Boosted Higgs Boson at the LHC

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Chateau Lake Louise

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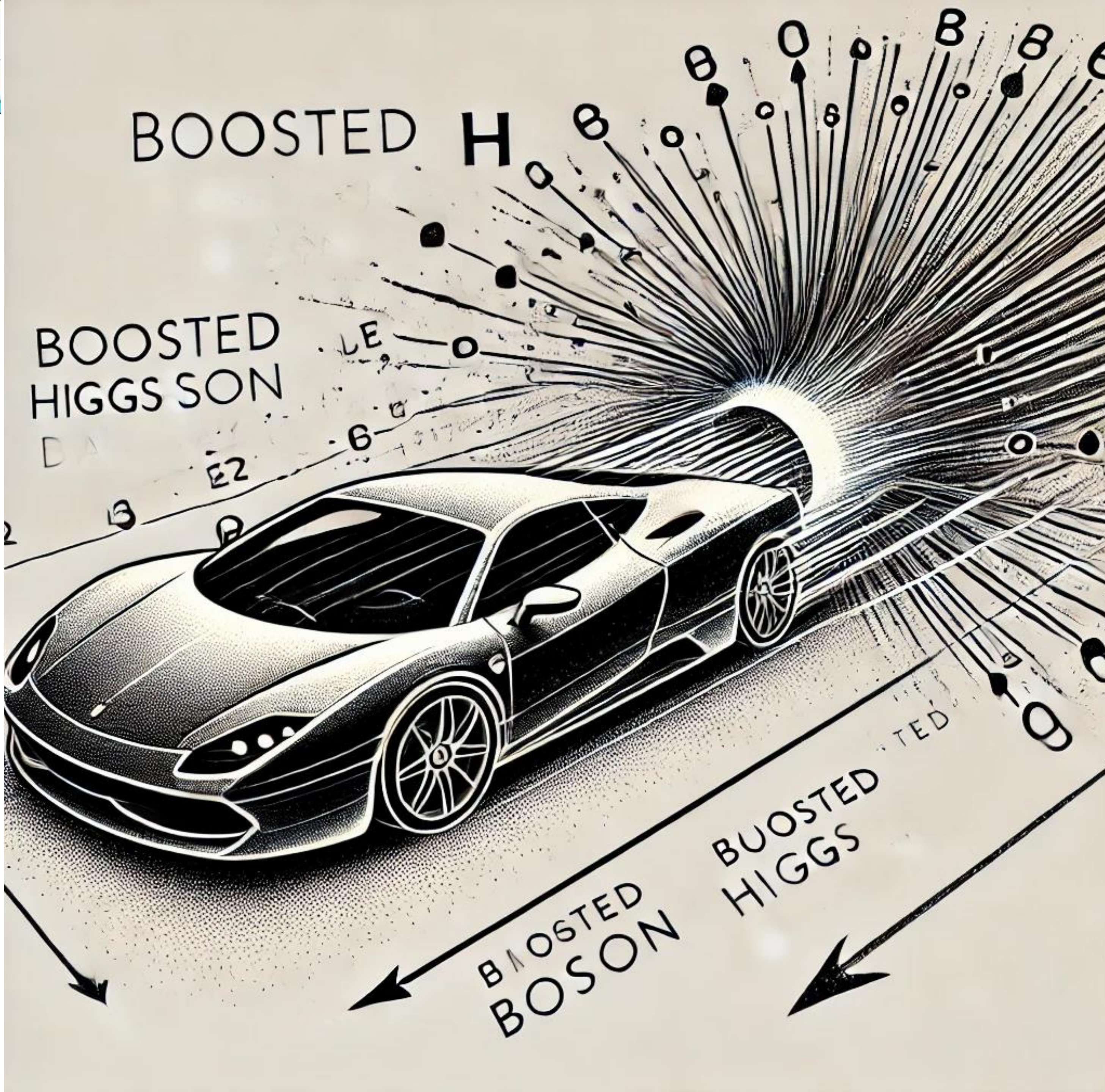
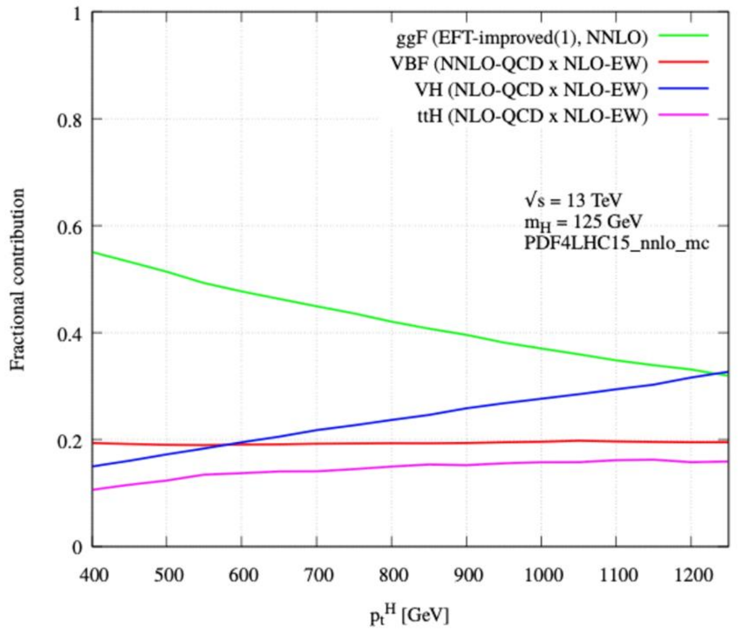


Boosted Higgs boson Search Motivation

- Why Study the Boosted Higgs Boson?
  - **Probing Beyond the Standard Model (BSM) Physics**
    - Boosted Higgs scenarios arise in various BSM models, including extended Higgs sectors, dark sector mediators, and exotic decays.
  - **Enhanced Sensitivity to Rare and Exotic Decays**
    - In highly boosted regimes, unconventional Higgs decay channels (e.g., long-lived particles, Higgs to invisible) become experimentally accessible.
  - **Discrimination Against Standard Model Backgrounds**
    - Boosted Higgs events produce unique jet substructure signatures, aiding in distinguishing signal from background.
  - **Precision Tests of the Higgs Sector**
    - Studying boosted kinematics allows for stringent tests of Higgs couplings, production mechanisms, and potential deviations from SM predictions.



- Comes with its own challenges and opportunities
  - Smaller XS, inefficient traditional reconstruction algorithm
  - Novel methods to tag boosted Higgs and use it in search for new physics

Current results

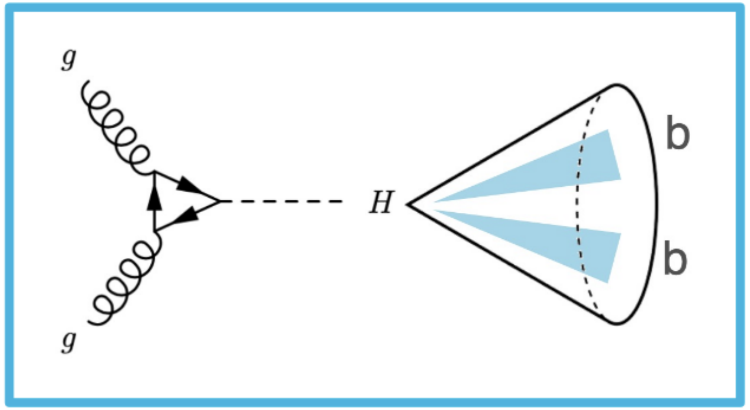
- Results are based on the full Run II analysis

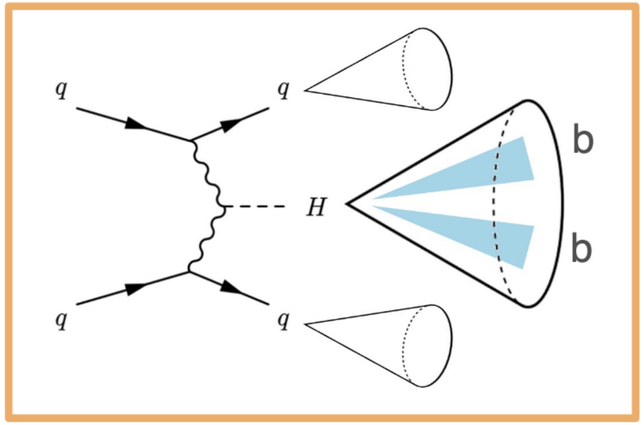
Channel	ATLAS	CMS
(ggH/VBF) Boosted H→bb	-	10.1007/JHEP12(2024)035
(VH- hadronic) Boosted H→bb	Phys. Rev. Lett. 132 (2024) 131802	-
(VH- leptonic) Boosted H→bb	https://arxiv.org/pdf/2410.19611	-
Boosted H → $\tau\tau$	-	10.1016/j.physletb.2024.138964
Boosted H→cc	-	*Phys. Rev. Lett. 131 (2023) 041801*
Boosted H(→ZZ/bb)+γ	-	https://arxiv.org/abs/2502.05665

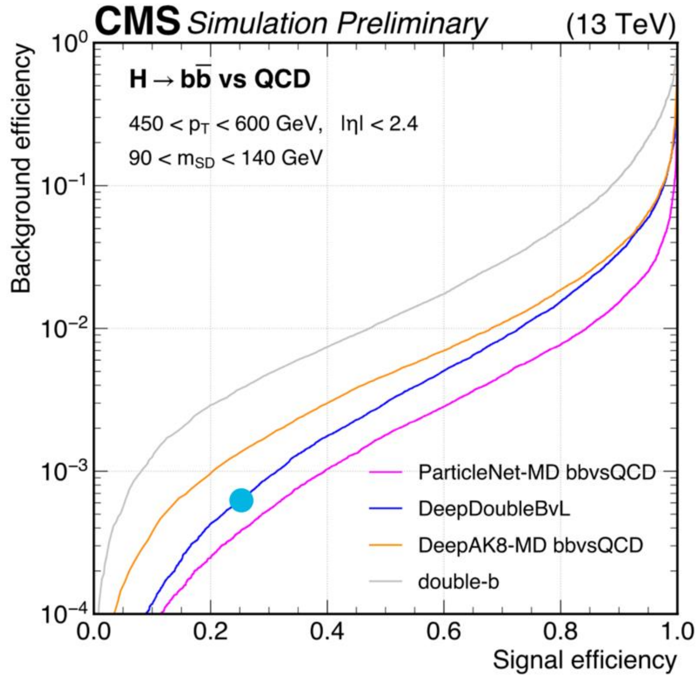
ggH/VBF H→bb

10.1007/JHEP12(2024)035

- H→bb has the highest branching fraction of any H decay mode in the SM
- Higgs appears as a single large-R jet in boosted regime
- The DDB tagger is based on a DNN, trained to distinguish large-radius jets containing X → bb decays from QCD
- Trained on jet features, such as the number of PF candidates and low-level quantities describing secondary vertices
- The addition of low-level features leads to a large improvement in performance
- 1% QCD mistag rate for 75% signal efficiency







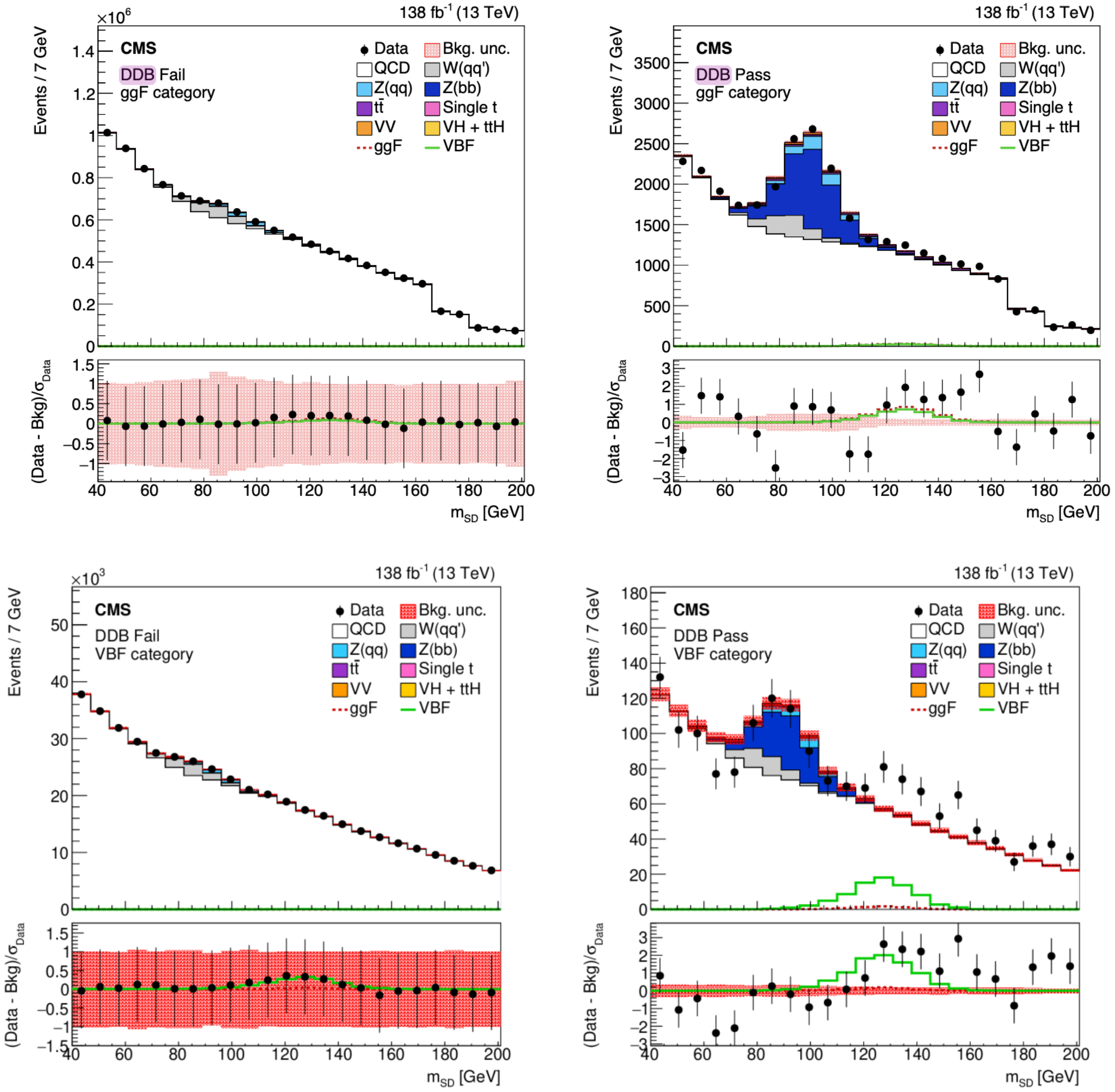
ggH/VBF H→bb

10.1007/JHEP12(2024)035

- Triggered with a soup of Jet and HT triggers
- Event selected if an Ak8 Jet of 450 GeV is found with soft drop mass between 40 to 200 GeV
- Veto muon, electron and tau lepton in the events
- Top rejection: MET < 140 GeV, No DeepCSV medium b-tagged jets
- DNN discriminators are employed to separate the H signal from the dominant QCD events
- N_2^{DDT} variable to identify two-prong jets by energy correlation function:

$$N_2^{DDT} = N_2 - f(p_T, \rho)$$

  - Function f constructed so that $N_2^{DDT} < 0$ has 26% efficiency on QCD jets
- Events are split into fail and pass categories and are fit simultaneously



ggH/VBF H→bb

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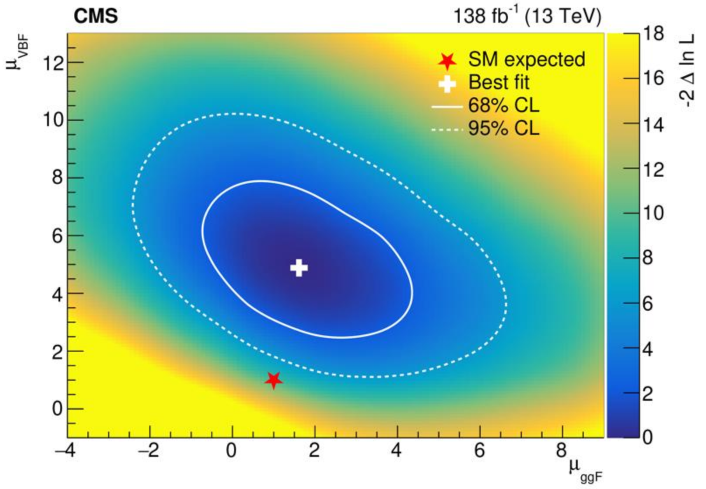
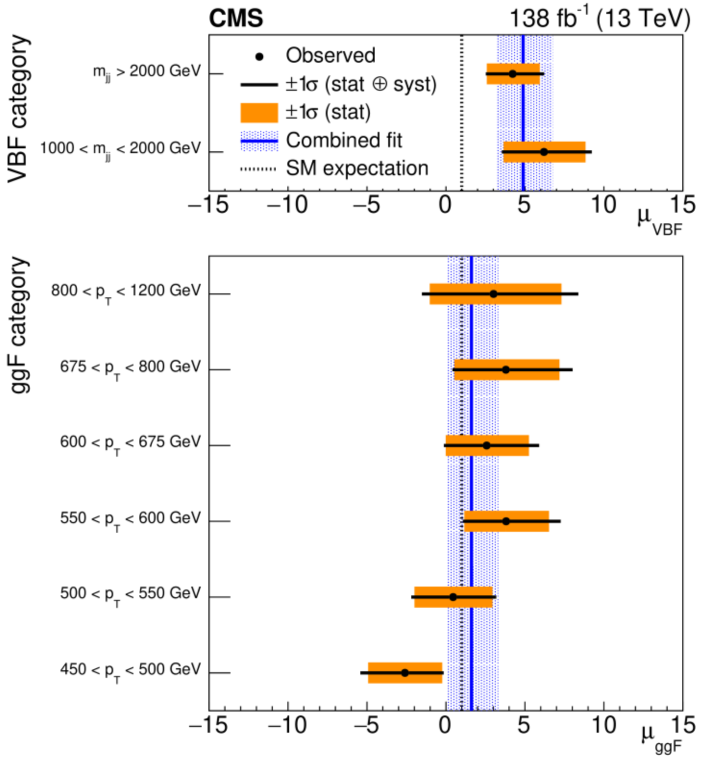
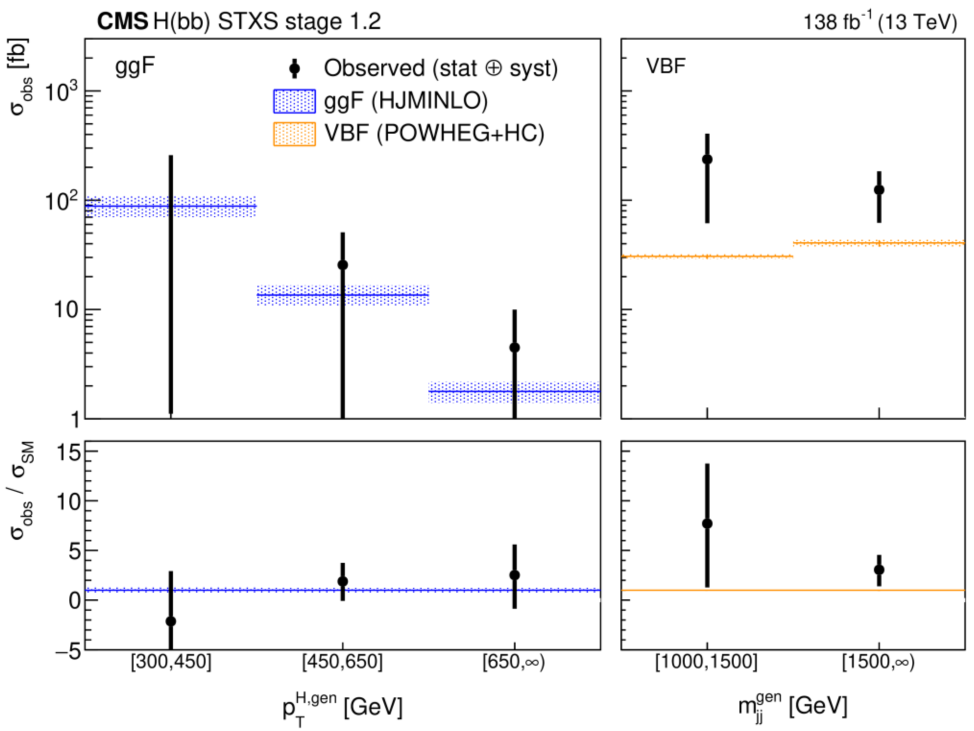


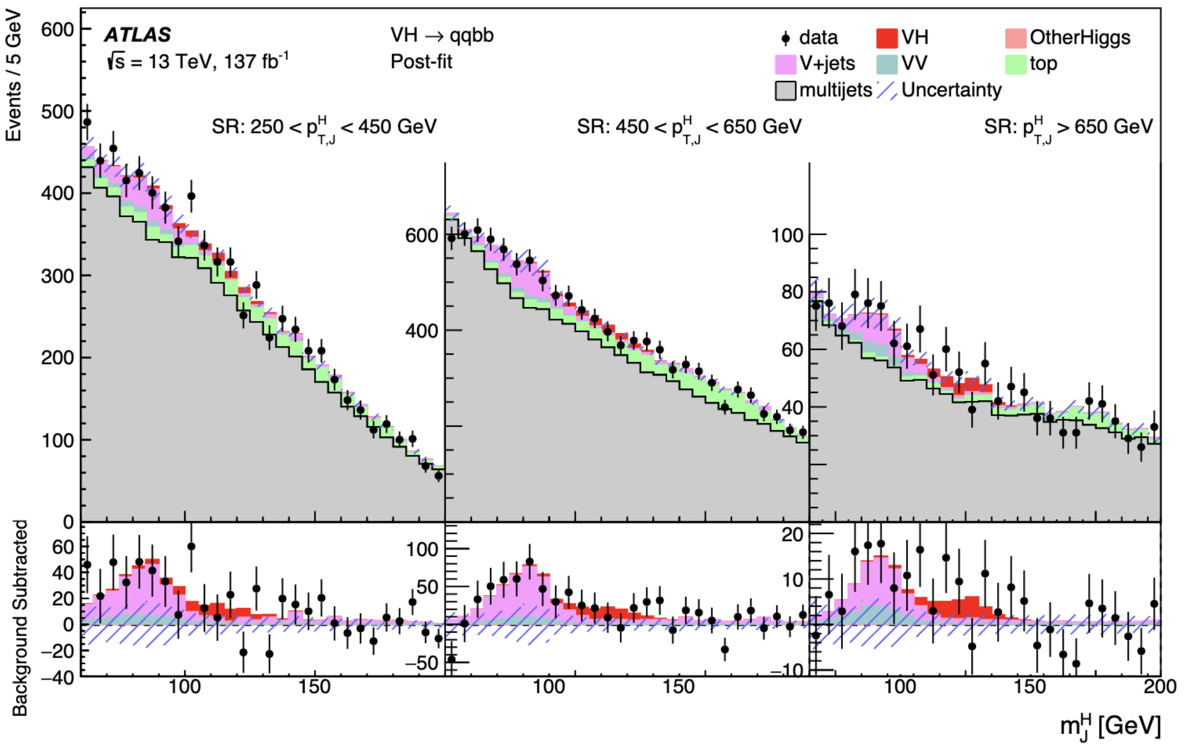


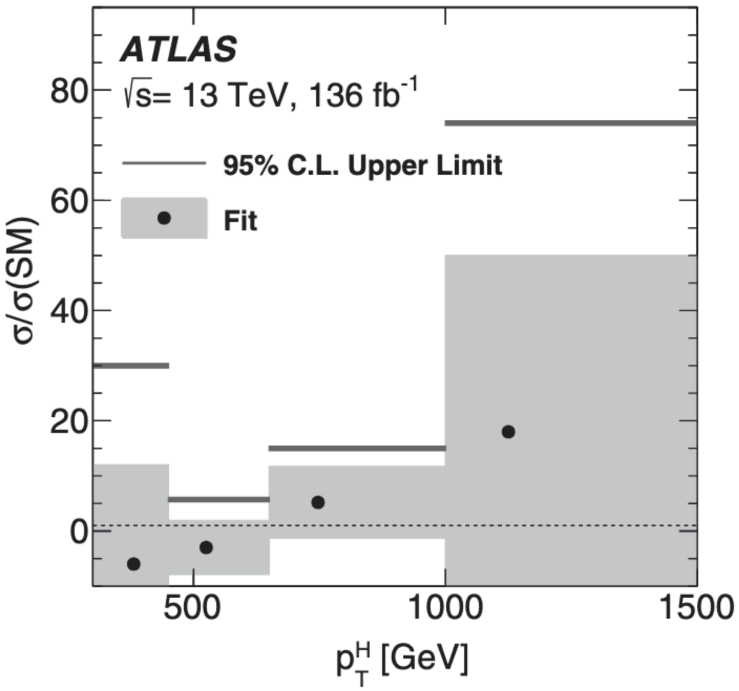


- Best fit differs from SM by 2.6σ, from (0,0) by 3.9σ
- Float 8 POI: μ_{VBF} in 2 mjj bins + μ_{ggF} in 6 p_T bins
- Differential cross section measured in the STXS framework in three Higgs p_T bins and two m_{jj} bins

Boosted (V→qq)H→bb

Phys. Rev. Lett. 132 (2024) 131802





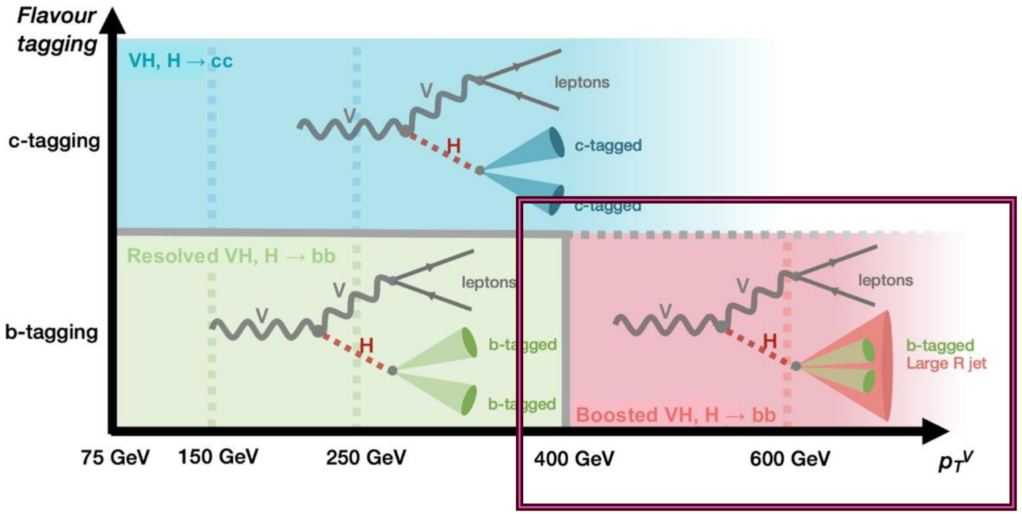
Kinematic region	Observed μ	Observed σ [fb]	Expected σ [fb]
$250 \le p_T^H < 450$ GeV, $\lvert y_H \rvert < 2$	$0.8^{+2.2}_{-1.9}$	47^{+125}_{-109}	57.0
$450 \le p_T^H < 650$ GeV, $\lvert y_H \rvert < 2$	$0.4^{+1.7}_{-1.5}$	2^{+10}_{-9}	5.9
$p_T^H \ge 650$ GeV, $\lvert y_H \rvert < 2$	$5.3^{+11.3}_{-3.2}$	6^{+13}_{-4} (<43)	1.2

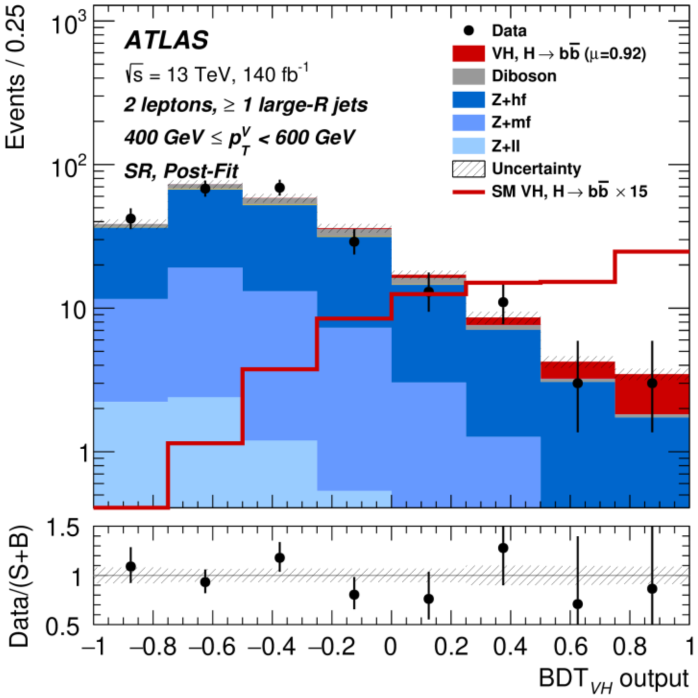
- The best-fit value of the signal-strength parameter is $\mu = 1.4^{+1.0}_{-0.9}$ for the inclusive fit
- Observed (expected) significance of 1.7 σ (1.2 σ) with respect to the null signal hypothesis

Boosted (V→ff)H→bb

https://arxiv.org/pdf/2410.19611

- ❑Events are split into categories based on lepton multiplicity and p_T of the bosons
- ❑Events are triggered either by the single electron, single muon or MET triggers
- ❑Several BDTs are designed to separate VH signal from VZ and other backgrounds





Boosted (V→ff)H→bb

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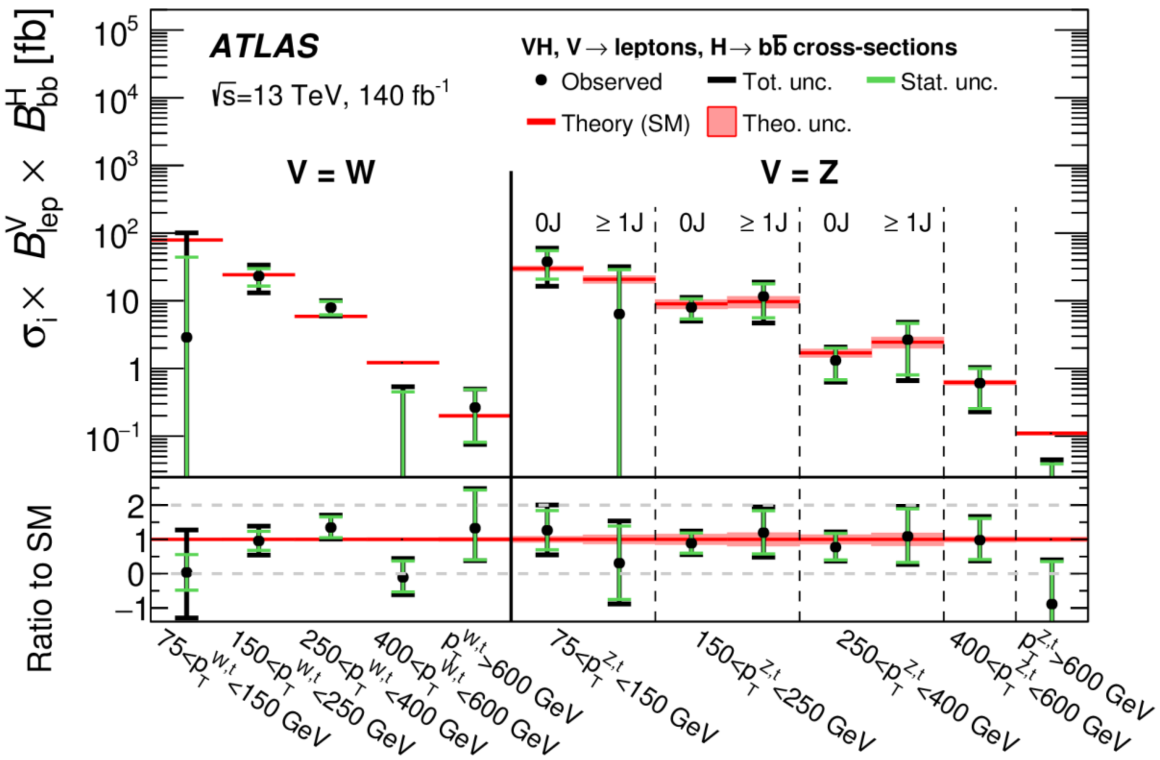
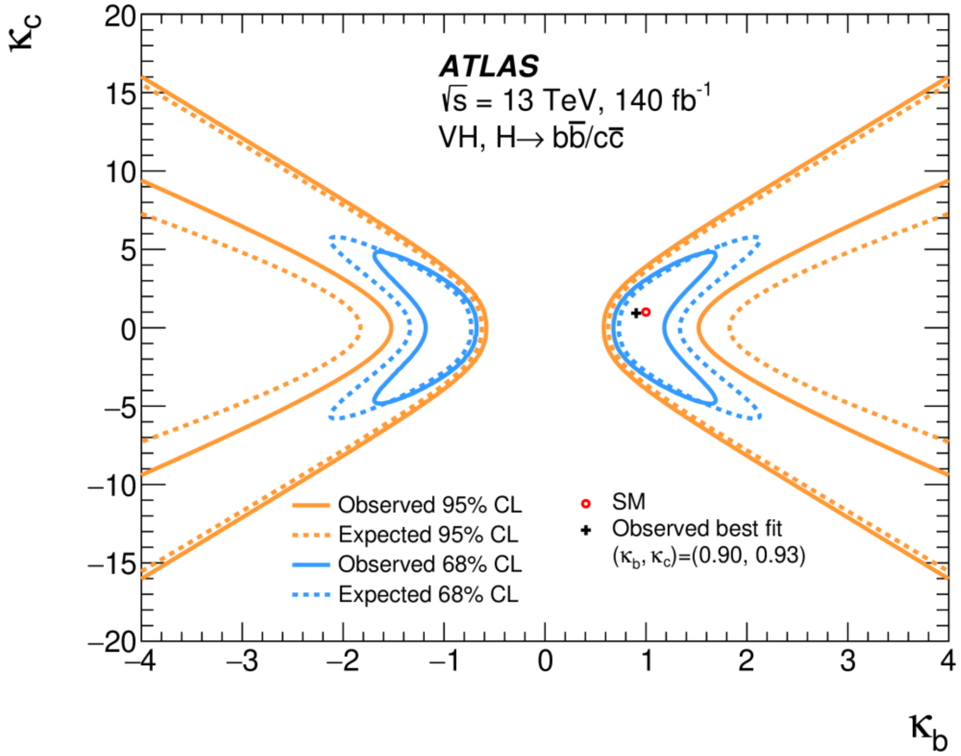


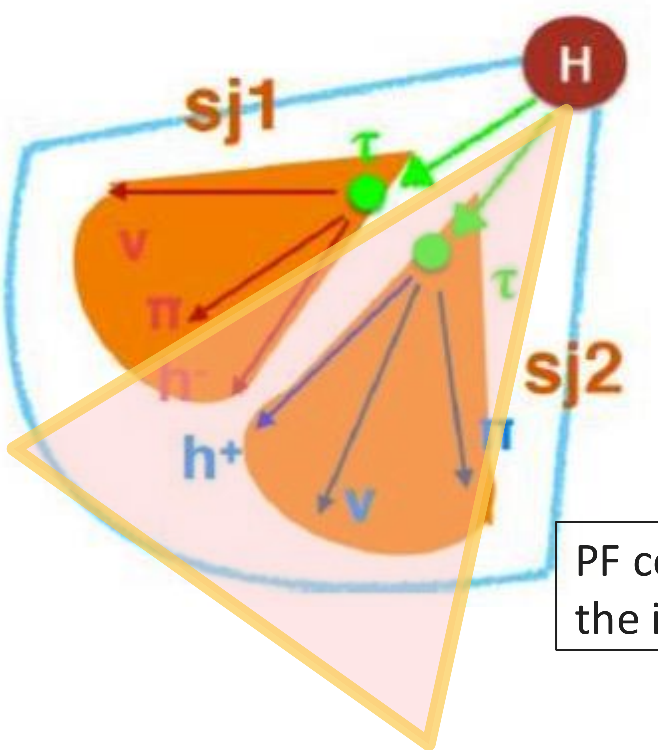


- The measured VH cross-sections times the V→ fermions and H→bb̄ branching fractions in the extended STXS scheme.
- Overall compatibility with the SM predictions is 90%

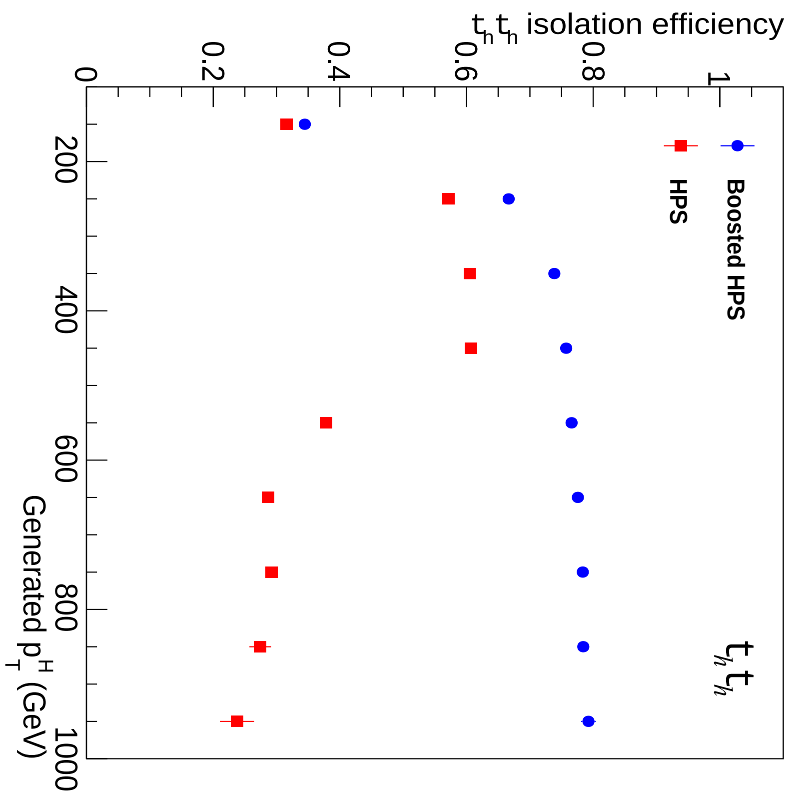
- constraints on κ_b and κ_c at 68% CL and 95% CL confidence levels

Boosted H→ ττ

10.1016/j.physletb.2024.138964



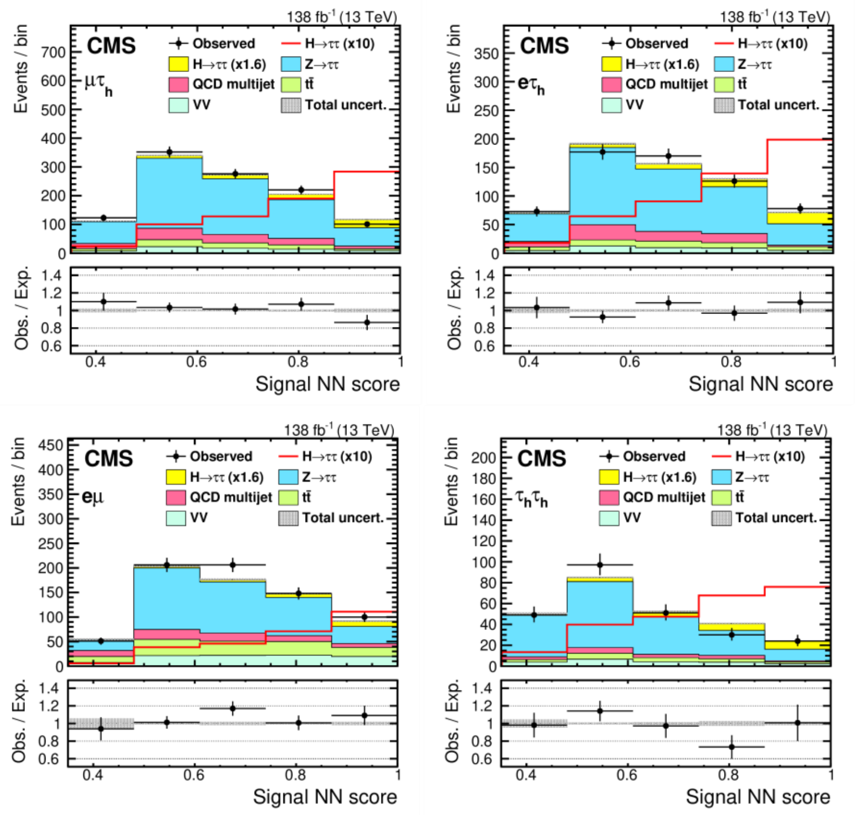
PF constituent of one tau spoils the isolation of the next tau !!

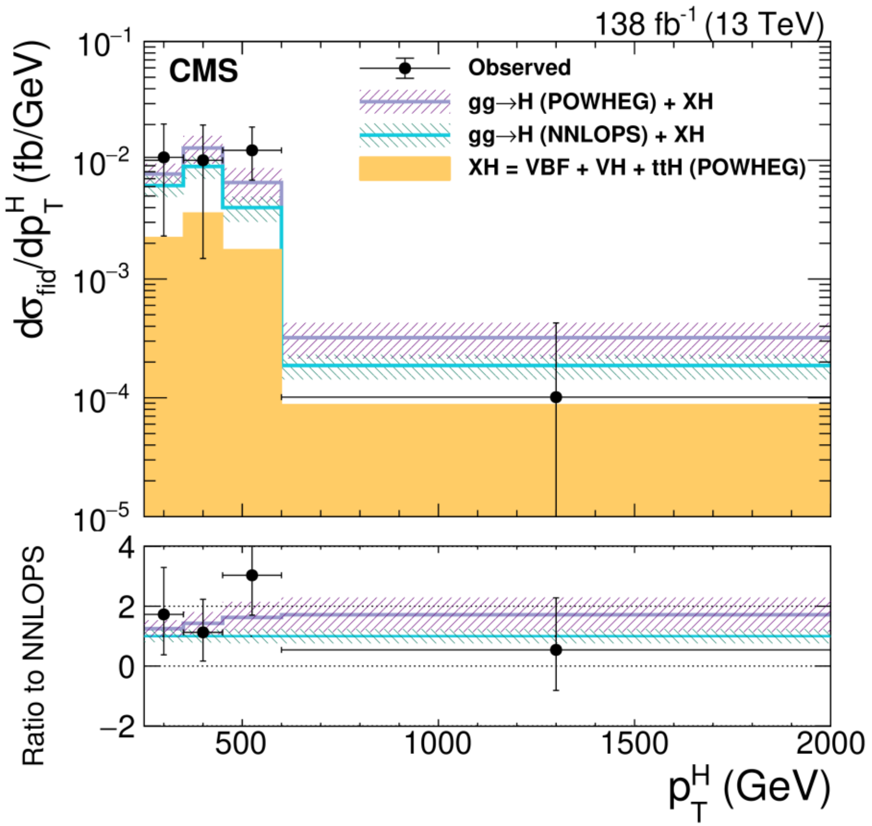


- ❑ Two tau leptons are required to be spatially close: $\Delta R < 0.8$.
- ❑ A dedicated algorithm is developed to reconstruct tau lepton in boosted topologies. Relies on Jet substructure technique
- ❑ The analysis is mostly sensitive in the tail of the Higgs/leading jet p_T distributions
  - ❑ Sensitive to the coupling to BSM!

Boosted $H \rightarrow \tau\tau$

10.1016/j.physletb.2024.138964



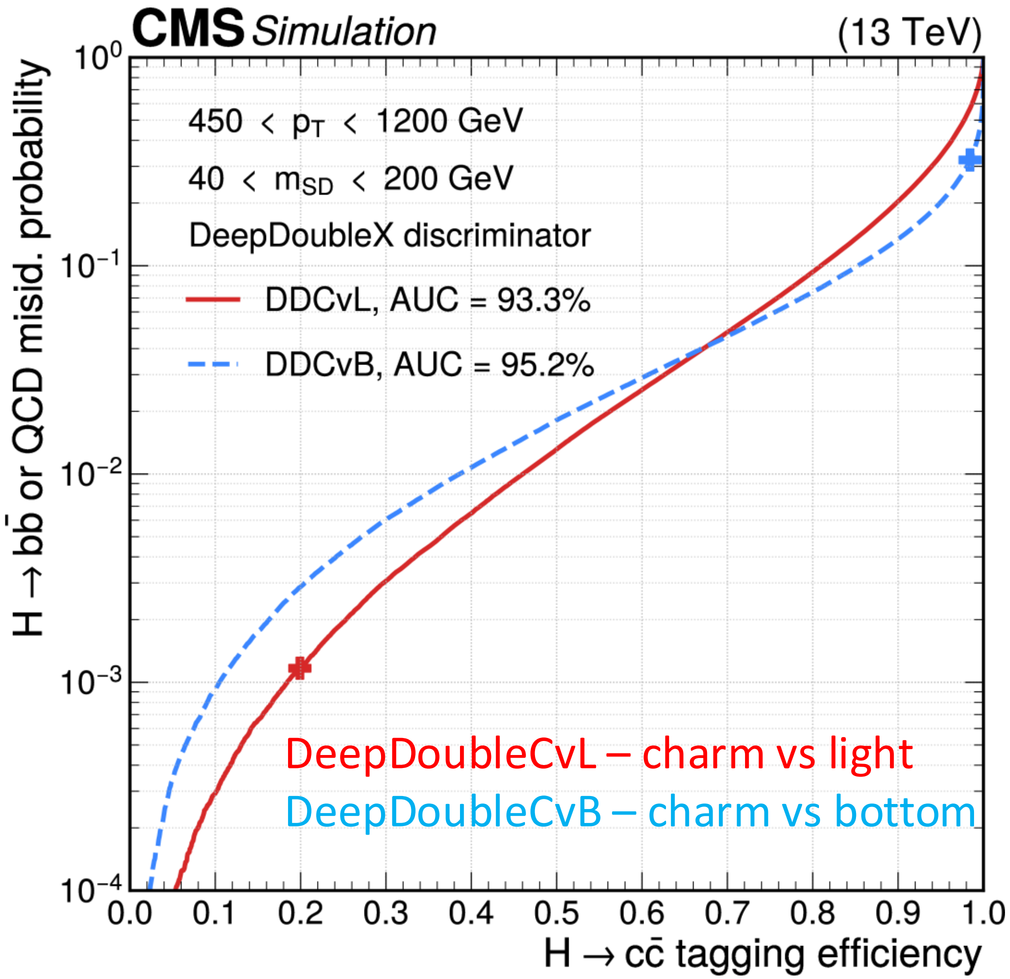


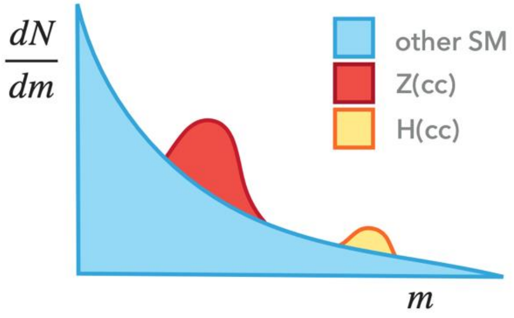
- ❑ A multiclass NN method is deployed to separate signal from major backgrounds in each final state
- ❑ The observed (expected) significance of the measured signal with respect to the standard model background-only hypothesis is 3.5 (2.2) standard deviations
- ❑ Fiducial differential production XS is measured as functions of the Higgs boson and leading jet transverse momenta

Boosted H→cc

[Phys. Rev. Lett. 131 (2023) 041801]

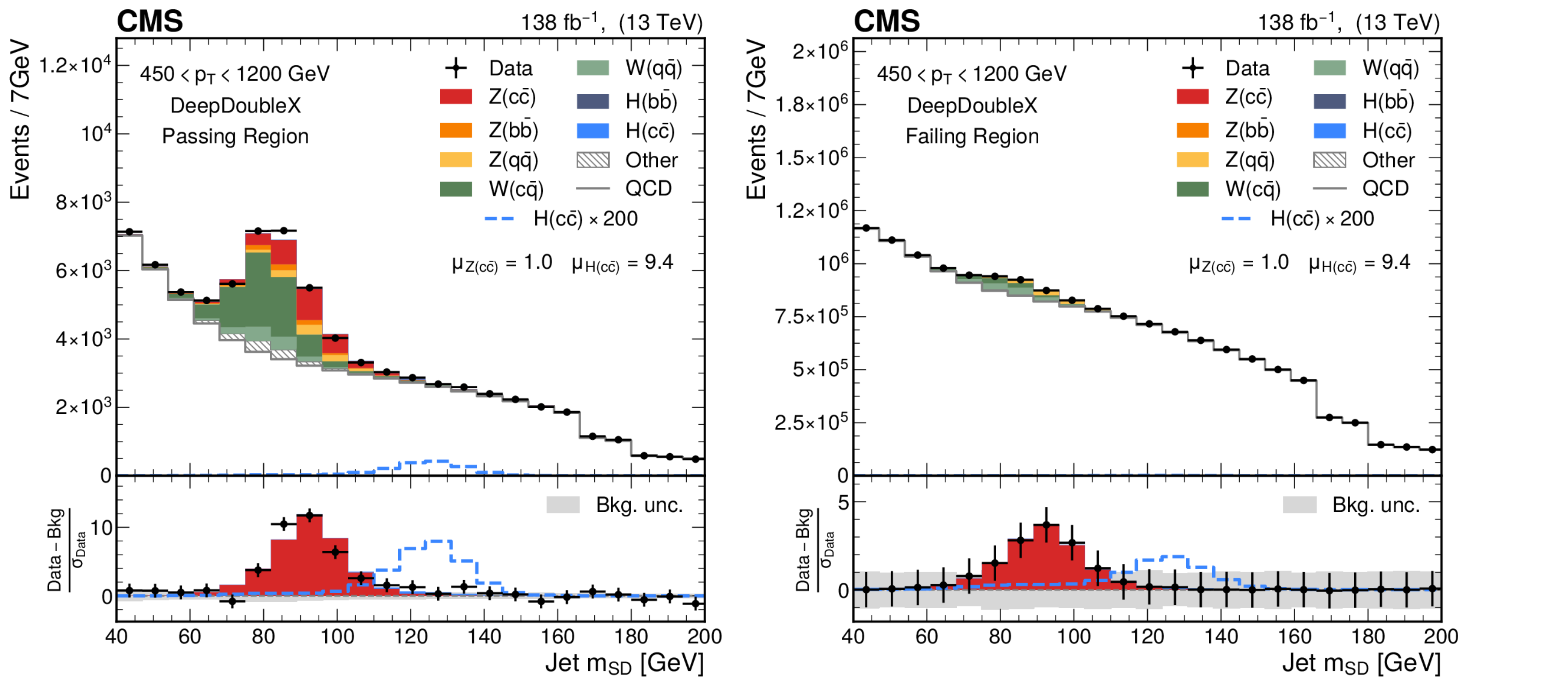
- ❑Smaller cross section compared to H→bb but with almost same background!
- ❑Event selection closely follows the H→bb event selection: i.e. trigger, lepton veto, jet selection, $\rho = 2\ln(m_{SD}/p_T)$, etc
- ❑Two Deep Double X discriminators have been developed to separate c-jets from light-jets and b-jets
- ❑Optimal working points:
  - ❑ DeepDoubleCvL: 20% c-tagging efficiency v.s. 0.5% light jet
  - ❑ DeepDoubleCvB: 98% c-tagging efficiency v.s. 30% b jet
- ❑Jet mass is used for statistical interpretations





Boosted H→cc

[Phys. Rev. Lett. 131 (2023) 041801](https://doi.org/10.1103/PhysRevLett.131.041801)

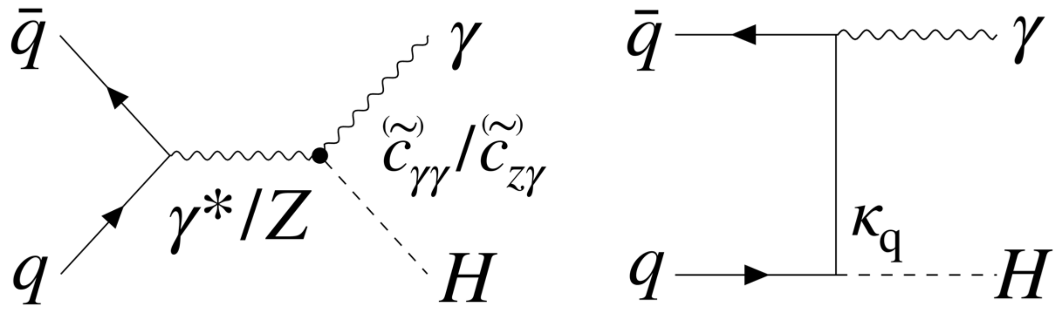


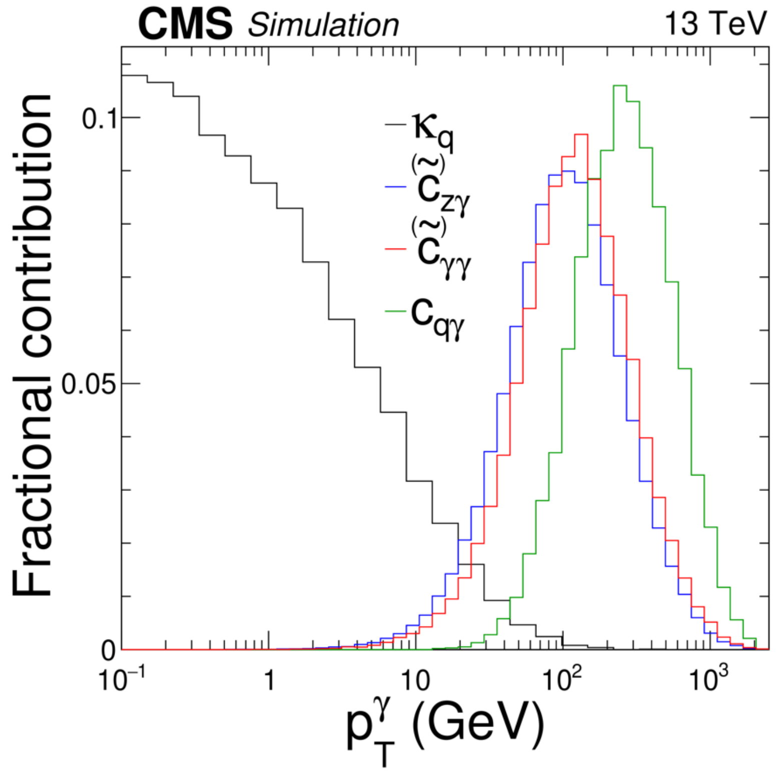
- Passing region where the all cuts are applied; Failing region is where all cuts applied except DDCvL
- SR and CR are subdivided into 23 evenly spaced bins of jet m_{SD} in the range 40–201 GeV and 6 p_T bins from 450 to 1200 GeV
- μ value for Z→cc : $1.00^{+0.17}_{-0.14}$ (syst) ± 0.08 (theo) ± 0.06 (stat), corresponding to significance of well over 5σ
- The observed (expected) upper limit on σ(H)B(H→cc) is set at 47 (39) times the SM prediction at 95% CL
- μ value for H→cc (9.4 +- 19.4)

Boosted γH

https://arxiv.org/abs/2502.05665

- First time γH been studied at the LHC; Does not happen at tree-level in SM
  - Small cross-section (< 5 fb)
  - Signal indicates BSM physics
- Various EFT operators can be present in this vertex
  - 4 in mass eigenstate basis (heavy particle in the loop)
    - CP-Even: $c_{z\gamma}$, $c_{\gamma\gamma}$
    - CP-odd $\tilde{c}_{z\gamma}$, $\tilde{c}_{\gamma\gamma}$
  - 6 in in weak eigenstate basis:
    - CP-Even: c_{HW}, c_{HWB}, c_{HB}
    - CP-Odd: $\tilde{c}_{HW}$, $\tilde{c}_{HWB}$, $\tilde{c}_{HB}$

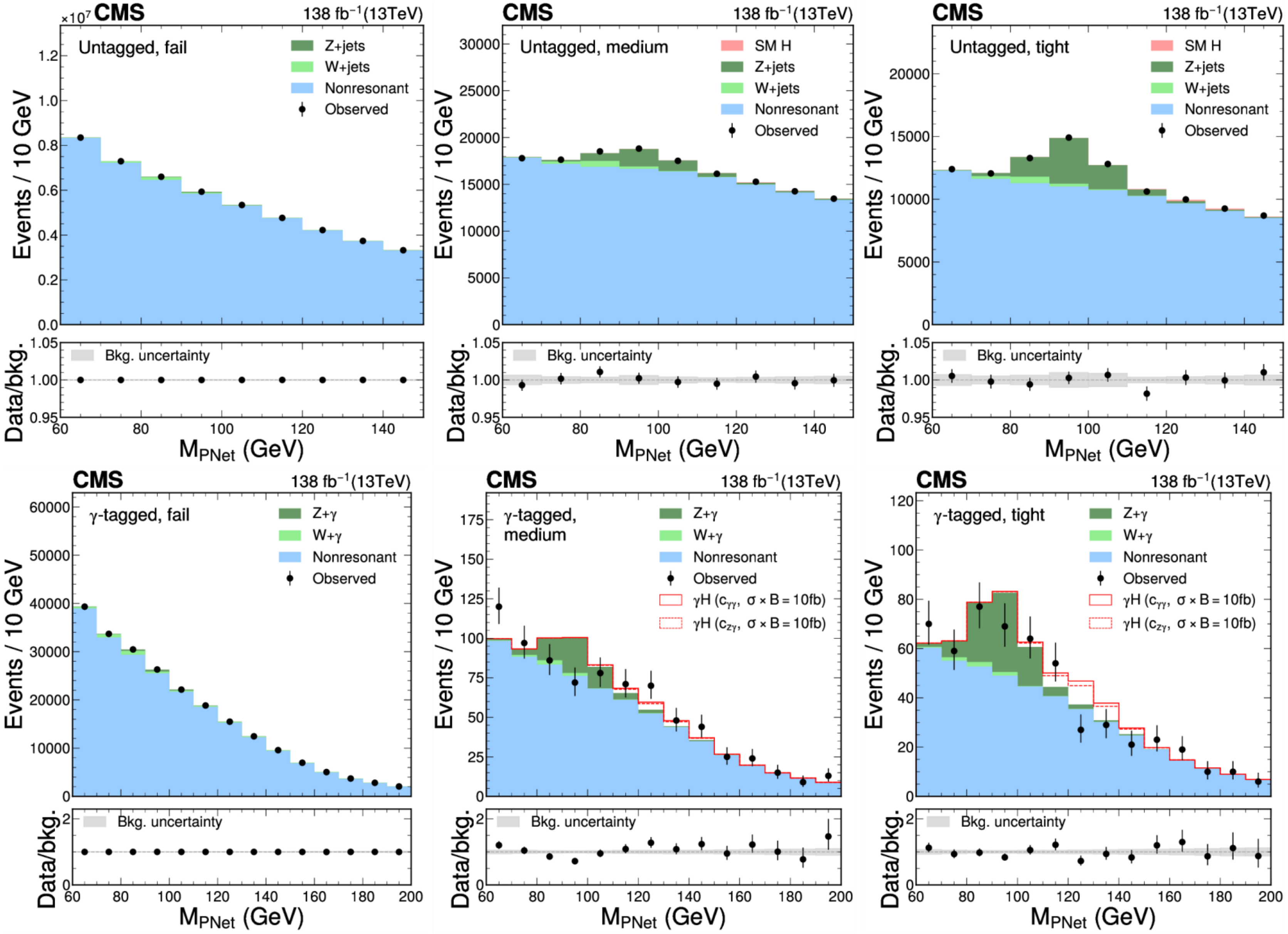




Boosted $\gamma H \rightarrow bb$

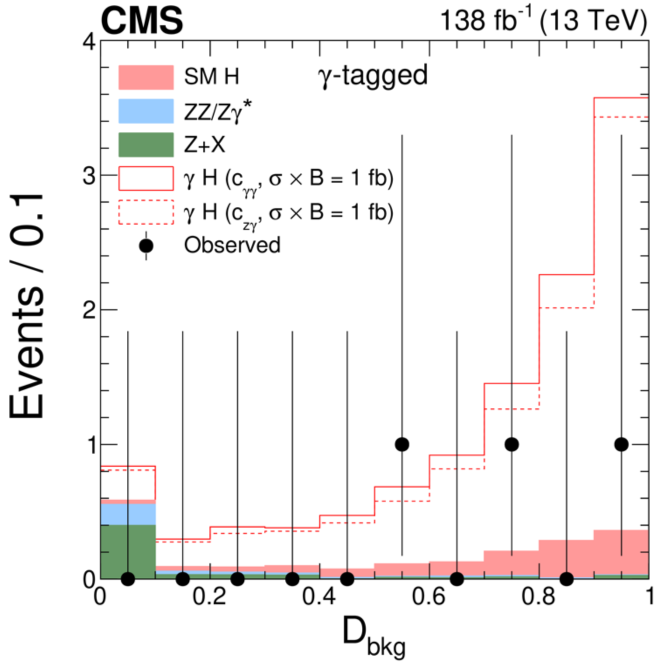
https://arxiv.org/abs/2502.05665

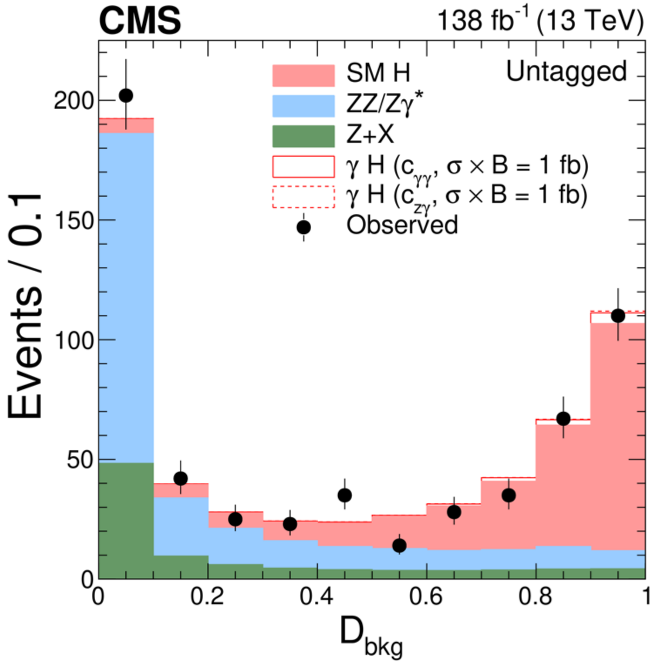
- Select photon + AK8 jet events with high pT
- 300 GeV AK8 & 300 GeV Photon w/ tight Id
- Fit the distribution of AK8 jet mass, using ParticleNet mass regression (M_{PNET})
- Searching for a Higgs mass bump
- Three regions based on the ParticleNet score (separate $X \rightarrow bb$ from QCD)
- Fit Untagged and γ-tagged regions simultaneously

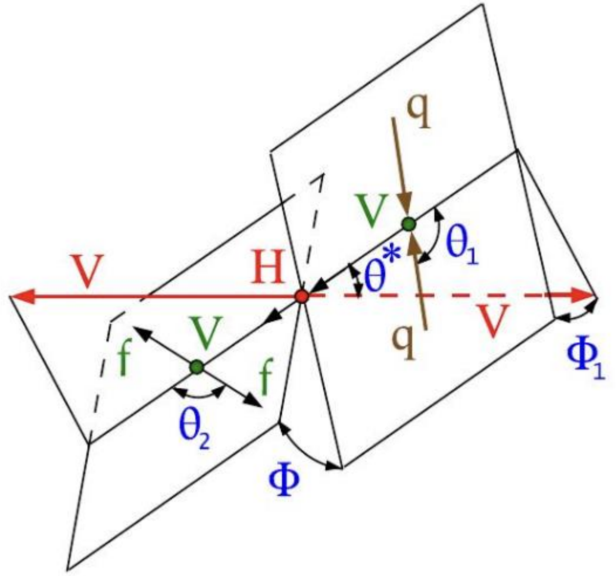


Boosted γH→ZZ

https://arxiv.org/abs/2502.05665





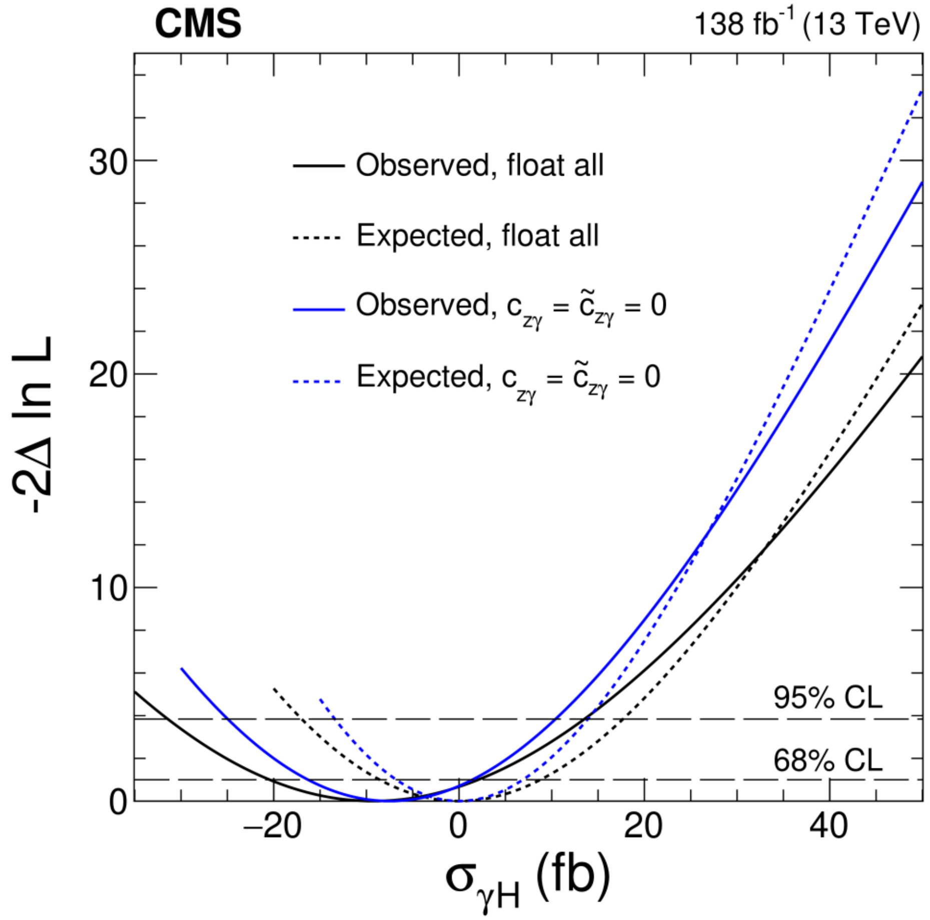


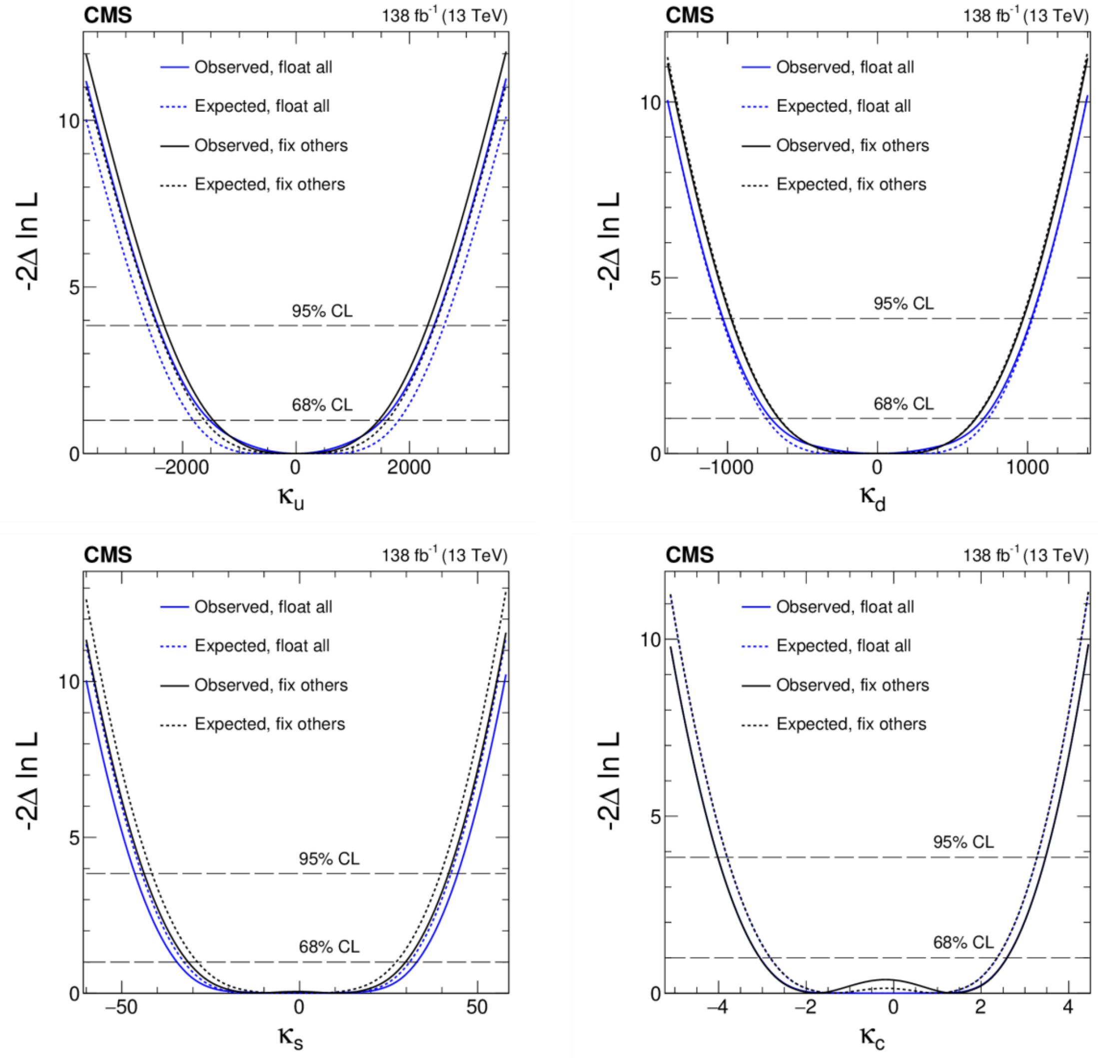
$$\mathcal{D}_{\text{bkg}}(\Omega) = \frac{\mathcal{P}_{\text{sig}}(\Omega)}{\mathcal{P}_{\text{sig}}(\Omega) + \mathcal{P}_{\text{bkg}}(\Omega)}$$

- Matrix Elements used to construct optimal observables
  - D_{bkg}: Matrix element based discriminator for separating H → 4l from background
  - Combines m_{4l} information along with decay kinematics
- Introducing two γH tag (p_T > 150 GeV and loose Id) and Untagged categories (to constrain systematics)

https://arxiv.org/abs/2502.05665

Boosted γH→ZZ/bb





- ❑ Constraints on $\sigma_{\gamma H}$ from the combination of the H → bb (dominant) and 4l channels
- ❑ Limits on γH production could be used to constrain the Yukawa couplings of light quarks (using HZZ channel)

Summary

- Extensive amount of work by both CMS and ATLAS experiments to explore Higgs boson in boosted topology in all production modes.
- Most results are still statistically limited. Run 3 and HL-LHC data will shed light on wehther some new physics are accessible thorugh Boosted Higgs boson or not.
- Techniques developed to tag Higgs boson in high transverse momentum can be used to to look for other new physics seraches. So more new results to come up with Boosted Higgs boson!

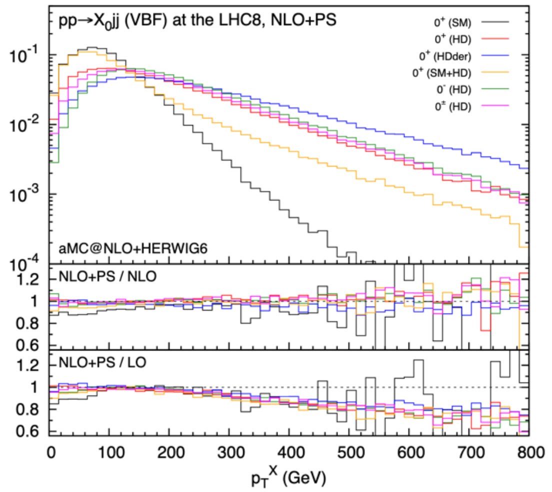
Boosted	$H \to bb$	$H \to cc$	$H \to \tau\tau$	$H \to ZZ$
ggH	✓	✓	✓	
VBF H	✓	✓		
$V(\to qq)H$	✓			
$V(\to ff)H$	✓			
γH	✓			✓

Back up

Challenges and Opportunities

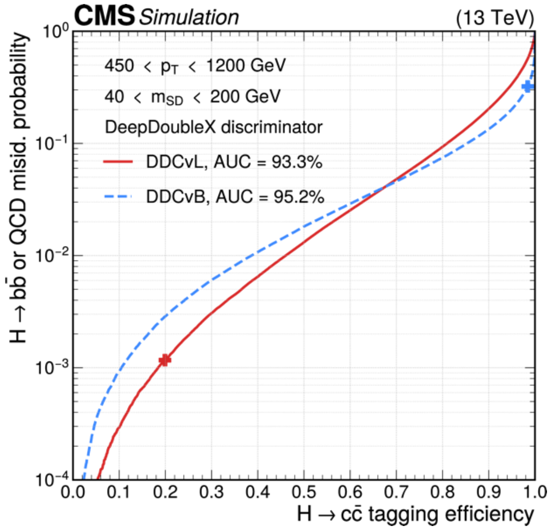
Challenges

- Have to pay the price of smaller cross section for Higgs bosons in high p_Ts
- Traditional jet and lepton reconstrcution alogorithms are no longer efficienct
  - High granularity tracking, jet substructure analysis, and advanced machine learning techniques are essential for reconstructing boosted Higgs.



Opportunities

- Pioneering boosted Higgs searches through innovative jet-tagging techniques, optimized event selection strategies, and future HL-LHC upgrades.
- Using boosted Higgs in HH searches and search for new physics such as massive resonances decaying to pair of (Higgs) bosons



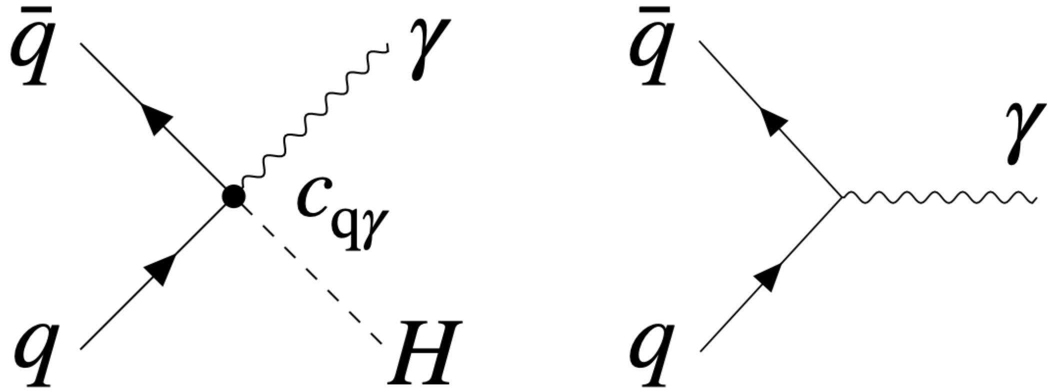


Figure 3: Feynman diagrams describing the $q\bar{q}$ annihilation with production of γH through a point-like EFT operator (left) and with photon production (right).

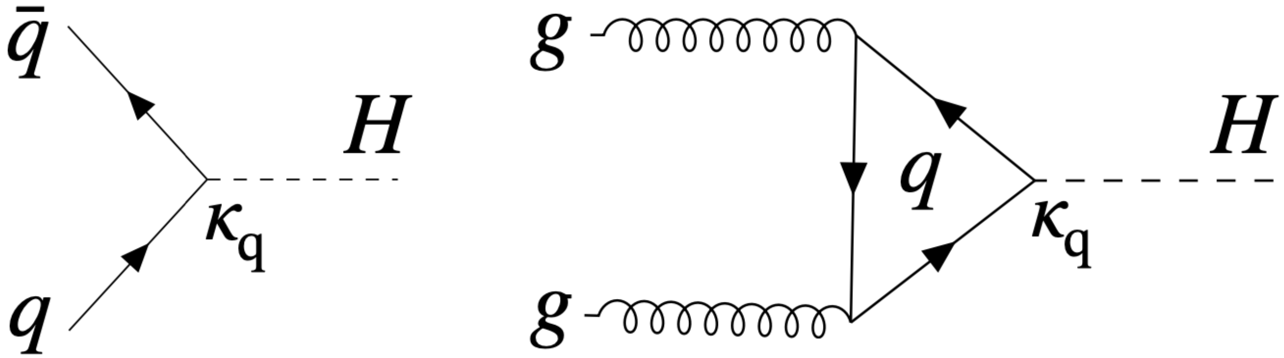


Figure 4: Feynman diagrams describing the H boson production at LHC through direct $q\bar{q}$ annihilation (left) and gluon fusion production (right).