Recent developments in Higgs searches

Riunione nazionale CMS Italia, 7-9 Ottobre 2024, Roma

Angela Zaza on behalf of the Higgs group of CMS Italia

University of Bari & INFN

- Run-2 **combinations**
  - Legacy HH
  - Legacy H
  - Full combination of differential cross sections
- $H \to \gamma\gamma$
  - mass measurement in Full Run-2 Legacy
  - $H \to \gamma\gamma$ + c and Higgs boson coupling to charm quarks

Run-3 status

Run-2 Highlights

- Standard candles: $H \to \gamma\gamma$ and $H \to ZZ \to 4l$
- **Trigger** developments:
  - New taggers
  - VBF and HH parking
- Higgs coupling with 2nd generation quarks:
  - $VH \to cc$ merged and resolved
  - $VBF\ H \to cc$
- Double Higgs: $HH \to 4b$

Outline

Run-2 combinations

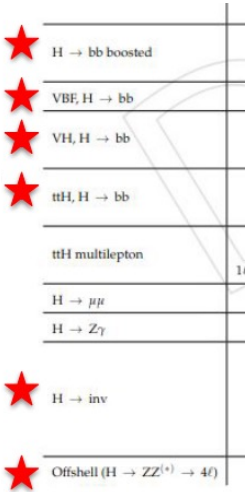
- Legacy H with all channels and SMEFT interpretations
  HIG-21-018

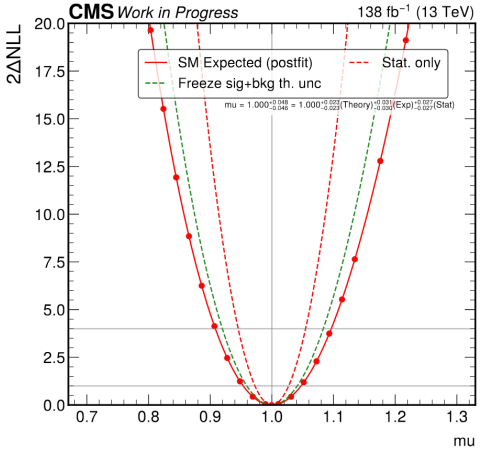
$$\pm 0.023(\text{theory})^{+0.031}_{-0.030}(\text{expt.}) \pm 0.027(\text{stat.})$$

Nature result (HIG-22-001):

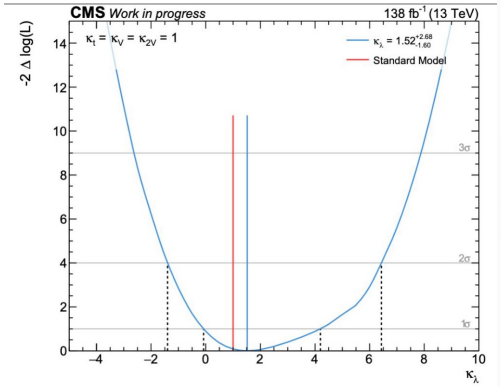
$$\mu = 0.993^{+0.036}_{-0.034}\,(theory)\,^{+0.033}_{-0.032}\,(expt)\,^{+0.028}_{-0.028}\,(stat)$$

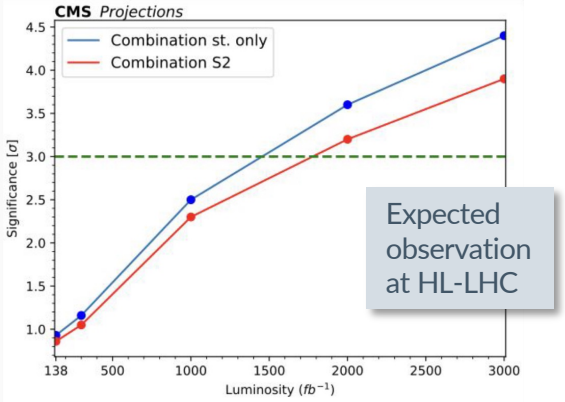
★ = new since Nature combination





- Legacy HH with all channels
  HIG-20-011
  preapproval talk June24





Run-2 combinations

- Full Run-2 combination of fiducial differential cross section $(H \to \gamma\gamma, H \to ZZ, H \to WW, H \to \tau\tau)$
  CMS-PAS-HIG-23-013
  no deviations from SM observed

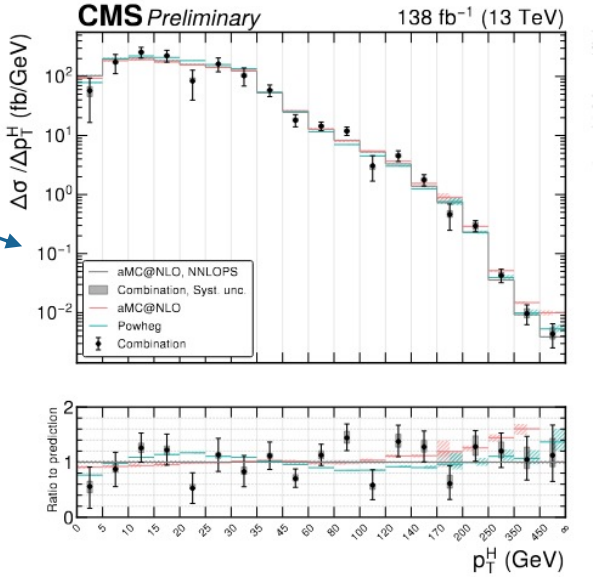
- SMEFT interpretation

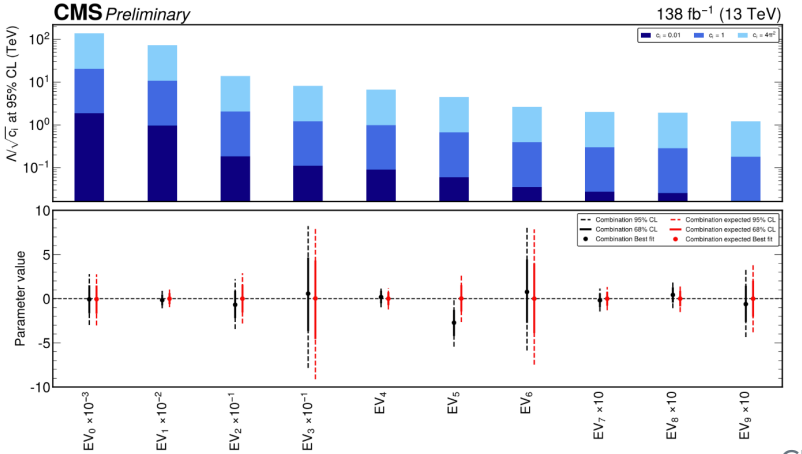
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

Wilson coeffiecients

SMEFT dim-6 operators

energy scale for new physics





- Constraints on linear combinations of EFT coefficients → in agreement with SM expectations
- Energy scale of the new physics they can constrain

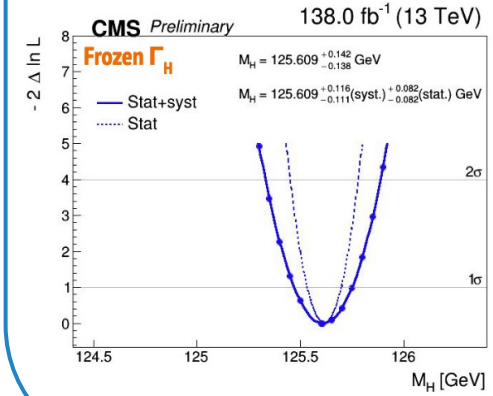
H→ $\gamma\gamma$ measurements

Higgs mass

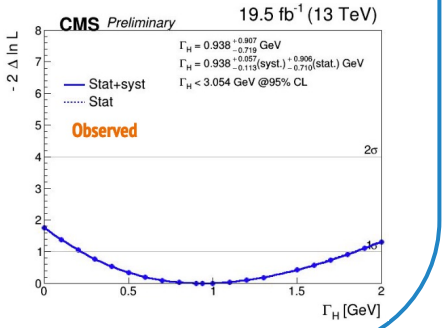
NEW Unblinding

- Ultra Legacy full Run2
- HIG-24-007
- Unblinding

M(H) = 125.609 ± 0.14 [0.08 (stat) ± 0.12 (sys)] GeV



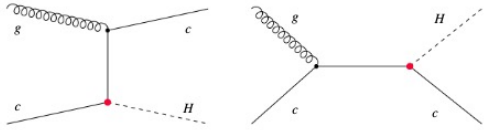
Under investigation
2016_preVFP → $\Gamma_H = 0.94^{+0.91}_{-0.72}$

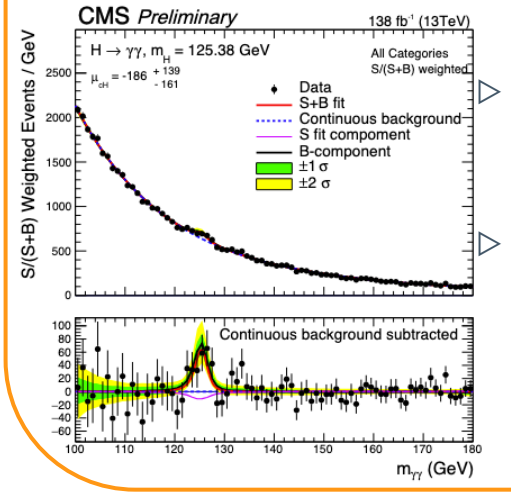


$H \to \gamma\gamma + c$

CMS-HIG-PAS-23-010

- Full Run-2 analysis
- Probe the Higgs boson coupling with charm quarks



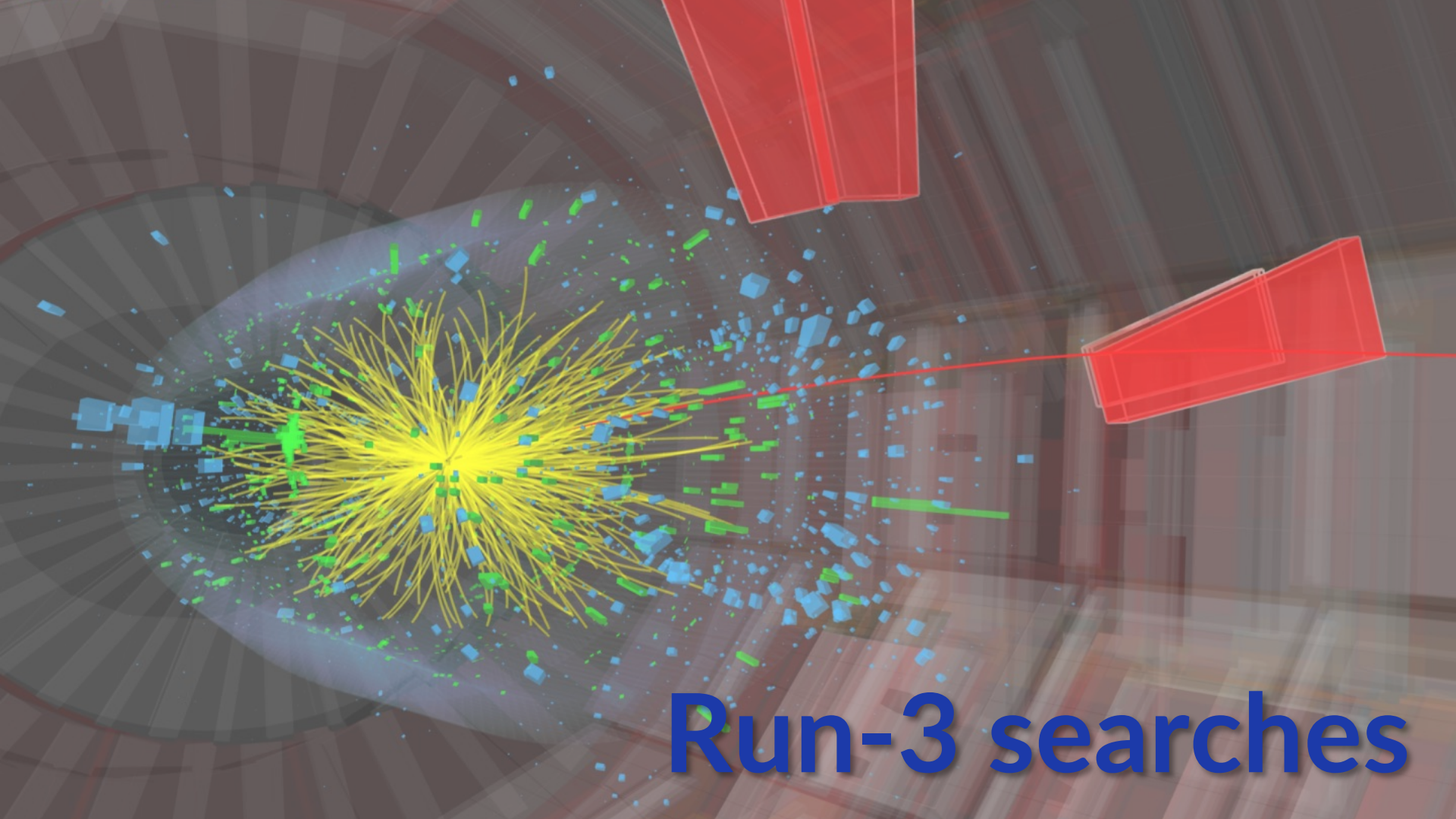


- UL on the signal strength @ 95% CL:

  $\mu_{H\gamma\gamma c} < 243(355)$

- UL on the coupling modifier @ 95% CL:

  $|k_c| < 38.1\ (72.5)$


Run-3 searches

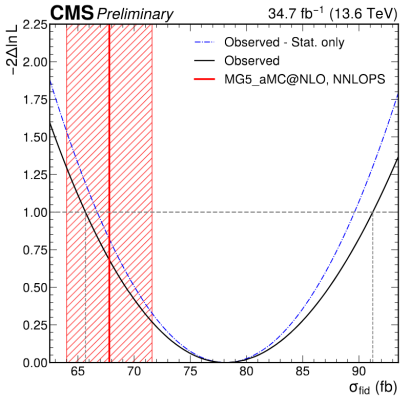
Higgs standard candles

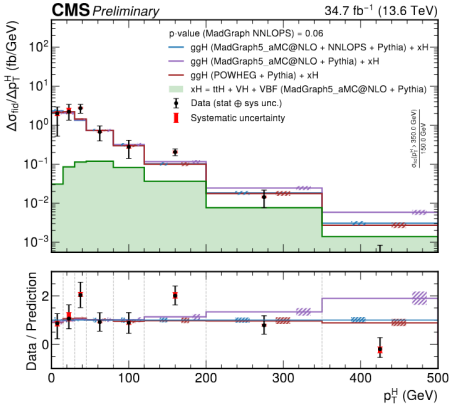
$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-23-014

- Inclusive and differential cross section measurement
- 2022 data (34.7 fb^{-1})
- Inclusive cross section in the fiducial phase space

$$\sigma_{fid} = 78 \pm 11\,(stat)\,^{+6}_{-5}\,(sys)\ fb^{-1}$$



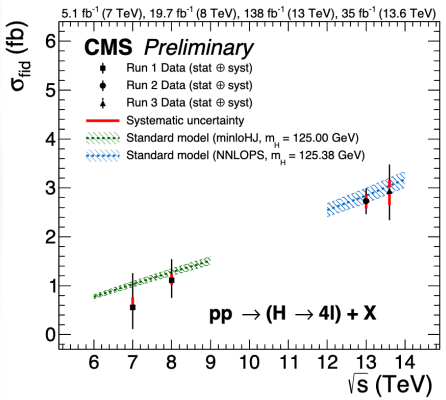


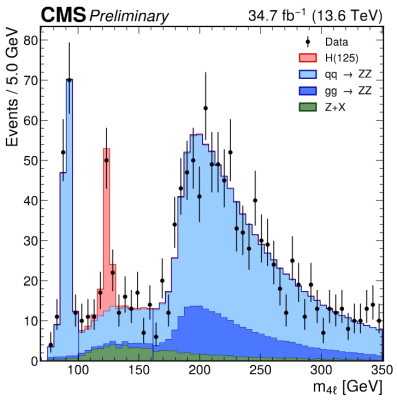
$H \rightarrow ZZ \rightarrow 4l$

CMS-PAS-HIG-24-013

- Inclusive and differential cross section measurement
- 2022 data (34.7 fb^{-1})
- Inclusive cross section in the fiducial phase space

$$\sigma_{fid} = 2.94\,^{+0.53}_{-0.49}\,(stat)\,^{+0.29}_{-0.22}\,(sys)\ fb^{-1}$$





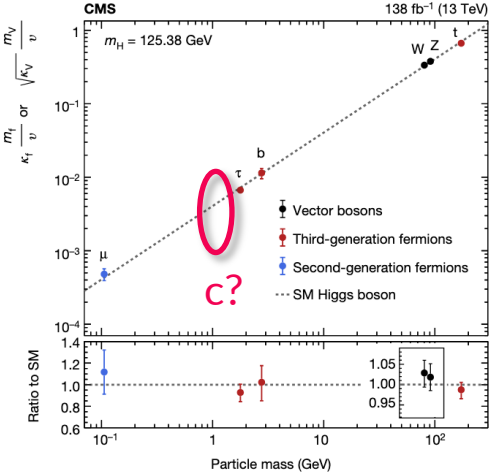
Run-3 Higgs physics program

Highest priority goals in Higgs searches:

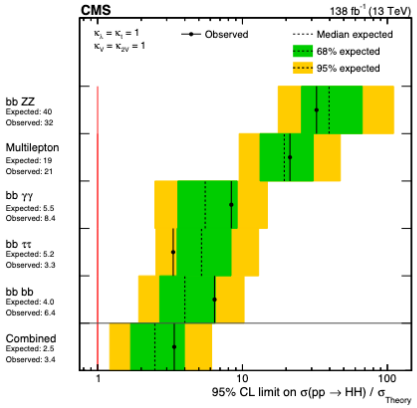
Expected UL

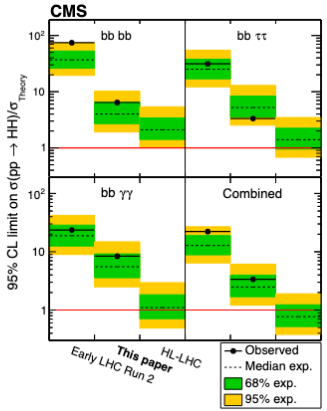
▷ Higgs **coupling to charm quarks**

	VHcc boosted	VHcc resolved	ttHcc (prelim.)	VBFHcc (prelim.)	ggF Hcc
Run2 results	8.8×SM	19.0×SM	7.8×SM	-	38×SM
Run2 + Run3 (500 fb^{-1})	4.7×SM	10×SM	4.1×SM	7.6×SM	20×SM



▷ Higgs **self coupling**

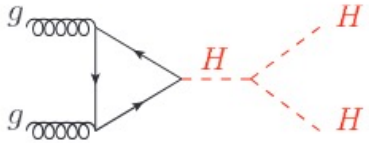




Higgs potential: $V = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda_3 \upsilon H^3 + \frac{1}{4}\lambda_4 H^4$

(Run-2) Observed limit on k_λ:

$$-1.2 < k_\lambda < 6.5$$



Trigger developments (1/2)

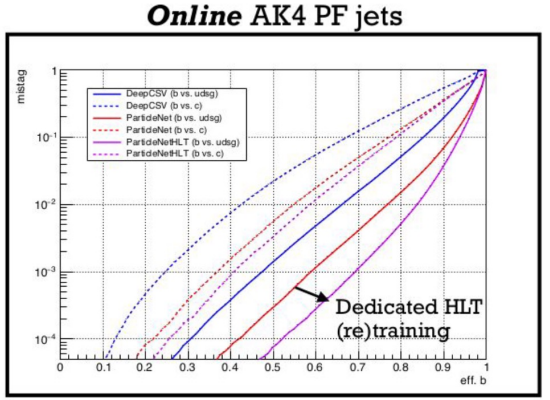
FLAVOUR TAGGING

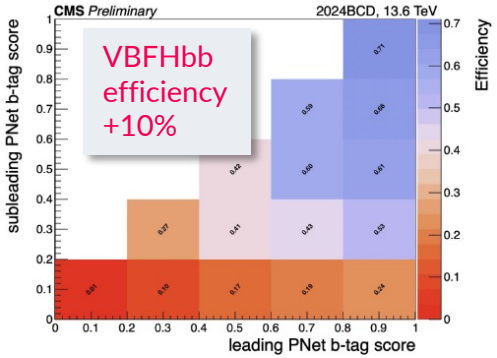
CMS DP-2022/030
CMS DP-2023/021

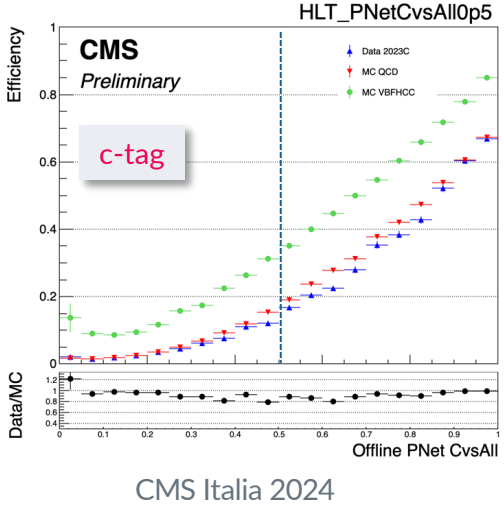
- DeepJet and ParticleNet **trained** with **HLT features** → **large gain** in performance
- Deployed online new triggers based on **ParticleNet** for
  - $HH \to 4b$ and $HH \to bb\tau_h\tau_h$
  - Boosted $H \to bb$ and $H \to \tau_h\tau_h$
  - $VBF\ H \to cc$ (first c-tagging online)

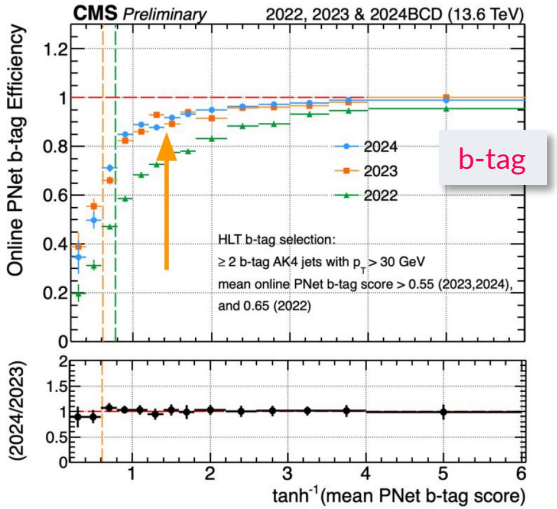
→ **Data-parking**

- All paths with b/c-tagging migrated to ParticleNet (2024)









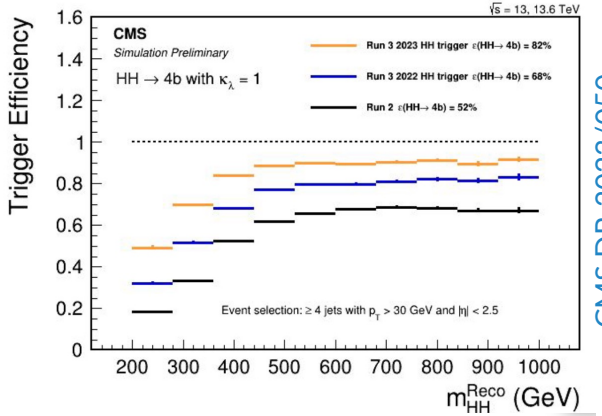
CMS DP-2023/089

Trigger developments (2/2)

PARKING STRATEGY

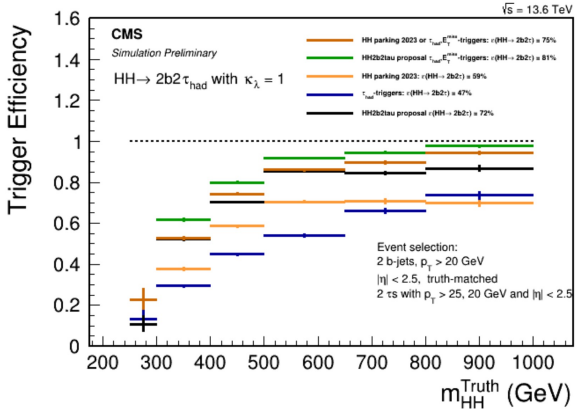
- **HH parking (330 Hz)**
  - **4j+2b**
    modified in 2024 to become more inclusive

    2023: HLT_**PFHT280_QuadPFJet30**_PNet2BTagMean0p55
    2024: HLT_**PFHT250_QuadPFJet25**_PNet2BTagMean0p55
  - **4jet+1b+1τ (new 2024)**
- **VBF parking (1 kHz)**
  - Inclusive triggers with tight requirements on the VBF jets
  - Specific triggers
    - VBF + 1 loose central object
    - Higgs specific VBF triggers (VBFHcc)



CMS DP-2023/050

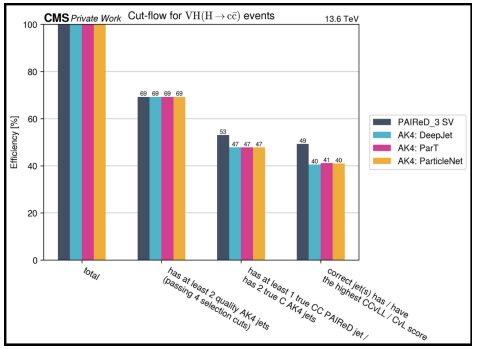
*HH→2b2τ_h efficiency vs. m_{HH}***



Search for charm decays

Resolved $VH \to cc$

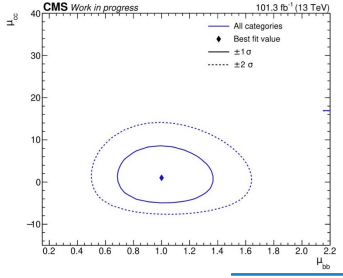
- ▷ new strategy for resolved analyses: **PAIReD**
  - New approach to reconstruct decays of heavy particles at a large
  - Define an ellipse in the $\eta - \phi$ plane around the two AK4 jets
  - Exploit correlation between the hadronization products of the two c-quarks

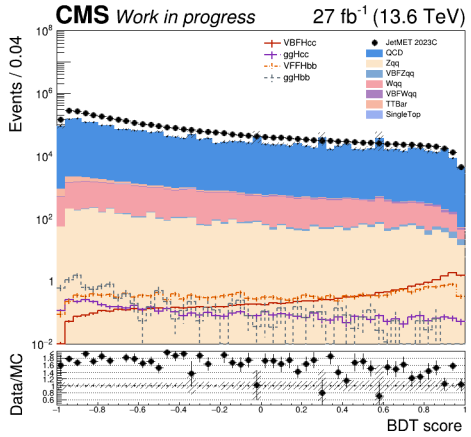


Boosted $VH \to bb/cc$

- ▷ Simultaneous measurement of $H \to bb$ and $H \to cc$
- ▷ H candidate reconstructed as a AK15 jet tagged with **ParT**
- ▷ Two cc and two bb orthogonal regions defined

Better sensitivity than ATLAS on μ_{cc}



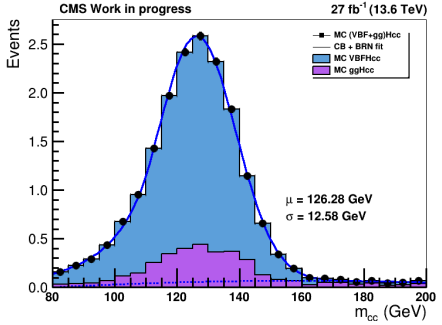


Higgs/Charm workshop in 2024

$VBF\ H \to cc$

- ▷ New trigger with ParticleNet c-tagging
- ▷ Signal/bkg discrimination with BDT based on **ParticleNet** CvsL and CvsB scores of the two c-jets and QvsG scores of the VBF jets
- ▷ Preliminary expected upper limit on the signal strength:

$\mu_{VBFHcc} < 30$ @ 95% CL



Search for double Higgs: $HH \rightarrow 4b$

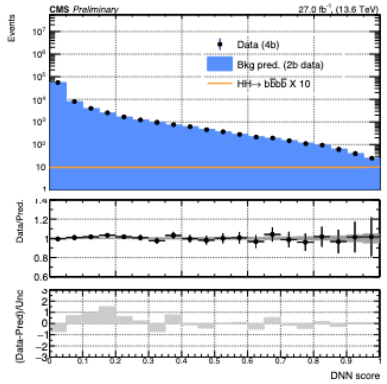
HIG-24-010
Preapproval talk

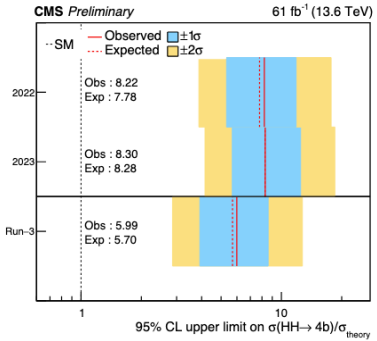
Resolved

- ▷ **4j2b trigger** with ParticleNet designed for this analysis
- ▷ 4 b-jets tagged with ParticleNet
- ▷ DNN for signal/bkg separation
- ▷ Expected upper Limit on the signal strength:

$\mu_{HH4b} < 5.70$

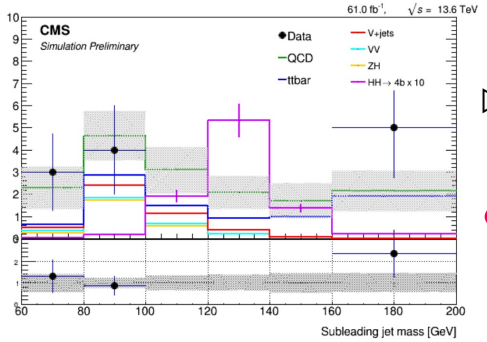
25-30% more sensitive than Full Run-2
2 times better scaled to Full Run-2 lumi





Boosted

- ▷ **Boosted Hbb trigger** with ParticleNet designed for this analysis
- ▷ 2 AK8 jets tagged with ParticleNet
- ▷ DNN multiclass for signal vs QCD and ttbar discrimination
- ▷ Simultaneous mass fit across 2022 (35 fb^{-1}) and 2023 (27 fb^{-1})



- ▷ Expected upper Limit on the signal strength:

$\mu_{HH4b} < 7.5$

Conclusions

Run-2

- ▷ Great effort ongoing for Run-2 HH and H Legacy combinations
- ▷ Full Run-2 combination of fiducial differential cross section → No deviations from SM observed
- ▷ Ongoing Full Run-2mass measurement in $H \to \gamma\gamma$ and recent publication $H \to \gamma\gamma + c$

Run-3

- ▷ Standard candles: $H \to \gamma\gamma$ and $H \to ZZ \to 4l$
- ▷ Trigger developments: new **taggers** and **data-parking**
- ▷ Great effort ongoing in $H \to cc$ searches: **VH** and **VBF** analyses
- ▷ Great effort ongoing in $HH \to 4b$ resolved and boosted searches

→ New triggers, taggers, anaysis techniques

→ Better sensitivity than Run-2 expected

Thank you for listening!

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- Run-2 **combinations**
  - Legacy HH
  - Legacy H
  - Full combination of differential cross sections
- $VH \rightarrow bb$ differential cross section
- $H \rightarrow \gamma\gamma$
  - mass measurement in Full Run-2 Legacy
  - $H \rightarrow \gamma\gamma + c$ and Higgs boson coupling to charm quarks

Run-3 status

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- ▷ VHbb fiducial differential cross section

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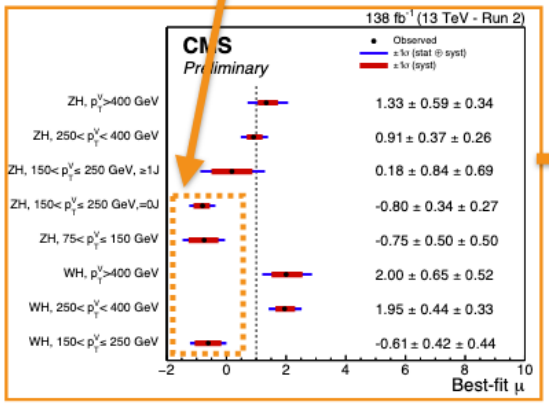
VH(bb) differential cross section

CMS Italia 2023

- Deviation > 3σ from SM prediction

CMS-PAS-HIG-20-001



changes:

- Decorrelation of Vb and Vbb processes
- Removal of a soft activity counter with 5 GeV threshold
- Correction of additional jet counter with 30 GeV threshold

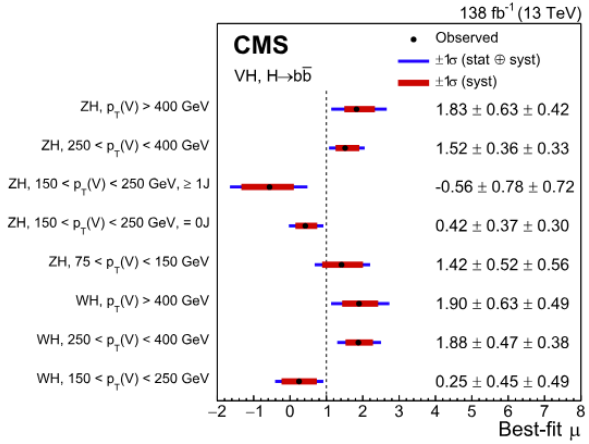
2024

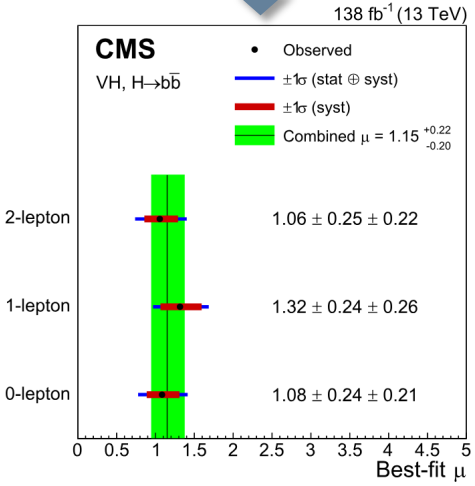
PhysRevD.109.092011

- STXS template
- Full Run-2 data
- Inclusive signal strength

$$\mu = 1.15^{+0.22}_{-0.20} \rightarrow Z = 6.3\ (5.6)\ \sigma$$

Each channel overall compatible with the SM





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  [HIG-21-018]

★ = new since Nature combination

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  $(H \to \gamma\gamma, H \to ZZ, H \to WW, H \to \tau\tau)$
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Nature result ([HIG-22-001]):

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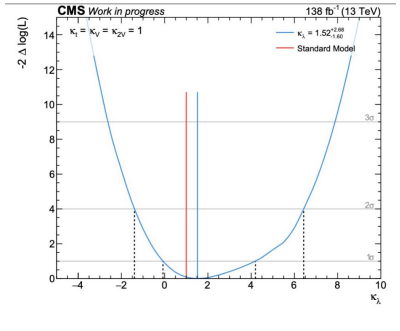
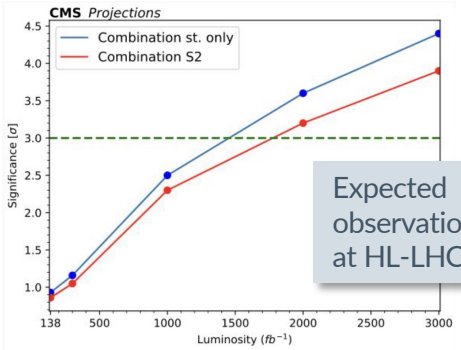
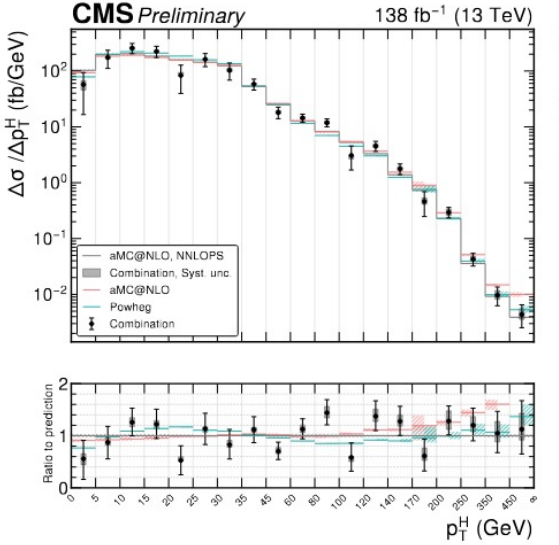
- Legacy HH with all channels
  [HIG-20-011]
  [preapproval talk June24]





Expected observation at HL-LHC



Higgs standard candles Run-2

$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-23-014

- Inclusive and differential cross section measurement
- 2022 data (34.7 fb^{-1})
- Inclusive cross section in the fiducial phase space

$$\sigma_{fid} = 73.4\ ^{+5.4}_{-5.3}\ (stat)\ ^{+2.4}_{-2.2}\ (sys)\ fb$$

$H \rightarrow ZZ \rightarrow 4l$

- doi:10.1007/JHEP08(2023)040
- Inclusive and differential cross section measurement
- Full Run-2 data (138 fb^{-1})
- Inclusive cross section in the fiducial phase space

$$\sigma_{fid} = 2.73 \pm 0.22(stat) \pm 0.15(sys)\ fb$$

- Higgs mass measurement in $H \to \gamma\gamma$
- Run-2 **combinations**
  - Full combination of differential cross sections
  - Legacy HH
  - Legacy H
- $H \to \gamma\gamma + \mathbf{c}$ and Higgs boson coupling to charm quarks
- $VH \to bb$ differential cross section
- Double Higgs: $HH \to bbVV$

Run-2 Highlights

- Standard candles: $H \to \gamma\gamma$ and $H \to ZZ \to 4l$
- **Trigger** developments:
  - VBF and HH parking
  - New taggers
- Higgs coupling with 2nd generation quarks:
  - $\mathbf{V}H \to cc$ merged and resolved
  - $VBF\ H \to cc$
- Double Higgs: $HH \to 4b$

Run-3 status

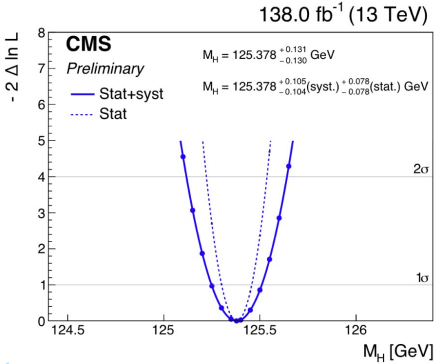
Outline

Run-2 Highlights

$H \rightarrow \gamma\gamma$

- Expected Full Run2 mass measurement recently obtained
- Preapproval talk June24

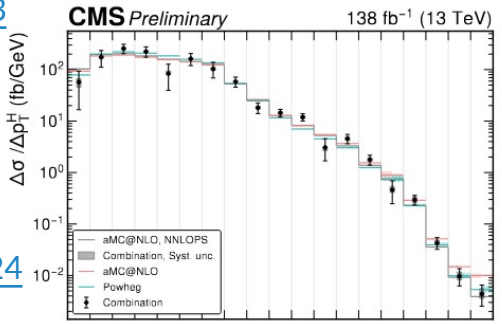
M(H) = 125.38 ± 0.13 [0.08(stat) ± 0.11 (sys)] GeV



Unc. (GeV)	Syst.	Stat.	Total
CMS H(γγ) 2016	0.18	0.18	0.26
ATLAS H(γγ)	0.09	0.11	0.14
CMS H(γγ)	**0.11**	**0.08**	**0.13**

Run-2 combinations

- Full Run-2 combination of fiducial differential cross section ($H \rightarrow \gamma\gamma, H \rightarrow ZZ, H \rightarrow WW, H \rightarrow \tau\tau$)
  CMS-PAS-HIG-23-013
  no deviations from SM observed

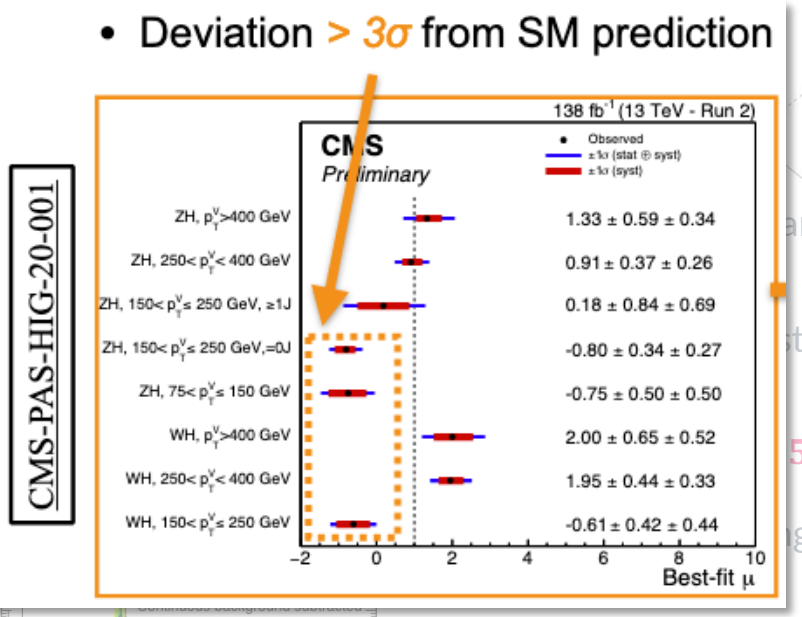


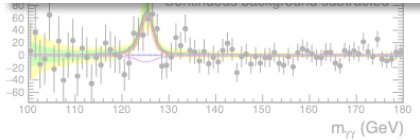
- Legacy HH with all channels preapproval talk June24
- Legacy H with all channels and SMEFT interpratations HIG-21-018

Run-2 Highlights

CMS Italia 2023

- Deviation > 3σ from SM prediction





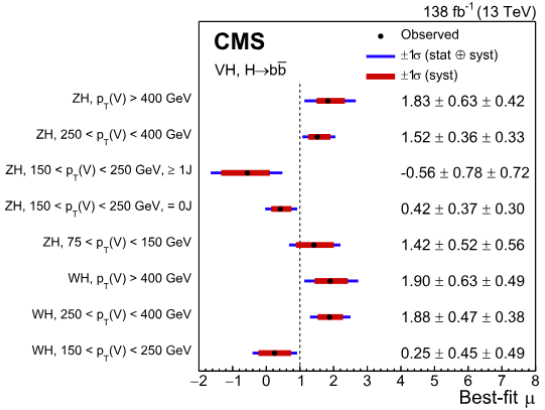
$|k_c| < 38.1\ (72.5)$

VH(bb) differential cross section

PhysRevD.109.092011

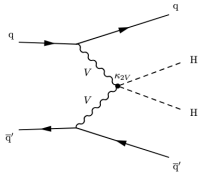
- ▷ STXS template
- ▷ Full Run-2 data
- ▷ Inclusive signal strength

$\mu = 1.15^{+0.22}_{-0.20} \rightarrow Z = 6.3\ (5.6)\ \sigma$



Run-2 Highlights

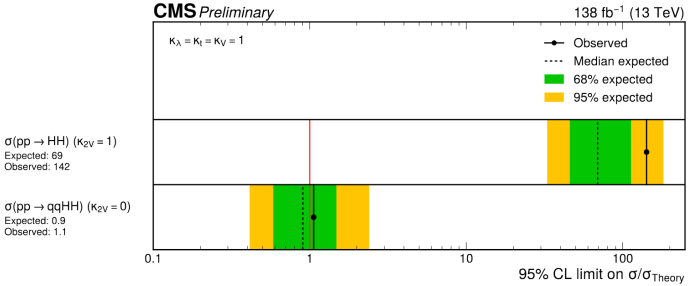
$HH \rightarrow bbVV$

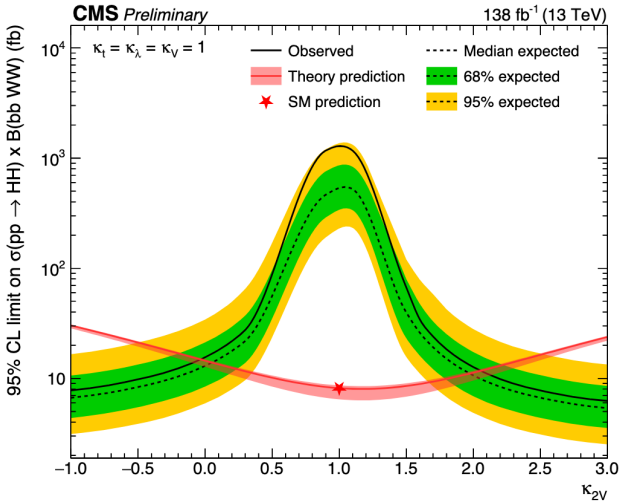


CMS-HIG-PAS-23-012

- Aim to constrain k_{2V}
- Full Run-2 analysis in high-m_{HH} regime
- All hadronic final states considered
- Second largest BR behind $HH \rightarrow 4b$
- $H \rightarrow bb$ identification with **PNet-MD**
- $H \rightarrow VV$ identification with **GloParT**

$k_{2V} \in [-0.04, 2.05]([0.05, 1.98])$ @ 95% CL

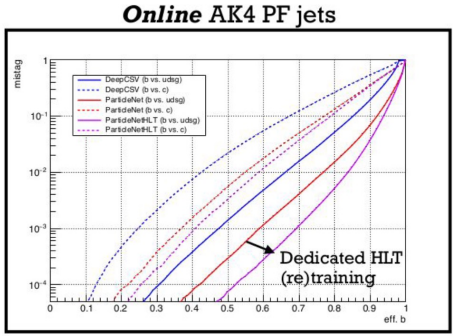


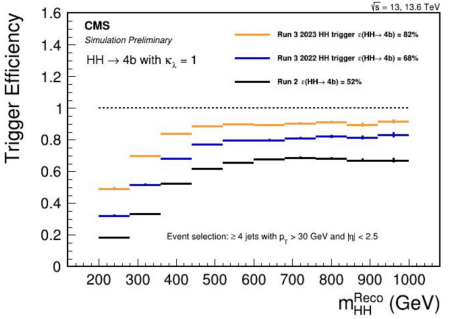


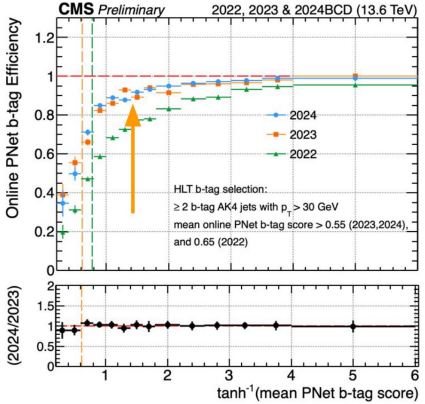
Trigger developments

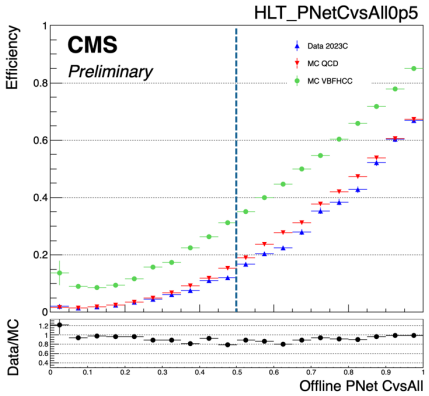
FLAVOUR TAGGING

- DeepJet and ParticleNet trained with HLT features → large gain in performance
- Deployed online new triggers based on **ParticleNet** for
  - $HH \to 4b$ and $HH \to bb\tau_h\tau_h$
  - Boosted $H \to bb$ and $H \to \tau_h\tau_h$
  - $VBF\ H \to cc$ (first c-tagging online)
- All paths with b/c-tagging migrated to ParticleNet (2024)



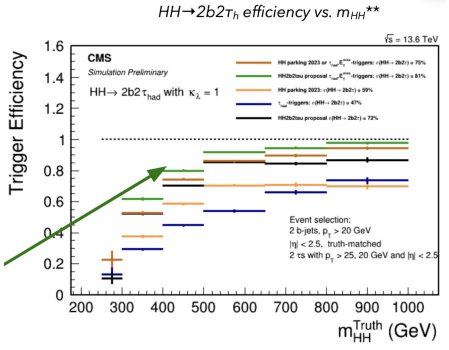






PARKING STRATEGY

- **HH parking**
  - 4b+2jet
  - 4jet+1b+1τ
- **VBF parking**
  - Inclusive triggers with tight requirements on the VBF jets
  - Specific triggers
    - VBF + 1 loose central object
    - Higgs specific VBF triggers



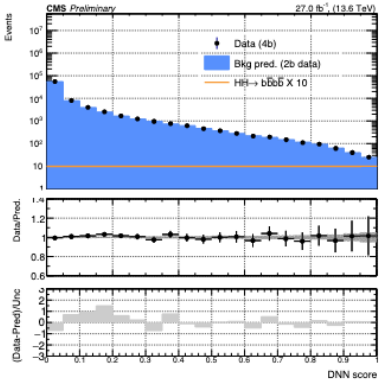
Search for double Higgs: $HH \rightarrow 4b$

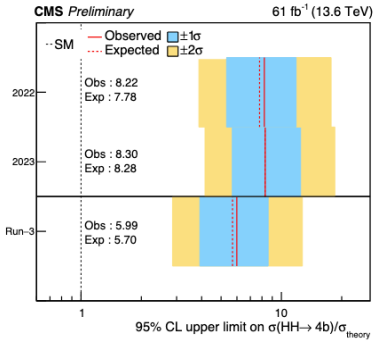
HIG-24-010
Preapproval talk

Resolved

- ▷ **4j2b trigger** with ParticleNet designed for this analysis
- ▷ 4 b-jets tagged with ParticleNet
- ▷ DNN for signal/bkg separation
- ▷ Expected upper Limit on the signal strength:

$\mu_{HH4b} < 5.70$ → 25-30% more sensitive than Full Run-2
2 times better scaled to Full Run-2

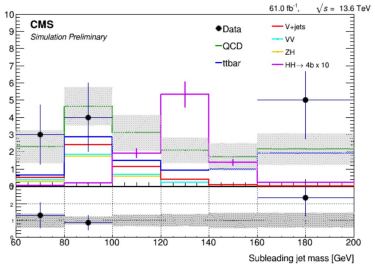




Boosted

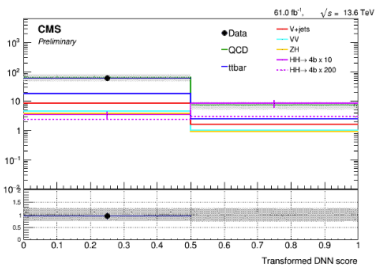
- ▷ **Boosted Hbb trigger** with ParticleNet designed for this analysis
- ▷ 2 AK8 jets tagged with ParticleNet
- ▷ DNN multiclass for signal vs QCD and ttbar discrimination
- ▷ Simultaneous fit across 2022 (35 fb^{-1}) and 2023 (27 fb^{-1})

▸ Mass-fit analysis



$\mu_{HH4b} < 7.56$ @ 95% CL

▸ DNN-fit analysis



$\mu_{HH4b} < 7.96$ @ 95% CL