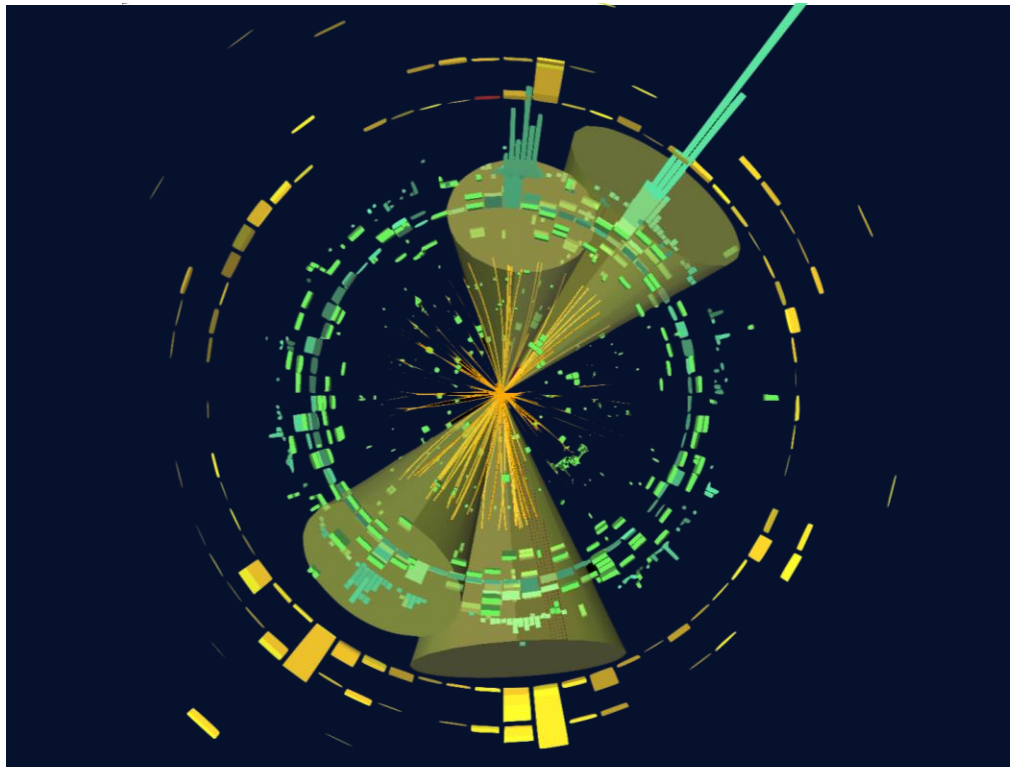
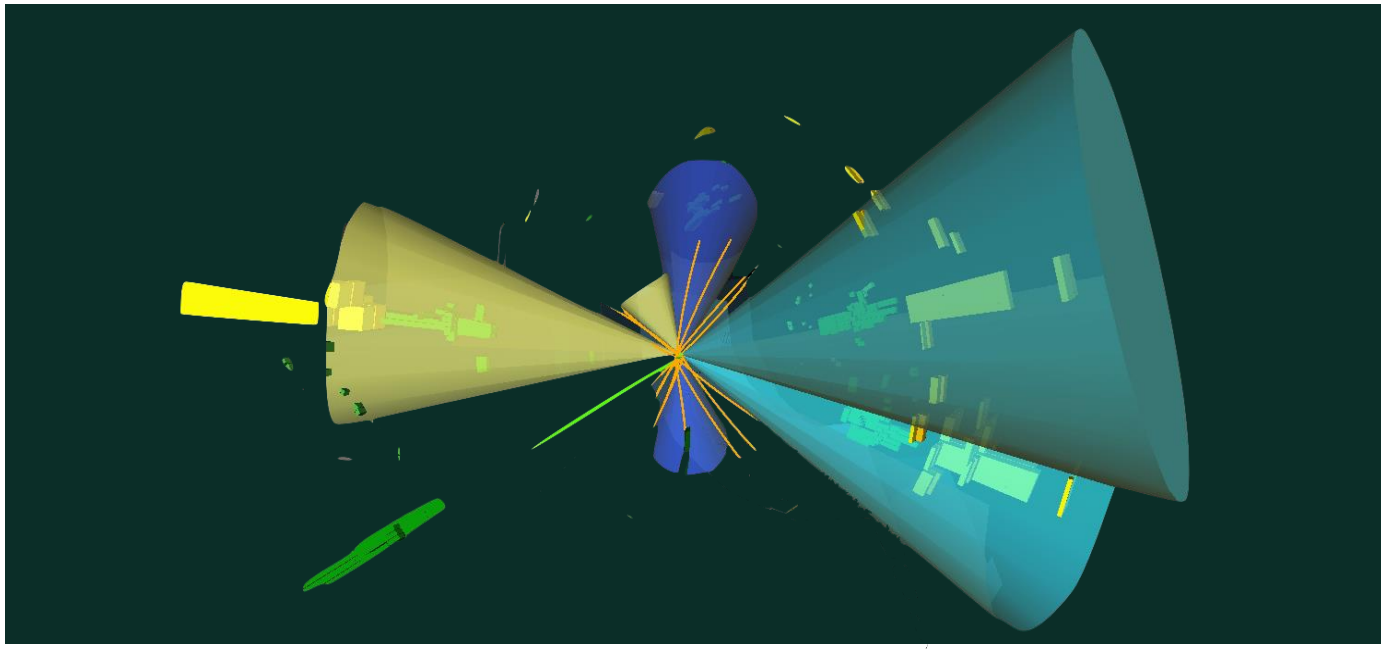




Higgs Boson Experiment: Status, Hot Topics* & Open Questions*

Elisabeth Schopf

(*my personal selection and bias)

Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

Beyond Flavour Workshop, June 2025, Siegen

Overview of experimental study subjects

Higgs boson properties
mass, CP properties, width, etc.

Higgs boson couplings
production (x-section/ kinematics), decays, etc.

Higgs boson self-interaction
di-/triple-Higgs production

Higgs sector as a tool to new particles
Add. scalars, Higgs→exotica, heavy resonances → Higgs, etc.

1. What can we deduce from this about the history of the universe?
2. Where is the new physics?

Overview of experimental study subjects

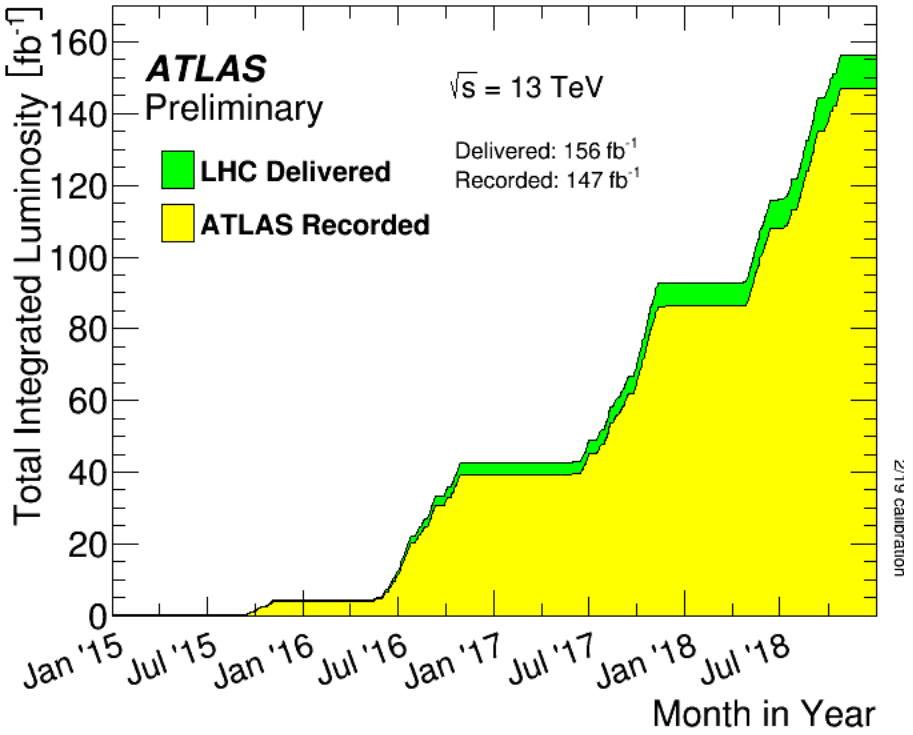
Higgs boson couplings
Yukawa
production (x-section/ kinematics), decays, etc.

Higgs boson self-interaction
di-/triple-Higgs production

Higgs (Quark) Yukawa Sector

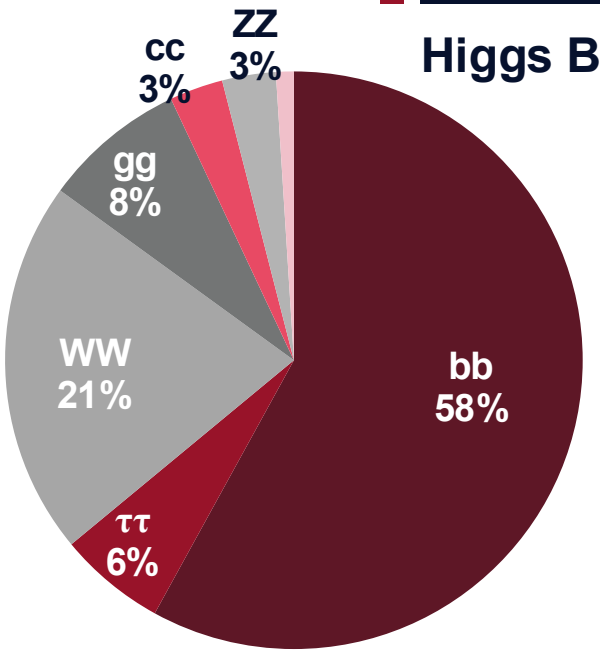
In the following assume SM Higgs with mass of 125 GeV

What do we have to work with?



x-section (pp, 13 TeV)	
ggF	~50 pb
VBF	~4 pb
WH	~1.4 pb
ZH	~0.9 pb
ttH	~0.5 pb
bbH	~0.5 pb
tH	~0.08 pb

Higgs BRs



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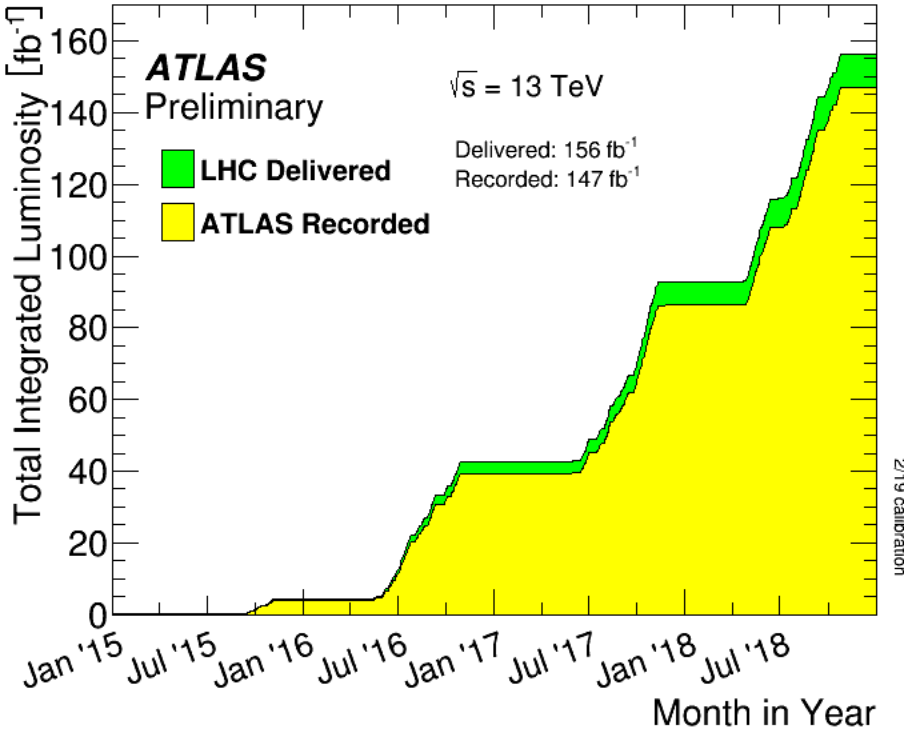

✖

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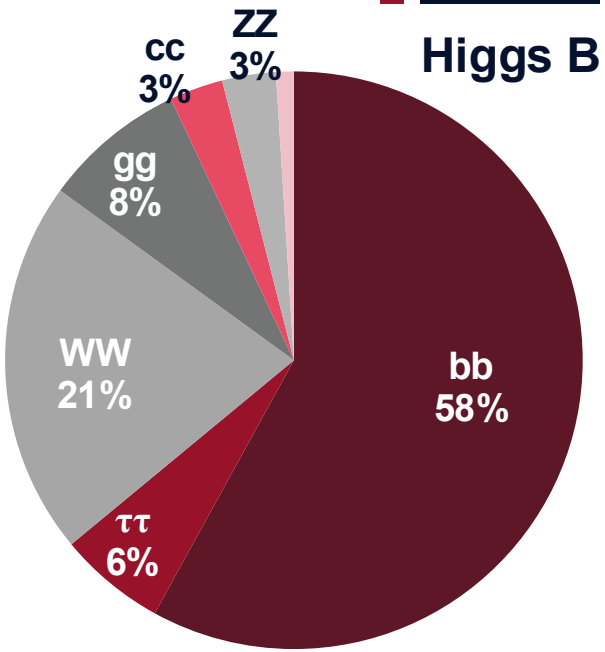
Higgs BRs

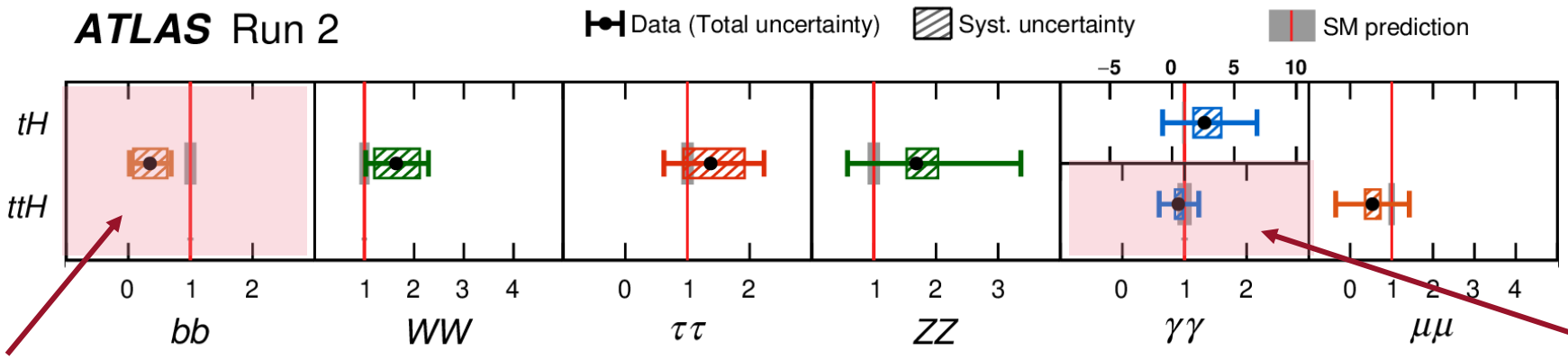


☺ **~10⁸ (SM) Higgs bosons @ 13 TeV**
~10⁸ (SM) Higgs bosons @ 13.6 TeV

- detector acceptance
- trigger efficiency
- reconstruction efficiency
- …

☹

Top Yukawa from ttH Production



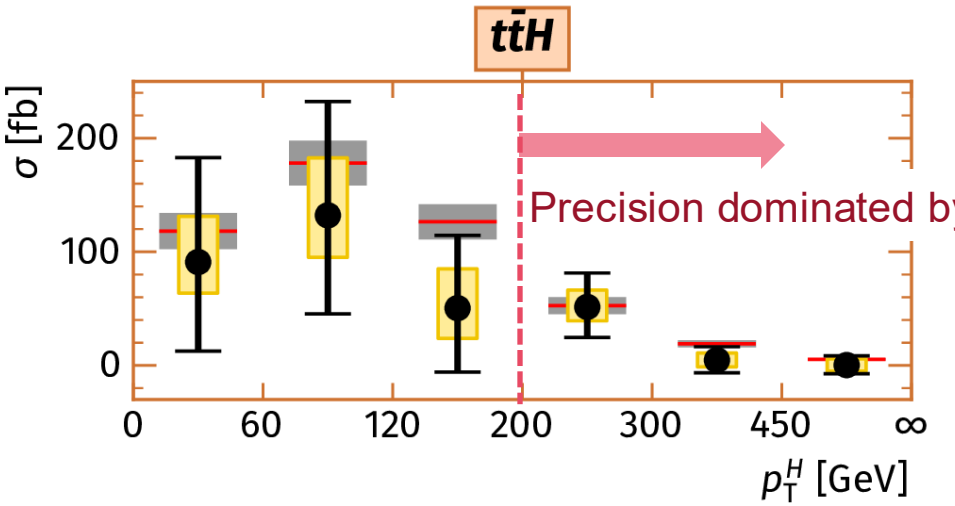
Nature 607 52 (2022)
HEPData

dominated by syst. unc.

30% stat. unc.

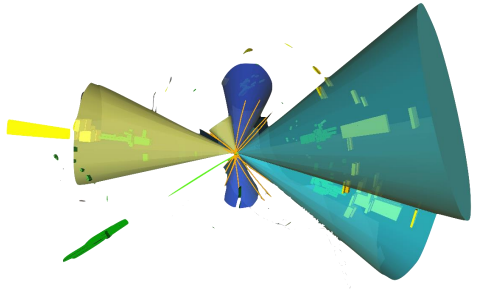
Why focus on ttH,H→bb?

→ Ability to probe phase space corners due to BR advantage (if systematic uncertainties can be controlled)



Eur. Phys. J. C 85 (2025) 210

Experimental Challenges of ttH,H→bb

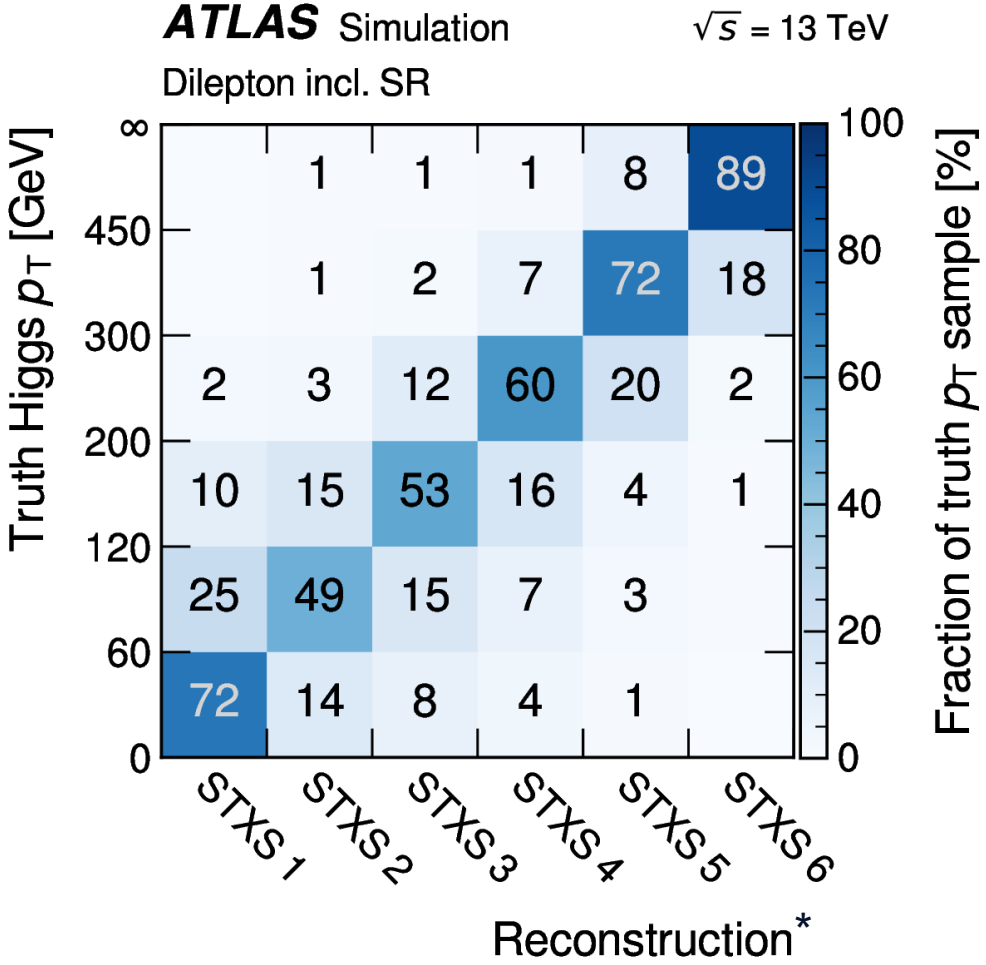


1. **Which jet is which?**

→ 2 b from top, 2 b from Higgs + chance of mis-identified jets

→ ID especially important for measurements as function of p_T^H

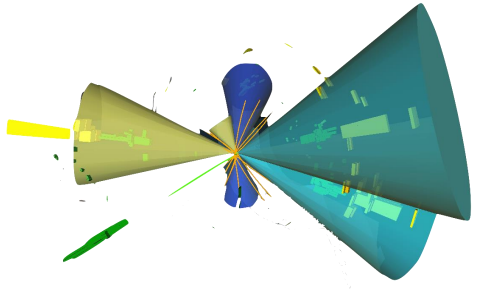
→ Higgs candidate jets identified using transformer networks



*off-diagonal elements due to wrong jets identified as Higgs + detector resolution effects

Eur. Phys. J. C 85 (2025) 210

Experimental Challenges of ttH,H→bb



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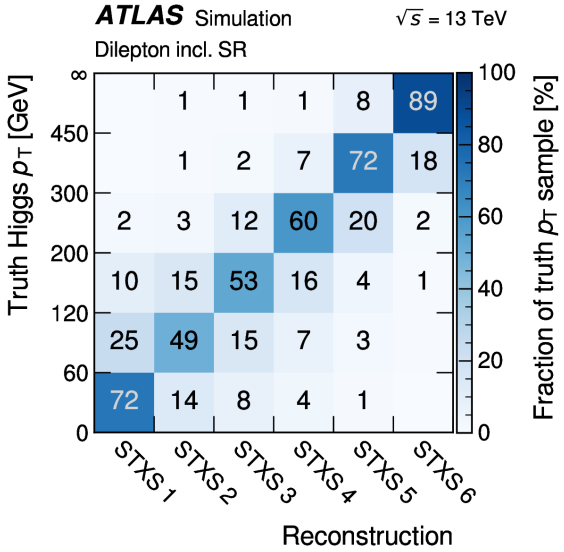
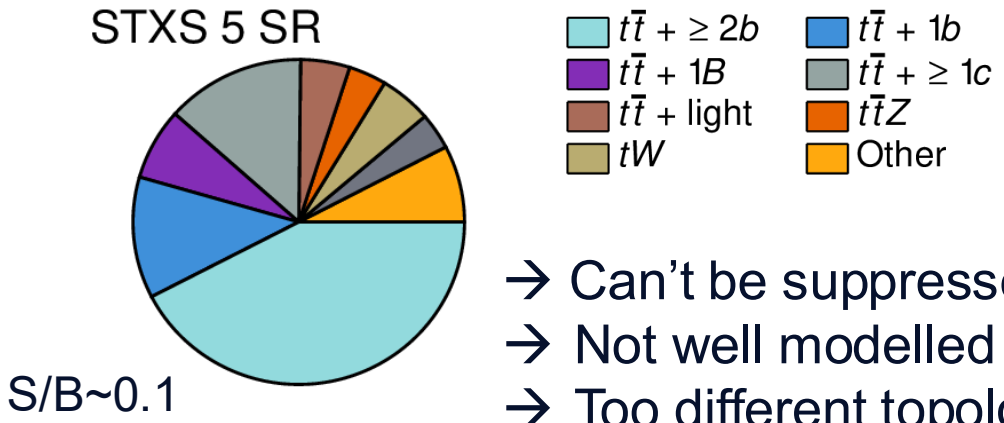


2. How to control all of these backgrounds?



S/B~0.1

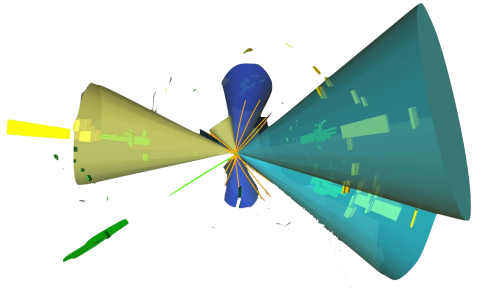
→ Can't be suppressed sufficiently enough
→ Not well modelled in MC
→ Too different topology/kinematics in BGs so there is no one-size-fits-all solution

tt+≥2b	*tt+1B*	*tt+1b*	*tt+≥1c*	*tt+light*
0.94 ± 0.08	$1.15^{+0.15}_{-0.14}$	1.06 ± 0.10	$1.51^{+0.19}_{-0.18}$	0.78 ± 0.08

Measured MC-to-data scale factors

Eur. Phys. J. C 85 (2025) 210

Experimental Challenges of ttH,H→bb



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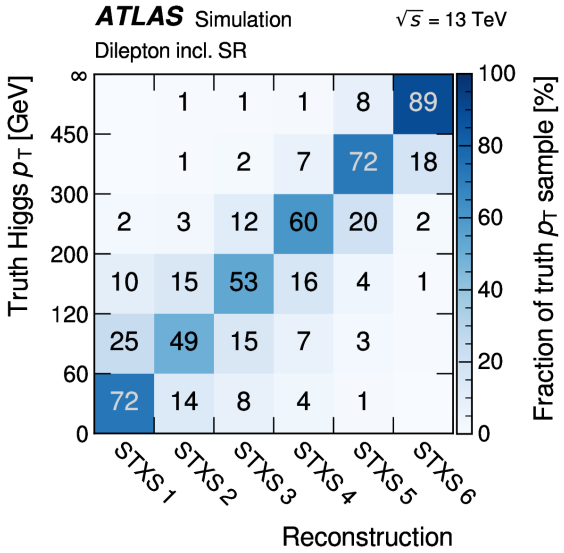

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tt+≥2b	*tt+1B*	*tt+1b*	*tt+≥1c*	*tt+light*
0.94 ± 0.08	$1.15^{+0.15}_{-0.14}$	1.06 ± 0.10	$1.51^{+0.19}_{-0.18}$	0.78 ± 0.08

3. Why are the systematic uncertainties to large?

- ttH theory uncertainties
- tt+X theory uncertainties
- Jet flavour ID

Eur. Phys. J. C 85 (2025) 210

A Closer Look: ttH,H→bb Systematics

Uncertainty source	$\Delta\sigma_{t\bar{t}H}$ (fb)	
Process modelling		
$t\bar{t}H$ modelling		
$t\bar{t}H$ radiation	+35	−21
$t\bar{t}H$ parton shower	+32	−19
$t\bar{t}H$ matching	<0.1	−0.3
$t\bar{t}H$ theory	+25	−17
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ radiation	±31	
$t\bar{t}+\geq 1b$ parton shower	±29	
$t\bar{t}+\geq 1b$ matching	±19	
$t\bar{t}+\geq 1c$ modelling	±18	
$t\bar{t}+$ light modelling	±5	
tW modelling	±16	
Minor background modelling	±19	
Flavour tagging	±36	
Jet modelling	±22	
Monte-Carlo statistics	±17	
Other instrumental	±10	
Total systematic uncertainty	+85	−75
Normalisation factors	±21	
Total statistical uncertainty	±54	
Total uncertainty	+101	−92

ttH

tt+≥1b

other (t)t+X

MC sample	Generator	Process	Parton shower	Matching/ Parton shower settings
POWHEG+PYTHIA8	POWHEG BOX v2	$t\bar{t}$ NLO	PYTHIA 8.230	POWHEG $h_{\text{damp}}=1.5m_{\text{top}}$ $p_{\text{T}}^{\text{hard}}=0$ globalRecoil recoilToColoured=ON
POWHEG+PYTHIA8 $t\bar{t}b\bar{b}$	POWHEG BOX RES	$t\bar{t}b\bar{b}$ NLO	PYTHIA 8.230	POWHEG BOX RES $h_{\text{bzd}}=5$ $p_{\text{T}}^{\text{hard}}=0$ globalRecoil

tt+≥1c
tt+light

tt+≥1b

→ Large uncertainty in **ttH and tt+b from radiation and parton shower** modelling
  → ttbb 4FS sample good in modelling certain variables but still lacking in others

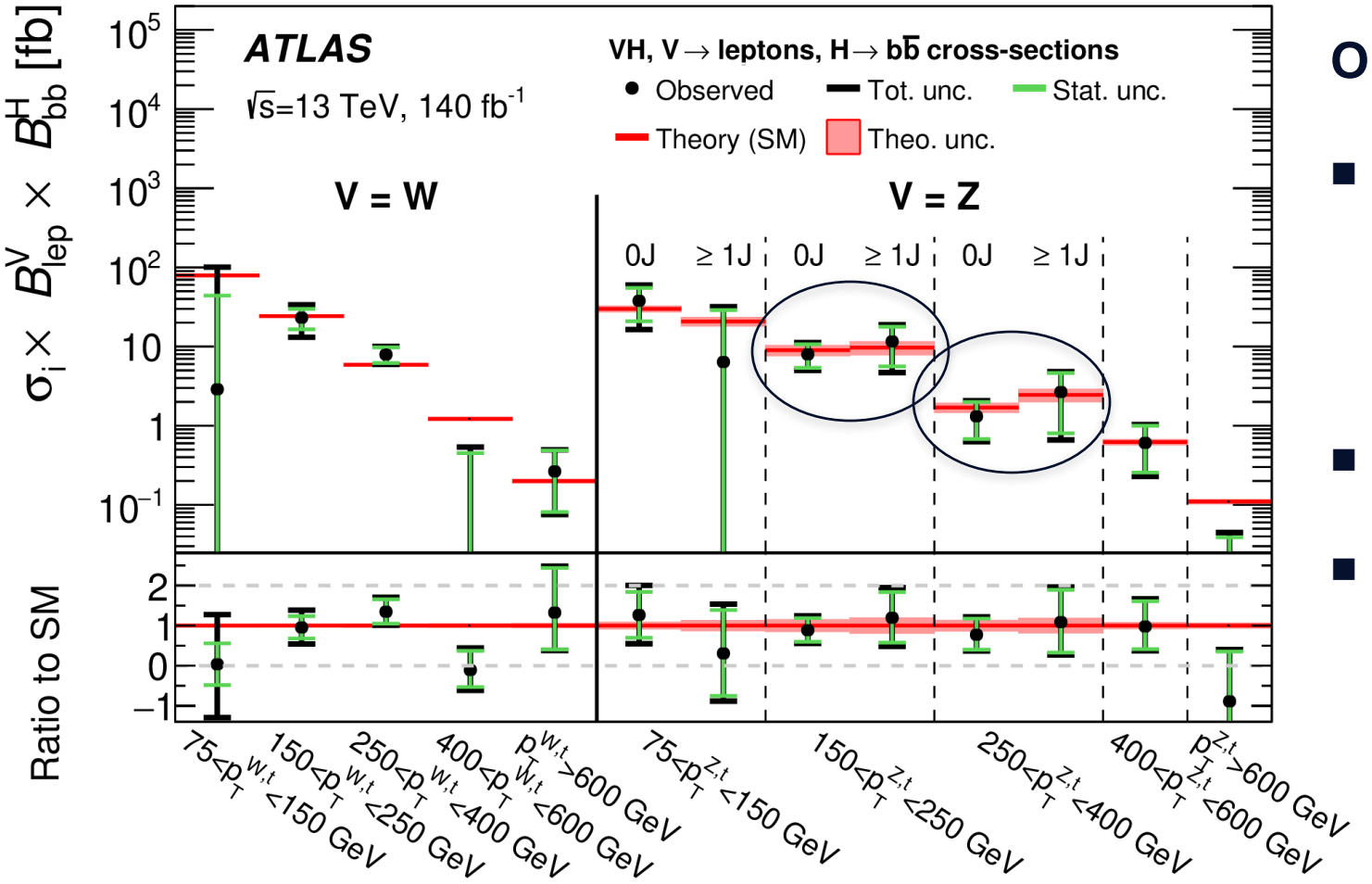
→ Measured **MC-to-data scale factors** in agreement with 1 for tt+b but significantly **deviating from 1 for tt+c and tt+light**

ttH,H→bb Open Questions

- How to improve ttH modelling?
- How to improve tt+bb modelling?
- A tt+cc 3FS sample?
- Better ways to make measurements less susceptible to dominating uncertainties?
- Should we measure other observables than p_T^H?
- A combined tt+hf and ttH EFT interpretation?

Bottom Yukawa

Current experimental sensitivity fully dominated by V(lep)H(bb) measurement



Open Questions:

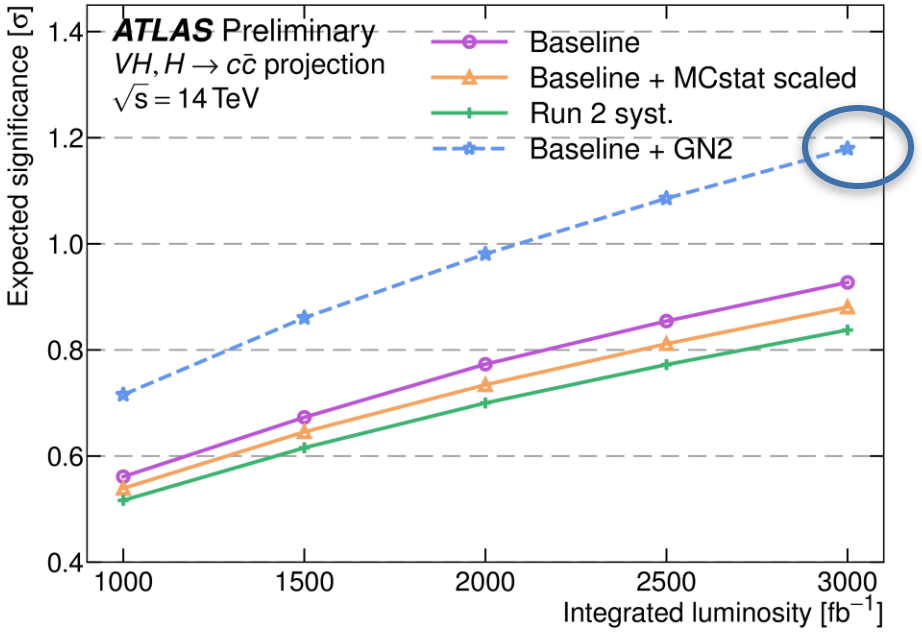
- Large theory uncertainties at intermediate p_T^Z regimes → When will there be an NLO MC for gg→ZH / loop-induced ZH?
- Measurements beyond p_T^V and nJet?
- Are we missing out by not having dedicated bbH measurements?

Charm Yukawa

- **H→cc searches improving rapidly,** with improving c-jet flavour identification being a major factor
  - For long time V(lep)H was the only player in the H→cc game but other channels are gaining traction and could significantly contribute to limit on Higgs-charm coupling

Latest ATLAS H→cc sensitivity:
Signal strength ≤11.5*SM expectation at 95% CL
$|\kappa_c| < 4.2$
JHEP 04 (2025) 075

For comparison H→$\mu\mu$ sensitivity: ~3σ

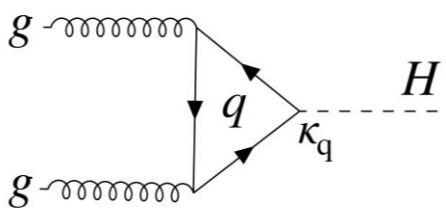


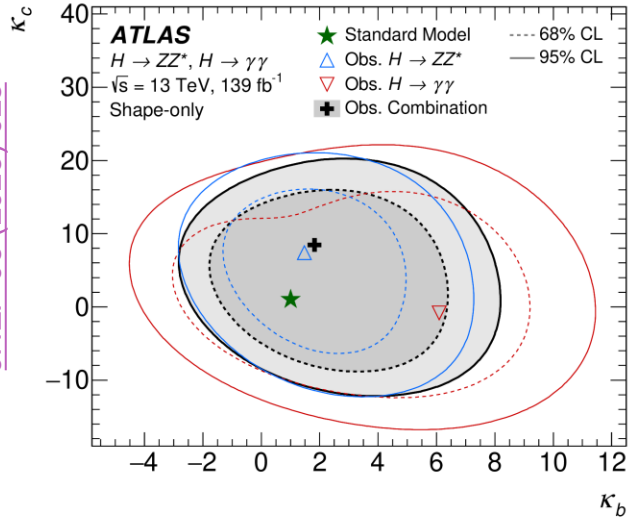
~1.2σ at HL-LHC with moderate c-ID improvements

ATL-PHYS-PUB-2025-012

Other Techniques to Extract κ_c
(and even Yukawas below charm)

p_T^H spectrum

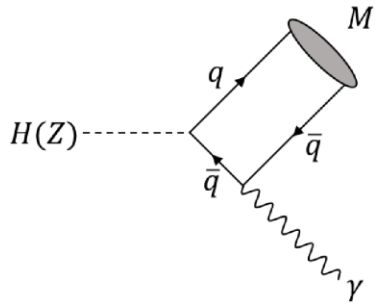




JHEP 05 (2023) 028

CMS even floats all quark kappa's simultaneously

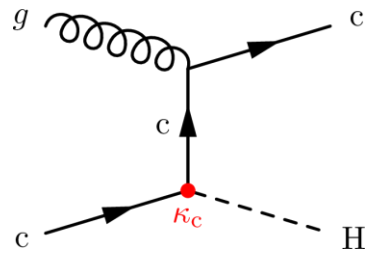
H→meson+y



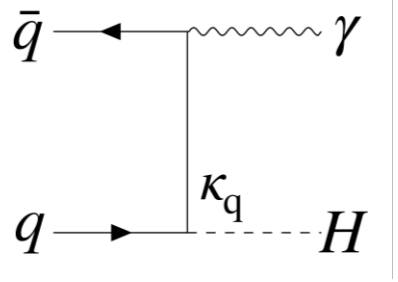
		BR upper limit (obs.)	BR (SM)	Ratio to SM
J/ψ	cc	2.1 x 10^{-4}	~3 x 10^{-6}	70
ψ(2S)	cc	10.9 x 10^{-4}	-	-
ϒ(1S)	bb	2.6 x 10^{-4}	~5.2 x 10^{-9}	50,000
ϒ(2S)	bb	4.4 x 10^{-4}	~1.4 x 10^{-9}	300,000
ϒ(3S)	bb	3.5 x 10^{-4}	~0.9 x 10^{-9}	400,000
ϕ	b=c=s=0	4.8 x 10^{-4}	~2.3 x 10^{-6}	210
ρ	b=c=s=0	8.8 x 10^{-4}	~1.7 x 10^{-5}	52
ω	b=c=s=0	1.5 x 10^{-4}	~1.5 x 10^{-6}	100
K*	s=1	8.9 x 10^{-5}	<10^{-11}	-

Phys. Lett. B 847 (2023) 138292
Phys. Lett. B 786 (2018) 134
JHEP 07 (2018) 127

H+jet production



H+y production



H+j / H+y: limits on quark Yukawas exist from CMS

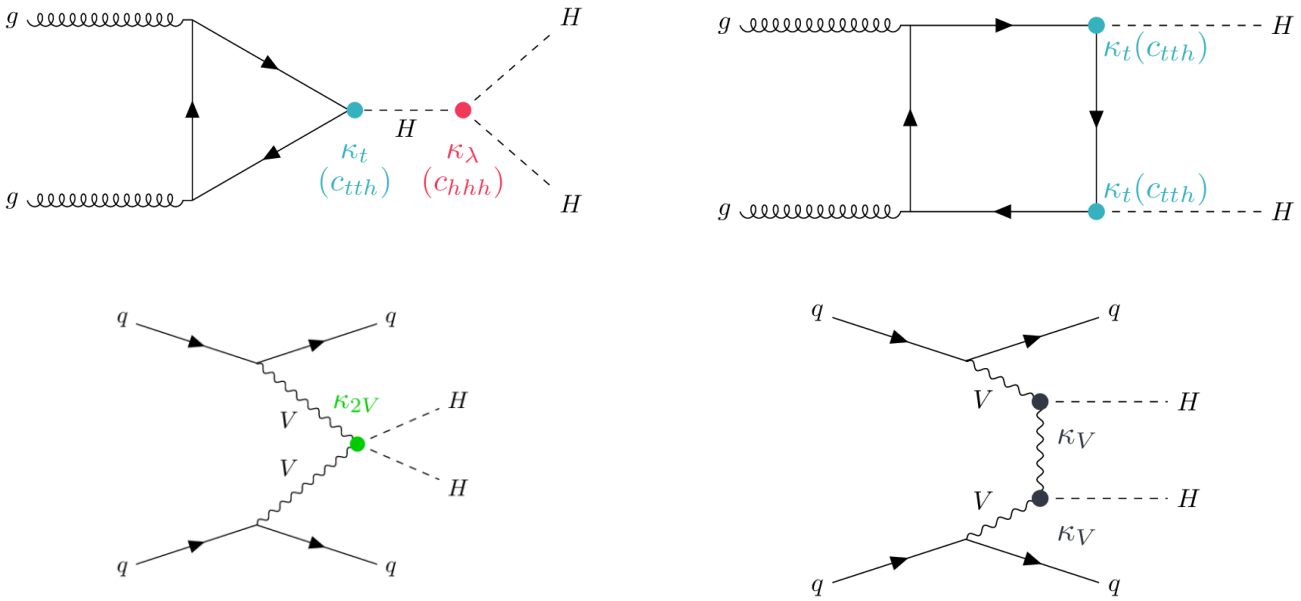
1st & 2nd Generation Yukawa Open Questions

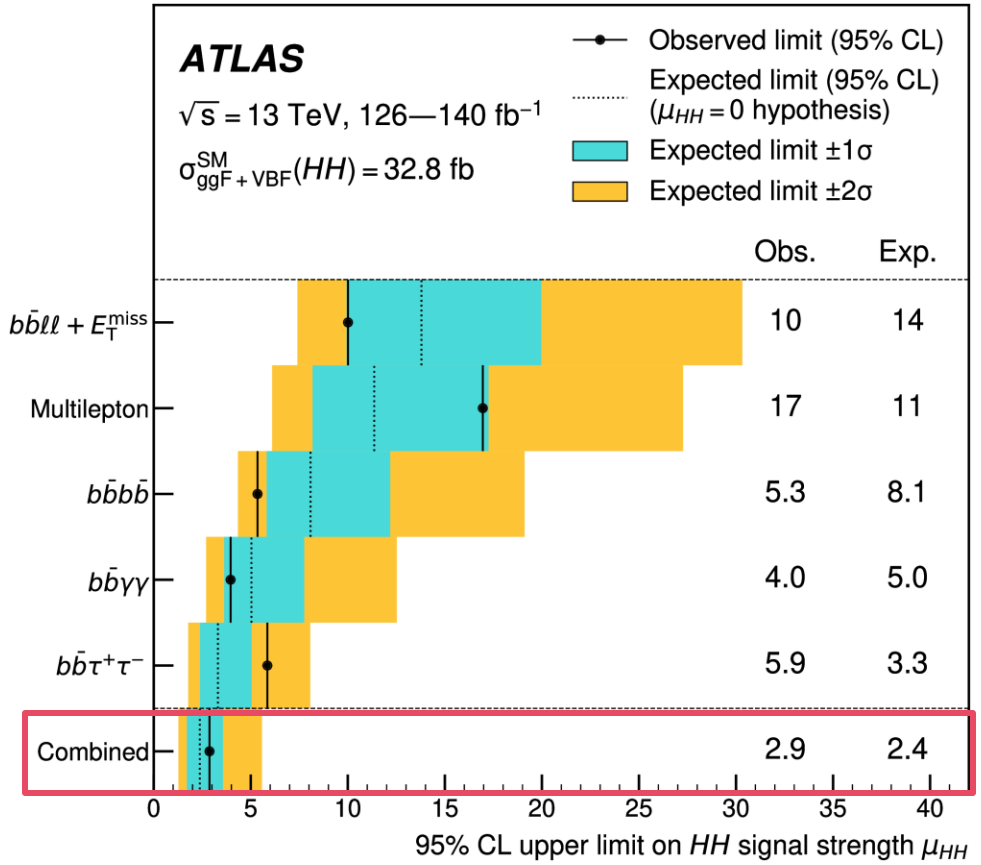
- Apart from setting limits, is there more we can do with H→cc searches?
- Are there alternative ways to access 1st and 2nd generation (quark) Yukawa couplings that are not yet probed?
  - What assumptions would they come with?

Multi-Higgs Production

Current Status of Di-Higgs Searches

Much lower production cross-sections: up to now only ~10,000 (SM) HH events produced at ATLAS





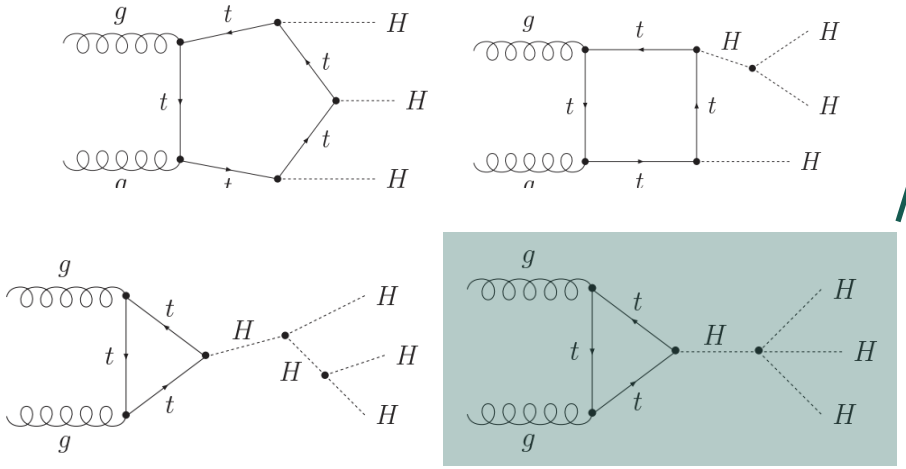
95% confidence level limits:
$1.2<\kappa_\lambda<7.2$ → triple Higgs-self-coupling vertex
$0.6<\kappa_{2V}<1.5$

Phys. Rev. Lett. 133 (2024) 101801

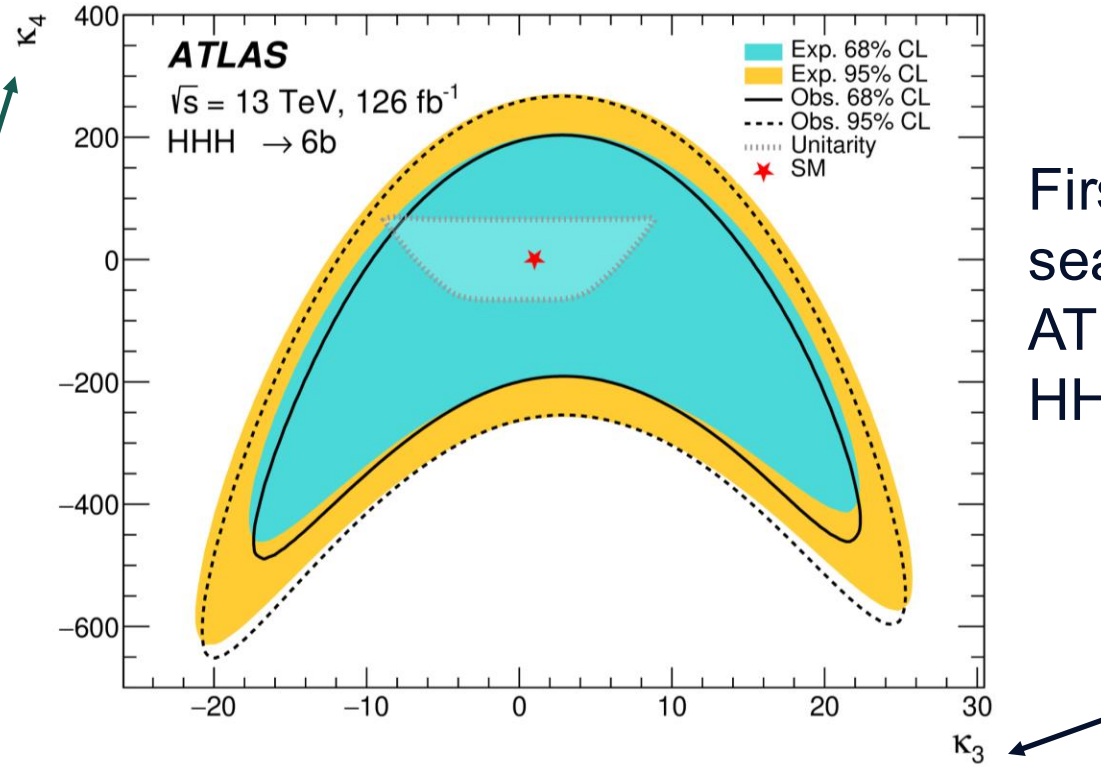
Quartic Higgs-Self Coupling in HHH

$$V(\Phi) = \sum_{n\geq 0} \frac{\lambda_n}{\Lambda^{2n}} \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^{2+n}$$

→ For full picture of Higgs-potential also probe higher orders of Higgs-self coupling



Quartic self-coupling



First HHH search from ATLAS HHH→bbbbbb

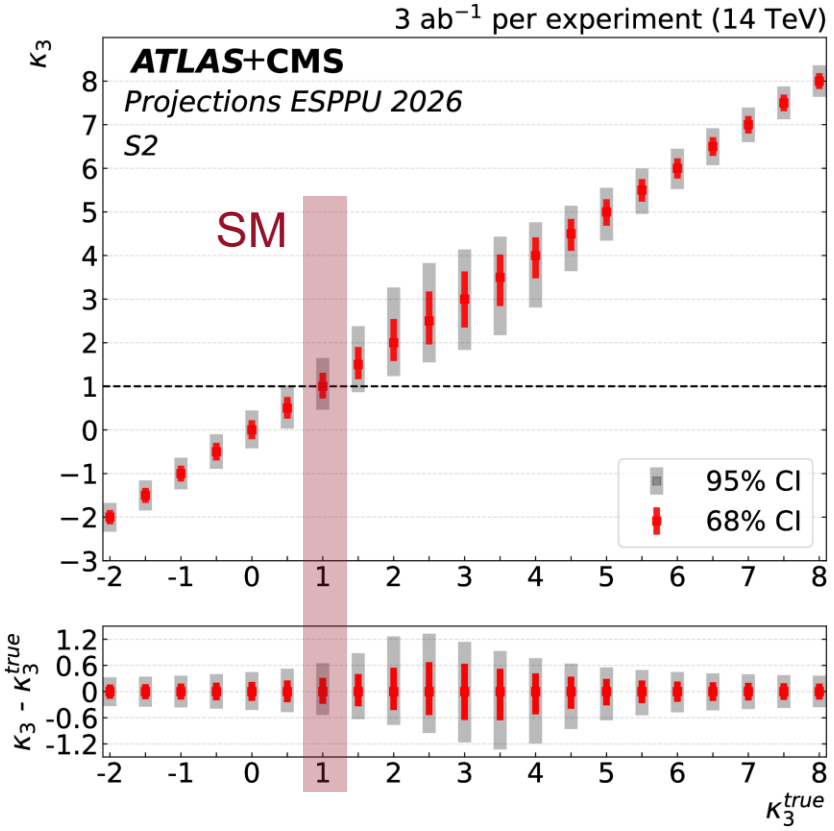
Triple self-coupling

Phys. Rev. D 111 (2025) 032006

Multi-Higgs: a Look Ahead

Projections of LHC Run-2 results (140 ifb) to HL-LHC shows that di-Higgs observation is in reach

Projected sensitivity to triple Higgs self-coupling



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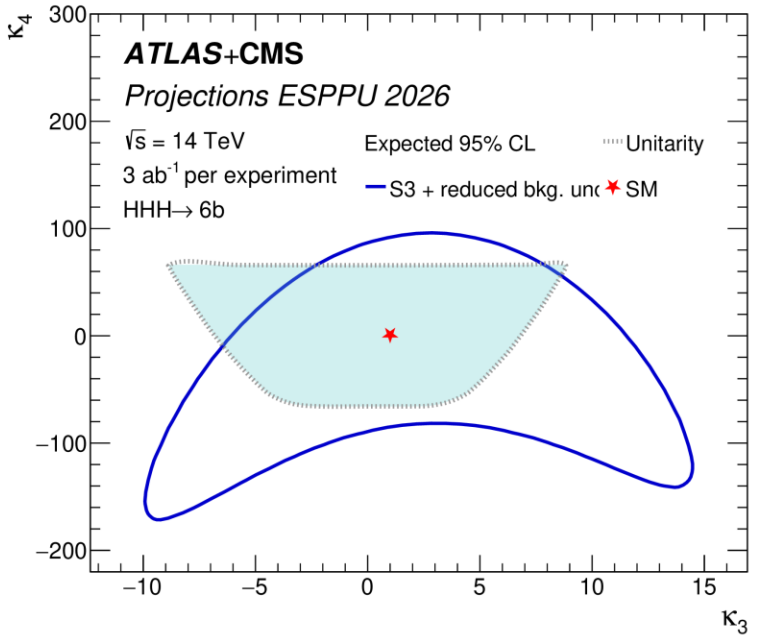
Projected quartic and triple Higgs-couplings



What kind of physics can we realistically do at HL-LHC?
How well can we simulate these multi-Higgs processes?
How well do we need to know backgrounds, incl. single-H?

Summary

Top and bottom Yukawa well measured these days

- Main challenge: signal and background modelling
- Where should those measurements go in the future?

2nd generation Yukawas in reach ($\mu\mu$ at LHC, cc at ~HL-LHC)

- Can we find other complementary ways to probe those couplings?
- What about 1st generation Yukawas?
- What about exotic Yukawas?

Multi-Higgs production in reach

- How well do we know this production and related backgrounds (simulation & measurement)?
- What do we want to focus on at HL-LHC?