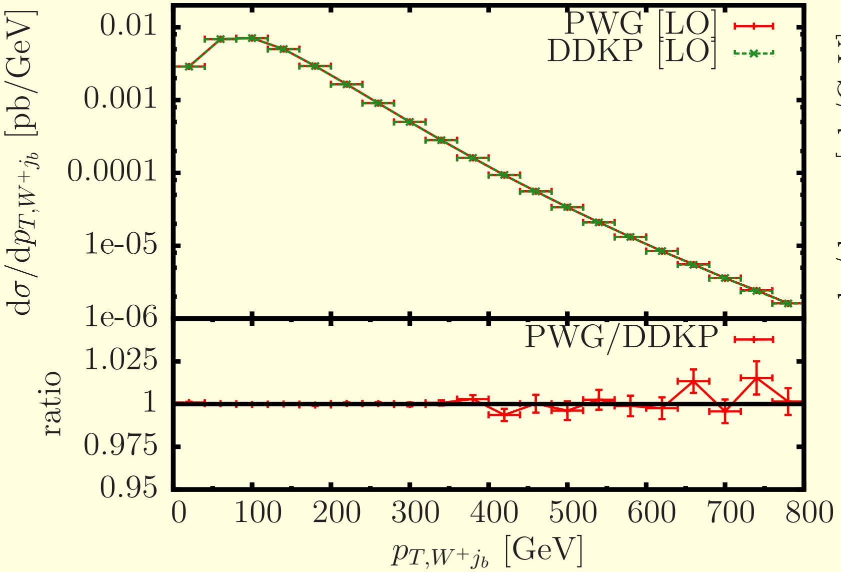
$$p_{T,l} > 20\,\mathrm{GeV}, \quad |\eta_l| < 2.5$$

where we require two b-jets in the final state (anti-k_T, $R = 0.5$)

- LO comparison: must yield identical results
- NLO comparison: our finite width corrections are only valid for NLO effects proportional to the Born term, i.e. soft and collinear real and virtual contributions.


PWG [LO]
DDKP [LO]
$d\sigma/dm_{W^+j_b}$ [pb/GeV]
0.5
0.4
0.3
0.2
0.1
0
PWG/DDKP
ratio
1.025
1
0.975
0.95
166
168
170
172
174
176
178
$m_{W^+j_b}$ [GeV]


PWG [LO]
DDKP [LO]
$d\sigma/dm_{W^+W^-j_bj_{\bar{b}}}$ [pb/GeV]
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
PWG/DDKP
ratio
1.025
1
0.975
0.95
200
300
400
500
600
700
800
$m_{W^+W^-j_bj_{\bar{b}}}$ [GeV]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DDKP [LO]
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0.0001
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1e-06
PWG/DDKP
ratio
1.025
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0.975
0.95
0
100
200
300
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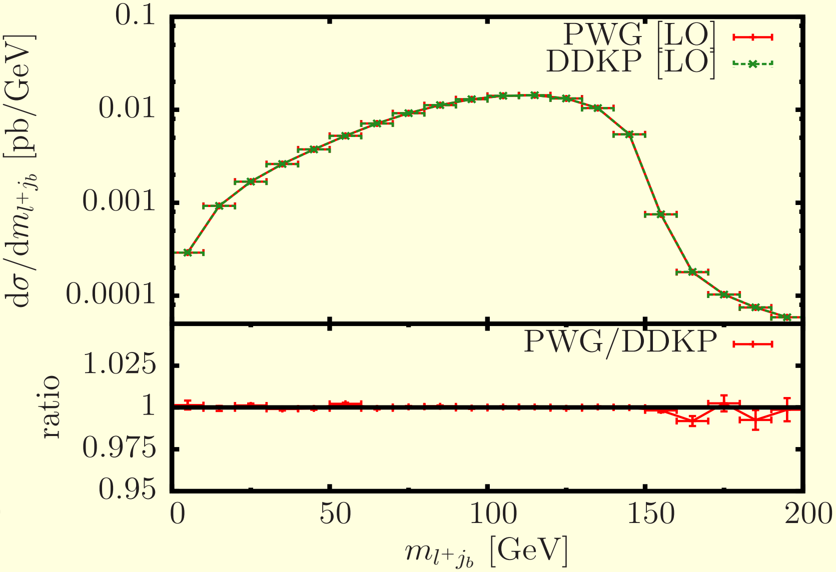
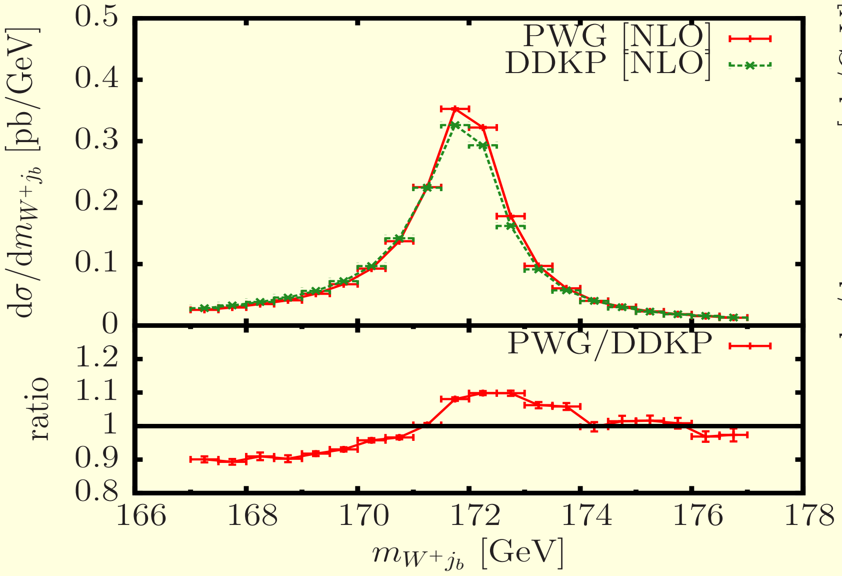
500
600
700
800
p_{T,W^+j_b} [GeV]


PWG [LO]
DDKP [LO]
$d\sigma/dm_{l^+j_b}$ [pb/GeV]
0.1
0.01
0.001
0.0001
PWG/DDKP
ratio
1.025
1
0.975
0.95
0
50
100
150
200
$m_{l^+j_b}$ [GeV]


PWG [NLO]
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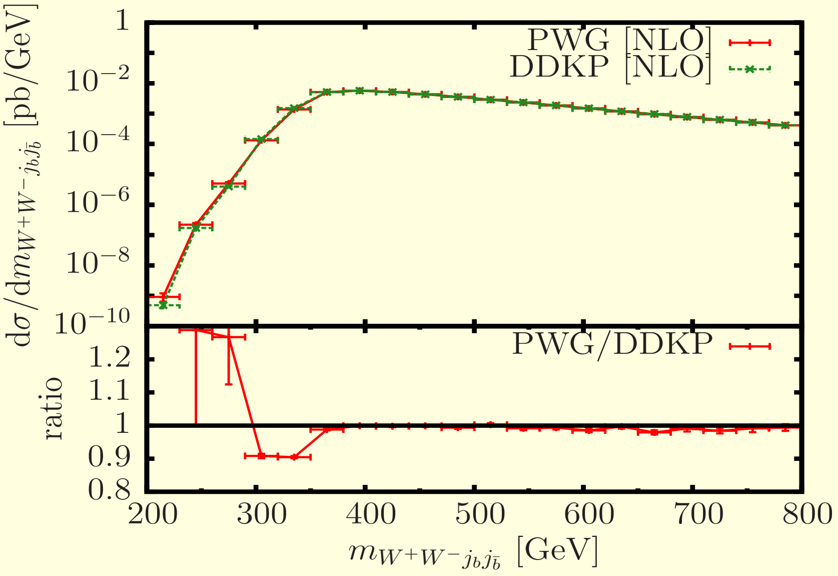
$d\sigma/dm_{W^+j_b}$ [pb/GeV]
0.5
0.4
0.3
0.2
0.1
0
ratio
1.2
1.1
1
0.9
0.8
166
168
170
172
174
176
178
$m_{W^+j_b}$ [GeV]


PWG [NLO]
DDKP [NLO]
PWG/DDKP
$d\sigma/dm_{W^+W^-j_bj_{\bar{b}}}$ [pb/GeV]
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
ratio
1.2
1.1
1
0.9
0.8
200
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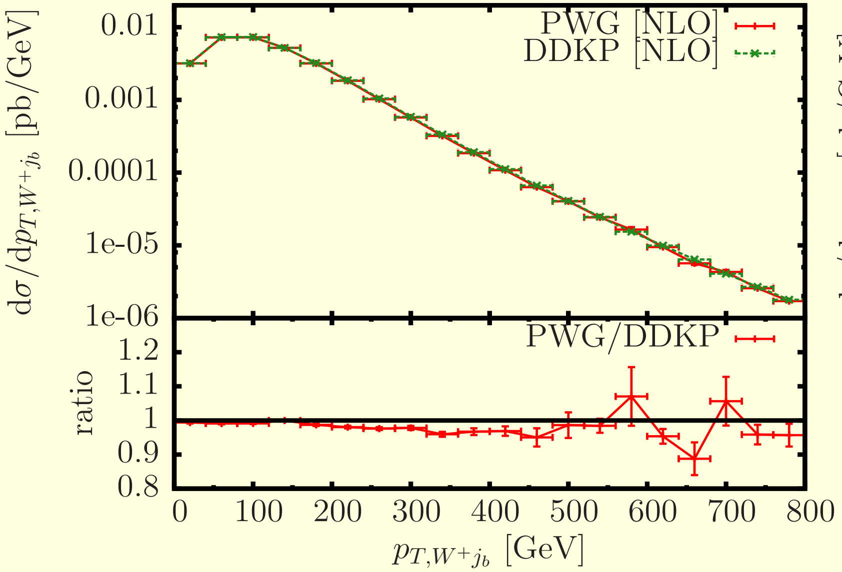
500
600
700
800
$m_{W^+W^-j_bj_{\bar{b}}}$ [GeV]


PWG [NLO]
DDKP [NLO]
PWG/DDKP
$d\sigma/dp_{T,W^+j_b}$ [pb/GeV]
0.01
0.001
0.0001
1e-05
1e-06
ratio
1.2
1.1
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0.9
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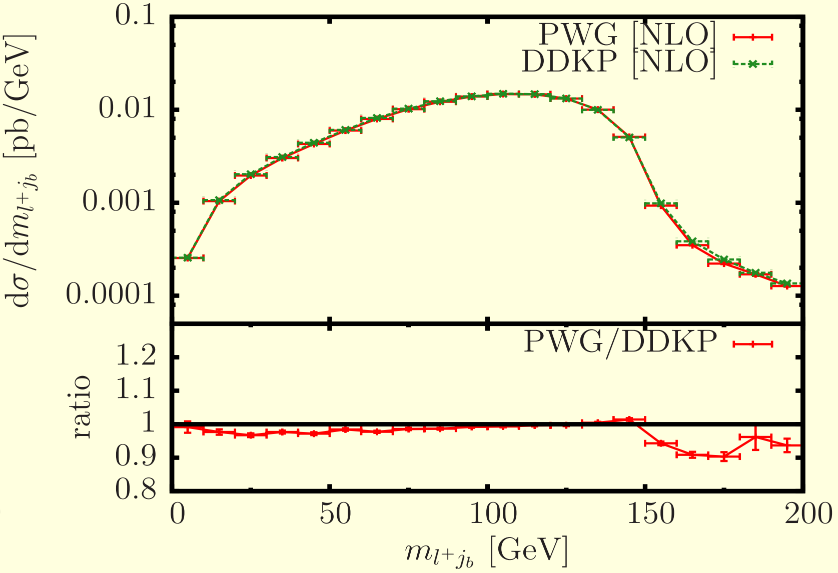
p_{T,W^+j_b} [GeV]

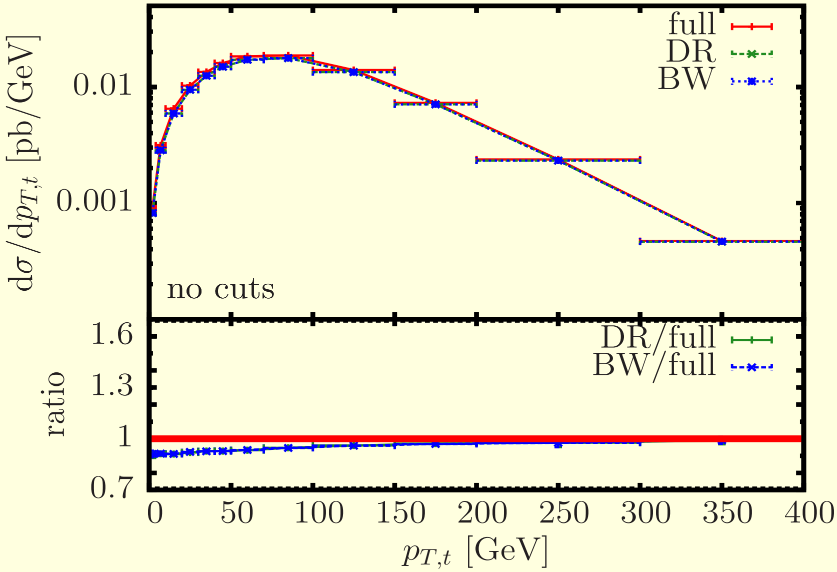

PWG [NLO]
DDKP [NLO]
PWG/DDKP
$d\sigma/dm_{l^+j_b}$ [pb/GeV]
0.1
0.01
0.001
0.0001
ratio
1.2
1.1
1
0.9
0.8
0
50
100
150
200
$m_{l^+j_b}$ [GeV]

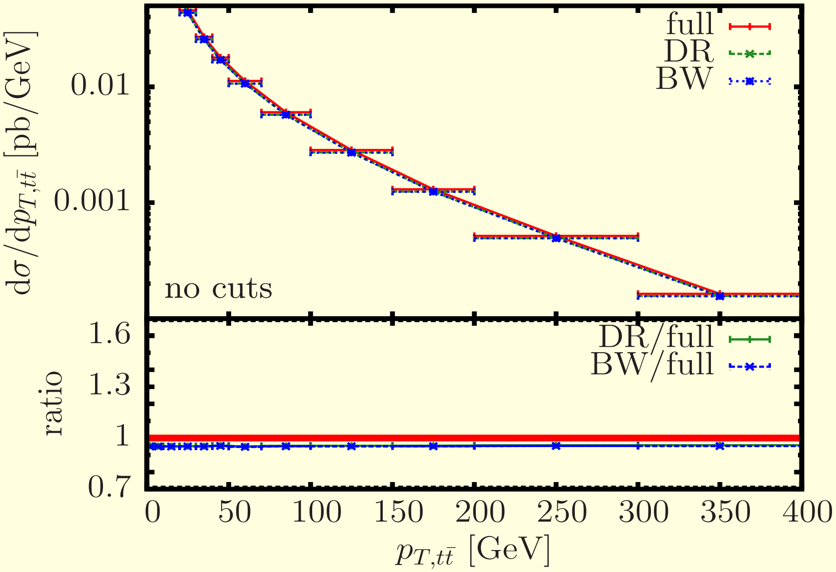
Comparison of full, DR and BW results

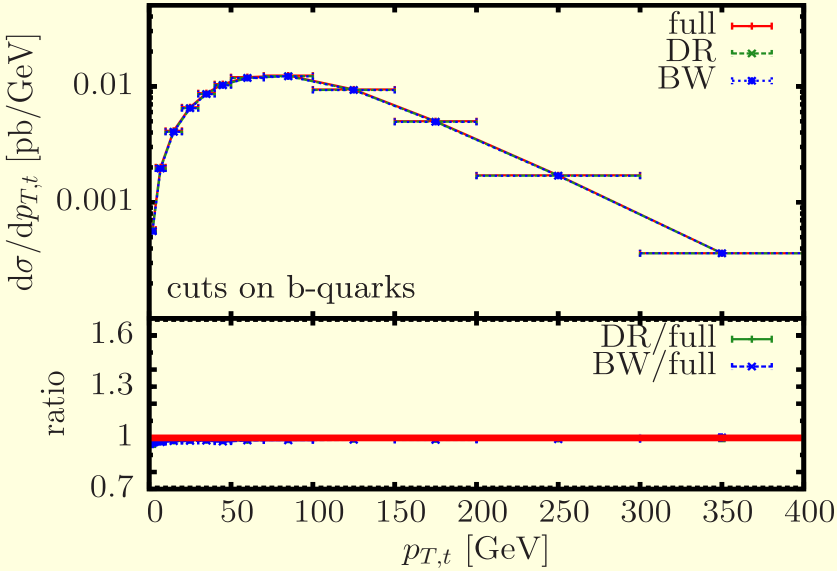
To test the soundness of our method for the implementation of off-shell effects, we compare our full, DR and BW results.

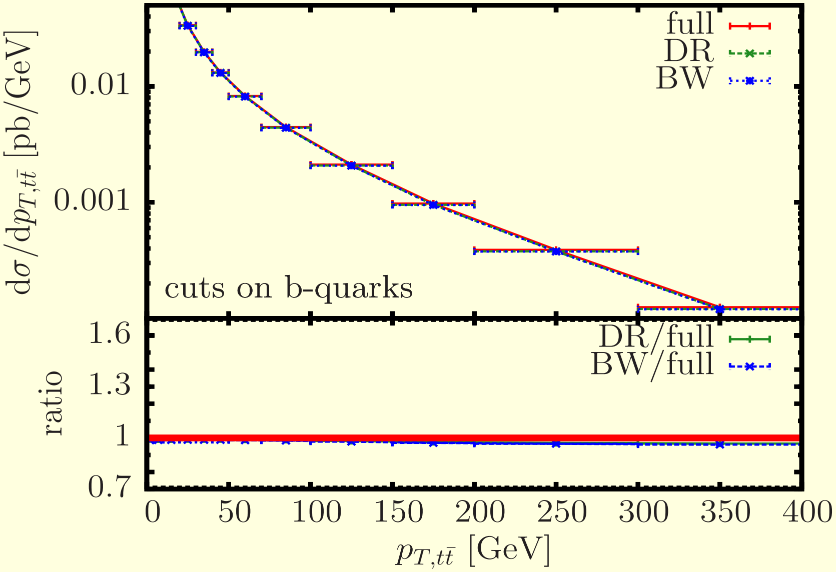
- DR and BW results are fairly compatible
- full result differs from DR and BW due to non-resonant configurations with $b\bar{b}$ pairs produced by gluon splitting or flavour excitation. Requiring: $p_{T,(b|\bar{b})} > 30\,\mathrm{GeV}$ and $\sqrt{(p_b + p_{\bar{b}})^2} > 30\,\mathrm{GeV}$ reduces these differences.

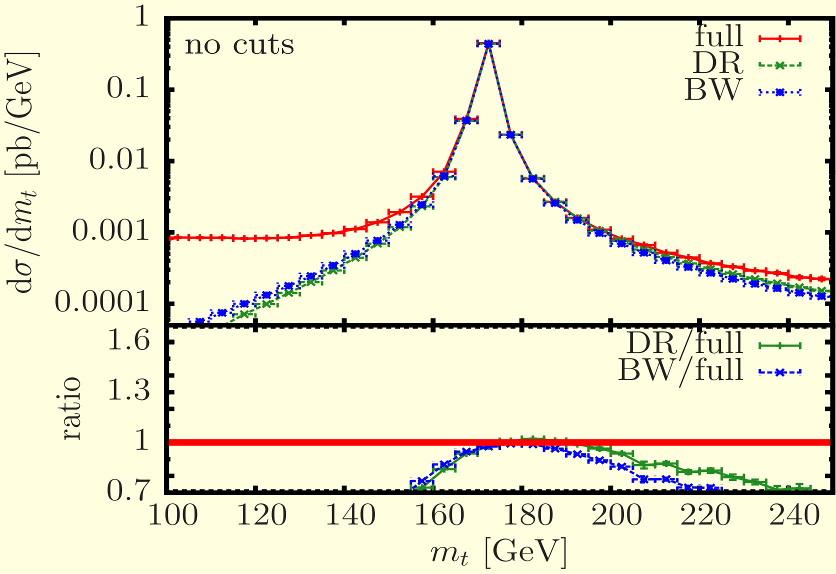
The message: the mapping procedure is not sensibly corrected by the exact matrix element reweighting (i.e. it is sound).

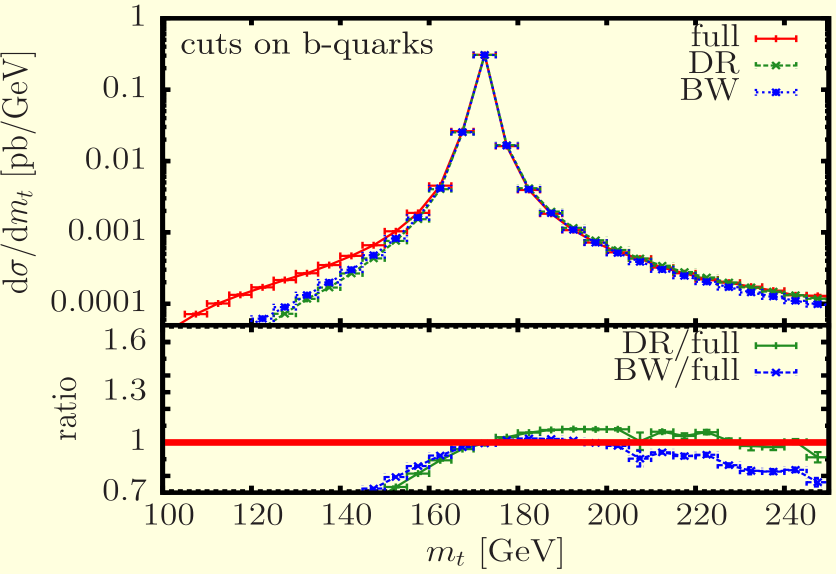

full
DR
BW
0.01
0.001
$d\sigma/dp_{T,t}$ [pb/GeV]
no cuts
DR/full
BW/full
1.6
1.3
1
0.7
ratio
0
50
100
150
200
250
300
350
400
$p_{T,t}$ [GeV]


full
DR
BW
0.01
0.001
$d\sigma/dp_{T,t\bar{t}}$ [pb/GeV]
no cuts
DR/full
BW/full
1.6
1.3
1
0.7
ratio
0
50
100
150
200
250
300
350
400
$p_{T,t\bar{t}}$ [GeV]


full
DR
BW
0.01
0.001
$d\sigma/dp_{T,t}$ [pb/GeV]
cuts on b-quarks
DR/full
BW/full
1.6
1.3
1
0.7
ratio
0
50
100
150
200
250
300
350
400
$p_{T,t}$ [GeV]


full
DR
BW
0.01
0.001
$d\sigma/dp_{T,t\bar{t}}$ [pb/GeV]
cuts on b-quarks
DR/full
BW/full
1.6
1.3
1
0.7
ratio
0
50
100
150
200
250
300
350
400
$p_{T,t\bar{t}}$ [GeV]


no cuts
full
DR
BW
$d\sigma/dm_t$ [pb/GeV]
1
0.1
0.01
0.001
0.0001
DR/full
BW/full
ratio
1.6
1.3
1
0.7
100
120
140
160
180
200
220
240
m_t [GeV]


cuts on b-quarks
full
DR
BW
$d\sigma/dm_t$ [pb/GeV]
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0.1
0.01
0.001
0.0001
DR/full
BW/full
ratio
1.6
1.3
1
0.7
100
120
140
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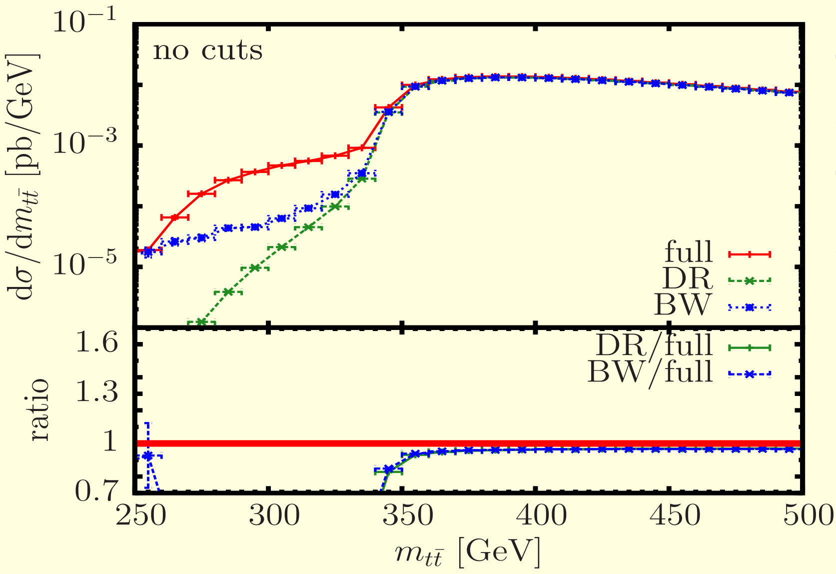
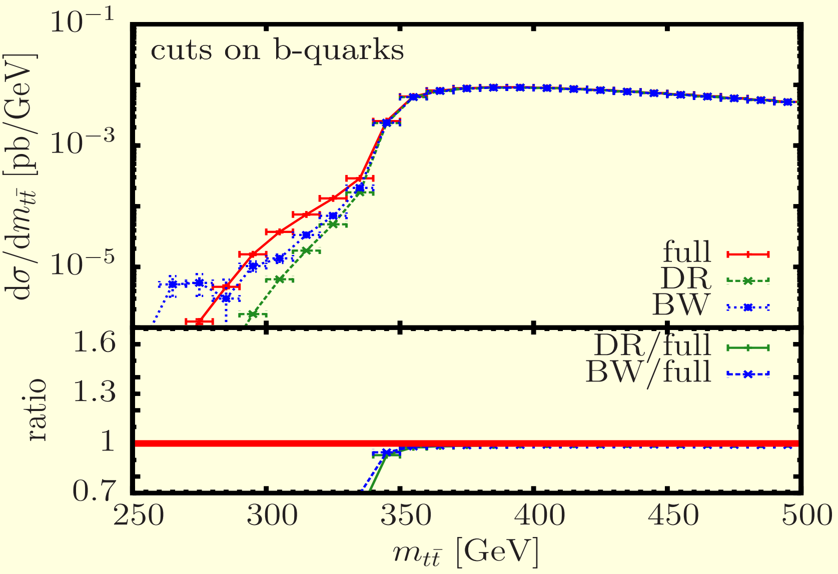
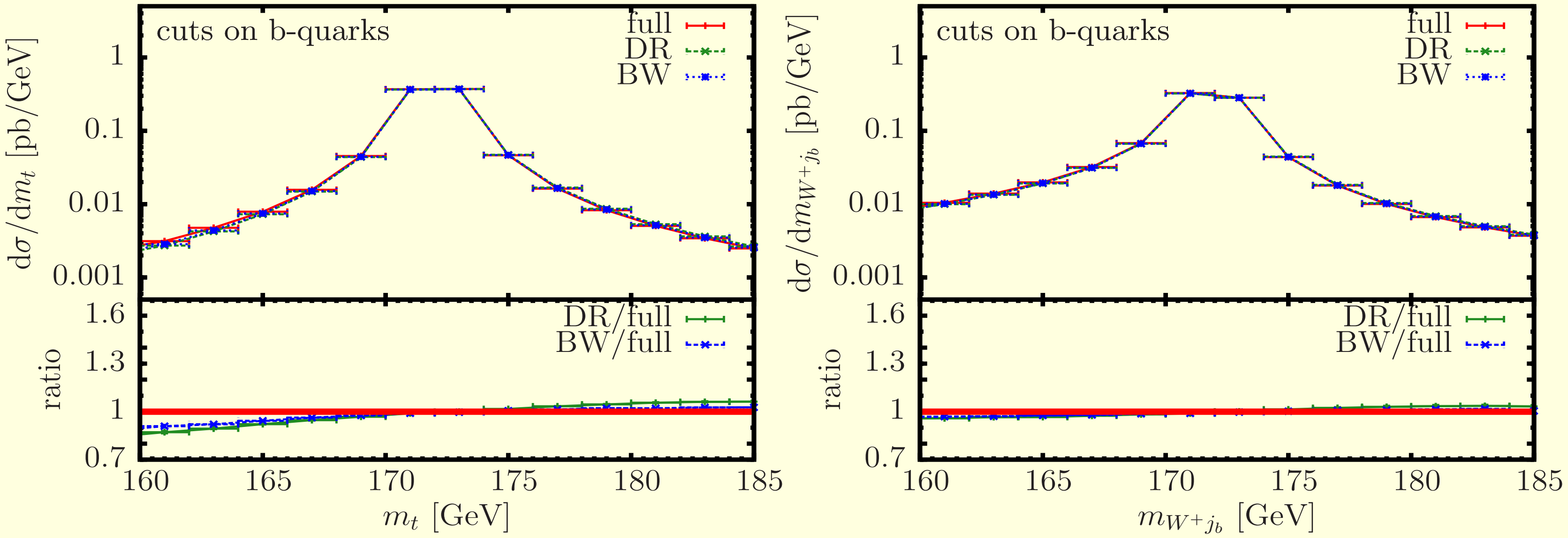
180
200
220
240
m_t [GeV]


no cuts
full
DR
BW
$d\sigma/dm_{t\bar{t}}$ [pb/GeV]
10^{-1}
10^{-3}
10^{-5}
DR/full
BW/full
ratio
1.6
1.3
1
0.7
250
300
350
400
450
500
$m_{t\bar{t}}$ [GeV]


cuts on b-quarks
full
DR
BW
$d\sigma/dm_{t\bar{t}}$ [pb/GeV]
10^{-1}
10^{-3}
10^{-5}
DR/full
BW/full
ratio
1.6
1.3
1
0.7
250
300
350
400
450
500
$m_{t\bar{t}}$ [GeV]

Observables probing the shape of the top resonance do not seem to be strongly sensitive upon the adopted procedure.



Relevance of off-shell effects for mass sensitive observables

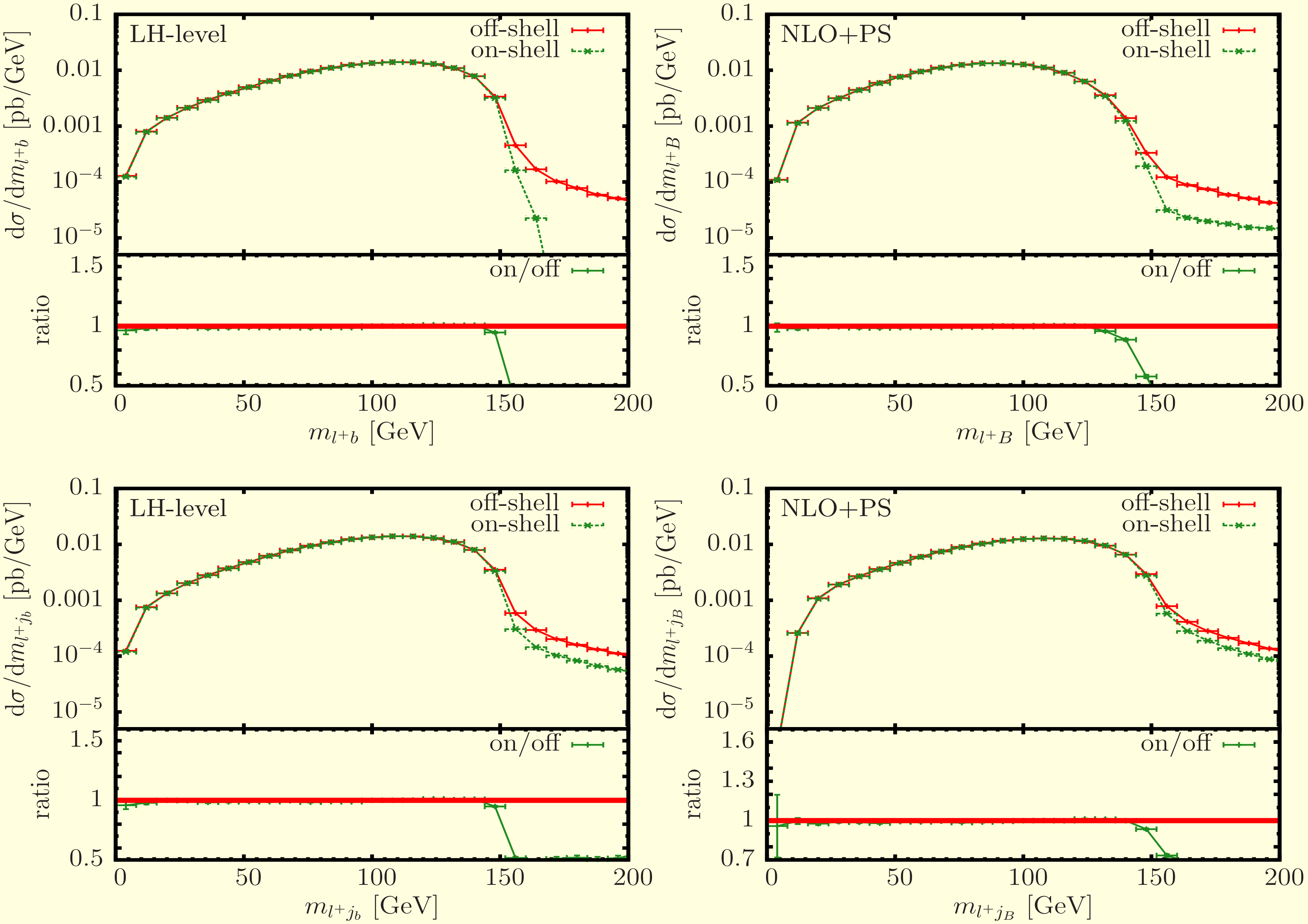
- Consider mass sensitive distribution, with realistic cuts, in the DR approximation, comparing zero width with finite width.

Cuts:

$$p_{T,j_b} > 30\,\mathrm{GeV}, \quad |\eta_{j_b}| < 2.5, \quad p_{T,\mathrm{miss}} > 20\,\mathrm{GeV},$$

$$p_{T,l} > 20\,\mathrm{GeV}, \quad |\eta_l| < 2.5$$

where we require two b-jets in the final state (anti-k_T, $R = 0.5$)


LH-level
off-shell
on-shell
on/off
$d\sigma/dm_{l^+b}$ [pb/GeV]
ratio
m_{l^+b} [GeV]
NLO+PS
off-shell
on-shell
on/off
$d\sigma/dm_{l^+B}$ [pb/GeV]
ratio
m_{l^+B} [GeV]
LH-level
off-shell
on-shell
on/off
$d\sigma/dm_{l^+j_b}$ [pb/GeV]
ratio
$m_{l^+j_b}$ [GeV]
NLO+PS
off-shell
on-shell
on/off
$d\sigma/dm_{l^+j_B}$ [pb/GeV]
ratio
$m_{l^+j_B}$ [GeV]
0.1
0.01
0.001
10^{-4}
10^{-5}
1.5
1
0.5
1.6
1.3
0.7
0
50
100
150
200

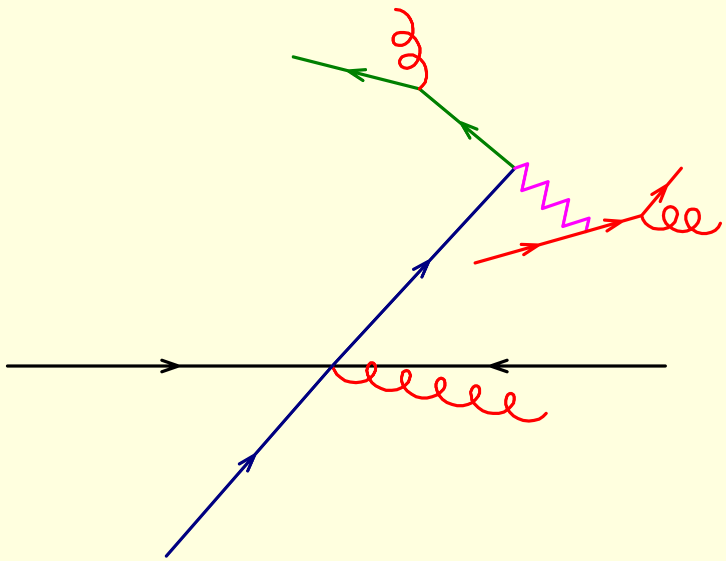
Multiplicative vs. additive corrections

In `POWHEG` only the hardest emission is generated. All remaining emissions are committed to the Shower generator.

In $t\bar{t}$ production we can have: a production emission, an emission from either t or $\bar{t}$, and an emission for each W decay, if applicable, for a total of 5 emissions. In `POWHEG` each emission is tried, and only the hardest one is kept. All the remaining one have to be generated by the shower.

Undesirable feature: the emission in hard production is more likely to have large transverse momentum. Emissions from decay become thus rare, and most of the time they will be handled by the shower.
It would be more desirable to have an emission from the hard production, plus one for each decaying resonance.

Present solution: keep hard radiation and the emissions from all decaying resonances, and merged them into a single radiation phase space with several radiated partons, up to one for each resonance.



From a given underlying Born configuration (take away the radiated gluons), in the longitudinal rest frame of the $t\bar{t}$ system:
ISR: transverse boost of the whole $t\bar{t}$ system
t radiation in decay: W boosted along its momentum in t rest frame
W radiation in decay: either q or $\bar{q}$ direction preserved. In order to combine all of them:

- Start from Born phase space, including W radiation in decay if present.
- If t radiation in decay is present, add the corresponding gluon, and replace the b and W momentum (boosting the W system along its momentum in the t rest frame)
- If ISR is present, perform transverse boost of $t\bar{t}$ system and add the gluon

This prescription guarantees that

- The hardest radiation is generated with full NLO accuracy, and the subsequent ones are at least accurate in the collinear limit
- Rotationally invariant shape observables for the resonance decays are all NLO accurate.

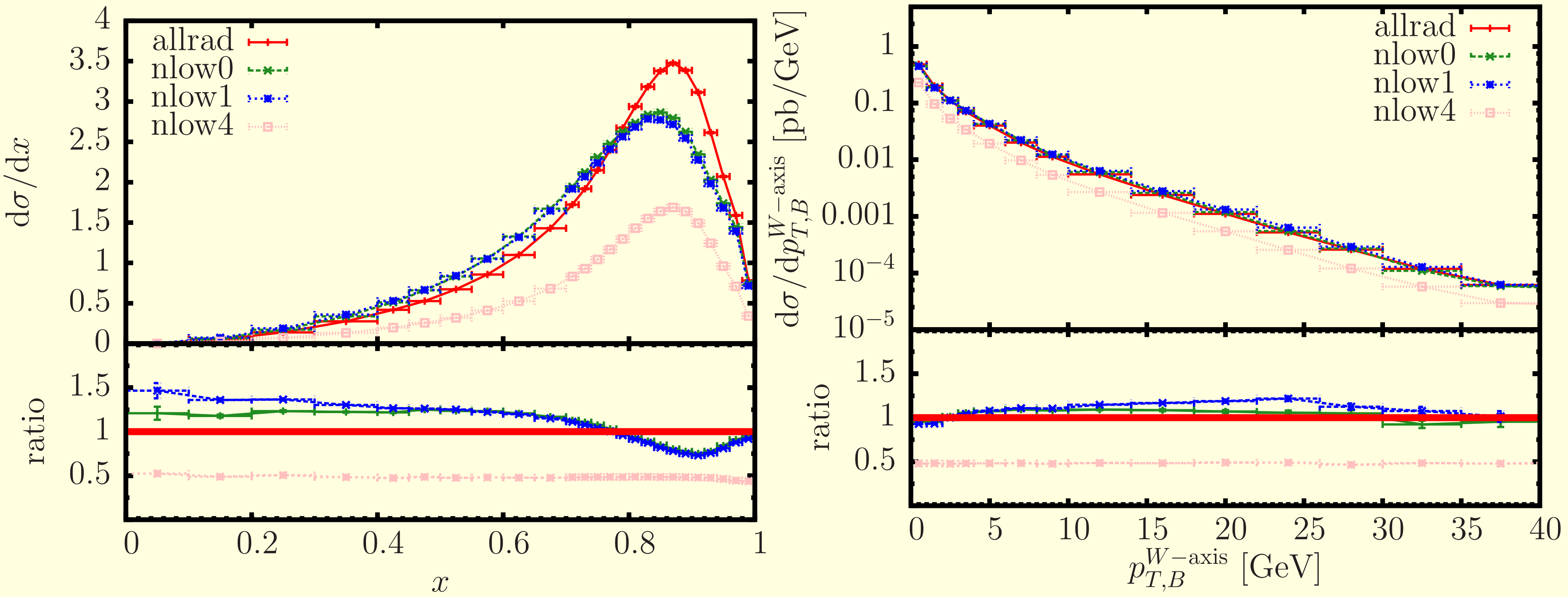
However: further radiation from the shower must be vetoed at different scales for radiation in production (scalup) and for each radiating resonance.

Standard LHIUP (Les Houches Interface for User Processes) allows only for a single scale for vetoing radiation ... Extensions are needed!

In practice: we follow the shower, and veto events that violate our requirements by hand, by restarting the shower on the same LH event.

Comparing the different variants on radiation in decays

- `allrad` set to 1 in the `powheg.input` (recommended procedure)
  ISR and radiation from each resonance decay are all kept. Radiation from the shower is vetoed both in production and in resonance decays, using respectively the p_T of ISR and the p_T in resonance decays as veto scales.
- `nlowhich` set to 0 in the `powheg.input`
  Only the hardest radiation is kept, and all radiation from the shower is vetoed using the scale of the hardest radiation.
- `nlowhich` set to 1 in the `powheg.input`
  Radiation from resonances is switched off in POWHEG. The shower provides all radiation in resonance decay.
- `nlowhich` set to 4 in the `powheg.input`
  Only radiation from t decay is generated by POWHEG. The shower provides all ISR and radiation from $\bar{t}$ decays.



B fragmentation in the t rest frame (x is the B energy over its maximum).

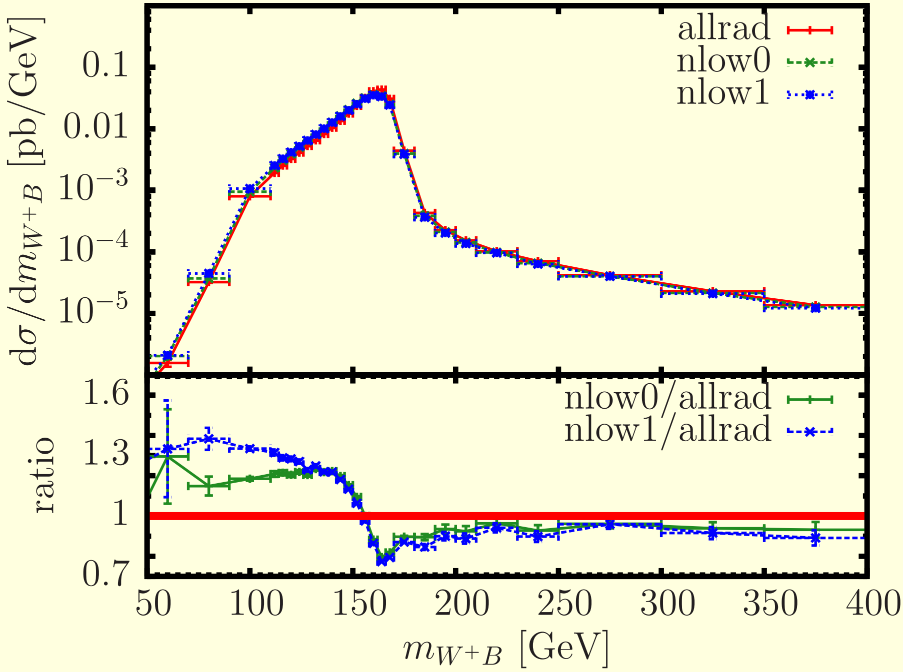
$p_{T,B}^{W-\text{axis}}$: $p_{T,B}$ relative to W direction in t frame.

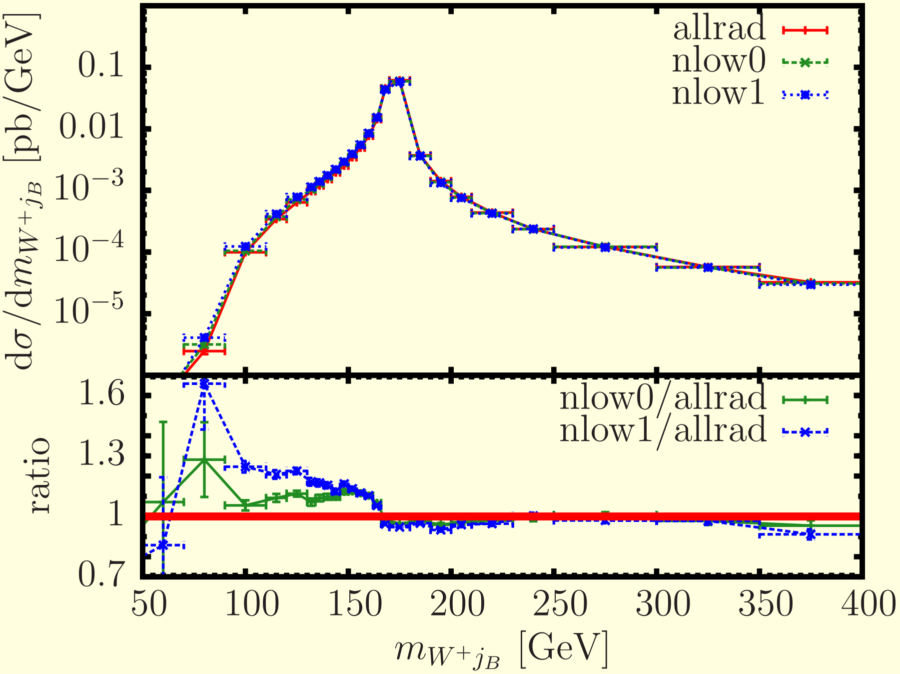
Blue: Pythia8 alone handles radiation in t decay;

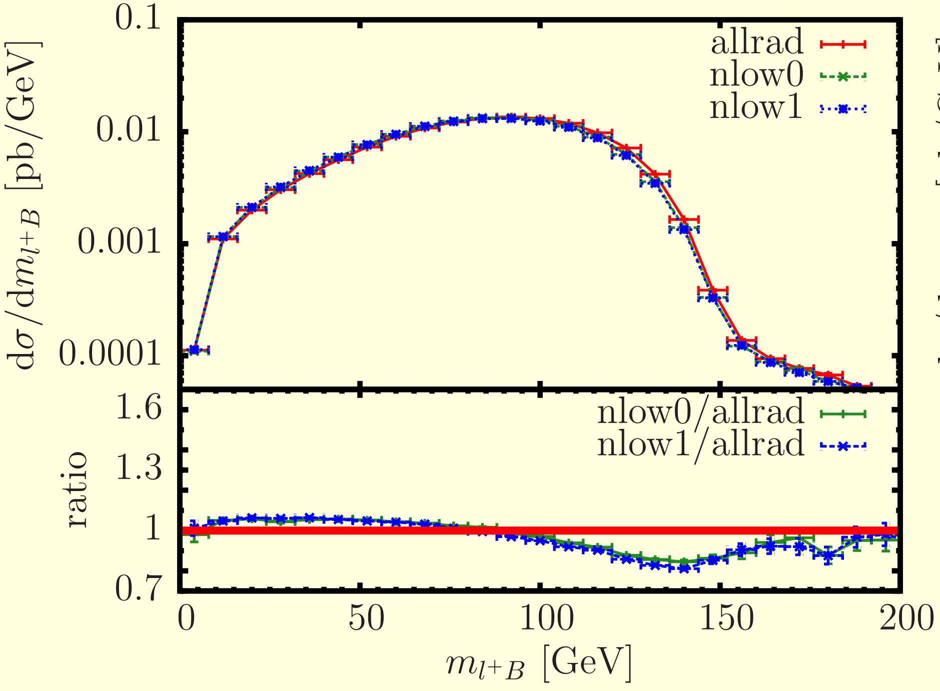
Green: POWHEG when radiation in t decay is the hardest;

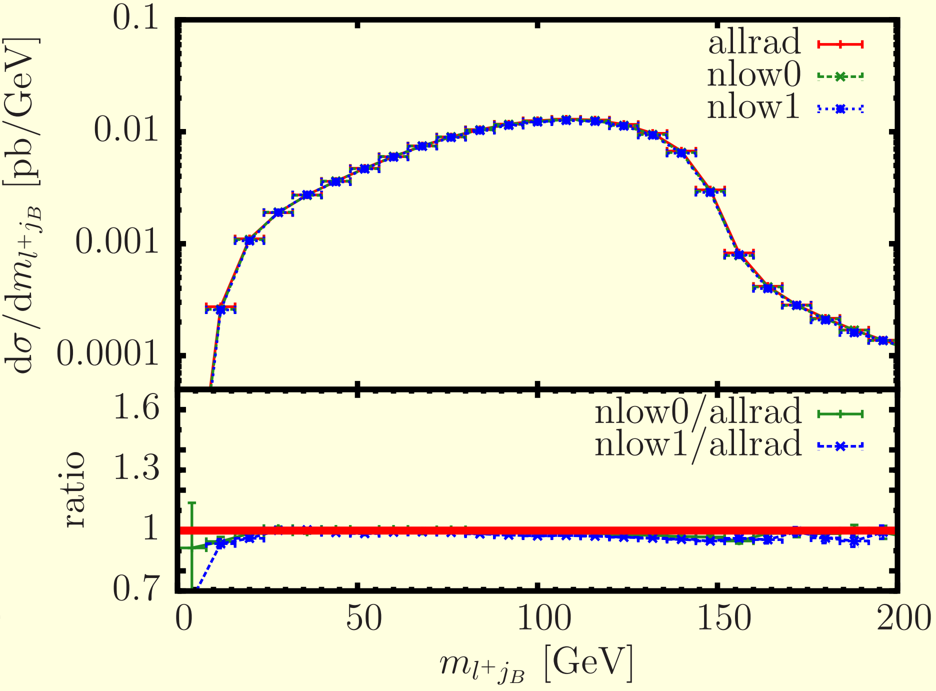
Red: Hardest radiation in t decay is always from POWHEG.

Different description of the fragmentation function leads to different behaviour of observable like the mass of the WB system; less dramatic if the B jet is used.






0.1
0.01
0.001
0.0001
dσ/dm_{l^+B} [pb/GeV]
allrad
nlow0
nlow1
1.6
1.3
1
0.7
ratio
nlow0/allrad
nlow1/allrad
0
50
100
150
200
m_{l^+B} [GeV]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0.01
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dσ/d$m_{l^+j_B}$ [pb/GeV]
allrad
nlow0
nlow1
1.6
1.3
1
0.7
ratio
nlow0/allrad
nlow1/allrad
0
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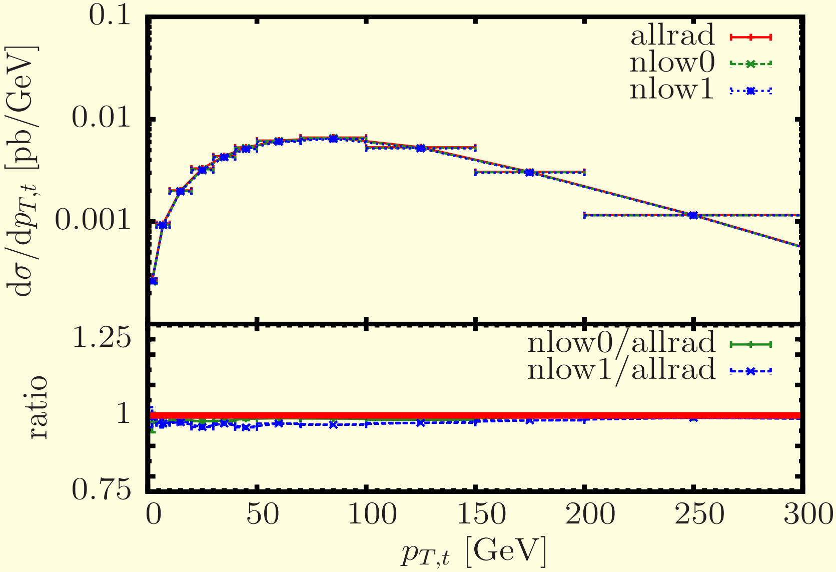
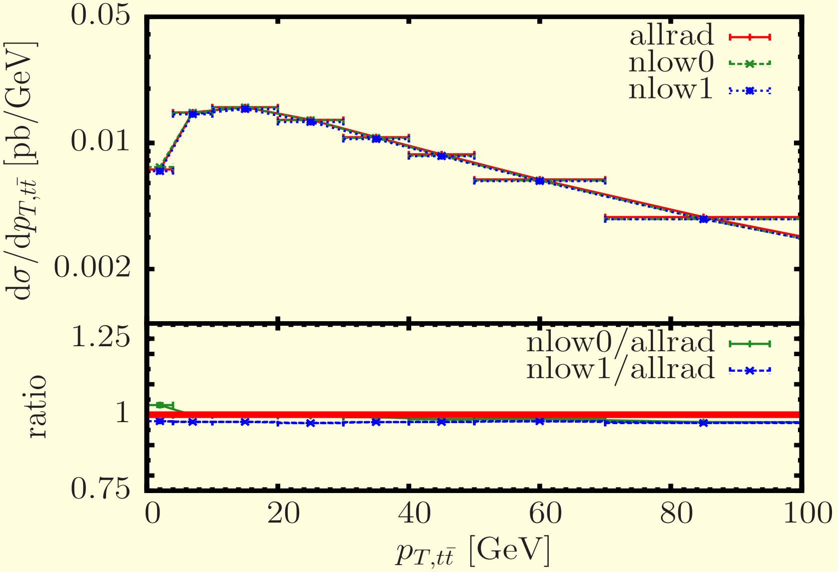
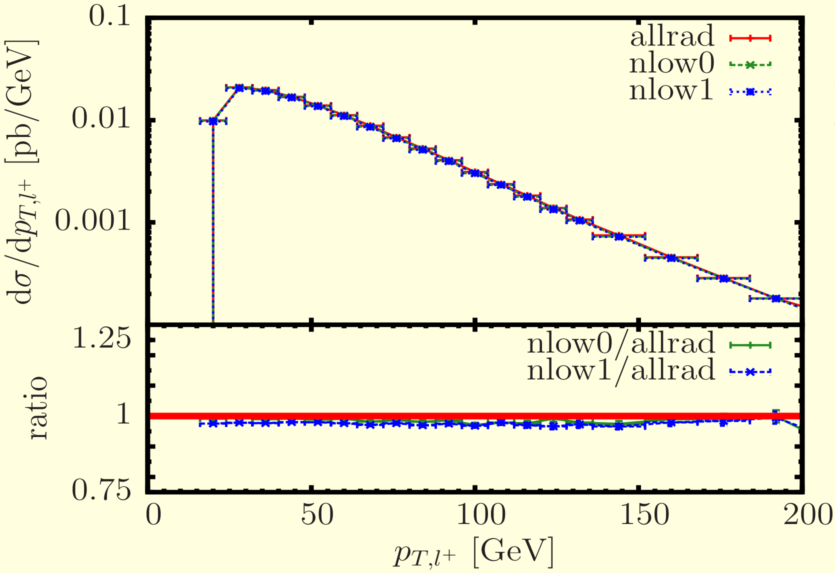
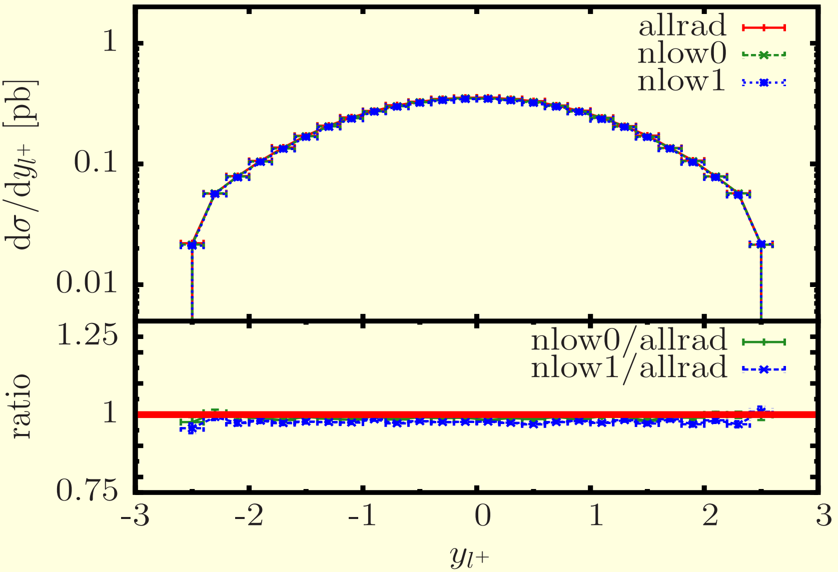
150
200
$m_{l^+j_B}$ [GeV]


allrad
nlow0
nlow1
nlow0/allrad
nlow1/allrad
dσ/d$p_{T,t}$ [pb/GeV]
ratio
0.1
0.01
0.001
1.25
1
0.75
0
50
100
150
200
250
300
$p_{T,t}$ [GeV]


allrad
nlow0
nlow1
nlow0/allrad
nlow1/allrad
dσ/d$p_{T,t\bar{t}}$ [pb/GeV]
ratio
0.05
0.01
0.002
1.25
1
0.75
0
20
40
60
80
100
$p_{T,t\bar{t}}$ [GeV]


allrad
nlow0
nlow1
nlow0/allrad
nlow1/allrad
dσ/dp_{T,l^+} [pb/GeV]
ratio
0.1
0.01
0.001
1.25
1
0.75
0
50
100
150
200
p_{T,l^+} [GeV]


allrad
nlow0
nlow1
nlow0/allrad
nlow1/allrad
dσ/dy_{l^+} [pb]
ratio
1
0.1
0.01
1.25
1
0.75
-3
-2
-1
0
1
2
3
y_{l^+}

Conclusions

- New tool for studying top physics at hadron colliders
- Top chain decays are handled, with radiative corrections included at NLO level, matched to the shower.
- Finite bottom mass effects fully included
- Several options and switches are available, to study the impact of the b fragmentation properties
- At present we have a consistent picture of b fragmentation from LEP, Tevatron and LHC data, as far as open b production is concerned. We expect top decays to be consistent with this picture. We are now in a position to perform a NLO study of the b fragmentation function, evolving it from Z to t decays.
- In perspective, at some point the problems with resonances will be overcome, allowing a consistent picture of finite width and interference effects. However, it is not clear how our factorized implementation of production and decays may be implemented in that case.