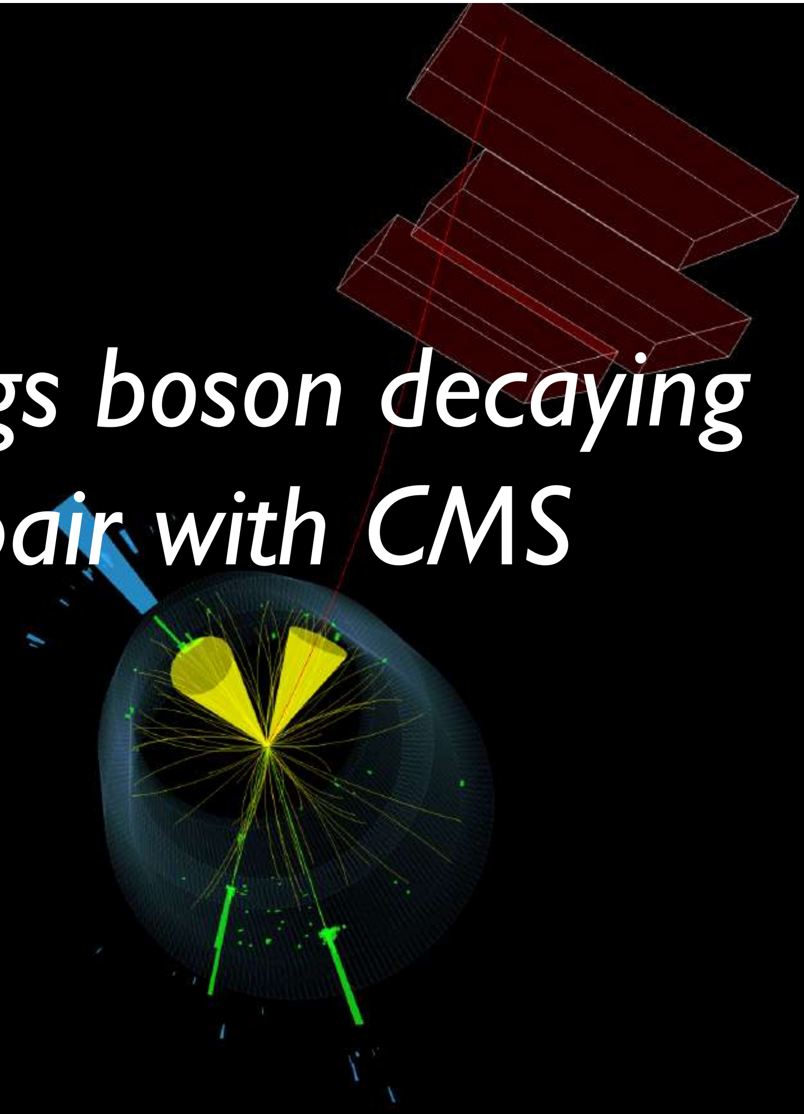
Direct search for the SM Higgs boson decaying to a charm quark-antiquark pair with CMS



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on behalf of the CMS Collaboration

IRN Terascale 2022 Bohn
28th March 2022

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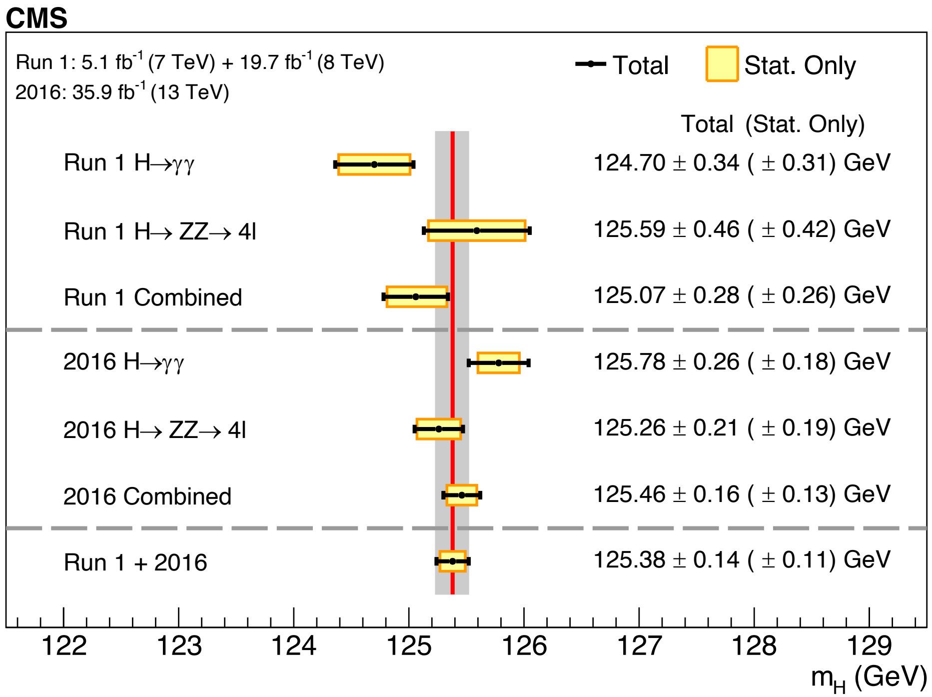
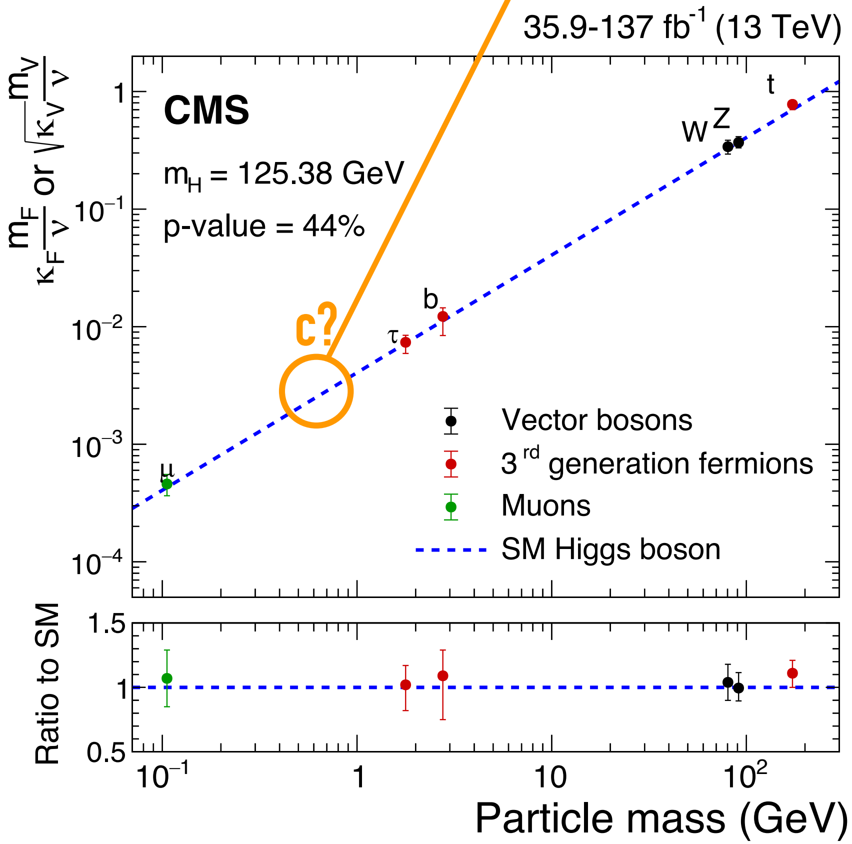
Understanding the Higgs boson

- Discovery of the Higgs boson in 2012: A new chapter of particle physics
- Tremendous progress in our understanding of the Higgs boson in the past ten years

- Probing Higgs coupling to 2nd generation quarks
- BSM effects enhanced given small value of SM k_c





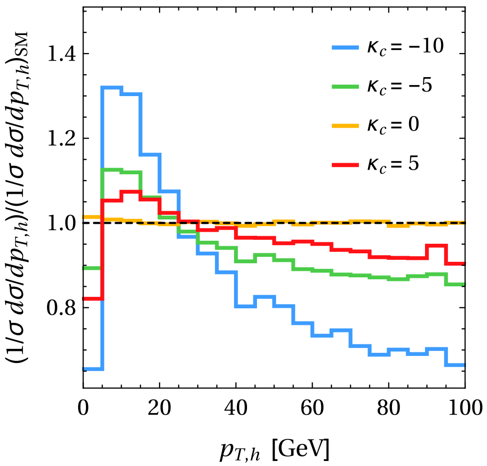
Probing the Higgs-charm coupling

- Several methods explored by CMS to probe the Higgs-charm Yukawa coupling (y_c)

Indirect constraint from Higgs kinematics

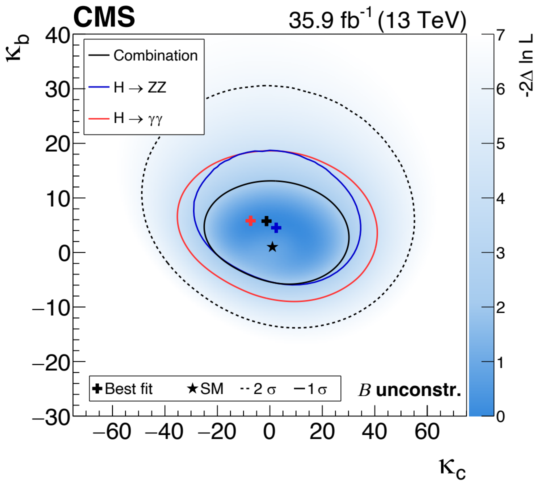
Search for exclusive H → J/Ψγ decays

Phys. Rev. Lett. 118, 121801



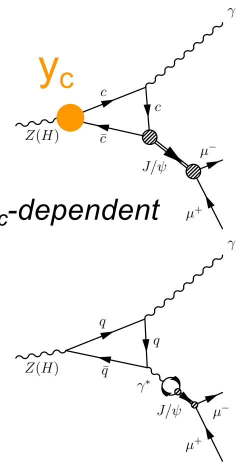
Variation of $p_T(H)$ shape as a function $\kappa_c = y_c/y_c^{SM}$

Phys. Lett. B 792 (2019) 369



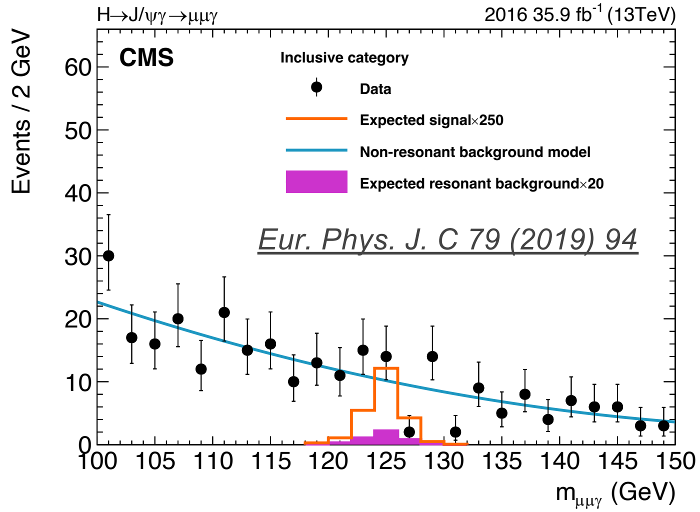
-33 < κ_c < 38 (obs.)

-31 < κ_c < 36 (exp.)



y_c-independent (dominant contribution)

Phys.Rev.D 90 (2014) 11, 113010
JHEP 08 (2015) 012
Phys.Rev.D 95 (2017) 5, 054018
Phys.Rev.D 100 (2019) 5, 054038



Eur. Phys. J. C 79 (2019) 94

$\mathcal{B}$(H → J/Ψγ) < 220x SM(obs.)

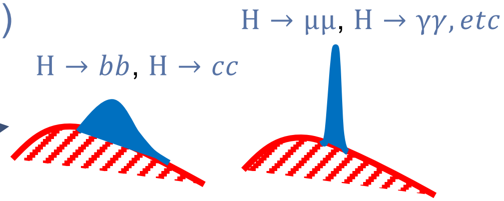
$\mathcal{B}$(H → J/Ψγ) < 170x SM(exp.)

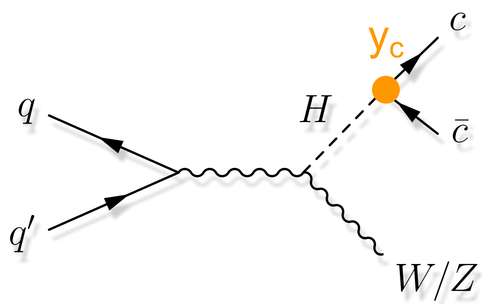
Roughly translates to κ_c < O(100)

Corresponding ATLAS analyses: ATLAS-CONF-2022-002; Phys. Lett. B 786 (2018) 134.

Direct search for H → cc

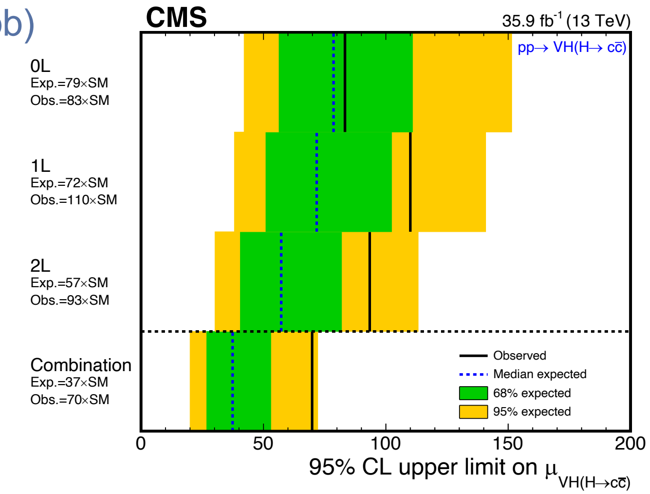
- Search for H → cc decays: directly sensitive to y_c, but very challenging
  - Quite small branching ratio (x20 smaller than H → bb)
  - QCD (reducible) and V+jets (irreducible) background
  - Relatively poor invariant mass resolution
  - ➔ charm quark identification + improvement of mass resolution play key roles





- Main backgrounds
  - V + jets, single and pair production of top quarks, dibosons, VH(H → bb)
- Exploit associated VH production (V = W, Z)
  - Leptonic decays of V ➔ handle to trigger events
  - Boost of V ➔ Reduce backgrounds
  - Three channels: Z → νν (0L), W → ℓν (1L), Z → ℓℓ (2L) [ℓ = e, μ]
- Previous result (36 fb^{-1}): [JHEP 03 (2020) 131]
- **Today: result with the full Run 2 data set (138 fb^{-1})**

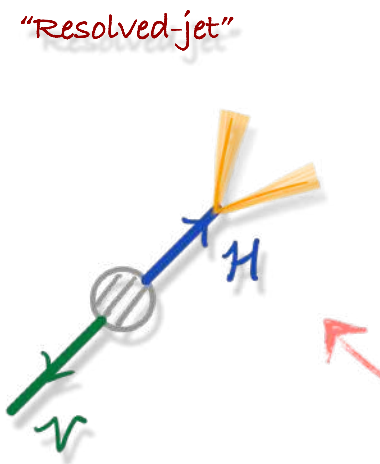
JHEP 03 (2020) 131

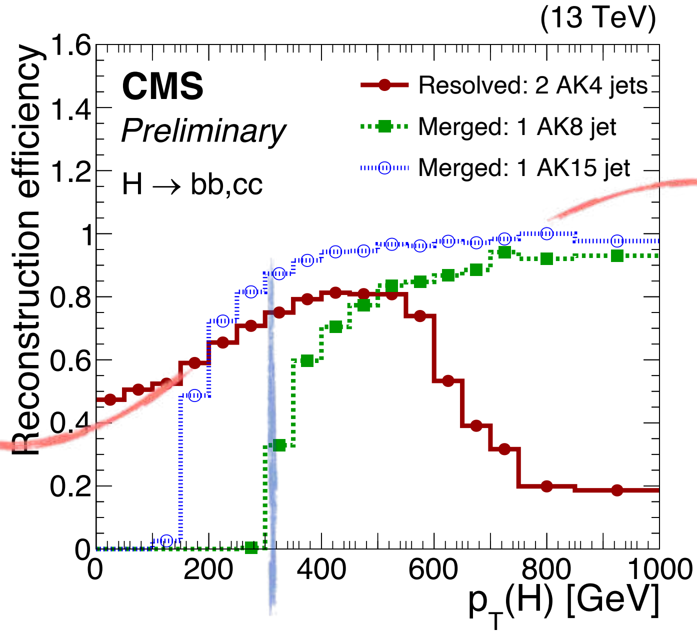


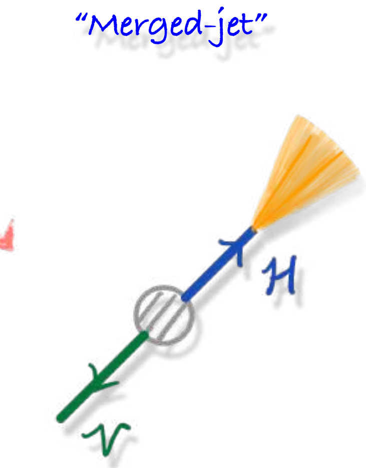
Corresponding ATLAS analysis: arXiv:2201.11428. See also recent LHC seminar by A. Chisholm.

Analysis overview

- $\Delta R(c,\bar{c}) \sim 2m(H)/p_T(H)$ ➔ Two complementary approaches for Higgs boson candidate reconstruction







Resolved-jet topology

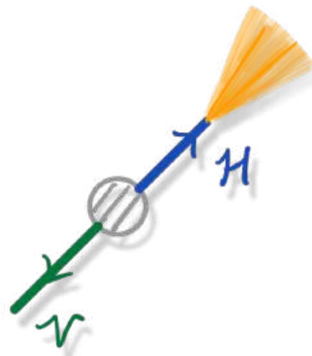
- reconstructs H → cc decay with two small-R jets (R=0.4, “**AK4**”)
- probes the bulk (>95%) of the signal phase space

Merged-jet topology

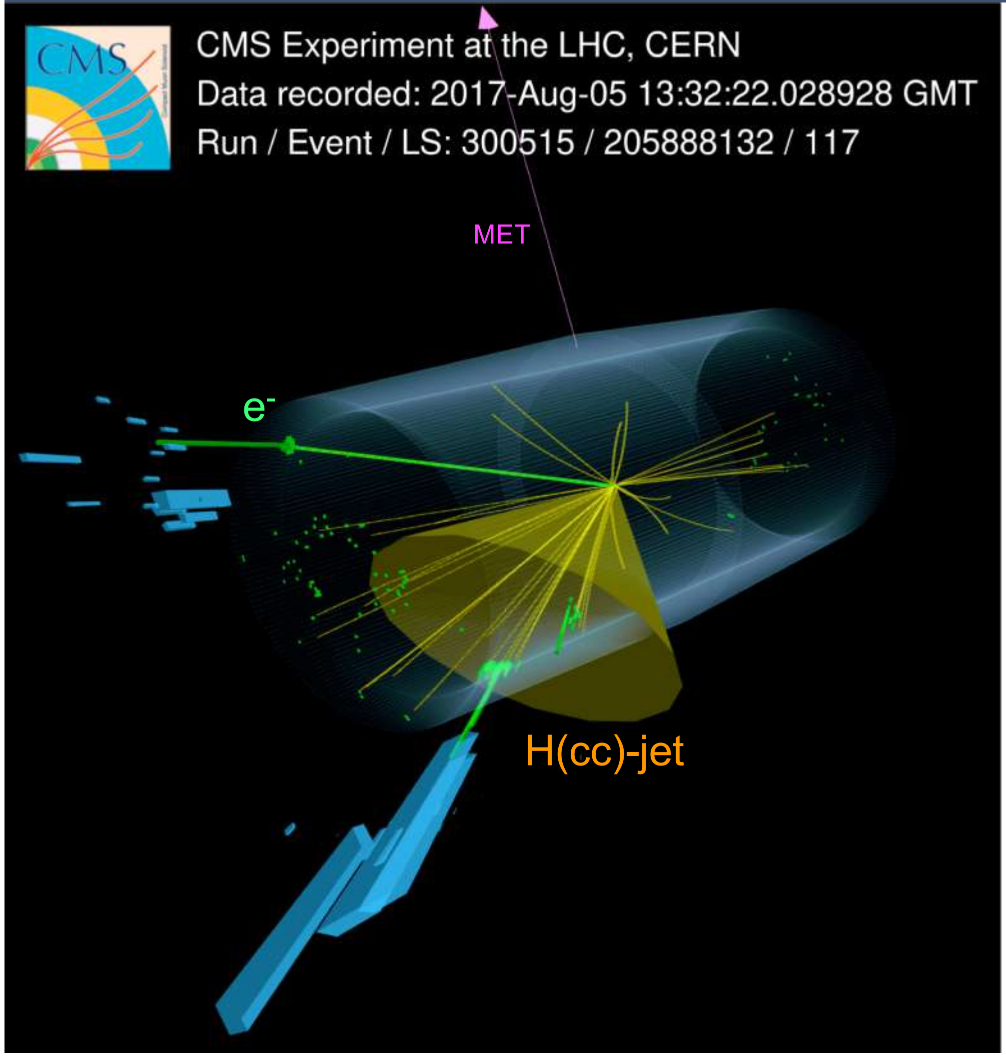
- reconstructs H → cc decay with one large-R jets (R=1.5, “**AK15**”)
- small signal acceptance (<5%) but higher purity
- better exploits the correlation between the two charm quarks

➔ The two topologies are made orthogonal via presence of AK15 jet with p_T > 300 GeV

Merged-jet topology



Overview of the merged-jet topology



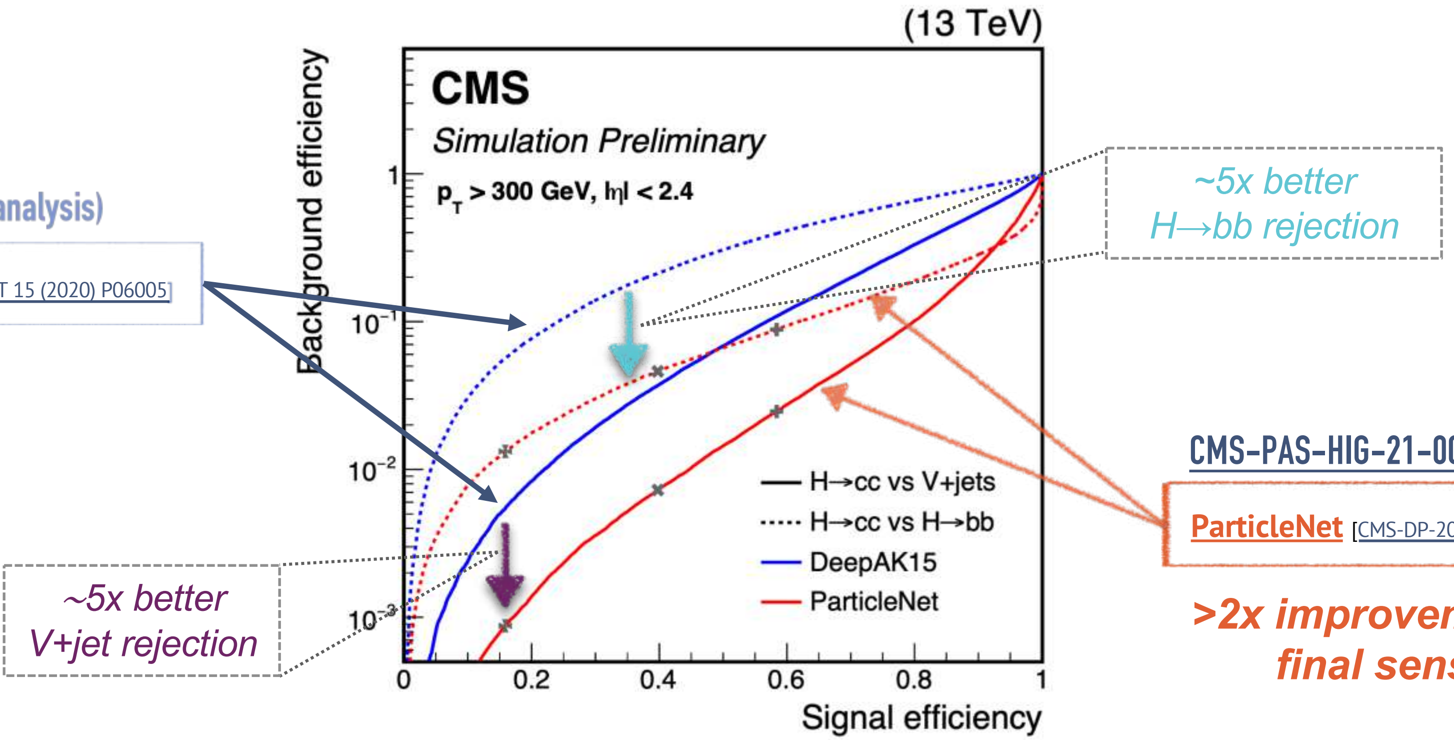
- Higgs candidate reconstruction
  - Select one AK15-jets with the highest p_T as H → cc jet
  - Identification of H → cc using ParticleNet tagger (dedicated calibration+mass sculpting mitigation)
  - Dedicated cc-jet mass regression for improved cc-jet mass scale and resolution
- Analysis strategy (three channels: 0L, 1L, 2L)
  - Control regions for background normalizations
  - Kinematic-BDT + cc-tagger score used for categorization
  - Fit to soft-drop mass

H → cc identification

- Merged-jet topology: Higgs boson candidate reconstructed via a single large-R jet (p_T > 300 GeV)
- **ParticleNet** tagger used to identify H → cc decay ➔ Large improvement vs previous techniques
- Multi-class DNN boosted jet classifier ➔Trained targeting hadronic decays of a spin-0 particle X (X → bb, cc)

JHEP 03 (2020) 131 (2016 analysis)

DeepAK8 (DeepAK15) [JINST 15 (2020) P06005]



CMS-PAS-HIG-21-008 (Run 2 analysis)

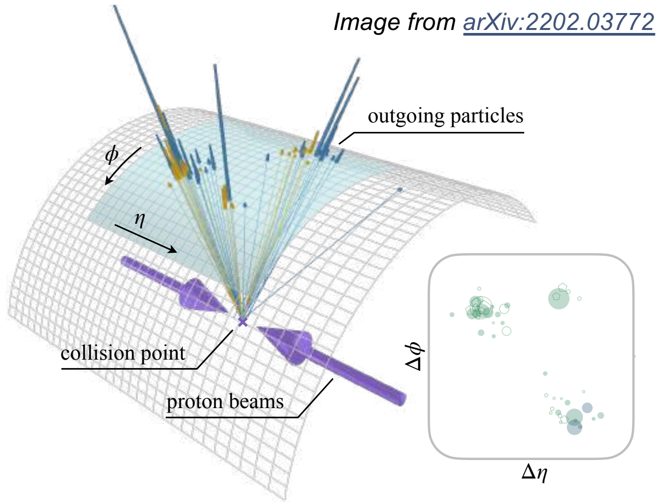
ParticleNet [CMS-DP-2020-002]

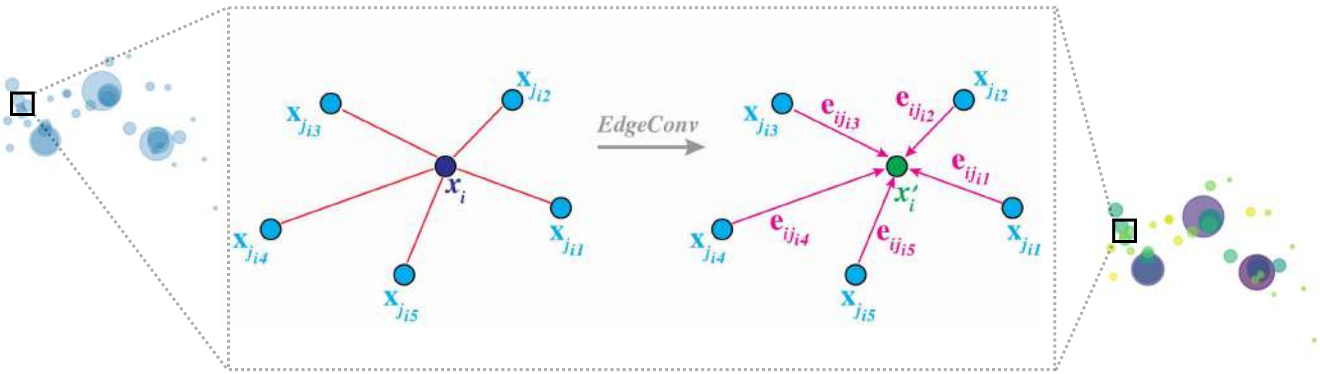
>2x improvement in the final sensitivity

ParticleNet architecture

- New jet representation: “particle cloud”
  - treating a jet as an unordered set of particles, distributed in the η — φ space
- ParticleNet [Phys.Rev.D 101 (2020) 5, 056019]
  - graph neural network architecture adapted from DGCNN [arXiv:1801.07829]
  - permutation-invariant architecture leads to significant performance improvement

Image from arXiv:2202.03772



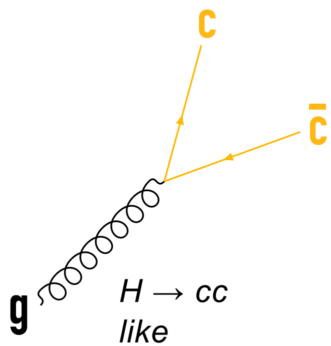


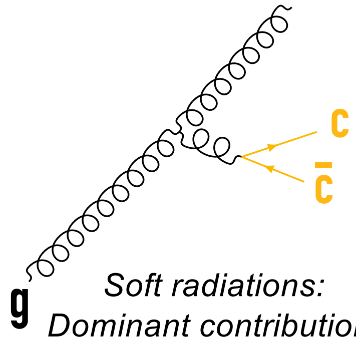
Performance on top quark tagging benchmark [SciPost Phys. 7, 014 (2019)]

	$1/\varepsilon_b$ at $\varepsilon_s = 30\%$
ResNeXt-50	1147 ± 58
P-CNN	759 ± 24
PFN	888 ± 17
ParticleNet-Lite	1262 ± 49
ParticleNet	$\mathbf{1615 \pm 93}$

Calibration of the cc-tagger

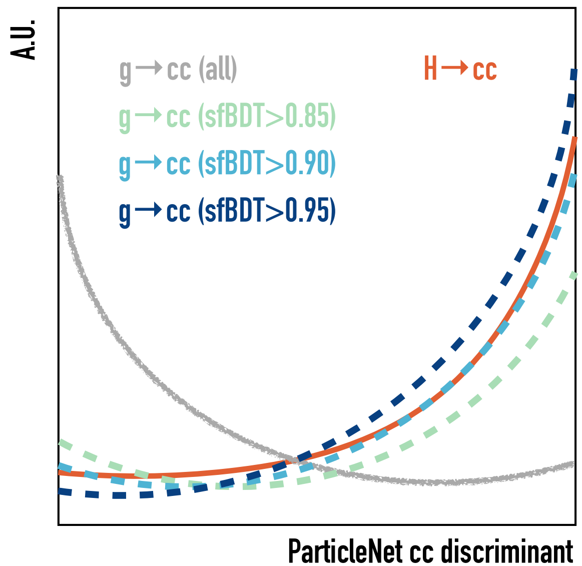
- Need to measure ParticleNet cc-tagging efficiency in data
  - No pure sample of H → cc jets (or even Z → cc) in data
  - Using g → cc in QCD multi-jet events as a proxy





- Difficulty: select a phase-space in g → cc that resembles H → cc
  - Solution: BDT developed to distinguish hard 2-prong splittings from soft cc
  - Adjust the similarity between proxy and signal jets via BDT cuts

Effects of the BDT

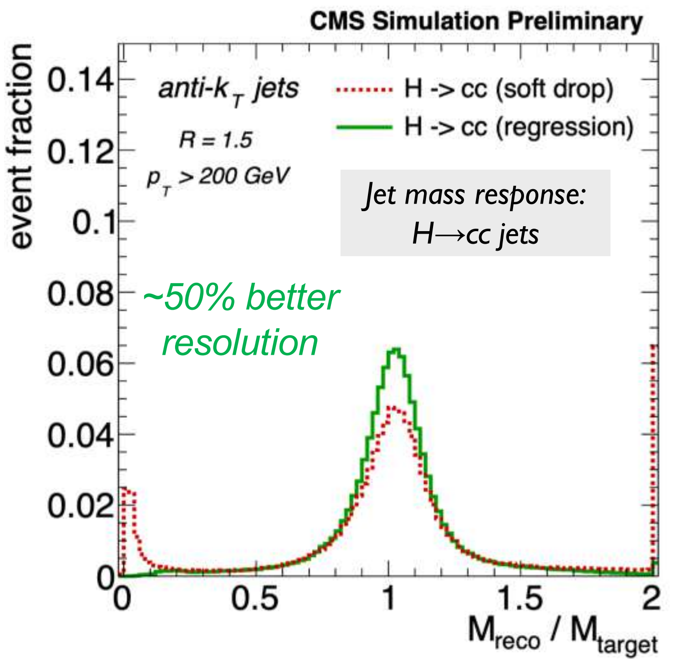


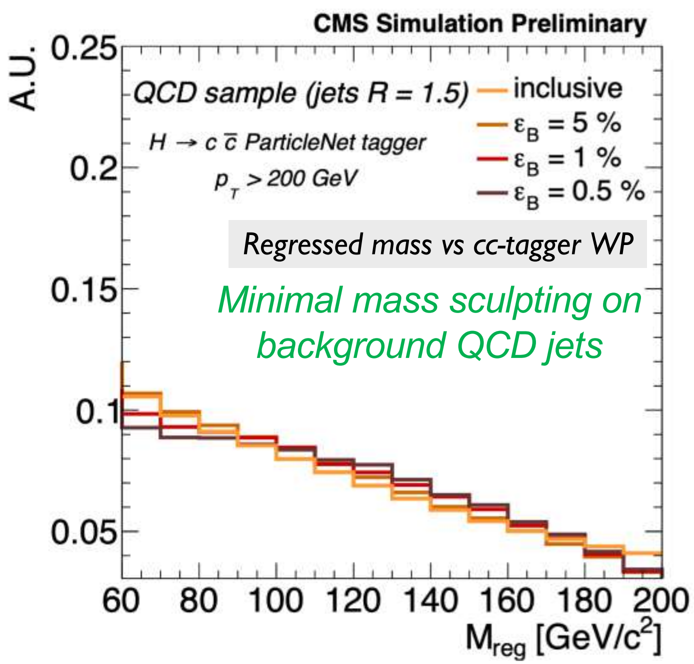
- Fit to the secondary vertex mass in the “passing” and “failing” regions simultaneously to extract the scale factors (typically 0.9—1.3)
  - three templates: cc (+ single c), bb (+ single b), light flavor jets
  - corresponding uncertainties are 20—30%

Large-R jet mass regression

CMS DP-2021/017

- Jet mass: one of the most powerful observable to distinguish signal and backgrounds
- New ParticleNet-based regression algorithm to improve the large-R jet mass reconstruction

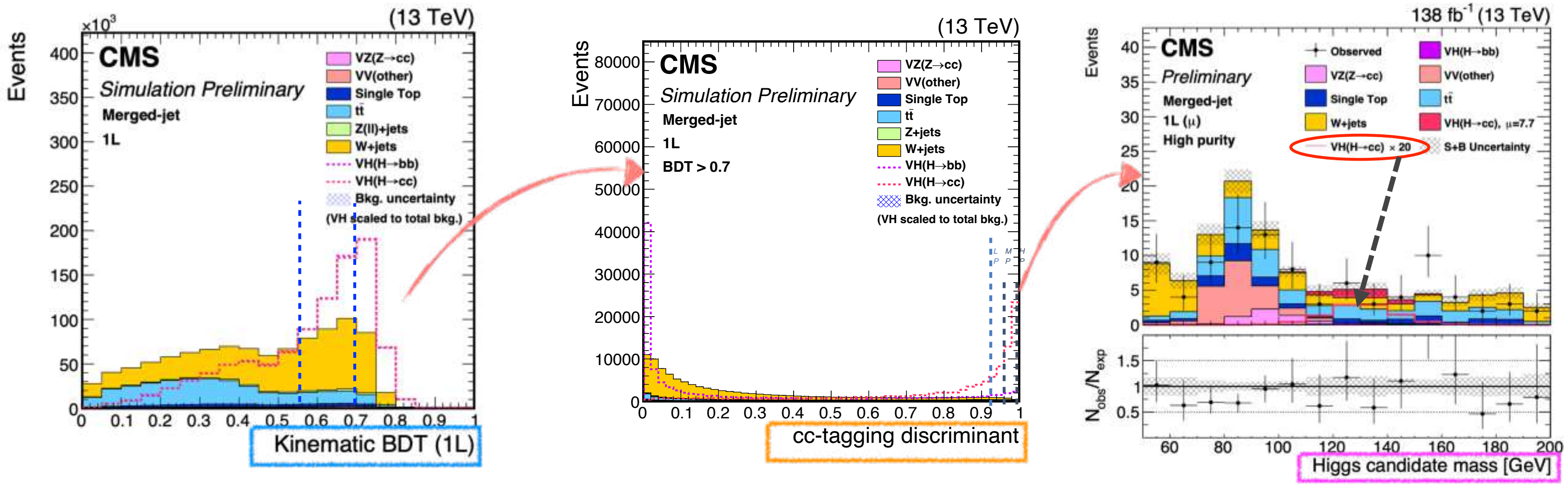




20 – 25% improvement in the final sensitivity

Analysis strategy – merged-jet topology

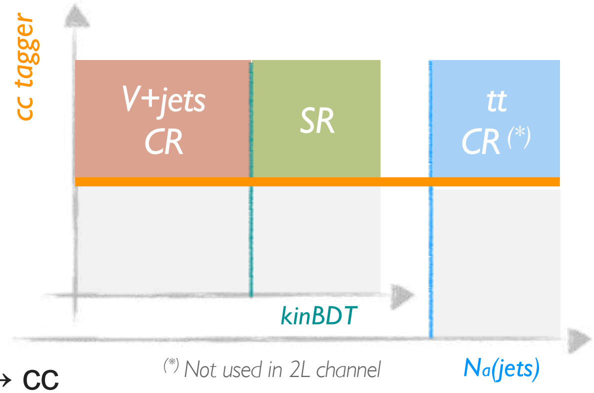
- ❑ Factorized approach for analysis design
  - event-level kinematic BDT developed in each channel to better suppress main backgrounds (V+jets, tt)
    - using only *event kinematics*, no intrinsic properties (e.g., mass/flavor) of the large-R jet
  - ParticleNet cc-tagger then used to define 3 cc-flavor enriched regions and reject light/bb-flavor jets
  - finally: fit to the ParticleNet-regressed large-R jet mass shape for signal extraction
- ❑ Kinematic BDT, ParticleNet cc-tagger and regressed jet mass largely independent of each other
  - Sand robust strategy for background estimation and signal extraction



Background estimation

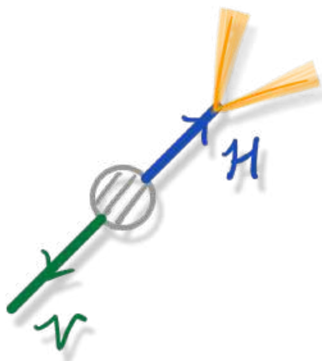
- Normalizations of main backgrounds estimated via dedicated data control regions (CRs)
  - V+jets CR: use the low kinematic BDT region
  - tt CR (0L & 1L): invert the cut on the number of additional small-R jets (i.e., $N_{aj} \geq 2$)
  - free-floating parameters scale the normalizations in CRs and signal regions (SRs) simultaneously

- CRs designed to have similar jet flavor composition as the SR
  - flavor-independent kinematic BDT + same cc-tagging requirement in CRs as in SR
  - allows to correct cc-tagging efficiency for backgrounds directly from data
  - cc-tagging SFs only needed for the signal VH(H → cc) process (and VZ(Z → cc))
    - conservative uncertainty (2x/0.5x) for the misidentification of H(Z) → bb as H(Z) → cc

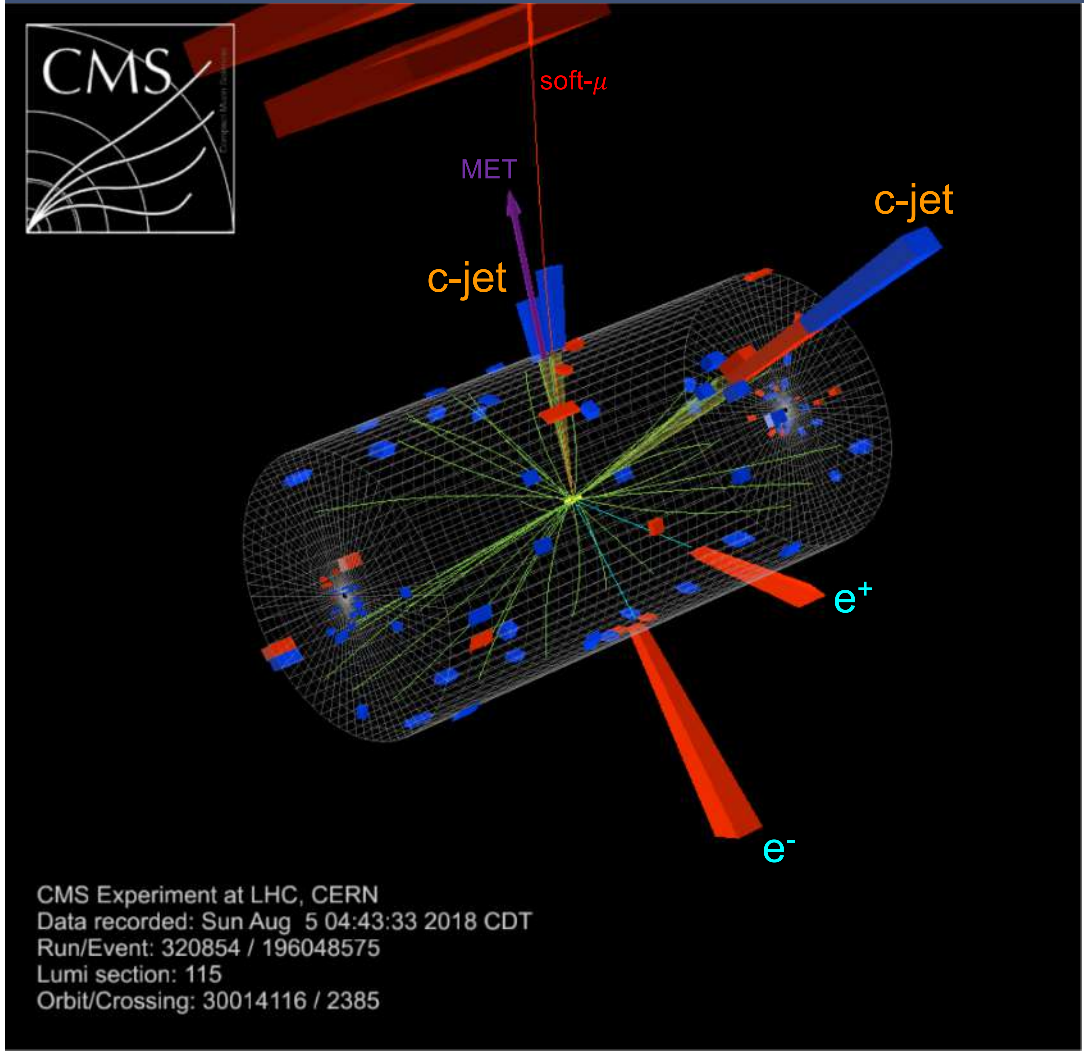


- Minor backgrounds (single top, dibosons, VH(H → bb)) estimated from simulation
  - dibosons: applying differential NNLO QCD + NLO EW corrections as a function of $p_T(V)$ [JHEP 2002 (2020) 087]

Resolved-jet topology



Overview of the resolved-jet topology



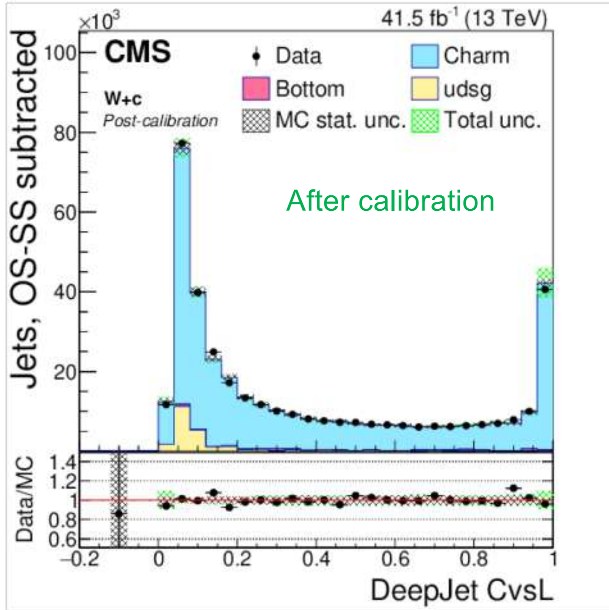
- Higgs candidate reconstruction
  - Select two AK4-jets with the highest c-tagger discriminant score as Higgs jets
  - Dedicated c-jet energy regression for improved c-jet energy scale and resolution (eg. recovery of neutrino, unclustered hadrons, etc.) + Recover FSR-jets
  - Kinematic-fit (2L channels)

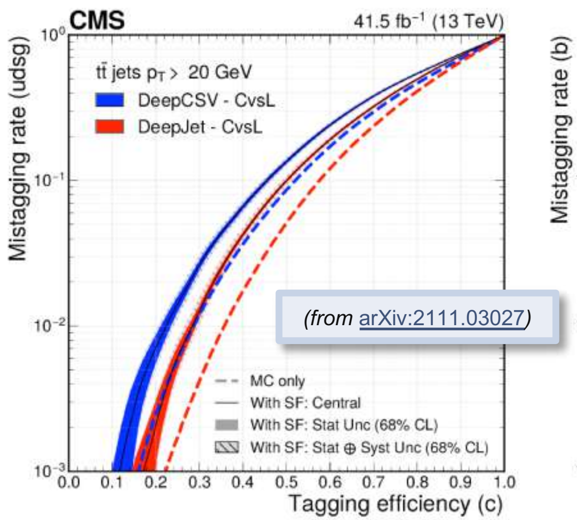
- Analysis strategy (three channels: 0L, 1L, 2L)
  - Control regions for background normalizations
  - BDT for final signal extraction

Charm-tagging in the resolved-jet topology

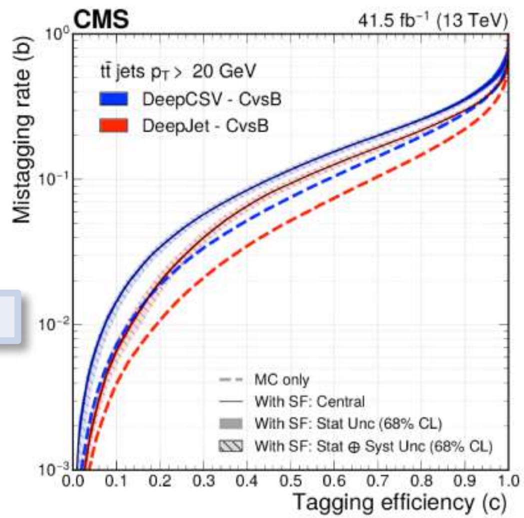
DeepJet algorithm as charm tagger

- C-jets have "intermediate" properties to b- and light-jets
  - Separate **c-jets** simultaneously from **light-jets** and **bottom jets**
- From DeepJet output score it is possible to build two c-jet taggers
  - CvsL: it is optimized to differentiate charm-jets form light- or gluon-jets
  - CvsB: it is optimized to differentiate charm-jets from bottom-jets





(from arXiv:2111.03027)



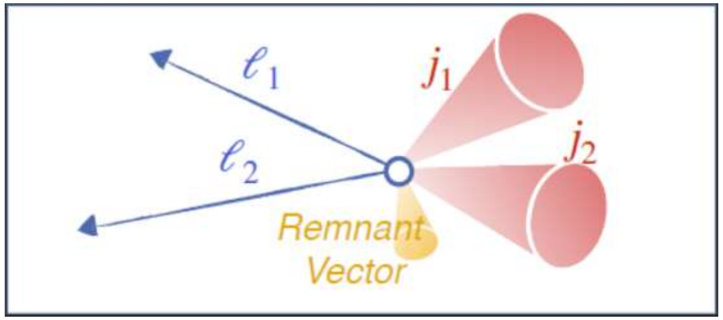
- Calibration in data with a novel technique!
- 2022 *JINST* **17** P03014 (**published by *JINST***)

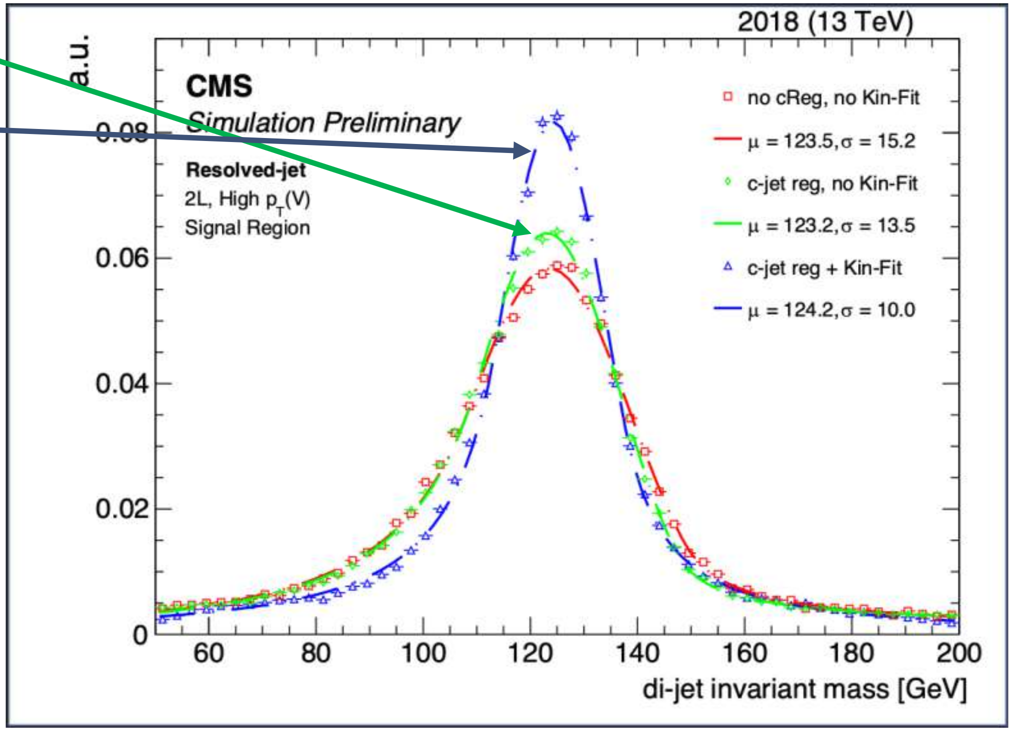
- Improvement vs DeepCSV (used in 2016 analysis)
  - Increase leading-jet c-tagging efficiency by ~30% for fixed b-jet and light-jet mis-tagging rate

Improvement of the di-jet invariant mass reconstruction

- Dedicated c-jet energy regression + FSR-jet recovery
  - **Up to ~15% improvement in Higgs mass resolution**

- kinematic fit in the 2L channel:
  - Constrain di-lepton system to the Z boson mass
  - Balance the $\ell\ell$+cc+jets system in the (p_x, p_y) plane
  - Allow MET to adjust within the experimental resolution





- Up to **~30% improvement in Higgs mass resolution**

Analysis categories and background estimation

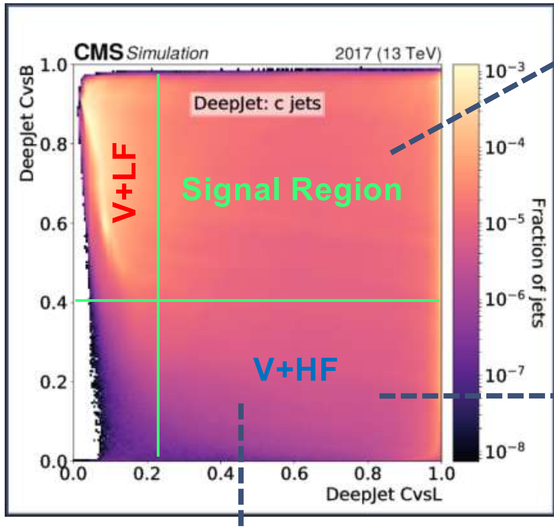
- Accurate modeling of jet flavor in V+Jet background is vital for proper signal extraction
  - Separate rate parameters for V+c, V+b, and V+light processes (no W+b) + $t\bar{t}$ +jets
  - Freely floating in each channel/year

- Selections optimized for the different decay of the vector boson considered

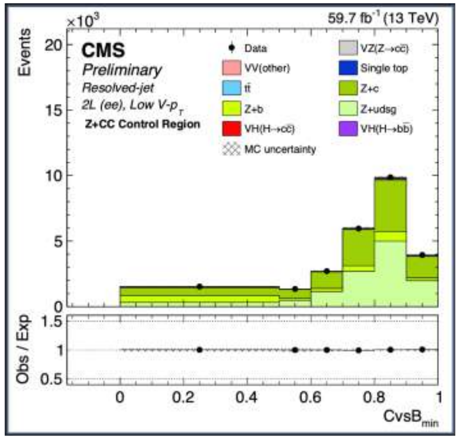
- Definition of 4 analysis categories
  - **0L**: $p_T(Z)>170$ GeV
  - **1L**: $p_T(W)>100$ GeV
  - **2L Low-p_T**: 60 GeV $<p_T(Z)<$150 GeV
  - **2L High-p_T**: $p_T(Z)>150$ GeV

- All the categories have TT, LF, HF and CC CRs (1L has not HF) + 1 SR

- Simultaneous fit to BDT in SR and tagger shapes in CRs

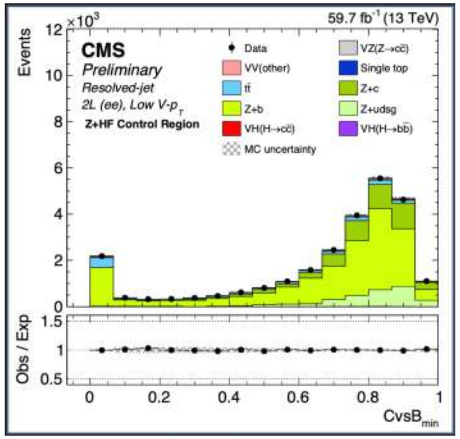


V+CC
⟺
Veto m(H) region



$t\bar{t}$
⟺
Invert Z mass (2L)
Require add jet (1L)*
Require add ℓ and jets (0L)

*1L: also require MET<170 GeV to keep orthogonal to 0L $t\bar{t}$ CR



Results

Uncertainties

- All correlated between topologies, except:
  - Background normalization SFs for V+jets and $t\bar{t}$
  - c-tagging efficiencies

- Main uncertainties
  - Limited statistics of data
  - Statistical uncertainties of V+jets samples
  - Charm tagging efficiencies

Uncertainty source	$\Delta\mu/\,(\Delta\mu)_{tot}$
Statistical	**85%**
Background normalizations	37%
Experimental	**48%**
Sizes of the simulated samples	37%
Charm identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Luminosity	6%
Lepton identification efficiencies	4%
Theory	**22%**
Backgrounds	17%
Signal	15%

VZ(Z→cc) results

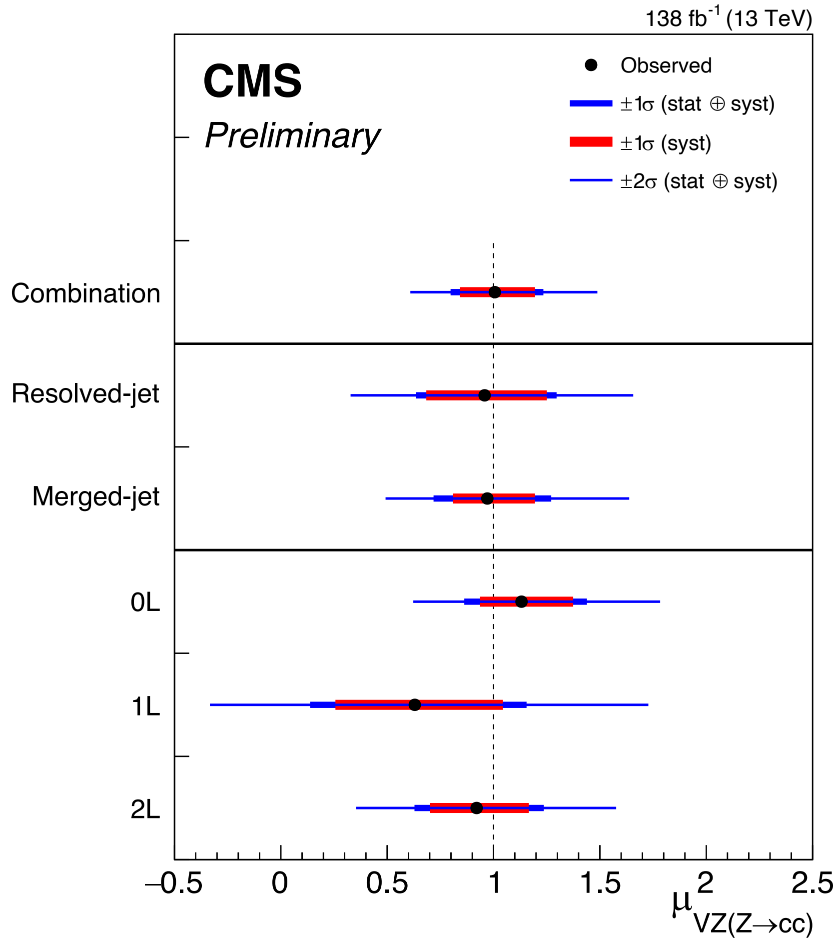
- Analysis validated by looking for VZ(Z→cc) process
  - Same analysis procedure, but extracting VZ(Z→cc) signal
  - Resolved-jet: retrained BDTs with VZ(Z→cc) as signal
  - VH(H→cc) fixed to SM expectation

- Observed (expected) signal strength for VZ(Z→cc):

$$\mu_{VZ(Z\to cc)} = 1.01^{+0.23}_{-0.21} (1.00^{+0.22}_{-0.20})$$

with a significance of 5.7σ (5.9σ)

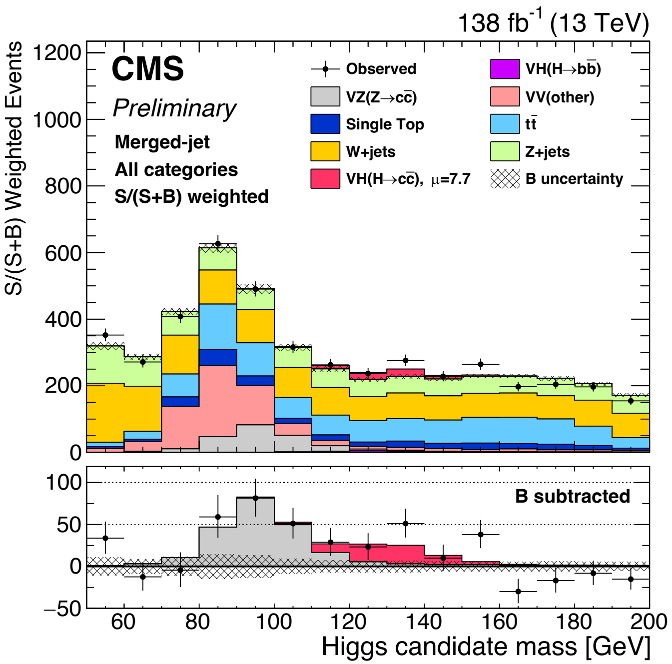
- **First observation of Z→cc at hadron collider!**



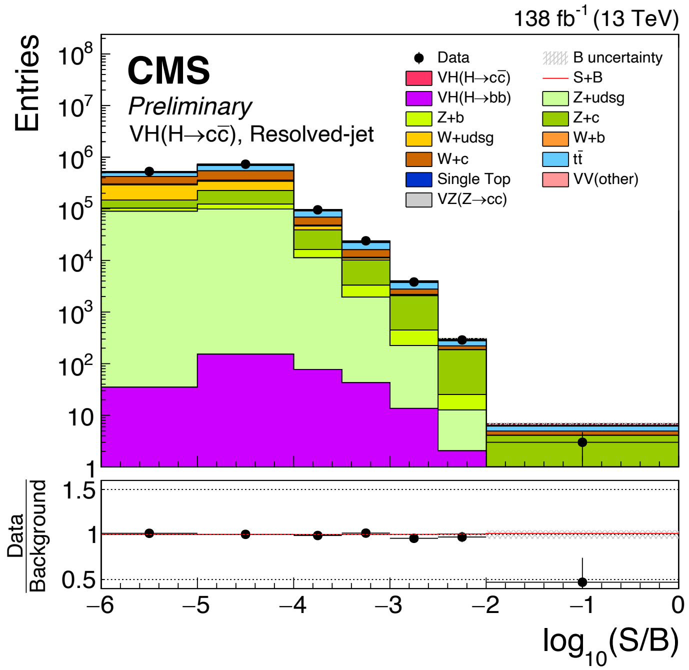
VH(H→cc) results

- ❑ Merged-jet topology: distribution of the Higgs boson candidate mass
- ❑ Resolved-jet topology and the combination: ordering the events by $\log_{10}(S/B)$

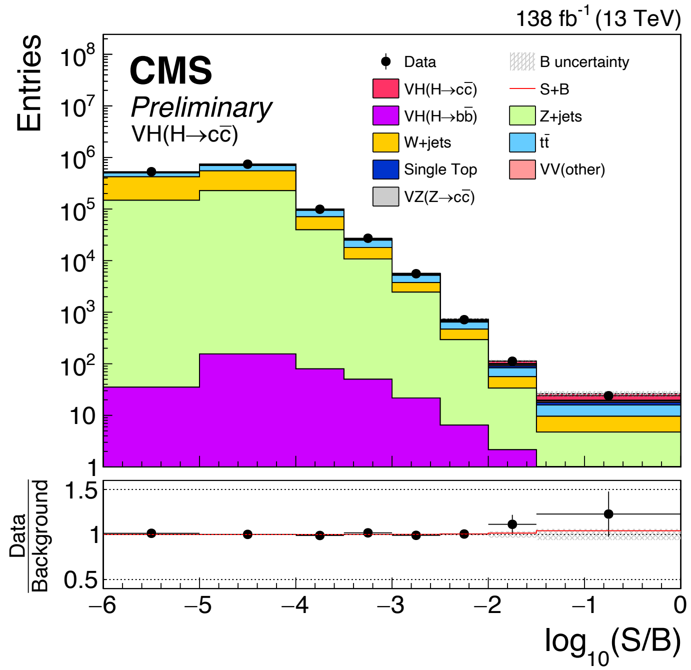
Merged-jet



Resolved-jet



Merged + Resolved

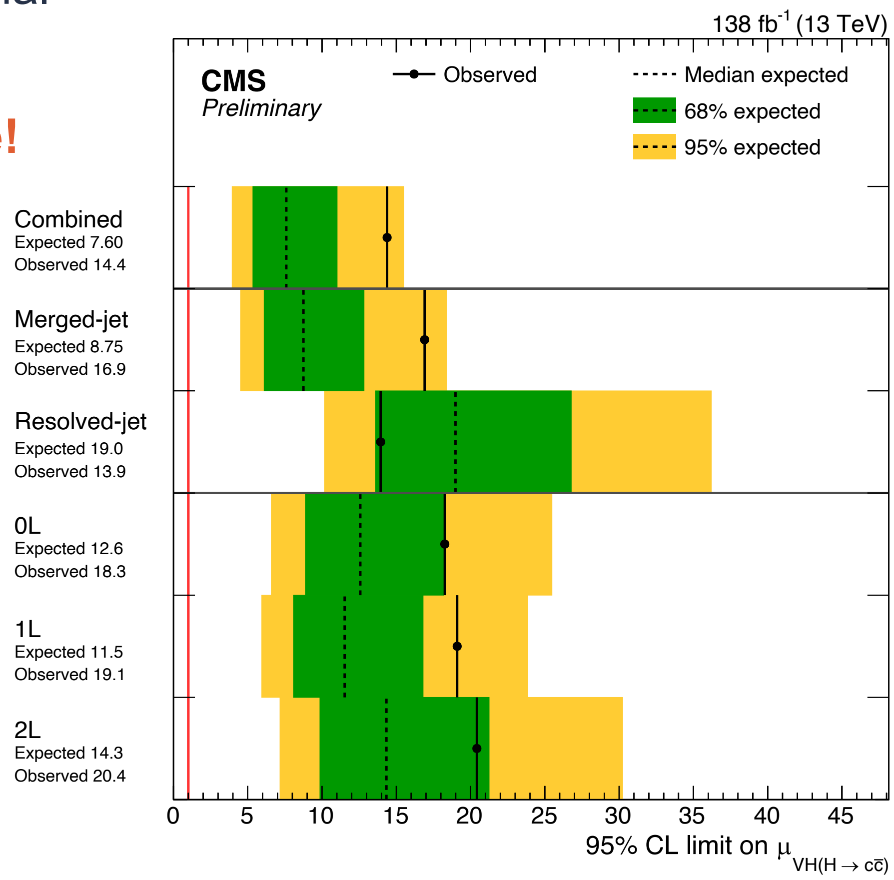


VH(H→cc) results

- Observed (expected) upper limit on VH(H→cc) signal strength at 95% CL: $\mu_{VH(H\to cc)} < 14\ (7.6^{+3.4}_{-2.3})$
  - **Strongest limits on VH(H→cc) process to date!**
  - ATLAS Full Run 2 result: $\mu_{VH(H\to cc)}$ < 26 (31) [arXiv:2201.11428]

- Best fit signal strength: $\mu_{VH(H\to cc)} = 7.7^{+3.8}_{-3.5}$
  - Consistent with the SM prediction within 2σ

- Obs. (Exp.) upper limits from each topology:
  - **Resolved-jet** topology: **14(19) × SM**
  - **Merged-jet** topology: **17(8.8) × SM**



VH(H→cc) results

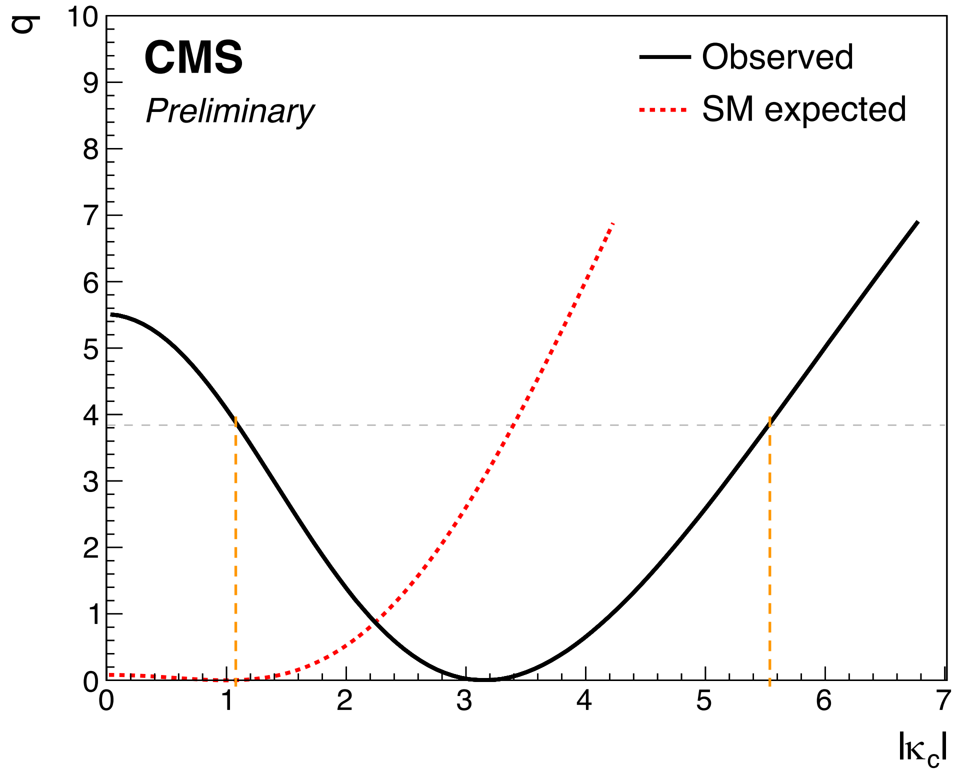
Results used to place new constraints on κ_c

- Only considering effects on $\mathcal{B}(\mathrm{H} \to \mathrm{cc})$ and fixing all other couplings to their SM values

$$\mu_{VH(H\to cc)} = \frac{\kappa_c^2}{1+\mathcal{B}_{SM}(H\to cc)\times(\kappa_c^2-1)}$$

- The 95% CL intervals obtained with likelihood scans
  - observed: $1.1 < |\kappa_c| < 5.5$
  - expected: $|\kappa_c| < 3.4$

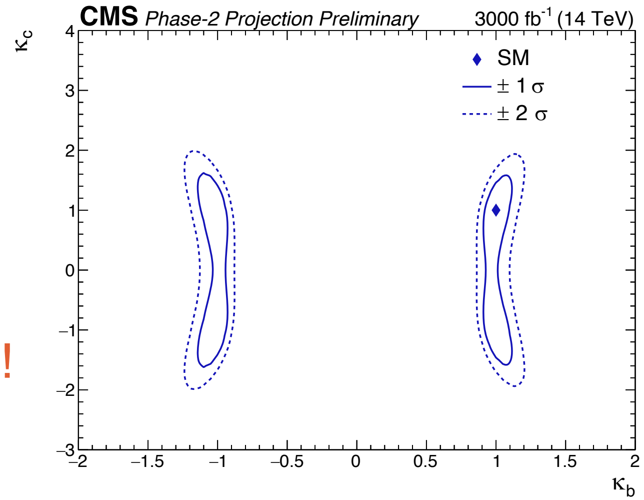
- **Strongest constraints on $|\kappa_c|$ to date**
  - Competitive with indirect measurements of $|\boldsymbol{\kappa_c}|$: PRD 92 (2015) 033016 and arXiv:2202.00487
  - Comparable to the previous projection for HL-LHC [ATL-PHYS-PUB-2021-039]



Conclusions

- New results of the CMS search for the VH(H→cc) process are presented
  - Benefit from the full Run 2 dataset
  - Substantial improvements in charm tagging performance
  - Major upgrades of analysis techniques, such as jet energy/mass regression, kinematic fits, etc.
- Analysis validated by measuring VZ(Z→cc) signal strength: $\mu_{VZ(Z \to cc)} = 1.01^{+0.23}_{-0.21}$
  - Significance of 5.7σ (5.9σ) ➔ First observation of Z→cc at a Hadron Collider!
- Upper limits on VH(H→cc): $\mu_{VH(H \to cc)} < 14$ (7.6 exp.)
  - ~5x increase in exp. sensitivity vs JHEP 03 (2020) 131
  - Constraints on Higgs-charm coupling:

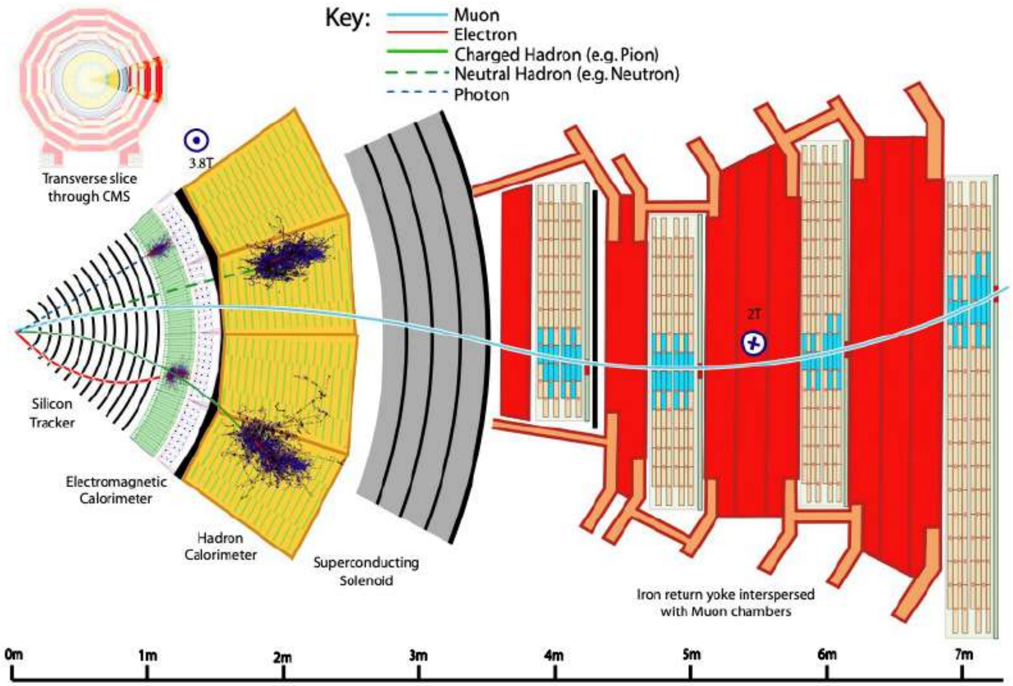
    $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$ exp.) — Most stringent to date!
- Projection for HL-LHC: $\mu_{VH(H \to cc)} < 1.6$ exp.



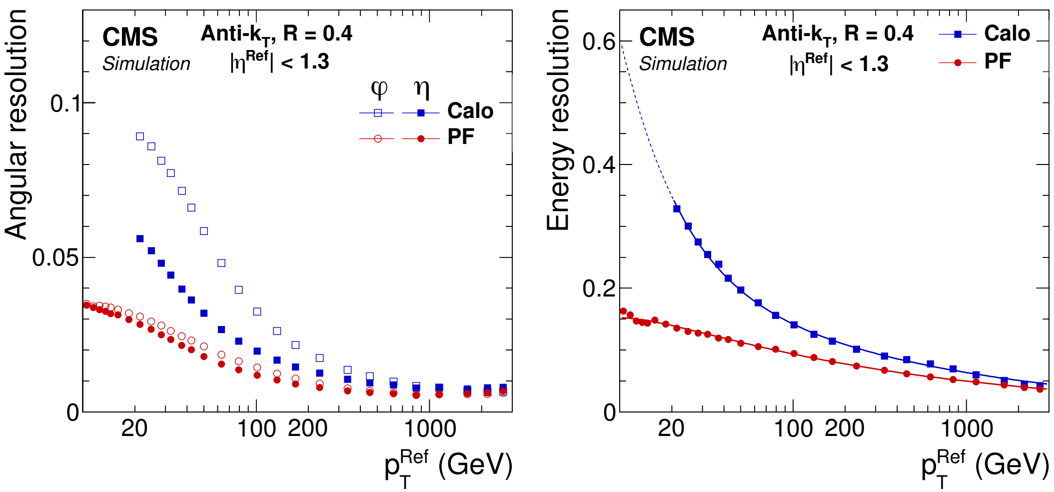
Backups

Particle-flow reconstruction

- Particle-flow (PF): powerful approach for jet reconstruction and flavor tagging
  - excellent energy and angular resolutions
  - each particle (PF candidate) contains a rich set of information from multiple sub-detectors — inputs to deep-learning

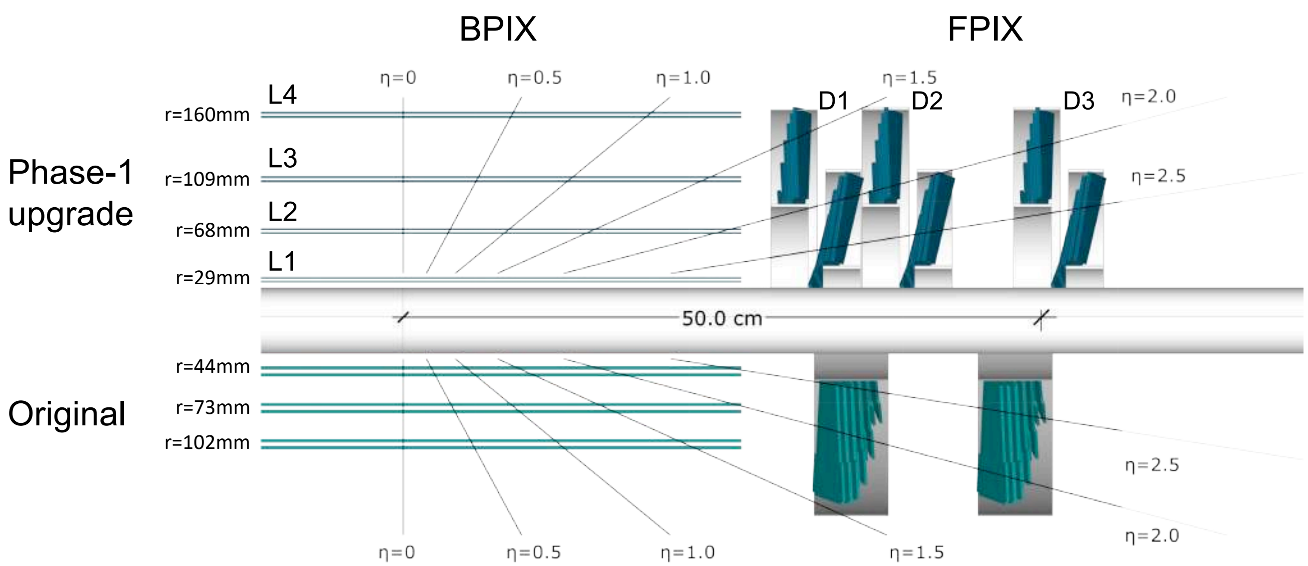


JINST 12 (2017) P10003

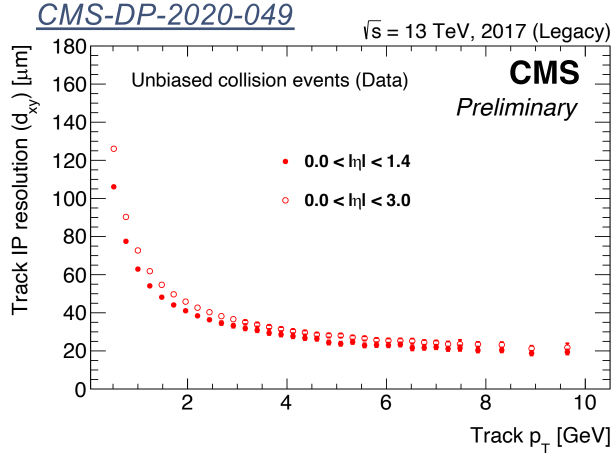


Phase-1 pixel detector upgrade

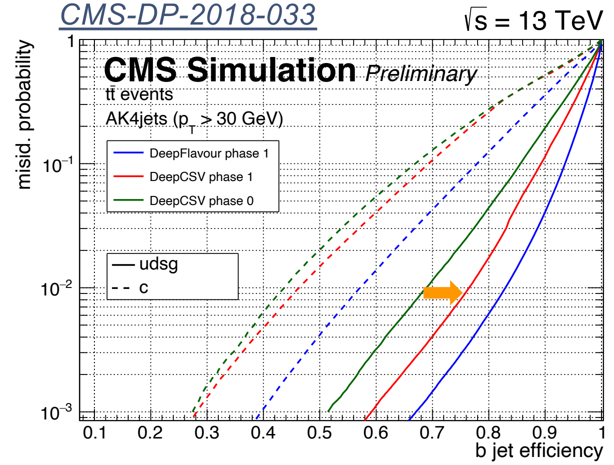
- New pixel detector installed during year-end stop 2016/2017



CMS-DP-2020-049



CMS-DP-2018-033



Improved tracking and flavour tagging performance in the 2017 — 2018 data set!

$H \rightarrow cc$ searches at the LHC

- ATLAS:
  - [Phys. Rev. Lett. 120 (2018) 211802] (36 fb^{-1})
  - [arXiv:2201.11428] (139 fb^{-1})
  - [ATL-PHYS-PUB-2021-039] (HL-LHC projection, 3000 fb^{-1})

- CMS:
  - [JHEP 03 (2020) 131] (36 fb^{-1})
  - [CMS-PAS-HIG-21-008] (138 fb^{-1}; HL-LHC projection, 3000 fb^{-1})

- LHCb:
  - [LHCb-CONF-2016-006] (1.98 fb^{-1})
  - [LHCb-PUB-2018-009] (HL-LHC projection, 300 fb^{-1})

Baseline event selections

Merged-jet topology

Variable	0L	1L	2L
p_T^ℓ	—	(>25,>30)	>20
Lepton isolation	—	(<0.06, —)	(<0.25, —)
$N_{a\ell}$	=0	=0	—
$M(\ell\ell)$	—	—	75–105
$N^{aj}_{small-R}$	<2	<2	<3
p_T^{miss}	>200	>60	—
$p_T(V)$	>200	>150	>150
$p_T(H_{cand})$	>300	>300	>300
$m\ (H_{cand})$	50–200	50–200	50–200
$\Delta\phi(V, H_{cand})$	>2.5	>2.5	>2.5
$\Delta\phi(\vec{p}_T^{miss}, j)$	>0.5	—	—
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	—	<1.5	—
Kinematic BDT	>0.55	0.55–0.7, >0.7	>0.55
$c\bar{c}$ discriminant			
High purity	>0.99	>0.99	>0.99
Medium purity	0.96–0.99	0.96–0.99	0.96–0.99
Low purity	0.90–0.96	0.90–0.96	0.90–0.96

Resolved-jet topology

Variable	0L	1L	2L low-$p_T(V)$	2L high-$p_T(V)$
p_T^ℓ	—	(>25,>30)	>20	>20
Lepton isolation	—	(<0.06, —)	(<0.25, —)	(<0.25, —)
$N_{a\ell}$	=0	=0	—	—
$M(\ell\ell)$	—	—	75–105	75–105
$p_T(j_1)$	>60	>25	>20	>20
$p_T(j_2)$	>35	>25	>20	>20
$CvsL(j_1)$	>0.225	>0.225	>0.225	>0.225
$CvsB(j_2)$	>0.4	>0.4	>0.4	>0.4
$N^{aj}_{small-R}$	—	<2	—	—
p_T^{miss}	> 170	—	—	—
p_T^{miss} significance	—	>4	—	—
$p_T(V)$	>170	>100	60–150	>150
$p_T(H_{cand})$	>120	>100	—	—
$m\ (H_{cand})$	<250	<250	<250	<250
$\Delta\phi(V, H_{cand})$	>2.0	>2.5	>2.5	>2.5
$\Delta\phi(\vec{p}_T^{miss}, j)$	>0.5	—	—	—
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	—	<2.0	—	—

Uncertainties

- Breakdown of the uncertainties in each topology

Merged-jet topology

Table 3: The relative contributions to the total uncertainty on $\mu_{VH(H\to c\bar{c})}$ in the merged-jet analysis, with a best fit value $\mu_{VH(H\to c\bar{c})} = 8.7^{+4.6}_{-4.0}$.

Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	**88%**
Background normalizations	39%
Experimental	**40%**
Sizes of the simulated samples	24%
Charm identification efficiencies	26%
Jet energy scale and resolution	15%
Simulation modeling	1%
Luminosity	5%
Lepton identification efficiencies	2%
Theory	**25%**
Backgrounds	21%
Signal	14%

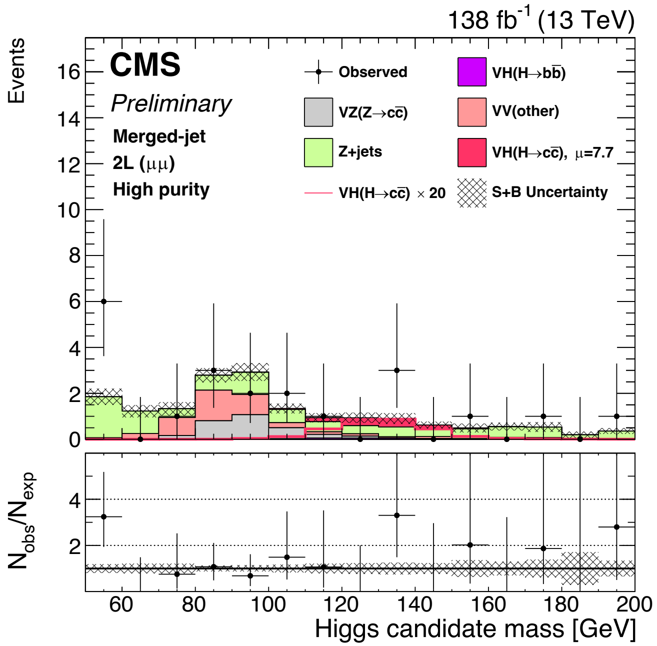
Resolved-jet topology

Table 4: The relative contributions to the total uncertainty on $\mu_{VH(H\to c\bar{c})}$ in the resolved-jet analysis, with a best fit value $\mu_{VH(H\to c\bar{c})} = -9.5 \pm 9.6$.

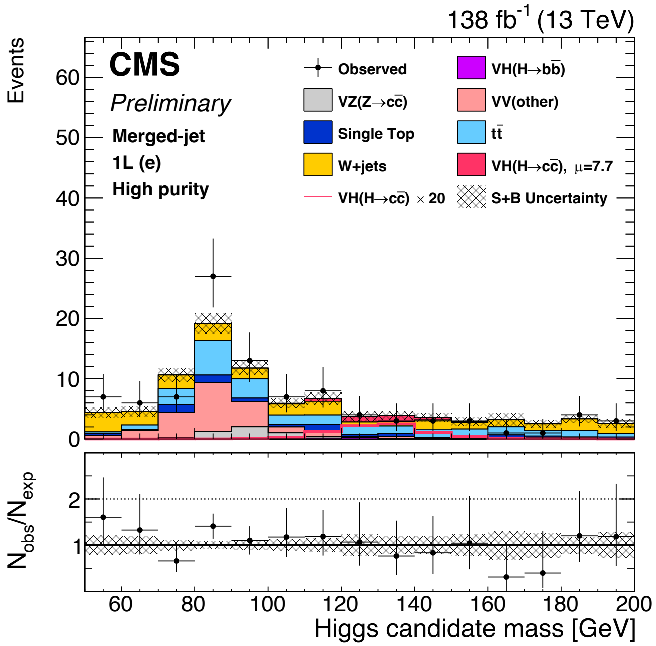
Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	**66%**
Background normalizations	28%
Experimental	**72%**
Sizes of the simulated samples	59%
Charm identification efficiencies	27%
Jet energy scale and resolution	17%
Simulation modeling	20%
Luminosity	13%
Lepton identification efficiencies	10%
Theory	**22%**
Backgrounds	21%
Signal	7%

Merged-jet topology: signal regions

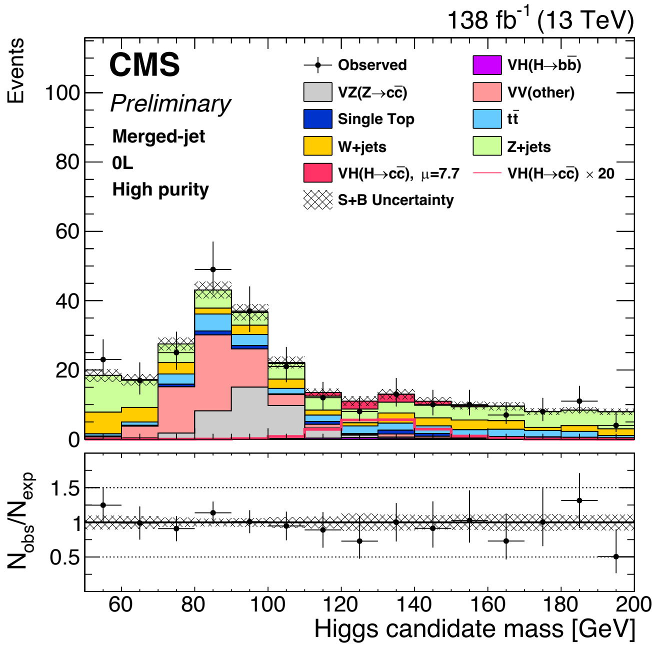
2L(μμ), high cc-purity



1L(e), high cc-purity

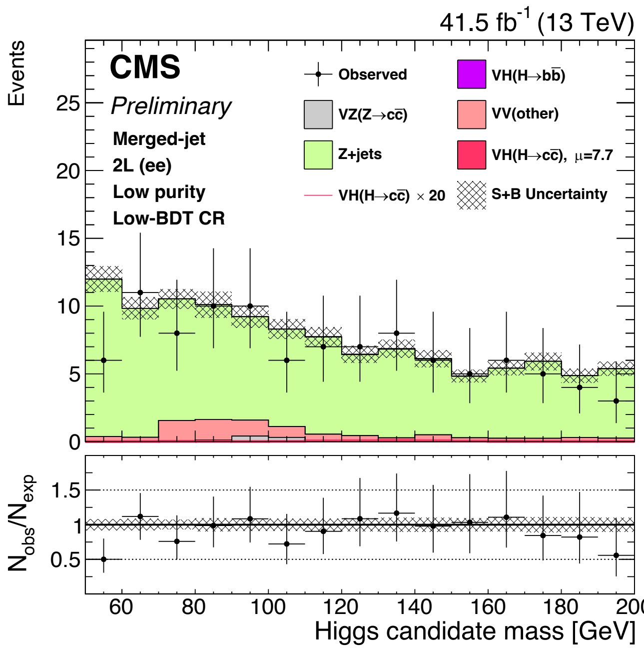


0L, high cc-purity

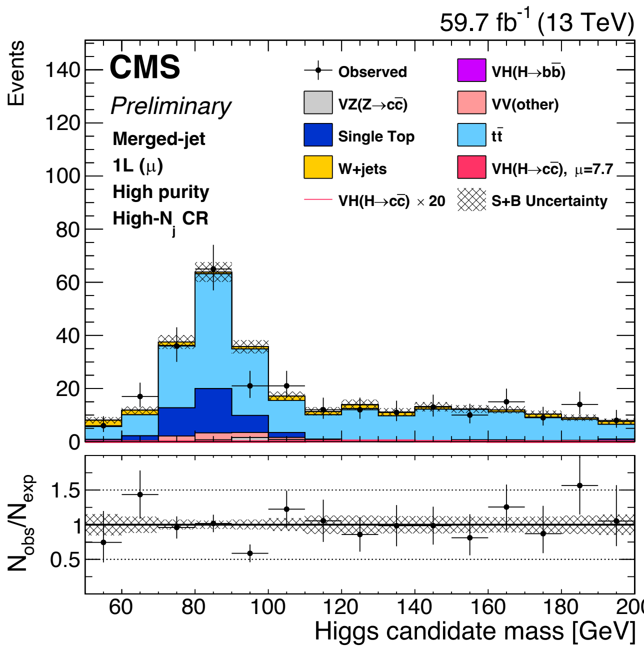


Merged-jet topology: control regions

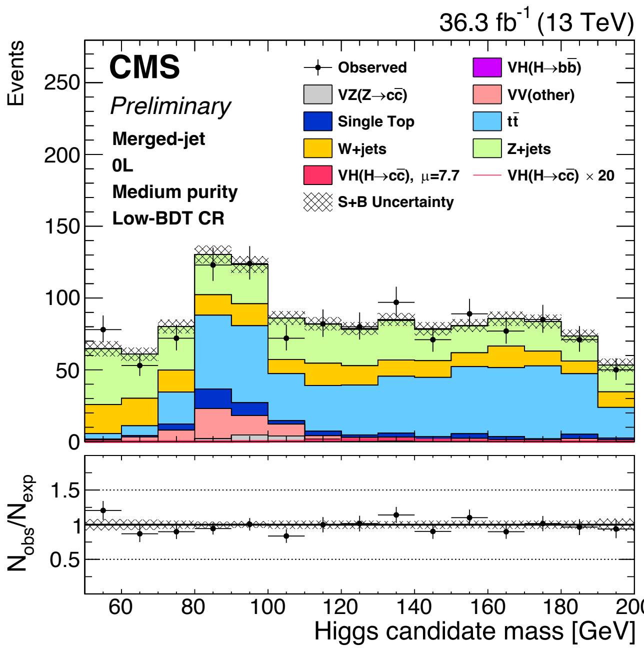
2L(ee), V+jets CR, low cc-purity



1L(μ), tt CR, high cc-purity

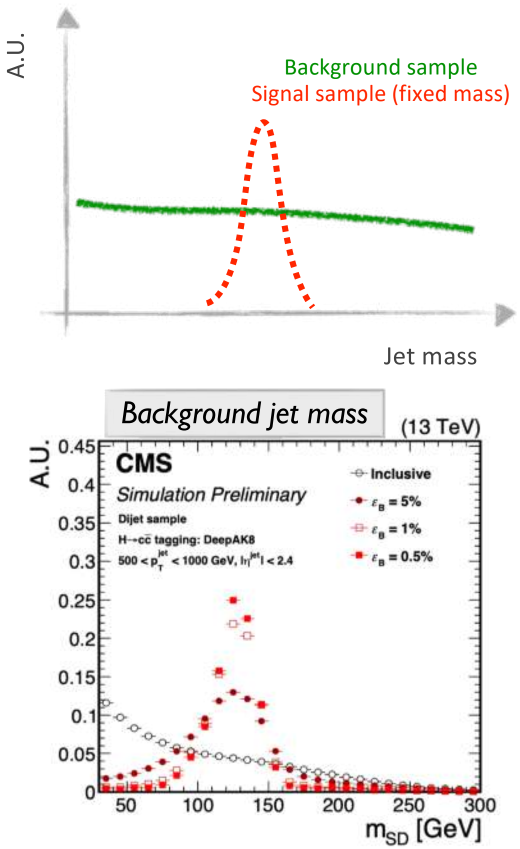


0L, V+jets CR, medium cc-purity

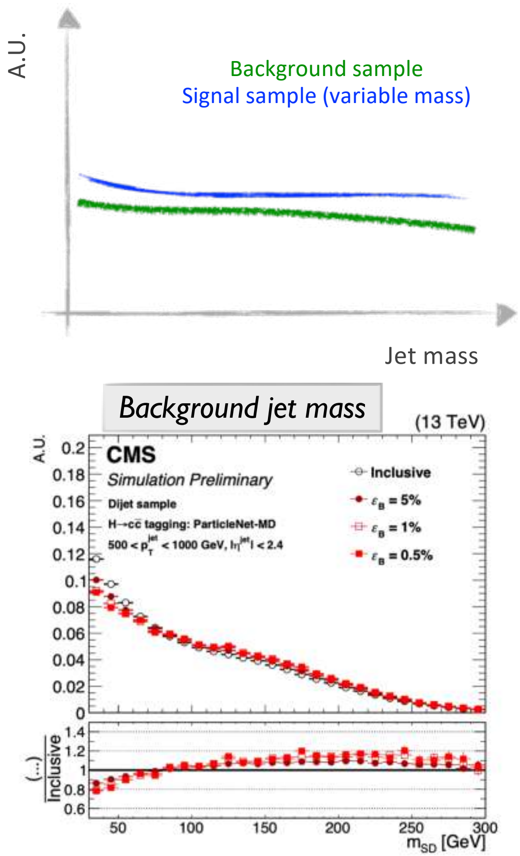


Mass decorrelation

Plain training:
no mass decorrelation



Mass-decorrelated
training

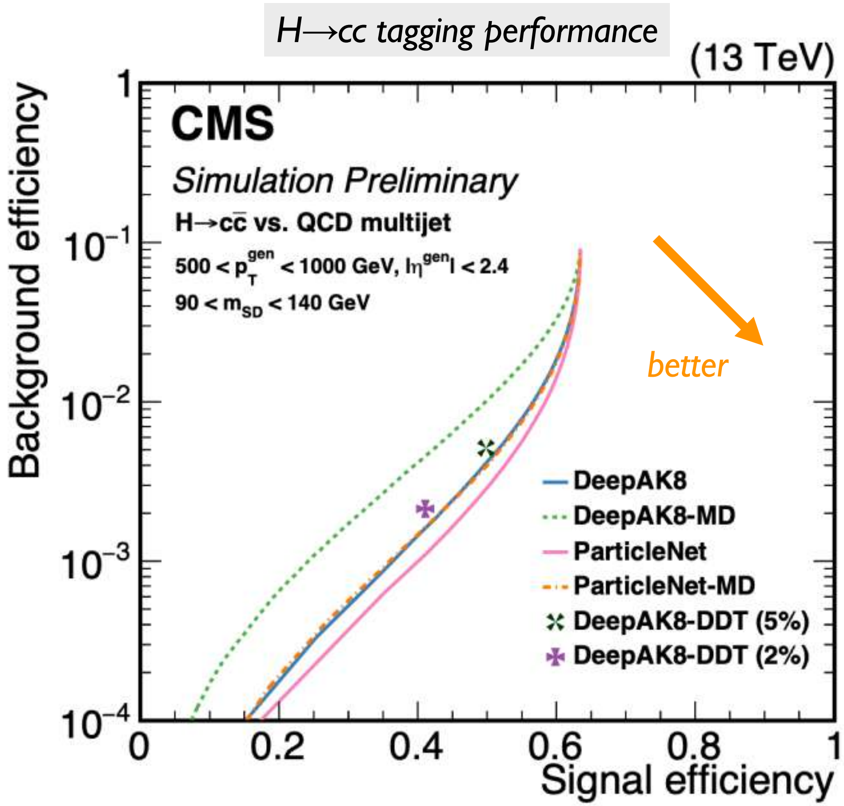


CMS-DP-2020-002

- "Mass sculpting": background jet mass shape becomes similar to signal after tagger selection
- New approach to prevent mass sculpting
  - using a special signal sample for training
    - hadronic decays of a spin-0 particle X
      - X → bb, X → cc, X → qq
    - not a fixed mass, but a **flat mass spectrum**
      - m(X) ∈ [15, 250] GeV
  - allows to easily reweight both signal and background to a ~flat 2D distribution in (p_T, mass) for the training
- Signal and background have the same (~flat) mass spectrum, thus no sculpting will develop in the training

Mass decorrelation (II)

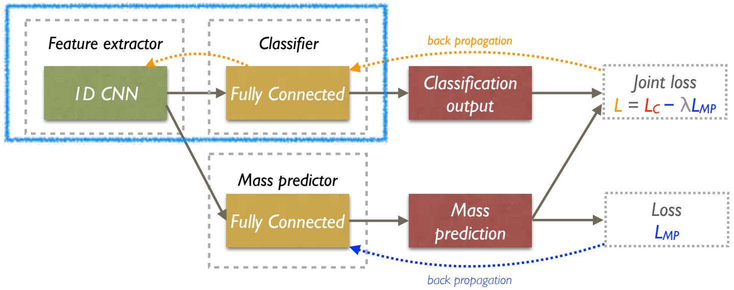
CMS-DP-2020-002



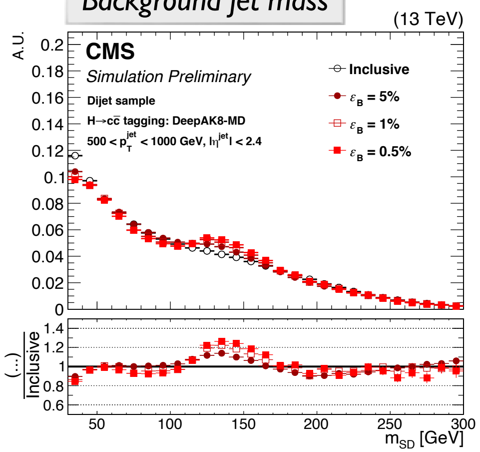
- "Mass sculpting": background jet mass shape becomes similar to signal after tagger selection
- New approach to prevent mass sculpting
  - using a special signal sample for training
    - hadronic decays of a spin-0 particle X
      - $X \to bb$, $X \to cc$, $X \to qq$
    - not a fixed mass, but a **flat mass spectrum**
      - $m(X) \in [15, 250]$ GeV
  - allows to easily reweight both signal and background to a ~flat 2D distribution in (p_T, mass) for the training
- Performance loss due to mass decorrelation greatly reduced compared to the previous approach (DeepAK8-MD, based on "adversarial training")

Comparison of mass decorrelation methods

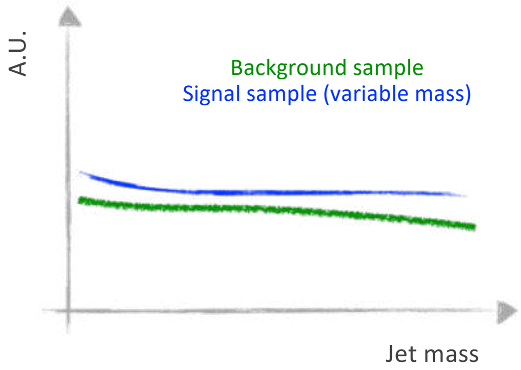
DeepAK8-MD



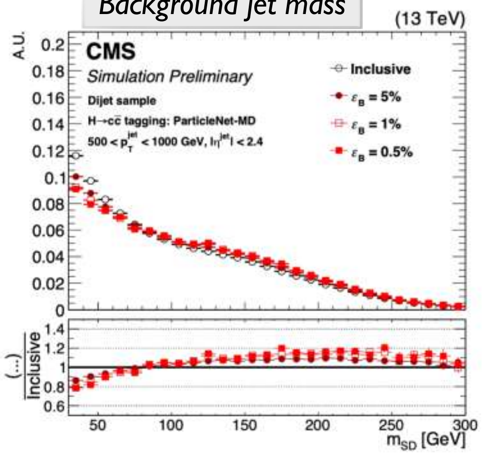
Background jet mass



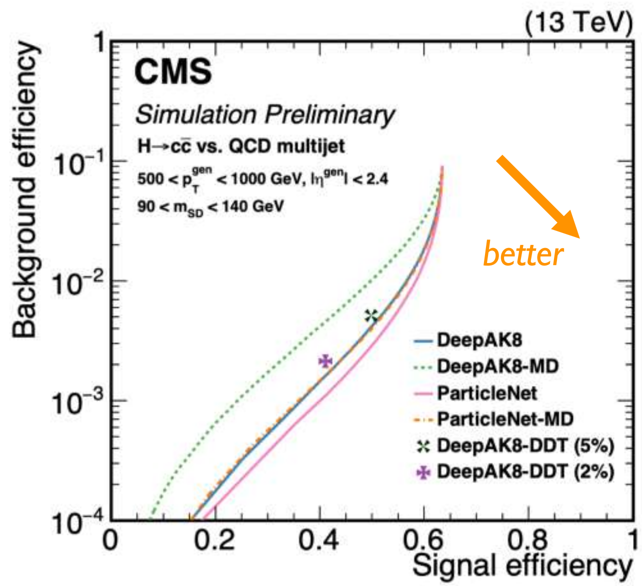
ParticleNet-MD



Background jet mass



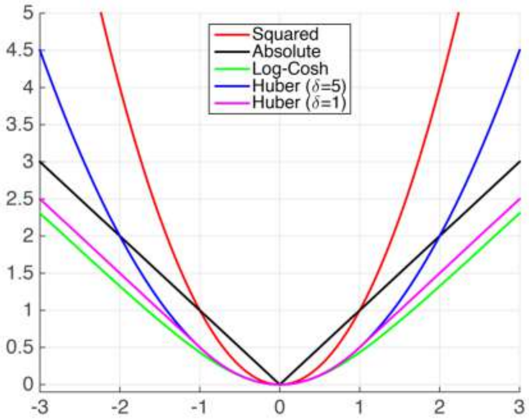
H→cc tagging performance



Large-R jet mass regression

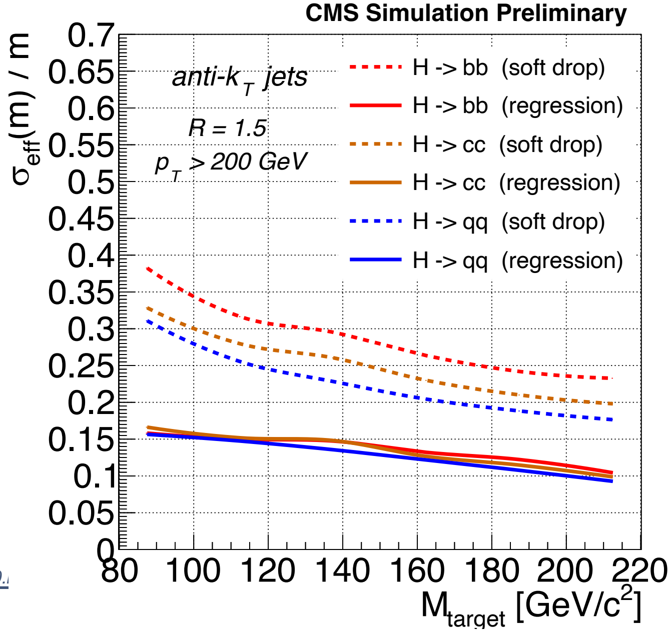
Loss function: LogCosh

$$L(y, y^p) = \sum_{i=1}^{n} \log(\cosh(y_i^p - y_i))$$

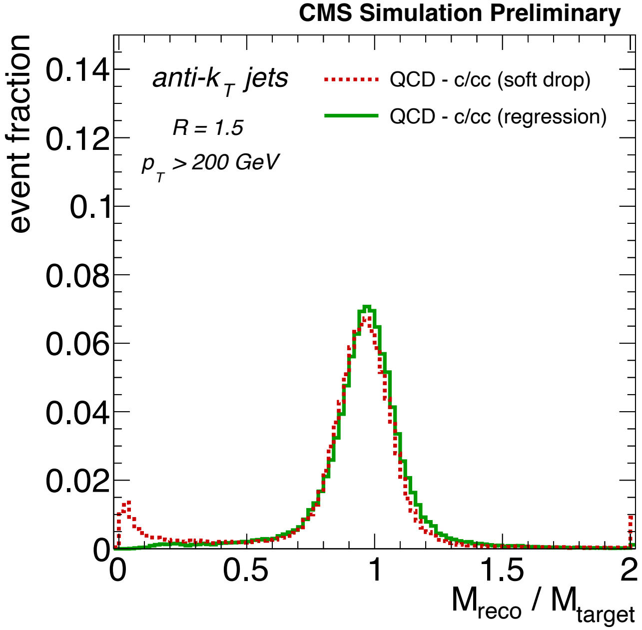


https://www.cs.cornell.edu/courses/cs4780/2015fa/web/lecturenotes/lecturenote10.

Signal jet mass resolution

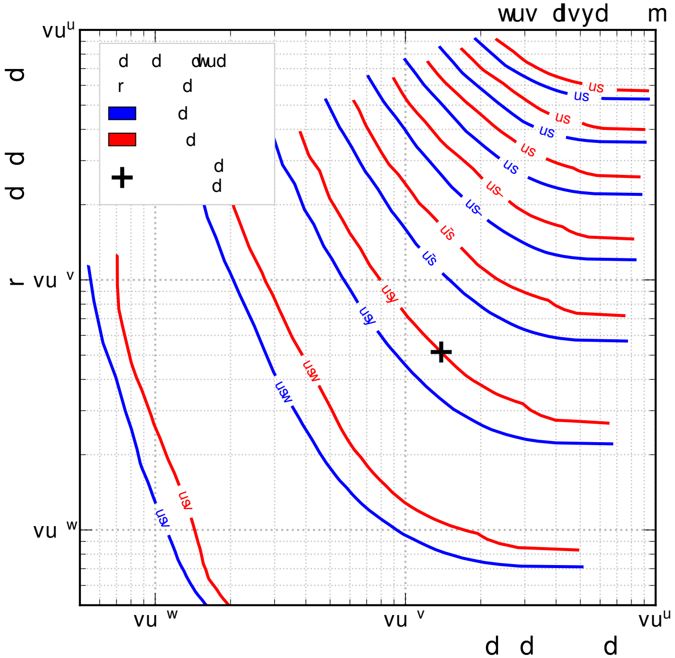


Background jet mass response

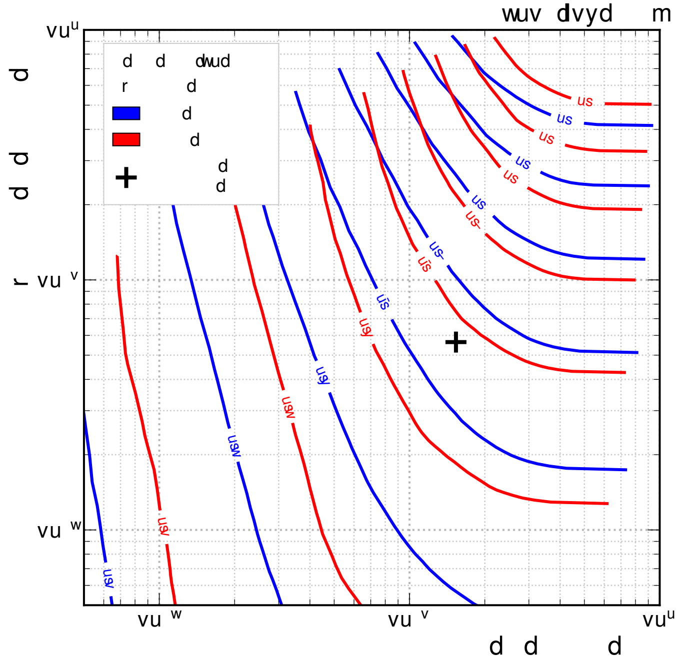


C-tagger ROC curves

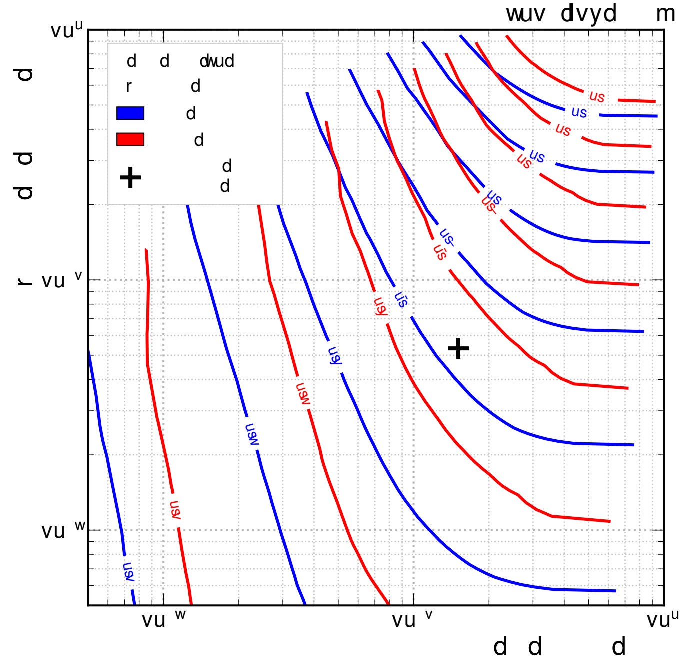
2016



2017



2018

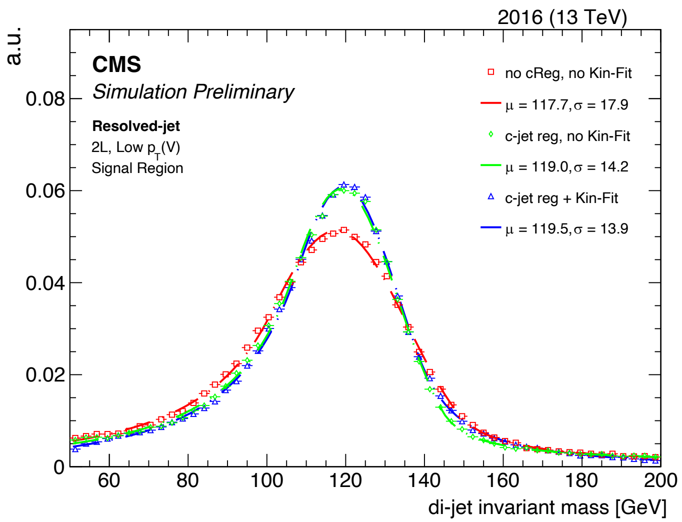


- CMS c-tagging WP: ~40% (c), ~16% (b), ~4% (light)
- ATLAS c-tagging WP [arXiv:2201.11428]: 27% (c), 8% (b), 1.6% (light)

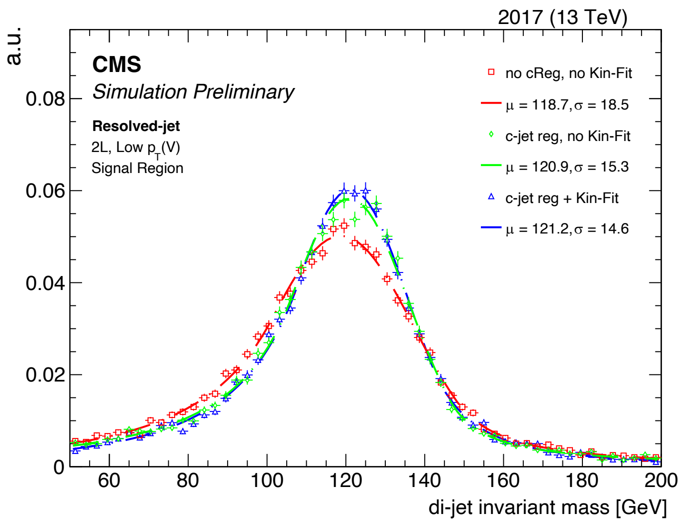
C-jet energy regression and kinematic fit

- 2-lepton Low-p_T(V) category – 60 GeV < p_T(V) < 150 GeV

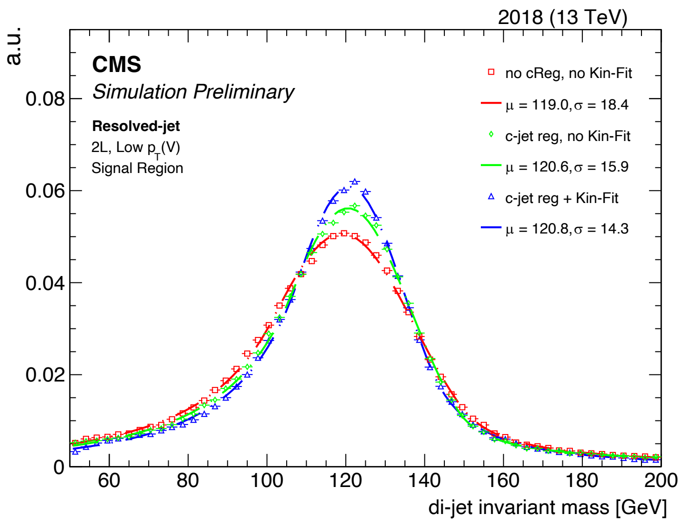
2016



2017



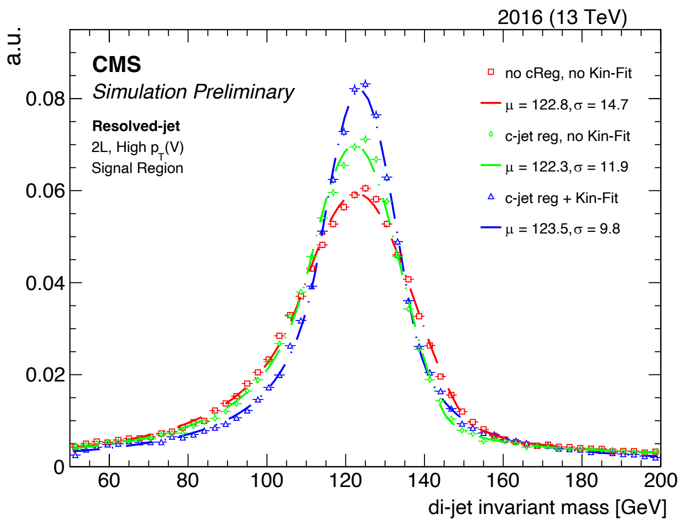
2018



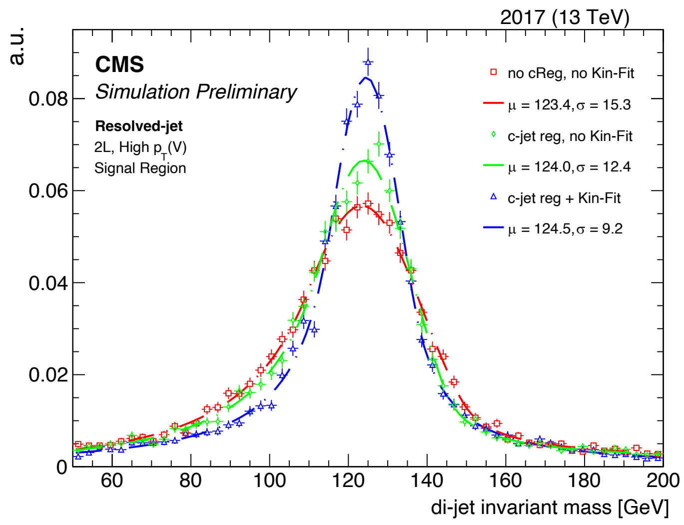
C-jet energy regression and kinematic fit

- 2-lepton High-p_T(V) category – p_T(V) > 150 GeV

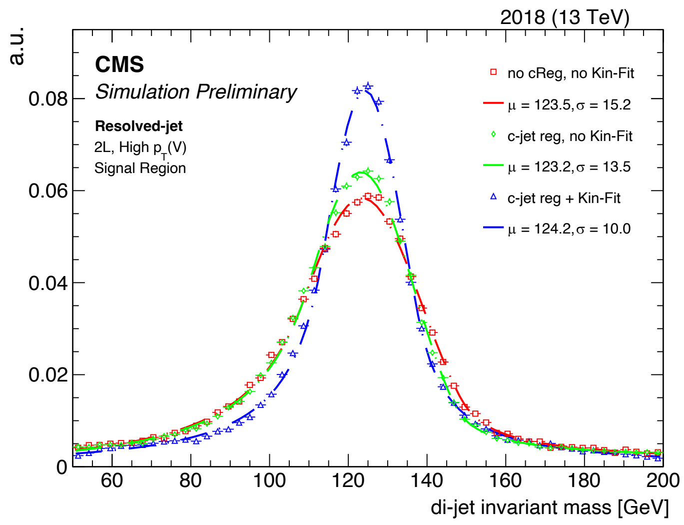
2016



2017



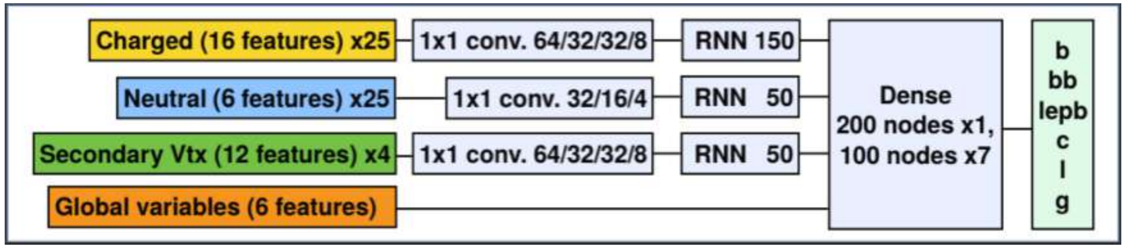
2018



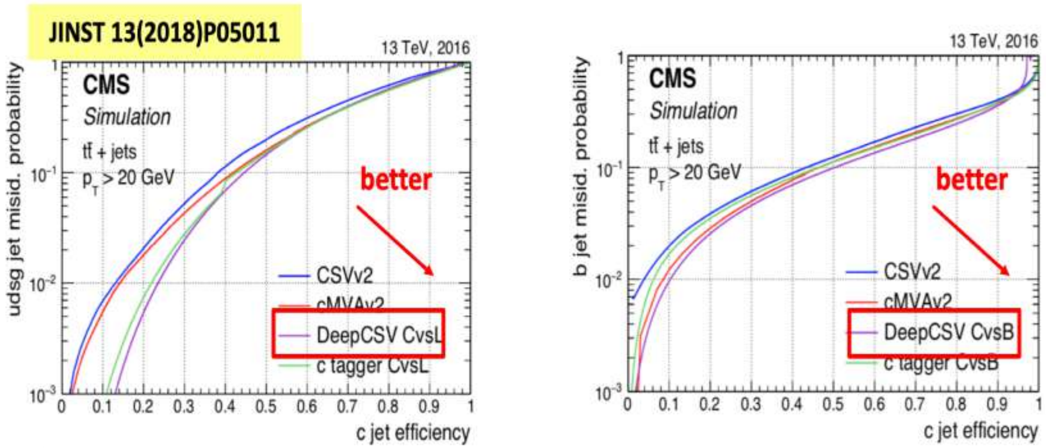
Charm-tagging in the “resolved-jet” topology

DeepJet algorithm – the cornerstone of the VH(cc) resolved-jet topology analysis

- ❑ Multiclassifier Deep Neural Network
  - Optimized for AK4-jets
  - Returns the probability for a given jet to be originated by a b-, c- or light-quark
- ❑ DNN architecture:
  - Separate 1D CNNs to process three low-level feature classes
    - For each class, concatenate multiple CNNs with decreasing dimensions
    - Compress the features to lower dimensional space
  - RNNs (LSTM type) applied after CNNs
    - Better handles the variable length sequence (PF candidates/SV)
  - Fully connected layer to connect all channels
- ❑ Input variables:
  - Properties of PF-candidates
  - Global jet features
  - Secondary vertices
- ❑ Output:
  - 6 raw scores



DeepJet architecture (from 2008.10519)

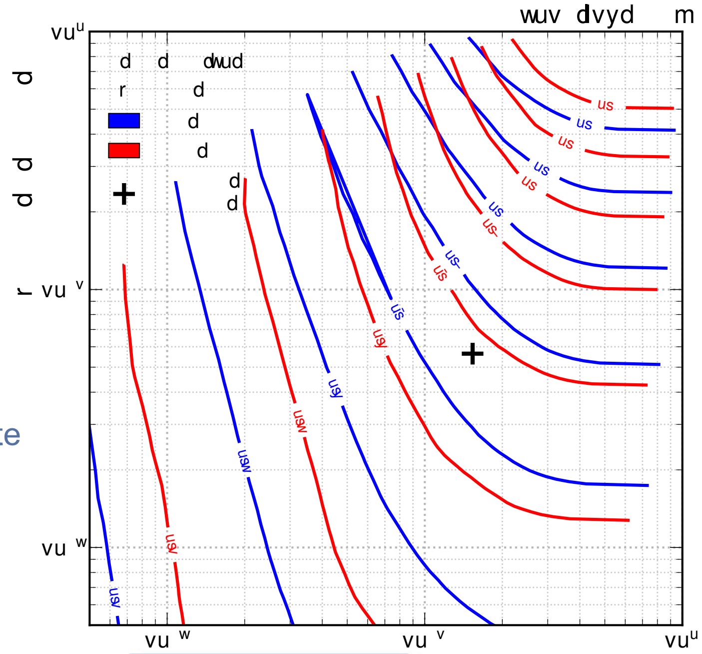


- DeepCSV: predecessor of DeepJet
- Used in the CMS VH(cc) analysis with 2016 data [*JHEP* **2020**,131]

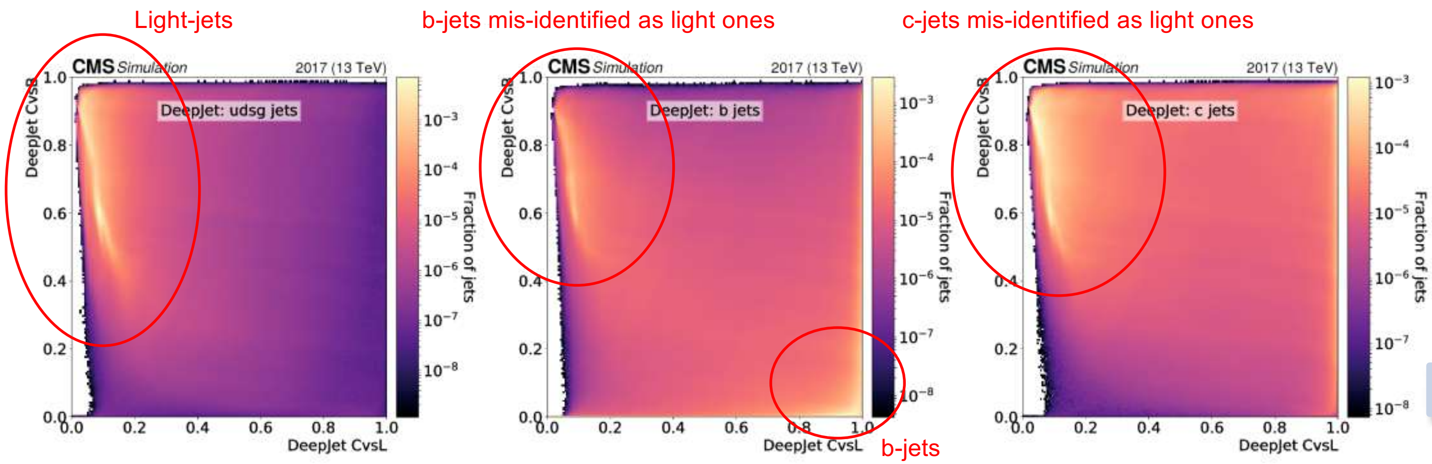
Charm-tagging in the "resolved-jet" topology

DeepJet algorithm as charm tagger

- Definition of leading-jet working point
  - Dedicated studies of the simulated jets distribution in the CvsB/CvsL 2D plane
  - It's possible to define regions to isolate c-jets vs b- and light-jets
  - **CvsL>0.225, CvsB>0.4** define the region with c-jet identification efficiency of ~43% with a b-jet and light-jet mis-tagging rate respectively of ~15% and ~4% (depending on the year)
- Improvement versus DeepCSV (used in the 2016 VH(cc) analysis)
  - Increase leading-jet c-tagging efficiency by ~30% for fixed b-jet and light-jet mis-tagging rate



(from CMS-PAS-21-008)



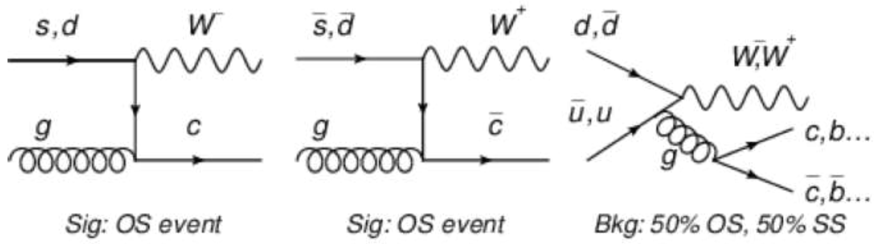
(from arXiv:2111.03027)

A new method to calibrate charm-taggers

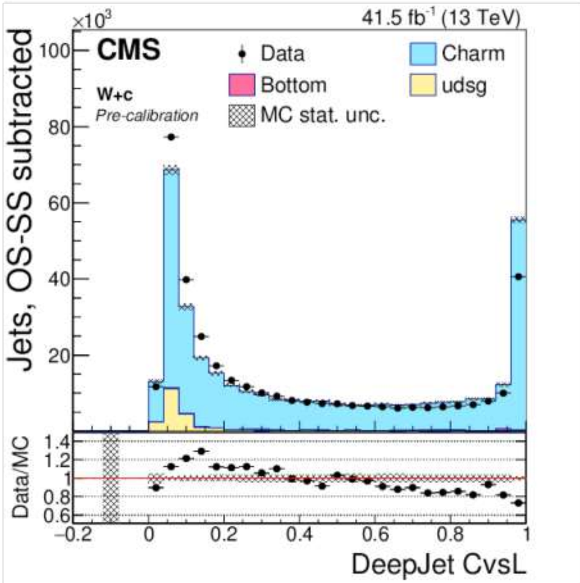
DeepJet algorithm calibration

- Methodology
  - Iterative approach exploiting three distinct control regions that are enriched with either b-jets, c-jets, or light-flavour and gluon jets
  - First time that a calibration method to correct the 2D distribution of c-tagging discriminator shapes is presented ➔ arXiv:2111.03027 (**accepted by *JINST***)

(from arXiv:2111.03027)

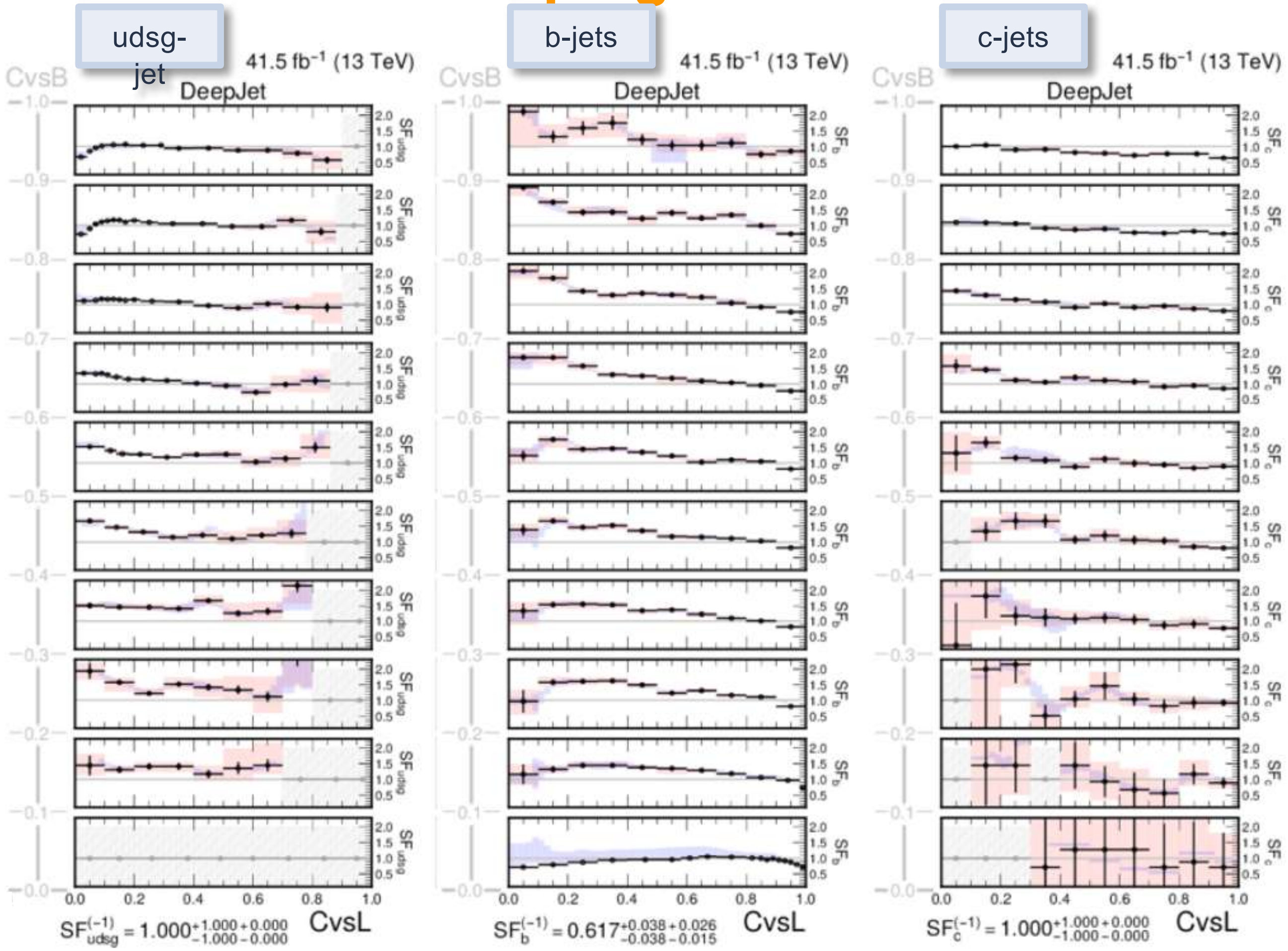


- Search for an abundant and pure source of charm-jets
  - Target W production in association with charm quarks
    - The relevant events involve a leptonically decaying W boson and a c-jet
    - These c-jets are identified using the semileptonic decay of the charmed hadrons, which produces a soft muon within the jet
  - Major background has 50% chance to have SS or OS final states ➔ performing an OS-SS subtraction reduces considerably the W+gluon process
  - To enrich in b-jets and light-jets, the semi-(di-)leptonic $t\bar{t}$+jets and DY(Z➔$\mu\mu/ee$)+jets processes are considered



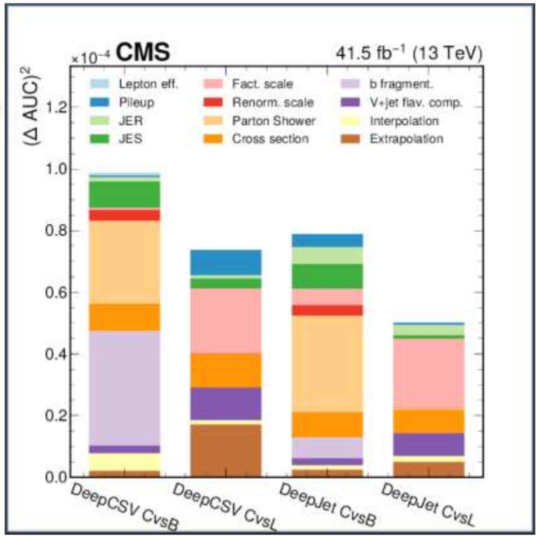
A new method to calibrate charm-taggers

Extraction of reshaping data-to-simulation scale factors



- SFs as a function of CvsL in bins of CvsB
  - Fixed bin width along CvsB and an adaptive binning scheme along CvsL (stat. depending)
  - Total uncertainties (red envelopes) relatively small in the region of interest of the analysis
  - Total uncertainties breakdown
    - Overall smaller than DeepCSV

(from arXiv:2111.03027)



A new method to calibrate charm-taggers

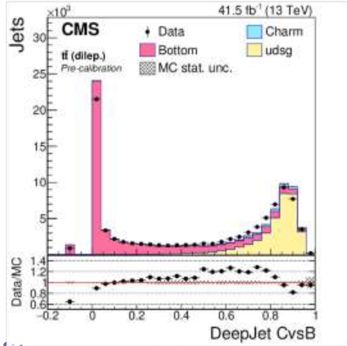
Validate robustness of the SFs derivation

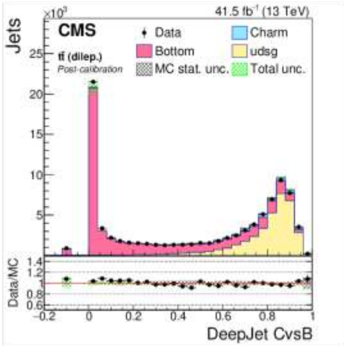
(*from* arXiv:2111.03027)

- ❑ Check possible bias due to the soft-μ-in-jet selection
  - SFs are derived without soft-μ selection
- ❑ Check possible bias between semileptonic or di-leptonic tt final states
  - SFs are derived also for the two separate processes independently
- ❑ Check possible bias due in the fit:
  - Inject *artificial* SFs to calculate the pulls between the fit result and the injected one

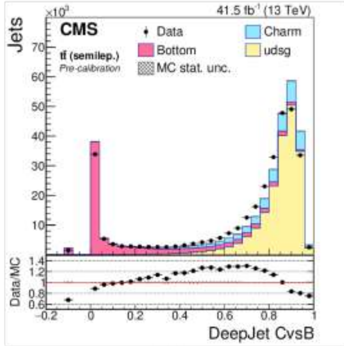
All the checks shown no bias in the SFs derivation

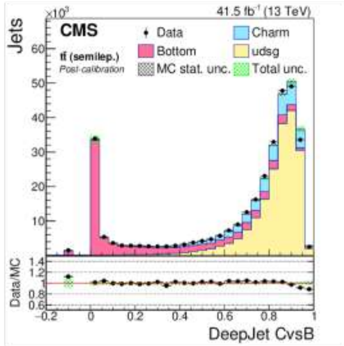
Only di-lep. tt
No soft-μ-in-jet



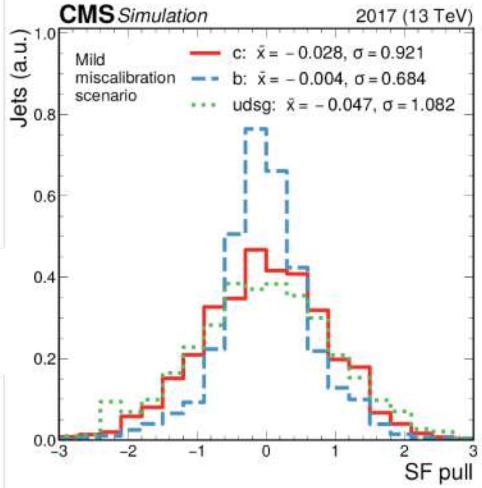


Only semi-lep. tt
No soft-μ-in-jet





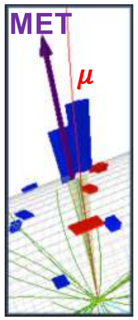
Bias test – pull distribution



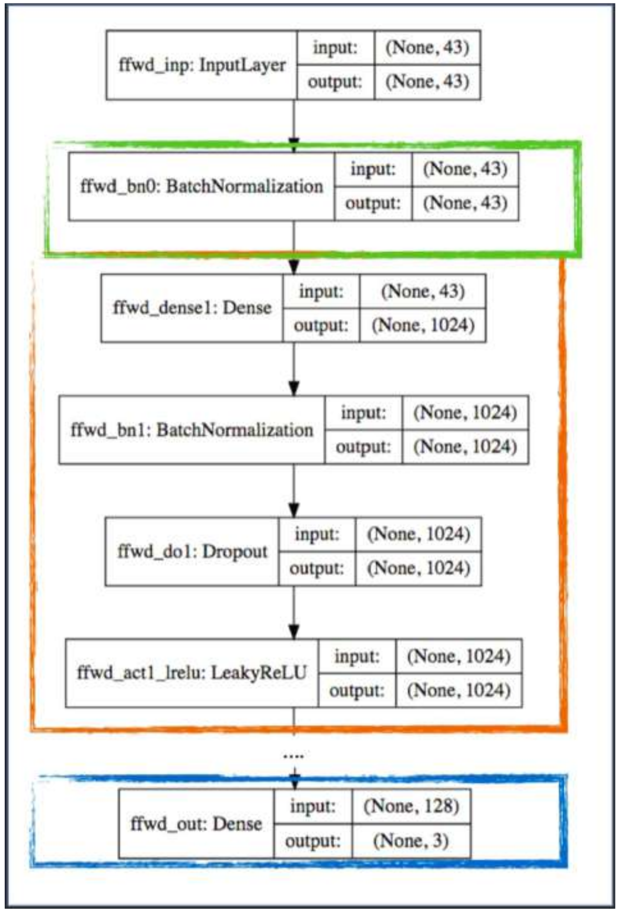
A dedicated charm-jet energy regression

Goal: improve c-jet energy scale and resolution

- Inspired by b-jet energy regression [arXiv:1912.06046]
  - Jet energy measurements not always accurate:
    - loss of neutrinos, hadrons outside jet radius. Effect enhanced in c-jets and b-jets
  - Dedicated algorithm to determine c-jet energy scale and resolution
  - Algorithm pioneered for the observation of the H→bb decay mode
- Regression performed using DNN architecture:
  - Feed-forward fully connected Deep NN (neurons with Leaky ReLu activation)
    - 6 hidden layers + batch normalization + dropout
  - Trained using c-jets collected from $W \rightarrow cq$ decays in $t\bar{t}$ MC events
  - Target is represented by p_T(gen)/p_T(reco)
- Input features
  - Total of 43 input variables in input to the network
  - Jets: kinematics, energy fraction, leading+soft-lepton tracks, pile-up, secondary vertexes
  - Jet energy shapes (e.g. energy fraction, etc), jet constituents, p_T(jet)/p_T(lepton)

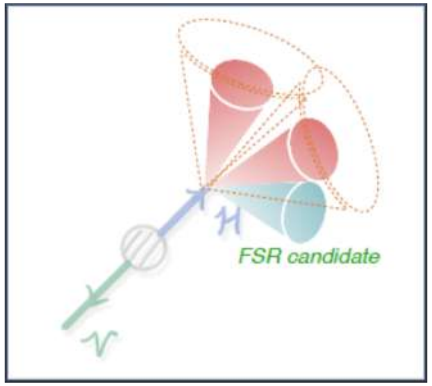


Charm-jet



FSR-jets recovery and H→cc reconstruction

- Higgs boson reconstructed using the two AK4 jets with highest CvsL scores
  - Energy regression is applied to the two Higgs jets
- FSR recovery used to further improve m(H) resolution
  - Jets with $p_T < 20$ GeV, $|\eta| < 3$, and within $\Delta R < 0.8$ of Higgs jets are included in Higgs 4-momentum



Variable	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T (V)	$Z(\ell\ell)H$ high-p_T (V)
$p_T(V)$	> 170	> 100	$[50-150]$	> 150
$m_{\ell\ell}$	–	–	$[75-105]$	$[75-105]$
p_T^{ℓ}	–	$(> 25(\mu), > 30(e))$	> 20	> 20
$p_T(j_1)$	> 60	> 25	> 20	> 20
$p_T(jtwo)$	> 35	> 25	> 20	> 20
$p_T(jj)$	> 120	> 100	–	–
$m(jj)$	< 250	< 250	< 250	< 250
$CvsL_{jone}$	> 0.225	> 0.225	> 0.225	> 0.225
$CvsB_{jtwo}$	> 0.40	> 0.40	> 0.40	> 0.40
N_{aj}	–	< 2	–	–
N_{al}	$= 0$	$= 0$	–	–
E_T^{miss}	> 170	–	–	–
METsig	–	> 4.0	–	–
Anti-QCD	Yes	–	–	–
$\Delta\phi(V,H)$(rad)	> 2.0	> 2.5	2.5	2.5
$\Delta\phi$(pfMET,trkMET)(rad)	< 0.5	–	–	–
$\Delta\phi$(pfMET,lep)(rad)	–	< 2.0	–	–

- Baseline selections shared with merged analysis
  - Resolved further split 2L:
    - High-p_T channel (p_T(V)>150 GeV)
    - Low-p_T channel (60<p_T (V)<150 GeV)
- Additional event selections placed based on tagger scores of leading Higgs Jet
  - CvsL > 0.225 and CvsB > 0.4

Signal extraction – BDT training in SRs

Variable	Description	0L	1L	2L
$m(\mathrm{H})$	H mass	✓	✓	✓
$p_T(\mathrm{H})$	H transverse momentum	—	✓	✓
$p_T(\mathrm{V})$	vector boson transverse momentum	—	✓	✓
$m_T(\mathrm{V})$	vector boson transverse mass	—	✓	—
p_T^{miss}	missing transverse momentum	✓	✓	—
$p_T(\mathrm{V})/p_T(\mathrm{H})$	ratio between vector boson and H transverse momenta	✓	✓	✓
$CvsL_{max}$	*CvsL* value of the leading *CvsL* jet	✓	✓	✓
$CvsB_{max}$	*CvsB* value of the leading *CvsL* jet	✓	✓	✓
$CvsL_{min}$	*CvsL* value of the subleading *CvsL* jet	✓	✓	✓
$CvsB_{min}$	*CvsB* value of the subleading *CvsL* jet	✓	✓	✓
$p_{T max}$	p_T of the leading *CvsL* jet	✓	✓	✓
$p_{T min}$	p_T of the subleading *CvsL* jet	✓	✓	✓
$\Delta\phi(\mathrm{V,H})$	azimuthal angle between vector boson and H	✓	✓	✓
$\Delta R(j_1, j_2)$	ΔR between leading and subleading *CvsL* jets	—	✓	✓
$\Delta\phi(j_1, j_2)$	azimuthal angle between leading and subleading *CvsL* jets	✓	✓	—
$\Delta\eta(j_1, j_2)$	difference in pseudorapidity between leading and subleading *CvsL* jets	✓	✓	✓
$\Delta\phi(\ell_1, \ell_2)$	azimuthal angle between leading and subleading p_T leptons	—	—	✓
$\Delta\eta(\ell_1, \ell_2)$	difference in pseudorapidity between leading and subleading p_T leptons	—	—	✓
$\Delta\phi(\ell_1, j_1)$	azimuthal angle between leading p_T lepton and leading *CvsL* jet	—	✓	—
$\Delta\phi(\ell_2, j_1)$	azimuthal angle between subleading p_T lepton and leading *CvsL* jet	—	—	✓
$\Delta\phi(\ell_2, j_2)$	azimuthal angle between subleading p_T lepton and subleading *CvsL* jet	—	—	✓
$\Delta\phi(\ell_1, p_T^{miss})$	azimuthal angle between leading p_T lepton and missing transverse momentum	—	✓	—
$\Delta\eta(\ell_1, t)$	difference in pseudorapidity between leading p_T lepton and b-tagged jet from top quark decay	—	✓	—
$\Delta\phi(\ell_1, t)$	azimuthal angle between leading p_T lepton and b-tagged jet from top quark decay	—	✓	—
$\Delta R(\ell_1, t)$	ΔR between leading p_T lepton and b-tagged jet from top quark decay	—	✓	—
$CvsL_t$	*CvsL* value of the b-tagged jet from top quark decay	—	✓	—
$CvsB_t$	*CvsB* value of the b-tagged jet from top quark decay	—	✓	—
$P(b+bb)_t$	*DeepJet prob(b+bb)* value of the b-tagged jet from top quark decay	—	✓	—
$m(t)$	Reconstructed top quark mass	—	✓	—
$N^{aj}_{small\text{-}R}$	Number of small-*R* additional jets after the FSR subtraction	—	✓	—
$\sigma_{cReg}(j_1)$	leading p_T jet resolution from c-jet energy regression	✓	✓	✓
$\sigma_{cReg}(j_2)$	subleading p_T jet resolution from c-jet energy regression	✓	✓	✓
$\Delta\eta(\mathrm{V,H})\|_{kinfit}$	difference in pseudorapidity between vector boson and H, after kinematic-fit	—	—	✓
$\Delta\phi(\mathrm{V,H})\|_{kinfit}$	azimuthal angle between vector boson and H, after kinematic-fit	—	—	✓
$m(\mathrm{H})\|_{kinfit}$	H mass after kinematic-fit	—	—	✓
$p_T(\mathrm{H})\|_{kinfit}$	H transverse momentum after kinematic-fit	—	—	✓
$p_{T max}\|_{kinfit}$	p_T of the leading *CvsL* jet after kinematic-fit	—	—	✓
$p_{T min}\|_{kinfit}$	p_T of the subleading *CvsL* jet after kinematic-fit	—	—	✓
$p_T(\mathrm{V})/p_T(\mathrm{H})\|_{kinfit}$	ratio between vector boson and H transverse momenta after kinematic-fit	—	—	✓
$\sigma(\mathrm{H})\|_{kinfit}$	H invariant mass resolution from kinematic fit	—	—	✓

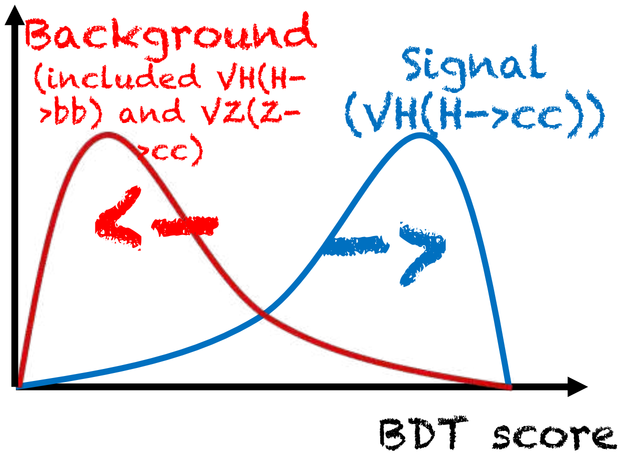
Higgs and vector boson properties

c-tagging score

event kinematics

Kinfit Variables (2L only)

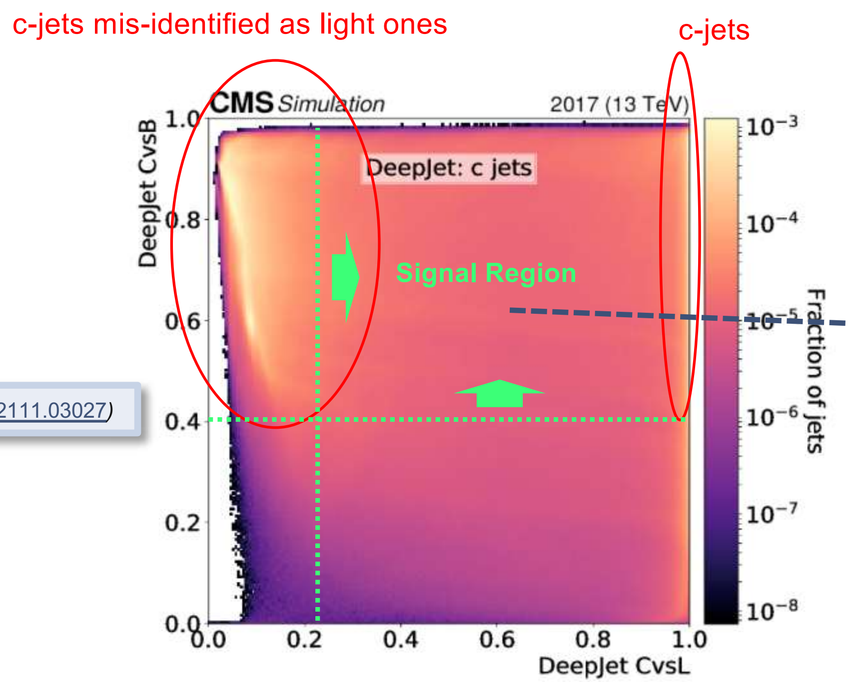
- ❑ BDT trained to separate signal from background samples
  - Use combination of kinematic observables and particle flavor variables (tagger informations)
- ❑ Separate BDTs trained for each channel and data taking year
  - Separate BDTs trained for high- and low-p_T(V) 2L
  - Variables used dependent on channel
- ❑ Reshaped BDT distribution used in SR during final fit



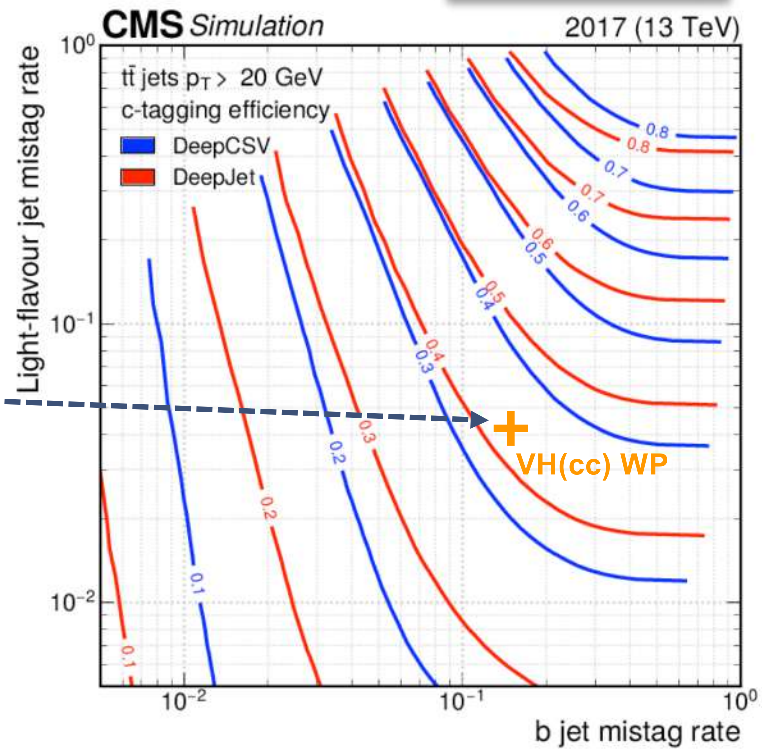
Charm-tagging in the resolved-jet topology

- Definition of leading-jet working point
  - Studies of CvsB/CvsL jet score distributions in 2D plane
  - **CvsL>0.225, CvsB>0.4** ➔ c-jet identification efficiency of ~43% with a b-jet and light-jet mis-tagging rate respectively of ~15% and ~4% (depending on the year)

(from arXiv:2111.03027)



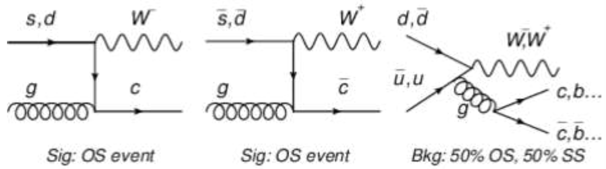
(from arXiv:2111.03027)

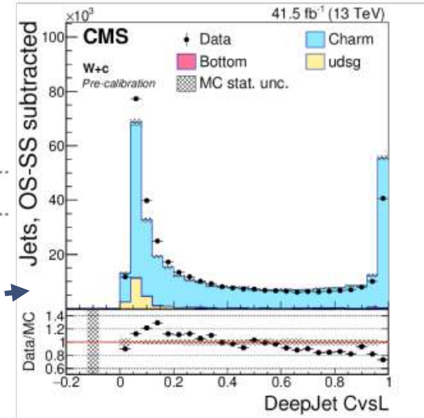


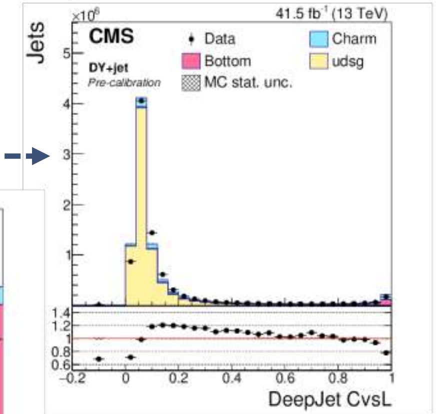
A new method to calibrate charm-taggers

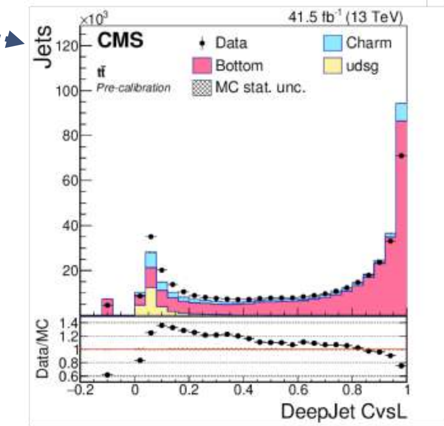
(from arXiv:2111.03027)

- Methodology
  - Iterative approach exploiting 3 distinct control regions, each enriched in b-jets, c-jets, or light-flavour jets
- Selecting an abundant and pure source of charm-jets
  - Target W production in association with charm quarks (W+c)
  - Major background has 50% chance to have SS or OS final states
    - performing an OS-SS subtraction reduces considerably the W+gluon process
  - To enrich in b-jets and light-jets: semi-(di-)leptonic $t\bar{t}$+jets and DY(Z→$\mu\mu$/ee)+jets









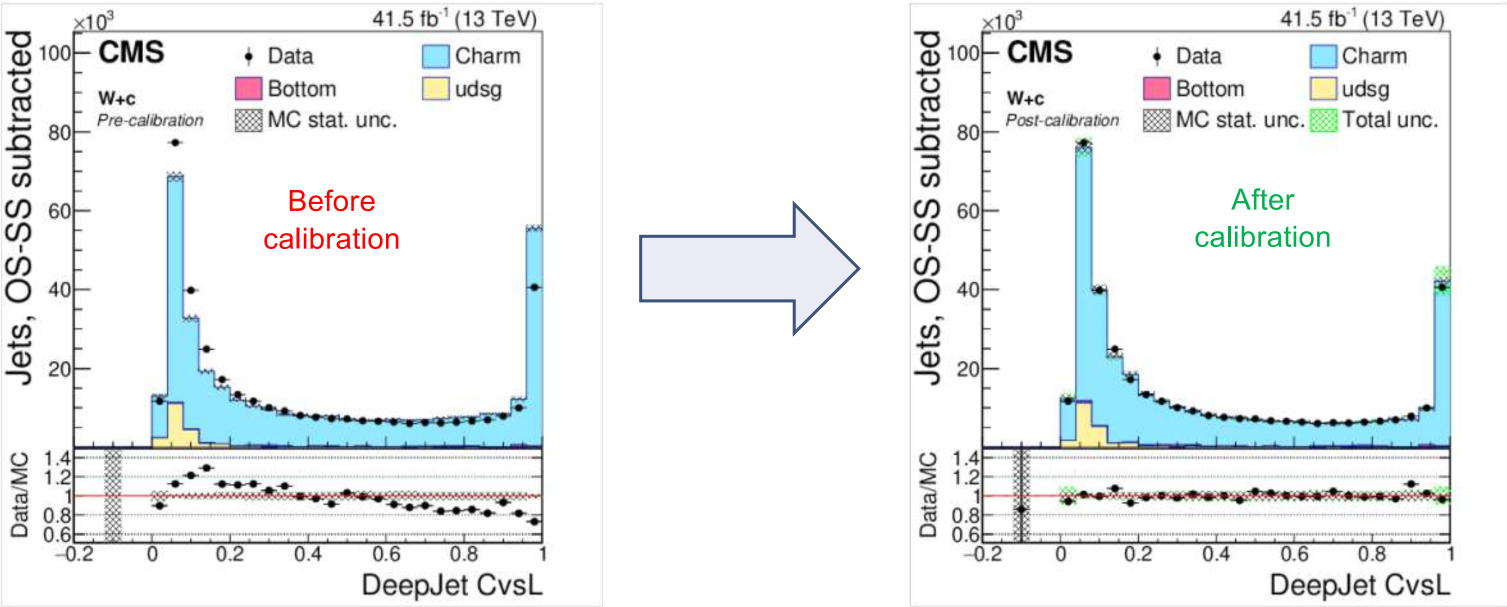
- First time that a calibration method to correct the 2D distribution of c-tagging discriminator shapes is presented

➔ arXiv:2111.03027 (**accepted by *JINST***)

A new method to calibrate charm-taggers

Application of the reshaping scale-factors

(from arXiv:2111.03027)

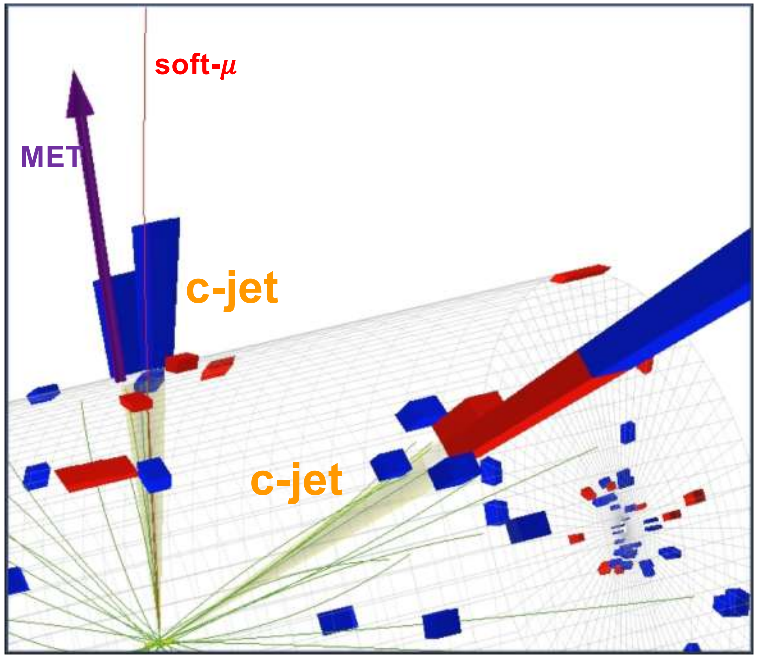


- Very good data/MC agreement after the calibration
  - Application through an event-by-event re-weighting: $w_i = \prod_{i=1}^{jets} sf_i(CvsL, CvsB)$

A dedicated charm-jet energy regression

Goal: improve c-jet energy scale and resolution

- Inspired by b-jet energy regression [arXiv:1912.06046]
  - Jet energy measurements not always accurate:
    - neutrinos, hadrons outside jet radius, etc. Effect enhanced in c-jets and b-jets
  - Dedicated algorithm to determine c-jet energy scale and resolution
  - A DNN algorithm pioneered for the observation of the H→bb decay

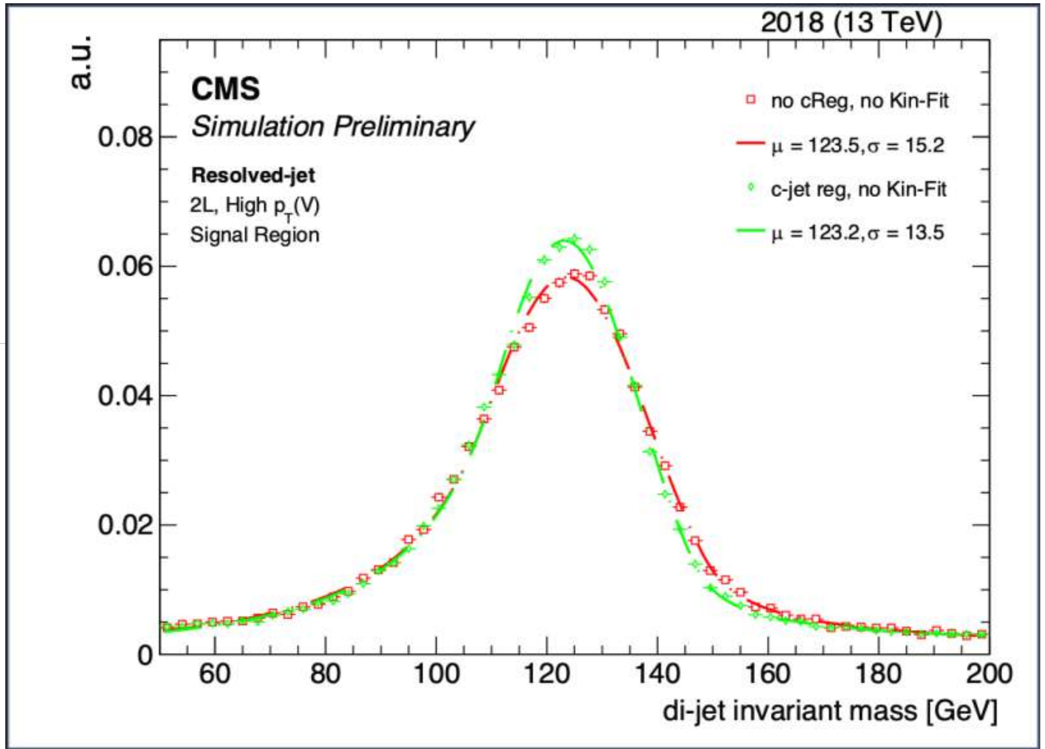


- Regression performed using DNN architecture:
  - Trained using c-jets collected from W→cq decays in $t\bar{t}$+jets MC events
  - Target is represented by p_T(gen)/p_T(reco)

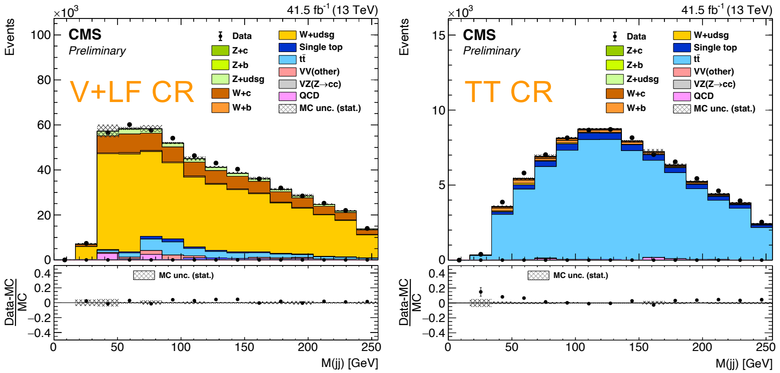
- Input features
  - Total of 43 input variables as input to the network
  - Jets: kinematics, energy fraction, leading+soft-lepton tracks, pile-up, secondary vertices
  - Jet energy shapes (e.g. energy fraction, etc), jet constituents, p_T(jet)/p_T(lepton)

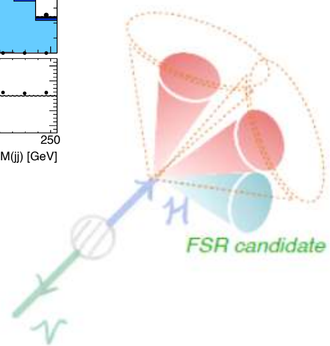
A dedicated charm-jet energy regression

- **~15% improvement in mass resolution**
  - Depending on the jet p_T



- Validated in VH(H→cc) control regions

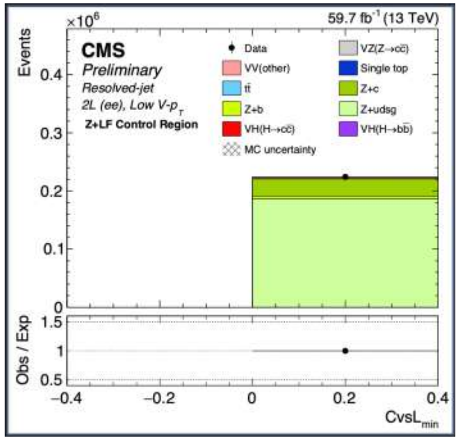


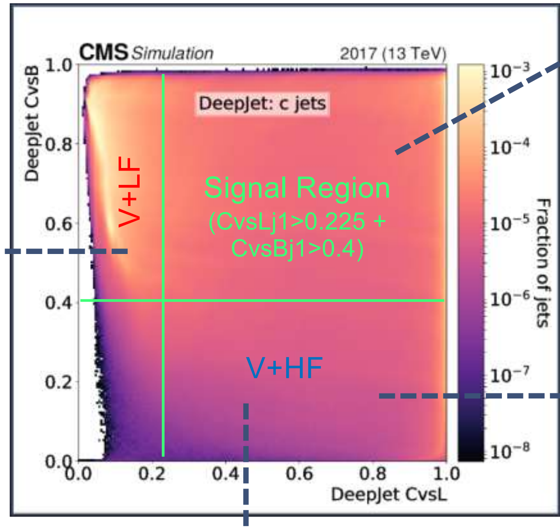


- FSR recovery
  - Further improve di-jet invariant mass resolution
  - Jets with $p_T < 20$ GeV, $|\eta| < 3$, and within $\Delta R < 0.8$ of Higgs jets are included in Higgs 4-momentum

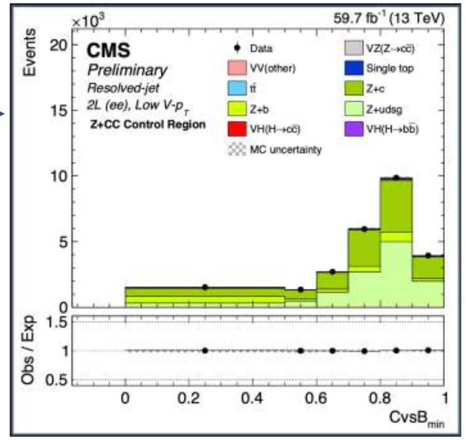
Background estimation – Resolved-jet

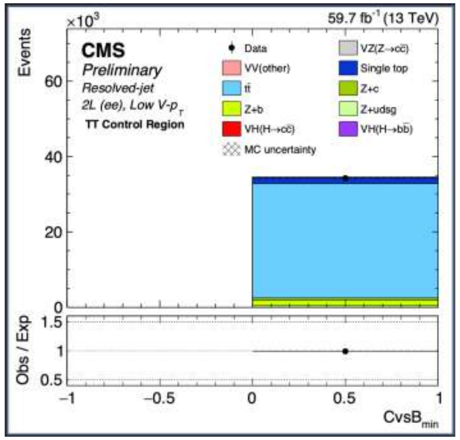
- Accurate modeling of jet flavor in V+Jet background is vital for proper signal extraction
  - Separate rate parameters for **V+c, V+b, and V+light** processes (no W+b)
  - Additional rate parameter for $t\bar{t}$ background





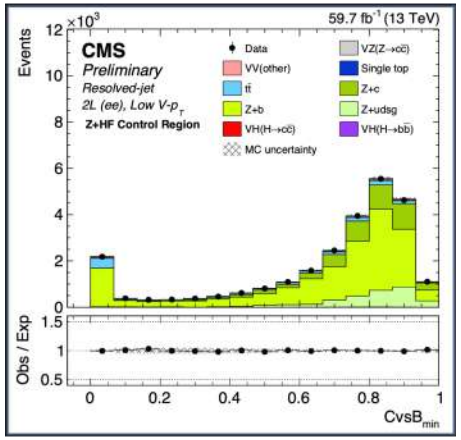
V+CC
⟺
Veto m(H) region





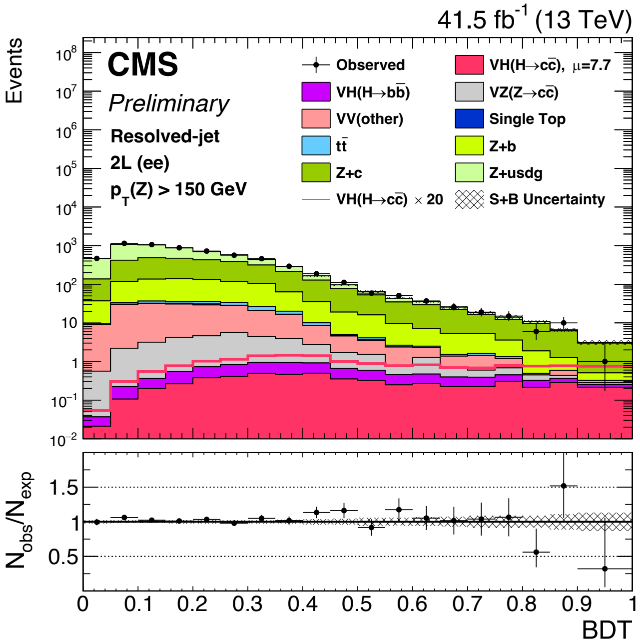
$t\bar{t}$
⟺
Invert Z mass (2L)
Require add jet (1L)*
Require add ℓ and jets (0L)

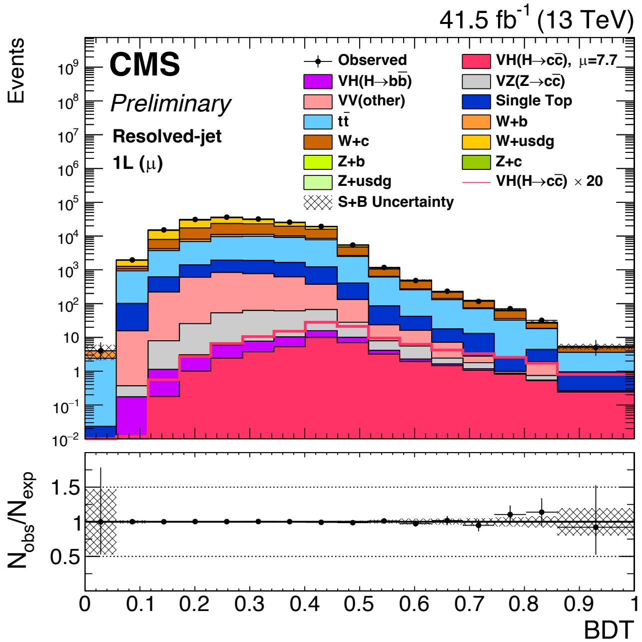
*1L: also require MET<170 GeV to keep orthogonal to 0L $t\bar{t}$ CR

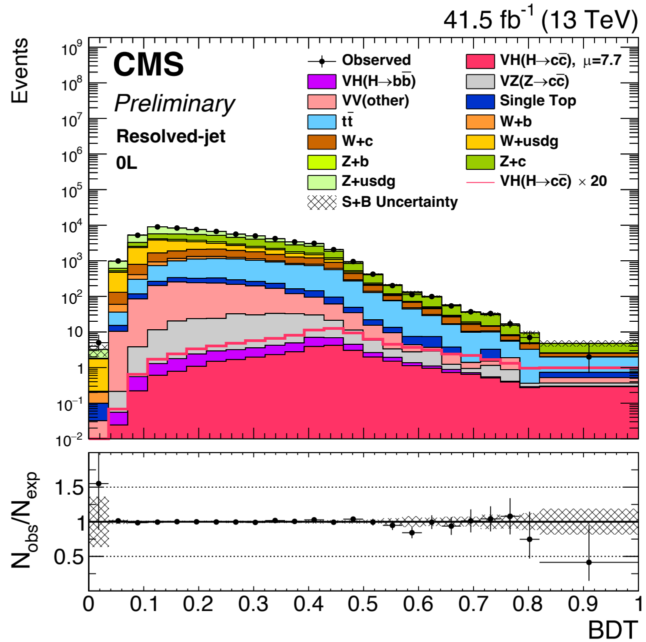


Postfit plots – Signal regions

- Postfit distribution of the BDT discriminant obtained with the 2017 data (more in the back-up)
  - 7 Signal regions in each year: 2L(ee/$\mu\mu$) Low-p_T(V) and High-p_T(V), 1L(e/μ), and 0L

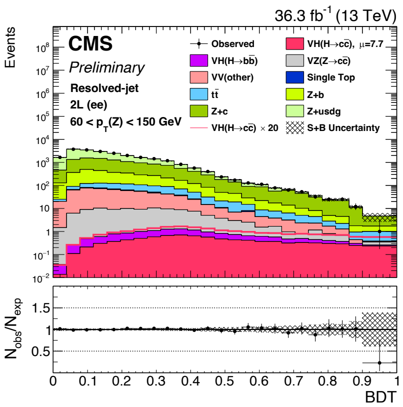


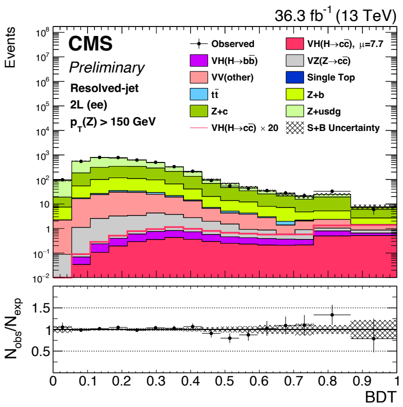


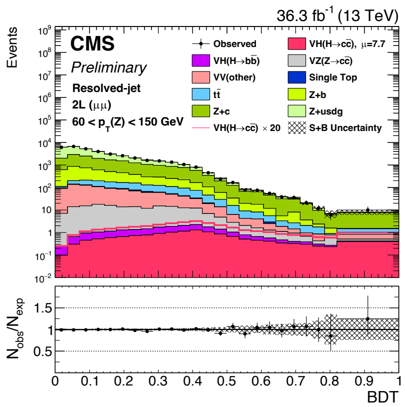


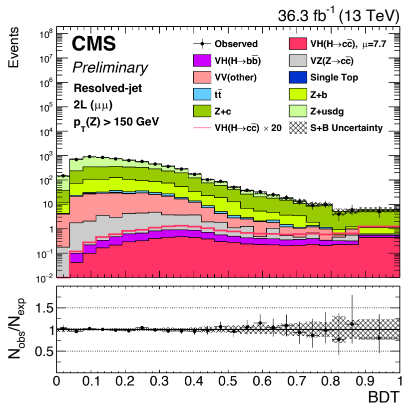
Postfit plots – Signal regions - 2016

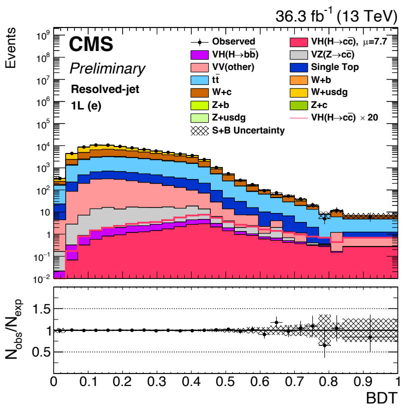
- Postfit distribution of the BDT discriminant obtained with the 2016 data
  - 7 Signal regions in each year: 2L(ee/μ) Low-p_T(V) and –High-p_T(V), 1L(e/μ) and 0L

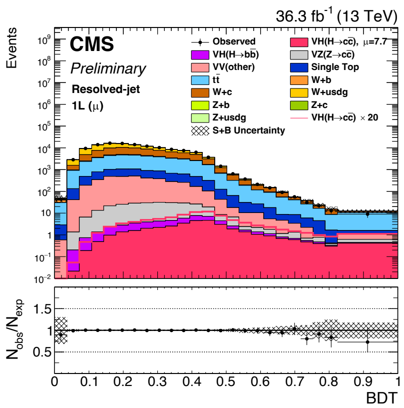


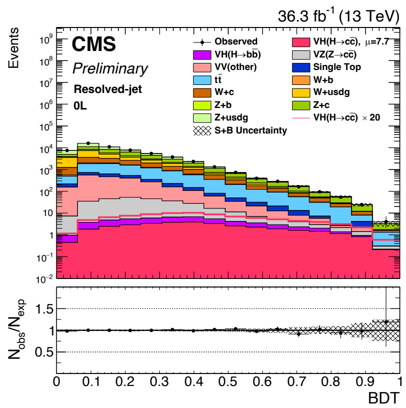






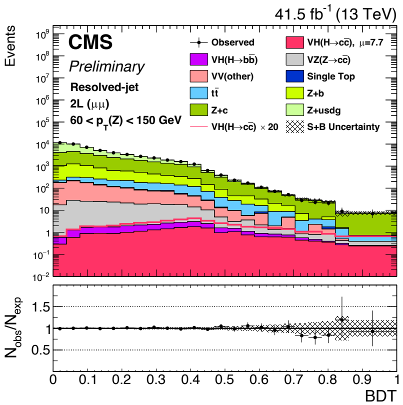


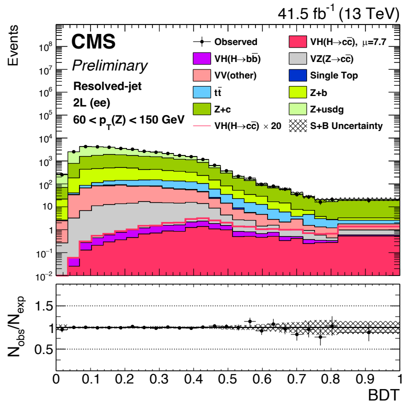


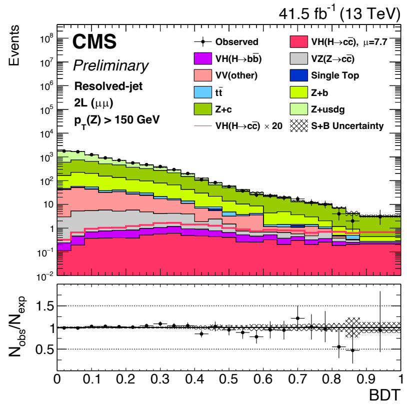


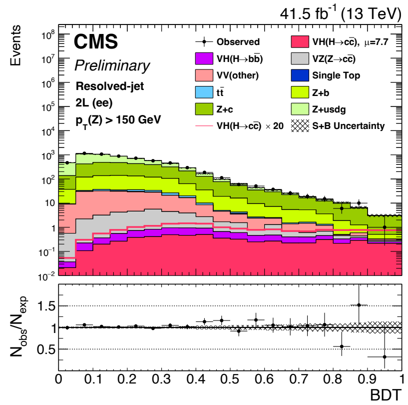
Postfit plots – Signal regions - 2017

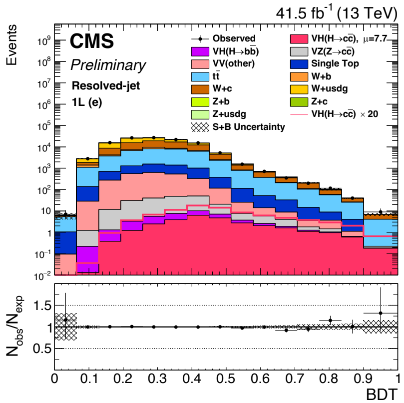
- Postfit distribution of the BDT discriminant obtained with the 2017 data
  - 7 Signal regions in each year: 2L(ee/μ) Low-p_T(V) and –High-p_T(V), 1L(e/μ) and 0L

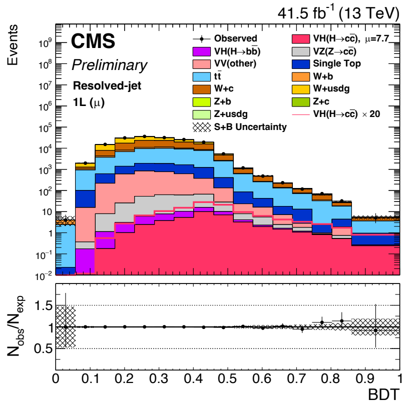


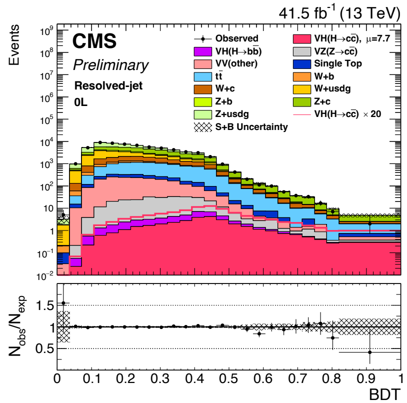






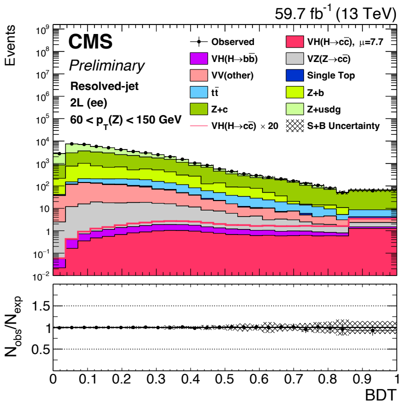


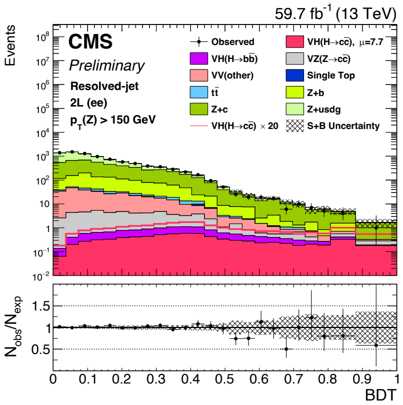


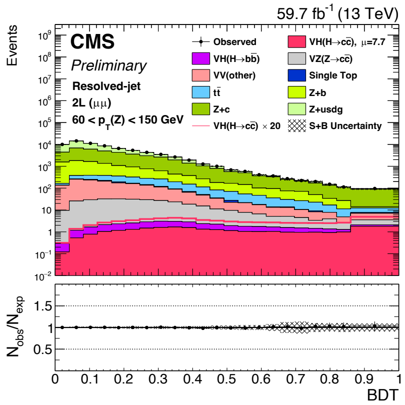


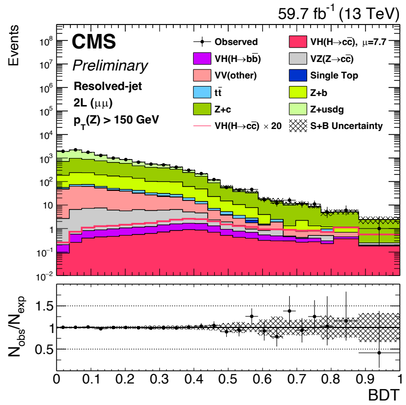
Postfit plots – Signal regions - 2018

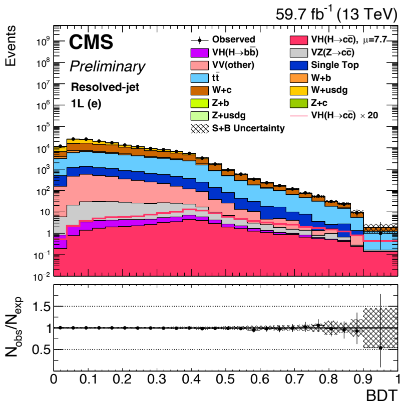
- Postfit distribution of the BDT discriminant obtained with the 2018 data
  - 7 Signal regions in each year: 2L(ee/μ) Low-p_T(V) and –High-p_T(V), 1L(e/μ) and 0L

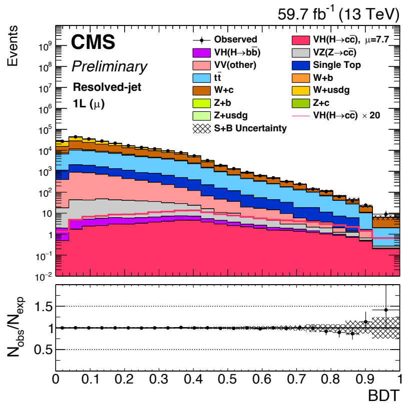


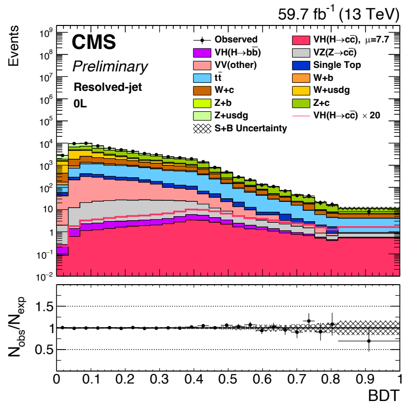






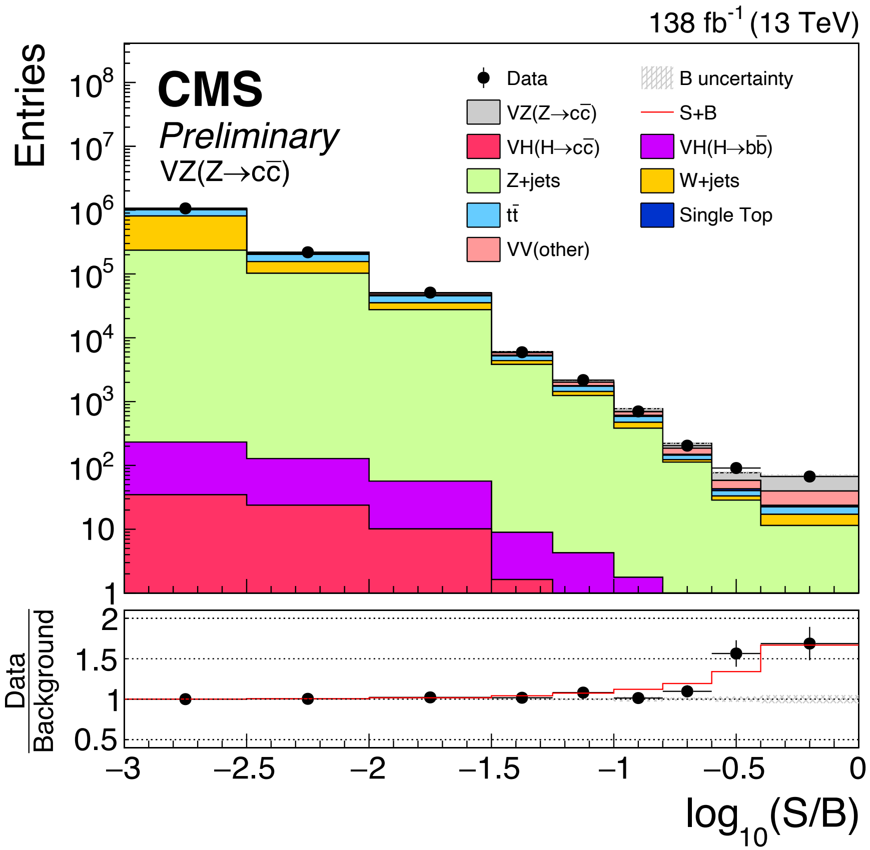






VZ(Z→cc) results

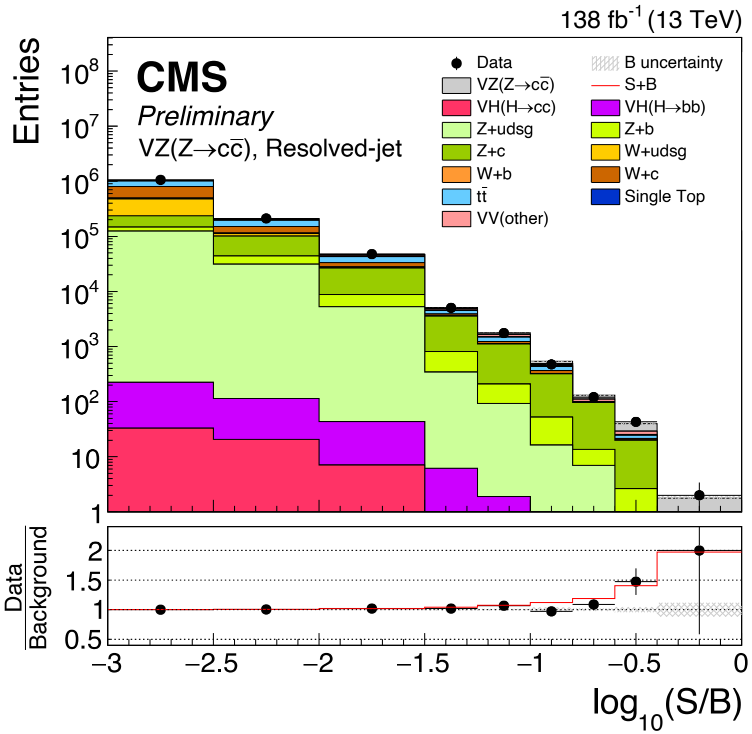
- Observing the excess: distribution of events ordered by $\log_{10}(S/B)$



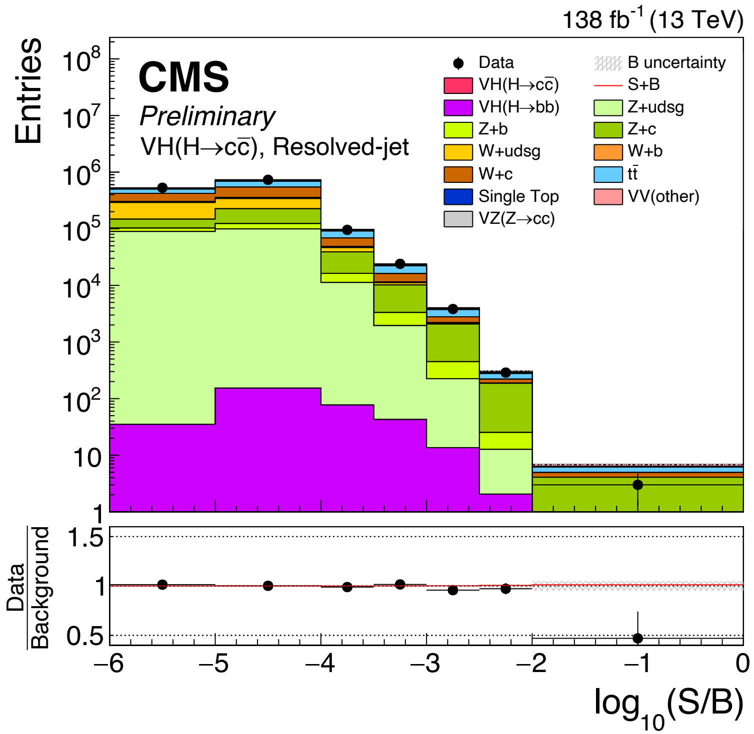
Resolved-jet topology - results

- Resolved-jet – all categories: **ordering the events by log_{10}(S/B)**

VZ(cc)



VH(cc)



Background normalization scale-factors

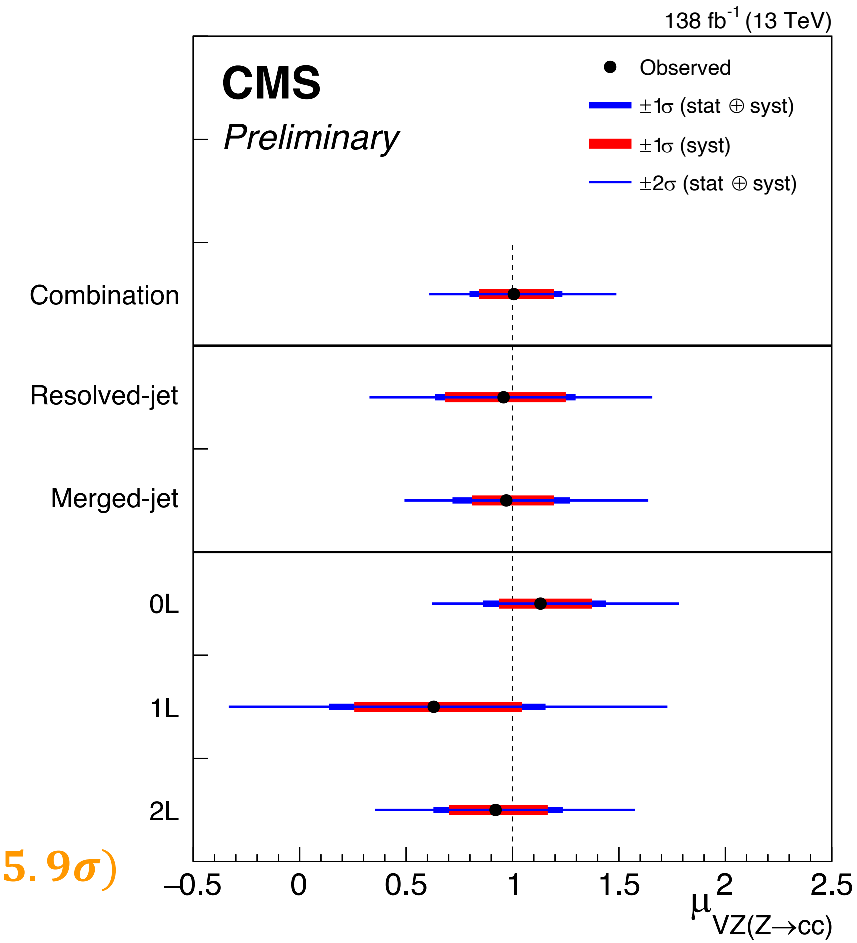
- Simultaneous fit to BDT in SR and tagger shapes in CRs
  - CvsL of CvsL-subleading jet in V+LF CR
  - CvsB of CvsL-subleading jet in V+HF, V+CC, and TT CRs
- Allow V+c, V+b, V+udsg, and $t\bar{t}$ SFs to float freely in each channel
  - Z+x rate parameters independent of channel
  - 1L and 0L channels share W+c and W+udsg rate parameters

	Year	Z+c	Z+b	Z+light	W+c	W+light	$t\bar{t}$
2L-High	2016	0.90 ± 0.07	0.99 ± 0.06	1.04 ± 0.05	—	—	0.95 ± 0.05
	2017	1.12 ± 0.08	1.21 ± 0.08	0.94 ± 0.05	—	—	0.96 ± 0.05
	2018	1.19 ± 0.09	1.22 ± 0.09	0.94 ± 0.06	—	—	0.99 ± 0.05
2L-Low	2016	0.81 ± 0.06	0.83 ± 0.05	1.05 ± 0.05	—	—	0.89 ± 0.04
	2017	0.96 ± 0.07	0.94 ± 0.06	0.98 ± 0.05	—	—	0.90 ± 0.04
	2018	1.18 ± 0.14	1.04 ± 0.08	0.95 ± 0.05	—	—	0.92 ± 0.05
1L	2016	—	—	—	0.97 ± 0.06	1.04 ± 0.04	0.93 ± 0.04
	2017	—	—	—	1.04 ± 0.07	1.04 ± 0.05	1.08 ± 0.05
	2018	—	—	—	1.20 ± 0.07	0.93 ± 0.05	1.05 ± 0.05
0L	2016	0.96 ± 0.12	1.16 ± 0.20	1.28 ± 0.09	0.97 ± 0.06	1.04 ± 0.04	0.83 ± 0.05
	2017	1.31 ± 0.17	1.28 ± 0.22	1.03 ± 0.09	1.04 ± 0.07	1.04 ± 0.05	1.13 ± 0.07
	2018	1.14 ± 0.12	0.90 ± 0.20	0.89 ± 0.07	1.20 ± 0.07	0.93 ± 0.05	1.00 ± 0.07

Combination – VZ(cc) results

- Analysis validated by first looking for VZ(Z→cc) process
  - Same analysis procedure but extracting VZ(cc) signal during final fit
  - **Resolved**: Use separate BDTs retrained with VZ(cc) as signal
  - VH(cc) fixed to SM expectation

	resolved-jet	merged-jet	combination				
	(p_T(H) < 300 GeV)	(p_T(H) ≥ 300 GeV)	0L	1L	2l	all	$\mu_{VZ(Z\to c\bar{c})}$
2016 (expected)	1.7σ	2.4σ	2.5σ	1.0σ	1.9σ	3.0σ	$1.00^{+0.42}_{-0.36}$
2016 (observed)	1.8σ	2.0σ	3.6σ	1.0σ	0.4σ	2.9σ	$1.02^{+0.41}_{-0.37}$
2017 (expected)	2.2σ	2.9σ	2.9σ	1.3σ	2.6σ	3.7σ	$1.00^{+0.35}_{-0.30}$
2017 (observed)	1.7σ	2.6σ	1.3σ	0.0σ	4.0σ	3.2σ	$0.84^{+0.32}_{-0.28}$
2018 (expected)	1.7σ	3.0σ	3.1σ	1.4σ	2.0σ	3.6σ	$1.00^{+0.39}_{-0.32}$
2018 (observed)	1.9σ	3.1σ	4.0σ	1.4σ	1.2σ	3.8σ	$1.23^{+0.45}_{-0.37}$
Full Run2 (expected)	3.3σ	4.7σ	4.8σ	2.1σ	3.7σ	5.9σ	$1.00^{+0.22}_{-0.20}$
Full Run2 (observed)	3.1σ	4.4σ	4.9σ	1.3σ	3.3σ	5.7σ	$1.01^{+0.23}_{-0.21}$



- Measure observed (expected) signal strength of:

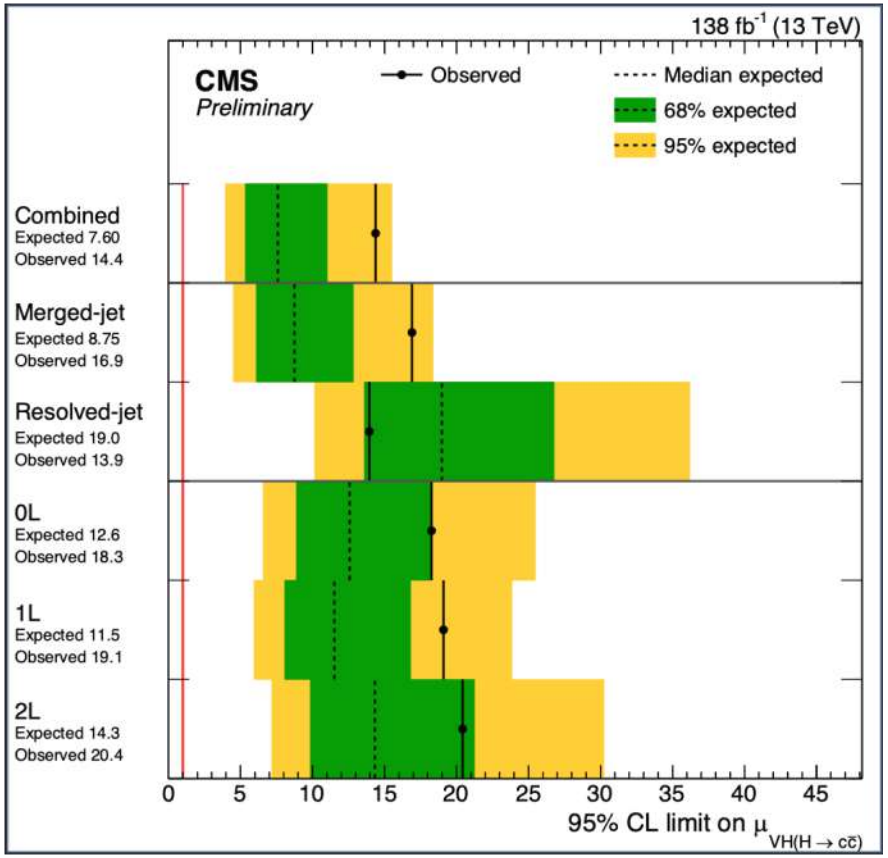
  $\mu_{VZ(cc)} = 1.01^{+0.23}_{-0.21}\left(1.00^{+0.22}_{-0.20}\right)$ **with significance of** $5.7\sigma\ (5.9\sigma)$

- **First observation of Z→cc at hadron collider!**

Combination – VH(cc) results

- Observed (expected) upper limit on $\mathrm{VH}(\mathrm{H} \rightarrow cc)$ signal strength at 95% CL: $\mu_{VH(cc)} < 14\ (7.6^{+3.4}_{-2.3})$
  - **Strongest limits on the VH(cc) process to date!**
  - ATLAS Full Run 2 result: $\mu_{VH(cc)} < 26\ (31)$ [arXiv:2201.11428]
- Best fit signal strength $\mu_{VH(cc)} = 7.7^{+3.8}_{-3.5}(^{+8.1}_{-6.6})\ (2\sigma)$
  - Consistent with the Standard Model prediction within 2σ

	resolved-jet ($p_T(\mathrm{H}) < 300\,\mathrm{GeV}$)	merged-jet ($p_T(\mathrm{H}) \geq 300\,\mathrm{GeV}$)	combination 0L	1L	2l	all	$\mu_{\mathrm{VH(H\rightarrow c\bar{c})}}$
2016 (expected)	34	19	26	25	30	16	$1.0^{+7.6}_{-7.1}$
2016 (observed)	28	20	21	43	21	18	$3.2^{+7.4}_{-7.3}$
2017 (expected)	32	17	24	25	26	15	$1.0^{+6.9}_{-6.1}$
2017 (observed)	24	24	29	26	31	18	$4.3^{+6.9}_{-6.2}$
2018 (expected)	33	14	20	18	24	12	$1.0^{+5.6}_{-4.9}$
2018 (observed)	26	26	34	18	42	21	$9.9^{+6.1}_{-5.1}$
Full Run2 (expected)	19	8.8	13	12	14	7.6	$1.0^{+3.7}_{-3.4}$
Full Run2 (observed)	14	17	18	19	20	14	$7.7^{+3.8}_{-3.5}$



- Obs. (Exp.) Run-2 single-analysis sensitivities: | Resolved: 14(19) xSM | Merged: 17(8.8) xSM |

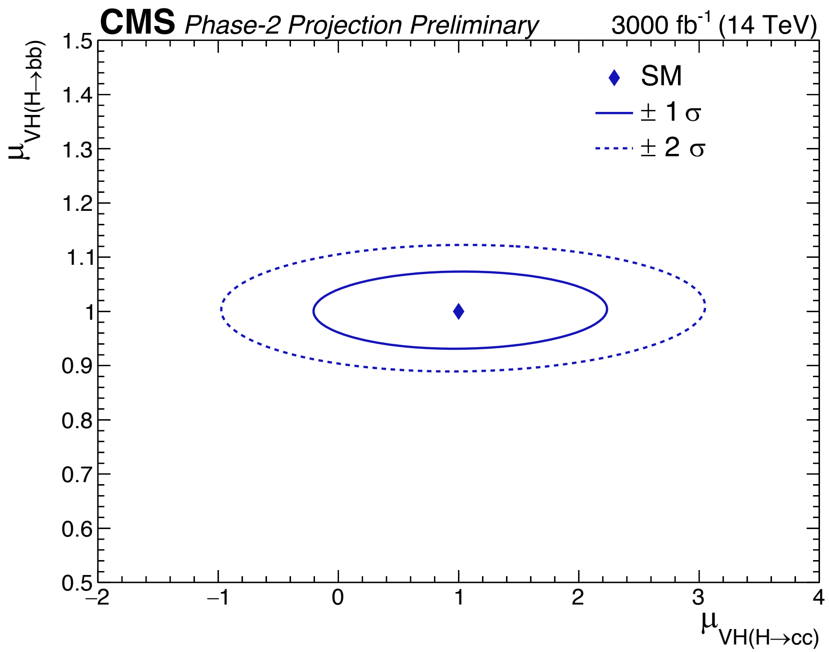
Projection at HL-LHC: Setup

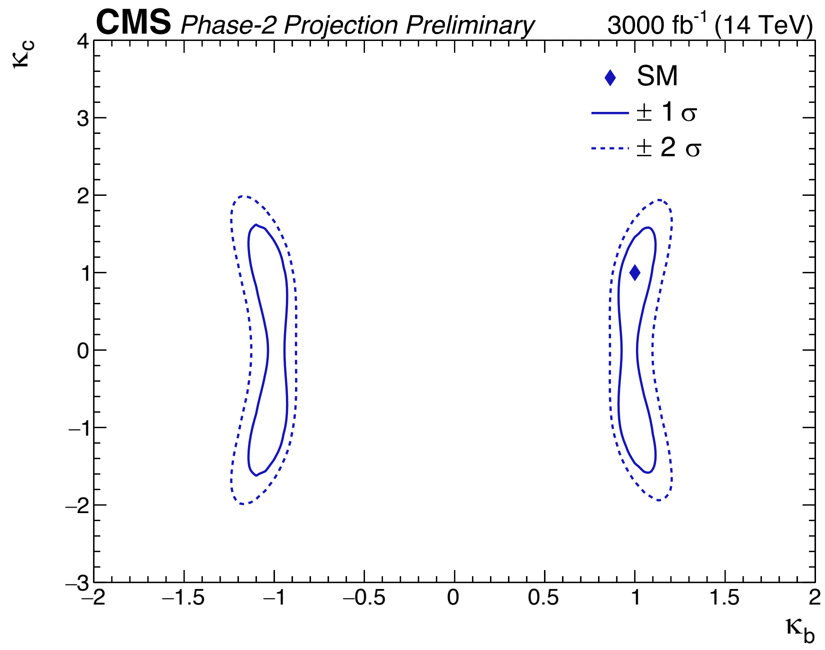
- Extrapolation of the merged-jet analysis to HL-LHC with 3000 fb^{-1} data
- Modifications to the Run 2 analysis to allow for a simultaneous constraint on $H \rightarrow bb$ and $H \rightarrow cc$
  - **addition of 3 categories enriched in $H \rightarrow bb$ decays**, selected with the ParticleNet bb-tagging discriminant
    - very small (1-2%) overlap of bb and cc categories – events assigned to a unique category
  - **large-R jet p_T threshold lowered from 300 GeV to 200 GeV** – increasing signal acceptance

- Systematic uncertainties adjusted according to the Yellow Report [CERN-2019-007]
  - theoretical uncertainties: reduced by half
  - most experimental uncertainties: scaled down with $\sqrt{\mathcal{L}}$
    - bb and cc tagging efficiencies: constrained by $VZ(Z \rightarrow bb)$ and $VZ(Z \rightarrow cc)$ events to ~3% and ~5%
    - misidentification of $H \rightarrow bb$ as $H \rightarrow cc$: a prominent uncertainty on $H \rightarrow cc$ measurement at HL-LHC
      - assumed to be reduced from ~100% (Run 2) to 20% in the projection

Projection at HL-LHC

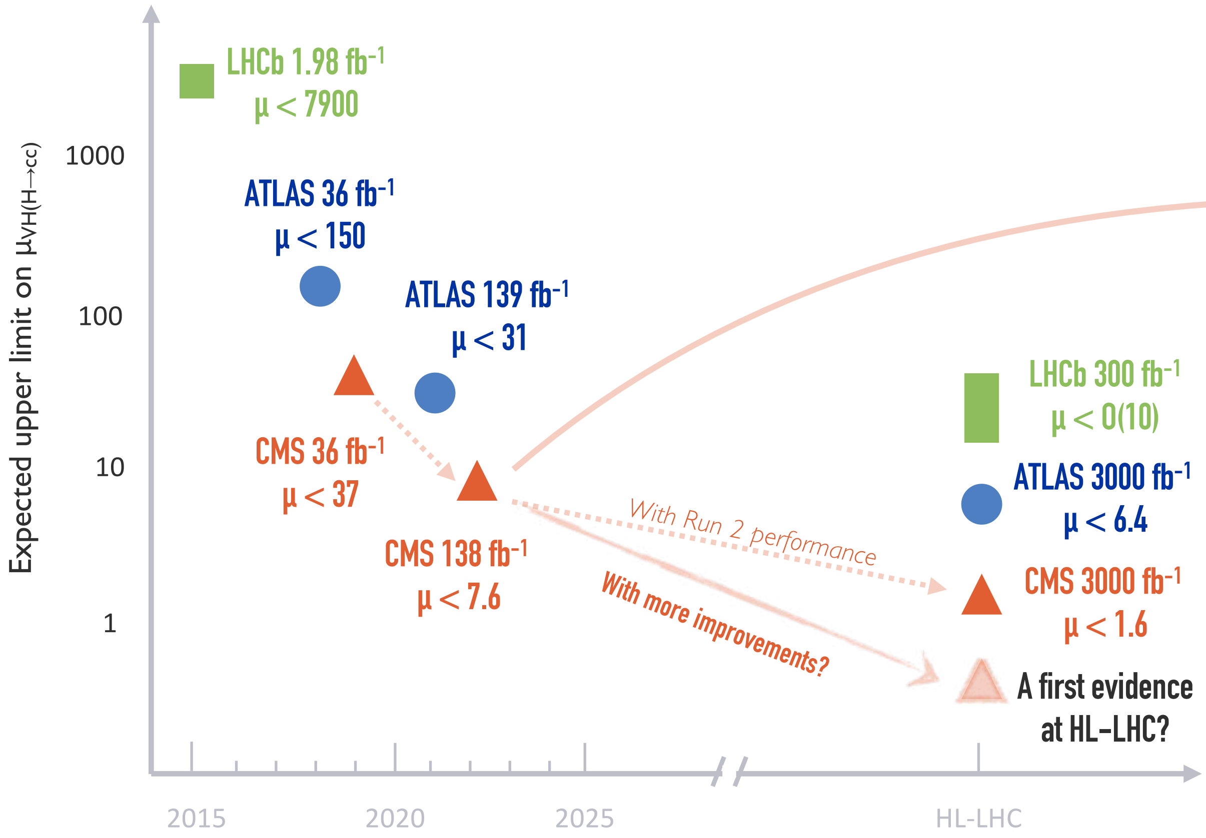
- Simultaneous extraction of the H → bb and H → cc signal strengths
  - $\mu_{VH(H \to bb)}$ = 1.00 ± 0.03 (stat.) ± 0.04 (syst.) = 1.00 ± 0.05 (total)
  - $\mu_{VH(H \to cc)}$ = 1.0 ± 0.6 (stat.) ± 0.5 (syst.) = 1.0 ± 0.8 (total)



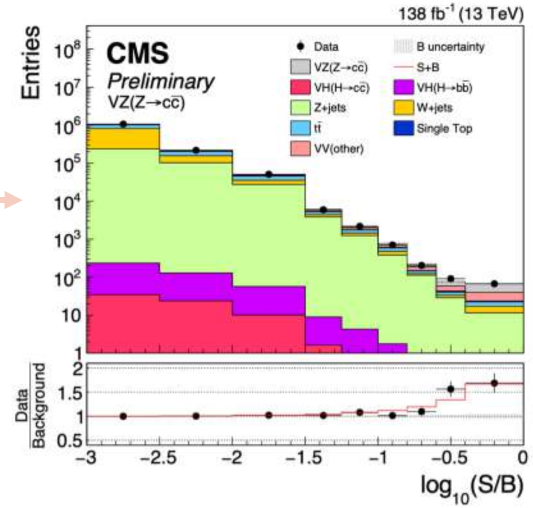


Expected sensitivity approaches the SM value for the Higgs-charm coupling.

A charming journey



From $\mathcal{O}(1000)$ to $\mathcal{O}(100)$ to $\mathcal{O}(10)$ in ~5 years.
A combined effort and creativity from instrumentation, physics objects and analysis techniques!



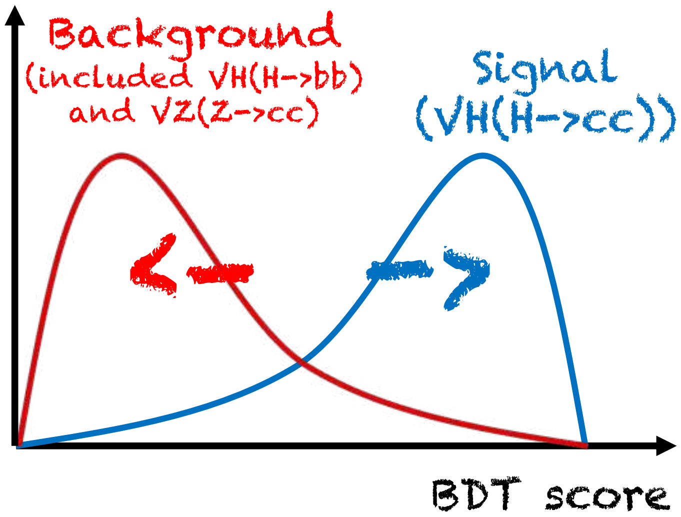
First observation of Z → cc at a hadron collider!
Opening a new era for future explorations.

- More channels: ttH(cc), VBF H(cc), indirect constraints, etc.
- Improvements in advanced analysis techniques (e.g., Deep Learning) and instrumentation (e.g., tracker)
- Reduction of systematic uncertainties: c-tagging, event modeling, theoretical uncertainties, . . .

A charming journey ahead!

Signal extraction – BDT training in SRs

- BDT trained to separate signal from background samples
  - Use combination of event kinematic observables, Higgs and vector boson properties, particle flavor variables (tagger information), and kinematic-fit variables (only in 2L channels)



- Separate BDTs trained for each channel and data taking year
  - Separate BDTs trained for high- and low-$p_T(V)$ 2L
  - Variables used dependent on channel

- Reshaped BDT distributions used in SR for the final fit