DPG Spring Meeting 2024
Karlsruhe

Simulation of on- and off-shell $t\bar{t}$ production with bb41 at CMS

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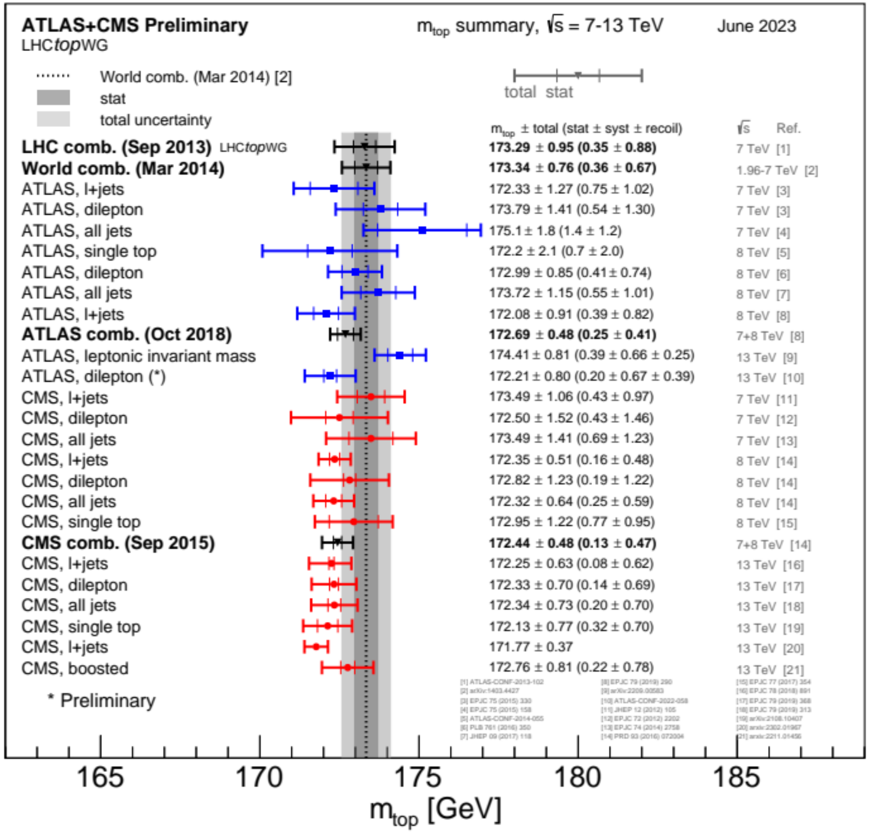
05.03.2024 | laurids.jeppe@desy.de | CMS-NOTE-2023-015

Motivation – top mass

- The top quark mass is important for many fundamental problems
  - Vacuum stability, global EW fits...
- Most precise top mass results from direct measurements
  - Fit of MC to data for sensitive observable
  - Requires precise MC prediction
    $\rightarrow$ control of generator uncertainties



Motivation – generator uncertainties

- Relevant generator uncertainties / effects:
  - Missing higher orders in QCD / EW
  - Initial & final state radiation
  - Interference between $t\bar{t}$/tW diagrams
  - Off-shell top effects
  - Renormalization schemes
  - Matching between matrix element and parton shower
    - e.g. recoil effects in the top decay
  - … and much more

All of these can shift the top mass in MC!

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    - e.g. recoil effects in the top decay ← (partly addressed)
  - … and much more

Addressed by bb4l (first four items)

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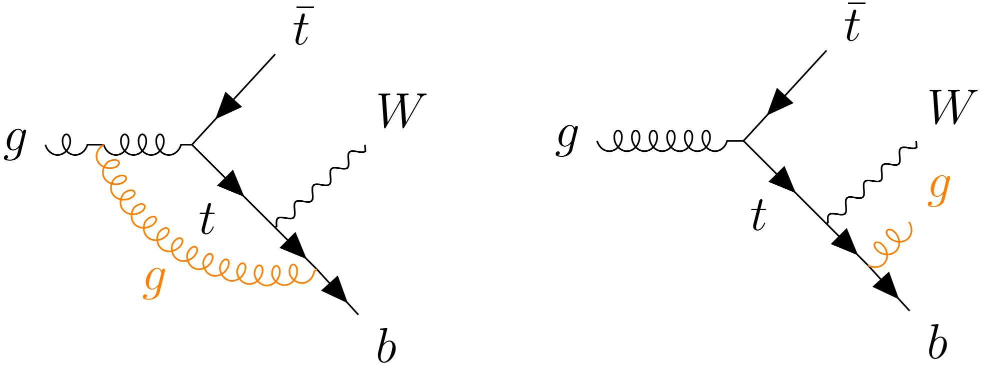
What is bb4l?

T. Ježo, P. Nason, JHEP 12 (2015) 065
T. Ježo et al, EPJC 76 (2016) 12, 691
T. Ježo, J.M. Lindert, S. Pozzorini, JHEP 10 (2023) 008

- MC generator for full process $pp \to b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ including all off-shell contributions at NLO, matched to a parton shower
- Implemented in the Powheg Box RES framework

➔ Includes NLO corrections for top decay and off-shell effects



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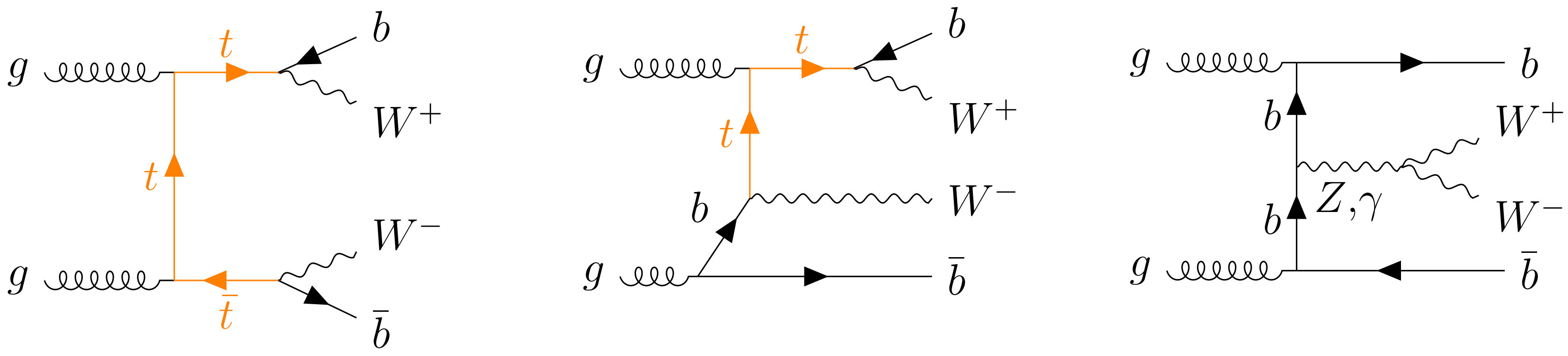
➔ Full description of interference between $t\bar{t}$ and tW



Comparison to other generators

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E. Re, EPJC 71 (2011) 1547

  - NLO in production; LO in decay with NLO ME corrections from Pythia
  - Narrow-width approximation (NWA): stable tops, smeared with top width
  - Ad-hoc $t\bar{t}$/tW interference removal schemes (uncertainty): diagram removal (DR) or diagram subtraction (DS)

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- `ttb_NLO_dec`:

  J. Campbell et al, JHEP 04 (2015) 114

  - NLO in production and decay separately in NWA
  - $t\bar{t}$/tW interference included at LO through reweighting

Generator predictions

- CMS study of `bb4l` [1]
  - 20M of events per generator
  - Extension to same-flavor leptons
  - Matched to Pythia 8 with FSR veto
  - 7-point ME scale variations (μ_R and μ_F)
- Also studies by ATLAS [2] & `bb4l` authors [3]
- New: updated `bb4l` version [4]
  - Several modeling improvements
  - Lepton+jets decays → future studies

Parameter	Value
Top quark mass	172.5 GeV
h_{damp}	1.38 m_t
μ_R and μ_F	dynamic (backup)
PDF set	NNPDF 3.1
Pythia version	8.307
Pythia tune	CP5

[1] CMS-NOTE-2023-015
[2] ATL-PHYS-PUB-2021-042
[3] S. Ferrario Ravasio et al, EPJC 78 (2018) 458
[4] T. Ježo et al, JHEP 10 (2023) 008

Results – $m_{b\ell}$

- Invariant b-ℓ mass, chosen as

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

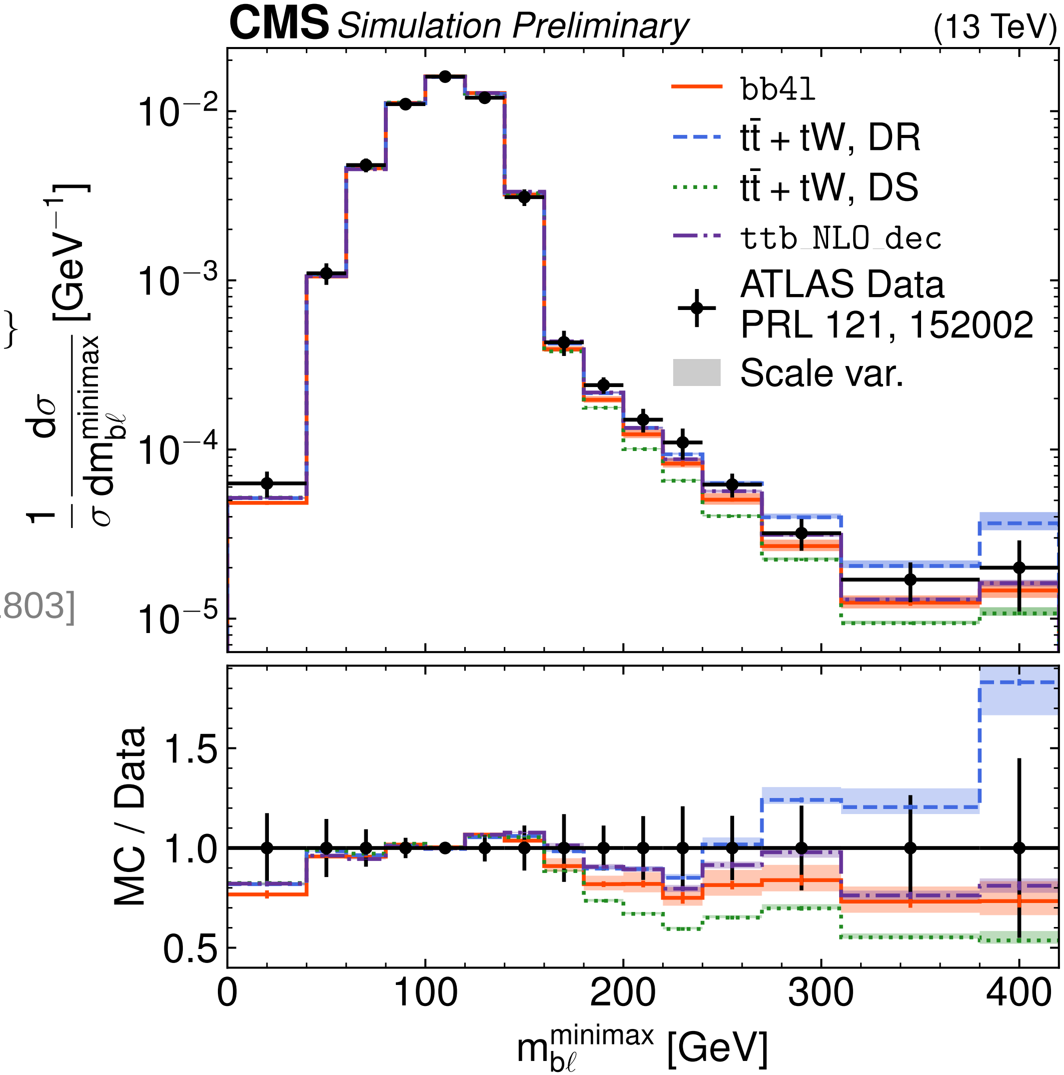
  - Kinematic cutoff at $\sqrt{m_t^2 - m_W^2}$, tail sensitive to tt̄/tW interference
  - Can be used to extract top width

[C. Herwig, T. Ježo, B. Nachmann, PRL 122 (2019), 231803]

- `bb4l` lies between the two interference handling schemes
- Agrees well with ATLAS data

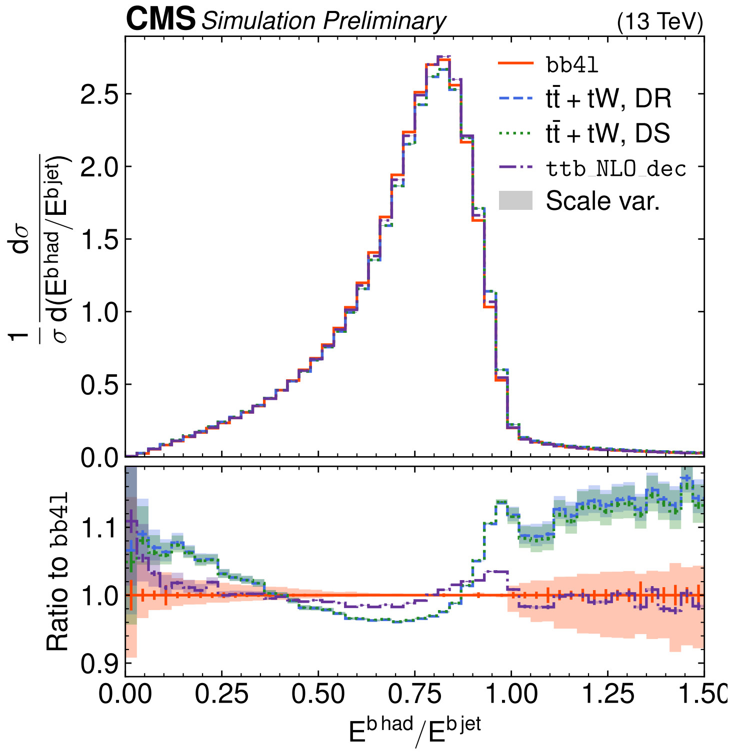
[ATLAS Coll., PRL 121 (2018), 152002]

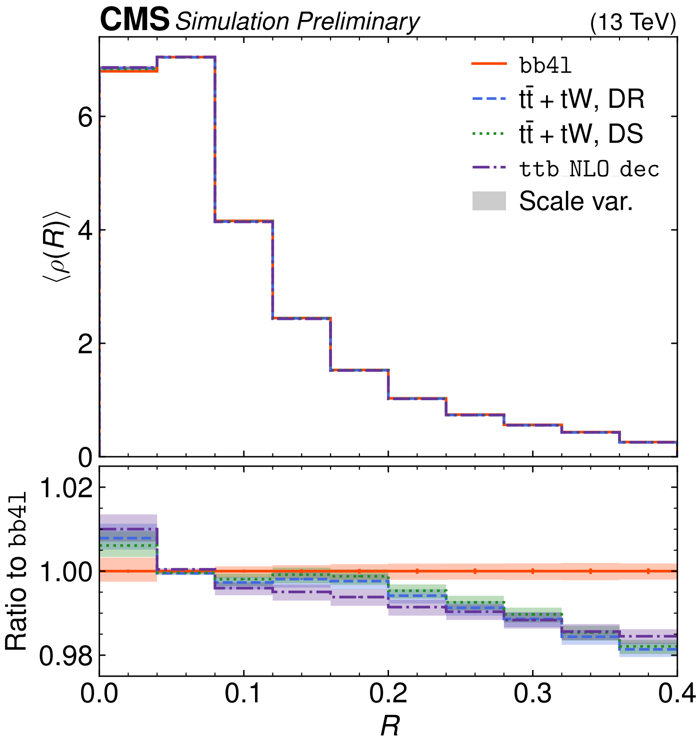
- `ttb_NLO_dec` also close



Results – final state radiation

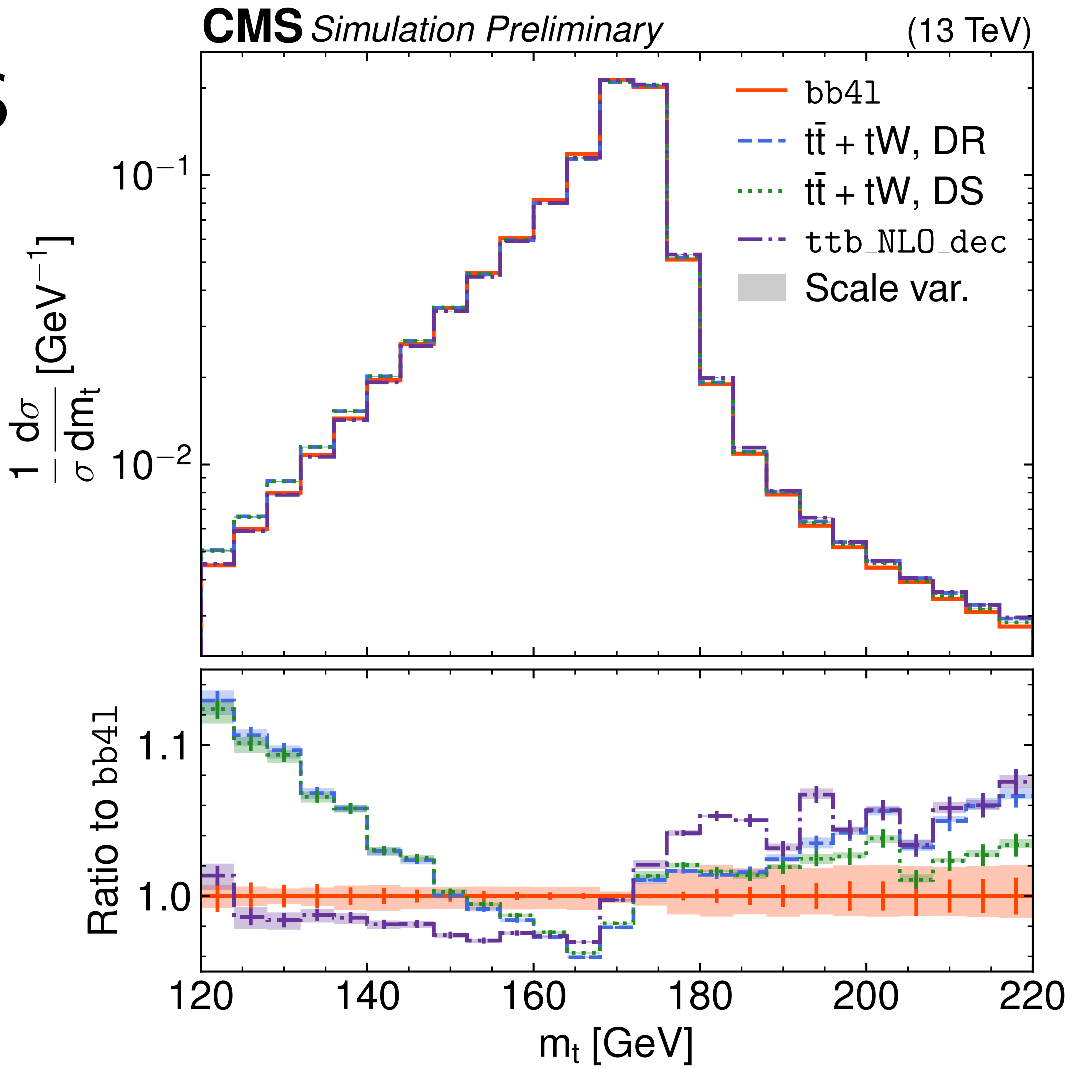
- FSR-sensitive observables: b fragmentation and differential b jet shape
- Both show more FSR / wider jets for `bb4l`



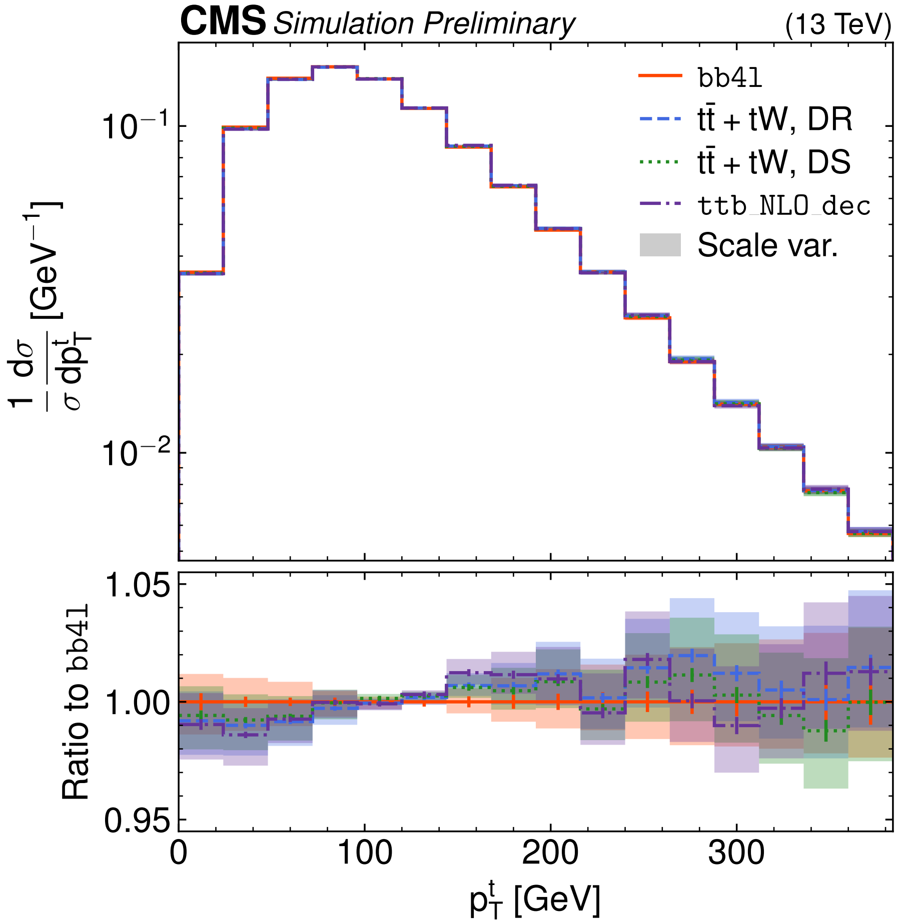


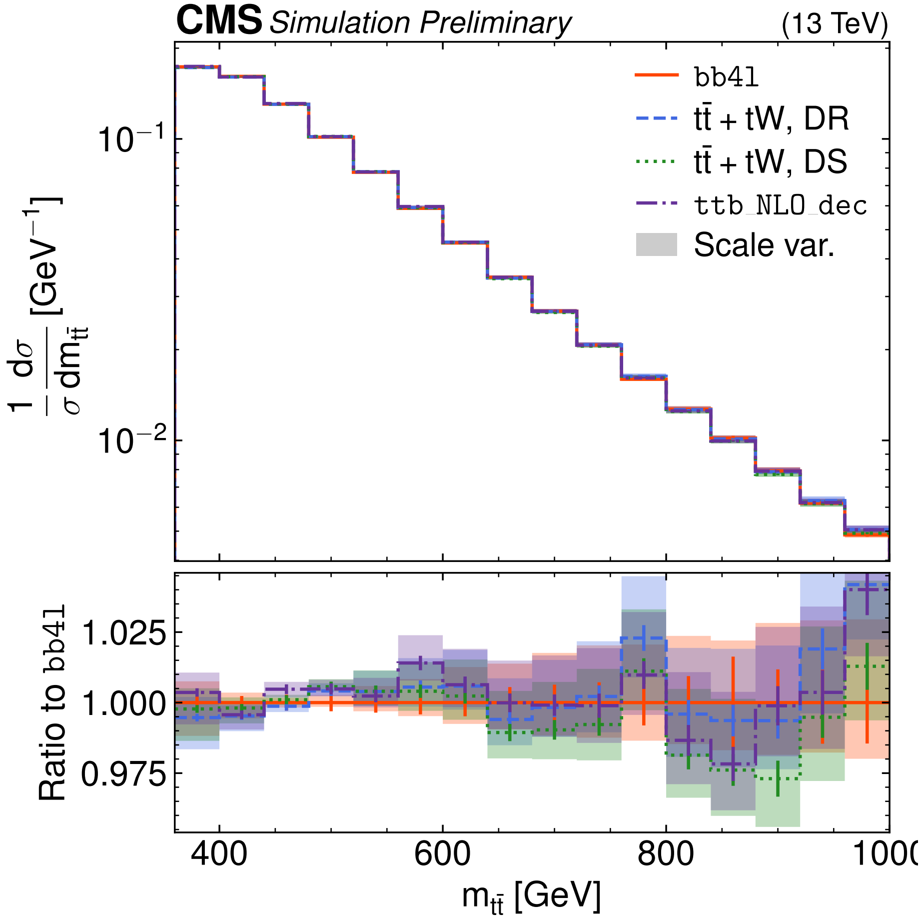
Results – top mass

- Reconstruct generator-level tops
  - Dressed leptons (p_T > 20 GeV) + truth neutrinos → W bosons
  - AK4 b tagged jets (p_T > 30 GeV)
  - Assign b and W by minimal Δm_t
- Shift in top mass for `bb4l` compared to $t\bar{t}$ + tW!
- Also smaller shift for `ttb_NLO_dec`



Results – top p_T and $m_{t\bar{t}}$

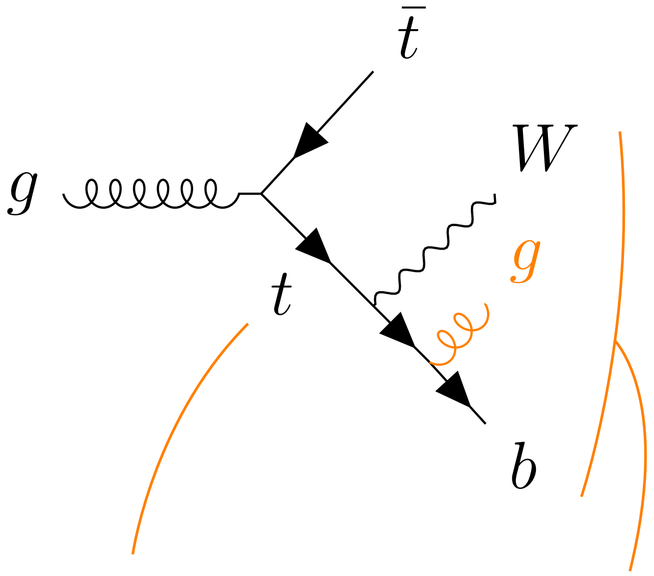




Shower recoil effects

- Problem in parton showers (i.e. Pythia):
  emissions in decays of colored resonances change the resonance mass
  - Can lead to shifts in the observed top mass
  - Recently studied by ATLAS [1]
  - Workaround in newest Pythia (v8.310)
    – but not widely used

- bb4l: first emission from the matrix element
  $\rightarrow$ no recoil issues
  - Issue still present for second emission



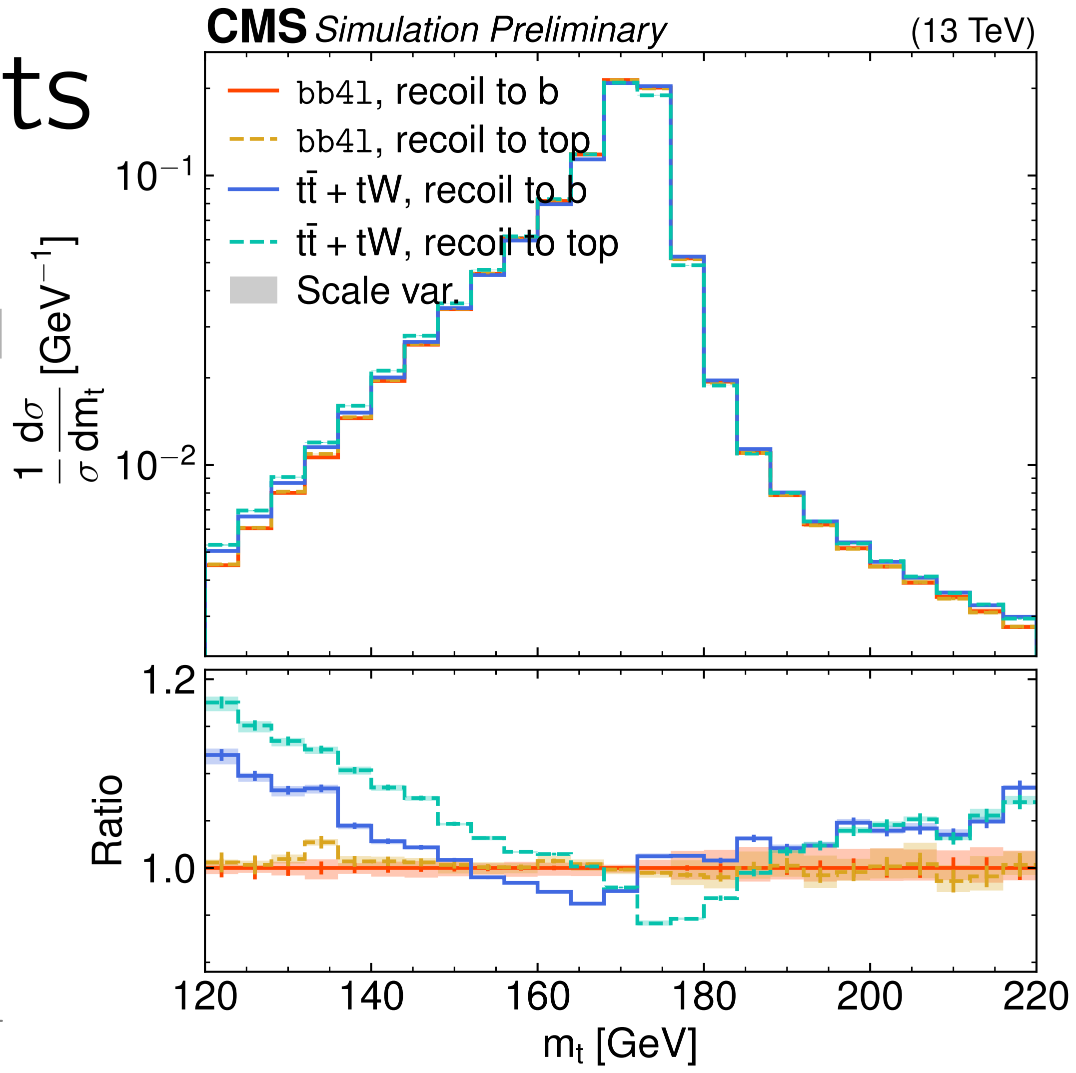
$$p_t^2 \neq (p_W + p_b + p_g)^2$$

before emission   after emission

[1] ATLAS Coll., JHEP 06 (2023) 019

Shower recoil effects

- Compare `bb4l` and tt+tW…
  - without the Pythia workaround [*] (“recoil to b”)
  - with the workaround (“recoil to top”)
- Large shift for $t\bar{t}$+tW
- Almost no shift for `bb4l` (within scale uncertainties)



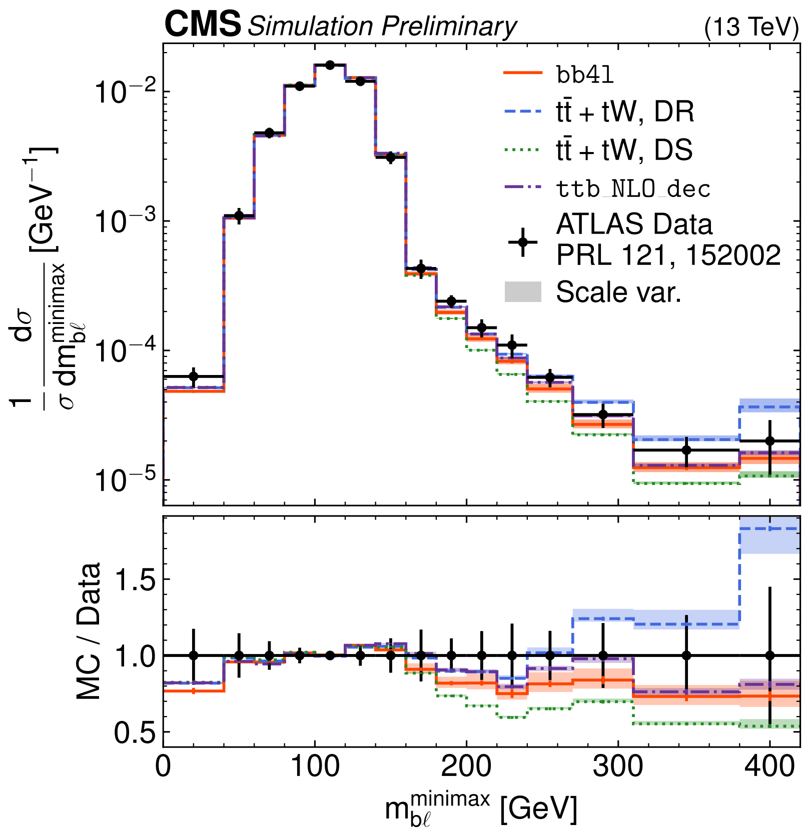
[*] Option `recoilStrategyRF` set to 1 resp. 2 in Pythia 8.310
See `https://pythia.org/latest-manual/TimelikeShowers.html`

Summary

- bb4l generates $t\bar{t}$/tW at full NLO including interference and finite width effects
- Working sample produced in CMS
- Compared to hvq + ST and to ttb_NLO_dec

- Good description of ATLAS data for $m_{b\ell}$
- Shift in top mass compared to hvq
- Not affected by shower recoil

➔ First step towards use of bb4l in future top mass & width measurements!



Backup

Dynamic scale definition

- `bb4l`:
  - For resonance histories containing a top quark (t$\bar{t}$ or tW):

$$\mu_R = \mu_F = \left[\left(m_t^2 + p_{T,t}^2\right)\left(m_{\bar{t}}^2 + p_{T,\bar{t}}^2\right)\right]^{\frac{1}{4}}$$

    (t and $\bar{t}$ are defined in terms of their decay products)
  - For resonance histories containing a neutral boson (Z,ɣ,H):

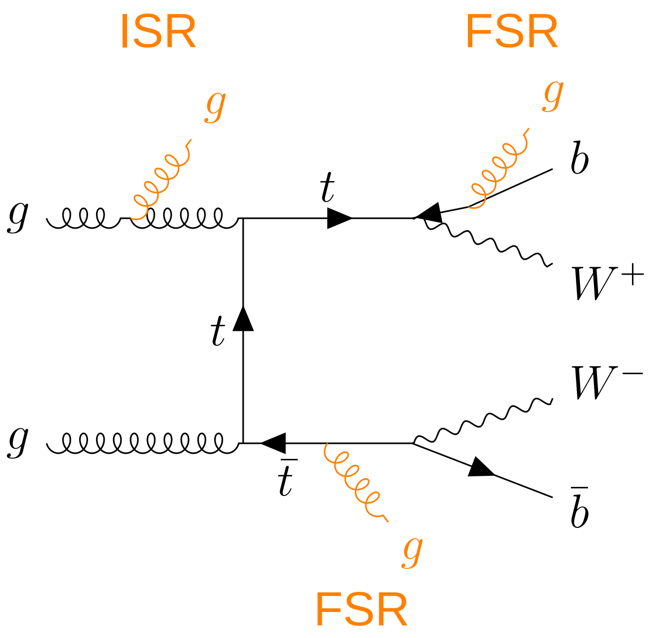
$$\mu_R = \mu_F = \frac{\sqrt{p_Z^2}}{2}$$

- `hvq`, `ST_wtch` and `ttb_NLO_dec`:

$$\mu_R = \mu_F = \sqrt{m_t^2 + p_{T,t}^2} \qquad \text{(at Born level)}$$

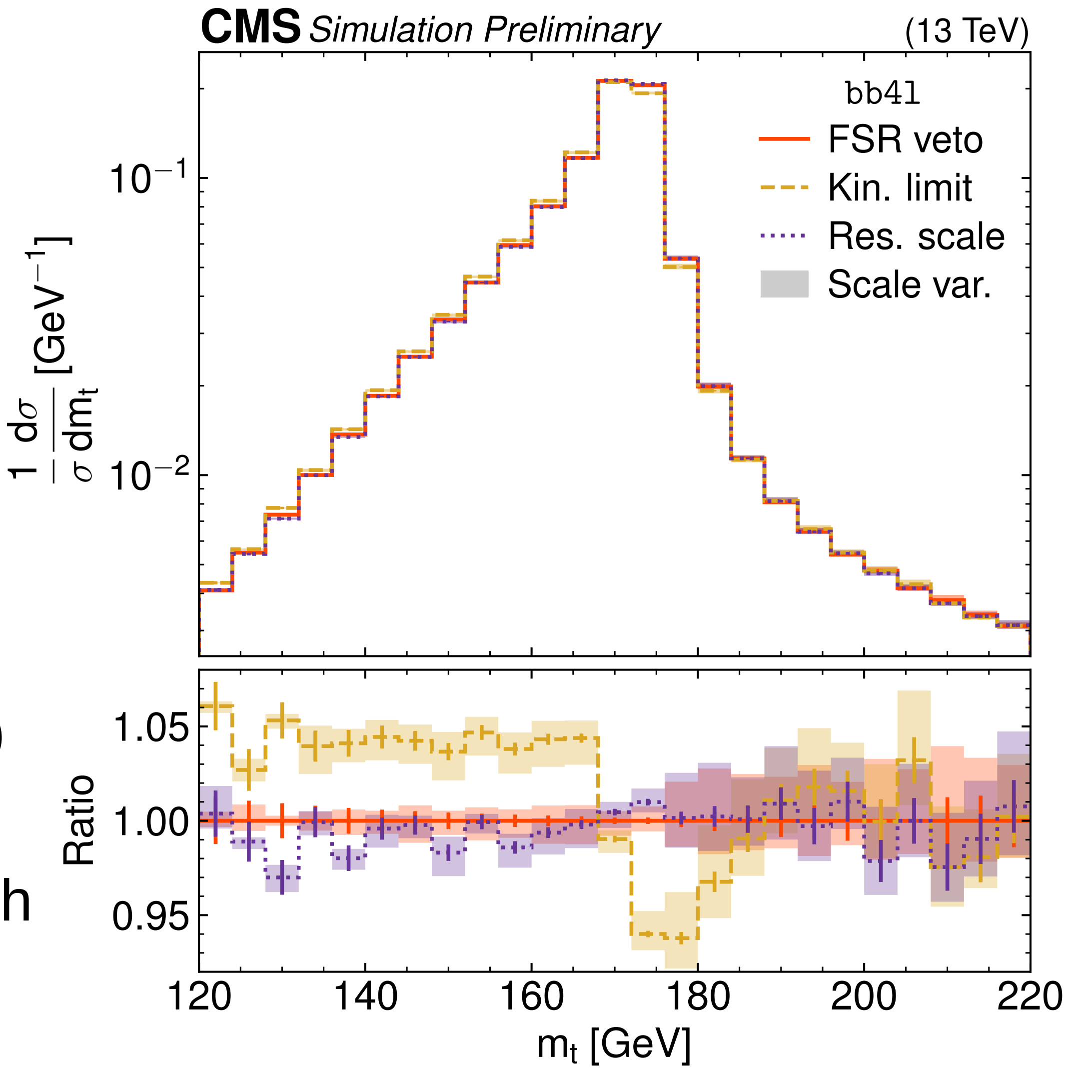
Shower matching

- `bb4l`: up to three real emissions:
  1 ISR + 1 FSR per resonance
- Needs special Pythia veto to prevent double-counting of FSR



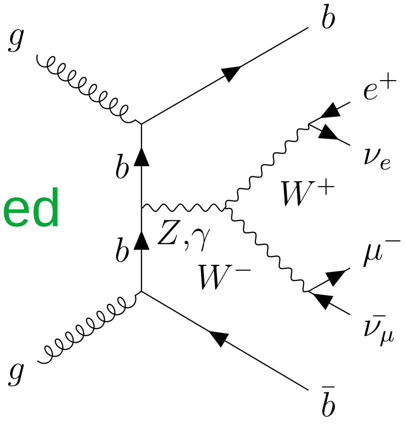
Shower matching

- `bb4l`: up to three real emissions: 1 ISR + 1 FSR per resonance
- Needs special Pythia veto to prevent double-counting of FSR
- Compare FSR veto to starting the shower at the...
  - kinematic limit ("naive" approach)
  - Hardness scale of the resonance
- Large difference to naive approach $\rightarrow$ importance of matching!

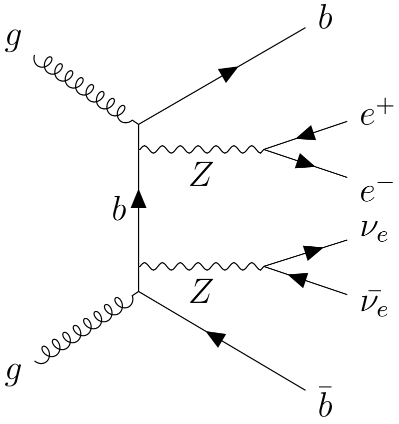


Same-flavor events

- `bb4l` only contains diagrams for opposite-flavor leptons:



included



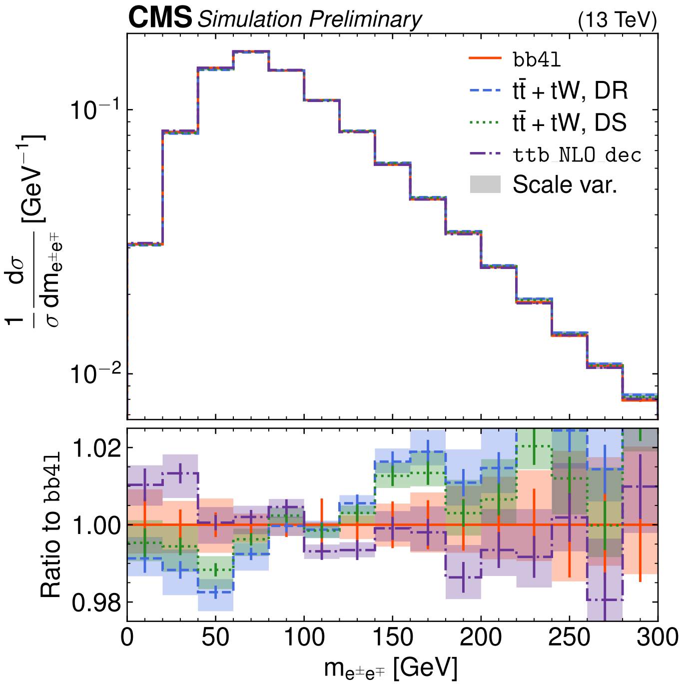
not included
...but negligible for $t\bar{t}$ analysis (with Z veto)

- We extended `bb4l` to same-flavor events, neglecting these diagrams
  - Relabeling of final state particles
  - Can use `bb4l` in all-flavor analyses – used for all plots shown here

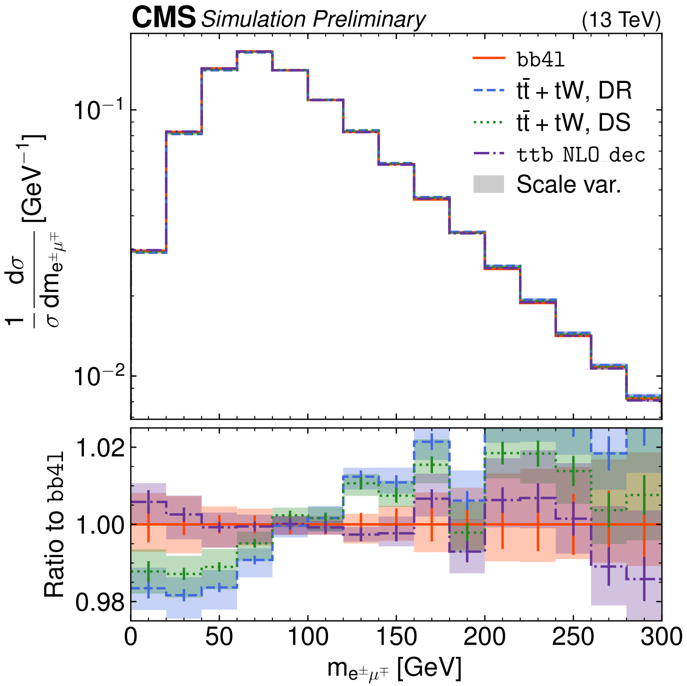
Same-flavor events

Showcase: invariant lepton mass for different flavors

ee



eμ



μμ