Recent developments in heavy flavour tagging and new HH and HHH triggers for Run 3

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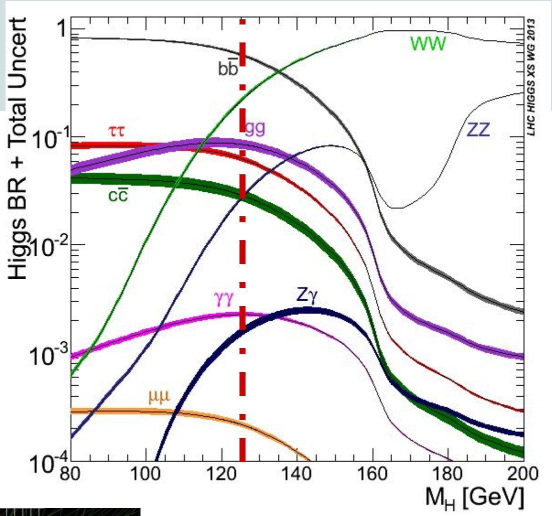
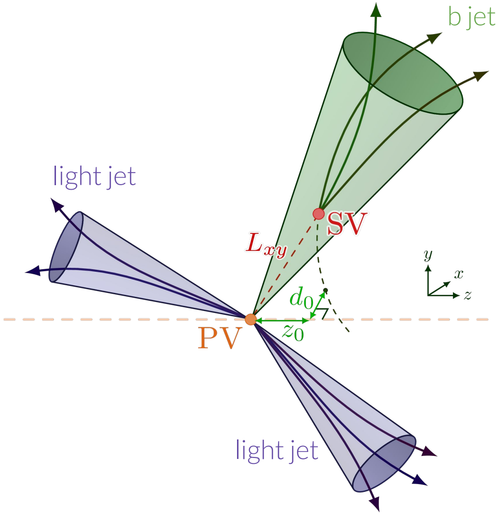
Heavy flavour jet tagging in CMS

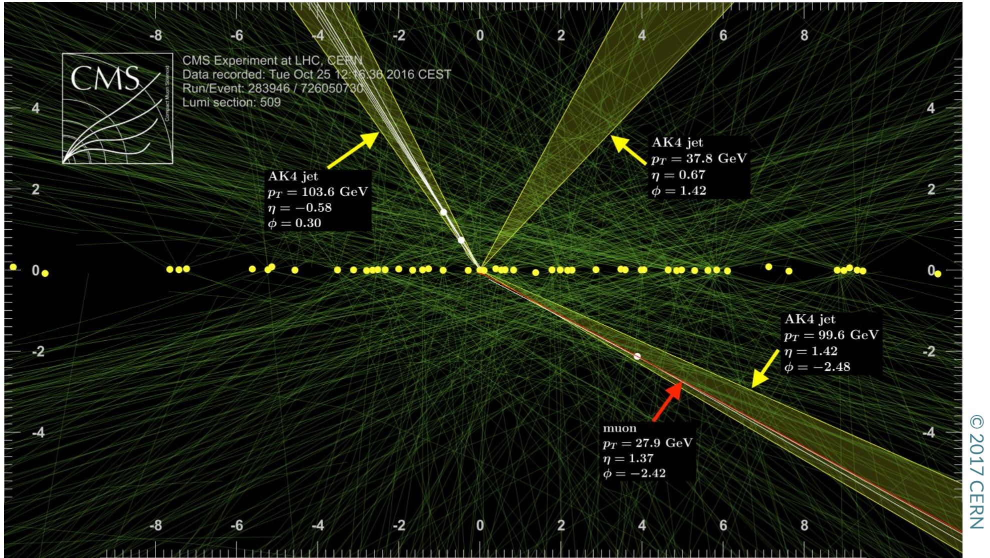
Heavy flavour b/c-jet tagging crucial for Higgs SM and BSM physics at the LHC

Unique signature:

- Sizeable lifetime of b/c hadrons (ps)
  - Displaced tracks (few mm) form a secondary vertex (SV)
- Harder fragmentation and larger mass compared to light-flavour quarks/gluons
- Presence of charged leptons in 20% (10%) of b (c) hadrons decays

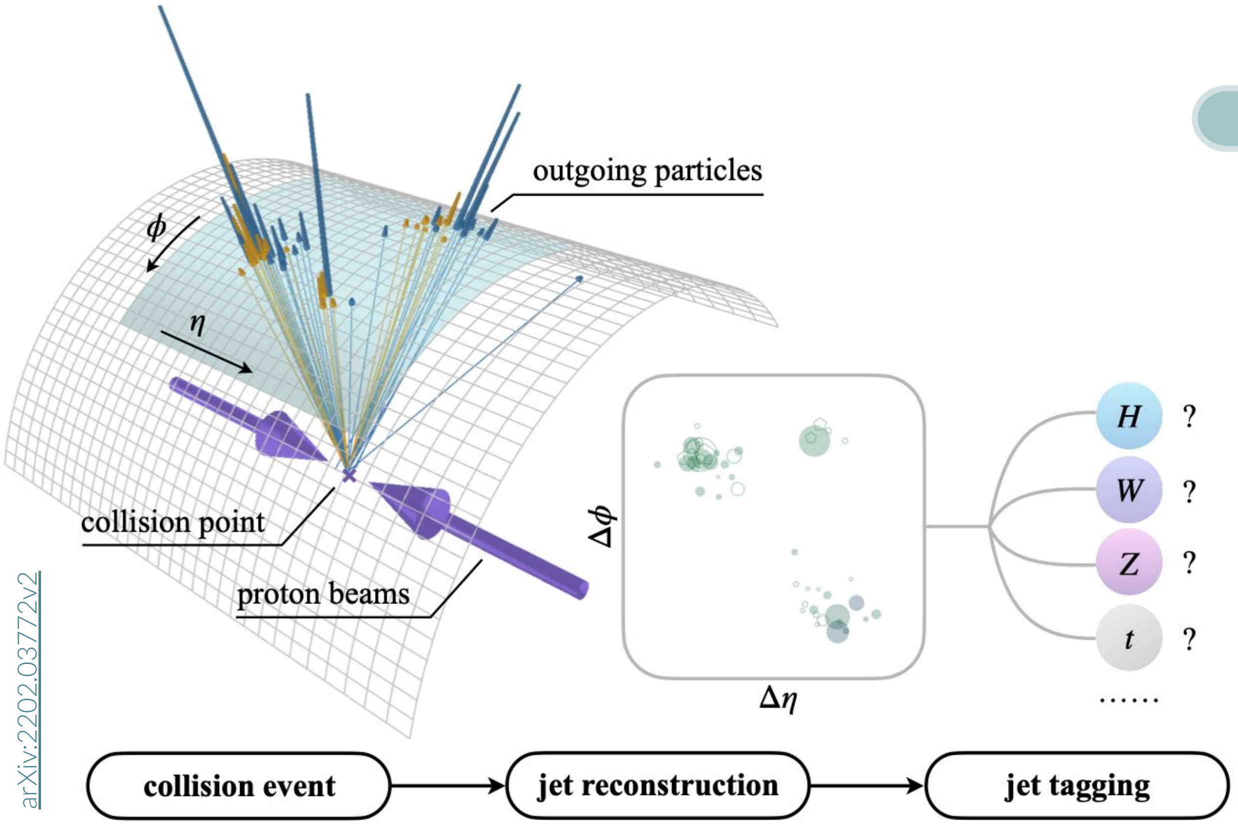






CMS collision event with 3 jets, 2 of which tagged with the **CSVv2** algorithm

Heavy flavour jet tagging in CMS



arXiv:2202.03772v2

- TCHE
- TCHP
- SSVHE
- SSVHP
- JP
- CSV
- JBP
- cMVAv2
- CSVv2
- DeepCSV
- DeepJet
- ParticleNet
- Particle Transformers

The CMS collaboration 2013 JINST 8 P04013

A.M. Sirunyan et al 2018 JINST 13 P05011

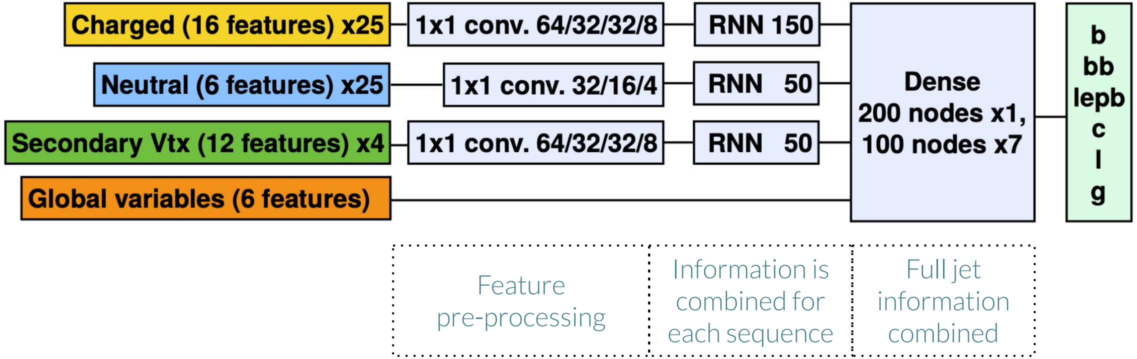
Lots of pioneer developments since Run 1

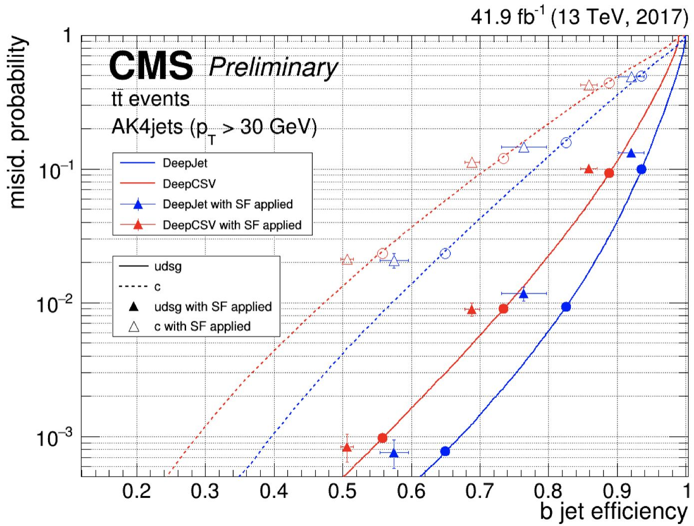
DeepJet

E. Bols et al 2020 JINST 15 P12012

DeepJet heavy flavour tagger has been widely used in Run 2 Legacy results

- Successor of DeepCSV and state-of-the-art in Run 2
- Uses ~650 input features:
  - Low-level: charged and neutral Particle Flow (PF) candidates and SV
  - Global-level: jet kinematics, track and SV multiplicities in jet, number of primary vertices in event
- DeepJet architecture:





CMS DP-2018-058

Multiclass output allows for b, c-jet identification and light quark vs gluon discrimination

DeepJet as a b tagger

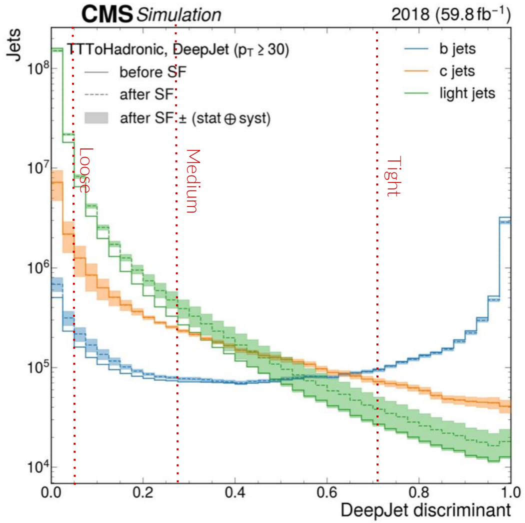
E. Bols et al 2020 JINST 15 P12012

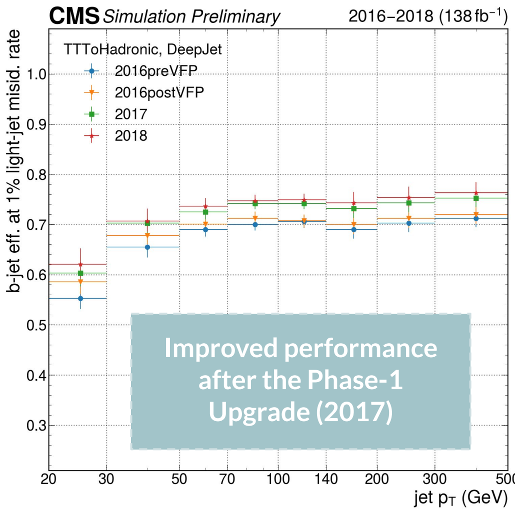
DeepJet b discriminant:

$$\frac{P(b) + P(bb) + P(b_{lep})}{P(uds) + P(g) + P(b) + P(bb) + P(b_{lep})}$$

Usage in CMS analyses:

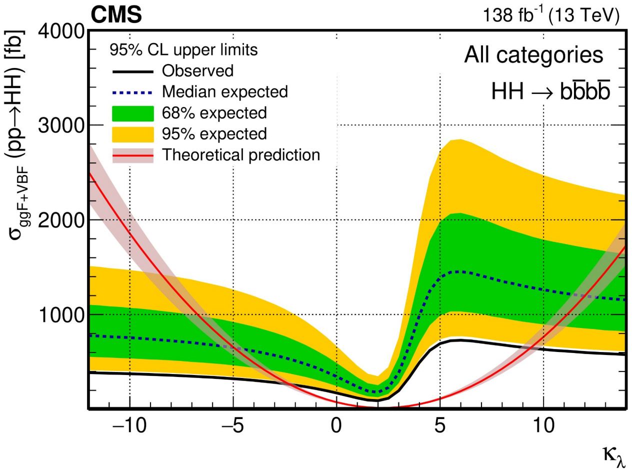
- 3 working points (WPs):
  - Loose : ≈91% b eff, 10% mis-id rate
  - Medium : ≈80% b eff, 1% mis-id rate
  - Tight : ≈65% b eff, 0.1% mis-id rate
- Per-jet scores used as inputs to ML algorithms





Improved performance after the Phase-1 Upgrade (2017)

CMS DP-2023-005



Fundamental role in HH ⟶ 4b search:
Most stringent observed constraints on HH cross section!

Phys. Rev. Lett. 129 (2022) 081802

DeepJet b calibration

CMS DP-2023-005

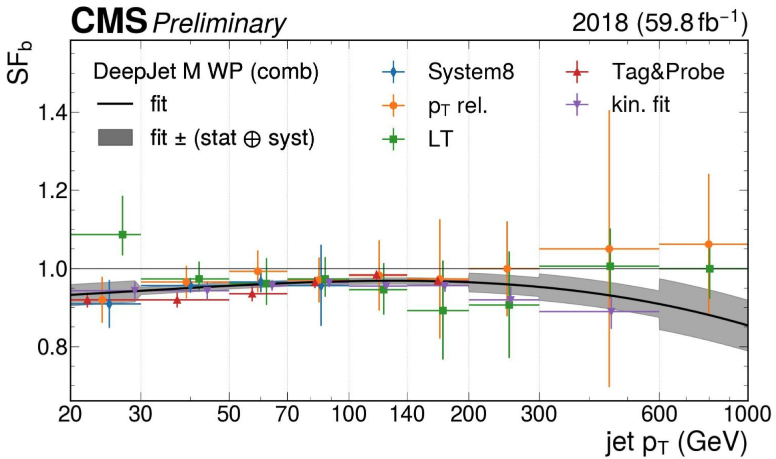
Different calibration techniques used to derive scale factors (SF) to ensure same performance of heavy-flavour tagging in simulation as in data

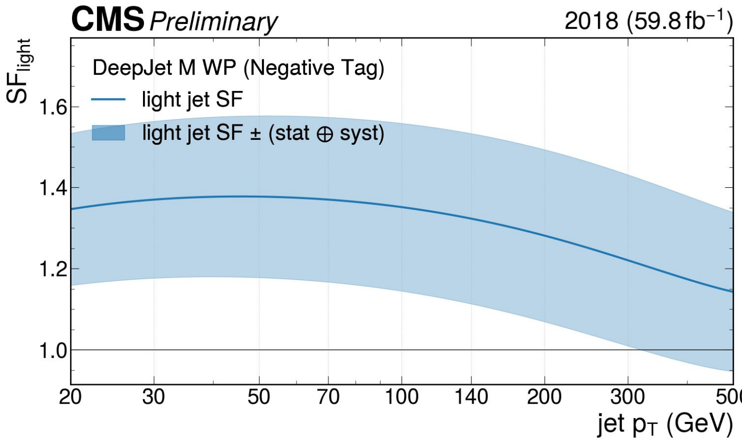
- b-tagging efficiency measured in **multijet** and **top pair production** events
    - **System8, pT rel., Lifetime (LT)**
    - **Kin. Fit, Tag & Probe**
- The **combination** of results is used to ensure robustness of the fixed WPs SF measurement

- Light-jet misidentification rate measured in multijet events
    - NegativeTag

Scale factors are also available for the full discriminant shape:

✓ Shape calibrations successfully applied in H→bb observation!
[CMS Collaboration Phys. Rev. Lett. 121, 121801]





DeepJet as a c jet tagger

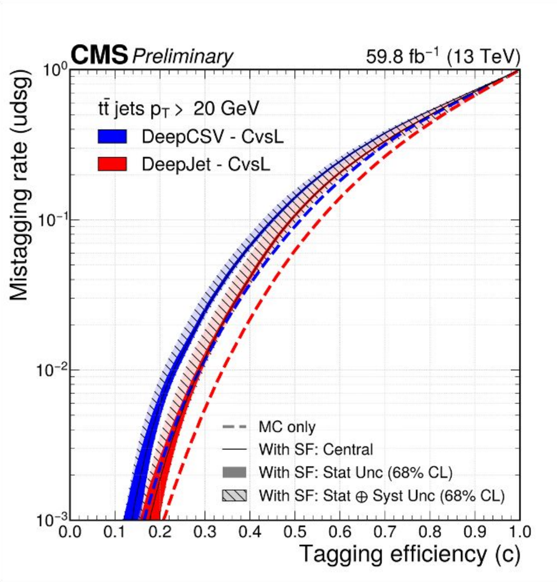
CMS DP-2023-006

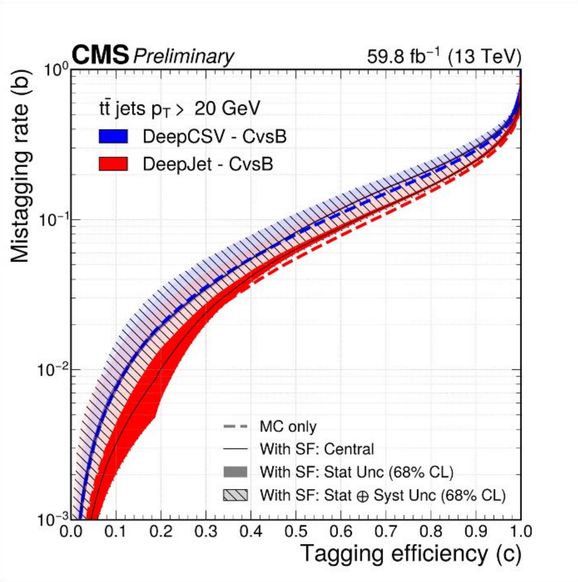
c hadrons: smaller lifetime, mass than b hadrons

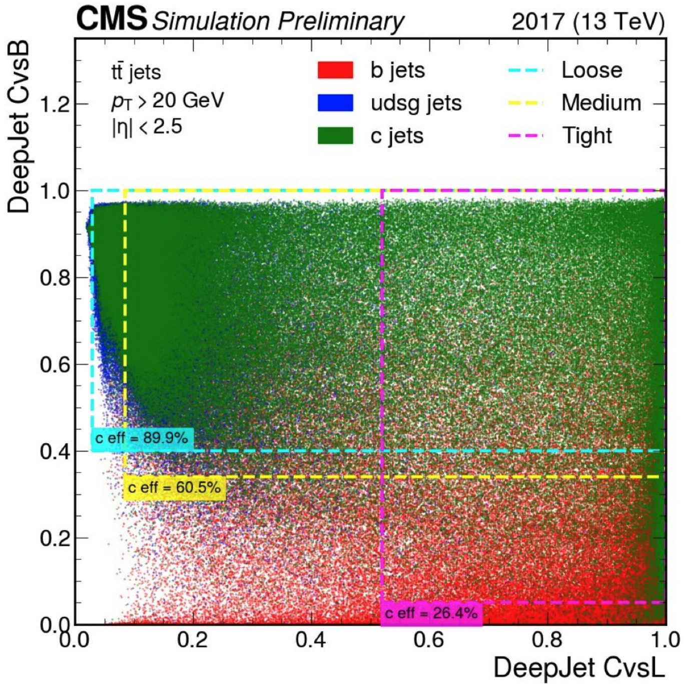
- Harder to distinguish c jets from light flavour jets, or even b jets
- Two discriminating variables: CvsL, CvsB

CvsL: $$\frac{P(\mathrm{c})}{P(\mathrm{c})+P(\mathrm{uds})+P(\mathrm{g})}$$

CvsB: $$\frac{P(\mathrm{c})}{P(\mathrm{c})+P(\mathrm{b})+P(\mathrm{bb})+P(\mathrm{b_{lep}})}$$







	CvsL cut	CvsB cut	c eff.	b eff.	udsg eff.
Loose	0.030	0.400	89.9%	28.2%	93.0%
Medium	0.085	0.340	60.5%	25.7%	26.0%
Tight	0.520	0.050	26.4%	31.0%	0.60%

DeepJet as a c jet tagger

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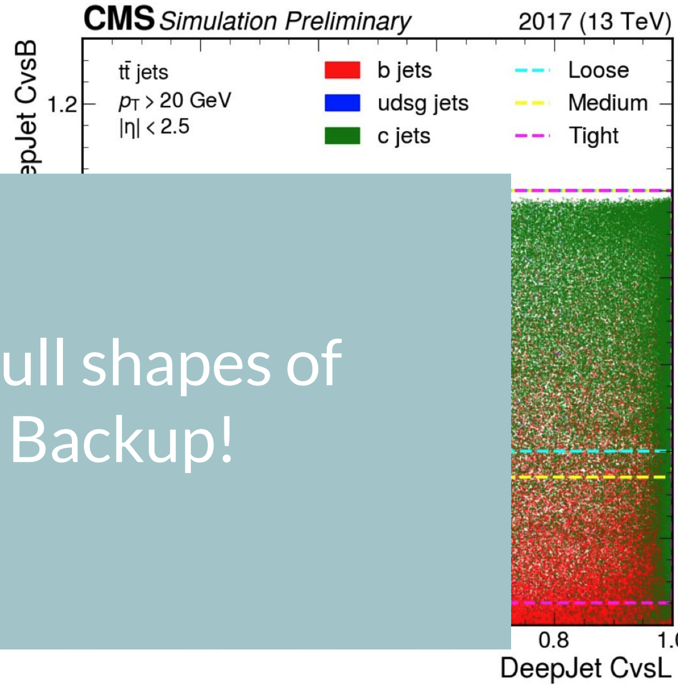
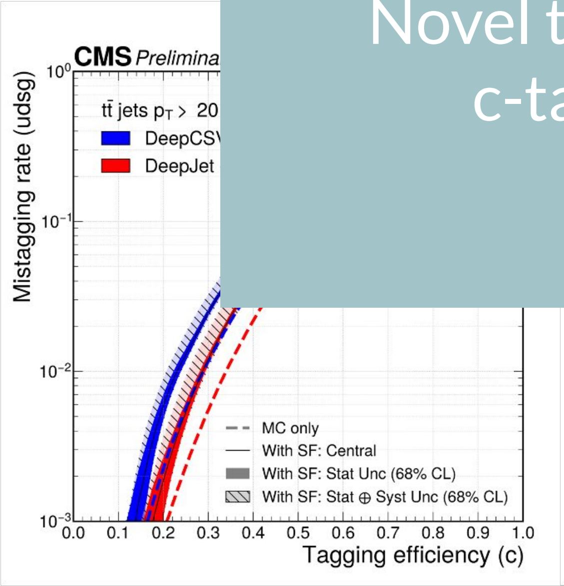
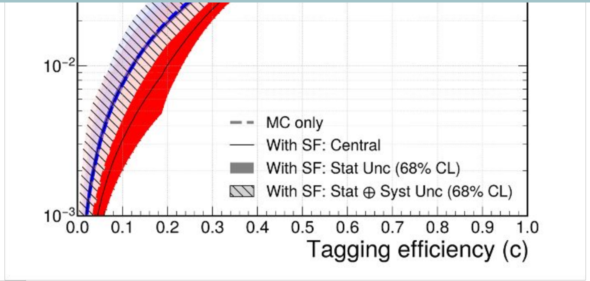
CvsL:



Novel technique to calibrate full shapes of c-tagging discriminants in Backup!





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Improving robustness of DeepJet with adversarial training

CMS-DP-2022-049

Jet tagging algorithms trained in simulation only.

- Mismodellings can lead to non-negligible differences in performance in data

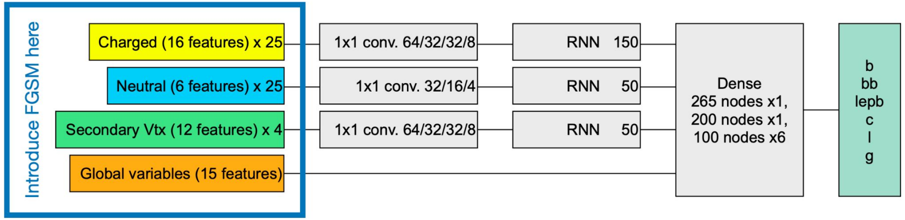
Adversarial attack: Adversarial inputs generated by the Fast Gradient Sign Method (FSGM):

$$x_{\mathrm{FGSM}} = x_{\mathrm{raw}} + \epsilon \cdot \mathrm{sgn}\left(\nabla_{x_{\mathrm{raw}}} J(x_{\mathrm{raw}}, y)\right)$$

x_{raw} : are the input features
ϵ : (small) distortion parameter
J : loss function
y : truth label

Adversarial training:

- Defense strategy to mitigate the impact of adversarial attacks
- Use of systematically distorted samples during training
- Apply FGSM attack in every step of the training
  - the network is less likely to learn simulation-specific properties of the training sample

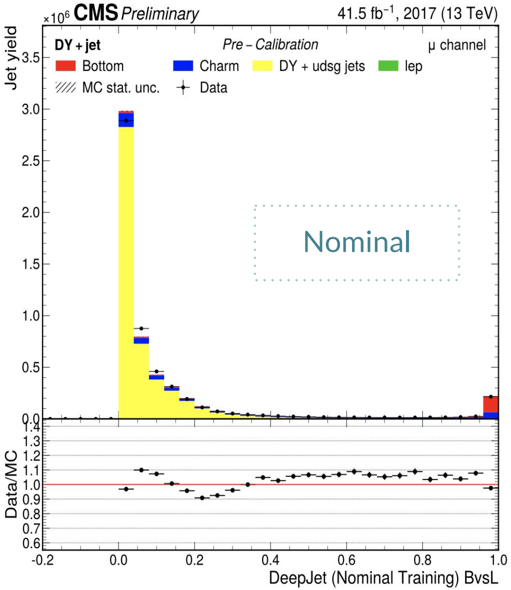


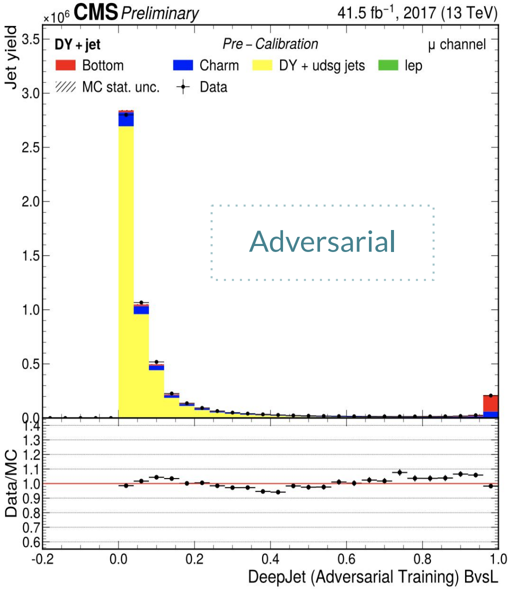
Improving robustness of DeepJet with adversarial training

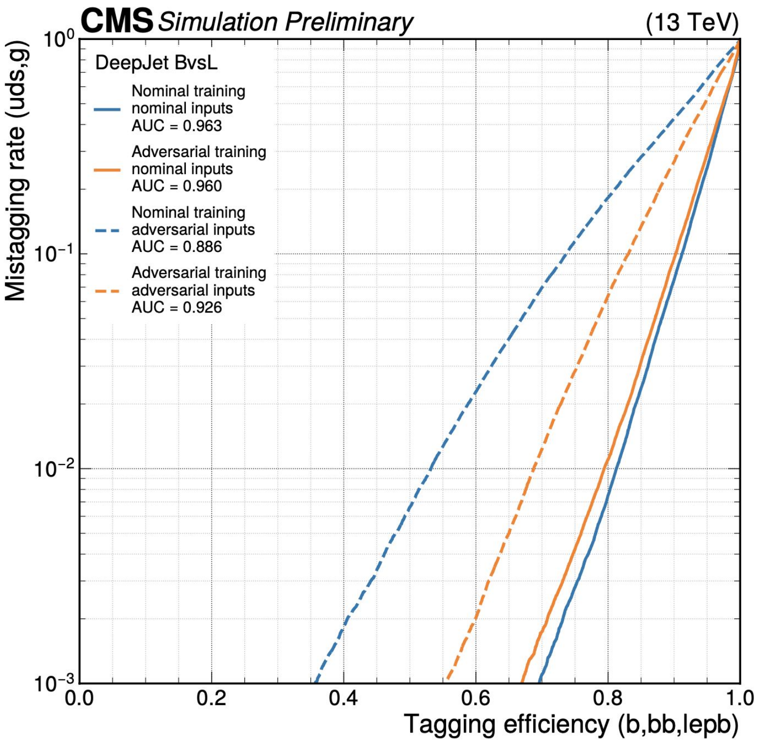
CMS-DP-2022-049

Adversarial training:

- Two tasks: optimizing classification & withstand distortions of inputs
- Reduces data-to-simulation differences prior to any calibration





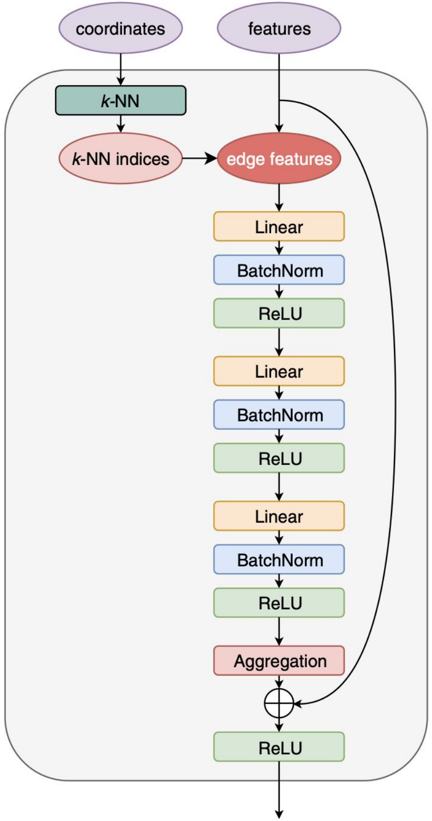


Trade-off between performance and robustness to systematic distortions

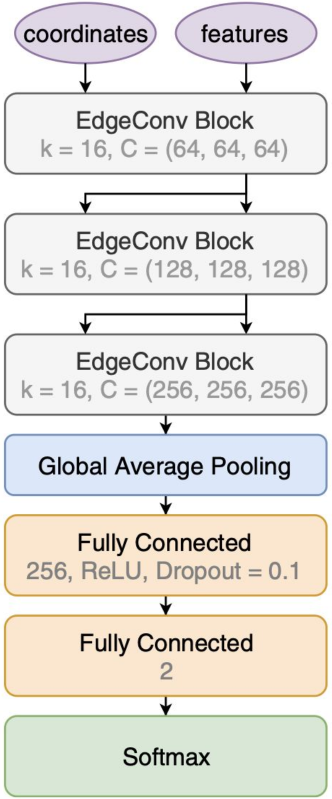
ParticleNet

PhysRevD.101.056019

- First **graph-based** tagger at the LHC!
- Jets represented as an **unordered set of particles in space** (*“particle clouds”*)
- Uses permutation-invariant graph-neural networks:
  Dynamic Graph Convolutional Neural Network (arXiv:1801.07829)
- Input nodes: (up to 100) PF jet constituents, SVs with set of features
- Neighboring nodes connected to learn relations
- Training performed on jets uniform in p_T /mass
- Initially used for boosted jet tagging:
  → Multi-class approach for t/W/Z/H tagging
- More recently explored for **small-cone** jet tagging



EdgeConv block



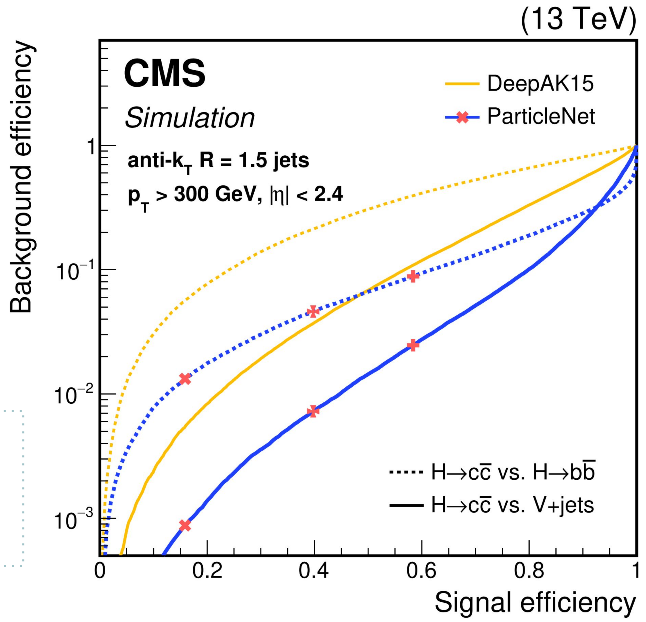
ParticleNet architecture

Run 2 physics highlights with ParticleNet

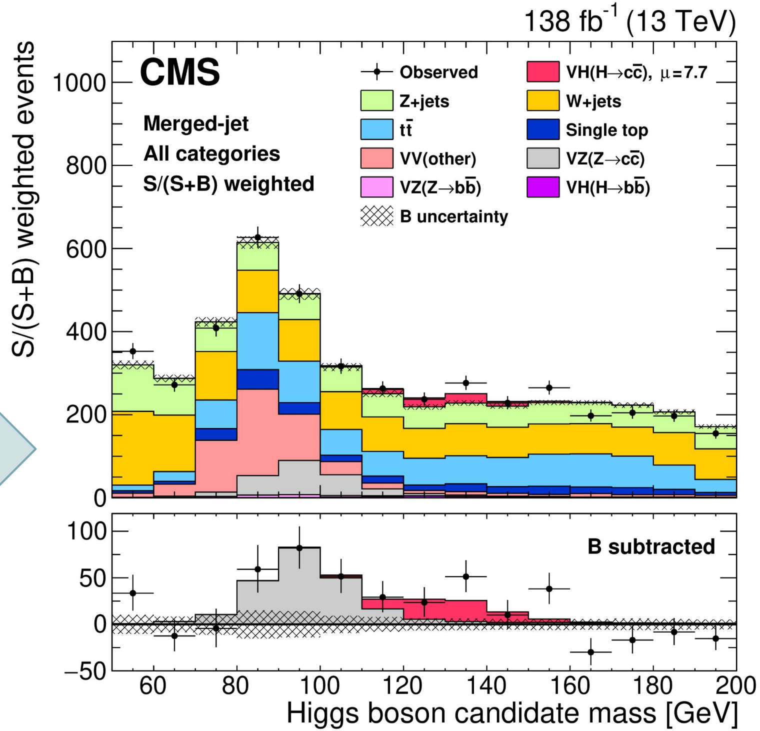
CMS HIG-21-008

- Search for **H→cc** in association with a leptonically decaying W/Z boson where H is Lorentz-boosted
- Use of ParticleNet to discriminate **H→cc** from **H→bb** and **V+jets**

Merged-jet H→cc identification
DeepJet Vs. ParticleNet



First observation of Z→cc at hadron collider (5.7σ)!

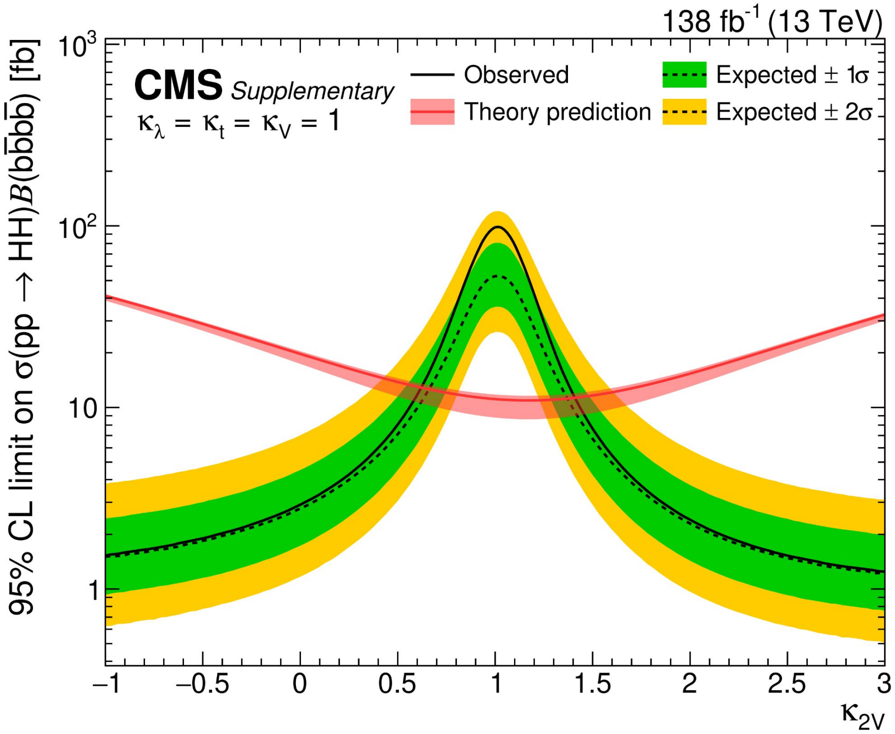


Run 2 physics highlights with ParticleNet

CMS B2G-22-003

Exclusion of κ_{2V}=0 for the first time (6.3 σ)!

- Search for non-resonant HH production via ggF and VBF in the 4b final state, with Lorentz-boosted H pairs
- Use of ParticleNet to discriminate between **H→bb** and **QCD-induced jets**
- Significant improvements in **tagging performance** and **jet mass decorrelation**
- Increased statistics (Run 2) and novel tagging techniques led to **a factor of 30 improvement** on 95% C.L. upper limits of HH production cross section wrt. previous search (2016 only)



ParticleNet Calibration of the mass-decorrelated ParticleNet tagger

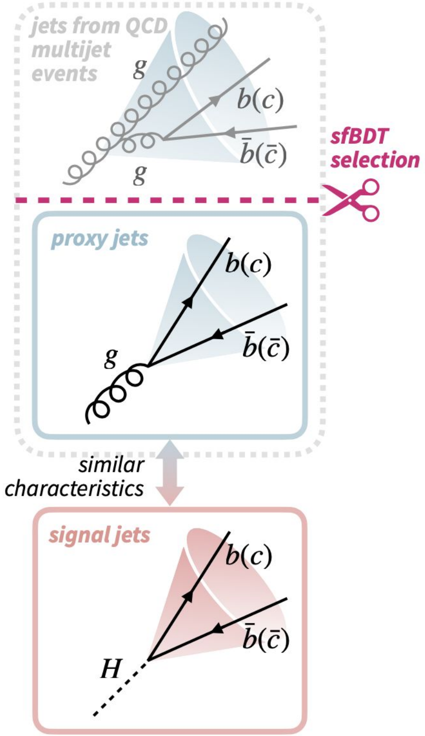
Calibration of ParticleNet MD $H\rightarrow bb$, $H\rightarrow cc$ tagger performed for fixed WPs and as a function of jet p_T

Proxy jets: Using $g \rightarrow b\bar{b}/c\bar{c}$ jets obtained from QCD multijet events in data passing a BDT selection (sfBDT):

- sfBDT trained with simulated gluon-splitting $g \rightarrow b\bar{b}/c\bar{c}$ QCD multijet events
- Separates jets with a clean composition of quarks, resembling more the $H\rightarrow bb(cc)$ jets, against the ones with large contamination of extra gluons
- Final state gluon contamination rate κ_g defined as:

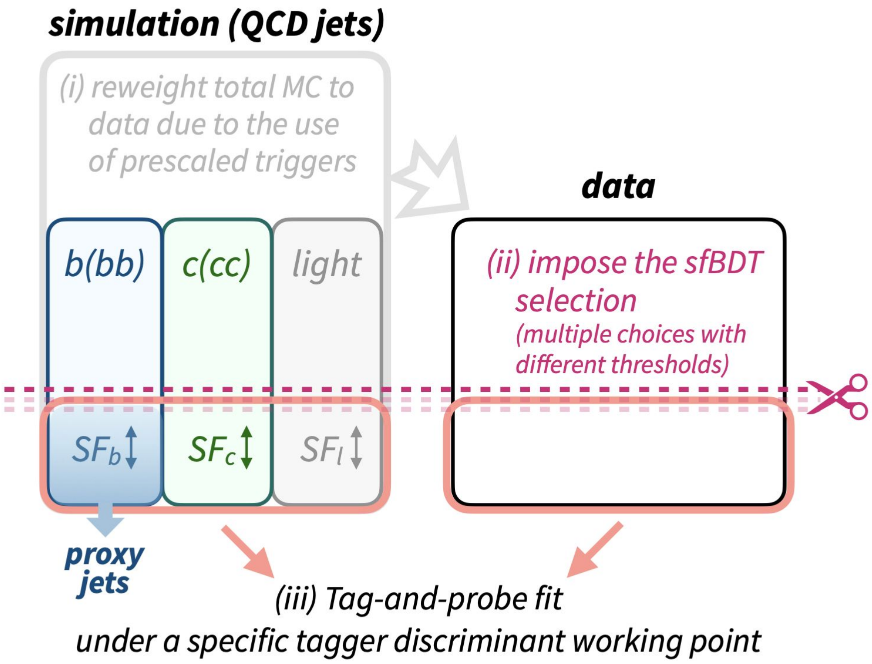
$$\kappa_g = \frac{\sum p_{T,g}}{\sum p_{T,g} + p_{T,q}}$$

- Quarks and gluons selected from parton-level truth particles associated with a jet
- Signal jets: $\kappa_g < 0.15$, background jets: $\kappa_g > 0.85$
- Input variables to the sfBDT:
  - basic kinematics of the subjets
  - secondary vertices associated with the jet



Workflow:

- All jets from the QCD multijet MC categorised into b(bb), c(cc), and light based on the truth-level matching
- Proxy of $H \to b\bar{b}$ or $H \to c\bar{c}$ jets built from the b(bb) or c(cc) class with a **specific selection on the sfBDT**
- Proxy jets fitted to data with **tag-and-probe**, under the specific tagger WP
- 3 free-floating rate parameters *SFb* , *SFc* , *SFl* assigned to the 3 classes
- Fit performed individually on multiple pT bins
- The post-fit parameter *SFb* (*SFc*) is then regarded as the SF for the $H \to b\bar{b}$ ($c\bar{c}$) signal jets



ParticleNet Calibration of the mass-decorrelated ParticleNet tagger

CMS DP-2022-005

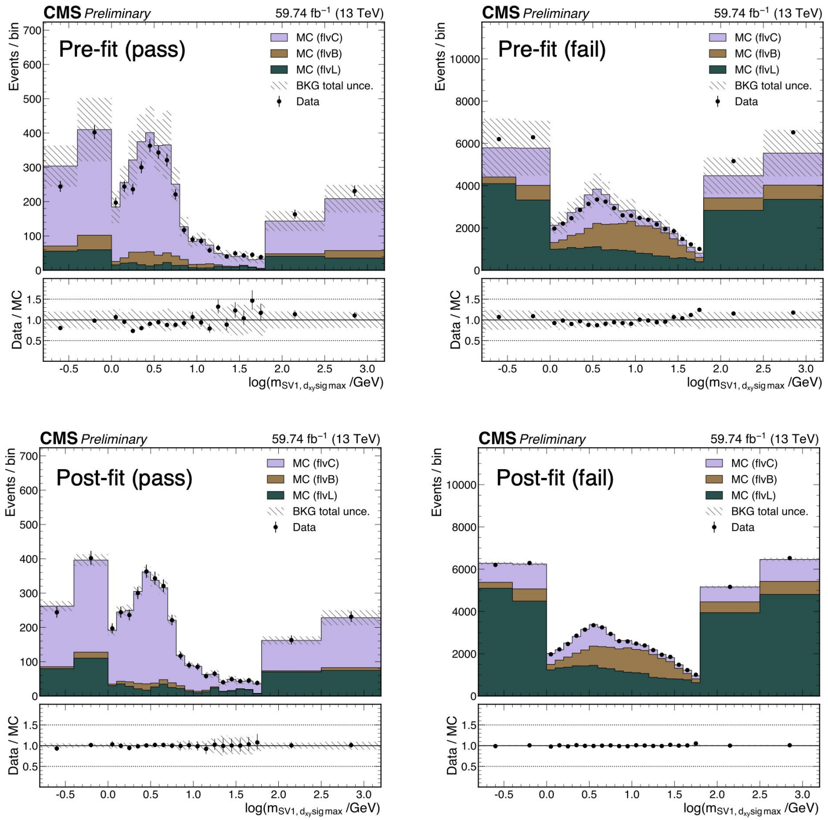
- Fit variable: **log(mSV1)** (SV1: leading SV associated with the jet with the highest impact parameter dxy significance)

Source	Uncertainties on three flavour templates		
	b(bb)	c(cc)	light
Luminosity	1.2–2.5%	1.2–2.5%	1.2–2.5%
Pileup reweighting	<0.5%	<0.6%	<1.9%
sfBDT variable data-to-MC reweighting	<0.2%	<0.2%	<0.2%
ISR parton shower uncertainty	1–3%	4–6%	3–5%
FSR parton shower uncertainty	2–6%	8–12%	17–20%
Fragmentation uncertainty on bottom quarks	14–16%	—	—
Fragmentation uncertainty on charm quarks	—	13–16%	—
Fragmentation uncertainty on light quarks	—	—	20%

Additional systematic uncertainty:

- For each calibration point:
  - 11 selections of the sfBDT →11 proxy jet collections → 11 fits (and scale factors)
- Max distance between all 11 scale factors & central value taken as an additional systematic uncertainty

Pre/post-fit distributions for a single calibration point and sfBDT selection



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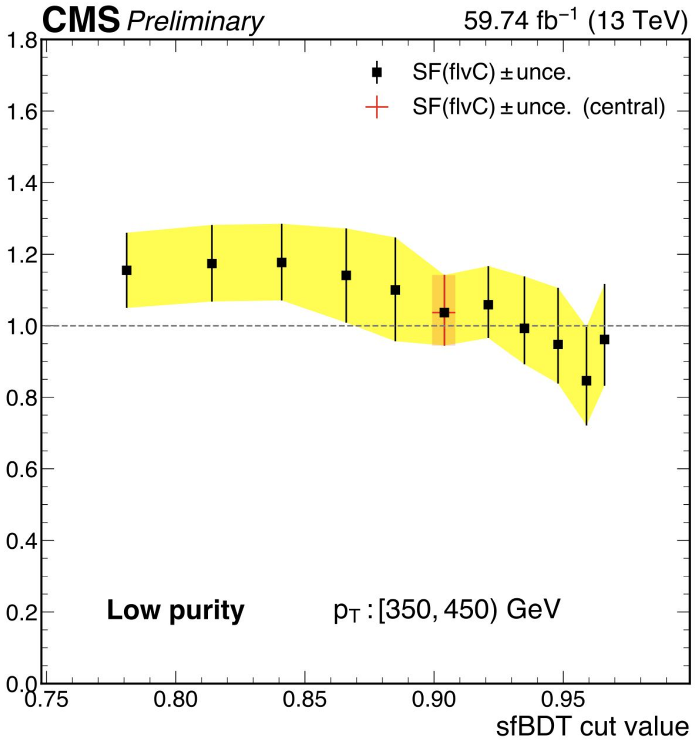

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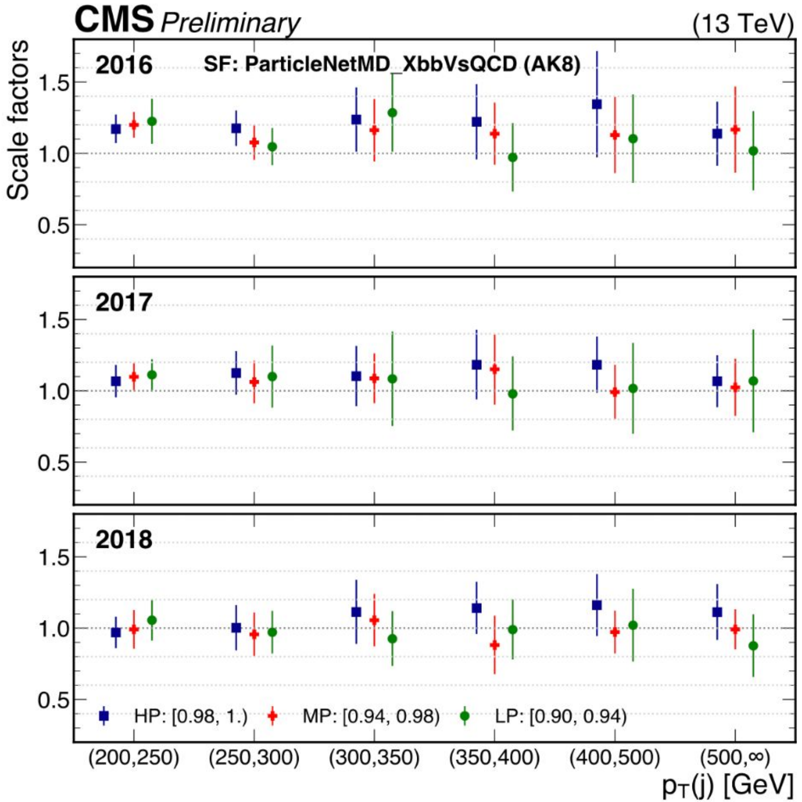
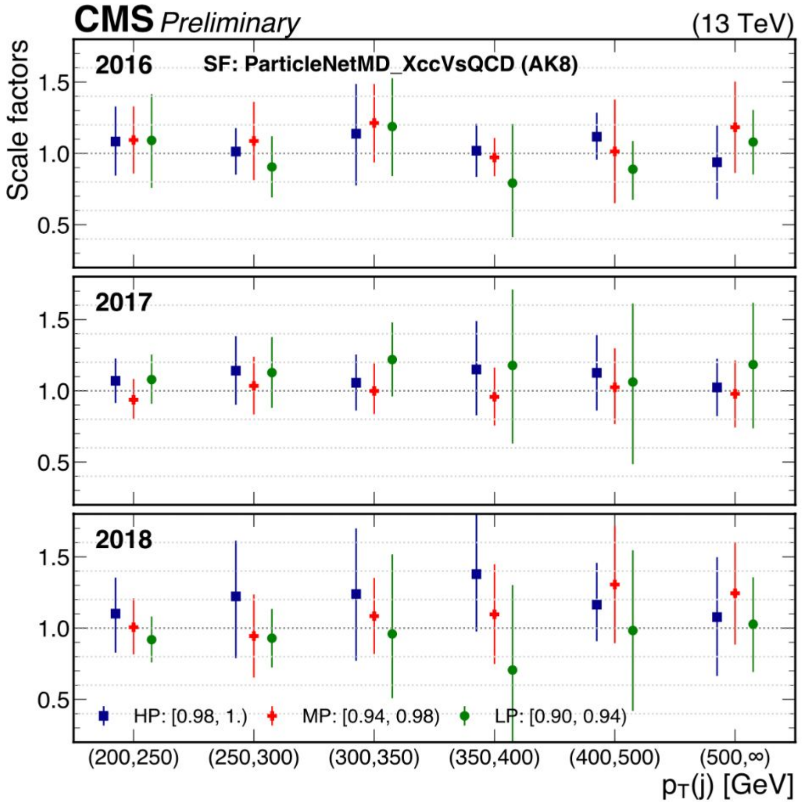
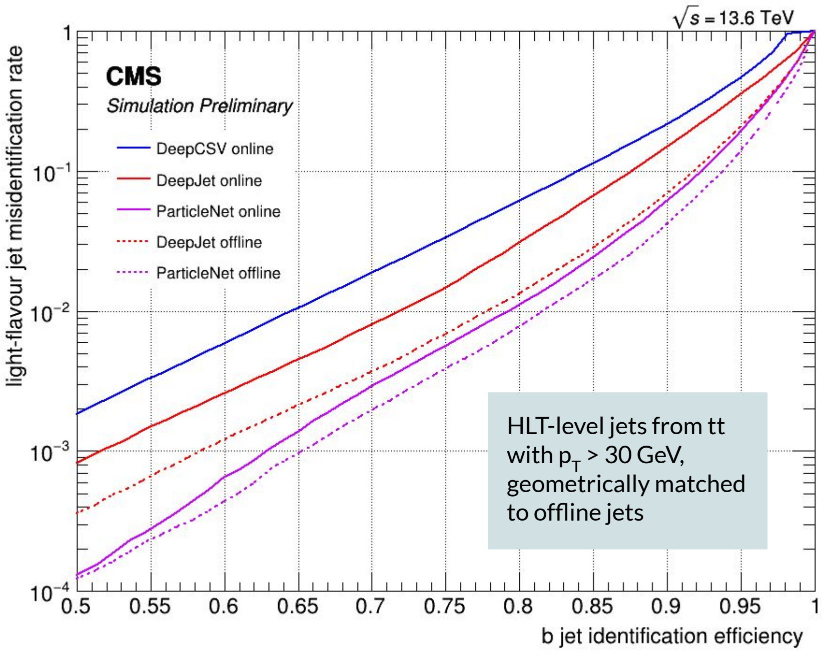


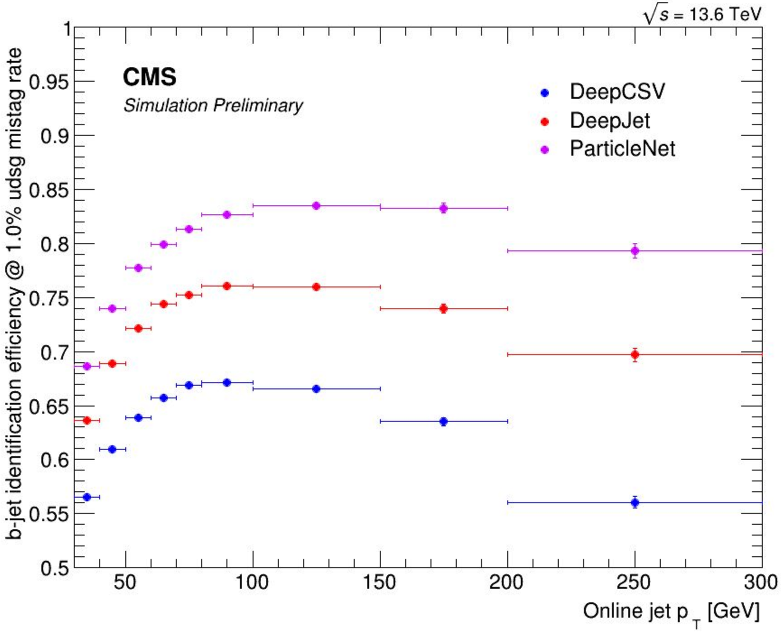


ParticleNet @ HLT

CMS DP-2023-021

Lighter version of ParticleNet deployed online since the beginning of Run 3





- ✓ Large improvements with respect to previous b taggers
- ✓ Closer online-offline performance

- ✓ 5-10% higher efficiency throughout the jet p_T range wrt. DeepJet

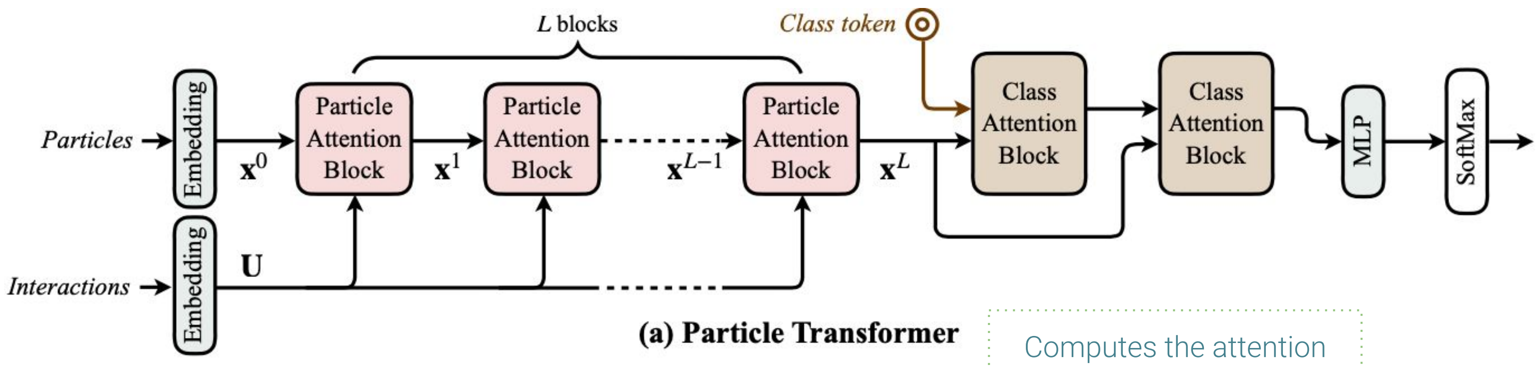
Particle Transformers

arXiv.2202.03772

- First **attention-based** tagger at the LHC!
- Inputs:
  - single particle inputs (kinematic variables, PID, trajectory displacements)
  - pairwise (physics motivated) features between particles
- Learn which neighbour particles are relevant through **attention mechanism**
- Trained on substantially larger dataset (JetClass), more inclusive in jet types

Interaction features for each pair of particles a, b:

$$\begin{aligned} \Delta &= \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}, \\ k_{\mathrm{T}} &= \min(p_{\mathrm{T},a}, p_{\mathrm{T},b})\Delta, \\ z &= \min(p_{\mathrm{T},a}, p_{\mathrm{T},b})/(p_{\mathrm{T},a} + p_{\mathrm{T},b}), \\ m^2 &= (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2, \end{aligned}$$



(a) Particle Transformer

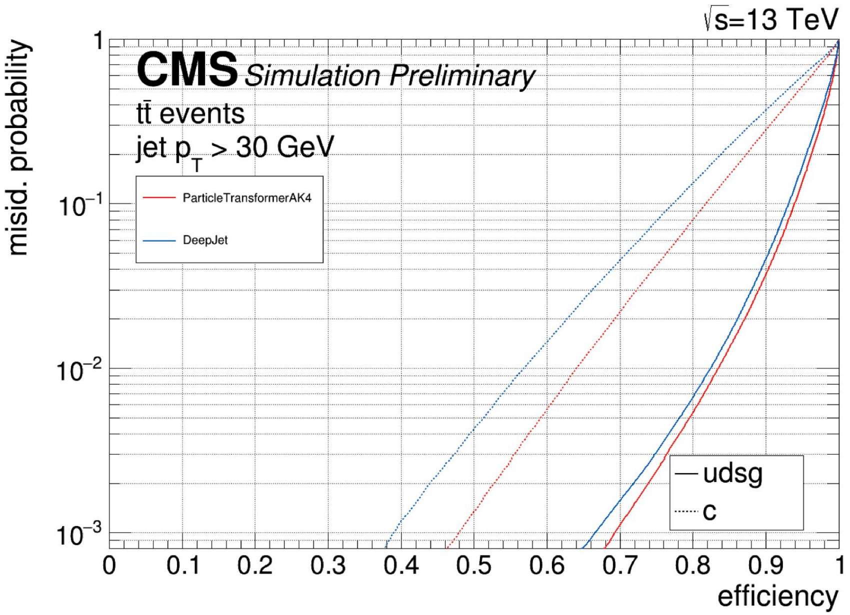
Computes self attention between particles

Computes the attention between a global class and all the particles

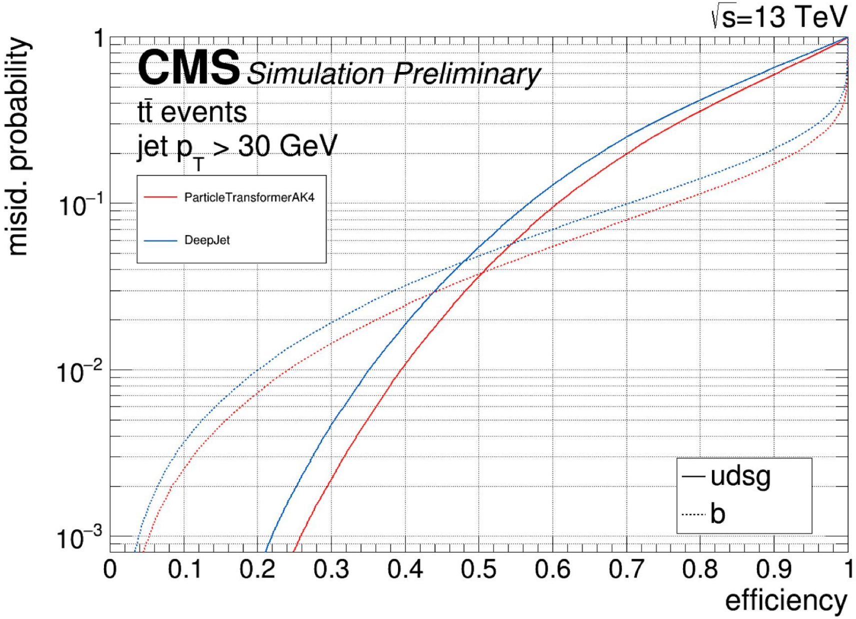
Particle Transformers performance

arXiv.2202.03772
CMS DP-2022-050

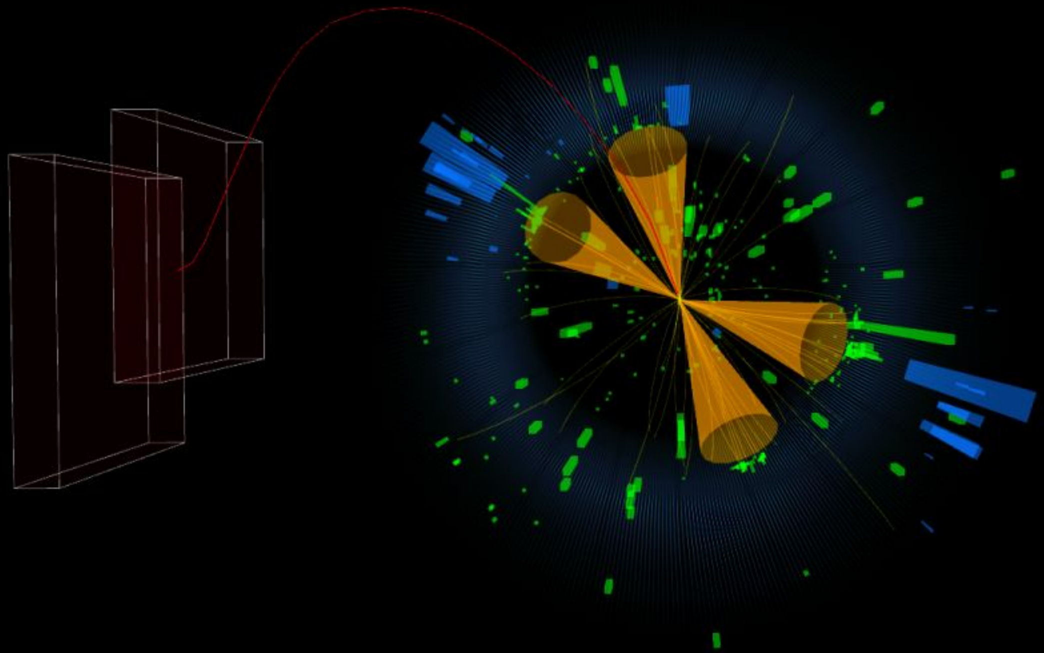
Probability of misidentifying **non-b → b jets** wrt. efficiency of identifying b jets



Probability of misidentifying **non-c → c jets** wrt. efficiency of identifying c jets



Novel trigger strategy targeting HH and HHH productions in Run 3



Novel trigger strategy targeting HH→4b in Run 3

Run 2 trigger targeting 4b final states (8 Hz @ 2E10^{34} cm^{-2} s^{-1}):
- Scalar sum of jets p_T (PF H_T) > 340 GeV
- ≥ 4 jets with p_T > 75, 60, 45, 40 GeV
- ≥ 3 jets tagged with **DeepCSV** algorithm

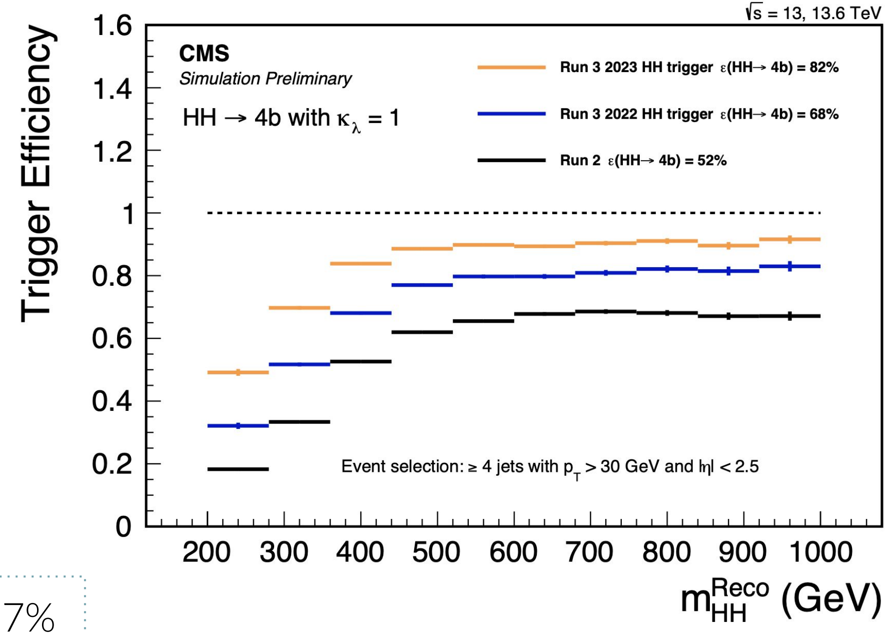
Run 3 2022 HH trigger (60 Hz):
- L1 H_T > 360 GeV
- ≥ 4 jets with p_T > 70, 50, 40, 35 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.65

Run 3 2023 HH trigger (180 Hz):
- L1 H_T > 280 GeV
- ≥ 4 jets with p_T > 30 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.55

Data Parking

✓ **Run 3 2023 HH trigger** achieves an 82% efficiency, 57% (20%) increase with respect to Run 2 (Run 3 2022) trigger!

Non-resonant HH→4b (κ_λ=1)



$$\varepsilon = \frac{N_{\text{events}}(\text{pass trigger and event selection})}{N_{\text{events}}(\text{pass event selection})}$$

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- Scalar sum of jets p_T (PF H_T) > 340 GeV
- ≥ 4 jets with p_T > 75, 60, 45, 40 GeV
- ≥ 3 jets tagged with **DeepCSV** algorithm

Run 3 2022 HH trigger (60 Hz):

- L1 H_T > 360 GeV
- ≥ 4 jets with p_T > 70, 50, 40, 35 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.65

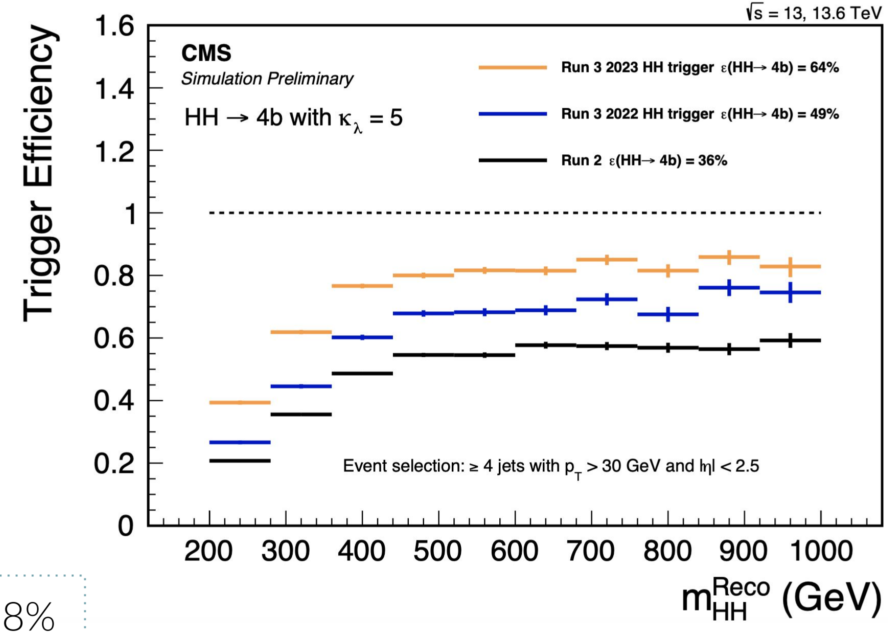
Run 3 2023 HH trigger (180 Hz):

- L1 H_T > 280 GeV
- ≥ 4 jets with p_T > 30 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.55

Data Parking

✓ **Run 3 2023 HH trigger** achieves an 64% efficiency, 78% (30%) increase with respect to Run 2 (Run 3 2022) trigger!

Non-resonant HH→4b (**κ_λ=5**)



$$\varepsilon = \frac{N_{\text{events}}(\text{pass trigger and event selection})}{N_{\text{events}}(\text{pass event selection})}$$

Novel trigger strategy targeting $HH \rightarrow 2b2\tau_{had}$ in Run 3

Run 3 τ_{had}-triggers require: [CMS DP-2023-024]

- $\geq 2\ \tau_{had}$ with $p_T > 35$ GeV, $|\eta|<2.1$ and tagged with DeepTau algorithm (50 Hz)
- $\geq 2\ \tau_{had}$ with $p_T > 30$ GeV, $|\eta|<2.1$ and tagged with DeepTau algorithm + 1 jet with $p_T > 60$ GeV (20 Hz)
- $\geq 1\ \tau_{had}$ with $p_T > 180$ GeV, $|\eta|<2.1$ (17 Hz)

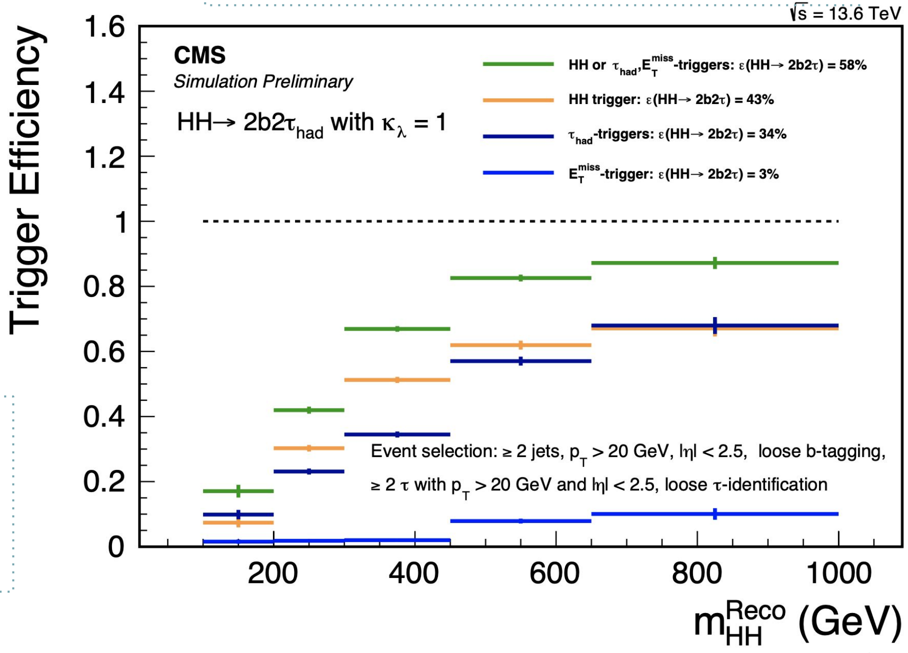
Run 3 E_T^{miss}-triggers require $E_T^{miss} > 120$ GeV [CMS DP-2023-016]

Run 3 2023 HH trigger (180 Hz):

- L1 $H_T > 280$ GeV
- ≥ 4 jets with $p_T > 30$ GeV
- 2 leading-in-ParticleNet jets have average b-disc > 0.55

✓ **Run 3 2023 HH trigger** complements **E_T^{miss}/τ_{had}**-triggers, reaching a combined overall efficiency of **58%**

Non-resonant $HH \rightarrow 2b2\tau_{had}$ ($\kappa_\lambda=1$)



Novel trigger strategy targeting $HH \to 2b2\tau_{had}$ in Run 3

Run 3 τ_{had}-triggers require: [CMS DP-2023-024]

- $\geq 2\ \tau_{had}$ with $p_T > 35$ GeV, $|\eta|<2.1$ and tagged with DeepTau algorithm (50 Hz)
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- $\geq 1\ \tau_{had}$ with $p_T > 180$ GeV, $|\eta|<2.1$ (17 Hz)

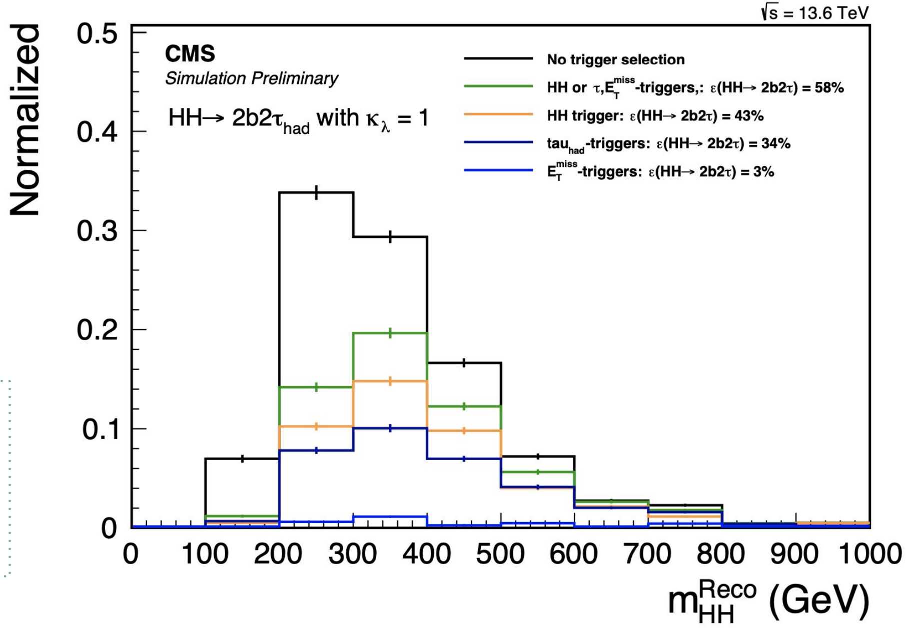
Run 3 E_T^{miss}-triggers require $E_T^{miss} > 120$ GeV [CMS DP-2023-016]

Run 3 2023 HH trigger (180 Hz):

- L1 $H_T > 280$ GeV
- ≥ 4 jets with $p_T > 30$ GeV
- 2 leading-in-ParticleNet jets have average b-disc > 0.55

✓ **Run 3 2023 HH trigger** increases the acceptance in the intermediate m_{HH} region

Non-resonant $HH \to 2b2\tau_{had}$ (κ_λ=1)



Novel trigger strategy targeting HH→2b2τ_{had} in Run 3

Run 3 τ_{had}-triggers require: [CMS DP-2023-024]

- ≥ 2 τ_{had} with p_T > 35 GeV, |η|<2.1 and tagged with DeepTau algorithm (50 Hz)
- ≥ 2 τ_{had} with p_T > 30 GeV, |η|<2.1 and tagged with DeepTau algorithm + 1 jet with p_T > 60 GeV (20 Hz)
- ≥ 1 τ_{had} with p_T > 180 GeV, |η|<2.1 (17 Hz)

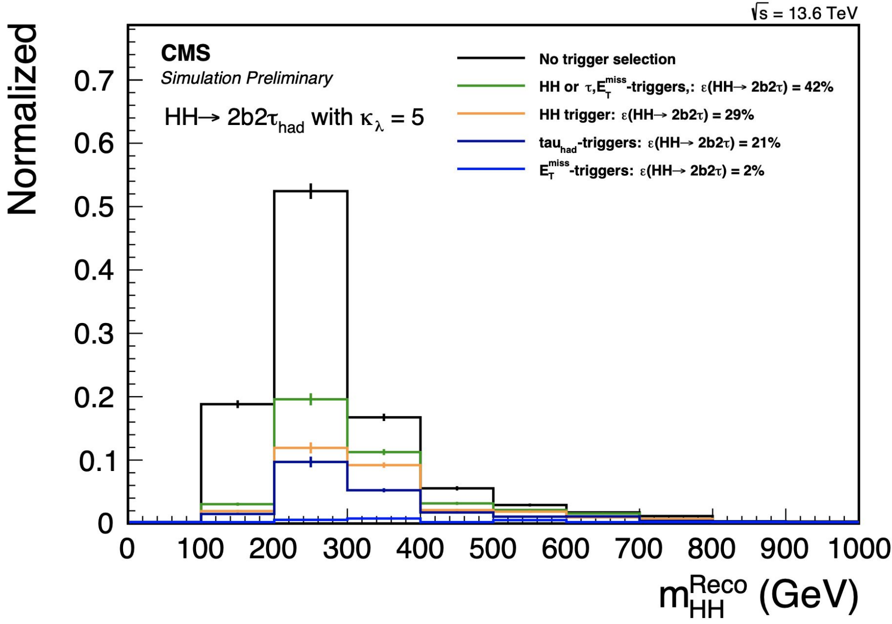
Run 3 E_T^{miss}-triggers require E_T^{miss} > 120 GeV [CMS DP-2023-016]

Run 3 2023 HH trigger (180 Hz):

- L1 H_T > 280 GeV
- ≥ 4 jets with p_T > 30 GeV
- 2 leading-in-ParticleNet jets have average b-disc > 0.55

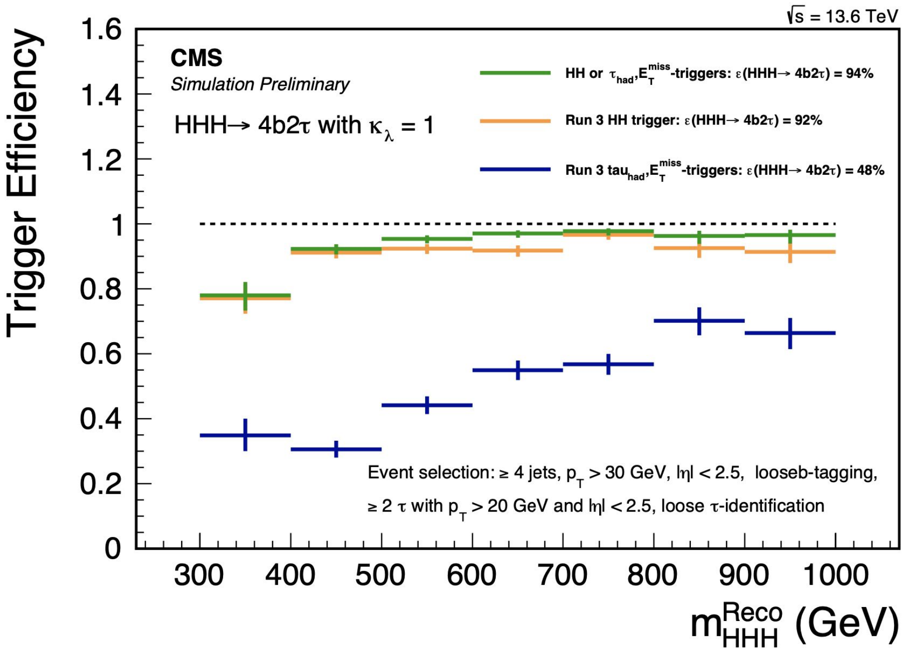
✓ **Run 3 2023 HH trigger** increases the acceptance in the intermediate m_{HH} region

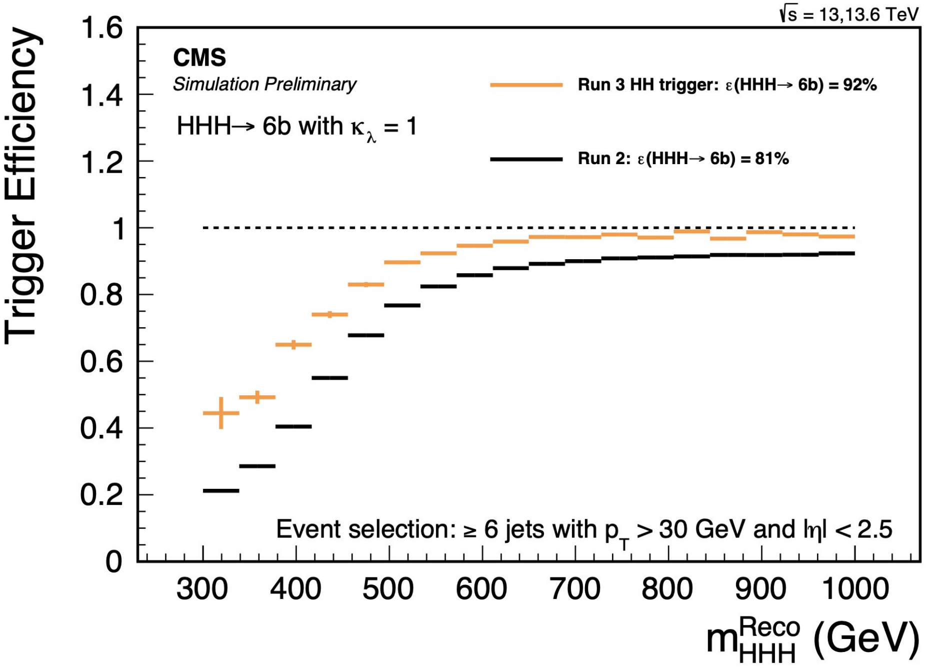
Non-resonant HH→2b2τ_{had} (κ_λ=5)



Novel trigger strategy targeting triple Higgs production

Same trigger(s) can be used in the search for triple Higgs production in the **$4b2\tau_{had}$** and **6b** final states, achieving **94%** and **92%** overall efficiency, respectively!





Summary

- Modern neural networks with sophisticated architectures bring considerable performance improvements in (heavy flavour) jet tagging in Run 3
- CMS introduces a novel method to calibrate H→bb/cc taggers
- Tagging algorithms can become more robust against simulation mismodellings with adversarial trainings

- ParticleNet@HLT introduced in Run 3 shows improved b-tagging performance
- New trigger targeting HH→4b signals now operates at 180 Hz
  - Large efficiency gain observed in HH→4b, HHH→6b, HH→$2b2\tau_{had}$, HHH→$4b2\tau_{had}$ final states!

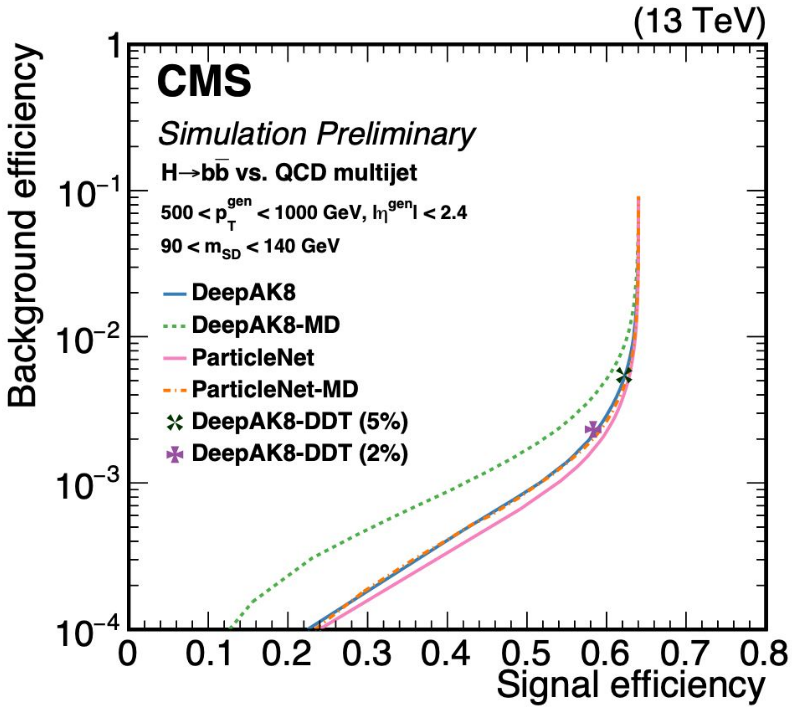
Thank you for your attention

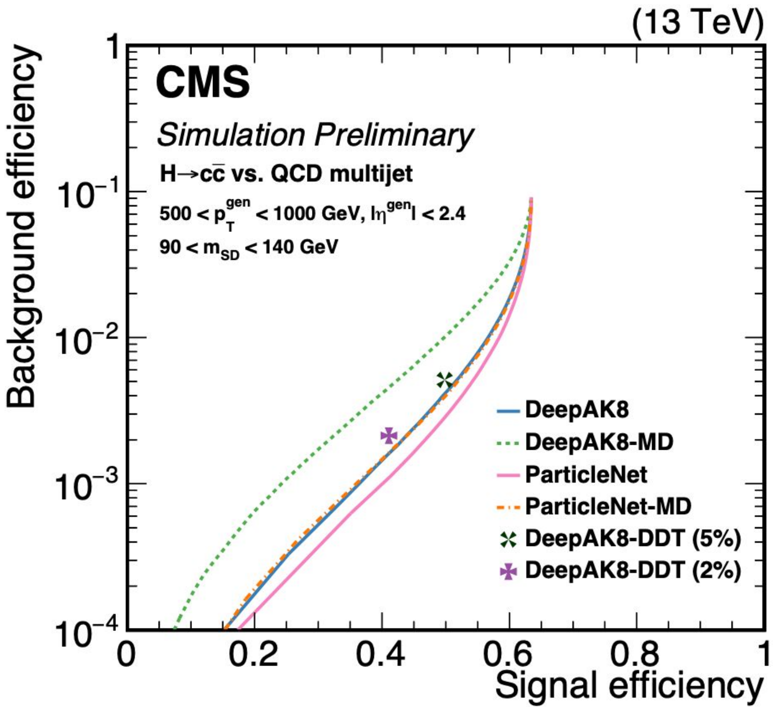
Stay tuned for Run 3 physics analysis results!

Backup

Backup Identification of highly Lorentz-boosted Higgs bosons

CMS DP-2020-002





$$X \to b\bar{b} \text{ vs. QCD} = \frac{P(X \to b\bar{b})}{P(X \to b\bar{b}) + P(\text{QCD})}$$

$$X \to c\bar{c} \text{ vs. QCD} = \frac{P(X \to c\bar{c})}{P(X \to c\bar{c}) + P(\text{QCD})}$$

Backup b calibration methods

A.M. Sirunyan et al 2018 JINST 13 P05011

CMS DP-2023-005

- **b-tagging efficiency measurements in multijet events:**
  - **$p_T$rel** – Method to measure the b-tagging efficiency in multijet events based on the transverse momenta of muons within jets with respect to the jet axis [4].
  - **System8** – Method to measure the b-tagging efficiency in multijet events with muons within jets by solving a system of 8 equations [4].
  - **Lifetime (LT)** – Method to measure the b-tagging efficiency in multijet events with muons within jets based on template fits to the distributions of the JP discriminator and secondary vertex mass [4].
  - **mu+jets** – Combination of b-tagging efficiency measurements from multijet events with jets containing muons (p_T rel., System8, LT).
- **b-tagging efficiency measurements in top pair events:**
  - **$t\bar{t}$** – Top quark antiquark pair production.
  - **Kin. fit** – Method to measure the b-tagging efficiency in $t\bar{t}$ events with two leptons, based on a template fit to an MVA discriminator combining several kinematic observables [4].
  - **Tag&Probe** – Method to measure the b-tagging efficiency in $t\bar{t}$ events with one lepton, based on a tag and probe method, where the medium WP is applied to one of the two b-jets expected from top pair production, while the other b jet is used as a probe [4].
  - **comb** – Combination of b-tagging efficiency measurements from $t\bar{t}$ events (Kin. fit, Tag&Probe) and multijet events with a muon (p_T rel., System8, LT).
- **Light-jet mistagging efficiency measurement in multijet events:**
  - **NegativeTag** – Method to measure the light jet mistagging efficiency in inclusive multijet events, using the tracks with negative sign of the impact parameter [4].

[arXiv.2202.03772](https://arxiv.org/abs/2202.03772)

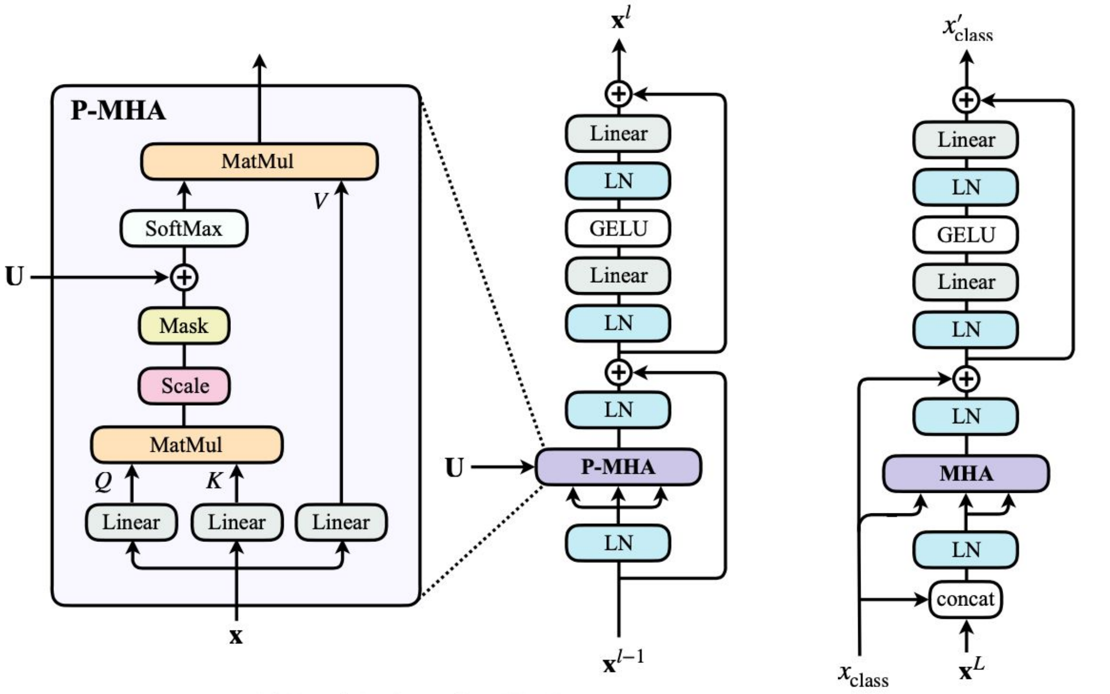
Particle Attention block:

Computes self attention between particles:

- The multi-head attention (P-MHA) module incorporates particle interaction features and modifies the dot-product attention weights

Class Attention block:

Computes the attention between a global class and all the particles though MHA



(b) Particle Attention Block

(c) Class Attention Block

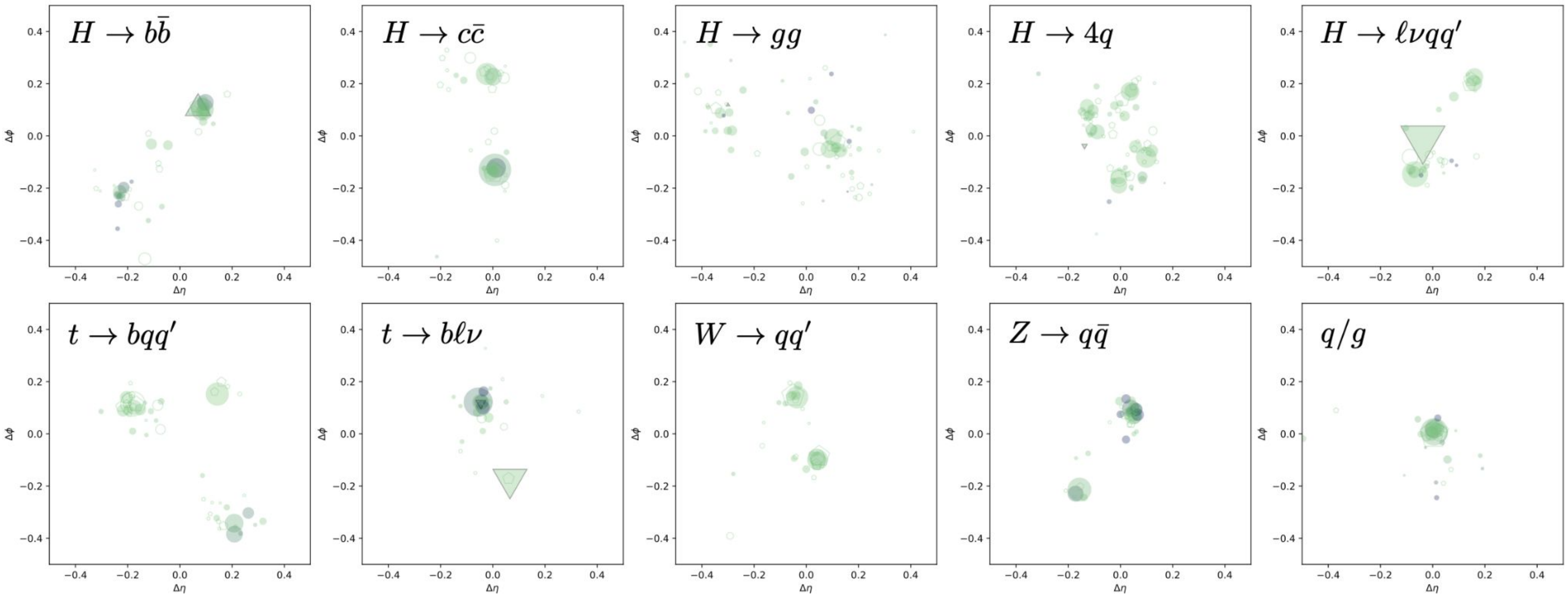
Backup Particle Transformers • input features

arXiv.2202.03772

Variable	Definition
$\Delta\eta$	difference in pseudorapidity between the particle and the jet axis
$\Delta\phi$	difference in azimuthal angle between the particle and the jet axis
$\log p_T$	logarithm of the particle's p_T
$\log E$	logarithm of the particle's energy
$\log \frac{p_T}{p_T(\text{jet})}$	logarithm of the particle's p_T relative to the jet p_T
$\log \frac{E}{E(\text{jet})}$	logarithm of the particle's energy relative to the jet energy
ΔR	angular separation between the particle and the jet axis ($\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$)
q	electric charge of the particle
`isElectron`	if the particle is an electron
`isMuon`	if the particle is a muon
`isChargedHadron`	if the particle is a charged hadron
`isNeutralHadron`	if the particle is a neutral hadron
`isPhoton`	if the particle is a photon
$\tanh d_0$	hyperbolic tangent of the transverse impact parameter of the track (in units of mm)
$\tanh d_z$	hyperbolic tangent of the longitudinal impact parameter of the track (in units of mm)
σ_{d_0}	error of the transverse impact parameter
σ_{d_z}	error of the longitudinal impact parameter

Backup Particle Transformers • jet types

arXiv.2202.03772



Training dataset: 100 M jets!

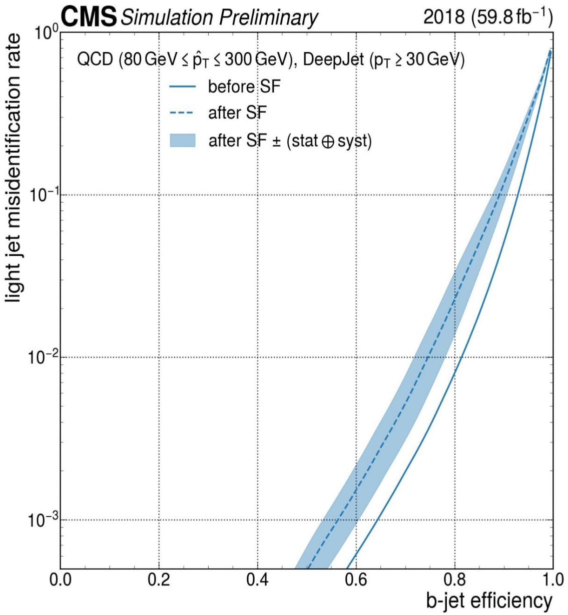
Backup b calibration • discriminant shape calibrations

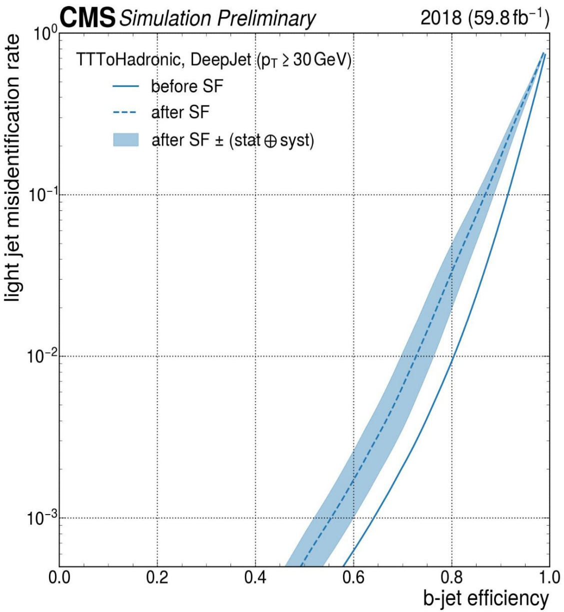
The full b discriminant shape is calibrated for b- and light-jet with an **iterative fit** method in top quark pair production events with two leptons (enriched in b jets) and Z+jet events (enriched in light-flavour jets)

- SFs are derived separately in bins of the b tagging discriminator distribution, p_T and **η**

Systematic uncertainties:

- Sample purity (the fraction of heavy-flavor jets is varied by ±20%)
- Jet energy scale
- Statistical uncertainty due to the limited statistics in each bin of the b discriminant
- Treatment of SF_c





Backup DeepJet c discriminant shape calibration

The CMS collaboration et al 2022 JINST 17 P03014

Calibration of c tagger done for both fixed WPs and full discriminant shapes

c discriminant shape calibrations performed in 3 samples:

W+c (c purity ~93%):

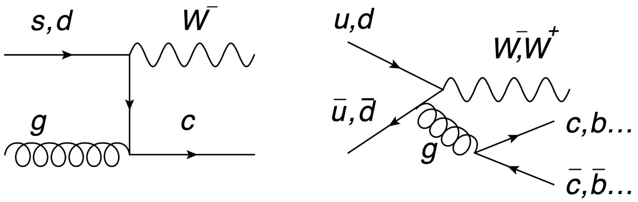
- p_T^{miss}, 1 isolated lepton coming from W→ lν (l=e, μ)
- At least 1 jet with a soft, non-isolated muon inside it (c jet)
- Events split into opposite-sign (OS), same-sign (OS)
- OS-SS subtraction to reduce main background

top pair (b purity ~81%):

- Semileptonic: 1 leptonically decaying W boson, a jet with a soft muon from the b hadron decay + additional hadronic jets
- Dileptonic: 2 leptonically decaying W bosons, two jets with at least one containing a soft muon.

DY+jet (udsg purity ~86%):

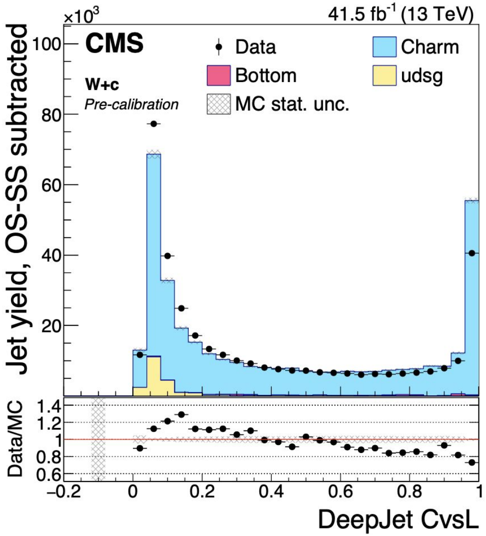
- ≥ 1 jet in association with a leptonically decaying Z boson

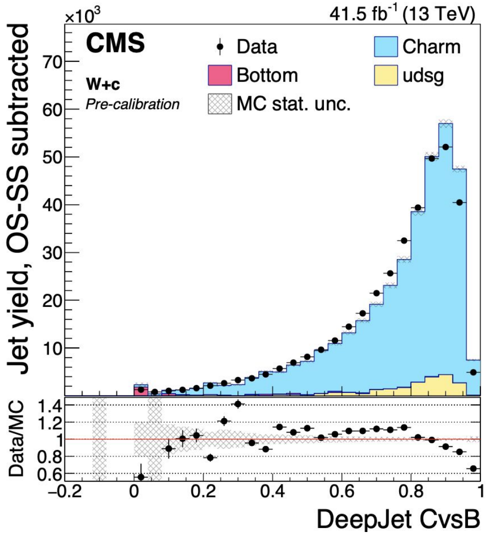


Sig: OS event

Bkg: 50% OS, 50% SS

Before calibration





Backup DeepJet c discriminant shape calibration

[The CMS collaboration et al 2022 JINST 17 P03014](#)

An **iterative fit** is performed on these samples to derive data-to-simulation SFs in the **2D plane of CvsL and CvsB** per jet flavour

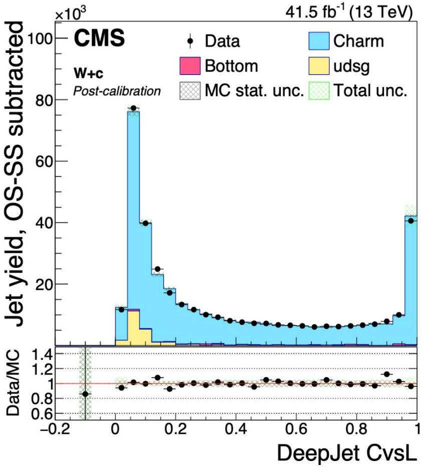
- Light/c/b components free to float until data-to-simulation differences are **minimised**
- two binning choices → a combined SF obtained through interpolation

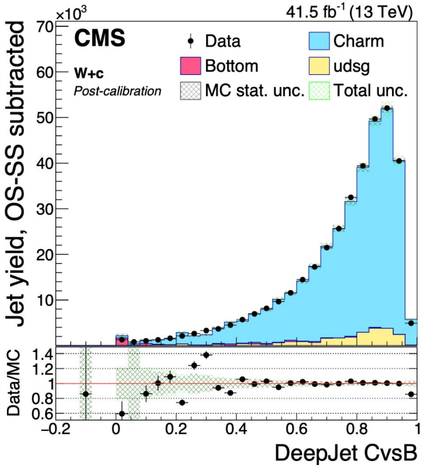
Main systematic uncertainties:

c-jets: interpolation & extrapolation

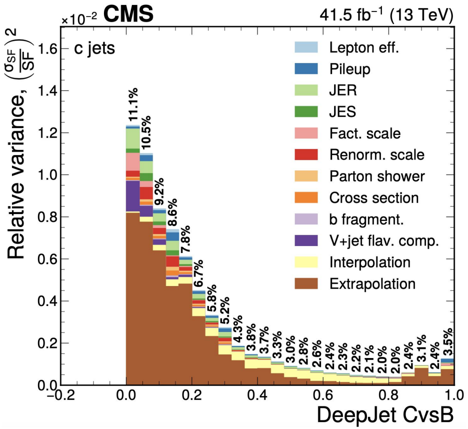
b-jets: factorisation scale

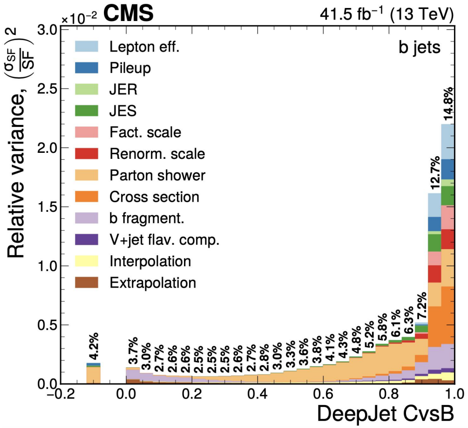
light-jets: ISR and FSR in the parton shower

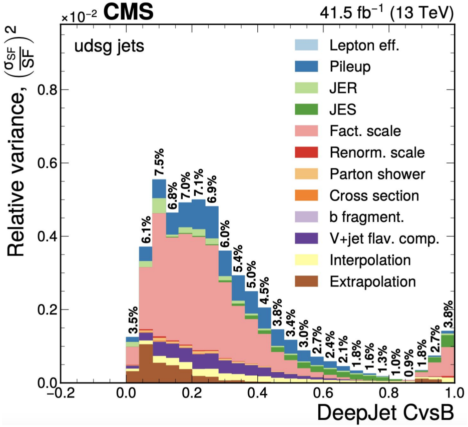




After calibration







Backup Run 3 triggers • Online rates

Trigger	Requirement	Rates at HLT at 2x10^34 cm-2s-1
2023 HH trigger	HT > 280 GeV, 4 jets with pT > 30 GeV, PNet@AK4(mean 2 highest b-tag score) > 0.55	180 Hz
2022 HH trigger	4 jets pT > 70, 50, 40, 35 GeV, PNet@AK4(mean 2 highest b-tag score) > 0.65	60 Hz
2018 triple b-tag [2,3]	HT > 340 GeV, 4 jets pT > 75, 60, 45, 40 GeV, 3 b-tags with DeepCSV > 0.24	8 Hz
Run 3 tau-triggers [4]	Double medium DeepTau taus with pT > 35 GeV |η| < 2.1 Double medium DeepTau taus with pT > 30 GeV |η| < 2.1 , PFJet 60 GeV Single loose DeepTau on hadronic tau with pT > 180 GeV |η| < 2.1	50 Hz 20 Hz 17 Hz
Run 3 MET-trigger [5]	Missing transverse energy (MET) (no muon) > 120 GeV, HT (no muon) > 120 GeV	42 Hz

[2] CMS-DP-2019/042 [3] CMS-DP-2019/026 [4] CMS-DP-2023/024 [5] CMS-DP-2023-016

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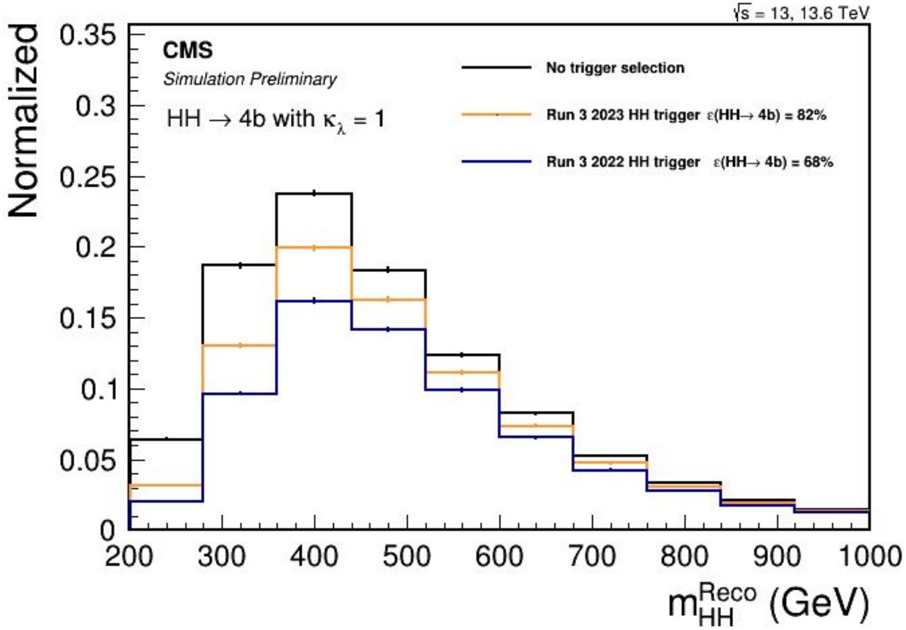
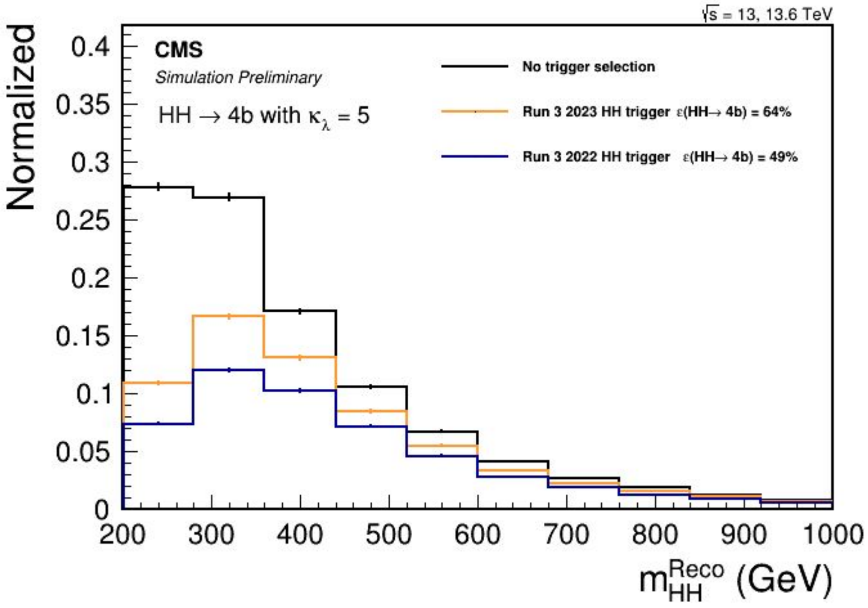
Backup Run 3 triggers • trigger acceptance on HH→4b signal





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