STANDARD MODEL AT THE LHC, Rome, May 7-10, 2024

Search for the Higgs boson decay in charm quarks at the CMS experiment

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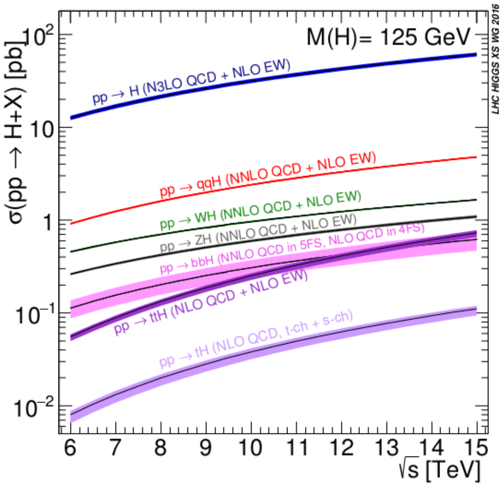
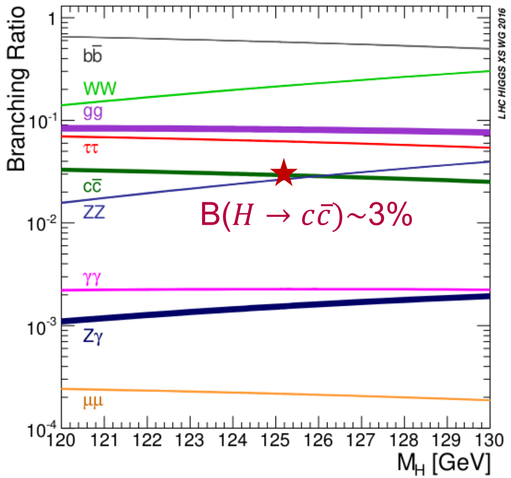
University of Bari & INFN

Higgs boson physics at LHC

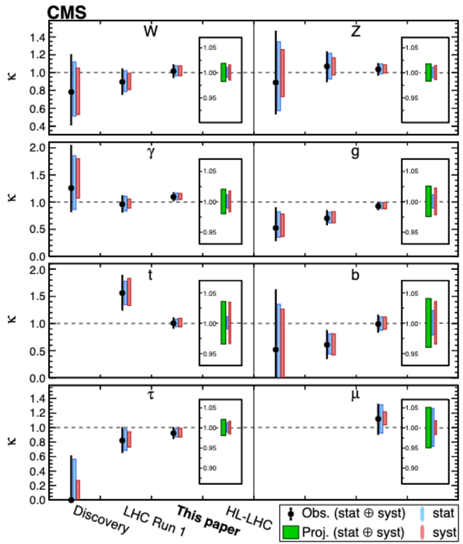
Production



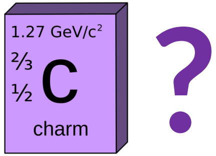
Decay



Couplings



- ▷ Couplings to weak bosons and third generation fermions measured with 10-20% precision → compatible with the SM
- ▷ Couplings to **charm** quarks **out of reach**
  extremely challenging: small rate and overwhelming QCD background

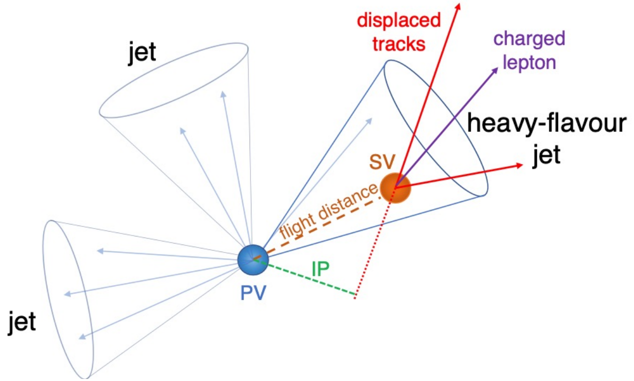


R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Charmed jets

Heavy flavour jets (b/c):

- ▷ Displaced tracks from secondary vertex (SV)
- ▷ Heavy hadron decay products with large p_T
- ▷ Soft electrons/muons

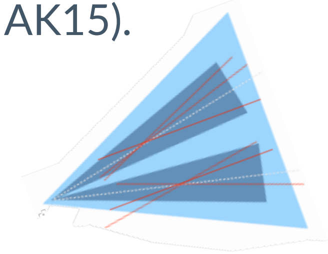


2018 JINST 13 P05011

1.27 GeV/c² ⅔ ½ c charm

c-tagging more complex than b-tagging:
discriminating variable distributions intermediate between b and light-jet ones

Fat Jets: Jets produced by the decay of a highly energetic Higgs boson (p_T >200 GeV) are collimated and can be reconstructed as a merged large radius jet (AK8 or AK15).



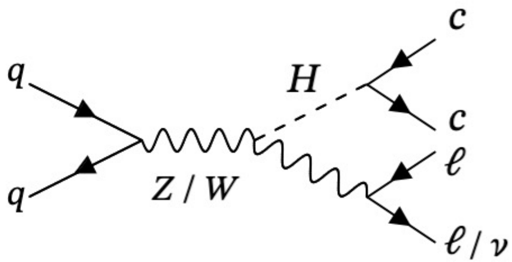
JHEP04(2008)063

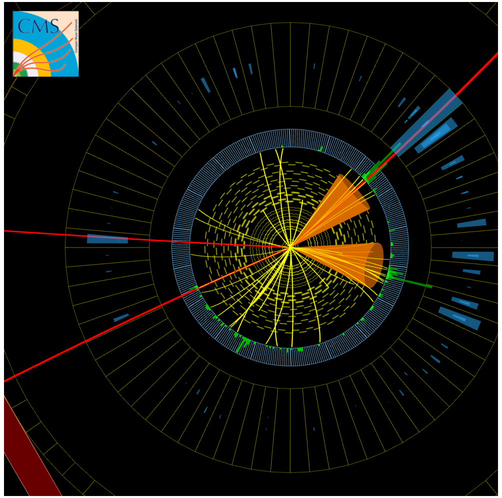
Heavy flavour tagging performed by combining many discriminating variables by means of MVA techniques

VH production mode (1/4)

https://cds.cern.ch/record/2682635?ln=it

- **Most sensitive** channel to the H→cc decay: QCD background suppressed by targeting the leptonic decays of the Z/W boson
- **Three analysis categories:**
  - **0L**: $Z \rightarrow \nu\nu$
  - **1L**: $W \rightarrow l\nu$
  - **2L**: $Z \rightarrow l^{+}l^{-}$
- **Dominant background**: Z+jets, W+jets, $t\bar{t}$ (1L), VZ, QCD (0L)
- Data collected during the **Run-2 of the LHC**: 138 fb^{-1}





Resolved analysis (p_T < 300 GeV)
Higgs boson reconstructed from 2 c-tagged AK4 jets (ΔR = 4)
→ 2-jets topology

+

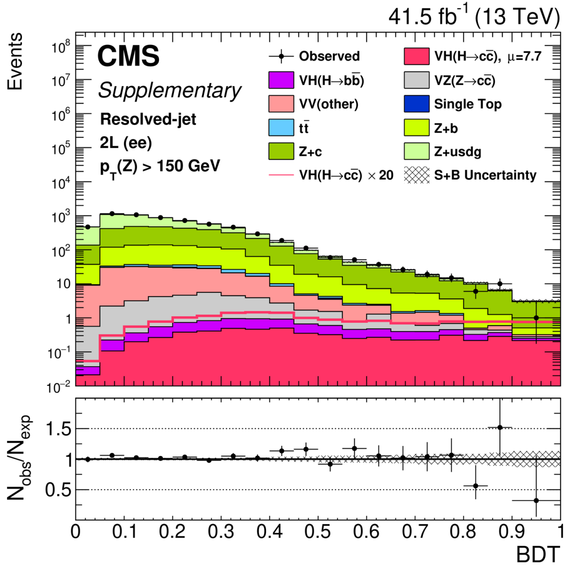
Boosted analysis (p_T > 300 GeV)
Higgs boson reconstructed as a single large radius AK15 jet (ΔR = 1.5)
→ Single-jet topology

CMS-PAS-HIG-21-008
https://arxiv.org/abs/2205.05550

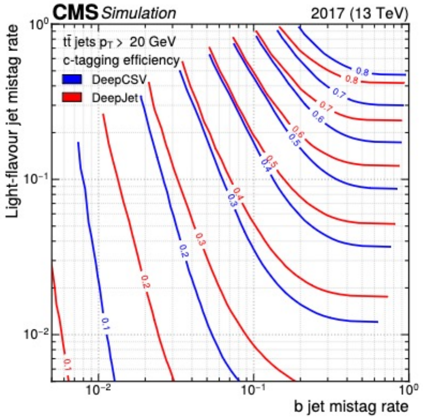
VH production mode (2/4)

Resolved analysis

- Higgs boson candidate reconstructed from **2 AK4 jets** tagged as **charmed** by means of the **DeepJet** algorithm



Post-fit distribution of the BDT score in the 2L (ee) category in 2017 data



2022 JINST 17 P03014 https://arxiv.org/abs/2008.10519

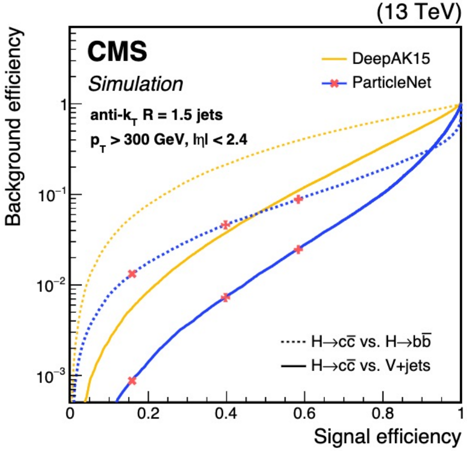
- **Boosted Decision Tree** (BDT) trained in each category for signal/background discrimination
- V+jets and $t\bar{t}$ bkgs extracted from data in dedicated control regions (CR)
- Signal strentgh modifier μ extracted from a maximum likelihood fit to data of the BDT output score

$$\mu = \frac{(\sigma B)_{obs}}{(\sigma B)_{SM}}$$

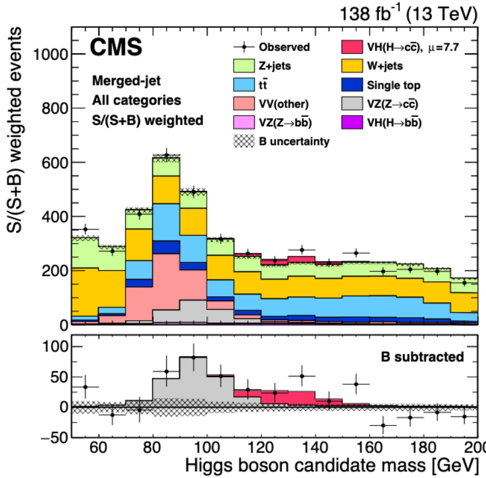
VH production mode (3/4)

Boosted analysis

- Higgs boson candidate (H_{cand}) reconstructed as a single **AK15 jet** tagged through the Run-2 state-of-the-art **ParticleNet** algorithm (graph neural network)
- **BDT** trained to discriminate signal from main bkg (V+jets, $t\bar{t}$) input variables not correlated with H_{cand} mass



https://doi.org/10.1103/PhysRevD.101.056019



- Signal extracted from a fit of the H_{cand} mass in each analysis category

VH production mode (4/4)

Combination

Best result up to date!

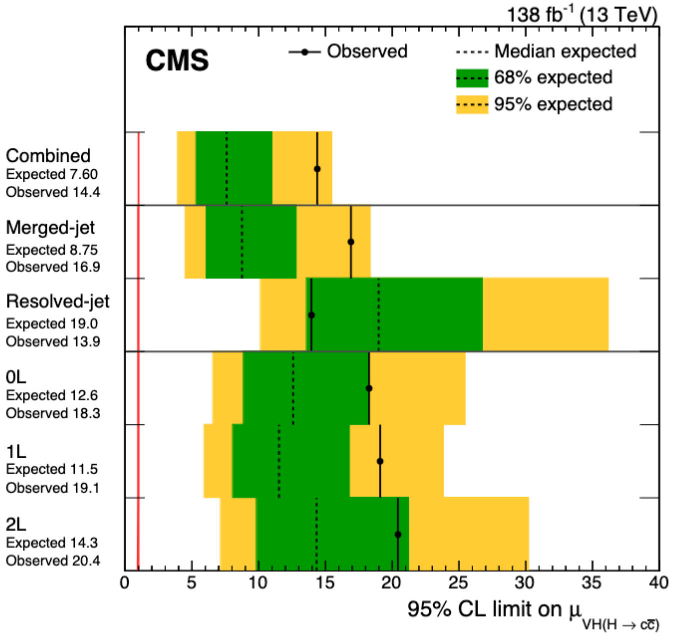
- Simultaneous fit of the two analyses → improved sensitivity
- Upper limit on the signal strength $\mu_{VH(cc)}$ at 95% CL:

$$\frac{\sigma(VH)\cdot B(H\to c\bar{c})}{\sigma(VH)_{SM}\cdot B(H\to c\bar{c})_{SM}} < 14$$

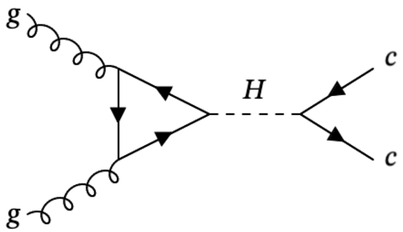
- Constraints on the Higgs-charm Yukawa coupling modifier k_c:

$$1.1 < |k_c| < 5.5$$

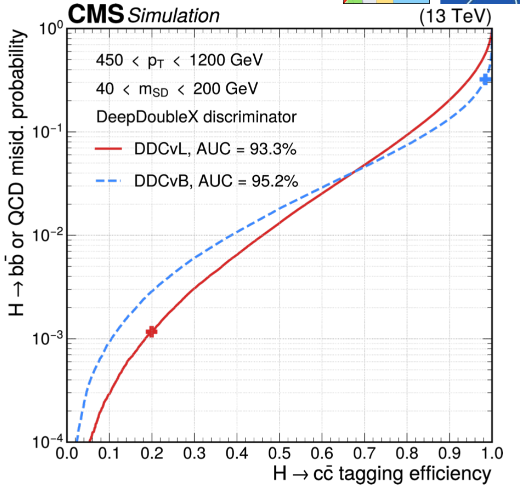
- Validation on **Z→cc**: first time observed at a hadron collider with a significance of **5.7σ**

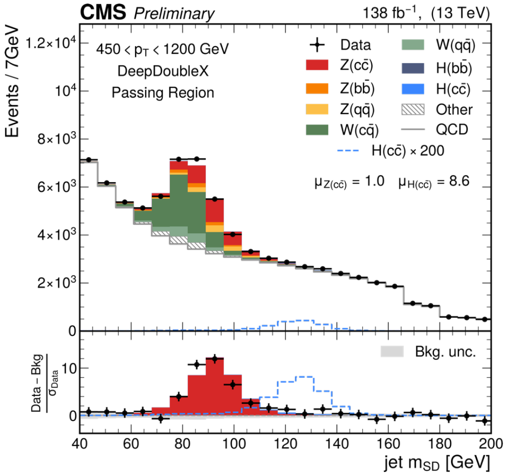


ggF production mode (1/2)



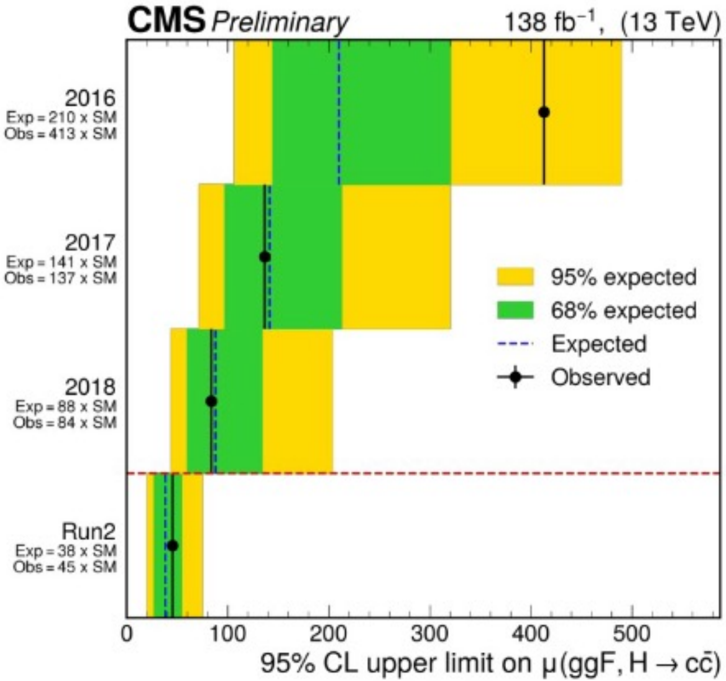
- Only **boosted analysis**:
  Higgs boson reconstructed from a single **AK8 jet** ($p_T > 450$ GeV), tagged with **DeepDoubleX**
- Soft-drop algorithm applied to the jet mass (m_{SD}) to remove soft and wide-angle radiation
- VBF and VH (orthogonal to VH analysis) are considered as signal





CMS-PAS-HIG-21-012

ggF production mode (2/2)



- ▷ Signal strength μ_H extracted from a binned (m_{SD}, p_T) maximum likelihood fit to data
- ▷ Upper limit on the signal strength $\mu_{VH(cc)}$ at 95% CL:

$$\frac{\sigma(ggH)\cdot B(H\to c\bar{c})}{\sigma(ggH)_{SM}\cdot B(H\to c\bar{c})_{SM}} < 45$$

- ▷ Validation on **Z→cc:**

  observed with **significance >> 5σ**

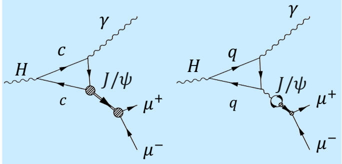
J/ψ final state

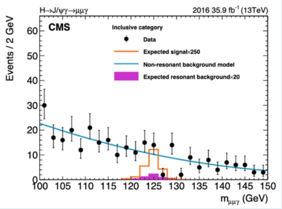
Searches performed by CMS: $\mathrm{H} \to J/\psi + \gamma$, $\mathrm{H} \to J/\psi + Z$, $\mathrm{H} \to J/\psi\, J/\psi$

▷ Target $J/\psi \to \mu\mu$

$\mathrm{H} \to J/\psi + \gamma$

- 2016 data: 36 fb^{-1}
- ggF, VBF, VH, ttH production considered



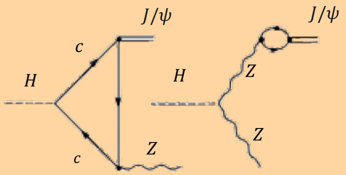


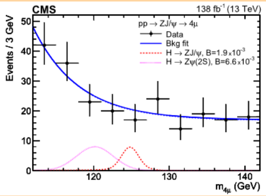
$$\frac{B(H\to J/\psi\,\gamma)}{B(H\to J/\psi\,\gamma)_{SM}} < 260$$

https://doi.org/10.1140/epjc/s10052-019-6562-5

$\mathrm{H} \to J/\psi + Z$

- 2016-2018 data: 138 fb^{-1}
- ggF and VBF considered



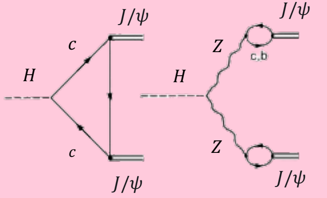


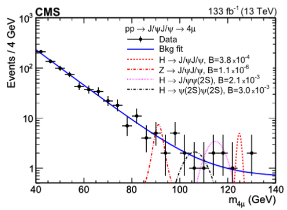
$$\frac{B(H\to J/\psi\,Z)}{B(H\to J/\psi\,Z)_{SM}} < 800$$

https://doi.org/10.1016/j.physletb.2022.137534

$\mathrm{H} \to J/\psi\, J/\psi$

- 2016-2018 data: 133 fb^{-1}
- ggF and VBF considered





$$B(H \to J/\psi J/\psi) < 3.8 \cdot 10^{-4}$$

https://doi.org/10.1016/j.physletb.2022.137534

Summary

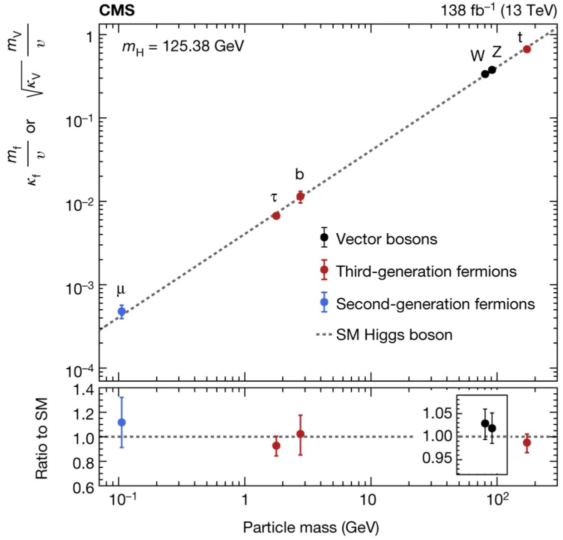
- Search for $H \to c\bar{c}$ extremely challenging:
  - Small Branching Ratio (~3%)
  - c-tagging more difficult than b-tagging

- Two Higgs production mechanisms explored:
  - VH (**highest sensitivity**)

    $\mu_{VH(cc)} < 14$ @ 95% CL, $1.1 < |k_c| < 5.5$
  - ggF

    $\mu_{ggH(cc)} < 45$ @ 95% CL

Best result up to date!



Nature 607, 60–68 (2022)

- During Run-3 of LHC (started in 2022) it would be possible to furtherly improve this result by investigating other production mechanisms and by increasing the statistics

Thank you for listening!

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Back-up

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