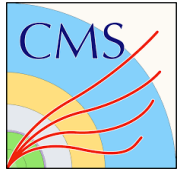
LHCTopWG Open Meeting

Simulation of on- and off-shell $t\bar{t}$ production with bb4l at CMS

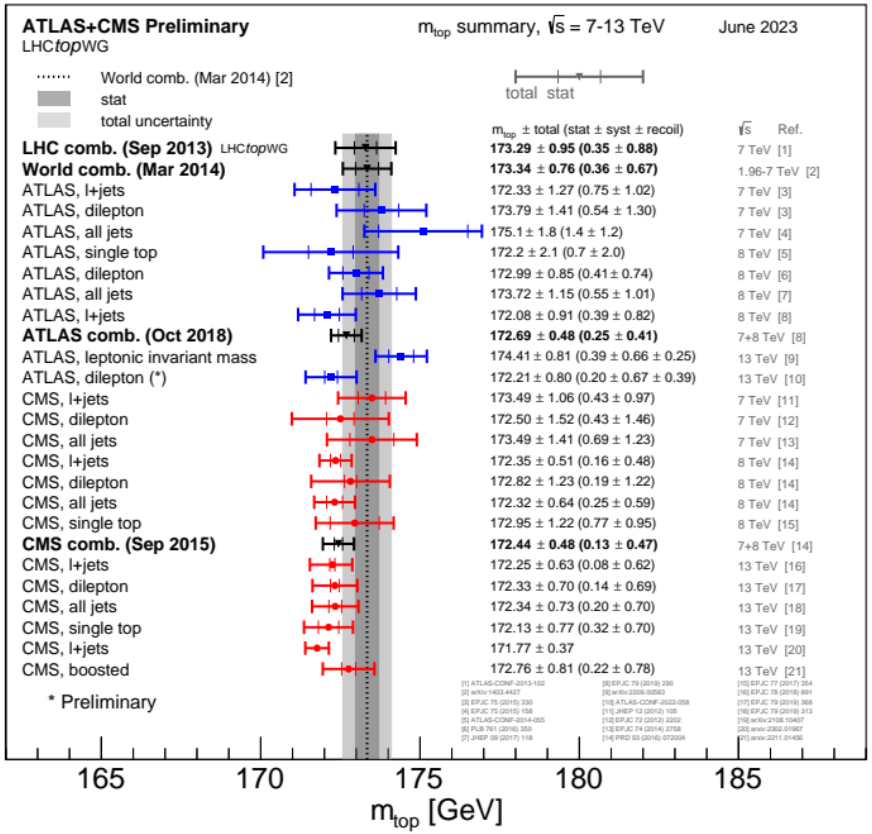
Laurids Jeppe for the CMS collaboration

30.11.2023 | laurids.jeppe@desy.de



Motivation

- Most precise top mass results from direct measurements
  - Fit of MC to data for sensitive observable
  - Requires precise MC prediction
- Subtleties can shift the top mass in MC:
  - Higher orders in QCD/EW
  - Off-shell top effects
  - Interference with tW diagrams
  - Matching to parton shower
  - Renormalization schemes
  - Gluon recoil in FSR etc...



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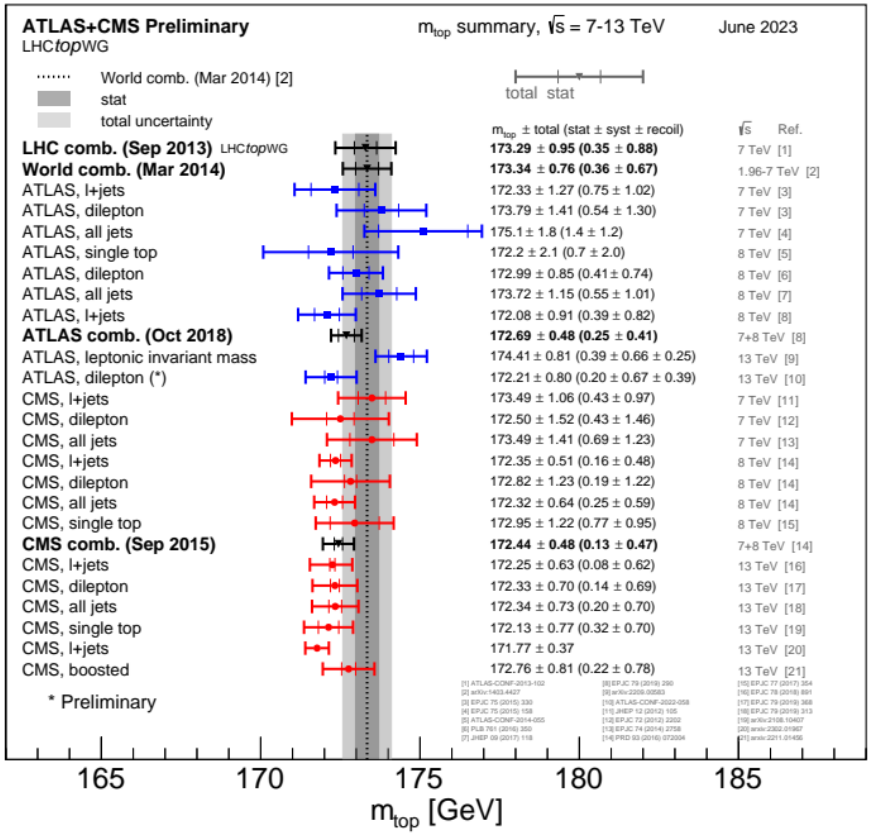
} bb4l

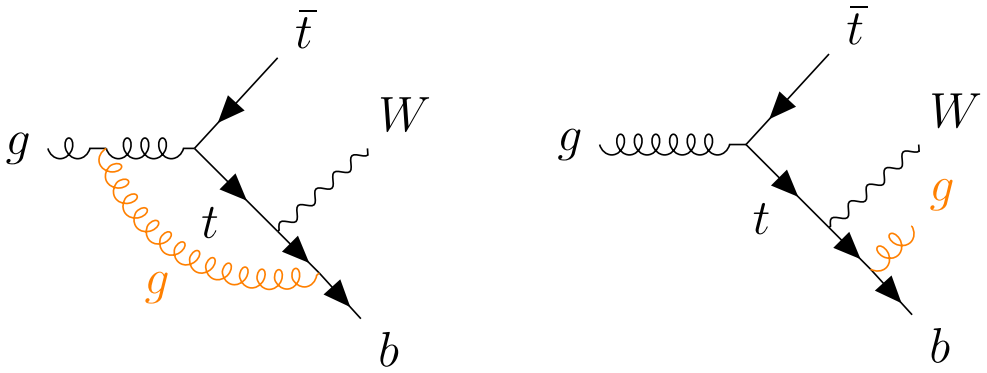


What is bb4l?

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+PS
- Implemented in the Powheg Box RES, matched to Pythia 8

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



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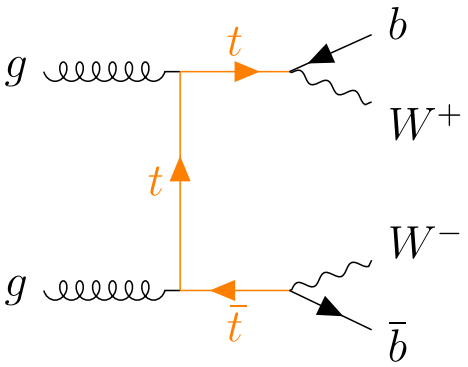
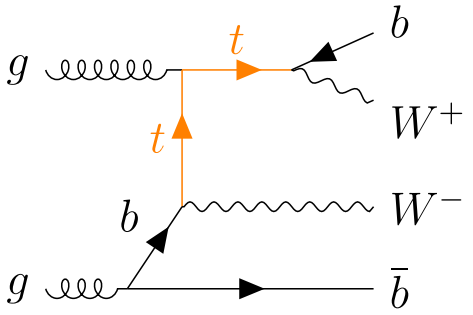
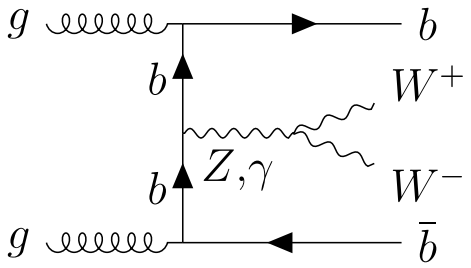
➔ Full description of interference between $t\bar{t}$ and tW







Event generation

- Generated 20M of `bb4l` events
- Matched to Pythia 8 with FSR veto (later)
- 7-point ME scale variations (μ_R and μ_F)

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

Comparison between generators

- `bb4l`: Full NLO for $t\bar{t}$ + tW + interference including decays
- `hvq` ($t\bar{t}$) and `ST_wtch` (tW):
  - 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:
    diagram removal (DR) or diagram subtraction (DS)

S. Frixione, P. Nason, G. Ridolfi, JHEP 09 (2007) 126
E. Re, EPJC 71 (2011) 1547

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

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

- See also studies by bb4l authors and ATLAS

ATL-PHYS-PUB-2021-042
S. Ferrario Ravasio et al, EPJC 78 (2018) 458

Results – $m_{b\ell}$

- Invariant b-ℓ mass, chosen as

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

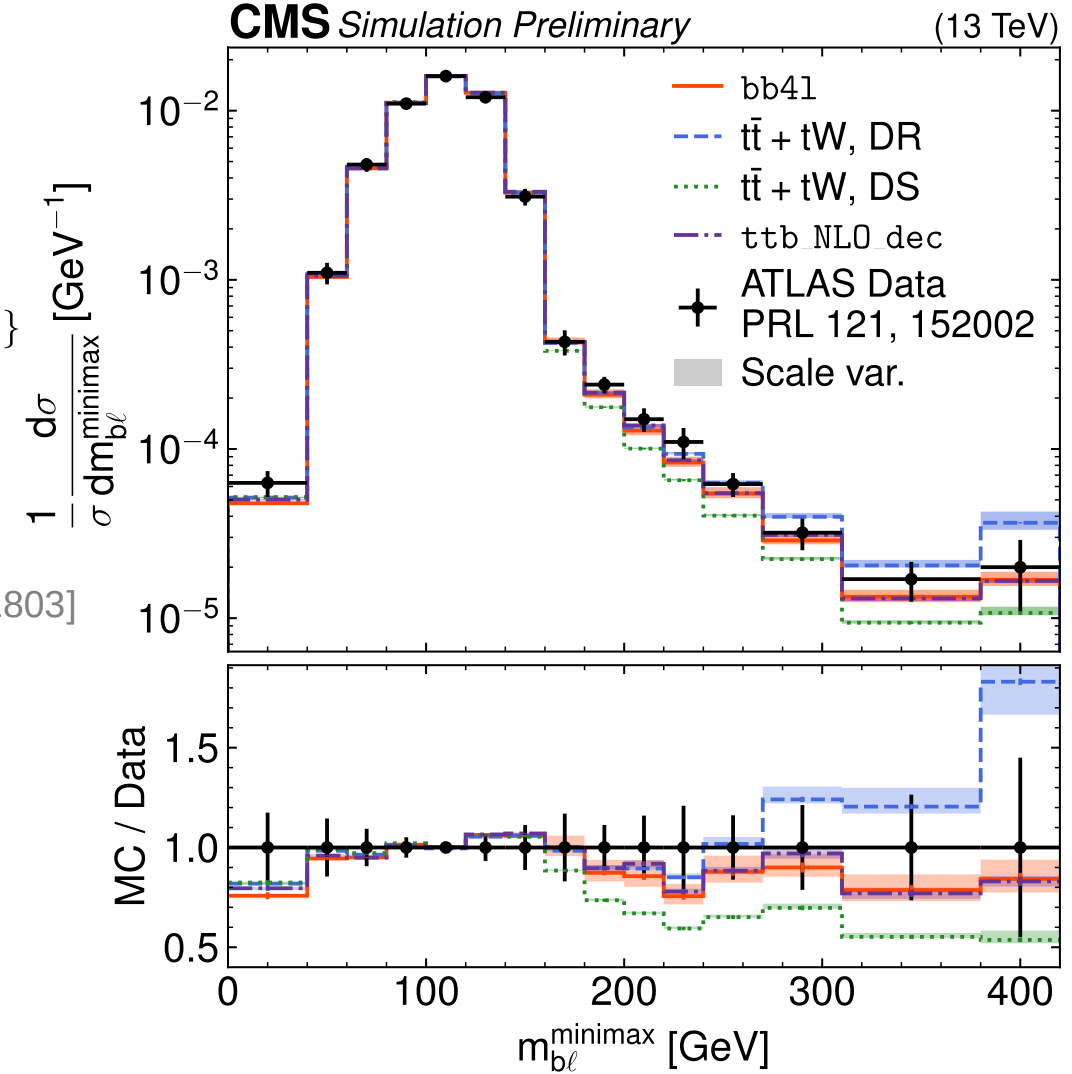
  - Kinematic cutoff at $\sqrt{m_t^2 - m_W^2}$, tail sensitive to tt̄/tW interference
  - Can be used to extract top width

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

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

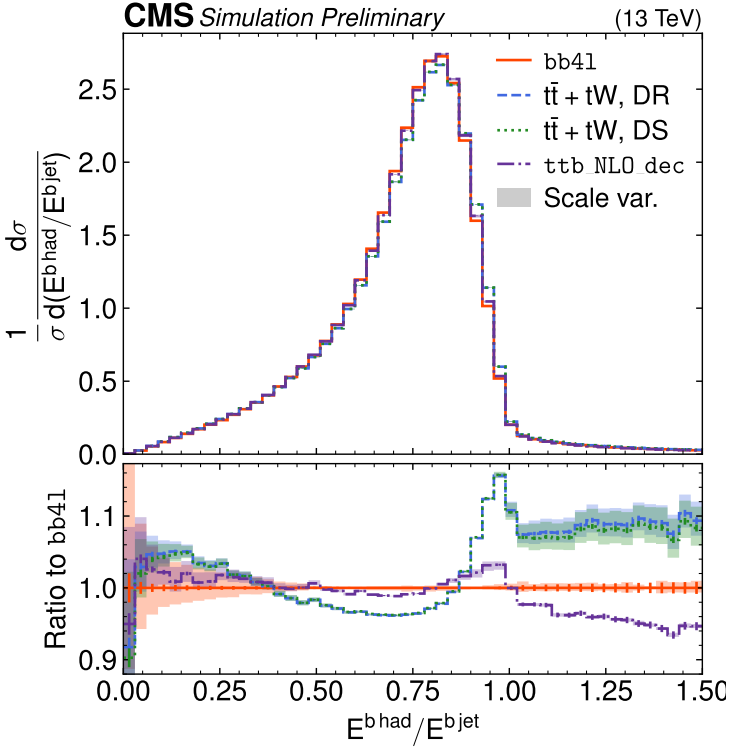
[ATLAS Coll., PRL 121 (2018), 152002]

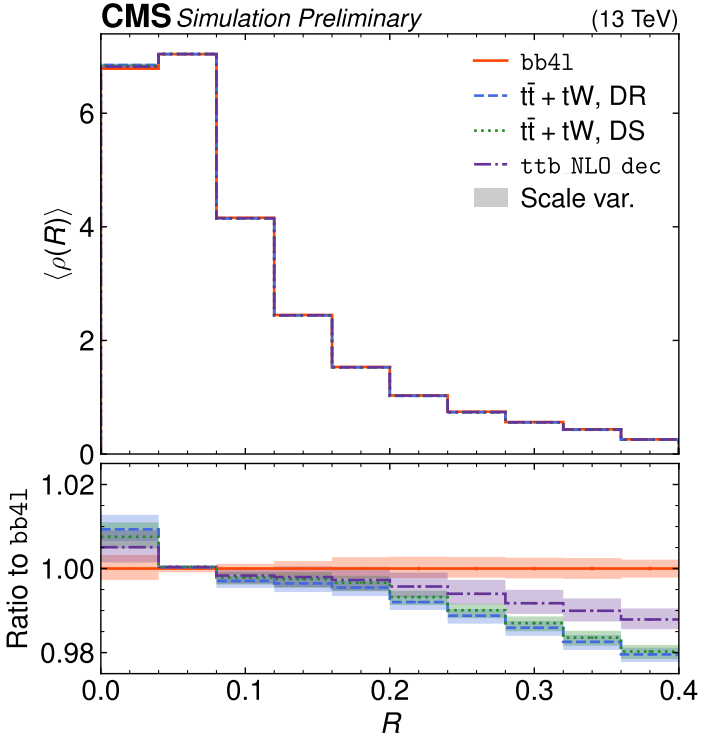
- ttb_NLO_dec also agrees



Results – FSR

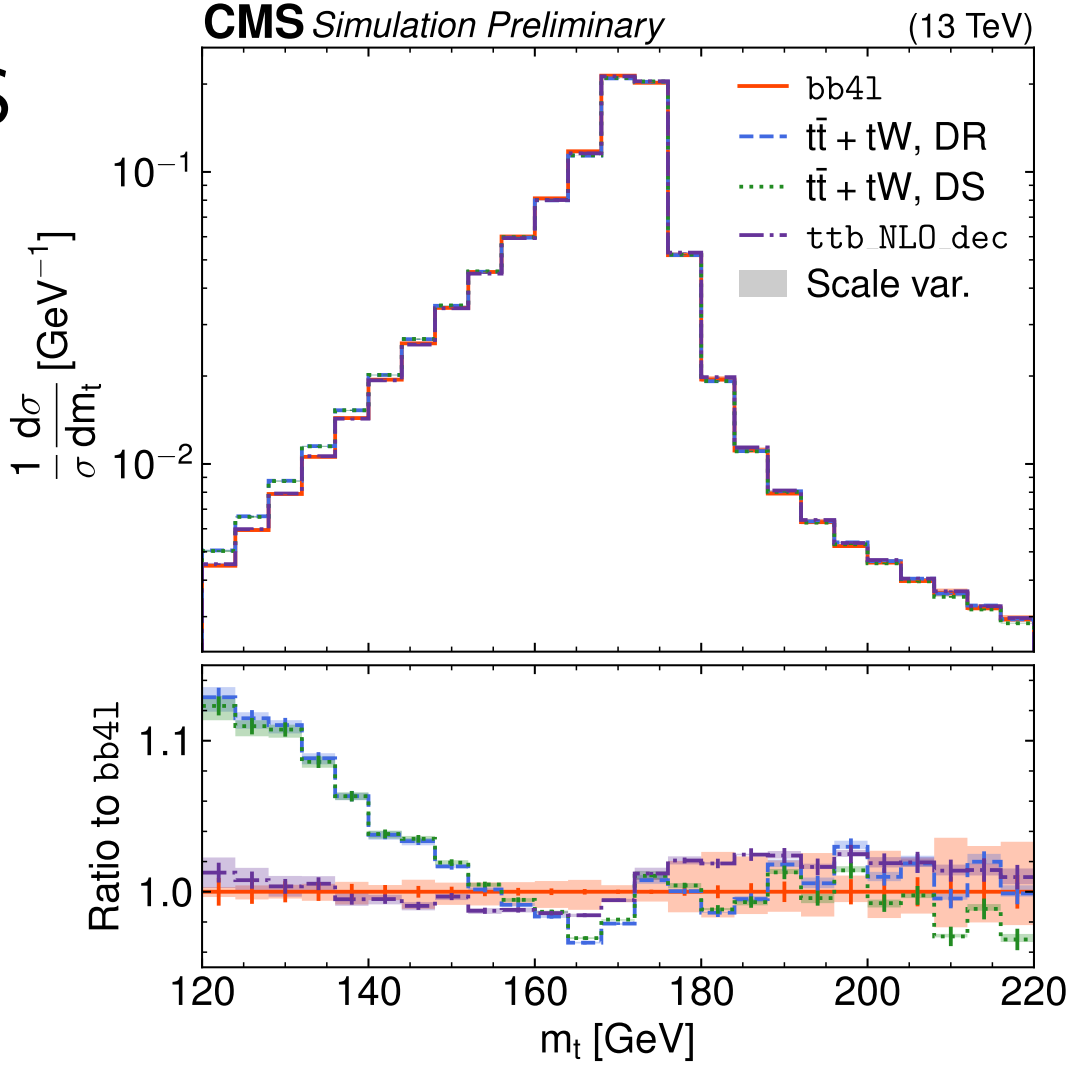
- FSR-sensitive observables: b fragmentation and differential b jet shape
- Both show more FSR / wider jets for bb4l



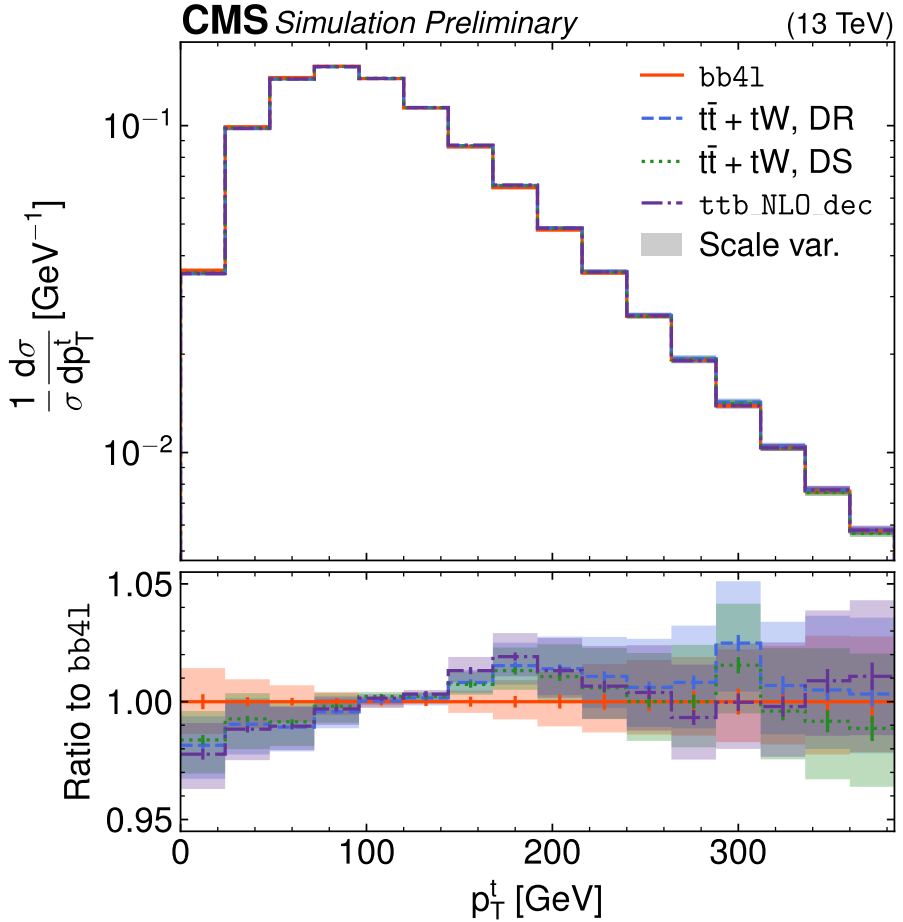


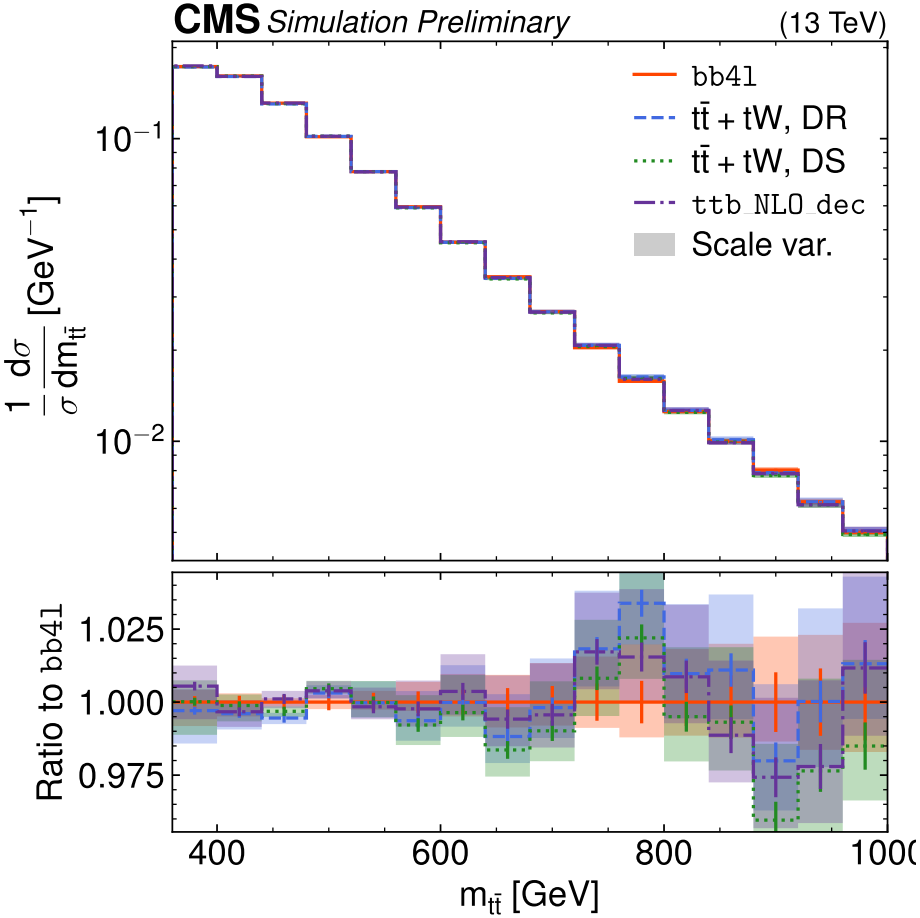
Results – top mass

- Reconstruct GEN-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 $m_{t\bar{t}}$

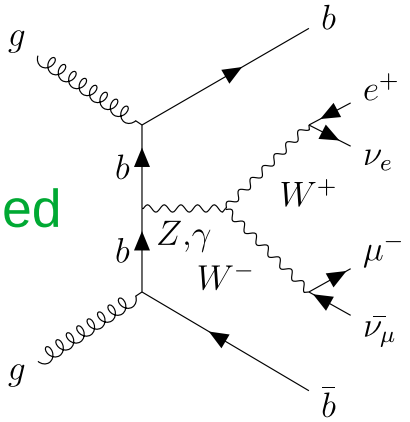


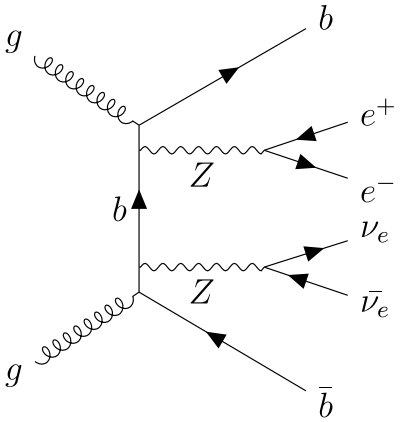


Same-flavor events

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

included





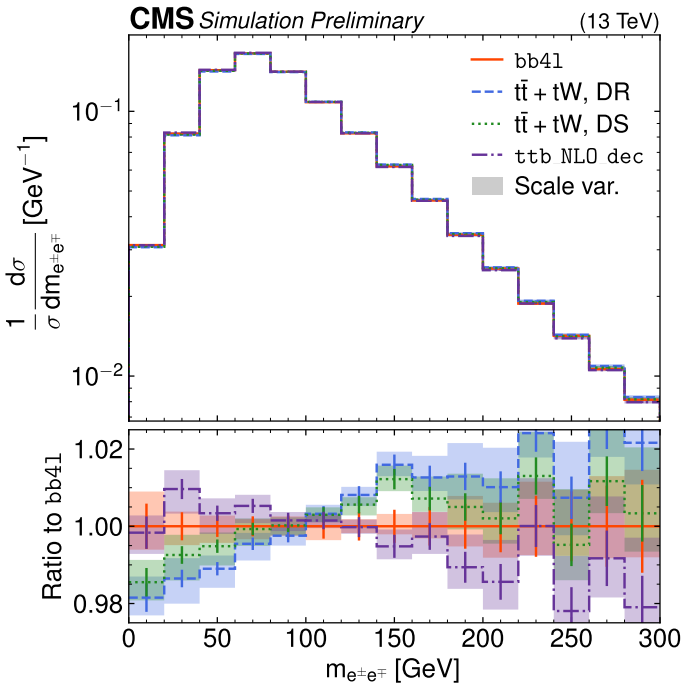
not included
...but negligible for $t\bar{t}$ analysis
(with Z veto)

- 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

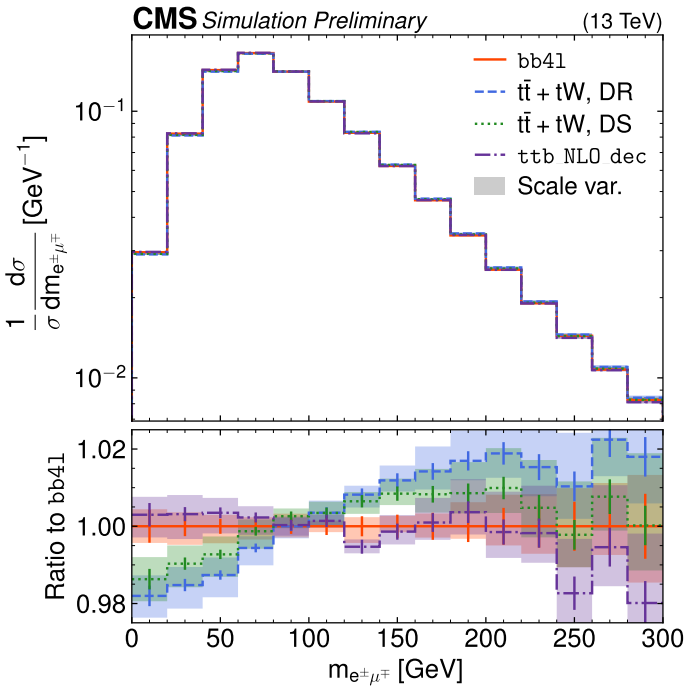
Same-flavor events

Showcase: invariant lepton mass for different flavors

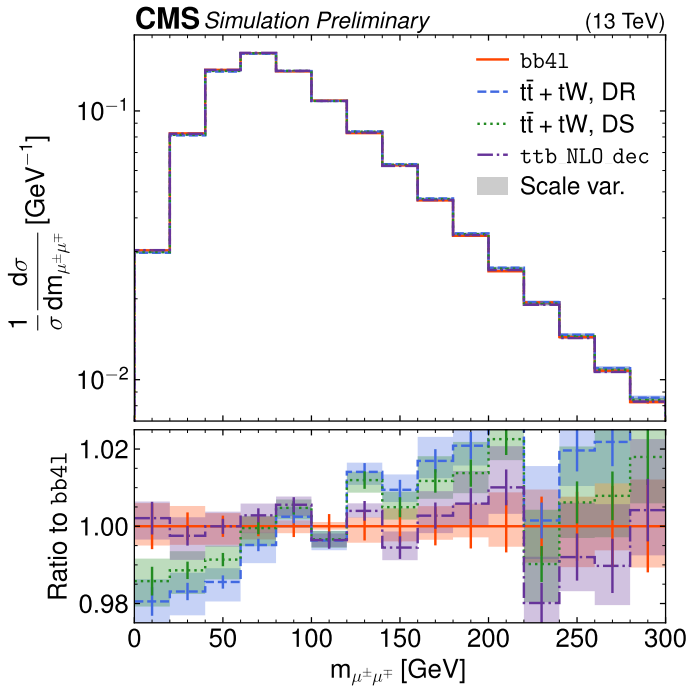
ee



eμ

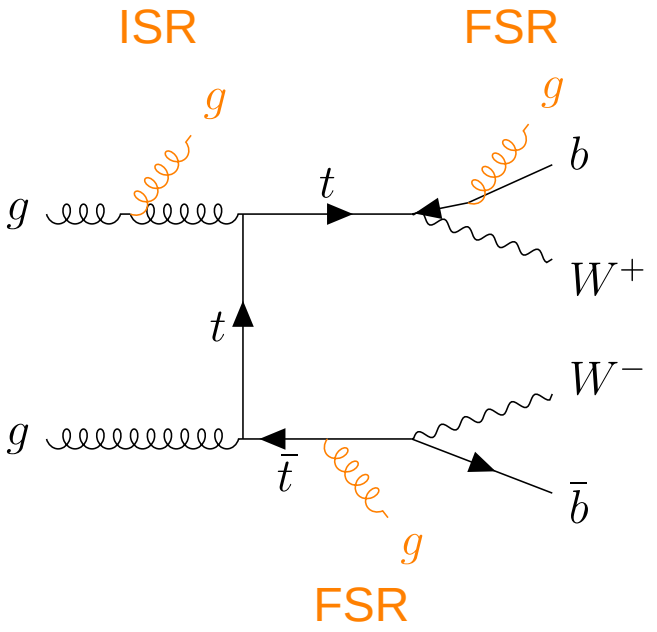


μμ



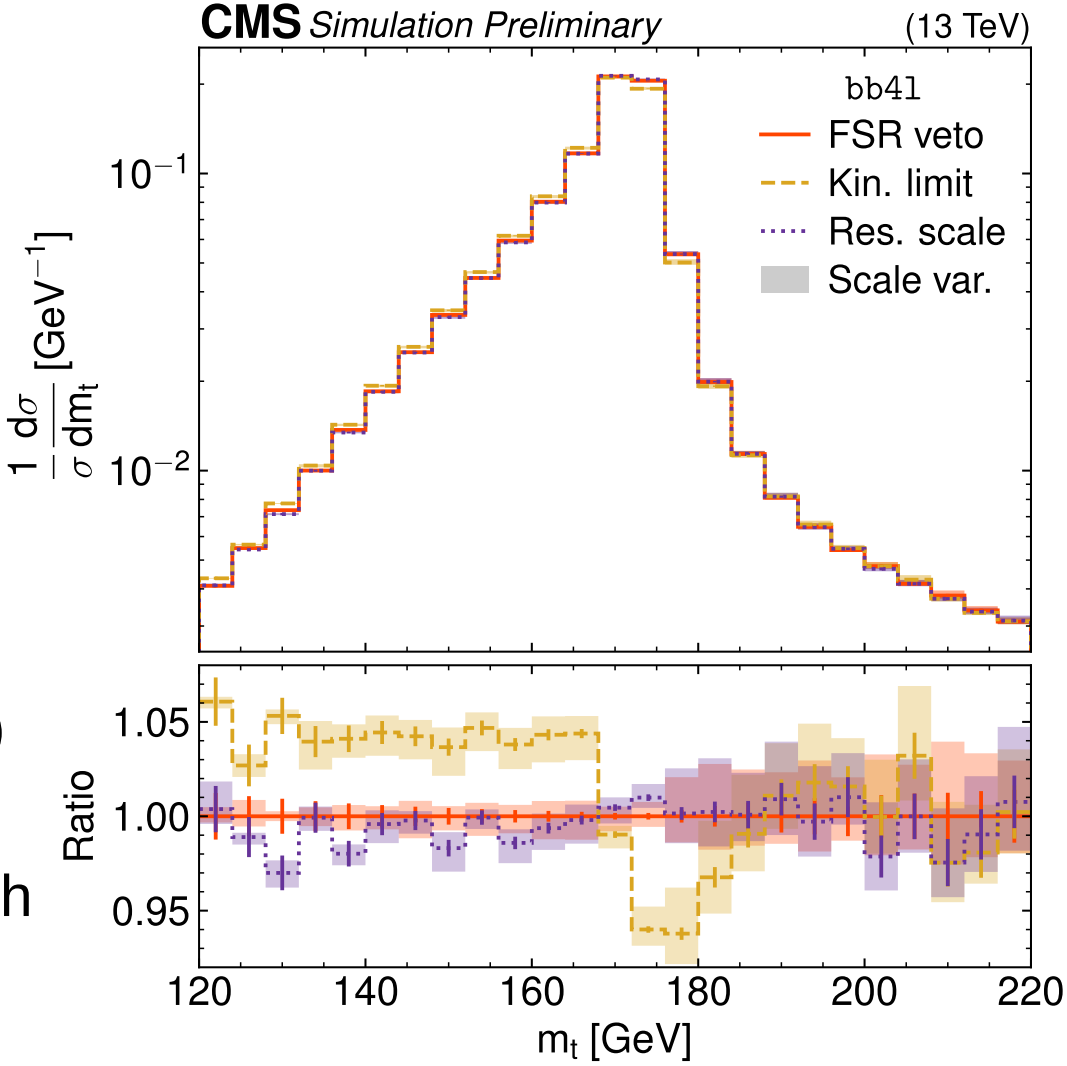
Shower matching

- `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 → importance of matching!

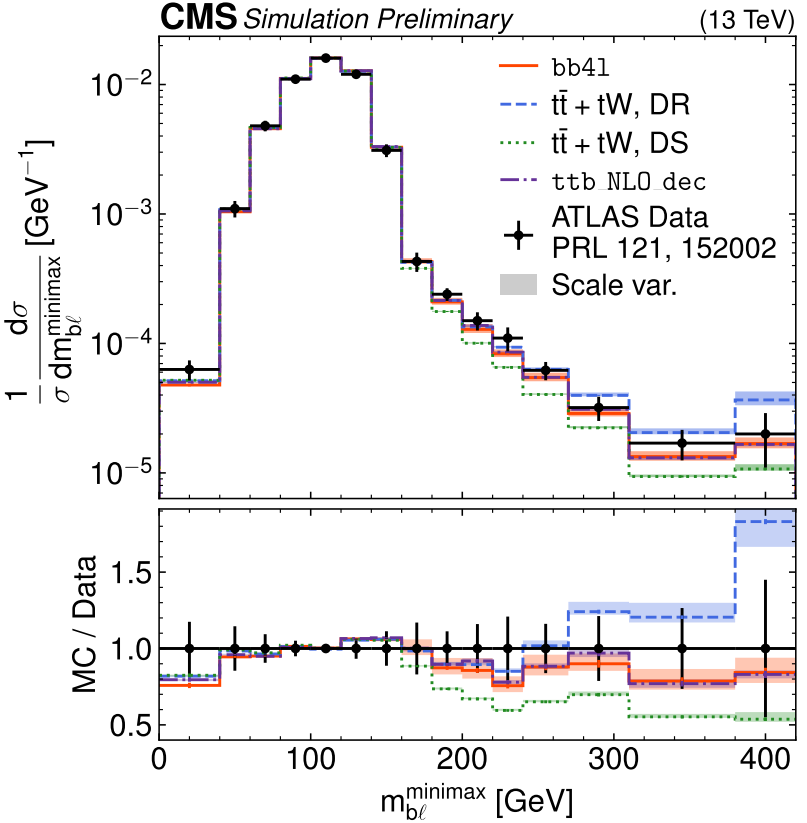


Summary

- bb4l generates $t\bar{t}$/tW at full NLO including finite width and interference
- 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

- Extension to same-flavor events
- Studied importance of shower veto



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`:

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