Theoretical issues in event generation

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Outline & Disclaimer

Impossible to cover everything!
Personal biased selection with highlights on future directions
Focus on NLOPS and NLOPS+multi-leg merging generators

- Status of NLO+PS for $t\bar{t}$ (and Wt) in `POWHEG BOX`
- $t\bar{t}$ production and decay in `Herwig7`
- $t\bar{t}$+jets merged simulations
- Status of fixed-order calculations for $t\bar{t}$ and $t\bar{t}X$ (more details in Worek's and Bevilacqua's talks)
- $t\bar{t}b\bar{b}$

Important topics not addressed

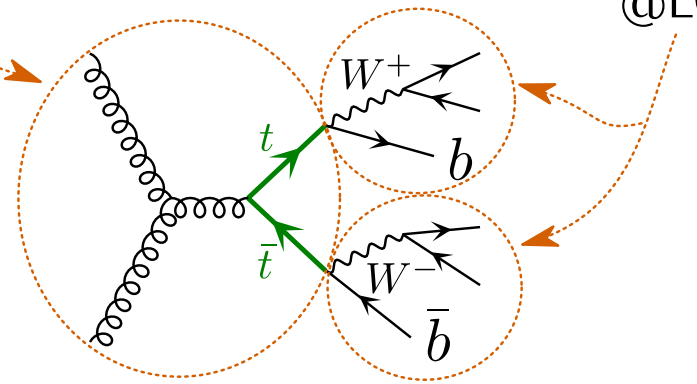
- $t\bar{t}$ at NNLO QCD (see Poncelet's and Catani's talks)
- bottom fragmentation function (see Mitov's talk)
- Top-mass interpretation

$t\bar{t}$ and Wt production in POWHEG

POWHEG method: hardest emission generated with the full real matrix element, while subsequent softer emissions included by parton showers (PS). [Nason, 2004]

$$\Delta(q) = \exp\left[-\int \frac{R(\Phi(\Phi_b, \Phi_{\rm rad}))}{B(\Phi_b)} d\Phi_{\rm rad} \Theta(p_\perp > q)\right]$$

@NLO @LO

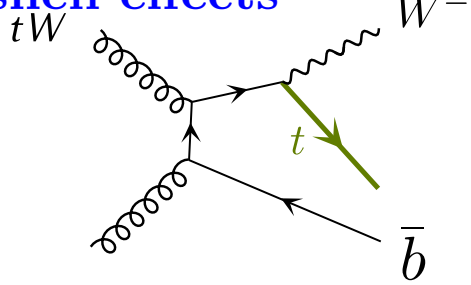


`hvq`: Heavy-quark pair @ NLO [Frixione, Nason, Ridolfi, 2007] With a reweighting technique

approximate LO decay:

→ approx **spin correlations**

→ approx **off-shell effects**

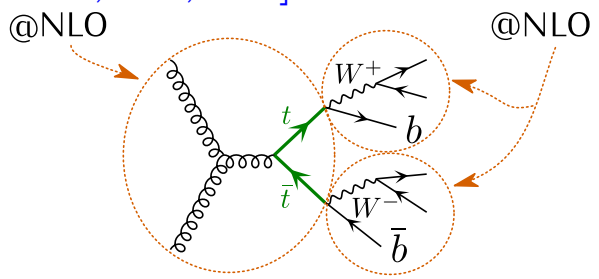


It requires an ad-hoc procedure to include `Wt` [Re, '10] contribution not to double count the quantum interference which appears at NLO in the **5FNS**

Pythia8 and **Herwig7** have Matrix-Element corrections for top-decay to correct the hardest emission probability from the decay!

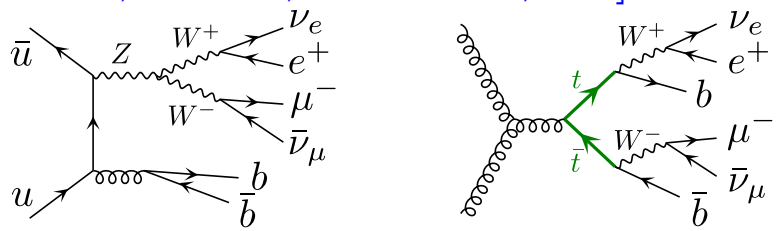
4FNS generators for $t\bar{t} + Wt$ in POWHEG

1. $t\bar{t}dec$ [Campbell, Ellis, Nason, Re, '14]:



$\Rightarrow$ NLO corrections in production and decay using the narrow-width-approximation (NWA);
$\Rightarrow$ spin correlation and offshell effects exact at LO;
$\Rightarrow$ interference with process sharing the same final state at LO (e.g. Wt).

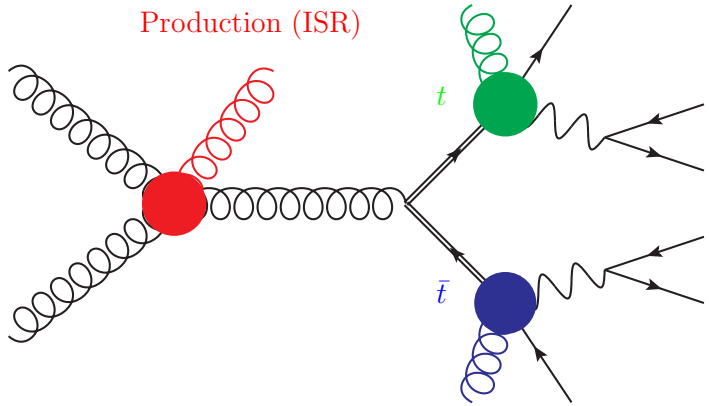
2. $b\bar{b}4\ell$ [Ježo, Lindert, Nason, Oleari, Pozzorini, '16]:



$\Rightarrow$ $pp \to b\bar{b}\ell\bar{\nu}_\ell l\bar{\nu}_l$ at NLO;
$\Rightarrow$ exact spin correlation and offshell effects at NLO;
$\Rightarrow$ interference with process sharing the same final state at NLO;
$\Rightarrow$ interference of radiation in production and decay;
$\Rightarrow$ full ME for semi-leptonic decay too inefficient, but inclusion of hadronic W decay for $b\bar{b}4\ell$ topologies possible [Ježo, Linder, Pozzorini, in preparation]

Resonance aware subtractions

- New generators include NLO QCD corrections also in **decay** with a **resonance-aware** formalism that **preserves the virtuality of the resonance** (more efficient **FKS** subtraction and correct R/B in the Sudakov) and allows the possibility to generate **multiple emissions** when using the `POWHEG` multiplicative matching. [Ježo, Nason, '15]



- `MadGraph5_aMC@NLO` NLOPS generator for single top production including off-shell effects and non-resonant contribution using the **MC@NLO** method **(no multiple emissions!)** [Frederix, Frixione, Papanastasiou, Prestel, Torrielli, '16].
- Resonance-aware subtraction in the **dipole method** in `Sherpa`. Not yet applied to **NLOPS**. [Höche, Liebschner, Siegert, '19].

Improving the resonance-aware POWHEG formalism

- When **multiple resonance histories** are possible, we need to separate them using projectors built using the BW propagators

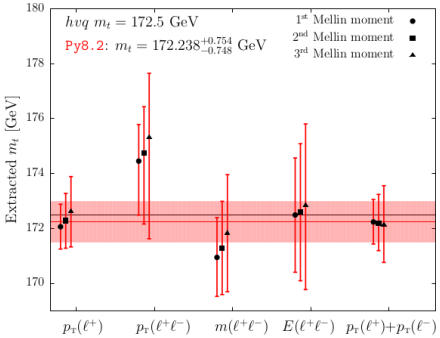
$$P(t,\bar{t}) = \frac{m_t^4}{(p_t^2 - m_t^2)^2 + \Gamma_t^2 m_t^2} \frac{m_t^4}{(p_{\bar{t}}^2 - m_t^2)^2 + \Gamma_t^2 m_t^2}$$

- From the point of view of the NLO efficiency integration, the **single-resonant** Wtb contribution can be described on the same footing of the $t\bar{t}$ **double-resonant** contribution. [Ježo, Nason, '15]
- Problems may arise when generating multiple emissions if radiation is included also from the b which does not belong to a t resonance. We can distinguish the 2 resonance histories by introducing a new projector

$$P(t,Wb) = \frac{m_t^4}{(p_t^2 - m_t^2)^2 + \Gamma_t^2 m_t^2} \frac{\alpha m_t^2}{E_{\perp,b}^2}$$

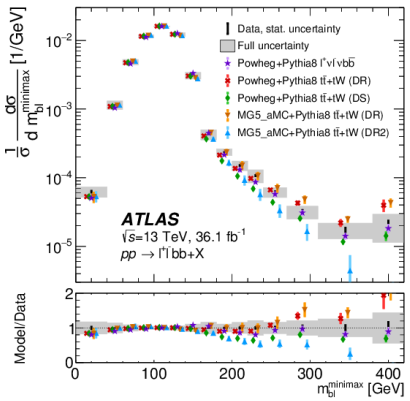
where α can be tuned to reproduce the correct tWb faction. Its variation can allow resonance assignment **uncertainties**.
Alternative separation achieved by means of **Born matrix elements**.
[Ježo, Pozzorini, in preparation]

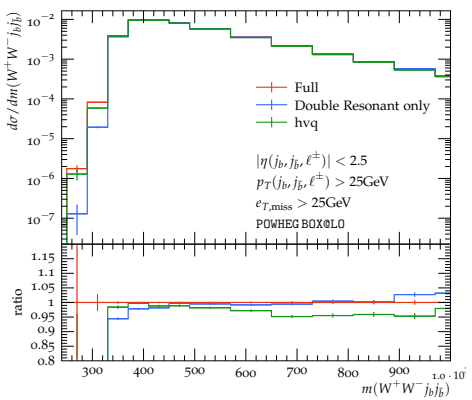
$b\bar{b}4\ell$ requires 2800 d CPU time for 12M events, while $t\bar{t}dec$ 46 d and hvq only 10 h BUT $b\bar{b}4\ell$ is necessary for



⇒ Correct treatment of spin-correlations, which are important e.g. for leptonic observables.

[ATLAS 1806.04667]





⇒ Correct treatment of the tt and Wt quantum interference and of off-shell effects (see more in Worek's talk!)

⇒ Correct μ_F and μ_R dependence, e.g. m_{Wb_j} peak:

$b\bar{b}4\ell\ ^{+86}_{-53}$ MeV, $t\bar{t}dec$ ±6 MeV, hvq ±7 MeV

[S.F.R, Ježo, Nason, Oleari '18, '19]

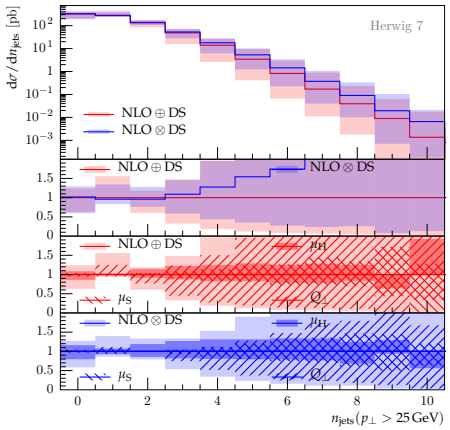
$t\bar{t}$ generators in Herwig7

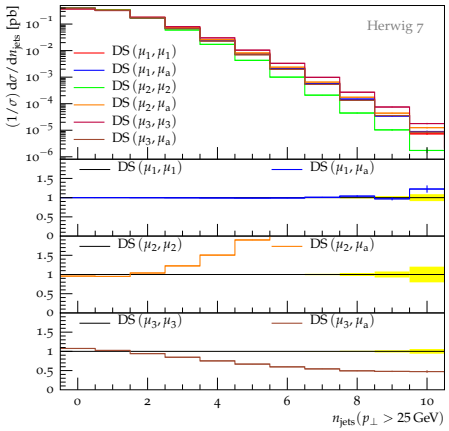
Recent updates in $t\bar{t}$ production and decay in `Herwig7`
[Cormier, Plätzer, Reuschle, Richardson, Webster, '18]

- NLO corrections to on-shell $t\bar{t}$ production in the **POWHEG** (multiplicative) and **MC@NLO** (additive) scheme via the **Matchbox** module [Gieseke, Plätzer, 1109.6256]
- Top-decay in NWA:
  $\Rightarrow$ POWHEG corrections in dipole shower
  $\Rightarrow$ MEC in angular-ordered parton shower
- The splitting kernel of both showers include quark mass effects in a covariant formalism
  $\Rightarrow$ mass effects necessary to model the correct bottom radiation pattern
- Inclusion of spin-correlations in both showers [Richardson, 2001, Richardson and Webster, 2018]

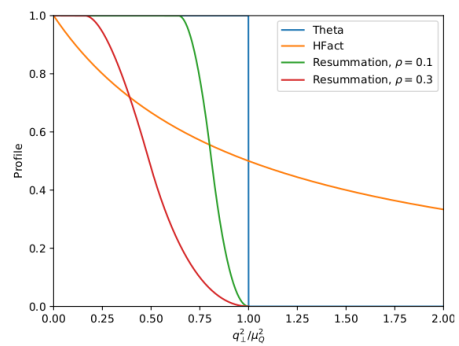
$t\bar{t}$ generators in Herwig7

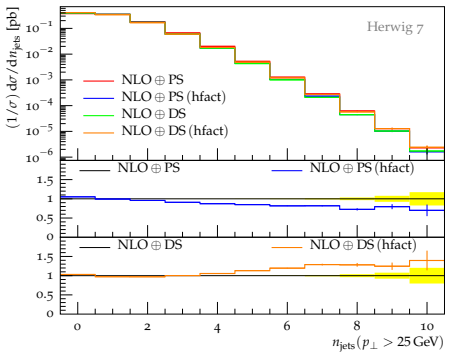
Good framework for matching uncertainties assessment:
μ_H: hard process scale, $Q_\perp$: shower starting scale, μ_S: α_s and PDF arg
(1) Variation of a factor 2 and (2) Several choices for μ_H and $Q_\perp$:
$\mu_1 = \frac{m_\perp^t + m_\perp^{\bar{t}}}{2}$, $\mu_2 = \mu_1/2$, $\mu_3 = m_{t\bar{t}}, \mu_a^2 = \langle m_{\perp,i}^2 \rangle$ [ATLAS 1407.0891]





Ambiguous separation of the hard real contribution: `hfact` vs `Resummation`





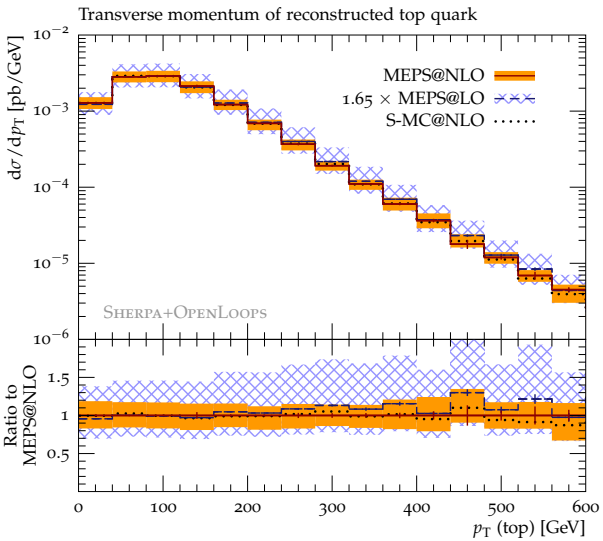
[Cormier, Plätzer, Reuschle, Richardson, Webster, '18]

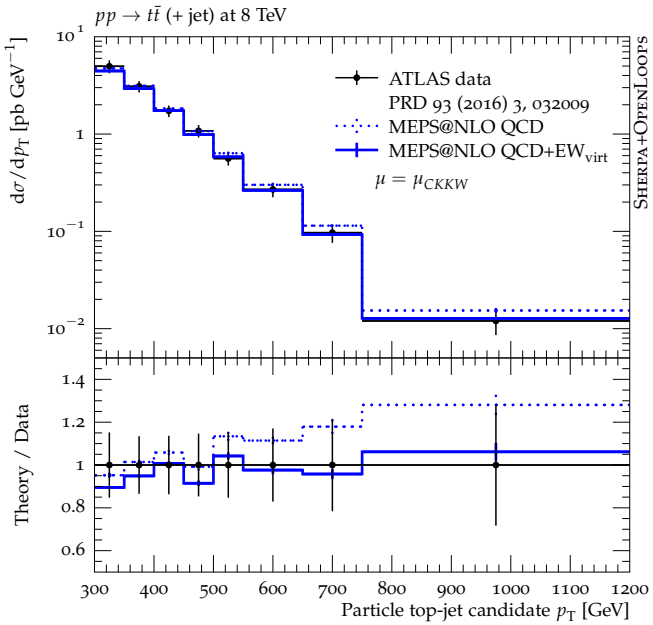
NLOPS for $t\bar{t}$ with jets

- `Openloops` + `Herwig7` (DS) multi-leg merging [Bellm, Gieseke, Plätzer, '17]
- `MADGRAPH5_aMC@NLO` + `PY8` `FxFx` matching [Frederix, Frixione '12]
- `Openloops` + `Sherpa`

$t\bar{t}$ +0,1,2 jet @NLO QCD [Höche, Krauss, Maierhöfer, Pozzorini, Shöenerr, Siegert '14.]

$t\bar{t}$ +0,1 jet @NLO QCD+(approx)EW, $t\bar{t}$+2,3,4 jets @LO [Gütschow, Lindert, Schönherr, '18] dominant virtual NLO EW corrections incorporated exactly, NLO QED bremsstrahlung is first integrated out and subsequently incorporated via YFS [ATLAS, 1510.03818]





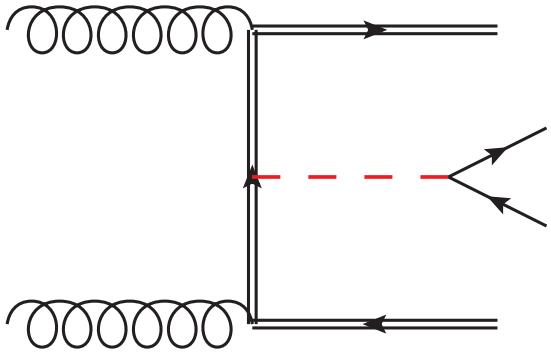
Status of NLO calculations = NLOPS wish list

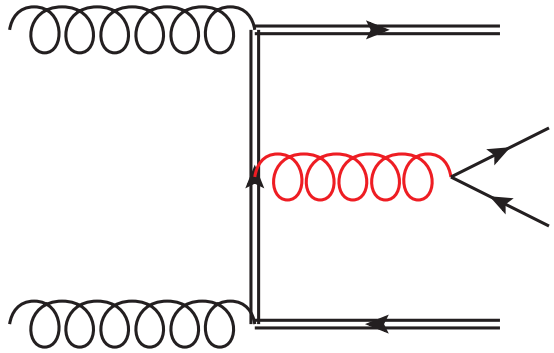
Most recent NLO (Helac and MoCaNLO+Recola) **off-shell** calculations, which also include **non-resonant** contributions, not yet NLOPS

- $\boxed{t\bar{t}j}$ with leptonic decay at NLO QCD
  [Bevilacqua, Hartanto, Kraus, Worek, '15]
- $\boxed{t\bar{t}\gamma}$ with leptonic decay at NLO QCD
  [Bevilacqua, Hartanto, Kraus, Weber, Worek, '18]
- $\boxed{t\bar{t}W}$ with leptonic decay at NLO QCD
  [Bevilacqua, Bi, Hartanto, Kraus, Worek, '20], [Denner, Pelliccioli, '20]
- $\boxed{t\bar{t}}$ with leptonic decay at NLO QCD and **EW**
  [Denner, Pellen, '16]
- $\boxed{t\bar{t}}$ with **semi-leptonic** decay at NLO QCD
  [Denner, Pellen, '17]
- $\boxed{t\bar{t}H}$ with leptonic decay at NLO QCD and **EW**
  [Denner, Lang, Pellen, Uccirati, '19]
- $\boxed{t\bar{t}b\bar{b}}$ with leptonic decay at NLO QCD (6 coloured legs!)
  [Denner, Lang, Pellen, '20]

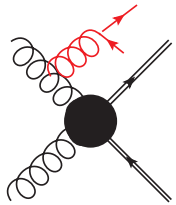
ttbb: present situation

$t\bar{t}b\bar{b}$ is the dominant QCD background for $t\bar{t}H + H \to b\bar{b}$.

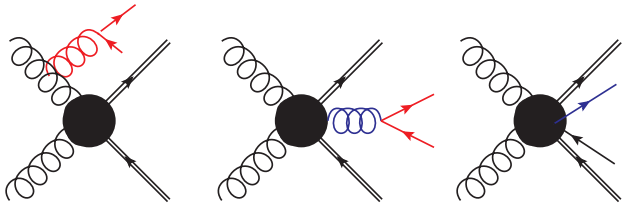




1. NLOPS $t\bar{t}$ with PS splitting $g \to b\bar{b}$



2. Multi-leg merged sample where the $b\bar{b}$ pair can come from the 5FNS ME or from the PS



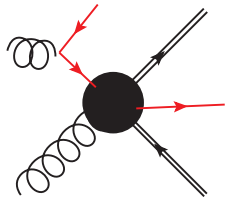
$\Rightarrow$ Quite-inefficient

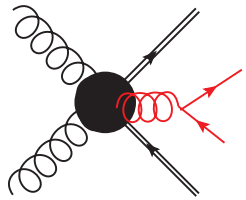
$\Rightarrow$ $b\bar{b}$ production rely on the PS accuracy

material taken from Siegert's talk at ZPW2020

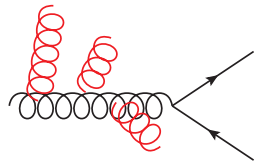
ttbb: present situation

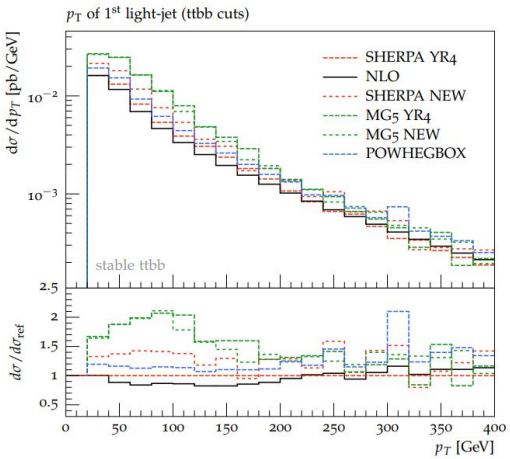
5. NLOPS generators for $t\bar{t}b\bar{b}$ in the 4FNS, PS provides furher emissions.
   - `Sherpa + OpenLoops`
     [Cascioli, Maierhöefer, Moretti, Pozzorini, Siegert, '13]
   - `PowHel + Pythia/Herwig`
     [Bevilacqua, Garzelli, Kardos, '18]
   - `POWHEG BOX + OpenLoops + Pythia/Herwig`
     [Ježo, Lindert, Moretti, Pozzorini, '17]
   - `MG5_aMC + Pythia/Herwig` , `Herwig7 + OpenLoops`





$\Rightarrow$ It misses radiation from the parent gluon,
[Ridolfi, Zaro, Ubiali, '19]





$\Rightarrow$ Huge disagreement among several MC!
Do we accept them as source of uncertainty
or we try to improve?

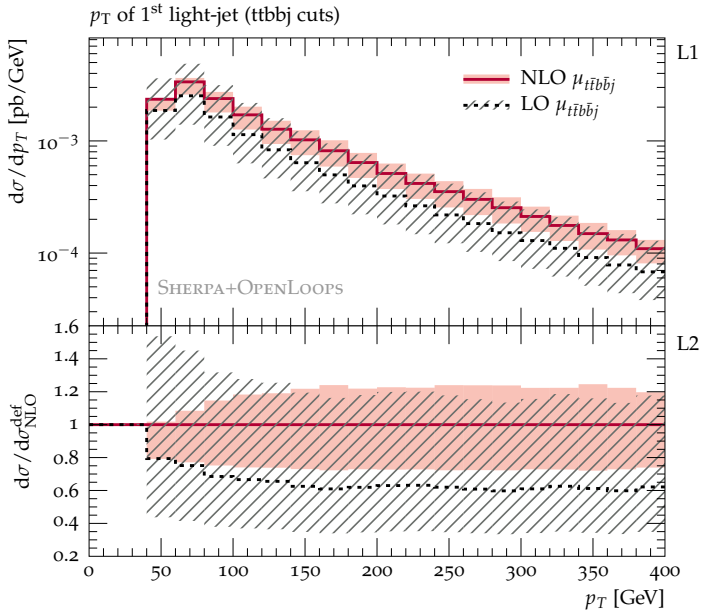
material taken from Siegert's talk at ZPW2020

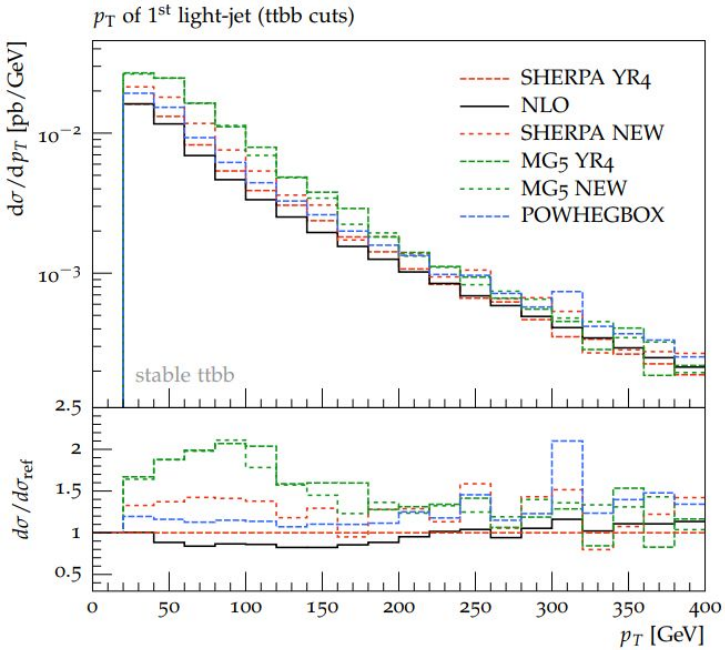
ttbbj@NLO to push ttbb NLOPS accuracy

material from Siegert's talk at ZPW2020

ttbbj@NLO with `OpenLoops` [Buccioni, Kallweit, Pozzorini, Zoller '19] as benchmark improve agreement, which has higher accuracy on extra-radiation observables.

$\Rightarrow$ which **scale** reduces the K-factor and shape-differences?





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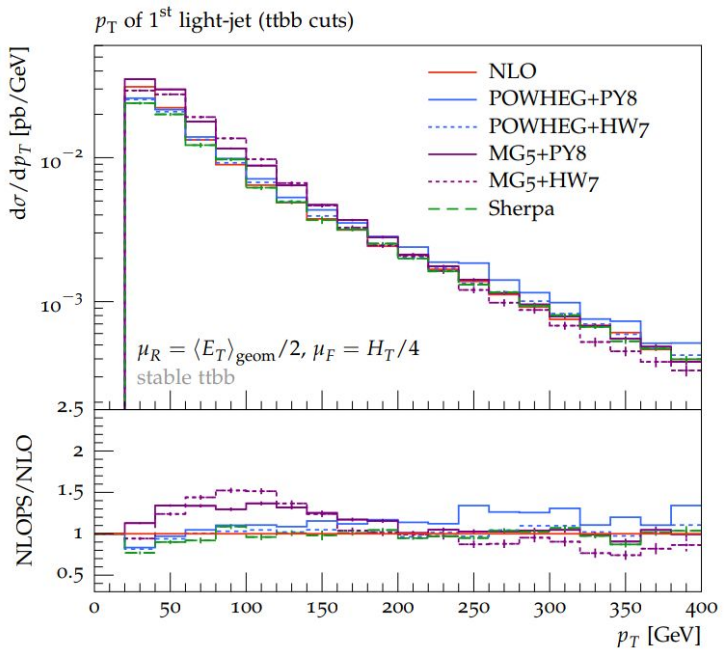
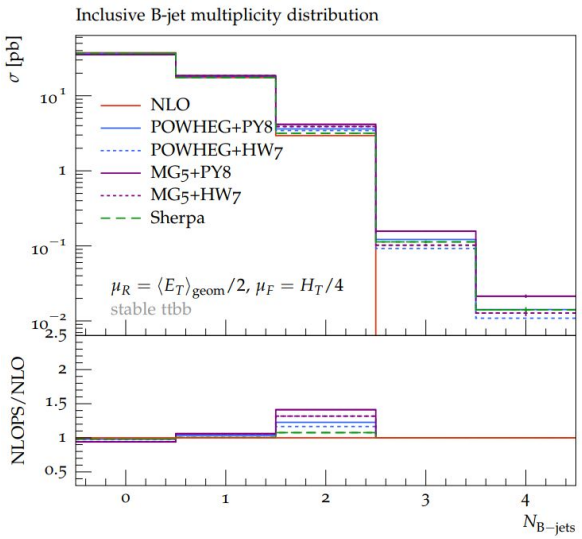
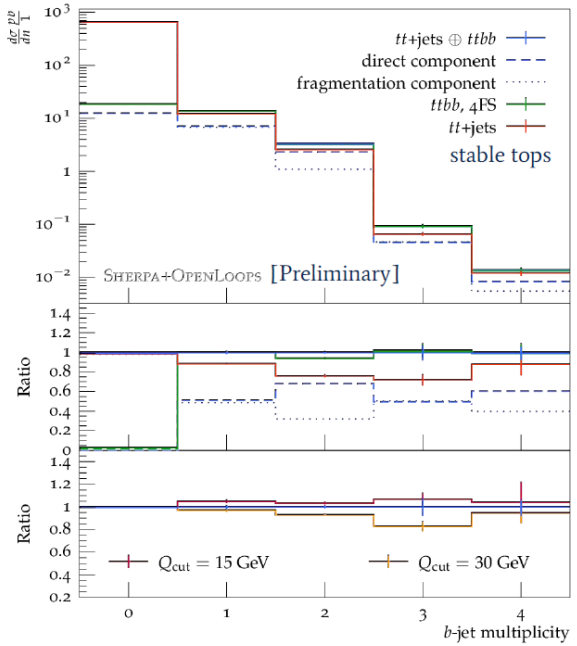


ttbb: fusing (Sherpa)

Large uncertaintiens in the b-jet multiplicity for $N_b = 2$





combine MEPS@NLO tt + 0,1j@NLO + 2,3j@LO and massive ttbb@NLO

[Katzy, Krause, Pollard, Siegert, in preparation]

Fusing [Höche, Krause, Siegert, '19]

- Remove all configurations from the 5FNS merged simulation of that have a PS history compatible with the reweighted massive computation.
- Midpoint between 5FNS and 4FNS, reproduces **FONLL** [Forte, Napoletano, Ubiali 2016].
- Parent gluon is dressed by further emissions, better description of $g \to b\bar{b}$.

Summary and outlooks

- To include **off-shell** and **non-resonant** contributions in a NLOPS generator, a **resonance-aware** framework is required.
- A lot of NLO calculations of $t\bar{t}X$ with off-shell and non-resonant contributions (by `Helac` and `MoCaNLO+Recola`) who are not (YET) matched to PS ☹.
- `Herwig7` can describe $t\bar{t}$ production and decay at NLO only in NWA, but offers the possibility to perform a systematic study of **matching uncertainties**.
- To describe the top-p_T we need **merged simulations** (with stable top), which are available in `Sherpa, Herwig7` (plus `Openloops`) and `MADGRAPH5_aMC@NLO+PY8`. In `Sherpa` we can also include approximate EW corrections, very important in the tail.
- $\mathbf{t\bar{t}b\bar{b}}$ important case of study ($t\bar{t}H$ background). Differences between **4FNS NLOPS** generators can be mitigated by suitable scale choices (fixed order studies with $\mathbf{t\bar{t}b\bar{b}j}$**@NLO** very useful). The **fusing** algorithm (`Sherpa`) could be a way to combine the advantages of 5FNS and 4FNS simulations.

THANKS FOR THE ATTENTION!