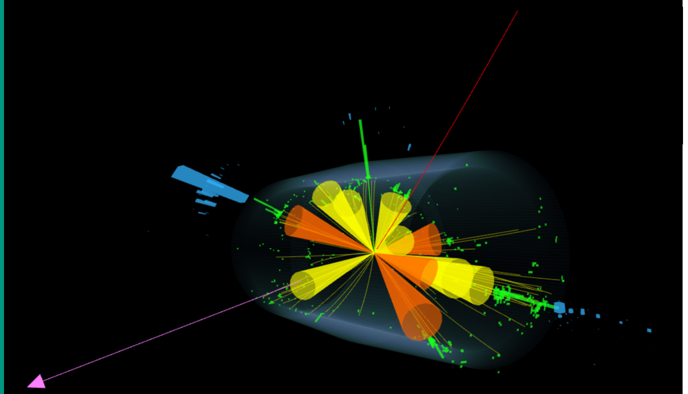
Measurement of $t\bar{t}t\bar{t}$ with the CMS detector

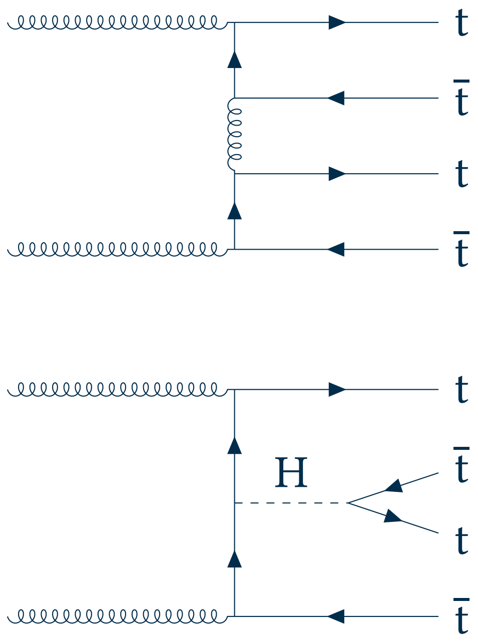


From rediscovery to future improvements

Torben Mohr | 15. June 2026

Why even bother with $\mathrm{t\bar{t}t\bar{t}}$?

- Heaviest final state ever observed at the LHC
- Extremely rare: $\sigma(pp \rightarrow \mathrm{t\bar{t}t\bar{t}})_{\mathrm{predicted}} \approx 13\,\mathrm{fb}$
- Probe of the top-Higgs Yukawa coupling
- Portal to BSM physics
  - sensitive to heavy new physics (e.g. additional heavy bosons)
  - sensitive to EFT (e.g. four-fermion contact terms)

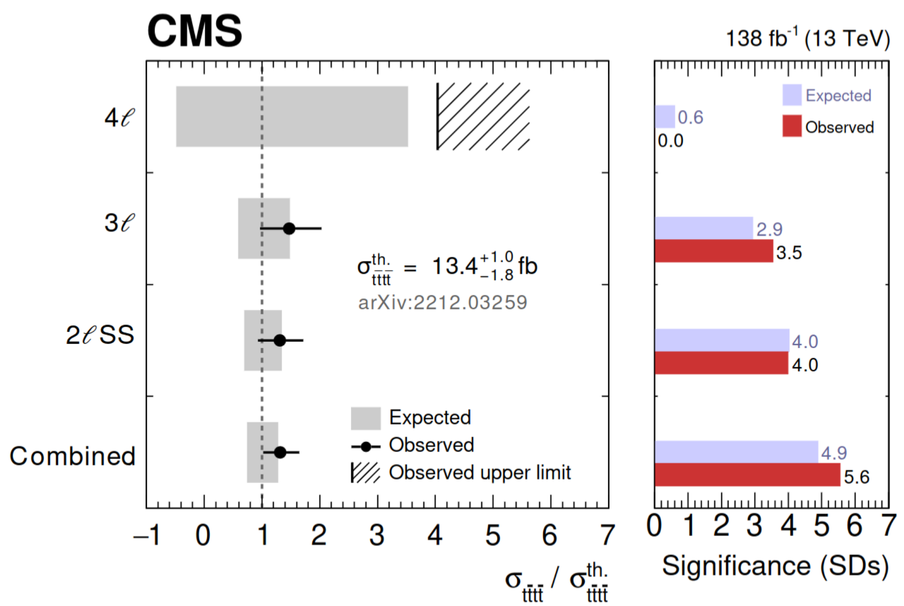


Experimental status and goals

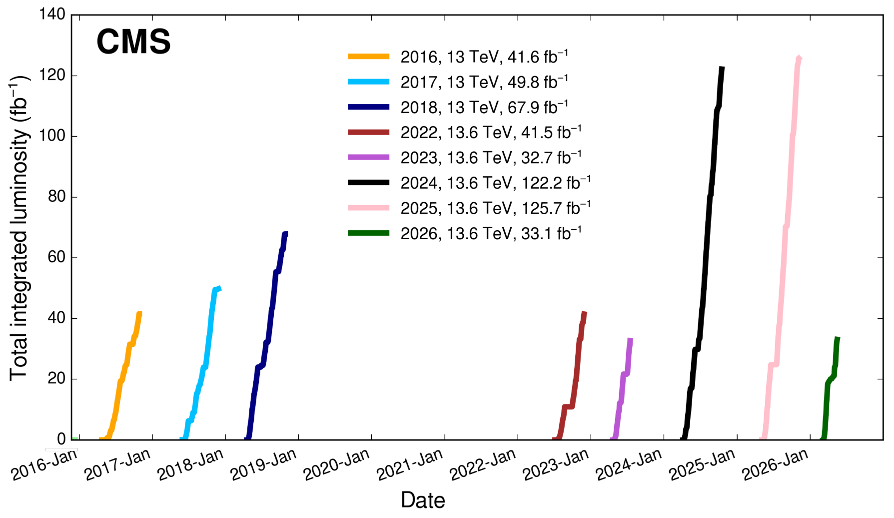
- Independently observed by the CMS and ATLAS collaborations in 2023 with 138 fb^{-1} of data at $\sqrt{s} = 13\,\mathrm{TeV}$
  - CMS: $17.7^{+4.4}_{-4.0}\,\mathrm{fb}$
  - ATLAS: $22.5^{+6.5}_{-5.5}\,\mathrm{fb}$
- Since then:
  - More data recorded at $\sqrt{s} = 13.6\,\mathrm{TeV}$ equal to $> 300\,\mathrm{fb}^{-1}$
  - Significant improvements in object identification using machine learning
- Goals of my work are to...

  ... establish an extensible baseline for future measurements, matching the sensitivity of the existing CMS result

  ... investigate the impact of improved object identification

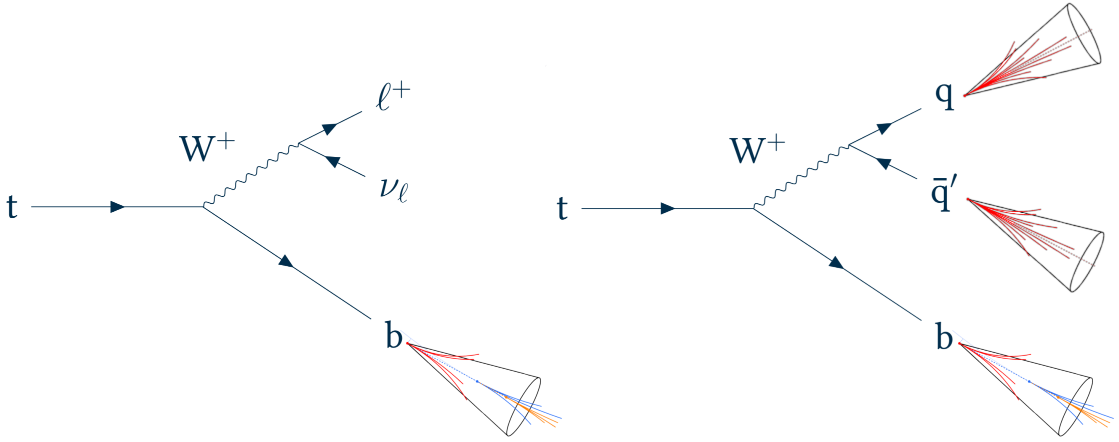


2305.13439

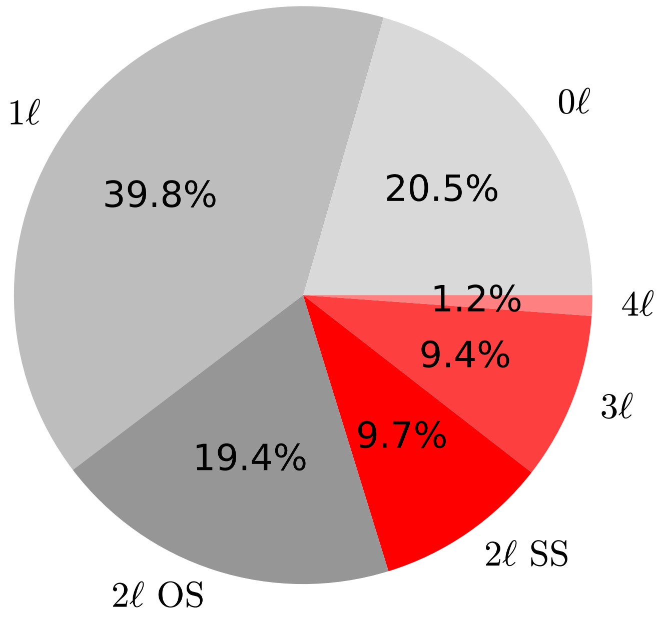


CMS Lumi POG

Signal signature



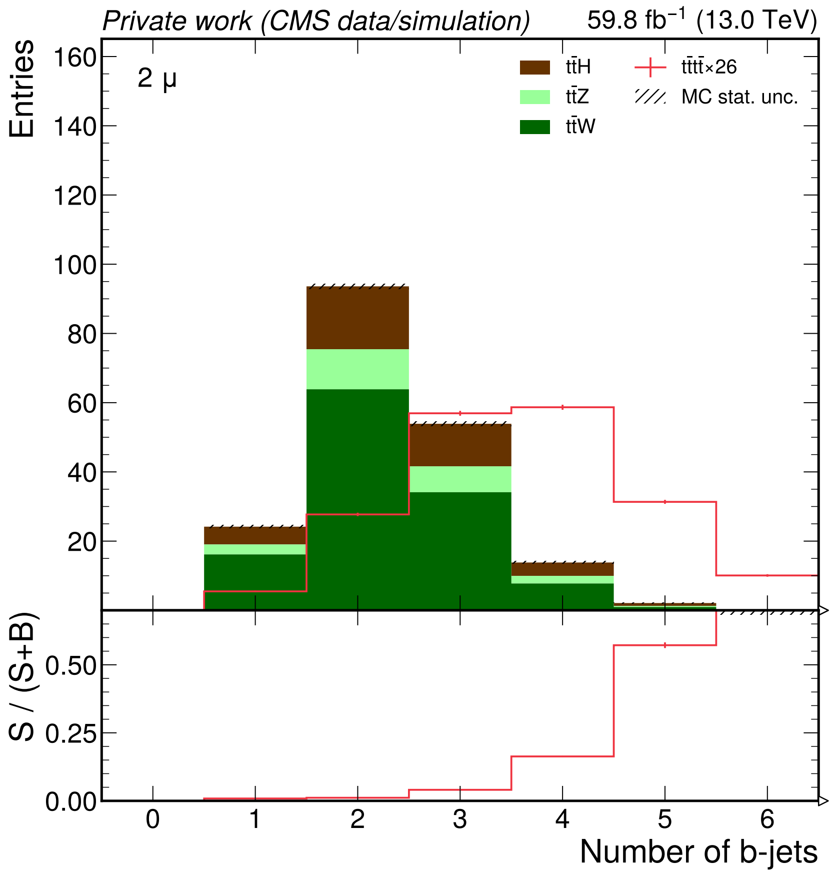
- Top quarks decay to W-boson and b-quark
  $\rightarrow$ Signature in detector:
    - Charged lepton + b-jet
    - Two light jets + b-jet
- For $\mathrm{t\bar{t}t\bar{t}}$ and ideal detector:
  - Between 0 and 4 charged leptons
  - Four b-jets
  - Between 0 and 8 light jets
- Analyze 2ℓ SS, 3ℓ, and 4ℓ final states
  - 0ℓ, 1ℓ, 2ℓ OS are dominated by QCD and $\mathrm{t\bar{t}}$ background



Main background 1: $t\bar{t}X$

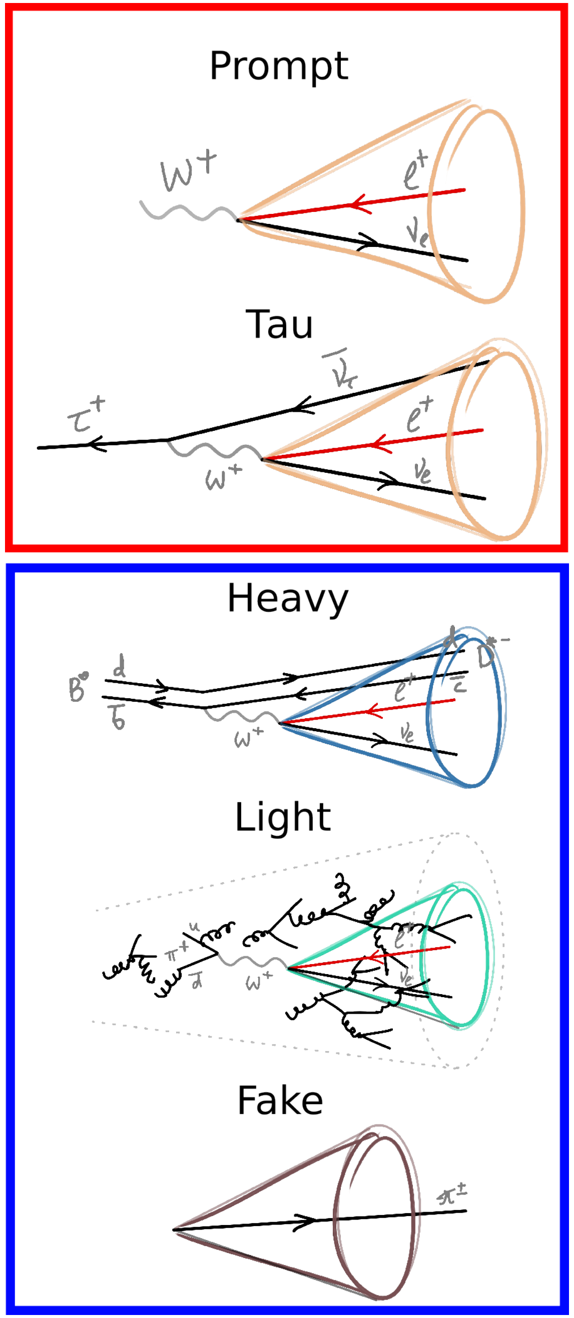
- $t\bar{t}$ production in association with bosons: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$
  - Bosons have to decay leptonically to enter phase space
  - Additional jet radiation required to enter phase space

  $\rightarrow$ Efficient identification of b-jets needed for background rejection!
- Especially important are $t\bar{t}W$ and $t\bar{t}Z$ due to higher contributions and underestimated cross-sections



Main background 2: Misidentified leptons

- Prompt leptons: hard interactions, leptonic top, W, Z, τ, γ
- Nonprompt leptons: misidentified hadrons and photons, semileptonic hadron decays
- Use BDT to distinguish nonprompt leptons
  - $\rightarrow$ Nonprompt lepton rate supressed to $\approx 10^{-2}$



K. Skovpen @ TOP workshop

Main background 2: Misidentified leptons

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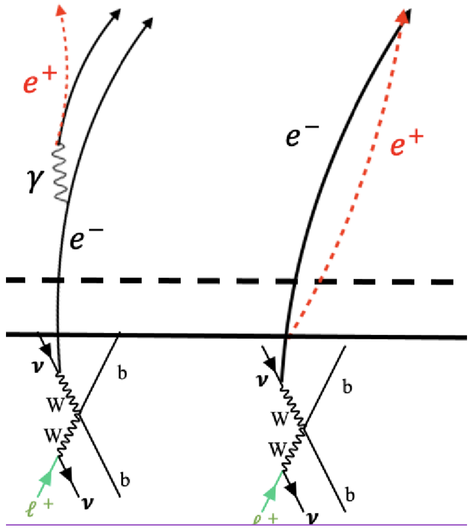
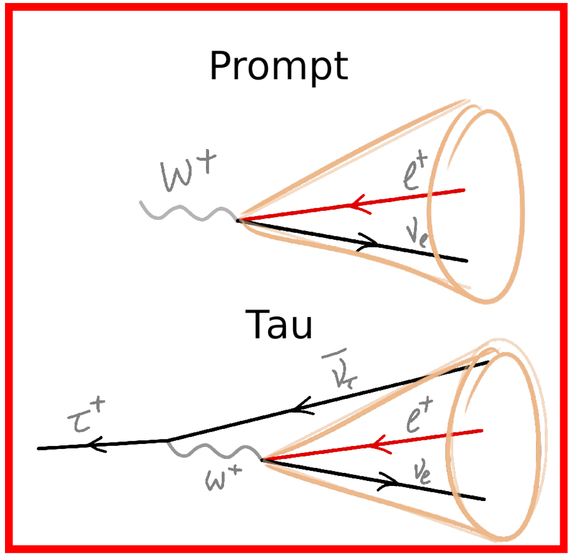
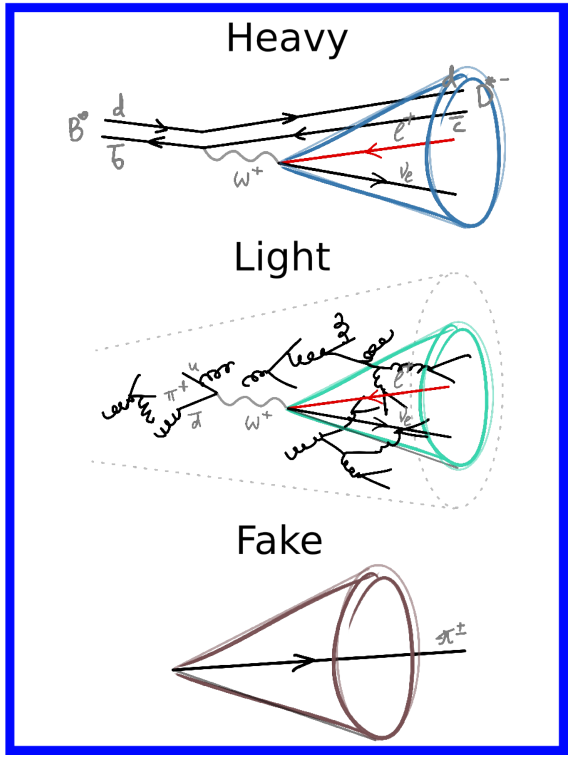
- Nonprompt leptons: misidentified hadrons and photons, semileptonic hadron decays
- Use BDT to distinguish nonprompt leptons
  - $\rightarrow$ Nonprompt lepton rate supressed to $\approx 10^{-2}$
- Electrons can be charge-misidentified due to small curvature or bremsstrahlung
- Contribution from $\mathrm{t\bar{t}}$ and $Z+$ jets through this misidentifications
  - $\rightarrow$ Sizeable contribution even though mis-id probabilities are small
- Absolute rate of misidentification and additional radiation often not well-modeled in MC
  - $\rightarrow$ Data-driven approaches



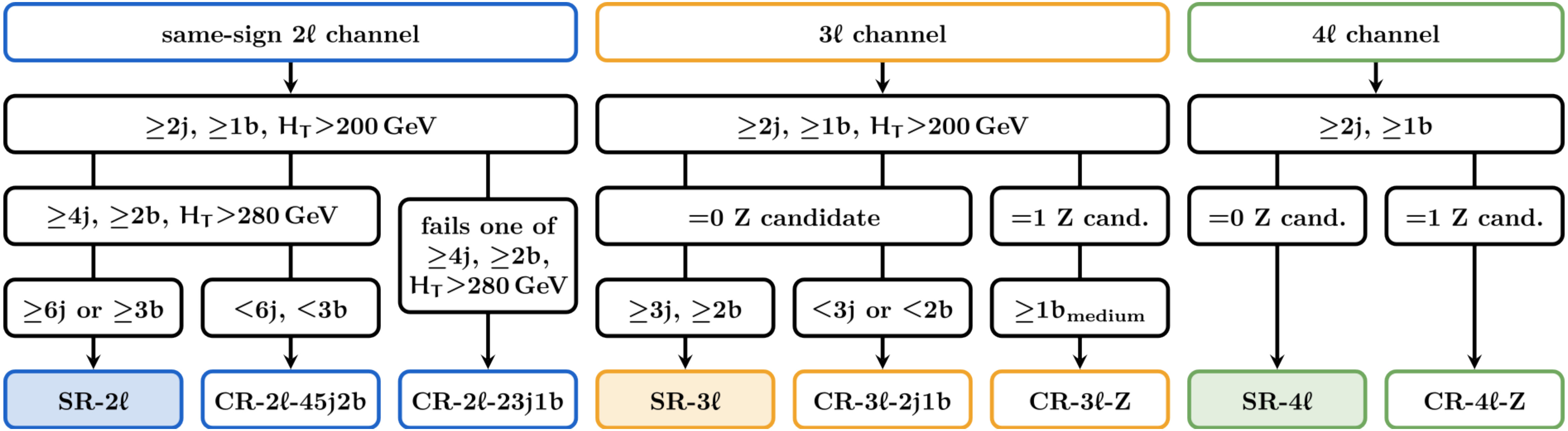




K. Skovpen @ TOP workshop

Analysis regions

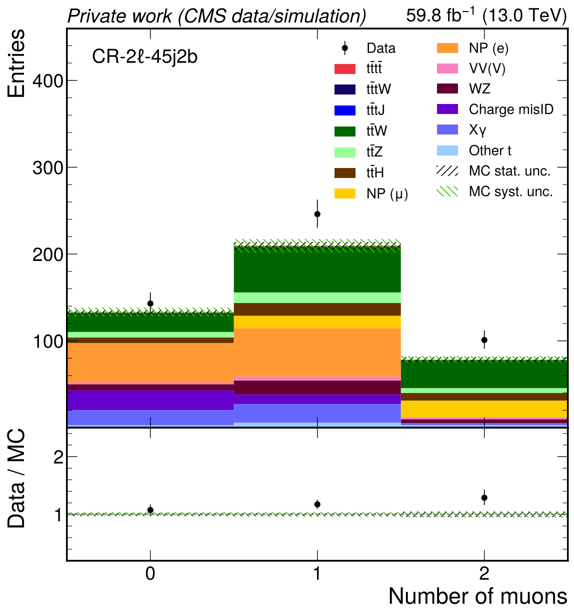
- Selections based on [2305.13439]
- Optimized signal regions for each lepton multiplicity
- Control regions to constrain contributions from $t\bar{t}W$, $t\bar{t}Z$ and nonprompt leptons

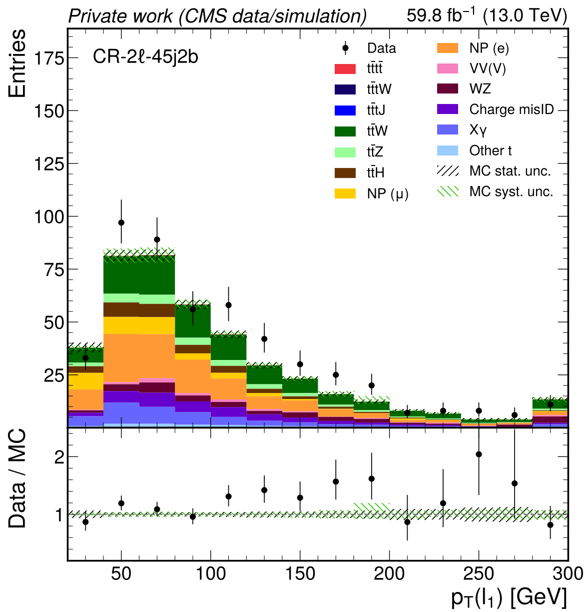


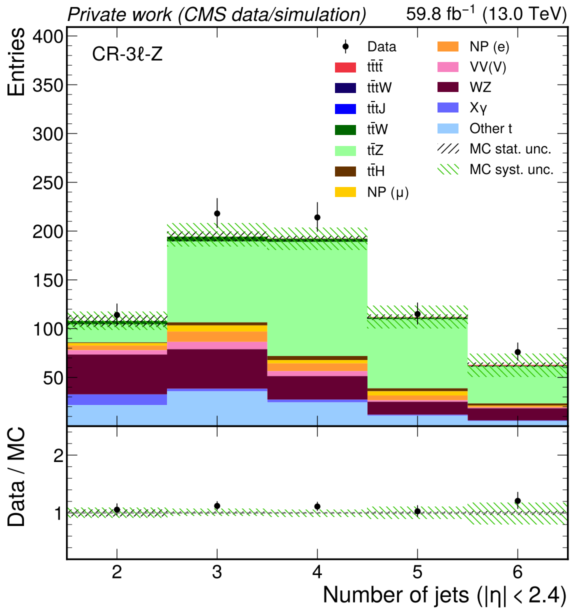
2305.13439

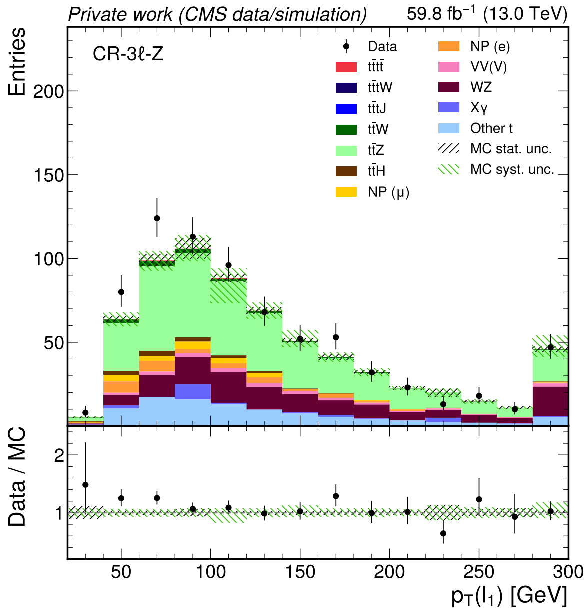
Validation in control regions

- Good agreement in control region for $t\bar{t}W$ and nonprompt contributions
  - Tendency to slight underprediction in MC
    $\rightarrow$ In agreement with dedicated $t\bar{t}W$ measurements
- Good agreement in $t\bar{t}Z$ control region
- Similar agreement in other control regions

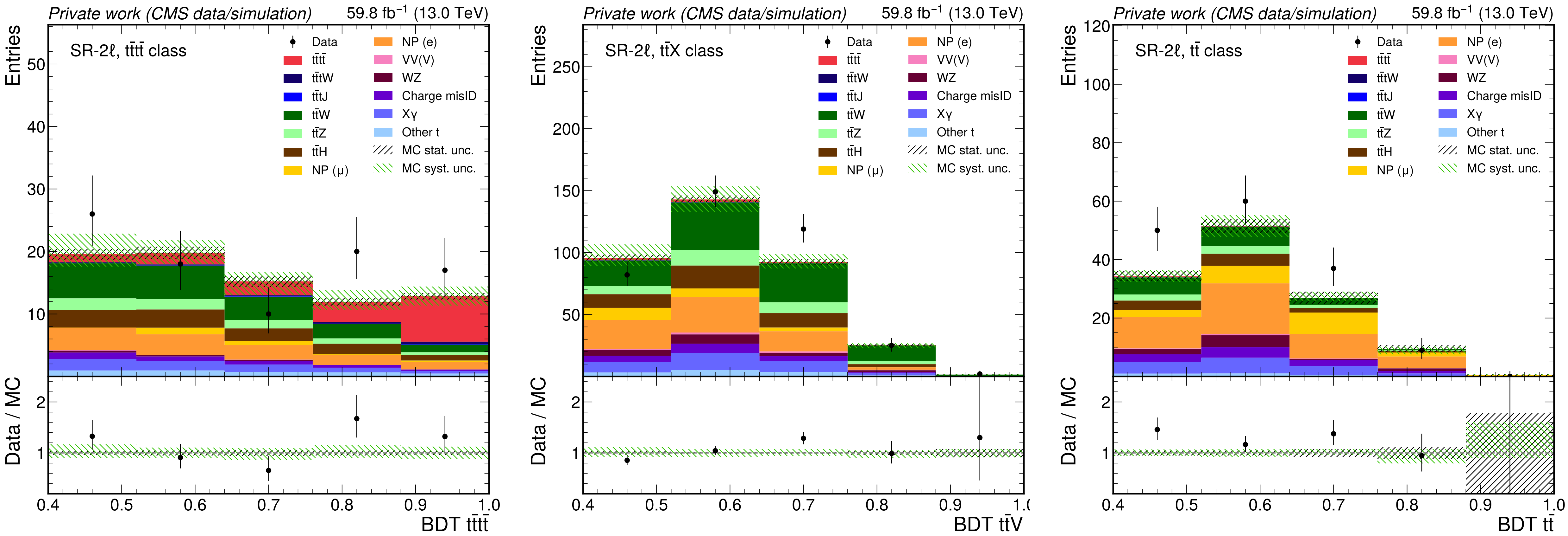








Background suppression: BDT



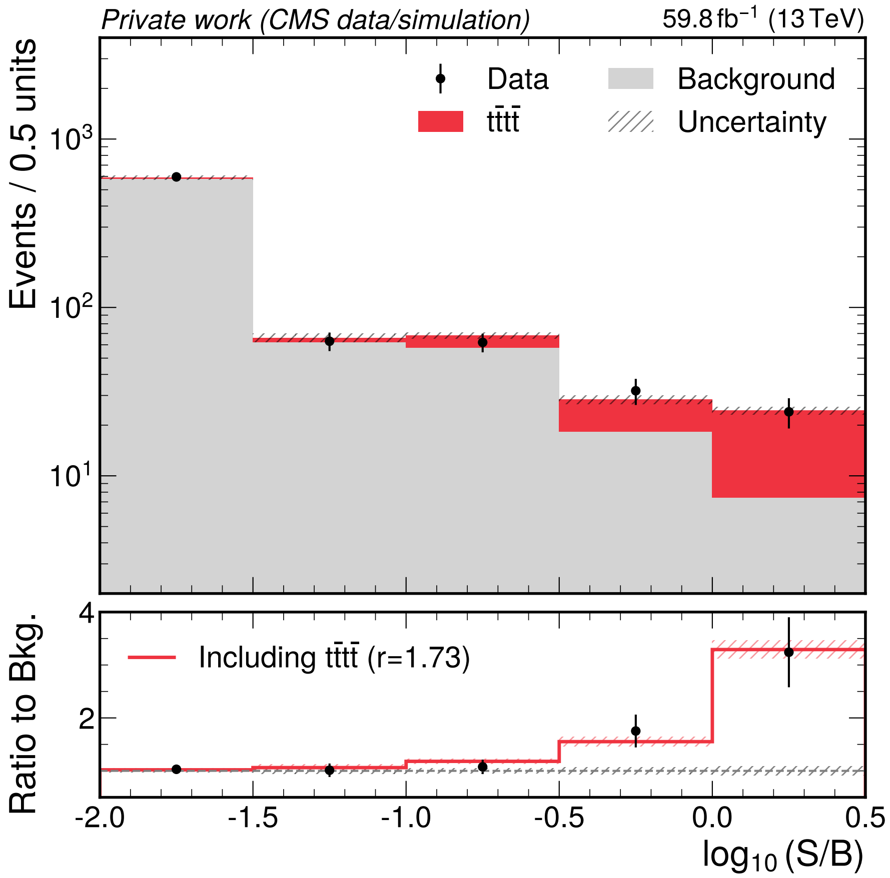
- Pre-trained BDT from [2305.13439]
- One BDT for SR-2ℓ and one for SR-3ℓ + SR-4ℓ
- Three output nodes: TTTT, TTX, TT
- Assign each event to exclusive class according to highest node
  $\rightarrow$ Can define pure regions in signal and backgrounds

Results

- Perform Binned Maximum Likelihood fit to extract cross section
  - In SRs: Use BDT to further split into $\mathrm{t\bar{t}t\bar{t}}$-enriched, $\mathrm{t\bar{t}}X$-enriched, and nonprompt-enriched regions
  - In CRs: Use dedicated distributions to constrain all important background contributions
- Focused just on part of the dataset, equal to 59.8 fb^{-1}

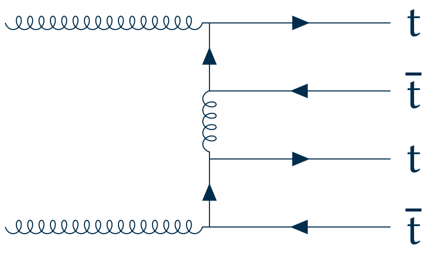
- Extracted cross section: $\sigma_{\mathrm{t\bar{t}t\bar{t}}} = 23.2^{+4.5}_{-3.0}$(syst.)$^{+5.5}_{-5.3}$(stat.) fb
  - Reference from [2305.13439]: $17.7^{+4.4}_{-4.0}$ fb (using full dataset)

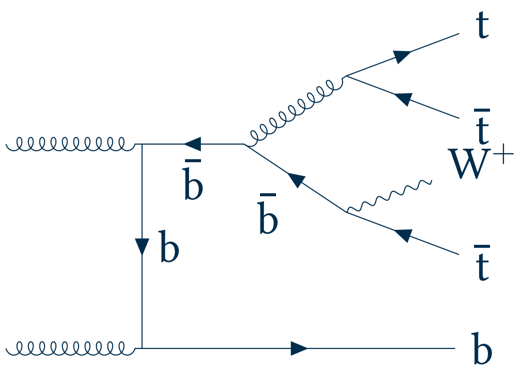
  $\rightarrow$ Compatible with previous results
- Significance of the excess: 5.3σ (3.49σ expected)

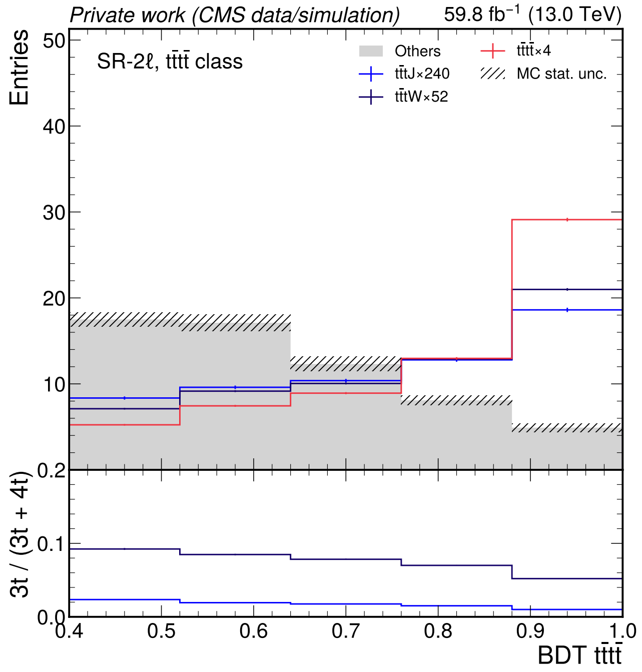


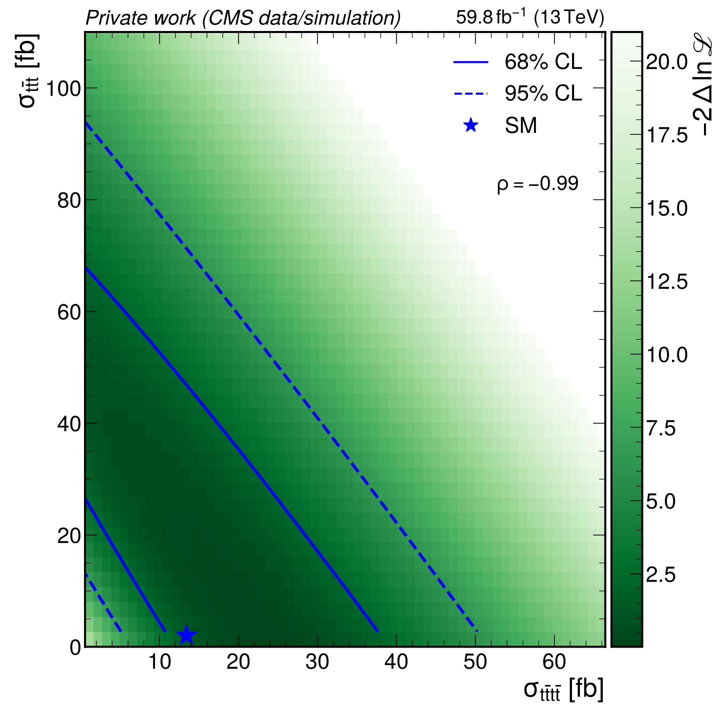
A puzzle for future analyses: ttt

- ttt is $\sim$ 10 rarer than $\mathrm{t\bar{t}t\bar{t}}$
- Can be produced with additional W-boson or jet: tttj, tttW
- Overlapping diagrams of $\mathrm{t\bar{t}t\bar{t}}$ and tttW at NLO QCD
- Distributions somewhat differ between $\mathrm{t\bar{t}t\bar{t}}$ and ttt, but are still pretty similar especially when comparing to background distributions
  - $\rightarrow$ BDT distribution looks similar
  - $\rightarrow$ Strongly anticorrelated when performing likelihood scan

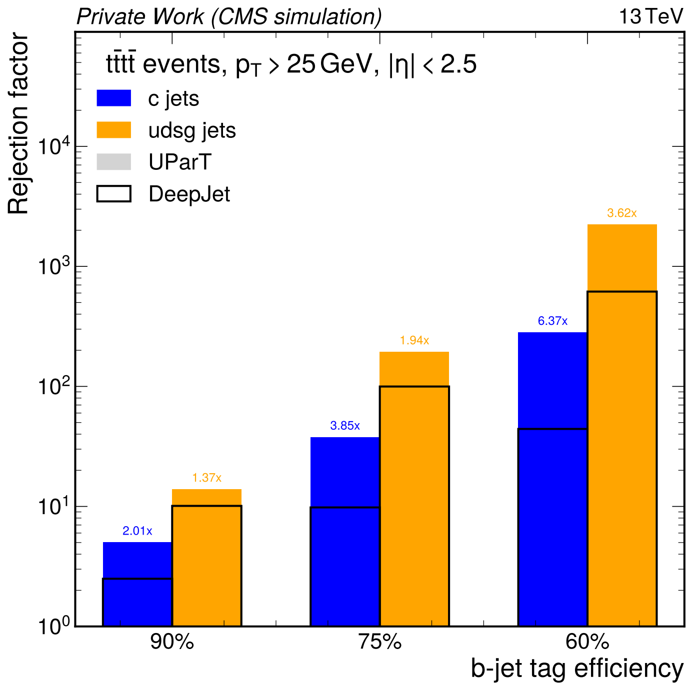








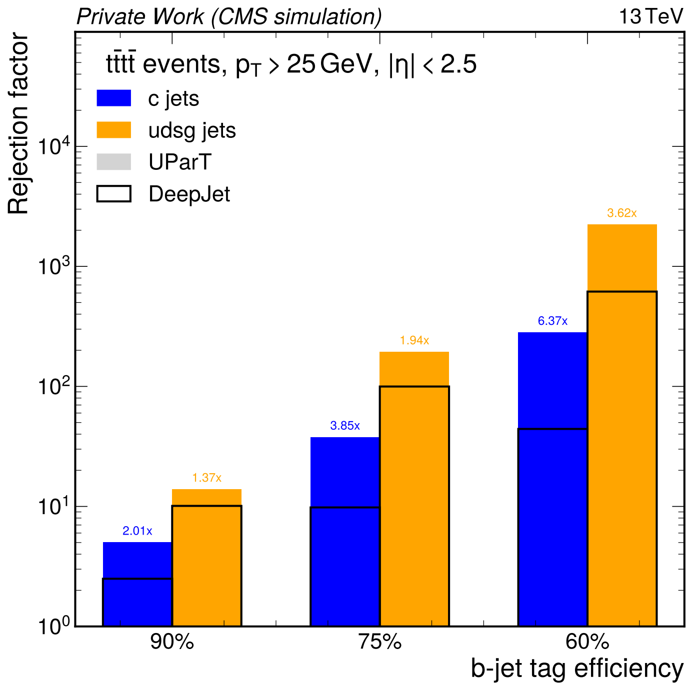
Improvements in object identification



b-jet identification

- Previously: DEEPJET [2008.10519]; DNN architecture
- Now available: UPART [2202.03772]; Transformer-based architecture
- More than 3 times higher rejection of light jets at fixed b-efficiency

Improvements in object identification



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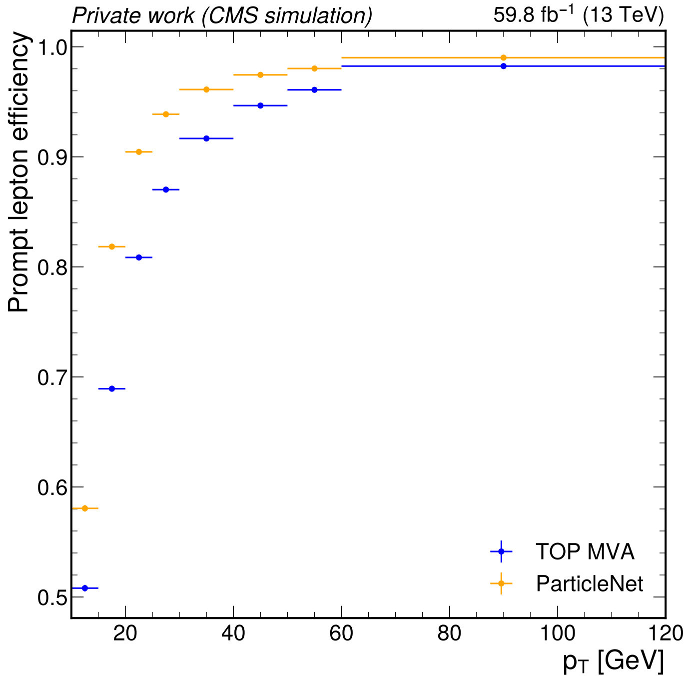


Prompt lepton identification

- Previously: TOP LEPTON MVA [2305.13439]; BDT architecture
- Now available: PARTICLENET [1902.08590]; Graph neural network
- Improvement in prompt lepton efficiency of $> 10\%$ for low-p_T region

Goal and setup of study

- Goal: Quantify gain through improved b-tagging and prompt lepton ID
  - $\rightarrow$ Build sensitive distributions and calculate expected sensitivity
- $\mathrm{t\bar{t}t\bar{t}}$ has highest b-jet multiplicity on average

  $\rightarrow$ b-jet ID directly helps in background rejection
- Lepton ID mainly improves signal efficiency

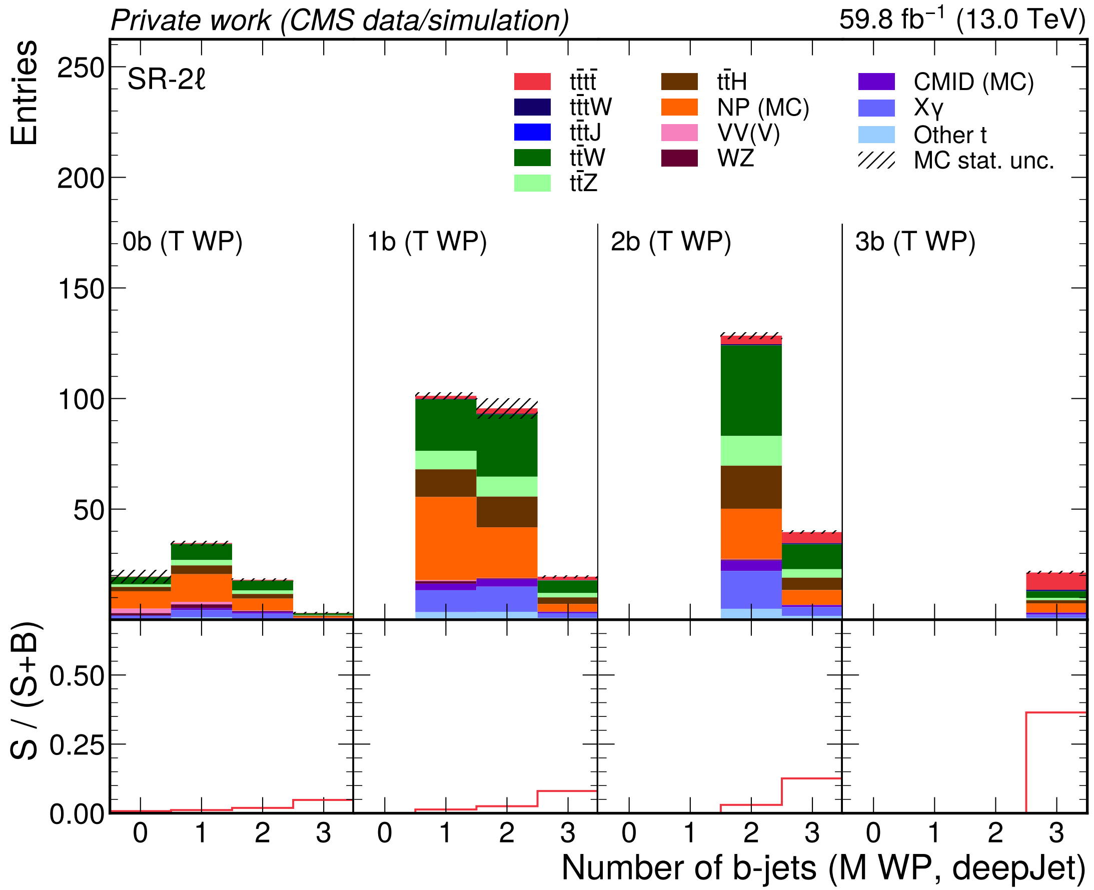
Goal and setup of study

- Goal: Quantify gain through improved b-tagging and prompt lepton ID
  - $\rightarrow$ Build sensitive distributions and calculate expected sensitivity
- $t\bar{t}t\bar{t}$ has highest b-jet multiplicity on average

  $\rightarrow$ b-jet ID directly helps in background rejection
- Lepton ID mainly improves signal efficiency

- Use variables with sensitivity to new b-jet ID
  - Cut on b-jet ID with fixed misidentification rate: working point (WP)
  - Utilize number of b-jets at different WPs

    $\rightarrow$ Identify signal-pure regions

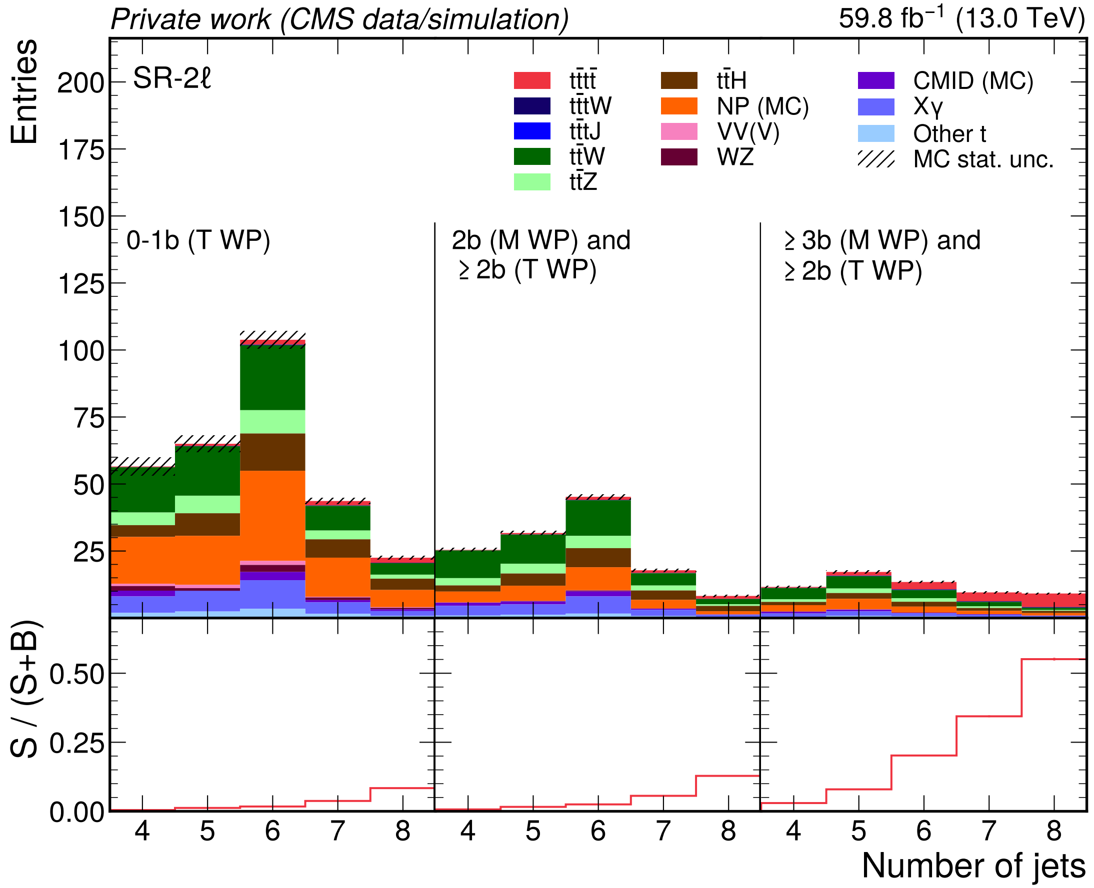


Manual approach

- Use signal-pure regions from previous slide
- Build final fit distribution together with n_{jet}

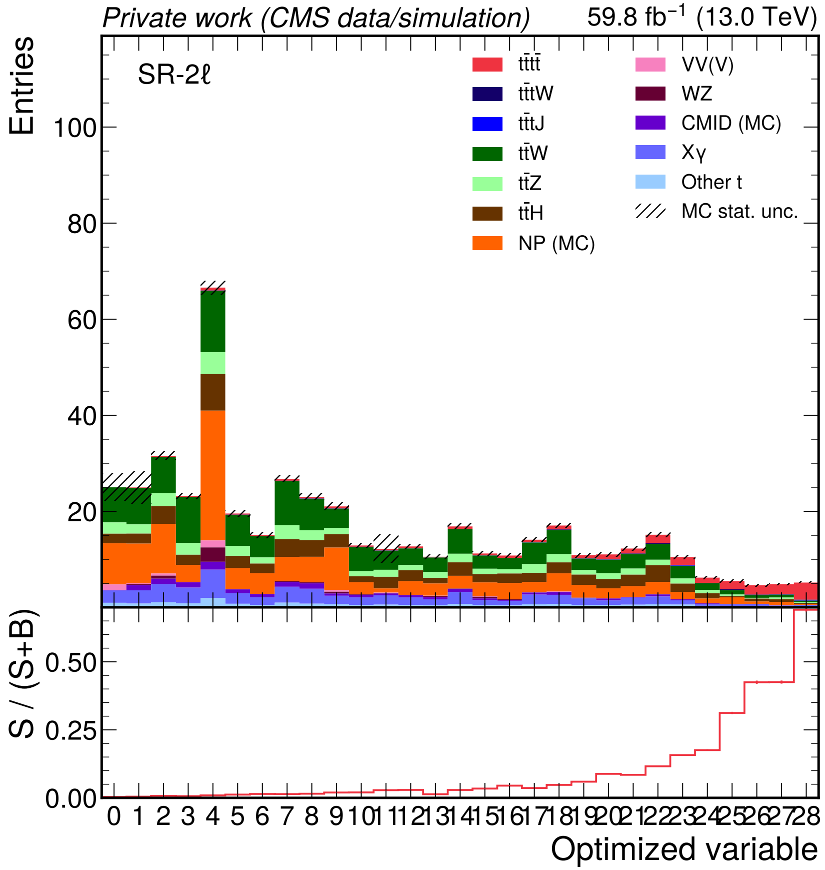
- Build the same distributions for the configurations with improved b-jet ID and prompt lepton ID

	Exp. Sign.	Rel. impr.
Nominal conf.	2.70	–
Impr. b-jet ID	2.92	8%
Impr. b-jet ID + Impr. Lepton ID	3.00	11%

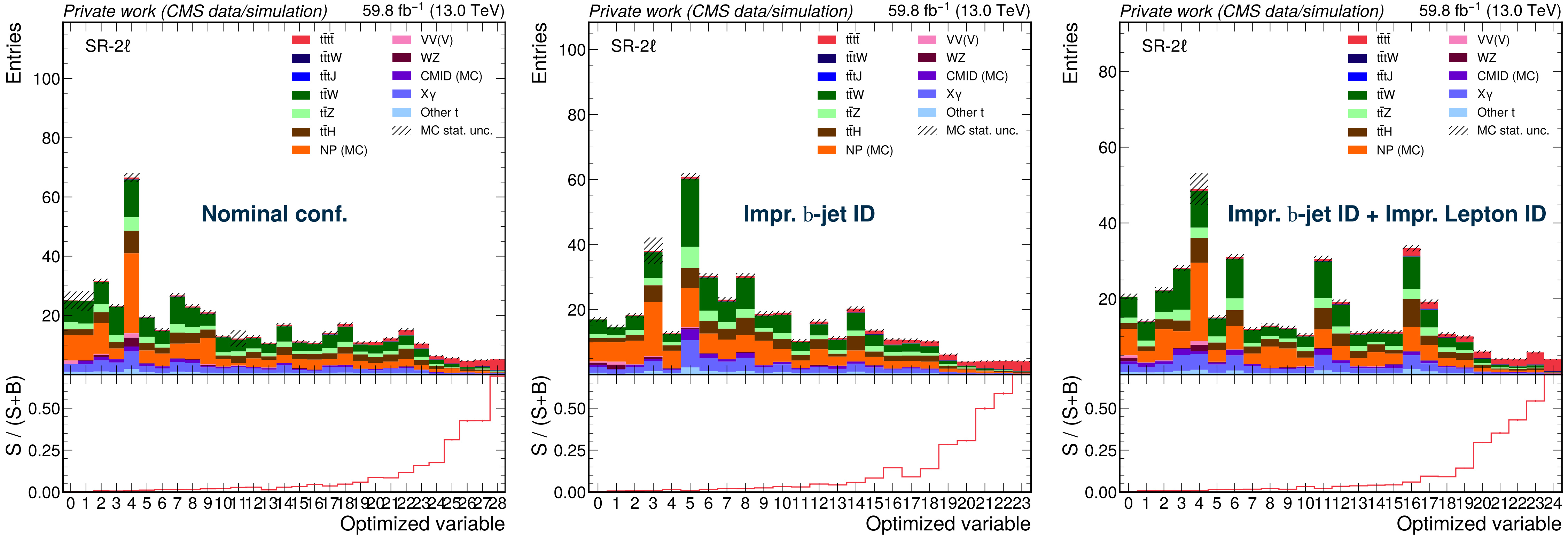


Bin optimization approach

- What if the chosen binning is not optimal? What if for one configuration another binning would be more optimal?
  $\rightarrow$ Build bin optimization algorithm that solves this problem
- Bin optimization:
  - Start with 4-dimensional histogram in $(n_{\mathrm{jet}}, n_{\mathrm{b-loose}}, n_{\mathrm{b-medium}}, n_{\mathrm{b-tight}})$
  - Merge bins to have at least $\sim$5 events per bin
  - Optimize for maximal signal purity
- Like a decision tree with four discrete variables



Bin optimization approach: Results



Exp. Sign.	3.62	3.93	4.01
Rel. impr.	-	9%	11%

- Comparable relative improvement to other approach
- Can achieve high significance with those simple cuts

Summary

Baseline measurement

- Successfully reproduced published results with partial dataset ($59.8\,\mathrm{fb}^{-1}$)
- Extracted cross section compatible with reference:

$$\sigma_{\mathrm{t\bar{t}t\bar{t}}} = 23.2^{+4.5}_{-3.0}\,\text{(syst.)}^{+5.5}_{-5.3}\,\text{(stat.)}\,\text{fb}$$

- Significance: 5.3σ (3.49σ expected)

Improved object identification

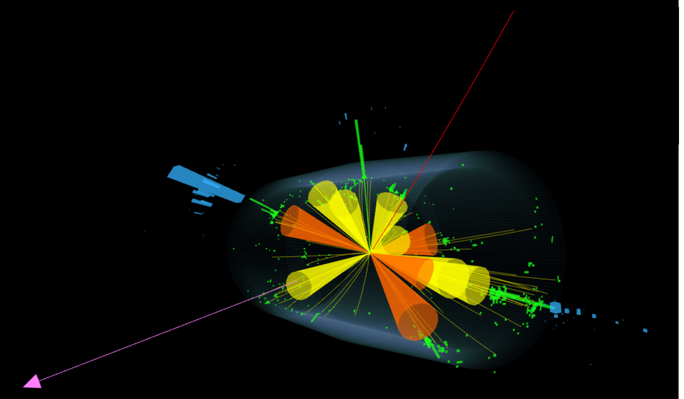
- UParT: $> 3\times$ better light-jet rejection over DeepJet
- ParticleNet: $> 10\%$ higher prompt lepton efficiency at low p_T
- Cut-based approach yields $\sim 11\%$ improvement in expected significance:

$$3.62\sigma \xrightarrow{\text{UParT}} 3.93\sigma \xrightarrow{+\text{ParticleNet}} 4.01\sigma$$

Next steps

- Extend analysis to full $13\,\mathrm{TeV}$ dataset
- Improved machine learning for background suppression
  - Better understanding of $\mathrm{t\bar{t}t\bar{t}}/\mathrm{ttt}$ interference
  - Better separation to backgrounds
- Combine with ongoing $13.6\,\mathrm{TeV}$ analysis for ultimate sensitivity

Backup



Object selection

Electrons

- $|\eta| < 2.5$
- $p_T > 10\,\mathrm{GeV}$
- $\mathrm{miniPFRelIso} < 0.4$
- $\mathrm{sip3d} < 8$
- $d_{xy} < 0.05$
- $d_z < 0.1$
- $n(\mathrm{lostHits}) \leq 1$
- No muon close by ($\Delta R < 0.05$)

Additionally for tight electrons:

- Conversion veto
- Charge consistency
- $\mathrm{electron.mvaTOP} > 0.81$

Muons

- $|\eta| < 2.4$
- $p_T > 10\,\mathrm{GeV}$
- $\mathrm{miniPFRelIso} < 0.4$
- $\mathrm{sip3d} < 8$
- $d_{xy} < 0.05$
- $d_z < 0.1$
- isGlobal
- isTracker
- isPFCand
- mediumID (cut-based ID)

Additionally for tight muons:

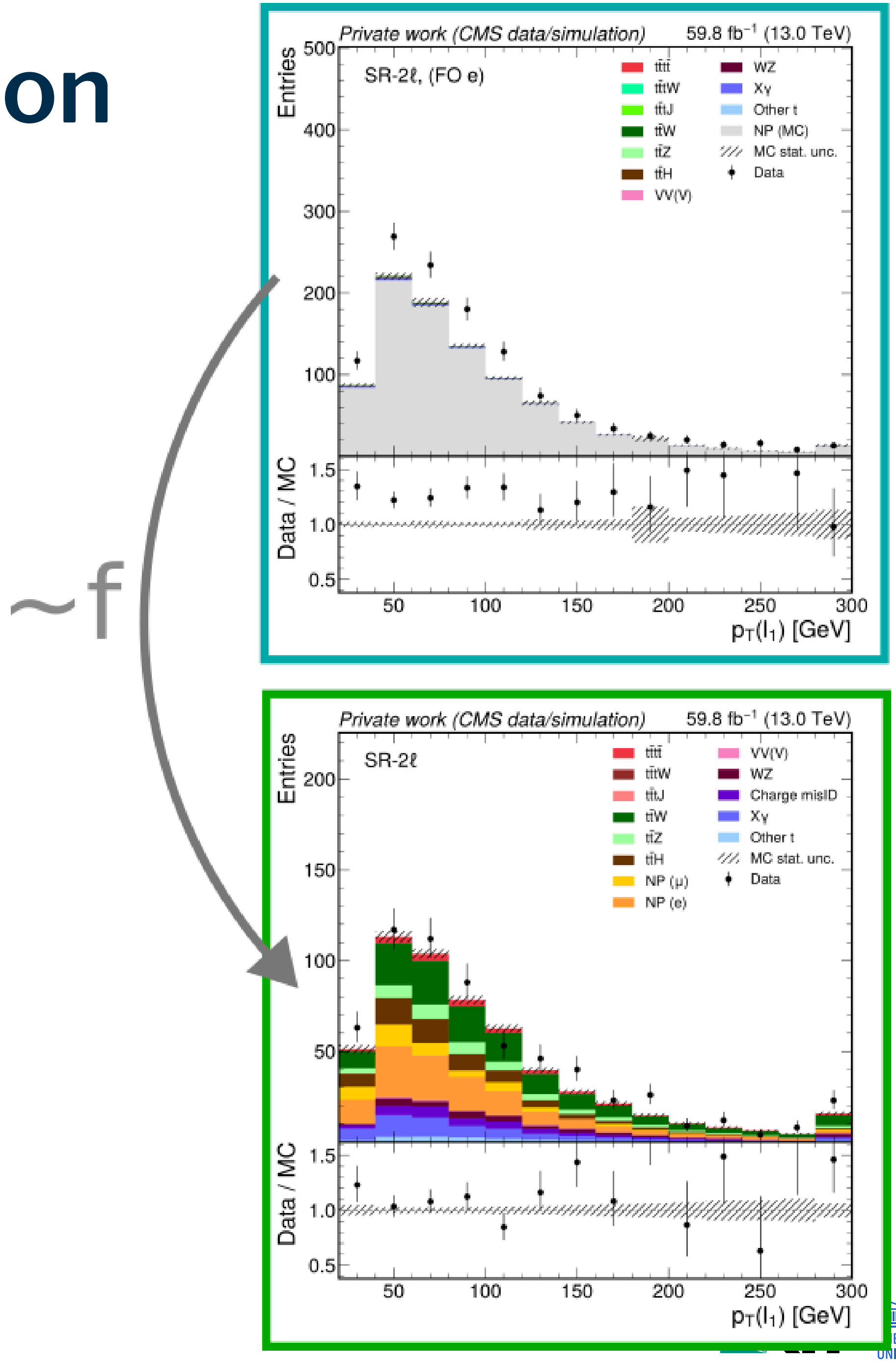
- $\mathrm{muon.mvaTOP} > 0.64$

Jets

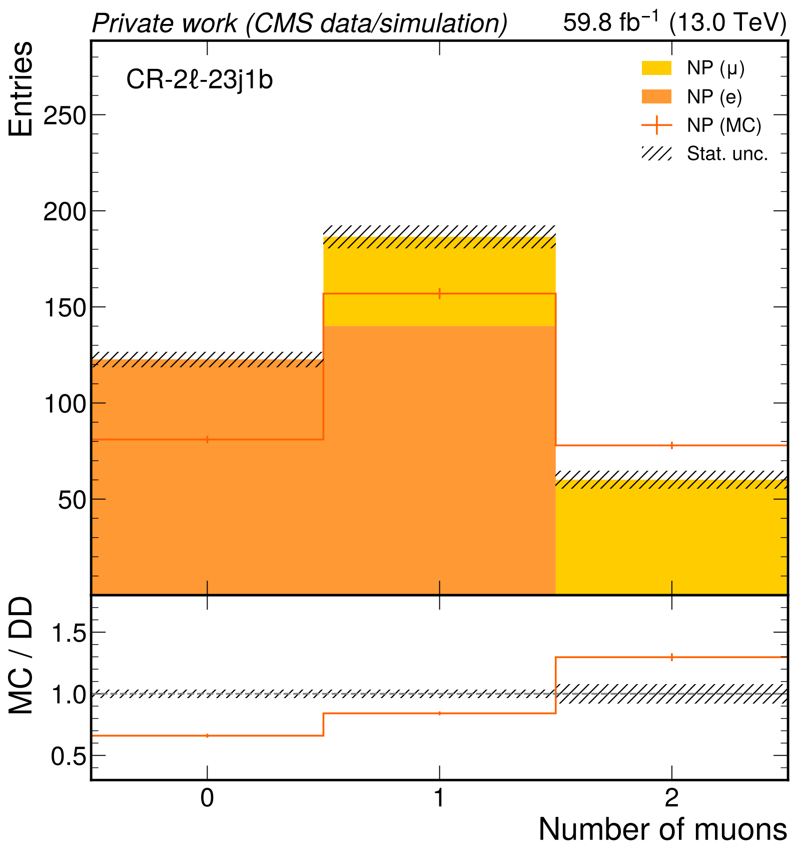
- $p_T > 25\,\mathrm{GeV}$
- $|\eta| < 2.4$
- $\mathrm{JetID} >= 2$ & $\mathrm{puID} >= 4$
- lepton ΔR veto

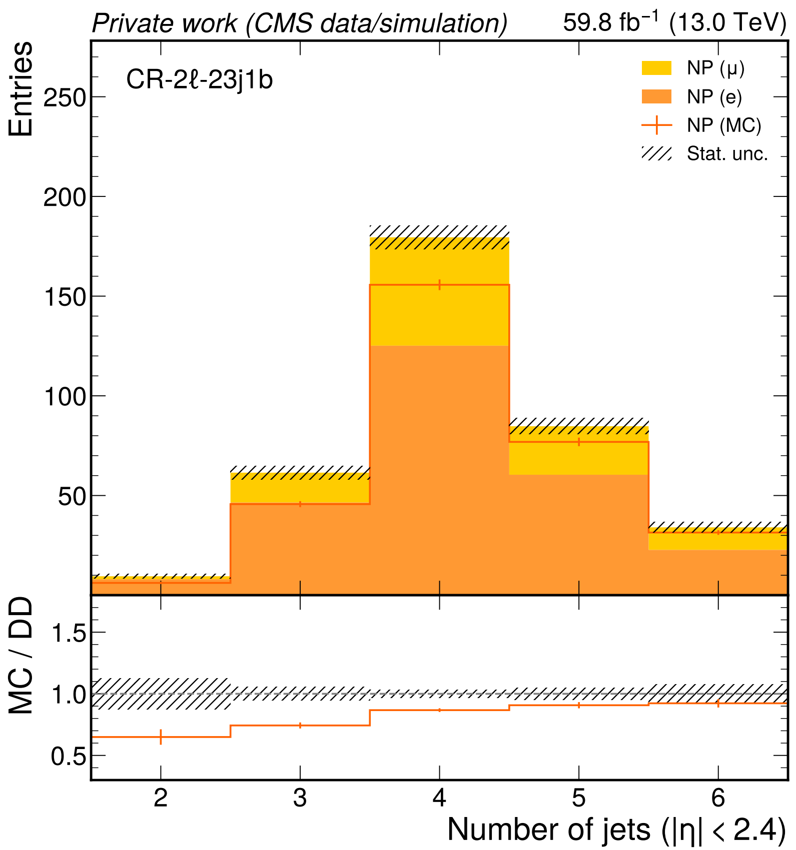
Nonprompt background: Estimation

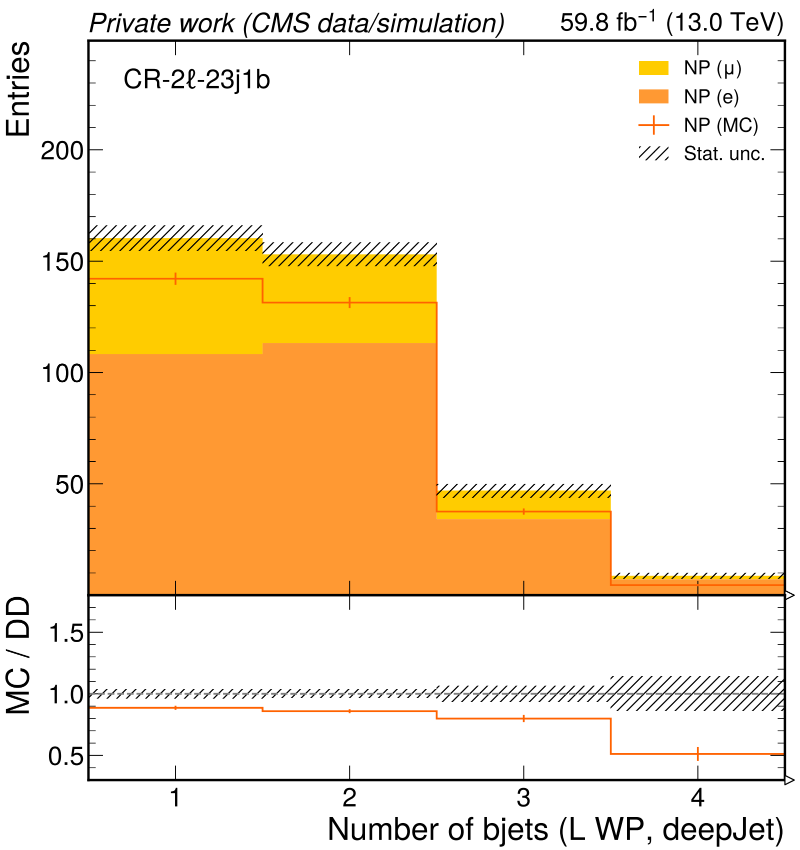
- Data-driven approach based on a sideband technique
  - Tight lepton selection: used to predict prompt MC contribution
  - Fakeable object (FO) lepton selection: looser version of tight selection; enriched in nonprompt leptons
- Measure *f* = probability for NP & FO lepton to pass tight definition
- Weight data in sideband region with factors of *f*



Nonprompt estimation: Comparison to MC-driven





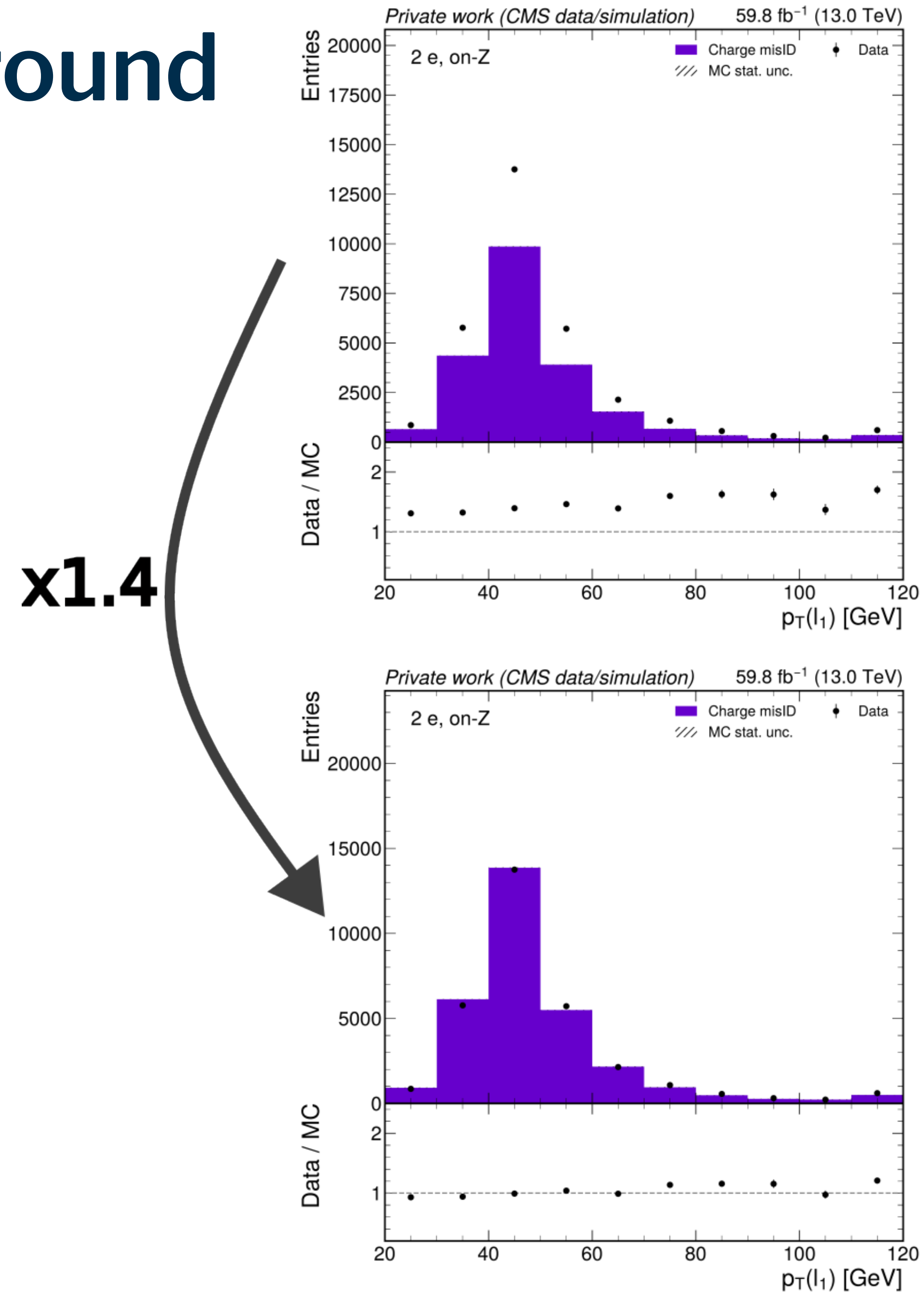


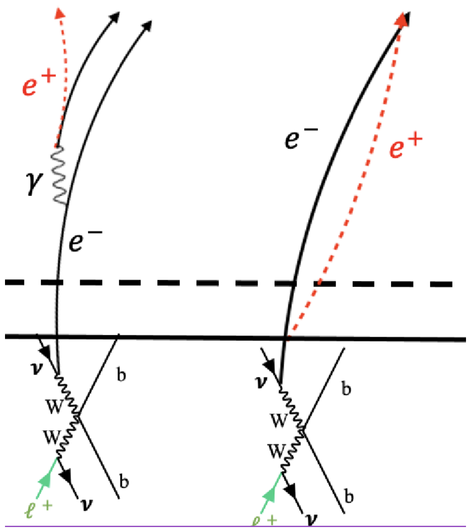
Charge misidentification background

- Electrons can be charge-misidentified (CMID) due to small curvature or bremsstrahlung

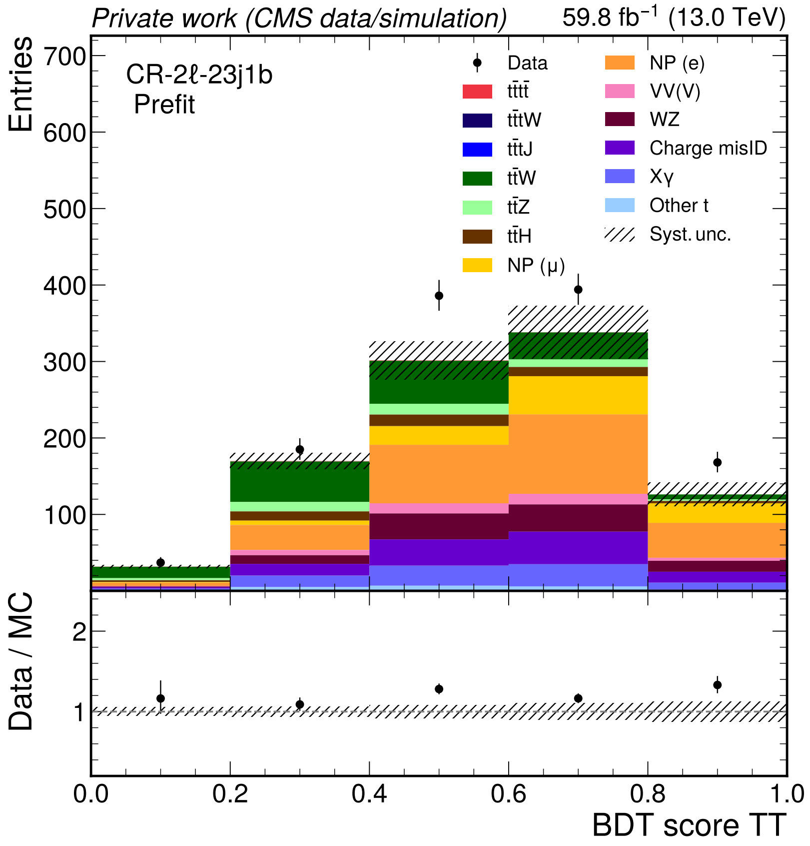
Semi-data-driven method

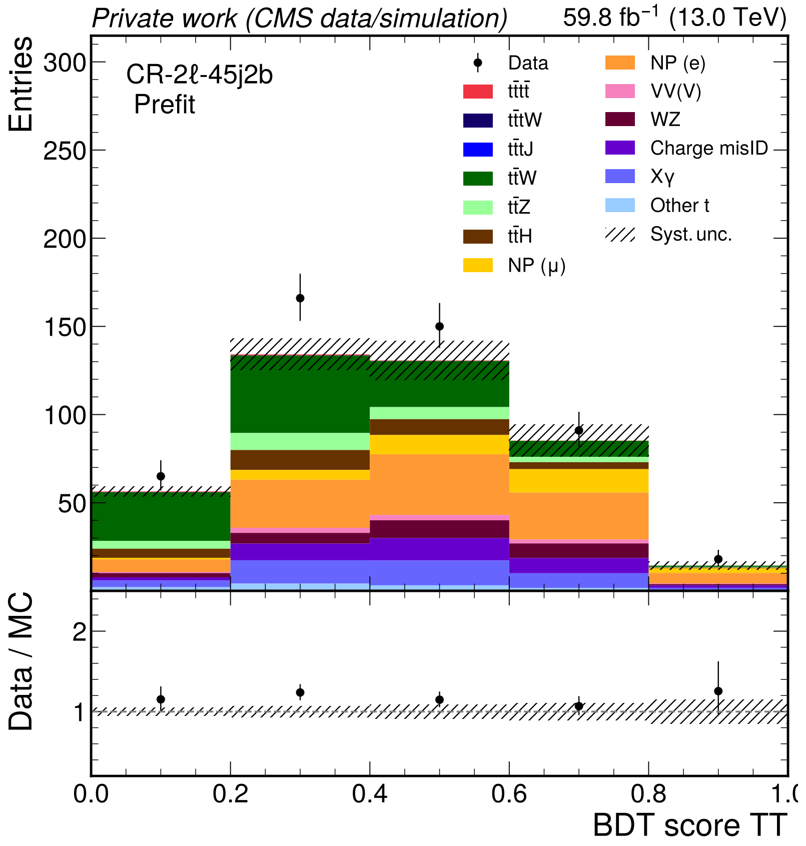
- estimate CMID probabilities in simulated Z+jets events
- flat correction factor derived in an on-Z region **in data**
- CMID estimate: 2eOS data events, reweighted with corrected probabilities from MC
- Residual trend in Data/“MC” due to Bremsstrahlung

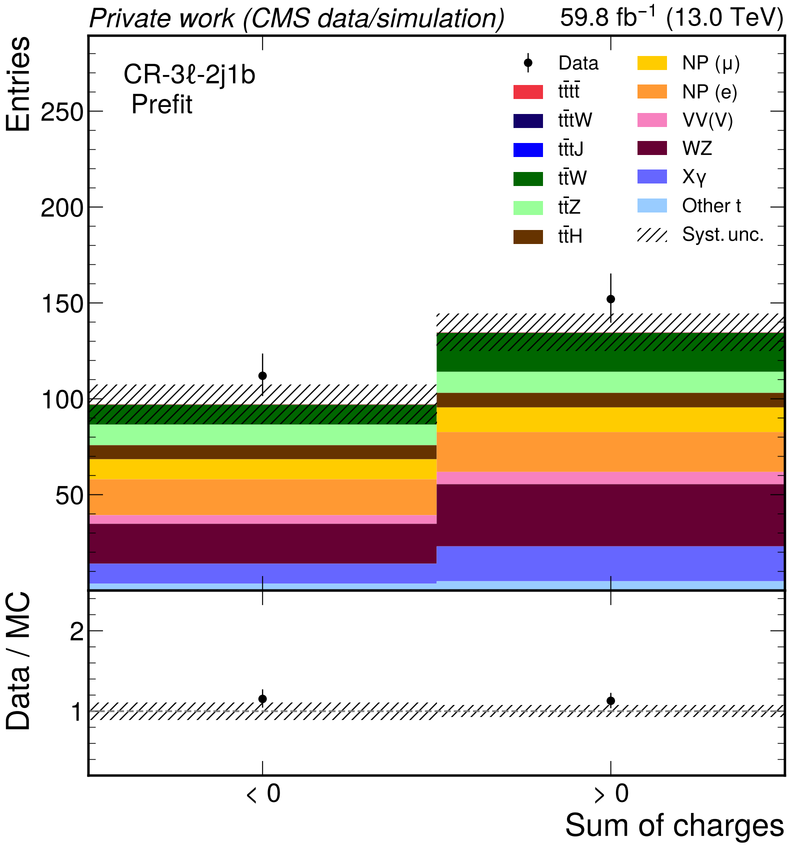




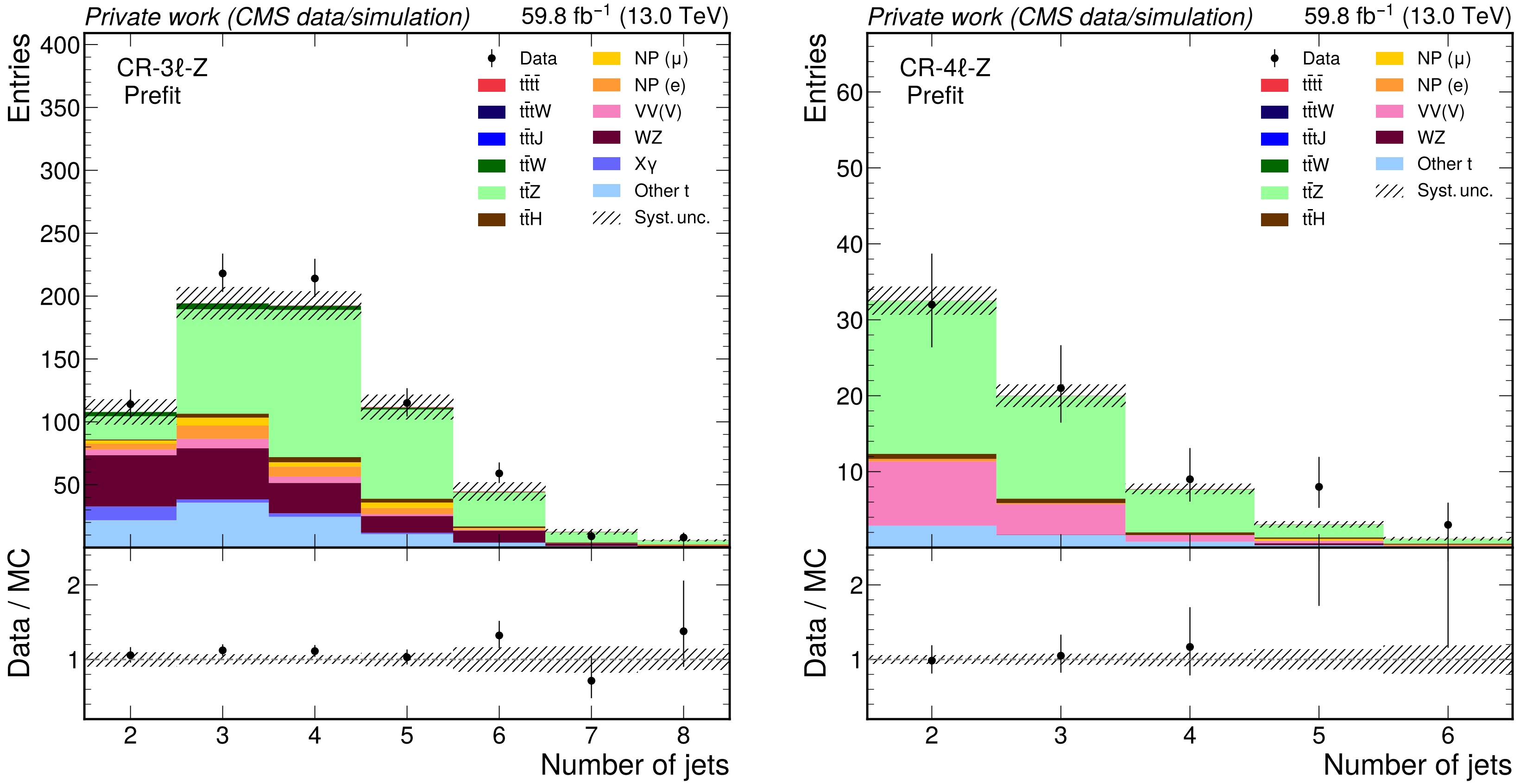
Prefit distributions: Control regions (1/2)



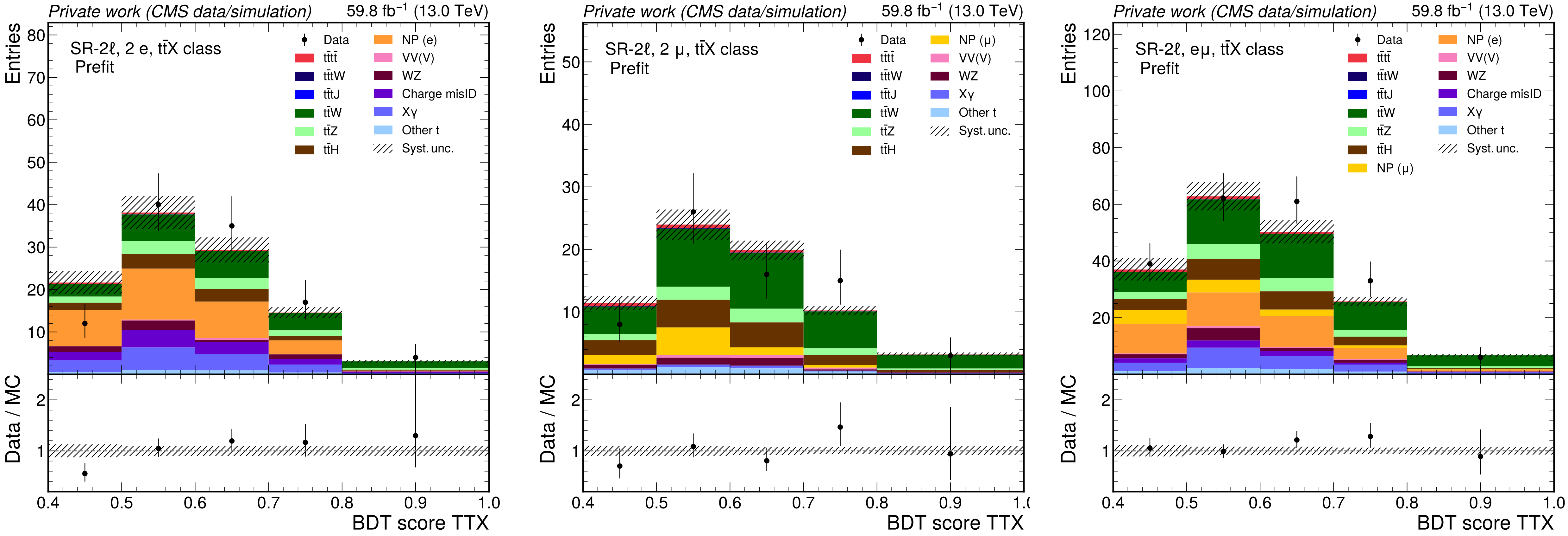




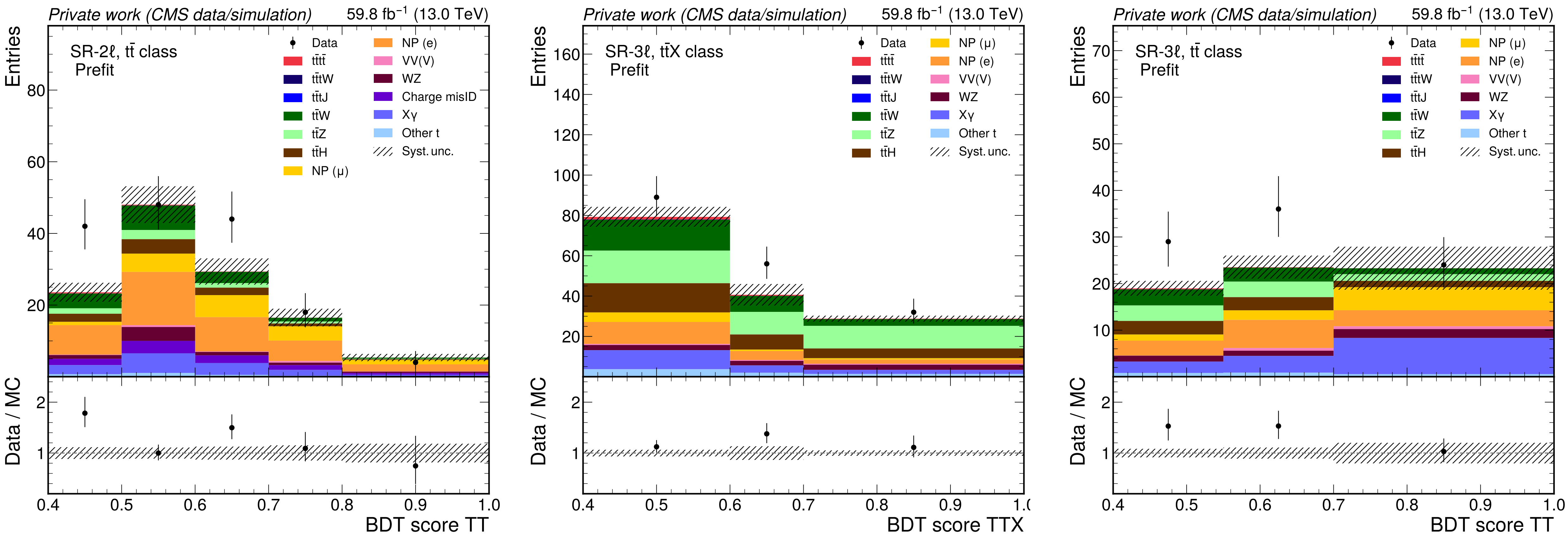
Prefit distributions: Control regions (2/2)



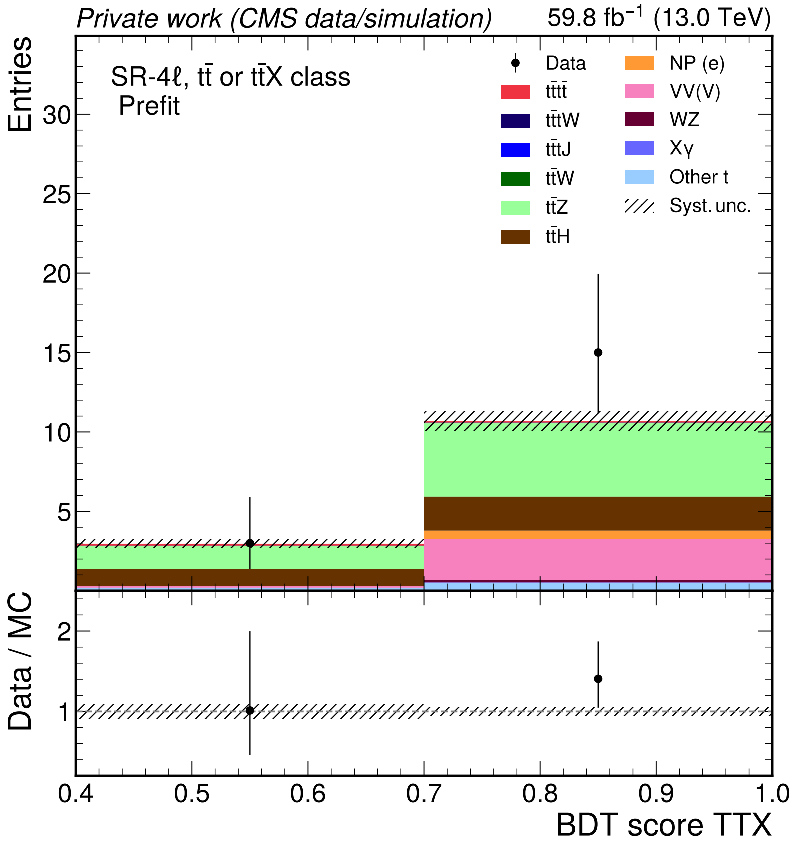
Prefit distributions: Signal regions, bkg. enriched (1/3)



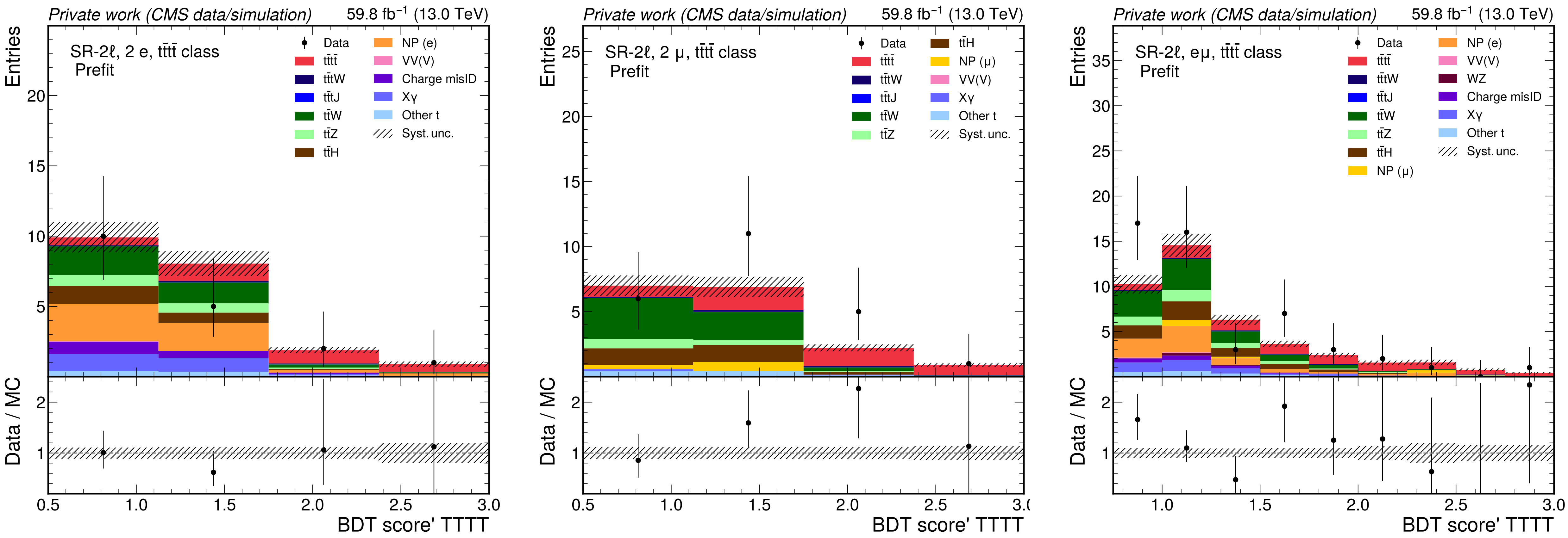
Prefit distributions: Signal regions, bkg. enriched (2/3)



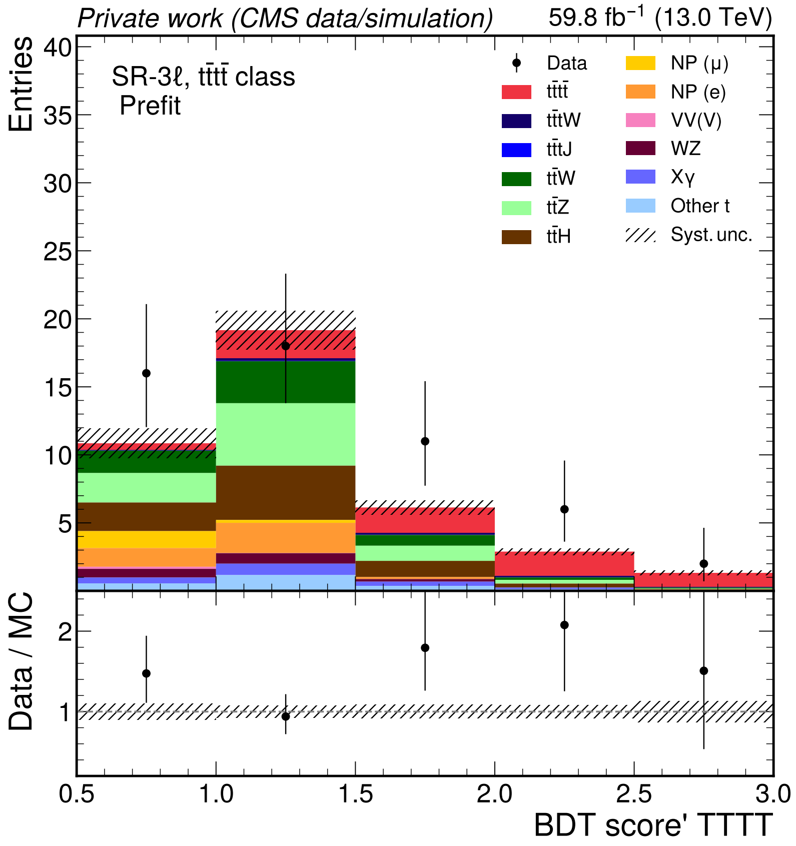
Prefit distributions: Signal regions, bkg. enriched (3/3)

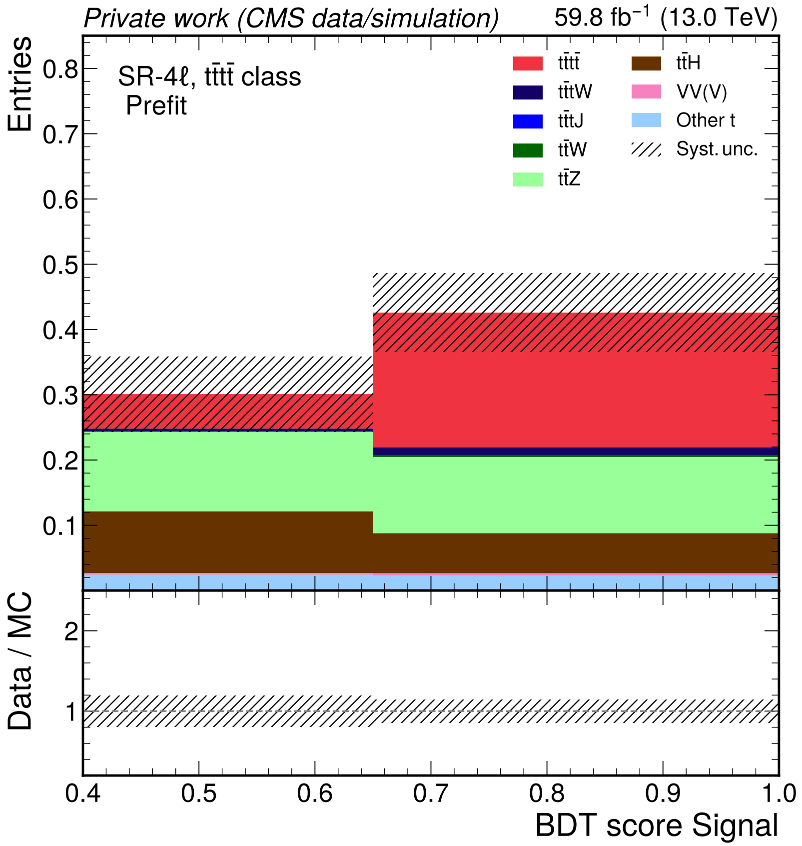


Prefit distributions: Signal regions, signal enriched (1/2)

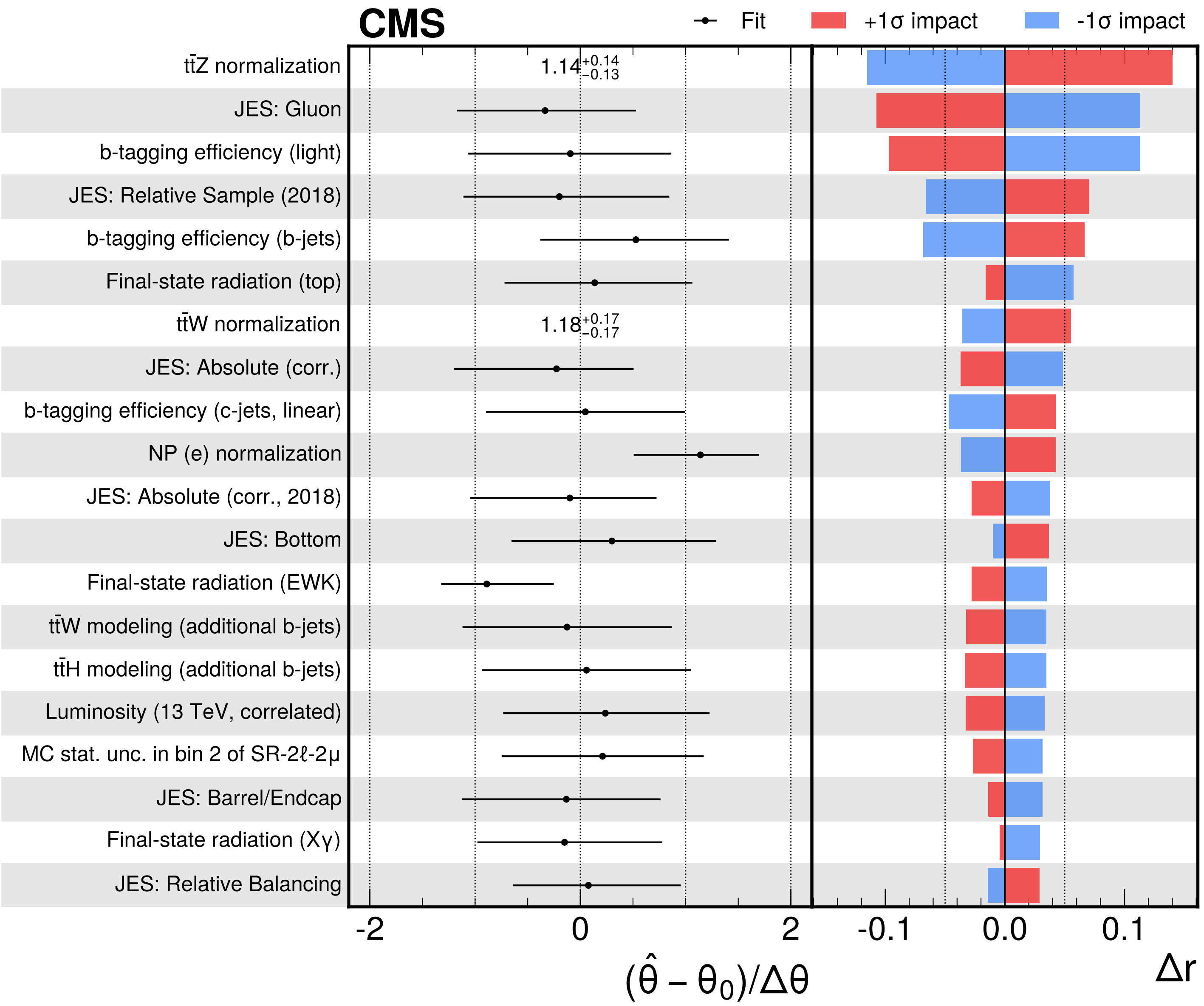


Prefit distributions: Signal regions, signal enriched (1/2)

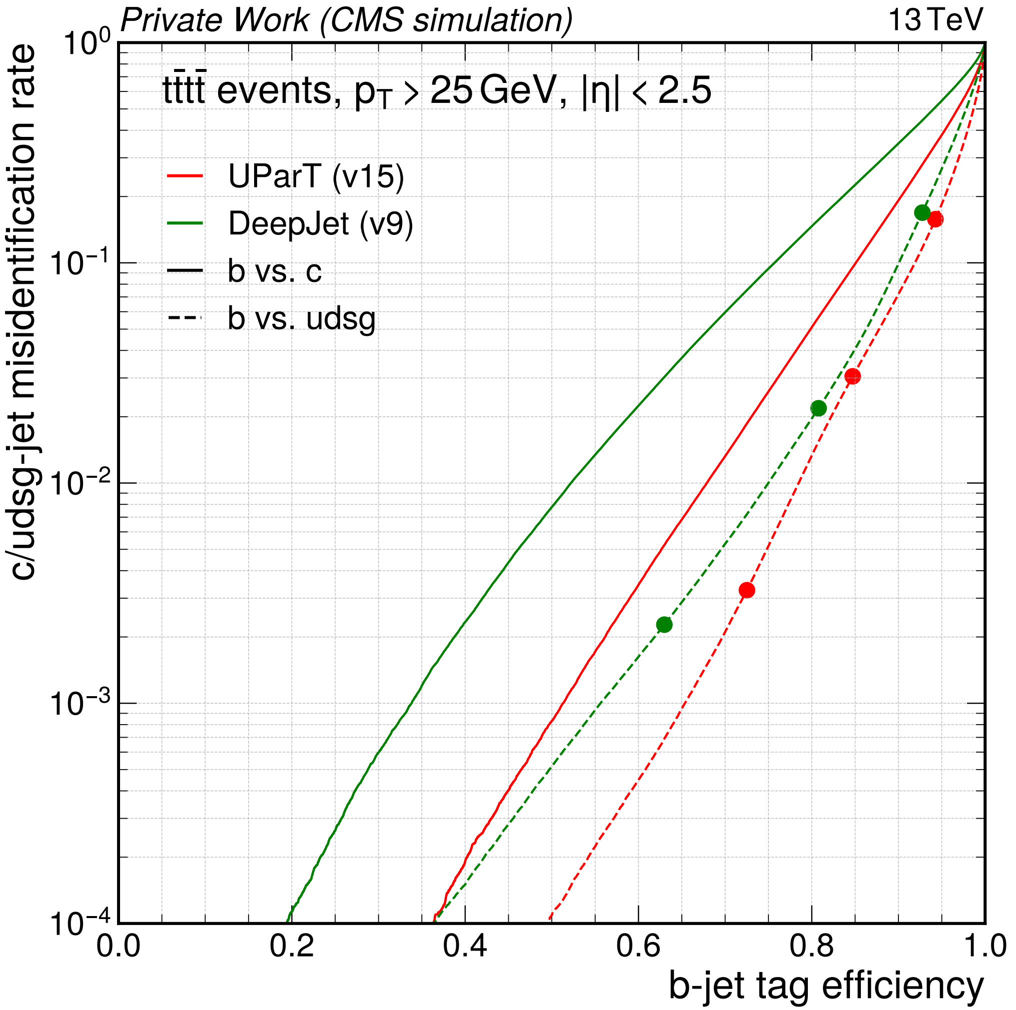


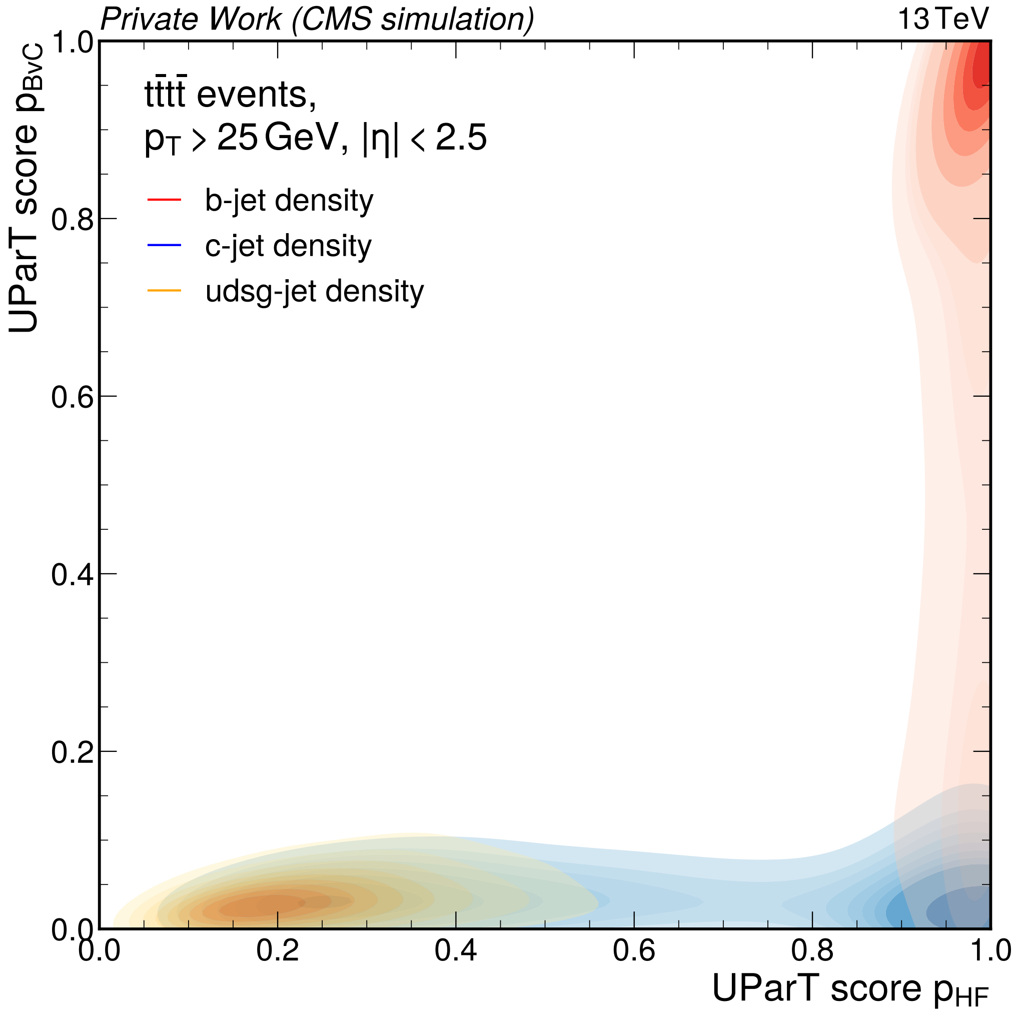


Impact of systematic uncertainties

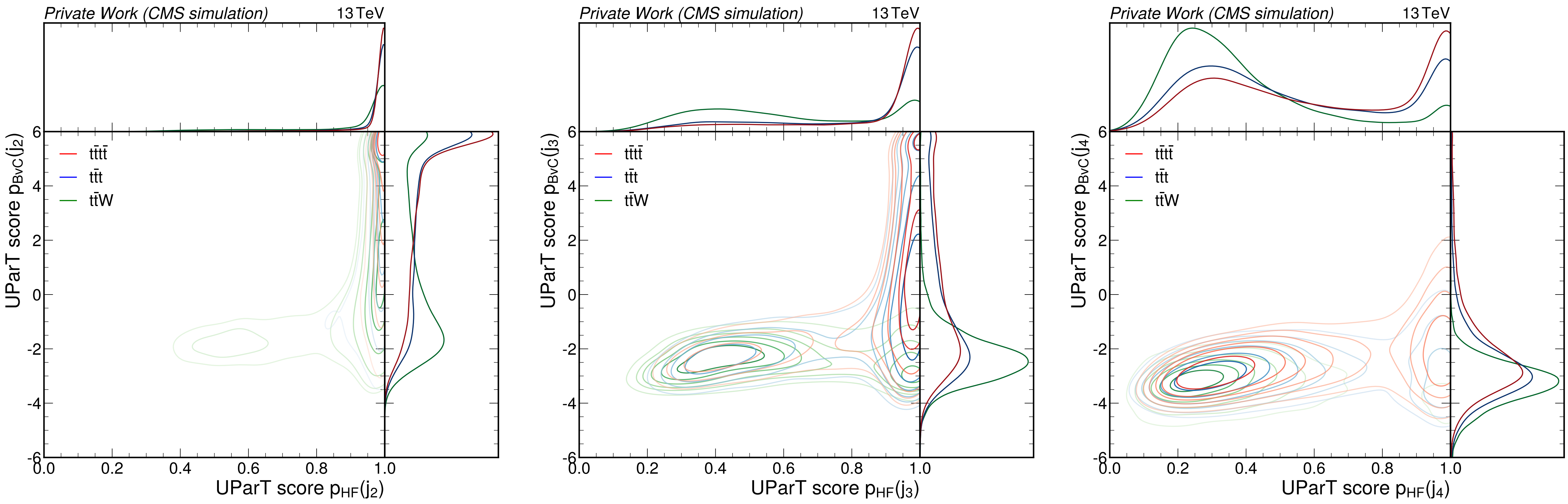


Improved b-tagging

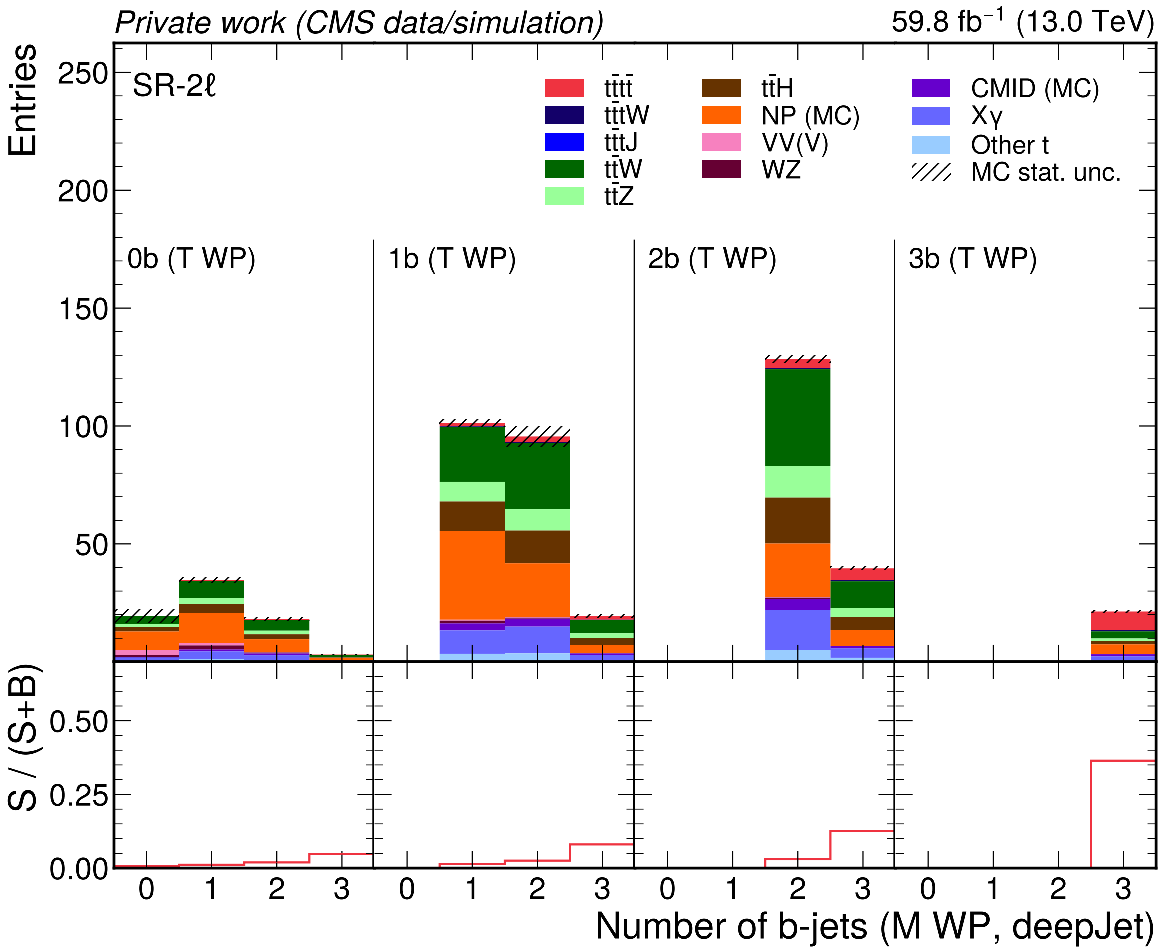


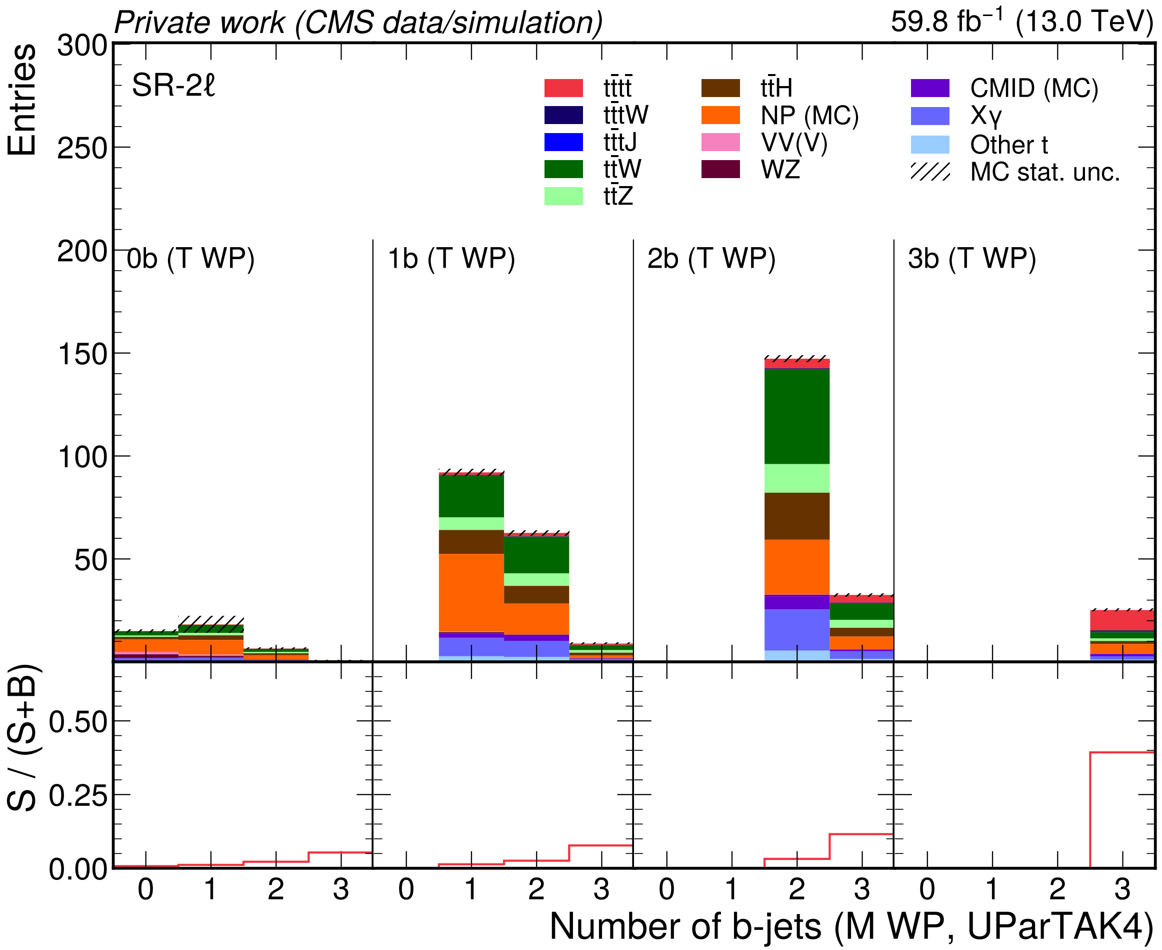


Possible use-case of 2d jet tagging

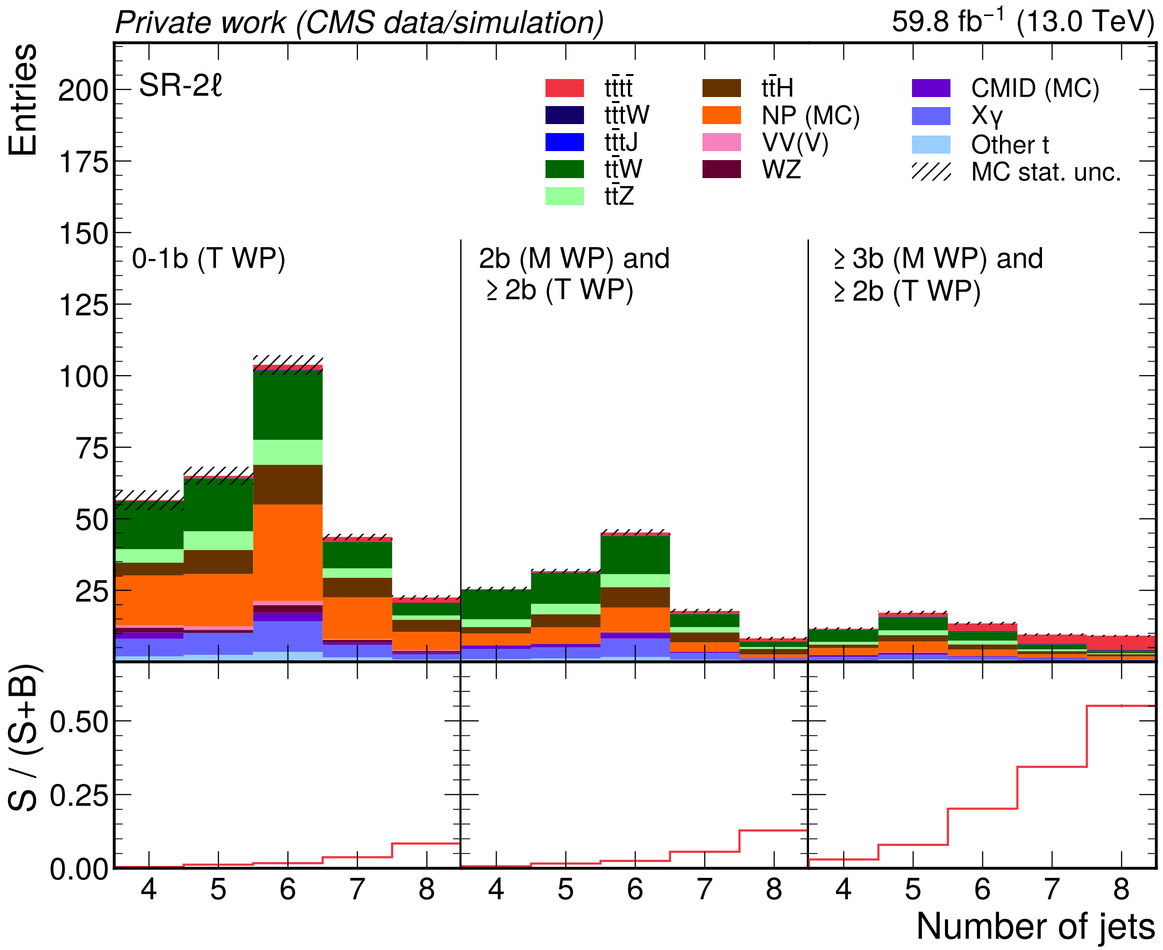


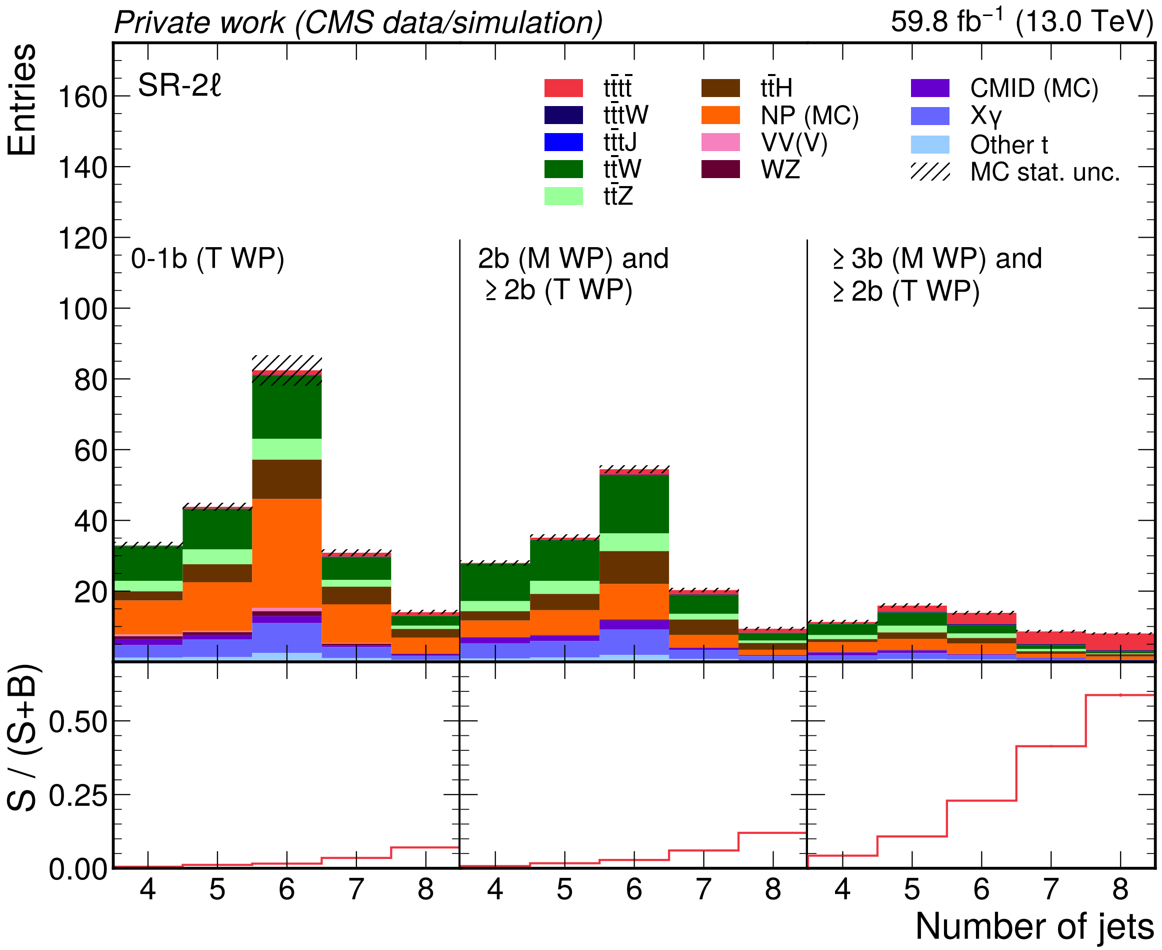
b-jet ID comparison (1/2)



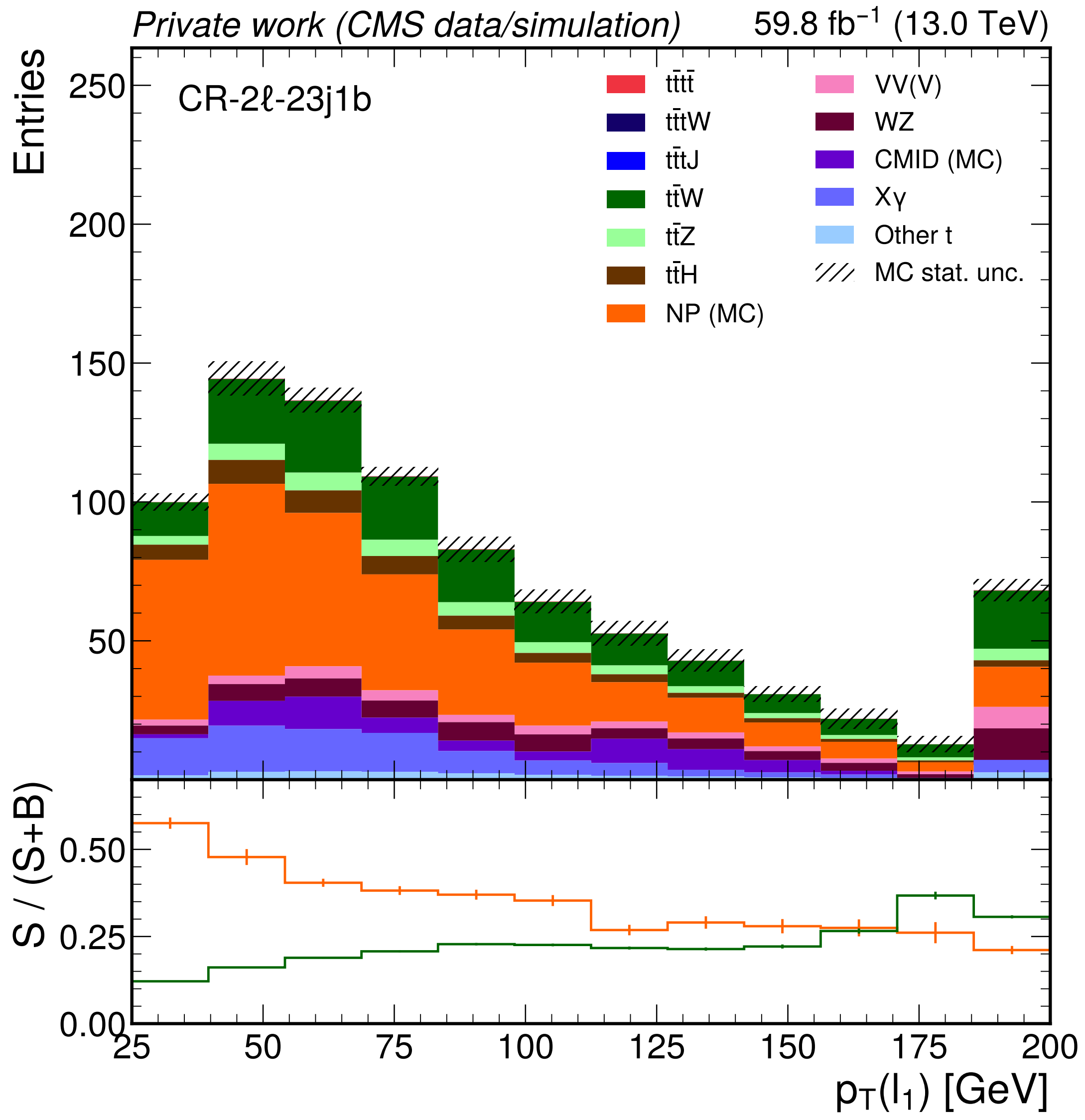


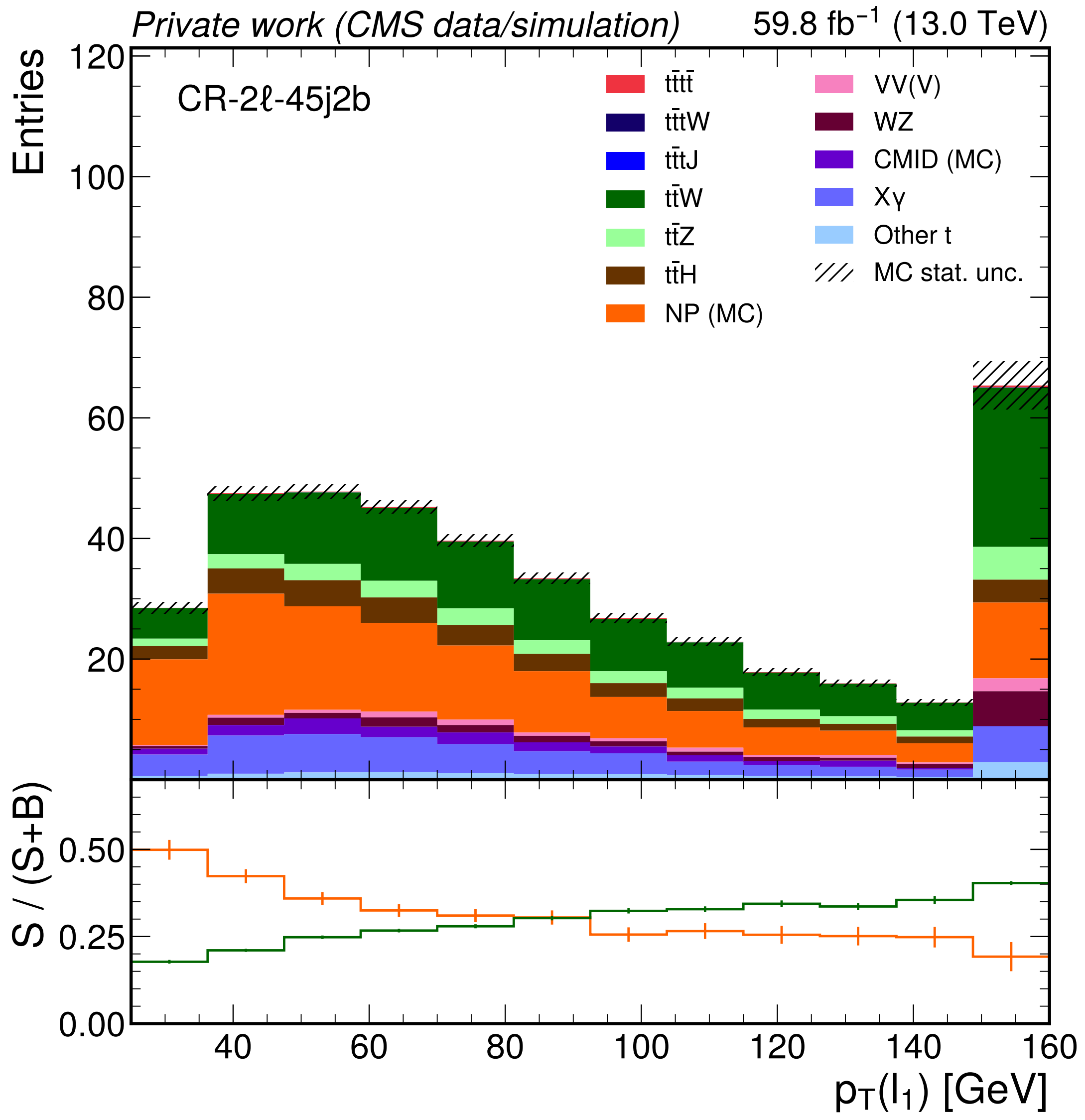
b-jet ID comparison (2/2)





Asimov fit: CR distributions





Improvement studies: test statistic distribution

- $q_0 = -2\ln\frac{\mathcal{L}(r=0,\hat{\hat{\nu}}(r=0))}{\mathcal{L}(\hat{r},\hat{\nu})}$
- Asymptotic approximation: Significance $Z = \sqrt{q_0^{\mathrm{obs}}}$
- Distribution of toy samples clearly deviates from PDF coming from asymptotic approximation