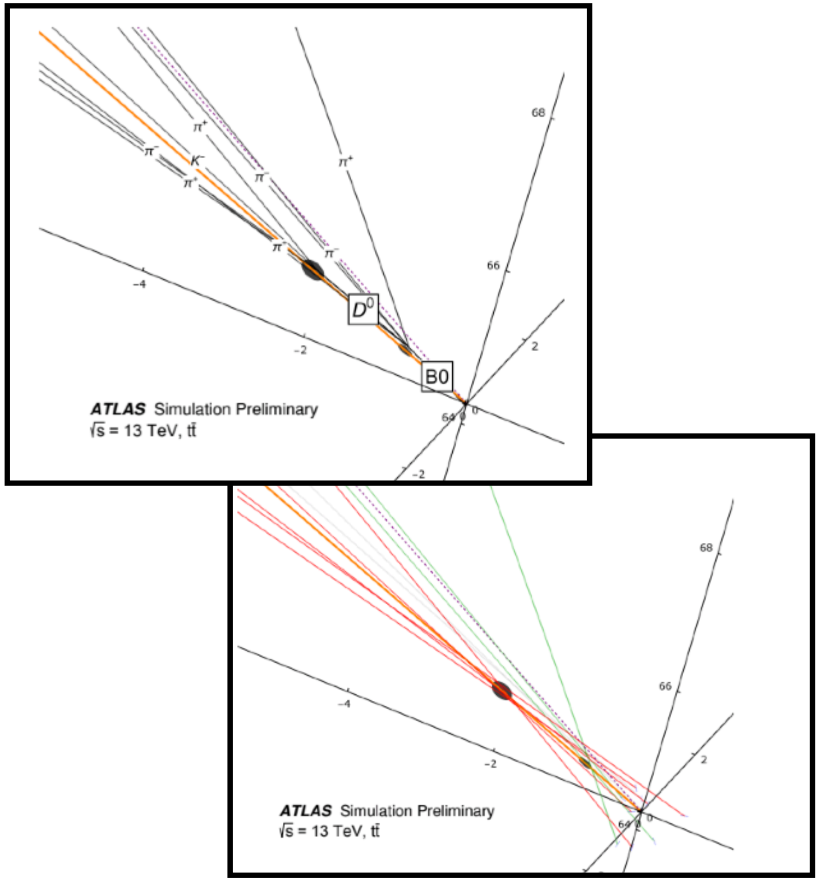
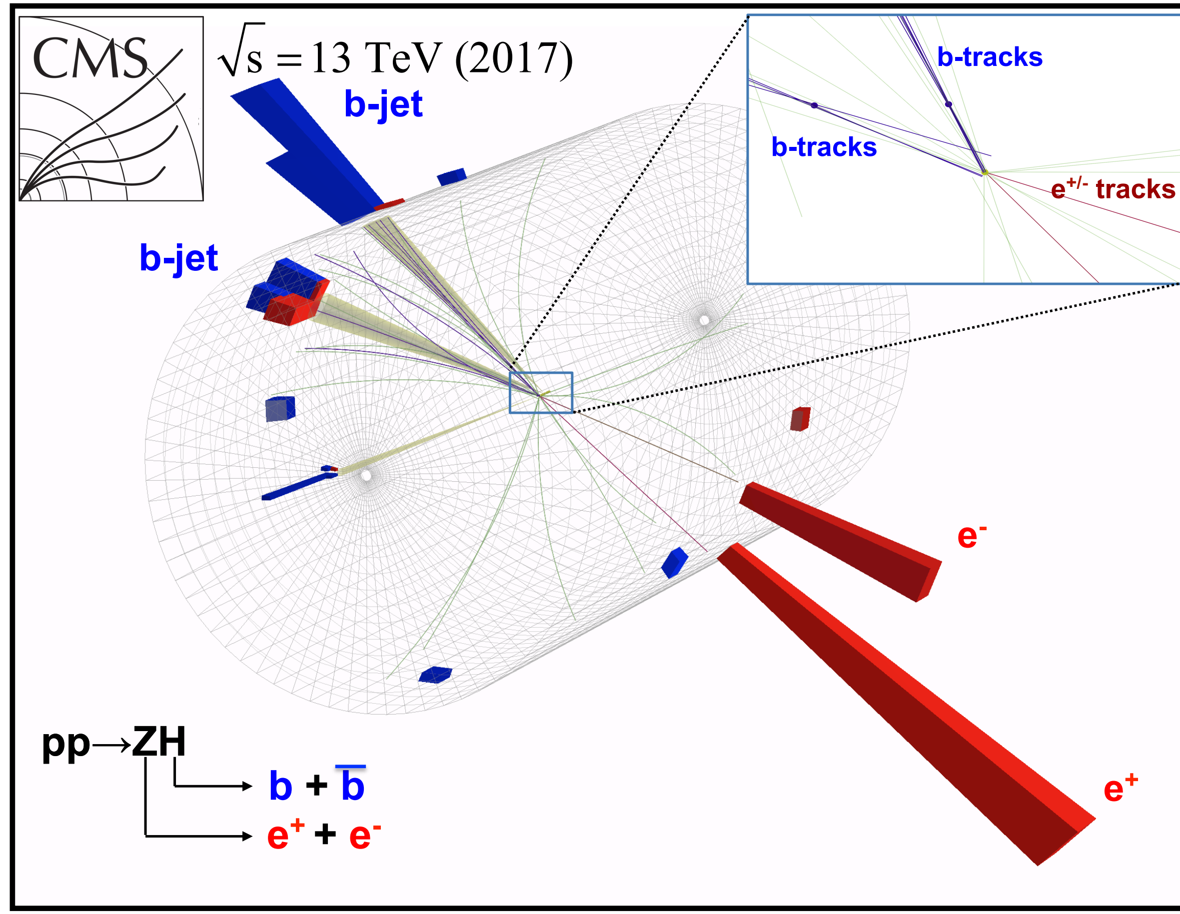




Heavy-Flavor Tagging at the LHC

John Alison

Carnegie Mellon University

Introduction

Heavy Flavor tagging critical element of physics program at LHC

Higgs / Top / Many BSM searches

Challenging, relies on state-of-the-art Machine Learning

Tagging calibration and uncertainties often leading systematics

Outline:

- Heavy Flavor tagging at the LHC
- Recent highlights of Heavy Flavor tagging in Analysis
- Focus on recent developments in calibration.
    - CMS: Calibration Method for charm and b-jet identification
    - ATLAS: Measurement of charm → b fake rate

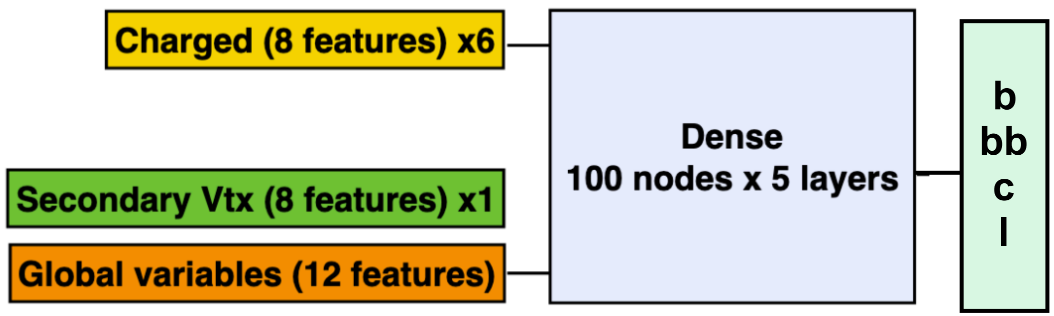
HF Tagging in CMS

Carnegie Mellon University

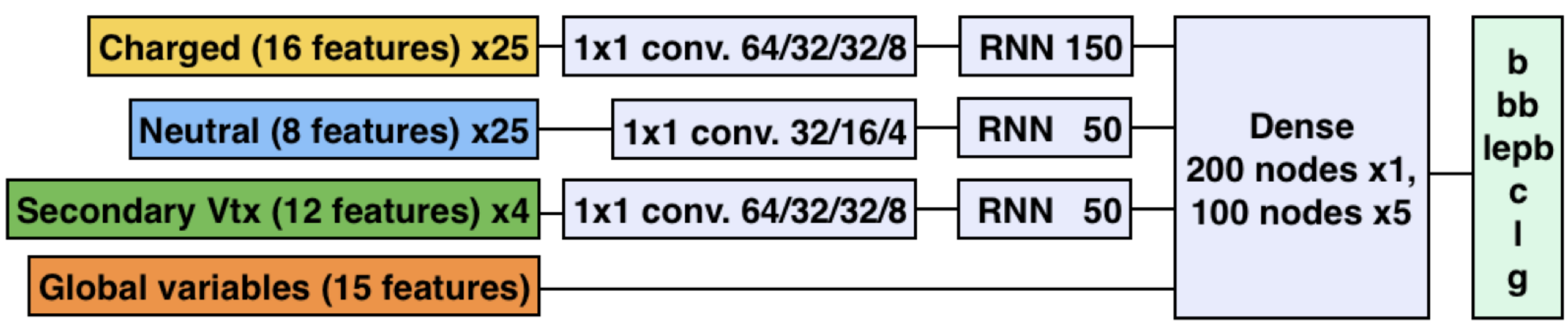
Evolution of Heavy Flavor tagging in Run 2

Theme: *Deeper, fancier networks with lower-level inputs*

DeepCSV:



DeepJet:



HF Tagging in CMS

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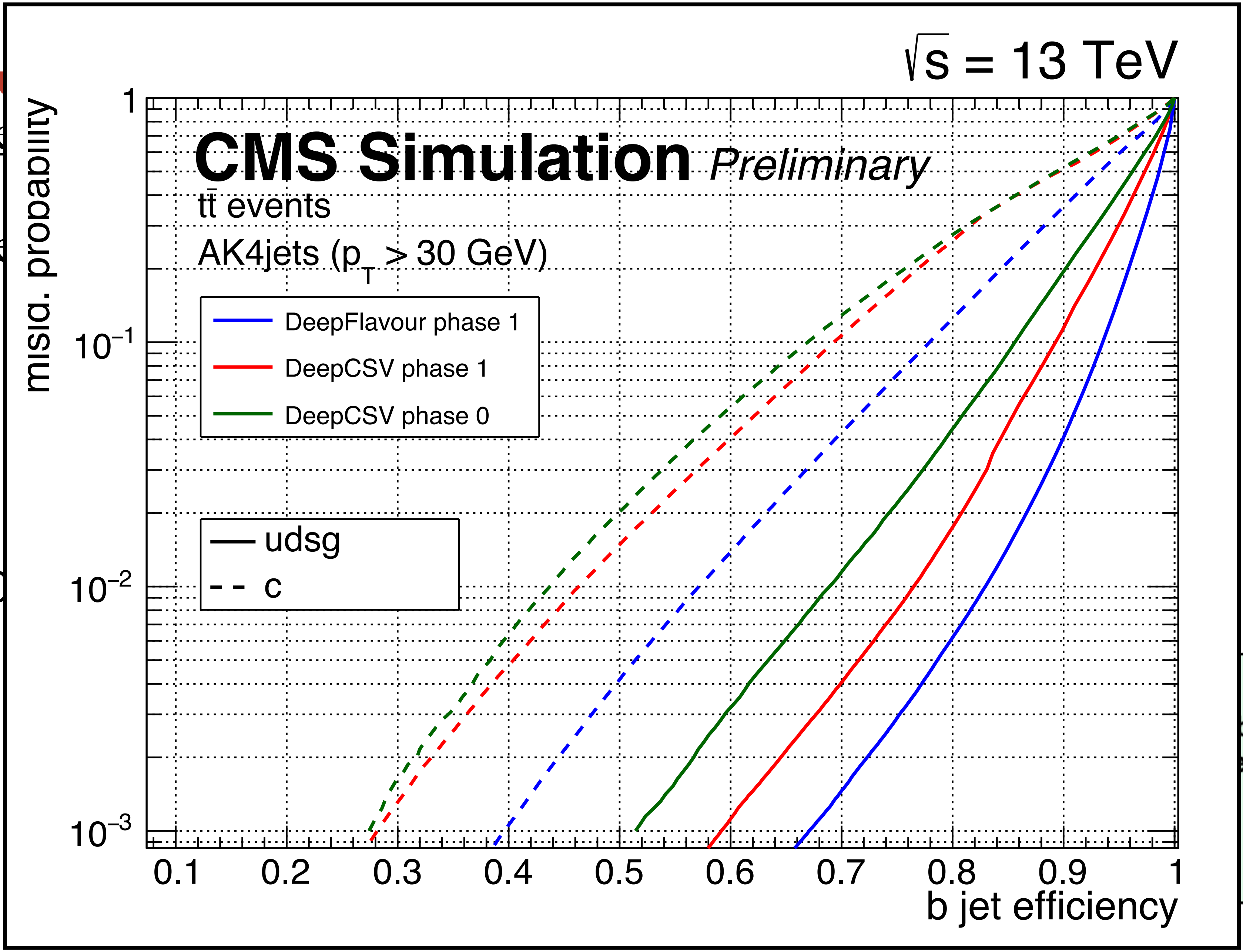

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HF Tagging in CMS

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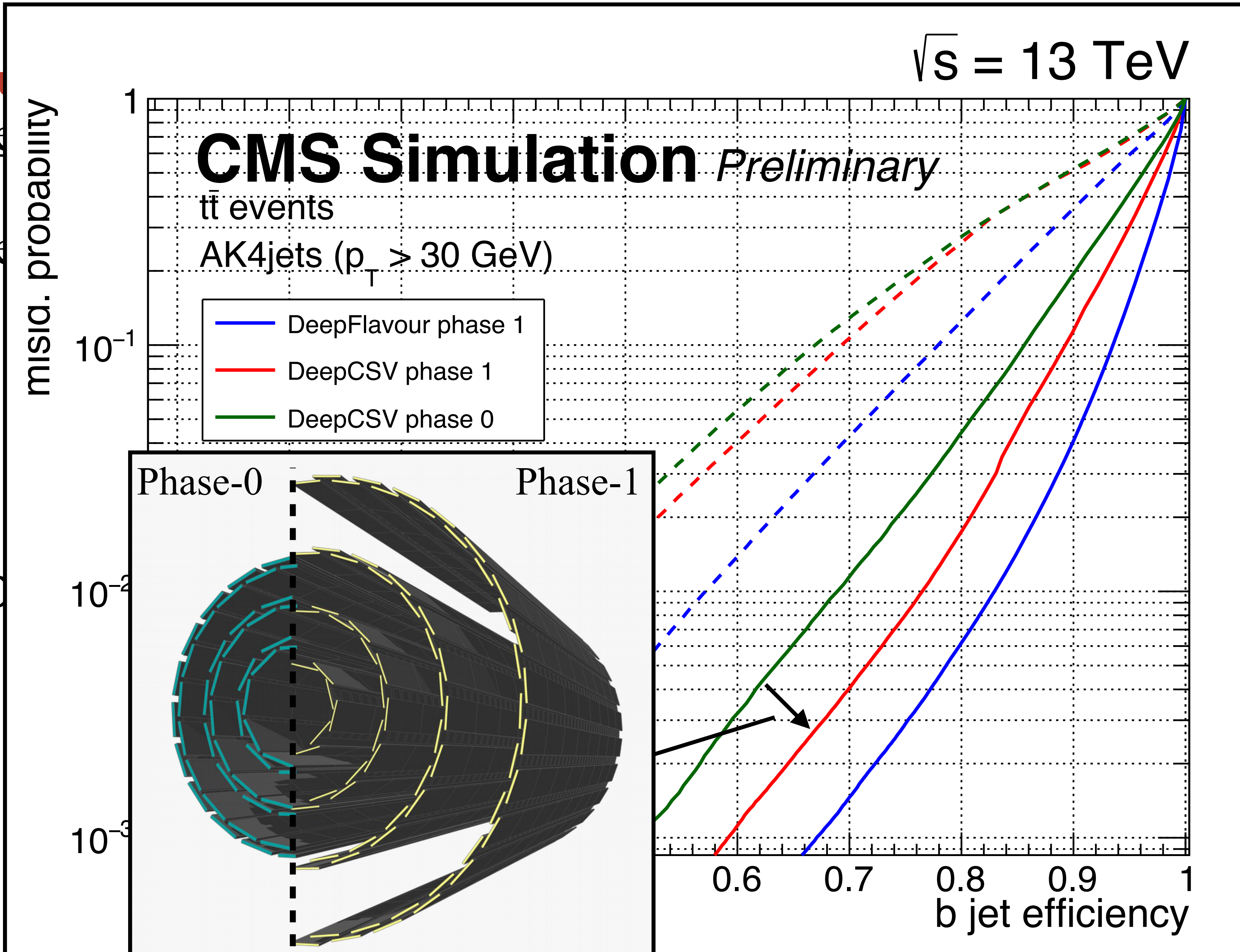

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HF Tagging in CMS

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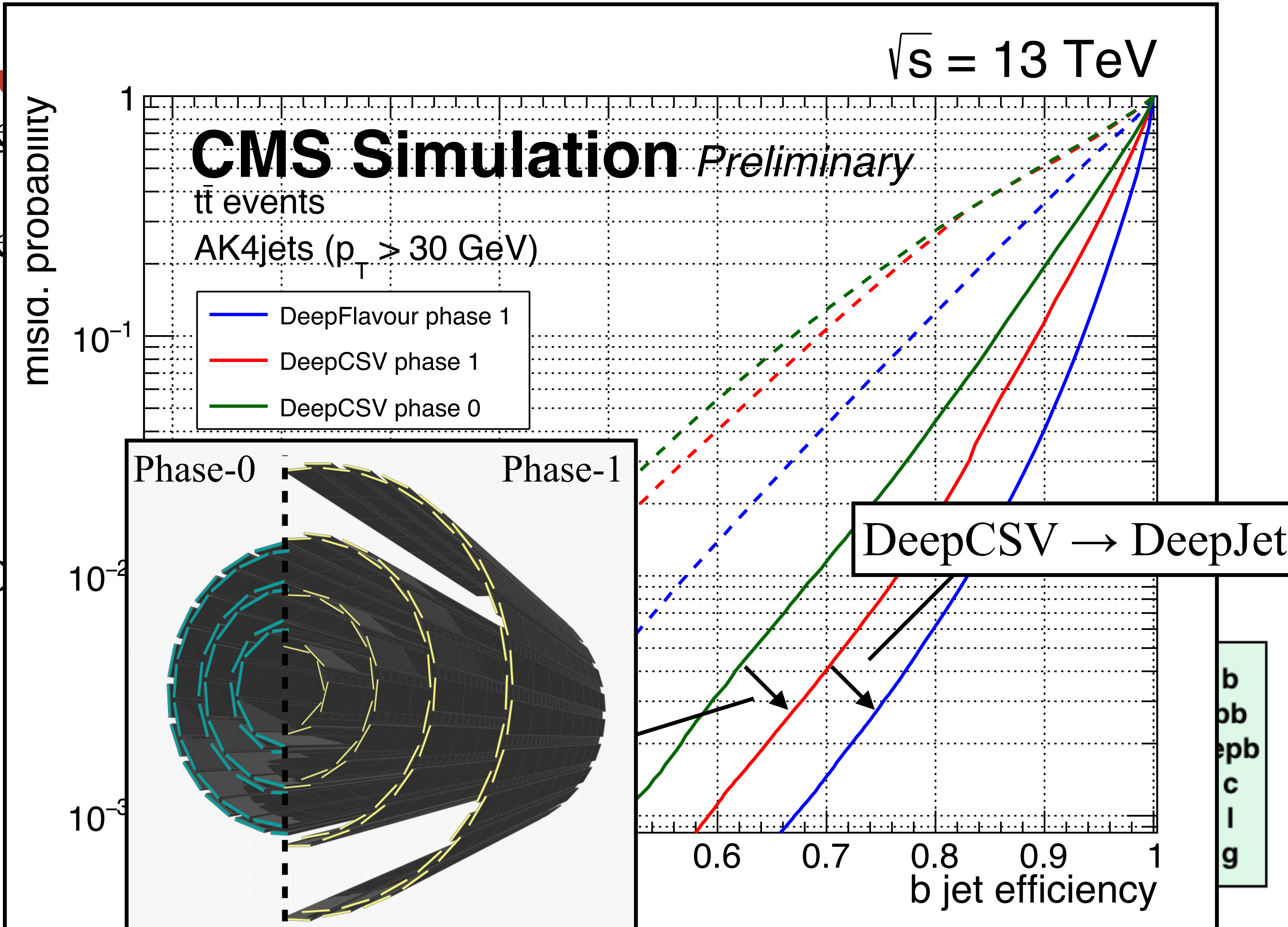

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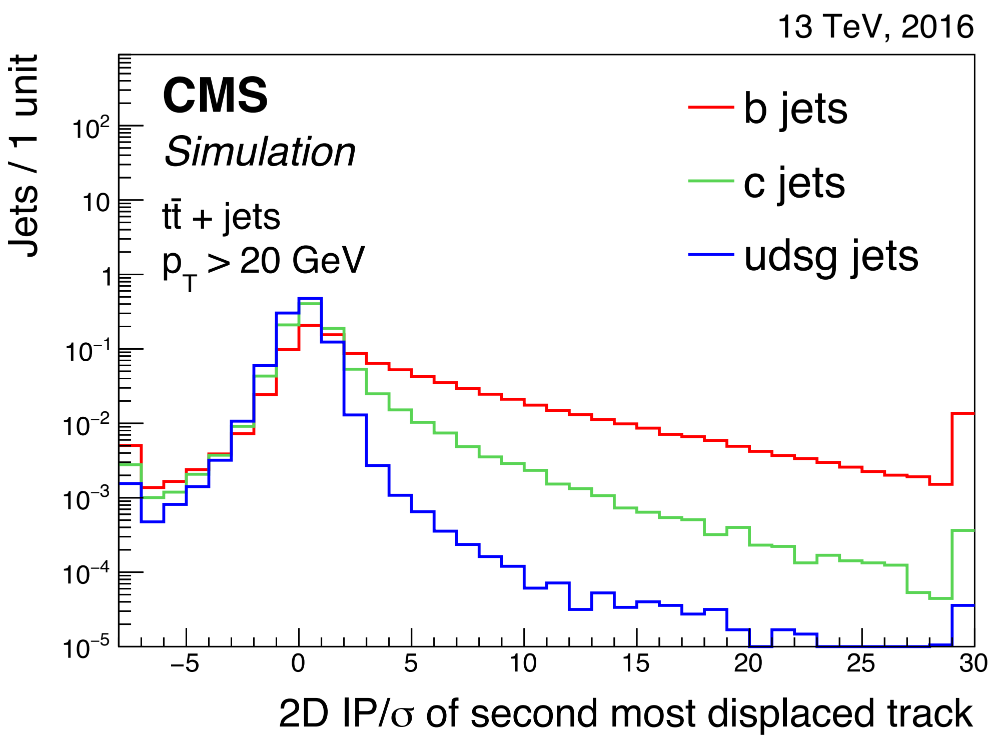
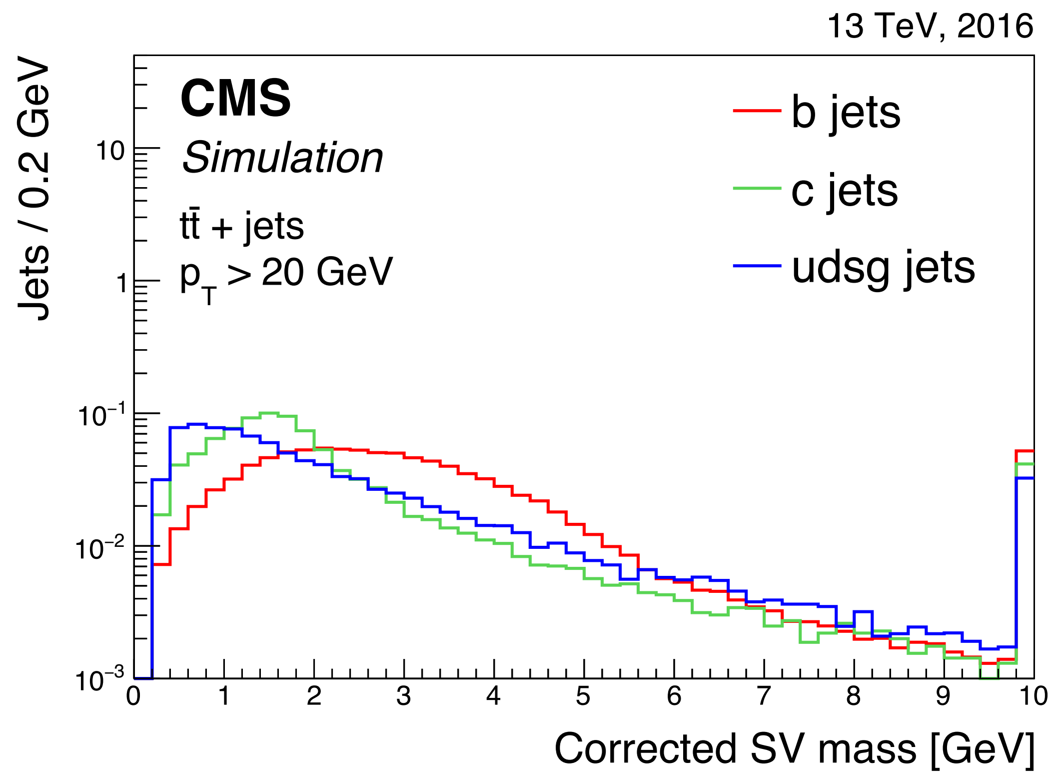
Charm Jet Tagging

Challenging, background from both sides:





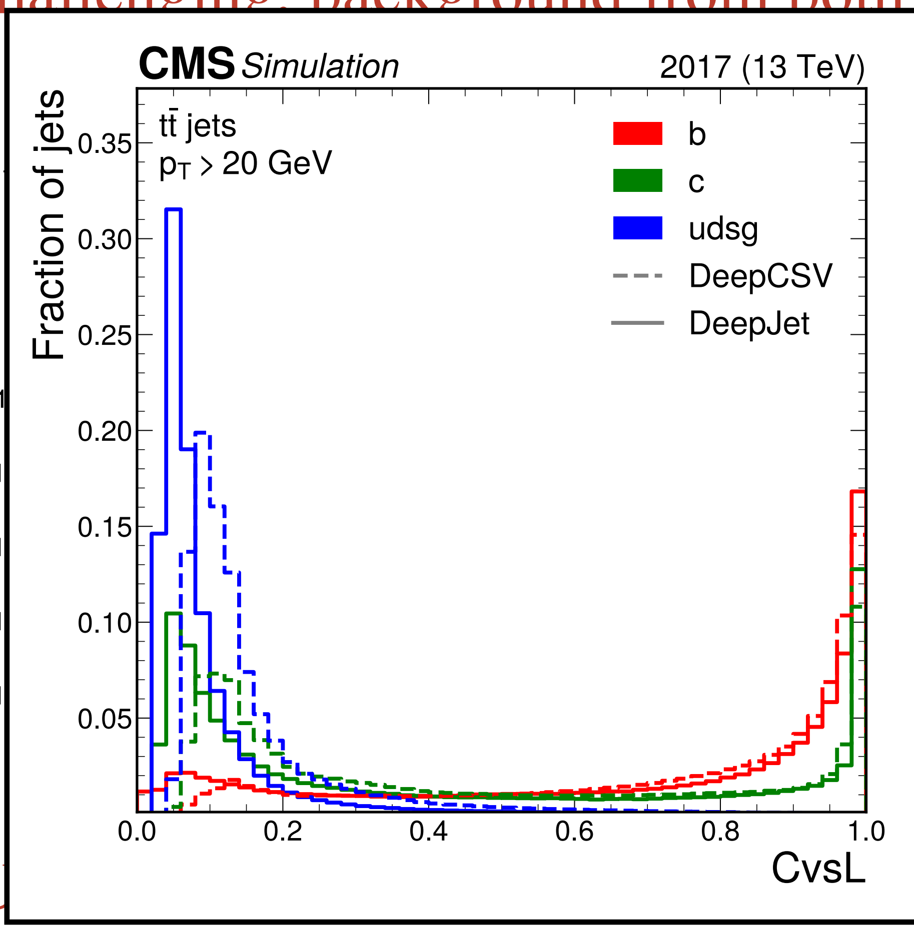
Use DeepJet outputs to define separate charm classifiers:

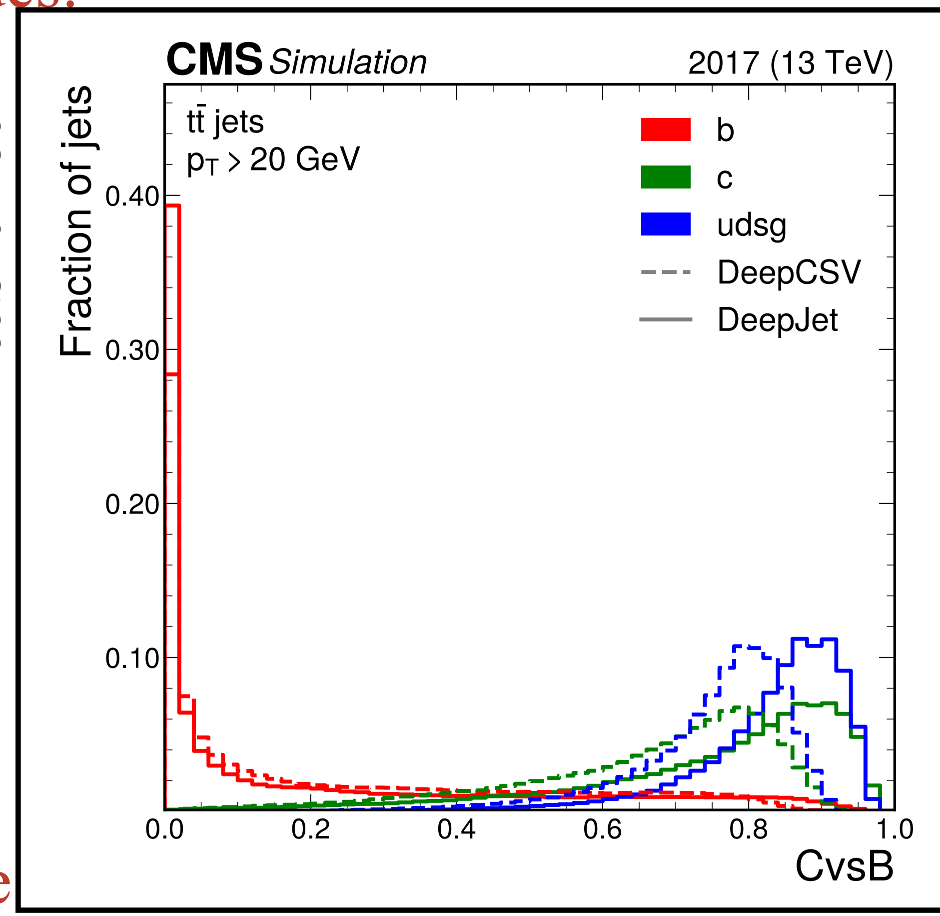
$$\mathrm{CvL} = \frac{\mathrm{P(c)}}{\mathrm{P(c) + P(udsg)}}$$

$$\mathrm{CvB} = \frac{\mathrm{P(c)}}{\mathrm{P(c) + P(b)}}$$

Charm Jet Tagging

Challenging background from both sides:





U rate

$$\mathrm{CvL} = \frac{\mathrm{P(c)}}{\mathrm{P(c)} + \mathrm{P(udsg)}}$$

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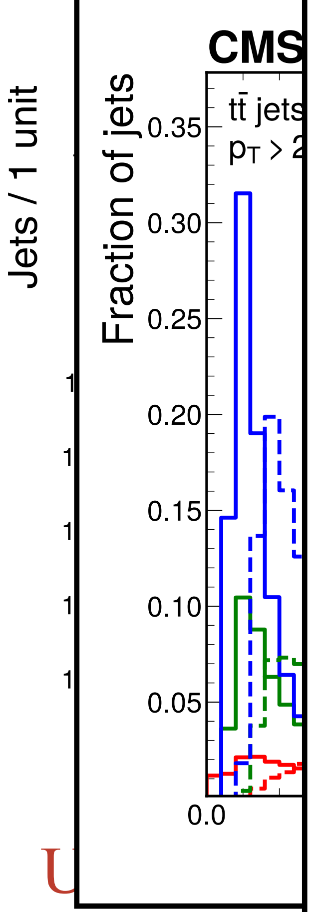
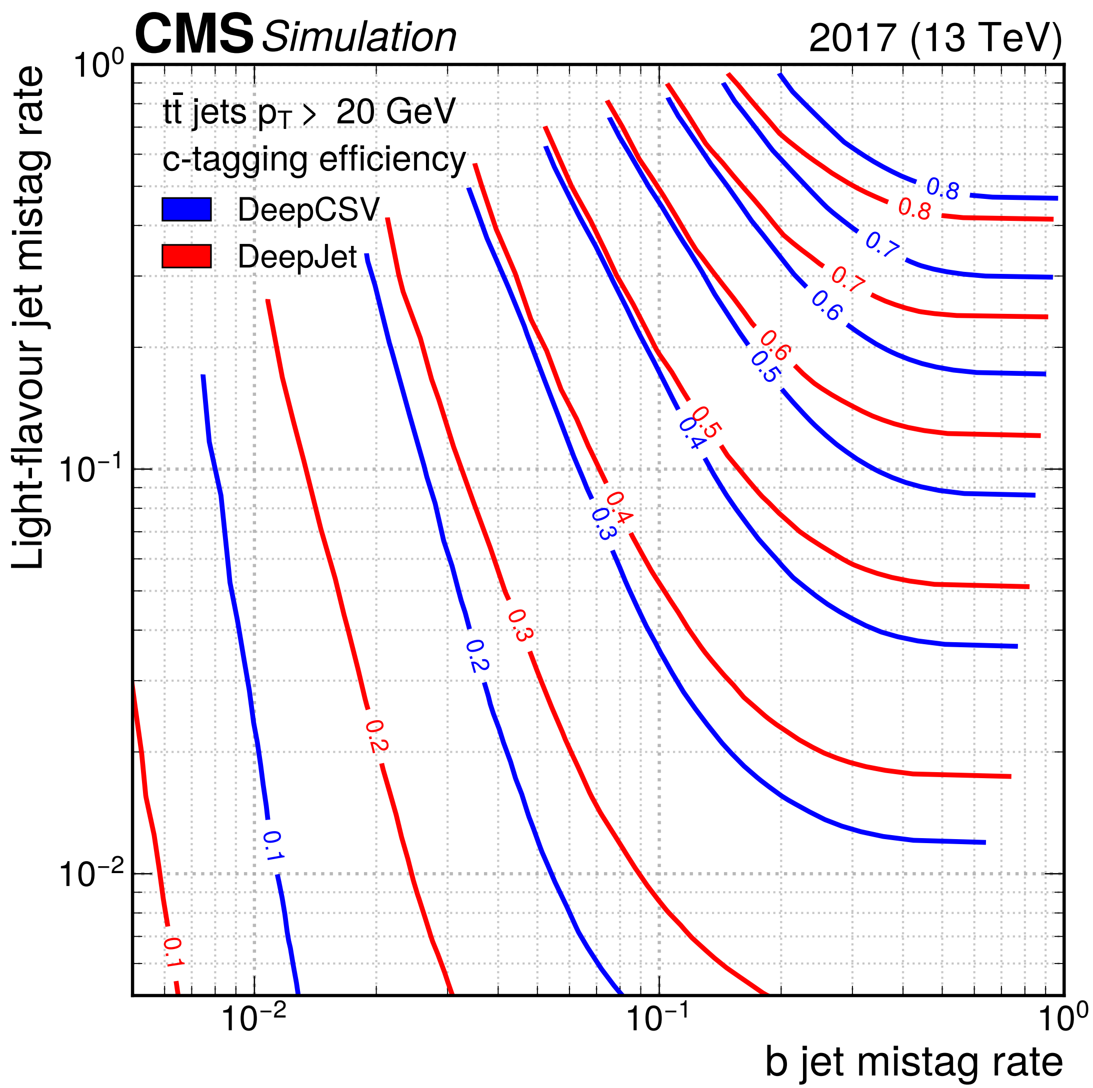
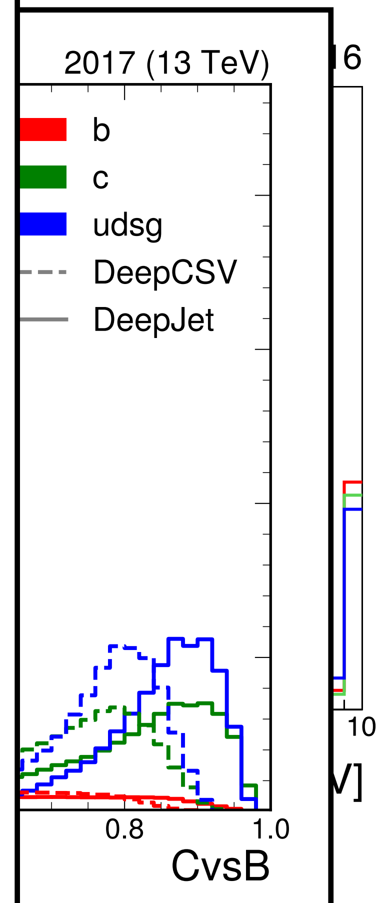
Charm Jet Tagging

Challengin



Inherently 2-dimensional problem.





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HF Tagging at the LHC

Similar story for ATLAS (details in backup)

ATLAS-CMS Flavour Tagging Workshop (Link)

Recent emphasis has been on

- More sophisticated Machine Learning Algorithms
  Graph Networks / Transformers / …
- Increasingly precise calibration
  Measure ε/fake rates in data *(fixed working points)*
- "Deep Calibration"
  Calibrate full shape of classifier output
- Boosted/High-p_T b/c tagging
- Improving b-tagging in trigger
  Reduce CPU footprint / Improve offline-online consistency

HF Tagging at the LHC

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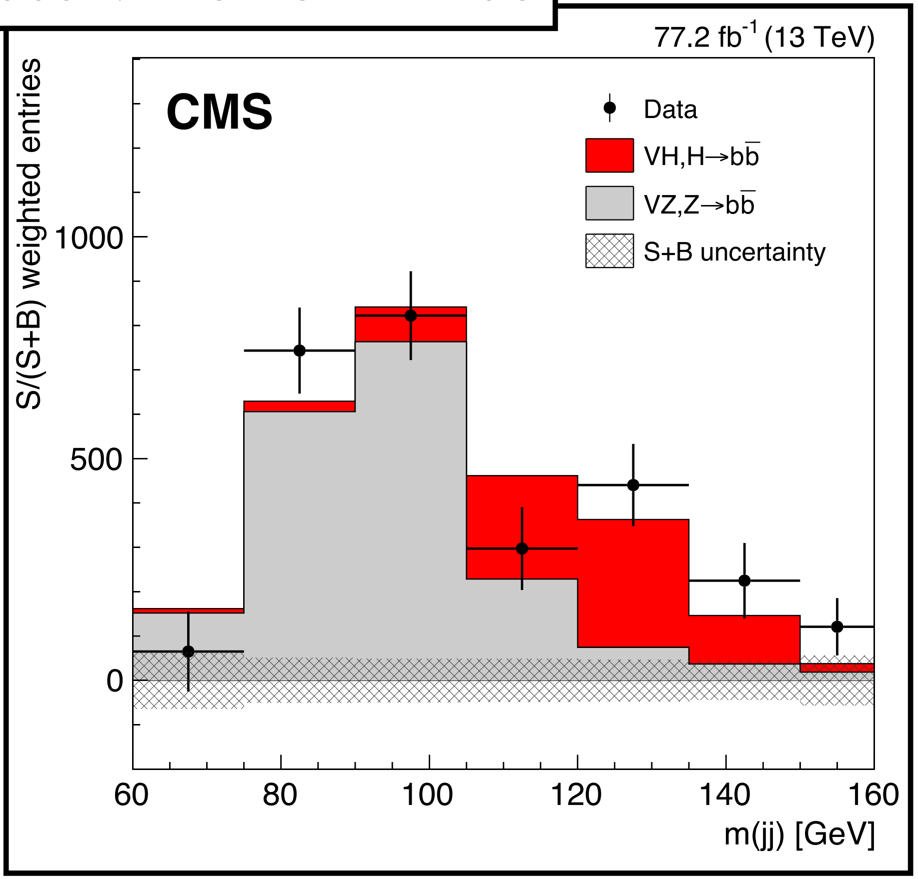
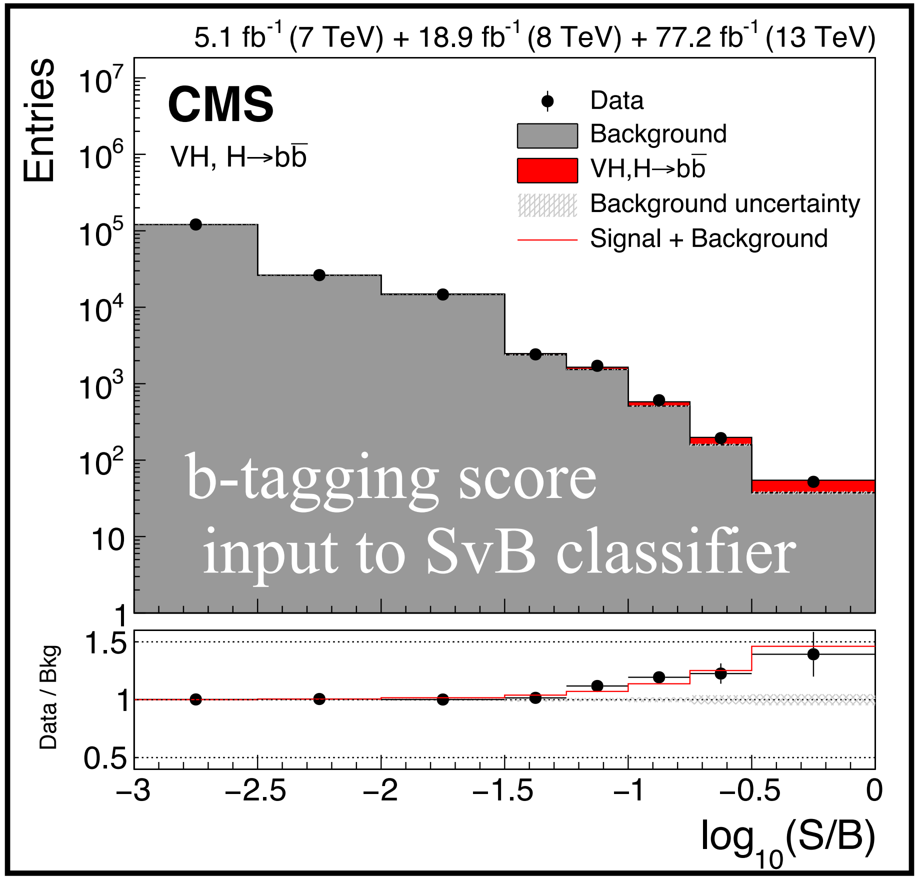
b-Tagging in Analysis

Carnegie Mellon University

Observation of H→bb

Phys. Rev. Lett. 121 (2018) 121801

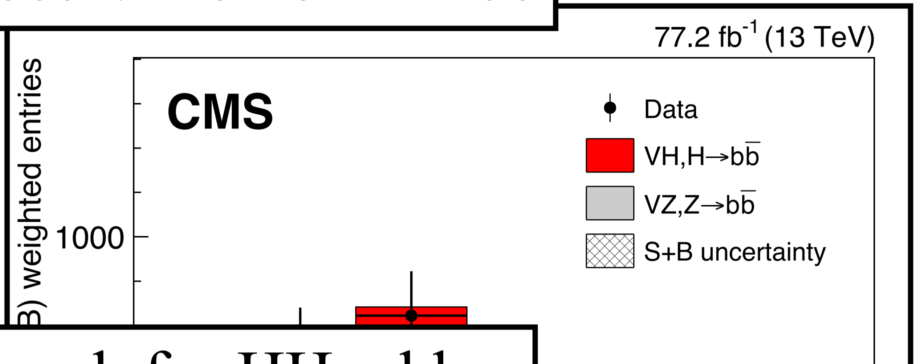


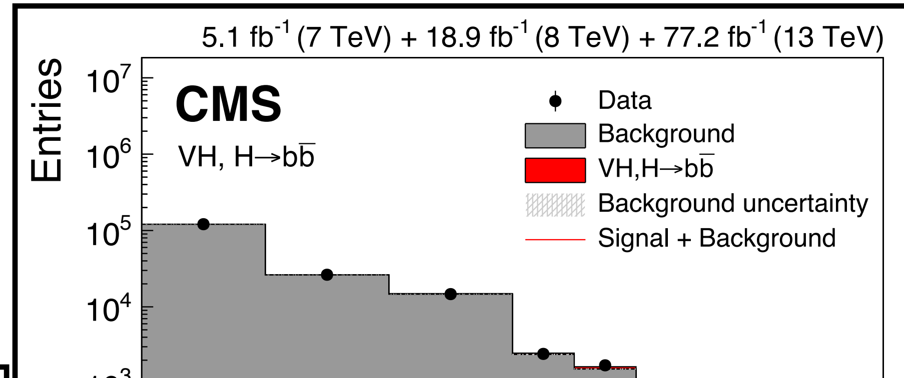


b-Tagging in Analysis

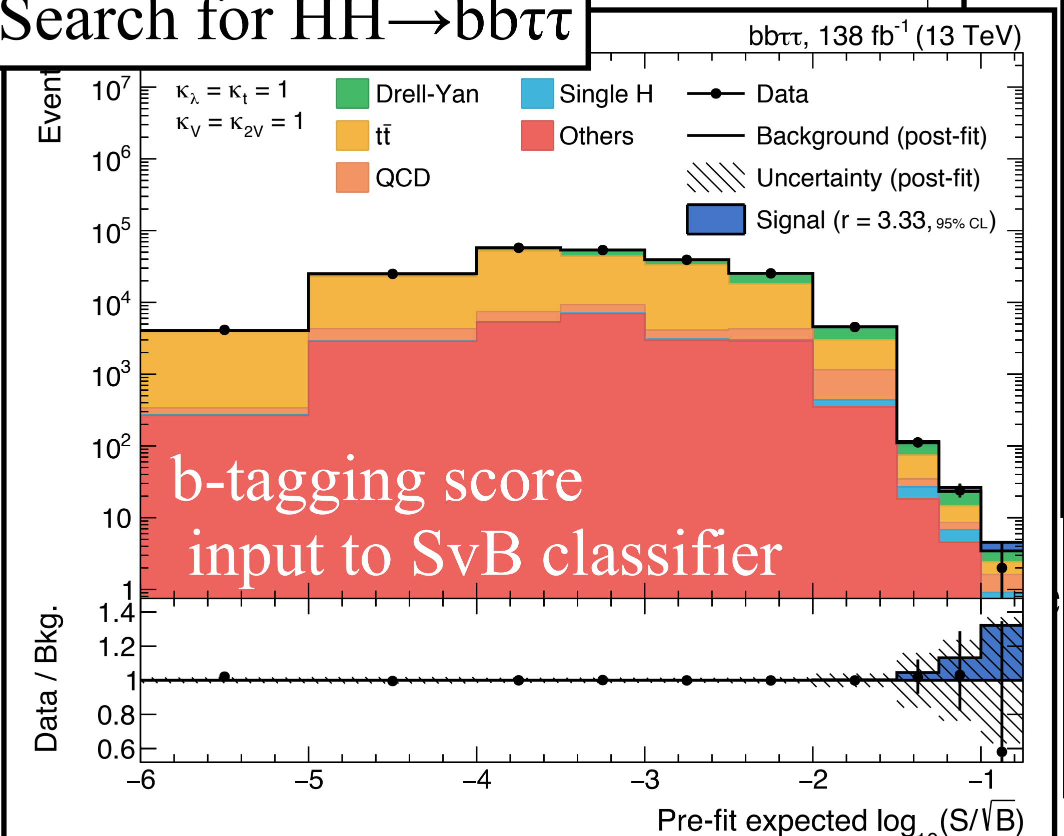
Observation of H→bb

[Phys. Rev. Lett. 121 (2018) 121801](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.121801)

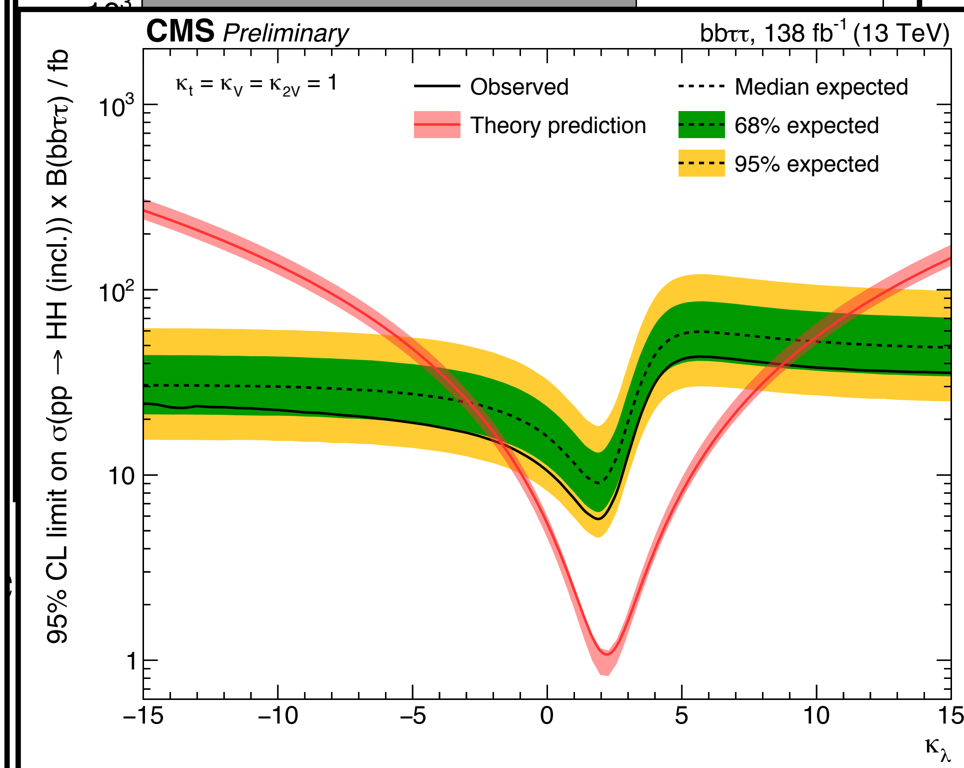




Search for HH→bbττ



b-tagging score
input to SvB classifier

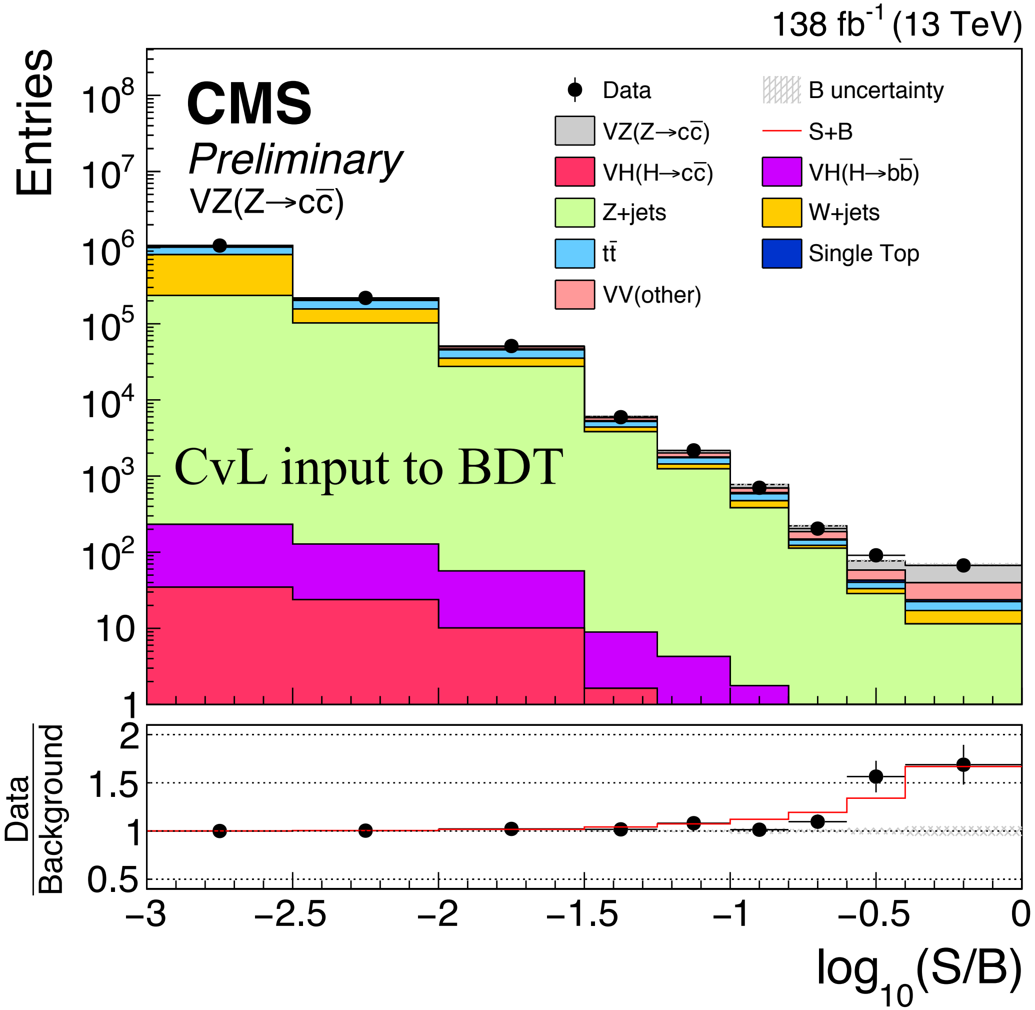


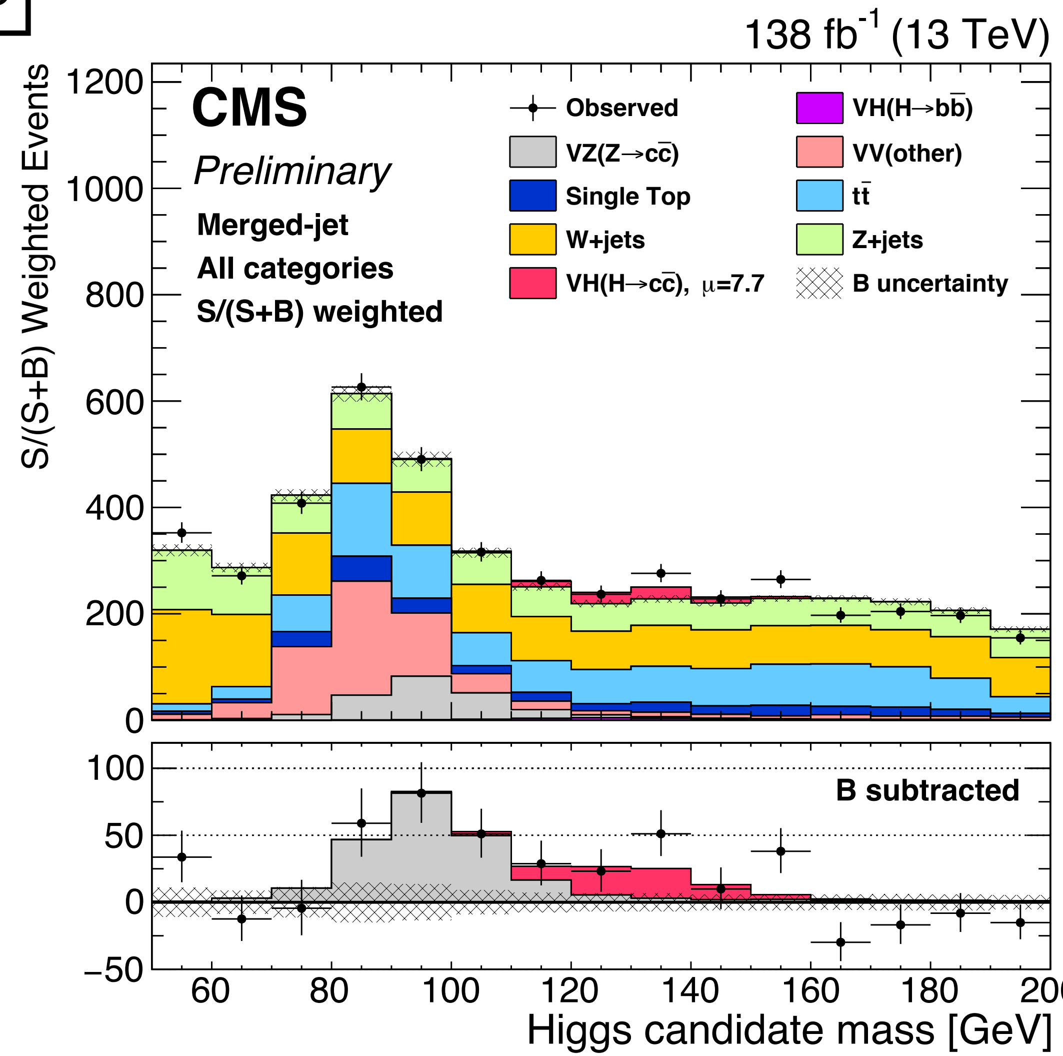
https://cds.cern.ch/record/2803419

c-Tagging in Analysis

Observation of Z→cc / Search H→cc

CMS-HIG-21-008





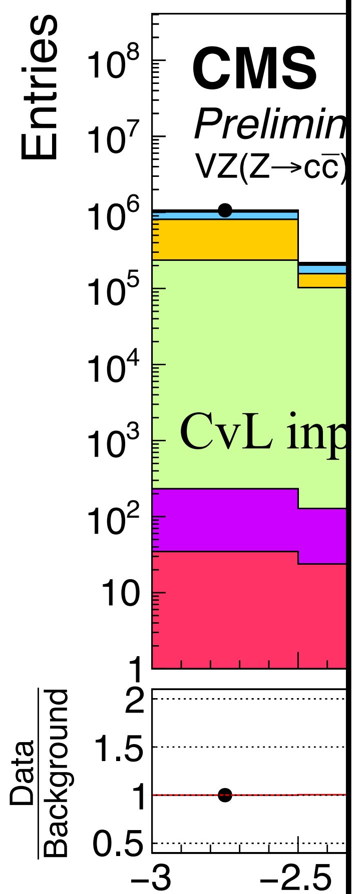
First observation of Z→cc at hadron collider !

$\mu_{H\to cc}$ < 14 observed (7.6 expected)

c-Tagging in Analysis

Observatio

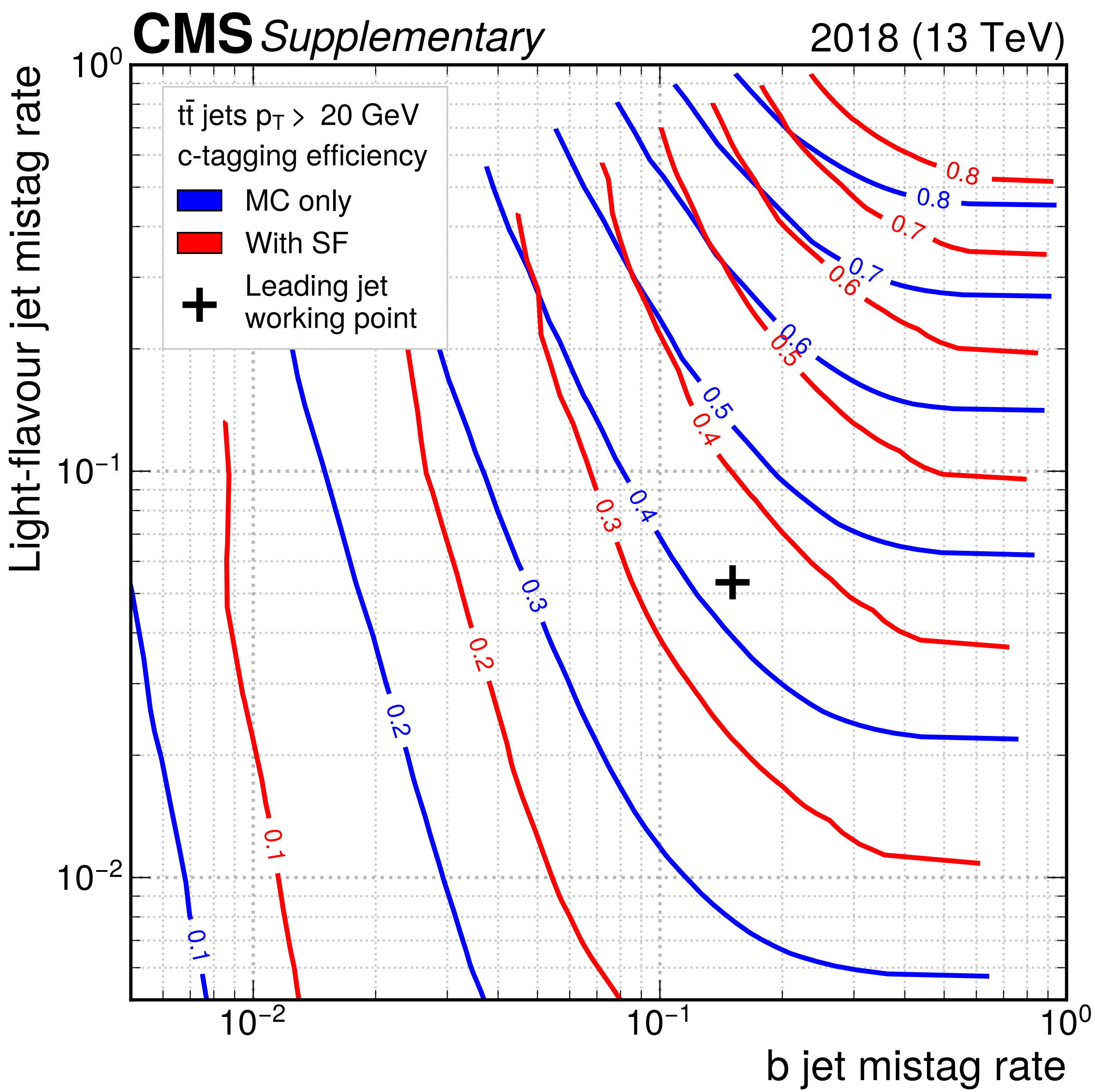
HIG-21-008

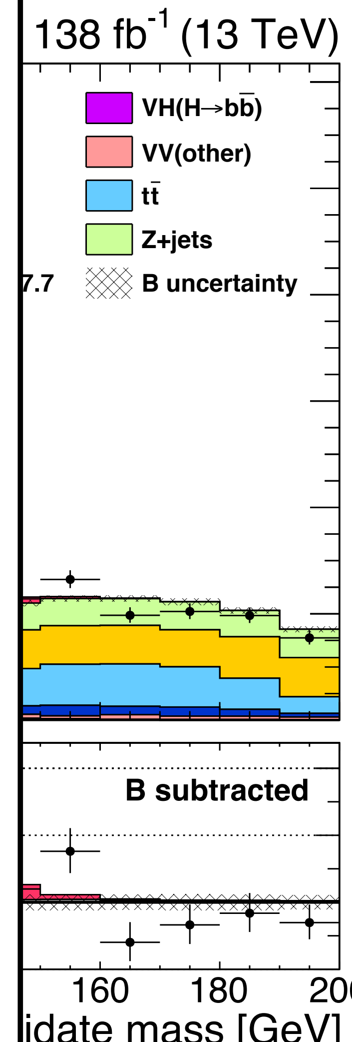


First obse

$\mu_{H \to cc} < 1$

c-tagging calibration critical to measurement





CMS: Charm-Jet Calibration

arXiv > hep-ex > arXiv:2111.03027

High Energy Physics – Experiment

[Submitted on 4 Nov 2021 (v1), last revised 21 Mar 2022 (this version, v2)]

A new calibration method for charm jet identification validated with proton-proton collision events at $\sqrt{s}$ = 13 TeV

CMS Collaboration

https://arxiv.org/abs/2111.03027

Efficiencies measured double differential in CvL and CvB

- Separately for b, c and light

MC Corrections derived iteratively in 2D bins in (CvL , CvB)

- Constrained by data in three control regions *(next slides)*
- Iterative approach used for convergence

Adaptive 2D Binning + Interpolation

- Fix width CvL bin / CvB bins optimized on observed statistics
- Fit SF to minimize data/MC differences
- Repeat with fixed width CvB bins
- Resulting SF maps combined interpolated in full 2D plane

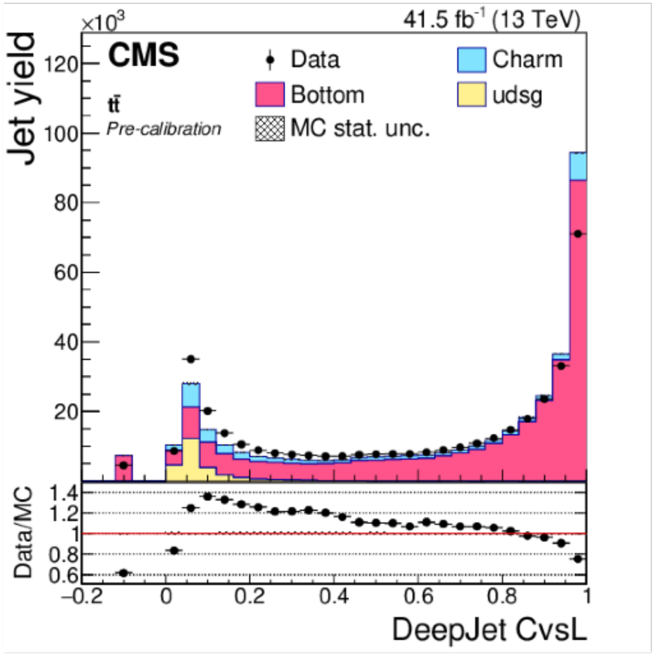
Control Regions

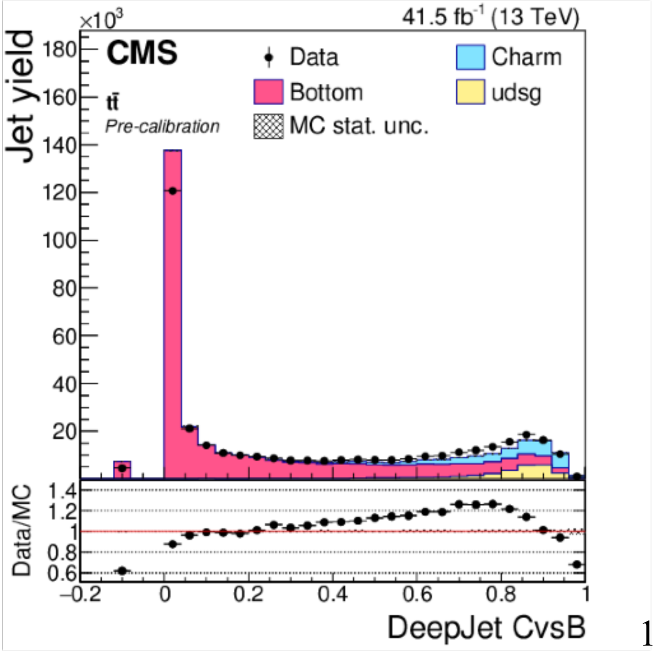
B-jet Control Region:

Target ttbar events (1L and 2L events)

1 e/μ + 4 jets (2 e/μ + 2 jets)

Require soft-μ tagged jet to increase b-jet purity





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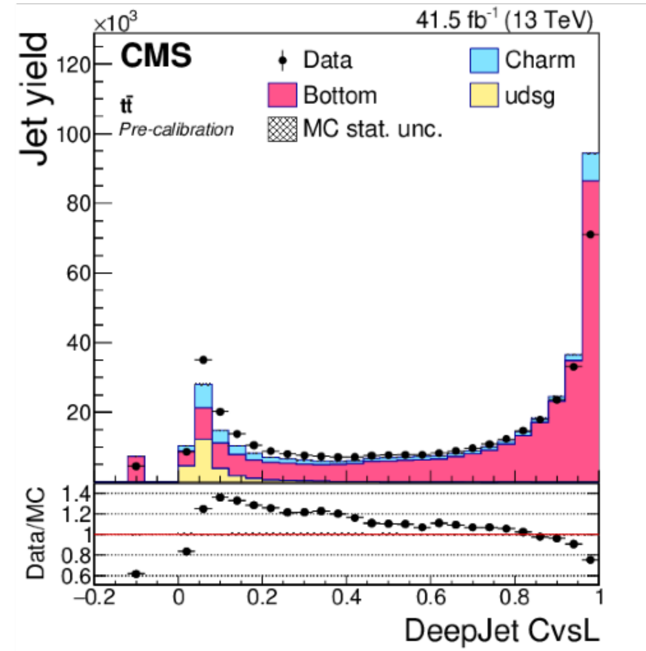
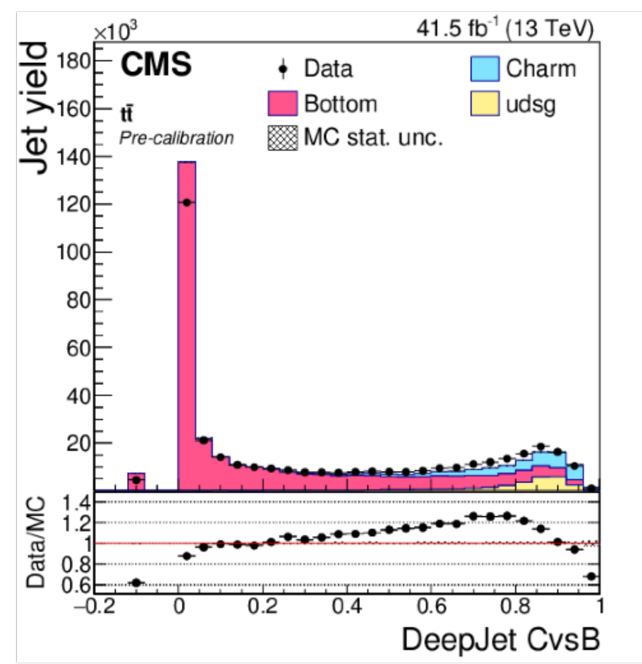
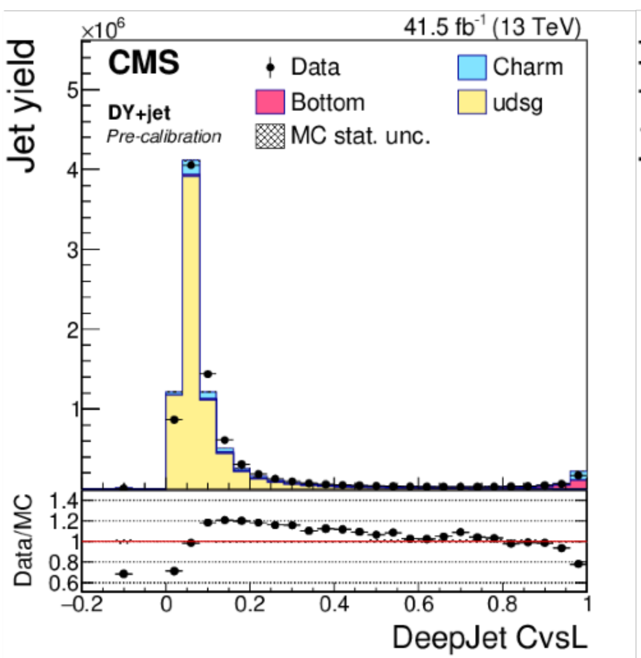
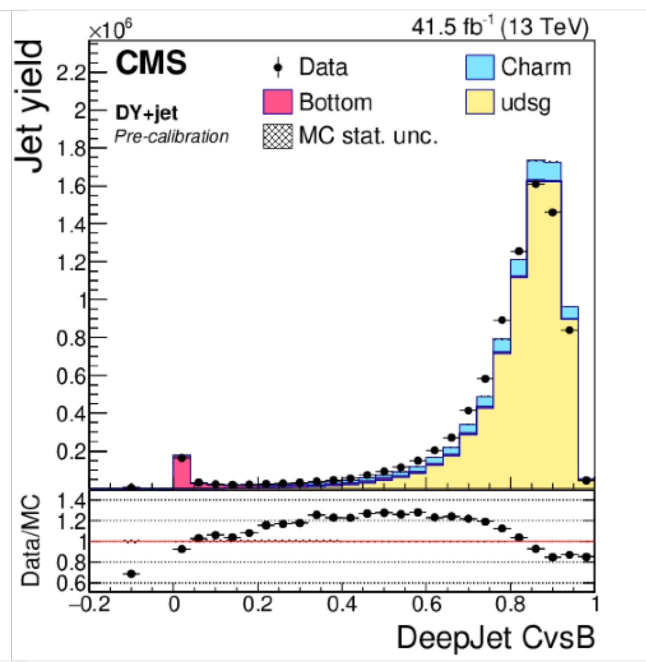




LF Control Region:

Z→ll + inclusive jet selection



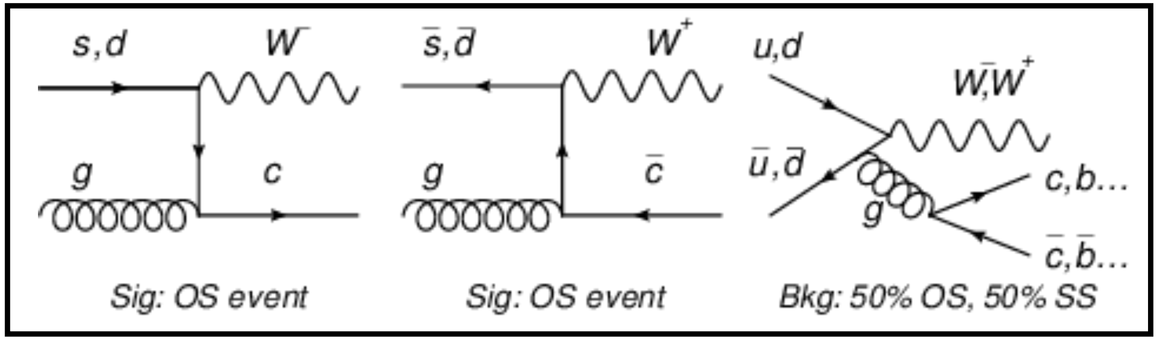


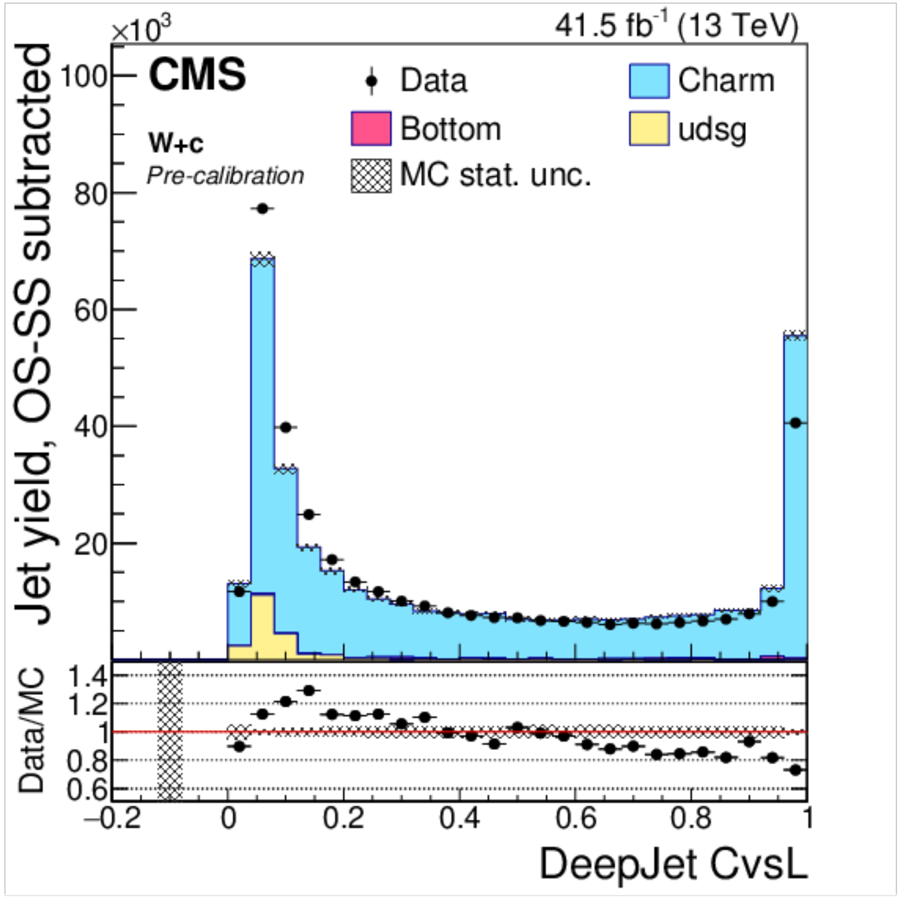
Charm-Jet Region

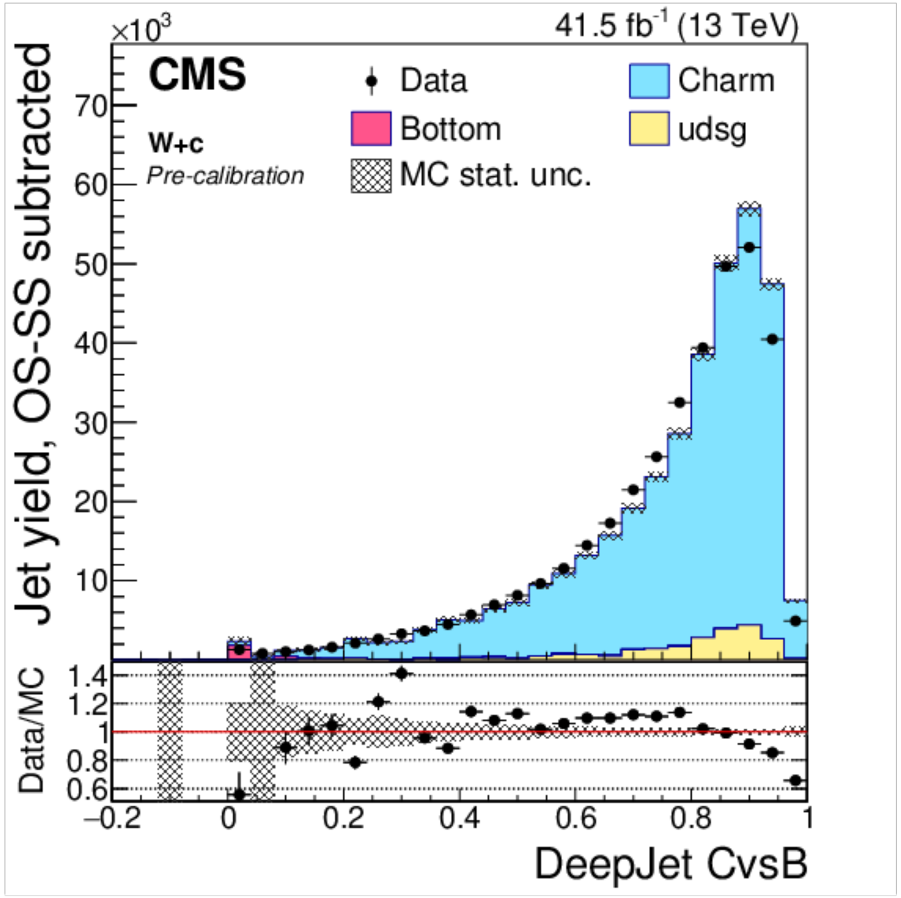
Target W+c events

W→lν + soft-μ tagged jet.

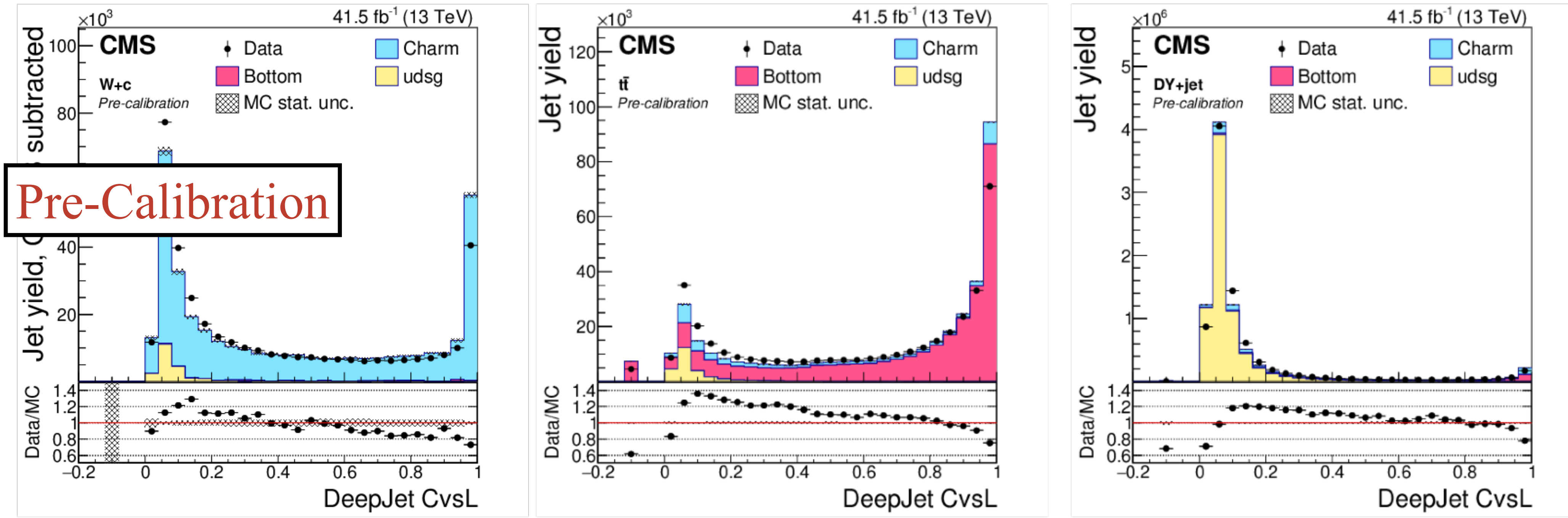
Use charge to subtract Bkg







Fit Results (CvL)



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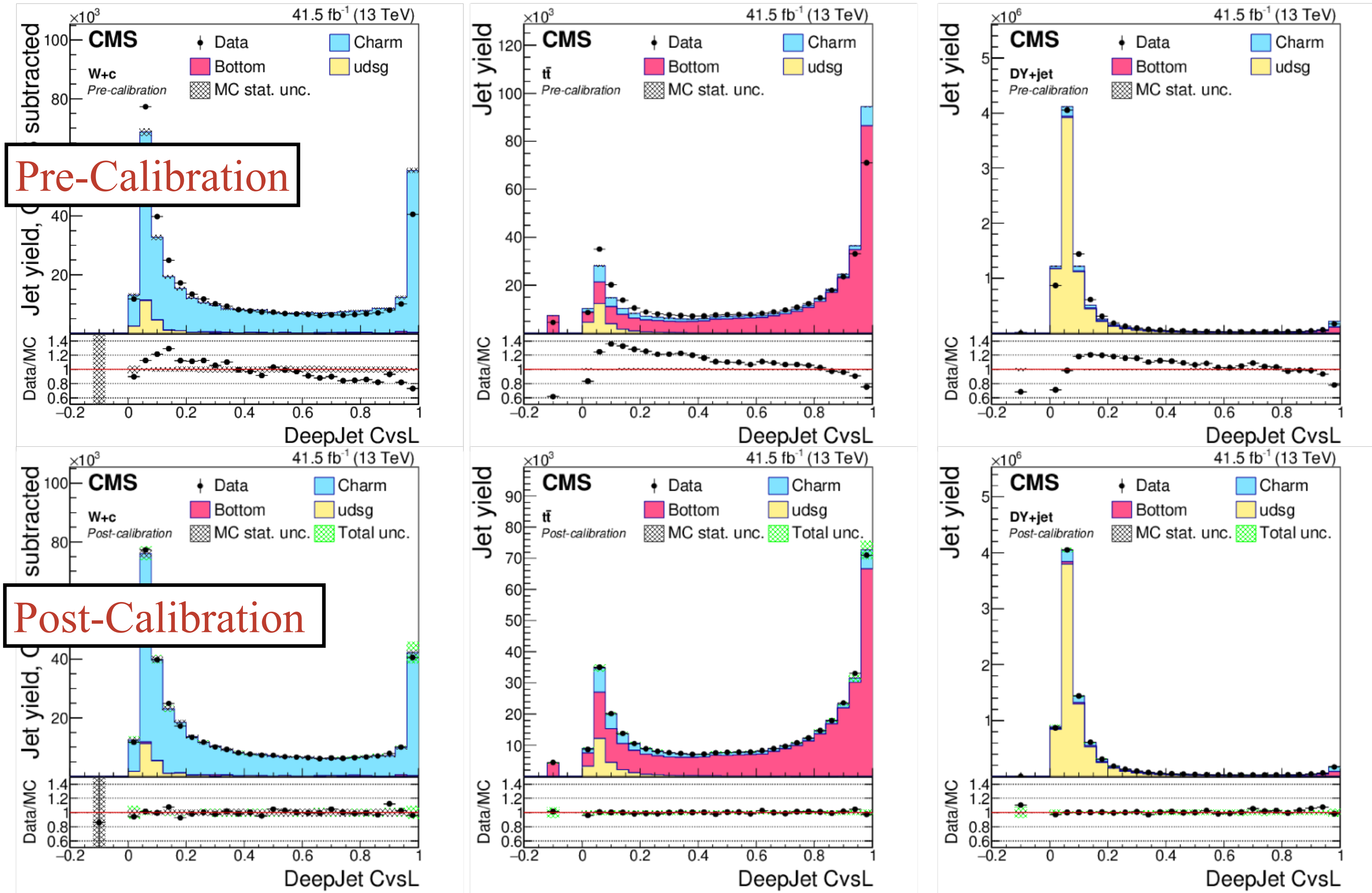
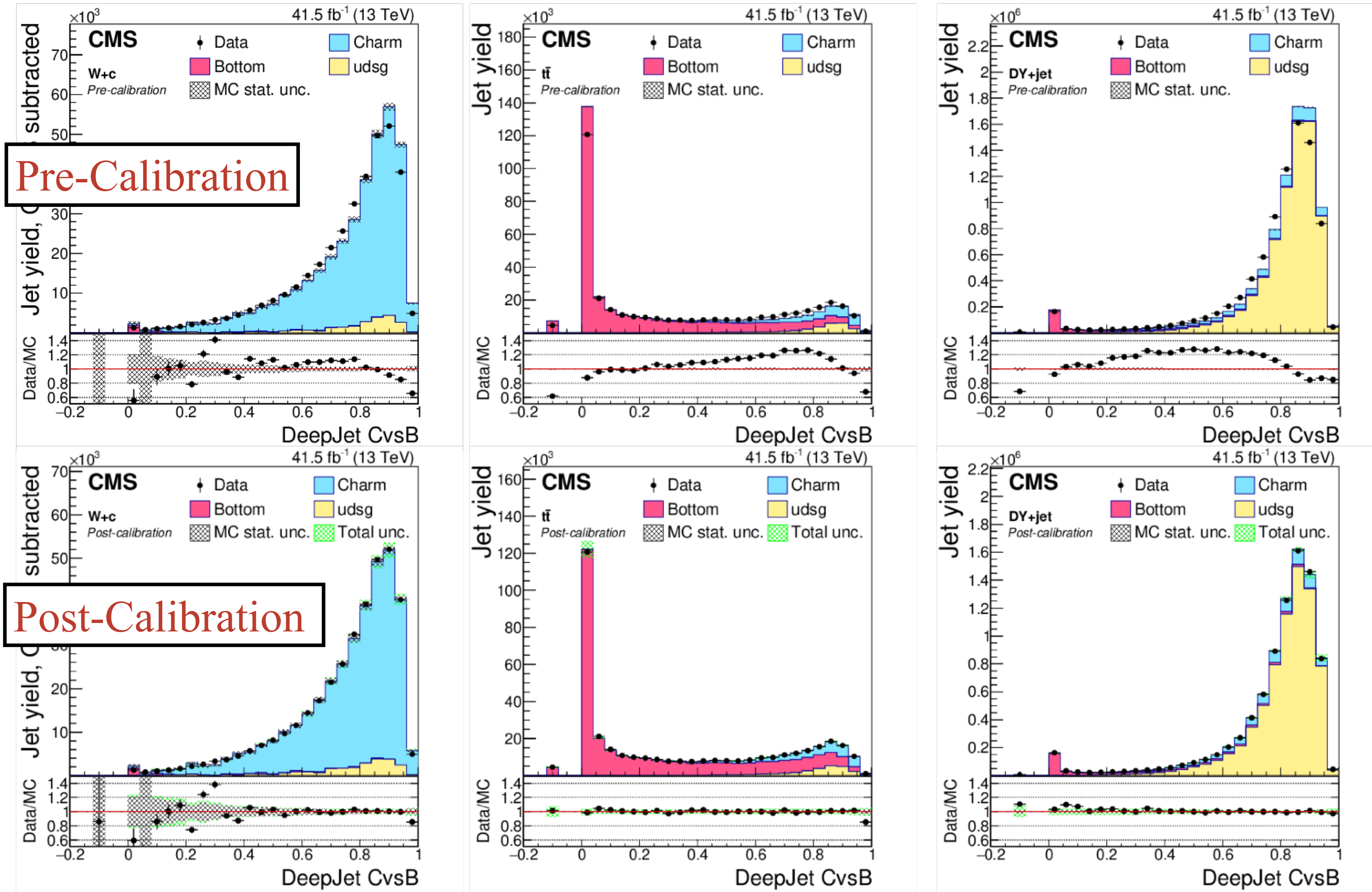


Fit Results (CvB)

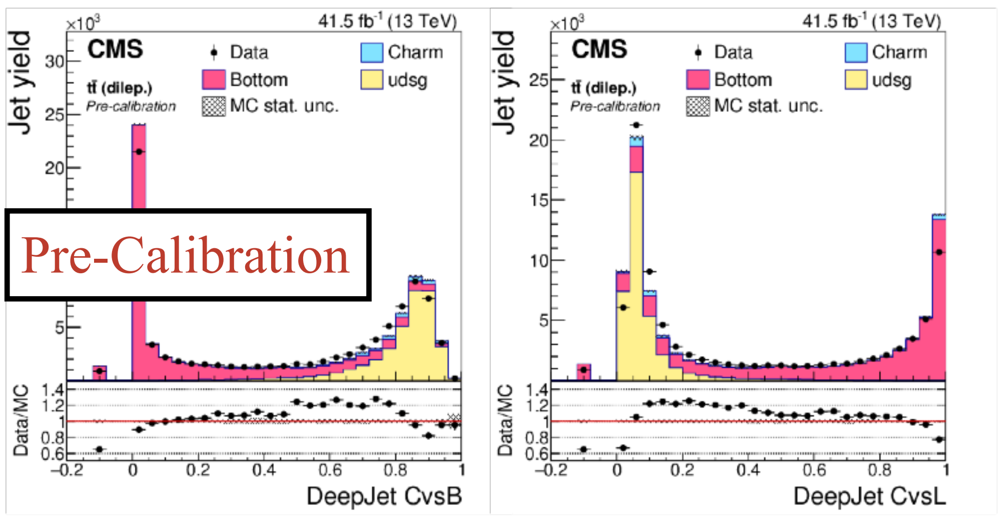


Inclusive Validation

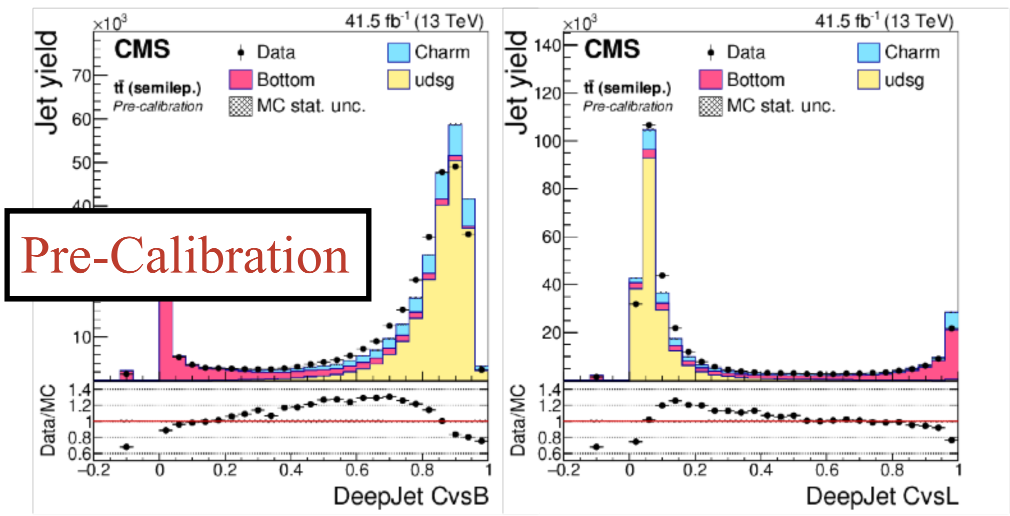
Carnegie Mellon University

Validation in orthogonal ttbar sample / Inclusive jet selection (no soft-μ tag)

Di-Lepton ttbar



Semi-lep (Hadronic W-candidate)



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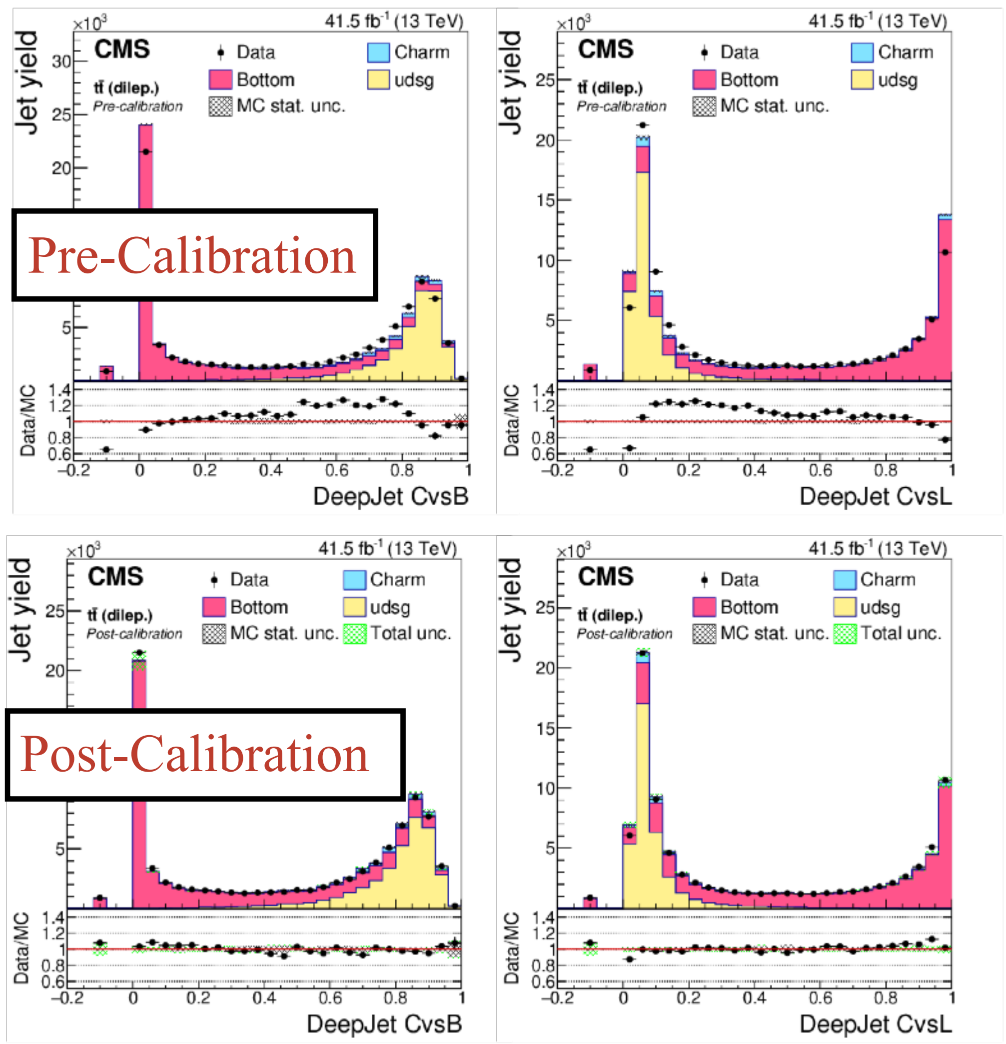

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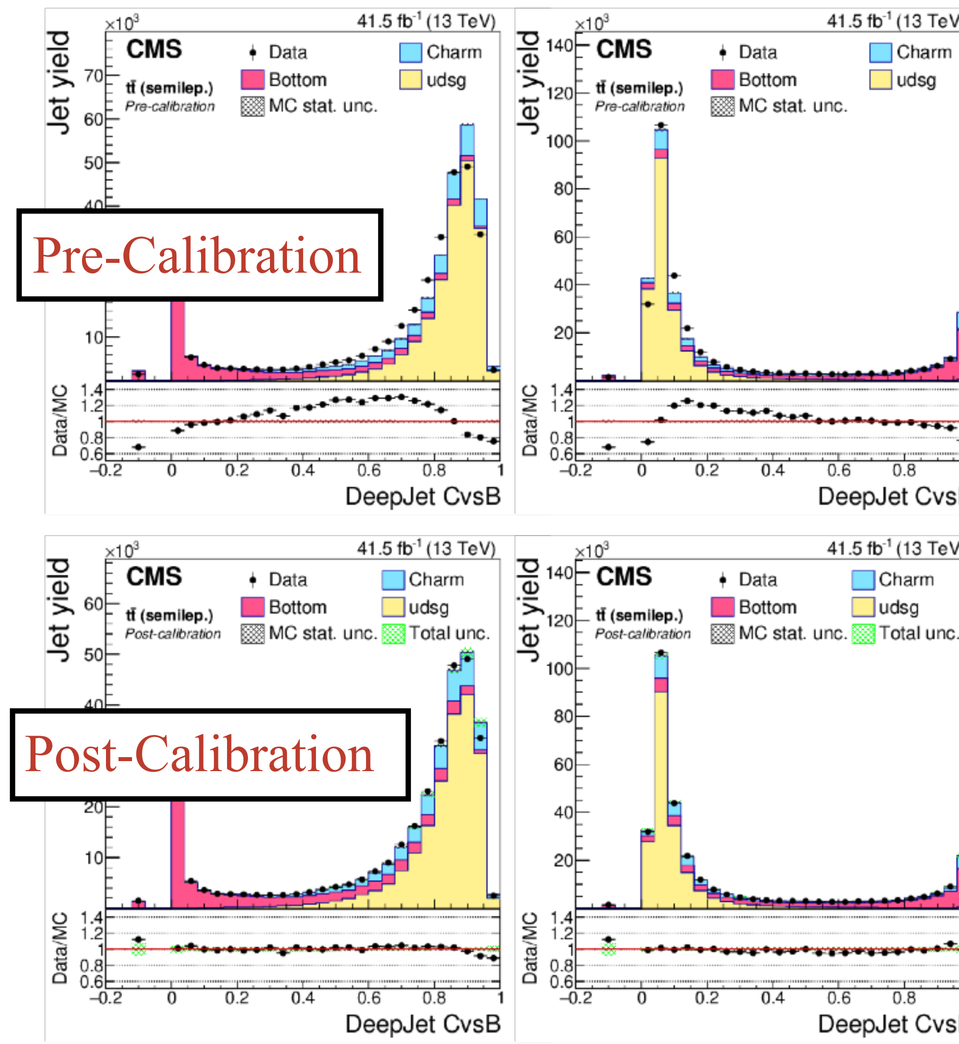
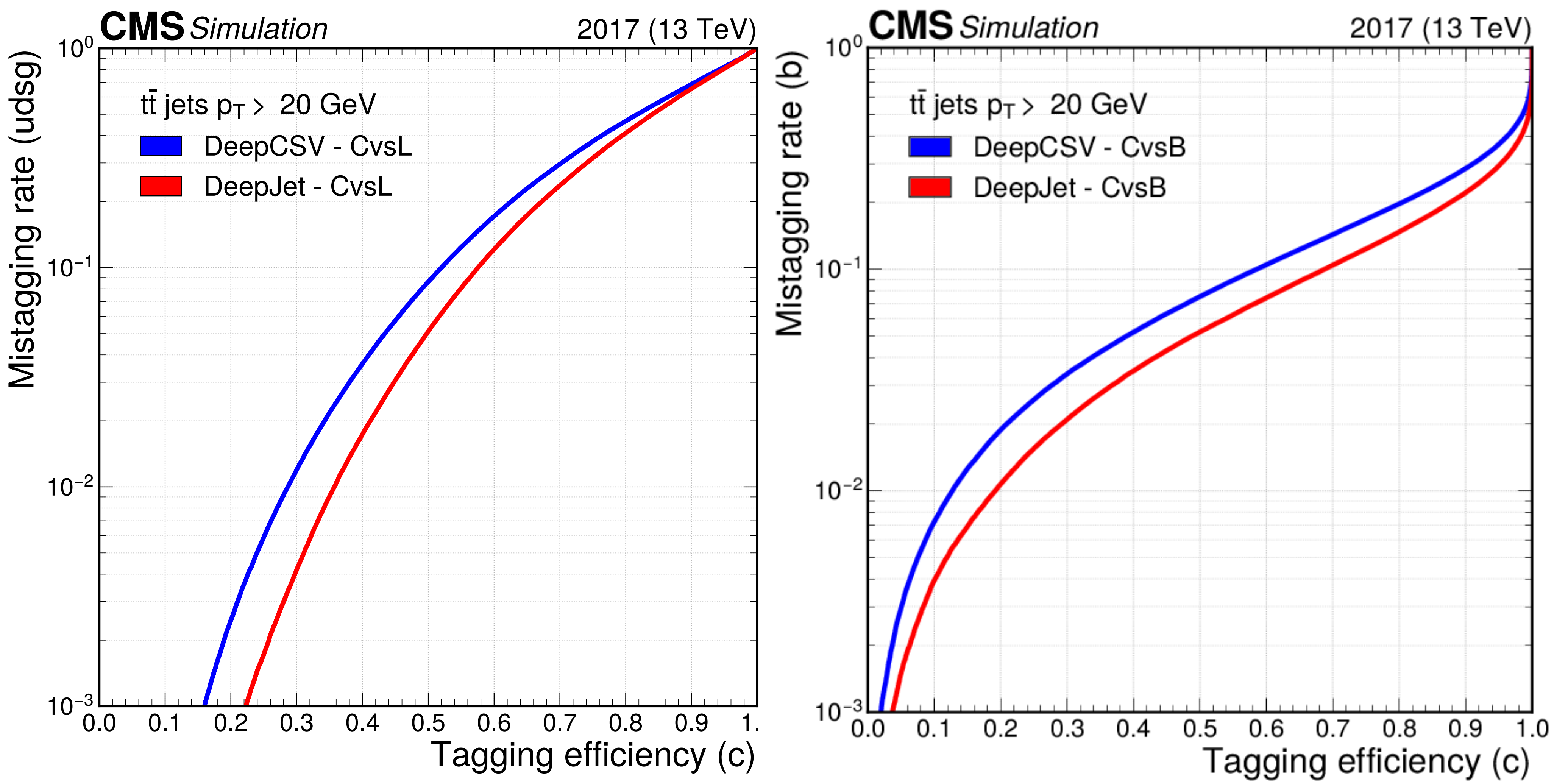
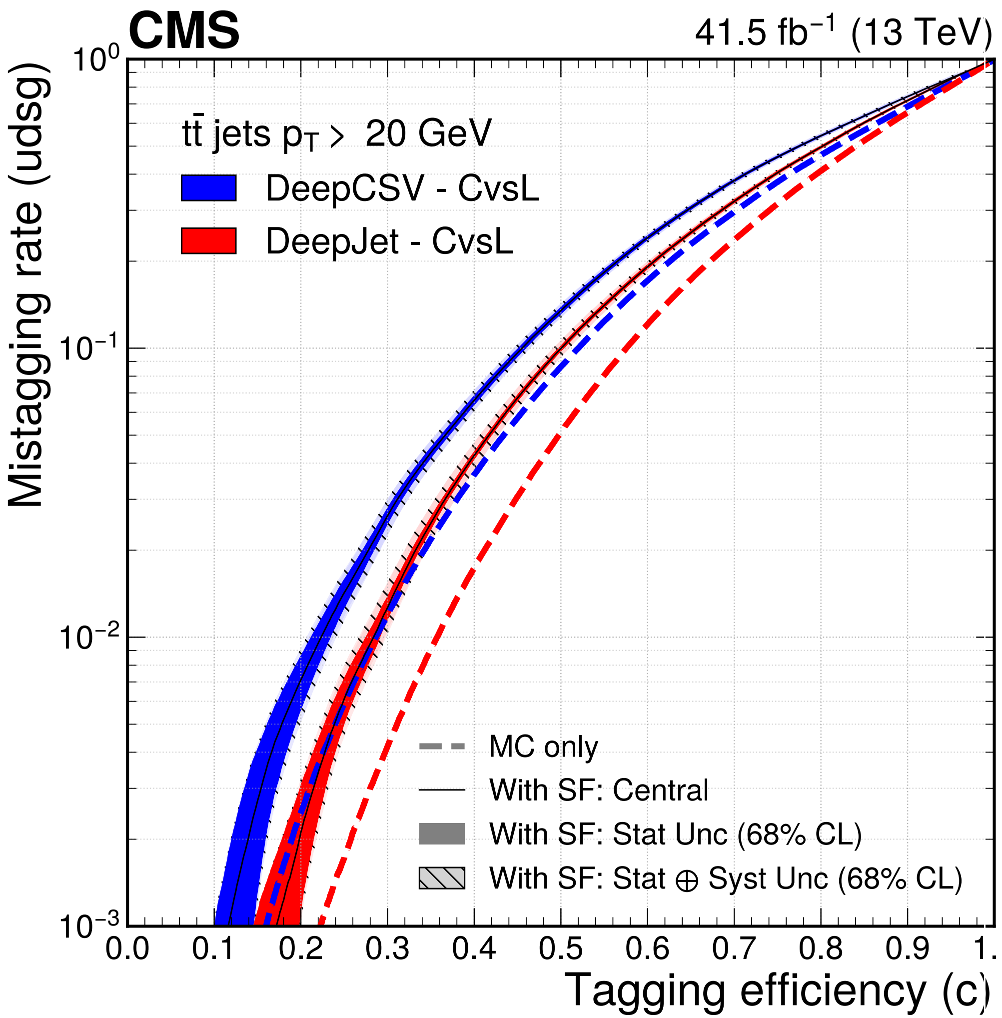


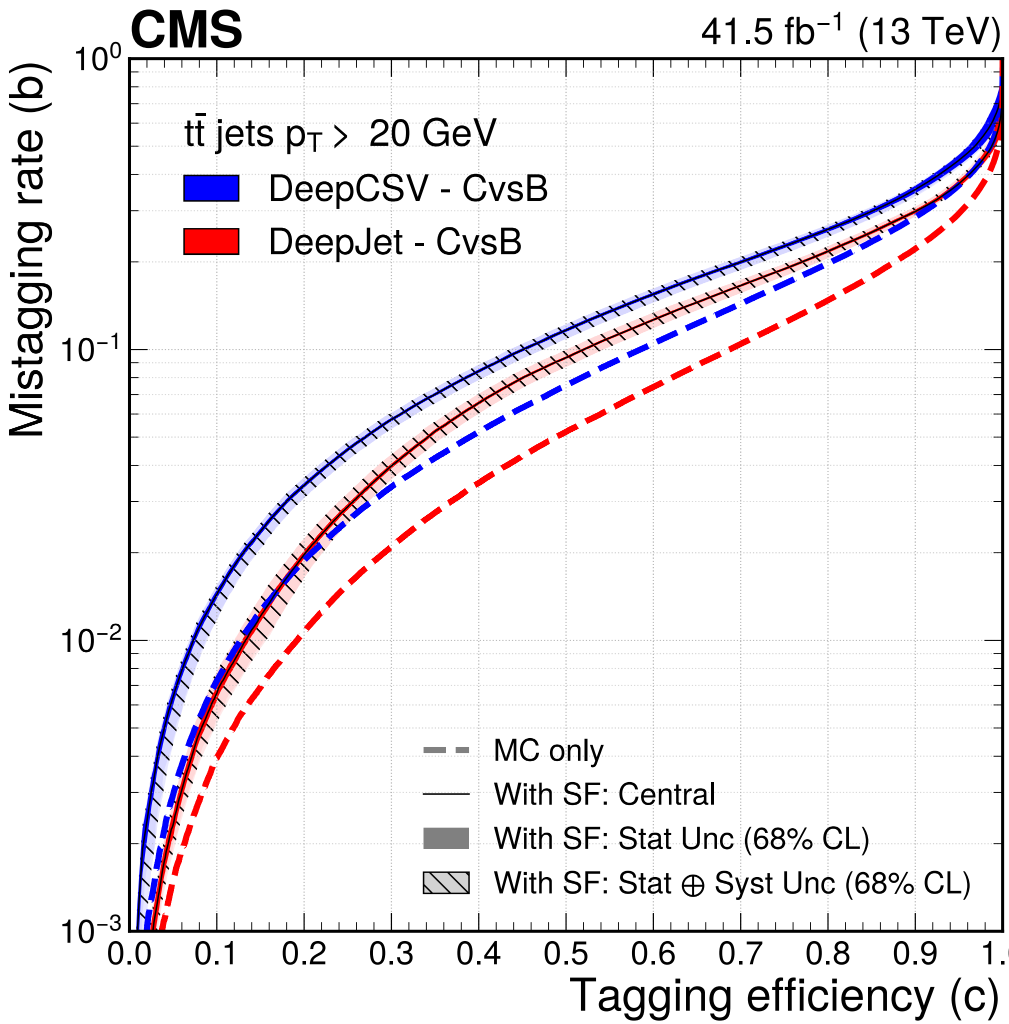
Calibrated Performance



Calibrated Performance

Carnegie Mellon University





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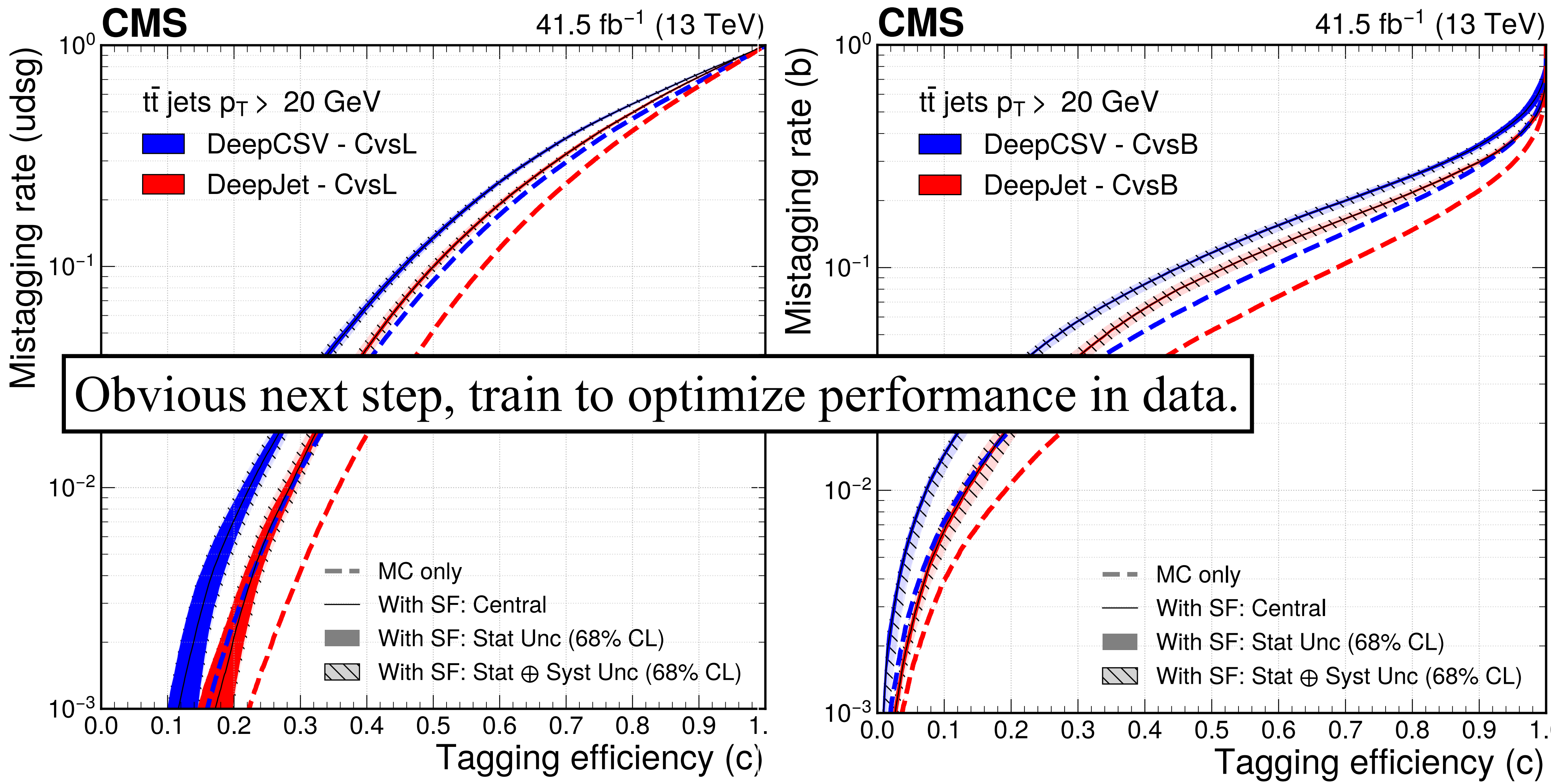


Obvious next step, train to optimize performance in data.

CMS

ATLAS: Charm-Jet mis-ID

Carnegie Mellon University

arXiv > hep-ex > arXiv:2109.10627

High Energy Physics – Experiment

[Submitted on 22 Sep 2021 (v1), last revised 8 Feb 2022 (this version, v2)]

Measurement of the c−jet mistagging efficiency in $t\bar{t}$ events using pp collision data at $\sqrt{s}$ = 13 TeV collected with the ATLAS detector

ATLAS Collaboration

https://arxiv.org/abs/2109.10627

- Analysis to measure the ε with which c-jets are mistagged as bjets

- Select semi-leptonic ttbar. Large (~30%) W→cs BR

- Kinematic likelihood: optimizes assignment of jets to decay products

- b-tagging discriminant compared to data *(differential in jet pT)*

- Advantage: measures inclusive c-decays

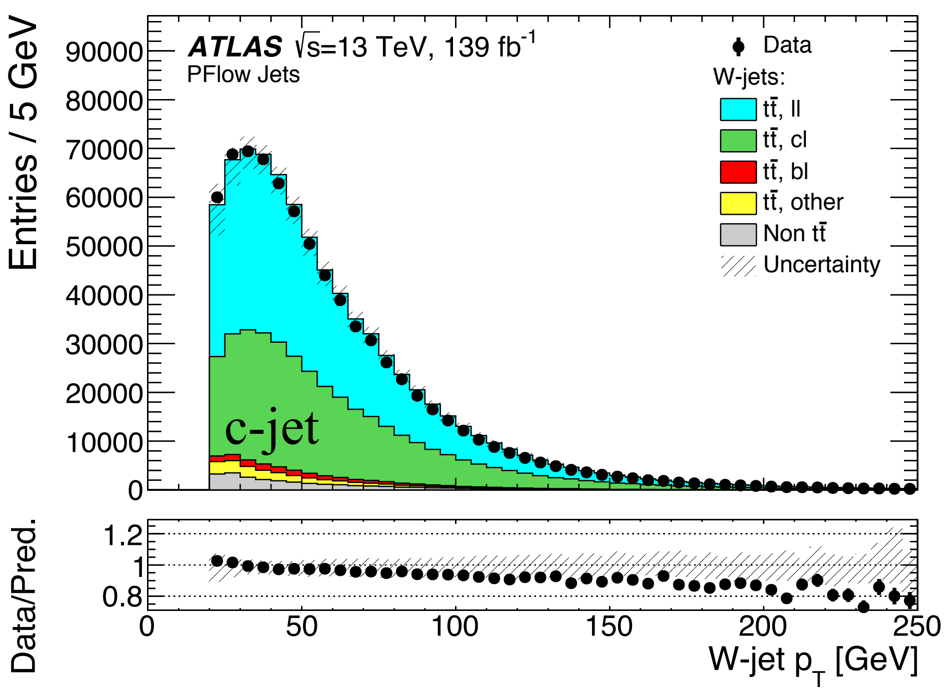
ATLAS: Charm-Jet mis-ID

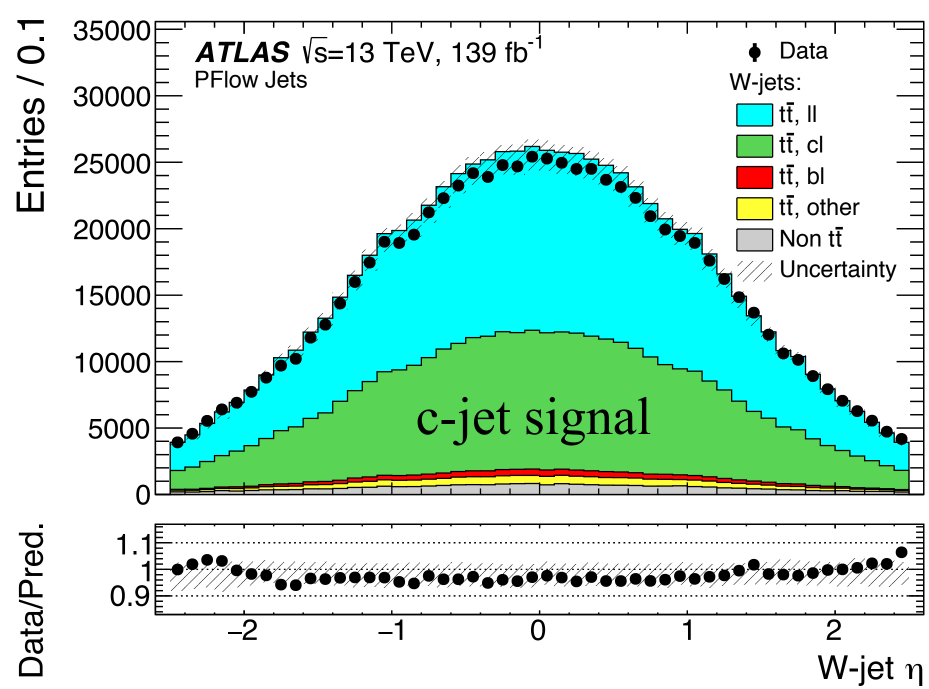
arXiv > hep-ex > arXiv:2109.10627

High Energy Physics – Experiment

tt-bar Likelihood:

- Inputs: MeT + jets/lepton 4-vectors (no b-tagging information)
- Optimizes jet assignment using invariant masses of the top and W
- After fit, require "top-jets" to be b-tagged. (~99% correct assignment)





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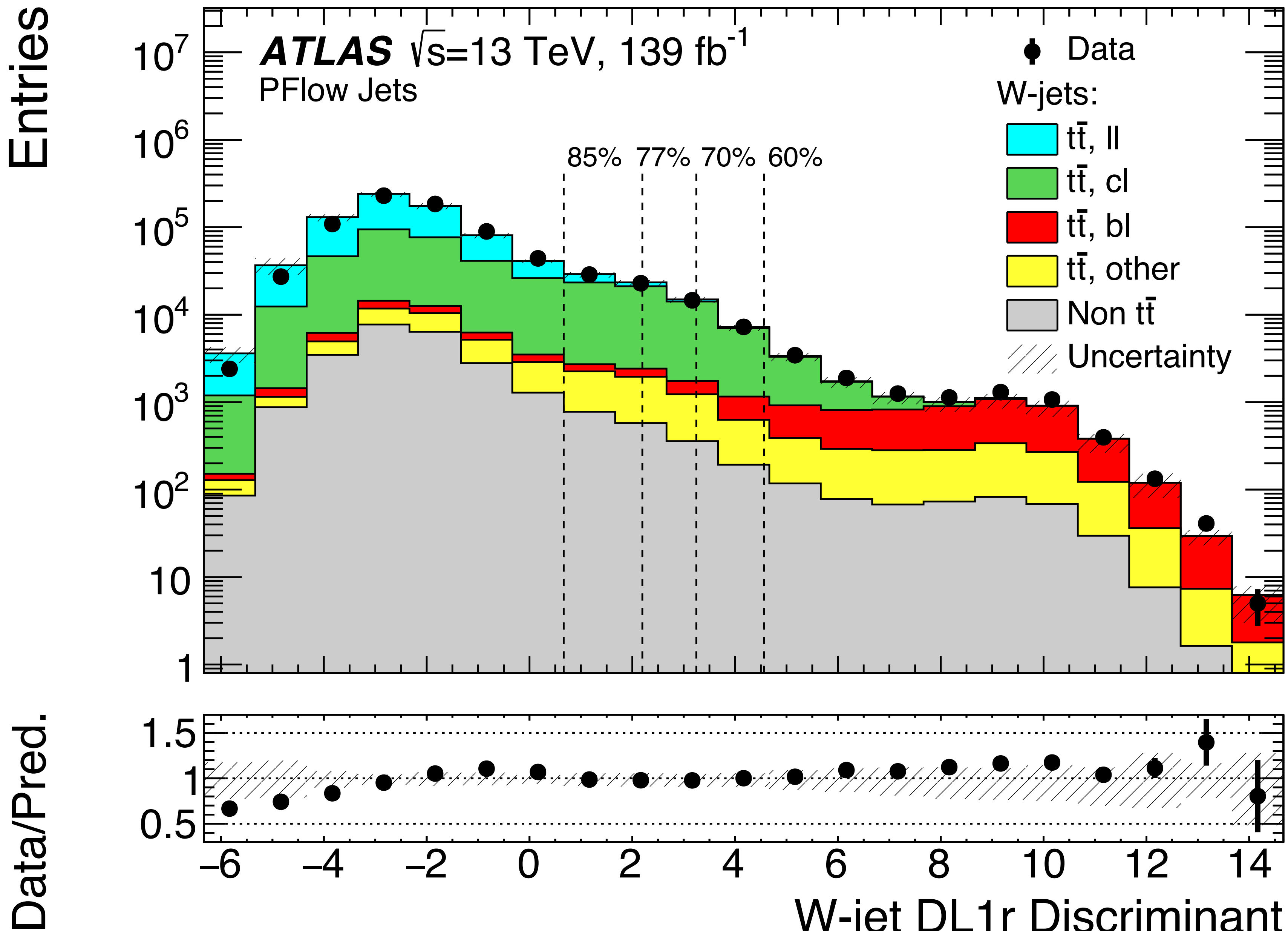

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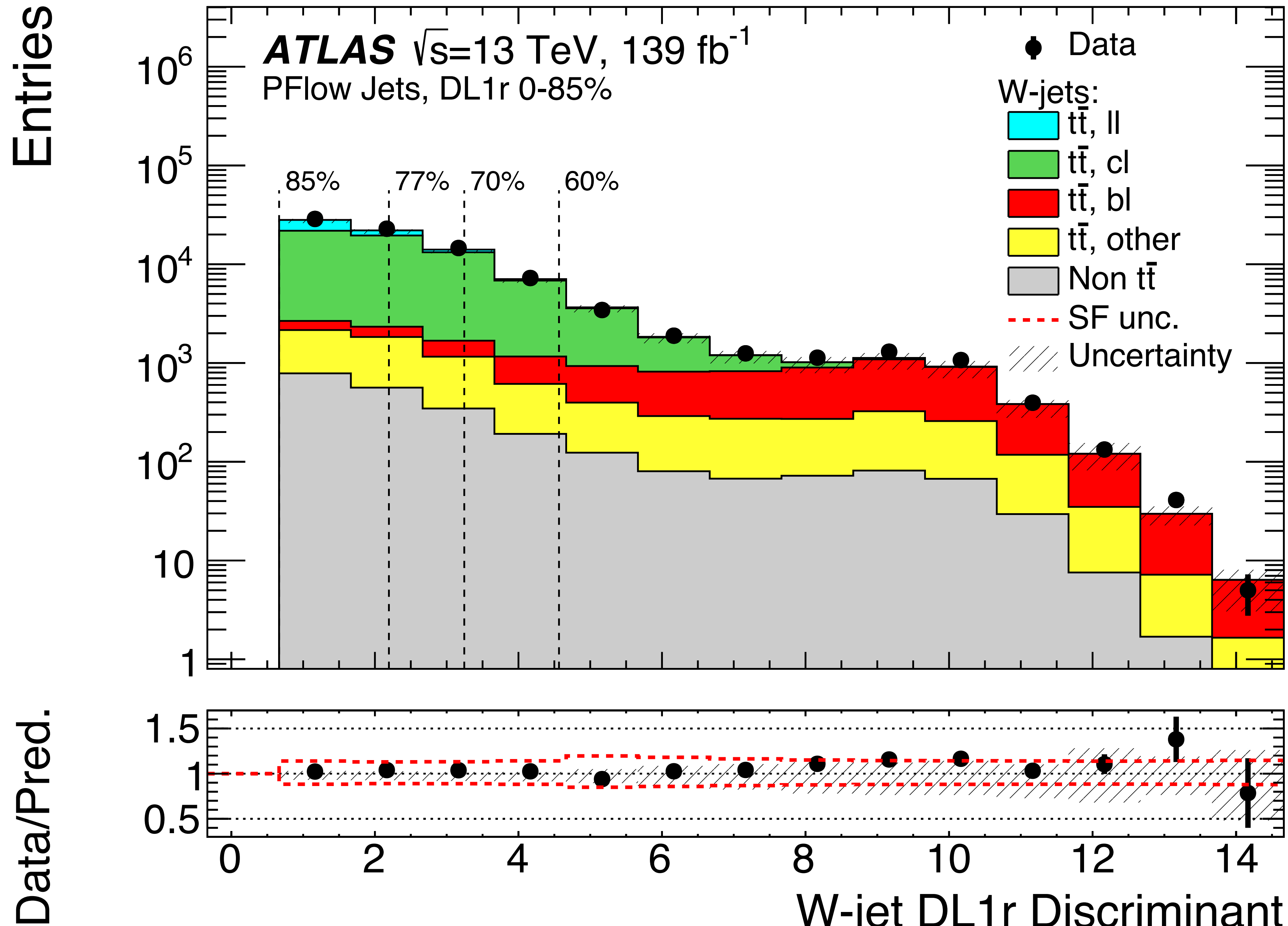

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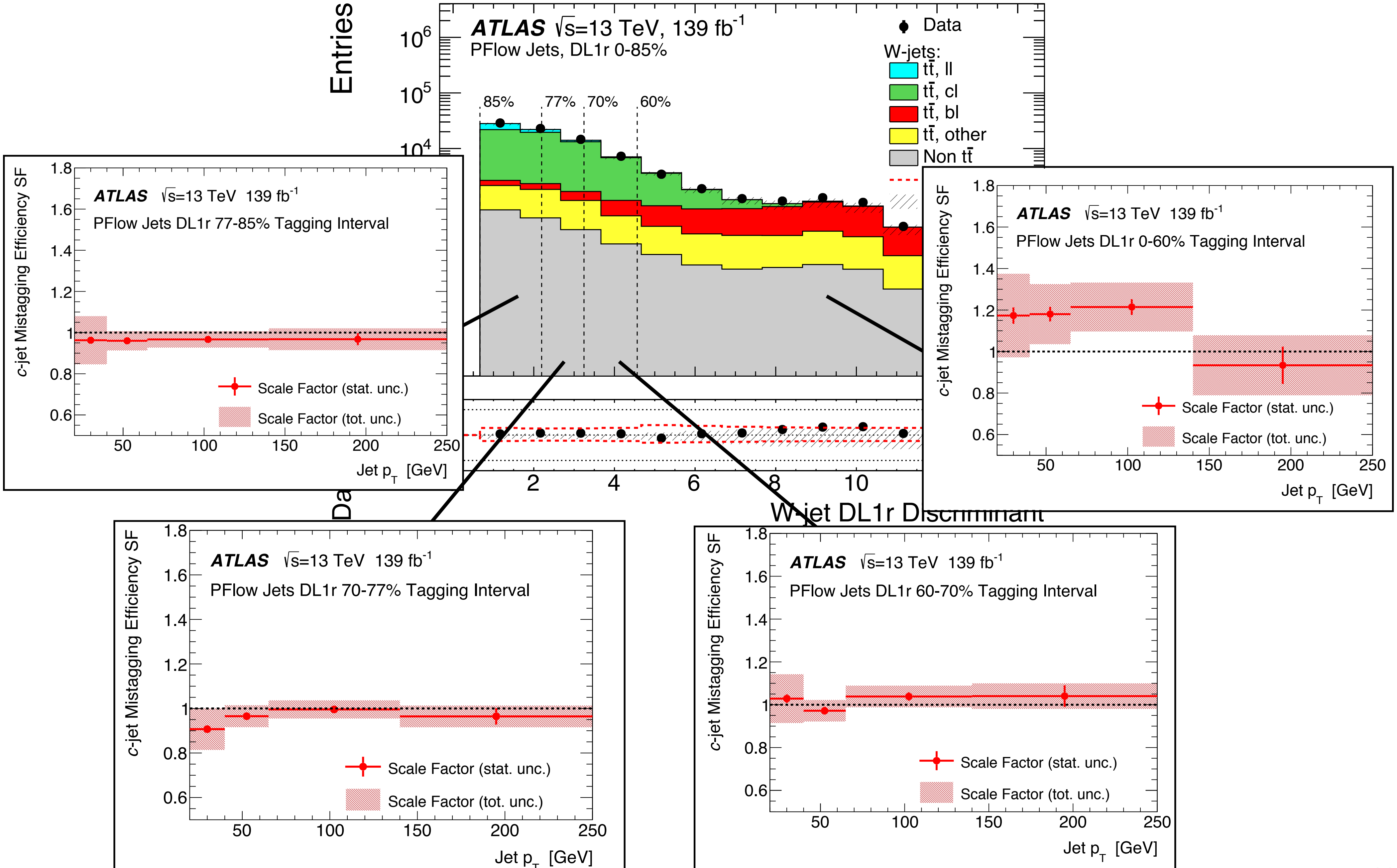


Conclusions

- Heavy flavor tagging a key component of the LHC physics program

- ATLAS-CMS Flavour Tagging Workshop comprehensive picture

- Charm tagging coming into its own in physics analyses

- Precise and differential measurements of tagging performance
  Both ε and fake rates, separated by jet flavor

- Future:
  - Deeper, more sophisticated taggers
  - Improvements in training to mitigate Data/MC differences
  - Better precision and more differential calibrations

Backup

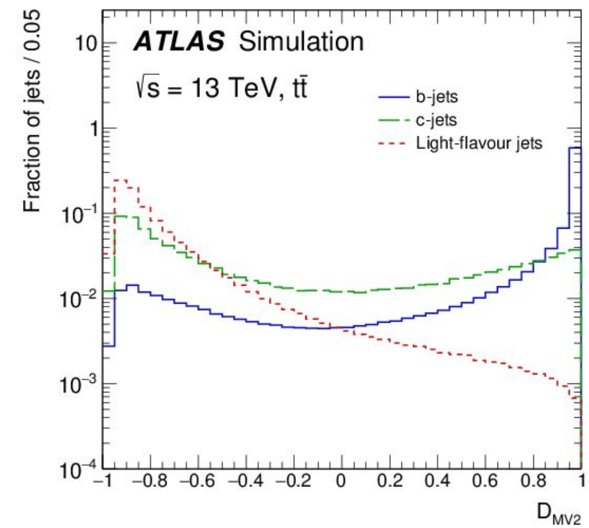
High-level tagger

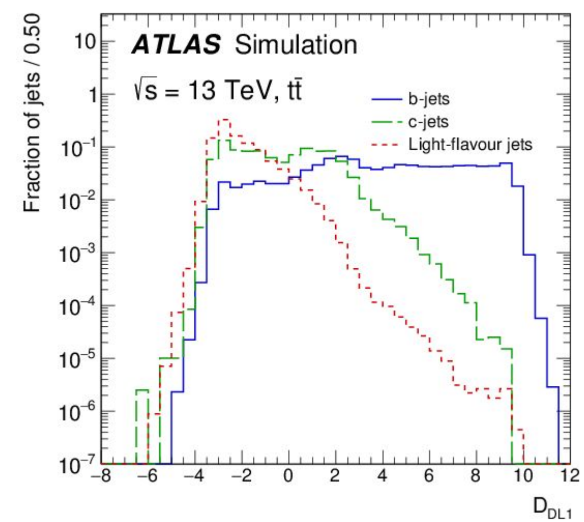
Basic principle: classified training with labels from MC; output then corrected with data-to-simulation scale factors

Different high-level taggers recommended over time

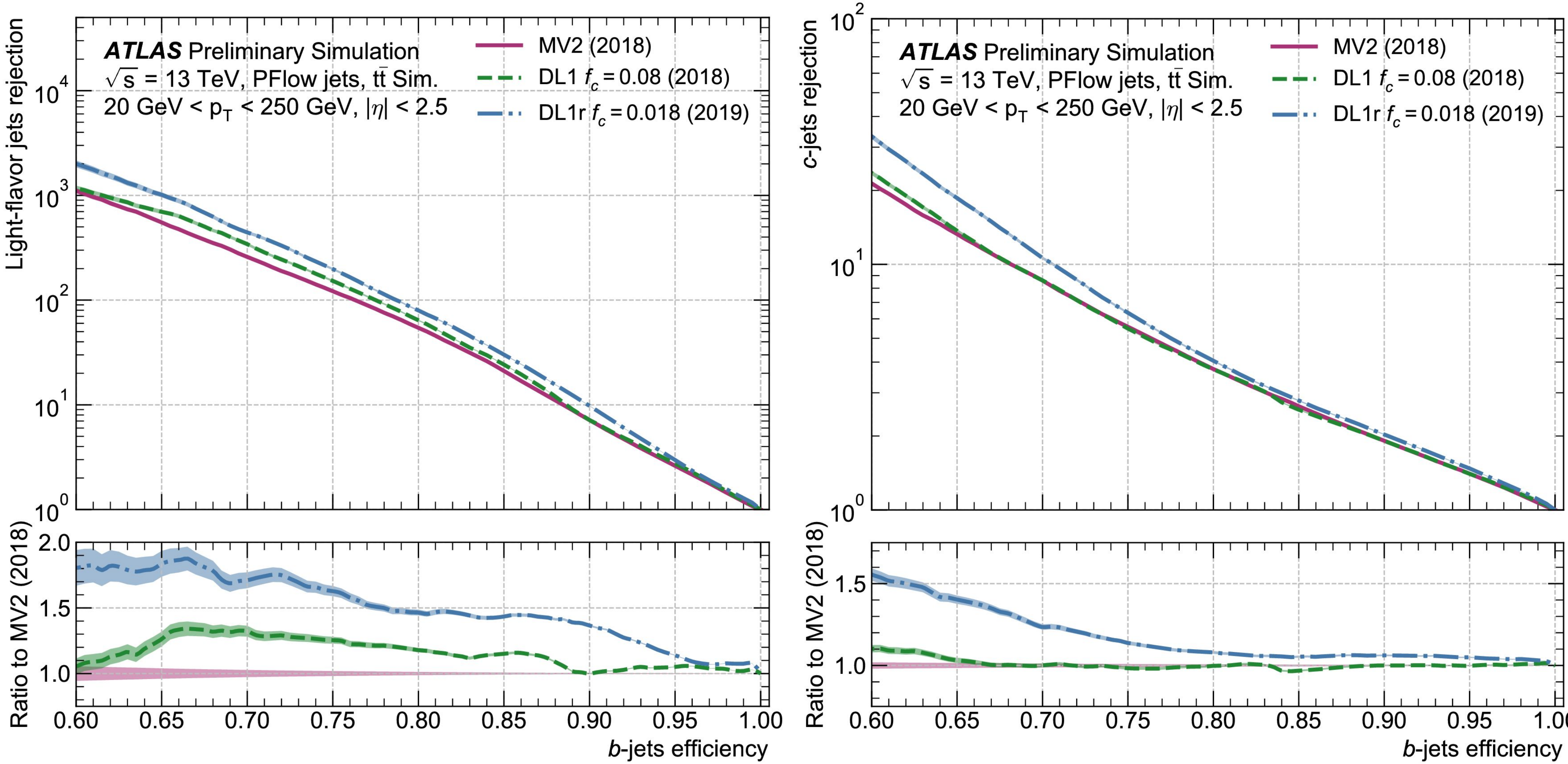
- MV2 is a BDT-based algorithm, the workhorse for years
- DL1 is a more recent ML-based algorithm
- DL1r is the most recent evolution with improved architecture and inclusion of RNN inputs
- Training for a long time on tt events, now on tt events up to 250 GeV and flat-mass Z' beyond 250 GeV

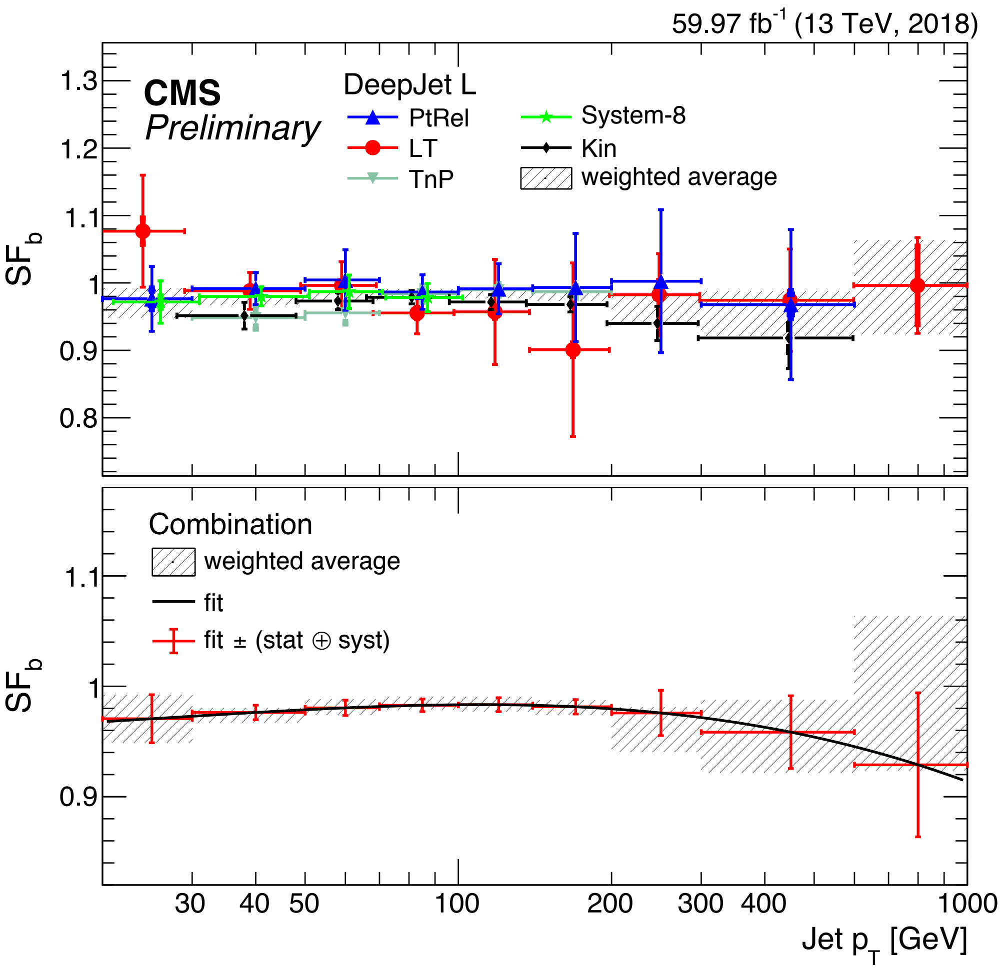
$$D_{\mathrm{DL1}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\mathrm{light}}}\right)$$

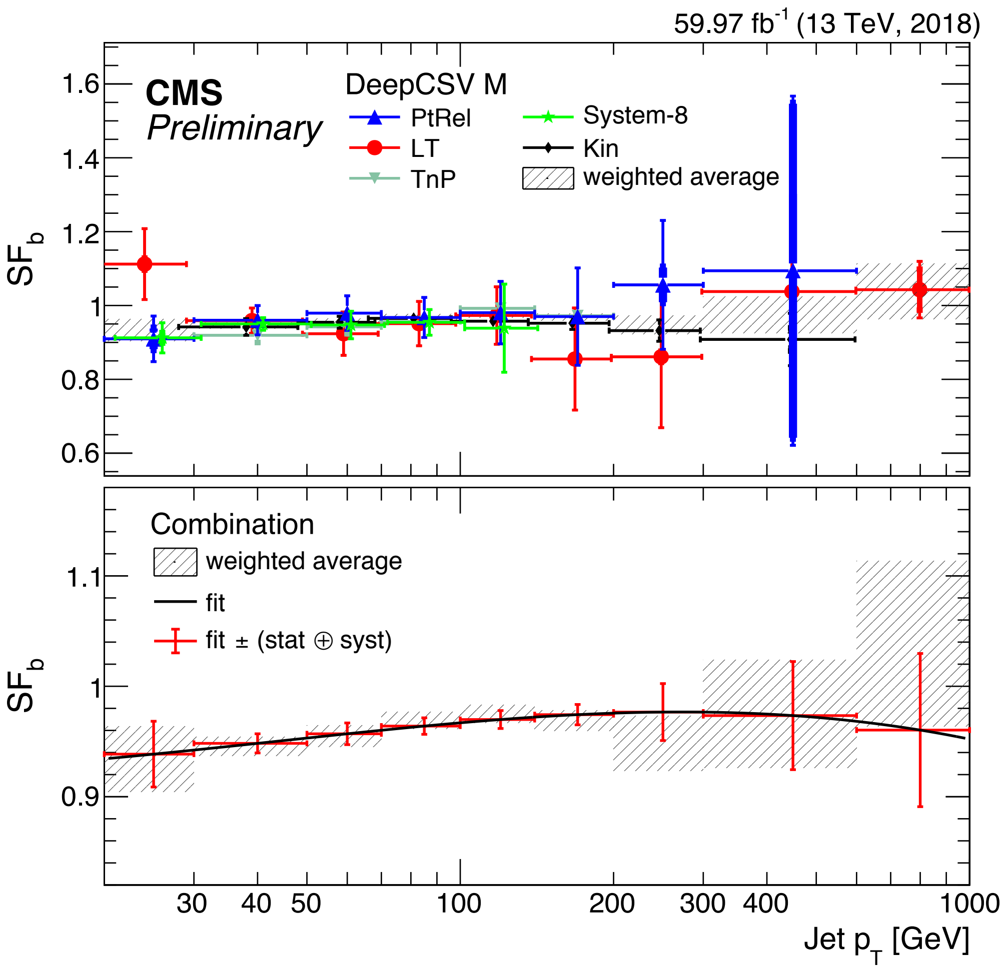




Performance




59.97 fb^{-1} (13 TeV, 2018)
CMS
Preliminary
DeepJet L
PtRel
LT
TnP
System-8
Kin
weighted average
Combination
weighted average
fit
fit ± (stat ⊕ syst)
SF_b
Jet p_T [GeV]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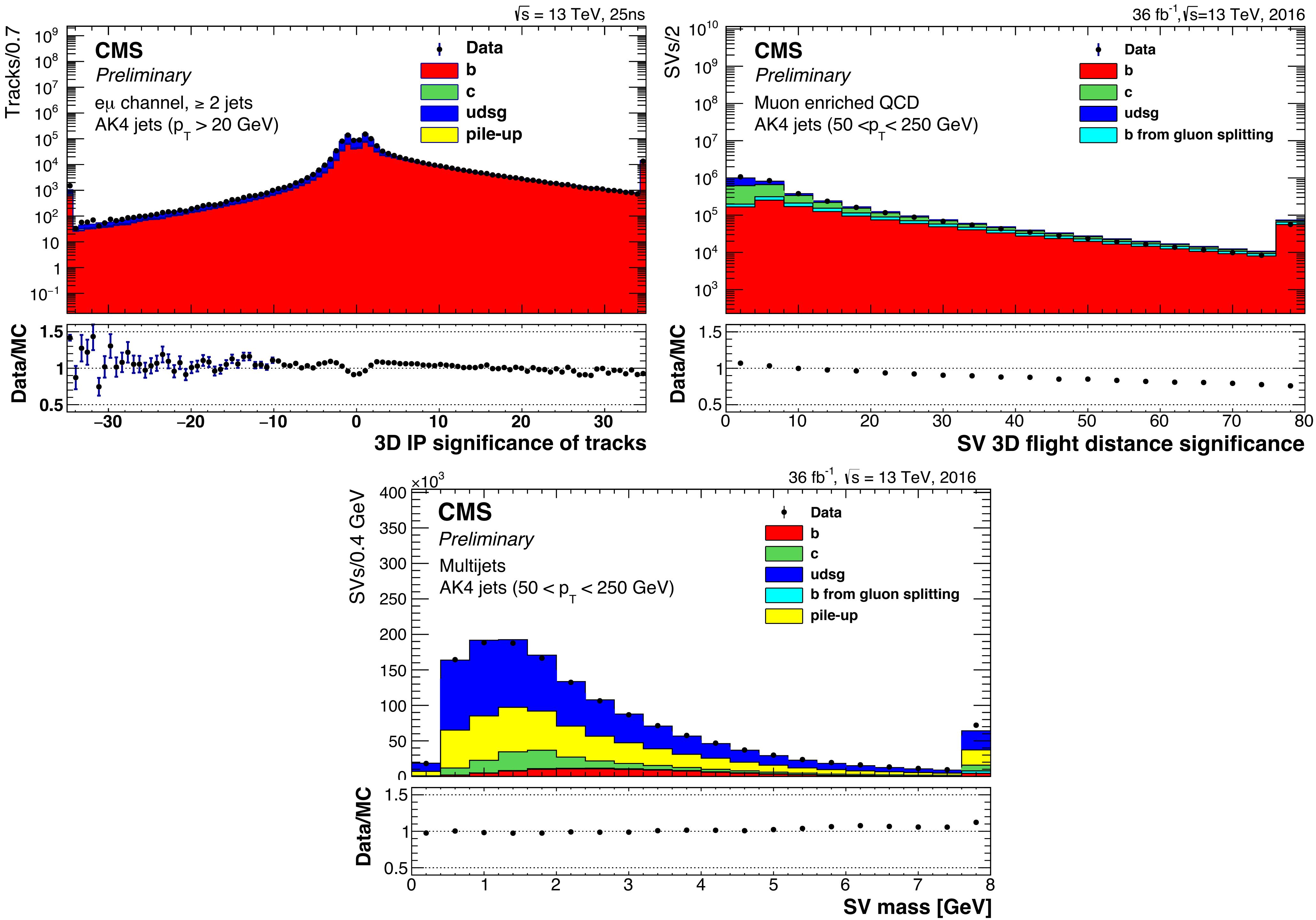
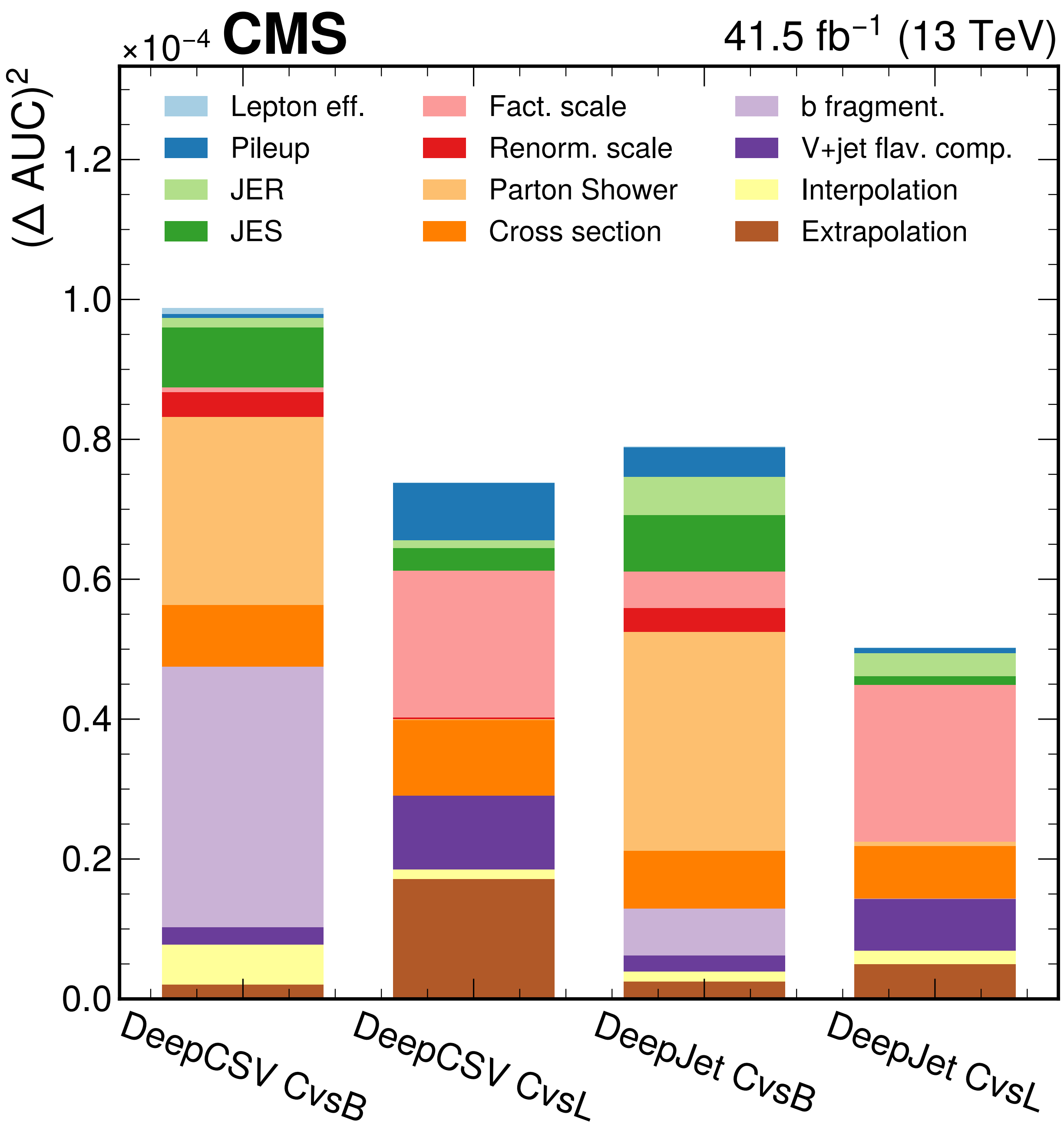
SF_b
Jet p_T [GeV]



√s = 13 TeV, 25ns
CMS
Preliminary
eμ channel, ≥ 2 jets
AK4 jets (p_T > 20 GeV)
Data
b
c
udsg
pile-up
Tracks/0.7
Data/MC
3D IP significance of tracks
36 fb^-1,√s=13 TeV, 2016
CMS
Preliminary
Muon enriched QCD
AK4 jets (50 <p_T< 250 GeV)
Data
b
c
udsg
b from gluon splitting
SVs/2
Data/MC
SV 3D flight distance significance
36 fb^-1, √s = 13 TeV, 2016
CMS
Preliminary
Multijets
AK4 jets (50 < p_T < 250 GeV)
Data
b
c
udsg
b from gluon splitting
pile-up
SVs/0.4 GeV
Data/MC
SV mass [GeV]

CMS: Charm-Jet Calibration



ATLAS: Charm-Jet mis-ID

Table 2: The contributions to the c-jet pseudo-continuous mistagging efficiency scale factor systematic uncertainties for particle-flow jets. Listed are the uncertainties related to the $t\bar{t}$ modelling, the jets and E_T^{miss}, the light-flavour jet scale factor, the b-jet scale factor, and all other sources.

		Systematic uncertainty in SF				
Tagging interval	Jet p_T range [GeV]	$t\bar{t}$ mod.	Jet/E_T^{miss}	Light tag	b-tag	Other
85%–100%	20–40	5.3%	0.8%	2.3%	–	0.1%
85%–100%	40–65	2.1%	0.3%	1.2%	–	–
85%–100%	65–140	1.9%	0.2%	0.9%	–	0.1%
85%–100%	140–250	2.0%	0.4%	0.9%	–	0.1%
77%–85%	20–40	8.3%	3.1%	8.2%	–	0.3%
77%–85%	40–65	3.0%	1.0%	3.5%	–	0.1%
77%–85%	65–140	3.2%	0.5%	2.4%	–	0.2%
77%–85%	140–250	3.9%	0.9%	2.3%	–	0.3%
70%–77%	20–40	9.7%	1.2%	2.5%	–	0.4%
70%–77%	40–65	4.7%	0.8%	1.1%	–	0.1%
70%–77%	65–140	3.7%	0.4%	0.8%	–	0.2%
70%–77%	140–250	3.1%	1.0%	0.9%	–	0.1%
60%–70%	20–40	11%	0.8%	1.6%	–	0.4%
60%–70%	40–65	4.7%	0.6%	0.9%	–	0.1%
60%–70%	65–140	4.4%	0.4%	0.6%	–	0.2%
60%–70%	140–250	2.6%	1.4%	0.8%	0.2%	0.2%
0%–60%	20–40	17%	3.1%	0.8%	0.2%	1.5%
0%–60%	40–65	11%	3.7%	0.4%	0.1%	0.9%
0%–60%	65–140	8.7%	3.0%	0.2%	–	0.7%
0%–60%	140–250	9.7%	7.1%	0.7%	–	1.7%