Search for VH→cc in CMS

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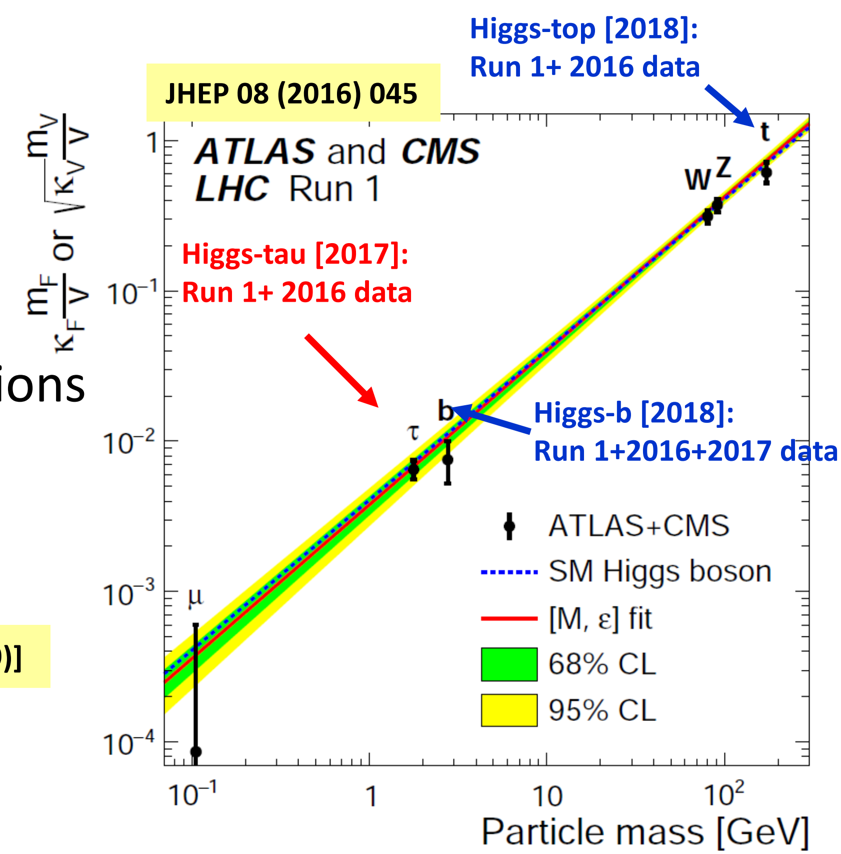
on behalf of the CMS collaboration

Introduction

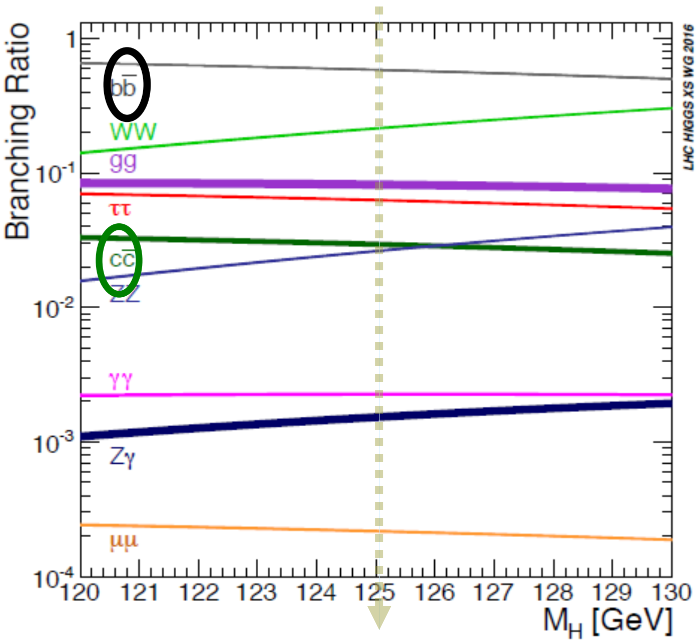
- LHC Run 1: Discovery of a Higgs boson with a measured mass:
  - $m_H = 125.09 \pm 0.24$ GeV (~0.2%)
- Then: measure the Higgs particle properties & interactions
  - Inclusive production rates & interactions with vector bosons (W,Z, γ)
    - Already established in Run 1
  - Interactions with fermions
    - Recently established couplings to 3rd-generation fermions
- Next milestone: couplings to 2nd-gen fermions
  - **H→μμ:** BR in SM ~2.2 x 10^{-4}; Upper limit (UL) on $\mu = \sigma/\sigma_{SM}$
    - CMS: μ < 2.9 (2.2) obs. (exp.) [Run1+2016] **[HIG-17-019, PRL 122,021801 (2019)]**
    - ATLAS: μ< 1.7 (1.3) obs (exp) Full Run2 **[ATLAS-CONF-19-028]**
  - **H→cc** — **This talk**



H→cc at the LHC

- Motivation: Establish Higgs couplings to up-type, 2nd-generation quarks
  - Higgs-charm coupling can be significantly modified by the presence of BSM
- H→cc: very challenging to hunt at the LHC
  - small BR: 2.9×10^{-2}
  - Very large backgrounds
    - H→bb is background in this search
  - **c-tagging** more challenging than b-tagging

Need novel tools and techniques to probe H→cc at the (HL-) LHC

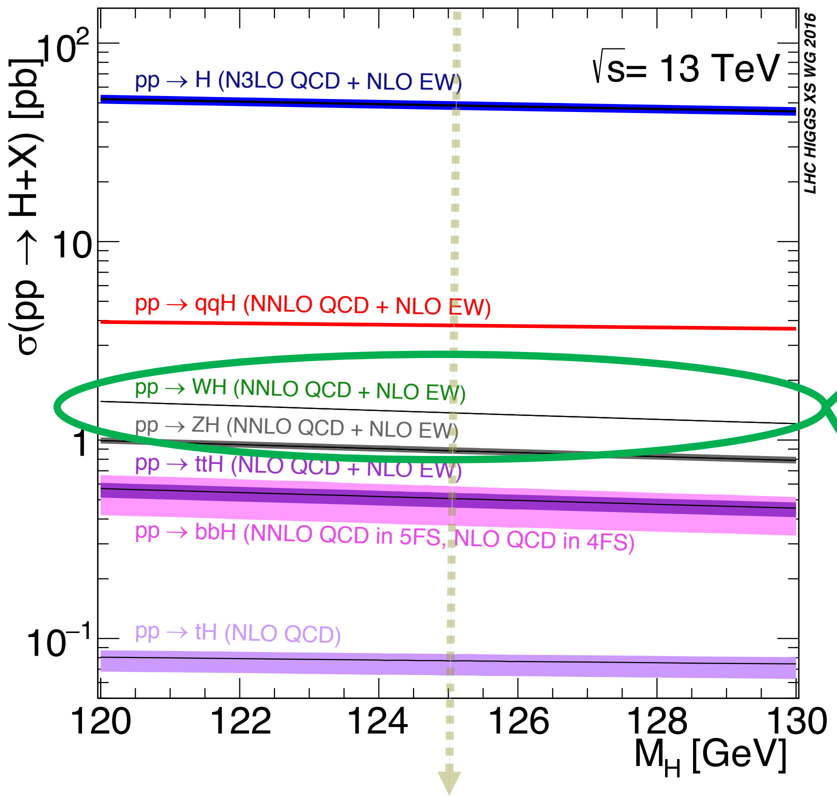


LHC Run 1: m_H=125.09 +/- 0.24 GeV

- Approaches explored so far:
  - **Direct H→cc search**: PRL 120 (2018) 211802
    - ATLAS in Z(→LL)H channel [2016]
      UL on $\mu = \sigma \times BR / \sigma^{SM} \times BR^{SM}$ < 110 (150) Obs (Exp)
  - **Exclusive decay modes** with charmonium, H→J/ψγ
    - ATLAS: 120 (100) x BR obs (exp) ; CMS: 220 (160) x BR obs (exp)

    CMS: EPJ C79 (2019) 94
    ATLAS: PLB 786 (2018) 134
  - **Indirect bounds:** $\kappa_c = y_c/y_c^{SM}$ from global fit to existing data: κ_c<6.2 PRD92(2015)
    results also from CMS HIG-17-028, PLB 792 (2019)

First direct H→cc search in CMS



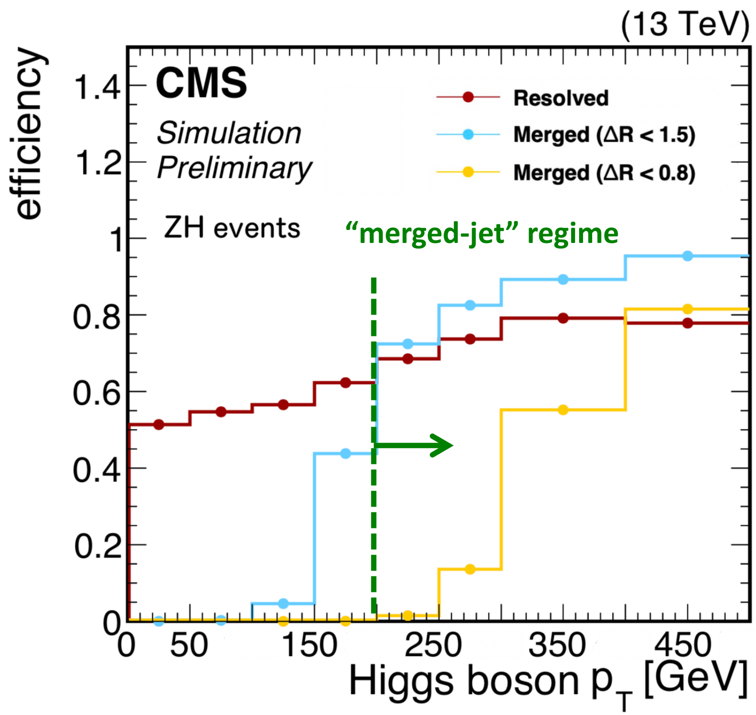
LHC Run 1: m_H=125.09 +/- 0.24 GeV

SM H→cc	Yields @ $36fb^{-1}$
ggH	~52K
VBF	~4K
VH	~2.4K

Target the VH production mode

- VH production: very clear signature
  - Vector boson recoiling against Higgs boson
  - Main BKG: V+jets and ttbar
    - QCD significantly suppressed
  - Very little activity in the event
- Higgs kinematics:
  - Improved signal purity in higher-p_T
  - Signal acceptance falls rapidly
    - ~5% of σ_{VH} for $p_T(V)$>200 GeV

General search strategy



- Events categorized based on the leptonic decays of V boson:

Channel	Resolved-jet	Merged-jet
Z(→νν)H: 0L	$p_T(Z) > 170$ GeV	$p_T(V) > 200$ GeV
W(→Lν)H: 1L	$p_T(W) > 150$ GeV	
Z(→LL)H: 2L	$p_T(Z) > 50$ GeV	

* L = e,μ

"Resolved-jet topology"

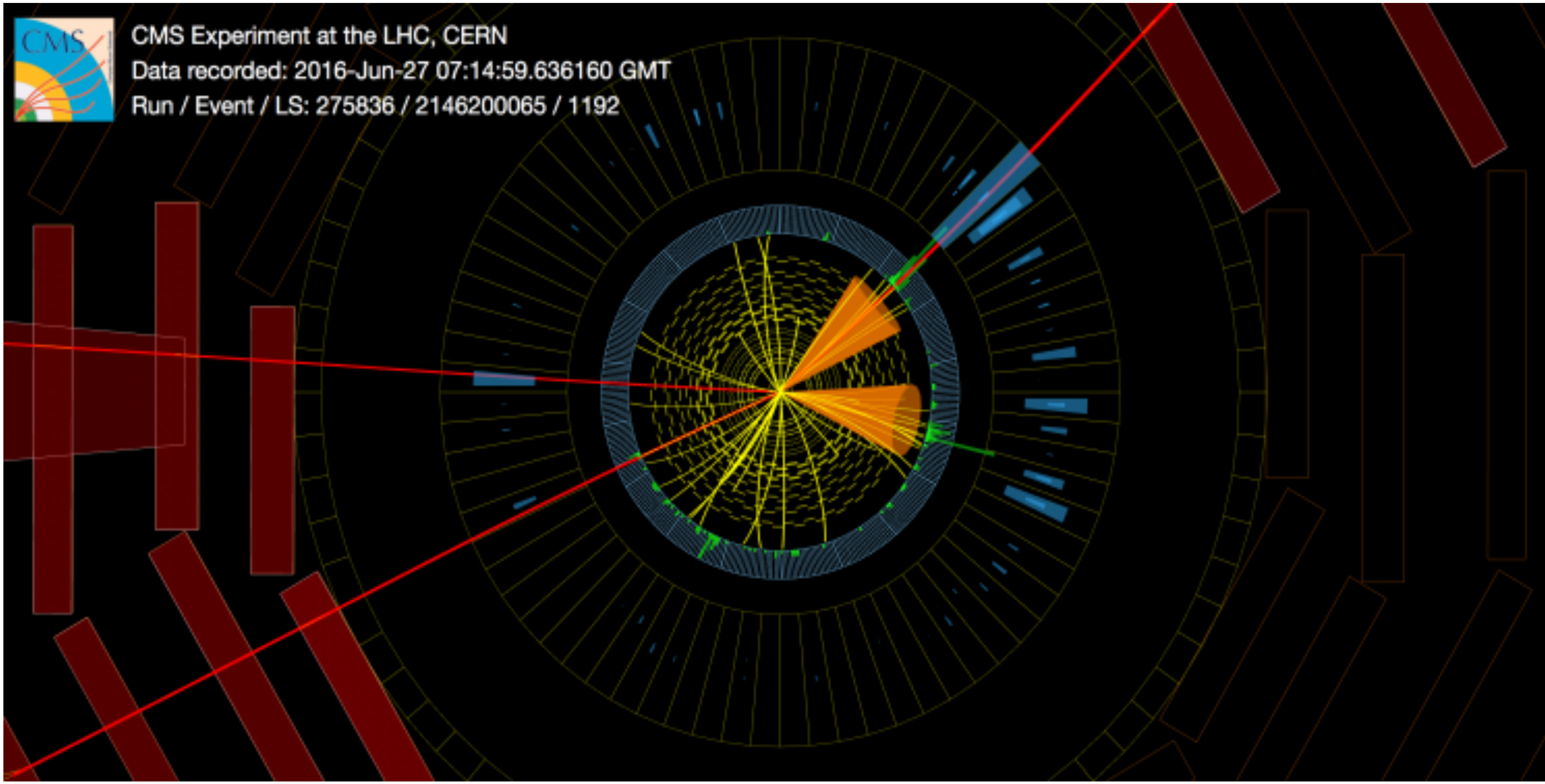
- Higgs decay products resolved in two AK4 (R=0.4) jets (di-jet)
- Probe larger fraction of the available signal cross-section

"Merged-jet topology"

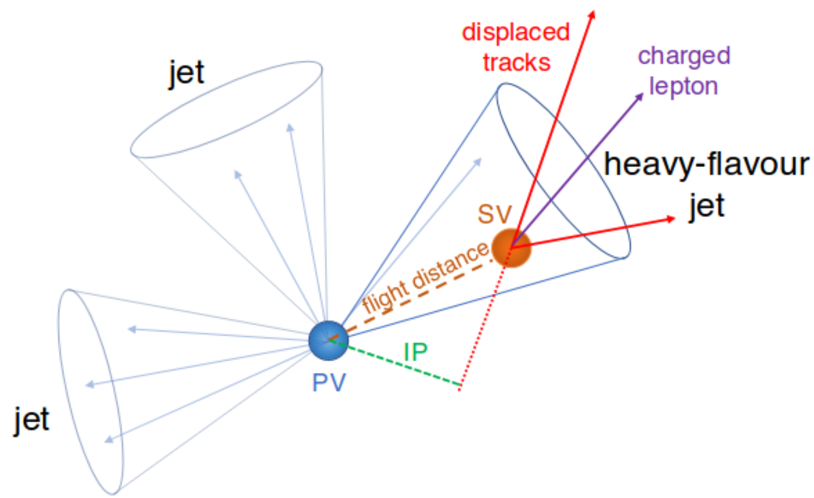
- A single AK15 (R=1.5) jet to reconstruct the H→cc decay
  - R=1.5: good balance between purity and acceptance
- Potentially allows to better exploit the correlation between the two charms

Final result: combination of the two topologies based on $p_T(V)$

H⟶cc candidate



The challenge:
Charm quark identification



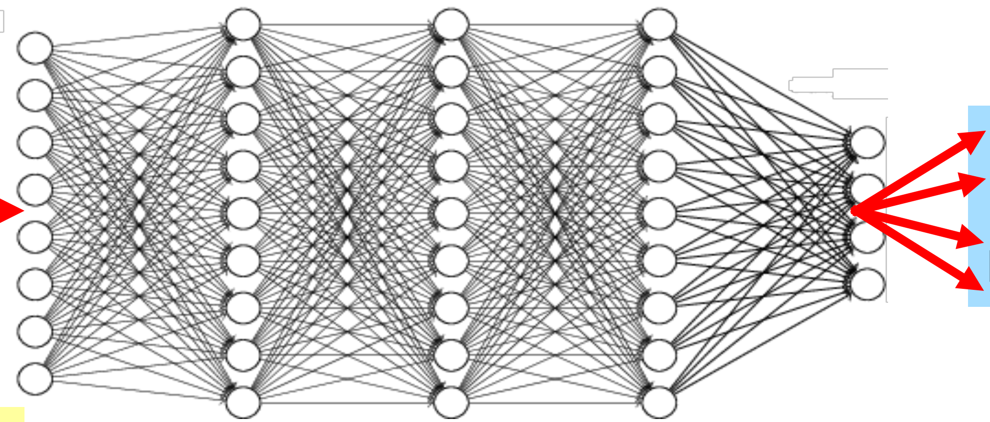
Charm tagging on "AK4" jets

- Challenging: charm has intermediate properties between light <u>and</u> b-jets
  - Exploit Deep Neural Networks (DNN) [5 hidden layers, 100 nodes]

Inputs

→ Use "human-made" (high-level) inputs

→ few more tacks (up to 6) wrt traditional approaches

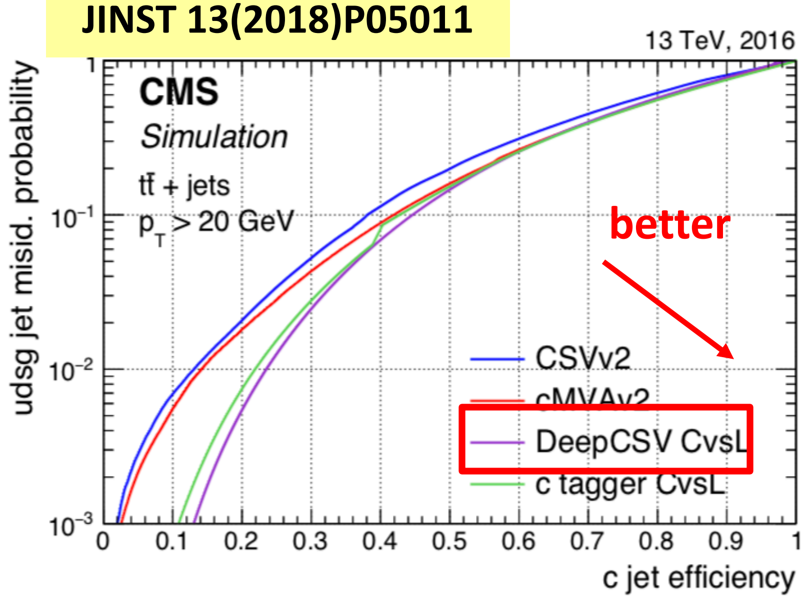


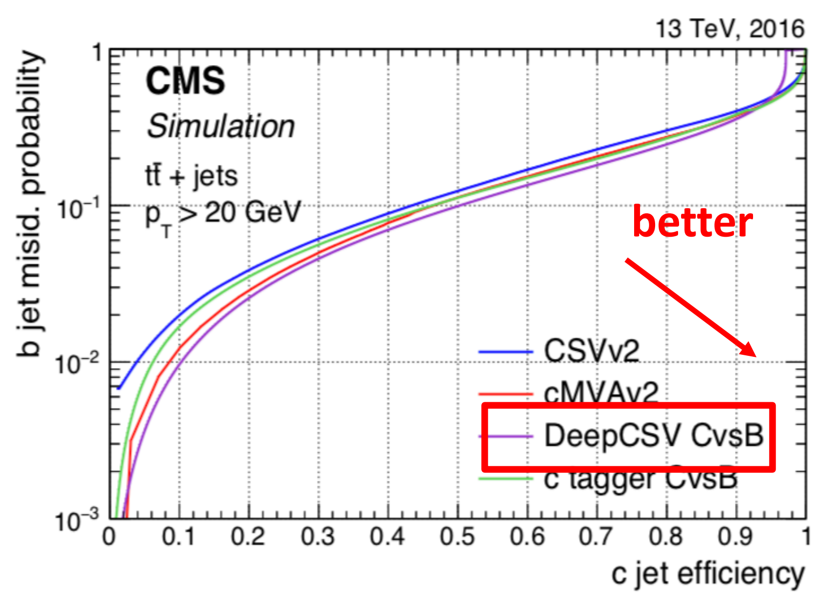
Output

Multiclass classifier

b, bb, c, light

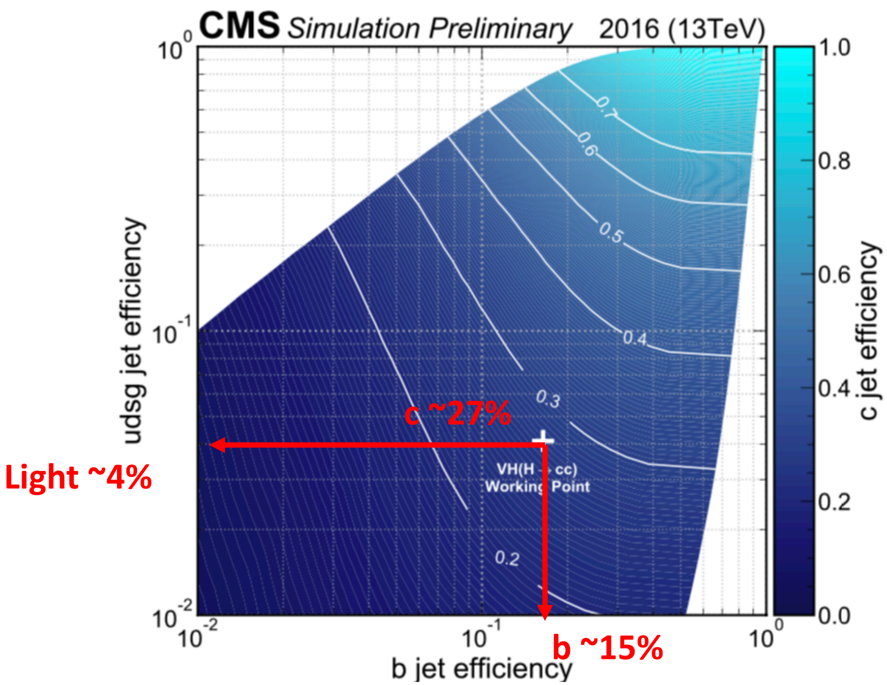
JINST 13(2018)P05011

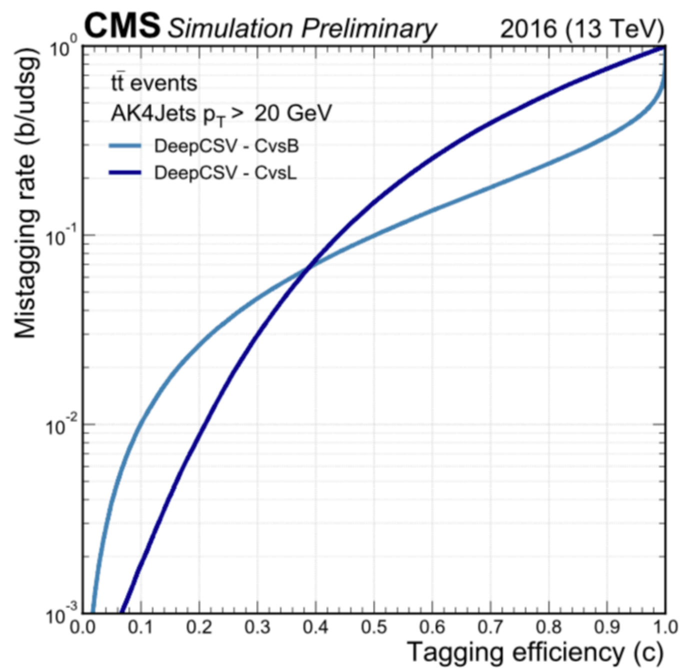




Charm tagging on "AK4" jets (II)

- Define two discriminants to separate c-jets from light and b-jets
  - **CvsL**: P(c) / [P(c) + P(light)]   and   **CvsB**: P(c) / [P(c) + P(b)]



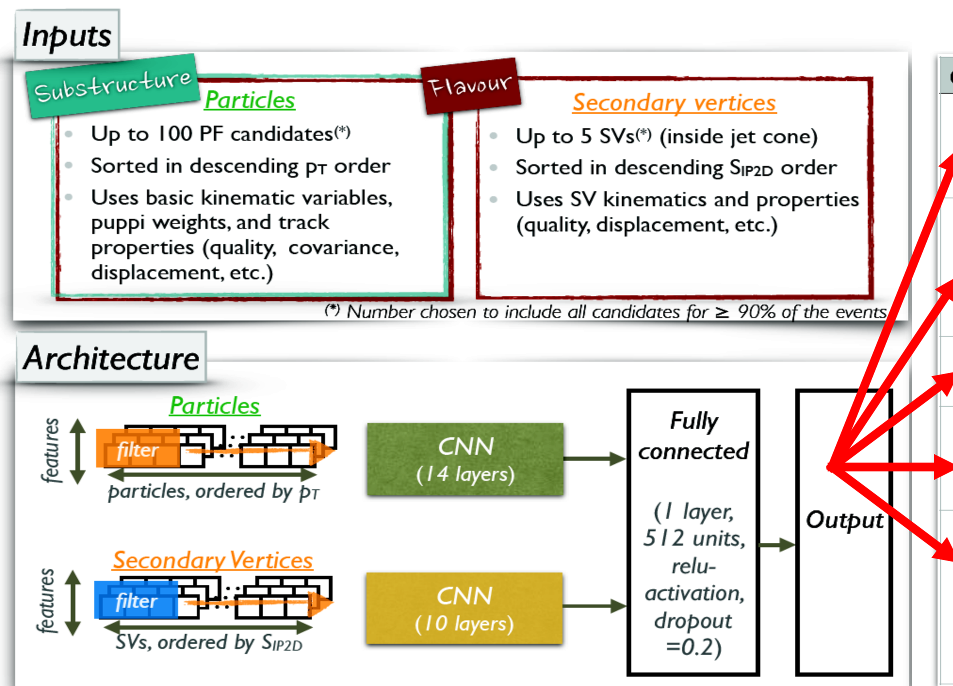


- Calibration in data:
  - c-tagger reshaping scale factors derived via simultaneous fit to the 2D plane (CvsL x CvsB) in three different data samples
    - Z→LL +jets (light-jet enriched), W + c (c-jet enriched), ttbar (b-jet enriched)

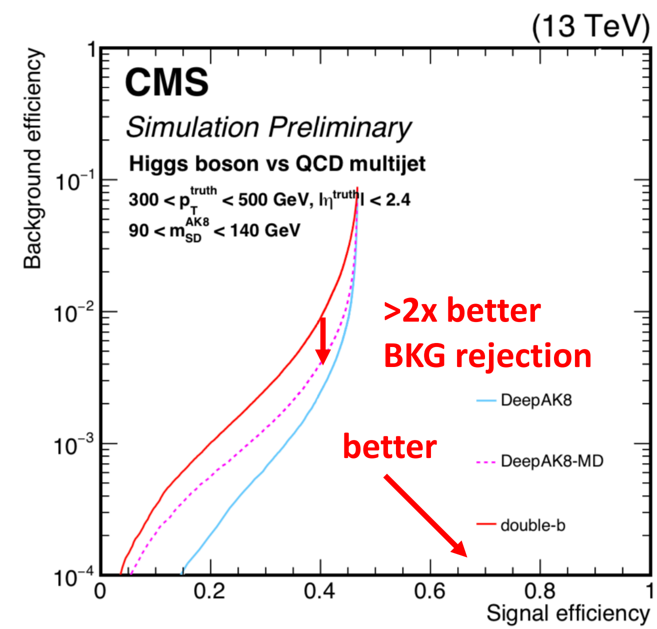
Double-Charm tagging on “AK15” jets

- Advanced boosted jet tagger “DeepAK8” adapted on AK15 jets
  - multi-class classifier for top, W, Z, Higgs, and QCD jets
    - subdivided based on decay modes (e.g. H→bb, H→cc, ..)
    - can be aggregated for flavour tagging (e.g., bb vs cc vs light)
  - Advanced DNN to directly process jet constituent (i.e. PF candidates & sec. vtx)
  - **Important:** Mass decorrelation techniques to mitigate mass sculpting

CMS-DPS-2017-049, NIPS 2017 paper, CMS-JME-18-002



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)



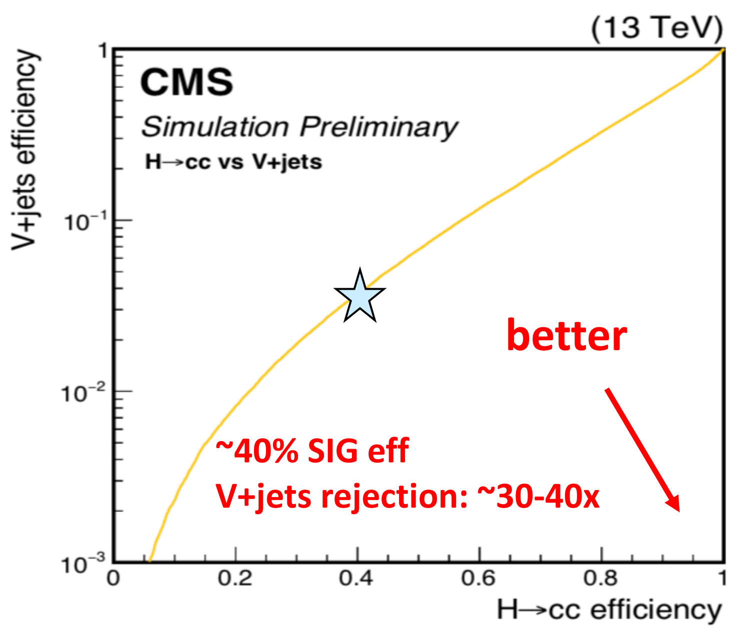
Significant gain in performance [even larger @ higher p_T]

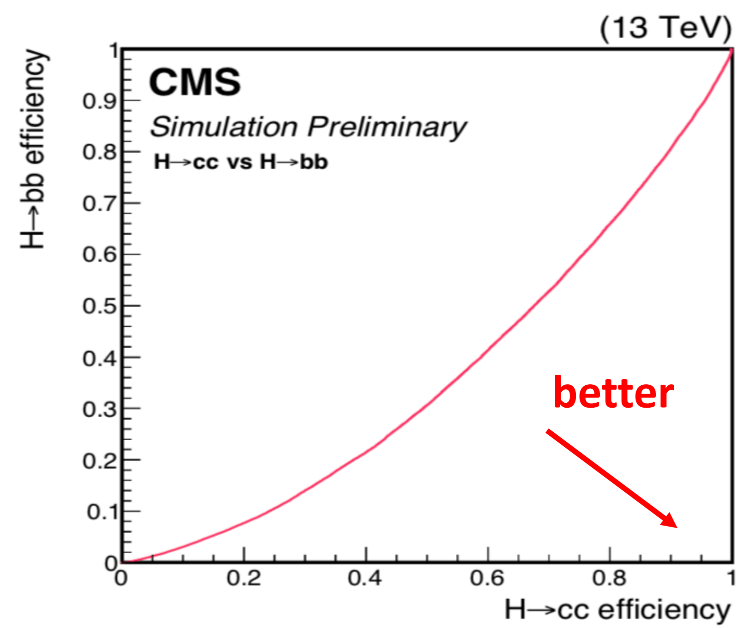
Double-Charm tagging on "AK15" jets (II)

- cc – tagging discriminant defined as:

$$\boxed{\frac{\mathrm{score}(Z \to c\bar{c}) + \mathrm{score}(H \to c\bar{c})}{\mathrm{score}(Z \to c\bar{c}) + \mathrm{score}(H \to c\bar{c}) + \mathrm{score}(\mathrm{QCD})}}$$

- Performance in MC:





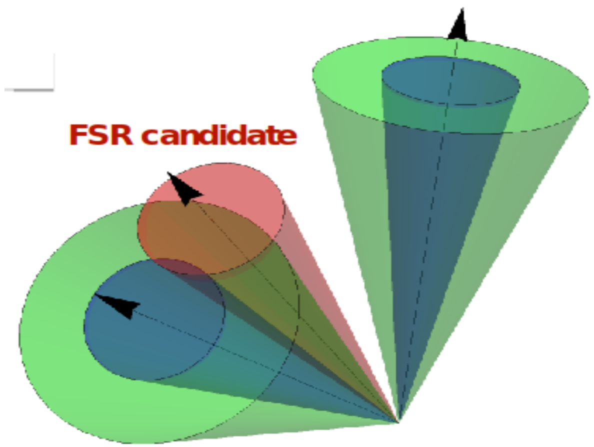
- Calibration in data:
  - Use of proxy jets from gluon→cc with similar characteristics to signal jets
  - Two data samples [QCD multijet and γ+jets]

Search strategy

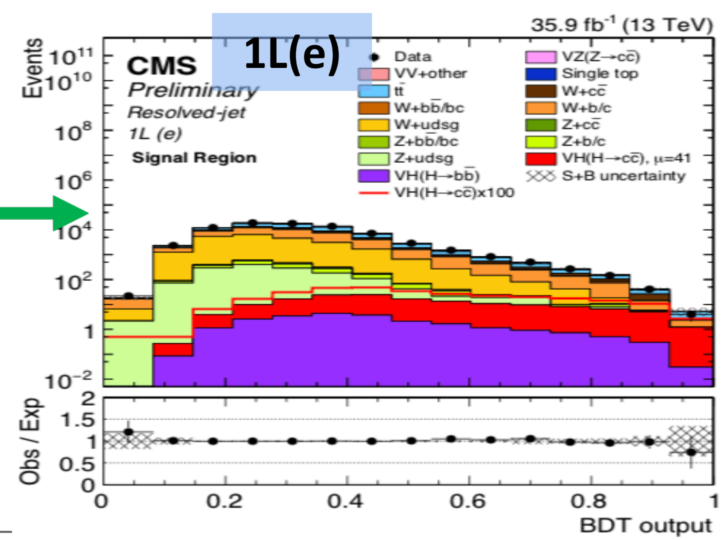
Resolved-jet: Search strategy

- Higgs candidate (H_{cand}): two highest "CvsL" AK4 jets
  - Further require: CvsL (max) >0.4 & CvsB (min)>0.2 for the leading jet
- FSR Recovery:
  - Improve mass resolution by recovering jets from final state radiation (FSR)

Up to ~5% improvement in mass resolution

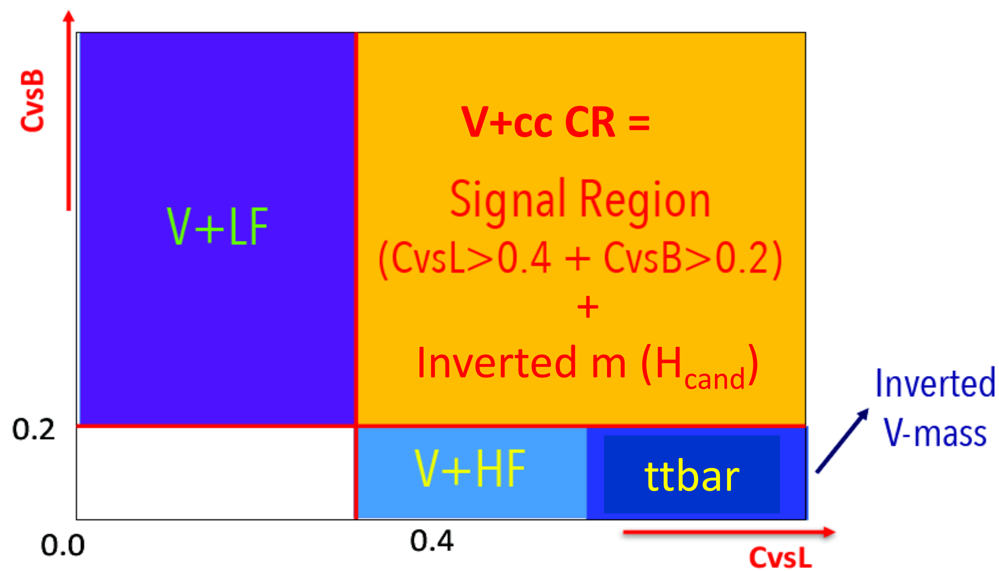


- **Event level separation:** Maximize sensitivity by developing BDTs to separate signal from background
  - **Inputs:** H_{cand} properties, V boson properties, c-tagging discriminants, event kinematics & object correlations
  - Use separate BDT for each channel
  - VH($\rightarrow$cc) signal extracted by fitting the BDT shapes



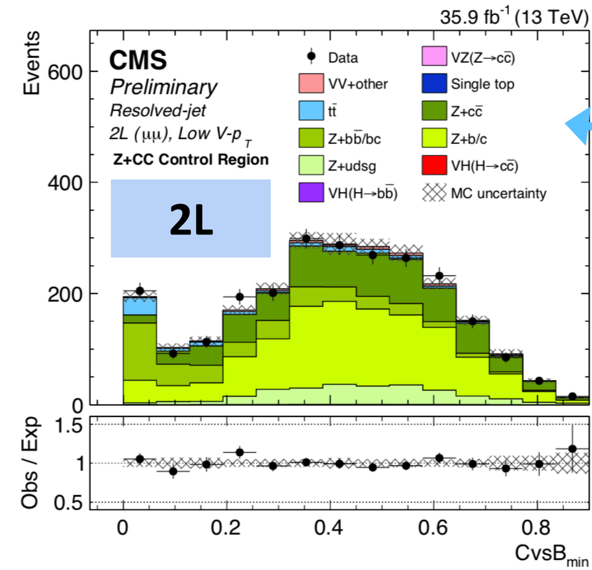
Resolved-jet: Background estimation

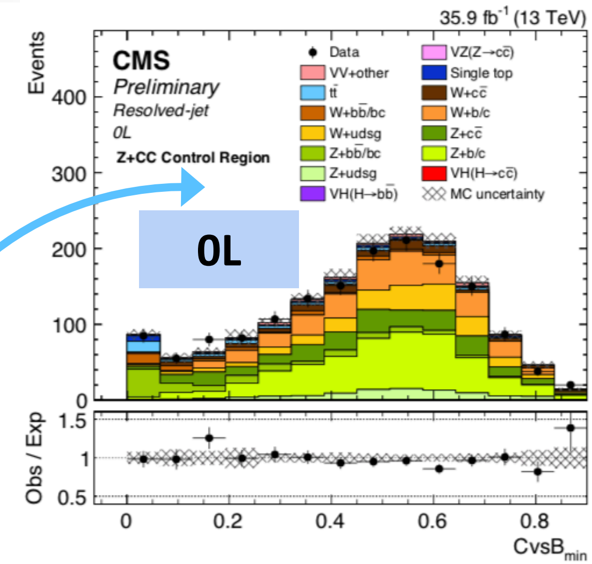
- Main backgrounds (i.e. V+jets and ttbar) are estimated from data control samples
  - V+jets: split based on flavour composition (V+cc, V+bb/bc, V+bl/cl, V+udsg)
- Control samples selected by inverting the CvsB and CvsL requirements

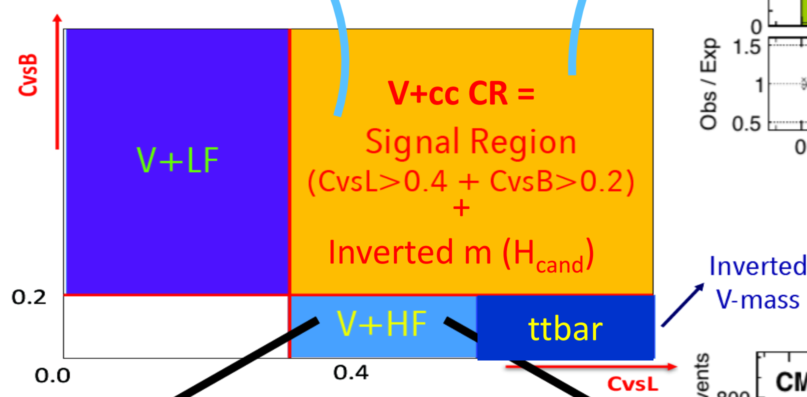


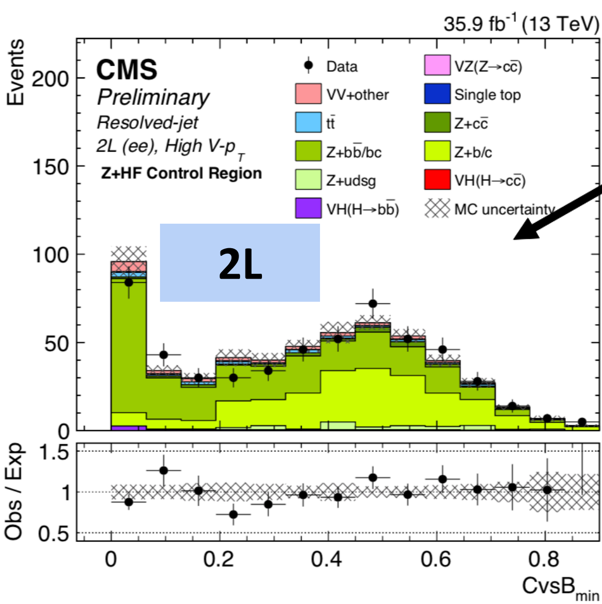
- Simultaneous fit to SRs and CRs
  - Fit c-tagging discriminant shape in CRs and BDT shapes in SR

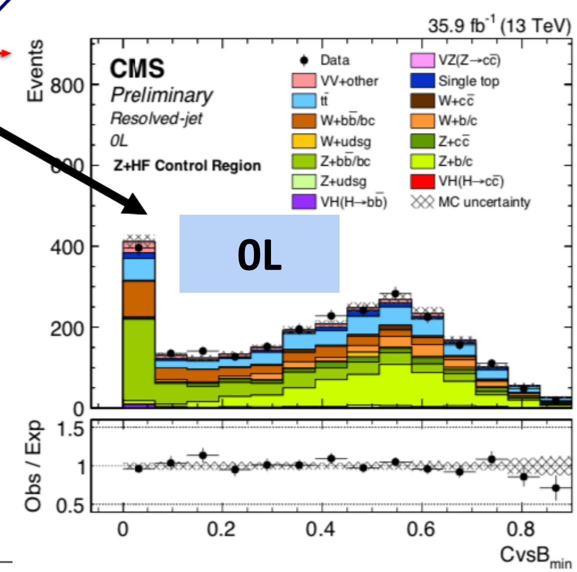
Resolved-jet: Background estimation (II)





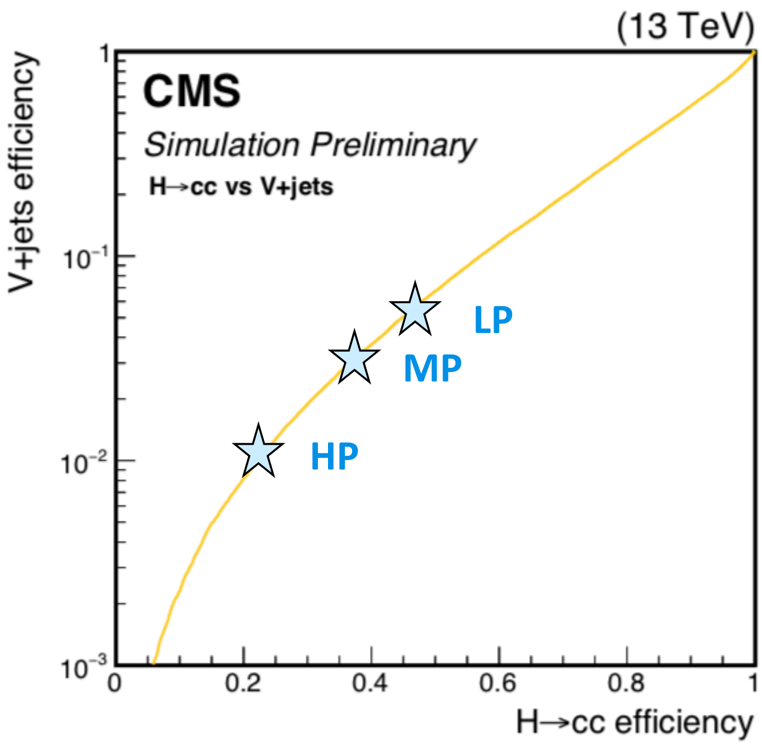






Merged-jet: Search strategy

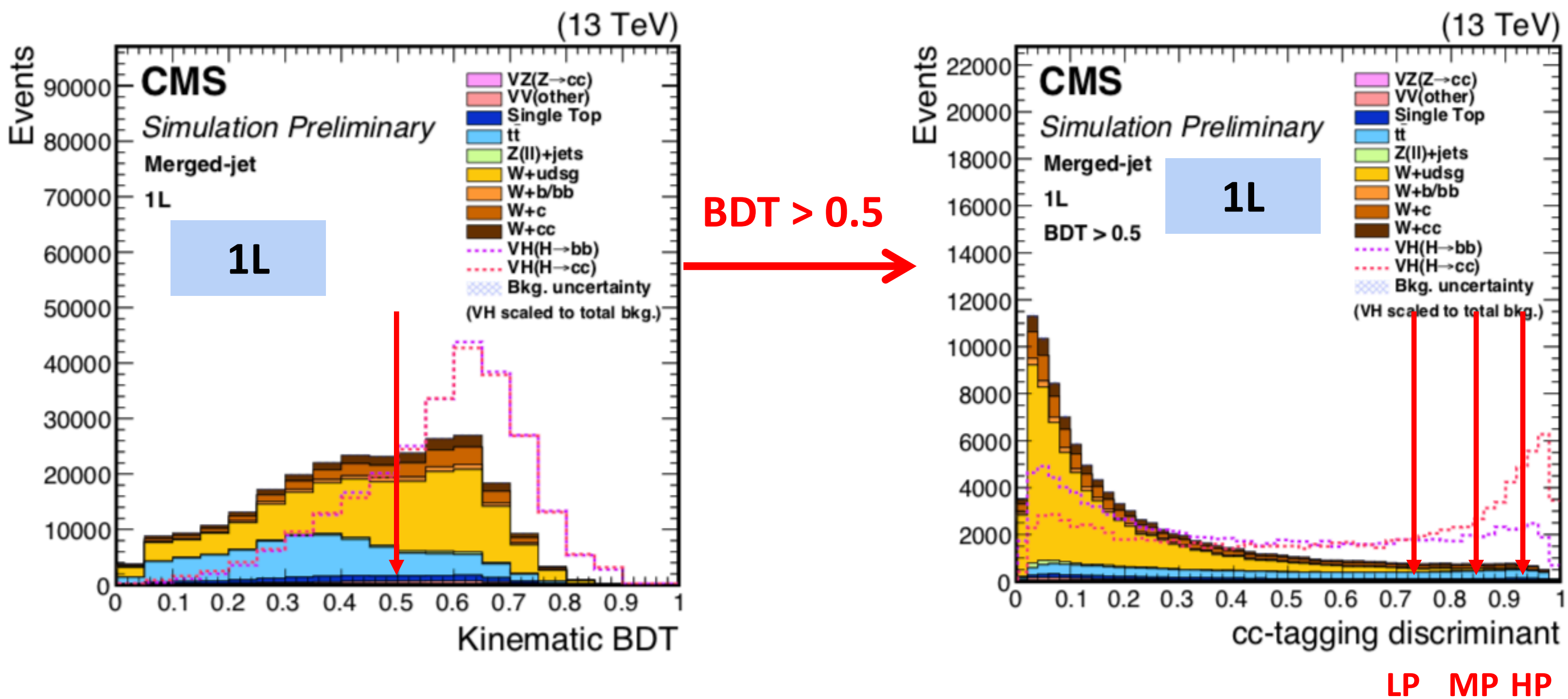
- H_{cand}: highest p_T AK15 jet [p_T>200 GeV, 50 < jet (mass) < 250 GeV]
  - Events categorized into three mutually exclusive categories based on the three WPs of the cc-discriminant
    - [High / Medium / Low purity (HP, MP, LP)]



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

Merged-jet: Search strategy (II)

- **Event-level separation:** BDT to suppress major backgrounds [i.e. V+jets, ttbar]
  - use only event kinematics, <u>NOT</u> the intrinsic properties (flavour/mass) of H_{cand}
  - Search region: BDT > 0.5 [same for all channels]

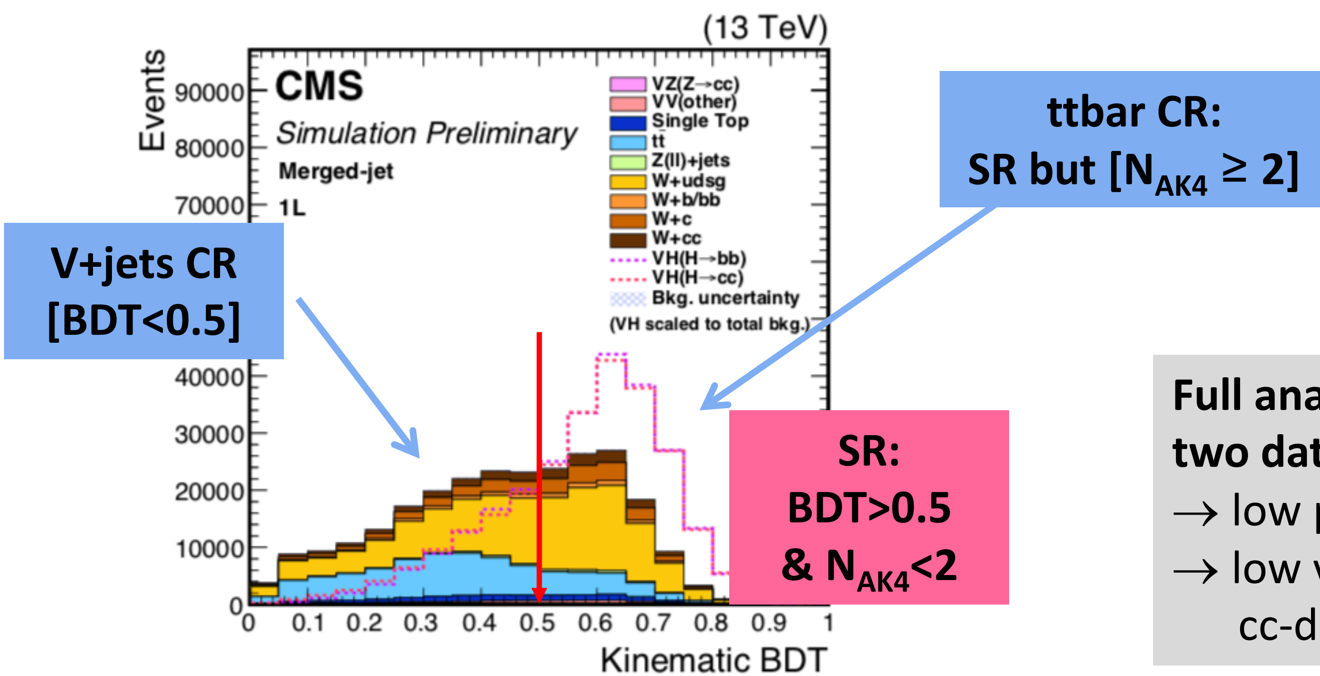


- BDT largely **uncorrelated** with <u>Higgs candidate mass</u> and <u>cc-discriminant</u>

m (H_{cand}) final fitted variable for signal extraction

Merged-jet: Background estimation

- Major backgrounds (i.e. V+jets and ttbar) estimated from data CRs
  - **V+jets CR:** low BDT score [i.e. BDT<0.5]
    - one overall normalization for V+jets (in each of the HP/MP/LP categories)
  - **ttbar CR:** As the SR but invert N_{AK4} (NB: N_{AK4}<2 requirement applied in SR)
- CRs are designed to have similar flavour composition as SRs
  - same cc-tagging requirement as the corresponding SR



Full analysis validated in two data samples:
→ low $p_T(V)$
→ low values of the cc-discriminant

- Simultaneous fit to SRs and CRs

Systematic uncertainties

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[1])		✓	✓
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 EW 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	✓	✓	✓

(*) Only affects VZ/VH processes (w/ Z/H→cc or Z/H→bb) in the merged-jet analysis

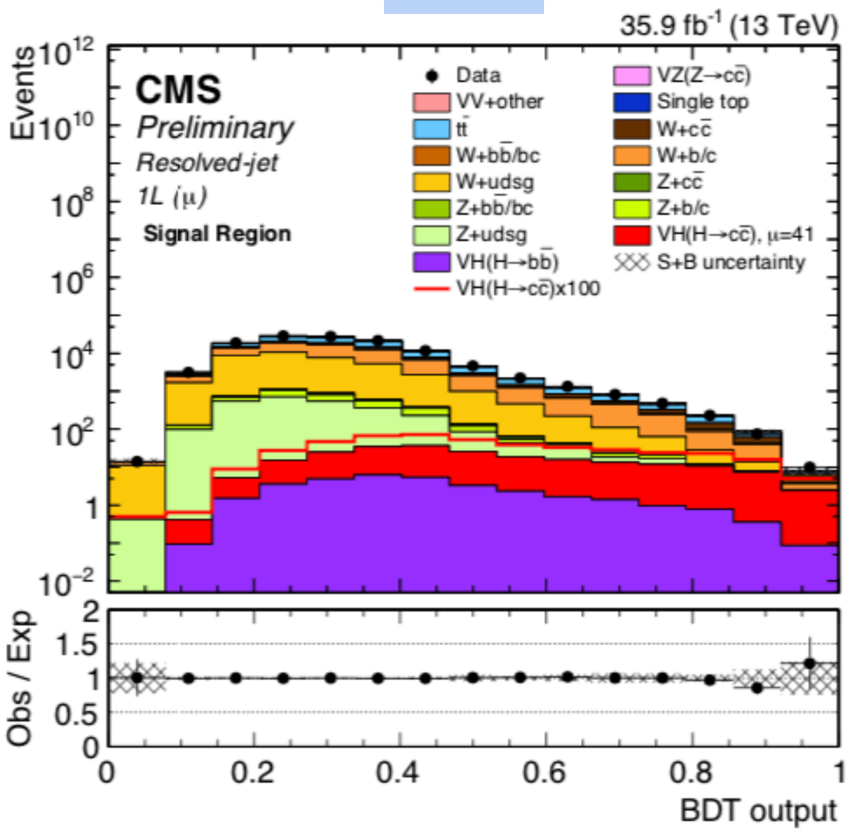
(1) Implemented as a rate uncertainty in the resolved-jet analysis

- Dominant sources:
  - statistical uncertainty of data control samples, c/cc-tagging, MC stats

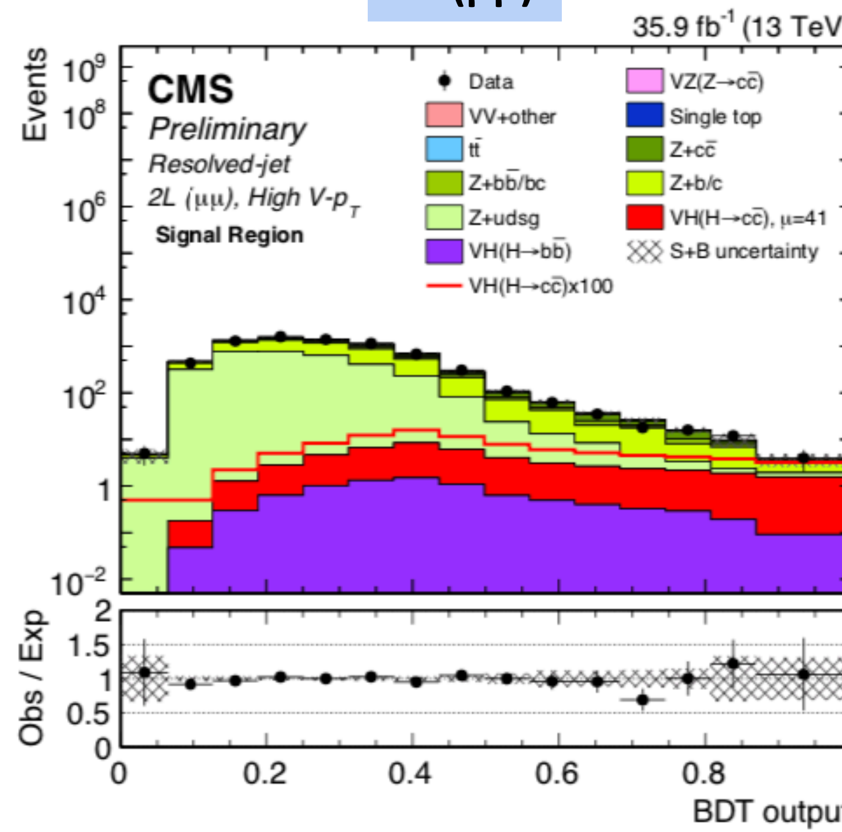
Results

Post-fit distributions: resolved-jet

1L (μ)

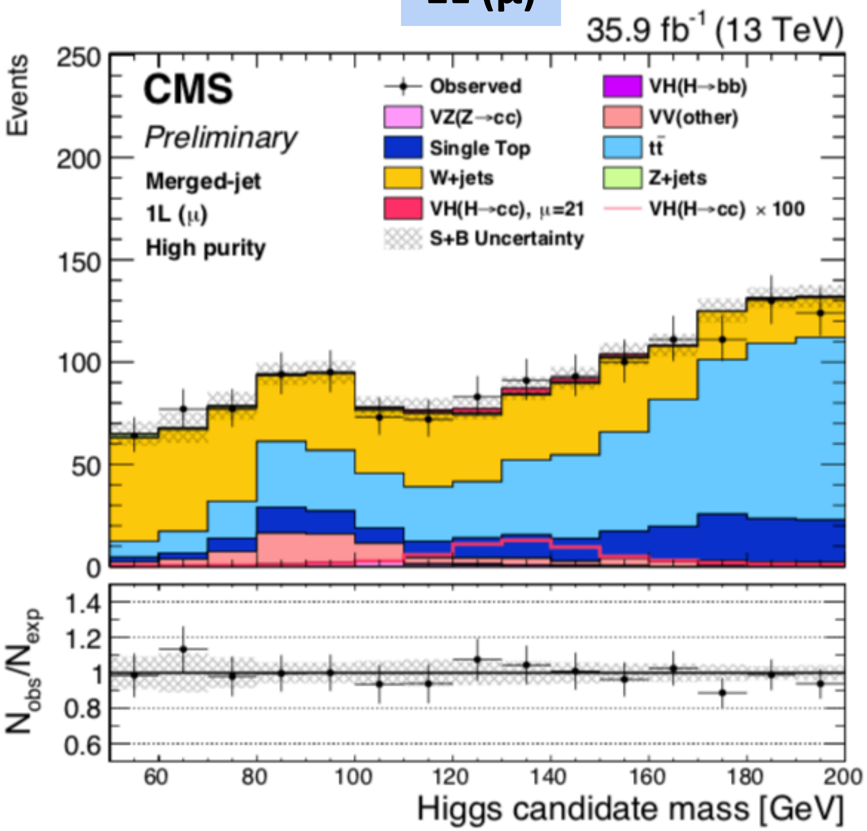


2L (μμ)

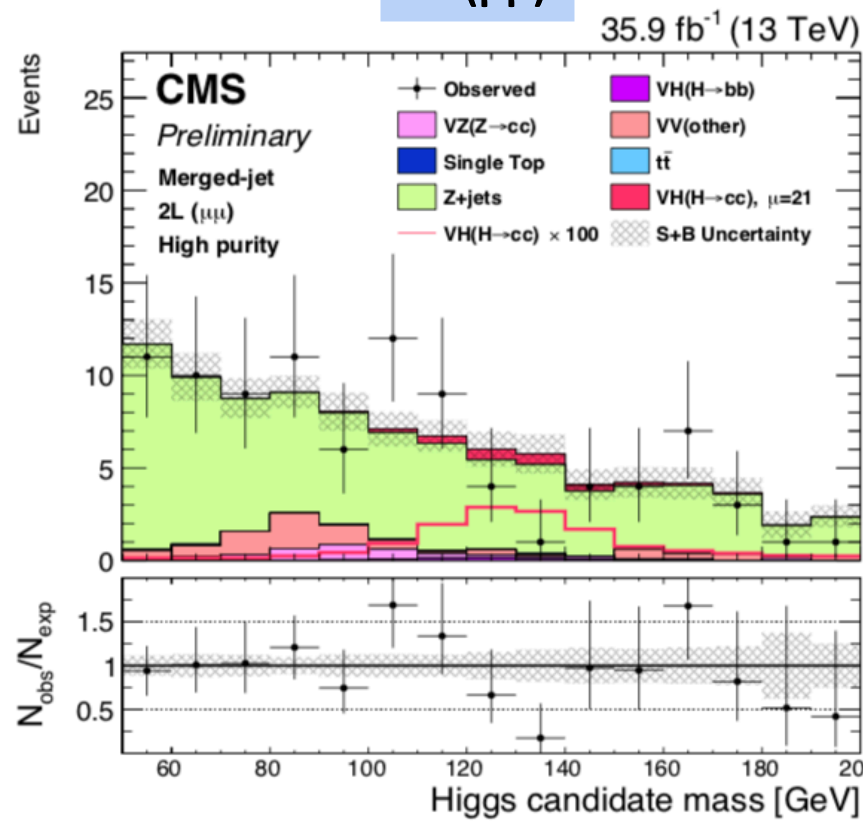


Post-fit distributions: merged-jet

1L (μ)



2L (μμ)



VH(→cc) results

- **First:** validate search by measuring the VZ(→cc) process
  - Same procedure as VH(→cc) but extract the VZ(→cc) signal

Topology	Significance obs (exp)	$\mu_{VZ(\to cc)}$
Resolved-jet	1.5 (1.2)	$1.35^{+0.94}_{-0.95}$
Merged-jet	0.9 (1.3)	$0.69^{+0.89}_{-0.75}$

Results consistent with SM expectation within uncertainties

- **Next:** VH(→cc) results in each topology:

95% C.L. exclusion limit on $\mu_{VH(\to cc)}$

	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

$\mu < 75$ obs. ($38\ \left(^{+16}_{-11}\right)\ \left[^{+35}_{-18}\right]$ exp. $(1\sigma)\ [2\sigma]$)

$\mu < 71$ obs. ($49\ \left(^{+24}_{-15}\right)\ \left[^{+59}_{-24}\right]$ exp. $(1\sigma)\ [2\sigma]$)

Best fit signal strength

Topology	$\mu_{VH(\to cc)}$
Resolved-jet	41^{+20}_{-20}
Merged-jet	21^{+26}_{-24}

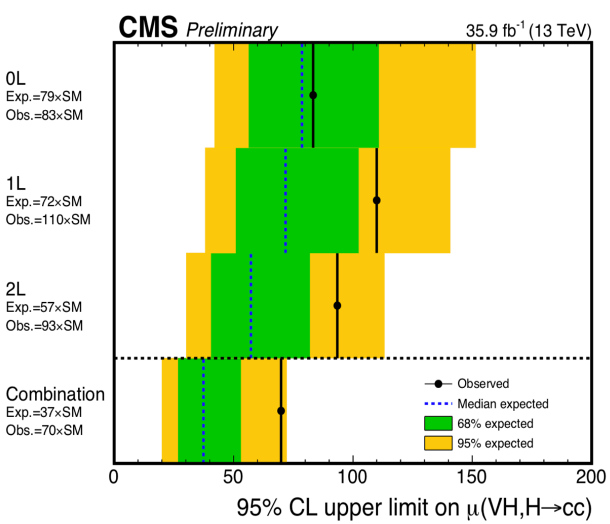
Combination

- Combination: **resolved-jet:** $p_T(V)$ < 300 GeV / **merged-jet:** $p_T(V)$ > 300 GeV
  - Systematics: correlated, but: c/cc-tagging efficiency & PDF, μ_R, μ_F for V+jets
- Validation with VZ(→cc) : $\mu_{VZ(\rightarrow cc)} = 0.55^{+0.86}_{-0.84}$ / signif: 0.7σ obs. (1.3σ exp.)

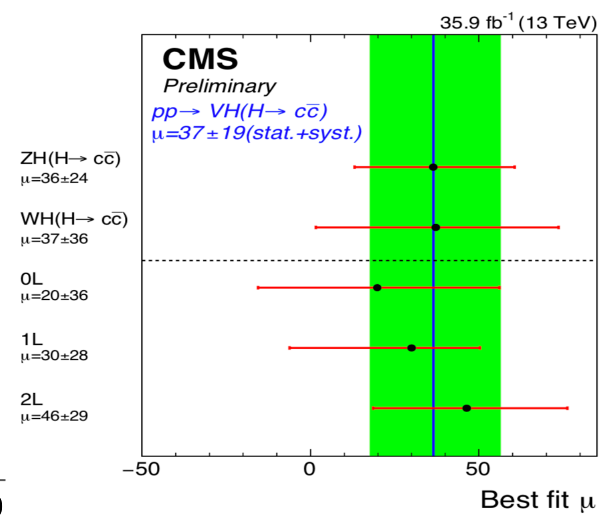
VH(→cc) results with 35.9 fb^{-1} (2016):

95% CL exclusion limit						
	resolved-jet ($p_T(V) < 300$ GeV)	merged-jet ($p_T(V) \geq 300$ 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} ($^{+35}_{-17}$ 2σ)
observed	86	75	83	110	93	70

95% C.L. exclusion limit on $\mu_{VH(cc)}$



Best fit signal strength



Summary

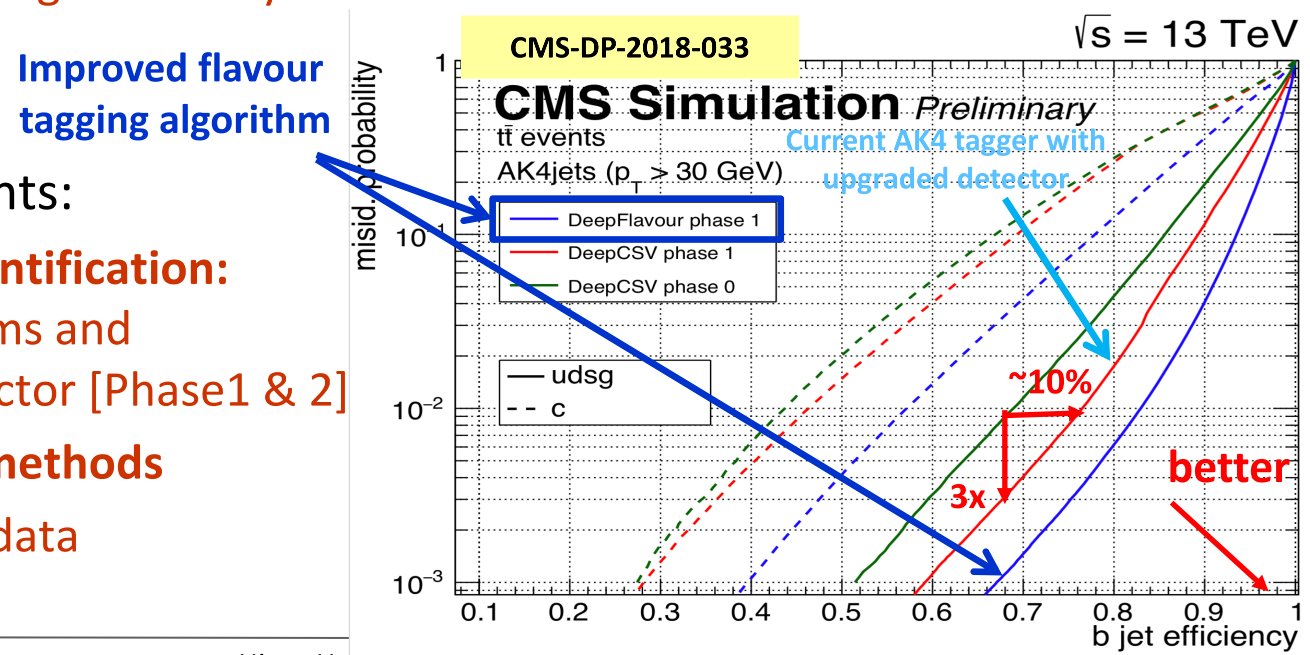
- First direct search for H→cc in CMS with 35.9 fb^{-1} (2016 data) **CMS-HIG-18-031**
    - VH production mode, carried out in 0L, 1L, 2L channels
- Exploits advanced methods for c/cc-identification and signal extraction
    - Effort pays off; strongest limit to date:

$$\boxed{\mu < 70 \text{ obs.} \quad \left(37 \left(^{+16}_{-10}\right) \left[^{+35}_{-17}\right]\right) \text{exp.}(1\sigma)[2\sigma]}$$

- Clearly, a long way ahead
    - Requires breakthroughs in many areas [and the HL-LHC]

ATLAS projections for HL-LHC:
UL on μ < 6.3 [Z→LL only] **ATL-PUB-2018-016**

- Planned improvements:
    - **Charm-tagging identification:** Improved algorithms and upgraded PIX detector [Phase1 & 2]
    - **Signal extraction methods**
    - Analyze Full Run2 data

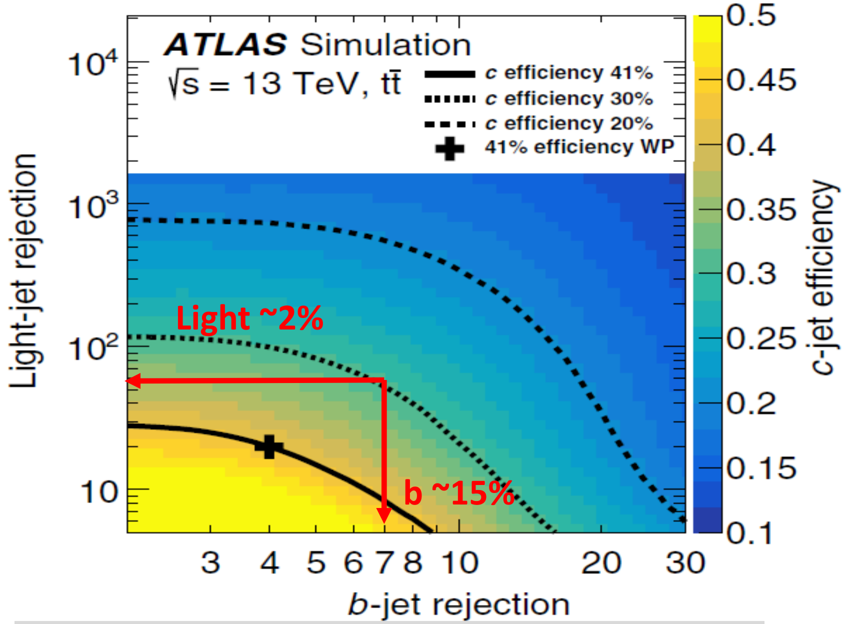


Backup

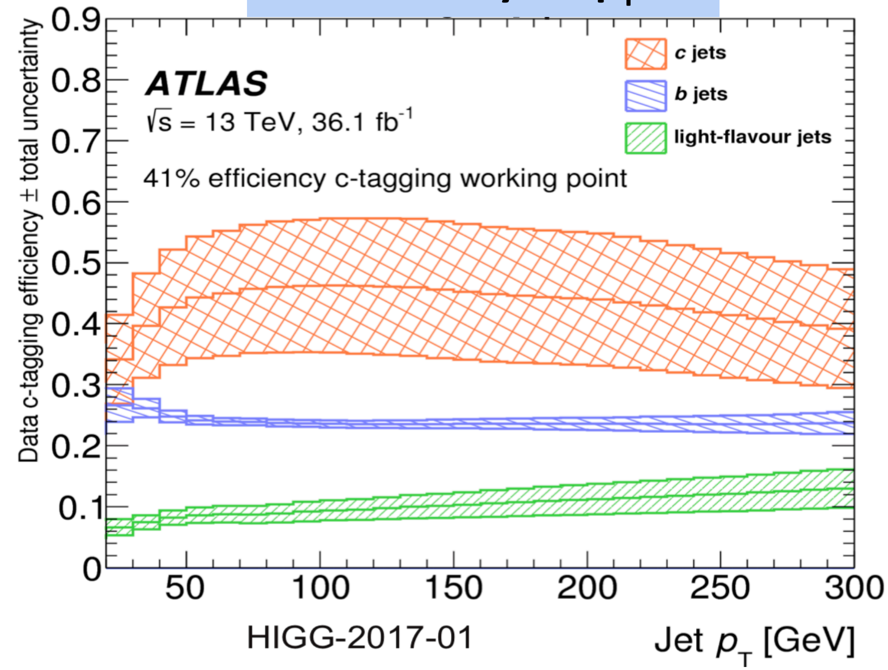
Direct H→cc search [ATLAS]

- 2015+2016 (~36.1 fb^{-1}) data [PRL 120 (2018) 211802]
  - Target the Z(→LL)H production mode
  - Exploit charm tagging to suppress backgrounds
  - "Cut-&-Count" approach:
    - Four categories based on $p_T(cc)$ and N_c; Fit m(cc) distribution for signal extraction

Charm tagging



Efficiency vs. p_T

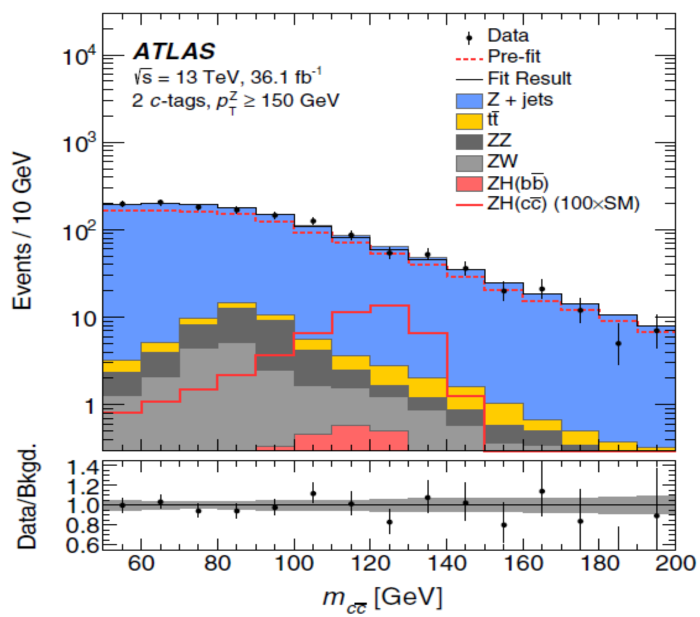


ATLAS WP: → c-tagging eff: 41%
→ b-mistag rate: ~25%
→ light-mistag rate: ~5%

Direct H→cc search [ATLAS] (II)

- 2015+2016 (~36.1 fb^{-1}) data [PRL 120 (2018) 211802]
  - Target the Z(→LL)H production mode
  - Exploit charm tagging to suppress backgrounds
  - "Cut-&-Count" approach:
    - Four categories based on p_T(cc) and N_c; Fit m(cc) distribution for signal extraction

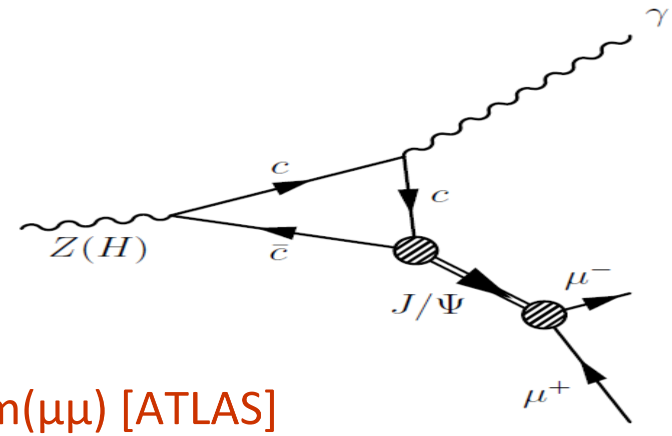
m(cc); 2 tags

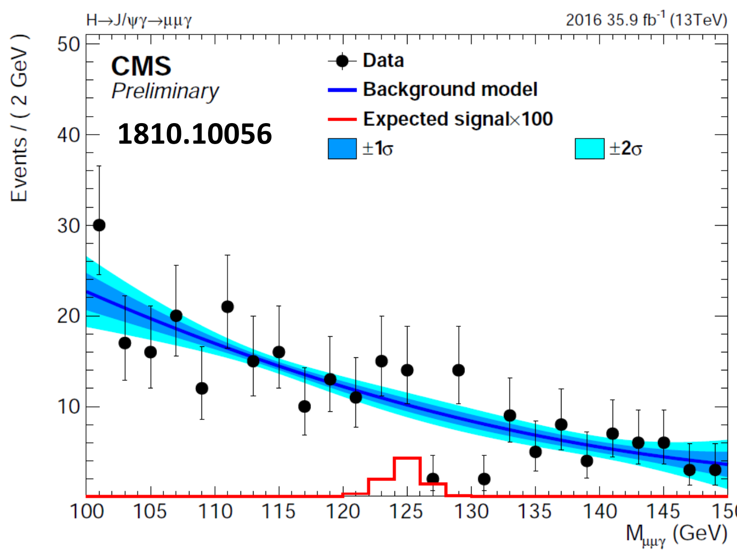


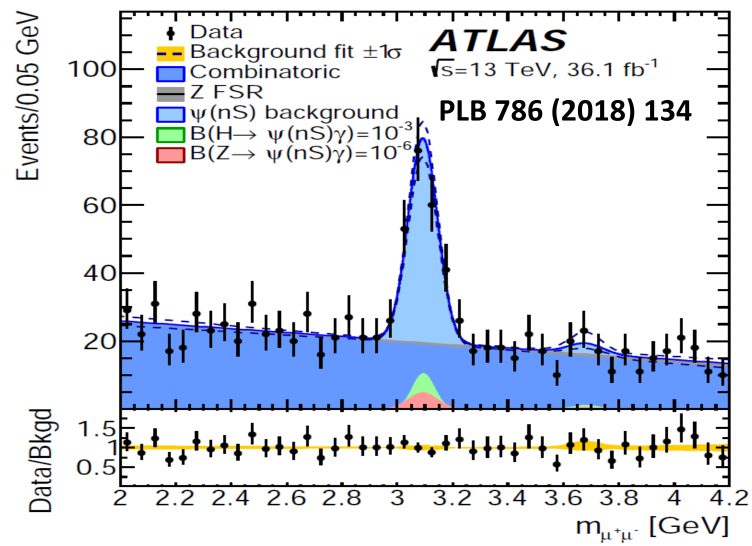
Observed (expected) upper limit on μ = σxBR / σ^{SM}xBR^{SM} < 110 (150)

Searches for exclusive decay modes

- Access κ_c via charmonium decays:
  - complementary to inclusive searches
  - Very rare process: BR ($H\to J/\psi\gamma$) = 2.99×10^{-6}
- Both ATLAS and CMS carried out searches in this mode focusing on the μμ final state
  - Signal extraction: m(μμγ) [CMS] and m(μμγ) vs. m(μμ) [ATLAS]





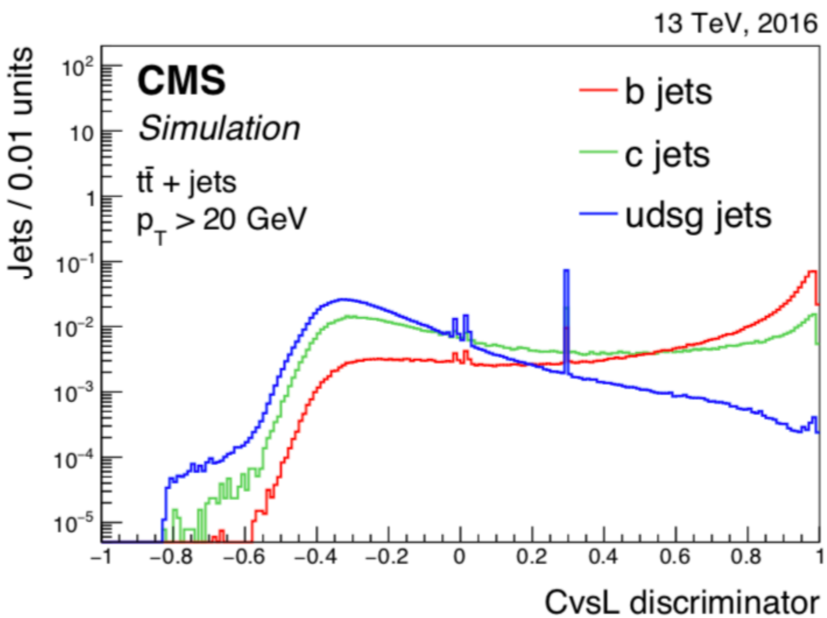


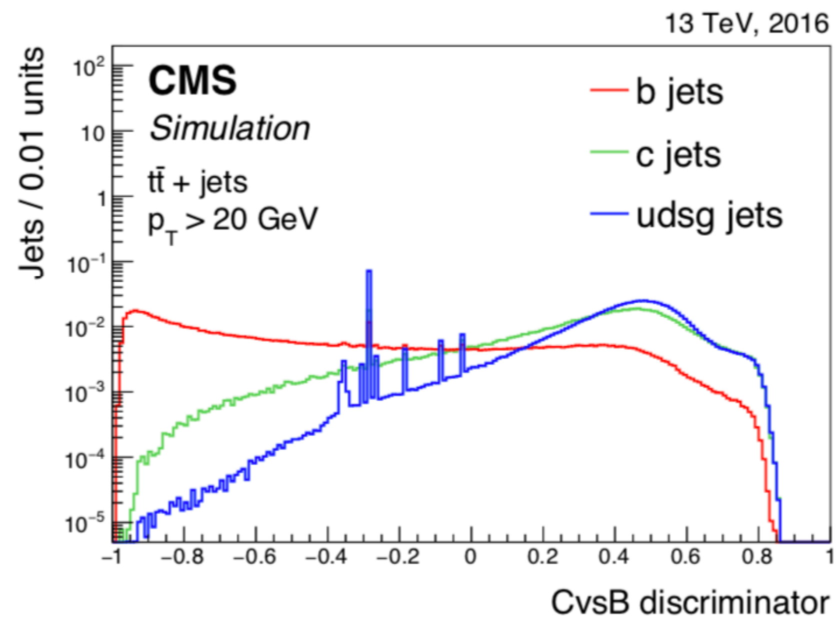
ATLAS: BR< 3.5×10^{-4} obs. (3×10^{-4} exp.); 120 (100) x BR^{SM}
CMS: BR< 7.6×10^{-4} obs. (5.2×10^{-4} exp.); 220 (160) x BR^{SM}

Sensitivity comparable to the direct $H\to cc$ search

Charm tagging on "AK4" jets: DeepCSV

- DeepCSV discriminants:



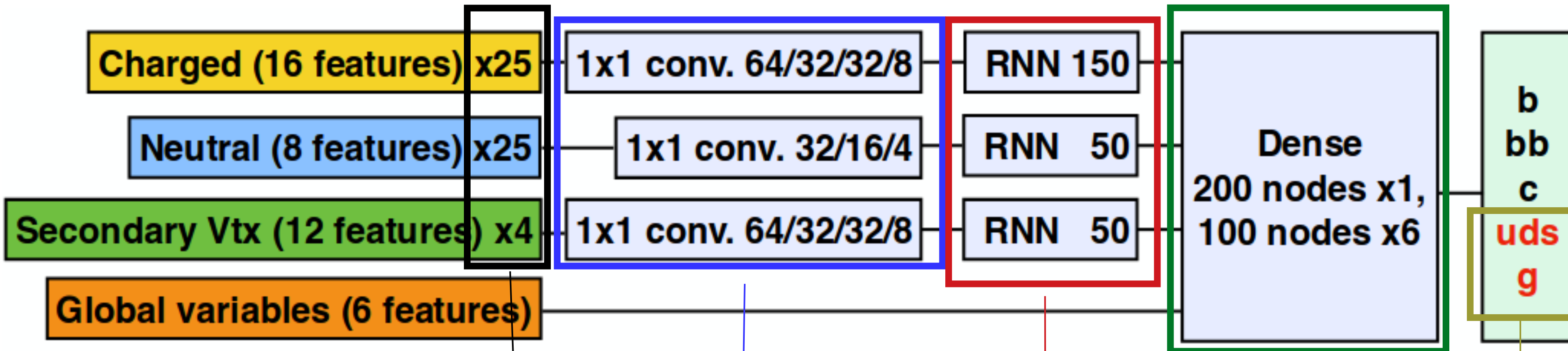


Charm tagging on "AK4" jets: calibration

- Construct the 2D plane (CvsL x CvsB) in three different data samples
  - Split in different bins
- For a given bin, find the sample with the larger purity [e.g. "b"]
  - Initialize the three SF: SF_c, SF_b, SF_L = 1.
  - Calculate $\chi^2_b = \frac{(SF_b \cdot N_{\mathrm{MC},b} - N_{\mathrm{data},b})^2}{N_{\mathrm{data},b}}$ where contributions from other flavours [e.g. c, light] are subtracted from $N_{data,b}$ using the corresponding SF.
  - Repeat above step to the second purest selection and calculate another χ^2 using the SF from the previous steps. Repeat for the other sample
  - This one iteration; repeat the last two steps until no improvement on χ^2
- Move to next bin.

Particle-based “AK4” jet tagging: DeepJet

- A multiclass classifier for: b, bb, c, uds, gluons
- Highlights from the architecture:



Number of particles/SV

LSTM layers
Builds a summary of the information extracted in each set of features

New wrt DeepCSV

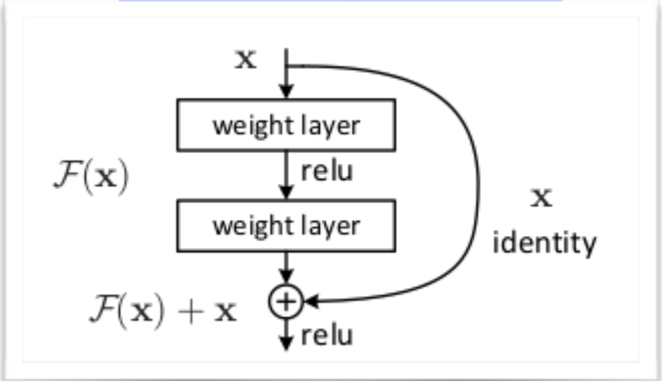
Feature extractor
convolution performed on each particle / SV [1x1]

Correlations and classification

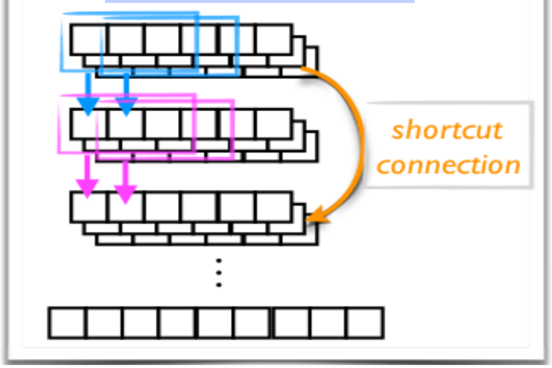
DeepBoostedJet(DeepAK8): Network architecture

- Advanced/Complex network architecture is necessary to achieve maximum performance
  - Architecture based solely on 1D-CNN
    - Less computationally expensive
  - Fairly deep network to better exploit correlations between particles
  - CNN architecture inspired by the ResNet model for image recognition
    - Improves performance in deep networks and makes training easier
  - “Move” in particle triplets
    - Exploit correlations between nearby particles faster

1512.03385,1603.05027



Particle triplets

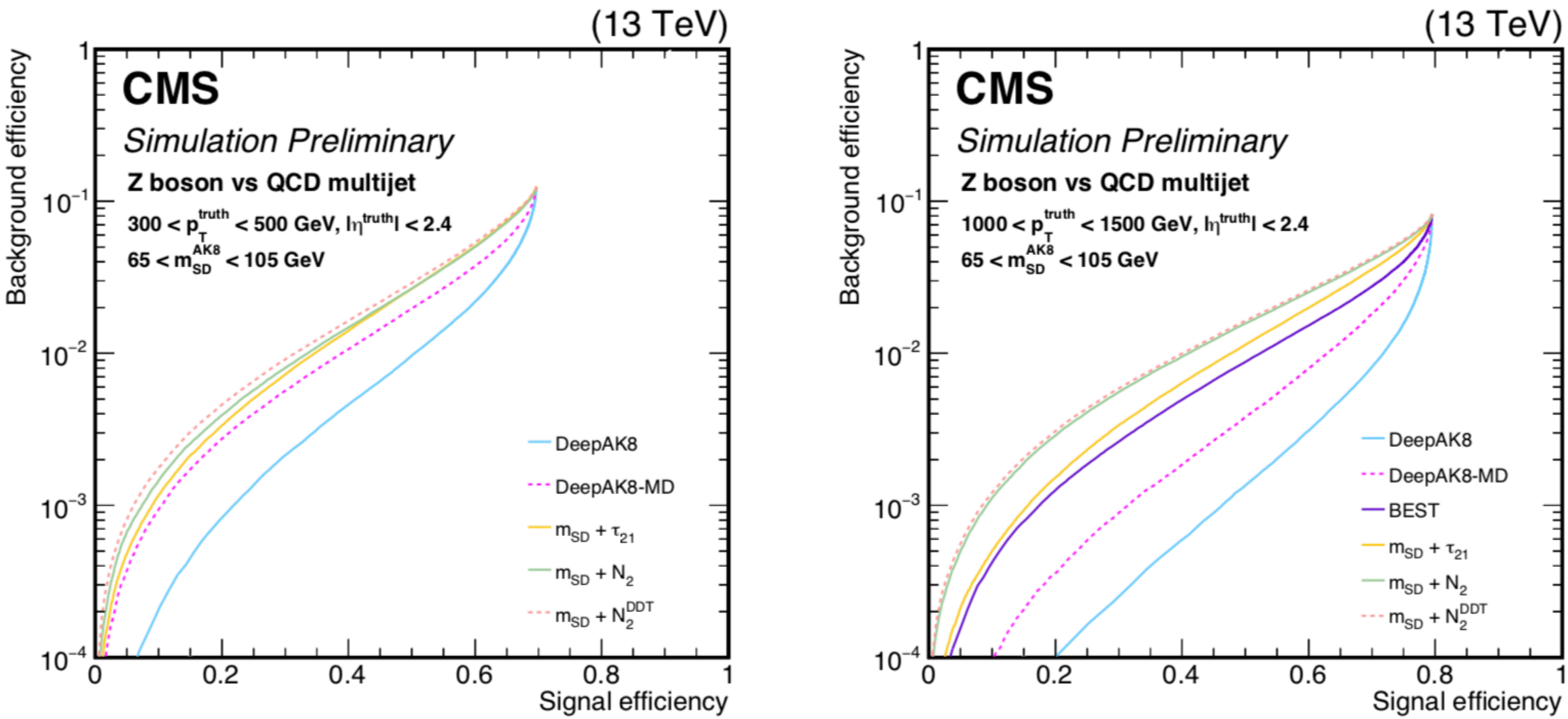


- Also: A version decorrelated with the jet mass
  - Same architecture and inputs as nominal version
  - Use of adversarial networks to predict the jet mass

Meged-Jet tagger: Performance Z

- DeepAK8 [CMS-JME-18-002]:

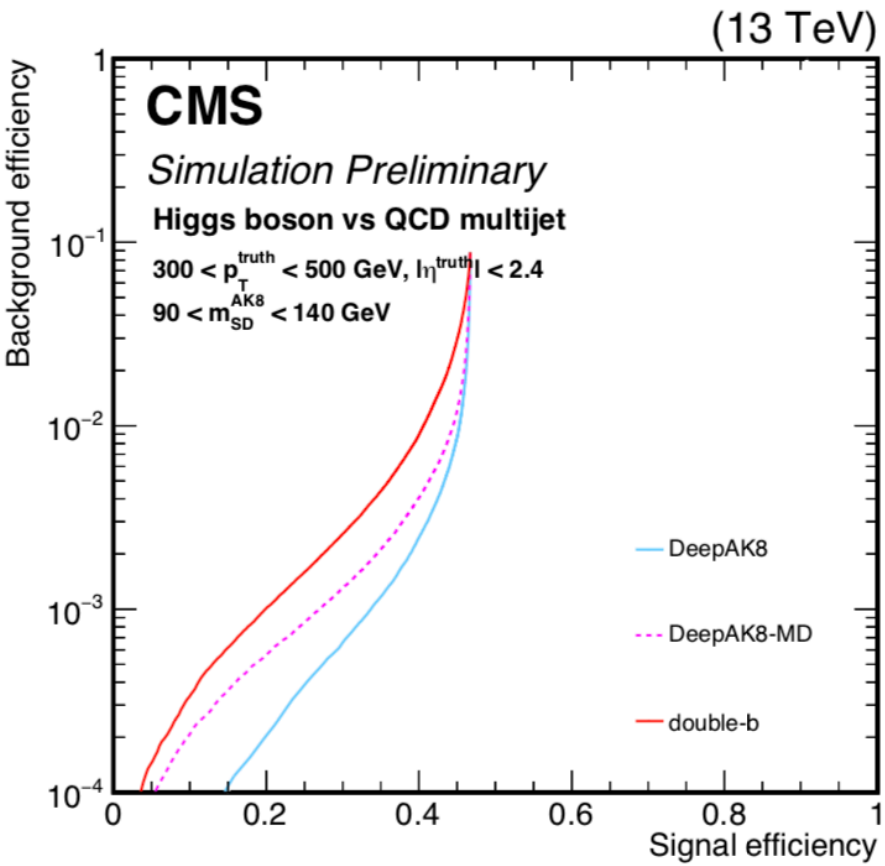
CMS-JME-18-002

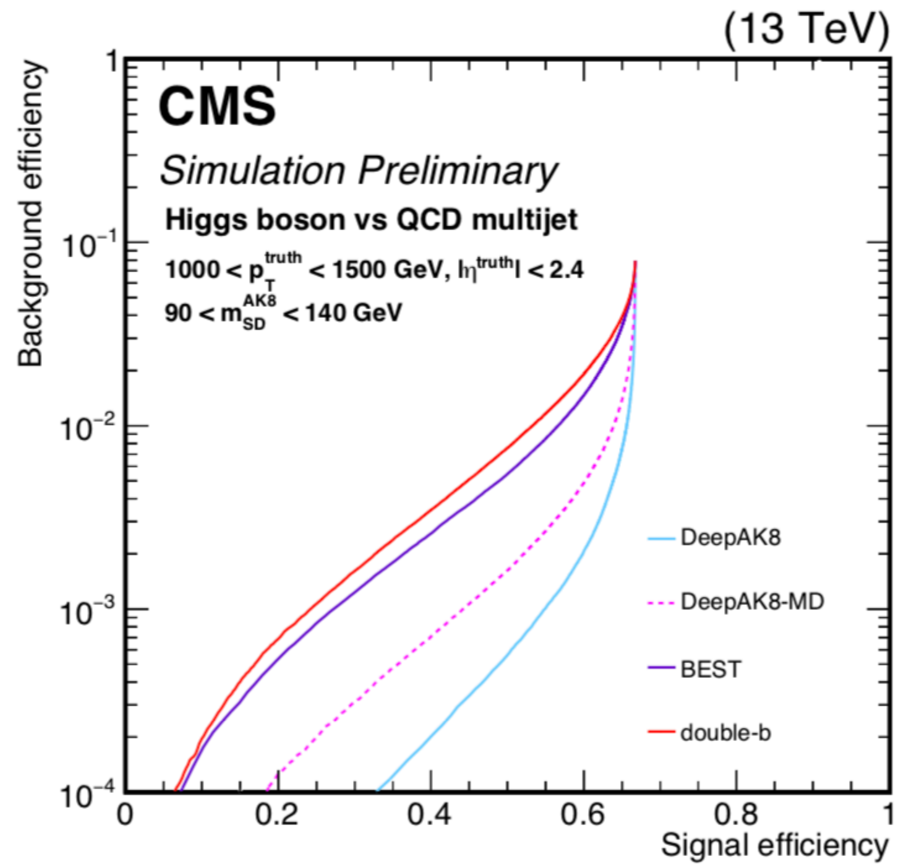


Meged-Jet tagger: Performance Higgs

- DeepAK8 [CMS-JME-18-002]:

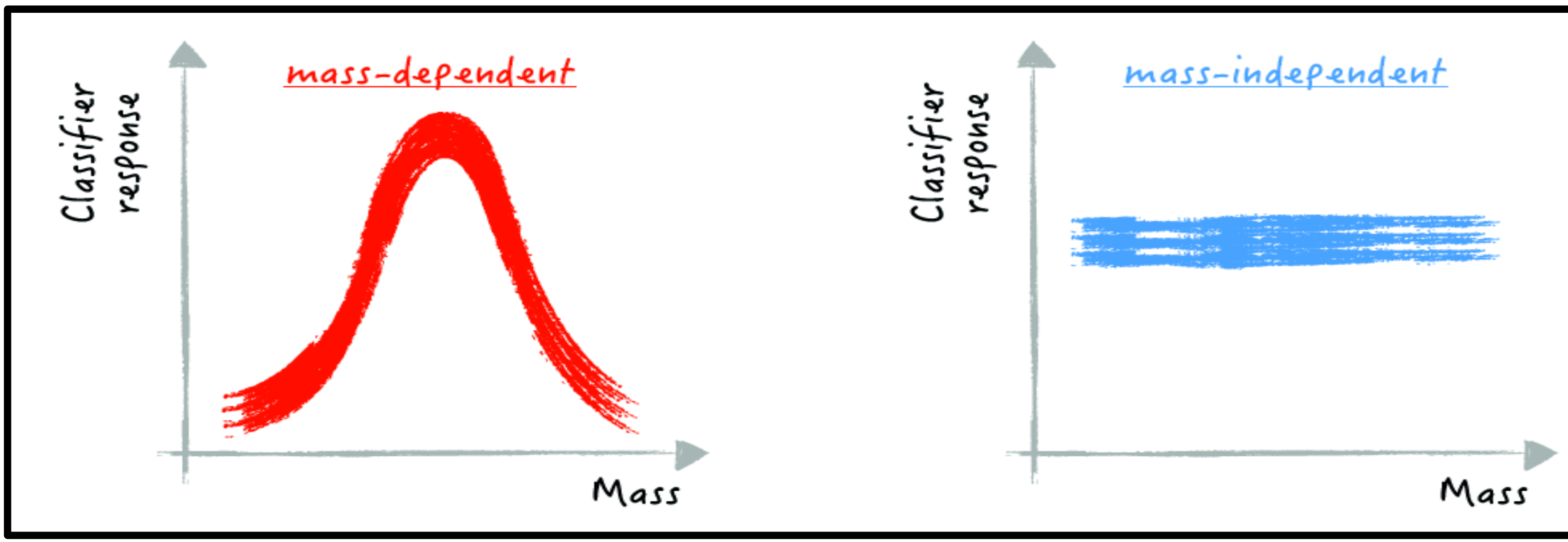
CMS-JME-18-002





Mass sculpting of BKG Jets

- Many of the ML-based algorithms “sculpt” the mass of the background jets -- signal-like structure.
- Is this a show-stopper?
  - Depends on the physics analysis
- What does “mass independence” means for a tagger?

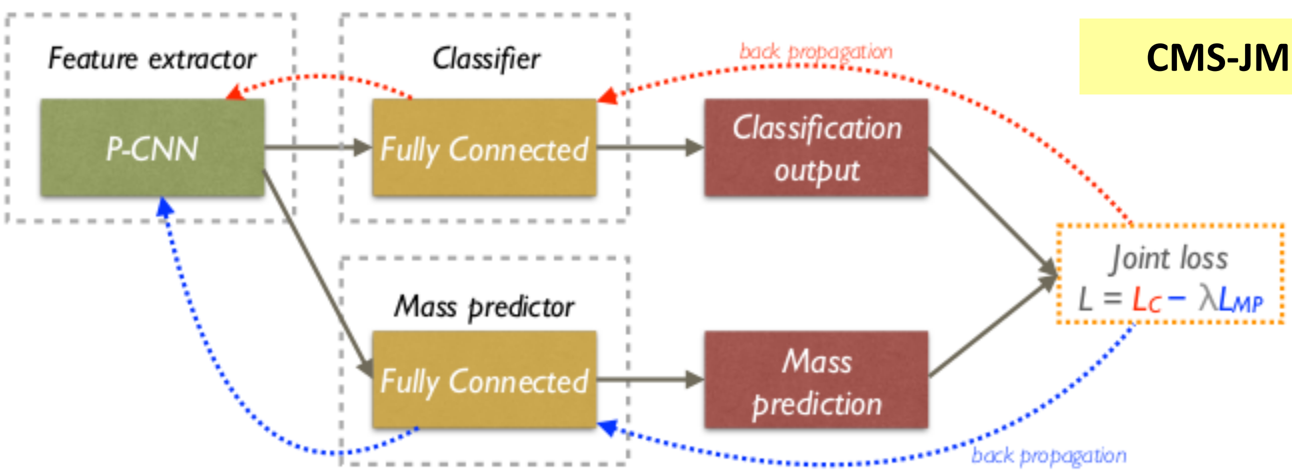


Classifier’s response is non-uniform in mass

Classifier’s response is uniform in mass

Merged-jet: mass decorrelation

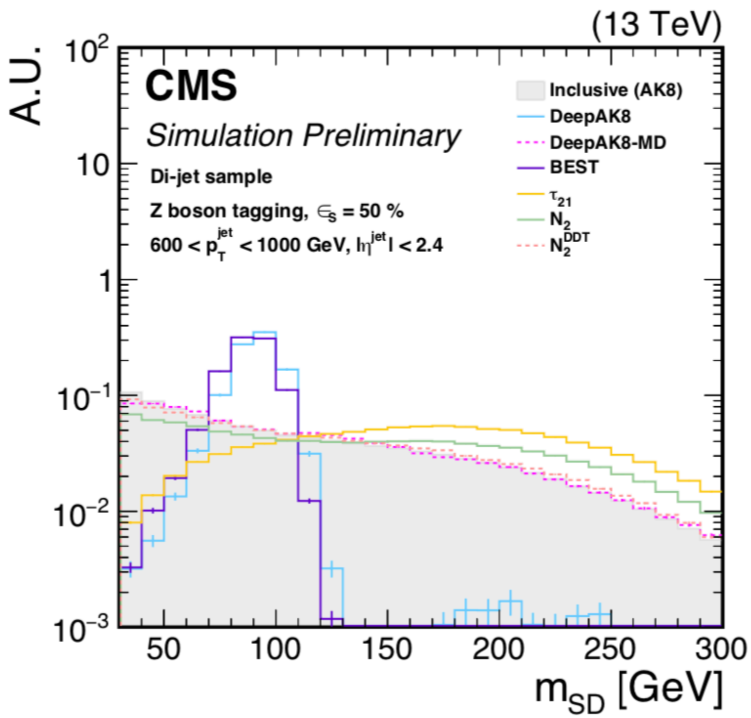
- Use adversarial training to regulate the behaviour of the network
  - Introduce a mass prediction network to predict the jet mass from the features extracted by the CNNs
  - It's loss (L_{MP}) is an indicator for mass correlation
    - Smaller L_{MP} more accurate mass prediction ; the features extracted by the CNNs have a higher correlation with jet mass
  - Introduce a joint loss: $L = L_C - \lambda L_{MP}$, second term a penalty on mass correlation
    - Minimizing L -> simultaneously improve classification & reduce mass correlation
    - λ: hyperparameter balancing between performance and mass independence

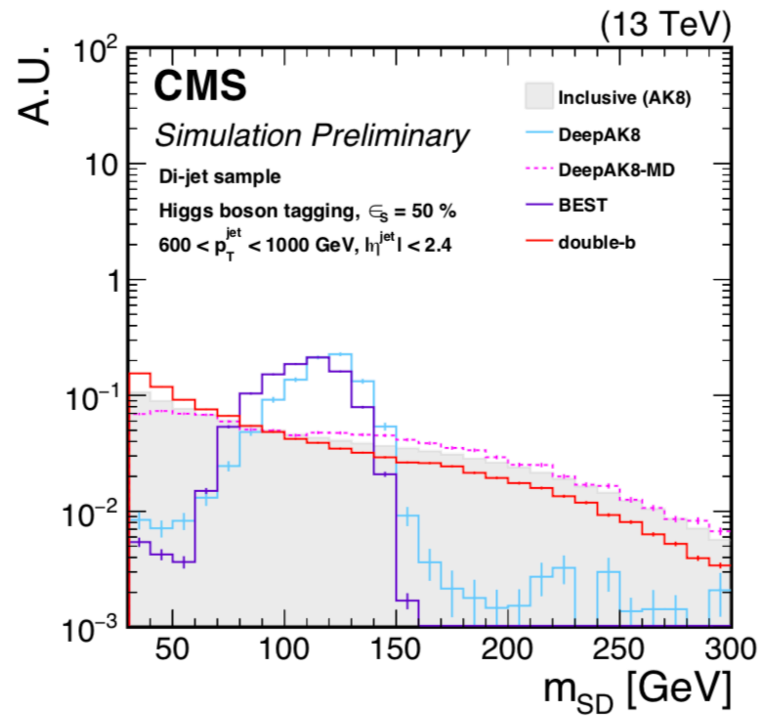


CMS-JME-18-002

Merged-jet: mass decorrelation (II)

CMS-JME-18-002





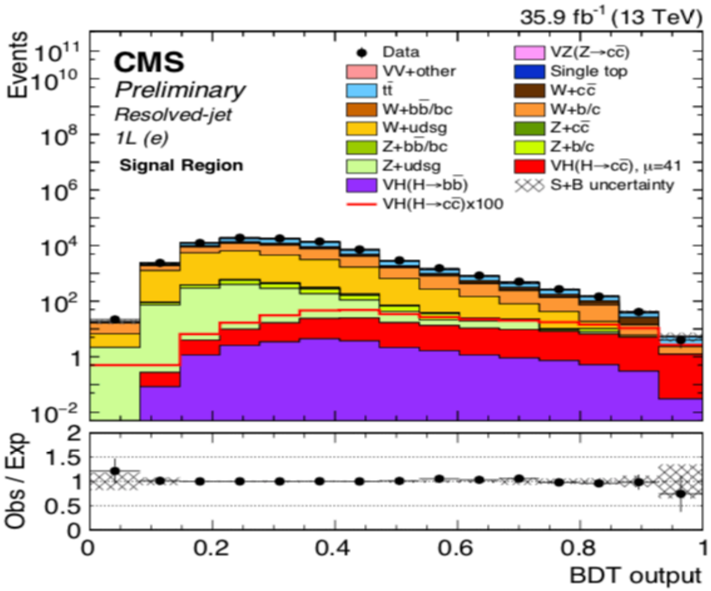
Resolved-jet: BDT inputs

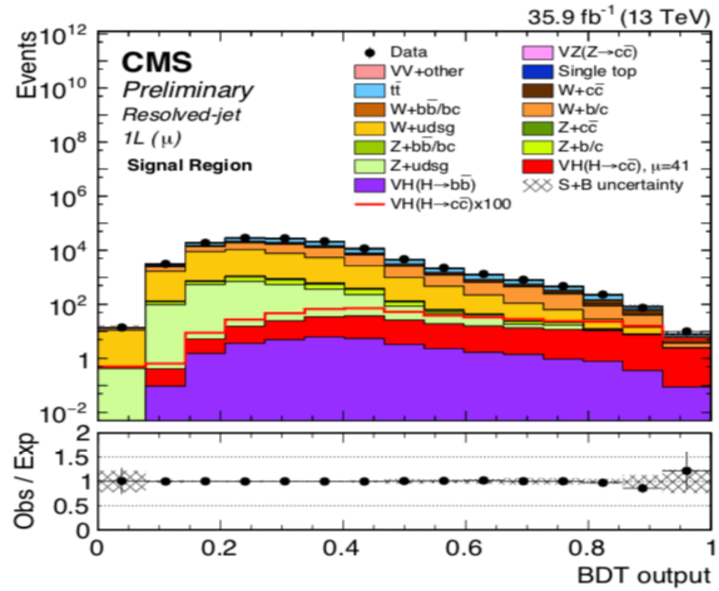
	Variable	Description	0-lepton	1-lepton	2-lepton
H_{cand} properties	$m(H_{\text{cand}})$	H_{cand} mass	✓	✓	✓
	$p_{\text{T}}\,(H_{\text{cand}})$	H_{cand} transverse momentum	✓	✓	✓
V properties	$p_{\text{T}}(\text{V})$	vector boson transverse momentum	✓	✓	✓
	$m(V)$	vector boson mass			✓
	$m_{\text{T}}(V)$	vector boson transverse mass		✓	
	$p_{\text{T}}^{\text{miss}}$	missing transverse momentum	✓	✓	
	$p_{\text{T}}(\text{V})/p_{\text{T}}(H_{\text{cand}})$	ratio between vector and H_{cand} transverse momentum	✓	✓	✓
c-tagging discriminants	$CvsL_{max}$	$CvsL$ likelihood of the leading-$CvsL$ jet	✓	✓	✓
	$CvsB_{max}$	$CvsB$ likelihood of the leading-$CvsL$ jet	✓	✓	✓
	$CvsL_{min}$	$CvsL$ likelihood of the sub-leading-$CvsL$ jet	✓	✓	✓
	$CvsB_{min}$	$CvsB$ likelihood of the sub-leading-$CvsL$ jet	✓	✓	✓
event kinematics/ object correlation	$p_{\text{T}max}$	p_{T} of the leading-$CvsL$ jet	✓	✓	✓
	$p_{\text{T}min}$	p_{T} of the sub-leading-$CvsL$ jet	✓	✓	✓
	$\Delta\phi(\text{V},\text{H})$	azimuthal angle between vector boson and H_{cand}	✓	✓	✓
	$\Delta R(j_1,j_2)$	difference in angular position between leading- and sub-leading-$CvsL$ jet		✓	✓
	$\Delta\phi(j_1,j_2)$	azimuthal angle between leading- and sub-leading-$CvsL$ jet	✓	✓	
	$\Delta\eta(j_1,j_2)$	difference in pseudorapidity between leading- and sub-leading-$CvsL$ jet	✓	✓	✓
	$\Delta\phi(\ell_1,\ell_2)$	azimuthal angle between leading- and sub-leading-p_{T} leptons			✓
	$\Delta\eta(\ell_1,\ell_2)$	difference in pseudorapidity between leading- and sub-leading-p_{T} leptons			✓
	$\Delta\phi(\ell_{1(2*)},j_1)$	azimuthal angle between (sub-)leading-p_{T} lepton and leading-$CvsL$ jet		✓	✓*
	$\Delta\phi(\ell_2,j_2)$	azimuthal angle between sub-leading-p_{T} lepton and sub-leading-$CvsL$ jet			✓
	$\Delta\phi(\ell_1,p_{\text{T}}^{\text{miss}})$	azimuthal angle between leading-p_{T} lepton and missing transverse momentum		✓	
additional activity	N_{aj}	number of small-R jets subtracted number of FSR-jets	✓	✓	✓
	$SA5$	number of soft jets with p_{T} 5 GeV	✓	✓	✓

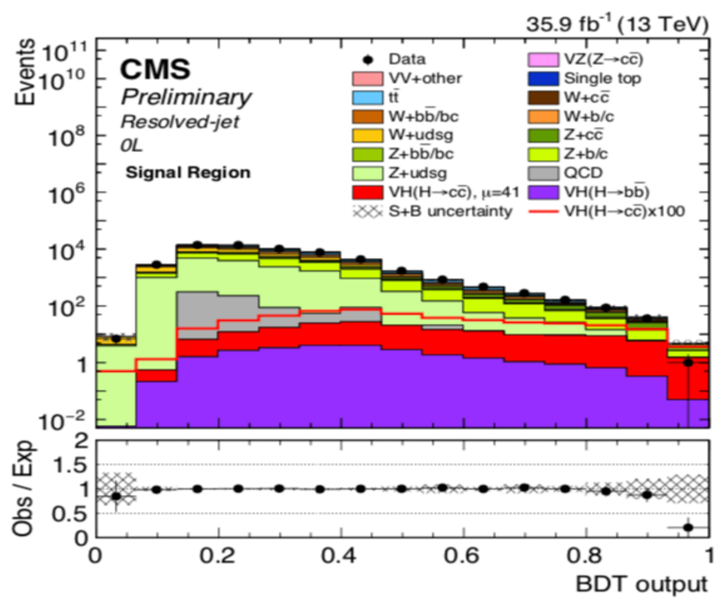
merged-jet: BDT inputs

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

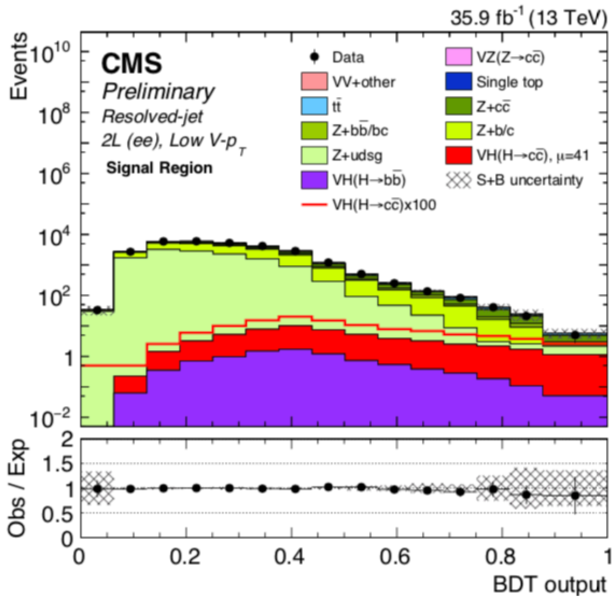
Resolved-jet: postfit 0L, 1L

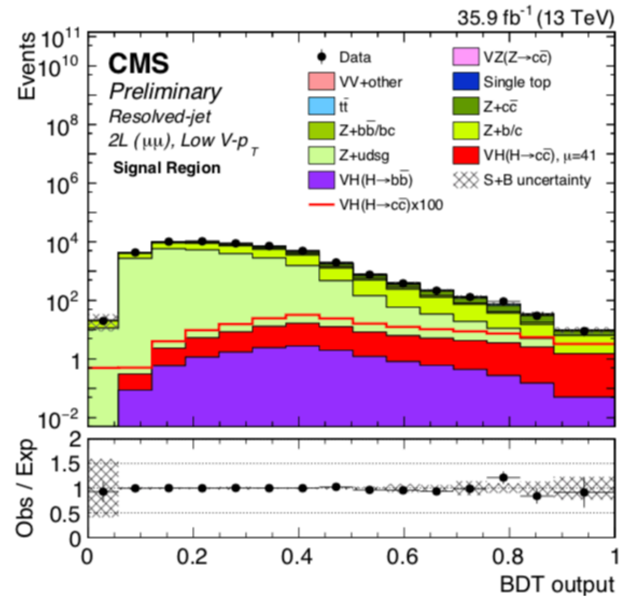


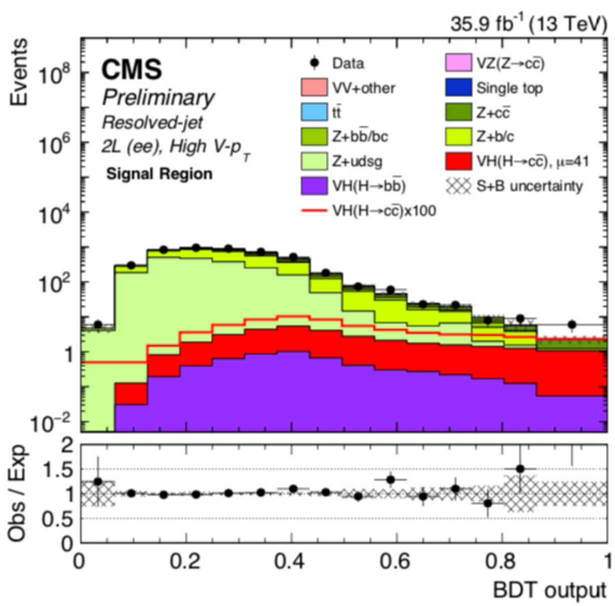


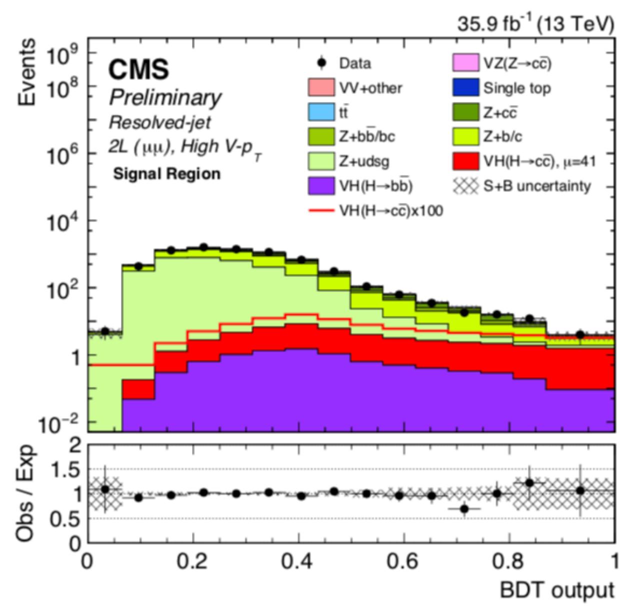


Resolved-jet: postfit 2L

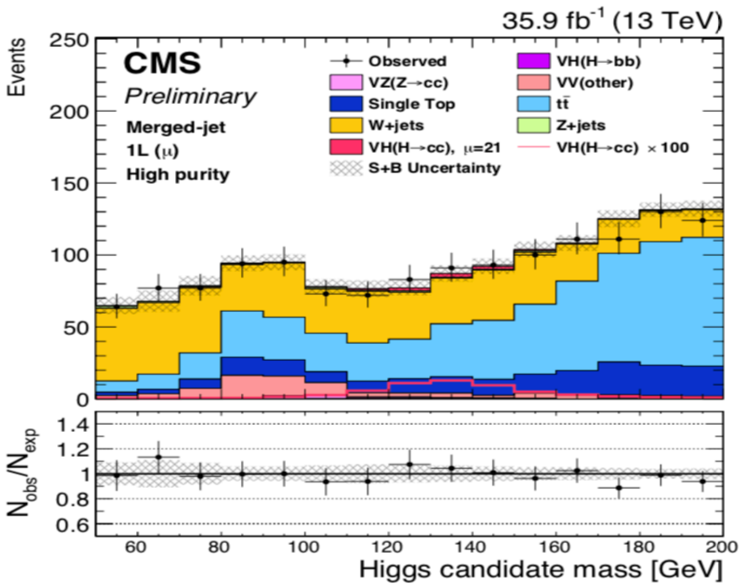


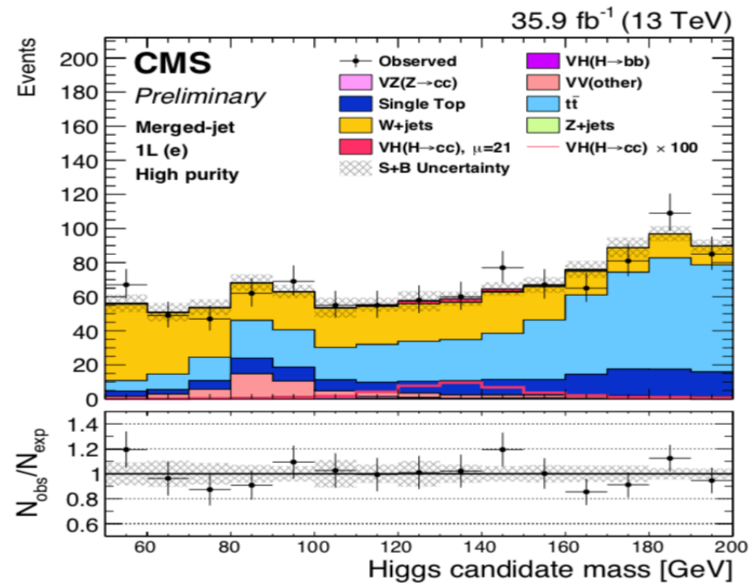


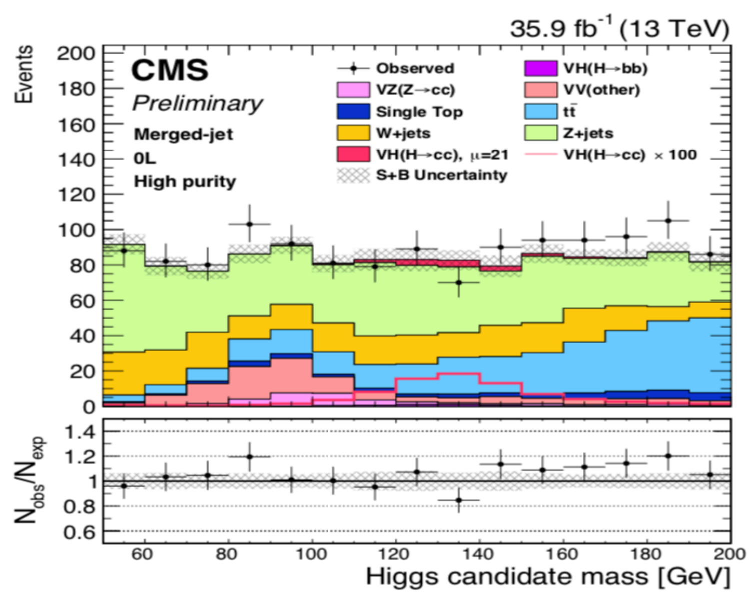




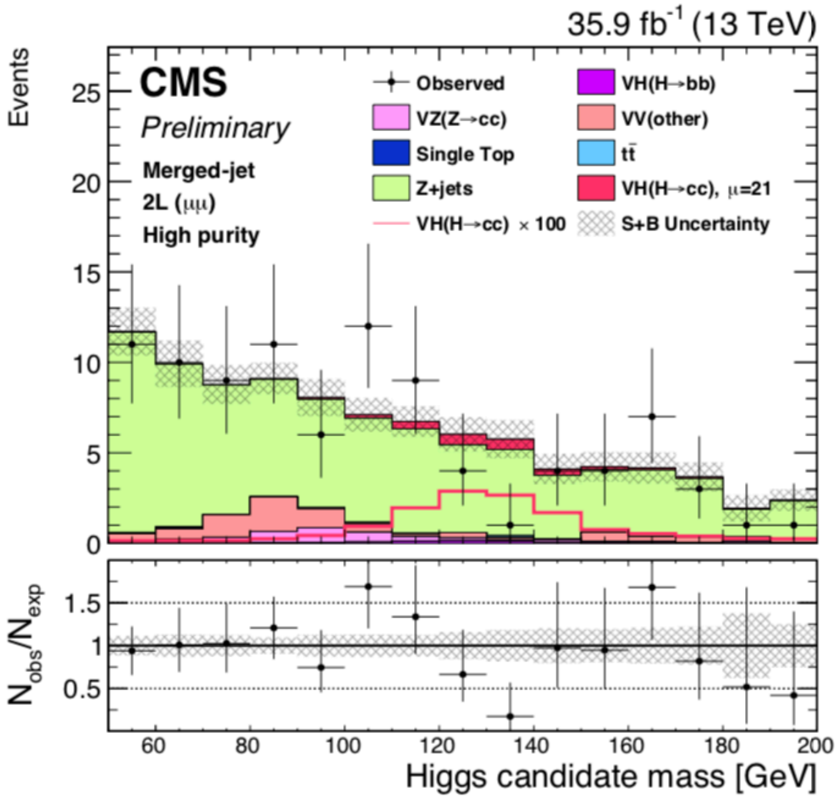
Merged-jet: postfit 0L, 1L

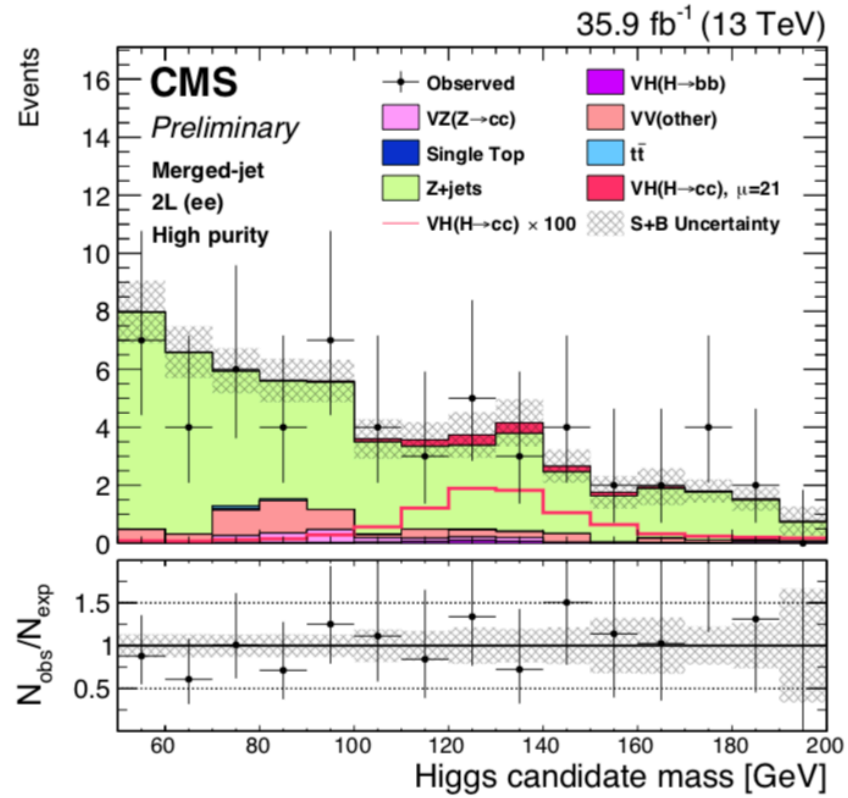






Merged-jet: postfit 2L





CMS VH(→bb) [2016]

- HIG-16-044

Channels	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
Combined	2.8	3.3

Process	0-lepton	1-lepton	2-lepton low-p_T(V)	2-lepton high-p_T(V)
Vbb	216.8	102.5	617.5	113.9
Vb	31.8	20.0	141.1	17.2
V+udscg	10.2	9.8	58.4	4.1
$t\bar{t}$	34.7	98.0	157.7	3.2
Single top quark	11.8	44.6	2.3	0.0
VV(udscg)	0.5	1.5	6.6	0.5
VZ(bb)	9.9	6.9	22.9	3.8
Total background	315.7	283.3	1006.5	142.7
VH	38.3	33.5	33.7	22.1
Data	334	320	1030	179
S/B	0.12	0.12	0.033	0.15