Simultaneous measurement of top quark mass and width with bb4l at CMS

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Workshop on top quark mass measurements, Valencia

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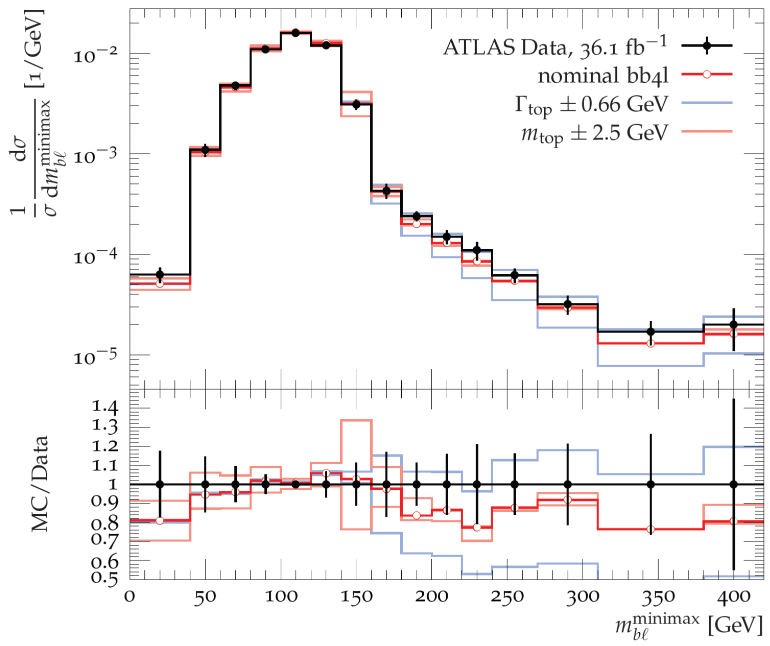
Introduction

Simultaneous extraction of top mass and width with Run 2 dataset

Why we measure top quark width?

- Poor experimental result from direct measurements: 1.9 $\pm$ 0.5 GeV (ATLAS)
- Sensitivity is highly restricted by theoretical uncertainties on $t\bar{t}$ and tW interference treatment
- bb4l generators resolves the interference problem, providing improved sensitivity to decay width

PoS(EPS-HEP2023)313



Top quark mass revisited

- Top quark mass is measured in single top or $t\bar{t}$ events
  - One of such processes has been treated as a background
- bb4l generator gives consistent picture of dominant top quark processes

Mass and width extraction from the fit on

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

Samples and object selections

Data samples

- CMS Run 2 dilepton and single lepton datasets

Simulated samples

- bb4l-dl
  - 9 × ($e\mu$ channel NLO cross section) = 9.653 * 9 = 86.877 pb (Tab. 4 of the bb4l paper)
  - $t\bar{t}$ hvq (l+jets, all jets)
  - Single top (s, t-channel)
  - DY (NLO), W+jets (NLO)
  - $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, VV

Triggers

- Dilepton + single lepton triggers

Object selections

- Leptons
  - Muon: Cut-based ID tight WP, $Iso_{rel} < 0.15$
  - Electron: MVA ID wp80, Ecal gap veto
  - p_T > 25 (20) GeV, $|\eta|$ < 2.4
- Dilepton pair: OS leptons, m_{ll} > 20 GeV
  - Use two leptons with highest p_T
  - ee, $\mu\mu$ (SF) channel: veto 76 < m_{ll} < 106 GeV
- MET: p_T^{miss} > 40 GeV for ee, $\mu\mu$ channel
- Jets: AK4Puppi, p_T > 30 GeV, $|\eta|$ < 2.4
  - b-tagging: DeepJet Medium WP
  - Jets are cleaned with respect to the selected leptons

Relevant PU, trigger, lepton, and jet corrections applied

Data / MC comparisons

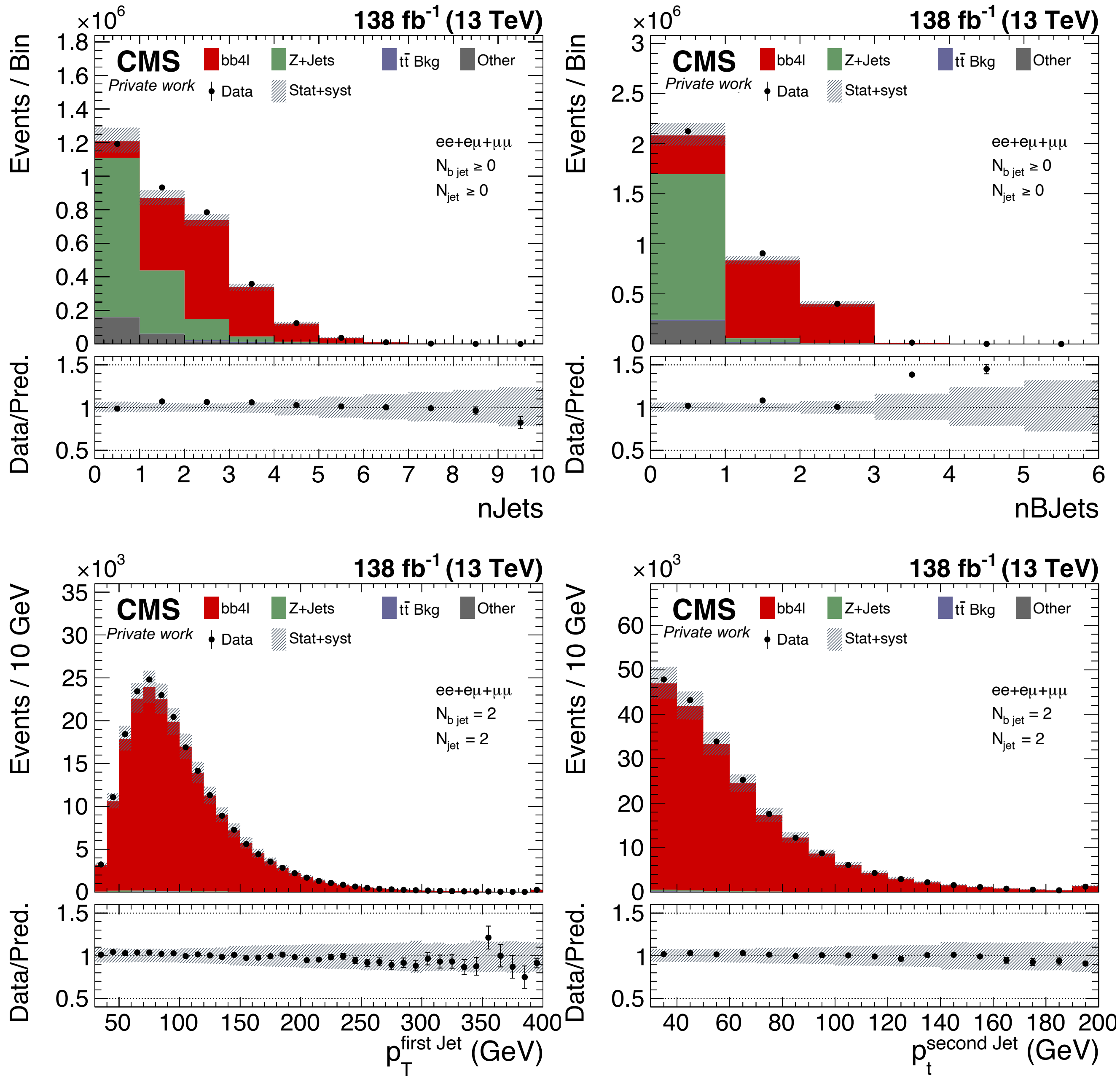
Jets

Jet multiplicities

- CMS uses pTdef = 1 for bb4l
- Good agreement up to 2 b-jets

Jet p_T

- Very good agreement



Data / MC comparisons

Leptons and other distributions

Lepton p_T

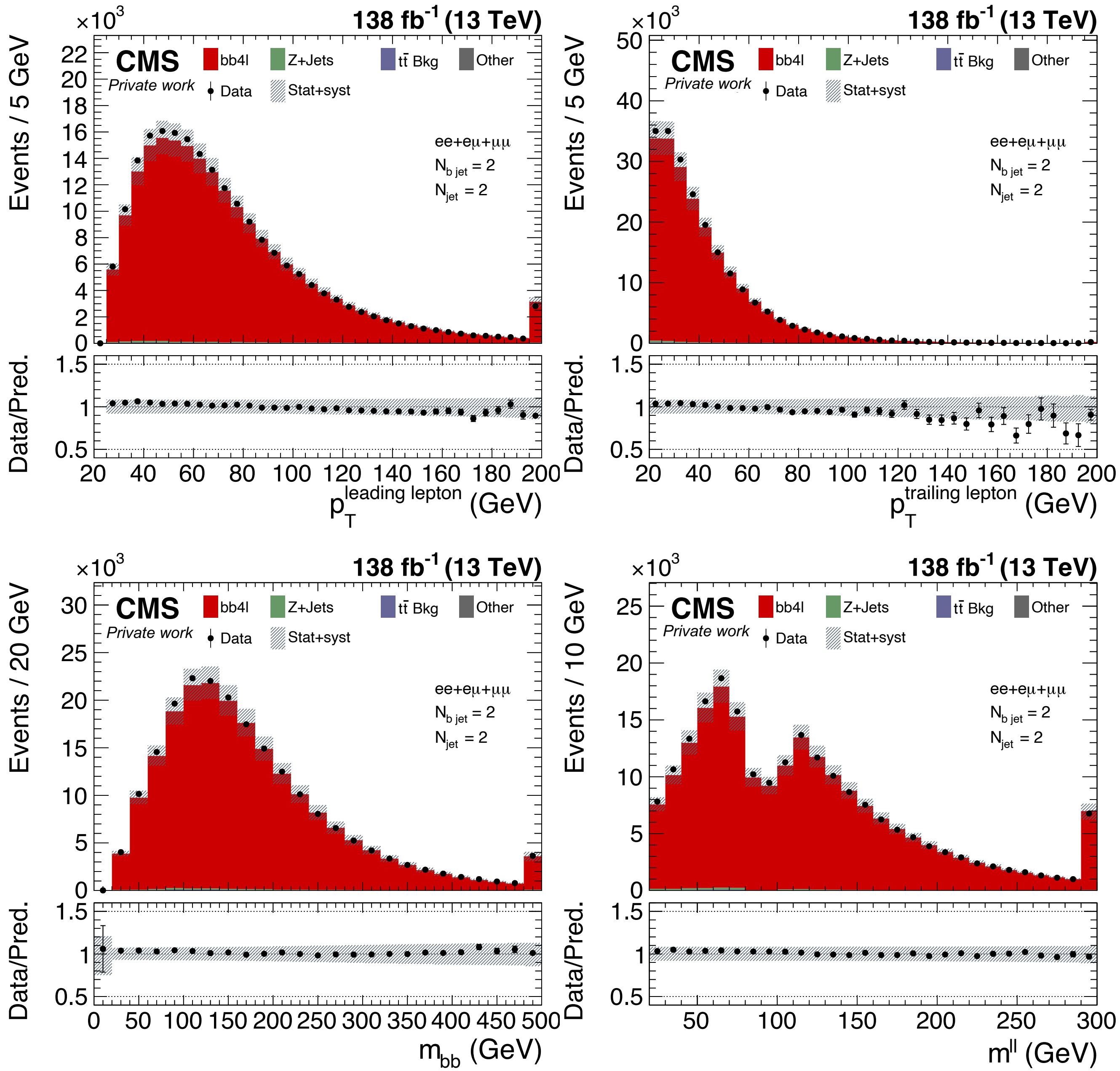
- Agree well with mild slope

m_{bb} and m_{ll}

- Very good agreement

bb4l-dl describes data very well in 2 jet & 2 b-jet selection

- $t\bar{t}$+tW consists over 99% of MC events



Observable: m_{lb}^{minimax}

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

- Data is blinded
- Uncertainty band includes all available modeling and experimental uncertainties except for m_t^{mc} and Γ_t

- Top quark width 30% variation is drawn
  - Up: 1.73 GeV / Down: 0.93 GeV
  - Currently, only small samples available for 2018

Systematic uncertainties

Experimental uncertainties

- Pileup, luminosity
- Lepton efficiencies and momentum corrections
- Unclustered energy (MET)
- JES and JER
- b-tagging
- L1 Prefiring for 2016-2017

Background normalization

- tt background: +4.2 -4.84%
- DY: 30%
- Other: 30%
- Limited statistics: Barlow-Beeston-lite approach

Modeling uncertainties

- Missing higher order (μ_F and μ_R)
- PS scale (kernel splitting ISR and FSR)
- ME-PS matching (h_{damp}): $t\bar{t}$ only, DCTR method
  - For bb4l, applied to the events with two top quarks
- B fragmentation: tt only, DCTR method
- NNPDF31 PDF α_S + 100 eigenvectors
- top quark mass: $\pm$ 3 GeV variation scaled by 1/3
- top quark width: $\pm$ 30% (1.73 / 0.93 GeV)

All recommended correlations across the years are considered

Missing sources

- To be discussed in the later part of the talk

DCTR method for systematic variations

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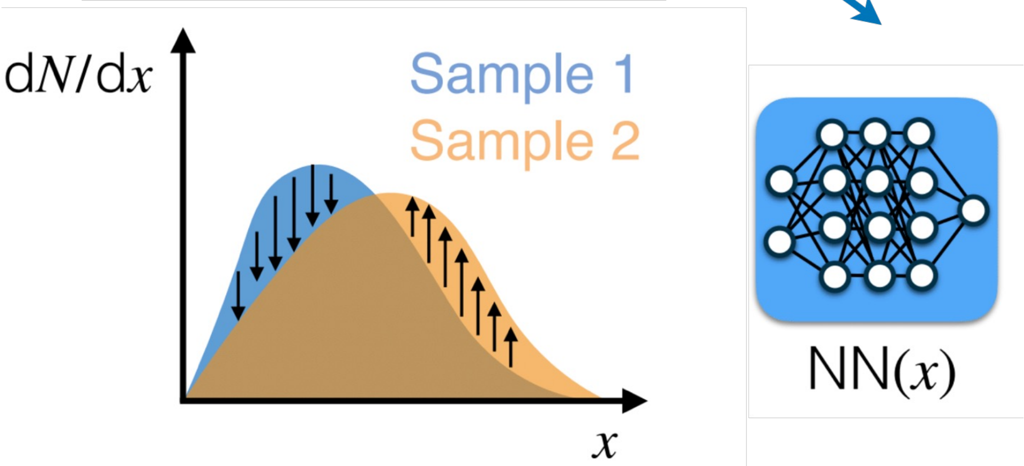
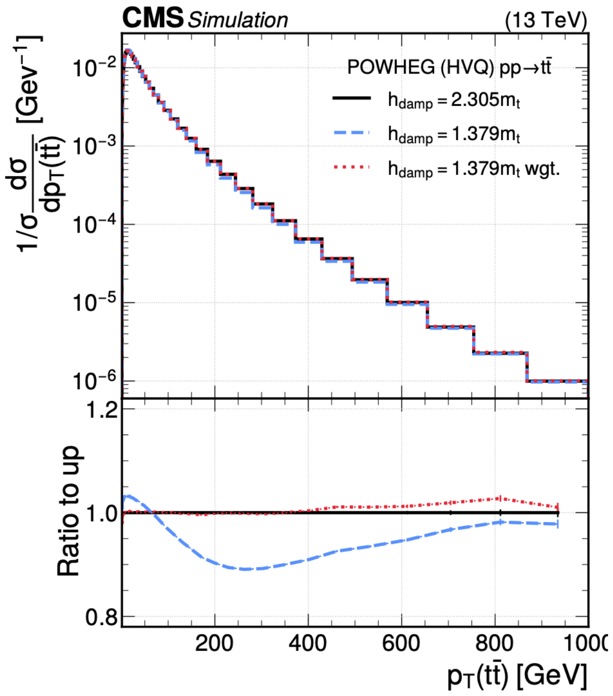
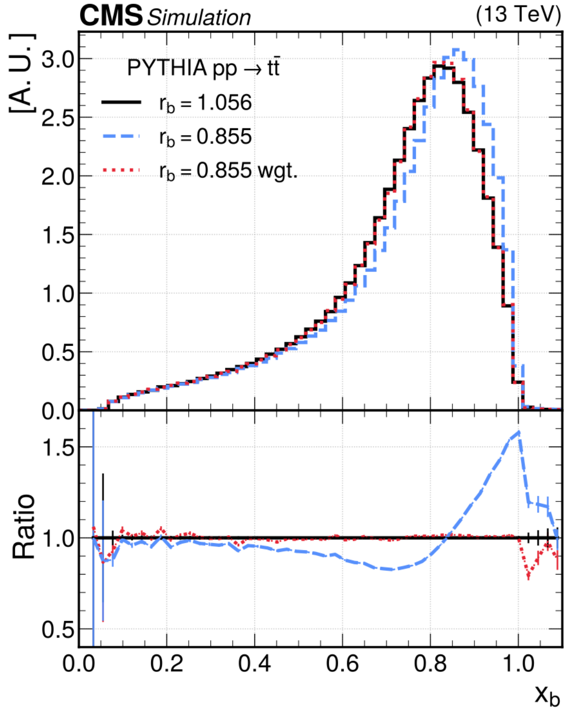
- MC modelling uncertainties limiting factor of most analyses, especially in Top Physics
- Many MC samples to take into account systematic uncertainties at high computational cost
  → Reweighting

$$dN/dx \mapsto w(x) \times dN/dx$$







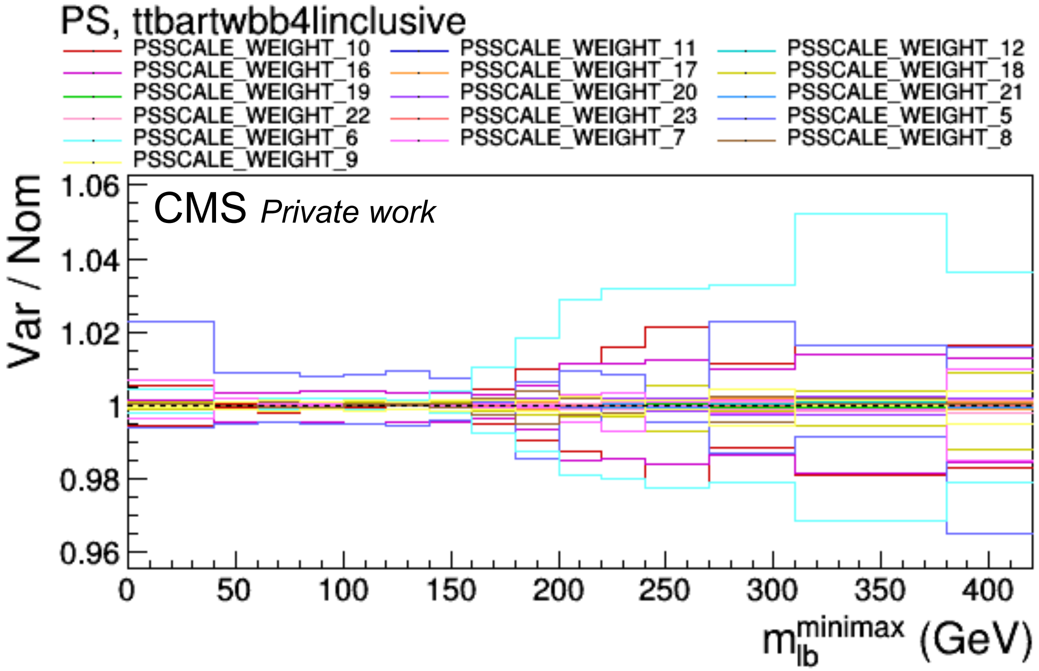
- ML to learn dependence on MC parameters by considering **event particle 4-vectors**
- **Used here for hdamp and b fragmentation**

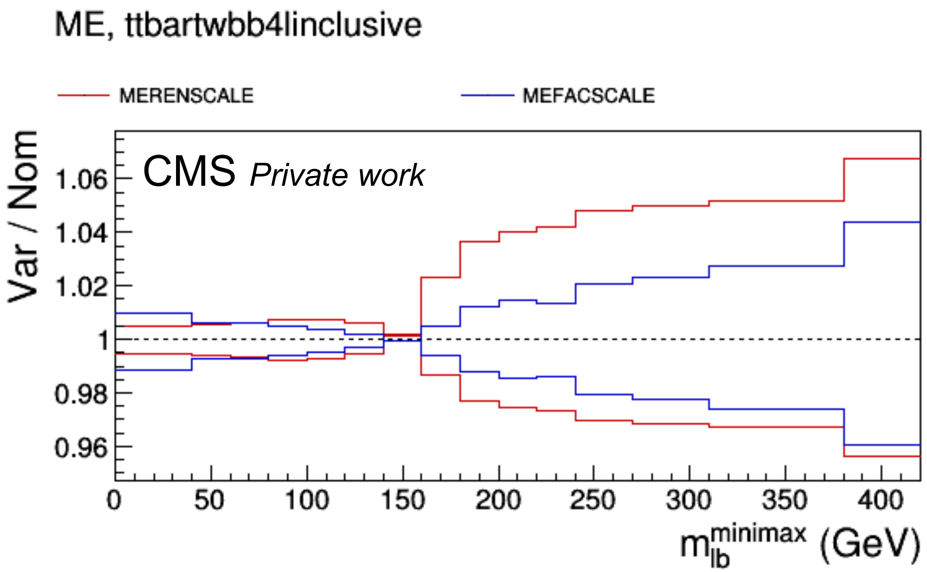
- h_{damp} reweighted in Powheg hvq at parton level (we are retraining with bb4l)
- B-fragmentation (rb) reweighted in Pythia at particle level

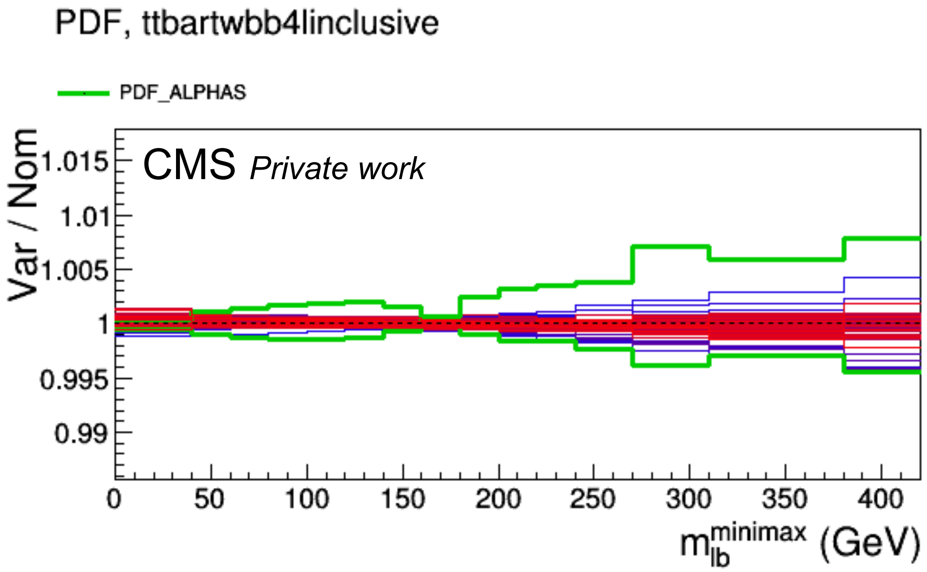
Systematic uncertainties in detector level

ME scales, PS scales, and PDF

- PS indices
  - 5 – 8: FSR muFrac, g2gg / g2qq / q2qg / **x2xg** (x = t, b)
  - 9-12: FSR cNS, g2gg / g2qq / q2qg / x2xg (x = t, b)
  - 16-19: ISR muFrac, g2gg / g2qq / q2qg / x2xg (x = t, b)
  - 20-23: ISR cNS, g2gg / g2qq / q2qg / x2xg (x = t, b)







Mass and width extraction + impacts and pulls

Run 2 combined fit with Asimov data

Perform Run 2 simultaneous binned maximum likelihood with to $m_{lb}^{\mathrm{minimax}}$

- Mass and width are included in the fit as unconstrained parameters
- Overall normalization of bb4l sample is modified by $\hat{r}$

Modeling unc. from DCTR are top-ranked

- Mostly dominated by experimental sources

Modeling uncertainties for bb4l

List of uncertainties

Powheg hard process

- μ_R and μ_F scale variation
- PDF uncertainties
- h_{damp}
- α_S in bb4l for Powheg Sudakov

Powheg-Pythia8 matching

- p_T^{hard} variation
- bb4l: scale resonance veto

Pythia8 parton shower

- CP5 tune variation (underlying event)
- Color reconnection
- PS kernel splitting (μ_R and c_{NS})
- Top recoil scheme
- PY8 vs Herwig7

ATLAS studies (ATL-PHYS-PUB-2025-036)

- **Powheg hard process**
  - μ_R, μ_F scale variation
  - PDF uncertainties
  - h_{damp}
  - $bb4\ell$: α_S in Powheg Sudakov
- **Powheg-Pythia8 matching**
  - $p_{\text{T}}^{\text{hard}}$ variation
  - $bb4\ell$: scale resonance veto
- **Pythia8 parton shower**
  - A14 Var1 tune variations (underlying event variation)
  - Colour reconnection
  - Pythia8 splitting kernel variations (μ_R and c_{NS})
  - Recoil uncertainty
  - Alternative parton shower: Herwig7

Modeling uncertainties for bb4l

Covered / preliminary works / missing

Powheg hard process

- μ_R and μ_F scale variation
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h_{damp} variation

Samples are generated with CMS core software for Run 2

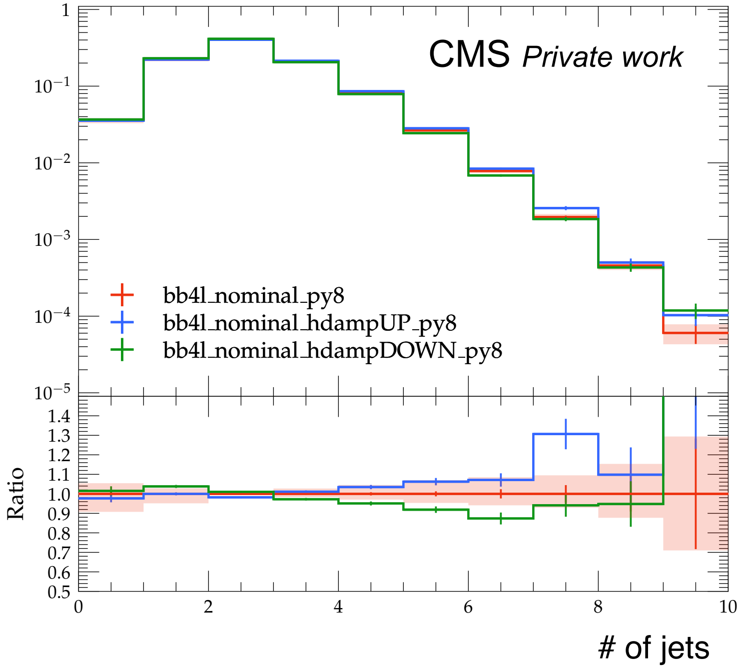
- Generated small private samples for MC study
- Pythia 8.240 and CP5 tune, showered with CMS Run 2 fragment
- bb4l user hook in CMSSW
- 2M for nominal / shower variations, otherwise 1M events tested
- Can be used for central sample production if needed

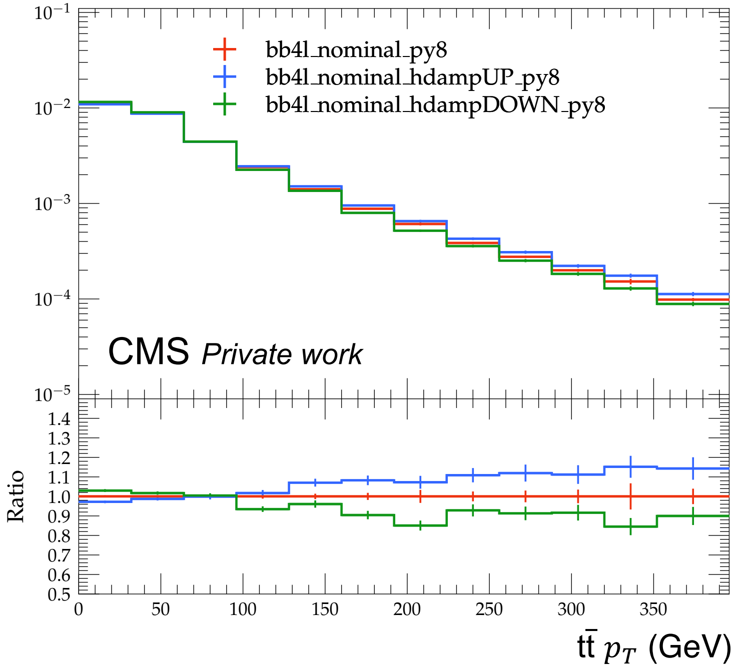
hdamp variations

- Nominal: 1.379 * m_{top} (CMS central gridpack)
- Up: 2.305 * m_{top} / Down: 0.874 * m_{top}

DCTR method in progress

- ML weights are already available for hvq samples
- Requires very large sample to train for high $t\bar{t}$ p_T



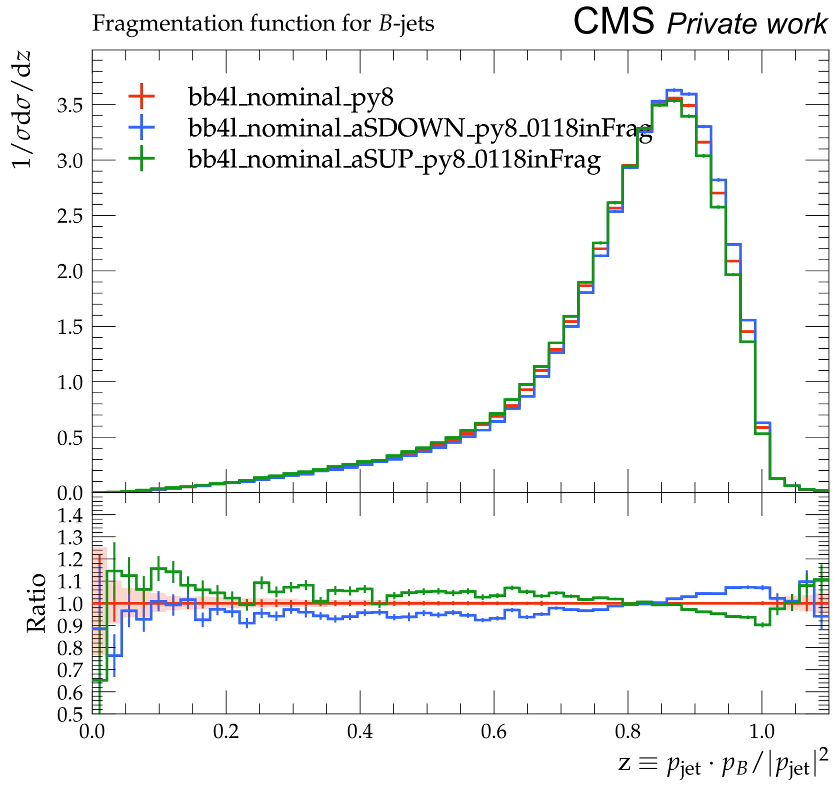


α_S in bb4l for Powheg Sudakov

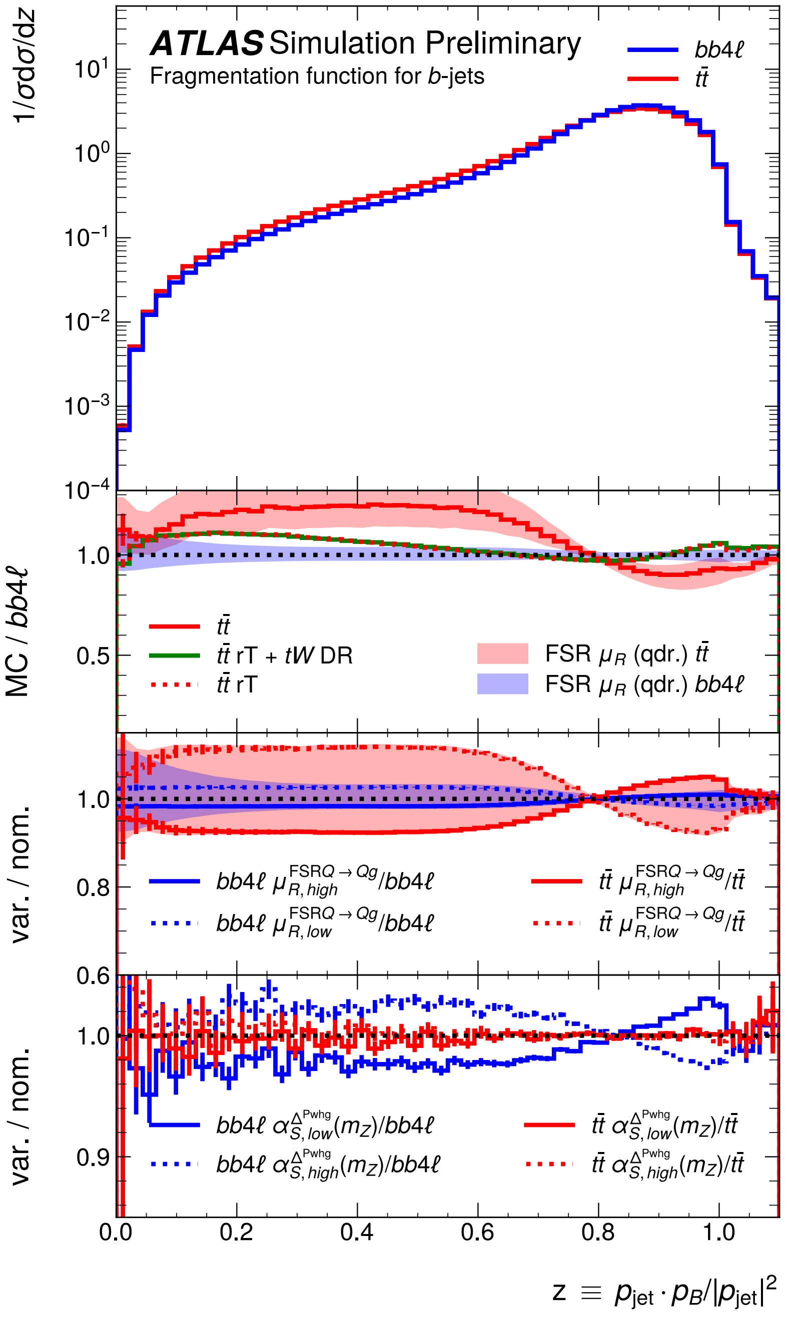
Migration from FSR

Gridpacks are generated with

- NNPDF31_nnlo_as_0112 / NNPDF31_nnlo_as_0124
  - Generated 1M events per each variation
- ATLAS used α_S = 0.115 / 0.121



Similar shape effect



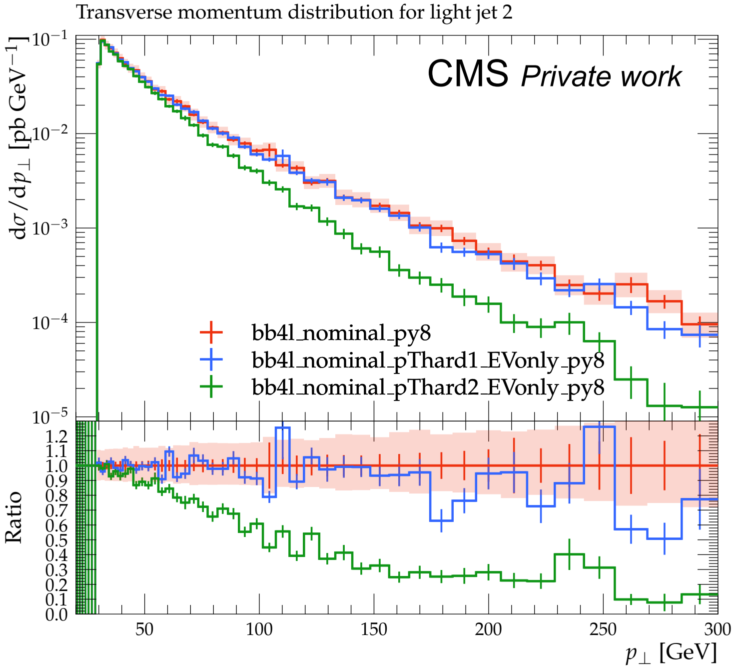
Choice of pThard

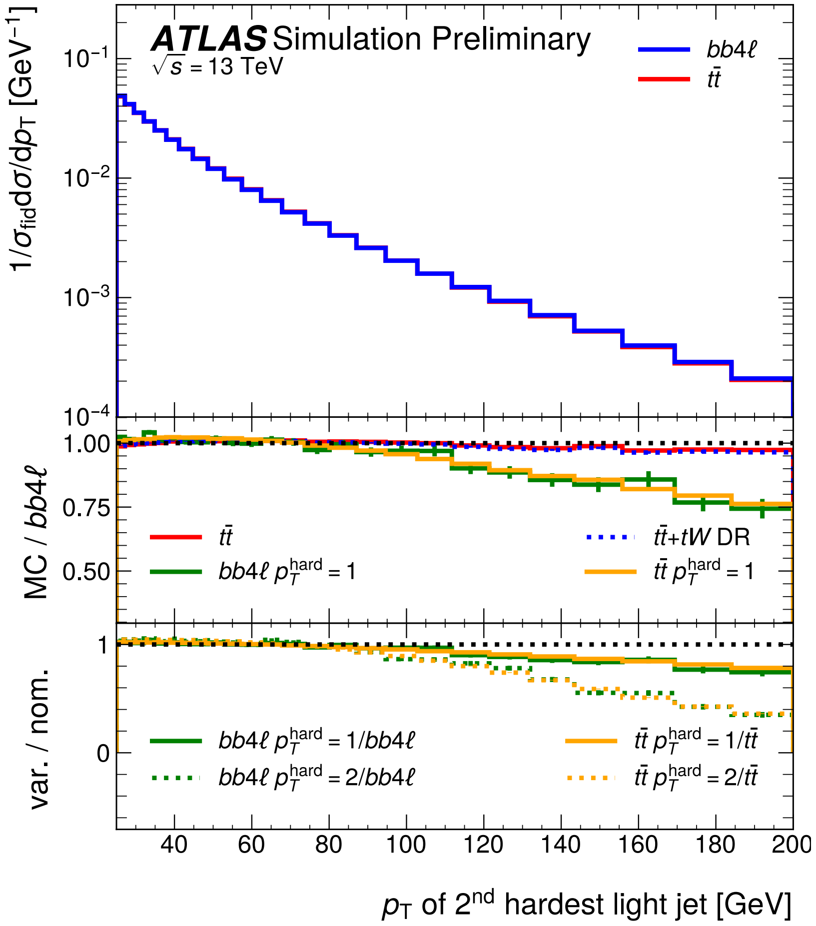
Descriptions taken from
LHCtopWG meeting, K. Voß

Matching uncertainty definition in production
= varying matching scale $k_{\mathrm{T}}^{\mathrm{ISR}}$

- $p_{\mathrm{T}}^{\mathrm{hard}} = 0$ (default): p_{T} of Powheg emission w.r.t. emitter (SCALUP)
- $p_{\mathrm{T}}^{\mathrm{hard}} = 1$ (uncert. def.): min p_{T} of Powheg emission w.r.t. all incoming and outgoing partons
- $p_{\mathrm{T}}^{\mathrm{hard}} = 2$: min p_{T} of all final-state partons w.r.t. all incoming and outgoing partons

- Implemented in CMSSW

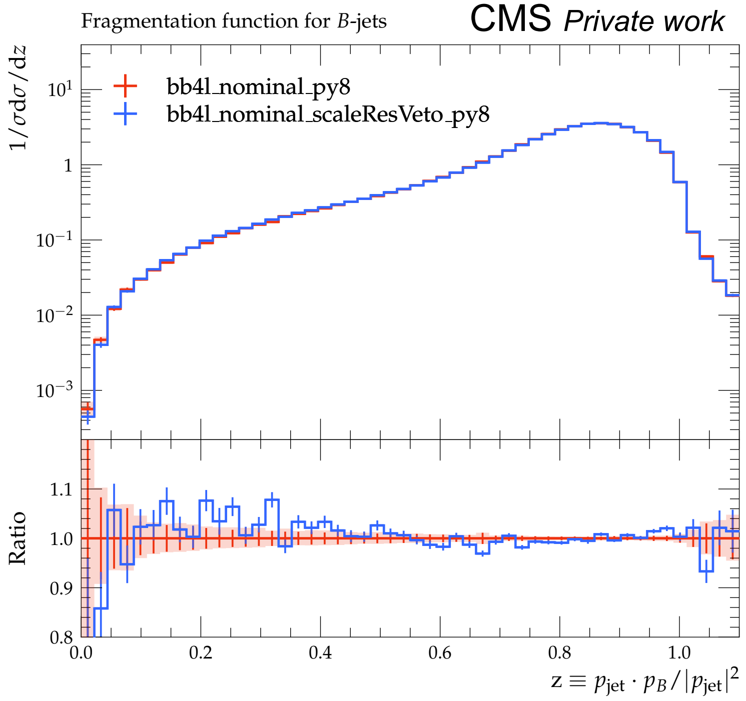


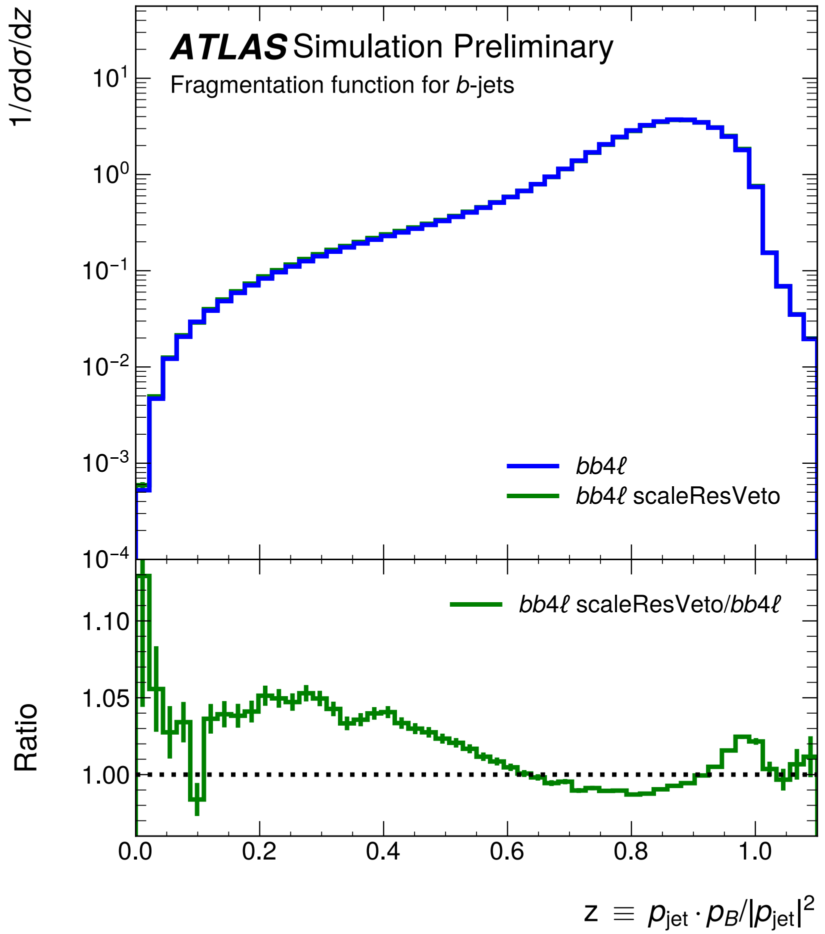


Scale resonance veto

Switch p_T definition of parton shower emissions

- POWHEG:bb4l:ScaleResonance:veto = 1
  POWHEG:bb4l:FSREmission:veto = 0
  in CMSSW implementation





CP5

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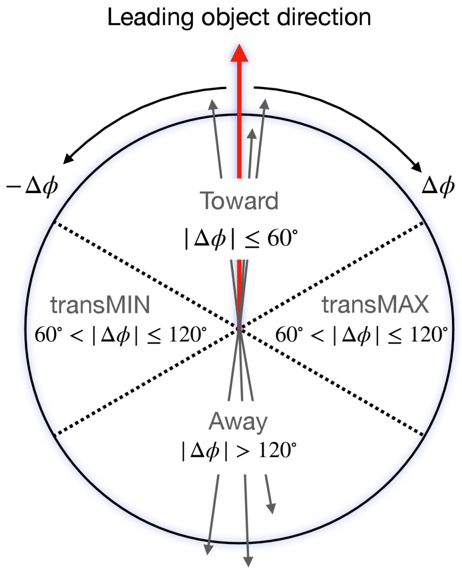
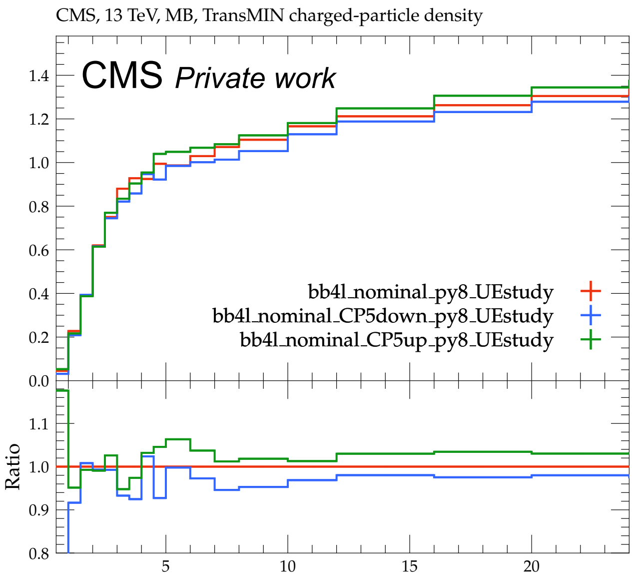
rivet CMS_2015_PAS_FSQ_15_007

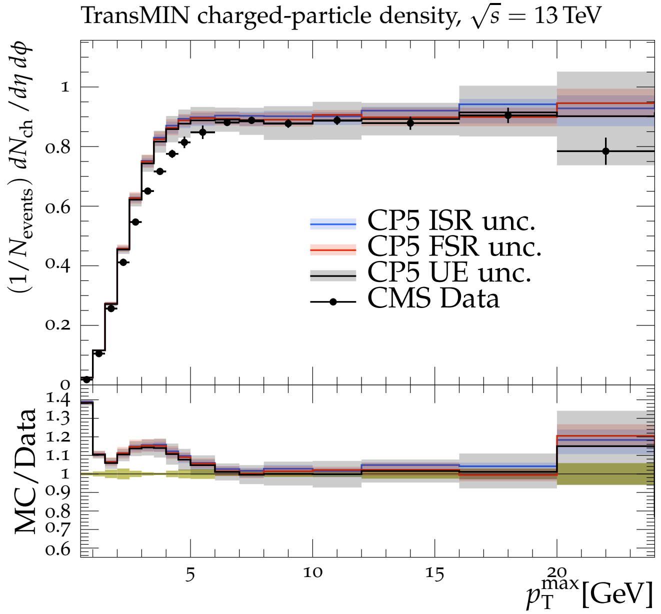
Variation of CP5 tune

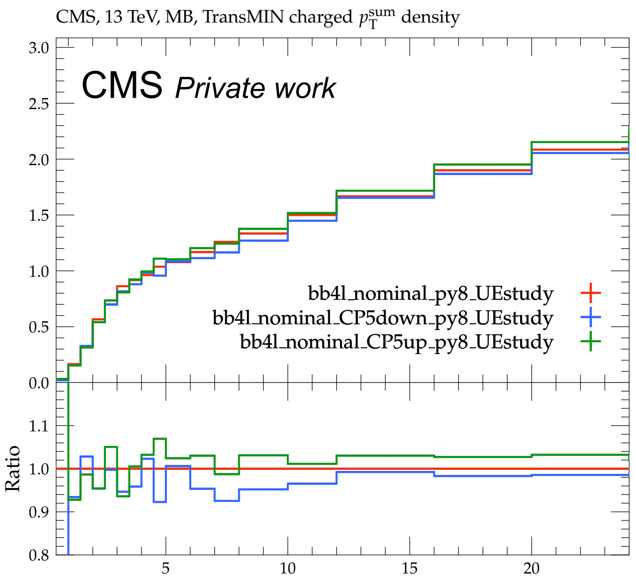
PYTHIA8 Parameter	CP5 Up	CP5 Down
MultipartonInteractions:pT0Ref [GeV]	1.41	1.46
MultipartonInteractions:ecmPow	0.03	0.03
MultipartonInteractions:coreFraction	0.43	0.73
MultipartonInteractions:coreRadius	0.67	0.69
ColourReconnection:range	4.88	4.69

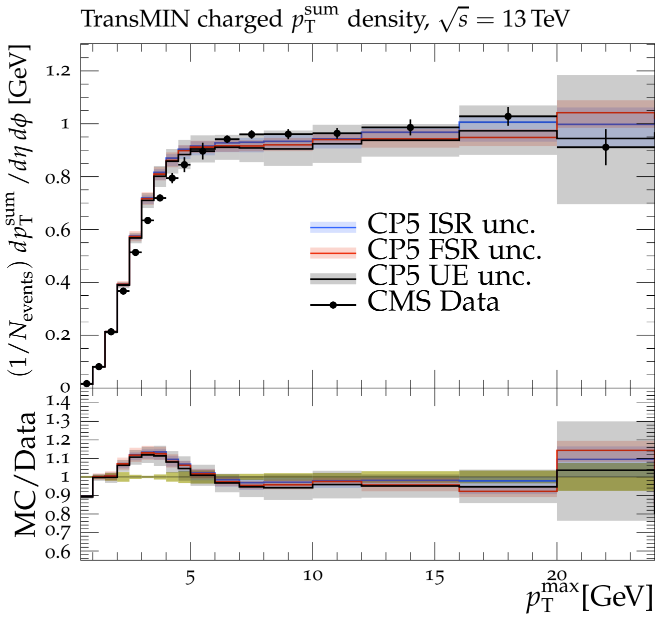
- Caution: *Not an apple-to-apple comparison*
- hvq + tW samples need to be tested











Color reconnection

Different CR tunes for CP5 setting

- No sizable effect observed

Early resonance decay

- Shifts top mass peak

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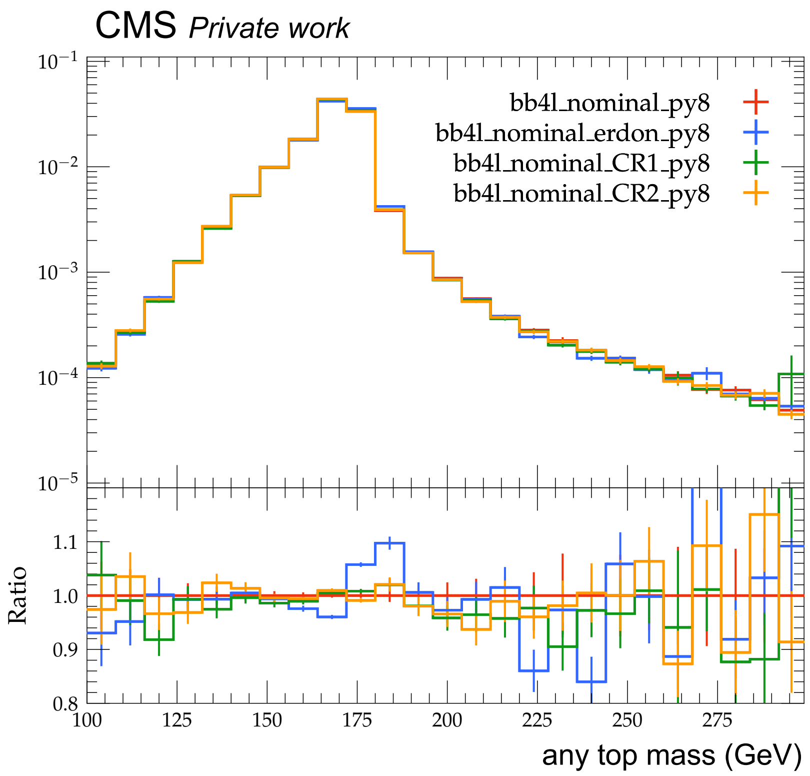
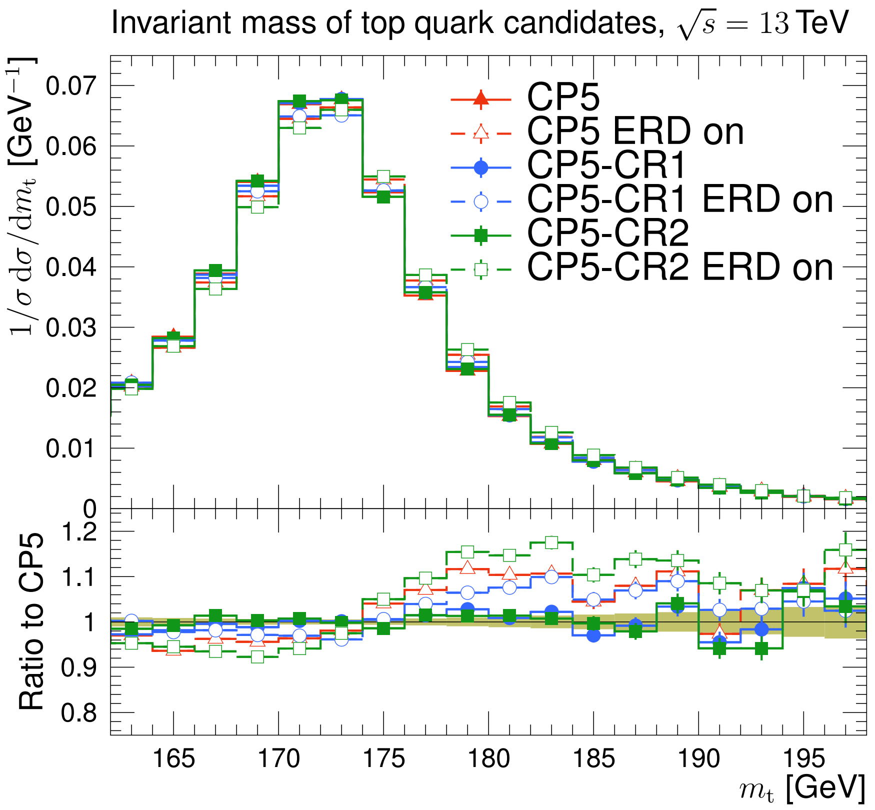
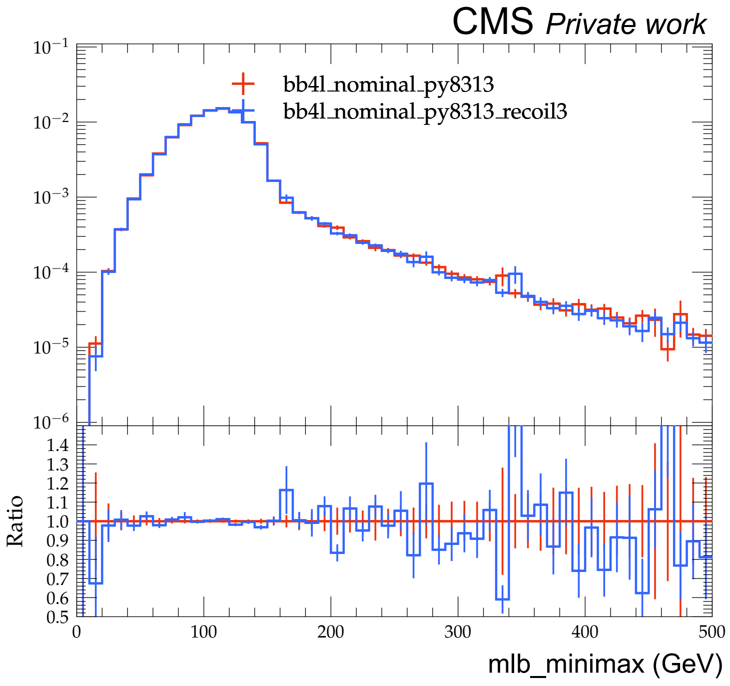


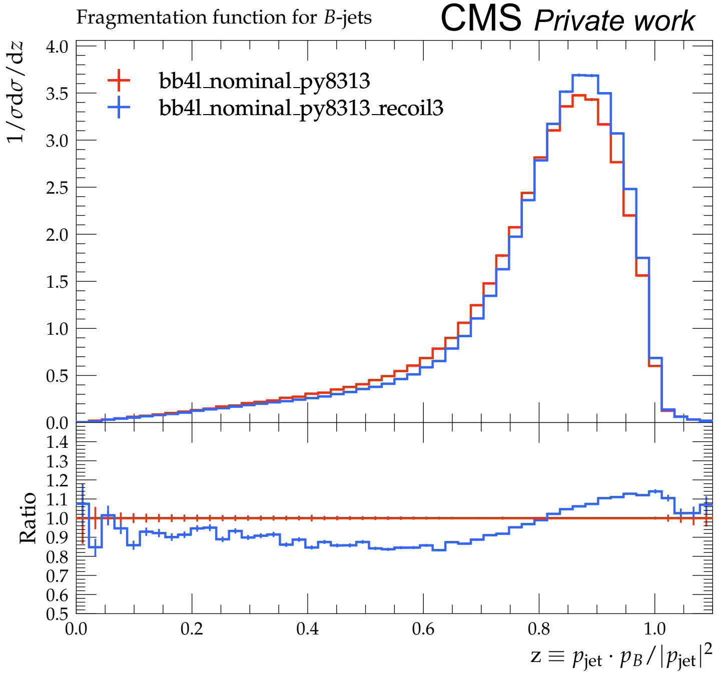


Top recoil scheme

Recoil to color (b) vs recoil to top ('recoil3')

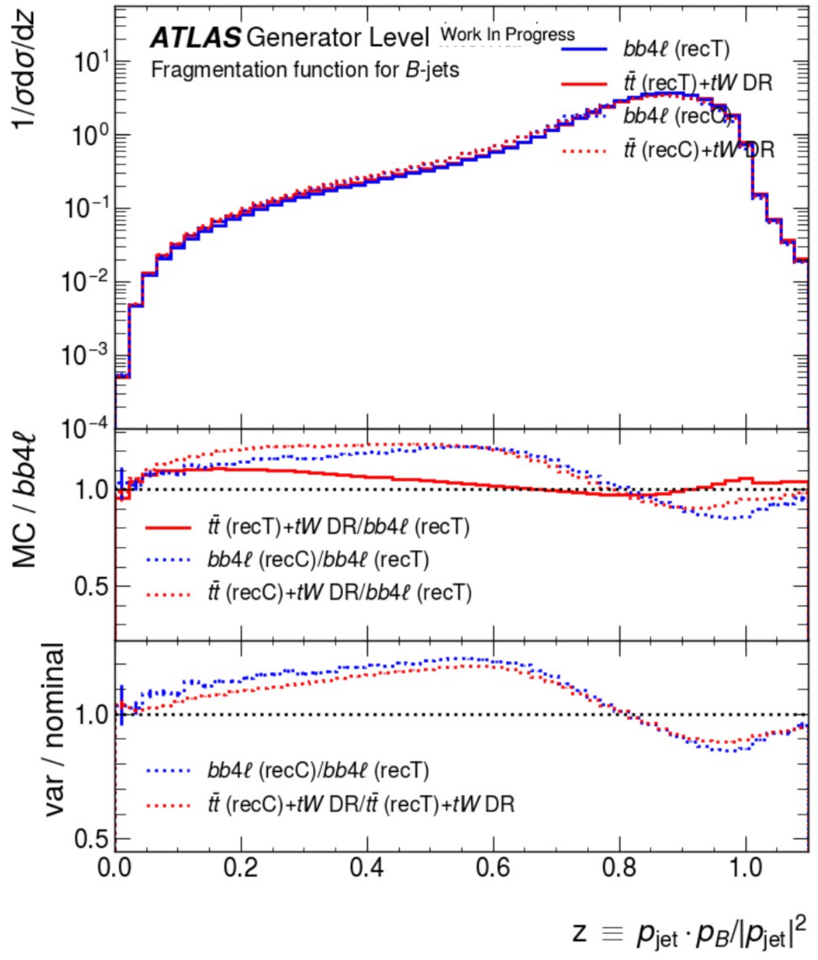
- Showered with Pythia 8.313
- All other environements are remained the same
- Sizable effect in b fragmentation
- No large variation in [150, 250] GeV in mlb_minimax





CMS nominal produced with recoil to color

-> *Ratio is inversed*



Outlook

Presented developing measurement on top mass & width with bb4l

- Started modeling uncertainty studies for CMS analyses

Remaining questions

- Which uncertainties are necessary for CMS / ATLAS analyses?
- Do the shower settings for hvq also work for bb4l? (e.g. PY8 tune)

Plan

- Harmonize bb4l modeling studies with ATLAS and submit CMS central samples
- Aim for a public result by next spring / summer

Thank you

Contact

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