Search for the Higgs boson decaying to charm quarks using large-radius jets with the CMS experiment

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on behalf of the CMS collaboration

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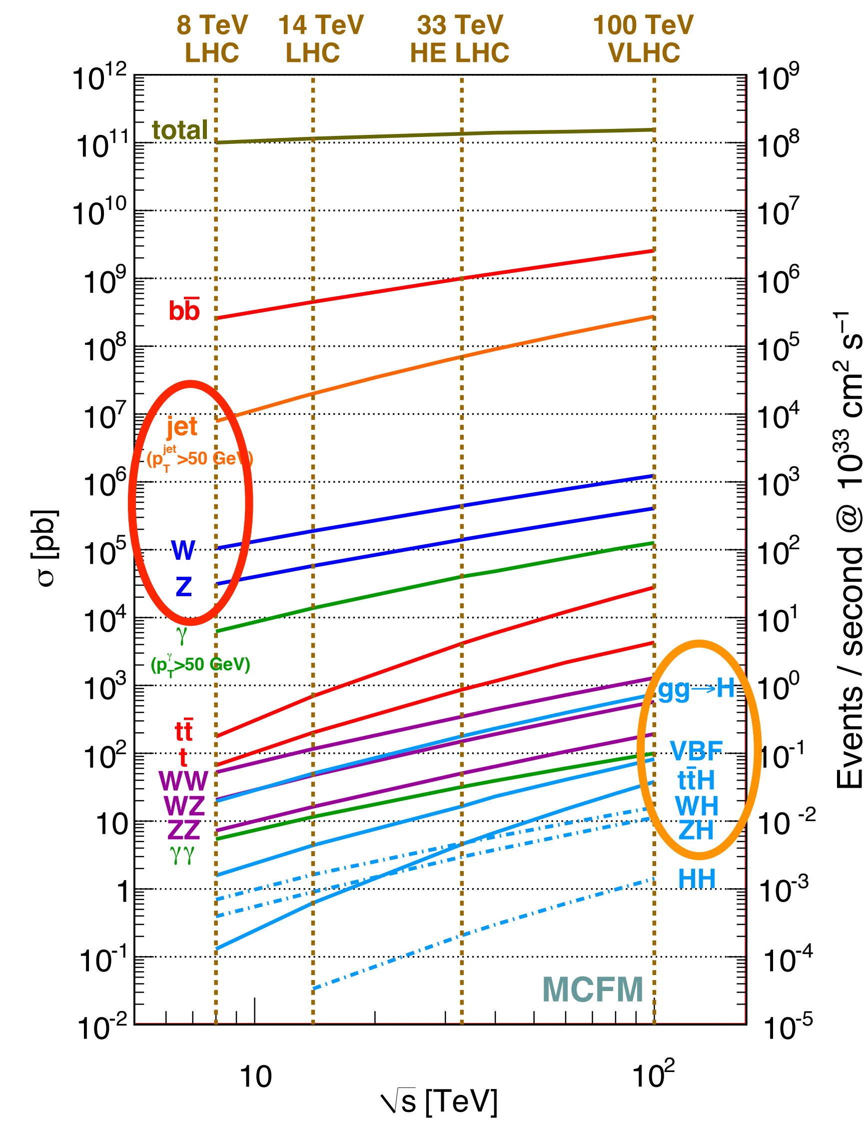
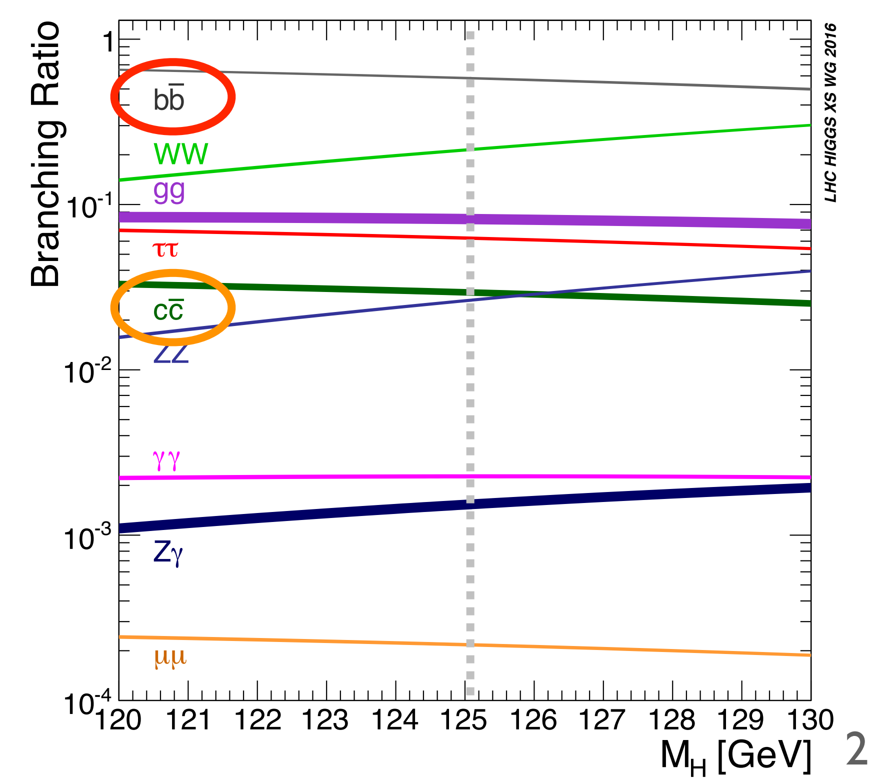
Introduction

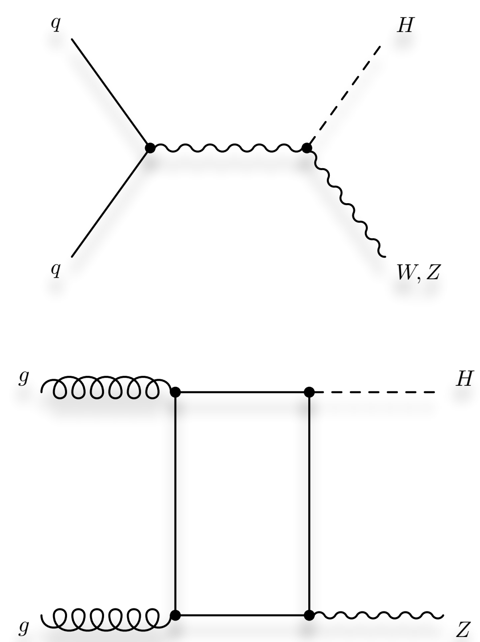
- Search for H→cc:
  - directly probes the Yukawa coupling to 2nd-generation quarks
  - next milestone in Higgs coupling measurements
- H→cc: very challenging to hunt at a hadron collider
  - small branching ratio in SM: ~2.9%
    - H→bb (BR=58%): a background in this search
  - very large (hadronic) backgrounds
  - charm quark identification is the key
- Approaches explored so far:
  - indirect bounds from a global fit to the existing data
    - $\kappa_c := y_c / y_c^{SM} < 6.2$ [Phys.Rev. D92 (2015) no.3, 033016]
  - search for rare exclusive decay to charmonium, H→J/Ψγ
    - upper limits on $\mu := (\sigma \times BR) / (\sigma_{SM} \times BR_{SM})$
      - ATLAS: μ < 120 (100) obs. (exp.) [PLB 786 (2018) 134]
      - CMS: μ < 220 (160) obs. (exp.) [Eur. Phys. J. C 79 (2019)94]
  - direct H→cc search
    - ATLAS: Z(→ll)H, 36.1 fb^{-1} data
      - μ < 110 (150) obs. (exp.) [PRL 120 (2018) 211802]
    - CMS: VH, 35.9 fb^{-1} data [CMS-PAS-HIG-18-031]

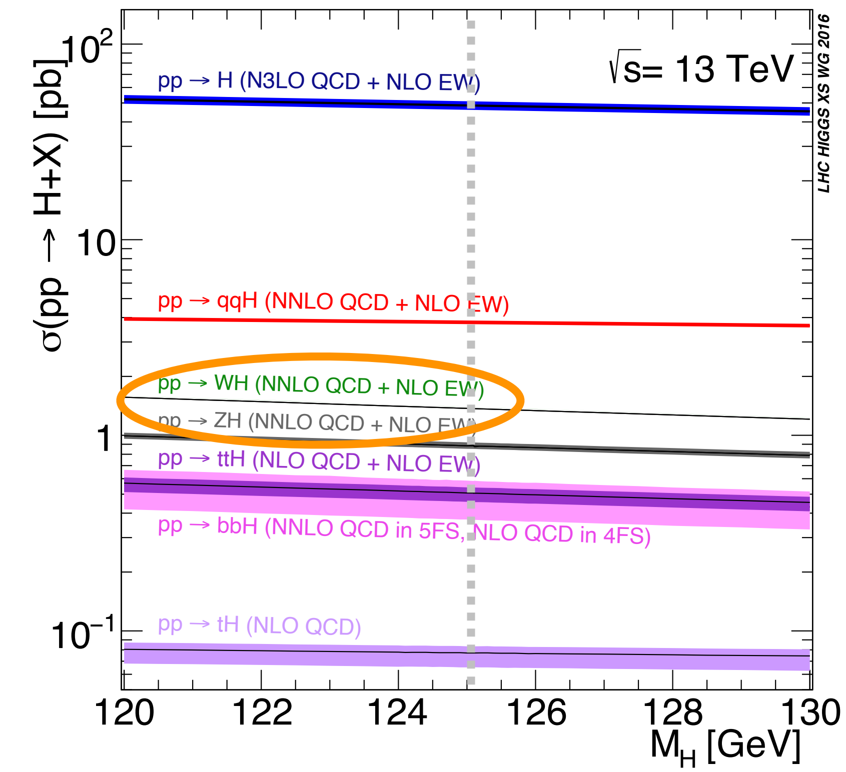


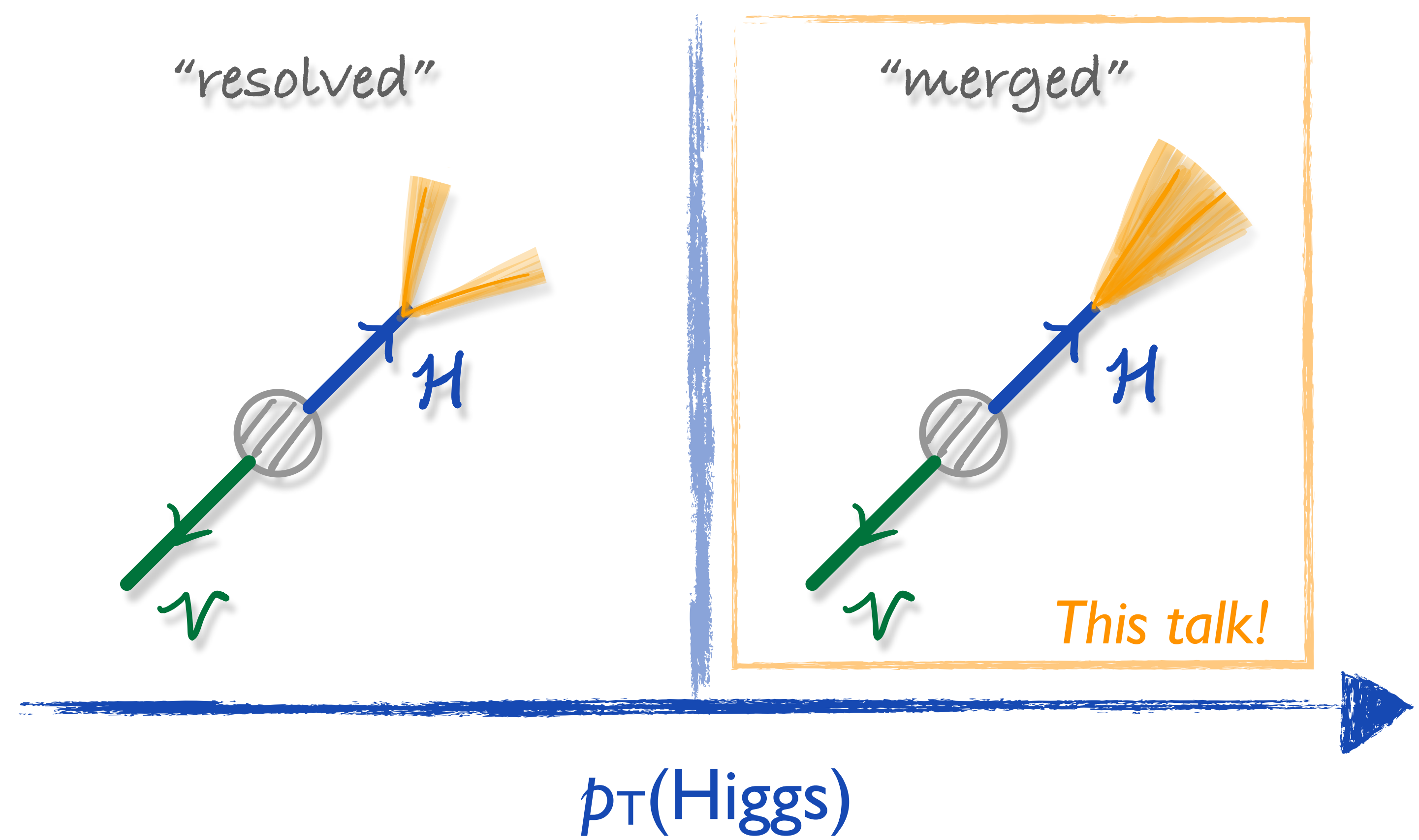


First Direct H→cc Search in CMS

- Exploits the VH production
  - leptonic V decay: Z→νν, W→lν, Z→ll
    - 3 mutually exclusive channels: 0L, 1L, and 2L (L = e, μ)
  - provides handles for event triggering and QCD background suppression
  - main backgrounds
    - W/Z + jets, ttbar, diboson
- Two complimentary approaches to fully explore the H→cc decay topology
  - resolved-jet topology: reconstruct H→cc decay with two resolved jets (R=0.4)
  - merged-jet topology: reconstruct H→cc decay with one large-R jets (R=1.5)
  - advanced charm-tagging techniques exploited

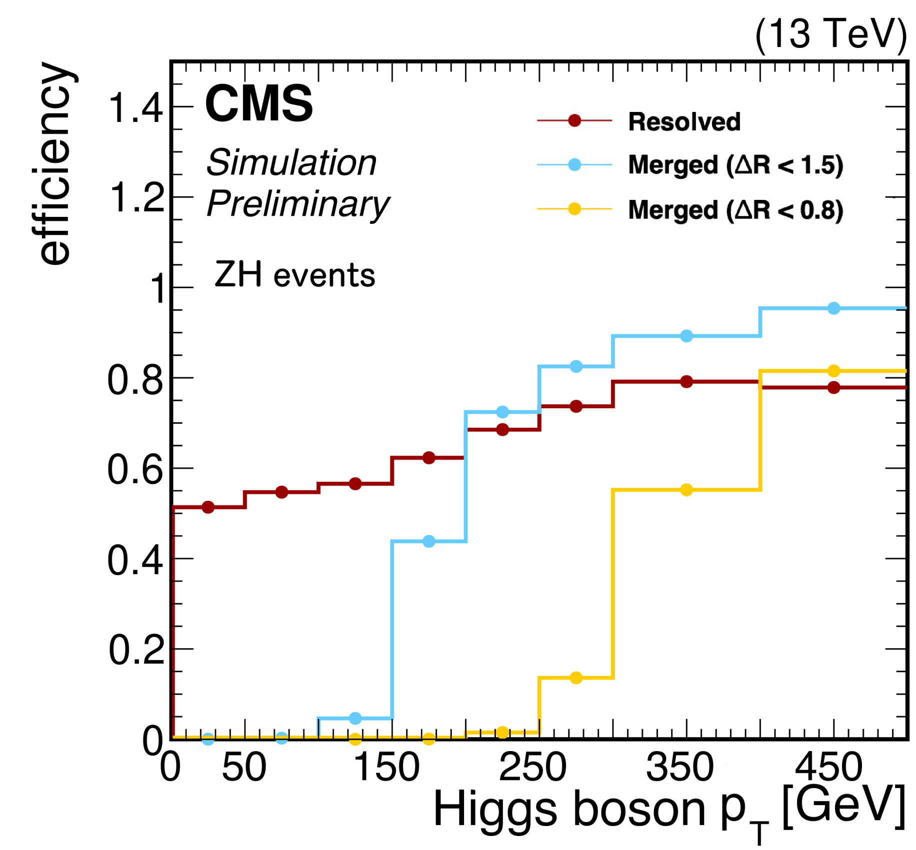






Higgs Boson Reconstruction

- The cornerstone of the merged-jet analysis is the reconstruction of the H→cc decay with a single large-R jet
  - focus on the boosted regime
    - better signal purity: the p_T spectrum in VH signals is harder than that in V+jets backgrounds
    - but lower signal acceptance: falling p_T spectrum in both signal and backgrounds
  - choosing a suitable jet size
    - angular separation of the decay products $\Delta R \sim 2m_H / p_T$
    - R = 1.5 jets:
      - good efficiency to capture both quarks from Higgs with $p_T >$ ~150 GeV
      - balance between signal purity and acceptance
  - capturing the showers of the two charm quarks in one jet can potentially lead to a better exploitation of the correlation between them

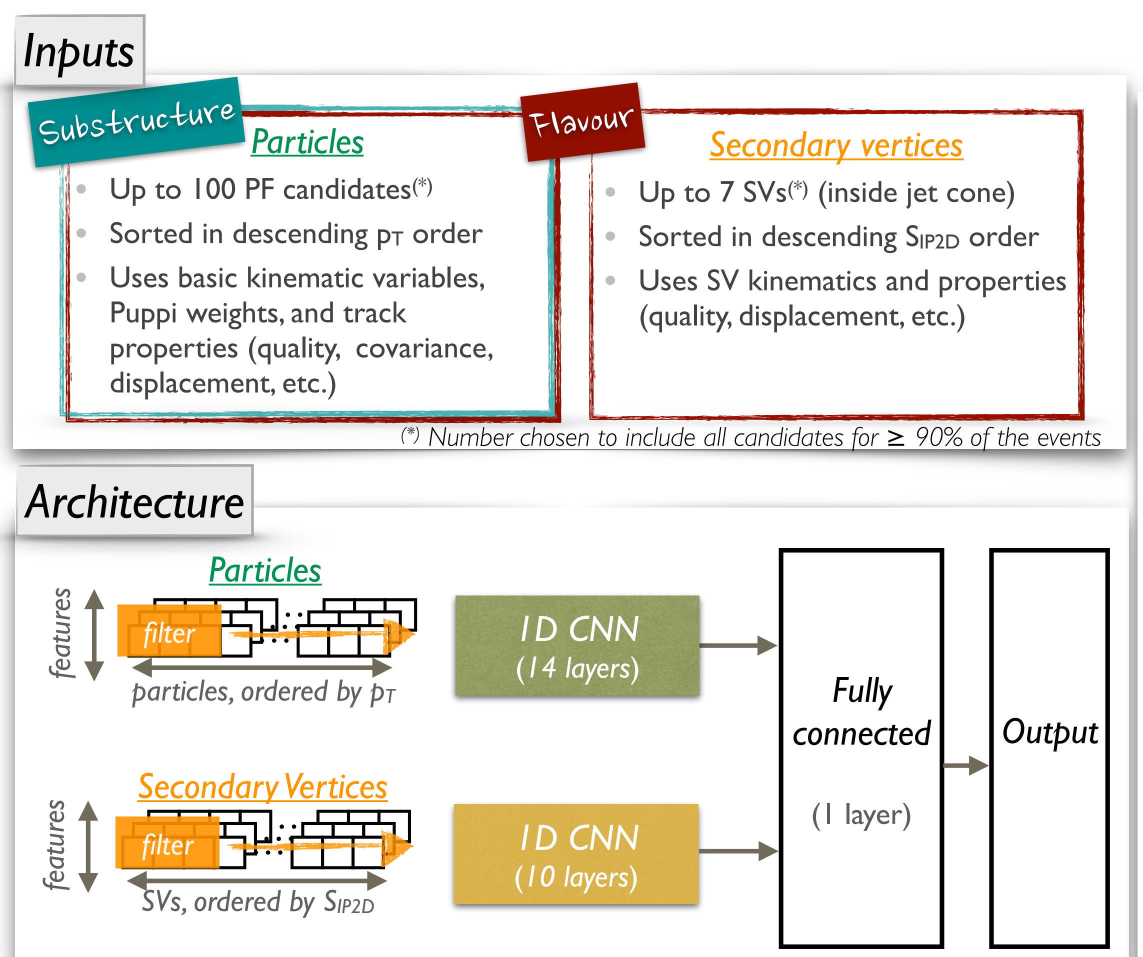


Reconstruction efficiency:

- *Merged (R=0.8 / R=1.5): both quarks contained in an AK8 / AK15 jet (with ΔR(jet, c-quark) < 0.8 / 1.5)*
- *Resolved: each quark is reconstructed as a resolved R=0.4 jet with p_T>25 GeV and |η|<2.4*

H→cc Identification

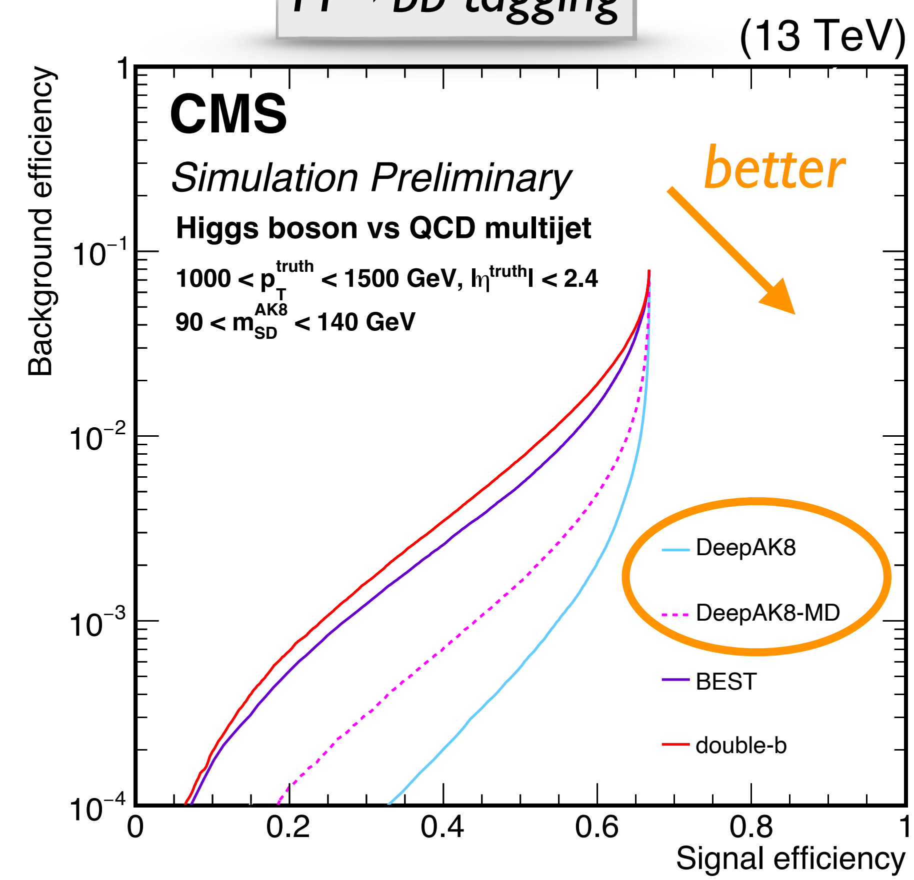
- Advanced machine learning-based algorithm to identify the H→cc decay: "DeepAK8"
  - multi-class classifier for top quark and W, Z, Higgs boson tagging
    - sub-classes based on decay modes (e.g., Z→bb, Z→cc, Z→qq)
    - output scores can be aggregated/transformed for different tasks -> highly versatile tagger
  - uses deep neural networks to directly process jet constituents (PF candidates / secondary vertices)
    - architecture: ResNet inspired 1D convolutional neural networks
  - significant performance improvement



Output

Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

H→bb tagging

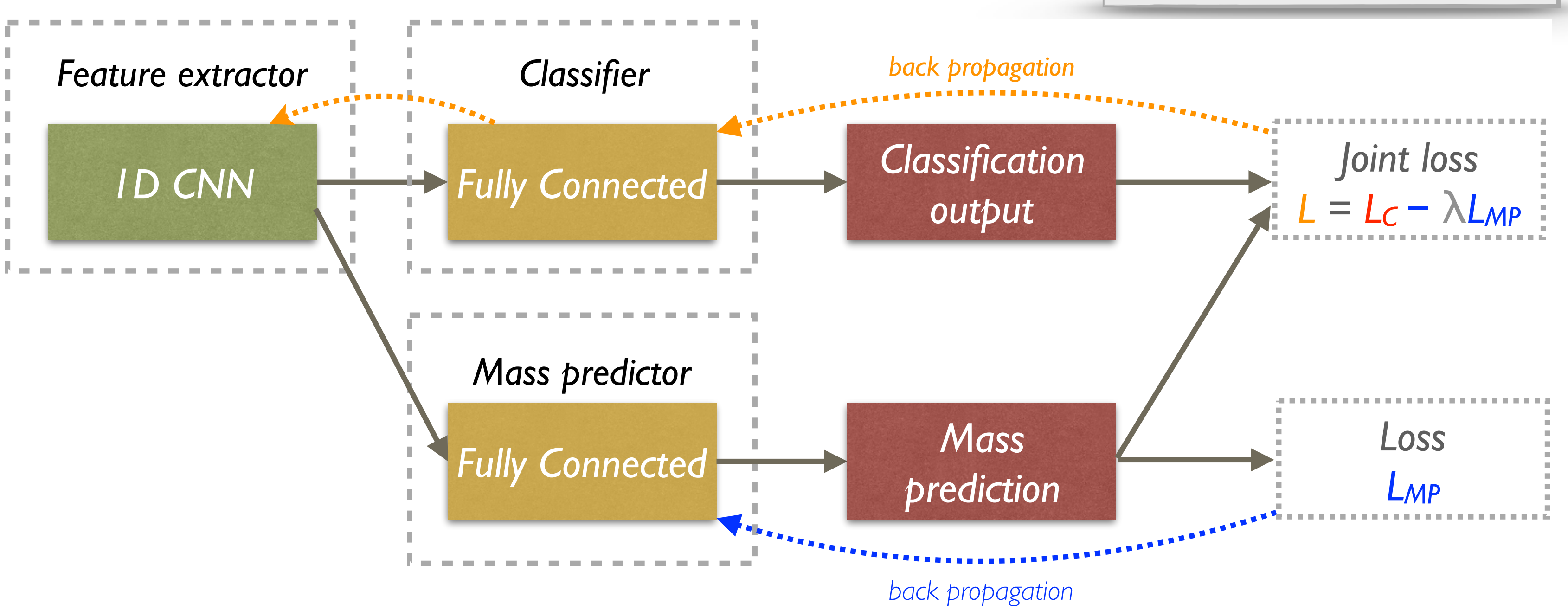


CMS-PAS-JME-18-002

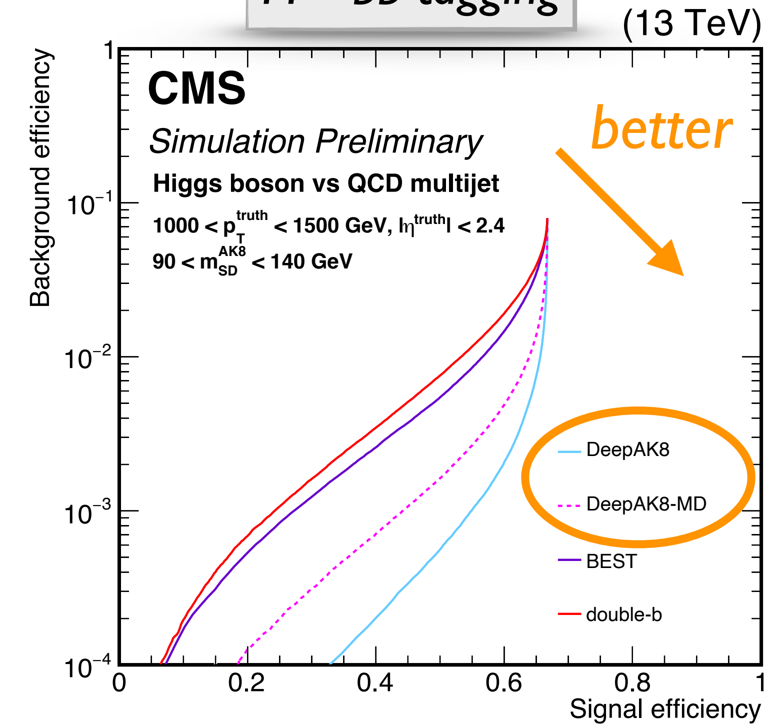
H→cc Identification (II)

- Mass-decorrelated tagger: "DeepAK8-MD"
  - the nominal version of DeepAK8 shows significantly improved performance, but also features strong "mass sculpting"
    - i.e., modification of the jet mass shape in background samples after tagging requirements
  - dedicated version designed to minimize mass sculpting
    - using "adversarial training" technique
  - significantly reduced mass sculpting yet still strong performance
    - allows us to fit the mass distribution for signal extraction

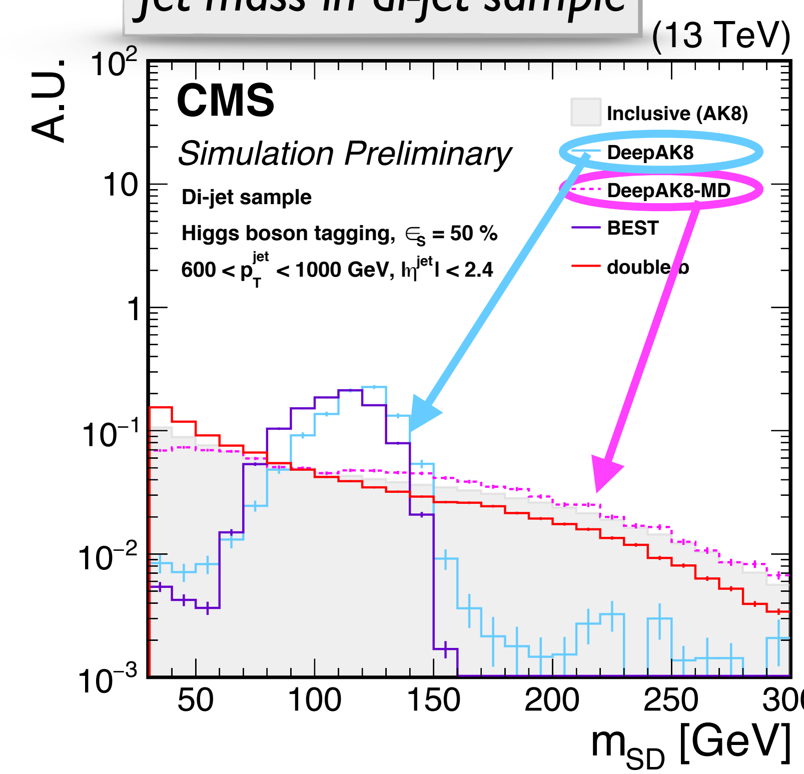
Adversarial training



H→bb tagging



Jet mass in di-jet sample



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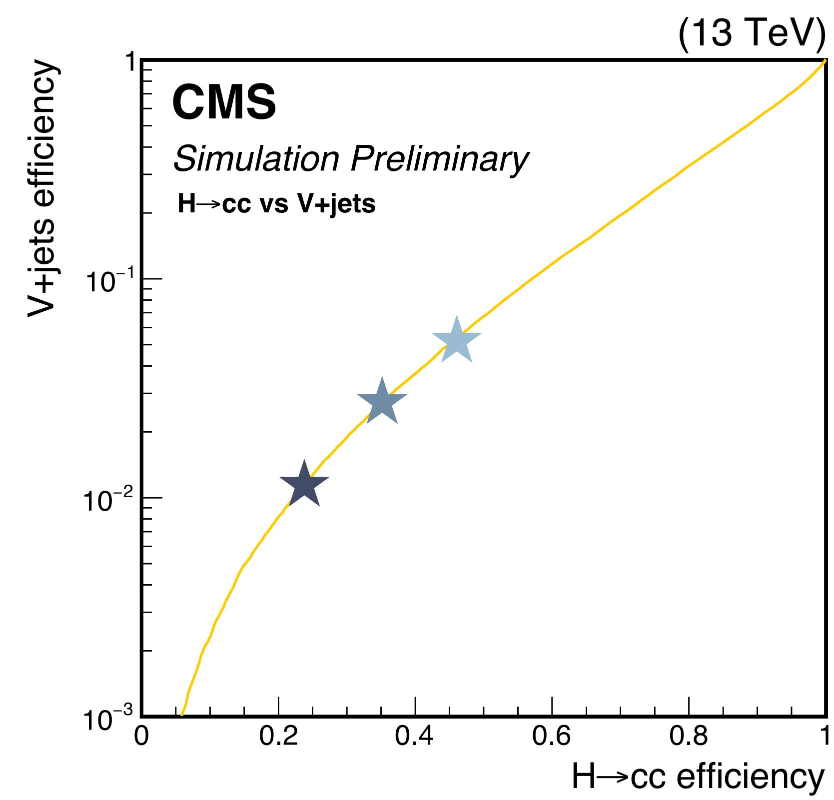
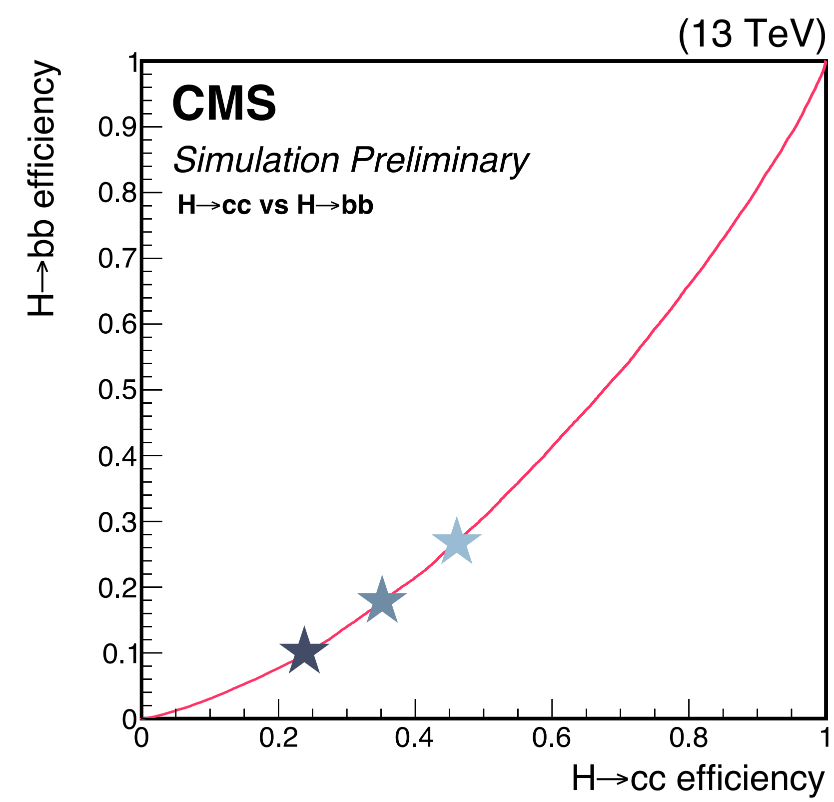
H→cc Identification (III)

- The DeepAK8-MD algorithm has been adapted to R=1.5 jets for the H→cc analysis with a dedicated training
  - cc-tagging discriminant defined as:
    $$\frac{\mathrm{score}(\mathrm{Z}\to c\bar{c})+\mathrm{score}(\mathrm{H}\to c\bar{c})}{\mathrm{score}(\mathrm{Z}\to c\bar{c})+\mathrm{score}(\mathrm{H}\to c\bar{c})+\mathrm{score}(\mathrm{QCD})}$$
  - right: performance in MC
- Three working points defined:

	Loose	Medium	Tight
cc-discriminant	>0.72	>0.83	>0.91
ε(V+jets)	5%	2.5%	1%
ε(H→cc)	46%	35%	23%
ε(H→bb)	27%	17%	9%

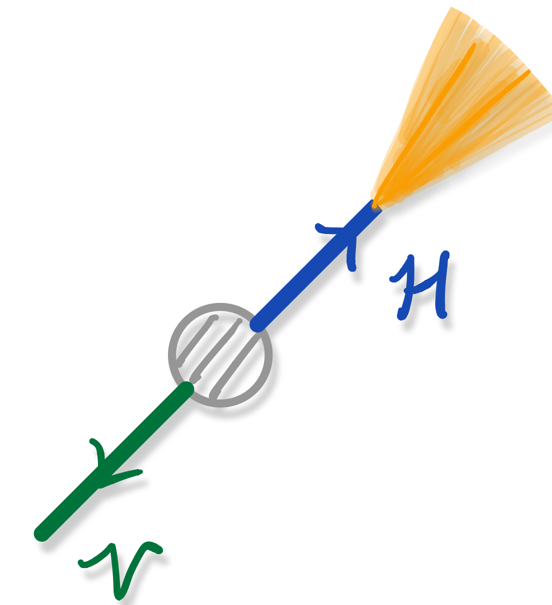
- Events are categorized into three mutually exclusive categories, based on the 3 WPs, to improve sensitivity
  - high/medium/low purity (HP/MP/LP) categories
- cc-tagging discriminant calibrated in data
  - using "proxy" jets from g(gluon)→cc
    - similar characteristics as signal jets
  - scale factors applied to H→cc / Z→cc jets





Baseline Event Selection

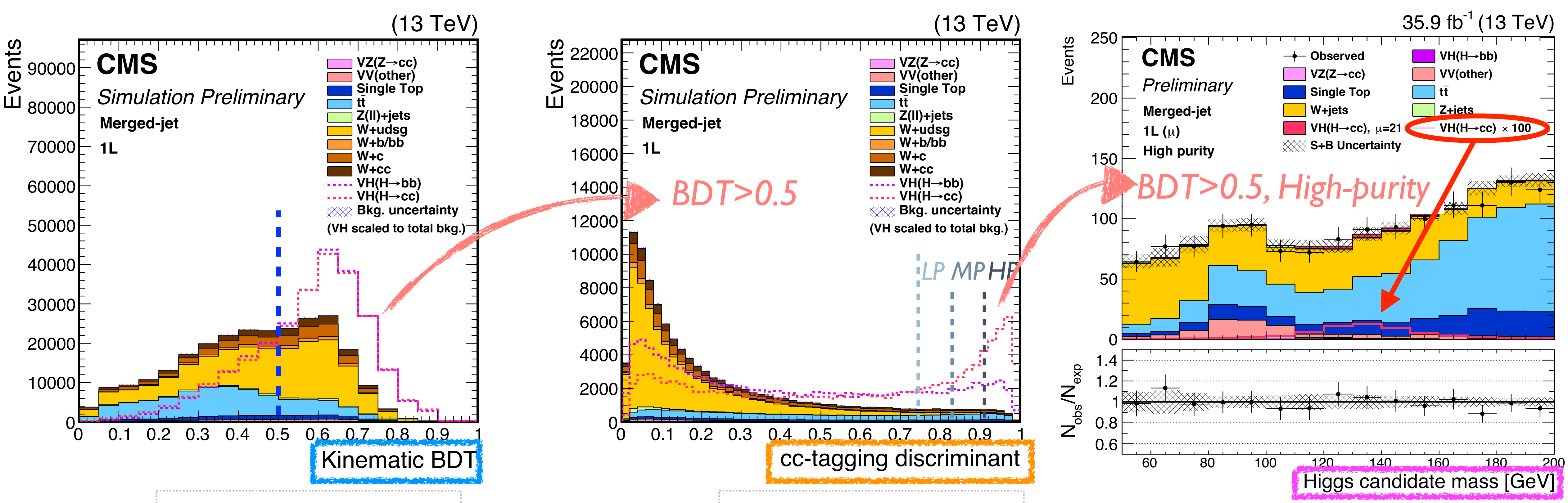
- VH events have a clear signature
  - vector boson recoiling against the Higgs boson
  - little additional activity in the event
- Vector boson reconstructed with lepton and/or missing transverse momentum (MET)
  - 2L: V:=opposite-sign same-flavor lepton pair; 75 < m(LL) < 105 GeV [compatible w/ Z mass]
  - 1L: V:=lepton + MET; $\Delta\varphi$(lep, MET)<2.0 [compatible w/ W decay]
  - 0L: V:=MET; MET>170 GeV [due to trigger requirement], $\Delta\varphi$(MET, j)>0.5, $\Delta\varphi$(pfMET, tkMET)<0.5 [suppress QCD]



- Baseline selection
  - high p_T (>200GeV) vector boson and H_{cand}, back-to-back ($\Delta\varphi(V, H_{cand})$>2.5)
  - the large-R jet leading in p_T selected as the Higgs candidate (H_{cand})
    - requires p_T > 200 GeV, soft-drop (SD) groomed jet mass $m_{SD}(H_{cand}) \in [50, 200]$ GeV
  - veto events with additional R=0.4 jets ($\Delta R(j, H_{cand})$>1.5) to suppress ttbar contribution

Analysis Strategy

- Analysis strategy overview
  - event-level kinematic BDT developed in each channel to better suppress the dominant backgrounds (V+jets, ttbar)
    - using only event kinematics, NOT the intrinsic properties (e.g., flavor/mass) of H_{cand}
  - cc-tagging discriminant used to select cc-flavor jets and reject light/bb-flavor jets
  - distinct $m(H_{cand})$ shapes between signal and V+jets/ttbar background: fit the $m(H_{cand})$ shape to extract the H→cc signal
- Kinematic BDT, cc-tagging discriminant and $m(H_{cand})$ largely independent of each other
  - allowing for a simple and robust strategy for background estimation and signal extraction

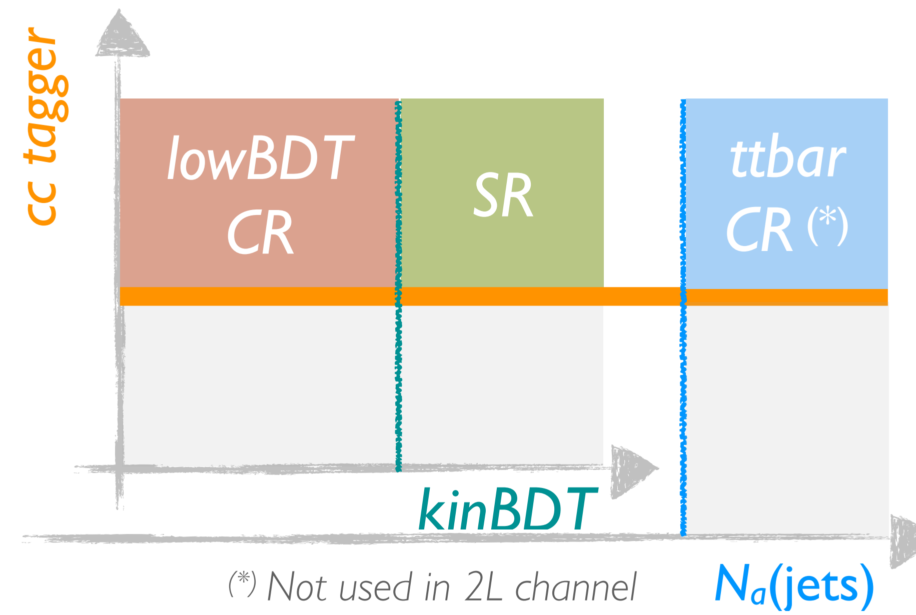


VH scaled to total BKG

VH scaled to total BKG

Signal Extraction

- The VH(cc) signal is extracted via a binned fit to the mass of the Higgs candidate [$m(H_{cand})$]
  - $m(H_{cand})$ shapes taken directly from MC
    - validated in control regions: very good data/MC agreement
- Dedicated control regions (CRs) are set up to constrain the normalizations of major backgrounds
  - V+jets: use low BDT region (i.e., BDT<0.5)
  - ttbar: invert the cut on N(additional R=0.4 jets) (i.e, N_{aj}>=2)
    - only for 0L and 1L; ttbar contribution is negligible for 2L
  - CRs designed to have similar flavour composition as SRs
    - by applying the same cc-tagging requirement as the corresponding SR
- Normalization of the major backgrounds (V+jets and ttbar) are obtained via a simultaneous fit of SR and the CRs
  - effects of the mistag SFs of the cc-tagging discriminant will be taken into account
    - because the same cc-tagging requirement is applied in CRs and the SR
    - therefore, cc-tagging SFs only needed for VH(cc)/VZ(cc) (not needed for BKGs)



Full analysis validated in two data samples:

- ✓ *low $p_T(V)$*
- ✓ *low values of the cc-discriminant*

Systematics

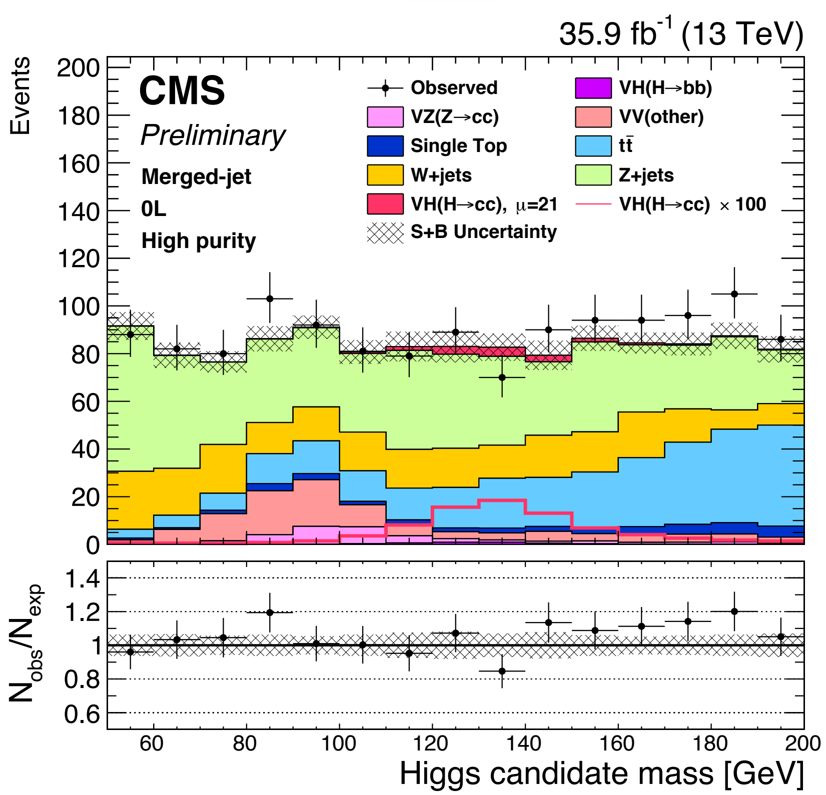
Source	Type	0-lepton	1-lepton	2-lepton
Size of simulated samples	shape	✓	✓	✓
Jet energy scale	shape	✓	✓	✓
Jet energy resolution	shape	✓	✓	✓
MET unclustered energy	shape	✓	✓	
c tagging efficiency	shape	✓	✓	✓
Lepton efficiency	shape (rate)		✓	✓
Pileup reweighting	shape	✓	✓	✓
top p_{T} reweighting	shape	✓	✓	✓
$p_{\mathrm{T}}(\mathrm{V})$reweighting	shape	✓	✓	✓
PDF	shape	✓	✓	✓
Renormalization and factorization scales	shape	✓	✓	✓
VH: $p_{\mathrm{T}}(\mathrm{V})$NLO EWK correction	shape	✓	✓	✓
Luminosity	rate	2.5%	2.5%	2.5%
MET trigger efficiency	rate	2%		
Single top cross section	rate	15%	15%	15%
Diboson cross section	rate	10%	10%	10%
VH: cross section (PDF)	rate	✓	✓	✓
VH: cross section (scale)	rate	✓	✓	✓

- Dominant sources:
  - size of the MC simulation / data control samples, cc-tagging, simulation modeling

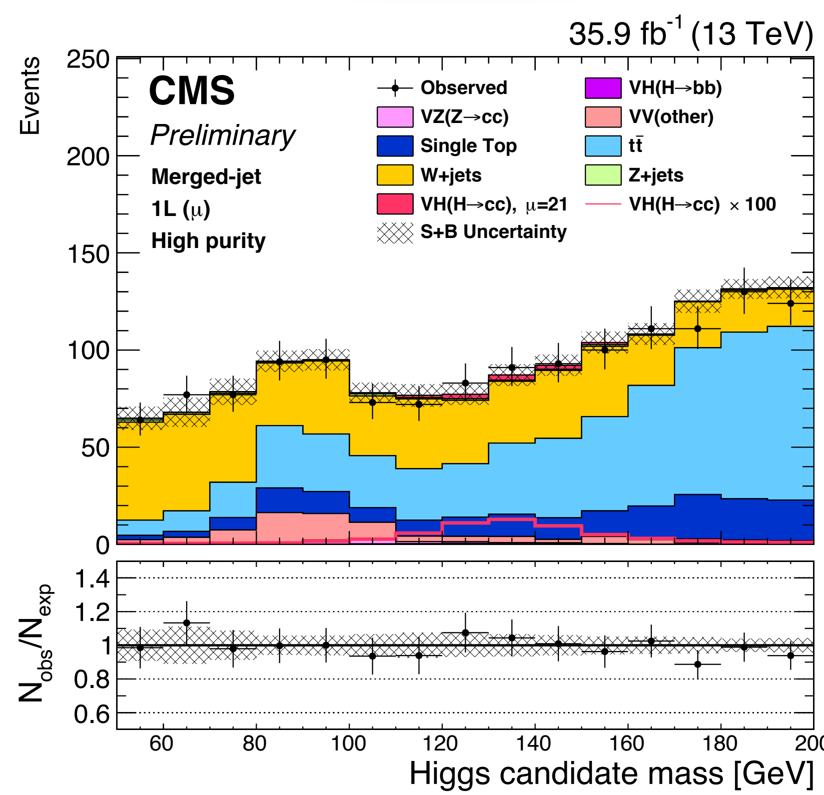
RESULTS: POST-FIT DISTRIBUTIONS

- Good agreement between the predicted background and the observed data

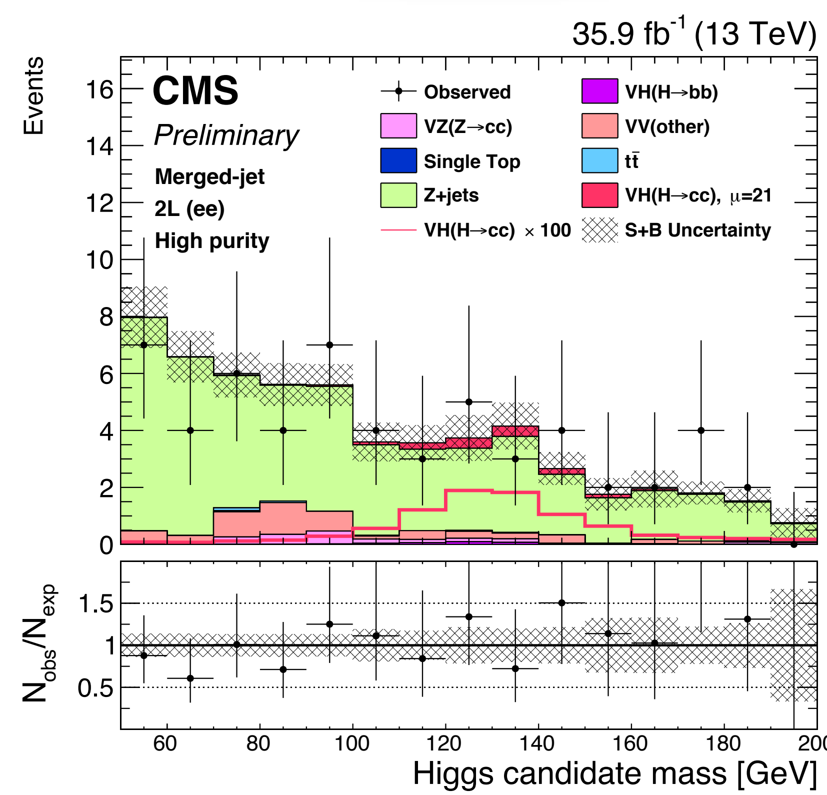
0L



1L (μ)



2L (ee)



VZ(cc) Validation

- The full procedure of this analysis is validated by measuring the VZ(cc) process
  - following exactly the same procedure, but extract the VZ(cc) signal strength instead of VH(cc)
  - VH(cc) fixed to the SM expectation
- Results:
  - best-fit signal strength: $\mu_{VZ(cc)} = 0.69 ^{+0.89}_{-0.75}$
    - consistent with SM expectation ($\mu_{VZ(cc)}$=1) within uncertainty
  - observed (expected) significance: 0.9 (1.3) σ

VH(cc) Results

- Upper limits on the signal strength $\mu_{VH(cc)}$ at 95% confidence level
  - $\mu_{VH(cc)} < 71$ obs. (49^{+24}_{-15} exp.)

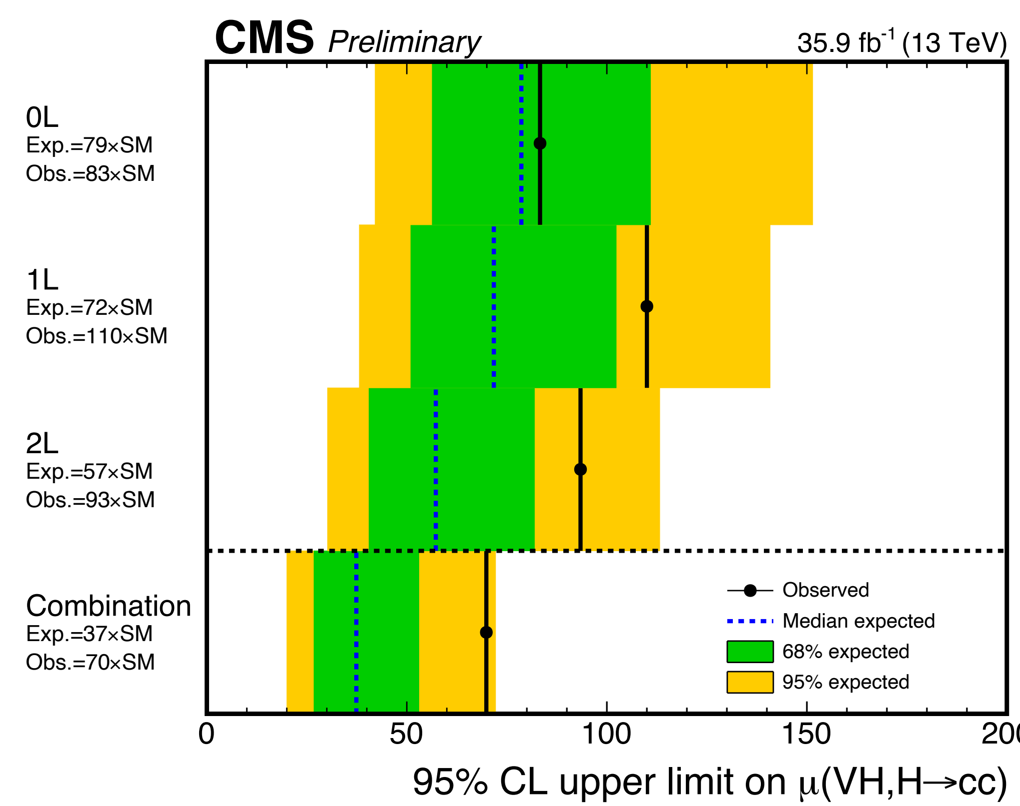
	Merged-jet (inclusive)			
	0L	1L	2L	All channels
Expected UL	81^{+39}_{-24}	88^{+43}_{-27}	90^{+48}_{-29}	49^{+24}_{-15}
Observed UL	74	120	76	71

- Best-fit signal strength: $\mu_{VH(cc)} = 21^{+26}_{-24}$

- Results are combined with resolved-jet analysis
  - to remove overlap, requires:
    - $p_T(V) < 300$ GeV for the resolved-jet topology
    - $p_T(V) >= 300$ GeV for the merged-jet topology
      - "inclusive" merged-jet analysis requires $p_T(V) > 200$ GeV

Upper limits at 95% confidence level

	resolved-jet ($p_T(V) < 300\,\mathrm{GeV}$)	merged-jet ($p_T(V) \geq 300\,\mathrm{GeV}$)	combination
expected	45^{+18}_{-13}	73^{+34}_{-22}	37^{+16}_{-11}
observed	86	75	70



Summary

- A search for the Higgs boson decaying to charm quarks using large-radius jets with the CMS experiment is presented
  - a novel approach
    - reconstructs both quarks from the Higgs decay with a single large-R jet
    - utilizes an advanced ML-based algorithm to identify H→cc decays
  - very competitive results
    - an observed (expected) upper limit on the VH production cross section times the H→cc branching ratio of 71 (49) times the SM expectation
- Still, a long way ahead
  - so far we have explored only ~25% of the collected Run 2 data, and less than ~1% of the full expected dataset of the (HL-)LHC
  - needs breakthroughs in many areas:
    - better charm quark (pair) identification algorithm
    - more advanced signal extraction / background estimation methods
    - reduced systematics with improved event generators / simulation tools
    - upgrades of the detector (tracking / timing / etc.)
- The charming journey has just started!

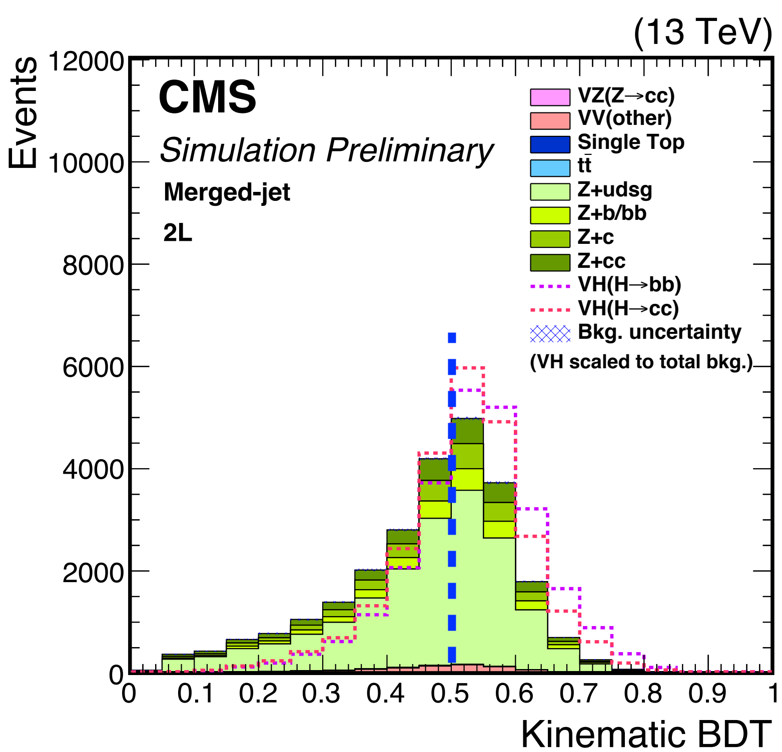
BACKUPS

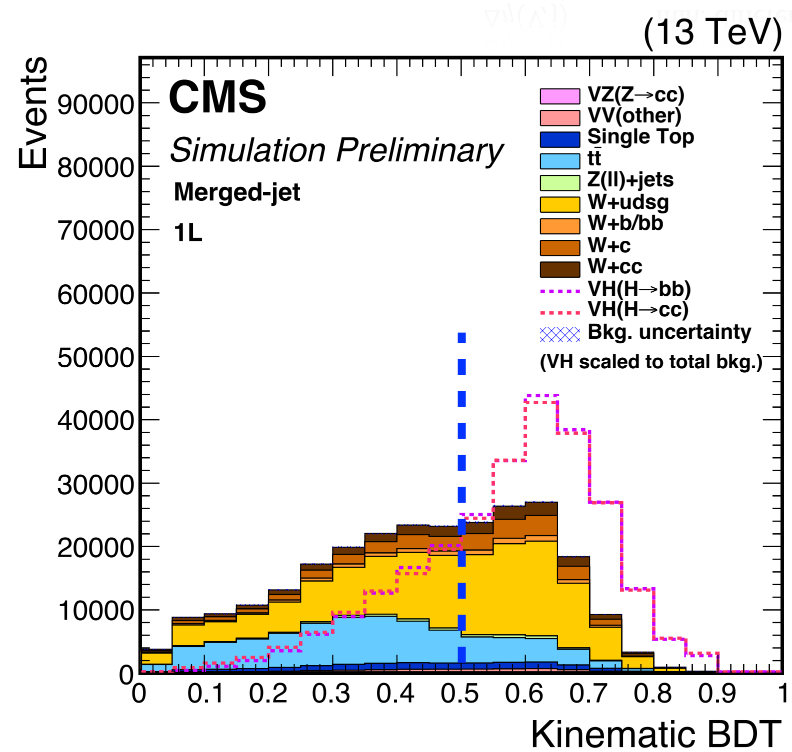
Kinematic BDT

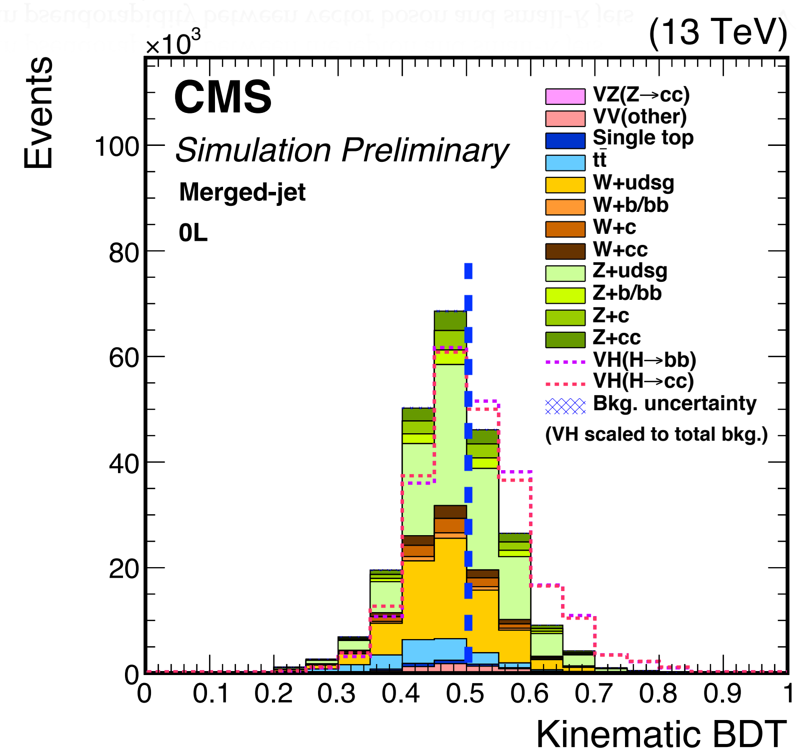
- Kinematic BDT developed to separate VH signals from major backgrounds (V+jets, ttbar)
  - using only event kinematics, NOT the intrinsic properties (e.g., flavor/mass) of H_{cand}
  - the resulting BDT is largely uncorrelated with mass and the cc-tagging discriminant of H_{cand}
- Two regions are defined based on the BDT
  - search region (SR): high BDT (>=0.5)
  - control region (CR): low BDT (<0.5)

BDT Inputs

Variable	Description	0L	1L	2L
$p_T(V)$	vector boson transverse momentum	✓	✓	✓
$p_T(H_{cand})$	H_{cand} transverse momentum	✓	✓	✓
$\|\eta(H_{cand})\|$	absolute value of the H_{cand} pseudorapidity	✓		
$\Delta\phi(V, H_{cand})$	azimuthal angle between vector boson and H_{cand}	✓	✓	✓
p_T^{miss}	missing transverse momentum		✓	
$\Delta\eta(H_{cand}, \ell)$	difference in pseudorapidity between H_{cand} and the lepton		✓	
$\Delta\eta(H_{cand}, V)$	difference in pseudorapidity between H_{cand} and vector boson			✓
$\Delta\eta(H_{cand}, j)$	min. difference in pseudorapidity between H_{cand} and small-R jets	✓	✓	✓
$\Delta\eta(\ell, j)$	min. difference in pseudorapidity between the lepton and small-R jets		✓	
$\Delta\eta(V, j)$	min. difference in pseudorapidity between vector boson and small-R jets			✓
$\Delta\phi(\vec{p}_T^{miss}, j)$	azimuthal angle between $\vec{p}_T^{miss}$ and closest small-R jet	✓		
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	azimuthal angle between $\vec{p}_T^{miss}$ and lepton		✓	
m_T	transverse mass of lepton $\vec{p}_T + \vec{p}_T^{miss}$		✓	
N_{aj}	number of small-R jets	✓	✓	✓







Signal scaled to total BKG

Calibration of cc-tagging Discriminant

- cc-tagging discriminant calibrated via proxy jets
  - impossible to isolate a pure Z/H→cc sample…
  - instead, uses proxy jets (gluon→cc) that share similar characteristics as signal jets
  - corrections are then transferred to signal jets
- Proxy jets obtained from a di-jet sample
  - requires the presence of at least one secondary vertex in each subjet
    - similar cc-tagging discriminant shapes between proxy and signal jets after this selection
    - further enhances g→bb/cc fraction
- Template fit method used to extract the data/MC scale factors (SFs)
  - define 3 MC templates: bb(+b), cc(+c) and udsg
  - fit variable: the CSVv2 b-tagging discriminant
- SFs typically between 0.9 to 1.4, with 10 - 30% uncertainty
  - also validated in γ+jets sample: consistent results
- SFs applied only on VH(cc) signal and VZ(cc)
  - and bb-mistag SF applied on VH(bb) and VZ(bb)
  - systematics uncertainties propagated
  - not applied on BKG (estimation is data-driven)

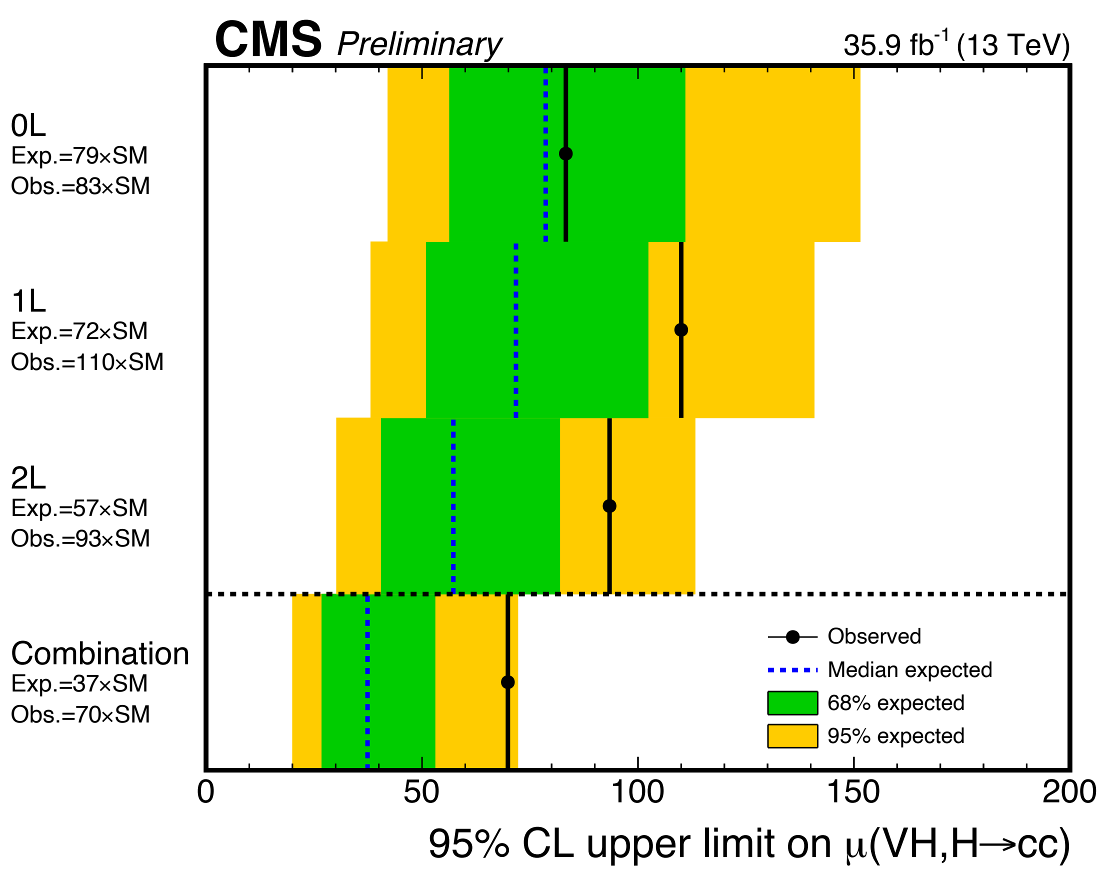
RESULTS (RESOLVED & MERGED)

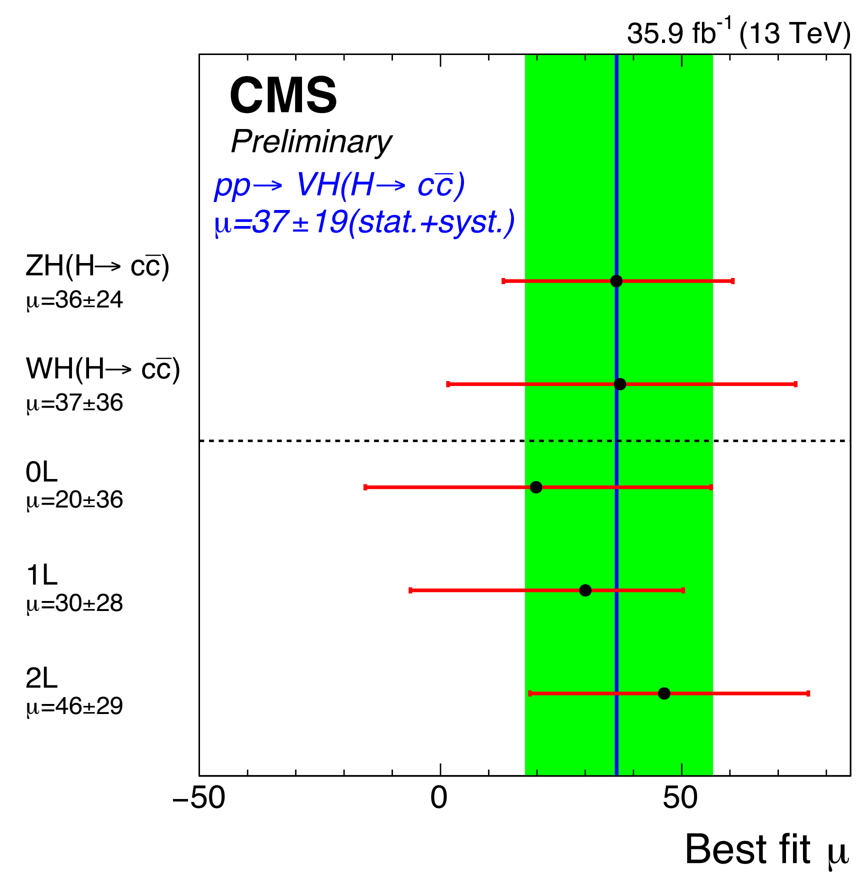
- Resolved & Merged: Inclusive

	Resolved-jet (inclusive)				Merged-jet (inclusive)			
	0L	1L	2L	All channels	0L	1L	2L	All channels
expected UL	84	79	59	38	81	88	90	49
observed UL	66	120	116	75	74	120	76	71

- Resolved & Merged: Exclusive & Combination

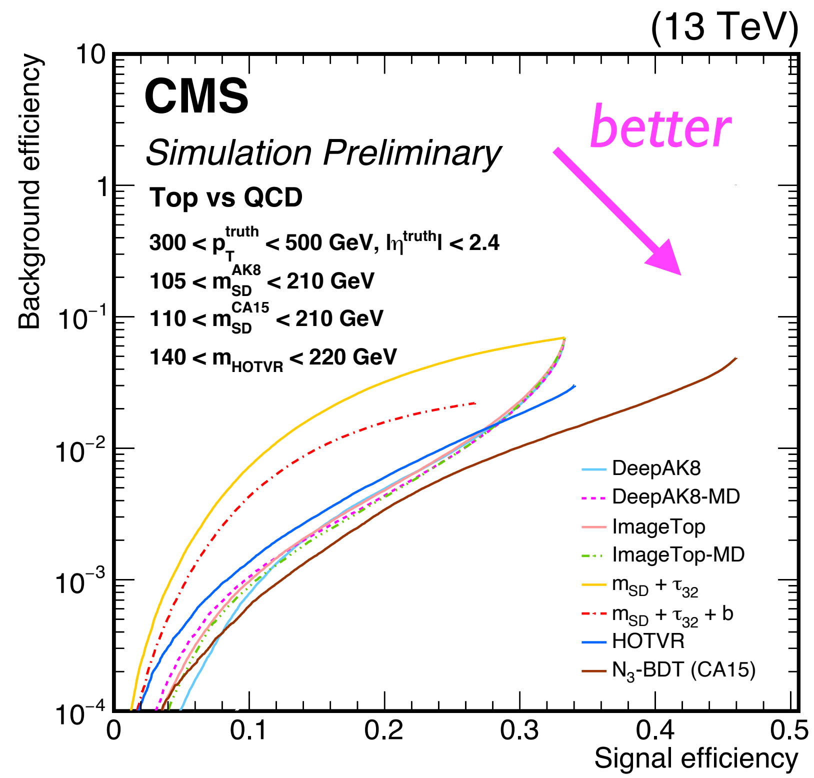
95% CL exclusion limit						
	resolved-jet ($p_{\mathrm{T}}(\mathrm{V}) < 300\,\mathrm{GeV}$)	merged-jet ($p_{\mathrm{T}}(\mathrm{V}) \geq 300\,\mathrm{GeV}$)	combination 0L	1L	2L	All channels
expected	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	37^{+16}_{-11}
observed	86	75	83	110	93	70

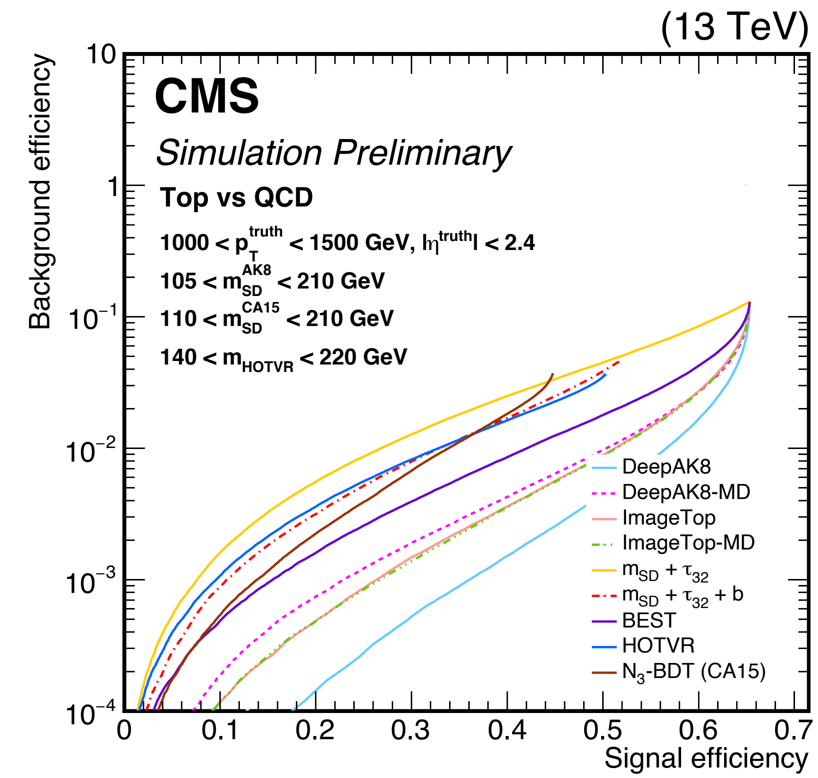




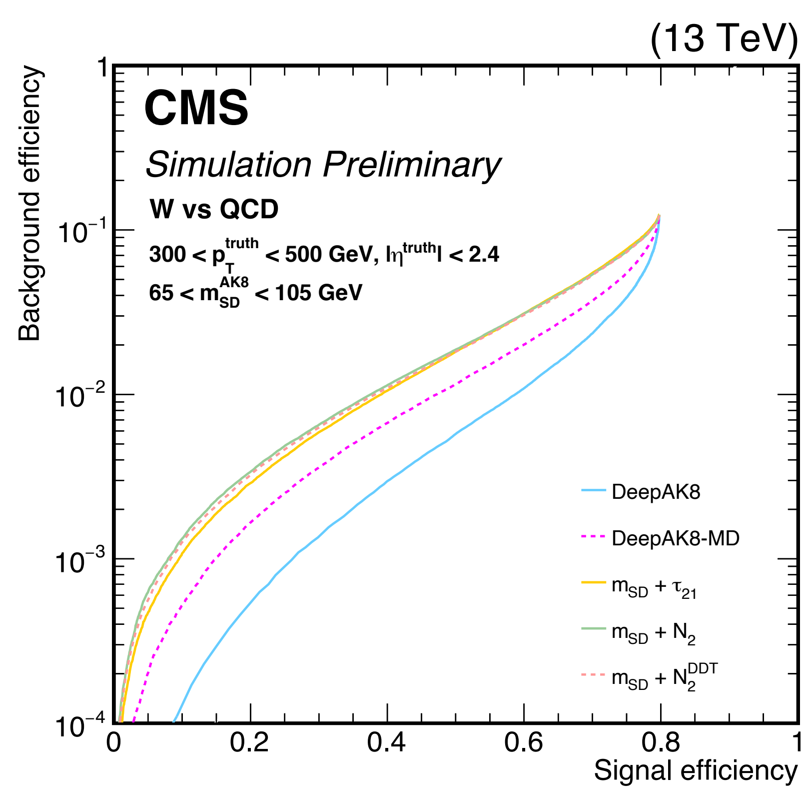
DeepAK8

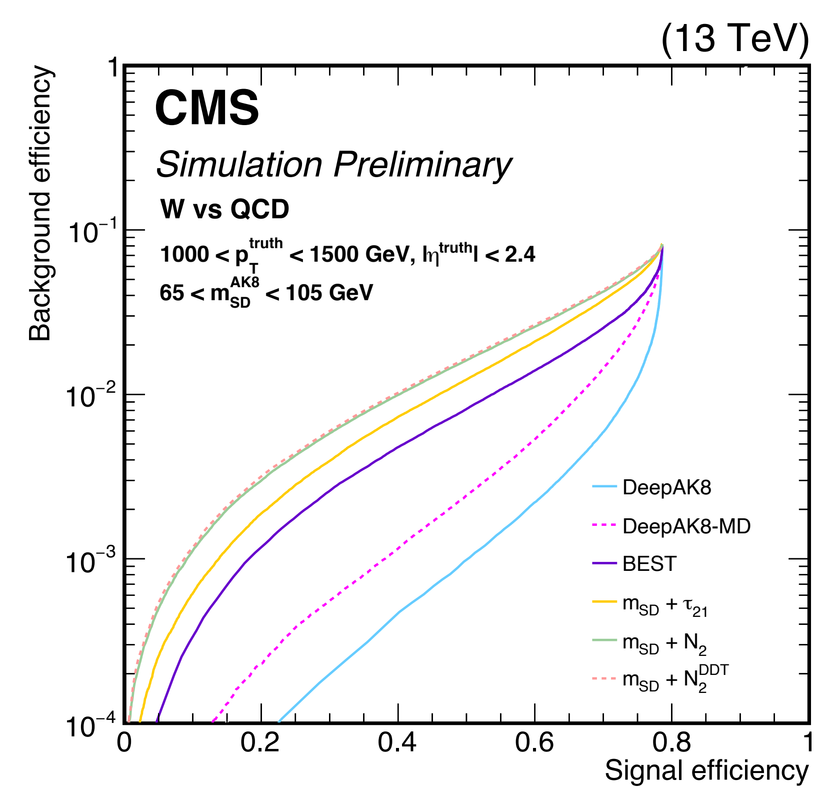
top vs QCD





W vs QCD





CMS-PAS-JME-18-002

Ablation Study of DeepAK8

- DeepAK8 shows substantial gain compared to traditional approaches [CMS-PAS-JME-18-002]
- To understand the main sources of the improvement, alternative versions of DeepAK8 were trained using a subset of the input features
  - Particle (kinematics): only kinematic info of PF candidates
    - four momenta, distances to the jet and subjet axes, etc.
  - Particle (w/o Flavour): adding experimental info
    - charge, particle identification, track quality, etc.
  - Particle Full + SV (the full DeepAK8): adding features related to heavy-flavour tagging
    - track displacement, track-vertex association, SV features, etc.