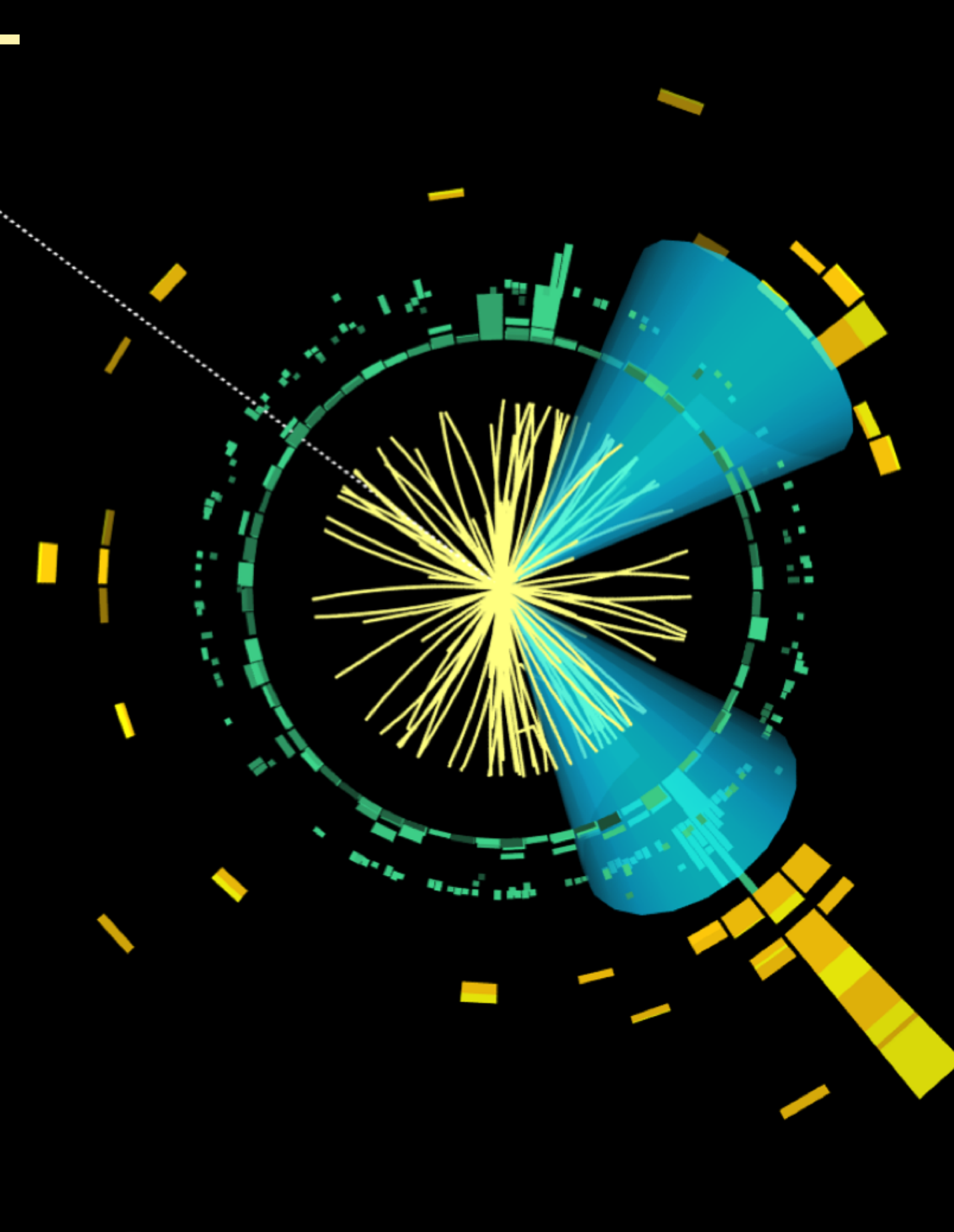
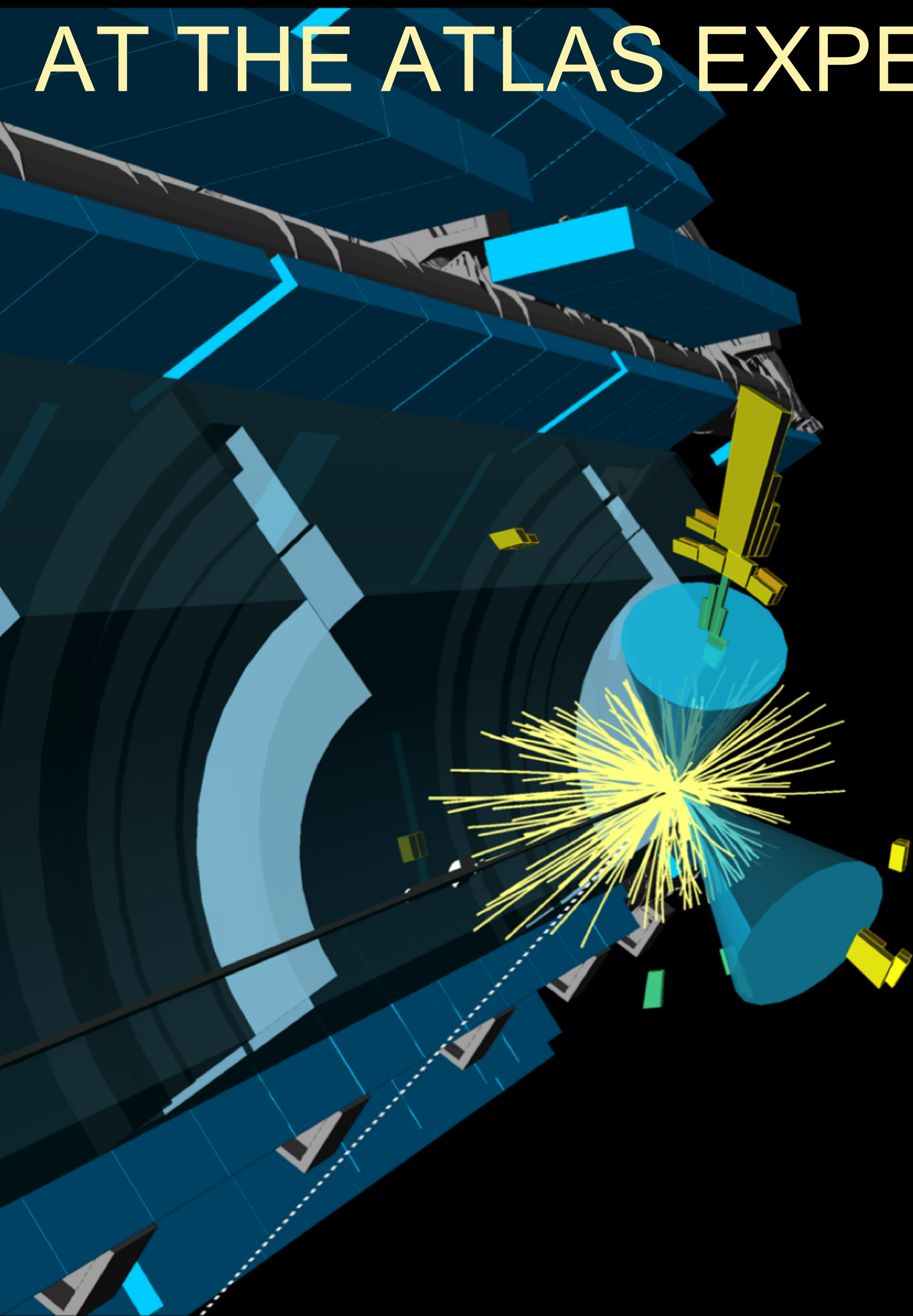
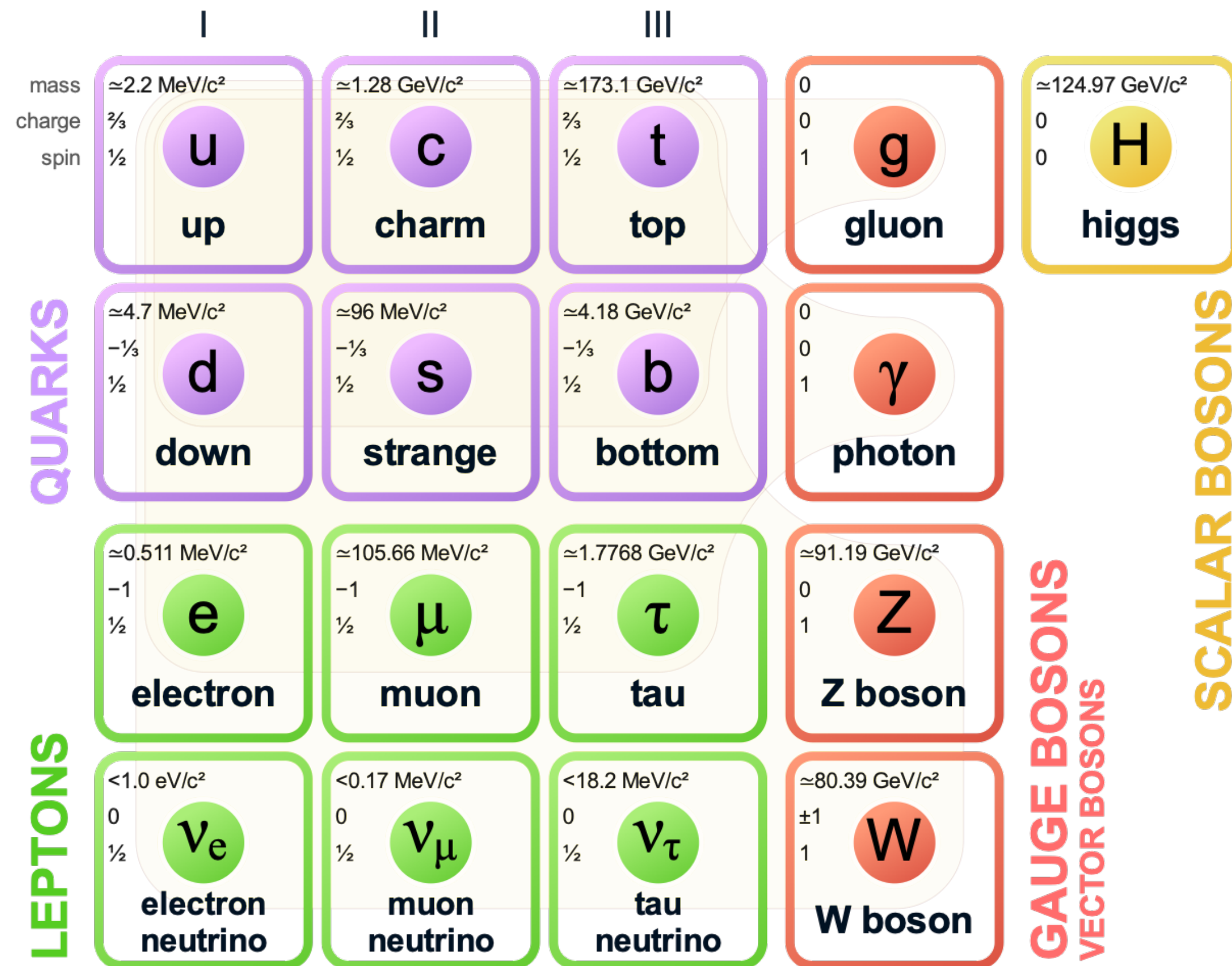


HIGGS BOSON COUPLINGS TO FERMIONS AT THE ATLAS EXPERIMENT



Tristan du Pree (Nikhef, NL)
On behalf of the ATLAS collaboration
WIN 2021 conference (7 – 10 June 2021)

THE STANDARD MODEL



- The Higgs boson has a central role
- Electroweak symmetry breaking
 - Masses bosons and fermions

OPEN QUESTIONS
 3 GENERATIONS? WHY?
 HIERARCHY OF MASSES?
 NEW PARTICLES?

IMAGE CREDIT: WIKIPEDIA USER MISSMJ

HIGGS TO BOSONS

	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
QUARKS	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS VECTOR BOSONS
					SCALAR BOSONS

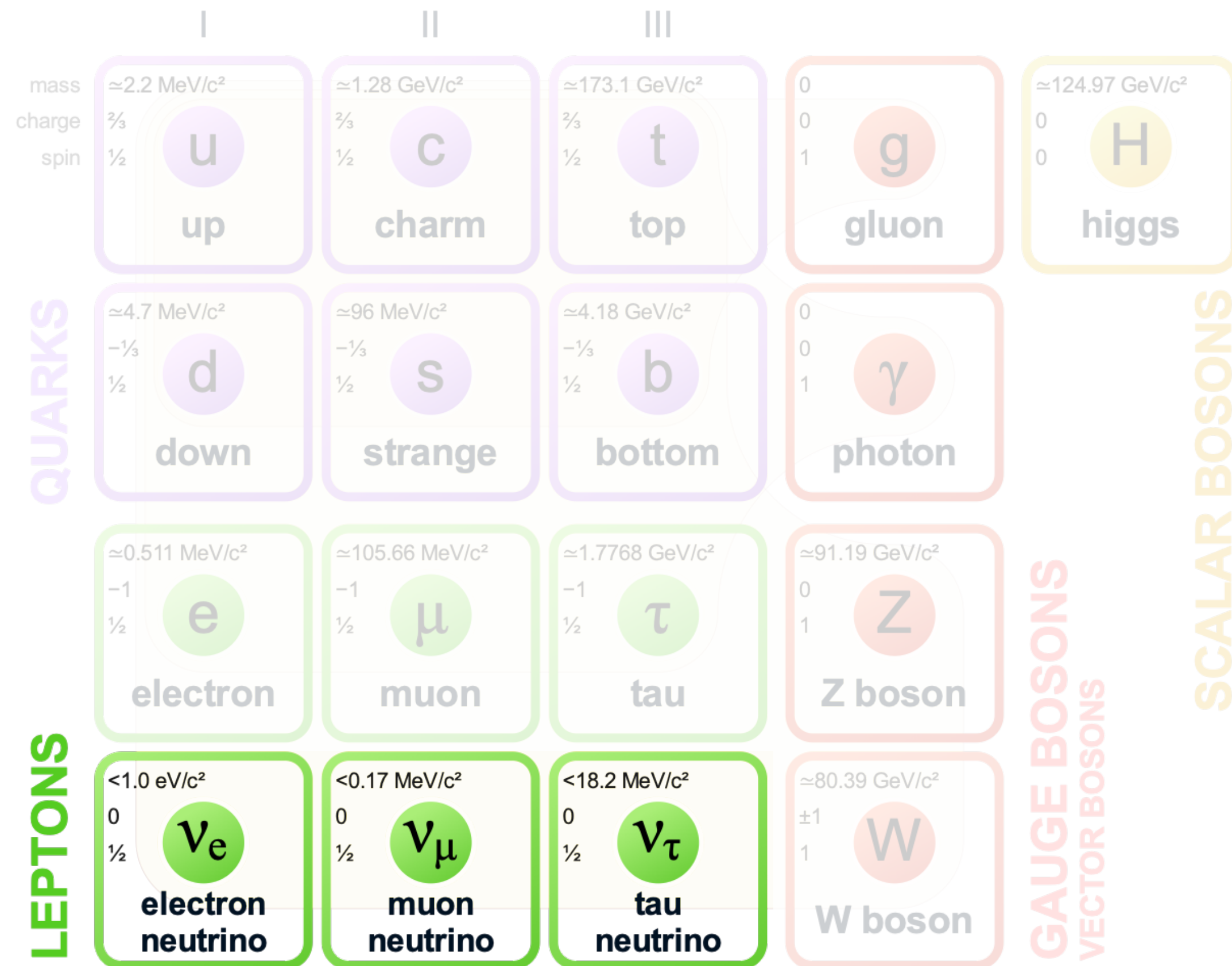
H → bosons:

- Discovery Higgs boson (2012)
- Evidence for BEH electroweak symmetry breaking mechanism

See talk by Luca Franco:

- Coupling to vector bosons
- Self coupling: di-Higgs

HIGGS TO INVISIBLE



H \rightarrow invisible:

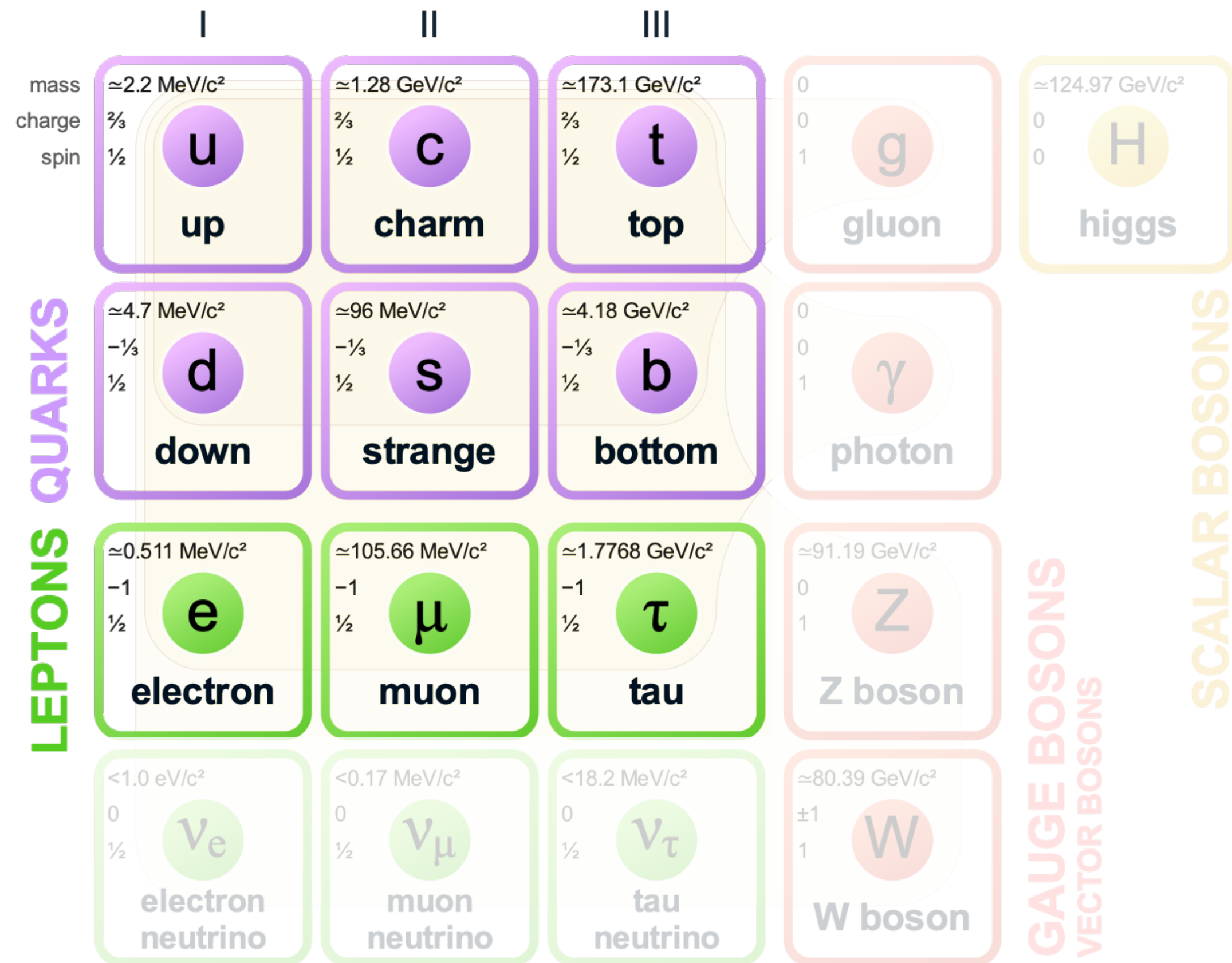
- Higgs coupling to neutrinos or dark matter?

See talk by Huacheng Cai:

- Higgs and BSM

HIGGS TO FERMIONS

WHAT WE LEARN:
2ND & 3RD GENERATION
QUARKS AND LEPTONS
LARGE MASS RANGE



This talk:

- ttH
- $H \rightarrow bb$
- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow cc$ (NEW!)

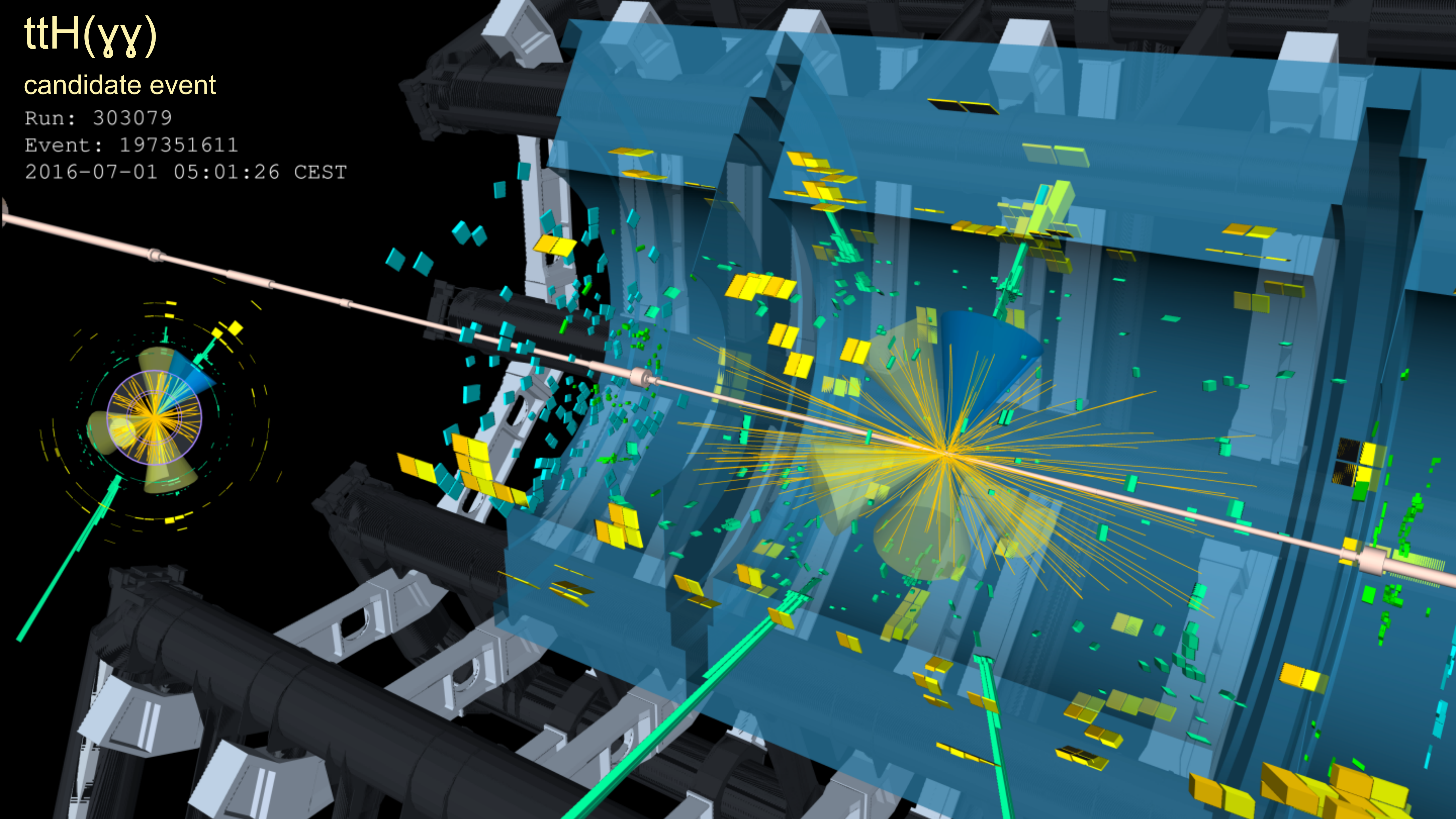
$ttH(\gamma\gamma)$

candidate event

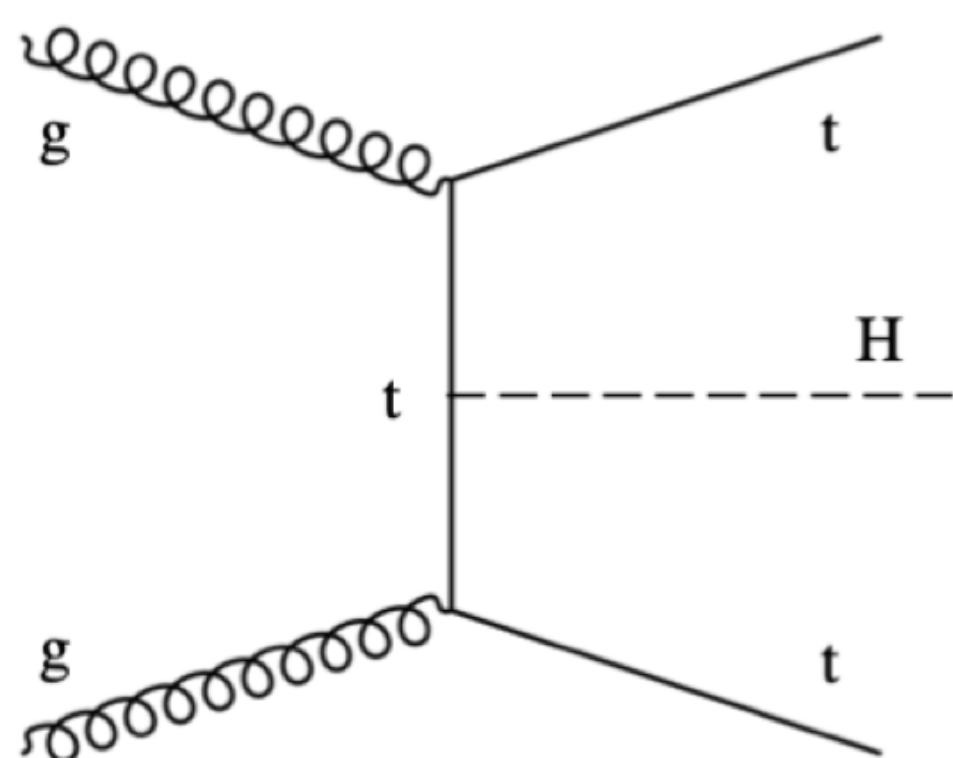
Run: 303079

Event: 197351611

2016-07-01 05:01:26 CEST

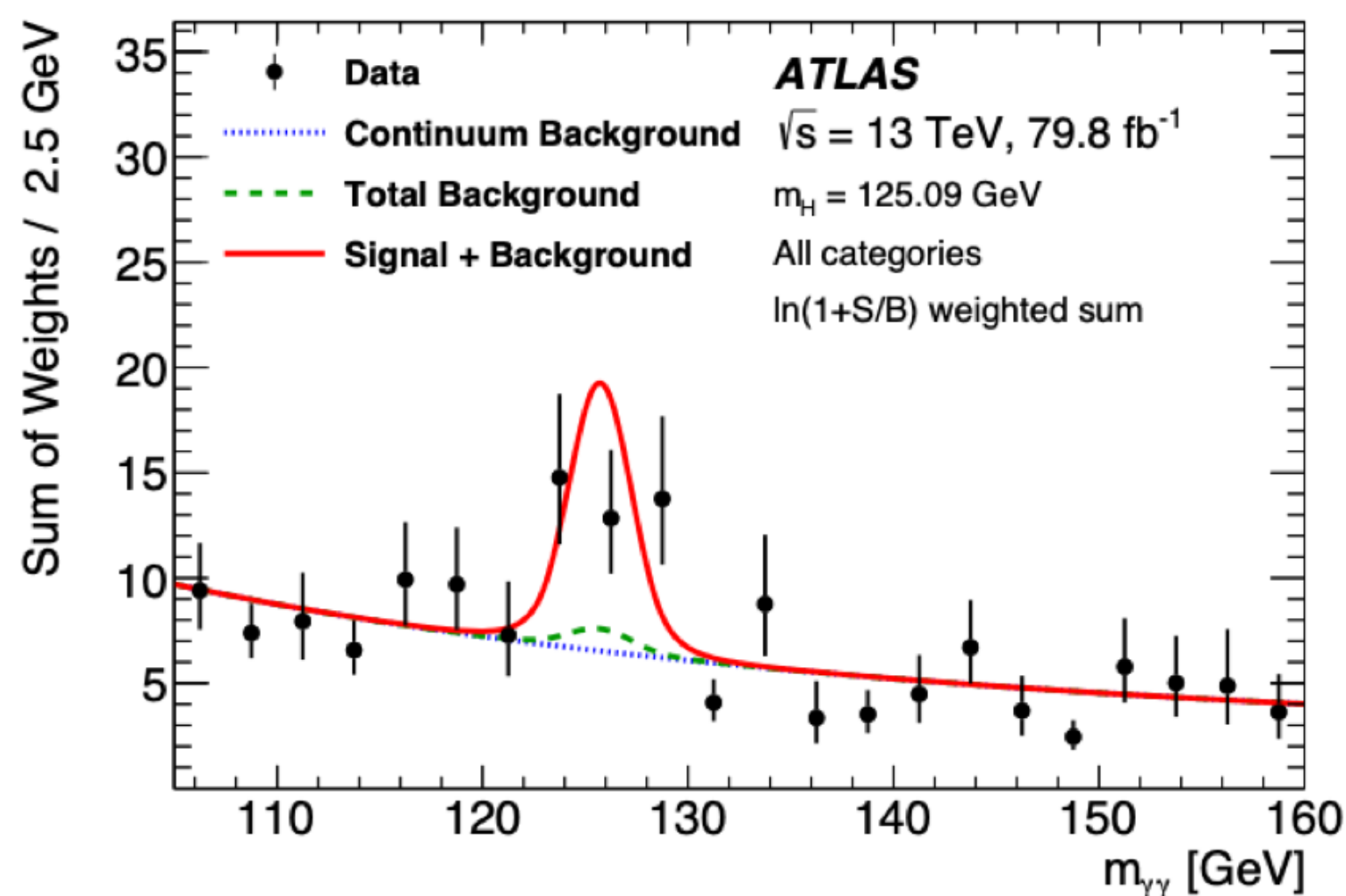


Coupling to heaviest fermion
Rich events: leptons, (b-)jets, MET



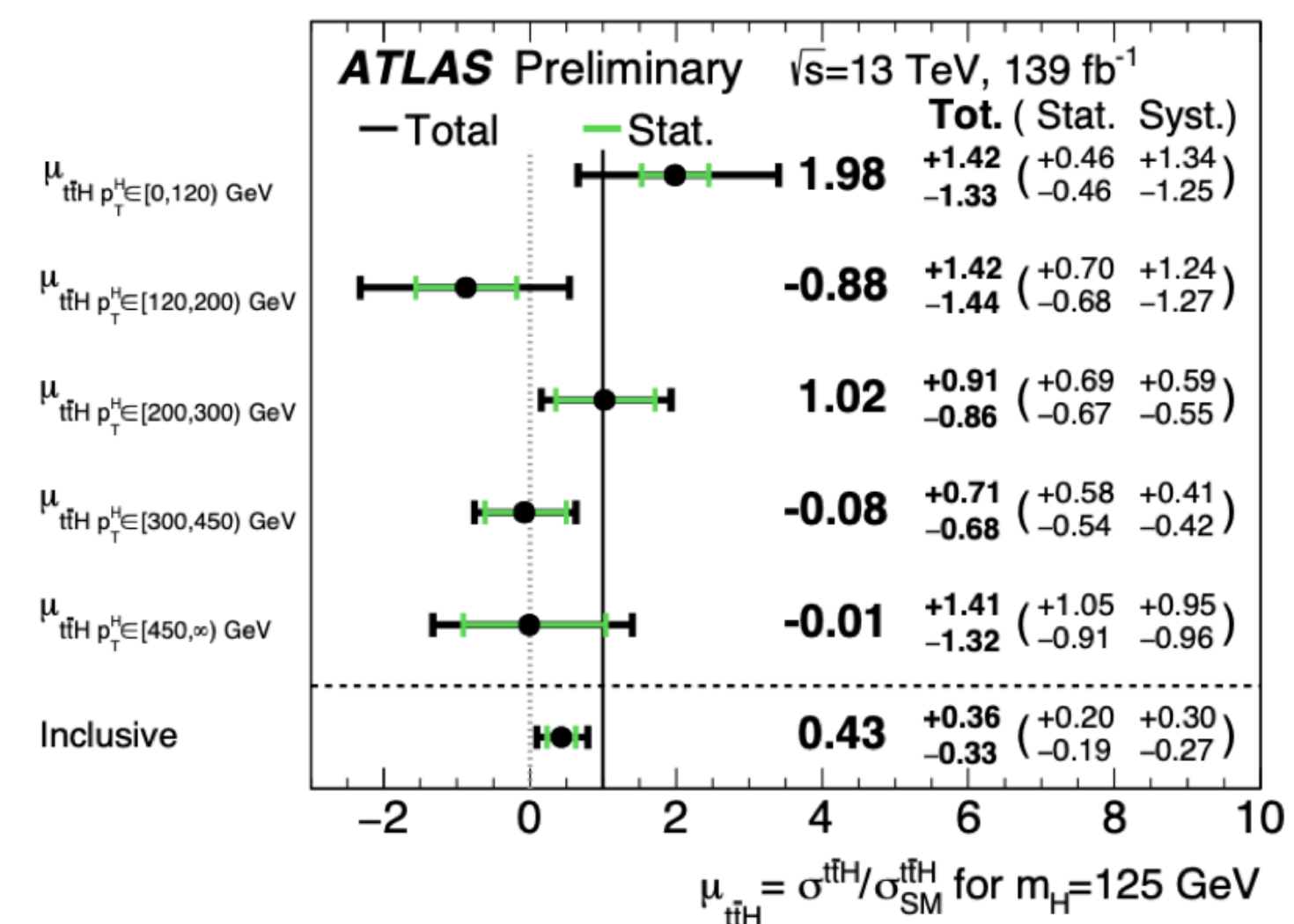
Signal optimization:
Event categorization and MVA

TTH, $H \rightarrow \gamma\gamma$
PHYS. LETT. B 784 (2018) 173



OBSERVATION: 6.3 SIGMA

TTH, $H \rightarrow BB$
ATLAS-CONF-2020-058



DIFFERENTIAL (STXS)



ATLAS

EXPERIMENT

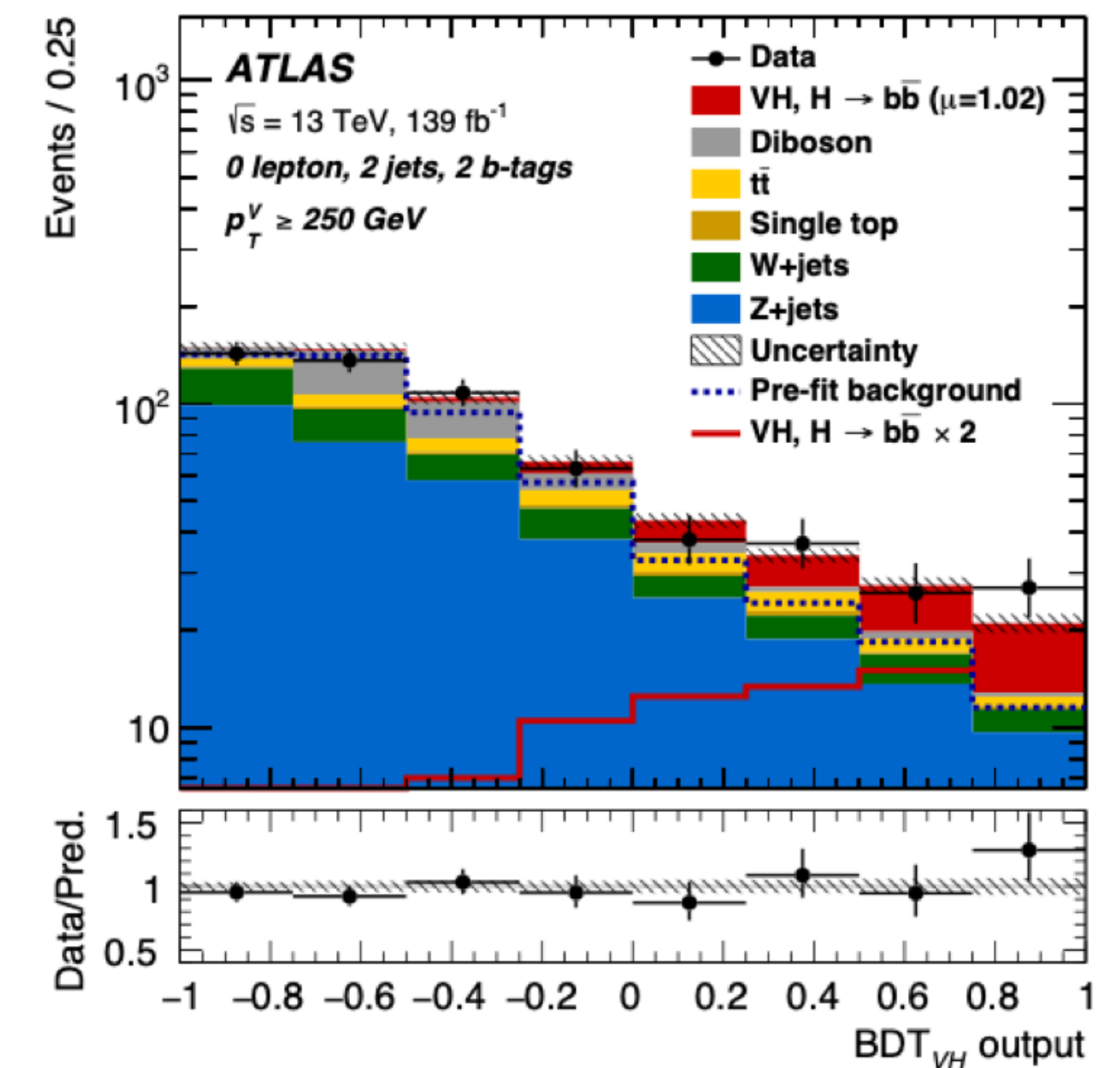
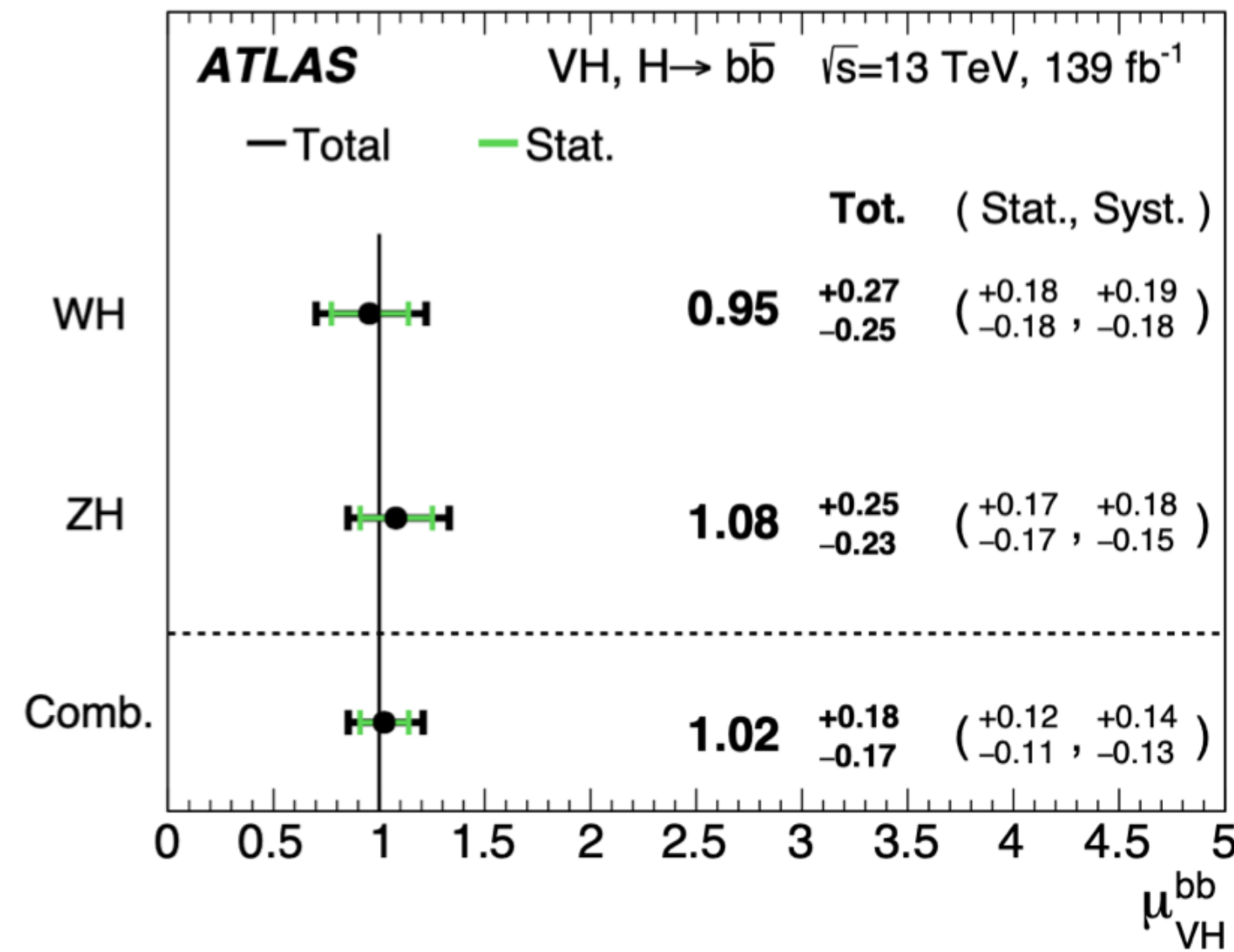
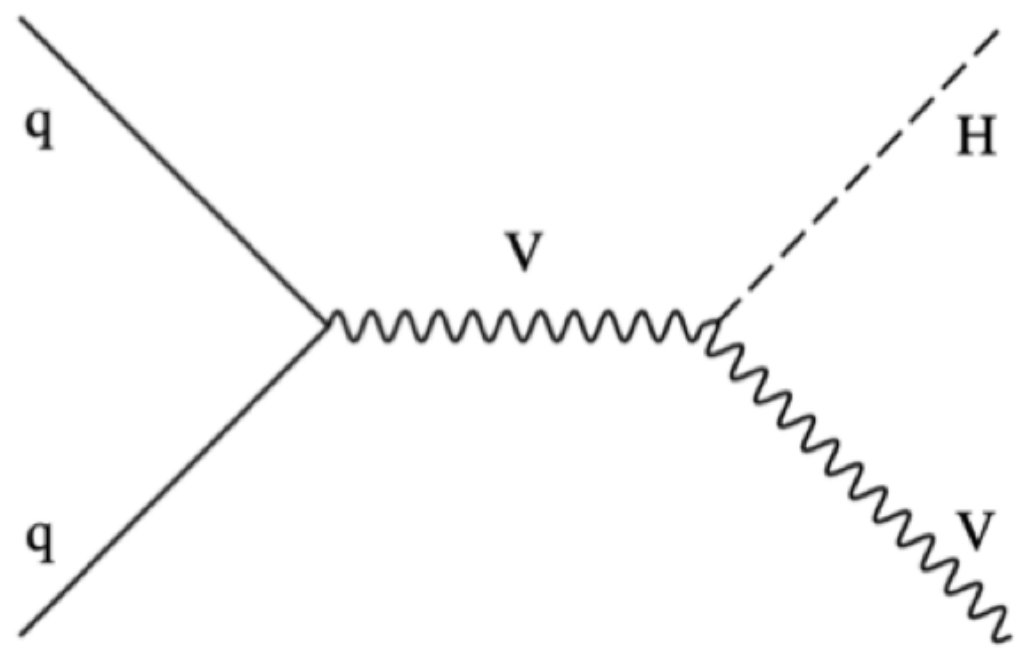
$Z(\mu\mu)H(bb)$
candidate event

Run: 309440
Event: 990753168
2016-09-27 14:35:10 CEST

VH(BB)

H → bb: largest branching ratio

VH: 0+1+2 lepton channels



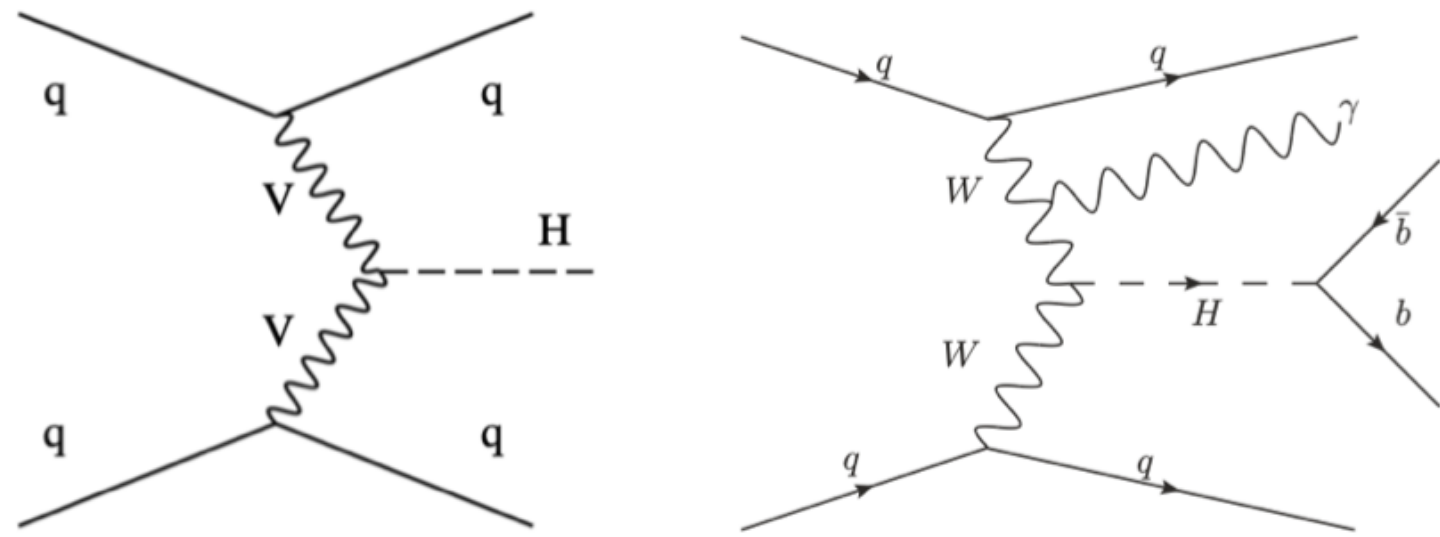
Backgrounds: ttbar, W+jets, Z+jets

BDT to optimize sensitivity

COMBINED H → BB SIGNIFICANCE: 6.7 SIGMA

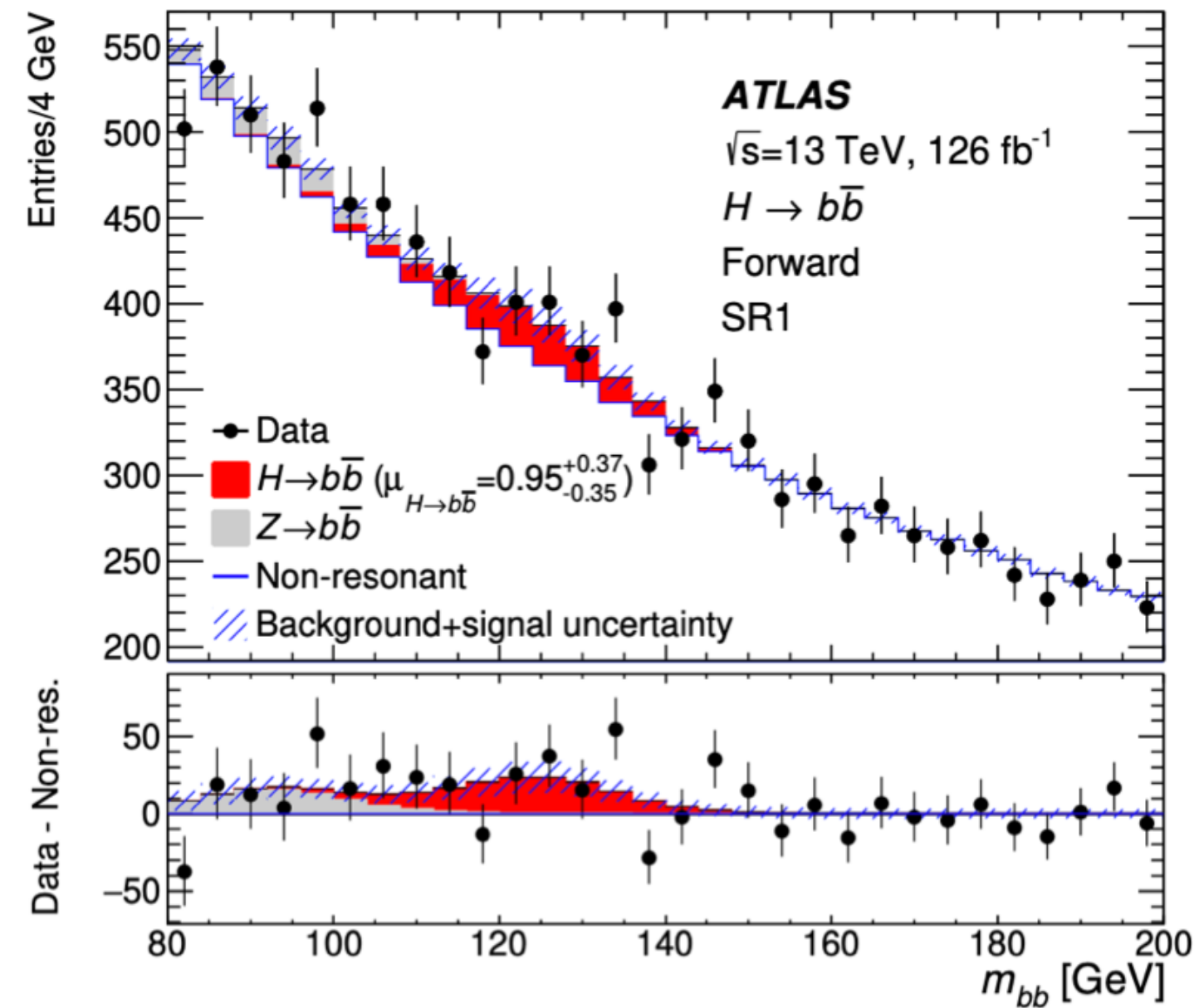
VBF $H \rightarrow BB$

VBF: all-hadronic
Backgrounds & trigger!



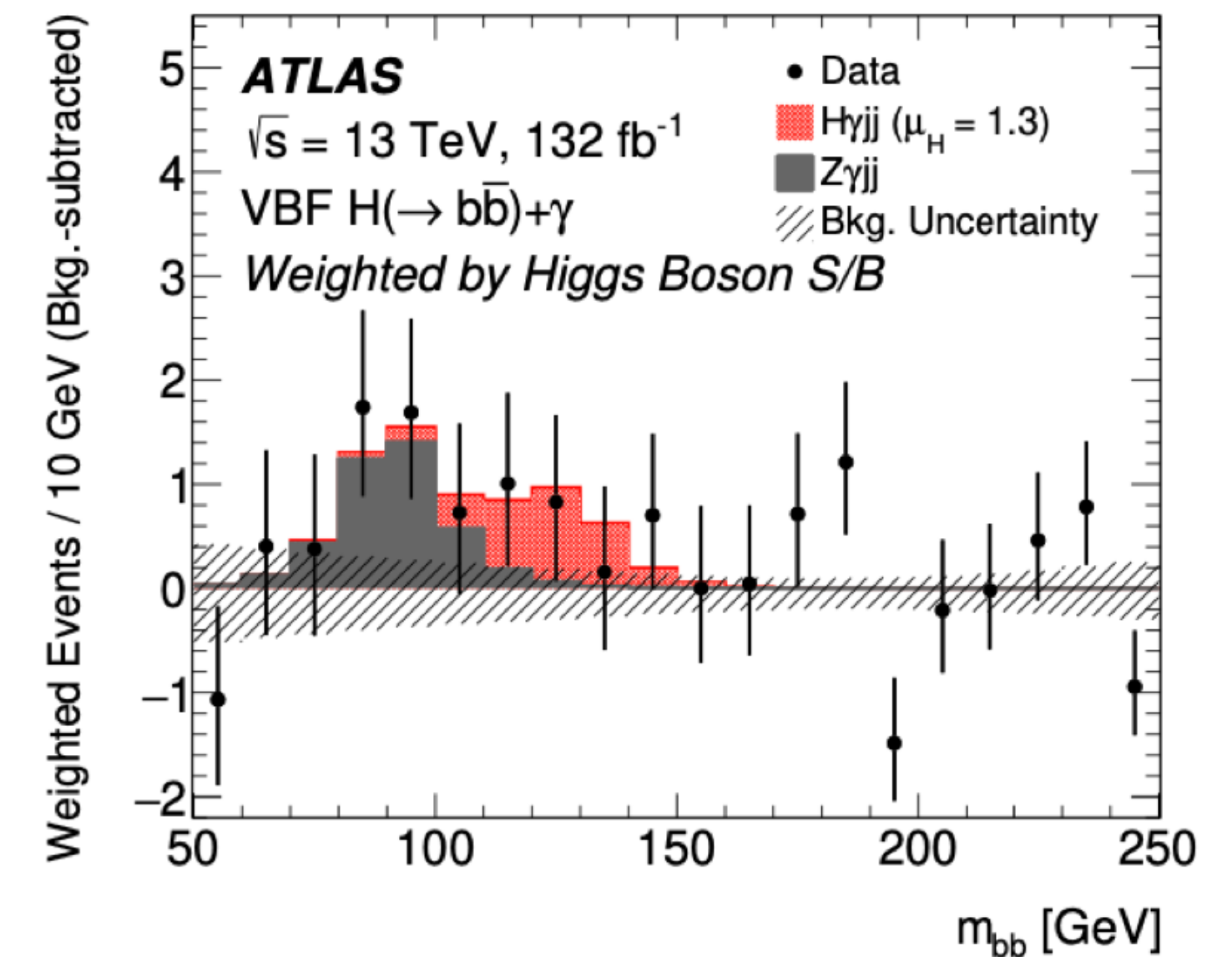
VBF+ γ : enhanced
trigger performance

VBF
ARXIV:2011.08280



VBF: 3 SIGMA EXCESS

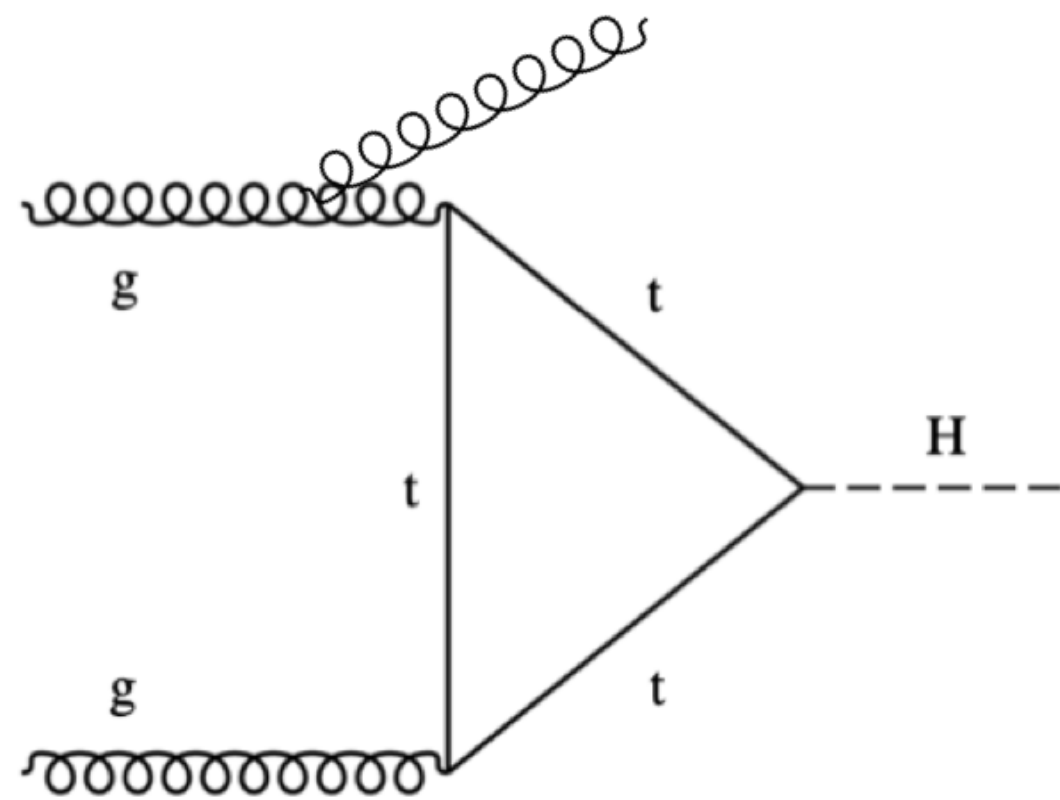
VBF+ γ
JHEP 03 (2021) 268



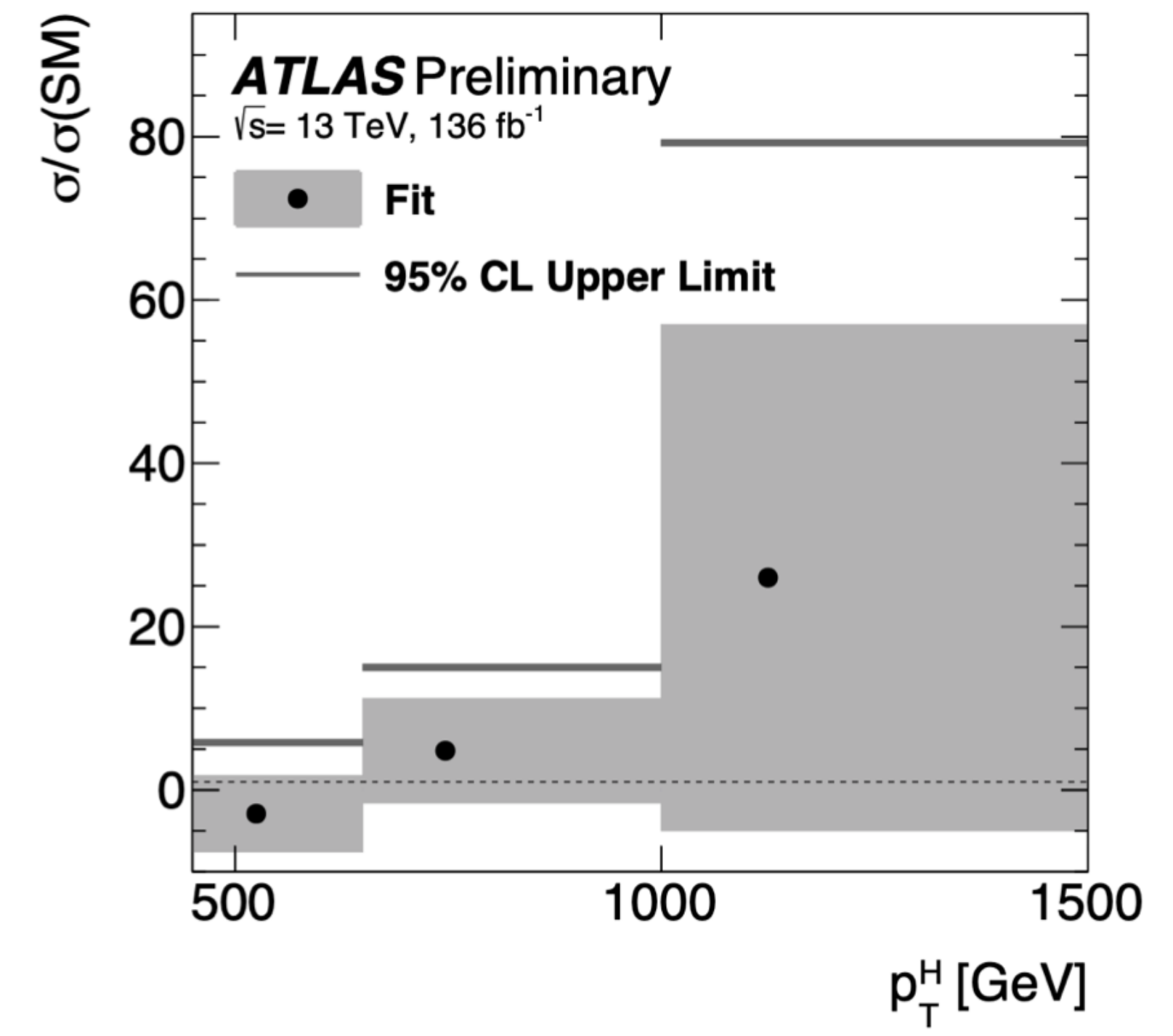
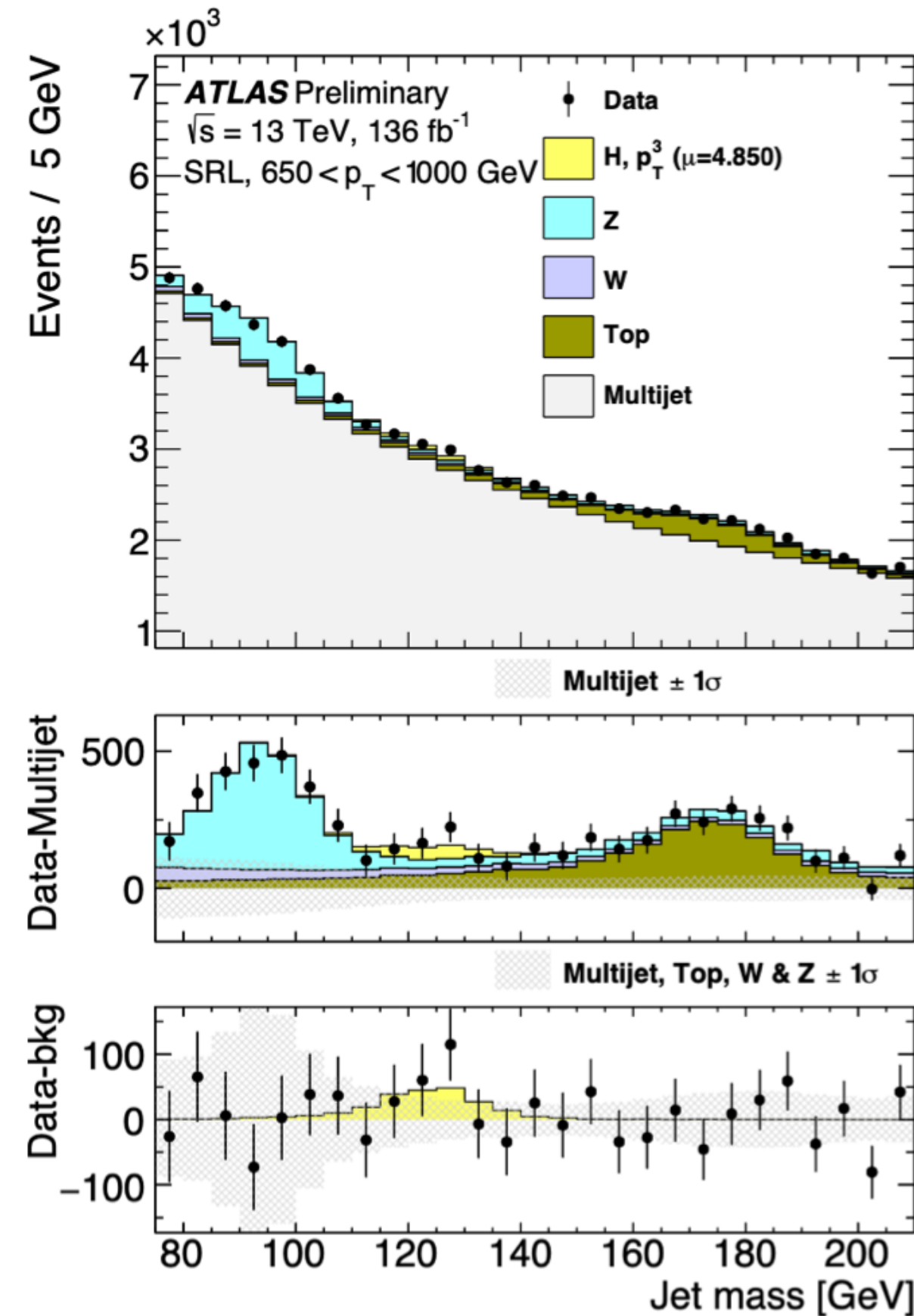
VBF+ γ : $\mu = 1.3 \pm 1.0$

H → BB BOOSTED

Boosted ggH(bb)
to go differential

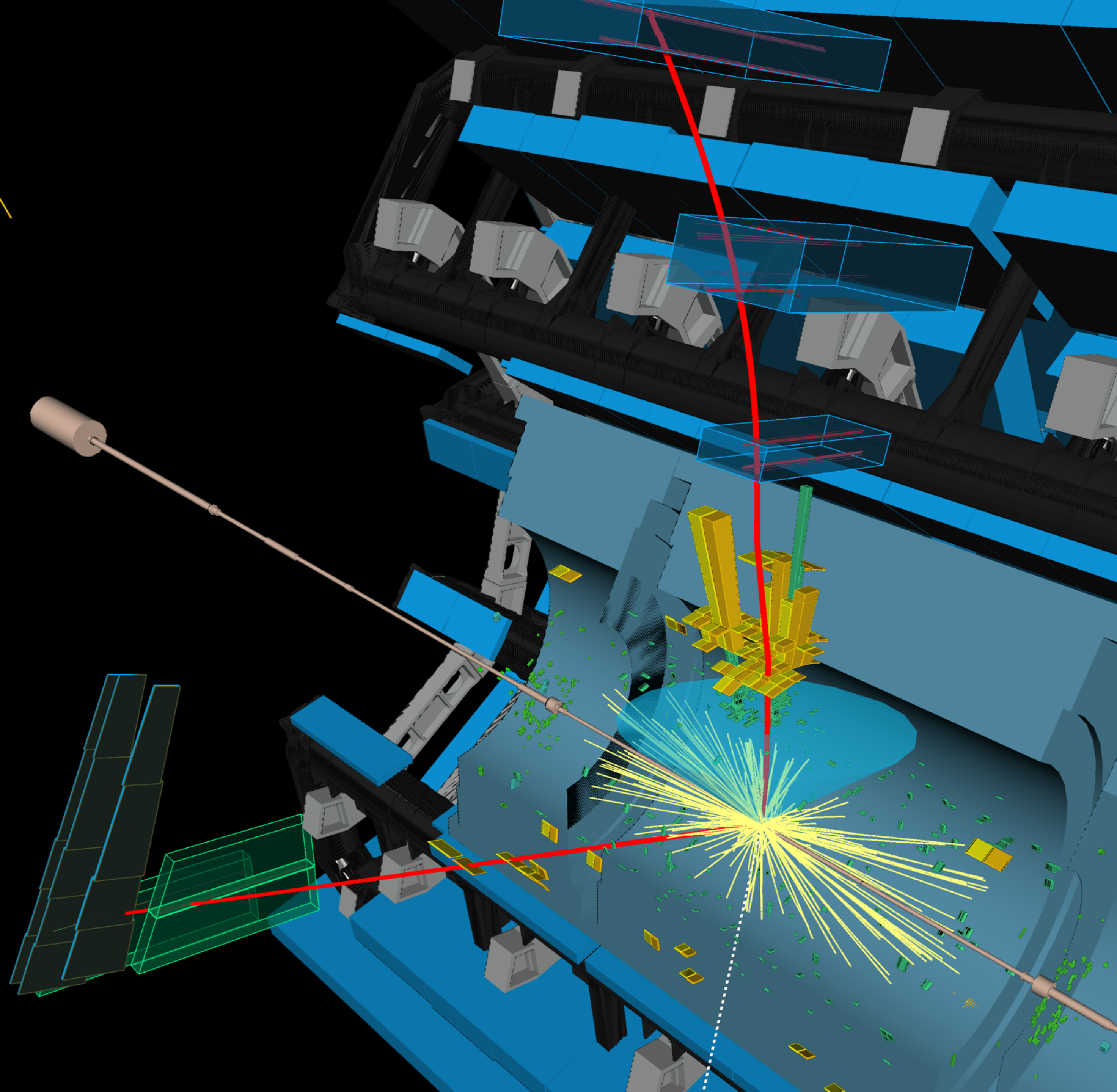
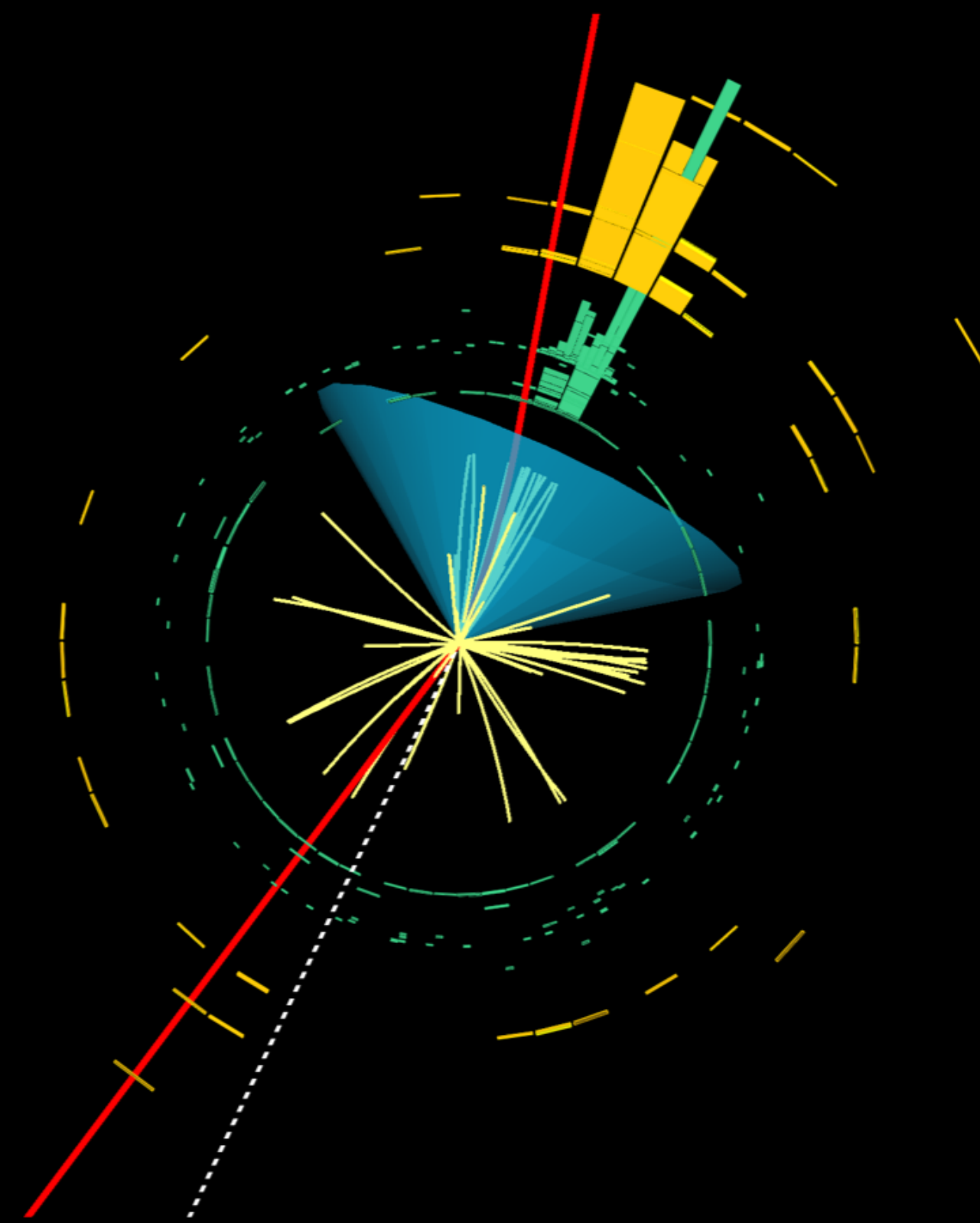


Fully hadronic final state
Use initial state radiation



→ PROBE VERY HIGH PT

Boosted
 $W(l\nu)H(bb)$
candidate event



Run: 338349

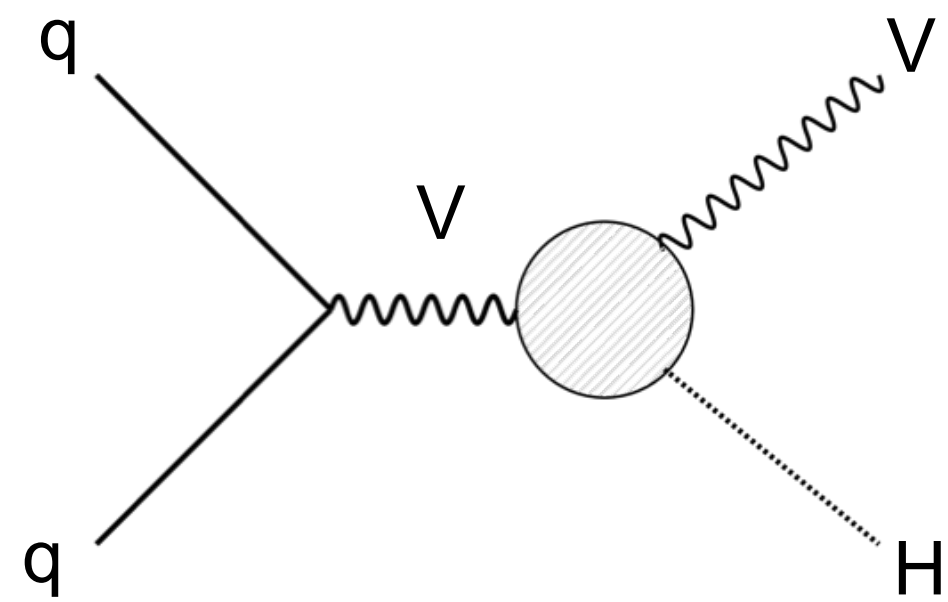
Event: 616525246

2017-10-16 20:24:46 CEST

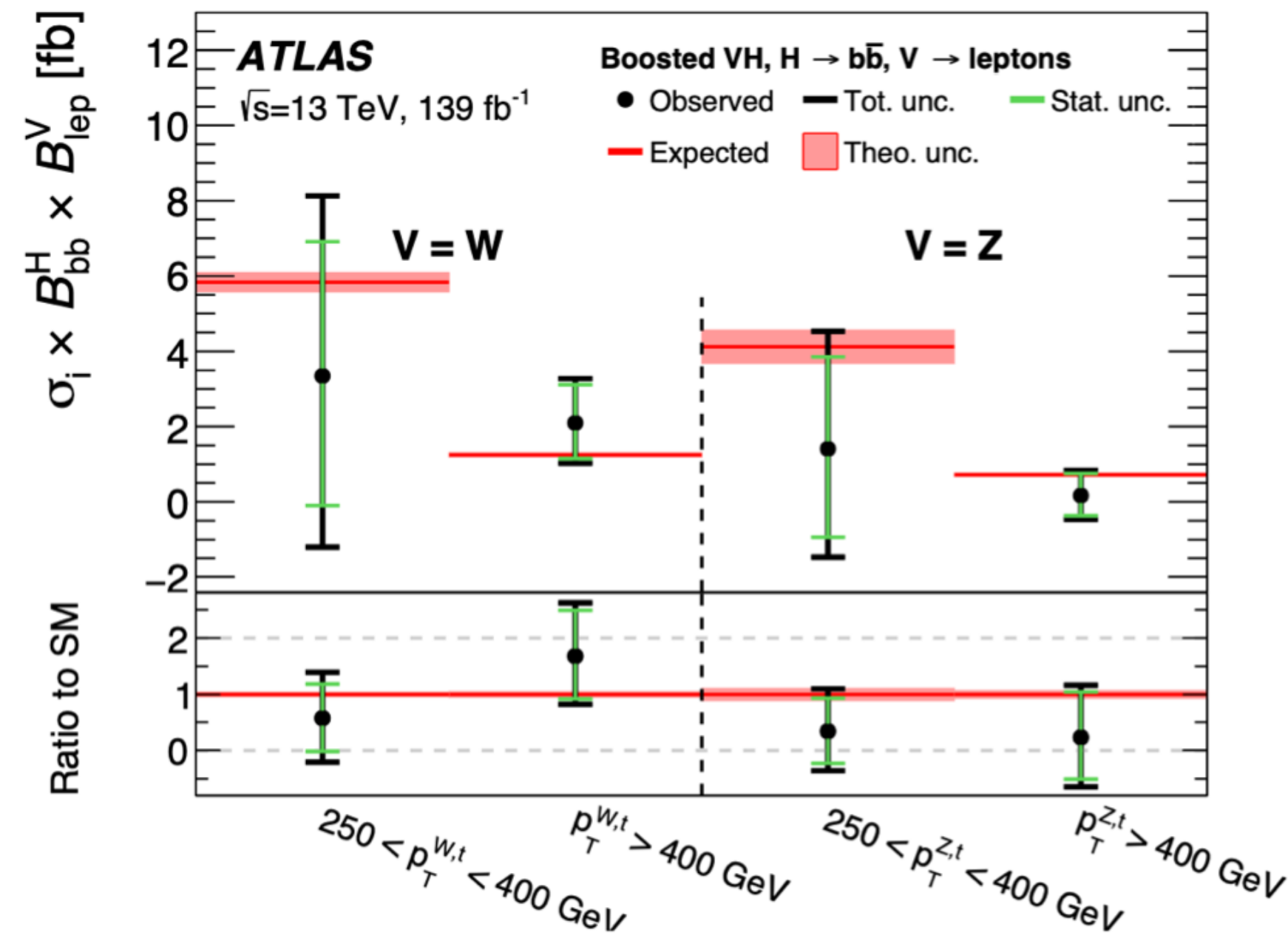
VH(BB) BOOSTED

PHYS. LETT. B
816 (2021) 136204

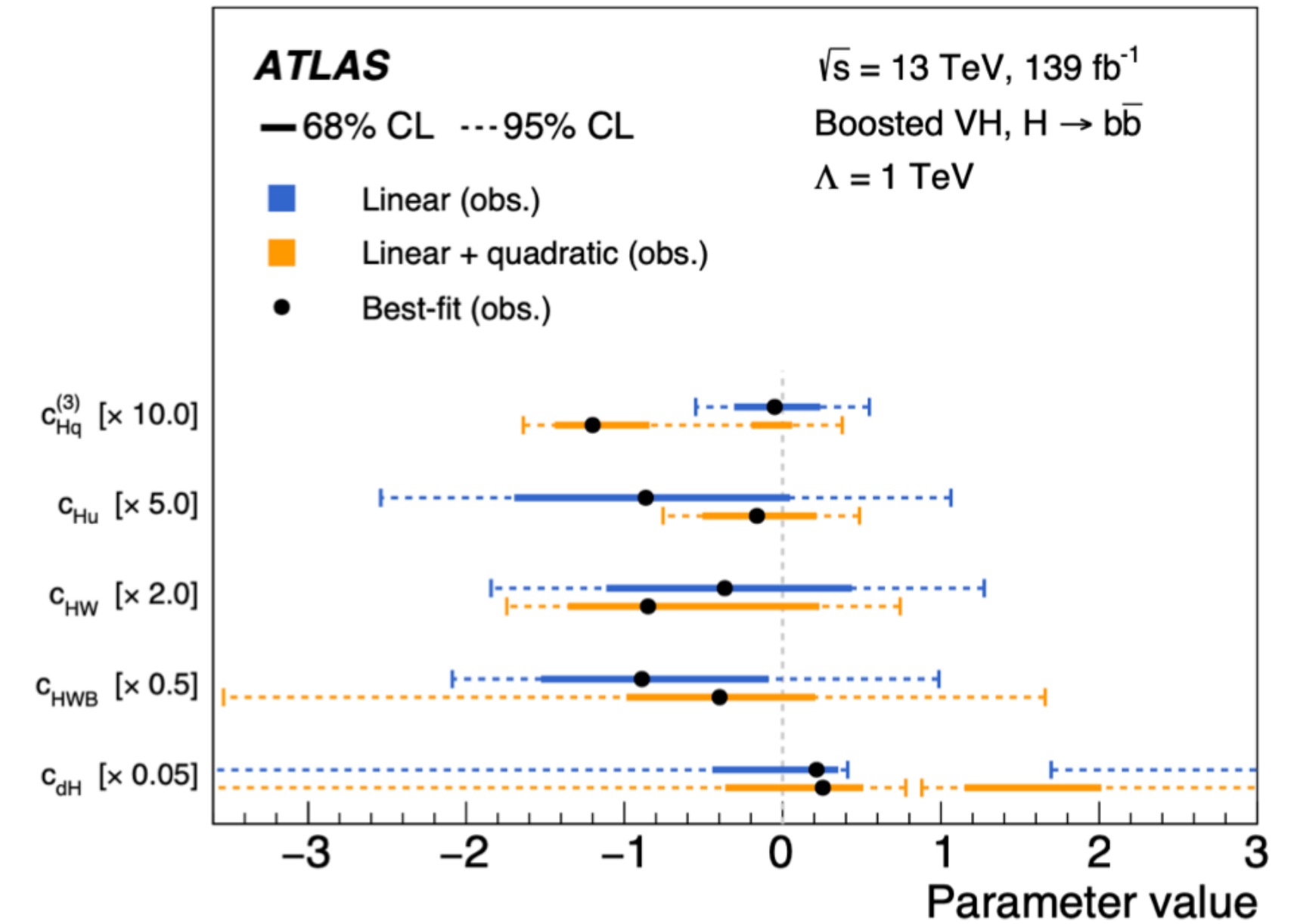
Dedicated boosted reconstruction



Large-R jet with b-tagging on tracks



➔ MEASURE VH(BB) AT HIGH PT



➔ SMEFT INTERPRETATIONS

H → $\tau\tau$

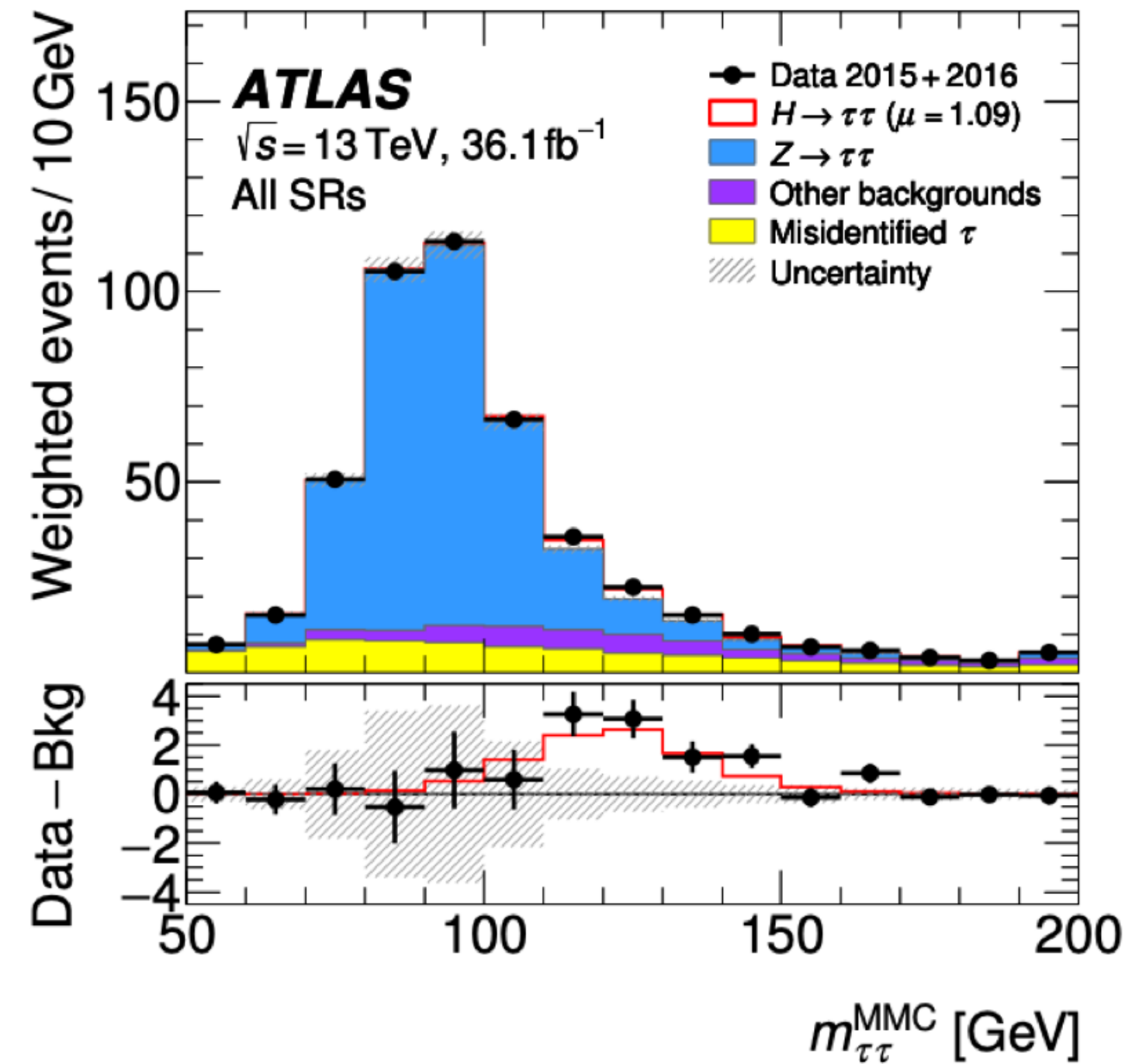
Coupling to heaviest lepton

OBSERVATION: 6.4 SIGMA

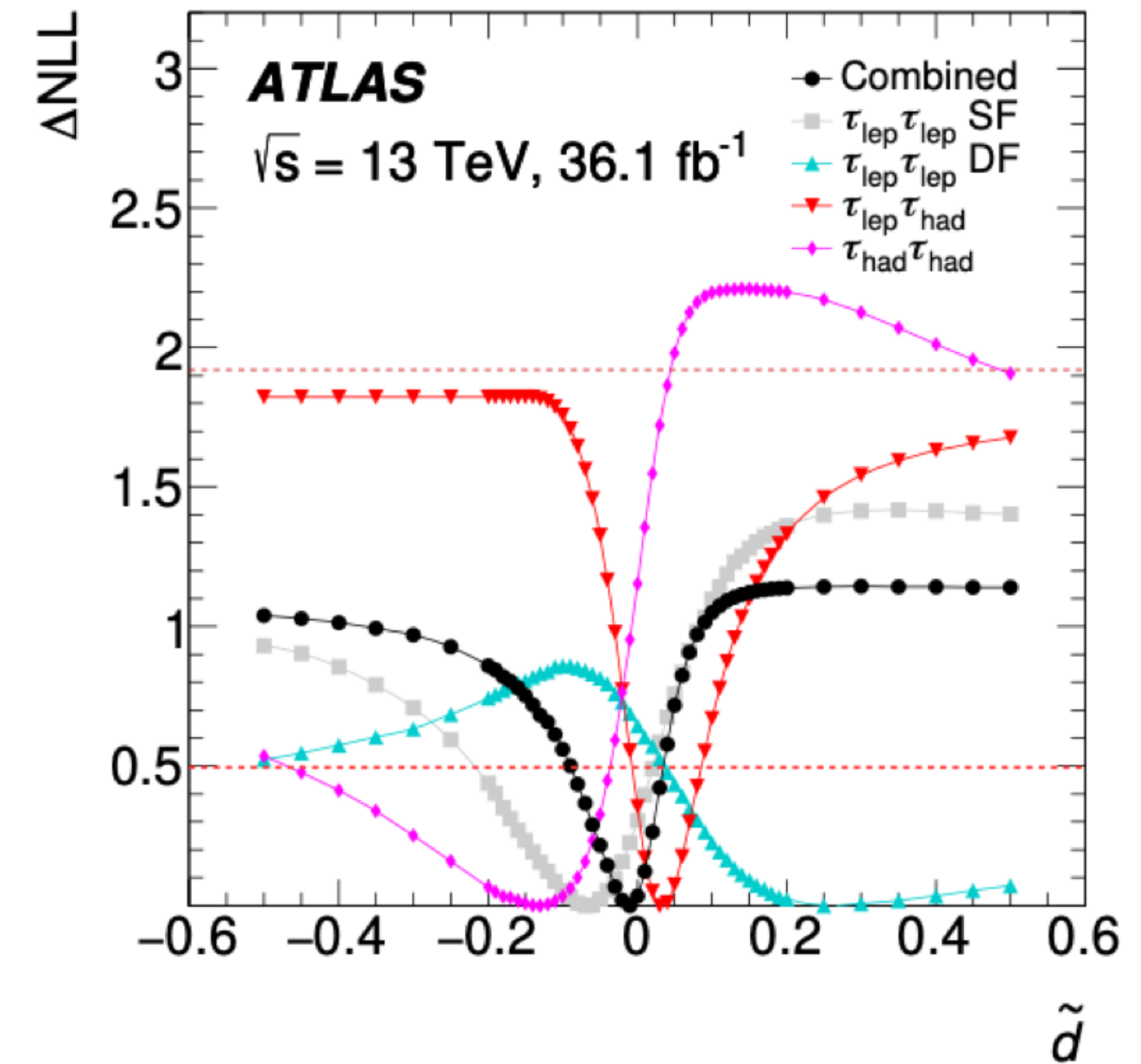
Test properties (e.g. CP)

CONSISTENT WITH NO CP VIOLATION

PHYS. REV. D 99, 072001 (2019)



PHYS. LETT. B 805 (2020) 135426



HIGGS TO 2ND GENERATION

	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

LEPTONS (vertical label on the left)

QUARKS (vertical label on the left)

GAUGE BOSONS (vertical label on the right)

VECTOR BOSONS (vertical label on the right)

SCALAR BOSONS (vertical label on the right)

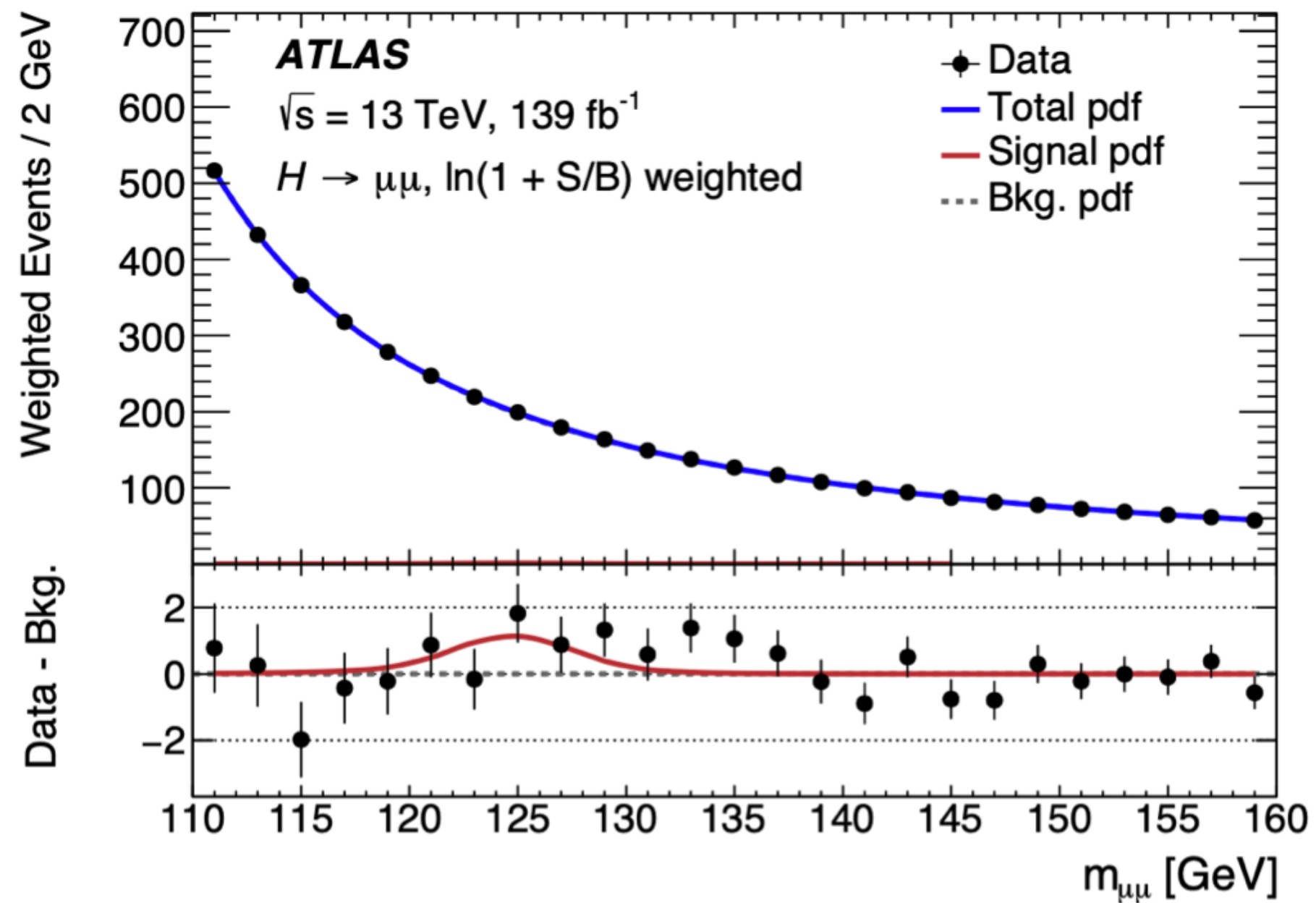
The next generation!

2ND GENERATION
 - LEPTONS: $H \rightarrow \mu\mu$
 - QUARKS: $H \rightarrow c\bar{c}$

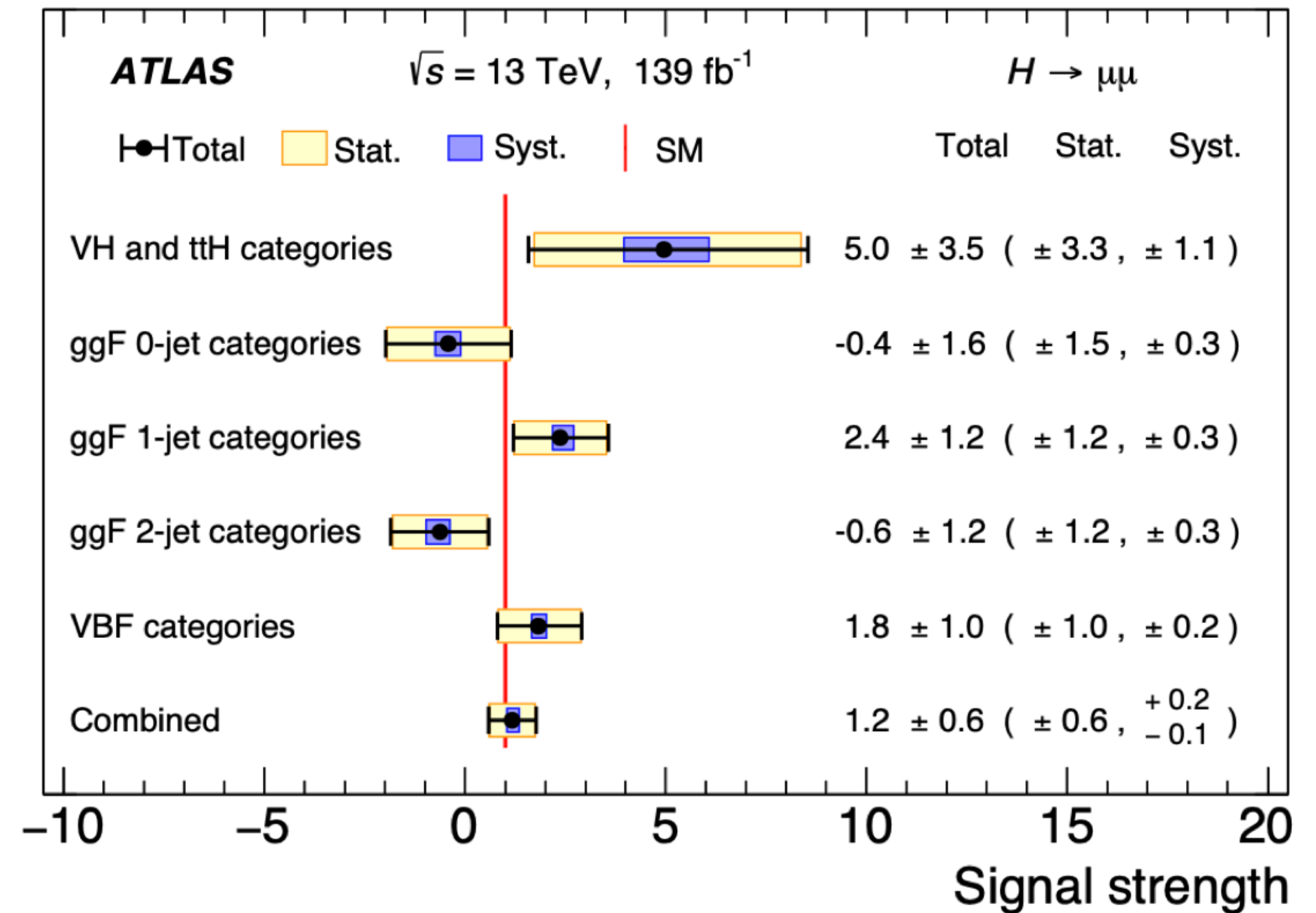
$H \rightarrow \mu\mu$

Fit to dimuon mass spectrum
in various event categories

→ Signal strength $\mu = 1.2 \pm 0.6$

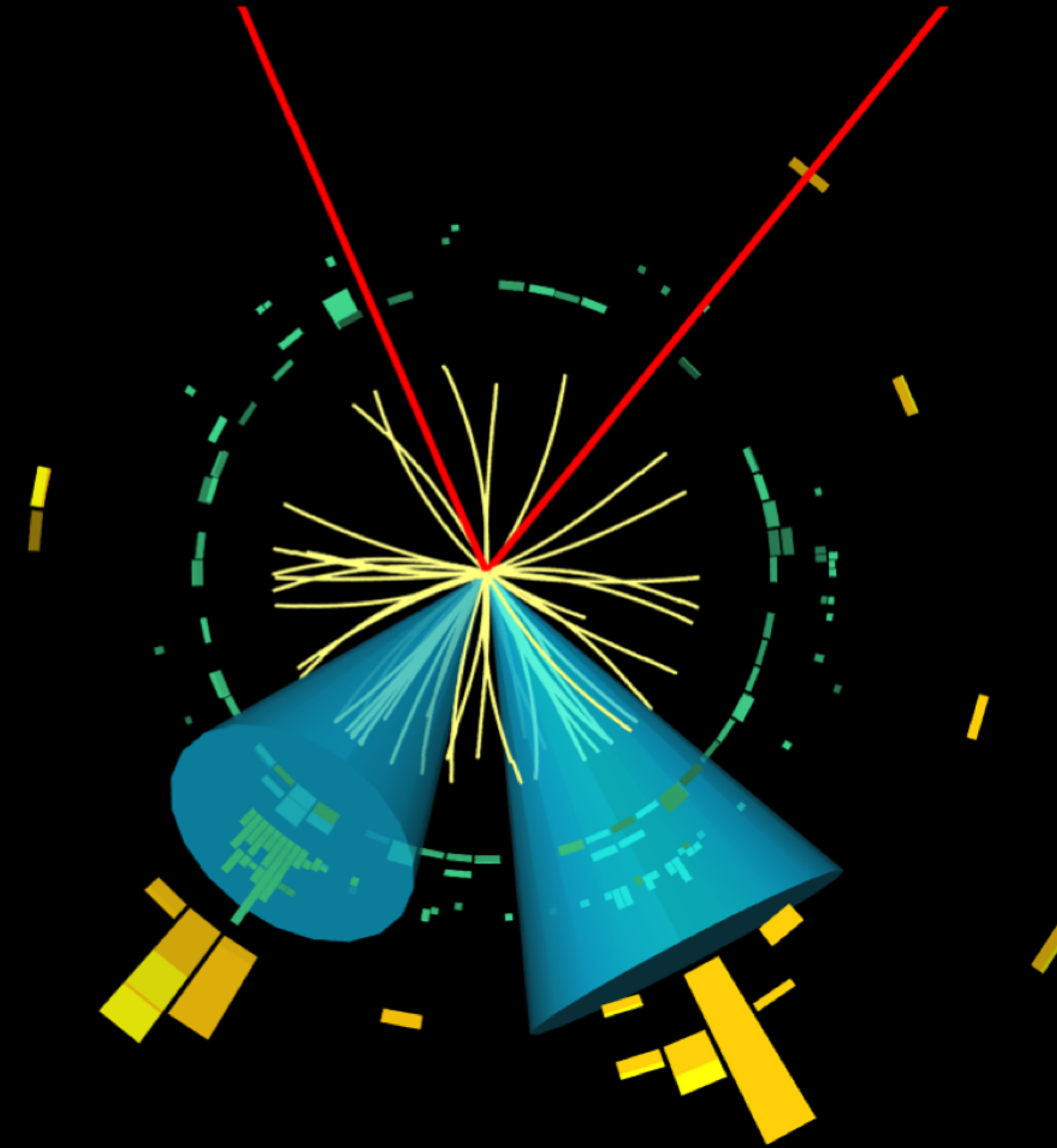
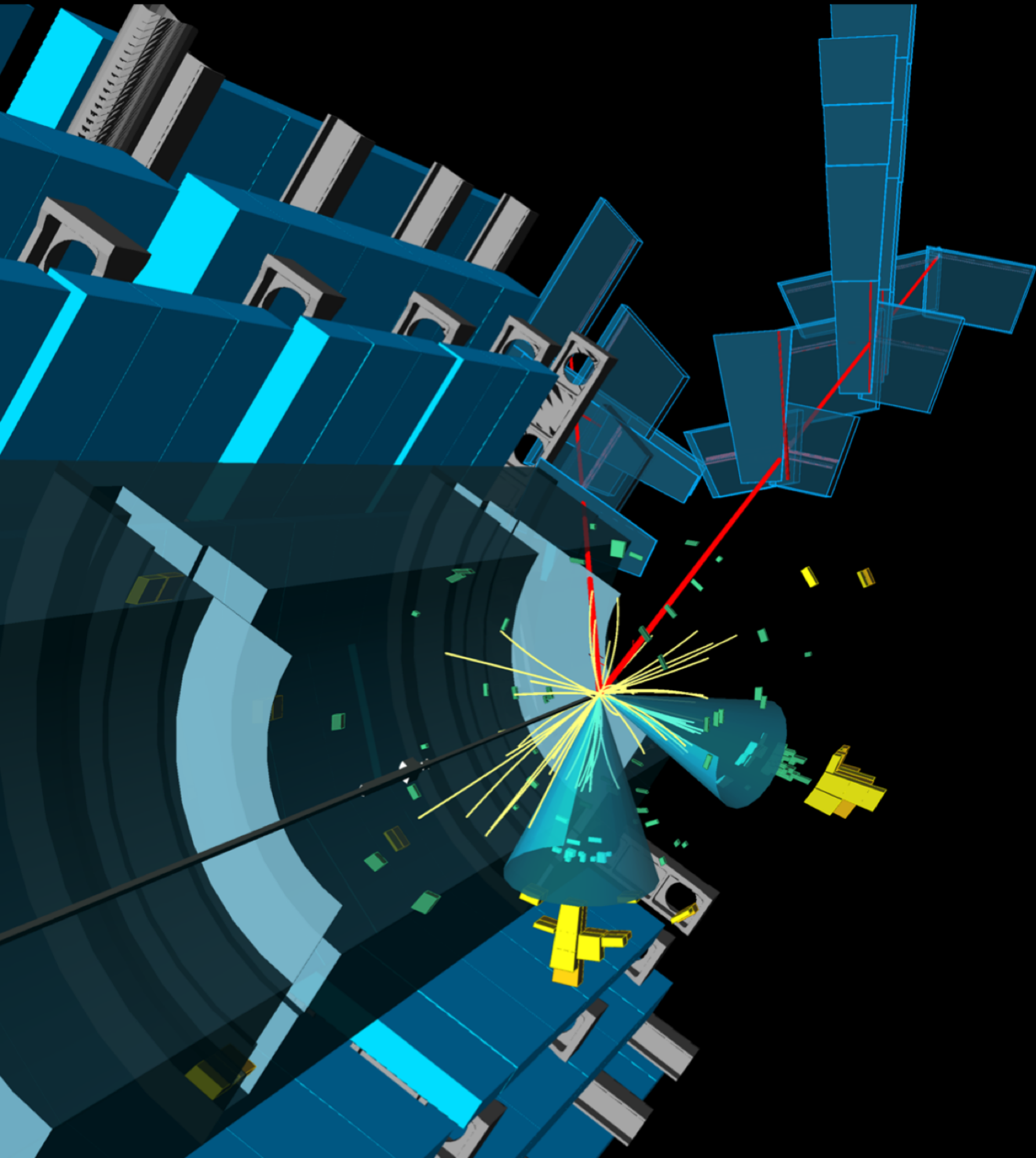


PHYS. LETT. B 812 (2021) 135980



→ Approaching observation of coupling to 2nd generation charged leptons

NEW: SEARCH FOR $VH \rightarrow CC$ WITH FULL RUN-2 DATA



$Z(H)H(CC)$ candidate event



Run: 309892

Event: 4866214607

2016-07-16 06:20:19 CEST

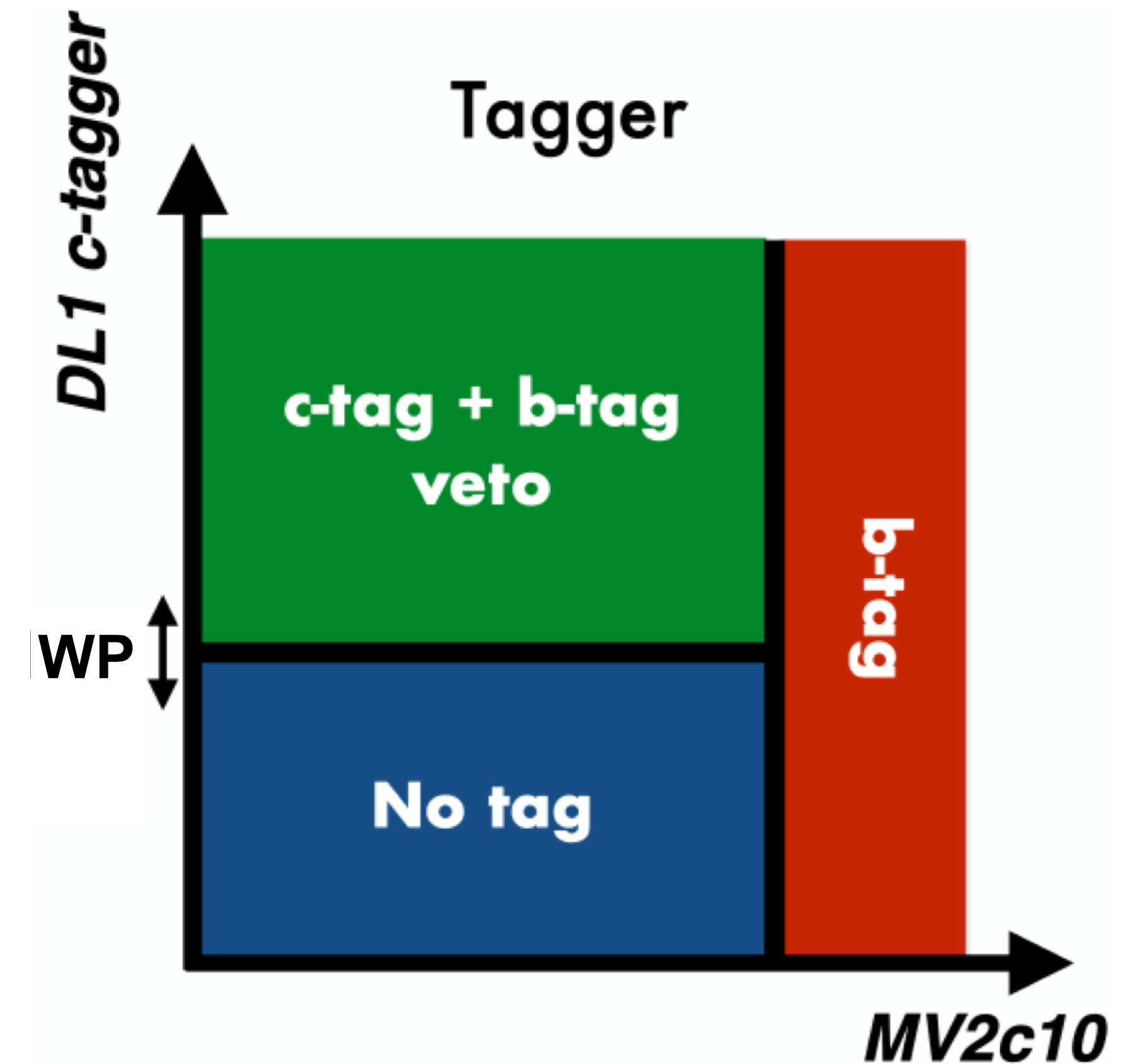
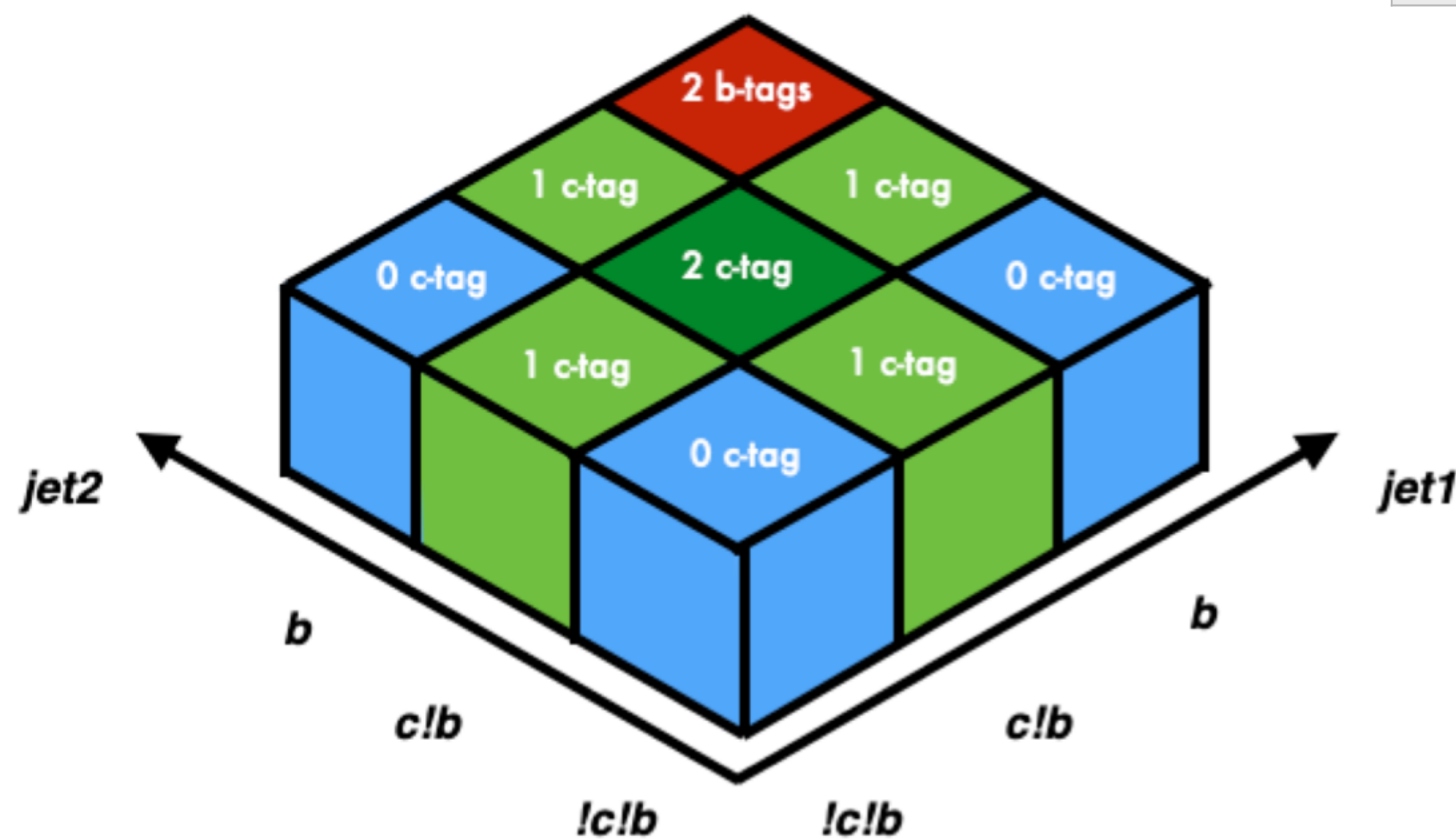
H → CC: ANALYSIS STRATEGY

NEW ATLAS-CONF-2021-021

VH production: 0+1+2 lepton

- Categories: $p_T(V)$, #jets
- Signal: 1c-tag & 2c-tag
- Control: 0c-tag

	c-tag eff
c-jets	27%
b-jets	8%
l-jets	1.6%



c-tag

+ b-tag veto to avoid overlap with H → bb

H → CC: MASS DISTRIBUTIONS

NEW ATLAS-CONF-2021-021

Main backgrounds:

Z+jets, W+jets, ttbar

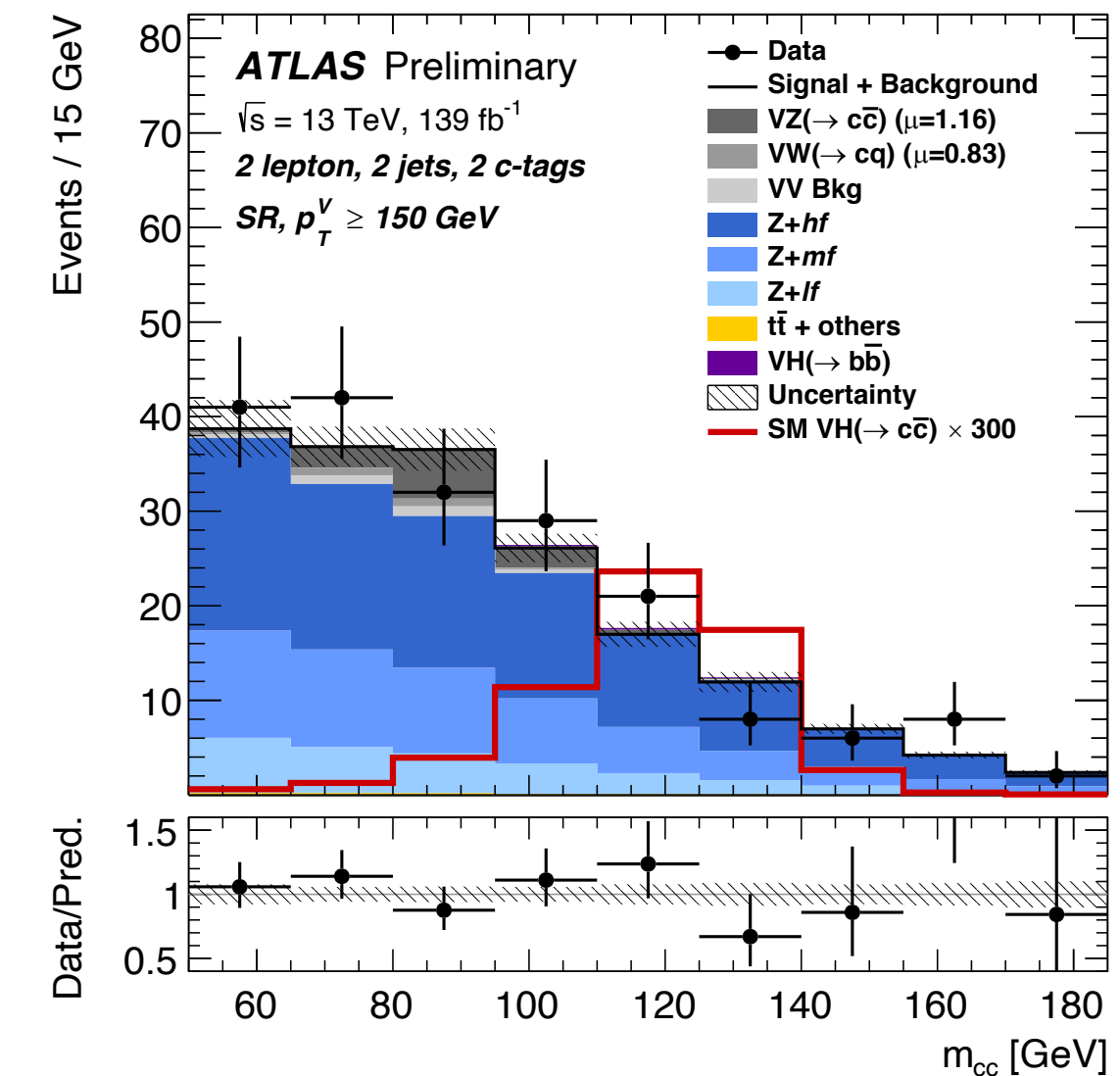
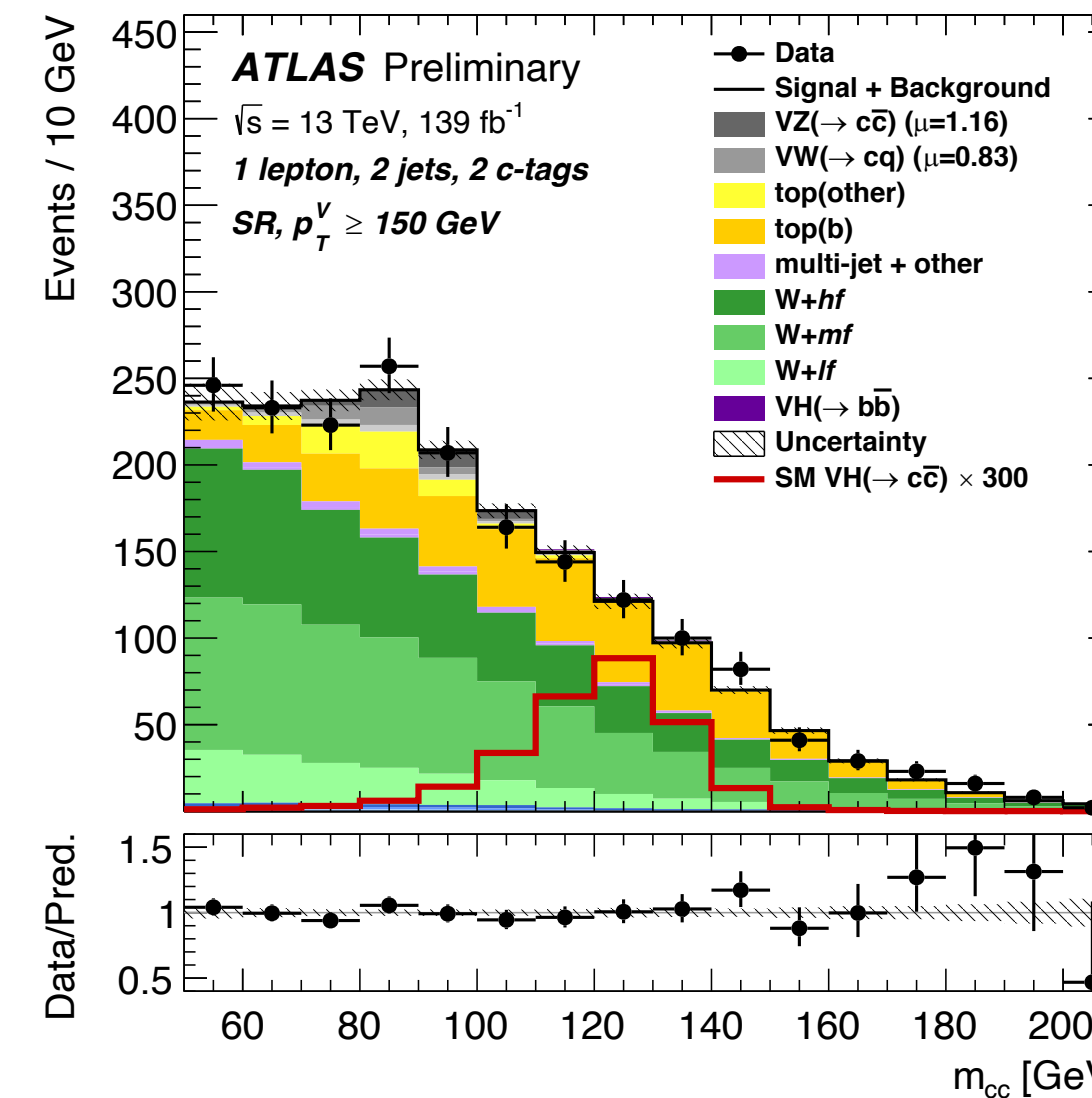
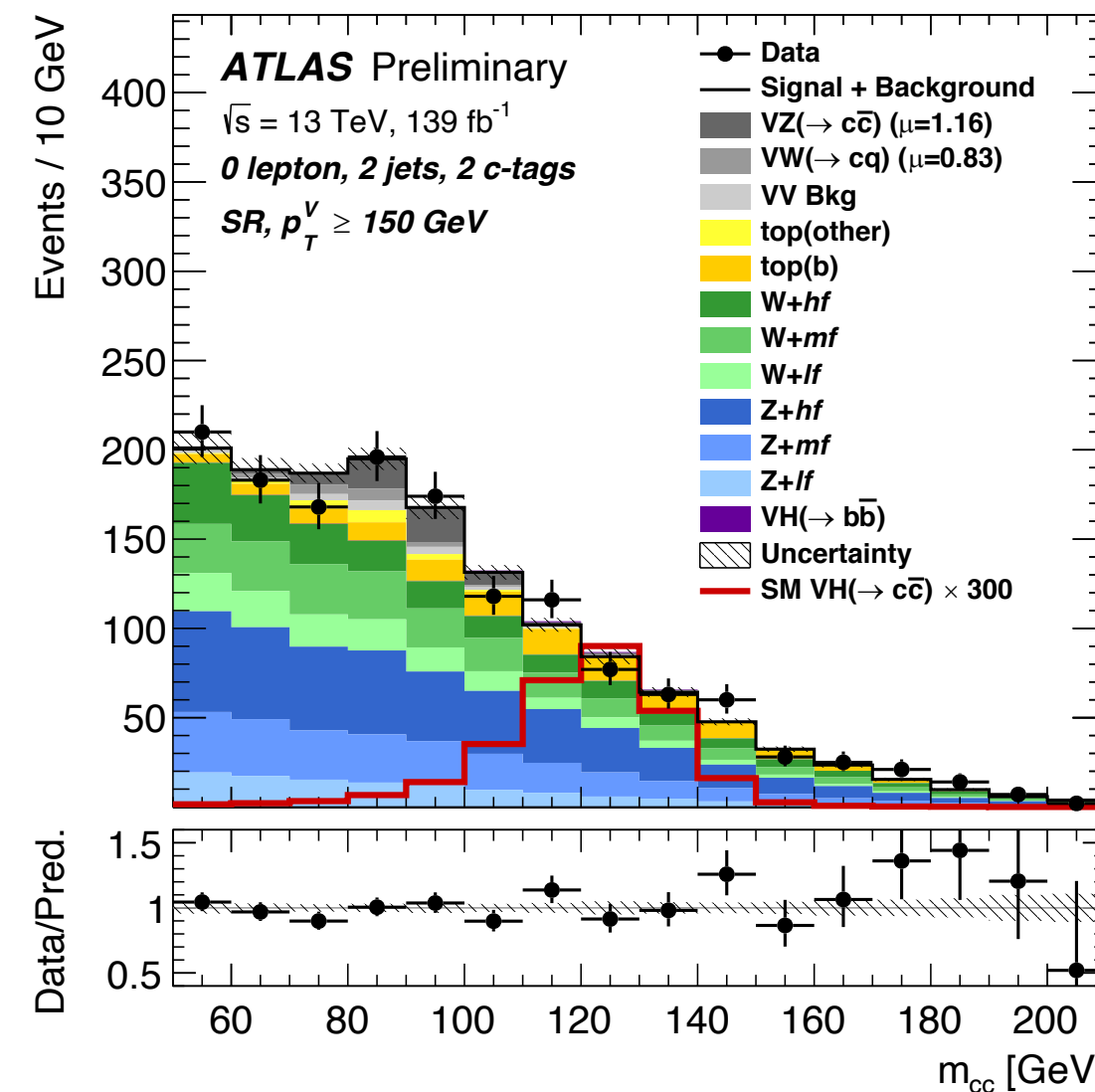
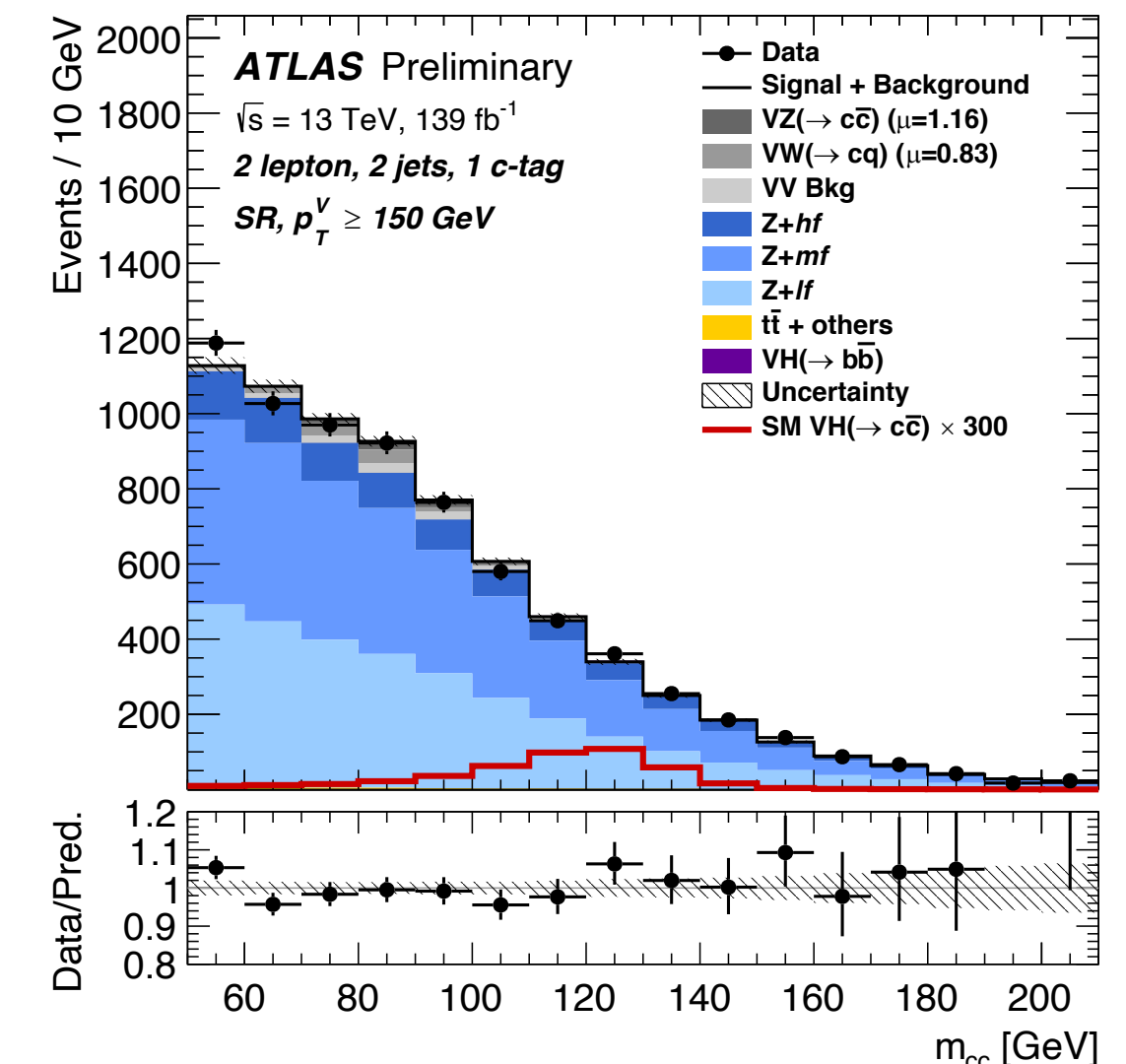
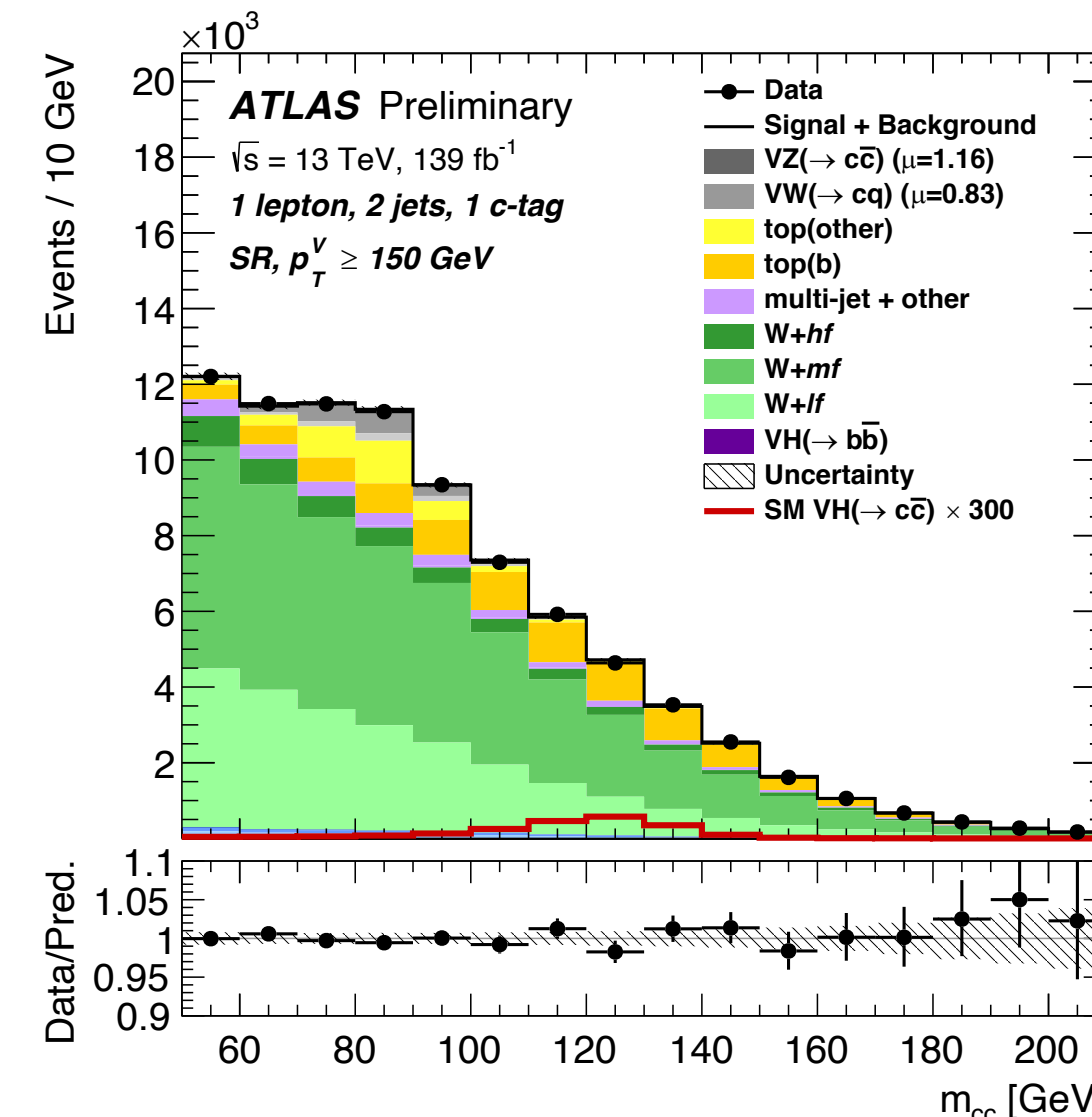
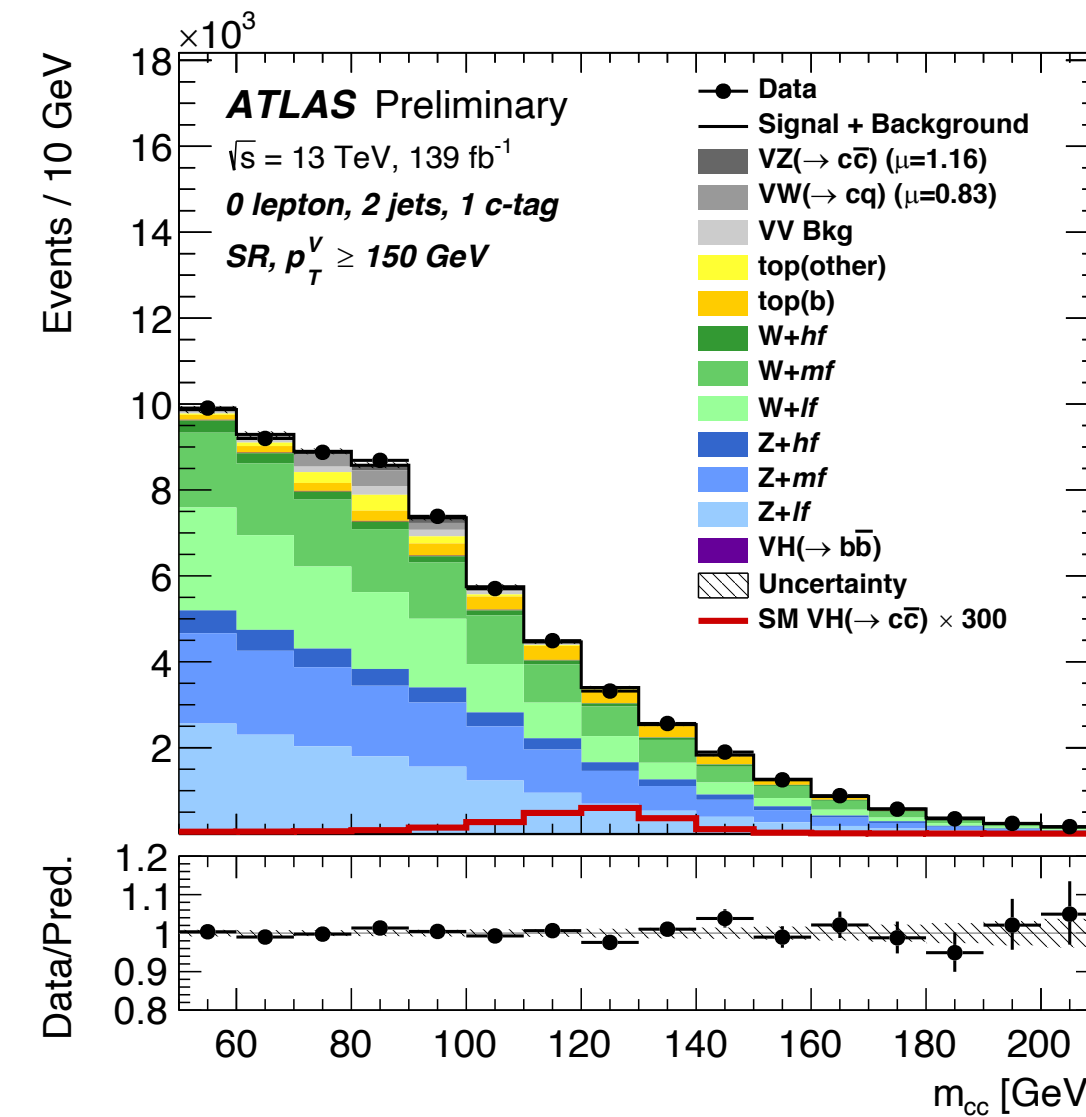
3POI:

VH(cc)

VW(cq)

VZ(cc)

Discriminant: M(cc)



H → CC: MASS DISTRIBUTIONS

NEW ATLAS-CONF-2021-021

M(cc) distributions:

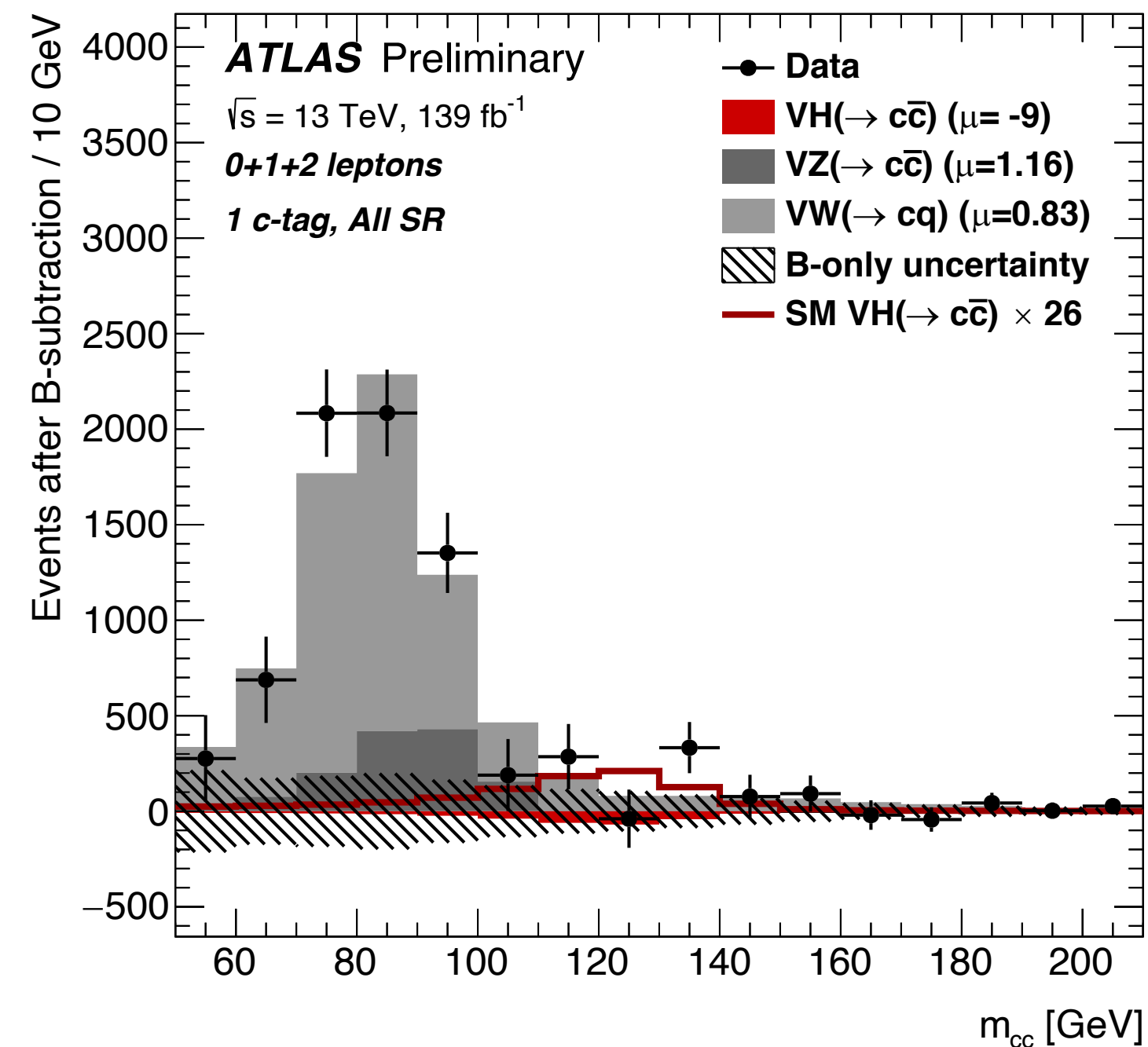
- 1c-tag and 2c-tag
- Background subtracted

Diboson fit results:

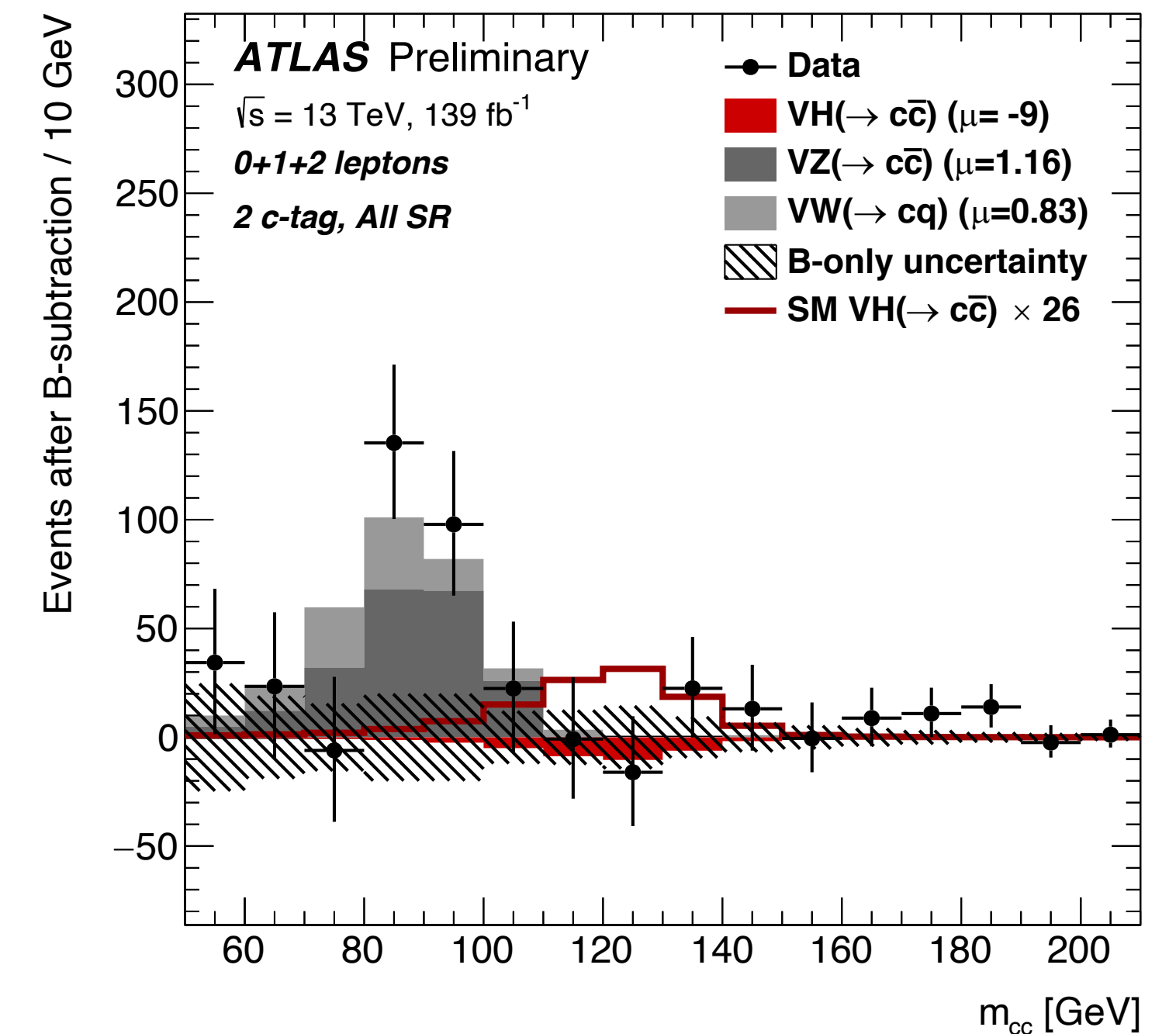
VW(cc): 3.8σ obs (4.6σ exp)

VZ(cc): 2.6σ obs (2.2σ exp)

1C-TAG



2C-TAG



H → CC: RESULT

NEW ATLAS-CONF-2021-021

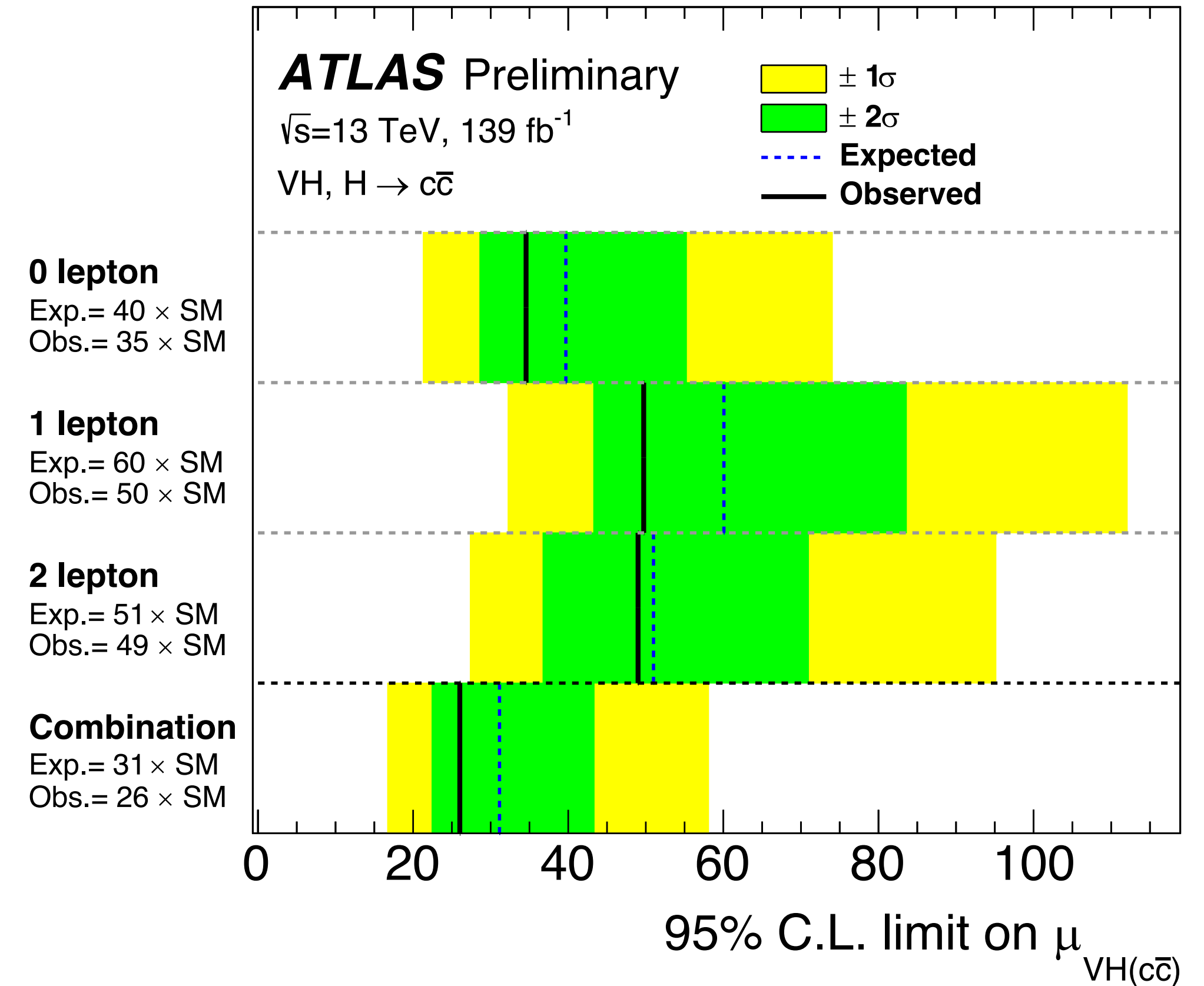
Combined fit of 0+1+2-lepton:
16 signal + 28 control regions

Limit @ 95%CL:

VH(cc) < 26 x SM obs (31 x SM exp)

Full Run-2 dataset:

World's best limit



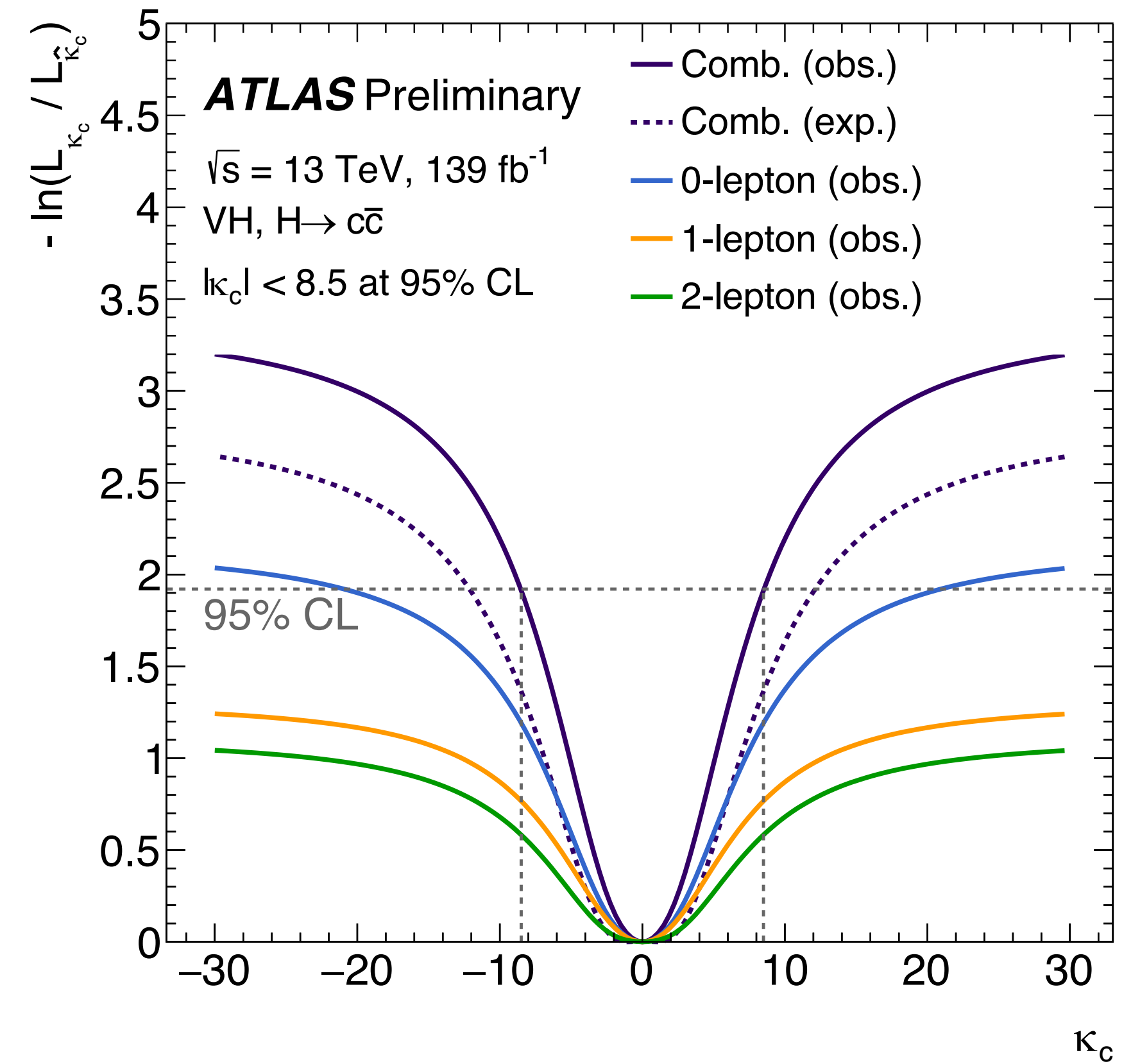
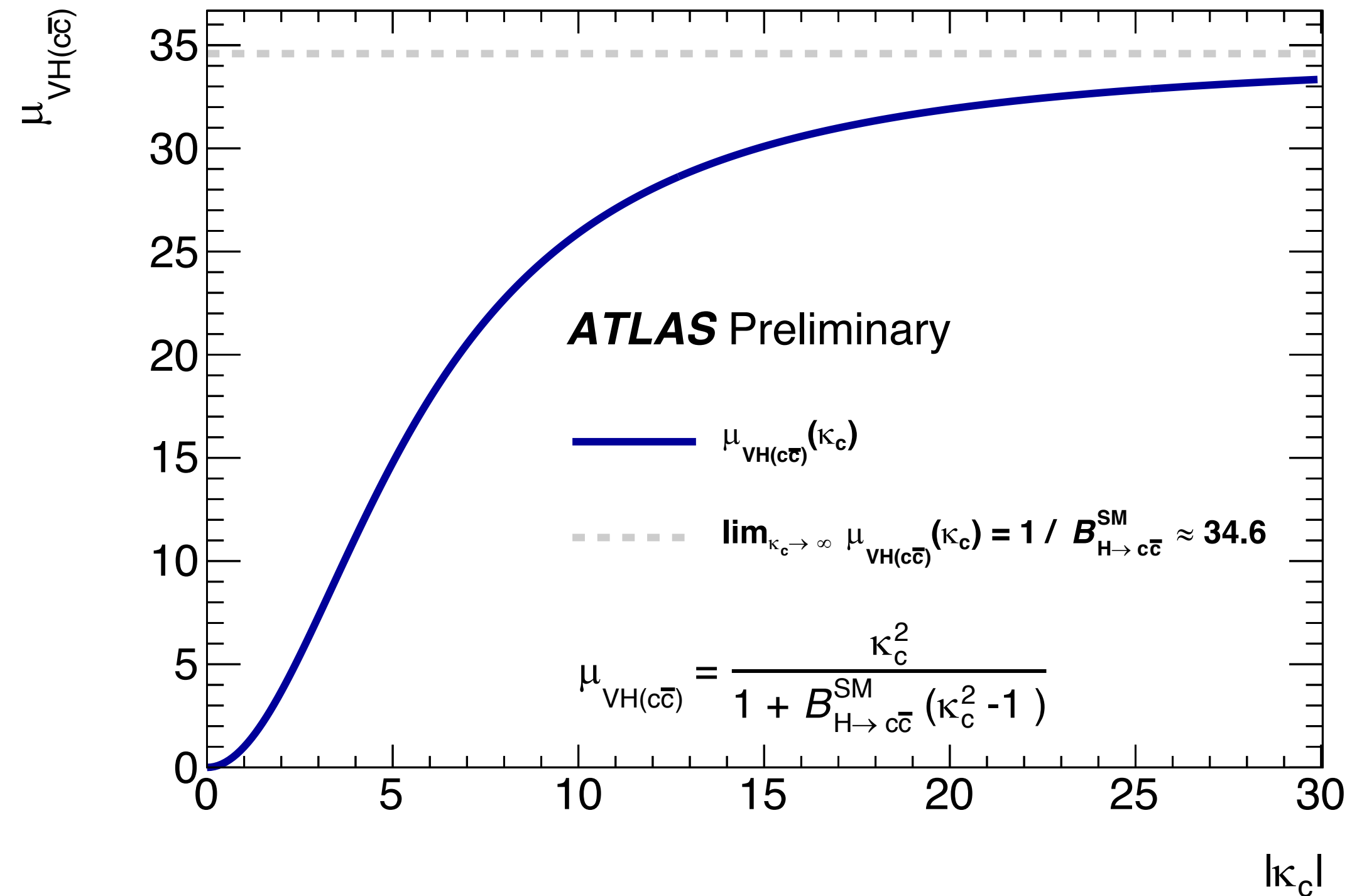
H → CC: INTERPRETATION

NEW ATLAS-CONF-2021-021

Direct constraint: Higgs-charm coupling

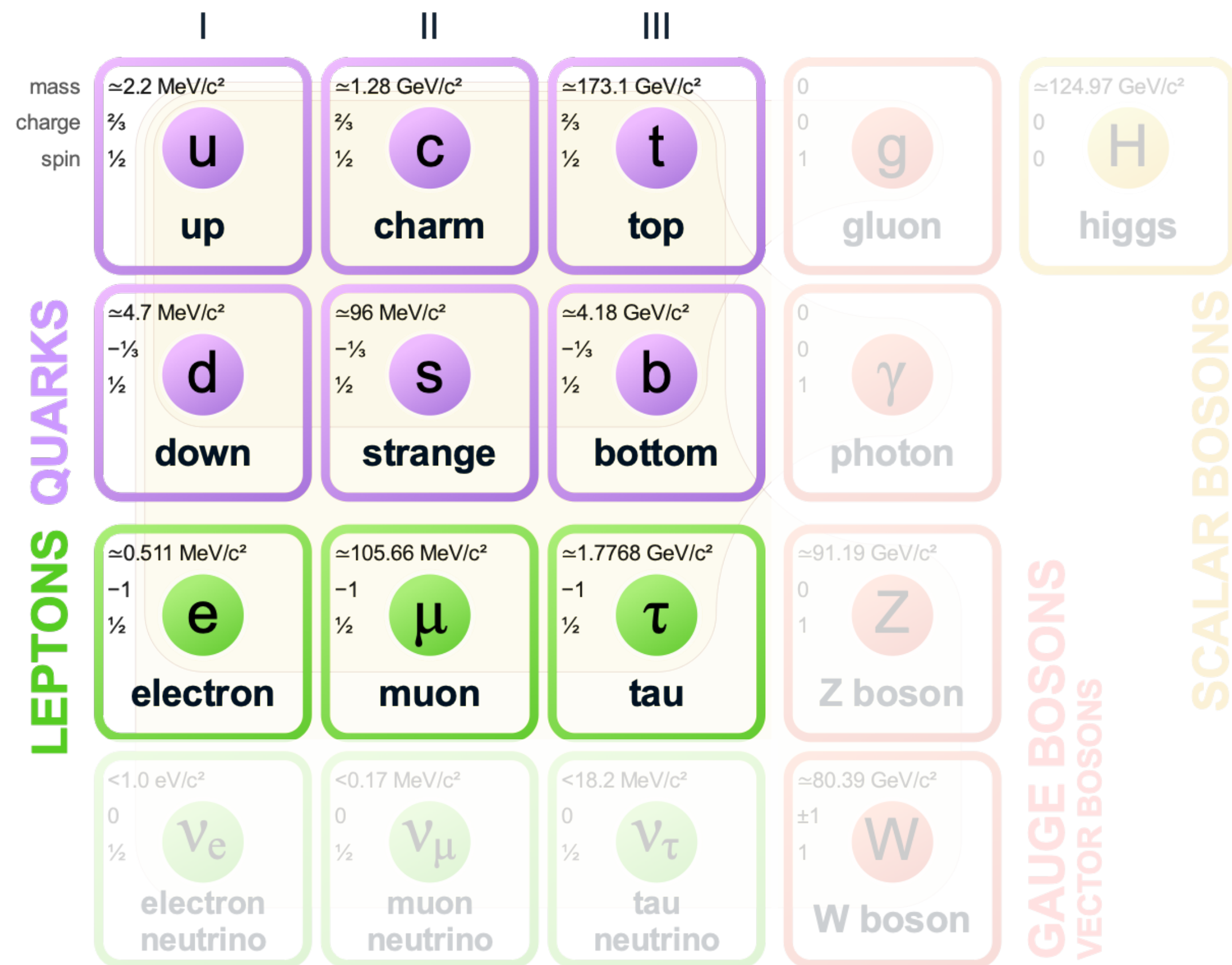
κ_c interpretation includes width effects

- All other couplings fixed to SM



→ $|\kappa_c| < 8.5 @ 95\% \text{ CL}$

ATLAS: HIGGS COUPLINGS TO QUARKS & LEPTONS



3rd gen

- $ttH, H \rightarrow bb, H \rightarrow \tau\tau$:
> 5 sigma, differential, EFT

2nd gen

- $H \rightarrow \mu\mu$: 2 sigma
- $H \rightarrow cc$: $|\kappa_c| < 8.5 @ 95\%CL$

➔ KEY ANALYSIS ELEMENTS: CATEGORIZATION, MVA, RECONSTRUCTION TECHNIQUES

THANK YOU
FOR YOUR
ATTENTION

W(ev)H(cc) candidate event



Run: 329964

Event: 500775771

2017-07-18 06:31:13 CEST