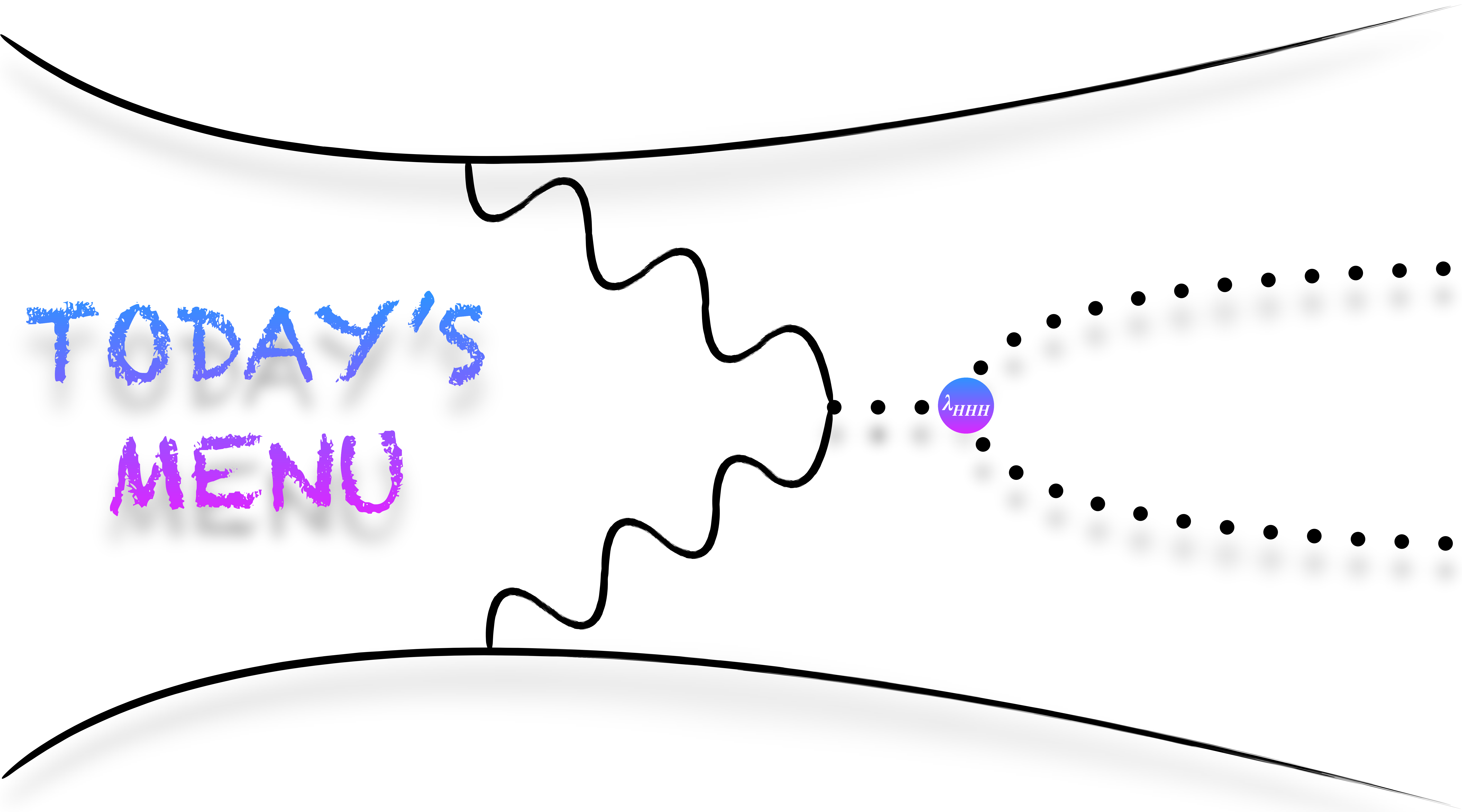
Di-Higgs searches at CMS

Jona Motta (Universität Zürich - UZH)
on behalf of the CMS Collaboration



Di-Higgs: what, why, and where?

Di-Higgs searches@ CMS

EFT interpretations and H combination

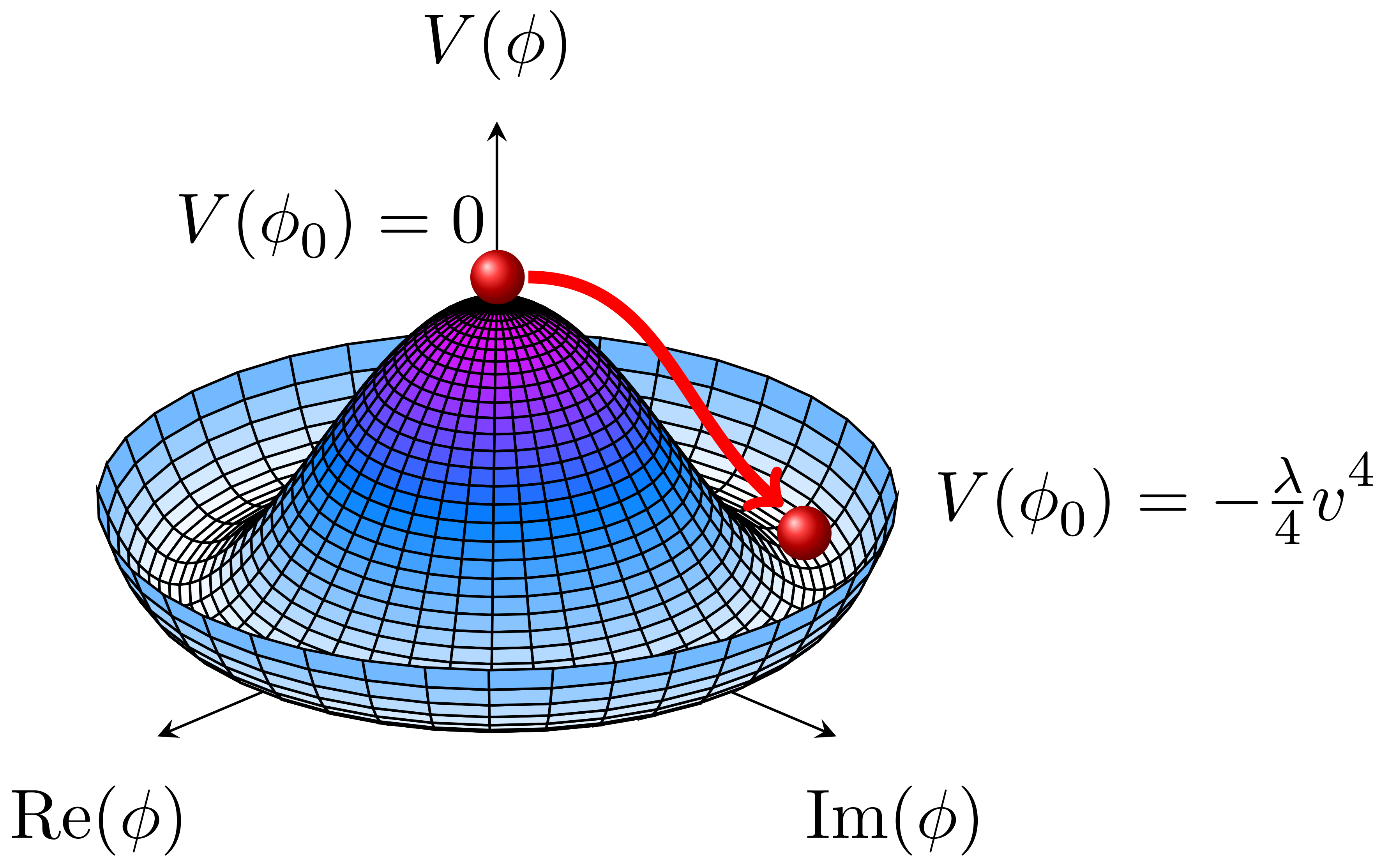
Outlook and conclusions

What, why, and where to look

The Higgs field is responsible for the spontaneous breaking of the Electro-Weak symmetry

$$V(H) = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v} H^4 - \frac{1}{4}\mu^2 v^2$$
$$= \frac{1}{2} m_H^2 + \lambda_{HHH} v H^3 + \lambda_{HHHH} H^4 - \frac{1}{8} m_H^2 v^2$$

$$\lambda_{HHH} = 4\lambda_{HHHH} = \frac{m_H^2}{v^2}$$



only parameter regulating field's shape + predicted by the SM once m_H and v are measured

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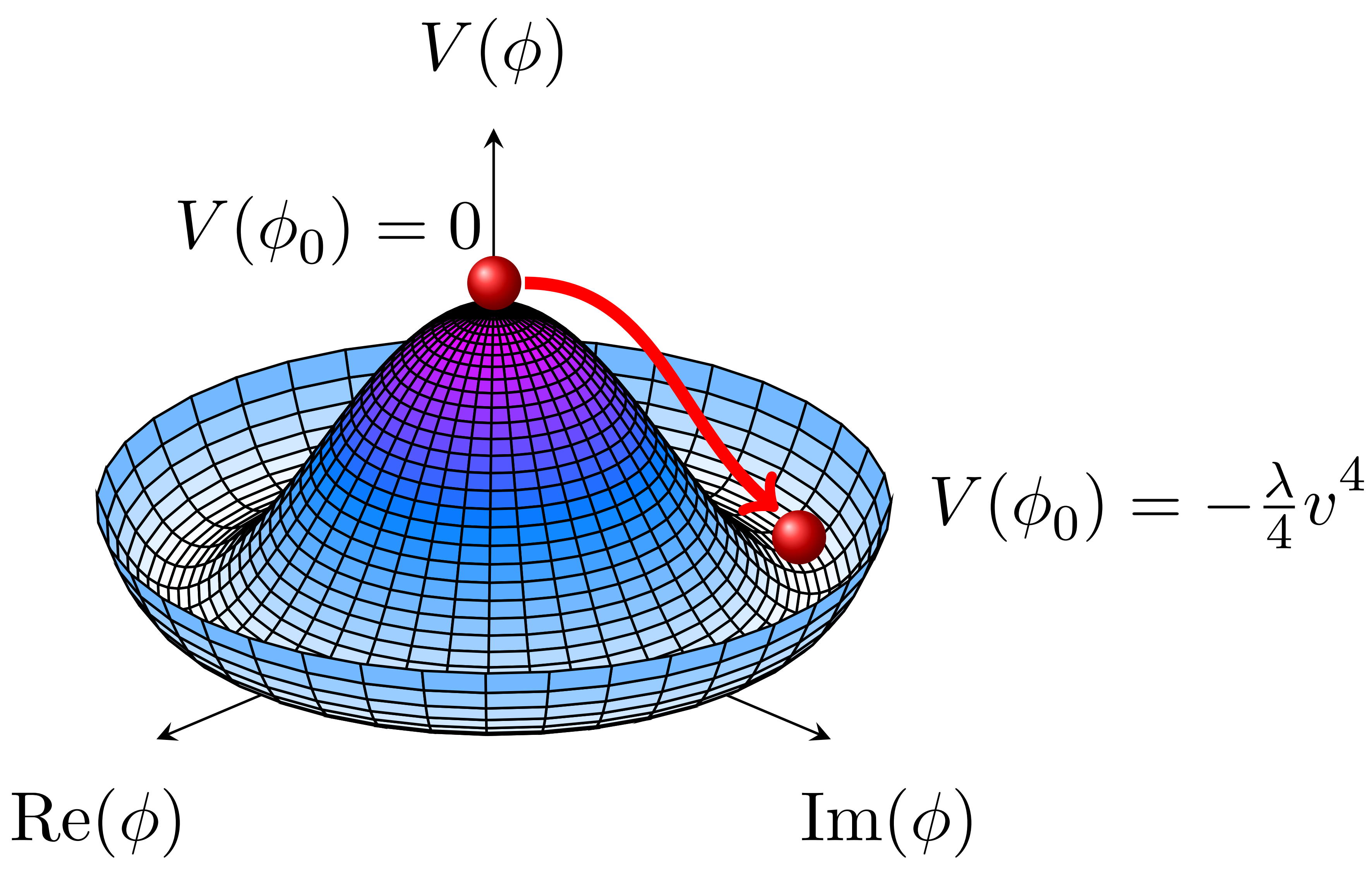


$$\lambda_{HHH} = 4\lambda_{HHHH} = \frac{m_H^2}{v^2}$$

only parameter regulating field's shape + predicted by the SM once m_H and v are measured

1. λ_{HHH} is not a free parameter
   → closure test of the SM

2. λ_{HHH} regulates field shape
   → test of EWSB and vacuum stability

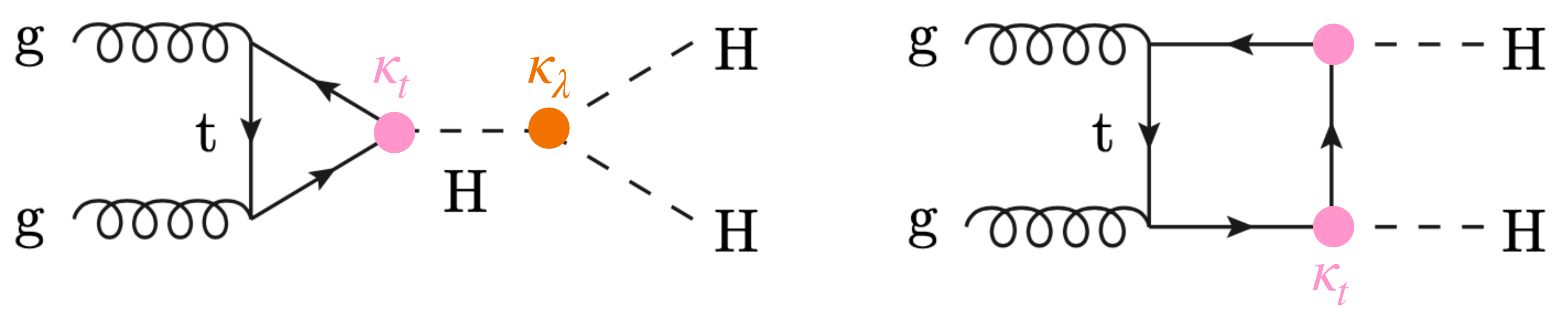
   Just heard about it in Tom's talk

3. λ_{HHH} deviations from SM compatible with first-order EWSB transition
   → test Electro-Weak baryogengesis

What, why, and where to look

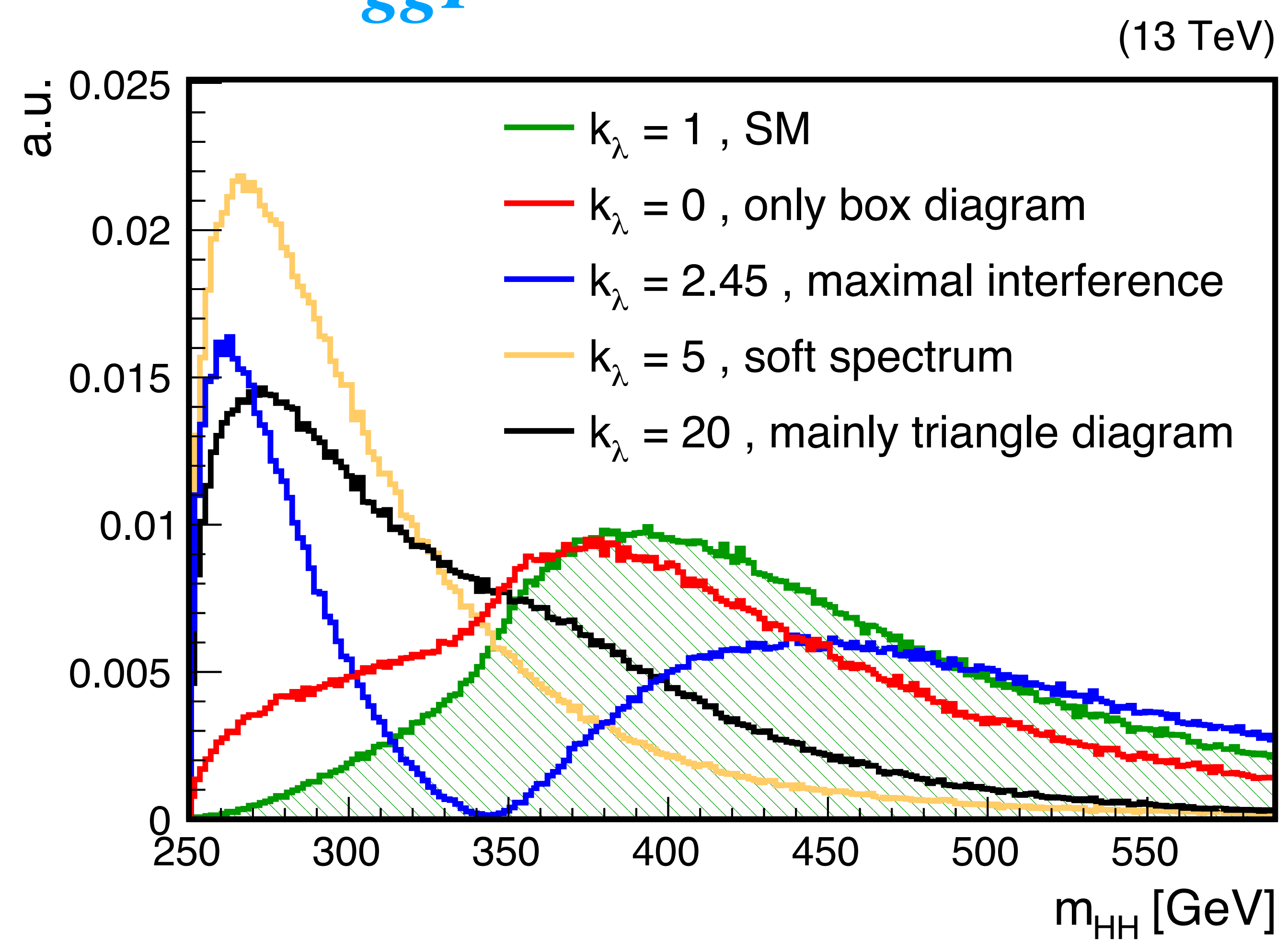
The search for **non-resonant Higgs boson pair production is the only direct method to probe λ_{HHH}** and:

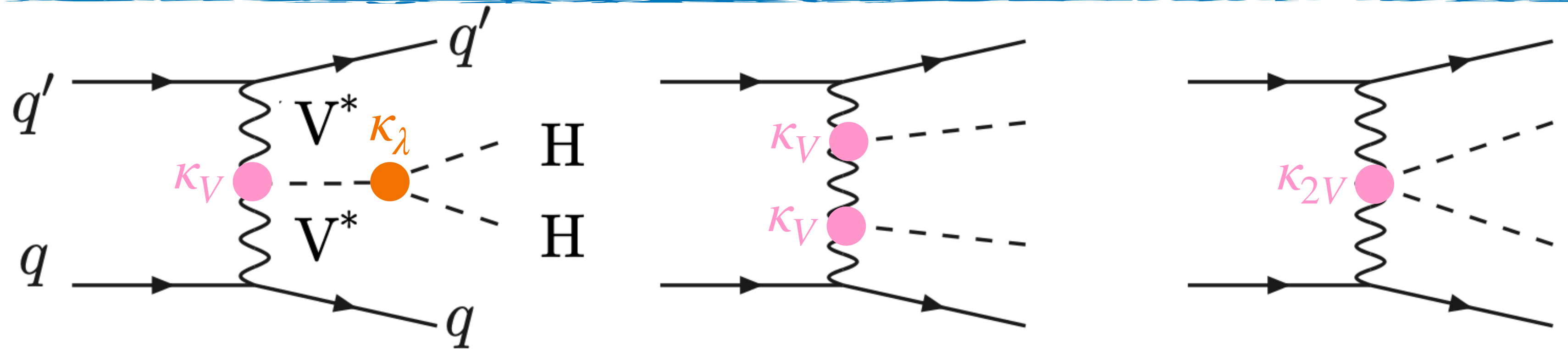
- Study **spontaneous electro-weak symmetry breaking**
- Set **limits** on main production mechanisms' **cross section**: **ggF** and **VBF**
- Test deviation from the SM couplings with **κ-framework**: κ_λ , κ_t , κ_V , κ_{2V} ($\kappa_X = c_X / c_X^{SM}$)
- Test **model-independent** non-resonant **EFT benchmarks**



DESTRUCTIVE INTERFERENCE

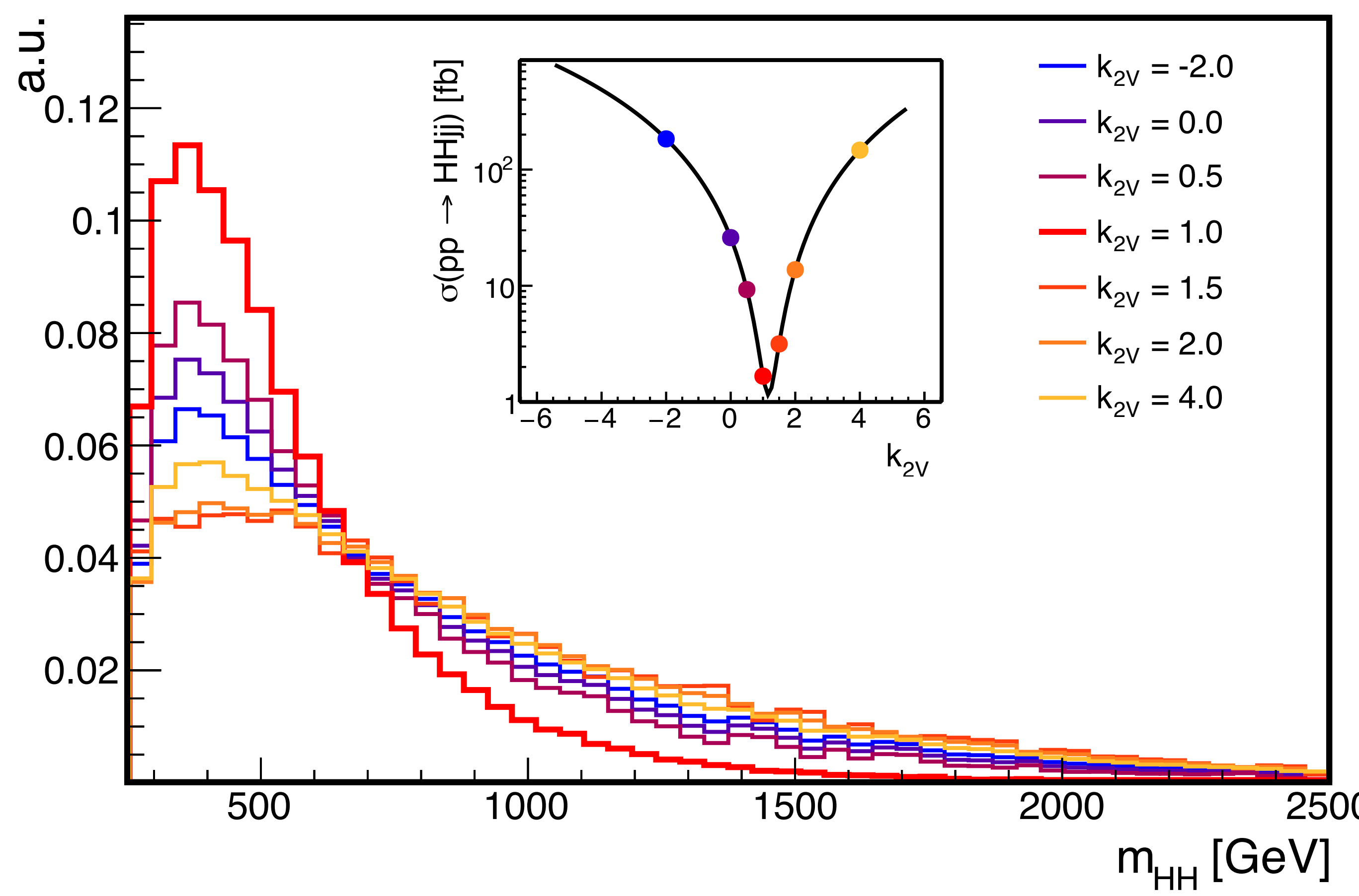
$\sigma_{ggF} = 31.05$ fb



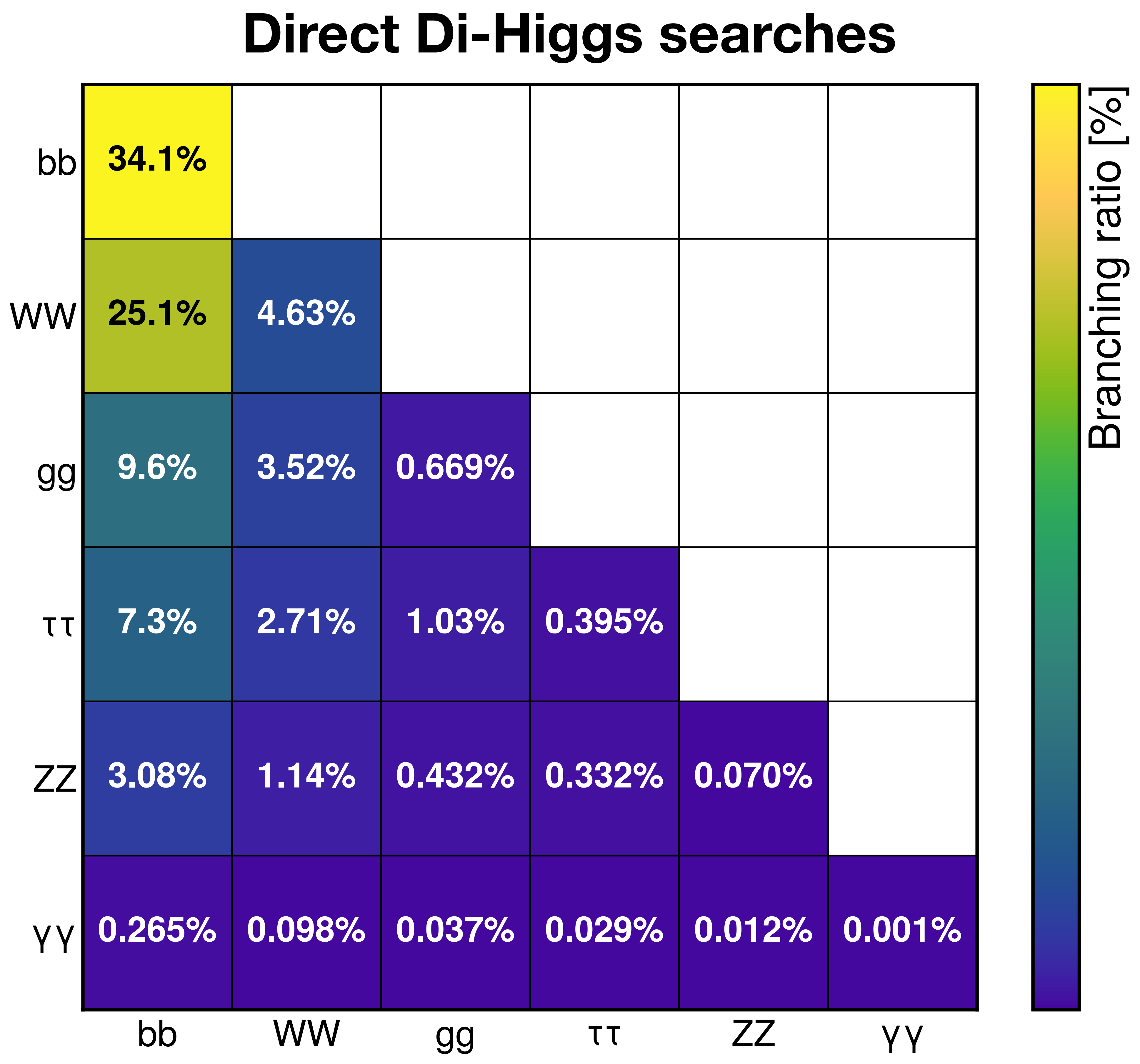


DESTRUCTIVE INTERFERENCE

$\sigma_{VBF} = 1.739$ fb



What, why, and where to look



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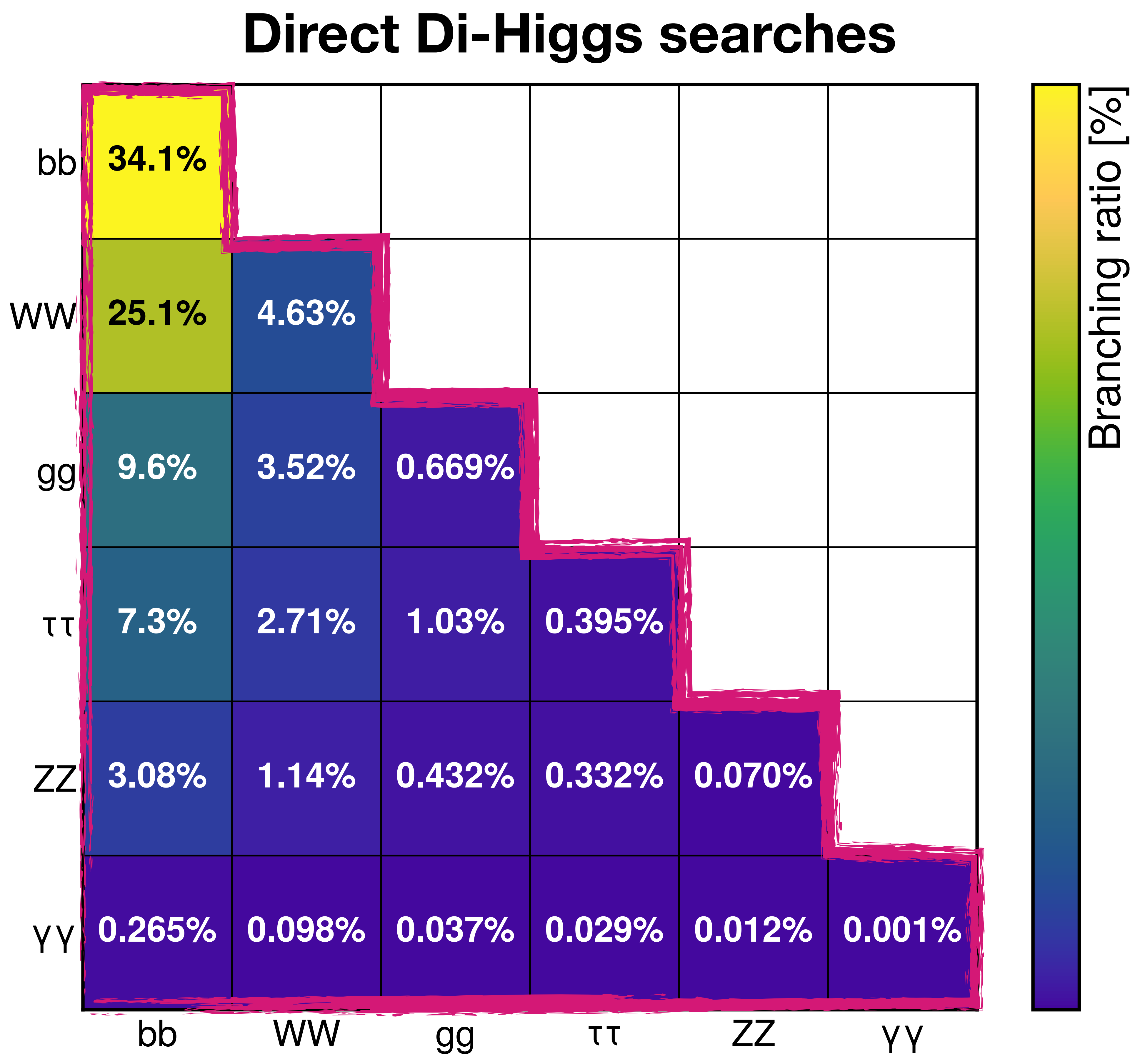
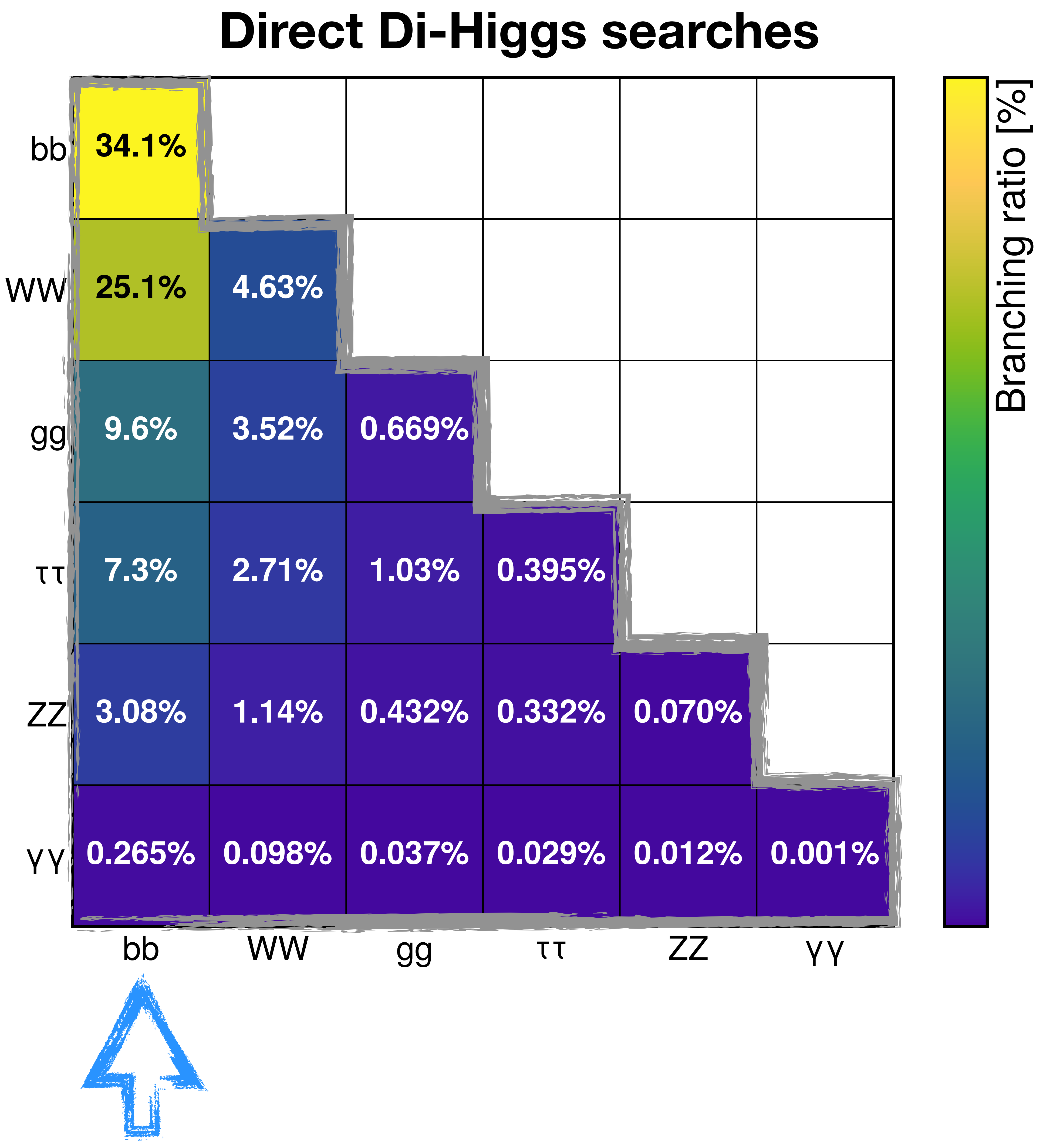


Ideally we would like to investigate all the possible decay modes of HH but given the current luminosity and the harsh experimental conditions, to achieve good sensitivity, we need:

What, why, and **where to look**



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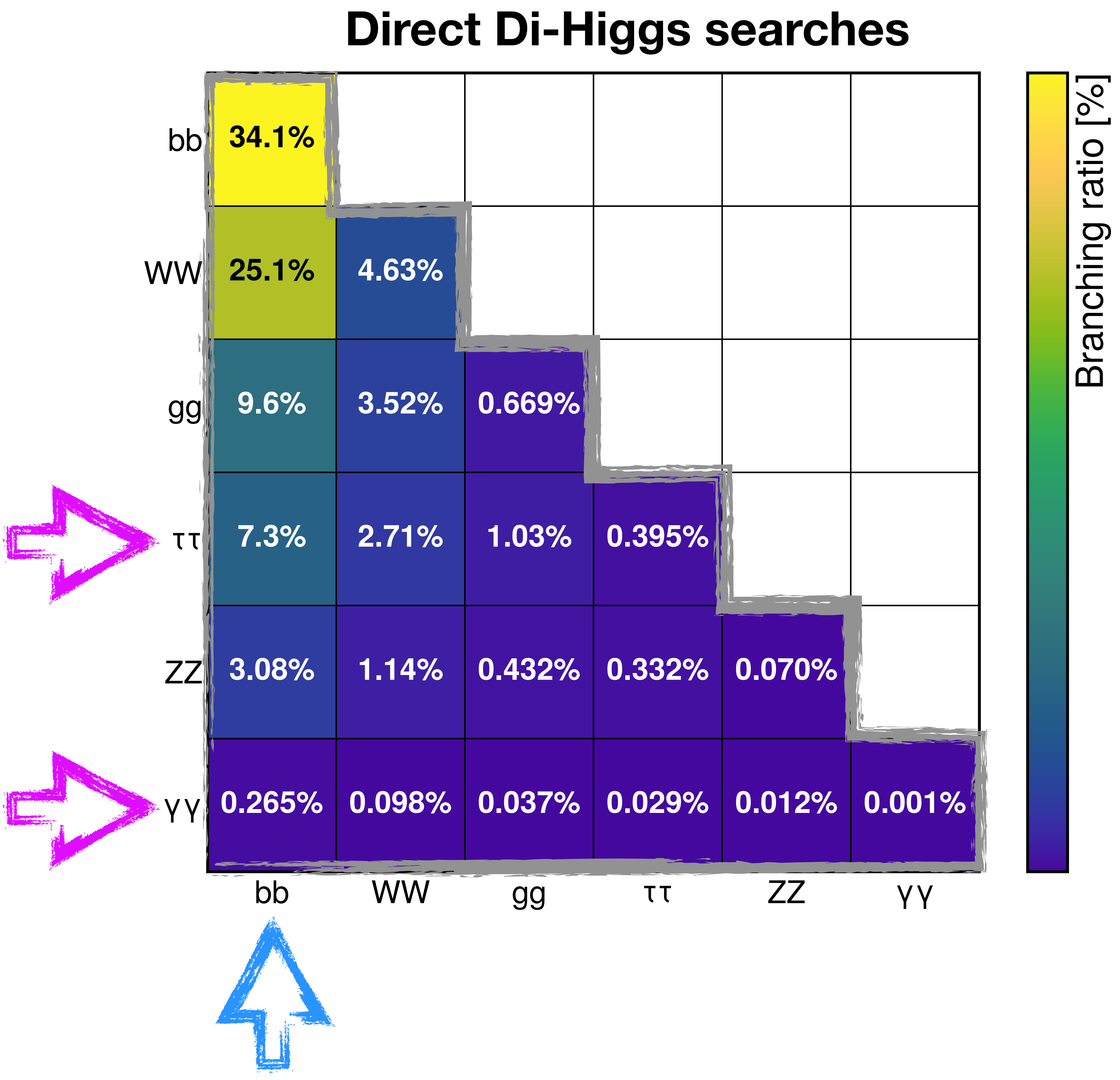
What, why, and **where to look**



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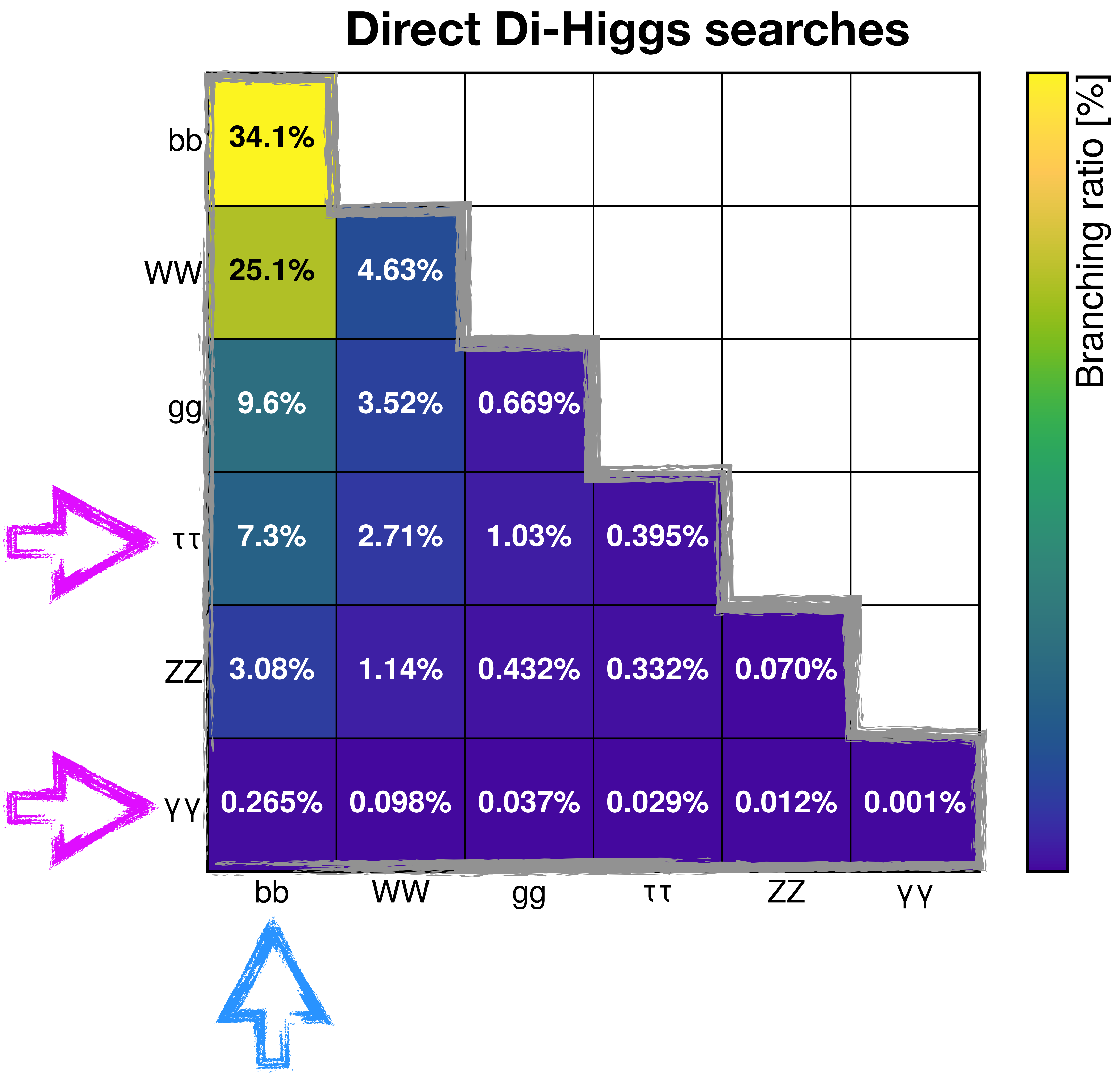
2. **Or very good selection purity**

What, why, and where to look



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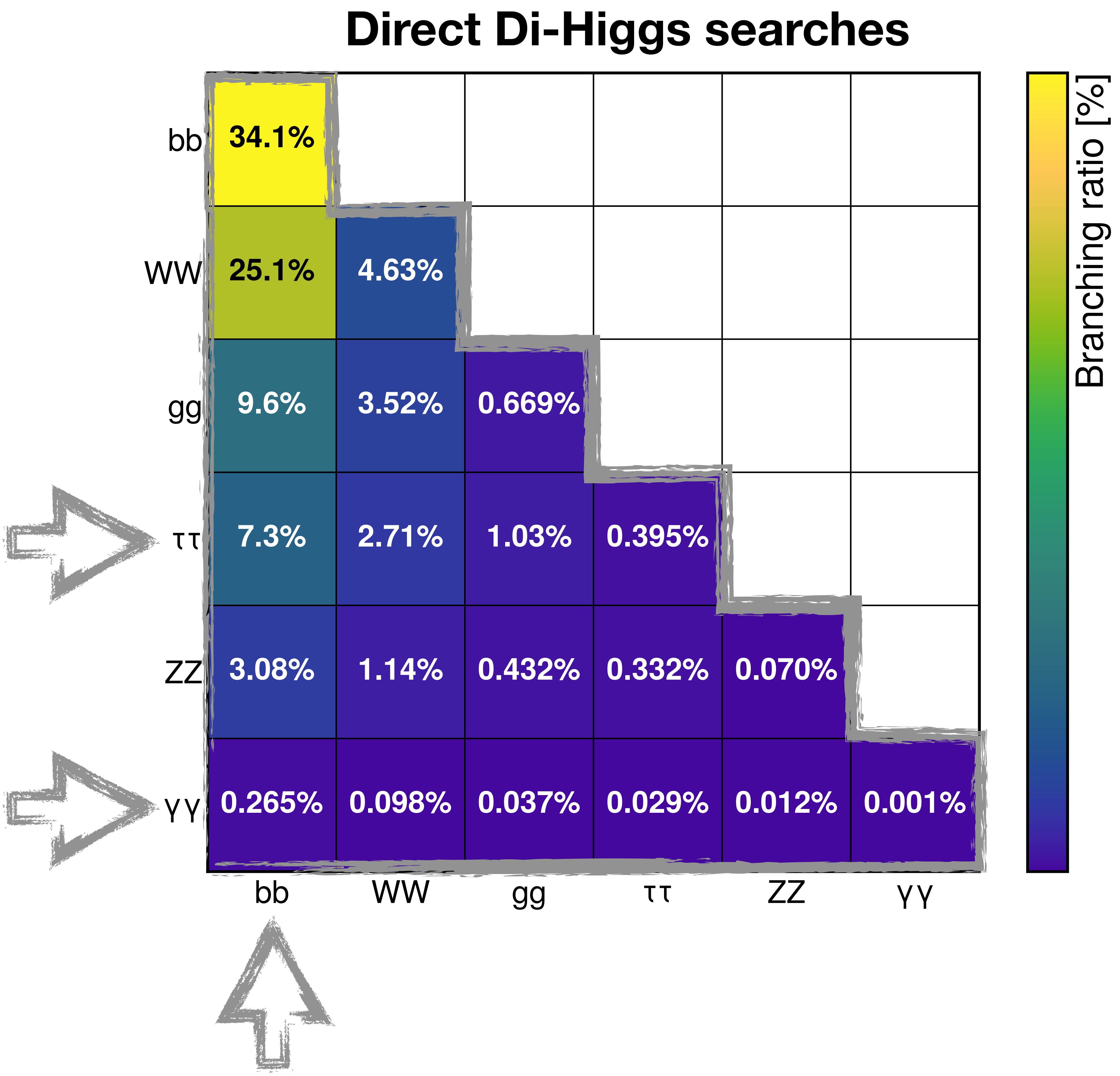
3. **Having both would be the best option**

What, why, and where to look



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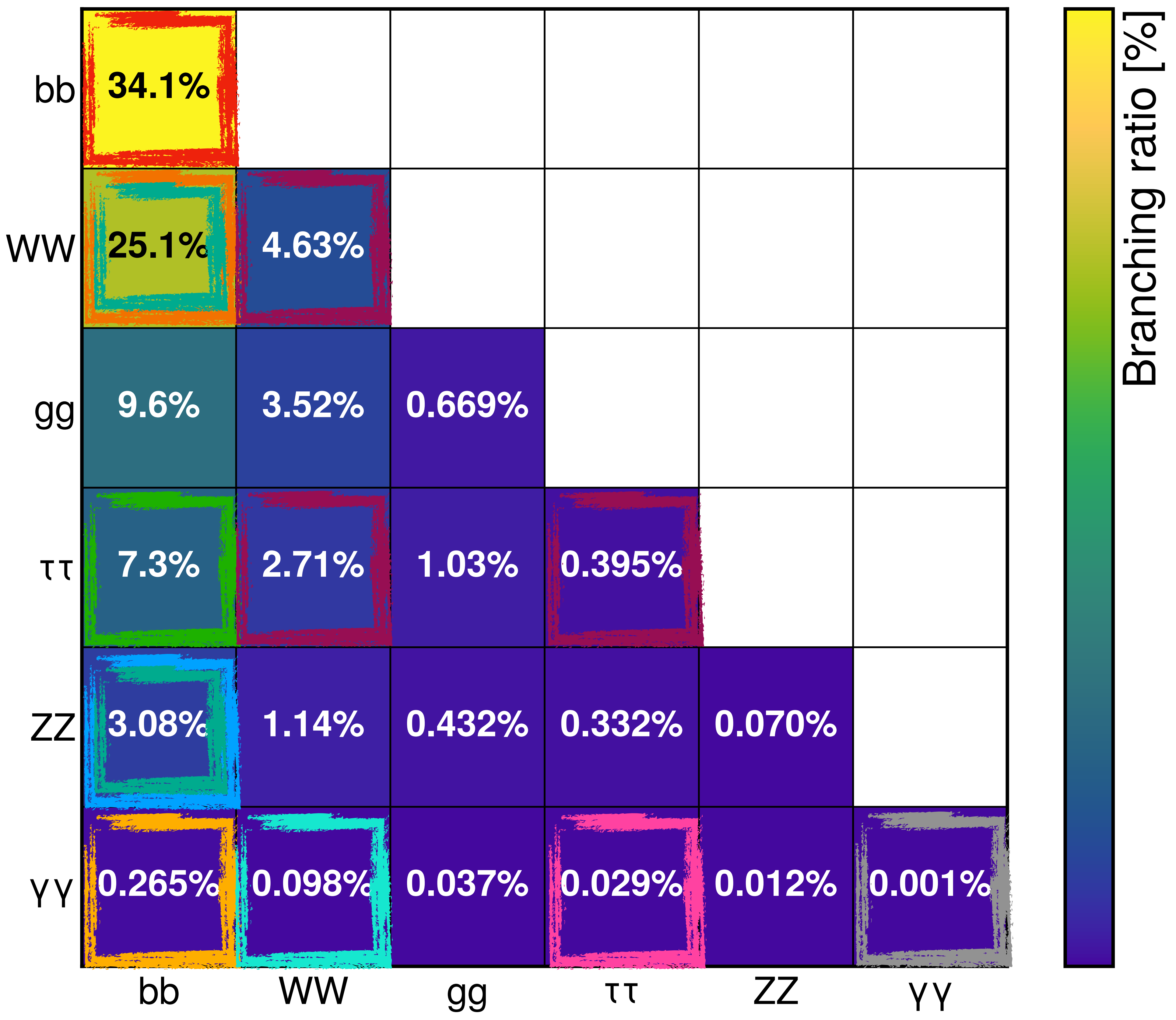
BUT

Thanks to ever-improving reconstruction techniques and identification methods **we are gradually escaping these two constraints!**

What, why, and where to look

Direct Di-Higgs searches



Complementary searches to constrain BSM models:

$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ [JHEP07 (2023) 148] [Phys. Rev. Lett. 131. 101801]

$H \rightarrow aa \rightarrow bb\tau\tau + bb\mu\mu$ [CMS-PAS-HIG-21-021] [CMS-PAS-HIG-22-007]

HH → bbbb Non-resonant, resolved topology Phys. Rev. Lett. 129.081802

Non-resonant, boosted topology Phys. Rev. Lett. 131.041803

Non-resonant, VHH production CMS-PAS-HIG-22-006

Resonant X→YH Phys. Lett. B 842.137392

HH → bb$\tau\tau$ Non-resonant Phys. Lett. B 842.137531

Resonant X→YH JHEP 11 (2021) 057

HH → bb$\gamma\gamma$ Non-resonant JHEP 03 (2021) 257

Resonant X→YH CMS-PAS-HIG-21-011

HH → bbZZ Non-resonant JHEP 06 (2023) 130

Resonant Phys. Rev. D. 102.032003

HH → bbWW Non-resonant + Resonant JHEP 07 (2024) 293

Resonant JHEP 05 (2022) 005

HH → bbVV Non-resonant, fully hadronic boosted topology CMS-PAS-HIG-23-012

HH → WW$\gamma\gamma$ Non-resonant CMS-PAS-HIG-21-014

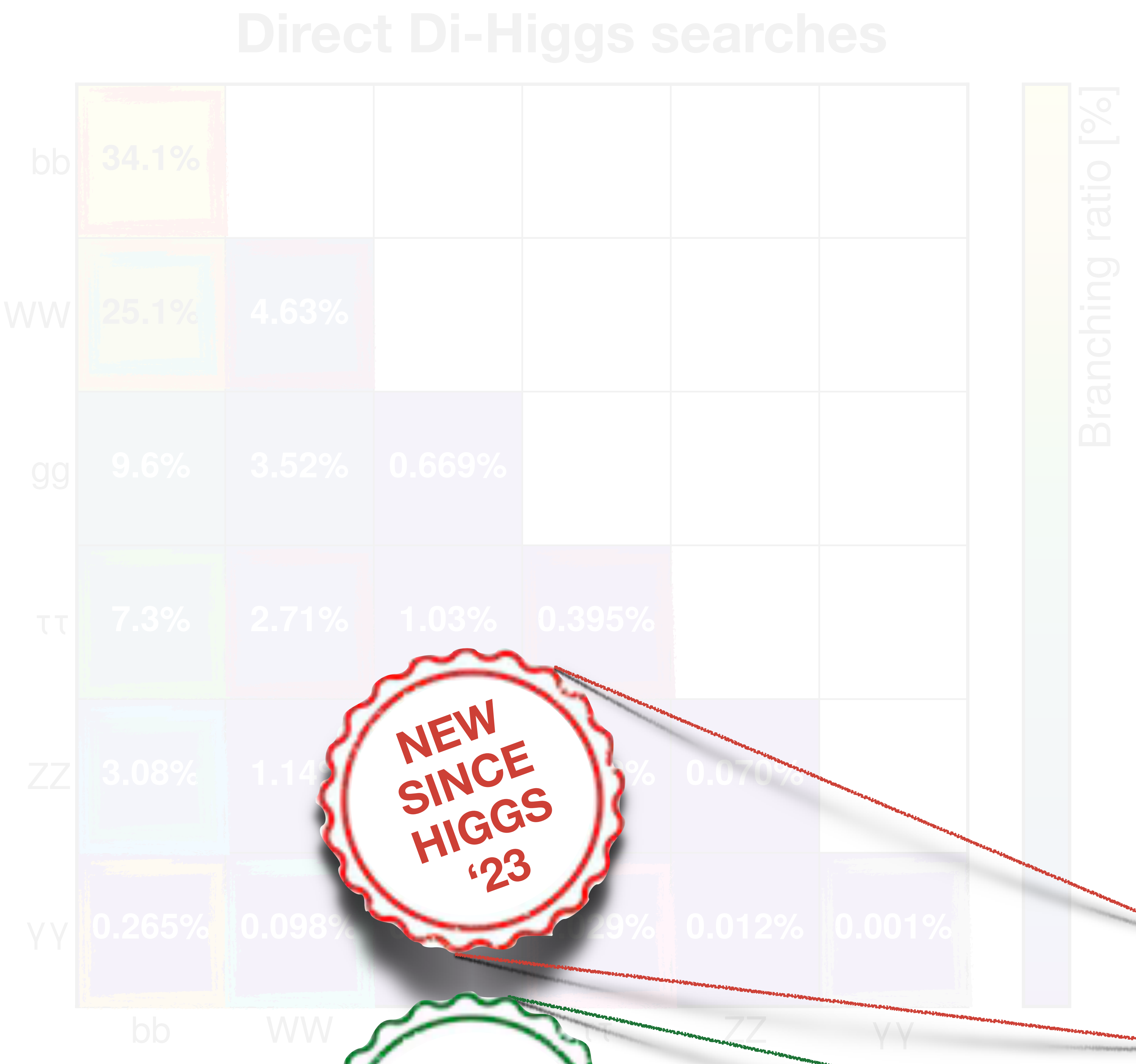
HH → $\gamma\gamma\tau\tau$ Non-resonant + Resonant CMS-PAS-HIG-22-012

HH → WWWW + WW$\tau\tau$ + $\tau\tau\tau\tau$ Non-resonant + Resonant JHEP 07 (2023) 095

HH combination Non-resonant + Interpretations CMS-PAS-HIG-20-011

H+HH combination Non-resonant + Indirect H effects CMS-PAS-HIG-23-006

What, why, and where to look



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NEW SINCE HIGGS '23 **HH → bbVV** Non-resonant, fully hadronic boosted topology CMS-PAS-HIG-23-012

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NEW SINCE HIGGS '23 **HH → $\gamma\gamma\tau\tau$** Non-resonant + Resonant CMS-PAS-HIG-22-012

HH → WWWW + $WW\tau\tau$ + $\tau\tau\tau\tau$ Non-resonant + Resonant JHEP 07 (2023) 095

NEW PUBLIC RELEASE **HH combination** Non-resonant + Interpretations CMS-PAS-HIG-20-011

NEW SINCE HIGGS '23 **H+HH combination** Non-resonant + Indirect H effects CMS-PAS-HIG-23-006

Complementary searches ... dels:

H→aa→$\gamma\gamma\gamma\gamma$ [JHEP ... Rev. Lett. 131, 101801]

H→aa→$bb\tau\tau$ + $bb\mu\mu$ ... -021] [CMS-PAS-HIG-22-007]

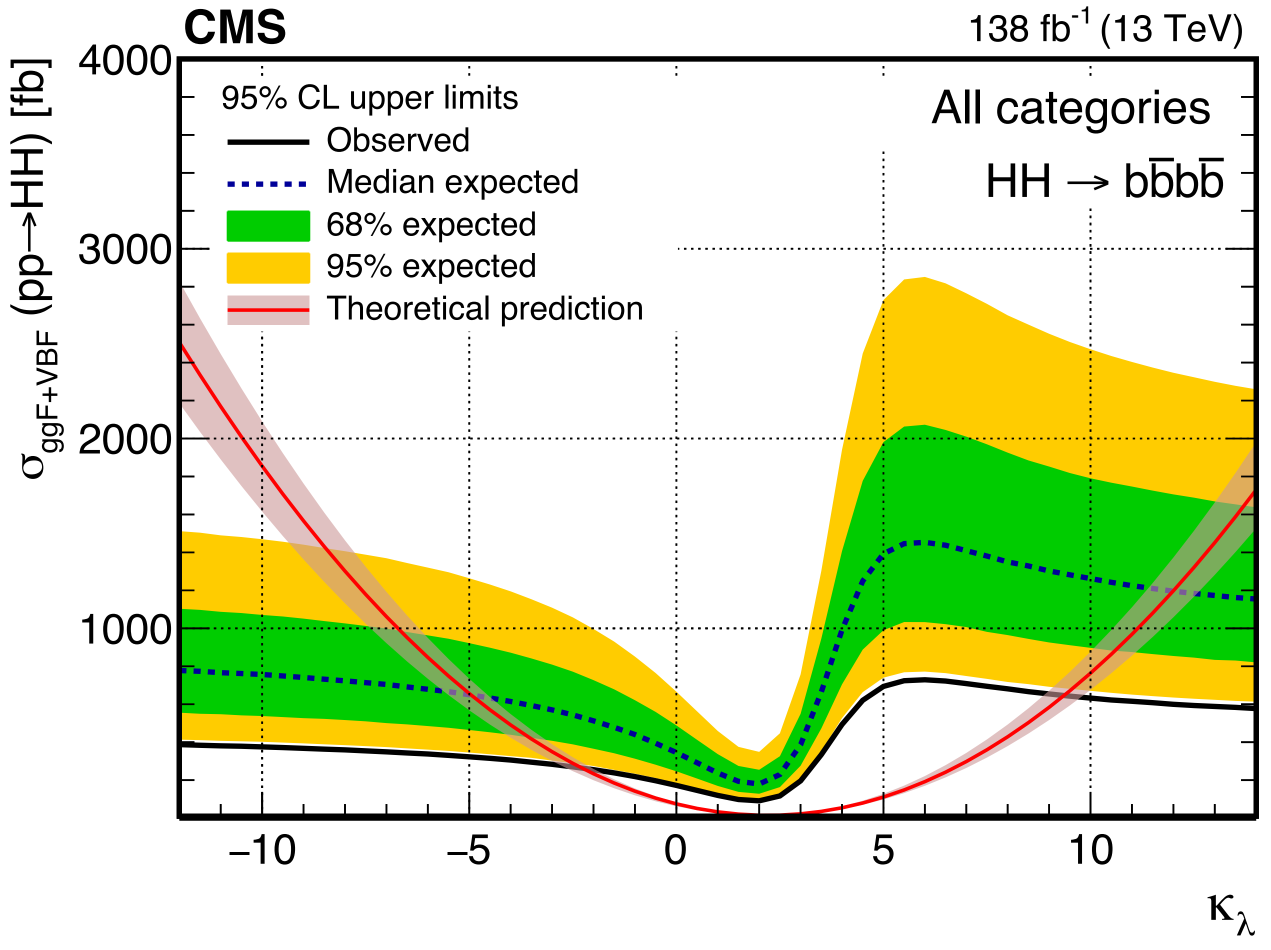
The three* historic channels

The three* historic channels

HH→bbbb resolved

Phys. Rev. Lett. 129.081802

- **Largest Br = 34%**
- **ID with deep NN** [ref.]
- Large QCD bkg
- Simultaneous fit of distributions : BDT for ggF and m_{HH} for VBF
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 3.9(7.9)$
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 226(412)$
- $\kappa_\lambda \in [-2.3, +9.4]$ **@ 95% CL**



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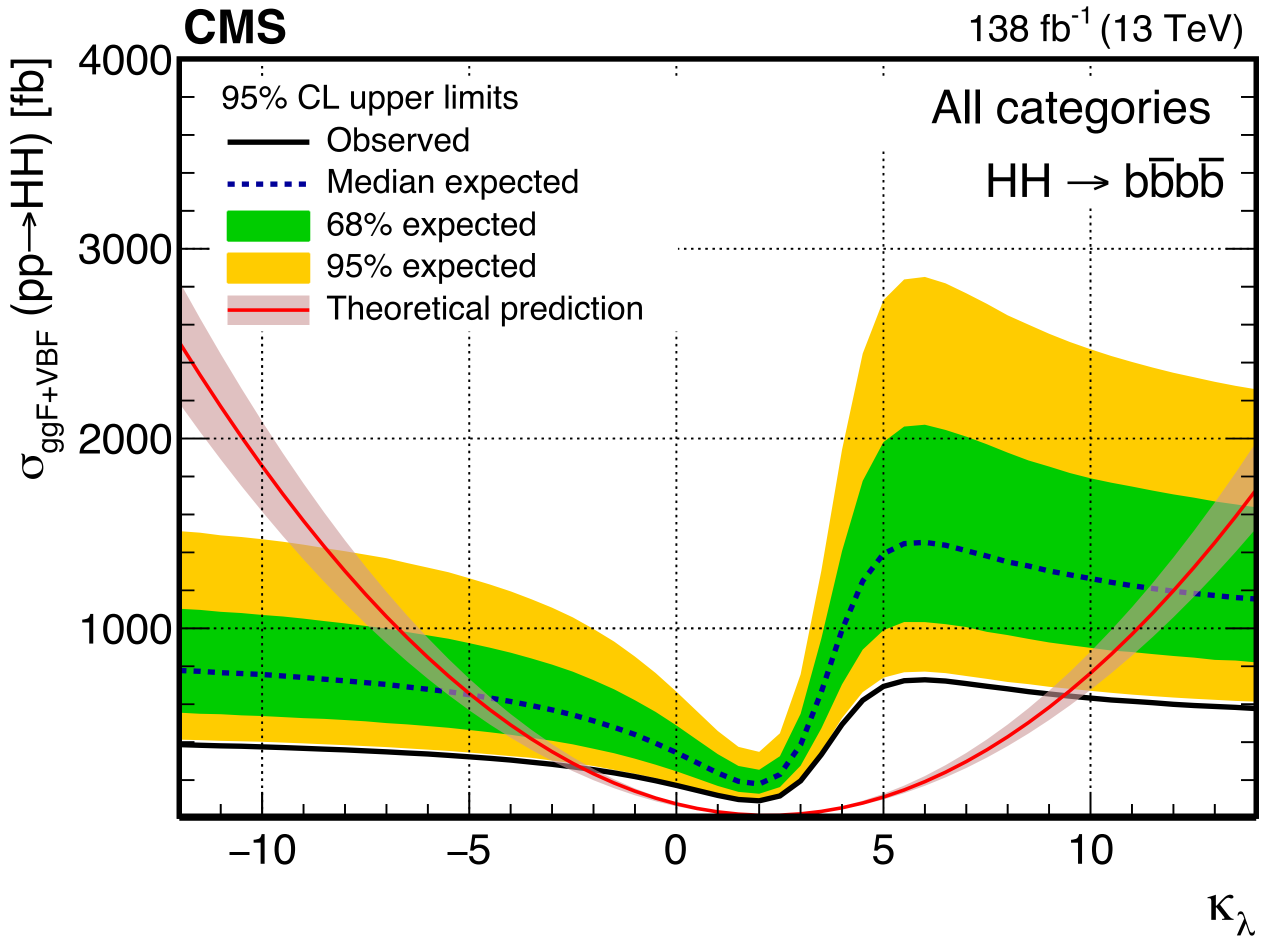

HH→bbbb boosted

Phys. Rev. Lett. 131.041803

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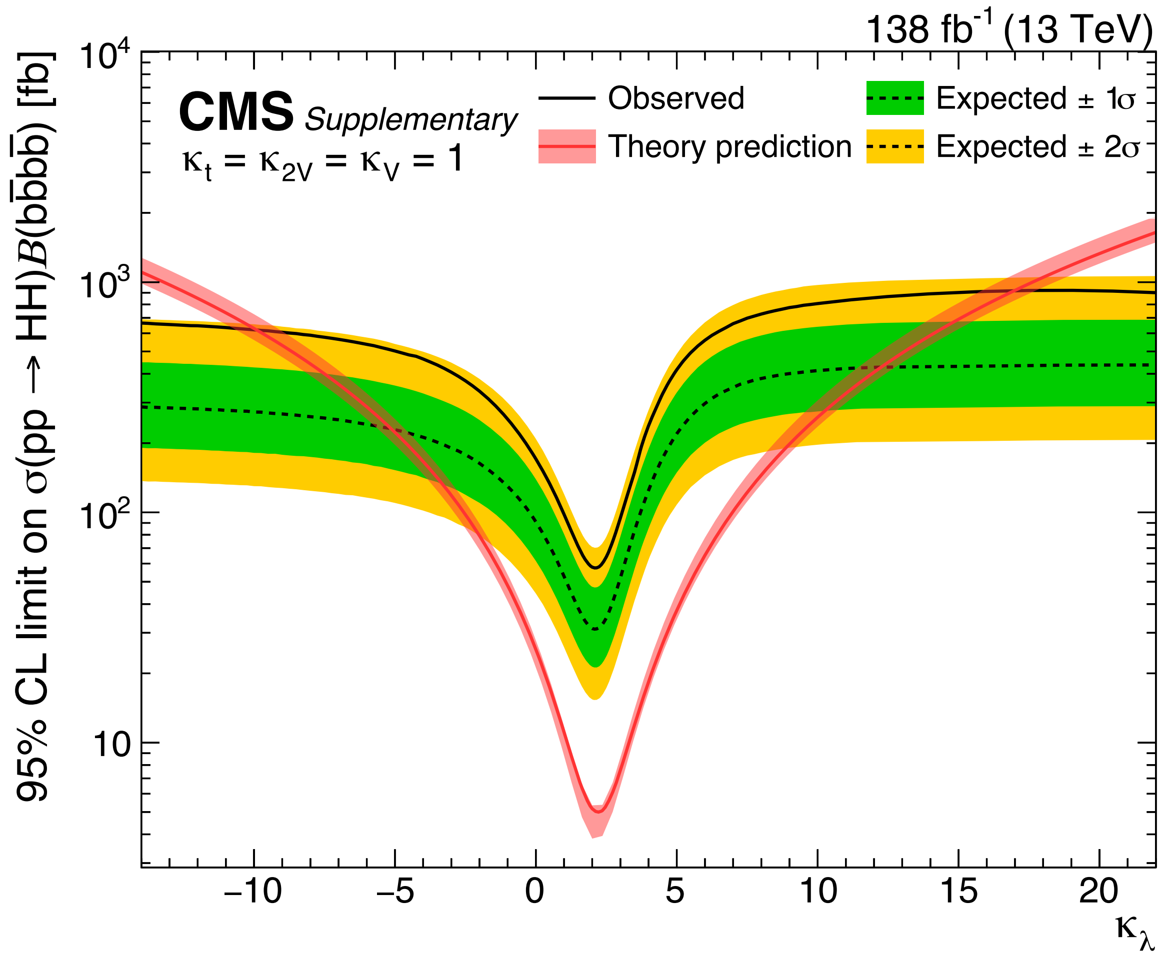

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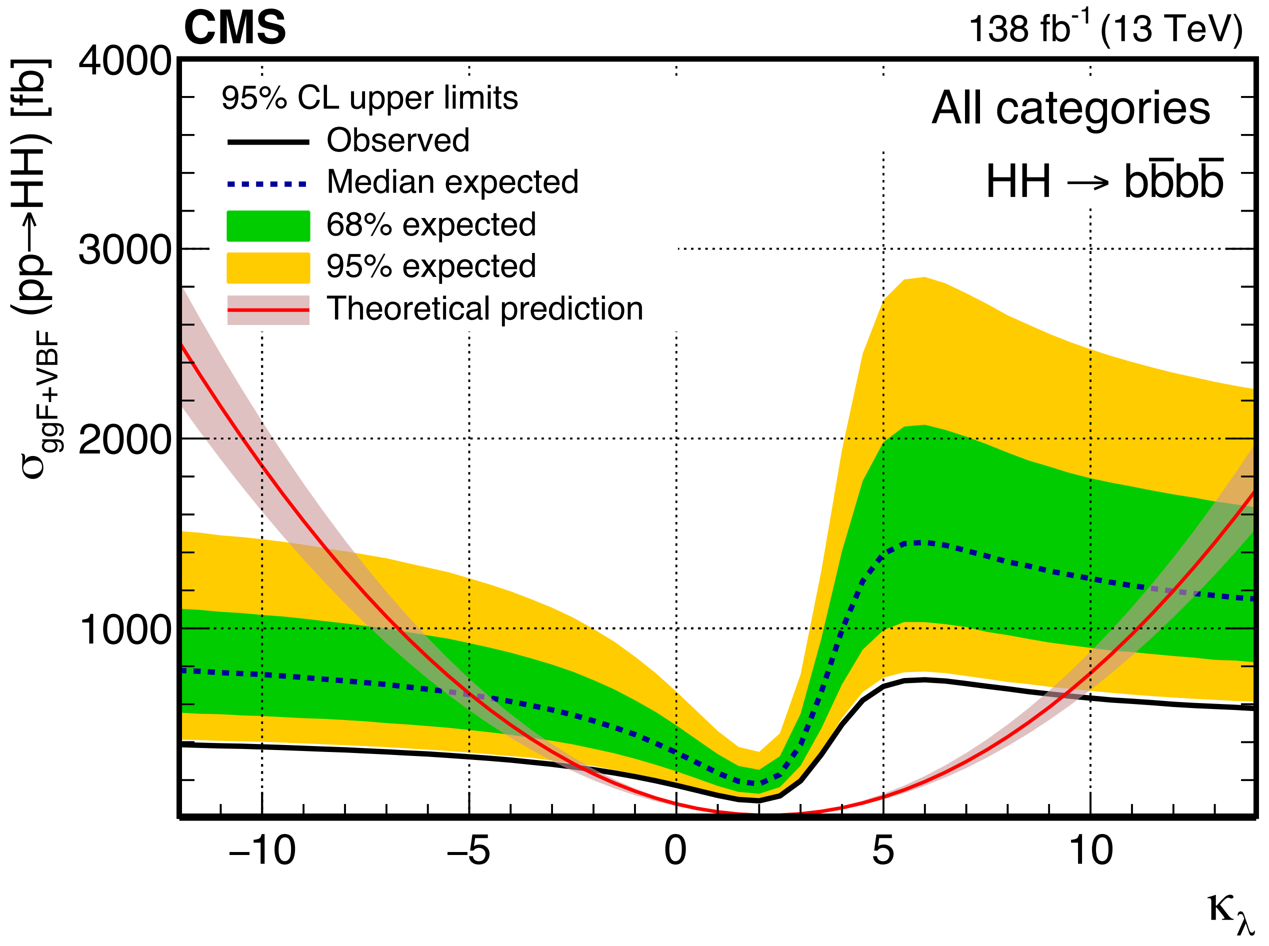

HH→bb$\tau\tau$

[Phys. Lett. B 842.137531]

- **Sizeable Br = 7.3%**
- **Jet/τ_h ID with deep NNs** [ref.][ref.]
- **Large tt̄ and DY bkg**
- Fit of DNN output in 72 signal regions
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 3.3(5.2)$
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 124(154)$
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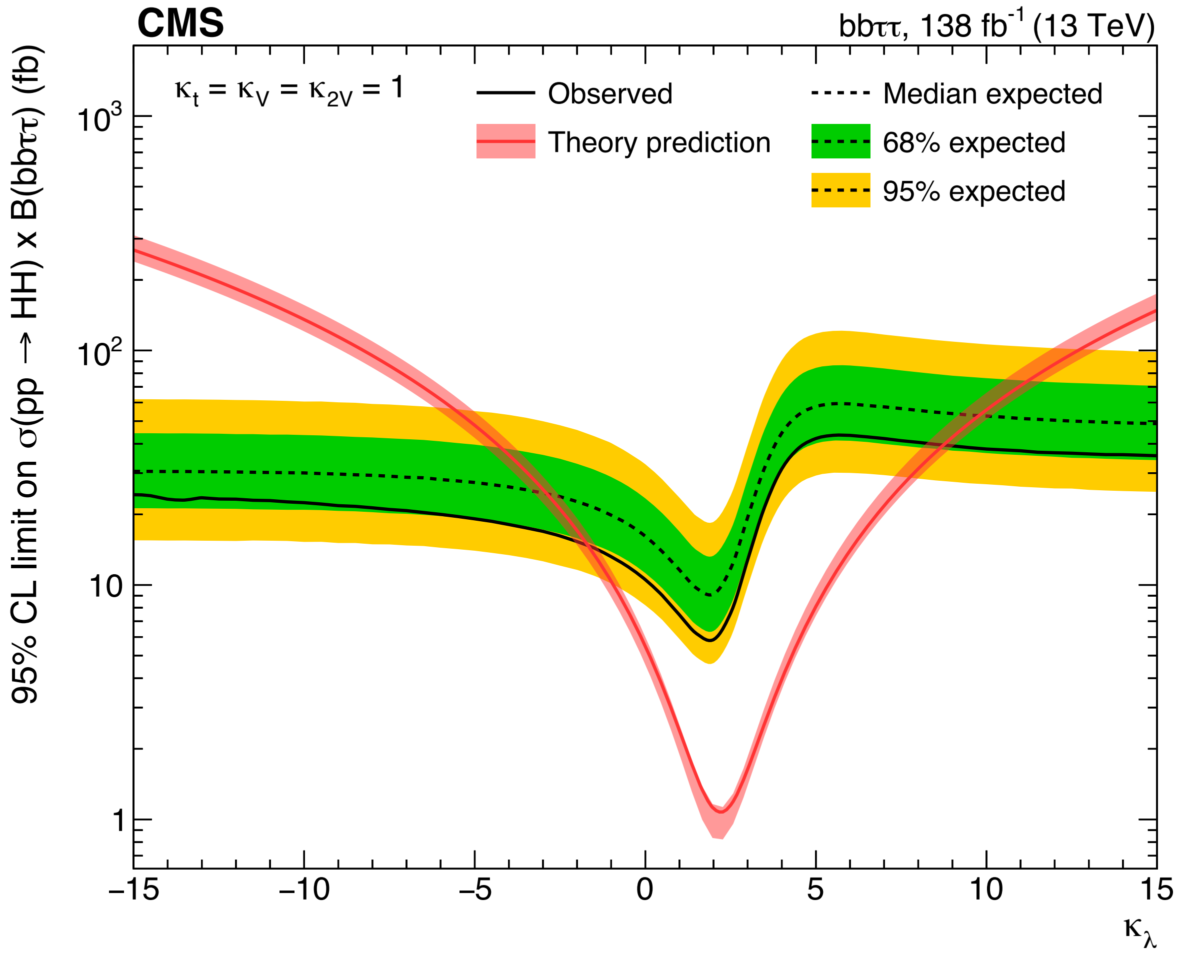
- $\kappa_{2V} \in [-0.4, +2.6]$ **@ 95% CL**



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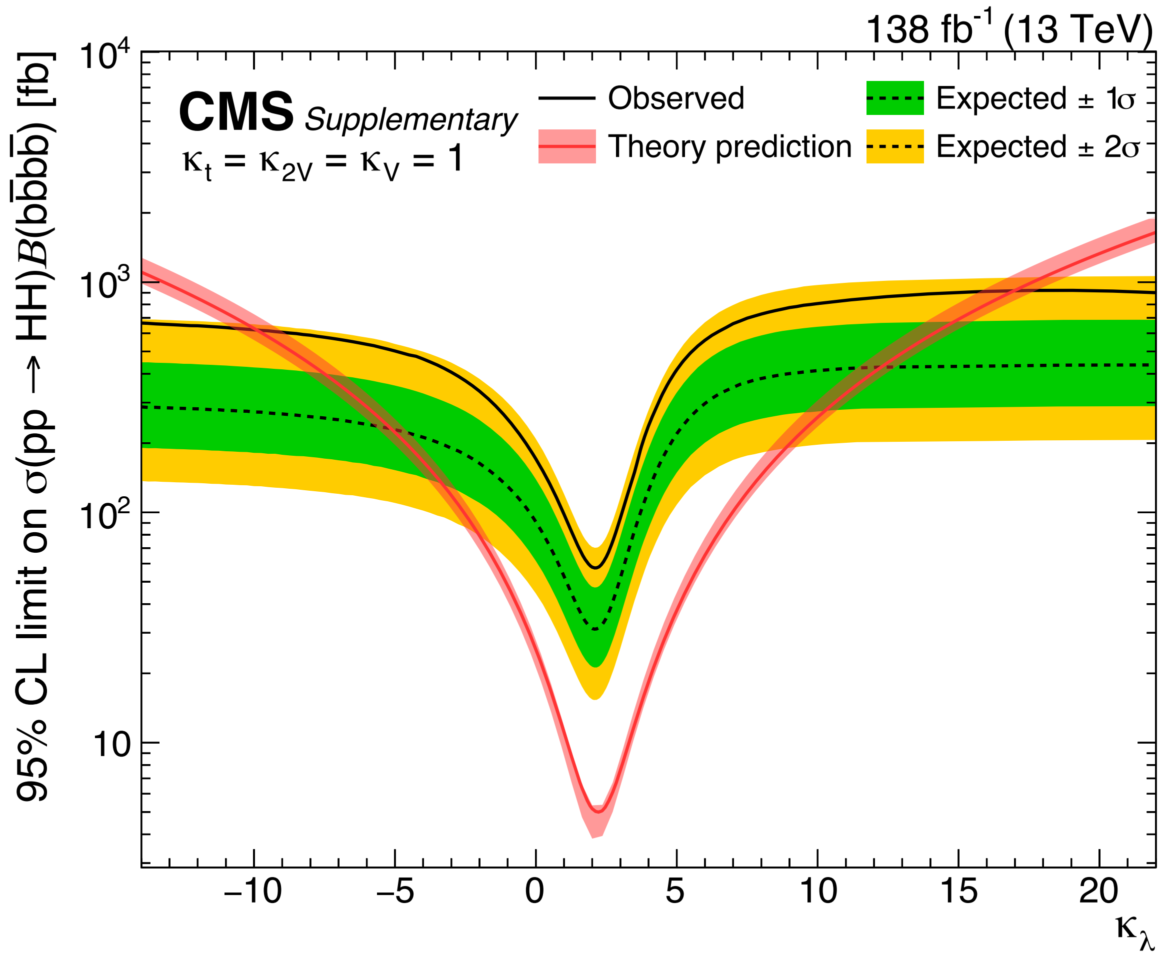

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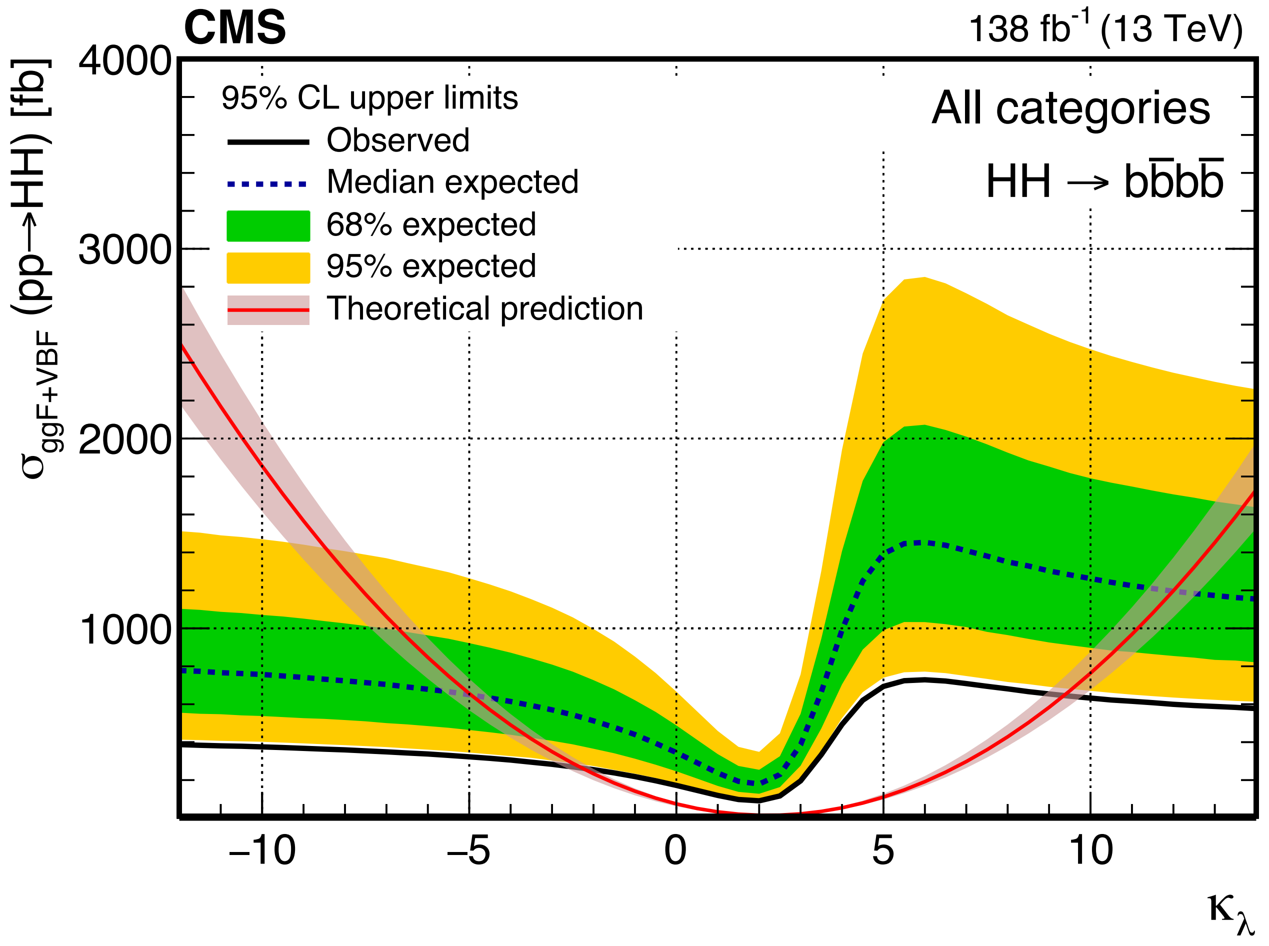

HH→bbττ

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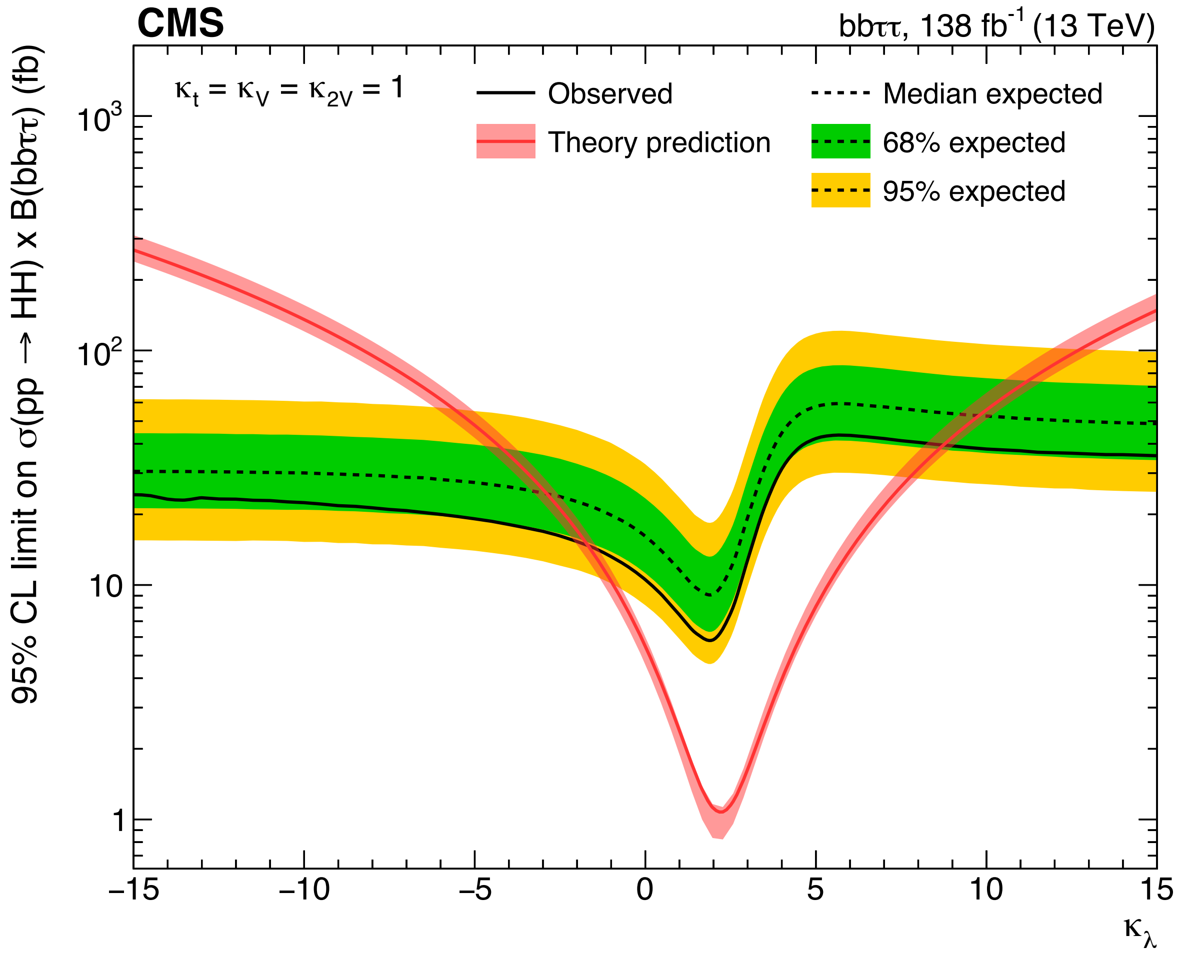

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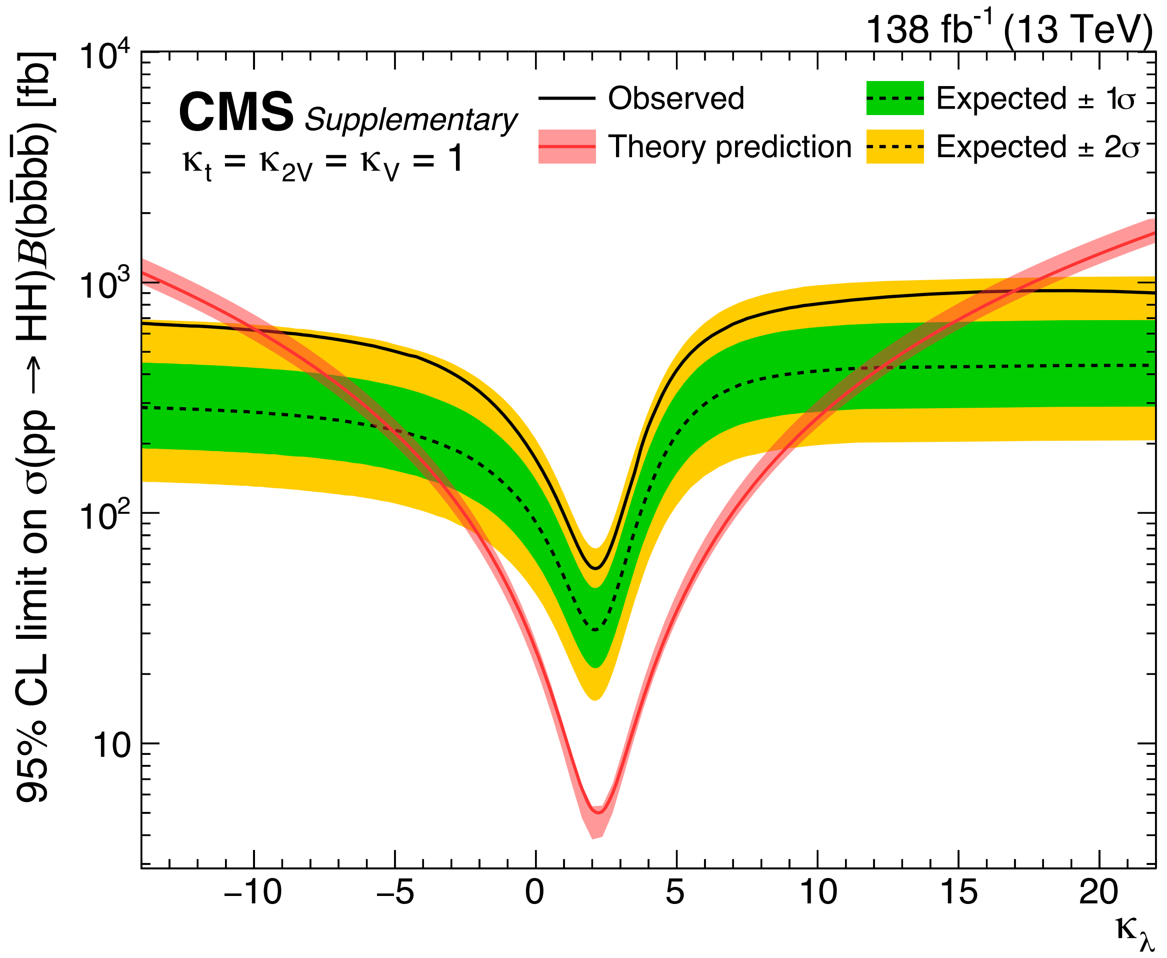
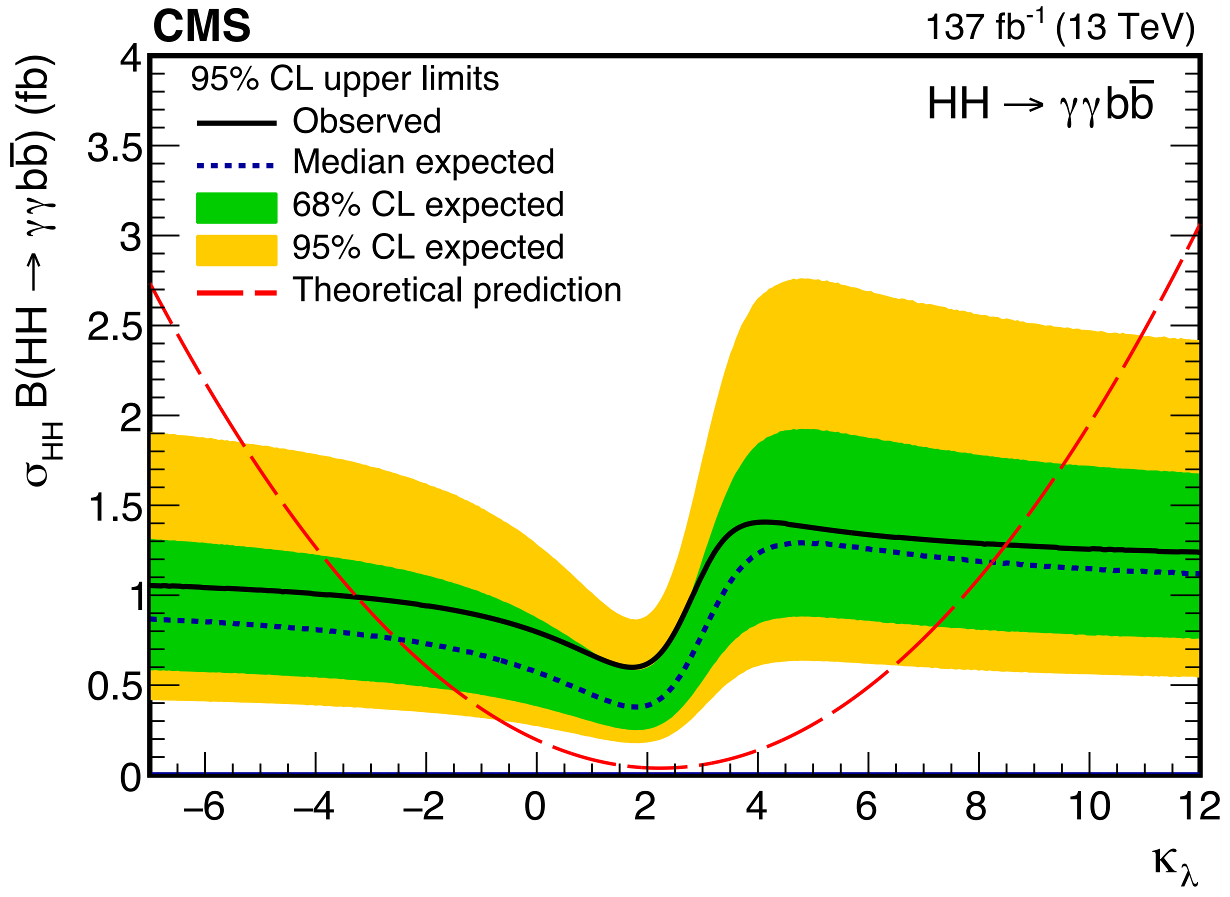


HH→bbγγ

[JHEP 03 (2021) 257]

- **Tiny Br = 0.3% + very good purity**
- b-jets ID with deep NN [ref.]
- Purely kinematical signal region definition
- $(m_{bb}, m_{\gamma\gamma})$ 2D maximum likelihood fit
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 7.7(5.2)$
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 225(208)$
- $\kappa_\lambda \in [-3.3, +8.5]$ **@ 95% CL**
- $\kappa_{2V} \in [-1.3, +3.5]$ **@ 95% CL**



NEW SINCE HIGGS '23

The new-comers

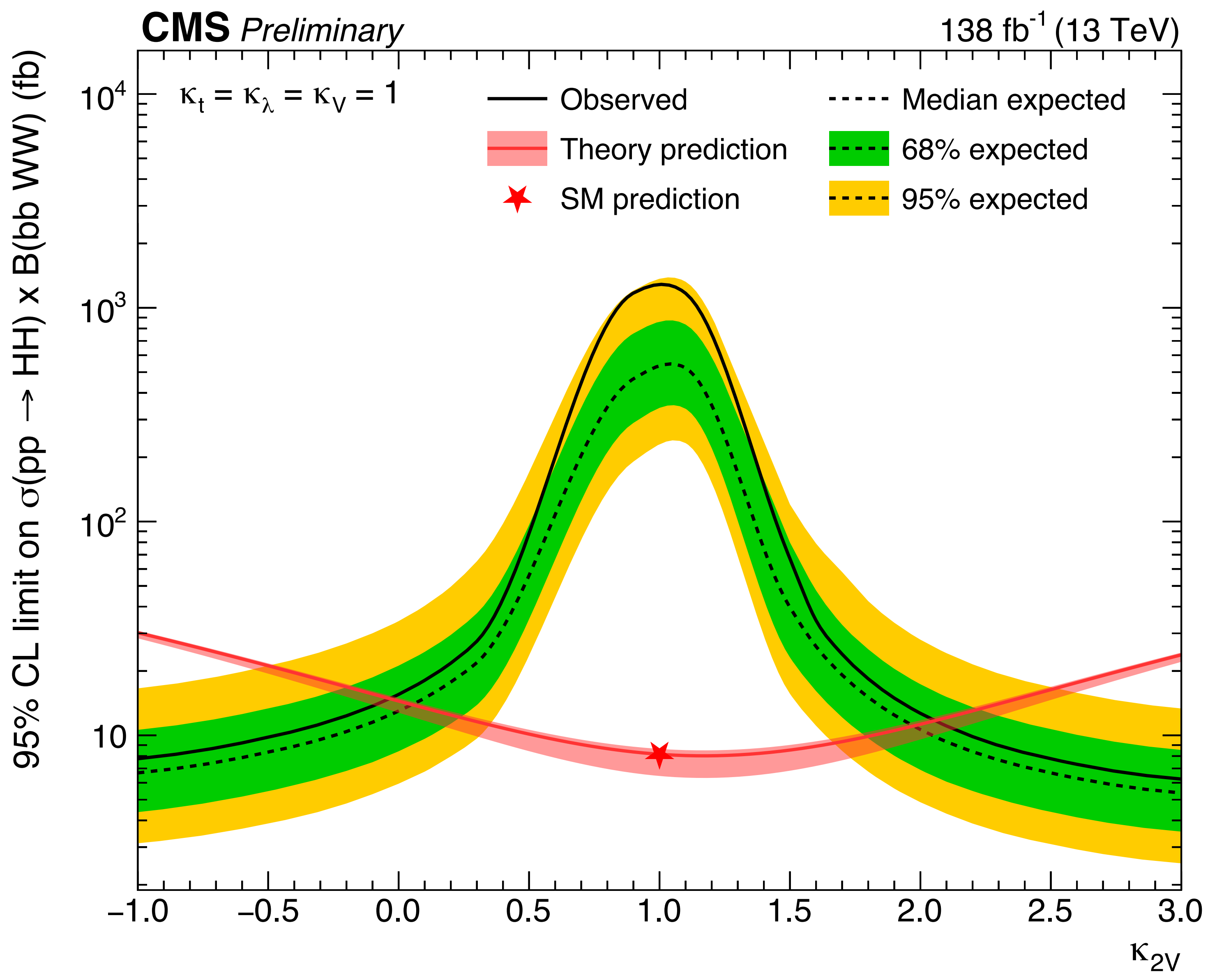
The new-comers

HH → bbVV (fully hadronic)

Only result in this channel @ LHC

CMS-PAS-HIG-23-012

- **Large Br = 28% (bbWW+bbZZ)**
- **Jets ID with GraphNN-based jet flavour identification** [ref.]
- Large QCD background rejected with dedicated BDT
- Simultaneous **fit of m_{bb}** in several BDT-based categories
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 142\ (69)$
- $\kappa_{2V} \in [-0.04, +2.05]\ ([0.05, 1.98])$ **@ 95% CL**



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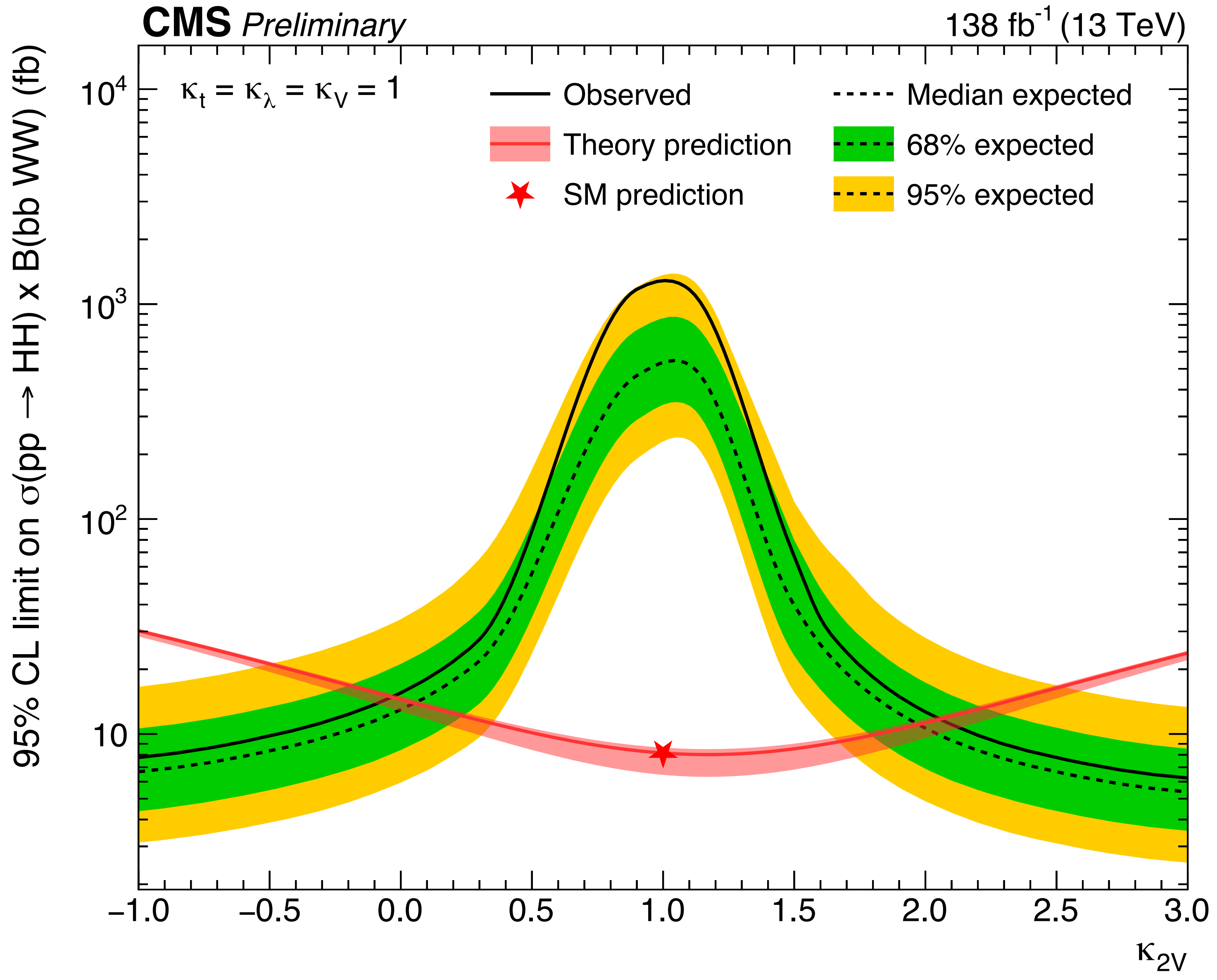
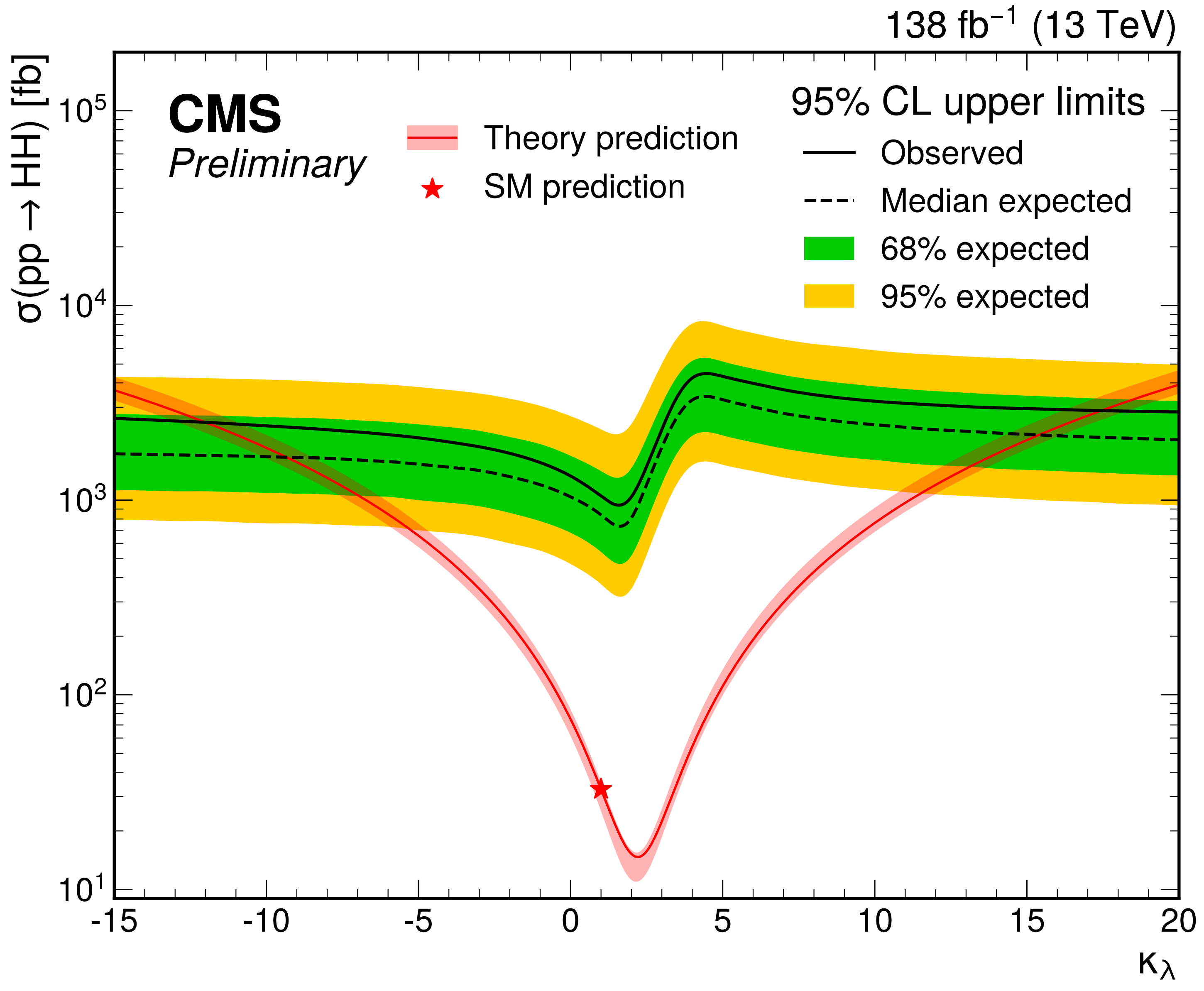


HH → $\gamma\gamma\tau\tau$

CMS-PAS-HIG-22-012

- **Tiny Br = 0.03%**
- **Very good $m_{\gamma\gamma}$ resolution and τ_h ID with deep NN** [ref.]
- Large photon continuum bkg rejected with dedicated BDT
- Simultaneous **fit of $m_{\gamma\gamma}$** in several BDT-based categories
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 33\ (26)$
- $\kappa_\lambda \in [-13, +18]$ ([−11,16]) **@ 95% CL**

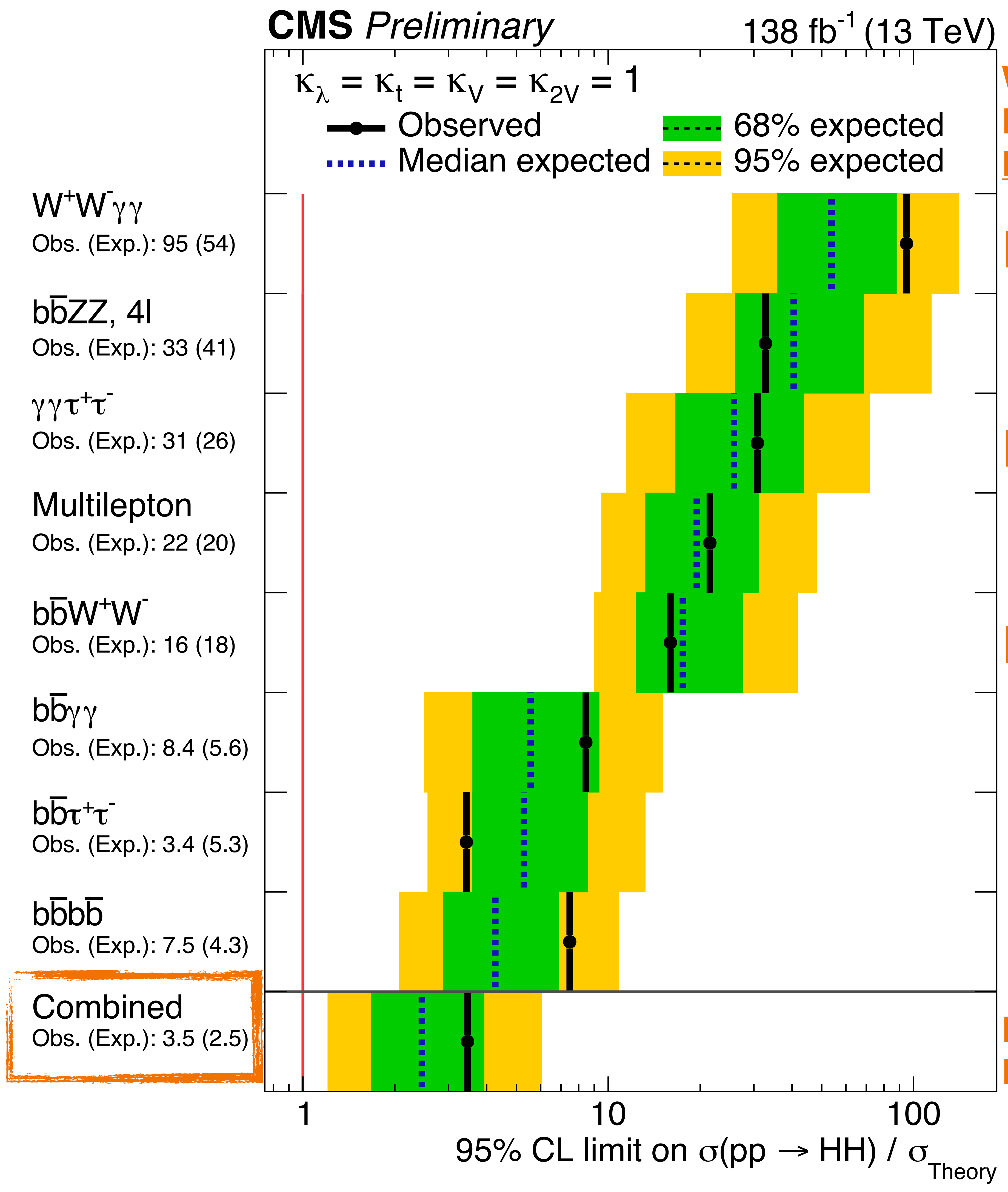


The HH combination

NEW PUBLIC RELEASE

CMS-PAS-HIG-20-011

Inclusive production



WRT PREVIOUS RUN-2 COMBINATION
Nature 607.7917

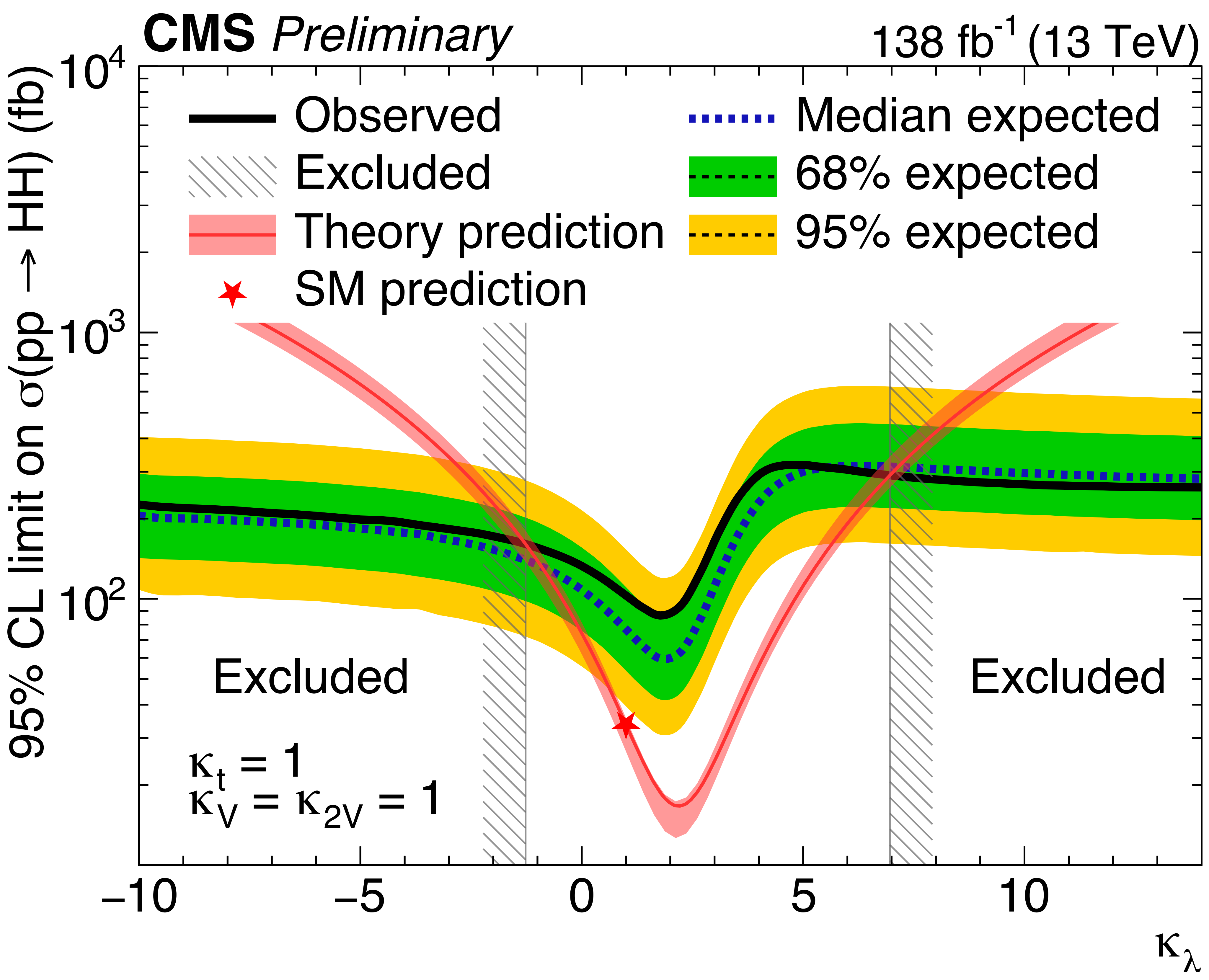
NEW

NEW

NEW

NEW OVERLAP REMOVAL

Most complete HH combination @ CMS



Observed : $\kappa_\lambda \in [-1.39, +7.02]$

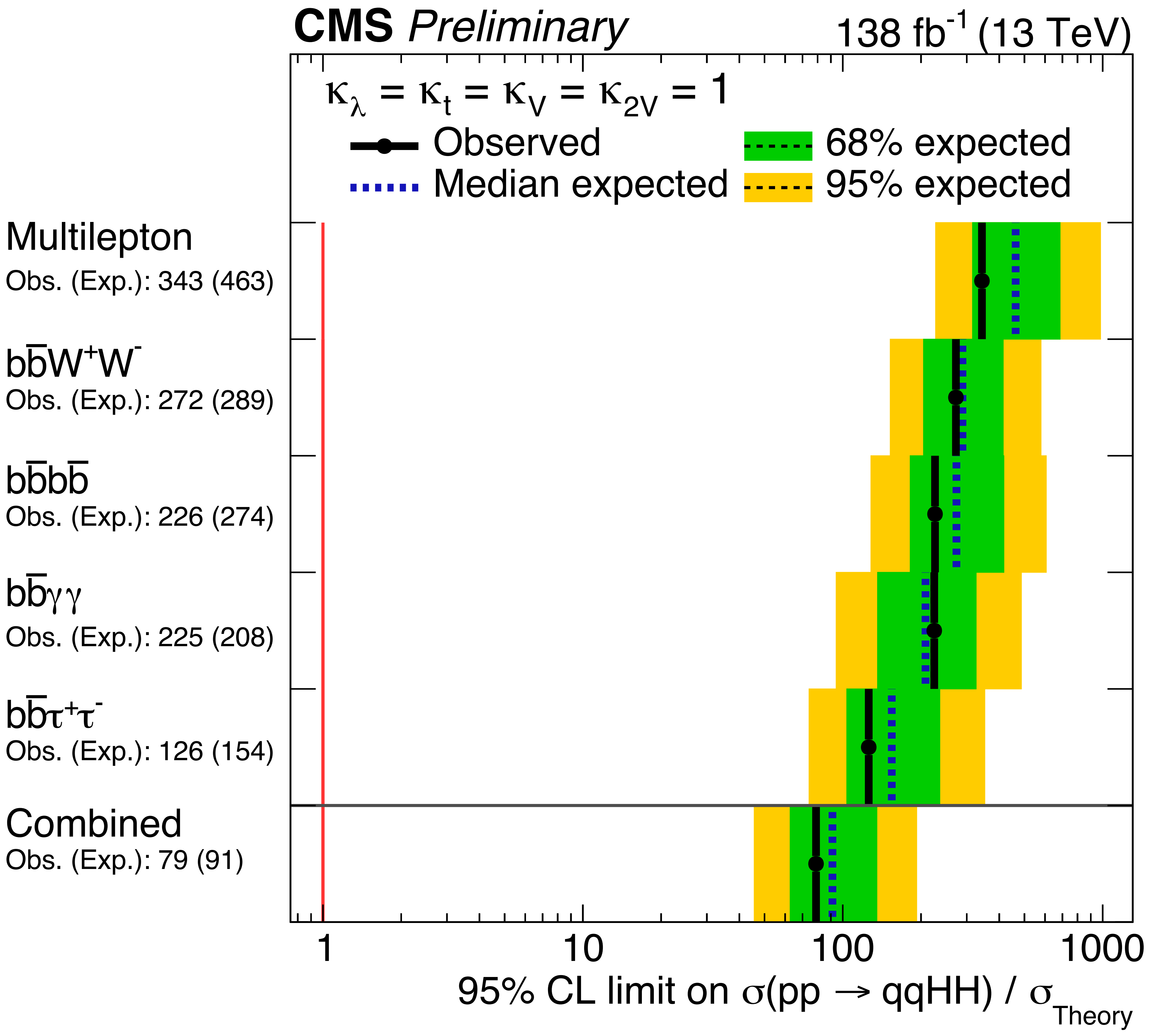
Expected : $\kappa_\lambda \in [-1.02, +7.19]$

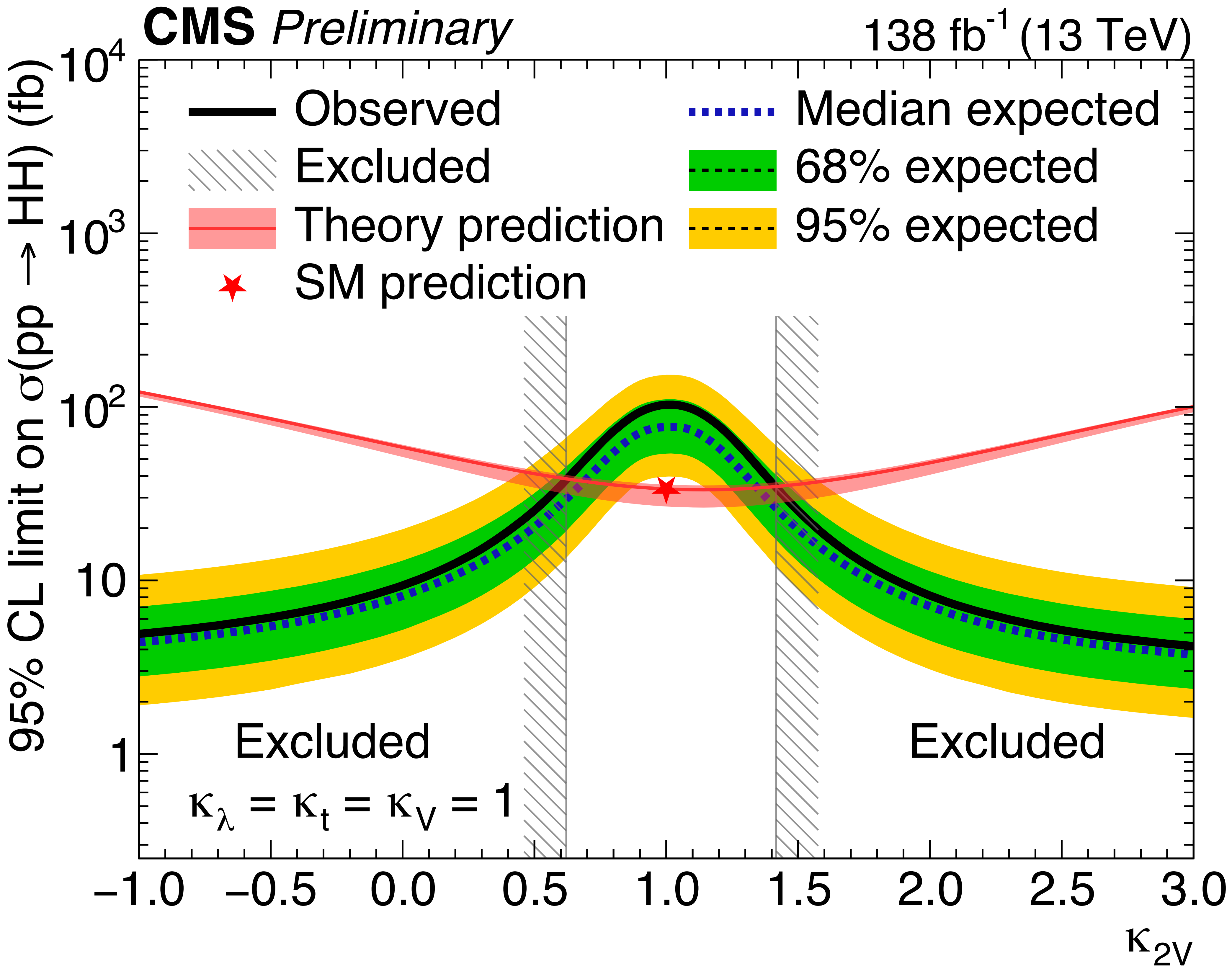
The HH combination

NEW PUBLIC RELEASE

CMS-PAS-HIG-20-011

VBF production





First combined VBF limit @ CMS:

Observed : $\sigma_{HH,VBF} = 79 \times \sigma^{SM}_{HH,VBF}$

Expected : $\sigma_{HH,VBF} = 91 \times \sigma^{SM}_{HH,VBF}$

Observed : $\kappa_{2V} \in [0.62, 1.42]$

Expected : $\kappa_{2V} \in [0.69, 1.35]$

VVHH coupling established at $\sim 7\sigma$ significance

The HH combination

NEW PUBLIC RELEASE

[CMS-PAS-HIG-20-011]

2D likelihood scans

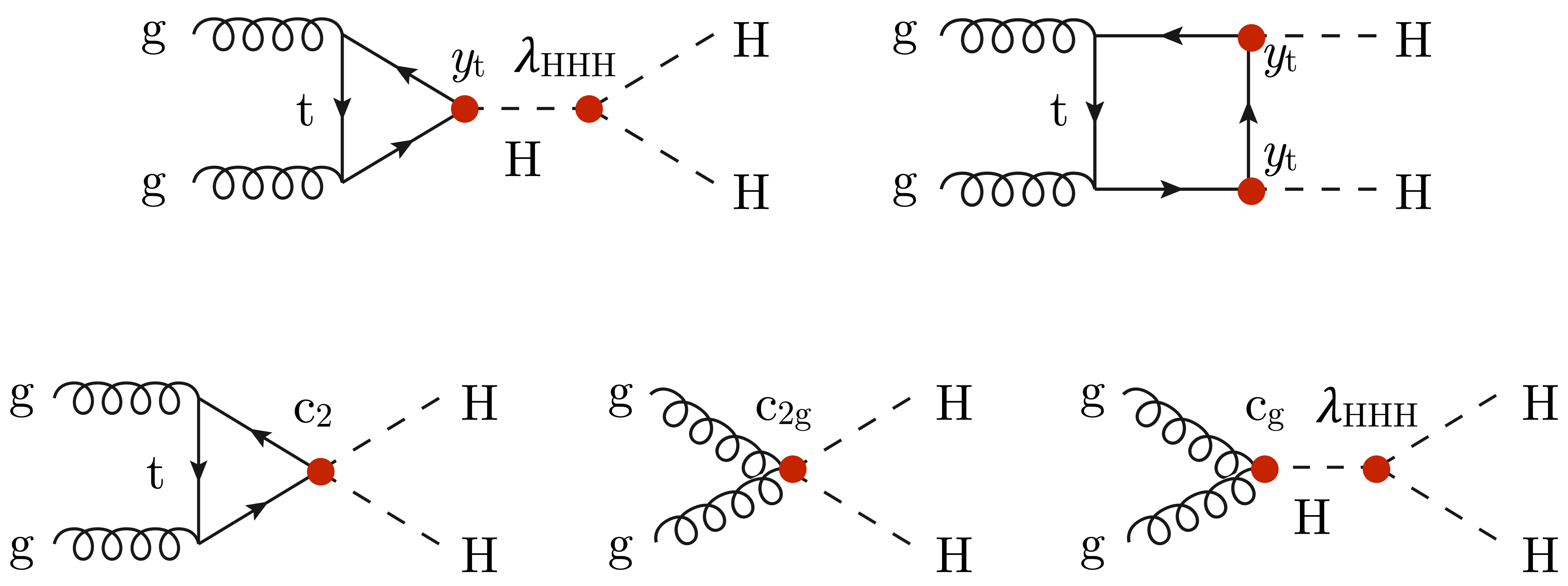
- 2D likelihood scans allows to study the **mutual interplay between the κ-modifiers** (couplings not being profiled are set to the SM expectation value)
- **Marginal degeneracy in κ-dependence** due to degeneracies $\sigma_{HH,GGF}$ and $\sigma_{HH,VBF}$
- **No significant deviation from the SM is observed in any of the scans**

The HH combination

NEW PUBLIC RELEASE

CMS-PAS-HIG-20-011

HEFT interpretations



The κ-modifiers approach is useful but has many limitations.

The Higgs Effective Field Theory (HEFT) is model independent approach to **extending the SM to account for new physics.**

HEFT approach posits **5 couplings** $(\lambda_{HHH}, y_t, c_2, c_g, c_{2g})$.

20 HEFT benchmarks defined, i.e. 5D phase space sub-regions

NEW PUBLIC RELEASE

The HH combination

CMS-PAS-HIG-20-011

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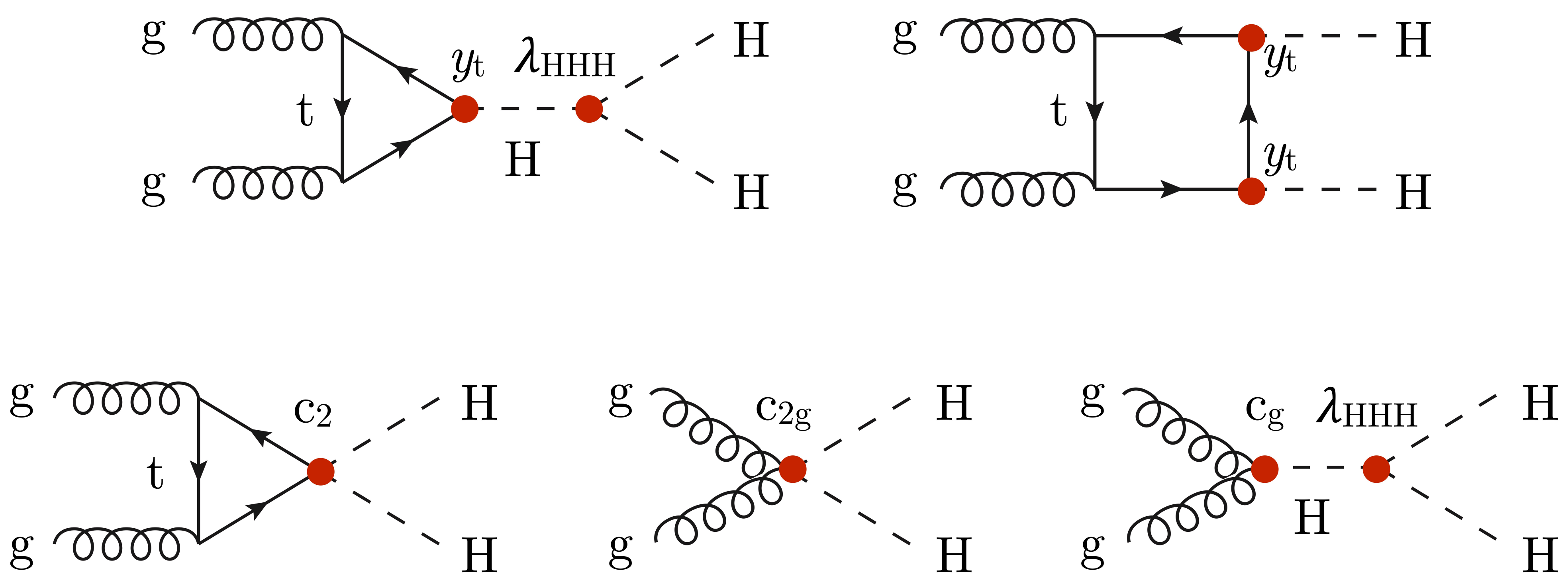

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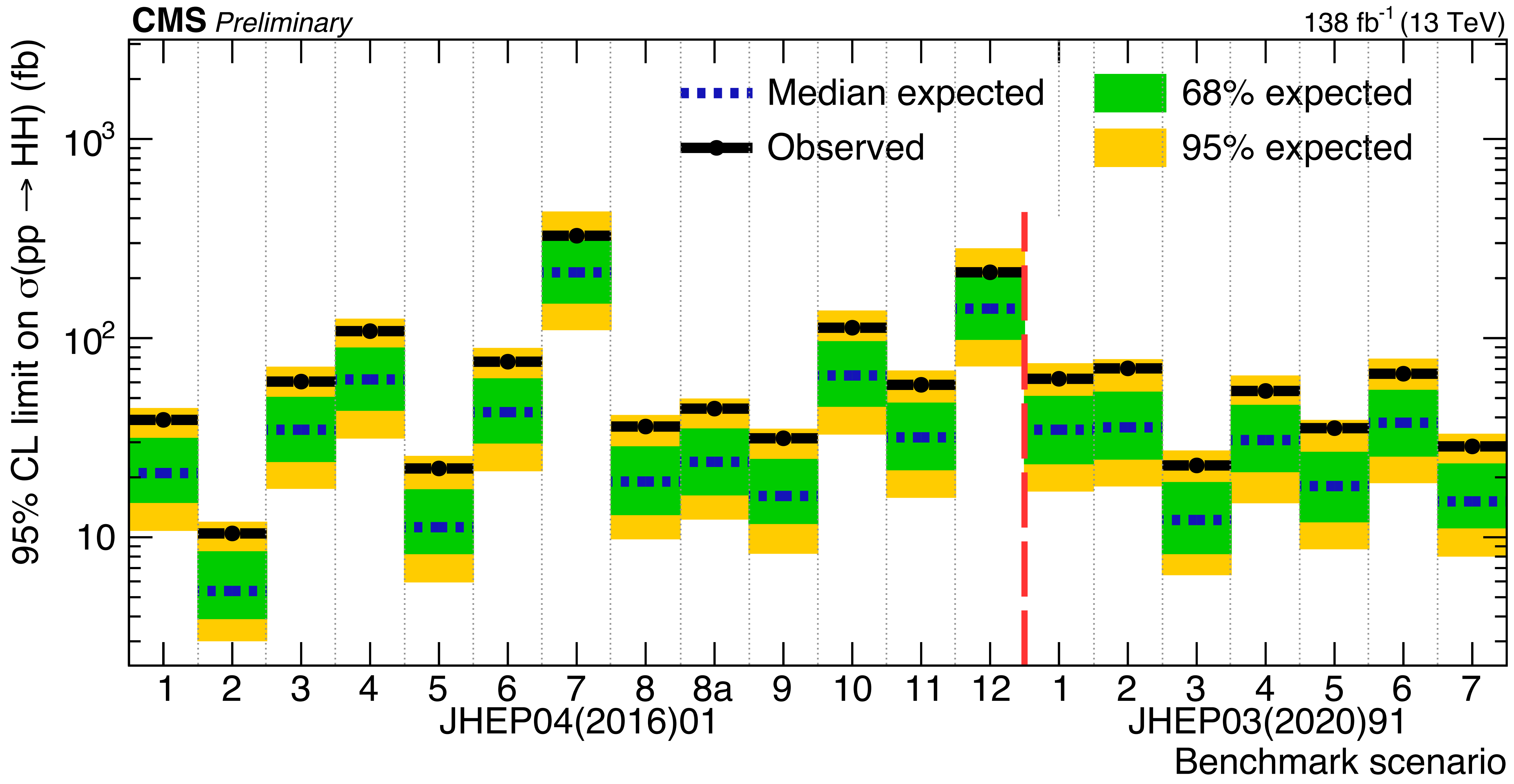
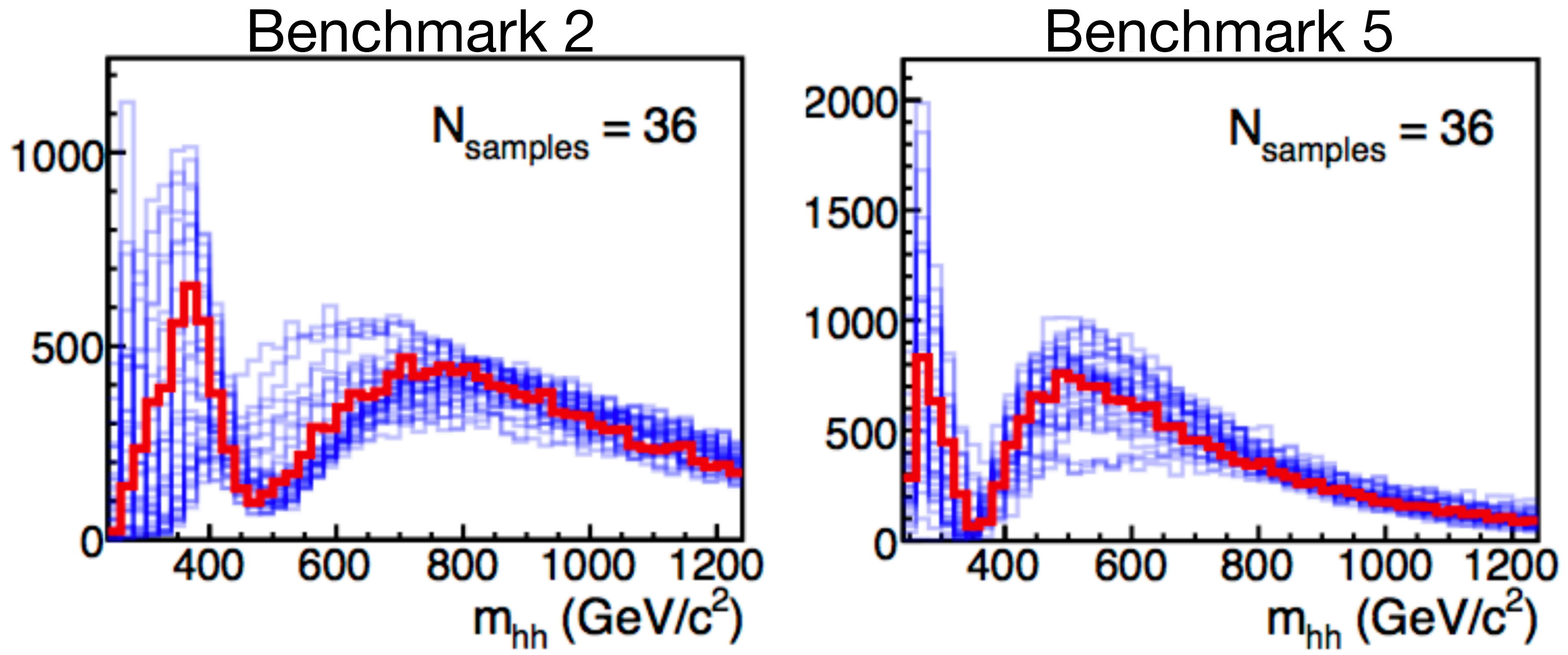


Most comprehensive HEFT interpretation @ CMS

Sensitivity driven by m_{HH} differential distribution

→ better sensitivity if σ_{HEFT} enhanced at large m_{HH}



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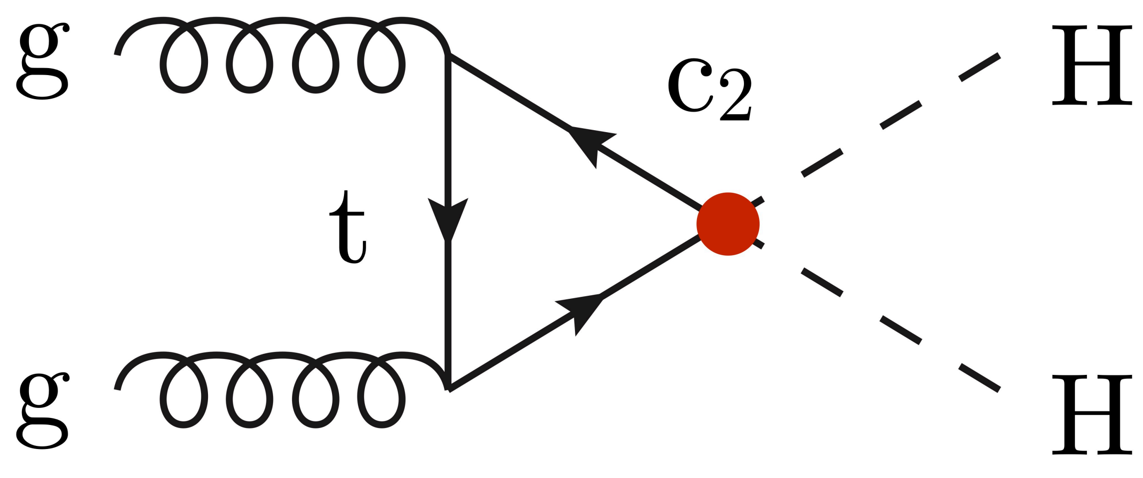


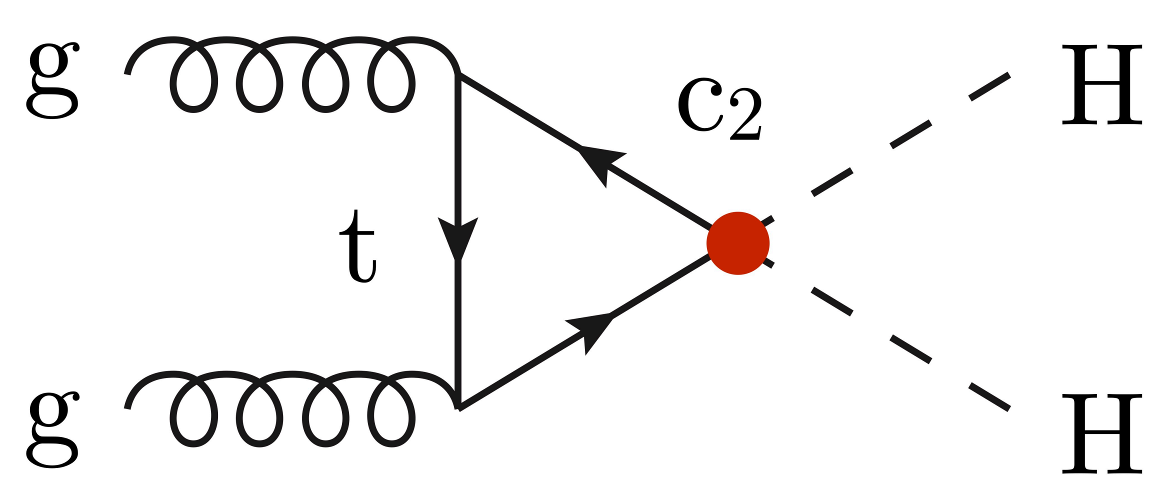
The study of c_2 is of particular interest as it is tightly correlated with the κ_t modifier.

Profound motivation to perform dedicated c_2 coupling scan.

The HH combination

CMS-PAS-HIG-20-011

HEFT interpretations



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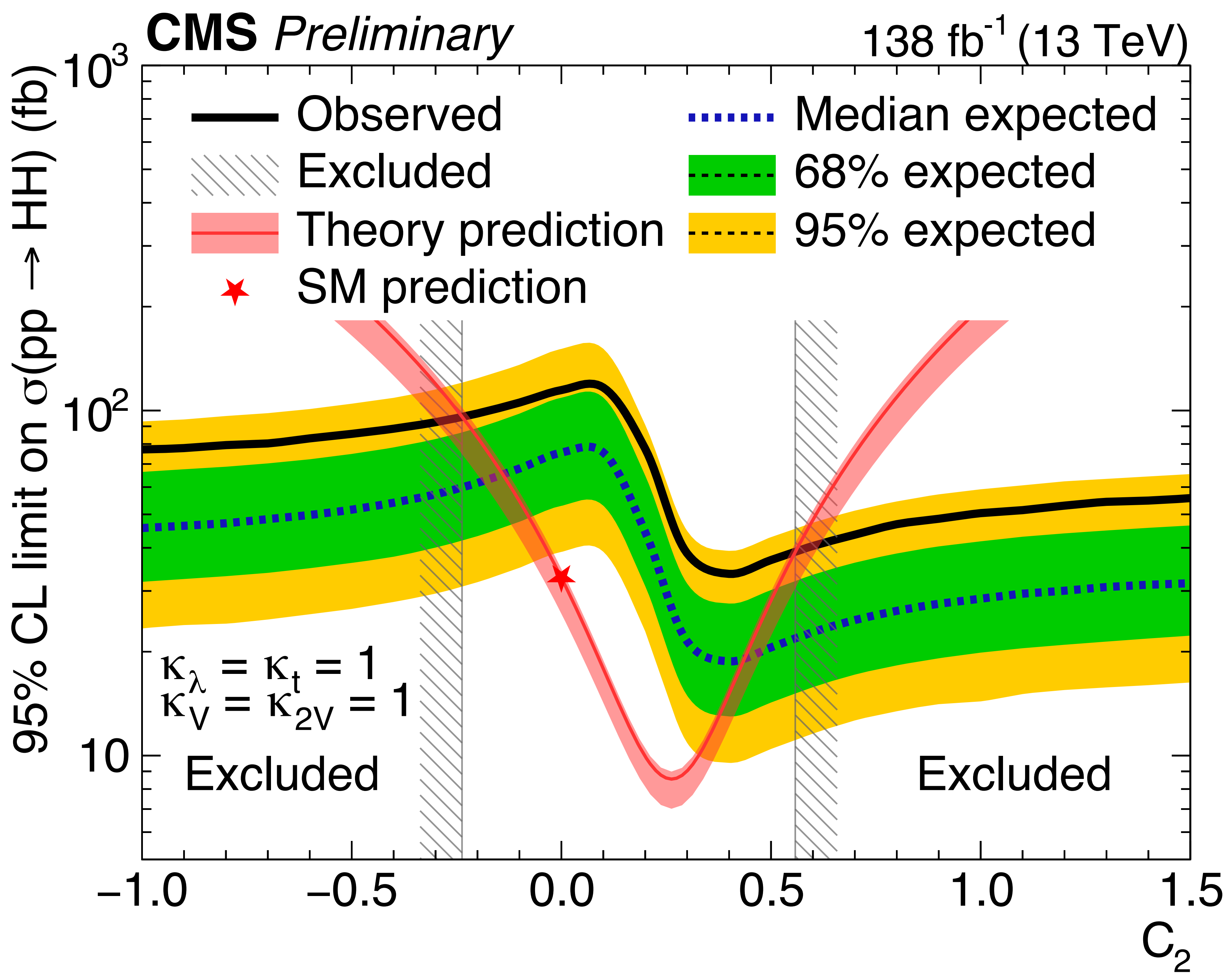


First combined c_2 scan @ CMS:

From 95% CL σ_{HH} scan:

Observed : $c_2 \in [-0.28, 0.59]$

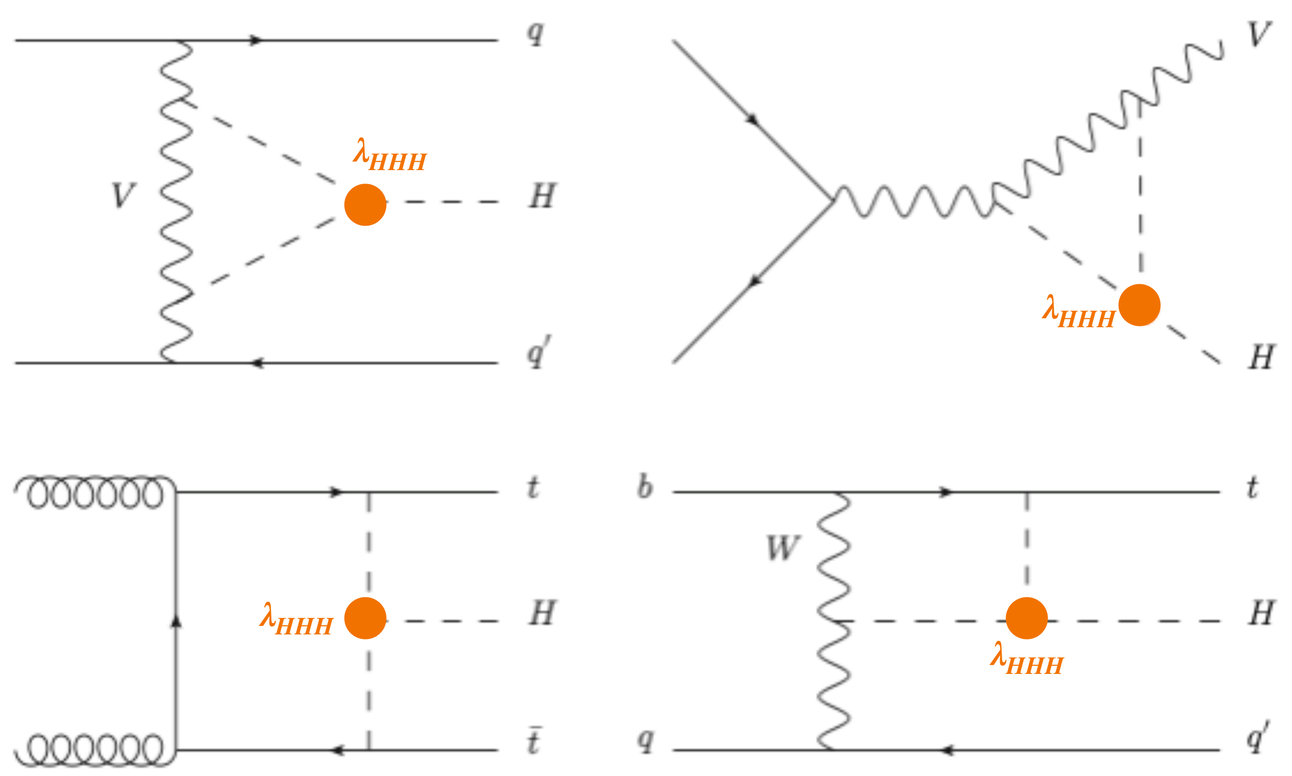
Expected : $c_2 \in [-0.17, 0.47]$

NEW SINCE HIGGS '23

The HH+H combination**

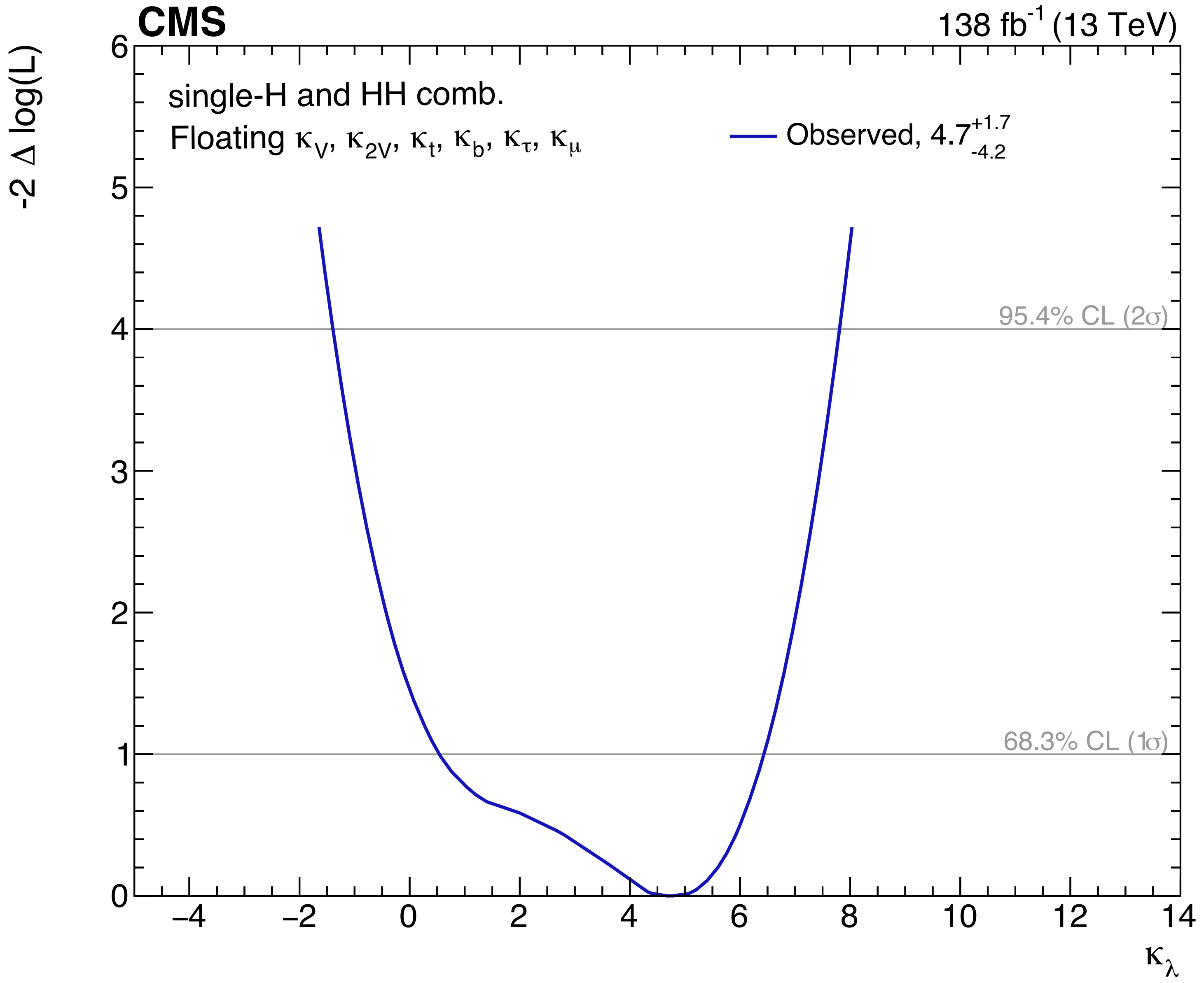
Submitted to Journal

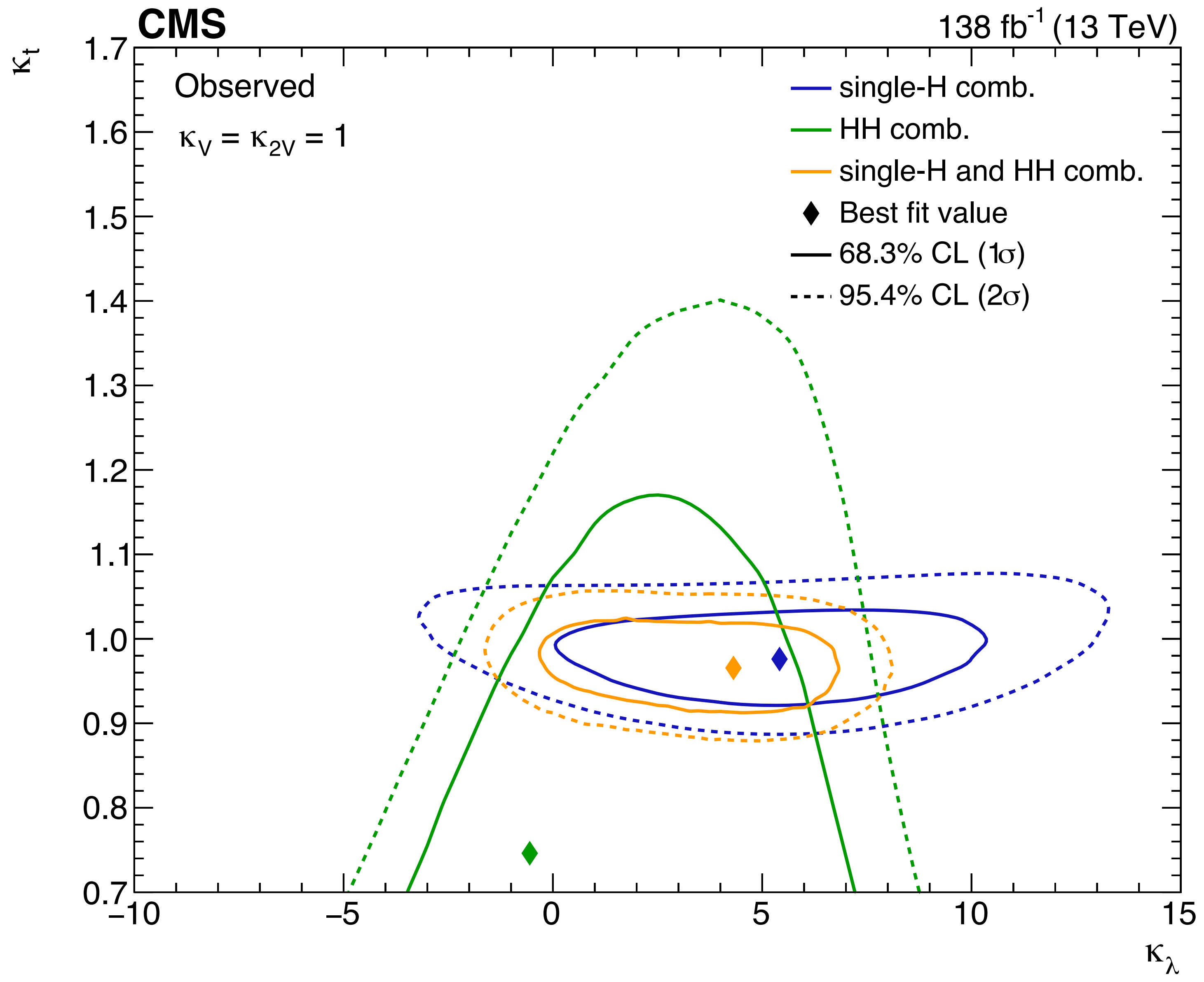
- At NLO EW correction, the single-H boson production includes processes sensitive to λ_{HHH} coupling

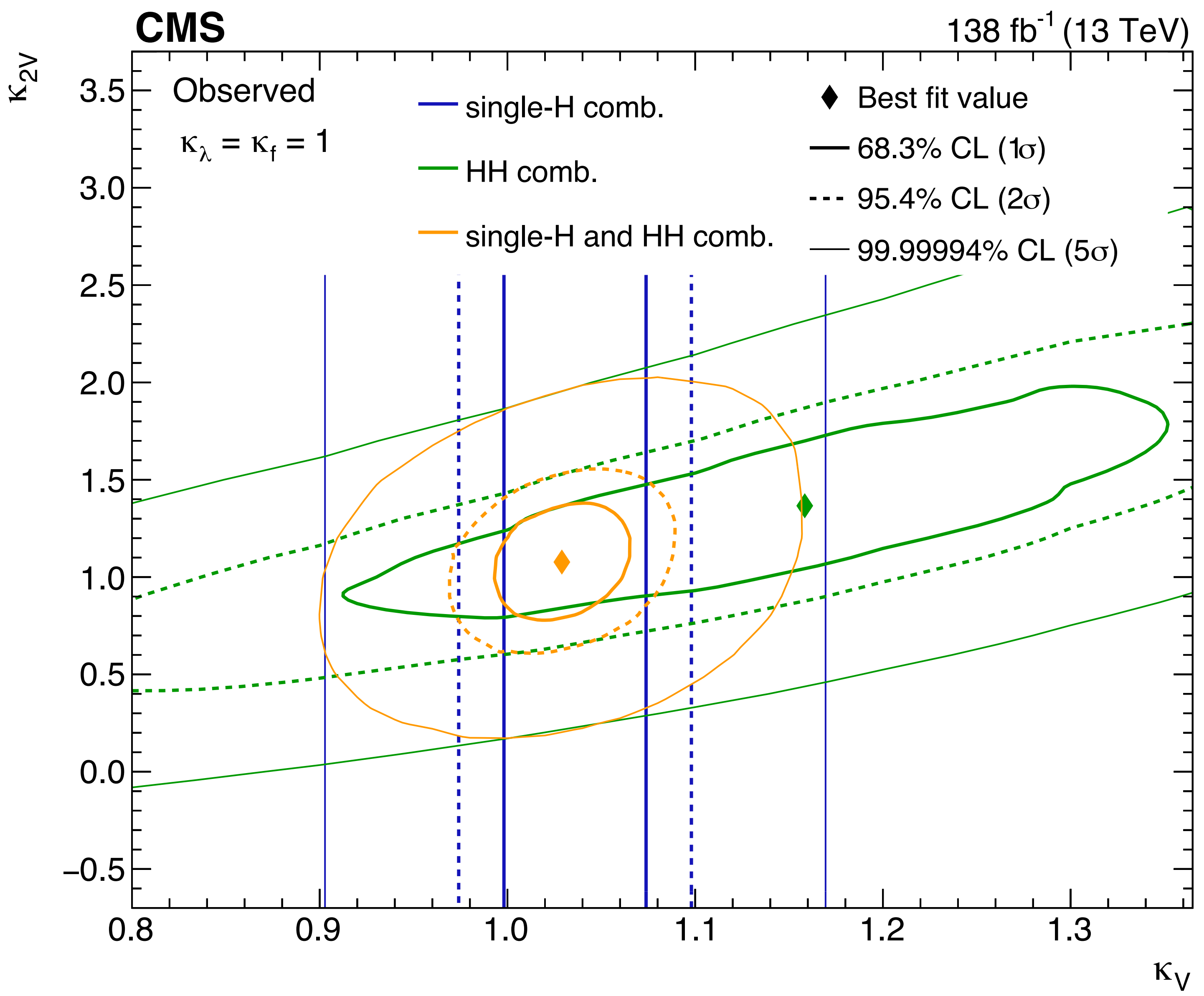


- The HH combination uses 3 more channels than HH+H combination

- **Relatively small improvement on κ_λ limit BUT can greatly relax assumptions on κ_V, κ_{2V}, and κ_f →HH and HH+H are complementary!**







** The list of analysis use in the HH+H combination can be found in the backup.

Outlook : Run-3 improvements

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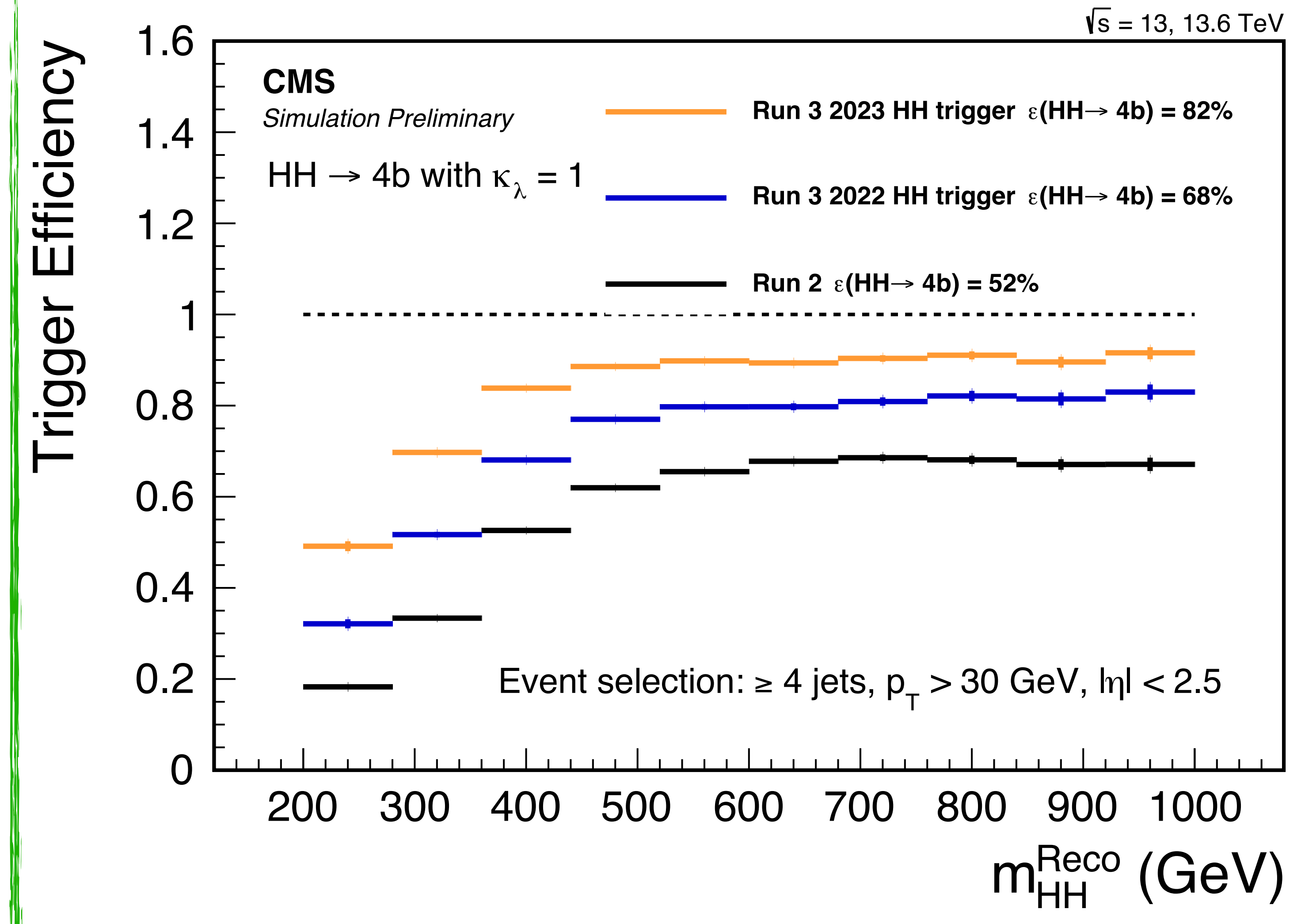
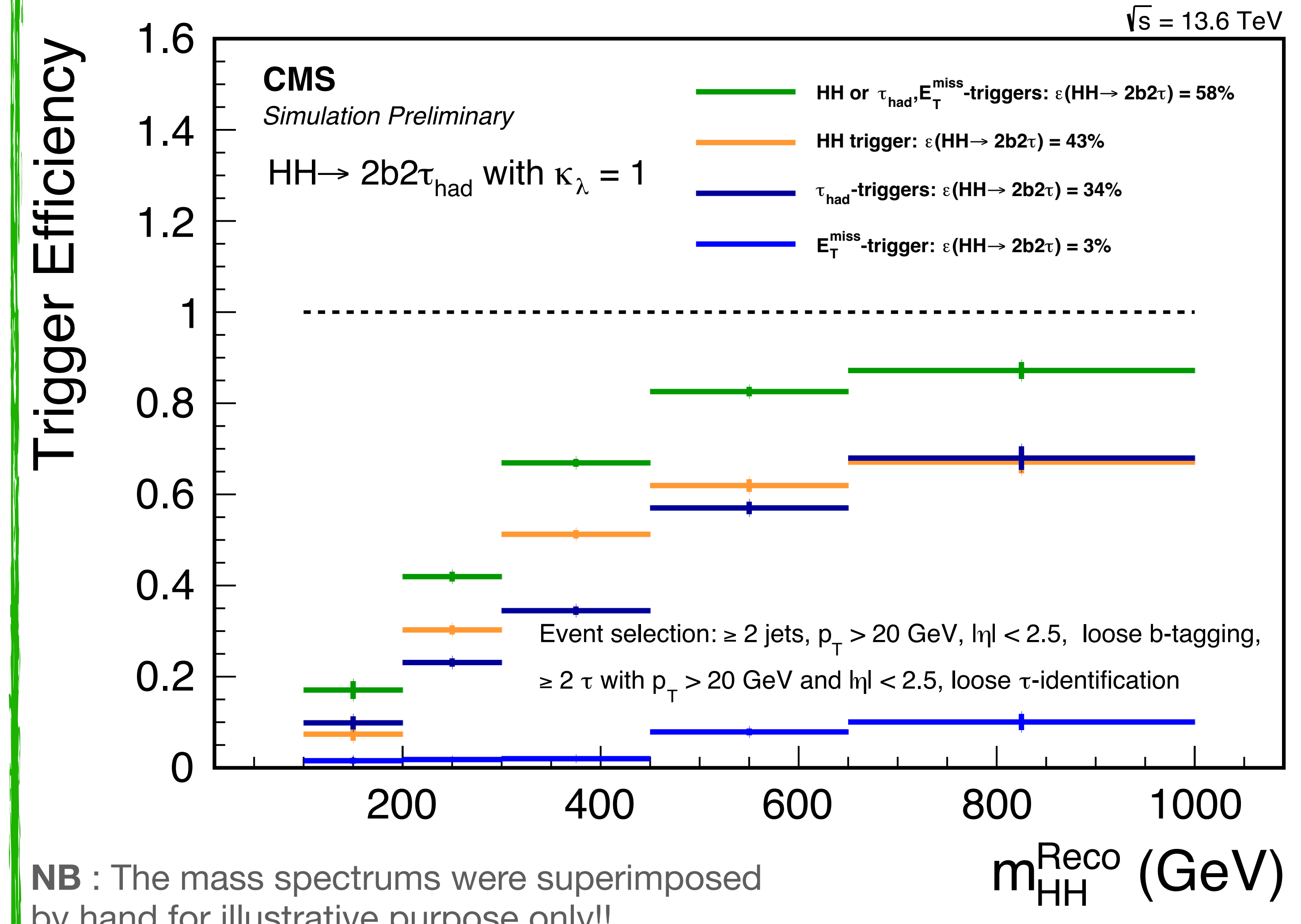
CMS-DP-2023-050

New triggers : Run-3 for CMS means higher integrated lumi at higher selection efficiency!





NB : The mass spectrums were superimposed by hand for illustrative purpose only!!

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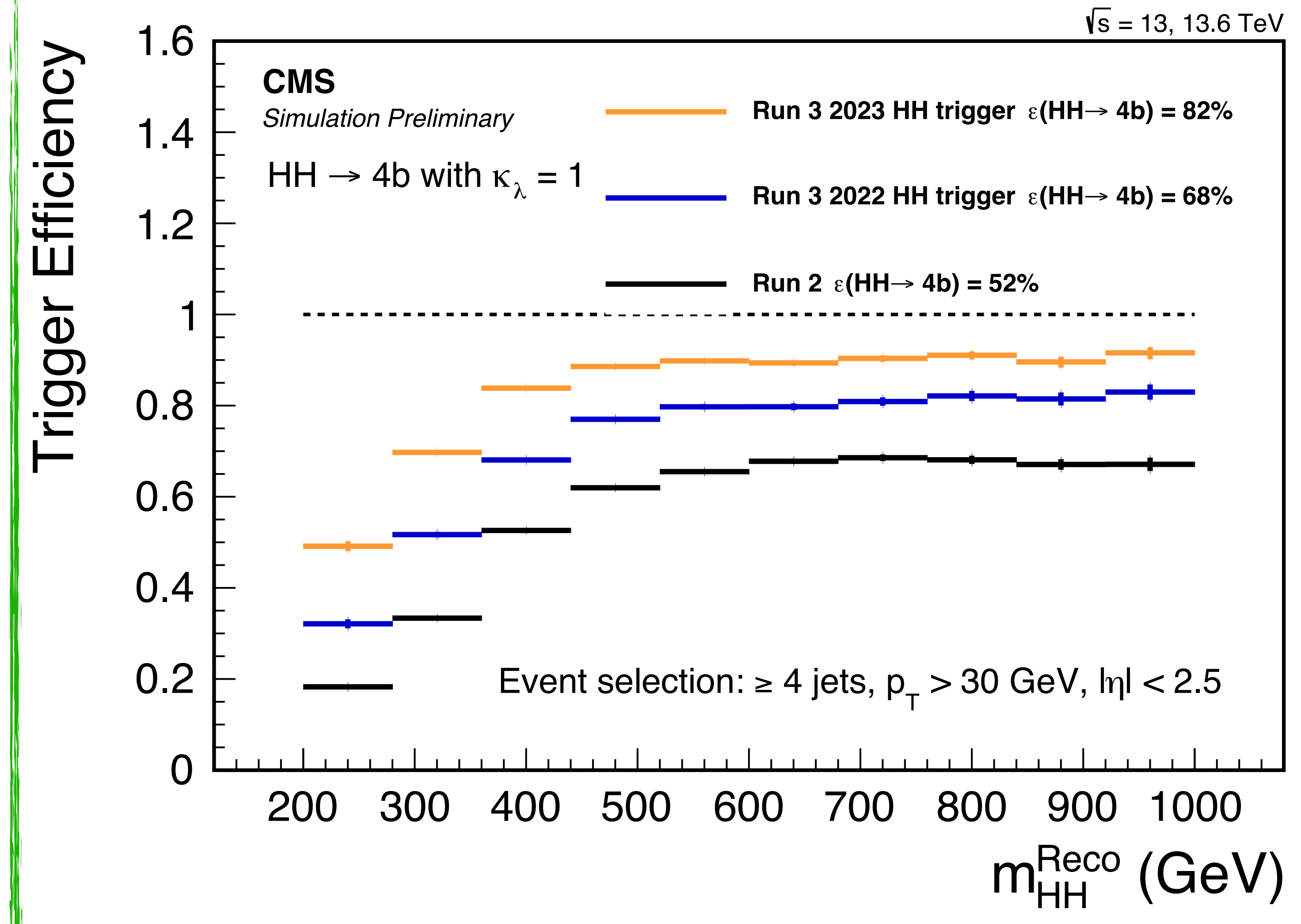

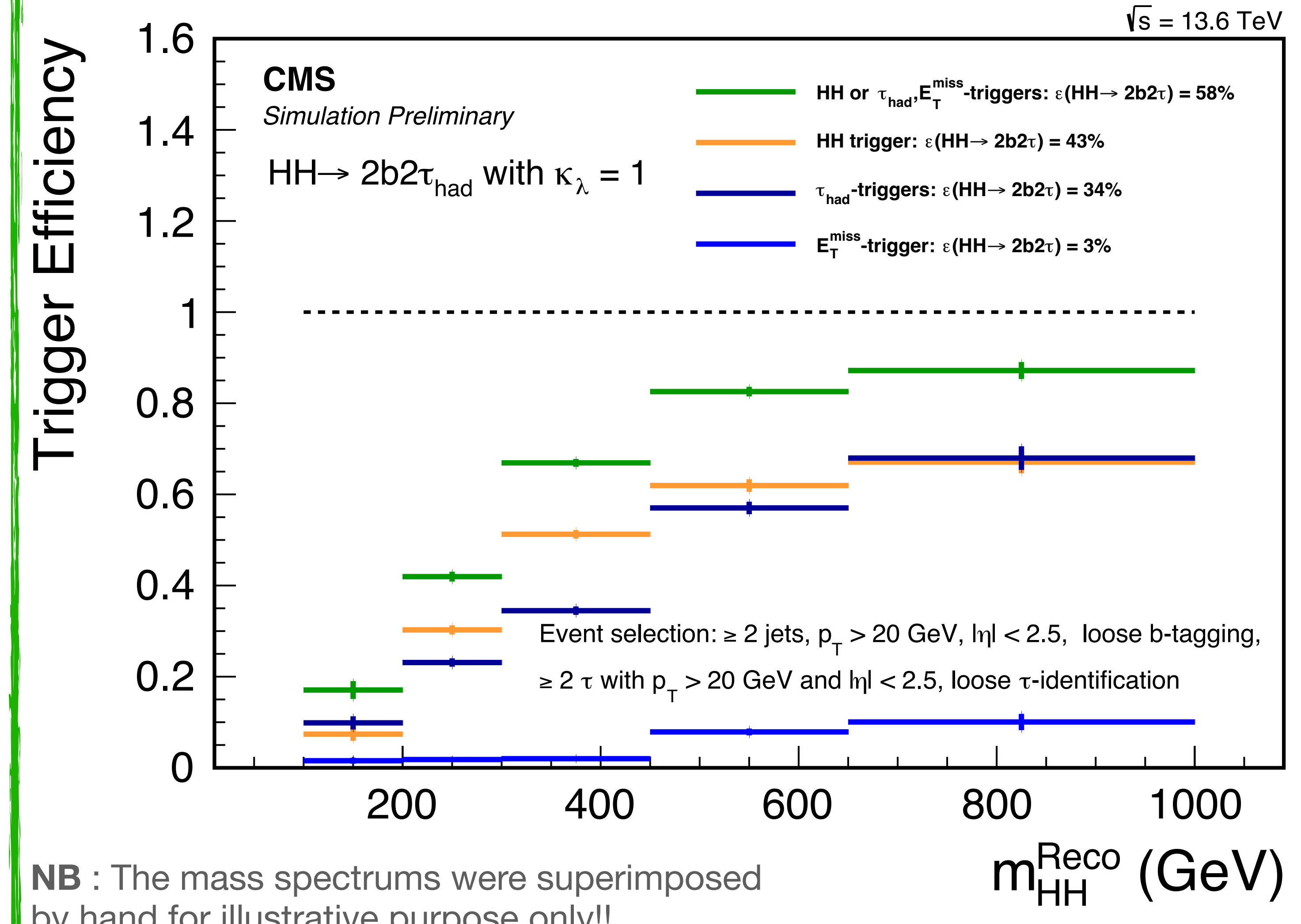

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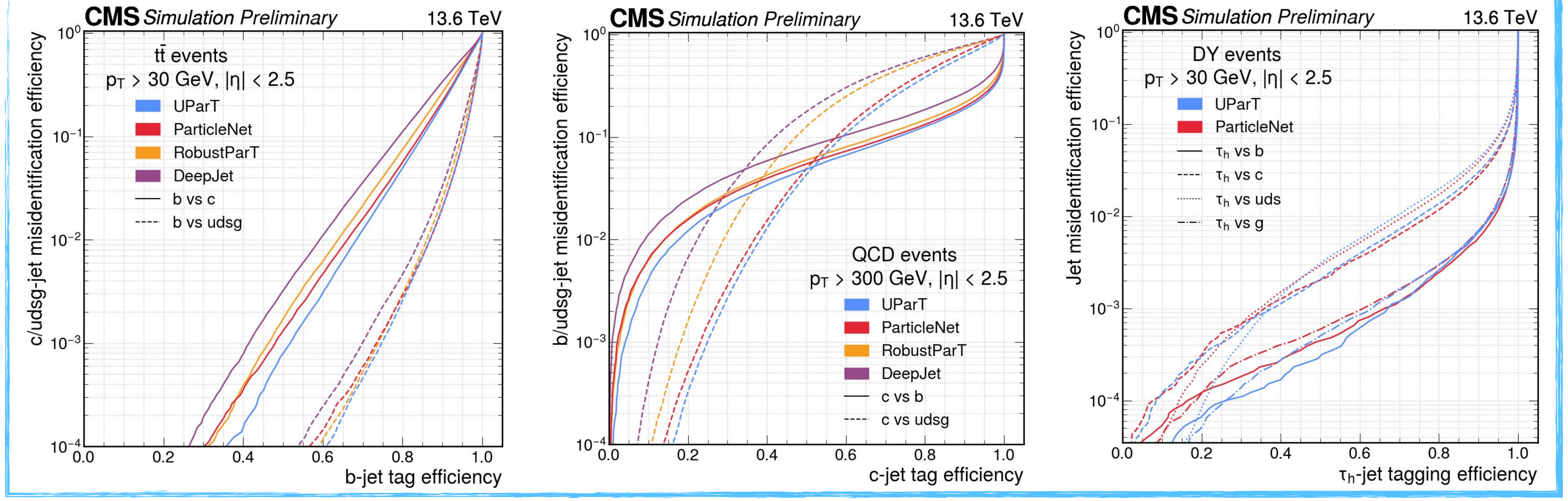
CMS-DP-2024-066

New taggers : targeting heavy- and light-flavour jet tagging, but also hadronic τ decays!



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CMS-DP-2023-050

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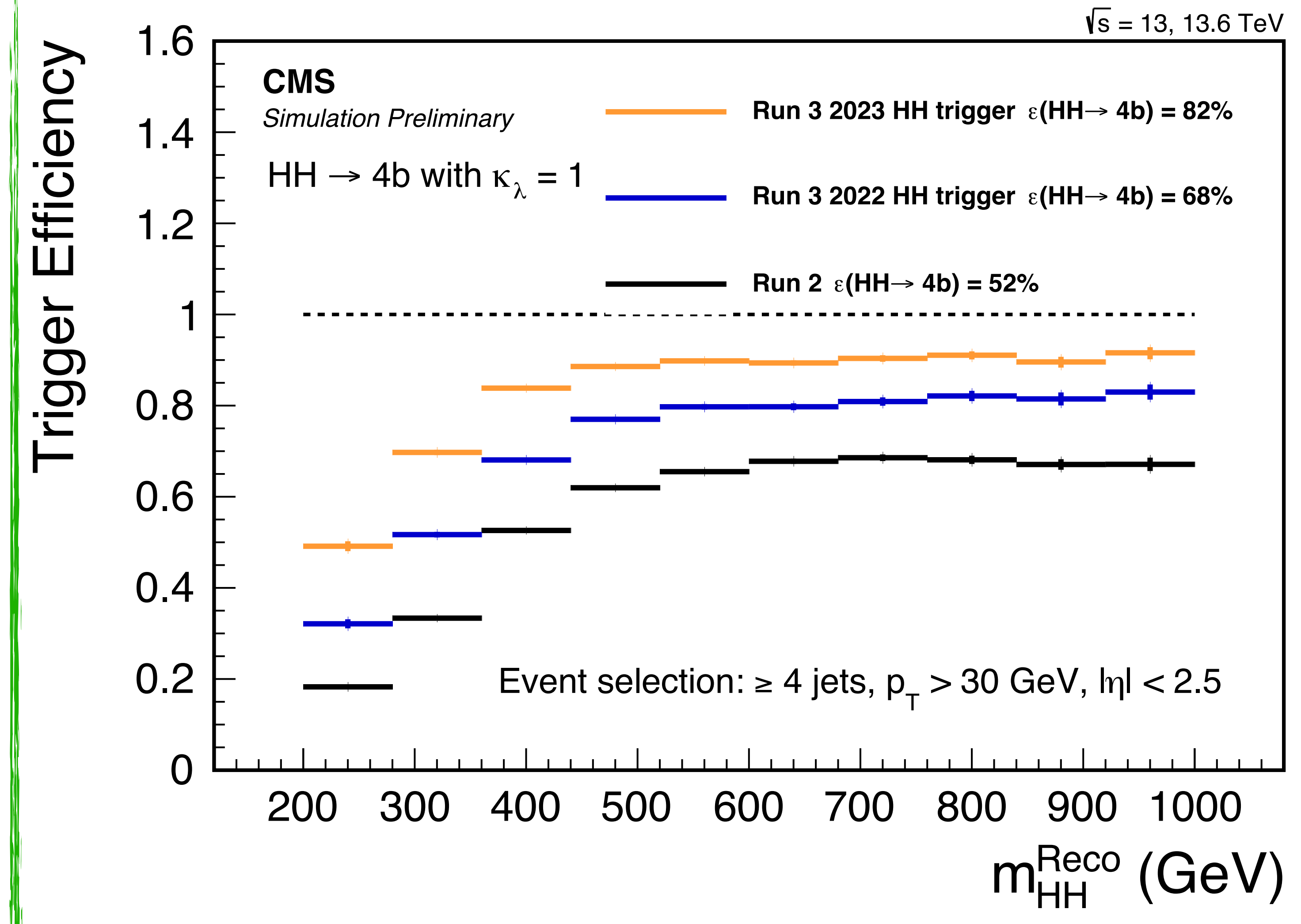

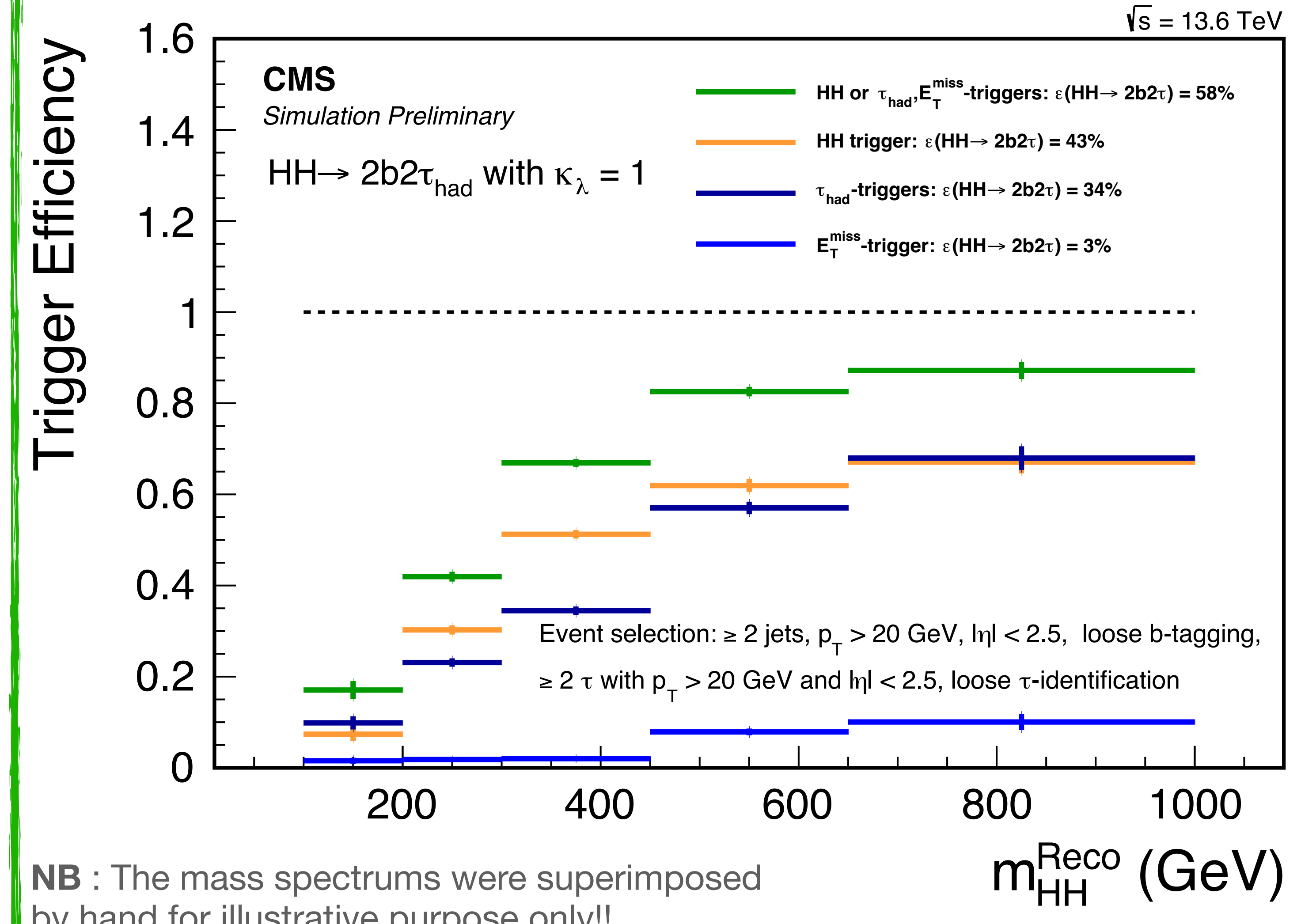

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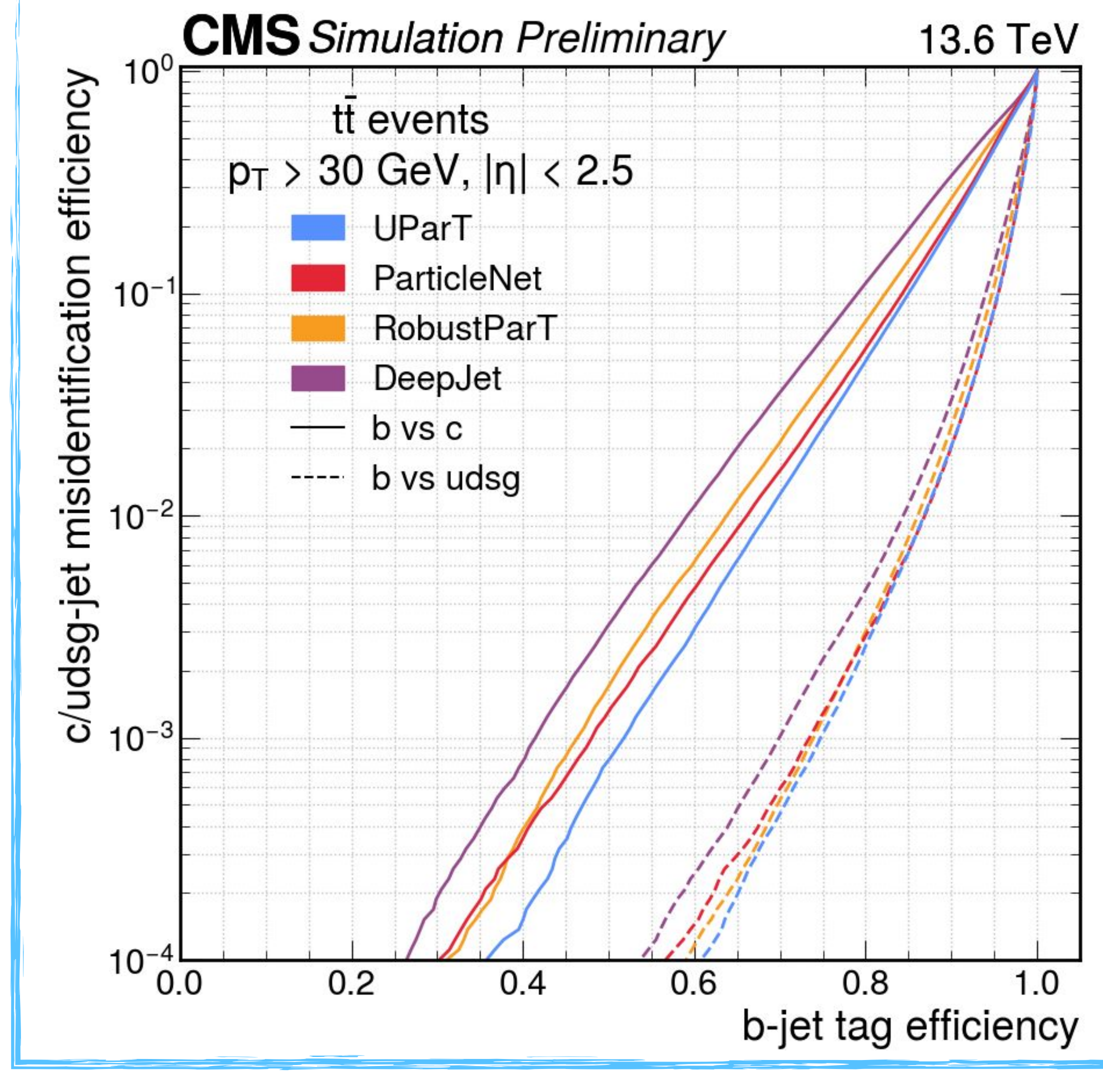
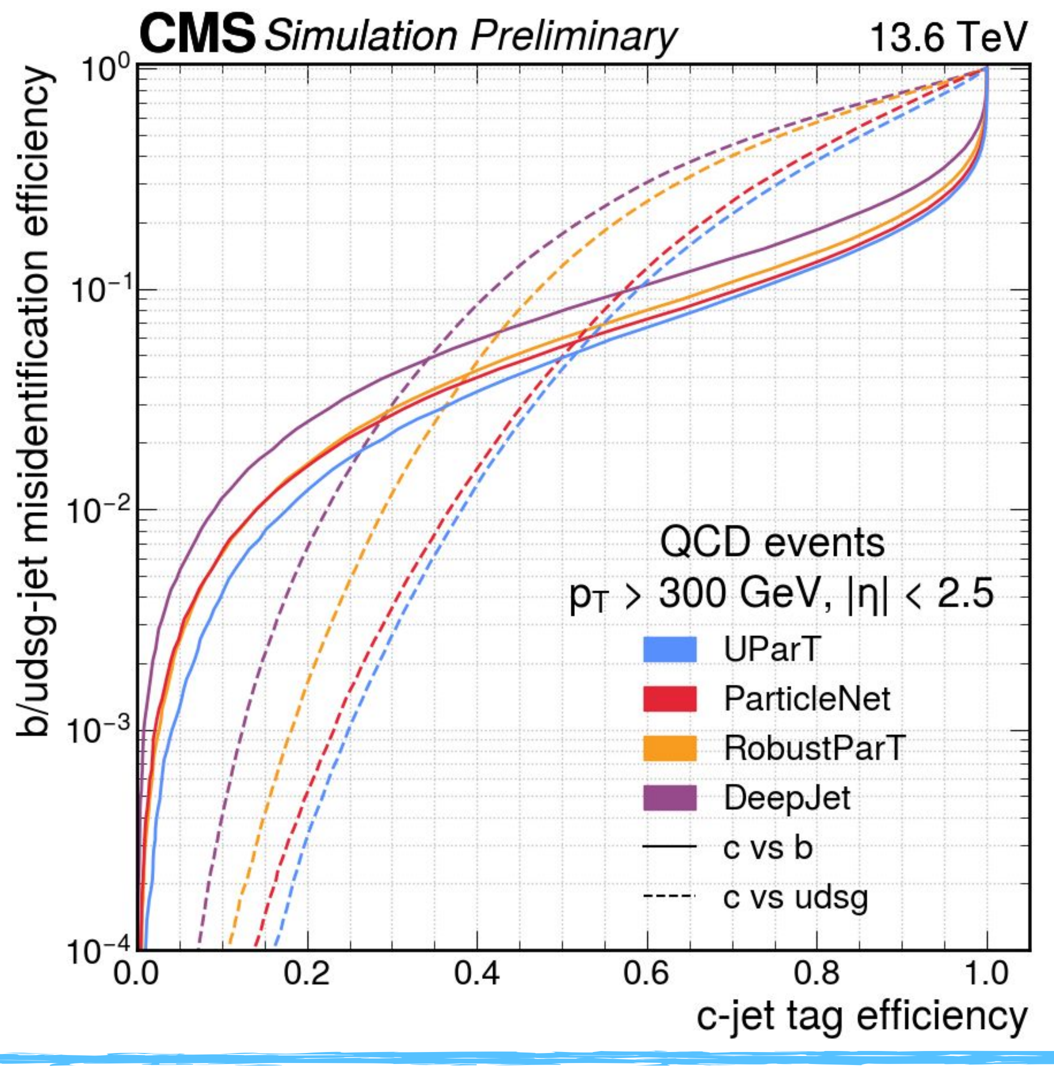
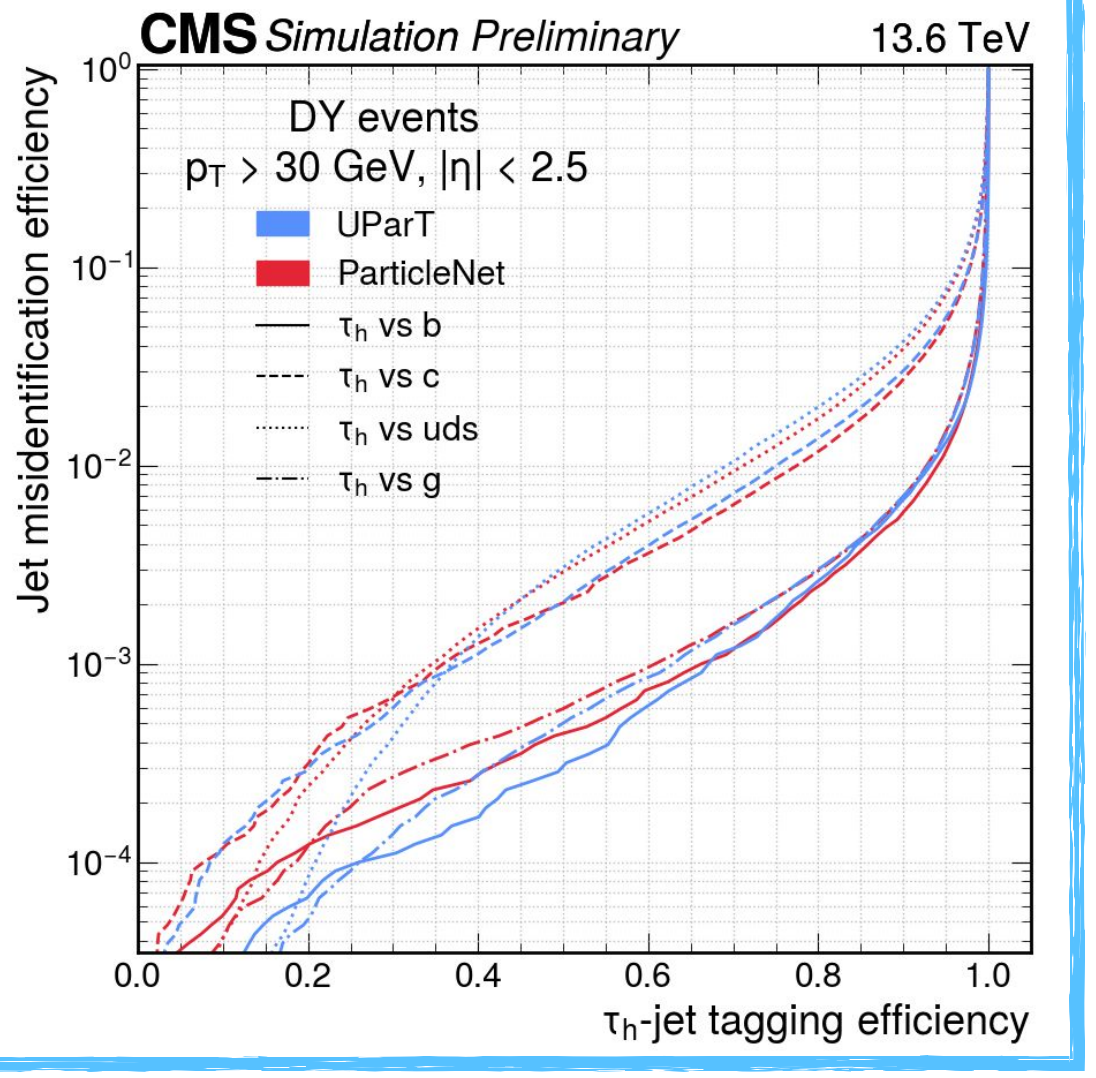
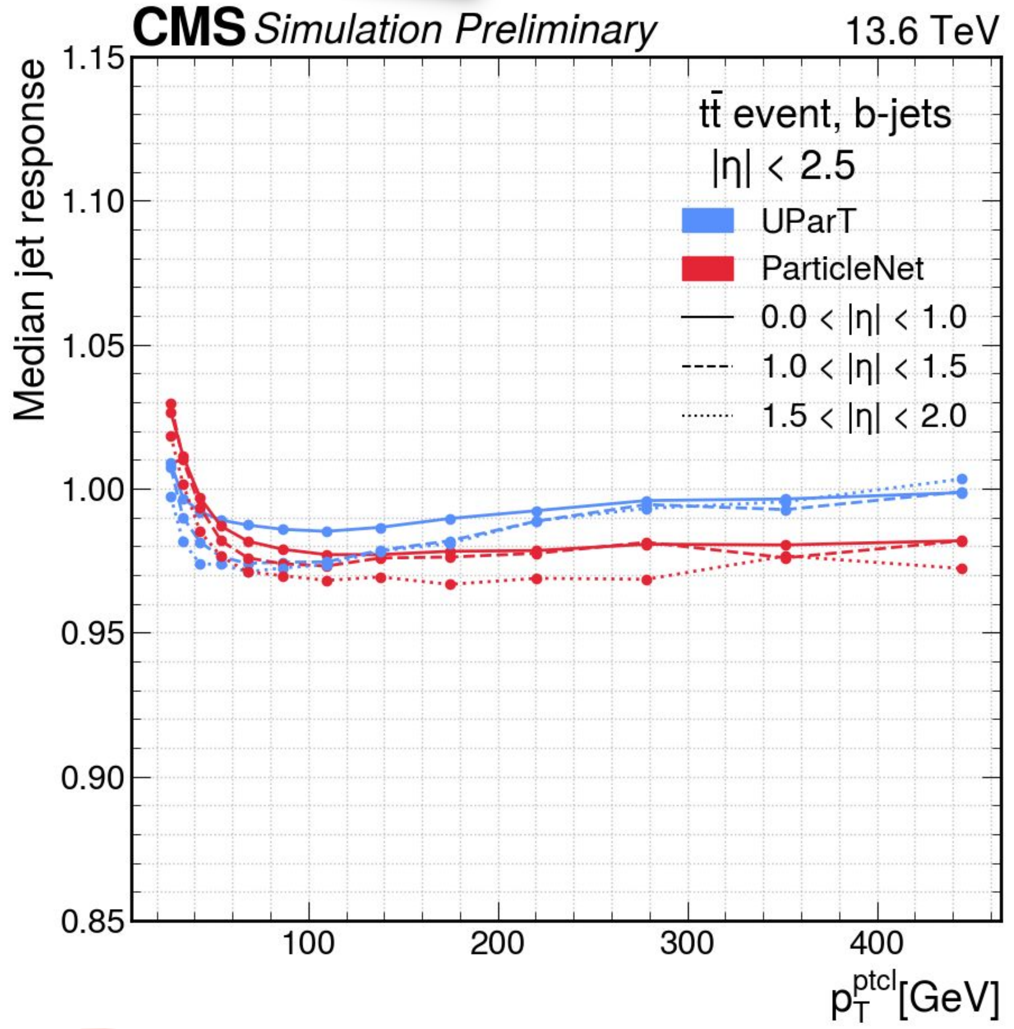


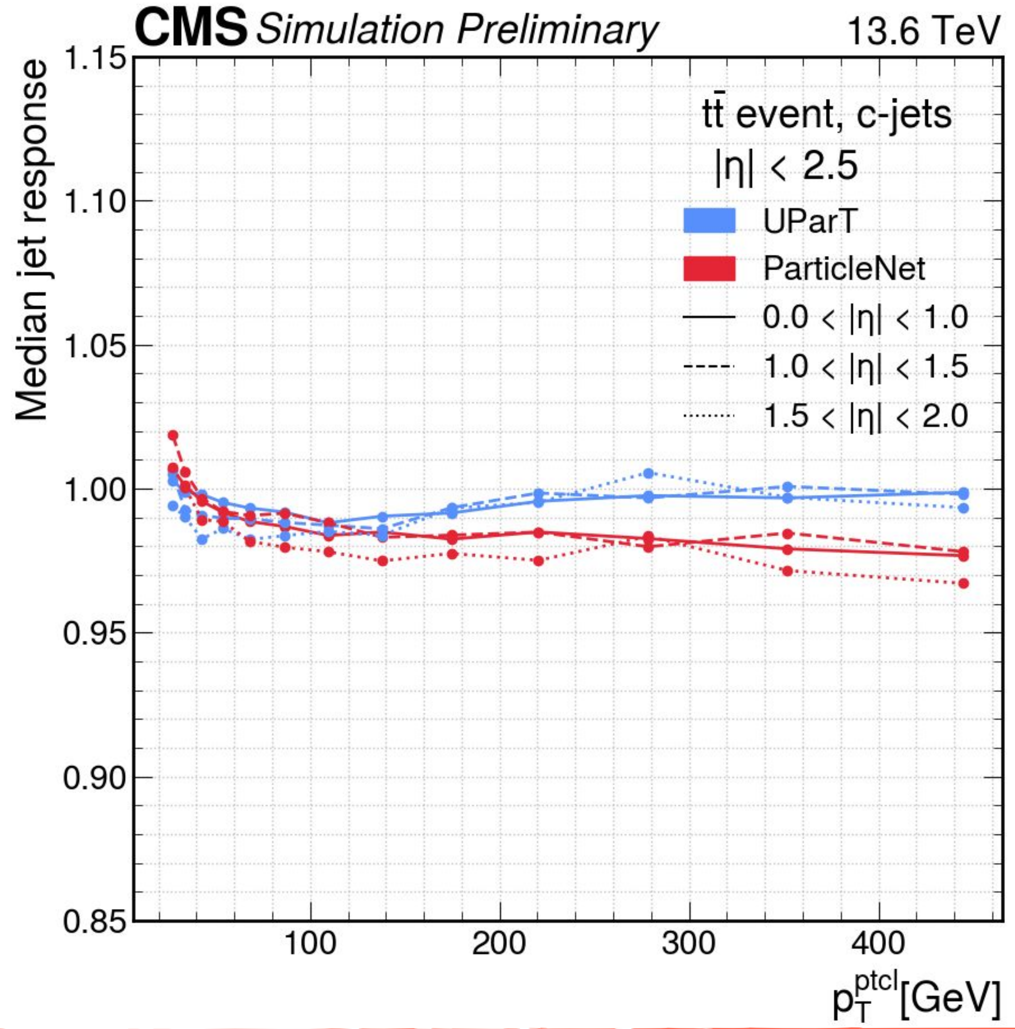




CMS-DP-2024-066

New p_T regressions : improve jet energy resolution!





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CMS-DP-2023-050

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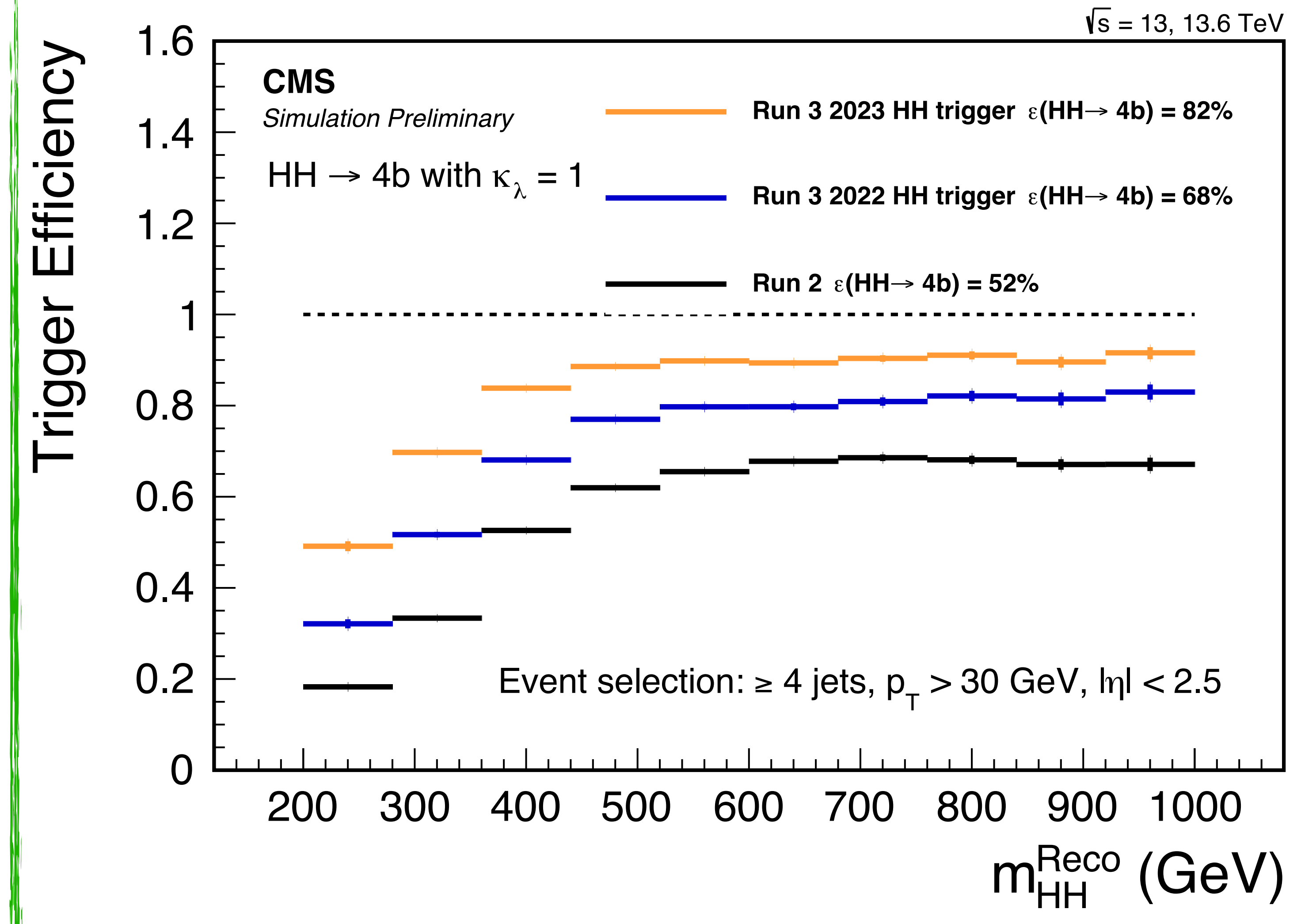

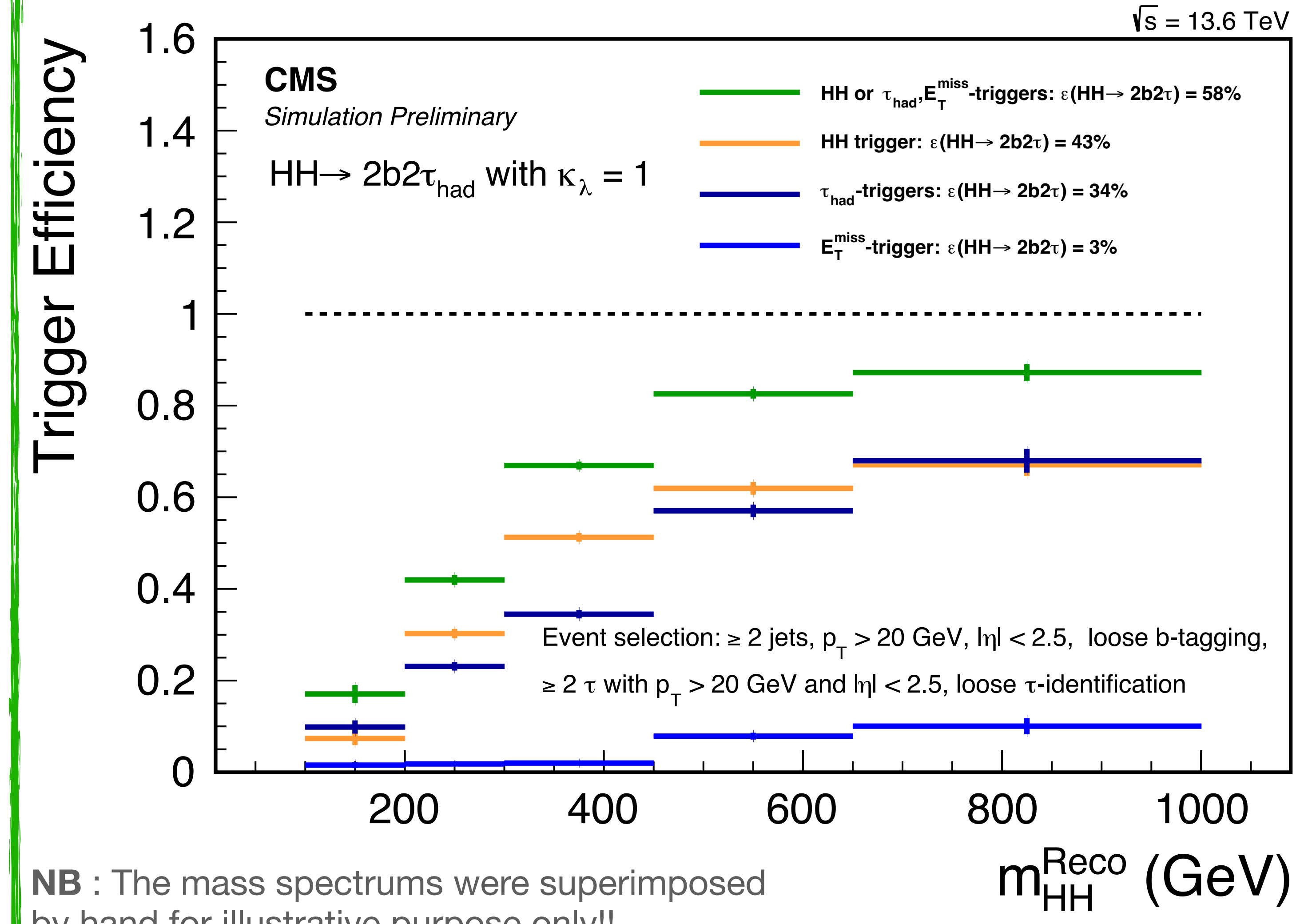

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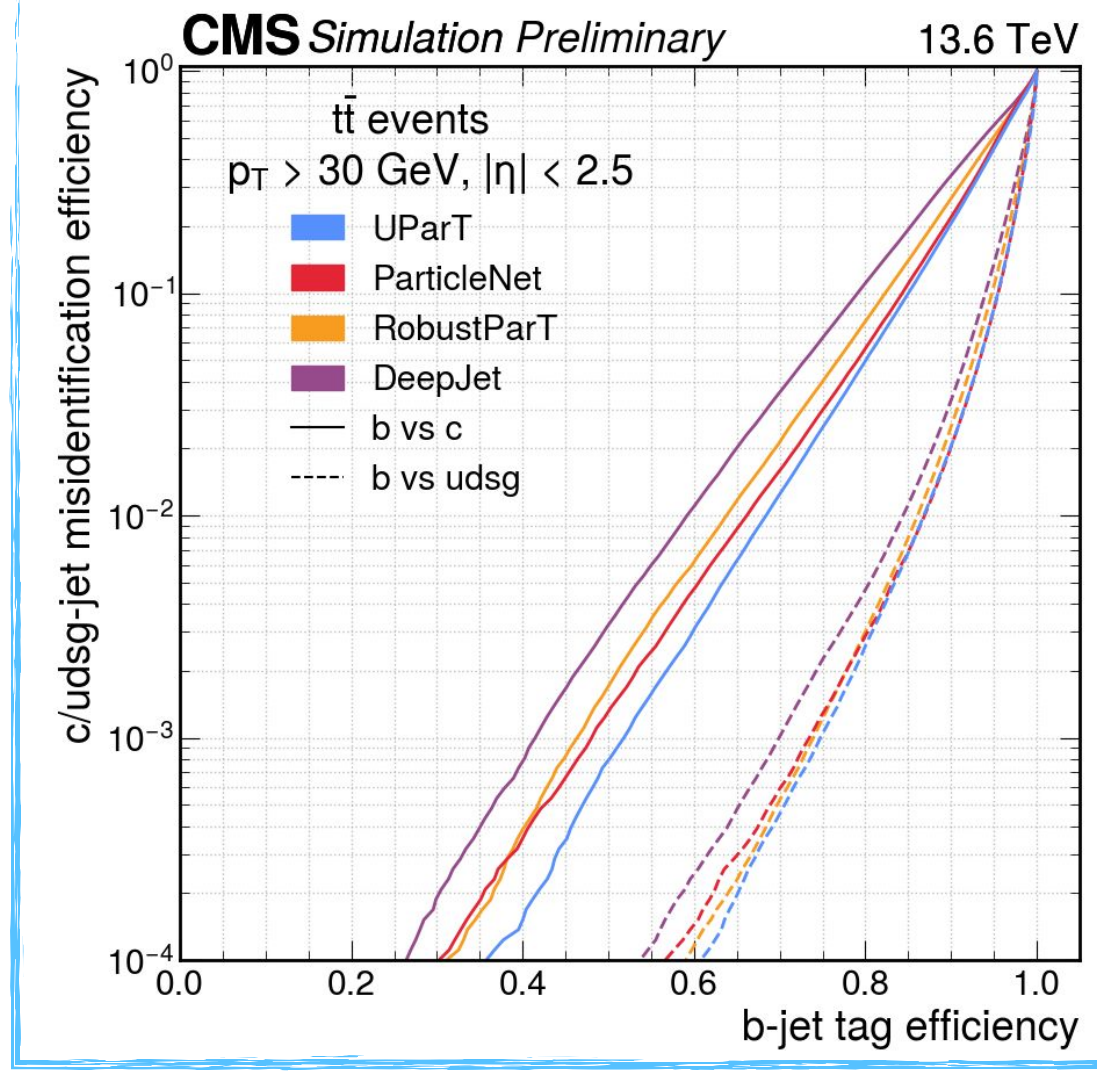

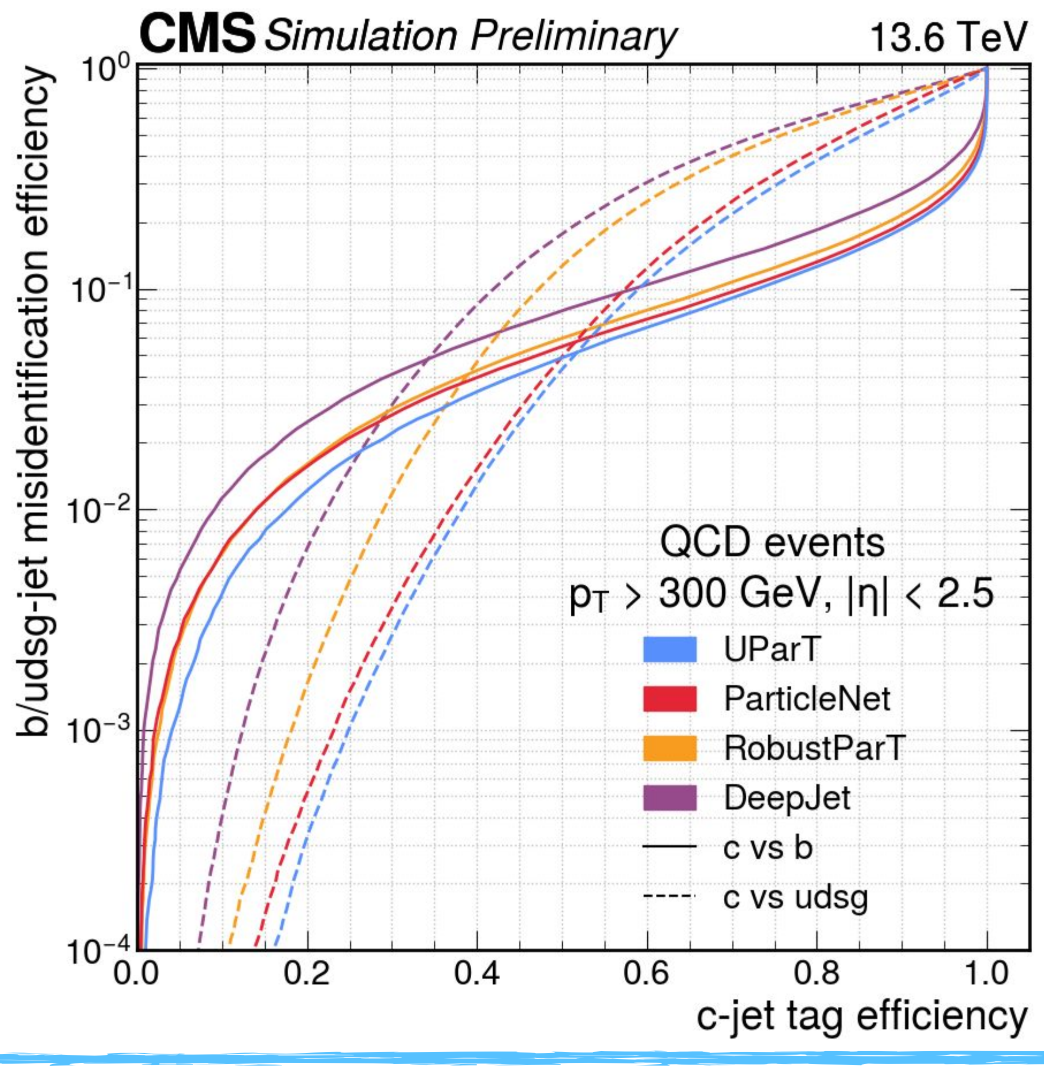

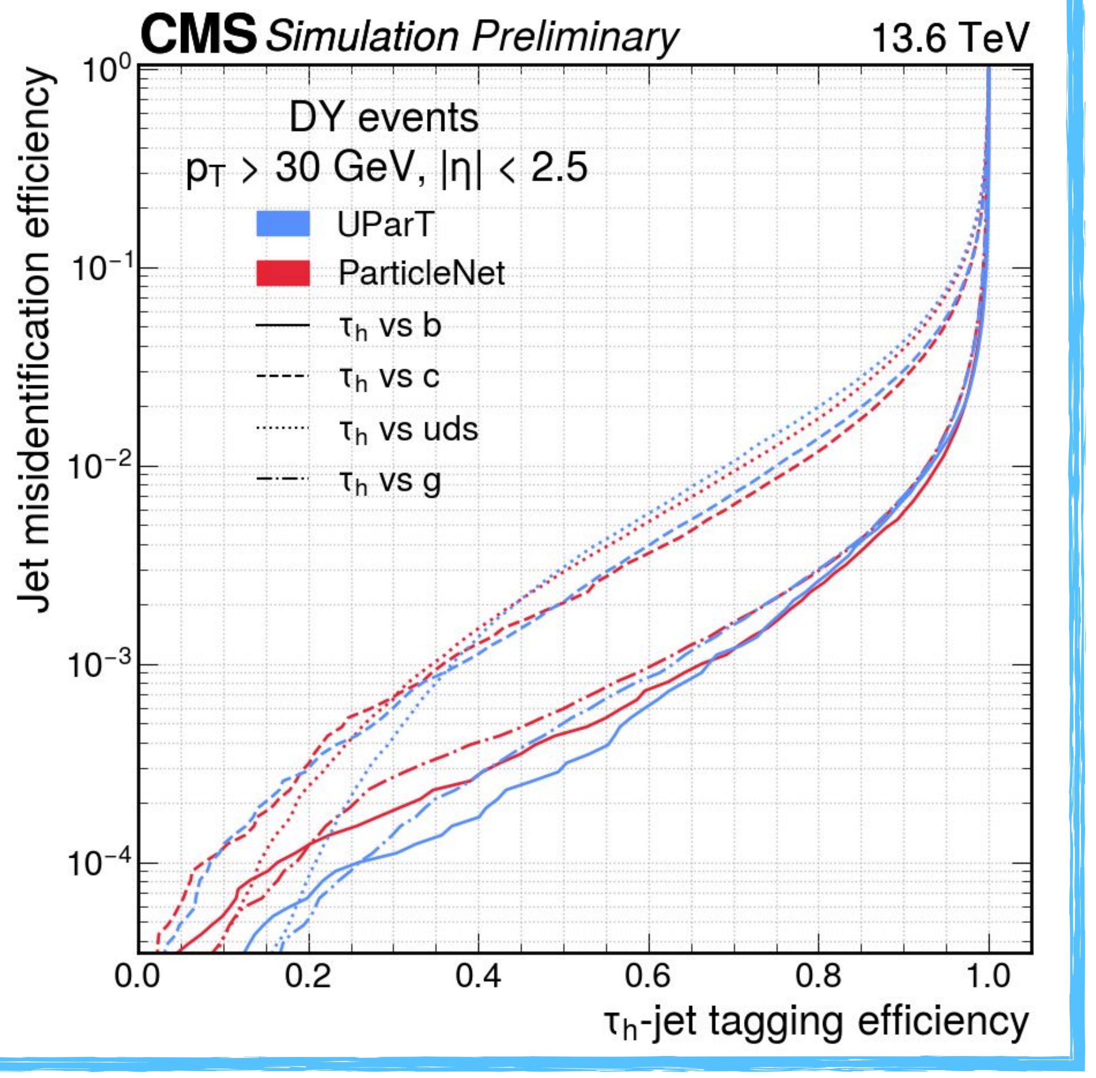

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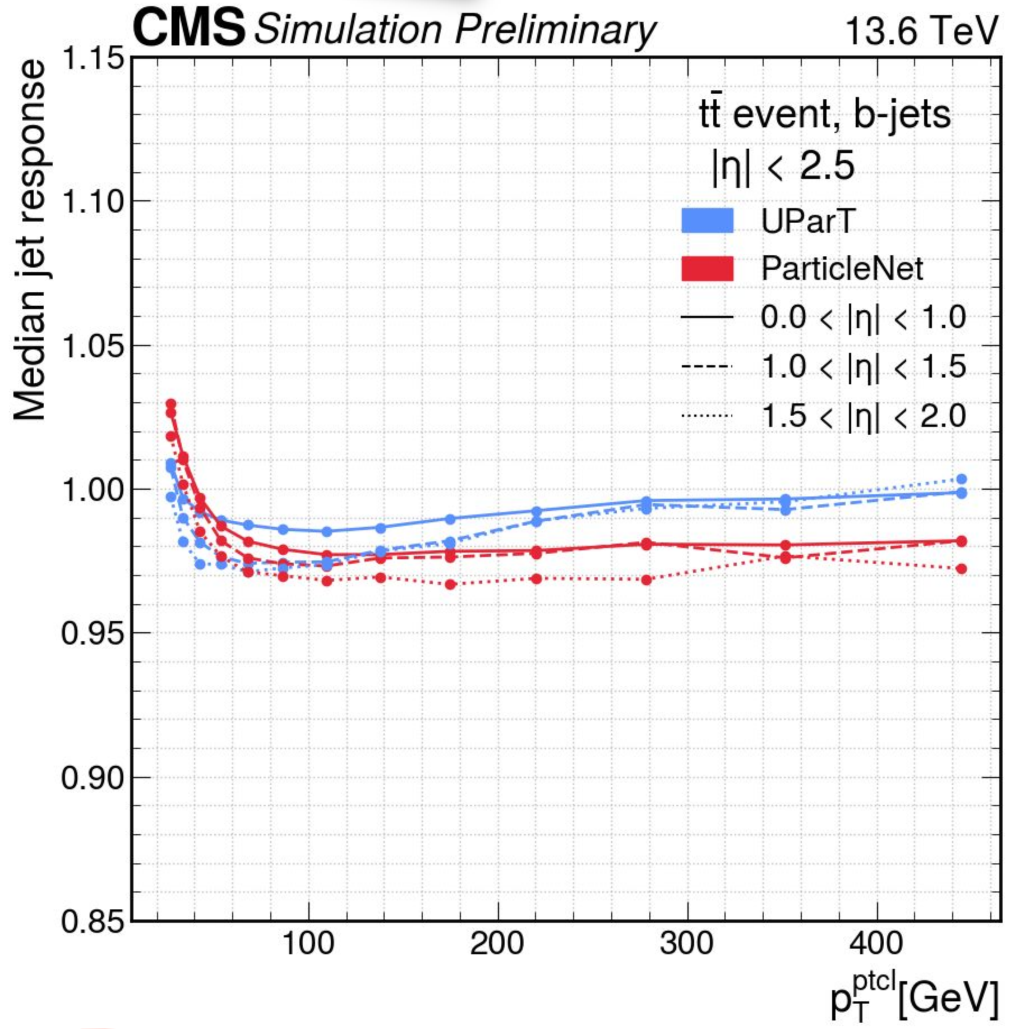
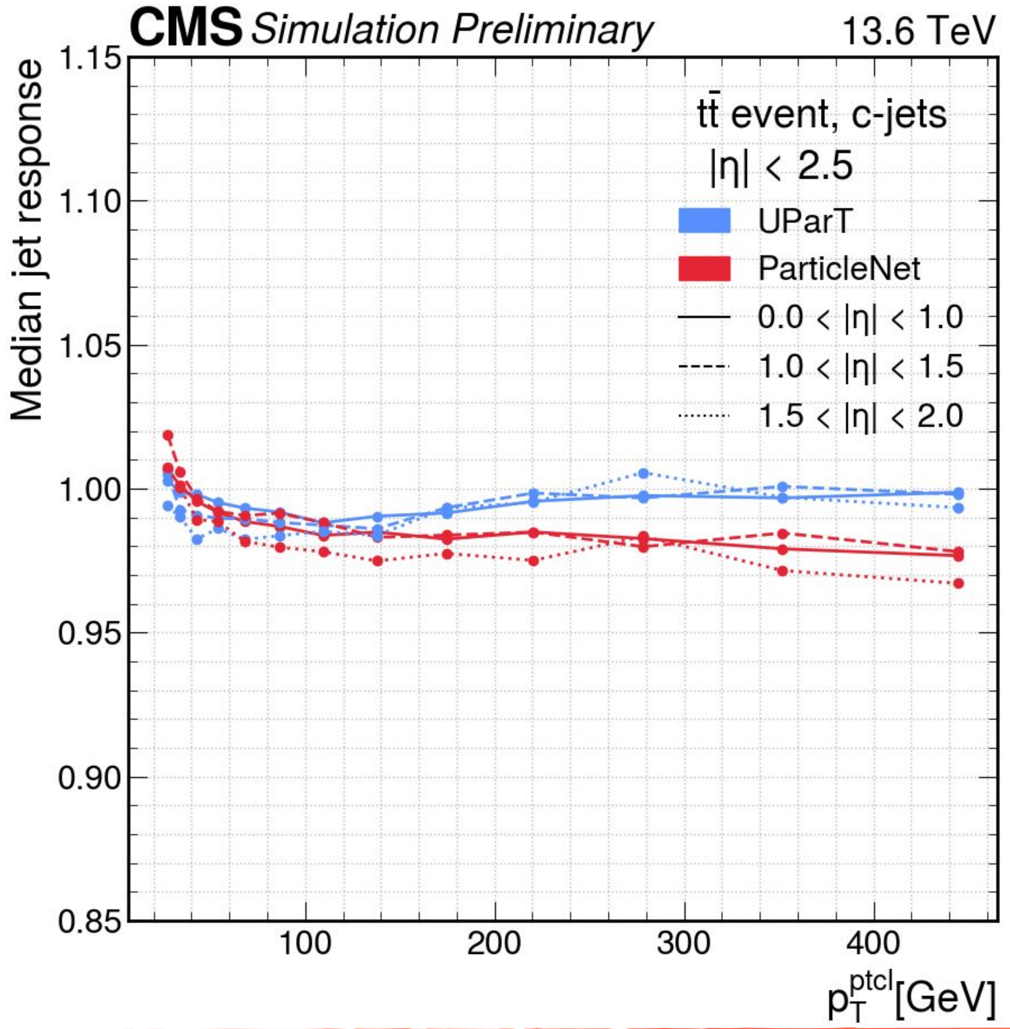




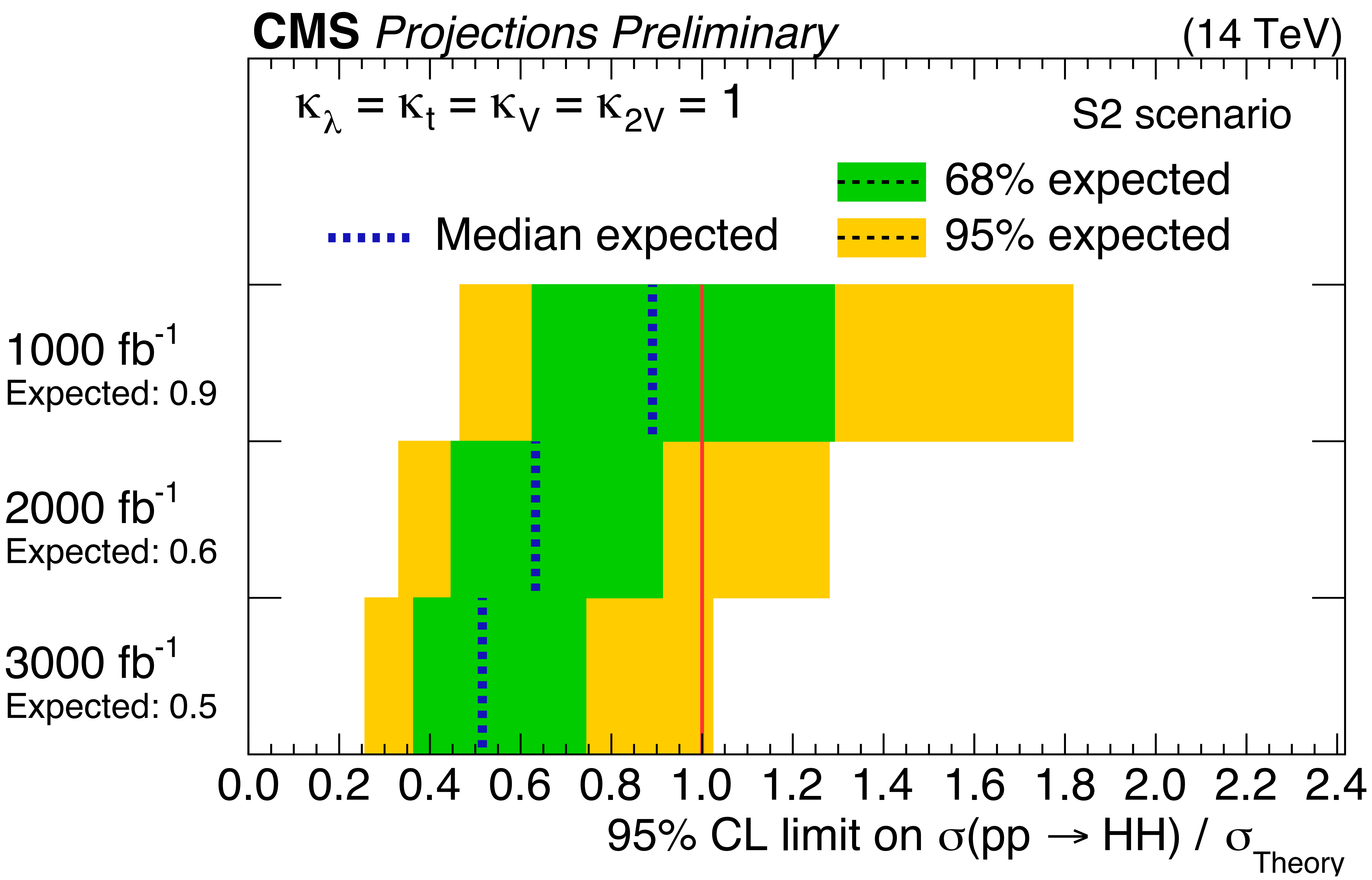
Follow Davide's talk on Friday to get the details about these, and much more!

Outlook : Projections to the HL-LHC

NEW PUBLIC RELEASE

CMS-PAS-HIG-20-011

- **Projection to the HL-LHC performed for: bbbb, bb$\tau\tau$, bb$\gamma\gamma$, bbWW, and Multileton**
- Run-2 results projected up to the full HL-LHC dataset (3000 fb^{-1})
- **S2** : stat. syst. reduced with luminosity, theory syst. halved, MC stat. removed
- **Results expressed in the hypothesis of HH not existing → combined limit < 1 shows that sensitivity is sufficient to establish HH existence**
- **These results are already very conservative as they do not include all the Run-3 improvement just discussed!!**



Follow Angela's dedicated talk tomorrow for all the juicy details

Conclusions

- **Di-Higgs searches, with the goal of probing λ_{HHH}, are one of the main goals we have for the coming years**
- **Run-2 analyses @ CMS showcased impressive improvement over previous expectations:**
  - $\sigma_{HH} = 2.5 \times \sigma_{HH}^{SM}$ and $\sigma_{HH,VBF} = 91 \times \sigma_{HH,VBF}^{SM}$
  - $\kappa_\lambda \in [-1.02, +7.19]$ current tightest constraint @ CMS
  - $\kappa_{2V} \in [0.69, 1.35]$ current tightest constraint @ LHC (κ_{2V} established at $\sim 7\sigma$)
- **Run-3 analyses are underway and will become public soon → they constitutes a huge opportunity to further improve the results we have from Run-2, possibly reaching unexpected goals**
- **Important trigger improvements have already been introduced for HH searches in Run-3**
- Run-3 also constitutes an important test-bench for new ideas that will ultimately be deployed at the HL-LHC

BACKUP

BACKUP : Analysis included in the HH+H combination

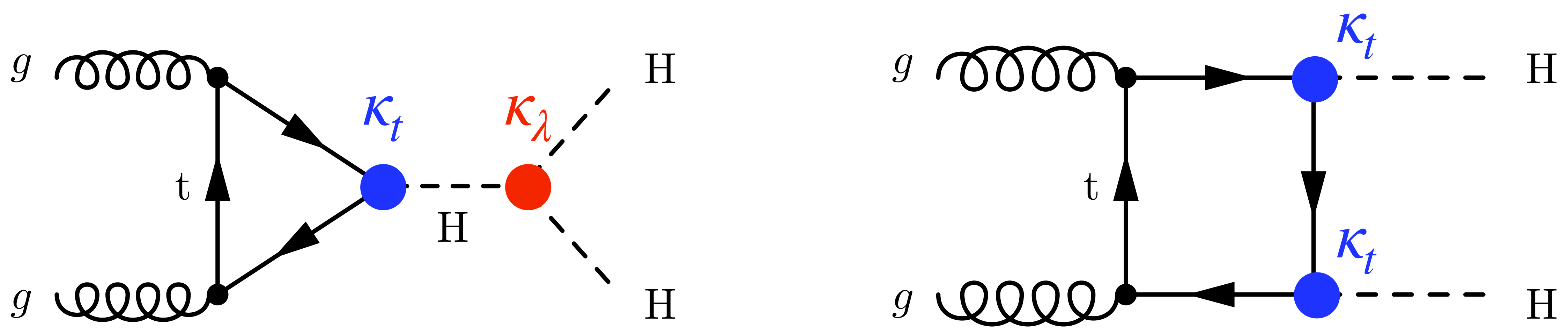
Di-Higgs Analysis included in the HH+H combination

Analysis	Int. luminosity (fb^{-1})	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH
$HH \to 4b$	138	ggHH and qqHH
HH (leptons)	138	ggHH
$HH \to WWb\bar{b}$	138	ggHH and qqHH
$VHH \to b\bar{b}b\bar{b}$	138	VHH

Single-Higgs analysis included in the HH+H combination : non-overlapping analyses are indicated by a ✓, overlaps removable with negligible impacts on the combination are indicated by a χ

single H/ HH analysis	$HH \to \gamma\gamma b\bar{b}$	$HH \to \tau\tau b\bar{b}$	$HH \to 4b$	$VHH \to b\bar{b}b\bar{b}$	HH (leptons)	$HH \to WWb\bar{b}$
$H \to \gamma\gamma$	$\mathcal{X}$	✓	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✓	$\mathcal{X}$	$\mathcal{X}$
$t\bar{t}H$ (leptons)	✓	$\mathcal{X}$	✓	✓	✓	$\mathcal{X}$
$H \to \mu\mu$	✓	✓	✓	✓	✓	✓
$H \to ZZ \to 4l$	✓	✓	✓	✓	✓	✓
$H \to b\bar{b}$ (ggH, VH, $t\bar{t}H$)	✓	$\mathcal{X}$	$\mathcal{X}$	✓	✓	$\mathcal{X}$
$H \to \tau\tau$	✓	$\mathcal{X}$	✓	✓	✓	✓
$VHH \to b\bar{b}b\bar{b}$	✓	✓	$\mathcal{X}$	✓	✓	✓

BACKUP : HH SM signal modelling



$$\mathscr{A} = \kappa_t \kappa_\lambda \mathscr{A}_\triangle + \kappa_t^2 \mathscr{A}_\square$$

$$\sigma(\kappa_t, \kappa_\lambda) \sim |\mathscr{A}|^2 = \kappa_t^2 \kappa_\lambda^2 |\mathscr{A}_\triangle|^2 + \kappa_t^4 |\mathscr{A}_\square|^2 + \kappa_t^3 \kappa_\lambda \mathscr{I}_{\triangle\square}$$

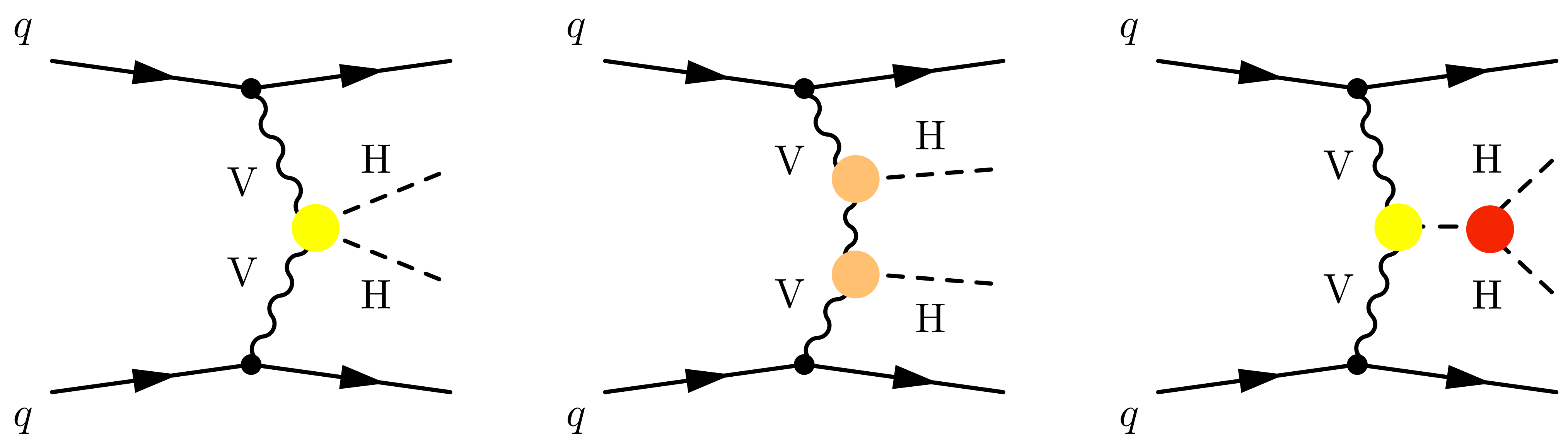
$$= \boldsymbol{k}(\kappa_t, \kappa_\lambda) \cdot \boldsymbol{A}$$

Model Couplings | Input couplings | Input samples

$$\sigma(\kappa_t, \kappa_\lambda) = \boldsymbol{k}^T(\kappa_t, \kappa_\lambda) \cdot \boldsymbol{K}^{-1} \cdot \boldsymbol{\Sigma}$$

with $\boldsymbol{\Sigma} = \boldsymbol{K} \cdot \boldsymbol{A} = \begin{pmatrix} k_1^1 & k_1^2 & k_1^3 \\ k_2^1 & k_2^2 & k_2^3 \\ k_3^1 & k_3^2 & k_3^3 \end{pmatrix} \begin{pmatrix} |\mathscr{A}_\triangle|^2 \\ |\mathscr{A}_\square|^2 \\ \mathscr{I}_{\triangle\square} \end{pmatrix}$

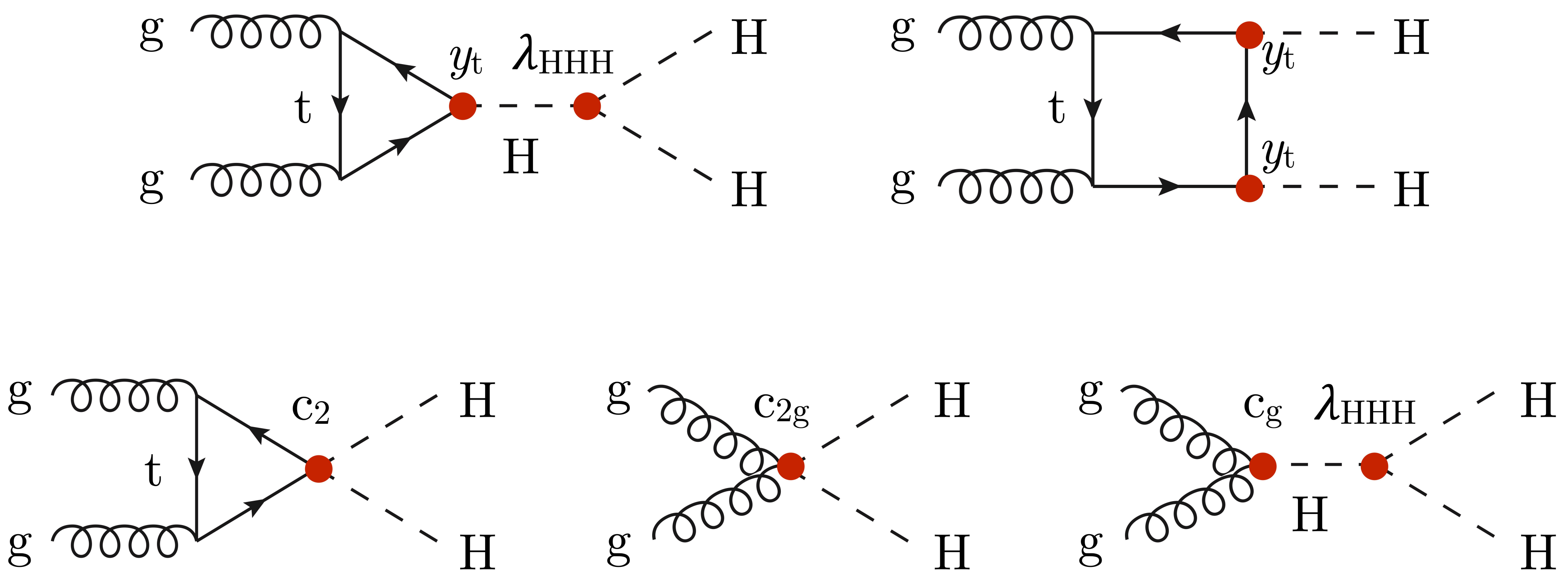
⇒ 3 MC samples solve the ggF system



⇒ 6 MC samples solve the VBF system

Signal modelling at inference time in the statistical model

BACKUP : HEFT signal modelling



Event-based reweighing technique common to all HH analyses to enhance statistics and keep MC generation at minimum

Merge all available NLO (LO) MCsamples
in a $(m_{HH}, |\cos\theta^*|)$ 2D-histogram

⇩

Reweigh with differential parametrisation

$$R^i_{HH} = \frac{\sigma^i_{HH}}{\sigma^{i,SM}_{HH}} = A^i_1\kappa_t^4 + A^i_2 c_2^2 + A^i_3\kappa_t^2\kappa_\lambda^2 + A^i_4 c_g^2\kappa_\lambda^2 + A^i_5 c_{2g}^2 + A^i_6 c_2\kappa_t^2 + A^i_7\kappa_\lambda\kappa_t^3 + A^i_8\kappa_t\kappa_\lambda c_2 + A^i_9 c_g\kappa_\lambda c_2$$

$$+A^i_{10}c_2c_{2g} + A^i_{11}c_g\kappa_\lambda\kappa_t^2 + A^i_{12}c_2\kappa_t^2 + A^i_{13}\kappa_\lambda^2 c_g\kappa_t + A^i_{14}c_{2g}\kappa_t\kappa_\lambda + A^i_{15}c_gc_{2g}\kappa_\lambda + A^i_{16}\kappa_t^3 c_g$$

$$+A^i_{17}\kappa_t c_2 c_g + A^i_{18}\kappa_t c_g^2\kappa_\lambda + A^i_{19}c_g\kappa_t c_{2g} + A^i_{20}\kappa_t^2 c_g^2 + A^i_{21}c_2 c_g^2 + A^i_{22}c_g^3\kappa_\lambda + A^i_{23}c_g^2 c_{2g}$$