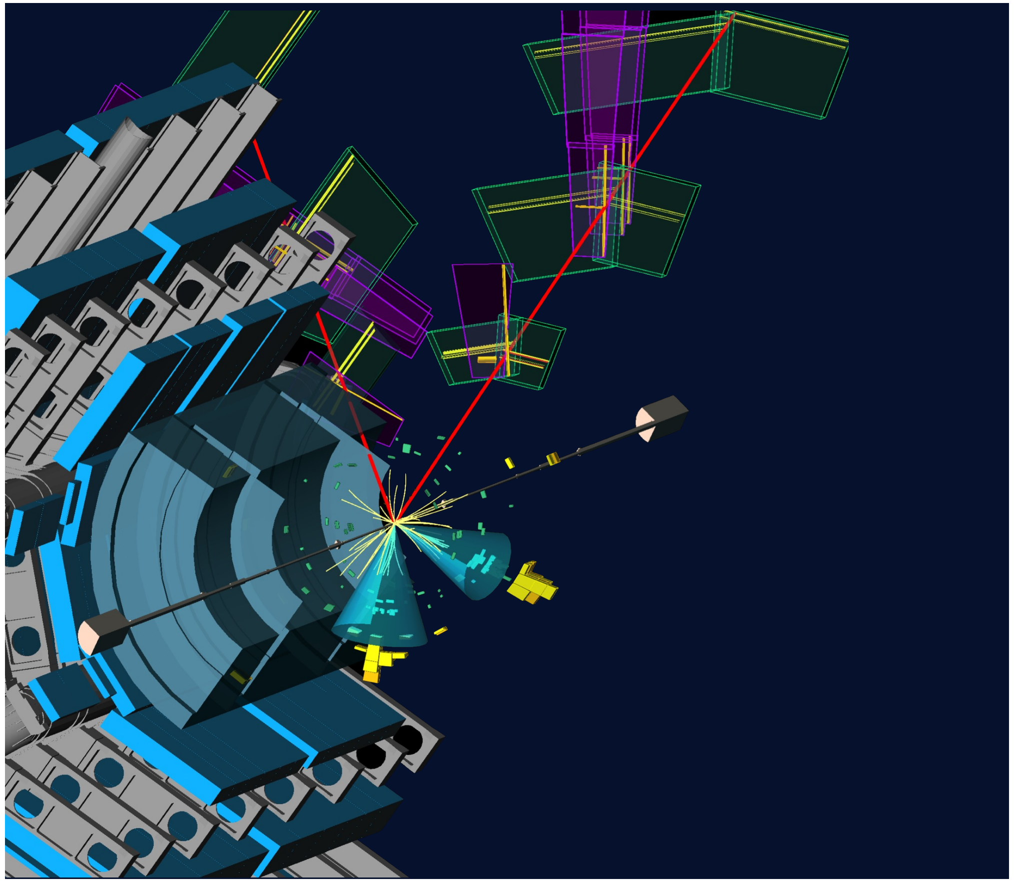
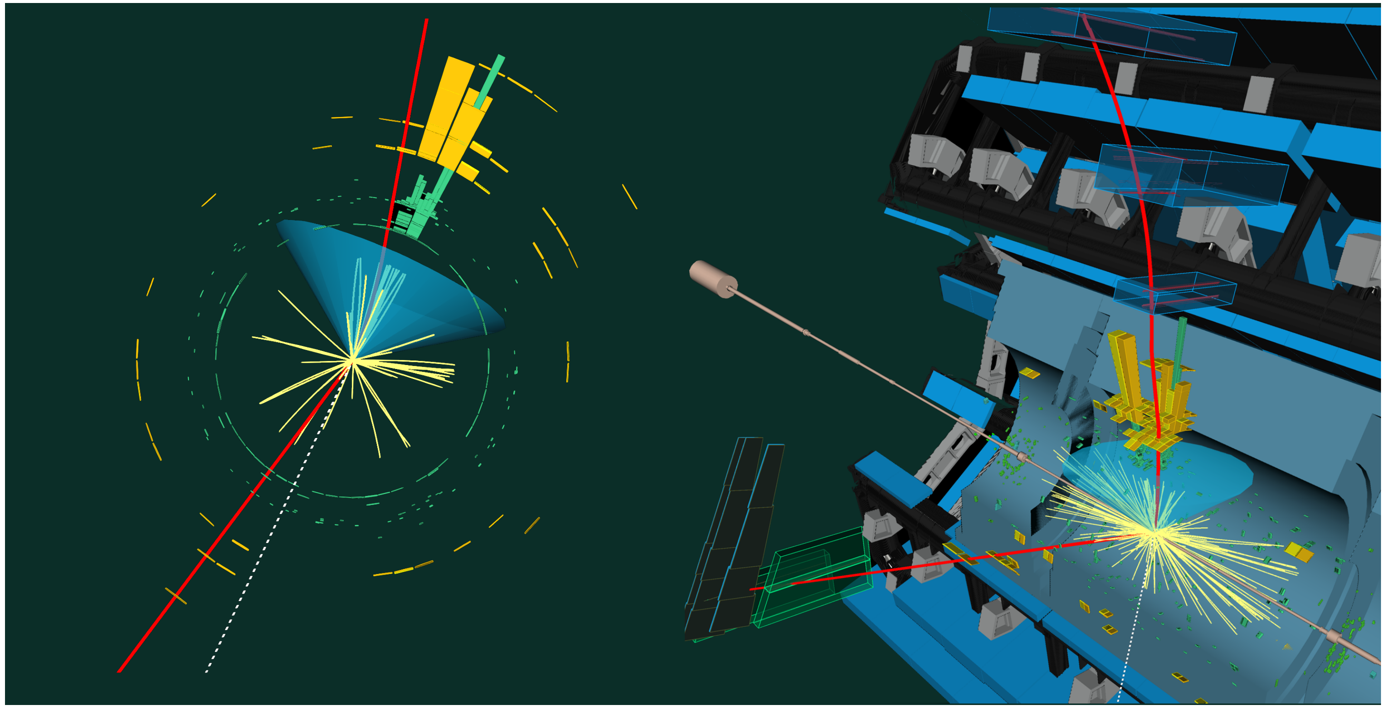




The Beauty and the Charm of the Higgs Boson

Elisabeth Schopf - Vorstellungsvortrag

ATLAS EXPERIMENT

Kolloquium, Physik, Universität Siegen
18. Dezember 2025

Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

...or how I became fascinated by hadronic Higgs-boson decays

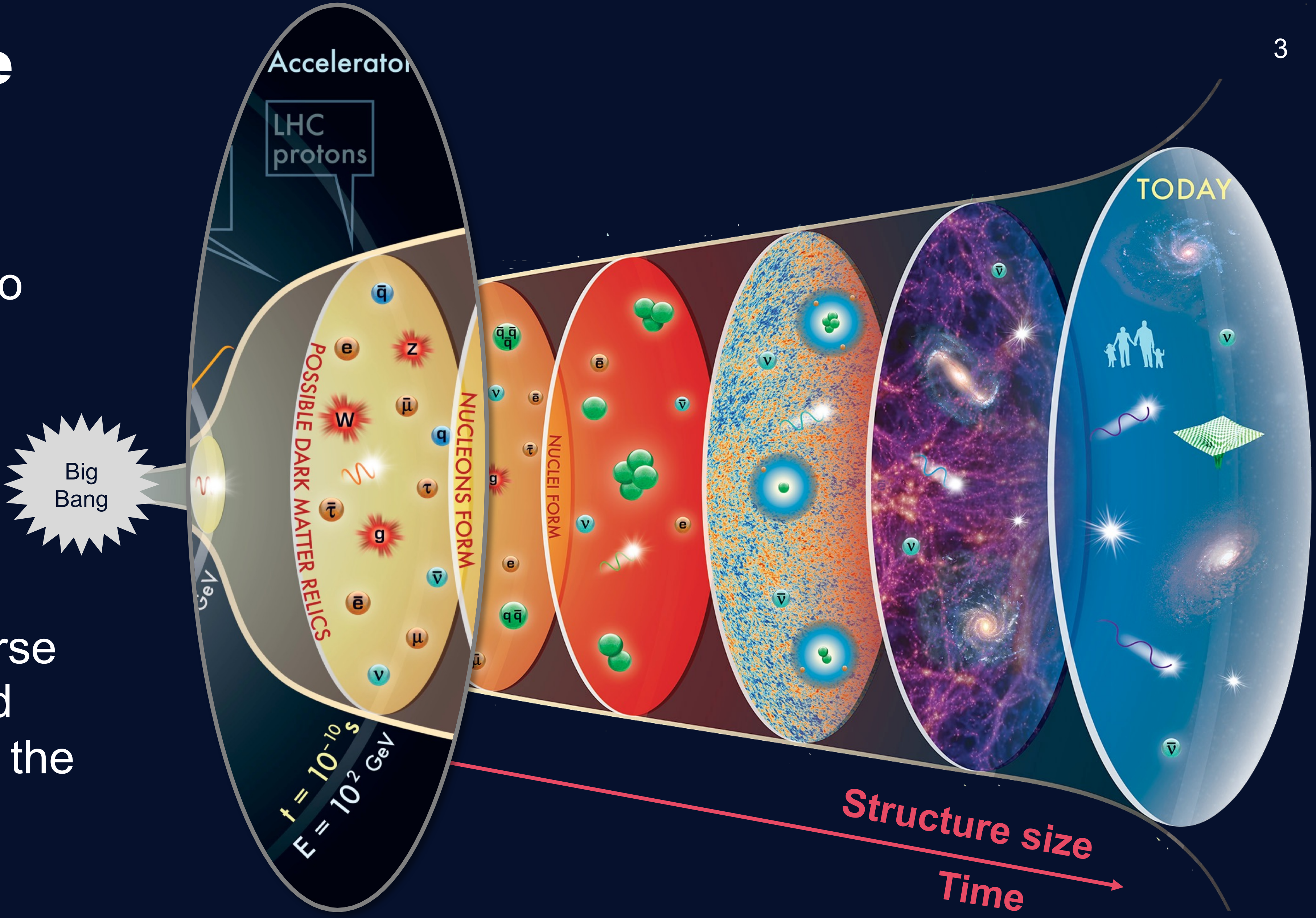
Postdoc in Oxford
(based at CERN)

PhD in Bonn

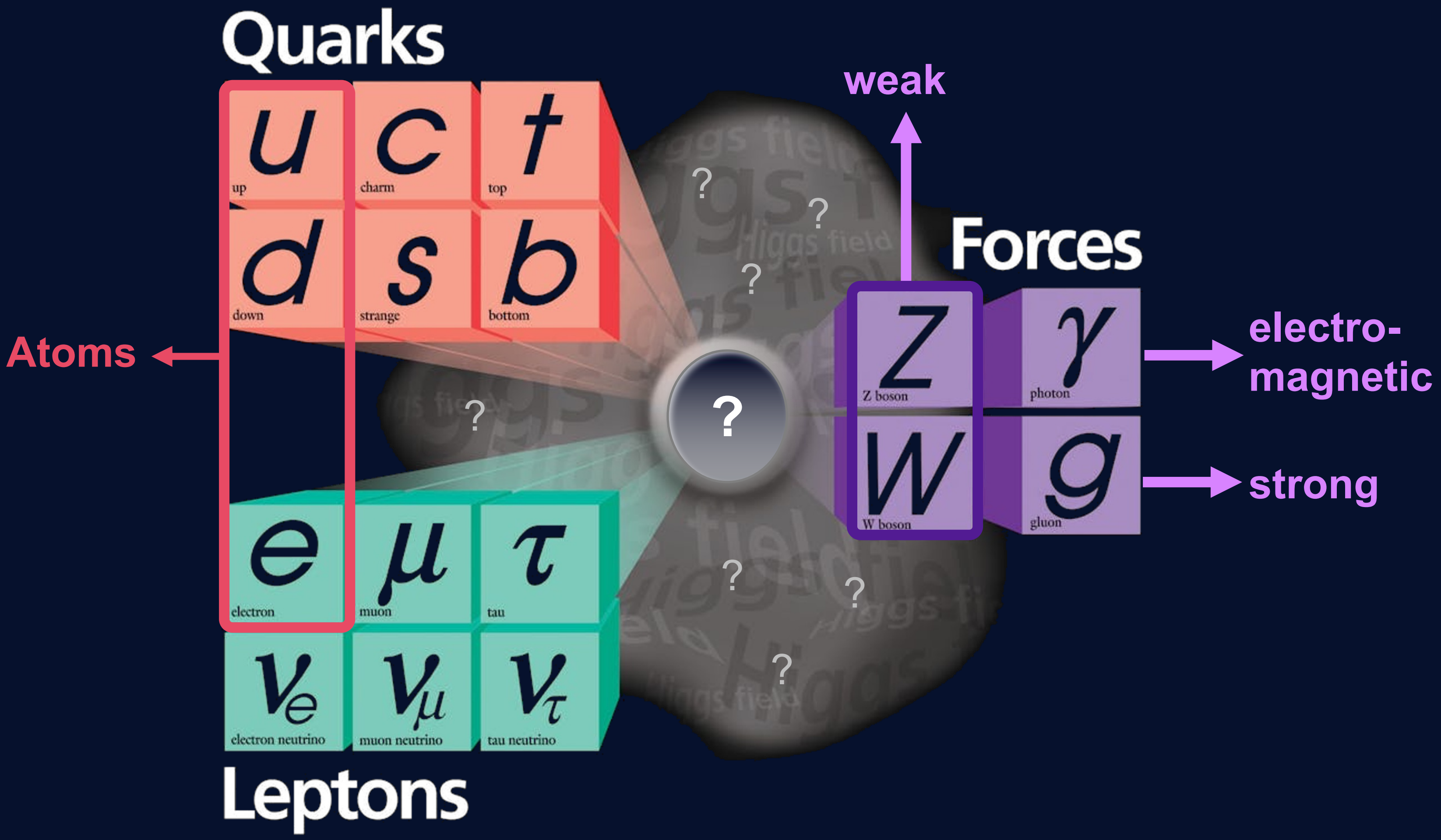
Why Particle Physics?

A look back in time to very early universe

Study of early universe matter formation and long term stability of the universe

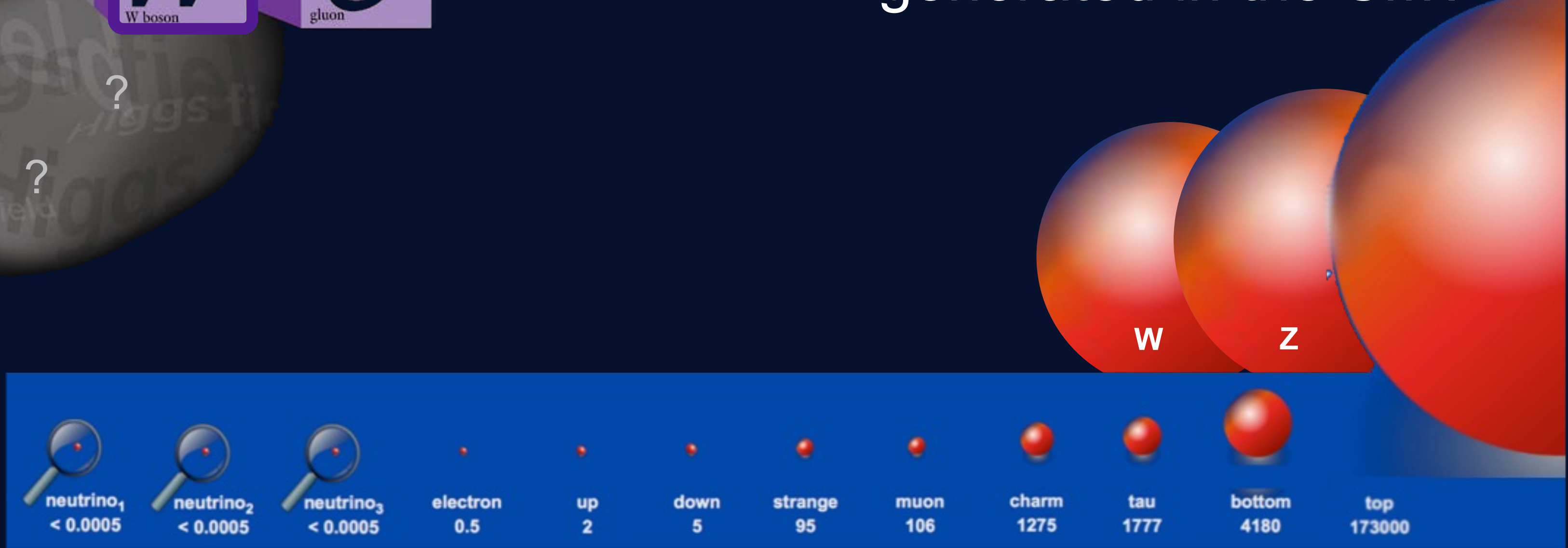


The Particles of the Standard Model
(before 2012)



Masses of particles span >10 orders of magnitude

→ How is mass generated in the SM?



The Higgs Mechanism

(Most) particles have non-zero mass

Higgs field present everywhere

- When "switched on" (10^{-12} s after Big Bang) W and Z boson masses generated by construction

Interactions of particles with Higgs field generate masses → added ad-hoc for fermions

- The more they interact, the heavier

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$ forces

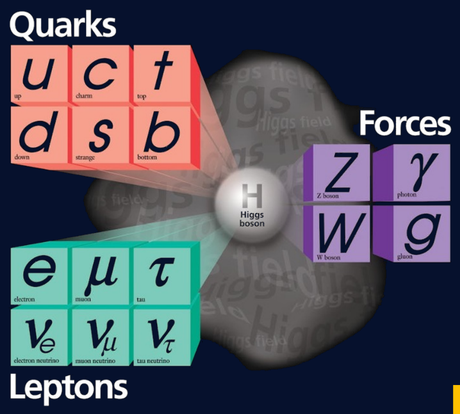
$$+ i\bar{\psi} \not{D} \psi + h.c.$$ interactions via forces

$$+ |D_\mu \phi|^2 - V(\phi)$$ Higgs mechanism

$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$ particle-Higgs interactions

→ New particle observable in experiments: Higgs boson

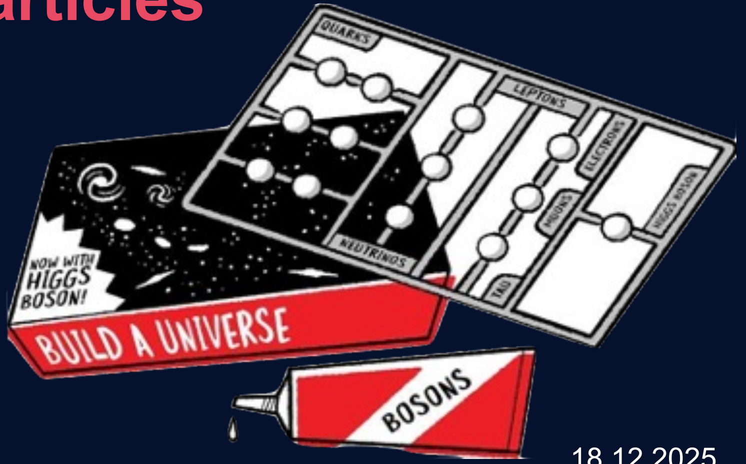
Putting it all together…



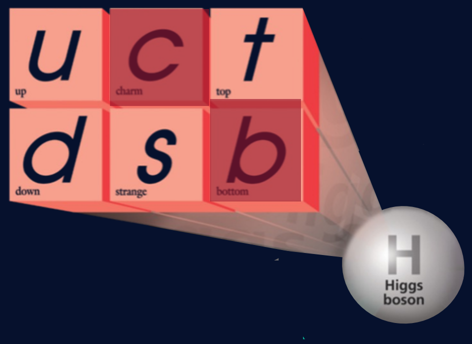
Free parameter of the theory: mass of Higgs boson
→ Discovery in 2012
→ Mass measurement (today): m_H=125.11±0.11 GeV

Knowledge of mass fixes predictions for Higgs-boson decay rates and production cross-sections

However, new (beyond SM) couplings or unknown particles interacting with Higgs boson would alter these rates



Why Study Higgs-Boson Decays to Bottom and Charm Quarks?



H→bb is most abundant decay (BR~60%)

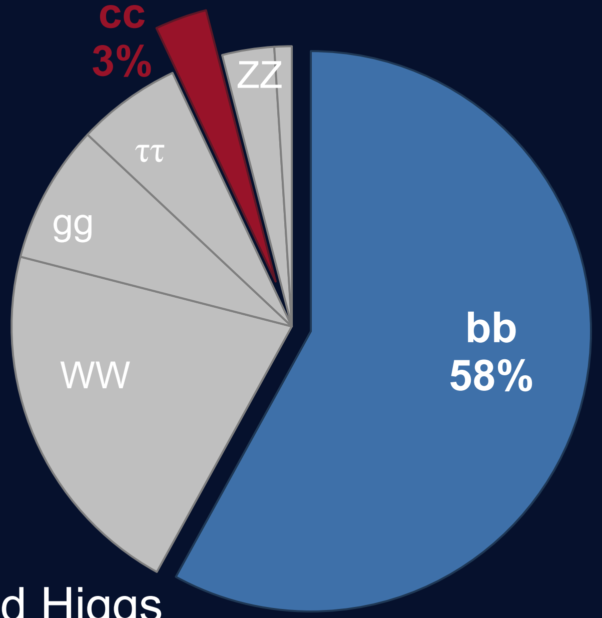
- Dominates Higgs decay width
- Allows probing rare production modes and kinematic regimes

H→cc is a rare decay (BR~3%)

- But, largest yet undiscovered Higgs-boson coupling

Probing both (simultaneously) tests theories that predict:

- The same couplings for all quarks?
- Different coupling mechanisms for 2nd and 3rd generation quarks?
- Different coupling mechanisms for up-type and down-type quarks?



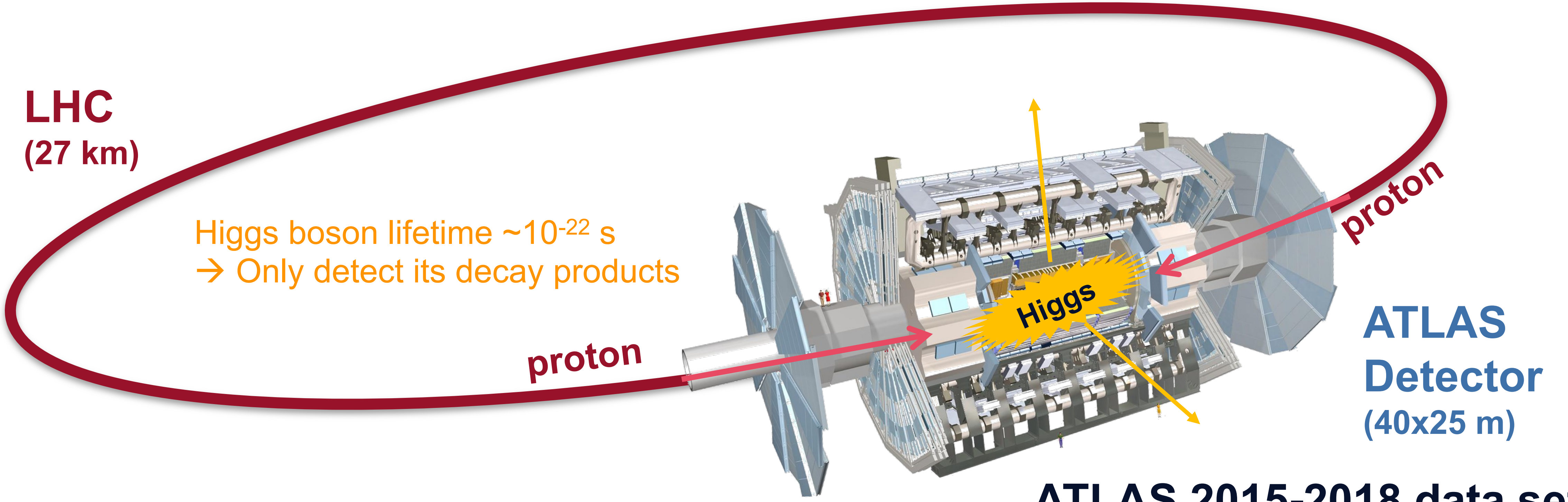
Expected Higgs boson branching ratios

Experimental Setup: LHC and ATLAS

Large Hadron Collider:

Proton-proton collision energy = 13 TeV (2015-2018)

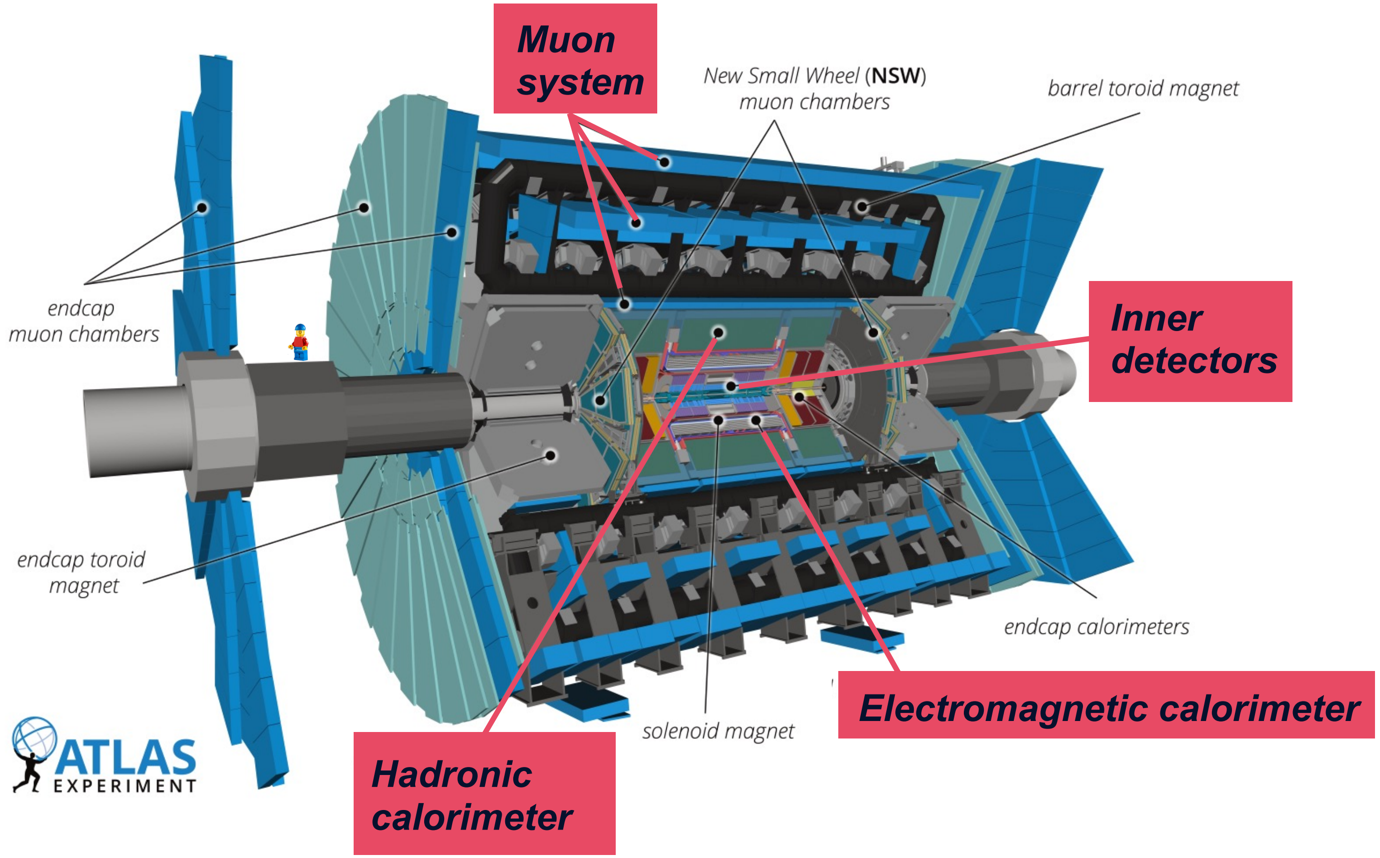
→1 in 1 billion pp-collisions produces Higgs boson



ATLAS 2015-2018 data set:

140 fb^{-1} → **~8 million Higgs bosons**

ATLAS: A Higgs Detection Machine



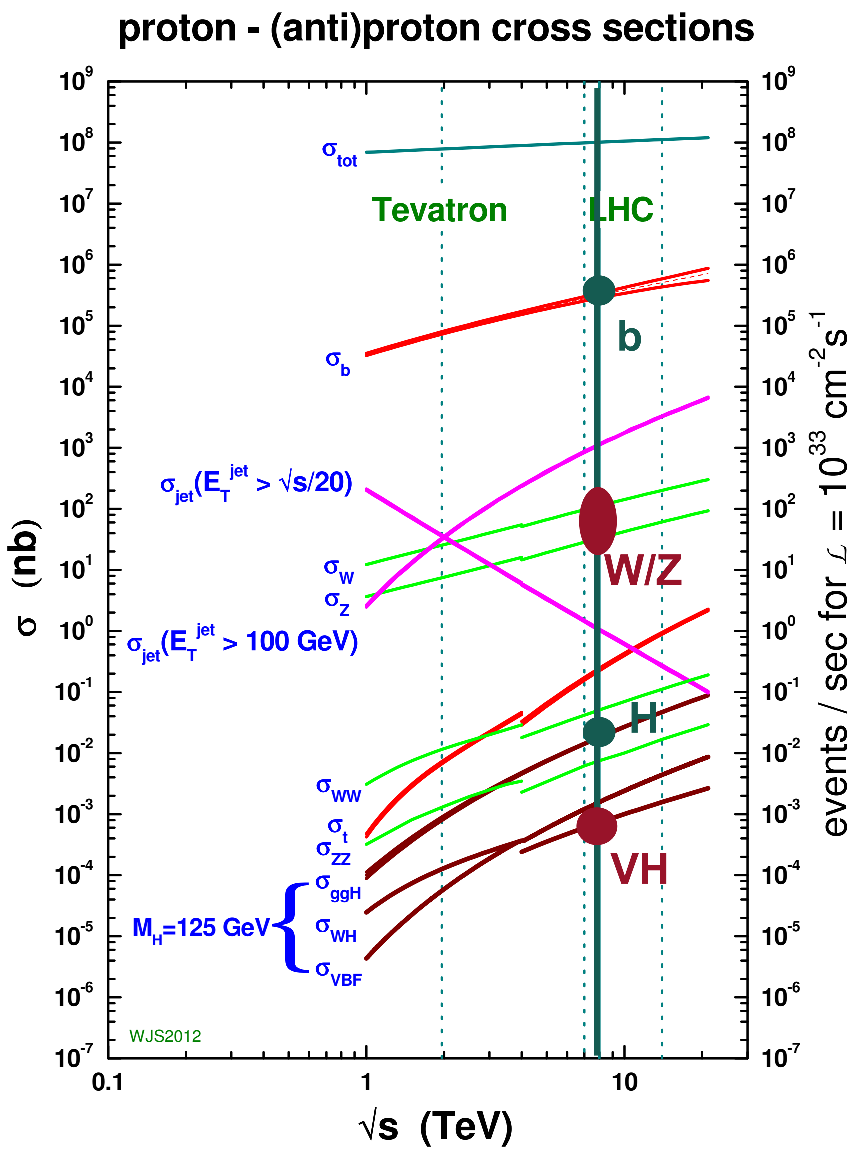
Inner detectors: high precision tracking (trajectories + momentum) and vertexing

EM calorimeter: electron and photon energy measurements

Hadronic calorimeter: hadron energy measurements, esp. “jet” reconstruction

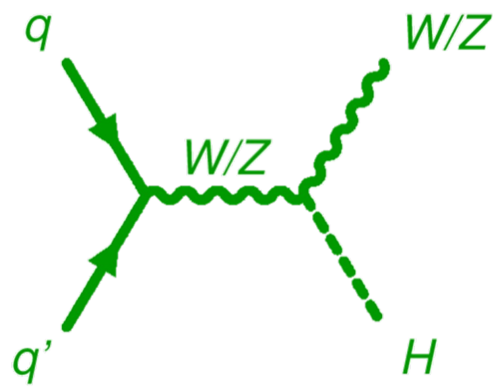
Muon system: muon tracking and identification

Challenge 1: “Jets Everywhere”



- Production of quarks (leading to jets) abundant in proton-proton collisions
  - → Impossible to record all events containing jets
  - → Overwhelming amount of background events

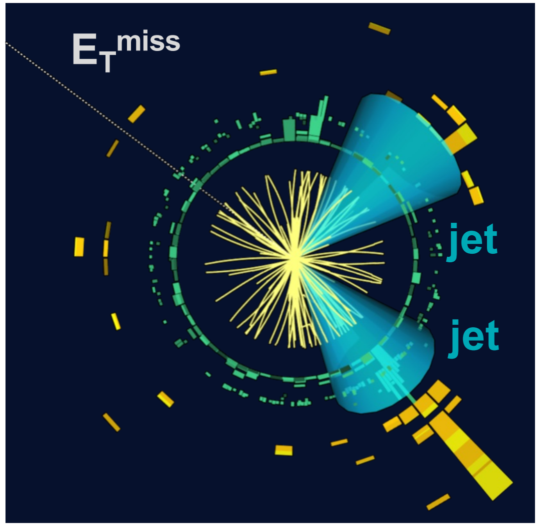
→ Target production in association with a W or Z (=V) with V→leptons decays



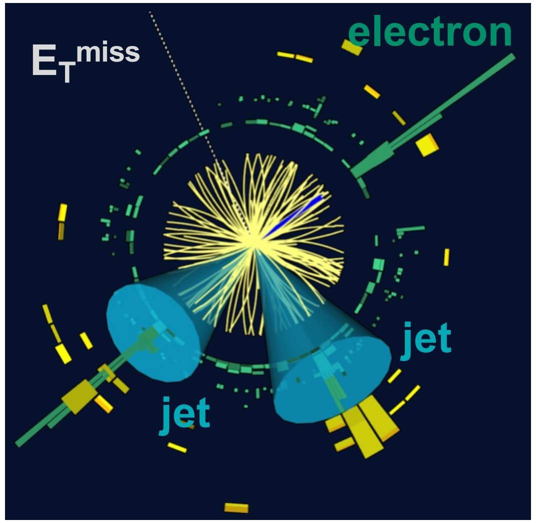
VH(bb/cc) Experimental Signatures

3 V-boson decay channels targeted:

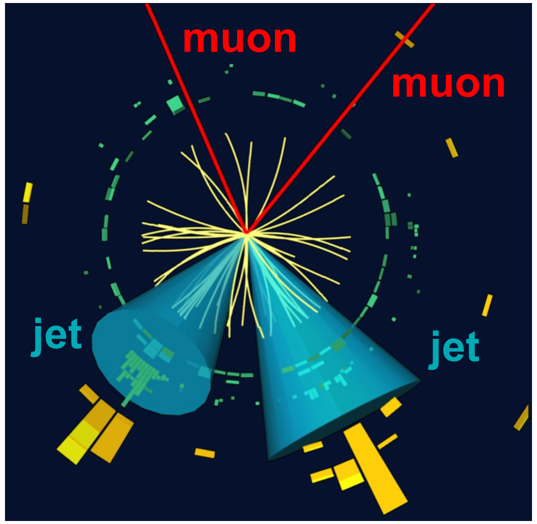
Z(νν)H (“0-lepton”)



W(ℓν)H (“1-lepton”)



Z(ℓℓ)H (“2-lepton”)



Exactly 0 (but large missing transverse momentum, E_T^{miss}), 1 or 2 electrons/muons + (at least) 2 jets

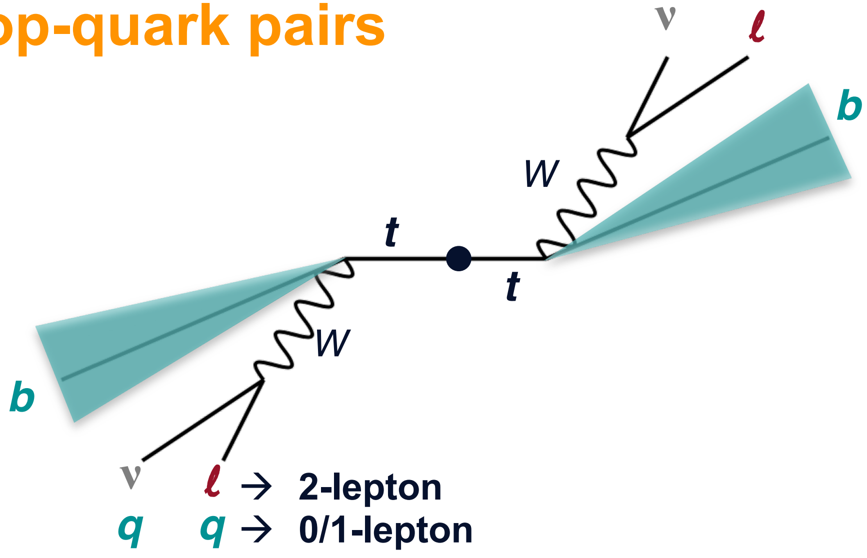
Kinematic regions with overwhelming background excluded (e.g. very low p_T^V)

Coarse selection based on expected correlation amongst objects for signal (e.g. minimum jet p_T)

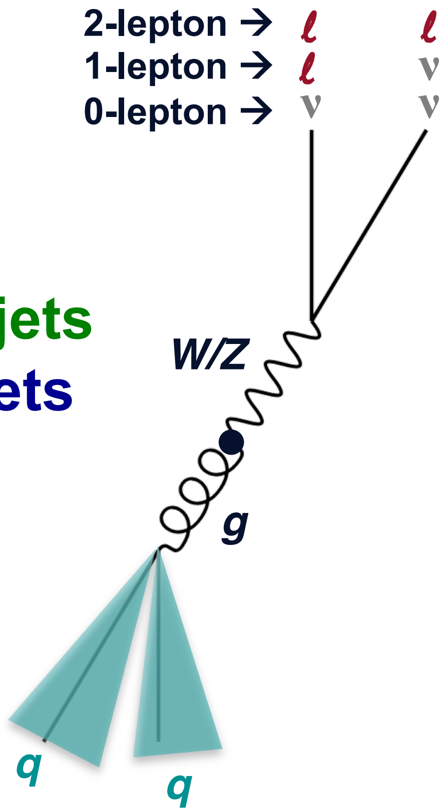
Jargon Alert: “Lepton” = lepton directly visible in detector = muon or electron (had. τ considered in WH channel)

Challenge 2: Still Too Much Background

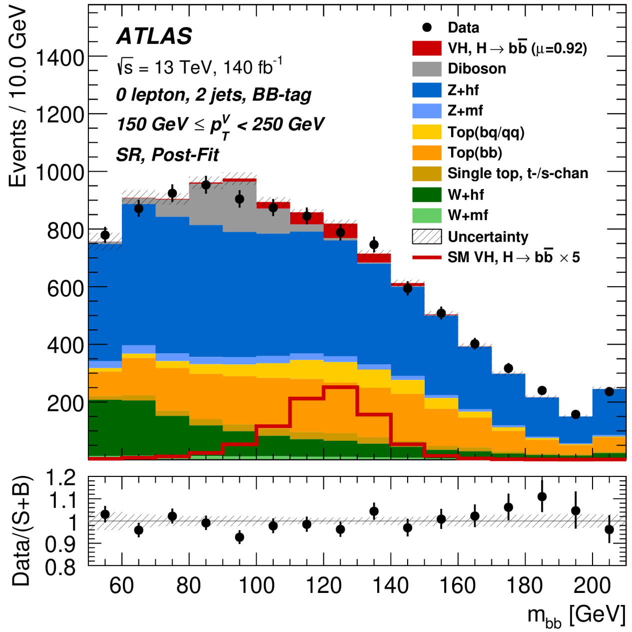
Top-quark pairs



W+jets
Z+jets



Invariant di-b-jet mass (0 lepton)

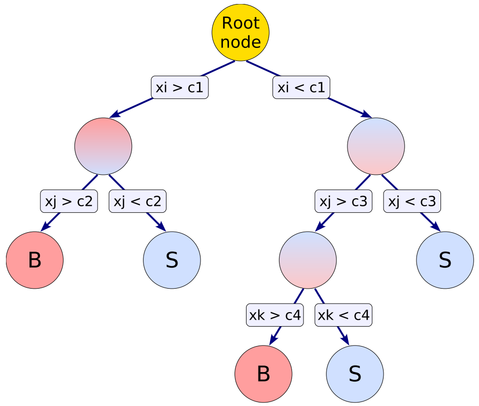


Sub-dominant contributions from:

- WZ/ZZ/WW production
- Single top-quark production
- QCD multi-jet production (1 lepton only)

Worse for VH(cc) → smaller signal BR, larger background cross-section, σ(V+cc)>σ(V+bb)

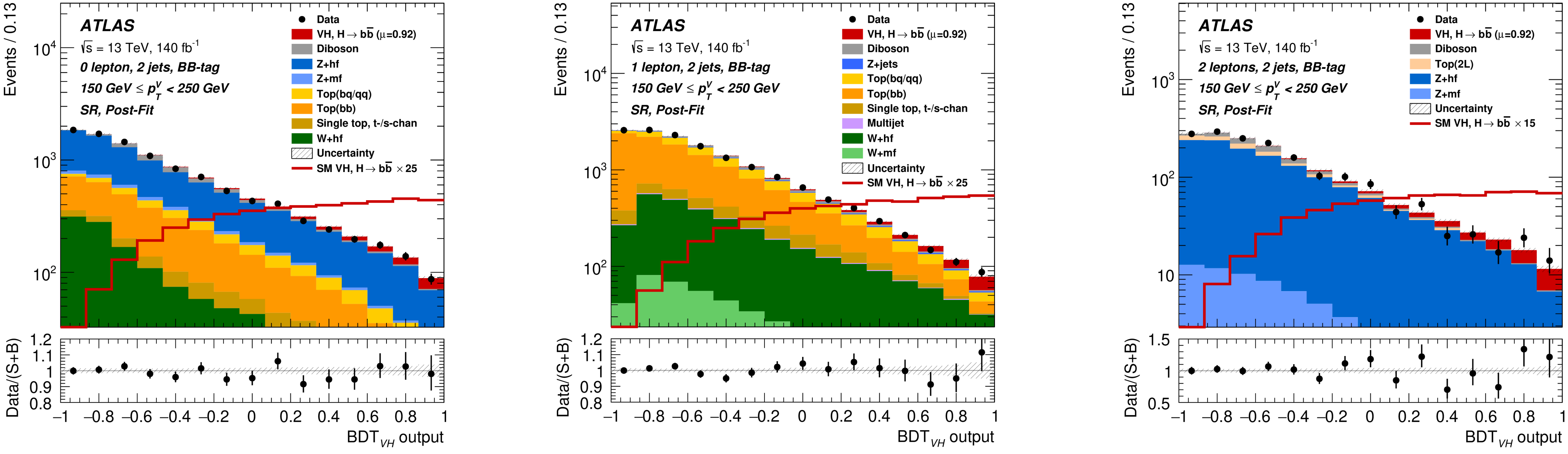
Machine Learning for Signal-Background Discrimination



"Fine selection" using machine learning (boosted decision trees)

→Instead of rejecting (potential signal) events **assign a signal probability** based on event kinematics and topology

input: angular distances, E_T^{miss}, momenta, etc.



JHEP 04 (2025) 075

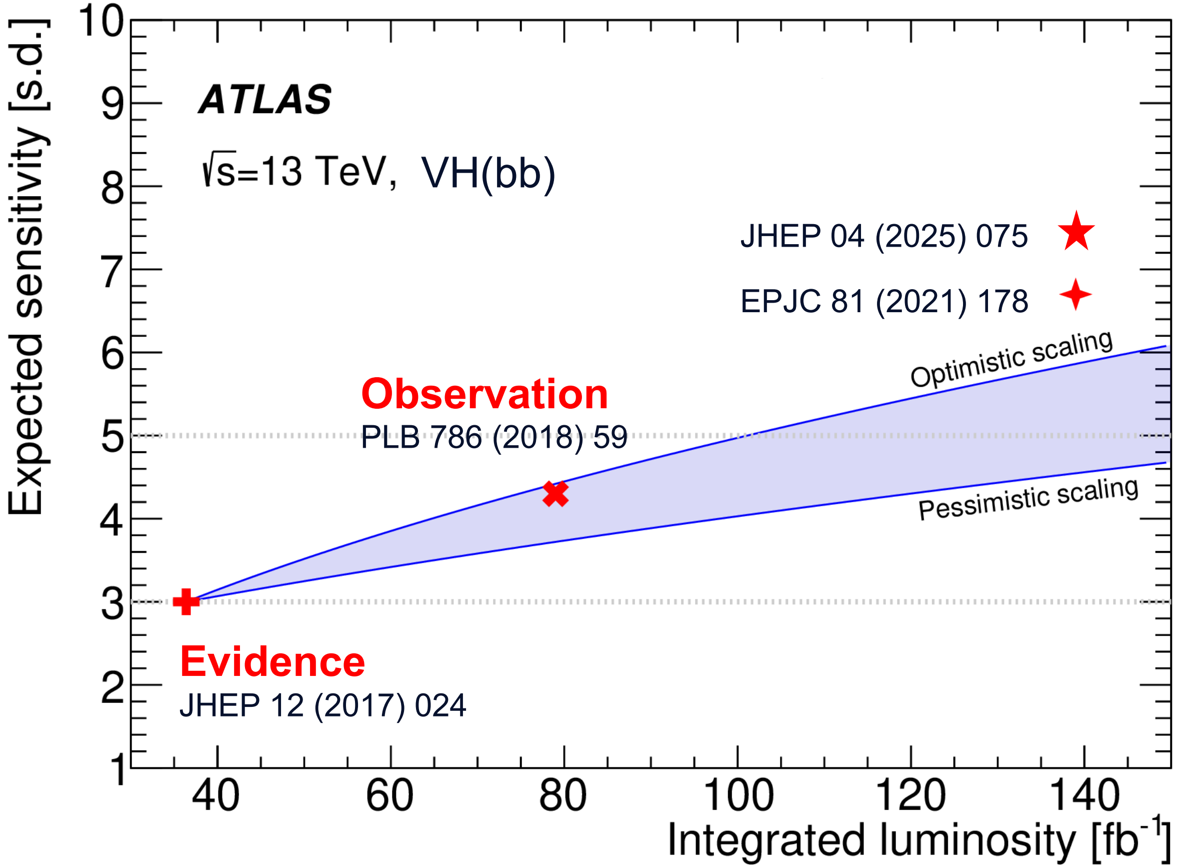
A Short History of H→bb Measurements

- 2018: observation of H→bb decays
  - Rejection of background-only hypothesis 5.4σ
  - VH(bb) "contributing" 4.9σ (4.3σ expected)

→ **Discovery of Higgs-boson couplings to quarks**

- **Latest VH(bb) measurement: 7.4 σ**
  → experimental precision improved far beyond "just adding more data"

Evolution of VH(bb) sensitivity (in std. deviations)



VH(cc) Enters the Game

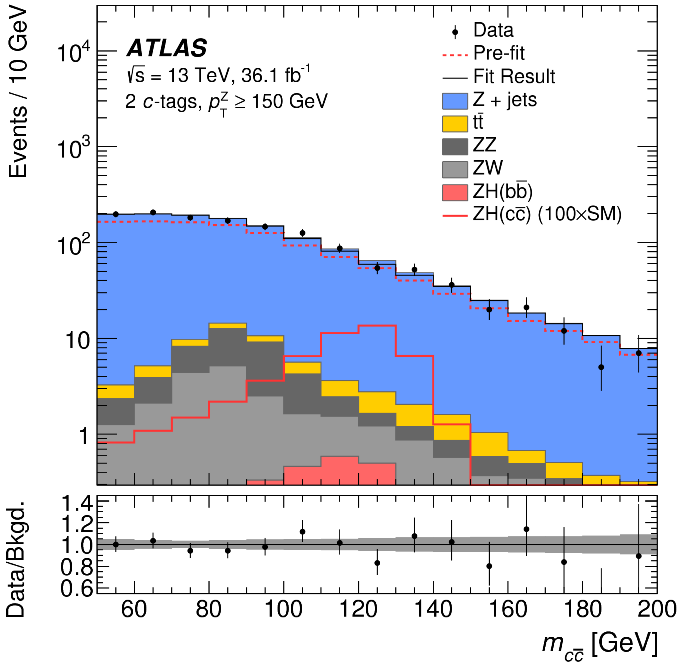
- Same experimental signature as VH(bb) but with 2 c-jets instead of 2 b-jets

→Shares experimental challenges with VH(bb) but with increased "difficulty level"

- → Much worse signal-to-background ratio
- → Identification of c-jets more challenging

→**2017**: first search for H→cc in the Z(ℓℓ)H channel
→ excluded enhancement factors of **110x SM expectation**

→Next step: simultaneous study of VH(bb) and VH(cc) to reach optimal sensitivity for both

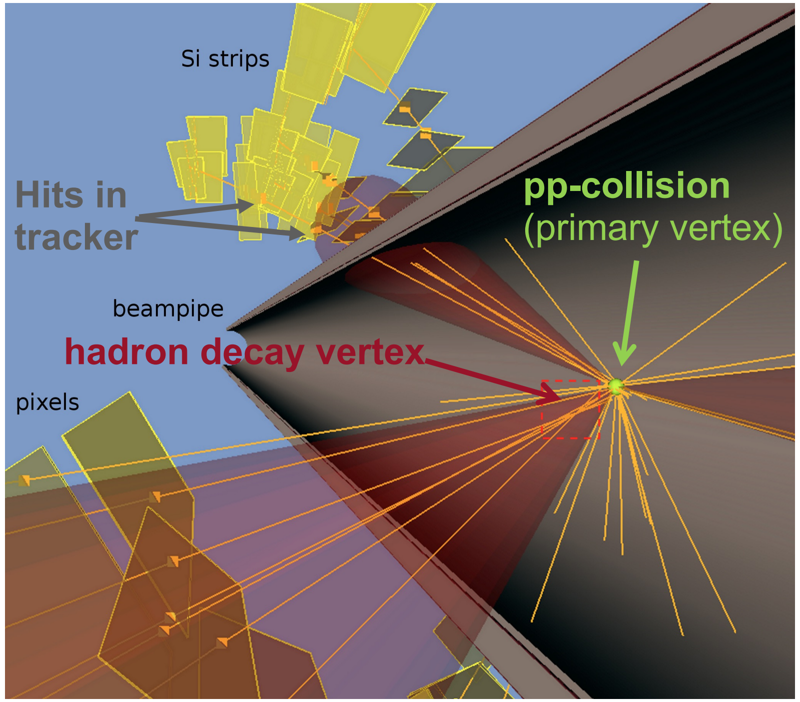


PRL 120 (2018) 211802

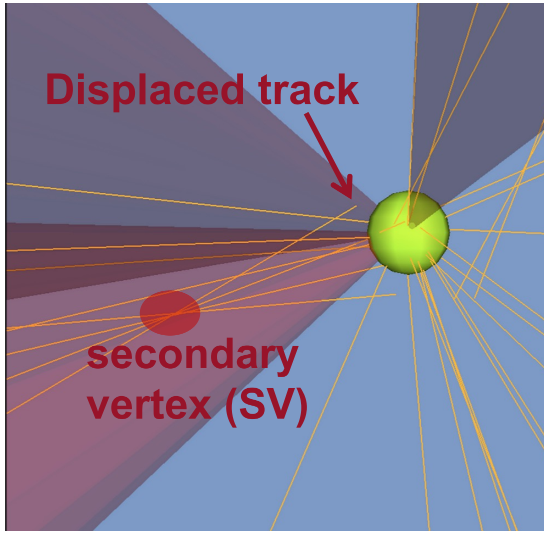
Challenge 3: b/c-Jet Identification

Hadrons containing b/c-quarks have measurable lifetimes

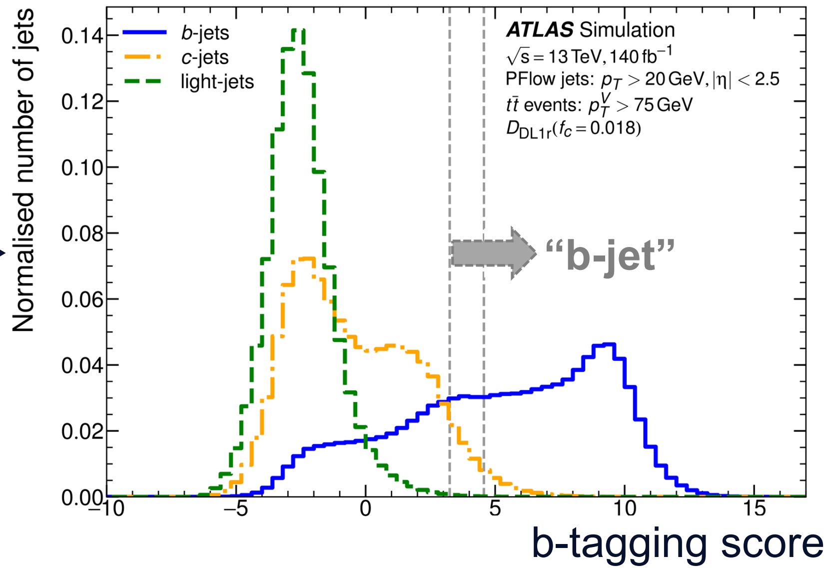
b-hadrons: cτ ~450 to 500 μm
c-hadrons: cτ ~150 to 300 μm



Zoom →



ML →



Combination of jet kinematics, SV and impact parameter information in neural-net algorithm

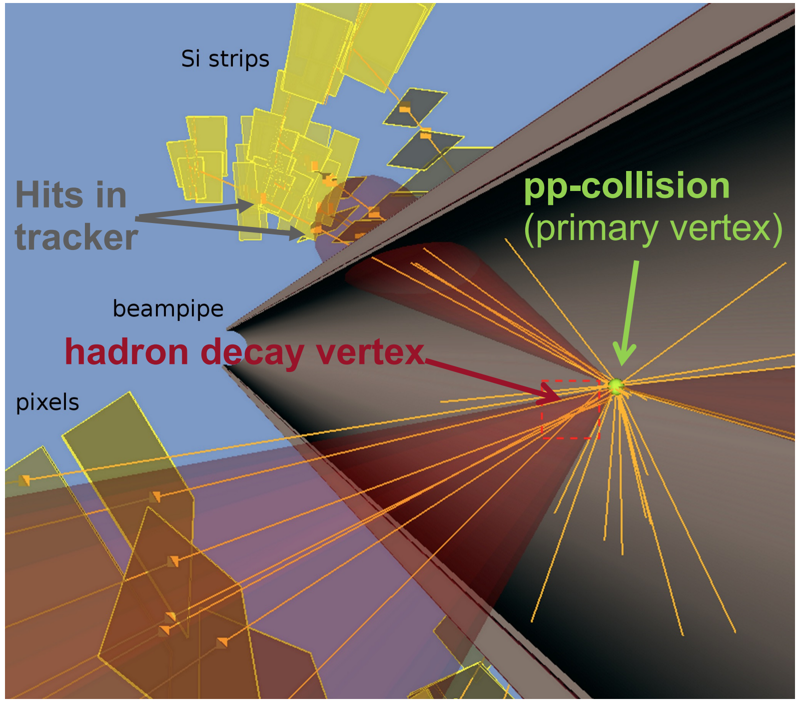
→ *b-probability*, *c-probability*, *light-probability*

→ **Probabilities combined into a "tagging score"**

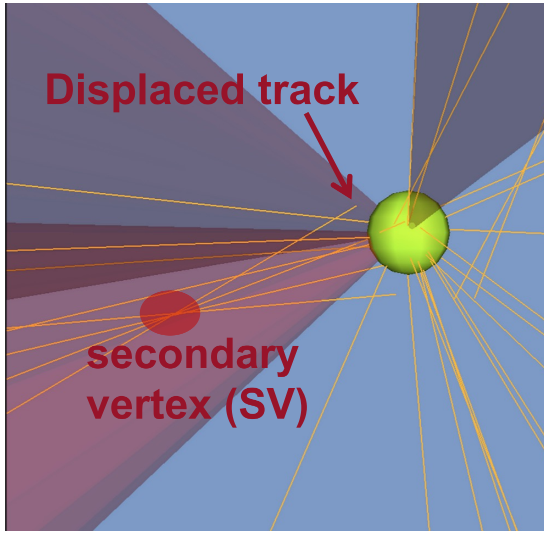
Challenge 3: b/c-Jet Identification

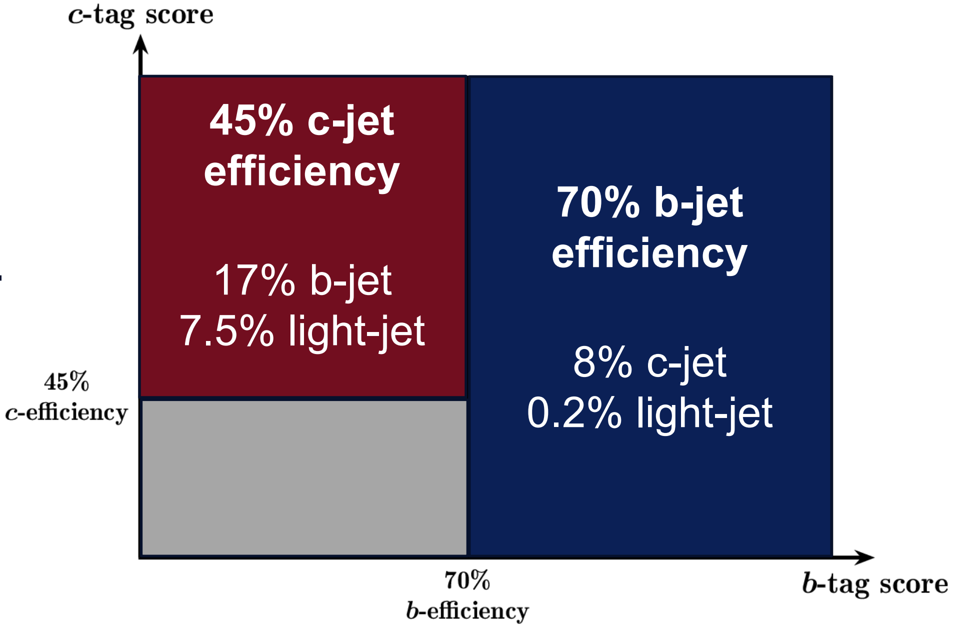
Hadrons containing b/c-quarks have measurable lifetimes

b-hadrons: cτ ~450 to 500 µm
c-hadrons: cτ ~150 to 300 µm



Zoom →





Combination of jet kinematics, SV and impact parameter information in neural-net algorithm

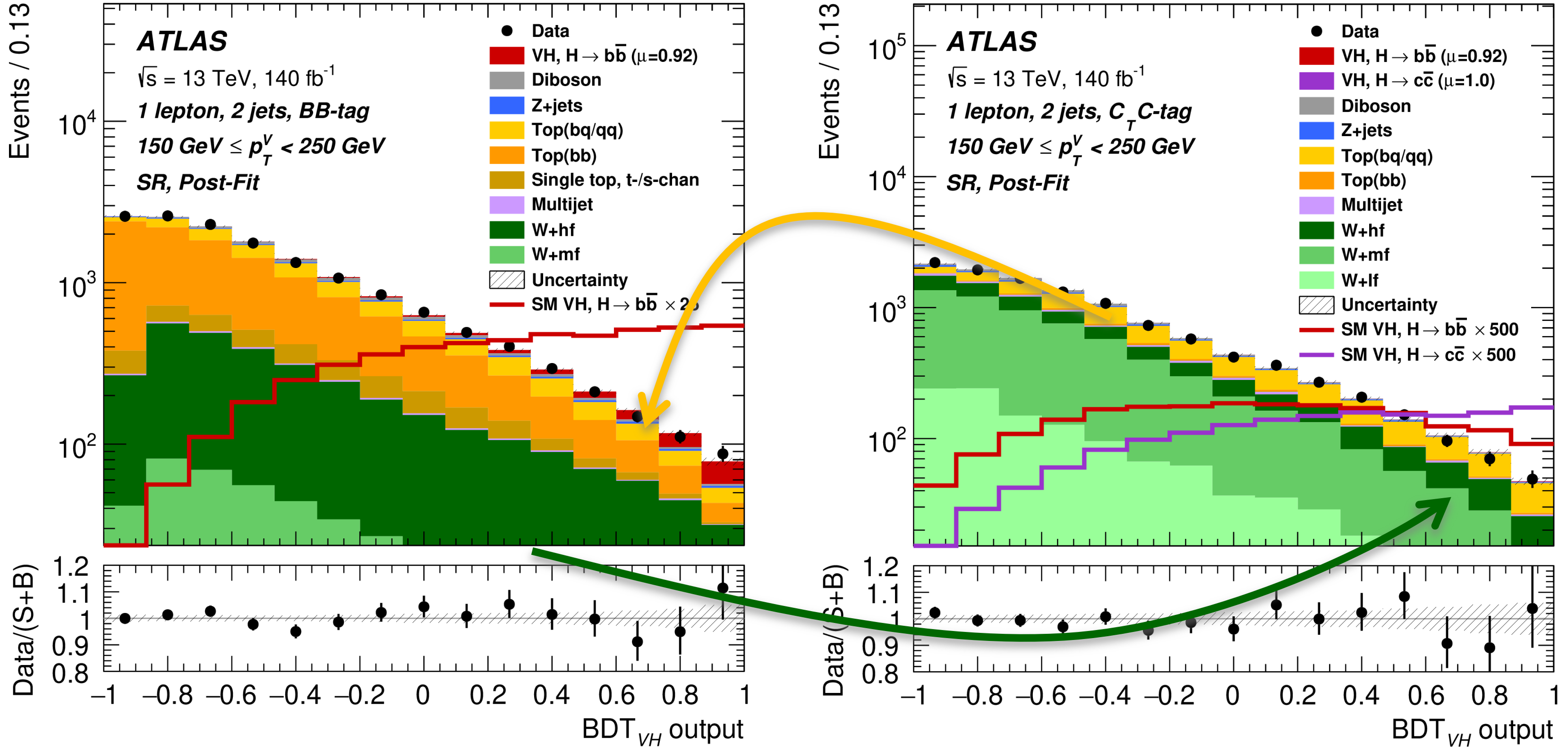
→ *b-probability*, *c-probability*, *light-probability*

→ **Probabilities combined into a "tagging score"**

VH(bb) and VH(cc): Side-by-Side

Example from 1-lepton

Same kinematic selection, only difference is b- vs. c-tagging



Diverse background composition, but the two regimes, cc-enriched and bb-enriched, “can learn from each other”

Challenge 4: Monte Carlo is not the Reality

- Expected background contribution estimated from simulated samples

→Simulation inaccuracies (x-section prediction, prediction of kinematic distributions) are major contributions to VH(bb/cc) measurement uncertainties

- → *Known issues: top p_T spectrum too hard, V+bb/cc x-section underestimated, regime of small distances ΔR between 2 b-jets (or 2 c-jets) mismodelled in V+jets, …*

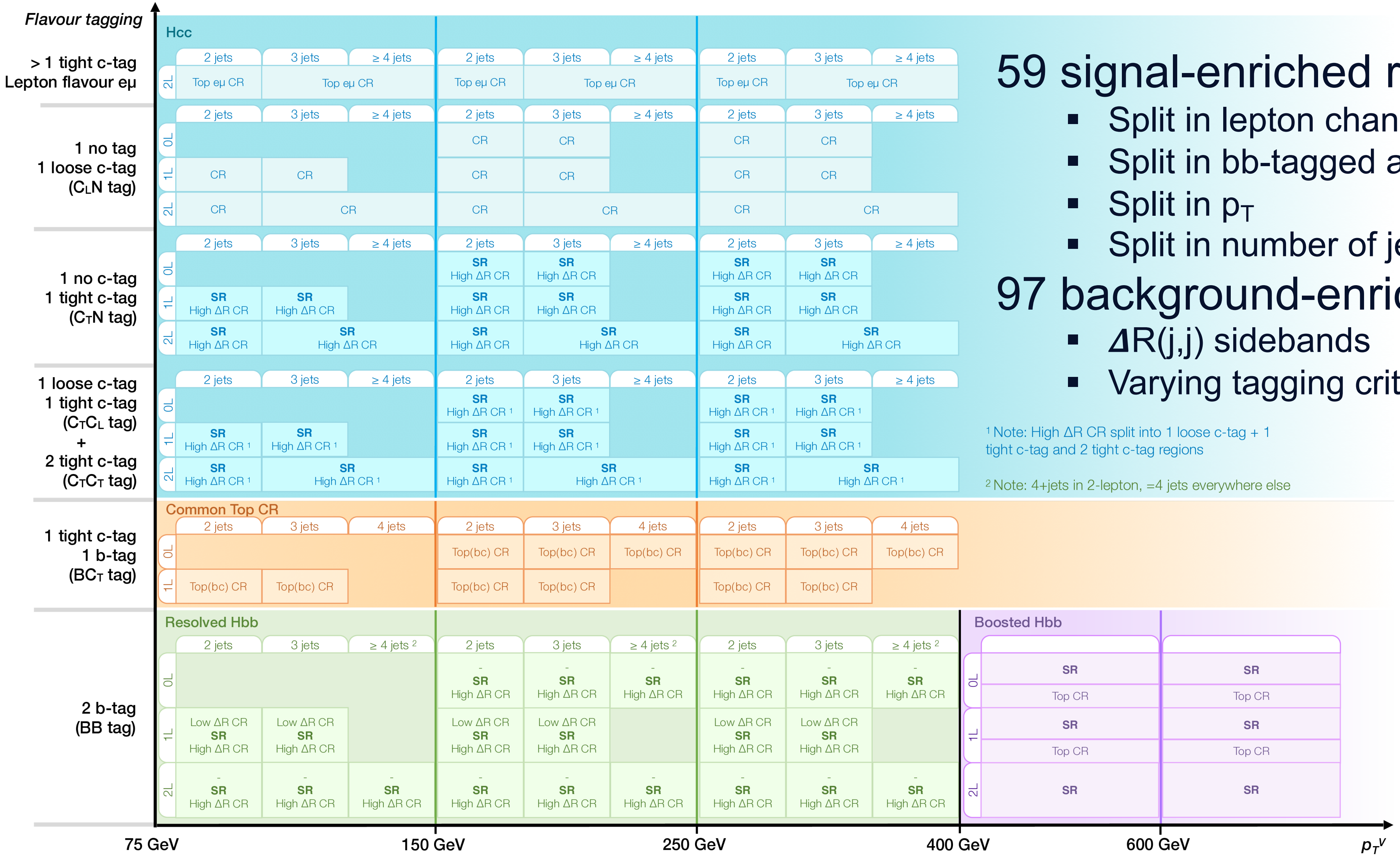
→In addition to using bb-enriched and cc-enriched regions simultaneously, large set of "control regions" defined to perform **auxiliary measurements of backgrounds** to

- → Determine normalisation of major backgrounds
- → Correct mis-modelled kinematic distributions

		Standalone		Simultaneous
WH(bb)	Impact from BG norm	6%	→	2%
	Impact from other BG modelling	10.3%		9.5%
VH(cc)	Contribution of BG norm to tot. unc.	8.6%	→	1%
	Contribution of other BG modelling to tot. unc.	35%		32%

JHEP 04 (2025) 075

+ don't attempt to read…



59 signal-enriched regions

- Split in lepton channels
- Split in bb-tagged and cc-tagged
- Split in p_T
- Split in number of jets

97 background-enriched regions

- $\Delta R(j,j)$ sidebands
- Varying tagging criteria

[1] Note: High ΔR CR split into 1 loose c-tag + 1 tight c-tag and 2 tight c-tag regions

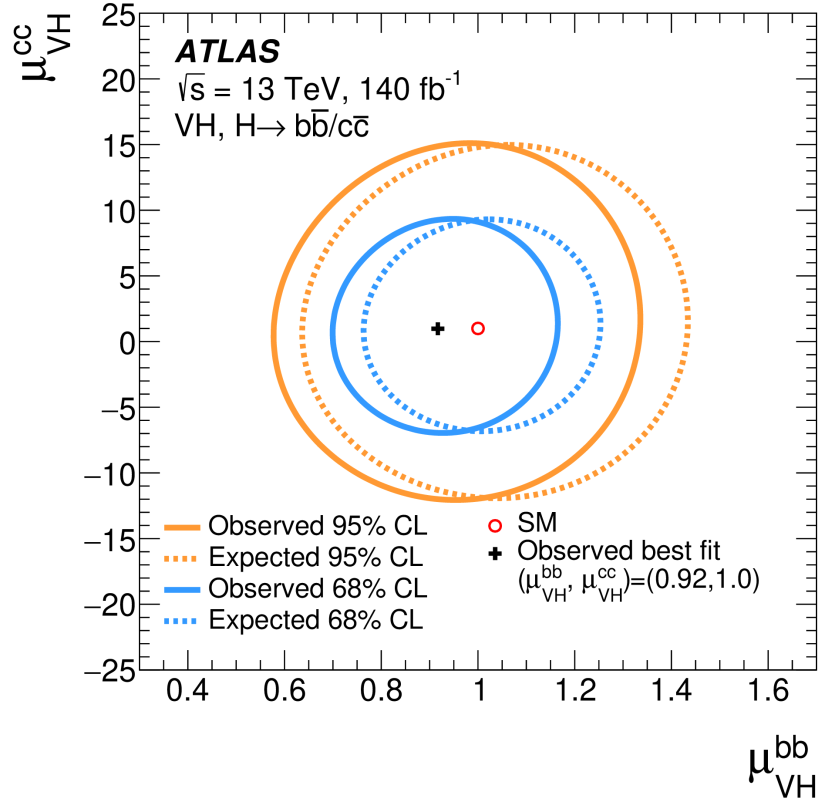
[2] Note: 4+jets in 2-lepton, =4 jets everywhere else

SR=signal region, CR=control region

JHEP 04 (2025) 075

Results: Simultaneous VH(bb) and VH(cc)

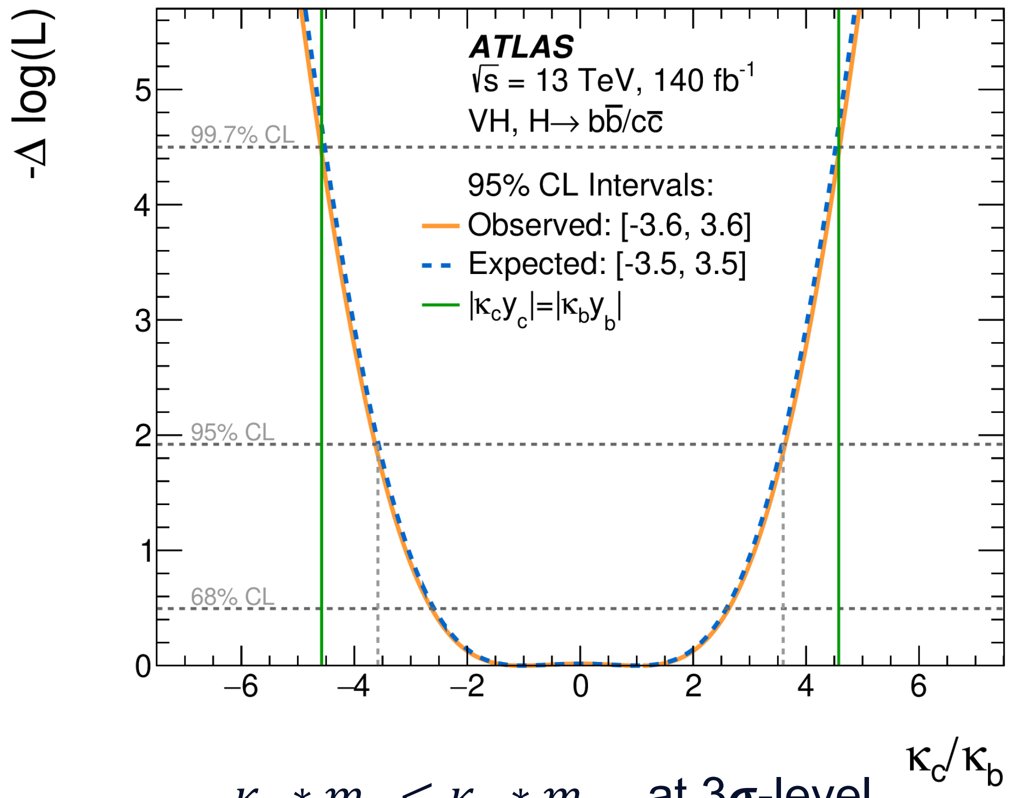
Signal Strengths $\mu = \frac{(\sigma * \mathrm{BR})_{\mathrm{measured}}}{(\sigma * \mathrm{BR})_{\mathrm{SM}}}$



$\mu_{VH(bb)} = 0.92 \pm 0.10\ (\mathrm{stat.})^{+0.13}_{-0.11}(\mathrm{syst.})$

$\mu_{VH(cc)} < 11.5$ x SM expectation (95% CL)

Higgs coupling modifiers (**κ**=1 for SM)



No SM assumptions injected

$\kappa_c * m_c < \kappa_b * m_b$ at 3**σ**-level

Higgs-boson coupling to charm quark weaker than to bottom quark

Why keep improving VH(bb)?

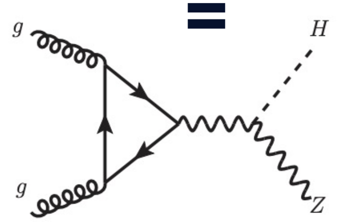
→"Nail down" the by far biggest piece of the "Higgs-boson decay pie"

→**Enable precise measurements of WH and ZH production**

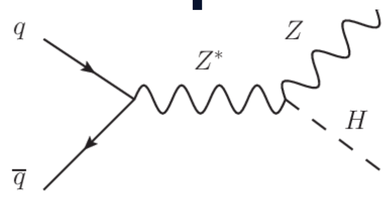
→Probe for new beyond-SM physics

ZH

=

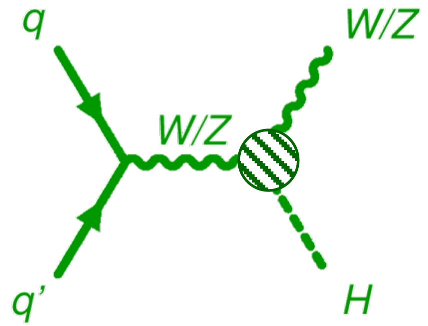


+

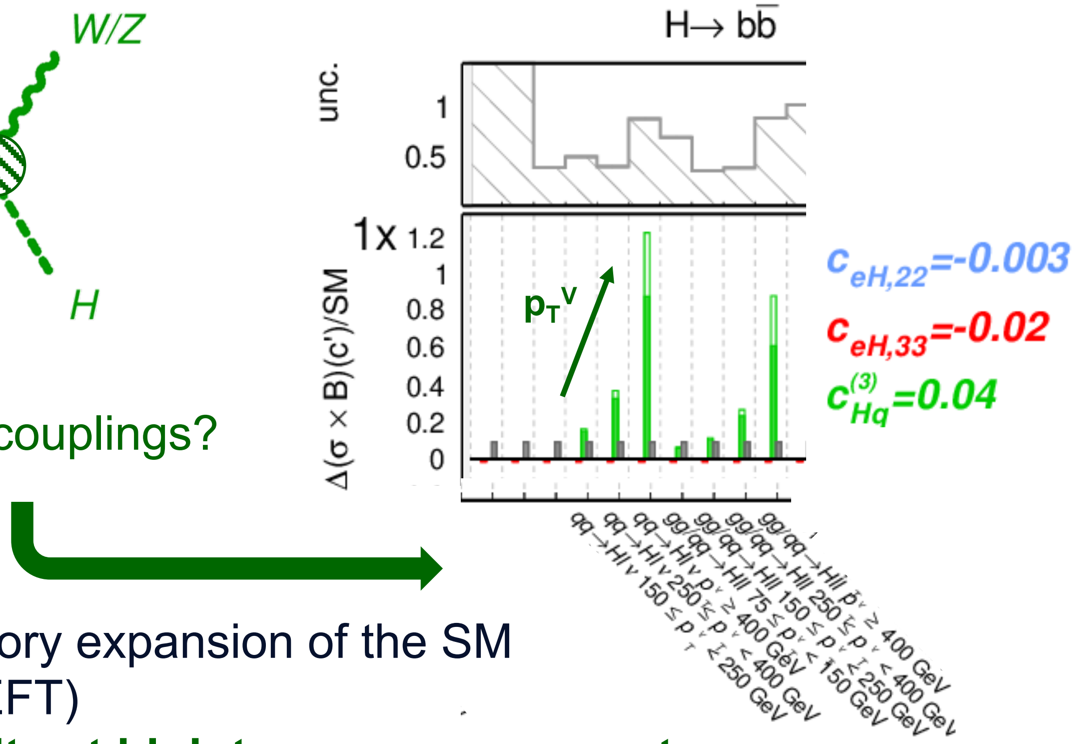


Unexpected loop contributions?

→ Higher sensitivity for gg→ZH at higher jet multiplicity



anomalous effective couplings?

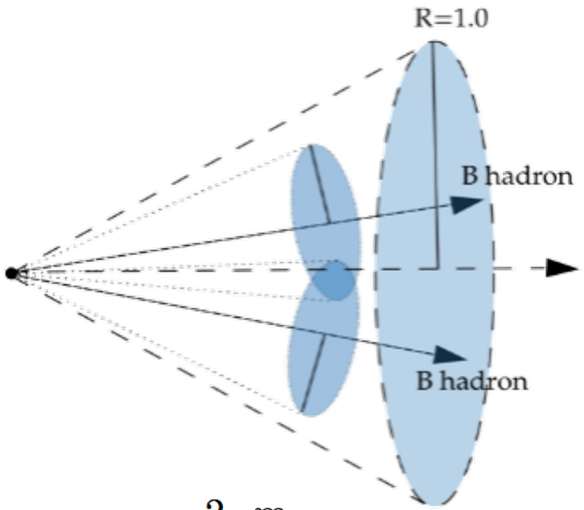


Effective field theory expansion of the SM Lagrangian (SMEFT)

→ High sensitivity at high transverse momenta

JHEP 11 (2024) 097

Introducing: Boosted VH(bb)

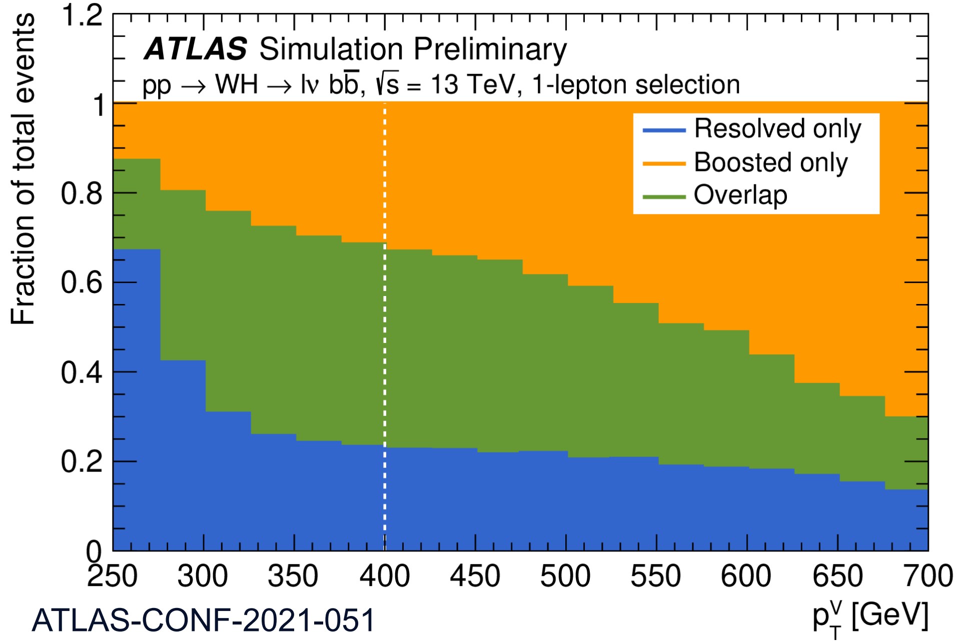


$$\Delta R(b_1, b_2) \approx \frac{2 \cdot m_H}{p_T^H}$$

At large transverse momenta, two jets from Higgs-boson decay start to overlap
→ **Reconstruct Higgs-boson decay as one large-radius jet**

At $p_T^V \gtrsim 400$ GeV boosted reconstruction more efficient
→ Switch from resolved to boosted to extend high p_T reach

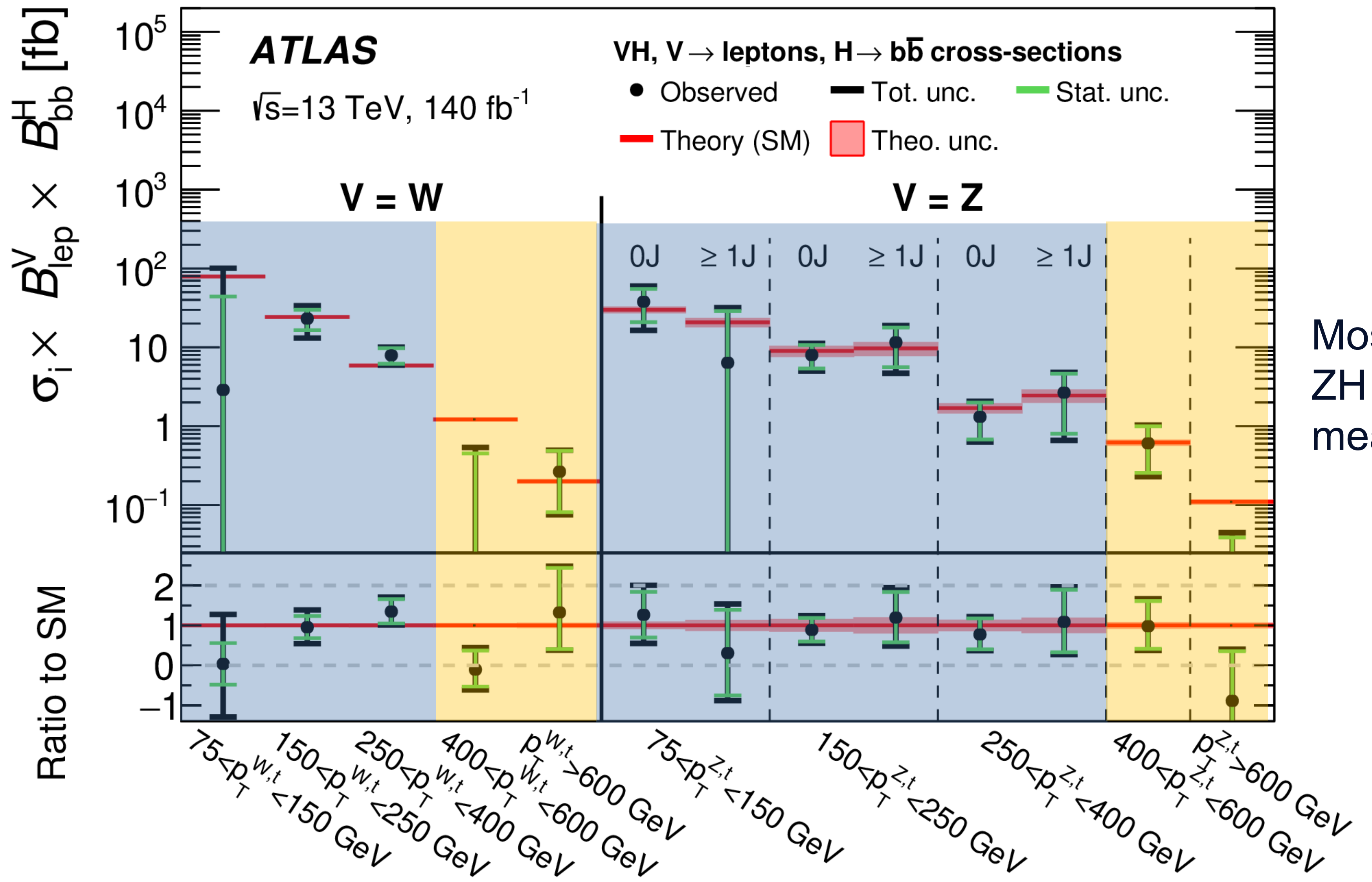
Reconstruction efficiencies
(2 small-R jets vs. 1 large-R jet)



ATLAS-CONF-2021-051

JHEP 04 (2025) 075

Results: Differential WH and ZH x-Section

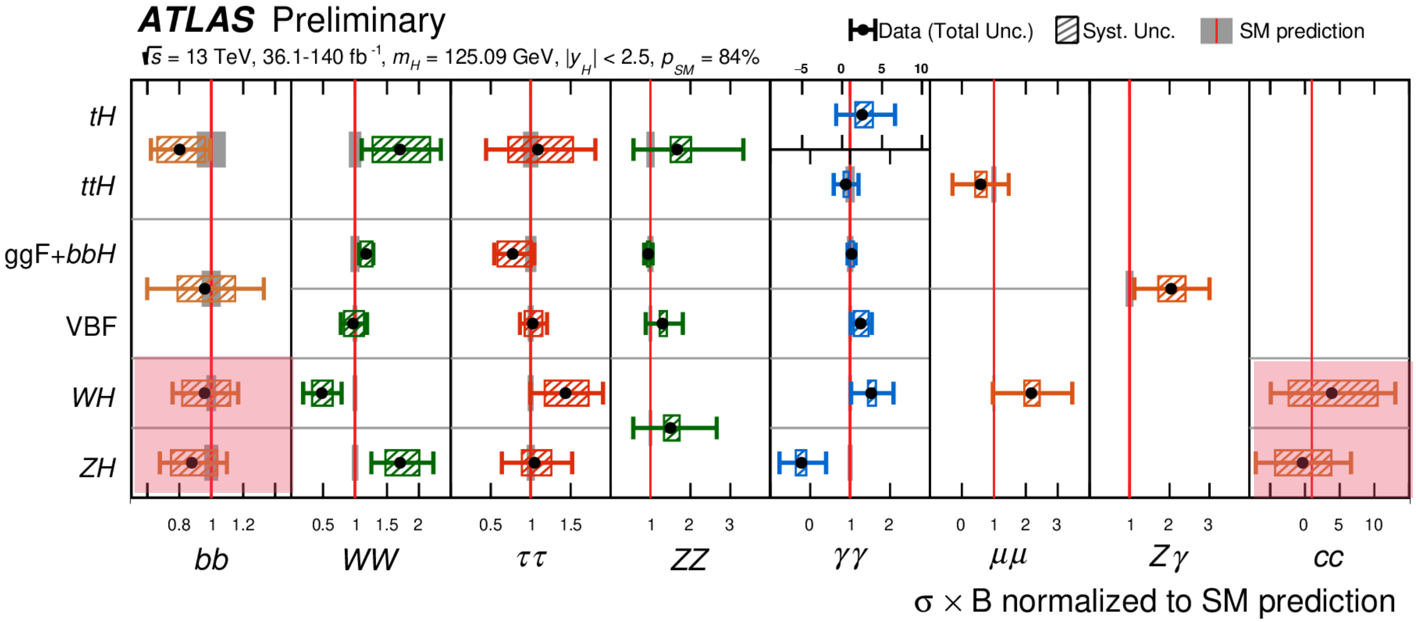


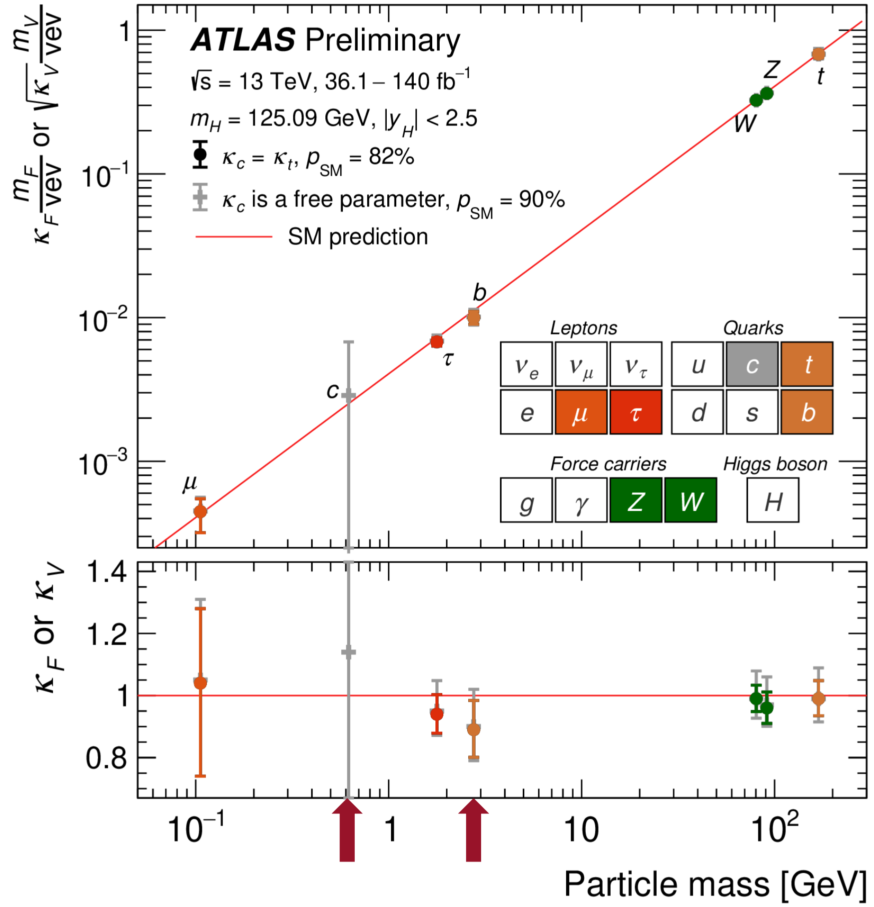
Most precise WH and ZH cross-section measurement to date

ATLAS Higgs-Boson Couplings Landscape

VH(bb)-VH(cc) is the main contributor to H→bb, WH and ZH sensitivity and sole contributor to H→cc sensitivity

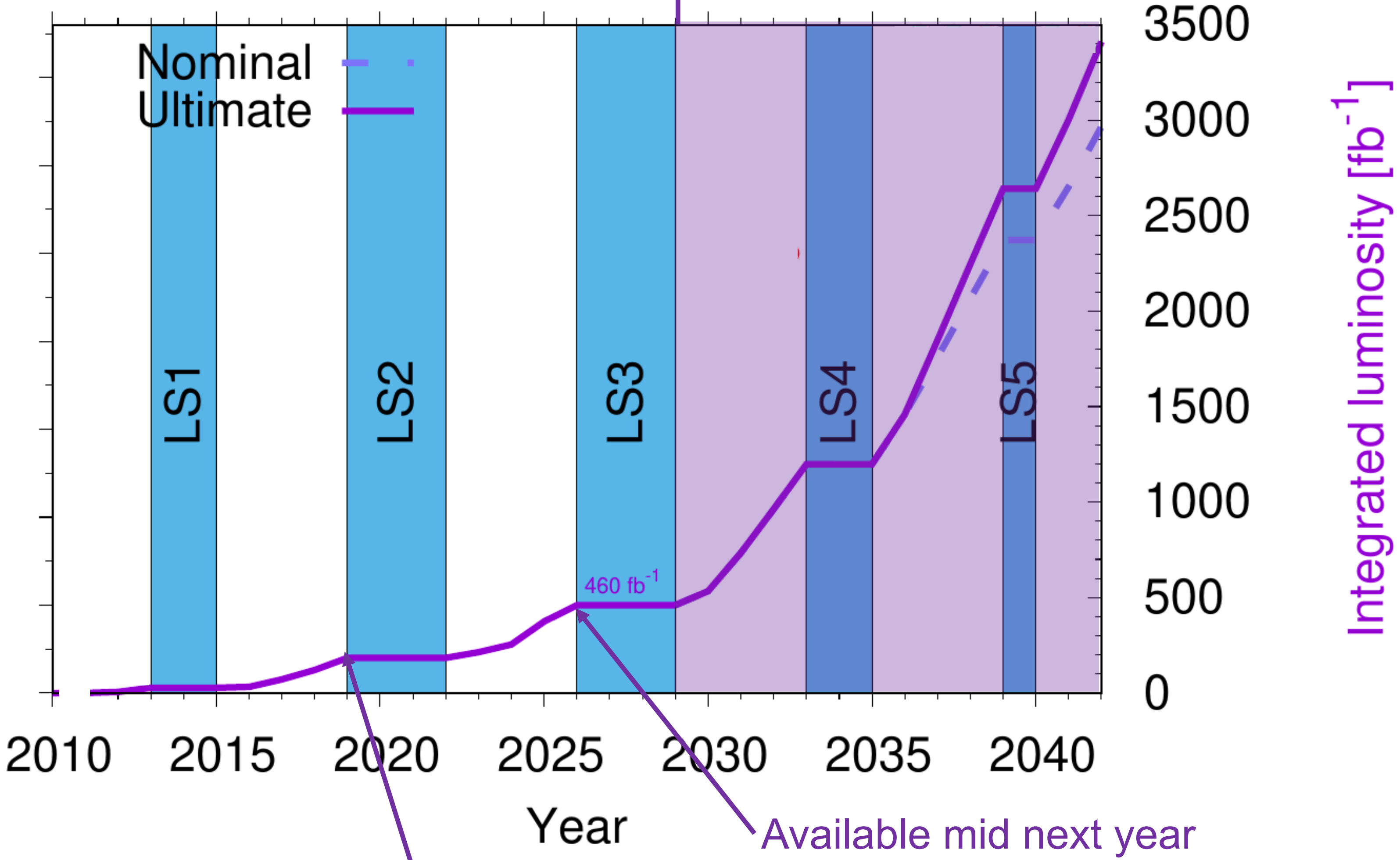
Current VH(cc) sensitivity allows for couplings measurements with fewer assumptions (κ_c left free floating rather than fixed)





Data: more is yet to come…

HL-LHC (upgraded accelerator and experiments)



Available mid next year

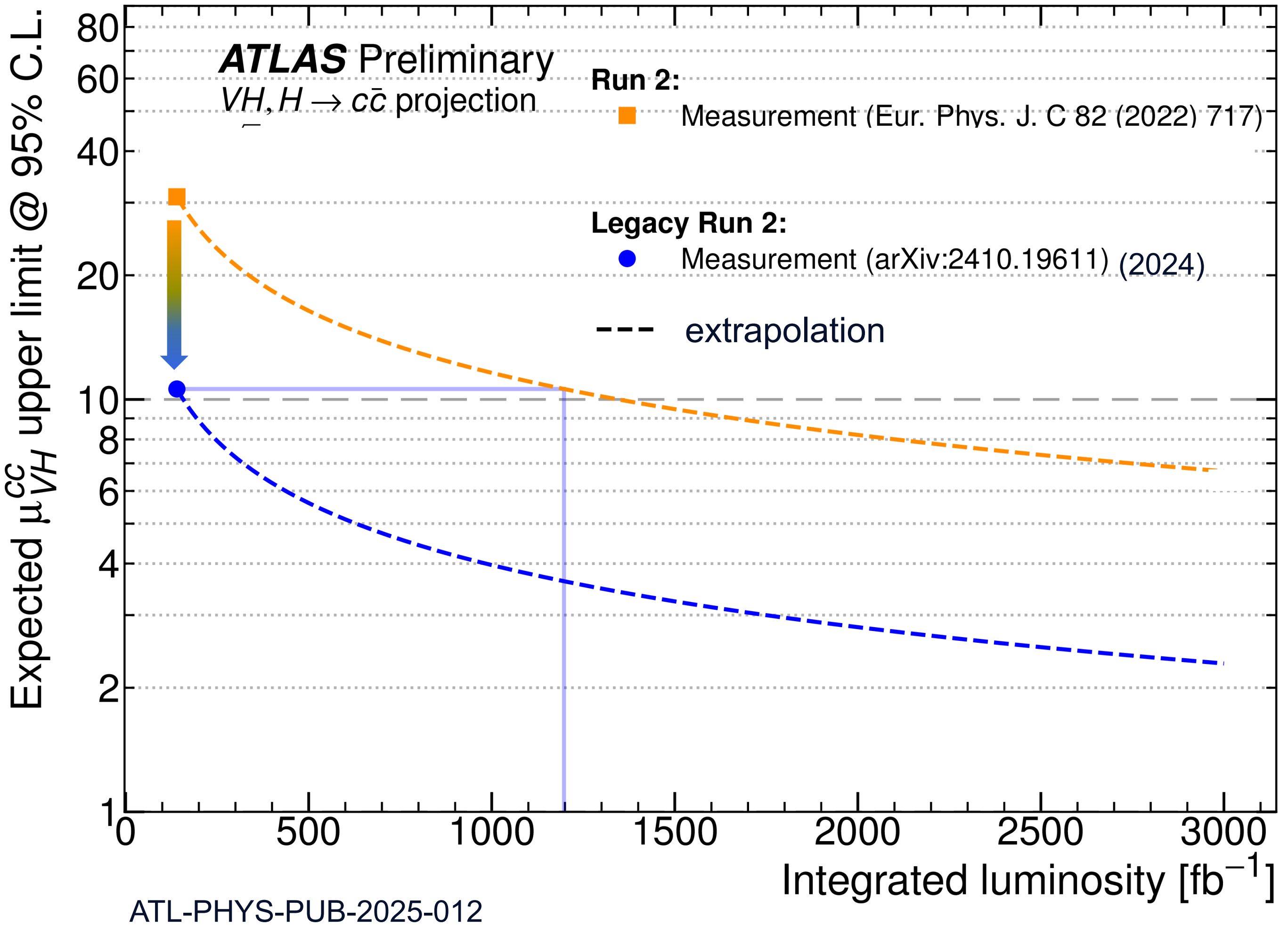
In presentation today

~3 times more data by end of 2026

~20 times more data to be delivered by HL-LHC

Impact of Improving Experimental Techniques

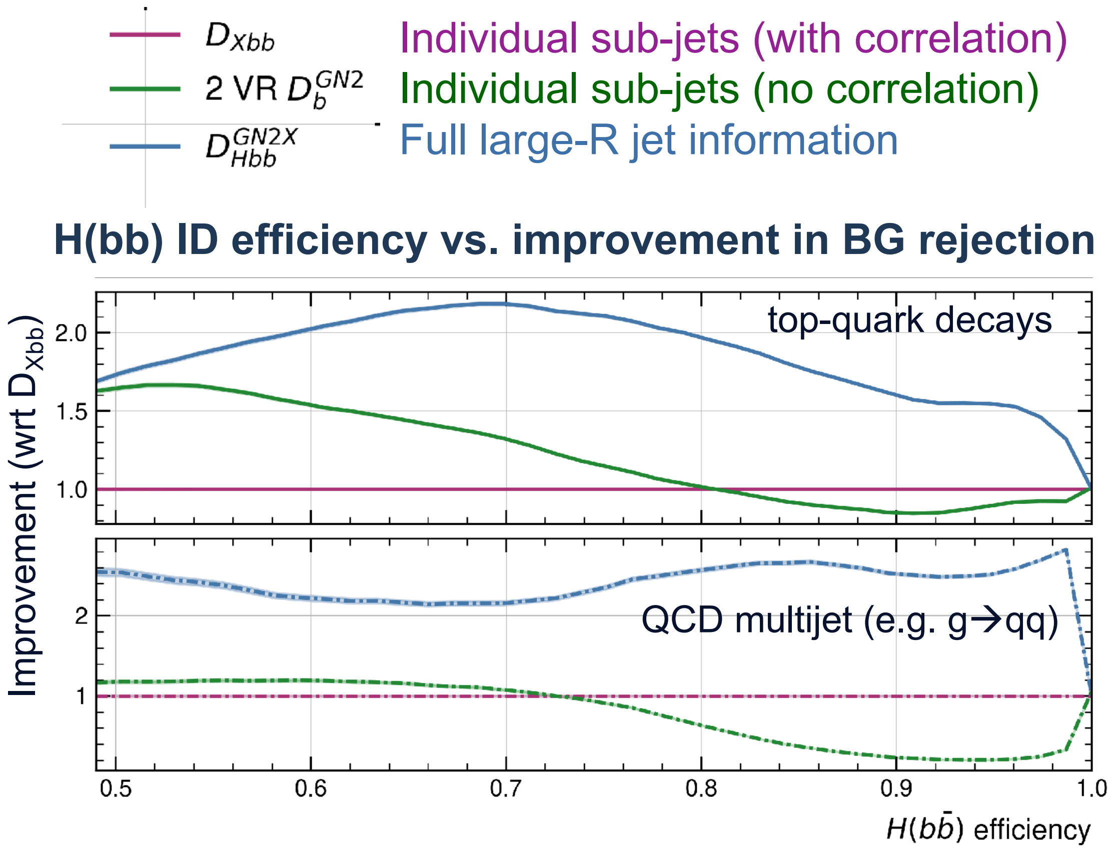
Solely improving experimental techniques



ATL-PHYS-PUB-2025-012

Improvements implemented for VH(bb)-VH(cc) measurement are **equivalent to factor 8.5 increase in data**

Honing Identification of Hadronic Higgs-Boson Decays

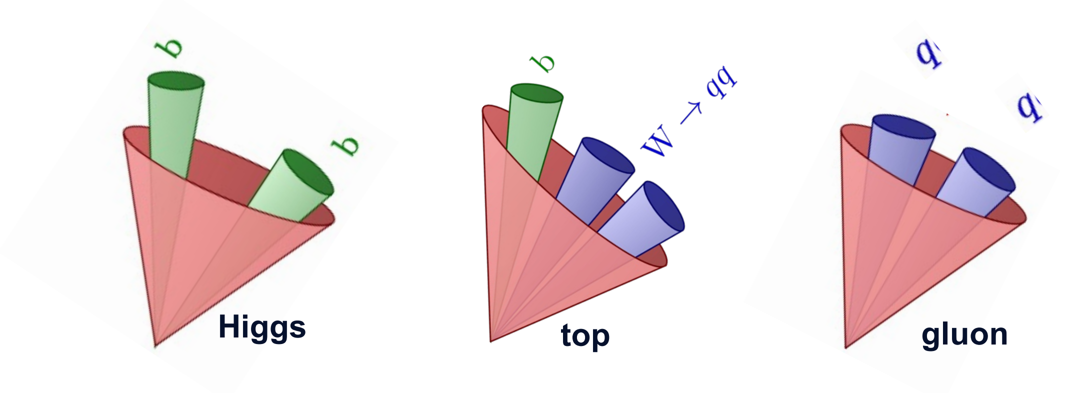


ATL-PHYS-PUB-2023-021

Boosted Higgs-boson decays: use all information about tracks associated to a large-radius jet in a transformer neural-net algorithm

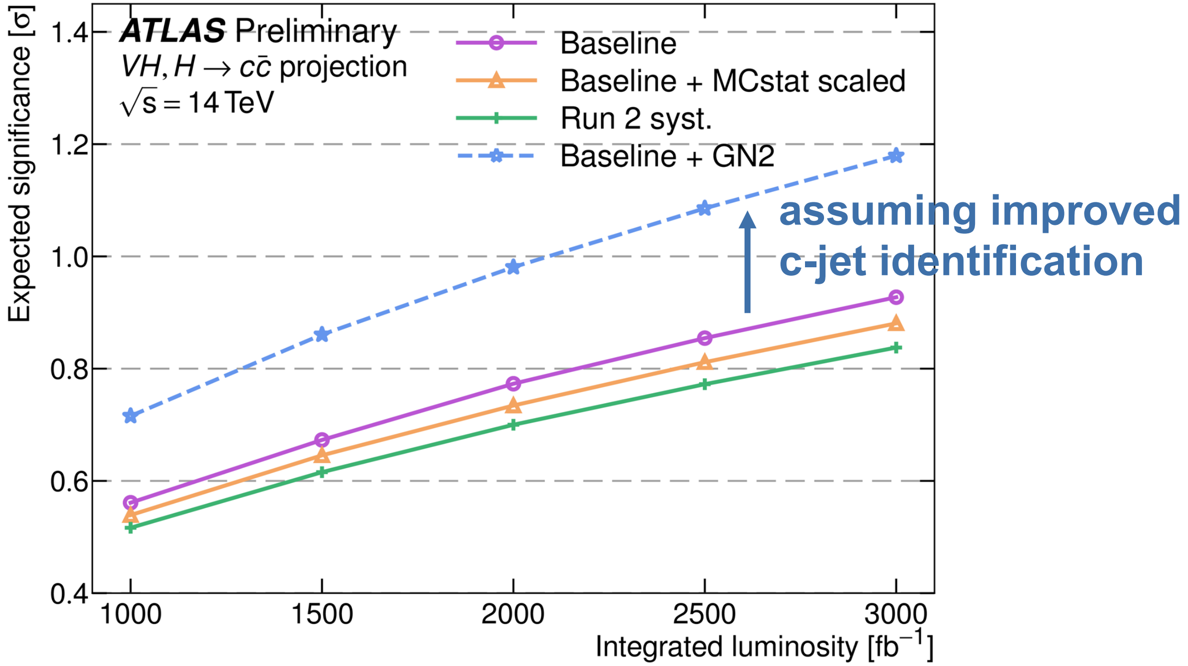
- Previously: identify sub-jets with shrinking cone and then apply b-tagging to those

→ Significant improvements will boost high p_T Higgs boson measurements



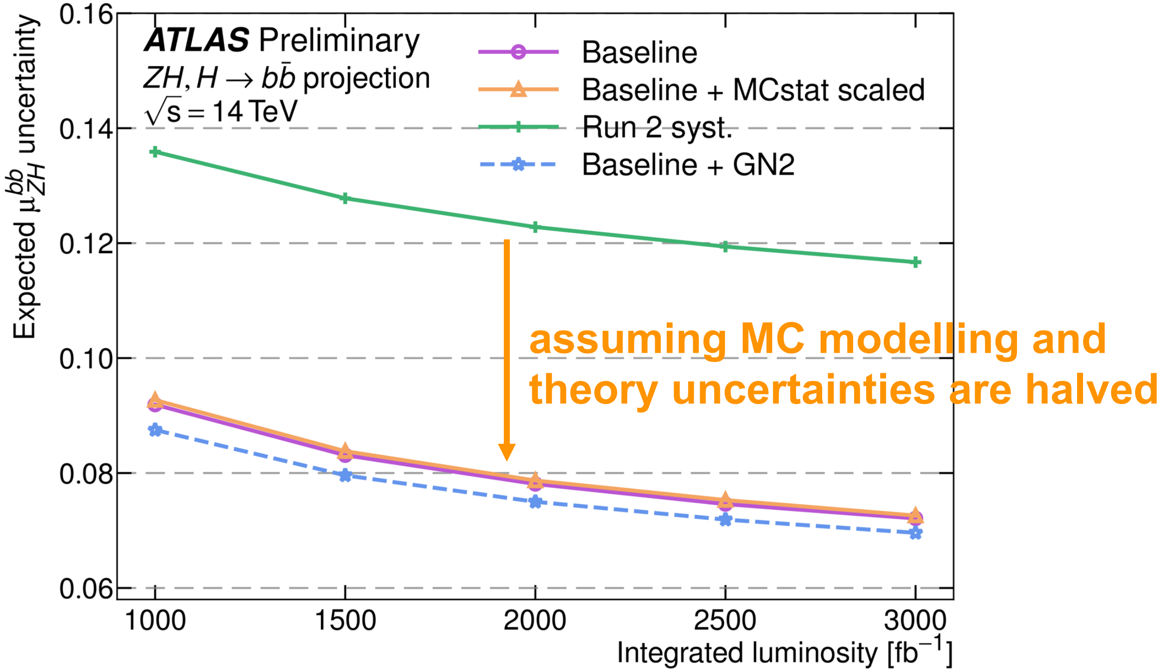
What to Expect at HL-LHC

Expected VH(cc) significance
(different scenarios)



>1σ estimated at HL-LHC using latest (2025) c-jet identification techniques

Impact of uncertainties on WH(bb) and ZH(bb) precision



Reducing MC modelling uncertainties will be key to improve precision

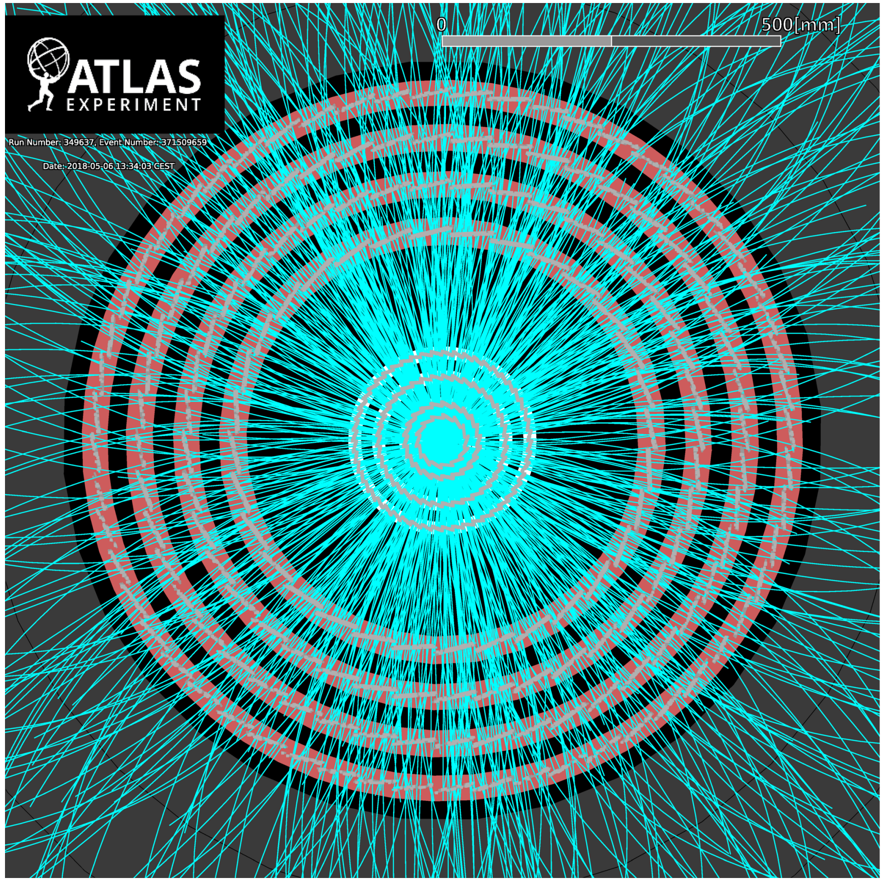
The Higgs Boson sits at the heart of the Standard Model, playing a crucial role in the emergence of mass in the universe

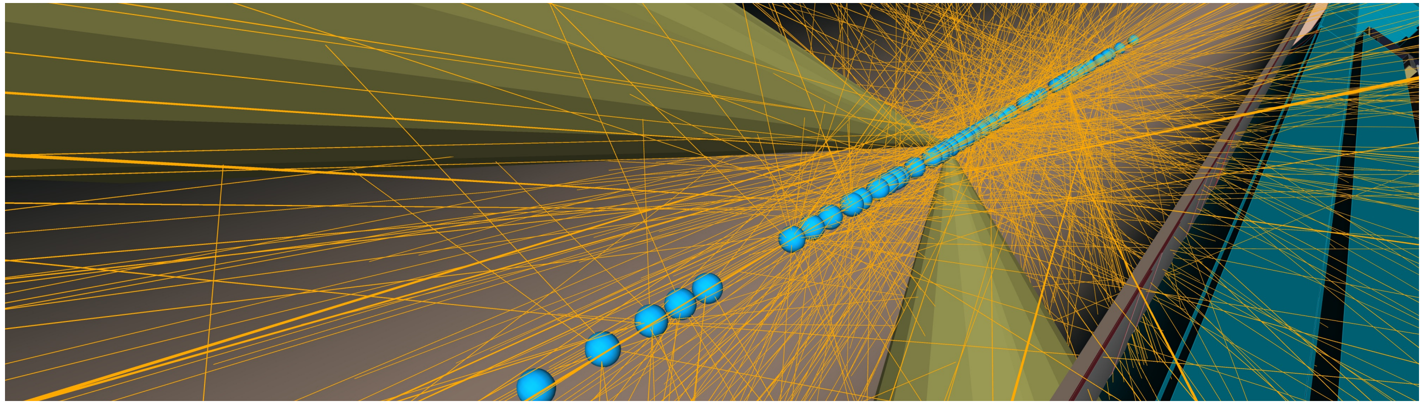
The experimental study of Higgs-boson couplings to bottom and charm quarks shines light on quark masses and probes for new beyond-SM effects

Experimental sensitivity with ATLAS 2015-2018 data reached unprecedented level due to significantly improved experimental techniques

Setting promising precedent to reach next milestones in Higgs-boson physics with (HL)LHC data

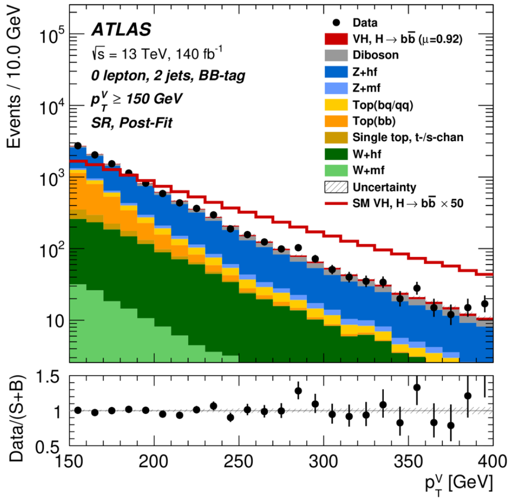
Typical Track and Pile-up Density

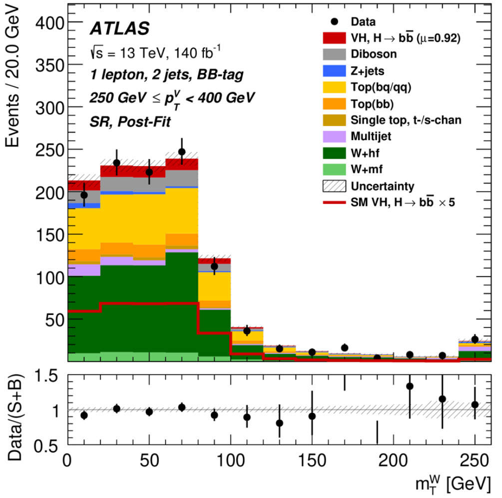


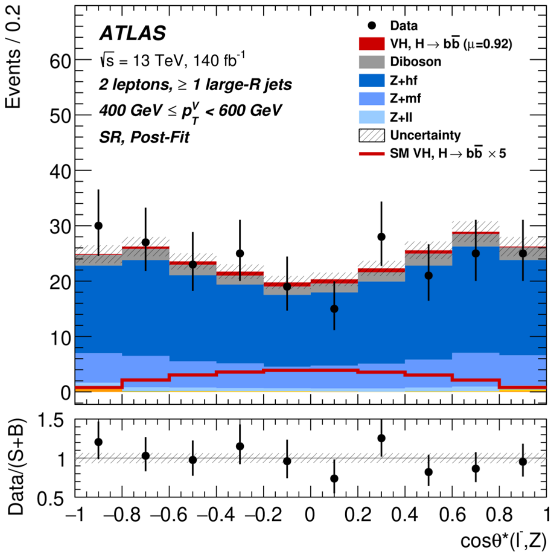


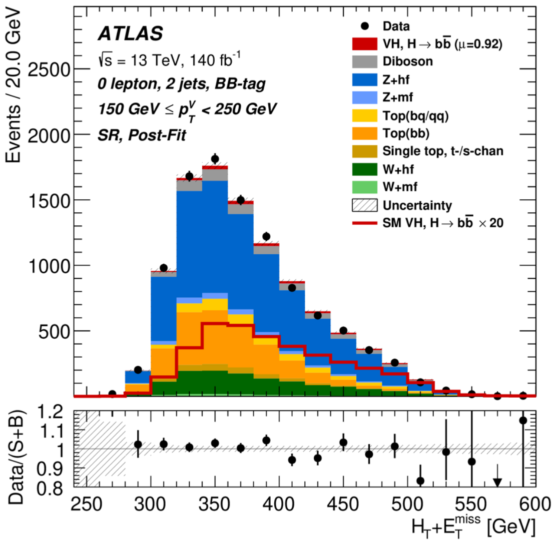
BDT Input Variables

Variable	Resolved $VH,\ H \to b\bar{b}, c\bar{c}$ 0-lepton	Resolved 1-lepton	Resolved 2-lepton	Boosted $VH,\ H \to b\bar{b}$ 0-lepton	Boosted 1-lepton	Boosted 2-lepton
m_H	✓	✓	✓	✓	✓	✓
$m_{j_1 j_2 j_3}$	✓	✓	✓			
$p_T^{j_1}$	✓	✓	✓	✓	✓	✓
$p_T^{j_2}$	✓	✓	✓	✓	✓	✓
$p_T^{j_3}$				✓	✓	✓
$\sum p_T^{j_i},\ i > 2$	✓	✓	✓			
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_1)$	✓	✓	✓	✓	✓	✓
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_2)$	✓	✓	✓	✓	✓	✓
p_T^V	$\equiv E_T^{\mathrm{miss}}$	✓	✓	$\equiv E_T^{\mathrm{miss}}$	✓	✓
E_T^{miss}	✓	✓		✓	✓	
$E_T^{\mathrm{miss}}/\sqrt{S_T}$			✓			
$\lvert\Delta\phi(\boldsymbol{V},\boldsymbol{H})\rvert$	✓	✓	✓	✓	✓	✓
$\lvert\Delta y(\boldsymbol{V},\boldsymbol{H})\rvert$		✓	✓		✓	✓
$\Delta R(\boldsymbol{j_1},\boldsymbol{j_2})$	✓	✓	✓	✓	✓	✓
$\min[\Delta R(\boldsymbol{j_i}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})],\ i > 2$	✓	✓				
N(track-jets in J)				✓	✓	✓
N(add. small-R jets)				✓	✓	✓
colour ring				✓	✓	✓
$\lvert\Delta\eta(\boldsymbol{j_1},\boldsymbol{j_2})\rvert$	✓					
$H_T + E_T^{\mathrm{miss}}$	✓					
m_T^W		✓				
m_{top}		✓				
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})]$		✓				
p_T^{ℓ}					✓	
$(p_T^{\ell} - E_T^{\mathrm{miss}})/p_T^V$					✓	
$m_{\ell\ell}$			✓			
$\cos\theta^*(\boldsymbol{\ell^-},\boldsymbol{V})$			✓			✓









Background Normalisations

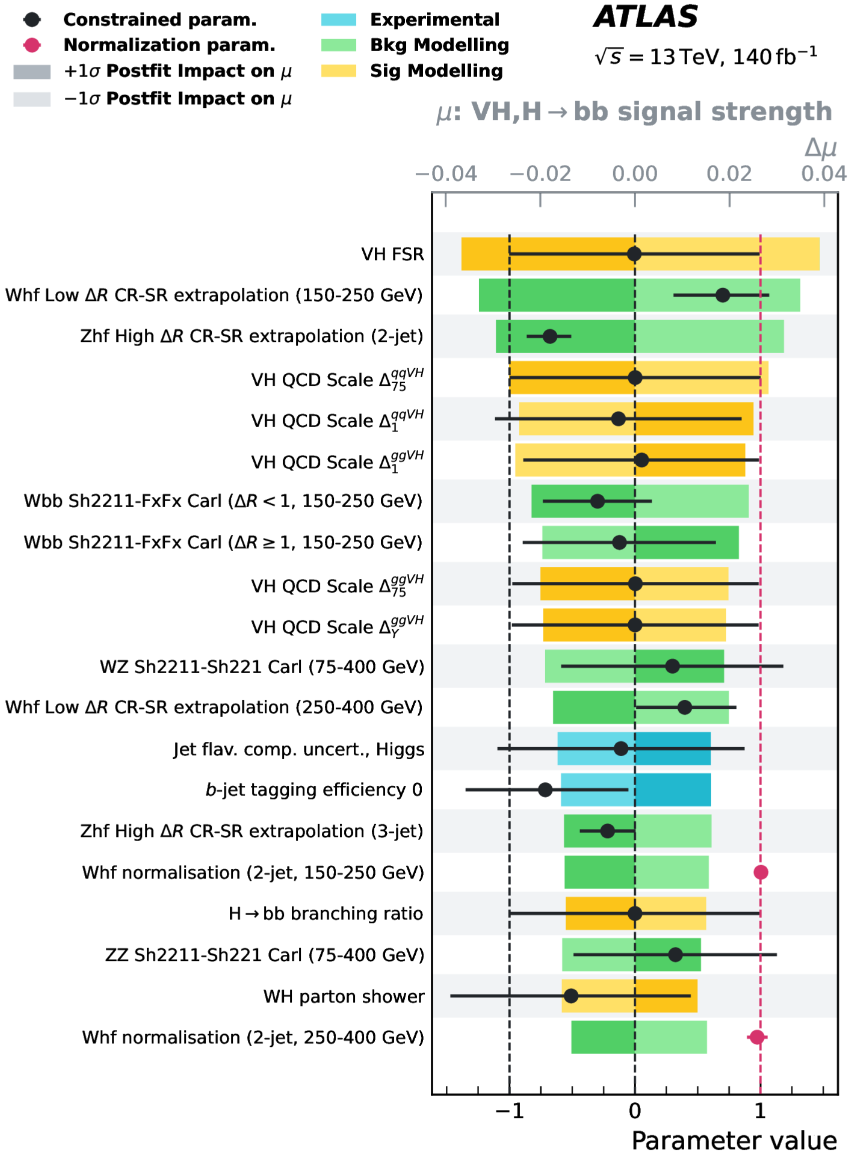
p_T^V interval	Number of jets	$W+hf$	$W+mf$	$W+lf$
75–150 GeV	2	1.09 ± 0.06	1.20 ± 0.03	1.03 ± 0.04
	≥3	1.30 ± 0.07	1.16 ± 0.04	1.07 ± 0.05
150–250 GeV	2	1.00 ± 0.05	1.31 ± 0.03	1.08 ± 0.03
	≥3	1.28 ± 0.07	1.31 ± 0.04	1.07 ± 0.04
250–400 GeV	2	0.97 ± 0.08	1.35 ± 0.07	1.05 ± 0.03
	≥3	1.46 ± 0.12	1.32 ± 0.07	1.10 ± 0.04
400–600 GeV	-	1.49 ± 0.25		–
> 600 GeV	-	2.03 ± 0.25		–

p_T^V interval	Number of jets	$Z+hf$	$Z+mf$	$Z+lf$
75–150 GeV	2	1.20 ± 0.04	1.04 ± 0.04	1.12 ± 0.03
	≥3	1.49 ± 0.06	1.11 ± 0.05	1.12 ± 0.05
	3/≥3	0.77 ± 0.03	–	–
150–250 GeV	2	1.30 ± 0.04	1.08 ± 0.04	1.17 ± 0.02
	≥3	1.59 ± 0.07	1.14± 0.05	1.17 ± 0.04
	3/≥3	0.80 ± 0.04	–	–
250–400 GeV	2	1.40 ± 0.07	1.31 ± 0.08	1.16 ± 0.03
	≥3	1.78 ± 0.09	1.32 ± 0.07	1.20 ± 0.04
	3/≥3	0.74 ± 0.04	–	–
>400 GeV	-	1.63 ± 0.13		–

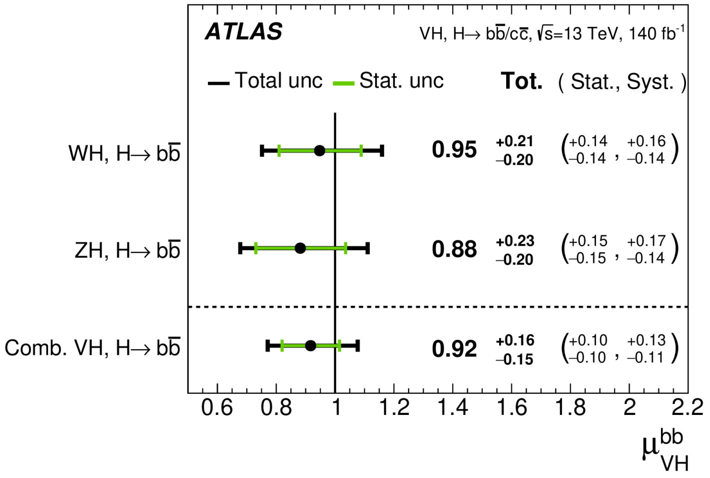
p_T^V interval	Number of jets	Top(bb)	Top(bq,qq)	Top 2L
75–150 GeV	2	1.02 ± 0.04	0.98 ± 0.05	1.05 ± 0.05
	3	0.97 ± 0.03	0.98 ± 0.03	0.98 ± 0.05
150–250 GeV	2	0.89 ± 0.05	0.83 ± 0.04	1.07 ± 0.16
	3	0.91 ± 0.03	0.86 ± 0.03	0.95 ± 0.14
	4	0.97 ± 0.02	0.95 ± 0.03	
250–400 GeV	2	0.78 ± 0.08	0.82 ± 0.05	1.10 ± 0.50
	3	0.83 ± 0.04	0.80 ± 0.03	
	4	0.93 ± 0.05	0.86 ± 0.04	
400–600 GeV	-	0.83 ± 0.05		–
>600 GeV	-	0.69 ± 0.07		–

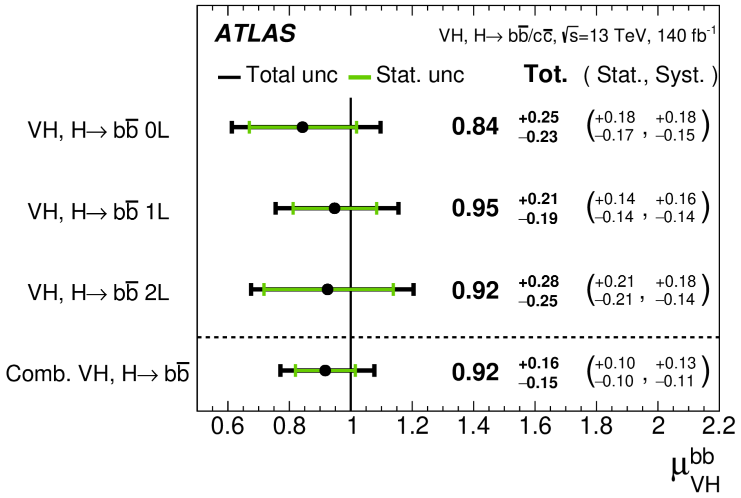
VH(bb)-VH(cc) Breakdown of Uncertainties

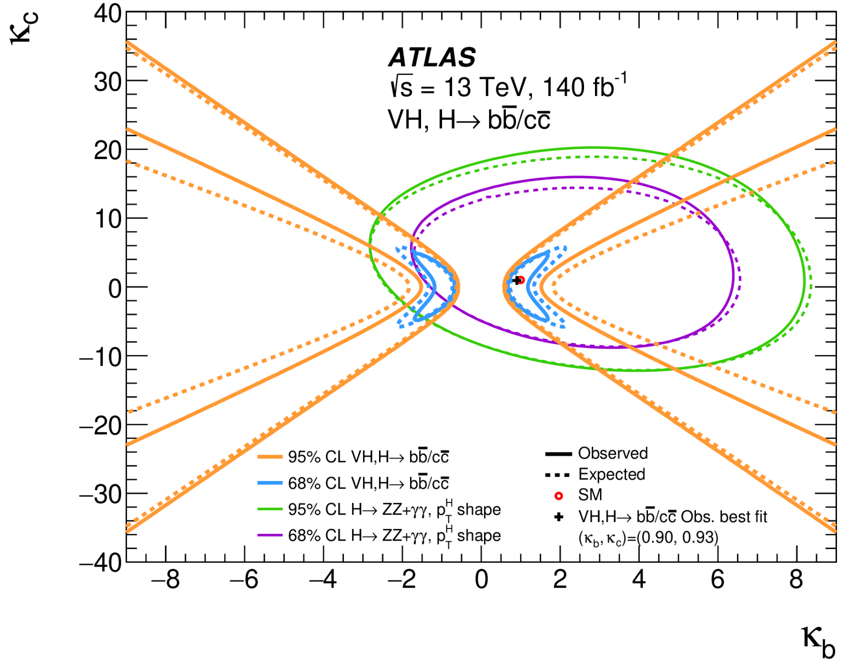
Source of uncertainty	σ_μ $VH, H \to b\bar{b}$	$WH, H \to b\bar{b}$	$ZH, H \to b\bar{b}$	$VH, H \to c\bar{c}$
Total	0.153	0.204	0.216	5.31
Statistical	0.097	0.139	0.153	3.94
Systematic	0.118	0.149	0.153	3.57
Statistical uncertainties				
Data statistical	0.090	0.129	0.139	3.67
$t\bar{t}$ $e\mu$ control region	0.009	0.014	0.027	0.08
Background floating normalisations	0.034	0.049	0.042	1.24
Other VH floating normalisation	0.007	0.018	0.014	0.33
Simulation samples size	0.023	0.033	0.030	1.62
Experimental uncertainties				
Jets	0.027	0.035	0.030	1.02
E_T^{miss}	0.010	0.005	0.021	0.23
Leptons	0.003	0.002	0.010	0.25
b-tagging: b-jets	0.020	0.018	0.026	0.29
b-tagging: c-jets	0.013	0.017	0.012	0.73
b-tagging: light-flavour jets	0.005	0.008	0.008	0.66
Pile-up	0.008	0.017	0.002	0.23
Luminosity	0.006	0.007	0.006	0.08
Theoretical and modelling uncertainties				
Signal	0.076	0.074	0.101	0.72
Z + jets	0.042	0.018	0.081	1.77
W + jets	0.054	0.087	0.026	1.42
$t\bar{t}$ and Wt	0.018	0.033	0.018	1.02
Single top-quark (s-, t-ch.)	0.010	0.018	0.002	0.16
Diboson	0.033	0.039	0.049	0.52
Multijet	0.005	0.010	0.005	0.55

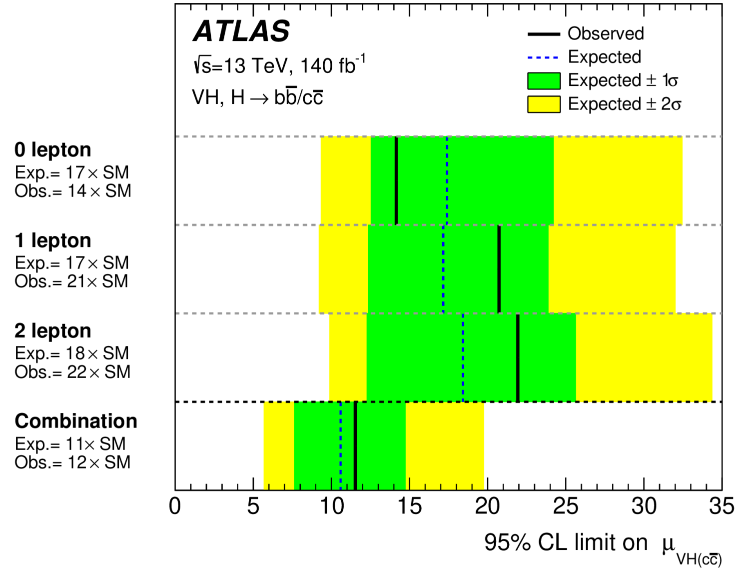


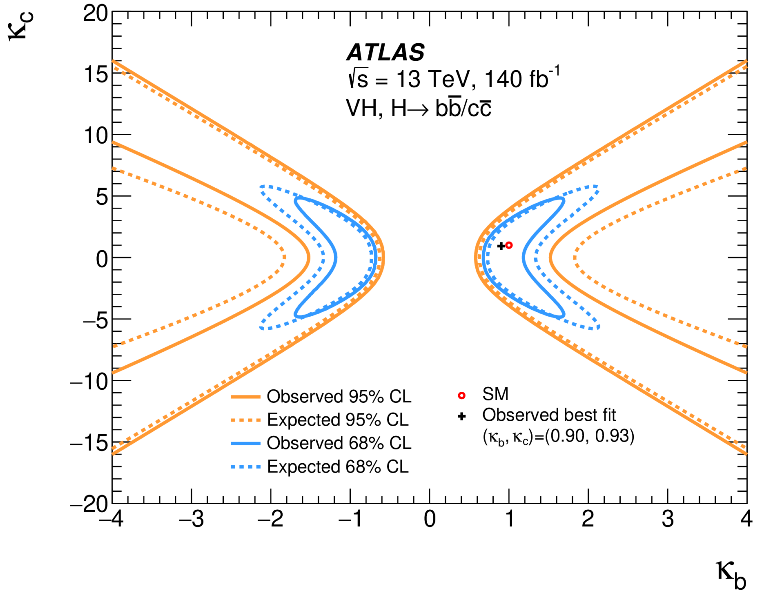
VH(bb)-VH(cc) Results: More Numbers



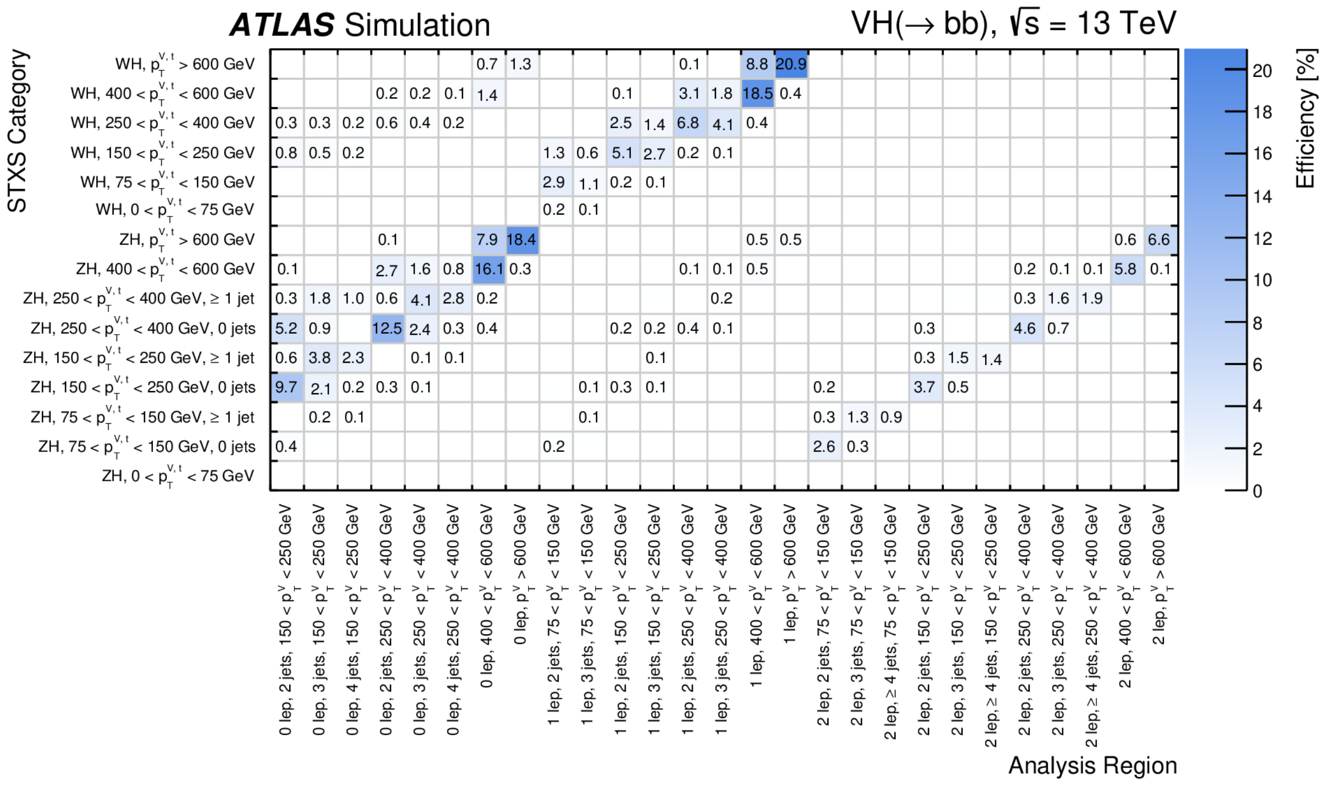


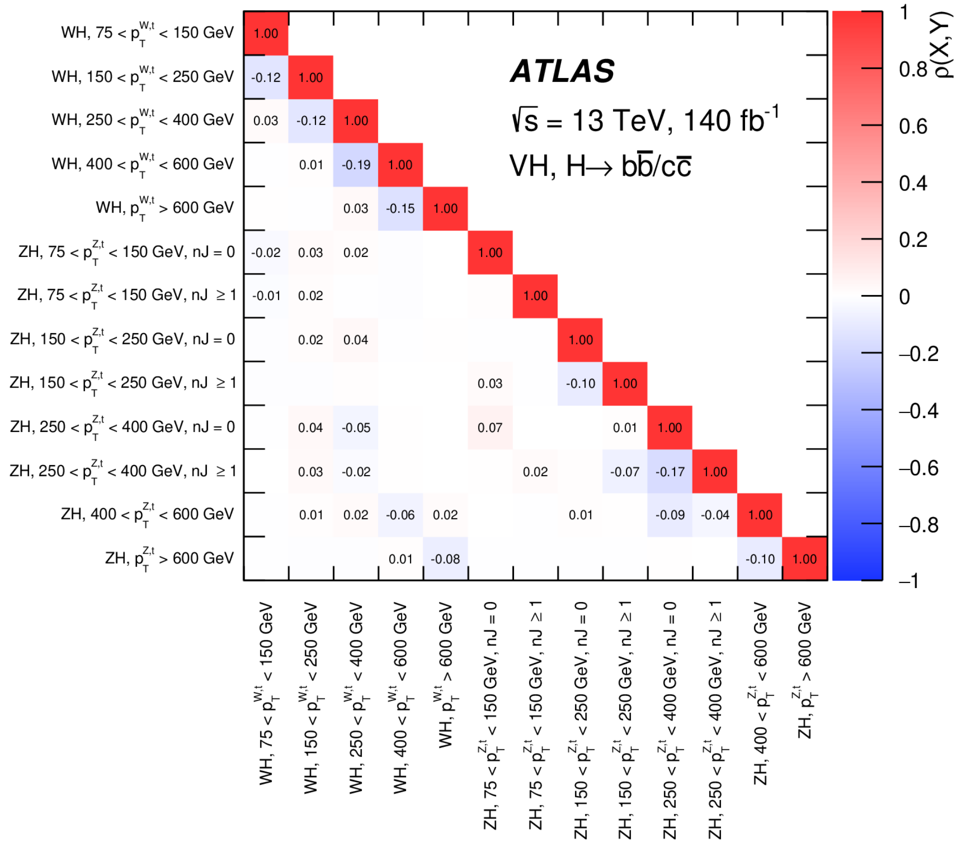




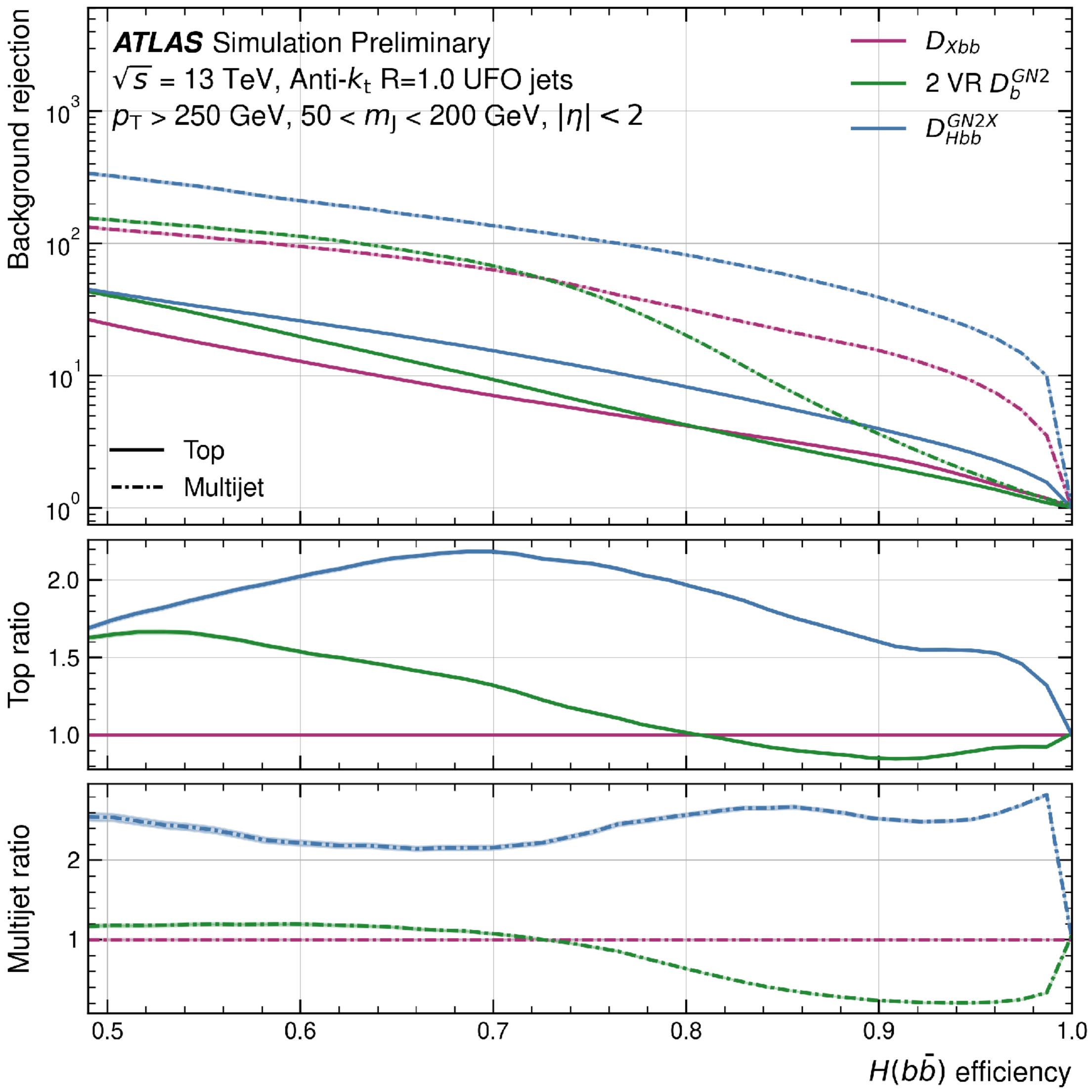


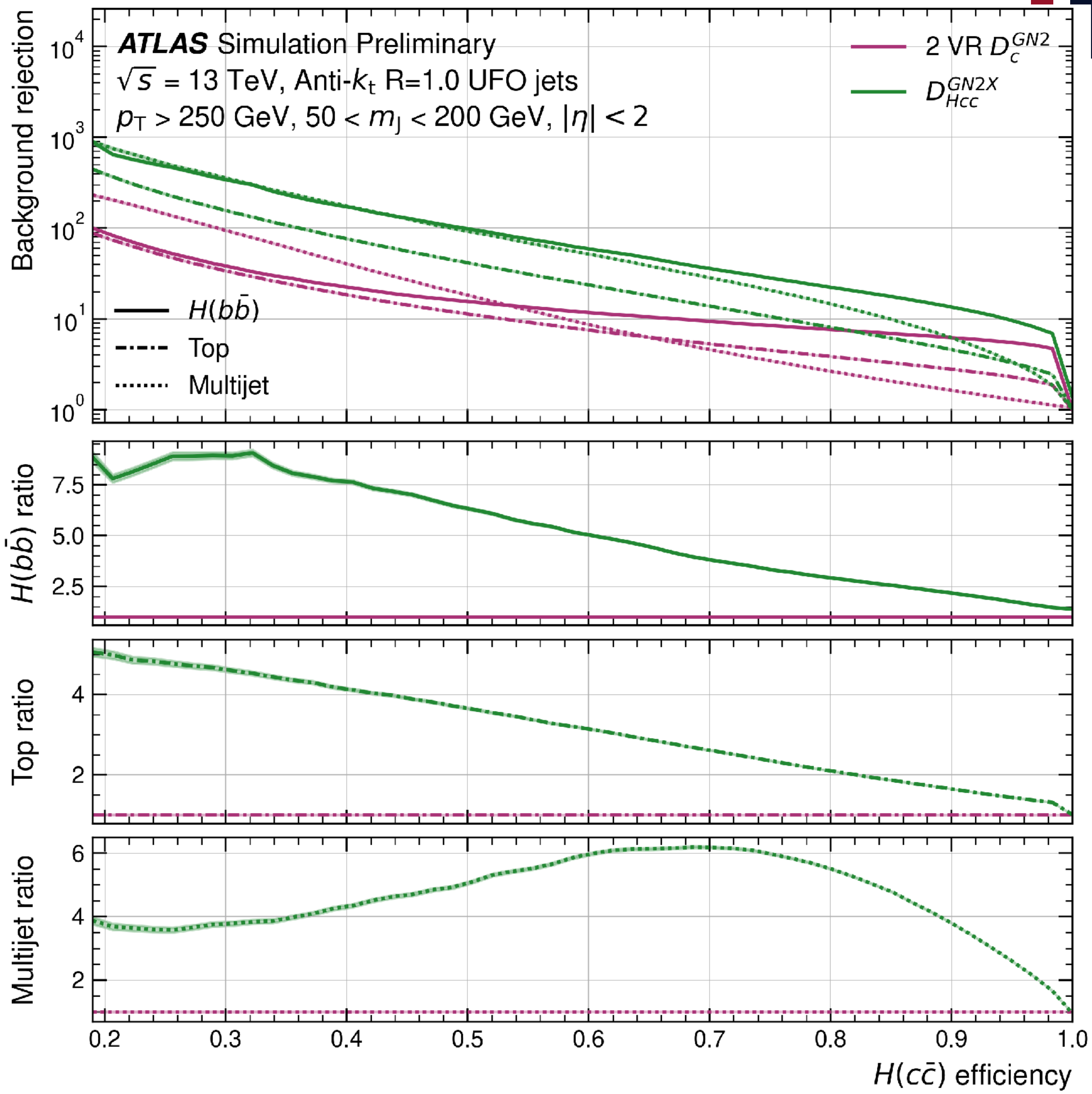
VH(bb) STXS – Migrations and Correlations





Boosted Higgs Tagging





VH(bb) HL-LHC Extrapolation: