Di-Higgs results from CMS
(aka, “Twice the Higgs, twice the fun")

Petar Maksimovic, Johns Hopkins
on behalf of the CMS collaboration

Higgs 2021

Goals

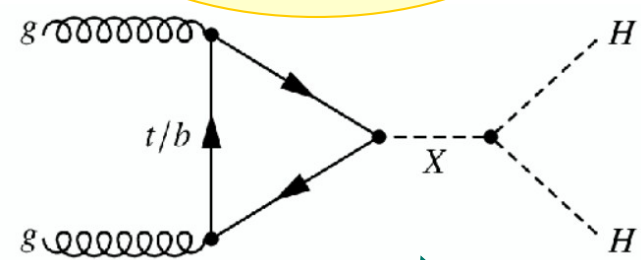
HH

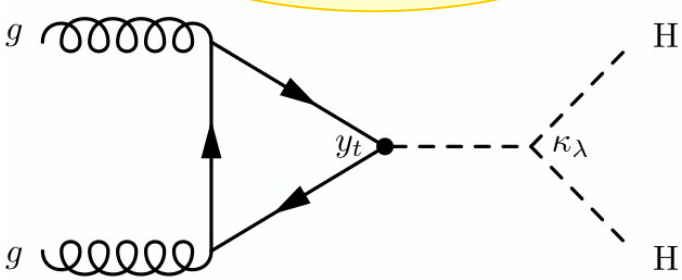
Non-Resonant

Resonant
$X \to HH$

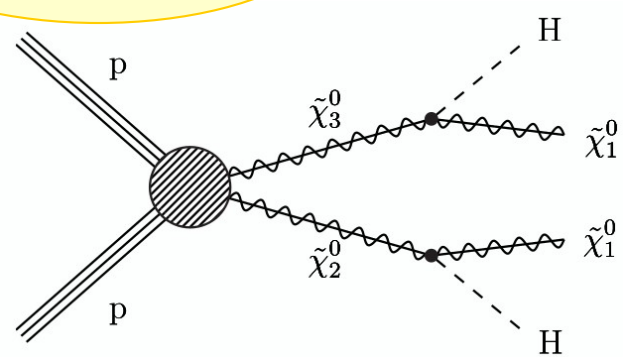
SM production

BSM contributions





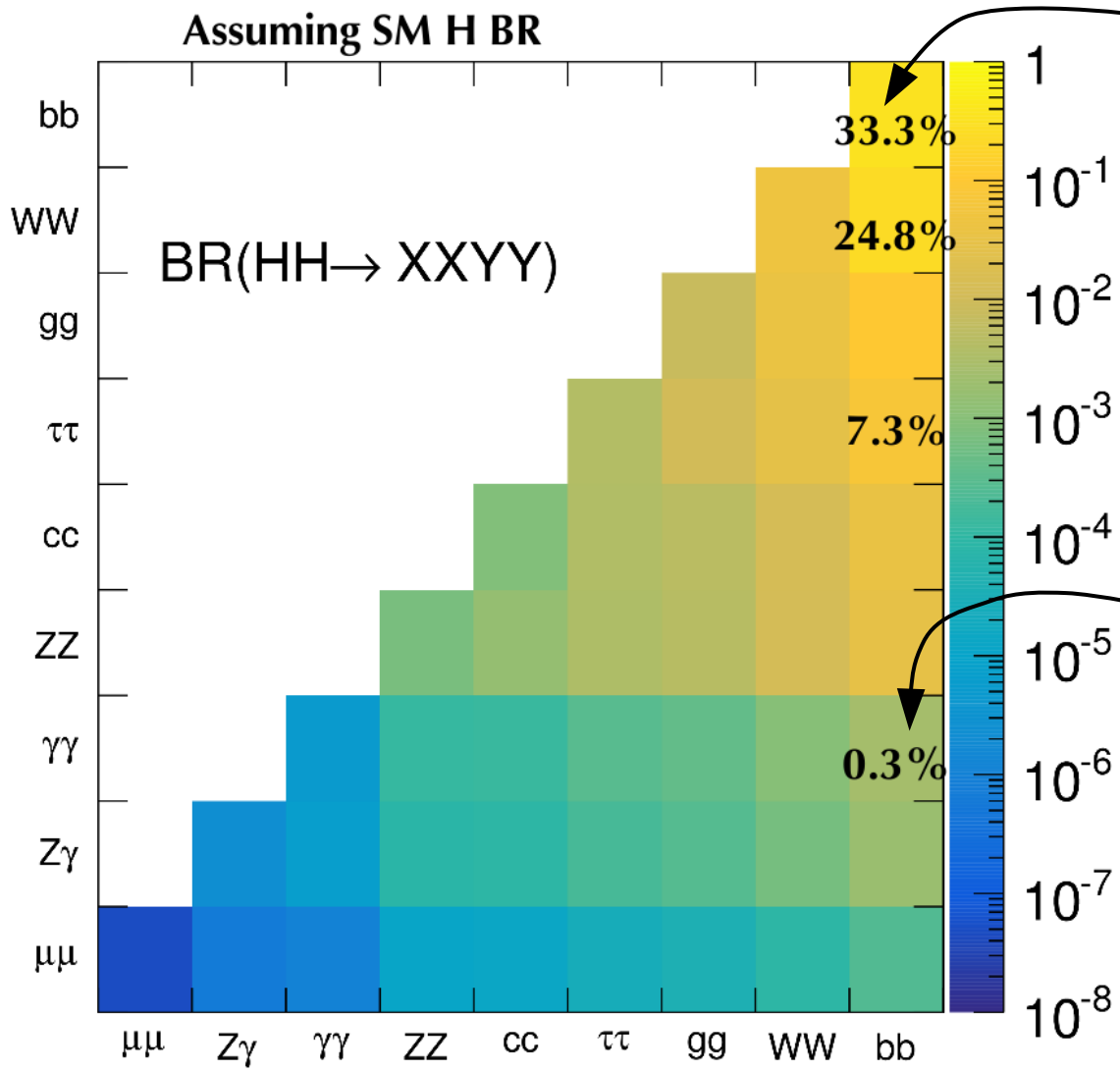
Last missing piece of SM



(Not covered in this talk)

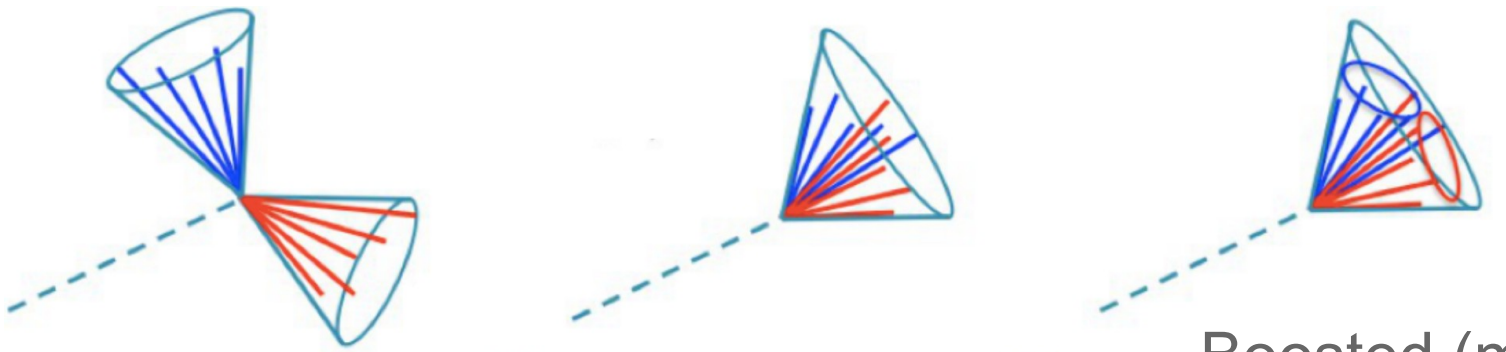
Probing many BSM models

Complementarity of channels



- One extreme: H(bb)
  - largest BR
  - high ϵ_b, low fake rate suppress light QCD background
  - but, bb QCD still high
- The other: H($\gamma\gamma$)
  - low BR, but
  - low backgrounds
  - excellent mass resolution

Kinematic regimes



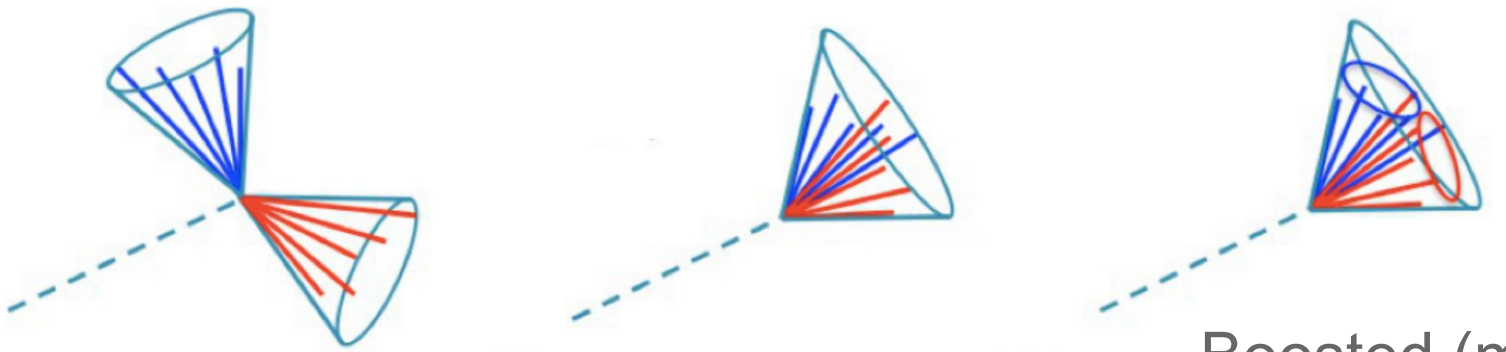
Resolved

- Two small-R jets (“AK4”)

Boosted (merged)

- H decay products in a single large-R jet (“AK8”)

Kinematic regimes



Resolved

- Two small-R jets (“AK4”)

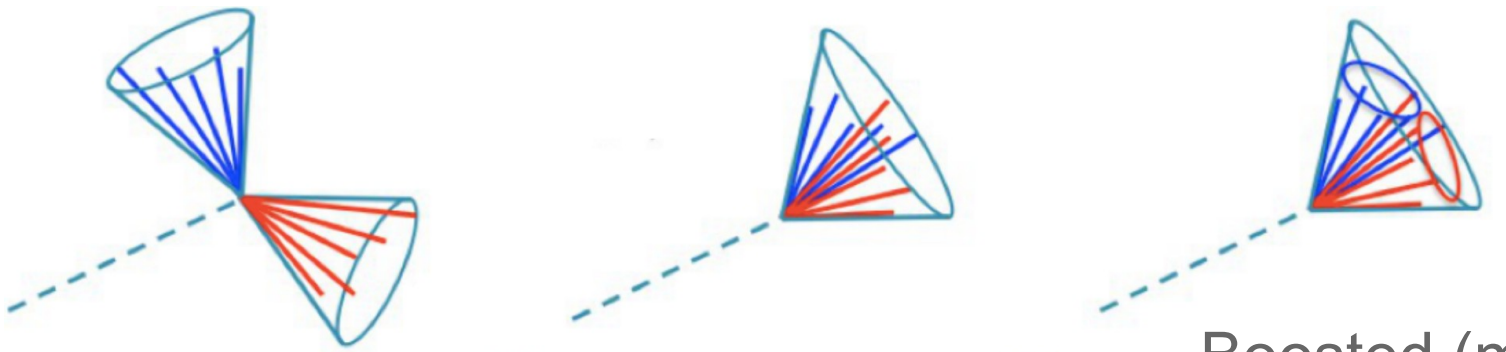
- High signal eff
- Large bkg from QCD

Boosted (merged)

- H decay products in a single large-R jet (“AK8”)

- Combinatorics “solved”
- Cutting-edge substructure tools

Kinematic regimes



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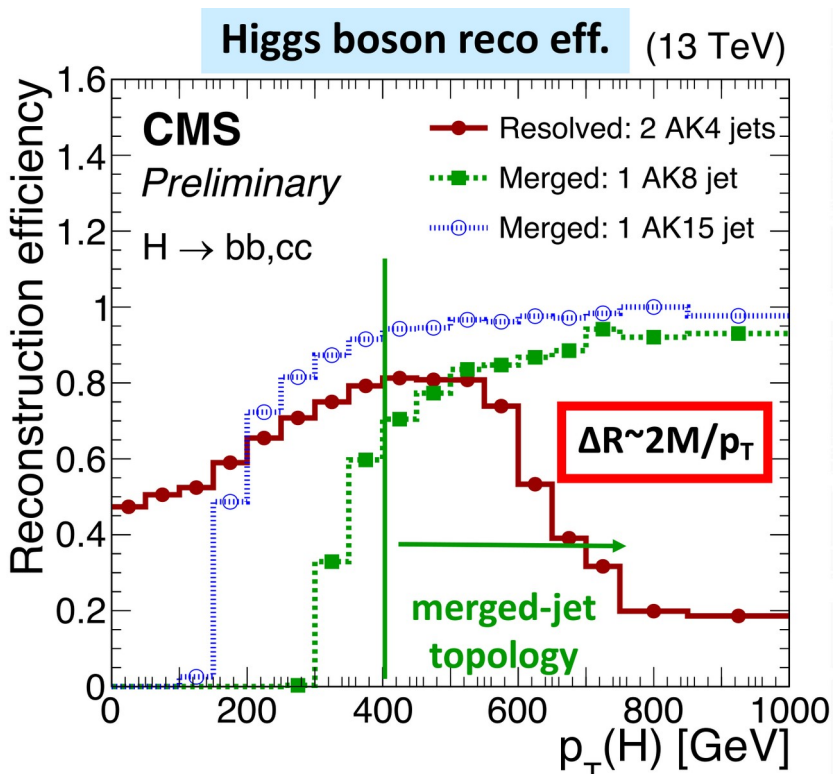
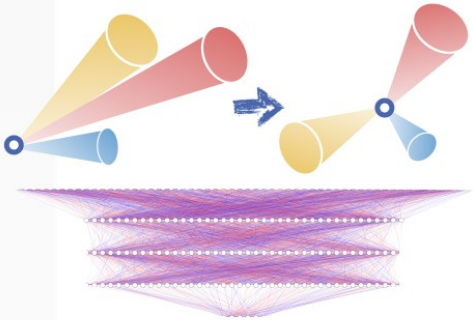


- H decay products in a single large-R jet ("AK8")
- Combinatorics "solved"
- Cutting-edge substructure tools

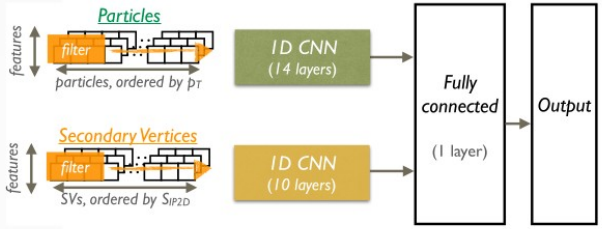
(Evolution of) Boosted H→bb algorithms

BDT *(high-level inputs)*

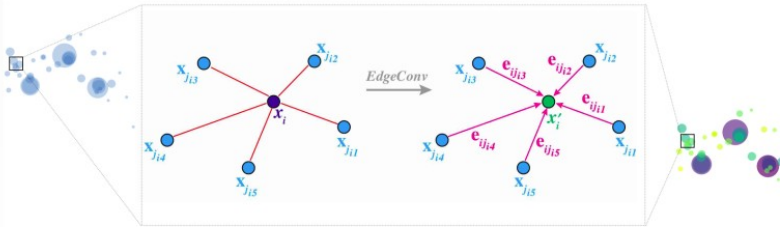
feed-forward NN *(high-level inputs)*



1D/2D CNN, RNN *(low-level inputs)*

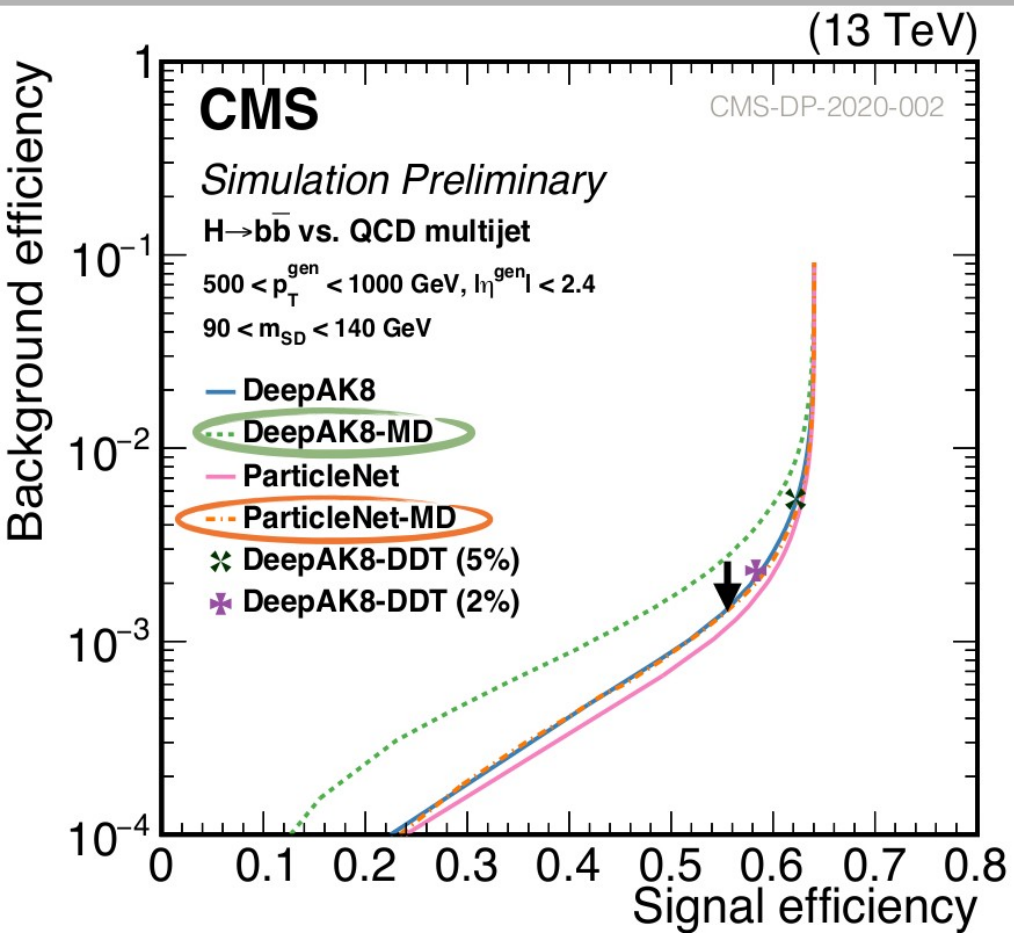


graph NN *(low-level inputs)*



- "double-b": HH results in 2016
- "Deep double-b": single boosted H→bb
  - Outperforms double-b by ~ x2
- "DeepAK8": X→HH searches in this talk
  - Slightly better ...
- "ParticleNet": VBF HH→4b in this talk
  - Outperforms DeepAK8 by ~x2

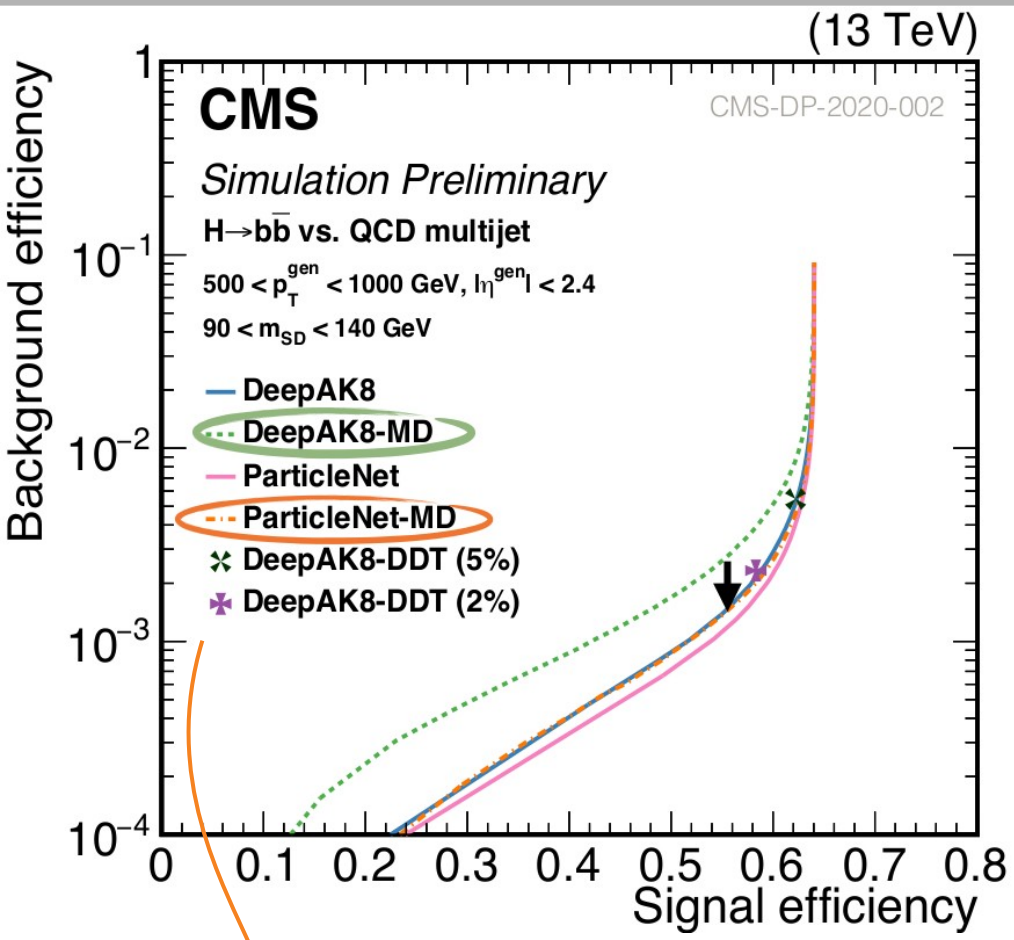
ParticleNet: state-of-the-art ML Hbb tagger



- Jet as a “particle cloud”
- Graph Neural Network
- Mass regression

  (~ 20% improvement)

ParticleNet: state-of-the-art ML Hbb tagger



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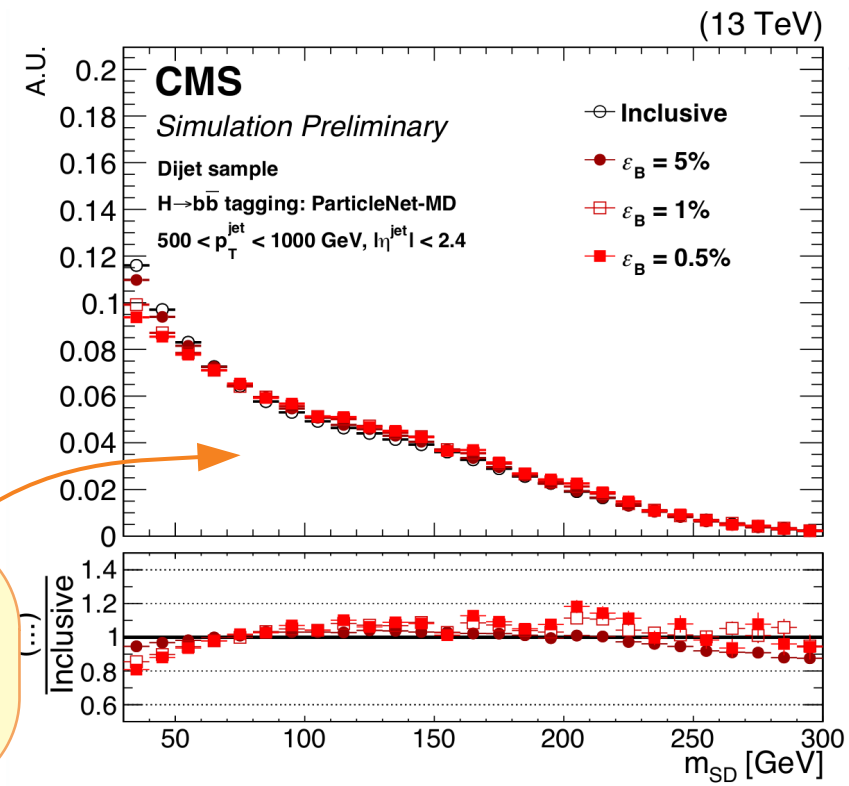
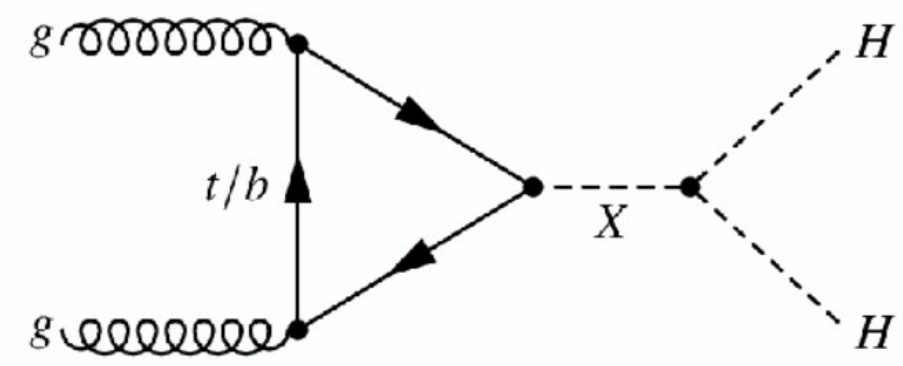


MD = "Mass Decorrelated"
No sign of sculpting of jet mass.
(crucial for bkg estimate!)

Resonant HH searches

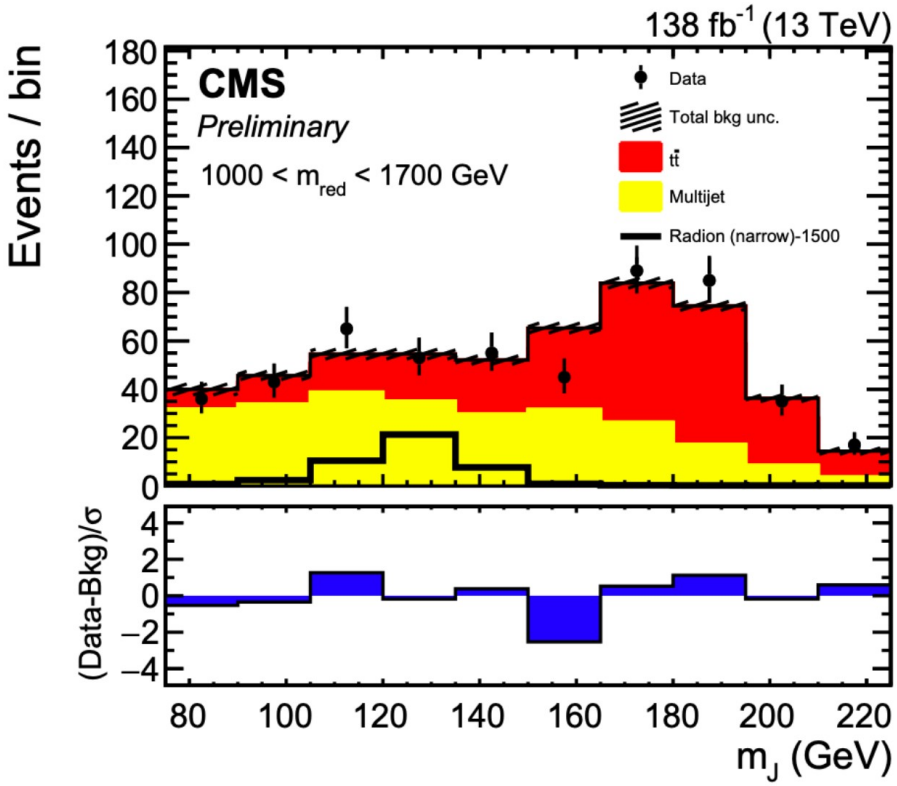
Two benchmark models for X:

- Radion (spin-0)
- Bulk graviton (spin-2)

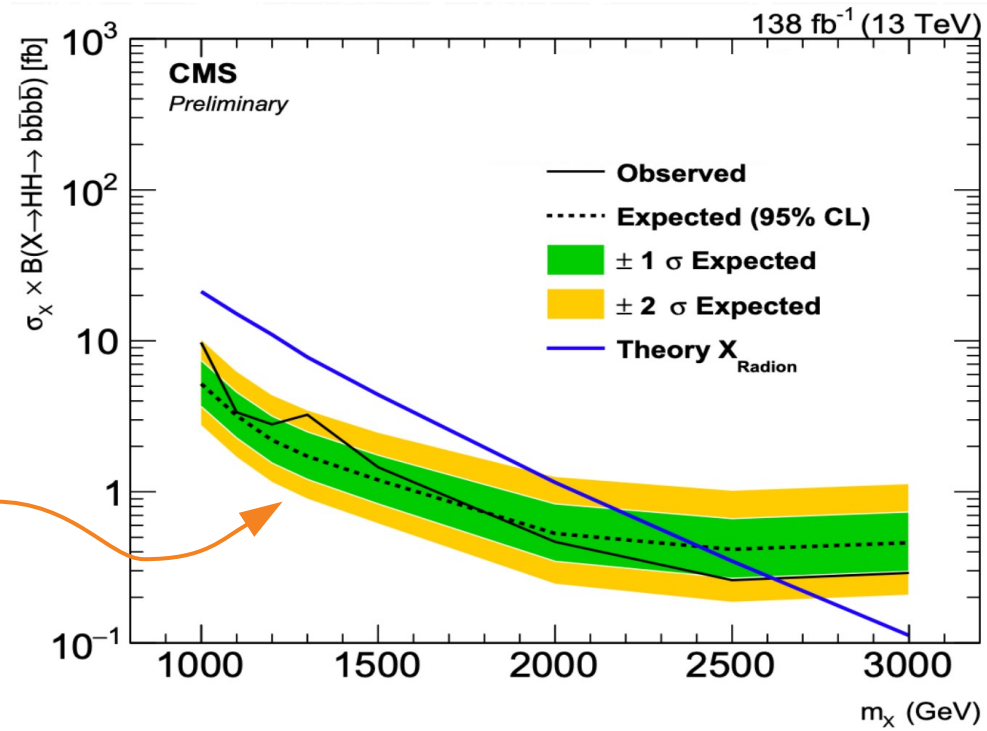


X→HH→4b (boosted)

B2G-20-004



- Two large-R jets (DeepAK8 Hbb)
- Or one large-R and two small-R jets (= semi-resolved channel)
- Bkg: dominant QCD from data, $t\bar{t}+\text{jets}$ templates from MC, fit to data in 2D ($m_{b\bar{b}}$ vs m_X)



In this channel,
the strongest limit to date!

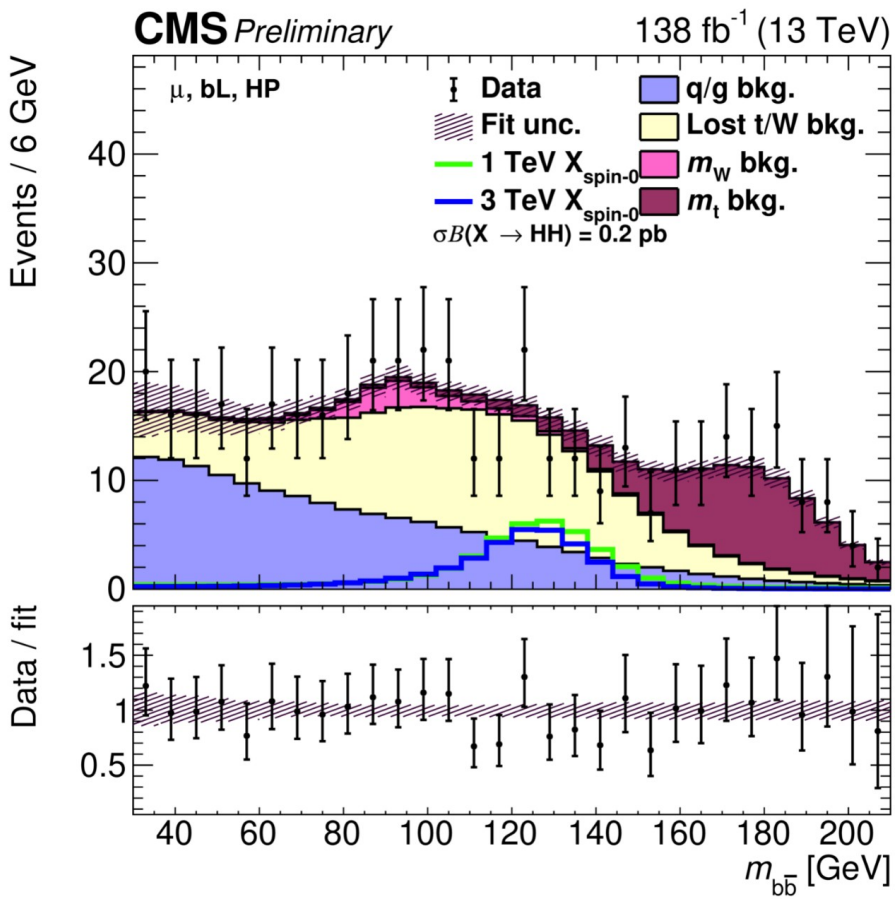
(Improvement by ~1 TeV
w.r.t 2016 result.)

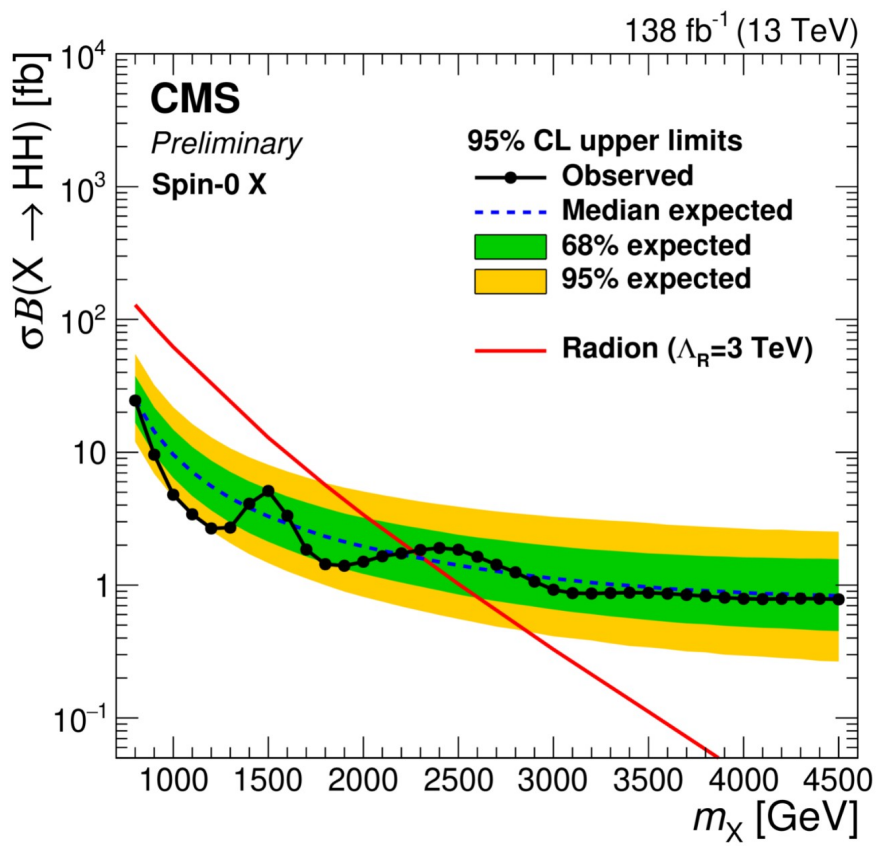
X→HH→bbWW→bb+lqq or bb+2l

B2G-20-007

- H→bb with DeepAK8 Hbb tag
- H→WW* or H→$\tau\tau$:
  - Two isolated leptons, or
  - Lepton + jet w/ 2-prong substr.

- Bkg: largest $t\bar{t}$ and $W + \text{jets}$ from templates fit to data
- Simultaneous 2D fit of $m_{b\bar{b}}$ vs m_X in 12 regions





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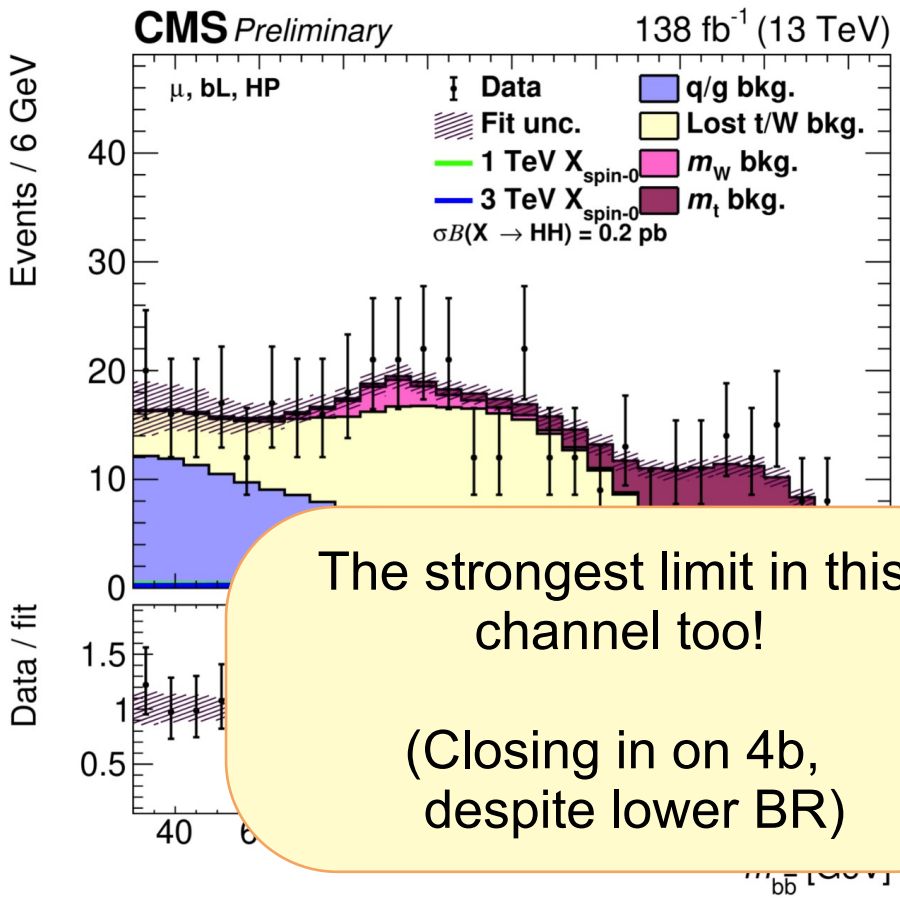
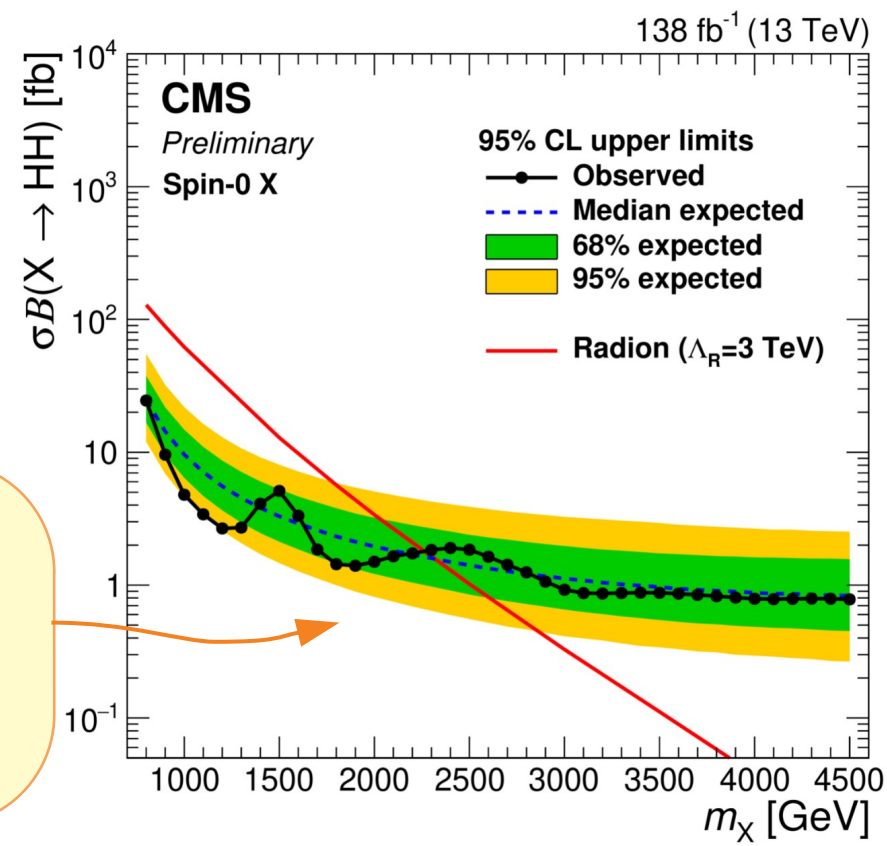




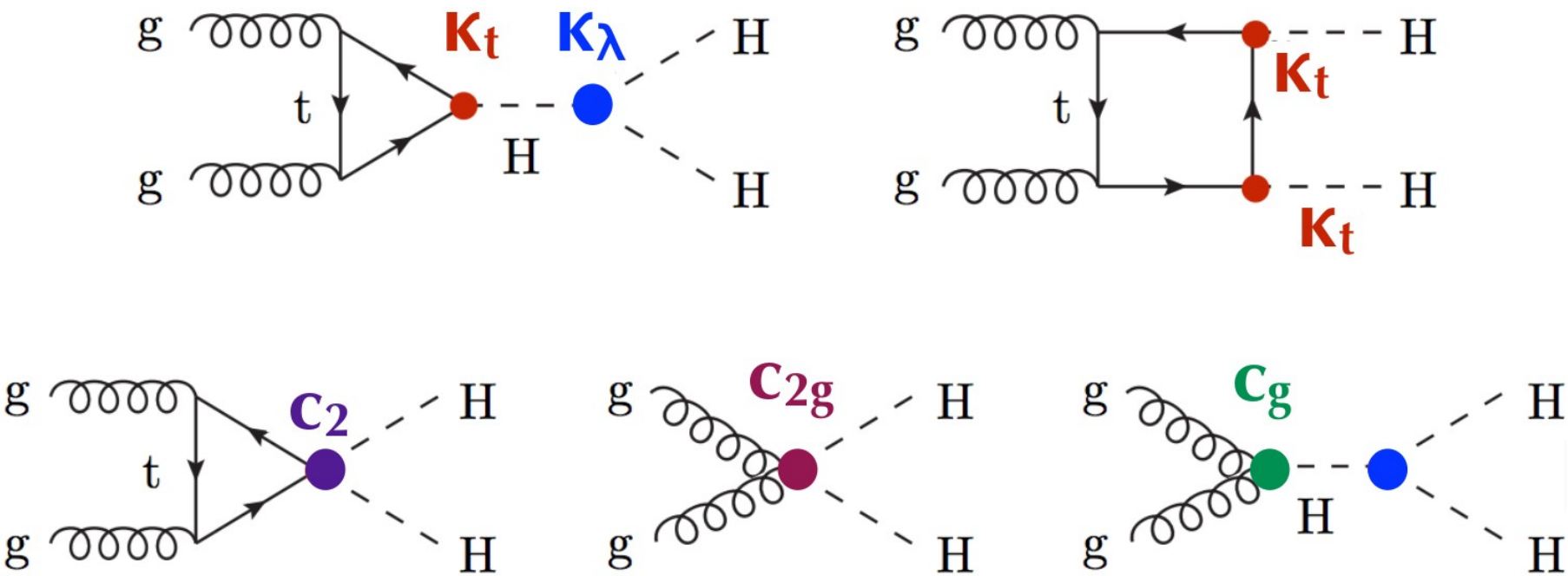
The strongest limit in this channel too!

(Closing in on 4b, despite lower BR)

Non-resonant HH searches (SM and BSM)

HH in BSM (non-resonant)

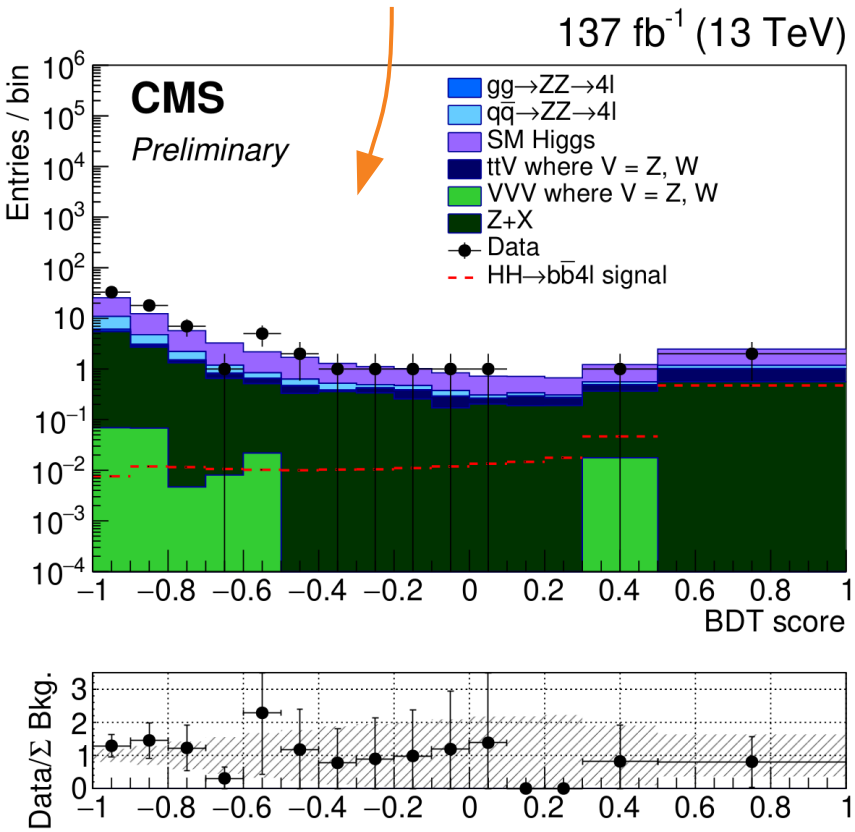
- BSM: dimension 6 operators. Parameterize using EFT approach:
  - modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ and $\kappa_t = y_t/y_{t,SM}$
  - three new interactions: c_2, c_{2g}, c_g

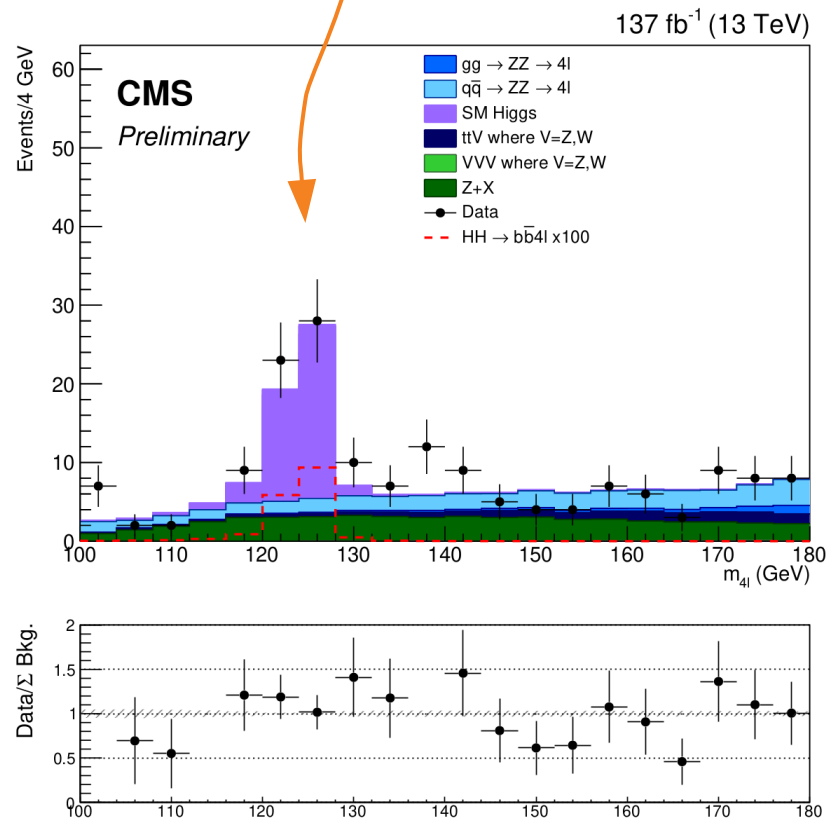


Non-resonant HH→bbZZ*(4l) (resolved)

HIG-20-004

- 2 pairs of OS leptons (4μ, 4e, 2e2μ) + 2 b-jets
- SR: $N_{\text{jets}} \geq 2$ and $|m_{4l} - 125| < 10$ GeV
- Bkg: largest is single Higgs production!
- Fit: BDT score





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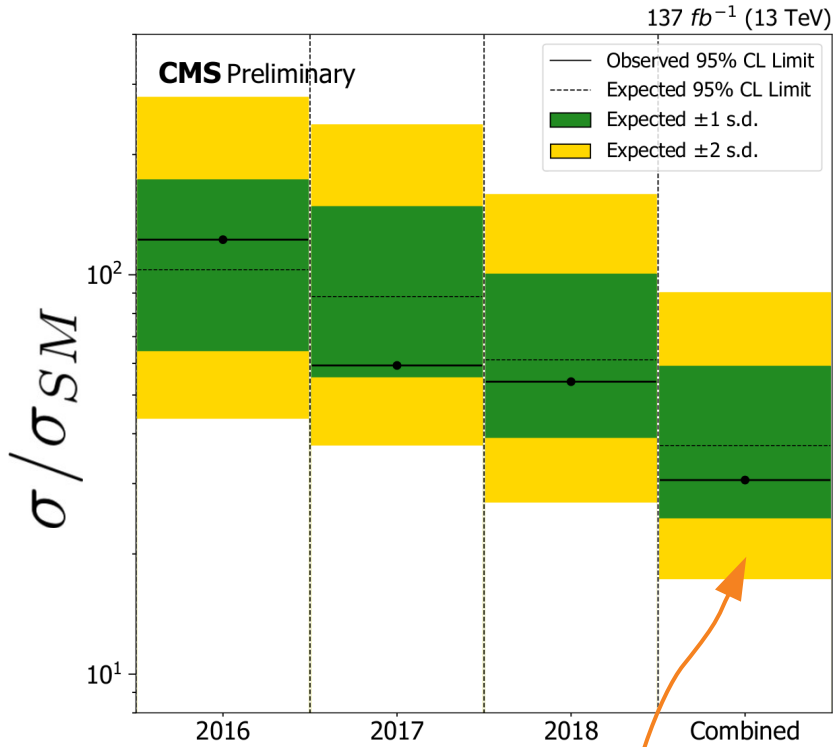
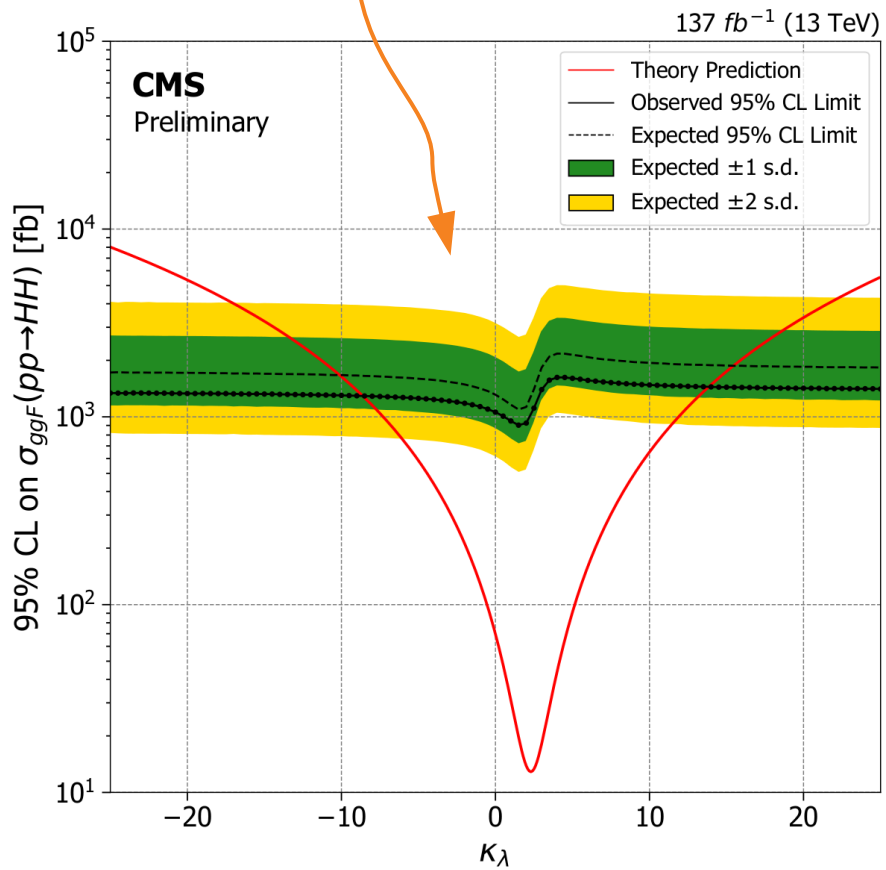


Upper limit on σ/σ_{SM} ~ 30

- Allowed (95% CL): $-9 < \kappa_\lambda < 14$



Non-resonant HH→bbγγ (resolved)

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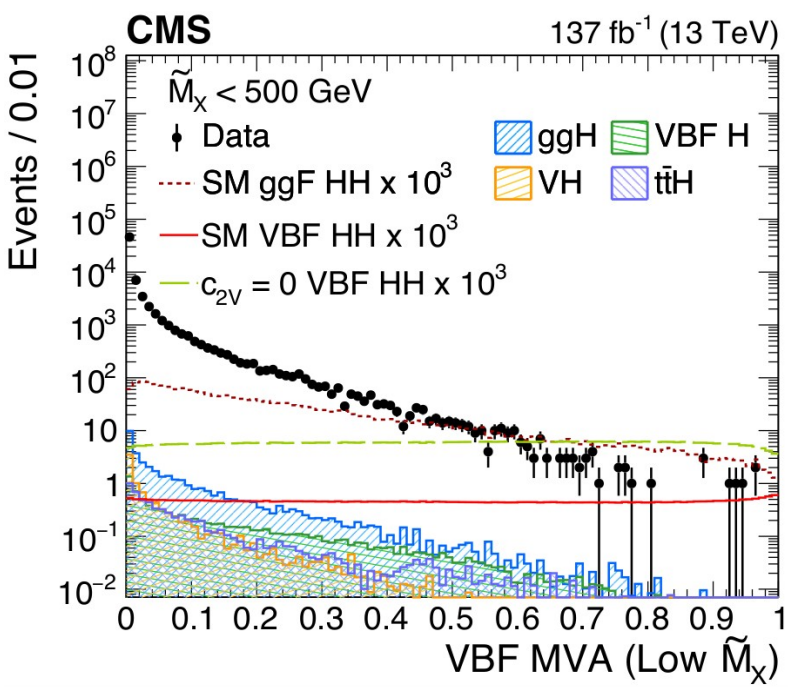
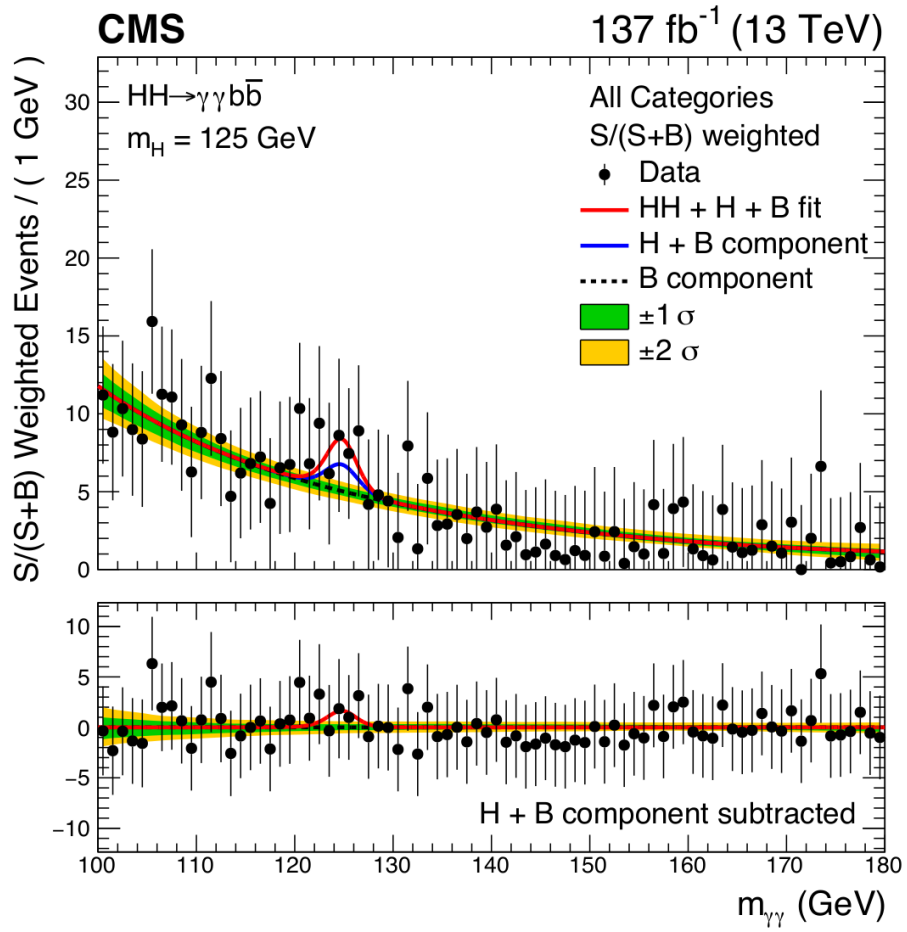
- Two small-R b-jets
- Novel $H \rightarrow b\bar{b}$ jet energy regression
- DNN rejects $t\bar{t}H$ bkg
- BDTs enhance ggF & VBF
- 14 search regions





Non-resonant HH→bbγγ (resolved)

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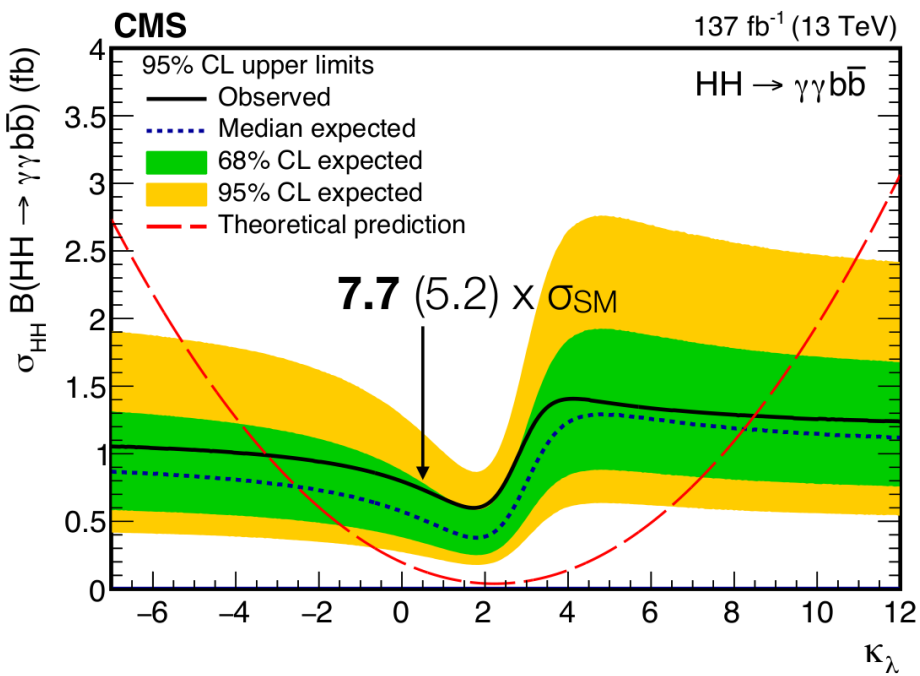
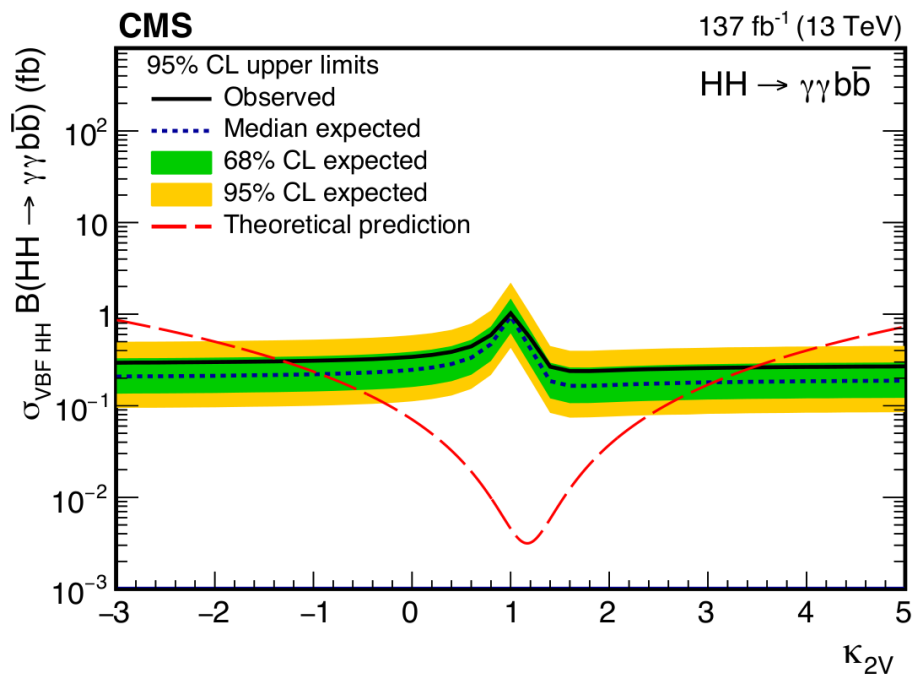




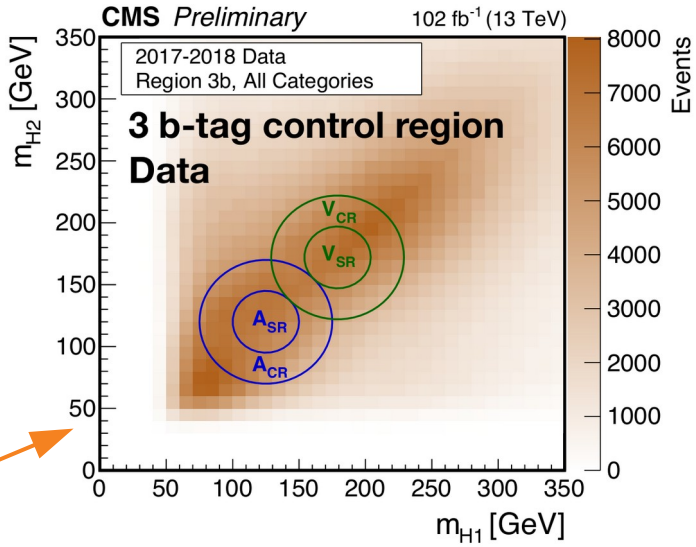
- Allowed (95% CL): $-3.3 < \kappa_\lambda < 8.5$
- Allowed (95% CL): $-1.3 < \kappa_{2V} < 3.5$

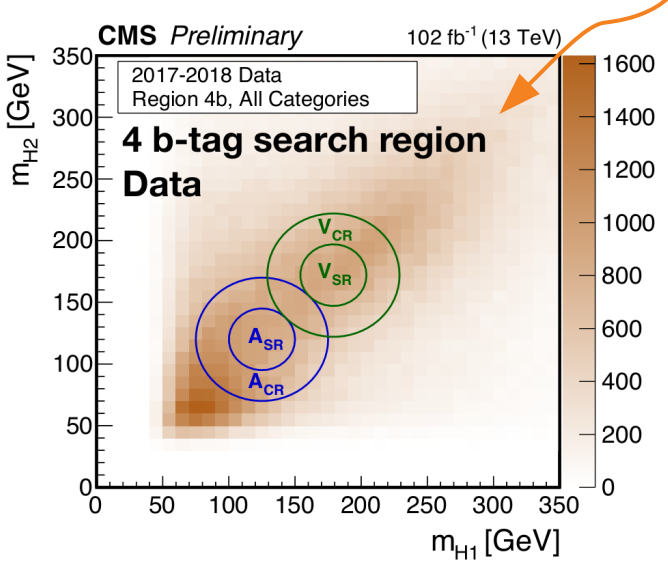
Sensitivity for the SM HH production improved by a factor of ~4 w.r.t. 2016-only result!

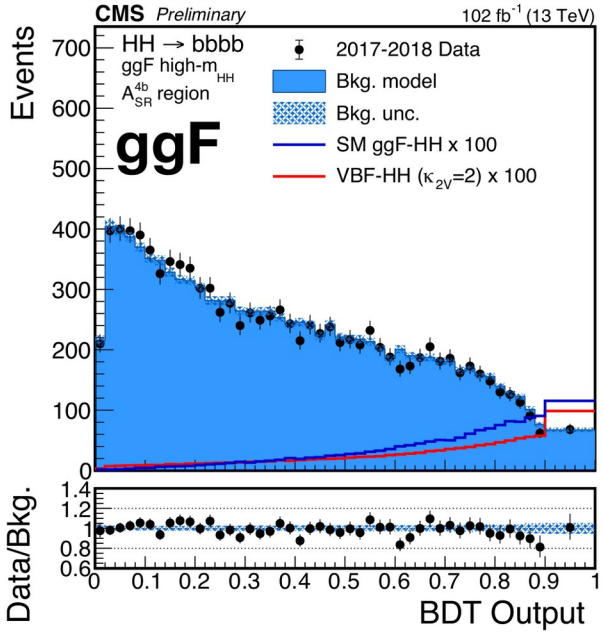
Non-resonant HH→4b (resolved) + VBF

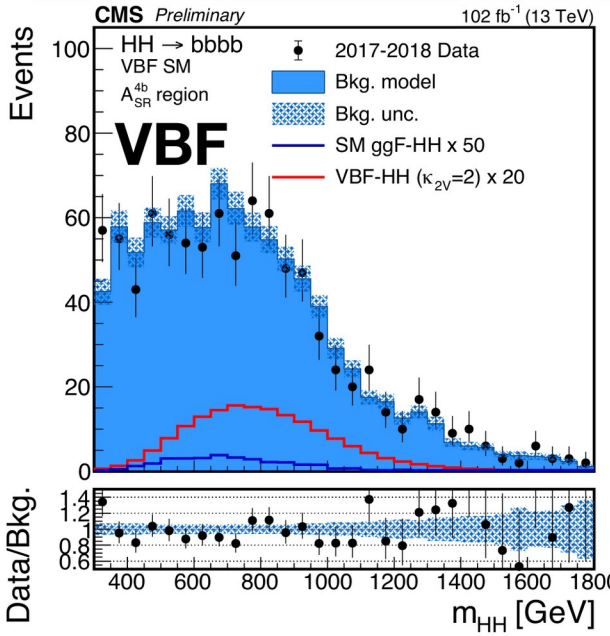
HIG-20-005

- 4 small-R b-tagged jets
- Multivariate energy regression
- New algo to build two H→bb candidates: 96% accurate
- Bkg: estimated from 4 jet / 3 btag region with BDT reweighting



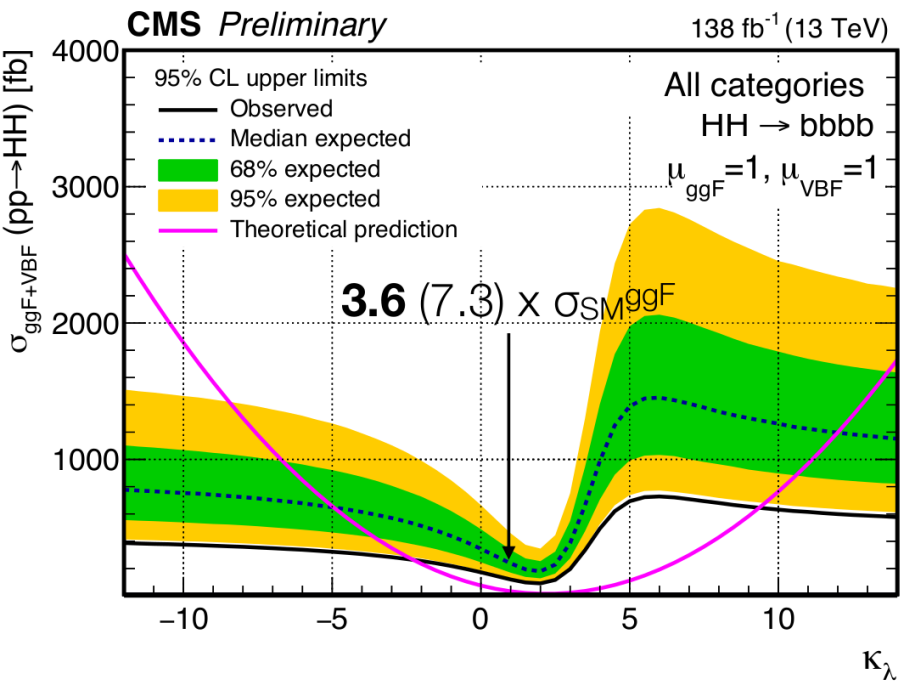


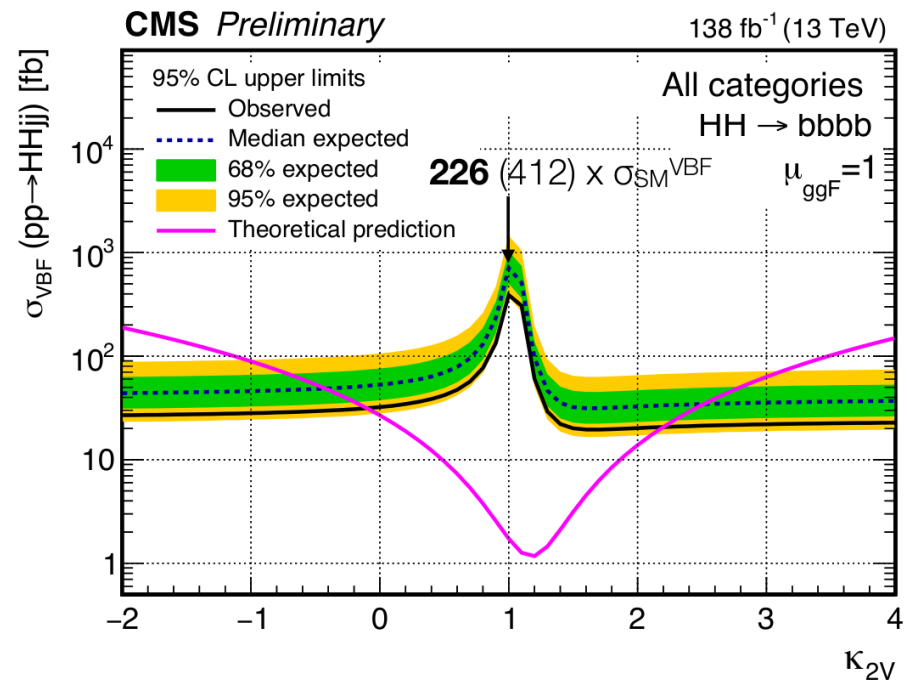




Non-resonant HH→4b (resolved) + VBF

HIG-20-005

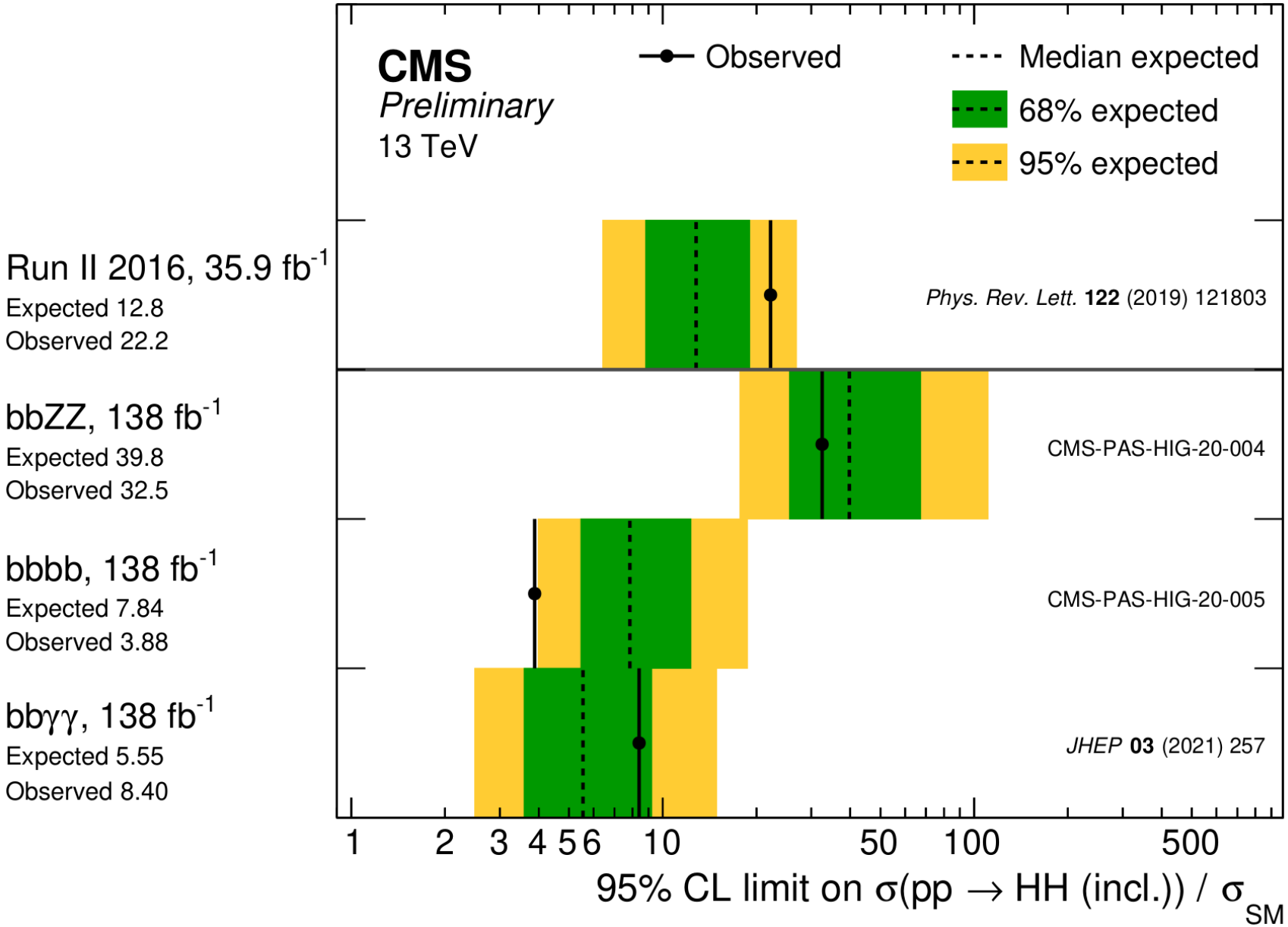




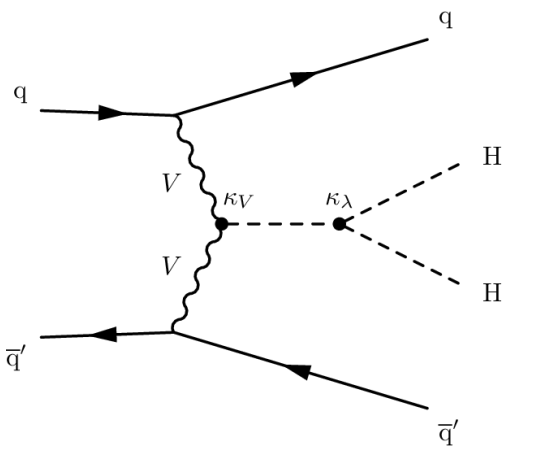
- Allowed (95% CL): $-2.3 < \kappa_\lambda < 9.4$
- Allowed (95% CL): $-0.1 < \kappa_{2V} < 2.2$

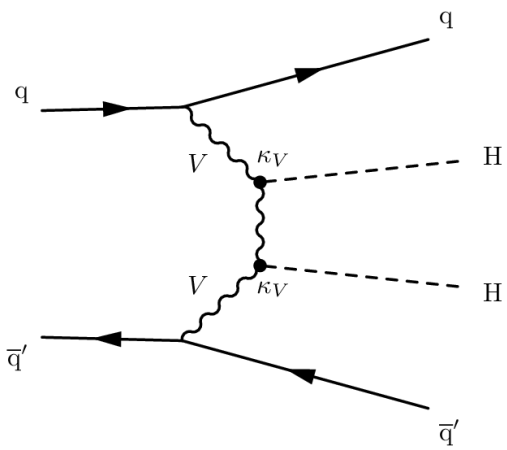
Strongest upper limits on ggF HH cross-sections with SM couplings!

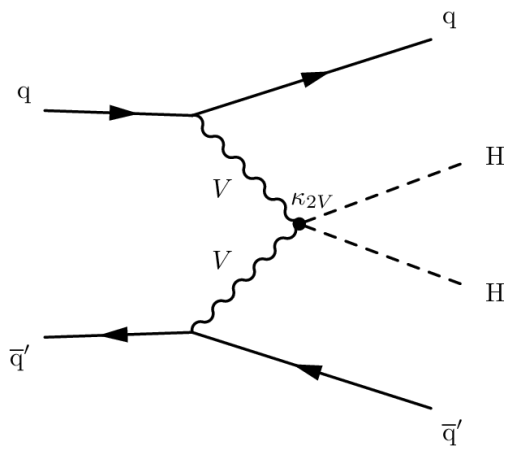
Comparison of limits on $\sigma/\sigma_{\mathrm{SM}}$



Non-resonant VBF HH→4b (boosted)







Negligible for high m_{HH}
(highly off-shell...)

Nearly cancel for $\kappa_V = 1,\ \kappa_{2V} = 1$

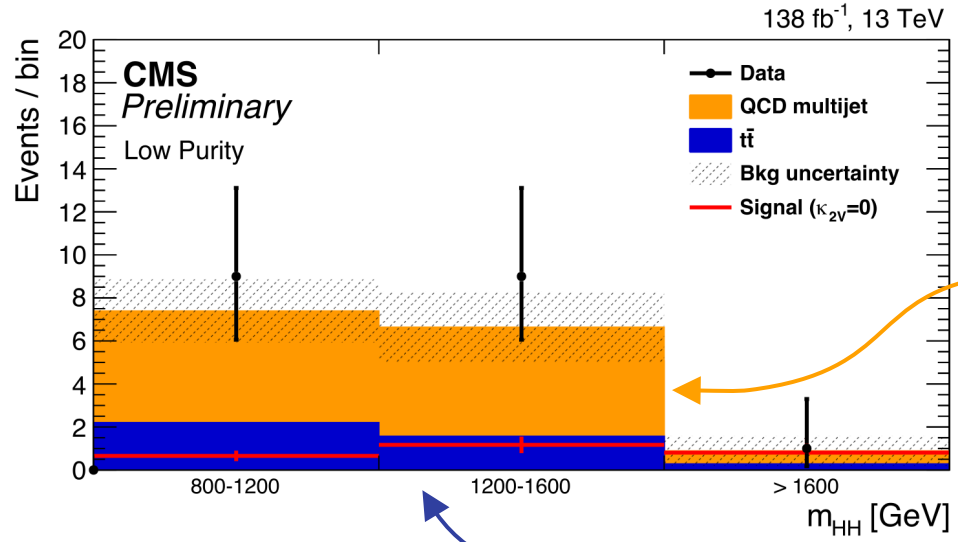
- Leading contribution to scattering amplitude:

$$\mathcal{A}(V_L V_L \to HH) \approx \frac{\hat{s}}{v^2}(\kappa_{2V} - \kappa_V^2)$$

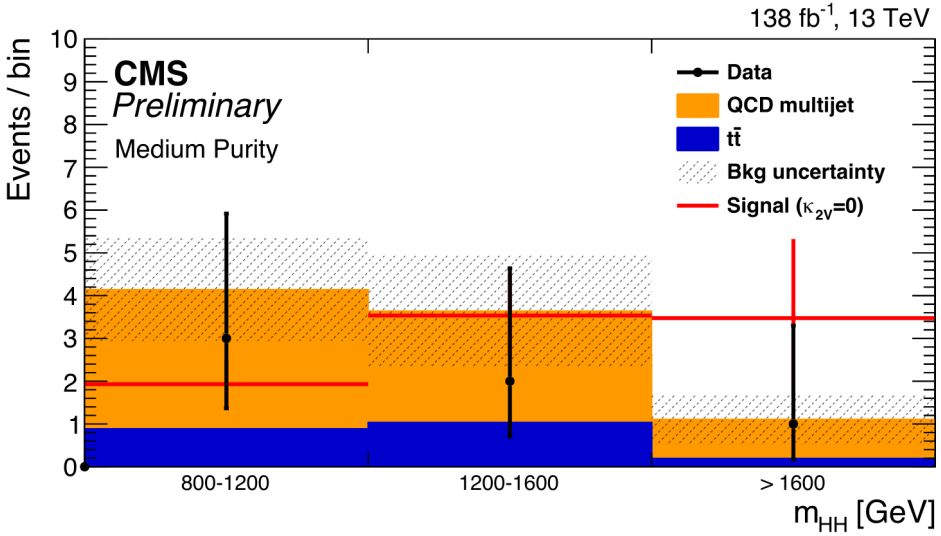
- Focus on events with high m_{HH}! → Two boosted H→bb jets
- The only channel with direct access to $HHVV$ coupling

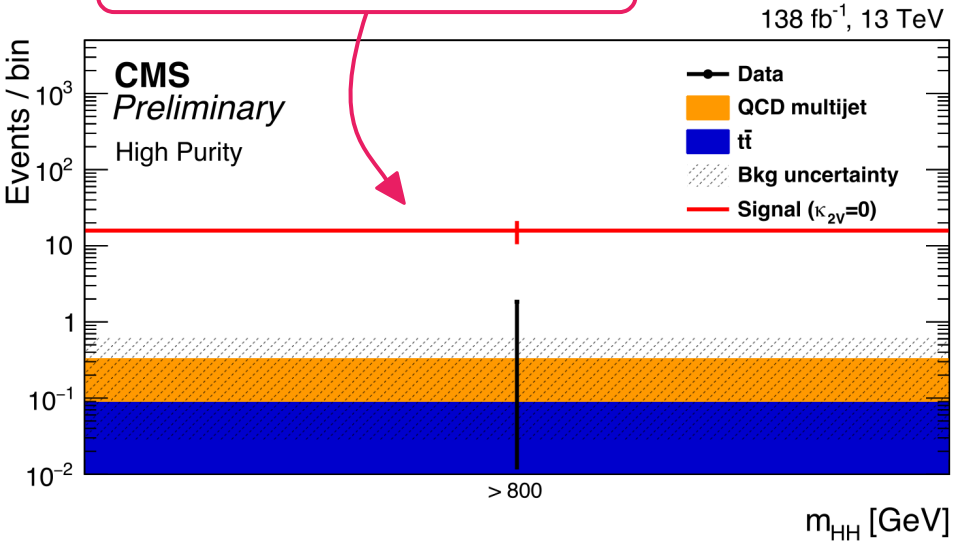
Non-resonant VBF HH→4b (boosted)

B2G-21-001



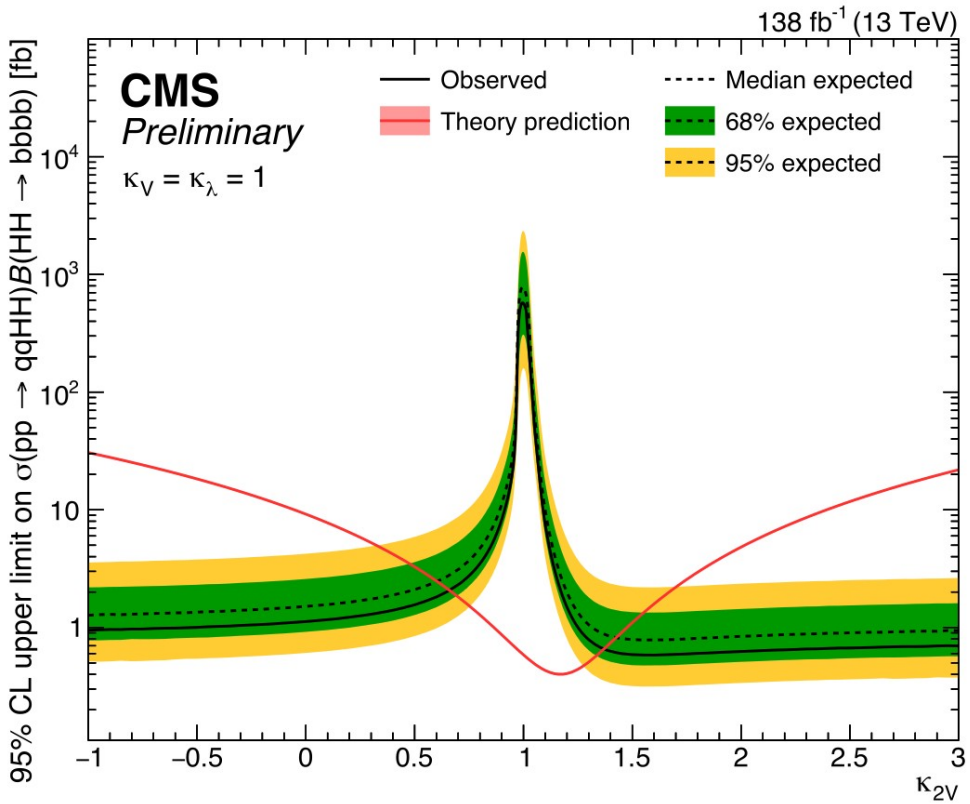
- Three disjunct regions (low, medium, high purity)
- Bkg: ABCD for QCD
  - (Possible because of mass decorrelation)
- $t\bar{t}$ from templates, fit to data.
- $\kappa_{2V} = 0$ scenario

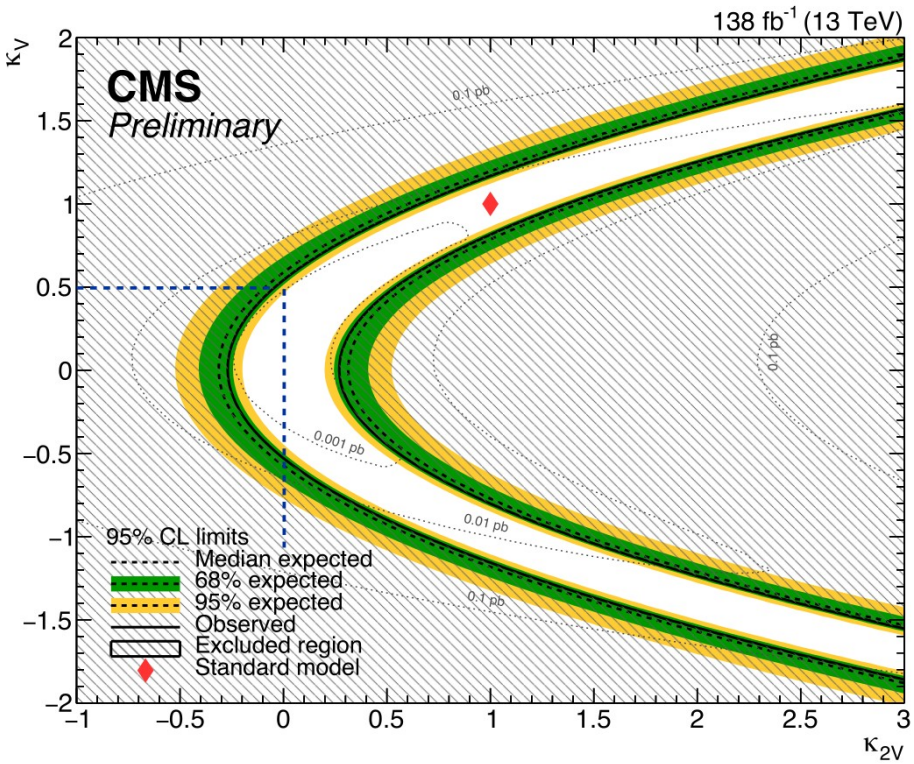




Non-resonant VBF HH→4b (boosted)

B2G-21-001





- Allowed: $0.6 < \kappa_{2V} < 1.4$

Strongest constraint on κ_{2V} to date!

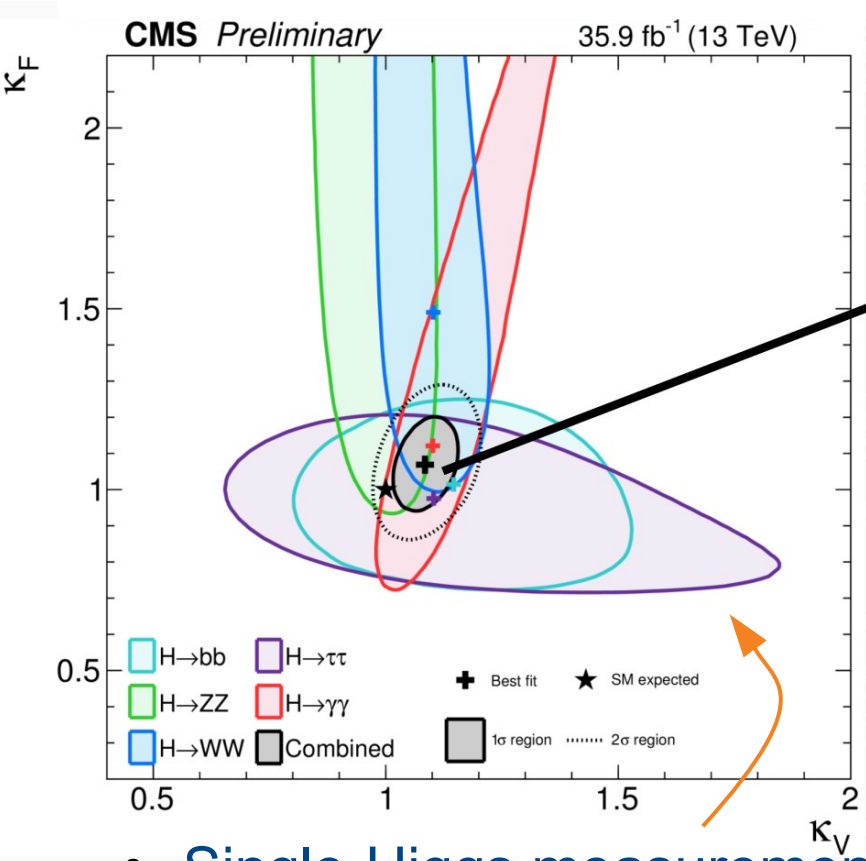
First evidence that $\kappa_{2V} > 0$

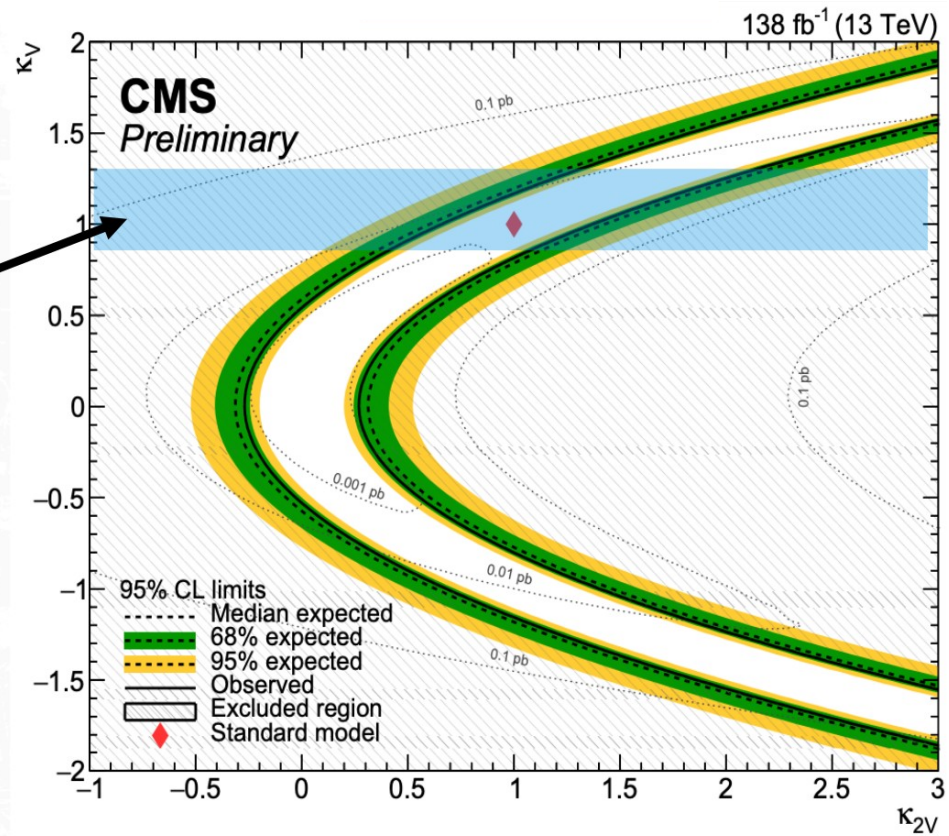
- 2D scan excludes $\kappa_{2V} = 0$ when $\kappa_V > 0.5$, with other couplings fixed to SM

$$\mathcal{A} \approx \frac{\hat{s}}{v^2}(\kappa_{2V} - \kappa_V^2)$$

Non-resonant VBF HH→4b (boosted)

B2G-21-001





- Single-Higgs measurements provide tightest constraints on κ_V
- Combined: $\kappa_V \sim 1.1$ with O(20%) at 2σ

$\kappa_{2V} = 0$ hypothesis highly disfavored when constraints on κ_V are considered

Summary

- CMS has a vibrant and exciting HH program
  - Only recent results shown today
- Inching closer to $\kappa_\lambda = 1$
- Significant improvements in VBF measurements
  - No HHVV coupling $(\kappa_{2V} = 0)$ is disfavored
- Experimentally, big strides forward in boosted H→bb jet tagging:
  - ParticleNet is the most performant on the market
  - Has excellent mass decorrelation (helps bkg estimates)
  - Same platform used for mass regression
- Finish Run 2 combinations and looking forward to Run 3!

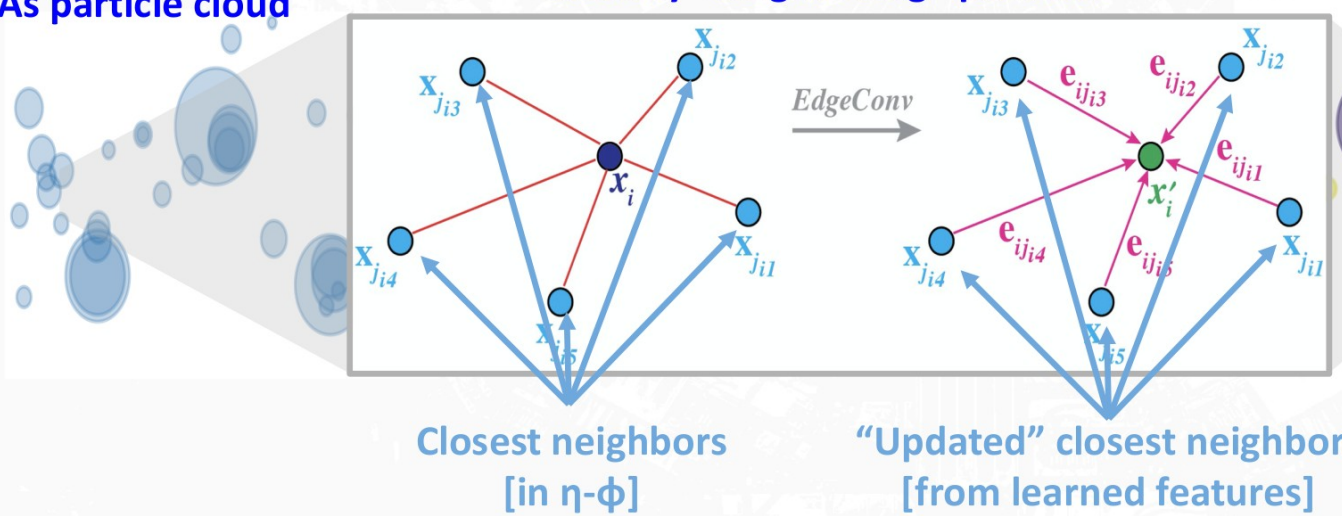
BACKUP MATERIAL

ParticleNet: state-of-the-art ML Hbb tagger

- Jet = a "particle cloud" (unordered set)
  - Architecture: Graph Neural Network
  - Input: particle flow candidates + secondary vertices
- Hierarchical learning approach
  - First learn "local" structures, next learn more "global" features
  - Treat the particle cloud as a graph:
    - **Particles** are the **vertices** of the graph
      Relationships between the particles are the **edges** of the graph

Jet:
As particle cloud

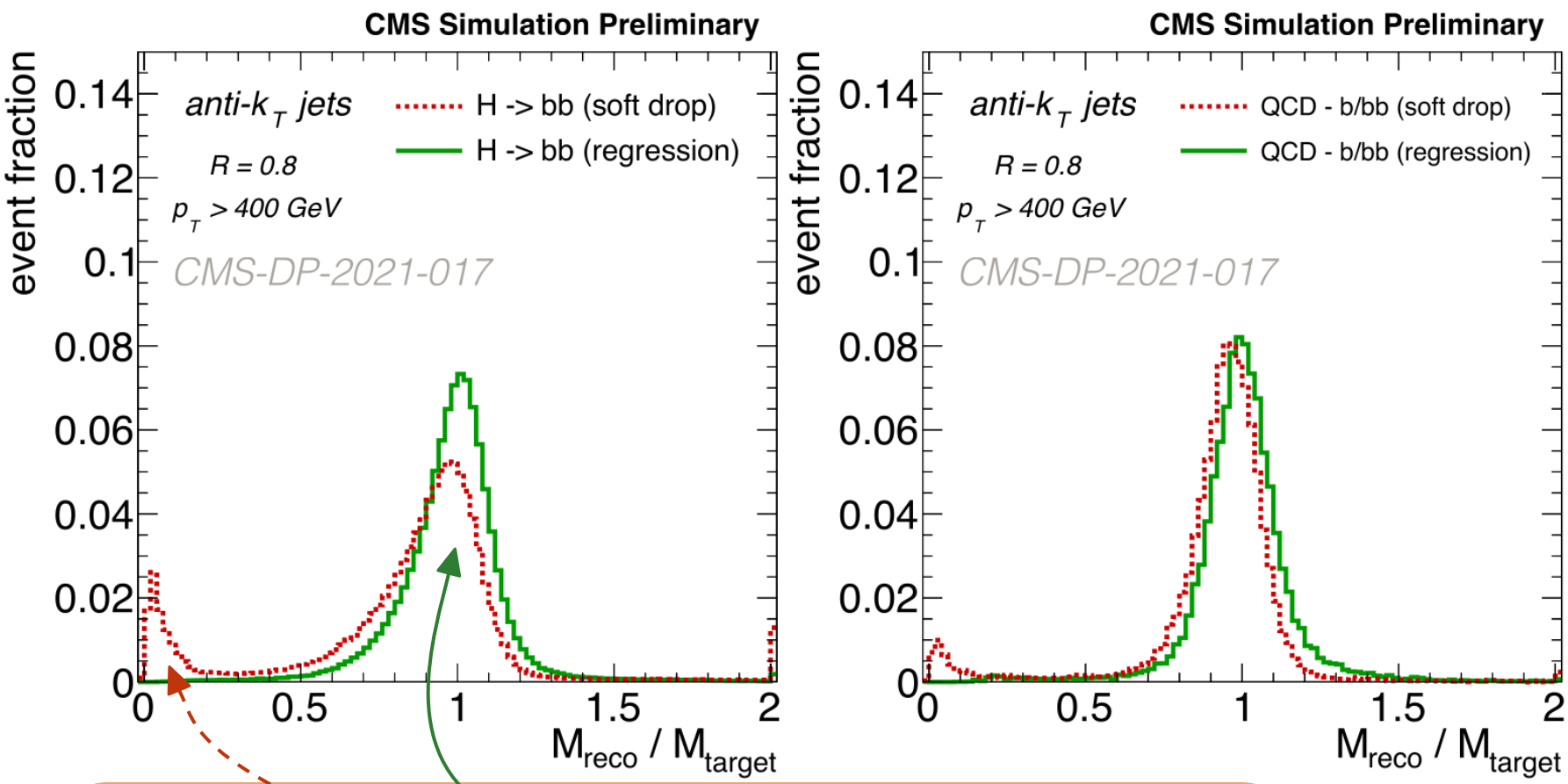
Identify "neighboring" particles



Category	Label
Top	bcq bqq bq cq
Higgs	bb cc VV*→qqqq
Z	bb cc qq
W	cq qq
QCD	g→bb g→cc b c others

Higgs jet mass regression with ParticleNet

- Use same architecture, inputs, training as for PN tagger
- Training target: pole mass (signal), gen-level mass (QCD)



No signal at 0, narrower peak $\Rightarrow$ Improvement ~ 20% !