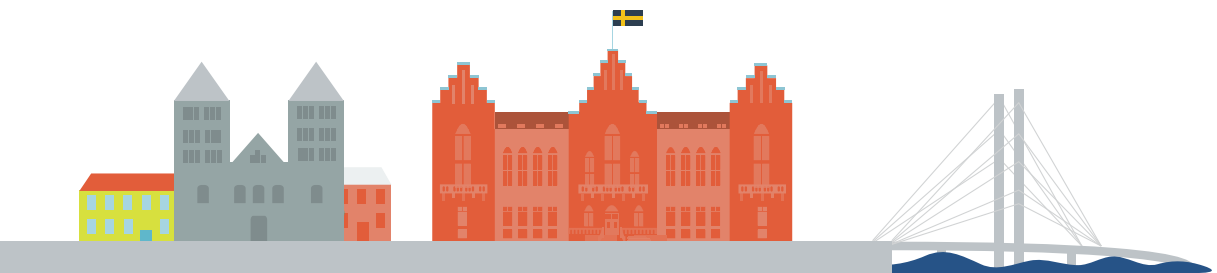
An NLO+PS generator for top-pair and Wt* production

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

Tomáš Ježo
Università di Milano-Bicocca
INFN, Sezione di Milano-Bicocca

In collaboration with:
J. Lindert, P. Nason, C. Oleari and S. Pozzorini

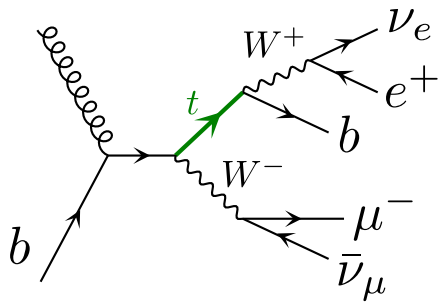
LHCP 14 June 2016

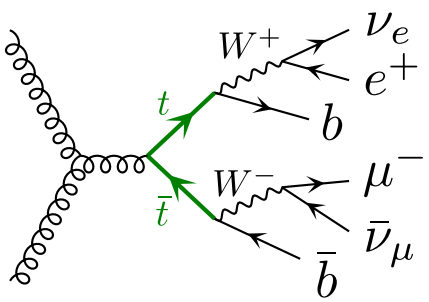


UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Introduction

- Production of top-pair and associated Wt; top decaying leptonically
  - 5F scheme, @LO

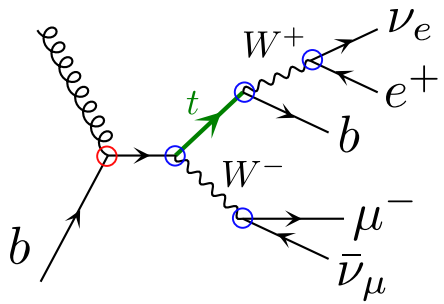


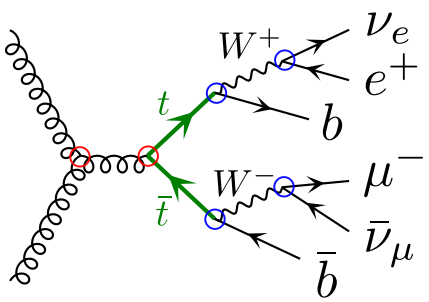


  - different processes
    - different final state
    - different power of α_S

Introduction

- Production of top-pair and associated Wt; top decaying leptonically
  - 5F scheme, @LO

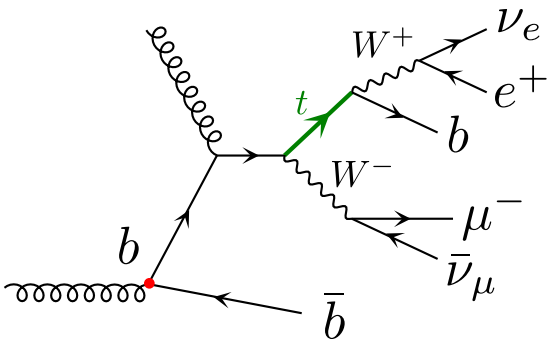


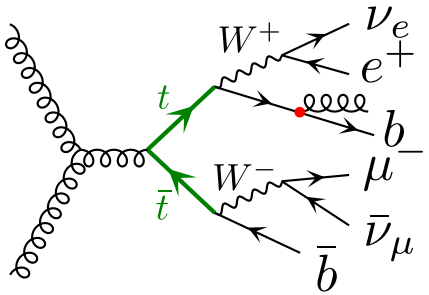


  - different processes
    - different final state
    - different power of α_S

Introduction

- Production of top-pair and associated Wt; top decaying leptonically
  - 5F scheme, @NLO

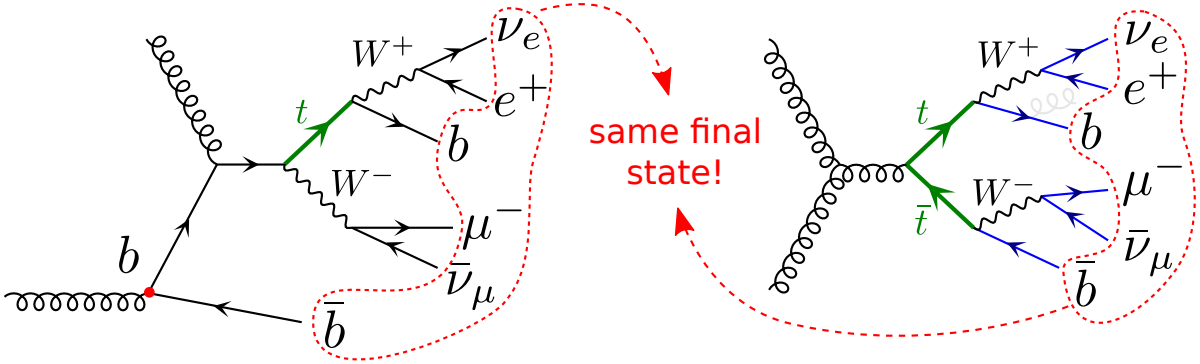




  - different processes
    - different final state
    - different power of α_S

Introduction

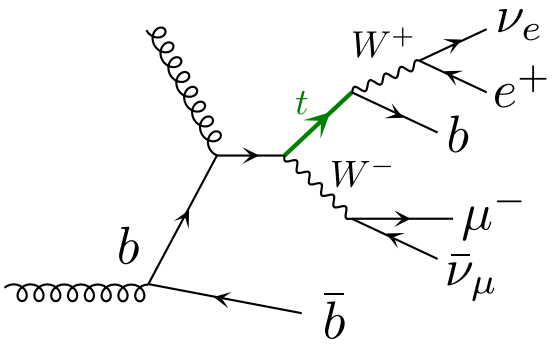
- Production of top-pair and associated Wt; top decaying leptonically
  - 5F scheme, Wt @NLO, top-pair @LO

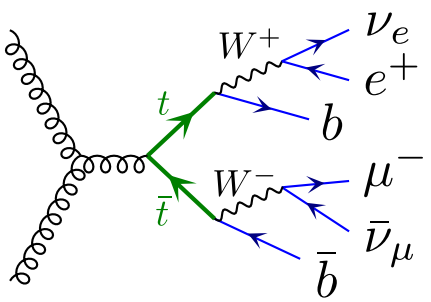


  - same processes
    - real correction to Wt production includes top-pair topology

Introduction

- Production of top-pair and associated Wt; top decaying leptonically
  - 4F scheme, @LO

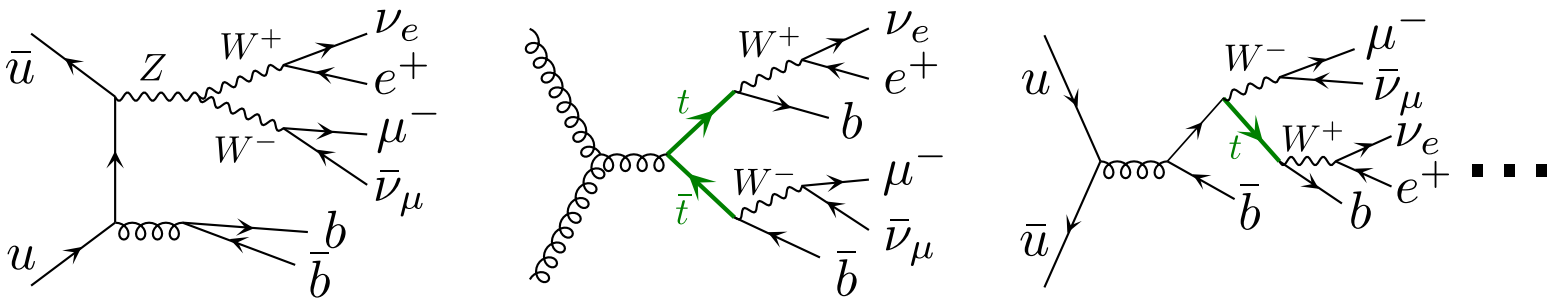




  - same processes
    - constitutes unified treatment for Wt and top-pair production

Generator details

- Process
  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO QCD

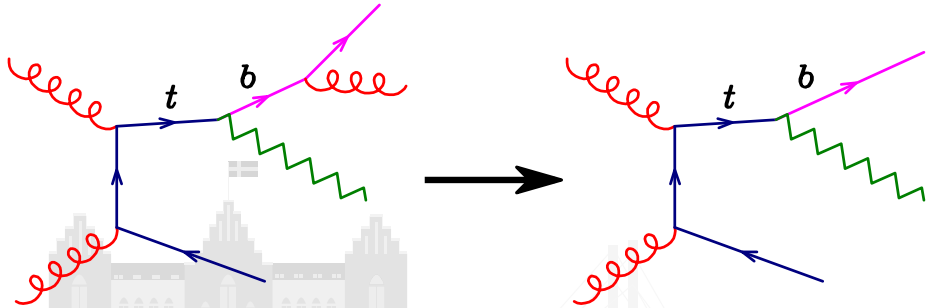


  - Born, real and virtual matrix elements by `OpenLoops`
  - 4F scheme
    - Unified description of top-pair and Wt production
    - Effects of b-quark mass included
    - Phase space with unresolved b-quarks accessible

Generator details

- Process
  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO QCD
  - Born, real and virtual matrix elements by `OpenLoops`
  - 4F scheme
    - Unified description of top-pair and Wt production
    - Effects of b-quark mass included
    - Phase space with unresolved b-quarks accessible

- NLO+PS generator
  - Resonance aware FKS subtraction & NLO+PS matching



NOW preserves the mass of the resonance

Generator details

- Process
  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO QCD
  - Born, real and virtual matrix elements by `OpenLoops`
  - 4F scheme
    - Unified description of top-pair and Wt production
    - Effects of b-quark mass included
    - Phase space with unresolved b-quarks accessible
- NLO+PS generator
  - Resonance aware FKS subtraction & NLO+PS matching
  - New version of `POWHEG BOX`: `POWHEG BOX RES`
- Shower Monte Carlo
  - `Pythia8`: interface beyond LH standard required
  - `Herwig7`: work in progress

Resonance "awareness"

- **NLO**
  - Counterterm kinematics does not preserve the mass of the resonance, spoiling IR cancellation
- **NLO+PS**
  - Real and underlying Born kinematics not on-shell at the same time when calculating the Sudakov form factor, potentially distorting the shape of radiation observables
- **PS**
  - Information about the resonance structure of the event not passed on to PS (not available), leading to the mass of the resonance not being preserved when reshuffling momenta

Resonance "awareness"

- **NLO**
  - Counterterm kinematics does not preserve the mass of the resonance, spoiling IR cancellation
- **NLO+PS**
  - Real and underlying Born kinematics not on-shell at the same time when calculating the Sudakov form factor, potentially distorting the shape of radiation observables
- **PS**
  - Information about the resonance structure of the event not passed on to PS (not available), leading to the mass of the resonance not being preserved when reshuffling momenta

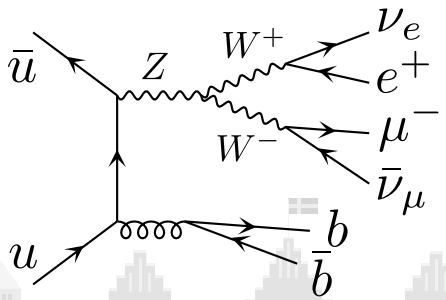
Can we require that the mass of the resonances is preserved?

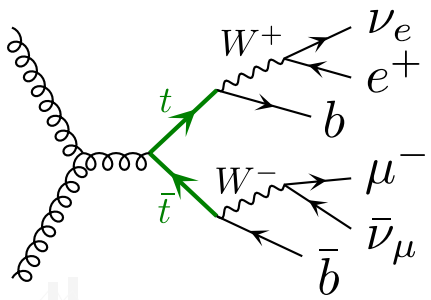
Resonance "awareness"

- **NLO**
  - Necessitates separation of integration into regions dominated by a single resonance structure
- **NLO+PS**
  - Trivial once the integration is separated (see above)
- **PS**
  - Trivial once the NLO+PS events are generated with a resonance structure

Resonance "awareness"

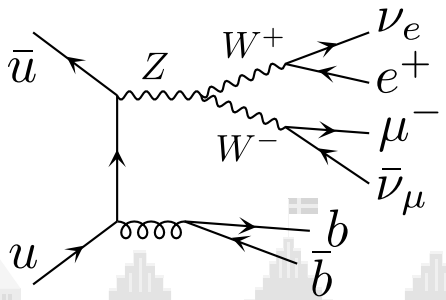
- **NLO**
  - Necessitates separation of integration into regions dominated by a single resonance structure
- **NLO+PS**
  - Trivial once the integration is separated (see above)
- **PS**
  - Trivial once the NLO+PS events are generated with a resonance structure
- In $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @LO: 2 resonance structures

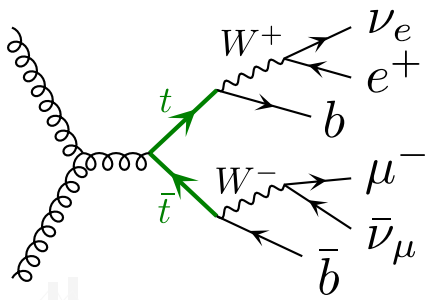




Resonance "awareness"

- **NLO**
  - Necessitates separation of integration into regions dominated by a single resonance structure
- **NLO+PS**
  - Trivial once the integration is separated (see above)
- **PS**
  - Trivial once the NLO+PS events are generated with a resonance structure
- In $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @LO: 2 resonance structures





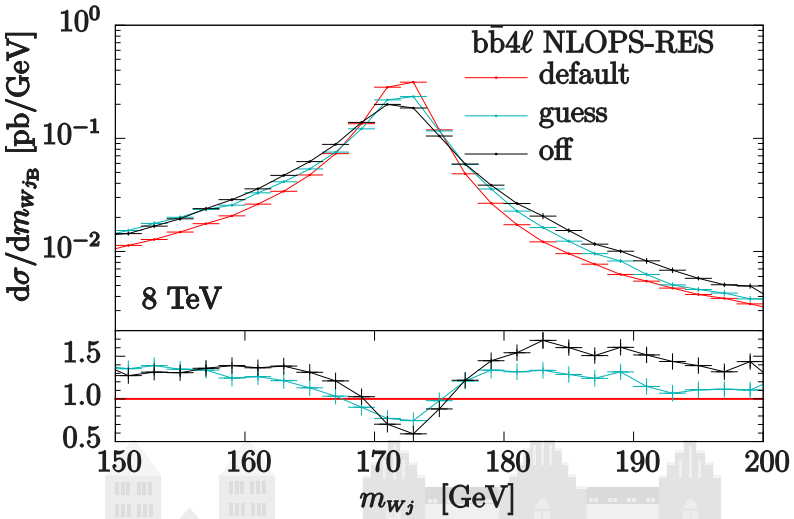
- Alternative solution in [Frederix, Frixione, Papanastasiou, Prestel, Torrielli 2016]

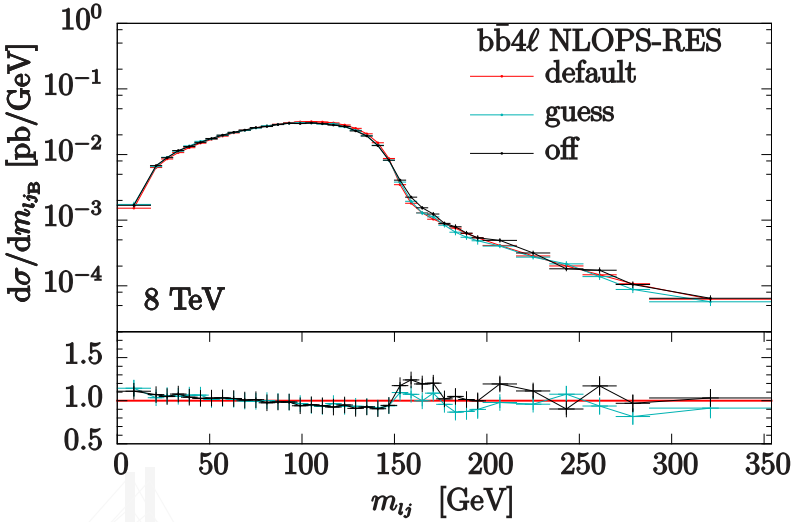
Results

- Study efficiency improvement with resonance treatment
  - NLO:
    - stage 1: `ncalls=80k, itmx=2`
    - stage 2: `ncalls=100k, itmx=4`
    - ncores: `64`
    - xsec rel. accuracy: **RES** = 0.11%, **NORES** = 0.79%/0.29%
  - efficiency of generation of radiation:
    - vetos per event: **RES** ~ 750, **NORES** ~ 15 000
  - speed of event generation:
    - events per hour: **RES** ~ 1500, **NORES** ~ 200

Results

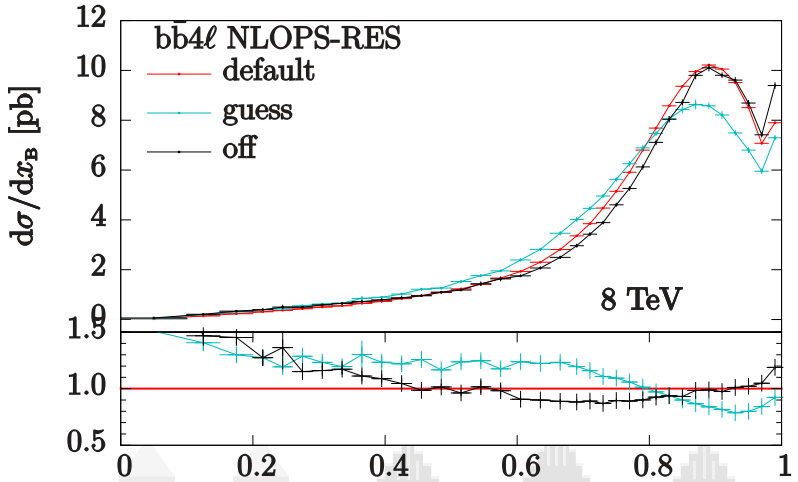
- Study impact of the resonance treatment:
  - default: resonant treatment on, hardest emission from resonance & hardest emission from the production
  - guess: resonant treatment off, resonance structure "guessed"
  - off: resonant treatment off

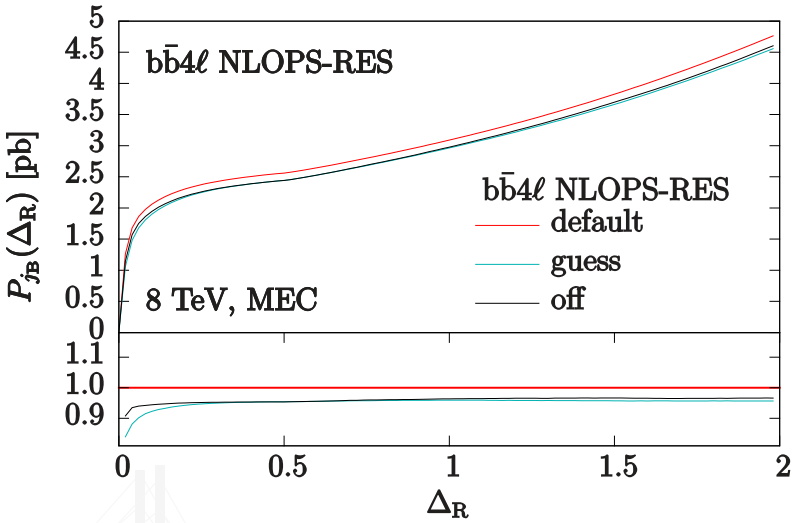




Results

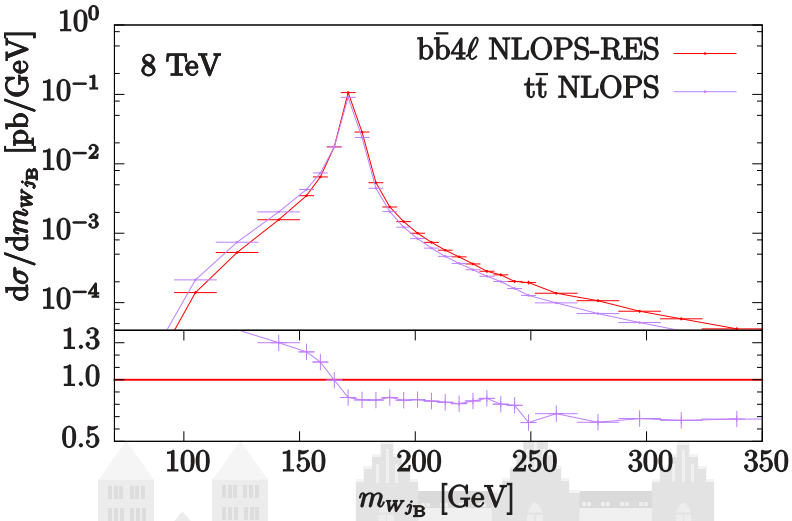
- Study impact of the resonance treatment:
  - default: resonant treatment on, hardest emission from resonance & hardest emission from the production
  - guess: resonant treatment off, resonance structure "guessed"
  - off: resonant treatment off

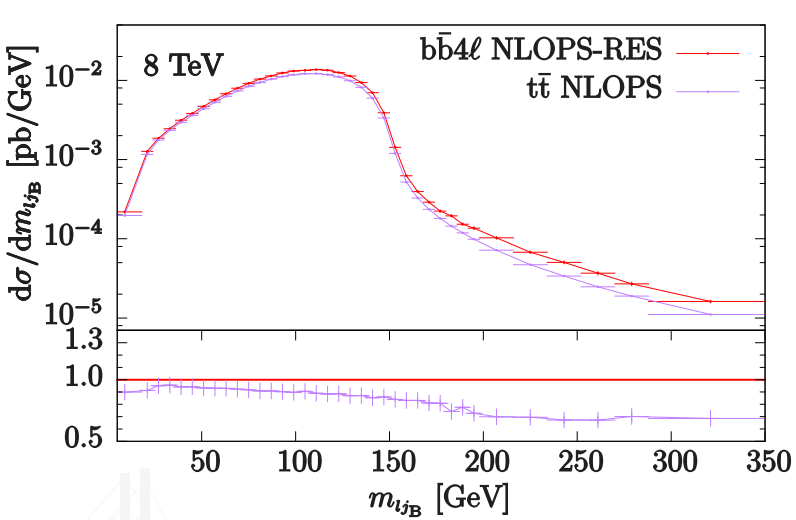




Results

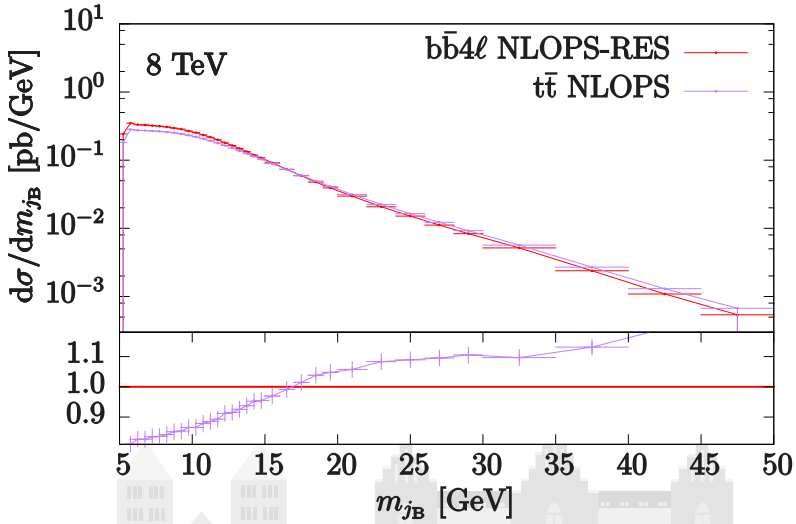
- Compare against older generators:
  - $\mathrm{b\bar{b}4\ell}$: resonant treatment on, hardest emission from resonance & hardest emission from the production
  - $\mathrm{t\bar{t}}$: `hvq`, top-pair production at NLO, top decay at LO

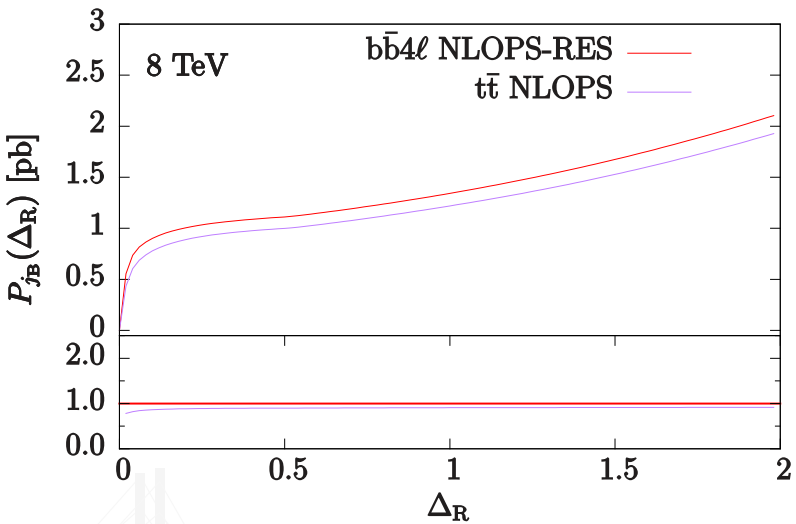




Results

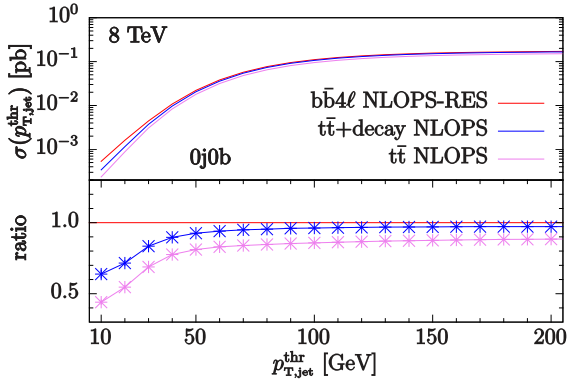
- Compare against older generators:
  - $b\bar{b}4\ell$: resonant treatment on, hardest emission from resonance & hardest emission from the production
  - $t\bar{t}$: `hvq`, top-pair production at NLO, top decay at LO

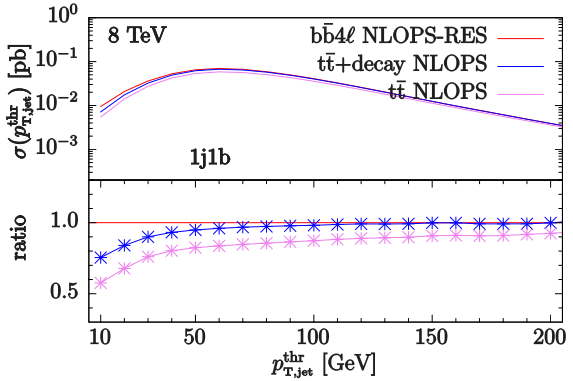


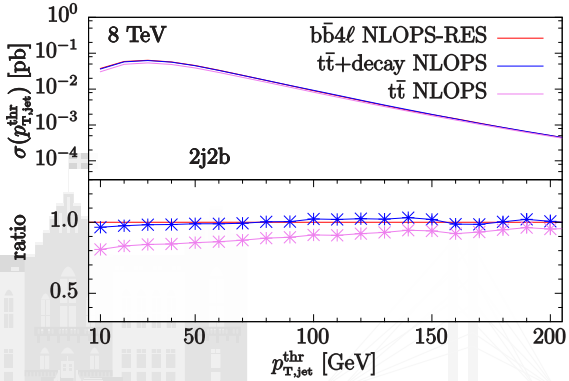


Results

- Investigate cross section as a function of $p_{\mathrm{T,jet}}^{\mathrm{thr}}$ in exclusive jet bins *njn*b with *n*={0,1,2} (we require eactly *n* b-tagged jets)







Summary

- We implement
  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO QCD
  - Born, real and virtual matrix elements by `OpenLoops`
  - 4F scheme
    - Unified description of top-pair and Wt production
    - Effects of b-quark mass included
    - Phase space with unresolved b-quarks accessible
- In `POWHEG BOX RES:` resonance aware NLO+PS generator
- Code available upon request

- First results
  - Impact of the resonance treatment on radiation observables very important
  - Considerable efficiency gain when resonance treatment switched on

- Starting from the last decaying resonance in the decay chain, and following recursively the decay chain in the backward direction, for each resonance V, we go to the V rest frame, and rescale all the momenta of the V decay products by the same factor, in such a way that energy is conserved with the newly assigned V virtuality, and with the newly assigned virtualities of the direct decay products of V (in case some decay products are resonances themselves).

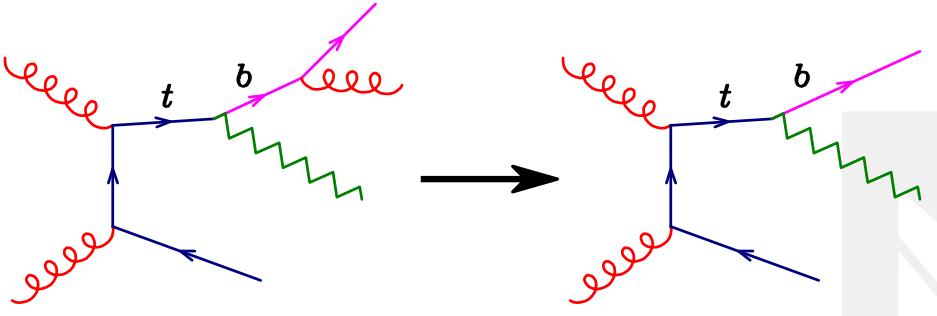
- If any of the direct decay products of V is itself a decaying resonance V', the rescaling of the V' momentum is accompanied by an appropriate longitudinal boost of all decay products (direct and indirect) of V' along the V' direction, performed in the V rest frame, such that momentum conservation holds in the decay.

- The last decaying resonance is the fictitious resonance comprising the direct products of the hard collision. Our procedure is applied also in this case, keeping the energy of the system fixed.

Problems with resonances @ NLO

- **NLO**
  - ▹ Counterterm kinematics does not preserve the mass of the resonance, spoiling IR cancellation

- FKS mapping does not preserve bgW mass:
  b direction preserved, recoiling system boosted along b direction



- When top-quark is on-shell in the real ME, it is off-shell in the counterterm

Problems with resonances @ NLO

- Evaluation of

$$\int d\mathbf{\Phi}_{n+1} \hat{\mathcal{R}}(\mathbf{\Phi}_{n+1})$$

- Leads to

$$\int d\mathbf{\Phi}_{n} d\xi \frac{1}{\xi} \left[f\left(k^2(\mathbf{\Phi}_{n}, \xi) \,|\mathbf{\Phi}_{n}, \xi\right) - f\left(k^2(\mathbf{\Phi}_{n}, 0) \,|\mathbf{\Phi}_{n}, 0\right) \right]$$

- with virtualities in real and counterterm contributions

$$k^2(\mathbf{\Phi}_{n}, \xi) \neq k^2(\mathbf{\Phi}_{n}, 0)$$

Problems with resonances @ NLO

- **NLO**
  - Counterterm kinematics does not preserve the mass of the resonance, spoiling IR cancellation
  - $\Gamma > 0$: will converge given enough time; the underlying Born kinematics is recovered in the soft limit
  - $\Gamma = 0$: will never converge; real and underlying Born kinematics are both strictly on-shell only in the soft limit
- Preserving resonance mass trivial if regions dominated by different resonance structures are intergated separately

Problems with resonances @ NLO+PS

- **NLO+PS**
  - Real and underlying Born kinematics not on-shell at the same time when calculating the Sudakov form factor, potentialy distorting the shape of radiation observables
  - Sudakov form factor for the hardest emission

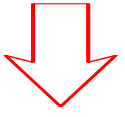
$$\Delta(p_T^2) = \exp\left[-\int \frac{R(\Phi_B, \Phi_{\text{rad}})}{B(\Phi_B)} \theta(k_T(\Phi_{\text{rad}}) - p_T) \mathrm{d}\Phi_{\text{rad}}\right]$$

  - R/B large violating the collinear approximanion
  - Shapes of radiation observables may be distorted

Problems with resonances @ NLO+PS

- Naive matching of NLO and PS doesn't work: overcounting
  - Both PS and NLO contain real and virtual contributions in the collinear limit
- Overcounting can be solved for example by modifying the Sudakov form factor for the first radiation

$$\Delta(p_T^2) = 1 - dP \qquad dP(t, t+dt) = \frac{\alpha_S}{2\pi}\frac{dt}{t}\int\frac{d\phi}{2\pi}\int P_{i,jl}(z)dz$$



$$\Delta(p_T^2) = \exp\left[-\int\frac{R(\Phi_B,\Phi_{\mathrm{rad}})}{B(\Phi_B)}\theta(k_T(\Phi_{\mathrm{rad}}) - p_T)\mathrm{d}\Phi_{\mathrm{rad}}\right]$$

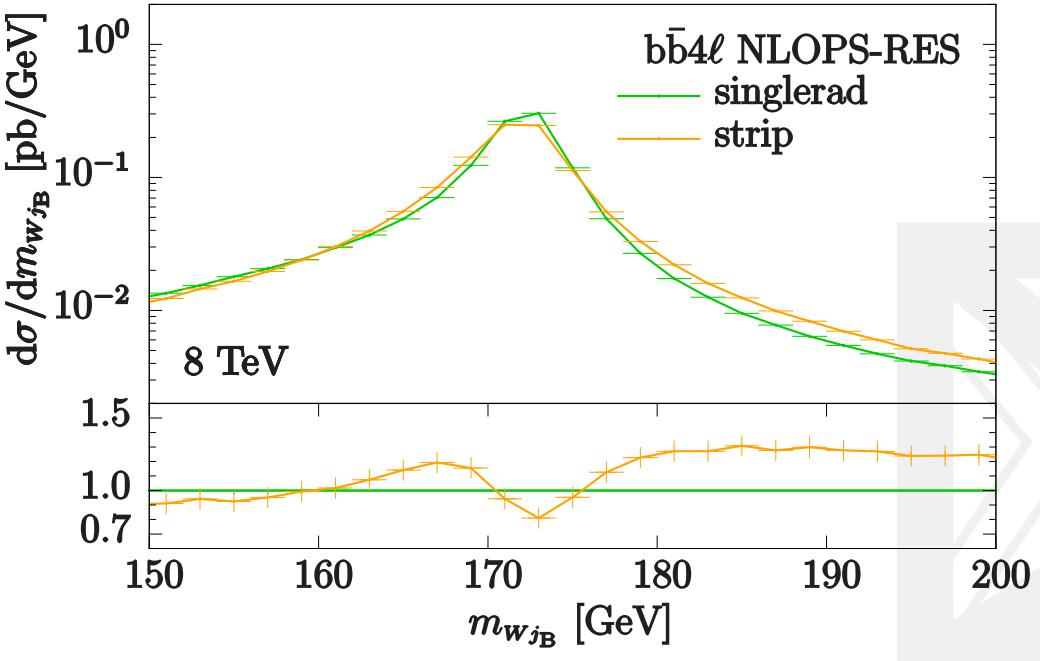
- Consecutive emissions can be attached using one of the common shower implementations with veto

Problems with resonances @ NLO+PS

- **NLO+PS**
  - Real and underlying Born kinematics not on-shell at the same time when calculating the Sudakov form factor, potentialy distorting the shape of radiation observables
  - Shapes of radiation observables are expected be distorted unless $m_{bg}^2/E_{bg} \ll \Gamma_t$
  - Moreover large R/B ratio leads to low efficiency of generation of the radiation
- Keeping real and unerlying Born kinematics on-shell at the same time feasible if regions dominated by different resonance structures are sampled separately

Problems with resonances @ NLO+PS

- **PS**
  - Information about the resonance structure of the event not passed on to PS (not available), leading to the mass of the resonance not being preserved when reshuffling momenta



Resonance weight factors: real

- Example: electroweak $u\bar{u} \to u\bar{d}\bar{u}d$
- Each singular region needs to be futrher split up into regions in which one resonance structure dominates

Resonance weight factors: real

- Example: electroweak $u\bar{u} \to u\bar{d}\bar{u}d$
- Each singular region needs to be futrher split up into regions in which one resonance structure dominates

$$\mathcal{R}_{\alpha_r=2} = \frac{d_{37}^{-1}}{(d_7^{-1} + \cdots + d_{67}^{-1})}\mathcal{R} \quad \rightsquigarrow \quad \mathcal{R}_{\alpha_r=2} = \frac{P_r^2 d_{37}^{-1}}{D_r}\mathcal{R}$$

$$\begin{aligned} D_r = {} & P_r^1 d_7^{-1} + P_r^2(d_{37}^{-1} + d_{47}^{-1}) + P_r^3(d_{57}^{-1} + d_{67}^{-1}) \\ & + P_r^4 d_7^{-1} + P_r^5(d_{37}^{-1} + d_{57}^{-1}) + P_r^6(d_{47}^{-1} + d_{67}^{-1}) \end{aligned}$$

$$P_r^2 = \frac{M_W^4}{(s_{347} - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \frac{M_W^4}{(s_{56} - M_W^2)^2 + \Gamma_W^2 M_W^2}$$

Summary

- In order to implement proper treatment for resonances:
  - implement splitting of Born and virtual contributions into regions dominated by single resonance structure
  - modify separation of real contribution such that each singular region is further split into regions dominated by single resonance structure
  - modify the mapping of the kinematics of each singular region into its underlying Born configuration preserving the mass of the resonance that radiates
  - generalize the calculation of soft-virtual contributions

$$\hat{\mathcal{V}} = \frac{\alpha_{\mathrm{S}}}{2\pi}\left(\mathcal{Q}\,\mathcal{B} + \sum_{\substack{i,j\in\mathcal{I}\\ i\neq j}} \mathcal{I}_{ij}\,\mathcal{B}_{ij} + \mathcal{V}_{\mathbf{fin}}\right)$$

  - separate the integration of non-singular real contributions according to their own phase space

POWHEG BOX RES

- Resonance treatment implemented in `POWHEG BOX RES`
- `POWHEG BOX RES` automatically calculates everything down to the generation of the hardest emission(s) provided the user specifies
  - Born matrix elements $\mathcal{B}(\mathbf{\Phi}_n)$
  - Renormalized virtual matrix elements $\mathcal{V}_{\mathrm{b}}(\mathbf{\Phi}_n)$
  - Real matrix elements $\mathcal{R}(\mathbf{\Phi}_{n+1})$
  - Automaticaly reconstructs resonance histories
  - Routine implementing Born phase space not required anymore