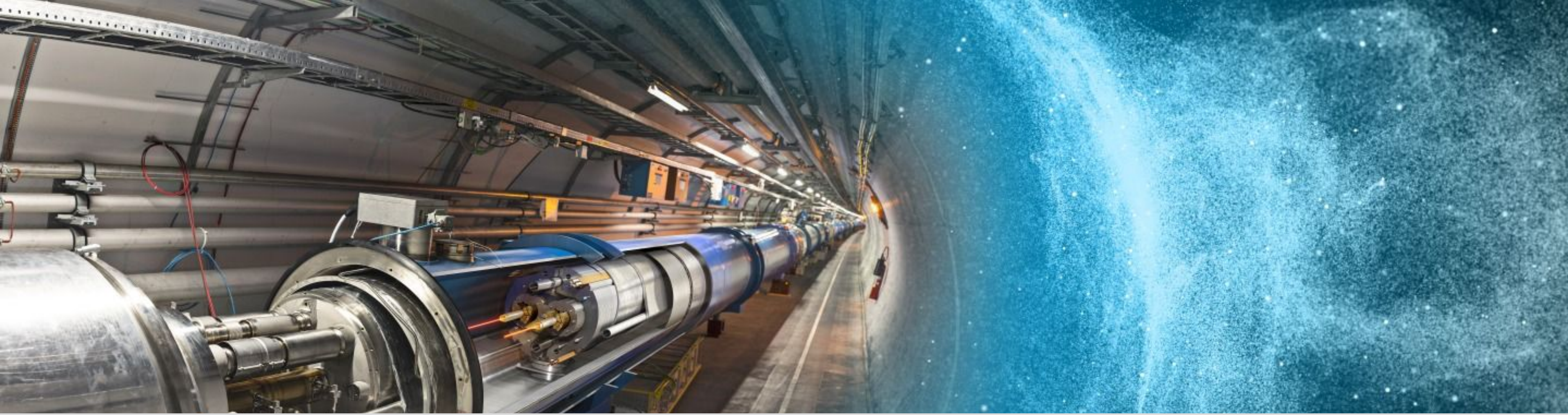


Searches for non-resonant Higgs boson pair production with the CMS experiment at the LHC

Marina Kolosova (University of Florida)

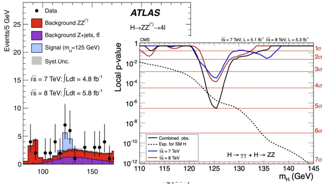
ICTEA 2026

What have we achieved so far?

2010

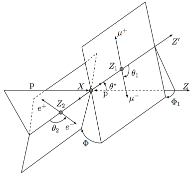
First Higgs boson searches begin

2012



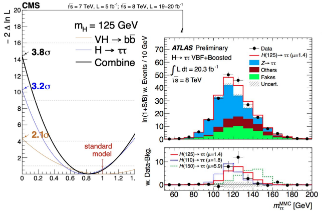
Discovery of the Higgs boson

2013



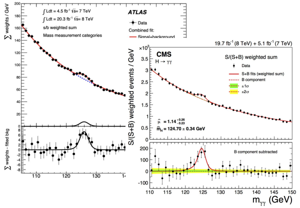
$J^P = 0^+$

2014



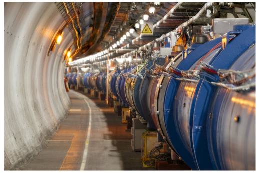
Evidence of Higgs boson decay to fermions

2014



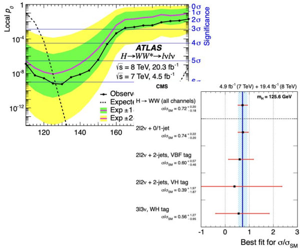
Higgs boson mass measurement

2015



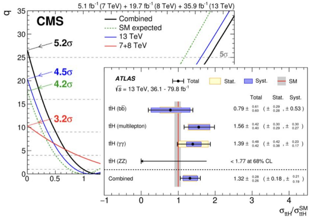
LHC @ 13 TeV, H production rates increase, start of precision measurements era

2015



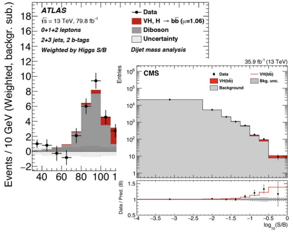
Evidence of $H \to WW^*$

2018



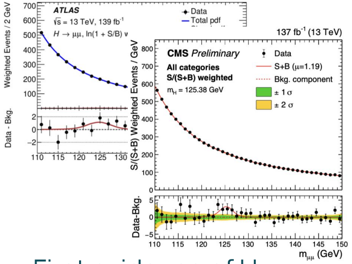
Observation of ttH

2018



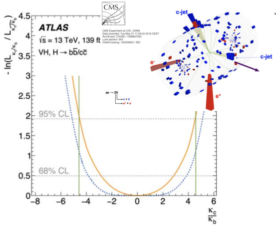
Observation of $H \to bb$

2020



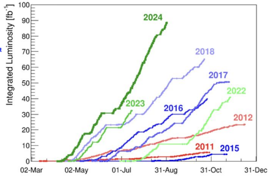
First evidence of $H \to \mu\mu$

2022



First search for $H \to cc$

2022-2026

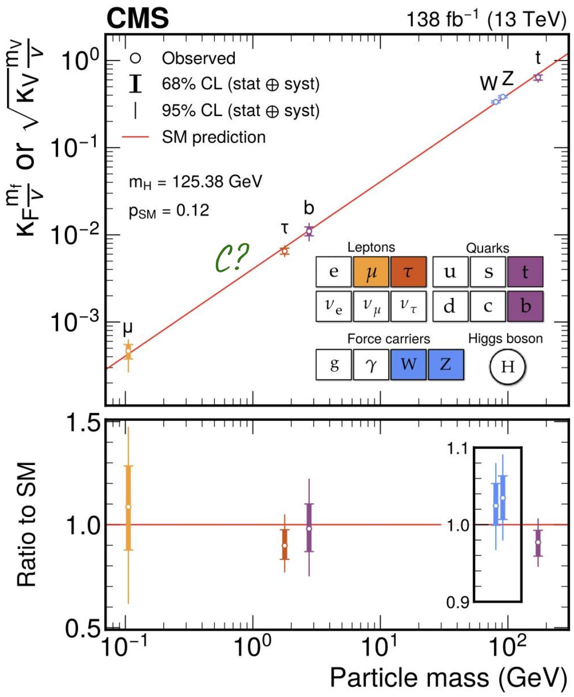


LHC @ 13.6 TeV

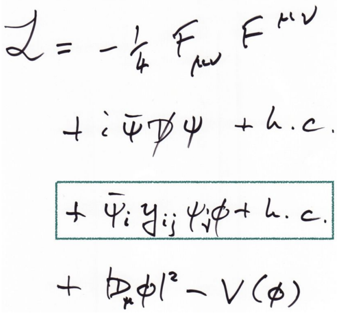
A non-exhaustive list of results representing an **impressive tour de force by the ATLAS and CMS Collaborations**

All measurements are consistent, within uncertainties, with the predictions of the Standard Model

What are we missing?

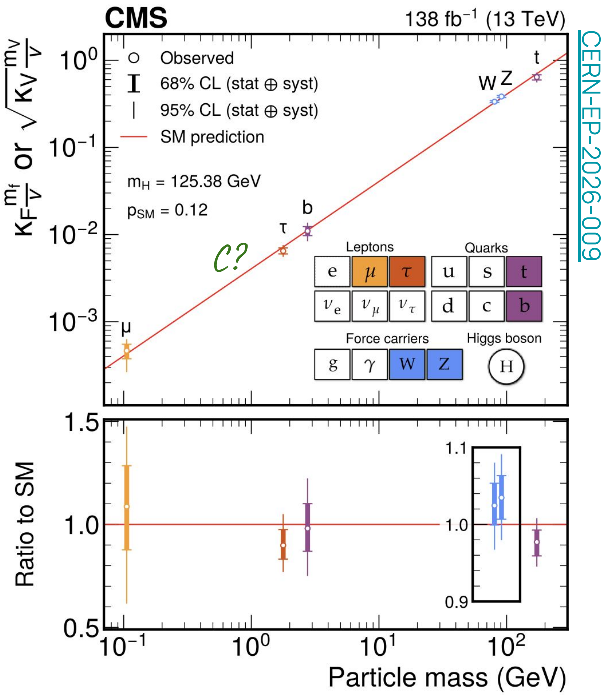


CERN-EP-2026-009



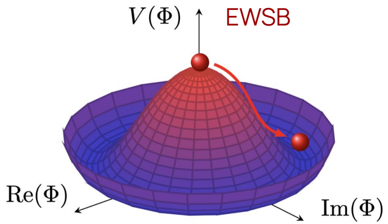
- H decays to vector bosons well established except Zγ
- H decays to 1st & 2nd generation fermions remain weakly constrained

What are we missing?



- H decays to vector bosons well established except Zγ
- H decays to 1st & 2nd generation fermions remain weakly constrained

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Why **double Higgs (HH) production**? *test how the Higgs boson interacts with itself*

Higgs potential after electroweak symmetry breaking (EWSB): $V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$

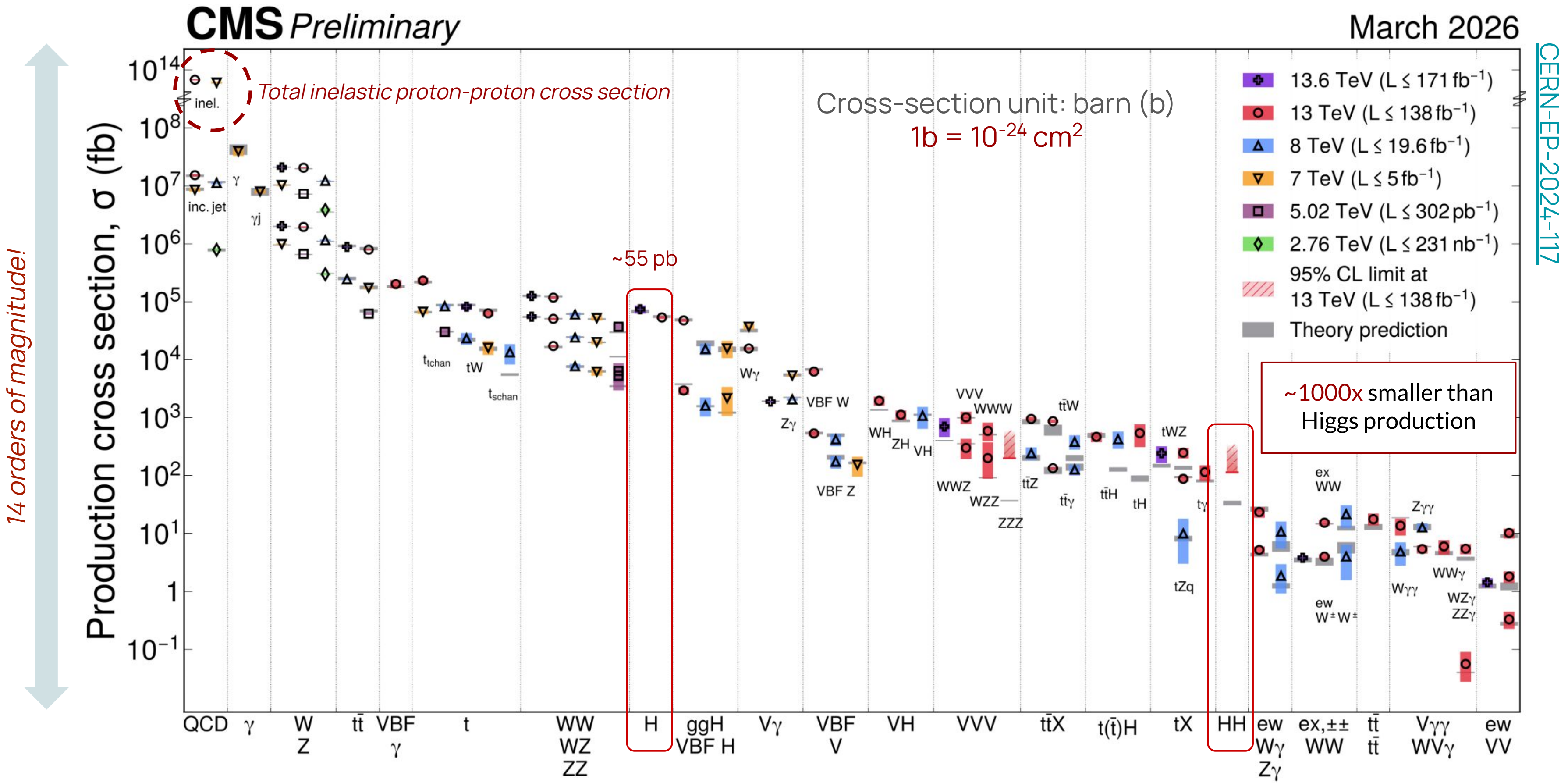
Expanding about minimum: $V(\phi) \to V(v+h)$

$$V = V_0 + \underbrace{\frac{1}{2}m_h^2 h^2}_{\text{mass term}} + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

$$\lambda_{hhh}^{SM} = \frac{m_h^2}{2v^2}$$

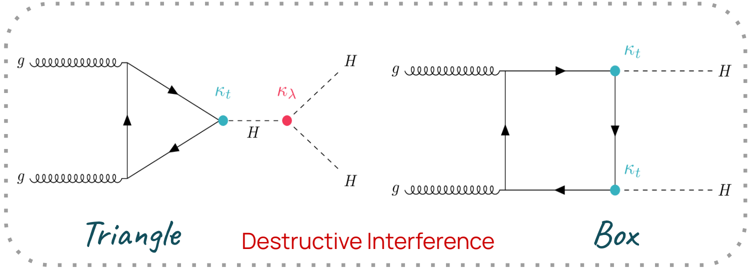
λ_{hhh} shapes the Higgs potential & governs the dynamics of electroweak symmetry breaking

What are we missing?

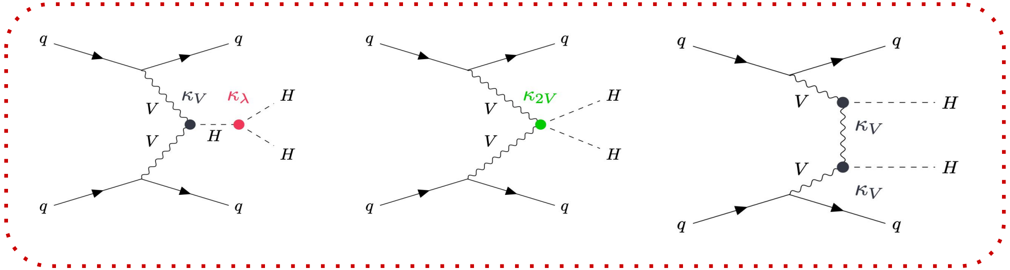


HH production at the LHC

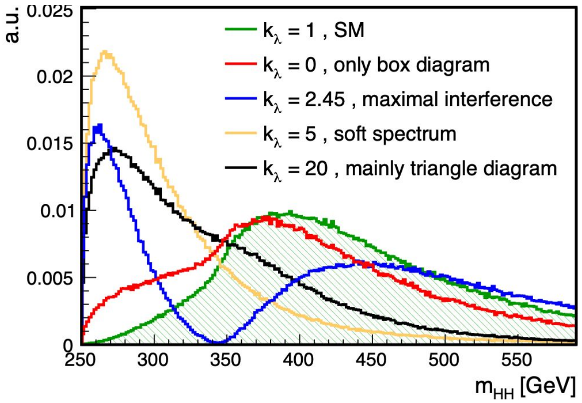
HH searches provide the only direct way to probe the shape of the Higgs potential, and in particular the trilinear coupling λ_{HHH}



$\sigma_{ggF\ HH}$ = 30.77 fb @ 13 TeV (34.1 fb @ 13.6 TeV)



$\sigma_{VBF\ HH}$ = 1.687 fb @ 13 TeV (1.874 fb @ 13.6 TeV)
Direct handle to VVHH and VVH coupling modifiers κ_{2V} and κ_V



Test accuracy & any deviation from the SM:

Kappa framework: $\kappa_\lambda = \lambda_{obs.} / \lambda_{SM}$

SM: κ_λ=1, κ_{2V}=1, κ_V=1

BSM modifications to κ_λ can lead to much *higher cross-sections*

HH production at the LHC

- Broad program of HH searches with most decay channels covered
- Channels with large branching ratios often accompanied by challenging signatures and substantial backgrounds
- Highest sensitivity channels: bbbb, bbττ, bbγγ

HH→bbbb

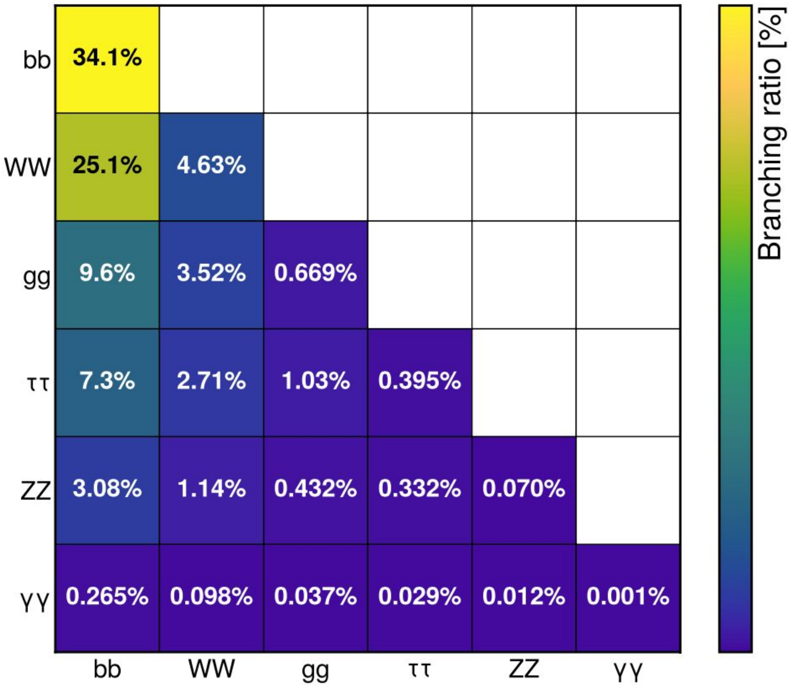
✓ Highest branching ratio
✗ Low purity due to large QCD multijet background

HH→bbττ

✓ Relatively large branching ratio
✓ Cleaner final state due to the presence of leptons

HH→bbγγ

✗ Tiny branching ratio
✓ Excellent $m_{\gamma\gamma}$ resolution $\sigma_{m_{\gamma\gamma}}/m_{\mathrm{H}} \approx 1\%$

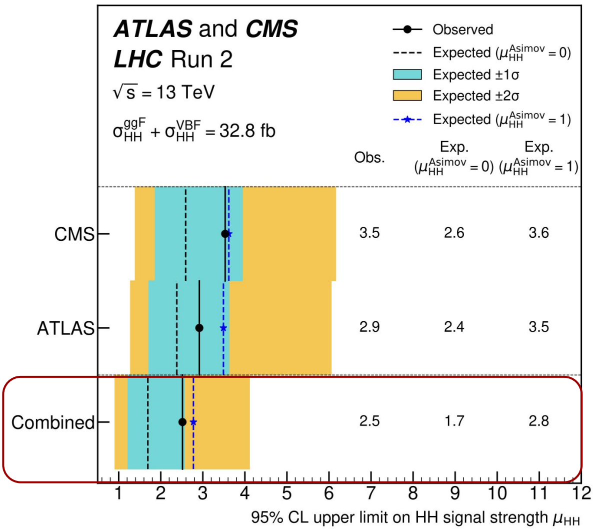


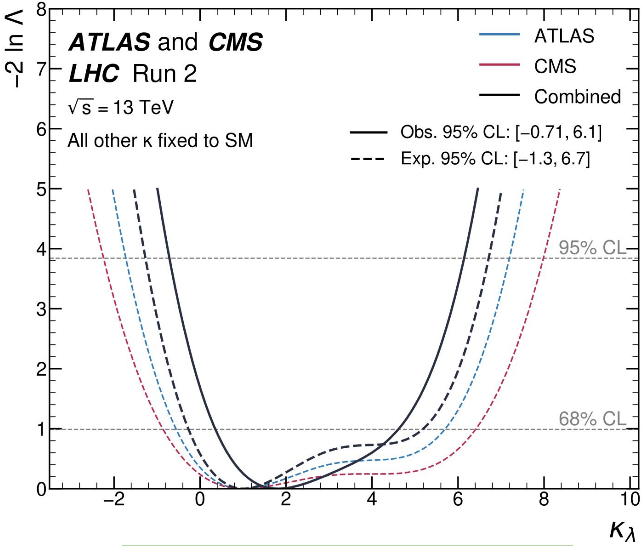
Statistical combination is key in this search!

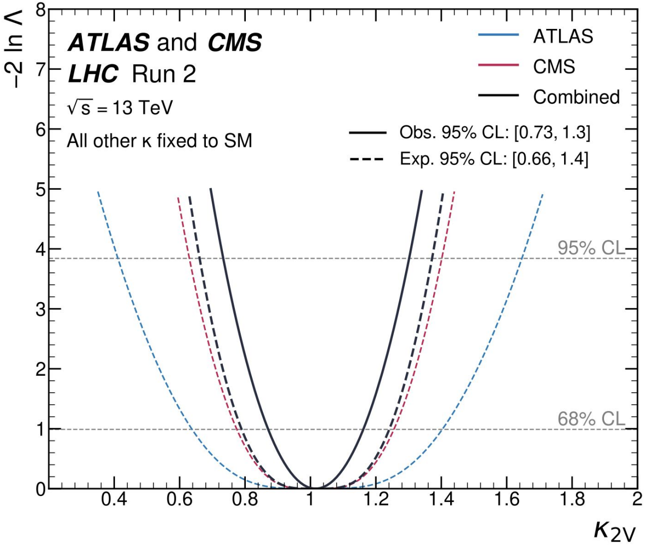
HH ATLAS & CMS Combination

Combination of HH searches performed by ATLAS & CMS Collaborations using Run 2 pp data (126-140 fb^{-1}) lead to an **observed** upper limit at 95% CL. on **$\mu_{HH}=\sigma_{HH}/\sigma_{SM}$ of 2.5**

- ATLAS: bbbb, bbγγ, bbττ, bbll+E_T^{miss}, mutilepton
- CMS: bbbb, bbγγ, bbττ, bbWW, multilepton
- Results compatible to SM predictions





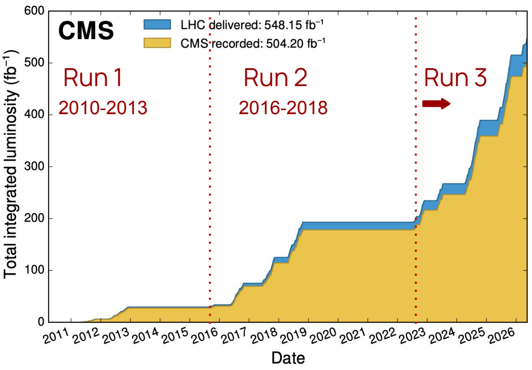


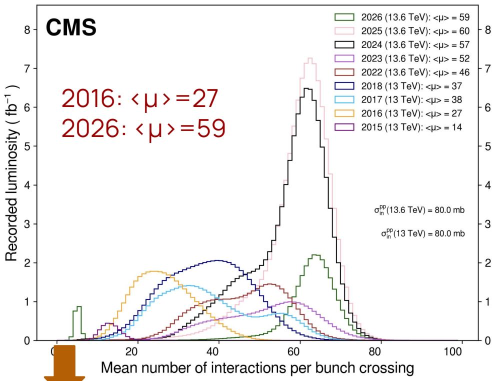
Observed: $-0.71 < \kappa_\lambda < 6.1$
Expected: $-1.3 < \kappa_\lambda < 6.7$

Observed: $0.73 < \kappa_{2V} < 1.3$
Expected: $0.66 < \kappa_{2V} < 1.4$

Dive into the experimental challenges of HH searches

500 fb^{-1} of LHC pp data recorded → 16K HH events produced





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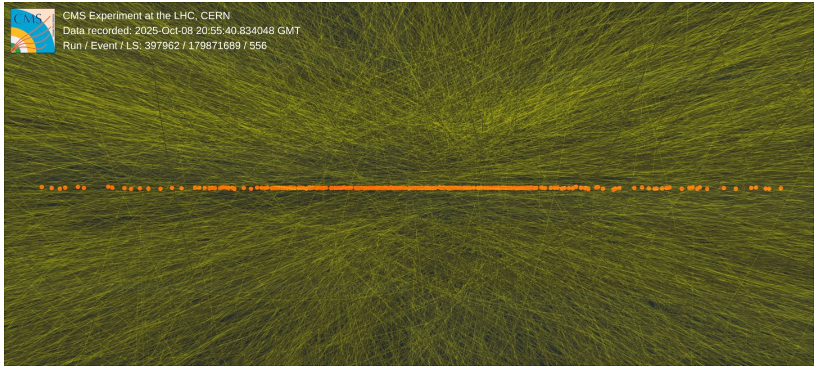


$$N_{\text{signal}} = \sigma_{HH} \times \mathcal{L}_{\text{int}}$$

- Run for longer time
- Increase instantaneous luminosity

Higher pileup ≡ more signal events **BUT**:

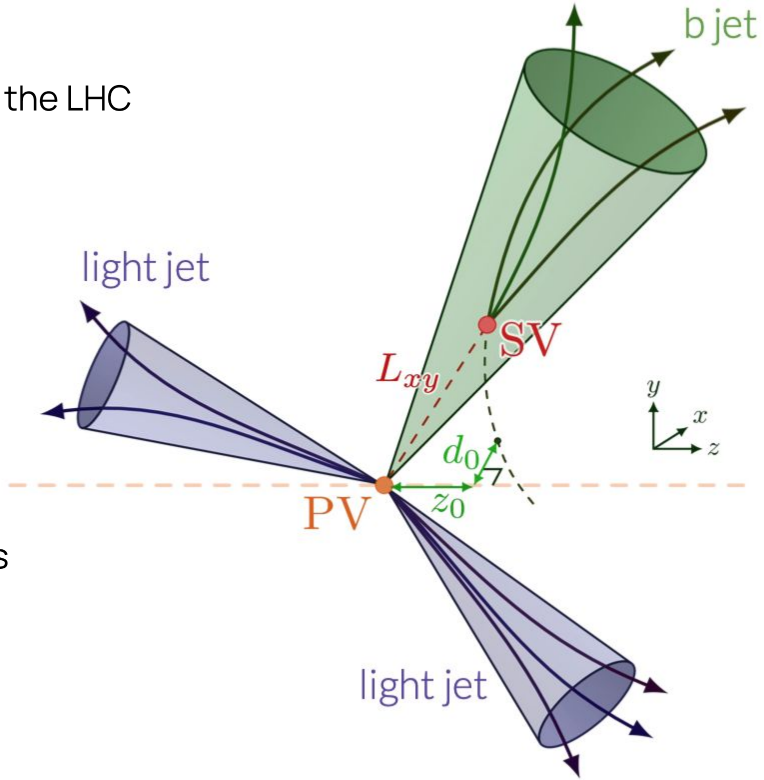
- Detector radiation damage
- Limitations on object reconstruction and identification
  jets, electrons, muons, hadronic taus, photons, missing transverse energy
- Limitations on heavy-flavor tagging performance
- Limitations on online selection (trigger)

Heavy flavor tagging for small-radius jets

Heavy flavor b/c-jet tagging **crucial** for Higgs and Di-Higgs physics at the LHC

Unique signature:

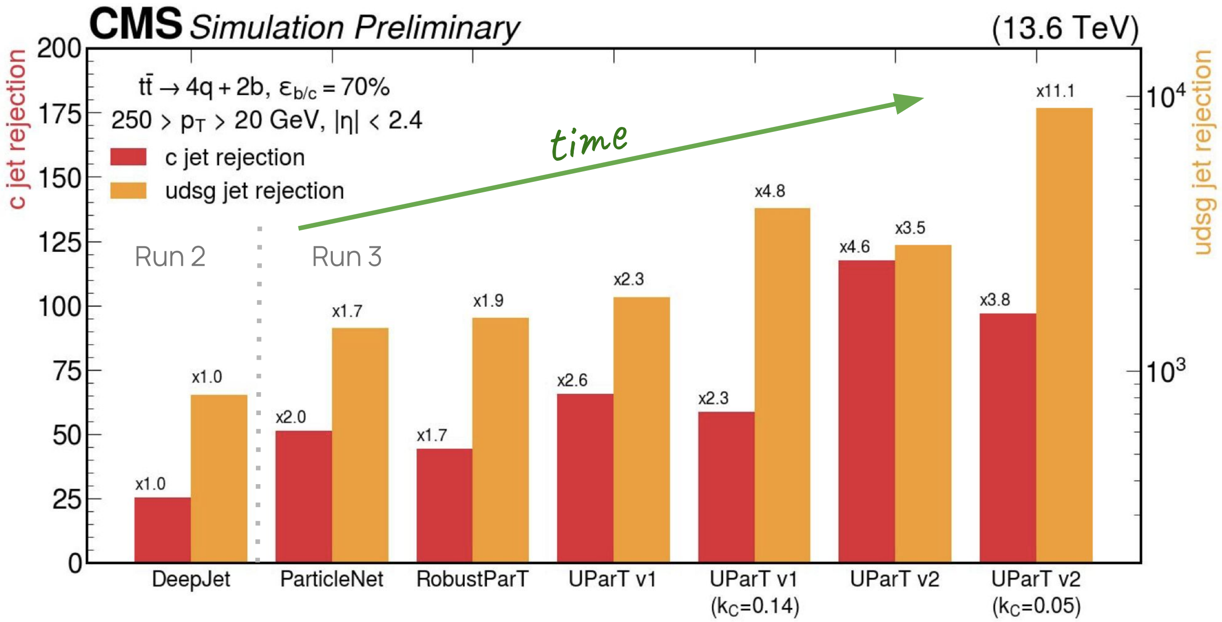
- Sizeable lifetime of b/c hadrons (few ps)
  - Displaced tracks (few mm) form a secondary vertex (SV)
- Harder fragmentation and larger mass compared to light-flavor quarks/gluons
- Presence of charged leptons in 20% (10%) of b (c) hadron decays



Heavy flavor tagging for small-radius jets

DP-2025-081

- A lot of pioneer developments on heavy-flavor tagging since Run 1
- Huge improvements since Run 1 due to advancements in machine learning (ML)



Heavy flavor tagging for small-radius jets

DP-2025-081

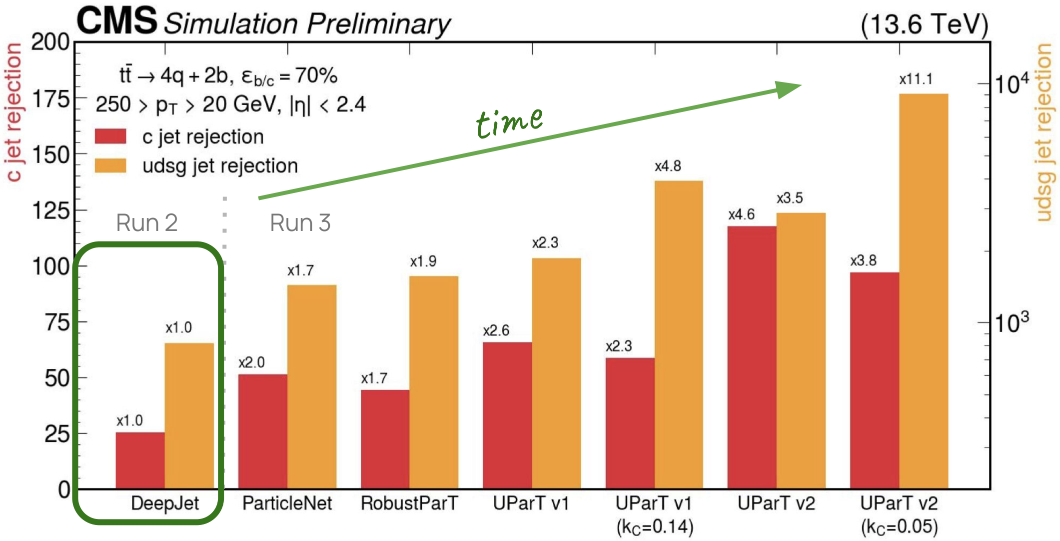
- A lot of pioneer developments on heavy-flavor tagging since Run 1
- Huge improvements since Run 1 due to advancements in machine learning (ML)

DeepJet

Based on **recurrent neural networks**

State-of-the-art in LHC Run 2

Utilizes information of up to 100 particles in each jet & jet related tracks and SVs



Heavy flavor tagging for small-radius jets

DP-2025-081
arxiv:1902.08570

- A lot of pioneer developments on heavy-flavor tagging since Run 1
- Huge improvements since Run 1 due to advancements in machine learning (ML)

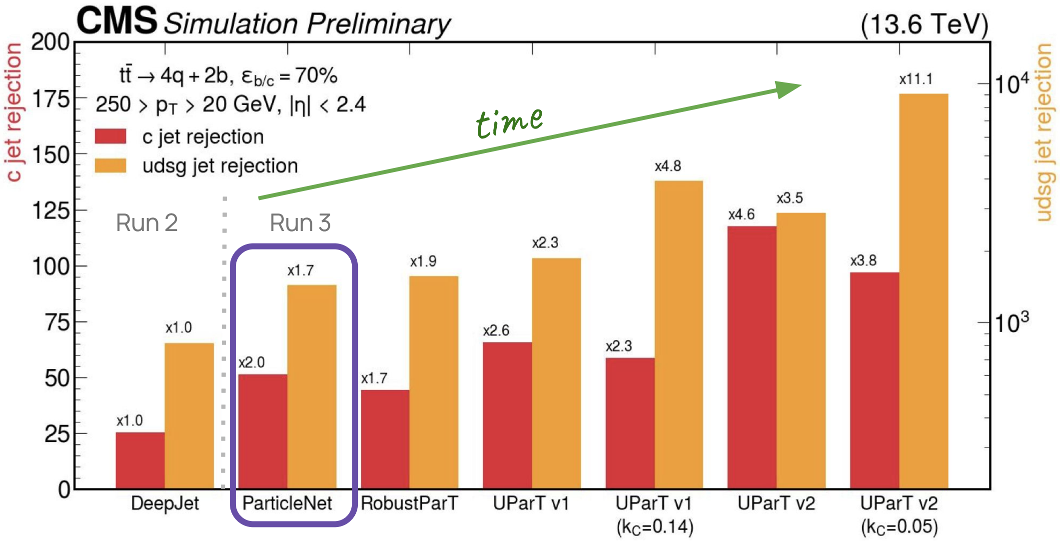
ParticleNet

First **graph-based** tagger at the LHC!

Jet represented as "*particle cloud*" (unordered set of constituents)

Performs first flavor-aware jet energy regression

State-of-the-art in early LHC Run 3



Partial Run 3 results presented here use ParticleNet

Heavy flavor tagging for small-radius jets

DP-2025-081

- A lot of pioneer developments on heavy-flavor tagging since Run 1
- Huge improvements since Run 1 due to advancements in machine learning (ML)

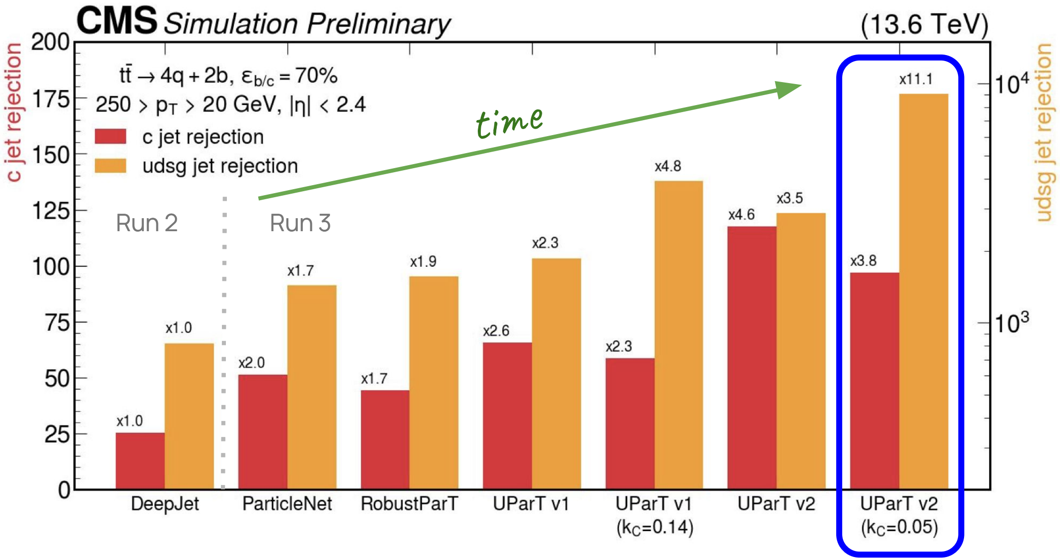
Unified Particle Transformer

Transformer-based

Jet represented as "*particle cloud*" (unordered set of constituents)

11x light/gluon jet rejection with respect to DeepJet

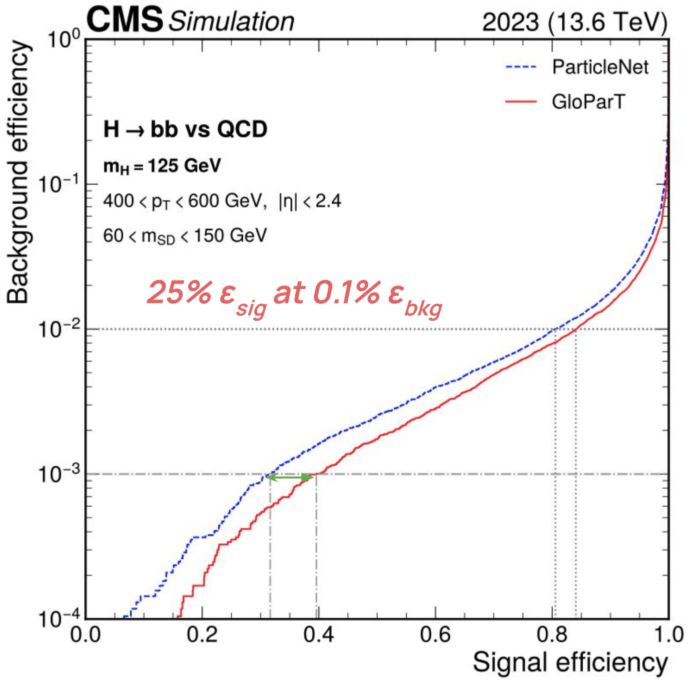
Performs tau and strange-jet tagging!

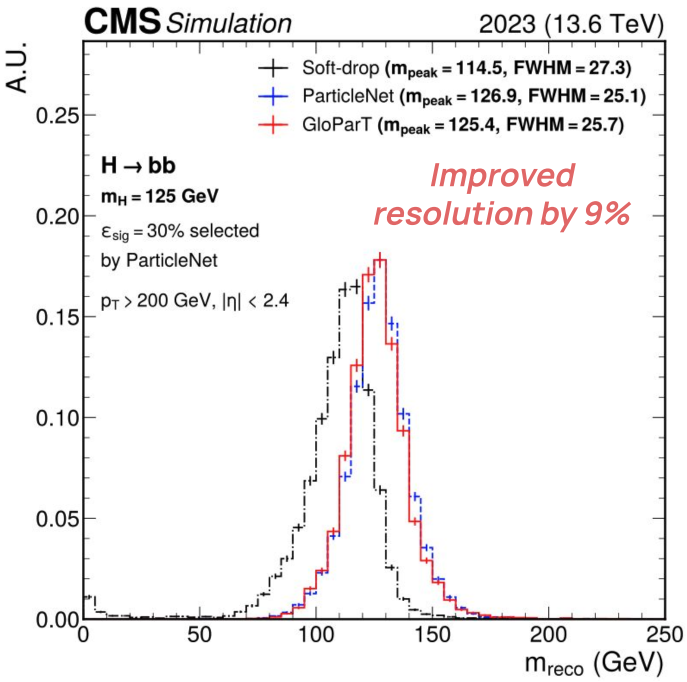


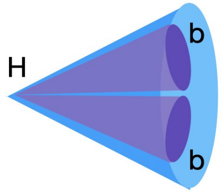
H→bb tagging

CMS-PAS-BTV-25-002

- Lorentz-boosted Higgs bosons with highly-collimated decay products can be reconstructed as large-radius jets
- Several algorithms developed since Run 2 to discriminate signal from QCD background jets







Referred to as "Merged" or "boosted" topology

Soft-drop algorithm
Prunes soft and collinear radiation

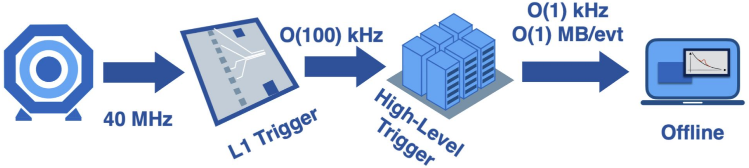
ParticleNet:
Leverages particle and PV information

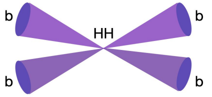
GloParT:
particle-transformer architecture with self-attention mechanism

Improved triggers for HH

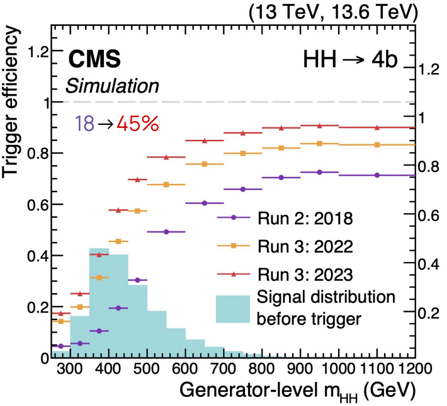
DP-2023-050 CERN-EP-2026-101 DP-2026-027

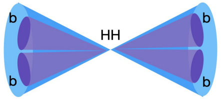
- Use of ML heavy-flavor, τ_h taggers @ HLT and higher rate allocation reduce trigger thresholds and improve signal efficiency



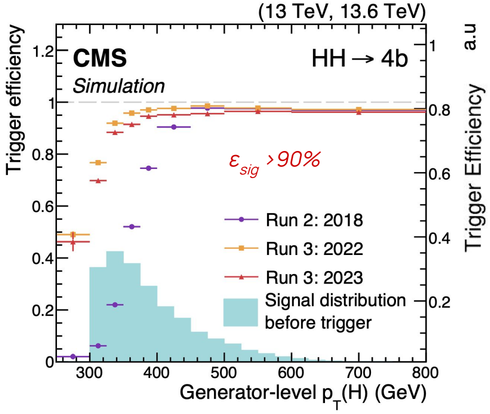


"Resolved" topology

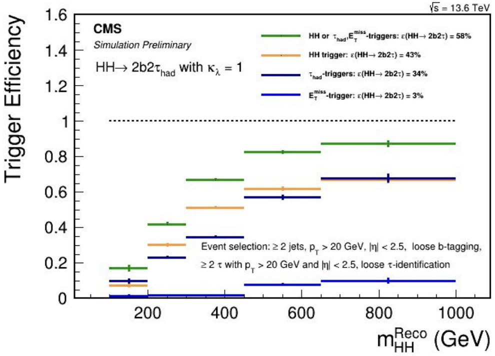




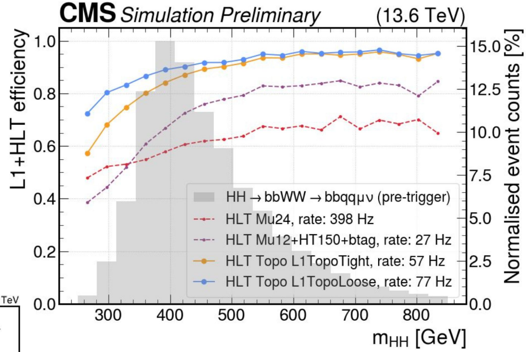
"Merged" topology



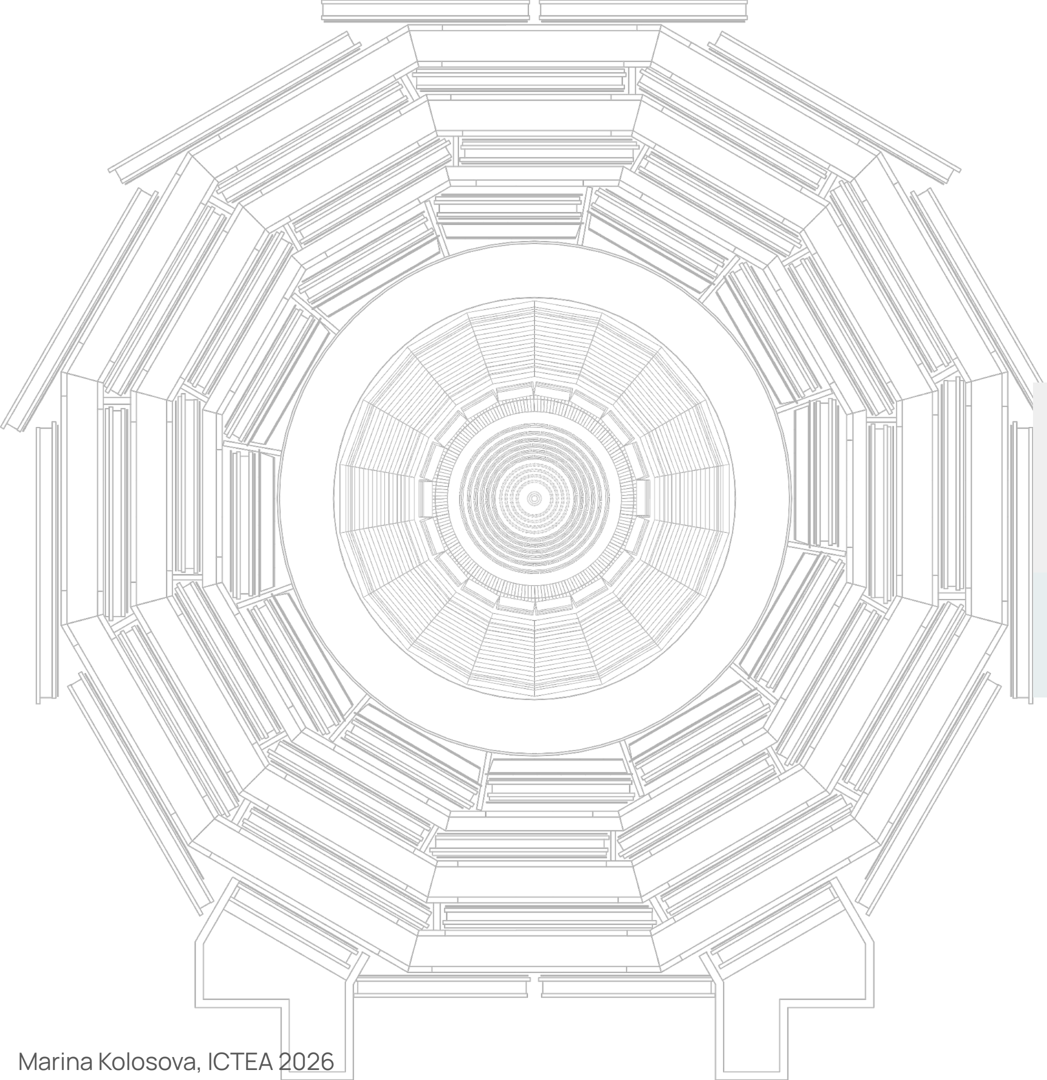
$HH \to bb\tau_h\tau_h$



$HH \to bbWW \to bb(qq)(\mu\nu)$



A non-exhaustive list of trigger improvements!

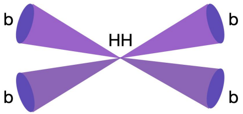


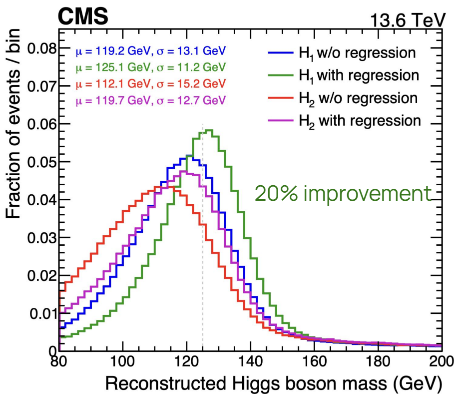
Recent CMS results on HH using partial Run 3 data

HH→bbbb, HH→bbγγ, HH→bbWW

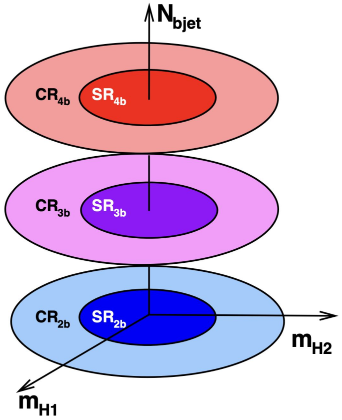
HH→bbbb ▪ Resolved regime

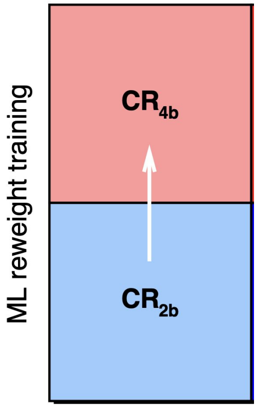
- Targets ggF and VBF HH production modes separately
- Online selection with 4j2b trigger (4j3b in Run 2)
- Uses graph-based heavy-flavor tagger (b-tagging, mass regression)
- HH candidates: four leading in b-tagging score jets
- Background: 95% QCD-multijet, ~5% ttbar





Signal regions (SRs) & control regions (CRs) defined based on $N_{\text{b-jets}}$ and distance of m_{H1}, m_{H2} from (125, 120)





ML reweighting to learn **kinematic differences** between the CR_{2b} and CR_{4b}

HH→bbbb ▪ Resolved regime

- Targets ggF and VBF HH production modes separately
- Online selection with 4j2b trigger (4j3b in Run 2)
- Uses graph-based heavy-flavor tagger (b-tagging, mass regression)
- HH candidates: four leading in b-tagging score jets
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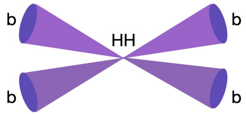
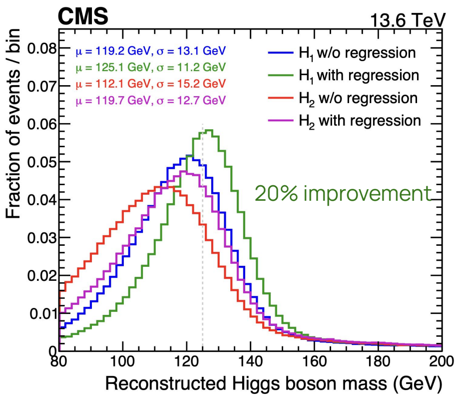
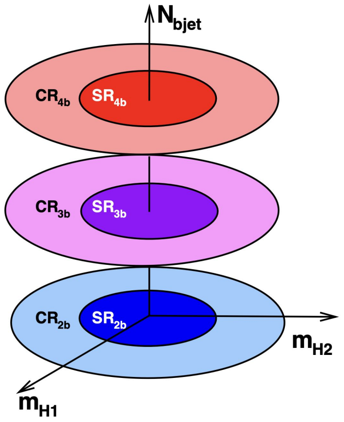
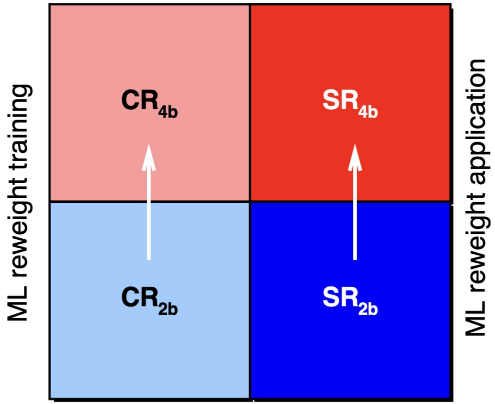




Signal regions (SRs) & control regions (CRs) defined based on $N_{b\text{-jets}}$ and distance of m_{H1}, m_{H2} from (125, 120)





ML weight applied to events in SR(2b) to estimate the background in SR(4b)

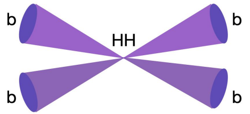
HH→bbbb ▪ Resolved regime

CERN-EP-2026-101

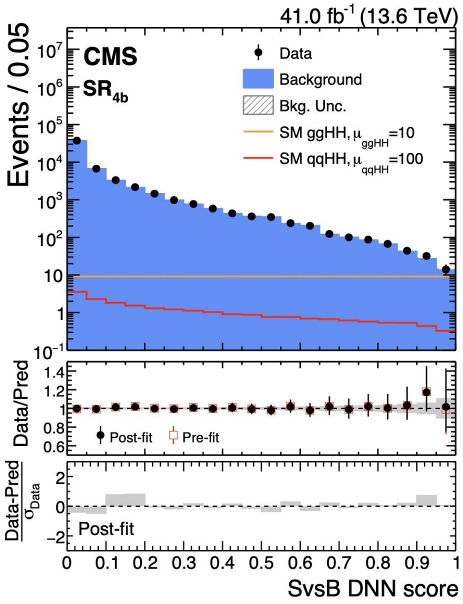
submitted to PRD

2022-2023 LHC pp data (62 fb^{-1})

- Targets ggF and VBF HH production modes separately
- Online selection with 4j2b trigger (4j3b in Run 2)
- Uses graph-based heavy-flavor tagger (b-tagging, mass regression)
- HH candidates: four leading in b-tagging score jets
- Background: 95% QCD-multijet, ~5% ttbar



- ML-based signal-vs-background (SvsB) discriminants used to extract the ggF and HH signal



No excess observed on top of expected background

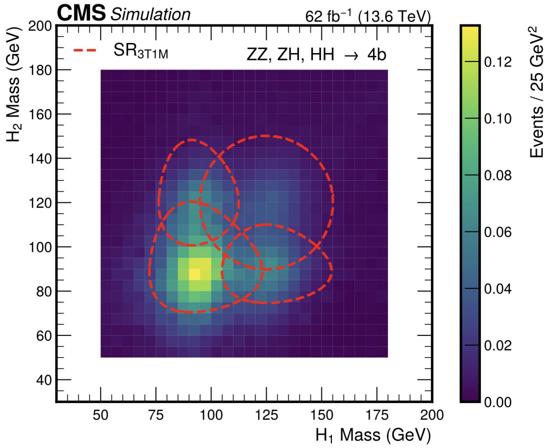
Observed (expected) upper limits set at 95% CL on μ_{HH}: 6.3 (5.3)

Scaling to Run 2 luminosity (138 fb^{-1}): x2 improvement!

HH→bbbb ▪ Resolved regime

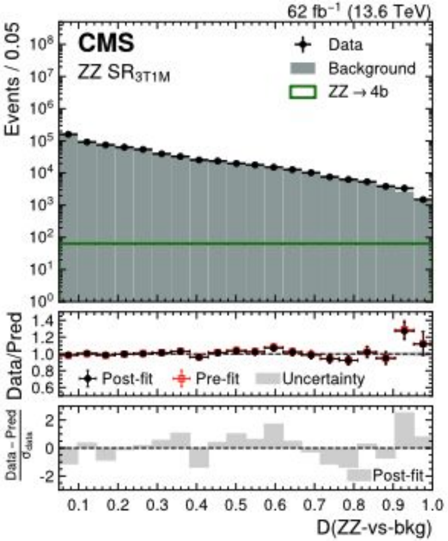
- ZZ→4b and ZH→4b processes have production cross sections 31 and 8 times larger than HH
- Same final state, same experimental challenges → Used as standard candles for HH

Enlarged SRs to capture ZZ and ZH processes



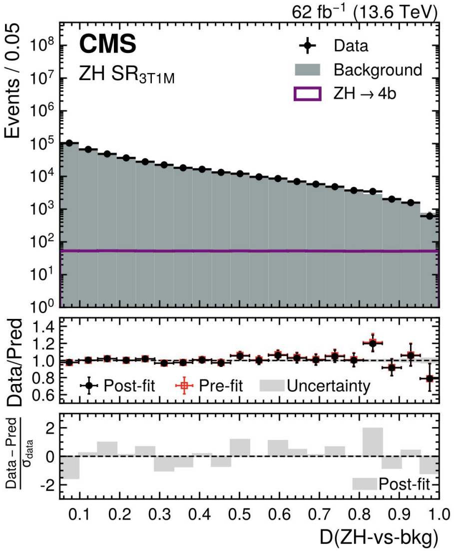
ML-based multiclassifier separates
HH, ZZ, and ZH signals from background

ZZ→ 4b



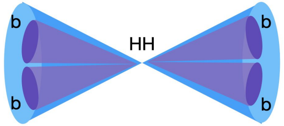
Observed (expected)
UL on μ_{ZZ} at 95% CL: 7.1 (3.8)

ZH→ 4b

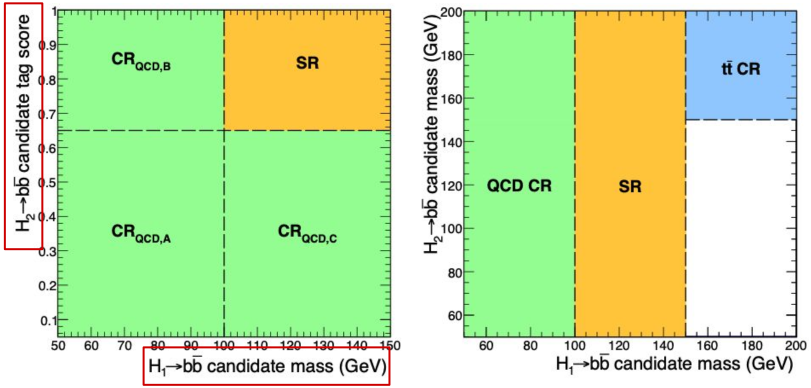


Observed (expected)
UL on μ_{ZH} at 95% CL: 3.5 (3.1)

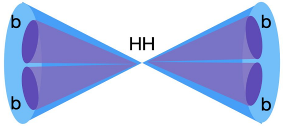
HH→bbbb ▪ Merged regime



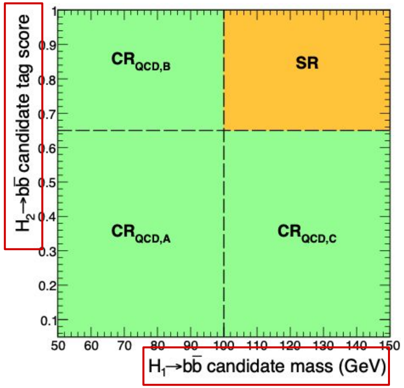
- Features new triggers, transformer-based H→bb tagging, and mass regression
- Events with two large-radius H→bb tagged jets split in SR, QCD CRs and tt CR based on:
  - H→bb candidate tag score and m_{H1} and m_{H2}
- Data-driven QCD-multijet background, ttbar estimated from simulations with data-driven corrections

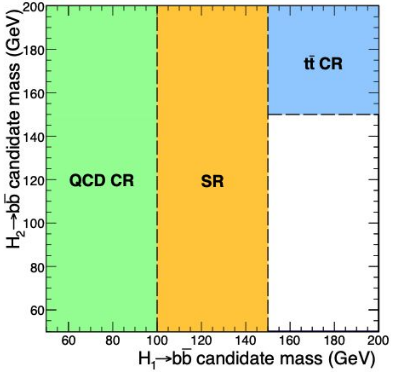


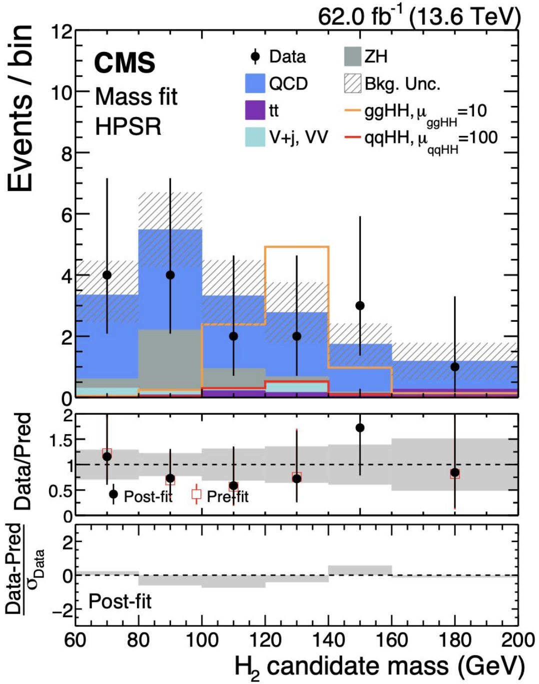
HH→bbbb ▪ Merged regime



- Features new triggers, transformer-based H→bb tagging, and mass regression
- Events with two large-radius H→bb tagged jets split in SR, QCD CRs and tt CR based on:
  - H→bb candidate tag score and m_{H1} and m_{H2}
- Data-driven QCD-multijet background, ttbar estimated from simulations with data-driven corrections



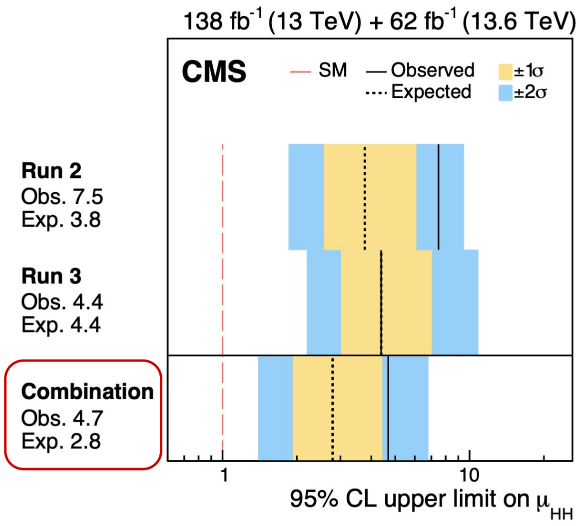




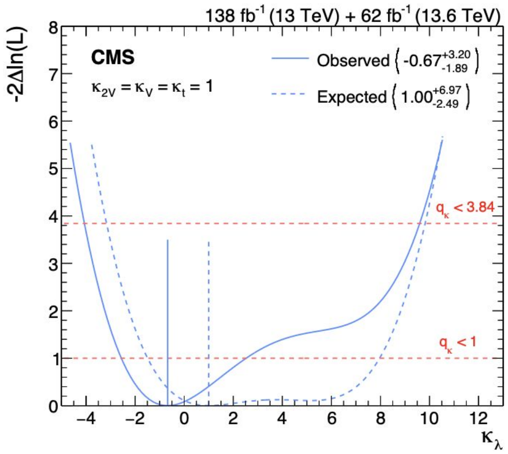
Observed (expected) UL set at 95% CL on μ_{HH}: 5.3 (6.6)

HH→bbbb ▪ Combination of Run 2 and 3 data

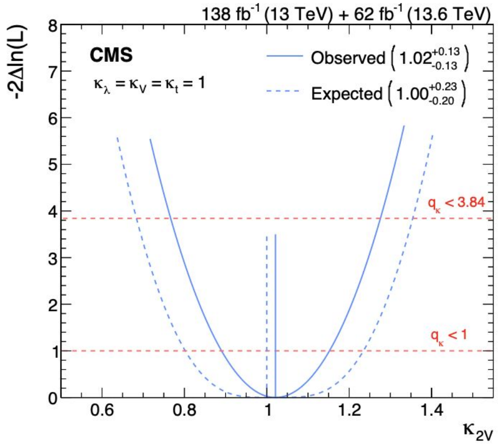
- Statistical combination of Run 2 and Run 3 LHC data performed with:
  - resolved and merged topologies with Run 3 data
  - reanalysis of Run 2 resolved analysis
  - Run 2 merged analysis



Observed: $-4.1 < \kappa_\lambda < 9.6$
Expected: $-3.2 < \kappa_\lambda < 9.8$



Observed: $0.77 < \kappa_{2V} < 1.27$
Expected: $0.69 < \kappa_{2V} < 1.35$



Most stringent constraints achieved in the HH→bbbb final state to date.

Most stringent constraints on κ_{2V} to date!

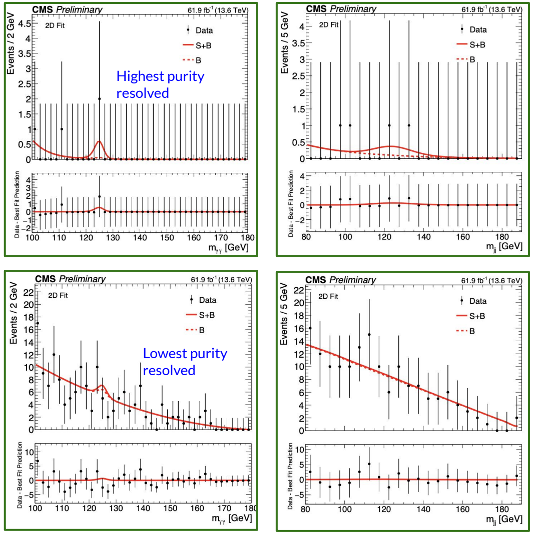
HH→bbγγ

[CMS-PAS-HIG-25-007](CMS-PAS-HIG-25-007)

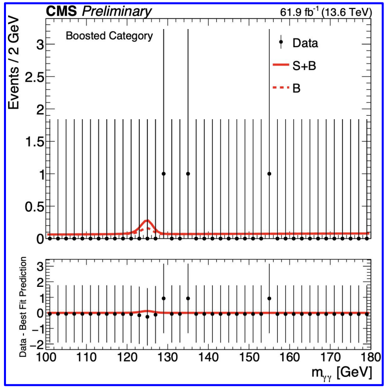
2022-2023 LHC pp data (62 fb^{-1})

- Targets ggF HH in the resolved and H→bb merged regimes
- Graph-based ParticleNet for heavy-flavor tagging on small-radius jets, H→bb tagging on large-radius jets
- ML-based multiclassifier for SvsB discrimination & definition of categories with different signal purities

2D-fit in resolved topology



1D-fit in merged topology



No excess observed above expected background

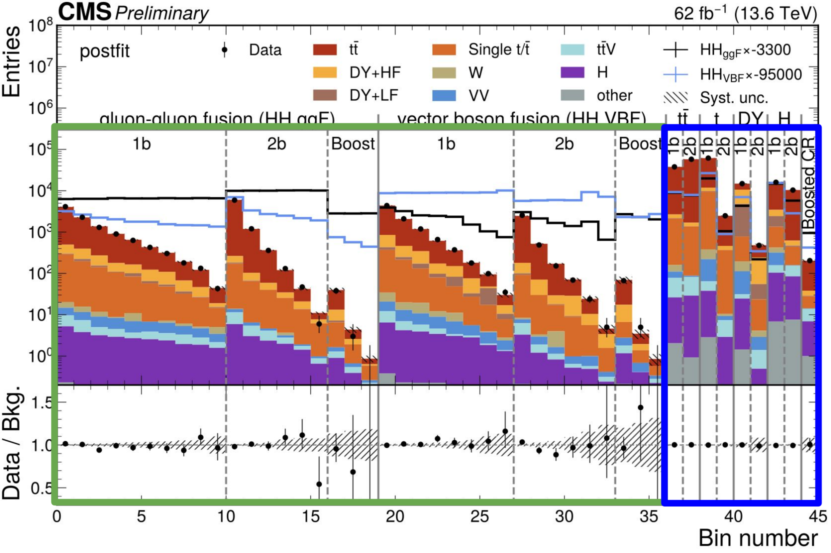
Observed (expected) UL on μ_{HH} set at 95% CL of 11 (7.3)

Constraints also set on κ_λ: [-6.1, 12.8]

Scaling to Run 2 luminosity (138 fb^{-1}):
15% improvement with half the data

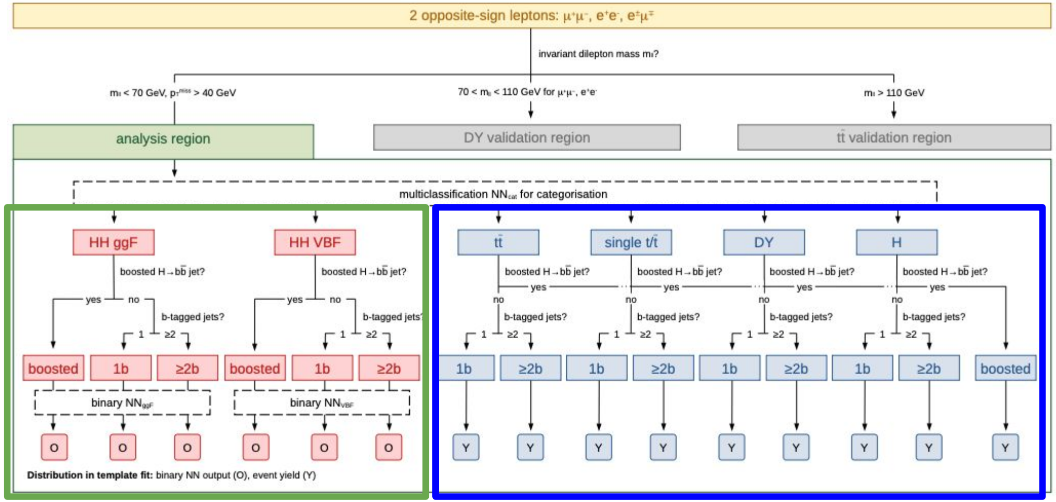
HH→bbWW

- Targets ggF & VBF HH in the 2 lepton ($e^+e^-/e^\pm\mu^\mp/\mu^+\mu^-$) final state (resolved & merged topologies)
- Main background: ttbar, single-t, Drell-Yan (DY), single Higgs (H) production
- Events split into **SRs** and **CRs** with a ML-based multiclassifier, $N_{b\text{-tagged jets}}$, and $N_{H\rightarrow bb\text{ tagged}}$



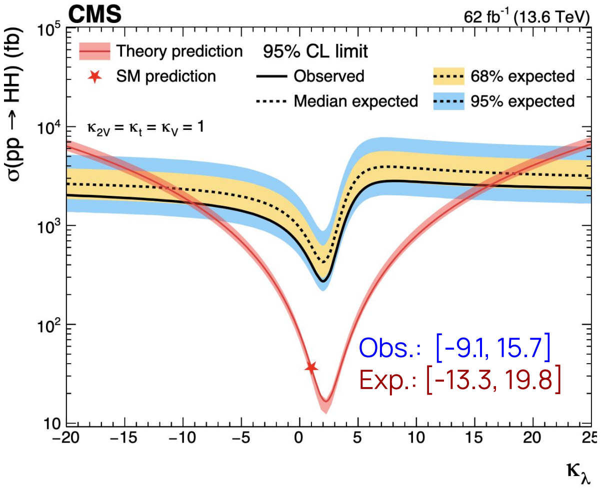
Binary classifier score distributions

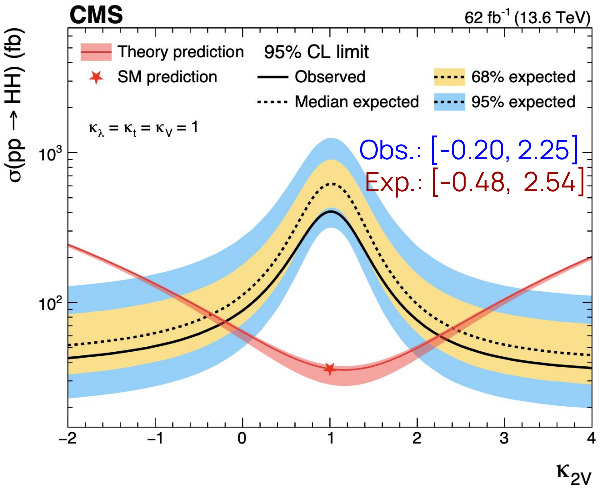
Background event yields



HH→bbWW

- Analysis remains statistically-limited, main systematic uncertainties related to:
  - H→bb tagging, theory uncertainties on HH cross-section, ttbar normalization
- Observed (expected) upper limits set at 95% CL on μ_{HH}: 12 (18.5)
- **~30%** improvement wrt Run 2 search:
  - refined event classification, improved b-tagging algorithm, new trigger strategy, higher center-of-mass energy





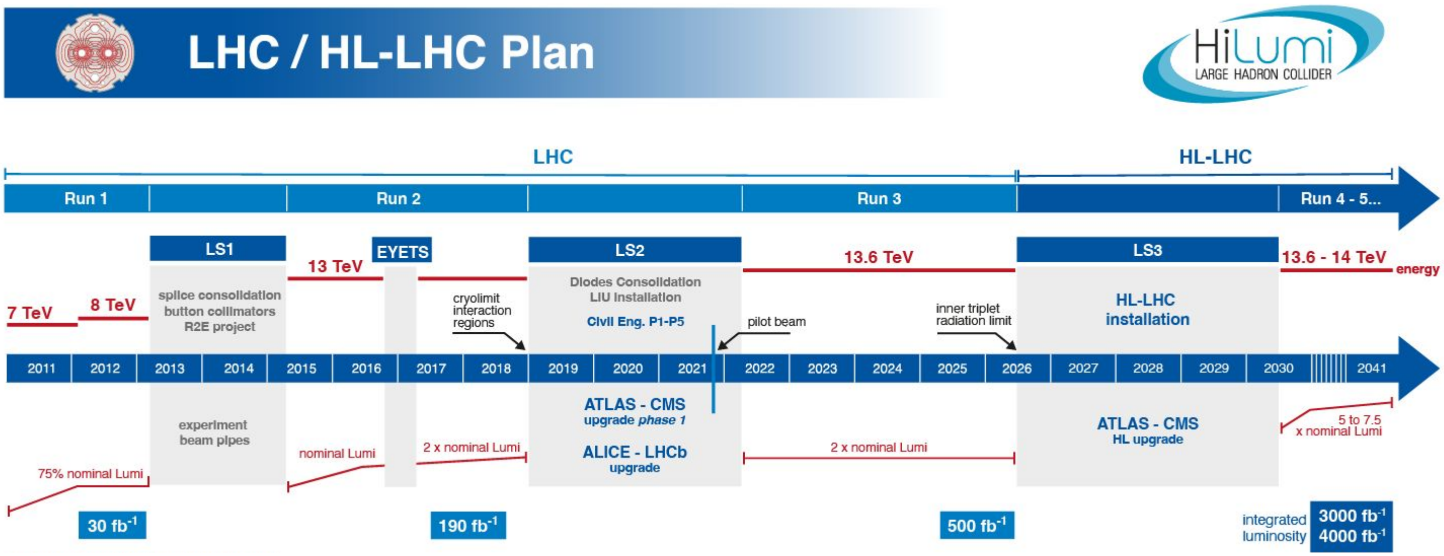
Summary

Several improvements in heavy-flavor tagging, trigger, analysis techniques using ML provide sensitivity boosts to HH searches

- HH→bbbb, HH→bbγγ, HH→bbWW (2L)

All HH searches remain statistically limited:

- combinations across channels & experiments are crucial for the next breakthroughs in Higgs physics
- larger datasets from (HL-)LHC



Sensitivity reach projections made based on Run 2 results:

- Scenario 2: reduced systematic uncertainties, 50% reduction in theoretical unc.
- Scenario 3: takes into account recent improvements in object reconstruction (i.e. 5% improvement in b-tagging)

	2 ab^{-1} ($S2$)		3 ab^{-1} ($S2$)		3 ab^{-1} ($S3$)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
HH statistical significance						
$b\bar{b}\tau^+\tau^-$	$3.0^\dagger$	1.9	$3.5^\dagger$	2.4	$\mathbf{3.8}^\dagger$	**2.7**
$b\bar{b}\gamma\gamma$	$2.1^\dagger$	$2.0^\dagger$	$2.4^\dagger$	$2.4^\dagger$	$\mathbf{2.6}^\dagger$	$\mathbf{2.6}^\dagger$
$b\bar{b}b\bar{b}$ resolved	0.9	$1.0^\dagger$	1.0	$1.2^\dagger$	**1.0**	$\mathbf{1.3}^\dagger$
$b\bar{b}b\bar{b}$ boosted	–	$1.8^\dagger$	–	$2.2^\dagger$	–	$\mathbf{2.2}^\dagger$
Multilepton	$0.8^\dagger$	–	$1.0^\dagger$	–	$\mathbf{1.0}^\dagger$	–
$b\bar{b}\ell^+\ell^-$	$0.4^\dagger$	–	$0.5^\dagger$	–	$\mathbf{0.5}^\dagger$	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	

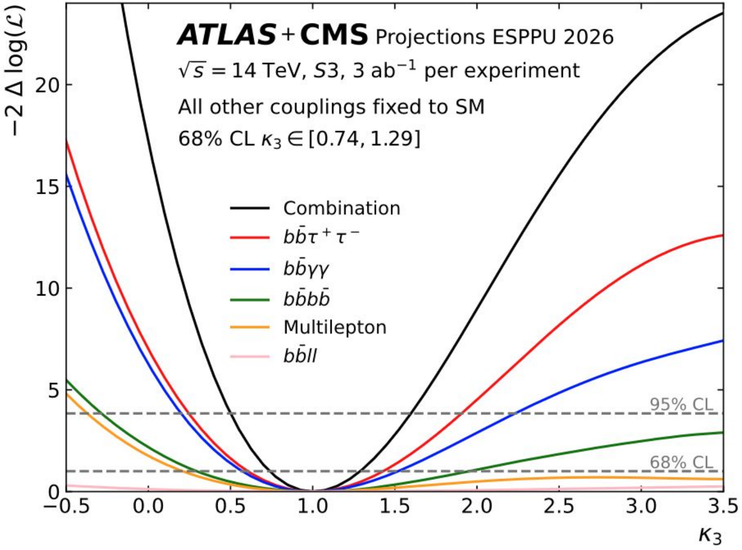
Single-experiment evidence of HH
ATLAS+CMS observation > 5σ

Single-experiment observation in reach

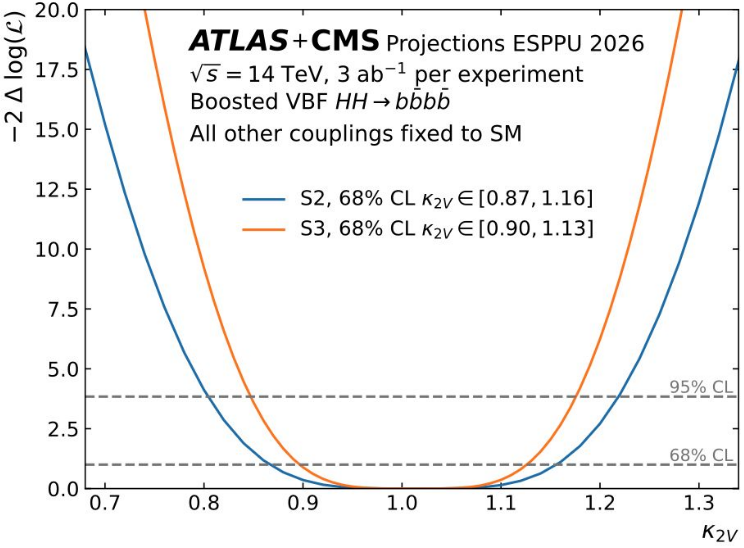
ATL-PHYS-PUB-2025-018 CMS-HIG-25-002

Sensitivity reach projections made based on Run 2 results:

- Scenario 2: reduced systematic uncertainties, 50% reduction in theoretical unc.
- Scenario 3: takes into account recent improvements in object reconstruction (i.e. 5% improvement in b-tagging)



κ_λ precision of 25%



κ_{2V} precision of 13%

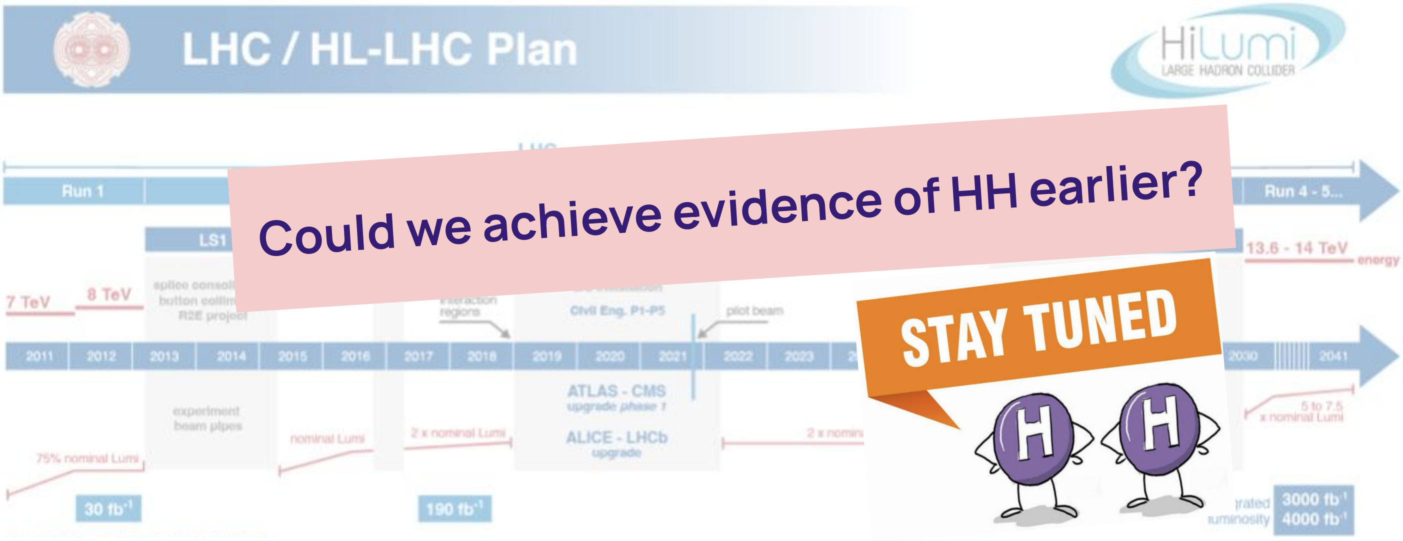
Summary

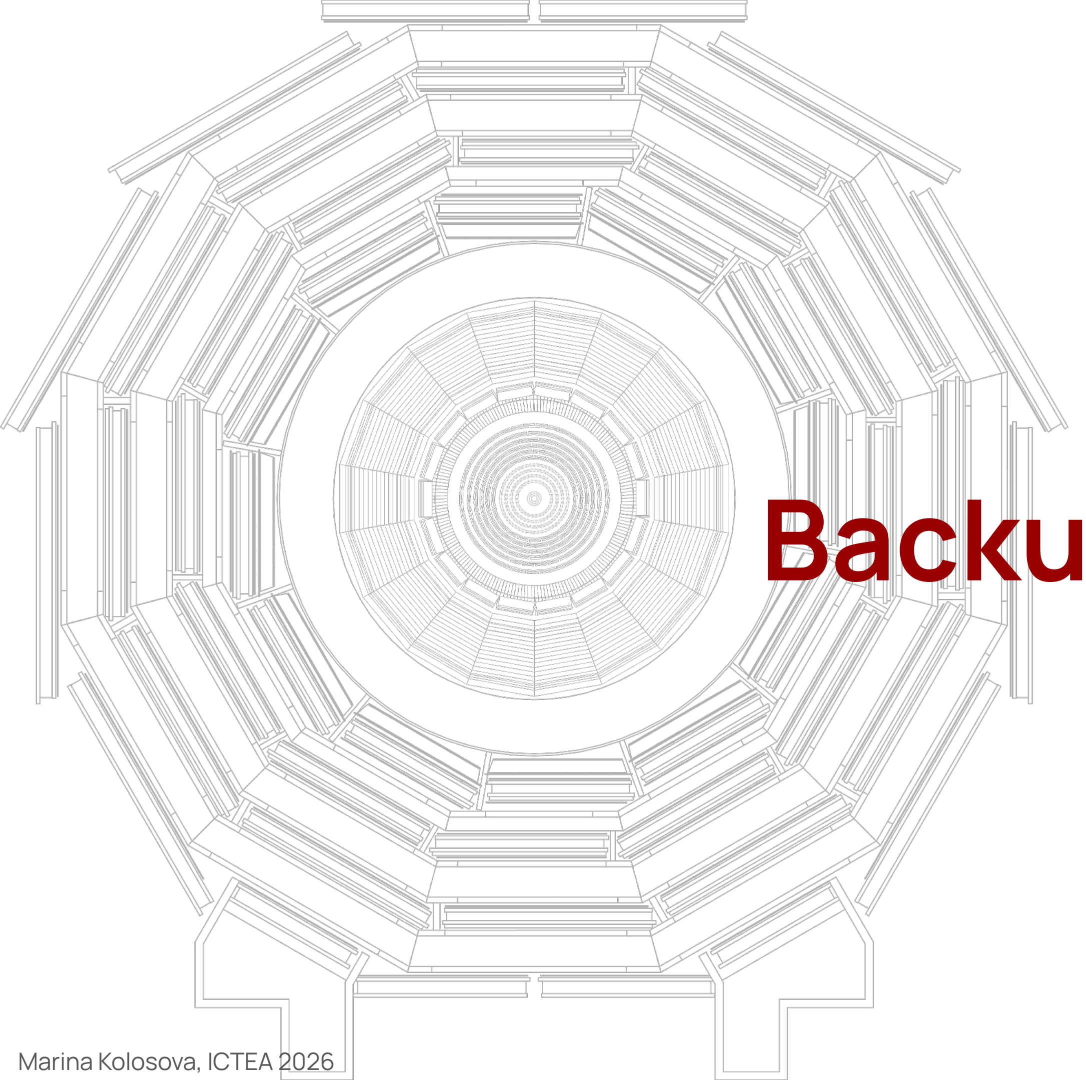
Several improvements in heavy-flavor tagging, trigger, analysis techniques using ML provide sensitivity boosts to HH searches

- $HH \rightarrow bbbb$, $HH \rightarrow bb\gamma\gamma$, $HH \rightarrow bbWW$ (2L)

All HH searches remain statistically limited:

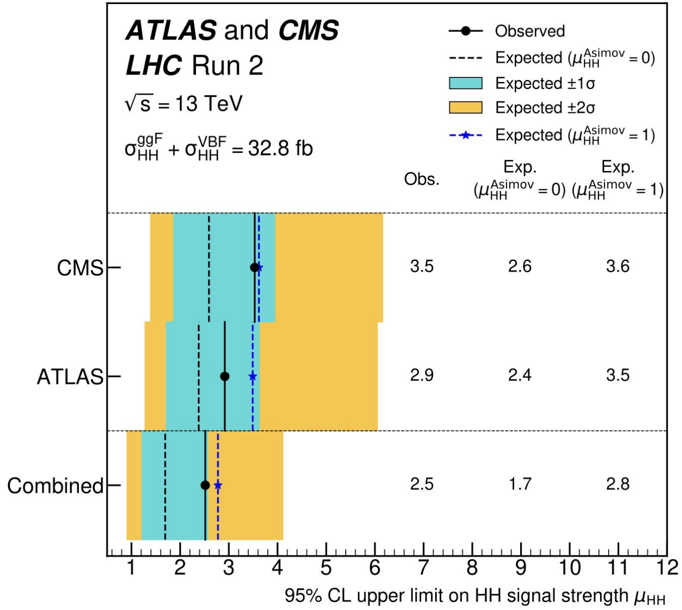
- combinations across channels & experiments are crucial for the next breakthroughs in Higgs physics
- larger datasets from (HL-)LHC





Backup

- Combination of HH searches performed by ATLAS & CMS Collaborations using Run 2 pp data (126-140 fb-1) lead to an observed upper limit at 95% CL. on $\mu_{HH}=\sigma_{HH}/\sigma_{SM}$ of 2.5



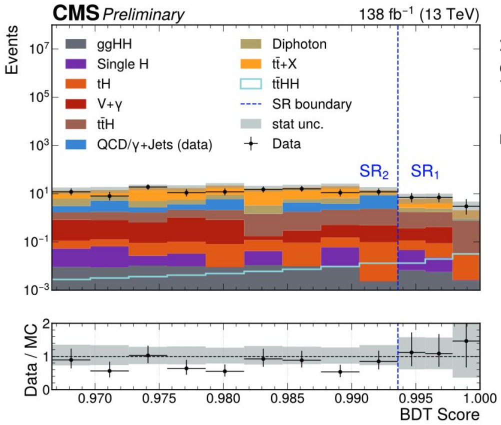
	Channel	Details	Expected			Observed		
			μ_{HH}	κ_λ	κ_{2V}	μ_{HH}	κ_λ	κ_{2V}
ATLAS	bbbb	[36, 38]	< 8.1	[−5.3, 12]	[0.38, 1.7]	< 5.4	[−3.4, 11]	[0.55, 1.5]
ATLAS	$bb\tau\tau$	[40]	< 3.3	[−2.6, 9.2]	[−0.24, 2.4]	< 5.8	[−3.3, 9.1]	[−0.51, 2.7]
ATLAS	$bb\gamma\gamma$	[42]	< 5.2	[−3.0, 7.9]	[−1.1, 3.3]	< 4.1	[−1.6, 7.0]	[−0.48, 2.7]
ATLAS	$bb\ell\ell + E_T^{miss}$	[44]	< 14	[−11, 17]	[−0.50, 2.7]	< 9.6	[−6.5, 13]	[−0.19, 2.4]
ATLAS	Multilepton	[51]	< 11	[−4.5, 9.6]	[−1.9, 4.1]	< 17	[−6.4, 12]	[−2.5, 4.7]
ATLAS	Combined	[48]	< 2.4	[−1.7, 7.2]	[0.41, 1.7]	< 2.9	[−1.3, 7.2]	[0.57, 1.5]
CMS	bbbb	[35, 37]	< 4.3	[−4.6, 12]	[0.63, 1.4]	< 7.0	[−5.0, 12]	[0.66, 1.4]
CMS	$bb\tau\tau$	[39]	< 5.4	[−4.2, 11]	[−0.64, 2.8]	< 3.5	[−1.9, 8.9]	[−0.32, 2.5]
CMS	$bb\gamma\gamma$	[41]	< 5.7	[−3.5, 8.8]	[−0.94, 3.1]	< 8.7	[−3.5, 8.0]	[−1.4, 3.6]
CMS	bbWW	[43]	< 19	[−9.4, 16]	[−1.4, 3.5]	< 15	[−6.1, 13]	[−1.0, 3.1]
CMS	Multilepton	[50]	< 20	[−8.0, 12]	[−2.5, 4.6]	< 22	[−5.8, 10]	[−3.4, 5.6]
CMS	Combined	[49]	< 2.6	[−2.2, 8.0]	[0.63, 1.4]	< 3.5	[−1.4, 6.6]	[0.66, 1.4]
ATLAS + CMS combined			< 1.7	[−1.3, 6.7]	[0.66, 1.4]	< 2.5	[−0.71, 6.1]	[0.73, 1.3]

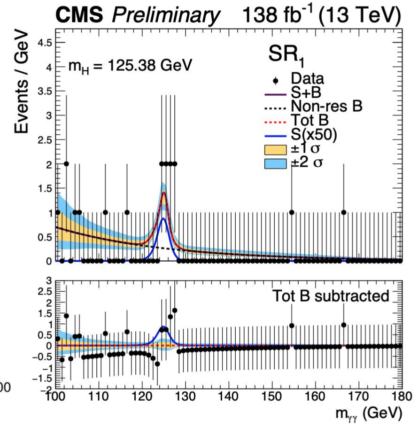
** Due to the technical complexity of the combination, the following CMS analyses are not included: ττγγ, bbZZ(4lep), WWγγ, bbWW(hadronic), VHH(HH→4b) (1% effect)*

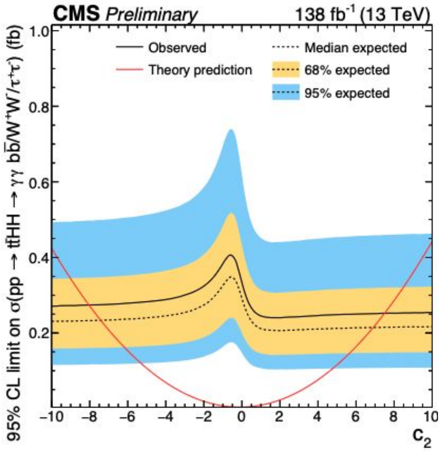
CMS-PAS-HIG-23-004

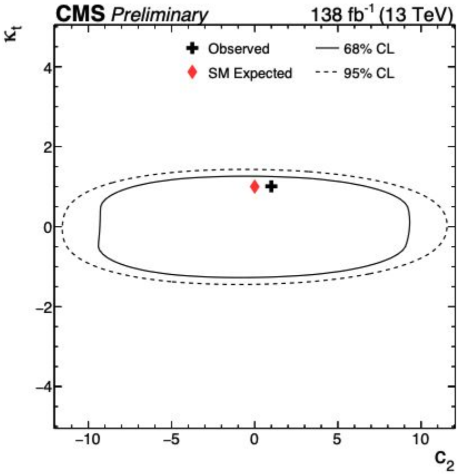
2016-2019 LHC pp data (138 fb^{-1})

- Search for ttHH in γγXX, XX=bb, ττ, WW using LHC Run 2 data of 138 fb^{-1}
- Use of MVA discriminant to separate signal from background
- γ+jets, QCD-multijet backgrounds modeled from data
- Signal extraction: fit on $m_{\gamma\gamma}$









No excess is observed and upper limits at the 95% CL are set on the ttHH signal strength:

- Obs.: μ_{ttHH} < 119.4
- Exp.: μ_{ttHH} < 85.9

Results interpreted in the HEFT framework:

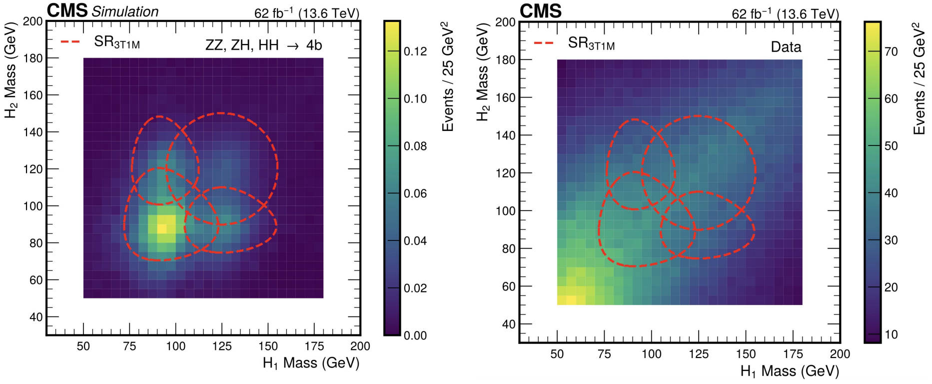
- Obs.: -8.0 < c_2 < 7.5
- Exp.: -7.4 < c_2 < 6.9

CERN-EP-2026-101

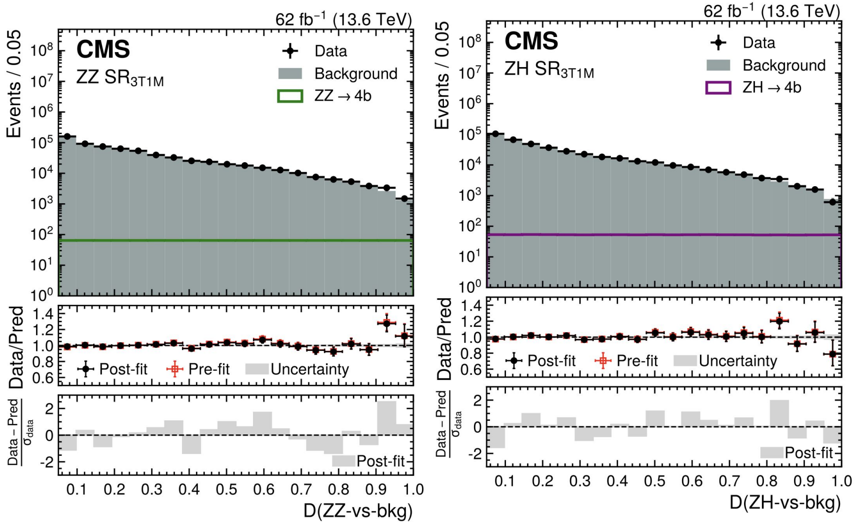
submitted to PRD

2016-2023 LHC pp data (200 fb^{-1})

- ZZ→4b and ZH→4b processes have production cross sections 31 and 8 times larger than HH
- Same final state, same experimental challenges → Used as standard candles for HH



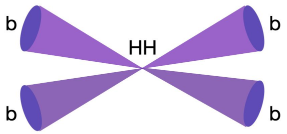
Enlarged SRs to capture ZZ and ZH processes

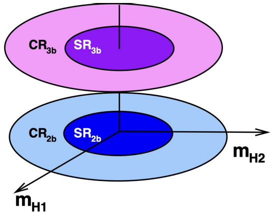


	Run 2 [32]		Run 3		Run 2 and Run 3	
	μ_{ZZ}	μ_{ZH}	μ_{ZZ}	μ_{ZH}	μ_{ZZ}	μ_{ZH}
Expected upper limit at 95% CL	3.8	2.9	3.8	3.1	2.6	2.1
Observed upper limit at 95% CL	3.9	4.8	7.1	3.5	4.2	3.2
Observed signal strength	$0.2^{+1.8}_{-1.7}$	$2.1^{+1.6}_{-1.4}$	$3.5^{+2.0}_{-1.8}$	$0.2^{+1.6}_{-1.5}$	$1.9^{+1.3}_{-1.3}$	$1.2^{+1.1}_{-1.1}$
Observed significance	0.1	1.5	2.0	0.2	1.5	1.2

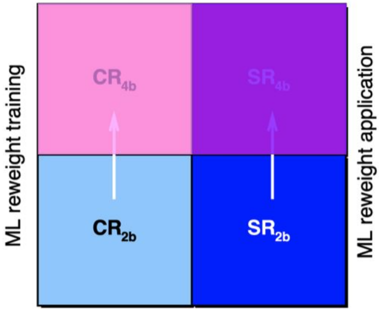
CERN-EP-2026-101
submitted to PRD
2022-2023 LHC pp data (62 fb^{-1})

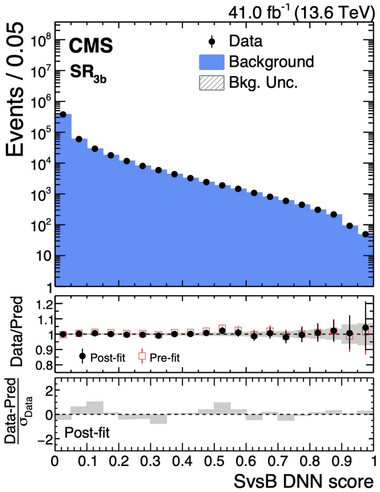
- Background: 95% QCD-multijet, ~5% ttbar
- Online selection with 4j2b trigger (4j3b in Run 2)
  - Increases ε_{sig}
  - More robust background estimation
- HH candidates: four leading in b-tagging score jets



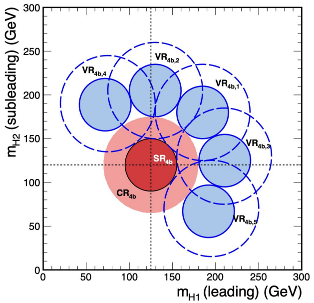


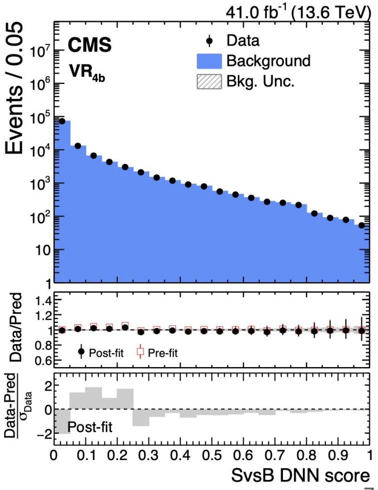
Validation in 3b signal-like region





Validation in 4b off-mass region



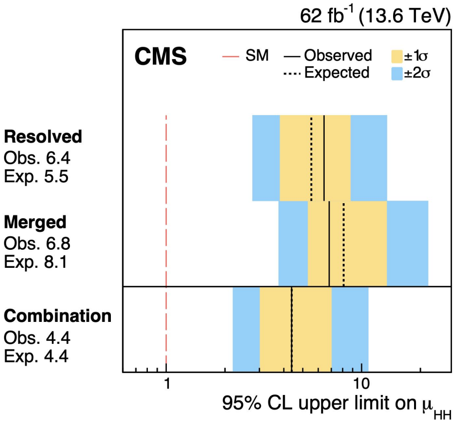


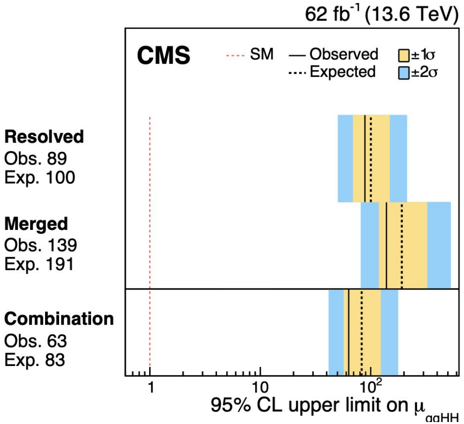
CERN-EP-2026-101

submitted to PRD

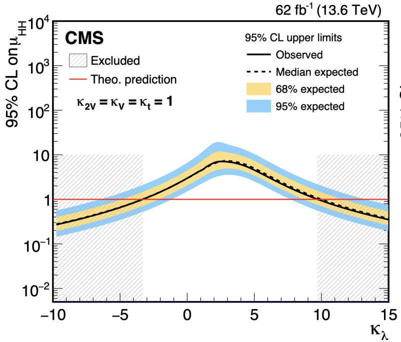
2016-2023 LHC pp data (200 fb^{-1})

- Run 3 resolved and merged approaches with the best expected sensitivity combined after event overlap removal
- Observed (expected) upper limits set on μ_{HH} at 95% CL: 4.4 (4.4)
- Observed (expected) constraints set on κ_λ and κ_{2V} also set at 95% CL

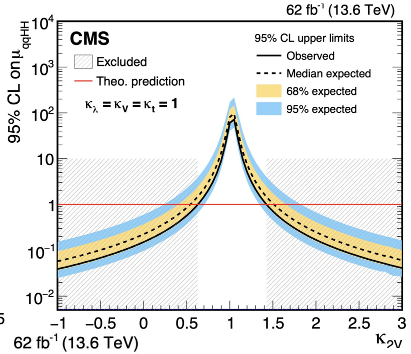


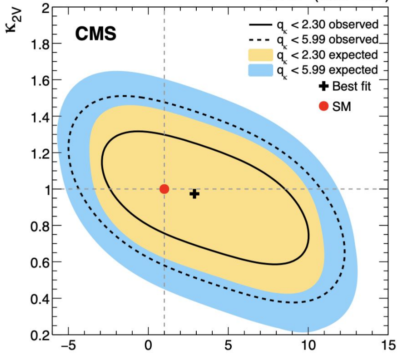


Obs.: $-3.3 < \kappa_\lambda < 9.7$
Exp.: $-3.4 < \kappa_\lambda < 10.0$



Obs.: $0.63 < \kappa_{2V} < 1.43$
Exp.: $0.54 < \kappa_{2V} < 1.51$

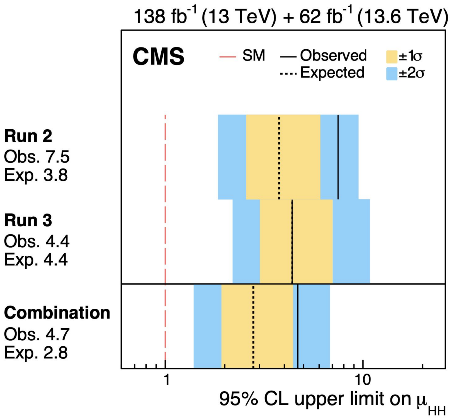


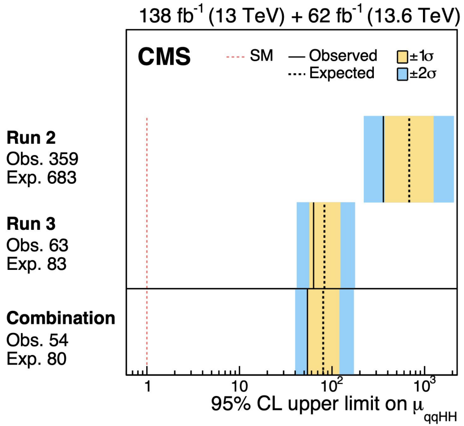


Search remains statistically limited. Dominant systematic uncertainties related to background estimation, theory uncertainty on σ_{HH}, b-tagging efficiency, JES & JER

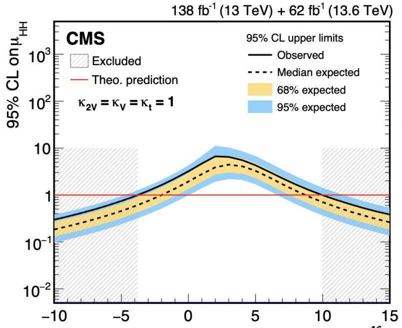
BACKUP · HH→bbbb · Run 2+3 combination

- Run 3 resolved and merged approaches with the best expected sensitivity combined after event overlap removal
- Observed (expected) upper limits set on μ_{HH} at 95% CL: 4.7 (2.8)
- Observed (expected) constraints set on κ_λ and κ_{2V} also set at 95% CL

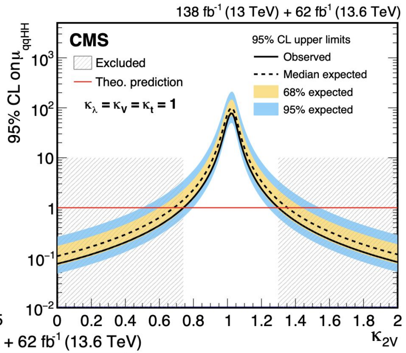


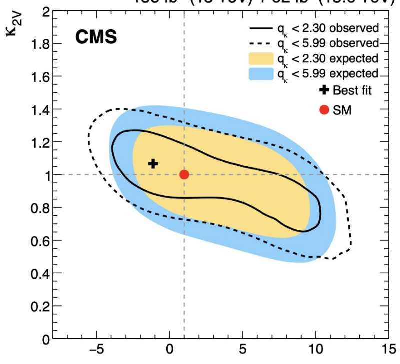


Obs.: $-4.1 < \kappa_\lambda < 9.6$
Exp.: $-3.2 < \kappa_\lambda < 9.8$



Obs.: $0.77 < \kappa_{2V} < 1.27$
Exp.: $0.69 < \kappa_{2V} < 1.35$





Search remains statistically limited. Dominant systematic uncertainties related to background estimation, theory uncertainty on σ_{HH}, b-tagging efficiency, JES & JER

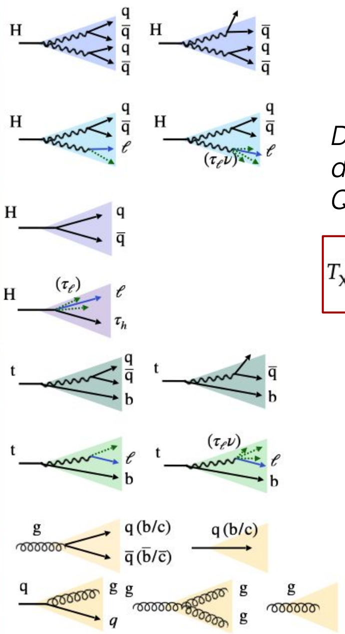
BACKUP · Transformer-based H→bb tagger GloParT

CERN-EP-2026-111
Submitted to JHEP

ParT: attention-based deep neural network identifies highly Lorentz-boosted resonances as single, multipronged jets

- Achieves >50% efficiency at a background efficiency of 1%
- Mass-decorrelated: training sample uniform in jet p_T and mass
- Input features: neutral & charged PF candidates, "lost tracks" not associated with any charged PF, and secondary vertices

Process	Final state		Flavor	Classes
H→WW (all-hadronic)	$q\bar{q}q\bar{q}$	⊗	0c / 1c / 2c	3
	$q\bar{q}q$			3
H→WW (semileptonic)	$e\nu q\bar{q}$	⊗	0c / 1c	2
	$\mu\nu q\bar{q}$			2
	$\tau_e\nu q\bar{q}$			2
	$\tau_\mu\nu q\bar{q}$			2
	$\tau_h\nu q\bar{q}$			2
H→$q\bar{q}$			$b\bar{b}$	1
			$c\bar{c}$	1
			$s\bar{s}$	1
			$q\bar{q}$ (q=u/d)	1
H→ττ	$\tau_e\tau_h$			1
	$\tau_\mu\tau_h$			1
	$\tau_h\tau_h$			1
t→bW (hadronic)	$bq\bar{q}$	⊗	1b + 0c / 1c	2
	bq			2
t→bW (leptonic)	$be\nu$	⊗	1b	1
	$b\mu\nu$			1
	$b\tau_e\nu$			1
	$b\tau_\mu\nu$			1
	$b\tau_h\nu$			1
QCD			b	1
			$b\bar{b}$	1
			c	1
			$c\bar{c}$	1
			others (udsg)	1



Discriminant differentiating H→bb from QCD jets:

$$T_{\mathrm{Xb\bar{b}}} = \frac{\mathcal{P}(\mathrm{X} \to \mathrm{b\bar{b}})}{\mathcal{P}(\mathrm{X} \to \mathrm{b\bar{b}}) + \mathcal{P}(\mathrm{QCD})}$$