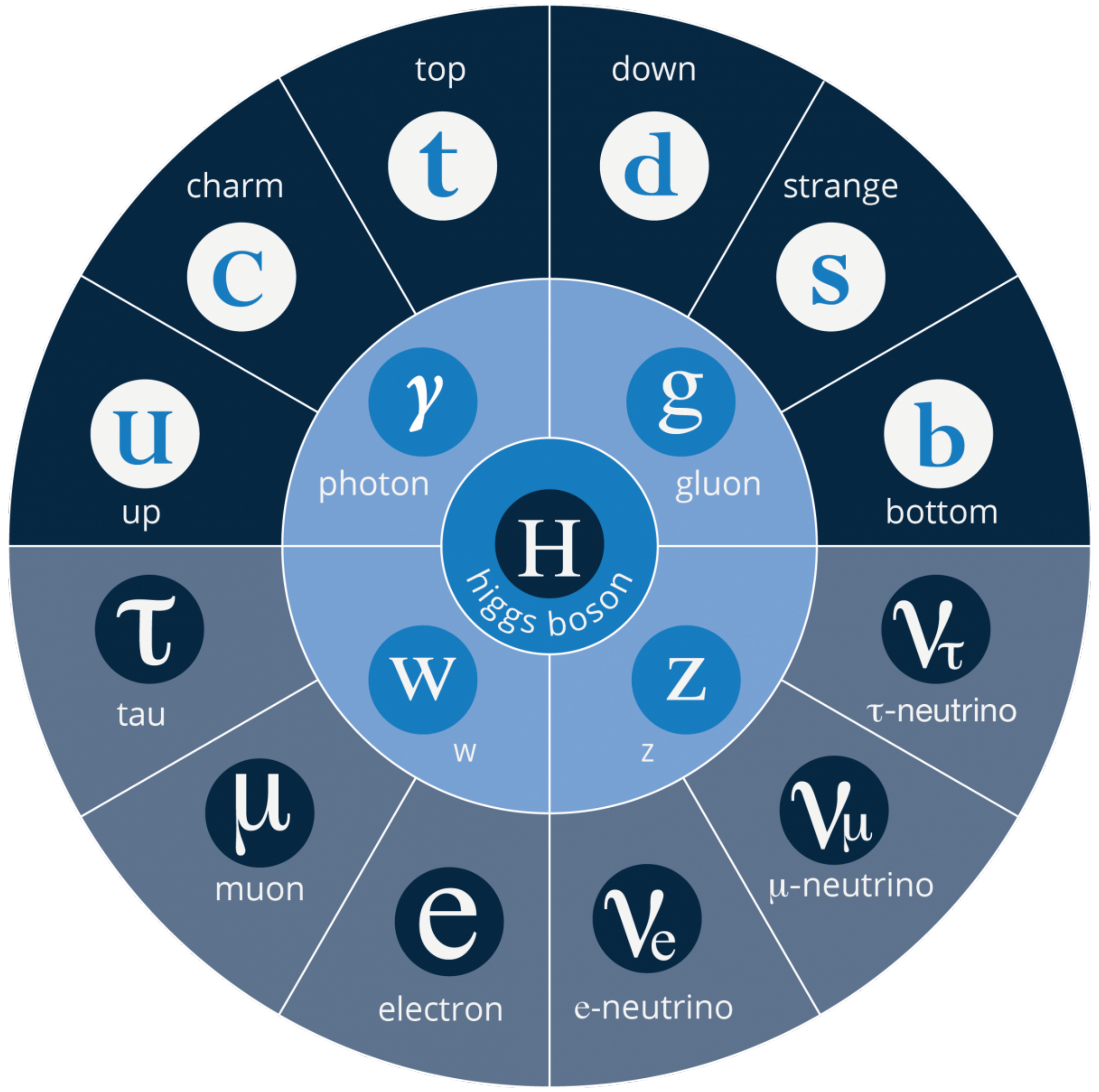
Charming Higgs bosons

Direct constraint on the Higgs-charm coupling with the ATLAS detector

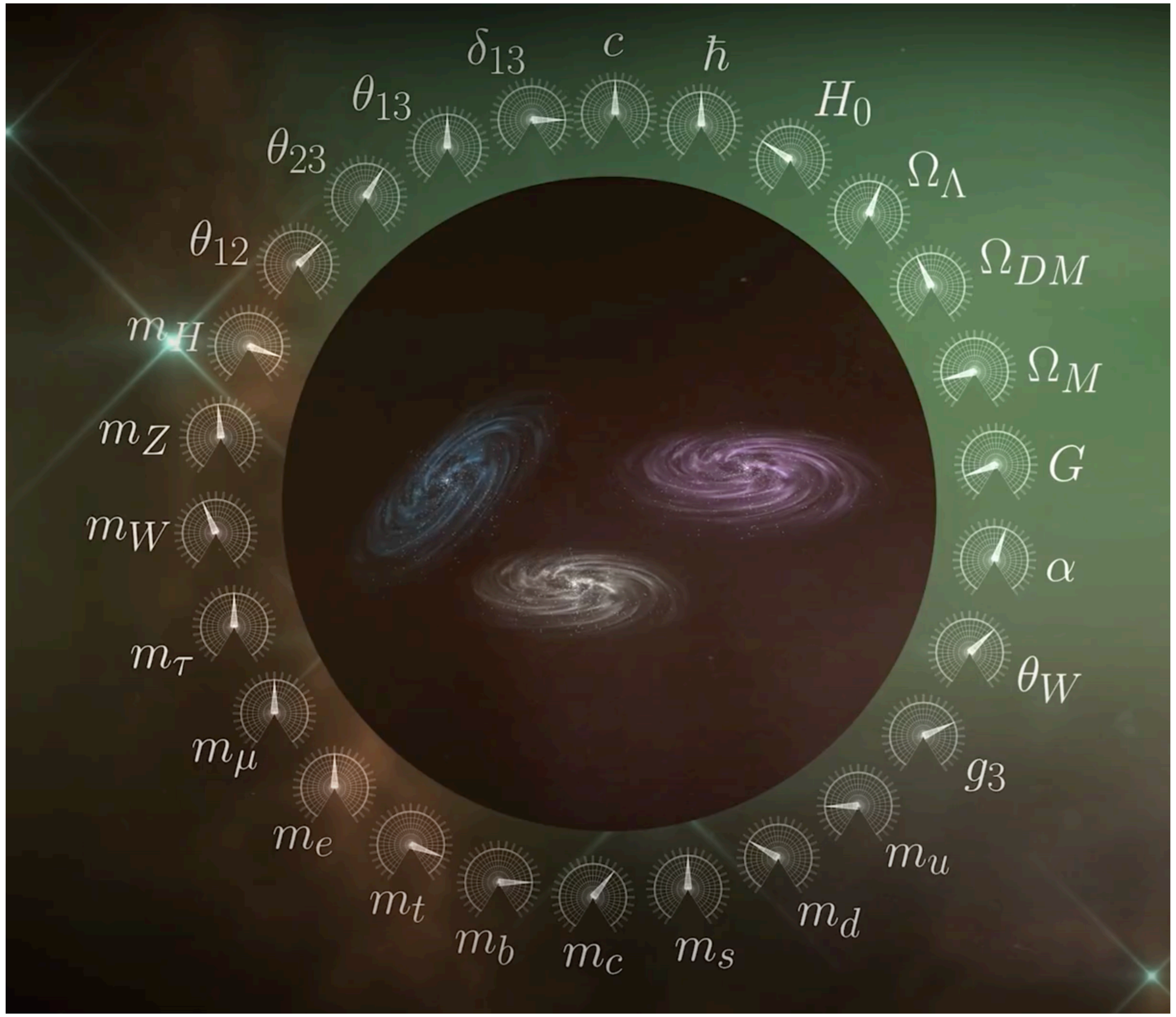


University of Zurich, 11.10.2021

Marko Stamenkovic

Fundamental constants of nature

Image credit: PBS space time

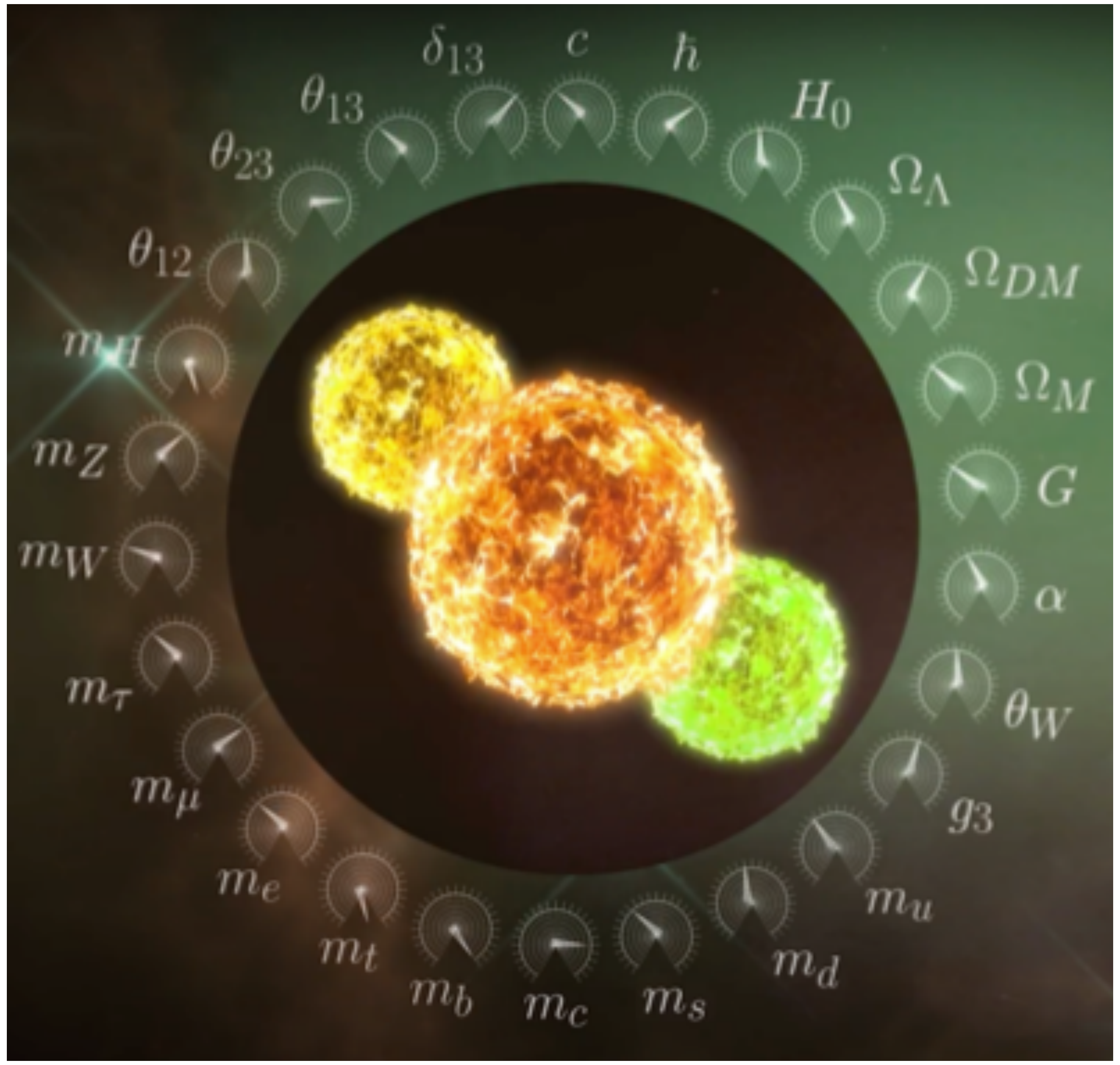


Standard Model and General Relativity = dynamical theories
→ Rely on free parameters measured experimentally!

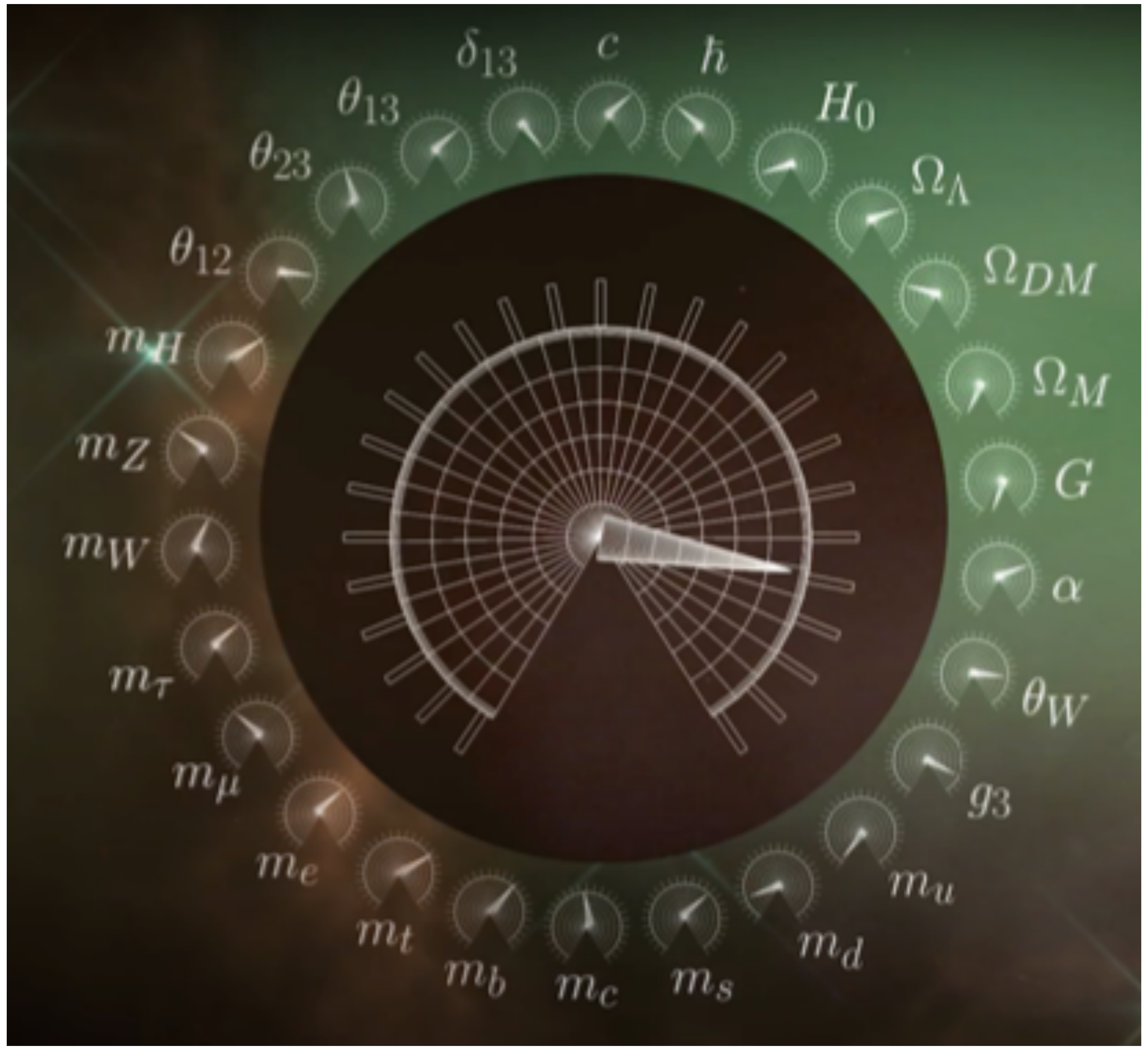
Fundamental constants of nature

Image credit: PBS space time

Random values?



Underlying theory?



Increasingly clear that these free parameters have a *good* value

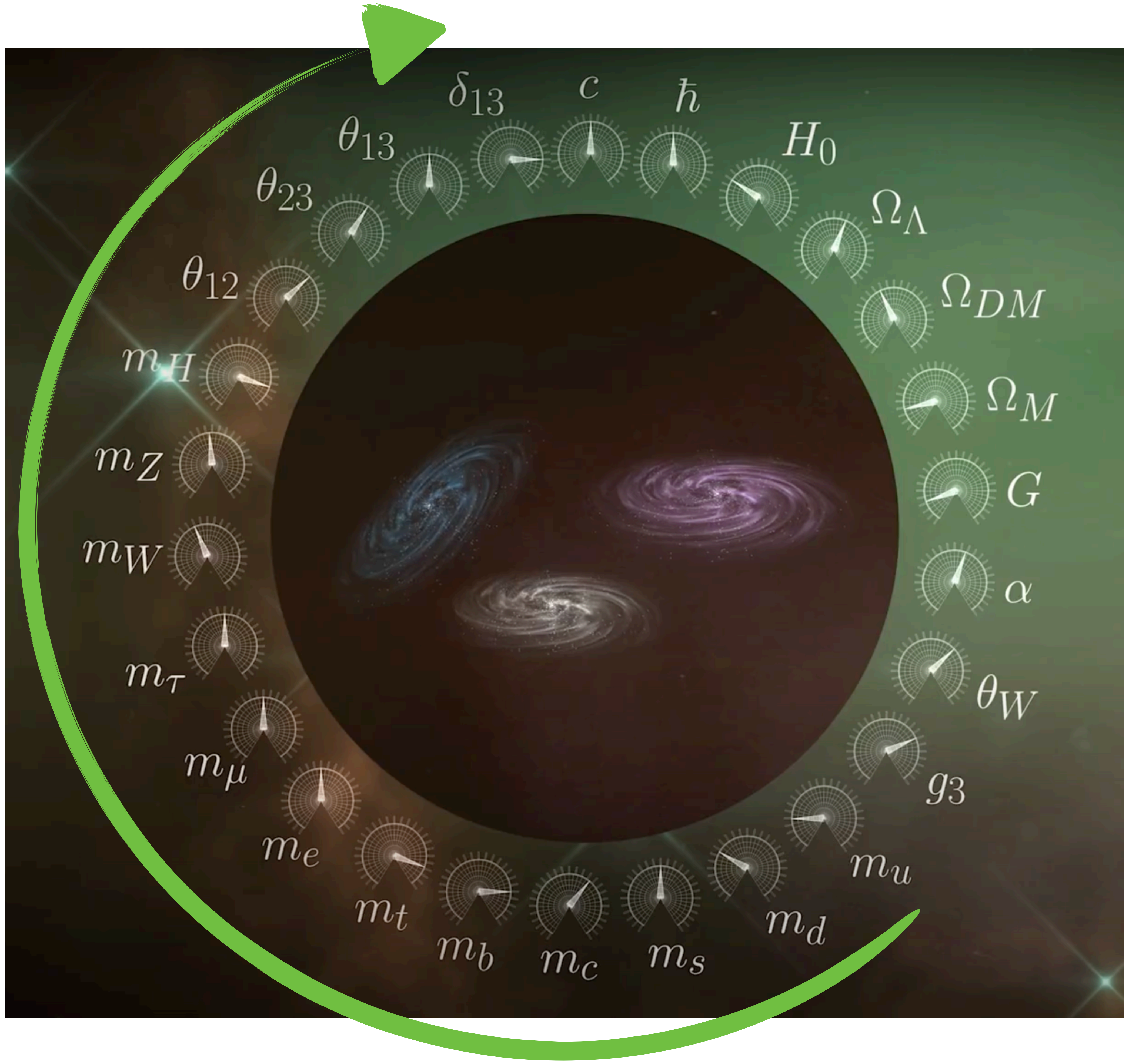
- Are the values randomly chosen?
- Is there an underlying unified theory to explain them?

→ Need to measure each parameters in many ways!

Fundamental constants of nature

Image credit: PBS space time

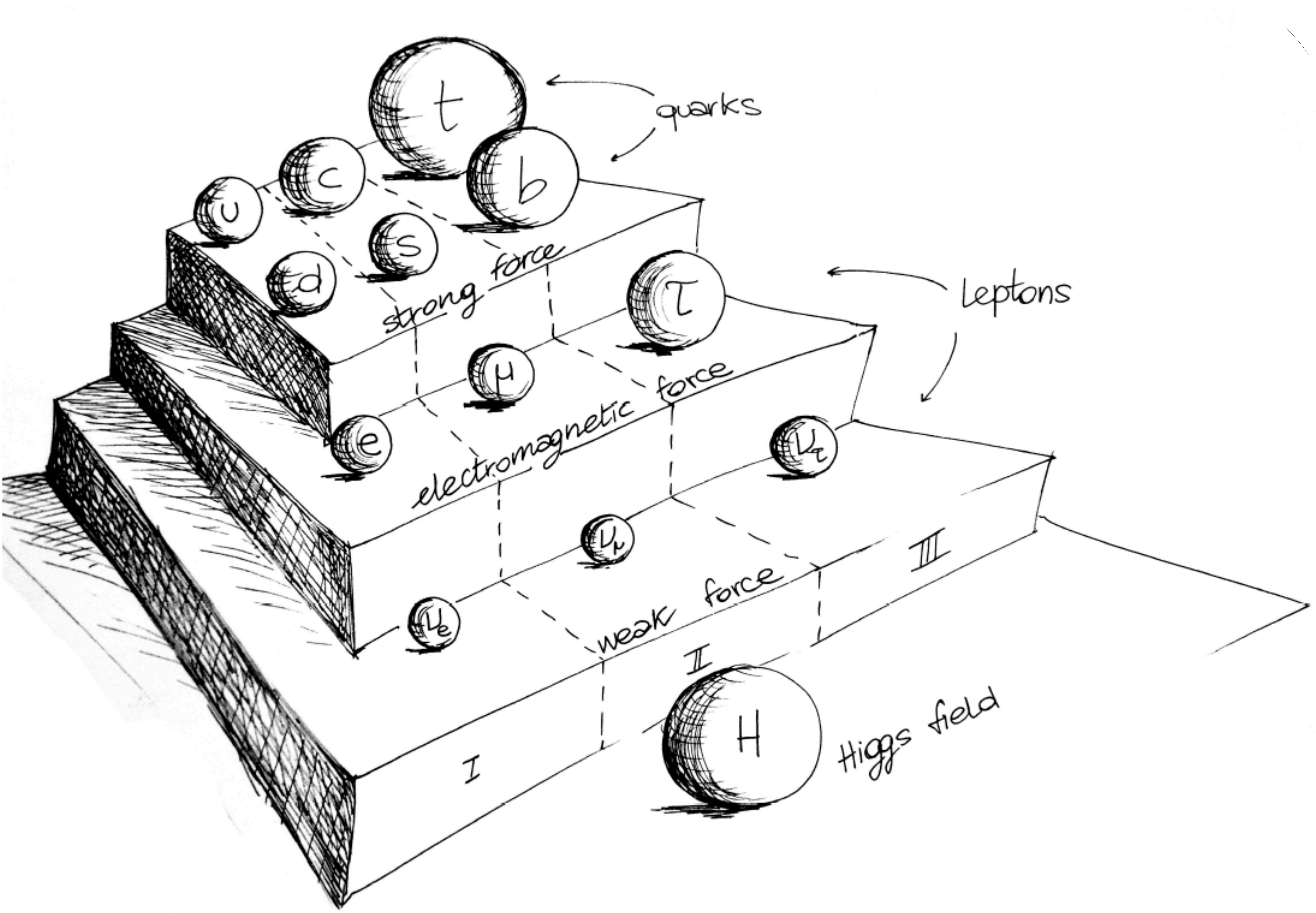
Depends on Higgs mechanism



Most of the free parameters related to Higgs mechanism
→ Studied in details experimentally

Fermions mass pattern

Image credit: S. Oggiro



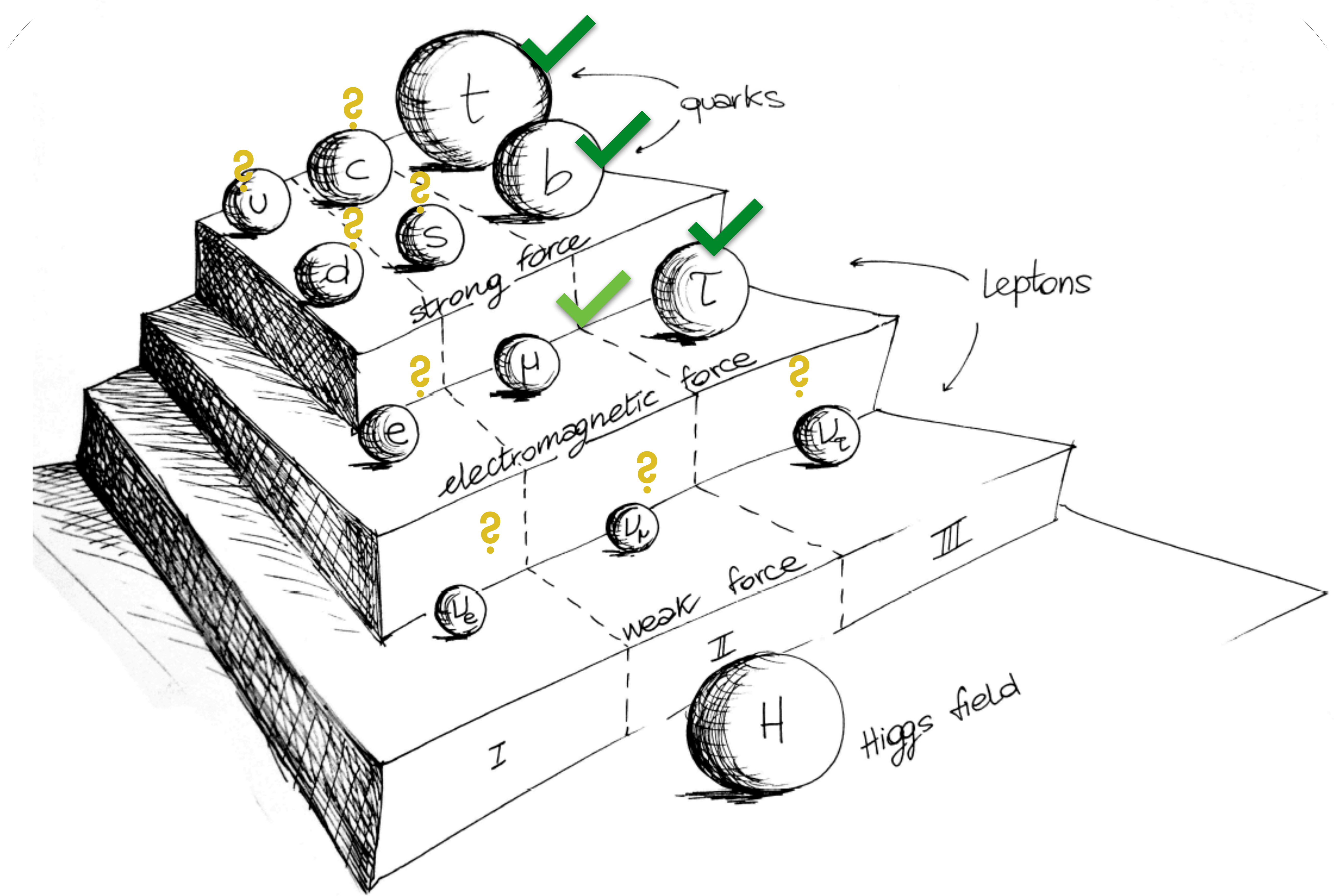
3 generations of fermions only distinguishable through their mass

- Theory: Higgs boson coupling proportional to mass of fermions

Do all particles get their mass from Higgs mechanism?

Fermions mass pattern

Image credit: S. Oggiro



Experimental observations of Higgs boson coupling to 3rd generation

Evidences of Higgs coupling to muons

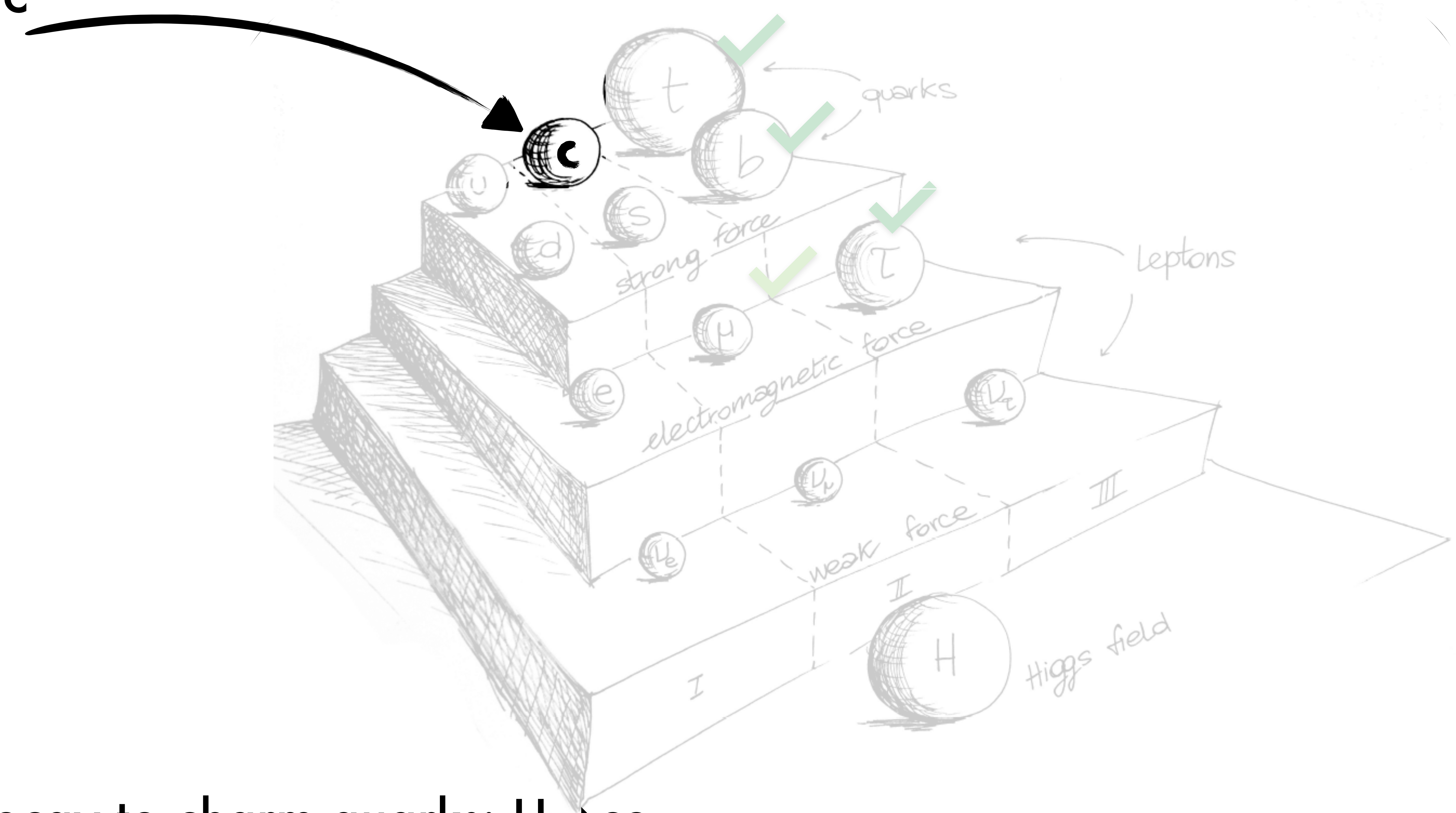
→ Compatible with the SM predictions

Currently no experimental proof that Higgs boson couples to other particles

Fermions mass pattern

Image credit: S. Oggiro

H→cc



Higgs decay to charm quarks: H→cc

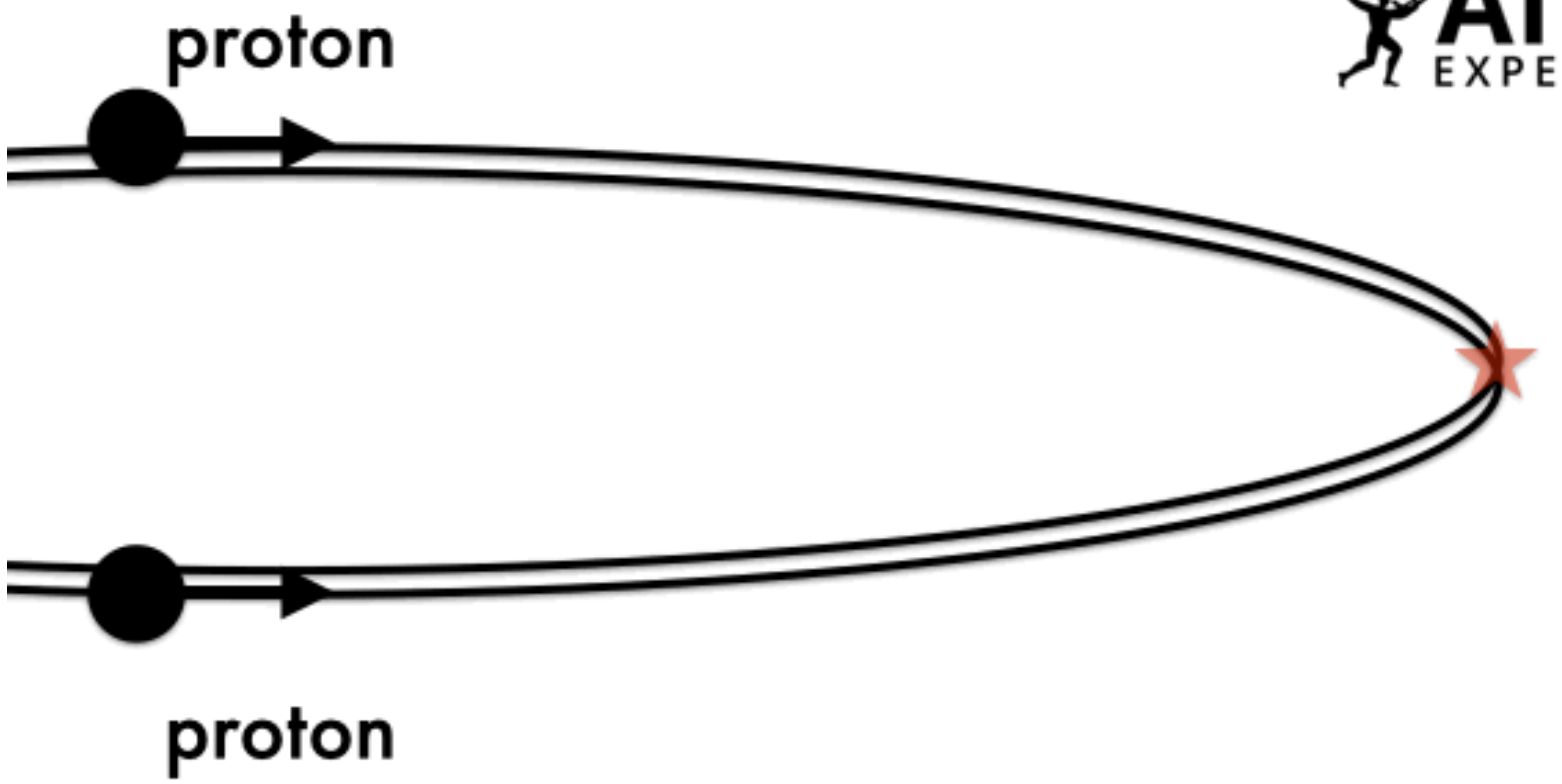
- Probes Higgs coupling to 2nd generations of quarks
- Next heaviest fermion: BR(H→cc) ≈ 3%
- Challenge: identification of c-quarks in the detector!
- Enhanced coupling to c-quarks → sign of new physics

How to measure H→cc

Large Hadron Collider

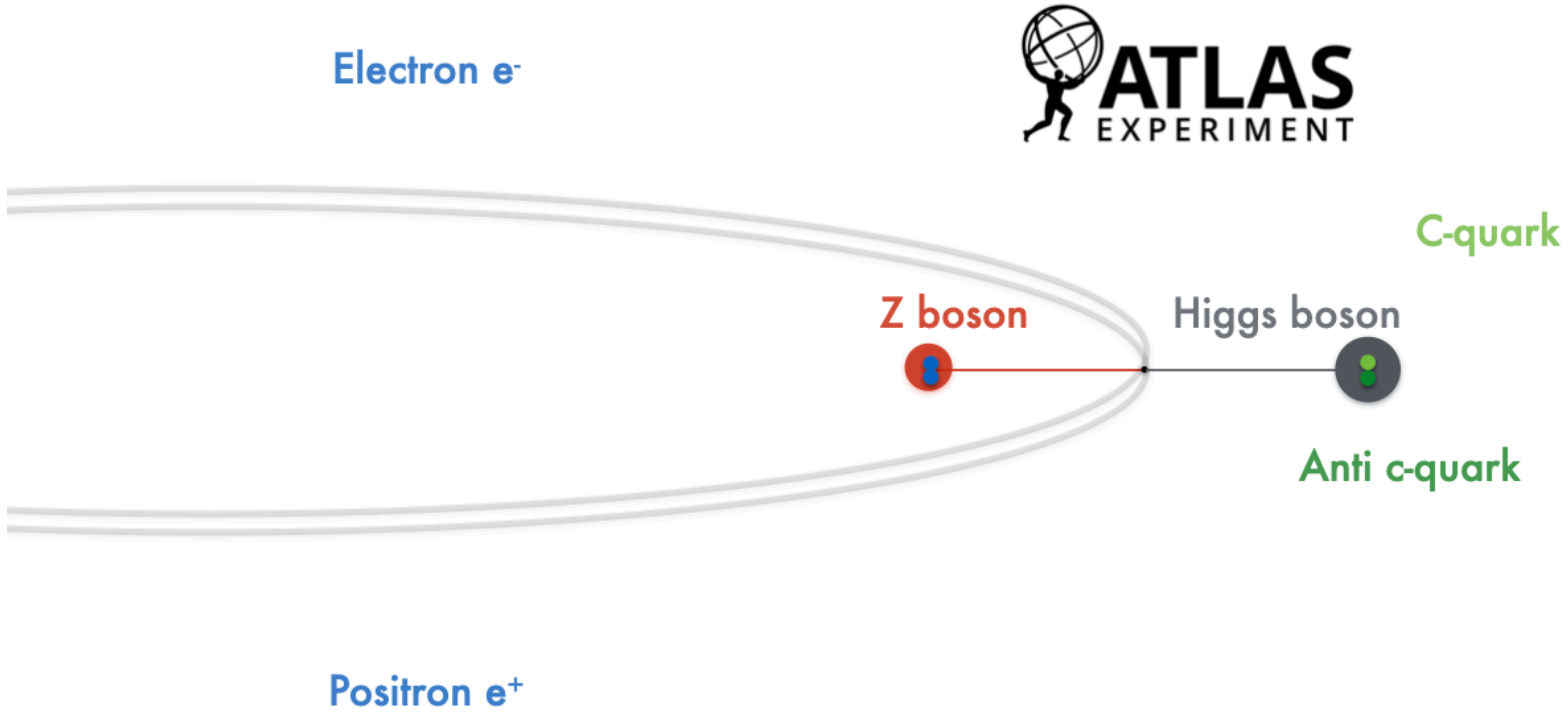
CERN

ATLAS
EXPERIMENT



How to measure H→cc

Large Hadron Collider



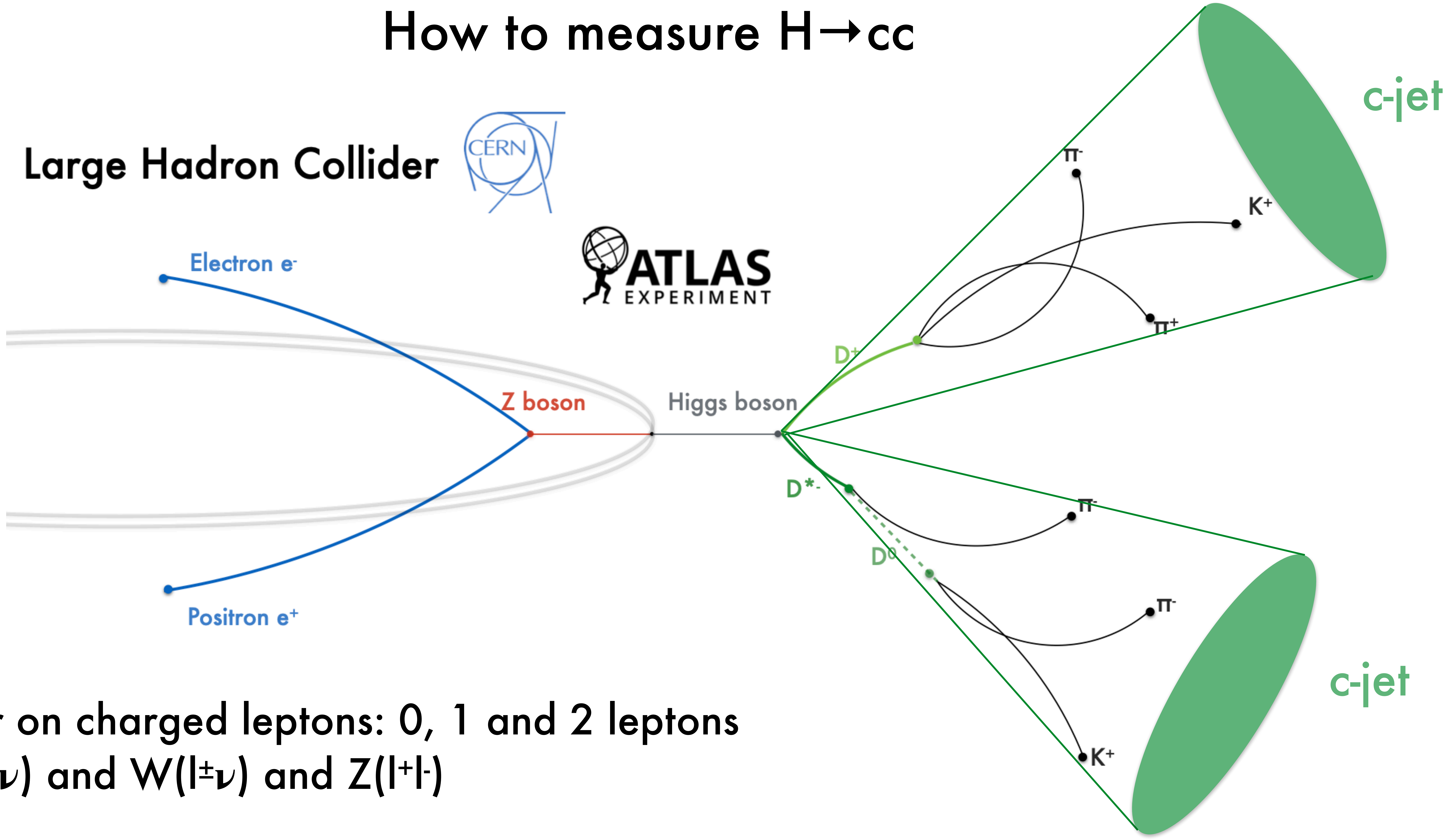
Production mode: Higgs associated with Z or W boson decay to leptons

- Trade-off: smaller production cross-section but cleaner signature to trigger

Quark hadronise when produced → Measure decay products of hadrons

How to measure $H\to cc$

Large Hadron Collider



Trigger on charged leptons: 0, 1 and 2 leptons

- $Z(\nu\nu)$ and $W(l^{\pm}\nu)$ and $Z(l^+l^-)$

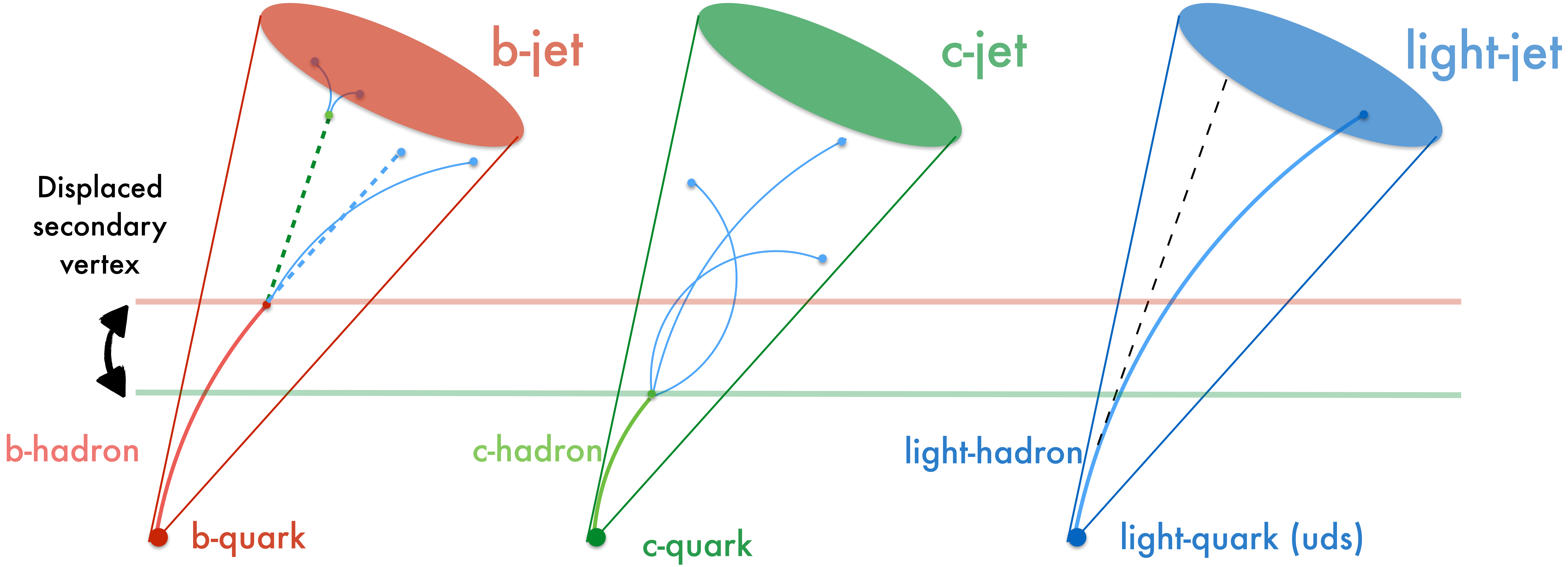
Reconstructed 2 or more jets from the Higgs boson decay

Run: 364214

Event: 117339266

2018-10-23 01:54:02 CEST During one of my ID shift

Charm tagging

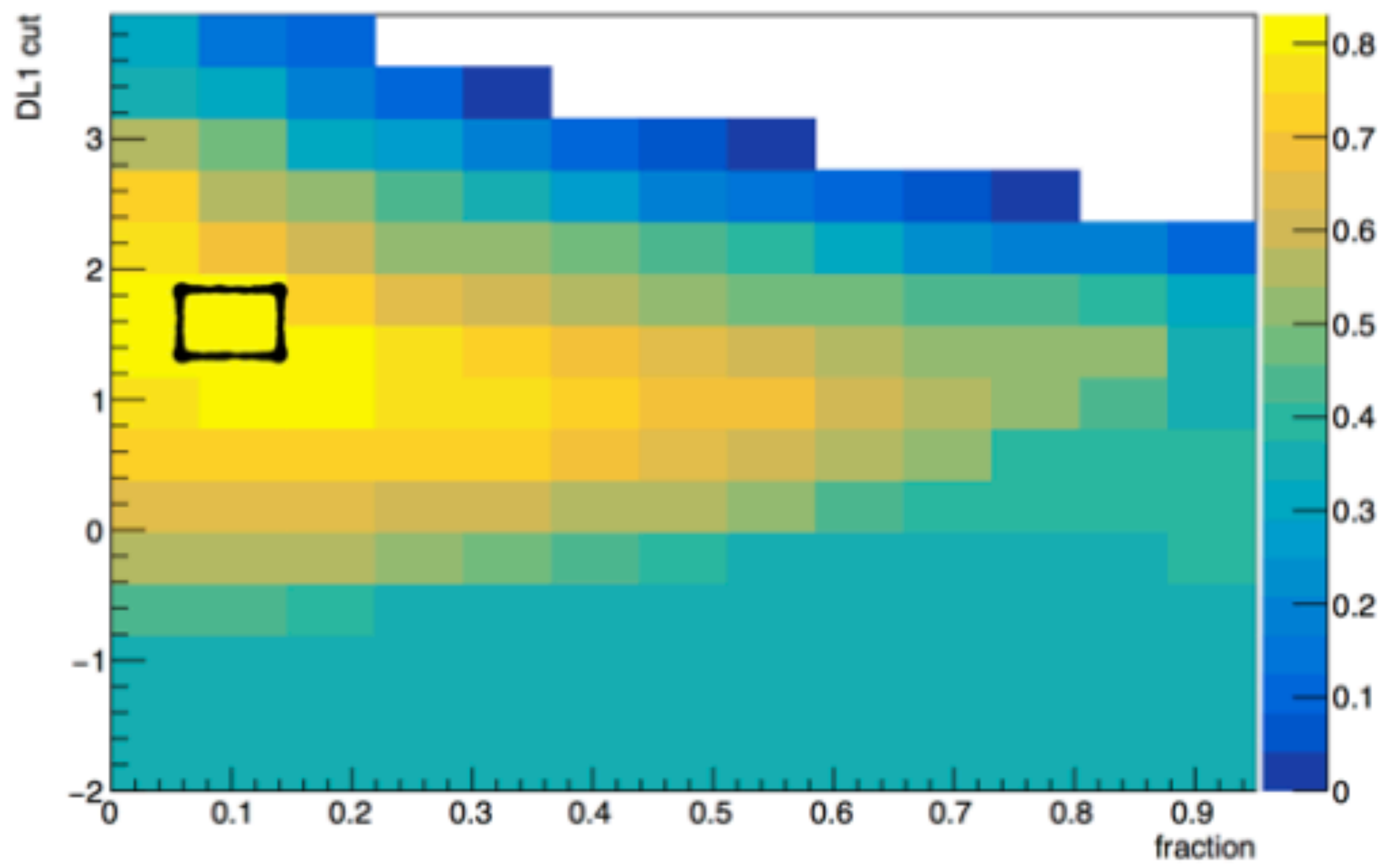


Charm tagging: identification of the flavour of the hadron inside the jet

- Exploit lifetime and mass properties of heavy hadrons
- 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

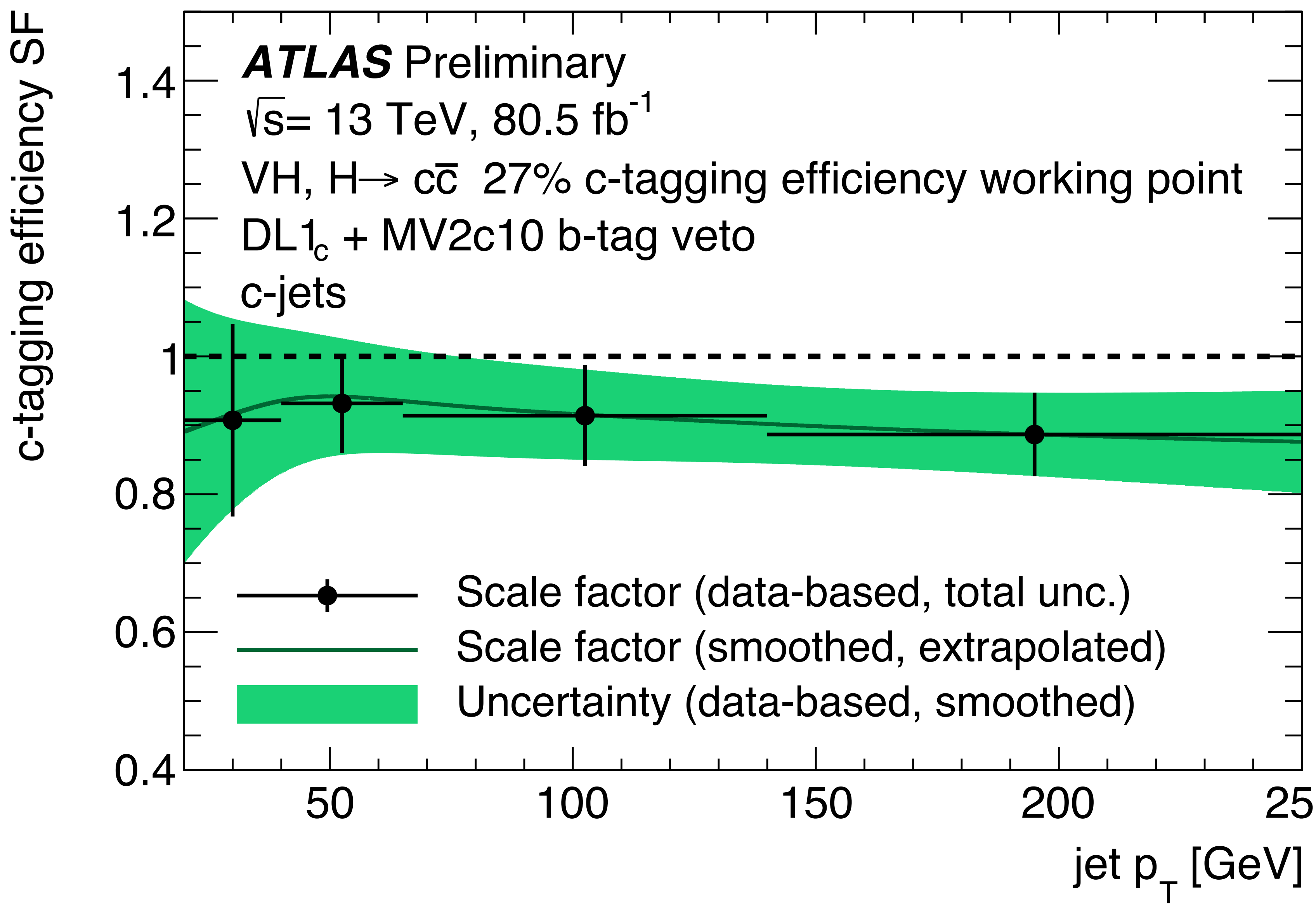
Charm tagging

Working point optimisation



$$DL1_{c-\mathrm{tag}} = \frac{p(c)}{fp(b) + (1-f)p(l)} > c$$

Calibrations



Charm-tagging performance: challenging but promising!

	b-tagger
b-jets	70%
c-jets	11%
light-jets	0,2%

	c-tagger + b-tag veto
c-jets	27%
b-jets	8%
light-jets	1,6%

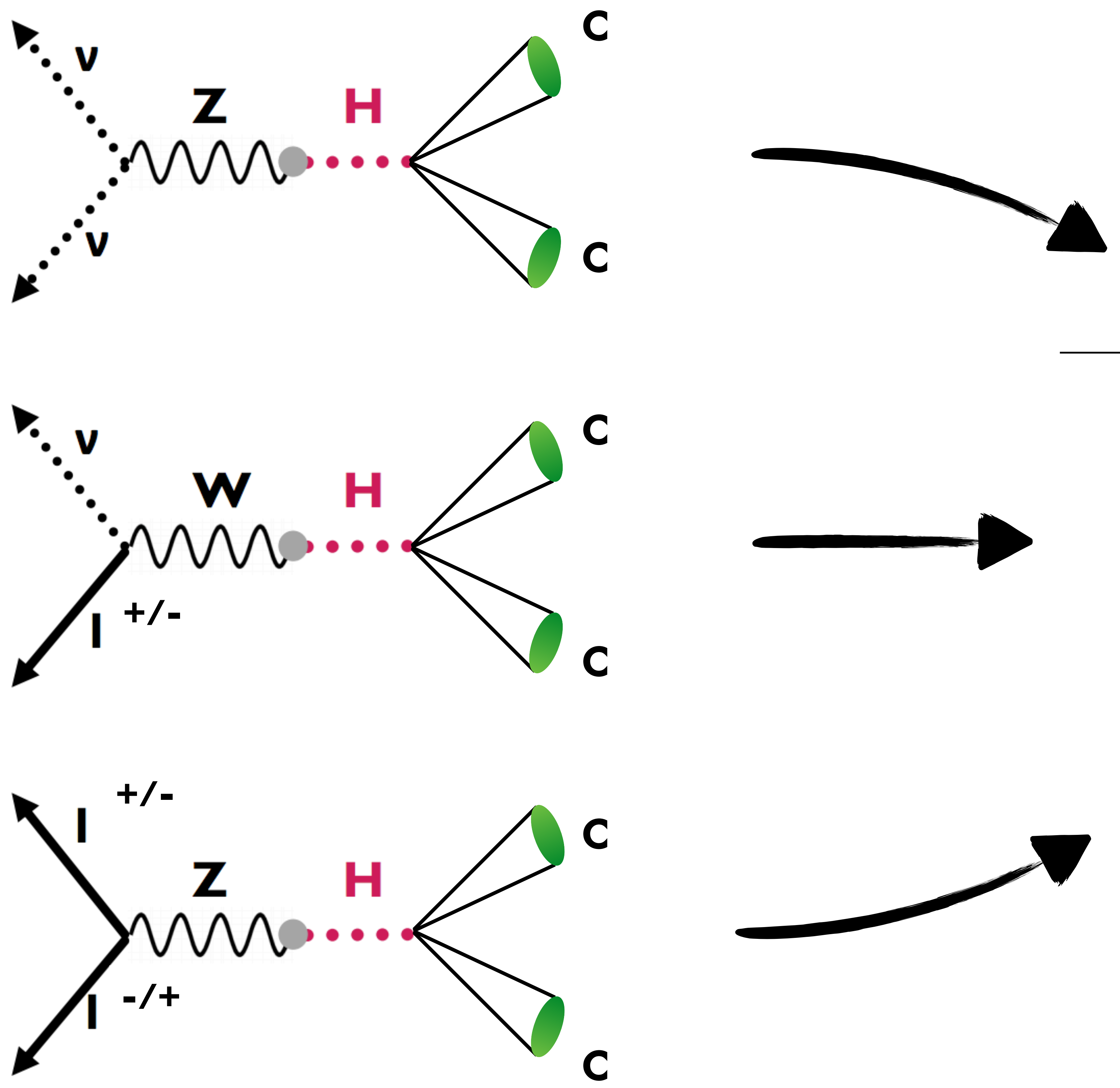
Flavour tagging categorisation

Signal: VH(cc)

0-lepton

1-lepton

2-lepton



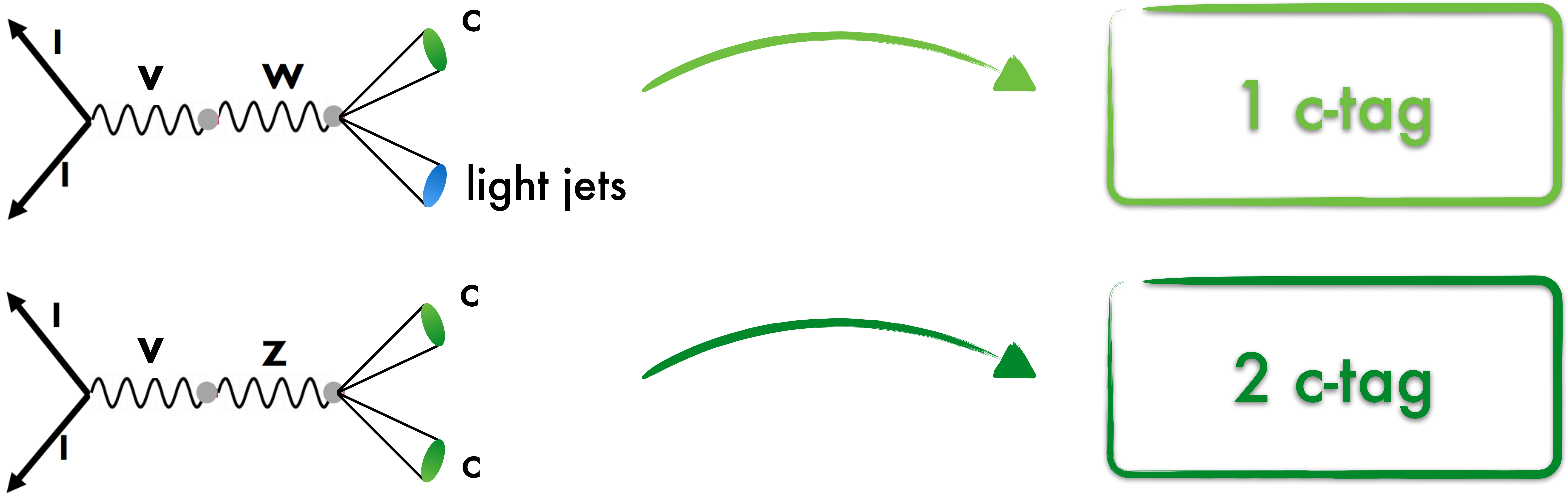
	1 c-tag	2 c-tag
Signal efficiency	~35%	~5%

Flavour tagging categorisation

- 2 c-tag: high sensitivity and lower background contamination
- 1 c-tag: recover part of the sensitivity lost in 2 c-tag due to c-tagging performance

Validation processes

VW(cl) and VZ(cc)



1 c-tag

2 c-tag

Validation: measure 2 processes of the SM

- VW(cl): mostly sensitive in 1 c-tag
- VZ(cc): mostly sensitive in 2 c-tag

Analysis strategy: how do I reconstruct my Higgs?

VHcc categorisation:

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

VHbb categorisation:

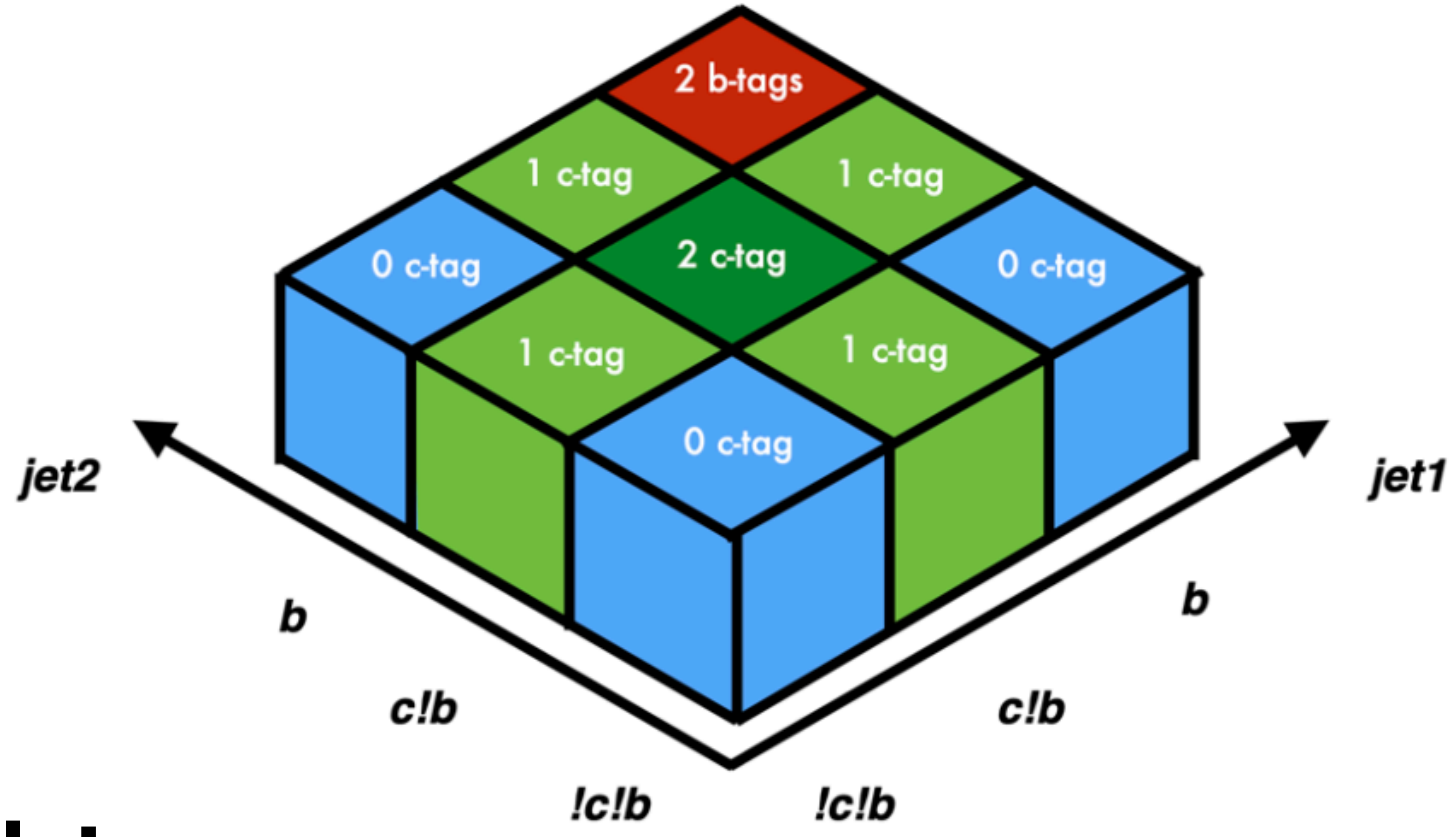
- **2 b-tag**

Orthogonality with VHbb:

- Always < 2 b-tagged jets

Combination with VH(bb) possible!

Categorisation of events with 2 jets



Problem due to flavour tagging perfomance

Background	1 c-tag	2 c-tag	Simulated events **NOT** used at the end
V+cc	~35%	~5%	**~60%**
V+cl	~53%	~0.4%	**~46%**

Low tagging efficiency on c-jets and b-jets / light-jets sizeable mis-tag rate

- Problem arising in simulation: most of the simulated events are **NOT** used
- Most problematic for background process already removed in event selection

→Consequence: larger systematic uncertainty due to size of simulated sample (= MC statistics error)

Solution: truth tagging method

Truth tagging weights

$$TT^{2c-\text{tag}}_{\text{weight}} = \epsilon_1 \times \epsilon_2,$$

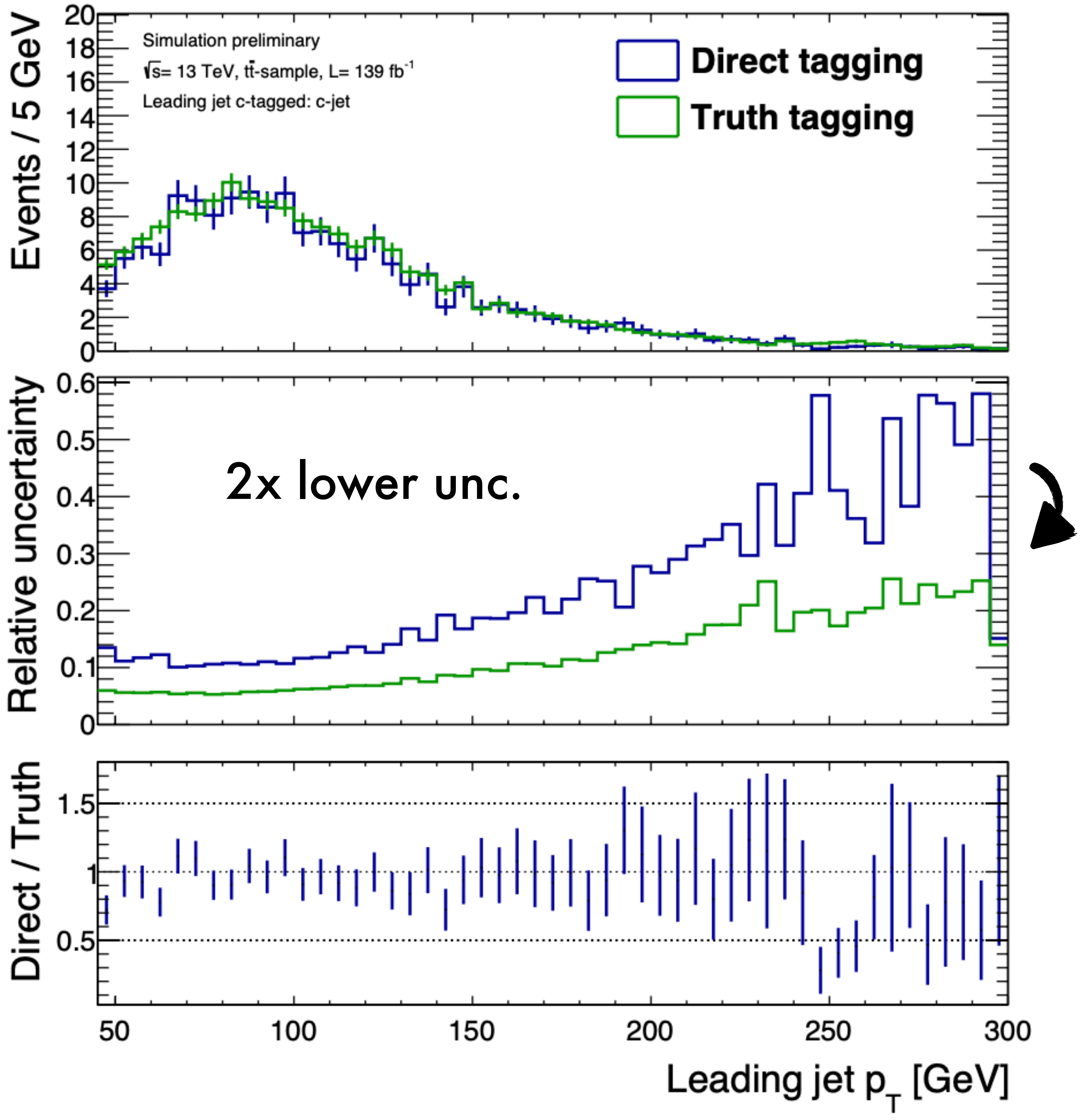
$$TT^{1c-\text{tag}}_{\text{weight}} = \epsilon_1 \times (1 - \epsilon_2) + (1 - \epsilon_1) \times \epsilon_2$$

Solution: truth tagging method

- Re-weight each event by probability to be in 2 c-tag, 1 c-tag, 0 c-tag
    - Calculate c-tagging efficiency per-jets on ttbar samples
    - Per jets: account for pT and eta dependence
- Effectively use the whole simulated sample in the signal region
- Apply to all samples except signal

→ Preserve MC statistics available!

ttbar example



Main backgrounds

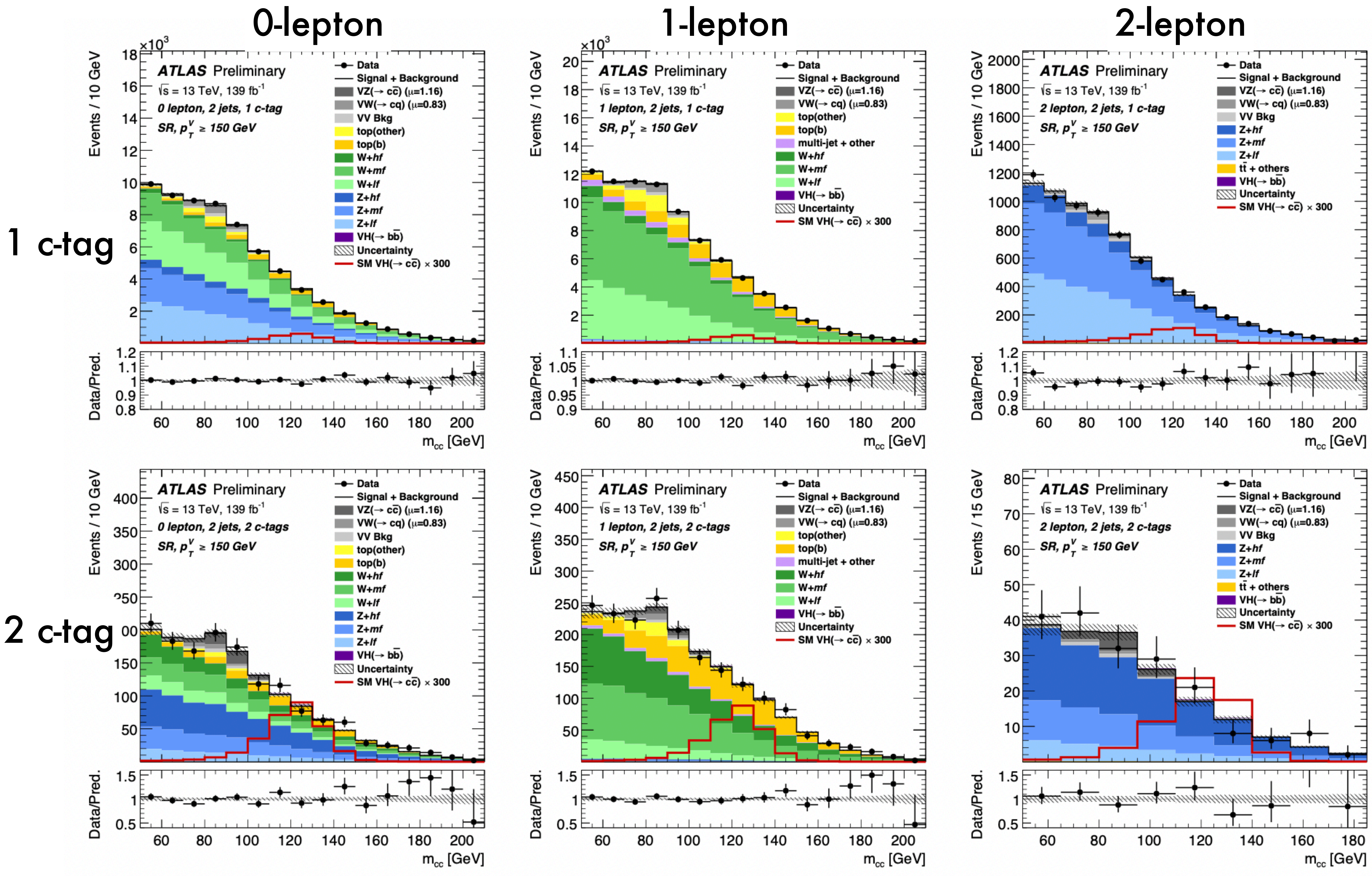
2 jet pTV > 150 GeV

Discriminant: **m(cc)**

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

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

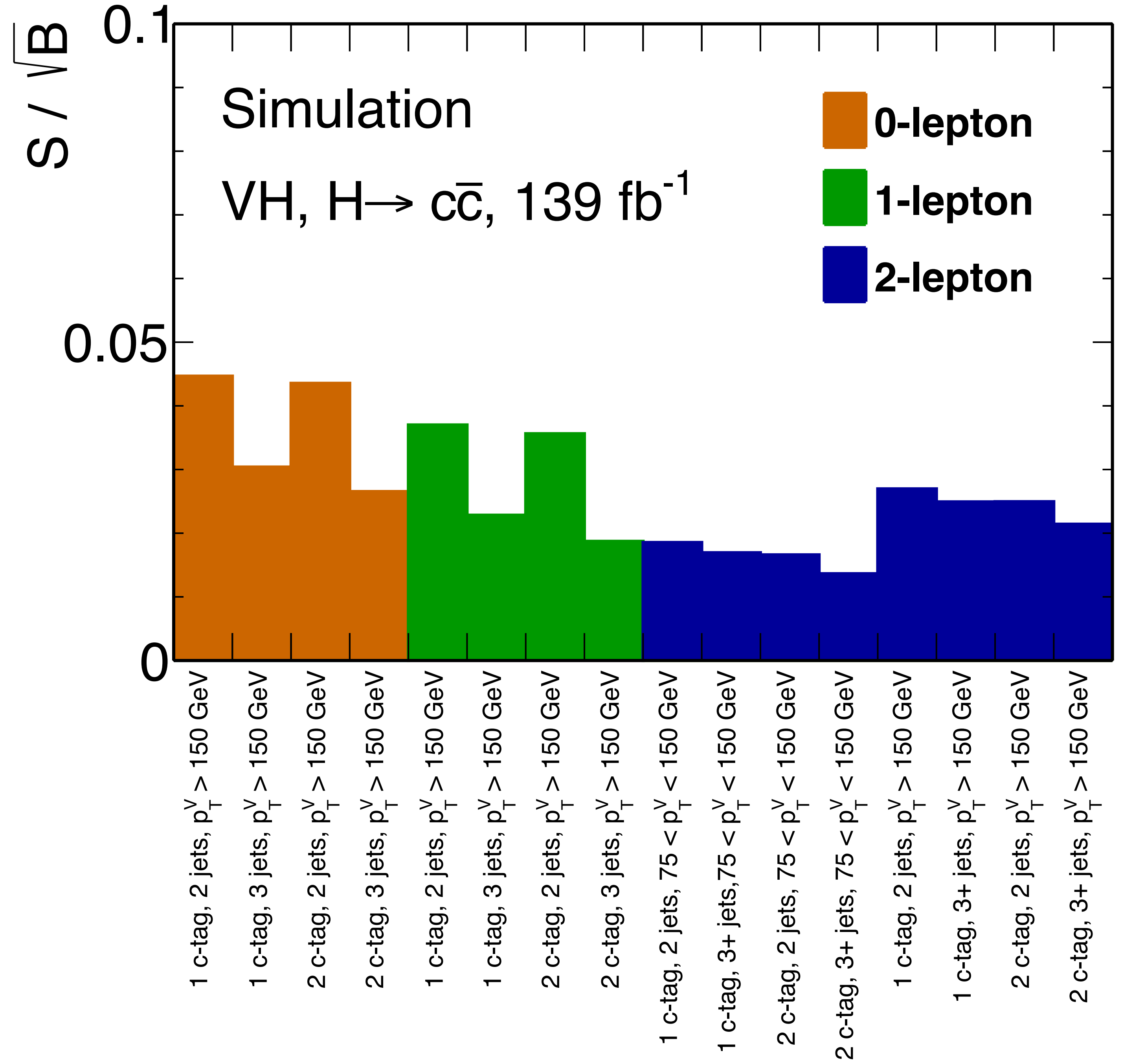
Signal:
VH(cc), VZ(cc),VW(cq)



Event categorisation: SR

Channel	c-tag	Jets	pTV
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



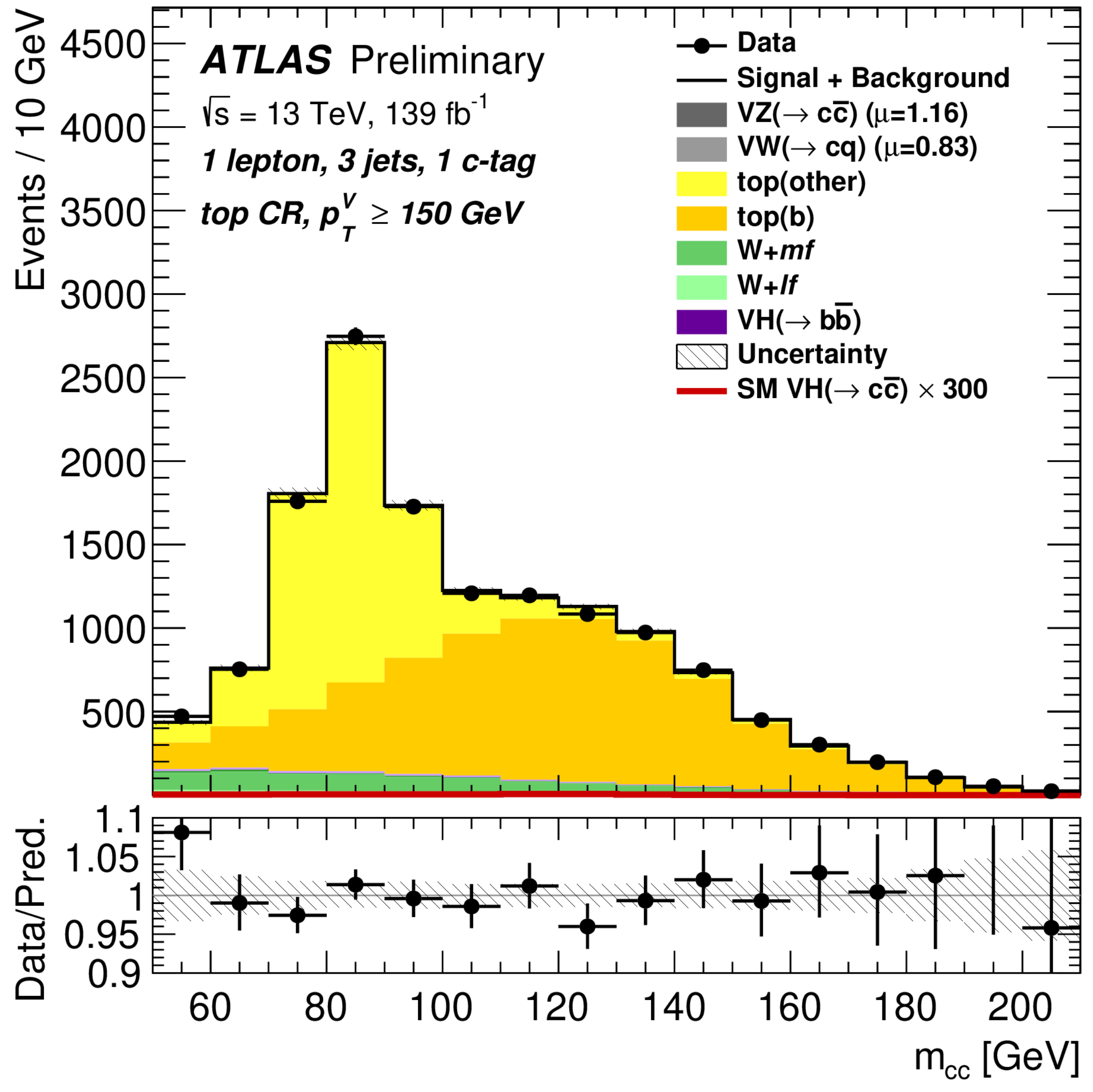
Event categorisation:

- Flavour tagging: 1 and 2 c-tag (similar sensitivity)
- Jet multiplicity: 2 and 3(+) jets (+3% total sensitivity stat-only w.r.t merged)
- pTV category: pTV > 150 GeV
    - 2-lepton only: 75 < pTV < 150 GeV (+5% total sensitivity stat-only)

Highest sensitivity ranking: 0-lepton, 2-lepton, 1-lepton (same outcome with full syst)

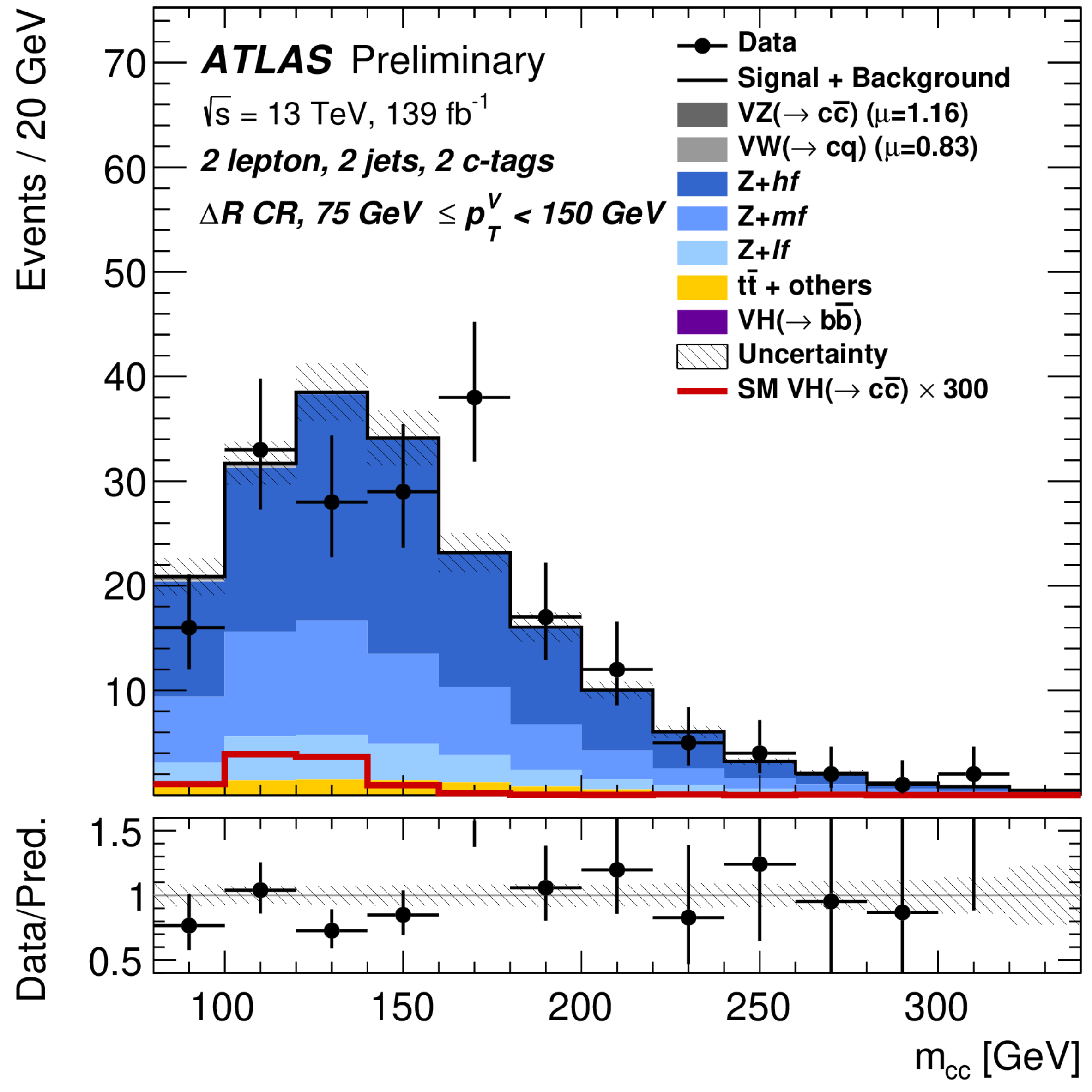
Control regions

Top CR



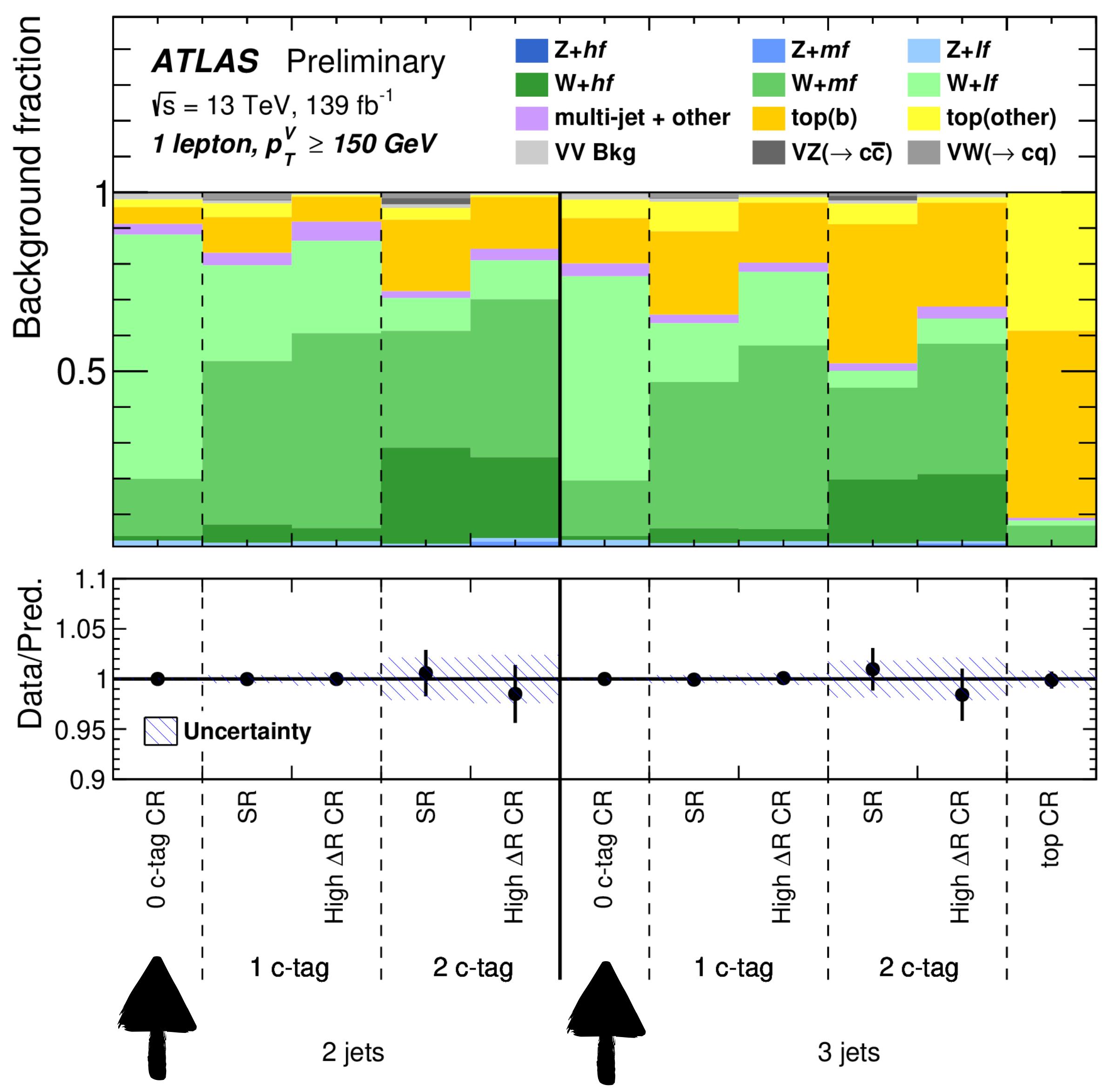
Constrain ttbar and W decays from ttbar

High ΔR CR



Constrain Z+jets and W+jets

0 c-tag CR



Constrain Z+light jets and W+ light jets

Additional CRs to fix the main background from data:
→ Ensure that signal is properly estimated

Signal and control regions

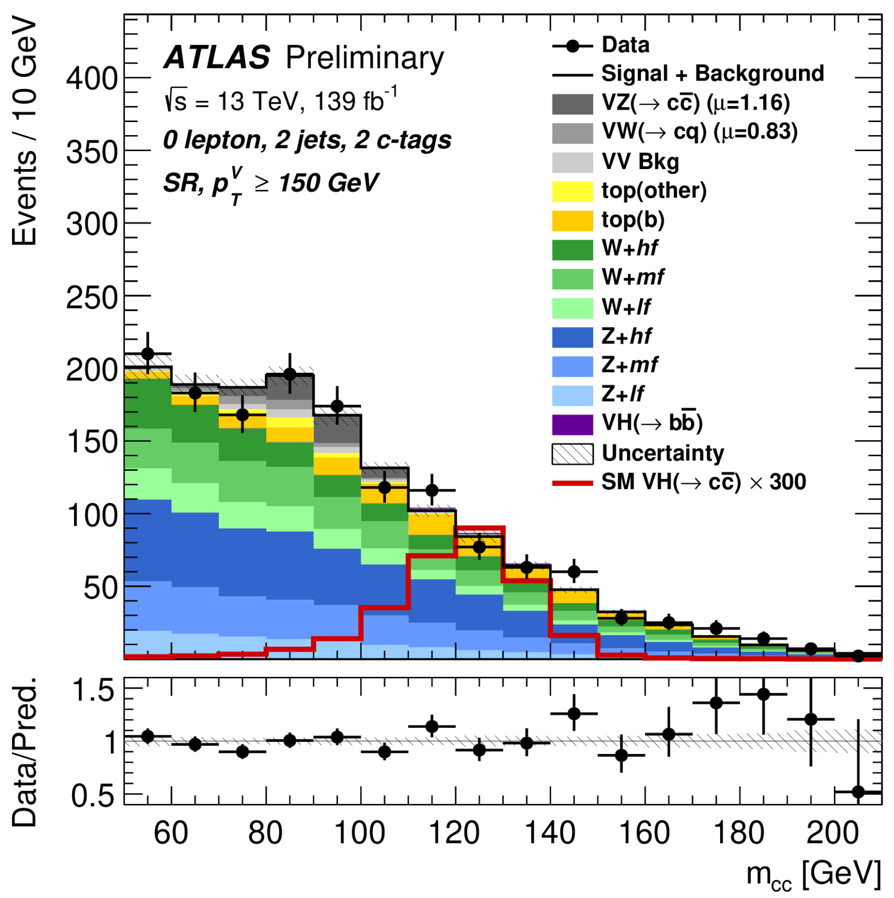
		ΔRcc < ΔRcc selection				ΔRcc selection < ΔRcc < 2.5	
		0 c-tag CR	SR		Top CR	ΔRcc CR	
0L	pTV > 150 GeV		1 c-tag 2 jet	2 c-tag 2 jet		1 c-tag 2 jet	2 c-tag 2 jet
			1 c-tag 3 jet	2 c-tag 3 jet	1 c-tag 3 jet	1 c-tag 3 jet	2 c-tag 3 jet
1L	pTV > 150 GeV	0 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet		1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag 3 jet	1 c-tag 3 jet	2 c-tag 3 jet	1 c-tag 3 jet	1 c-tag 3 jet	2 c-tag 3 jet
2L	75 < pTV < 150 GeV	0 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet	1 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet	1 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet
	pTV > 150 GeV	0 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet	1 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet	1 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet

Fit model: 16 SRs +28 CRs

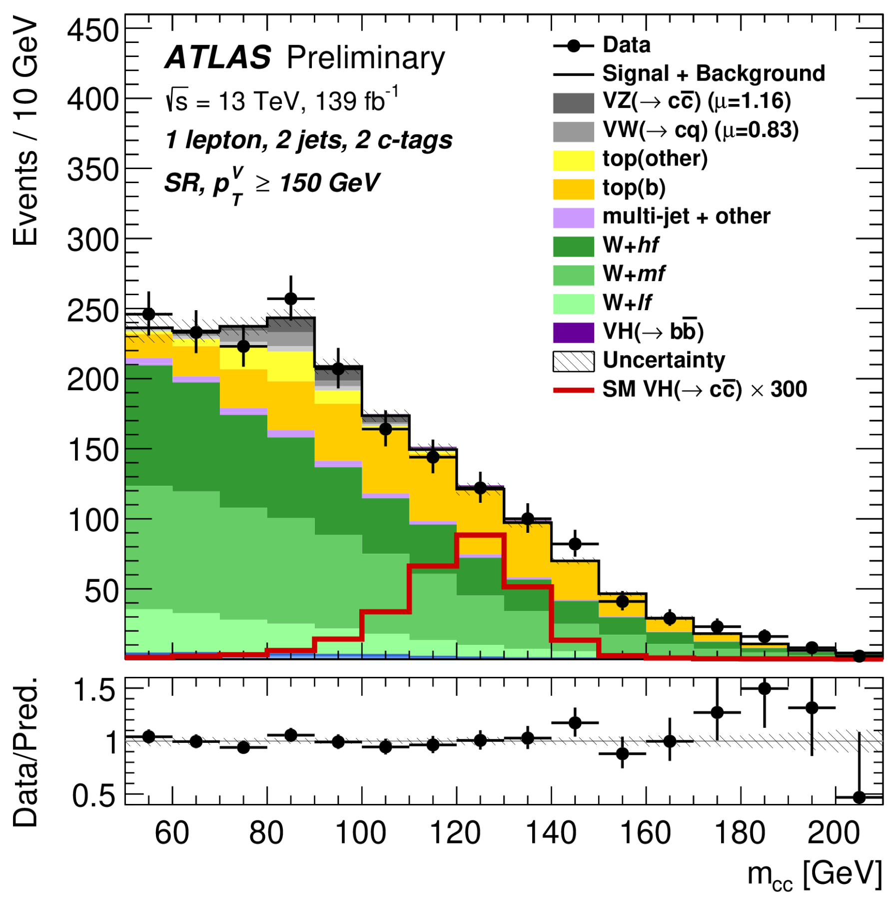
Fit to extract signal strength

2-lepton example

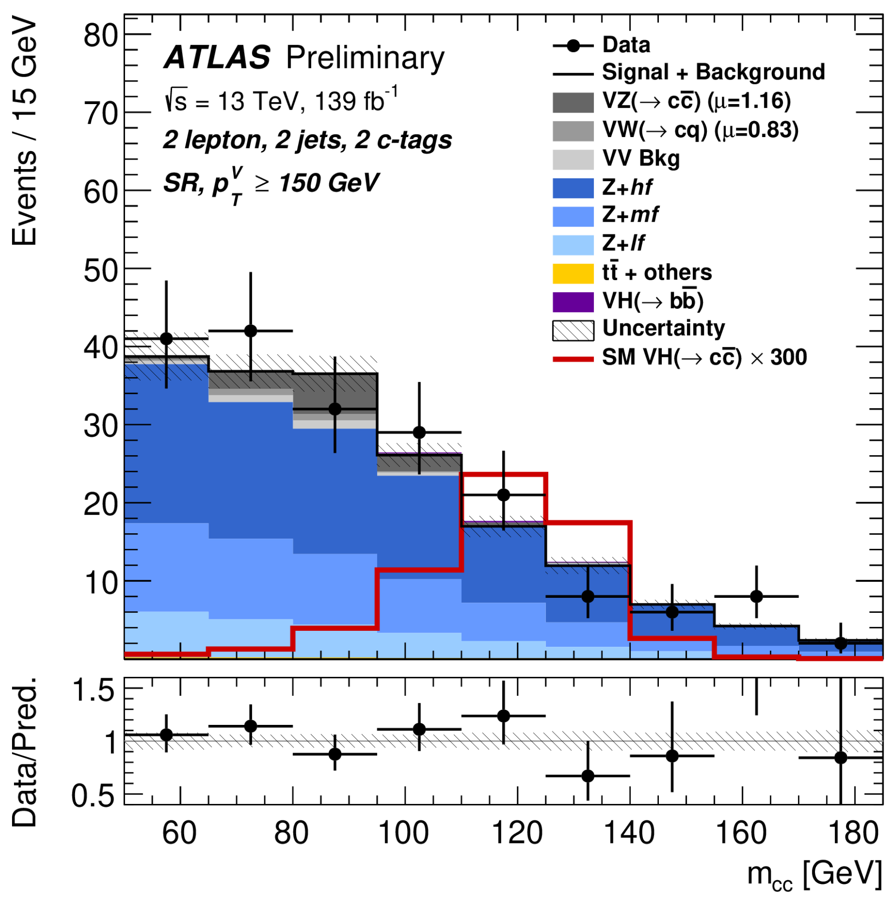
0-lepton



1-lepton



2-lepton



$$\mu_{VH(\to c\bar{c})} = \frac{\sigma^{obs}_{VH} \times BR^{obs}(H \to c\bar{c})}{\sigma^{SM}_{VH} \times BR^{SM}(H \to c\bar{c})}$$

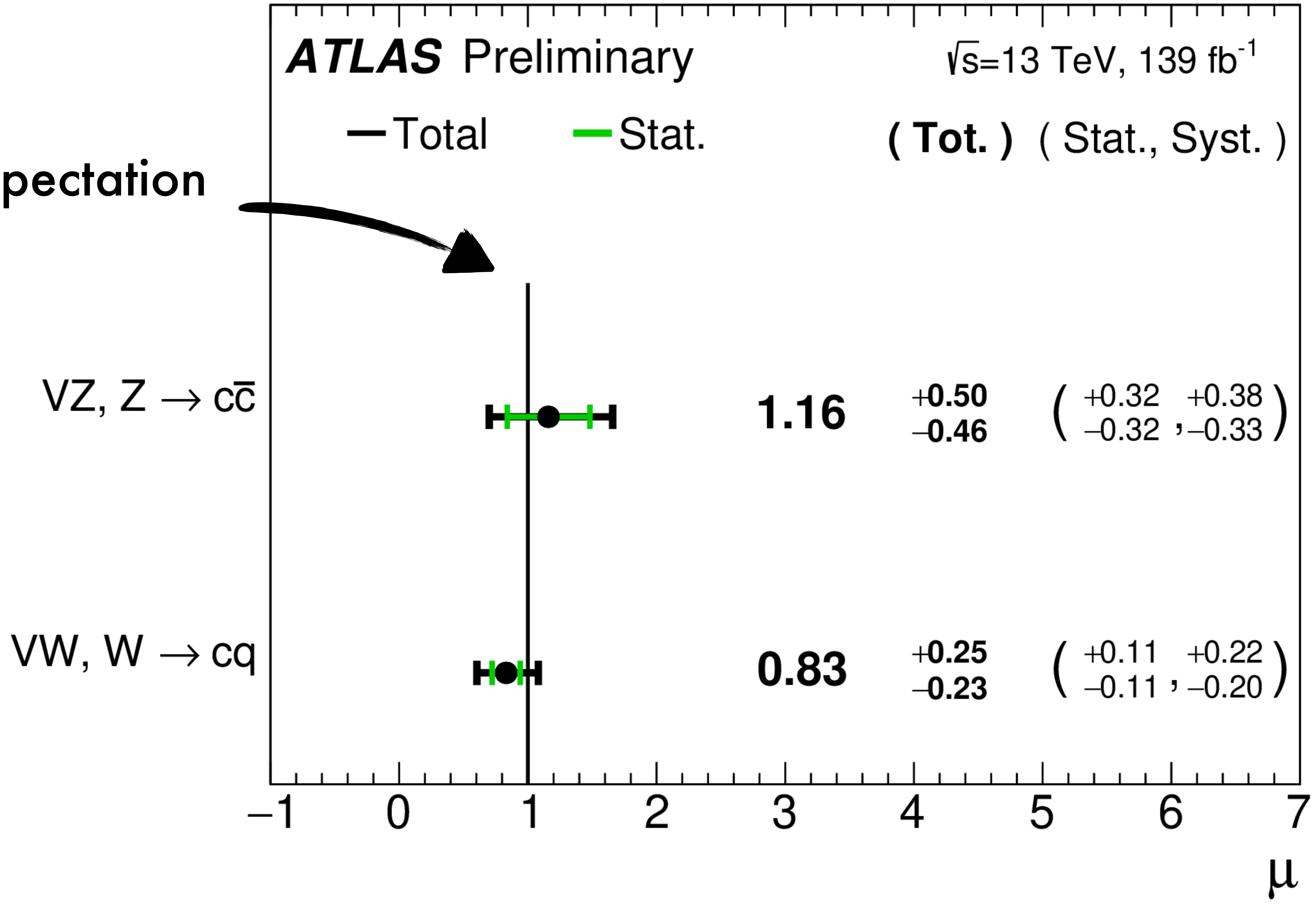
Fit to the data to extract signal strength: quantify data agreement with SM expectation

- All systematics included: detector, flavour tagging, modelling
- Floating normalisations for main backgrounds: ttbar, Z+jets and W+jets
- Perform fit with 3 parameters of interest (POIs): μ_{VWcl}, μ_{VZcc}, μ_{VHcc}

Goal of the analysis: measure the signal strength μ_{VHcc}

Results

Measurements of VW(cl) and VZ(cc)



Standard Model expectation

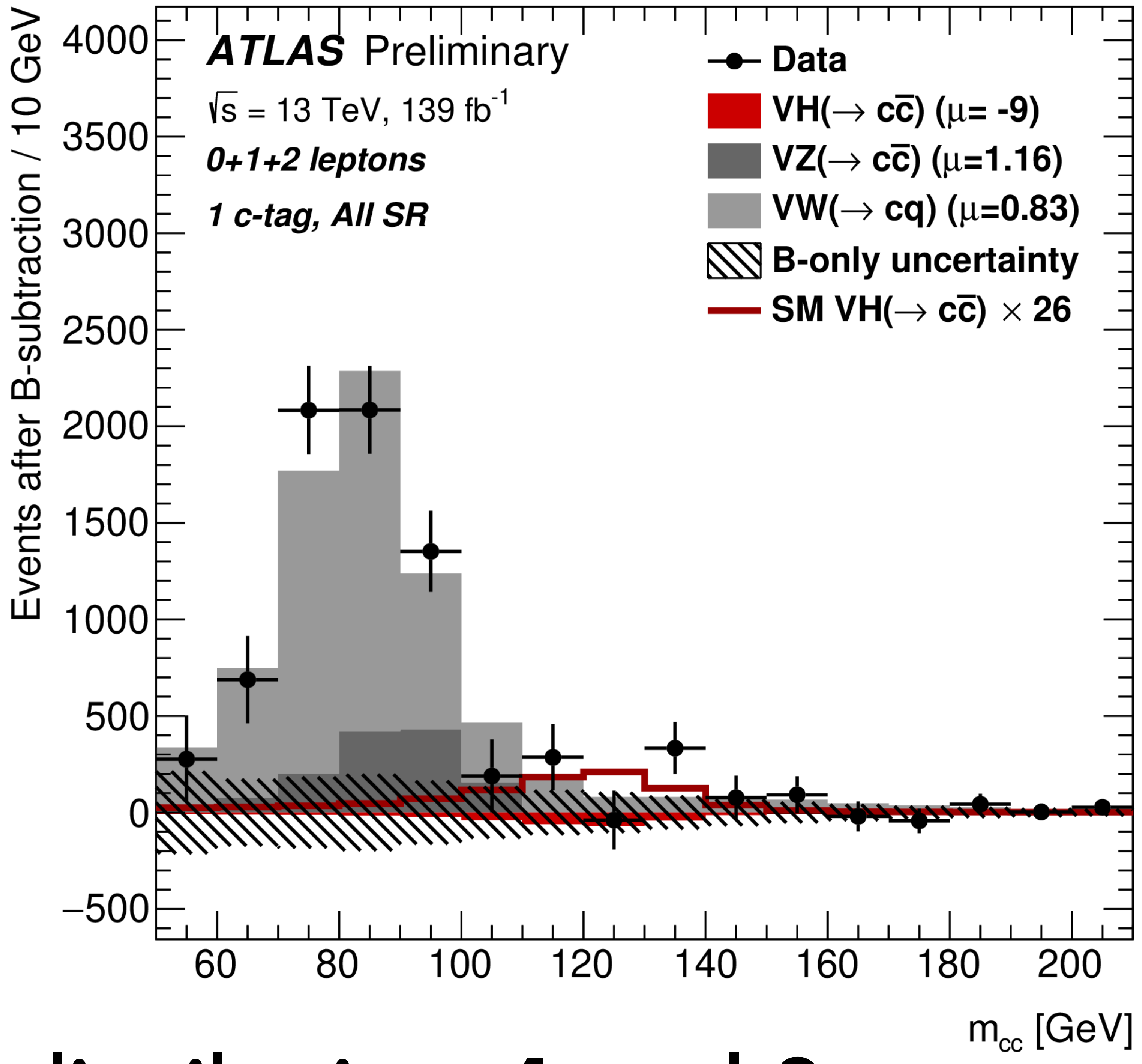
Measurement of validation process:

- VW(cl) and VZ(cc) measurement in agreement with the SM

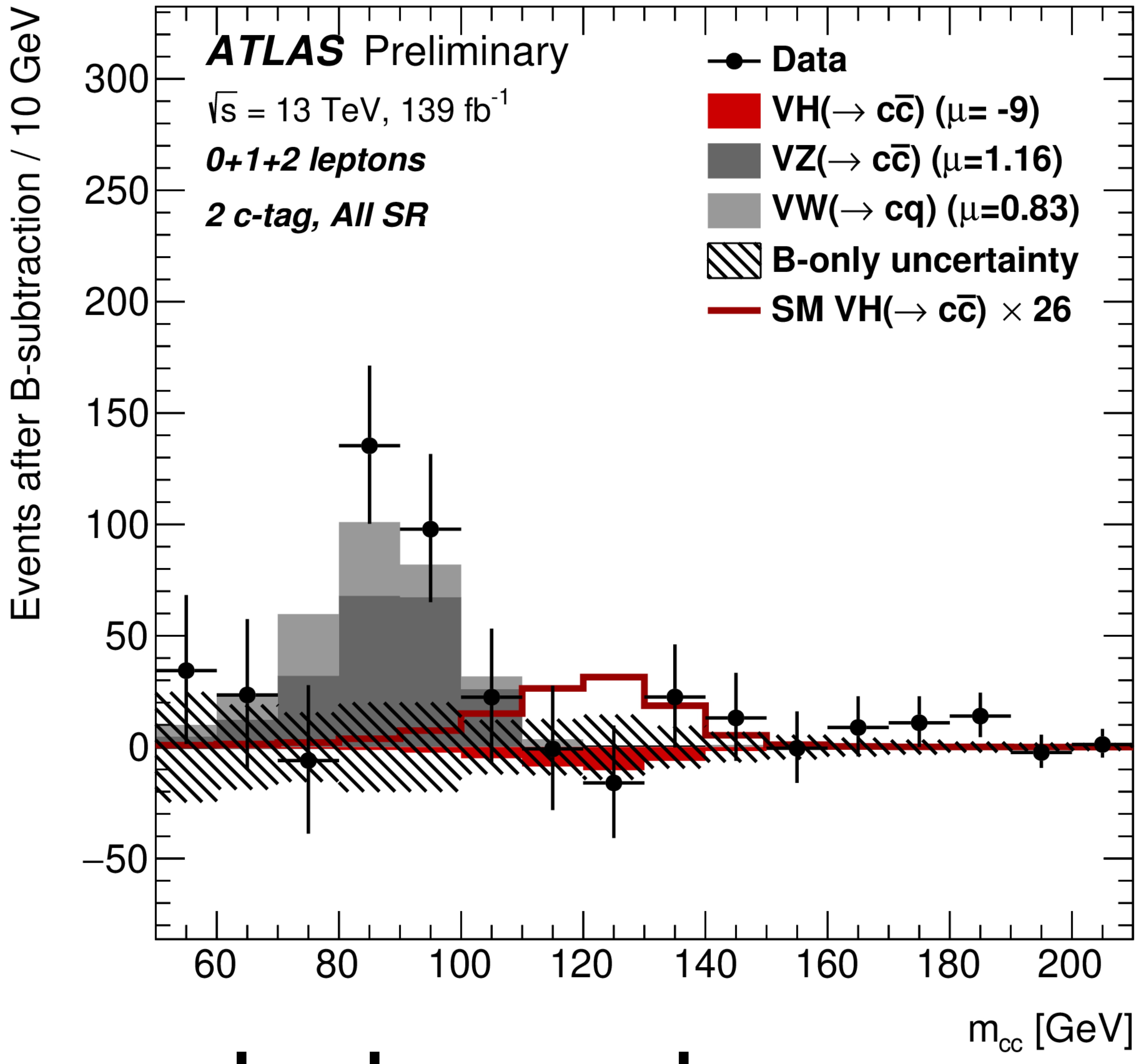
  →Validation of the 1 c-tag and 2 c-tag categories

Mass distributions

1 c-tag



2 c-tag

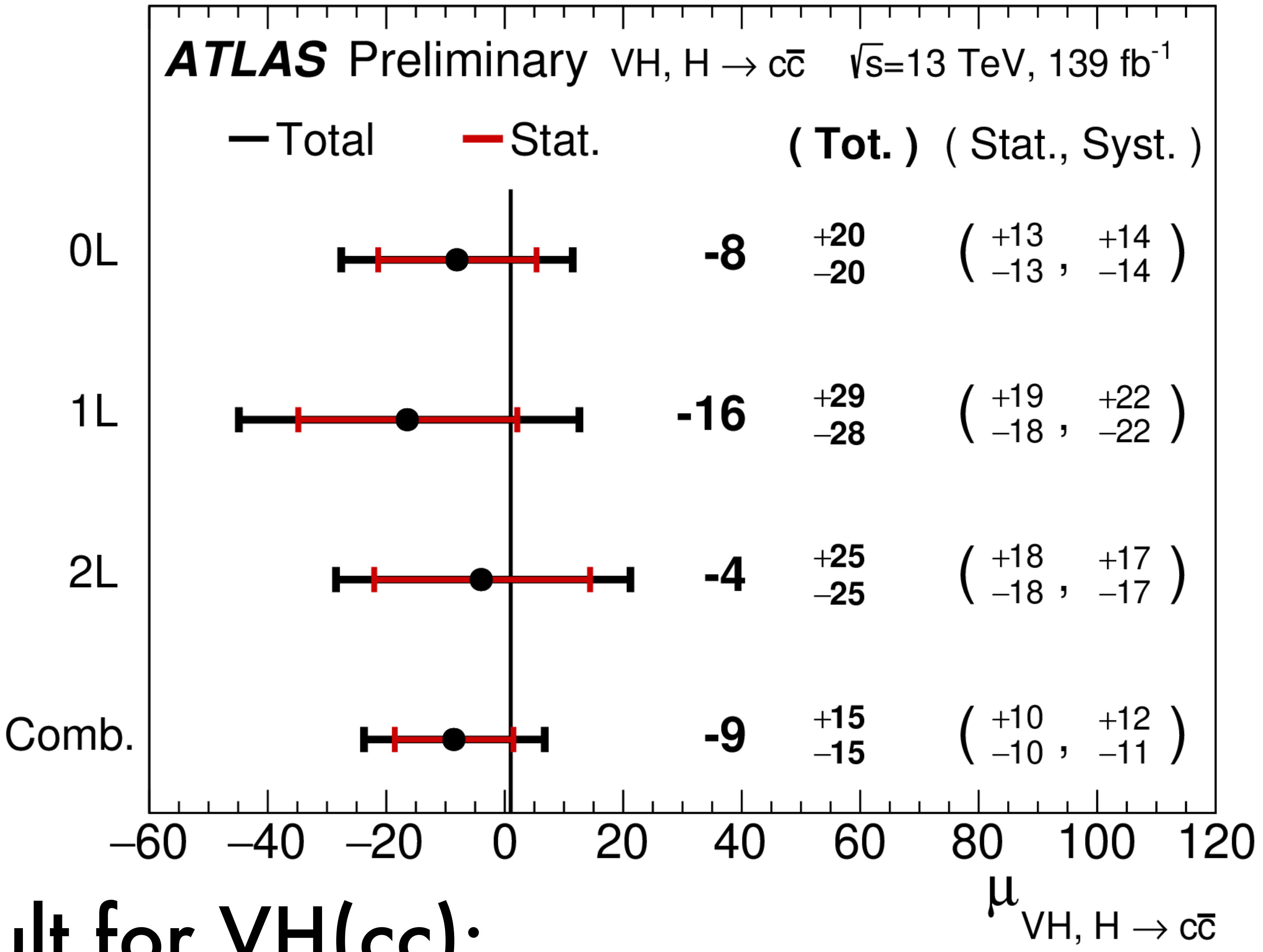


M(cc) distribution: 1 and 2 c-tag with background subtracted

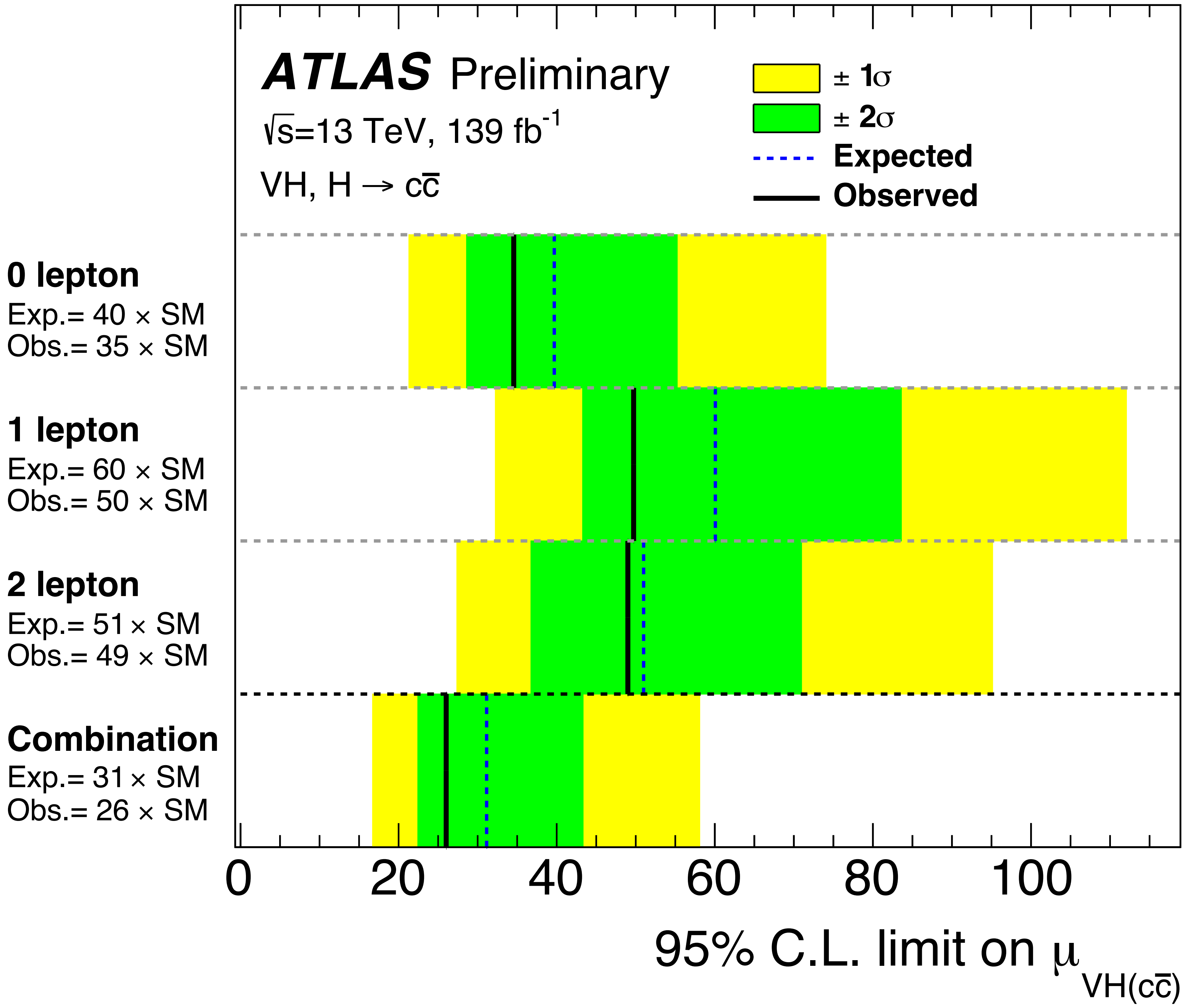
Diboson fit results: validation of the analysis
VZ(cc): **2.6σ observed** (2.2 expected)
VW(cl): **3.8σ observed** (4.6 expected)
→ First measurement of VZ(cc) and VW(cl) using c-tagging!

Results: limit and signal strength

VHcc signal strength



Limits on VH(cc) signal strength

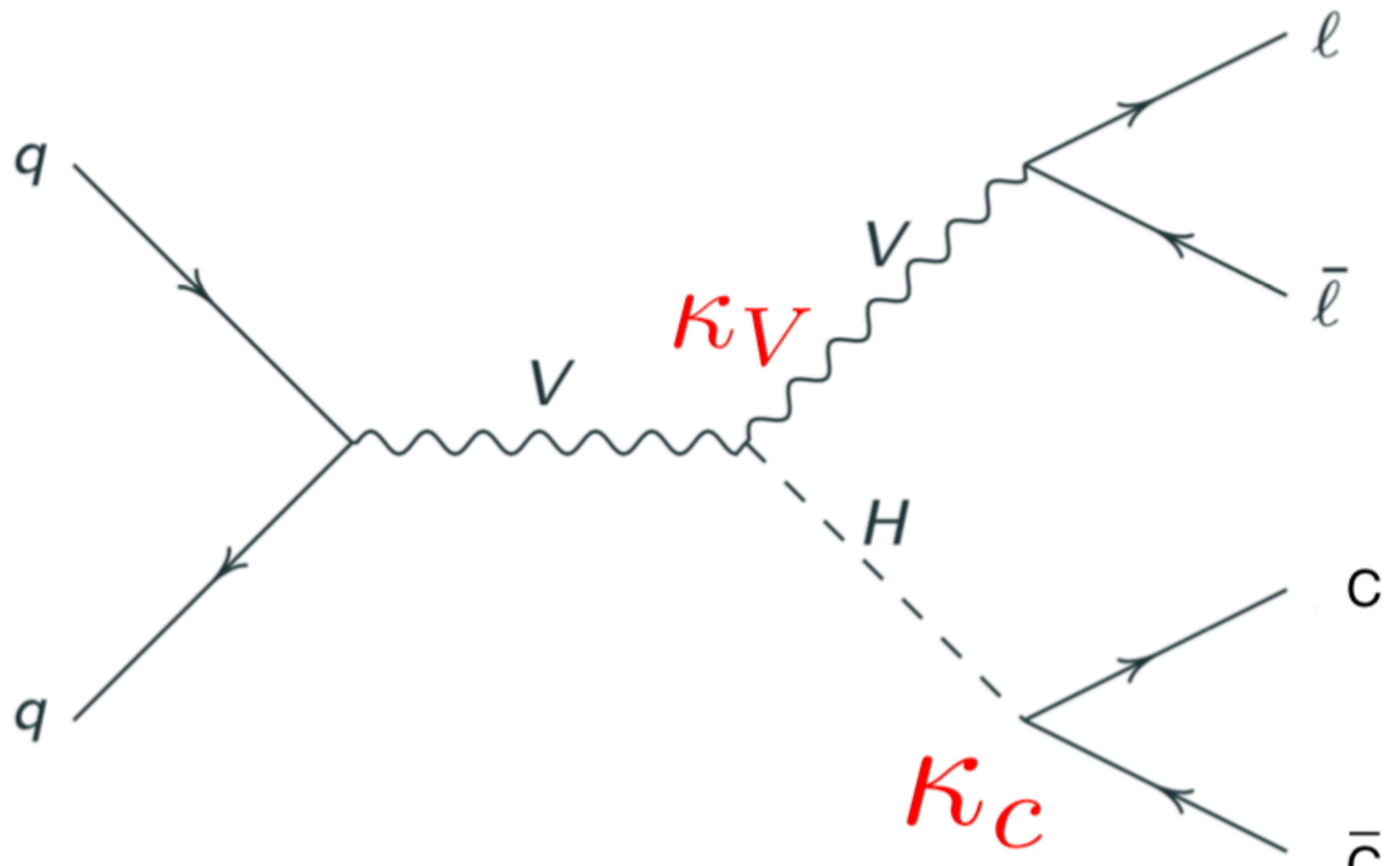


Result for VH(cc):

- 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)

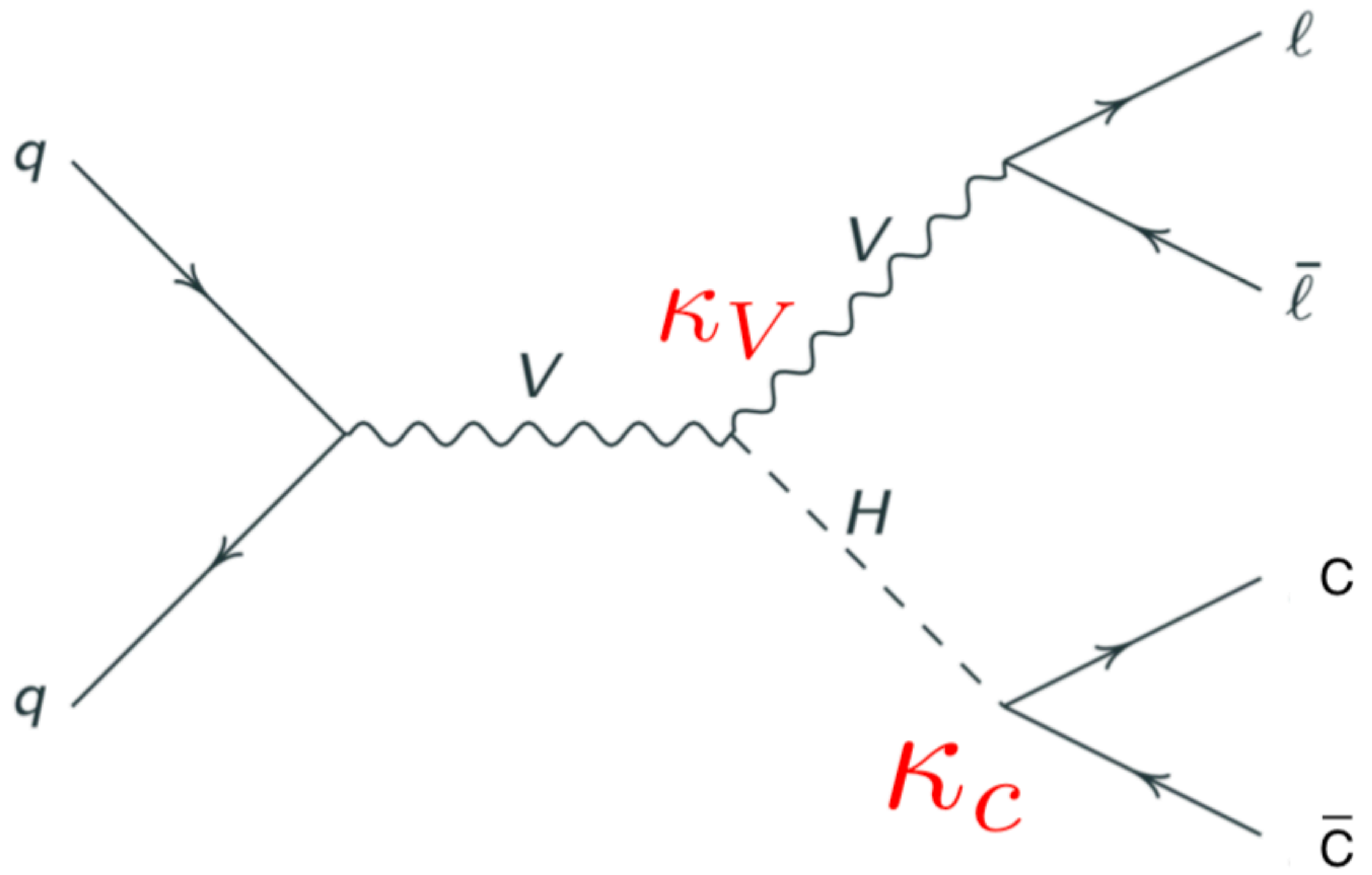
→ Best limit on VH(cc) up to this day!

κ framework



$$g_i \rightarrow g_i \times \kappa_i$$

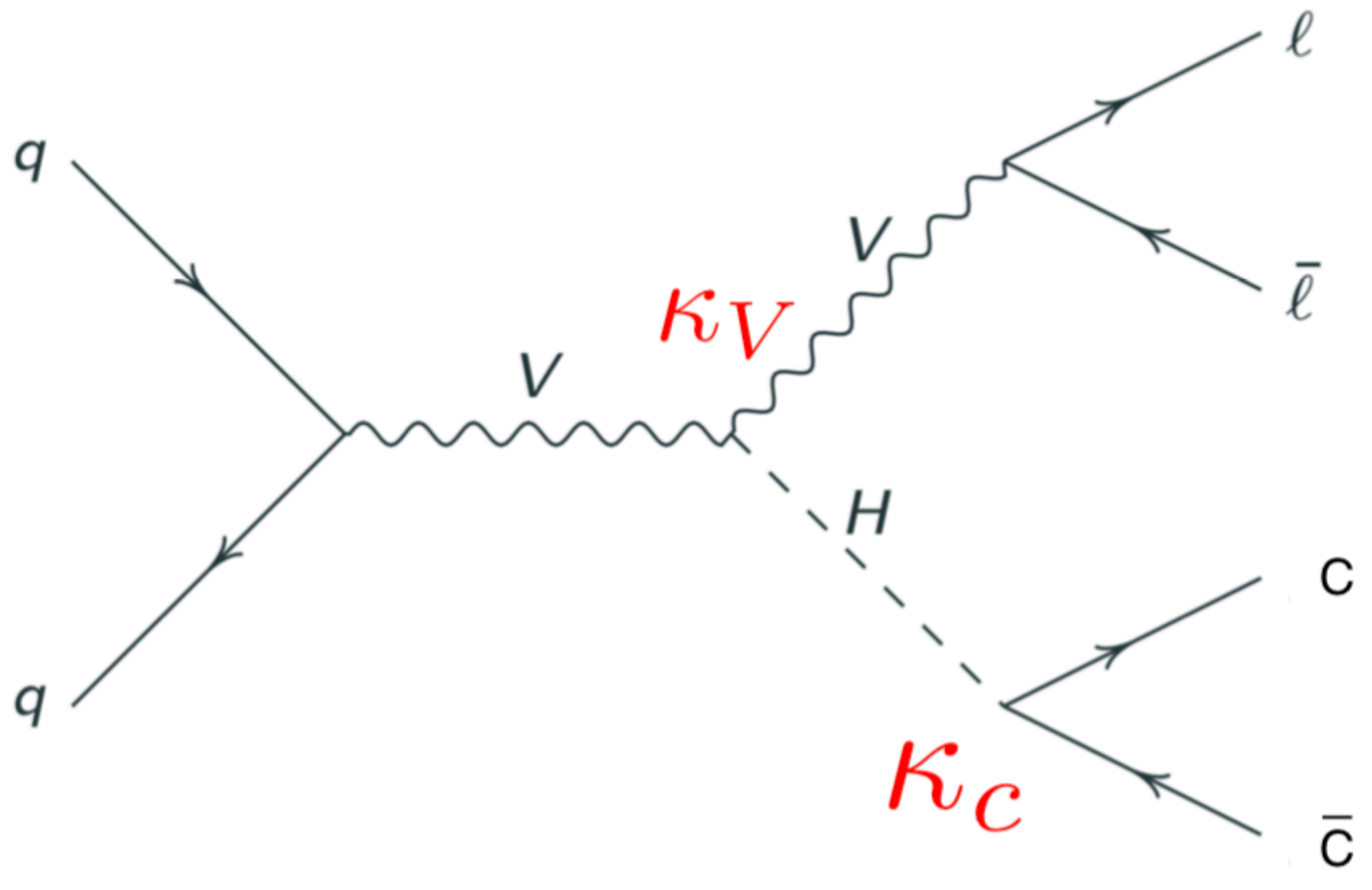
κ framework



$$g_i \rightarrow g_i \times \kappa_i$$

$$\sigma_{pp\rightarrow VH} \times BR_{H\rightarrow c\bar{c}} = \sigma^{SM}_{pp\rightarrow VH} \times BR^{SM}_{H\rightarrow c\bar{c}} \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$$

κ framework



$$g_i \rightarrow g_i \times \kappa_i$$

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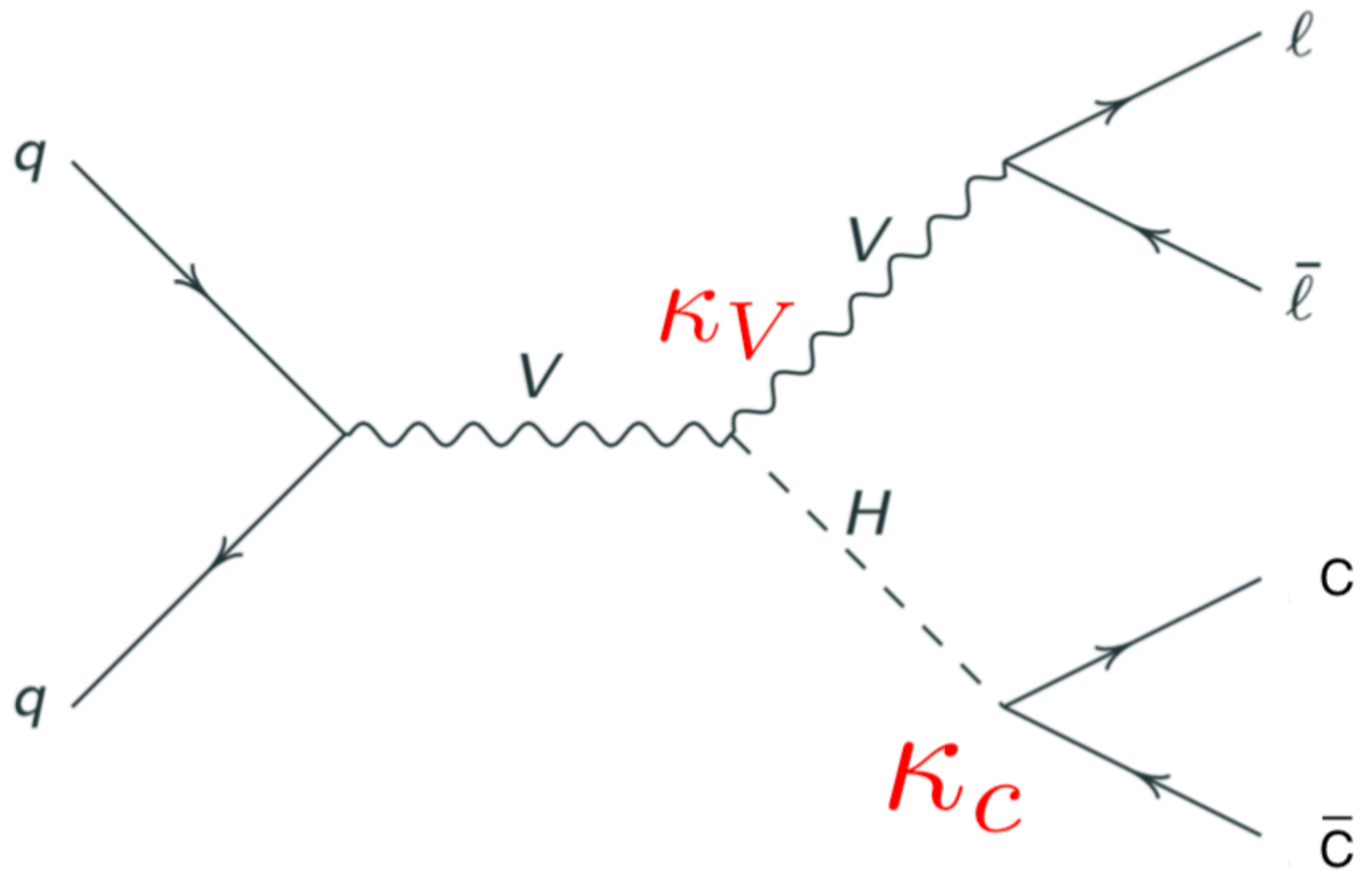
$$\mu_{VHcc} = \frac{\sigma_{pp\rightarrow VH} \times BR_{H\rightarrow c\bar{c}}}{\sigma^{SM}_{pp\rightarrow VH} \times BR^{SM}_{H\rightarrow c\bar{c}}} = \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$$

κ framework



$$g_i \rightarrow g_i \times \kappa_i$$

$$\sigma_{pp\rightarrow VH} \times BR_{H\rightarrow c\bar{c}} = \sigma^{SM}_{pp\rightarrow VH} \times BR^{SM}_{H\rightarrow c\bar{c}} \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$$

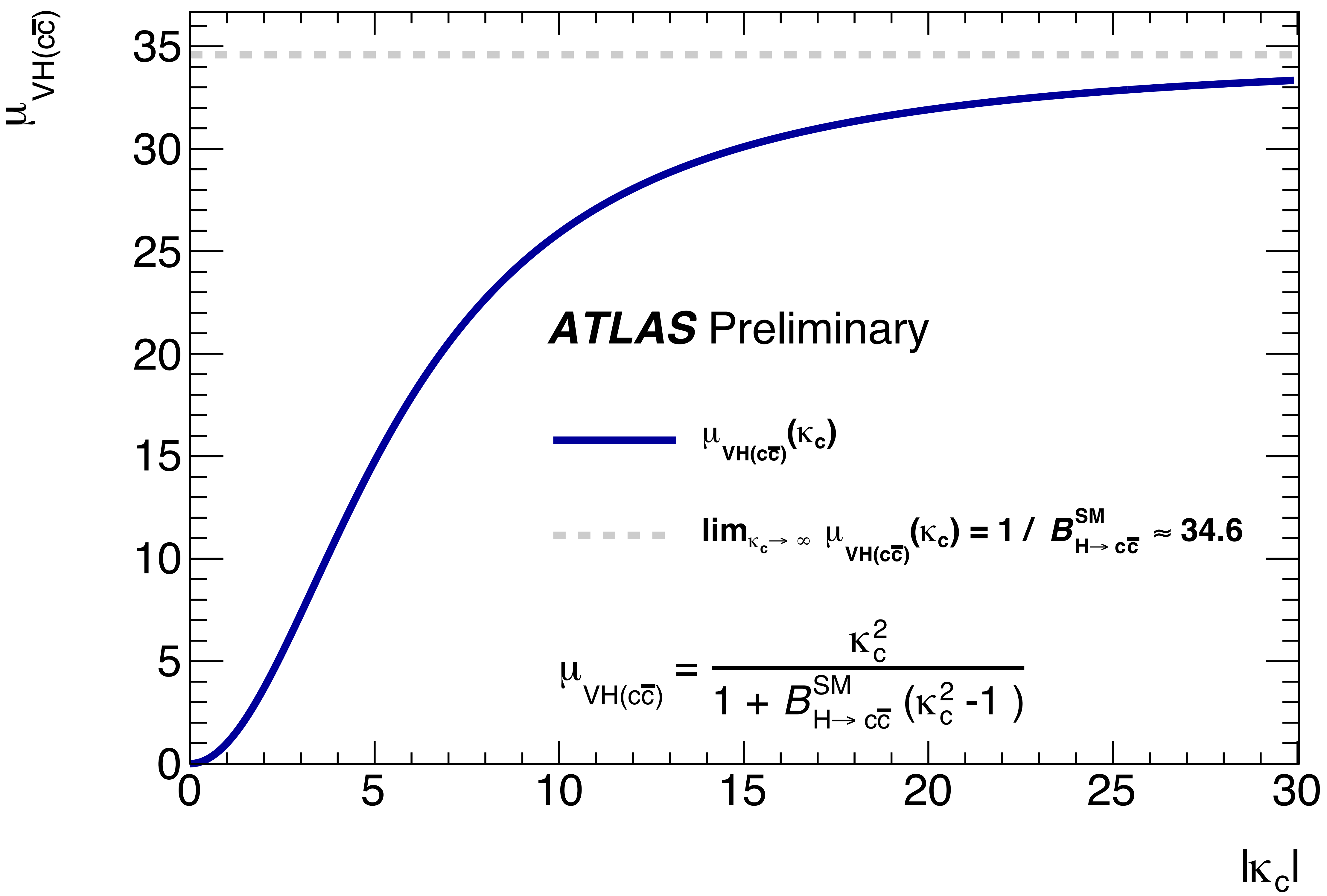
$$\mu_{VHcc} = \frac{\sigma_{pp\rightarrow VH} \times BR_{H\rightarrow c\bar{c}}}{\sigma^{SM}_{pp\rightarrow VH} \times BR^{SM}_{H\rightarrow c\bar{c}}} = \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$$

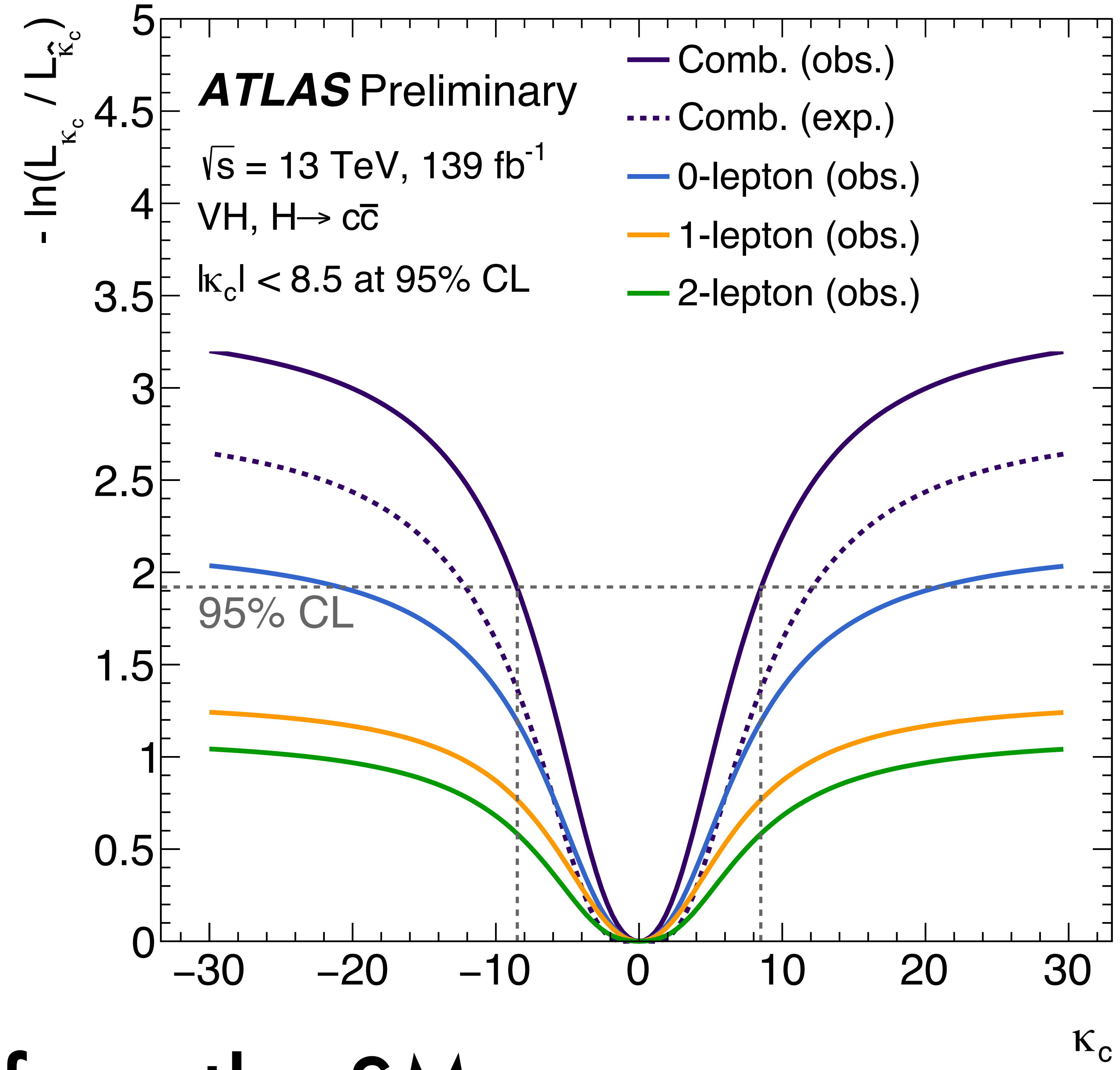
$$\mu_{VHcc} = \frac{\kappa_c^2}{1 - BR_{H\rightarrow c\bar{c}} + \kappa_c^2 BR_{H\rightarrow c\bar{c}}}, \forall \kappa_i = 1, i \neq c$$

κ framework: quantify possible deviations from the SM

- Effectively modifies the number of VH(cc) events
  - For example κ_c = 0 means Higgs boson doesn't couple to c-quarks

κ_c interpretations



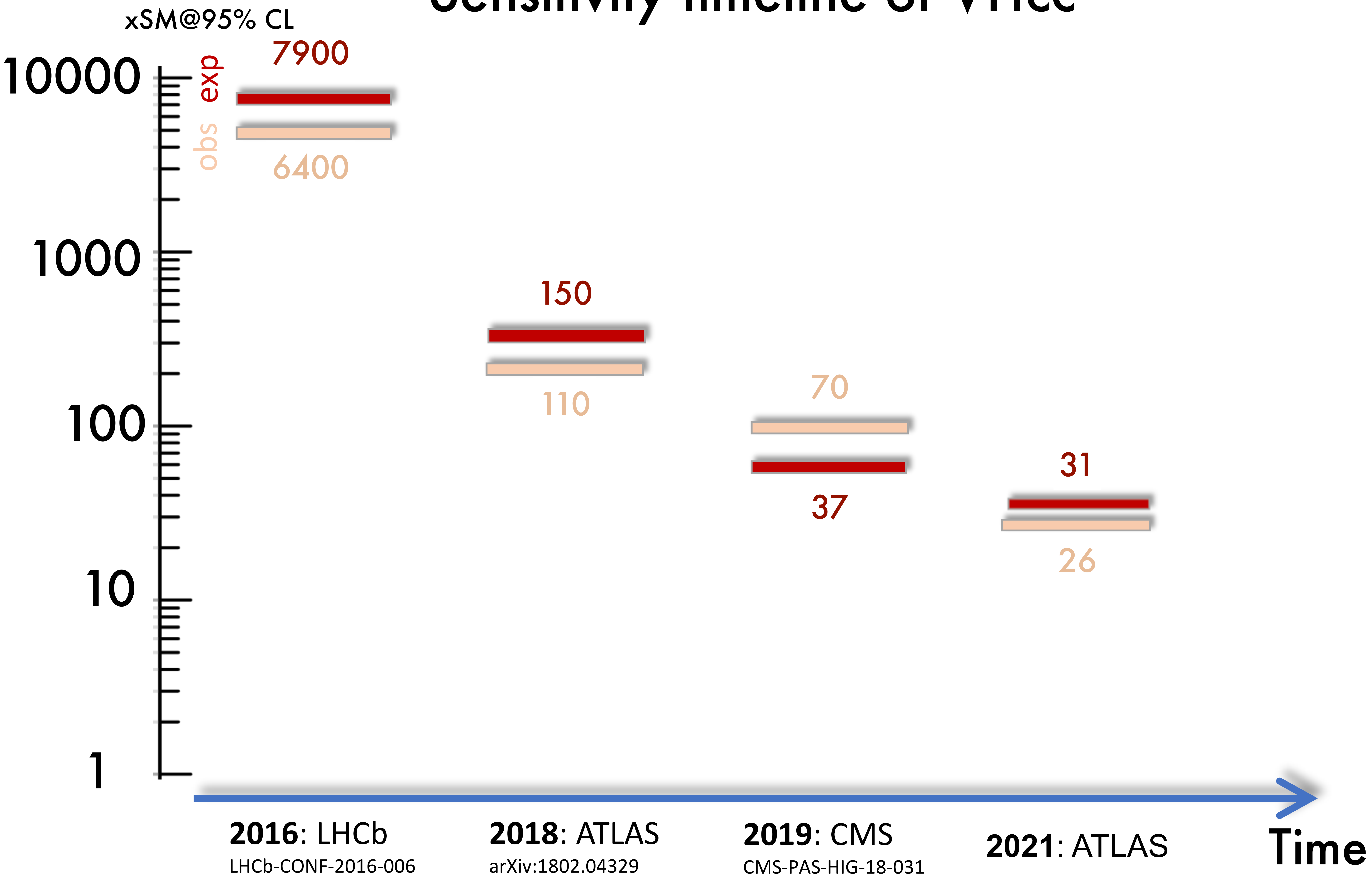


κ_c interpretation: quantify possible deviations from the SM

- Assume κ_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: **| κ_c | < 8.5 @ 95% CL** (<12.4 @ 95%CL expected)

Comparison with other VHcc results?

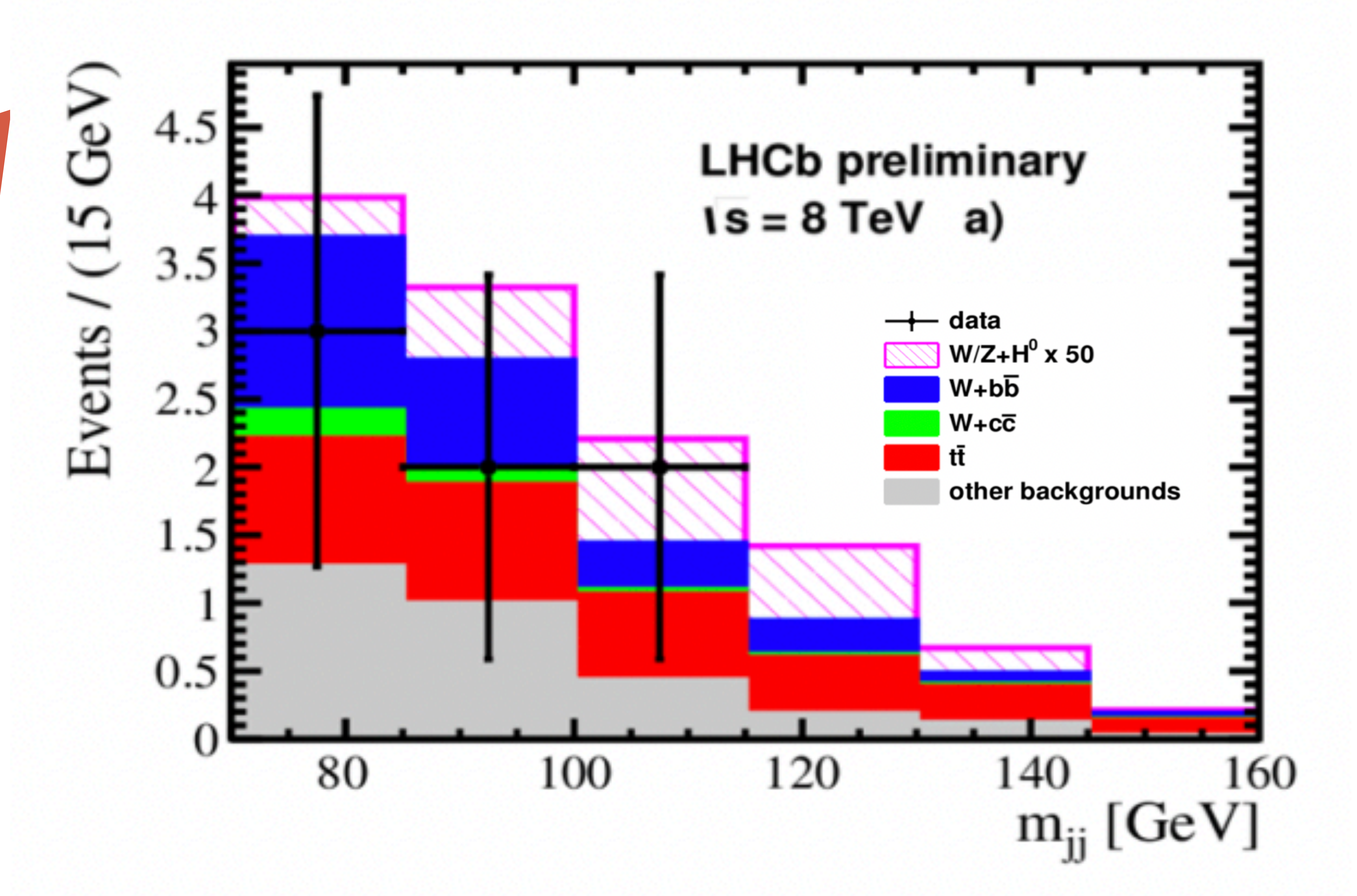
Sensitivity timeline of VHcc



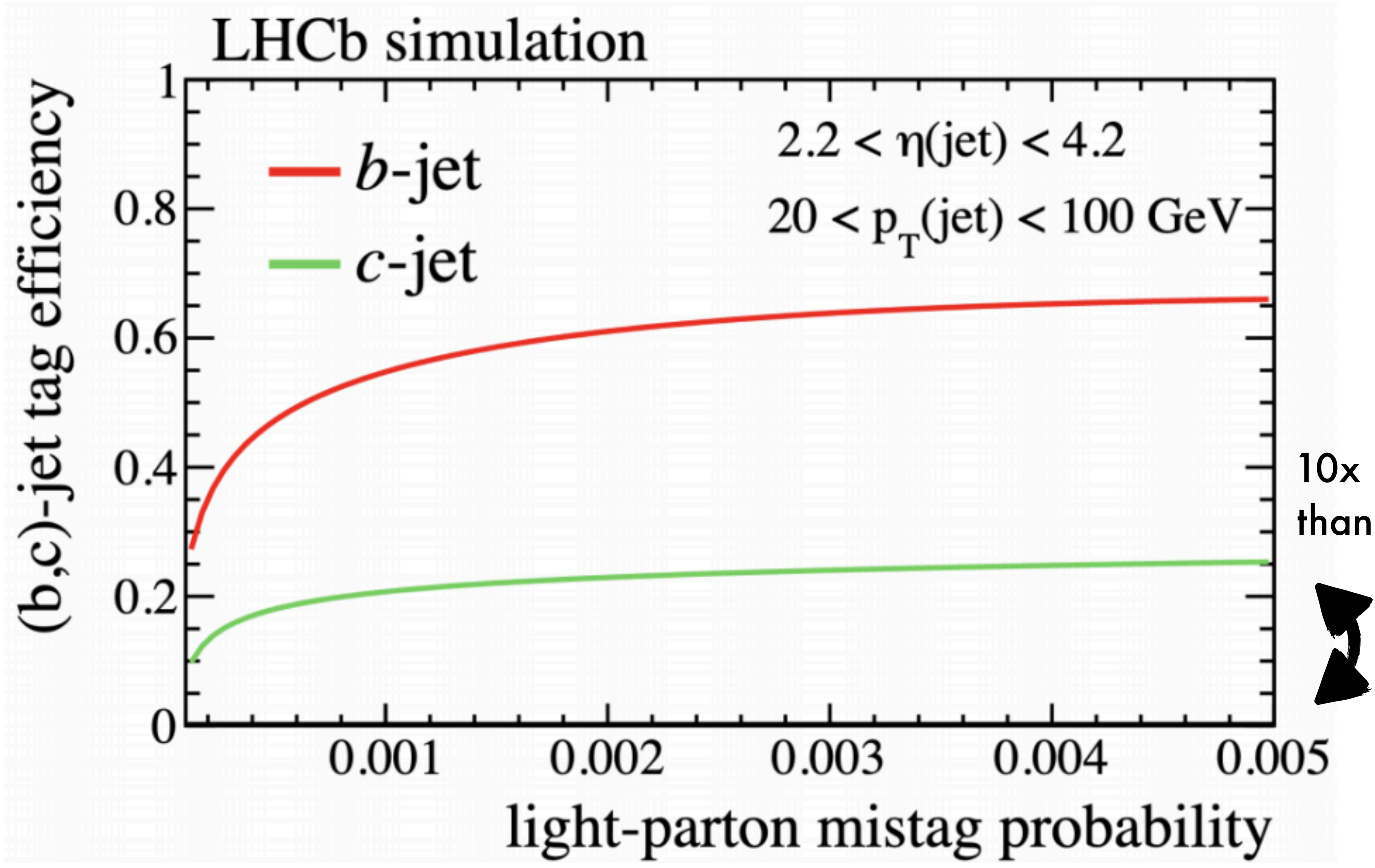
Higgs to heavy flavours at LHCb

D. Zuliani@H2020

Higgs mass



b-jet and c-jet tagging

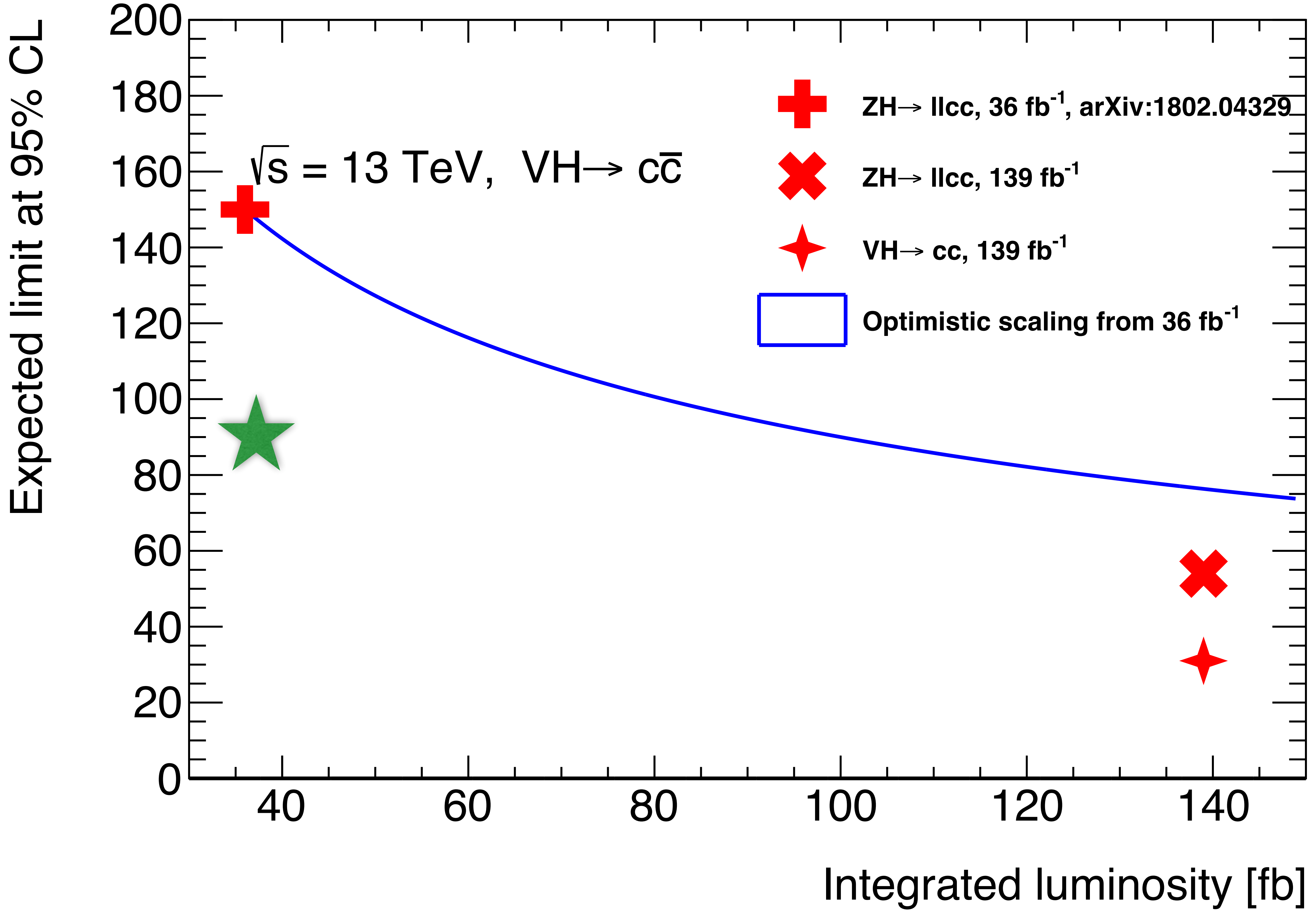


10x better light-jet rej. than ATLAS and CMS

Direct search for VHbb/ VHcc at LHCb with Run 1 data (2/fb)

- Challenging measurement: focus with event with at least one lepton reconstructed
- Current sensitivity: $y^b < 7y^b_{SM}$, $y^c < 80y^c_{SM}$ ~6400x SM
- Flavour tagging performance:
  - b-tagging similar to ATLAS and CMS and c-tagging 10x better on light jet rejection
- Projection for HL-LHC with upgrades of LHCb detector: **4x** SM

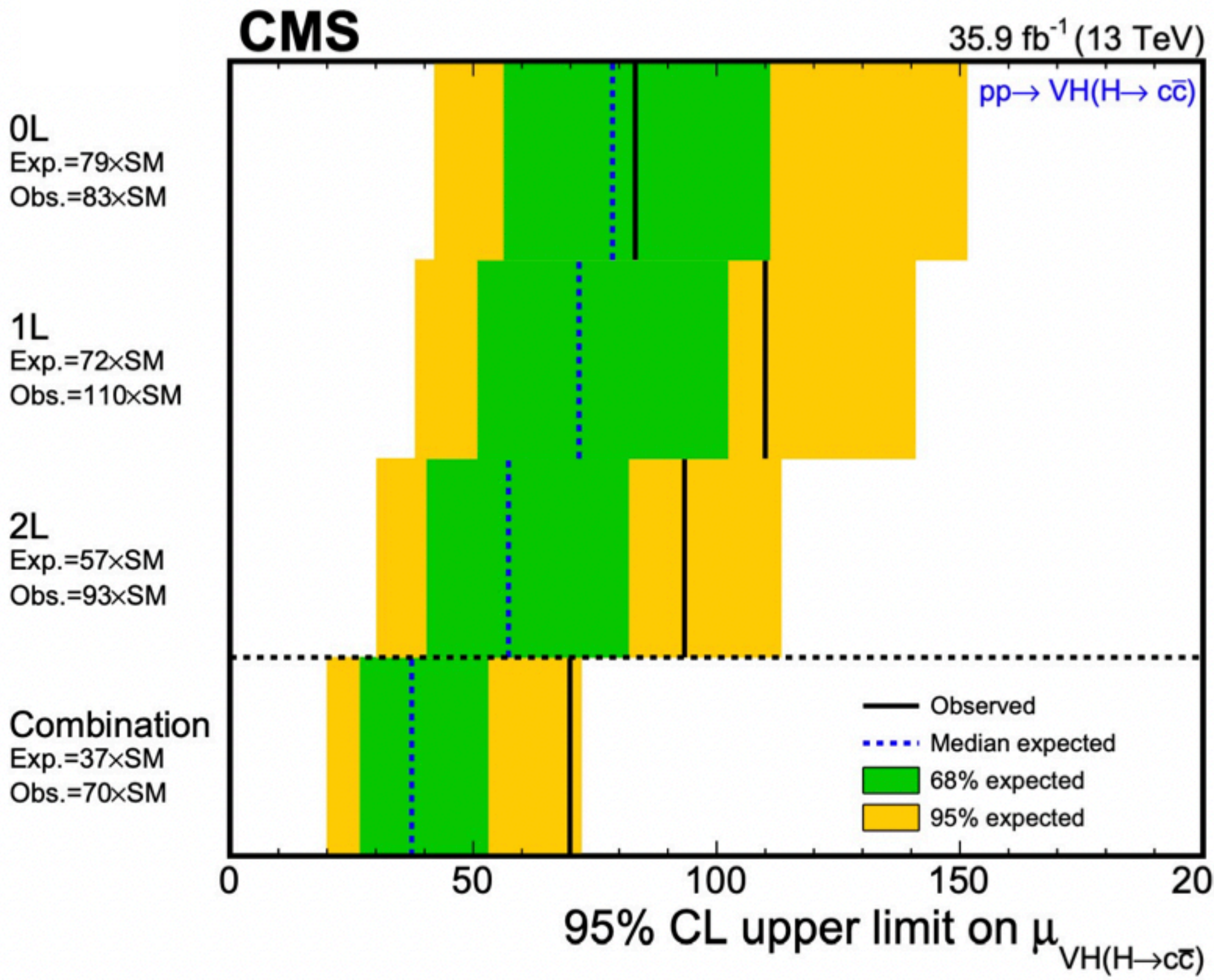
Sensitivity timeline of VHcc

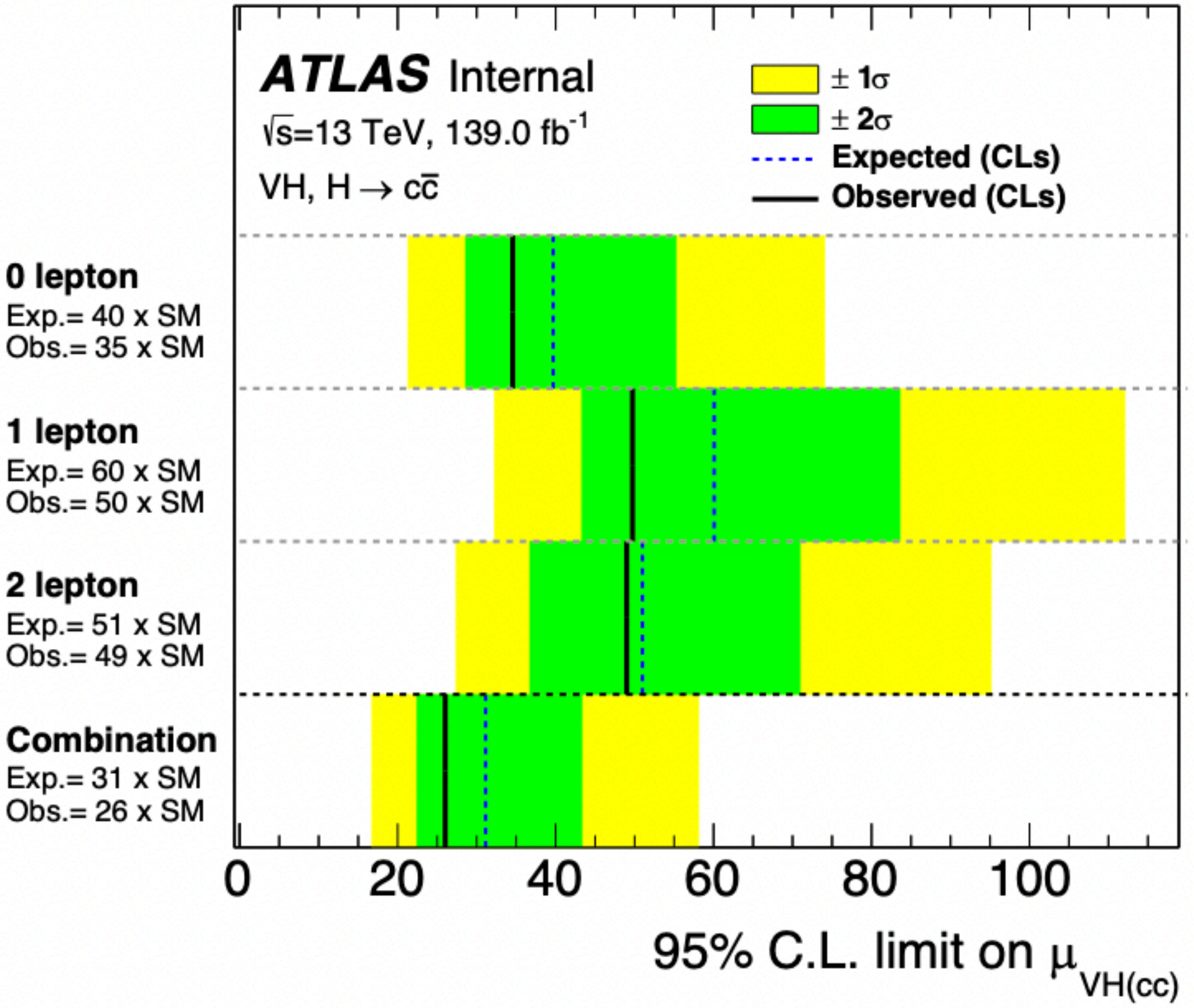


Improvements with respect to Z(ll)H(cc) 36/fb ATLAS result:

- Comparison 2-lepton only with 36/fb: **+43% sensitivity** in latest analysis
- Better performance of flavour tagger + full Run 2 updated calibrations
- Additional control regions to constrain main backgrounds
- Outperforming optimistic scaling: assuming that both stat. and syst. scale with luminosity

Comparison ATLAS vs CMS





Comparison with CMS:

- CMS expected limit: **37xSM** with 36/fb
- ATLAS expected limit: **31x SM** with 139/fb
- ATLAS expected limit only **20%** better than CMS with 4x more data

Comparison ATLAS vs CMS

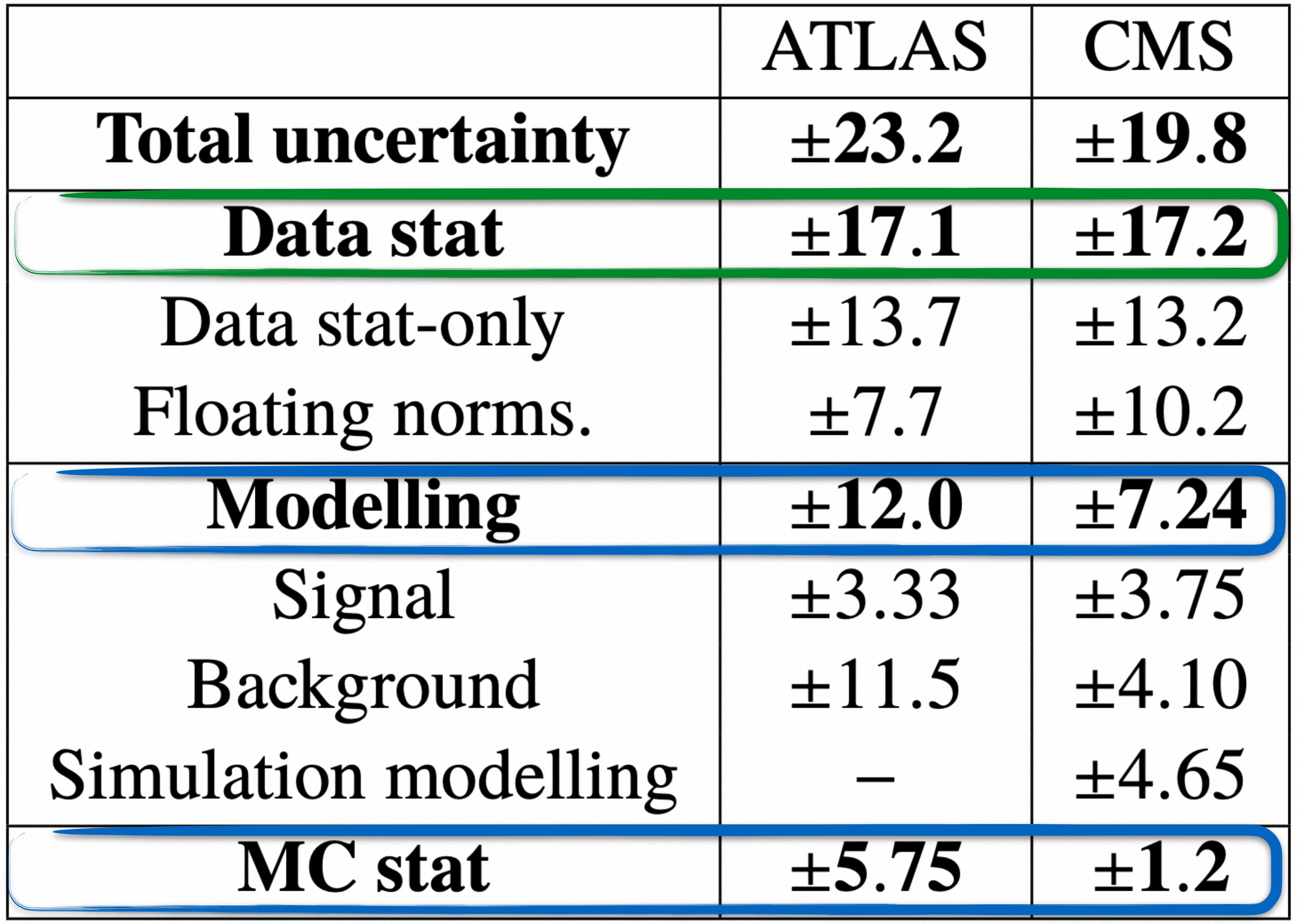
Main differences	ATLAS 139/fb	CMS 36/fb
Categorisation	1 c-tag, 2 c-tag	2 c-tag
Discriminant	m(cc)	MVA
VH(bb) treatment	Orthogonal	Overlap

Charm tagging	ATLAS 139/fb	CMS 36/fb
c-jets	27%	27%
b-jet	**8%**	**17%**
light-jets	**1.6%**	**4%**

Key differences between ATLAS and CMS:

- Flavour tagging categorisation: CMS uses 2 c-tag only
- CMS sensitivity optimised using a machine learning approach
- VH(bb) treatment: ATLAS analysis orthogonal to VH(bb)
- Charm tagging: ATLAS performance 2x higher in background rejection
  - Partly due to insertable b-layer in ATLAS tracker

Comparison ATLAS vs CMS: breakdown of uncertainties



	ATLAS	CMS
Total uncertainty	**±23.2**	**±19.8**
Data stat	**±17.1**	**±17.2**
Data stat-only	±13.7	±13.2
Floating norms.	±7.7	±10.2
Modelling	**±12.0**	**±7.24**
Signal	±3.33	±3.75
Background	±11.5	±4.10
Simulation modelling	–	±4.65
MC stat	**±5.75**	**±1.2**

Comparison of uncertainties for ATLAS and CMS at 36/fb

- Statistical sensitivity: similar results between ATLAS and CMS
- CMS: lower uncertainty on theoretical prediction and size of simulated sample
  - Rely more on control regions for the backgrounds + larger size of simulated sample

HL-LHC slide

Conclusion

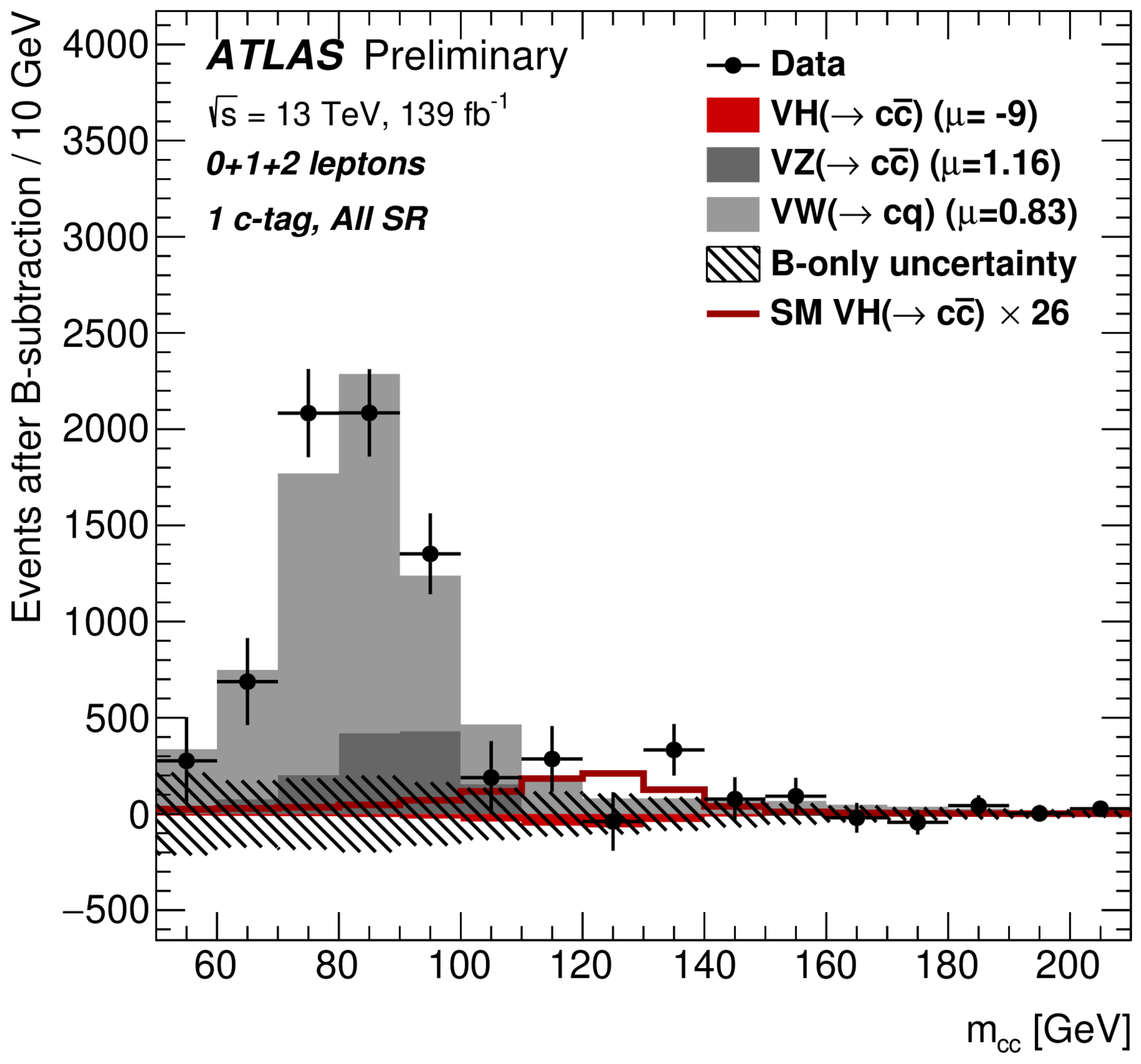
New result from the ATLAS on Higgs coupling to c-quarks

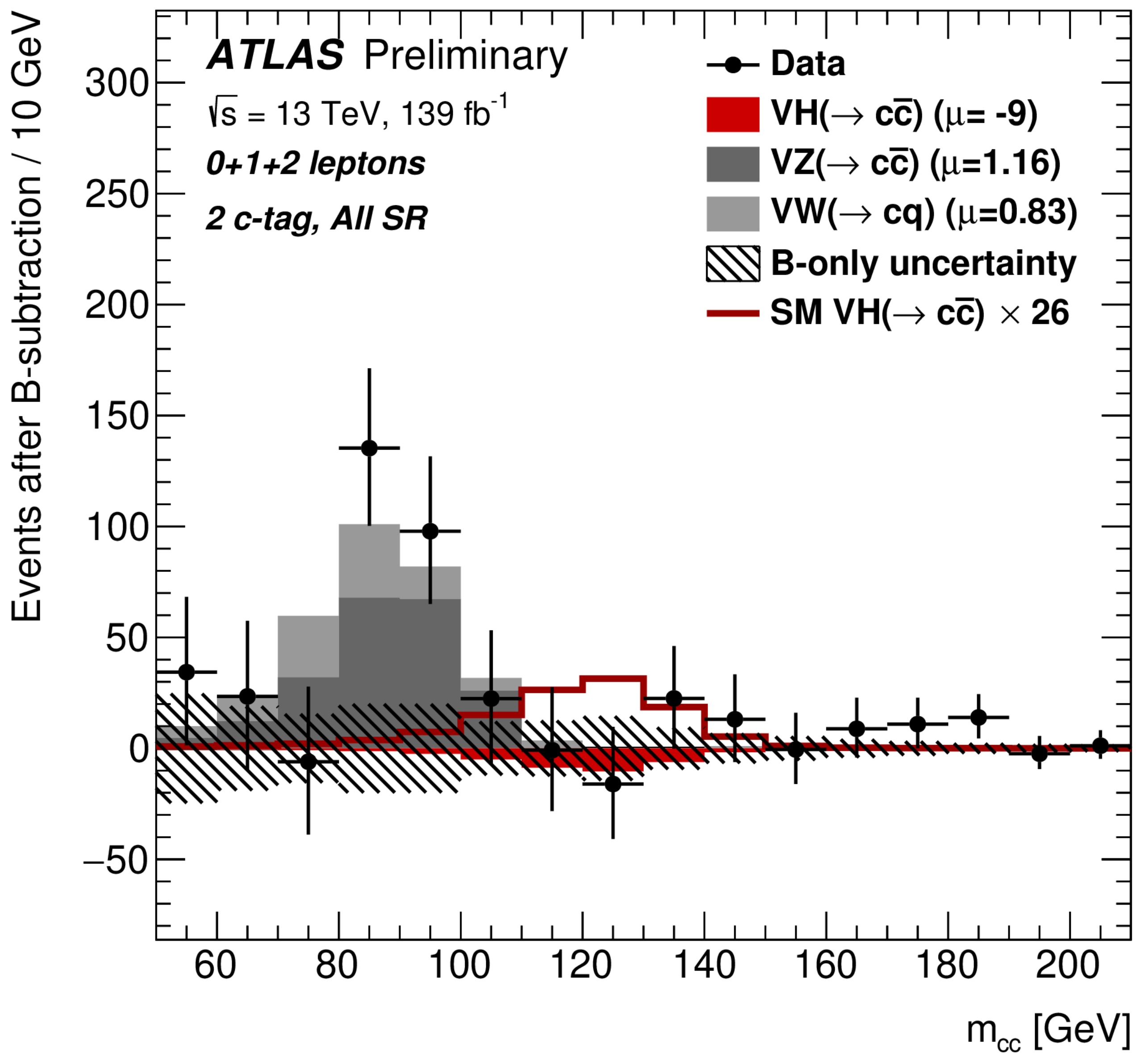
- Limit on the signal strength: **< 26** x SM at 95% confidence level
- Direct constraint on **$|\kappa_c|$ < 8.5** @ 95% CL
- Excess of VZ(→cc) events observed: **2.6σ**
- Excess of VW(→cq) events observed: **3.8σ**

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

Prospects for Higgs physics and c-tagging at LHC:

- More and more physics analyses using c-tagging
- ATLAS, CMS and LHCb working towards measuring Higgs coupling to charm
  - Evidence at the end of HL-LHC using a combination?





Back up

Combination with VH(bb)?

Combination of VH(bb) and VH(cc)

Stand-alone analysis

$$\mu_{VH(cc)} = \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$$

$$\mu_{VH(bb)} = \frac{\kappa_V^2 \kappa_b^2}{\kappa_H^2}$$

$$\longrightarrow$$

Combined measurement

$$\frac{\mu_{VH(cc)}}{\mu_{VH(bb)}} = \frac{\kappa_c^2}{\kappa_b^2}$$

Combination of VH(bb) and VH(cc):

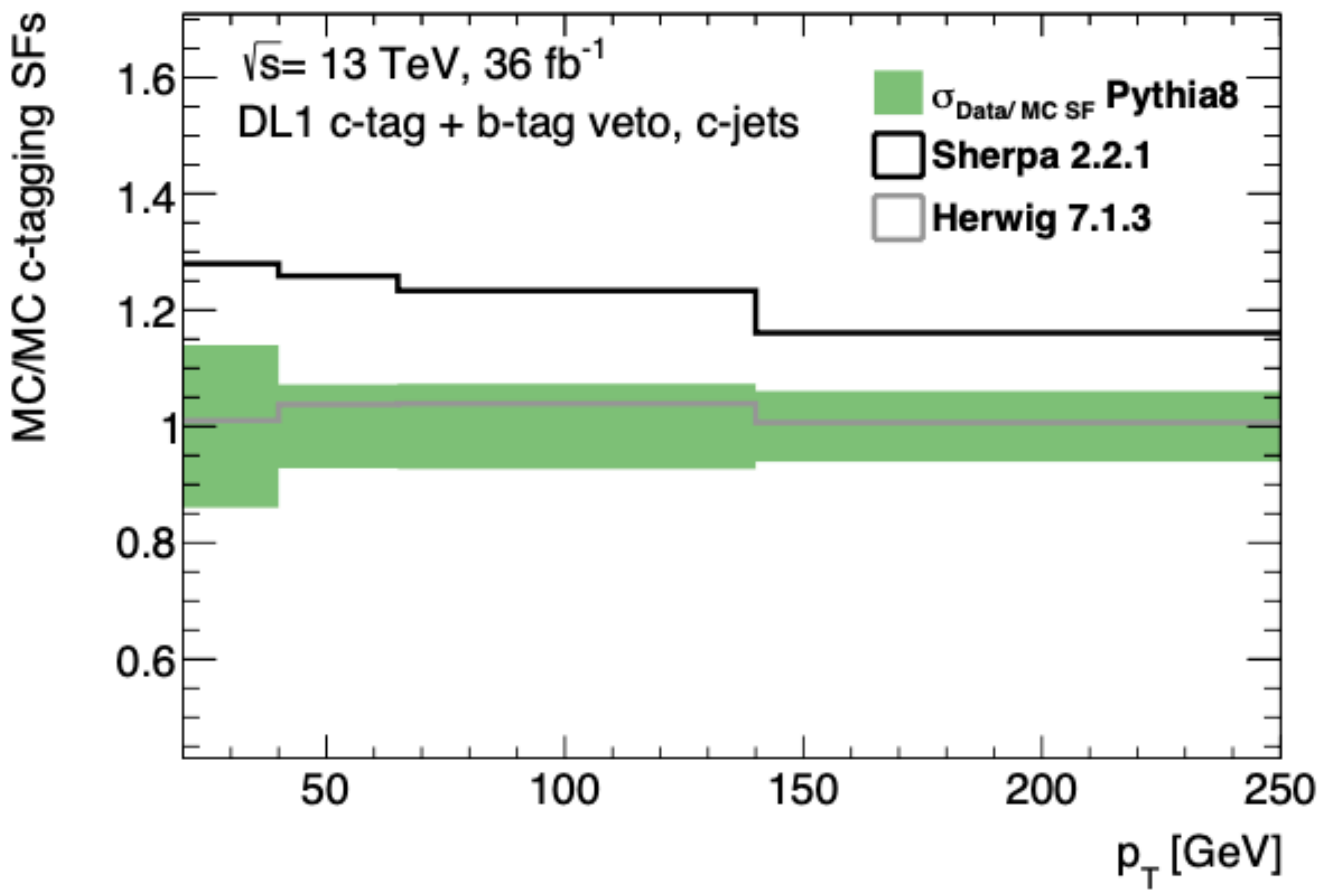
- Allows better interpretation of Higgs boson properties with minimal assumptions
- Not sensitive to contributions of new physics particles to the Higgs boson decay width
- Direct probe of the Higgs coupling to charm and bottom quarks only

Comparison ZHcc and CMS

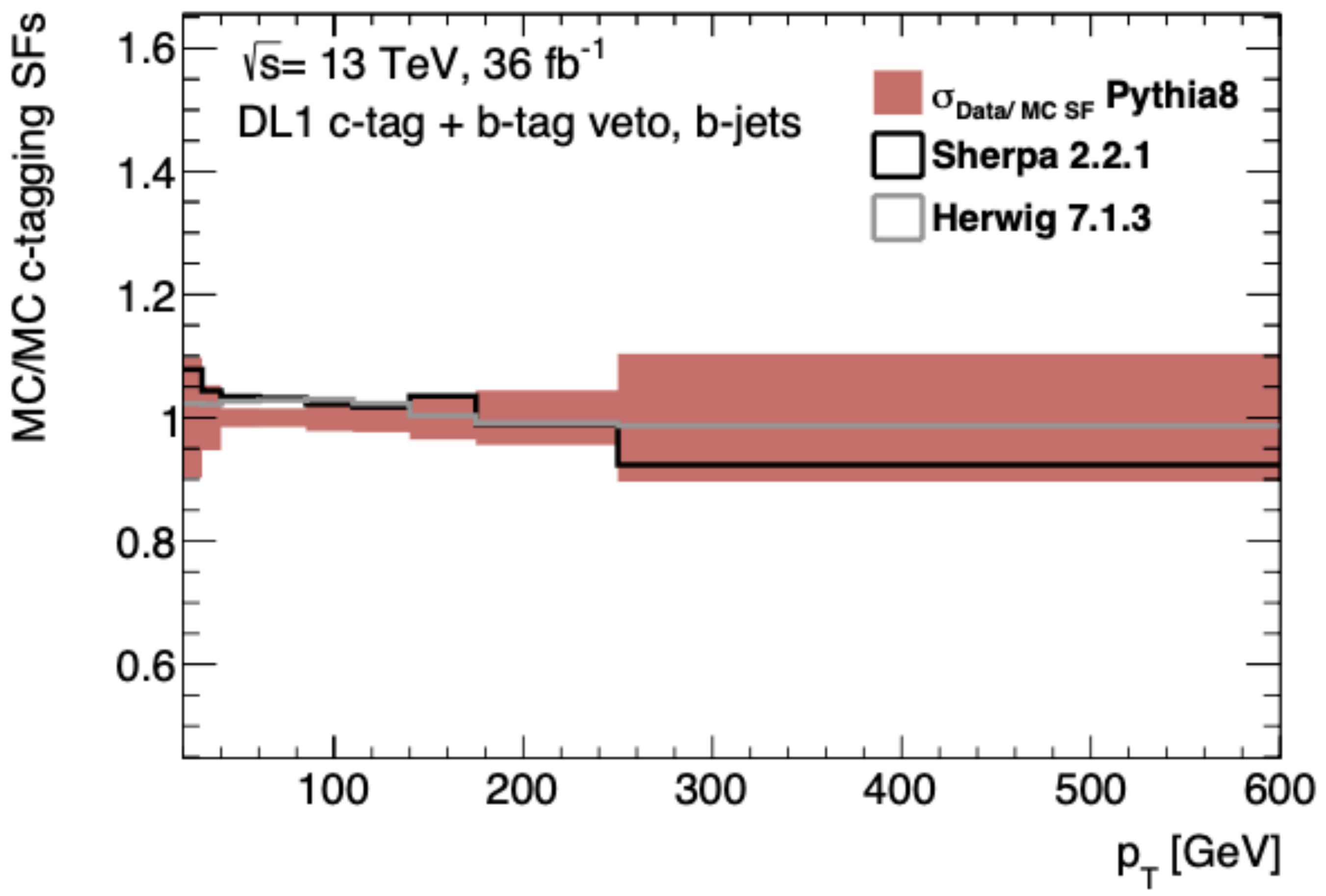
Comparison VHcc 139/fb vs ZHcc 36/fb

	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**

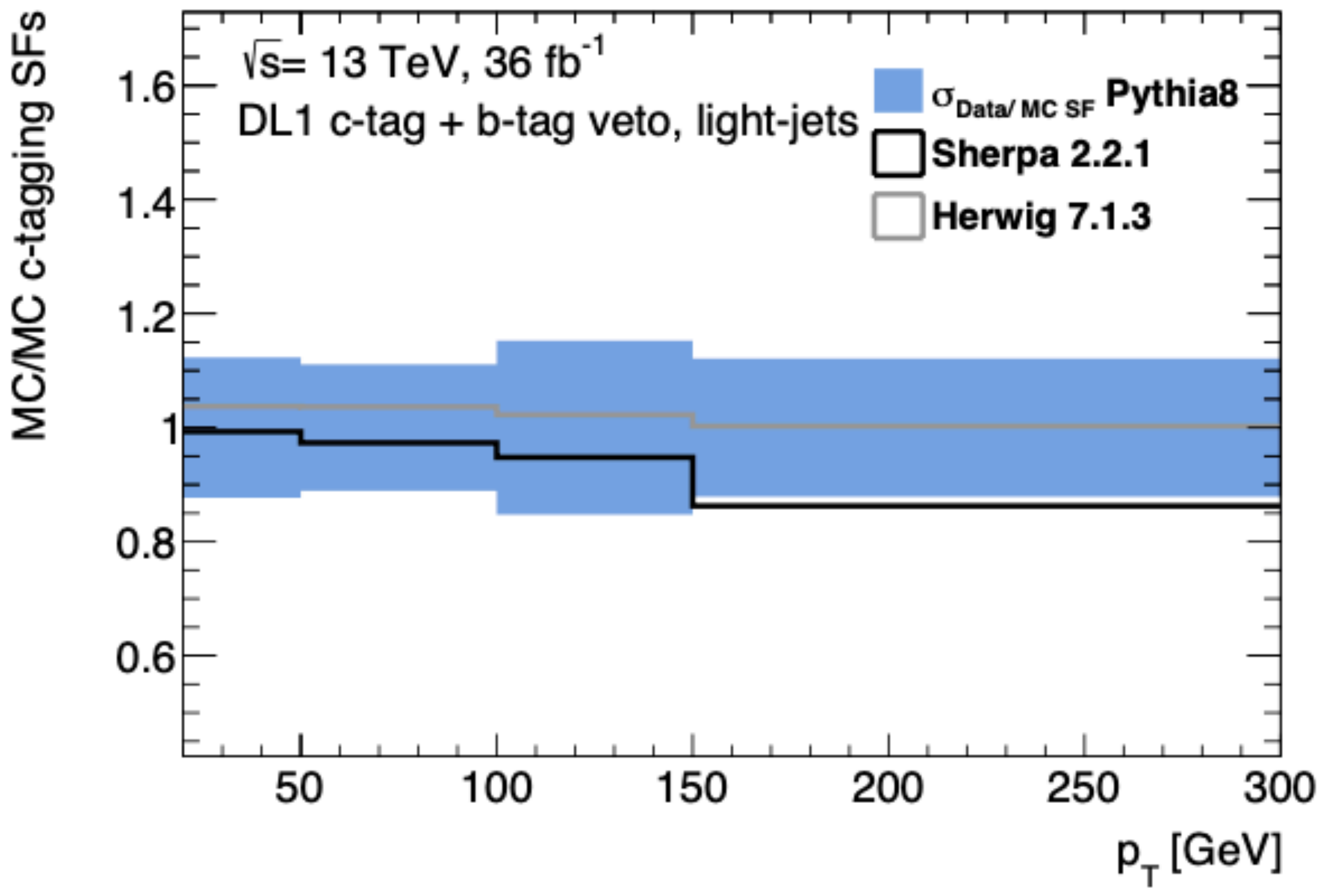
MC/MC



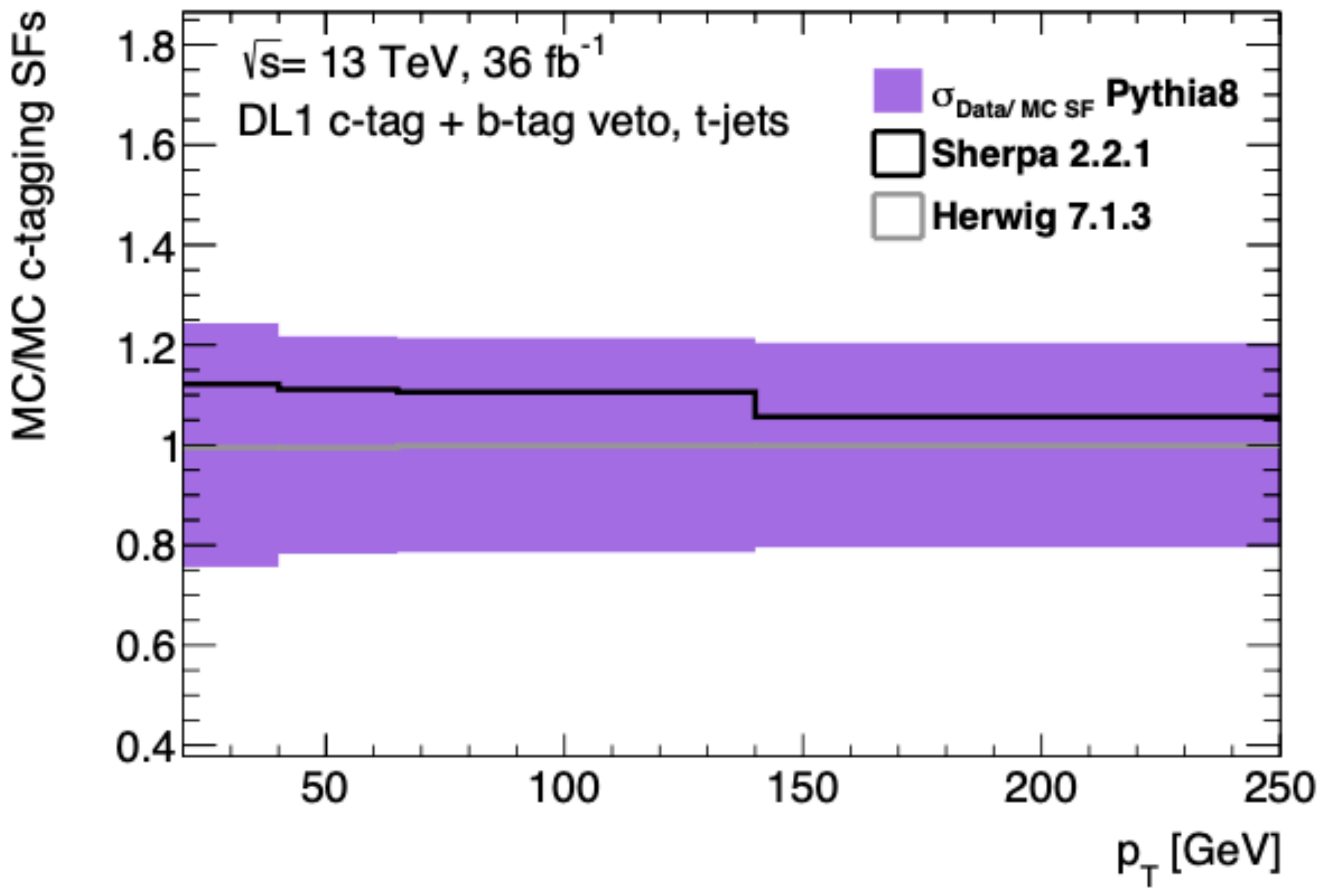
(a) MC/MC scale factor c-jets



(b) MC/MC scale factor b-jets



(c) MC/MC scale factor light-jets



(d) MC/MC scale factor τ-jets

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)

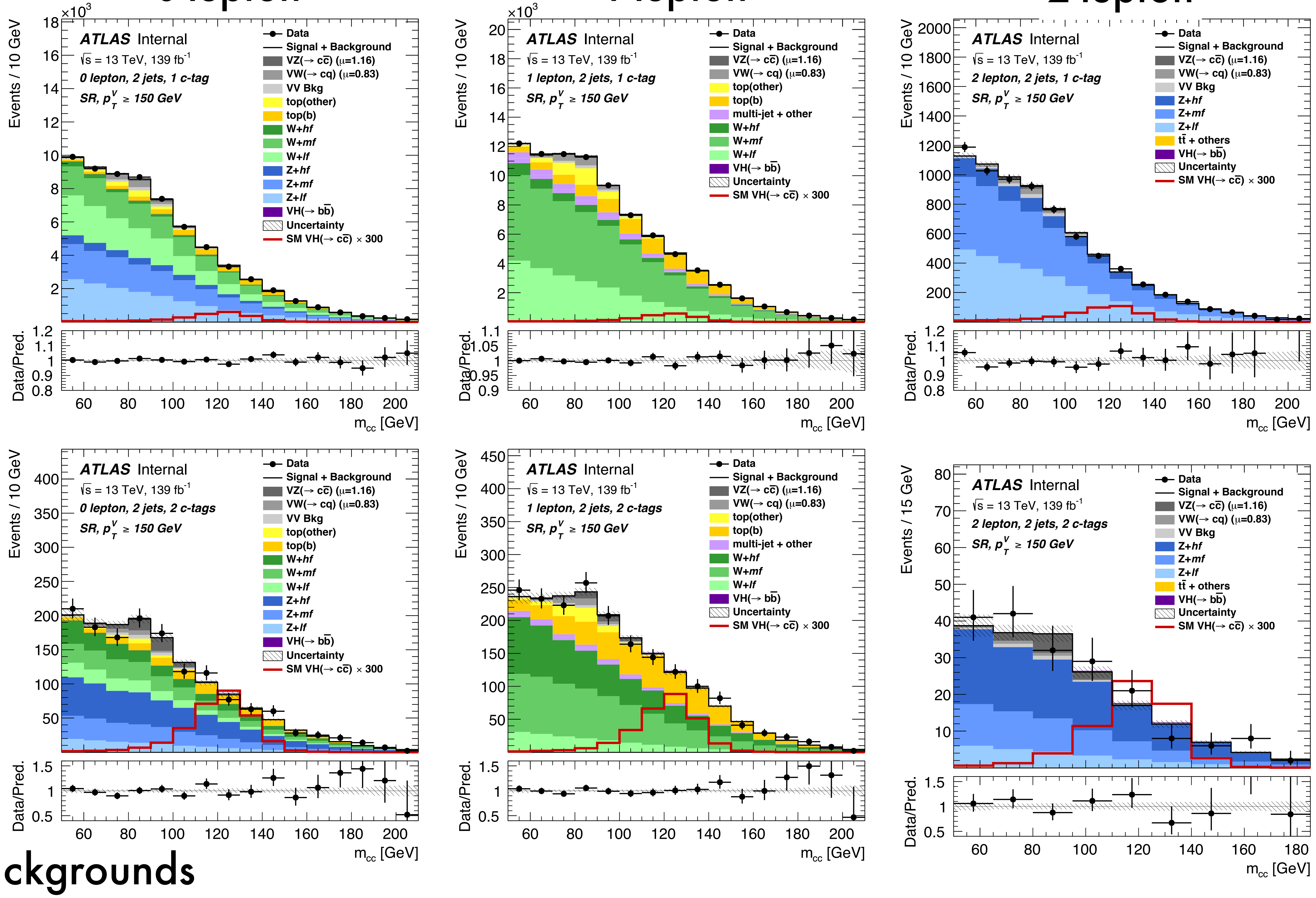
Signal region: example

2 jets, pTV > 150 GeV

0-lepton 1-lepton 2-lepton

1 c-tag

2 c-tag



Process	Label	Description
Z+(bb,cc)	Z+hf	Heavy flavours
Z+(cl,bl,bc)	Z+mf	Mixed flavours
Z+(ll)	Z+lf	Light flavours
W+(bb,cc)	W+hf	Heavy flavours
W+ (cl,bl,bc,bτ,cτ)	W+mf	Mixed flavours
W+(ll,lτ)	W+lf	Light flavours
ttbar + Wt	top(b)	≥1 b-jet
	top(other)	0 b-jet

Main backgrounds

- 0-lepton: Z+hf, Z+mf, Z+lf, W+hf, W+mf, W+lf, top(b), top(other)
- 1-lepton: W+hf, W+mf, W+lf, top(b), top(other)
- 2-lepton: Z+hf, Z+mf, Z+l

Subdominant backgrounds: VH(bb), single top s+t, QCD multi-jets, diboson (non c-jets)

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

Background modelling

Floating normalisations:

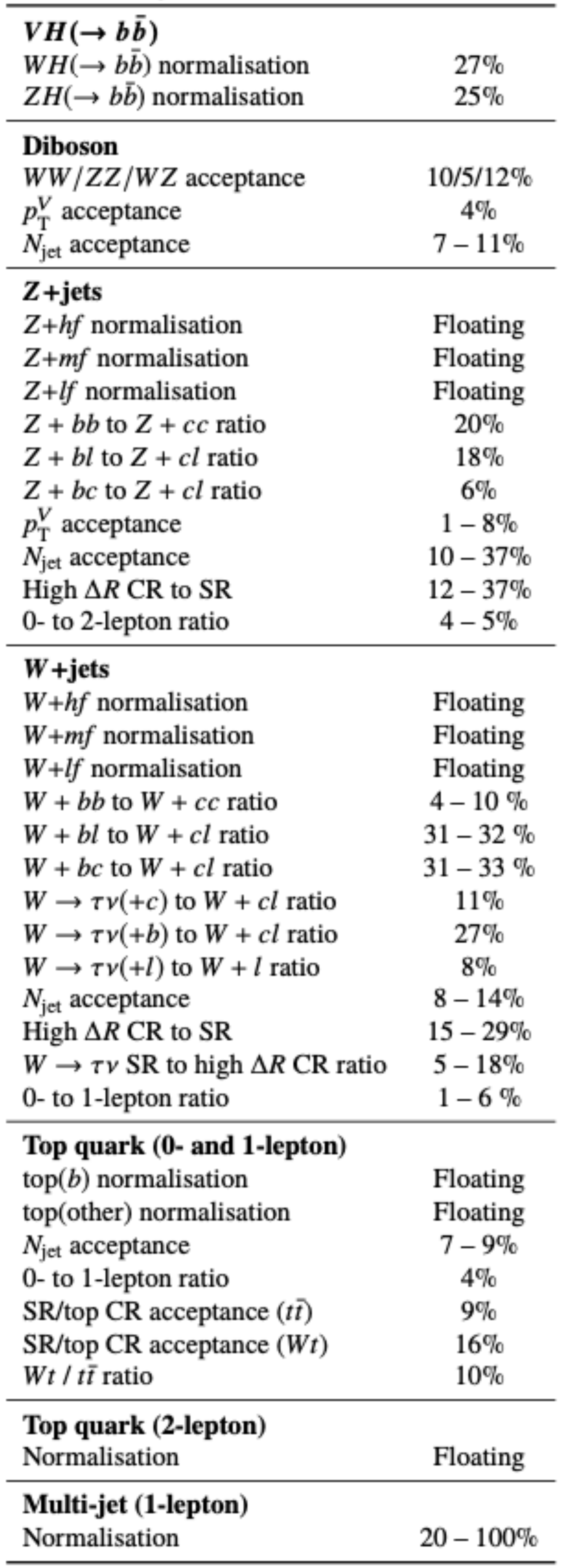
- Heavy flavour: Zhf and Whf
- Mixed flavour: Zmf and Wmf
- Light flavour: Zlf and Wlf
- top(b) and top(other) (0- and 1-lepton)
- ttbar (2-lepton)

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

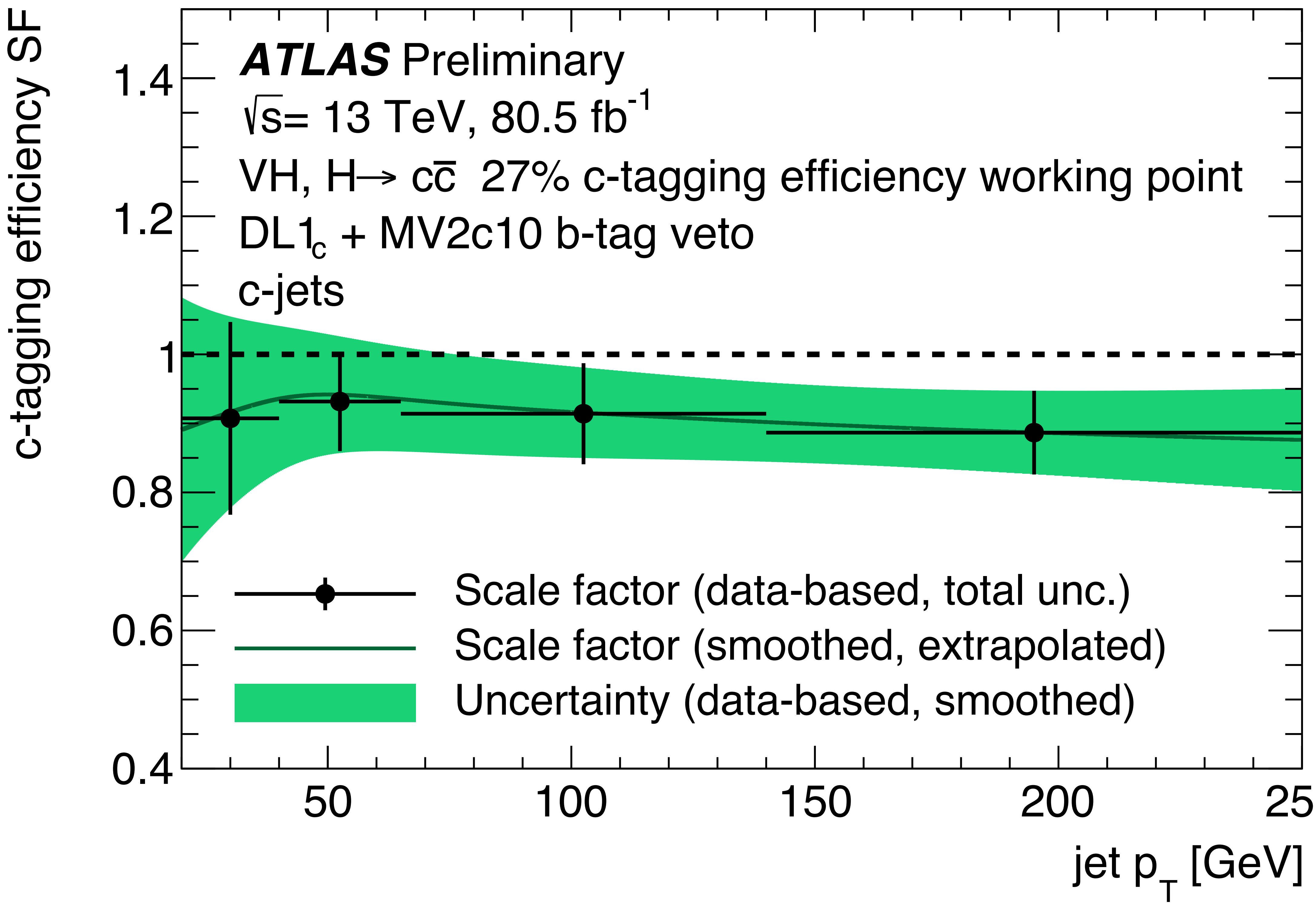
Shape uncertainties: on m(cc) for each bkg subcomponent

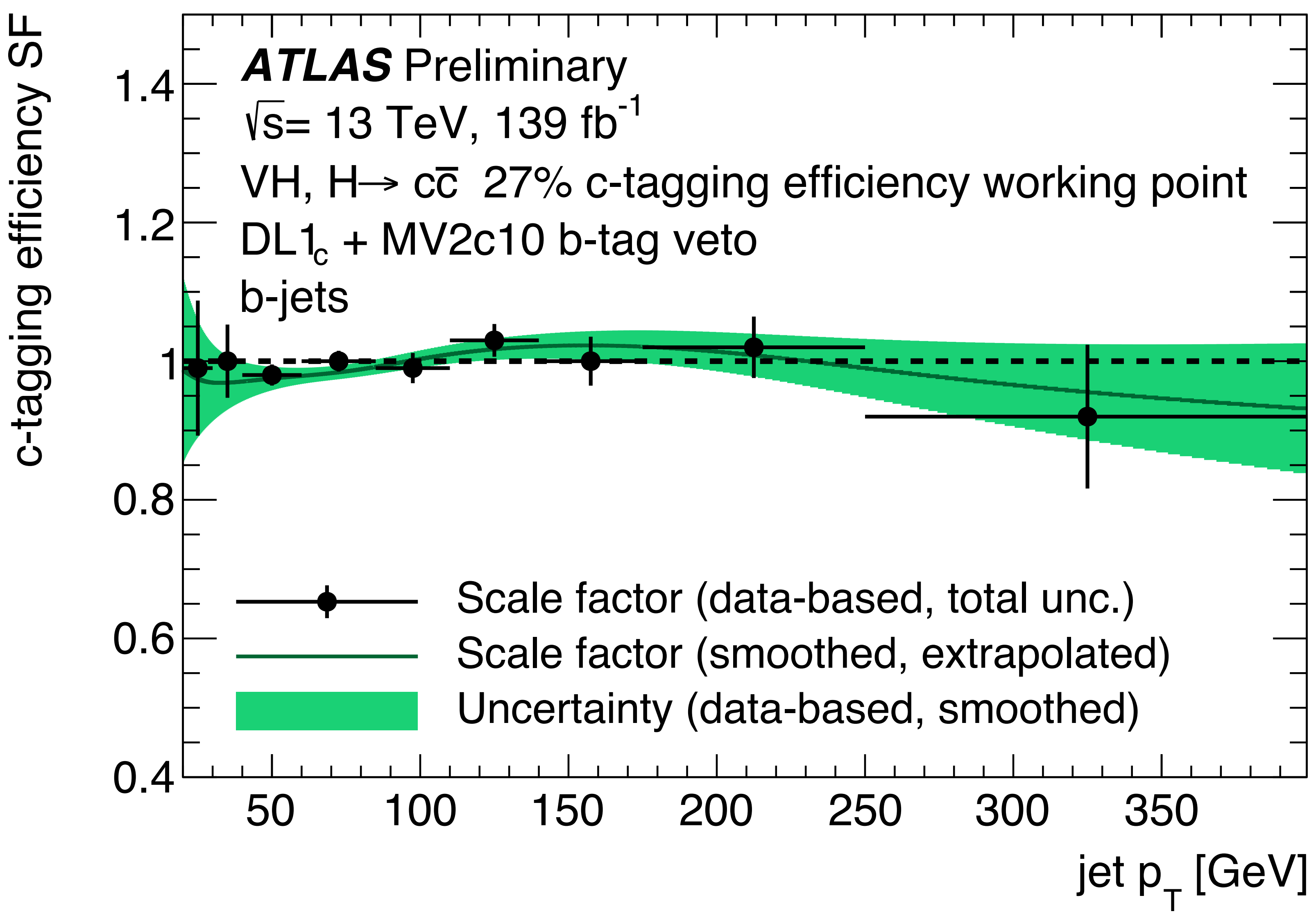
Data driven: QCD multi-jets in 1-lepton

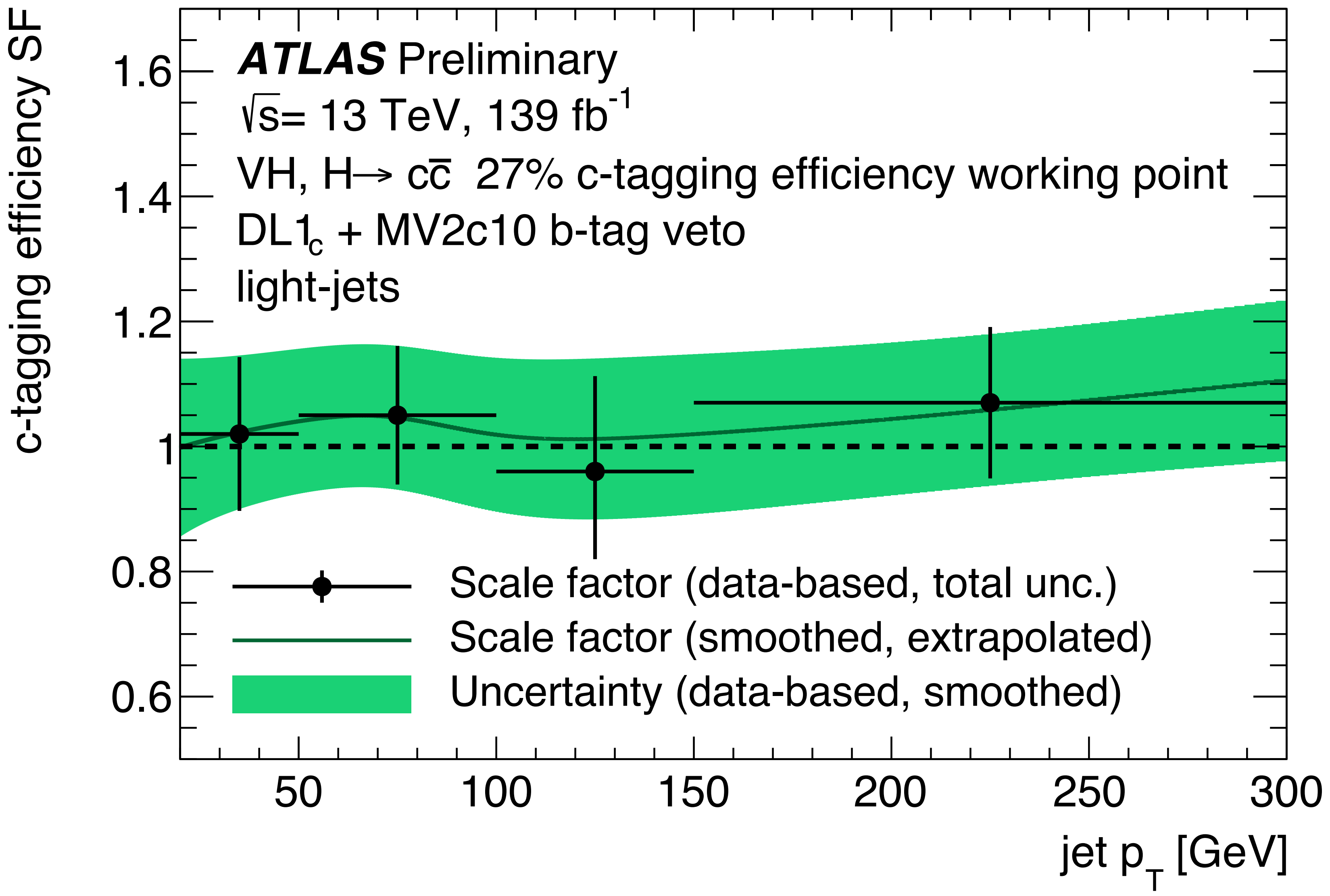


$VH(\rightarrow b\bar{b})$	
$WH(\rightarrow b\bar{b})$ normalisation	27%
$ZH(\rightarrow b\bar{b})$ normalisation	25%
Diboson	
$WW/ZZ/WZ$ acceptance	10/5/12%
p_T^V acceptance	4%
N_{jet} acceptance	7 – 11%
Z+jets	
Z+hf normalisation	Floating
Z+mf normalisation	Floating
Z+lf normalisation	Floating
$Z + bb$ 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 %
$W \rightarrow \tau\nu(+c)$ to $W + cl$ ratio	11%
$W \rightarrow \tau\nu(+b)$ to $W + cl$ ratio	27%
$W \rightarrow \tau\nu(+l)$ to $W + l$ ratio	8%
N_{jet} acceptance	8 – 14%
High ΔR CR to SR	15 – 29%
$W \rightarrow \tau\nu$ 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%

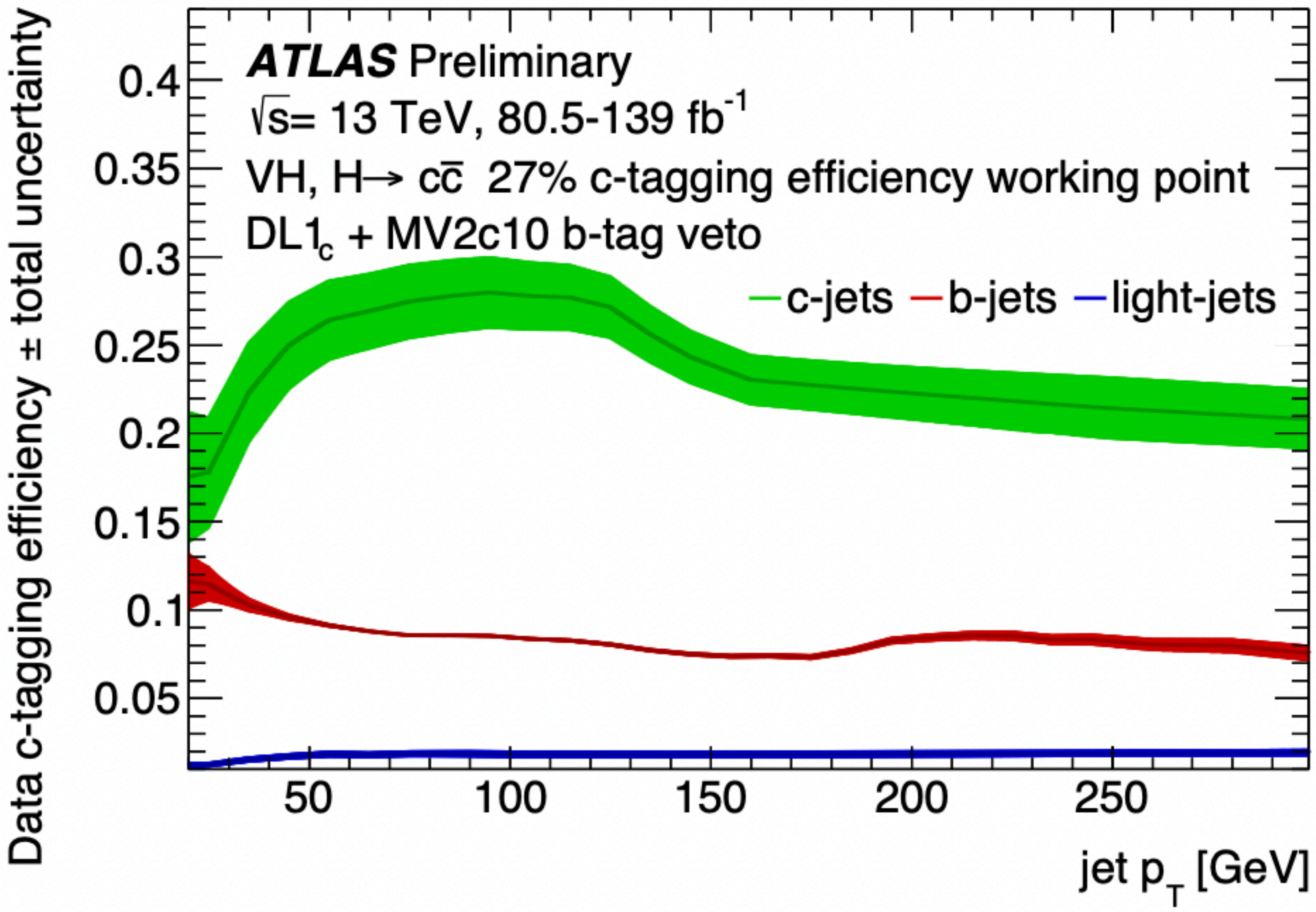
Charm tagging calibrations



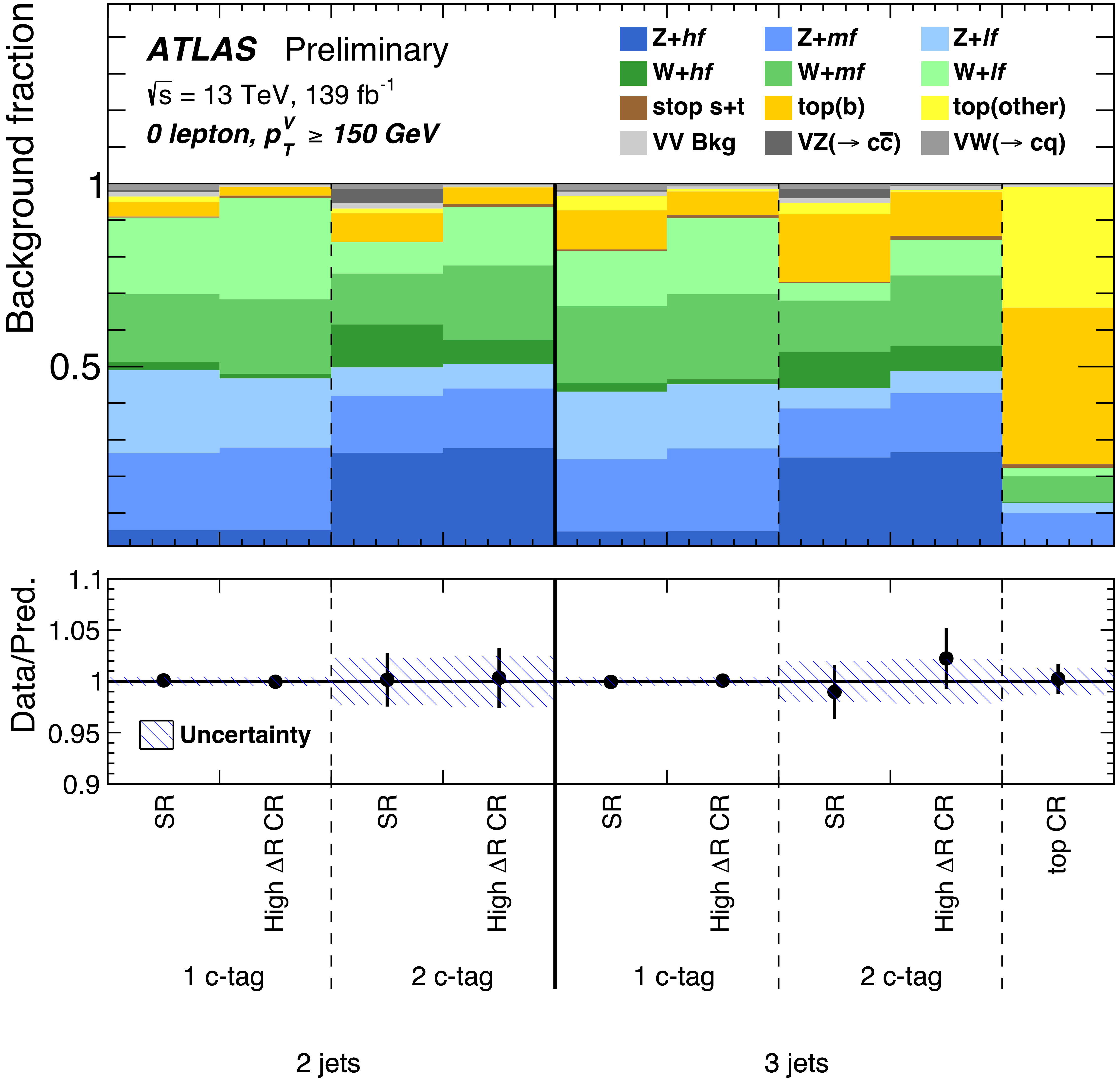




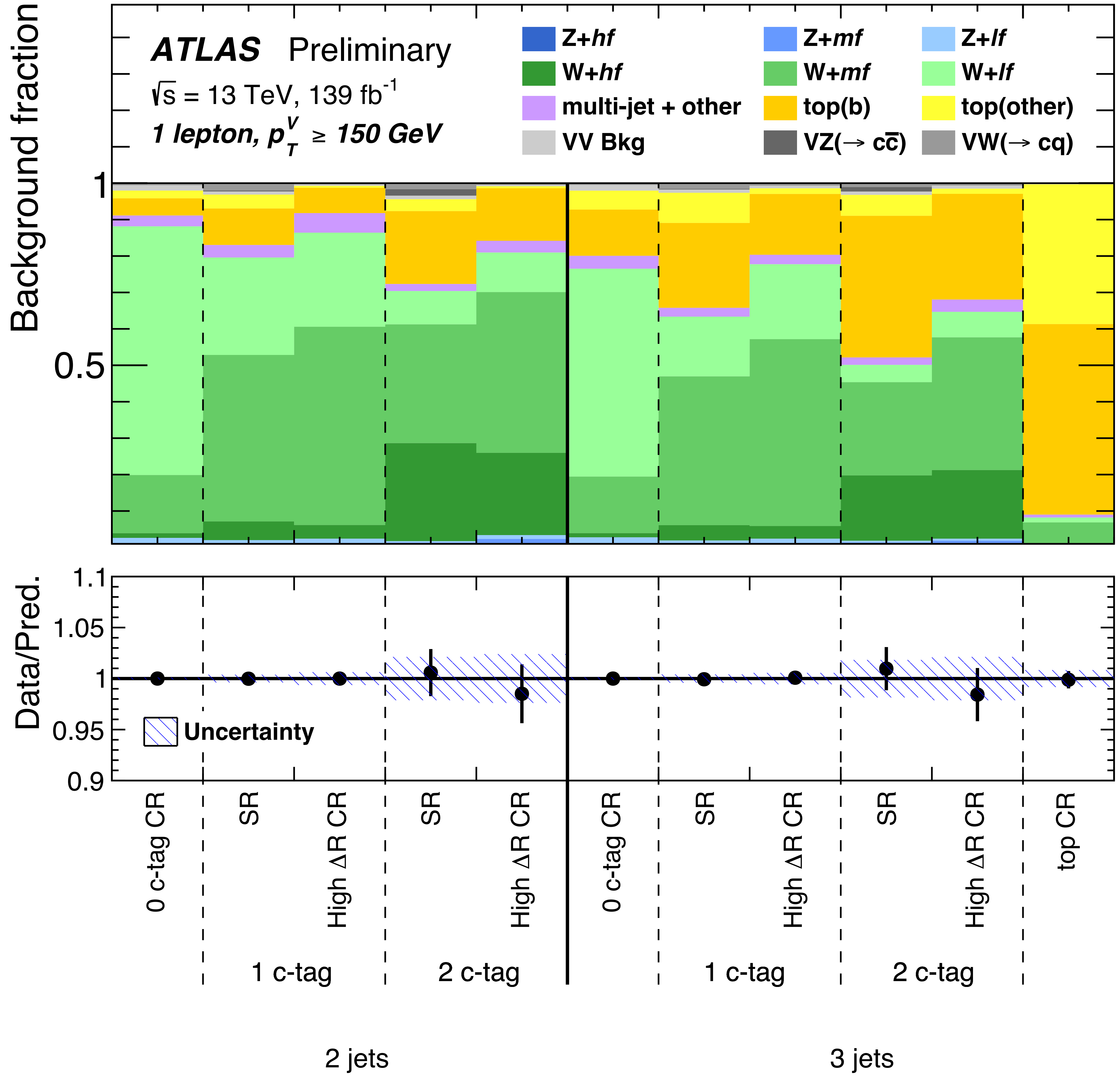
Charm tagging performance



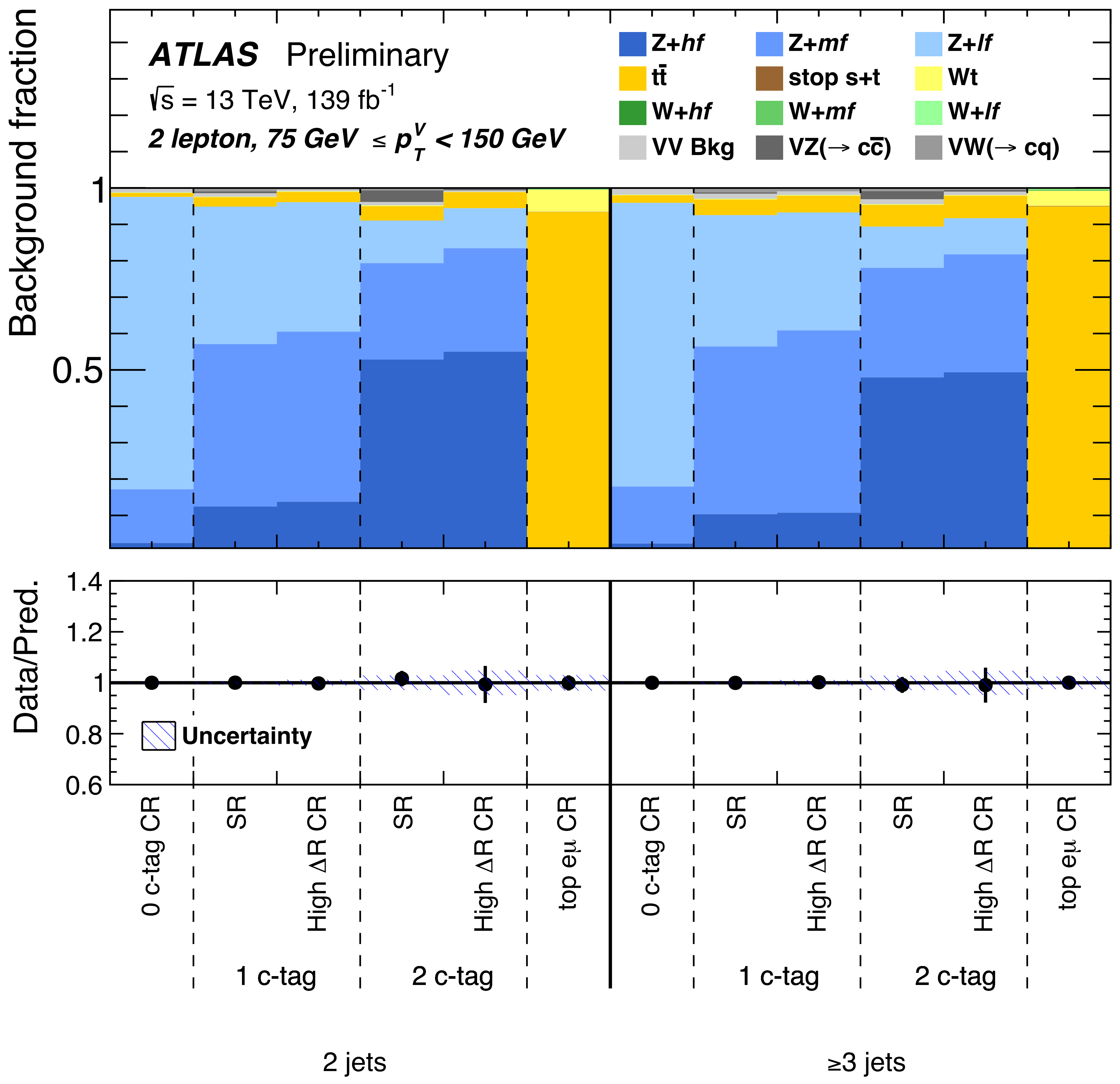
Background composition plots: postfit 0-lepton

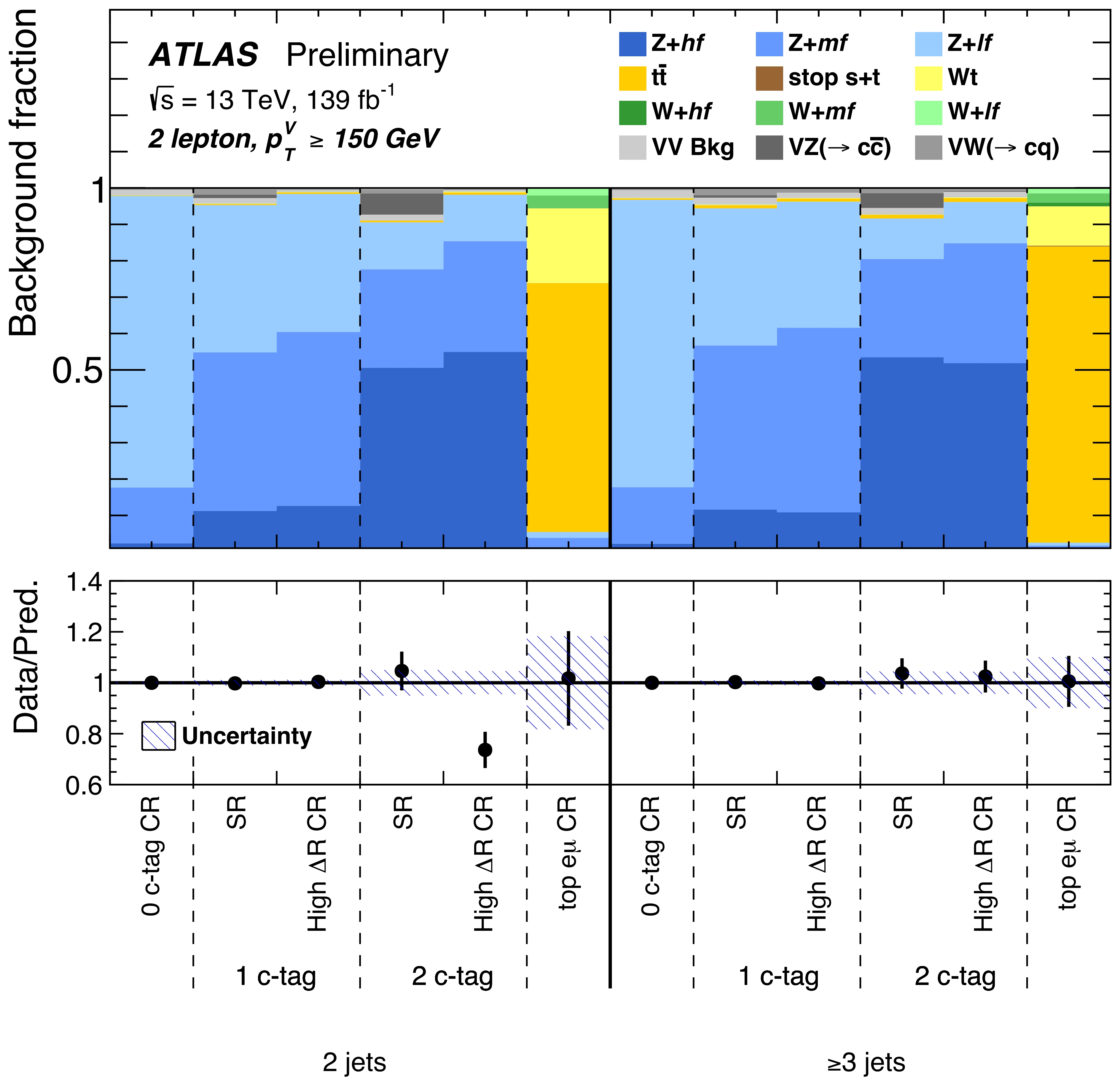


Background composition plots: postfit 1-lepton



Background composition plots: postfit 2-lepton





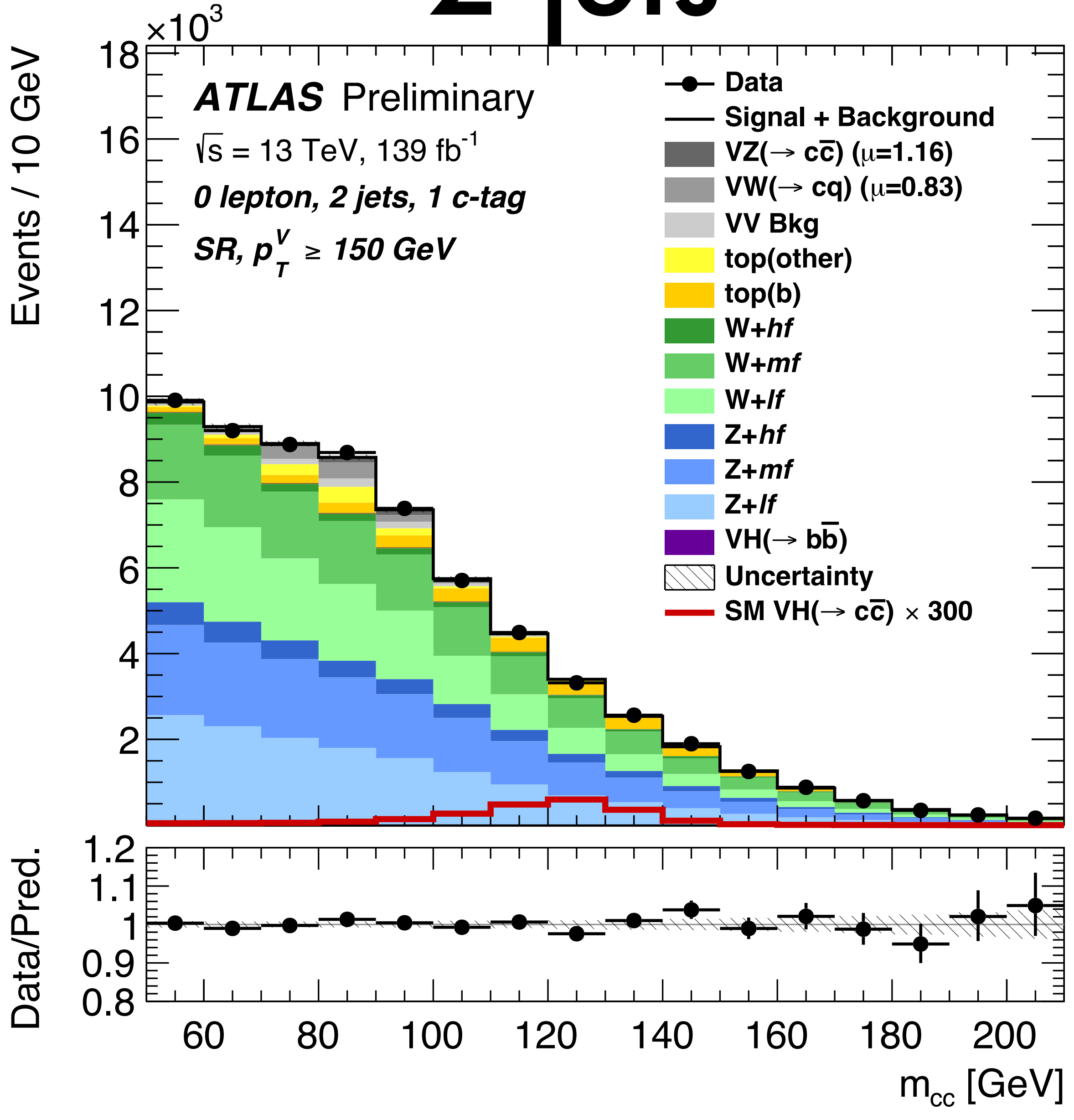
Postfit SR

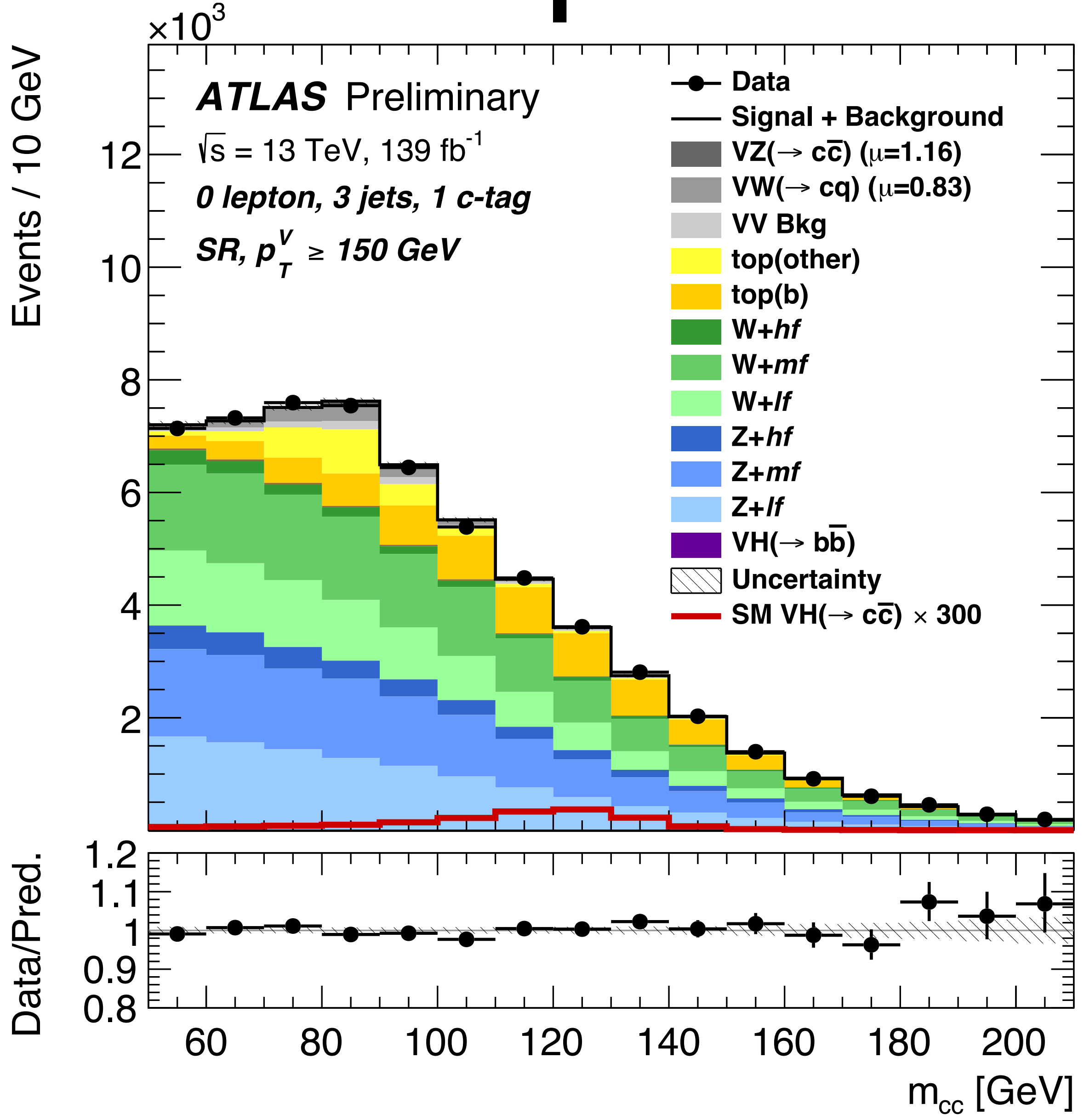
Postfit distributions: 0-lepton

2 jets

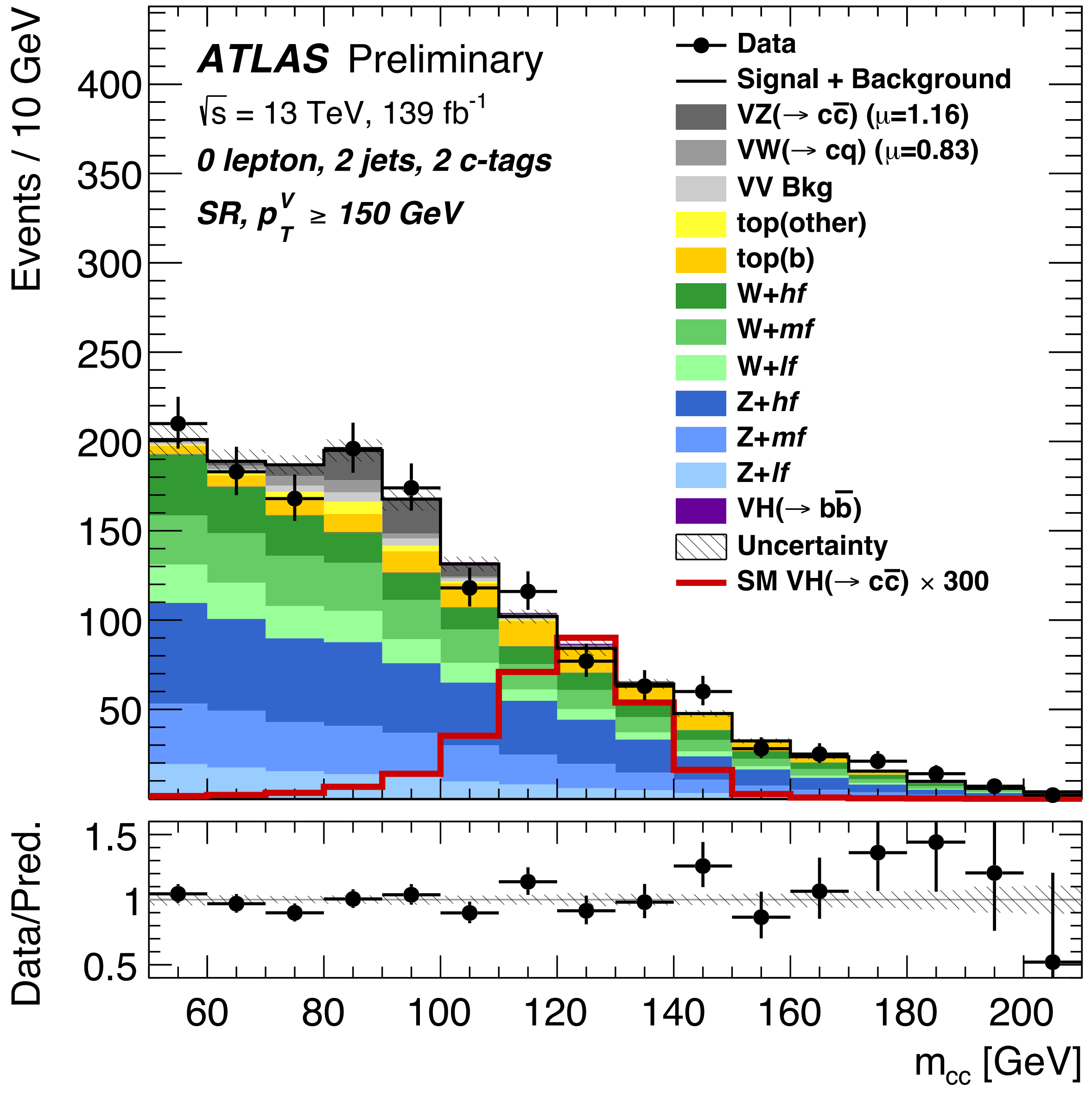
3 jets

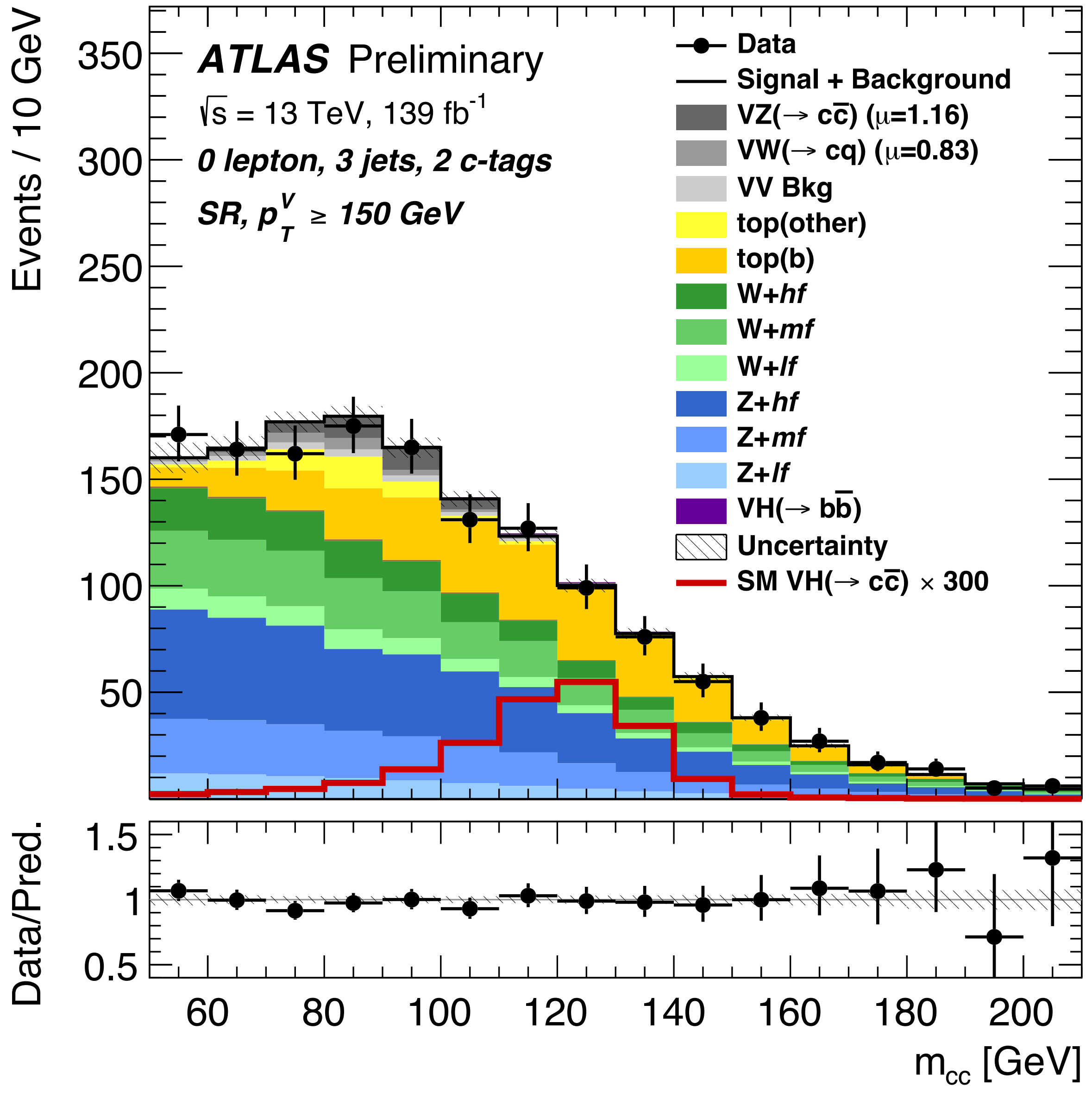
1 c-tag





2 c-tag





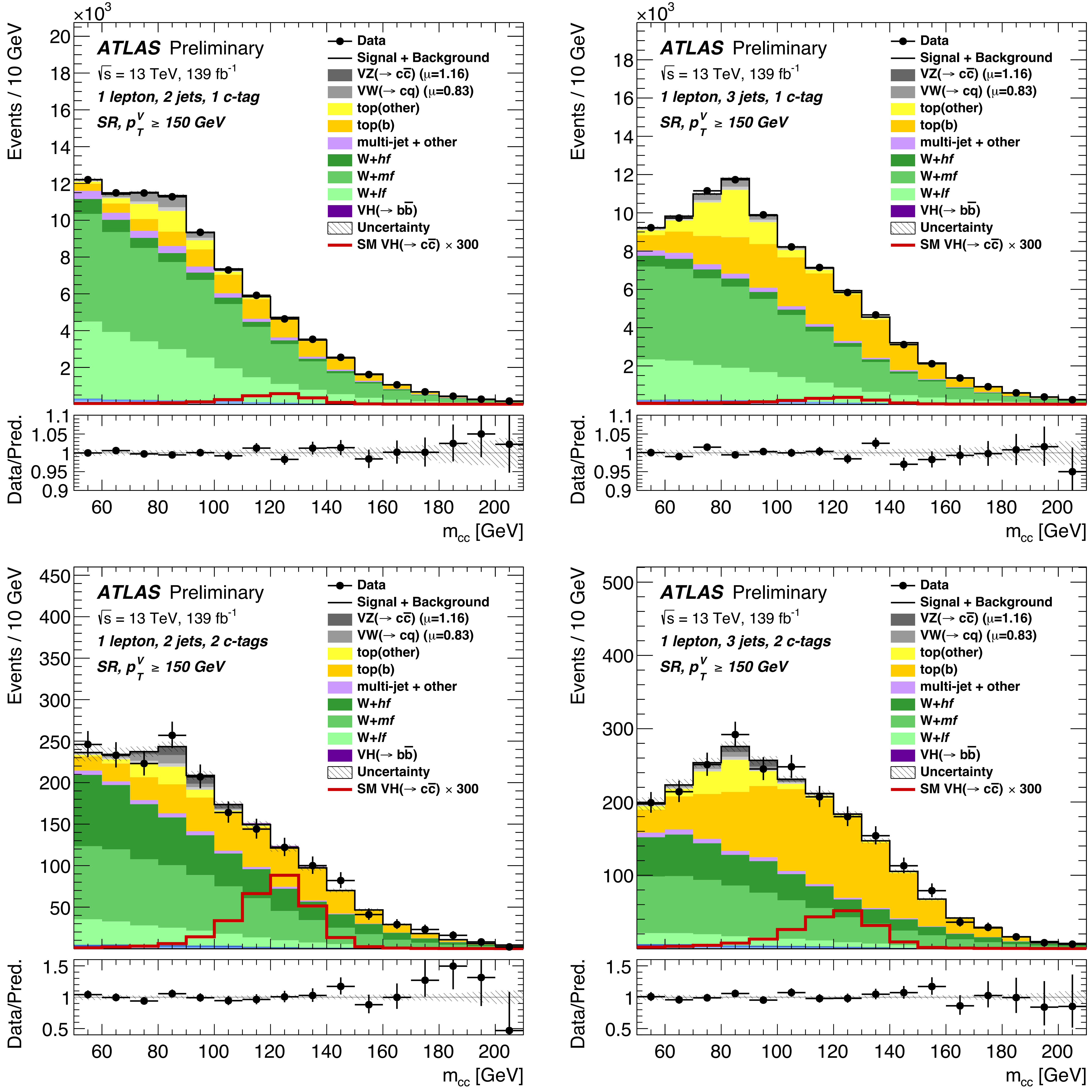
Postfit distributions: 1-lepton

2 jets

3 jets

1 c-tag

2 c-tag



Postfit distributions: 2-lepton

75 GeV < pTV < 150 GeV

pTV > 150 GeV

2 jets

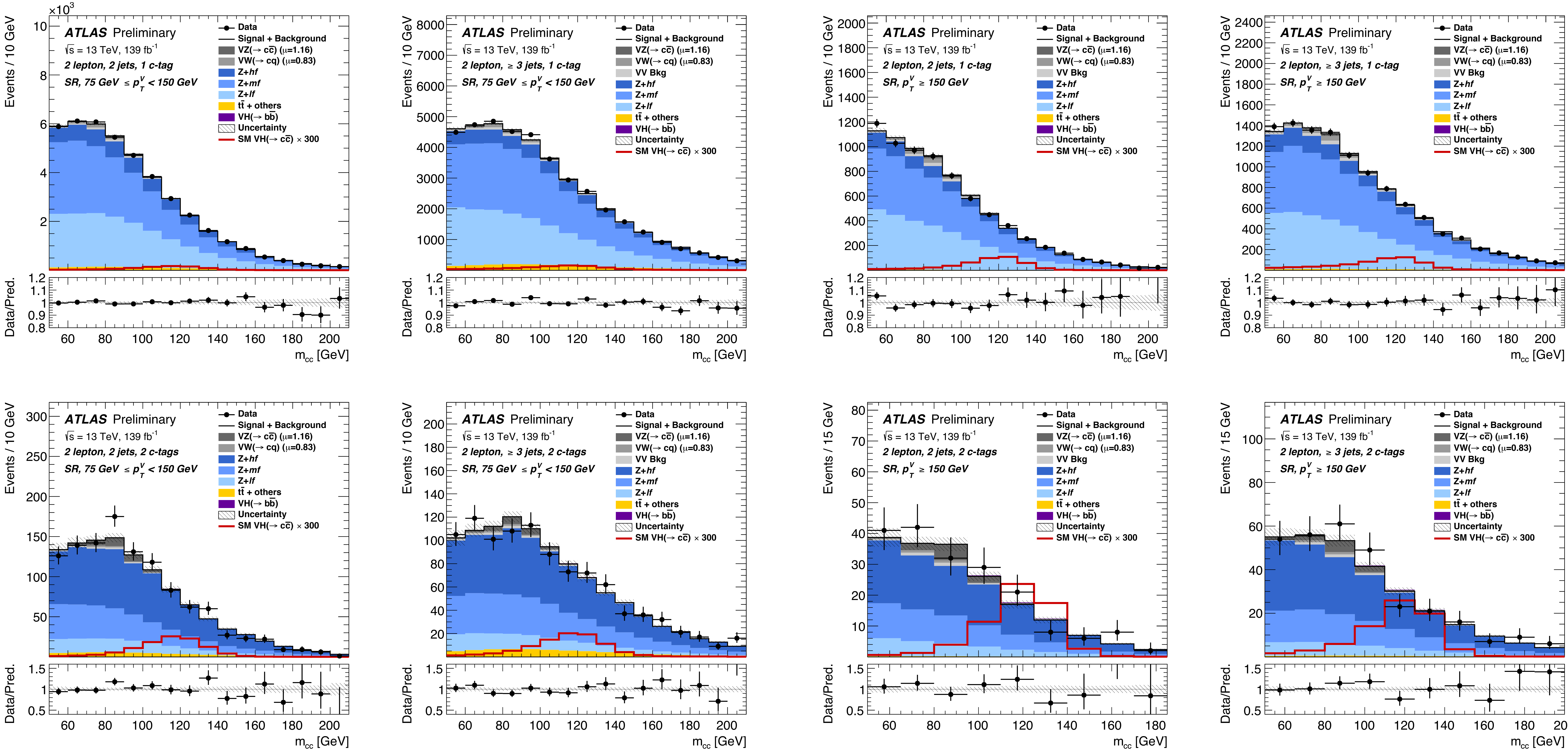
3+ jets

2 jets

3+ jets

1 c-tag

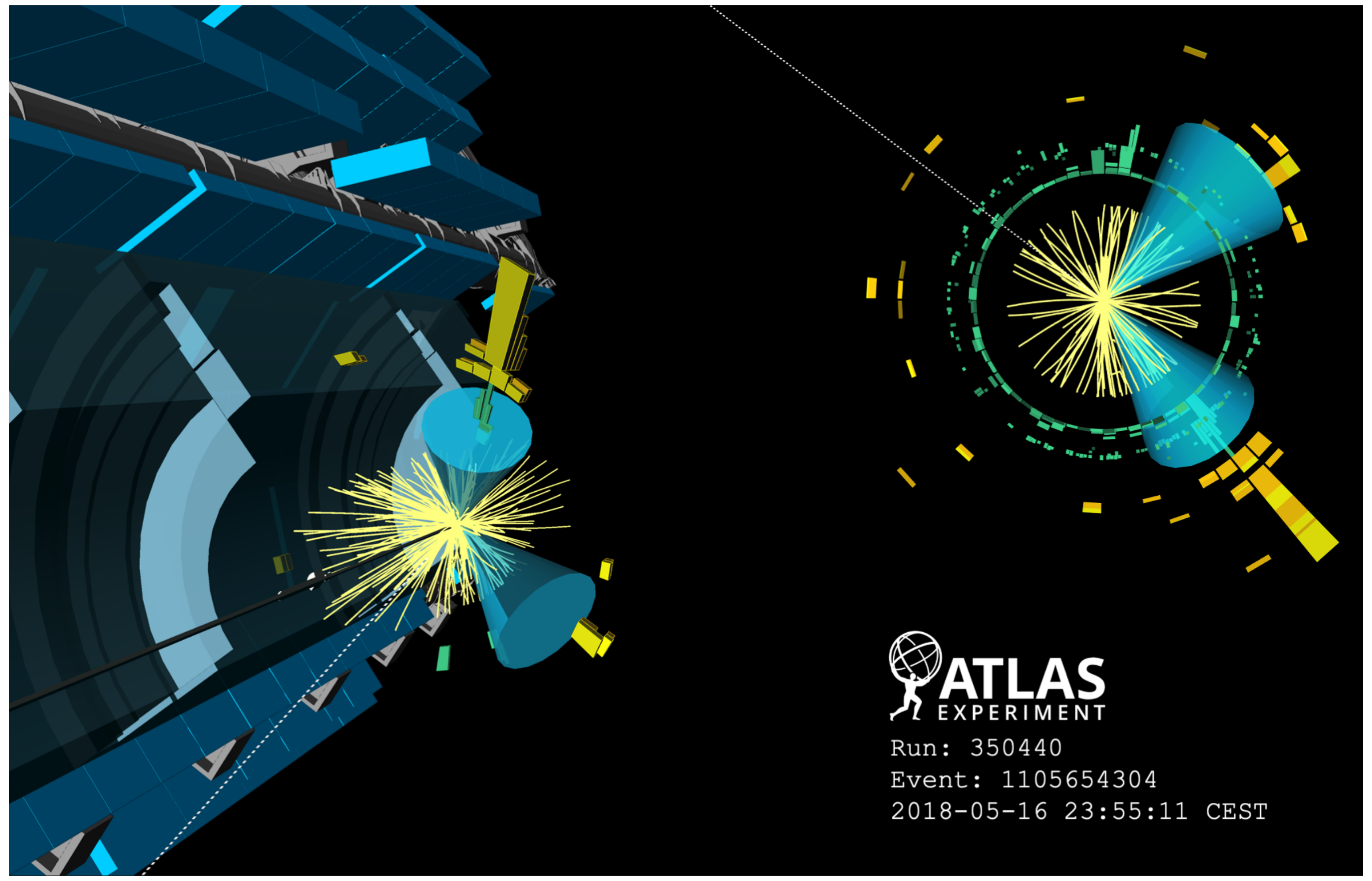
2 c-tag



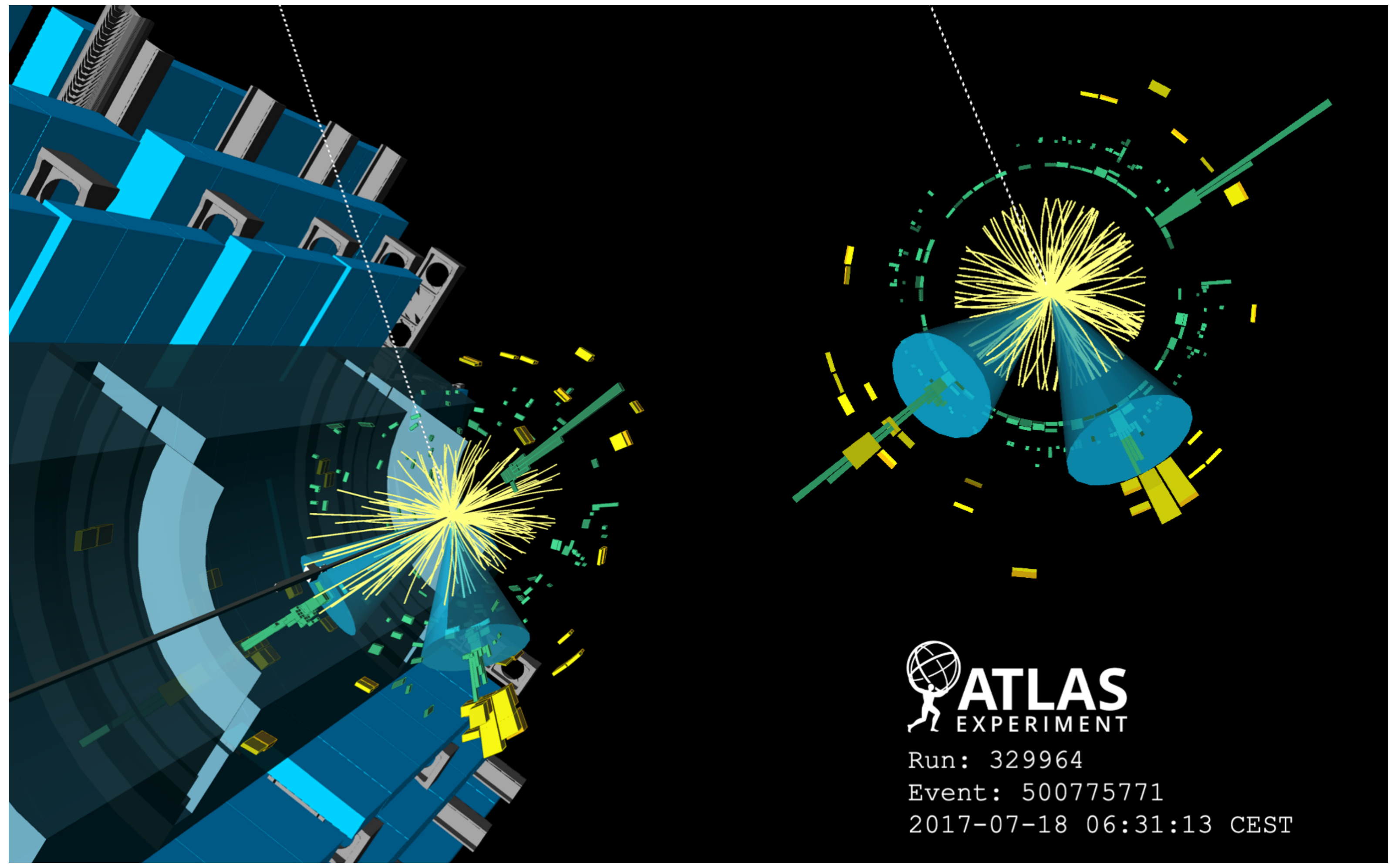
Event displays

Event displays

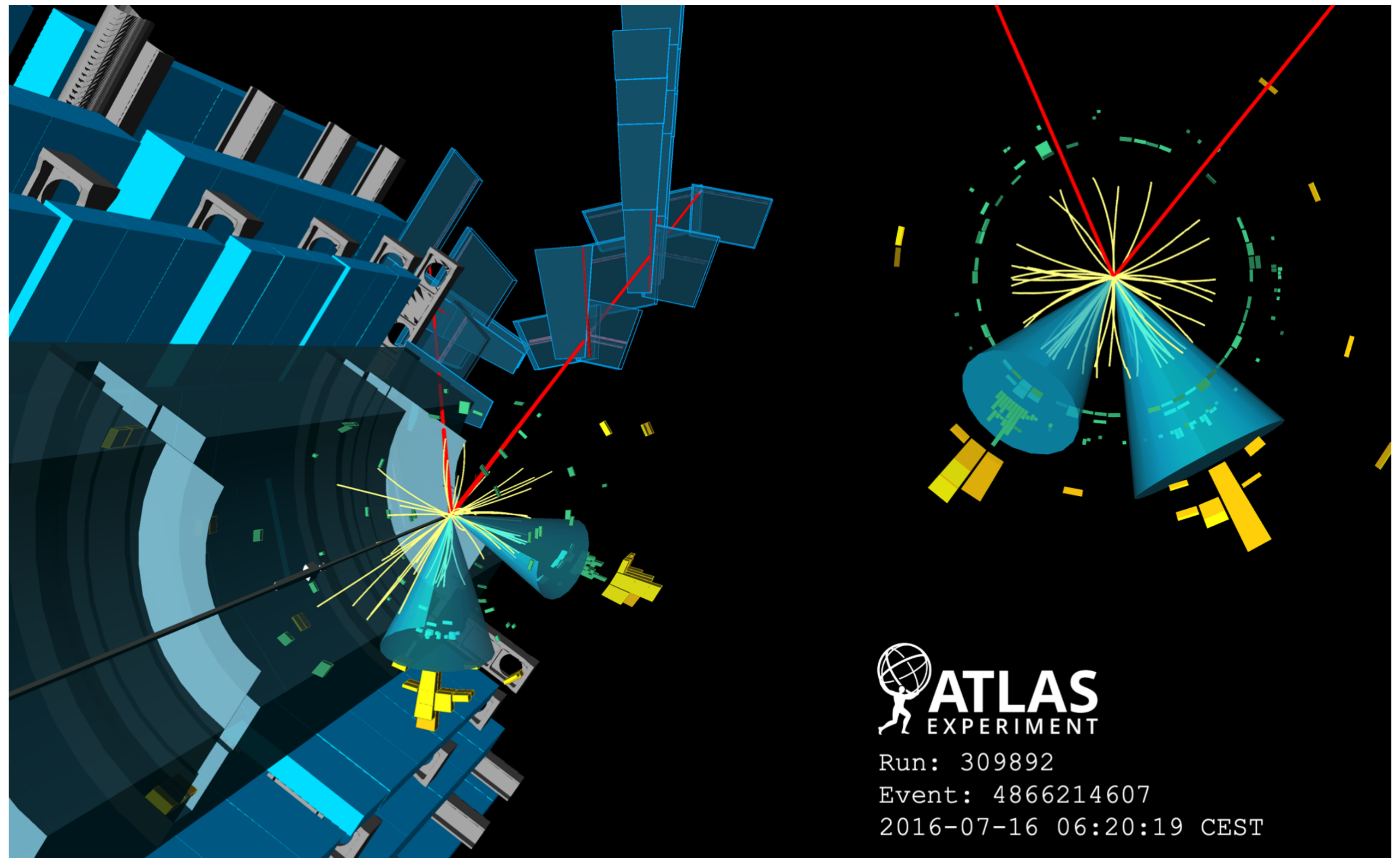
0-lepton



1-lepton



2-lepton



Fit strategy

$$\mathcal{L}(\mu,\vec{\theta},\vec{\gamma}) = \prod_{i\in\text{bins}} \text{Pois}(N_i|\mu s_i(\vec{\theta})+\gamma_i b_i(\vec{\theta})) \times \prod_{\theta\in\vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i\in\text{bins}} \text{Gauss}(\beta_i|\gamma_i\beta_i,\sqrt{\gamma_i\beta_i})$$

POI Poissonian likelihood Constraint on NPs Constraints on MC statistics

Binned profile likelihood fit on m(cc) distribution simultaneously in all regions

3 parameters of interest (POIs):

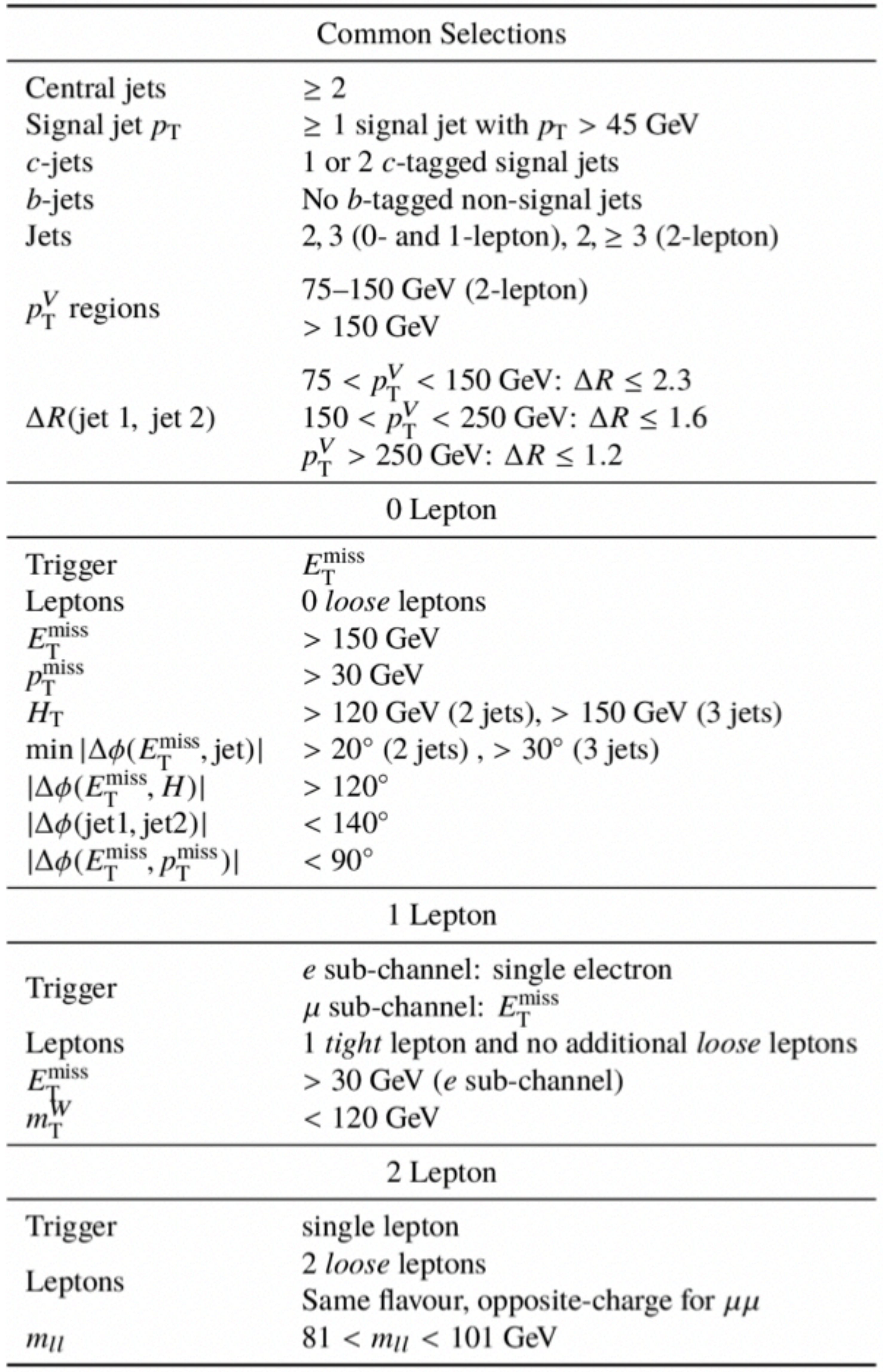
- $\mu_{VH(cc)}$: signal strength of VH(cc) signal
- $\mu_{VZ(cc)}$: signal strength of VZ(cc) diboson → validation of 2 c-tag category
- $\mu_{VW(cq)}$: signal strength of VW(cq) diboson → validation of 1 c-tag category

Background: floating normalisations of main backgrounds

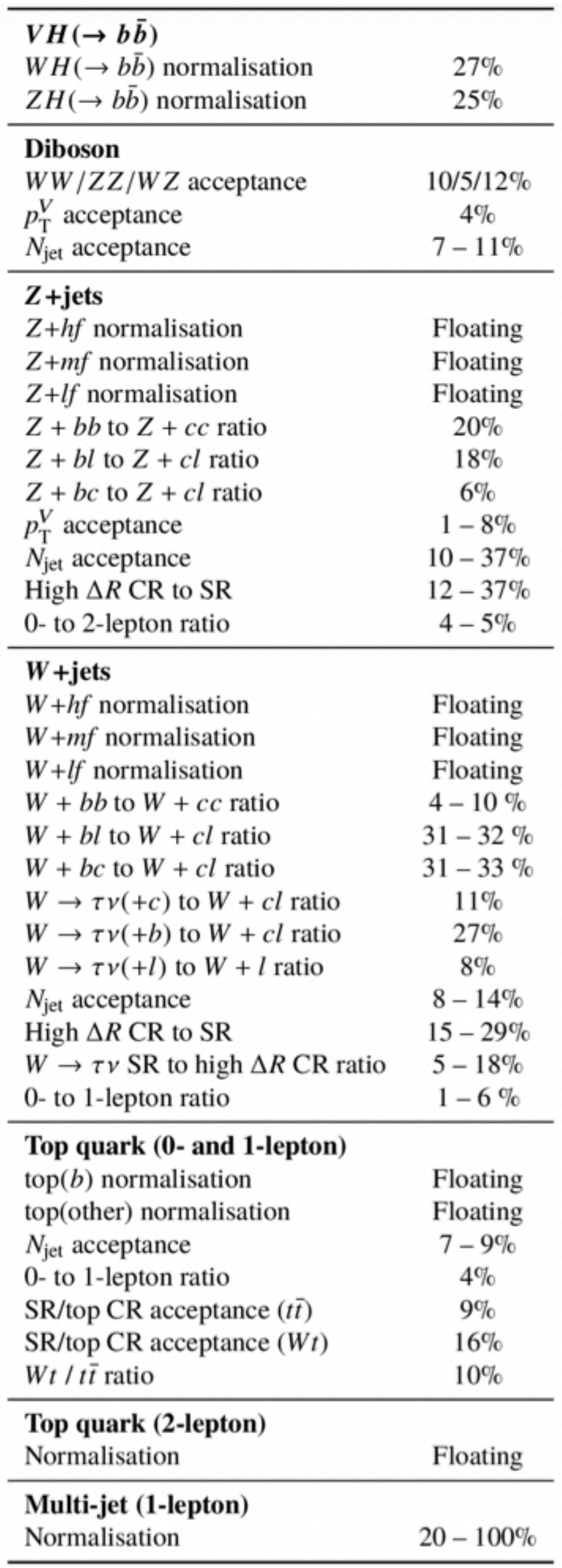
Nuisance parameters (NPs)

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

Event selection / Uncertainties



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: $\Delta R \leq 1.2$
0 Lepton	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	0 *loose* leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV
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)
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, H)\rvert$	$> 120°$
$\lvert\Delta\phi(\mathrm{jet1}, \mathrm{jet2})\rvert$	$< 140°$
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}})\rvert$	$< 90°$
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



$VH(\to b\bar{b})$	
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$ZH(\to b\bar{b})$ 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 %
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$W \to \tau\nu(+c)$ to $W+cl$ ratio	11%
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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
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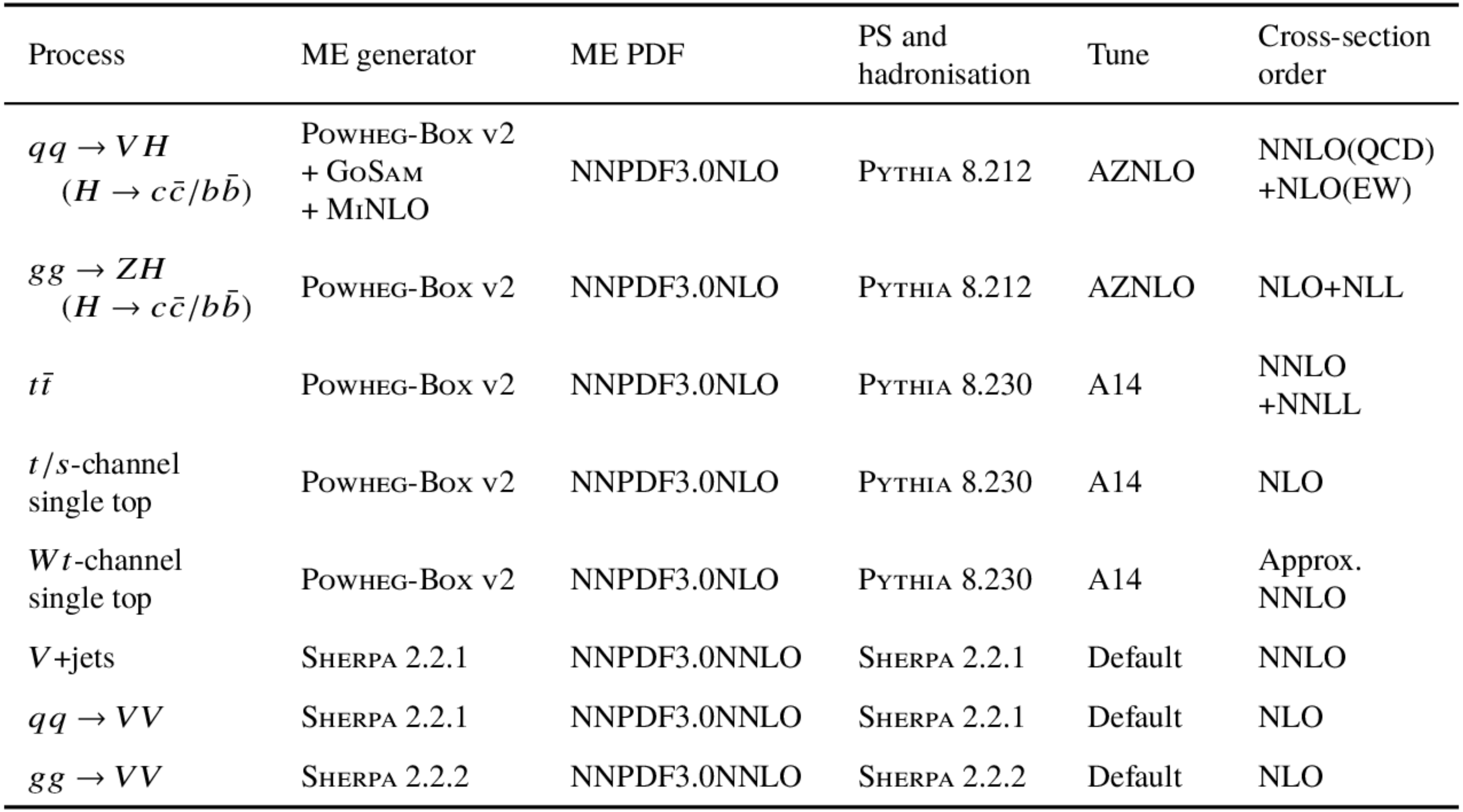
SR/top CR acceptance ($t\bar{t}$)	9%
SR/top CR acceptance (Wt)	16%
Wt / $t\bar{t}$ ratio	10%
Top quark (2-lepton)	
Normalisation	Floating
Multi-jet (1-lepton)	
Normalisation	20 – 100%

Generators



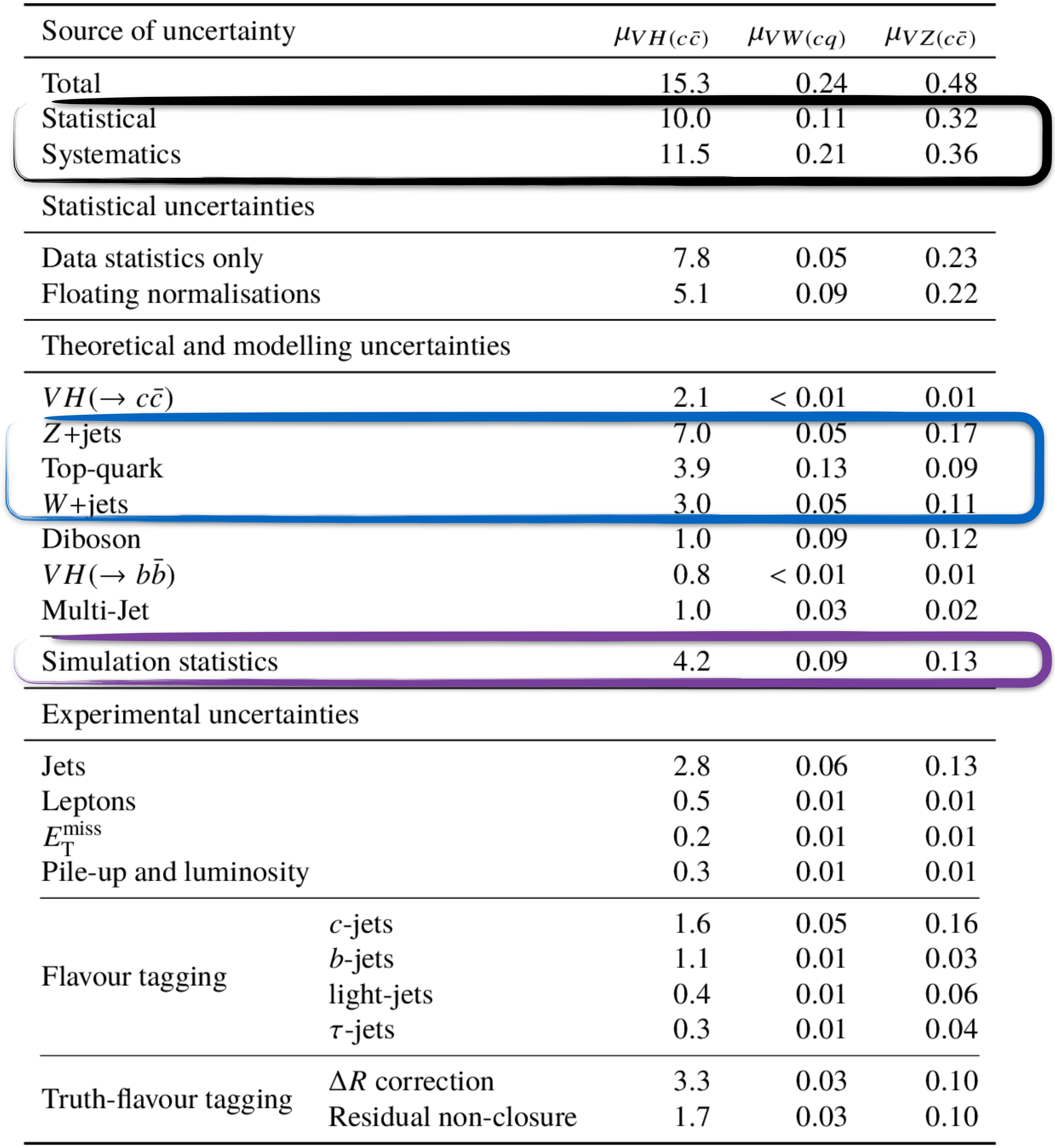
Process	ME generator	ME PDF	PS and hadronisation	Tune	Cross-section order
$qq \to VH$ $(H \to c\bar{c}/b\bar{b})$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO	Pythia 8.212	AZNLO	NNLO(QCD) +NLO(EW)
$gg \to ZH$ $(H \to c\bar{c}/b\bar{b})$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NLO+NLL
$t\bar{t}$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NNLO +NNLL
t/s-channel single top	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NLO
Wt-channel single top	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	Approx. NNLO
V+jets	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$qq \to VV$	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

Breakdown of uncertainties

Breakdown of uncertainties

- Similar statistical and systematic uncertainties
- Dominant systematic uncertainties:
  - Background modelling: V+jets and ttbar
  - Simulation statistics: MC stat

Will improve with latest generators and more simulated events!



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				
$VH(\to c\bar{c})$		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
$VH(\to b\bar{b})$		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_T^{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

Theory motivation

2 Higgs doublet model

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h_1 \end{pmatrix}, \ \phi' = \frac{1}{\sqrt{2}}\begin{pmatrix} H^+ \\ h_2 + ih_3 \end{pmatrix}$$

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Physical bosons

$$\begin{aligned} h &= \sin(\beta - \alpha) h_1 + \cos(\beta - \alpha) h_2, \\ H &= -\cos(\beta - \alpha) h_1 + \sin(\beta - \alpha) h_2 \end{aligned}$$

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Affects Yukawa coupling of 125 GeV Higgs boson

$$\lambda^h_{q_u,\bar{q}_u} = y^{SM}_{q_u}\sin(\beta - \alpha) + y'_{q_u}\cos(\beta - \alpha)$$
$$\lambda^h_{q_d,\bar{q}_d} = y^{SM}_{q_d}(\sin(\beta - \alpha) + \xi\cos(\beta - \alpha))$$

Spontaneous flavour violation: arXiv:1908:11376

- FCNC avoided by keeping Yukawa matrices of second doublet diagonalisable with first doublet

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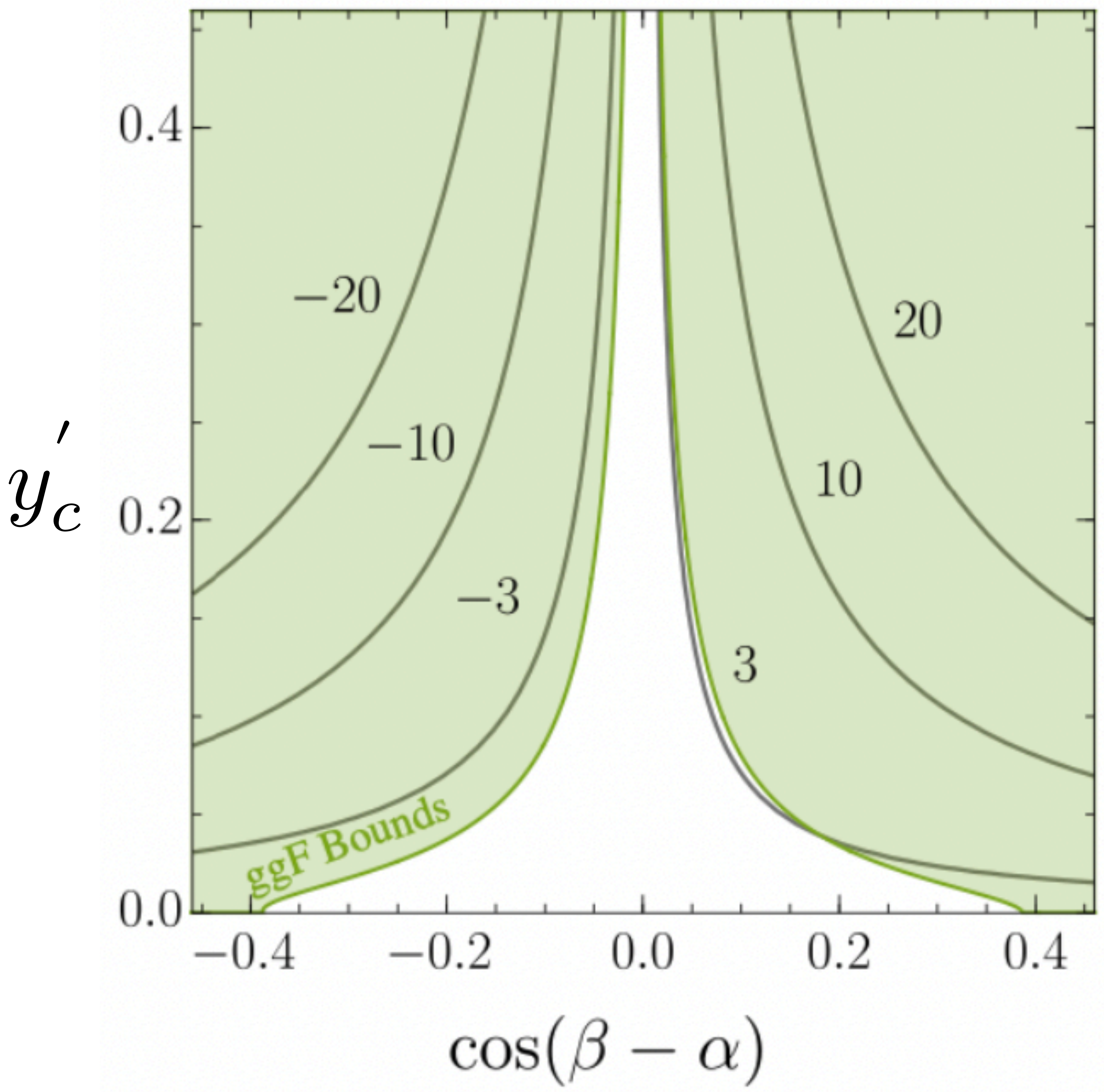
$$\lambda^h_{c,\bar{c}} / \lambda^{h,SM}_{c,\bar{c}} = \kappa_c$$



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- FCNC avoided by keeping Yukawa matrices of second doublet diagonalisable with first doublet
- Higgs boson coupling to charm quarks potentially enhanced by **factor 3**!

Alternative theories predict similar enhancements - up to b- and c-quark universality

Theory enhanced H->cc couplings

2HDM : paper
TeV scale new physics lambda = 1.5 TeV: paper

Enhanced coupling 3-5x SM in c,s,d,u yukawa