VH(H→cc) search at CMS

with full Run 2 data

Spandan Mondal[1]

On behalf of the CMS Collaboration

LHC Higgs WG1,
CERN
12.05.2022

1

RWTH AACHEN UNIVERSITY

Outline

- Simulations
- Analysis strategy
- Resolved-jet approach
  - c-tagging and full discriminator calibration
- Merged-jet approach
  - cc-tagging and sfBDT-based calibration
- Results
- Conclusion and outlook

Simulation

- Signals

Sample	Generator	Order	Comments
qqZH	POWHEG+MiNLO	NLO	XSec reweighted to NNLO QCD + NLO EWK as function of $p_T(V)$
qqWH			
ggZH	POWHEG	LO	

Simulation

- Backgrounds

Sample	Generator	Order	Comments
Z+Jets	aMC@NLO	NLO	Upto two additional partons
W+Jets			Split into $p_T(V) \otimes$ nJet bins
			Large statistics; no c-jet filter
$t\bar{t}$ and SingleTop	POWHEG	NLO	XSec reweighted to NNLO+NNLL
			Diff. XSec as f(p_T(t)) reweighted to NNLO QCD + NLO EWK
WW	POWHEG	NLO	XSec reweighted to NNLO QCD + NLO EWK as function of $p_T(V_2)$
WZ	aMC@NLO	NLO	
ZZ			

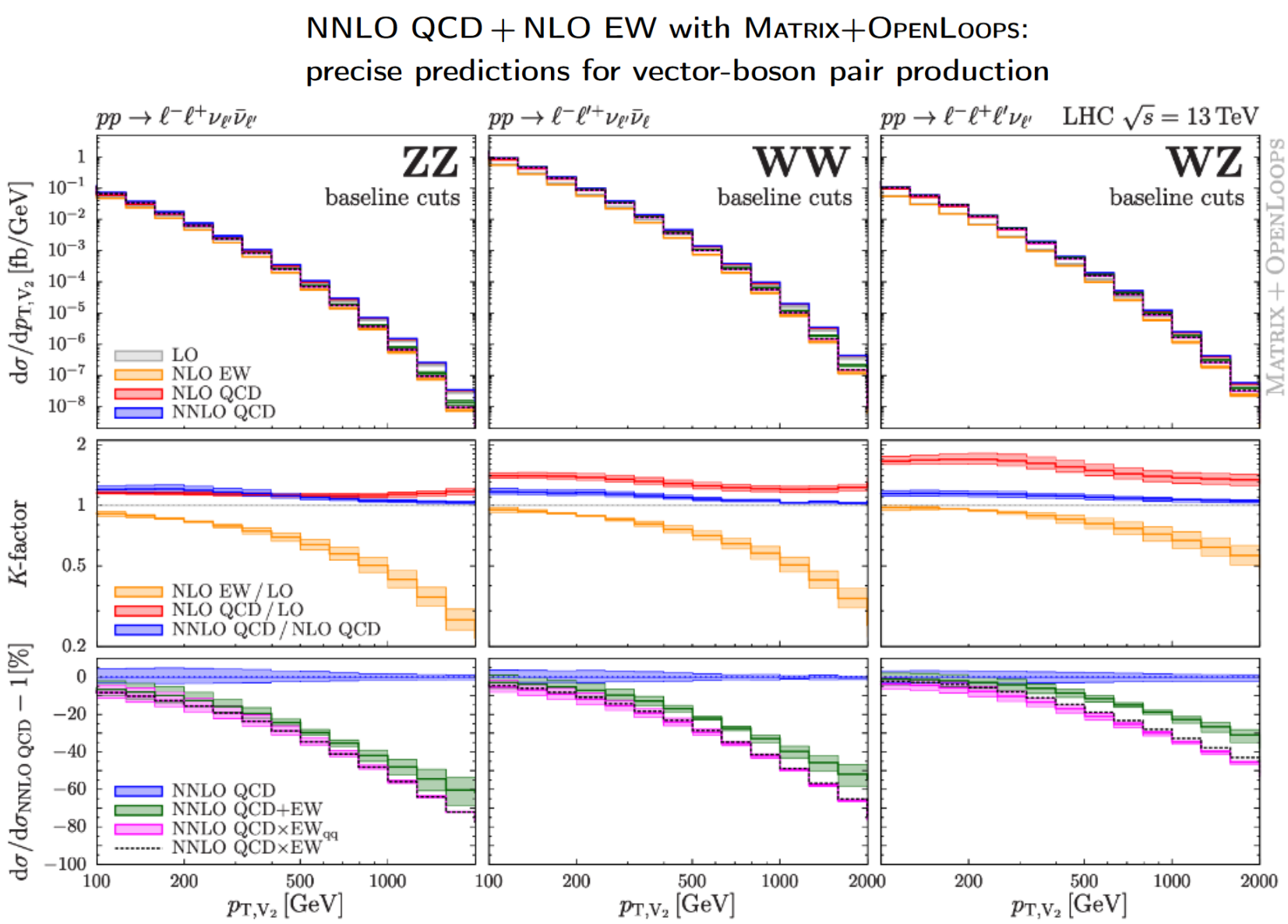
Simulation: Diboson

Step1: Derive inclusive k-factors (separate for 2016 and 2017/18):

- Start with gen XSec (NLO QCD)
- Apply fiducial cuts to match selection in [arXiv:1912.00068]

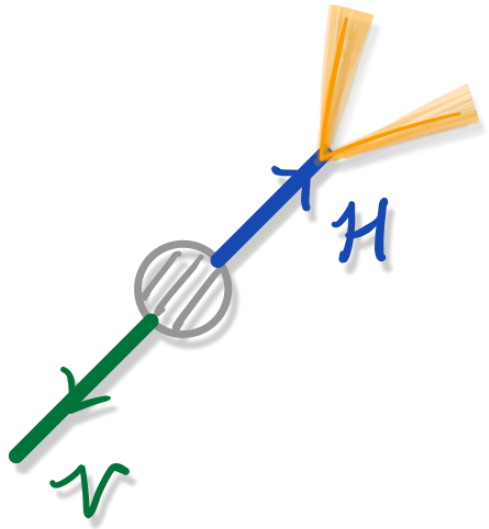
Step 2: Derive differential corrections

- Apply inclusive k-factor
- Derive differential XSec as $f(p_T(V_2))$: Correct each bin by $\frac{\sigma_{NNLO\ QCD+NNLO\ EWK}}{\sigma_{NLO\ QCD} \times k\text{-}factor}$ differentially in $p_T(V_2)$



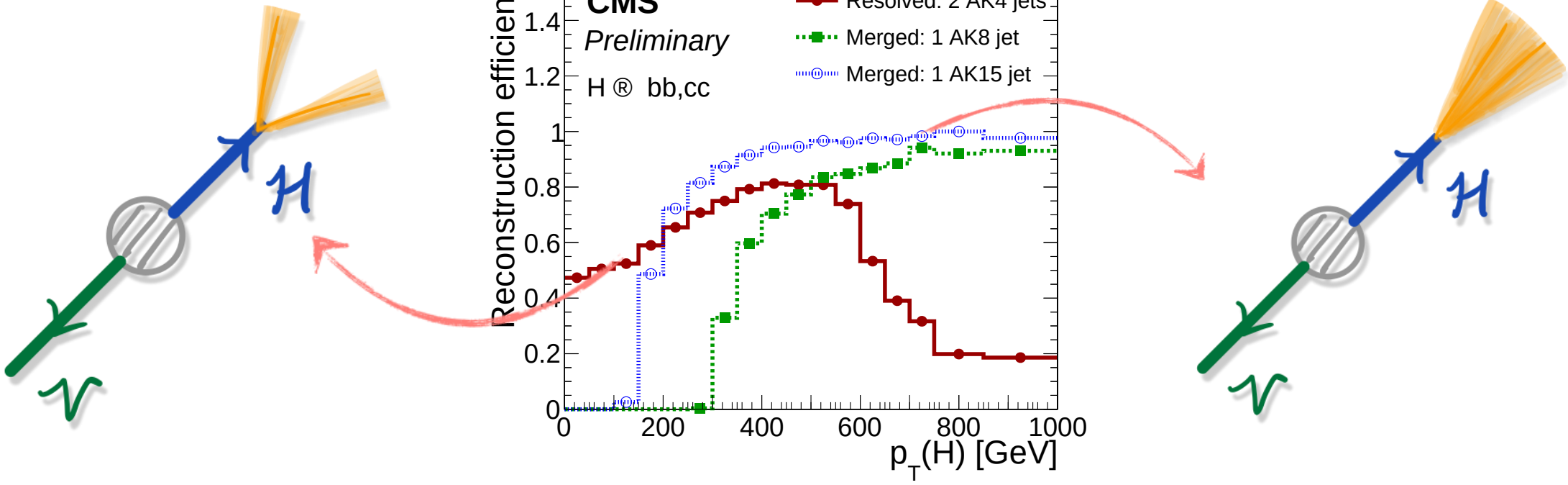
Analysis strategy

- Exploit associated Higgs production with a vector boson (W/Z)
  - Leptonically decaying: **Z → νν (0L), W → ℓν (1L), Z → ℓℓ (2L)** [ℓ = e, μ]
- Reconstruct a high-p_T vector boson recoiling against a Higgs candidate
  - Higgs candidate defined using presence of (di-)charm jet(s)
- Main backgrounds: V+jets, $t\bar{t}$, diboson



Analysis strategy

- $\Delta R(c,\overline{c}) \sim 2m(H)/p_T(H)$

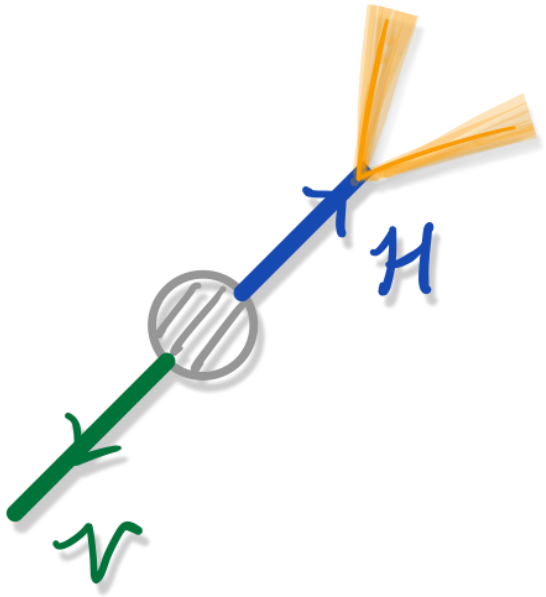


Resolved jet:

- Two small radius AK4 jets (R=0.4) for 2 c jets
- Probes >95% of the signal phase space

Merged jet:

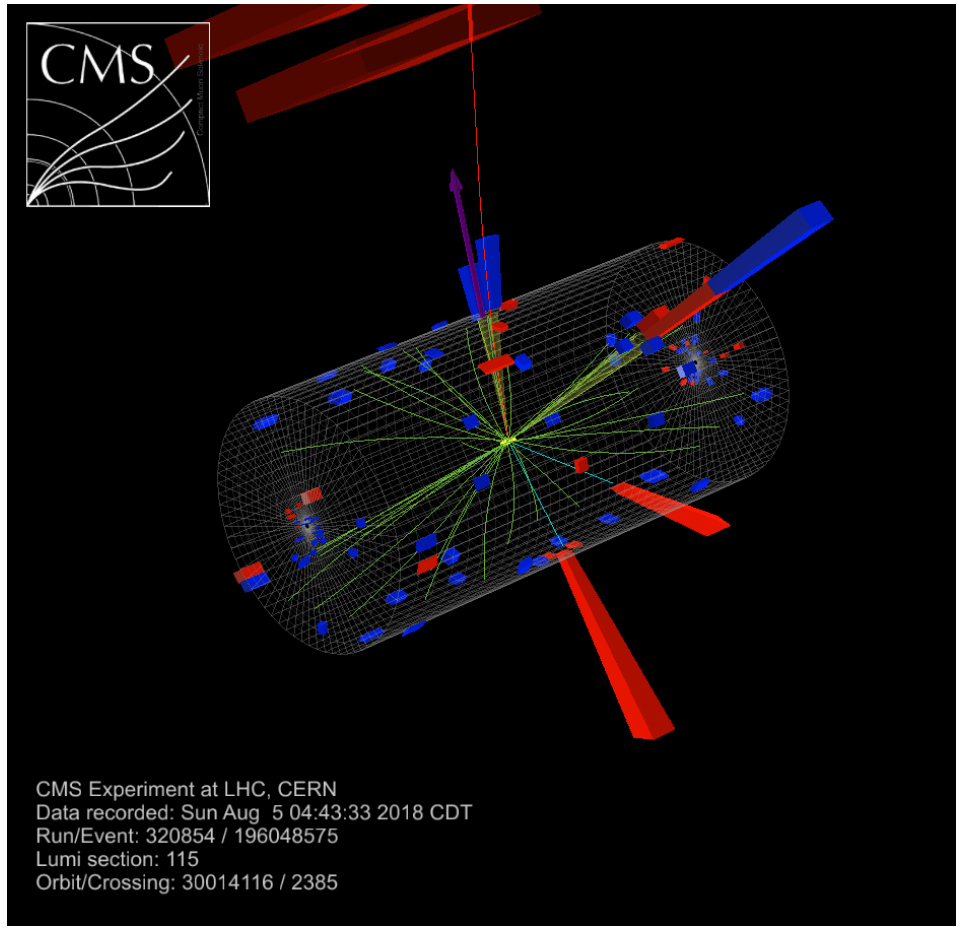
- One large radius AK15 jets (R=1.5) for the full Higgs decay with 2 charm quarks
- Exploits correlation between two charm quarks



Resolved jet topology

Overview

Resolved



Higgs reconstruction:

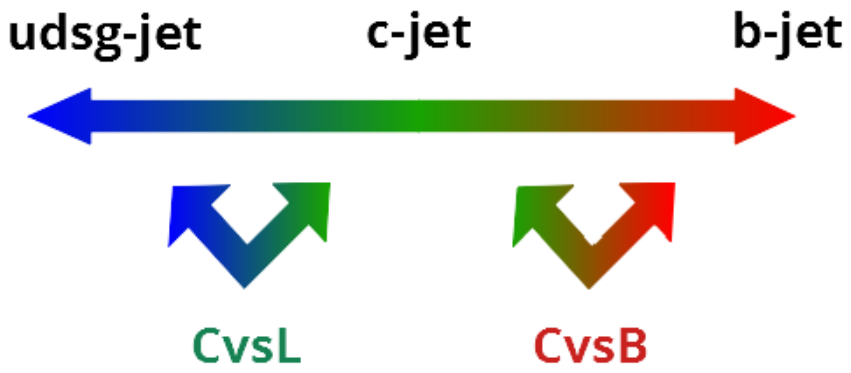
- Select two AK4 jets with highest “c-tagger score”
- c-jet energy regression
- Kinematic fit in 2L channel

Analysis:

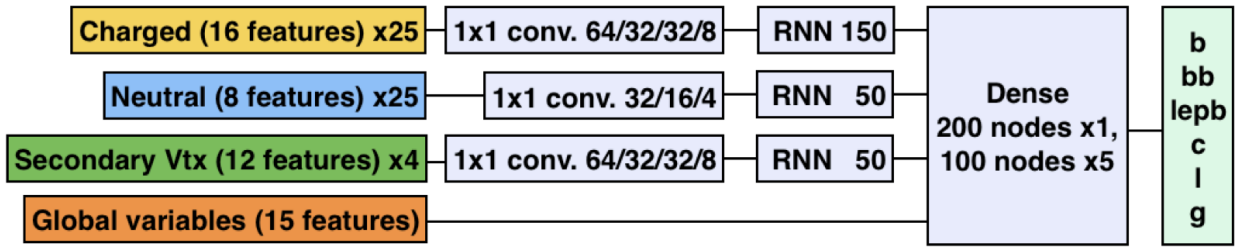
- Predict background normalizations from control regions
- Train signal-vs-background BDT in signal region to extract signal

Charm tagging

- Discriminate c simultaneously against b and udsg



"DeepJet"

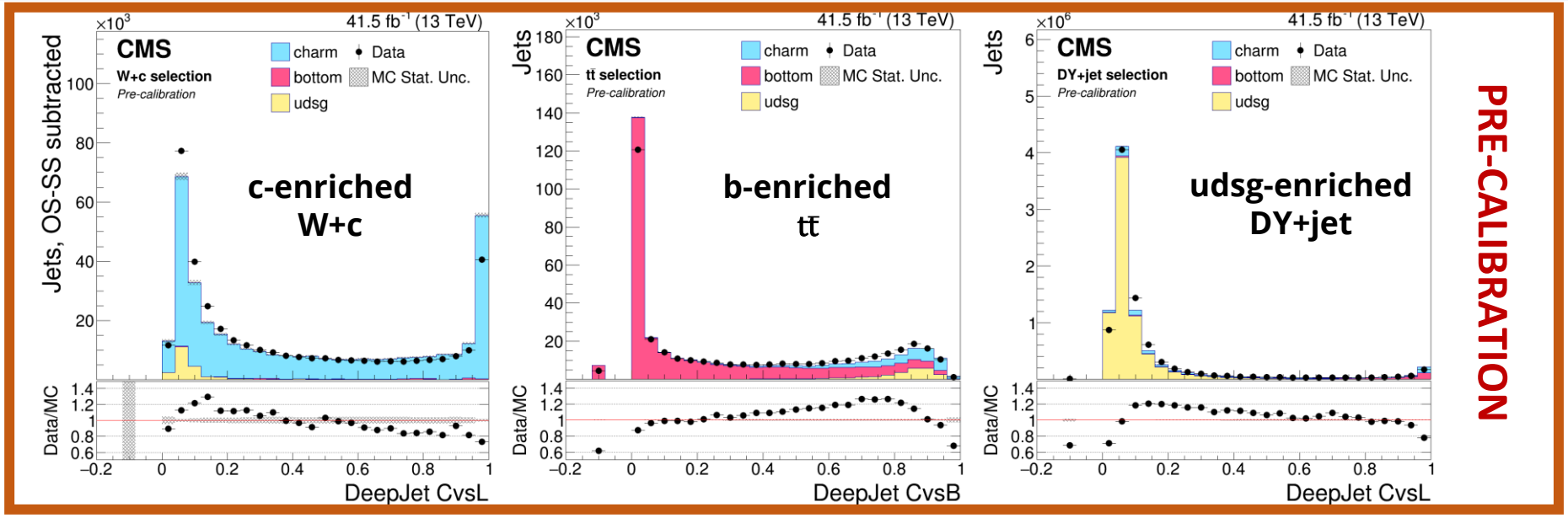


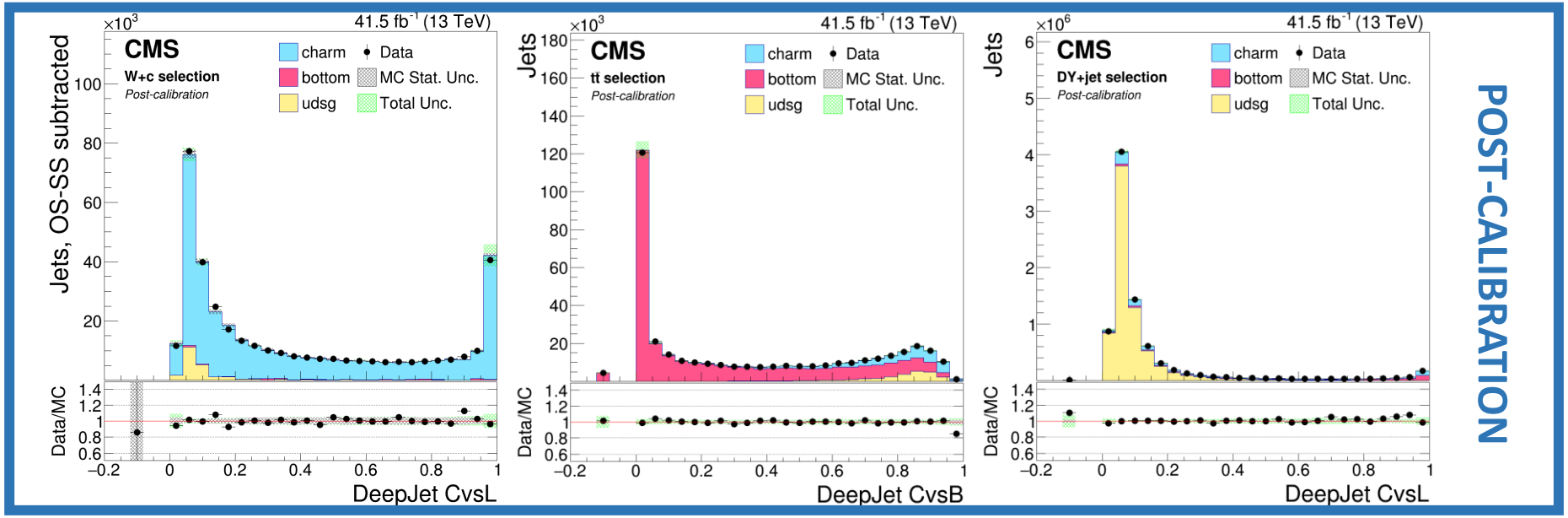
Trained on MC simulated jets

Two scores for each jet:

- **CvsL** = $\frac{P(c)}{P(c)+P(udsg)}$
- **CvsB** = $\frac{P(c)}{P(c)+P(b)}$

Charm tagging calibration





Resolved

- Full discriminator calibration
- Simultaneously calibrate CvsL and CvsB
- Systematic variations

Legend:

- c-jets
- b-jets
- udsg-jets

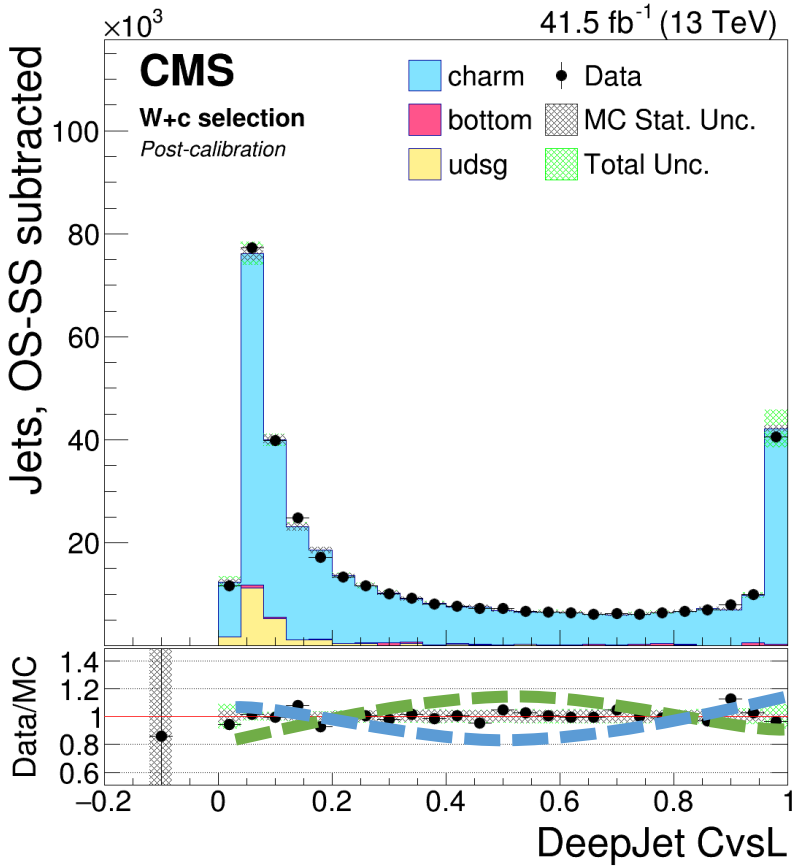
2022 *JINST* **17** P03014

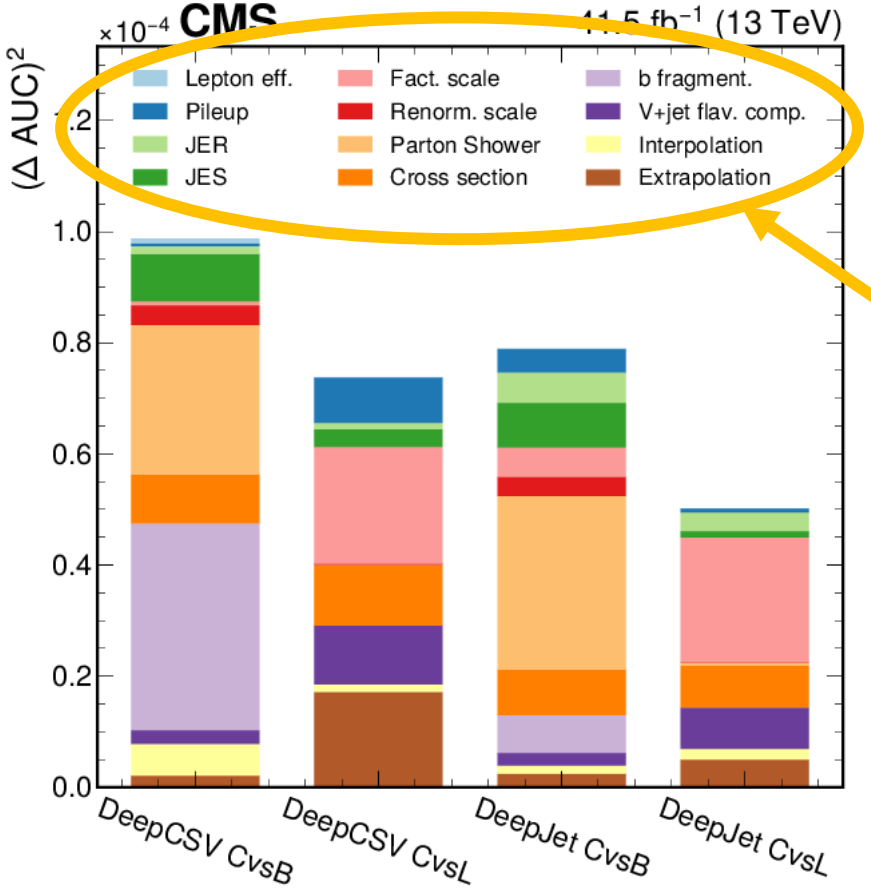
Charm tagging calibration

Resolved

Shape nuisances: Systematics that affect the c-tagger shapes are propagated as NPs to the fit by varying the shape of the tagger

Magnitude of these shape variations are flavour dependent…

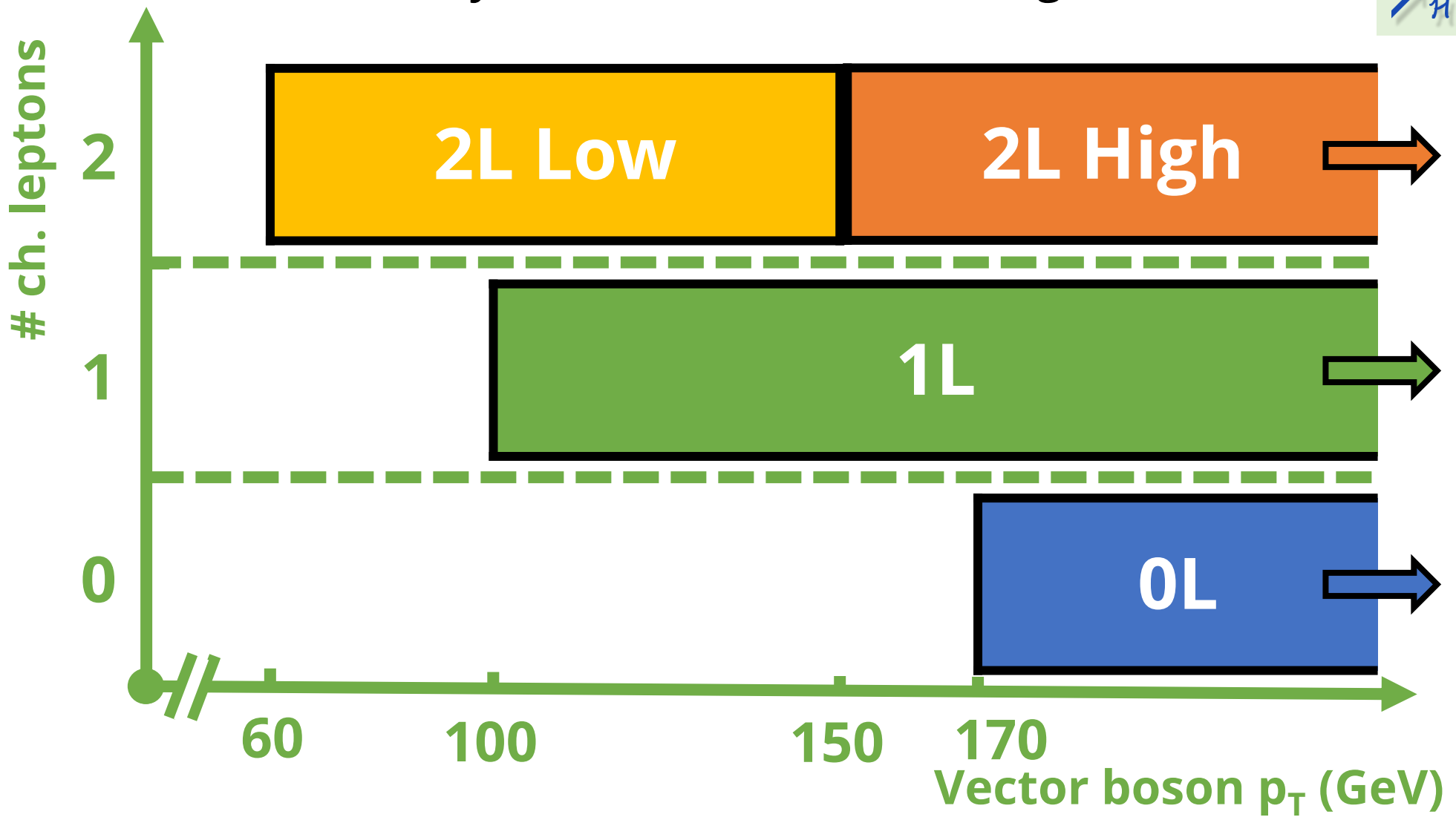




c-tagger corrections contribute to 12 nuisance parameters

Signal and control regions

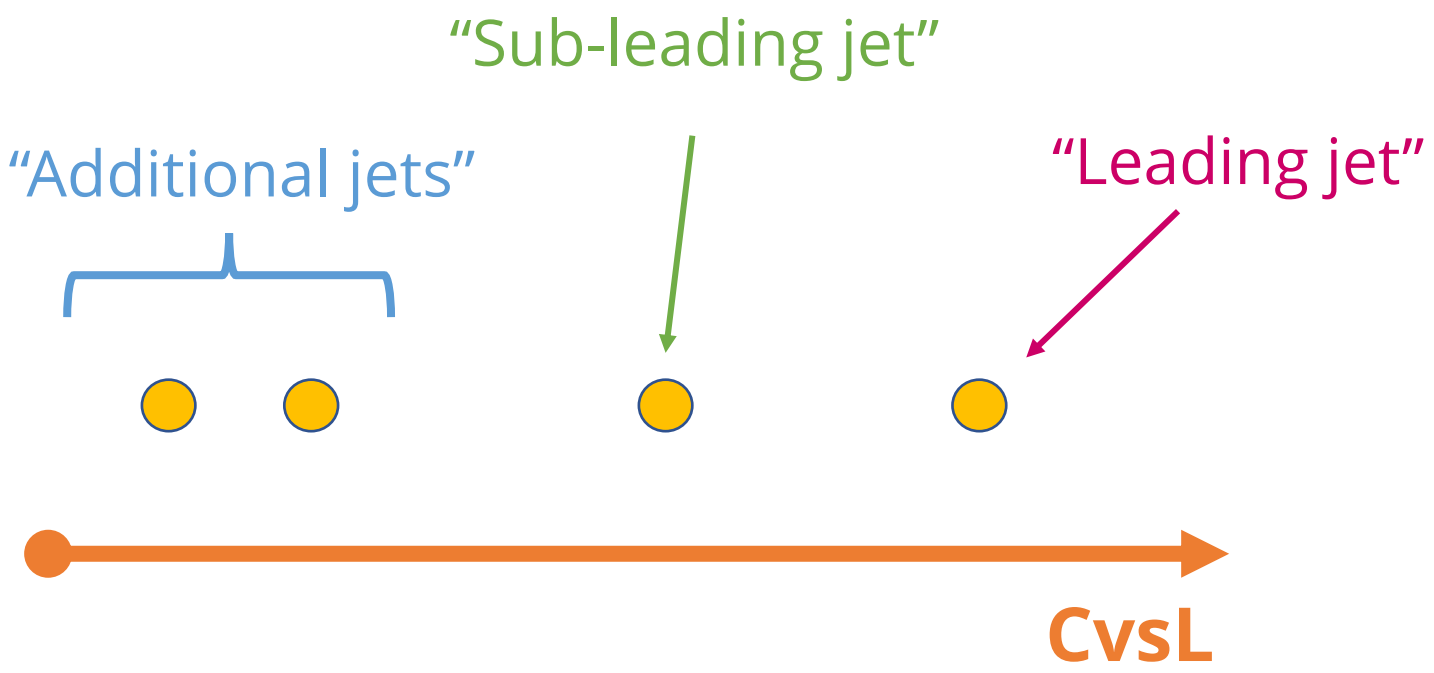
Analysis divided into four categories



Signal and control regions

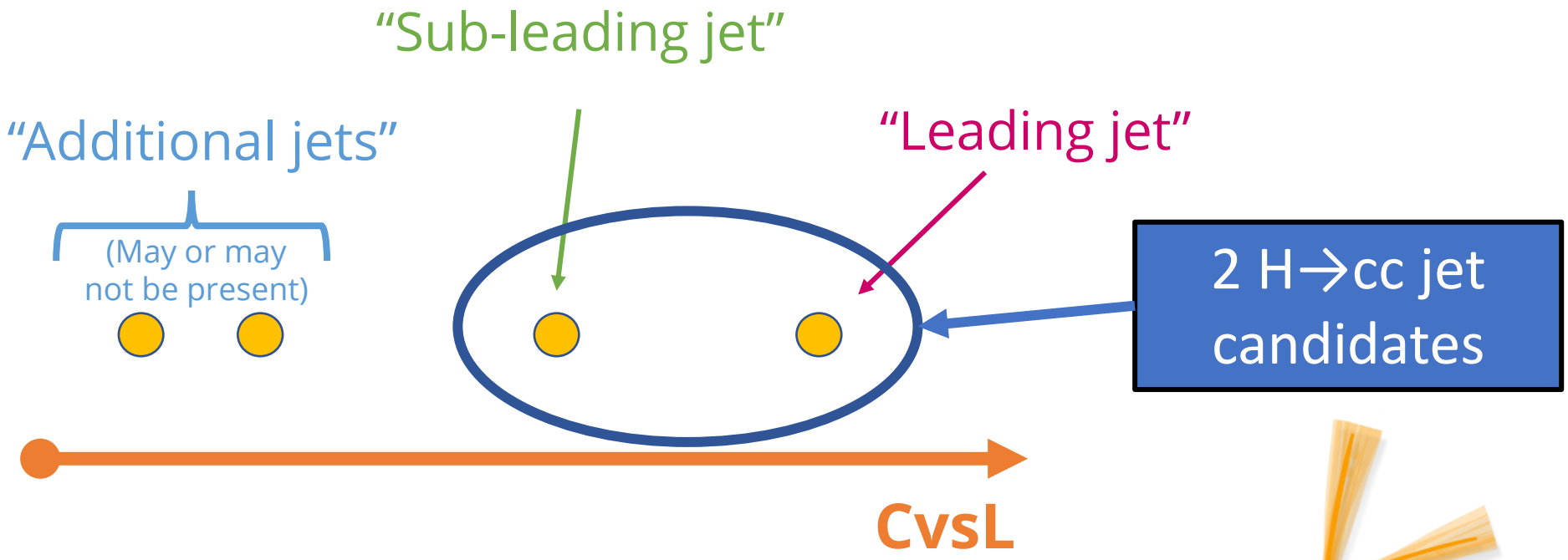
Resolved

Sort jets in an event by CvsL score:



Signal and control regions

Sort jets in an event by CvsL score:



Signal and control regions

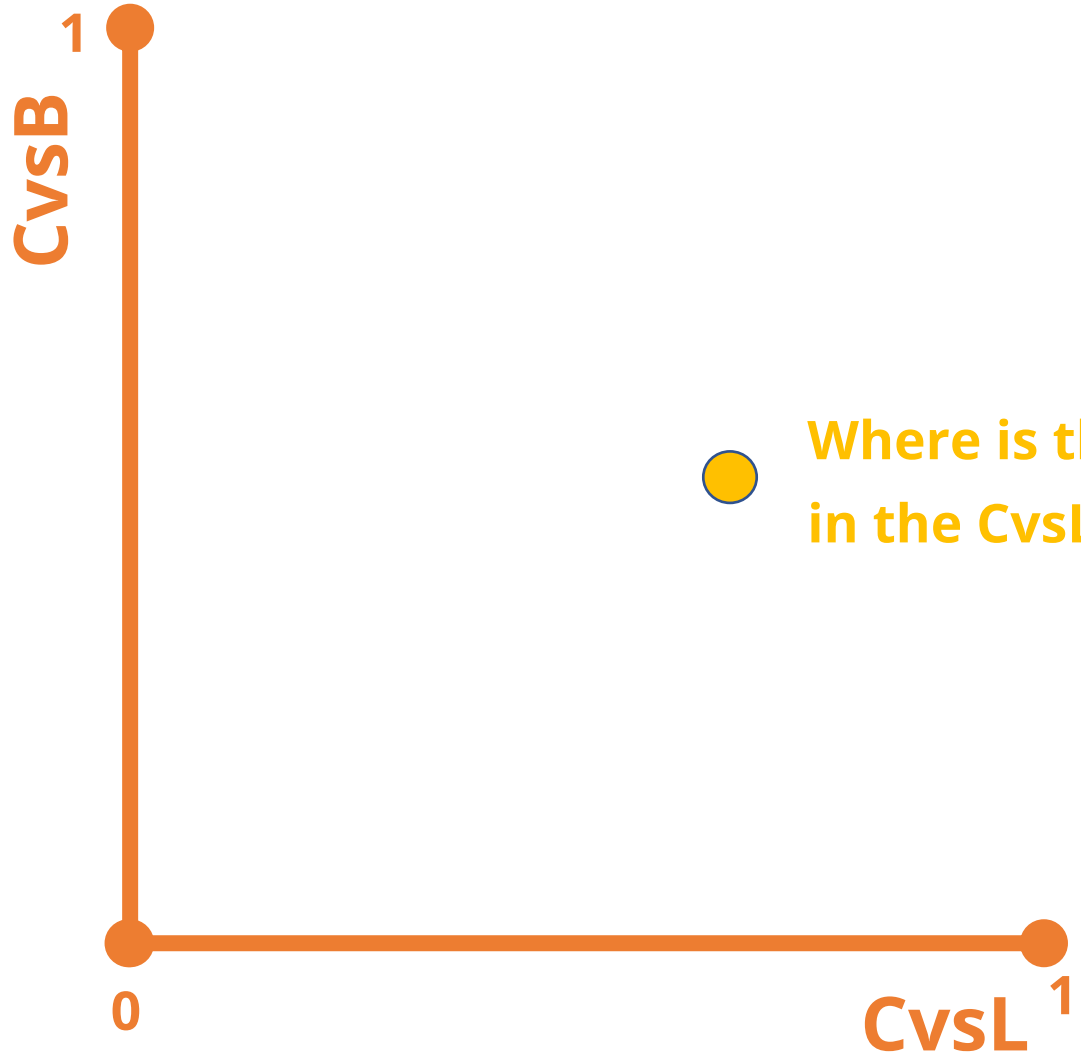
Resolved

Channel		%-age of times we get it right		
		p_T	CvsL	CvsB
0L	Zνν	**73.47**	73.20	71.43
1L	Wμν	59.29	**66.91**	51.93
	Wεν	58.57	**66.47**	51.18
2L	Zμμ	59.84	**66.57**	50.88
	Zεε	59.66	**66.46**	50.76

Signal and control regions

Resolved

- Define regions depending on the leading jet:

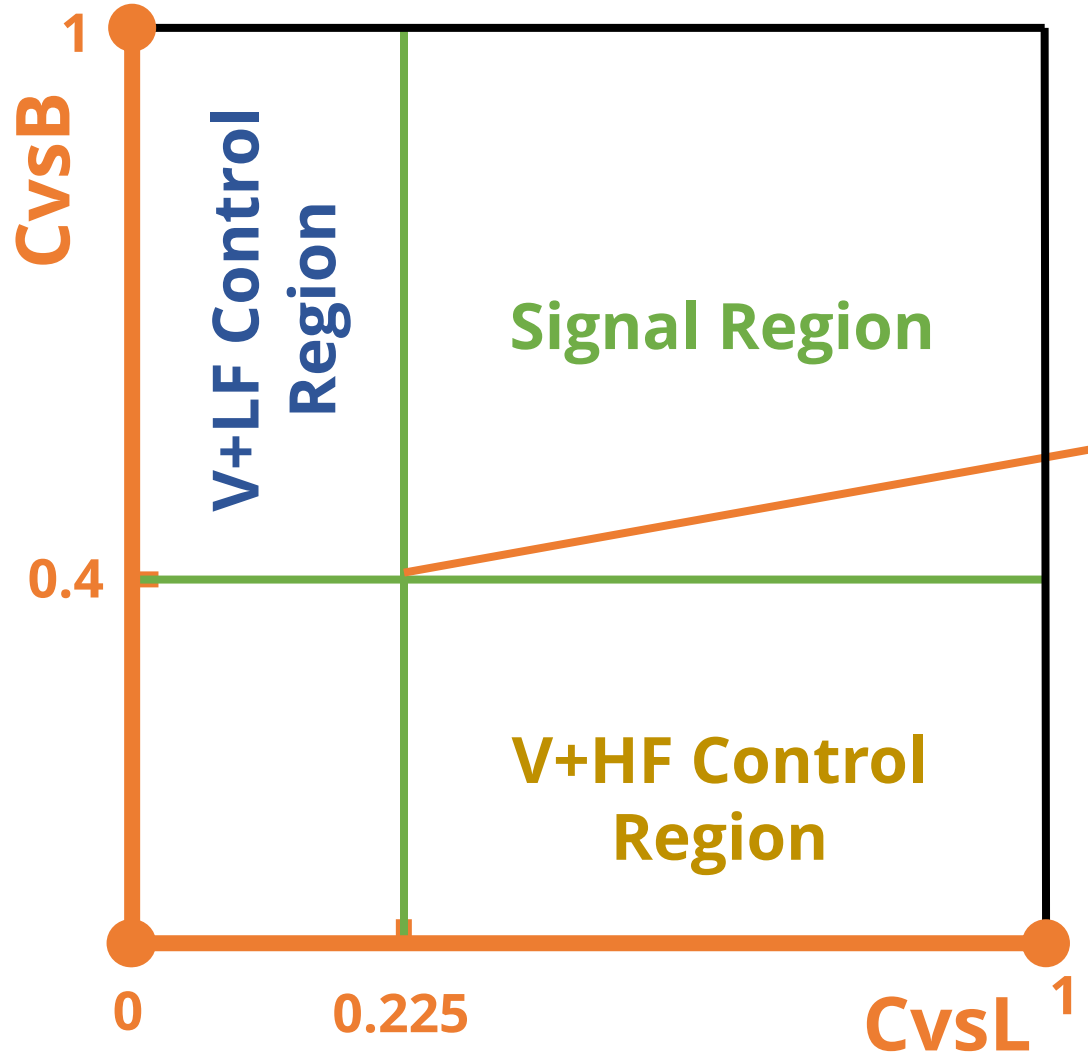


Where is the "leading jet" located in the CvsL-CvsB plane?

Signal and control regions

Resolved

- Define regions depending on the leading jet:



Represents:
- ~42% c efficiency
- ~5% light mistag
- ~15% b mistag

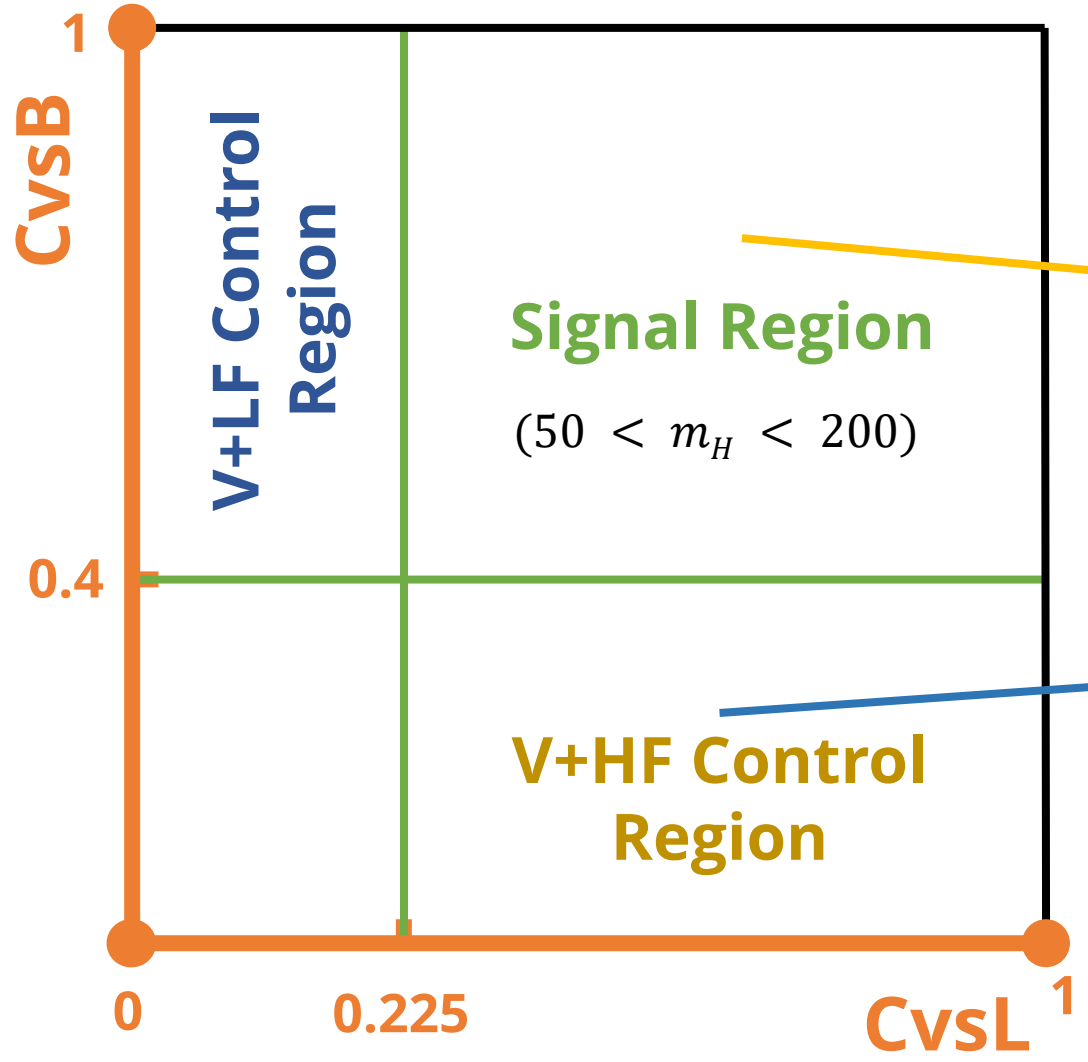
LF = Light flavour

HF = Heavy flavour

Signal and control regions

Resolved

- Define regions depending on the leading jet:



V+cc Control Region:

$m_H \notin [50, 200]$

$t\bar{t}$ Control Region:

- **2L: invert Z mass selection**
- **1L: Require 2 add. Jets**
- **0L: Require add. lep & jet**

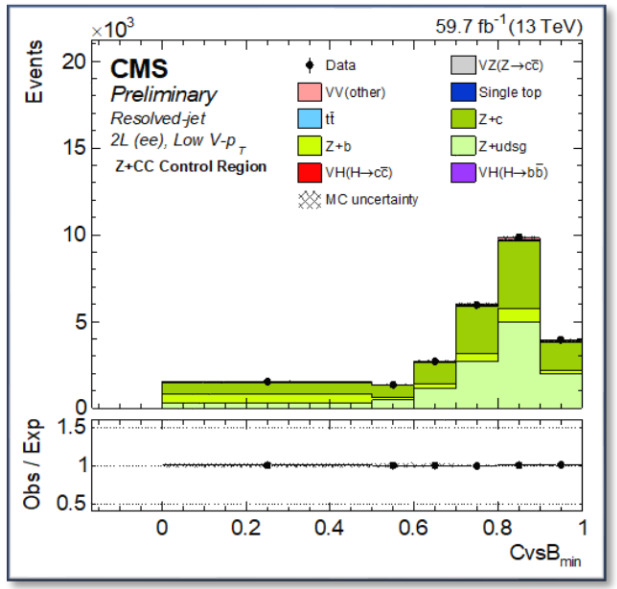
LF = Light flavour

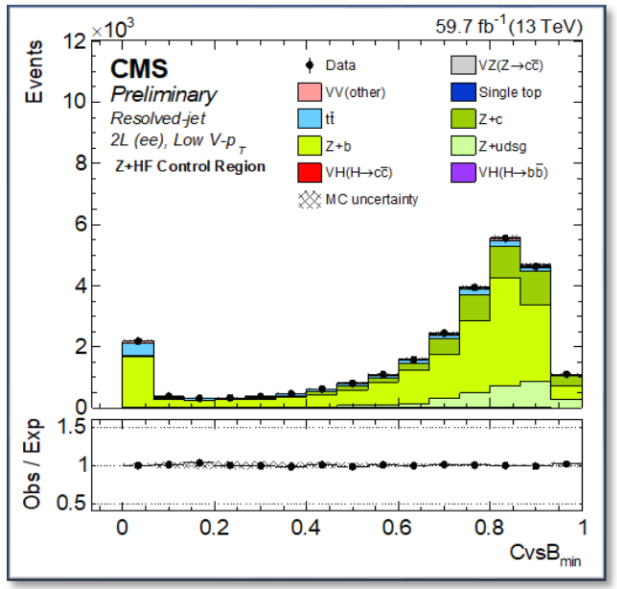
HF = Heavy flavour

$m_H = m_{j_1 j_2}$

Fit strategy

- 4 channels: 0L, 1L, 2LL(Low), 2LH(High)
  - 1L, 2LL, 2LH divided by lepton flavour (e/μ)
- 1 SR and 4 CR per channel: SR, LF, HF, cc, $t\bar{t}$
- Estimate major backgrounds using data in CRs:
  - **V + light jet:** No heavy flavour jet
  - **V + c jet:** No b jet and at least 1 c jet
  - **V + b jet:** At least 1 b jet
  - $t\bar{t}$





Resolved

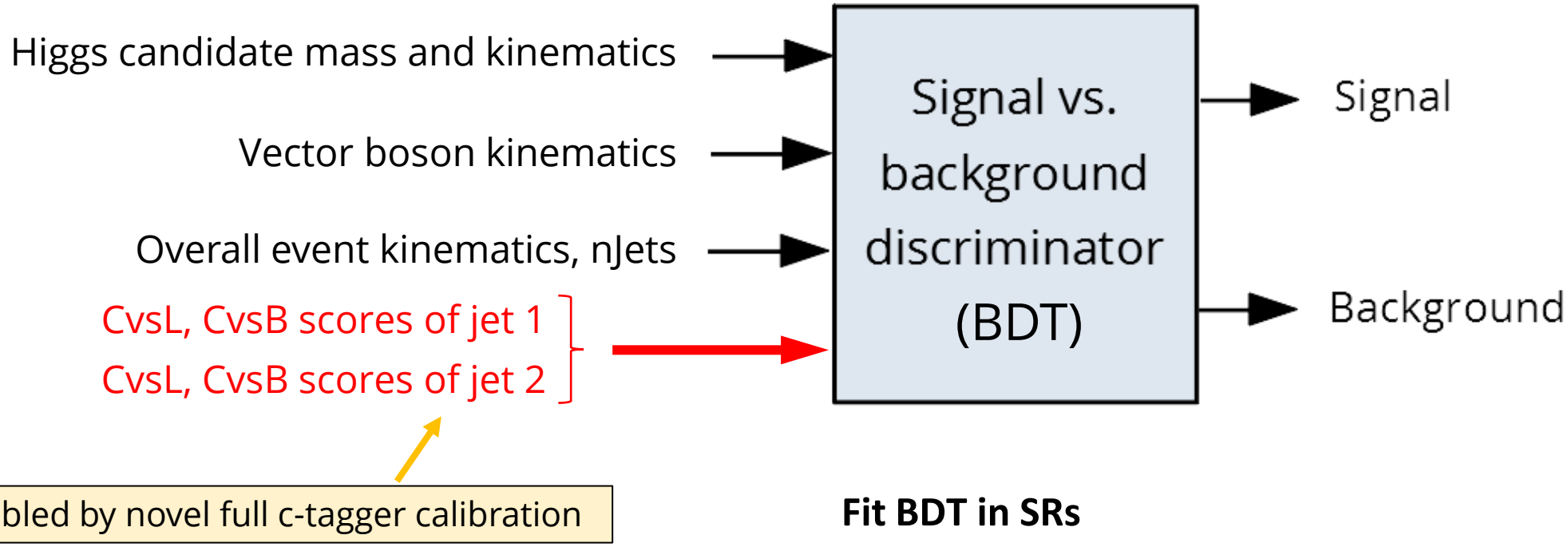
cc CR in 2LL

HF CR in 2LL

(Tagger scores of sub-leading jet)

Fit strategy

- Train BDT to separate signal from background in SRs
  - Separate BDT for each channel
  - Separate BDT for each data year



Fit BDT in SRs
Fit tagger distributions in CRs

Fit strategy

Resolved

All regions…

Channel		SR	LF CR	HF CR	cc CR	tt̄ CR
0L		✓	✓	✓	✓	✓
1L	e	✓	✓		✓	✓
	μ	✓	✓		✓	✓
2LL	ee	✓	✓	✓	✓	✓
	μμ	✓	✓	✓	✓	✓
2LH	ee	✓	✓	✓	✓	✓
	μμ	✓	✓	✓	✓	✓

- W+HF events have the same shape as tt̄ events in 1L
- Issues in fit convergence with two processes with same templates
- Older 2016 standalone analysis gave us high normalization factors for W+HF

Solution: We merge W+HF with W+cc rate parameter

Fit strategy

Resolved

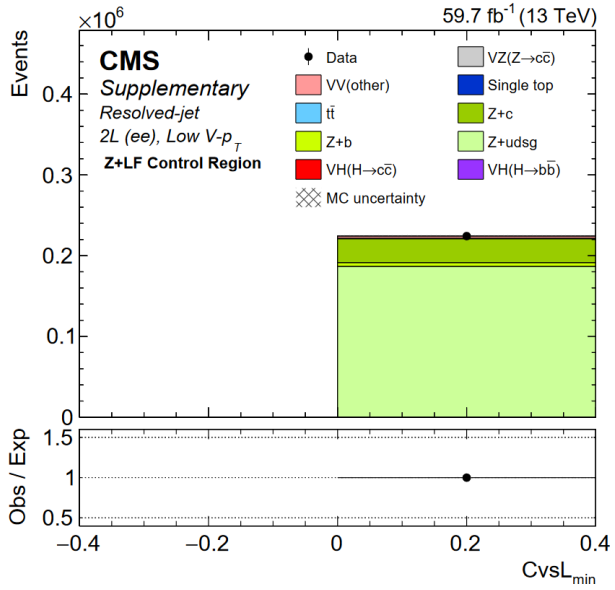
All regions…

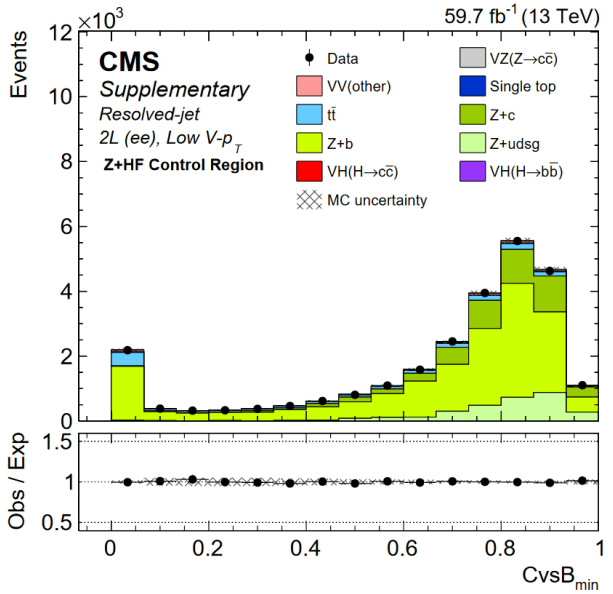
Channel		SR	LF CR	HF CR	cc CR	tt̄ CR
0L		✓	✓	✓	✓	✓
1L	e	✓	✓		✓	✓
	μ	✓	✓		✓	✓
2LL	ee	✓	✓	✓	✓	✓
	μμ	✓	✓	✓	✓	✓
2LH	ee	✓	✓	✓	✓	✓
	μμ	✓	✓	✓	✓	✓

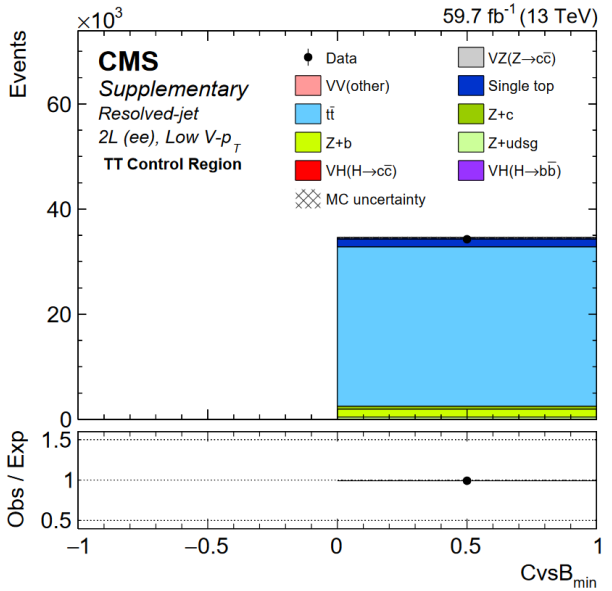
…to constrain these normalization factors

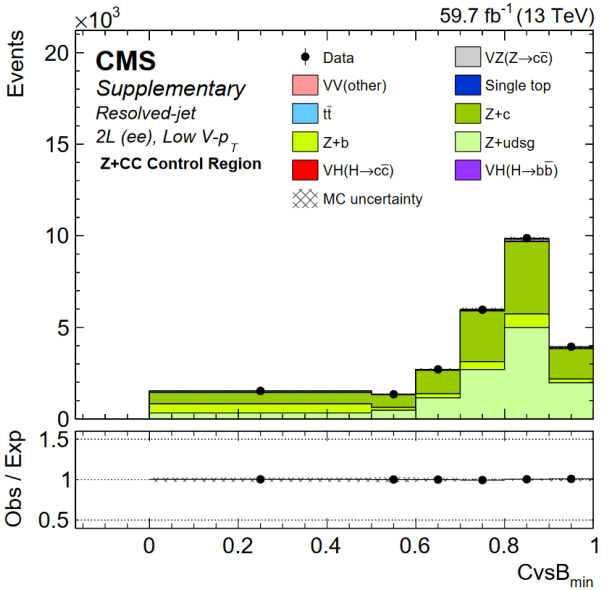
Channel	Z+LF	Z+HF	Z+cc	W+LF	W+HF	W+cc	tt̄
0L	✓	✓	✓	✓	✓		✓
1L							✓
2LL	✓	✓	✓				✓
2LH	✓	✓	✓				✓

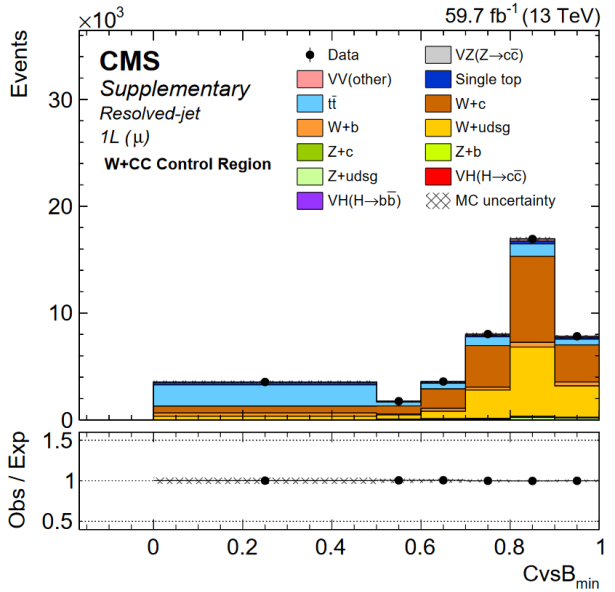
Control Regions

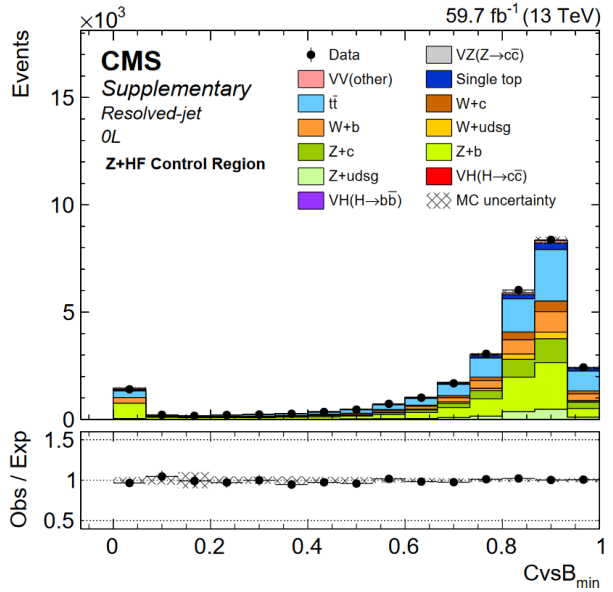


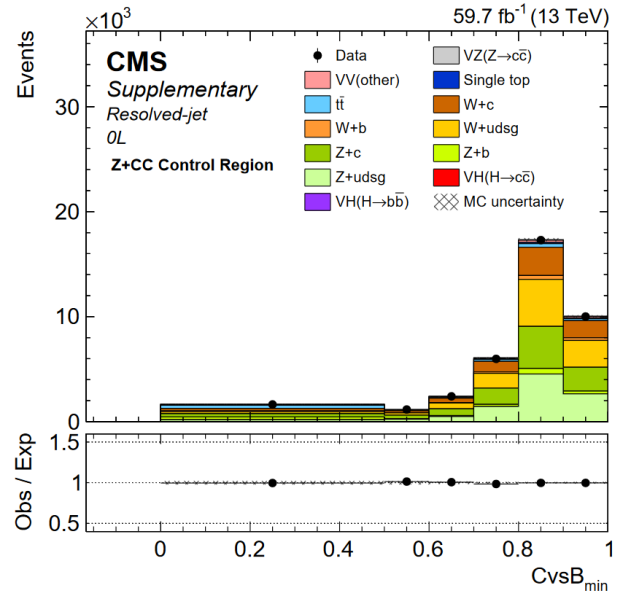












Nuisances

Resolved

Systematic	Type	Comments
Jet energy scale	Shape	Acceptance effects also considered
Jet energy resolution		
E_T^{miss} unc		
Pileup reweighting	Shape	
Lepton efficiencies	LogNormal	
c-tagger SFs	Shape	Split into multiple sources
LHE PDF	LogNormal	Applied uncorrelated across all processes
Factorization scale	Shape	
Renormalization scale		
Other theory uncertainties	LogNormal	Only on signal
XSec uncertainties	LogNormal	Diboson and SingleTop; W+HF in 1L
Luminosity	LogNormal	

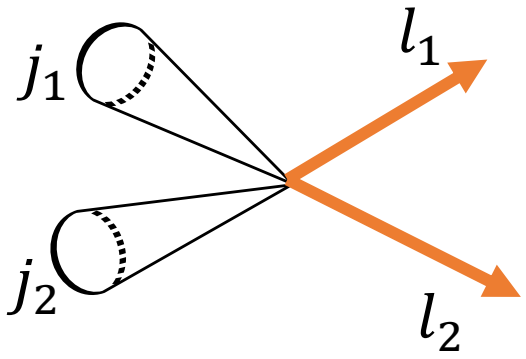
Additional Nuisances

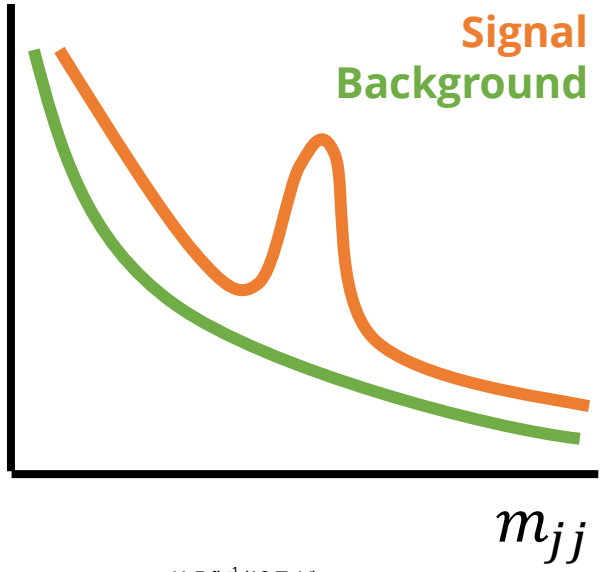
- Residual mismodeling at low $p_T(\mathrm{Z})$ in 2L channel
  - Dedicated reweighting from CR

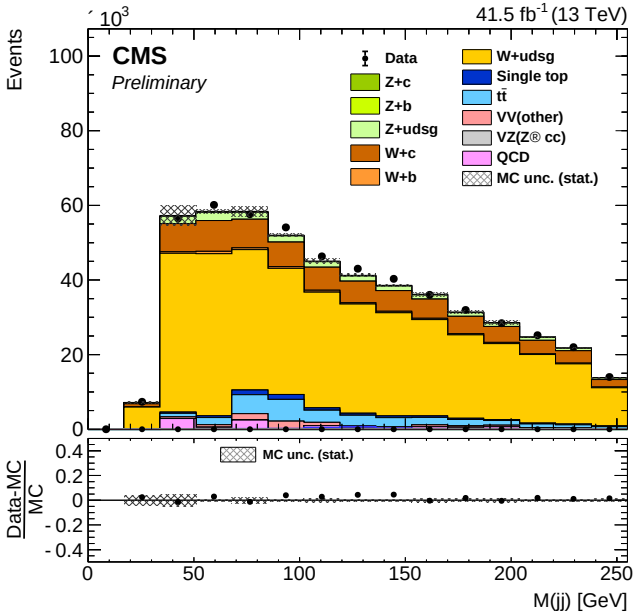
- Residual mismodeling in V+jets at low $\Delta R(j_1, j_2)$ in resolved regime
  - Dedicated reweighting to data using **V+LF CR**, polynomial function of $\Delta R(j_1, j_2)$; uncertainties from fit
  - Minor flavour dependence in $\Delta R(j_1, j_2)$ shape; uncorrelated corrections across flavours
  - Uncertainties for heavy flavours at $\Delta R(j_1, j_2) < 0.55$ inflated by 100%;
    around 5% (1%) of total V+c (b) events fall in this region
  - Merged regime: Fit variable (m_H) relatively unaffected due to dedicated mass regression of cc jet

Additional Nuisances: Jet energy smearing

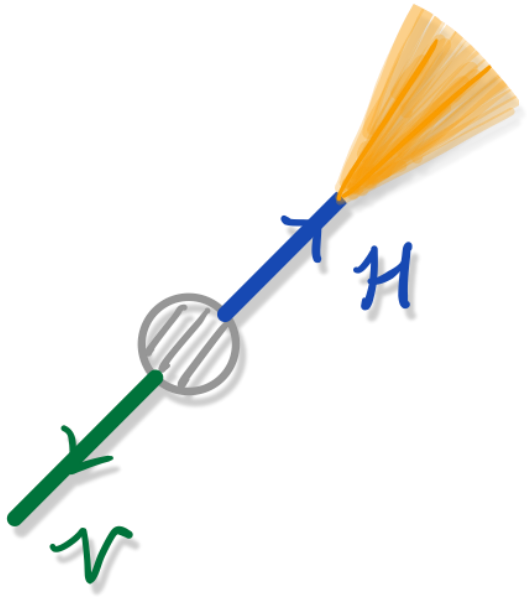
- Corrections derived using 2-jet $Z \rightarrow ll$ events: balance jets against Z
- Signal and other "peaky" samples:
  - Smearing applied
  - Uncertainties from smearing propagated as NPs
- Background samples:
  - Smearing applied
  - Uncertainties covered by standard jet energy uncertainties; not propagated
- Post smearing distributions validated on data in CRs





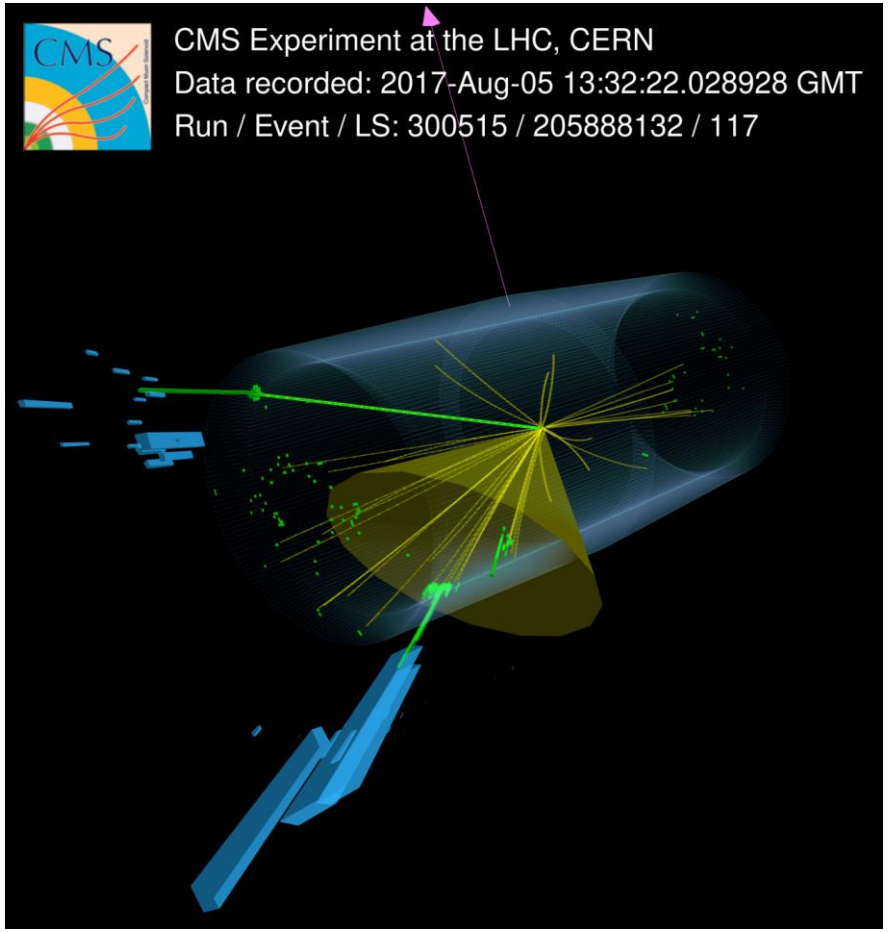


Resolved



Merged jet topology

Overview



Merged

Higgs reconstruction:

- One large AK15 jet as H→cc jet
- Tagging cc jets using powerful ParticleNet tagger
- cc-jet mass regression for improved cc-jet mass scale and resolution

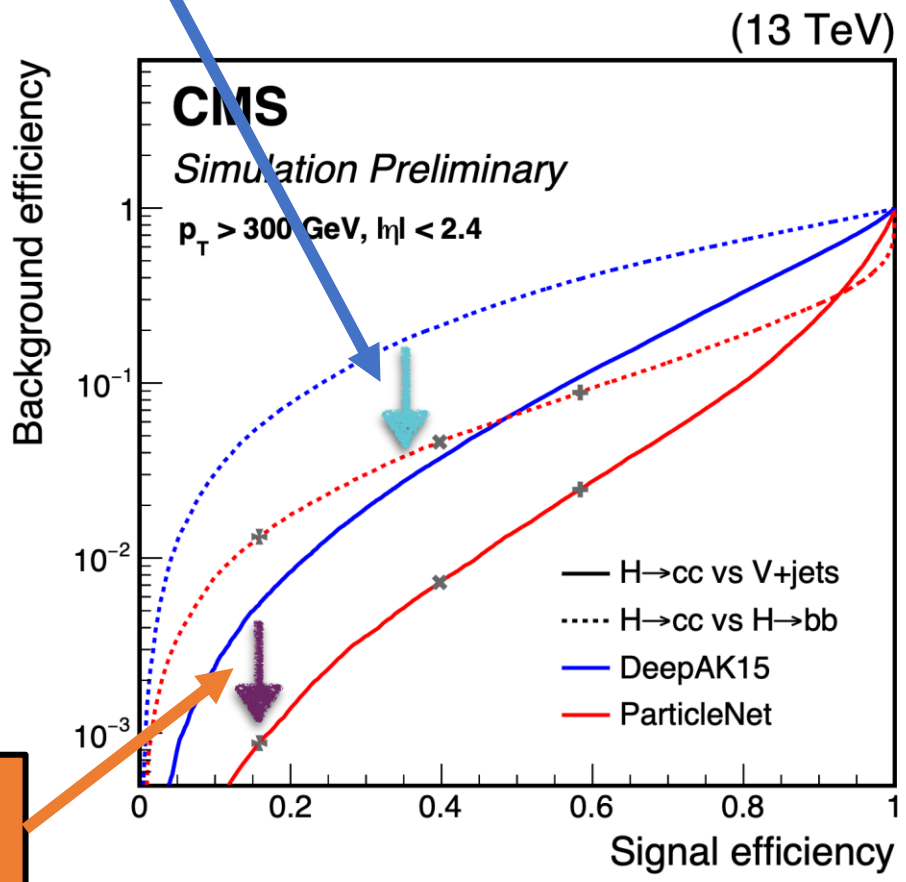
Analysis:

- Kinematic BDT and cc-tagger to categorize events
- Predict background normalizations from control regions
- Fit cc jet mass to extract signal

Di-charm tagging

- ParticleNet tagger on AK15 jets: significant improvement in cc jet tagging
- 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

~5x better H→bb rejection

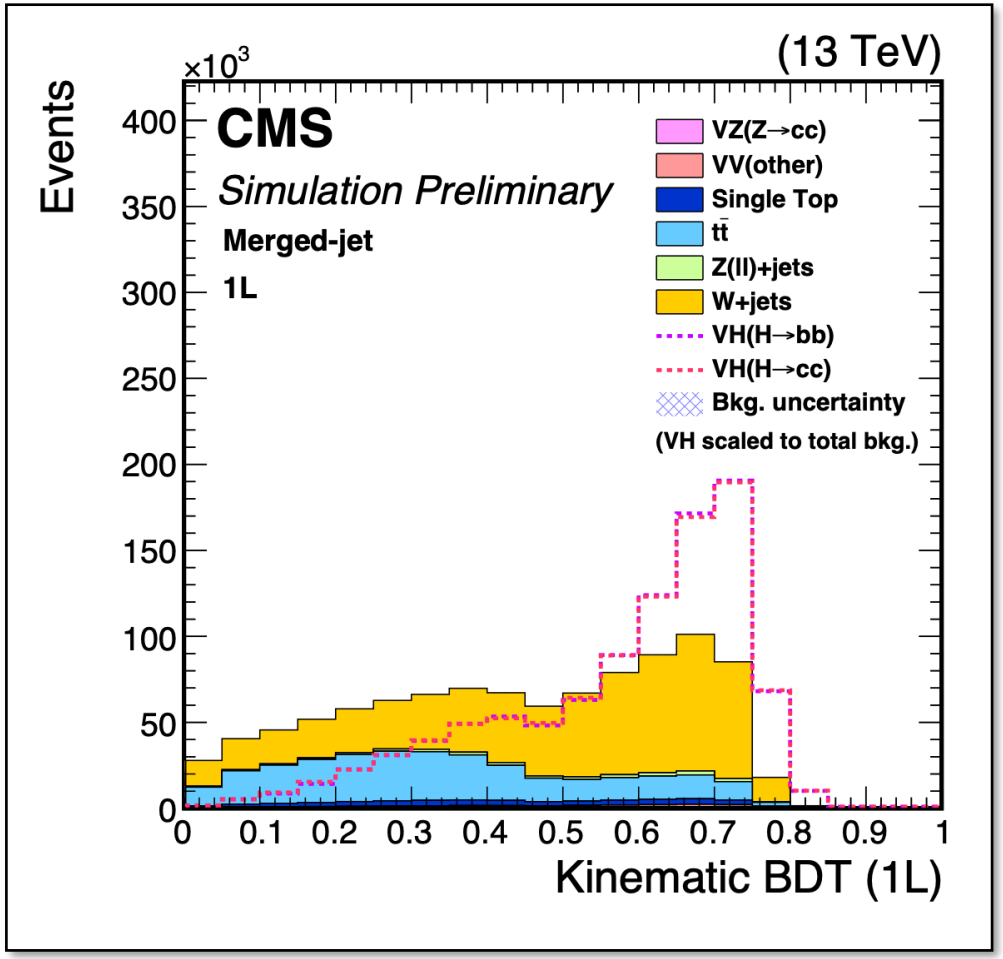


~5x better V+jet rejection

Fit strategy

Merged

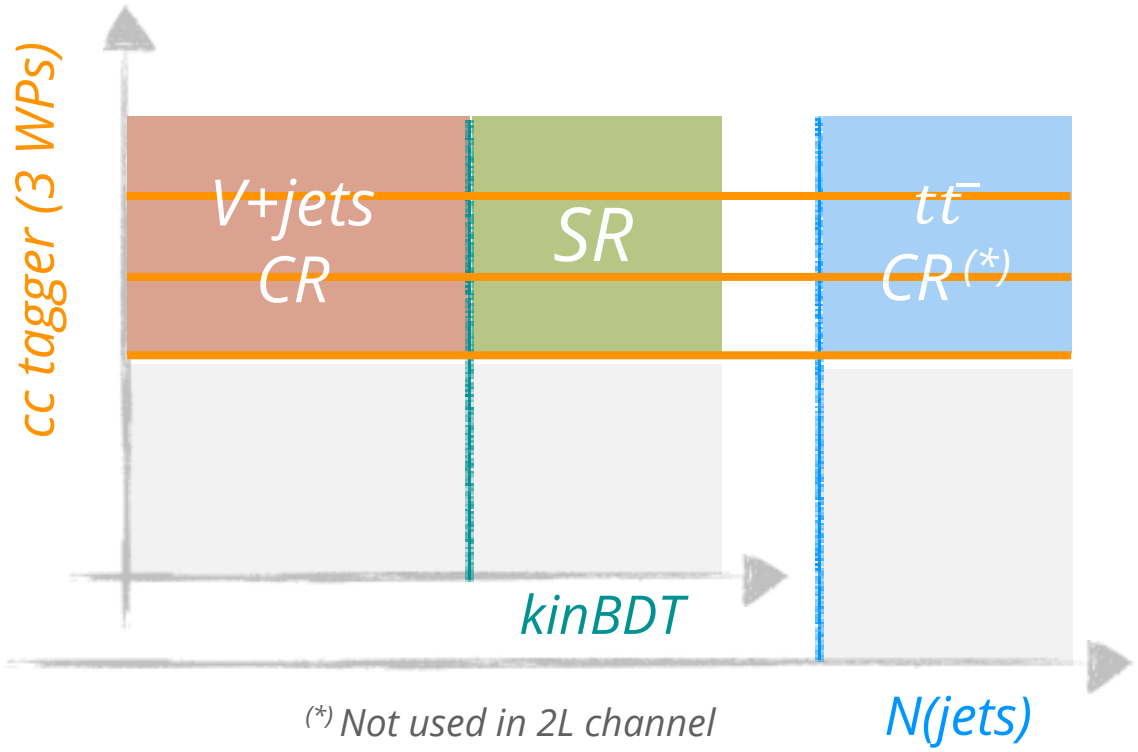
- **Kinematic BDT:**
  - Use event kinematic properties to suppress main backgrounds (V+jets, $t\bar{t}$)
  - Does not use tagger score or jet mass as input
  - Used to define CRs
- **ParticleNet cc tagger score:**
  - Use tagger score to reject light and bb jets:
- Fit the **jet mass**
- Three largely-independent variables



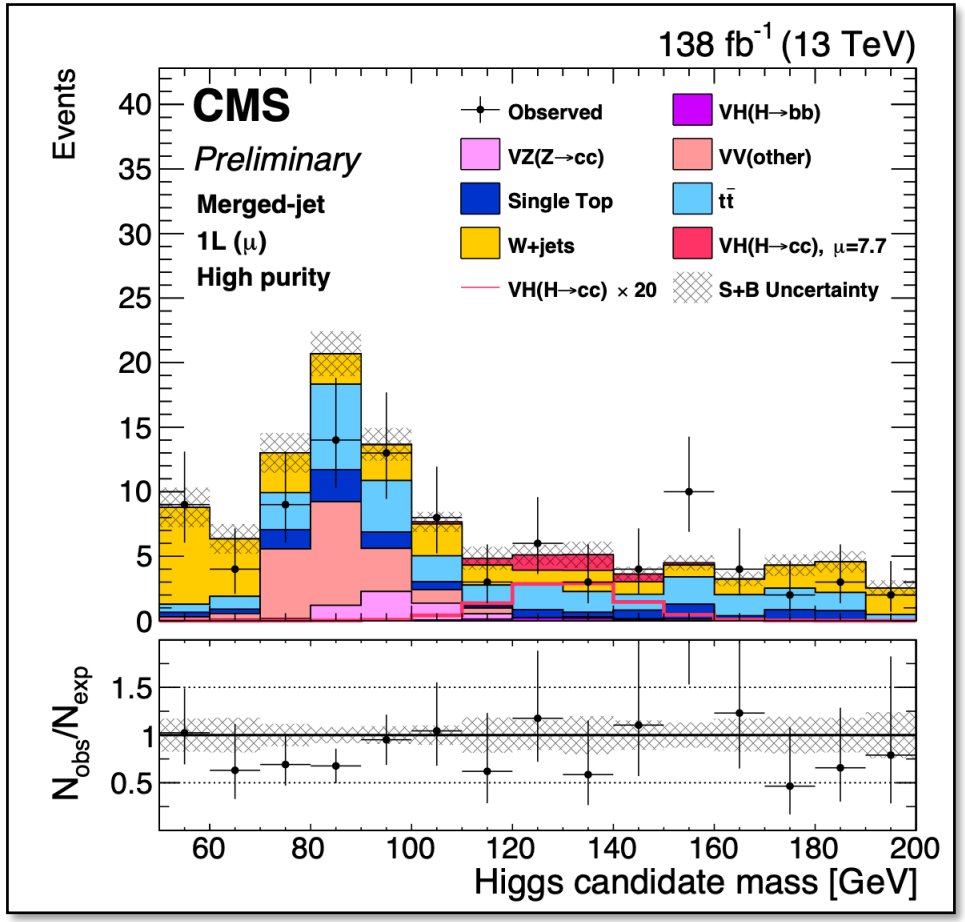
Fit strategy

Merged

- V+jets and $t\bar{t}$ backgrounds estimated from CRs
- CRs have same jet flavour composition as SR
- Fit jet mass simultaneously in SRs and CRs



(*) Not used in 2L channel



Fit strategy

Merged

All regions

Channel		SR		V+Jets CR	tt̄ CR
0L		✓		✓	✓
1L	e	Low BDT ✓	High BDT ✓	✓	✓
	μ	Low BDT ✓	High BDT ✓	✓	✓
2L	ee	✓		✓	
	μμ	✓		✓	

Each further split by purity: LP, MP, HP

1L SR is split into two categories by Kinematic BDT score

Fit strategy

Merged

All regions

Channel		SR		V+Jets CR	tt̄ CR
0L		✓		✓	✓
1L	e	Low BDT ✓	High BDT ✓	✓	✓
	μ	Low BDT ✓	High BDT ✓	✓	✓
2L	ee	✓		✓	
	μμ	✓		✓	

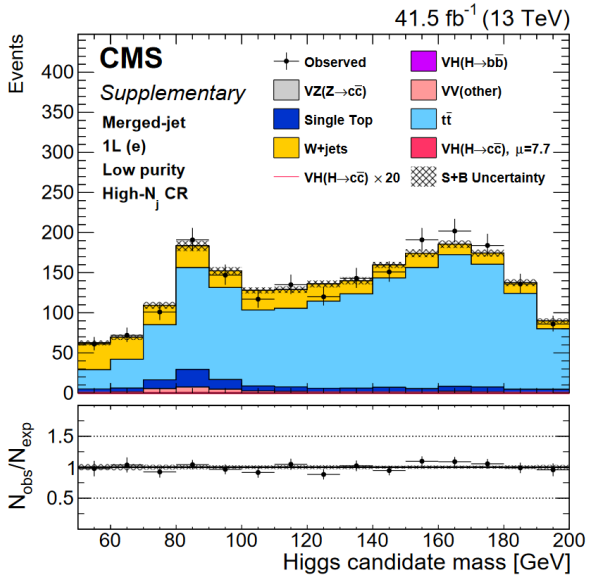
Each further split by purity: LP, MP, HP

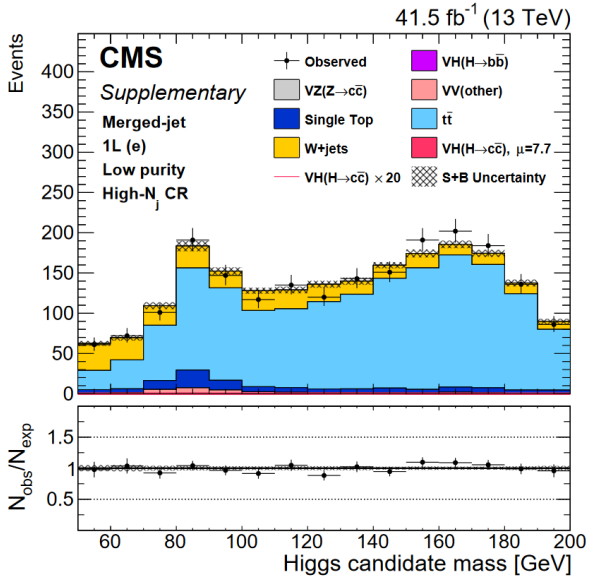
Normalization factors

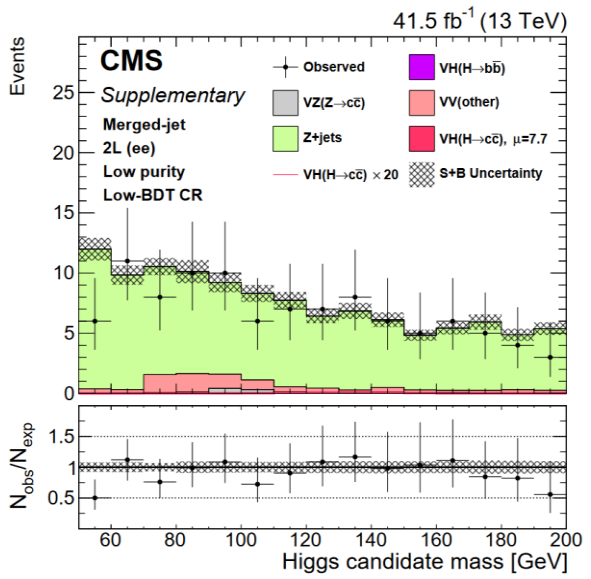
Channel	W+j	Z+j	tt̄ (top)	tt̄ (W)	tt̄ (other) nJet<2	tt̄ (other) nJet≥2
0L	✓	✓	✓	✓	✓	✓
1L						
2L		✓		VW		

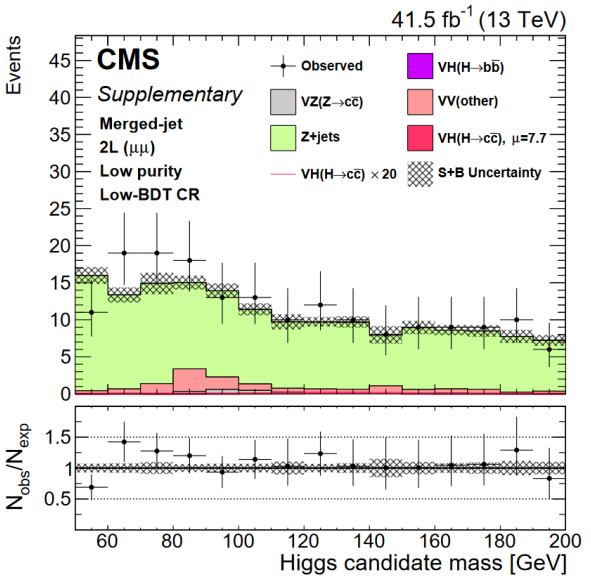
- tt̄ further split by which component lies inside the AK15 jet
- Same RP used for SingleTop (and VW in 2L)
- Each RP further split by purity: LP, MP, HP

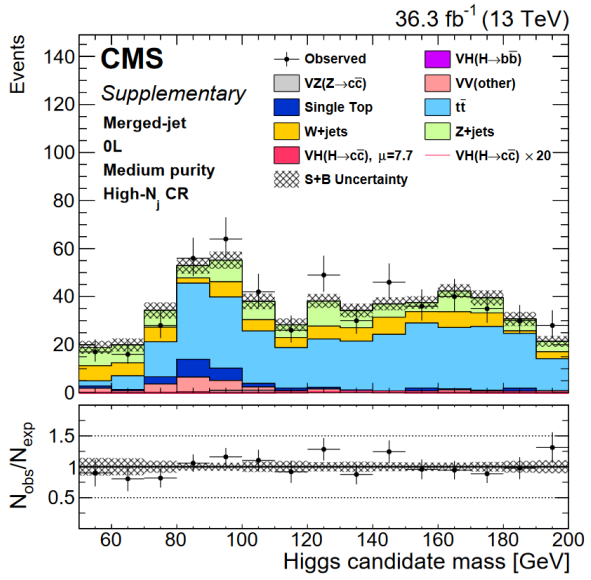
Merged-jet Control Regions

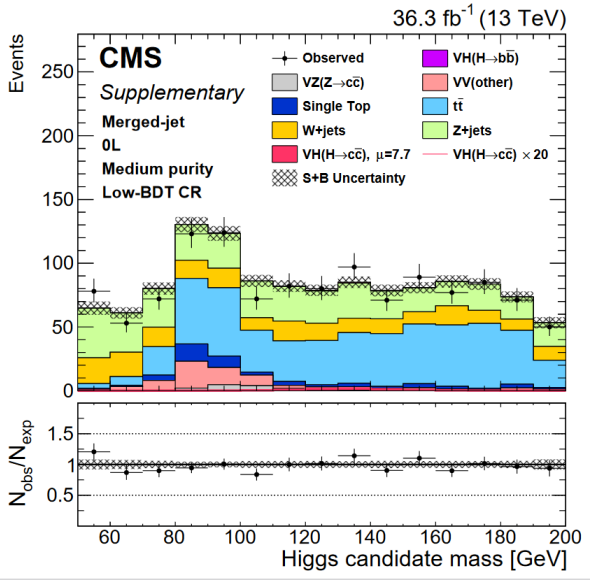


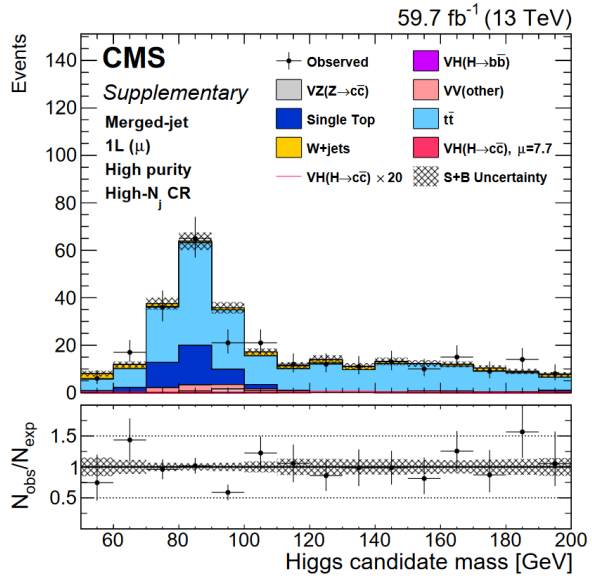


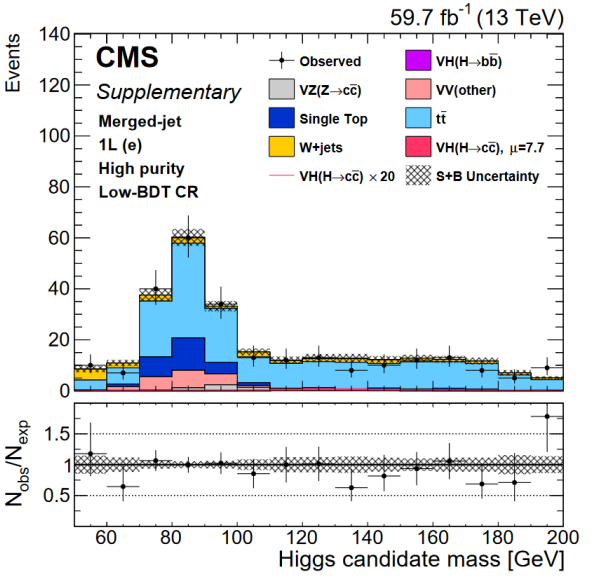


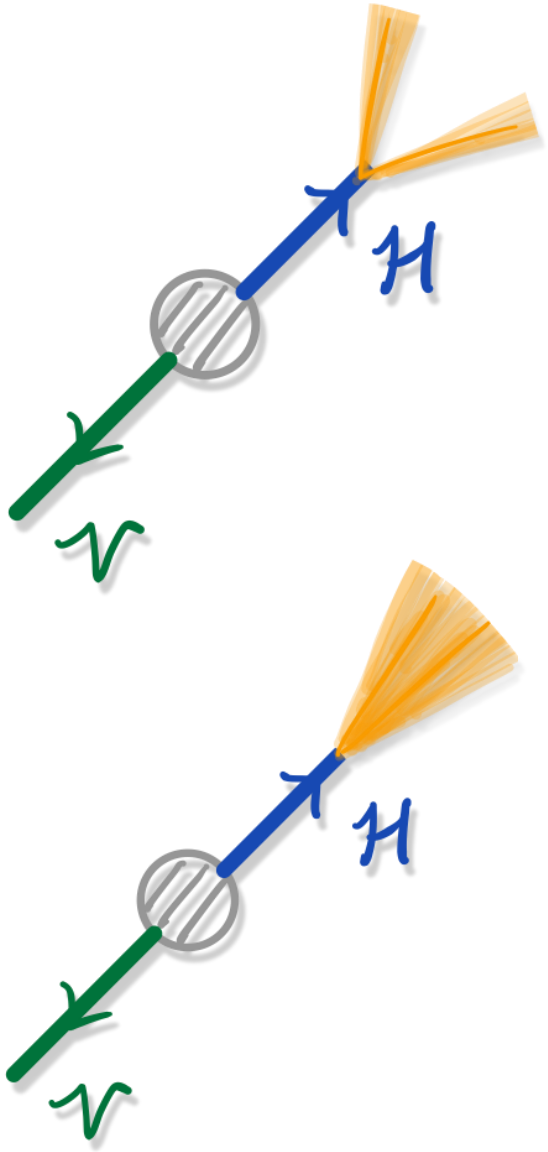






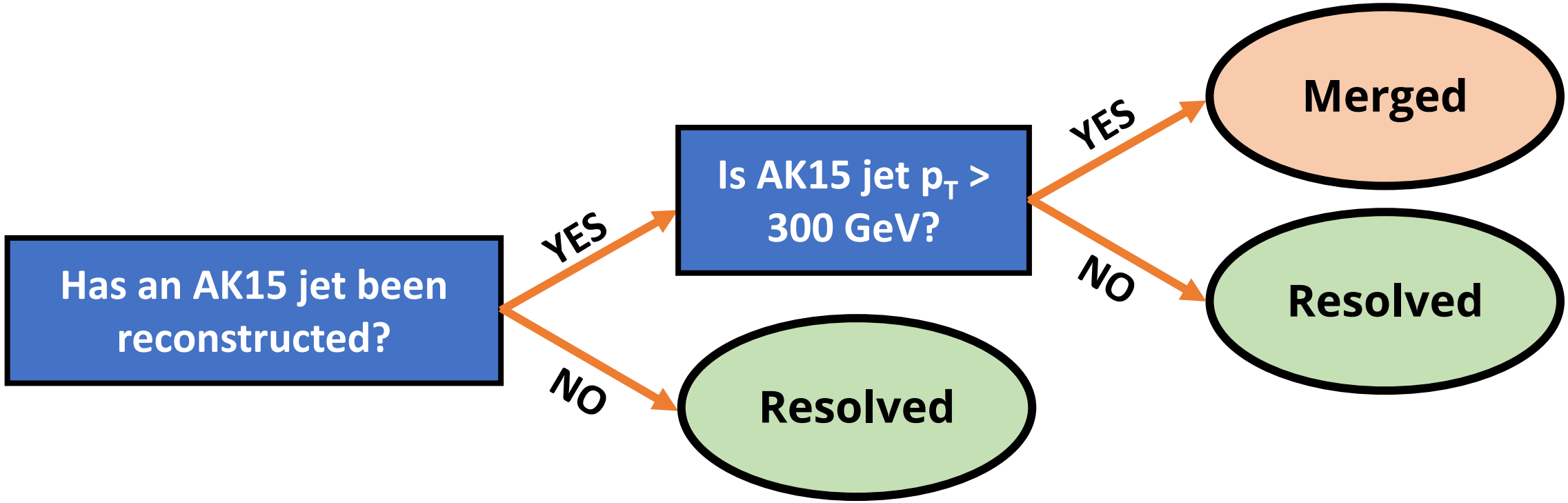






Combination and results

Combination strategy



- Orthogonal sets of events
- Resolved probes larger part of the signal
- Merged has a cleaner signal and effectively exploits correlations between two quarks

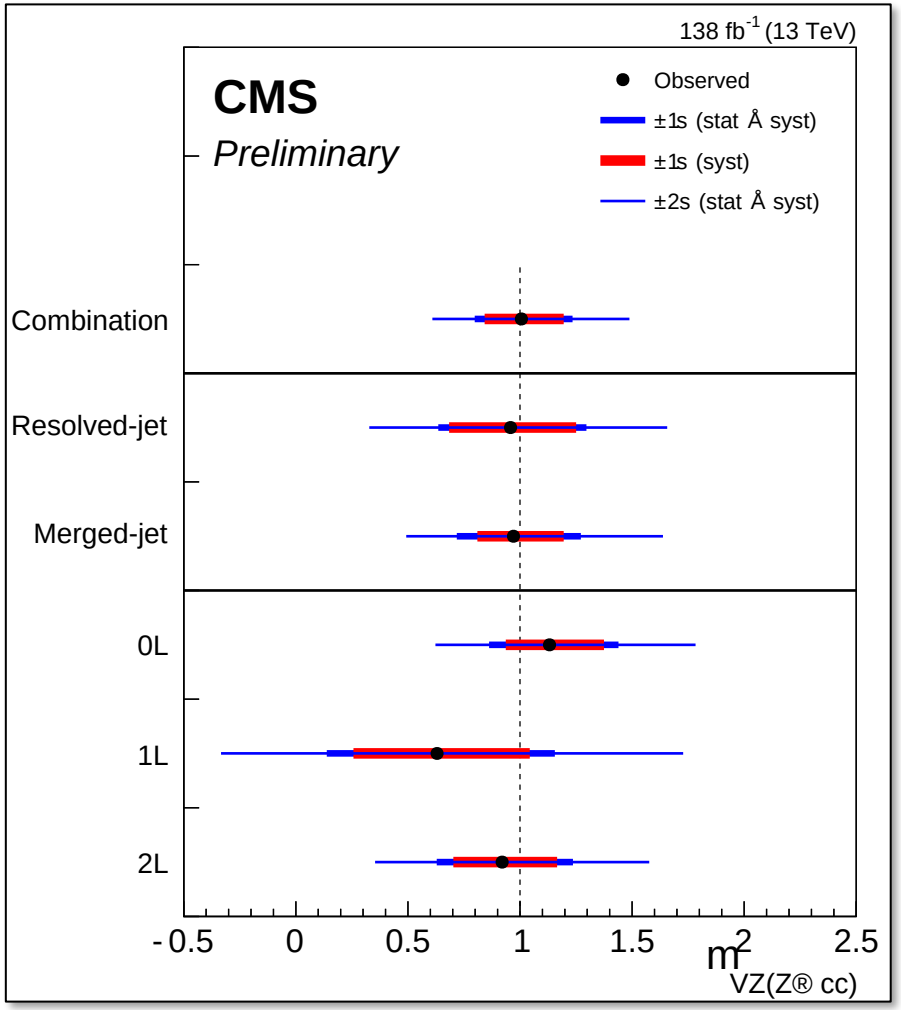
Combination strategy

- Uncertainties correlated between two regimes
  - Except c-tagging SFs and background normalizations

Uncertainty source	$\Delta\mu / (\Delta\mu)_{\text{tot}}$
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

- Resolved: Train separate BDT (same inputs) in SRs for VZ(Z→cc) vs. backgrounds
- Merged: Extract VZ(Z→cc) signal from the mass fit
- **Significance of 5.7σ (5.9σ), first observation at hadron colliders**



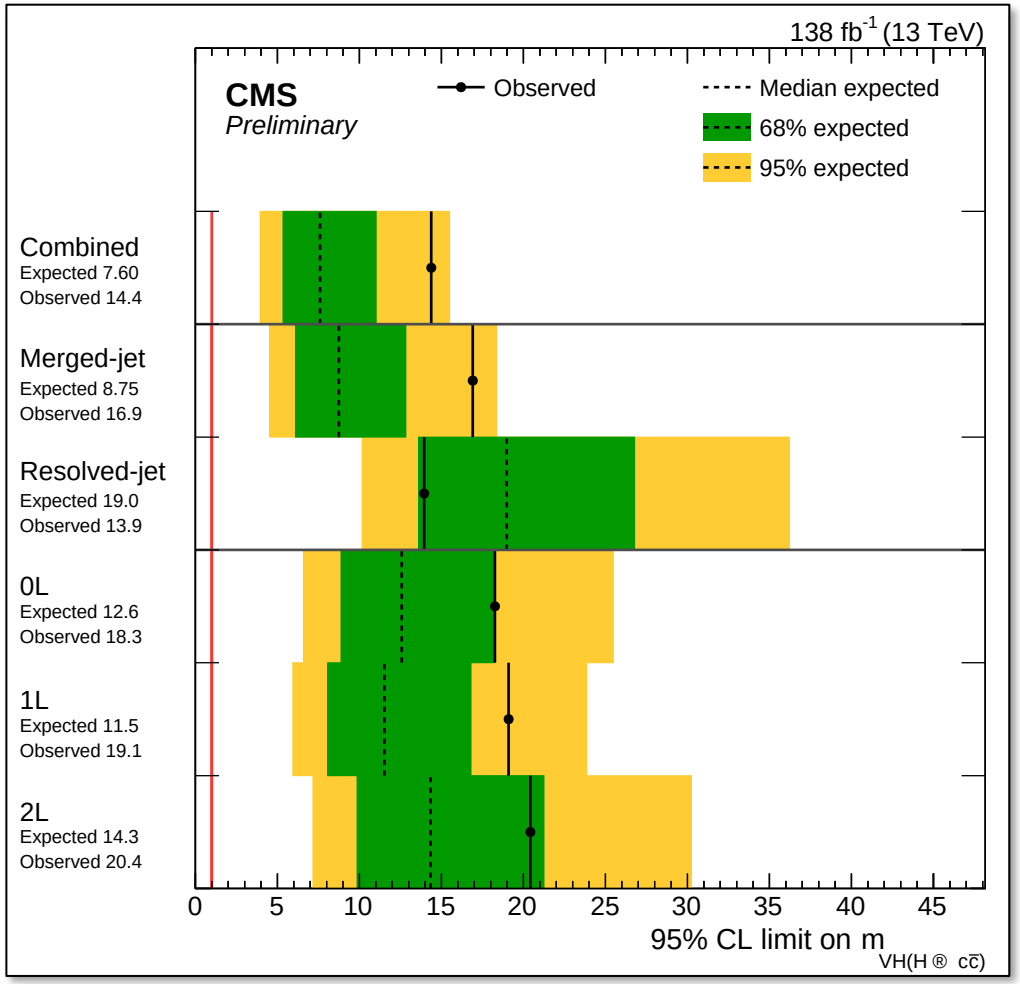
VH(H→cc) Results

- Observed (expected) upper limit on VH(H→cc) signal strength at 95% CL:

$$\mu_{\mathrm{VH(H\to cc)}} < 14\ (7.6^{+3.4}_{-2.3}) \times \mathrm{SM}$$

Strongest limits on VH(H→cc) process to date

- Expected upper limits from each topology:
  - Resolved-jet topology: 19 × SM
  - Merged-jet topology: 8.8 × SM



Conclusion and outlook

- New VH(H→cc) search at CMS:
  - Full LHC Run-2 data
  - Substantial improvement in charm tagging and calibration methods
  - Charm jet energy/mass regression, kinematic fit, and many other improvements
- First observation of VZ(Z→cc) process at hadron colliders
- Strongest limit on VH(H→cc) process and strong constraint on Higgs-charm coupling modifier
- Results comparable with HL-LHC predictions: enabled by new analysis techniques

THANK YOU!

Backup

Resolved-jet selections

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)
$p_{\mathrm{T}}(\mathrm{V})$	> 170	> 100	$[50 - 150]$	> 150
$m_{\ell\ell}$	–	–	$[75 - 105]$	$[75 - 105]$
p_{T}^{ℓ}	–	$(> 25(\mu), > 30(e))$	> 20	> 20
$p_{\mathrm{T}}(\mathrm{j}_1)$	> 60	> 25	> 20	> 20
$p_{\mathrm{T}}(jtwo)$	> 35	> 25	> 20	> 20
$p_{\mathrm{T}}(\mathrm{jj})$	> 120	> 100	–	–
$m(\mathrm{jj})$	< 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}	$= 0$	$= 0$	–	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 170	–	–	–
METsig	–	> 4.0	–	–
Anti-QCD	Yes	–	–	–
$\Delta\phi(\mathrm{V},\mathrm{H})$(rad)	> 2.0	> 2.5	2.5	2.5
$\Delta\phi$(pfMET,trkMET)(rad)	< 0.5	–	–	–
$\Delta\phi$(pfMET,lep)(rad)	–	< 2.0	–	–

DRAFT

Merged-jet selections

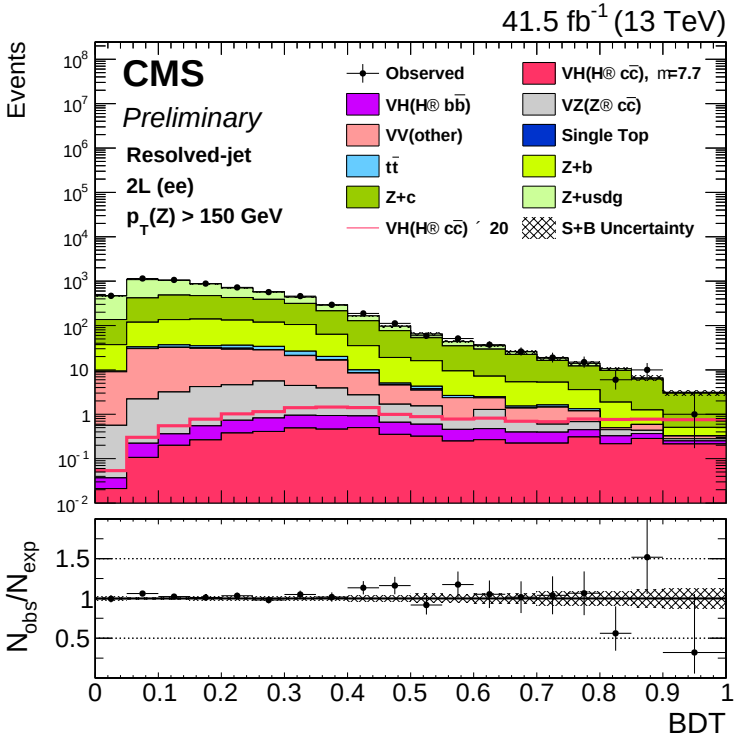
Variable	0-lepton	1-lepton	2-lepton
$p_{\mathrm{T}}(\mathrm{V})$	>200	>150	>150
$M(\ell\ell)$	—	—	[75, 105]
p_{T}^{ℓ}	—	(> 25, > 30)	>20
p_{T} ($\mathrm{H_{cand}}$)	>200	>200	>200
$M_{\mathrm{reg}}(\mathrm{H_{cand}})$	[50, 200]	[50, 200]	[50, 200]
$\Delta\phi(\mathrm{V}, \mathrm{H_{cand}})$	>2.5	>2.5	>2.5
N_{j}	<2	<2	<3
$N_{\mathrm{a}\ell}$	=0	=0	—
$p_{\mathrm{T}}^{\mathrm{miss}}$	>200	>60	—
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j})$	>0.5	—	—
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{trk}))$	<0.5	—	—
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \ell)$	—	<1.5	—
Lepton isolation	—	(<0.06, —)	(<0.25, —)
Kinematic BDT	>0.55	(0.55, 0.7], >0.7	>0.55
cc-tagging discriminant			
High purity (HP)	> 0.99	> 0.99	> 0.99
Medium purity (MP)	(0.96, 0.99]	(0.96, 0.99]	(0.96, 0.99]
Low purity (MP)	(0.90, 0.96]	(0.90, 0.96]	(0.90, 0.96]

Resolved SRs

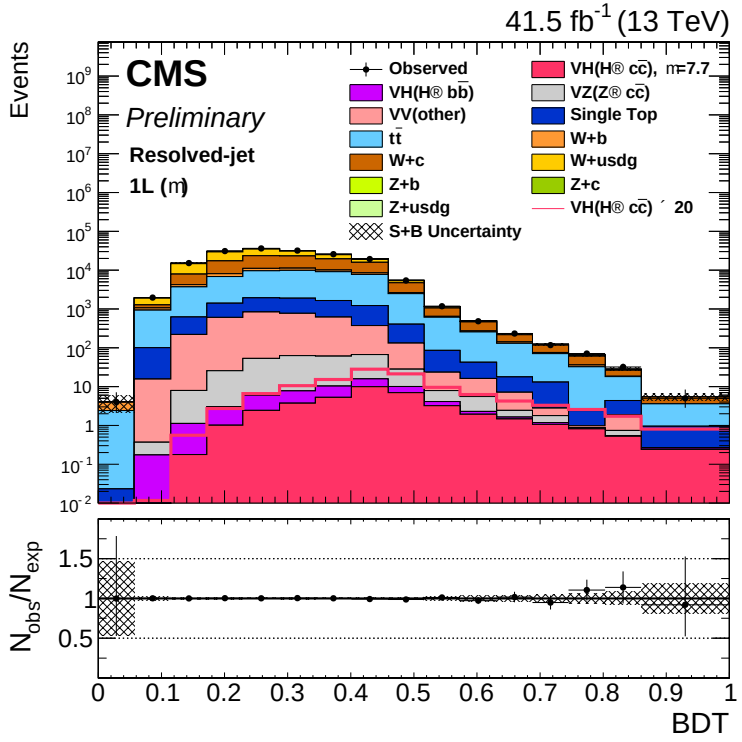
- Post-fit distributions (2017 data)

Resolved

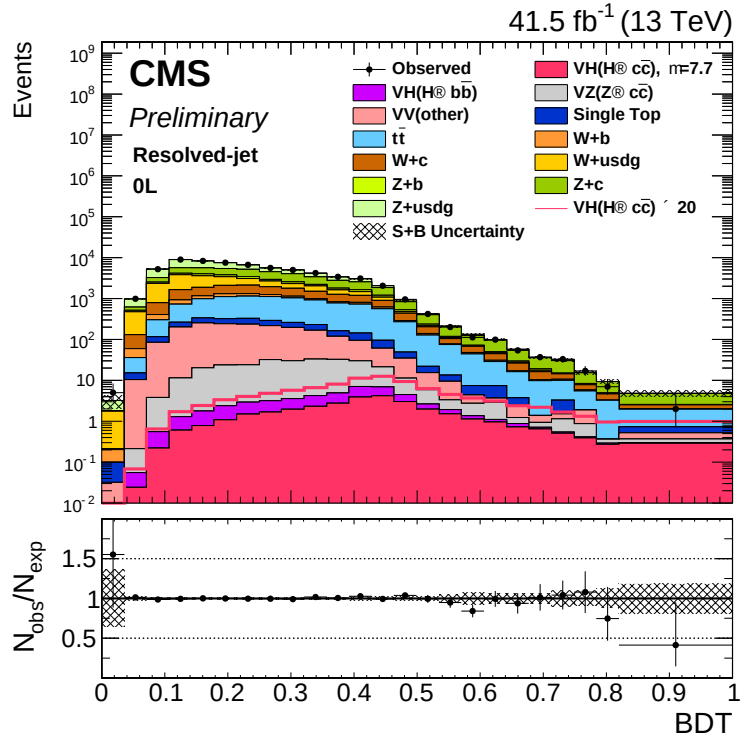
2L



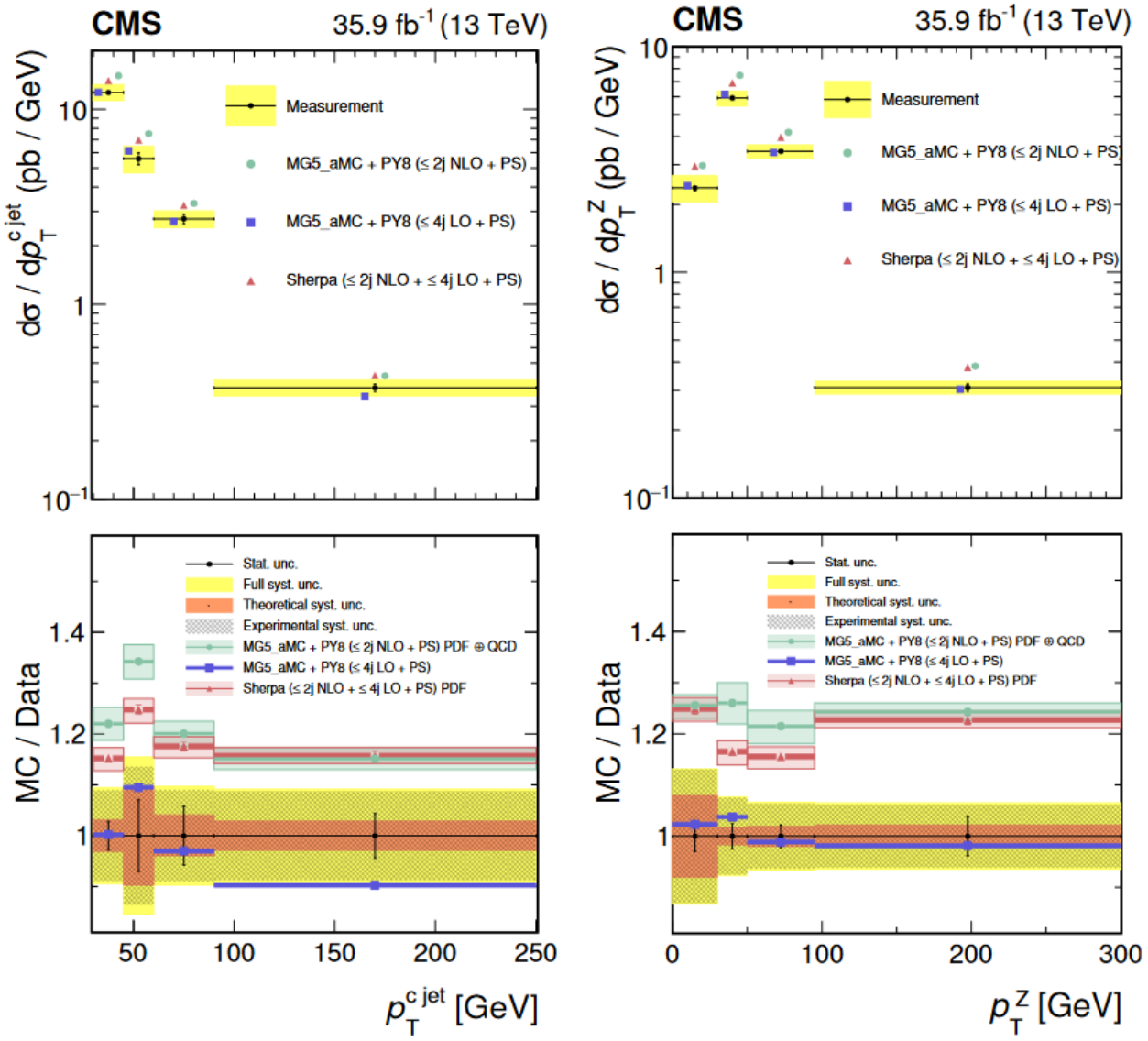
1L



0L



MG5 and Sherpa



The Higgs boson

- 2012: Discovery of the Higgs boson, a milestone

Phys. Lett. B 716 (2012) 30

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration

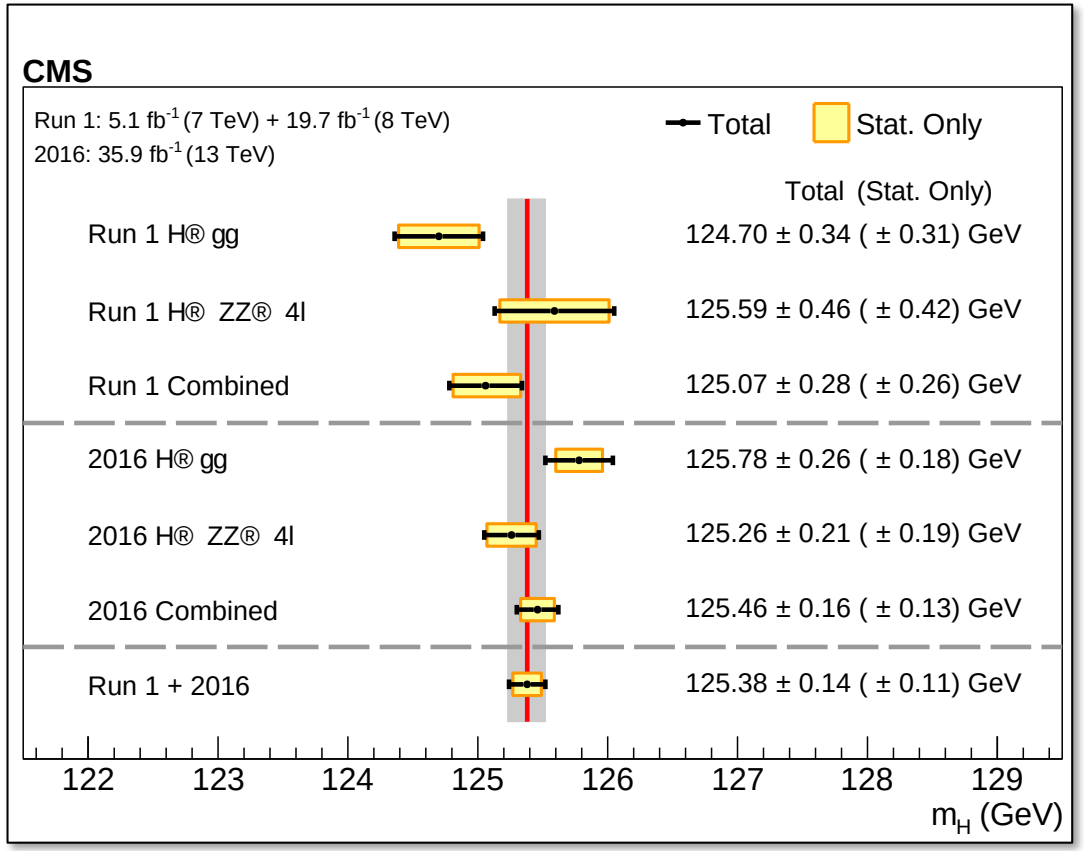
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

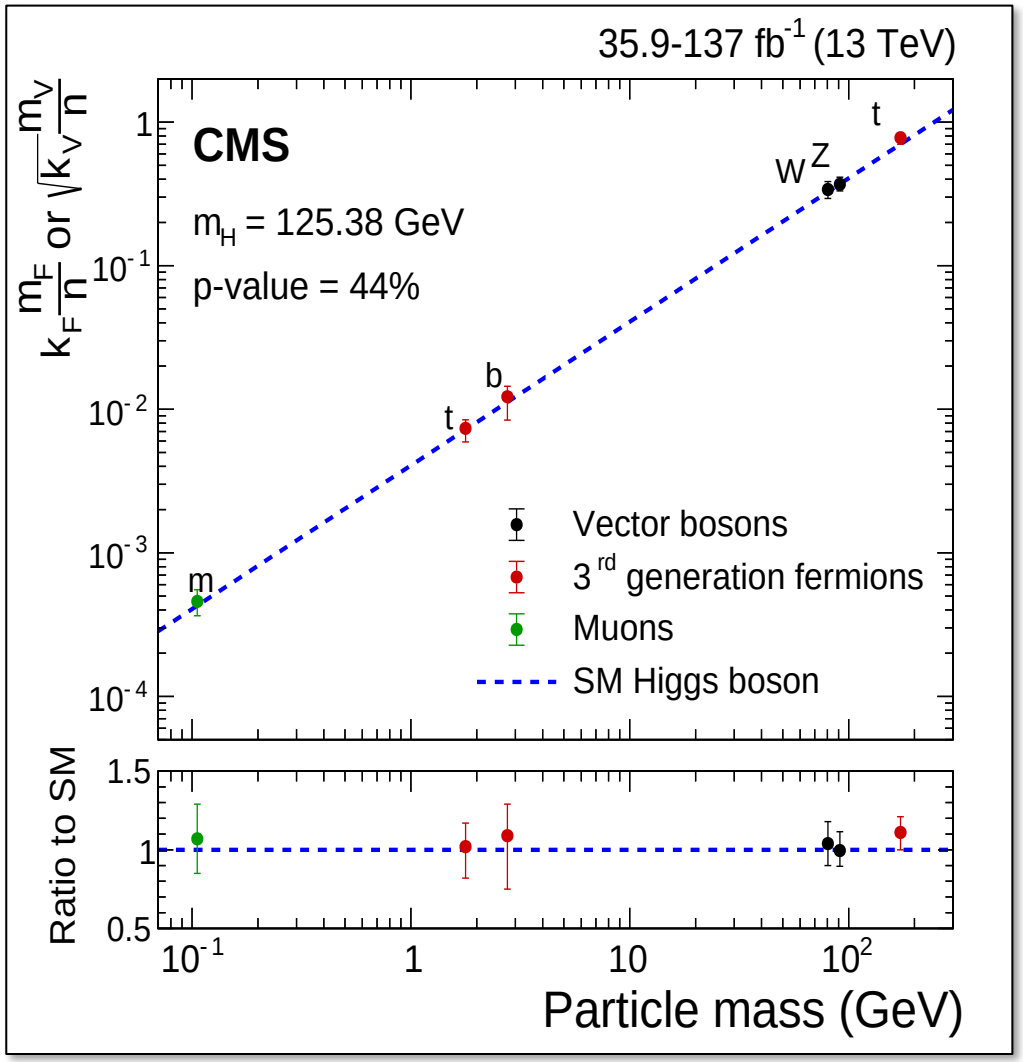
The ATLAS Collaboration

Phys.Lett. B716 (2012) 1-29

The Higgs boson

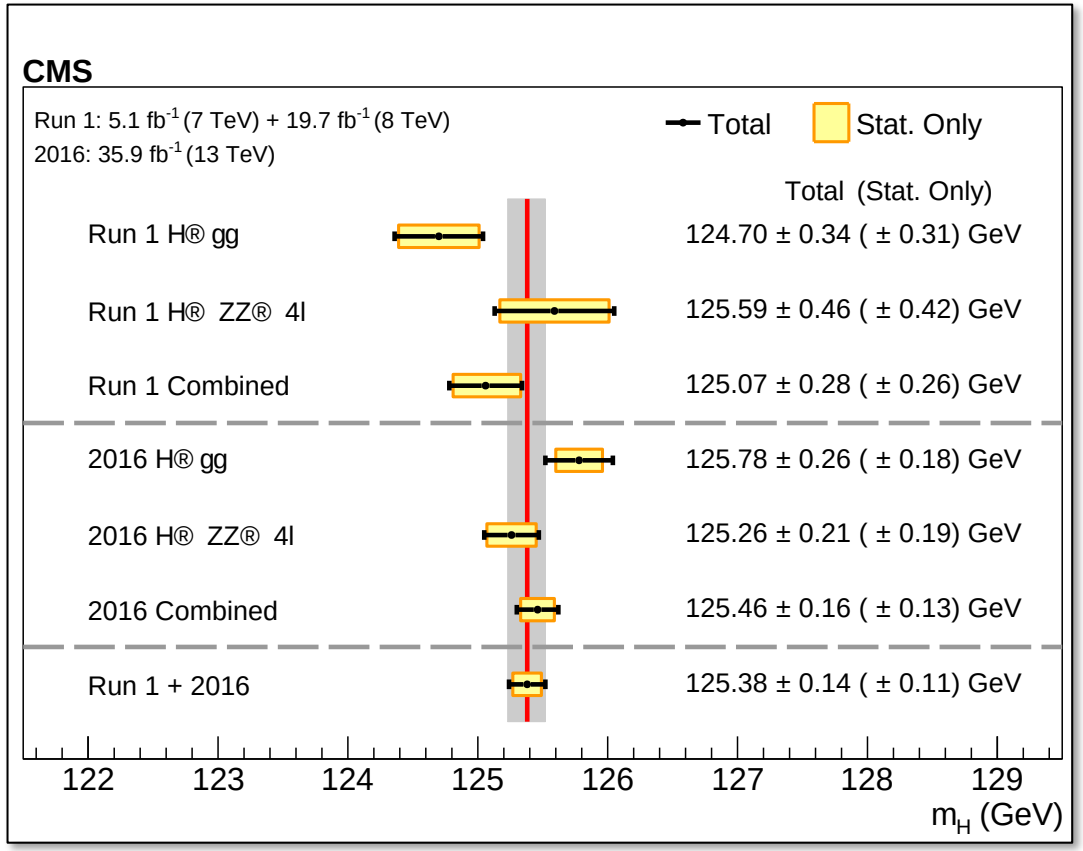
- A lot of progress since then…

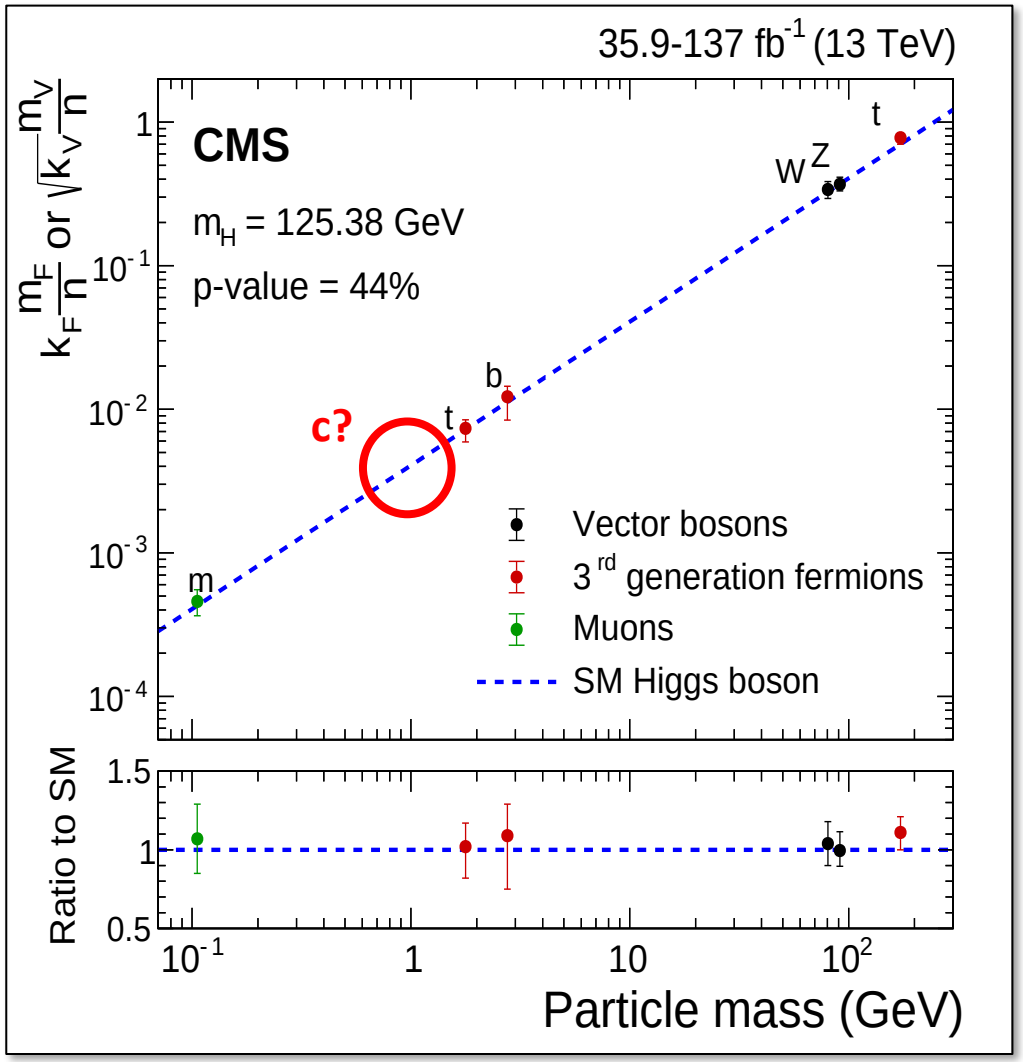




The Higgs boson

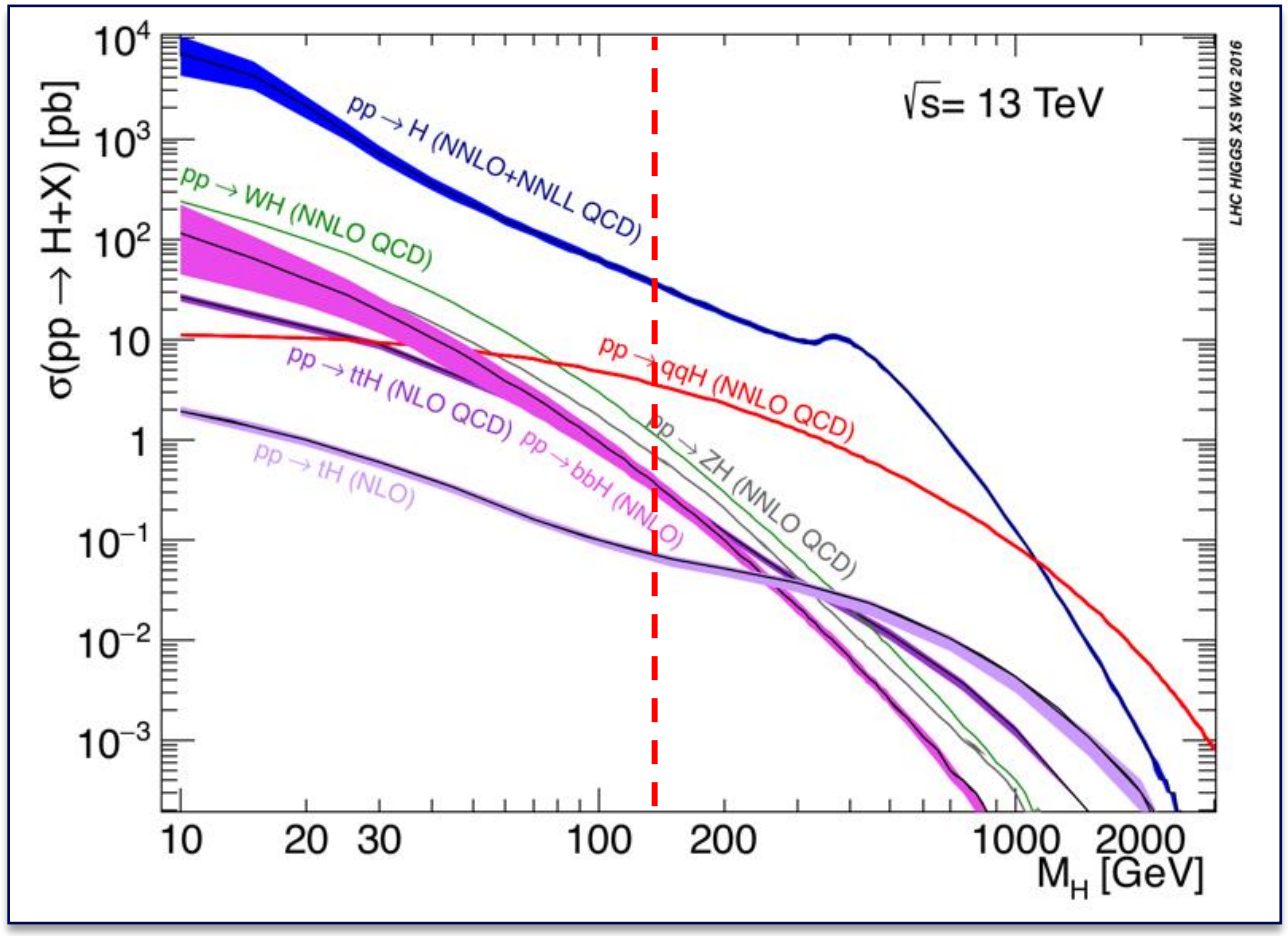
- A lot of progress since then…

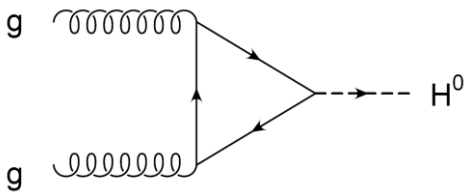




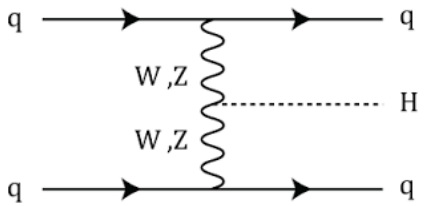
Higgs boson at the LHC

- Main Higgs production mechanisms at the LHC

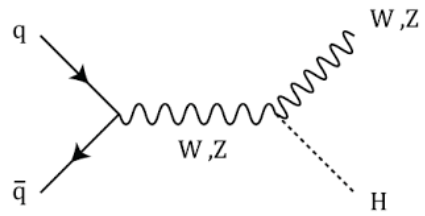




GGF: ~87%



VBF: ~7%

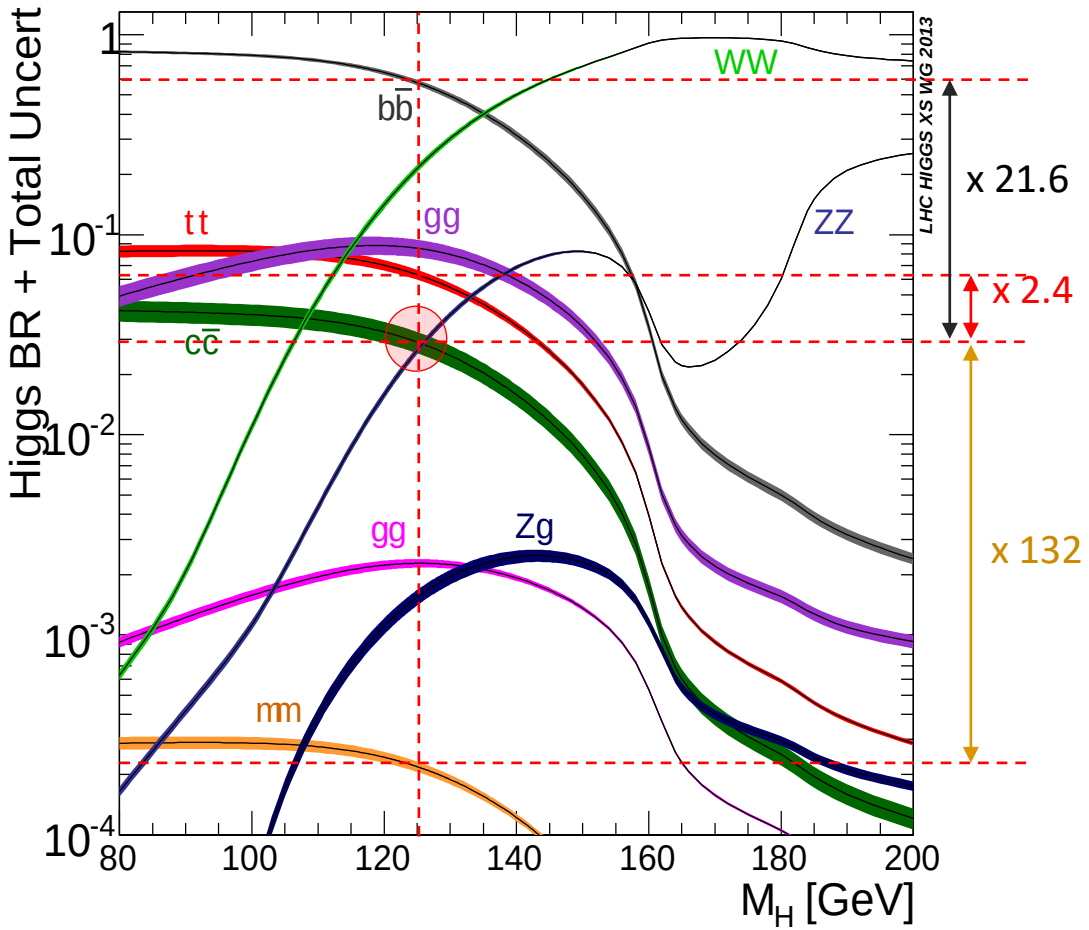


WH: ~3%

ZH: ~2%

Higgs boson at the LHC

- Branching fractions



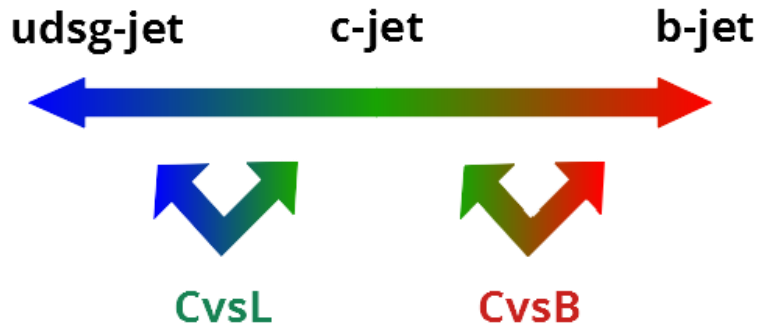
H→cc:

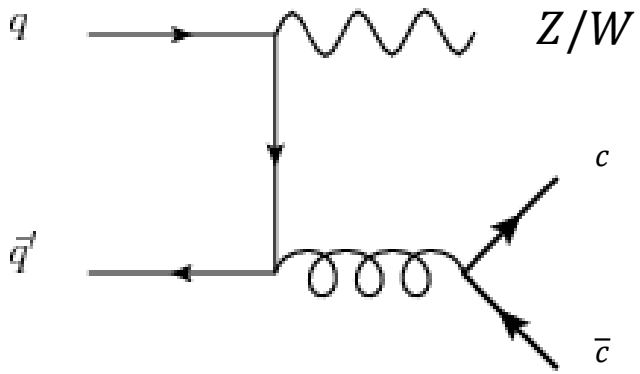
- BR 21 times smaller than H→bb BR
- Poorer mass resolution compared to μμ and γγ

Currently the largest Higgs BR without an experimental evidence

Challenges of H→cc search

- H→cc BR 21 times smaller than H→bb BR
- Poorer mass resolution compared to μμ and γγ
- Tagging c is difficult!
  - Properties intermediate to b and light jets
- QCD and/or vector boson (V)+jets are large irreducible backgrounds
- Even H→bb is an irreducible background!





Z/W + jets

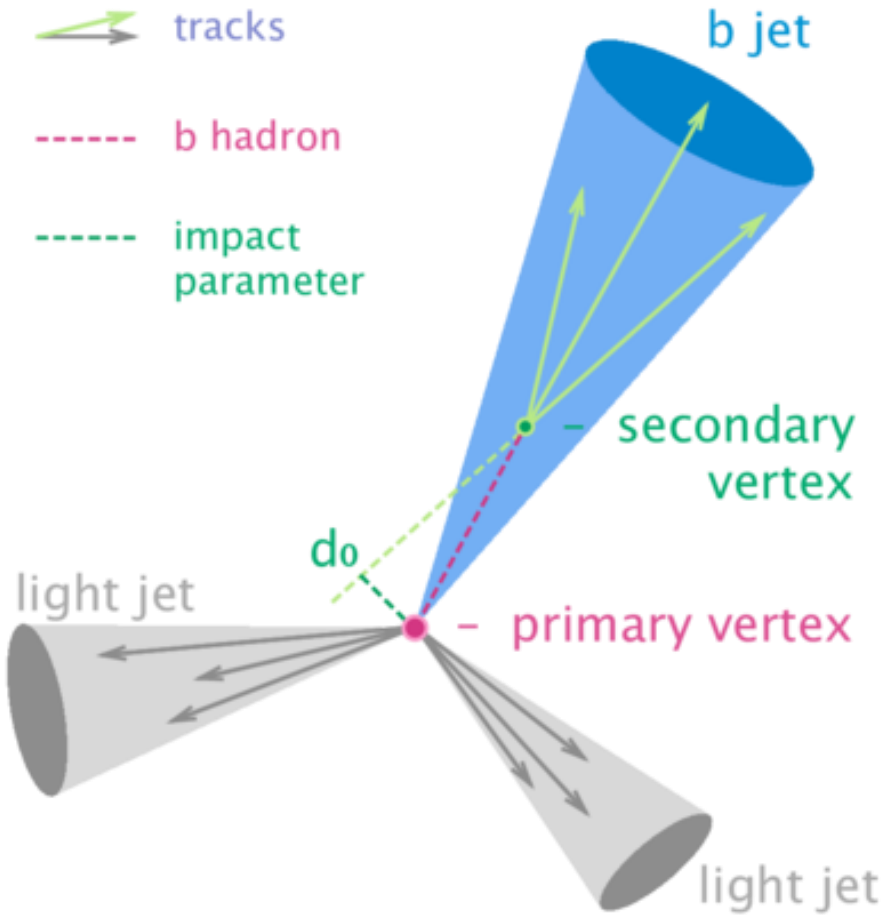
Previous searches

Year	Experiment	Dataset	Upper limit*	Comments
2016	LHCb	Run-1	6400 (7900)	Only 1L channel
2018	ATLAS	2016	110 (150)	Only 2L channel
2019	CMS	2016	70 (37)	2L, 1L and 0L channels
2021	ATLAS	Full Run-2	26 (31)	RTG talk by Tristan Du Pree, 26.10.2021

*observed (expected) times the SM prediction

This talk: CMS results with full Run-2 data (138 fb^{-1})

Flavour tagging



Flavour tagging:

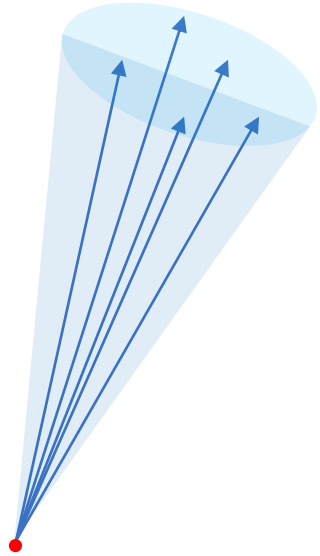
Identification of flavour of quark/gluon that initiated a jet

Use distinctive features of heavy flavour jets

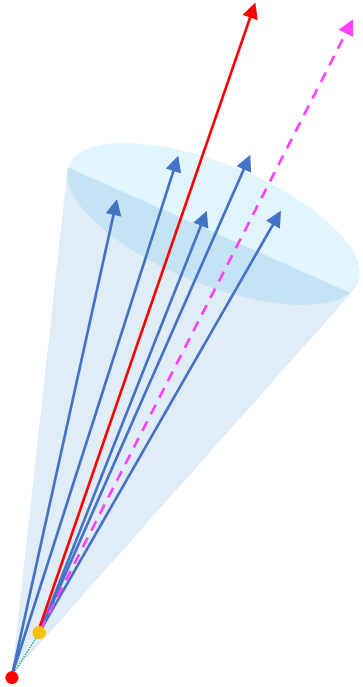
b-tagging has been in use for long

Flavour tagging

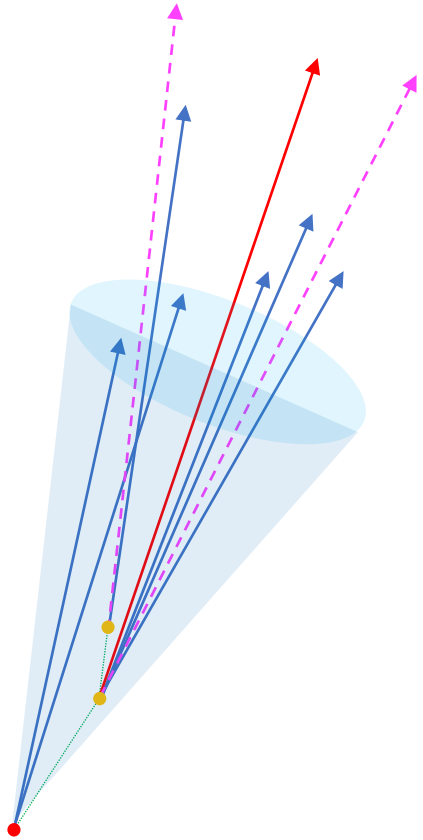
- c jets have properties intermediate to udsg and b jets
  - D-hadrons live shorter; smaller probability of soft lepton, $p_{\mathrm{T}}^{\mathrm{miss}}$; fewer SVs…



Light jet
(udsg)



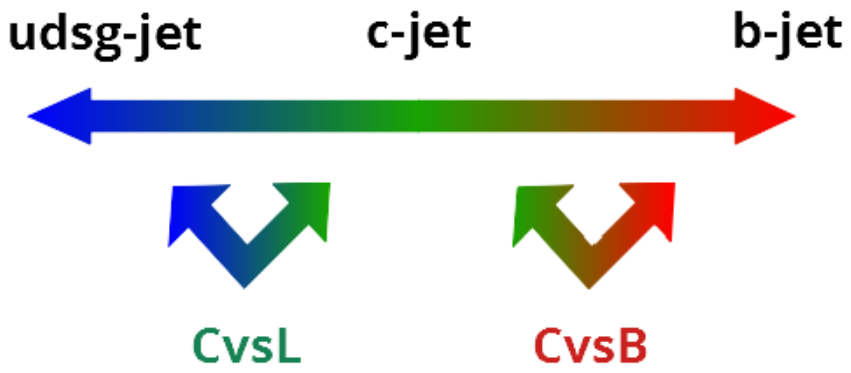
c jet



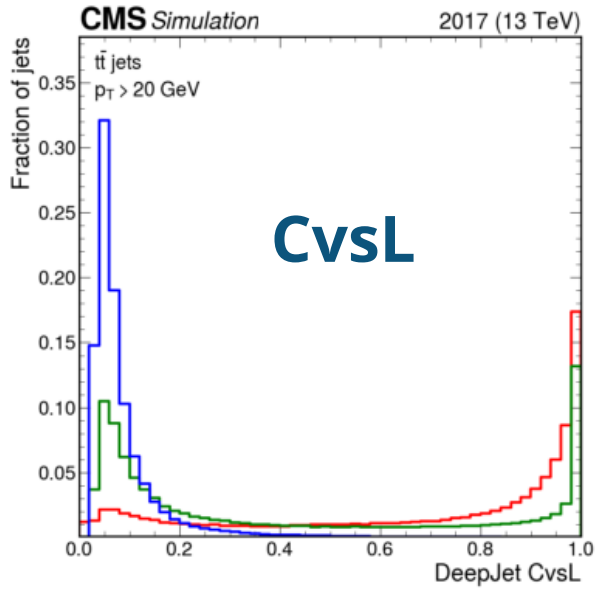
b jet

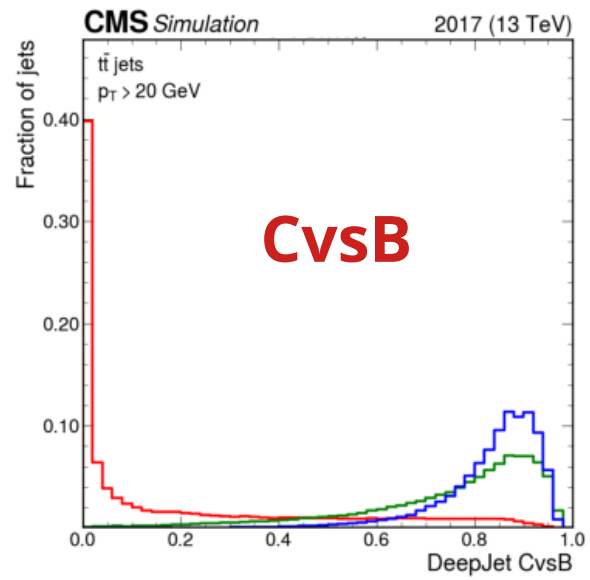
Charm tagging

- Discriminate c simultaneously against b and udsg

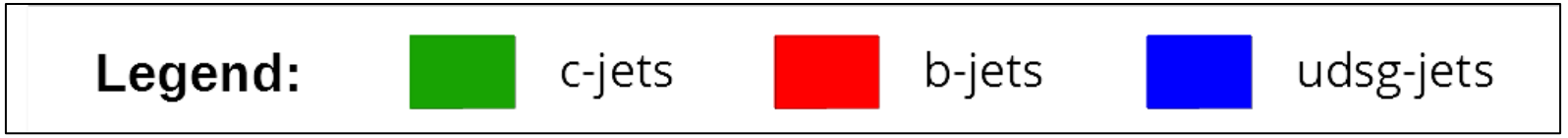


Distributions of MC simulated jets:



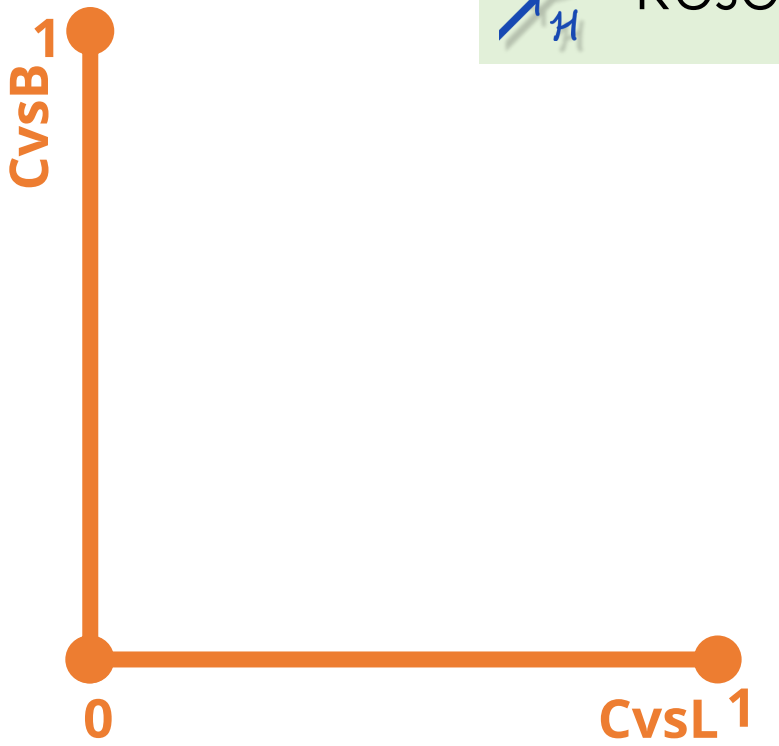


...may be different in data!



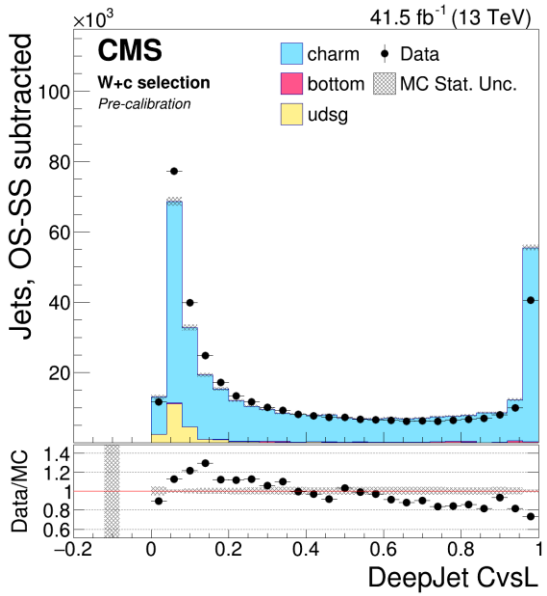
Charm tagging calibration

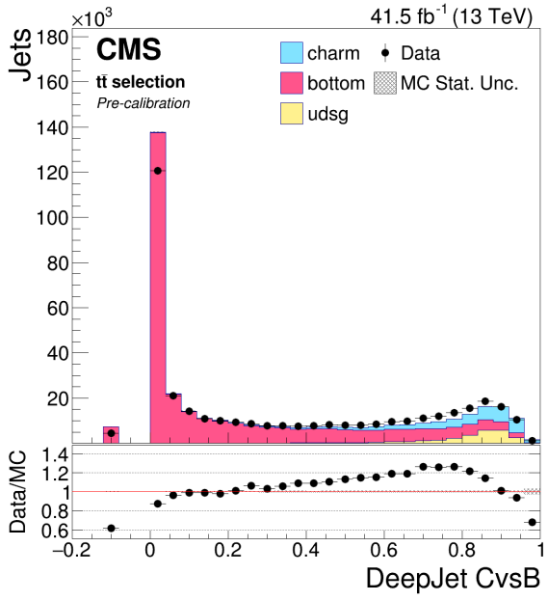
- Novel method to calibrate full discriminator shapes
- Simultaneously calibrate CvsL and CvsB
  - 2-dimensional corrections
- Exploit 3 different selections of jets in data:
  - c-enriched W+c selection
  - b-enriched $t\bar{t}$ selection
  - Light enriched DY+jet selection

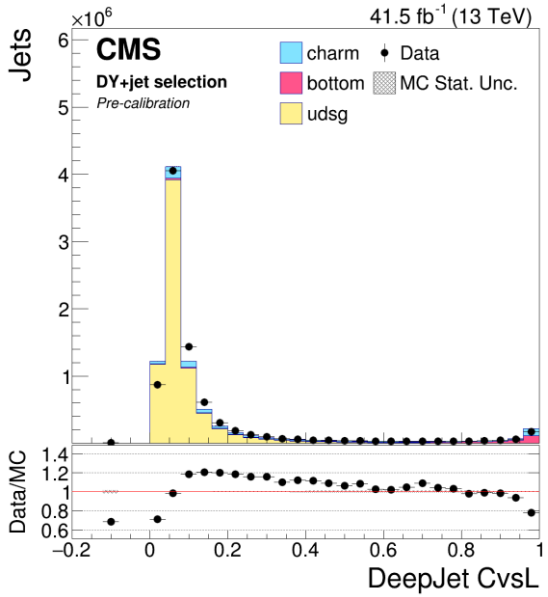


- Perform a **simultaneous, iterative fit** to minimize a χ^2-based data-MC difference, in the **2D CvsL-CvsB plane**

Charm tagging calibration



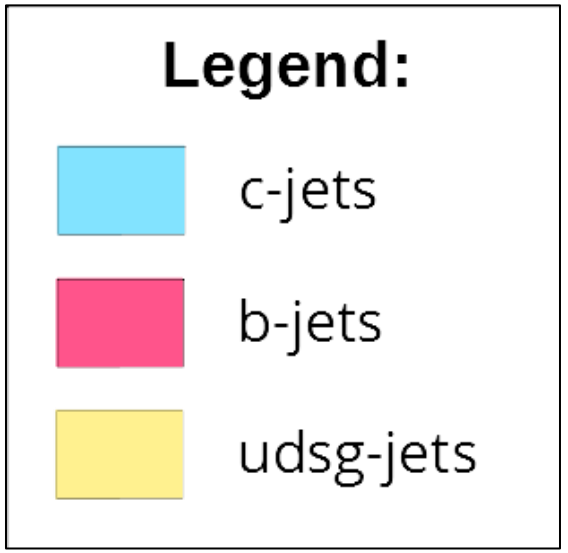




W+c selection
(c-enriched)

$t\bar{t}$ selection
(b-enriched)

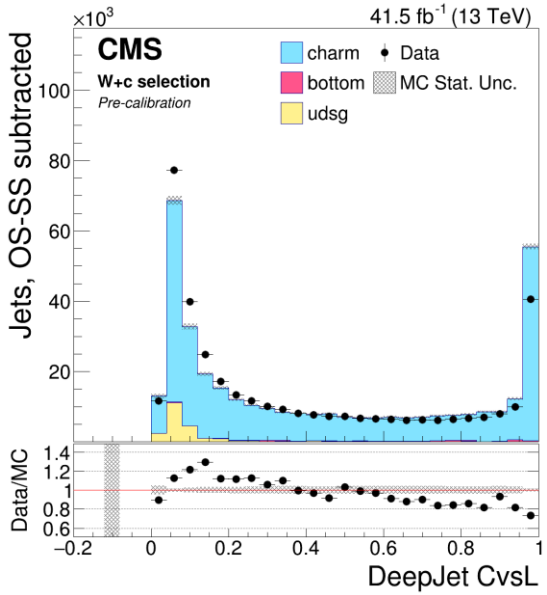
DY+jet selection
(udsg-enriched)



2022 *JINST* **17** P03014

Significant data-MC disagreement in pre-calibration plots

Charm tagging calibration



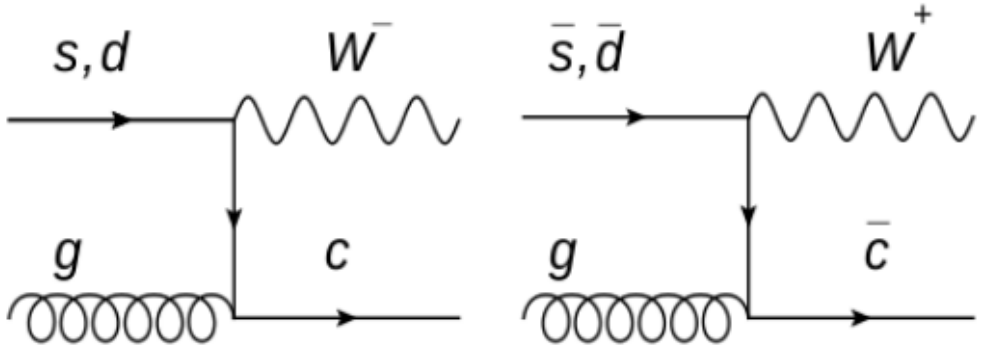
W+c selection
(c-enriched)

- W and jet charge asymmetry in signal
- OS – SS gives pure W+c

- Leptonically decaying W
- Jet with a soft muon inside

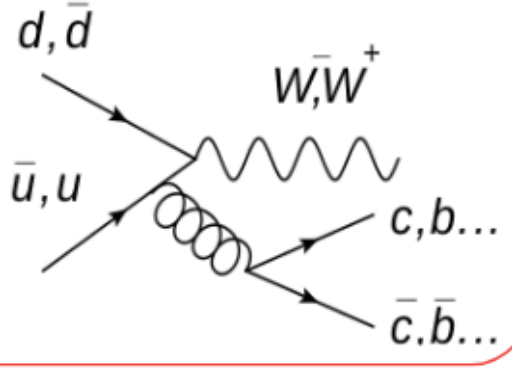
Signal

W and c always oppositely charged



Background

W and "tagged" c:
Same sign: 50%
Opp. sign: 50%



Ideally:

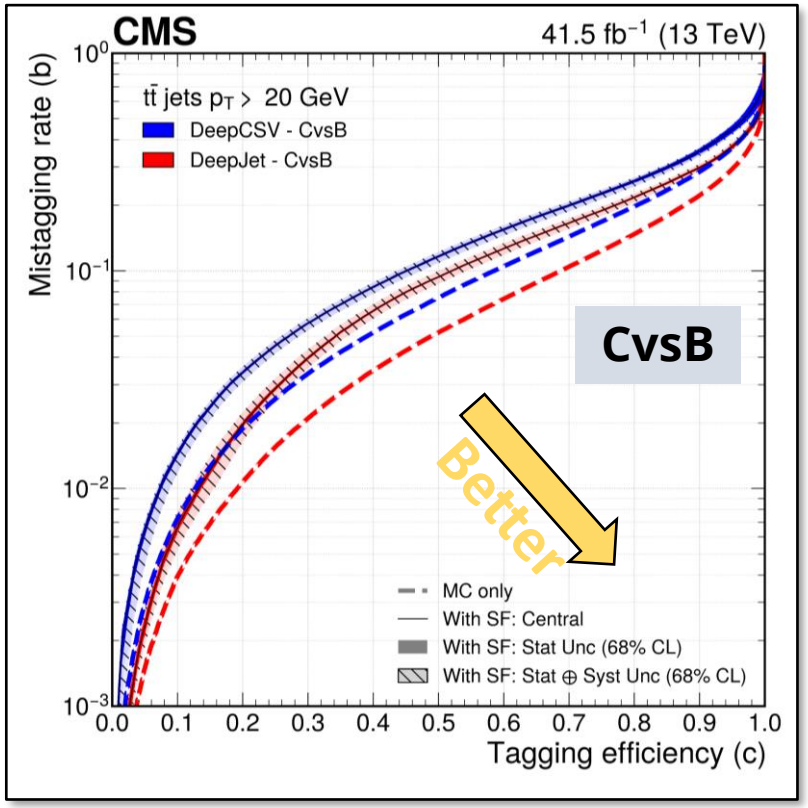
$$\mathrm{OS} = \mathrm{Sig} + \frac{\mathrm{Bkg}}{2}$$

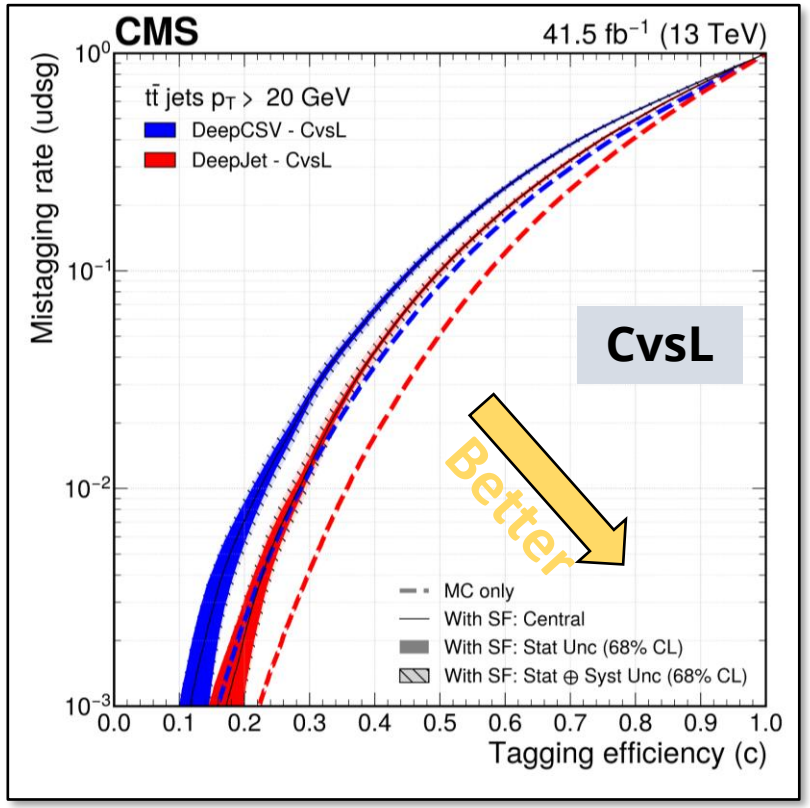
$$\mathrm{SS} = \frac{\mathrm{Bkg}}{2}$$

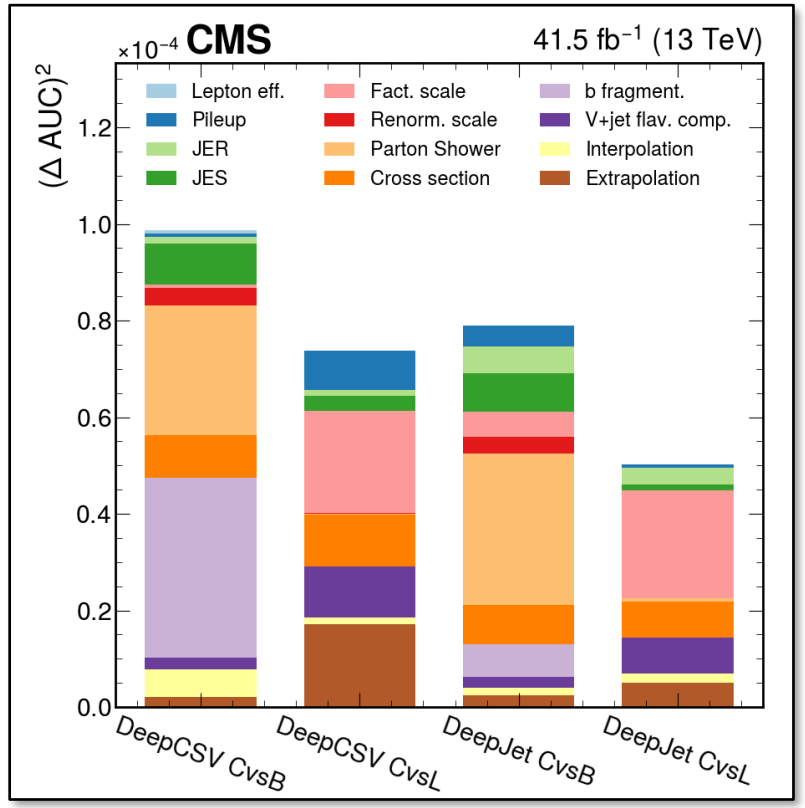
$$\mathrm{OS} - \mathrm{SS} = \mathrm{Sig}$$

Charm tagging calibration

- Full set of statistical and systematic uncertainties derived

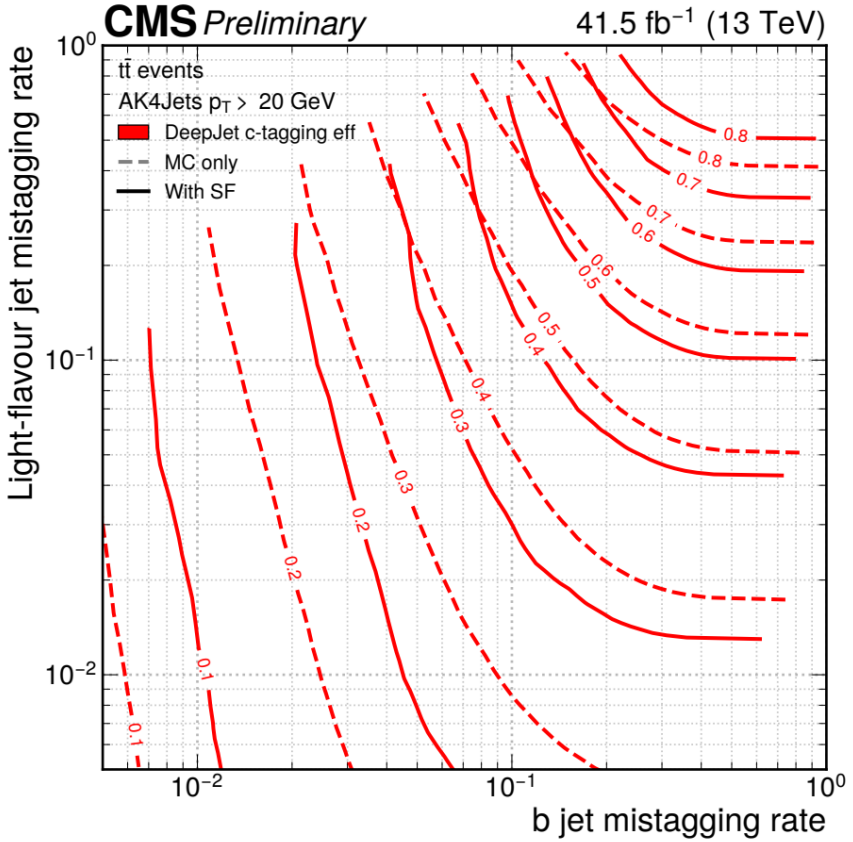






Resolved

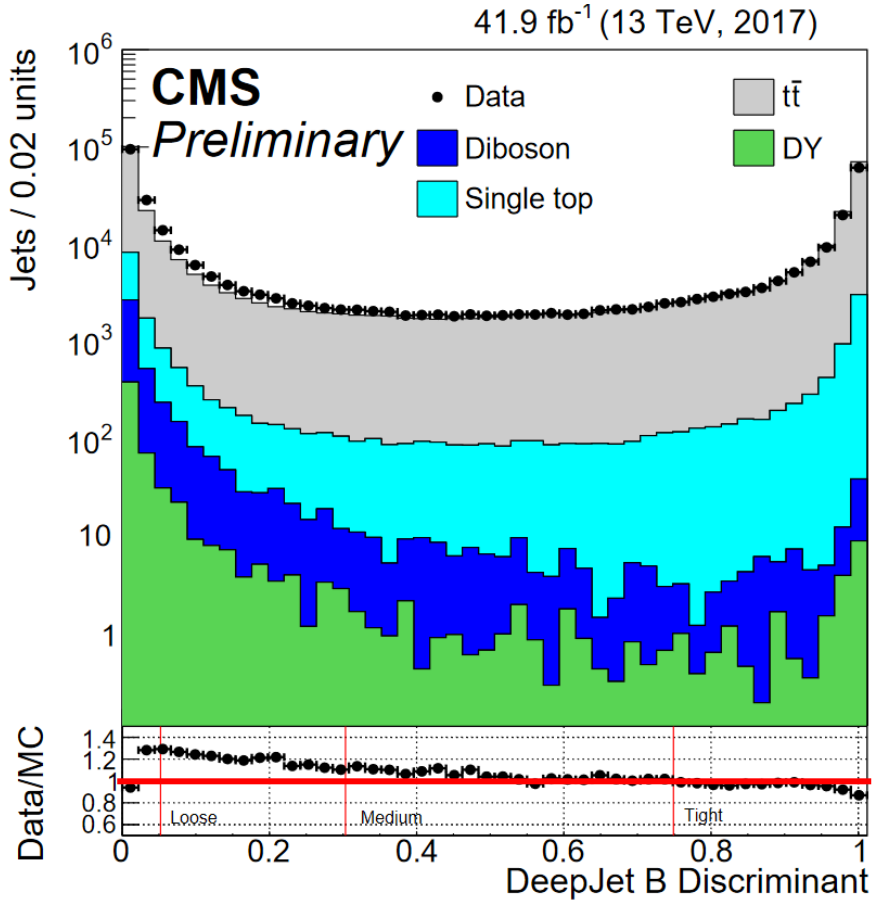
c-tagger Performance



Traditional calibration: b-tagging

- Traditional calibrations are measured on a “Working Point” basis
- Example for b-tagging (1-dimensional):

Traditional WP-based calibrations

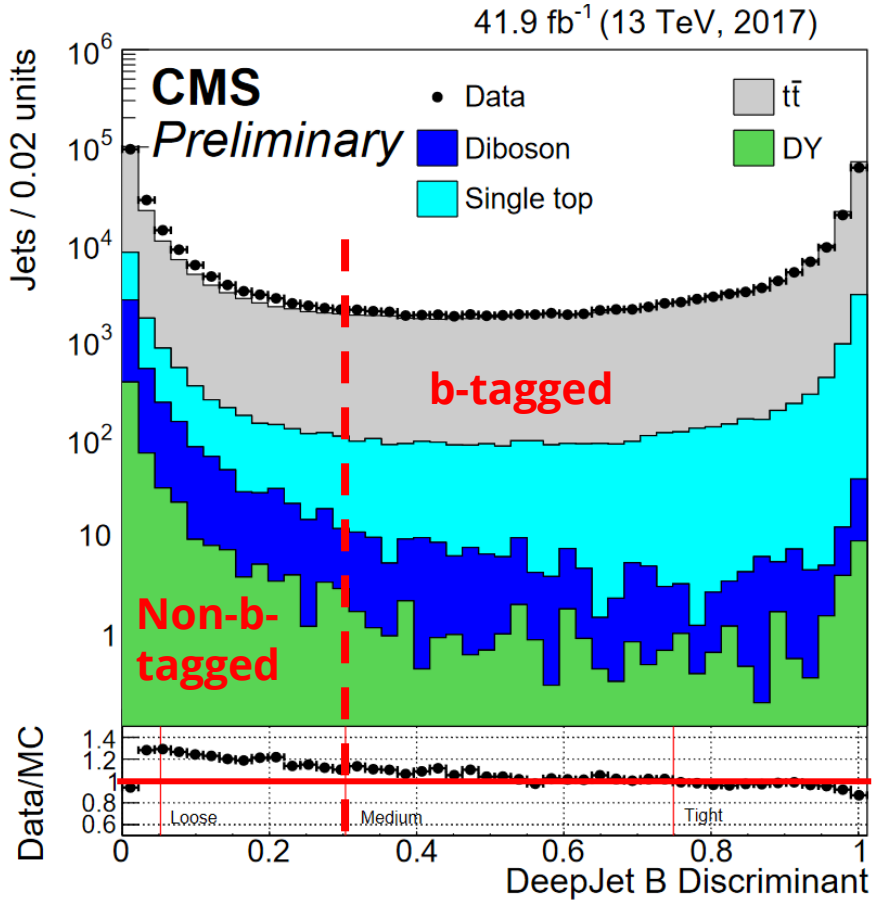


CMS DP-2018/058

Traditional calibration: b-tagging

- Traditional calibrations are measured on a “Working Point” basis
- Example for b-tagging (1-dimensional):

Traditional WP-based calibrations



- Count jets in MC passing a cut
- Count jets in data passing same cut

Different, in general!

A correction factor is derived centrally by CMS to account for this discrepancy

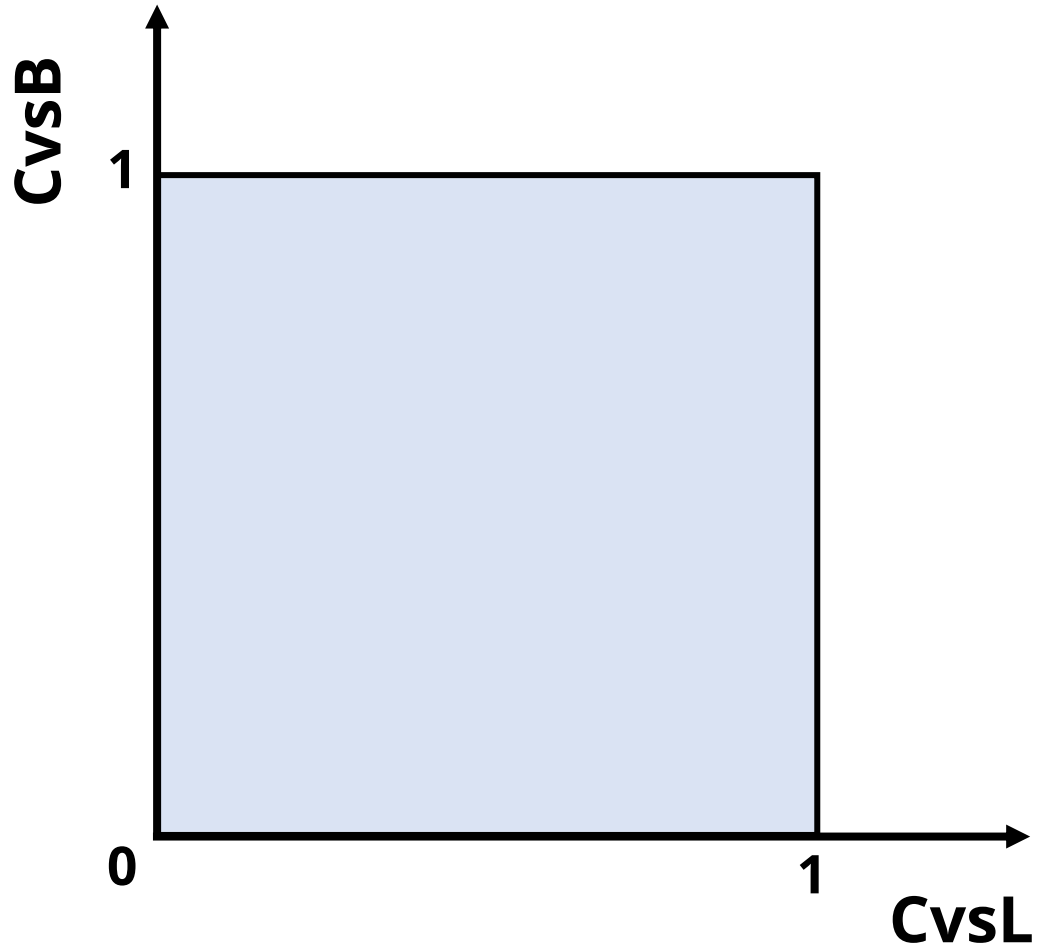
- Use this factor in all analyses

CMS DP-2018/058

Traditional calibration: c-tagging

- Example for c-tagging (2-dimensional):

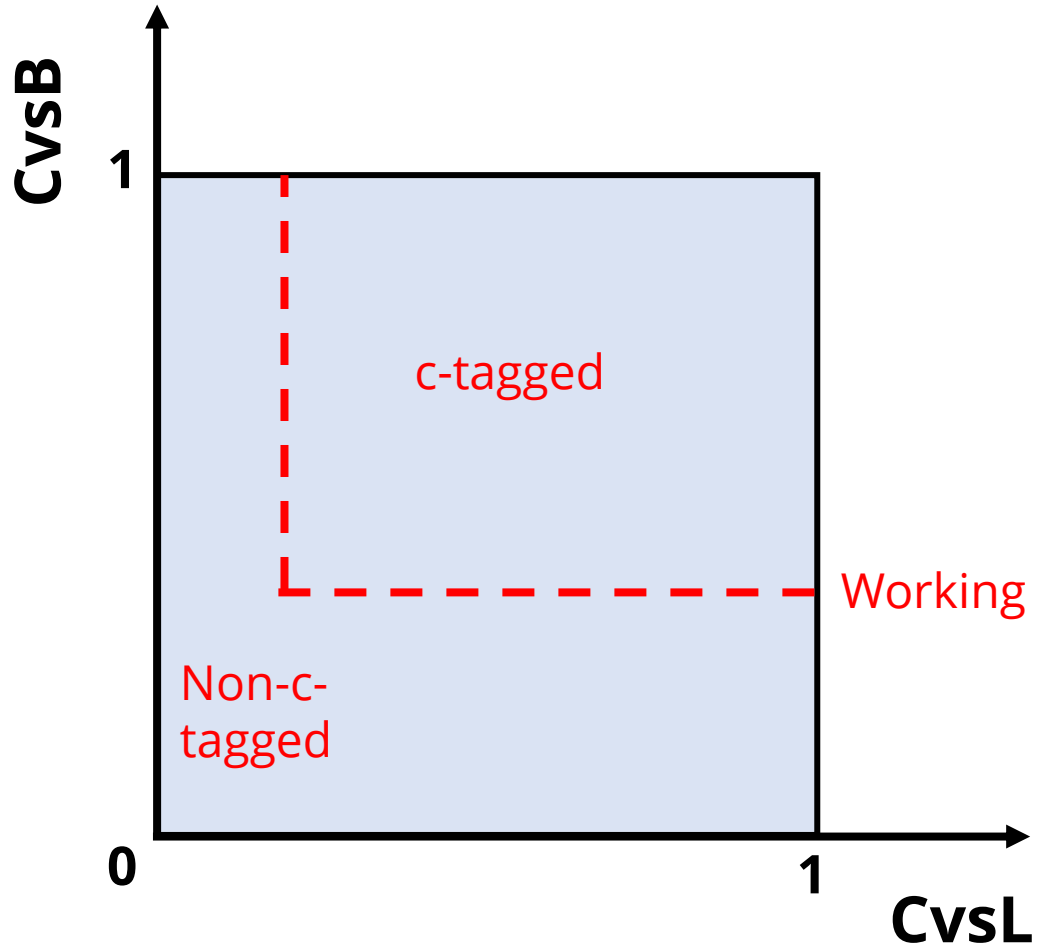
Traditional WP-based calibrations



Traditional calibration: c-tagging

- Example for c-tagging (2-dimensional):

Traditional WP-based calibrations



Ratio of **c-tagged jets in data** to **c-tagged jets in MC** measured, at fixed working points.

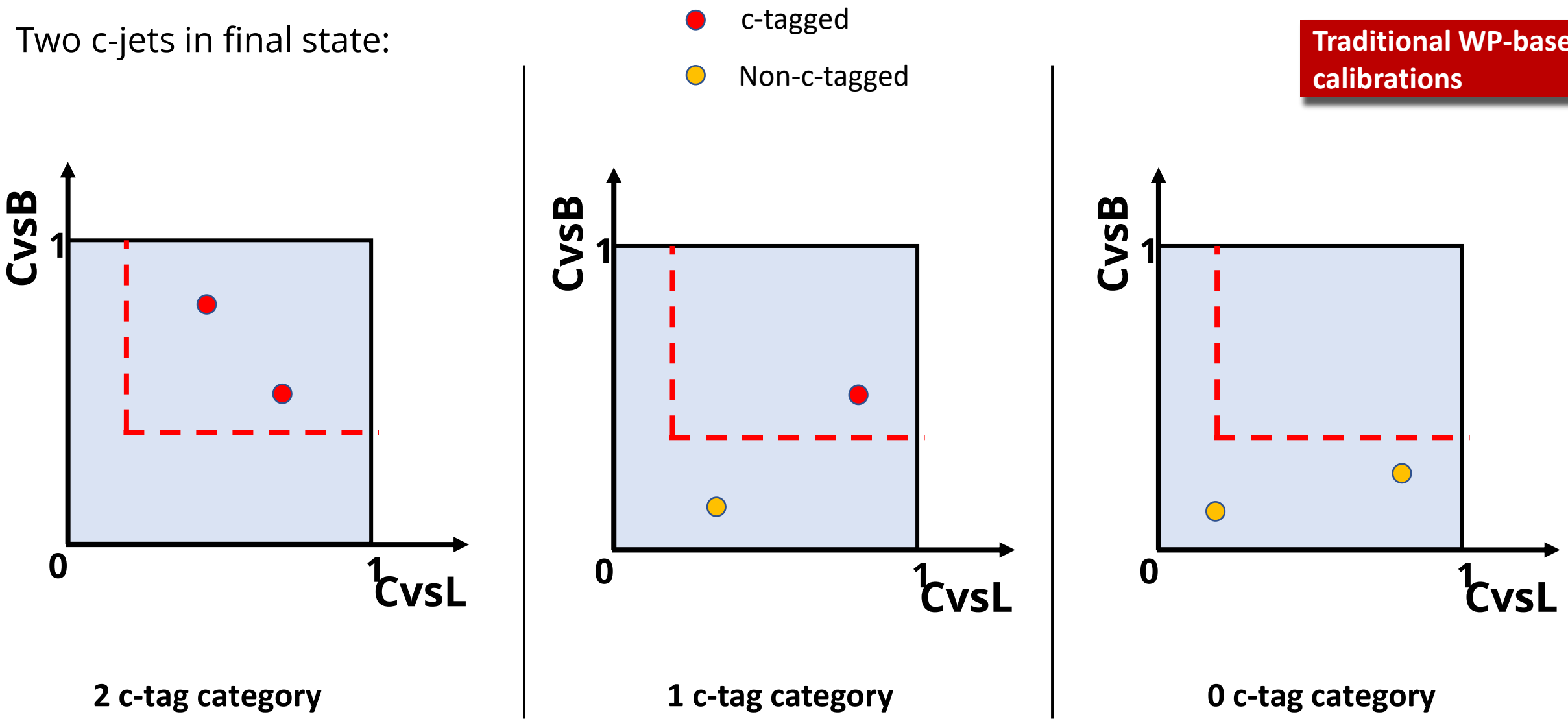
- Count jets in MC passing a cut
- Count jets in data passing same cut

Different, in general!

Traditional calibration: $H \to c\bar{c}$

- Two c-jets in final state:

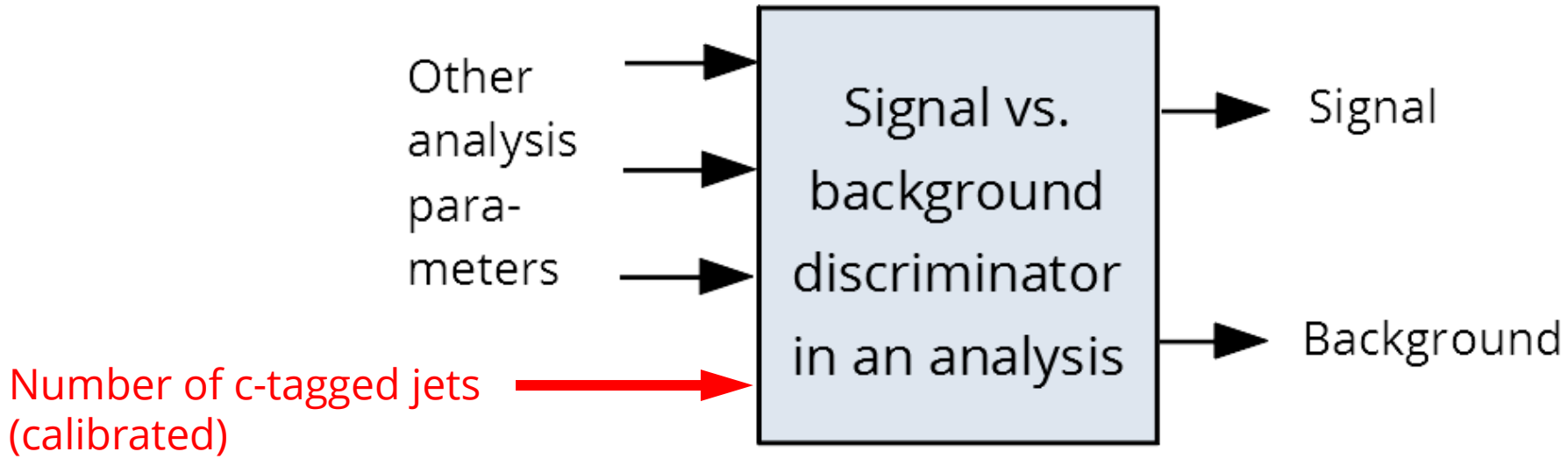
Traditional WP-based calibrations



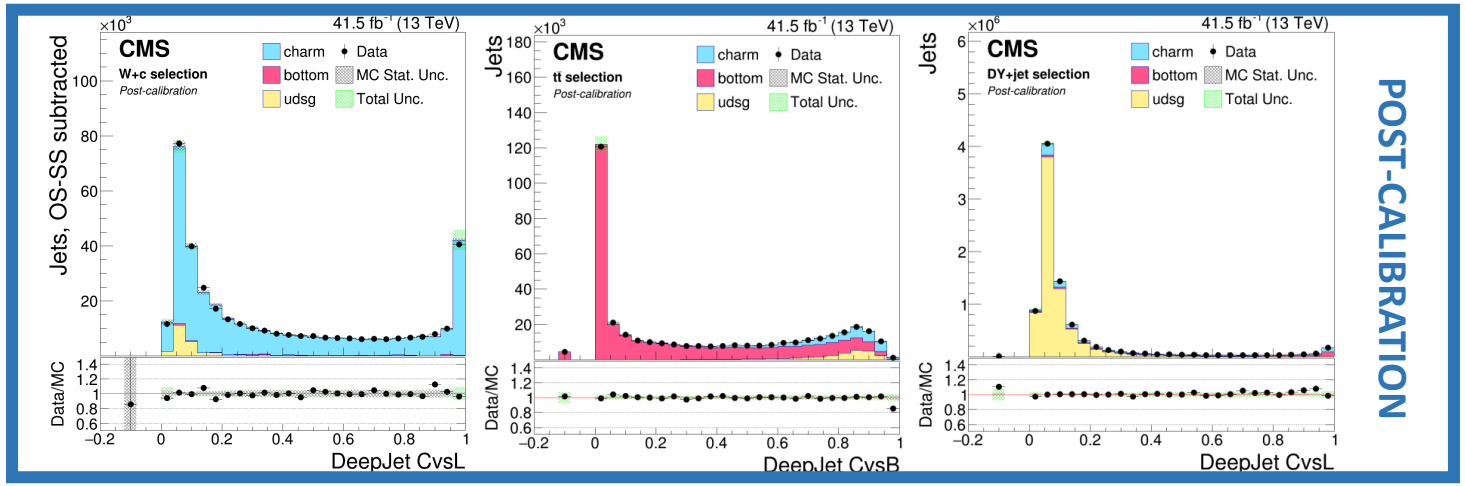
Traditional calibration: $H \to c\bar{c}$

Traditional WP-based calibrations

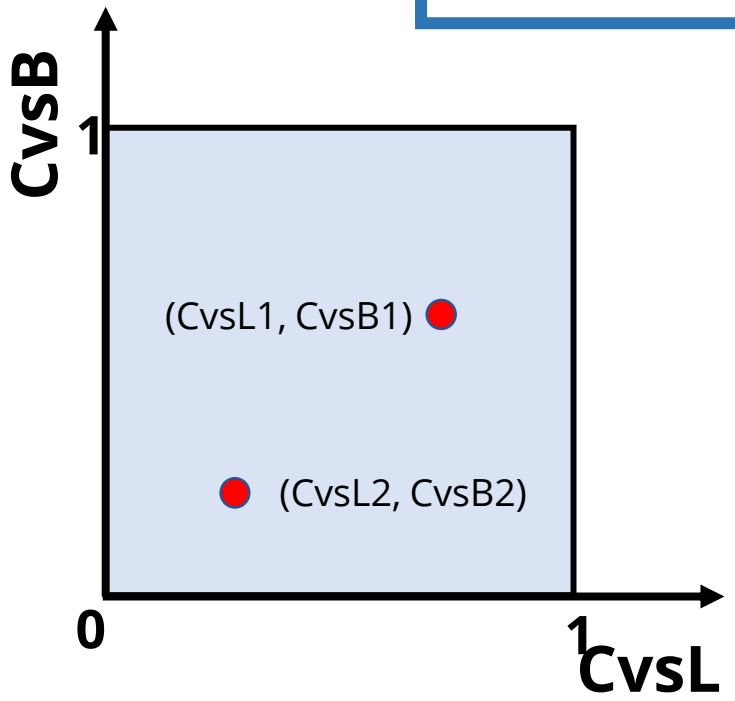
- As corrections are derived for this WP, we can calculate a “weight” for each event in each category.
- Use the calibrated c-tagged jet count as input to signal-background discriminator



New Calibration Technique



Full discriminator calibration

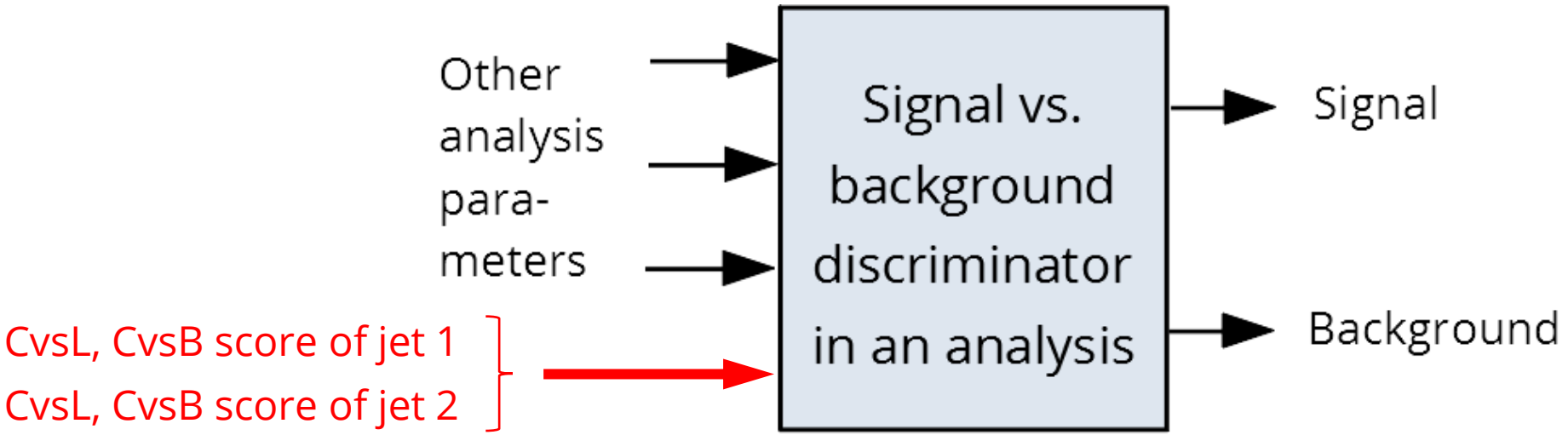


- Fully calibrated discriminator allows direct usage of per-jet c-tagger score (coordinates in plane)
- Potentially contains more information than just the count of jets passing a WP

New Calibration Technique

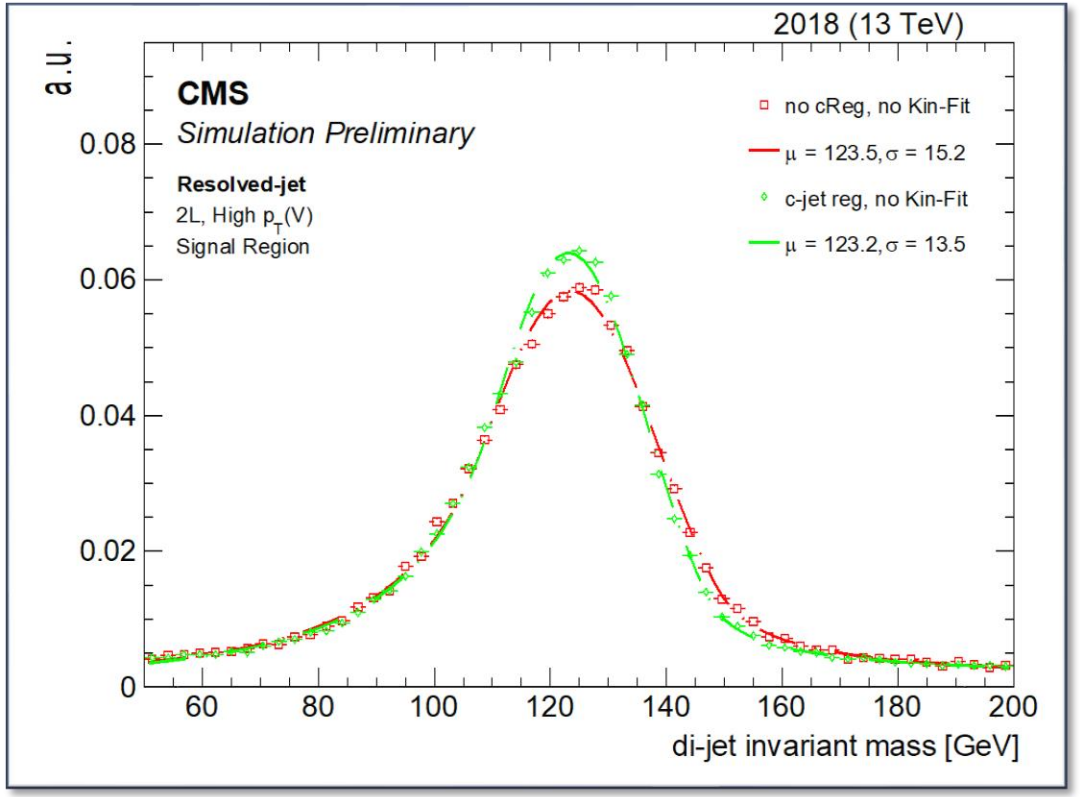
- Use c-tag score as input to signal-background discriminator

Full discriminator calibration



Charm jet energy regression

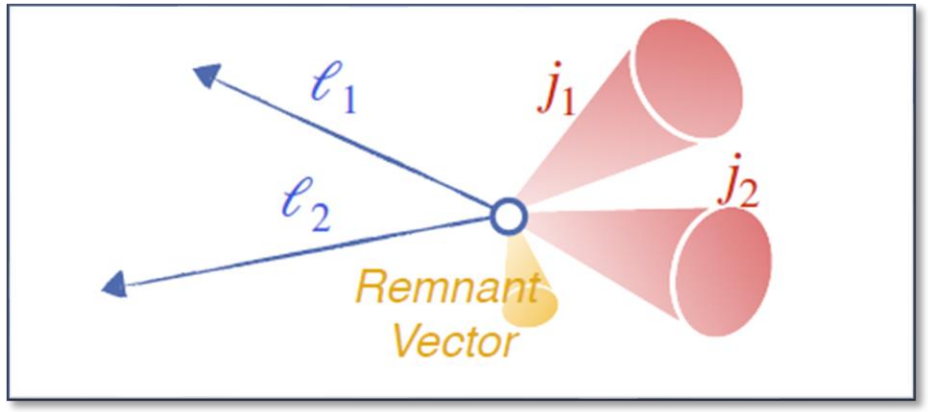
- Jet energy measurements are not always accurate:
  - Neutrinos, hadrons outside jet radius…
  - Effect enhanced for b and c jets
- DNN regression using simulated jets
  - Inputs: global jet features, tracks, secondary vertices, energy fractions in concentric rings, etc.
  - Output: **p_T(gen)/p_T(reco)**, and resolution estimate per jet

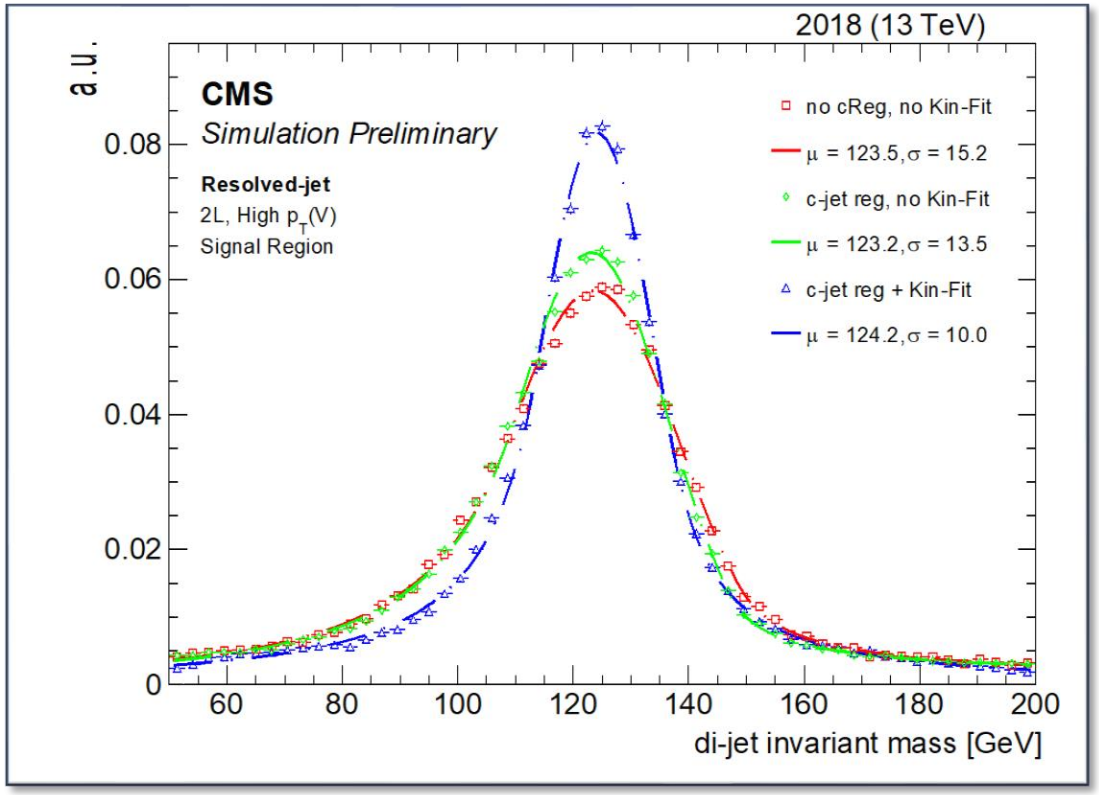


~15% improvement in mass resolution

Kinematic fit (2 lepton channel)

- No missing energy (neutrinos) in the Z($\ell\ell$)H(cc) process
- Improve jet p_T measurement through a kinematic fit:
  - 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



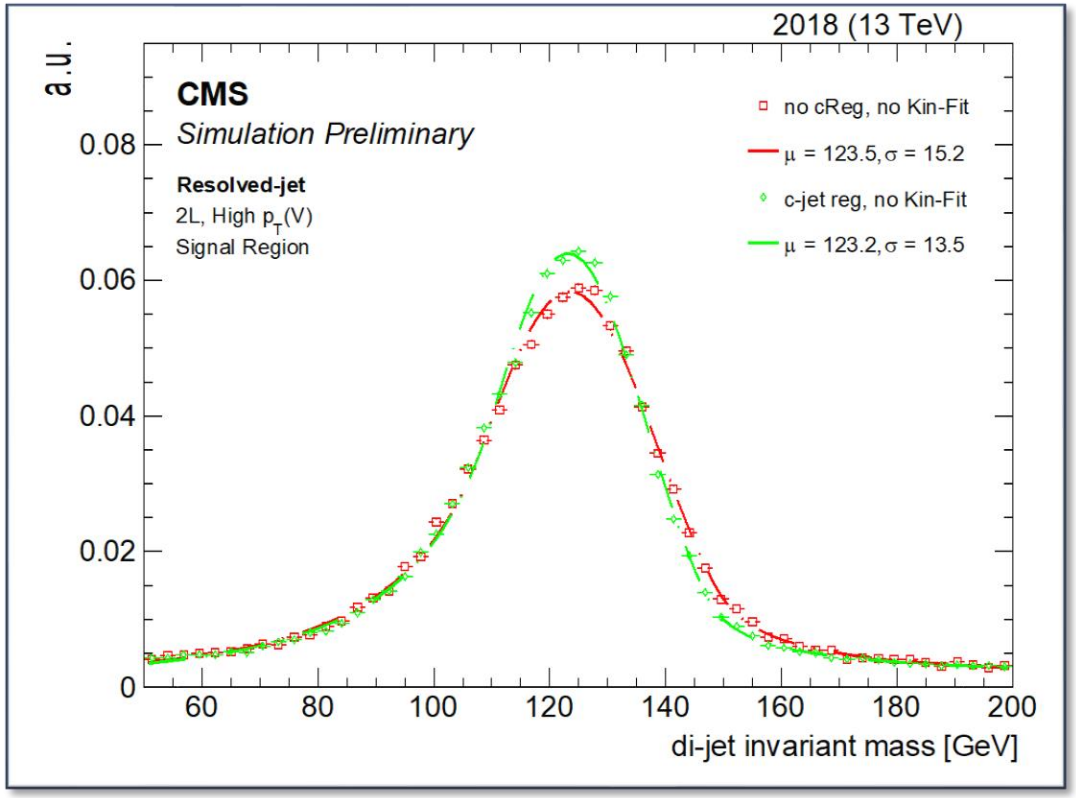


Upto 30% improvement in Higgs mass resolution

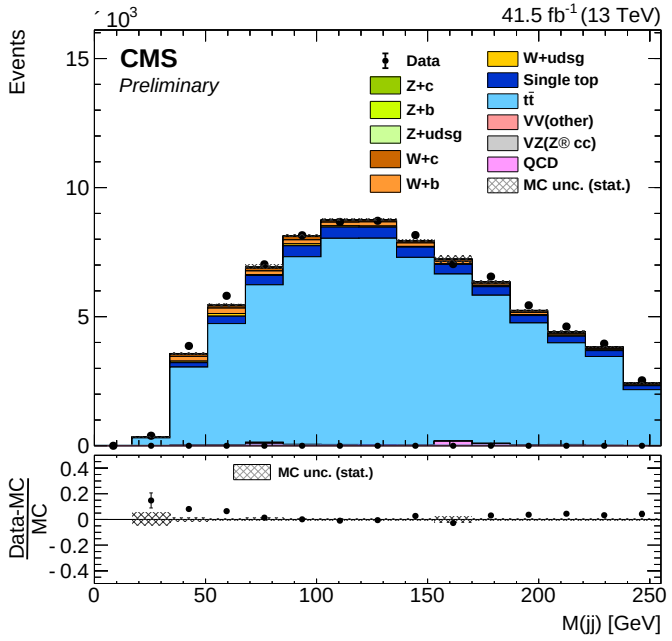
Charm jet energy regression

- ~15% improvement in mass resolution

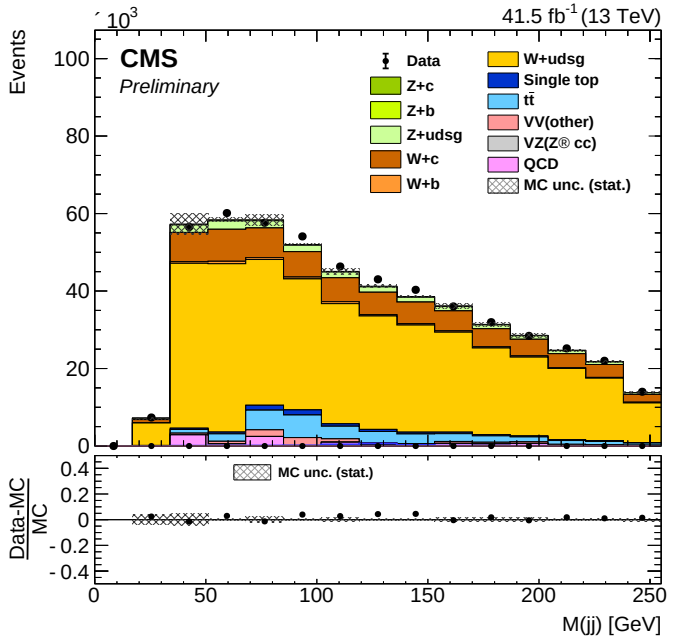
Resolved



$t\bar{t}$ selection



Light-flavour selection

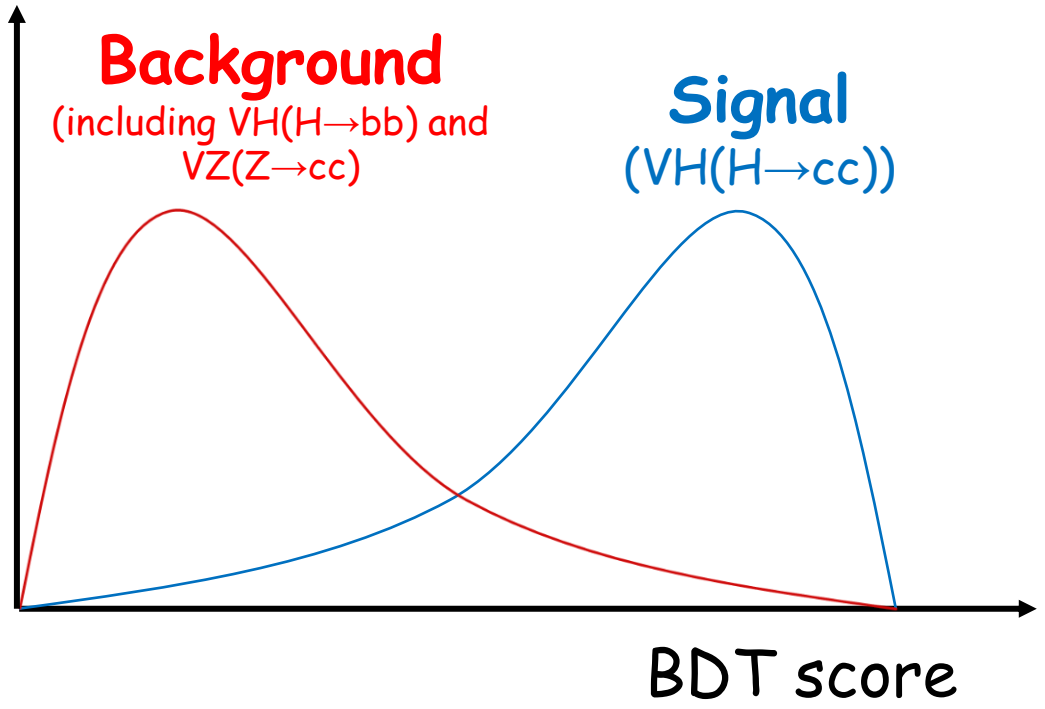


Validated on data in VH(H→cc) control regions

Fit strategy

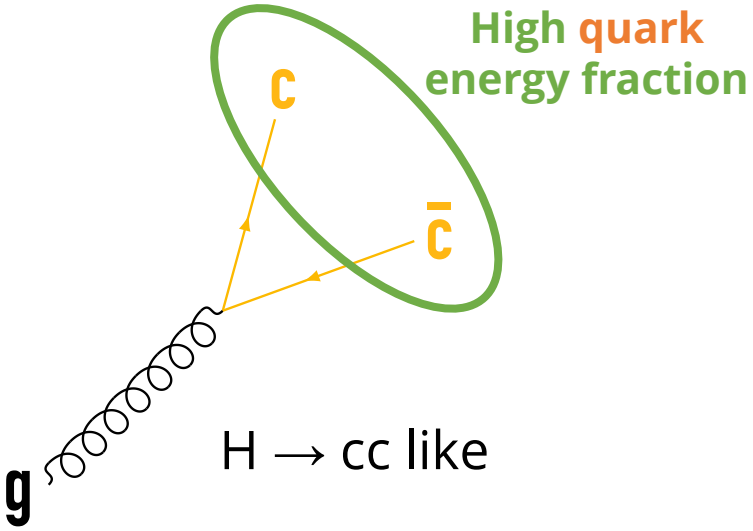
- Train BDT to separate signal from background in SRs
  - Separate BDT for each channel
  - Separate BDT for each data year

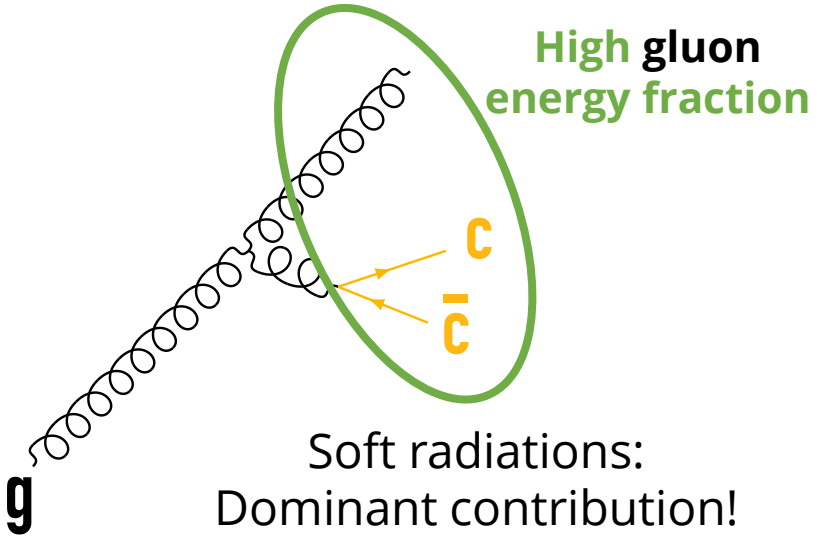
- **Fit BDT in SRs**
- **Fit tagger distributions in CRs**



Di-charm tagger calibration

- Calibration requires cc jet selections in data
- Enough H→cc or Z→cc events impossible to isolate
- Use g→cc events as proxy
  - Only those that “look like” H→cc

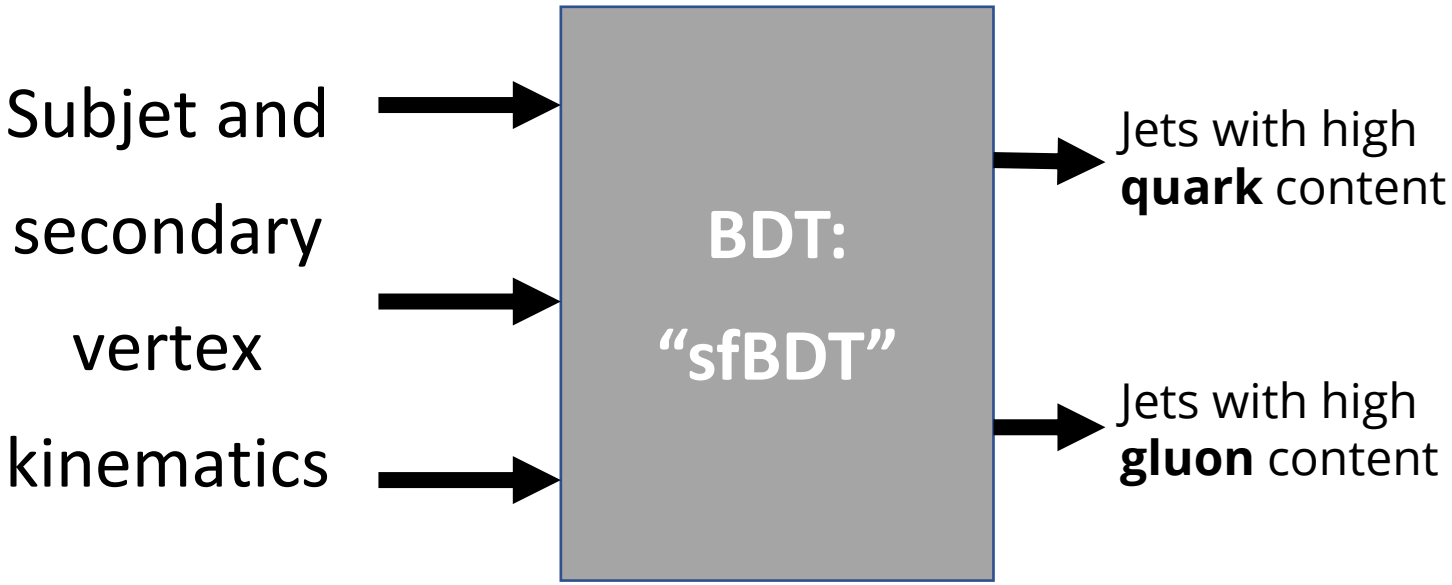


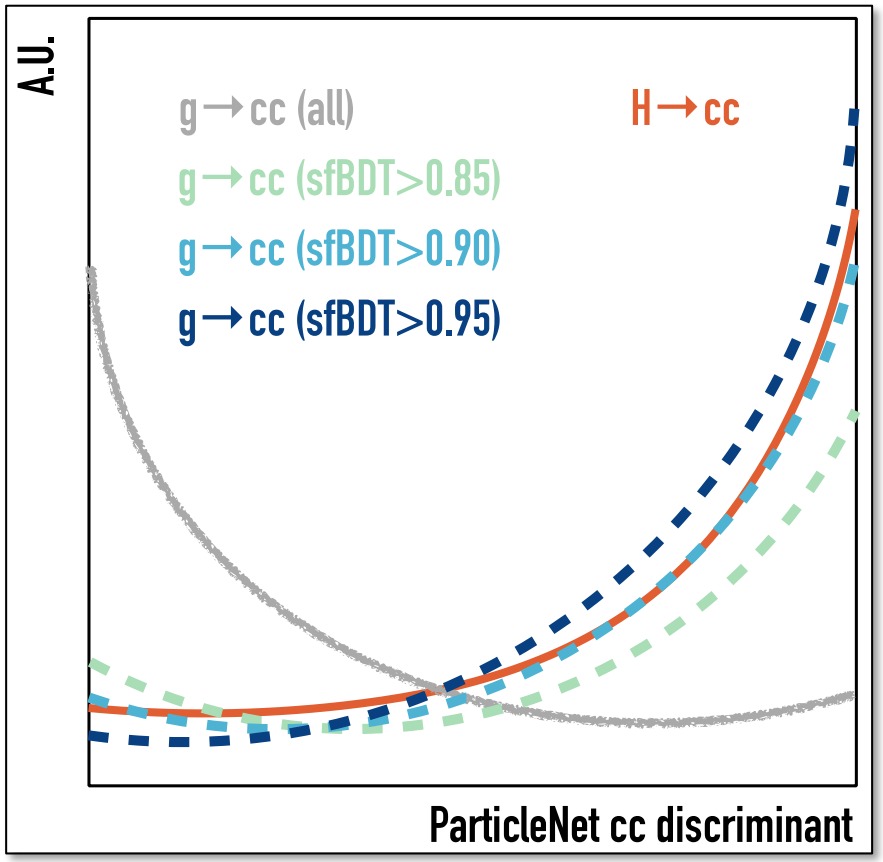


Di-charm tagger calibration

Merged

- Use g→cc events as proxy
  - Only those that "look like" H→cc

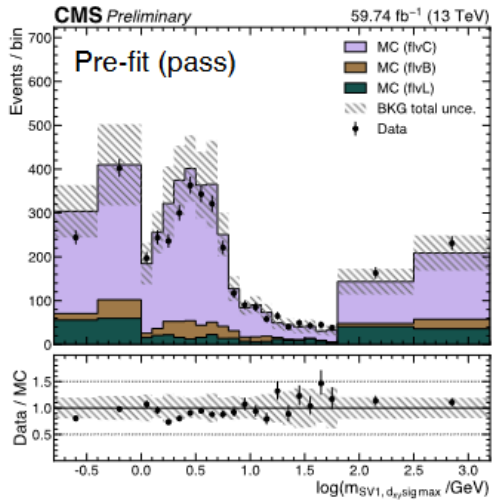


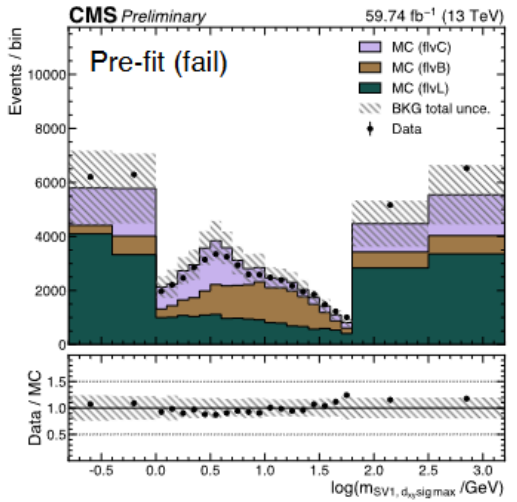


Di-charm tagger calibration

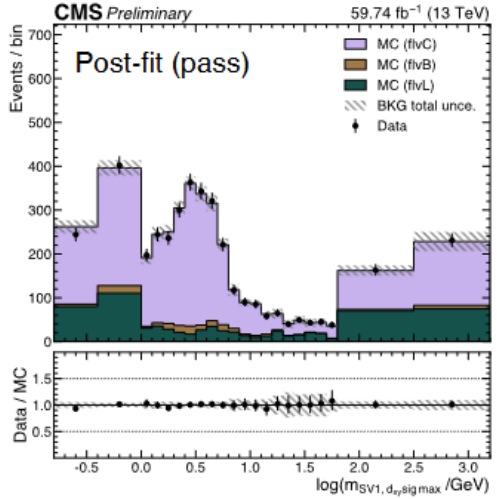
Merged

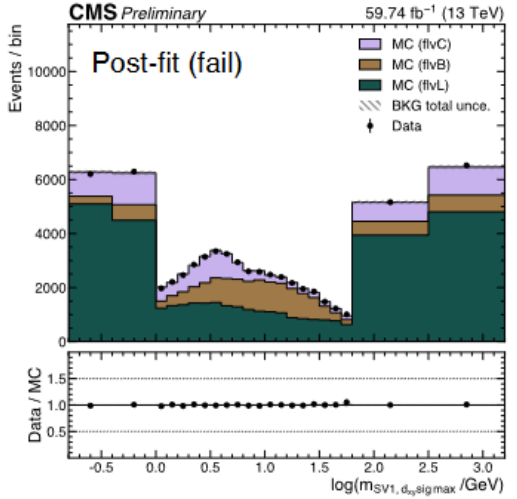
- Simultaneous fit of the secondary vertex mass in the “passing” and “failing” regions to extract scale factors
- Data/MC values range between 0.9-1.3 with 20-30% uncertainties





Prefit





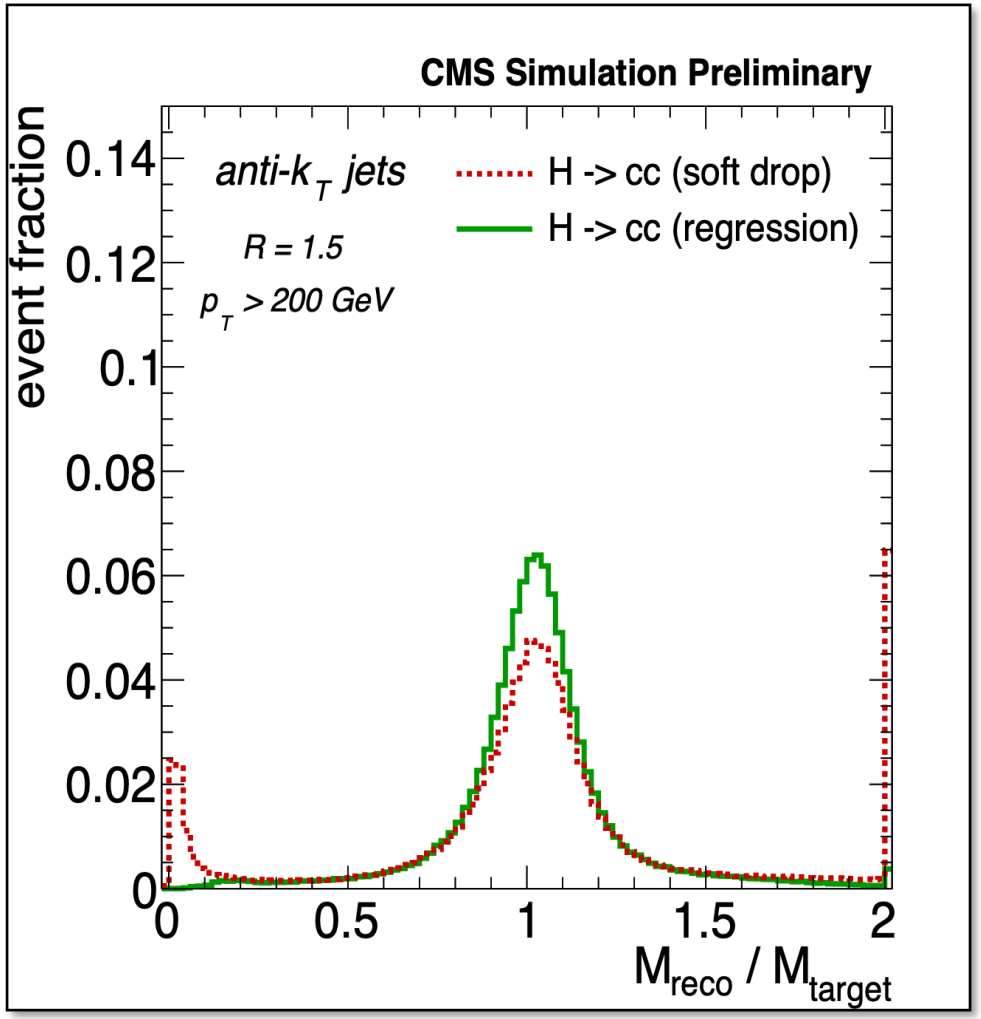
Postfit

Di-charm mass regression

Merged

- Dedicated regression algorithm to predict correct jet “soft-drop” mass
- Same inputs and architecture as ParticleNet
- Trained to predict $m_{\text{reconstructed}}/m_{\text{generated}}$

20 – 25% improvement in the final sensitivity



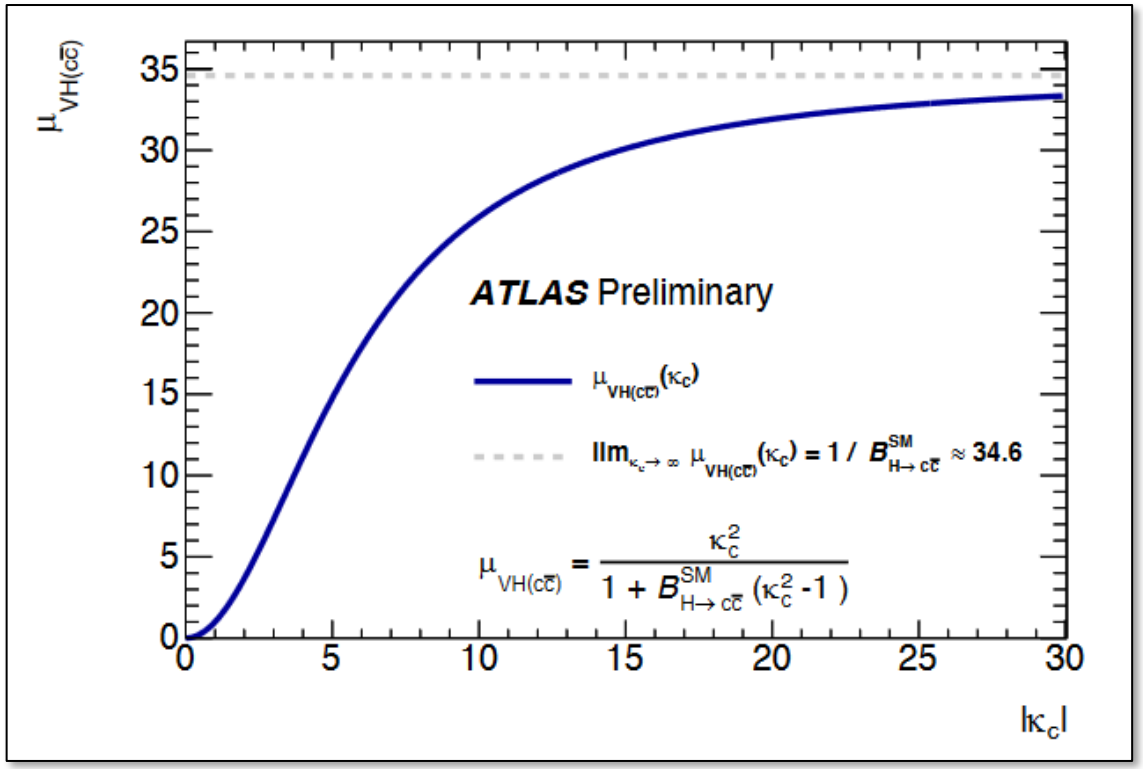
VH(H→cc) Results

- Signal strength with Higgs-charm coupling modifier κ_c:

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

with other couplings set to SM.

- μ values < ~35 let us set direct constraint on $|\kappa_c|$.



T. du Pree

VH(H→cc) Results

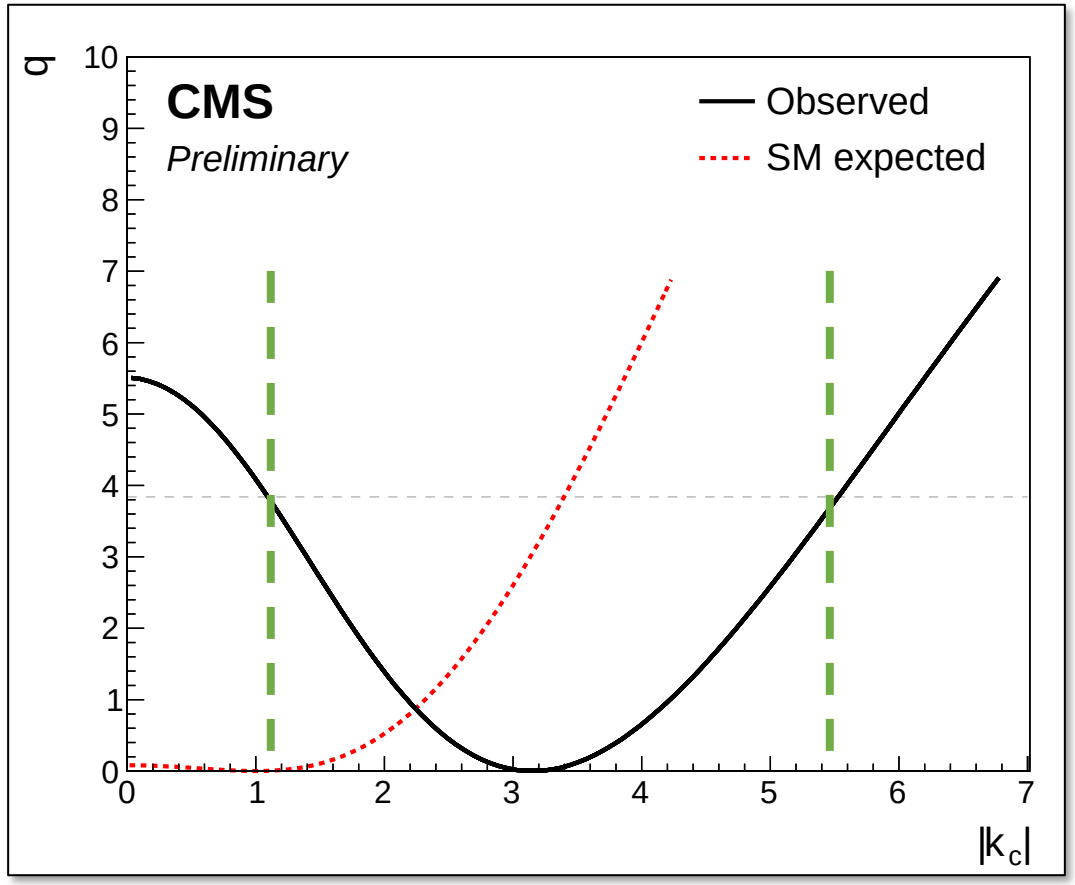
- Signal strength with Higgs-charm coupling modifier κ_c:

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

with other couplings set to SM.

- μ values < ~35 let us set direct constraint on $|\kappa_c|$.
- The 95% CL intervals obtained with likelihood scans
  - observed: 1.1 < $|\kappa_c|$ < 5.5
  - expected: $|\kappa_c|$ < 3.4

Strongest constraint on $|\kappa_c|$ to date



Dedicated likelihood scan for $|\kappa_c|$

VZ(Z→cc) Results

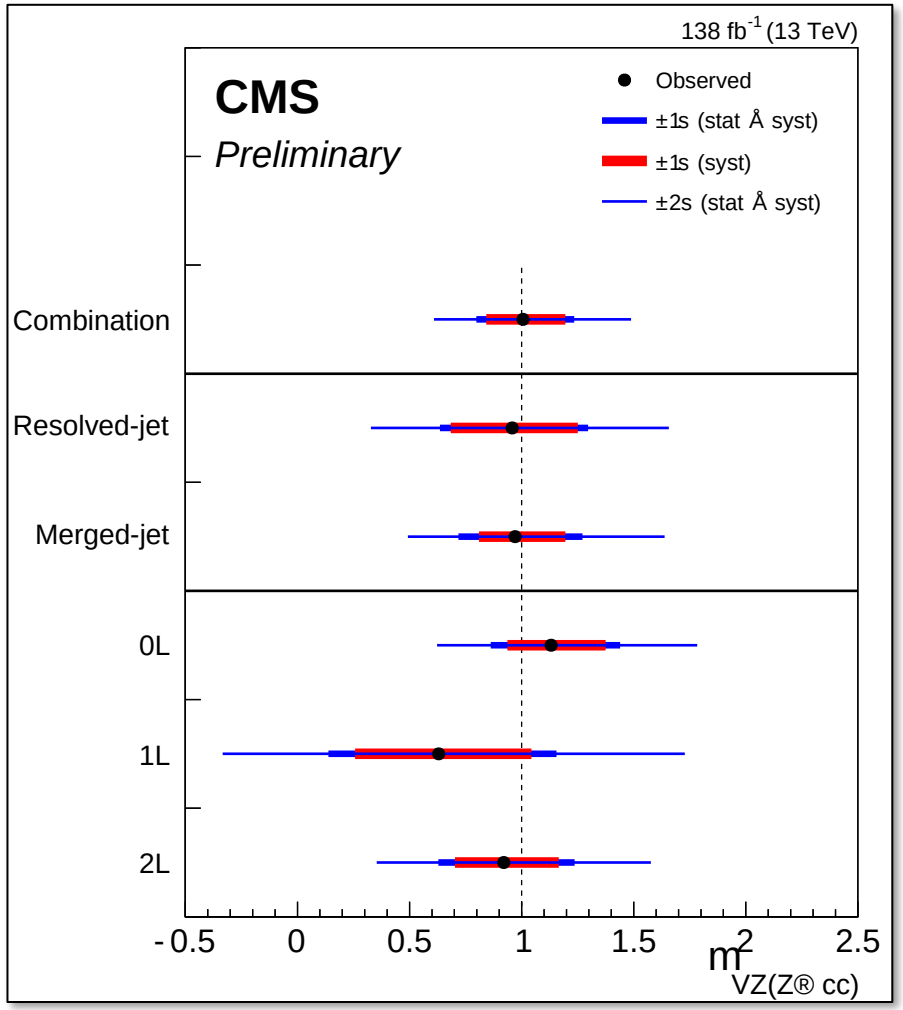
- Same analysis also sensitive to VZ(Z→cc) process
- Resolved: Train new BDT in SR for VZ(Z→cc) vs. backgrounds
- Merged: Extract VZ(Z→cc) signal from the mass fit

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

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

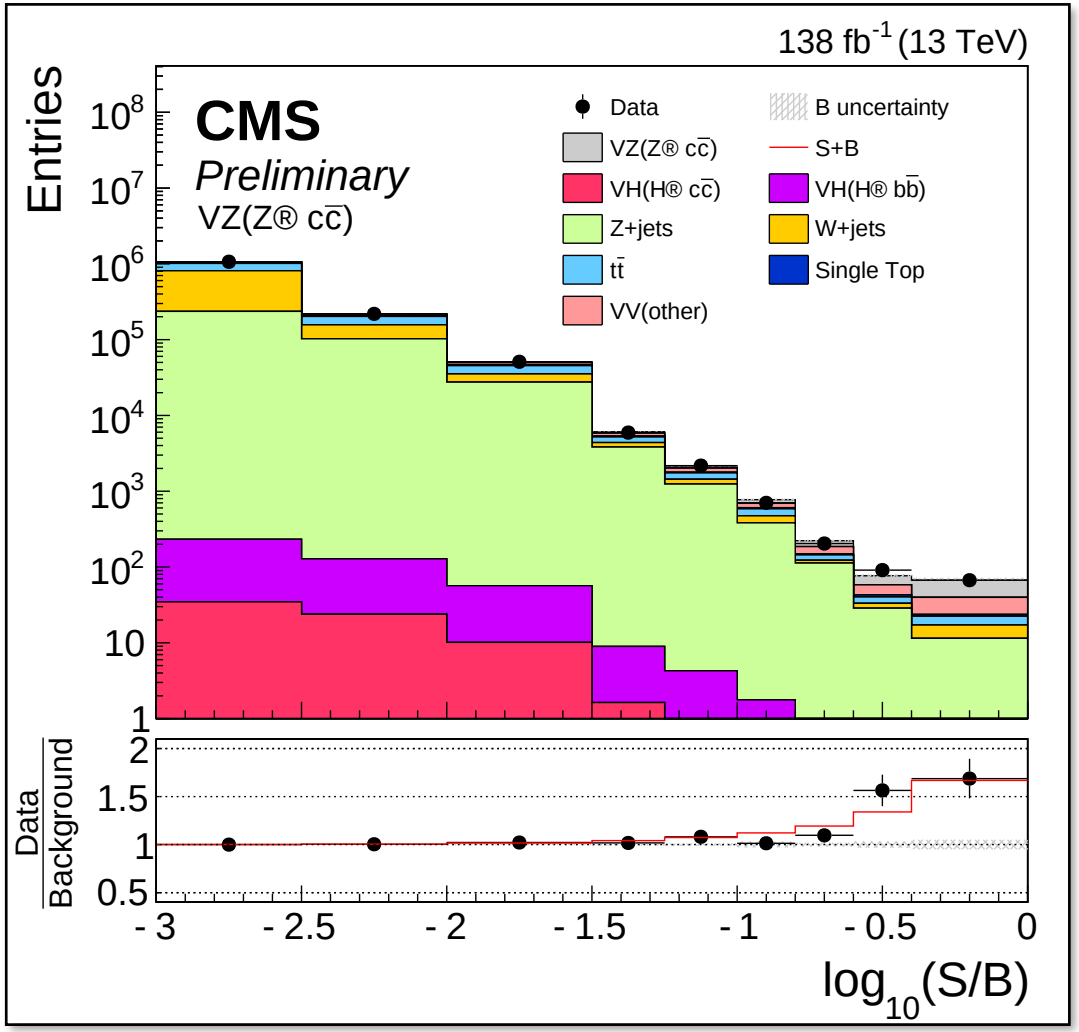
with a significance of 5.7σ (5.9σ)

First observation of VZ(Z→cc) process at hadron colliders!



VZ(Z→cc) Results

- Observing the excess:



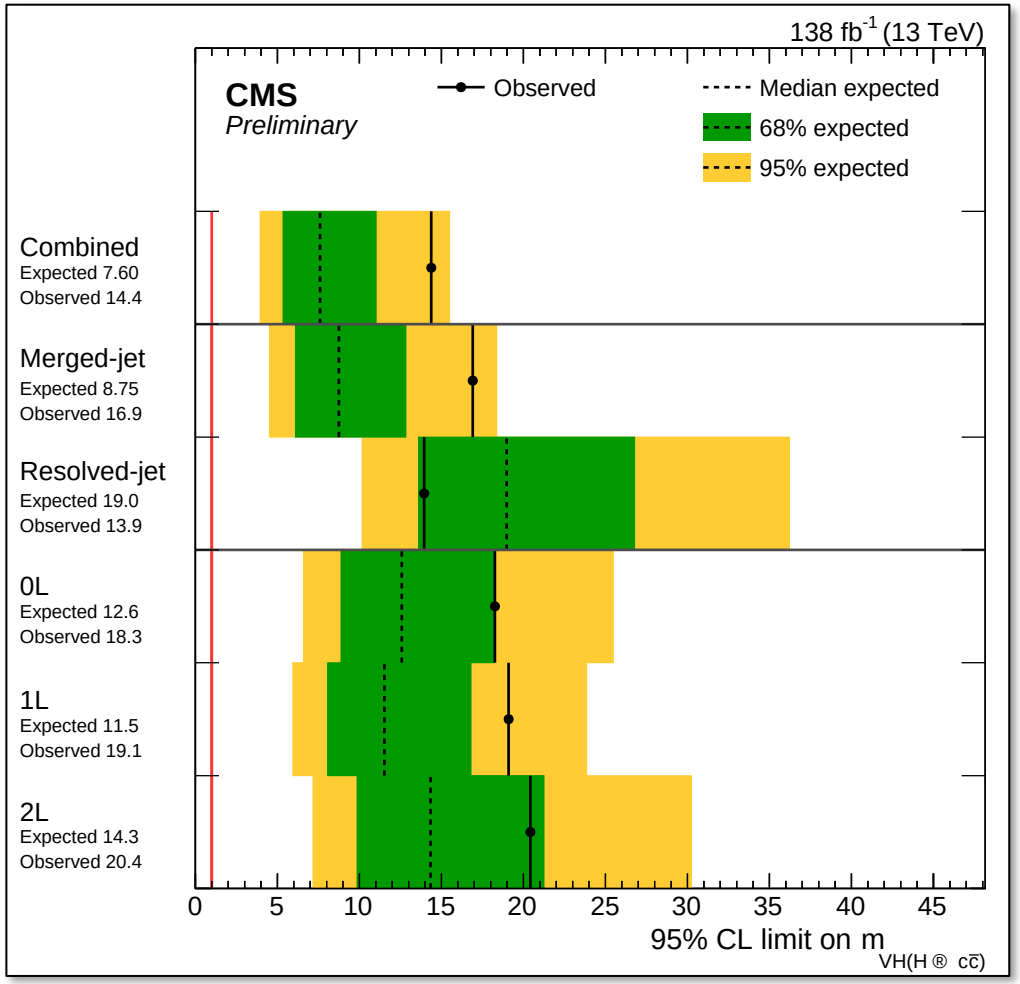
VH(H→cc) Results

- Observed (expected) upper limit on VH(H→cc) signal strength at 95% CL:

$$\mu_{VH(H\to cc)} < 14\ (7.6^{+3.4}_{-2.3}) \times SM$$

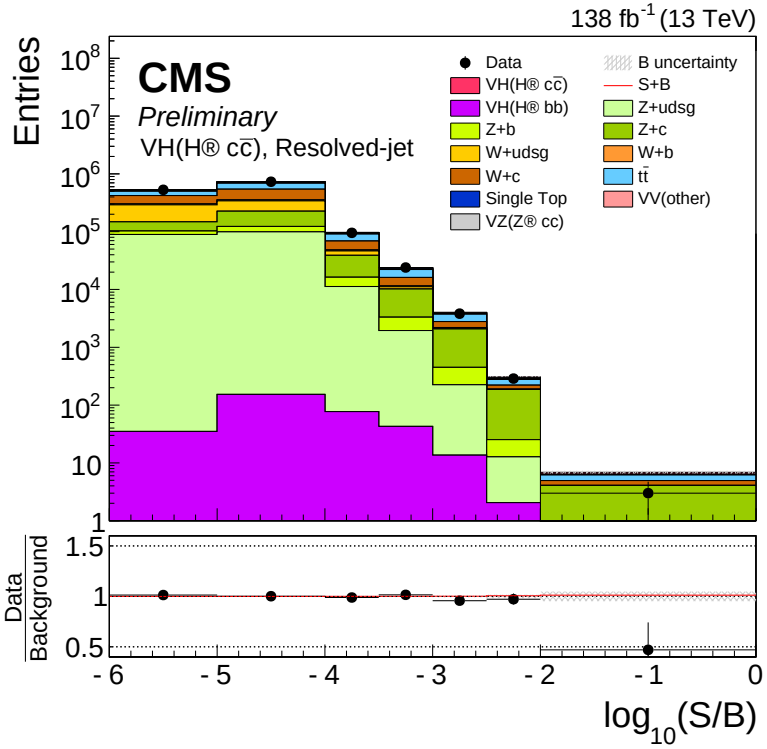
Strongest limits on VH(H→cc) process to date!

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

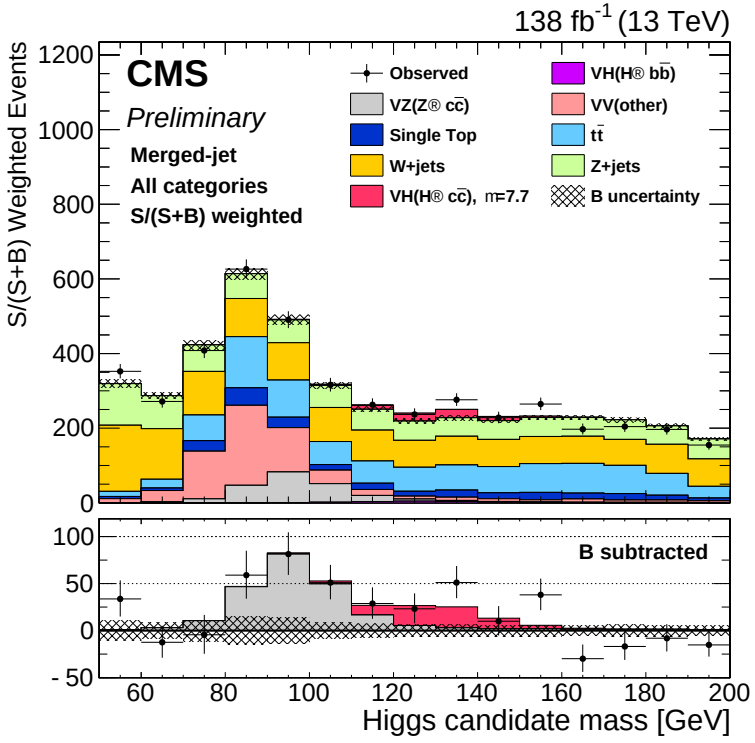


VH(H→cc) Results

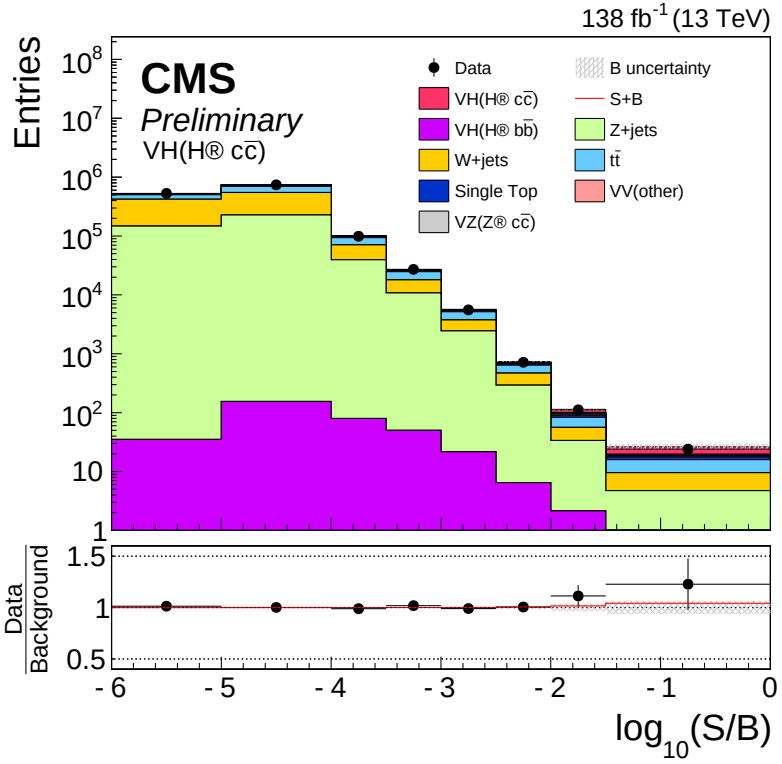
Resolved-jet

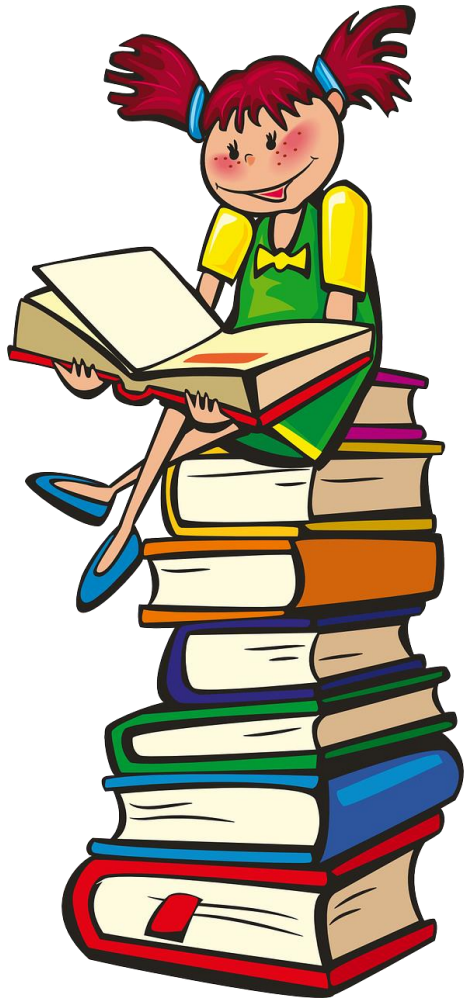


Merged-jet



Merged+Resolved-jet



Bibliography

- Resolved-jet:
  - DeepJet (jet flavour tagger): *JINST 15 (2020) P12012*
  - Charm tagger full discriminator calibration: *2022 JINST 17 P03014*
  - Charm jet energy regression: *L. Bödeker, RWTH Bachelorarbeit*
    - Inspired by b jet energy regression: *Comp. Softw. for Big Sc. 4 (2020) 10*
  - Kinematic fit: *G. R. Pérez, RWTH Masterarbeit*
- Merged-jet:
  - ParticleNet (jet flavour tagger): *Phys. Rev. D 101, 056019 (2020)*
  - cc-tagger calibration with sfBDT method: *CERN-CMS-DP-2022-005*
- Latest VH(H→cc) search at CMS: *CMS PAS HIG-21-008*