Overview of current experimental knowledge on Di-Higgs production (ATLAS+CMS)

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ATLAS EXPERIMENT CMS Laboratoire Leprince-Ringuet cnrs ÉCOLE POLYTECHNIQUE IP PARIS

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Standard Model at the LHC 2024, Rome (Italy)

Why search for di-Higgs?

- The **precision measurement** of the Higgs boson properties is one of the **primary targets @LHC**
- The **Higgs boson** so far behaves in a **very SM-like** manner, its couplings consistent with the BEH mechanism

More profound questions still unanswered

- Is the Higgs boson elementary or composite?
- Can the invisible Higgs boson width be associated with DM?
- Is it possible to measure the Higgs field potential directly?
- Does the Higgs boson interact with itself?

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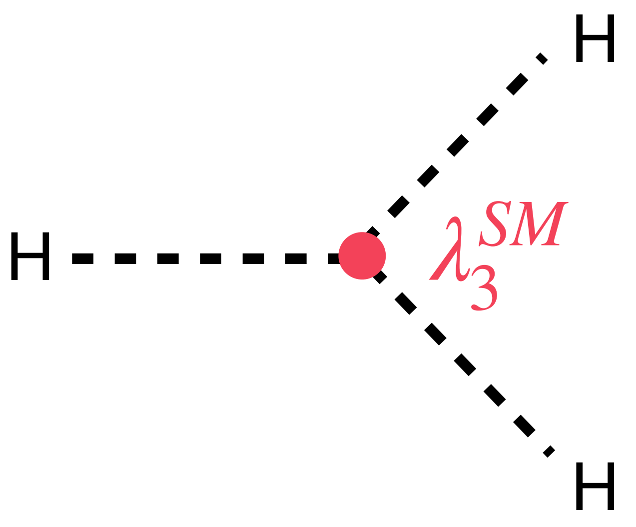
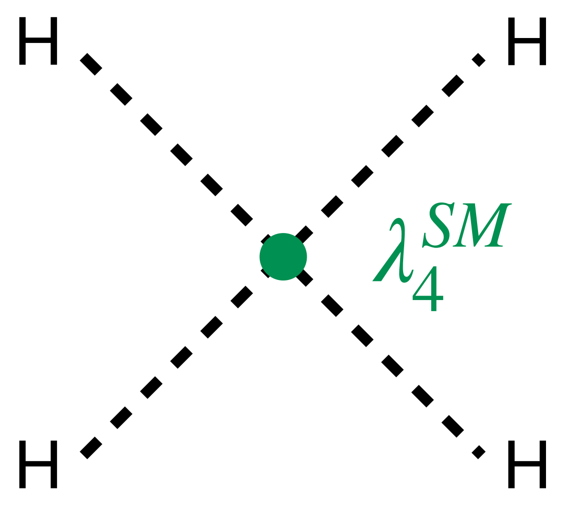
- **Does the Higgs boson interact with itself?**

- The SM description of the **Higgs potential** is encoded with two parameters: m_h, λ_3^{SM}
- Given the Higgs boson mass m_h and VEV v, the **Higgs self-coupling** λ_3^{SM} is fully **determined**



$$\mathscr{L} \subset -\frac{m_h^2}{2}h^2 - \lambda_3^{SM} v h^3 - \lambda_4^{SM} h^4 \quad \Longrightarrow \quad \lambda_3^{SM} = 4\lambda_4^{SM} = \frac{m_h^2}{v^2} \simeq 0.13$$

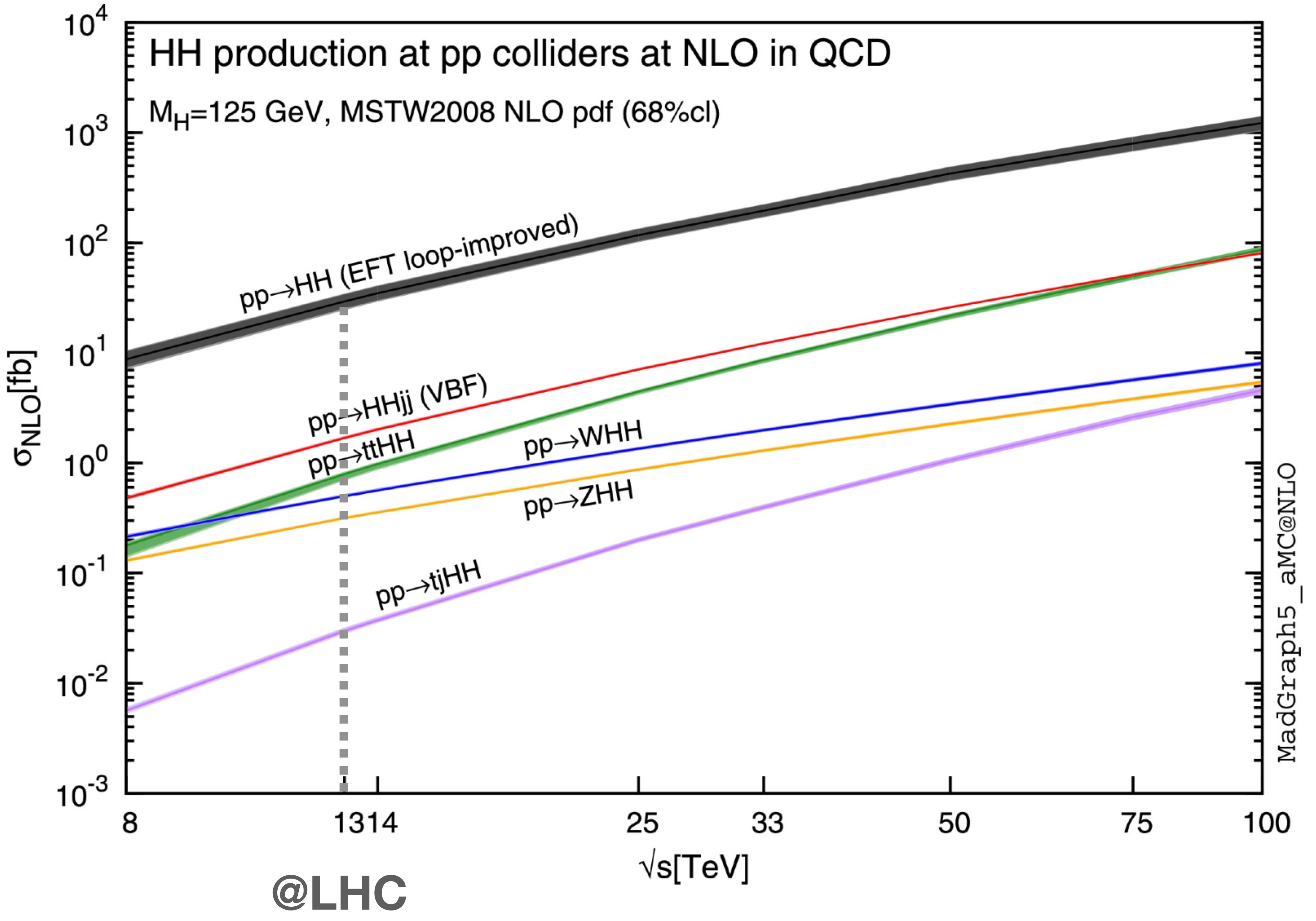


- For a **closure test** of the SM a direct measurement of the Higgs self coupling is necessary
  → the best way is to look for **HH production**

The di-Higgs production

- The di-Higgs cross section depends on the production mode, but it's **~1000 times rarer than single-Higgs**

$$\sigma^{SM}(\mathrm{pp} \to \mathrm{HH}) \sim \frac{1}{1000} \cdot \sigma^{SM}(\mathrm{pp} \to \mathrm{H})$$



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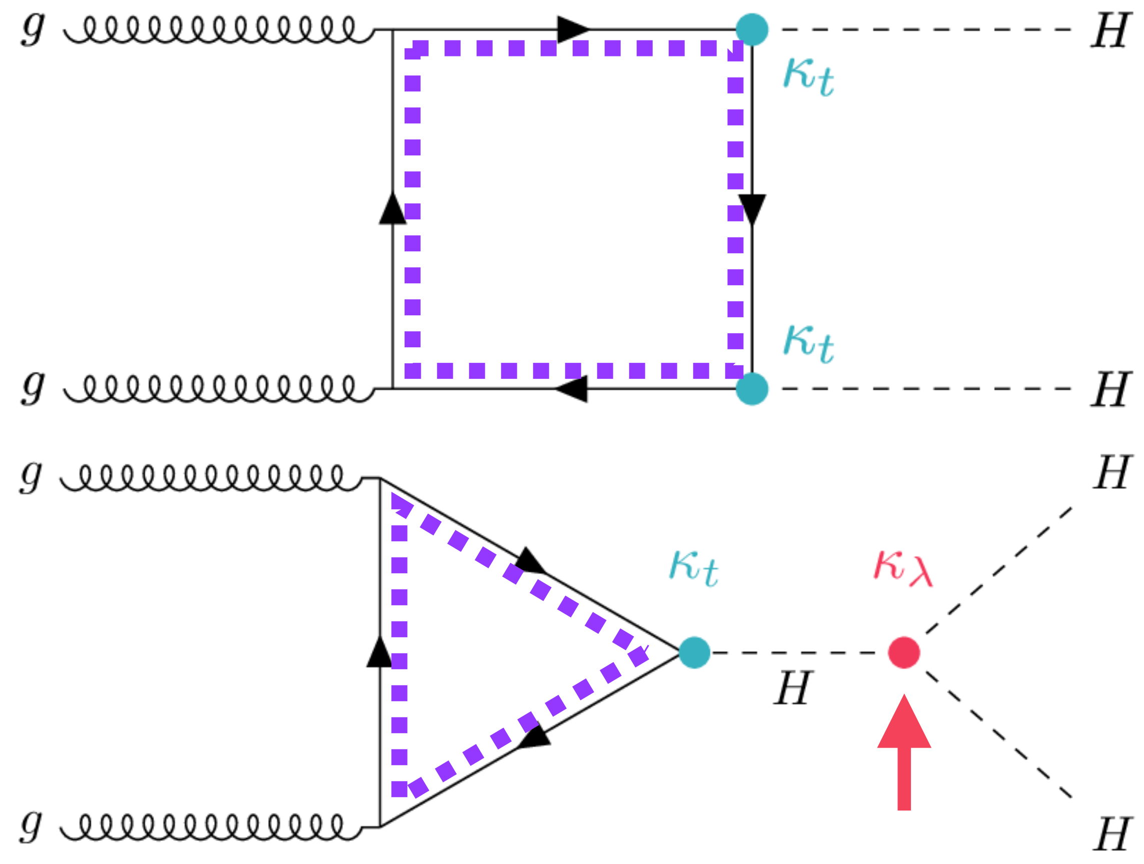
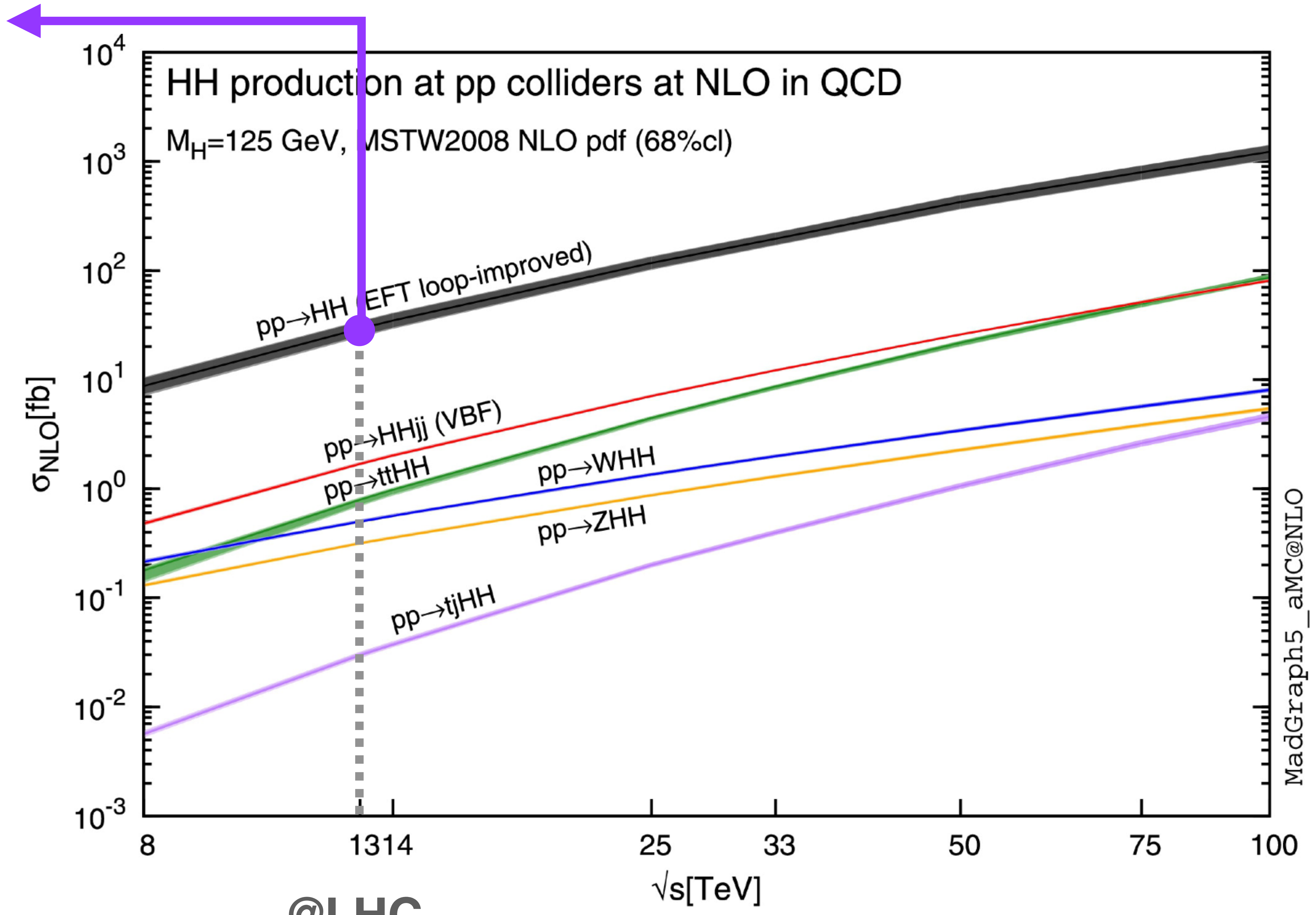
Gluon-Gluon Fusion

- Leading HH production mode
- Destructive interference between square and triangle

σ_{ggF} = 31.05 fb @NNLO



- Direct access to **k$_\lambda$** $k_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$



@LHC

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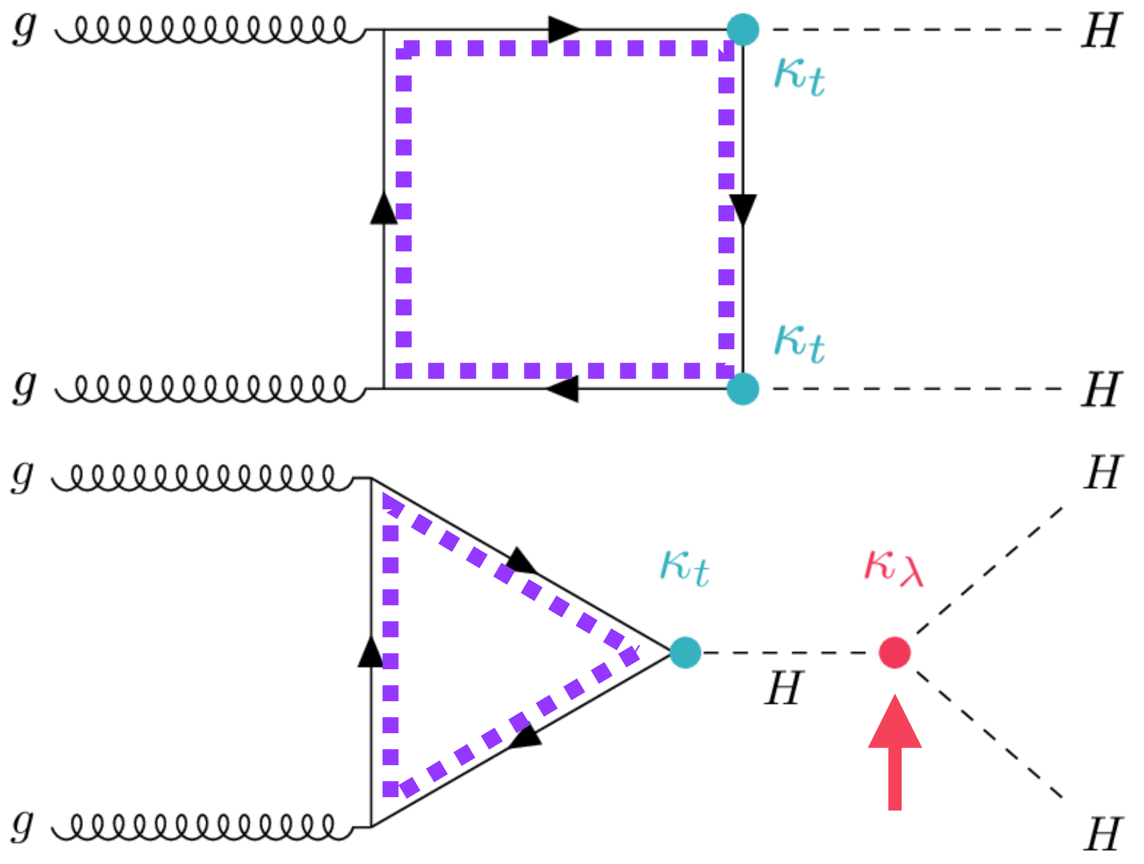
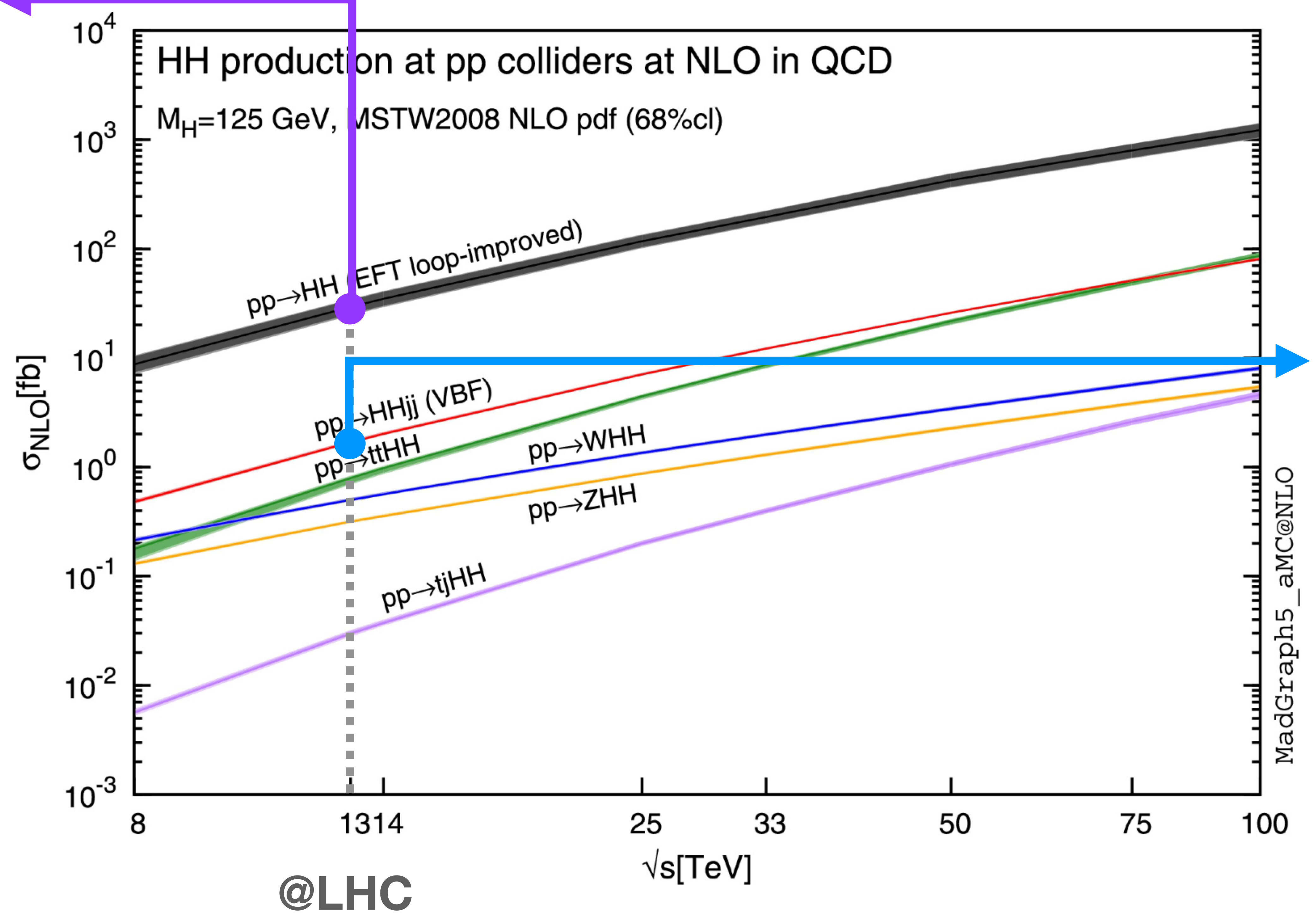


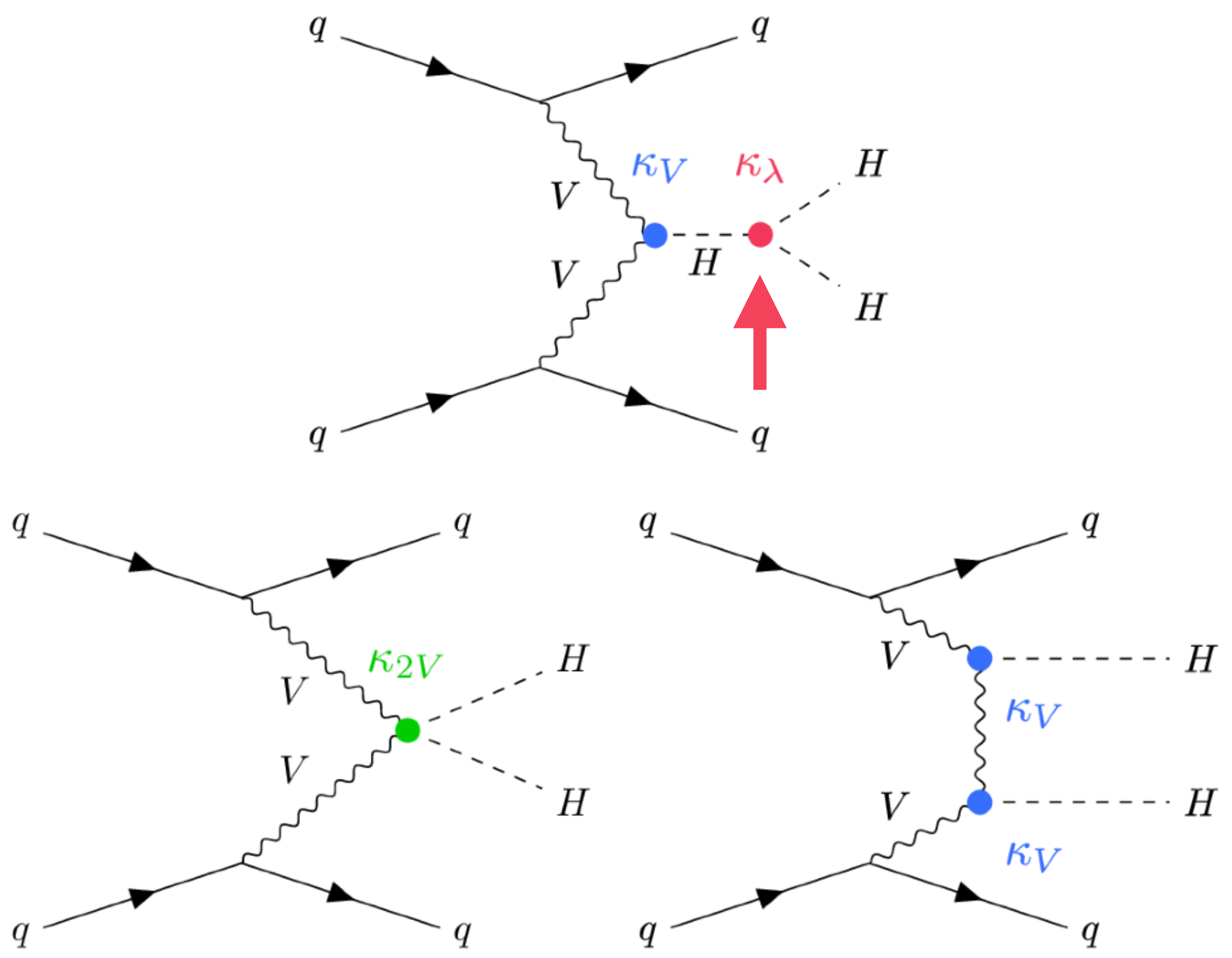
▸ Direct access to k_λ $k_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$



Vector Boson Fusion

- Second leading production
- Signature from high energy jets

σ_{VBF} = 1.73 fb @N3LO



▸ Direct access to k_λ, k_V, k_{2V}

The di-Higgs final states

- Given the current **luminosity** and the harsh **experimental conditions**, a good sensitivity is achieved with
  - **Large branching ratio** ($H \to bb$)
  - **Very good selection purity** ($H \to \tau\tau$, $H \to \gamma\gamma$)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

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▸ **Run 1**
Only few channels covered

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▸ **Early Run 2**
At least one H→bb or multileptons

≥1 HH→bb

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Multileptons

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- **Run 1**
  Only few channels covered
- **Early Run 2**
  At least one H→bb or multileptons
- **Full Run 2**
  several new final states and production modes investigated by ATLAS and CMS

	bb	WW	ττ	ZZ	γγ
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Not a single golden channel but many (at least three) silver bullets

The di-Higgs final states

- Many different final states covered by both CMS and ATLAS: the ones covered in this presentation are ☆

CMS

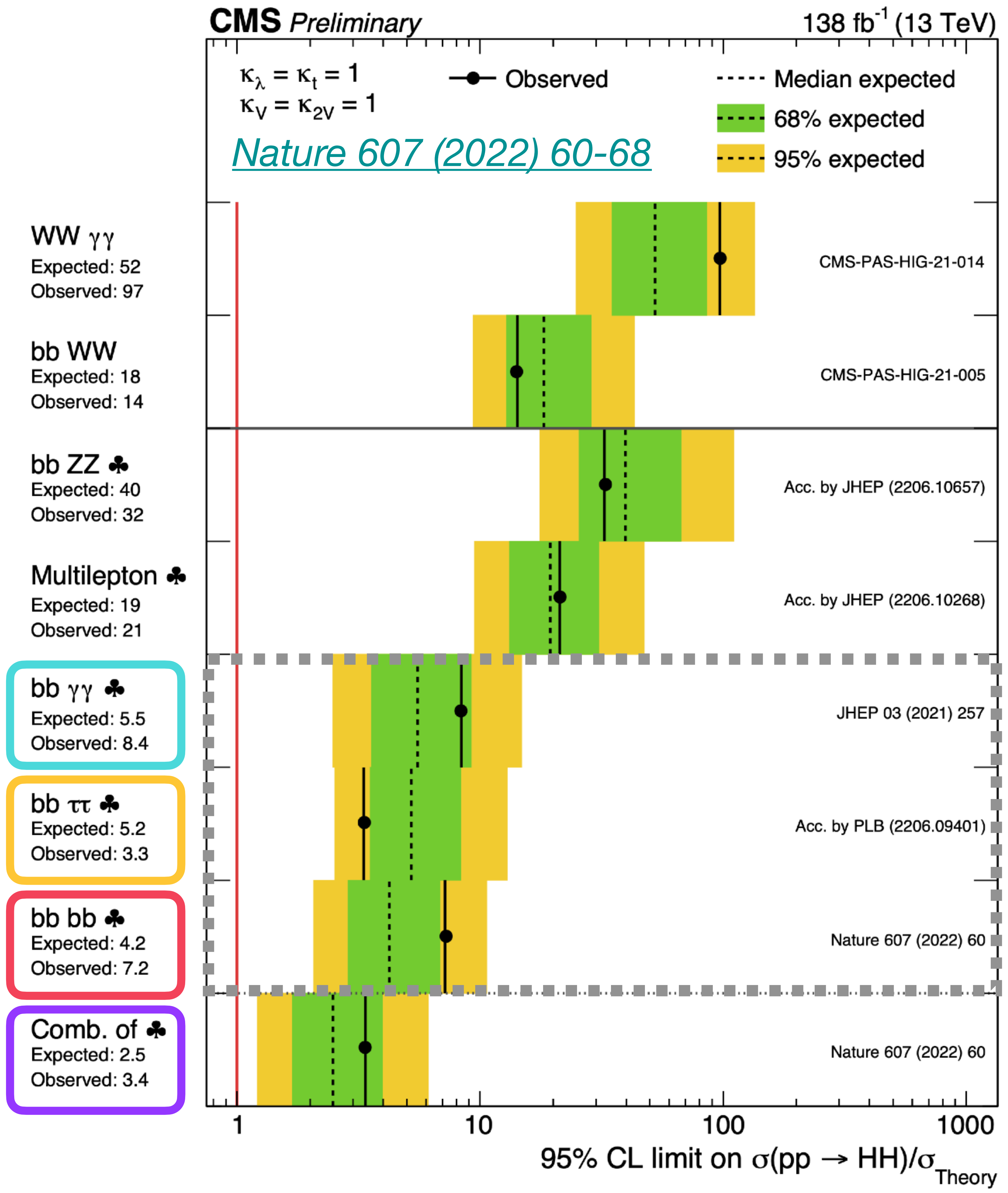
- $HH \to b\bar{b}b\bar{b}$
  - Phys. Rev. Lett. 129, 081802 (resolved)
  - CMS-PAS-B2G-21-001 (VBF boosted)
  - Submitted to JHEP (VHH)
  - Submitted to Eur. Phys. J. C (ZZ/ZH) ☆
- $HH \to b\bar{b}\tau\tau$
  - Phys. Lett. B 842 (2023) 137531
- $HH \to b\bar{b}\gamma\gamma$
  - Phys. Lett. B 842 (2023) 137531
- $HH \to b\bar{b}VV$ / Multileptons
  - JHEP 07 (2023) 095 (4W/WWττ/4τ, ≥2l)
  - JHEP 06 (2023) 130 (bbZZ, 4l)
  - CMS-PAS-HIG-21-005 (bbWW, ≥1l)
  - CMS-PAS-B2G-21-001 (γγWW)
  - CMS-PAS-HIG-22-012 (γγττ) ☆

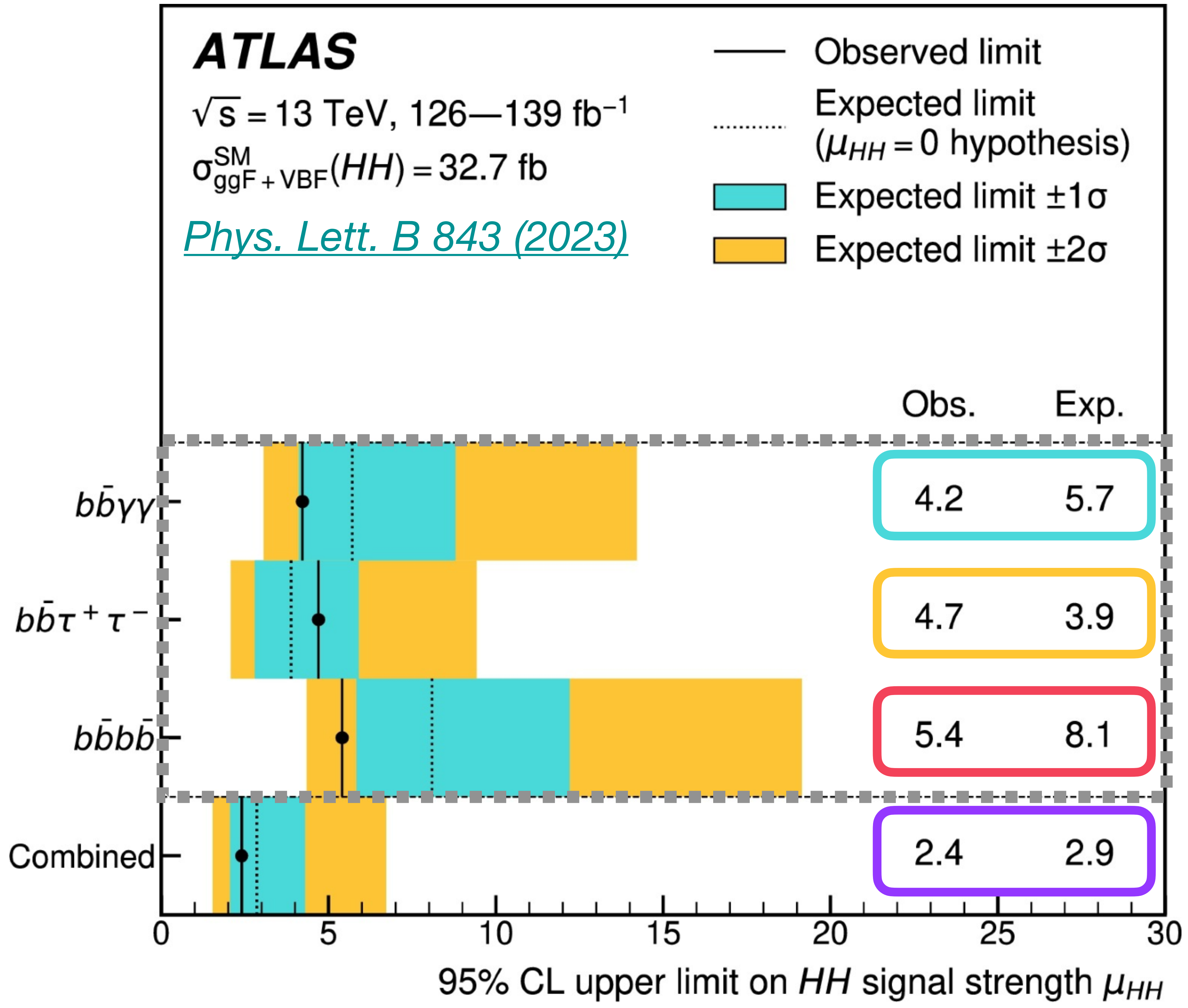
ATLAS

- $HH \to b\bar{b}b\bar{b}$
  - Phys. Rev. D 108, 052003 (resolved)
  - ATLAS-CONF-2024-003 (VBF boosted) ☆
  - Eur. Phys. J. C 83 (2023) 519 (VHH)
- $HH \to b\bar{b}\tau\tau$
  - ATLAS-CONF-2023-071 (re-analysis)
  - JHEP 07 (2023) 040
- $HH \to b\bar{b}\gamma\gamma$
  - JHEP 01 (2024) 066 (re-analysis)
  - Phys. Rev. D 106, 052001
- $HH \to b\bar{b}VV$ / Multileptons
  - JHEP 02 (2024) 037 (bb+ZZ/WW/ττ, 2l+MET)
  - ATLAS-CONF-2024-005 ☆ (bbZZ/4V/2V2τ/4τ/2γ2V/2γ2τ)

Limits on di-Higgs production

- The most stringent upper limits on the di-Higgs cross section come from the **combination** of different **final states**





CMS

$\sigma_{HH} < \mathbf{3.4}\ \sigma^{SM}_{HH}$

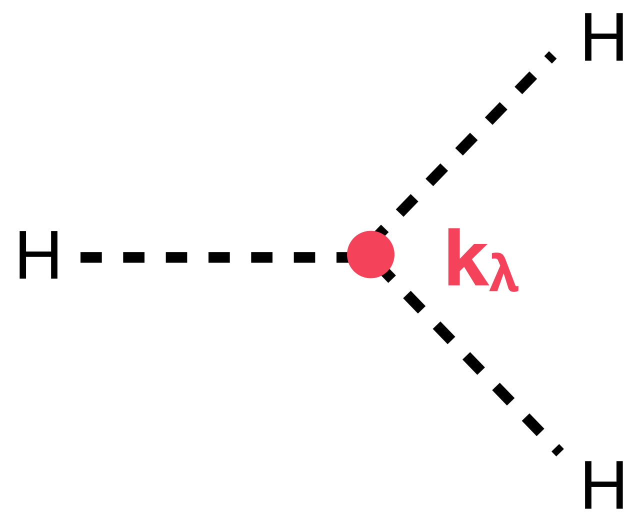
ATLAS

$\sigma_{HH} < \mathbf{2.4}\ \sigma^{SM}_{HH}$

No channel dominating overall sensitivity

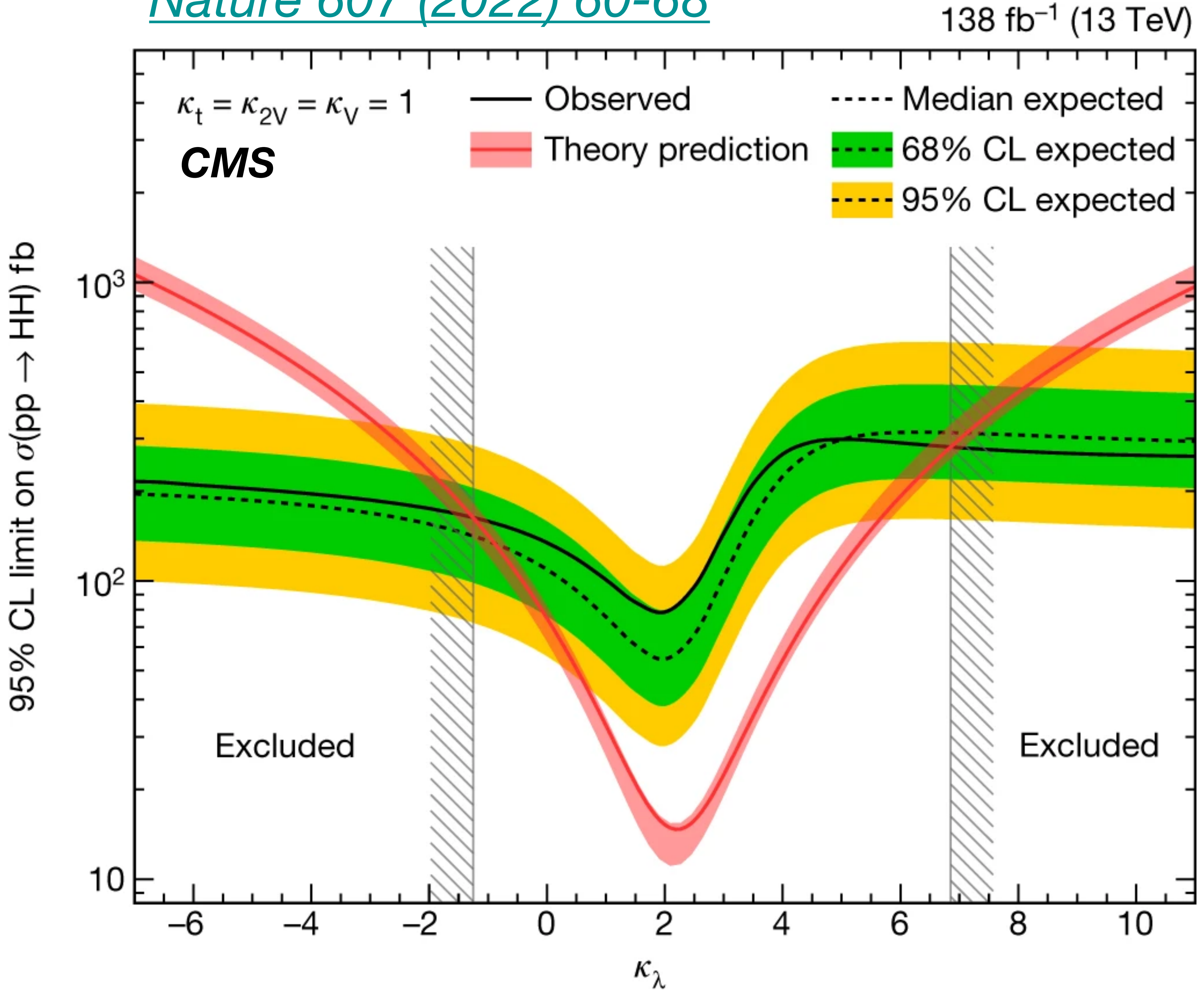
Combination is the key

Limits on anomalous couplings

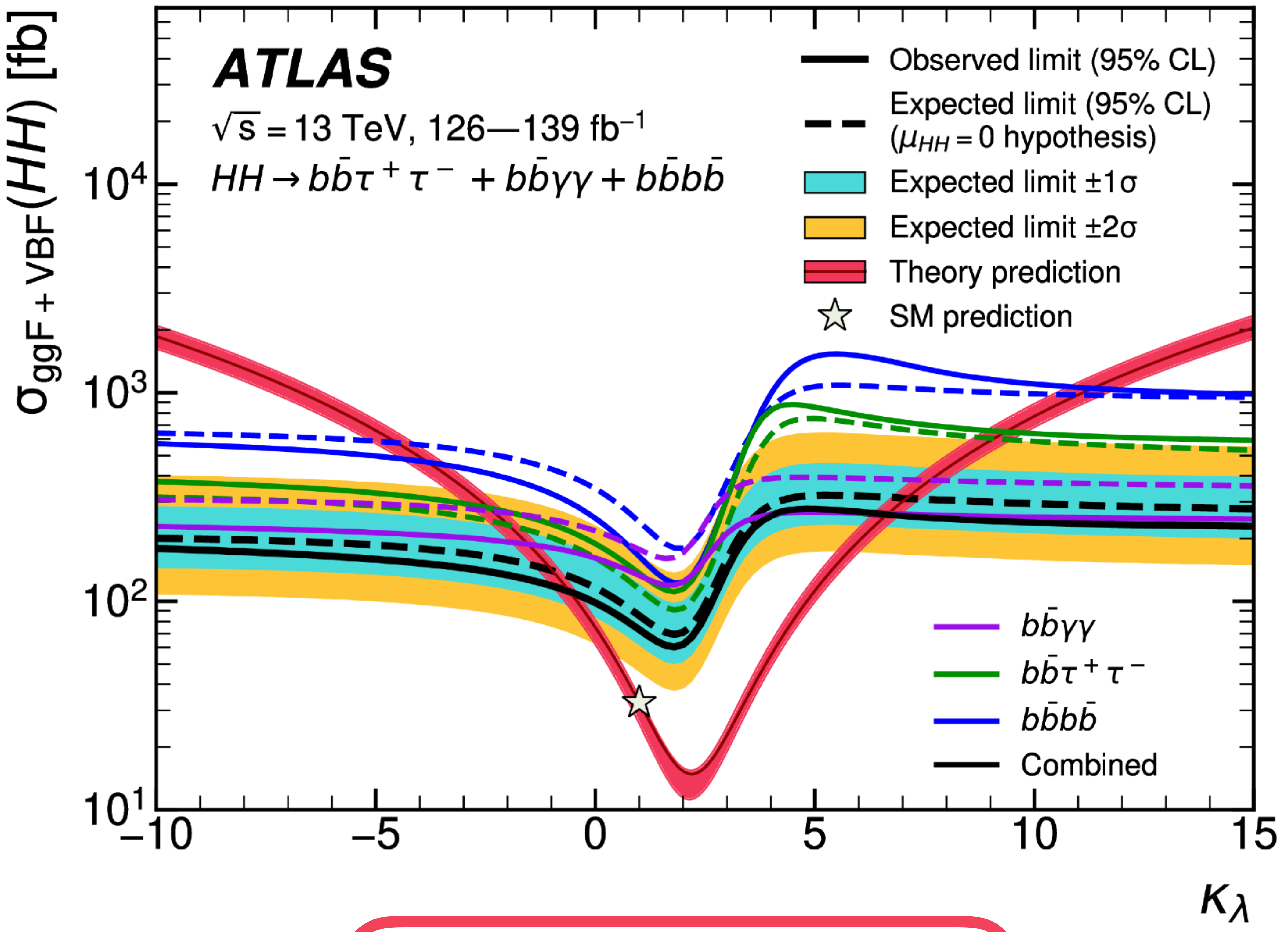


- The limits on di-Higgs production cross section show a **strong dependence** on the k_λ and k_{2V}

Nature 607 (2022) 60-68



Phys. Lett. B 843 (2023)



CMS

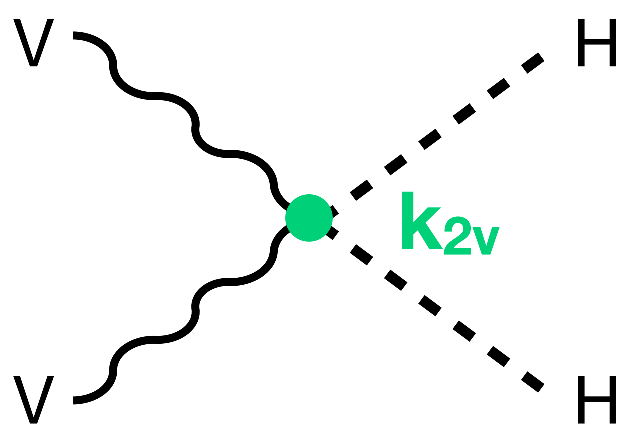
-0.6 < k_λ < 6.6 *

ATLAS

-1.24 < k_λ < 6.49 *

* Assuming other couplings to SM value

Limits on anomalous couplings



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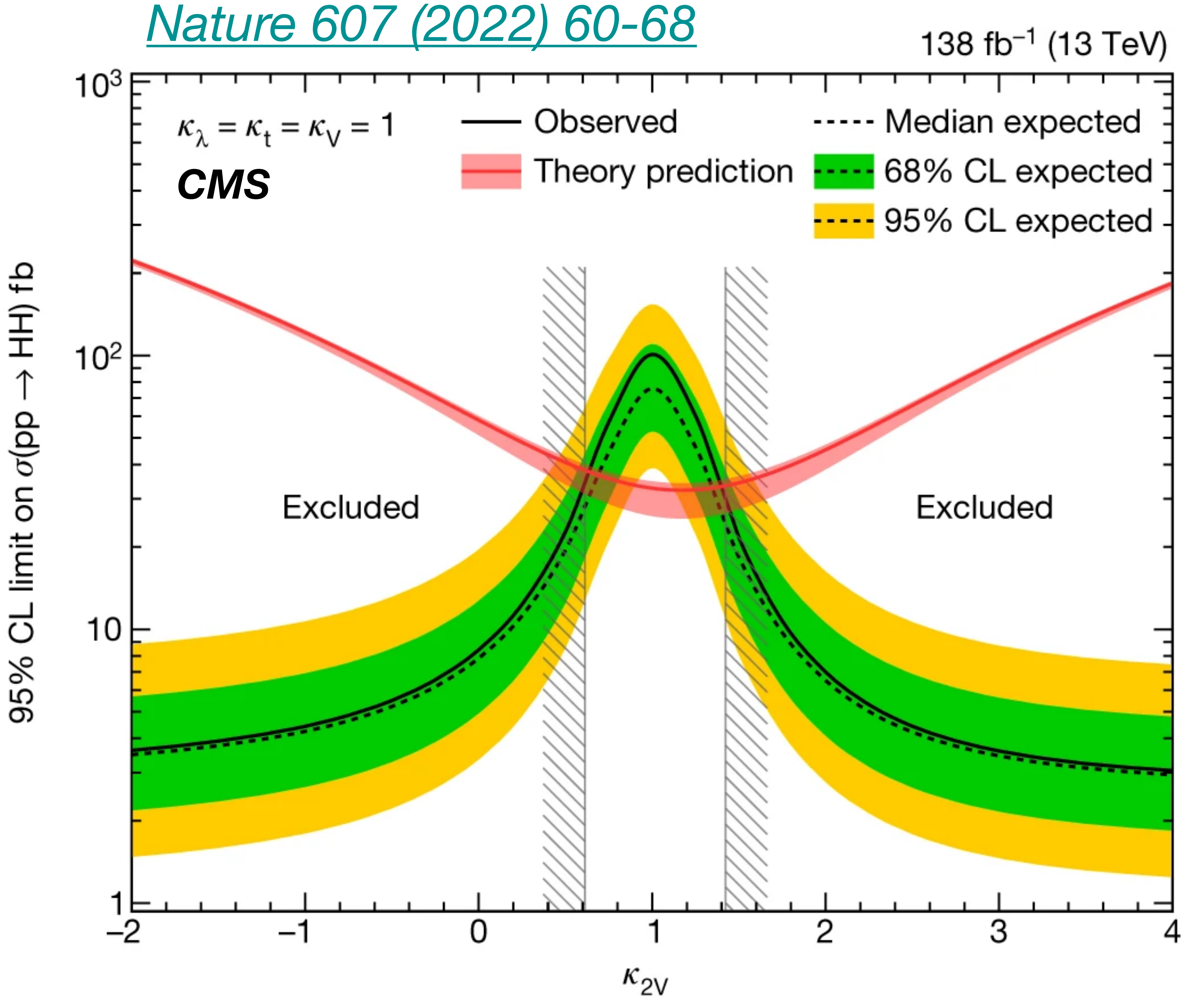

CMS
0.67 < k_{2V} < 1.38 *

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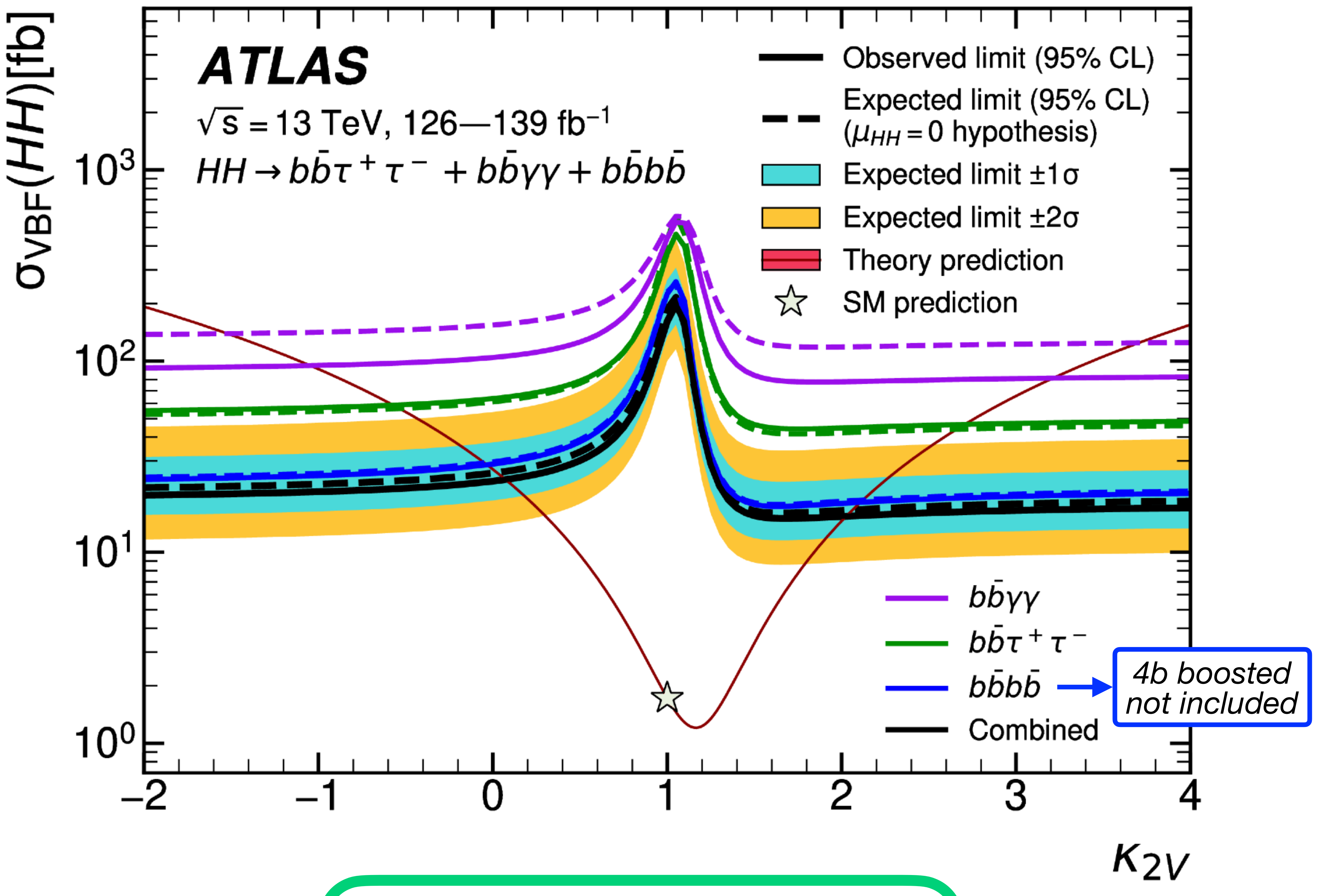
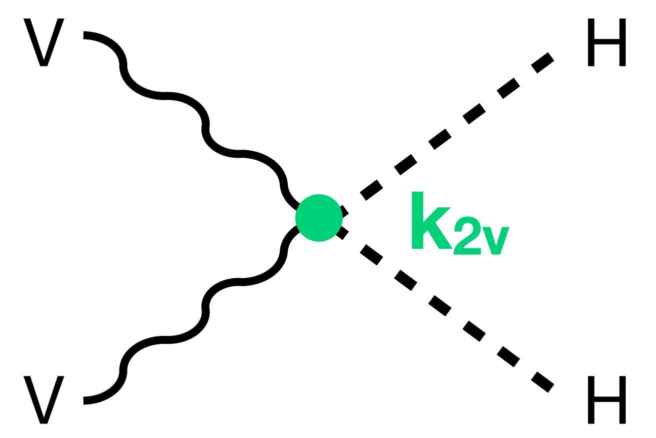


ATLAS
-2.1 < k_{2V} < 7.8 *

* Assuming other couplings to SM value

Limits on anomalous couplings



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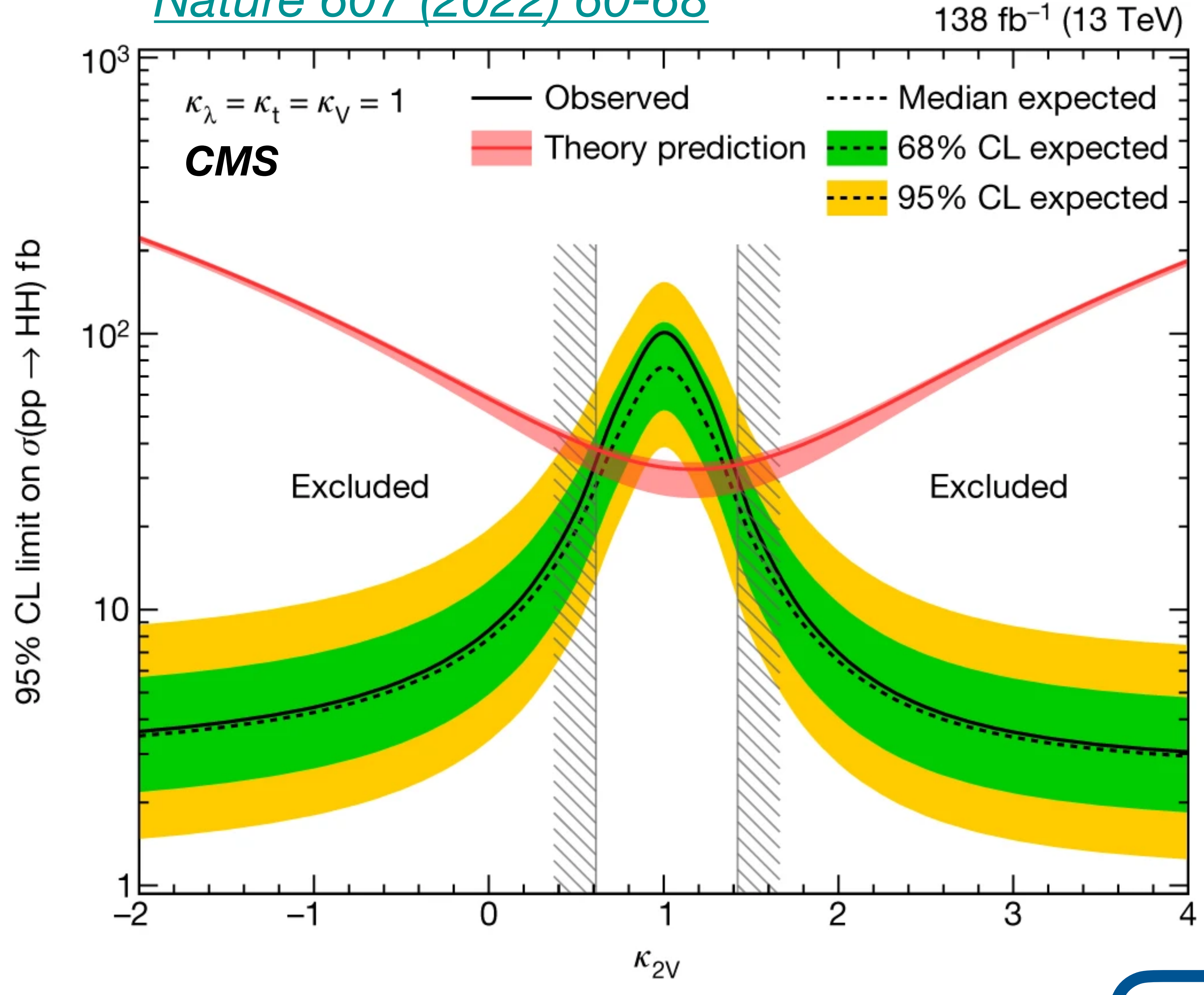

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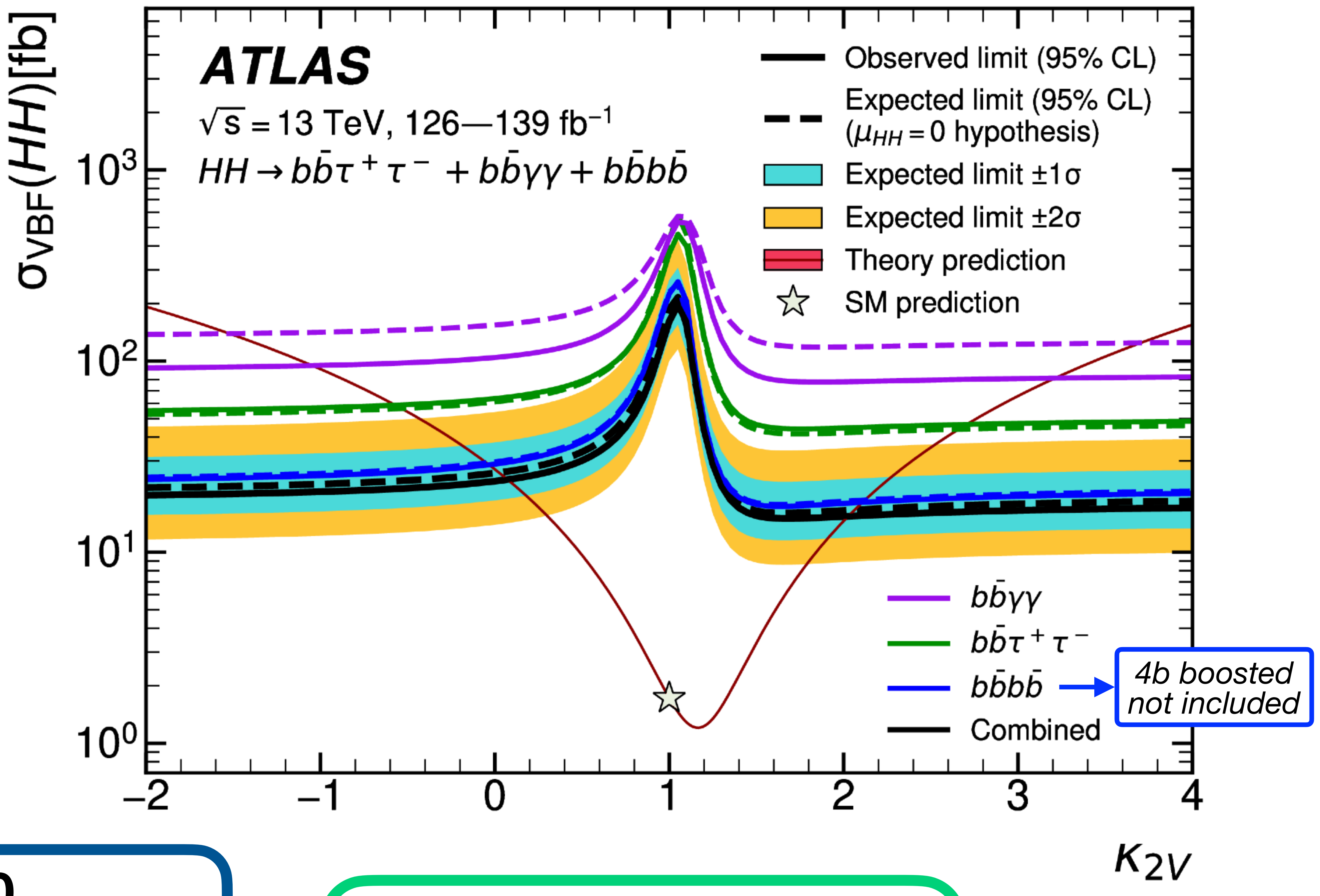

CMS
0.67 < k_{2V} < 1.38 *

$k_{2V} \neq 0$
Existence of VVHH coupling

ATLAS
-2.1 < k_{2V} < 7.8 *

* Assuming other couplings to SM value

Limits on anomalous couplings

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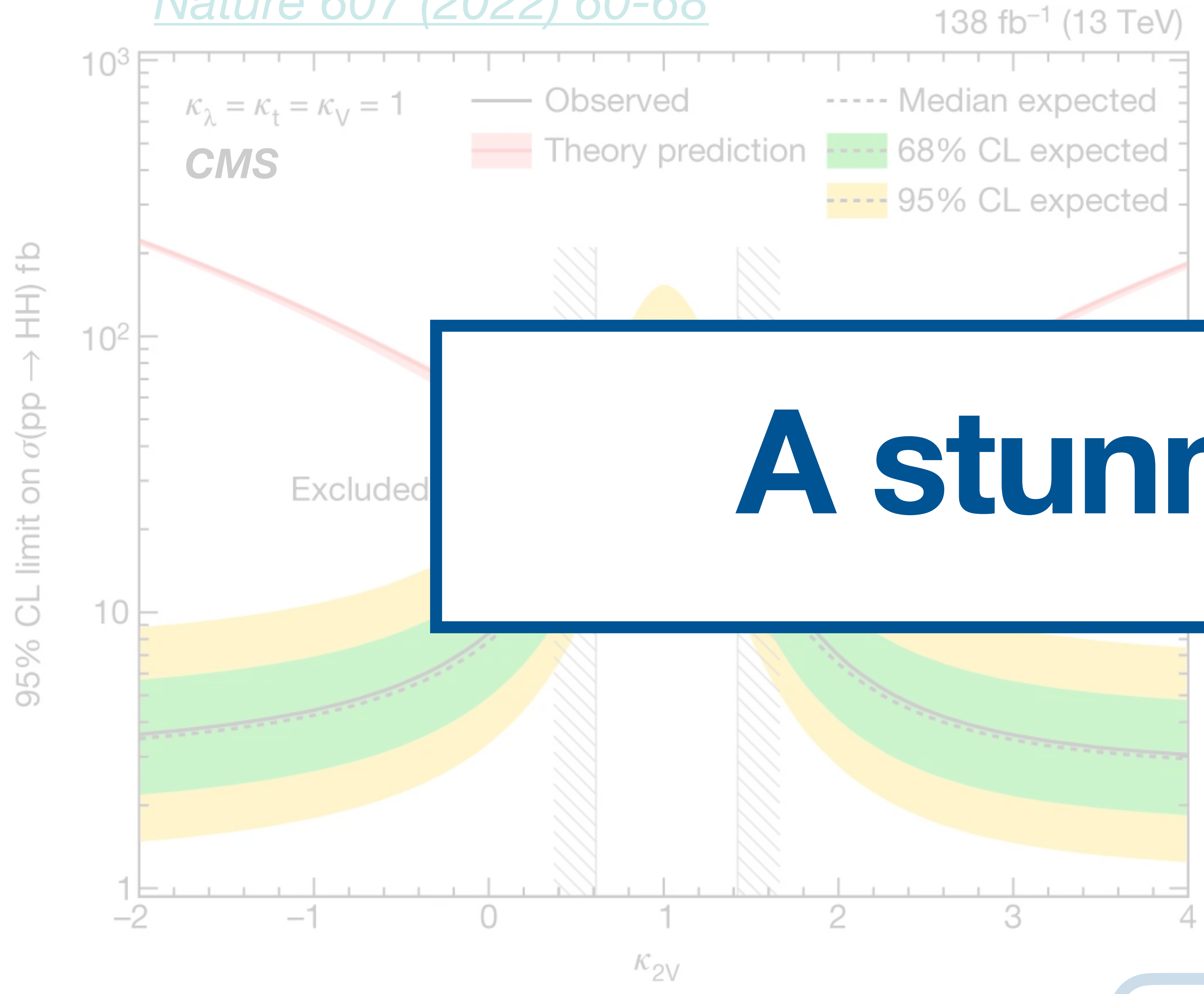

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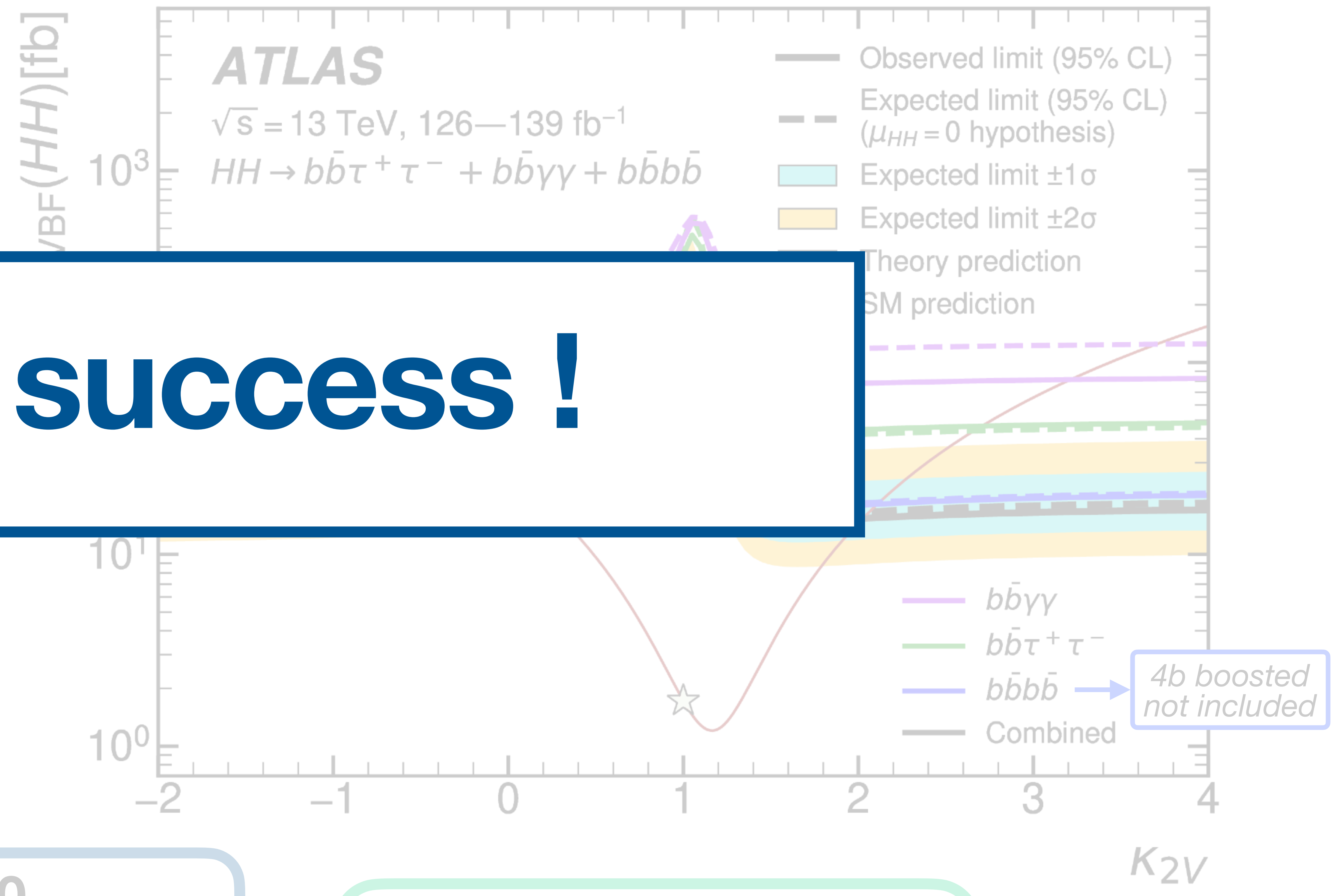

A stunning success !

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$k_{2V} \neq 0$
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-2.1 < k_{2V} < 7.8 *

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How to improve sensitivity?

Multiple directions

- Run 3 and beyond…
- More advanced analysis techniques
- Combination with Single-Higgs
- Better background modelling
- Include new final states
- Investigate new regimes

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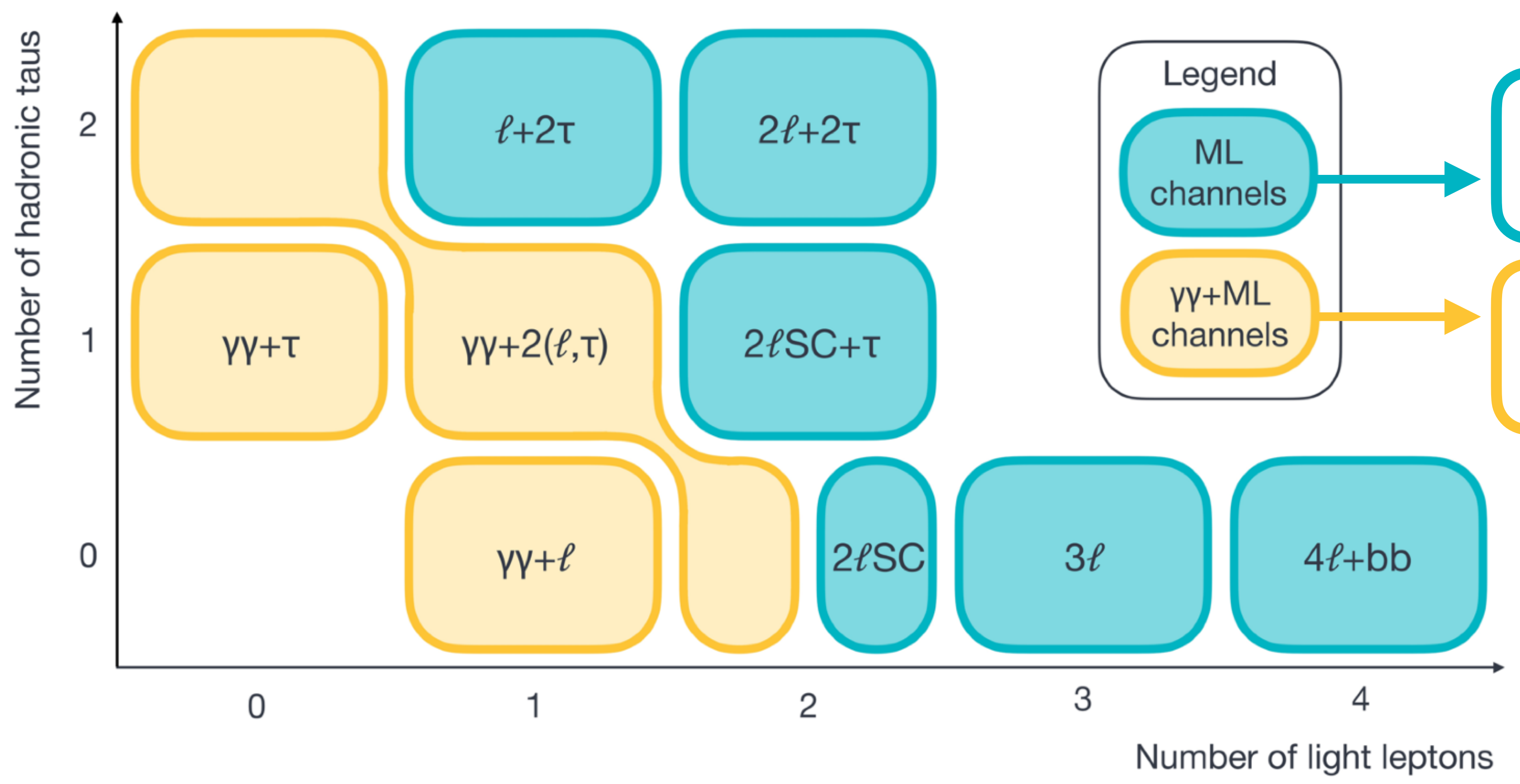
HH Multilepton (ATLAS) NEW

- Search for HH production in multilepton decay with a **holistic way**, performed for the **first time by ATLAS**
  - Targeting HH→4V, HH→VVττ, HH→4τ, HH→γγVV, HH→bbZZ
  - Categories based on multiplicity of e/μ, τ_h and γ

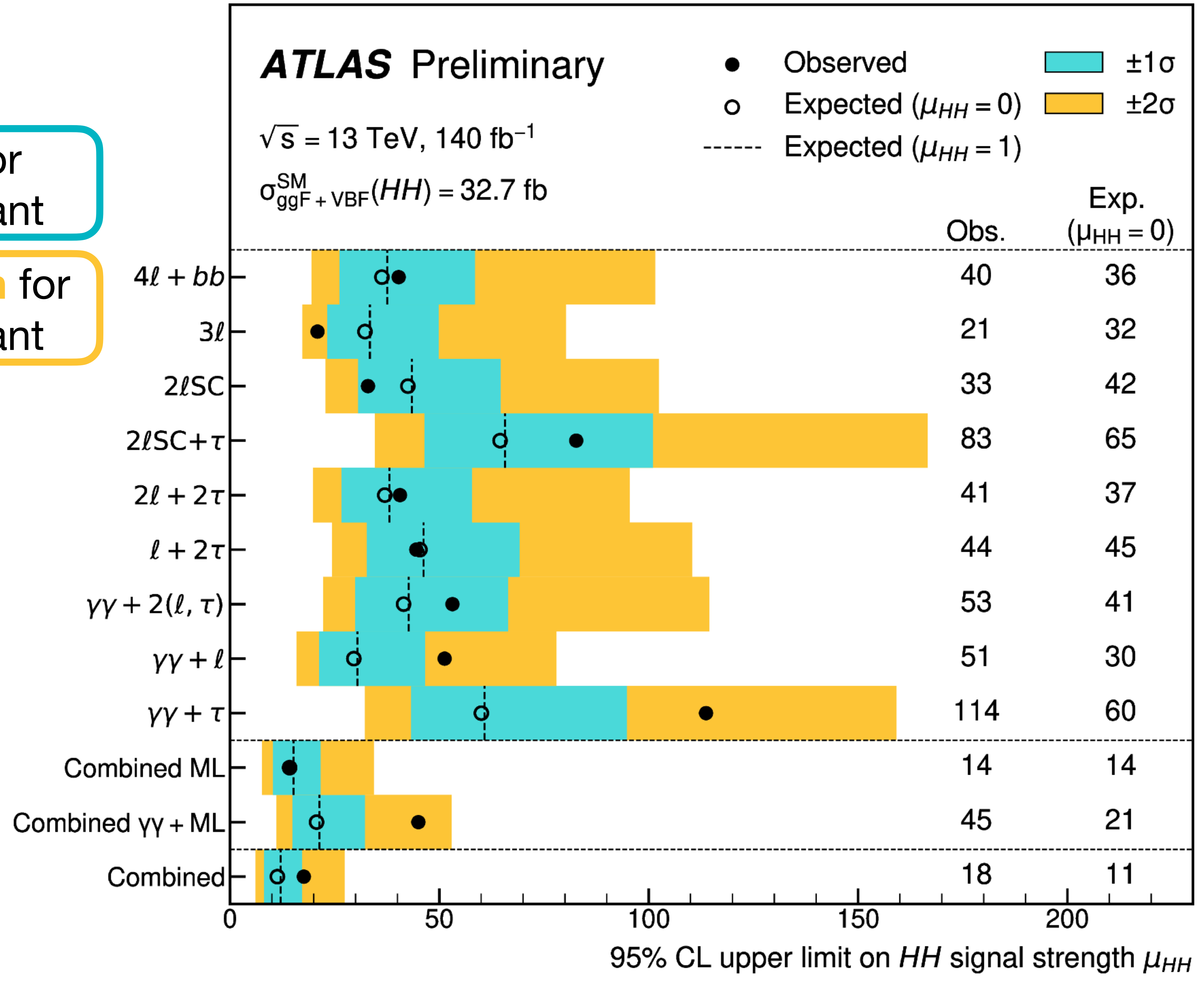


BDT score for final discriminant

$m_{\gamma\gamma}$ distribution for final discriminant

$\sigma_{HH} < 18\ (11)\ \sigma^{SM}_{HH}$

ATLAS-CONF-2024-005



- Result interpreted in terms of **signal strength** limit
- **No single channel** dominating the sensitivity

How to improve sensitivity?

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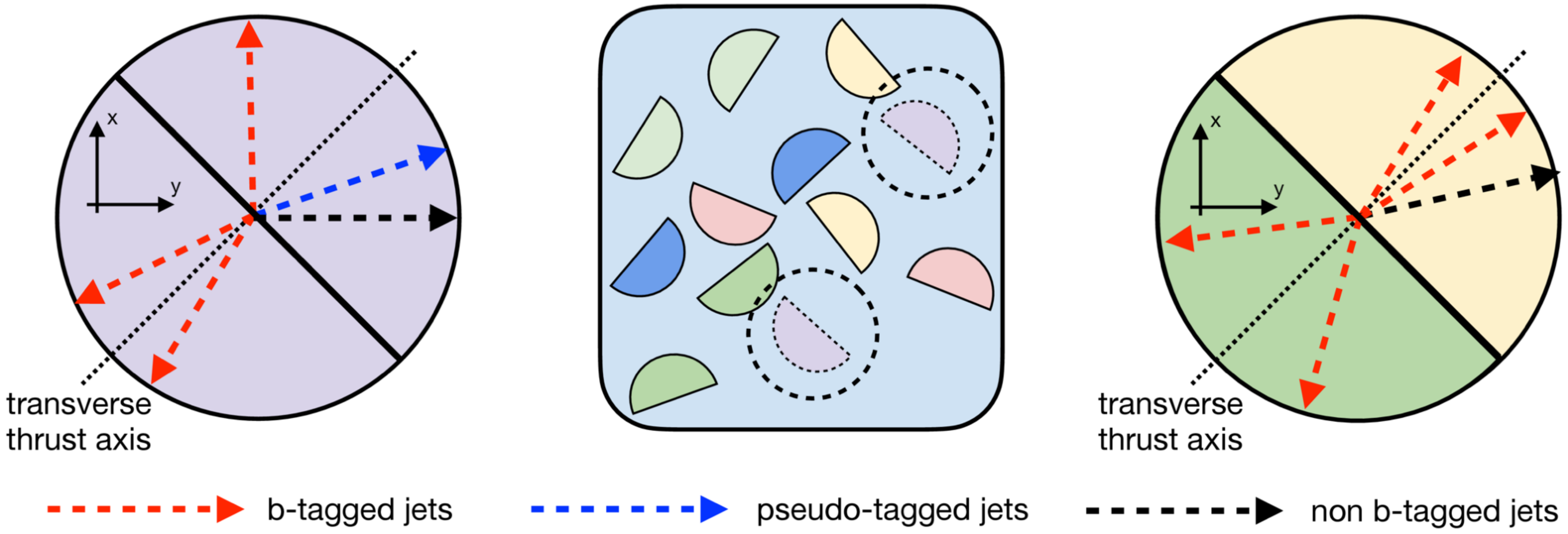
Investigate new regimes

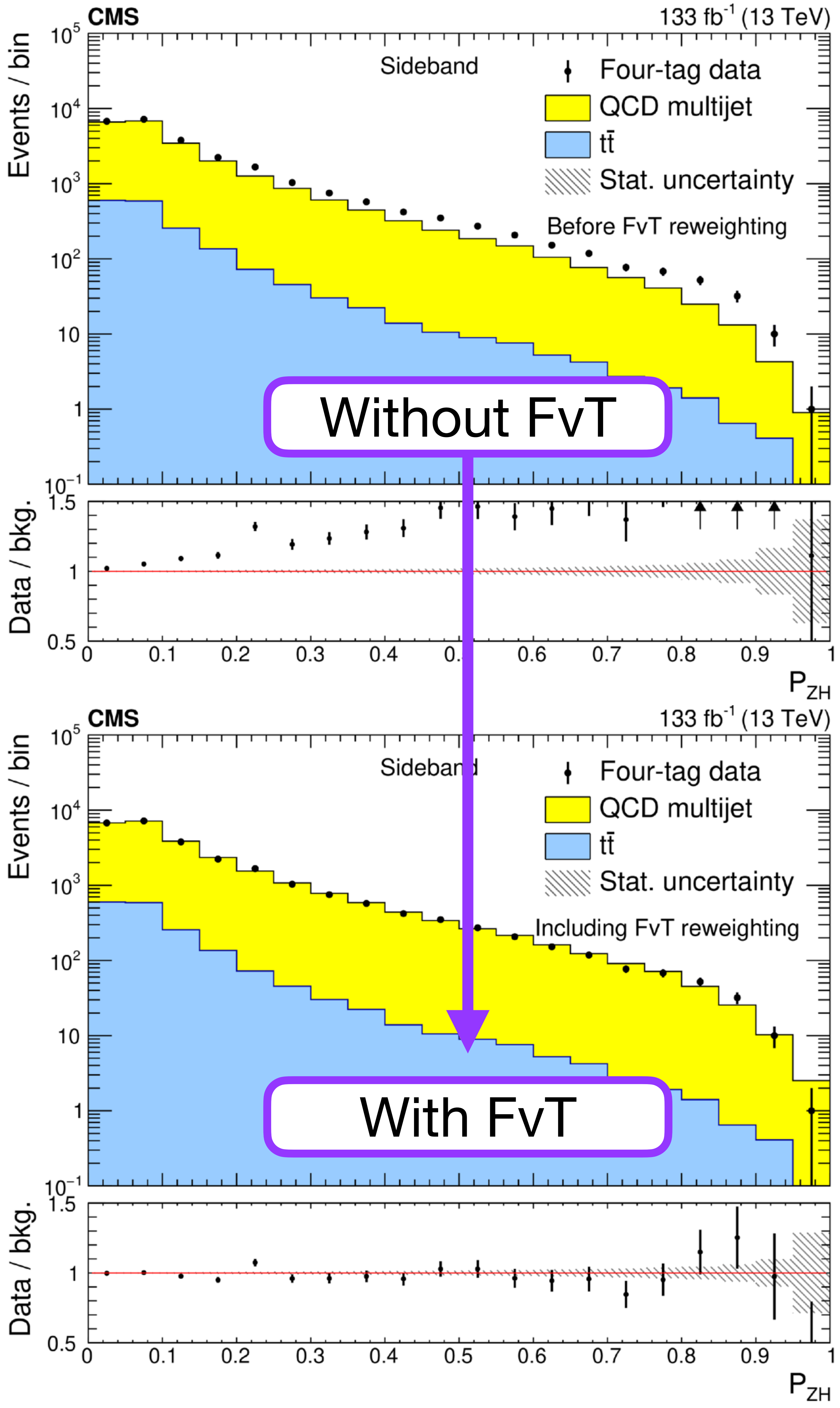
Include new final states

ZZ/ZH→4b (CMS) NEW

[Submitted to Eur. Phys. J. C](#)

- Search for ZZ/ZH production in the 4b final state as a **validation of HH→4b**
  - Four VS Three (FvT) re-weighting: 3 b-tagged jets CR (17× more stats) corrections applied to 4 b-tagged jets SR
  - Synthetic dataset produced with hemisphere mixing to increase statistics





$\mu_{ZZ} = 0.0\ {+2.0}/{-1.7}$

$\sigma_{ZZ} < 3.8\ (3.8)\ \sigma^{SM}_{ZZ}$

$\mu_{ZH} = 2.2\ {+0.9}/{-0.8}$

$\sigma_{ZH} < 5.0\ (2.9)\ \sigma^{SM}_{ZH}$

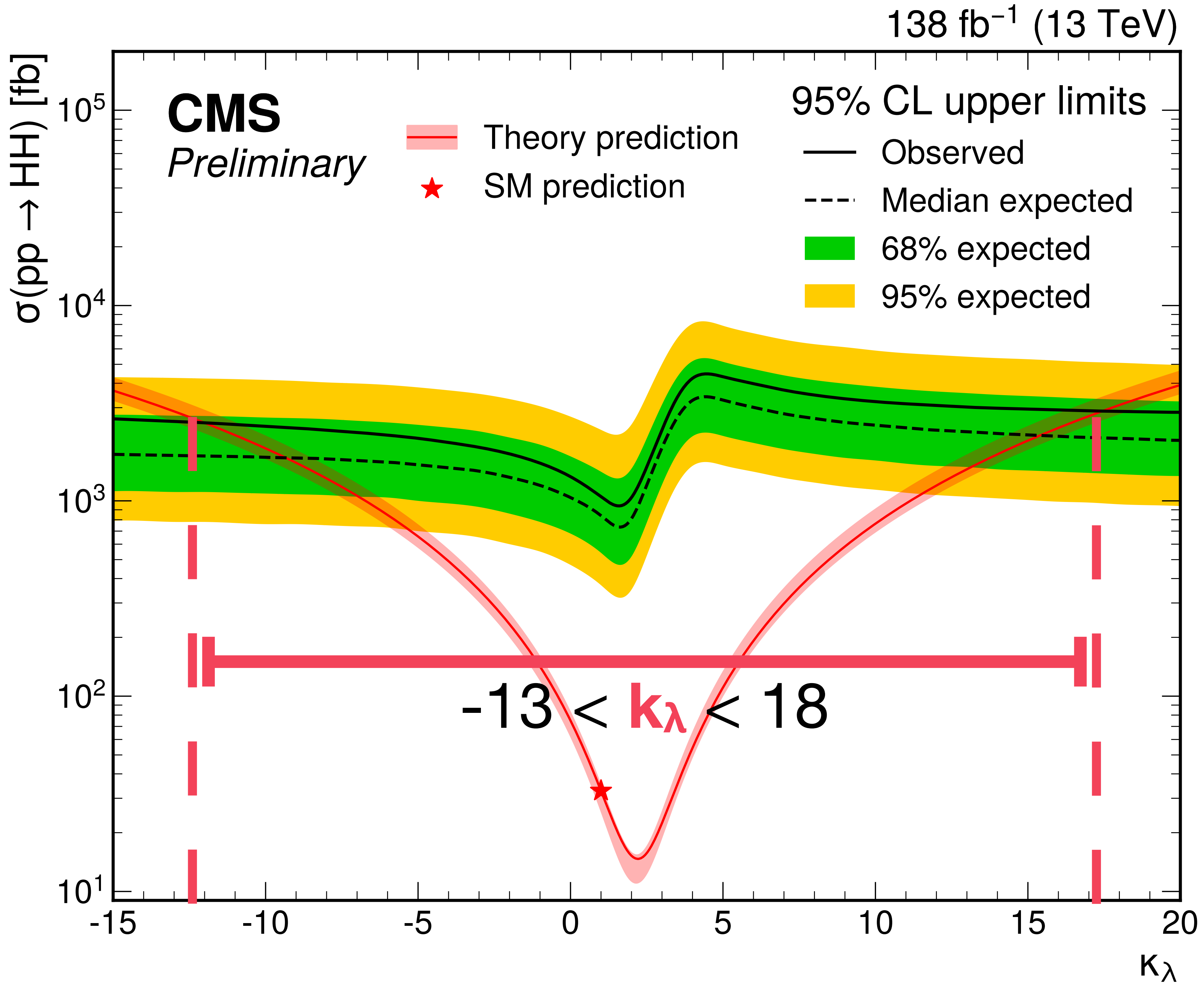
▸ The observation of ZZ/ZH→4b will soon be possible

How to improve sensitivity?

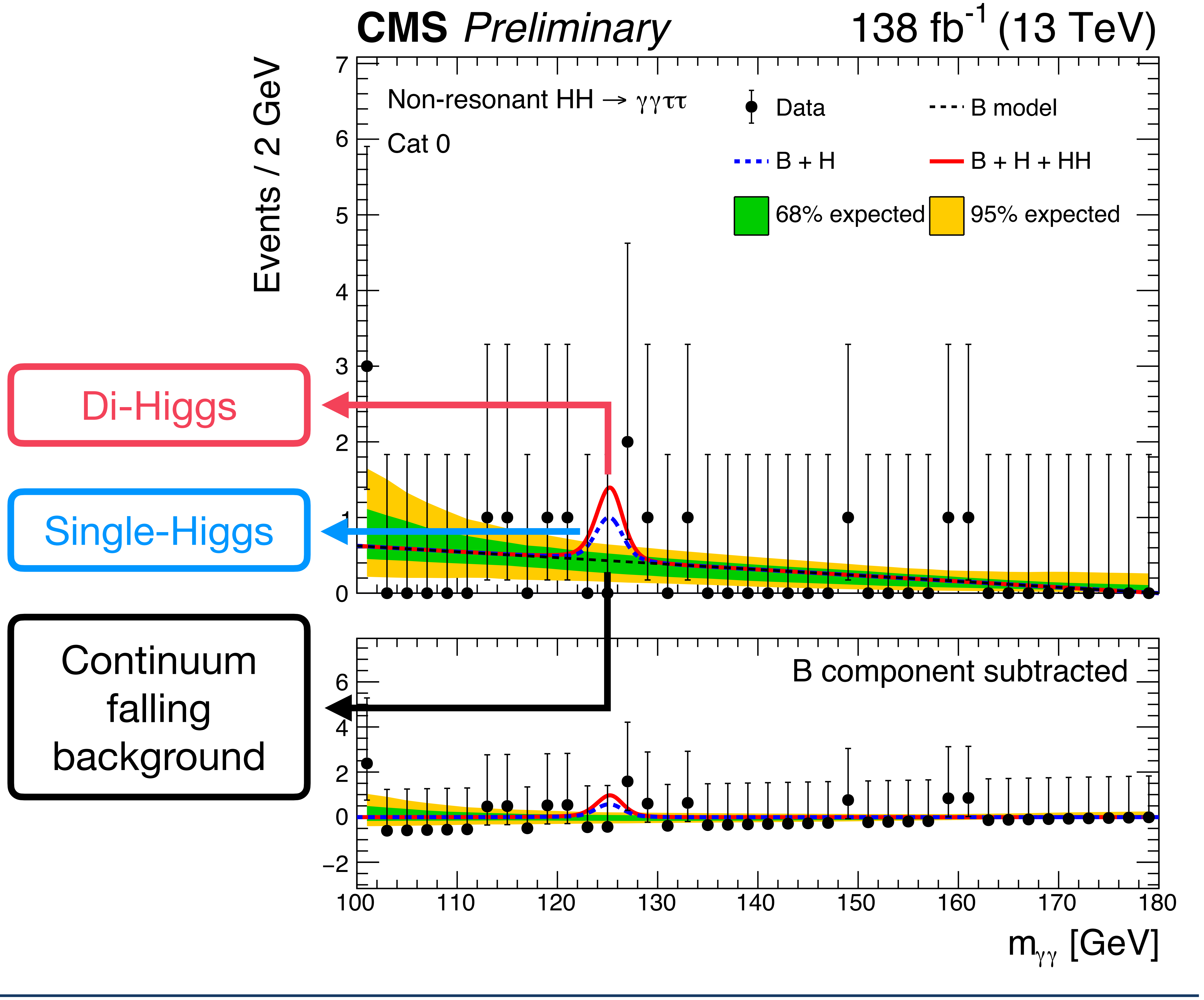
HH→γγττ (CMS) NEW

- Search for HH production in the γγττ final state, covered for the **first time by CMS**
  - Very low branching ratio, but benefit from good di-photon resolution
  - The main challenge comes from limited statistics

CMS-PAS-HIG-22-012



- Low stand-alone sensitivity
- Powerful result if added to combinations



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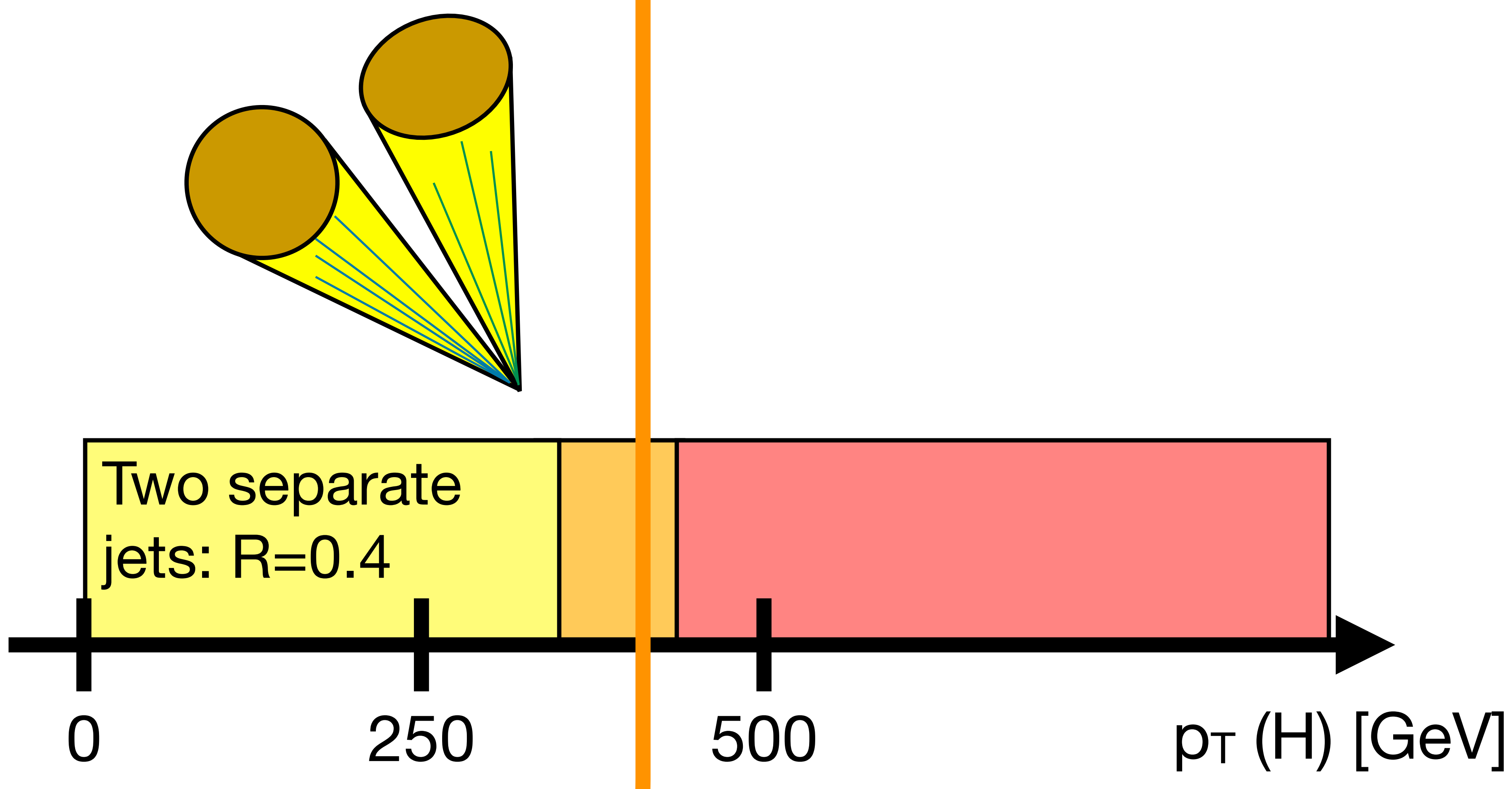
VBF HH→4b (ATLAS) NEW

- Search for HH production in 4b final state via **ggF** and **VBF** in resolved and boosted regimes

Resolved

- H reconstructed as two jets
- Largest fraction of signal
- Large multi-jet QCD background
- Dominating low p_T region



Jet clustering with Anti-kT (AK) algorithm

CMS-PAS-B2G-21-001
ATLAS-CONF-2024-003

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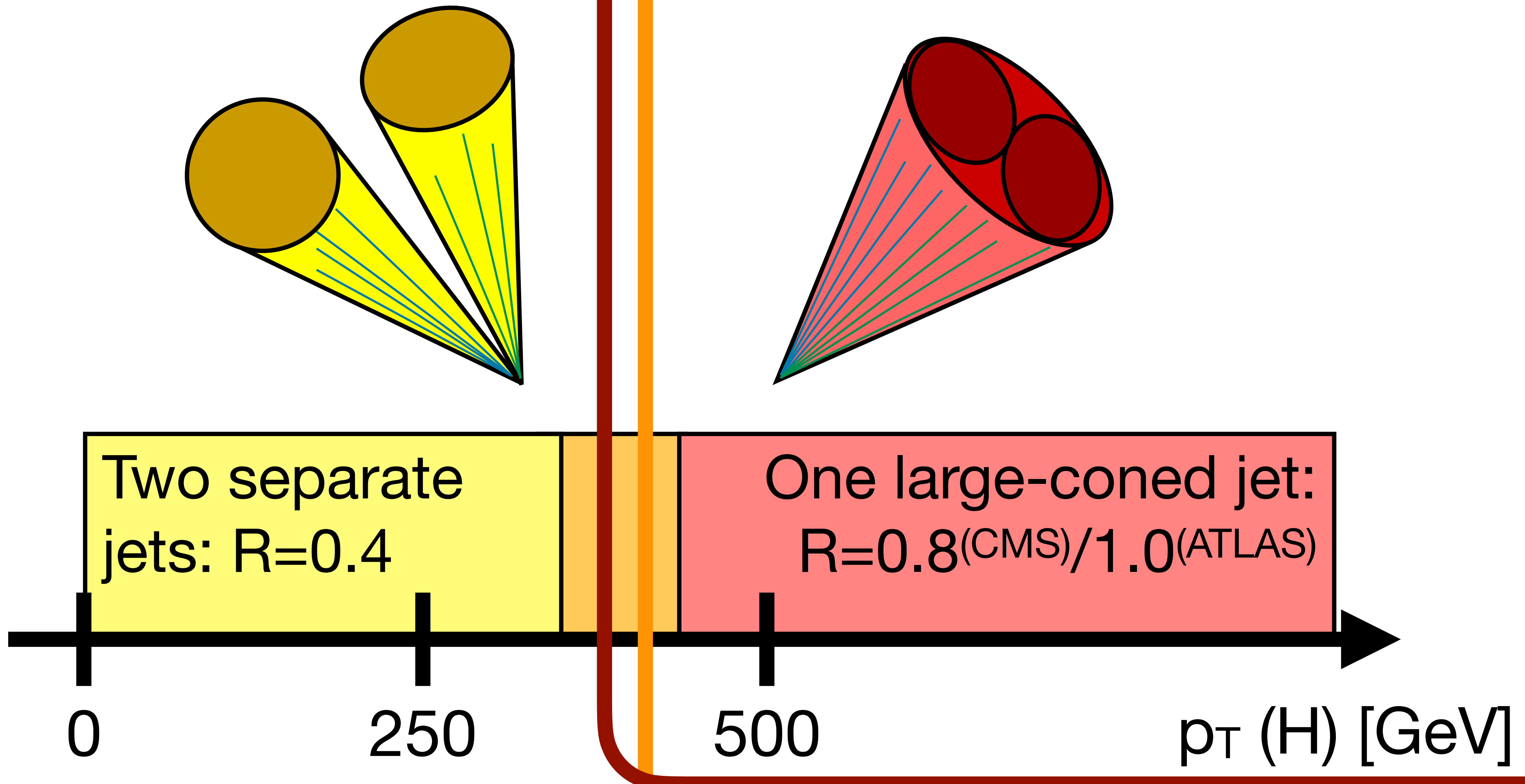
Boosted

- H reconstructed as large jet
- O(%) signal acceptance
- Lower multi-jet QCD contribution
- Improvement in boosted object reconstruction



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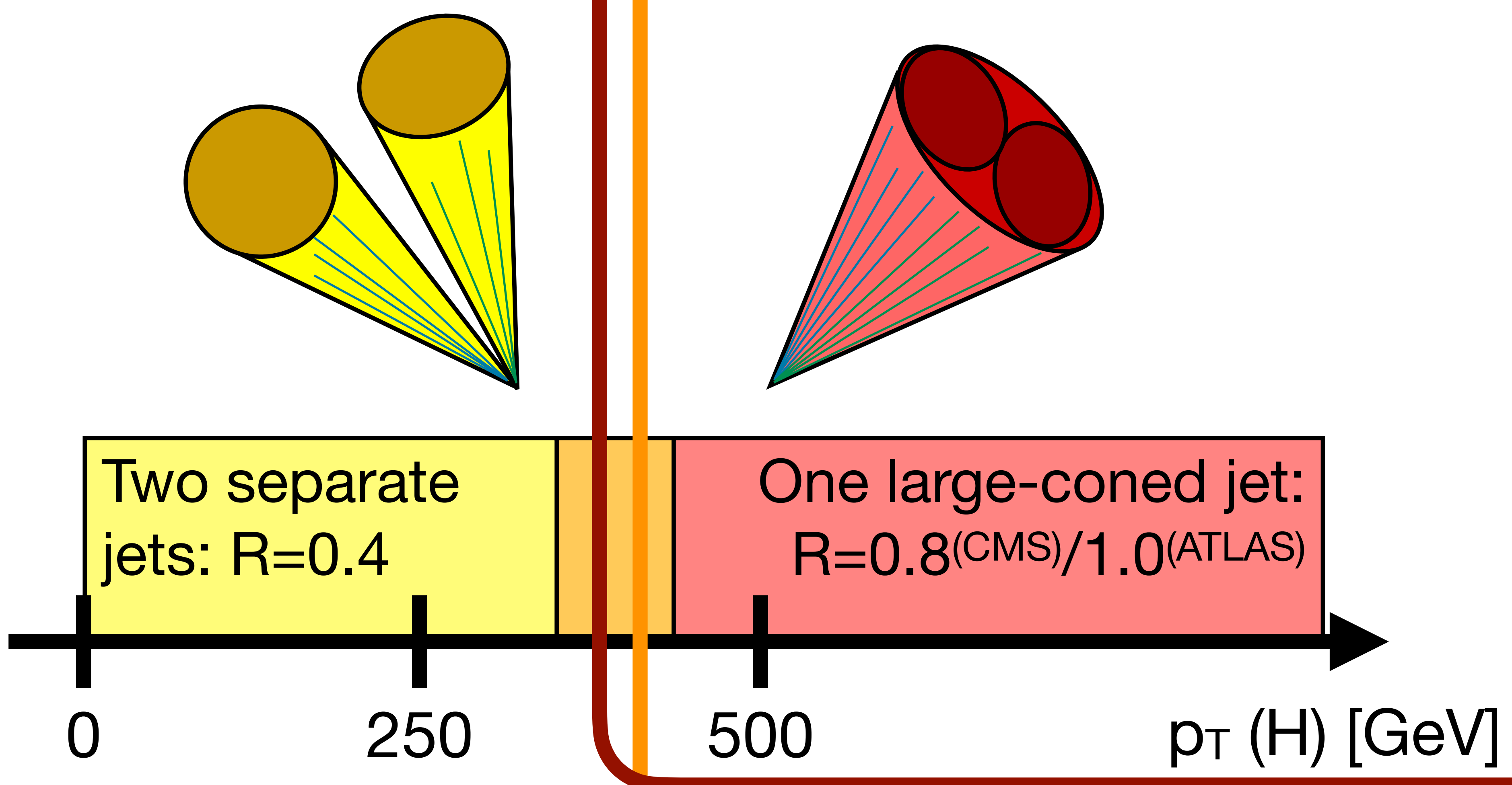
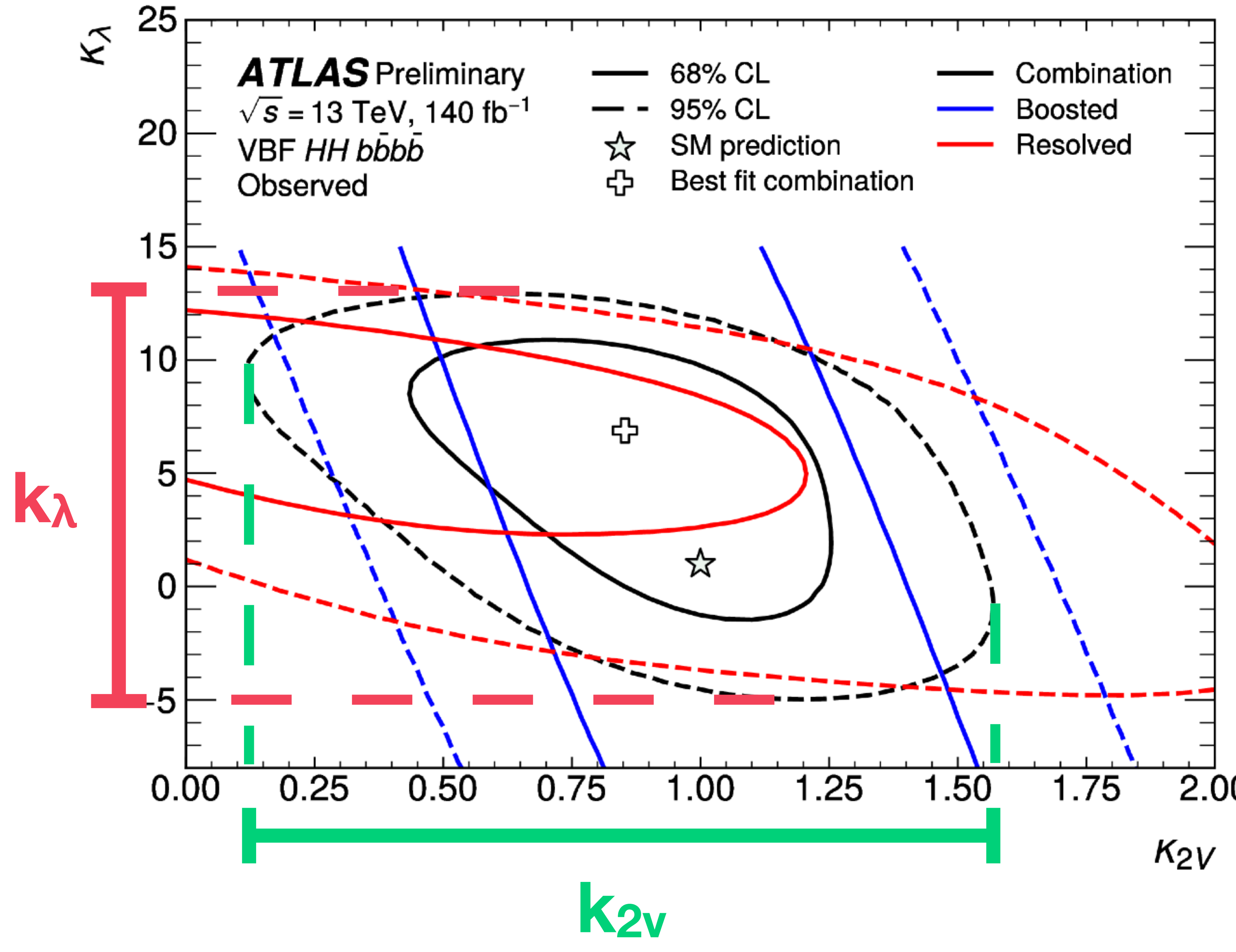


Jet clustering with Anti-kT (AK) algorithm

ATLAS-CONF-2024-003



- k_λ sensitivity driven by **resolved**
- k_{2V} sensitivity dominated by **boosted**

$k_{2V} \neq 0$ for any value of k_λ

How to improve sensitivity?

Run 3 and beyond…

More advanced analysis techniques

Combination with Single-Higgs

Multiple directions

Better background modelling

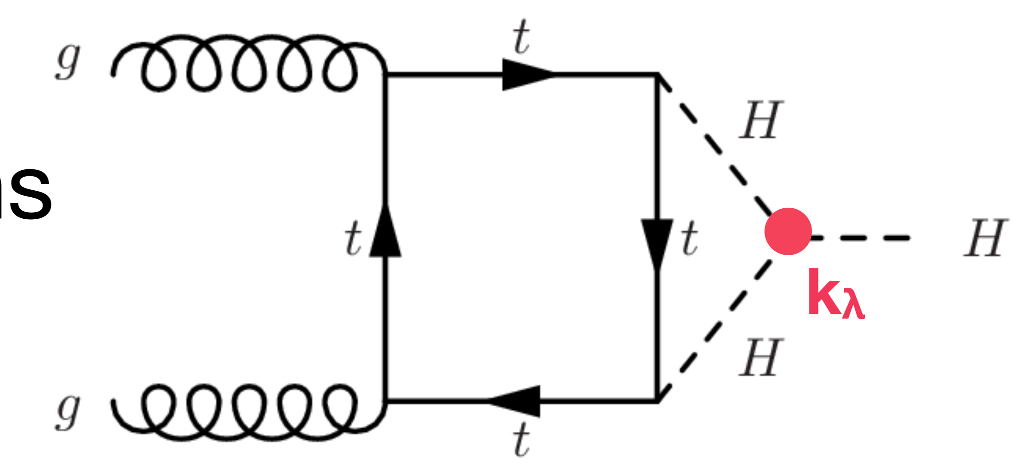
Investigate new regimes

Include new final states

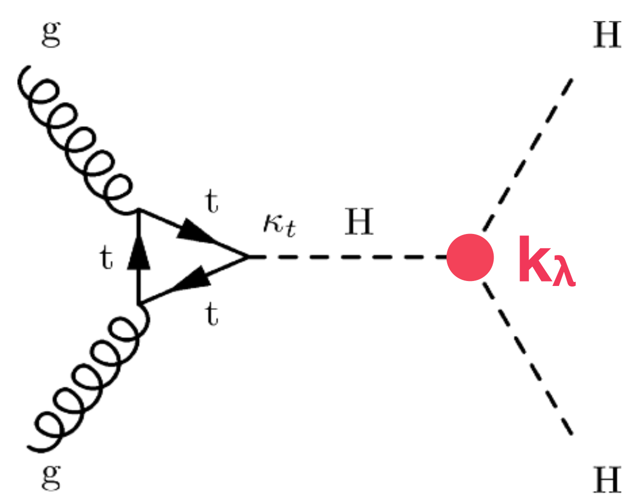
Combination H+HH

Single-Higgs

- Constrain H couplings to fermions and vector bosons
- Access to k_λ via NLO EW corrections

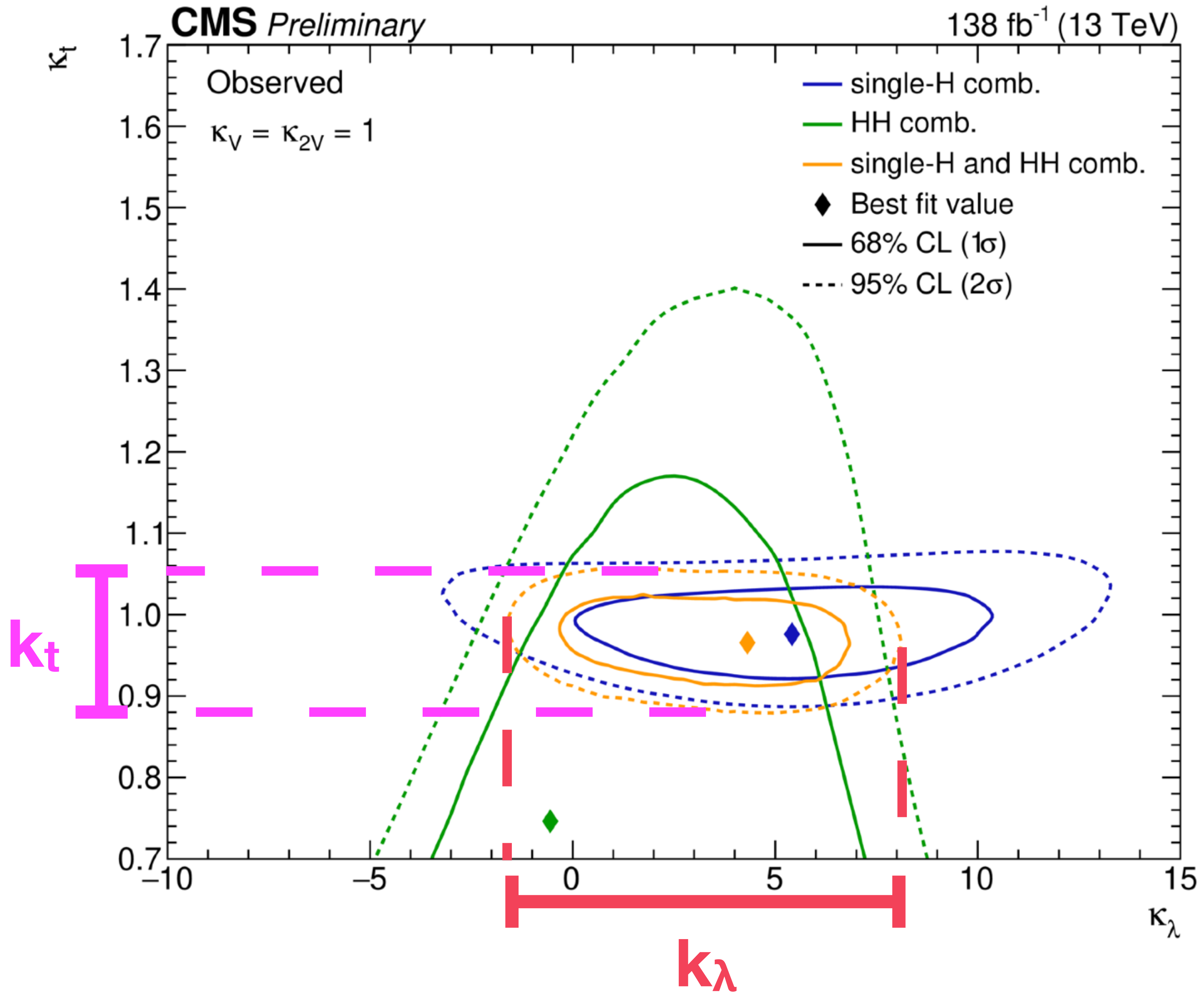


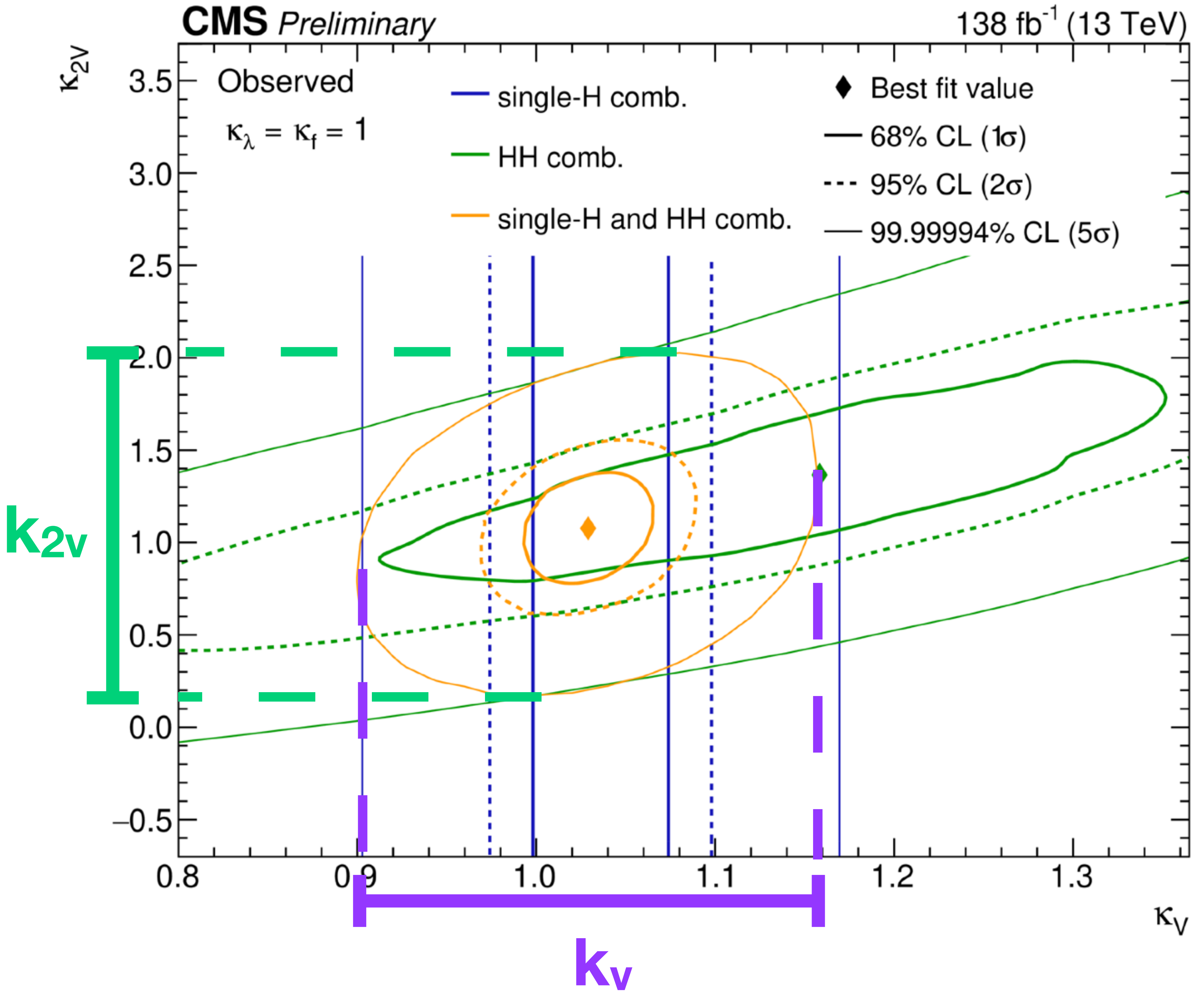
Di-Higgs



- High sensitivity to k_λ and k_{2V}
- Weak constraints on other couplings

CMS-PAS-HIG-23-006





- Constraints on k_t and k_V are driven by **Single-Higgs**
- Constraints on k_λ and k_{2V} are driven by **Di-Higgs**

k_{2V} = 0 excluded at > 5σ
for any value of k_V

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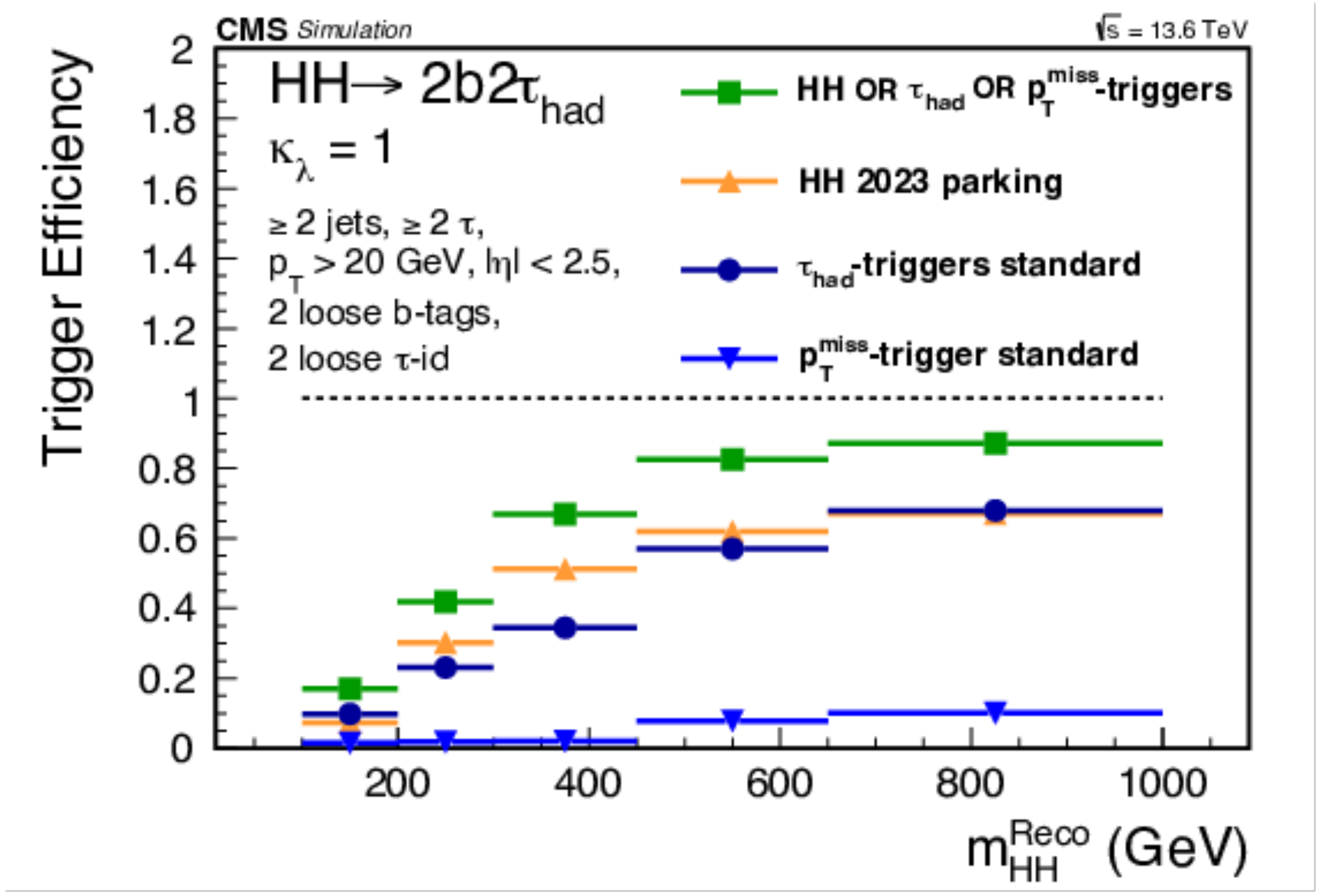
Run 3 and beyond

Run 3 as an opportunity

- Improved trigger strategy both for ATLAS and CMS
  - HH→4b and HH→bbττ triggers [CMS-DP-2023-050] [ATLAS-TauTrigger]
  - Data parking allows for lower object thresholds [CERN-EP-2024-068]
- Improved object identification Deep/Graph Neural Network Taggers

CERN-EP-2024-068



Run 3 and beyond

Run 3 as an opportunity

- Improved trigger strategy both for ATLAS and CMS
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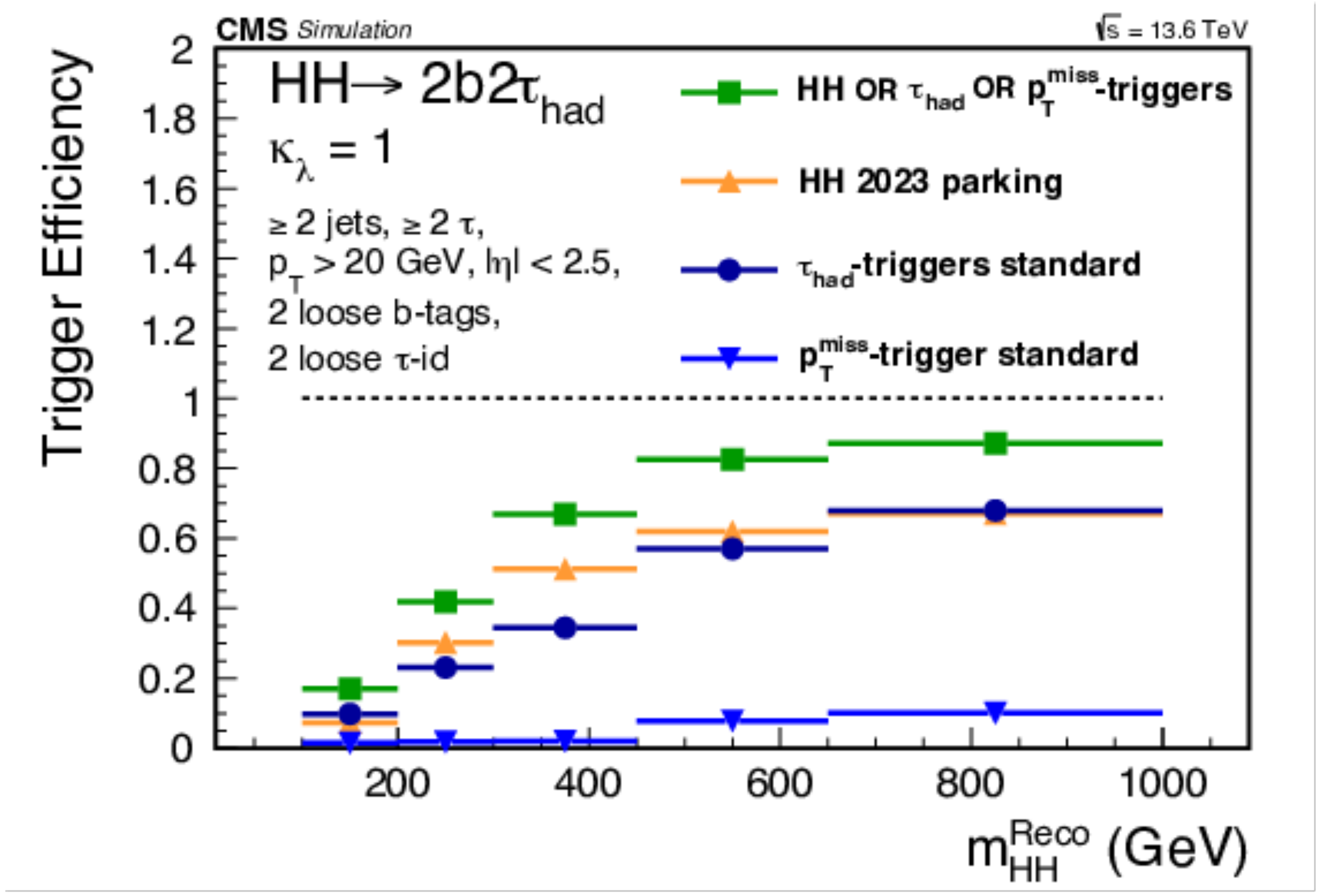
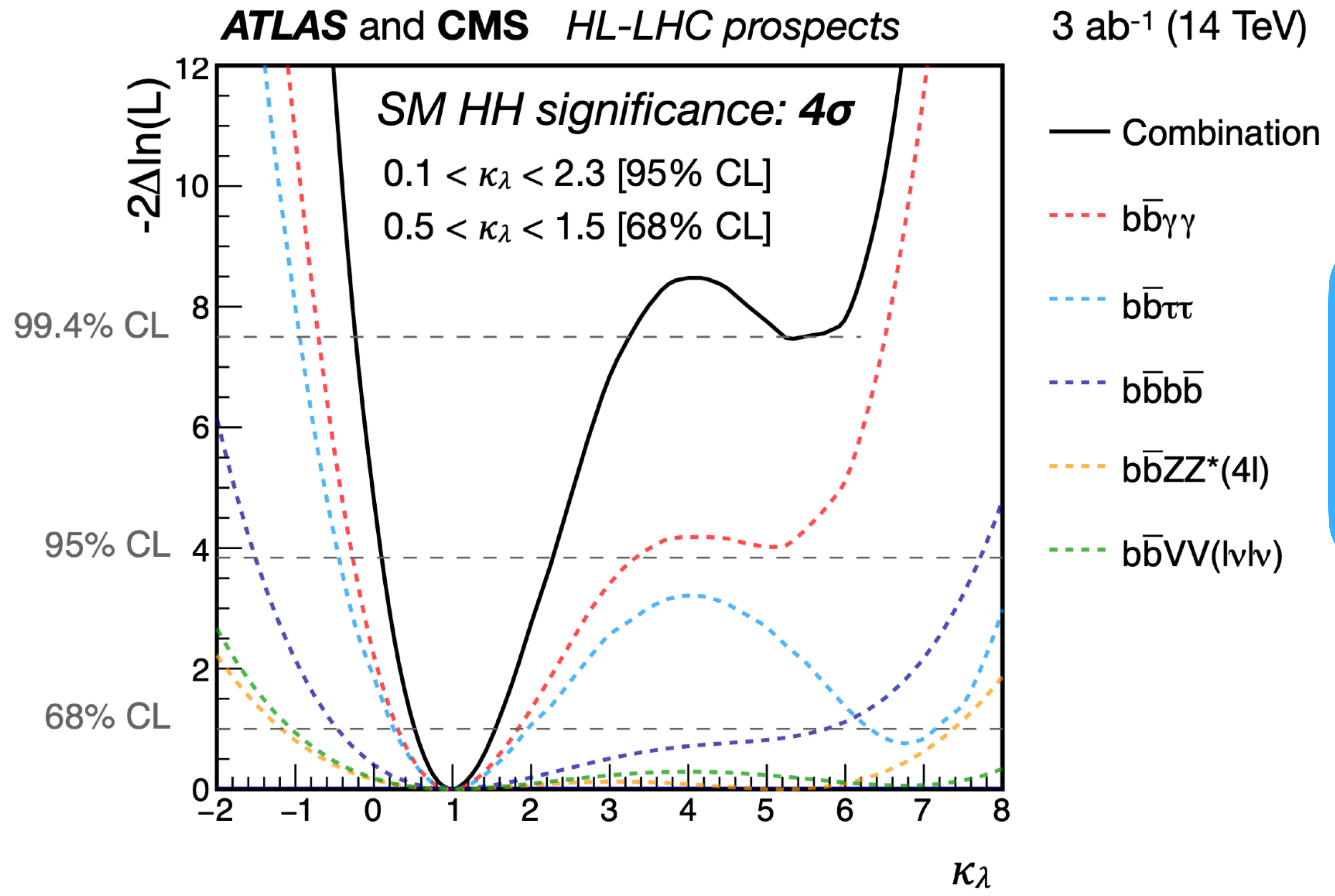
CERN-EP-2024-068





Towards HL-LHC

- Largest impact from higher luminosity
  - Access new production/decay modes
- Benefit from phase-2 upgrades (forward region for VBF)

- ▸ HH production expected to reach 4σ significance
- ▸ 50% precision on the Higgs self-coupling

(based on partial Run 2 → sensitivity already improved a lot!)

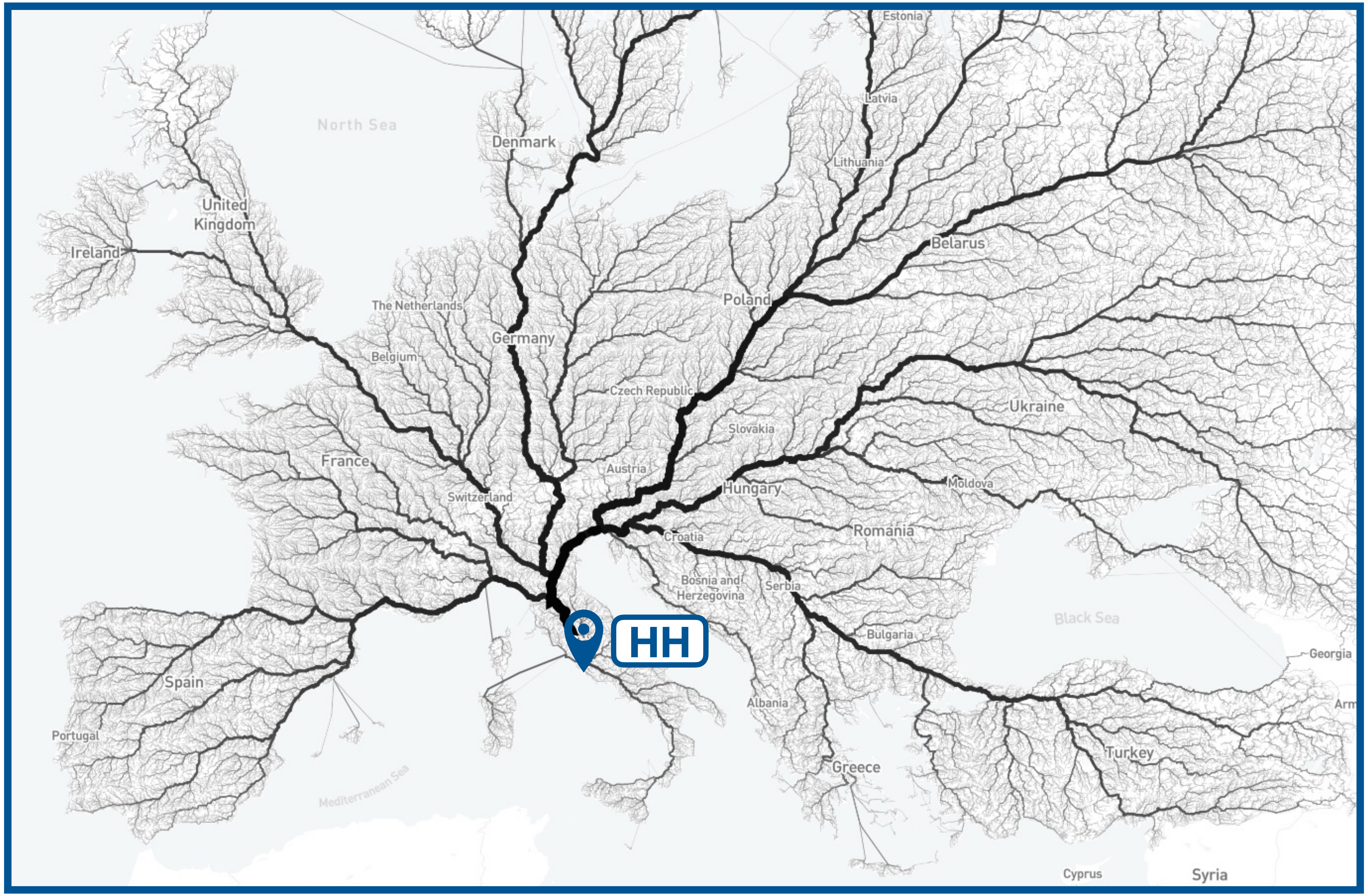
Conclusions

- Probing the **Higgs boson self-interaction** is one of the **primary targets** of Higgs Physics for the coming years
- A **spectacular improvement** in the experimental HH programme has been achieved during the **LHC Run 2**
- Innovative analyses techniques enabled sensitivities well **beyond the most optimistic expectations**
  - Upper limit on HH cross section by each experiment: $\boldsymbol{\sigma_{HH} < 2\text{-}3 \times \sigma^{SM}_{HH}}$
  - Self coupling constrained to approximately: $\boldsymbol{-1 < k_{\lambda} < 6}$
  - Excluded the absence of VVHH at > 5σ: $\boldsymbol{k_{2V} \neq 0}$

- The **LHC Run-3** is **underway** and constitutes a huge opportunity to further improve sensitivity
  - Important trigger improvements introduced for HH searches
  - Test-bench for new ideas and analysis strategies
- Remarkable progress in the field opens to **excellent prospects** for the **HL-LHC**
  - Direct the effort towards measuring di-Higgs production and Higgs boson self-interaction

Multiple directions to be taken …

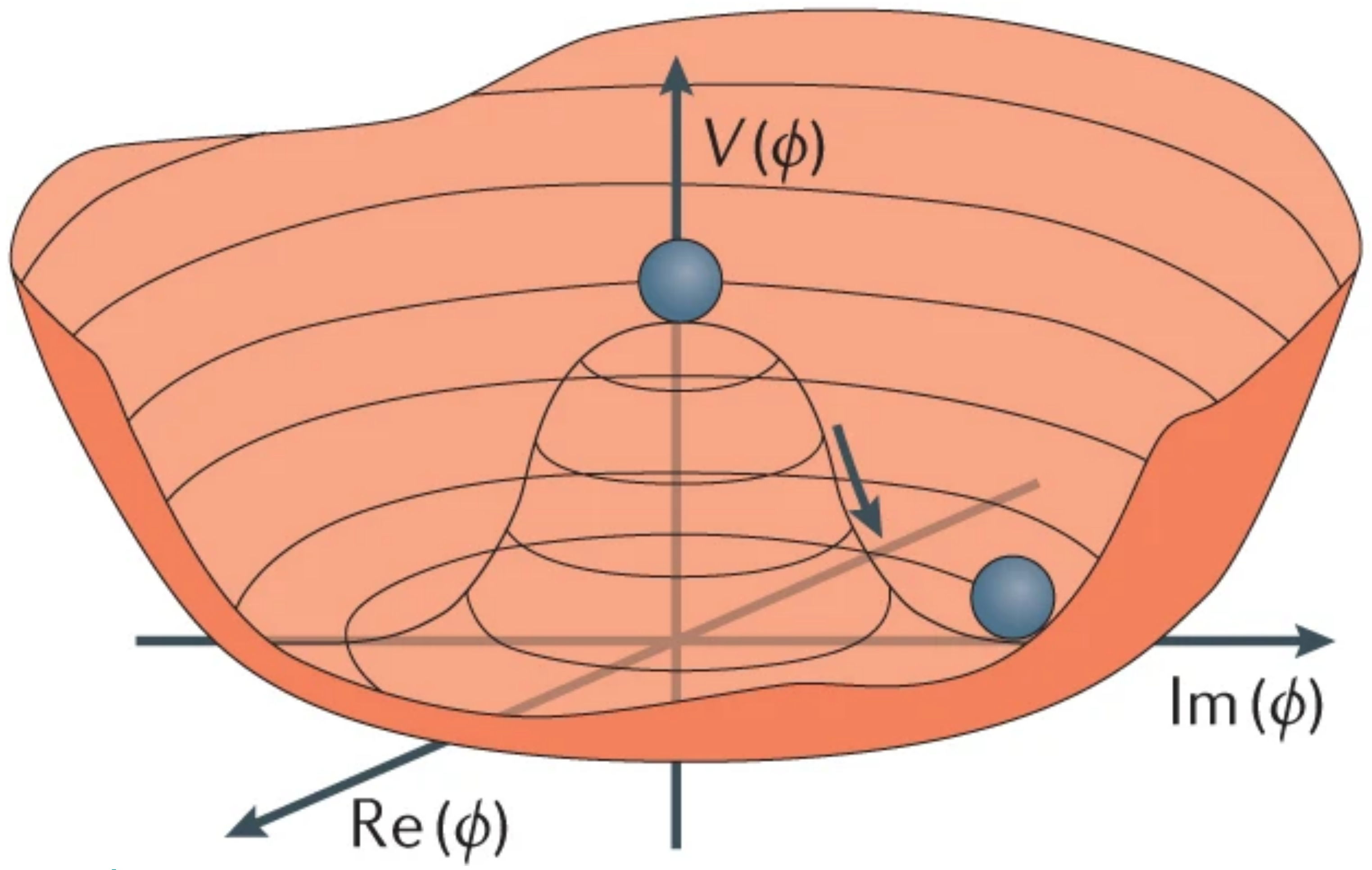
All roads lead to ~~Rome~~ HH

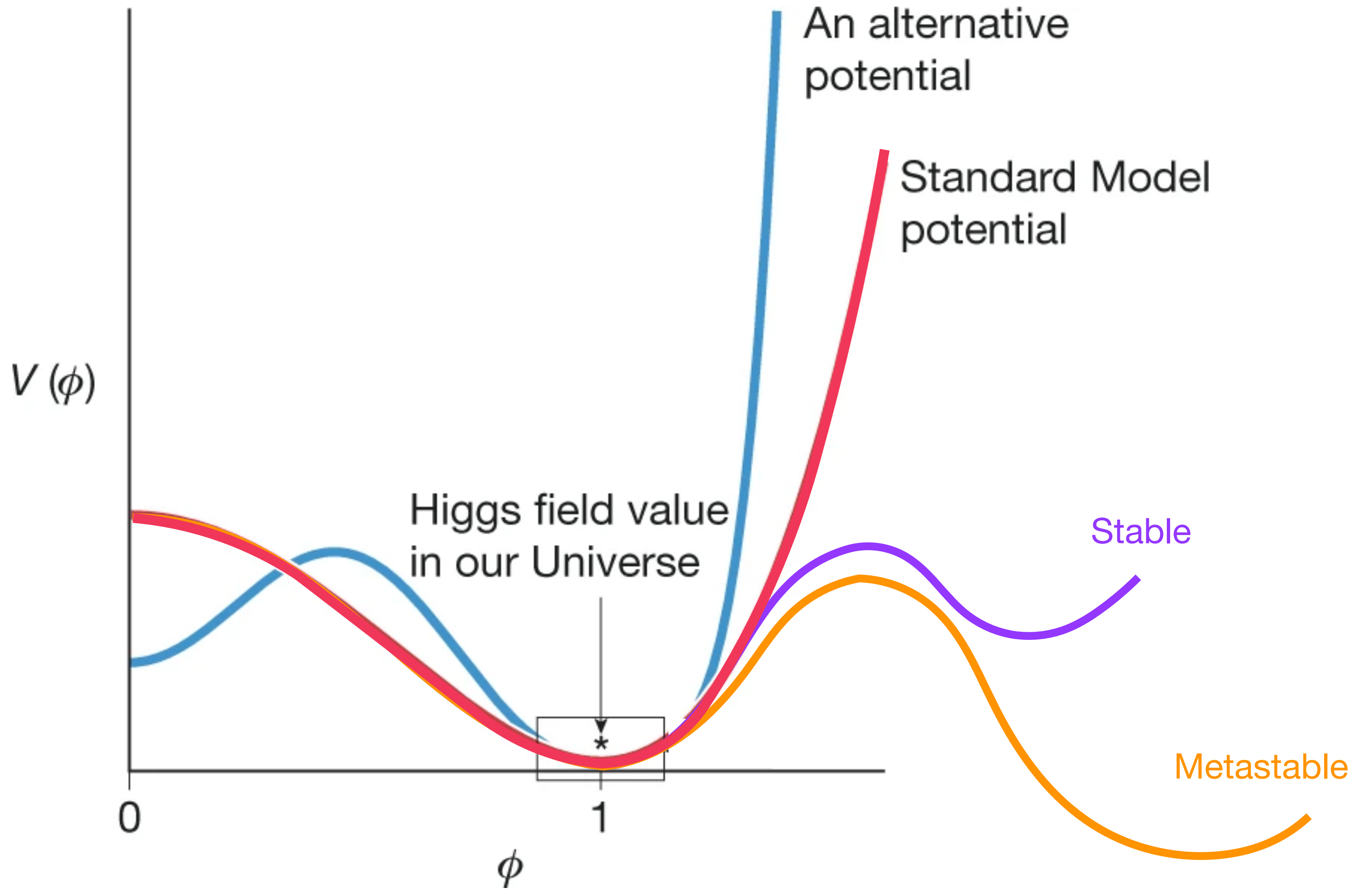


Back-up

Higgs self-coupling beyond SM

- Searching for **di-Higgs production** is a crucial way of testing the EWSB mechanism: **direct** access to the **trilinear coupling** λ_3^{SM} (Higgs boson self-interaction)
  - Investigate **alternative hypotheses** for the Higgs potential
  - Deviations from the SM potential could point to a **vacuum metastability** (second minimum)
- BSM deviations of these parameters may lead to differences in HH production rates and kinematics
- Test possible **coupling modifiers** with respect to SM: $\mathbf{k_\lambda, k_V, k_{2V}, k_t}$





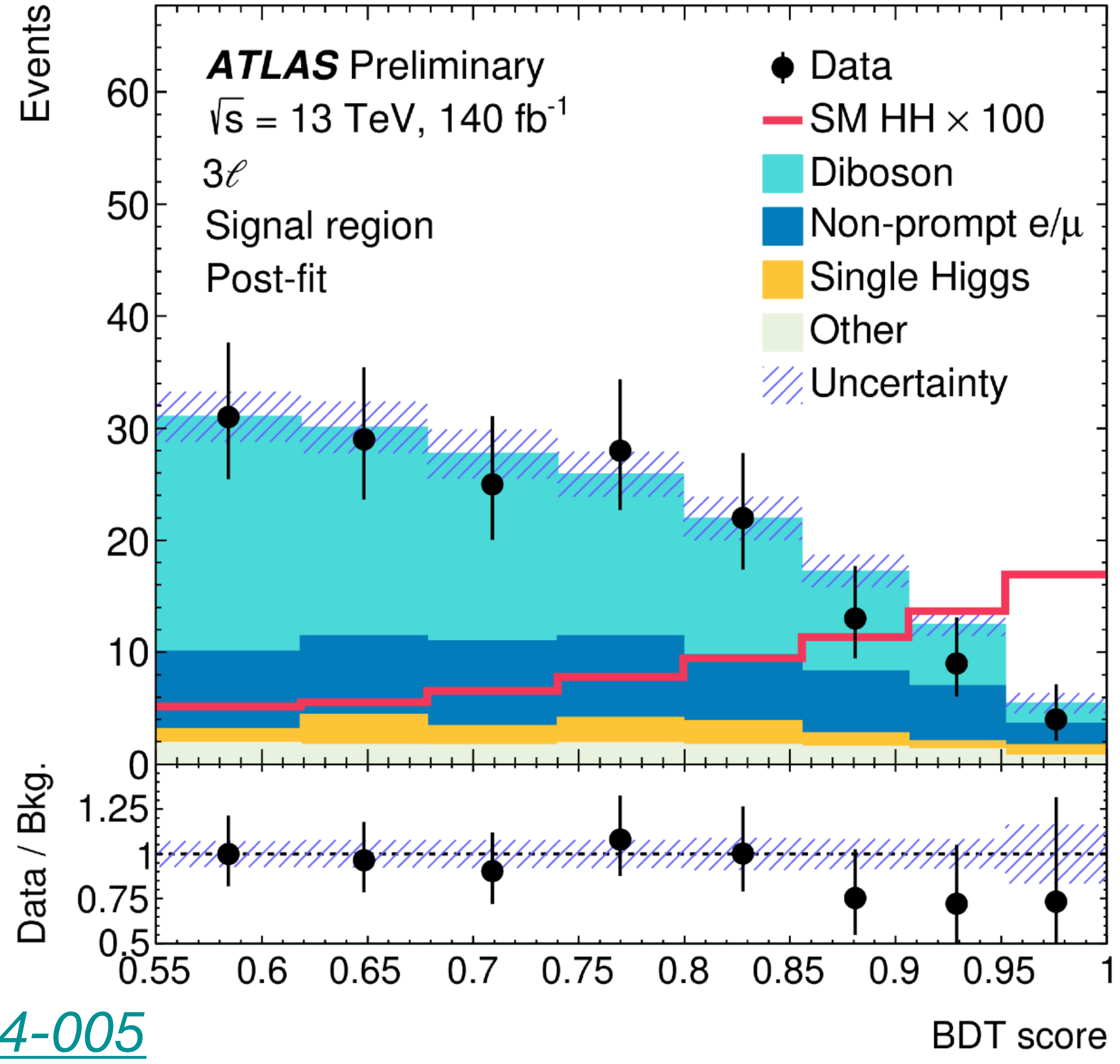
[Nature 607, 41–47 (2022)]
[Nat Rev Phys 3, 608–624 (2021)]

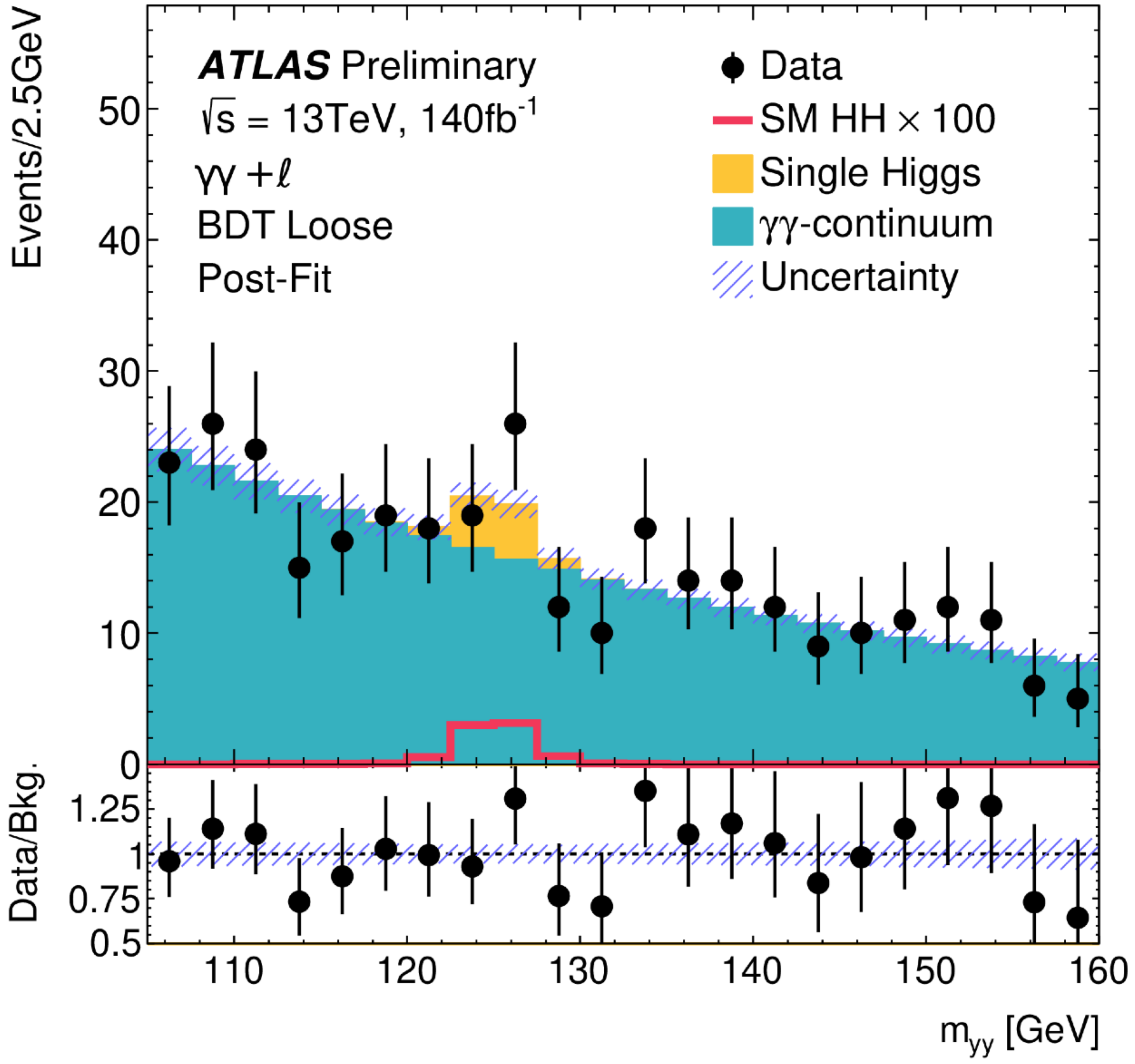
HH Multilepton (ATLAS)

- Search for HH production in multilepton decay with a **holistic way**, performed for the **first time by ATLAS**
  - Multileptonic channels (ML): **BDT score** for final discriminant
  - $\gamma\gamma$ + leptons channels ($\gamma\gamma$+ML): **$m_{\gamma\gamma}$ distribution** for final discriminant

BDT score for final discriminant

$m_{\gamma\gamma}$ distribution for final discriminant

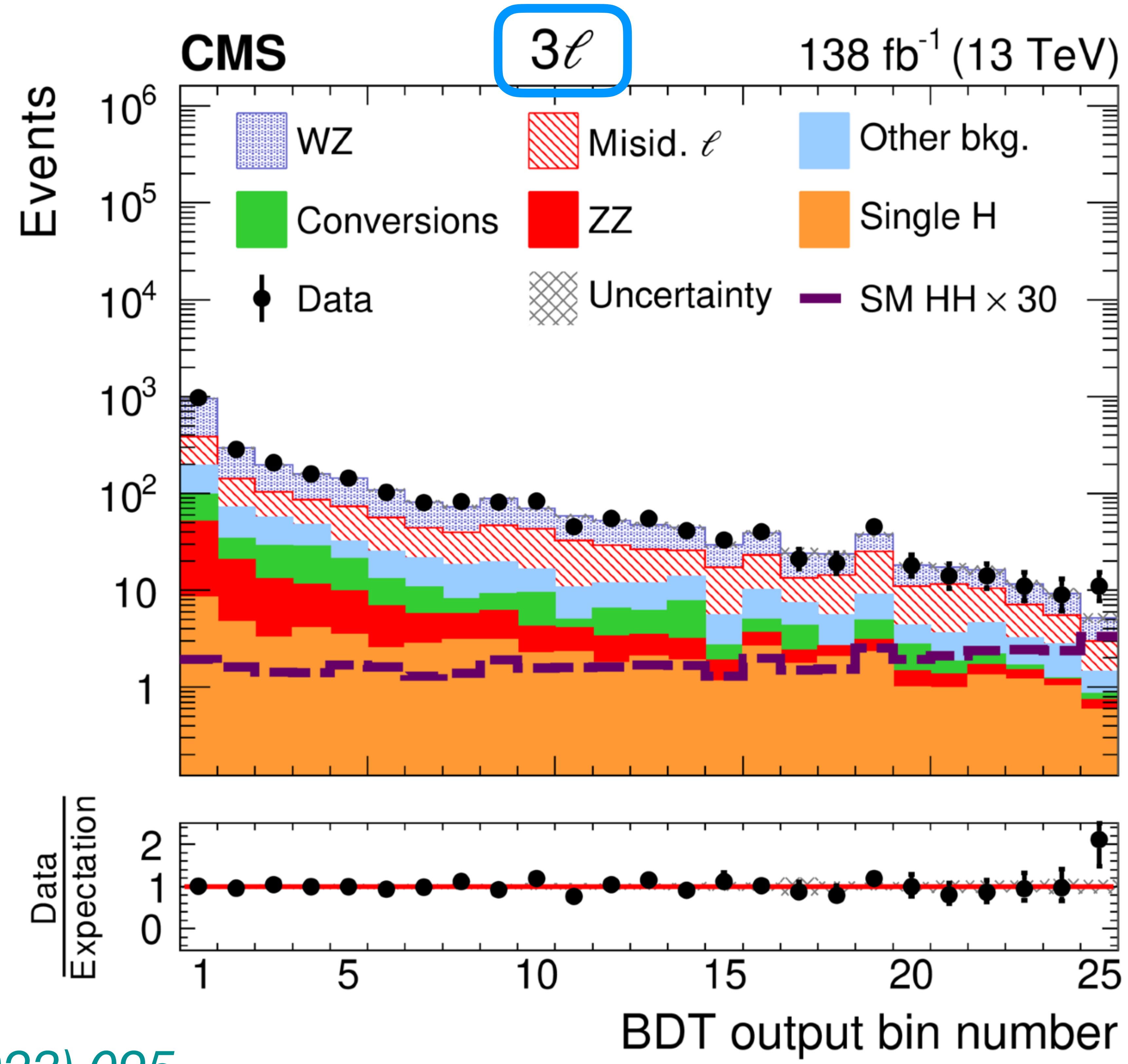


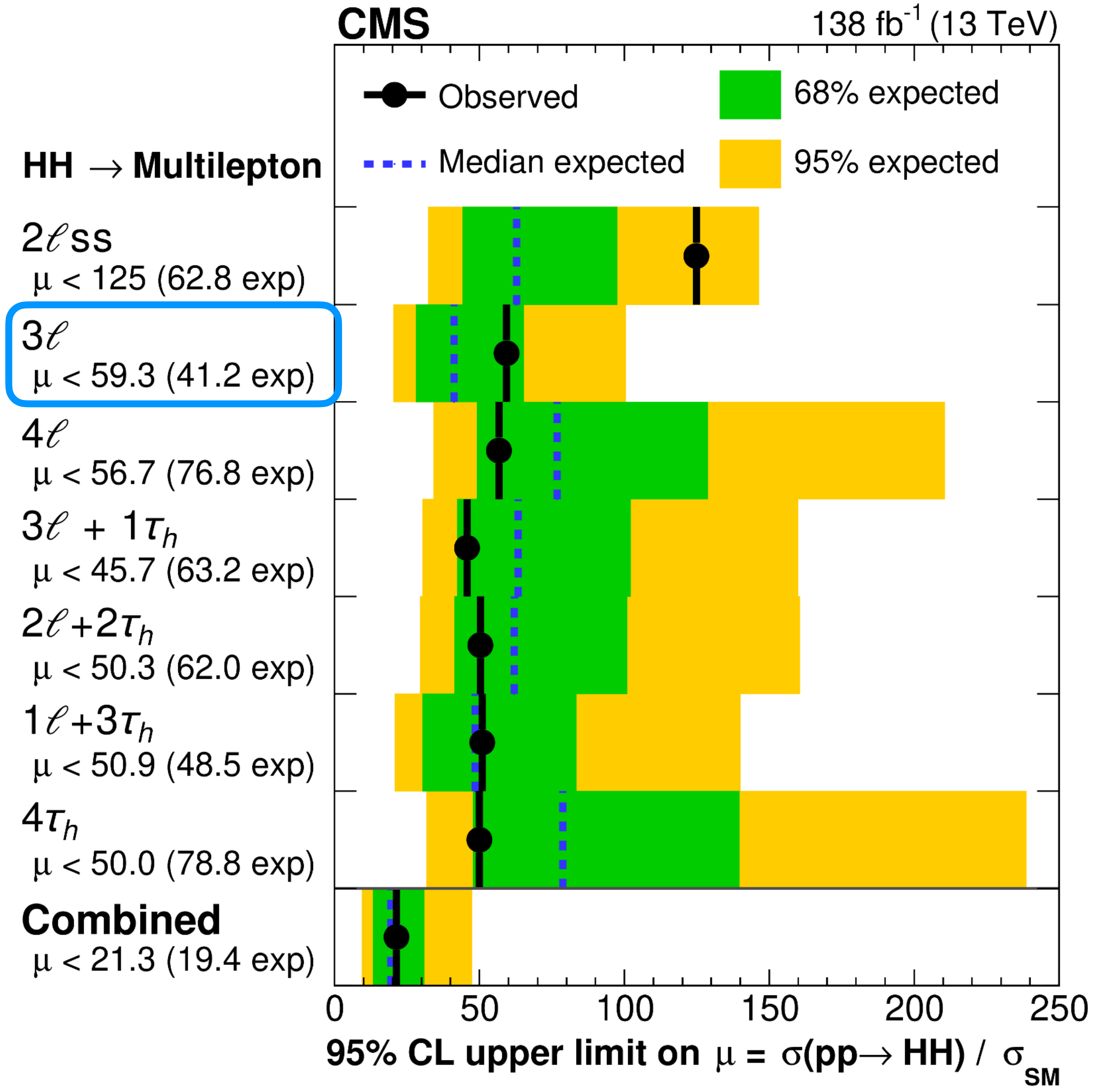


ATLAS-CONF-2024-005

HH Multilepton (CMS)

- Search for HH production in **multilepton** decay by CMS, targeting **HH→4V, HH→VVττ, HH→4τ**
  - Di-photon and bb4l channels not included in the analyses
  - Wider interpretation in terms of k_λ, k_{2V}, EFT benchmarks, search for Spin-0 and Spin-2 resonances

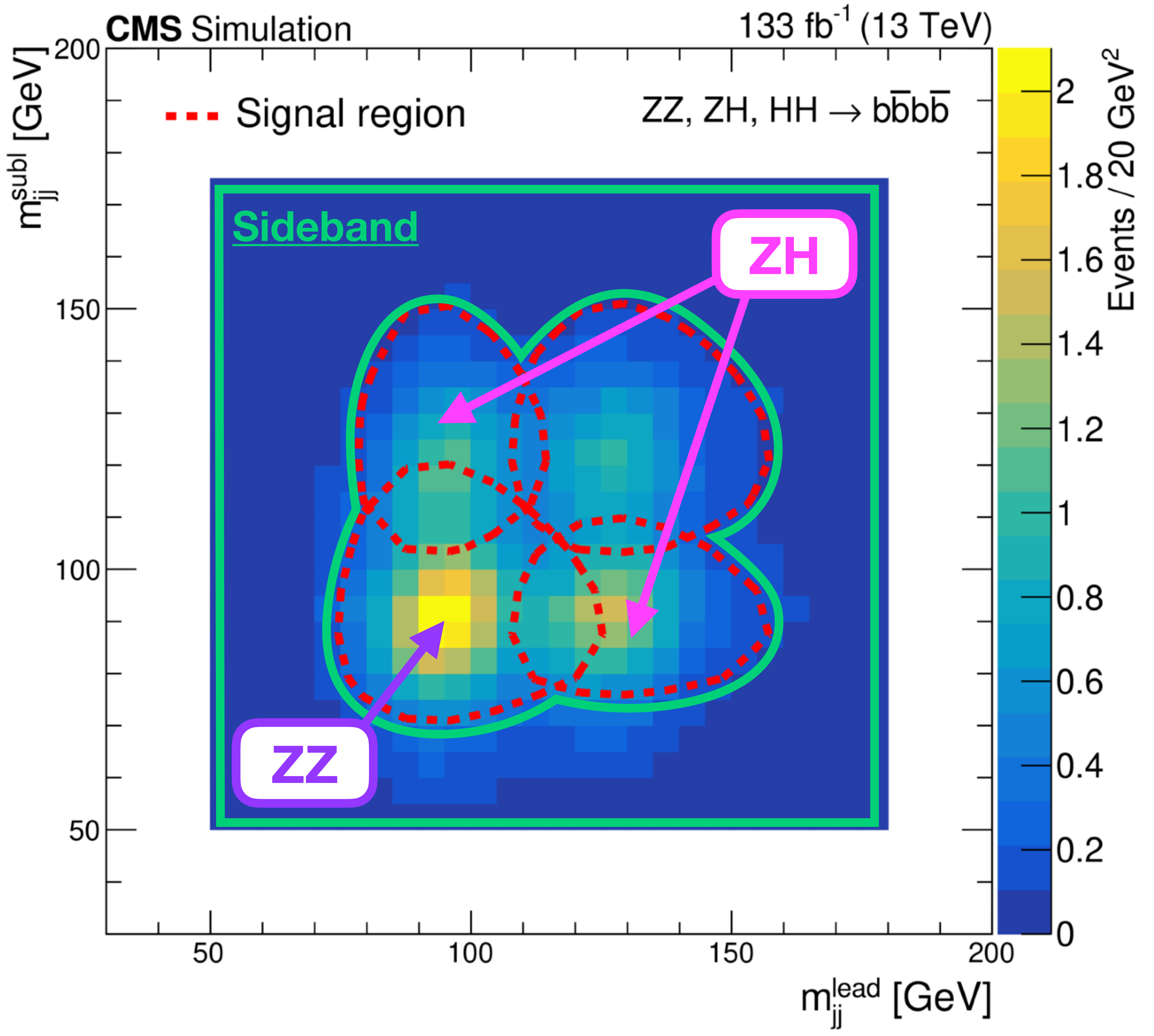


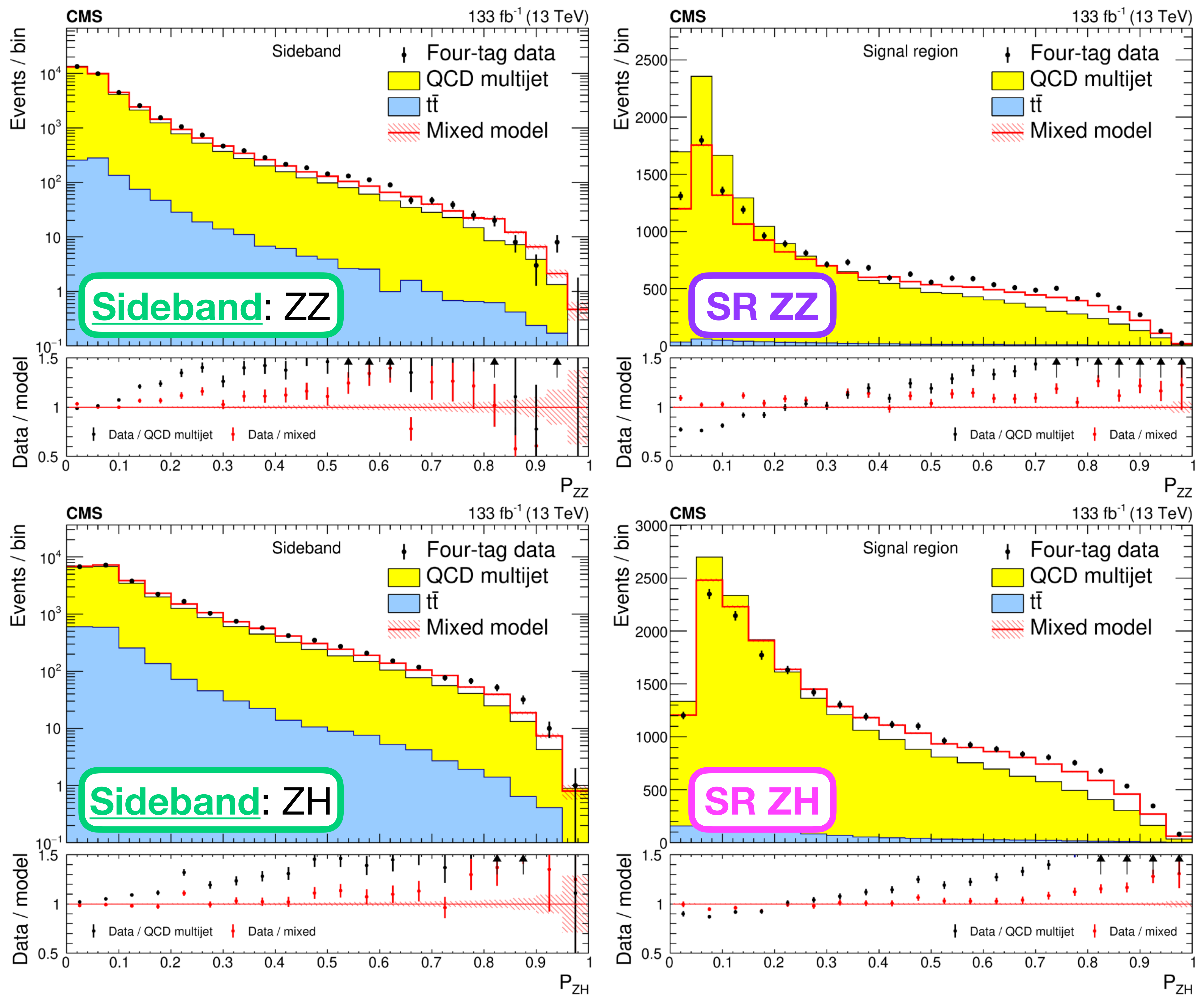


JHEP07 (2023) 095

ZZ/ZH→4b (CMS)

- Search for ZZ/ZH production in the 4b final state as a **validation of HH→4b**
  - Sideband to validate QCD multijet background
  - Cross section of ZZ(ZH) is 31(7) times larger than HH





[Submitted to Eur. Phys. J. C]

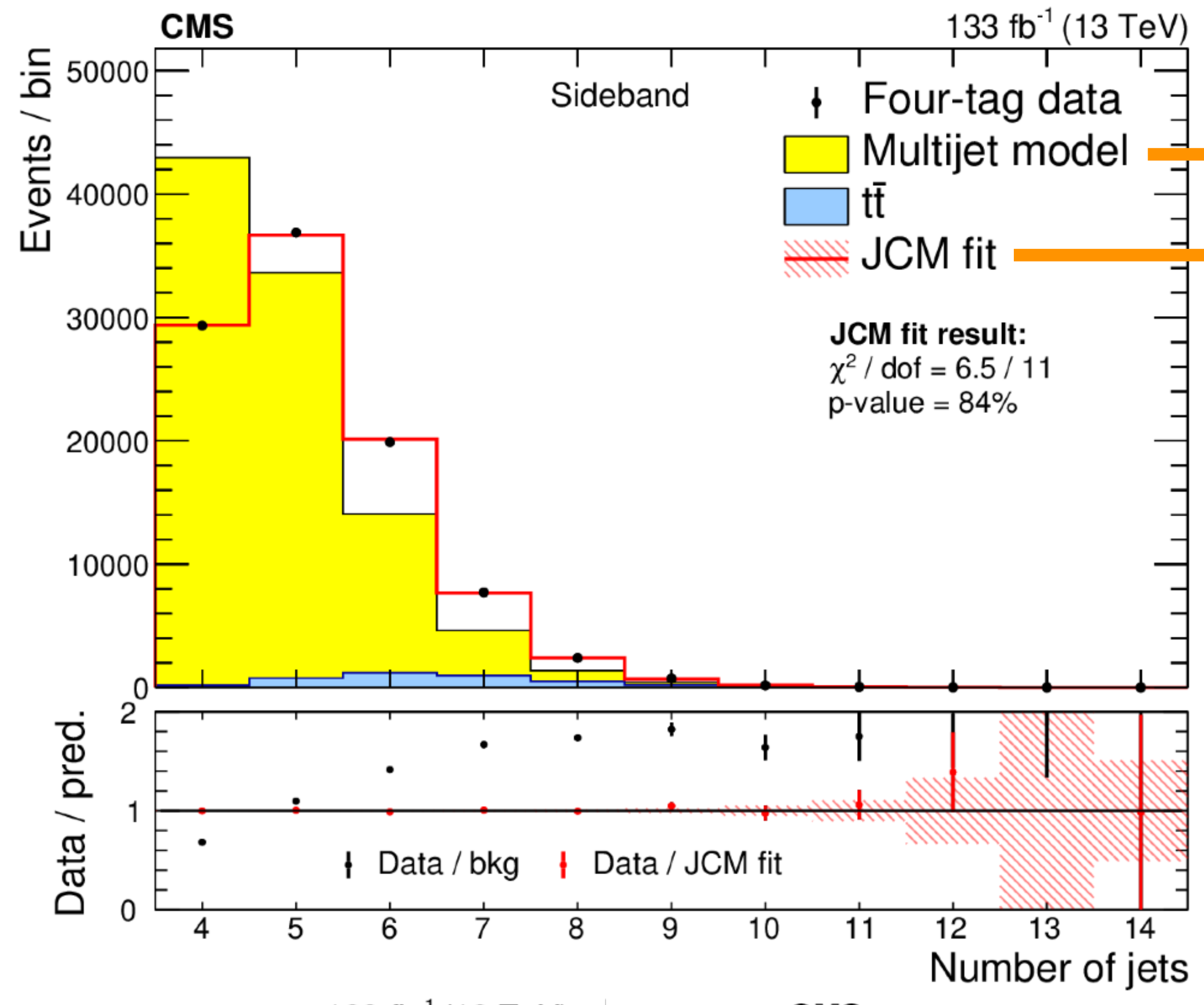
ZZ/ZH→4b (CMS)

- Search for ZZ/ZH production in the 4b final state as a **validation of HH→4b**
  - Background modelling in 3 b-tagged jets CR
  - Application to 4 b-tagged jets SR

1. Jet Combinatorial model

4b-tag SR has larger multiplicity than 3b-tag CR

JCM



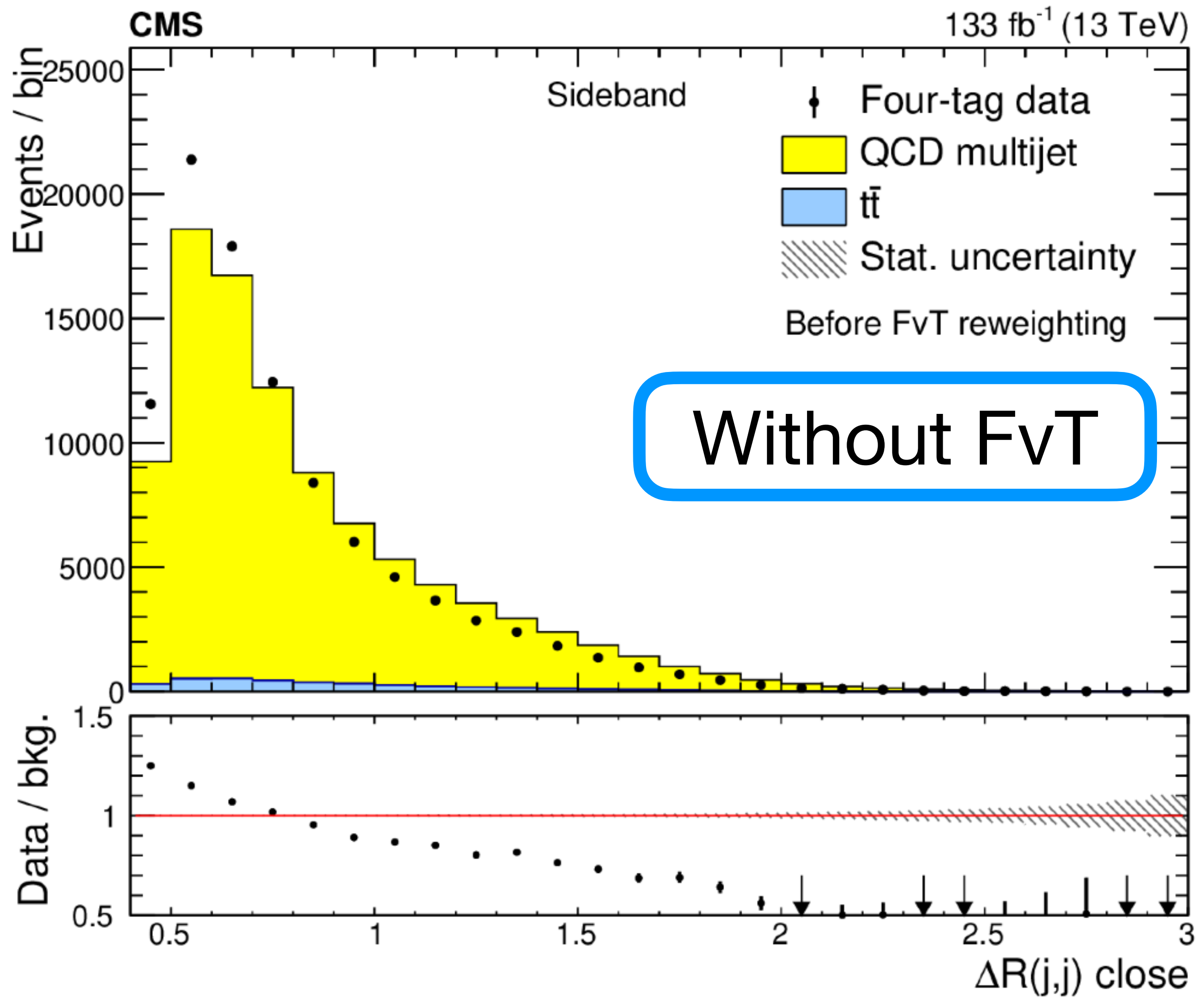
Without JCM

With JCM

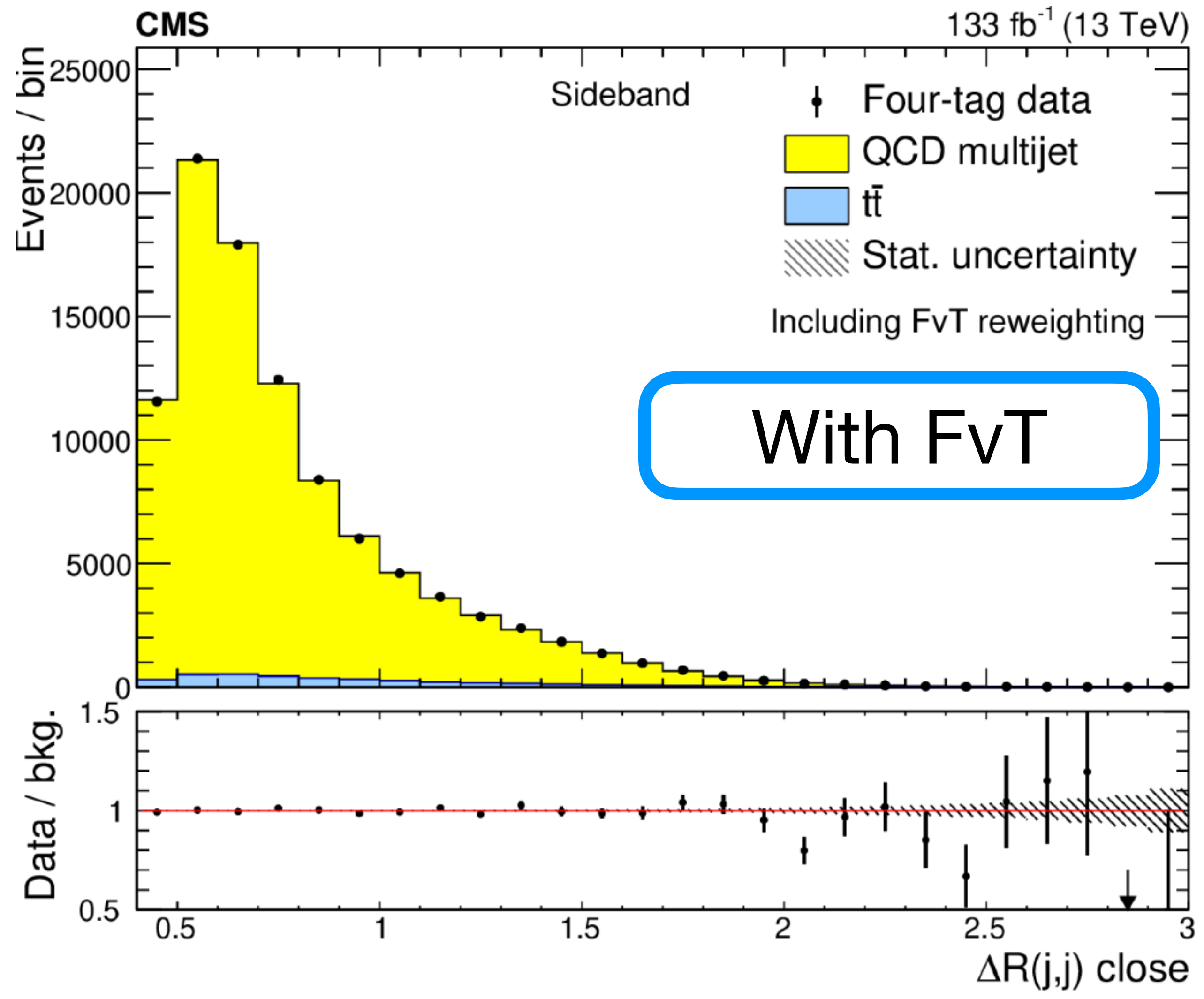
2. Kinematic re-weighting

different kinematic dependence of the b-tagging efficiency

FvT



Without FvT

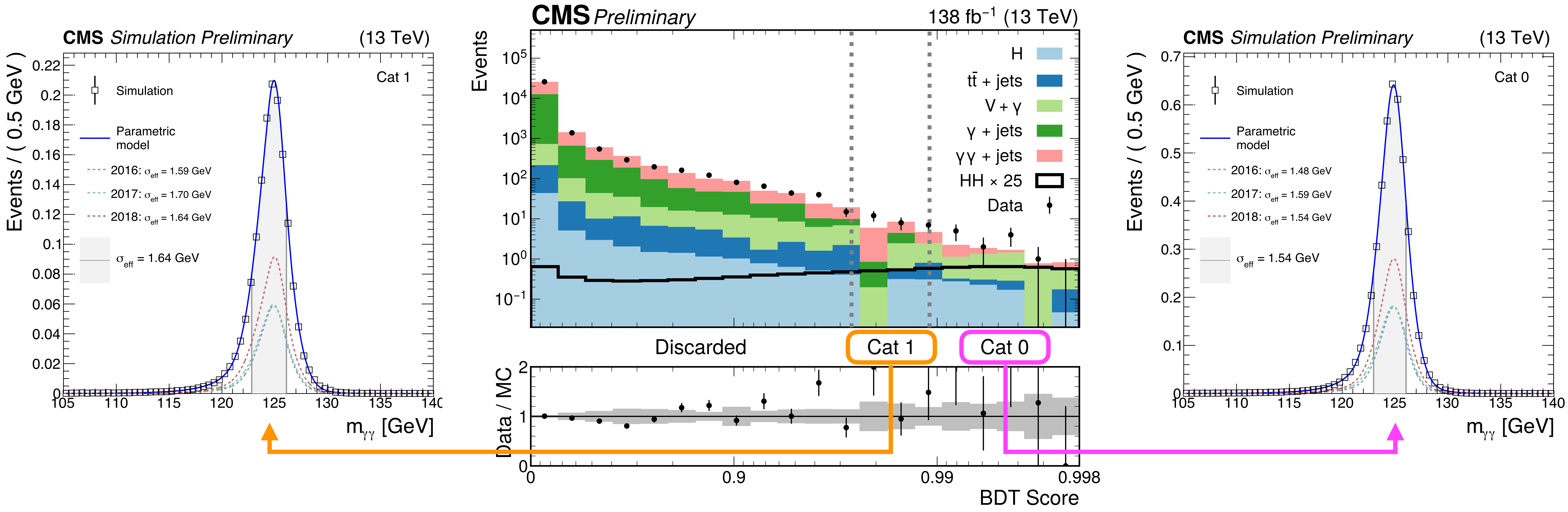


With FvT

Submitted to Eur. Phys. J. C

HH→γγττ (CMS)

- Search for HH production in the γγττ final state, covered for the **first time by CMS**
  - BDT score to define categories with different signal purities: **Cat 0** and **Cat 1**

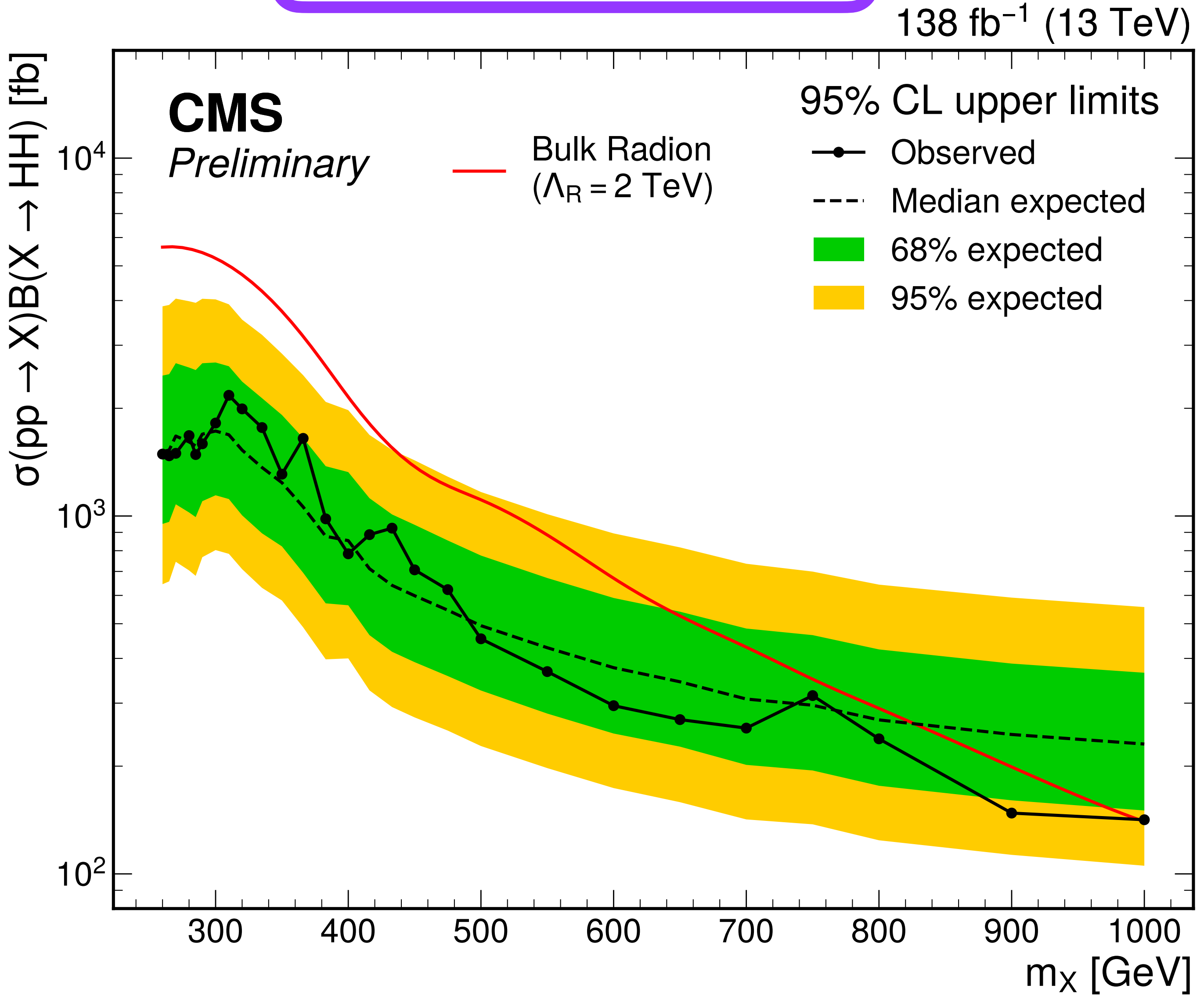


CMS-PAS-HIG-22-012

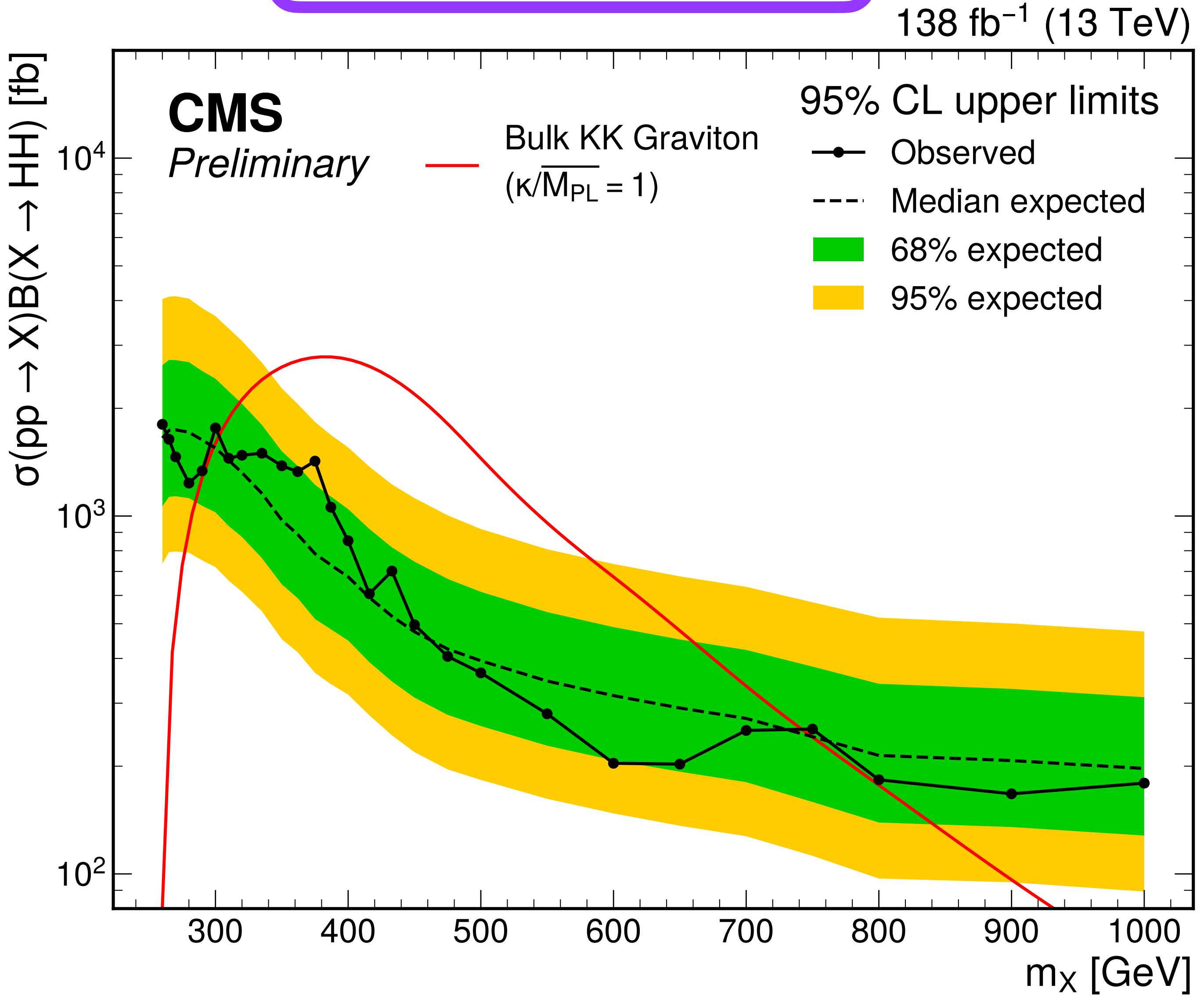
HH→γγττ resonant (CMS)

- Search for HH production in the γγττ final state, covered for the **first time by CMS**: investigation of several resonant hypotheses with Narrow Width Approximation (NWA)
  - Category optimisation to allow good background modelling while keeping high sensitivity on upper limit
  - **X→HH** (Spin-0 and Spin-2)
  - **X→HY** (H→γγ, Y→ττ), (H→ττ, Y→γγ)

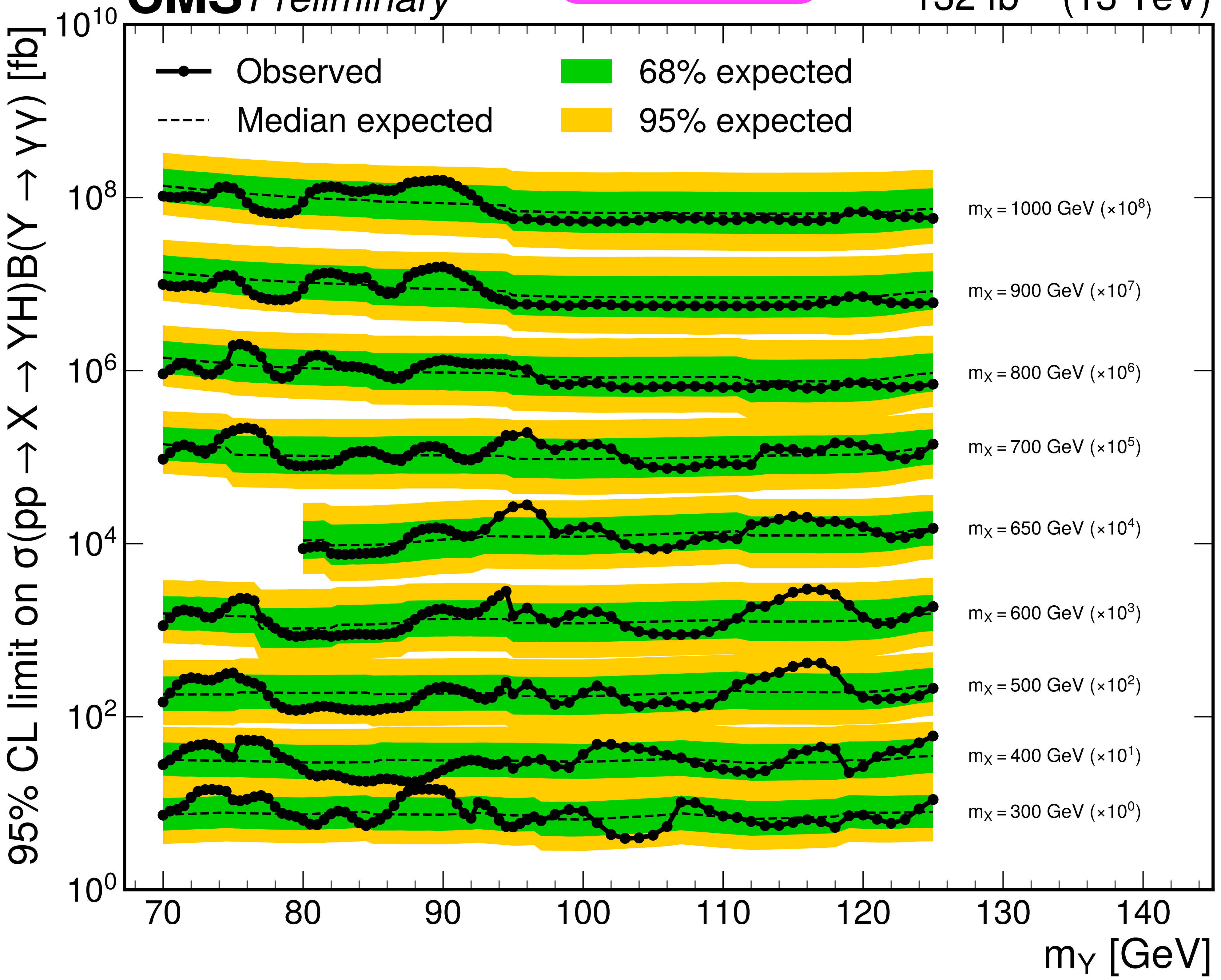
X→HH (Spin 0)



X→HH (Spin 1)



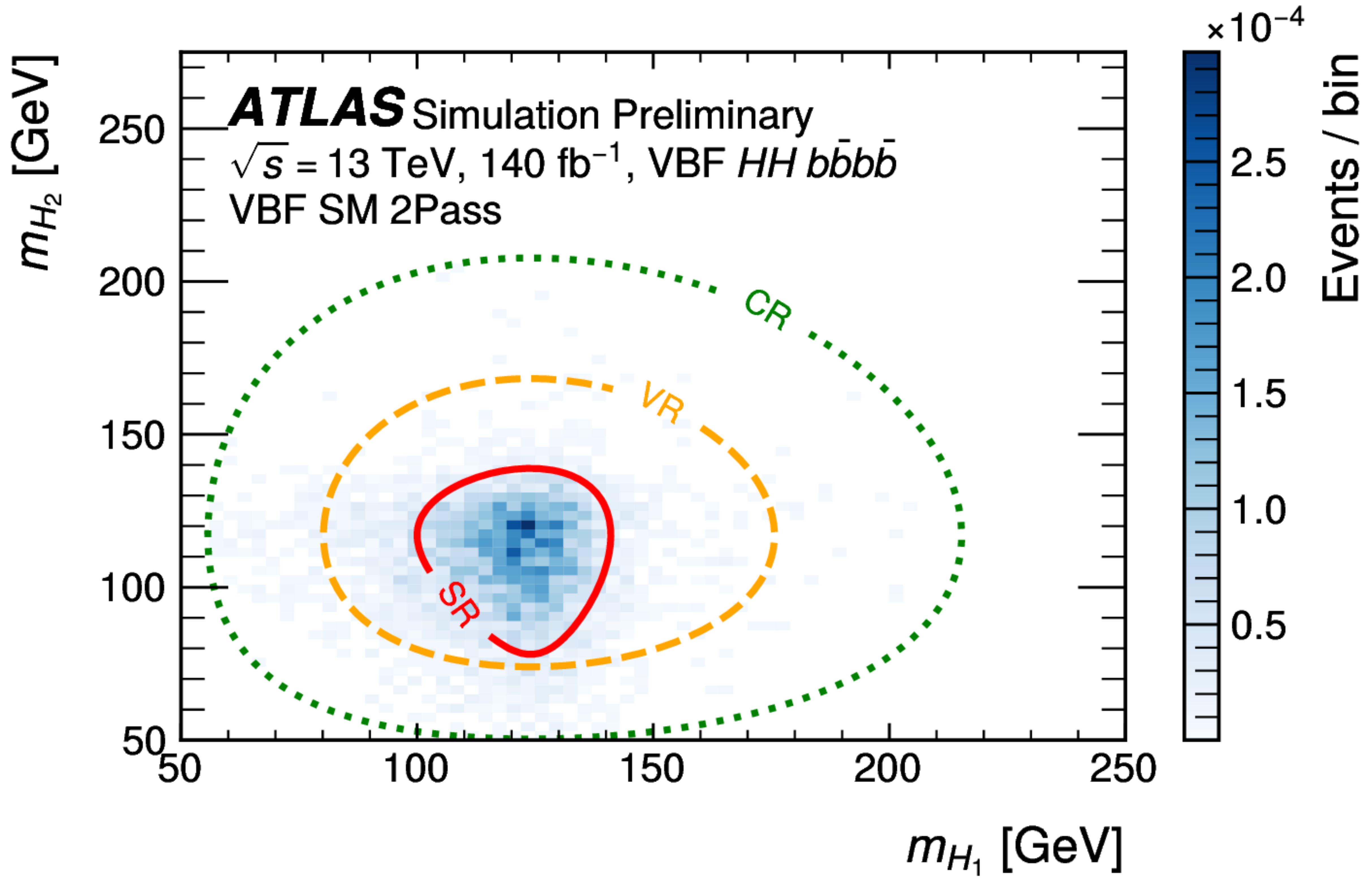
X→HY

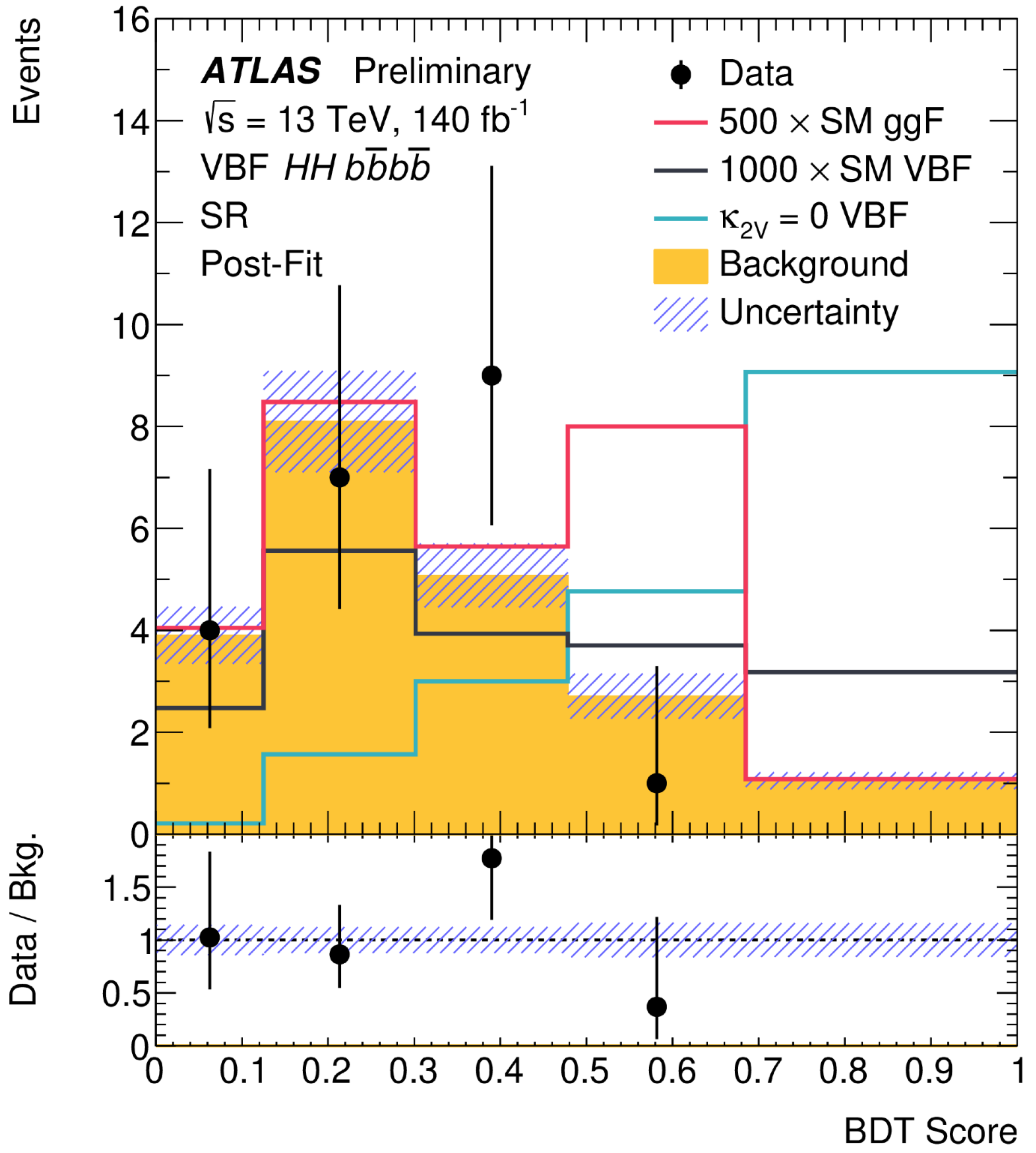


CMS-PAS-HIG-22-012

VBF HH→4b (ATLAS)

- Search for HH production in 4b final state via **ggF** and **VBF** in resolved and boosted regimes
  - Optimization of analysis selection to target VBF category
  - BDT score distribution used for final discriminant



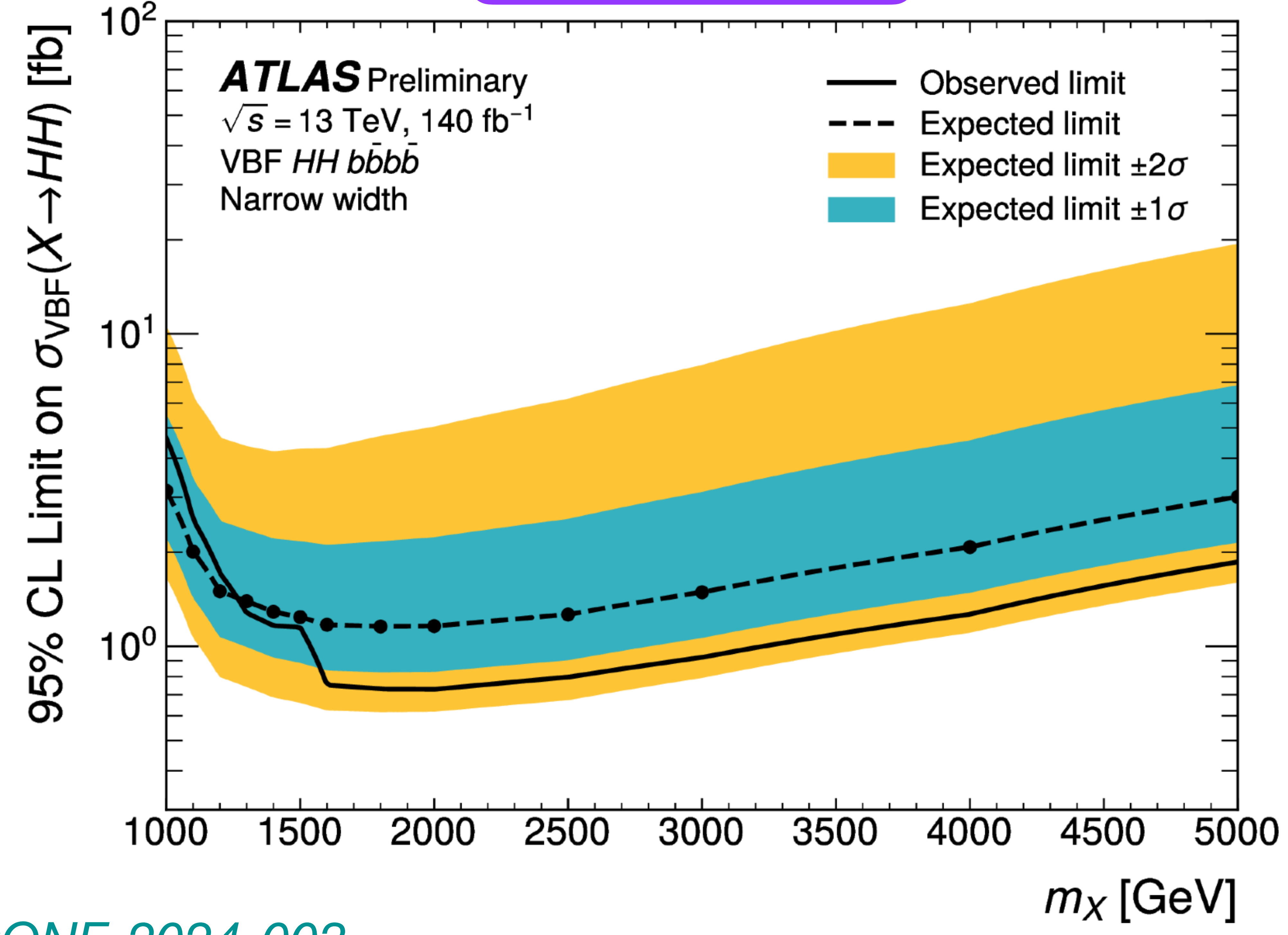


ATLAS-CONF-2024-003

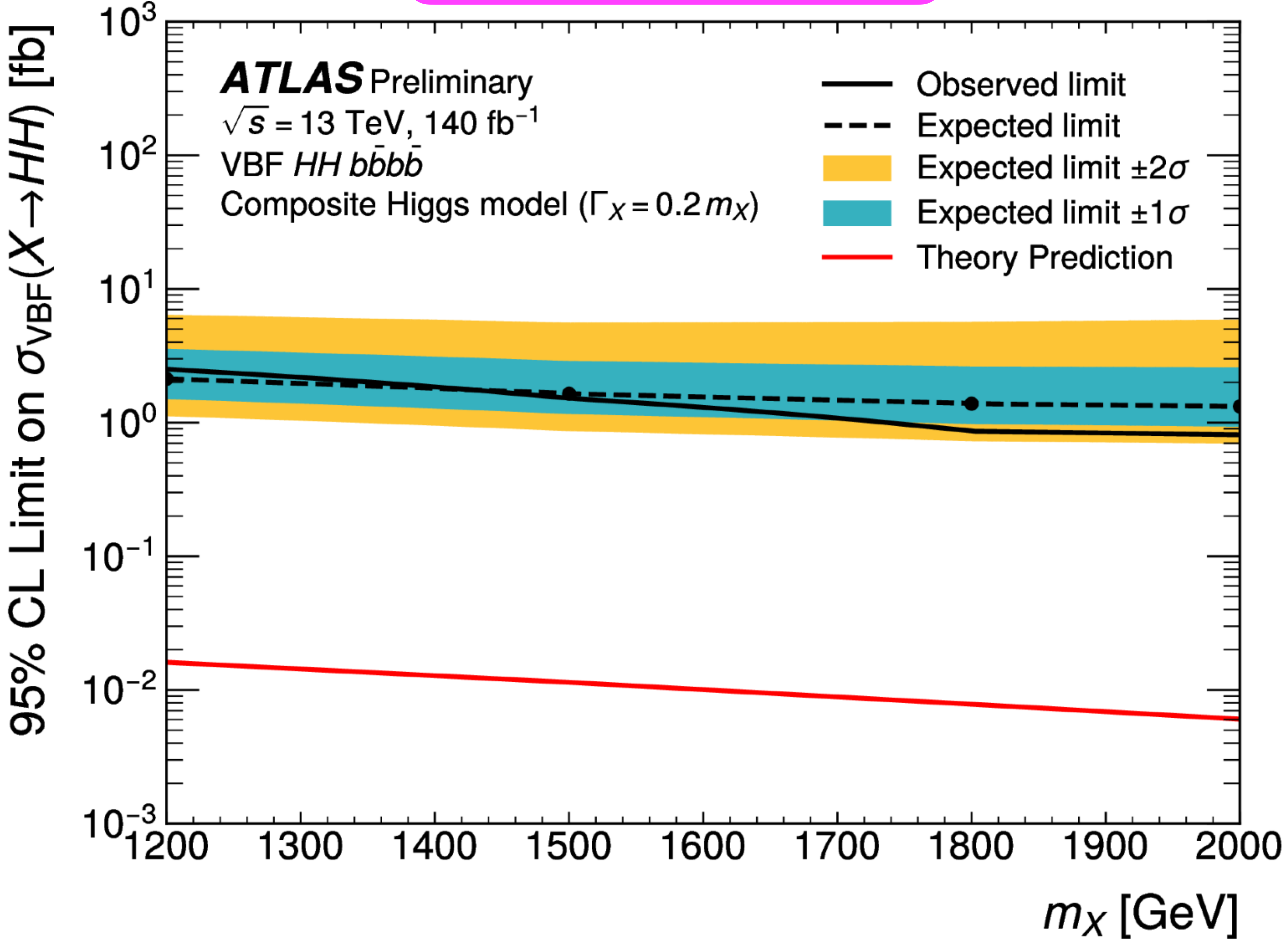
VBF HH→4b resonant (ATLAS)

- Search for HH production in 4b final state via **ggF** and **VBF** in resolved and boosted regimes: investigation of resonant hypotheses with high benefit from boosted regime
  - **Narrow Width Approximation** (NWA)
  - Broad width assumption based on **Composite Higgs Model** (Γ_X = 20% of M_X) → for the first time in HH

NWA X→HH



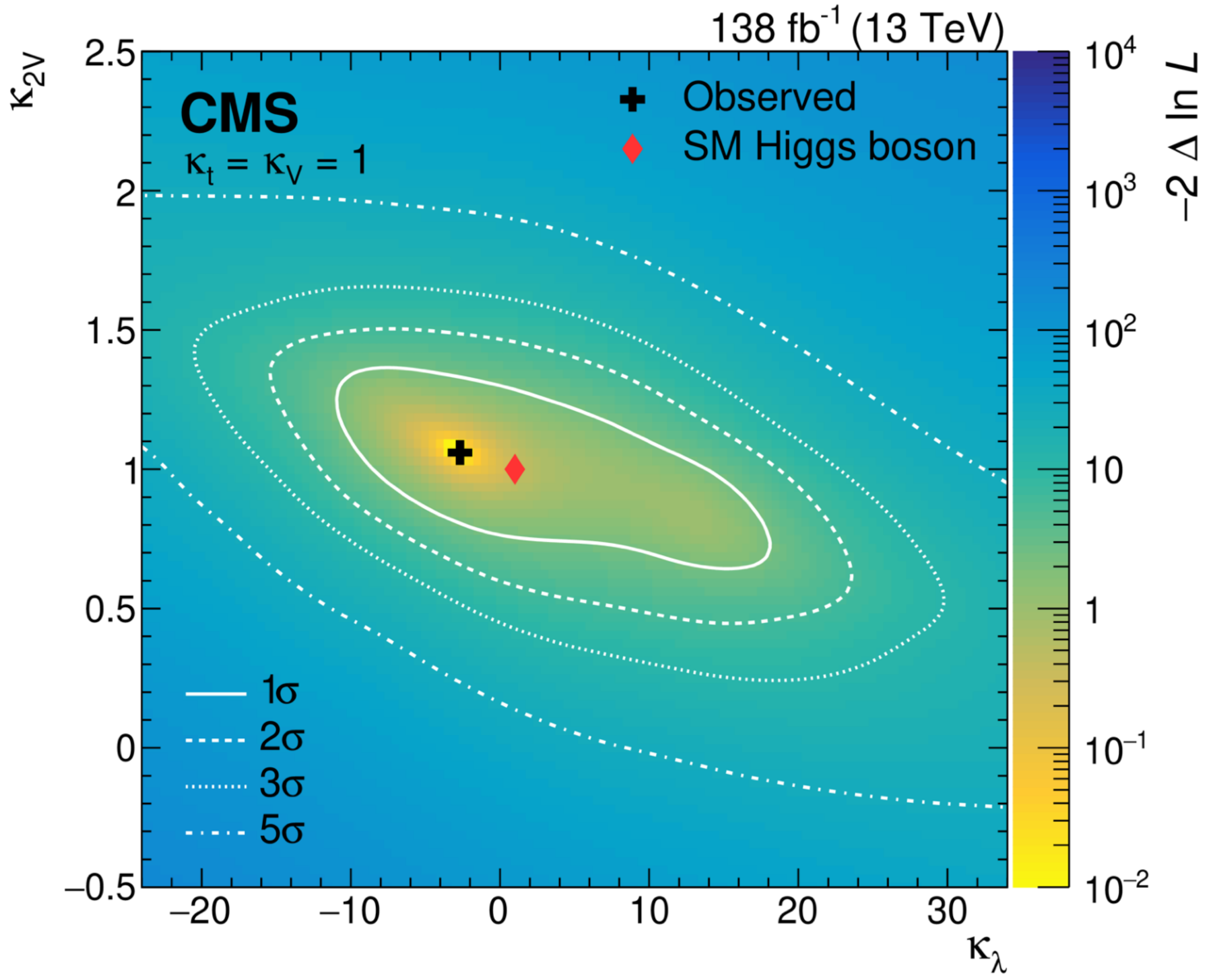
Composite X→HH

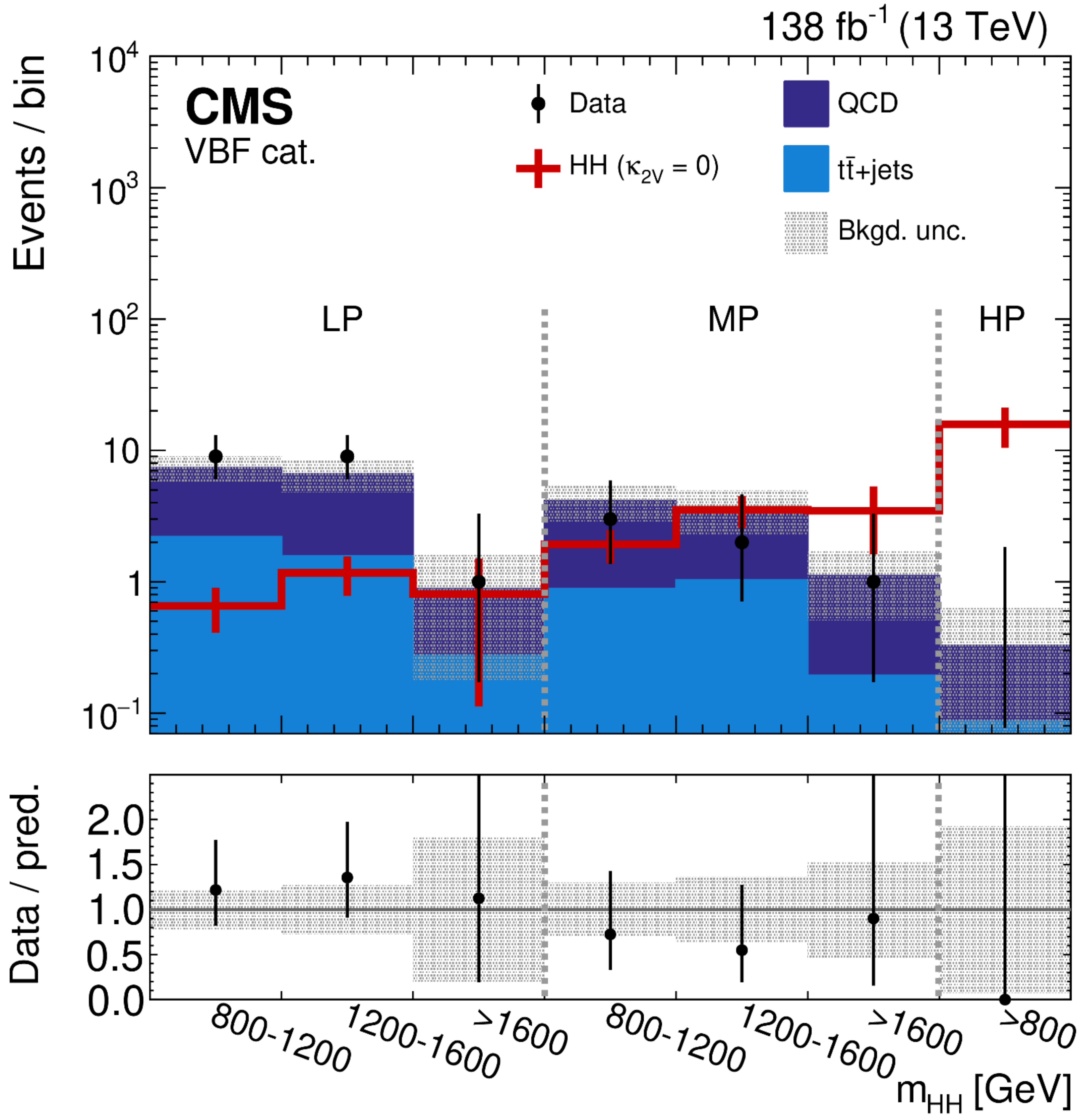


ATLAS-CONF-2024-003

Boosted HH→4b (CMS)

- Search for HH production in 4b final state focused on a phase space region where both Higgs bosons are **highly Lorentz boosted**
  - Final fit performed on m_{HH}, D_{bb}, m_{reg}, and BDT distribution
  - Exclusion of $k_{2V} \neq 0$ when other couplings to SM value





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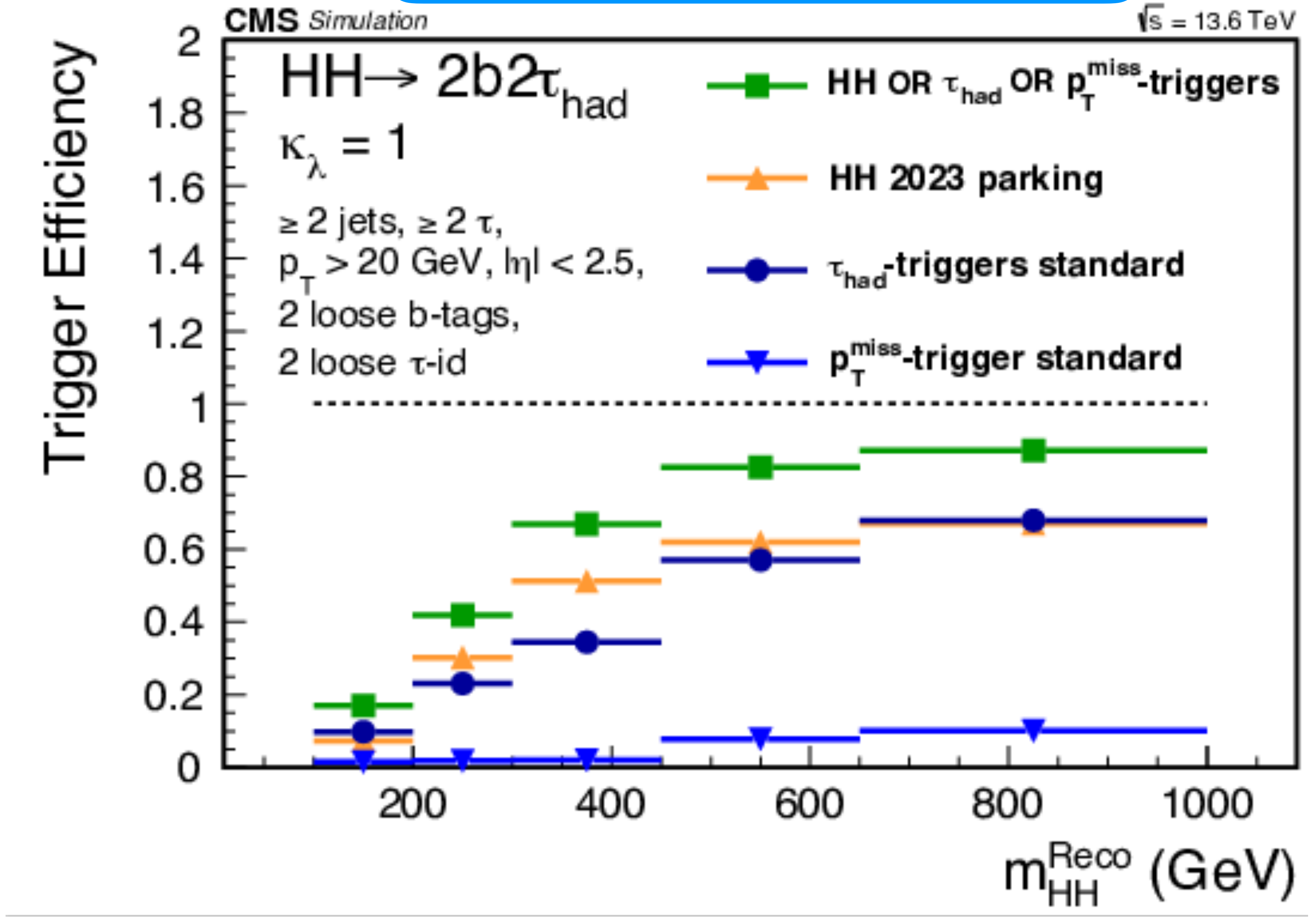
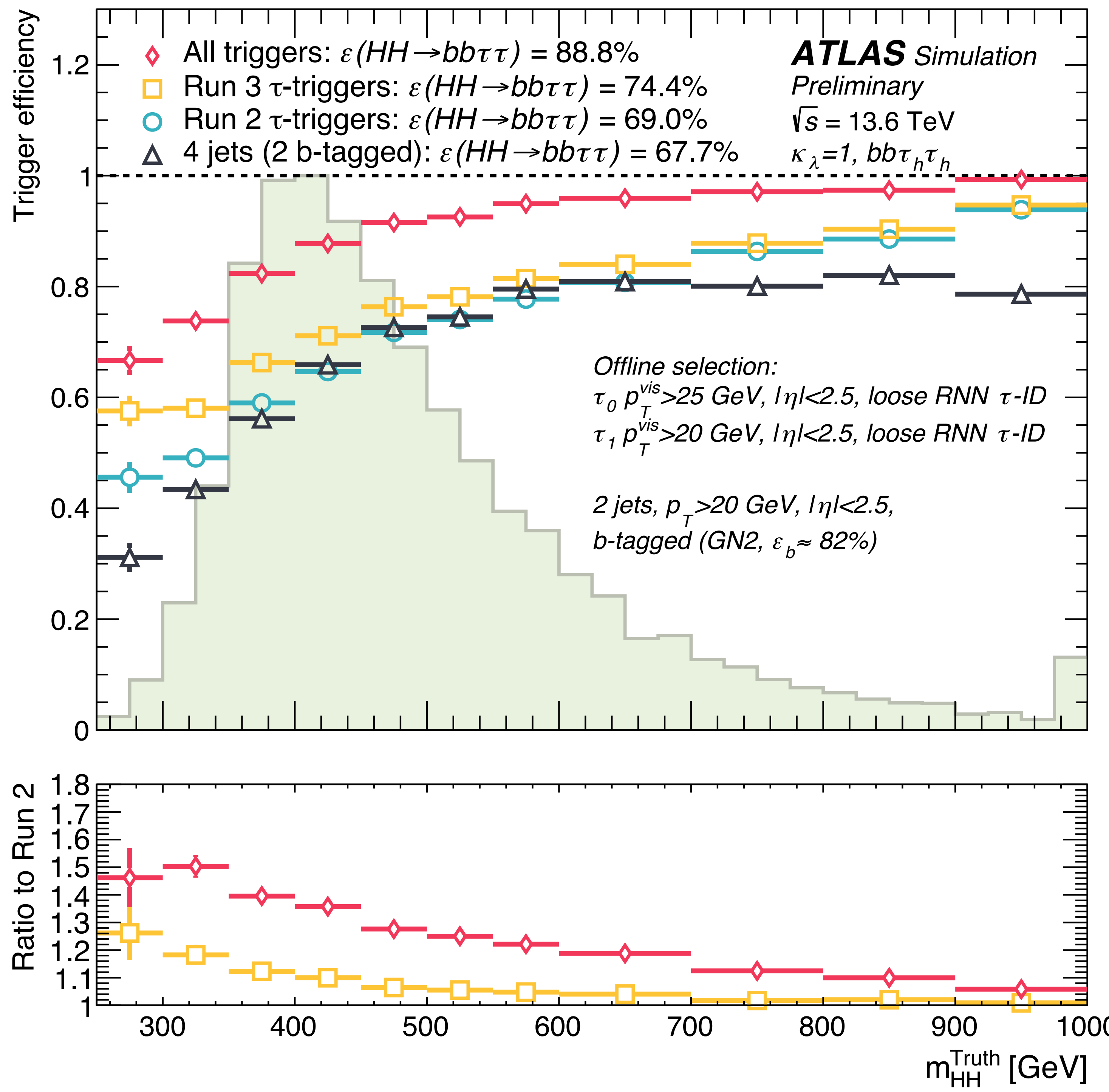
Run 3 and beyond

- Improved Run 3 **trigger strategy** both for ATLAS and CMS
  - HH→4b and HH→bbττ triggers
- Largest **HL-LHC** impact from higher luminosity and upgrades

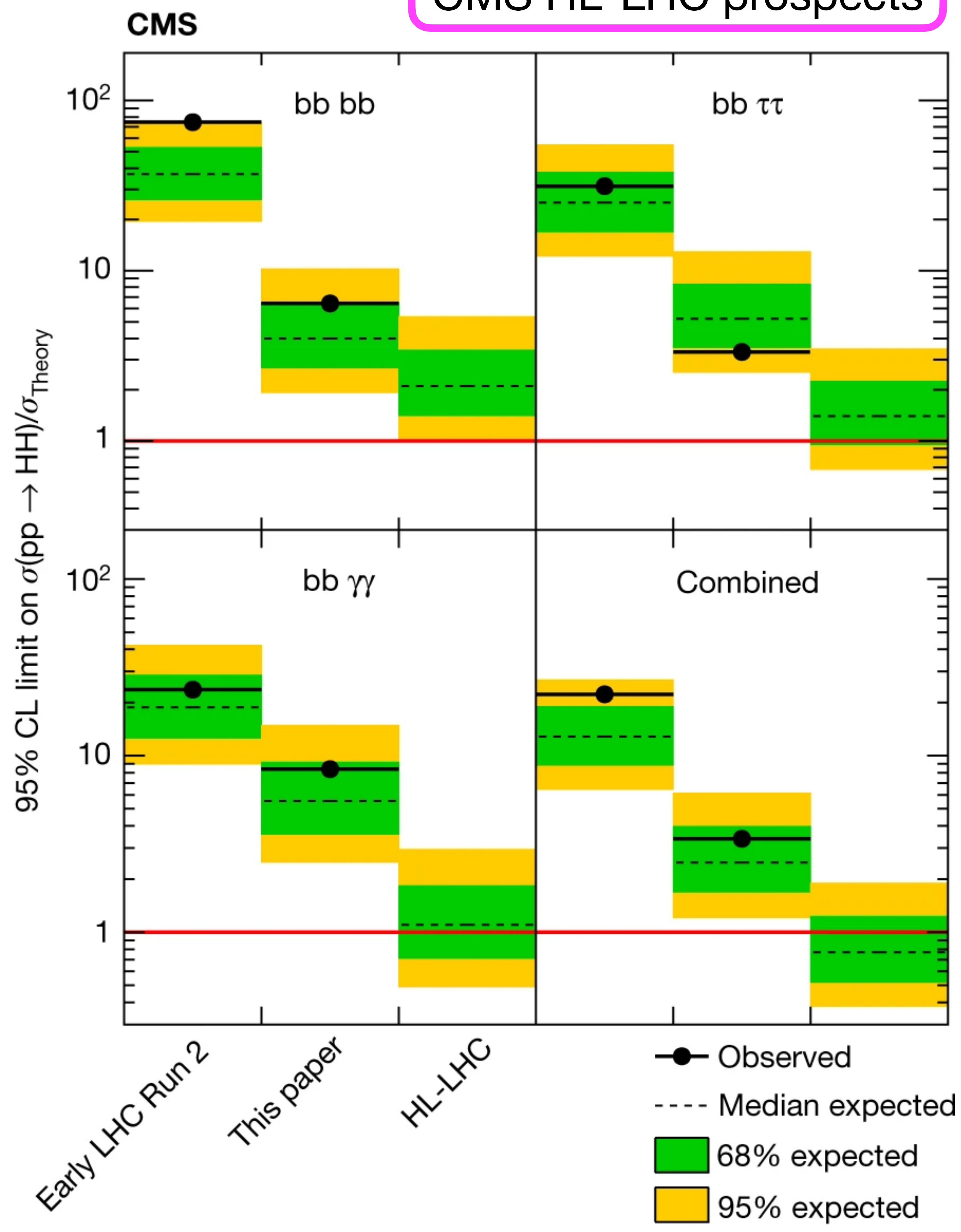
CMS HH→bbττ trigger



ATLAS HH→bbττ trigger



CMS HL-LHC prospects



CMS-DP-2023-050

ATLAS-TauTrigger

Nature 607, 41–47 (2022)