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$t\bar{t}b\bar{b}$ at NLO precision in a variable flavor number scheme

Stefan Höche

Fermi National Accelerator Laboratory

ttH/tH WG meeting

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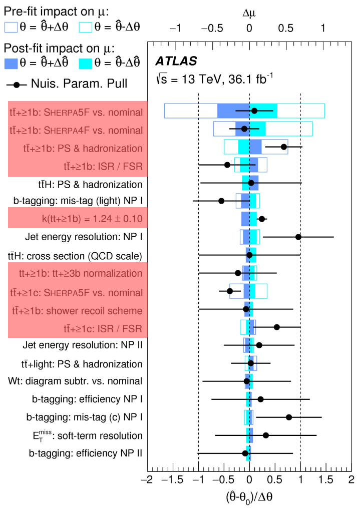
Introduction

[ATLAS] arXiv:1712.08895



- MC is single largest source of uncertainty on extracted signal strength in $t\bar{t}b\bar{b}$
- Traditional approaches to the problem
  - **Five-flavor scheme**:
    - "Inclusive" NLO+PS $t\bar{t}$ sample with HF from parton shower $g \to b\bar{b}$
    - Multi-leg merged $t\bar{t}$+jets sample with HF from higher-order MEs or parton shower $g \to b\bar{b}$ splitting
  - **Four-flavor scheme**:
    - NLO+PS $t\bar{t}b\bar{b}$ using matrix elements (and showers) with massive b-quarks

Introduction

- Heavy flavor production processes have been studied intensely
  - From theoretical perspective (Fixed order, NLL, FONLL)

    [Cacciari,Frixione,Houdeau,Mangano,Nason,Ridolfi,. . .]
    arXiv:1205.6344, hep-ph/0312132, hep-ph/9801375, NPB373(1992)295 . . .
  - In the context of particle-level Monte Carlo

    [Norrbin,Sjöstrand], hep-ph/0010012, [Gieseke,Stephens,Webber] hep-ph/0310083,
    [Schumann,Krauss] arXiv:0709.1027, [Gehrmann-deRidder,Ritzmann,Skands] arXiv:1108.6172 . . .
  - Regarding matching & merging of (N)LO and parton showers

    [Frixione,Nason,Webber] hep-ph/0305252, [Frixione,Nason,Ridolfi] arXiv:0707.3088,
    [Mangano,Moretti,Pittau] hep-ph/0108069 . . .

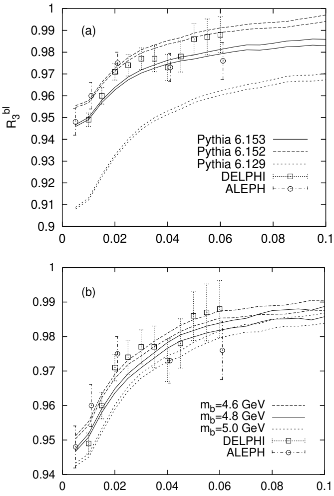
- $t\bar{t}b\bar{b}$ has unique features, but similar rules still apply
  - Parton shower uncertainties can be hard to judge and reduce

    [Cascioli,Maierhöfer,Moretti,Pozzorini,Siegert] arXiv:1309.5912
  - To compute truly inclusive predictions, matching is needed

    [Krause,Siegert,SH] arXiv:1904.09382, [Ferencz,Katzy,Siegert,SH] arXiv:2402.15497

Challenges in modeling HF production

- Both high-energy limit and threshold region should be described as well as possible, but
- Infrared finite prediction for $g \to Q\bar{Q}$ leaves splitting functions somewhat arbitrary
- Soft gluon emission off light/heavy quarks associated with $\alpha_s(k_T^2)$, i.e. “correct” scale is k_T^2 [Amati et al.] NPB173(1980)429, but no such argument to set scale for $g \to Q\bar{Q}$
  $\to$ HQ production rate not very stable w.r.t. parton shower variations
- A number of different prescriptions, e.g.
  [Norrbin,Sjöstrand], hep-ph/0010012,
  [Gieseke,Stephens,Webber] hep-ph/0310083,
  [Schumann,Krauss] arXiv:0709.1027,
  [Gehrmann-deRidder,Ritzmann,Skands] arXiv:1108.6172
  varying success in describing expt. data



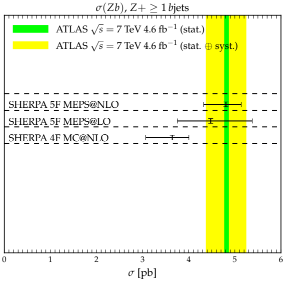
[Norrbin,Sjöstrand] hep-ph/0010021

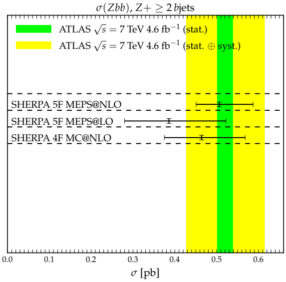
Heavy flavor production as a multi-scale problem

- Initial-state $g \to Q\bar{Q}$ splitting generates logarithms of the form

$$\int^{Q^2} \frac{\mathrm{d}t}{t - m_q^2} P_{g \to Q\bar{Q}} \sim \log \frac{Q^2}{m_b^2}$$

  - Resum logarithms in b-quark PDF $\to$ 5 flavor scheme (5FS)
  - Keep logarithms as they are generated $\to$ 4 flavor scheme (4FS)
- Five flavor scheme slightly preferred at high energies
  e.g. Z+jets [Krauss,Napoletano,Schumann] arXiv:1612.04640



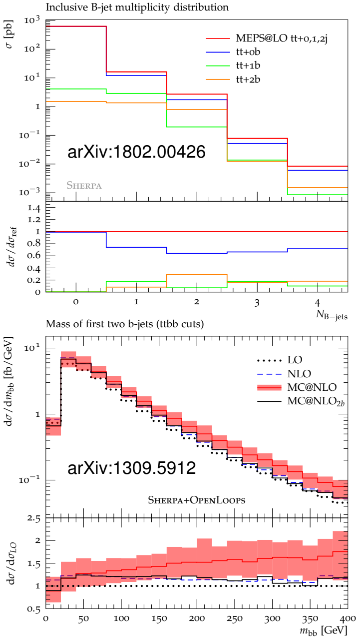


$t\bar{t}b\bar{b}$ modeling at the LHC

- **5 flavor scheme**:
  - "Inclusive" NLO+PS $t\bar{t}$ sample with HF from parton shower $g \to b\bar{b}$
  - Multi-leg merged $t\bar{t}$+jets sample with HF from higher-order MEs (hard b) or parton shower $g \to b\bar{b}$ (soft/coll b)

  Surprising feature:
  - Jet production described by hard MEs, but b-jets not always from b-MEs!
  - soft/collinear $g \to b\bar{b}$ from PS can transform light jets into b-jets
- **4 flavor scheme**:
  - NLO+PS $t\bar{t}b\bar{b}$ using matrix elements with massive b-quarks

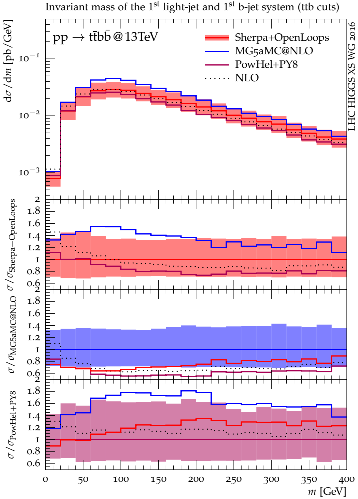
  Surprising feature:
  - Secondary $b\bar{b}$ from $g \to b\bar{b}$ in PS can convert light jet into b-jet $\to$ event interpretation changes



$t\bar{t}b\bar{b}$ modeling in the 4F scheme

- Several tools on the market
  - Sherpa + OpenLoops [Cascioli,Maierhöfer, Moretti,Pozzorini,Siegert] arXiv:1309.5912
  - PowHel + Pythia/Herwig [Bevilacqua,Garzelli,Kardos] arXiv:1709.06915
  - PowhegBox + OpenLoops + Pythia/Herwig [Jezo,Lindert,Moretti,Pozzorini] arXiv:1802.00426
  - MG5_aMC + Pythia/Herwig
  - Herwig7 + OpenLoops
- History of out-of-the-box comparisons:
  - Large discrepancies
  - Due in part to pQCD uncertainties
  - But also beyond: Parton Shower, NLO+PS matching algorithm
- Tuned comparison by HXSWG E.g. https://indico.cern.ch/event/740110

[HXSWG] arXiv:1610.07922

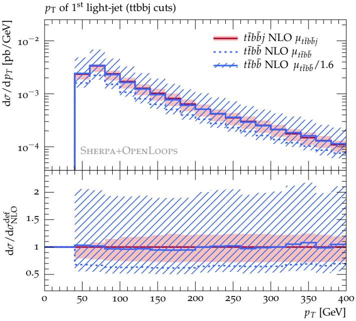


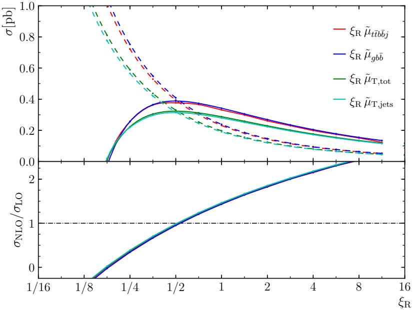
$t\bar{t}b\bar{b}$ modeling in the 4F scheme

[Buccioni,Kallweit,Pozzorini,Zoller] arXiv:1907.13624

- Fixed-order study of $t\bar{t}b\bar{b}j$ at NLO determined optimal scale
- Stabilization of K-factor for $\mu_R = (E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}}p_{T,j})^{1/5}$
- Recommended choice for $t\bar{t}b\bar{b}$ obtained by tuned comparison:

$$\mu_R = (E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}})^{1/4}/1.6$$





A possible solution: FONLL matching of 4FS and 5FS

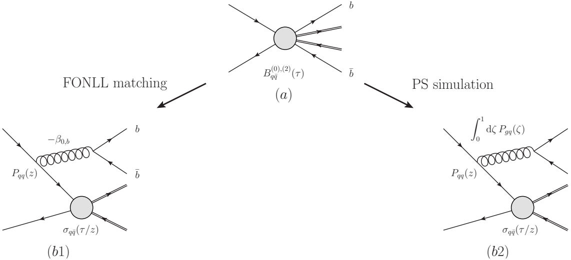
- General idea of FONLL: Treatment of logarithms in 4FS/5FS can be matched by
  - Re-expressing both in same renormalization scheme
  - Subtracting the overlap

$$\sigma^{\text{FONLL}} = \sigma^{\text{massive}} + (\sigma^{\text{massless}} - \sigma^{\text{massive},\,0})$$

- This has been applied extensively to inclusive observables

  [Cacciari,Frixione,Mangano,Nason,Ridolfi] hep-ph/0312132,
  [Forte,Napoletano,Ubiali] arXiv:1508.01529, arXiv:1607.00389, ...

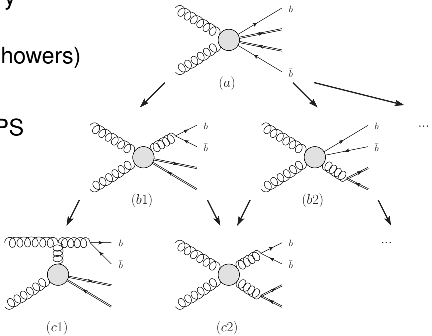
- Extension to differential observables needed for $t\bar{t}b\bar{b}$



Matching X+jets & $Xb\bar{b}$

[Krause,Siegert,SH] arXiv:1904.09382

- **Interpret $Xb\bar{b}$ as part of Xjj**
  1. Cluster to obtain parton shower history
  2. Apply $\alpha_s(\mu_R^2) \to \alpha_s(p_T^2)$ reweighting
  3. Apply Sudakov factors $\Delta(t,t')$ (trial showers)
- **Remove double-counting**
  1. Cluster PS-level event using inverse PS
  2. Look at leading two emissions
     - Heavy Flavour $\to$ keep from $Xb\bar{b}$ ("direct component")
     - Light Flavour $\to$ keep from X+jets ("fragmentation component")
     - Subleading $g \to b\bar{b}$ splittings not from $Xb\bar{b}$ ME, but $X4j$ MEPS



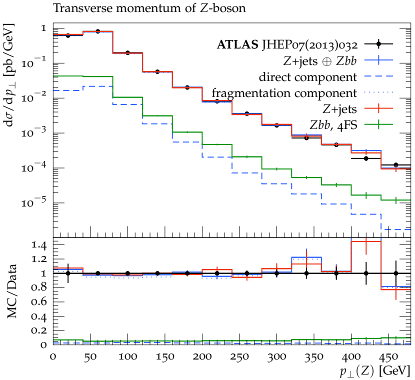
- **Match 5F→4F in PDFs and α_s**
  1. Use 5F PDF / α_s to be consistent with Xjj
  2. Use matching coefficients to correct to 4F scheme
     [Buza,Matiounine,Smith,van Neerven] hep-ph/9612398, [Forte,Napoletano,Ubiali] arXiv:1607.00389
     $\to$ Coefficients up to (N)LL generated by (N)LO parton shower!
  3. Reweighting needed only for α_s in hard ME

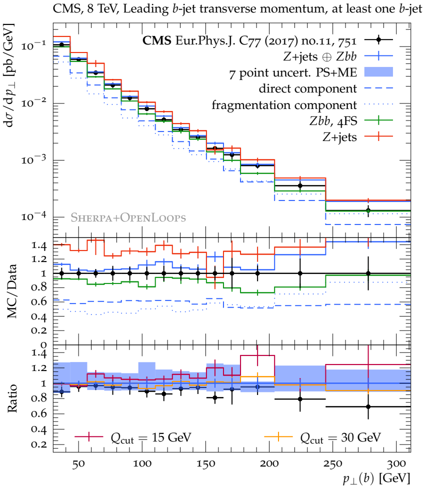
Can be applied to LO and NLO merging!

Cross-check: Z+jets & $Zb\bar{b}$

- Validation with LHC data

[Krause,Siegert,SH] arXiv:1904.09382

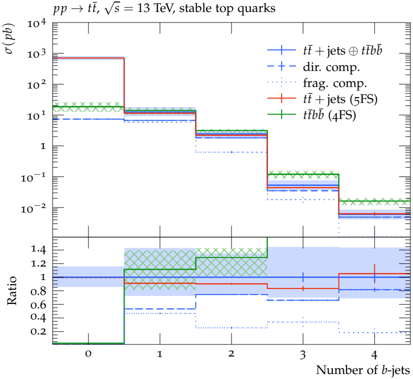


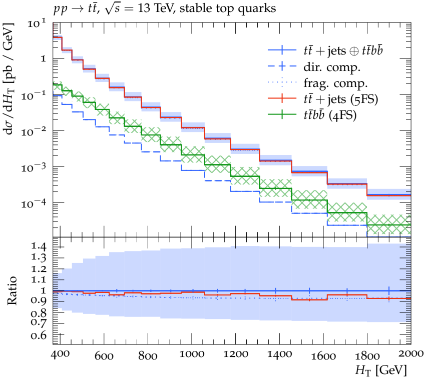


	Data [pb]	**Fusing** [pb]
$Z+\geq 1b$	$3.55 \pm 0.24_{\text{comb}}$	$3.80(5) \pm \begin{smallmatrix}0.83\\0.33\end{smallmatrix}$
$Z+\geq 2b$	$0.331 \pm 0.037_{\text{comb}}$	$0.282(4) \pm \begin{smallmatrix}0.027\\0.022\end{smallmatrix}$

Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497

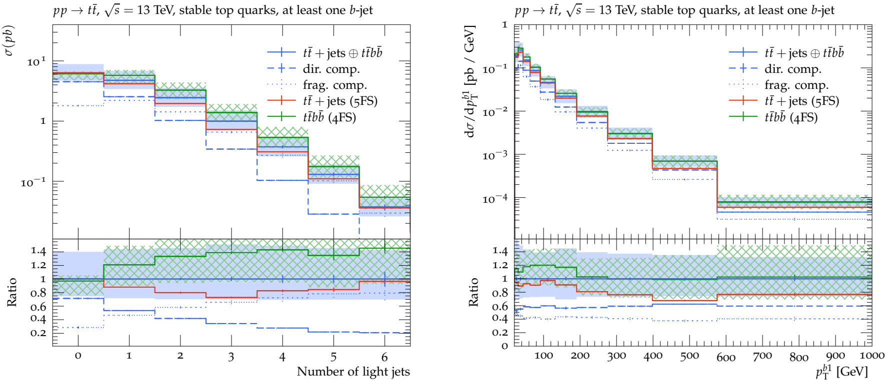




- Inclusive $t\bar{t}$ selection, stable top quarks
- Good agreement between fusing & 5FS calculation

Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

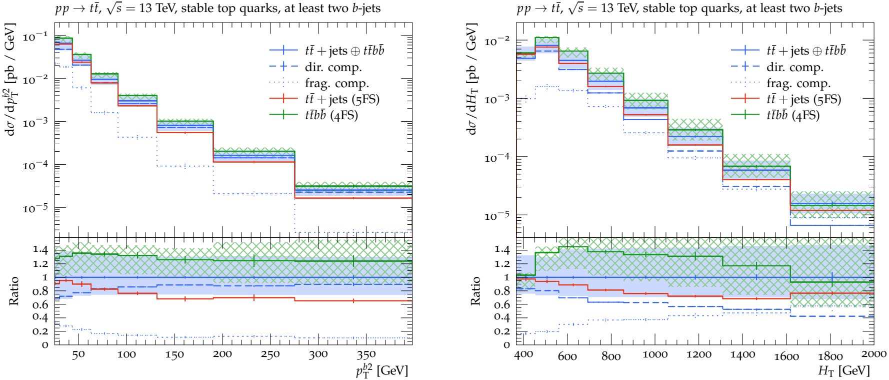
[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497



- One-b-jet region, stable top quarks
- Good agreement between fusing & 5FS
- Reduced multi-jet rates compared to 4FS

Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

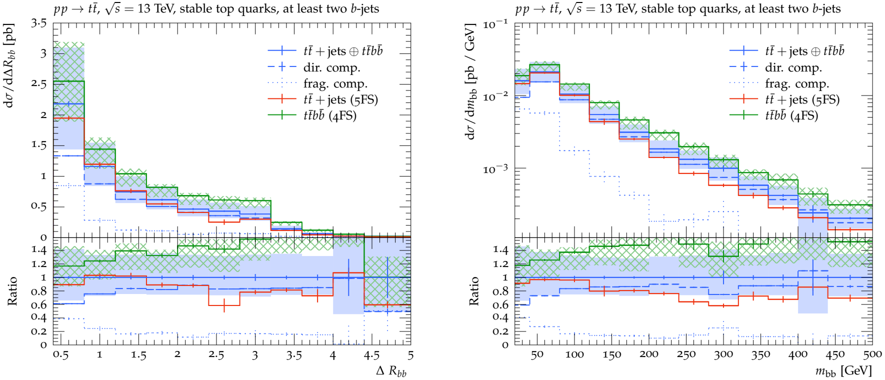
[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497



- Two-b-jet region, stable top quarks
- Fusing “interpolates” between 4FS & 5FS

Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497



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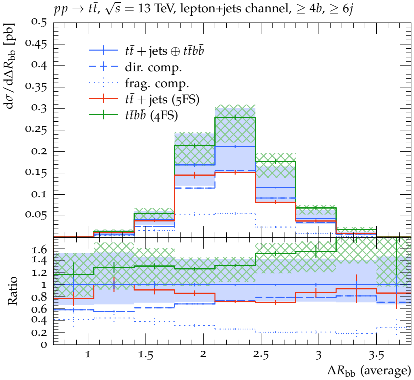
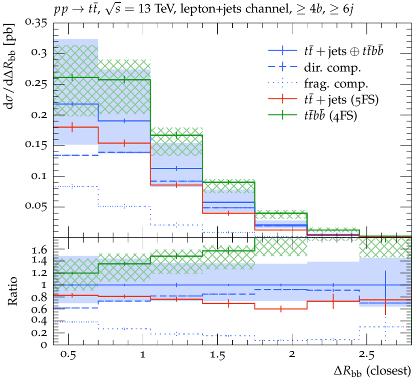
Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497

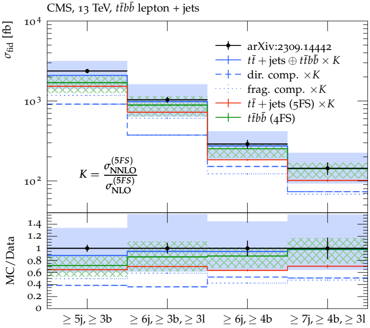


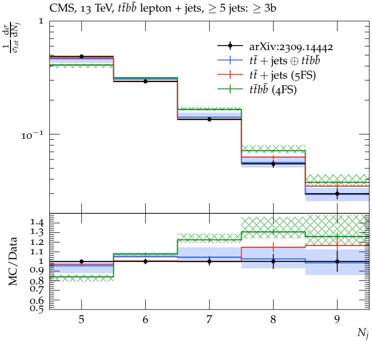


- Decayed top quarks, lepton+jets channel
- Large direct component, but still closer to 5FS than 4FS

Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497

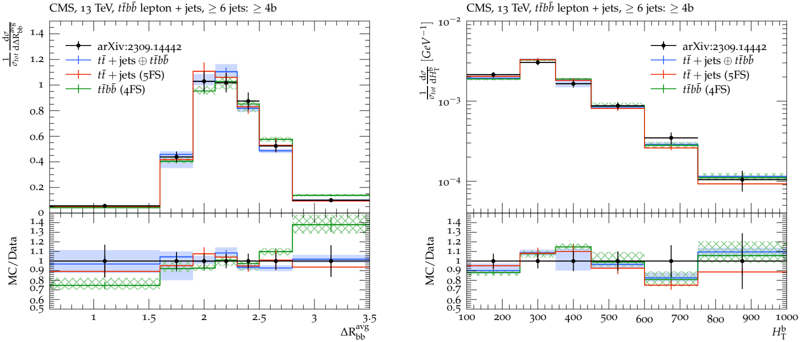




- Comparison to CMS data from arXiv:2309.14442

Fusing $t\bar{t}$+jets & $t\bar{t}b\bar{b}$

[Ferencz,Katzy,Siegert,SH] arXiv:2402.15497



- Comparison to CMS data from arXiv:2309.14442

Summary

- $t\bar{t}b\bar{b}$ a particularly striking example for challenges in HF simulation
- Historically 5FS used in MC predictions, recently 4FS at NLO
- Scales can be adjusted based on NLO for higher multiplicity
- Fully differential 4FS & 5FS results can be combined
  in an automated fashion based on multijet merging
- Promising first results in comparison to LHC data