New experimental techniques and new analysis ideas for probes of quark Yukawa interactions (excluding top)

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Standard Model at the LHC 2024

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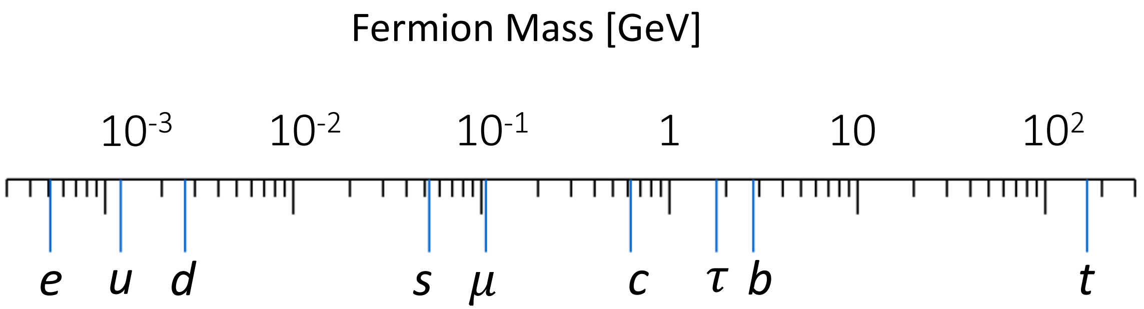
CMS

ATLAS EXPERIMENT

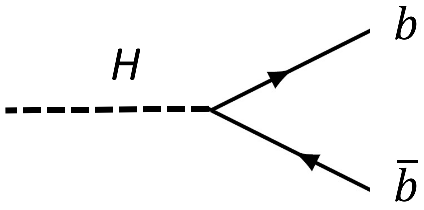
Introduction

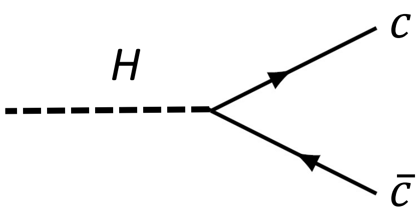
- Couplings of Higgs field to quarks and leptons – Yukawa couplings - are a potential source of the fermion masses
- Interaction so far only observed for 3rd generation of fermions (top, bottom and tau) and evidence found for coupling with muons
- Measurement of Yukawa couplings probe Standard Model expectation
- There is no guarantee all Higgs fermion couplings behave in a similar way
- Deviations could give insight into origin of the fermion mass hierarchy
- Of utmost importance to measure all Higgs couplings to fermions with best possible precision!



Heavy quark Yukawa couplings

- Probability of Higgs boson decays to bottom/charm quarks of 58.2%/3.9% in Standard Model
- **Standard Model Higgs** Yukawa **coupling** to charm quarks is rather **small** ($y_c = \sqrt{2}\, m_c(\mu{=}m_H)/\nu \simeq 0.2 \times y_b$)
- **One of largest contributions to Γ_H** (by SM expectations) **yet to be established experimentally**
- Both decay modes are susceptible to **significant modifications** in some **new physics** scenarios (e.g. two Higgs doublet models, EFTs)
- H → $b\bar{b}$ analyses in **precision measurement** phase of cross-section and Yukawa coupling
- H → $c\bar{c}$ analyses in search phase, **improving sensitivity** to decay and coupling





Probe options

- Different probes of the $Hb\bar{b}/c\bar{c}$ coupling have been proposed and investigated by the ATLAS and CMS experiments

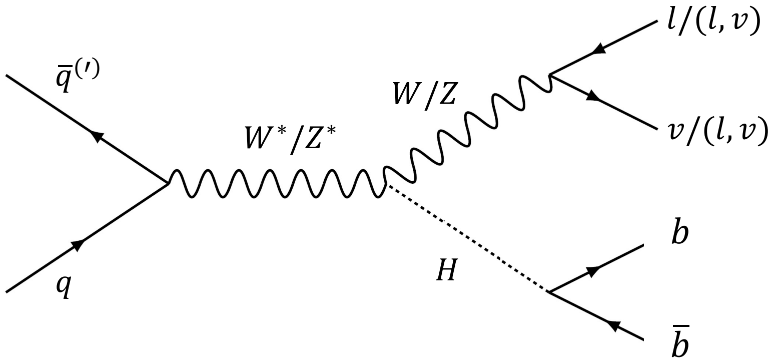
- **Inclusive** $H \to b\bar{b}/c\bar{c}$ **decays**
  - Direct access to coupling
  - Usually targeting **VH production (V = W, Z** boson**)**
    - **Enhanced Signal over Background ratio** w.r.t to inclusive Higgs production
    - Built around the use of **b/c-jet tagging algorithms**

    Leptonic mode

    - W/Z boson decays into leptons allow for a **convenient trigger strategy**
    - **Suppression of multi-jet backgrounds**

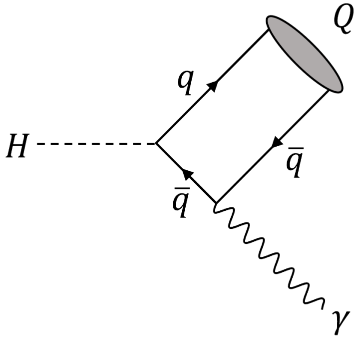
    All hadronic mode

    - W/Z boson decays into quarks, **increasing statistics**
    - **Dominant multi-jet background**

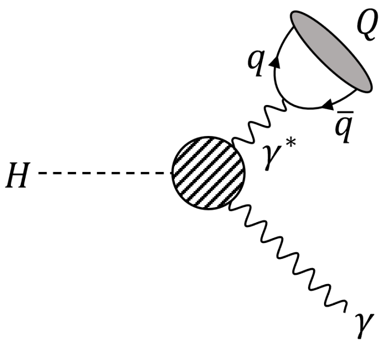


Probe options II

- **Exclusive** H→J/ψ γ **decays** (other rare decay modes can also probe lighter quark couplings)
  - Rare decay but **experimentally clean** probe (Phys. Rev. D 88 (2013) 053003)
  - Direct amplitude sensitive to the **magnitude and sign of the Higgs-charm coupling**
  - **Indirect amplitude** constitutes **dominant** contribution to the Higgs boson width
  - Production rate is dominated by the indirect contribution, hindering the sensitivity to the coupling



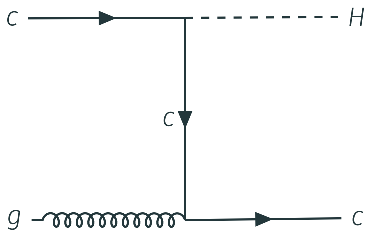
Direct contribution

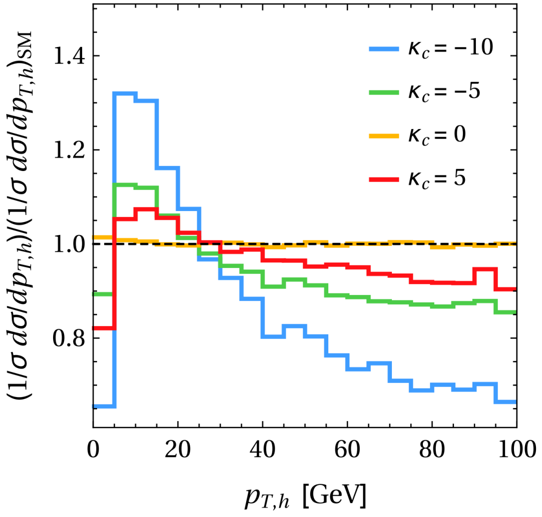


Indirect contribution

Probe options III

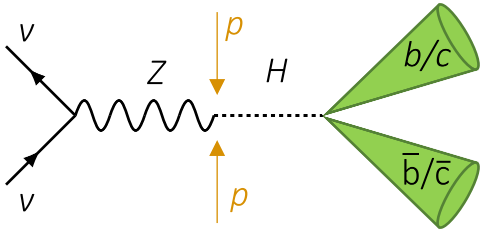
- **Loop induced gluon-gluon fusion and quark initiated Higgs boson production**
    - **Higgs production with quark contribution**, e.g., via gg→ Hg, gb/gc→ Hb/Hc, $b\bar{b}$/$c\bar{c}$→ Hg (Phys. Rev. Lett. 118 (2017) 121801)
    - Sensitivity to coupling via total production **differential cross-section measurements**
    - **p_T^H shape and normalisation** will be changed in case of Yukawa couplings different to SM prediction
    - Normalisation effects coupled to Higgs width changes
    - Obtained **constraints on $Hb\bar{b}$ ($Hc\bar{c}$)** coupling **not as stringent (comparable)** as the ones set by inclusive Higgs decays searches
    - Subject to **different assumptions and sources of uncertainty**
    - Complementary **sensitivity to the sign** of the coupling modifiers





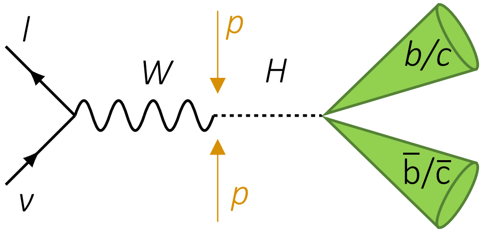
VH Production: “Resolved” regime

Note:
l = e, mu



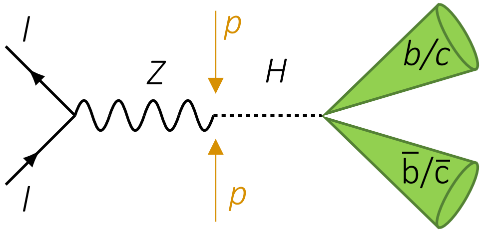
0 lepton channel

- Targets Z(*νν*)H(bb̅/cc̅) production
- Large missing transverse energy in events (due to neutrinos)



1 lepton channel

- Targets W(*lν*)H(bb̅/cc̅) production
- Large missing transverse energy
- One electron or muon



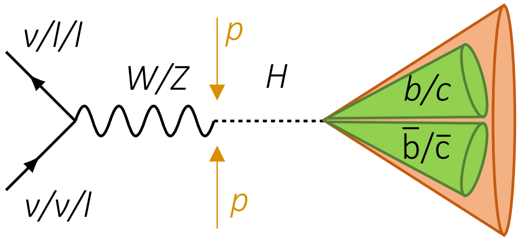
2 lepton channel

- Targets Z(*ll*)H(bb̅/cc̅) production
- e^+e^- or $\mu^+\mu^-$ pairs

Drives sensitivity up to p_T^V of 250-400 GeV (where p_T^V is p_T of associated vector boson produced)

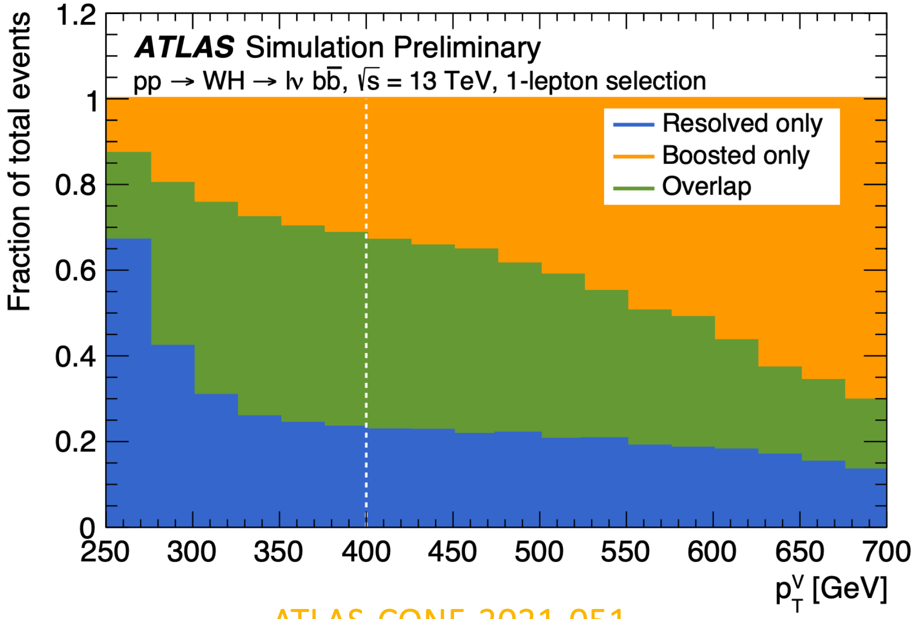
VH Production: “Boosted” leptonic regime

Note:
l = e, mu



0/1/2 lepton channel

- Targets Z(νν)H(bb̄/cc̄), W(lν)H(bb̄/cc̄), Z(ll)H(bb̄/cc̄) production
- Large radius jet, with substructure exploited



ATLAS-CONF-2021-051

Resolved/boosted overlap

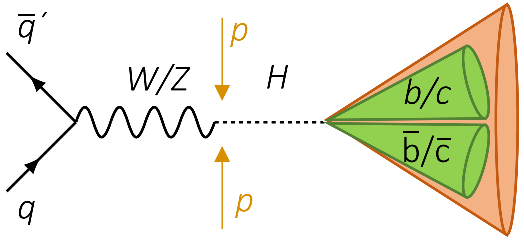
- Slightly different treatments between ATLAS and CMS
- Common factor – priority in event allocation given to resolved regime in overlap region as improves expected sensitivity and decreases uncertainties
- Events used only once

VH Production: "Boosted" hadronic regime

D/GNN: Deep/Graph Neural Network

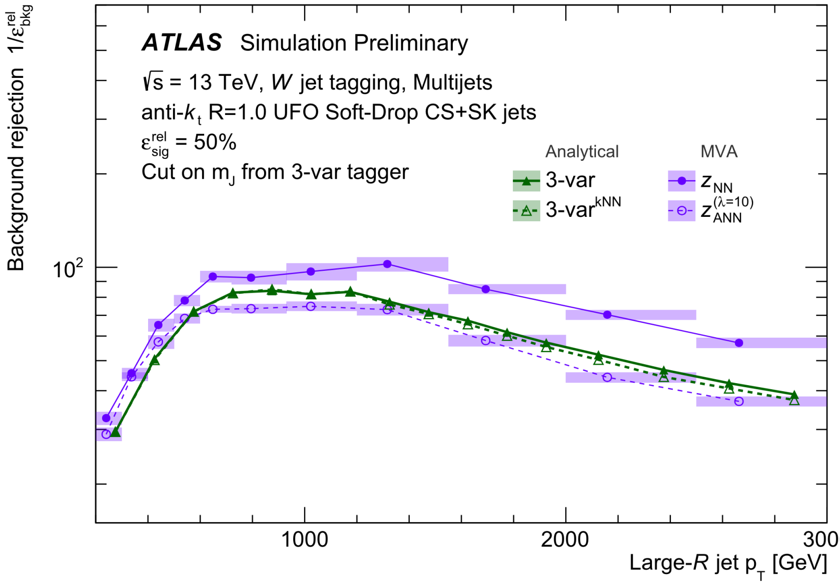
Hadronic channel

- Targets V(qq)H($b\bar{b}$/$c\bar{c}$) production
- Vector boson tagged via dedicated taggers



Hadronically decaying W/Z boson tagging

- First ATLAS **hadronic VH, H($b\bar{b}$)** analysis (PhysRevLett.132.131802) made use of a cut-based tagger, exploiting jet mass, number of tracks and substructure variables as energy correlation function ratios
- Performance improvements found in **DNN/GNN and transformers** architectures using jet constituents' energy and kinematics



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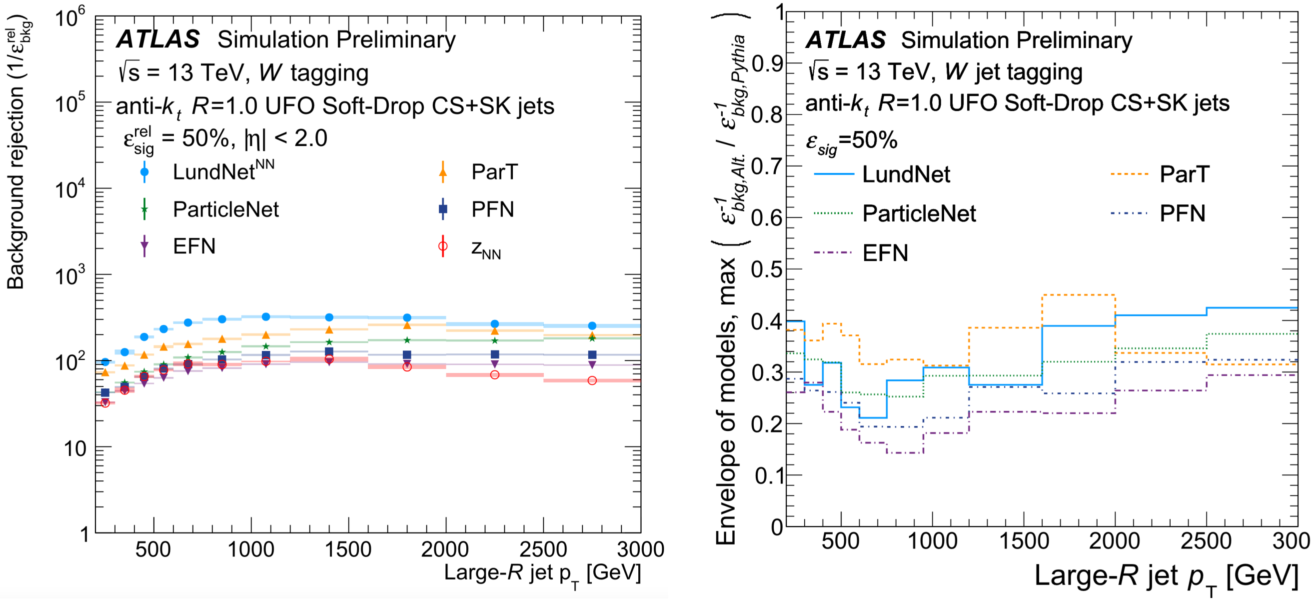

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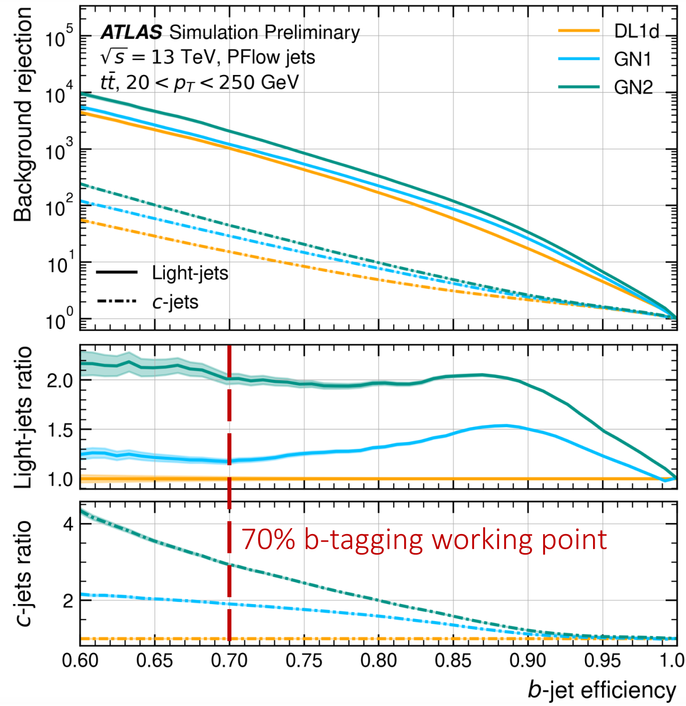
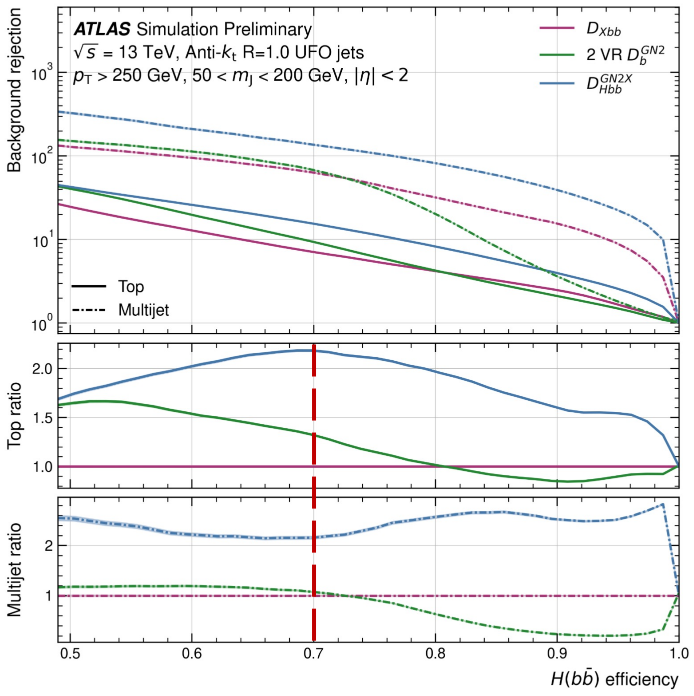
VH Production: Jet Heavy Flavour Tagging

CNN: Convolutional Neural Network

- **Bottom or charm Higgs candidate jet**s identified via **jet flavour tagging algorithms**
- Taggers optimised separately for **resolved or boosted regime**
- Targeting both **Higgs to bottom and charm decays**
- **DNN/CNN-based taggers** being used in most of latest analyses
- Further improvements found in **graph and transformer neural network** architectures, by **better exploiting jet internal structure**



ATLAS GNN Flavour Tagging



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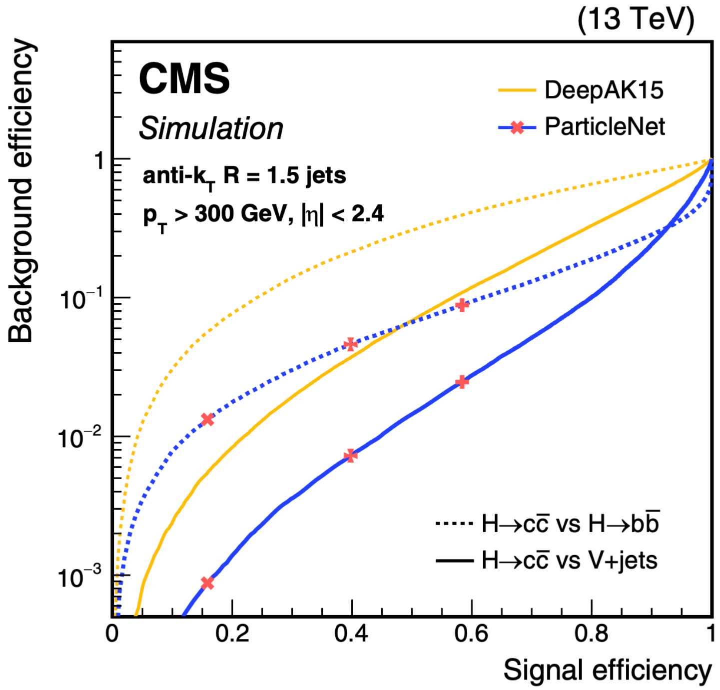


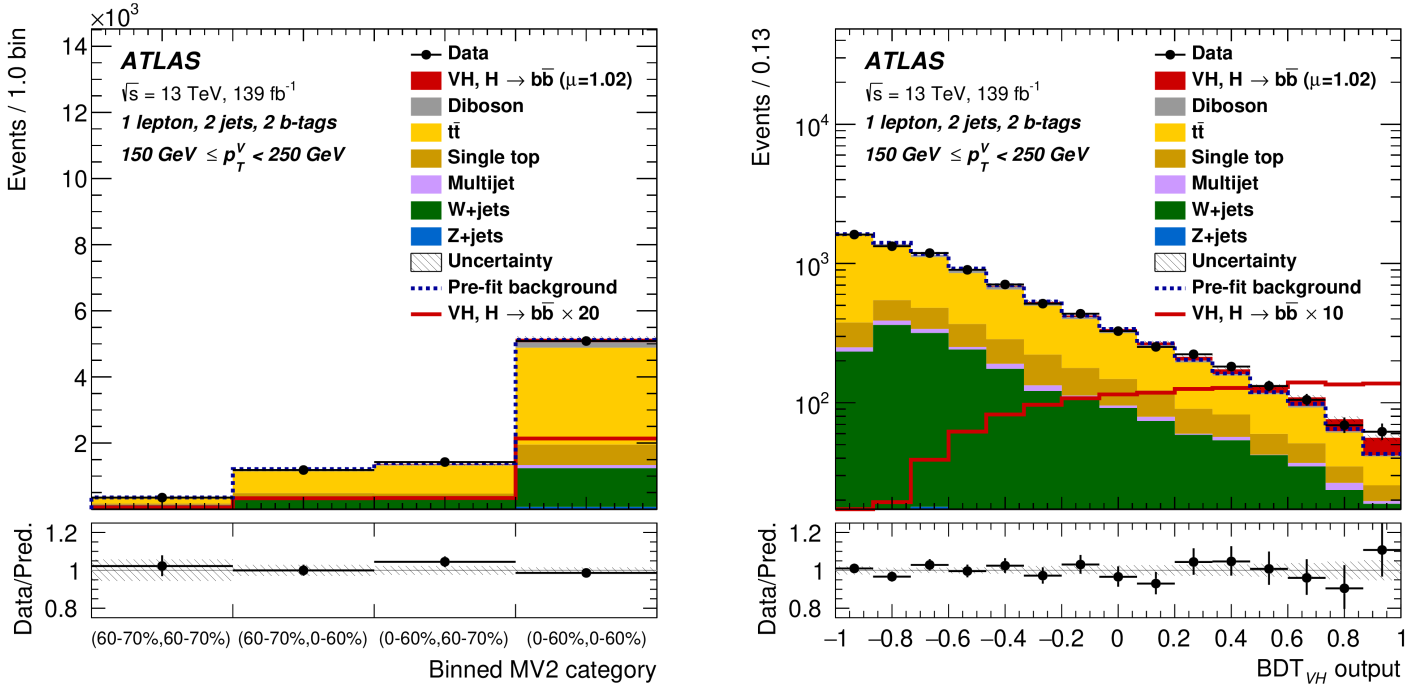
PhysRevLett.131.061801

VH Production: Event selection

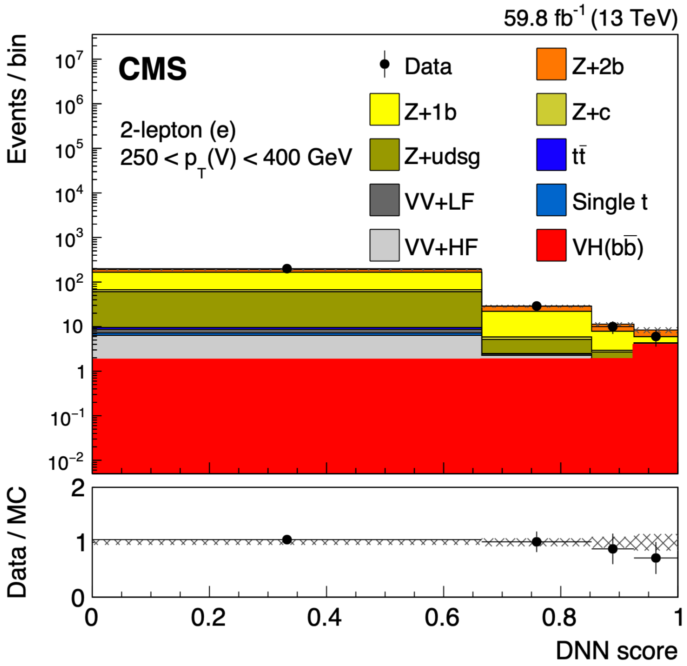
BDT: Boosted Decision Tree

Key aspects

- **Categorisation** of events for **optimised selections and signal sensitivity**
- **Data-driven methods/control regions** to estimate ttbar, W/Z+jets and multijet backgrounds
- Flavour tagging discriminants used along with jet mass and transverse momentum to **discriminate VH production from backgrounds** via BDTs/NNs



[Eur. Phys. J. C (2021) 81:178]



[arXiv:2312.07562]

VH Production: Main uncertainties

V(lep/had)H($b\bar{b}$)

- Starting to be dominated by **systematic uncertainties in resolved regime**
- **Statistical uncertainties** still very relevant **in boosted regime**

V(lep)H($c\bar{c}$)

- **Statistical and systematic uncertainties** of the **same magnitude**

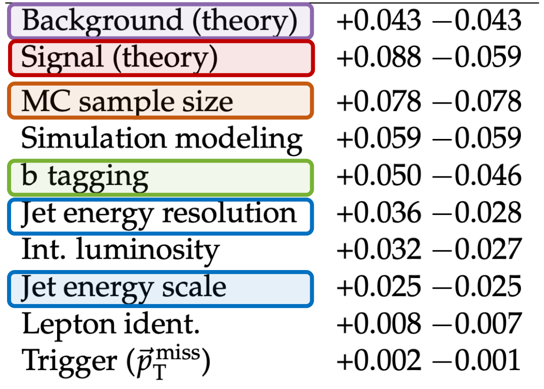
Leading systematic uncertainties

- Background modelling: ttbar, W/Z+jets, multijet
- Signal modelling
- Jet flavour tagging uncertainties
- Jet energy scale and resolution uncertainties
- Statistical uncertainty from limited size of MC samples

→ More data will improve results directly and indirectly (better modelling, reduced uncertainties)

arXiv:2312.07562

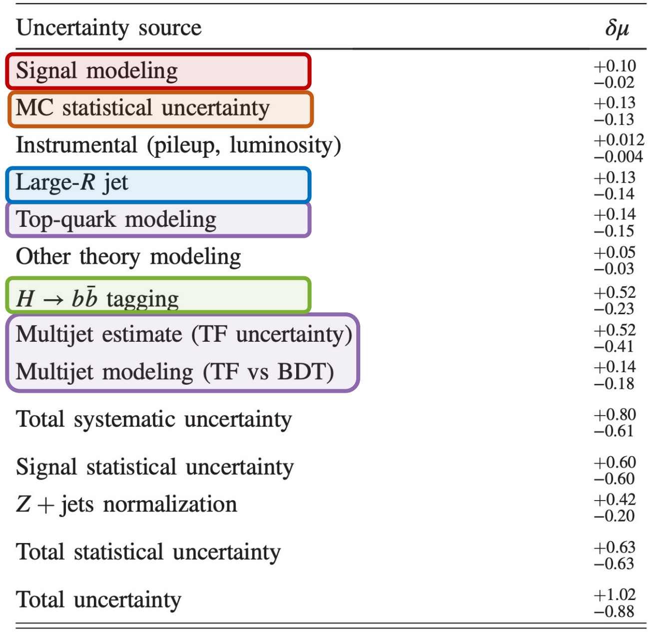
CMS V(lep)H(bb)



	$\Delta\mu$
Background (theory)	+0.043 −0.043
Signal (theory)	+0.088 −0.059
MC sample size	+0.078 −0.078
Simulation modeling	+0.059 −0.059
b tagging	+0.050 −0.046
Jet energy resolution	+0.036 −0.028
Int. luminosity	+0.032 −0.027
Jet energy scale	+0.025 −0.025
Lepton ident.	+0.008 −0.007
Trigger ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$)	+0.002 −0.001

PhysRevLett.132.131802

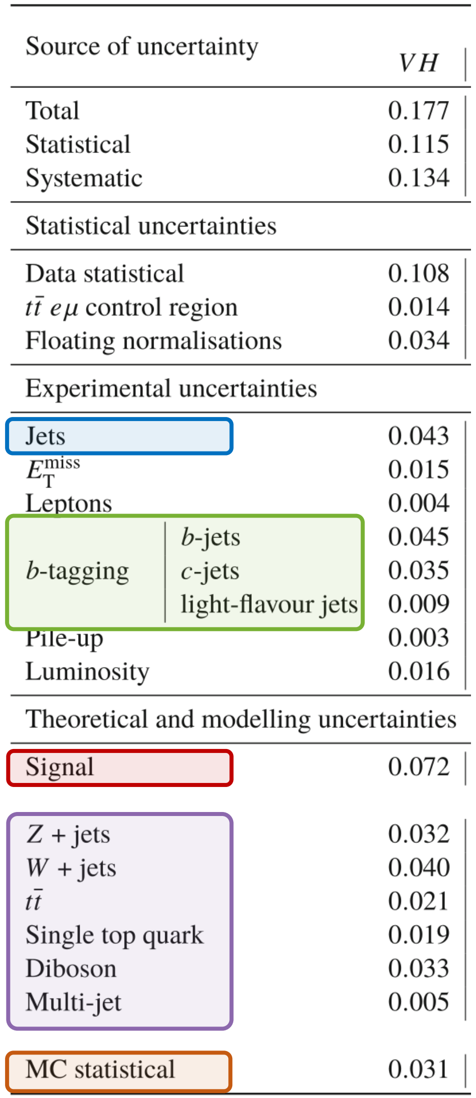
ATLAS boosted V(had)H(bb)



Uncertainty source	$\delta\mu$
Signal modeling	$^{+0.10}_{-0.02}$
MC statistical uncertainty	$^{+0.13}_{-0.13}$
Instrumental (pileup, luminosity)	$^{+0.012}_{-0.004}$
Large-R jet	$^{+0.13}_{-0.14}$
Top-quark modeling	$^{+0.14}_{-0.15}$
Other theory modeling	$^{+0.05}_{-0.03}$
$H \to b\bar{b}$ tagging	$^{+0.52}_{-0.23}$
Multijet estimate (TF uncertainty)	$^{+0.52}_{-0.41}$
Multijet modeling (TF vs BDT)	$^{+0.14}_{-0.18}$
Total systematic uncertainty	$^{+0.80}_{-0.61}$
Signal statistical uncertainty	$^{+0.60}_{-0.60}$
$Z +$ jets normalization	$^{+0.42}_{-0.20}$
Total statistical uncertainty	$^{+0.63}_{-0.63}$
Total uncertainty	$^{+1.02}_{-0.88}$

Eur. Phys. J. C (2021) 81:178

ATLAS resolved V(lep)H(bb)



Source of uncertainty		VH
Total		0.177
Statistical		0.115
Systematic		0.134
Statistical uncertainties		
Data statistical		0.108
$t\bar{t}$ $e\mu$ control region		0.014
Floating normalisations		0.034
Experimental uncertainties		
Jets		0.043
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.015
Leptons		0.004
b-tagging	b-jets	0.045
	c-jets	0.035
	light-flavour jets	0.009
Pile-up		0.003
Luminosity		0.016
Theoretical and modelling uncertainties		
Signal		0.072
$Z +$ jets		0.032
$W +$ jets		0.040
$t\bar{t}$		0.021
Single top quark		0.019
Diboson		0.033
Multi-jet		0.005
MC statistical		0.031

H(b$\bar{\text{b}}$) Overview

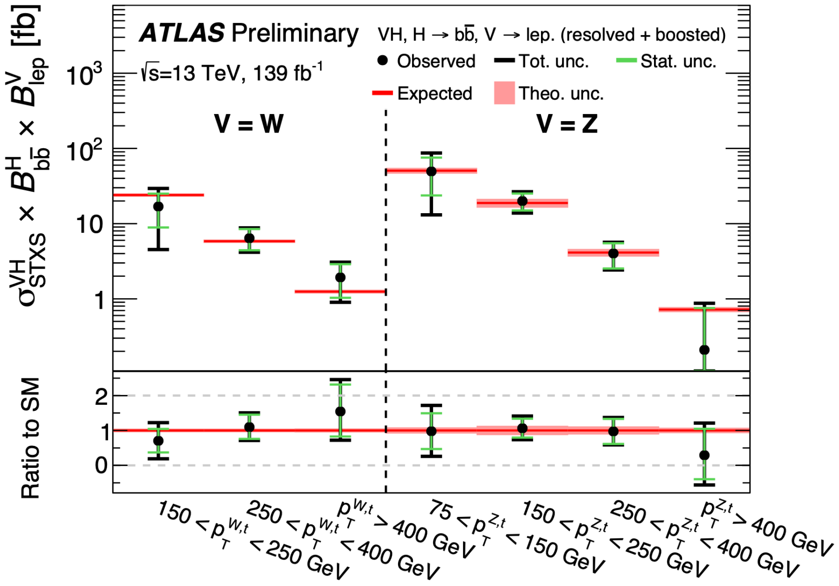
VH(b$\bar{\text{b}}$) analyses

Analysis	Fitted signal strength $\mu_{VH\ (H \to b\bar{b})}$
ATLAS resolved V(lep)H(b$\bar{\text{b}}$)	$1.02^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}\text{(stat.)}^{+0.14}_{-0.13}\text{(syst.)}$
ATLAS boosted V(lep)H(b$\bar{\text{b}}$)	$0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}\text{(stat.)}^{+0.26}_{-0.22}\text{(syst.)}$
ATLAS resolved+boosted V(lep)H(b$\bar{\text{b}}$)	$1.00^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}\text{(stat.)}^{+0.14}_{-0.13}\text{(syst.)}$
CMS resolved+boosted V(lep)H(b$\bar{\text{b}}$)	$1.15^{+0.22}_{-0.20}$
ATLAS boosted V(had)H(b$\bar{\text{b}}$)	$1.4^{+1.0}_{-0.9} = 1.4^{+0.6}_{-0.6}\text{(stat.)}^{+0.8}_{-0.7}\text{(syst.)}$

- Moving towards precision measurements
    - SXTS and differential cross-section measurements being undertaken

STXS Measurements

- Simplified Template Cross-Sections (STXS) involve categorisation of events in bins designed to separate different production modes



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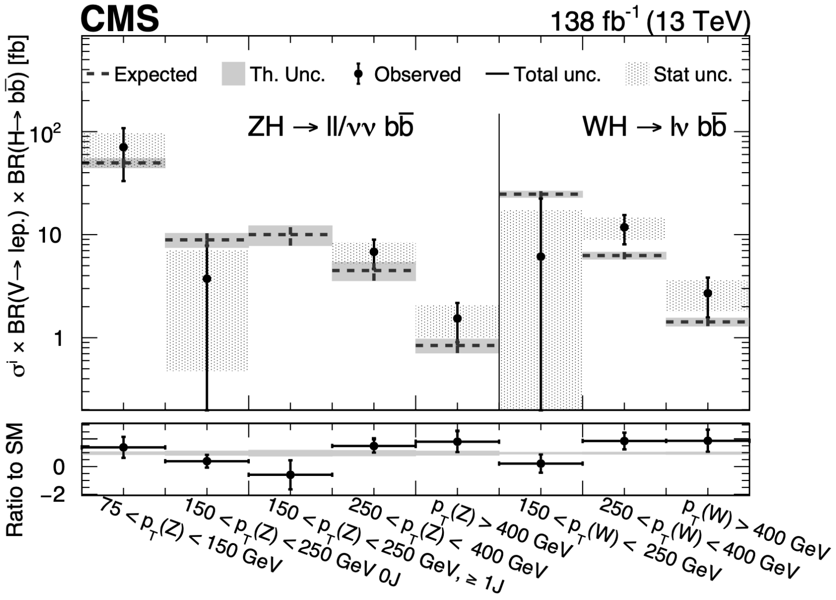
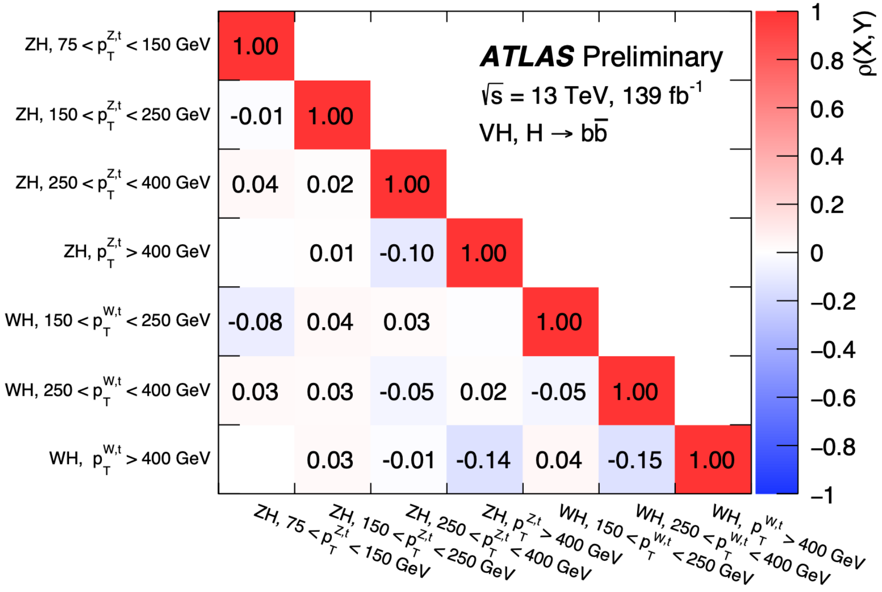


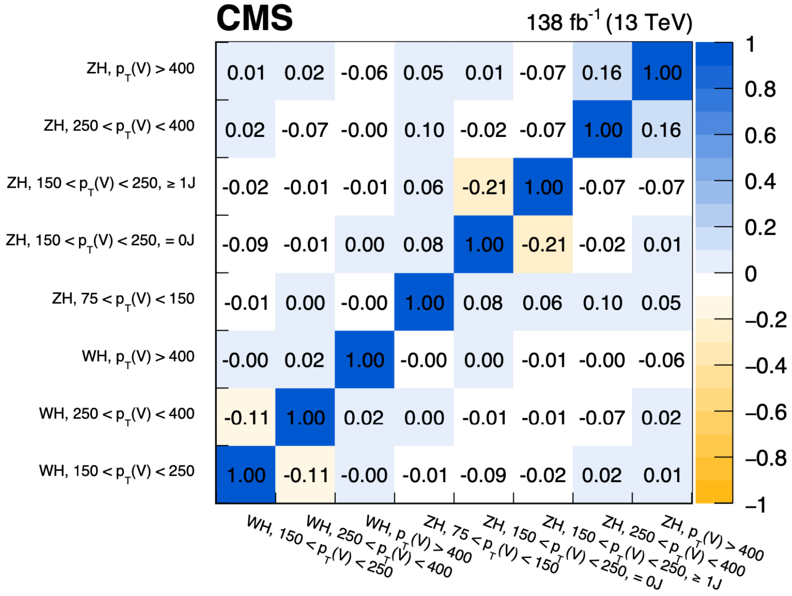
arXiv:2312.07562

STXS Measurements II

- Cross-contamination generally negligible between different STXS production bins
- Some WH contribution in ZH bins via 0 lepton channel



	ZH, $75 < p_T^{Z,t} < 150$ GeV	ZH, $150 < p_T^{Z,t} < 250$ GeV	ZH, $250 < p_T^{Z,t} < 400$ GeV	ZH, $p_T^{Z,t} > 400$ GeV	WH, $150 < p_T^{W,t} < 250$ GeV	WH, $250 < p_T^{W,t} < 400$ GeV	WH, $p_T^{W,t} > 400$ GeV
ZH, $75 < p_T^{Z,t} < 150$ GeV	1.00						
ZH, $150 < p_T^{Z,t} < 250$ GeV	-0.01	1.00					
ZH, $250 < p_T^{Z,t} < 400$ GeV	0.04	0.02	1.00				
ZH, $p_T^{Z,t} > 400$ GeV		0.01	-0.10	1.00			
WH, $150 < p_T^{W,t} < 250$ GeV	-0.08	0.04	0.03		1.00		
WH, $250 < p_T^{W,t} < 400$ GeV	0.03	0.03	-0.05	0.02	-0.05	1.00	
WH, $p_T^{W,t} > 400$ GeV		0.03	-0.01	-0.14	0.04	-0.15	1.00



	WH, $150 < p_T(V) < 250$	WH, $250 < p_T(V) < 400$	WH, $p_T(V) > 400$	ZH, $75 < p_T(V) < 150$	ZH, $150 < p_T(V) < 250$, = 0J	ZH, $150 < p_T(V) < 250$, ≥ 1J	ZH, $250 < p_T(V) < 400$	ZH, $p_T(V) > 400$
ZH, $p_T(V) > 400$	0.01	0.02	-0.06	0.05	0.01	-0.07	0.16	1.00
ZH, $250 < p_T(V) < 400$	0.02	-0.07	-0.00	0.10	-0.02	-0.07	1.00	0.16
ZH, $150 < p_T(V) < 250$, ≥ 1J	-0.02	-0.01	-0.01	0.06	-0.21	1.00	-0.07	-0.07
ZH, $150 < p_T(V) < 250$, = 0J	-0.09	-0.01	0.00	0.08	1.00	-0.21	-0.02	0.01
ZH, $75 < p_T(V) < 150$	-0.01	0.00	-0.00	1.00	0.08	0.06	0.10	0.05
WH, $p_T(V) > 400$	-0.00	0.02	1.00	-0.00	0.00	-0.01	-0.00	-0.06
WH, $250 < p_T(V) < 400$	-0.11	1.00	0.02	0.00	-0.01	-0.01	-0.07	0.02
WH, $150 < p_T(V) < 250$	1.00	-0.11	-0.00	-0.01	-0.09	-0.02	0.02	0.01

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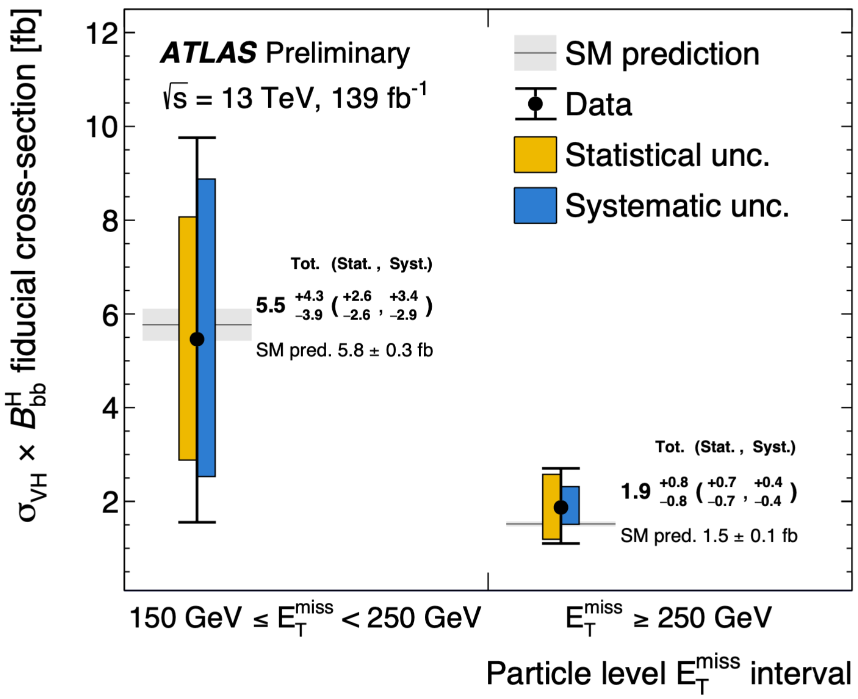
arXiv:2312.07562

Differential Cross-section Measurements

- **Current statistics** and **understanding of systematic uncertainties** allow for differential cross-section measurements to be undertaken

- ATLAS performed such measurement in the 0 lepton channel (Z(*νν*)H($b\bar{b}$))
    - Remaining channels constrain the SM background via one-binned regions
- **Detector effects corrected** for via profile-likelihood unfolding procedure
- Impacted by **usual systematic uncertainties**, with some reduced contraints due to one-binned regions
- Results also affected by **migration of events from outside fiducial phase-space**



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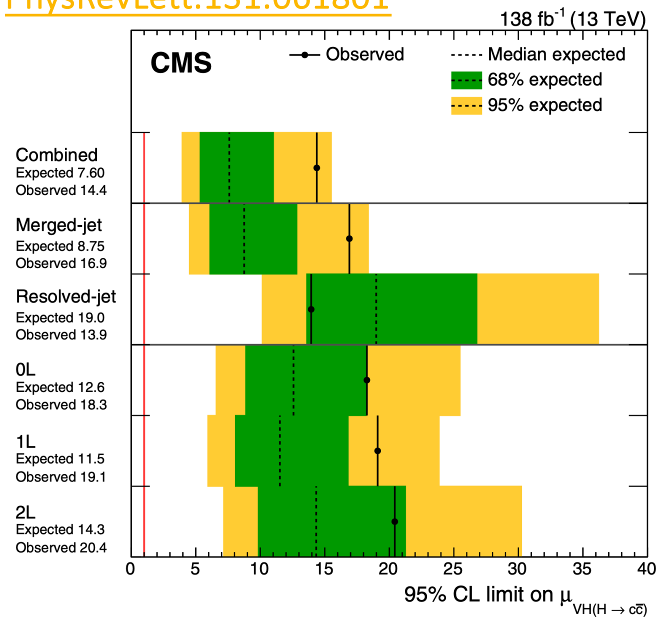
H($c\bar{c}$) Overview

H($c\bar{c}$) analyses

Analysis	Observed (Expected) 95% CL limit on $\mu_{VH\,(H\rightarrow c\bar{c})}$
ATLAS resolved V(lep)H($c\bar{c}$) H($b\bar{b}$)	$26.0 \times$ SM $(31^{+12}_{-8} \times$ SM$)$
CMS resolved+boosted V(lep)H($c\bar{c}$)	$14.4 \times$ SM $(7.6^{+3.4}_{-2.3} \times$ SM$)$
CMS boosted ggF H($c\bar{c}$)	$47.0 \times$ SM $(39 \times$ SM$)$

- Improving sensitivity
  - Use of MVA techniques in analysis design and jet flavour tagging methods bringing significant enhancements in sensitivity
  - Boosted regime can further exploit such tools to bring additional relevant contributions

PhysRevLett.131.061801



κ Framework

- Measure **deviations of Higgs couplings** from SM
- Inspired by **leading order diagrams** of Higgs couplings
- Assumes Higgs boson resonance at 125 GeV and narrow width approximation

$$\sigma \times \mathrm{BR}(i \to H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H}$$

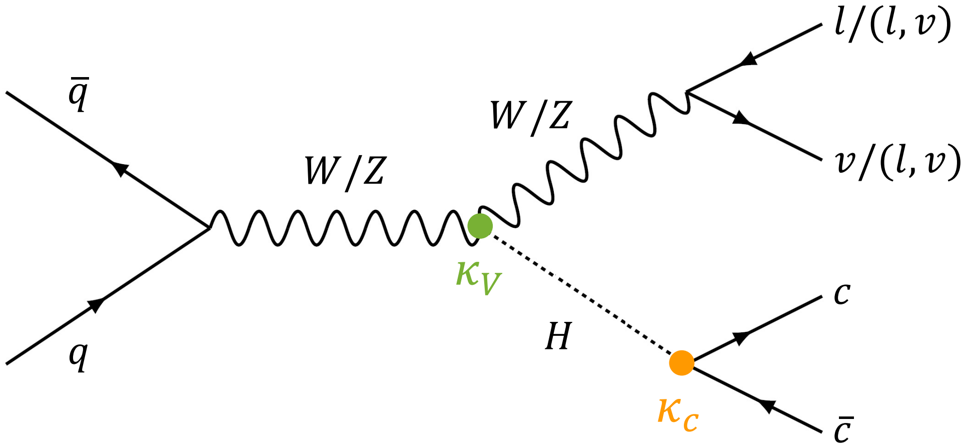
$$+$$

$$y_j \to \kappa_j y_j$$

$$\downarrow$$

$$\sigma \times \mathrm{BR}(i \to H \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \times \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2}$$

$$\downarrow$$



$$\sigma \times \mathrm{BR}(\mathrm{V} \to \mathrm{H} \to c\bar{c}) = \sigma_{SM} \times \mathrm{BR}(\mathrm{V} \to \mathrm{H} \to c\bar{c})_{SM} \times \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}\ ,\ \kappa_H^2 = \frac{\Sigma_j \Gamma_j^{SM} \times \kappa_j^2}{\Gamma_H^{SM}}$$

κ_c Interpretation

- V(lep)H(c$\bar{c}$) analyses sensitive to exclude some parts of κ_c parameter space (parametrisation below used)
- $\mu = \frac{\kappa_c^2}{[(1-BR_{Hcc})+BR_{Hcc}*\kappa_c^2]}$ (other coupling modifiers set to 1, no BSM contributions to Higgs width)

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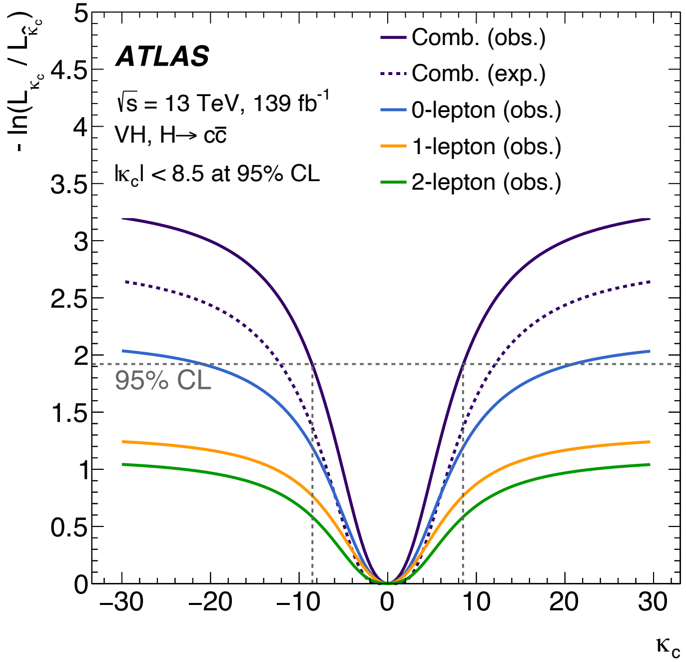
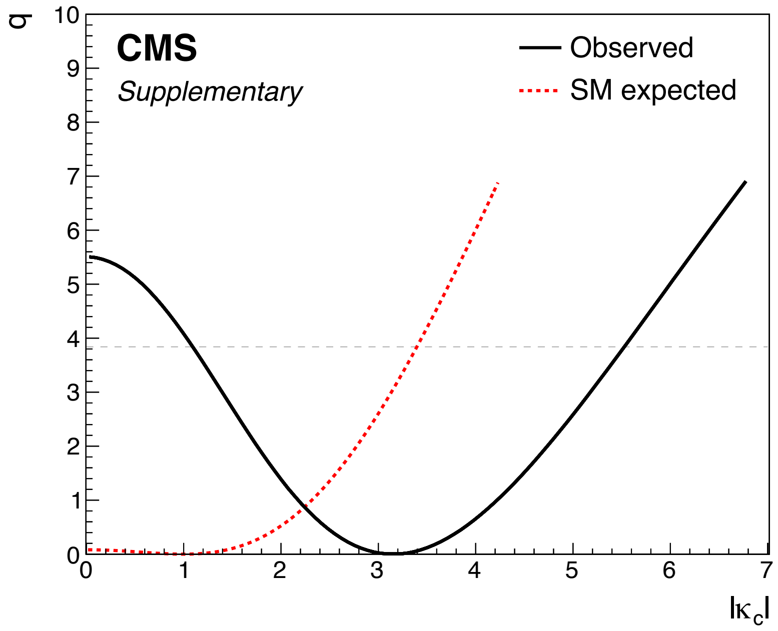


$|\kappa_c| \leq 8.5$ at 95% CL

PhysRevLett.131.061801



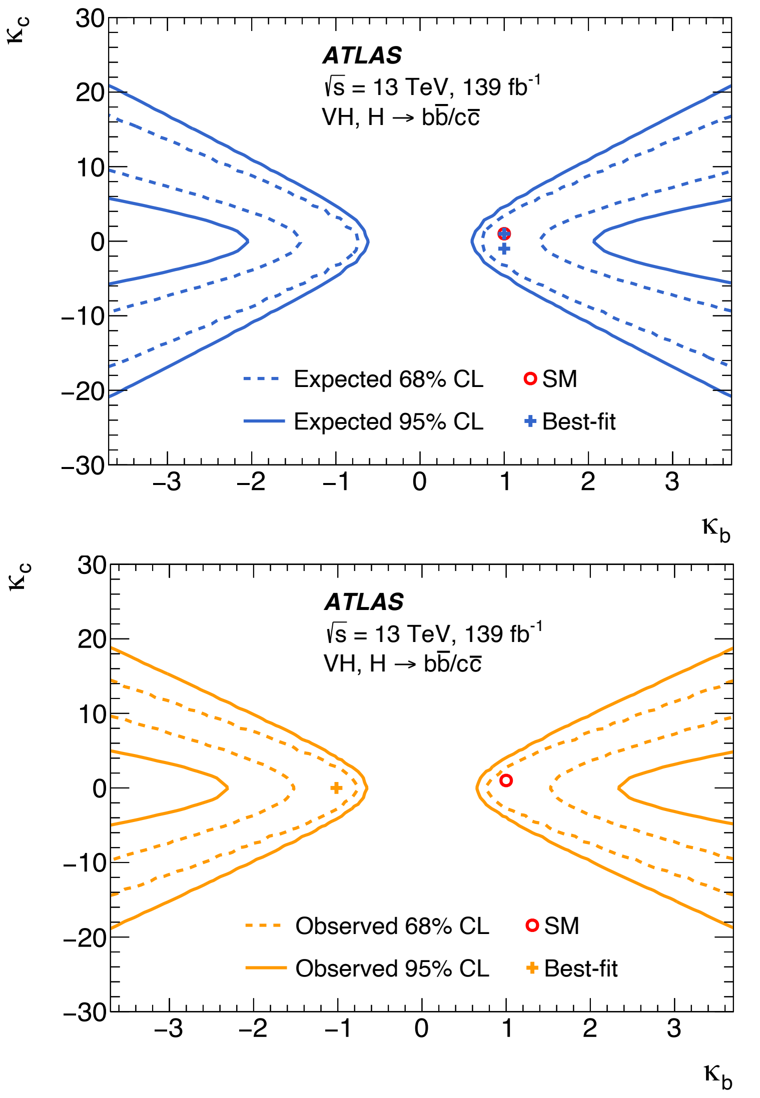
$|\kappa_c| \leq 3.4$ ($1.1 < \kappa_c < 5.5$) at 95% CL

κ_c and κ_b Interpretation

Eur. Phys. J. C (2022) 82:717

- **V(lep)H(b$\bar{b}$)** and **V(lep)H(c$\bar{c}$) combined** likelihood parametrised in terms of both **κ_c and κ_b**
- Other coupling modifiers set to their SM predictions
- Gluon-initiated ZH production has no explicit parametrisation as function of κ_c
    - Only taken into account for κ_b
    - Only has an impact for large values of κ_b ($\kappa_b \gtrsim 10$)
- Non Drell-Yan-like qq → VH production also neglected given the low values of κ_c that the combination probes

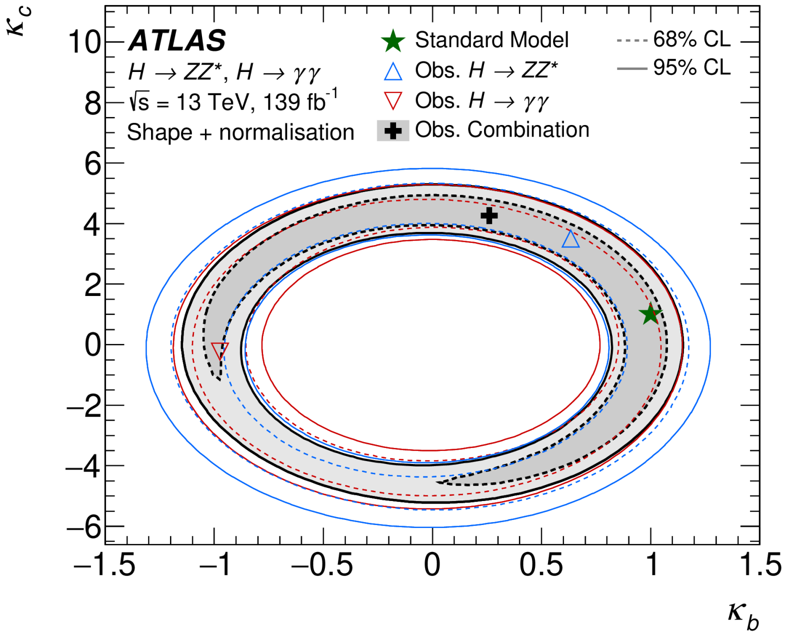
- Observed best fit value $(\kappa_b, \kappa_c) = (-1.02, 0)$
- Difference in value of the log-likelihood between best-fit value and $(\kappa_b, \kappa_c) = (+1.02, 0)$ is 0.02
    - Analysis has little power to constrain the sign of κ_b
    - Small likelihood asymmetry coming from b-quark loop contributions to gg → ZH production

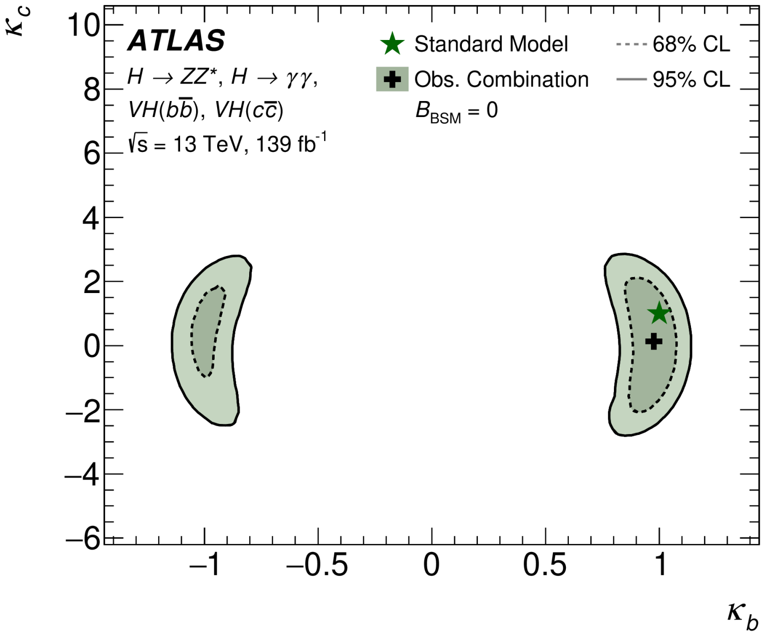


κ_c and κ_b Interpretation II

JHEP05(2023)028

- Precision measurements of **p_T^H cross-section in H → ZZ* and H → $\gamma\gamma$** channels provide **complimentary** information on couplings
- Individual analyses **dominated by statistical uncertainty**
- **Statistical combination between them** and in addition with **V(lep)H($b\bar{b}$)** and **V(lep)H($c\bar{c}$)** analyses allows for improved constraints
- Results for **shape and normalisation effects considered** shown here, different assumptions on backup

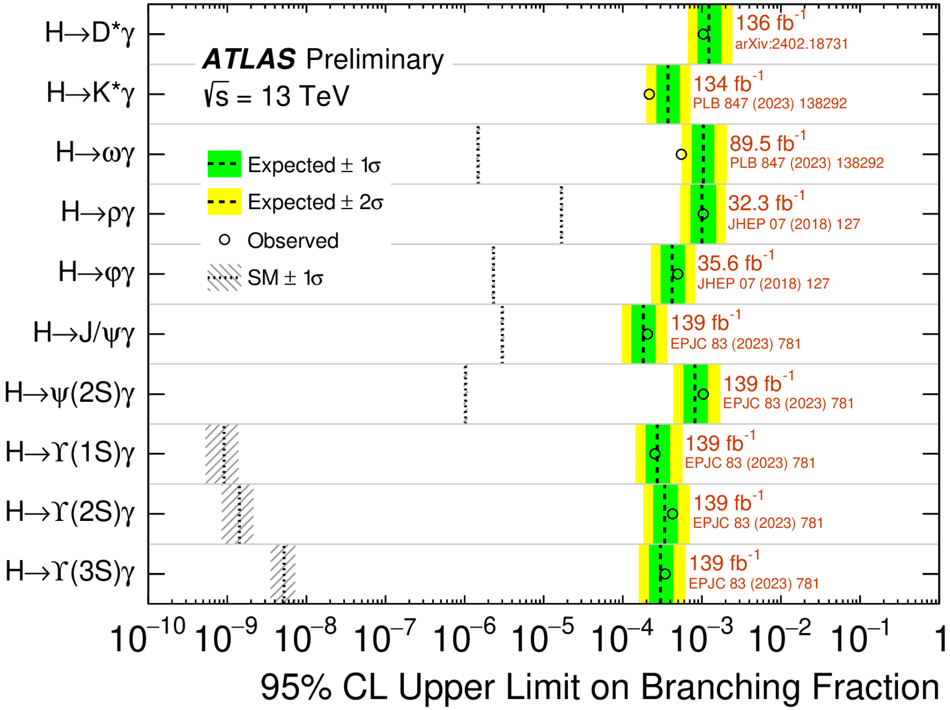




Probing lighter quark Yukawas

$q\bar{q} \rightarrow H(\rightarrow WW) + \gamma$ differential XS measurement as alternative probe: PhysRevLett.132.121901, in backup

- Rare **exclusive decays** of the Higgs boson into a meson and a photon allow **access to coupling to lighter flavour quarks** (up, down, strange) in addition to bottom and charm quarks
- Also used as probe of potential **flavour-violating Higgs boson interactions**
- **Dedicated triggers**, different **production modes**, **event selection with BDTs** and **background modelling enhancements improving sensitivity**



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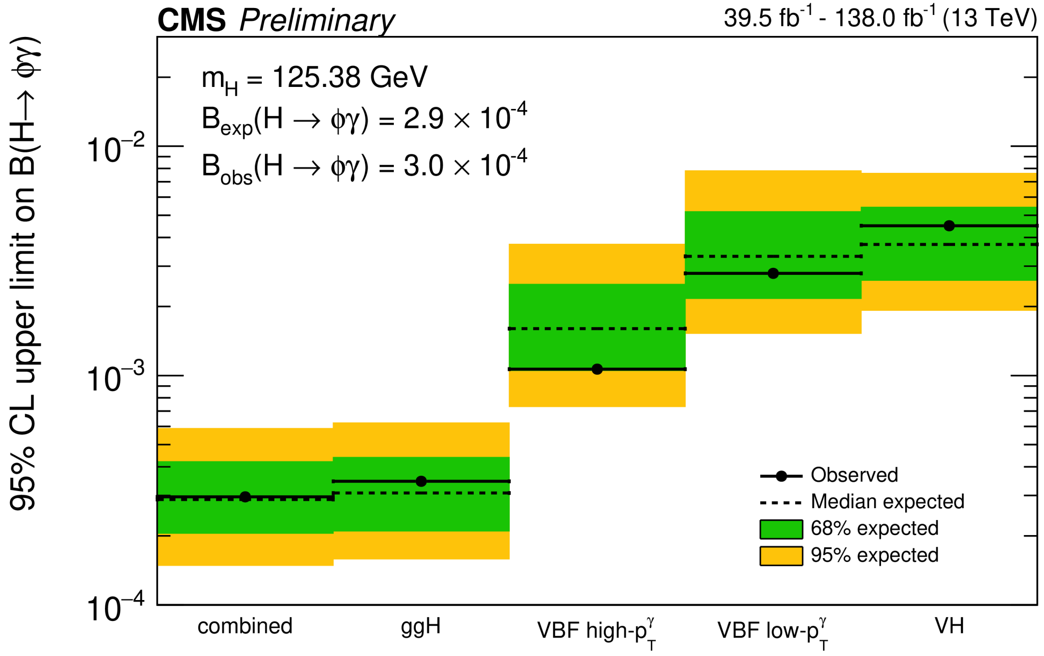


CMS-PAS-HIG-23-005, more CMS results on rare decays in backup

Summary

- Different probes sensitive to Higgs quark Yukawa couplings are available
  - Leading sensitivity to **heavy quark Yukawa** couplings currently via **Higgs production in association with W/Z bosons**
  - **Loop induced ggF and quark initiated Higgs production** and **exclusive Higgs boson decays into meson+photon** provide **complimentary information** on these couplings and give insight into **lighter quark couplings**

- Machine-learning improvements in analysis design and jet tagging techniques leading to continuous enhancements in sensitivity
  - Exploited both in **resolved** and **merged** jet topologies
  - Possible **tagging of Higgs candidates and/or W/Z bosons**
  - MVA discrimination of **Higgs signal** with respect to **backgrounds**

- Main uncertainties related to modelling, flavour tagging and jet contributions or statistics

- Different suite of measurements currently possible, from STXS bins to coupling modifiers

Backup

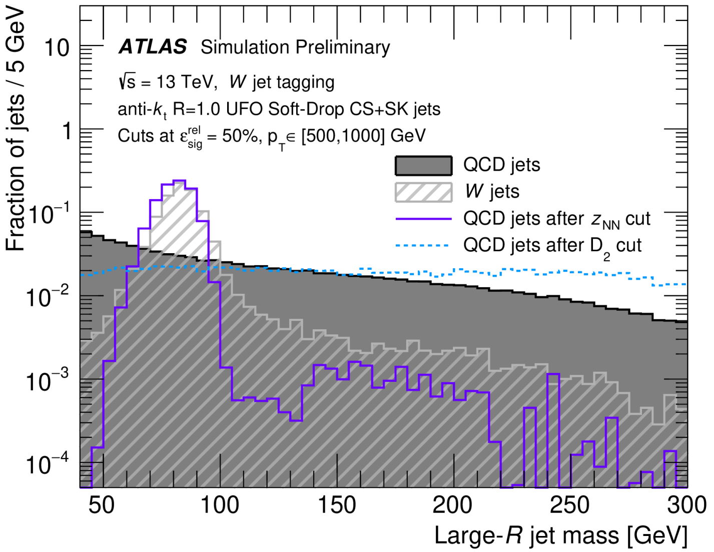
Vector boson DNN tagger

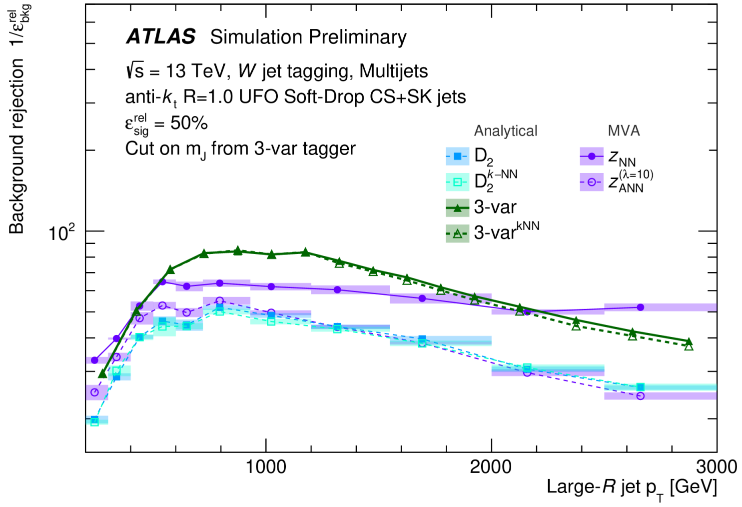
ATL-PHYS-PUB-2021-029

- DNN trained on high-level jet substructure quantities

Variable	Description
D_2, C_2	Energy correlation ratios
τ_{21}	N-subjettiness
R_2^{FW}	Fox-Wolfram moment
$\mathcal{P}$	Planar flow
a_3	Angularity
A	Aplanarity
Z_{cut}, $\sqrt{d_{12}}$	Splitting scales
$Kt\Delta R$	k_t-subjet ΔR

- Algorithm **decorrelated from jet mass** to prevent **bias in background jet-mass** distribution from being around the **W boson mass**
- Achieved via **sequential training of jet classification DNN and jet mass inferring adversarial NN** (ANN)
  - Classification DNN first optimised
  - DNN fixed, ANN optimised
  - Combined optimisation of both algorithms

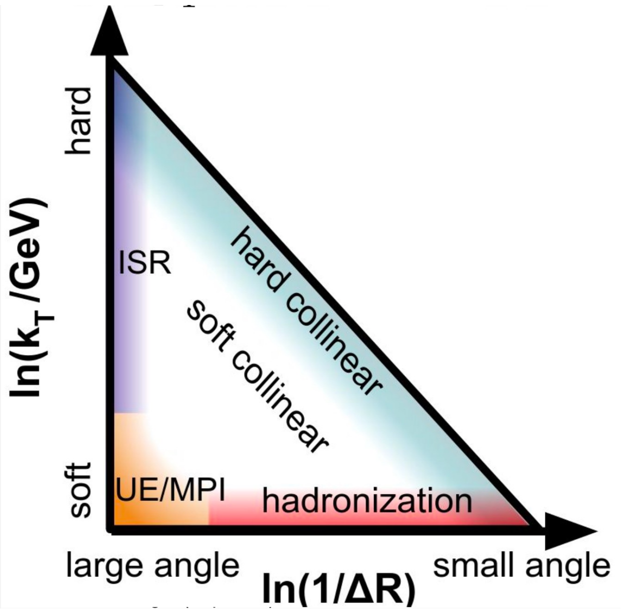


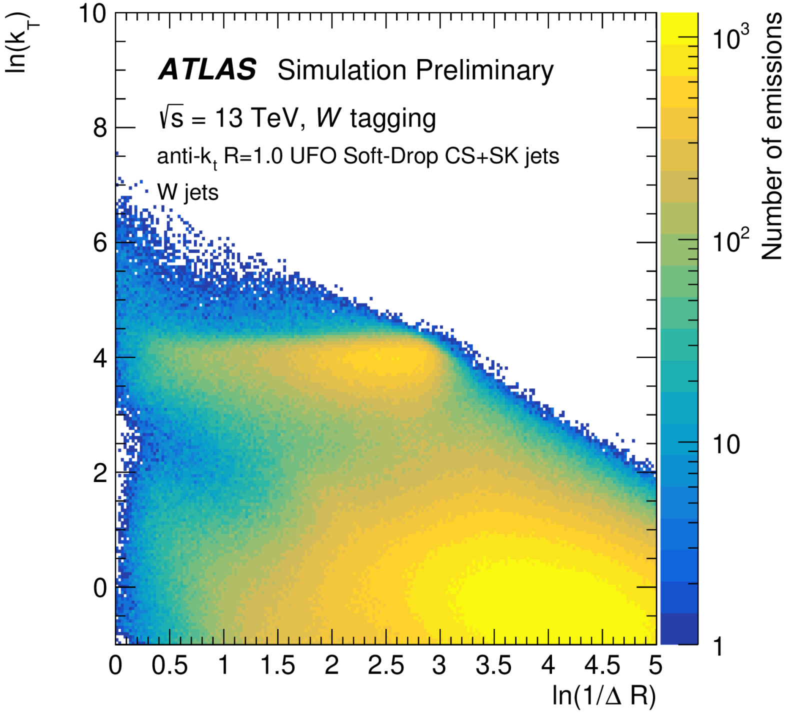


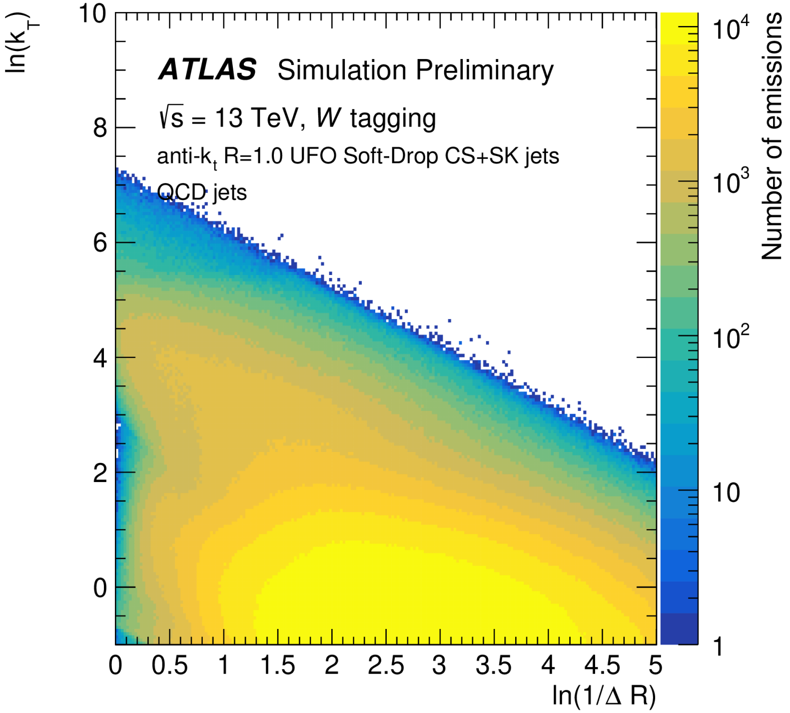
Lund jet planes

$$\Delta R_{ij} = \sqrt{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}, \qquad z = \frac{p_T^j}{p_T^i + p_T^j}, \qquad k_t = p_T^j \Delta R_{ij}$$

- **Lund jet plane** represents **two-dimensional** space built from the **opening angle** and the **momentum fraction** of a given **gluon emission with respect to its emitter**







Jet substructure at high-pT

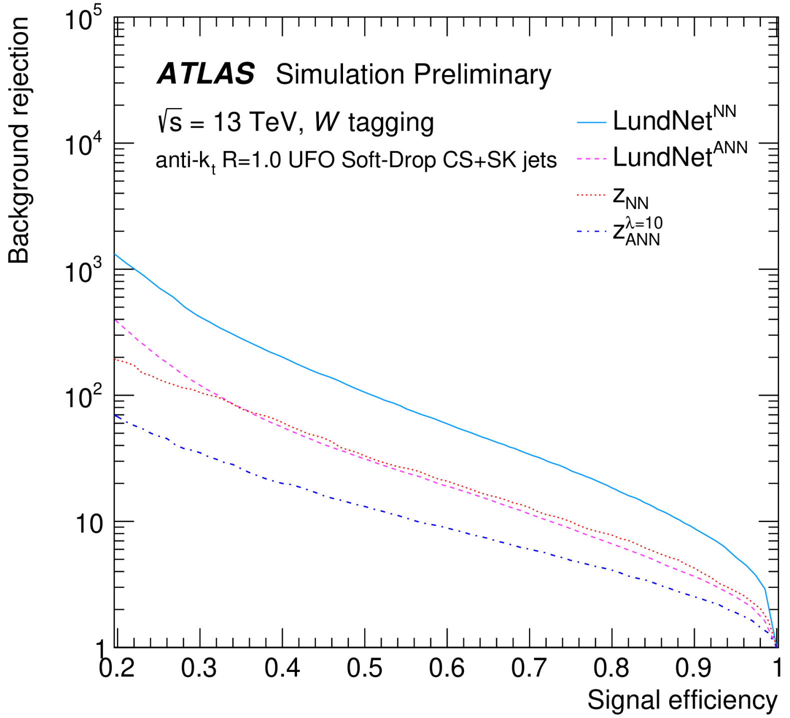
ATL-PHYS-PUB-2023-017

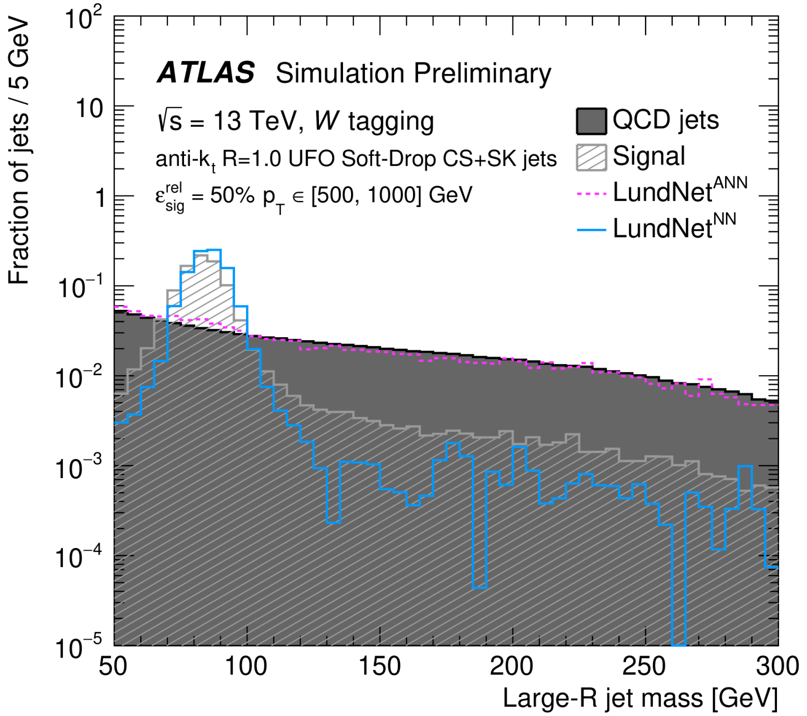
LundNet Performance

ATL-PHYS-PUB-2023-017

$$\Delta R_{ij} = \sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}, \qquad z = \frac{p_{\mathrm{T}}^j}{p_{\mathrm{T}}^i + p_{\mathrm{T}}^j}, \qquad k_t = p_{\mathrm{T}}^j \Delta R_{ij}$$

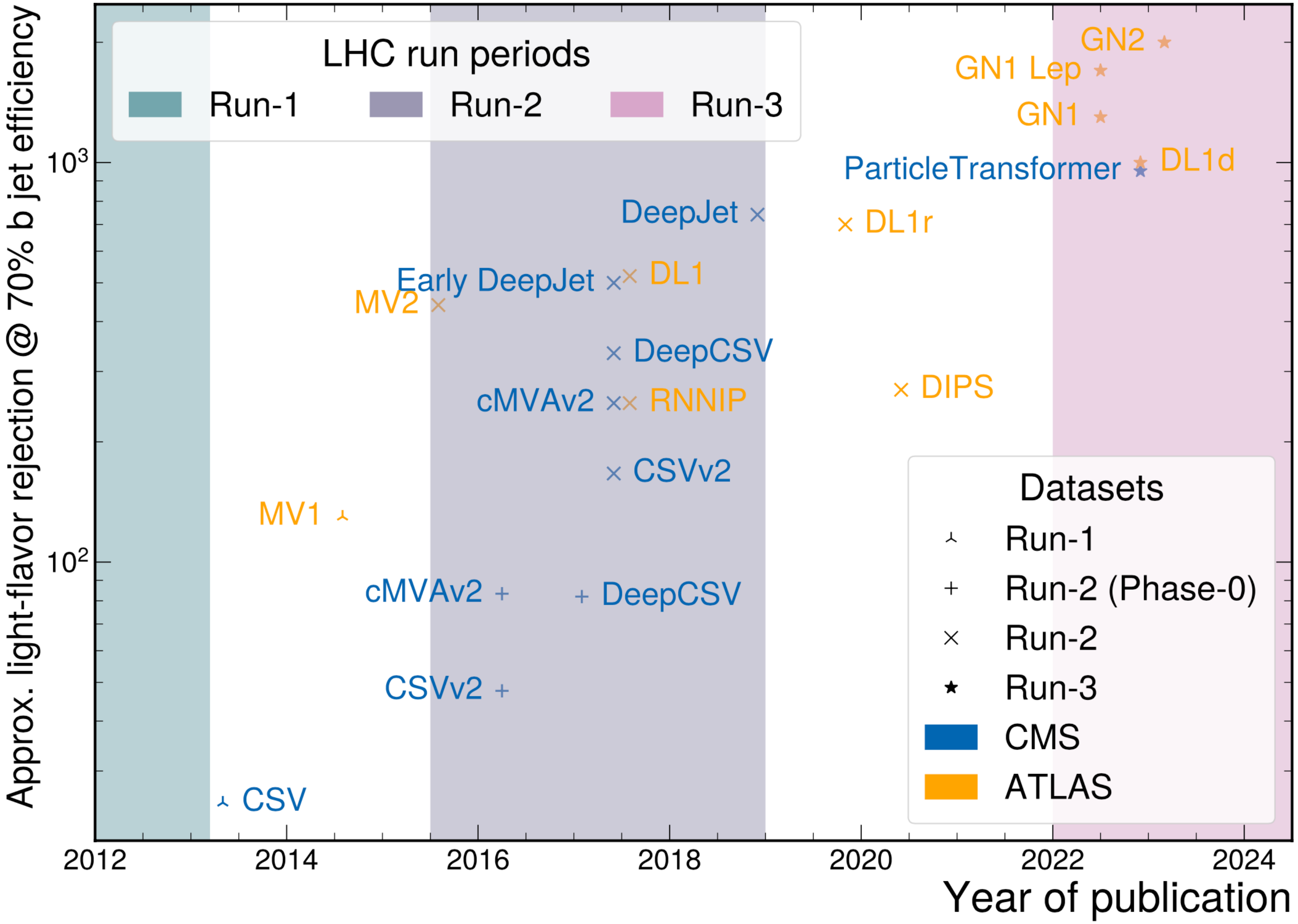
- **Sequence of jet emissions** coming from the full declustering of large radius jet can be **represented as a graph**
- **GNN inputs** include **ln(1/ΔR), ln(k), ln(1/*z*)** and **number of tracks**
- Algorithm **decorrelated from jet mass** to prevent **bias in background jet-mass** distribution from being around the **W boson mass**
- Achieved via **combined training of jet classification GNN and jet mass inferring adversarial NN** (ANN)





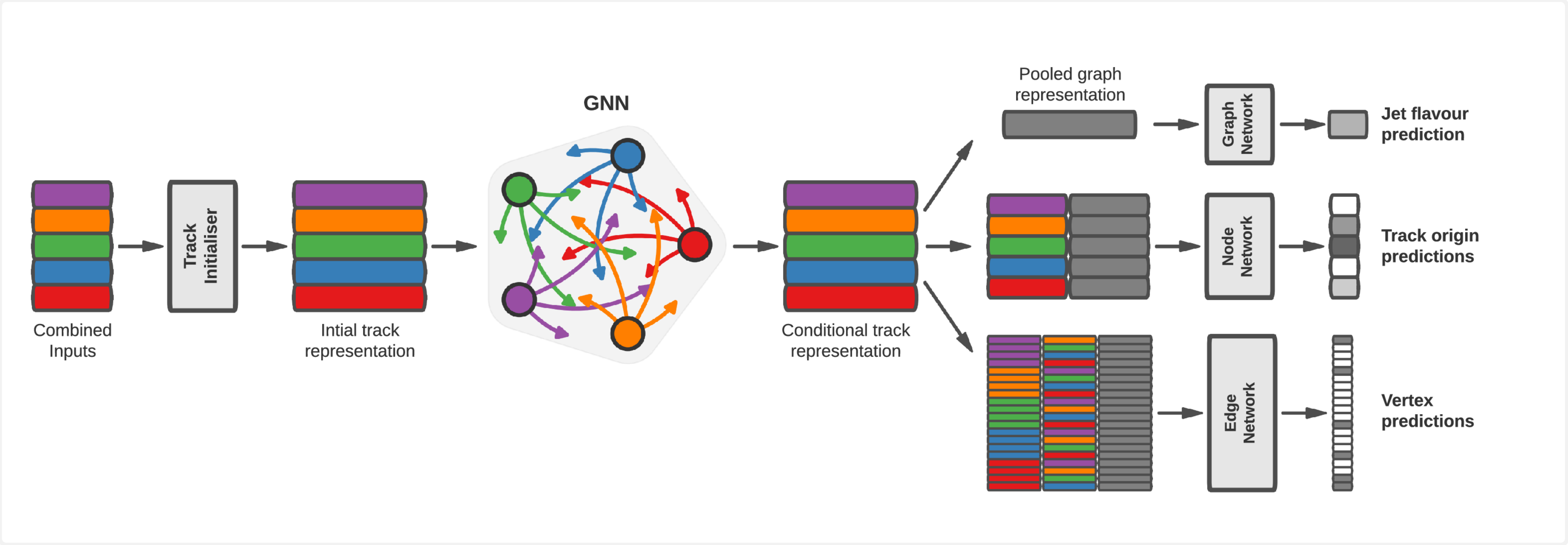
Comparison of different jet taggers

arXiv:2404.01071



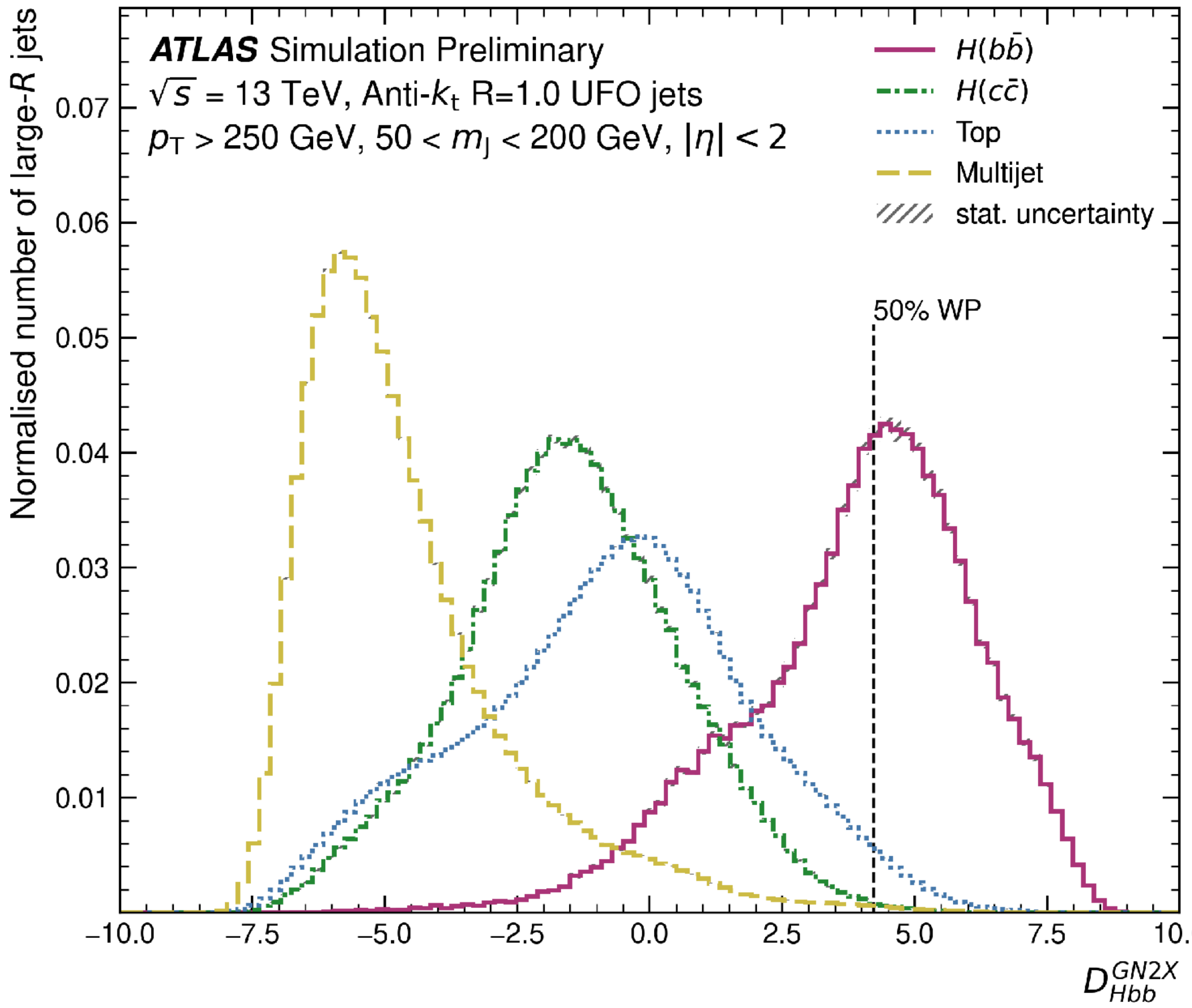
GN1 Architecture

ATL-PHYS-PUB-2022-027



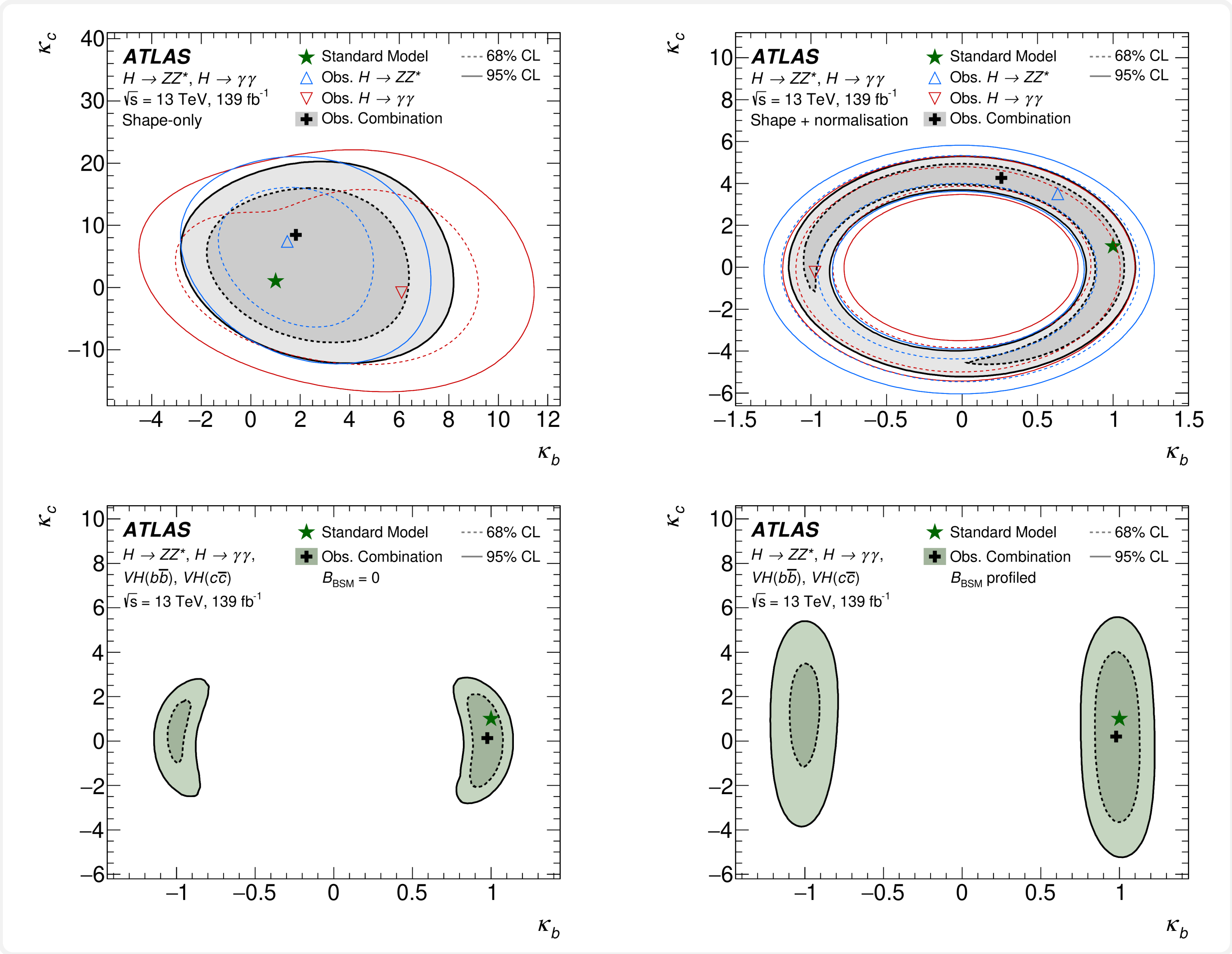
GN2X Performance

ATL-PHYS-PUB-2023-021

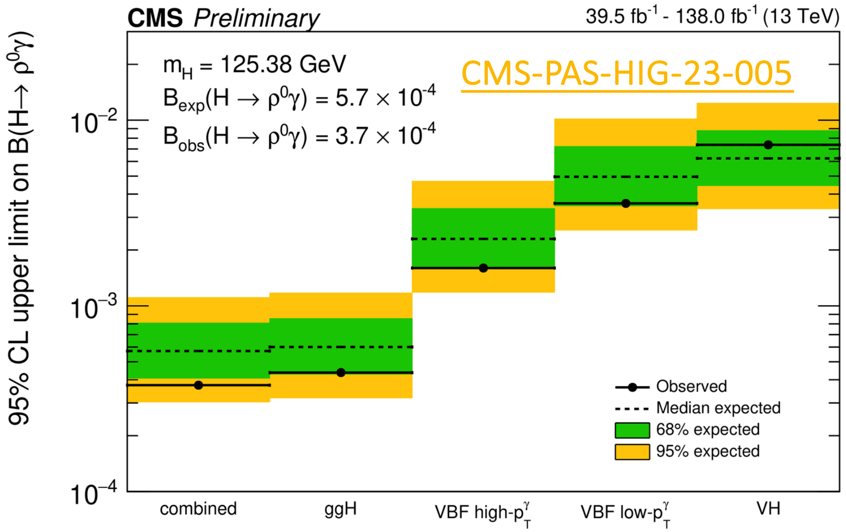


κ_c and κ_b Interpretation

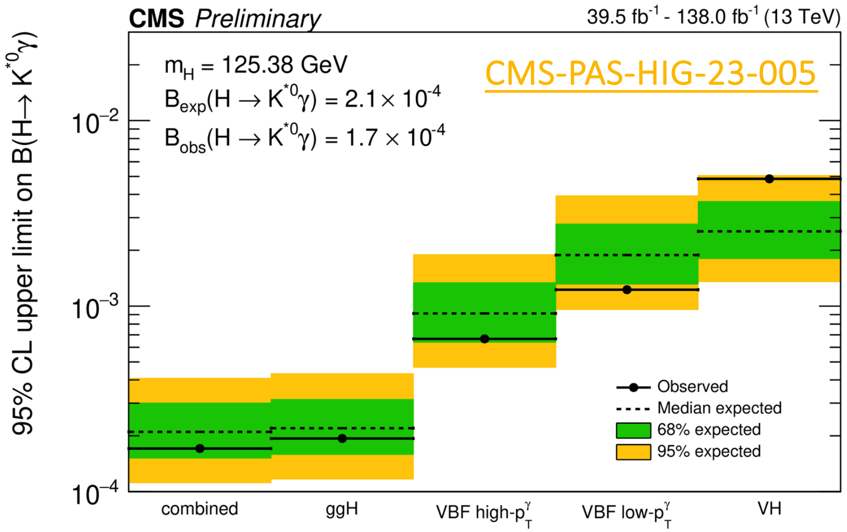
JHEP05(2023)028



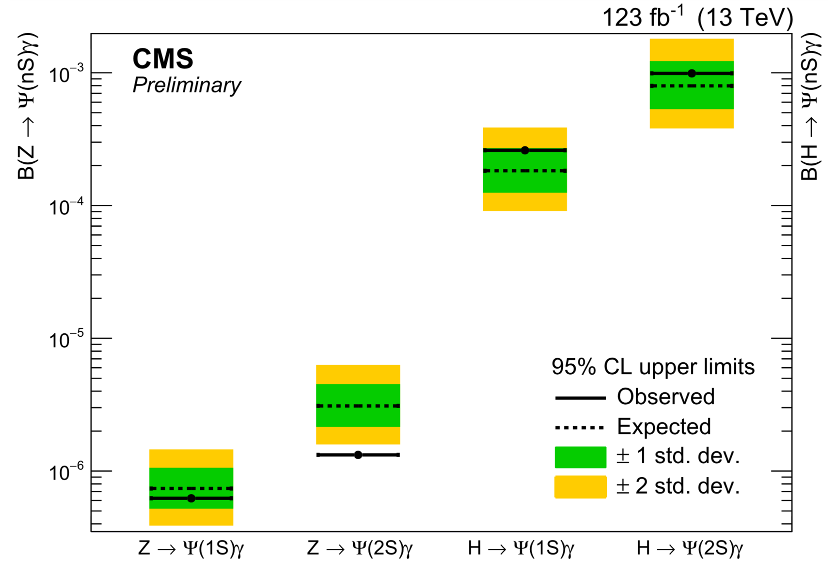
CMS Higgs to meson + photon searches



CMS-PAS-HIG-23-005



CMS-PAS-HIG-23-005

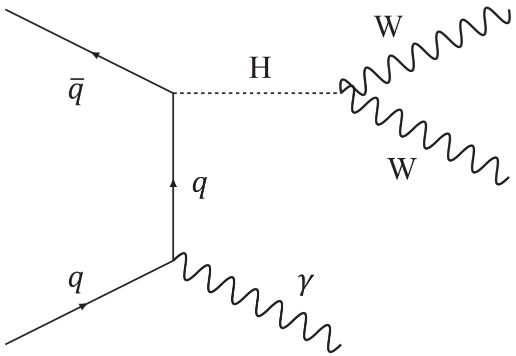


CMS-PAS-SMP-22-012

CMS Higgs + photon XS measurement

PhysRevLett.132.121901

- **Gluon initiated contribution disappears** according to Furry's theorem
- Sensitive to Higgs quark Yukawas
- Cut-based analysis, **statistical and systematic uncertainties** with similar magnitude
- Other coupling modifiers set to their SM predictions

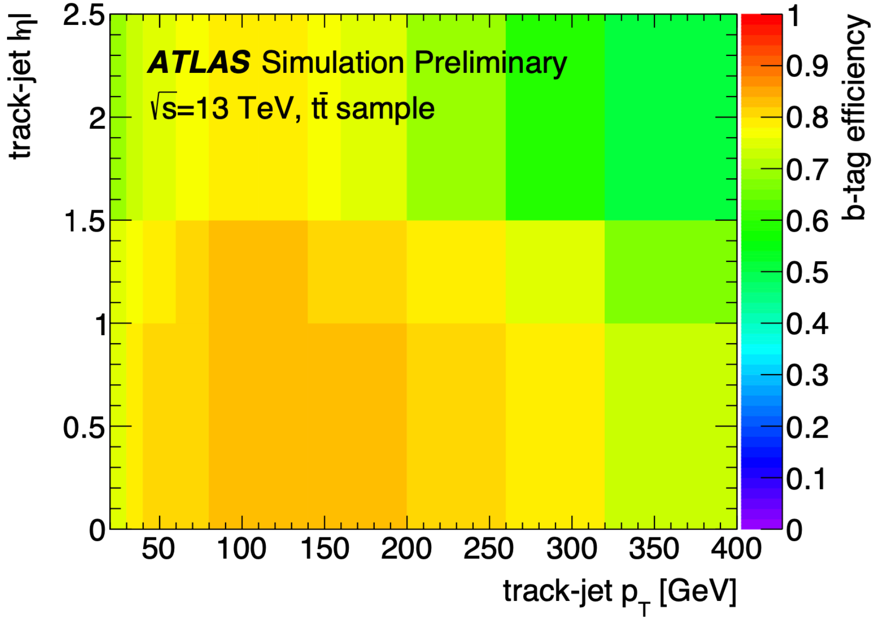


Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% C.L.
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	86 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	66 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	88 (66)	$\lvert\kappa_c\rvert \leq 190$ (110)

Truth flavour jet tagging

- Accepting/rejecting (“**direct tagging**”) events based on jet flavour tagging discriminants significantly **reduces available background** (e.g., V+light flavour jets processes) **statistics** due to **enhanced rejection** factors in latest algorithms
- ATLAS has implemented a **“truth-flavour tagging”** approach in recent **V(lep)H($b\bar{b}$)** and **V(lep)H($c\bar{c}$) analyses**
    - Consists in applying **tagging (in-)efficiency** of the Higgs candidate jets **as event weights**
    - **Efficiency maps** usually parametrised as **function of jet p_T and η**
- Leads to **reduction of background statistical uncertainties**, since all available events are used
- Some **systematic uncertainties can arise** from differences to direct tagging approach (e.g. due to close-by jets) – **still resulting in better sensitivity**

PhysRevLett.132.121901



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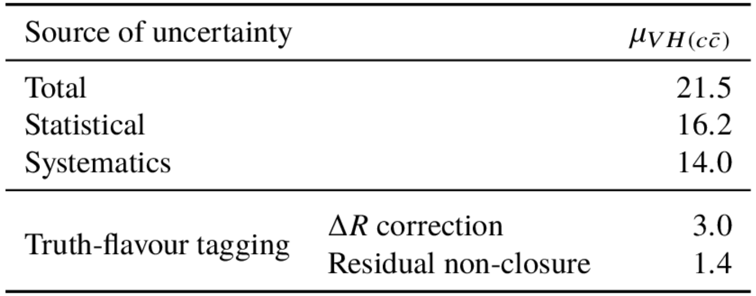
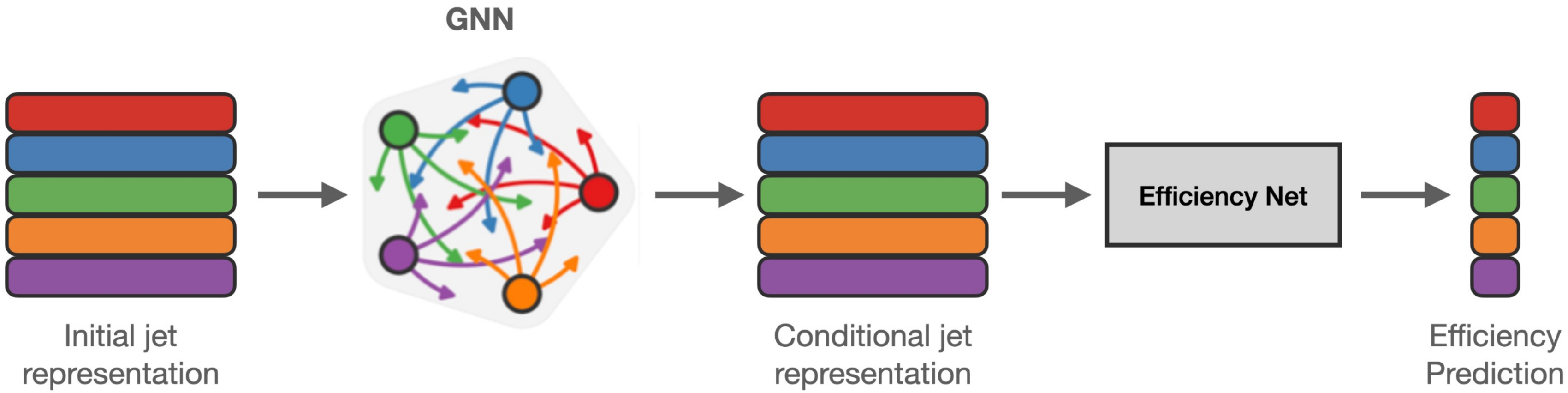


Source of uncertainty		$\mu_{VH(c\bar{c})}$
Total		21.5
Statistical		16.2
Systematics		14.0
Truth-flavour tagging	ΔR correction	3.0
	Residual non-closure	1.4

Truth flavour jet tagging with GNNs

PhysRevLett.132.121901

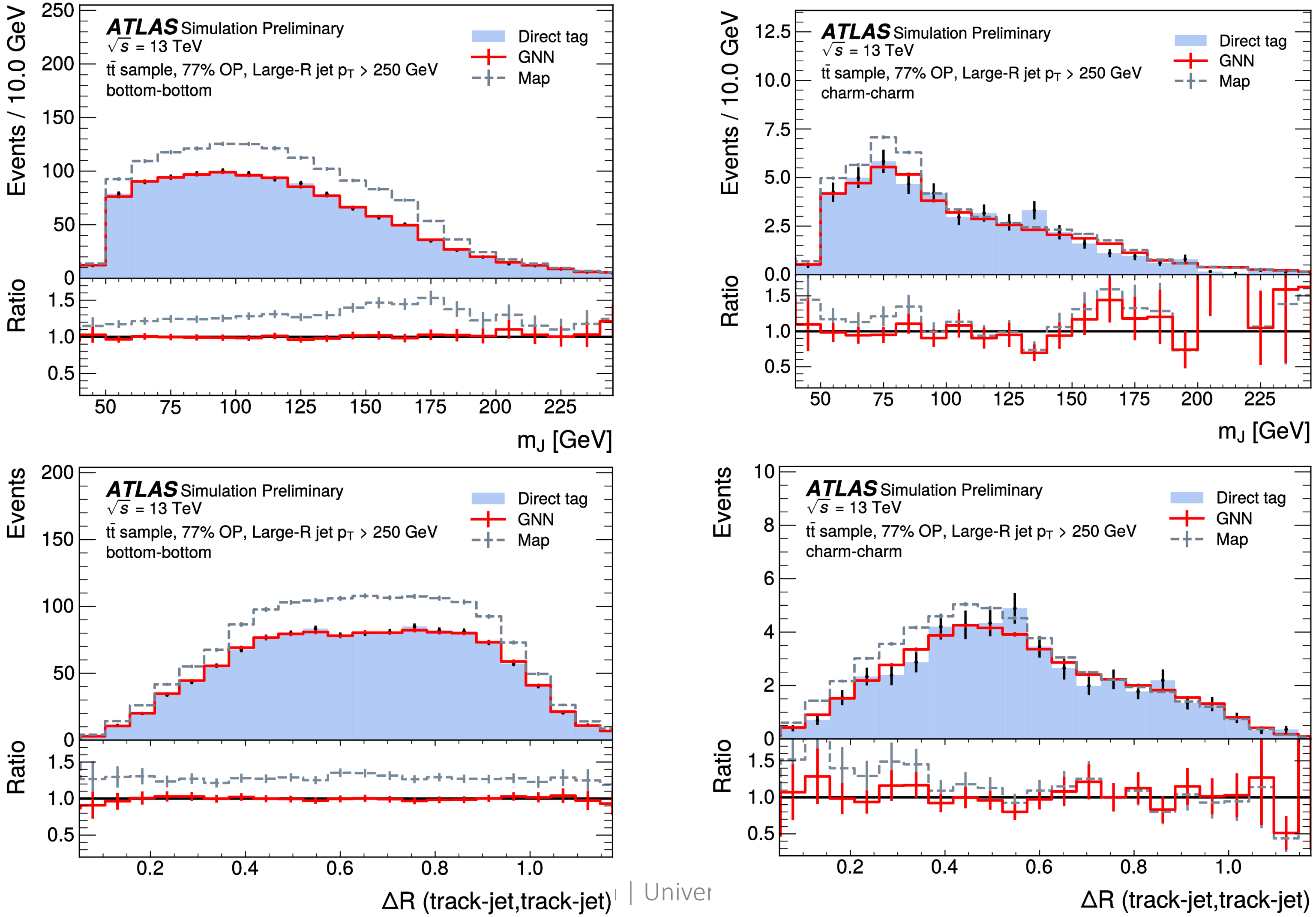
- **Efficiency maps fail to capture all kinematic correlations**, and can be **affected by binning choices**
- A **GNN** can potentially solve these problems, capturing **high-dimensional correlations between the jets** and leading to **smooth output efficiency distributions**
- **GNN inputs** include jet, event and jet-pair variables, trained with ttbar events and large radius jets



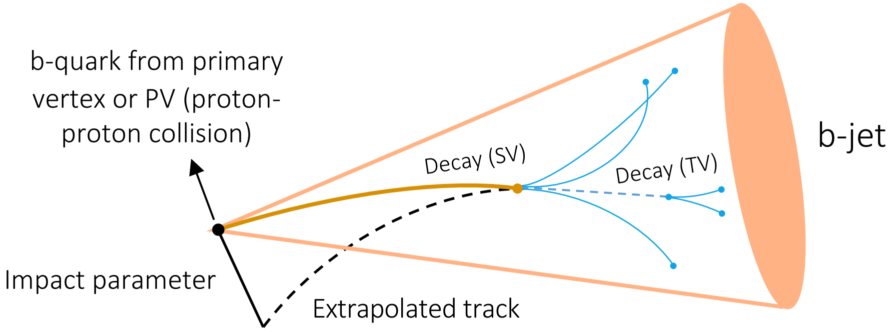
Truth flavour jet tagging with GNNs II

PhysRevLett.132.121901

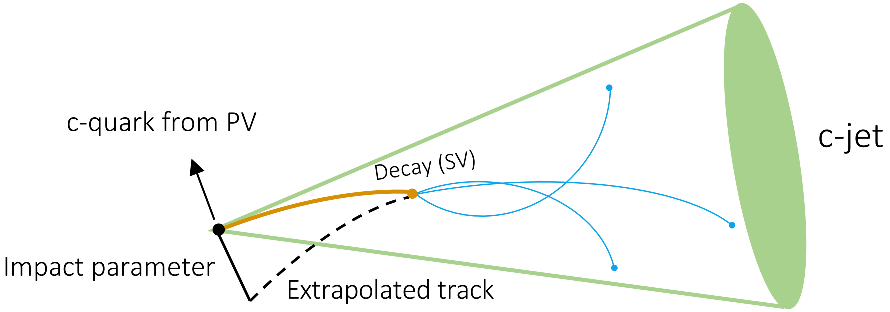
- **GNN-based approach** generally with **similar or better agreement with direct tagging** approach when **compared to efficiency maps** approach, particularly for very **close-by jets**



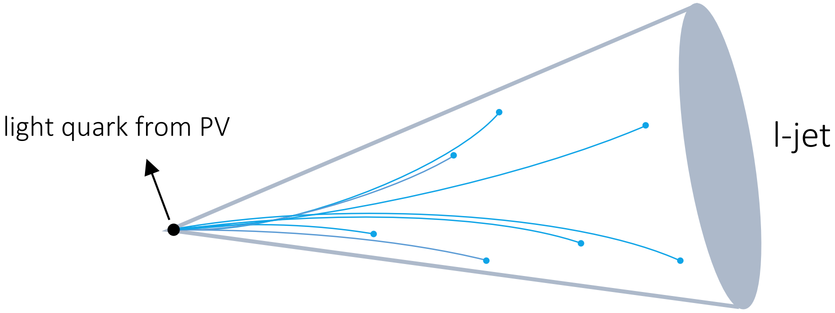
Flavoured Jets



- b-quark fragments into b-hadron carrying around **80% of the jet energy**
- **High** b-hadron **decay product multiplicities** (around 5 charged particles per decay)
- Most b-hadrons (≈ 90%) **decay into c-hadrons**
- b(c)-hadron **decay vertex often displaced** from the PV(SV) by a few mm
- Tracks from both of these vertices often have **large impact parameters**



- c-quark fragments into c-hadron carrying around **55% of the jet energy**
- 2 to 3 times **lower** c-hadron **decay product multiplicities** than for b-hadrons (around 2 charged particles/decay)
- c-hadron **decay vertex often displaced** from the PV by a few mm
- Tracks from this vertex can often have **large impact parameters**



- Light quark hadronises into **many light hadrons sharing the jet energy**
- Tracks from this vertex can often have **impact parameters consistent with zero**
- Long-lived light hadrons can be produced, but more likely to decay cms away from PV