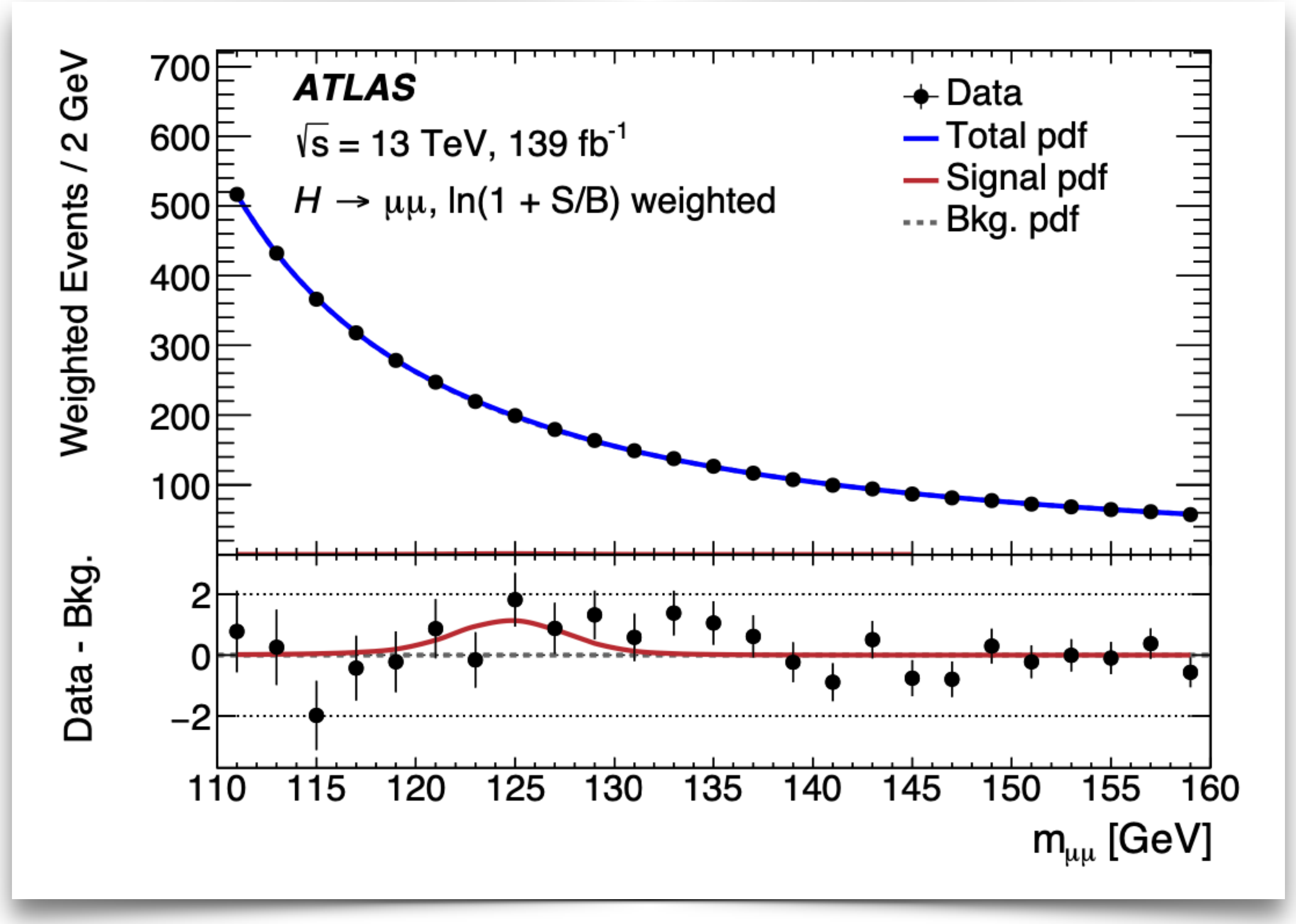
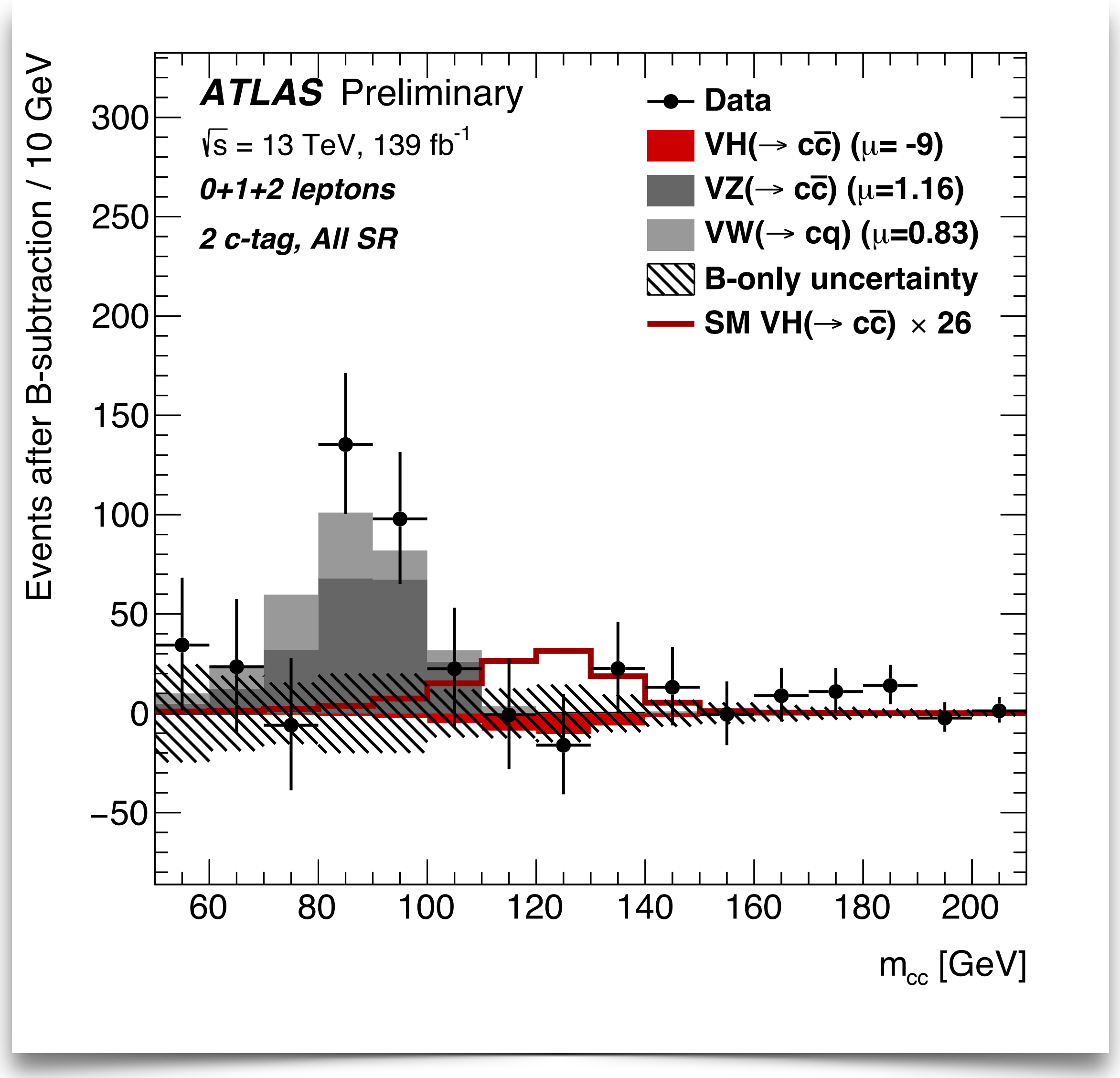
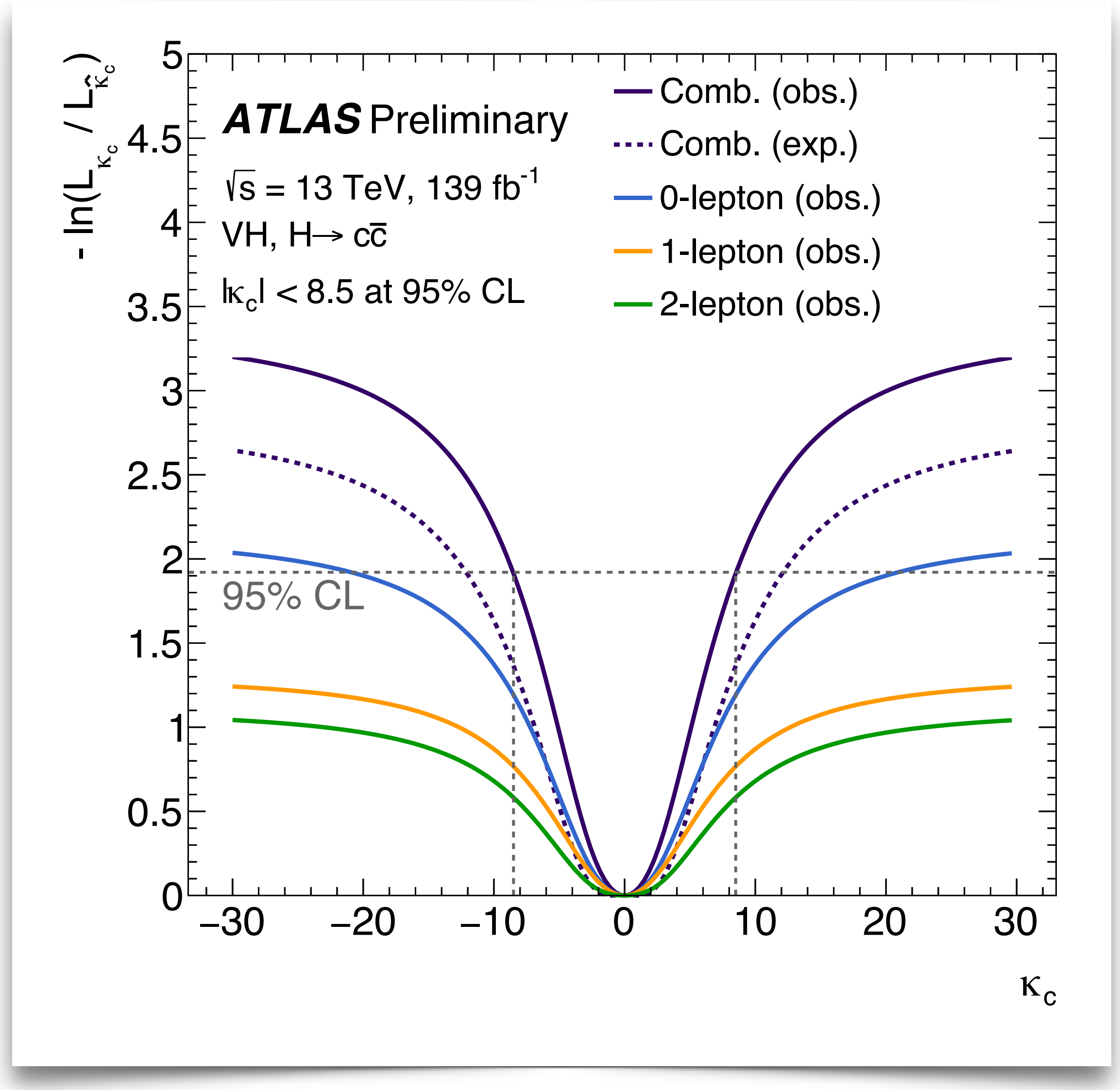
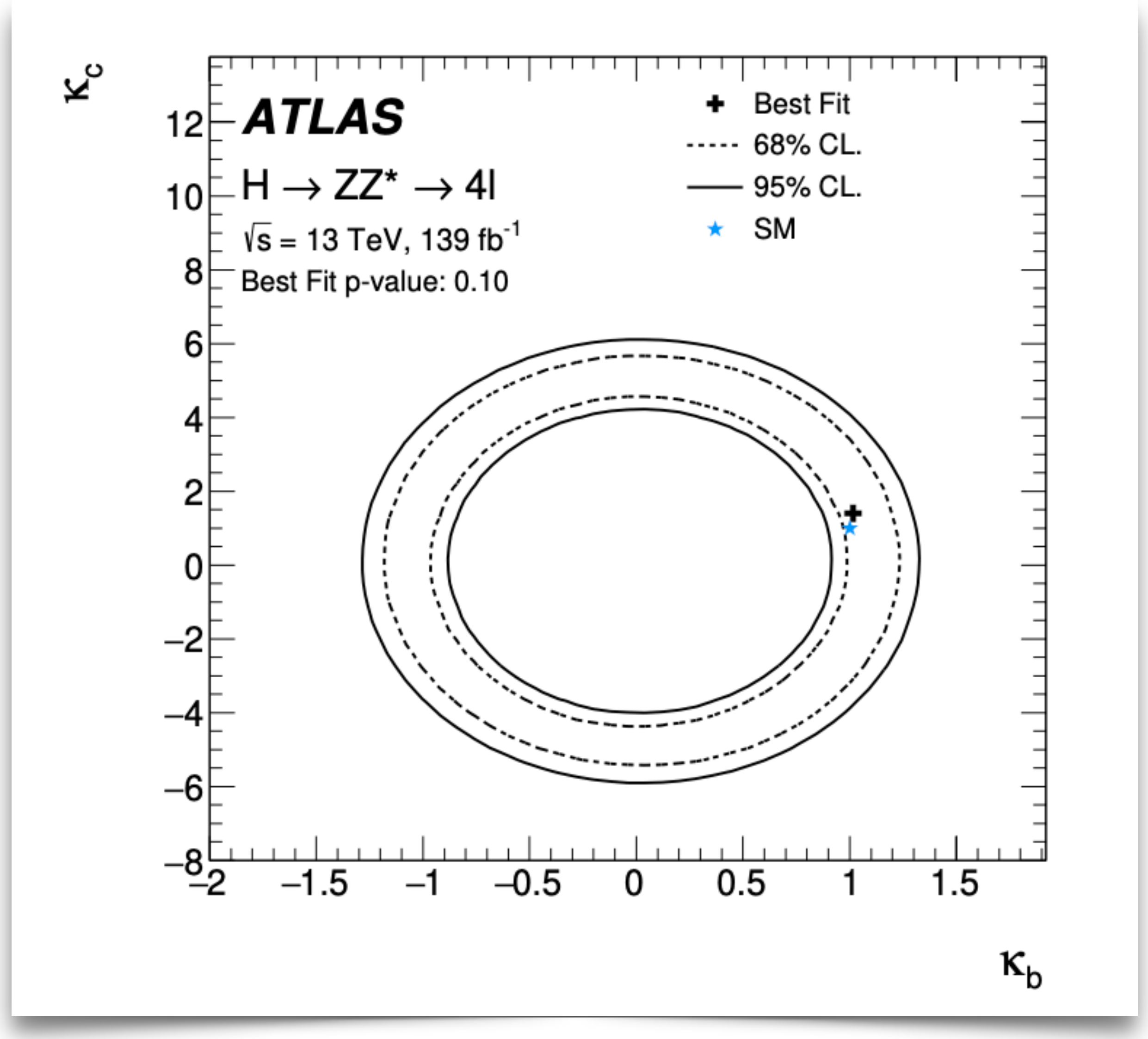
Higgs boson coupling to second generation fermions with the ATLAS detector









EPS-HEP conference, 26.07.21

Marko Stamenkovic (Nikhef) on behalf of the ATLAS collaboration

Motivation: Higgs to second generation?

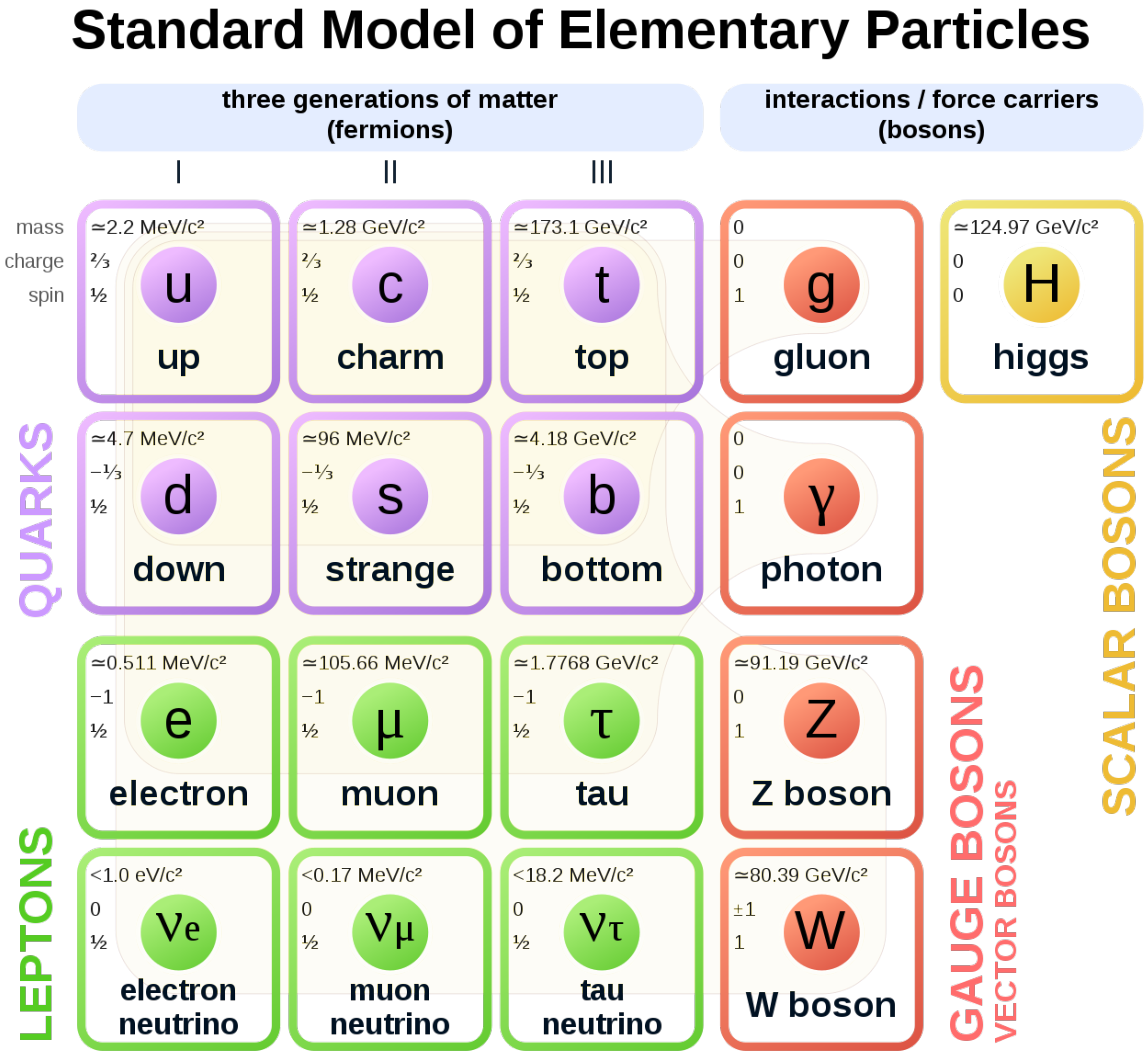
Higgs boson:

- Discovered in 2012
- Interacts proportional particles' masses
  - W and Z bosons
  - Charged fermions

BEH mechanism: free parameters

- Higgs mass + vacuum expectation value
- 9 Yukawa couplings for fermions

→ Needs to be measured experimentally!



Standard Model of Elementary Particles

	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin QUARKS	≃2.2 MeV/c^2 ⅔ ½ u up	≃1.28 GeV/c^2 ⅔ ½ c charm	≃173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c^2 0 0 H higgs SCALAR BOSONS
QUARKS	≃4.7 MeV/c^2 −⅓ ½ d down	≃96 MeV/c^2 −⅓ ½ s strange	≃4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	
LEPTONS	≃0.511 MeV/c^2 −1 ½ e electron	≃105.66 MeV/c^2 −1 ½ μ muon	≃1.7768 GeV/c^2 −1 ½ τ tau	≃91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≃80.39 GeV/c^2 ±1 1 W W boson GAUGE BOSONS VECTOR BOSONS	

Motivation: Higgs to second generation?

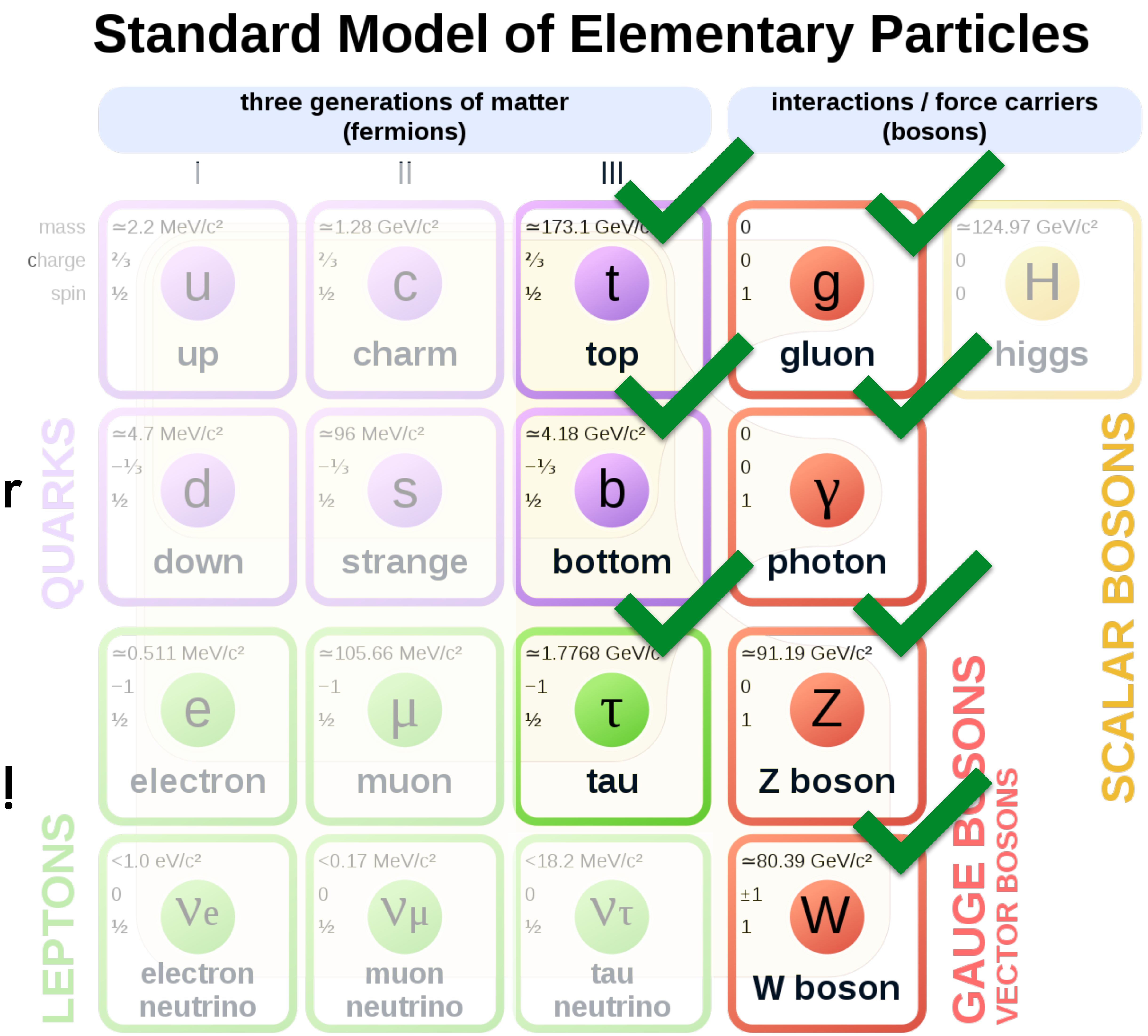
Higgs boson:

- Discovered in 2012
- Interacts proportional particles masses
  - For W and Z bosons
  - Charged fermions

Higgs boson interactions: observed so far

- Interaction with gauge bosons
- Interaction with 3rd generation

→ In agreement with Standard Model!



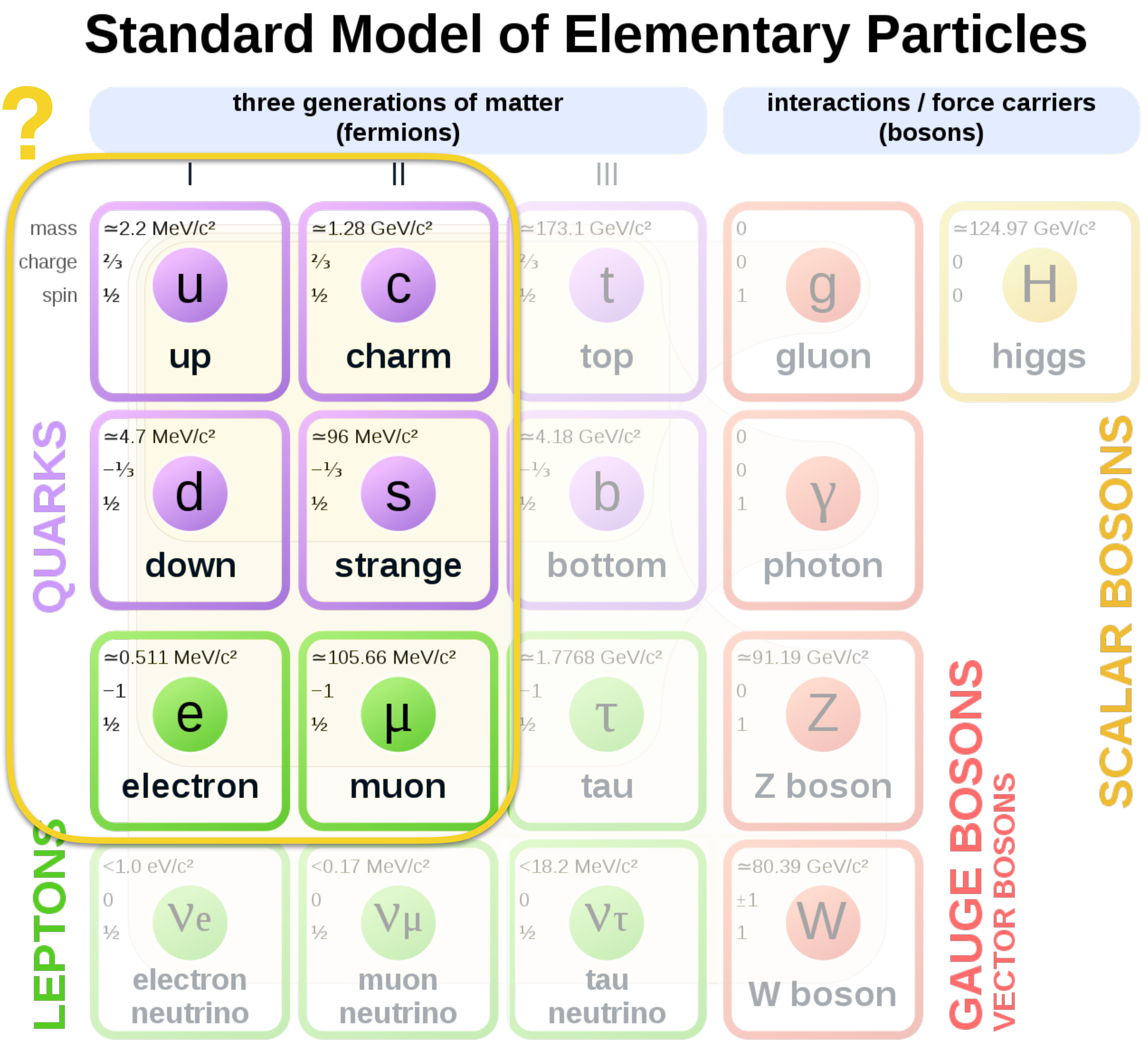
Motivation: Higgs to second generation?

Higgs boson:

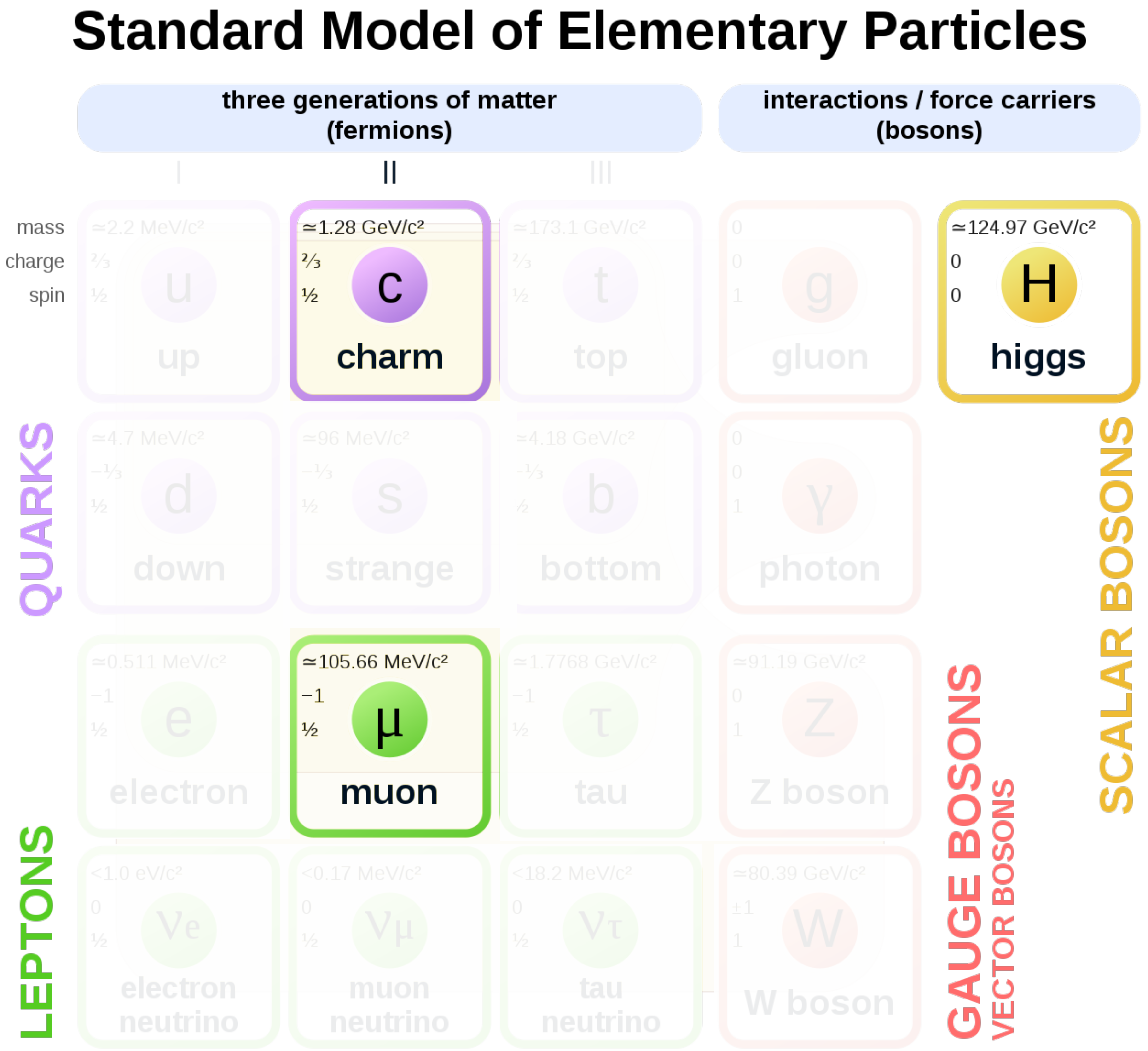
- Discovered in 2012
- Interacts proportional particles masses
  - For W and Z bosons
  - Charged fermions

1st and 2nd generation:

- No experimental observation
- Any deviations = new physics



Motivation: Higgs to second generation?

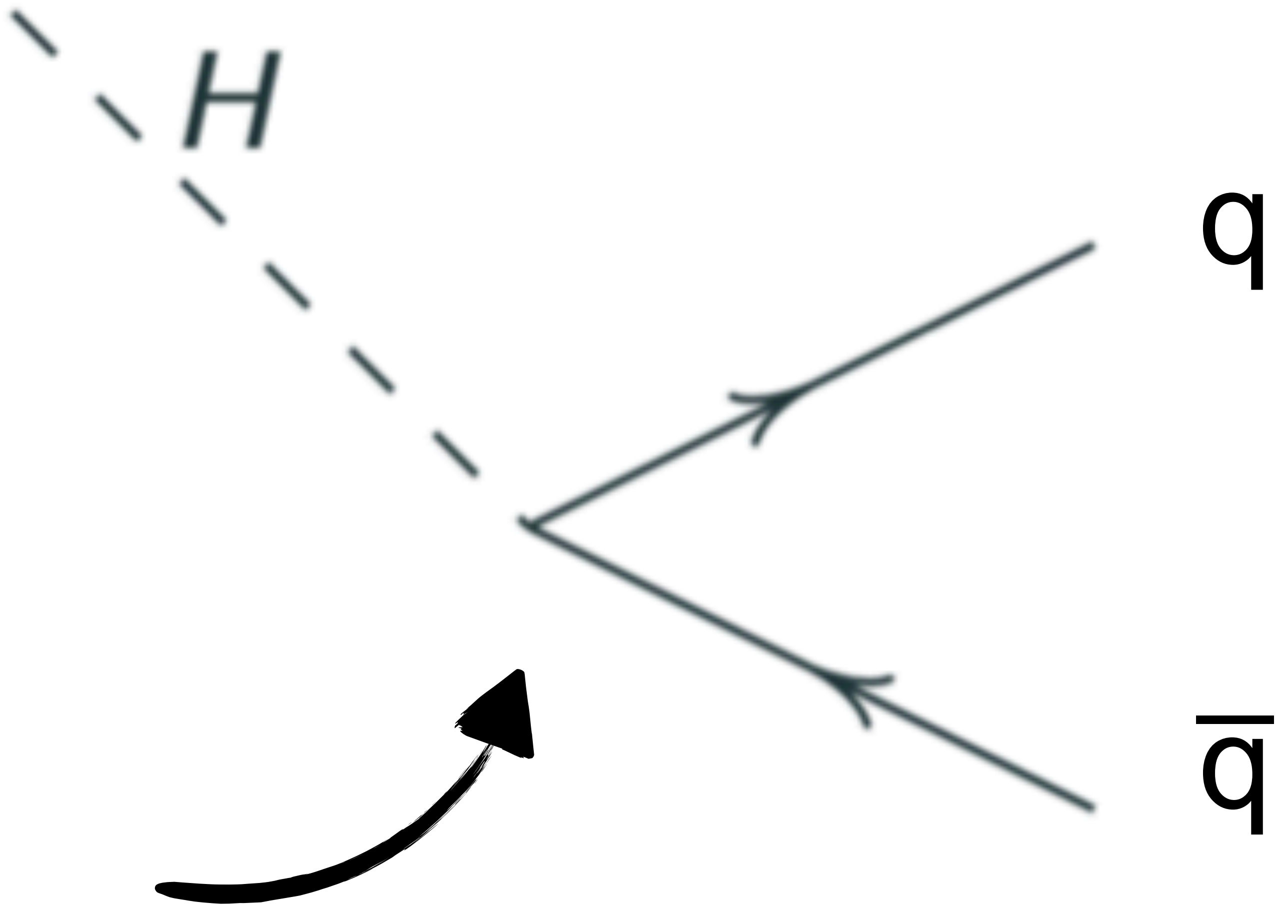


Next most promising measurements: Higgs coupling to muons and charm quarks!

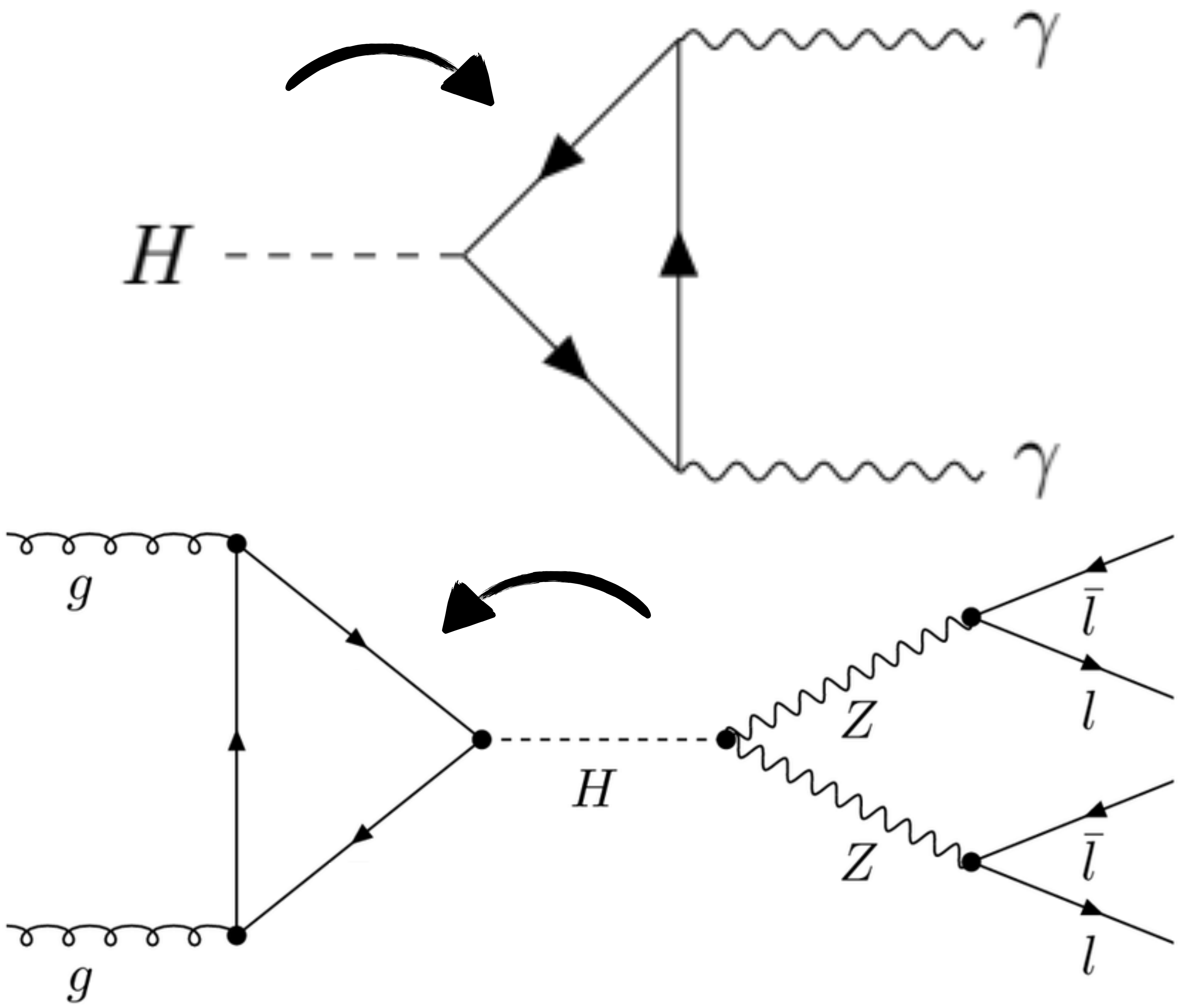
→Probes of Higgs coupling to 2nd generation with ATLAS

Direct and indirect measurements

Direct



Indirect



Higgs coupling to second generation:

- BR(H→μμ) ~ 0.02% and BR(H→cc) ~ 3%
- Direct: access to H→μμ and H→cc
- Indirect: sensitive to Higgs coupling to charm quarks in virtual loop contributions
  - Use precise H→γγ and H→ZZ*

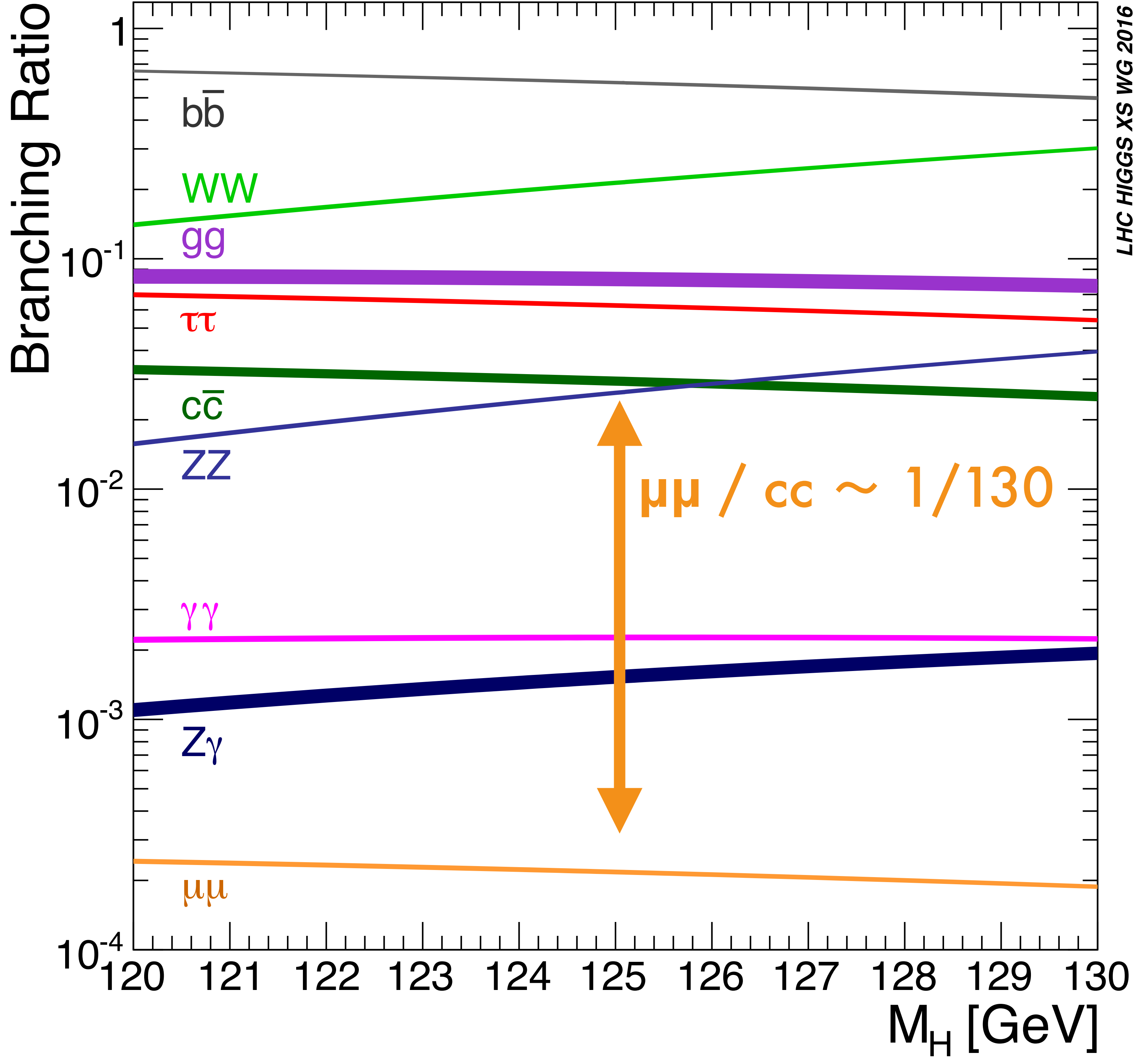
Run: 281411
Event: 312608026
2015-10-11 18:40:58 CEST

$H \rightarrow \mu\mu$

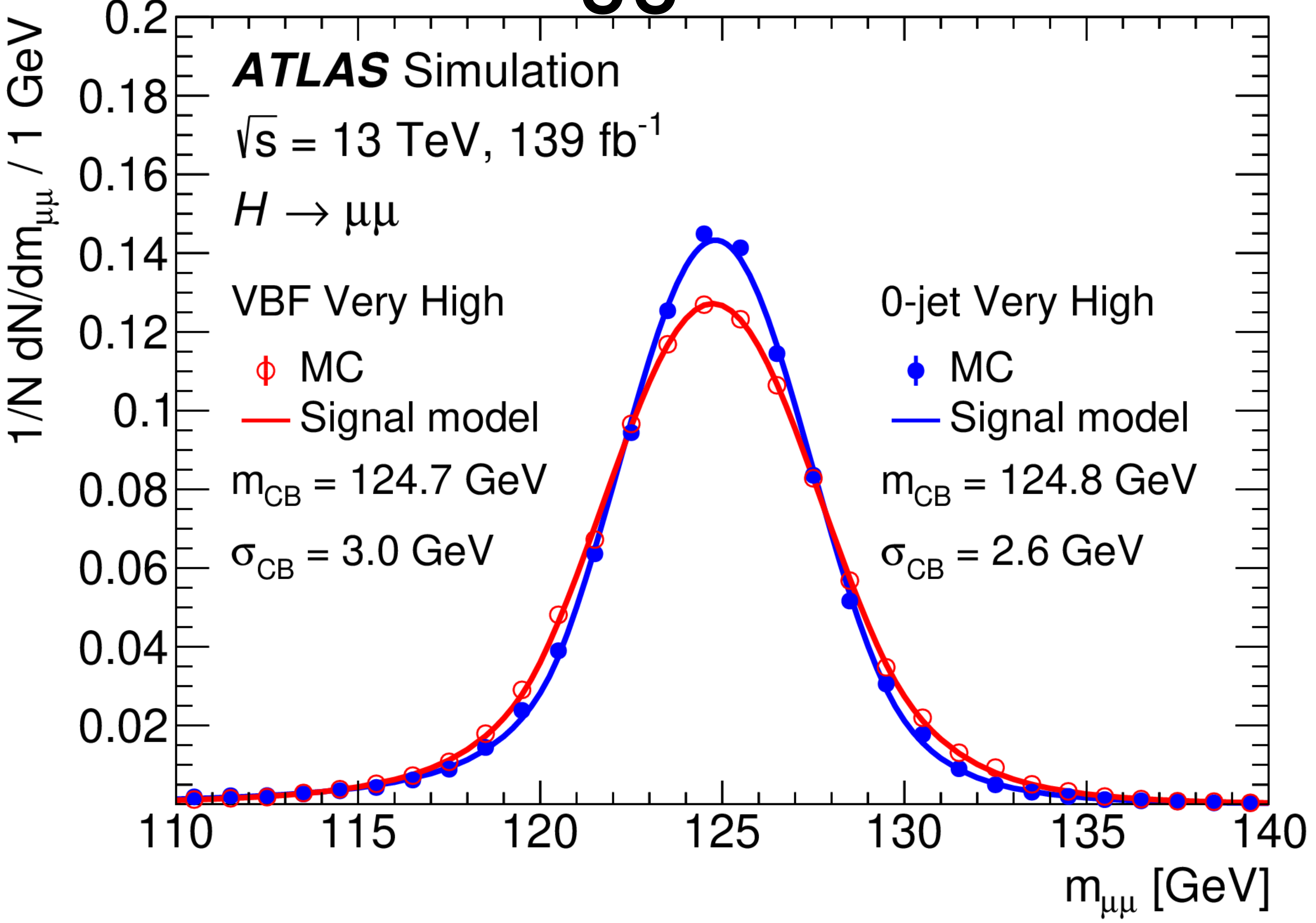
Higgs coupling to muons

[Phys. Lett. B 812 (2021) 135980]

Higgs branching ratios



Higgs mass



$H \to \mu\mu$: direct probe of Higgs coupling to second generation

- Challenge: low branching ratio BR($H \to \mu\mu$) ~ 0.02%
- Good mass resolution $\sigma_m/m(\mu\mu)$ ~ 2% (for comparison $\sigma_m/m(qq)$ ~ 10-15%)
- Dominant background $Z/\gamma^* \to \mu\mu$: searching for peak in falling background spectrum

Analysis strategy: H→μμ

Phys. Lett. B 812 (2021) 135980

Sensitivity optimised with BDT categorisation

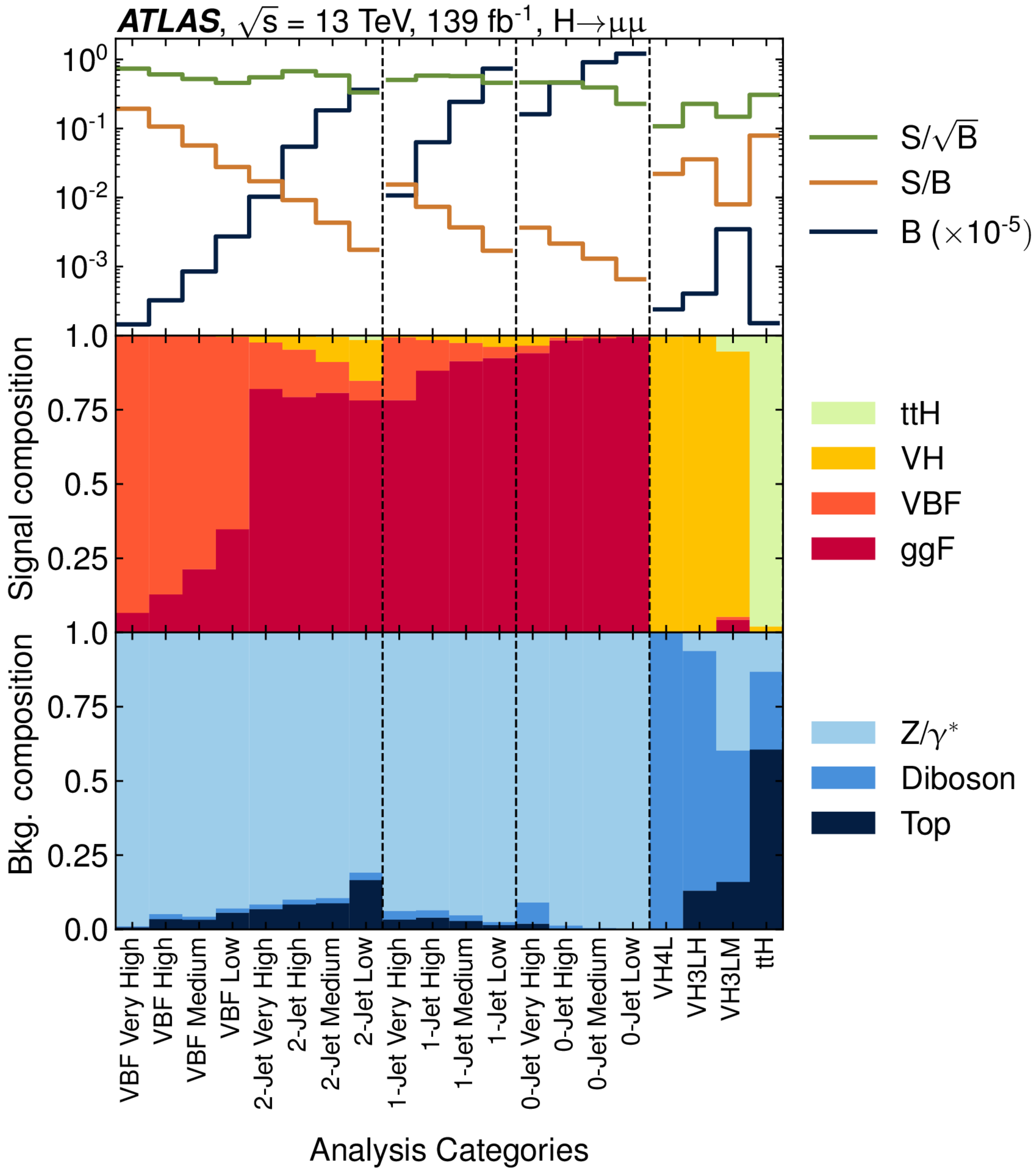
Signal production mode:

- ttH, VH, VBF, ggF
- Similar sensitive across all categories
  - Most sensitive categories: **VBF** and **ggF**

Signal modelling: double-sided crystal ball

Background modelling: empirical function

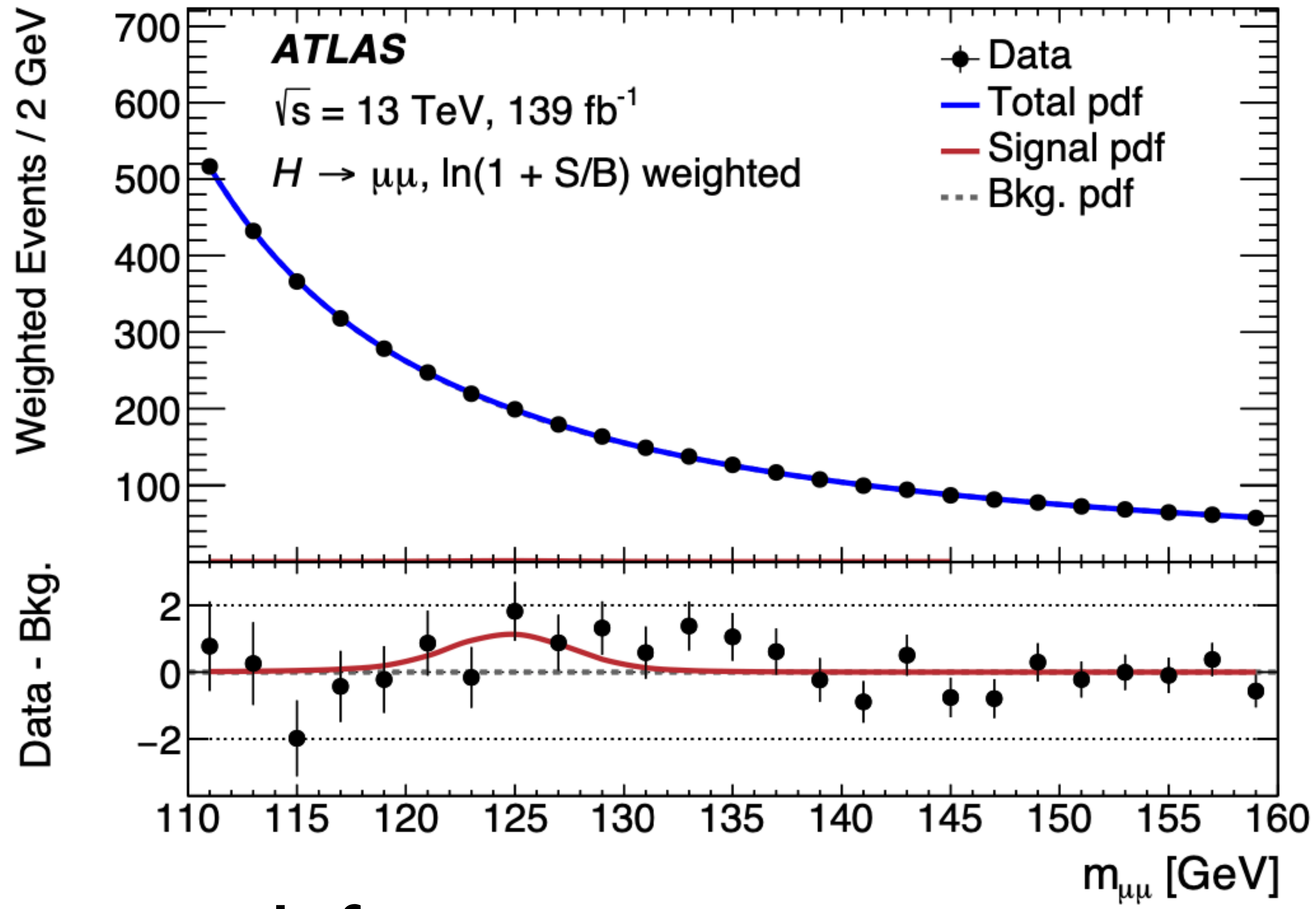
→ Complex and challenging analysis



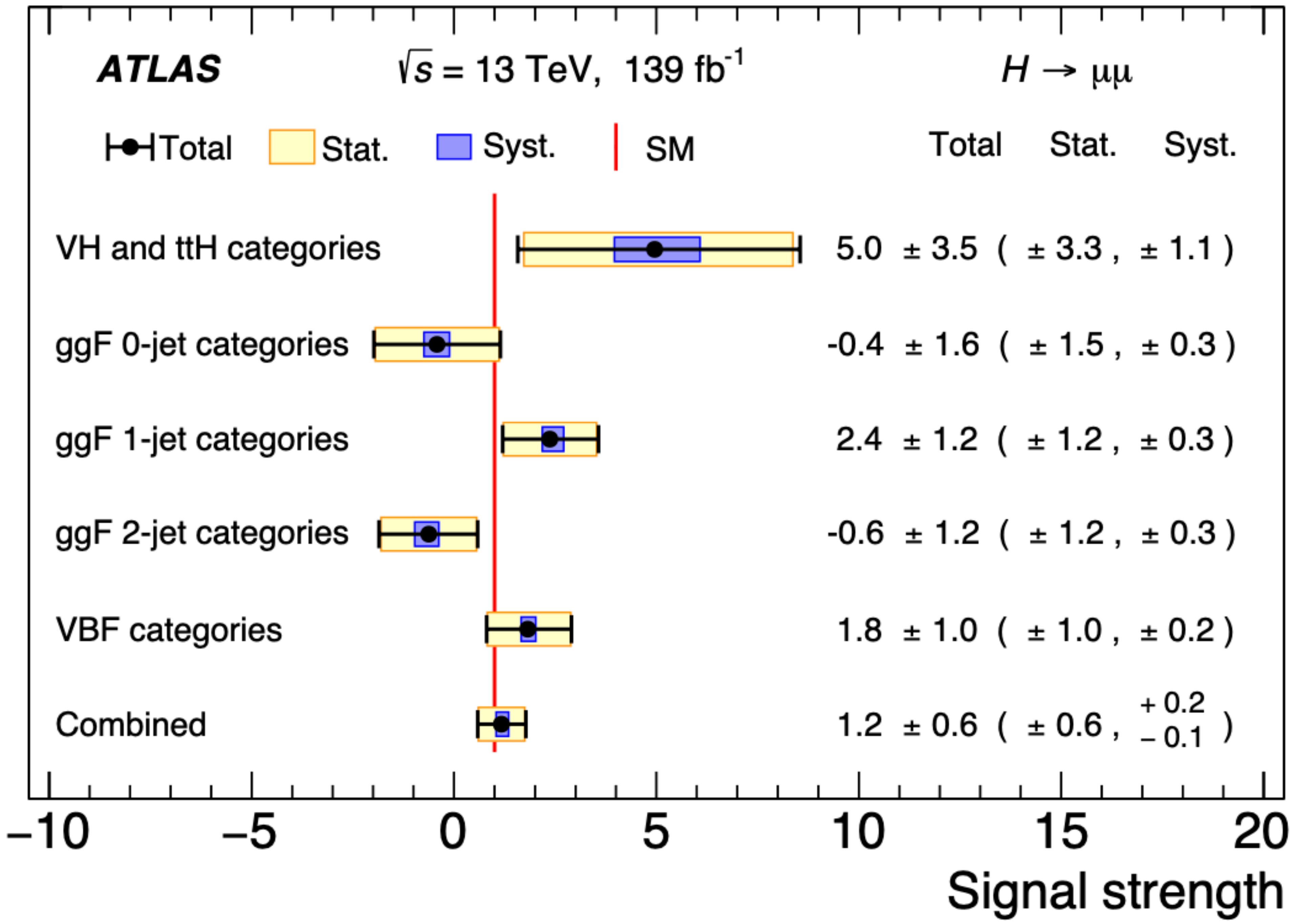
Higgs coupling to muons

Phys. Lett. B 812 (2021) 135980
ATLAS-CONF-2020-027

Higgs mass



Signal strength



Direct search for H→μμ:

- Signal strength fitted in m(μμ) in 20 regions: $\boldsymbol{\mu_{H\to\mu\mu}}$ **=1.2 +- 0.6**
  - Dominated by **statistical uncertainty** and muon momentum resolution
- Result: **2.0σ observed** (1.7σ expected)
- Interpretation: κ_μ **= 1.1 +- 0.3**

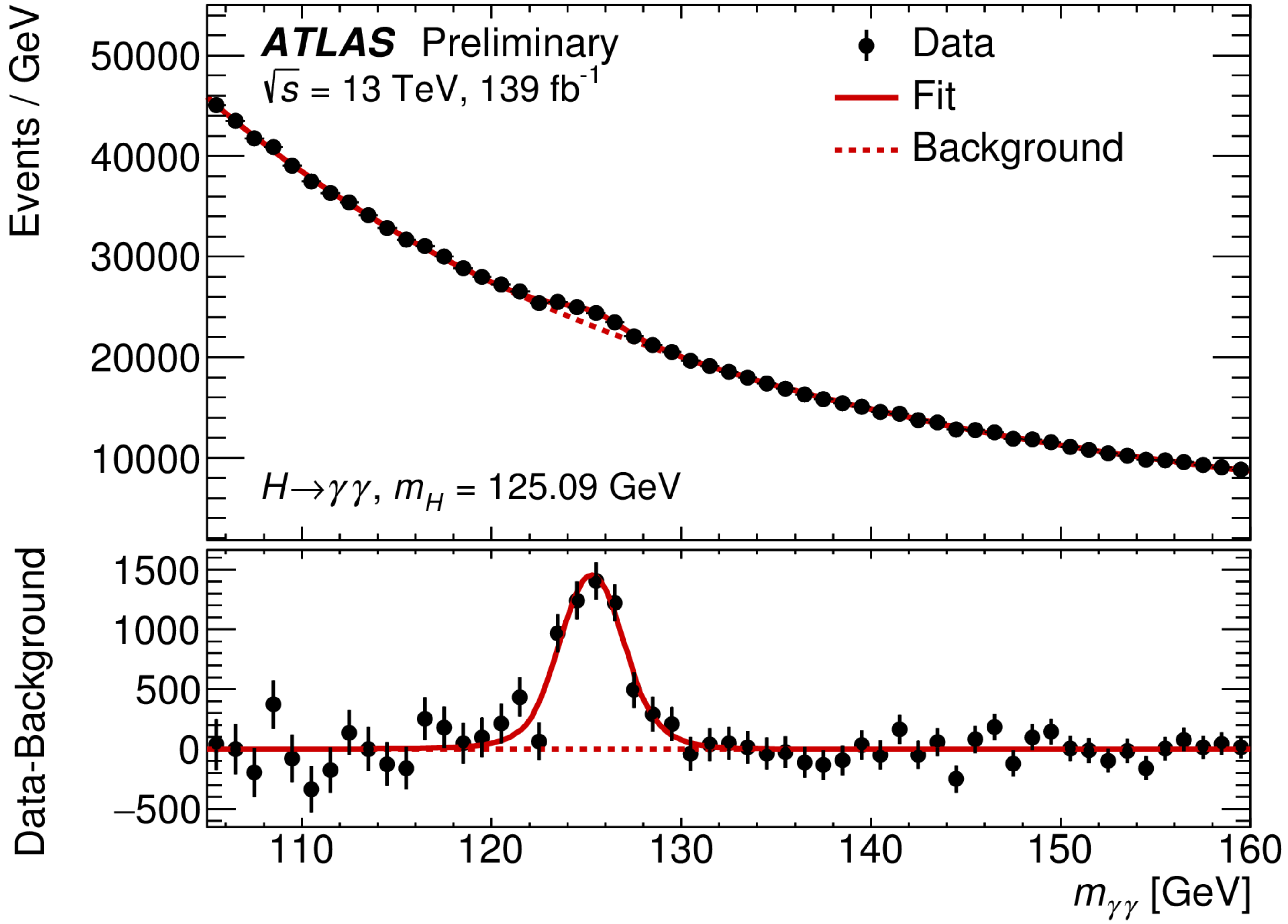
→ Approaching observation of Higgs coupling to second generation leptons

Indirect constraint: $H \rightarrow ZZ^* \rightarrow 4l$

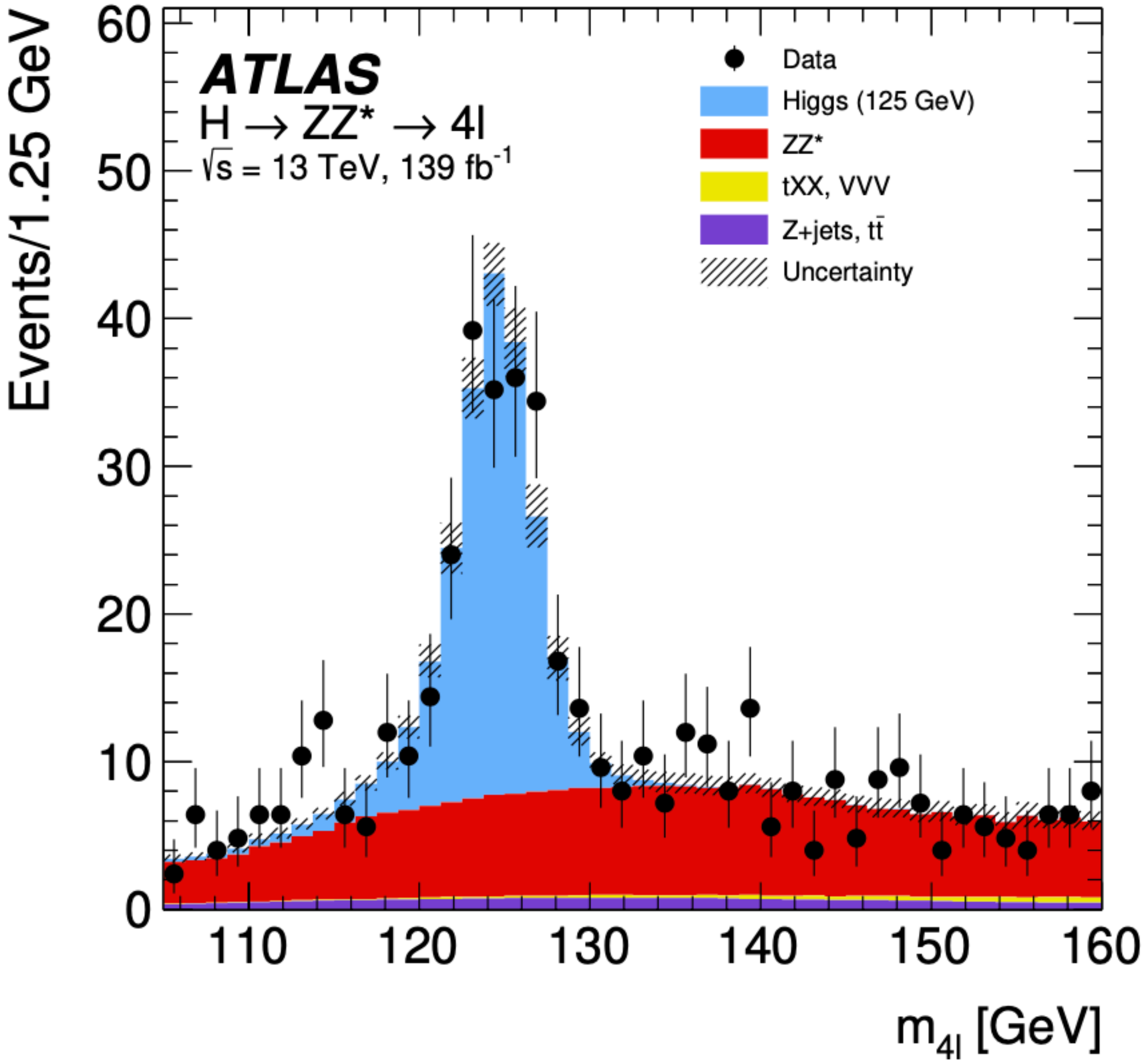
Run: 280862
Event: 53564866
2015-10-02 16:24:44 CEST

Precision measurements: H→γγ and H→ZZ*→4l

H→γγ (see talk E. Rossi)



H→ZZ*→4l (see talk C. Anastopoulos)



High precision achieved in H→γγ and H→ZZ*→4l

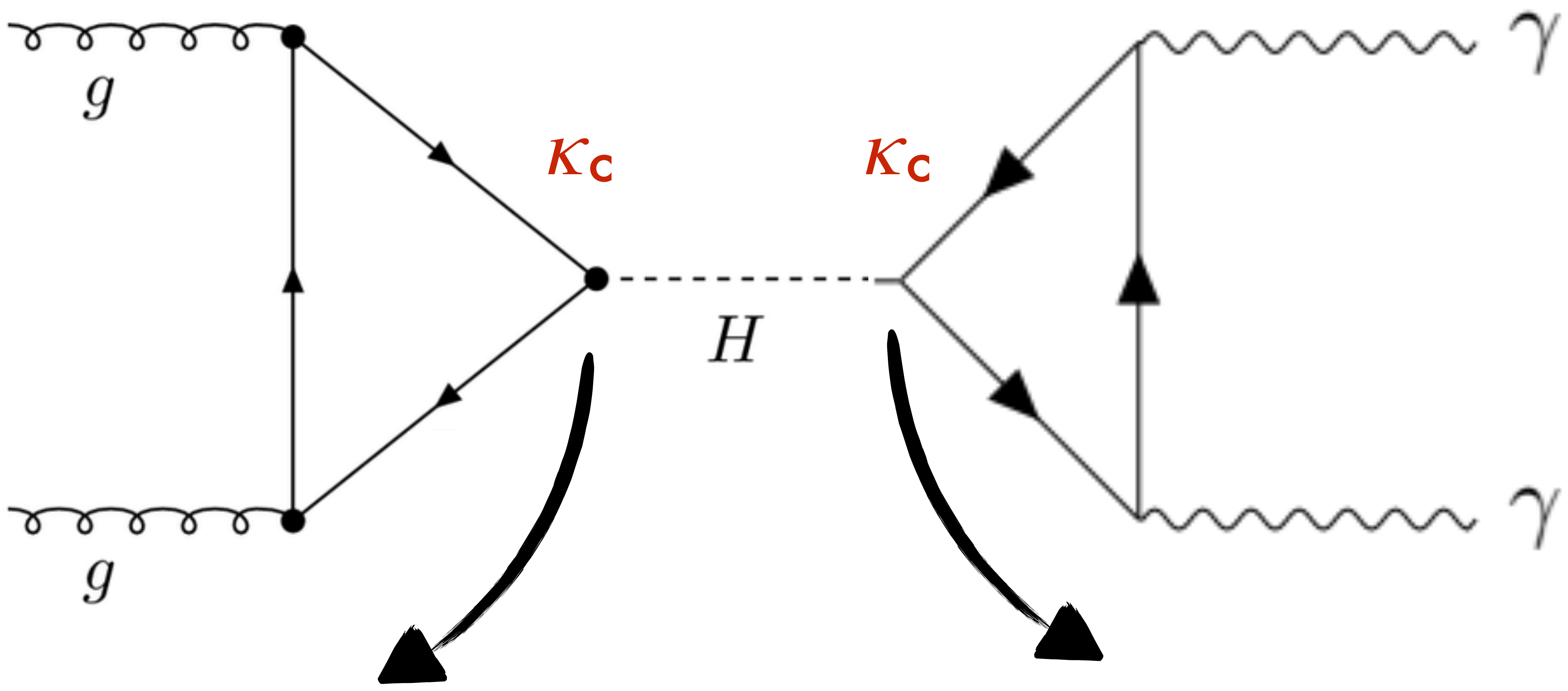
- Fit to invariant mass of Higgs Boson m(γγ) and m(ZZ*)
- Inclusive and differential cross-section measurements
- Unfolding procedure to compare to any kind of theory predictions

Eur. Phys. J. C 80 (2020) 942

ATLAS-CONF-2019-029

Indirect constraint from H→γγ

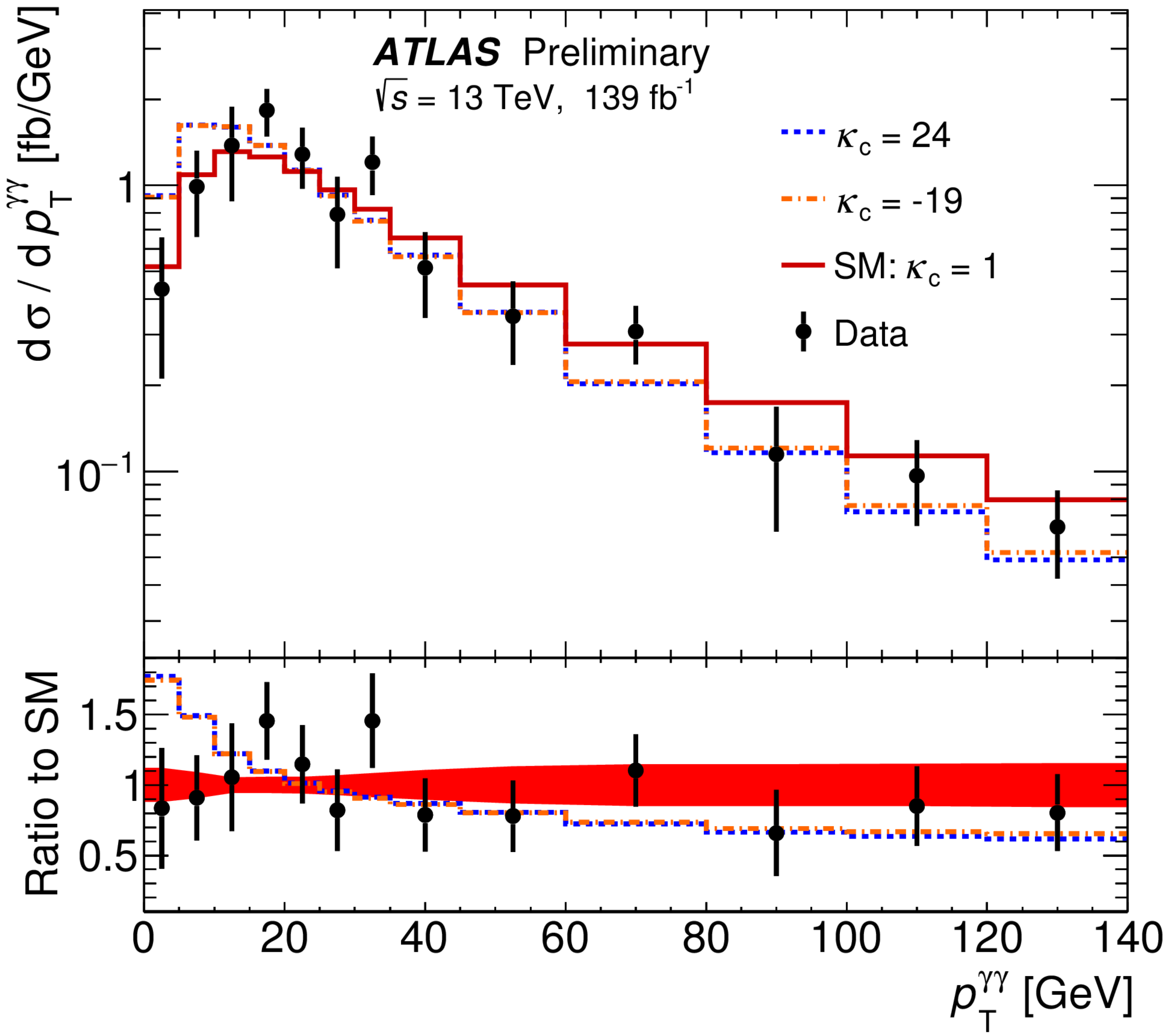
ATLAS-CONF-2019-029



Affects cross-section and kinematics

Affects branching ratio and Higgs decay width

Shape effect $p_T(H)$



Enhanced Higgs coupling to bottom / charm quarks:

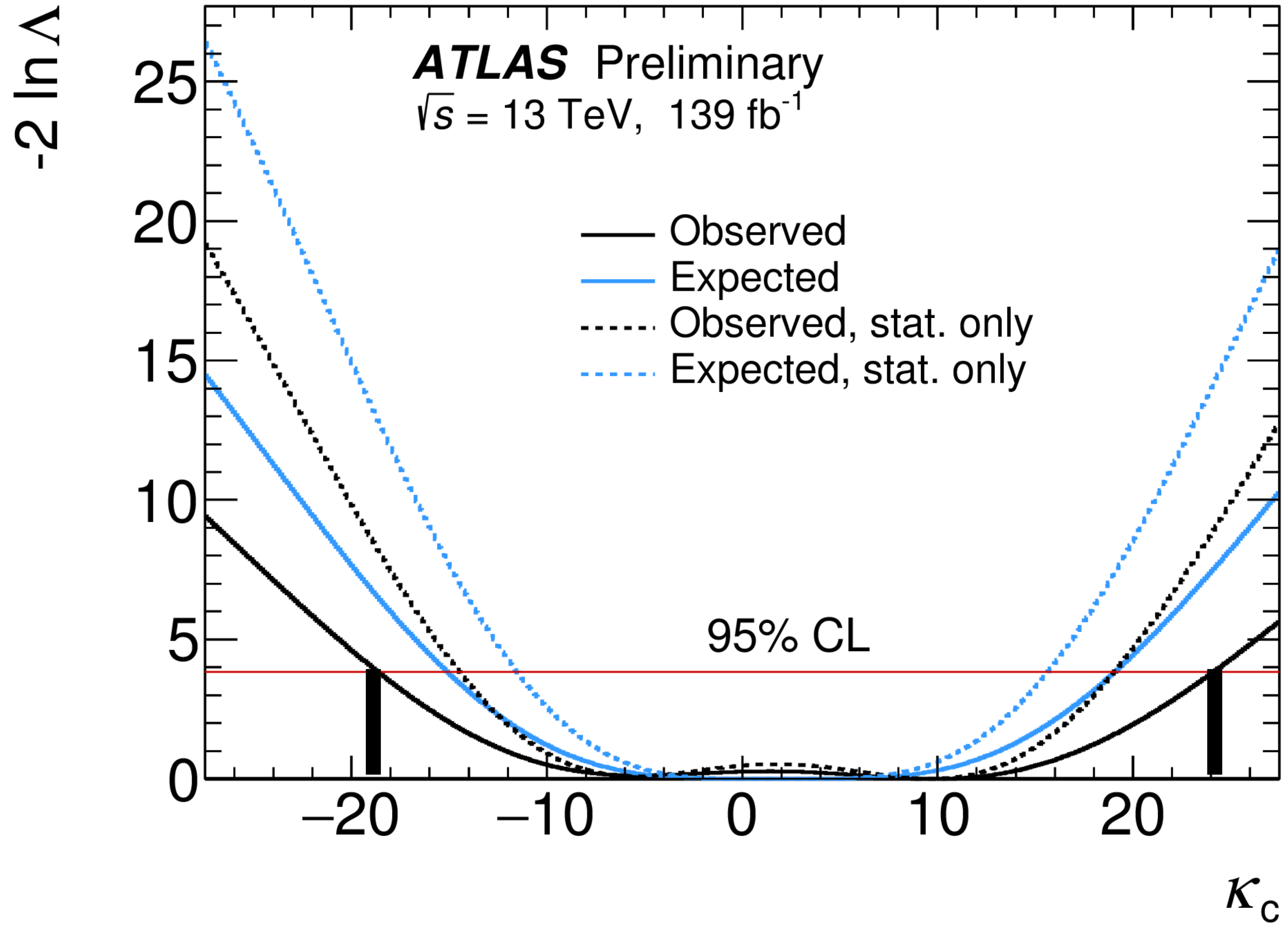
- Affect H→γγ and H→ZZ*→4l in loops
- Effect on the shape and normalisation of the $p_T(H)$ spectrum
- Sensitive to effects in differential measurements

Indirect constraint on κ_c

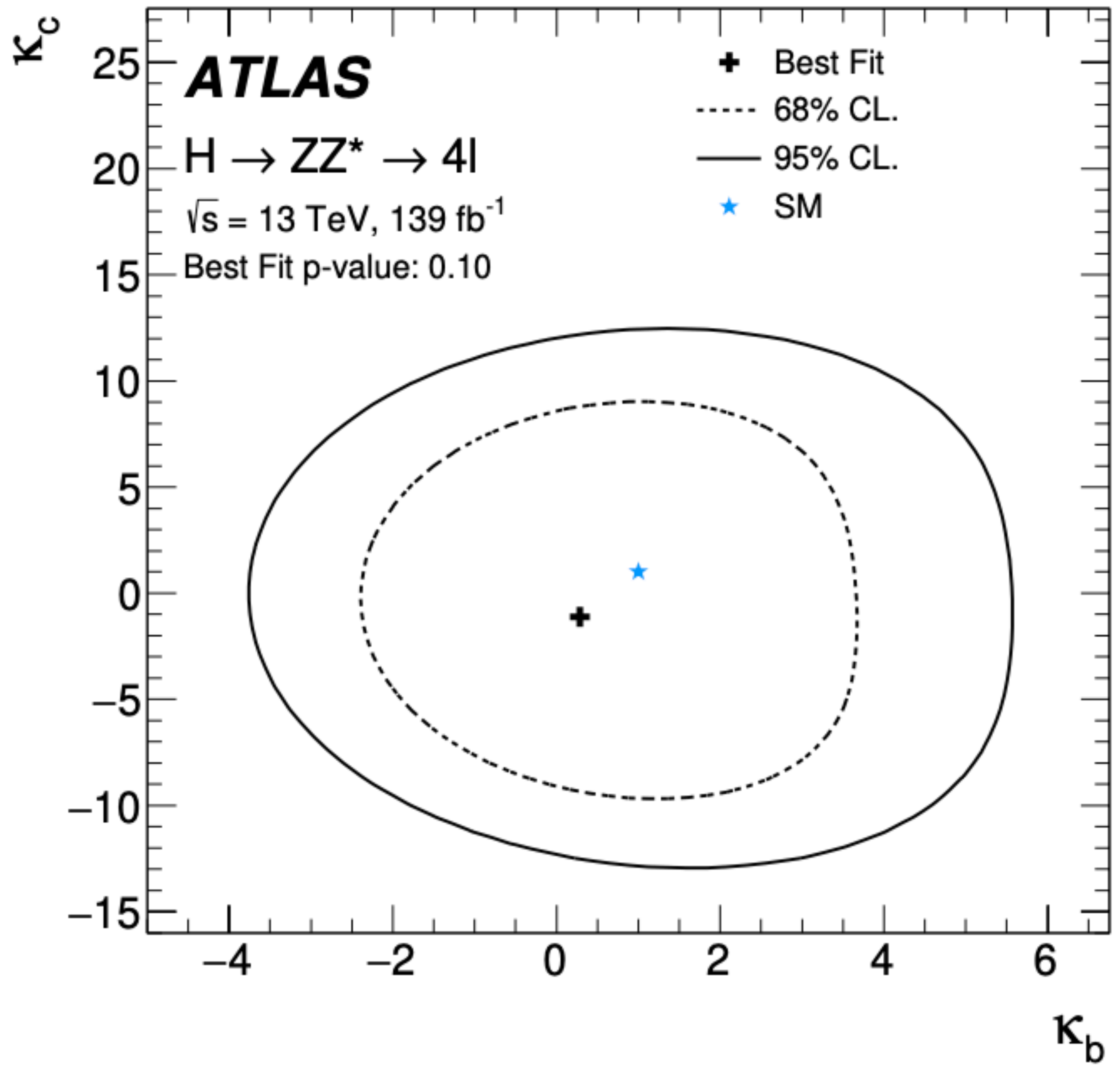
Eur. Phys. J. C 80 (2020) 942

ATLAS-CONF-2019-029

H→γγ



H→ZZ*→4l



Constraint on κ_c modifiers: sensitivity for H→γγ and H→ZZ*→4l for shape-only

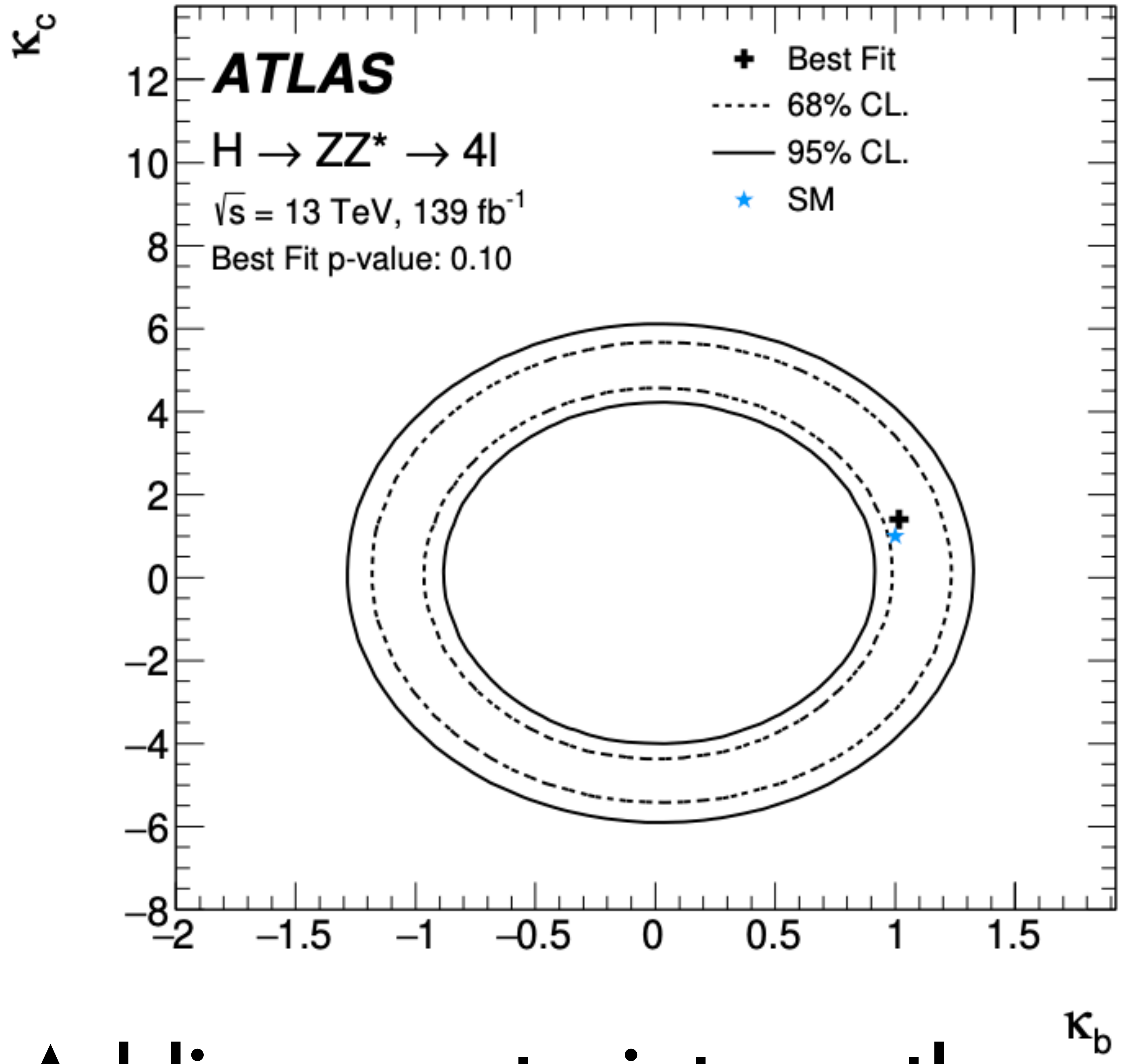
- Assumption $\kappa_t = 1$
- H→γγ: **$-19 < \kappa_c < 24$** ($\kappa_b = 1$)
- H→ZZ*→4l: **$-11.7 < \kappa_c < 10.5$**

→ Constraining power on κ_c

Indirect constraint on κ_b and κ_c

Eur. Phys. J. C 80 (2020) 942
ATLAS-CONF-2019-029

H→ZZ*→4l



Interpretation	H→γγ	H→ZZ*→4l
p_T^H shape-only	[−19, 24]	[−11.7, 10.5]
p_T^H shape and normalisation	-	[−7.46, 9.27]

Adding constraints on the cross-section and the branching ratio

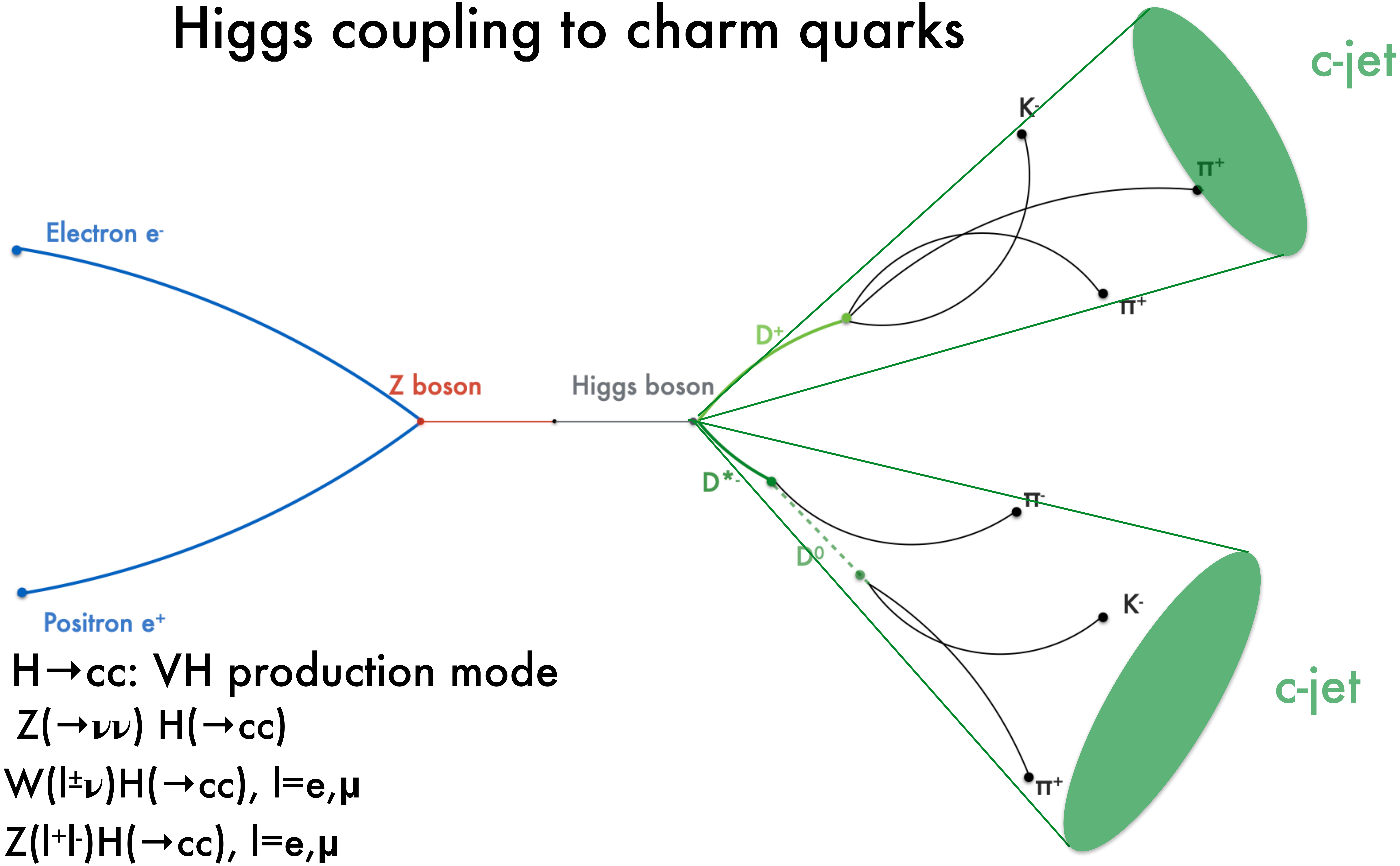
- Assumption κ_i = 1 for other fermions and bosons and no BSM contributions to Higgs width
- H→ZZ*→4l: **−7.5 < Kc < 9.3**

→ Better constraining power coming from the Higgs width modification

VH, H→cc

ATLAS
EXPERIMENT
Run: 309892
Event: 4866214607
2016-07-16 06:20:19 CEST

Higgs coupling to charm quarks



Search for H→cc: VH production mode

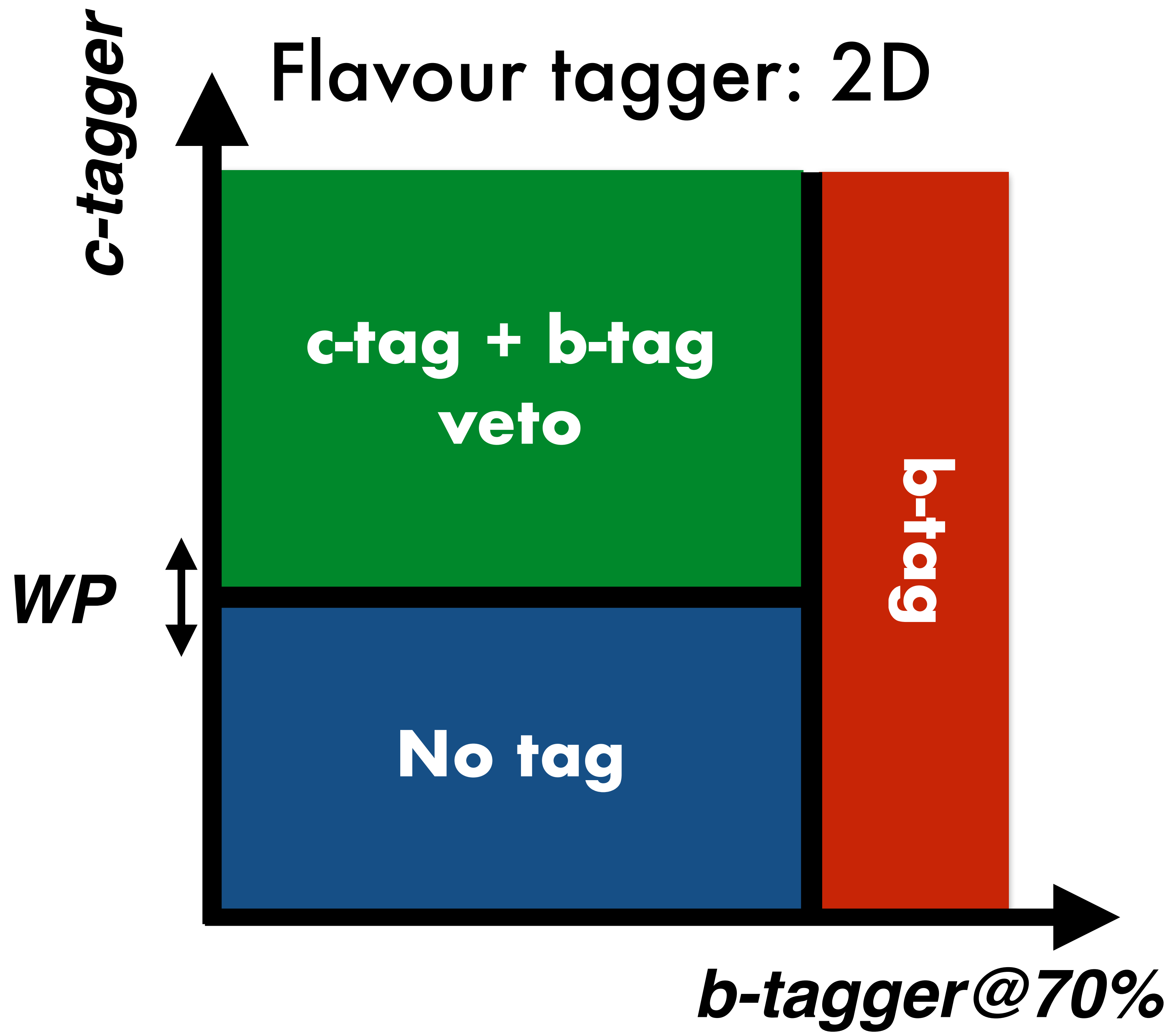
- 0-lepton: $Z(\rightarrow \nu\nu)\ H(\rightarrow cc)$
- 1-lepton: $W(l^{\pm}\nu)H(\rightarrow cc)$, l=e,μ
- 2-lepton: $Z(l^{+}l^{-})H(\rightarrow cc)$, l=e,μ

Higgs boson reconstructed from at least 2 jets in the events

Flavour tagging strategy

New ATLAS-CONF-2021-021

Flavour tagger: 2D



Performance

	c-tagging efficiency
c-jets	27%
b-jets	8%
light-jets	1.6%

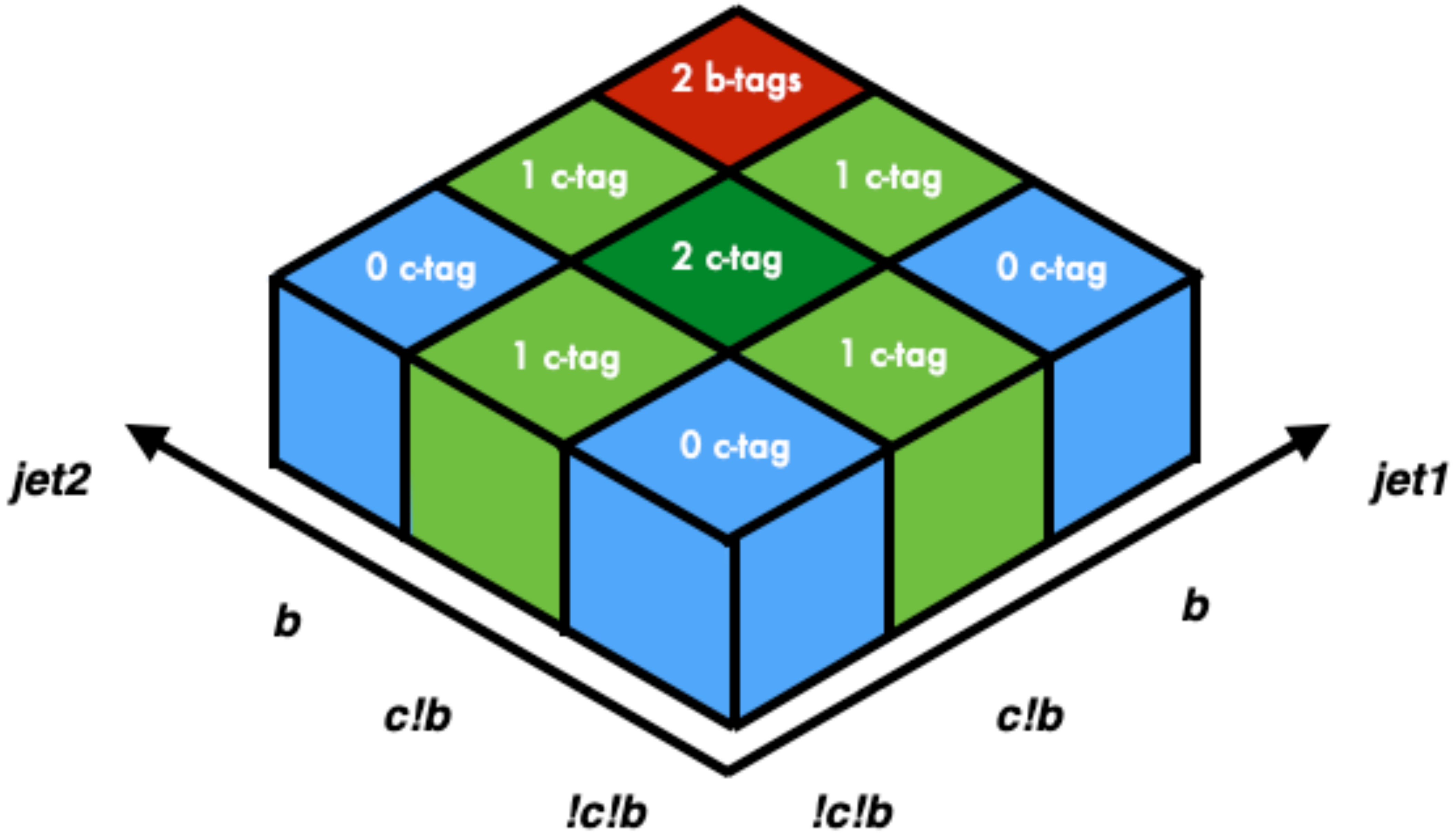
Flavour tagging: c-tag + b-tag veto

- Goal: identify c-jets and minimise contamination of b-jets and light-jets
- Optimisation of c-tagging WP for VH(cc) sensitivity
- Additional b-tag veto based on VH(bb) b-tagging strategy
  → Goal: achieve statistical independence with VH(bb) analysis

Flavour tagging categorisation

New ATLAS-CONF-2021-021

Events with 2 jets



Categorisation of events with 2 jets

- VH(cc) analysis: use events with 1 c-tag and 2 c-tag
- VH(bb) analysis: use events with 2 b-tag

→ VH(cc) and VH(bb) **statistically independent** by construction

Signal region: example

New ATLAS-CONF-2021-021

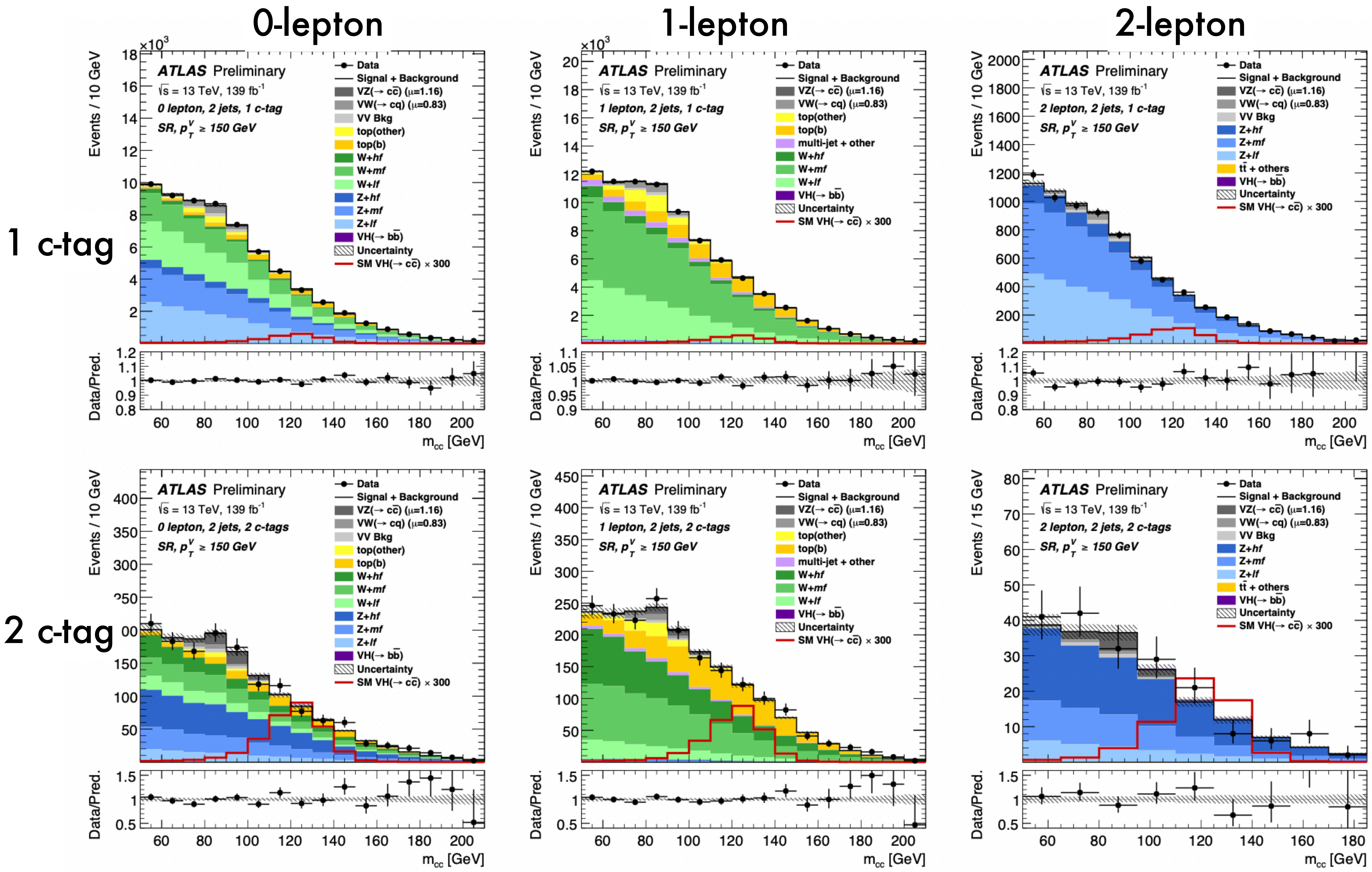
Discriminant: **m(cc)**

Main backgrounds:
Z+jets, W+jets and ttbar

Subdominant backgrounds:
VH(bb), VV (non c-jets)

Signal:
VH(cc), VZ(cc),VW(cq)

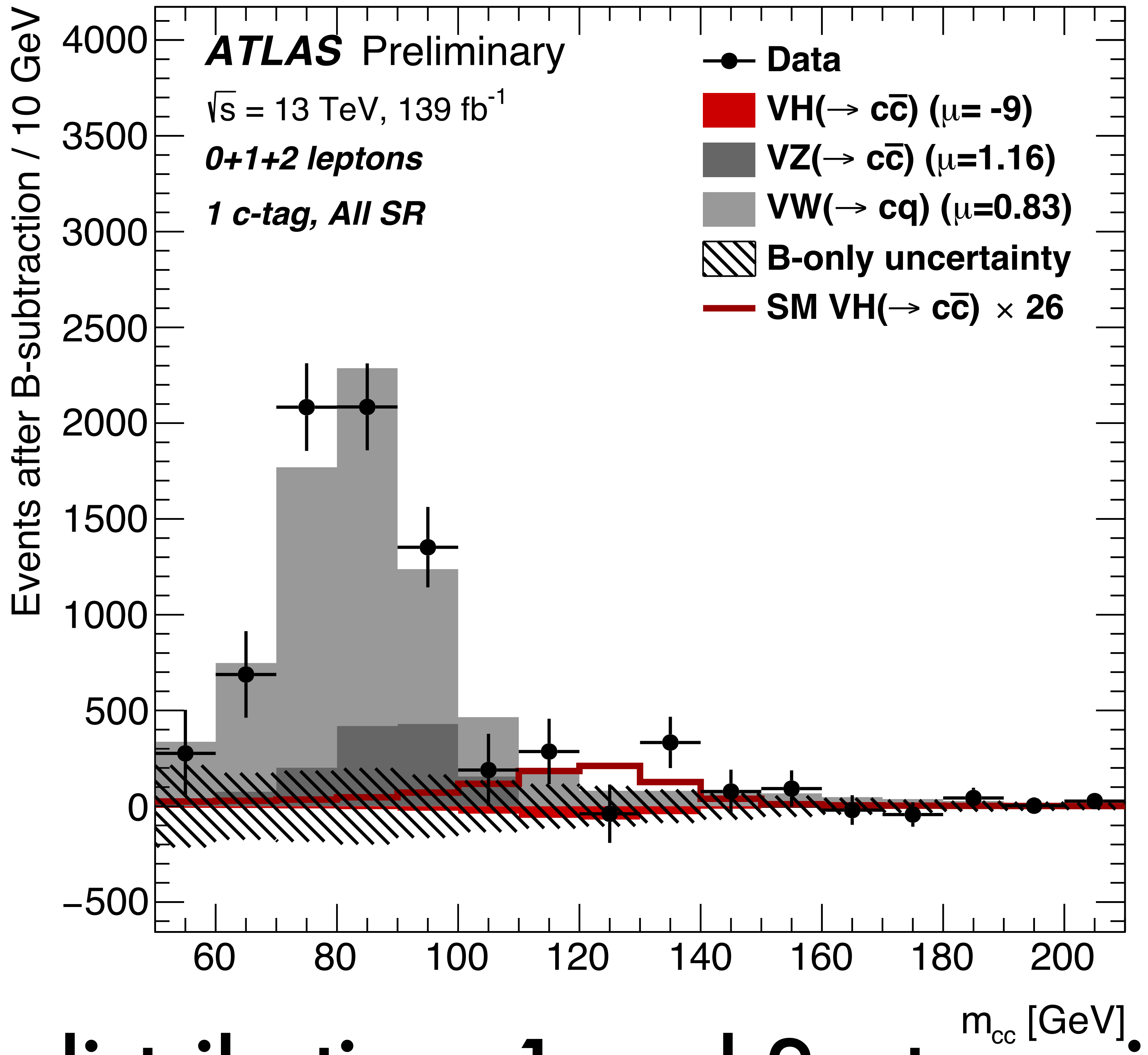
Total: 16 SRs + 28 CRs
(see back-up for details)



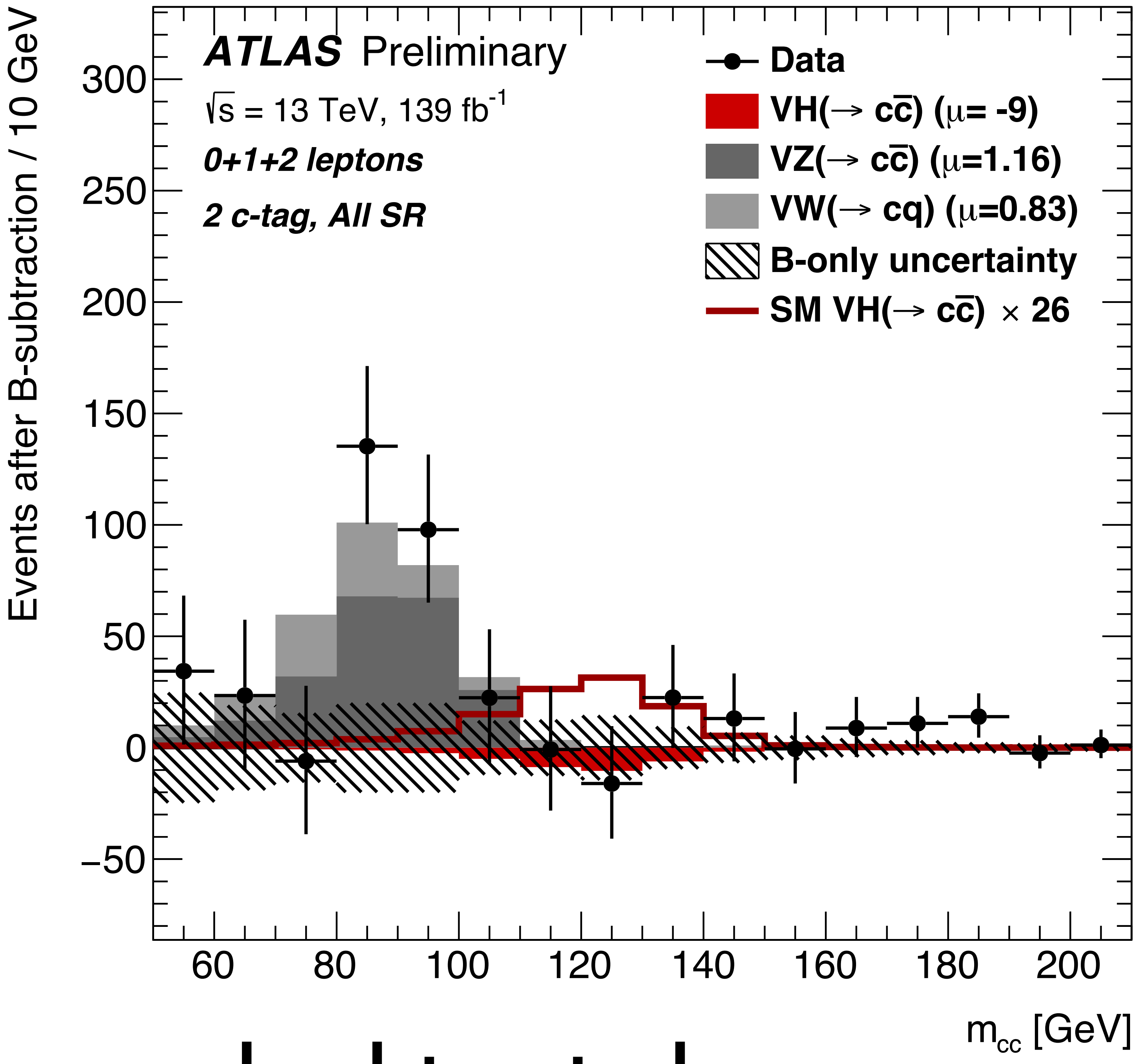
Mass distributions

New ATLAS-CONF-2021-021

1 c-tag



2 c-tag



M(cc) distribution: 1 and 2 c-tag with background subtracted

Diboson fit results: validation of the analysis

VZ(cc): **2.6σ observed** (2.2 expected)

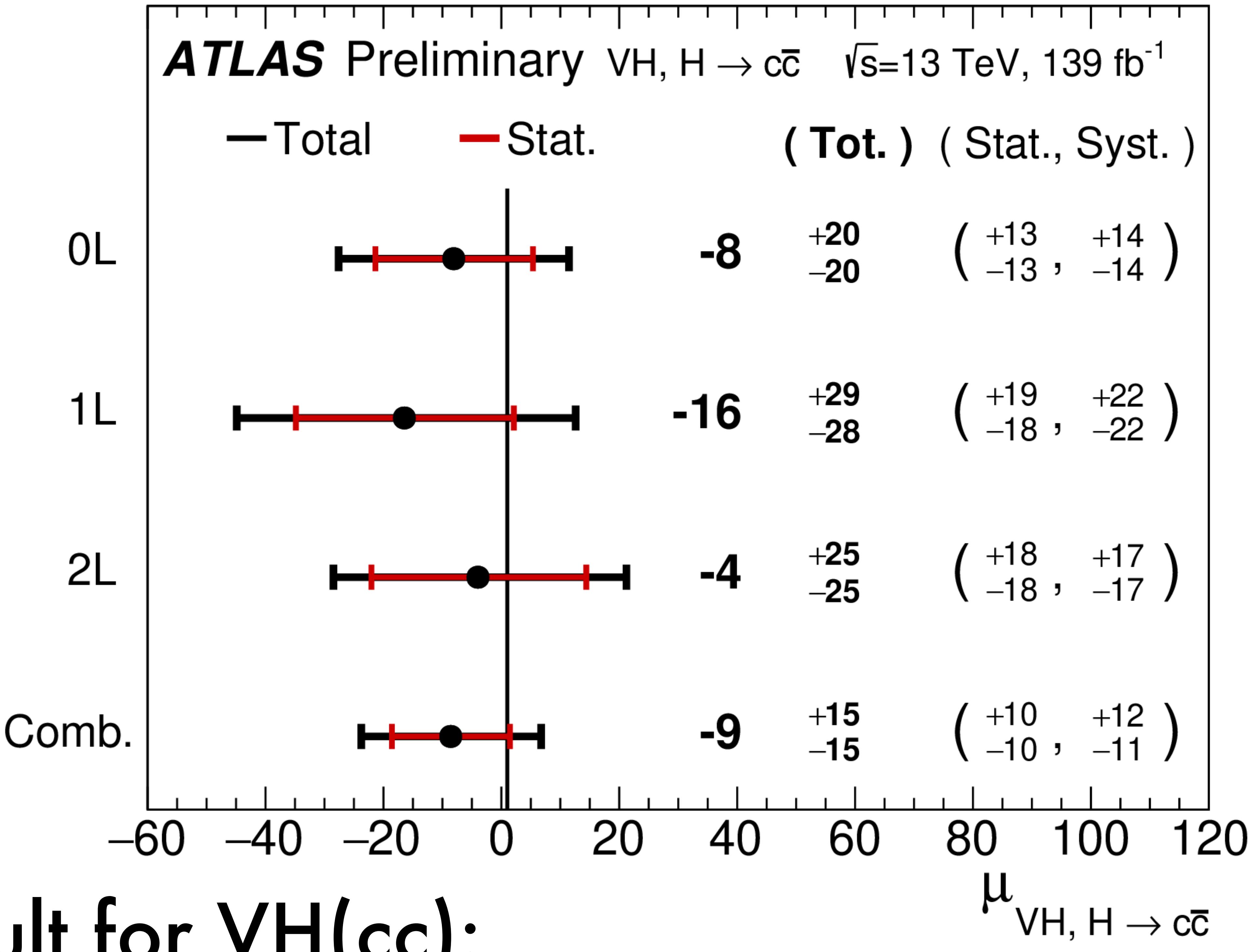
VW(cq): **3.8σ observed** (4.6 expected)

→ First measurement of VZ(cc) and VW(cq) using c-tagging!

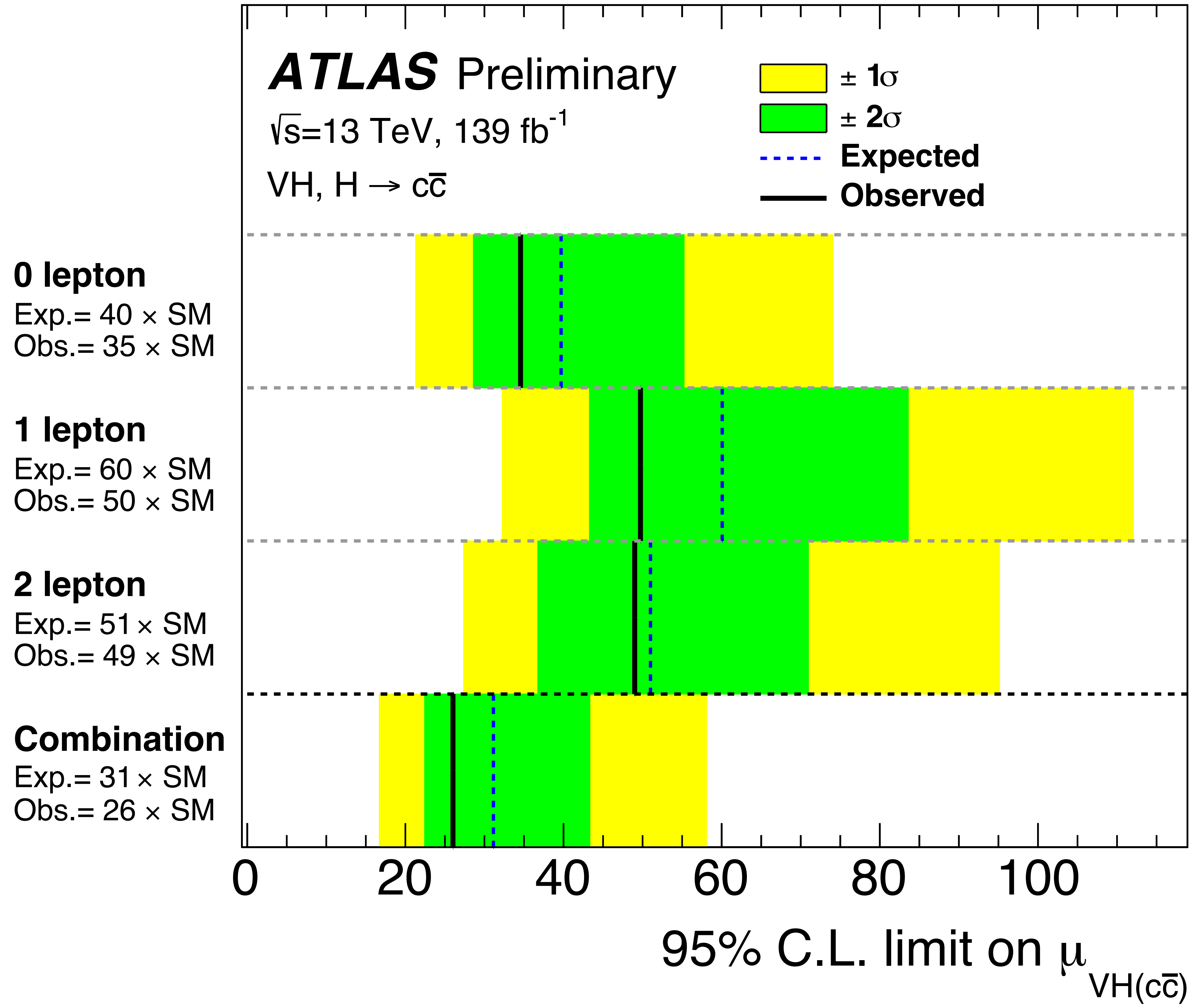
Results: limit and signal strength

New ATLAS-CONF-2021-021

VHcc signal strength



Limits on VH(cc) signal strength



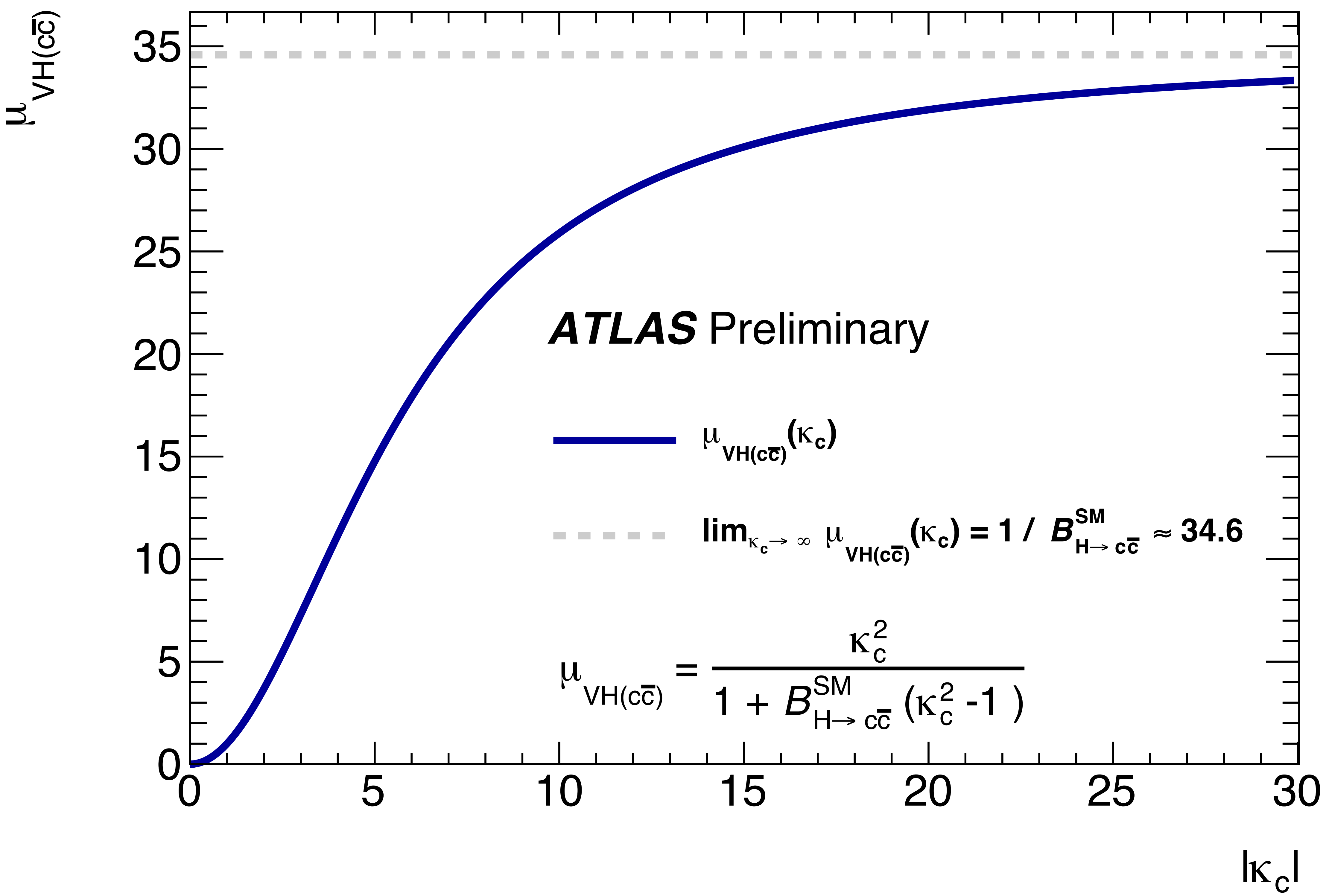
Result for VH(cc):

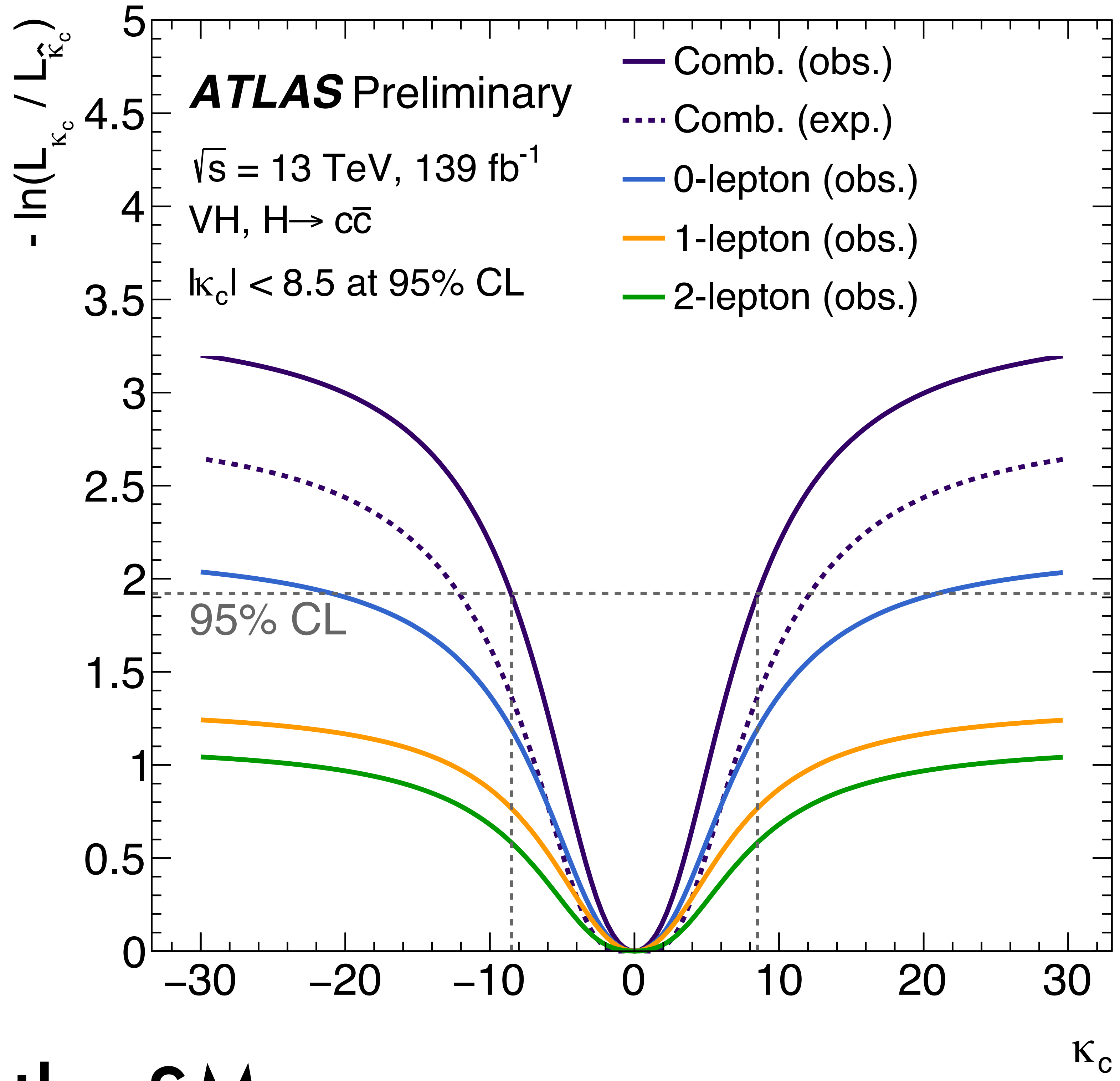
- VH(cc) signal strength: **-9 ± 10 (stat) ± 12 (syst)**
  - Similar size statistical and systematic uncertainties
  - Dominant uncertainties: V+jets and top modelling
- Limit on signal strength: **$\mu_{H\to cc}$< 26 x SM**@95% confidence level (< 31x SM expected)

→ Best limit on VH(cc) up to this day!

κ_c interpretations

New ATLAS-CONF-2021-021





κ_c interpretation: quantify possible deviations from the SM

- Assume $\kappa_i = 1$ for other fermions and bosons and no BSM contributions to Higgs width
- Only sensitive to κ_c if μ < 35 due to Higgs width in parametrisation
- Direct constraint: **$|\kappa_c| < 8.5$ @ 95% CL** (<12.4 @ 95%CL expected)
- Similar sensitivities to κ_c between direct and indirect constraints

→ Complementary approaches

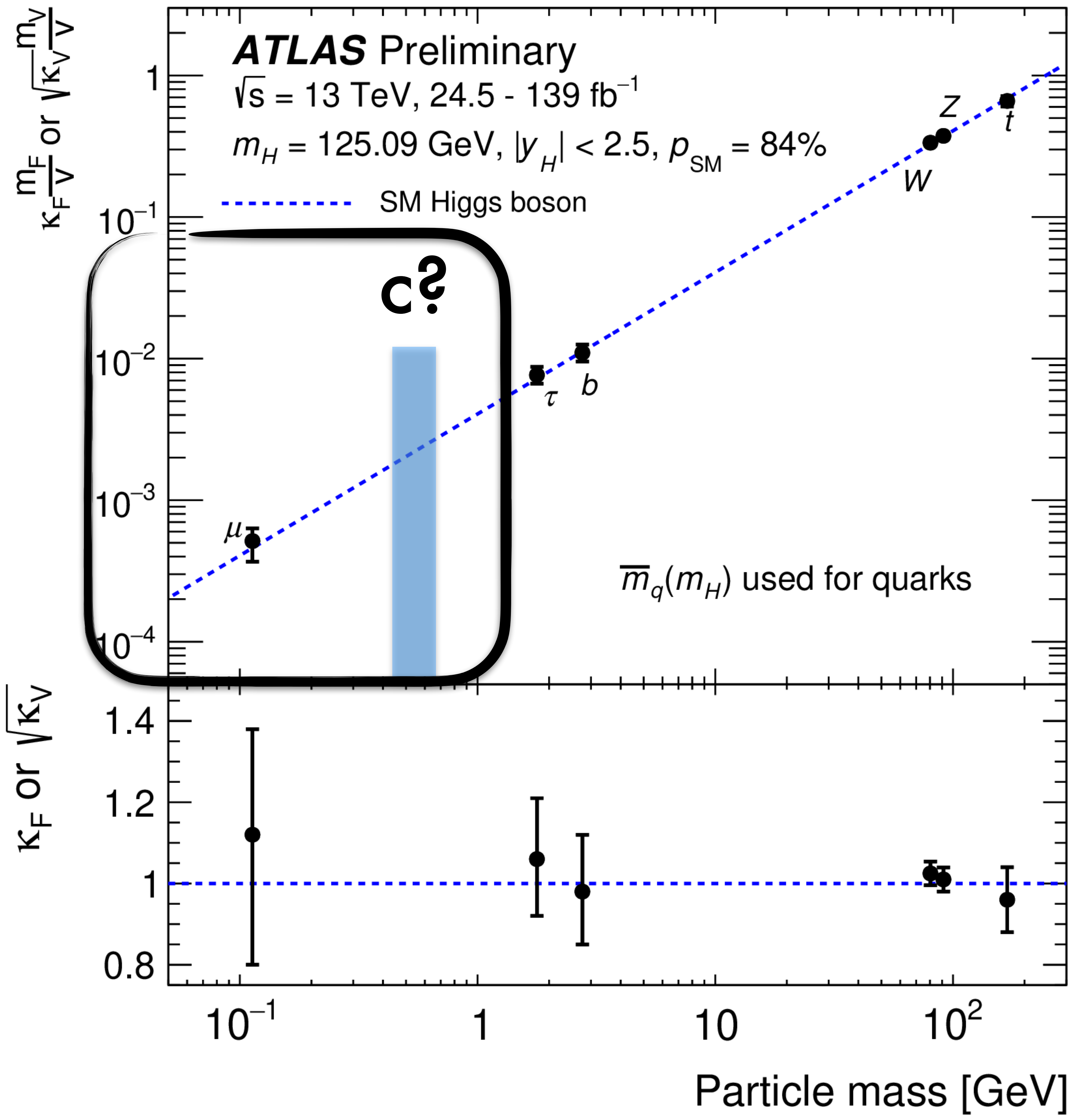
ATLAS: Higgs coupling to second generation

Direct measurement:

- $H \to \mu\mu$:
  - 2.0σ excess observed
  - $\kappa_\mu = 1.1 \pm 0.3$
- $H \to cc$:
  - $\mu_{H\to cc} < 26 \times$ SM @ 95% CL observed
  - $|\kappa_c| < 8.5$
  - VZ(cc) and VW(cq) measurements

Indirect measurement:

- $H \to \gamma\gamma$: $-19 < \kappa_c < 23$
- $H \to ZZ^* \to 4l$: $-11.7 < \kappa_c < 10.5$
- Additional Higgs width assumption:
  - $H \to ZZ^* \to 4l$: $-7.5 < \kappa_c < 9.3$

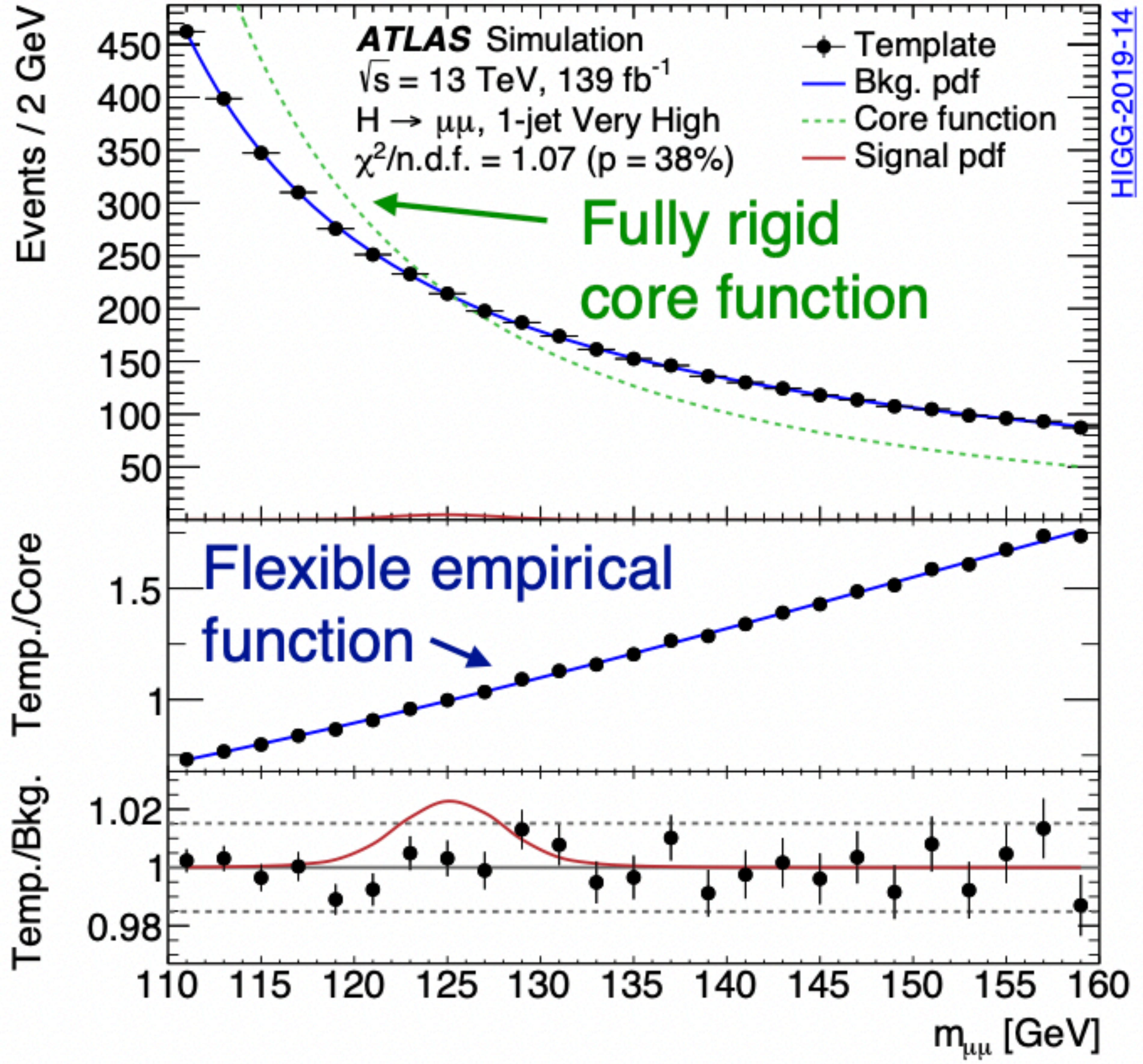


Great results with Run 2! Many reasons to get excited for Run 3!

Back up

Hmumu back up

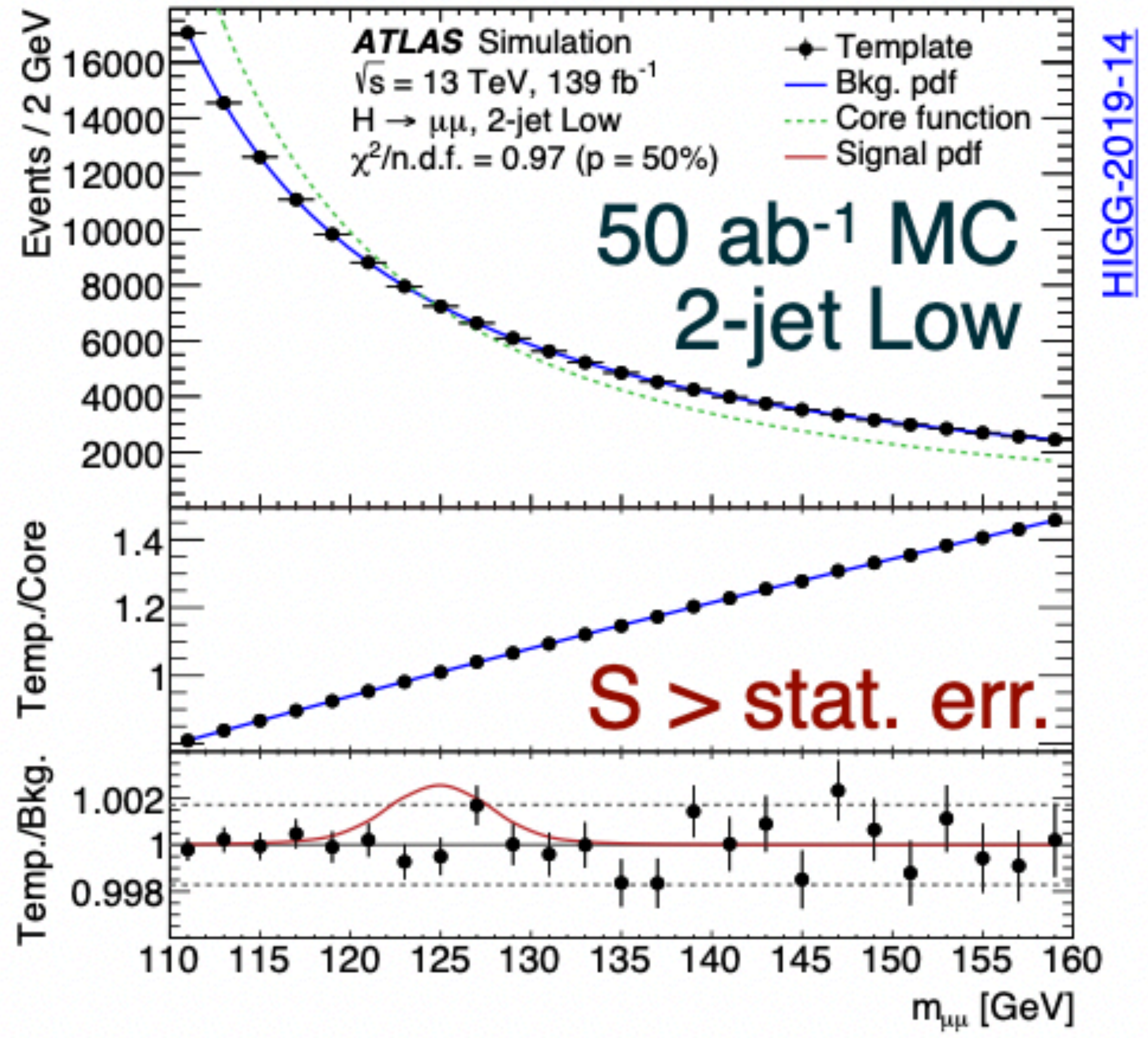
Hmumu



Fully rigid core function

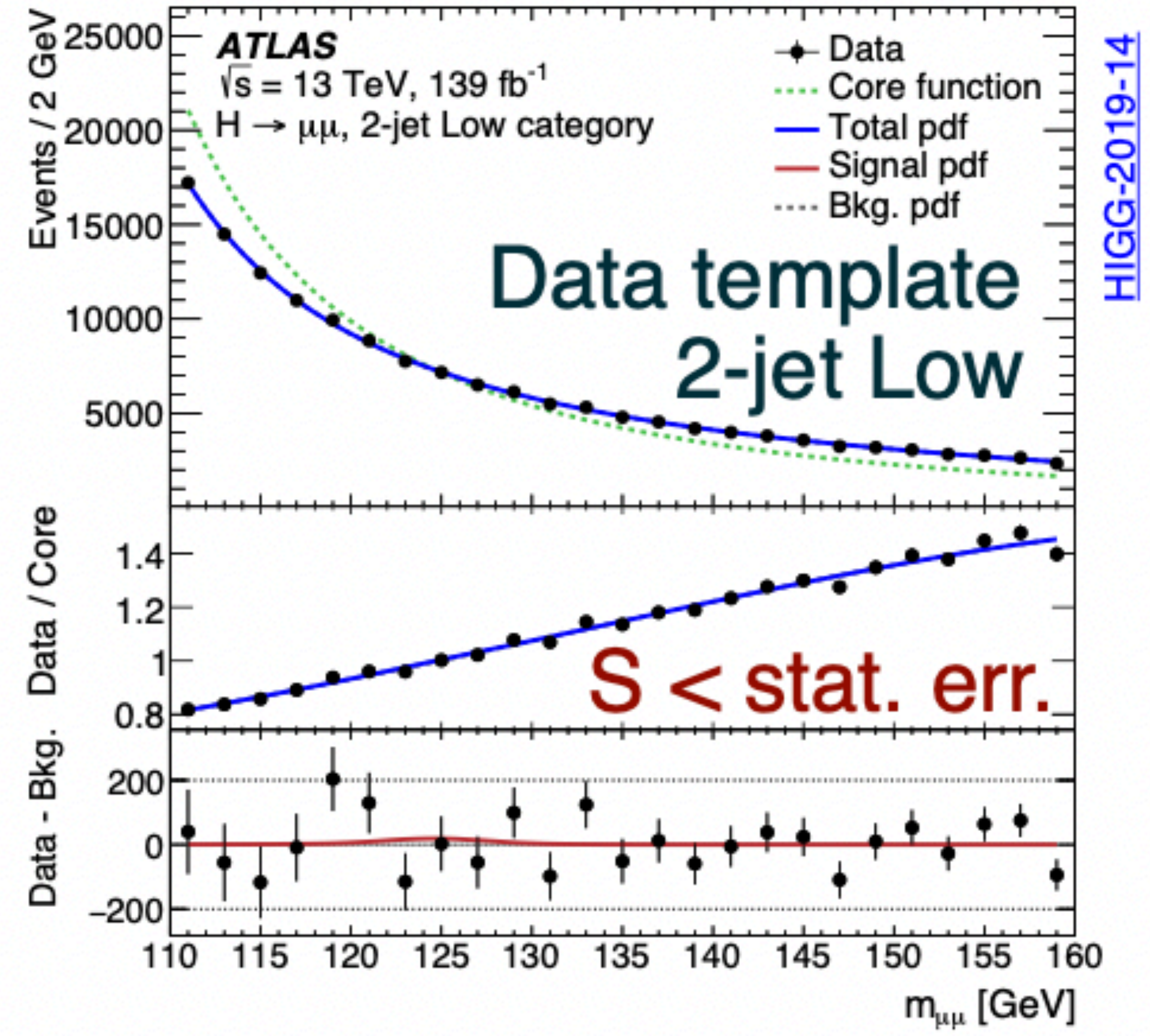
Flexible empirical function

Empirical functions	
PowerN	$m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+...+a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + ... + a_N m_{\mu\mu}^N)$



50 ab^{-1} MC 2-jet Low

S > stat. err.



Data template 2-jet Low

S < stat. err.

Hcc backup

Event categorisation: SR

New ATLAS-CONF-2021-021

Channel	c-tag	Jets	p_T^V
0-lepton	1 and 2 c-tag	2 and 3 jets	pTV > 150 GeV
1-lepton			
2-lepton		2 and ≥3 jets	pTV > 150 GeV
			75 < pTV < 150 GeV

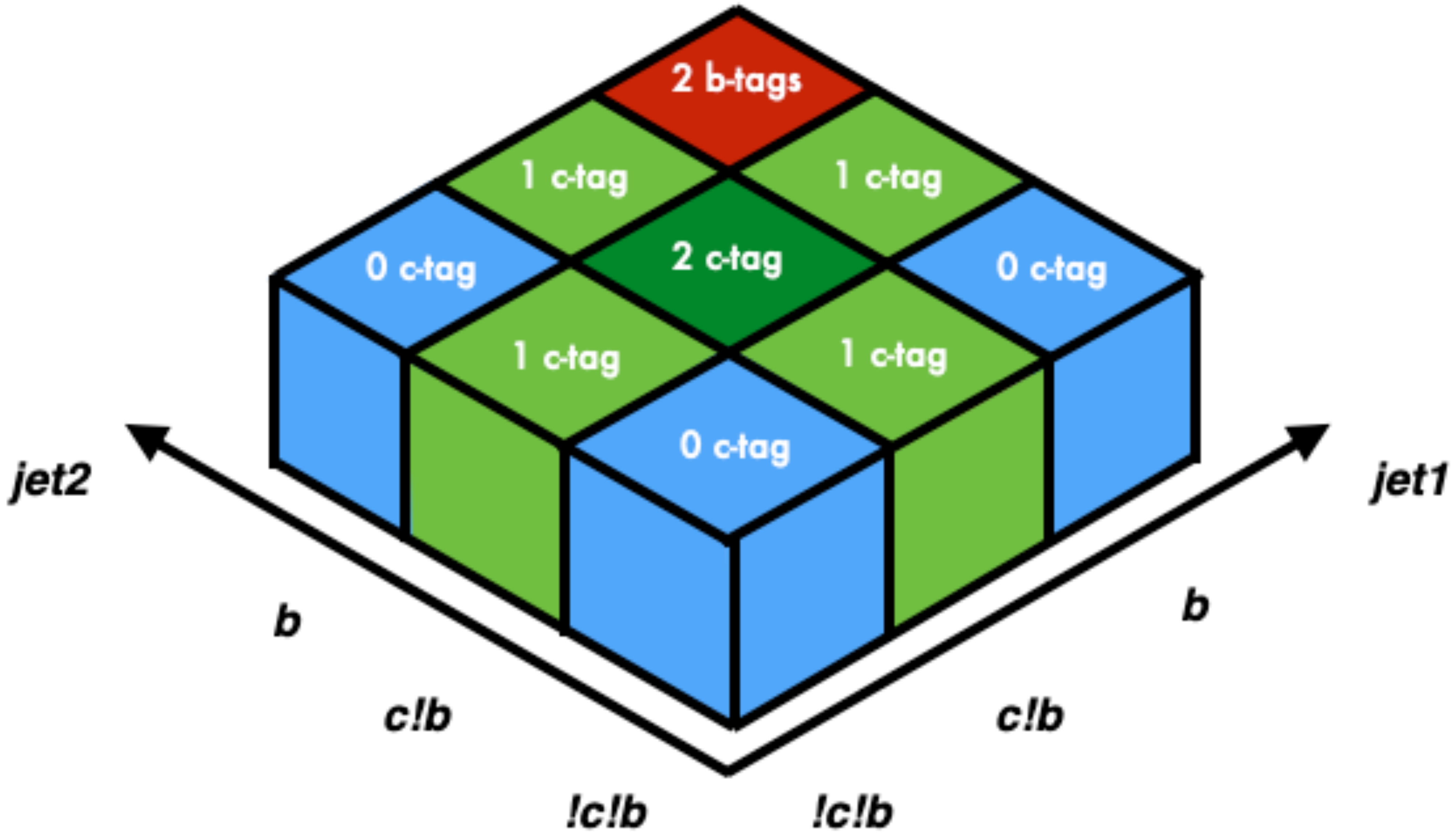
= Total: 16 SRs

Event categorisation:

- Flavour tagging: 1 and 2 c-tag (similar sensitivity)
- Jet multiplicity: 2 and 3(or more) jets → Exploit better resolution in 2 jets category
- pTV category: pTV > 150 GeV → Exploit better S/B at high pT(Higgs)
  - 2-lepton only: 75 < pTV < 150 GeV

Flavour tagging categorisation

Events with 2 jets



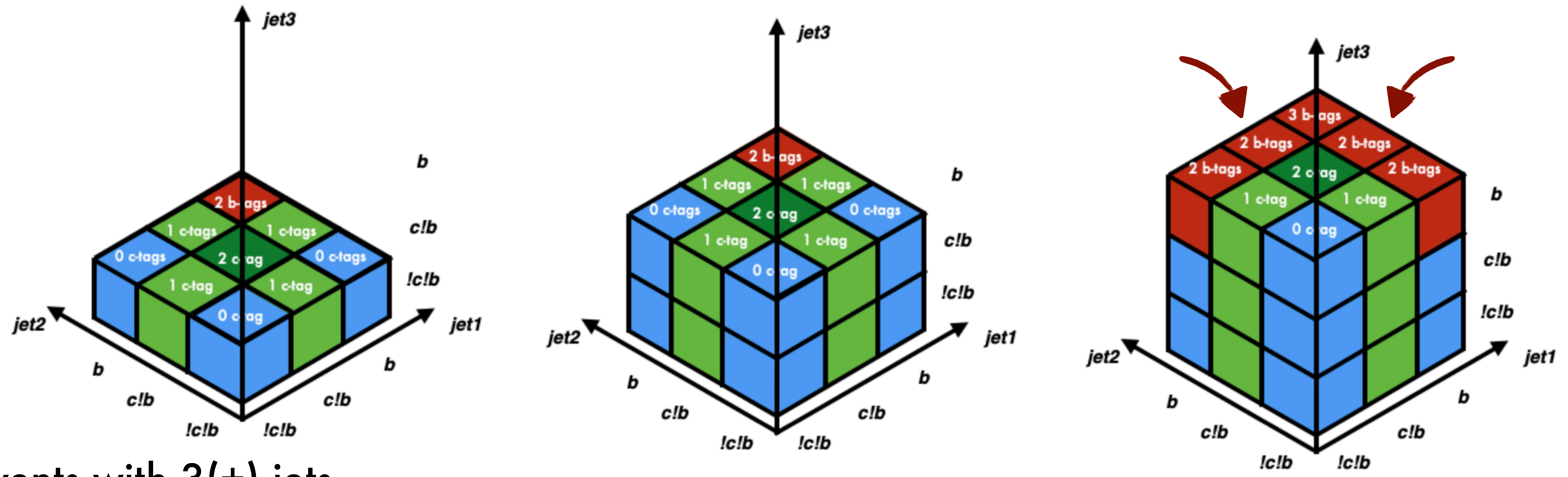
Categorisation of events with 2 jets

- VH(cc) analysis: use events with 1 c-tag and 2 c-tag
- VH(bb) analysis: use events with 2 b-tag

→ VH(cc) and VH(bb) **orthogonal** by construction in events with 2 jets

Flavour tagging categorisation

Events with 3 jets



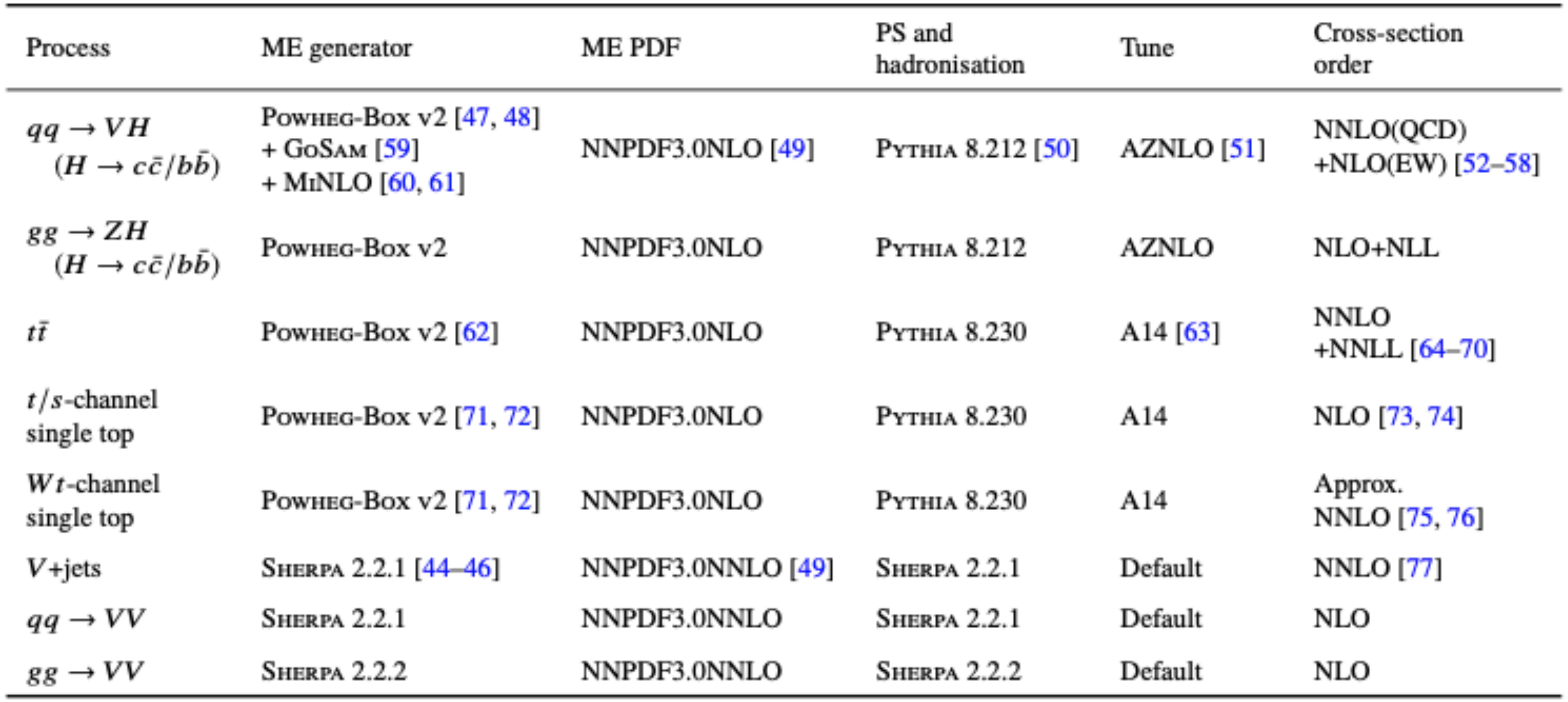
Events with 3(+) jets

- VH(cc) analysis: Higgs boson reconstructed from 2 jets with highest pT in event
- VH(bb) analysis: Higgs boson reconstructed from any 2 b-tagged jets
  - VH(bb) strategy tested in VH(cc) and less sensitive (-7% loss of significance)

Categorisation of events with 3(+) jets: overlap in 1 c-tag and 2 b-tag if 3rd jet b-tagged

→ To achieve orthogonality: apply b-tag veto on 3rd jet and more in the event!

Simulation samples



Process	ME generator	ME PDF	PS and hadronisation	Tune	Cross-section order
$qq \to VH$ $(H \to c\bar{c}/b\bar{b})$	Powheg-Box v2 [47, 48] + GoSam [59] + MiNLO [60, 61]	NNPDF3.0NLO [49]	Pythia 8.212 [50]	AZNLO [51]	NNLO(QCD) +NLO(EW) [52–58]
$gg \to ZH$ $(H \to c\bar{c}/b\bar{b})$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NLO+NLL
$t\bar{t}$	Powheg-Box v2 [62]	NNPDF3.0NLO	Pythia 8.230	A14 [63]	NNLO +NNLL [64–70]
t/s-channel single top	Powheg-Box v2 [71, 72]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [73, 74]
Wt-channel single top	Powheg-Box v2 [71, 72]	NNPDF3.0NLO	Pythia 8.230	A14	Approx. NNLO [75, 76]
V+jets	Sherpa 2.2.1 [44–46]	NNPDF3.0NNLO [49]	Sherpa 2.2.1	Default	NNLO [77]
$qq \to VV$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO

Nominal simulation samples:

- VH(cc) and VH(bb): PowhegPythia8
- V+jets: Sherpa 2.2
- ttbar and single top: PowhegPythia8
- VV: Sherpa 2.2

Same samples used for the VH(bb) analysis

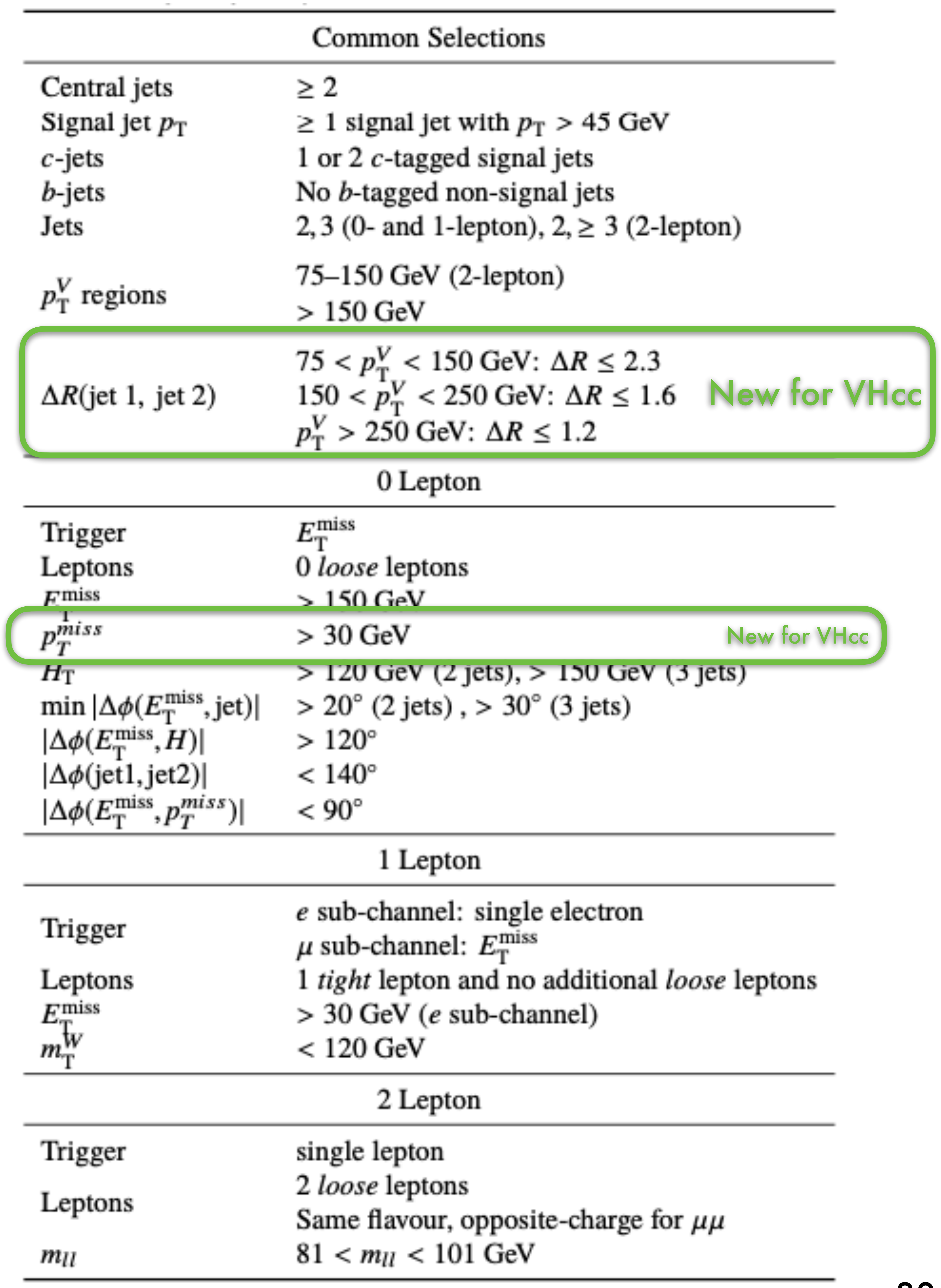
Event selection

Revisited event selection for VH(cc):

- ΔR(cc) selection optimised for VH(cc) sensitivity
- 0-lepton: non-collisional background rejection

Jet energy corrections:

- Smaller improvement w.r.t VH(bb) due to less semi-leptonic decays
- Muon-in-jet correction applied in all channels
- Improved m(cc) resolution: 6%
- Tested KF correction in 2-lepton
  - Improved m(cc) resolution by 37%
  - Induced disagreement between direct and truth tagging → Not used in the final analysis



Common Selections		
Central jets	≥ 2	
Signal jet p_{T}	≥ 1 signal jet with $p_{\mathrm{T}} > 45$ GeV	
c-jets	1 or 2 c-tagged signal jets	
b-jets	No b-tagged non-signal jets	
Jets	2, 3 (0- and 1-lepton), 2, ≥ 3 (2-lepton)	
p_{T}^{V} regions	75–150 GeV (2-lepton) > 150 GeV	
ΔR(jet 1, jet 2)	$75 < p_{\mathrm{T}}^{V} < 150$ GeV: $\Delta R \leq 2.3$ $150 < p_{\mathrm{T}}^{V} < 250$ GeV: $\Delta R \leq 1.6$ $p_{\mathrm{T}}^{V} > 250$ GeV: $\Delta R \leq 1.2$	New for VHcc
0 Lepton		
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	
Leptons	0 *loose* leptons	
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	
p_{T}^{miss}	> 30 GeV	New for VHcc
H_{T}	> 120 GeV (2 jets), > 150 GeV (3 jets)	
$\min \lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})\rvert$	$> 20°$ (2 jets) , $> 30°$ (3 jets)	
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, H)\rvert$	$> 120°$	
$\lvert\Delta\phi(\mathrm{jet1}, \mathrm{jet2})\rvert$	$< 140°$	
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{T}^{miss})\rvert$	$< 90°$	
1 Lepton		
Trigger	e sub-channel: single electron μ sub-channel: $E_{\mathrm{T}}^{\mathrm{miss}}$	
Leptons	1 *tight* lepton and no additional *loose* leptons	
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV (e sub-channel)	
m_{T}^{W}	< 120 GeV	
2 Lepton		
Trigger	single lepton	
Leptons	2 *loose* leptons Same flavour, opposite-charge for $\mu\mu$	
m_{ll}	$81 < m_{ll} < 101$ GeV	

Summary: SR and CR

ΔR_{cc} cuts		
	75 GeV $< p_{TV} <$ 150 GeV	ΔR_{cc} cut = 2.3
	150 GeV $< p_{TV} <$ 250 GeV	ΔR_{cc} cut = 1.6
	$p_{TV} >$ 250 GeV	ΔR_{cc} cut = 1.2

		$\Delta R_{cc} < \Delta R_{cc}$ cut				ΔR_{cc} cut $< \Delta R_{cc} < 2.5$	
		0tag CR	SR		Top CR	ΔR_{cc} CR	
0 L	pTV > 150 GeV		1tag 2jet	2tag 2jet		1tag 2jet	2tag 2jet
			1tag 3jet	2tag 3jet	1 tag 3 jet	1tag 3jet	2tag 3jet
1 L	pTV > 150 GeV	0tag 2jet	1tag 2jet	2tag 2jet		1tag 2jet	2tag 2jet
		0tag 3jet	1tag 3jet	2tag 3jet	1 tag 3 jet	1tag 3jet	2tag 3jet
2 L	Low pTV	0tag 2 jet	1tag 2jet	2tag 2jet	1tag 2 jet	1tag 2jet	2tag 2jet
		0tag 3+jet	1tag 3+jet	2tag 3+jet	1tag 3+jet	1tag 3+jet	2tag 3+jet
	pTV > 150 GeV	0tag 2 jet	1tag 2jet	2tag 2jet	1tag 2 jet	1tag 2jet	2tag 2jet
		0tag 3+jet	1tag 3+jet	2tag 3+jet	1tag 3+jet	1tag 3+jet	2tag 3+jet

Legend
- Binned SR
- Binned CR
- One-bin CR

16 SRs
+ 28 CRs
= 44 regions

Fit to data performed simultaneously on 16 SRs + 28 CRs

Background modelling

Process	Nominal	Alternative
VH(cc), VH(bb)	Powheg+Pythia8	Powheg+Herwig7 QCD μ_R and μ_F scale variations
VV	Sherpa2.2.1 (qq) Sherpa 2.2.2 (gg)	Powheg+Pythia8 QCD μ_R and μ_F scale variations
Z+jets and W+jets	Sherpa2.2.1	MadGraph5+Pythia8 QCD μ_R and μ_F scale variations
ttbar + single top	Powheg+Pythia8	MadGraph5+aMC@NLO+Pythia8 Powheg+Herwig7 ISR / FSR
Single top only		Diagram subtraction + removal

Difference between nominal and alternative MC generators taken as uncertainty:

- **Normalisation uncertainties**: relative difference on total yield predictions
  - Applied to subdominant processes (i.e. Diboson, VH): phase space acceptance
- **Acceptance ratios**: relative differences in predictions for categories
  - pTV and Njet
- **Flavour composition ratios**: different flavour / processes predictions per categories
- **Channel extrapolations**: different predictions per channel
- **SR / CR extrapolation**: different predictions per region
- **M(cc) Shape uncertainties**: account for differences in binned m(cc) distribution prediction
- In addition: theory uncertainties for cross-section and branching fraction for VH(cc)

Background modelling

Floating normalisations:

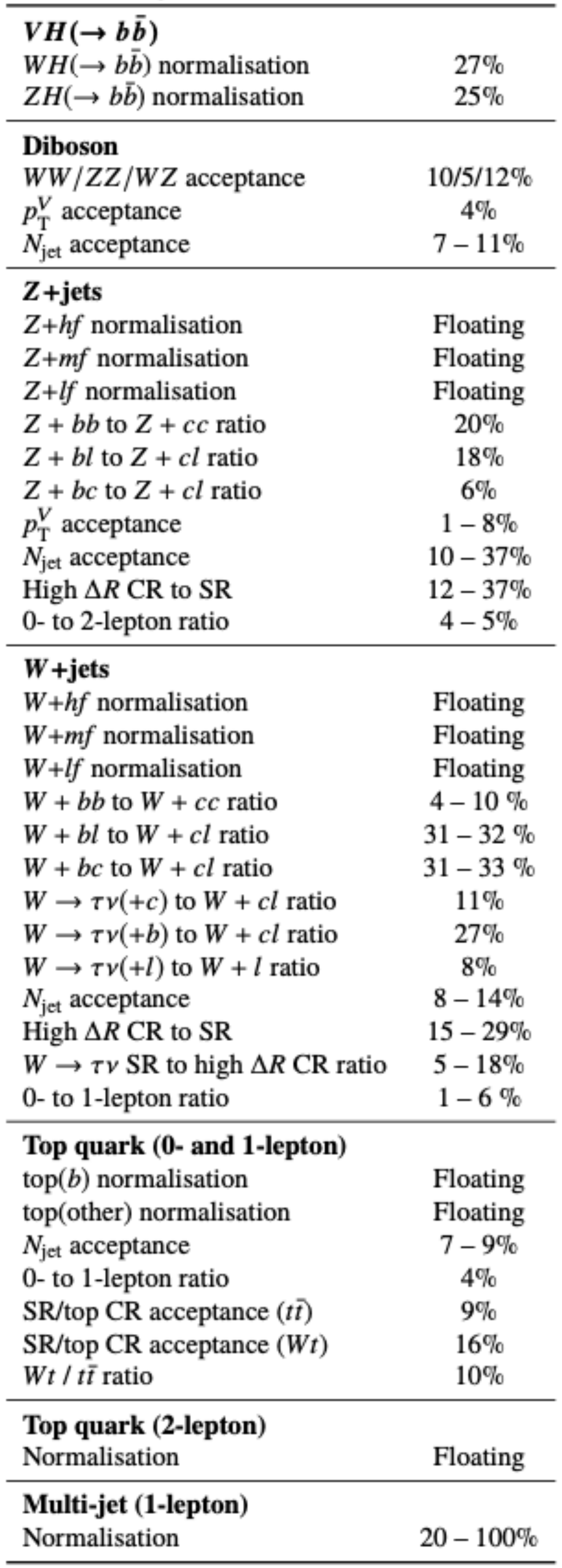
- Heavy flavour: Zhf and Whf
- Mixed flavour: Zmf and Wmf
- Light flavour: Zlf and Wlf
- top(b) and top(other) (0- and 1-lepton)
- ttbar (2-lepton)

Acceptance, flavour and channel ratios:

- pTV (2-lepton): high pTV / low pTV
- Njet: 3 jets / 2 jets for V+jets and 2 jets / 3 jets for ttbar
- Flavour composition:
  - bb / cc, bl / cl , bc/ cl for W+jets and Z+jets
  - bτ / cl, cτ / cl, lτ / l for W+jets
  - Wt / ttbar for top(b)
- SR / top CR, high ΔR CR / SR
- Channel: 0-lepton / 1-lepton, 0-lepton / 2-lepton

Shape uncertainties: on m(cc) for each bkg subcomponent

Data driven: QCD multi-jets in 1-lepton



$VH(\to b\bar{b})$	
$WH(\to b\bar{b})$ normalisation	27%
$ZH(\to b\bar{b})$ normalisation	25%
Diboson	
$WW/ZZ/WZ$ acceptance	10/5/12%
p_T^V acceptance	4%
N_{jet} acceptance	7 – 11%
Z+jets	
$Z+hf$ normalisation	Floating
$Z+mf$ normalisation	Floating
$Z+lf$ normalisation	Floating
$Z+bb$ to $Z+cc$ ratio	20%
$Z+bl$ to $Z+cl$ ratio	18%
$Z+bc$ to $Z+cl$ ratio	6%
p_T^V acceptance	1 – 8%
N_{jet} acceptance	10 – 37%
High ΔR CR to SR	12 – 37%
0- to 2-lepton ratio	4 – 5%
W+jets	
$W+hf$ normalisation	Floating
$W+mf$ normalisation	Floating
$W+lf$ normalisation	Floating
$W+bb$ to $W+cc$ ratio	4 – 10 %
$W+bl$ to $W+cl$ ratio	31 – 32 %
$W+bc$ to $W+cl$ ratio	31 – 33 %
$W\to\tau\nu(+c)$ to $W+cl$ ratio	11%
$W\to\tau\nu(+b)$ to $W+cl$ ratio	27%
$W\to\tau\nu(+l)$ to $W+l$ ratio	8%
N_{jet} acceptance	8 – 14%
High ΔR CR to SR	15 – 29%
$W\to\tau\nu$ SR to high ΔR CR ratio	5 – 18%
0- to 1-lepton ratio	1 – 6 %
Top quark (0- and 1-lepton)	
top(b) normalisation	Floating
top(other) normalisation	Floating
N_{jet} acceptance	7 – 9%
0- to 1-lepton ratio	4%
SR/top CR acceptance ($t\bar{t}$)	9%
SR/top CR acceptance (Wt)	16%
Wt / $t\bar{t}$ ratio	10%
Top quark (2-lepton)	
Normalisation	Floating
Multi-jet (1-lepton)	
Normalisation	20 – 100%

Fit strategy

$$\mathcal{L}(\underbrace{\mu}_{\text{POI}},\vec{\theta},\vec{\gamma}) = \prod_{i\in \text{bins}} \underbrace{\text{Pois}(N_i|\mu s_i(\vec{\theta})+\gamma_i b_i(\vec{\theta}))}_{\text{Poissonian likelihood}} \times \prod_{\theta\in\vec{\theta}} \underbrace{\frac{1}{\sqrt{2\pi}} e^{-\theta^2/2}}_{\text{Constraint on NPs}} \times \prod_{i\in \text{bins}} \underbrace{\text{Gauss}(\beta_i|\gamma_i\beta_i,\sqrt{\gamma_i\beta_i})}_{\text{Constraints on MC statistics}}$$

Binned profile likelihood fit on m(cc) distribution simultaneously in 16 SRs and 28 CRs

3 parameters of interest (POIs):

- $\mu_{VH(cc)}$: signal strength of VH(cc) signal
- $\mu_{VZ(cc)}$: signal strength of VZ(cc) diboson → validation of 2 c-tag category
- $\mu_{VW(cq)}$: signal strength of VW(cq) diboson → validation of 1 c-tag category

Background: floating normalisations of main backgrounds

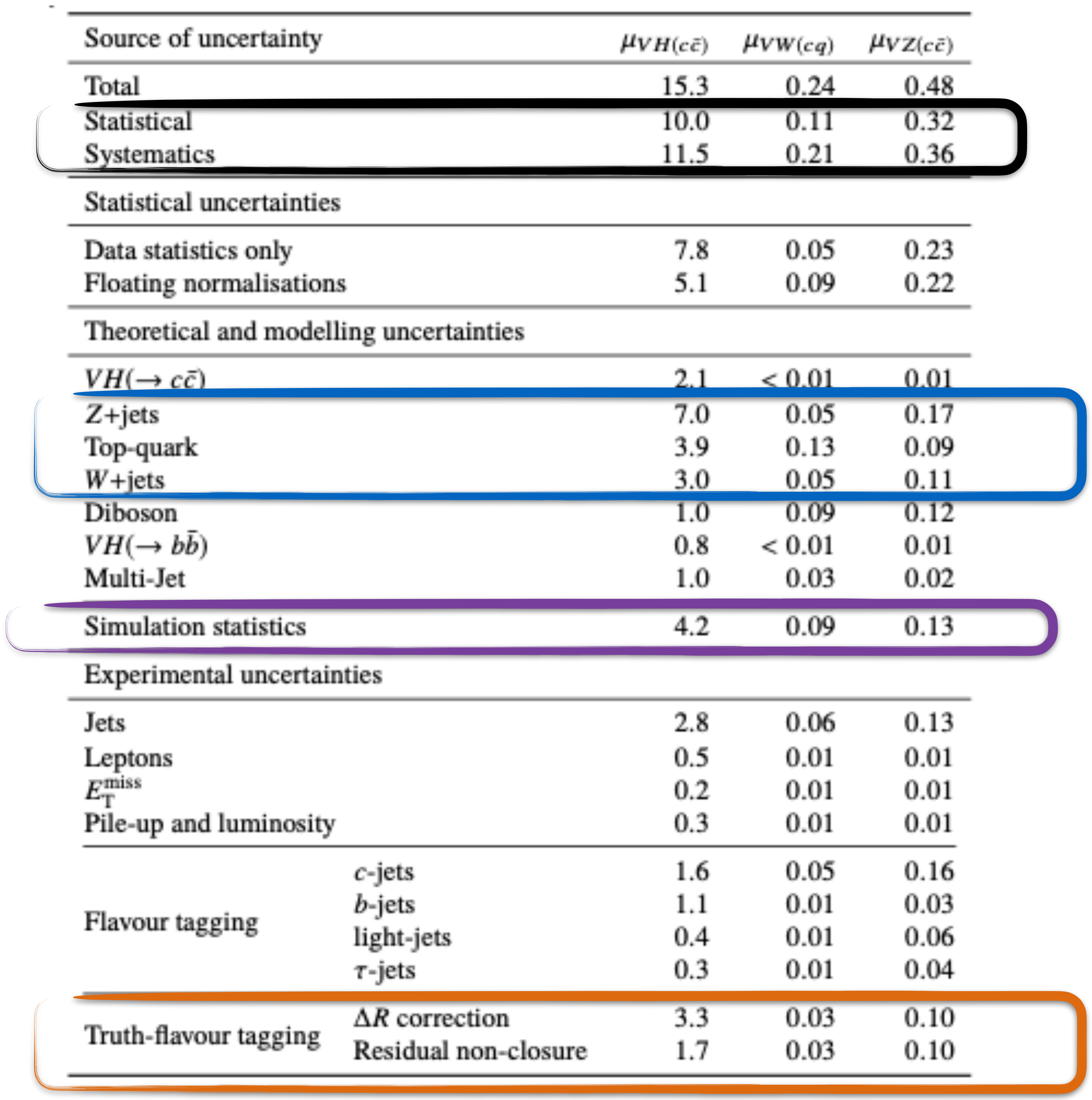
Nuisance parameters (NPs)

- Full set of detector systematics: trigger, jets, leptons, c/b-tagging, pile-up, luminosity
- Full set of modelling uncertainties
- MC stat. uncertainty

Breakdown of uncertainties

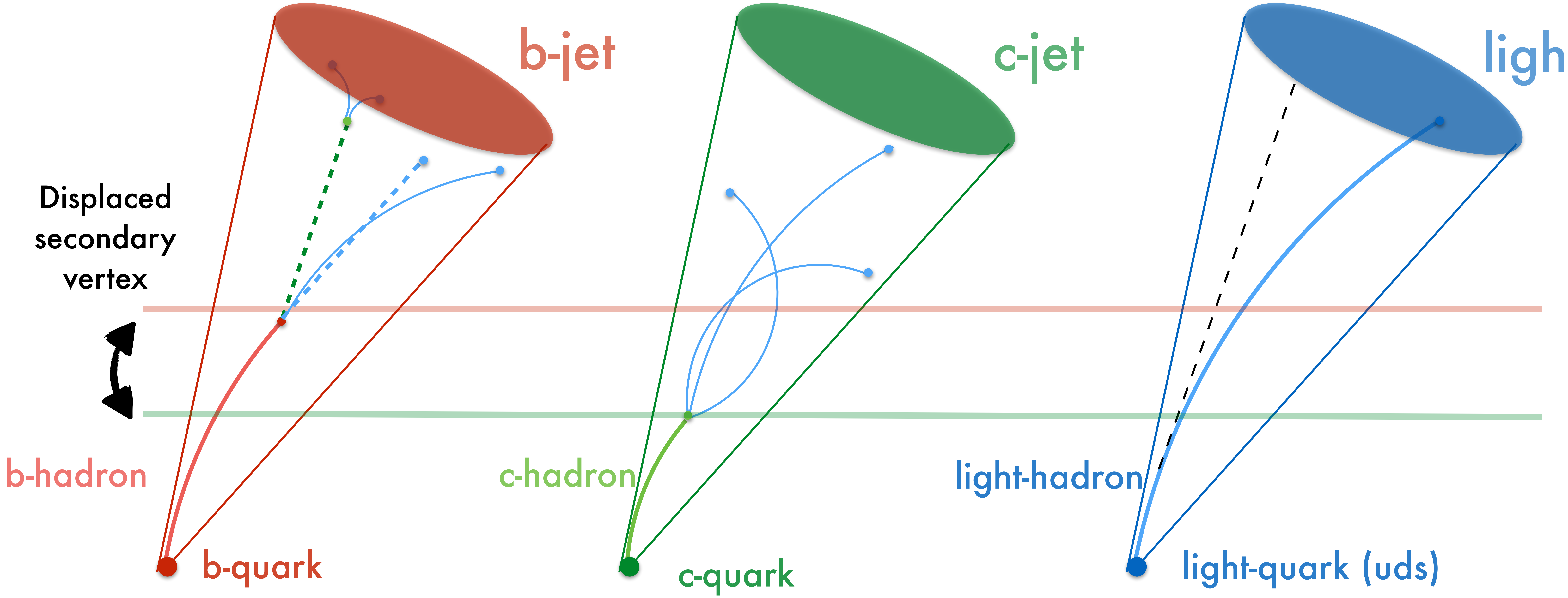
Breakdown of uncertainties

- Similar statistical and systematic uncertainties
- Dominant systematic uncertainties:
  - Background modelling: V+jets and ttbar
  - Simulation statistics
  - Truth flavour tagging (improvement from using truth tagging still 10% better than direct tagging)
    → Possible improvements with more simulated events and updating to the latest MC generators



Source of uncertainty		$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total		15.3	0.24	0.48
Statistical		10.0	0.11	0.32
Systematics		11.5	0.21	0.36
Statistical uncertainties				
Data statistics only		7.8	0.05	0.23
Floating normalisations		5.1	0.09	0.22
Theoretical and modelling uncertainties				
$VH(\rightarrow c\bar{c})$		2.1	< 0.01	0.01
Z+jets		7.0	0.05	0.17
Top-quark		3.9	0.13	0.09
W+jets		3.0	0.05	0.11
Diboson		1.0	0.09	0.12
$VH(\rightarrow b\bar{b})$		0.8	< 0.01	0.01
Multi-Jet		1.0	0.03	0.02
Simulation statistics		4.2	0.09	0.13
Experimental uncertainties				
Jets		2.8	0.06	0.13
Leptons		0.5	0.01	0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.2	0.01	0.01
Pile-up and luminosity		0.3	0.01	0.01
Flavour tagging	c-jets	1.6	0.05	0.16
	b-jets	1.1	0.01	0.03
	light-jets	0.4	0.01	0.06
	τ-jets	0.3	0.01	0.04
Truth-flavour tagging	ΔR correction	3.3	0.03	0.10
	Residual non-closure	1.7	0.03	0.10

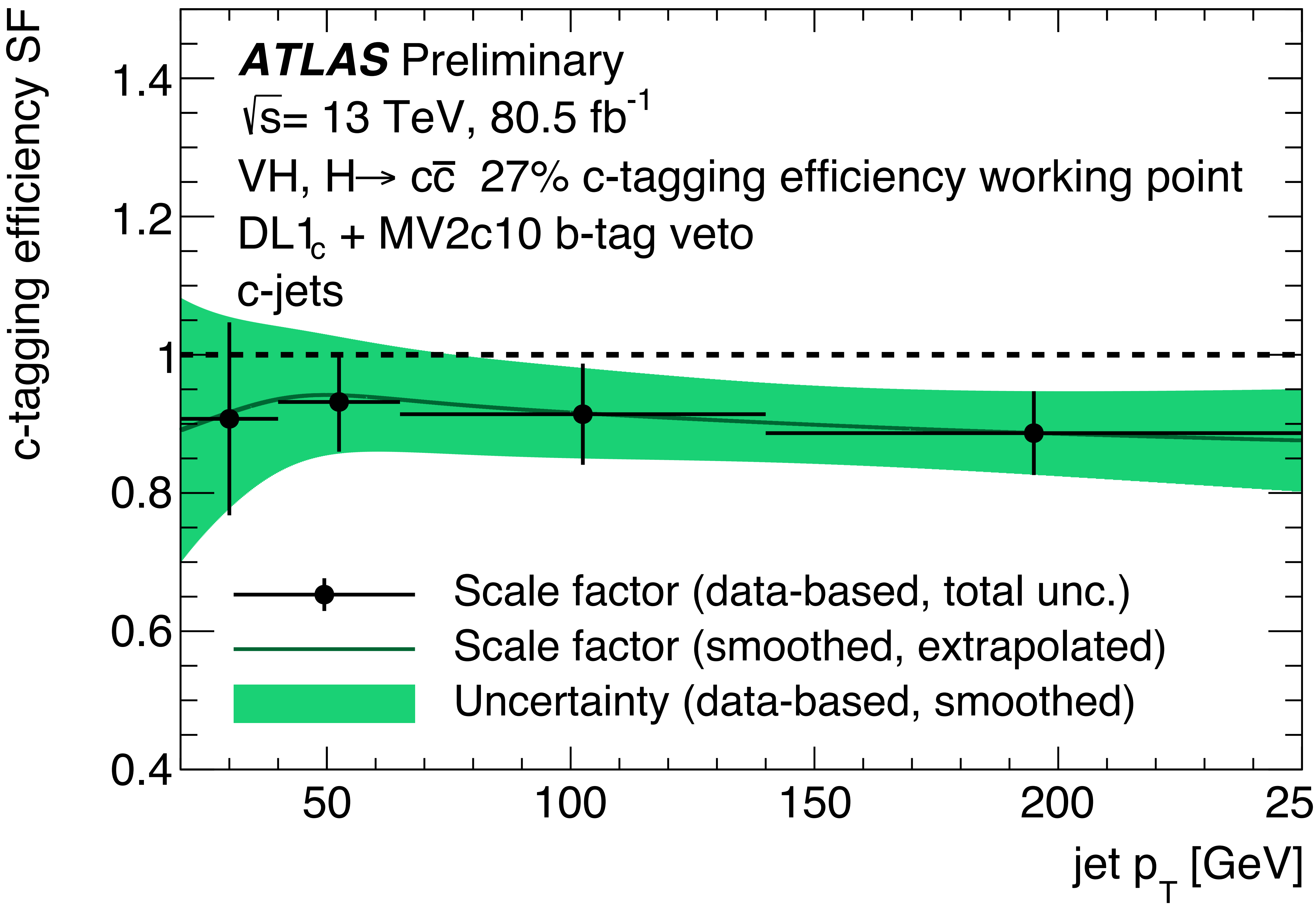
Charm tagging

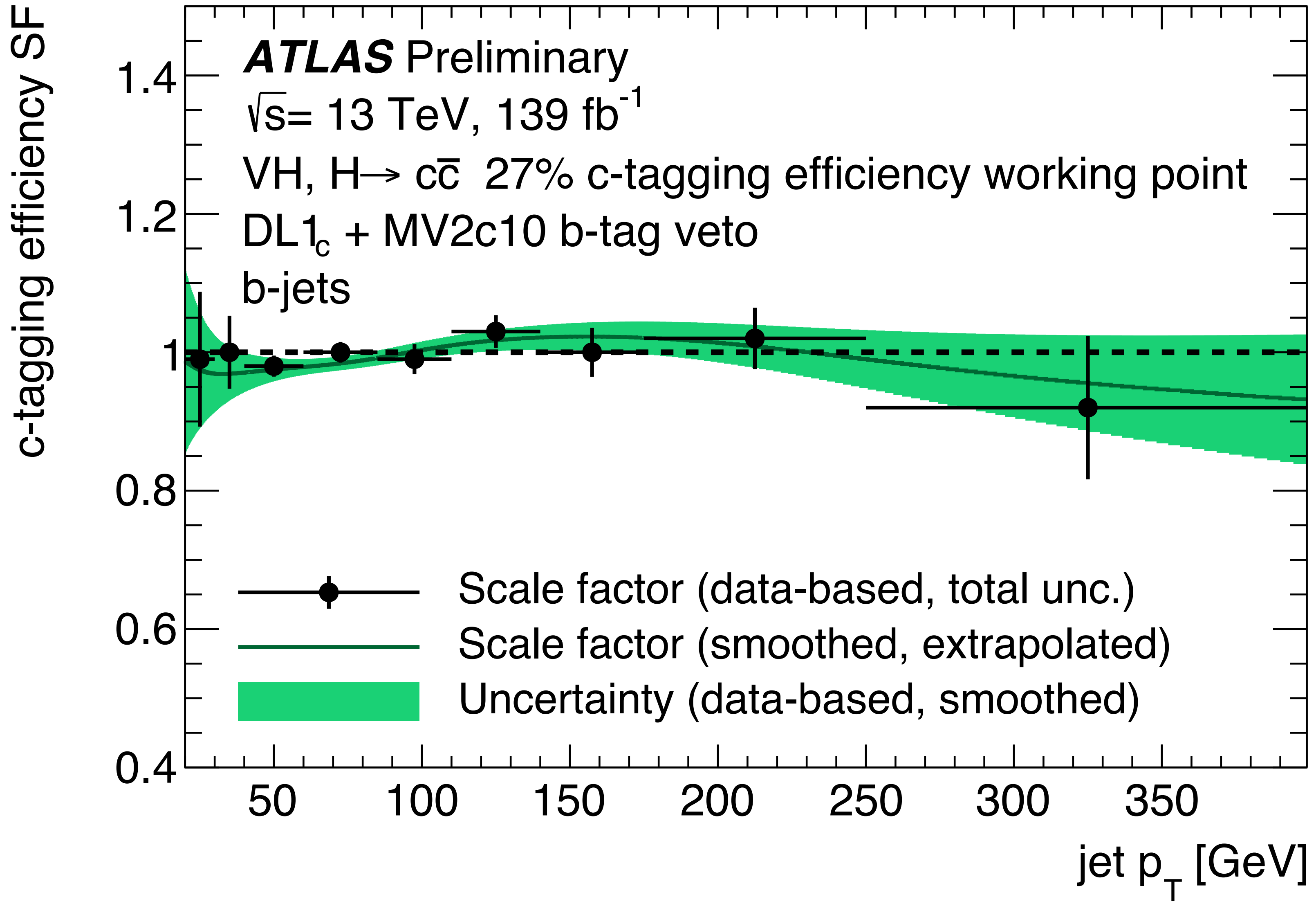


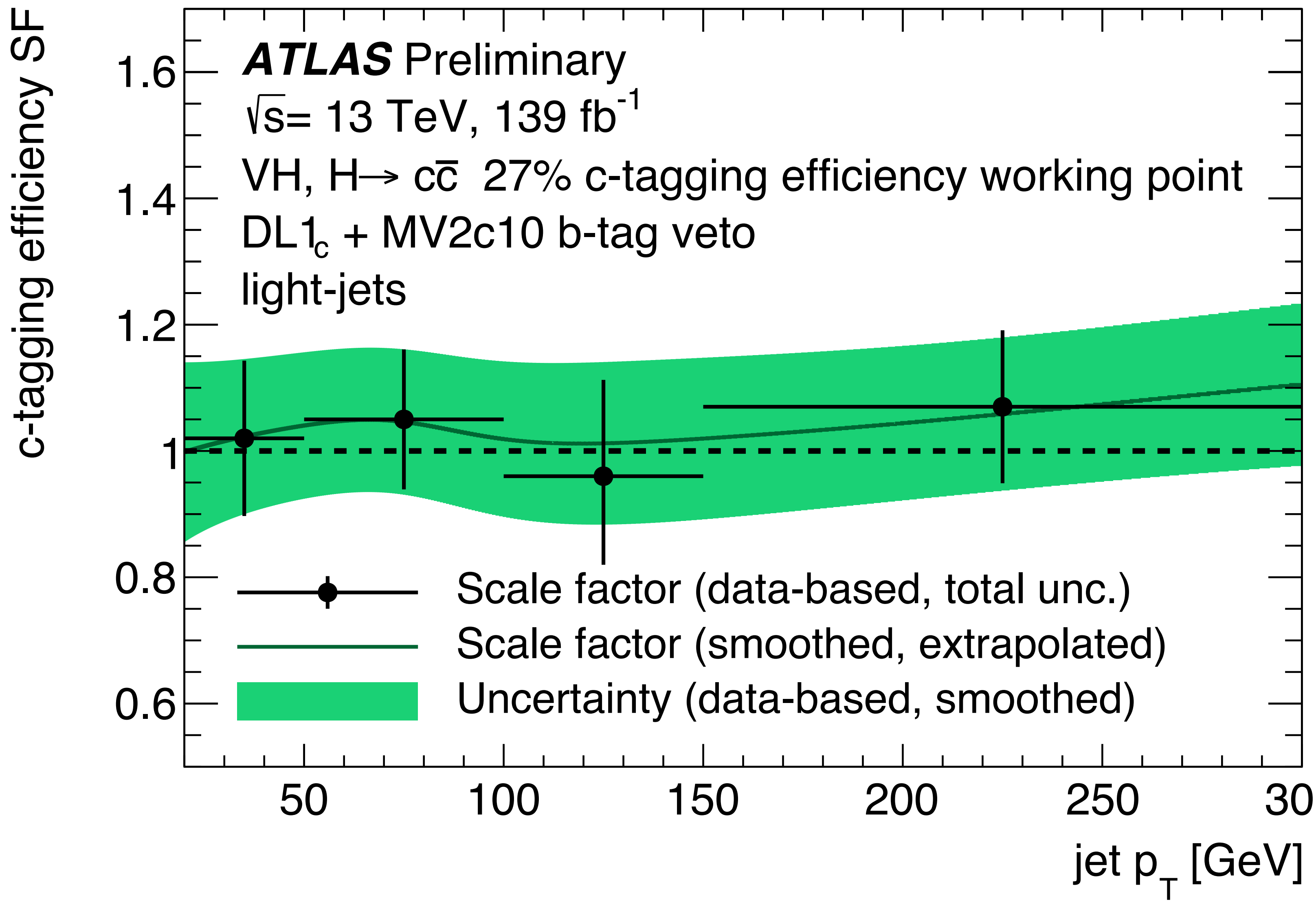
Tagging c-jets is challenging

- Lifetime and mass of c-hadrons in between b-hadron and light hadrons measured in detector
- Use Machine Learning to distinguish signal = c-jets from background = b-jets and light-jets

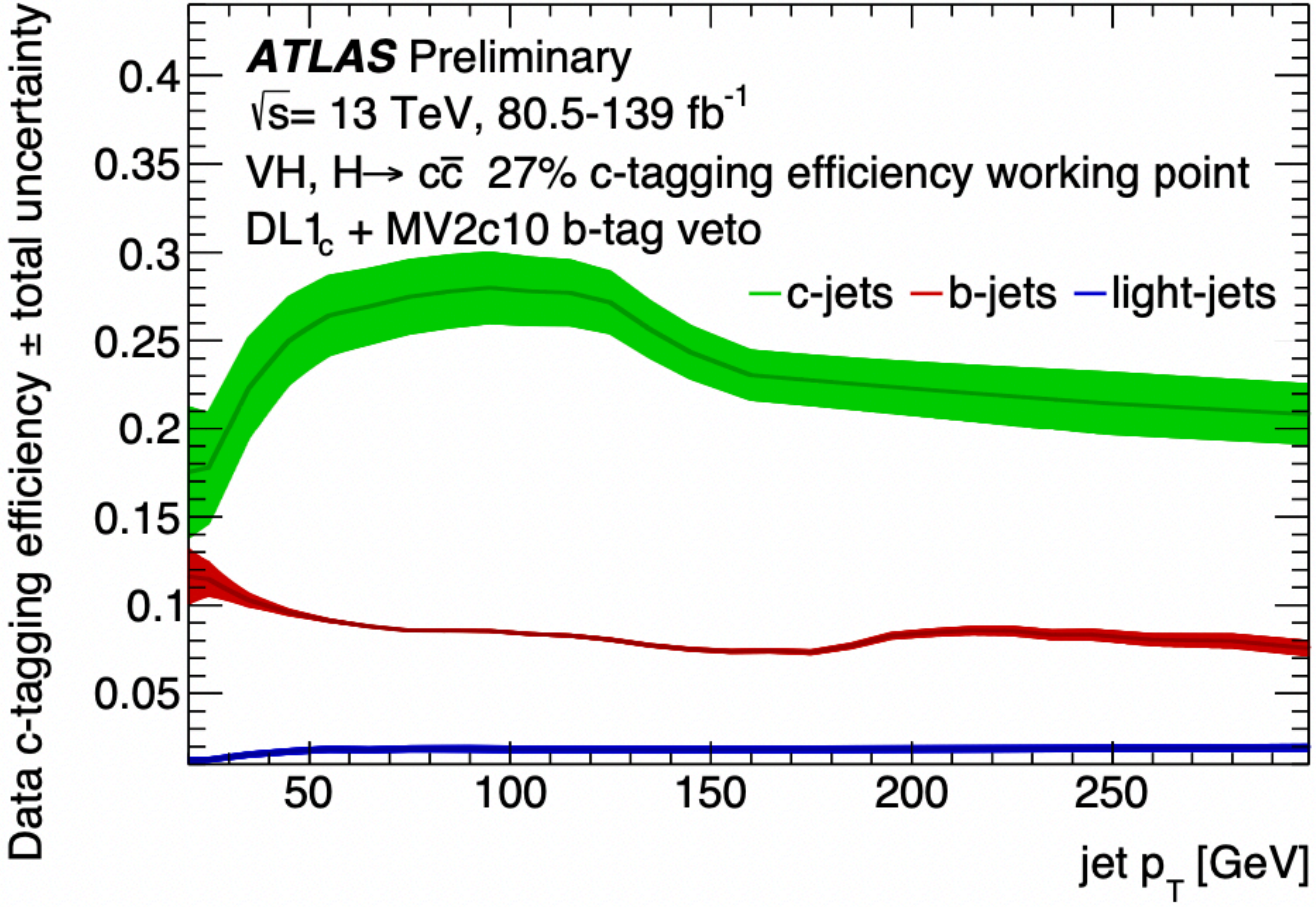
Charm tagging calibrations







Charm tagging performance



Analysis strategy: how do I reconstruct my Higgs?

VHcc categorisation:

- **2 c-tag + b-veto**
- **1 c-tag + b-veto**

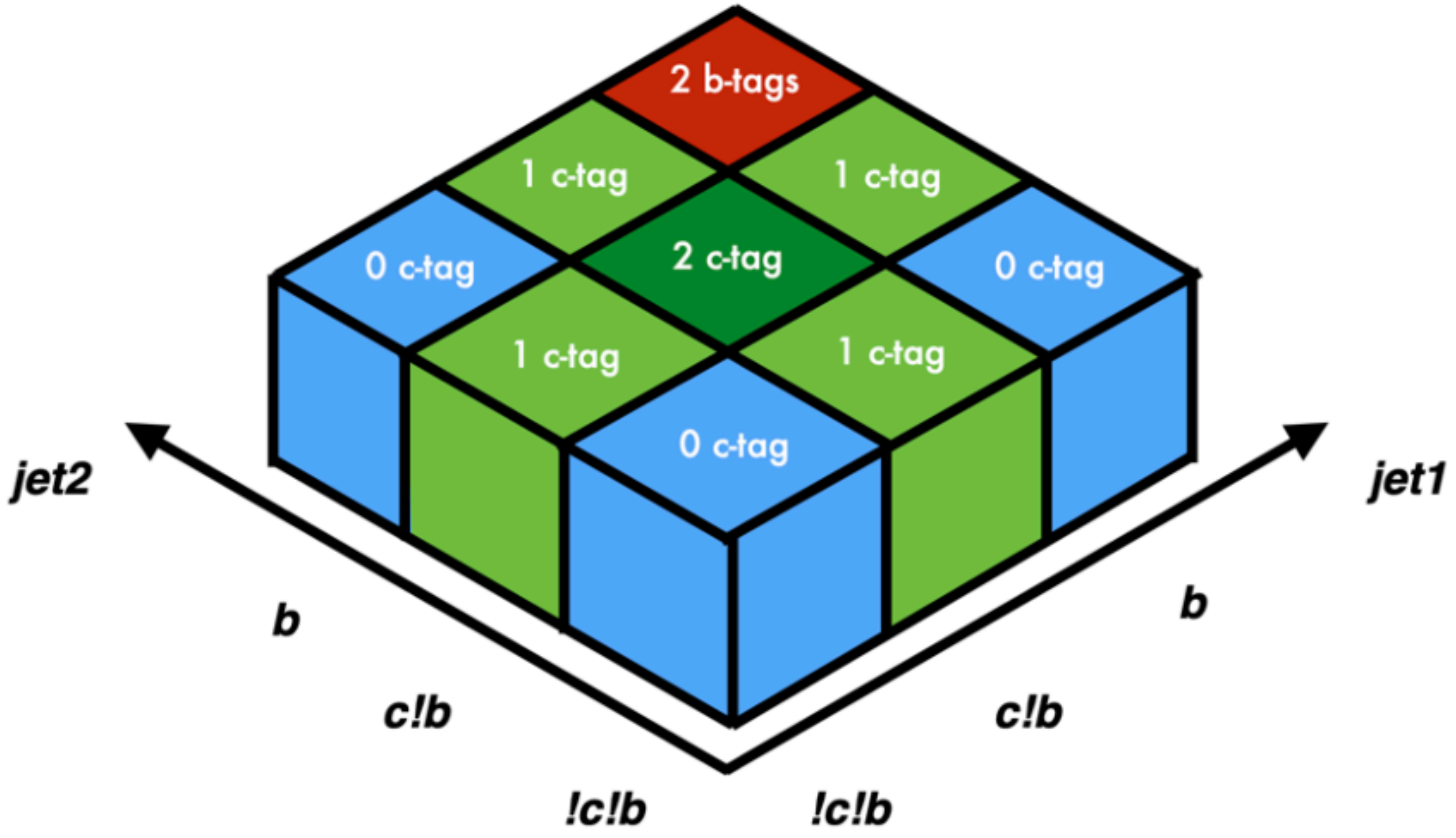
VHbb categorisation:

- **2 b-tag**

Orthogonality with VHbb:

- Always < 2 b-tagged jets

Categorisation of events with 2 jets



Analysis strategy: how do I reconstruct my Higgs?

VHcc categorisation:

- **2 c-tag + b-veto**
- **1 c-tag + b-veto**
- Additional **b-veto** on 3+jets

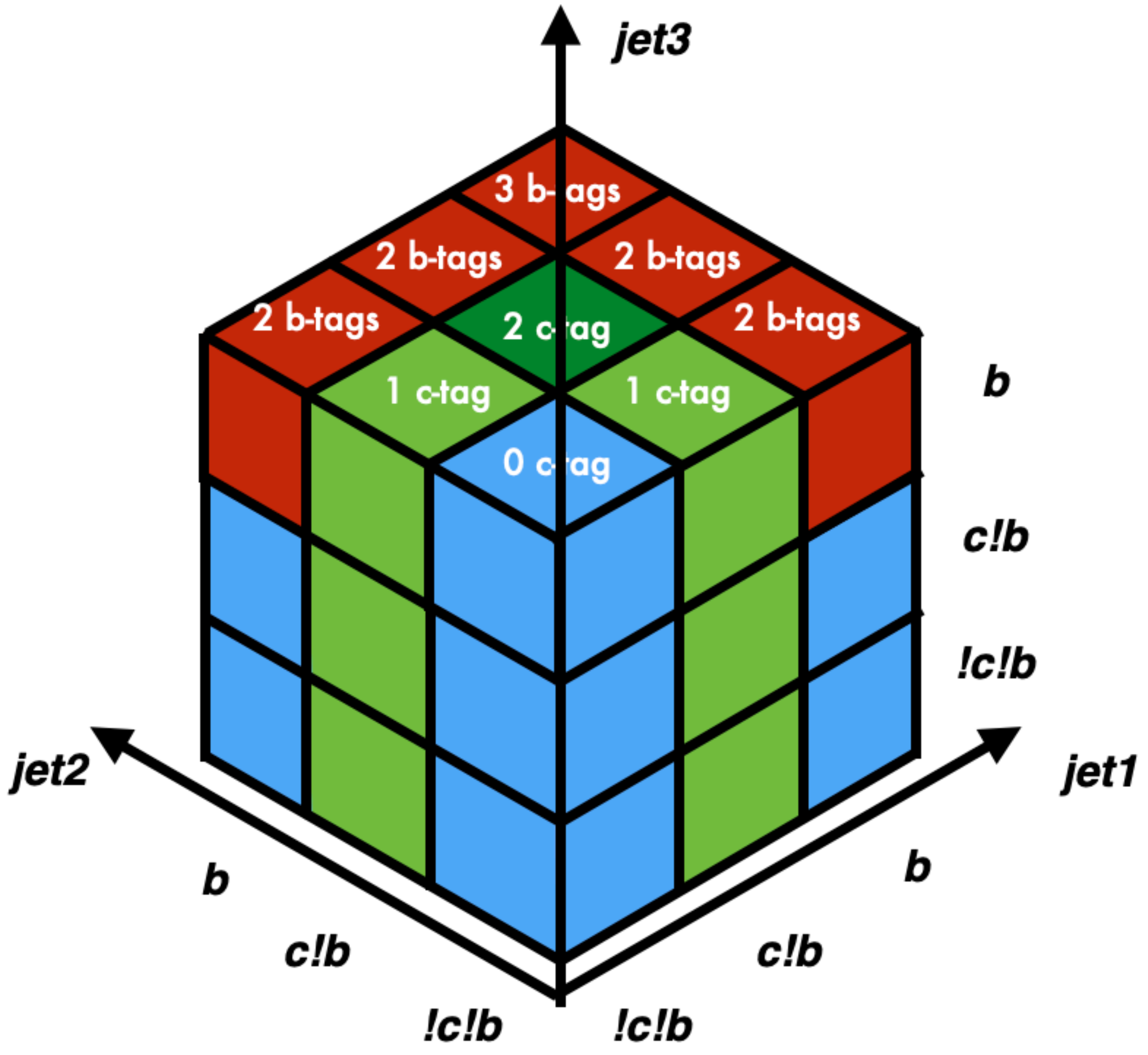
VHbb categorisation:

- **2 b-tag**

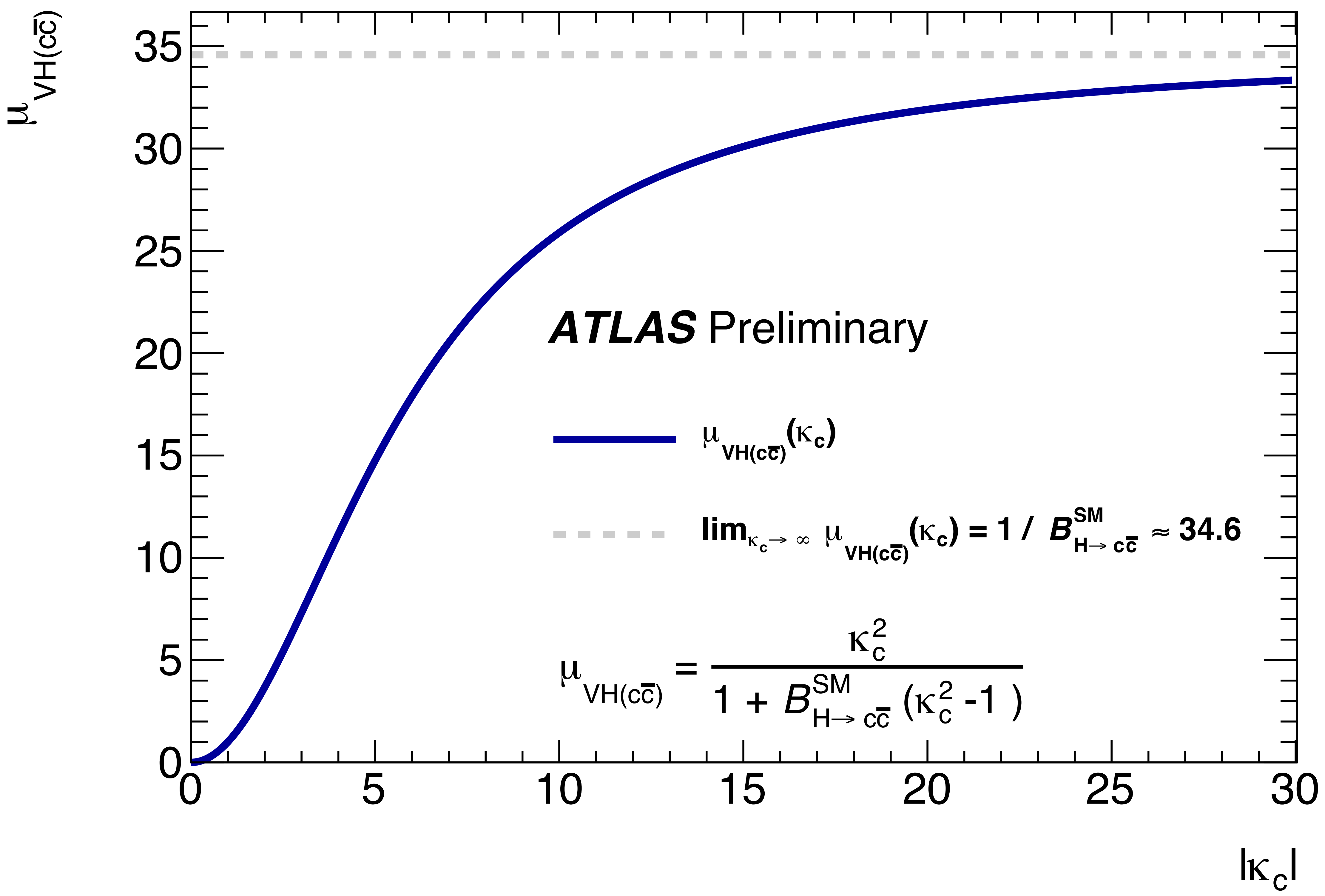
Orthogonality with VHbb:

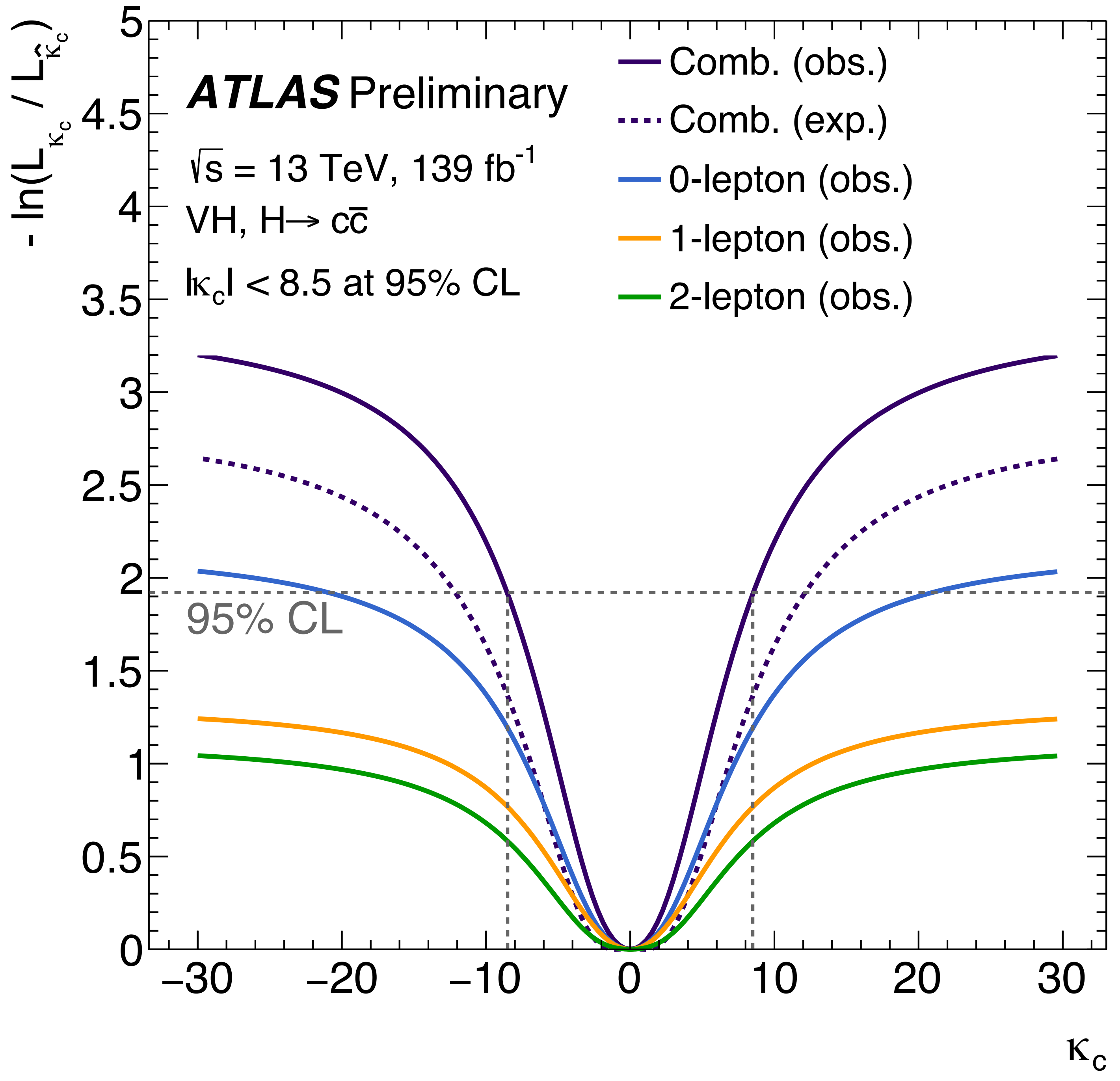
- Always < 2 b-tagged jets

Categorisation of events with 3 jets



Kc interpretations





Kc interpretation: quantify possible deviations from the SM

- Parametrise signal strength as a function of coupling enhancement Kc
- Assume Ki = 1 for other fermions and bosons
- Only sensitive to Kc if **μ** < 35 due to Higgs width in parametrisation
- Direct constraint: |Kc| < 8.5 @ 95% CL (<12.4 @ 95%CL expected)
  - Only sensitive to Kc through combination of 0-, 1 and 2-lepton

Breakdown of uncertainties

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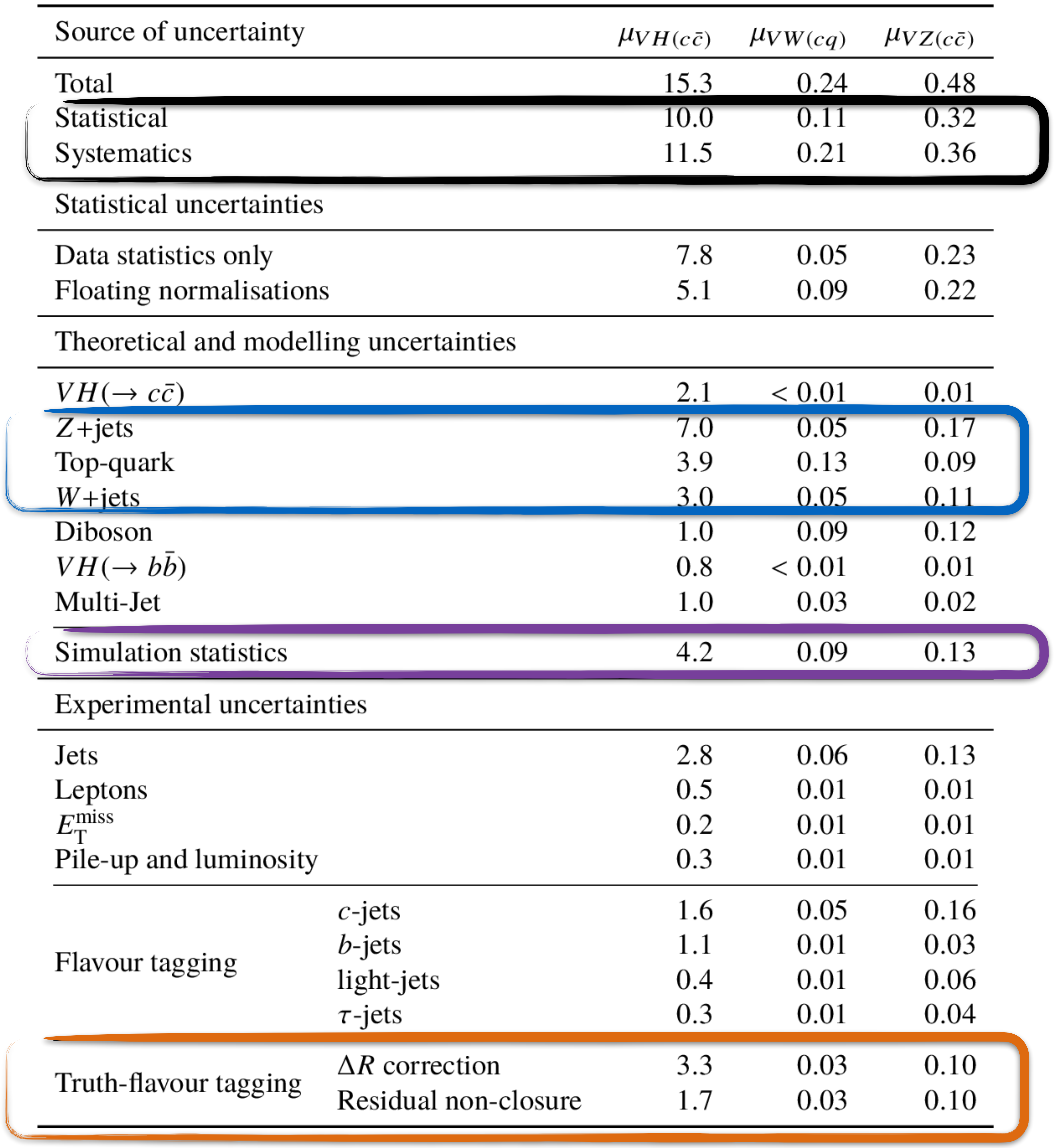
  - Simulation statistics
  - Truth flavour tagging



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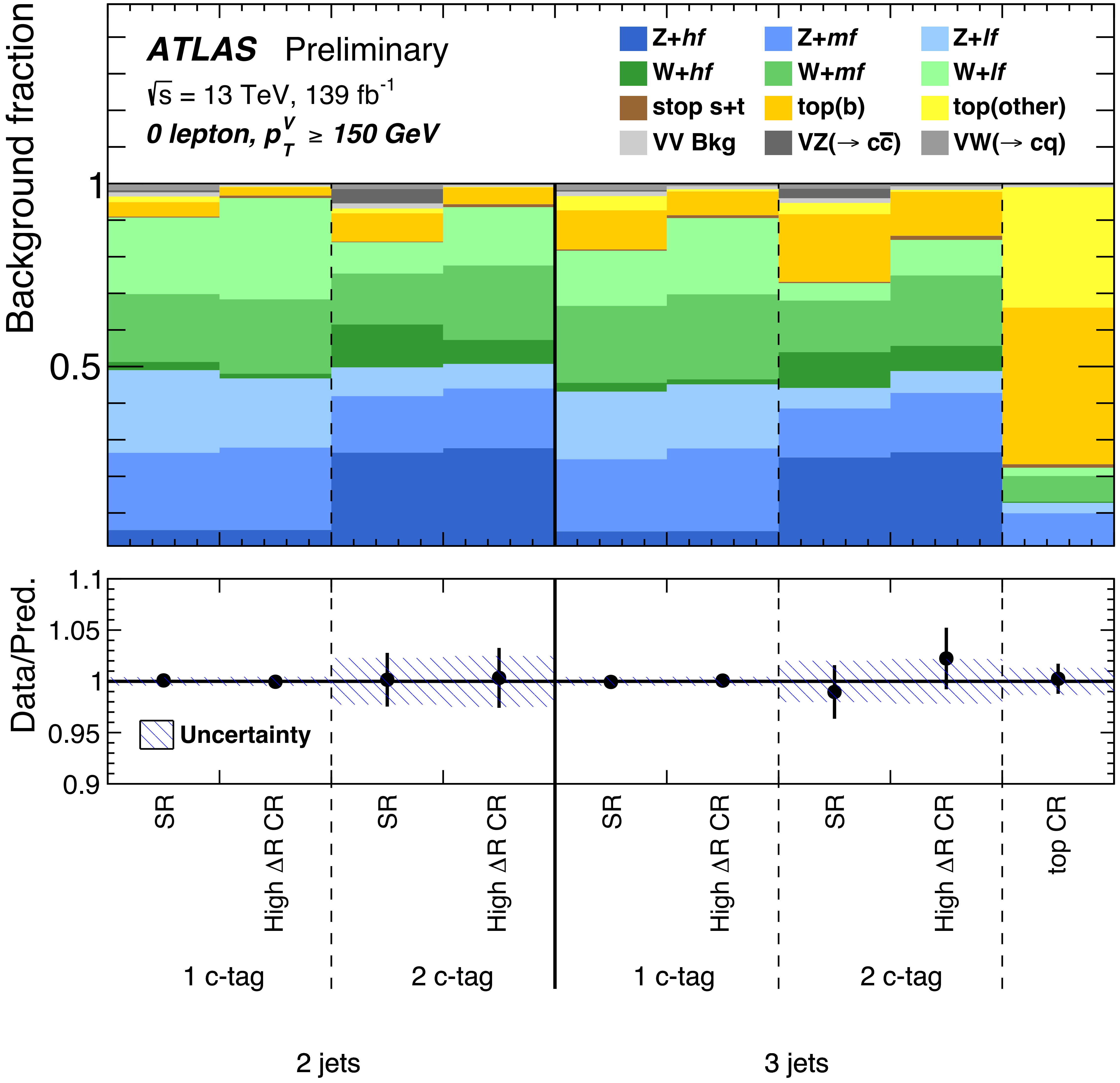
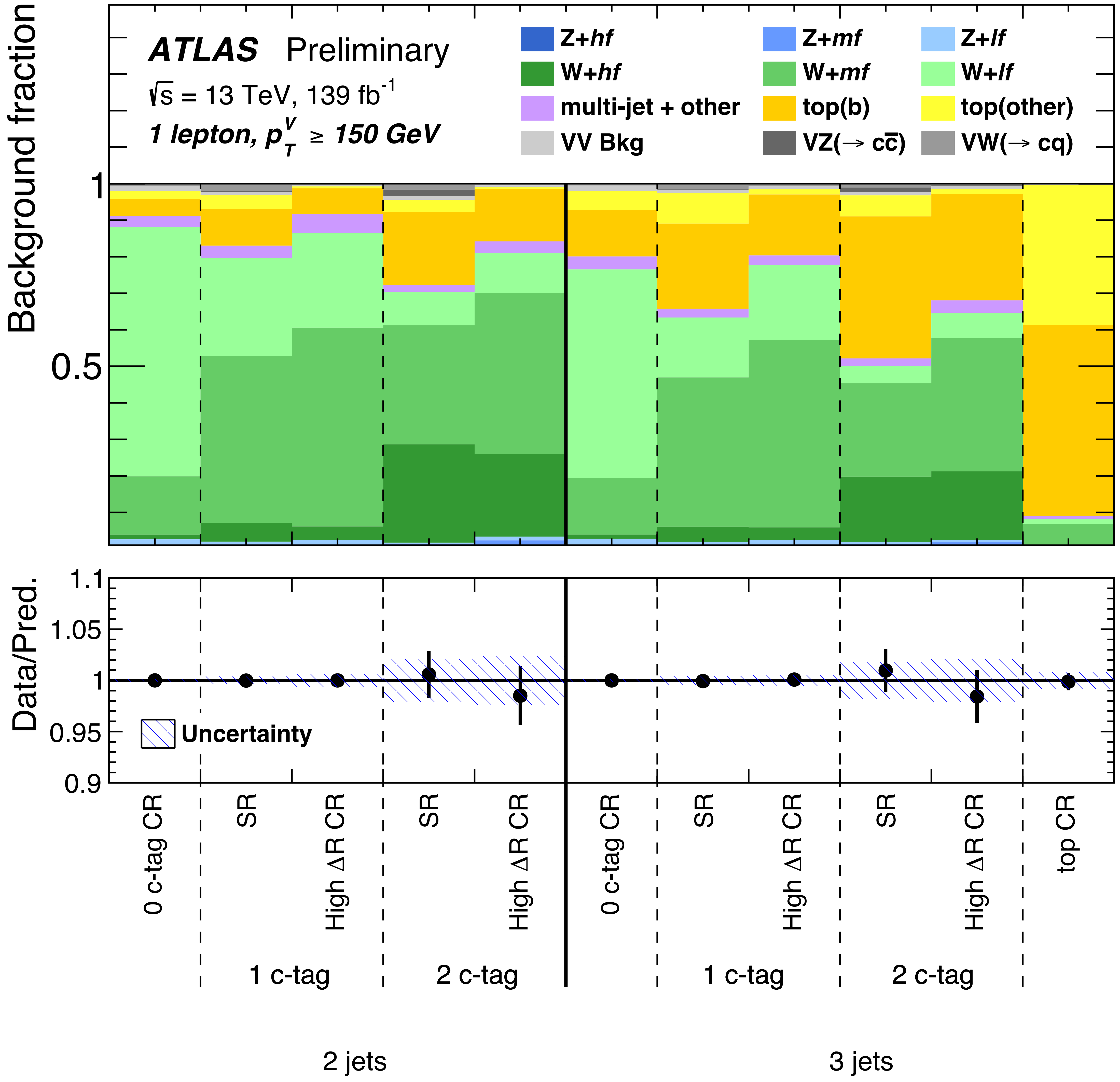
	τ-jets	0.3	0.01	0.04
Truth-flavour tagging	ΔR correction	3.3	0.03	0.10
	Residual non-closure	1.7	0.03	0.10

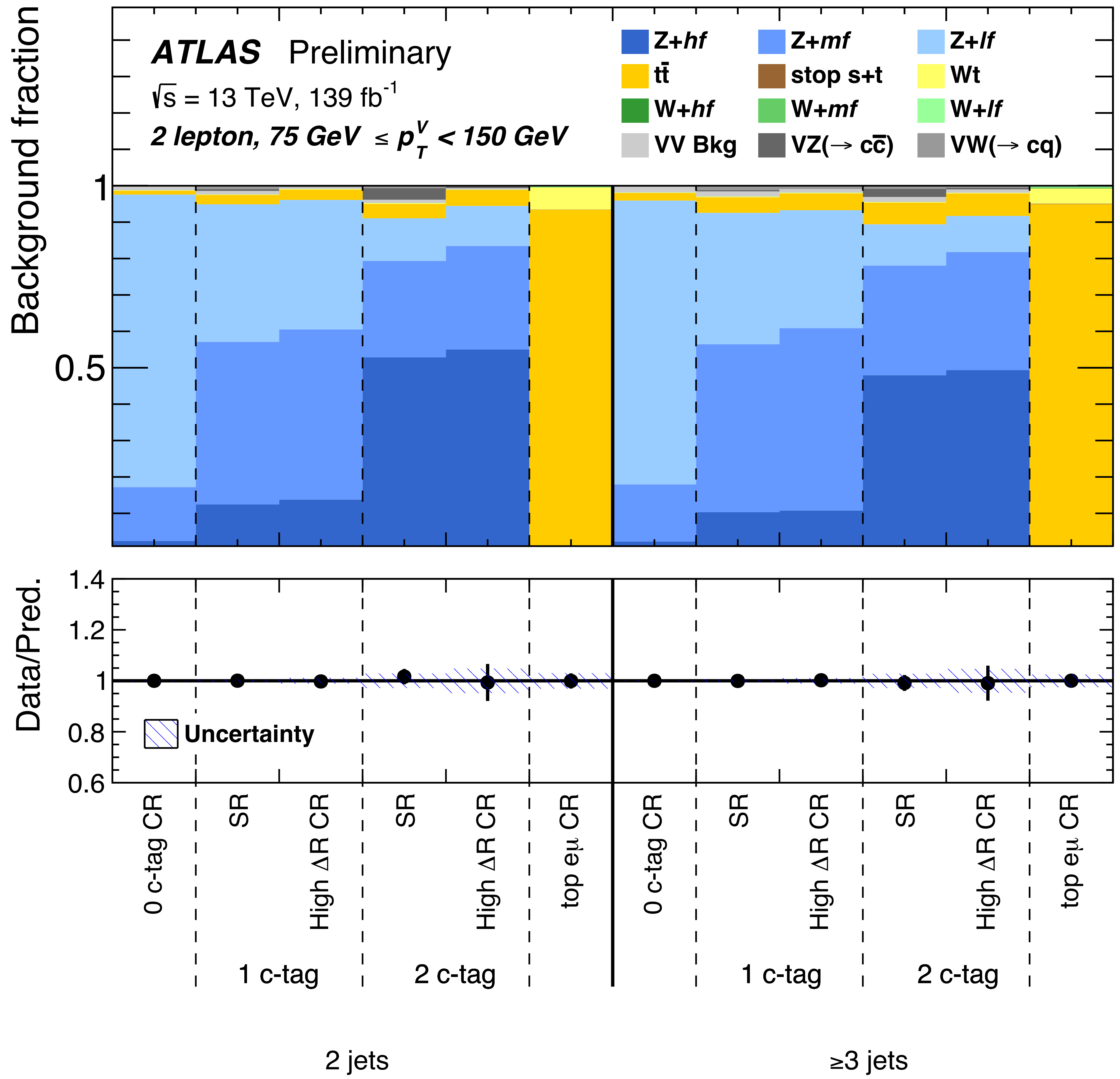
Background composition plots: postfit 0-lepton

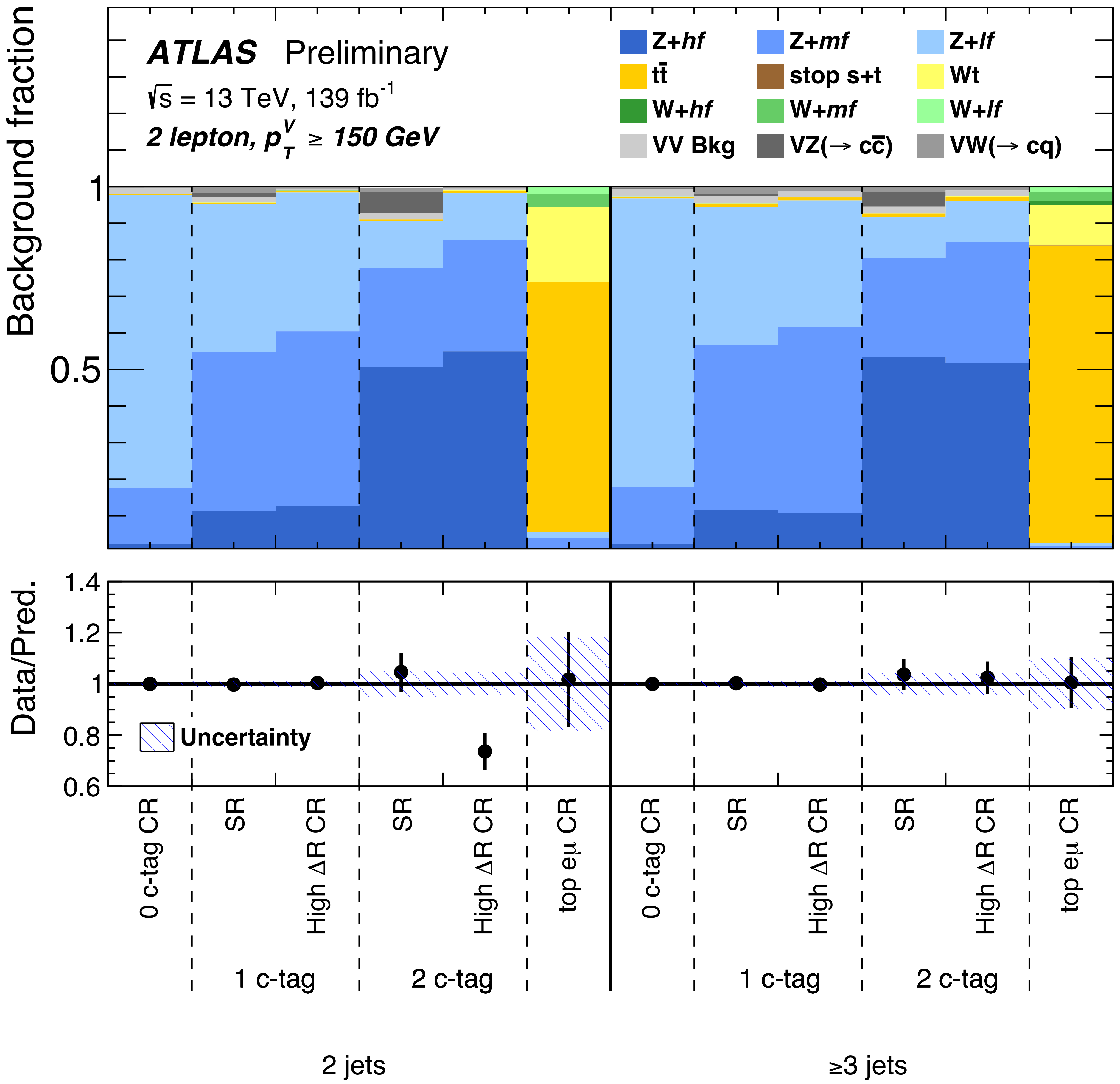


Background composition plots: postfit 1-lepton



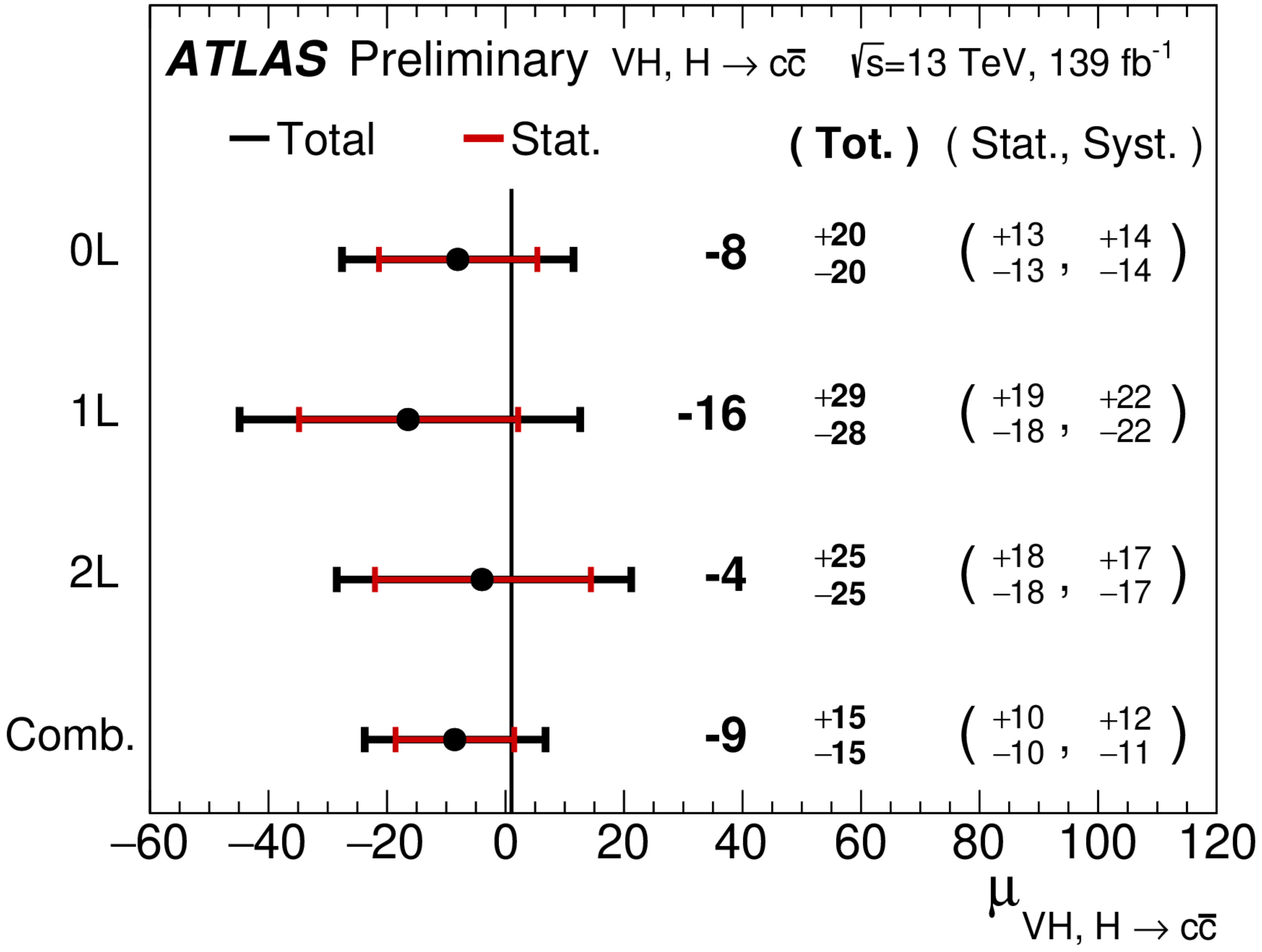
Background composition plots: postfit 2-lepton



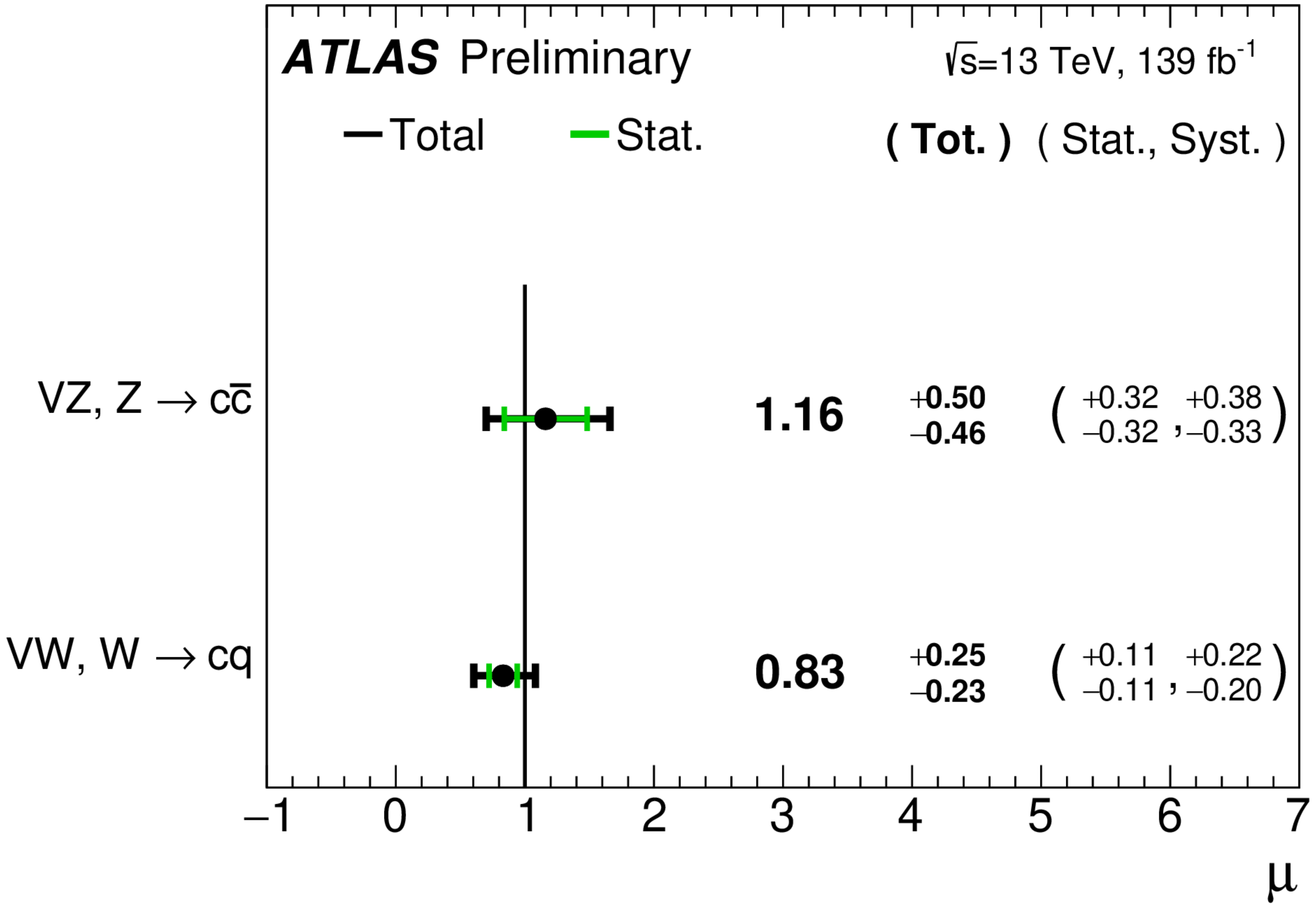


Results: signal strength

VH(cc) POI



VZ(cc) and VW(cq) POI



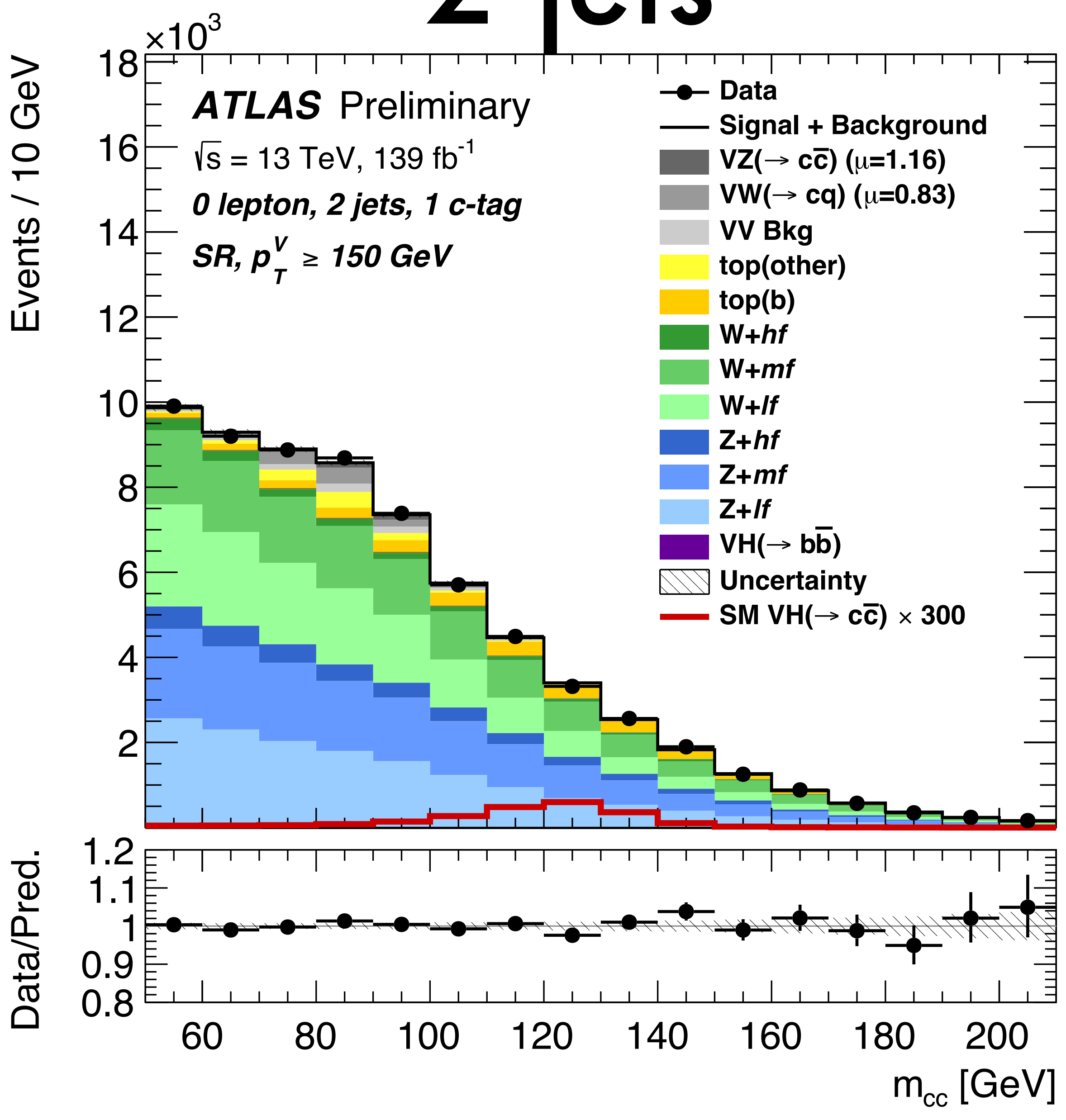
Postfit SR

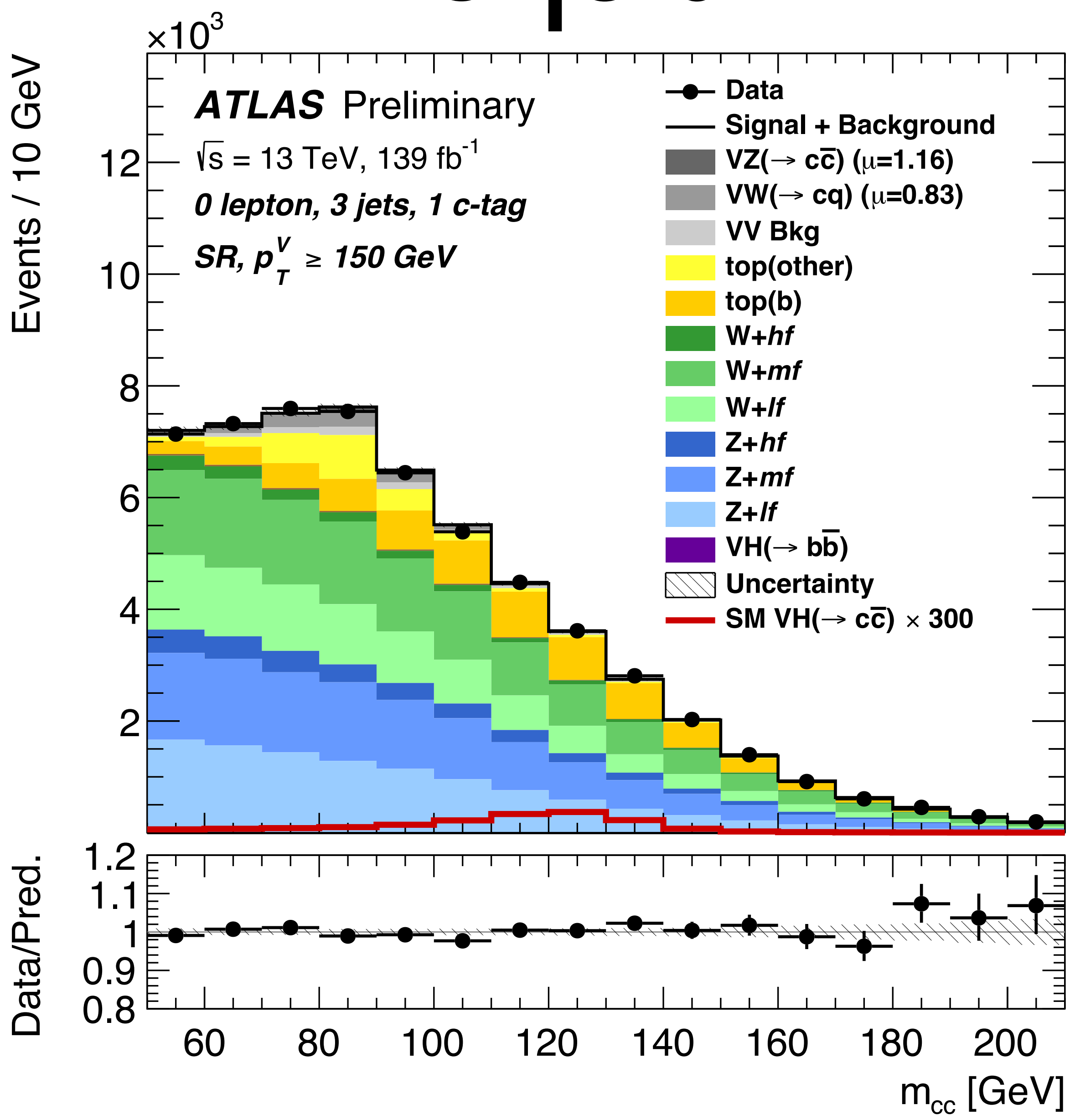
Postfit distributions: 0-lepton

2 jets

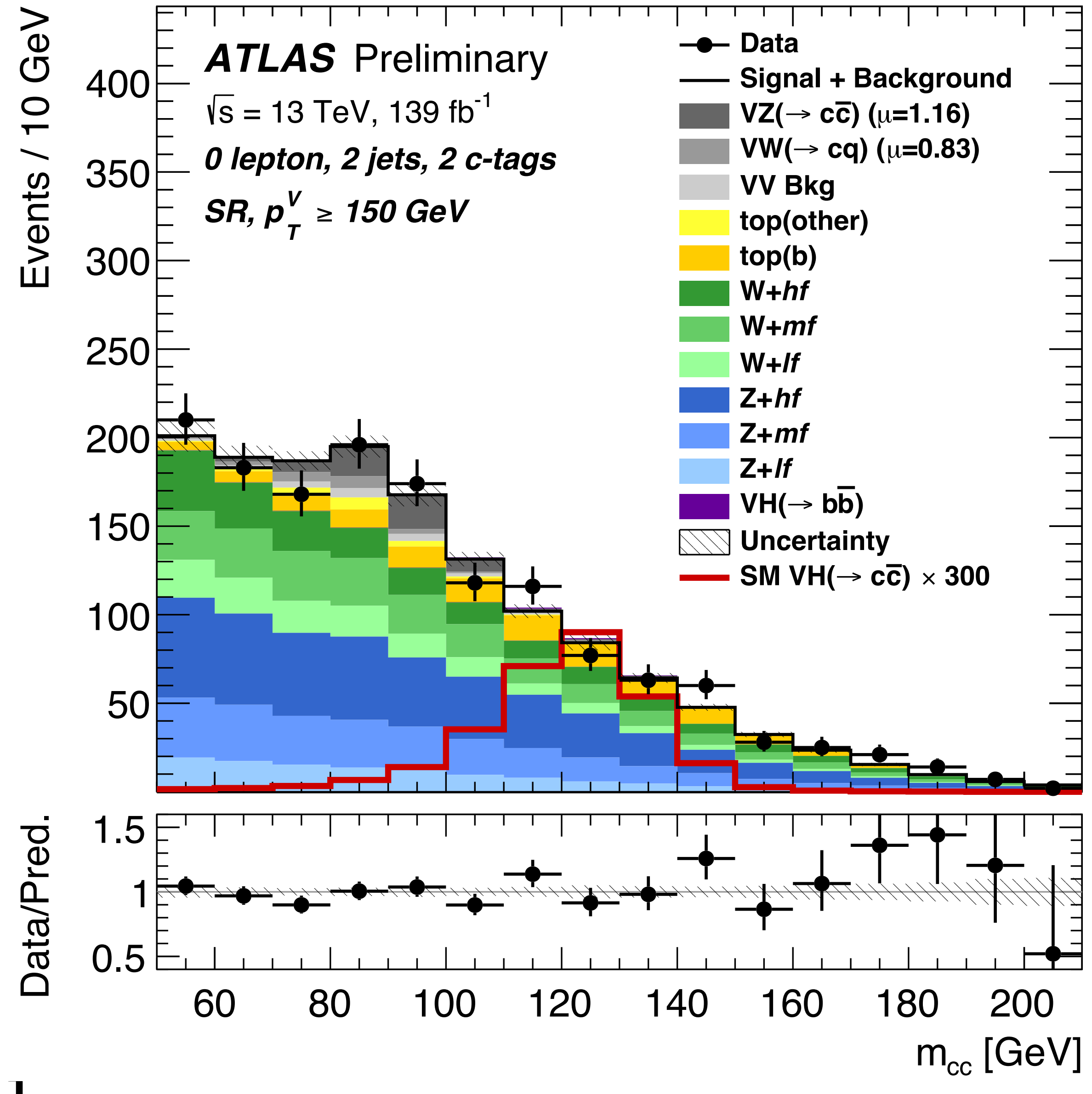
3 jets

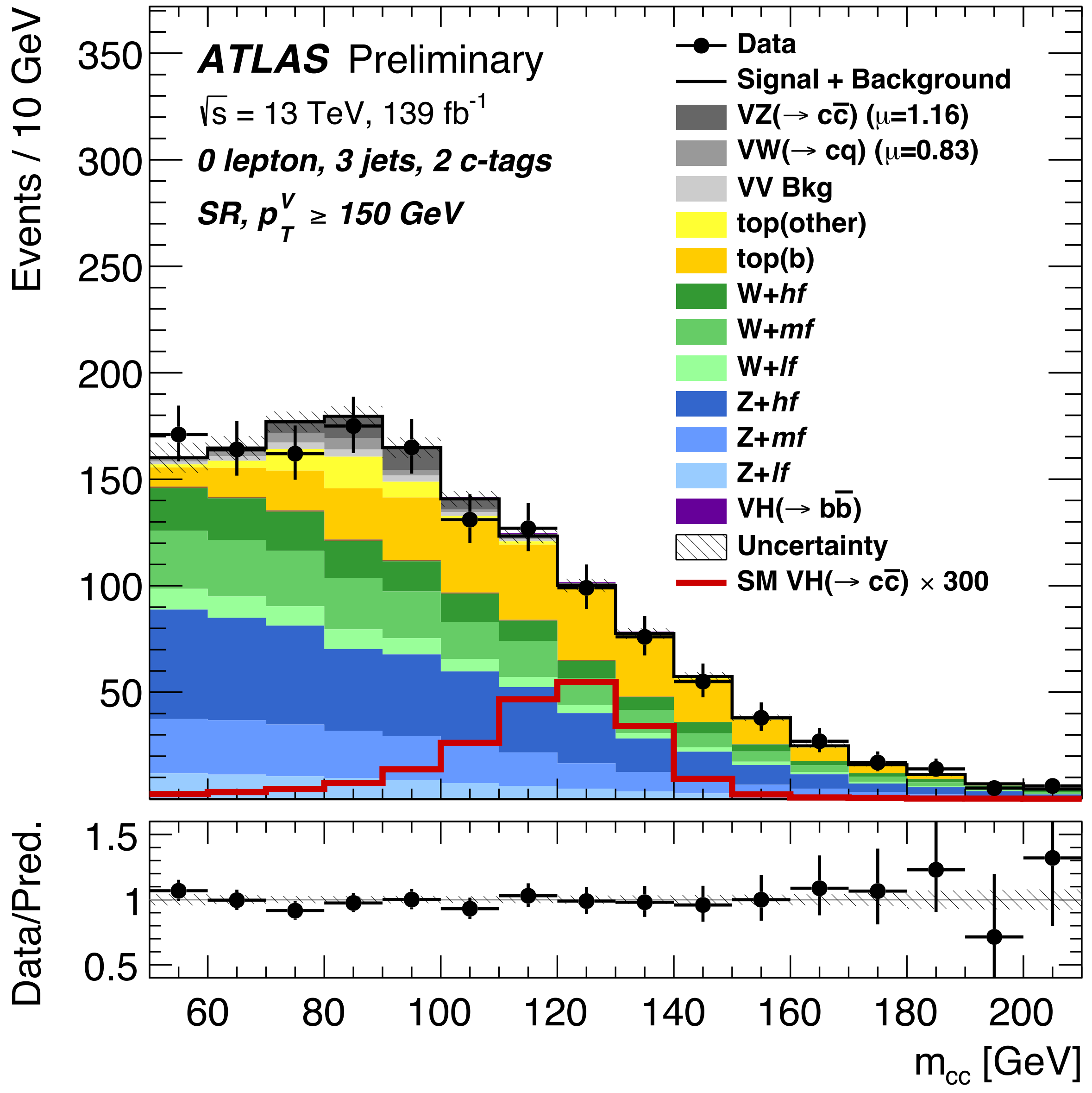
1 c-tag





2 c-tag





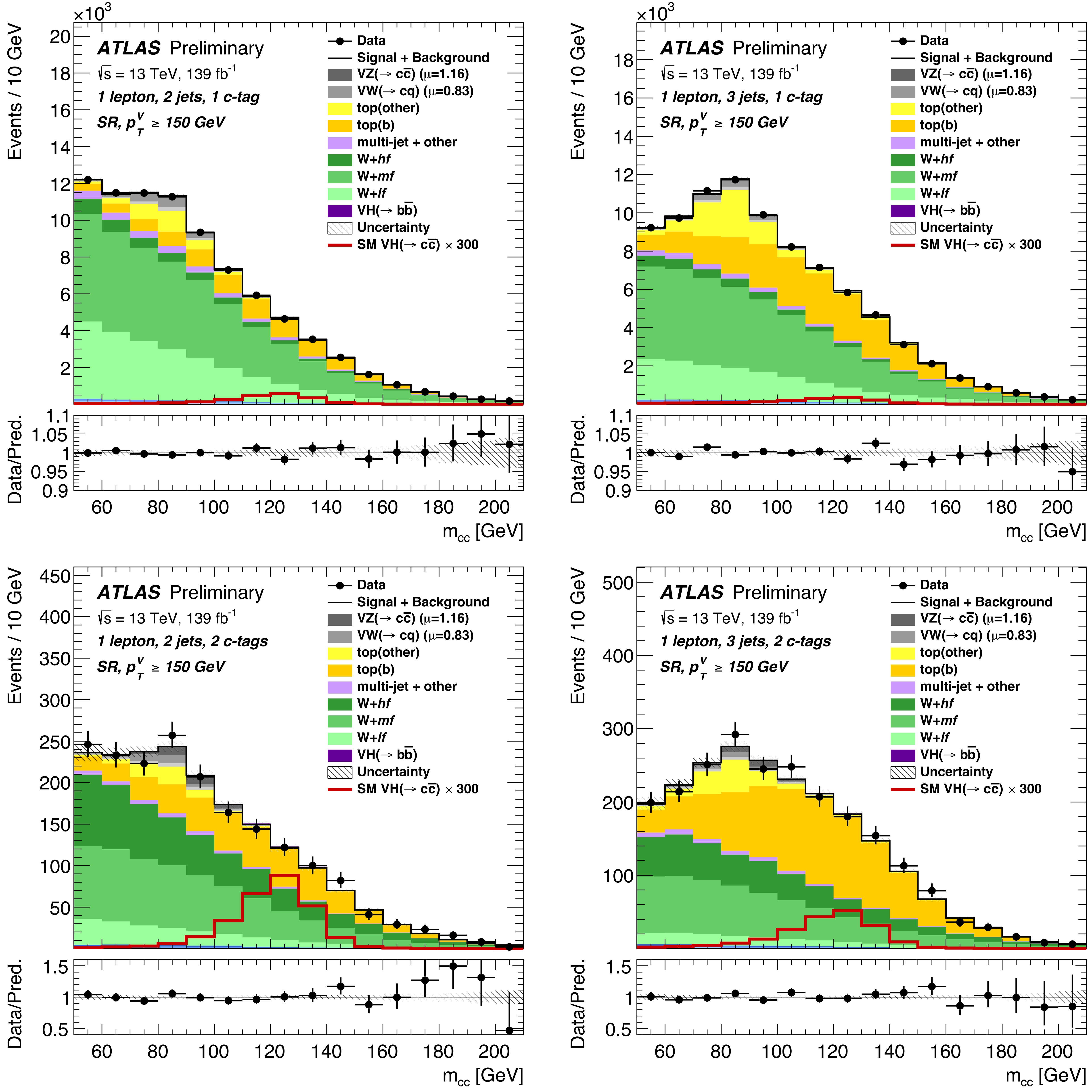
Postfit distributions: 1-lepton

2 jets

3 jets

1 c-tag

2 c-tag



Postfit distributions: 2-lepton

75 GeV < pTV < 150 GeV

pTV > 150 GeV

2 jets

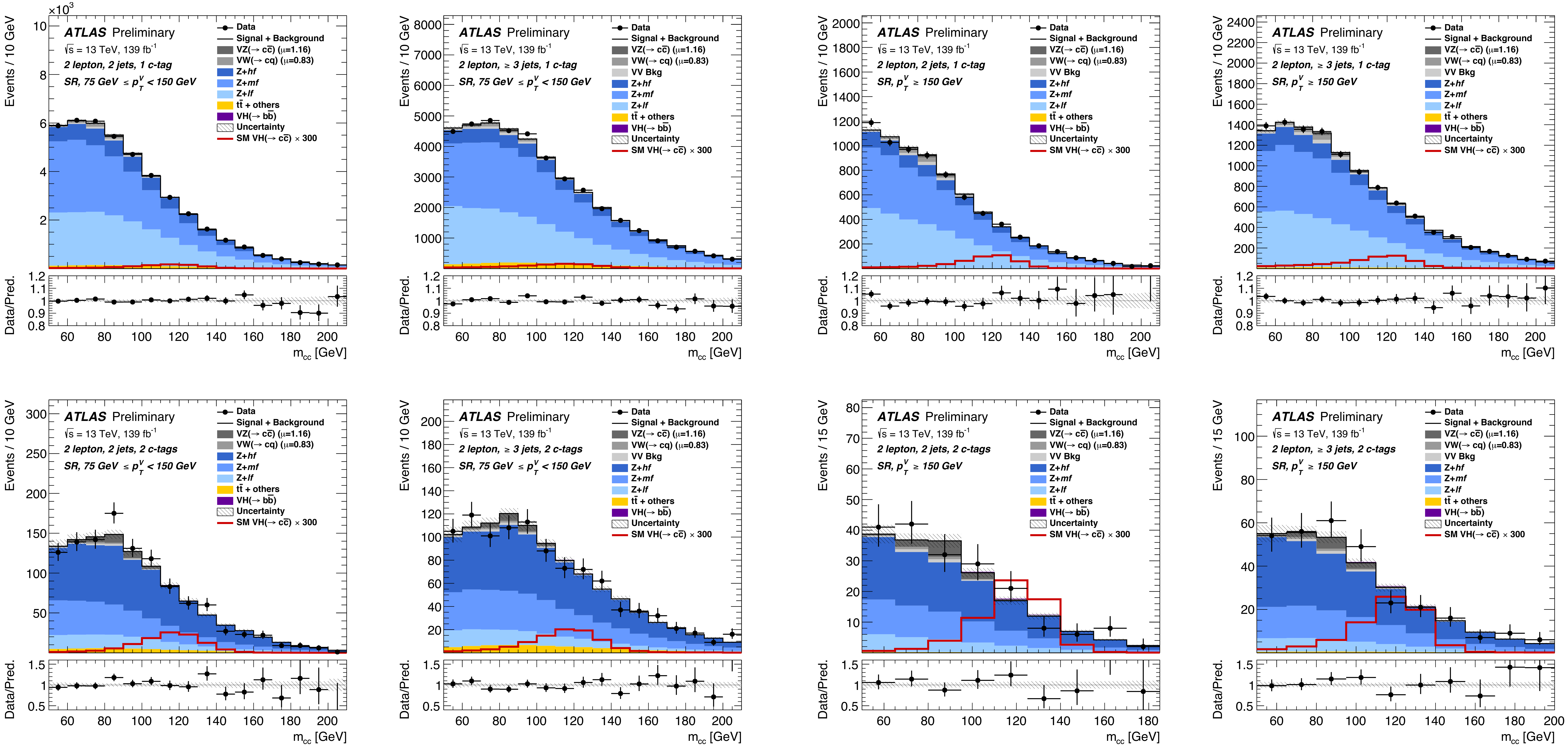
3+ jets

2 jets

3+ jets

1 c-tag

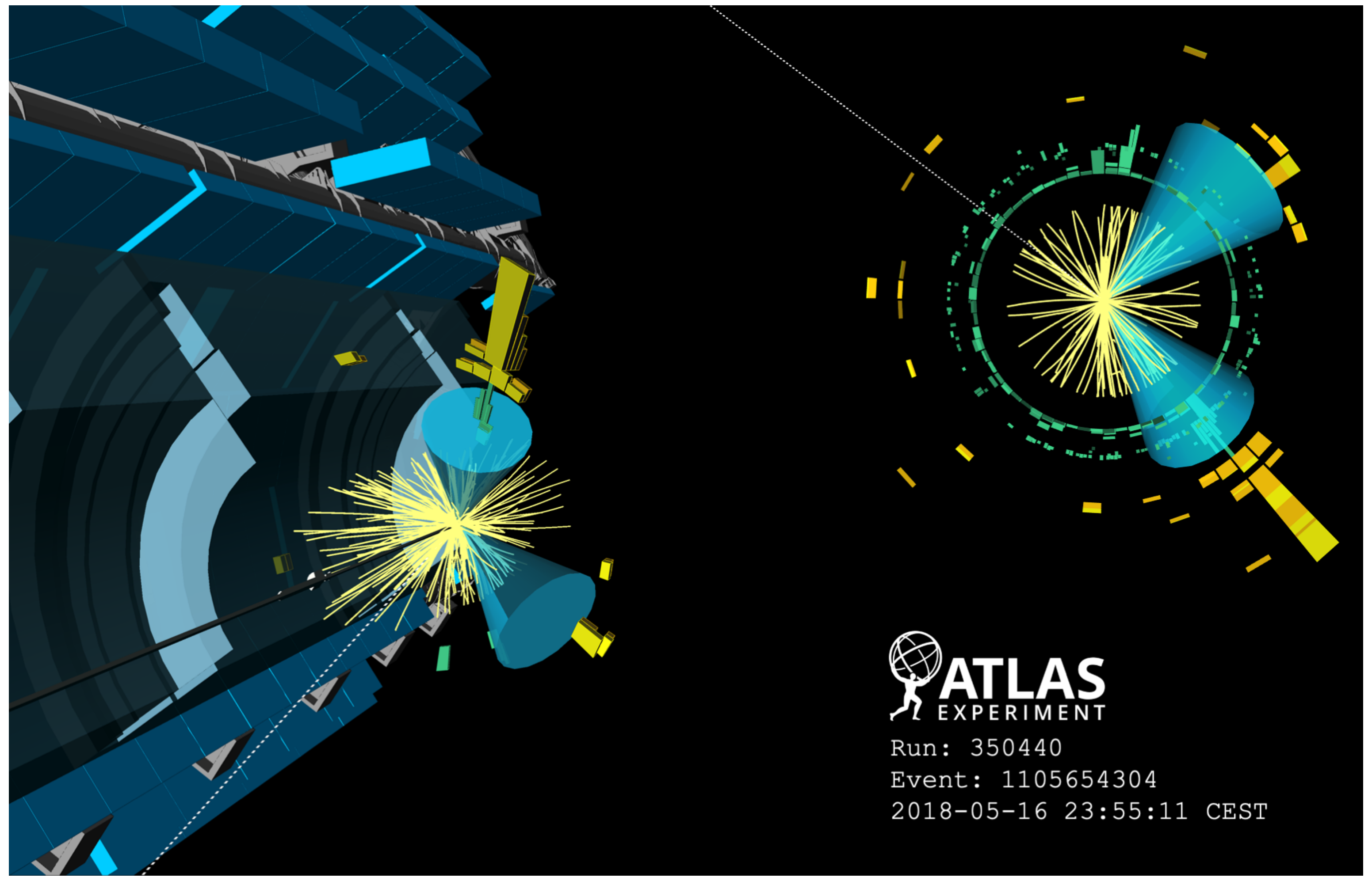
2 c-tag



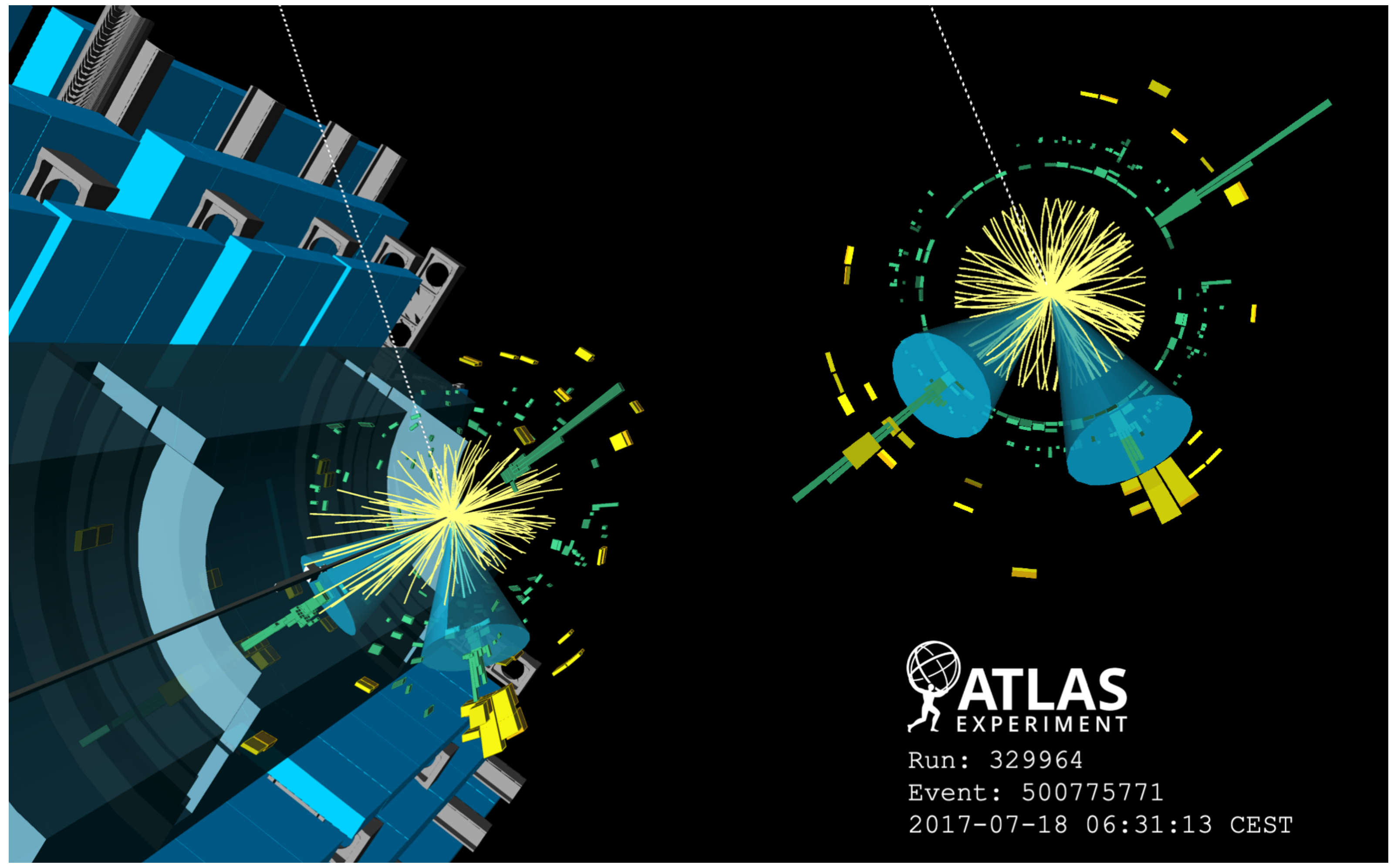
Event displays

Event displays

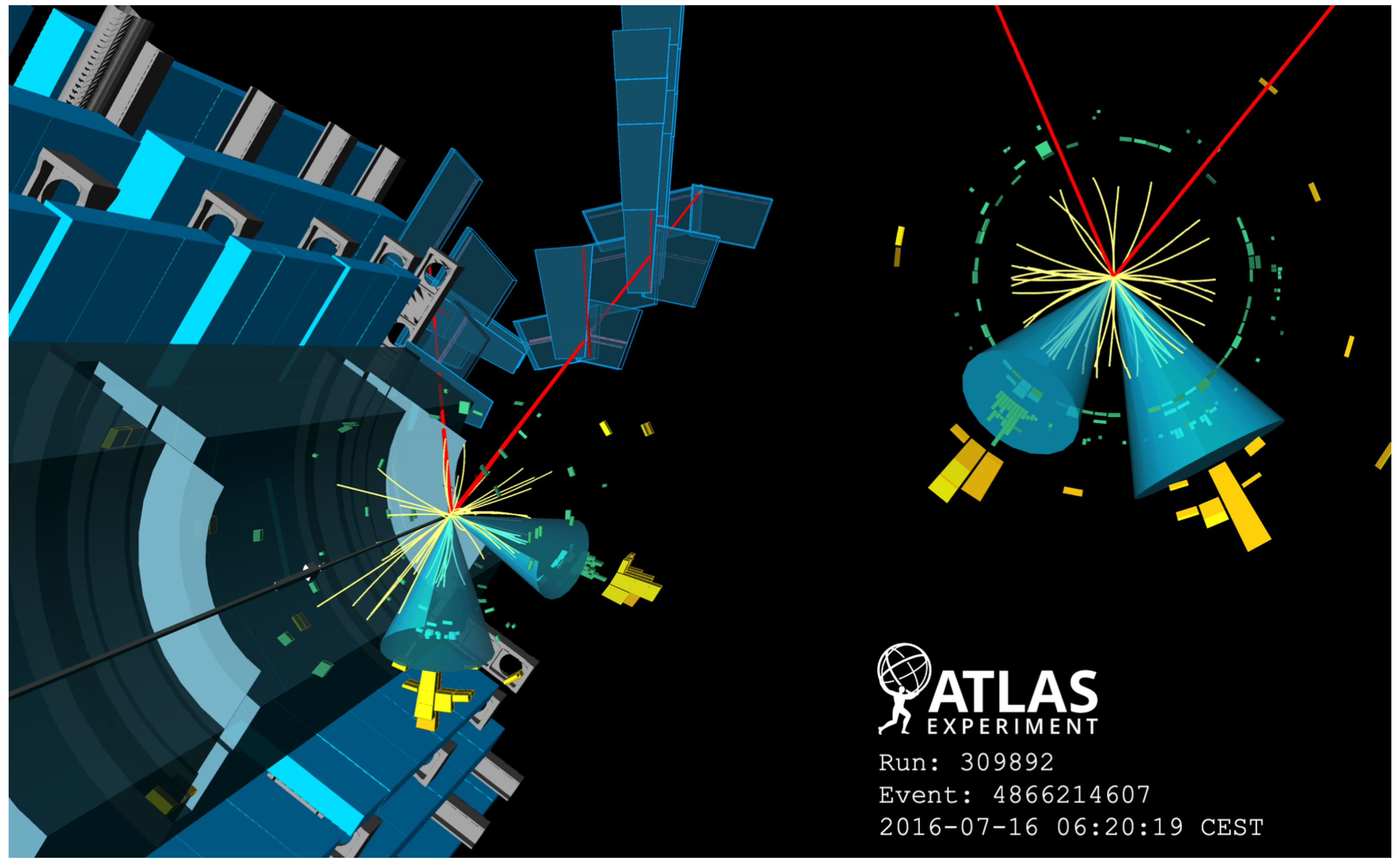
0-lepton



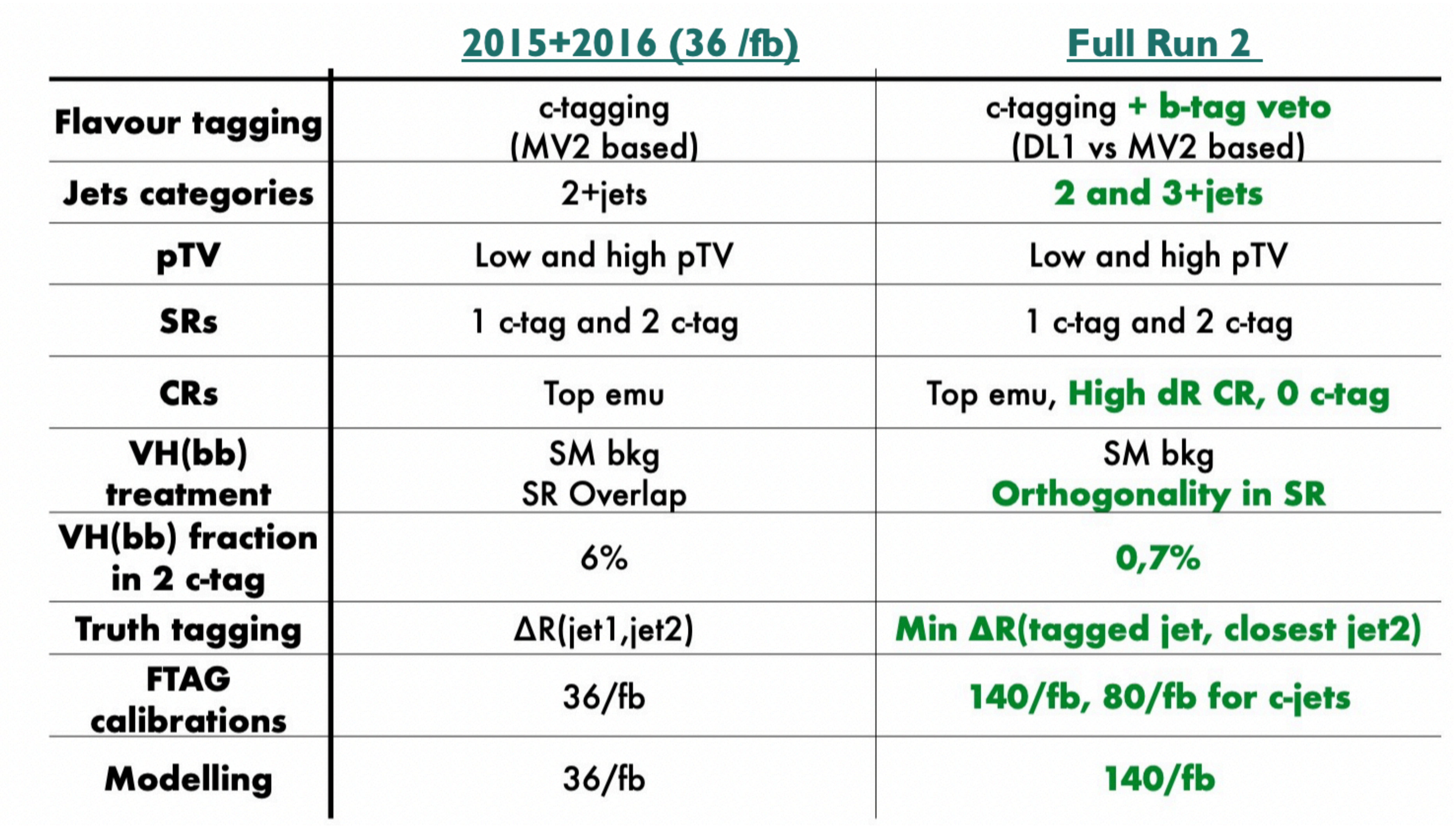
1-lepton



2-lepton



Comparison VHcc 139/fb vs ZHcc 36/fb



	2015+2016 (36 /fb)	Full Run 2
Flavour tagging	c-tagging (MV2 based)	c-tagging **+ b-tag veto** (DL1 vs MV2 based)
Jets categories	2+jets	**2 and 3+jets**
pTV	Low and high pTV	Low and high pTV
SRs	1 c-tag and 2 c-tag	1 c-tag and 2 c-tag
CRs	Top emu	Top emu, **High dR CR, 0 c-tag**
VH(bb) treatment	SM bkg SR Overlap	SM bkg **Orthogonality in SR**
VH(bb) fraction in 2 c-tag	6%	**0,7%**
Truth tagging	ΔR(jet1,jet2)	**Min ΔR(tagged jet, closest jet2)**
FTAG calibrations	36/fb	**140/fb, 80/fb for c-jets**
Modelling	36/fb	**140/fb**