Non-resonant HH searches: status and prospects

Higgs 2023, Nov 27th - Dec 2nd 2023

Marco Valente (on behalf of the ATLAS and CMS collaborations)
Particle Physics department
TRIUMF, Canada's particle accelerator centre
marco.valente@cern.ch

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Non-resonant HH production

- **Two kind** of HH production modes sensitive to **BSM physics:**

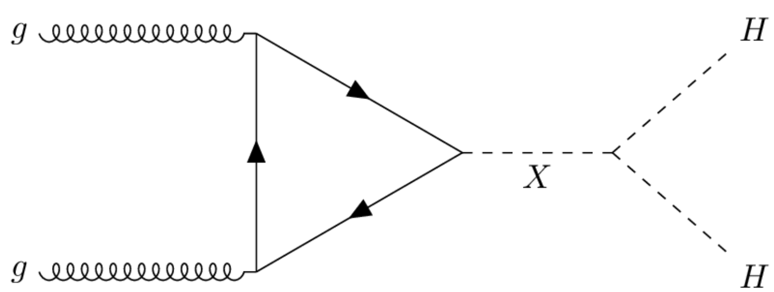
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Non-resonant HH production

- **Two kind** of HH production modes sensitive to **BSM physics:**

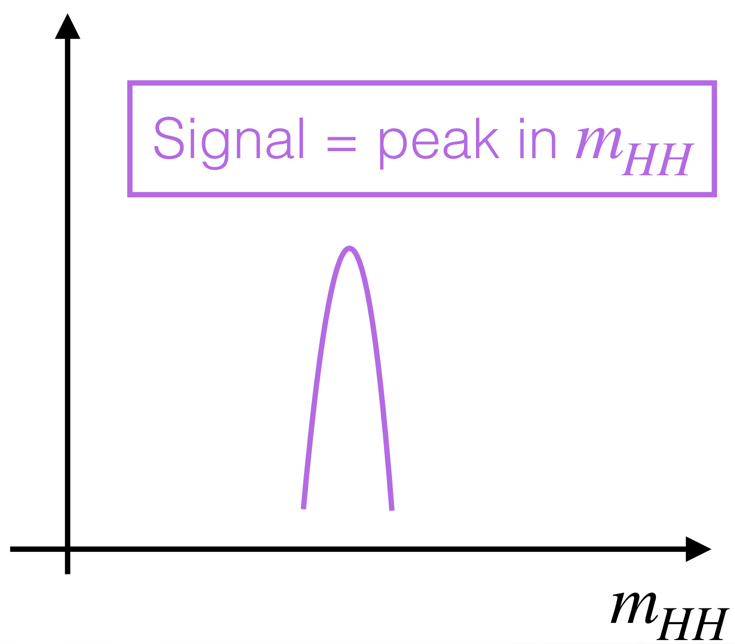
Resonant HH production

- Higgs pair produced from heavy resonance X:



- BSM physics effects parametrized by heavy resonance mass m_X.

Signal = peak in m_{HH}



Covered in next talk by Jan Steggemann!

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Physics department
TRIUMF, Canada's particle accelerator Centre

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Resonant HH production

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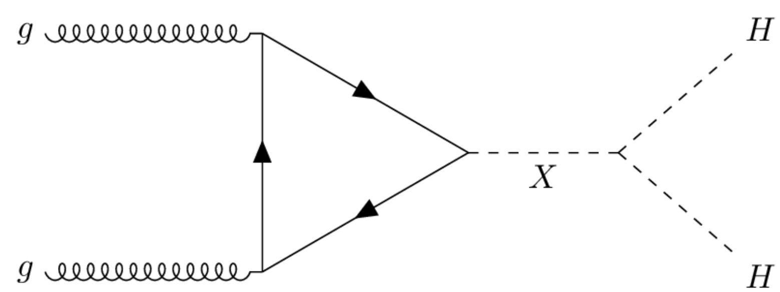

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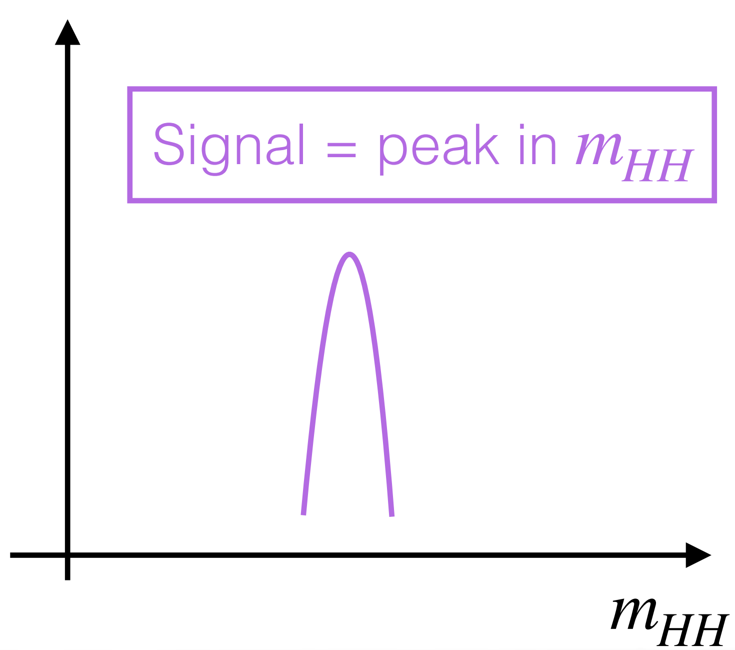

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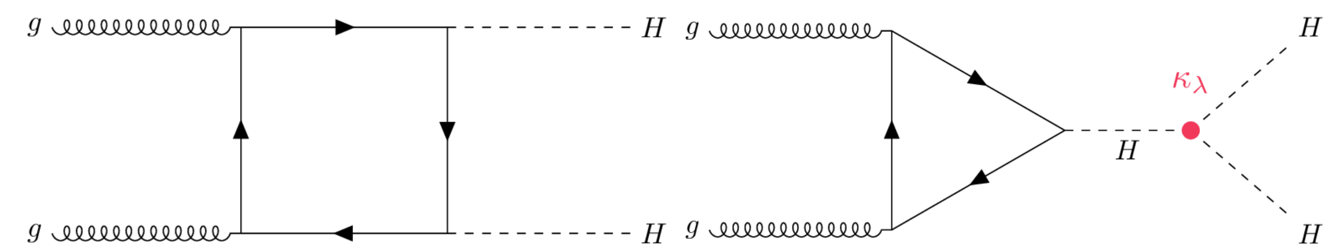
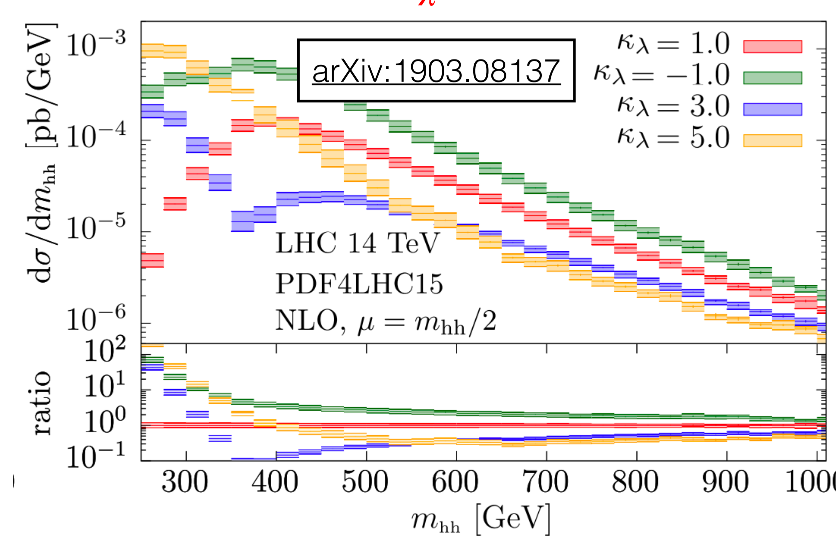
Non-resonant HH production (SM)

Box diagram

Triangle diagram



- Involves diagrams with intermediate "light" SM particles:
  - Very tiny SM cross-section: $\sigma_{\mathrm{ggF}} = 31.05$ fb
  - BSM physics effects parametrized by **coupling modifier κ_λ.**



BSM effects have complex signal kinematic due to diagram interference!

The main focus of this talk!

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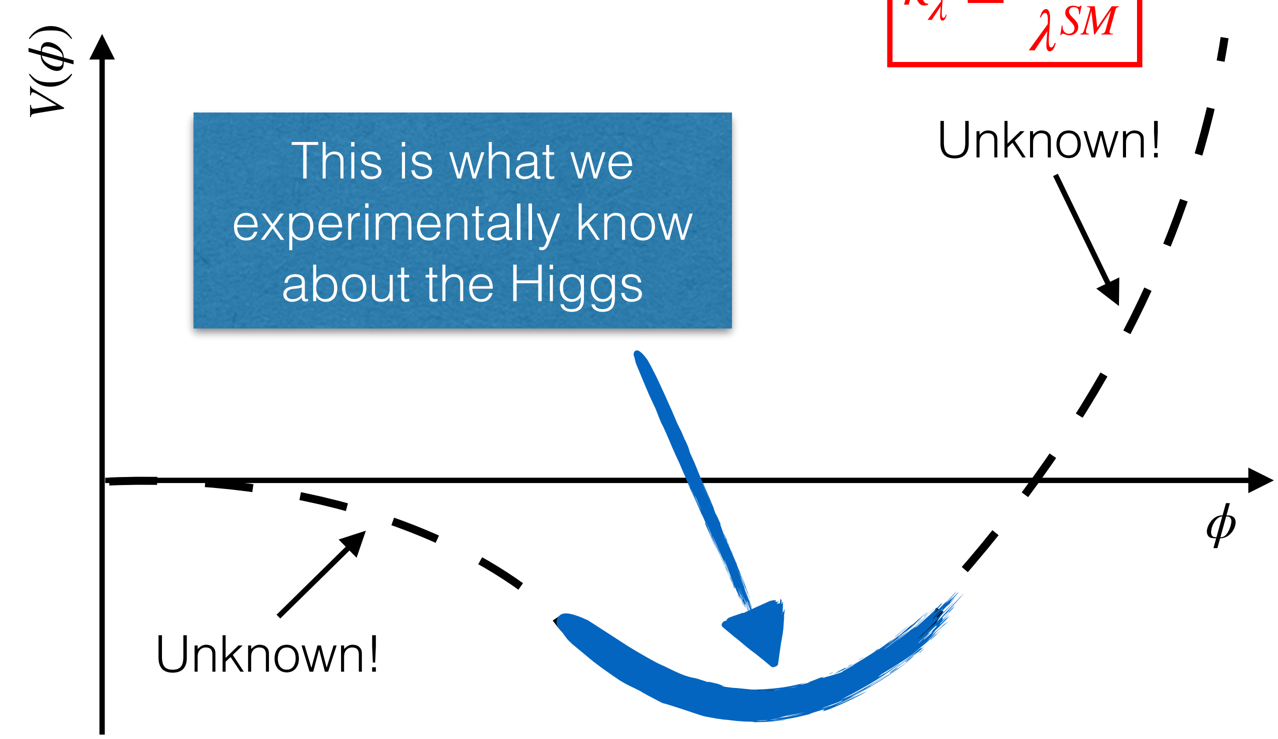
Physics department
TRIUMF, Canada's particle accelerator Centre

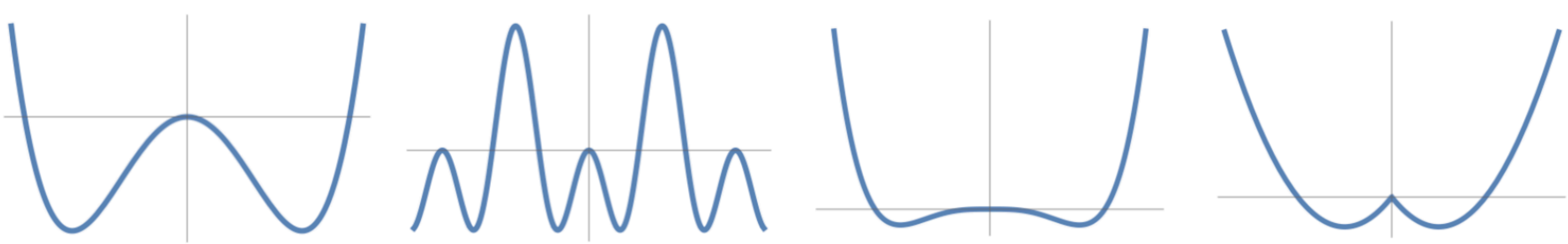
Why is non-resonant HH interesting?

- κ_λ gives **access to the shape of the Higgs potential** via measurement of λ:
  - Many **different potential shapes could have caused the same physics** we see today!
  - **Differences** in the potential shape are **well motivated** by cosmology and BSM theories (more details in other talks).

$$\boxed{V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2}$$

$$\boxed{\kappa_\lambda \equiv \frac{\lambda}{\lambda^{SM}}}$$





Landau-Ginzburg Higgs | **Nambu-Goldstone Higgs** | **Coleman-Weinberg Higgs** | **Tadpole-Induced Higgs**

Phys. Rev. D 101, 075023

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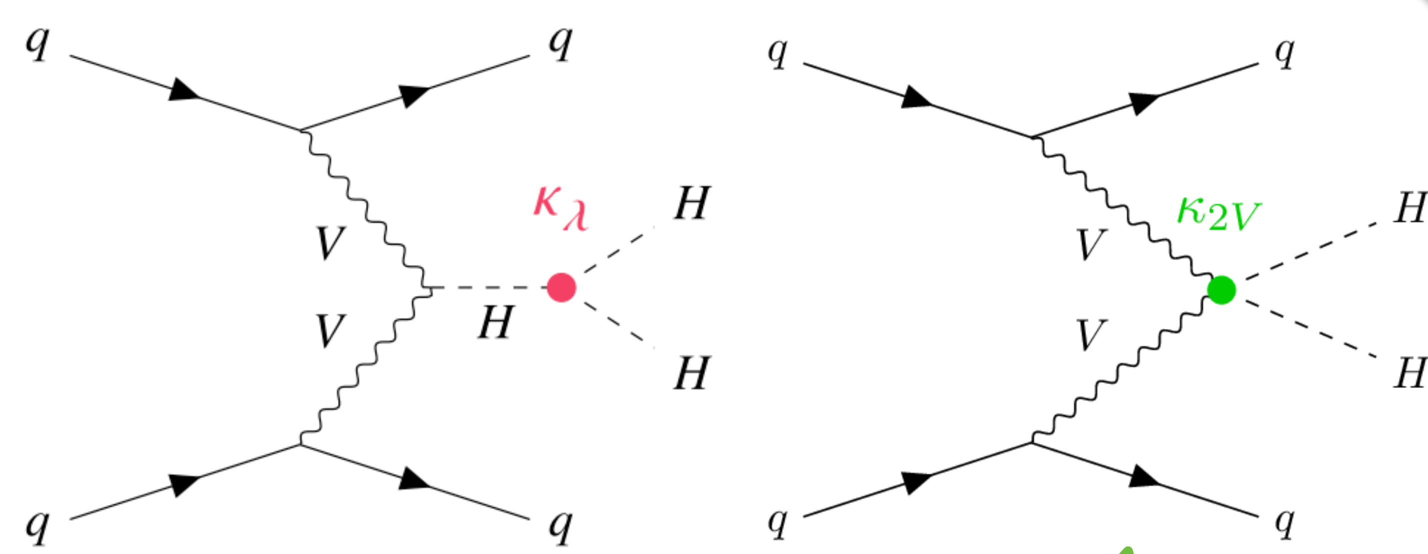
Physics department
TRIUMF, Canada's particle accelerator Centre

Other non-resonant production modes

Vector Boson Fusion, VHH

Vector-boson fusion (VBF)

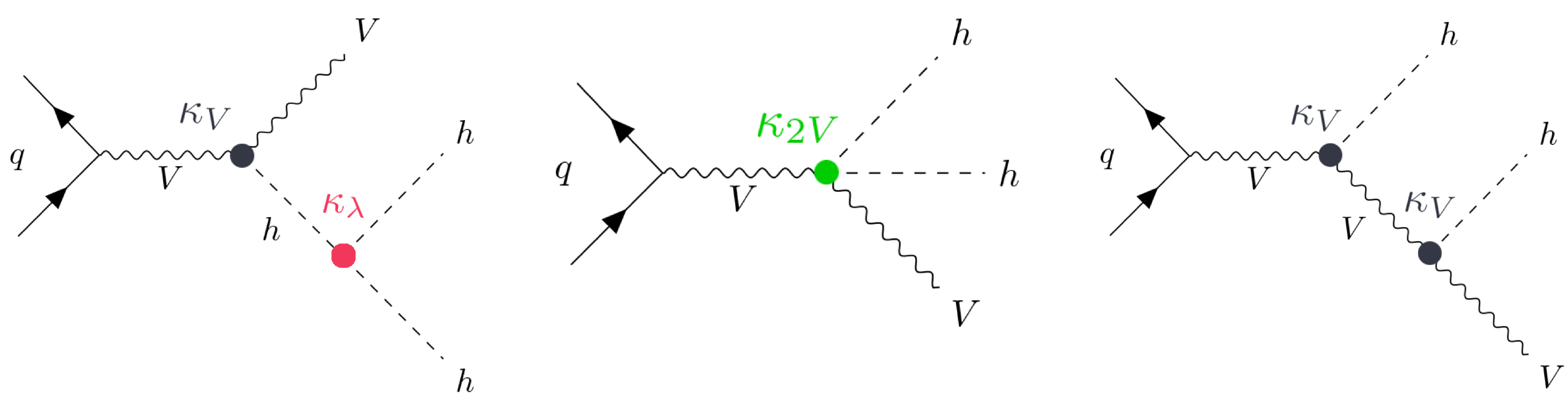
- Signature: 2 Higgs + 2 quarks close to the beamline.
- **Very tiny** cross-section: $\sigma_{\text{VBF}} = 1.72$ fb (20x lower than ggF HH!).
- Interesting because:
    1. Provide **additional sensitivity** to κ_λ (+6% HH signal).
    2. Access also to **VVHH process** (never measured before!) **through** k_{2V} **coupling modifier.**



$$\kappa_{2V} \equiv \frac{c_{2V}}{c_{2V}^{SM}}$$

Association with Vector-boson (VHH)

$\sigma_{VHH} = 0.86$ fb (2x lower than VBF)



So… how do we measure these non-resonant HH processes?

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

HH decays and final states

- For $\sigma^{SM}_{\text{ggF+VBF}} = 32.78$ fb, ATLAS and CMS provided with approximately **9k HH** events ($\mathscr{L}^{\text{ATLAS+CMS}}_{\text{int}} = 280\ \text{fb}^{-1}$).
- **Maximal sensitivity** to these 9k HH events **requires multiple analyses** targeting different HH final states!

Final states covered in this talk

First Higgs decay

Higher BR

Second Higgs decay

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

ATLAS results covered in this talk:

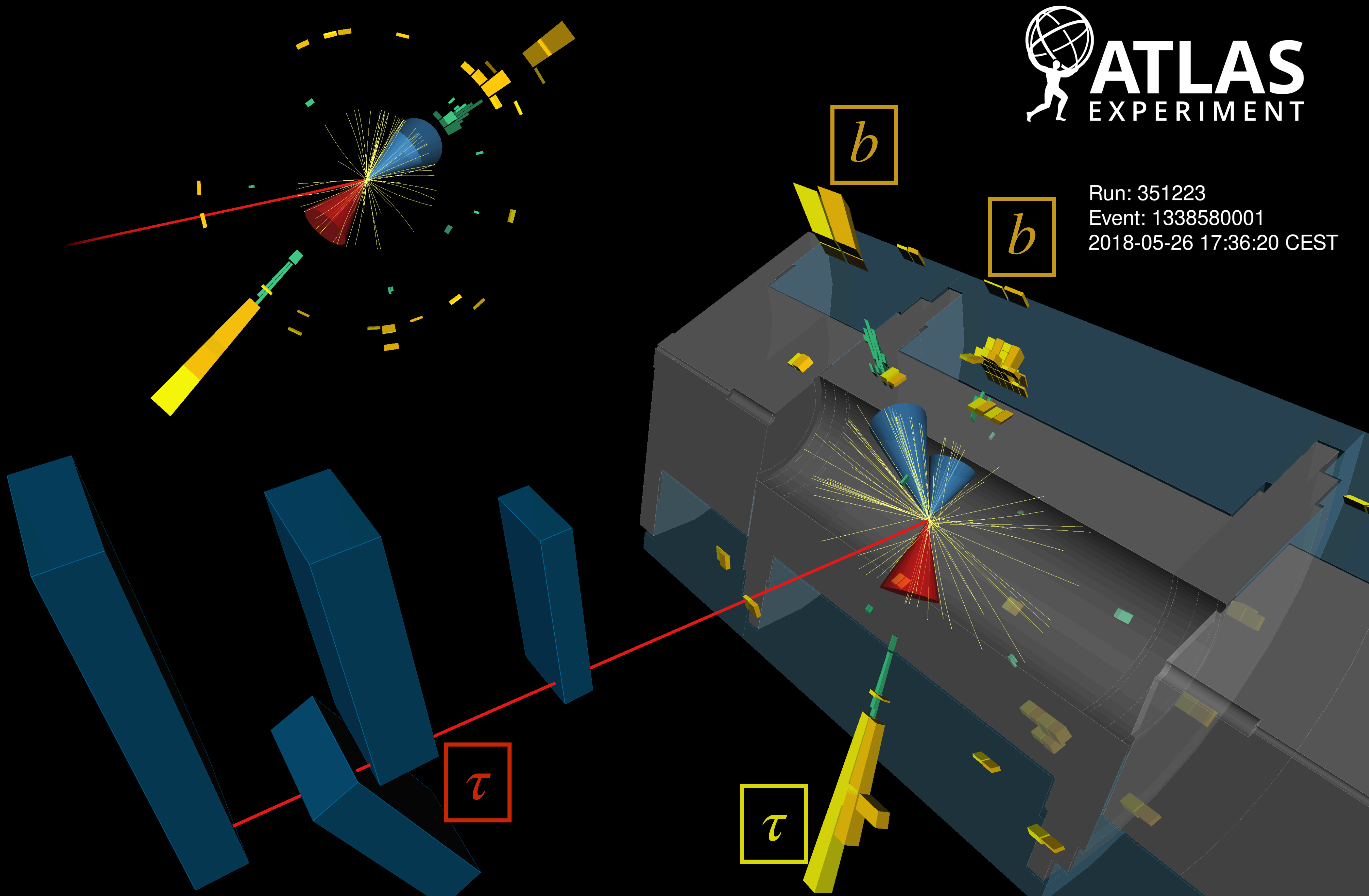
- ATL-CONF-2023-078 ($b\bar{b}\tau\tau$)
- PRD 108 (2023) 052003 ($b\bar{b}b\bar{b}$)
- arXiv:2310.12301 ($b\bar{b}\gamma\gamma$)
- arXiv:2310.11286 ($b\bar{b}l^+l^-$)
- PLB 843 (2023) 137745 (H+HH combinations)
- ATLAS-PHYS-PUB-2022-053 (HL-LHC projections)

CMS results covered in this talk:

- PRL 129, 081802 ($b\bar{b}b\bar{b}$ resolved)
- PRL 131, 041803 ($b\bar{b}b\bar{b}$ boosted)
- PLB 842 (2023) 137531 ($HH \to b\bar{b}\tau\tau$)
- JHEP 03 (2021) 257 ($HH \to b\bar{b}\gamma\gamma$)
- CMS-PAS-HIG-21-005 ($HH \to b\bar{b}WW$)
- Nature 607 (2022) 60 (Combinations)
- CMS-PAS-HIG-23-006 (H+HH)

Additional results (not covered here):
- CMS-PAS-HIG-22-006 CMS VHH(4b)

$$HH \to b\bar{b}\tau^+\tau^-$$



$HH \to b\bar{b}\tau\tau$

ATL-CONF-2023-071

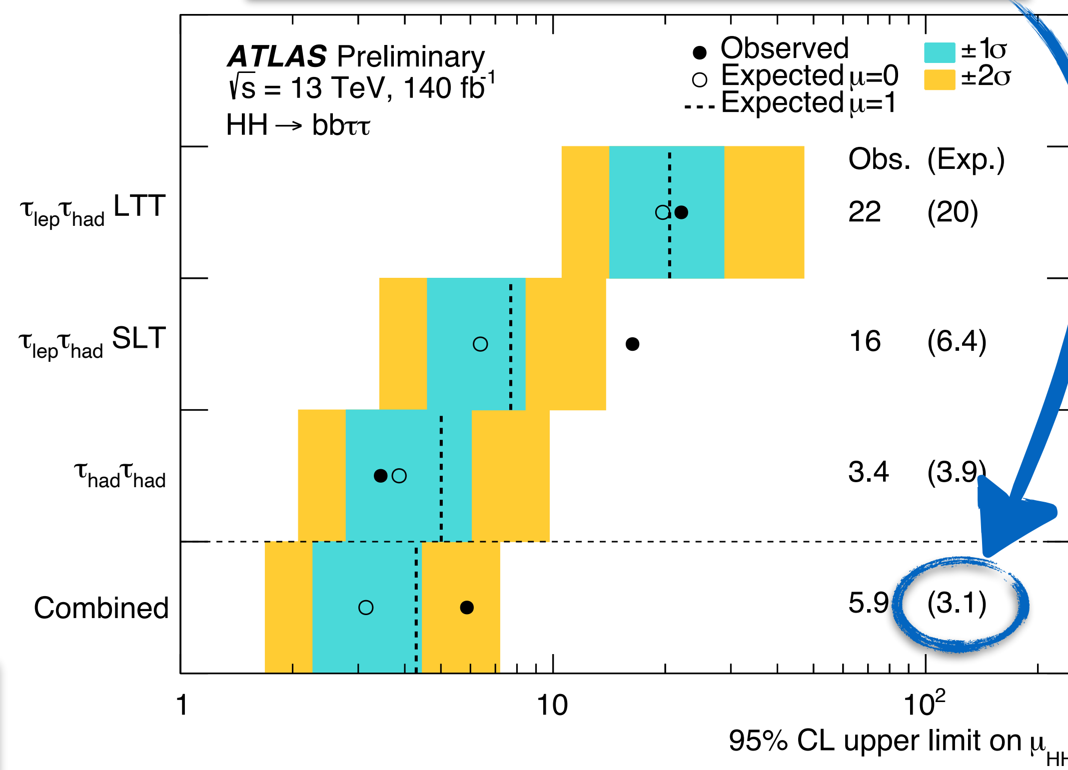
- **Good portion HH BR** (7.3%) with relatively **clean environment** and **low background**.
- Selection: **2 b-jets** (77% DL1r) + **2 τ leptons** ($\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$).
- **9 categories:** 3 split by τ decay mode+trigger, each split in 3 by HH production+kinematic.

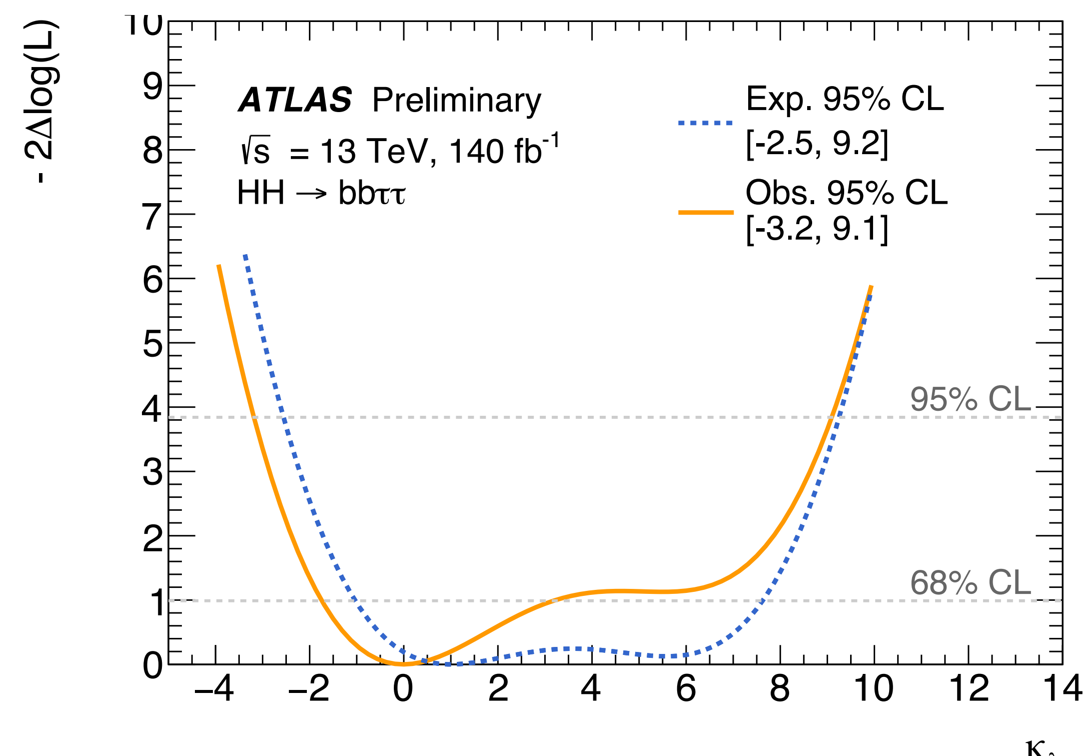
Category	Triggers
$b\bar{b}\tau_{had}\tau_{had}$	Single-tau + di-tau triggers
$b\bar{b}\tau_{lep}\tau_{had}$ SLT	Single lepton trigger (SLT)
$b\bar{b}\tau_{lep}\tau_{had}$ LTT	Lepton+tau trigger (LTT)

$\times$ 3 categories: 1 VBF and 2 ggF (high and low m_{HH})

- Final observation: **simultaneous binned fit of BDT scores in all categories.**
- Latest CMS observed (expected) results [PLB 842 (2023) 137531]:
  - $\mu_{SM}^{95\%CL} = 3.3$ (5.2)
  - $\kappa_\lambda \in [-1.7, 8.7]$ ($[-2.9, 9.8]$)

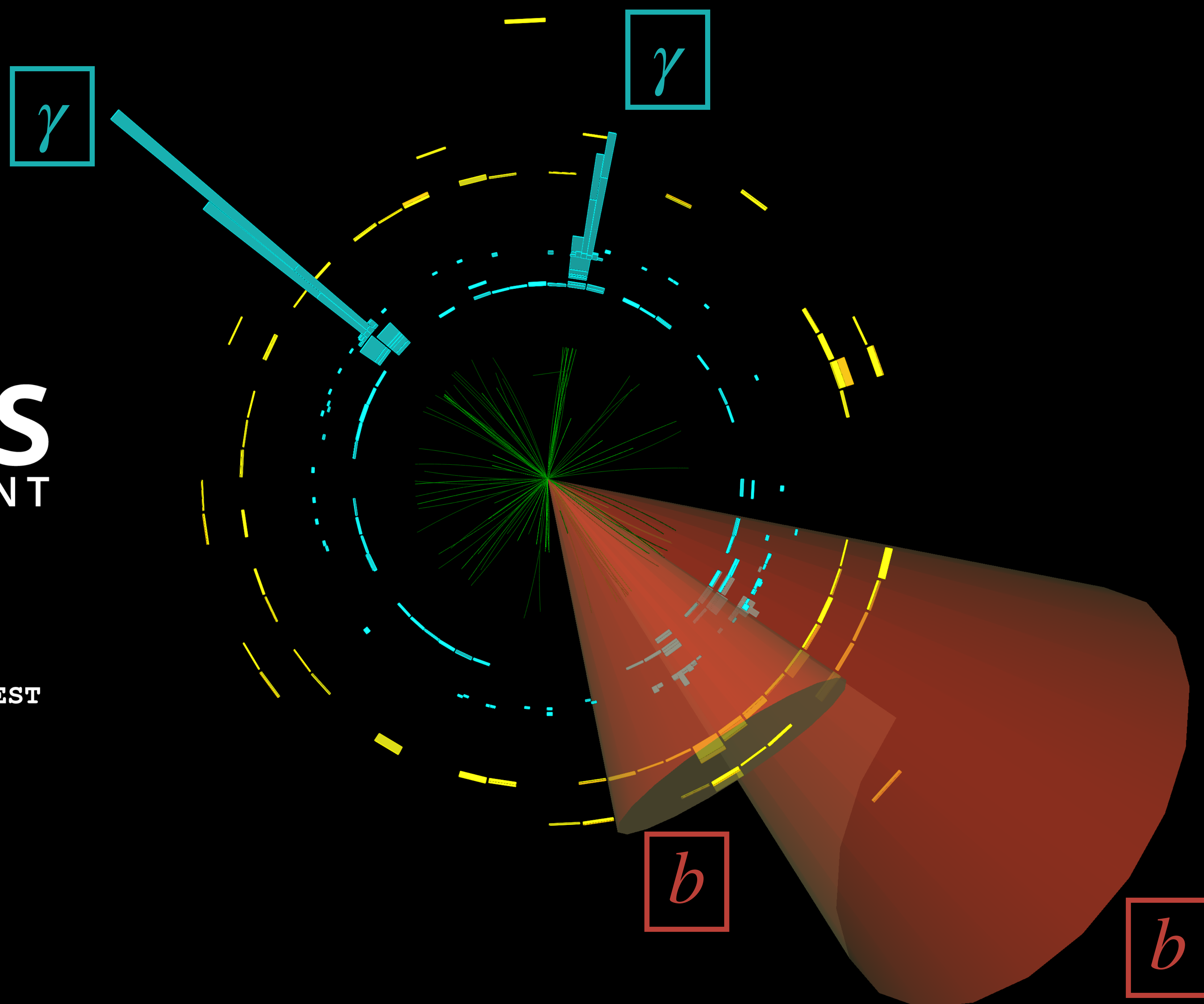
20% with respect to expected limit of previous Run 2 analysis!





Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

$HH \to b\bar{b}\gamma\gamma$



ATLAS EXPERIMENT

Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

$HH \rightarrow b\bar{b}\gamma\gamma$

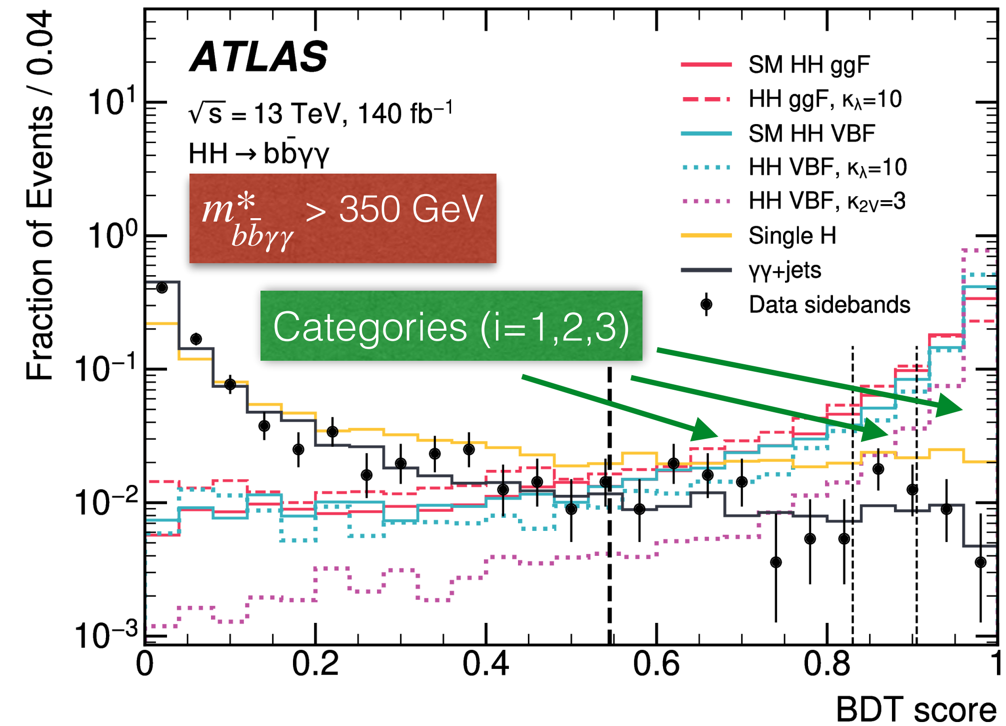
arXiv:2310.12301

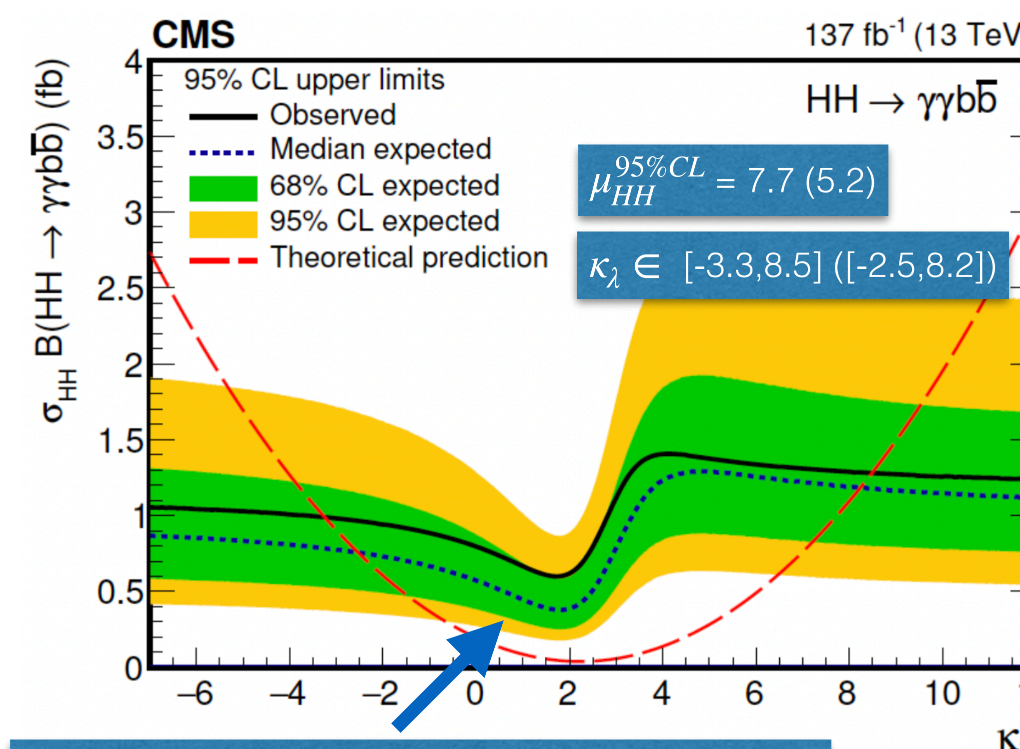
- **Very small BR** (0.26%), but **very clean signature** (excellent acceptance and reconstruction resolution).
- Selection:
  - **2 photons** (tight and isolated) + **2 b-jets** (77% DL1r).
  - **MVA outputs to separate backgrounds** and **signals**.
- **7 Categories:** split in $m^*_{b\bar{b}\gamma\gamma}$ at 350 GeV, and BDT output score.

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250 \text{ GeV}$$

- Final observation: **simultaneous likelihood fit of** $m_{\gamma\gamma}$ in all 7 categories.
- Latest ATLAS observed (expected) results:
  - $\mu^{95\%CL}_{SM} = 4.0$ (5.0)
  - $\kappa_\lambda \in [-1.4, 6.9]$ ($\kappa_\lambda \in [-2.8, 7.8]$)
  - $\kappa_{2V} \in [-0.5, 2.7]$ ($[-1.1, 3.3]$)

-12% from previous Run 2 ATLAS result





Very similar sensitivity to CMS $bb\gamma\gamma$ (JHEP 03 (2021) 257)

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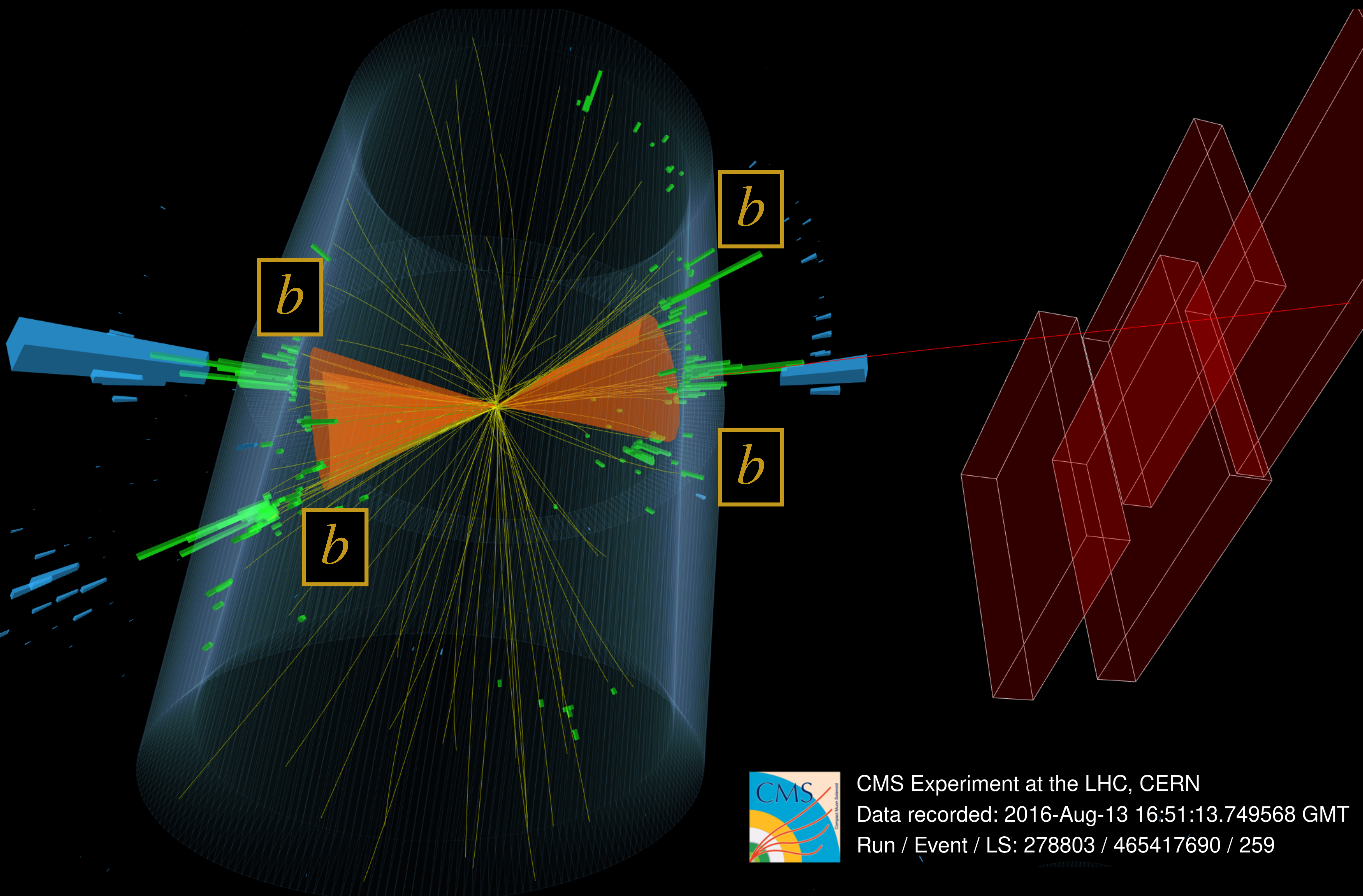
Physics department
TRIUMF, Canada's particle accelerator Centre

$HH \to b\bar{b}b\bar{b}$

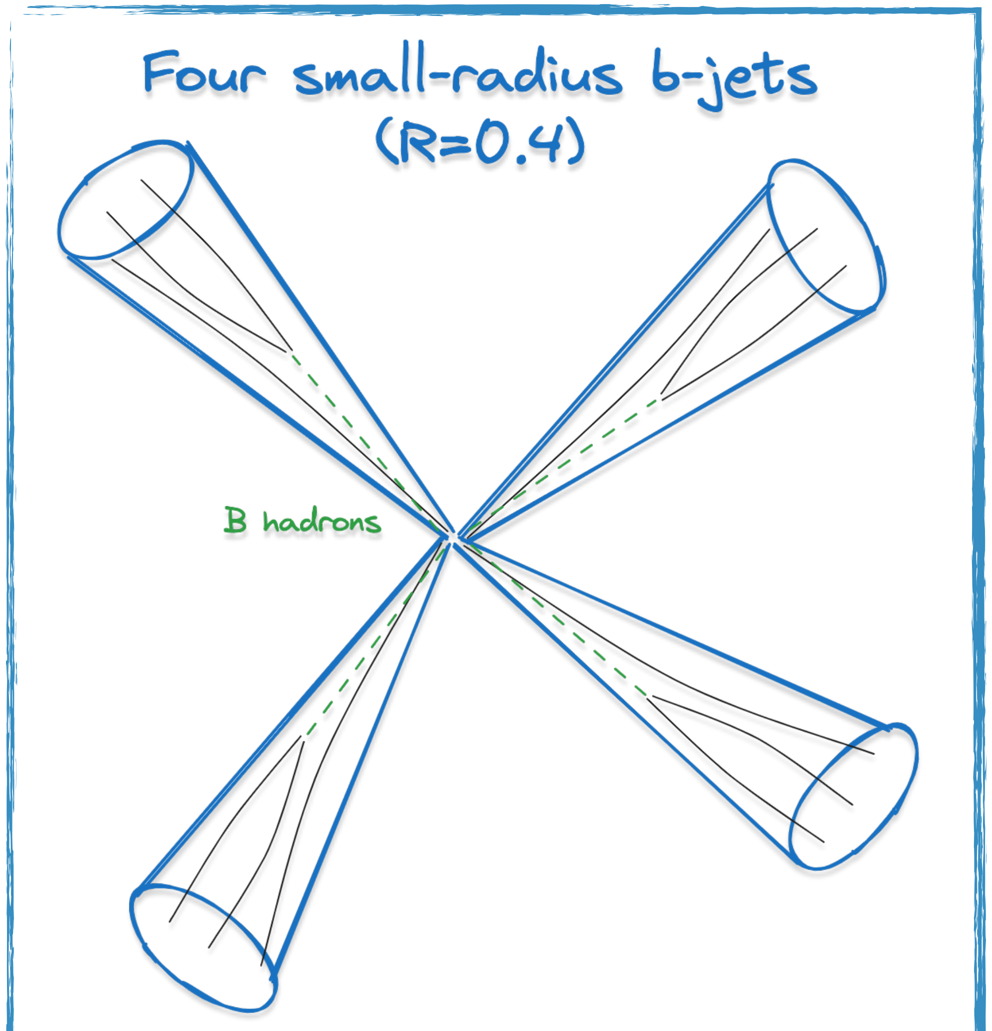


$HH \to b\bar{b}b\bar{b}$ kinematic regimes

Resolved vs boosted

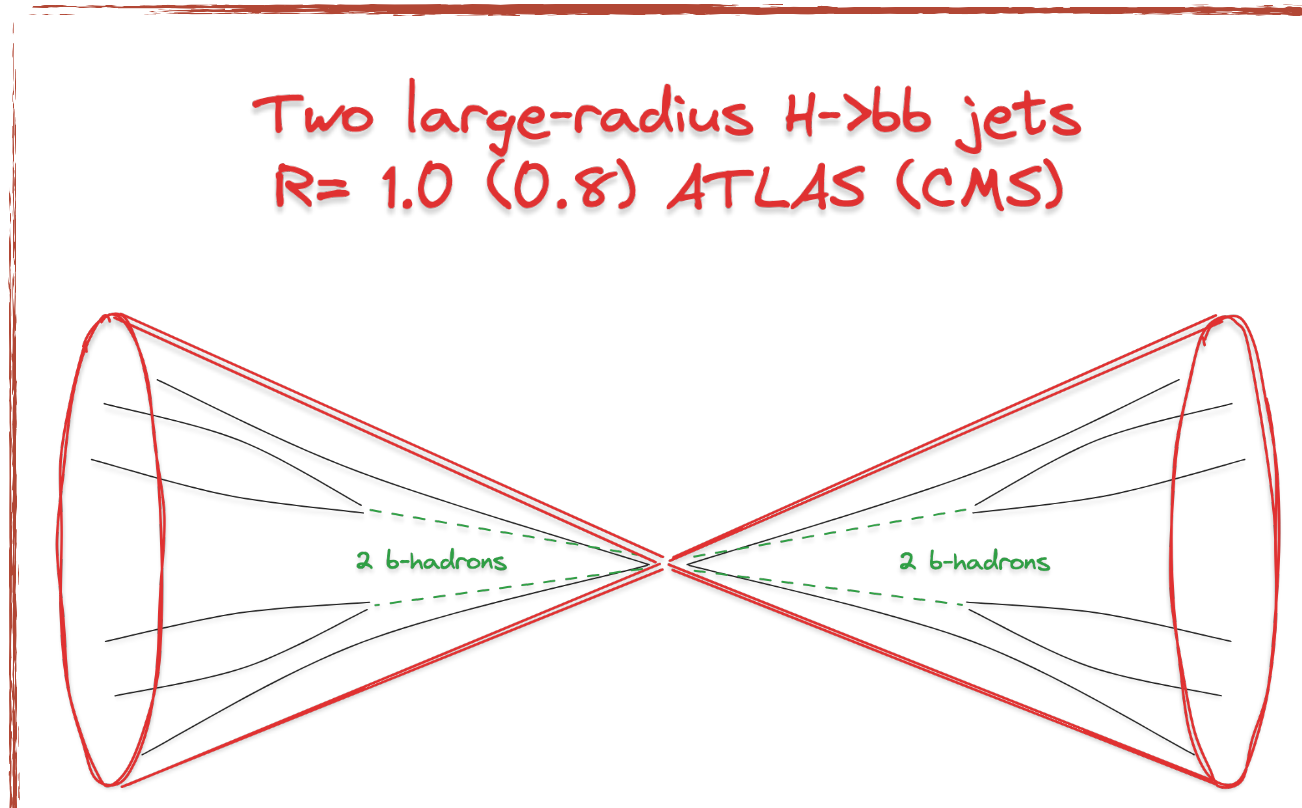
- **Largest signal BR** (33%), but large QCD multi-jet backgrounds.
- Higher statistics **allow to target different kinematic regimes**!

Resolved regime



Explored by **both ATLAS and CMS**

Boosted regime



$$p_T \sim \frac{2m}{R} \geq 250 - 300 \text{ GeV}$$

Explored **by CMS**

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Physics department
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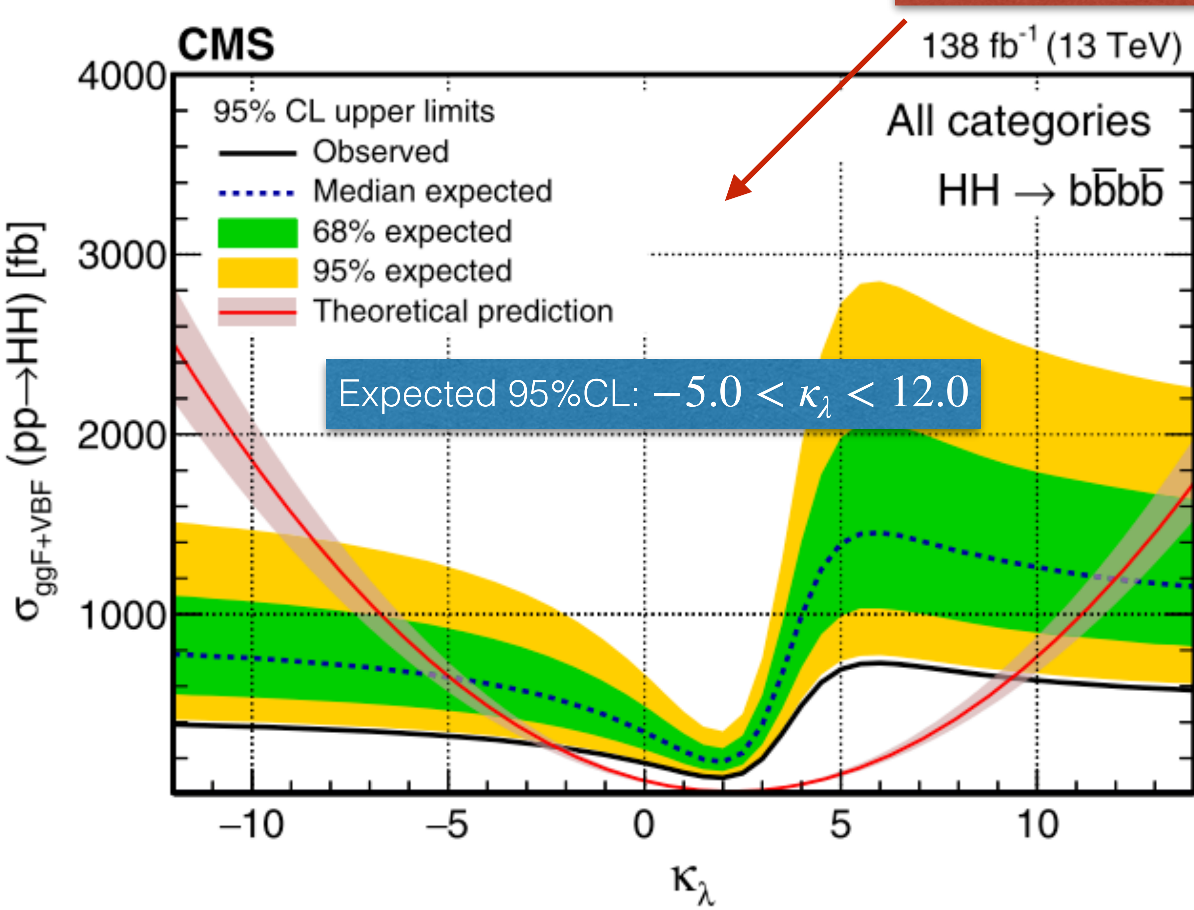
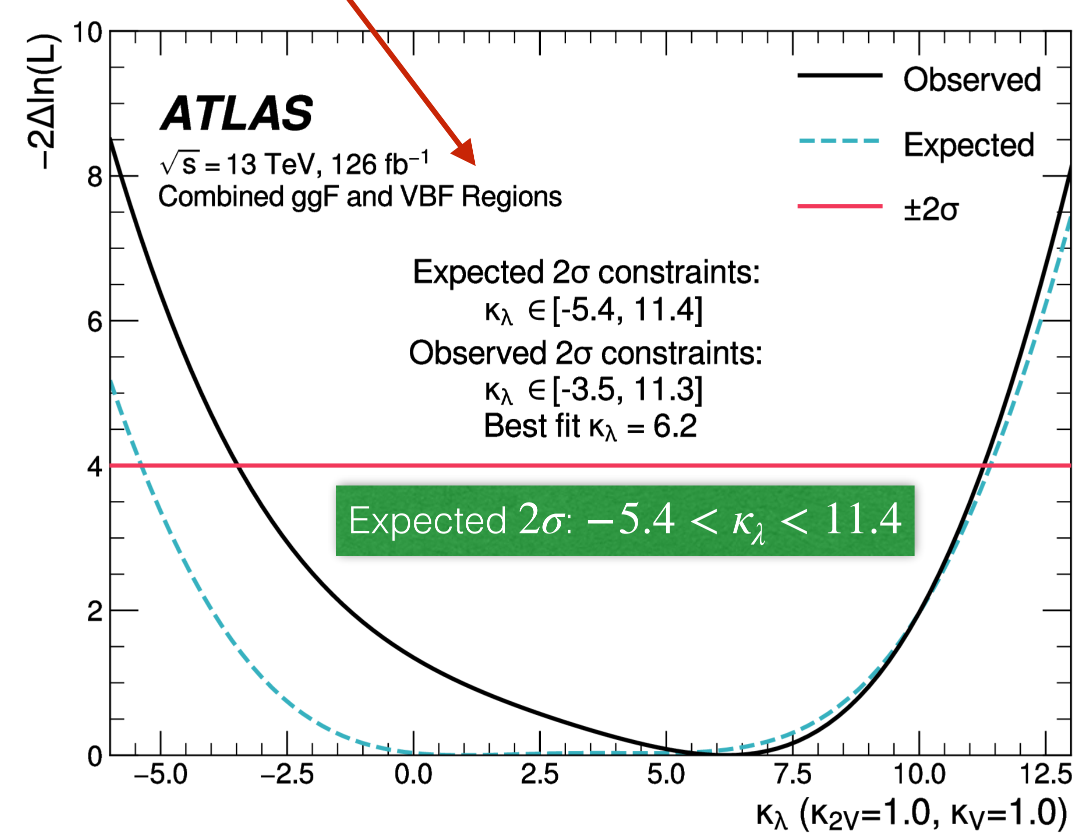
Resolved $HH \rightarrow b\bar{b}b\bar{b}$

ATLAS (**PRD 108 (2023) 052003**) and CMS (**PRL 129, 081802**)

- A **similar approach** between ATLAS and CMS:
  - **4 b-jets** with QCD background estimated through **data-driven techniques** (more details in next talk by N. Hartmann and M. Roguljic).
- But with **some differences**:
  1. B-jet pairing: based on $\Delta R(b,b)$ at ATLAS and (m_{H1}, m_{H2}) mass-plane information at CMS.
  2. Background estimation: data-driven methods based on low-tag to high-tag corrections. ATLAS estimates with 2b events, while CMS with 3b (triggers).
  3. Final discriminant: m_{HH} (ATLAS) and DNN output (CMS)

Similar sensitivities to κ_λ



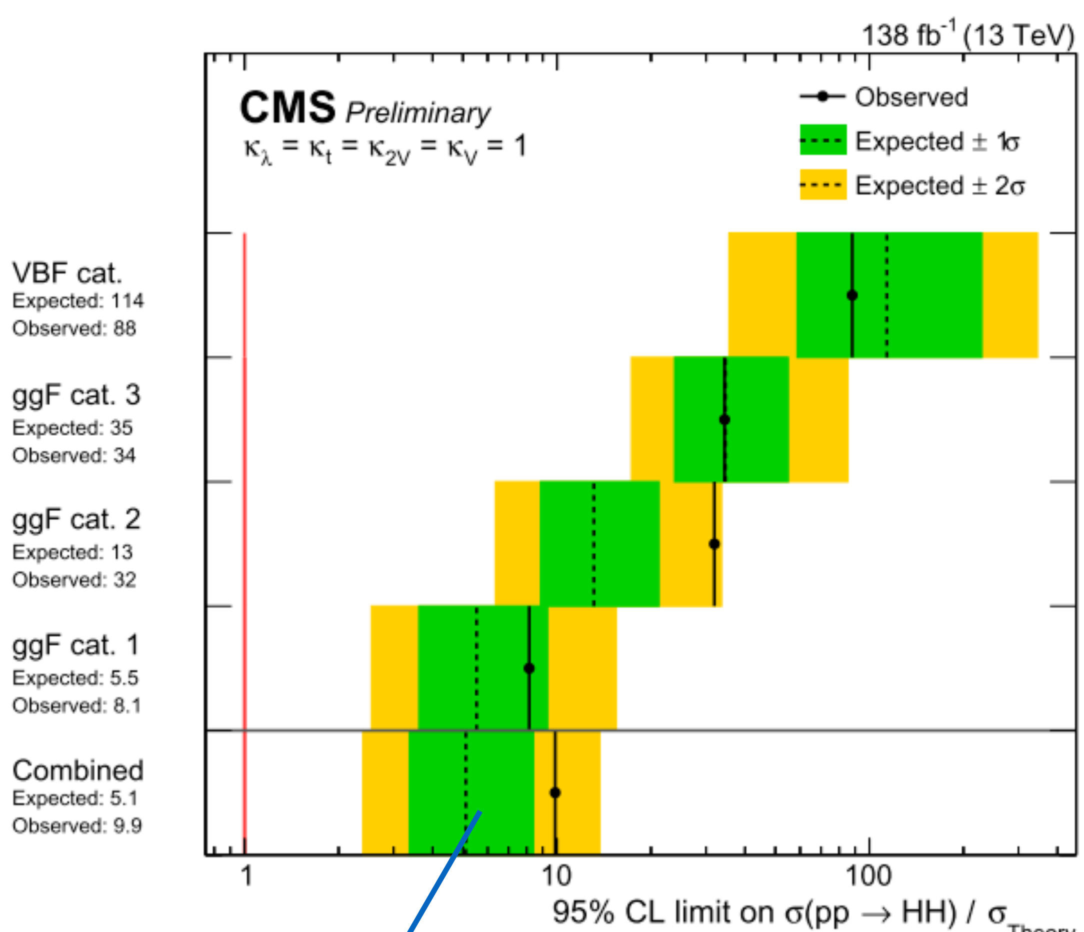


CMS Boosted $HH \rightarrow b\bar{b}b\bar{b}$ (1)

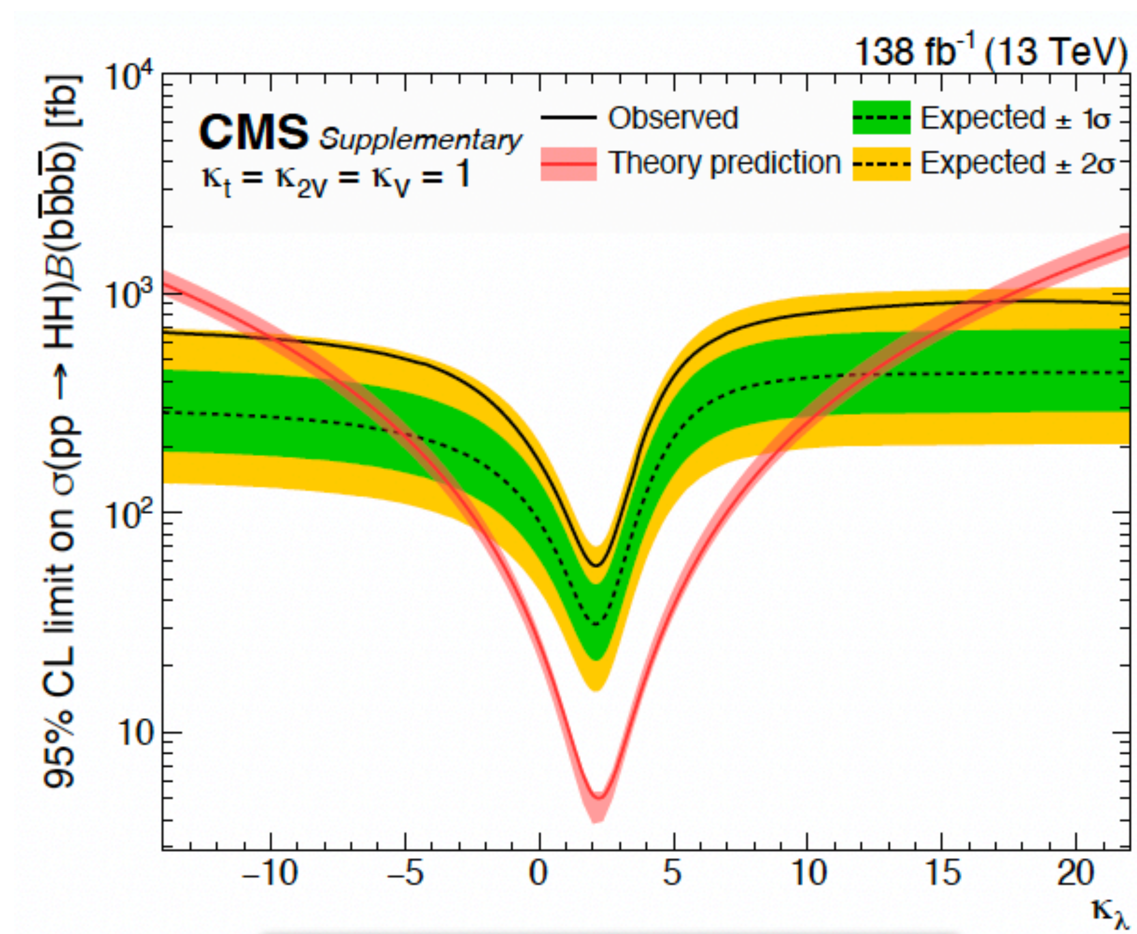
ggF production and κ_λ sensitivity

Phys. Rev. Lett.131.041803

- **Impressive sensitivity achieved thanks to state-of-the-art GNN $H \rightarrow b\bar{b}$ taggers** (ParticleNet).
  - 2 large-radius jets R=0.8 with $p_T > 300$ GeV and multiple categories based on signal kinematics and ParticleNet scores.
- Challenges: control of trigger turn-on effects, accurate calibration of $H \rightarrow b\bar{b}$ taggers and large-radius jet masses.



x30 times better than previous result!



Expected κ_λ range similar to resolved topology!

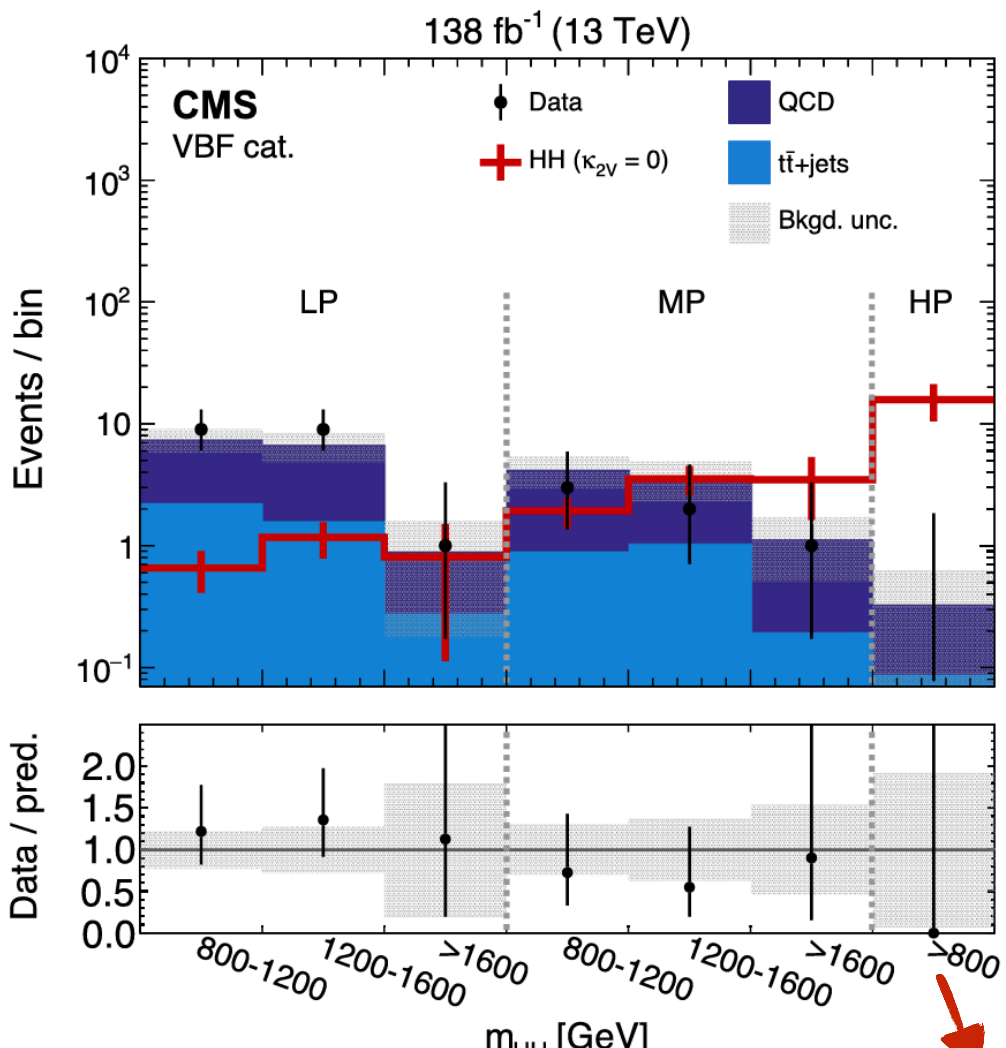
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

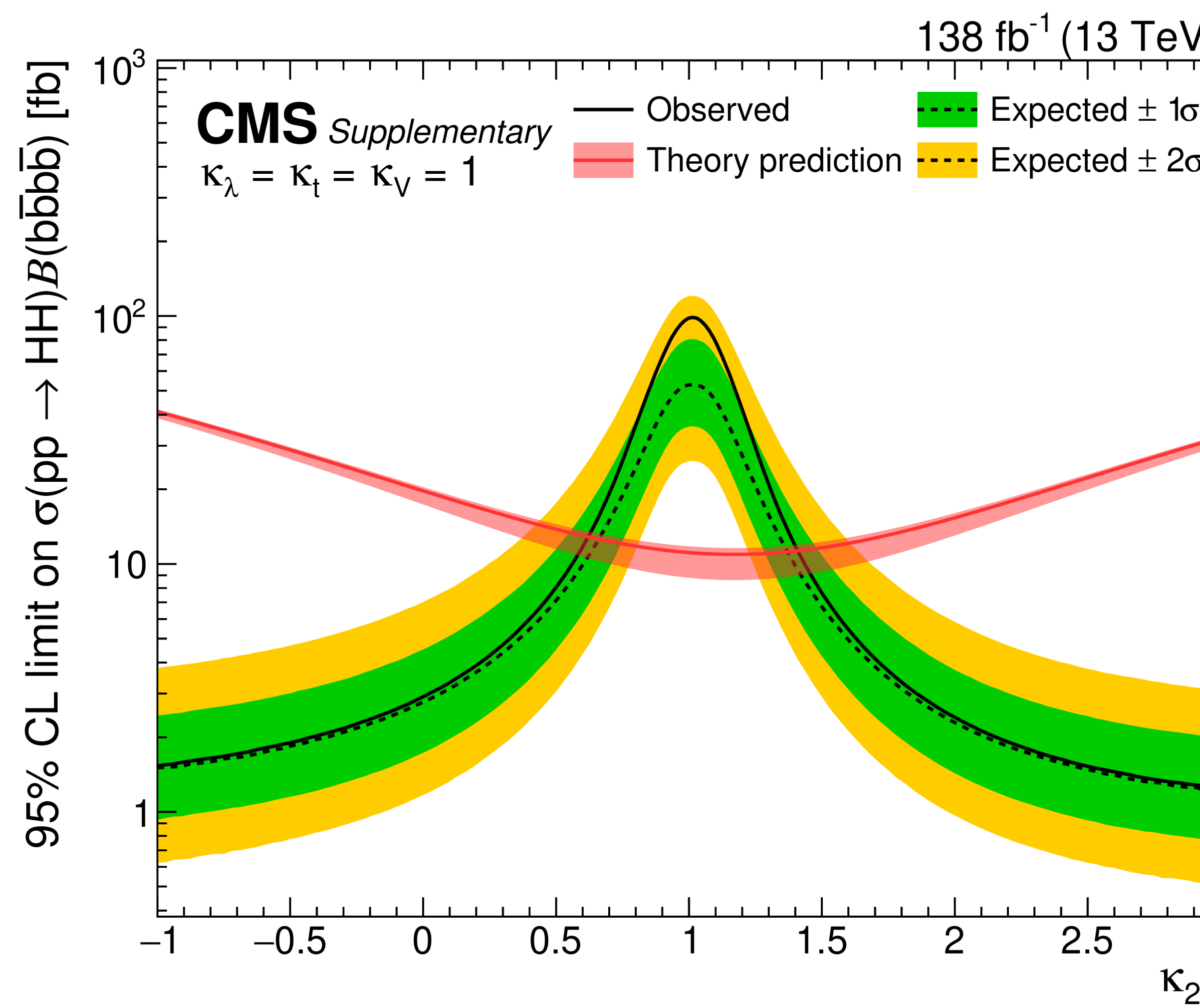
CMS Boosted $HH \to b\bar{b}b\bar{b}$ (2)

VBF production and k_{2V}

Phys. Rev. Lett.131.041803

- Boosted regime well suited to **target variations of κ_{2V} in VBF production.**
- **Multiple categories** split in kinematic selections and ParticleNet scores (LP,MP,HP)
- Observed (Expected) κ_{2V} ranges: $[0.6,1.4]$ ($[0.65,1.4]$)! **Most sensitive measurement to k_{2V}!**
  - **$\kappa_{2V} = 0$ excluded with more than 6σ significance!**





Rapidly evolving $H \to b\bar{b}$ taggers are progressively **allowing us to overcome the challenge of QCD backgrounds in $HH \to b\bar{b}b\bar{b}$!**

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Physics department
TRIUMF, Canada's particle accelerator Centre

$$HH \to b\bar{b}WW$$

[arXiv:2310.11286](https://arxiv.org/abs/2310.11286) **(ATLAS)**

[CMS-PAS-HIG-21-005]() **(CMS)**

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Physics department
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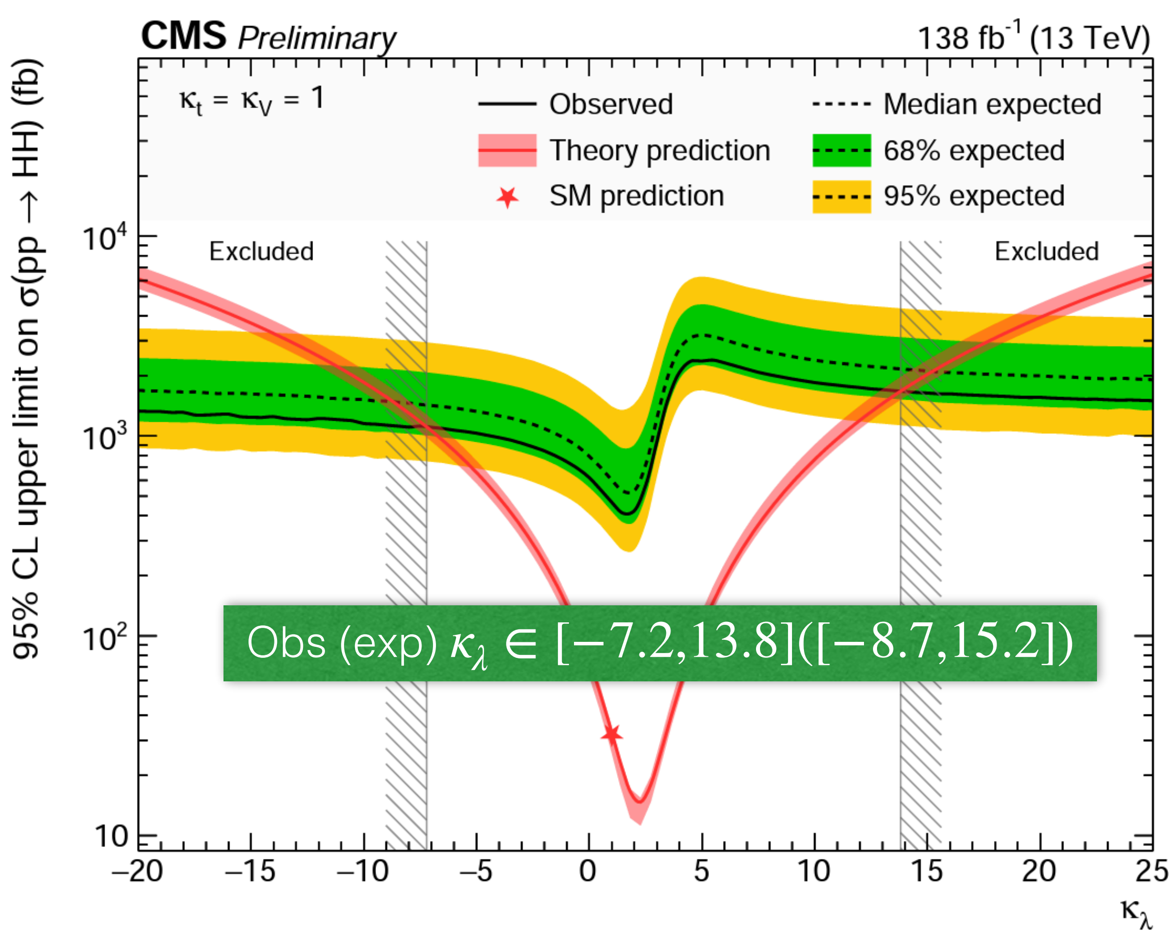
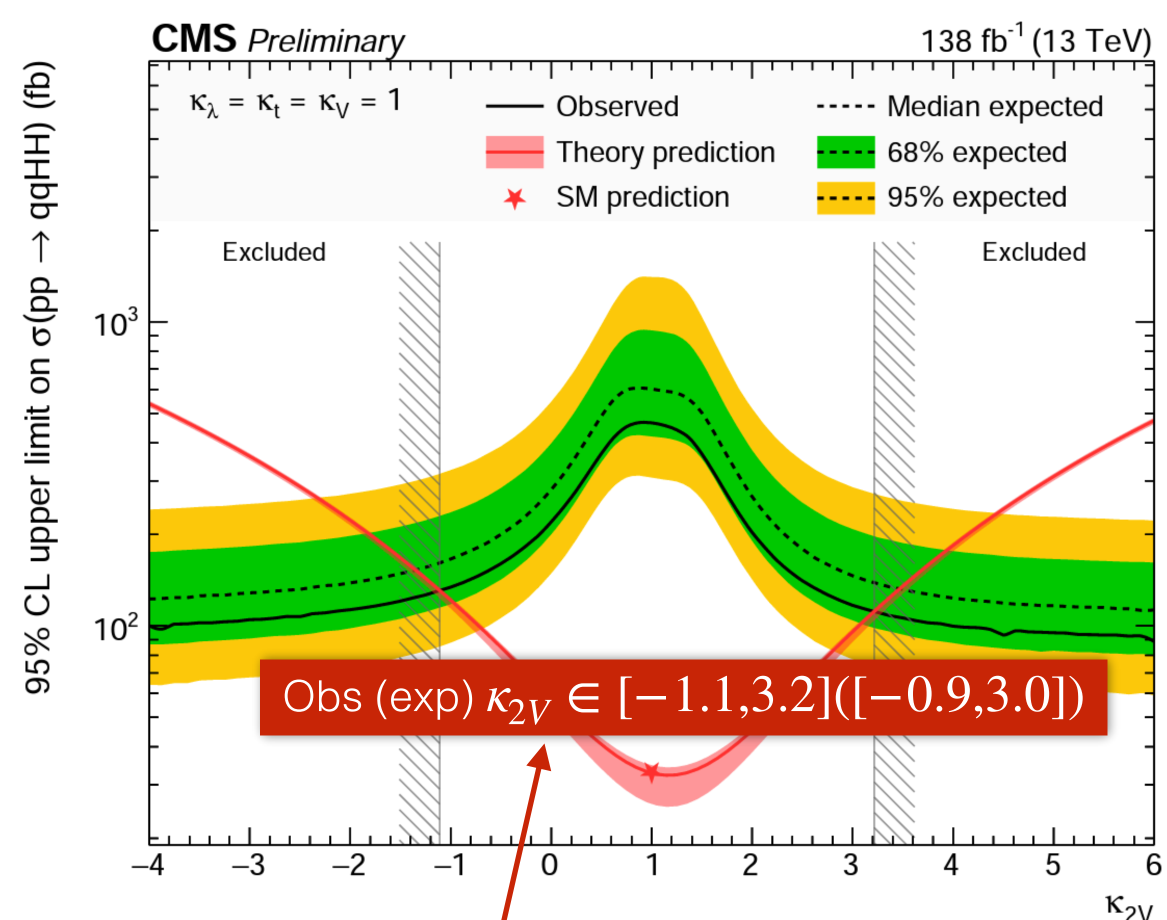
CMS $HH \to b\bar{b}W^+W^-$

CMS-PAS-HIG-21-005

- $HH \to bbW^+W^-$ has the **second largest HH BR (25%)**.
- Two channels to target leptonic W decays: single lepton and di-lepton.
  - **18 categories** (resolved and boosted) to enhance sensitivity to both ggF and VBF HH productions.
- Final discriminants: DNN scores (1 for ggF, 1 for VBF)





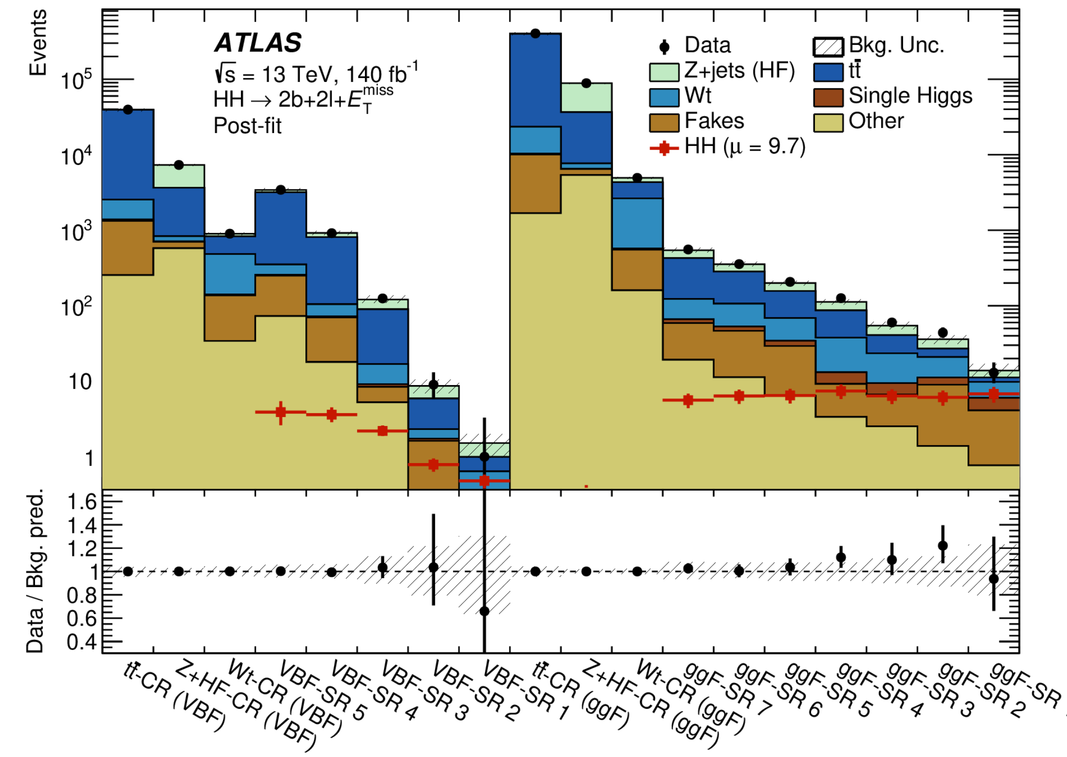
Expected k_{2V} range comparable to CMS $bb\gamma\gamma$ channel!

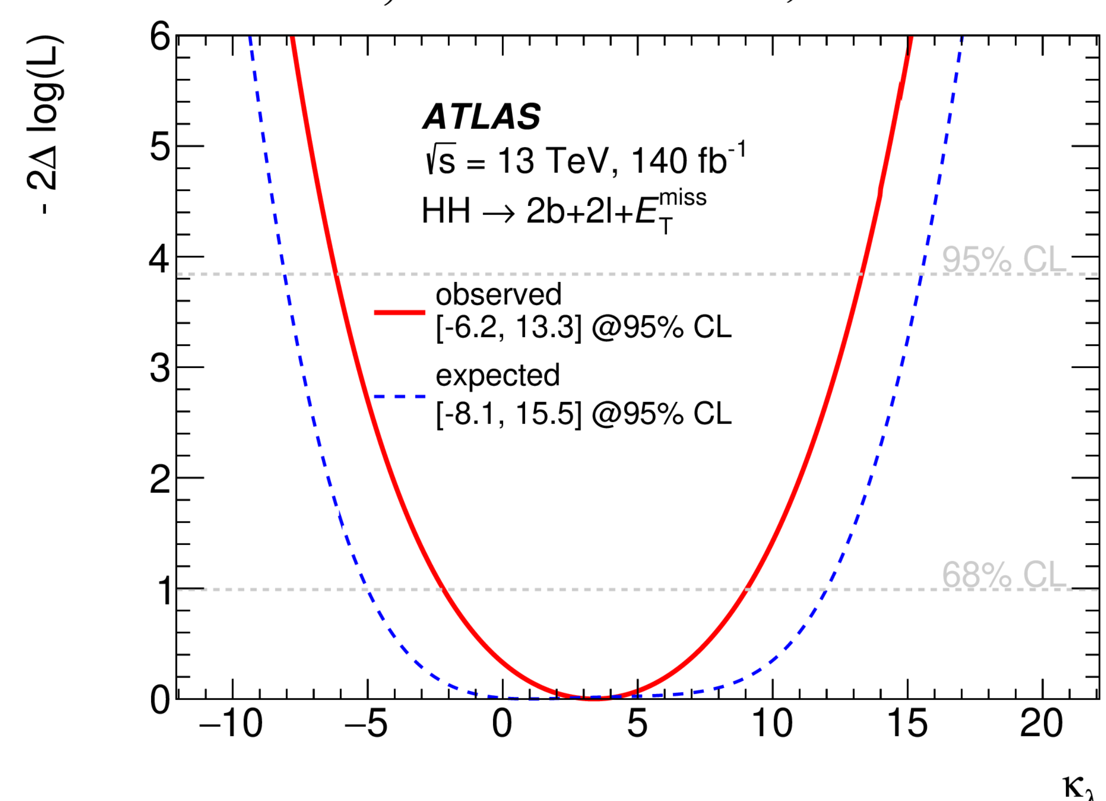
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS $HH \to b\bar{b}\, l^+ l^- \nu\nu$

arXiv:2310.11286

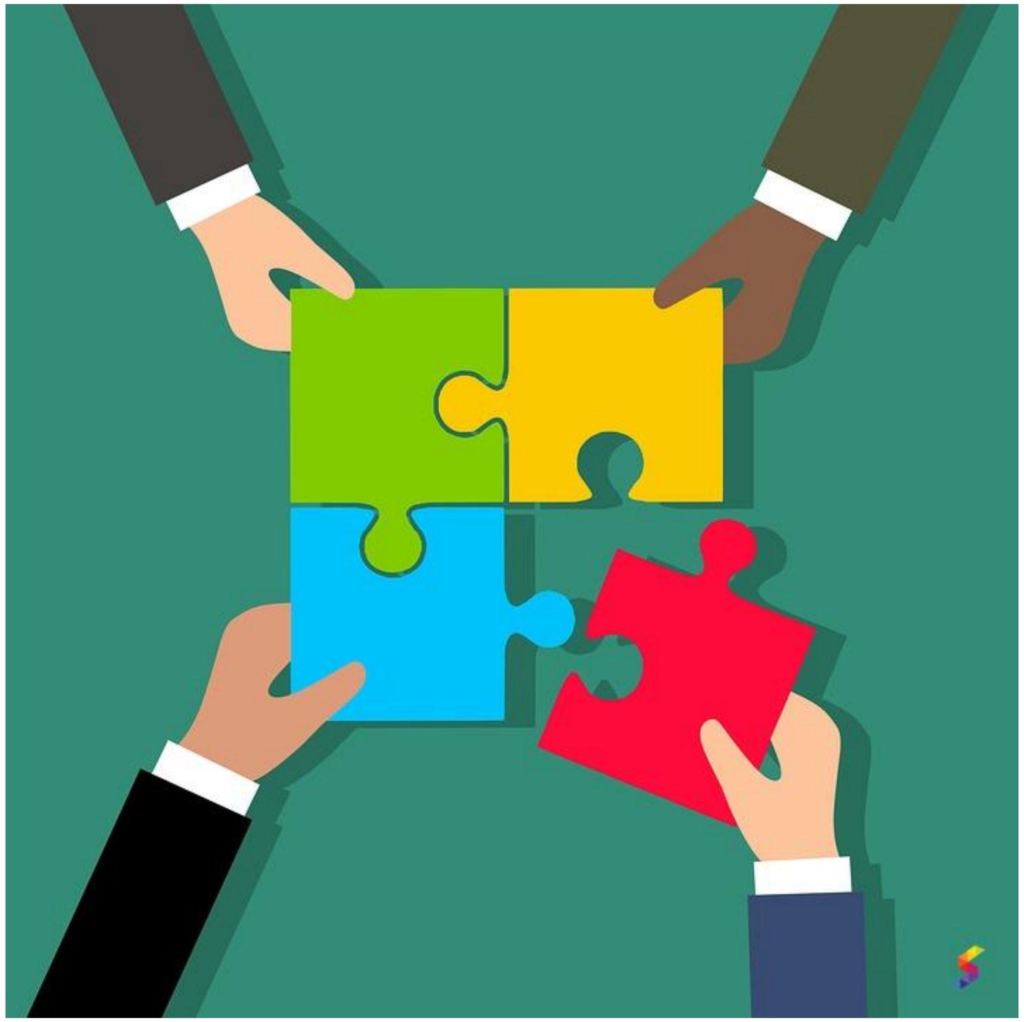
- Targeted signals:
  $HH \to b\bar{b} + WW/ZZ/\tau\tau \to b\bar{b} + l^+l^-$ + neutrinos
- Selection:
  - **2 b-jets** (77% DL1r) + **2 leptons** (e/μ)
  - **DNNs** to separate HH signals from backgrounds
- **2 categories:** 1 for ggF and 1 for VBF
- Final observation: **simultaneous likelihood fit of DNN score** in 2 categories.
- Observed (expected) results:
  - $\mu_{SM}^{95\%CL} = 9.7\ (16.2)$
  - $\kappa_{2V} \in [-0.17, 2.4]\ ([-0.51, 2.7])$.





Not very far from $b\bar{b}\tau\tau$ in ATLAS!

Combinations

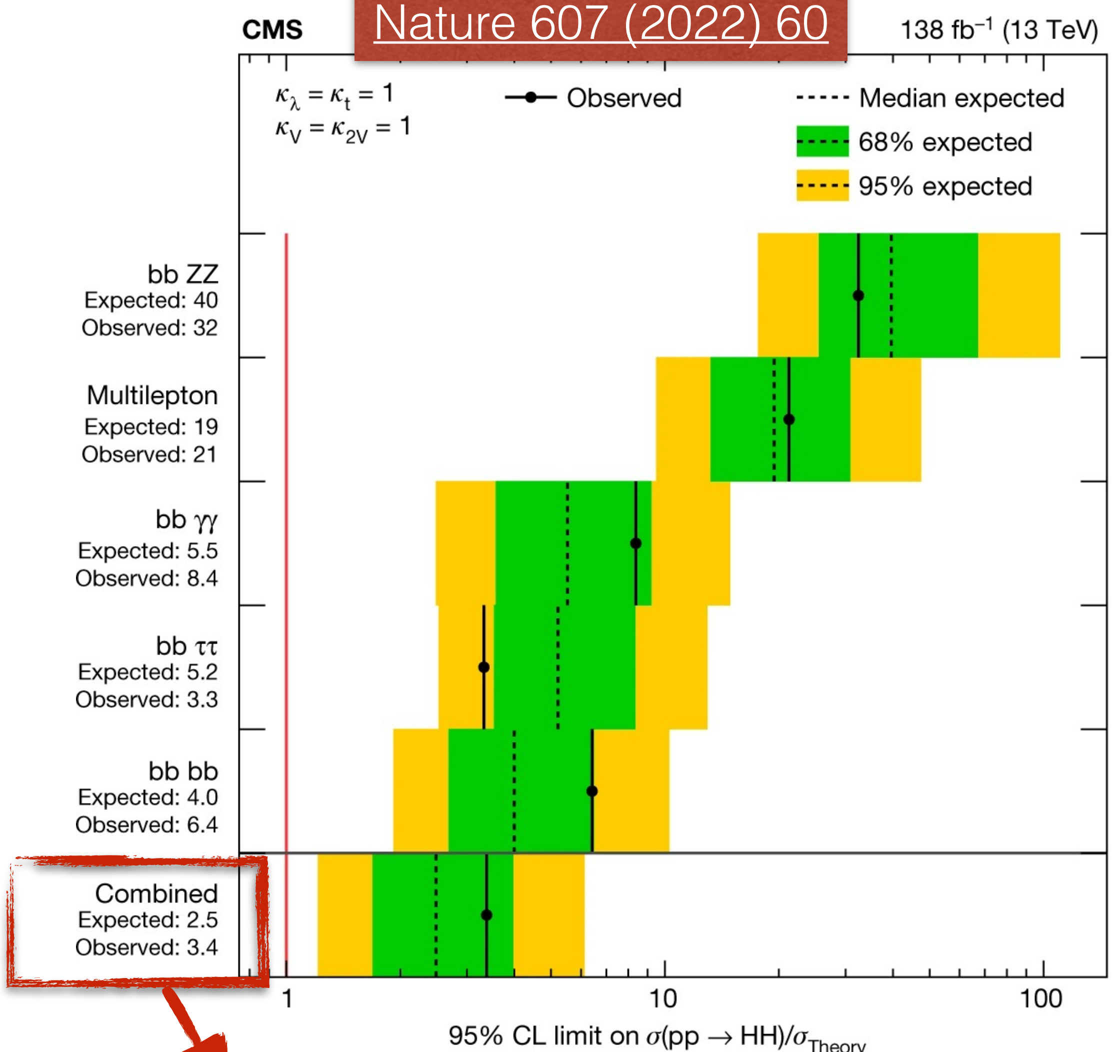


Combined results (1)

SM signal strength upper limits

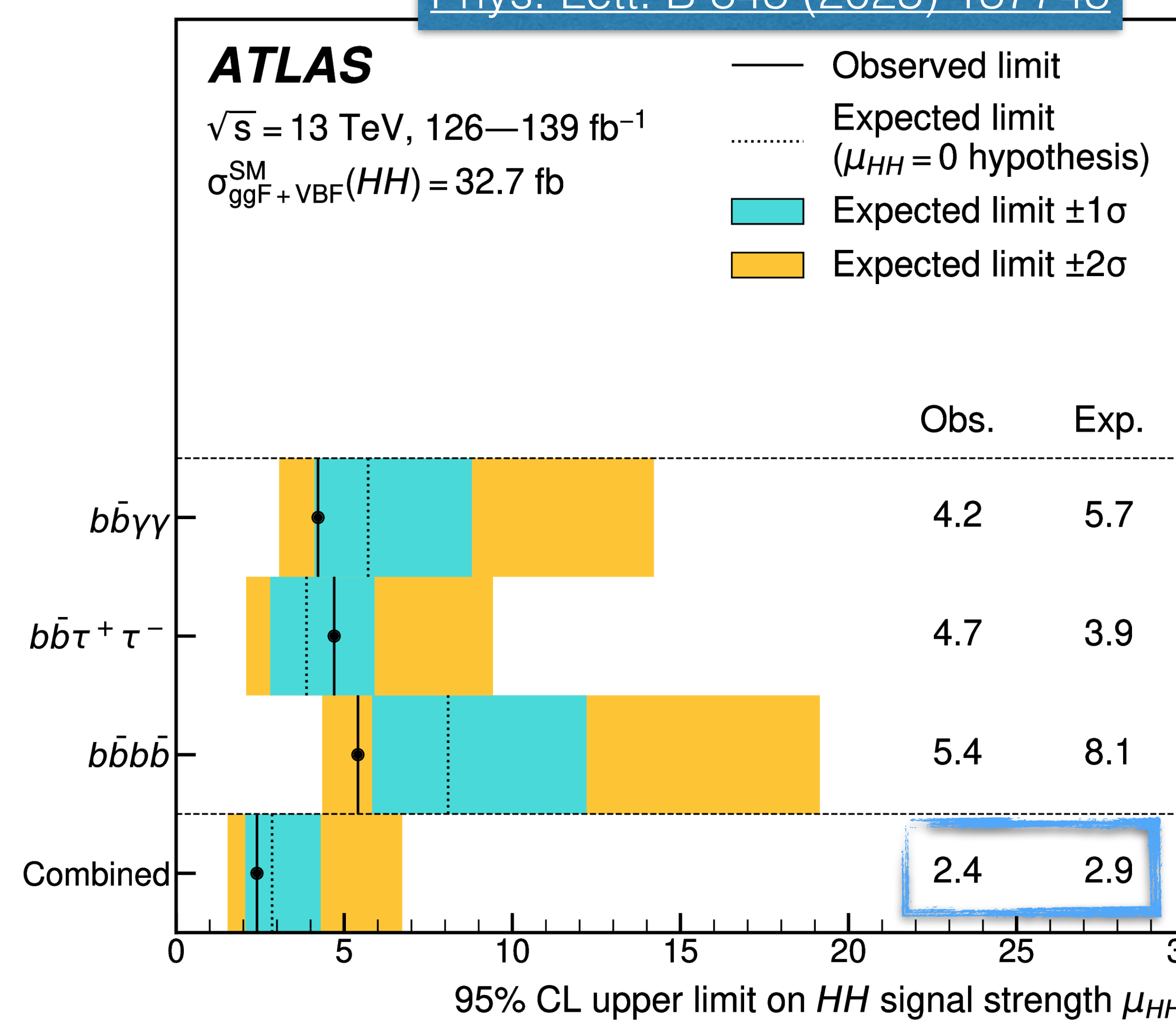
- Maximal sensitivity obtained through **statistical combinations**:
  - Very **comparable sensitivities** between 2 experiments (ATLAS dominated by $b\bar{b}\tau\tau$, CMS by $b\bar{b}b\bar{b}$).
  - A **lot of improvement** thanks to **improved reconstruction/ID techniques** (e.g. DL1r, ParticleNet) and **analysis techniques** (more categories, extensive use of Machine Learning).

Nature 607 (2022) 60



5x better than 36 fb^{-1} combination

Phys. Lett. B 843 (2023) 137745



3.5x better than 36 fb^{-1} combination

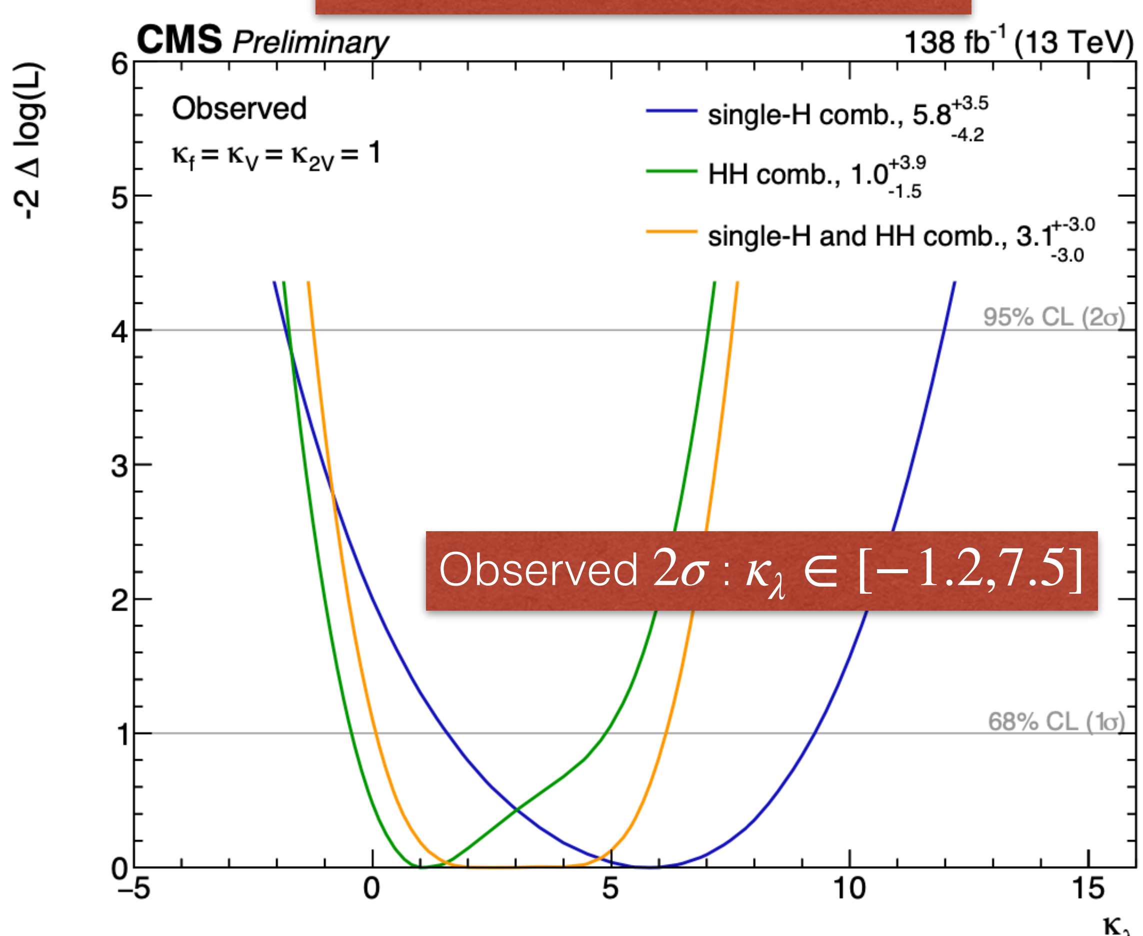
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Combined results (2)

Self-coupling constraints (κ_λ)

- **Constraint of κ_λ also largely improved** with respect to partial Run 2 results**!**
  - Very similar expected 95% CL constraints between the 2 experiments.
  - Indirect **single-Higgs measurements now also included** in the constraint.
  - Rapidly approaching the exclusion of $\kappa_\lambda = 0$!

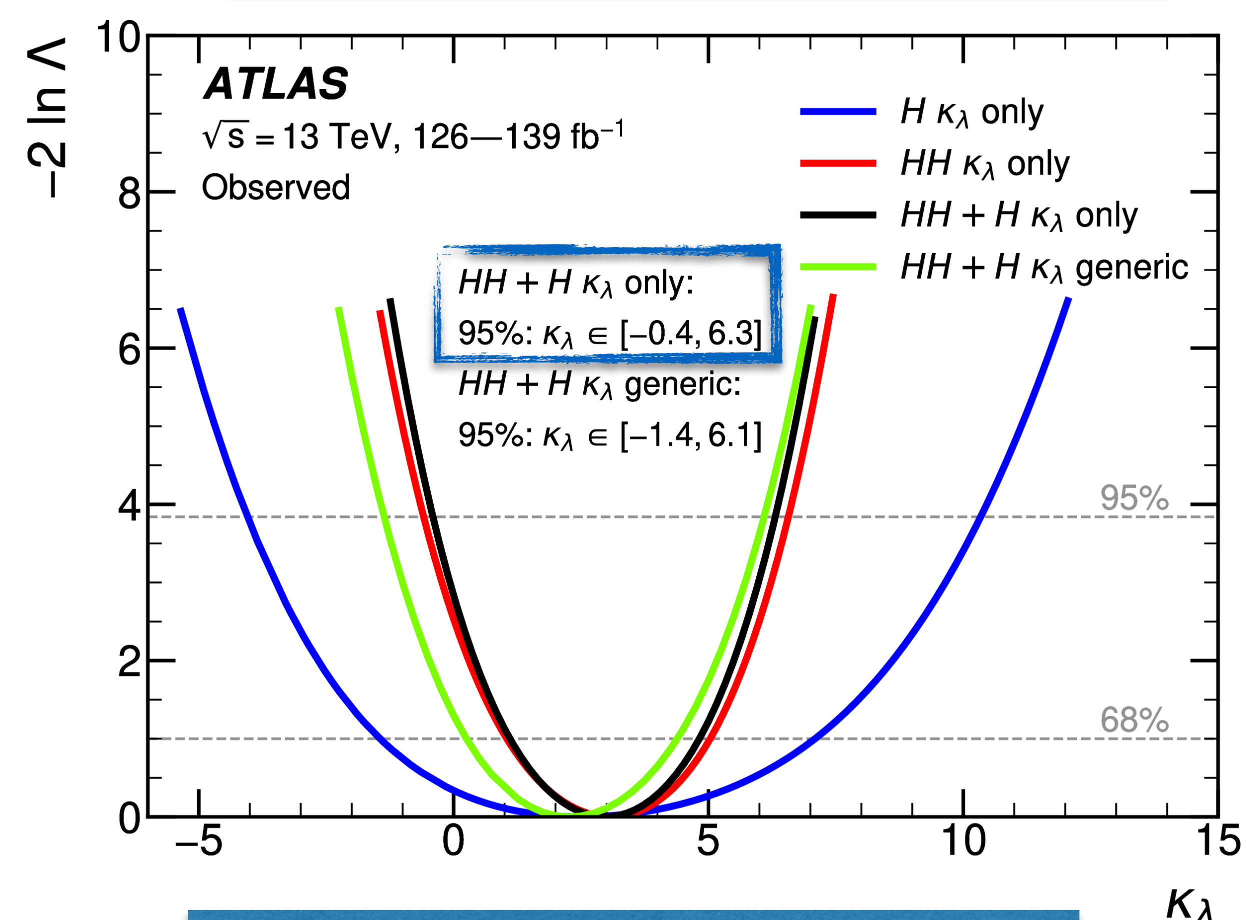
CMS-PAS-HIG-23-006



Observed 2σ : $\kappa_\lambda \in [-1.2, 7.5]$

Expected 2σ : $\kappa_\lambda \in [-2.0, 7.7]$

Phys. Lett. B 843 (2023) 137745



Expected (H+HH κ_λ only) $\kappa_\lambda \in [-1.9, 7.6]$

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Physics department
TRIUMF, Canada's particle accelerator Centre

The future

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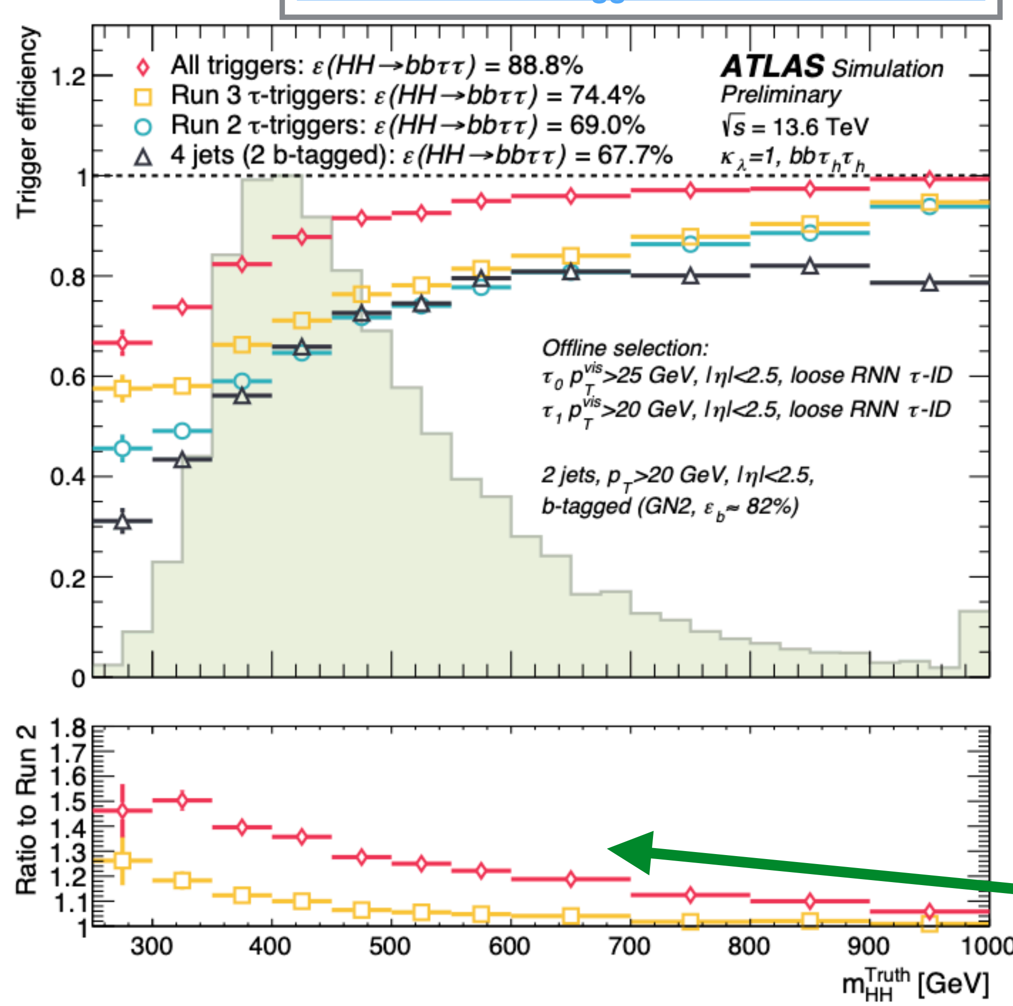
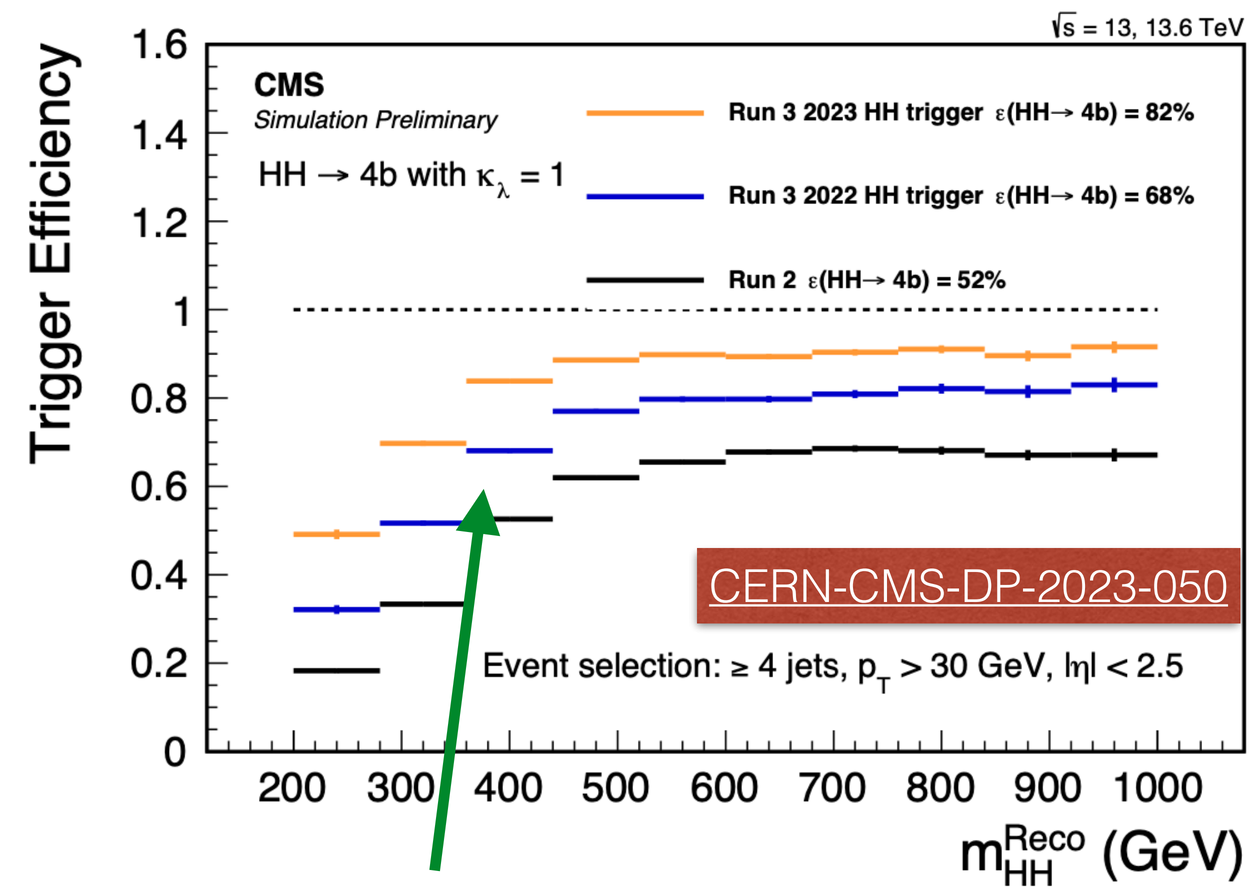
The immediate future: Run 3

- Run 3 will provide us: more **luminosity** (~ 400 fb^{-1} for Run 2+3 per experiment), more **energy** (+10% HH at $\sqrt{s} = 13.6$ TeV) and **better detector performance**.
    - Some examples: better triggers and improved flavour tagging (e.g. GN2 in ATLAS)
    - With all these improvements, Run 3 should bring us **very close to SM HH** ($\mu_{SM}^{95\%CL} \sim$ 1.0)!
    - **If something is very BSM-like** in the Higgs potential, **we might start to see it** in Run 3!

ATLAS Public Tau Trigger Plots for Collision Data



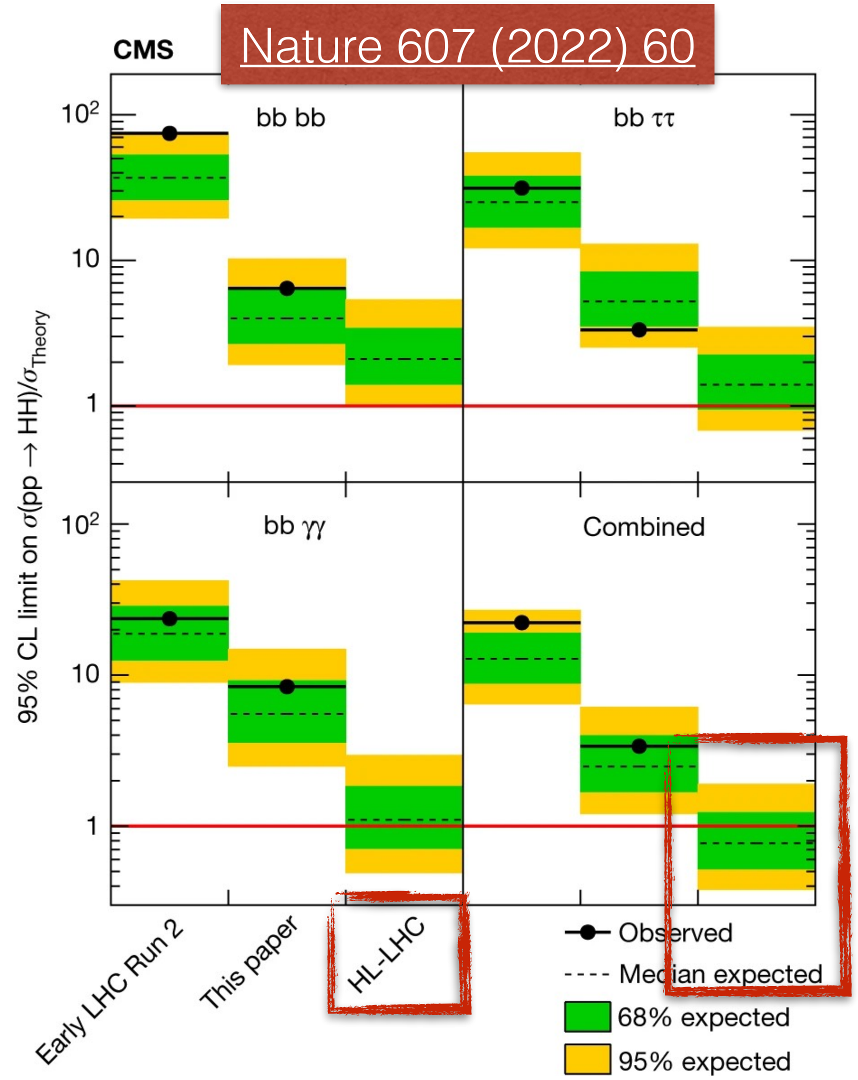


~50% more signal in Run 3!

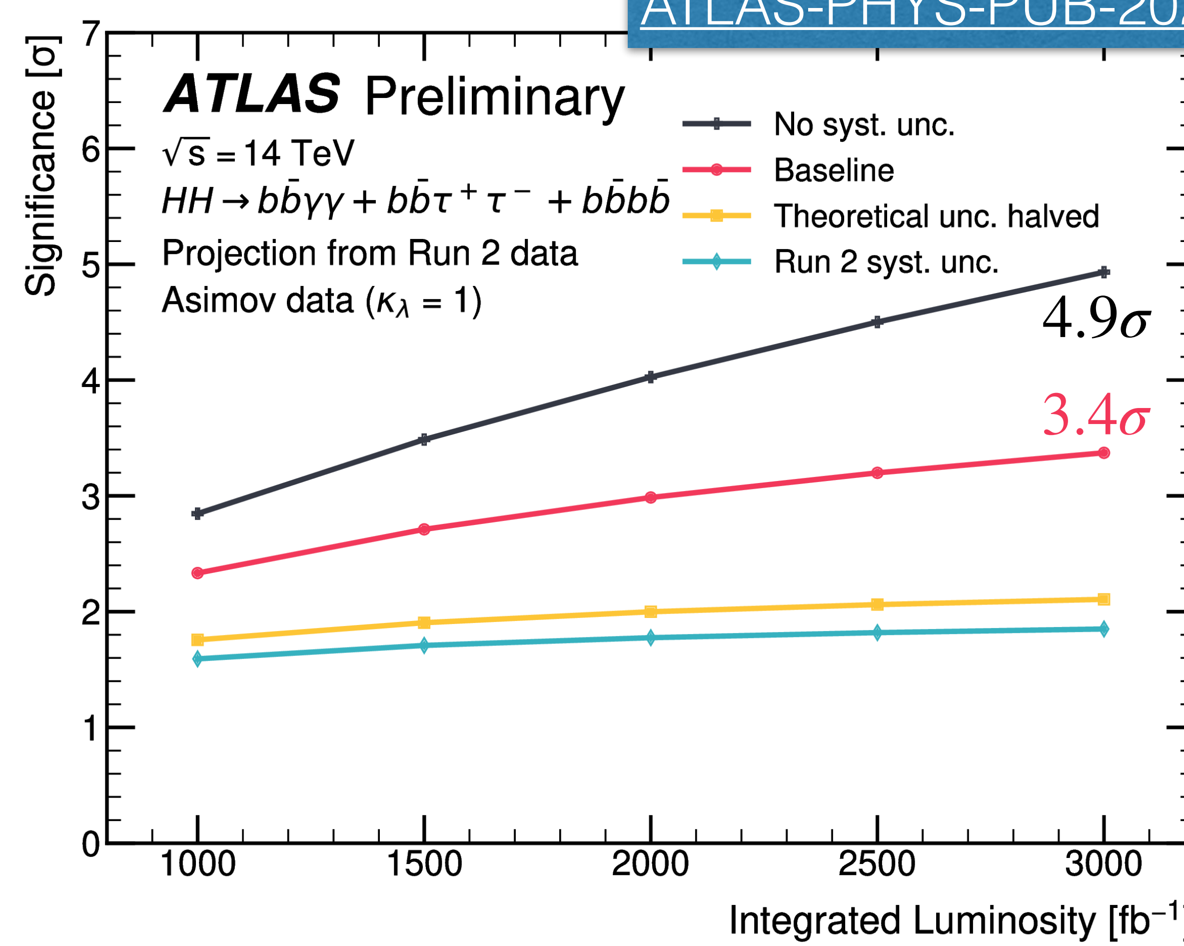
The distant future: HL-LHC

- **ATLAS expects a statistical evidence (3.4σ) for SM HH** ($\kappa_\lambda = 1$) with $3000\ \text{fb}^{-1}$ assuming same Run 2 detector performance and reduction of systematics.
  - 5σ **should be well within reach** of a combined ATLAS and CMS HL-LHC result!
  - ATLAS expects to constraint κ_λ **to** $[0.5,1.6]$ **at 68% CL** with $3000\ \text{fb}^{-1}$. Combination with CMS **could bring us close to [0.65,1.3]?**

Nature 607 (2022) 60



ATLAS-PHYS-PUB-2022-053



Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

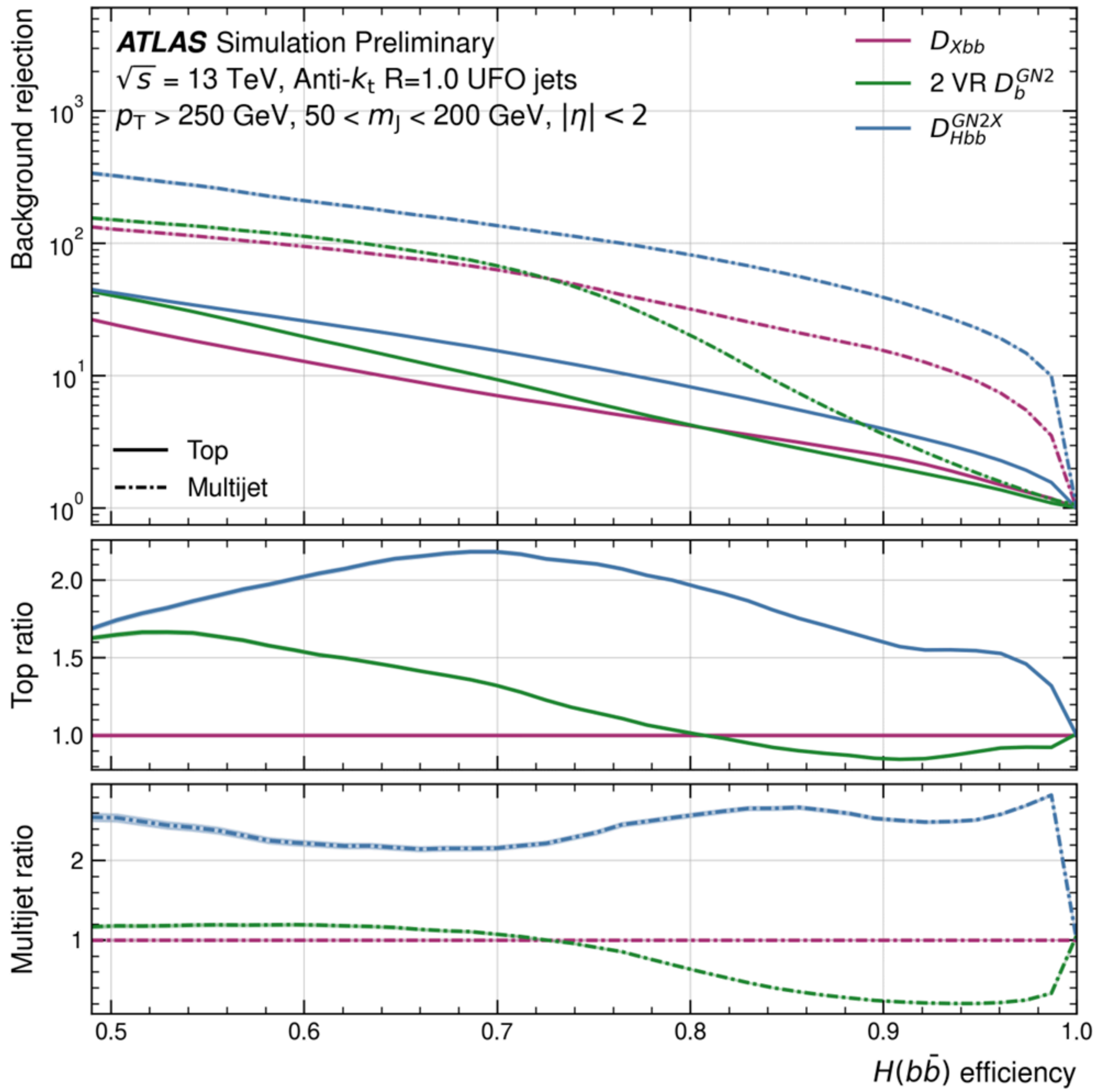
Summary and outlook

- Summarised recent status non-resonant HH searches.
- **No significant excess** above the SM (for now), and **exclusion limits have been set to:**
  - Obs (exp) $\mu_{HH}^{95\%CL}$: **2.4 (2.9) at ATLAS** and **3.4 (2.5) at CMS**
  - Obs(exp) κ_λ ranges: **[-0.4,6.3] ([-1.9,7.6]) at ATLAS** and **[-1.2,7.5]([-2.0,7.7]) at CMS**
  - Obs(exp) κ_{2V} ranges: **[0.1,2.0] ([0.0,2.1]) at ATLAS** and **[0.62,1.4] ([0.66,1.37]) at CMS (boosted $HH \rightarrow b\bar{b}b\bar{b}$)**
- **Large improvements** not only due to increased luminosity in Run 2, but also **constantly improved analysis and reconstruction techniques** (e.g. DL1d, ParticleNet, etc.).
- The future will be exciting:
  - Important **BSM deviations from the SM Higgs potential could start to be detected with Run 2+3 datasets!**
  - At HL-LHC, 5σ **discovery well accessible** combining ATLAS and CMS, and combined κ_λ precision could be in the ~30-35% range (50% expected for ATLAS-only).

Backup

GN2 $H \rightarrow b\bar{b}$

ATL-PHYS-PUB-2023-021

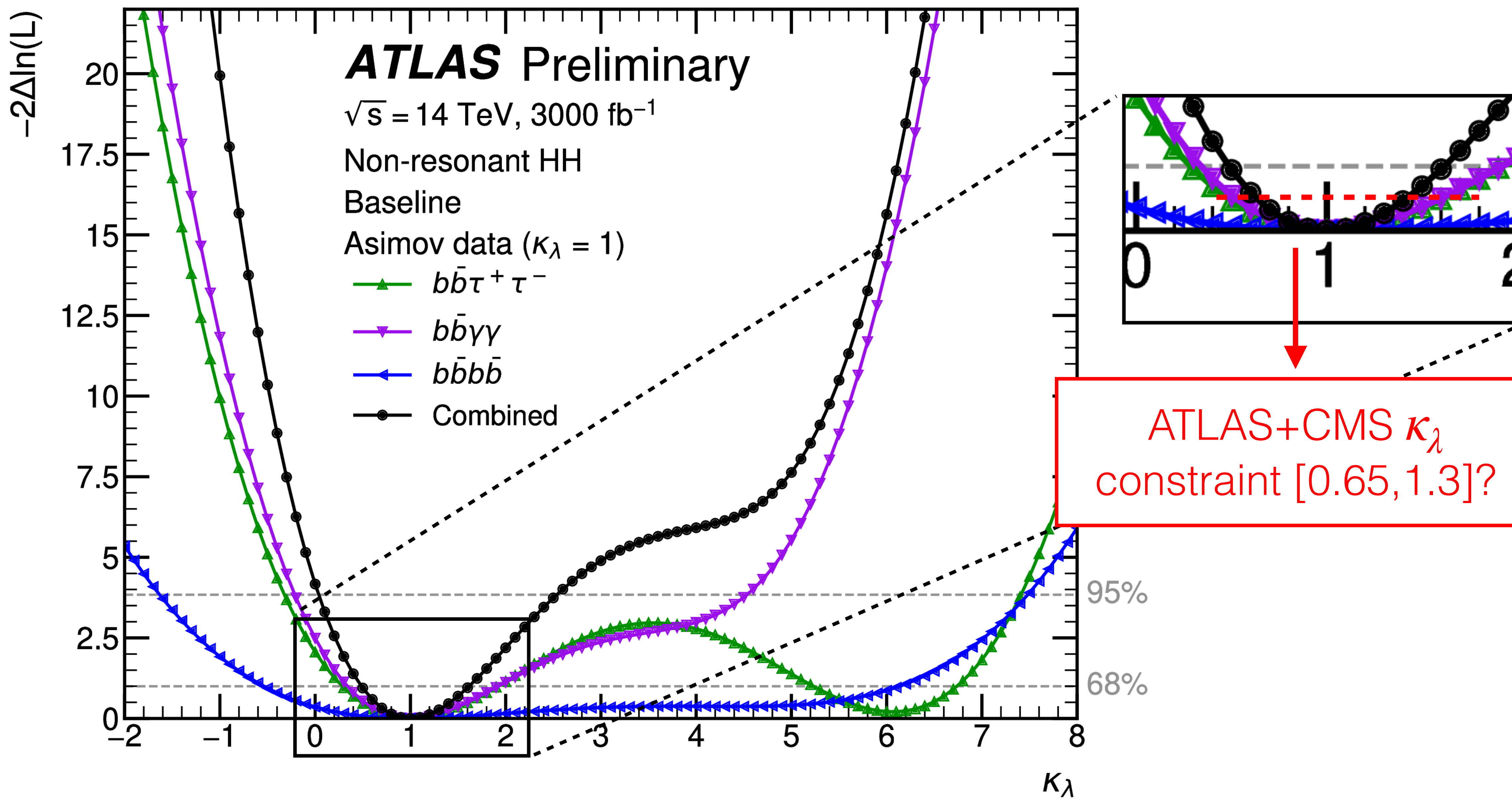


Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

My personal HL-LHC estimation

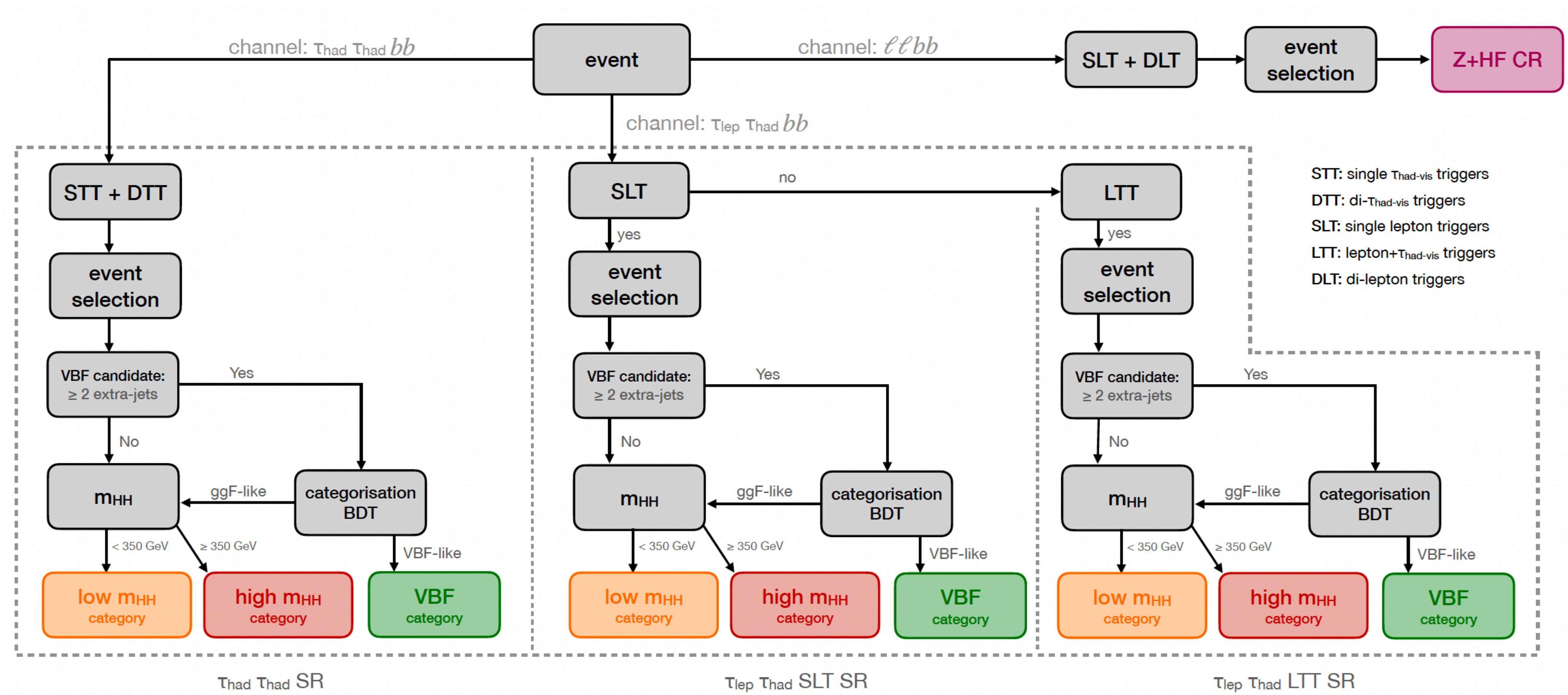
ATLAS-PHYS-PUB-2022-053



ATLAS+CMS κ_λ constraint [0.65,1.3]?

ATLAS legacy $HH \to b\bar{b}\tau\tau$ (1)

Detailed event selection

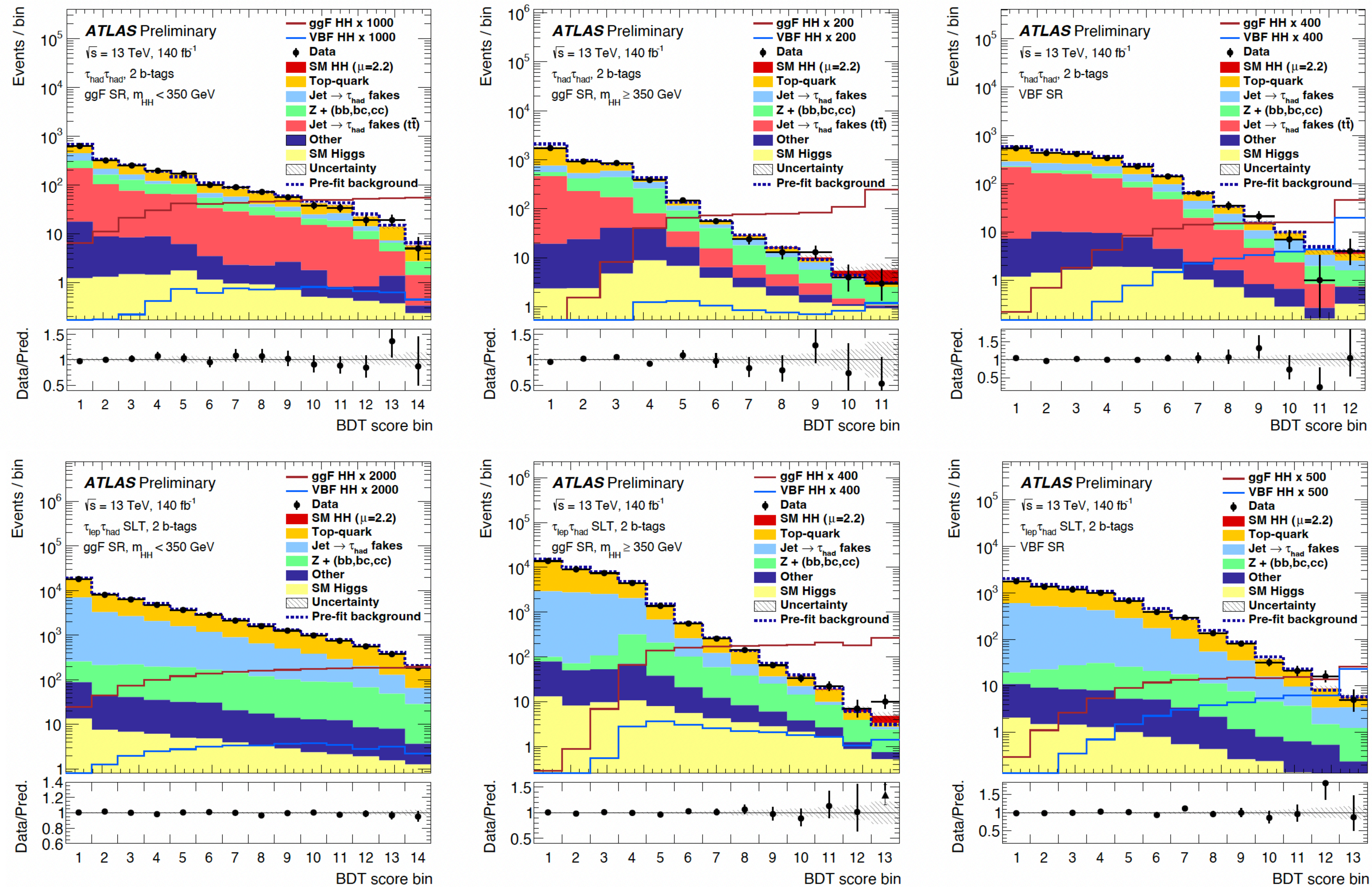


Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

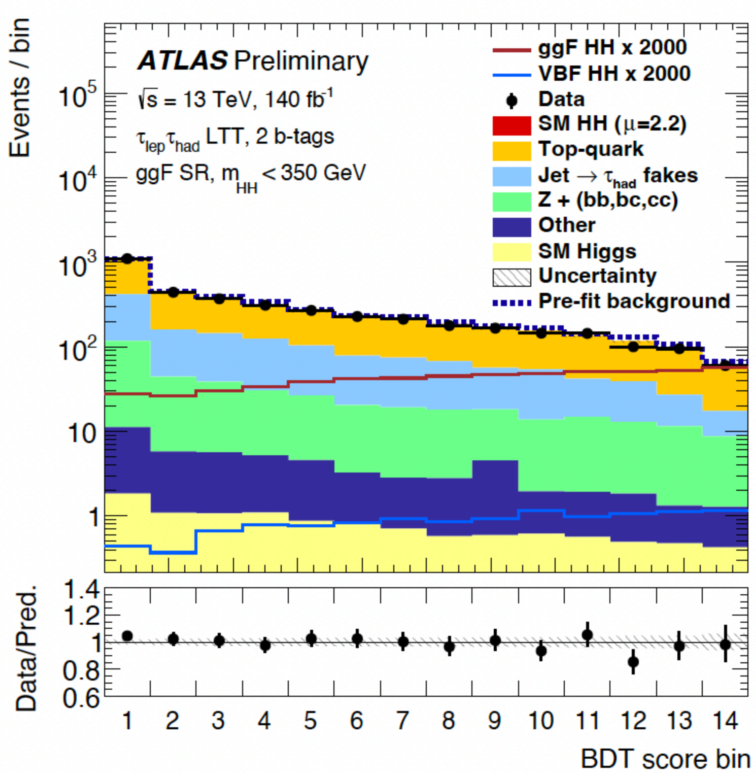
ATLAS legacy $HH \to b\bar{b}\tau\tau$ (2)

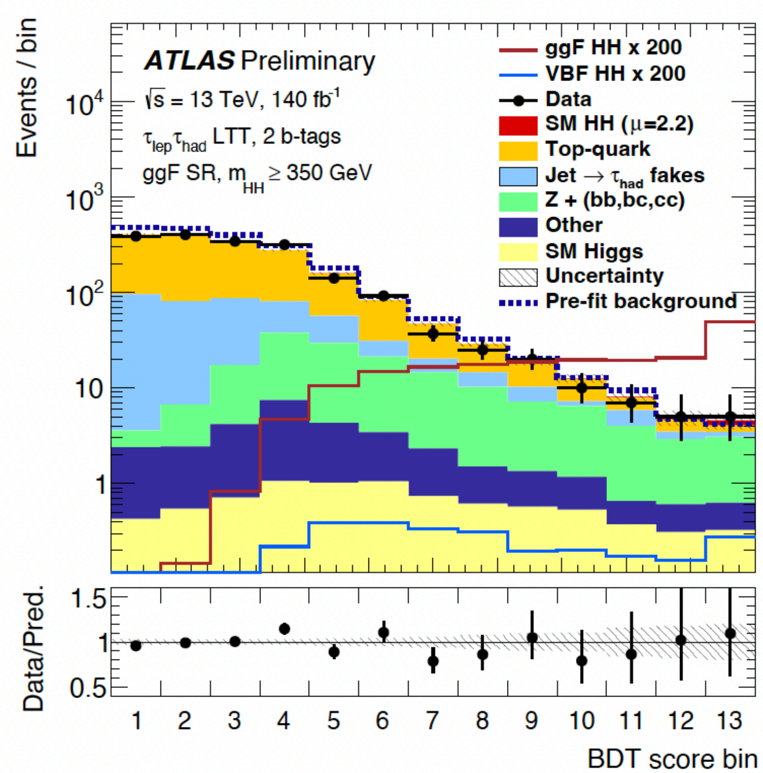
Data/background distributions

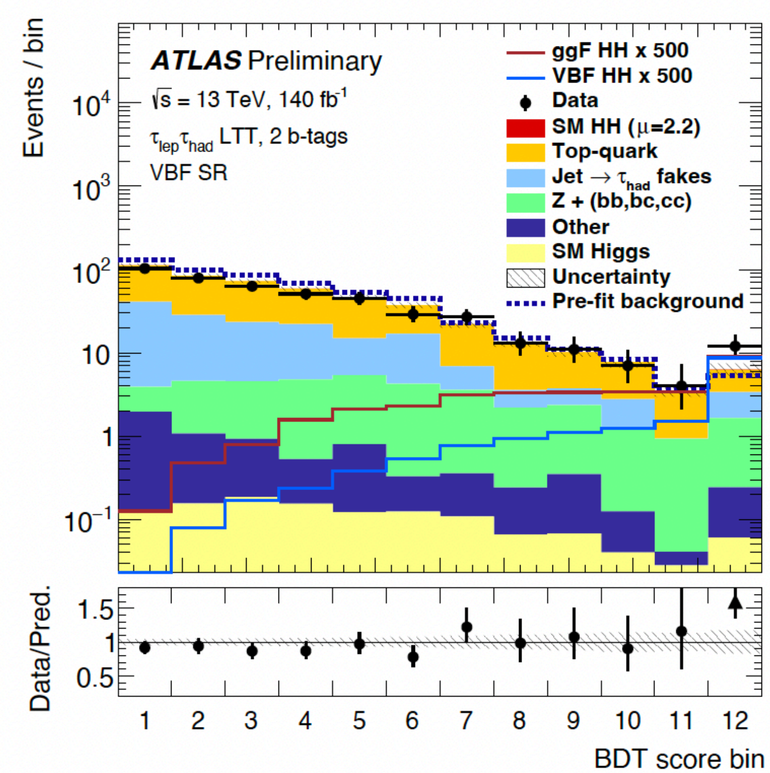


ATLAS legacy $HH \rightarrow b\bar{b}\tau\tau$ (3)

Data/background distributions





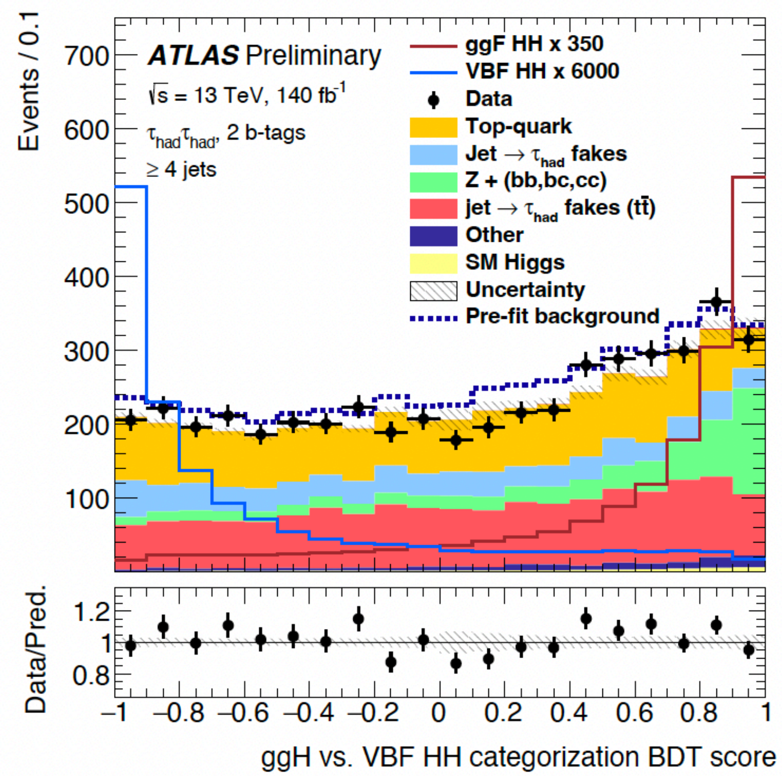


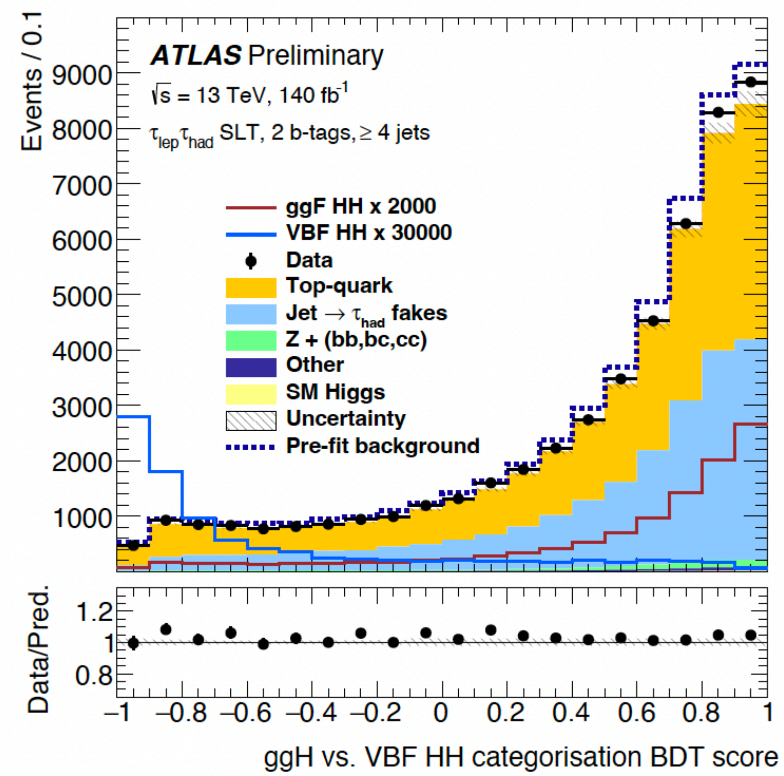
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

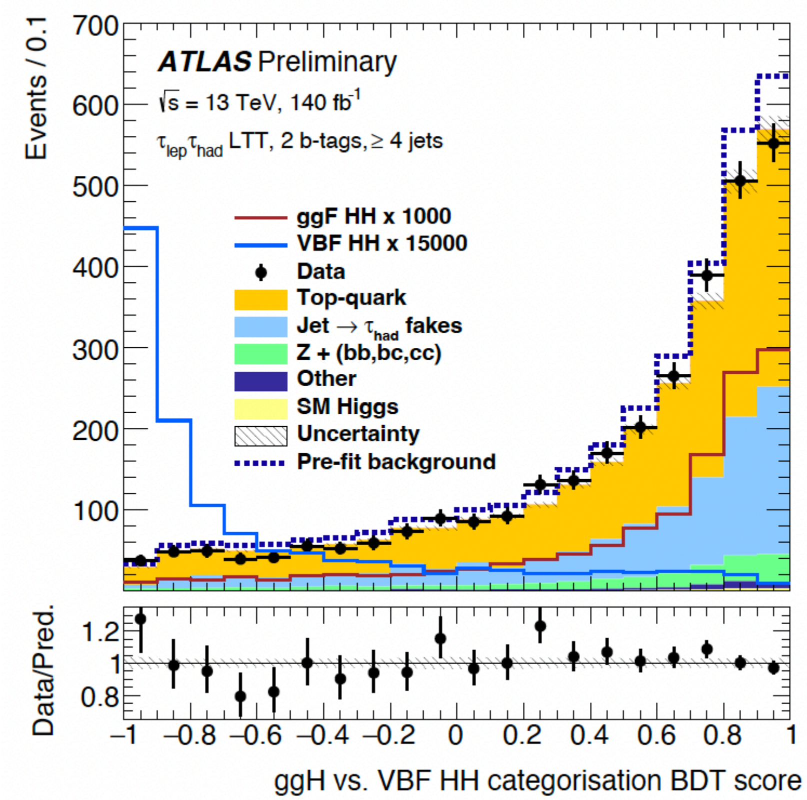
ATLAS legacy $HH \rightarrow b\bar{b}\tau\tau$ (4)

VBF BDT

Variable	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ SLT	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{\mathrm{VBF}}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{\mathrm{VBF}}$	✓		
$\Delta R_{jj}^{\mathrm{VBF}}$		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓



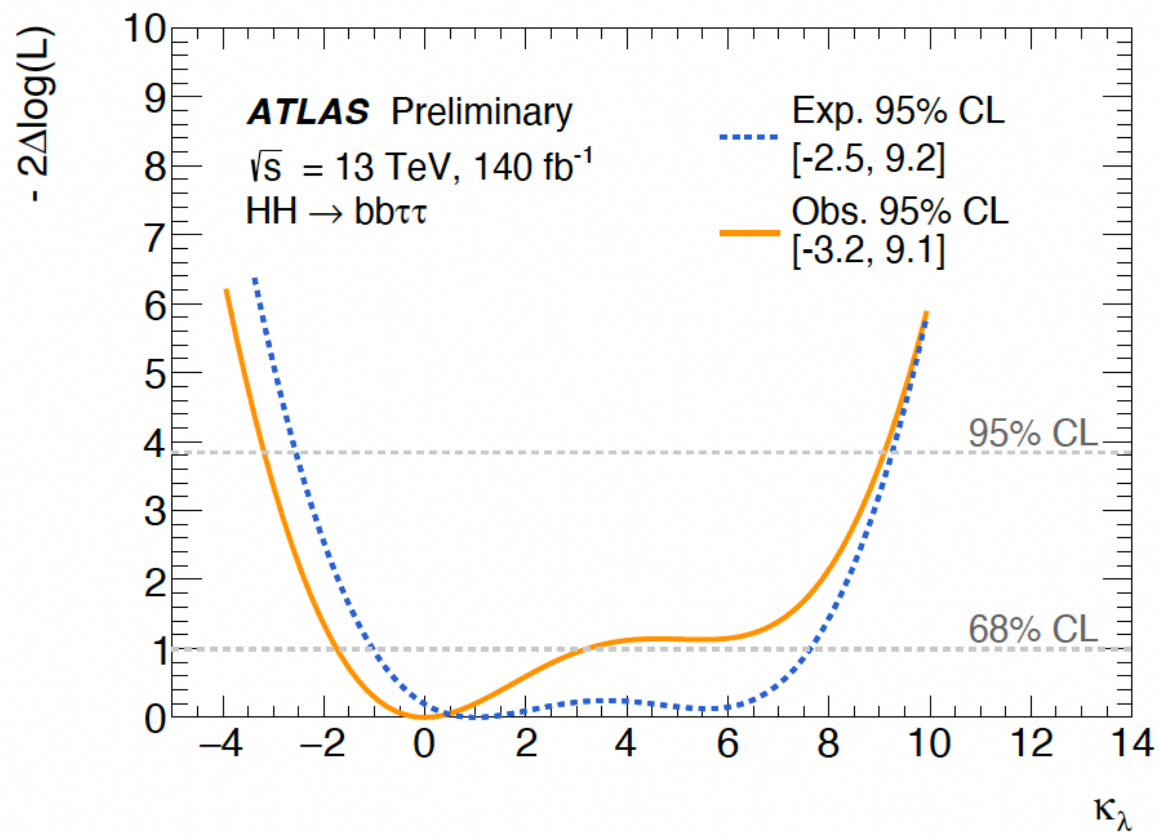


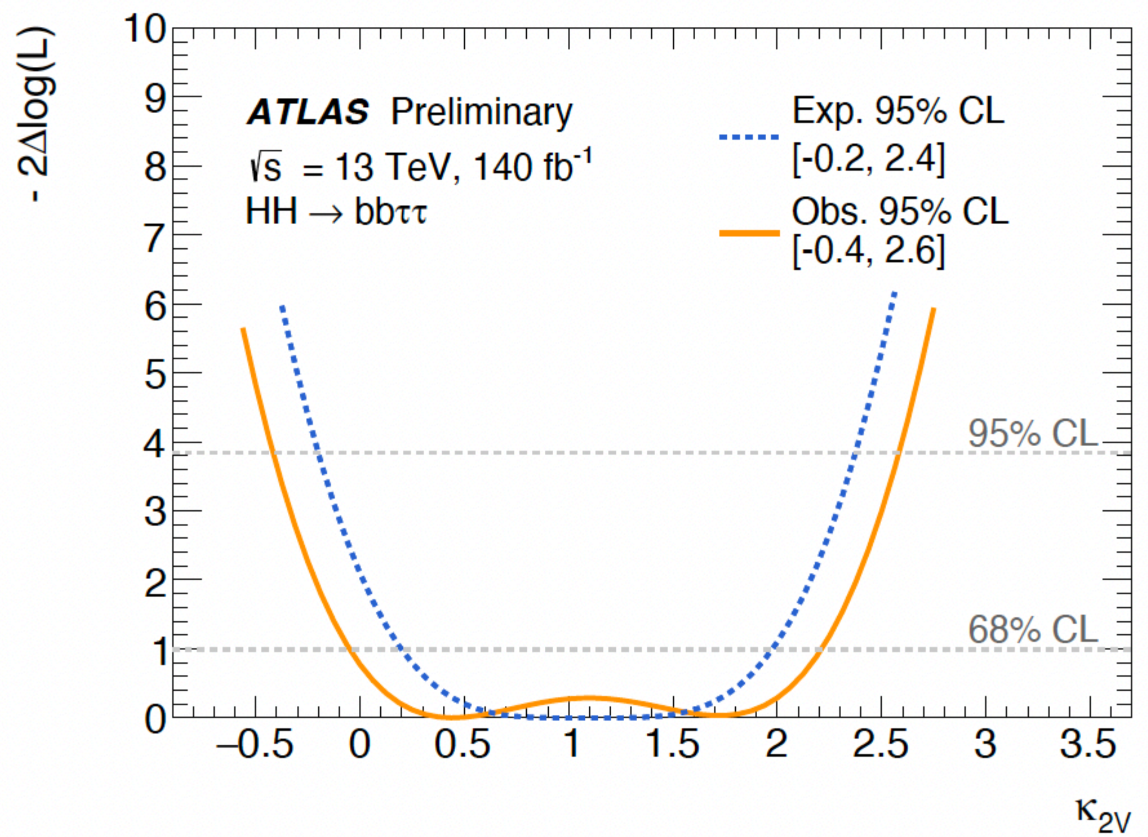


Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS legacy $HH \to b\bar{b}\tau\tau$ (5)

κ_λ and κ_{2V} likelihood scans

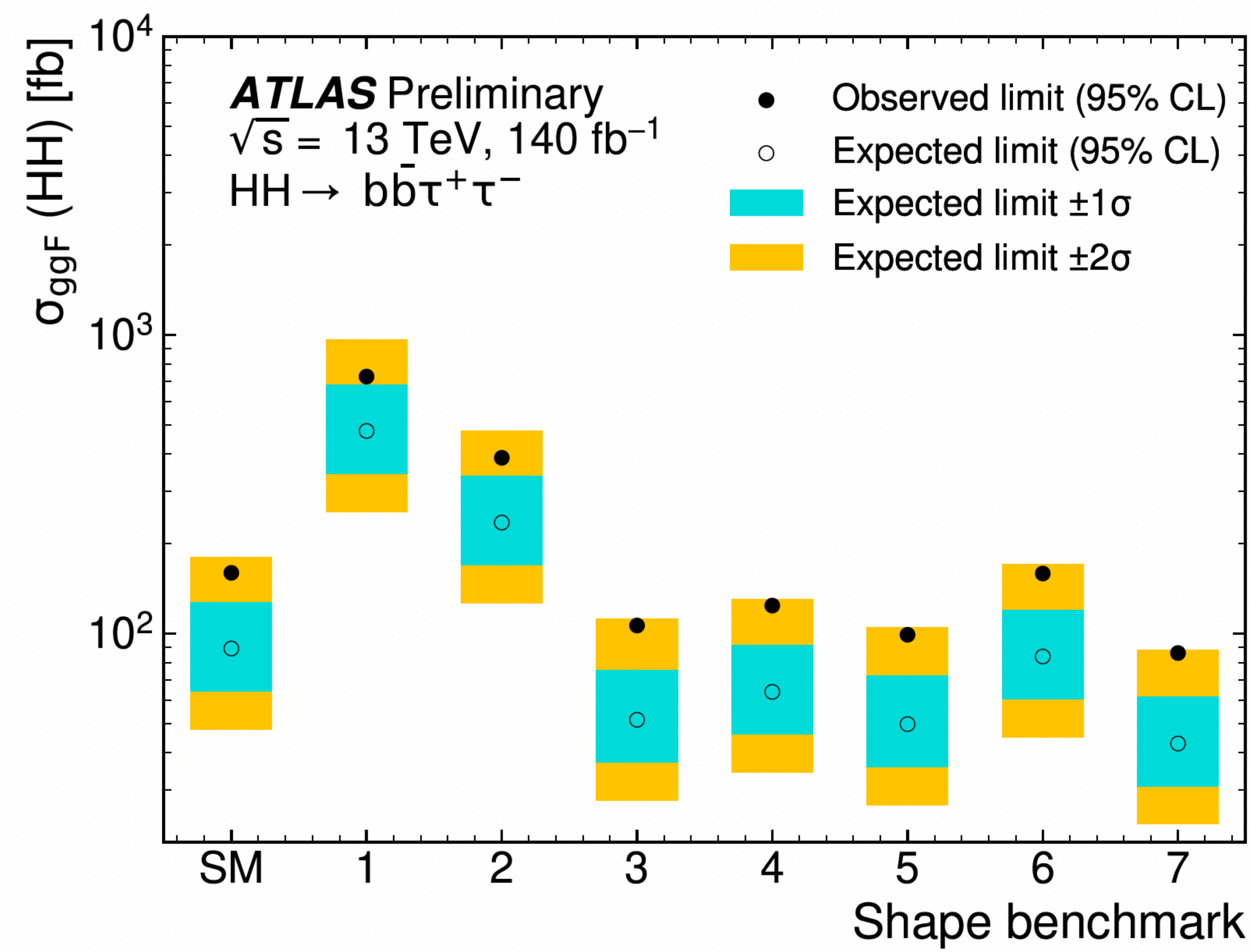




Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS legacy $HH \to b\bar{b}\tau\tau$ (6)

EFTs

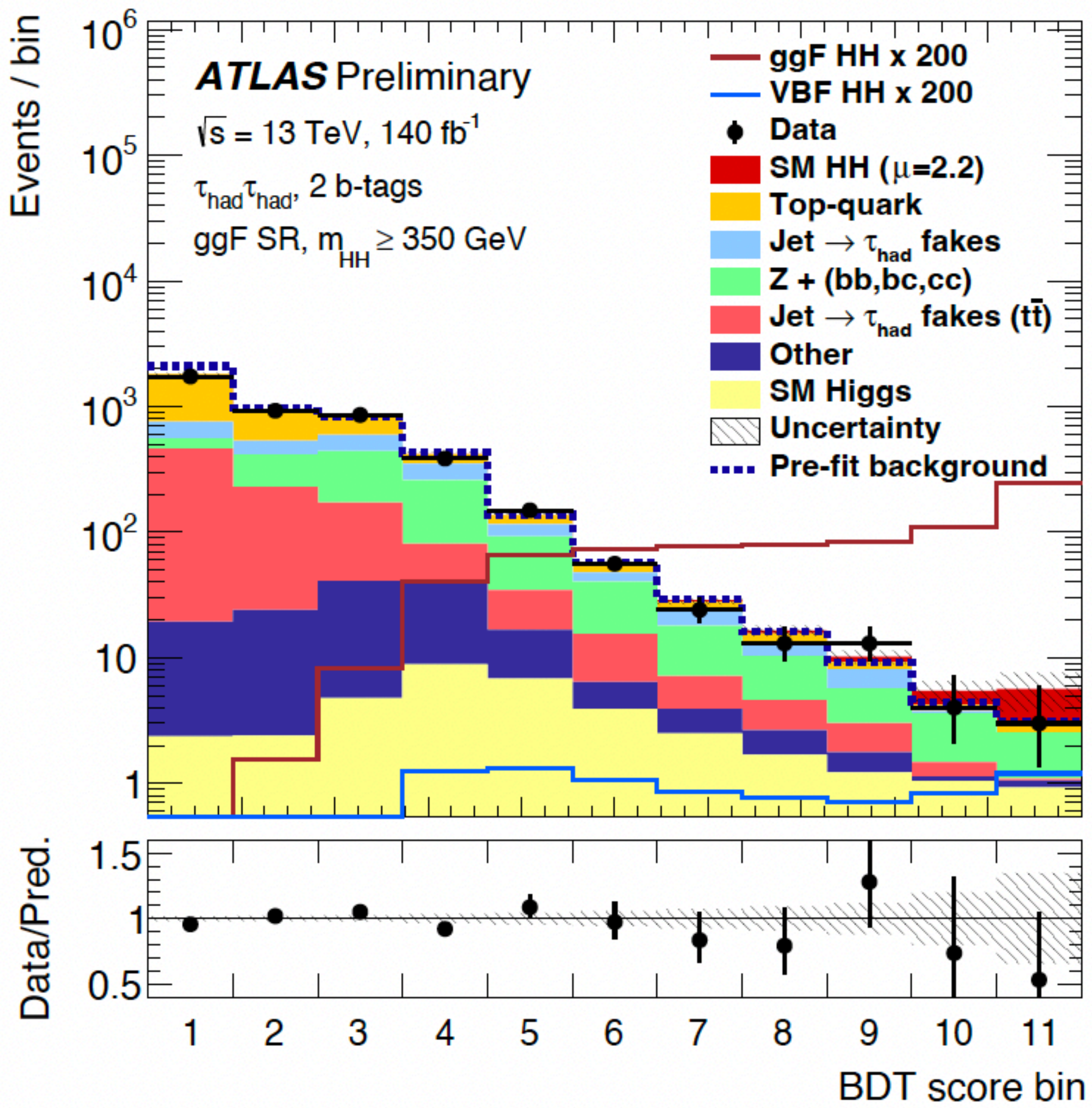


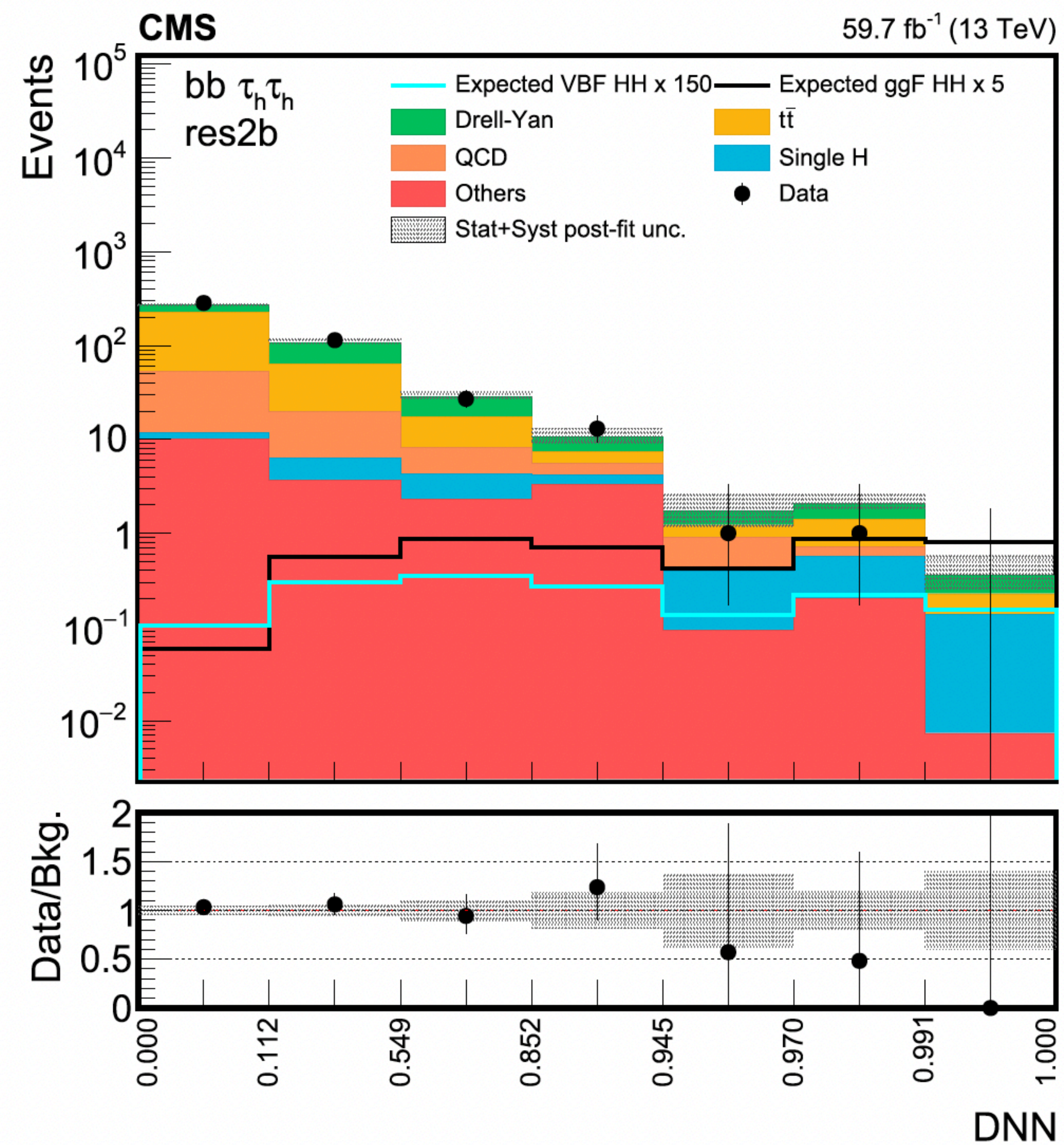
Non-resonant HH searches: status and perspectives
Higgs2023 [Nov 27- Dec 2]
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS vs CMS $HH \to b\bar{b}\tau\tau$

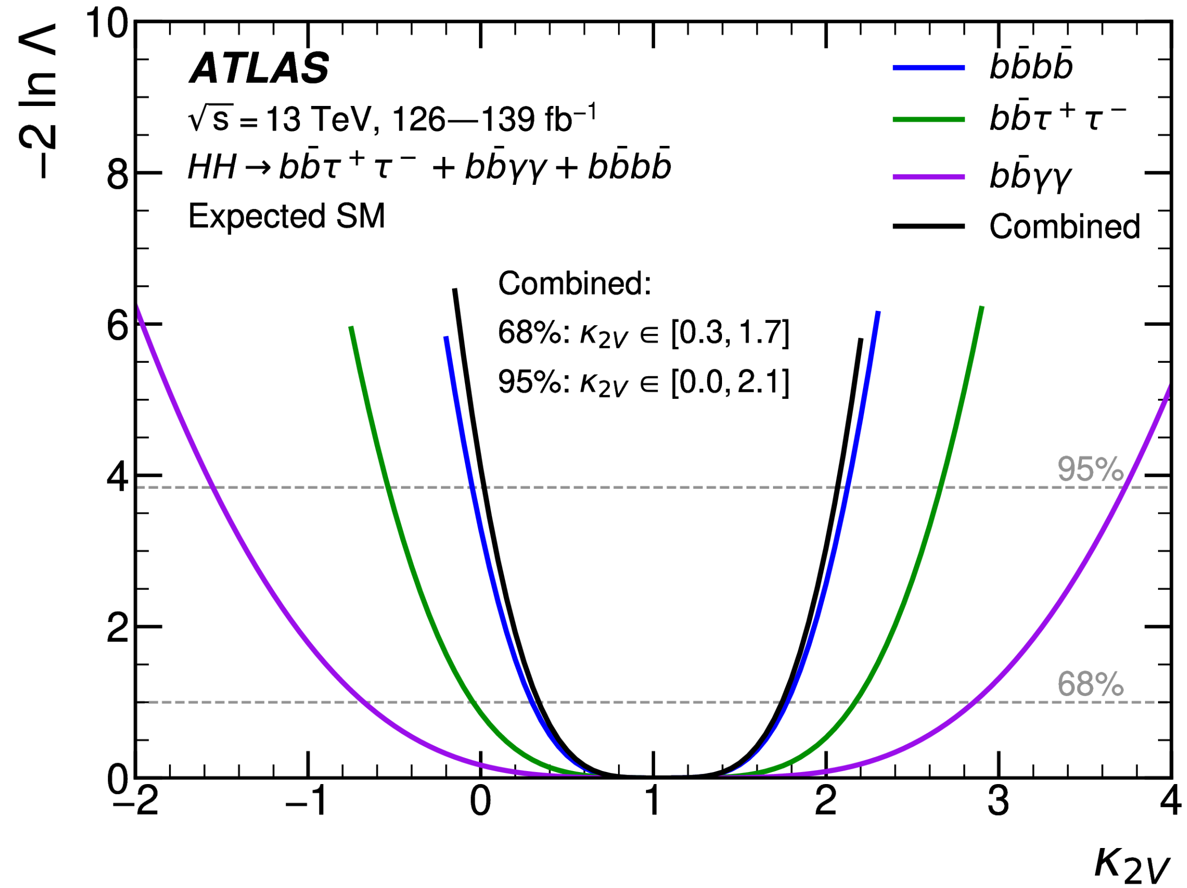
Data/background distributions in most sensitive ggF categories





ATLAS H+HH combination (1)

Phys. Lett. B 843 (2023) 137745

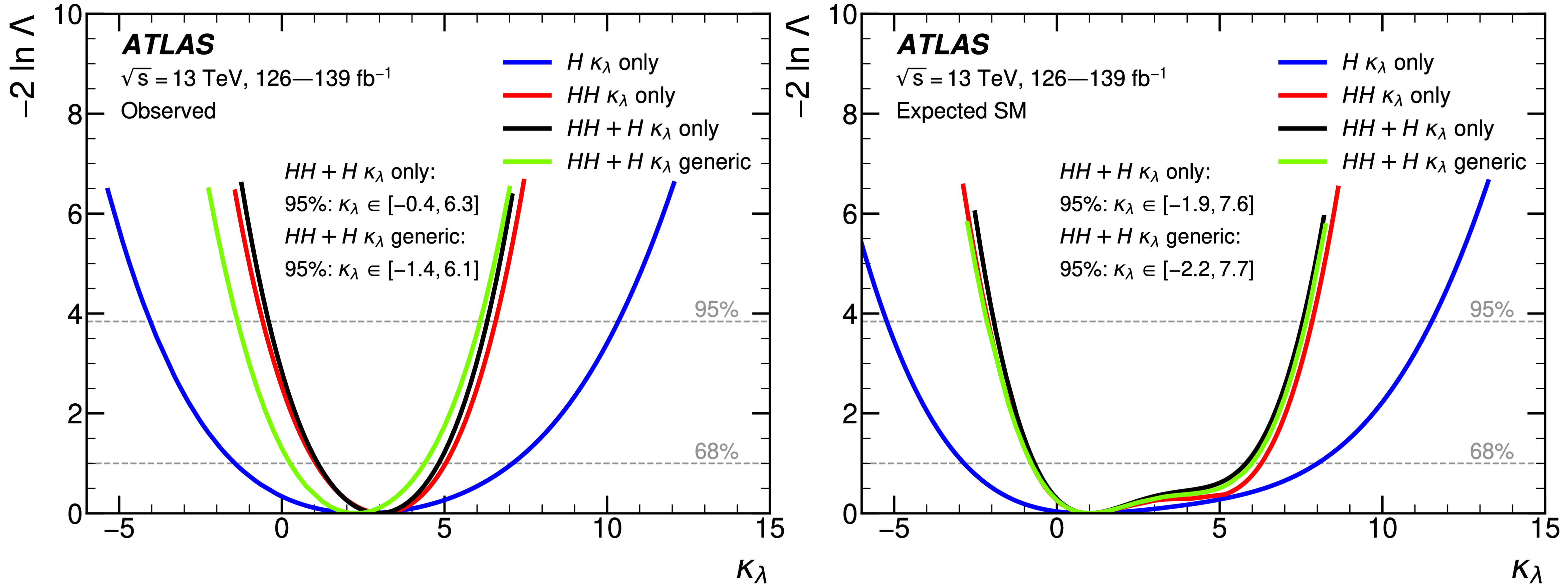


Final state	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
$HH \to b\bar{b}\gamma\gamma$	$-0.8 < \kappa_{2V} < 3.0$	$-1.6 < \kappa_{2V} < 3.7$	$\kappa_{2V} = 1.1^{+1.0}_{-1.0}$
$HH \to b\bar{b}\tau^+\tau^-$	$-0.6 < \kappa_{2V} < 2.7$	$-0.5 < \kappa_{2V} < 2.7$	$\kappa_{2V} = 1.5^{+0.7}_{-1.7}$
$HH \to b\bar{b}b\bar{b}$	$0.0 < \kappa_{2V} < 2.1$	$0.0 < \kappa_{2V} < 2.1$	$\kappa_{2V} = 1.0^{+0.7}_{-0.6}$
HH combination	$0.1 < \kappa_{2V} < 2.0$	$0.0 < \kappa_{2V} < 2.1$	$\kappa_{2V} = 1.1^{+0.6}_{-0.6}$

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

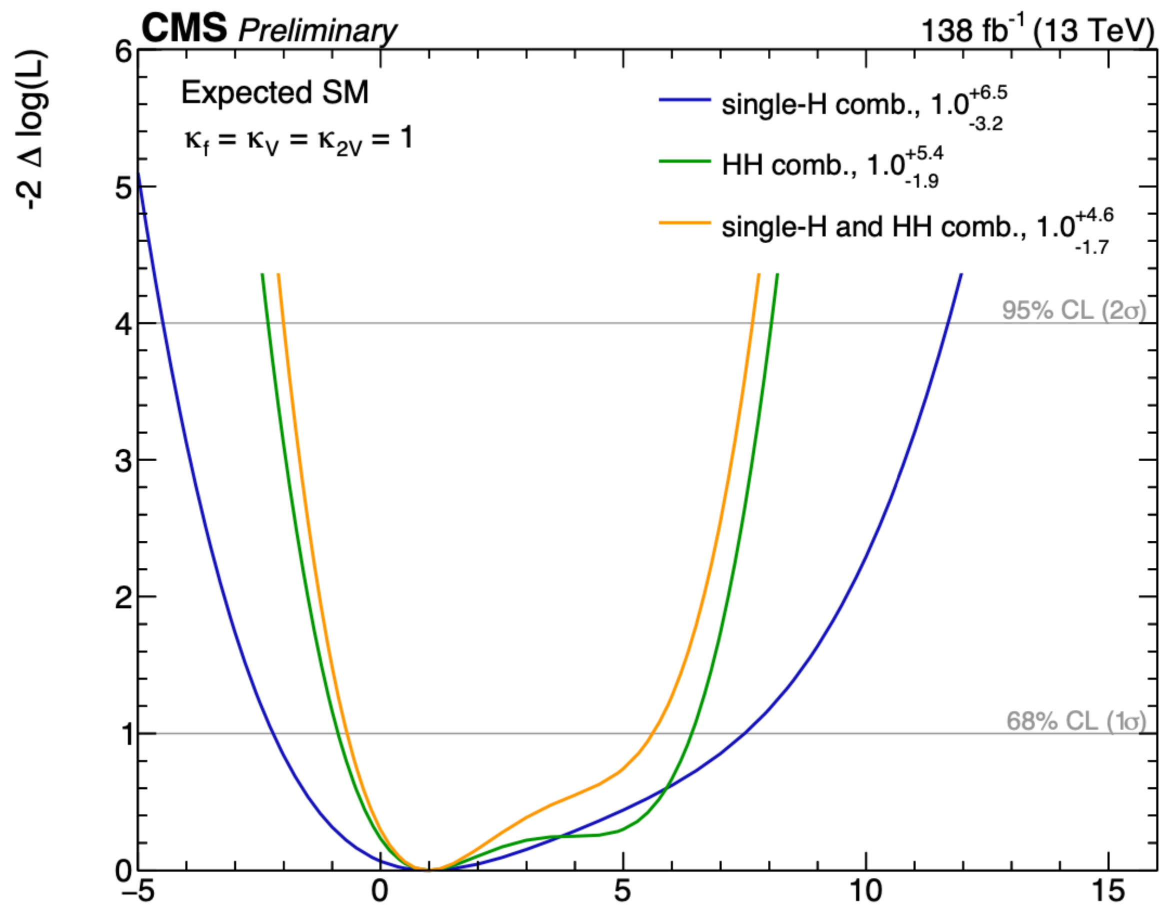
ATLAS H+HH combination (2)

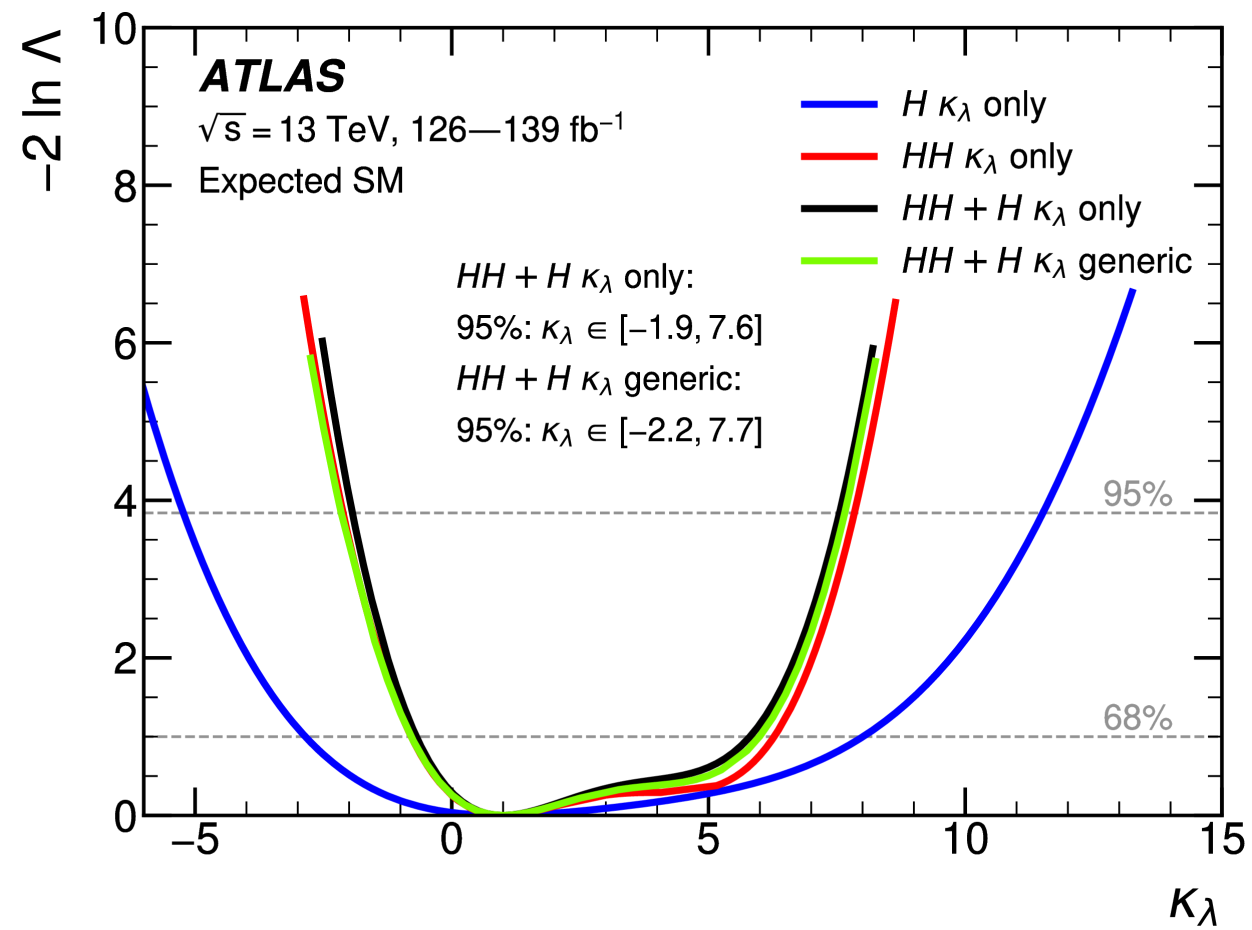
Phys. Lett. B 843 (2023) 137745



Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

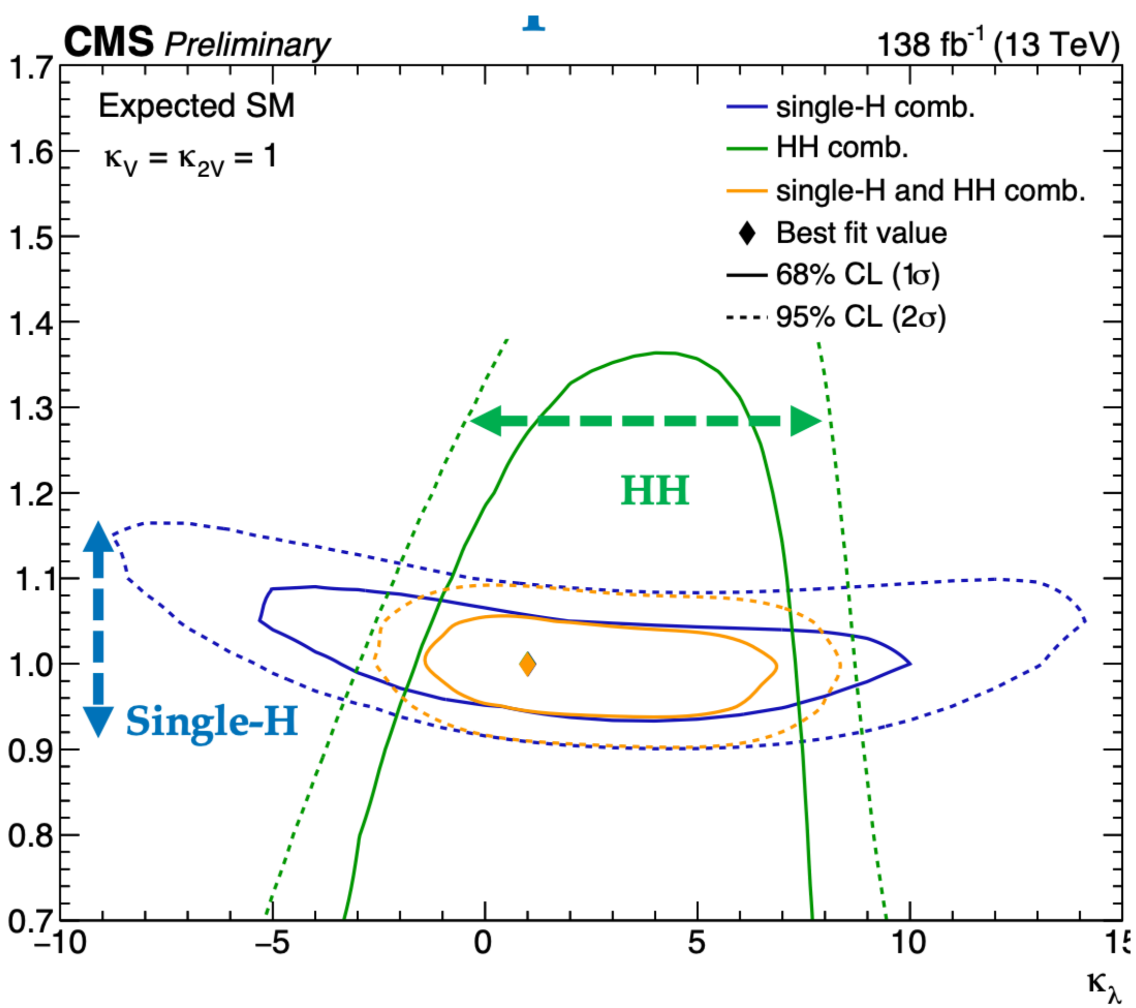
H+HH combination (ATLAS vs CMS)

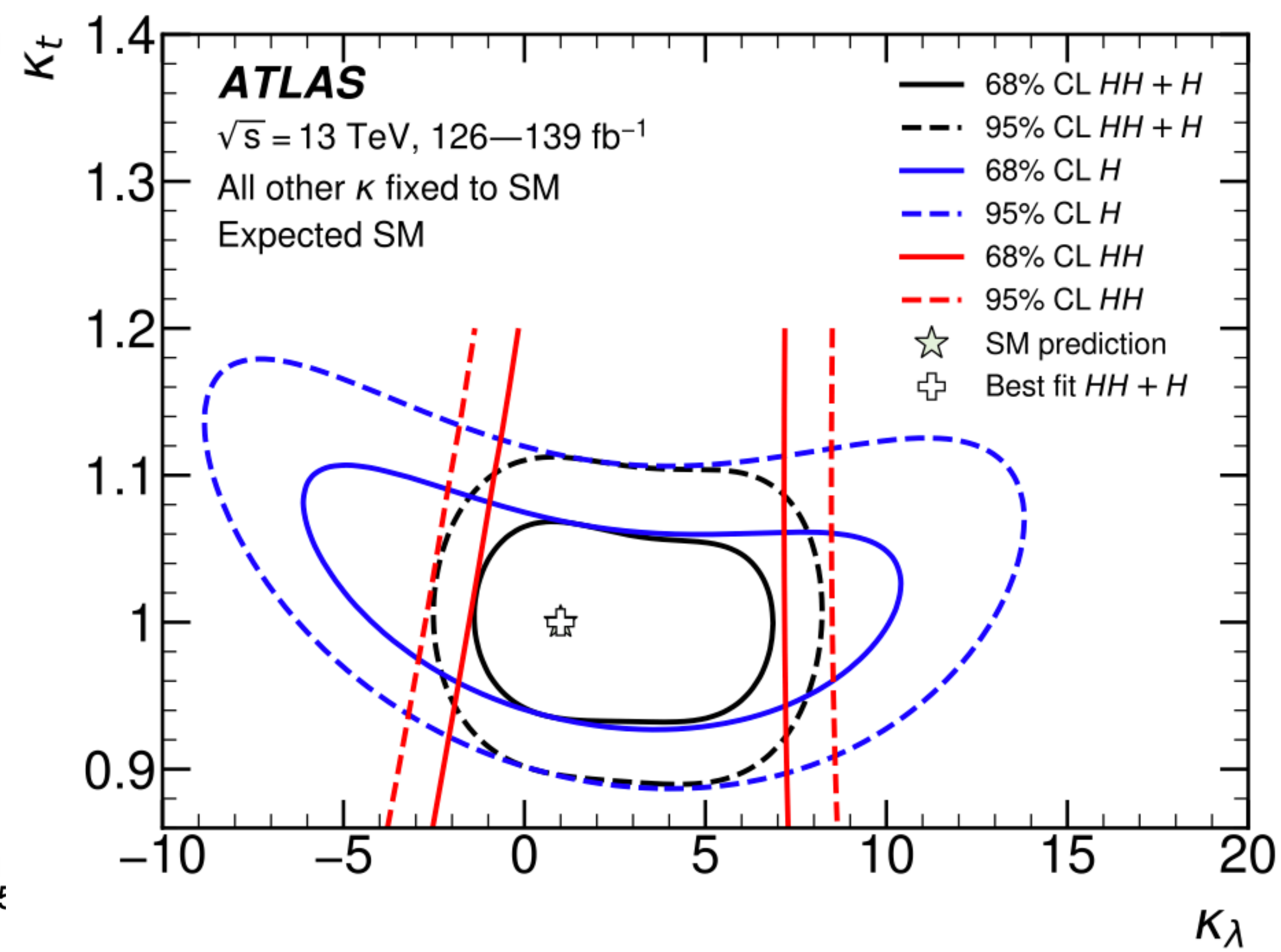




Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

H+HH combination (ATLAS vs CMS)

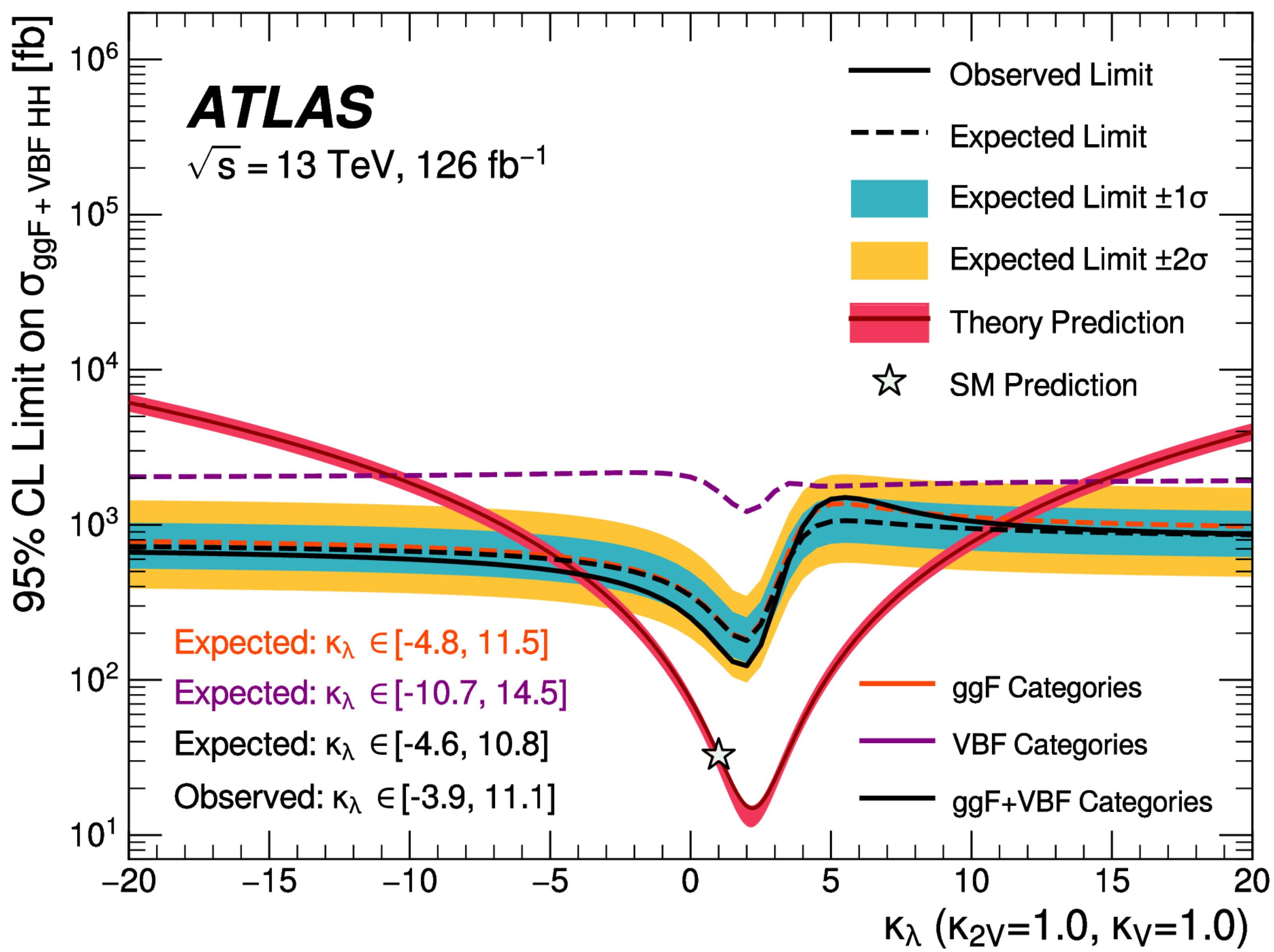




Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS resolved $HH \rightarrow b\bar{b}b\bar{b}$

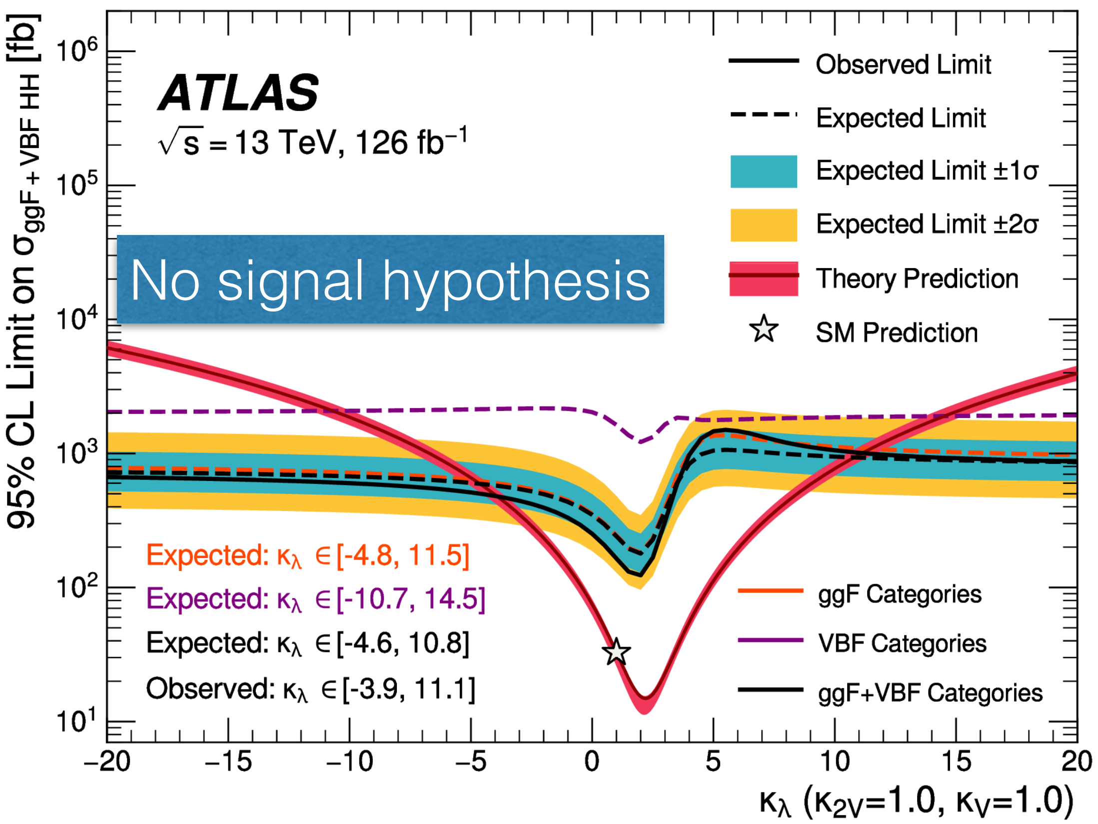
Additional material

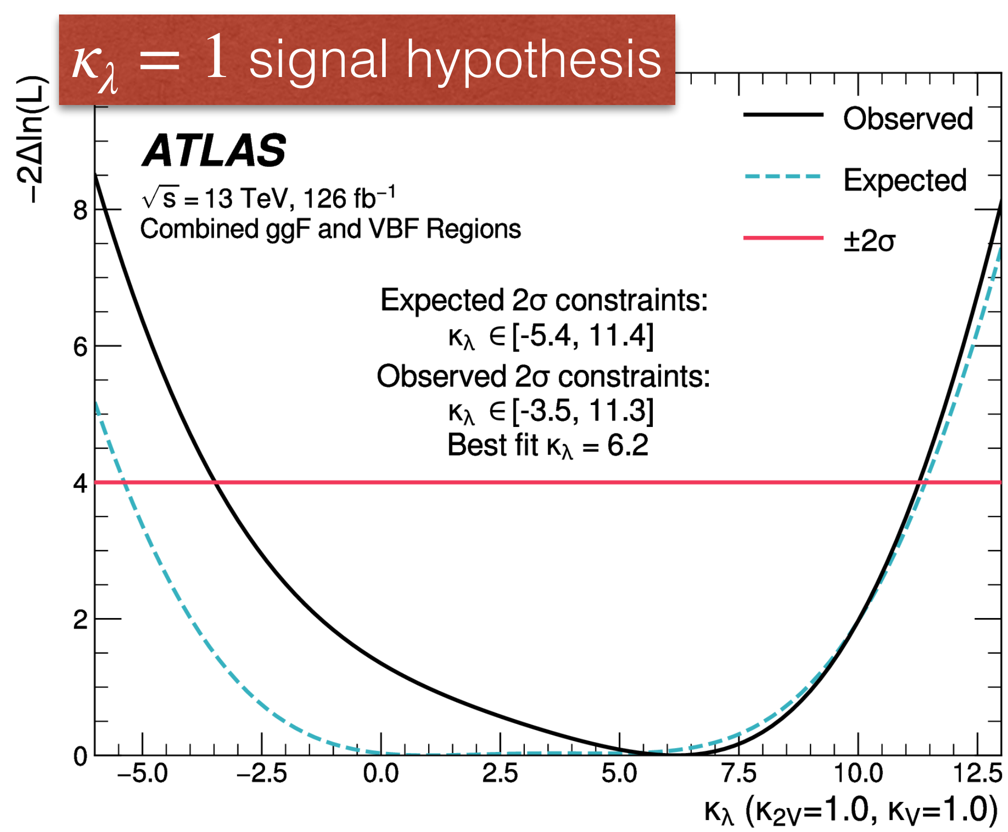


Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

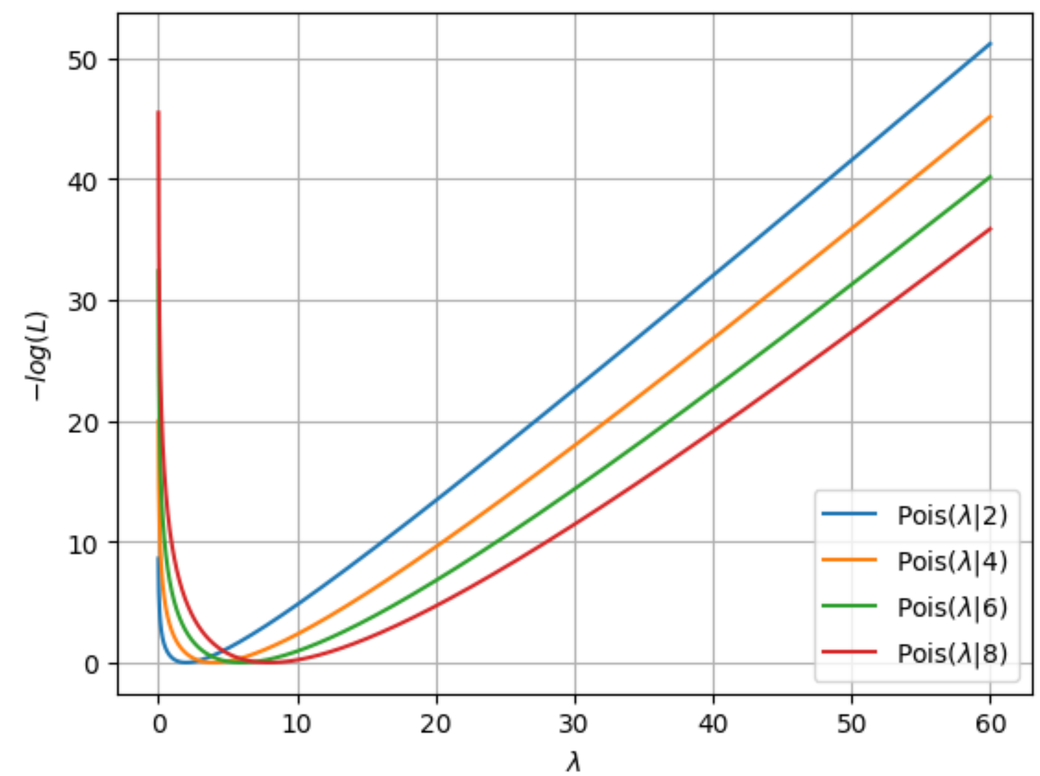
ATLAS resolved $HH \rightarrow b\bar{b}b\bar{b}$

Likelihood vs cross-section





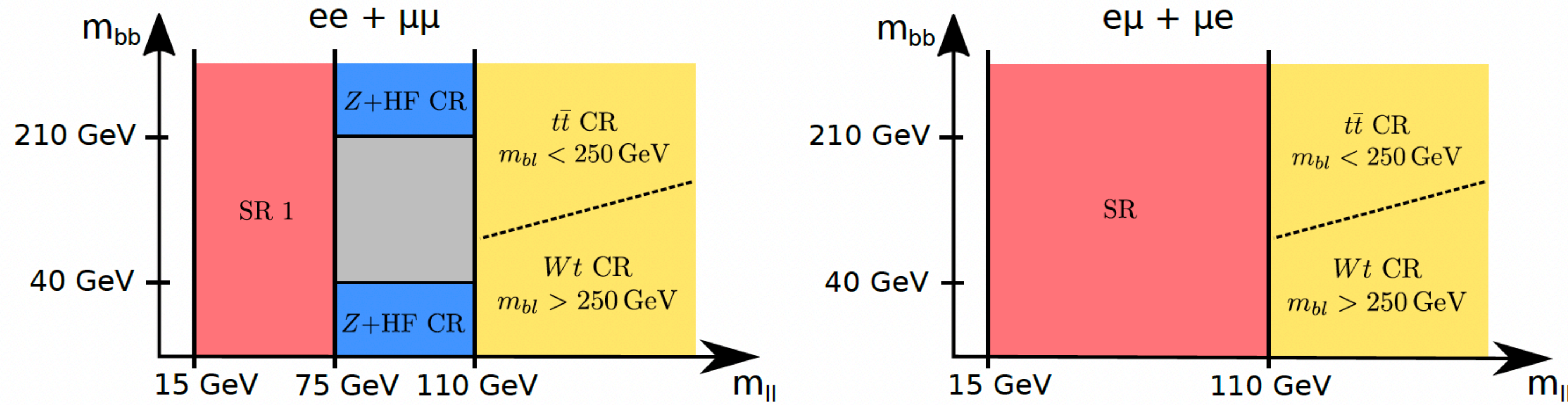
With Poisson pdf, no signal hypothesis should give more stringent limit (i.e. cross-section scan more stringent than likelihood scan)



Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS $HH \to b\bar{b}\, l^+ l^- \nu\nu$ (1)

arXiv:2310.11286



(a) (b)

Figure 3: Definition of signal and control regions for same lepton flavour (a) and different lepton flavour (b) events. The greyed-out region is excluded as it makes a negligible contribution to the final results. The $m_{b\ell}$ discriminant variable [54] is used to further separate the top CR into separate $t\bar{t}$ and Wt control regions.

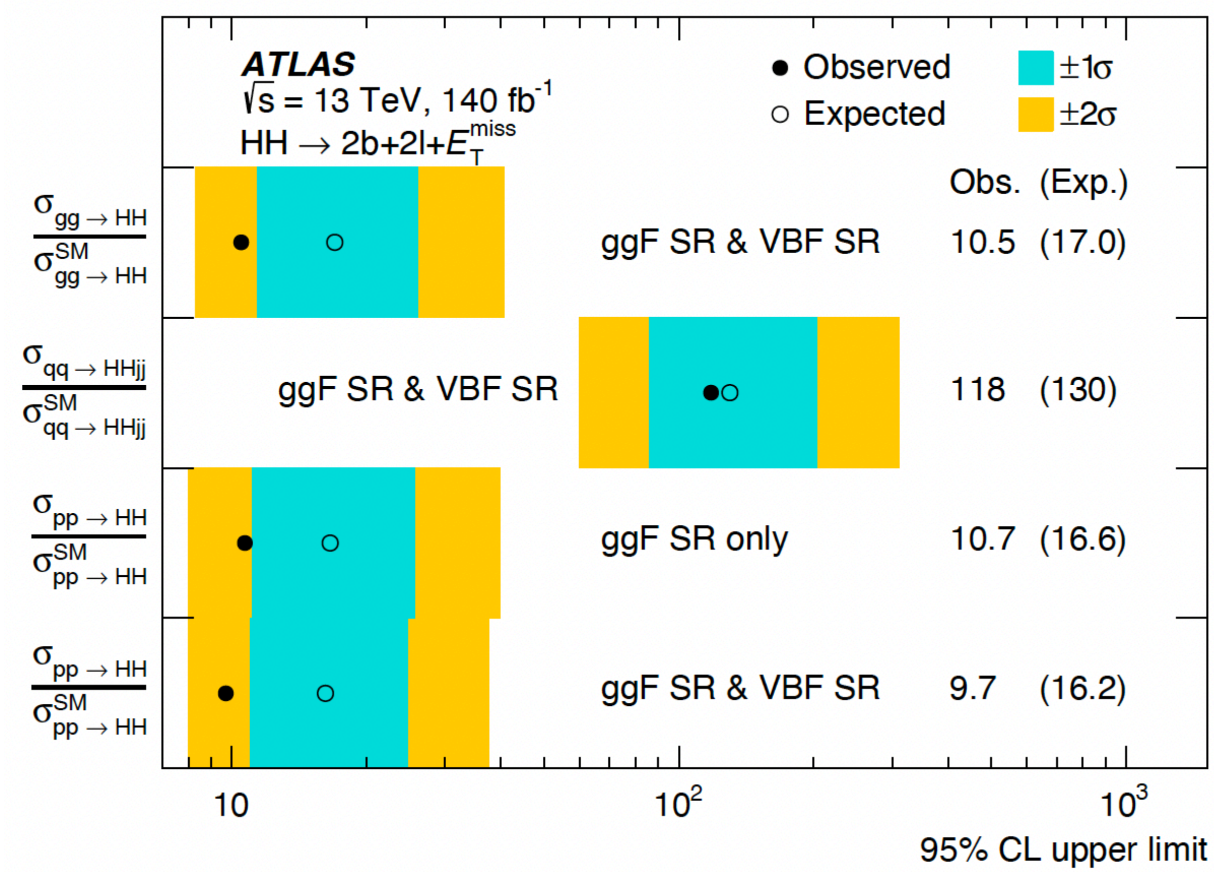
Table 2: Cutflow for event selection using SM $gg/qq \to HH$ signal samples in various decay channels. For both ggF and VBF signal samples, the SM HH cross-section, σ, and branching ratio, $\mathcal{B}$, are assumed when computing event yields for a luminosity of $\mathcal{L} = 140\,\text{fb}^{-1}$. Efficiencies are different for $bbZZ(\to 2\ell 2\nu)$ compared to $bbZZ(\to 2\ell 2q)$ since the initial number of events considers $Z \to \tau\tau$ while the former does not.

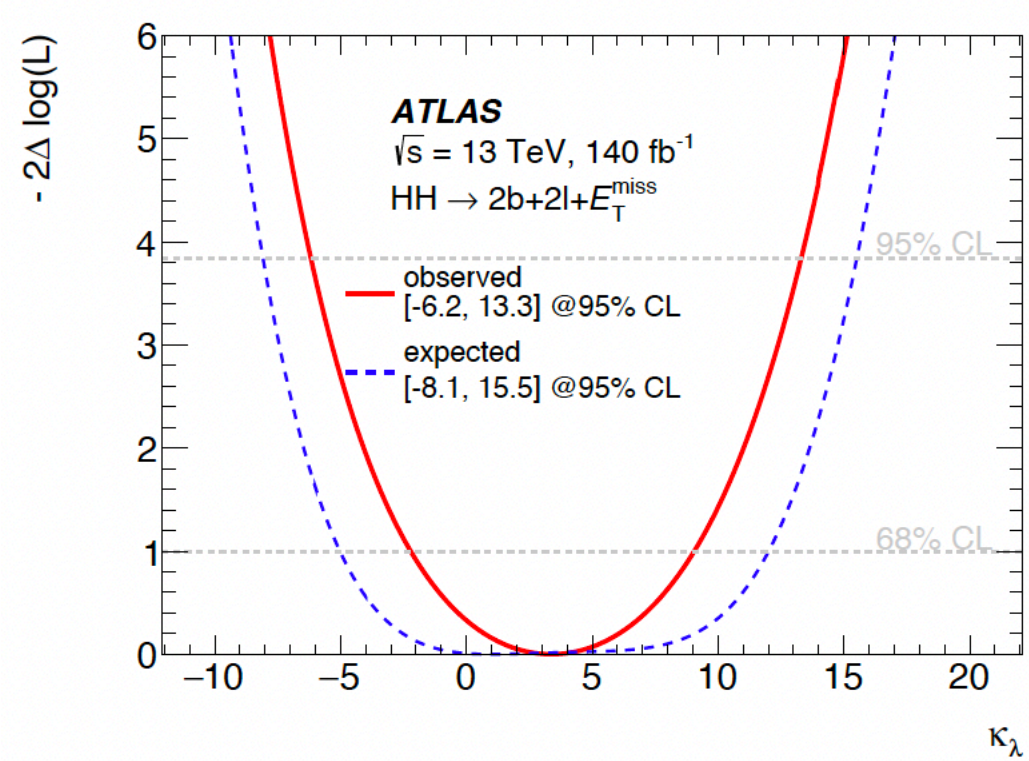
ggF and VBF event selection cut	$bbWW$		$bb\tau\tau$		$bbZZ(\to 2\ell 2\nu)$		$bbZZ(\to 2\ell 2q)$	
	ggF	VBF	ggF	VBF	ggF	VBF	ggF	VBF
Initial number of events ($\mathcal{L} \times \sigma \times \mathcal{B}$)	70	3.9	39	2.2	3.8	0.21	18	1.0
$N_{\text{leptons}} = 2$, opposite sign, pass trigger requirement	22	0.99	8.3	0.35	1.3	0.057	3.6	0.17
$N_{b\text{-jets}} = 2$	9.8	0.39	3.7	0.14	0.57	0.022	1.6	0.067

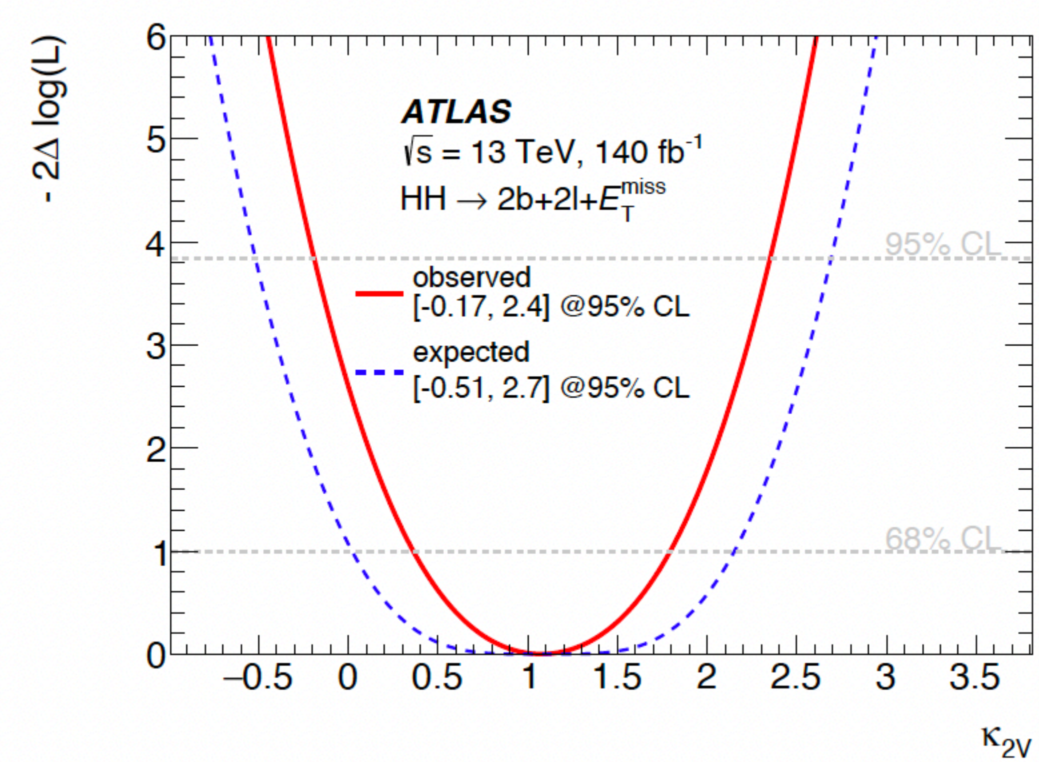
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS $HH \rightarrow b\bar{b}\, l^+ l^- \nu\nu$ (2)

arXiv:2310.11286







Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

ATLAS $HH \to b\bar{b}\,l^+l^-\nu\nu$ (3)

DNN variables

Table 4: Input features used for the DNN in the ggF category. Indices 0 and 1 refer to p_{T}-leading and p_{T}-sub-leading objects respectively.

Input feature	Description
same flavour	unity if final state leptons are ee or $\mu\mu$, zero otherwise
p_{T}^{ℓ}, p_{T}^{b}	transverse momenta of the leptons, b-tagged jets
$m_{\ell\ell}$, $p_{\mathrm{T}}^{\ell\ell}$	invariant mass and the transverse momentum of the di-lepton system
m_{bb}, p_{T}^{bb}	invariant mass and the transverse momentum of the b-tagged jet pair system
m_{T2}^{bb}	stransverse mass of the two b-tagged jets [125, 126]
$\Delta R_{\ell\ell}$, ΔR_{bb}	ΔR between the two leptons and two b-tagged jets
$m_{b\ell}$	$\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$ [54]
$\min \Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$m_{bb\ell\ell}$	invariant mass of the $bb\ell\ell$ system
$E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$-sig	missing transverse energy and its significance [127]
$m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of the p_{T}-leading lepton with respect to $E_{\mathrm{T}}^{\mathrm{miss}}$
$\min m_{\mathrm{T},\ell}$	minimum value of $m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$ and $m_{\mathrm{T}}(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$
$H_{\mathrm{T2}}^{\mathrm{R}}$	measure for boostedness[6] of the two Higgs bosons

Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

CMS $HH \rightarrow b\bar{b}W^{+}W^{-}$(1)

CMS-PAS-HIG-21-005

Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
WJets + Other	Inclusive		

Table 1: The summary of the categories of events according to the DNN based multiclassification and $H \rightarrow b\bar{b}$ topology for the single lepton channel.

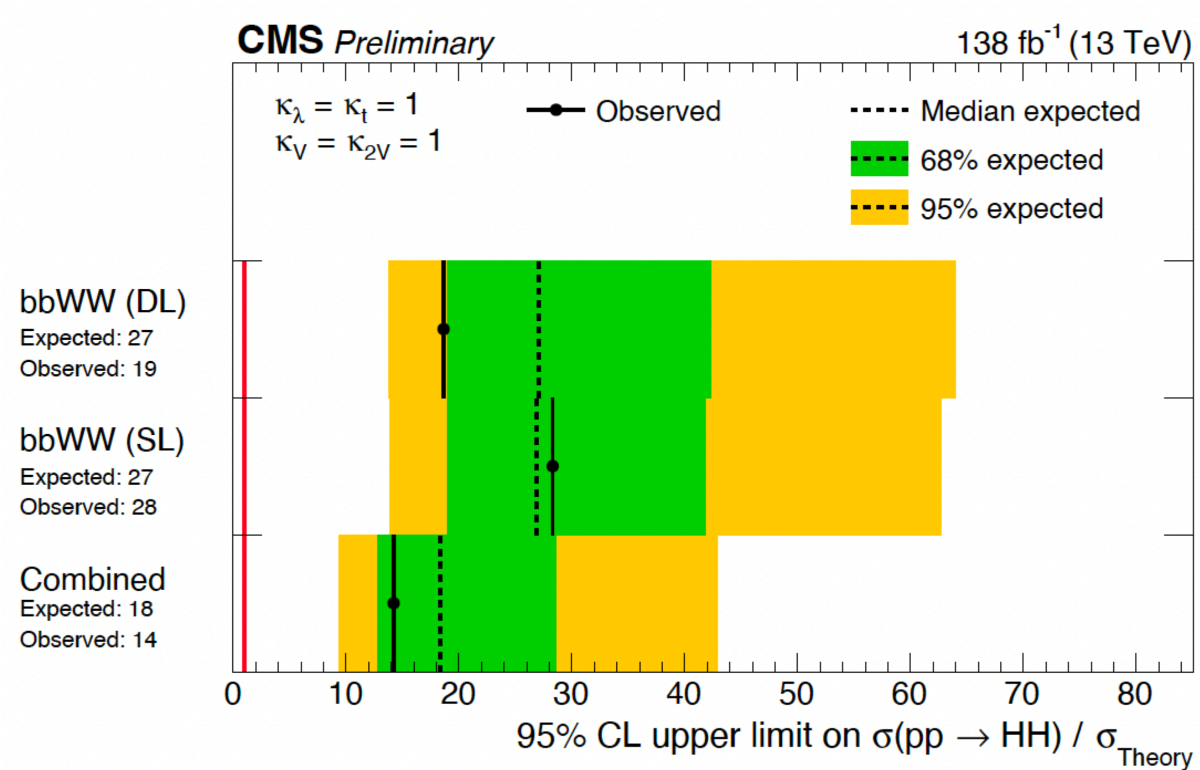
Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + Multi-boson	Inclusive		

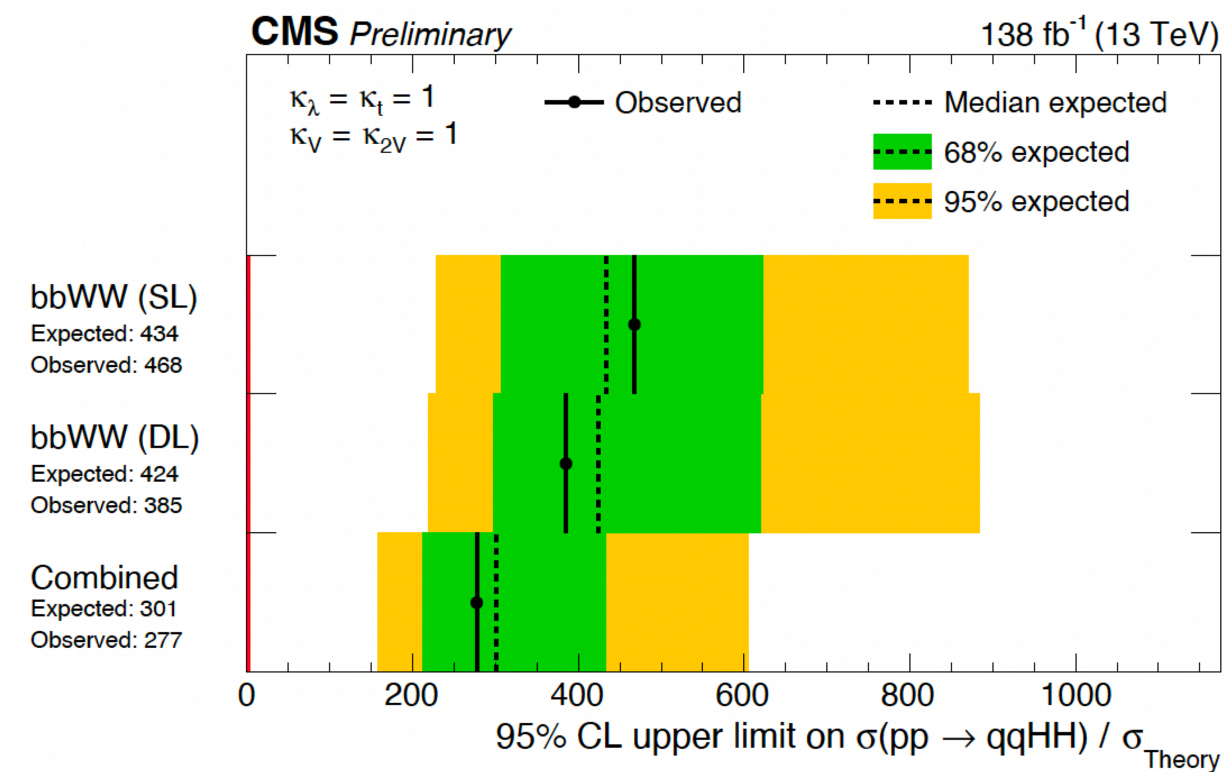
Table 2: The summary of the categories of events according to the DNN based multiclassification and $H \rightarrow b\bar{b}$ topology for the dilepton channel.

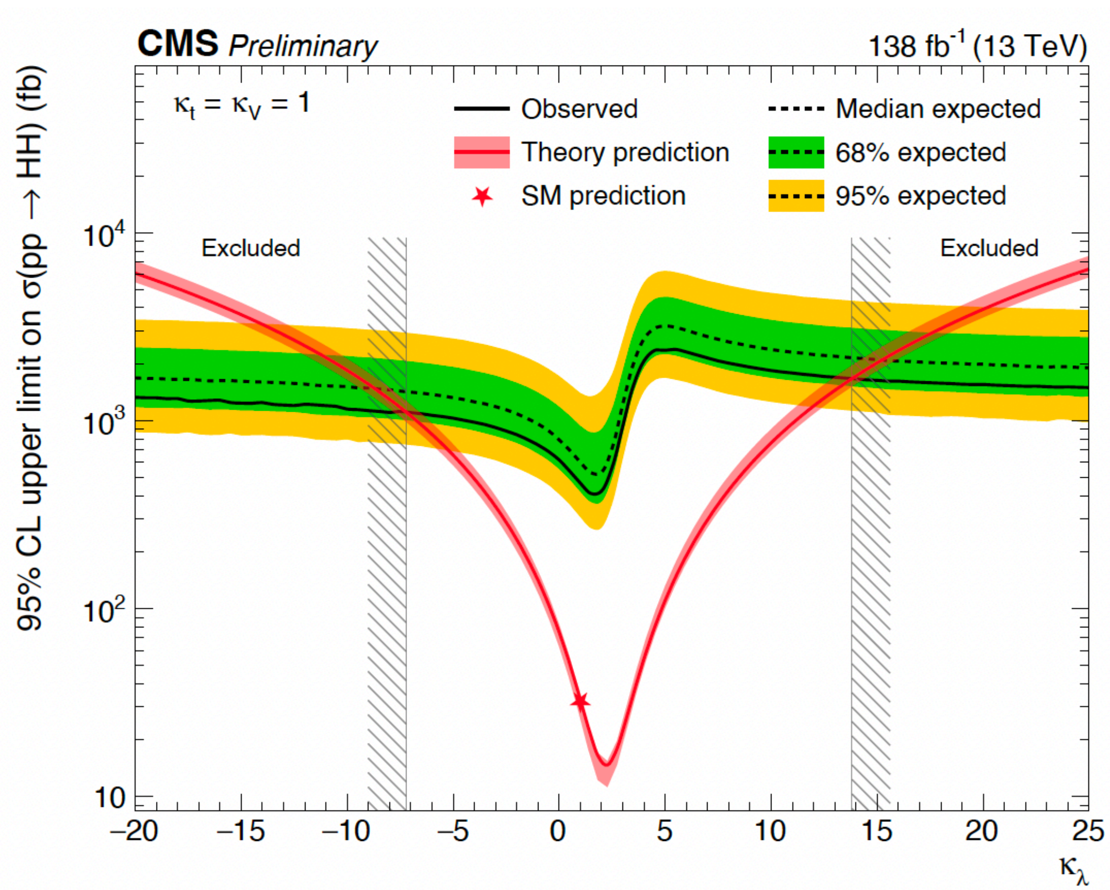
Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre

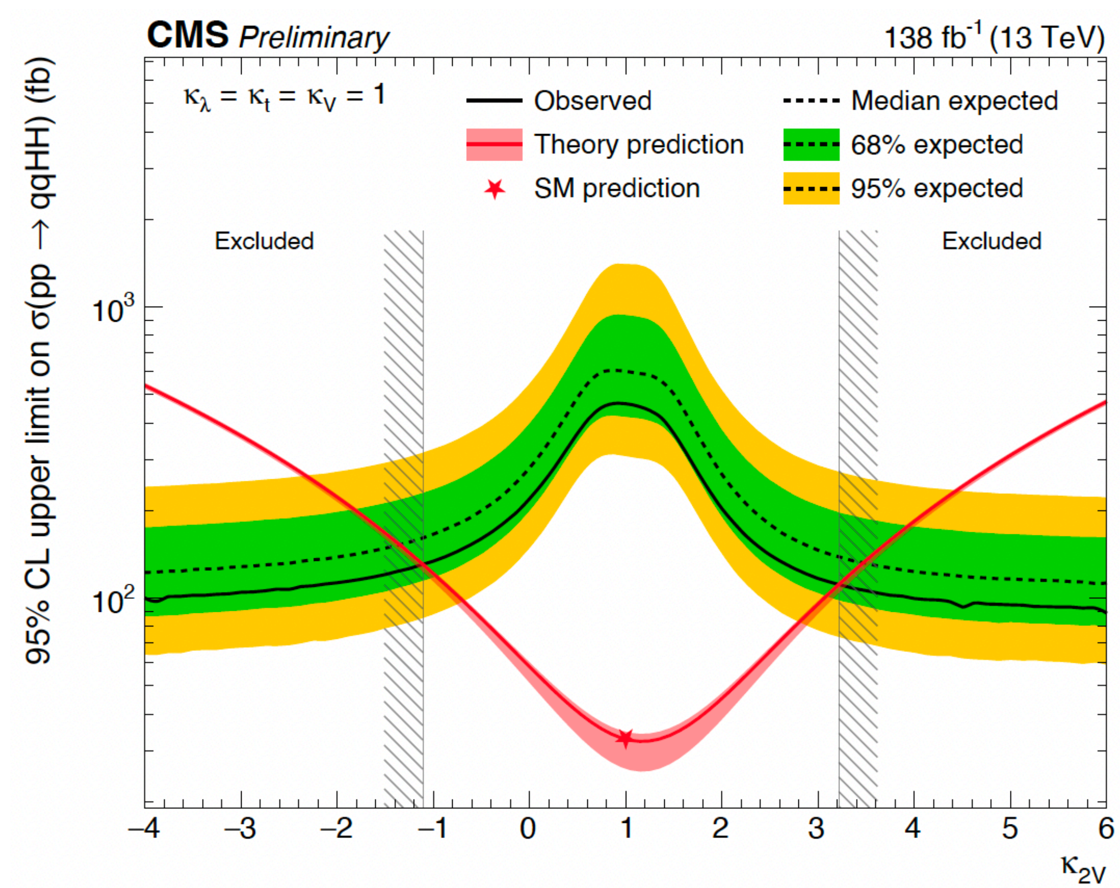
CMS $HH \to b\bar{b}W^+W^-$ (2)

CMS-PAS-HIG-21-005









Marco Valente
Physics department
TRIUMF, Canada's particle accelerator Centre