MC simulation of heavy flavor production

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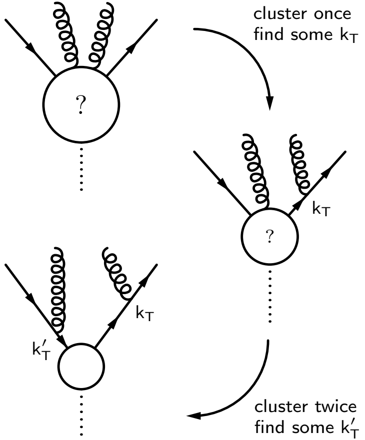
Overview

- This talk: Heavy Flavor $= t$
- Studied intensely, both at fixed order
  - NNLO QCD [Czakon,Fiedler,Mitov '13], [Czakon,Heymes,Mitov '16]
  - NLO QCD / EW in production $\times$ decay [Bernreuther,Brandenburg,Si '04], [Melnikov,Schulze '09], [Campbell,Ellis '15], [Bernreuther,Si '10]
  - NLO QCD / EW $WWb\bar{b}$ [Bevilacqua,Czakon,vanHameren,Papadopoulos,Worek '11], [Denner,Dittmaier,Kallweit,Pozzorini '11+'12], [Heinrich,Maier,Nisius,Schlenk,Winter '14], [Frederix '14], [Cascioli,Kallweit,Maierhöfer,Pozzorini '14], [Denner,Pellen '16]
  - NLO QCD $t\bar{t}$+(multi-)jet [Dittmaier,Uwer,Weinzierl '07], [Bevilacqua,Czakon,Papadopoulos,Worek '10], [Maierhöfer,Moretti,Pozzorini,Siegert,SH '16]
- and in the context of particle-level Monte Carlo
  - NLO QCD+PS [Frixione,Nason,Webber '03], [Frixione,Nason,Ridolfi '07]
  - NLO QCD+PS in production $\times$ decay [Campbell,Ellis,Nason,Re '15]
  - NLO QCD+PS $WWb\bar{b}$ [Garzelli,Kardos,Trocsanyi '14], [Jezo,Lindert,Nason,Oleari,Pozzorini '16]
  - NLO QCD+PS $t\bar{t}$+(multi-)jet [Kardos,Papadopoulos,Trocsanyi '11], [Alioli,Moch,Uwer '11], [Huang,Luisoni,Schönherr,Winter,SH '13], [Krauss,Maierhöfer,Pozzorini,Schönherr,Siegert,SH '14]
- Will focus on
  - NLO QCD for $t\bar{t}$+multi-jets
  - Matching to parton shower and (N)LO merging
  - Parton shower uncertainties

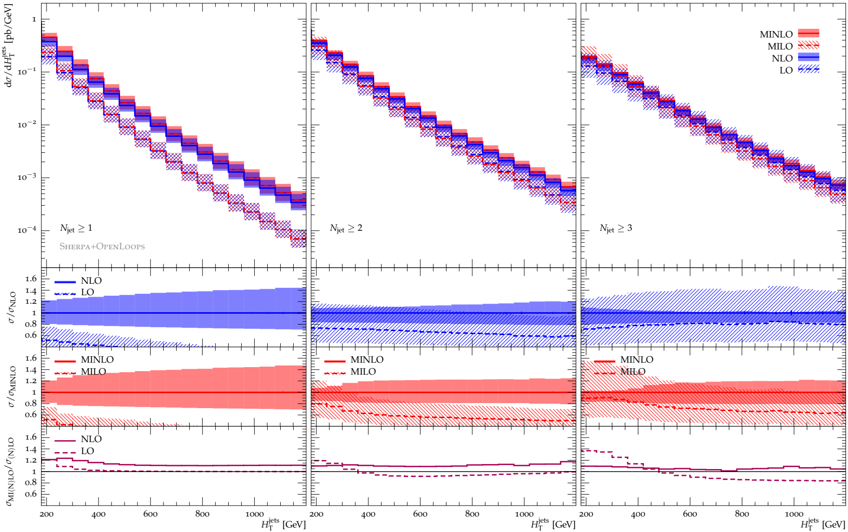
Top-quark pairs – A QCD scale uncertainty study

- Renormalization/factorization scale typically used at very high multiplicity: sum of transverse mass $H_{T,m} = \sum m_\perp$
- Has been criticized for being 'too large' and insensitive to dynamics of process
- Very different scale defined by MINLO [Hamilton,Nason,Zanderighi] arXiv:1206.3572
  - Interpret event in terms of QCD branchings, like in a parton-shower
  - Assign transverse momentum scales q to splittings, evaluate one α_s at each of these scales
  - Multiply with NLL Sudakov factors, subtract first-order expansion
- MINLO scale probes detailed dynamics, typically very small → good candidate for comparison to $H_{T,m}$



Top-quark pairs – A QCD scale uncertainty study

[Maierhöfer,Moretti,Pozzorini,Siegert,SH '16]



Matching to parton showers

Two possible ways to match NLO calculations and parton showers

Additive (MC@NLO-like)

[Frixione,Webber '02]

- Use parton-shower splitting kernel as NLO subtraction term
- Multiply LO event weight by Born-local K-factor including integrated subtraction term and virtual corrections
- Add hard remainder function consisting of subtracted real-emission correction

Multiplicative (POWHEG-like)

[Nason '04]

- Use matrix-element corrections to replace parton-shower splitting kernel by full real-emission matrix element in first shower branching
- Multiply LO event weight by Born-local NLO K-factor (integrated over real corrections that can be mapped to Born according to PS kinematics)

Both cases: Beware of sub-leading color, spin correlations & off-shell effects!

Matching – Full vs leading color

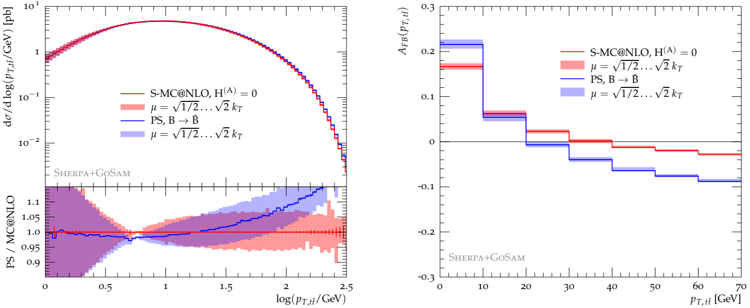
[Huang,Luisoni,Schönherr,Winter,SH '13]

- Standard MC@NLO: Soft-gluon kinematics ignored by fading out real-emission correction to account for leading color MC subtraction terms

$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\bar{\mathrm{B}}^{(\mathrm{K})}\,\mathcal{F}^{(0)}_{\mathrm{MC}}(\mu_Q^2,O) + \int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{K})}\,\mathcal{F}^{(1)}_{\mathrm{MC}}(t(\Phi_R),O)$$

$$\bar{\mathrm{B}}^{(\mathrm{K})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \int \mathrm{d}\Phi_1\left[\mathrm{S} - \mathrm{B}\,\mathrm{K}\right] f(\Phi_1)\,, \quad \mathrm{H}^{(\mathrm{K})} = \left[\mathrm{R} - \mathrm{B}\,\mathrm{K}\right] f(\Phi_1)$$

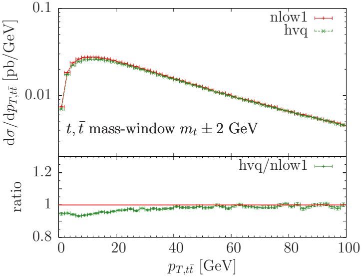
- Appropriate for sufficiently inclusive observables, problematic e.g. for A_{FB}
  Similar issues could arise in other observables that break PS unitarity

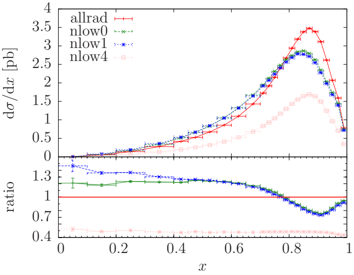


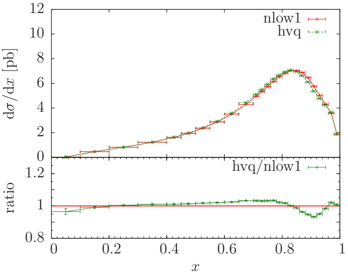
Matching – Production vs decay

[Campbell,Ellis,Nason,Re '15]

- POWHEG simulation including top decays and off-shell effects (via remapping to on-shell kinematics & BW reweighting)
- Moderate differences compared to LO decays & no spin correlations
- Sizable differences for varying shower parameters (removing decay ME correction in Pythia improves agreement)







Matching – Processes with intermediate resonances

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[Jezo,Nason '15]

- NLO subtraction methods do not preserve virtuality of possible resonances
  IR cancellation takes place highly non-locally $\rightarrow$ efficiency problem
- Problem worsens in POWHEG, as uncontrollable ratios are exponentiated:

$$\Delta(\Phi_B, p_T) = \exp\left\{ -\sum_\alpha \int \mathrm{d}\Phi_1 \frac{\mathrm{R}(\Phi_R^{(\alpha)})}{\mathrm{B}(\Phi_B)}\, \Theta(p_T - k_T) \right\}$$

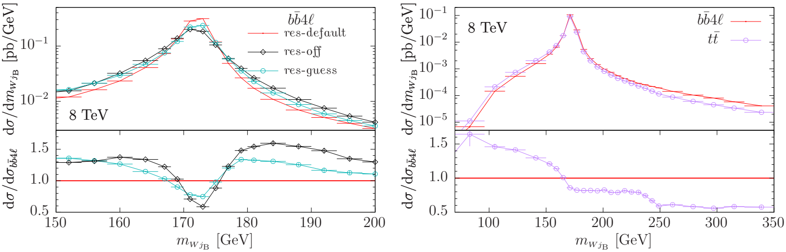
- Proposed solution:
  - Partition phase space such that each region corresponds to a unique resonance history
  - Within each region modify subtraction mappings such that resonance mass is preserved
- Assignment of resonance histories requires algorithm
  $\rightarrow$ Use kinematic proximity to resonance

$$\Pi_{f_b} = \frac{P_{f_b}}{\sum_{f_b' \in \text{res hists}} P_{f_b'}}\,, \quad P_{f_b} = \prod_{i \in \text{ress}} \frac{M_i^4}{(s_i - M_i^2)^2 + \Gamma_i^2 M_i^2}$$

Matching – Wt vs $t\bar{t}$

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

- Wt production in the 5F scheme:
  - NLO corrections swamped by LO $t\bar{t}$ decay
  - Requires ad-hoc subtraction prescription (DR/DS)
- Wt production in the 4F scheme:
  - Unified treatment of Wt and $t\bar{t}$ (identical at LO)
  - Requires off-shell $WWb\bar{b}$ calculation
- Sizable differences compared to resonance-unaware matching and to narrow-width approach [Frixione,Nason,Ridolfi '07]

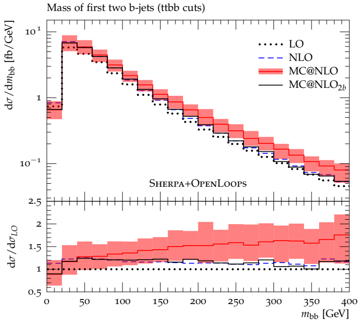


Matching – $t\bar{t}b\bar{b}$

[Cascioli,Maierhöfer,Moretti,Pozzorini,Siegert ’13]

- Matching of $t\bar{t}b\bar{b}$ NLO calculations requires special care
- Secondary $b\bar{b}$ pair(s) from $g \to b\bar{b}$ splitting in PS can have larger invariant mass than primary pair if PS scale high enough
  $\to$ distortion of MC@NLO spectrum compared to NLO

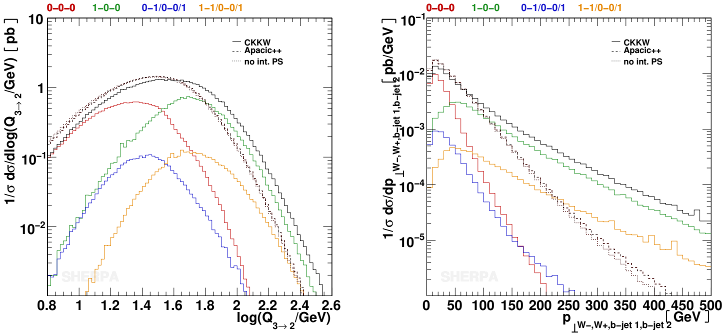
	ttb	ttbb($m_{bb} > 100$)
$\sigma_{LO}[fb]$	$2644^{+71\%+14\%}_{-38\%-11\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
$\sigma_{NLO}[fb]$	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.15
$\sigma_{MC}[fb]$	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$181.0^{+20\%+8.1\%}_{-20\%-6.0\%}$
σ_{MC}/σ_{NLO}	1.01	1.28
$\sigma_{MC}^{2b}[fb]$	3299	146
$\sigma_{MC}^{2b}/\sigma_{NLO}$	1.00	1.03



Merging in $t\bar{t}$+jets – Production vs decay

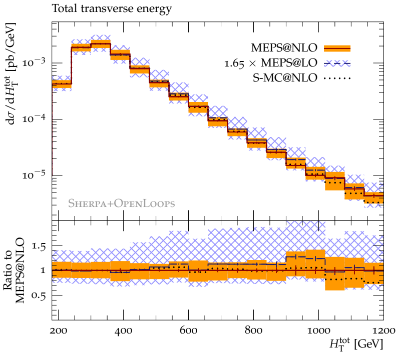
[SH (PhD thesis) '08]

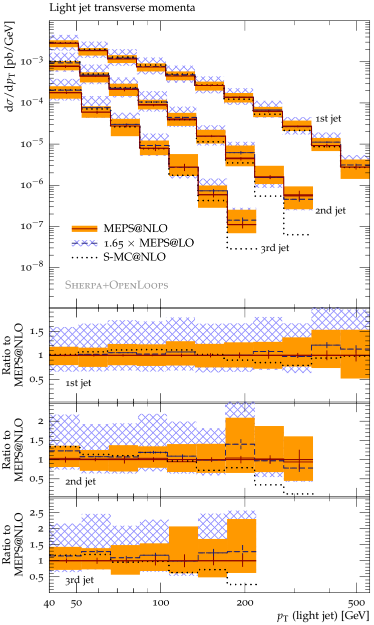
- ME+PS merging possible in top production and decay independently
- Effect of merging in decay negligible for most jet observables



Merging in $t\bar{t}$+jets – NLO

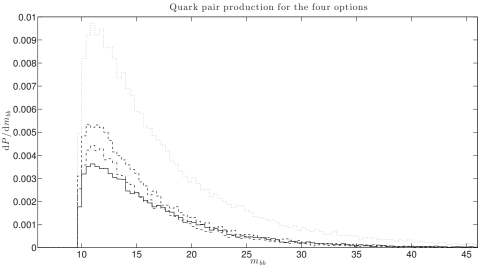
- NLO-Matched & merged simulations now up to $t\bar{t}$+2j (+ any jets at LO) [Frederix,Frixione '12], [Krauss,Maierhöfer,Pozzorini,Schönherr,Siegert,SH '14]
- Decays & spin correlations at LO
- Largely reduced $\mu_{R/F}$ variations, central value agrees well with LO merged prediction





Parton shower uncertainties – Splitting functions

- Splitting functions for heavy flavor ambiguous
- Example: FSR $g \to Q\bar{Q}$ in Pythia8 [Jimenez (Masters Thesis) LU-TP 14-15]
  - $w_1 = \beta\,[1 - 2z(1-z)]\ ,\ \beta = \sqrt{1 - 4m_Q^2/Q^2}$
  - $w_2 = \beta\left[1 - 2z(1-z)(1 - 8m_Q^2/Q^2)\right]$
  - $w_4 \to$ full $\gamma^* \to Q\bar{Q}$ ME correction



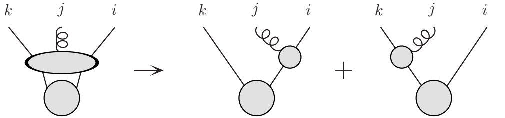
w_1 →solid
w_2 →dashed
w_4 →dash-dotted

- Also: Effects of massive recoil partners in momentum mapping

Parton shower uncertainties – Shower model

- Old angular ordered / vetoed parton showers do not fill full phase space
  Dipole showers lack parton interpretation $\to$ prefer alternative to both
- Can preserve parton picture by partial fractioning soft eikonal
  $\leftrightarrow$ soft enhanced part of splitting function [Catani,Seymour '96]

$$\frac{p_ip_k}{(p_ip_j)(p_jp_k)} \to \frac{1}{p_ip_j}\frac{p_ip_k}{(p_i+p_k)p_j} + \frac{1}{p_kp_j}\frac{p_ip_k}{(p_i+p_k)p_j}$$



- "Spectator"-dependent kernels, singular in soft-collinear region only
  $\to$ capture dominant coherence effects (3-parton correlations)

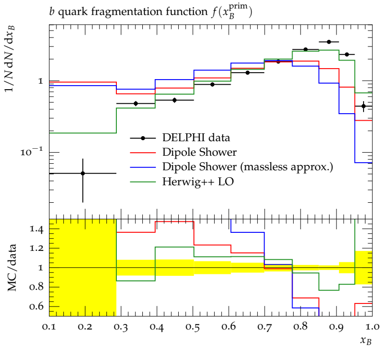
$$\frac{1}{1-z} \to \frac{1-z}{(1-z)^2+\kappa^2} \qquad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

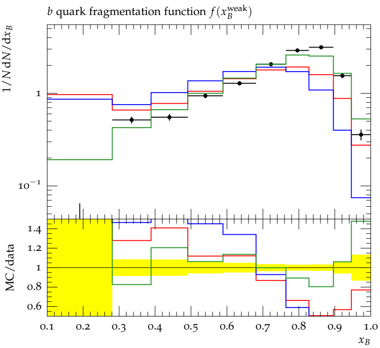
- For correct soft evolution, ordering variable must be identical
  at both "dipole ends" ($\to$ recover soft eikonal at integrand level)

Parton shower uncertainties – Shower model

[Stoll (Diploma thesis)], [Plätzer (IPPP HF WS '16)]

- Something odd in this model for $g \to b\bar{b}$ splittings
  - Not a bug, consistent between generators (Herwig7, Sherpa, ...)
  - Not fixed by a scale choice (p_T vs. $m_{q\bar{q}}$)
  - Not a kinematics/ordering effect





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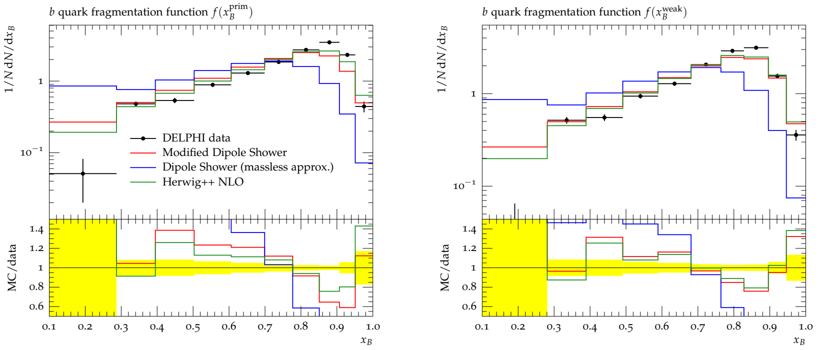
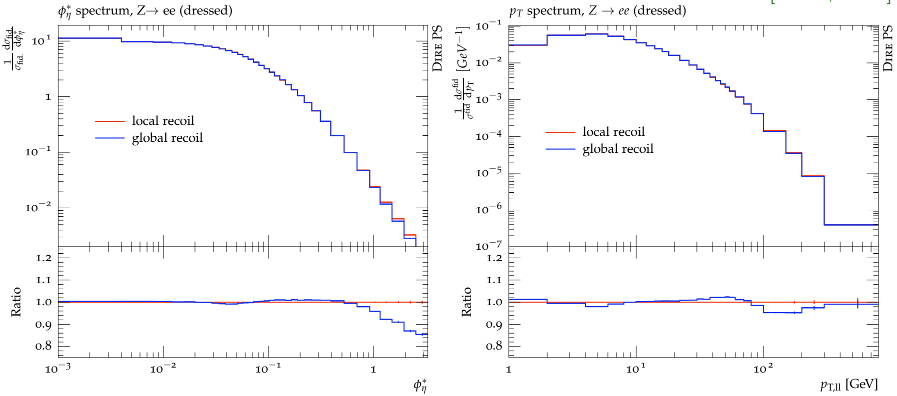


Parton shower uncertainties – Kinematics

[Prestel,SH '15]



- Two mapping schemes for IF dipoles → local [Catani,Seymour '96] and global [Plätzer,Gieseke '09], [Schumann,Siegert,SH '09]
- Negligible impact e.g. on q_T-spectrum of Drell-Yan lepton pairs
- Less well investigated in more exclusive observables and heavy flavor

Summary

Heavy Flavor particularities

- Resonance-aware matching for top

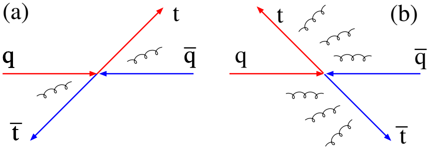
Major sources of uncertainty

- 4F vs. 5F scheme in hard process
- Splitting kernels and scales in PS
- Shower model (partons vs dipoles)

All of them under constant investigation

[Skands,Webber,Winter] arXiv:1205.1466
[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703

- Parton-shower unitarity broken by splitting of emission phase space
- Events with $\Delta y_{t\bar{t}} > 0$ have fewer phase space for radiation



- But inclusive asymmetry is mainly generated by momentum mapping

$$\Delta\sigma_{+-} = -2\int \underbrace{\mathrm{d}\sigma_{LO}|_{\Delta y>0}(1-\Delta_+)P_{+-}}_{\text{subdominant as } \Delta_- < \Delta_+ \text{ ((b) vs. (a))}} + 2\int \underbrace{\mathrm{d}\sigma_{LO}|_{\Delta y<0}(1-\Delta_-)P_{-+}}_{\text{dominant as } \Delta_+ > \Delta_- \text{ ((a) vs. (b))}}$$

P_{-+}/P_{+-} - probabilities for Δy to increase / decrease in splitting

- Dipole showers generate positive rapidity shift in each emission

$$\Delta y_t = \frac{1}{2}\ln\left(1+\frac{p_q p_g}{p_q p_t}\left(\frac{1-z}{z}+\frac{m_t^2}{p_q p_t}\right)\frac{\tilde{p}_q^+}{\tilde{p}_t^+}\right) > 0$$

Similar finding for any dipole-like recoil scheme → positive asymmetry