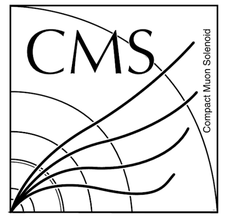
Searches for pairs of Higgs bosons at CMS

Cristina Mantilla-Suarez (Fermilab, UVA)
For the CMS collaboration

ICHEP 2024

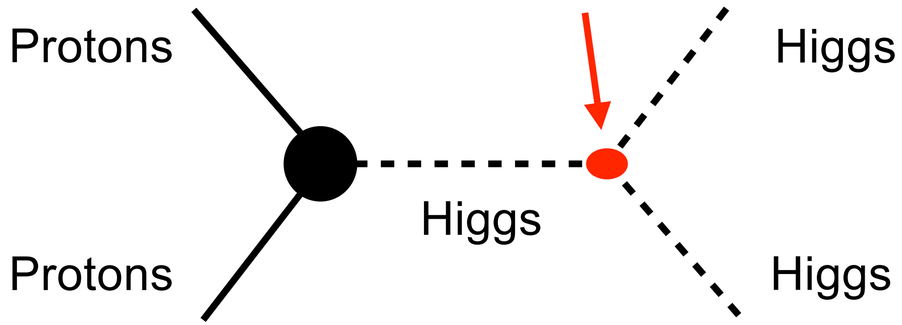


Outline

- HH: motivation and phenomenology
- Survey of CMS results with 13 TeV data
- NEW result with 13 TeV data
- Run-3 prospects
- Summary

Higgs pair production

- A direct probe of the Higgs self-interaction (λ)



Higgs pair production

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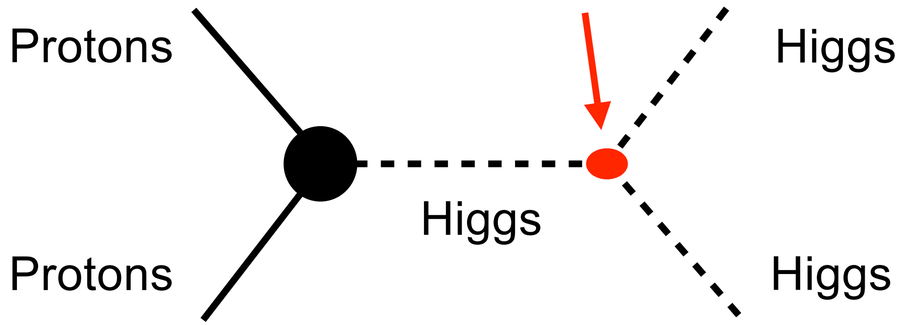


- This term helps to map out the shape of the Higgs potential

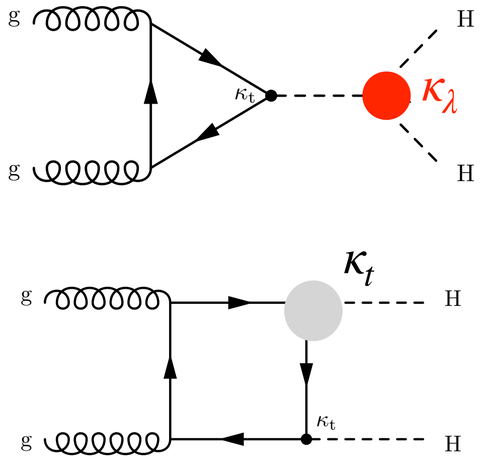
The SM prediction of V:
(expansion at the minimum)

$$V(h) = V_0 + \underbrace{\frac{1}{2}m_H^2 h^2}_{\text{Mass Term}} + \underbrace{\lambda_{hhh} v h^3}_{\text{HH production}} + \underbrace{\frac{1}{4}\lambda_{hhhh} h^4}_{\text{HHH production}}$$

- In the SM: $\lambda_{hhh} = \lambda_{hhhh} \sim 1/8$

HH production predictions

- Goal is to *accurately* and *precisely* measure $\kappa_\lambda = \lambda_{\text{obs}}/\lambda_{SM} = 1$
- HH small at the LHC: **~1000x** smaller than H
  - Destructive interference between diagrams, for example in ggHH:



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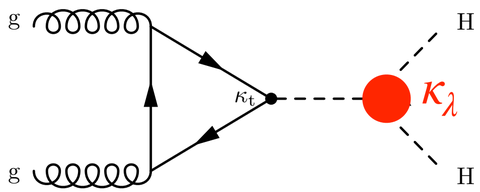
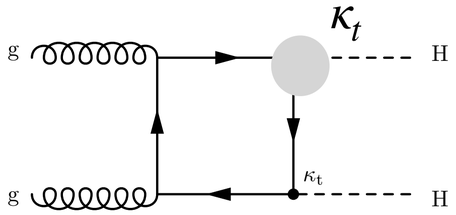
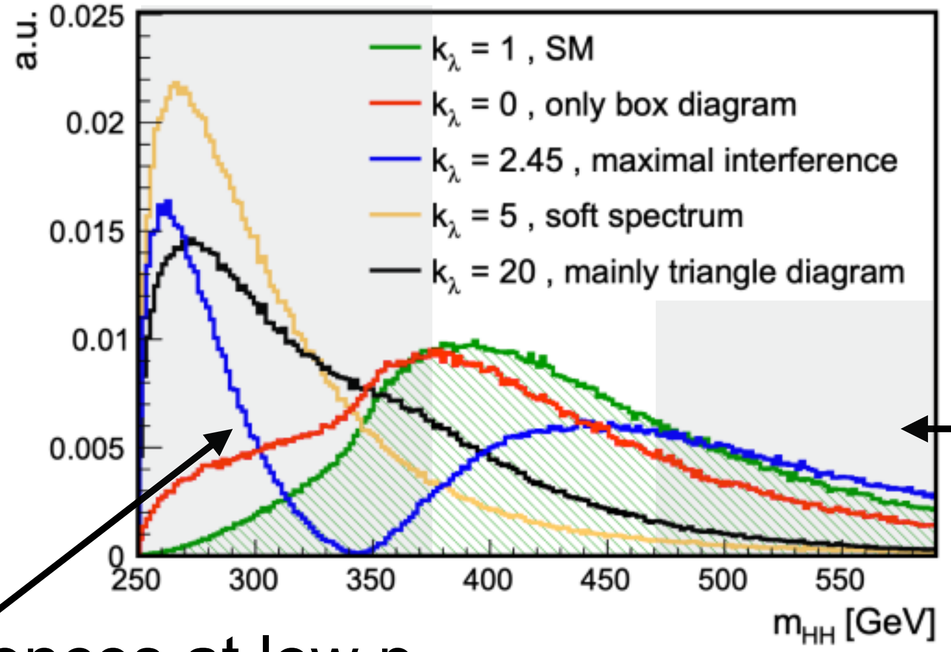
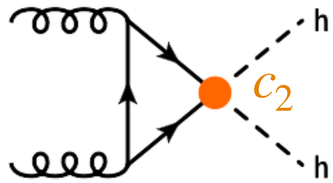








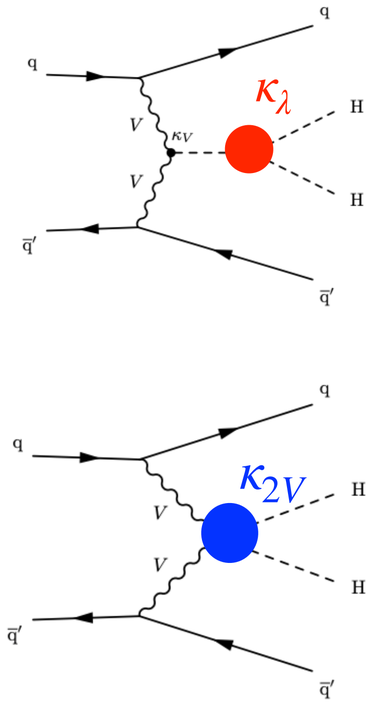
Activate new vertices: HEFT

I. Dutta talk

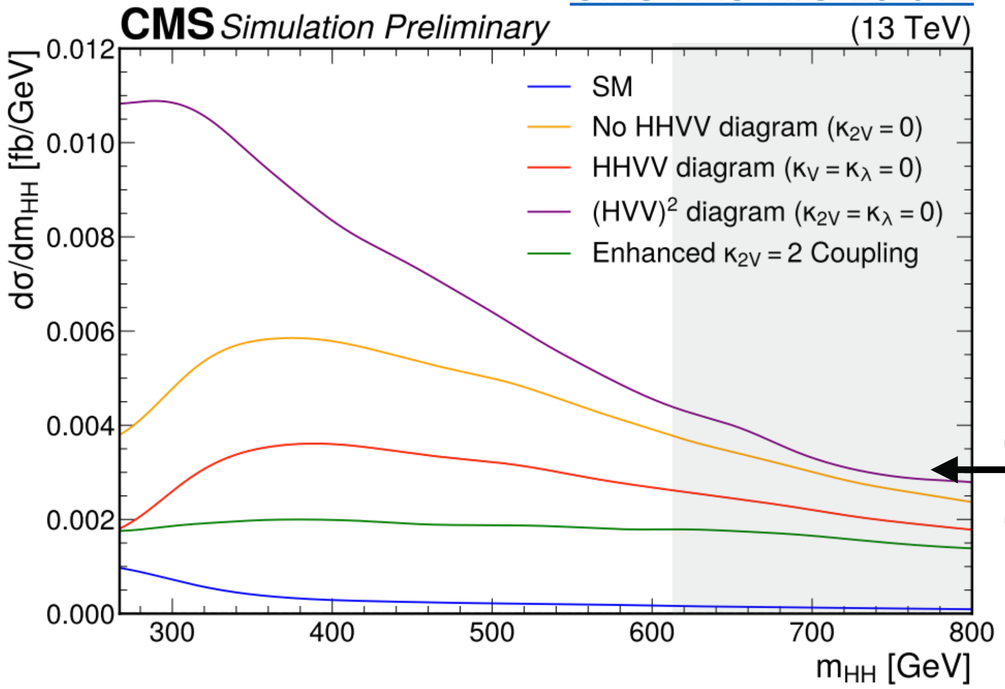
Modify λ_{hhhh} : differences at low p_T

HH production beyond the self-coupling

- HH pairs *also* probe other couplings
- For example: VBF production probes HHVV interaction, κ_{2V}



CMS-PAS-HIG-23-012



Differences still relevant at high p_T

Survey of HH results by CMS

- Higgs boson decay branching ratios result in rich set of final states
- "Big 3" final states driving the sensitivity

	$b\bar{b}$	$WW_{>=1\ell}$	WW_{4q}	$\tau\tau$	ZZ	$\gamma\gamma$
$b\bar{b}$	34%					
$WW_{>=1\ell}$	13.4%	1.3%				
WW_{4q}	11.6%	1.1%	2.1%			
$\tau\tau$	7.3%	1.4%	1.2%	0.39%		
ZZ	3.1%	0.6%	0.2%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.05%	0.04%	0.028%	0.012%	0.0005%

Rarer decay

Rarer decay

bbbb:

ggFHH, VBFHH:
(Boosted) Phys. Rev. Lett. 131, 041803
(Resolved) Phys. Rev. Lett. 129, 081802
VVHH: arXiv:2404.08462

bb$\tau\tau$:

ggFHH, VBFHH:
Phys. Lett. B 842 (2023) 137531

bb$\gamma\gamma$:

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JHEP03 (2021) 257

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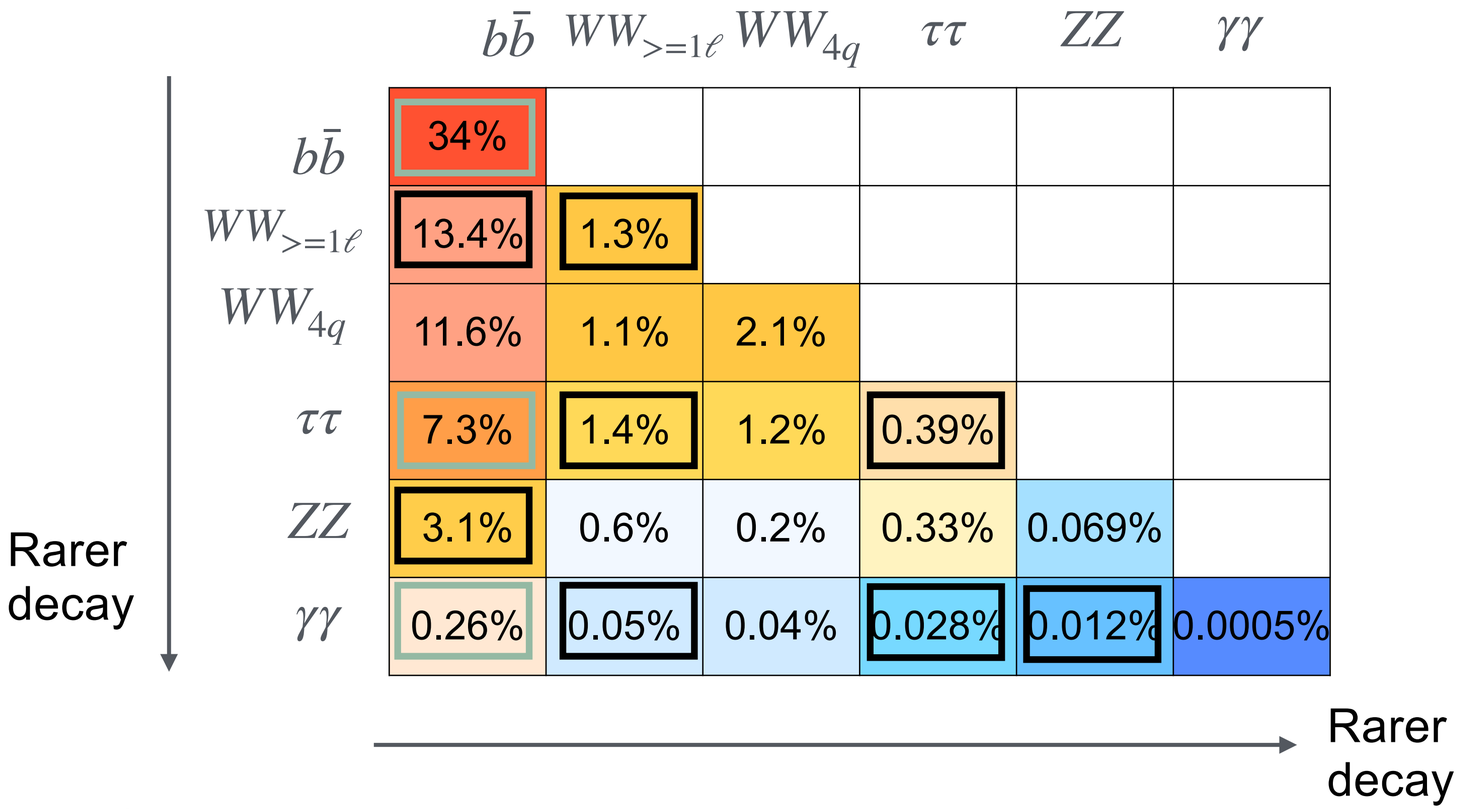

Beyond the "big 3":

$WW(WW, \tau\tau)$, $\tau\tau\tau\tau$: multilepton: ggFHH+VBFHH
JHEP 07 (2023) 095

$bbZZ(4\ell)$: ggFHH
JHEP 06 (2023) 130

$bbWW$, W leptonic: ggFHH+VBFHH
arXiv:2403.09430

$WW\gamma\gamma$: ggFHH+VBFHH
CMS-HIG-PAS-21-014

$\tau\tau\gamma\gamma$: ggFHH
CMS-PAS-HIG-22-012

Survey of HH results by CMS

- Higgs boson decay branching ratios result in rich set of final states
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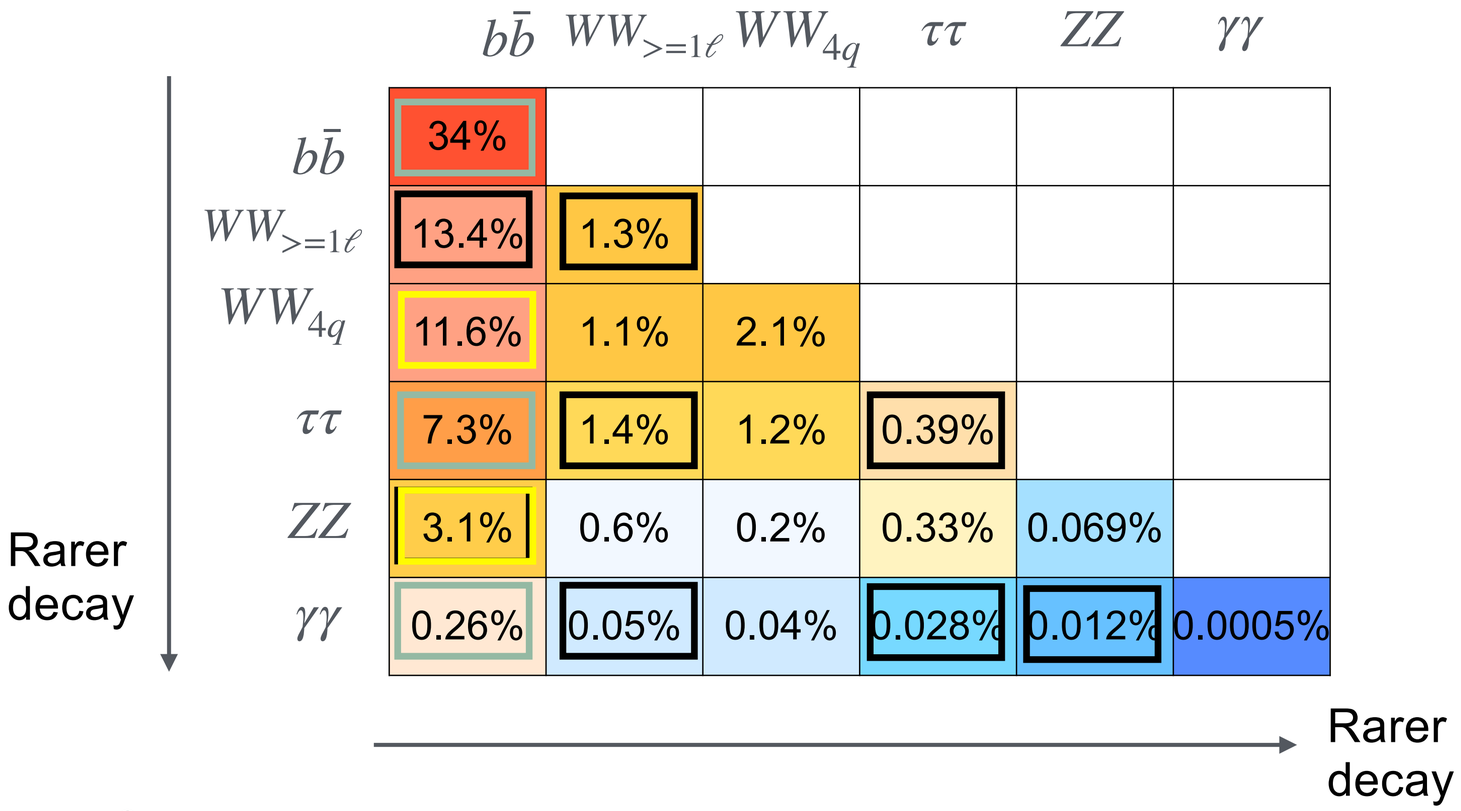


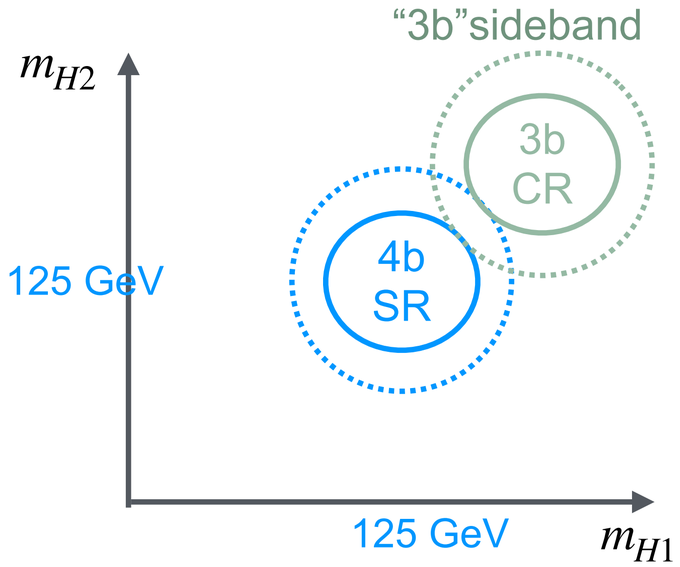
bbVV (all-hadronic):

CMS-PAS-HIG-23-012

New for ICHEP

The “big 3” channels

bbbb:



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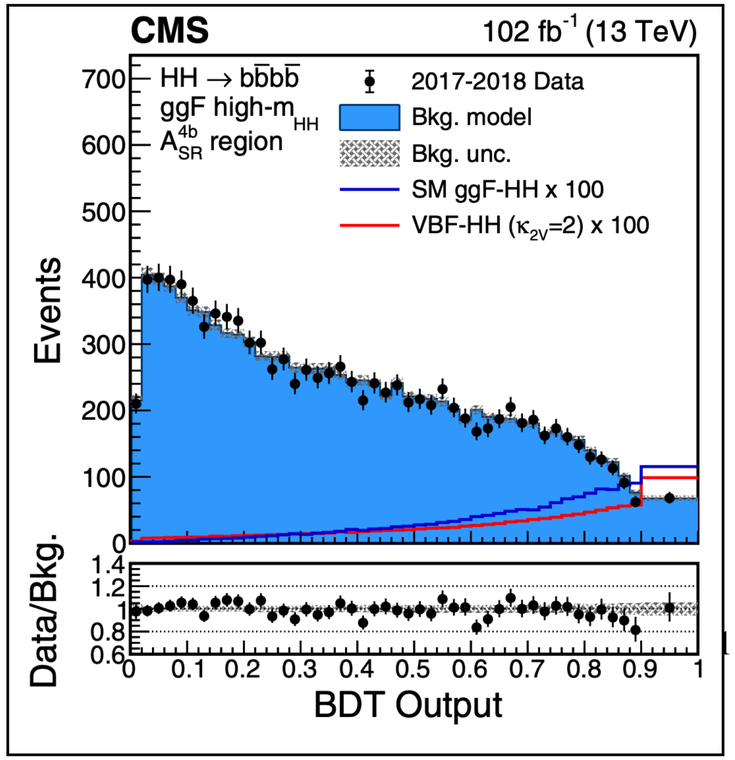
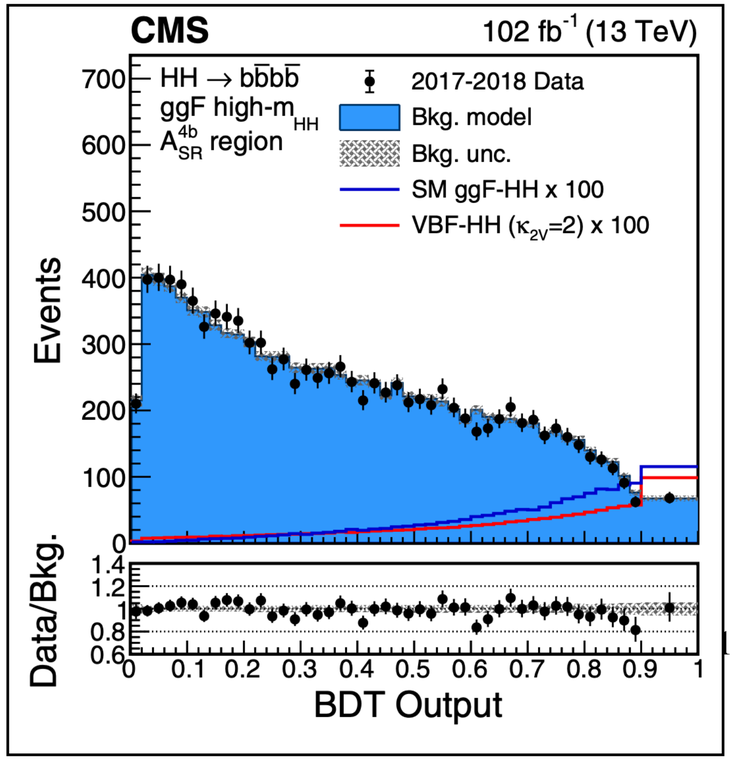


Controlling background uncertainties at O(%)

The “big 3” channels

bbbb:



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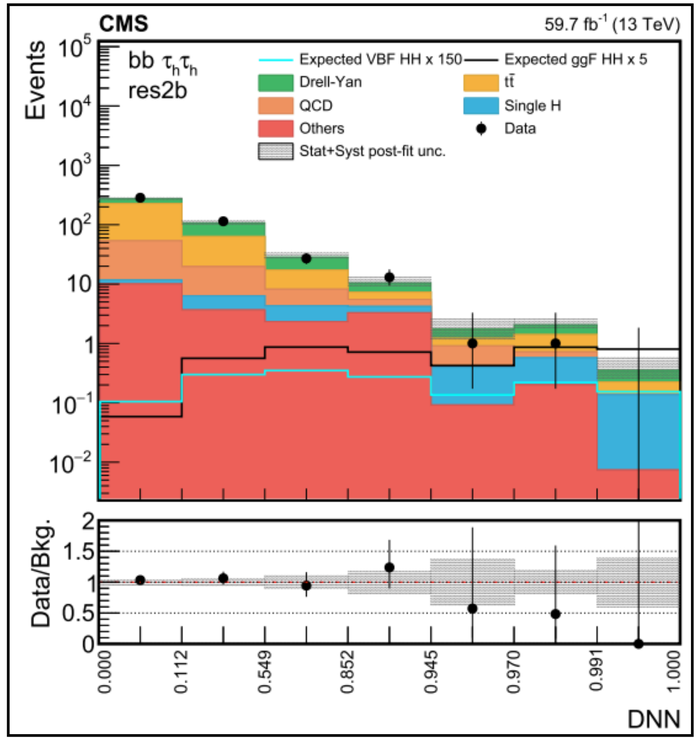

Sensitivity driven by $\tau_h\tau_h$.
Hadronic tau triggers are critical

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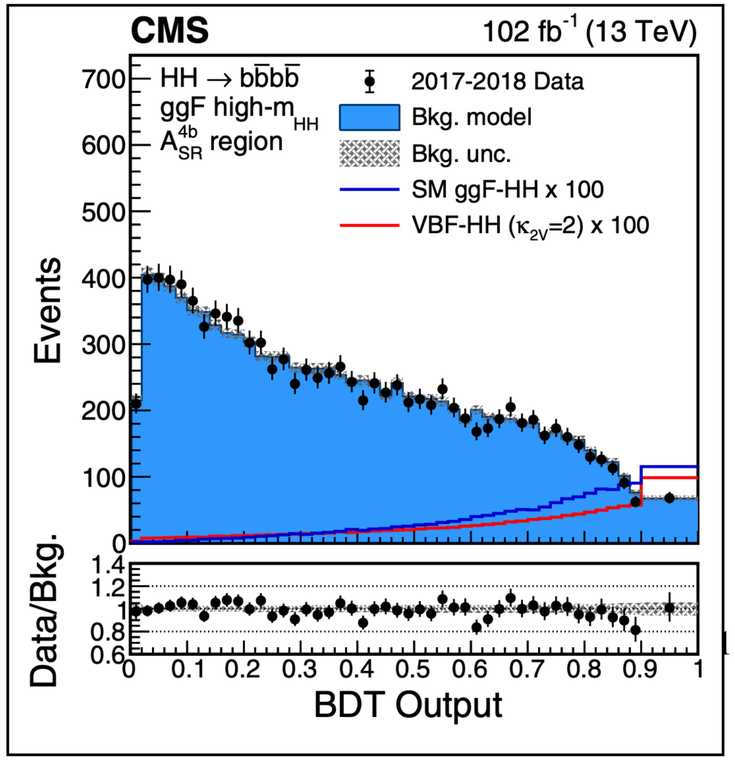

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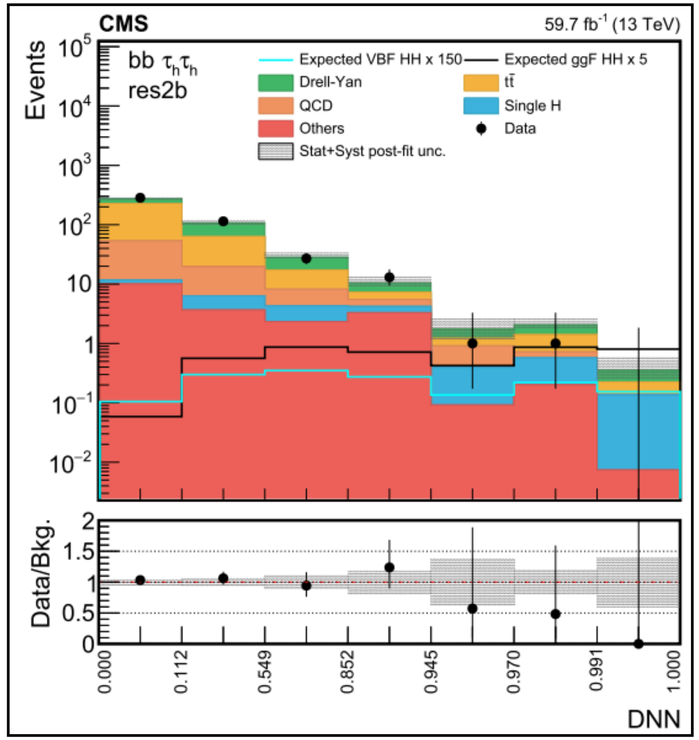

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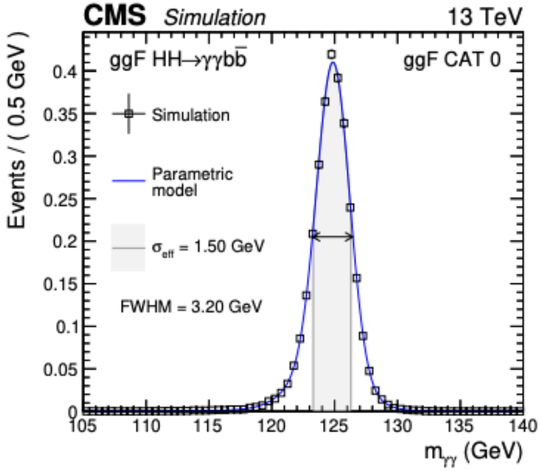

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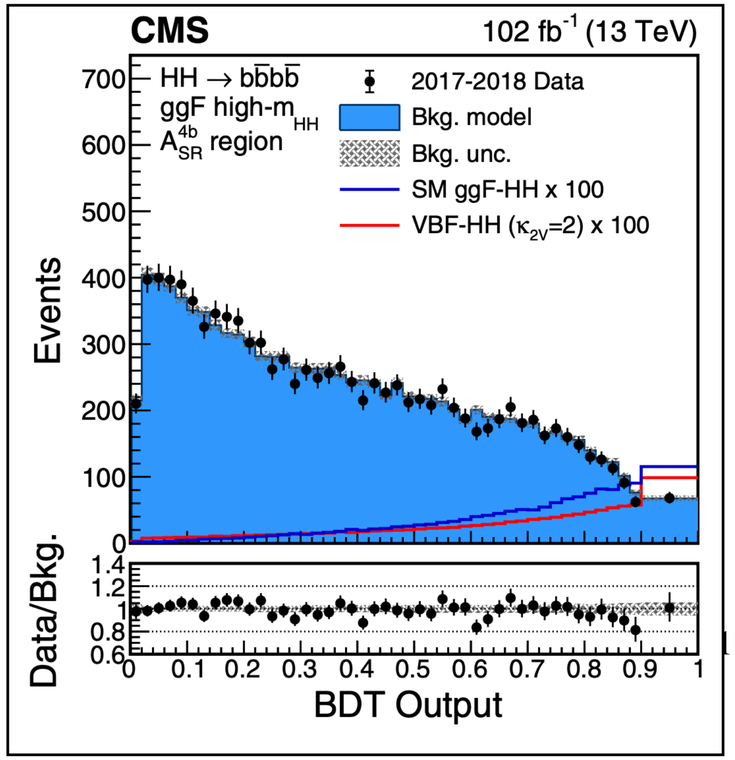

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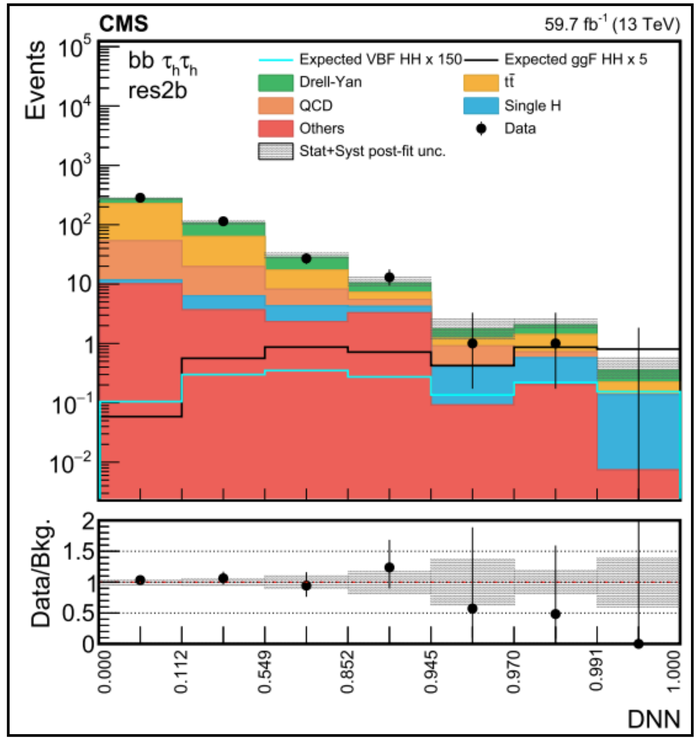

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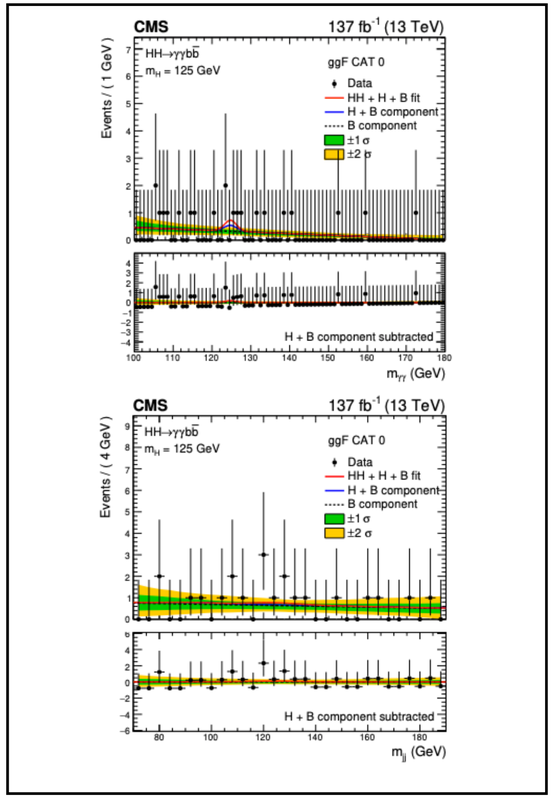
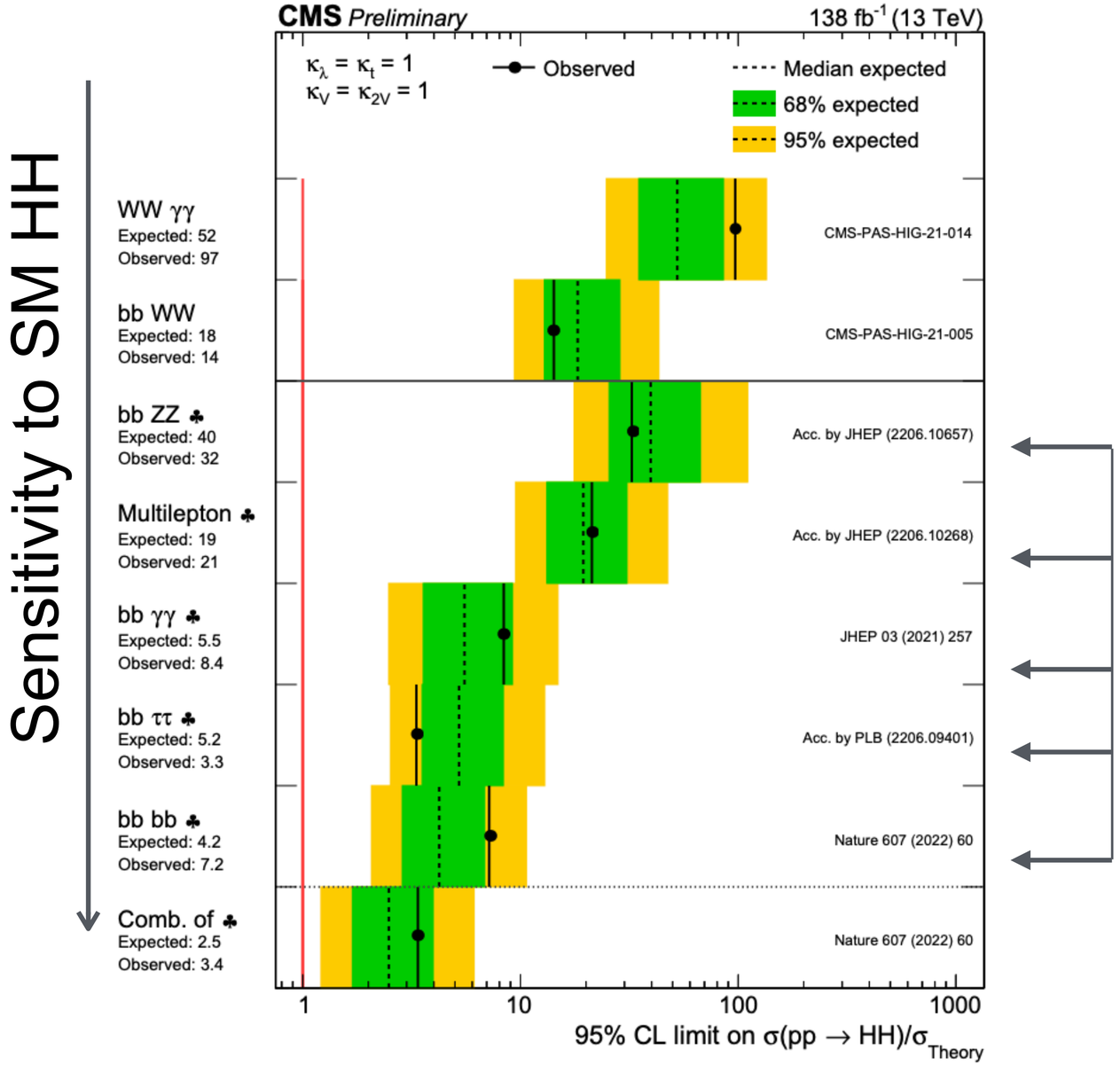


Fit both $m_{\gamma\gamma}$ and m_{jj}.
Energy resolution is key.

Run-2 so far: relative sensitivities



[CMS Summary Results]

Combined sensitivity on σ/σ_{SM}:*

$k_\lambda \in [-1.24, 6.49]$

$k_{2V} \in [0.67, 1.38]$

$k_{2V} > 0$ driven by boosted regime

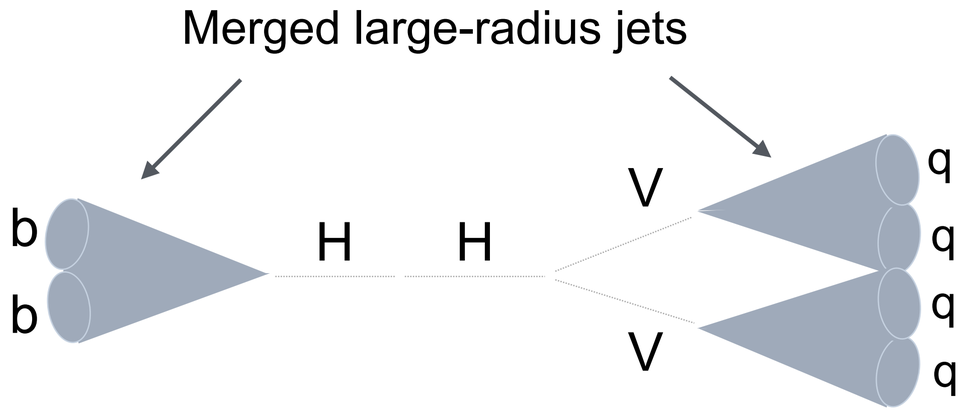
* assuming other couplings set to 1

HH (bb VV): all-hadronic

CMS-PAS-HIG-23-012

- Unexplored final state at the LHC
  - **Includes W(qq), Z(qq) decays**: BR = 13%

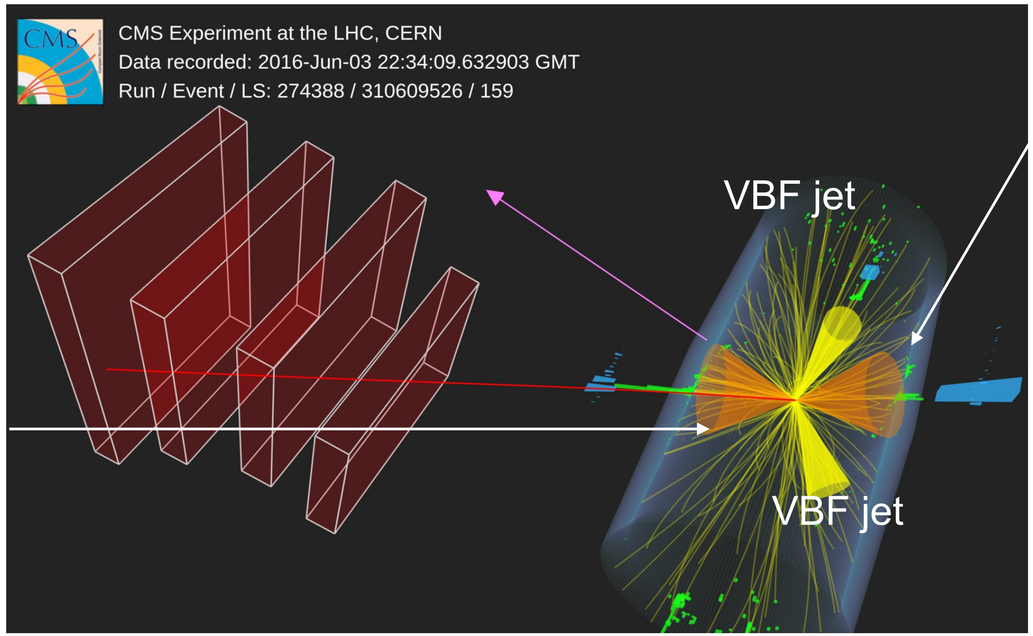
- **Focus on "boosted" regime**, high p_T
  - QCD background dominant, but reduced
  - Study ggF and VBF production: target k_{2V} modifications at high m_{HH}



HH (bb VV): tagging

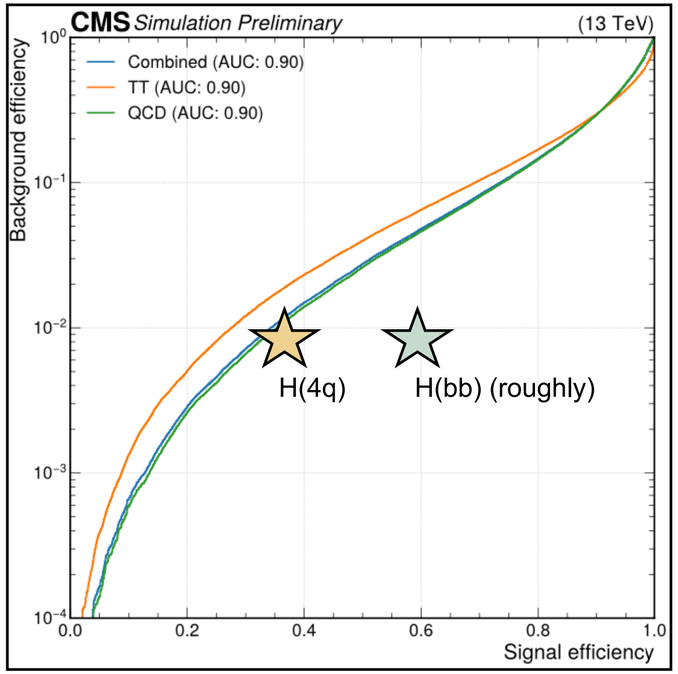
- A “likely” VBF HH(bb VV) event:

bb-tagged Jet



VV-tagged Jet

First use of ParticleTransformer.
Identify **3 or 4 quarks inside a jet:**
30% less efficient than bb



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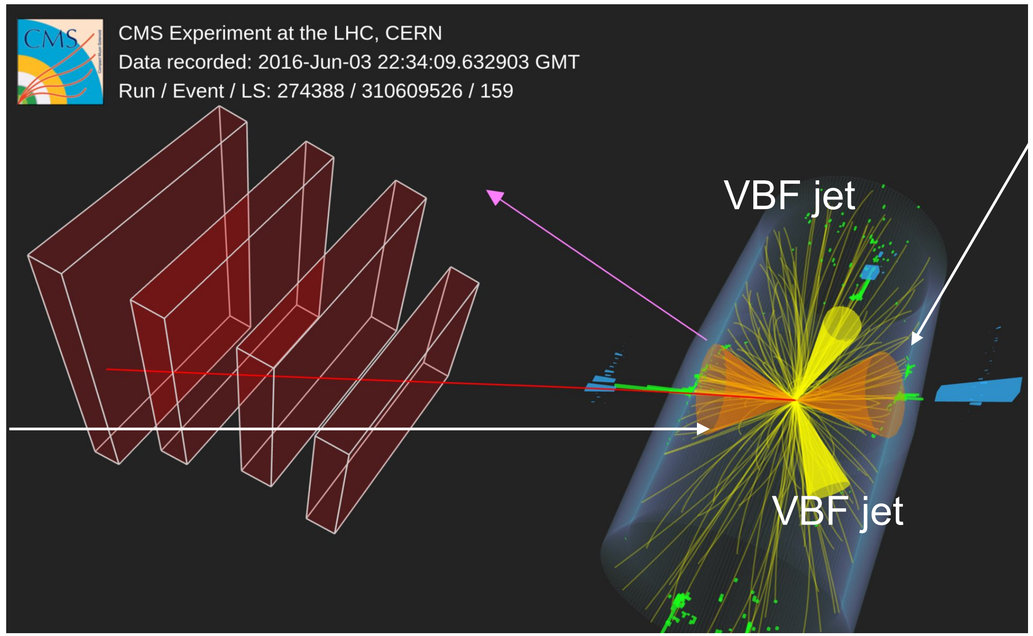

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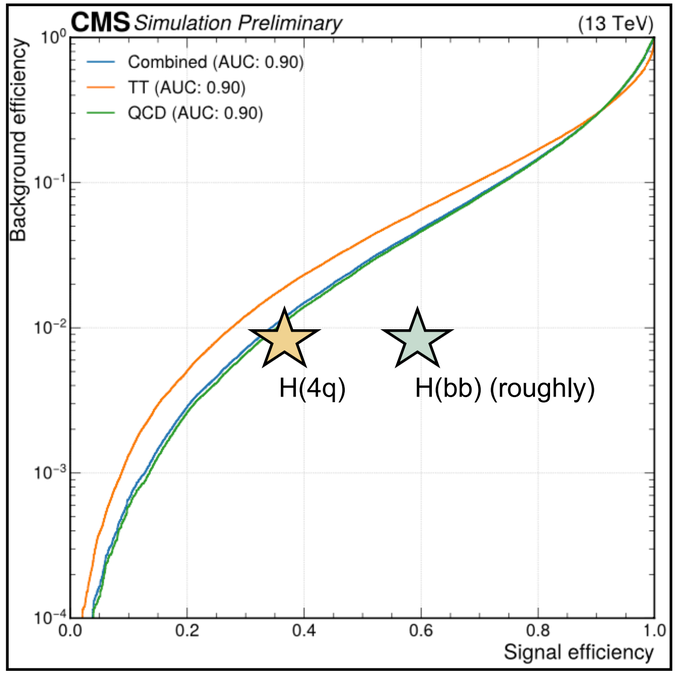
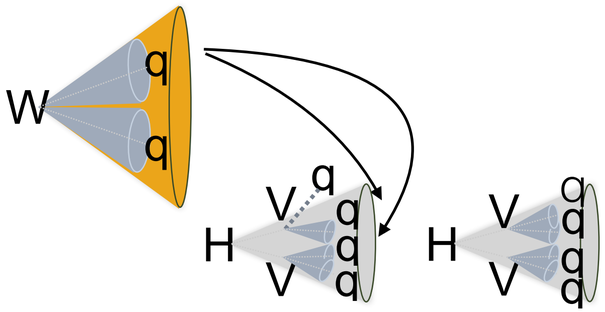
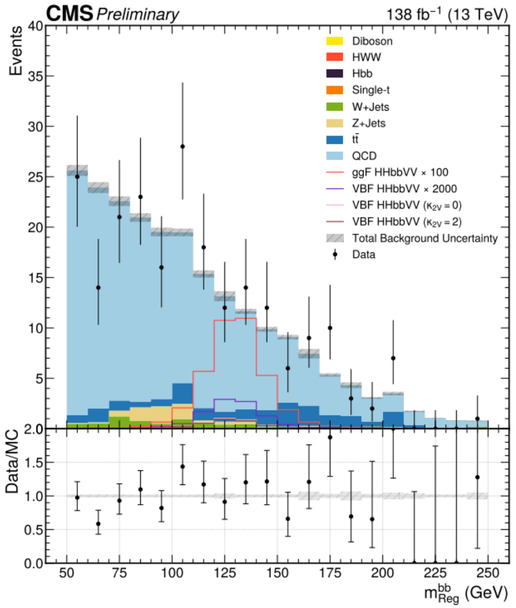


Extra challenge: **calibrate** signal efficiency **per subjet** (see LundPlane poster)

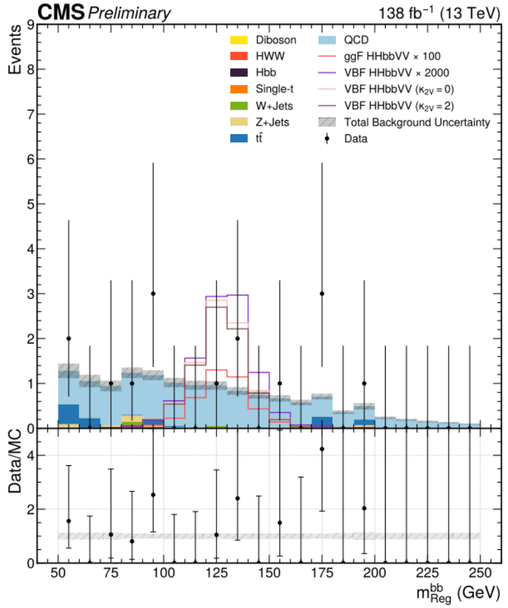


HH (bb VV): results

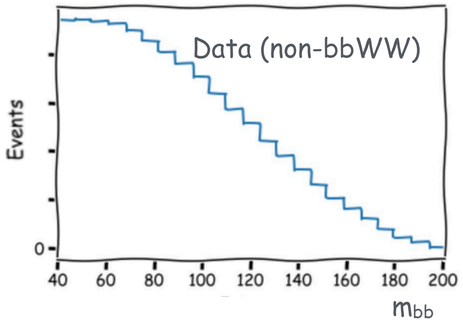
ggF region



VBF region



- Data-driven background
  - Parametric “transfer factor” from QCD enriched region



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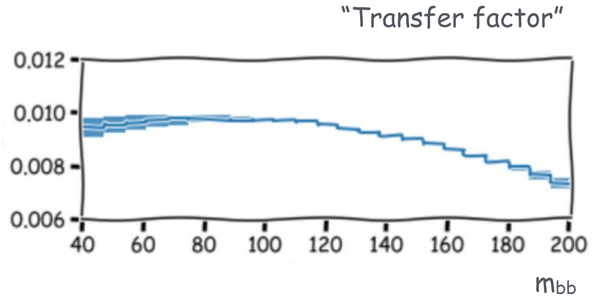

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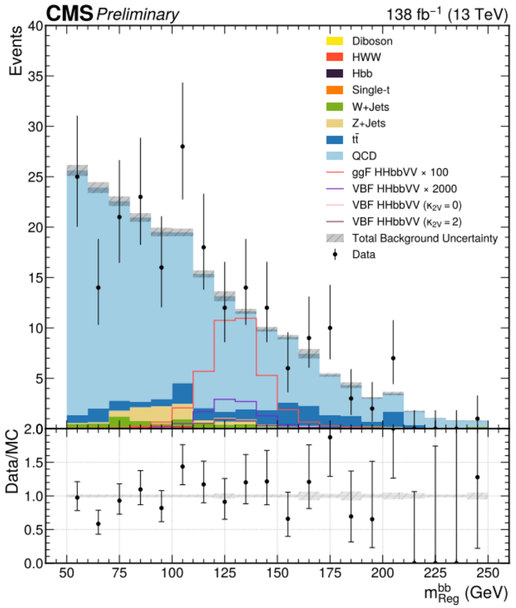

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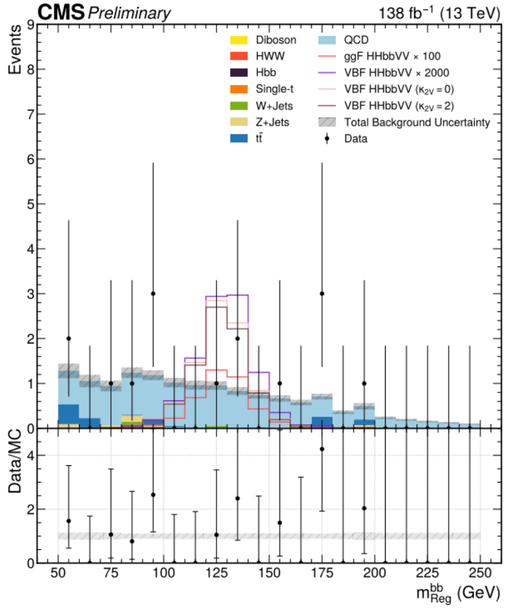

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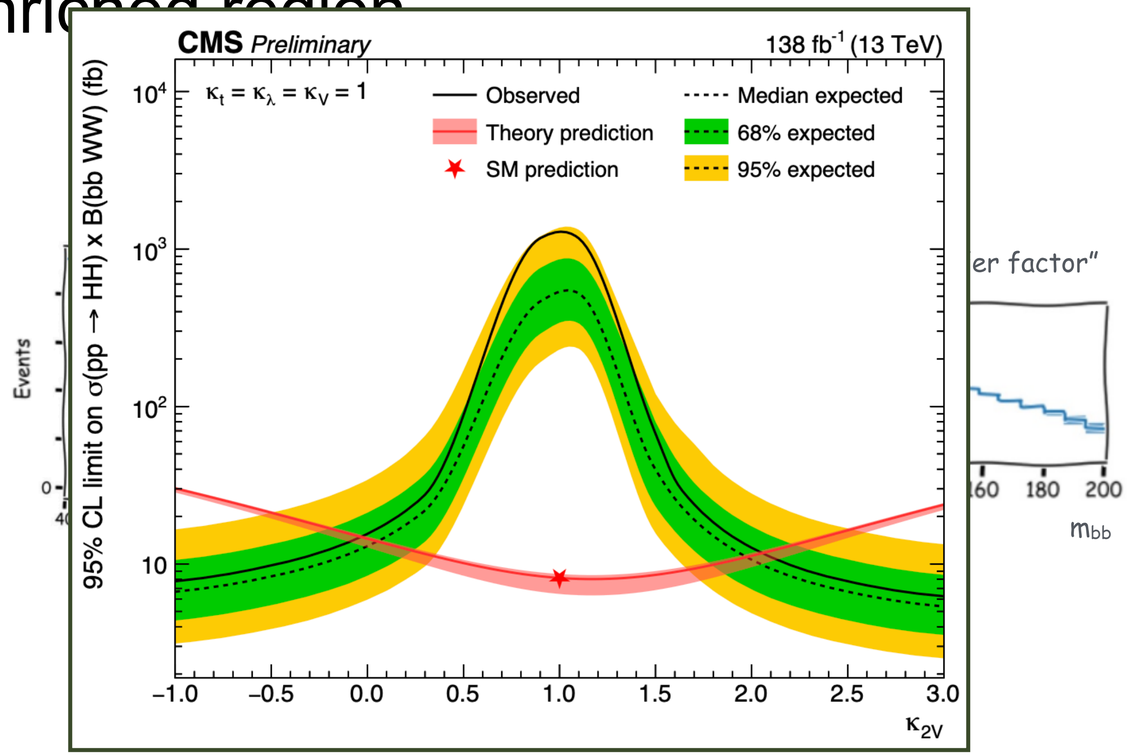
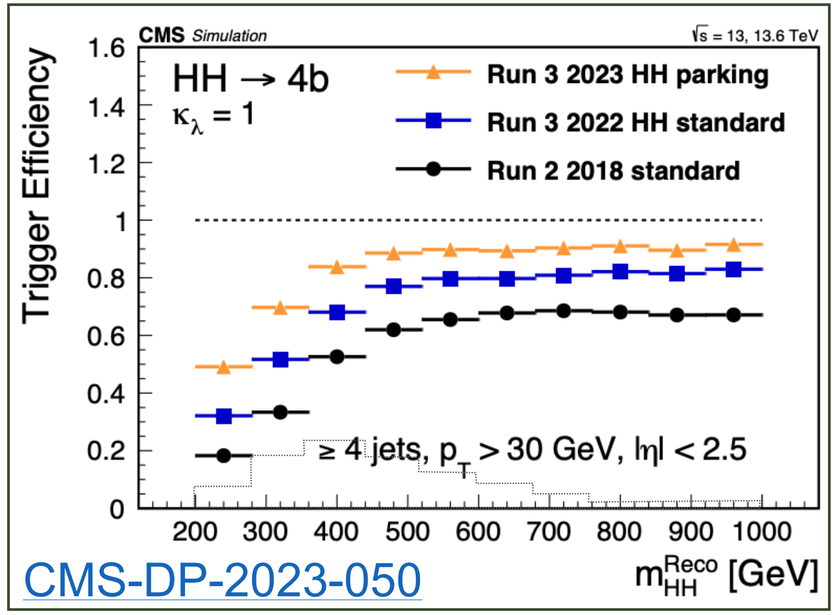


- No relevant constraint to κ_λ
  - SM HH cross section < $(69)142 \times$ SM
- But, powerful constraint on κ_{2V}

$k_{2V} \in [-0.04, 2.05]$

The imminent “future”: Run-3



CMS-DP-2023-050

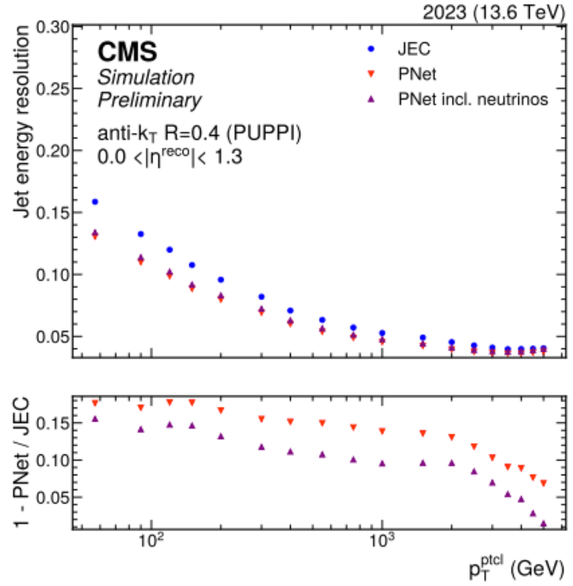
Trigger improvements:

ML in trigger: ParticleNet, DeepTau

Added data streams (“Parking”)

Lower p_T threshold for bbbb, bb$\tau\tau$

CMS-DP-2024-064



Reconstruction improvements:

Jet p_T regression with ParticleNet

improves response resolution by ~15% (after calibration)

Improvements applicable for other bbXX channels (e.g. bb$\gamma\gamma$, bbVV)

Summary

- Extensive study of HH production with Run-2 data
- Exploring “new” channels:
  - Less sensitive but potential in combination
  - Boosted regime: powerful constraints of k_{2V}
- Measurement of κ_λ is a cornerstone of HL-LHC:
  - Well-established search channels
  - Critical to overcome limitations from hadronic triggers and reconstruction
- **Exciting prospects for Run-3**, and 13.6 TeV data!