

Production of heavy resonances and matching

Tomáš Ježo

nCTEQ collaboration

ITP, WWU

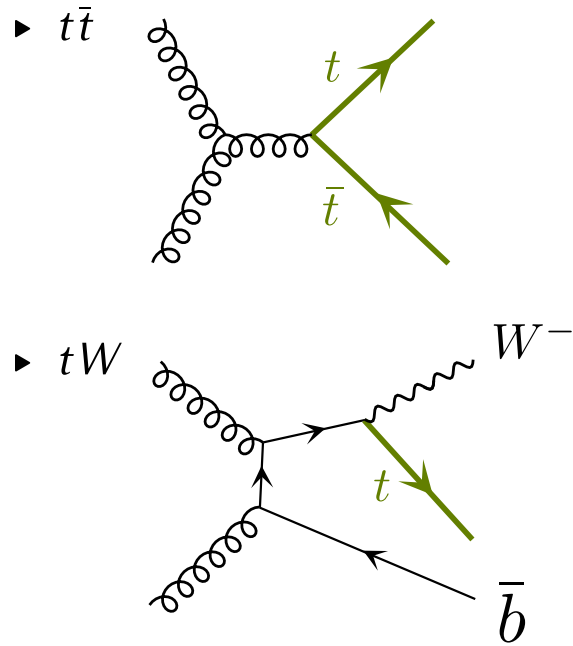
SFB 1225 isoQuant



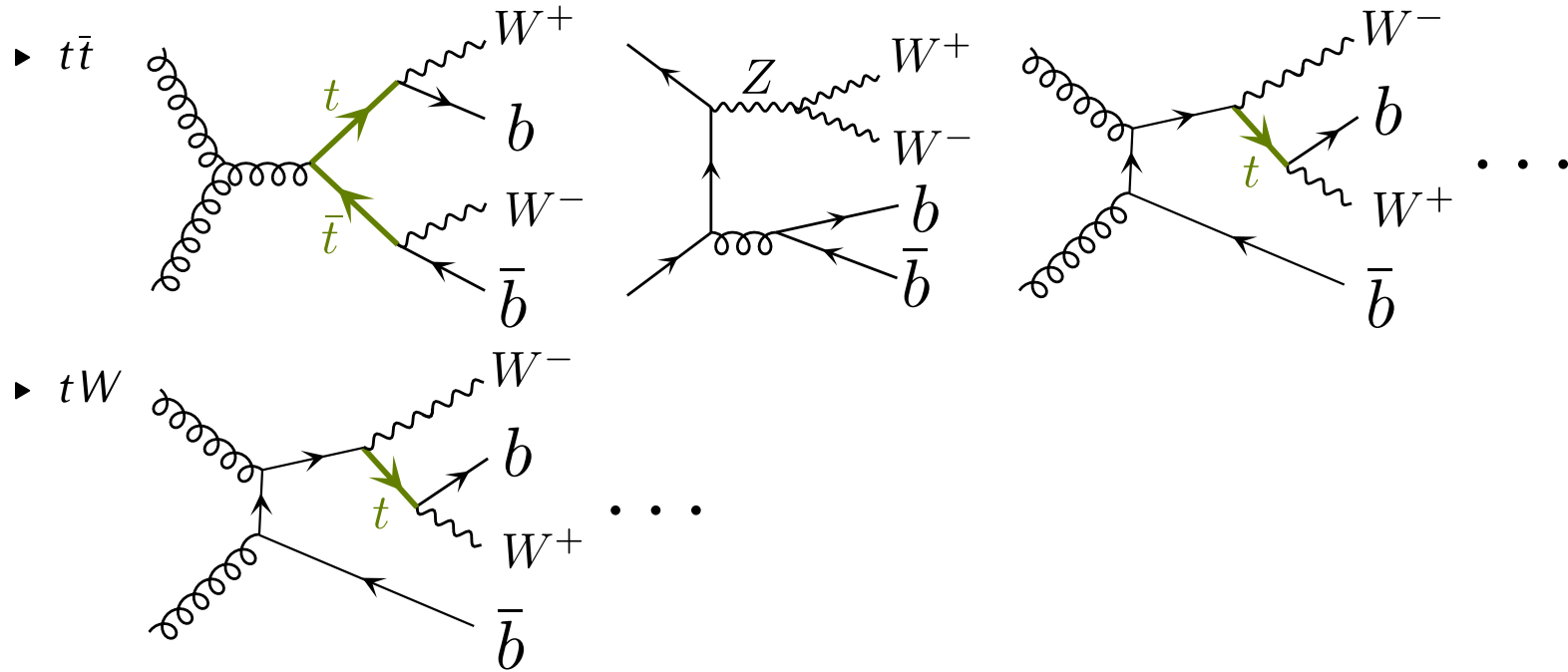
Production of heavy resonances and matching

- Outline
 - ▶ Processes with decaying resonance that can radiate
 - ▷ Review resonance aware NLO+PS matching with POWHEG
 - ▷ Report on status elsewhere and highlight developments in e^+e^-
 - ▶ Treatment of resonances in showers
 - ▷ Discuss shower stage in resonance aware NLO+PS
 - ▶ (If time allows) Heavy quark mass effects in POWHEG BOX

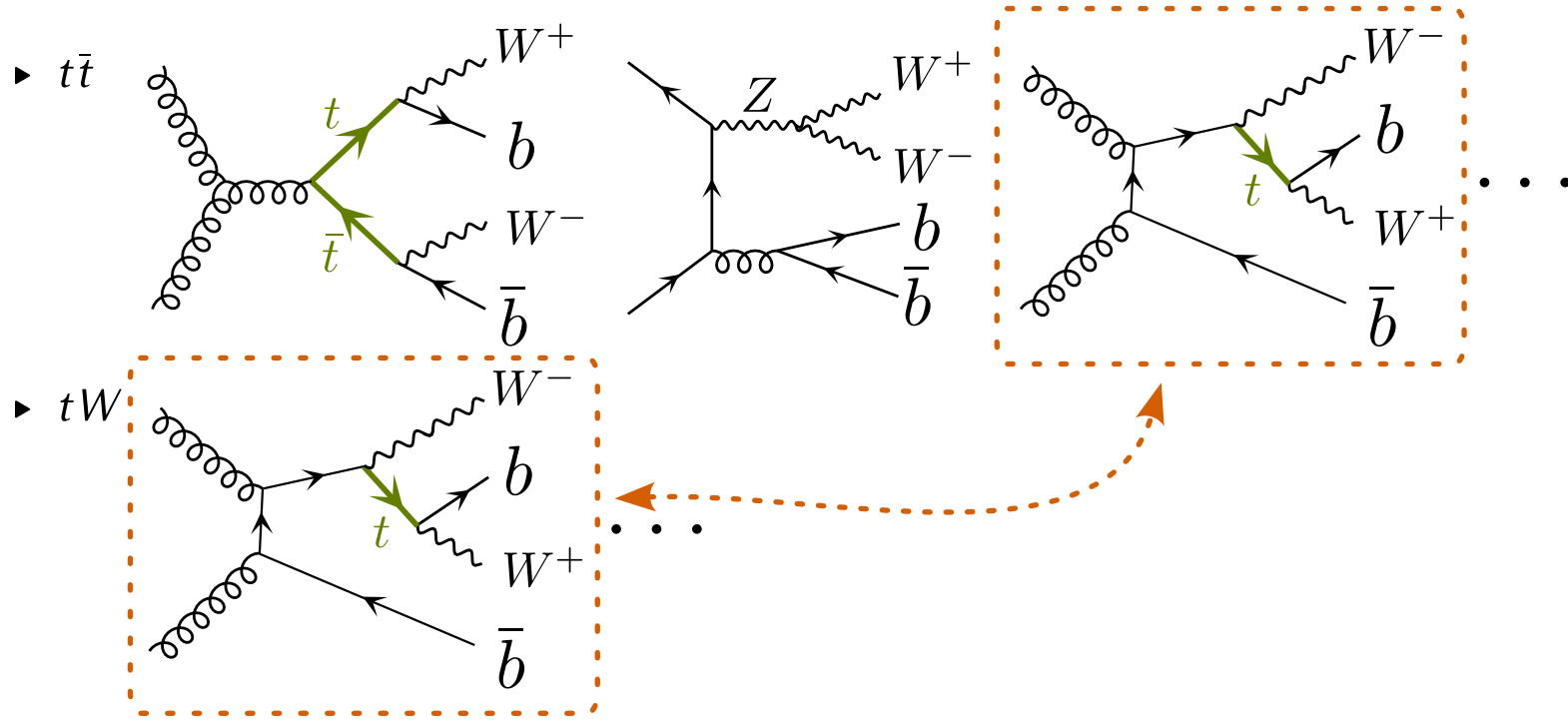
Example: $t\bar{t}$ and tW production at LHC



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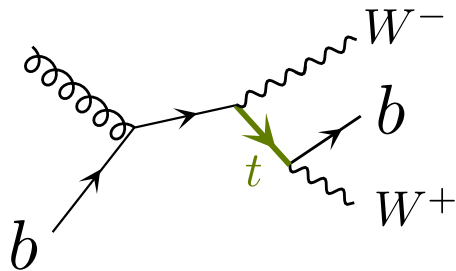
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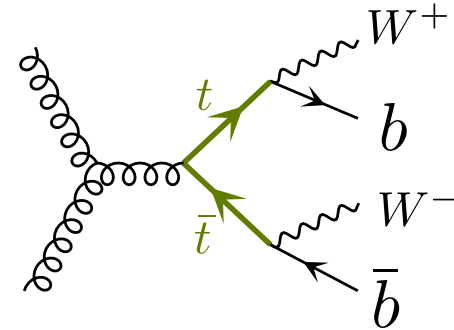
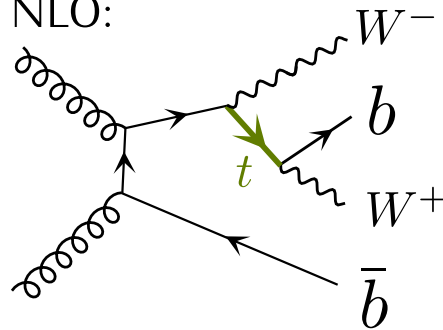
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- tW 5FNS (b in proton, $m_b = 0$)

LO:



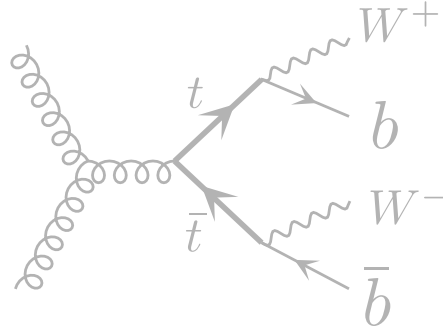
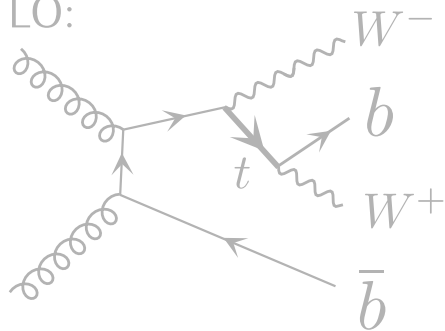
NLO:



- ▶ Requires a procedure to remove $t\bar{t}$ contribution. But what about interference?

- tW 4FNS (no b in proton, $m_b > 0$)

LO:

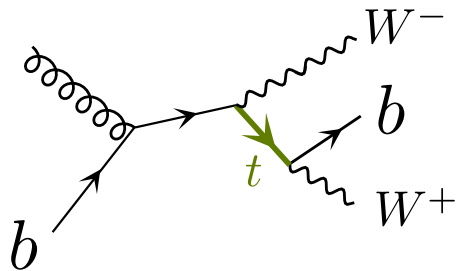


- ▶ Unified treatment of $t\bar{t}$ and tW . Including interference!

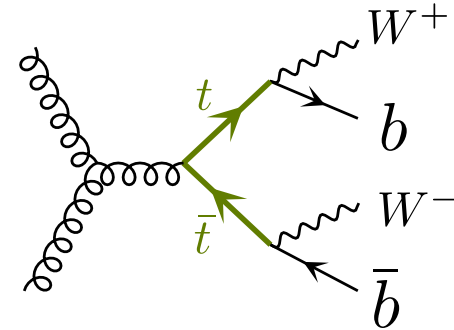
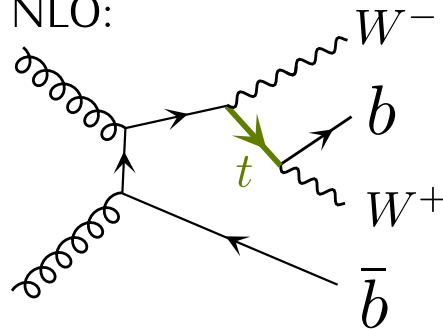
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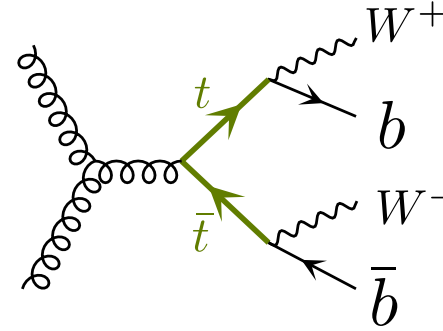
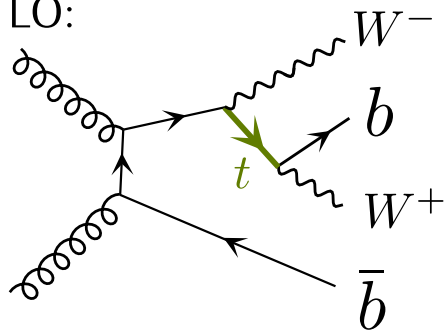
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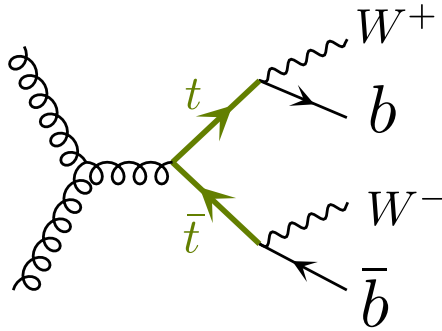
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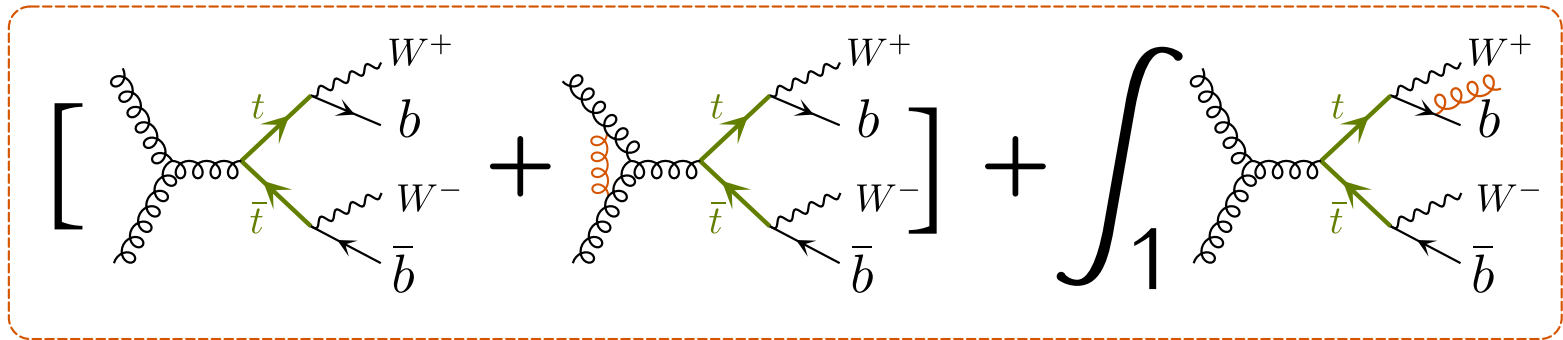
NLO+PS in POWHEG BOX



$$d\sigma = \bar{B}(\Phi_B) d\Phi_B \left[\Delta(q_{\text{cut}}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)} d\Phi_{\text{rad}} \right]$$

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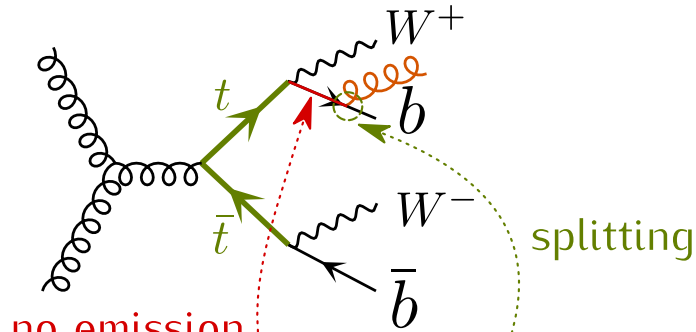
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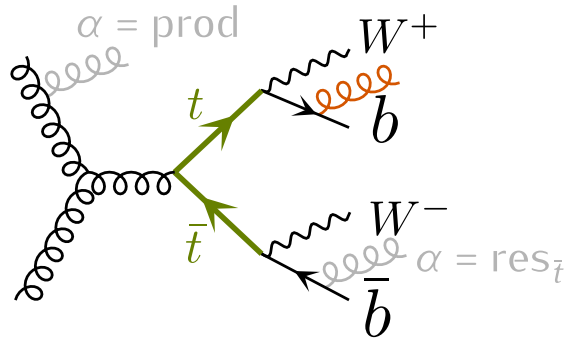
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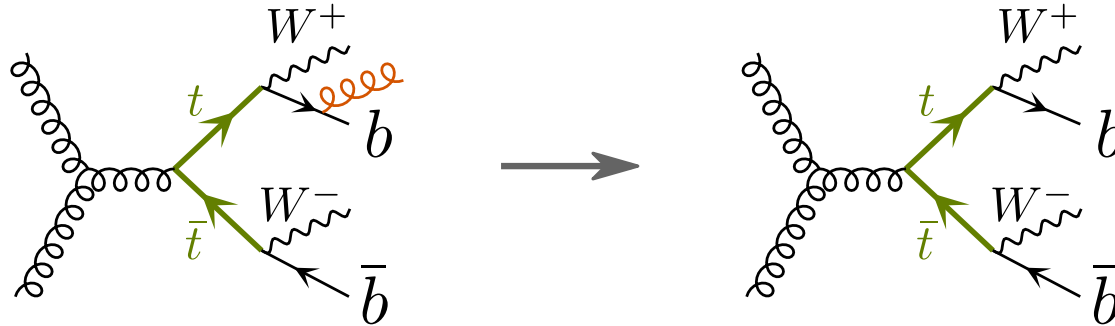
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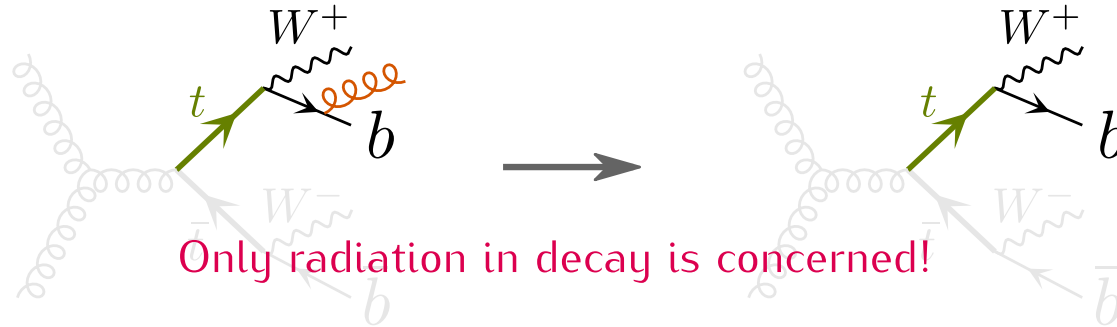


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- In standard formulation of the POWHEG method:
 - ▶ $n + 1 \leftrightarrow n$ mapping **doesn't preserve** top virtuality
 - ▶ Leading to **unphysical suppression** away from collinear singularities

NLO+PS in POWHEG BOX

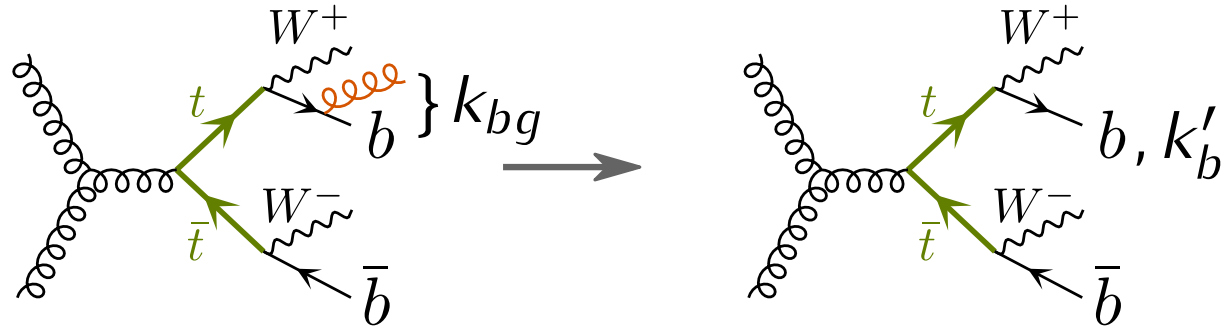


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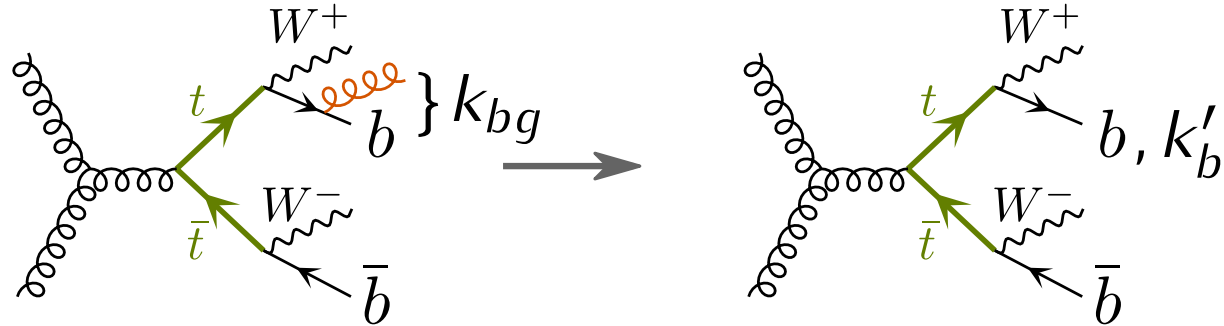
NLO+PS in POWHEG BOX



- Standard FKS final state mapping proceeds as follows:
 - ▶ k'_b direction chosen such that $\vec{k}'_b \parallel \vec{k}_{bg}$
 - ▶ $k_{W^+W^-b}$ boosted along \vec{k}_{bg} such that 3-momentum is preserved
 - ▶ $|k'_b|$ set such one preserves final state CM energy
 - ▶ Preserves:
 - ▷ Virtuality of the final state system and of the recoiling system
 - ▷ **But not t virtuality!**^a

^aIssue not limited to FKS.

NLO+PS in POWHEG BOX

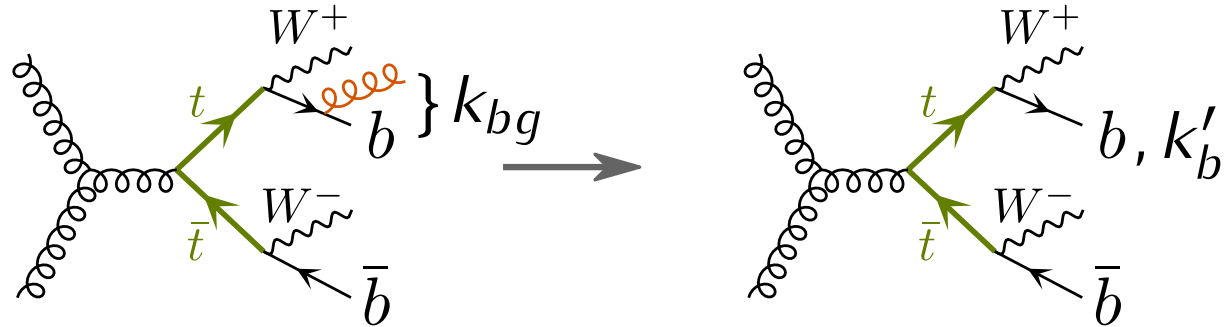


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 - ▷ But not t virtuality!^a ← Can be identified? 🤔

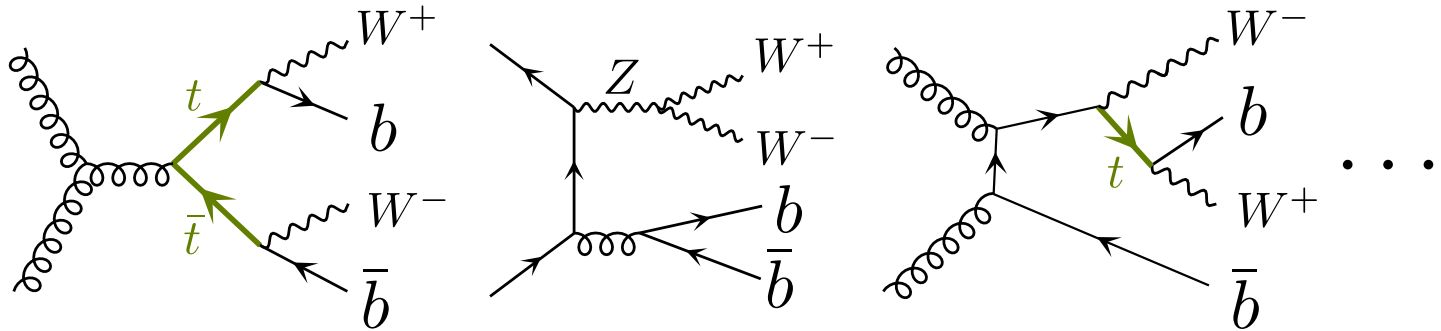
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NLO+PS in POWHEG BOX RES



- Resonance virtuality preserving FKS final state mappings
 - ▶ Same as standard FKS final state mappings
 - ▶ But applied in resonance rest frame instead of CM
 - ▶ But which resonance? 🤖

NLO+PS in POWHEG BOX RES

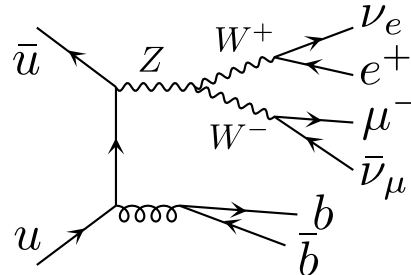
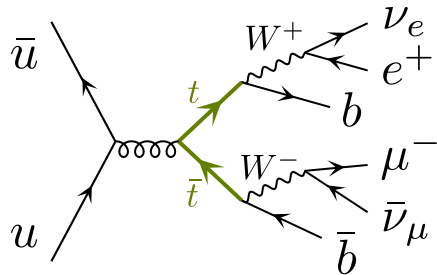


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NLO+PS in POWHEG BOX RES

- There are typically several production modes resonance-wise: “resonance-histories”
 - ▶ The phase space needs splitting up:



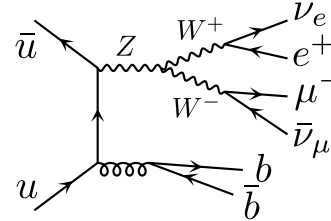
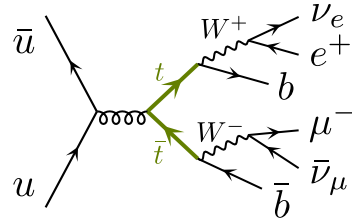
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2 + m_t^2 \Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2 + m_t^2 \Gamma_t^2} \times \dots$$

$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2 + m_Z^2 \Gamma_Z^2} \times \dots$$

$$d\sigma = \frac{P_1}{P_1+P_2} d\sigma + \frac{P_2}{P_1+P_2} d\sigma$$

- ▶ Because we now use the FKS FS mapping in different rest frames
 - ▷ There is a new contribution to calculate: “soft mismatch”

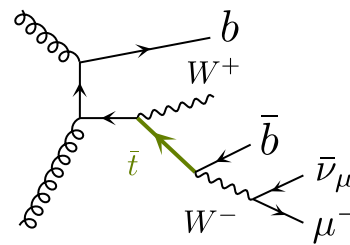
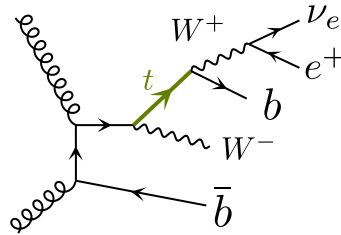
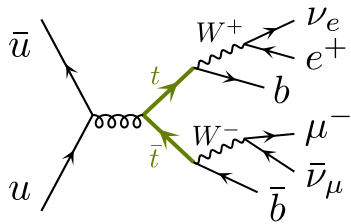
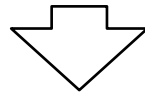
NLO+PS in POWHEG BOX RES



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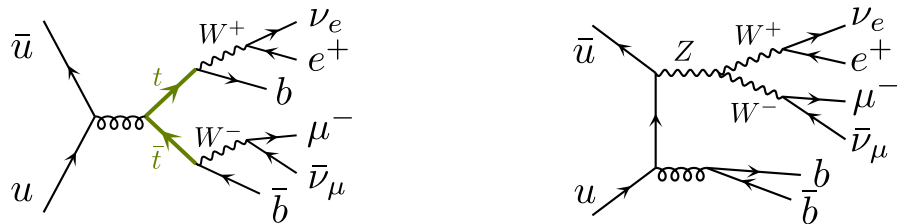
$$P_1 = B_{t\bar{t}}$$

$$P_2 = B_{tW^+}$$

$$P_3 = B_{\bar{t}W^-}$$

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NLO+PS in POWHEG BOX RES

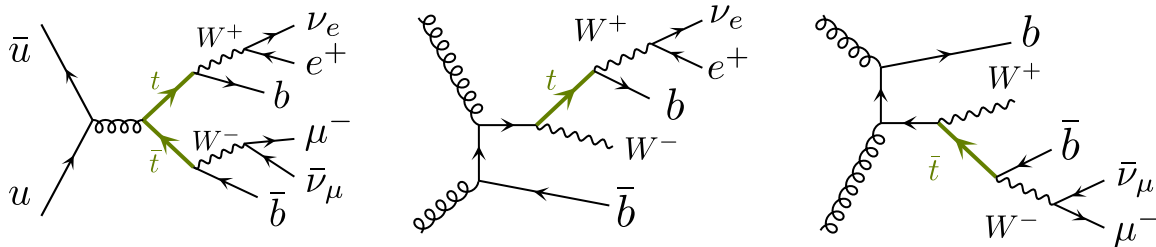
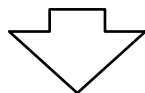


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Old: products of resonance propagators

$$d\sigma = \frac{P_1}{P_1+P_2} d\sigma + \frac{P_2}{P_1+P_2} d\sigma$$



$$P_1 = B_{t\bar{t}}$$

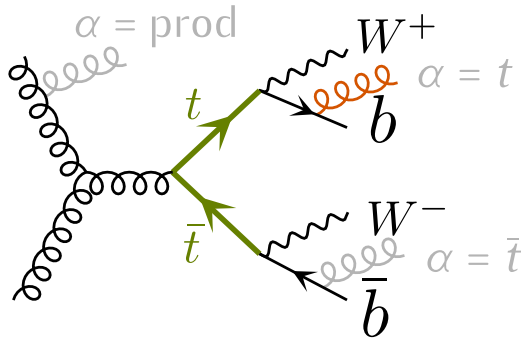
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New: amplitudes squared

$$d\sigma = \frac{P_1}{P_1+P_2+P_3} d\sigma + \frac{P_2}{P_1+P_2+P_3} d\sigma + \frac{P_3}{P_1+P_2+P_3} d\sigma$$

NLO+PS in POWHEG BOX RES

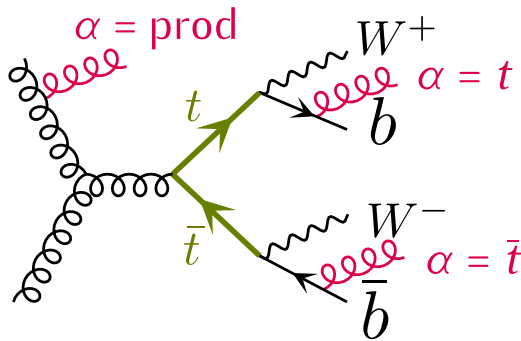


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- In new “resonance-aware” formulation of the POWHEG method:
 - ▶ $n + 1 \leftrightarrow n$ mapping **preserves** top virtuality
 - ▶ **No unphysical distortions** of the top line shape
 - ▶ **Keeps multiple emissions**: from production and each resonance

NLO+PS in POWHEG BOX RES

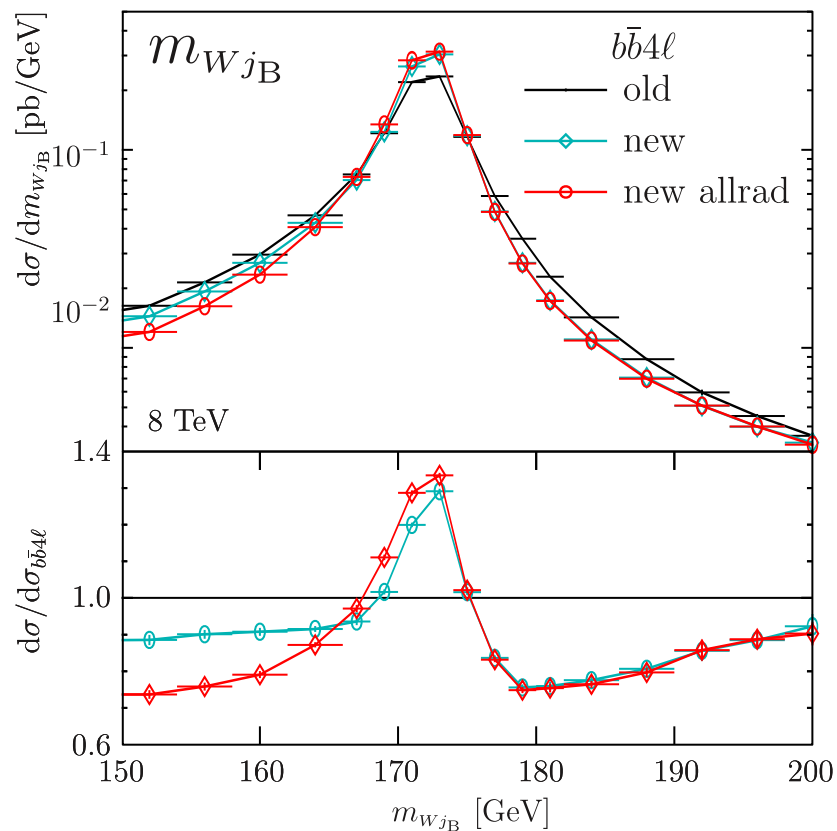


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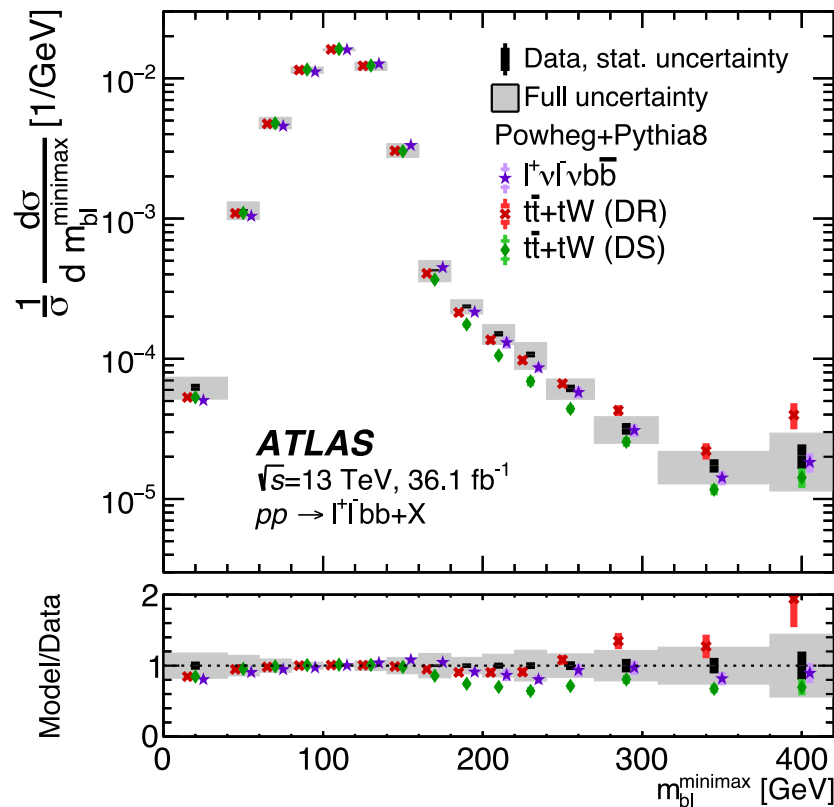
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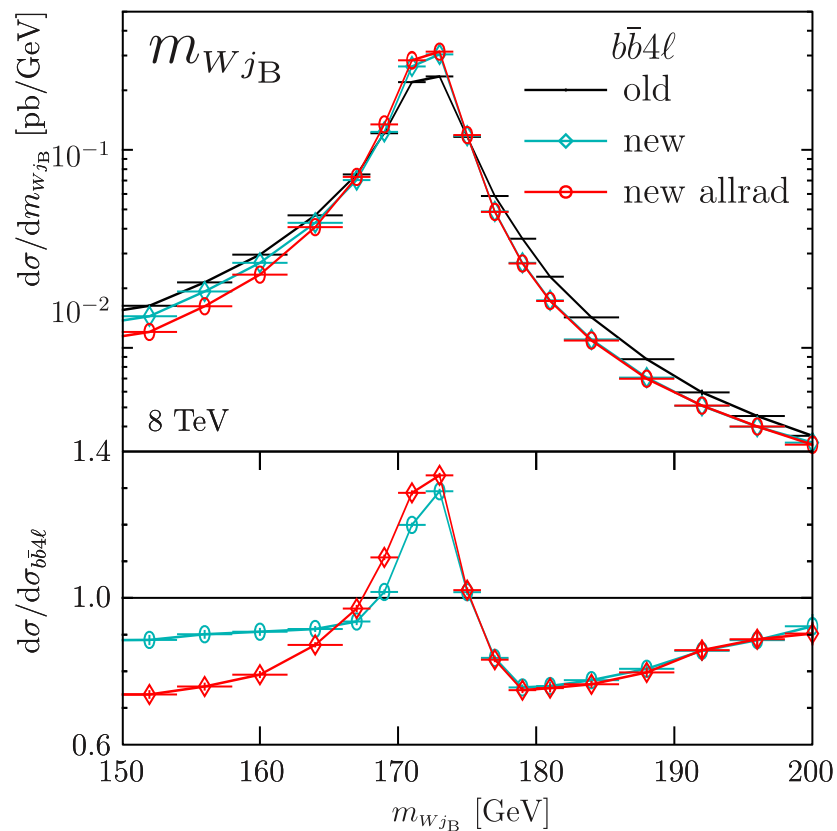


[TJ, Lindert, Nason, Oleari, Pozzorini '16]

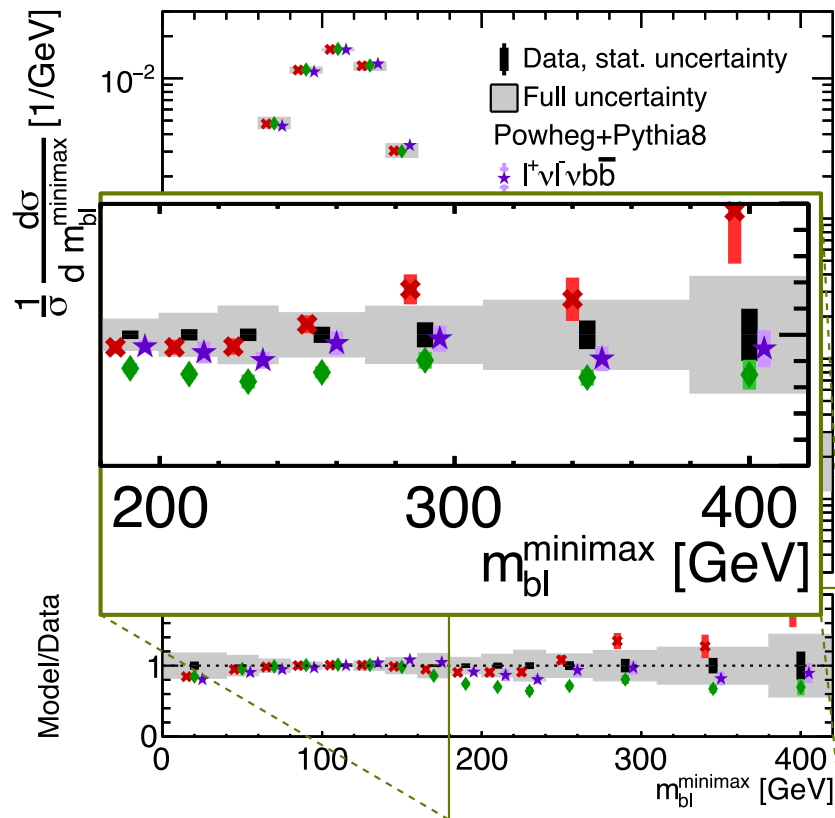


[PRL 121, 152002]

NLO+PS in POWHEG BOX RES



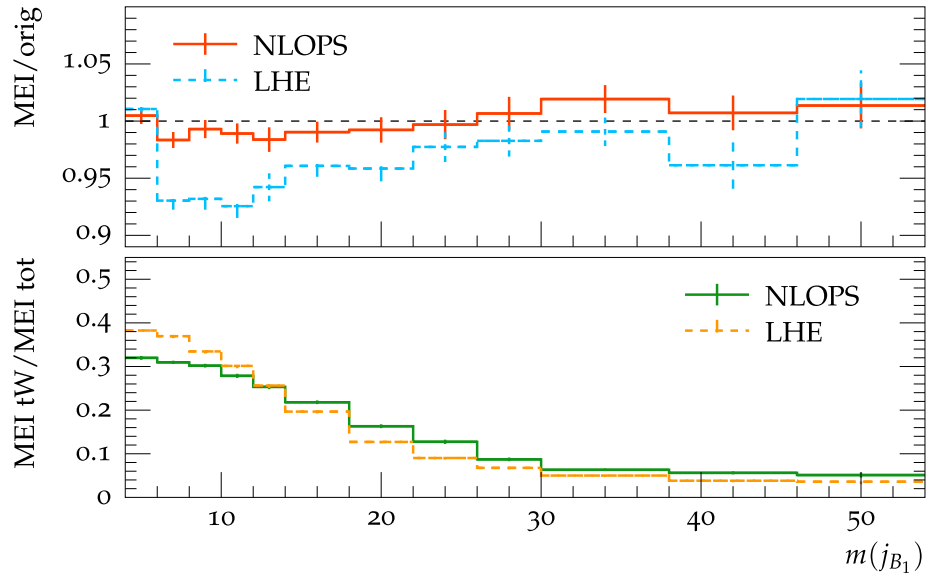
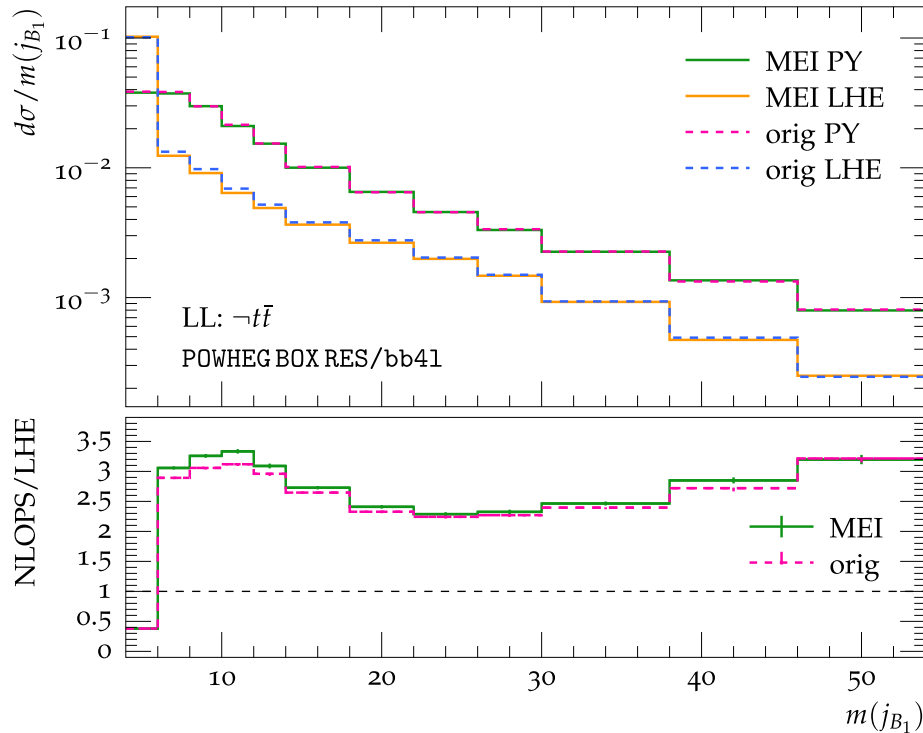
[TJ, Lindert, Nason, Oleari, Pozzorini '16]



[PRL 121, 152002]

Improved resonance history projectors

- Different resonance history projector prescriptions agree extremely well, the worst agreement we found was in m_{j_B} spectrum:



Shower Monte Carlos in NLO+PS

- Typical procedure: POWHEG BOX(RES), MG5_aMC@NLO
 - ▶ NLO+PS programs generate n particle events and attach one (or more) hardest emissions
 - ▶ Output: list of particles and momenta, the scale of the hardest emission, ...
 - ▶ Communication channel: LHE with scalup
 - ▶ SMCs attach PS vetoing emissions harder than scalup
 - ▶ Masses of intermediate resonances are preserved
 - ▶ allrad requires extra veto in resonance decays
 - ▶ Remaining SMC steps unaffected[†]
- Other options: Herwig7/Matchbox, Sherpa, Whizard, KrkNLO, ...
- I focus on POWHEG BOX RES+Pythia8 and POWHEG BOX RES+Herwig7

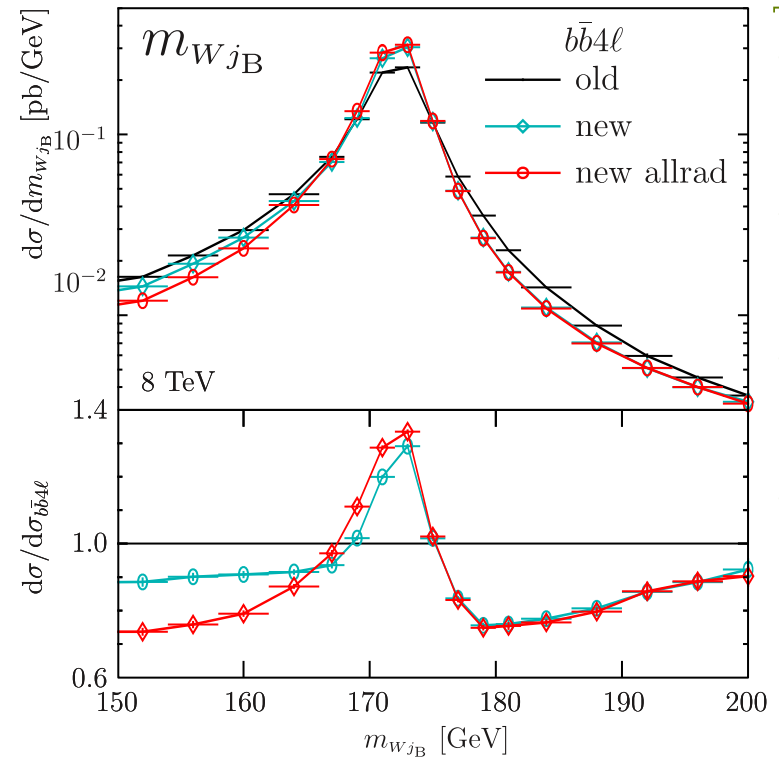
Shower Monte Carlos in NLO+PS

- POWHEG BOX RES+Pythia8
 - ▶ Option 1: `ptMaxMatch=1` evolve starting from `scalup`
 - ▷ `scalup` definitions in POWHEG BOX and Pythia8 differ, no veto in decays[†]
 - ▶ Option 2: `ptMaxMatch=2` shower unrestricted + UserHooks veto
 - ▶ UserHooks:
 - ▷ Executed each time shower emission is attached
 - ▷ Various hooks available: `doVetoISREmission`, `doVetoFSREmission`, ...
 - ▷ Veto in production: `PowhegHooks`, in resonance decays `PowhegHooksBB4L`
 - ▶ Matrix Element Corrections (MEC):
 - ▷ MEC for $t \rightarrow Wb$ decays available in Pythia8
 - ▷ Are MEC substitute for `allrad`? Also available: `MEafterFirst`
 - ▶ Remember to synchronize shower cutoffs `ptsqmin`!

Shower Monte Carlos in NLO+PS

- POWHEG BOX RES+Pythia8

- ▶ Option 1: `ptMaxMatch=1` evolve starting from the NLO scale
 - ▶ `scalup` definitions in POWHEG BOX
- ▶ Option 2: `ptMaxMatch=2` shower unreweighted
- ▶ UserHooks:
 - ▶ Executed each time shower emission occurs
 - ▶ Various hooks available: `doVetoI`, `doVetoII`, `doVetoIII`
 - ▶ Veto in production: `PowhegHooks`, `doVetoI`, `doVetoII`, `doVetoIII`
- ▶ Matrix Element Corrections (MEC):
 - ▶ MEC for $t \rightarrow Wb$ decays available
 - ▶ Are MEC substitute for `allrad`?
- ▶ Remember to synchronize shower cut



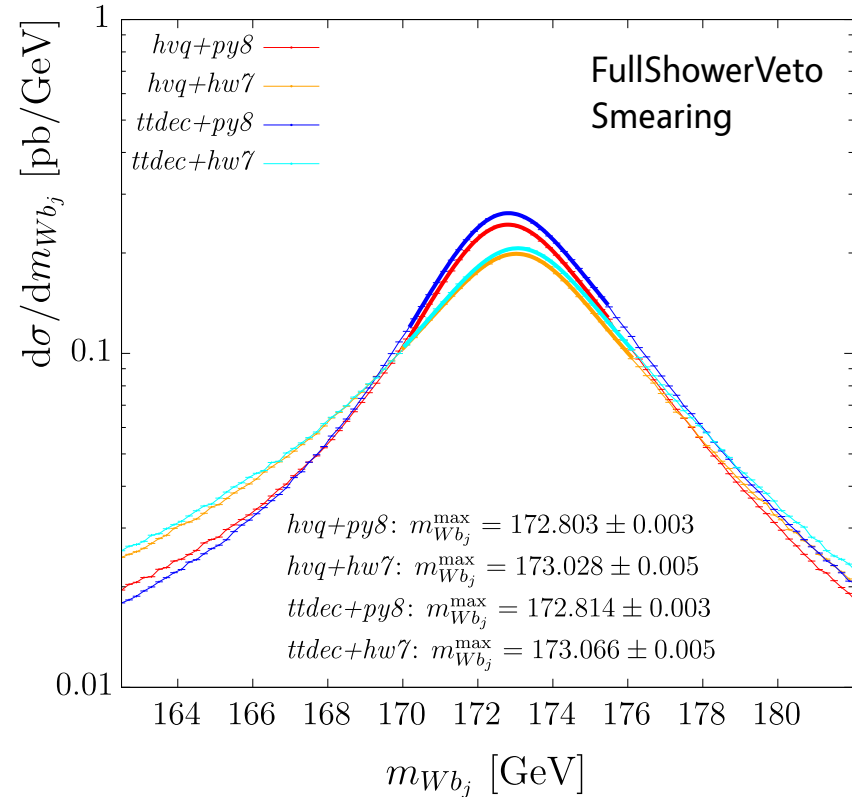
[TJ, Lindert, Nason, Oleari, Pozzorini '16]

Shower Monte Carlos in NLO+PS

- POWHEG BOX RES+Herwig7

- ▶ scalup used as shower starting scale
- ▶ Resonance decay veto via ShowerVeto or FullShowerVeto
- ▶ Our default option FullShowerVeto
 - ▷ Executed after the event has been fully showered
 - ▷ Includes an additional veto to preserve the phase space volume and to mimic the kinematic reconstruction in Herwig 7
- ▶ Matrix element corrections available
- ▶ Remember to synchronize shower cutoffs ptsqmin!

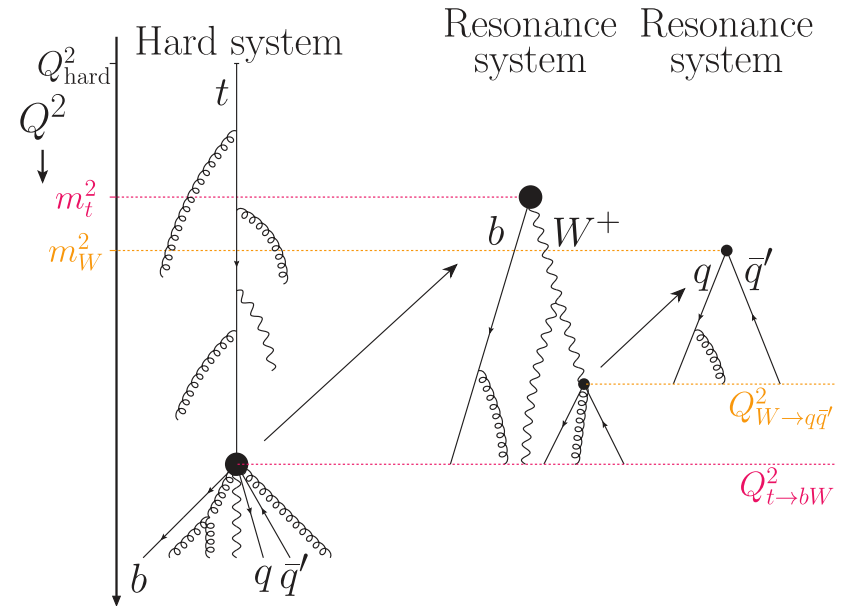
[TJ, Ferrario Ravasio, Nason, Oleari '18, '19]



Plot from Silvia Ferrario Ravasio

New: interleaved shower in resonance decays

- [Brooks, Skands, Verheyen '21]
 - ▶ Shower in resonance decays in Pythia8 and Herwig7 independent from ISR and FSR showers
 - ▶ Vincia implements an interleaved shower
 - ▶ The differences between the two are important

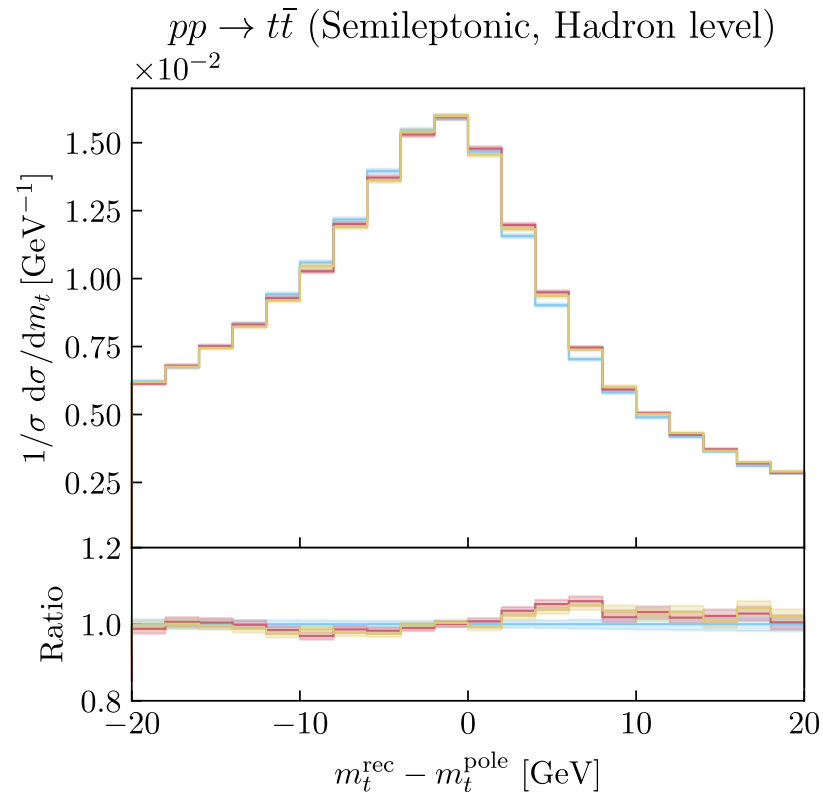


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- Sequential
- Interleaved, Γ_0
- Interleaved, $P(m)$



List of processes available in POWHEG BOX RES

- tt & tW NWA: `ttb_NLO_dec` [Campbell, Ellis, Nason, Re '14]
- tj : `t_mg` [TJ, Nason '15]
- tt & tW : `b_bbar_4l` [TJ, Lindert, Nason, Oleari, Pozzorini '16]
- $W\gamma$: `Wgamma` [Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, Vicini '16]
- HV , HVj : `H[WZ](j)_ew` [Granata, Lindert, Nason, Oleari, Pozzorini '17]
- Same sign WW VBS: `vbs-ssww-nloew` [Chiesa, Denner, Lang, Pellen '19]
- VV' : `diboson_ew` [Chiesa, Oleari, Re '20]
- $gg \rightarrow VV'$: `gg4l` [Alioli, Ferrario Ravasio, Lindert, Röntsch '21]
- $Z\gamma$: `ZgamJ` [Lombardi, Wiesemann, Zanderighi '20, '21]
- W^+W^- : `WWj` [Lombardi, Wiesemann, Zanderighi '21]
- ZZ : `ZZj` [Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi '21]
- Leptoquarks: `LQ-s-chan` [Buonocore, Greljo, Krack, Nason, Selimovic, Tramontano, Zanderighi '22]
- HV & VBF Hjj : `HJJ_ew` [Jäger, Scheller '22]

Resonance-awareness elsewhere

- MG5_aMC@NLO [Frederix, Frixione, Papanastasiou, Prestel, Torrielli '16]
 - ▶ Phase space remapping & prescription for including the resonance in LHE
 - ▶ $pp \rightarrow tj$
 - ▶ SMC: Herwig6, Pythia8[†]
- Whizard [Chokouf  Nejad, Kilian, Lindert, Pozzorini, Reuter, Weiss '16]
 - ▶ Resonance-aware FKS with $Z \rightarrow b\bar{b}$ and $H \rightarrow b\bar{b}$ RH
 - ▶ Fixed order $e^+e^- \rightarrow t\bar{t}$ & $e^+e^- \rightarrow t\bar{t}H$
- Sherpa [H che, Liebschner, Siegert '18]
 - ▶ Resonance-aware CS subtraction
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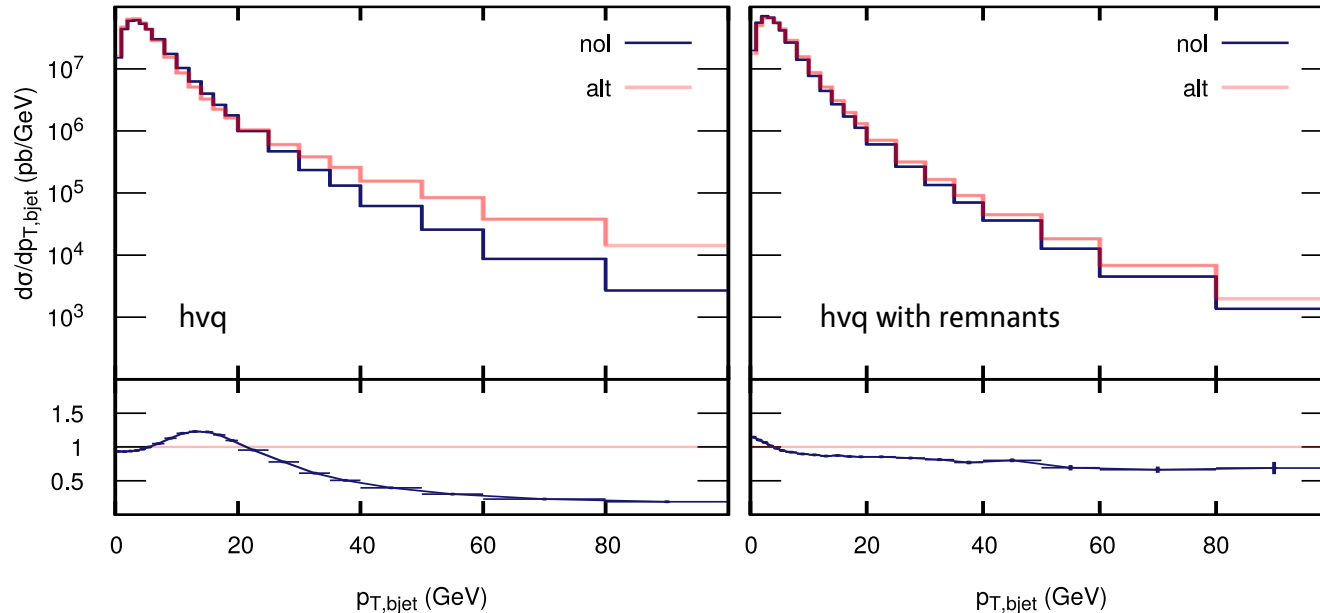
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Quark mass effects in POWHEG BOX

- pre 2012
 - ▶ Heavy quarks treated as very heavy with mass as cutoff for collinear singularities
- [Barzé, Montagna, Nason, Nicrosini, Piccinini '12]
 - ▶ Introduces treatment of collinear radiation from a heavy particle, this requires:
 - ▷ Singular regions with massive emitters
 - ▷ Appropriate phase space factorization
 - ▷ Suitable hardness scale for radiation
 - ▷ New radiation upper bounding function
- [Buonocore, Nason, Tramontano '17]
 - ▶ Implements more efficient algorithm
 - ▶ Studies impact on heavy quark production
 - ▶ Not yet available in the public version of POWHEG BOX

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Summary

- I reviewed state-of-the-art of modelling processes with decaying resonances at NLO+PS
 - ▶ With particular focus on resonance aware POWHEG matching
 - ▶ Reported on status in MG5_aMC@NLO, Sherpa and Whizard
 - ▶ Resonance aware subtraction for e^+e^- available[†]
- I talked about the treatment of resonance decays in SMCs
 - ▶ Details of interfacing POWHEG BOX RES to Pythia8 and Herwig7
 - ▶ Reported on new interleaved shower in decays
- Briefly summarized quark mass treatment in POWHEG BOX