Search for the SM H→cc Decay With the ATLAS Experiment

Elisabeth Schopf on behalf of the ATLAS Collaboration

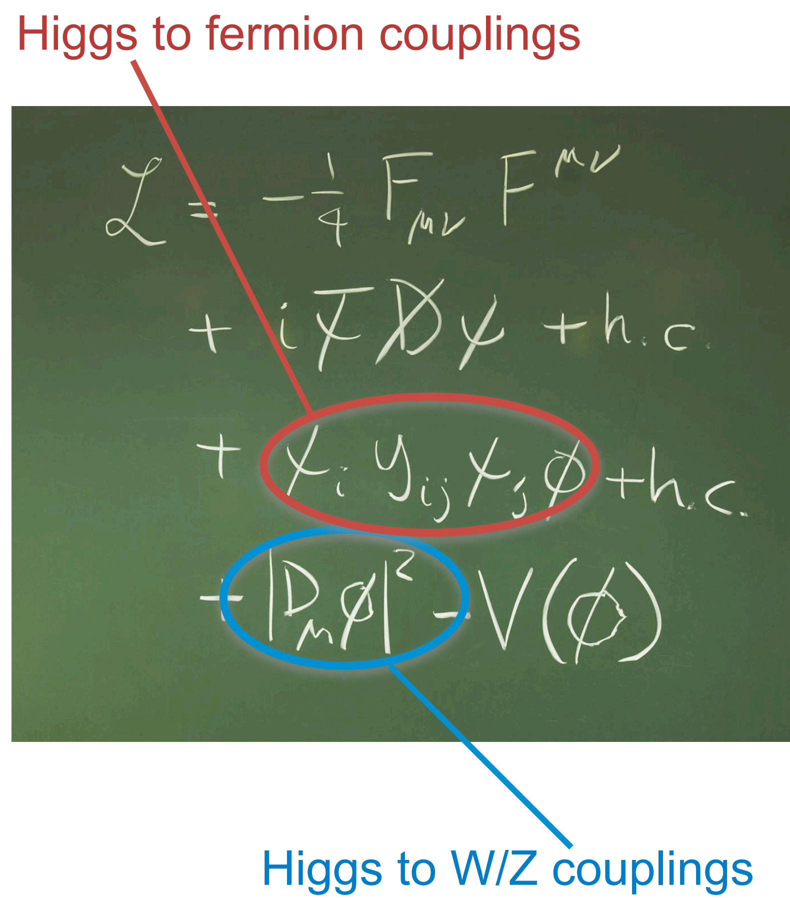
Higgs Couplings 2018

Fermion Sector of the Higgs Mechanism

→Ad-hoc term in Standard Model Lagrangian for Higgs-fermion interactions

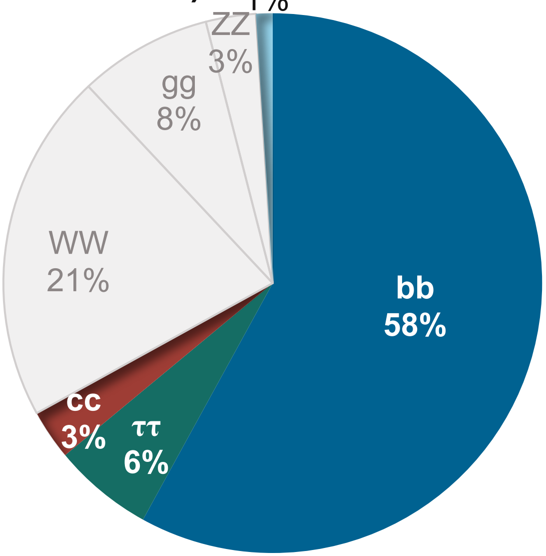
→Generates fermion masses

→Strength of Higgs-fermion coupling proportional to fermion mass

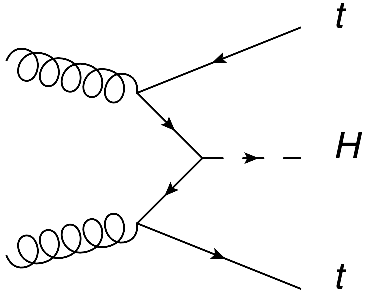


Status of ATLAS Higgs-Fermion Coupling Results

Branching ratios (m_H = 125 GeV)



Production with pair of top quarks (1% of σ(pp→H) at 13 TeV)



- (heavy) 3rd generation fermions:
  - H→ττ, H→bb, ttH production → observed
- (light) 2nd & 1st generation fermions:
  - H→μμ: σ×BR < 2.1×SM exp.
  - BR(H→ργ) < 52×SM exp. (u,d-quarks)
  - BR(H→φγ) < 208×SM exp. (s-quarks)
  - BR(H→J/ψγ) < 117×SM exp. (c-quarks)
  - **H→cc ⟹ in this talk**

Why Search for H→cc Decays?

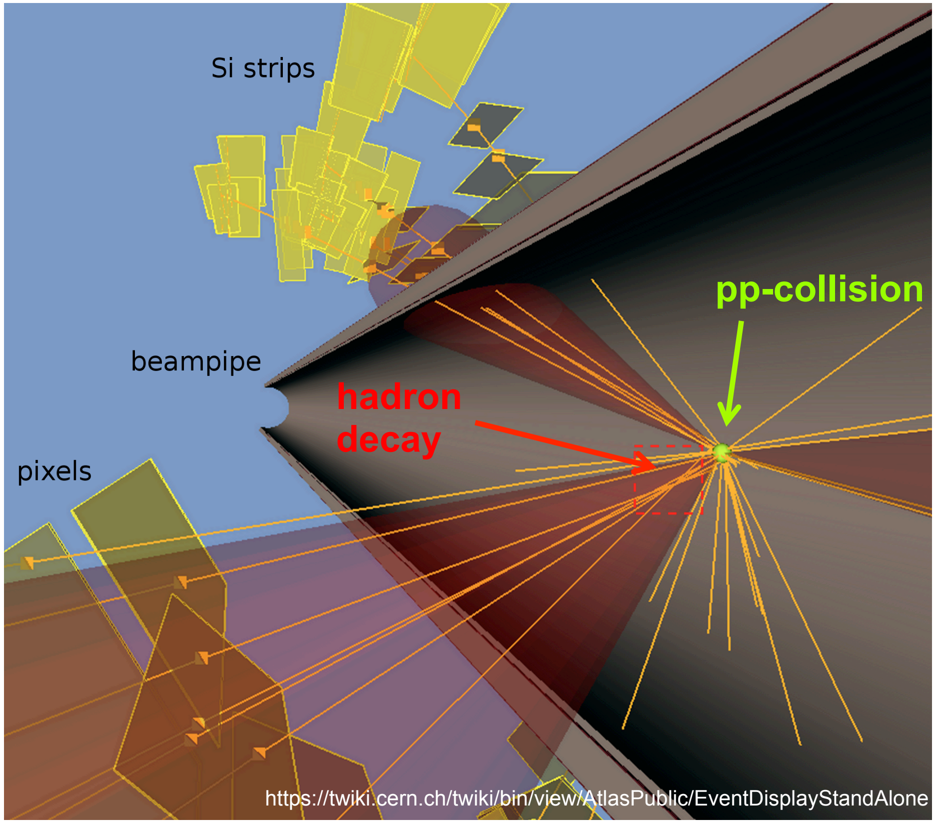
- Smallness of charm-Higgs coupling make it susceptible to measurable modifications from new physics
- One of largest unobserved contributors to Higgs boson total width
- So far only experimental evidence exists for 3rd generation fermion-Higgs couplings
  - Experimental constraints on light quark-Higgs couplings are loose and (mostly) indirect
- H→cc search offers window for direct constraint on charm-Higgs coupling

Identification ("Tagging") of Charm Jets

- Hadrons containing c-quarks have measurable lifetime(*):
  - → Hadron decay vertex
  - → Large track impact parameter

→ Information combined in two multivariate ID algorithms:

- b-jet vs. c-jet discrimination
- c-jet vs. light jet discrimination



(*) c-hadrons: $c\tau$ ~120 to 300 μm
b-hadrons: $c\tau$ ~450 to 500 μm

c-Jet Tagging Performance(*)

- c-jet ID efficiency: 41%
- b-jet (mis-)ID efficiency: 25%
- light jet (mis-)ID efficiency: 5%

(*) studied in simulated top quark pair events

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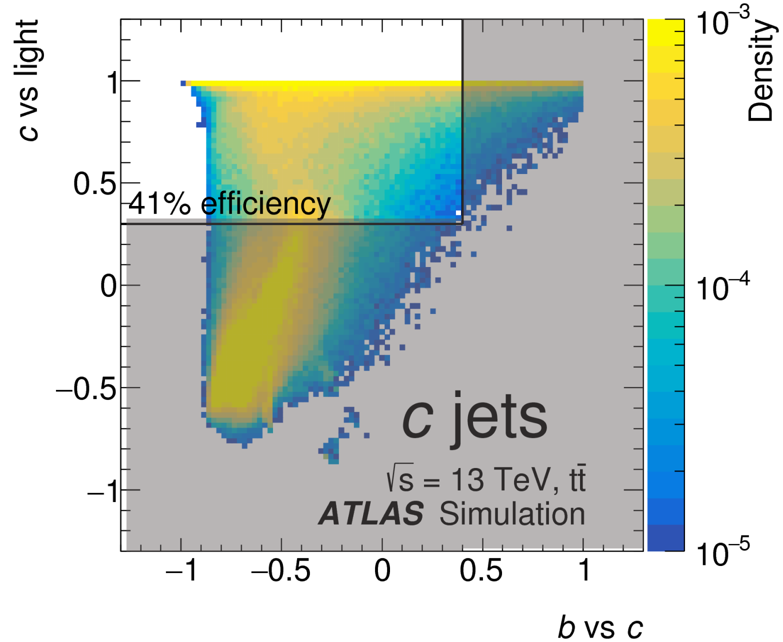

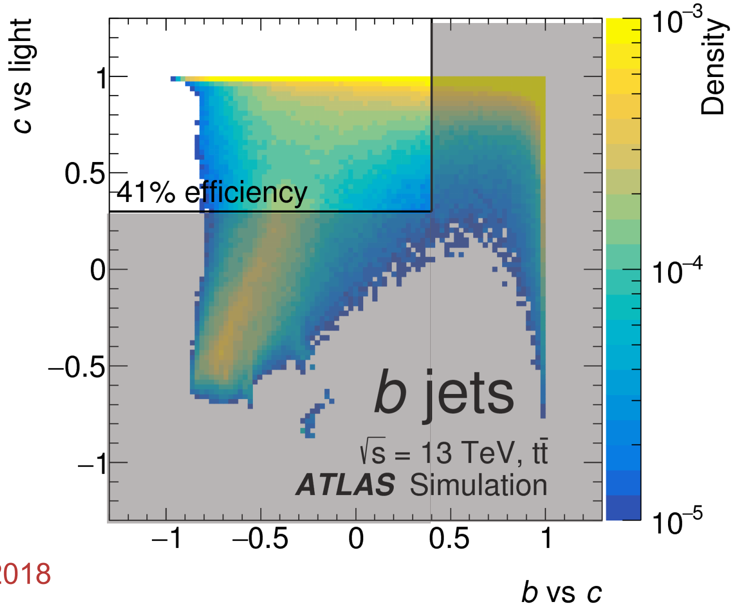

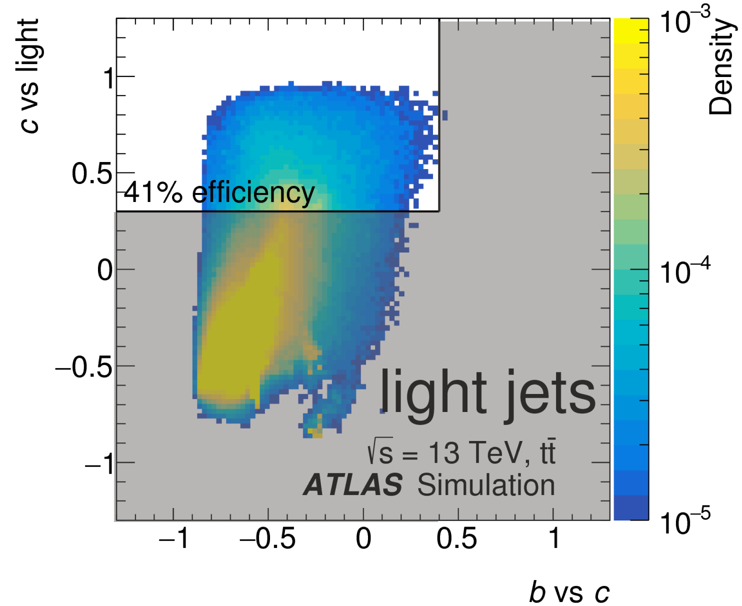

Selection of H→cc Candidate Events

Target (Z→ee,μμ)(H→cc) events for manageable trigger rates and background suppression

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Higgs boson candidate:
2 highest p_T jets with at least 1 c-tag and $p_T > 45$ GeV

Z boson candidate:
2 electrons or 2 muons with $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$

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2 electrons or 2 muons with 81 GeV < $m_{\ell\ell}$ < 101 GeV

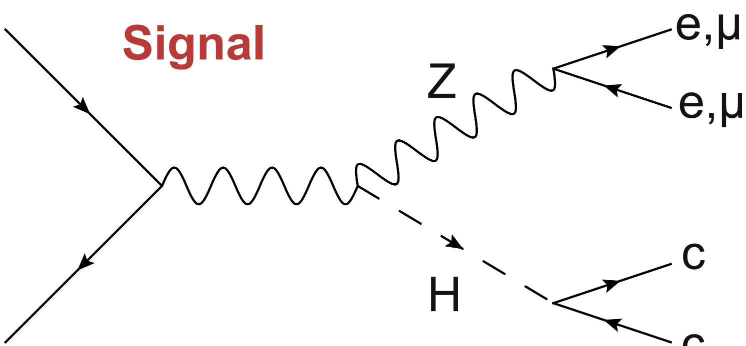
Additional background suppression:

- p_T^Z > 75 GeV
- p_T^Z dependent max. ΔR between Higgs candidate jets

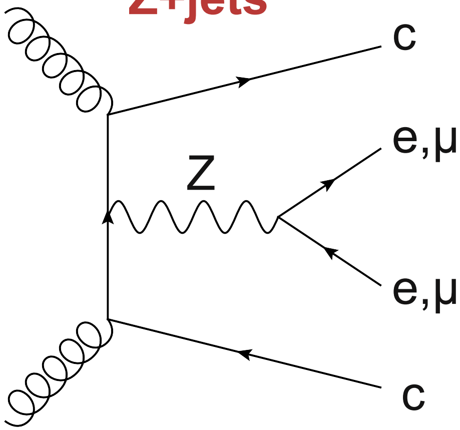
Selected Signal and Background Events

(data set: 36.1 fb^{-1} of pp-collisions at 13 TeV)

Signal



Main background: Z+jets



- ZH→ℓℓcc: 5 events → acceptance ~8%
- Background processes: 96000 events
- Background includes ZH→ℓℓbb (fixed to SM): 58 events → acceptance ~4.5%

Results of the ZH→ℓℓcc Search

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- Simultaneous fit to data using m_{cc} in 4 different phase spaces:

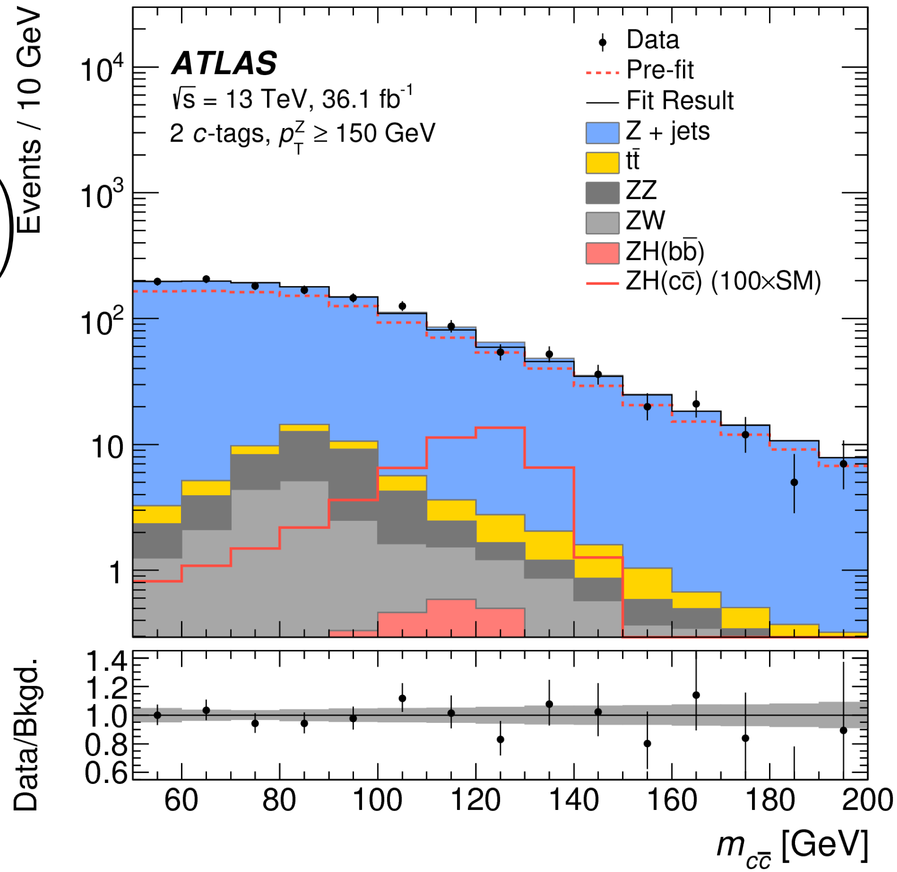
$$\begin{pmatrix} 1\ c\text{-jet} \\ 2\ c\text{-jets} \end{pmatrix} \times \begin{pmatrix} 75\ \text{GeV} < p_T^Z < 150\ \text{GeV} \\ p_T^Z > 150\ \text{GeV} \end{pmatrix}$$

- Expected 95% CL limit:

$$\sigma(pp \to ZH) \times \text{BR}(H \to cc) < 3.9^{+2.1}_{-1.1}\ \text{pb}$$

- Measured 95% CL limit:

σ(pp→ZH)×BR(H→cc) < 2.7 pb
or
σ(pp→ZH)×BR(H→cc) < 110×SM exp.



Probing Di-Boson Production

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- Analysis strategy cross check using ZV events:
  - 55% of selected ZZ events are ZZ→$\ell\ell$cc decays
  - 65% of selected WZ events are WZ→(cs,cd)$\ell\ell$ decays
- Simultaneous fit to data using m_{cc} in same analysis phase space
  - SM H→cc and H→bb fixed to SM expectation
- Measured signal strength (w.r.t. SM exp.): $\mu_{VZ} = 0.6^{+0.5}_{-0.4}$
- Observed (expected) VZ significance: 1.4 (2.2) σ

ZH→ℓℓcc Analysis Prospects

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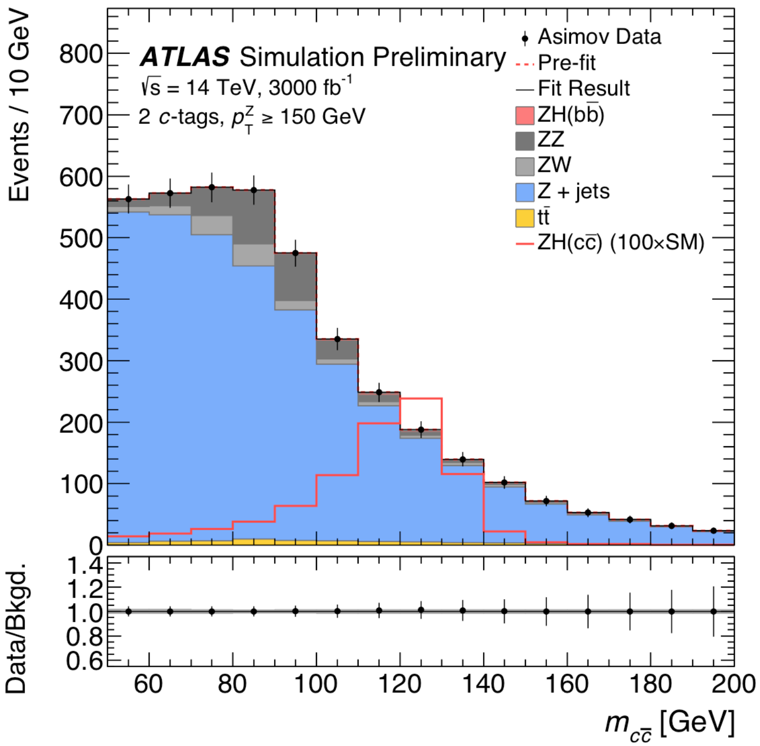
- Assume 3000 fb^{-1} of proton-proton collision at 14 TeV
- Same analysis strategy but tighter c-jet ID requirement:
  - 18% c-jet , 5% b-jet, 0.5% light jet efficiencies
- Expected signal strength (no systematic uncertainties):

$$\mu_{ZH(cc)} < 6.3^{+2.5}_{-1.8} \text{ (w.r.t SM exp.)}$$

$$\mu_{ZH(cc)} = 1.0 \pm 3.2$$

- Other potential improvements: c-jet ID, inclusion of (W→ℓν)H and (Z→νν)H, multivariate analysis



Summary

- Direct probe of charm quark to Higgs boson couplings in search for H→cc decays with ATLAS
- H→cc analysis targets (Z→ee,μμ)(H→cc) events
- Usage of c-jet identification techniques
- Upper limit (95% CL): **σ(pp→ZH)×BR(H→cc) < 2.7 pb**
  →corresponds to 110 × SM expectation
- Assuming 3000 fb^{-1} of 14 TeV pp collisions:

$$\mu_{ZH(cc)} < 6.3^{+2.5}_{-1.8} \text{ (w.r.t SM exp.)}$$

Additional Material

Publications:

“Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment “ - Phys. Rev. Lett. 120 (2018) 211802 – ATLAS

“Prospects for *H→cc* using Charm Tagging with the ATLAS Experiment at the HL-LHC” - ATL-PHYS-PUB-2018-016 – ATLAS

“Search for Higgs and Z Boson Decays to J/psi gamma and Upsilon(nS) gamma with the ATLAS Detector” - Phys. Rev. Lett. 114 (2015) 121801 – ATLAS

“Search for exclusive Higgs and Z boson decays to $\varphi\gamma$ and $\rho\gamma$ with the ATLAS Detector” - JHEP 07(2018) 127 – ATLAS

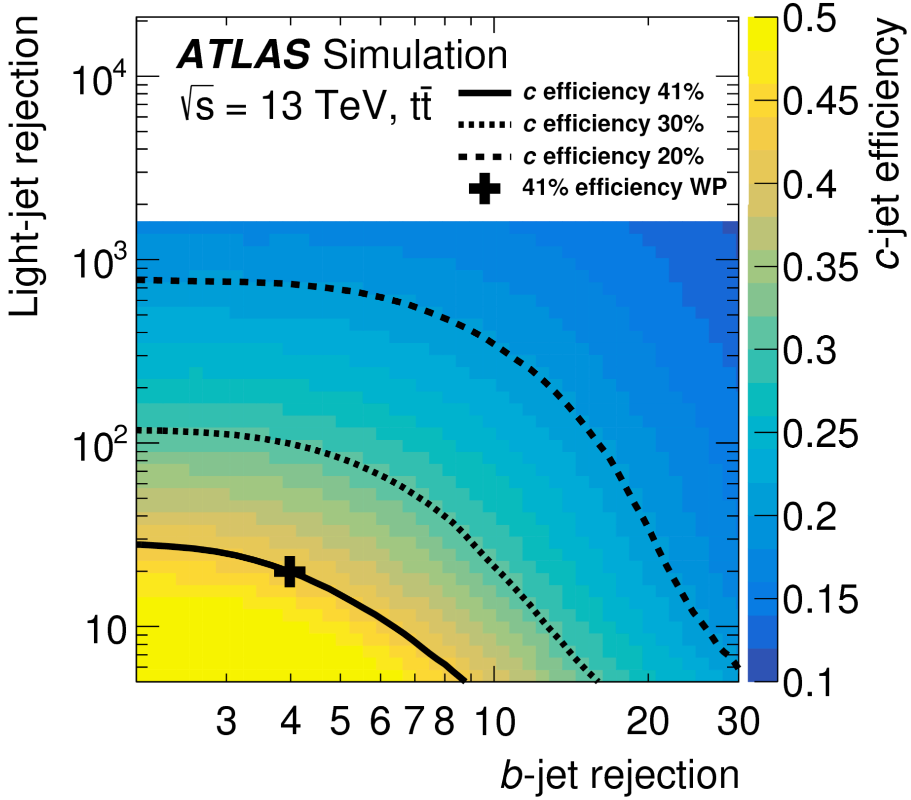
“A search for the rare decay of the Standard Model Higgs boson to dimuons in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector” - ATLAS-CONF-2018-026 -ATLAS

Other presentations at Higgs Couplings 2018:

“Analyses on H to bb and cc at ATLAS” – Douglas Schaefer

c-jet Identification

Iso-efficiency curves for different c-jet efficiencies



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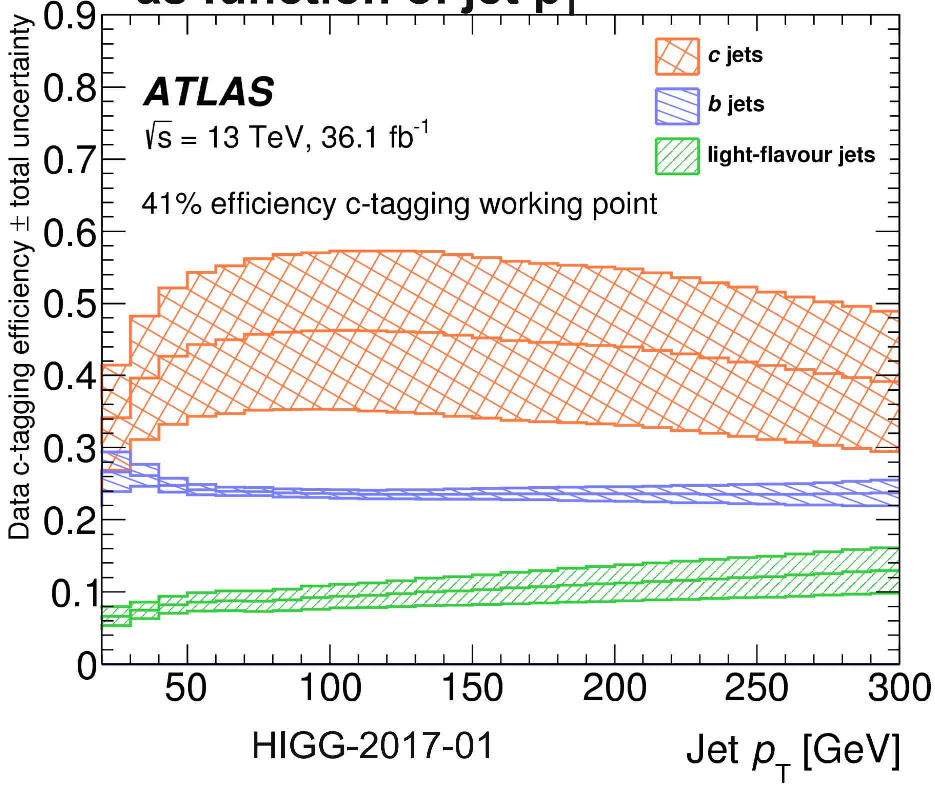
Efficiencies incl. uncertainties as function of jet p_T



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Monte Carlo Generators for Signal and Background Prediction

Process	Event Generator (alternative)	Parton Shower (alternative)	PDF (alternative)	Tune	Cross-section
$q\bar{q} \to ZH$	POWHEG-BOX v2 [28] +GOSAM [35] +MINLO [45,46]	PYTHIA 8 (HERWIG 7 [47])	PDF4LHC15NLO [33] /CTEQ6L1 [36,37]	AZNLO [34] (A14 [48])	NNLO (QCD)* +NLO (EW) [38,39,40,41,42,43,44]
$gg \to ZH$	POWHEG-BOX v2	PYTHIA 8 (HERWIG 7)	PDF4LHC15NLO /CTEQ6L1	AZNLO (A14)	NLO+NLL (QCD) [49,50,51,15]
$t\bar{t}$	POWHEG-BOX v2	PYTHIA 8 (HERWIG 7)	NNPDF3.0NLO [52] /NNPDF2.3LO	A14	NNLO+NNLL [53]
ZW, ZZ	SHERPA 2.2.1 [29] (POWHEG-BOX)	SHERPA (PYTHIA 8)	NNPDF3.0NNLO	SHERPA	NLO
Z+jets	SHERPA 2.2.1 (MG5_aMC)	SHERPA (PYTHIA 8)	NNPDF3.0NNLO (NNPDF2.3LO)	SHERPA (A14)	NNLO [54]

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Signal and Background Yields (Post-Fit)

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Sample	Yield, 50 $GeV < m_{c\bar{c}} <$ 200 GeV			
	1 c-tag		2 c-tags	
	$75 \leq p_T^Z < 150\,GeV$	$p_T^Z \geq 150\,GeV$	$75 \leq p_T^Z < 150\,GeV$	$p_T^Z \geq 150\,GeV$
Z + jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

+ m_{cc} in all Phase Space Regions

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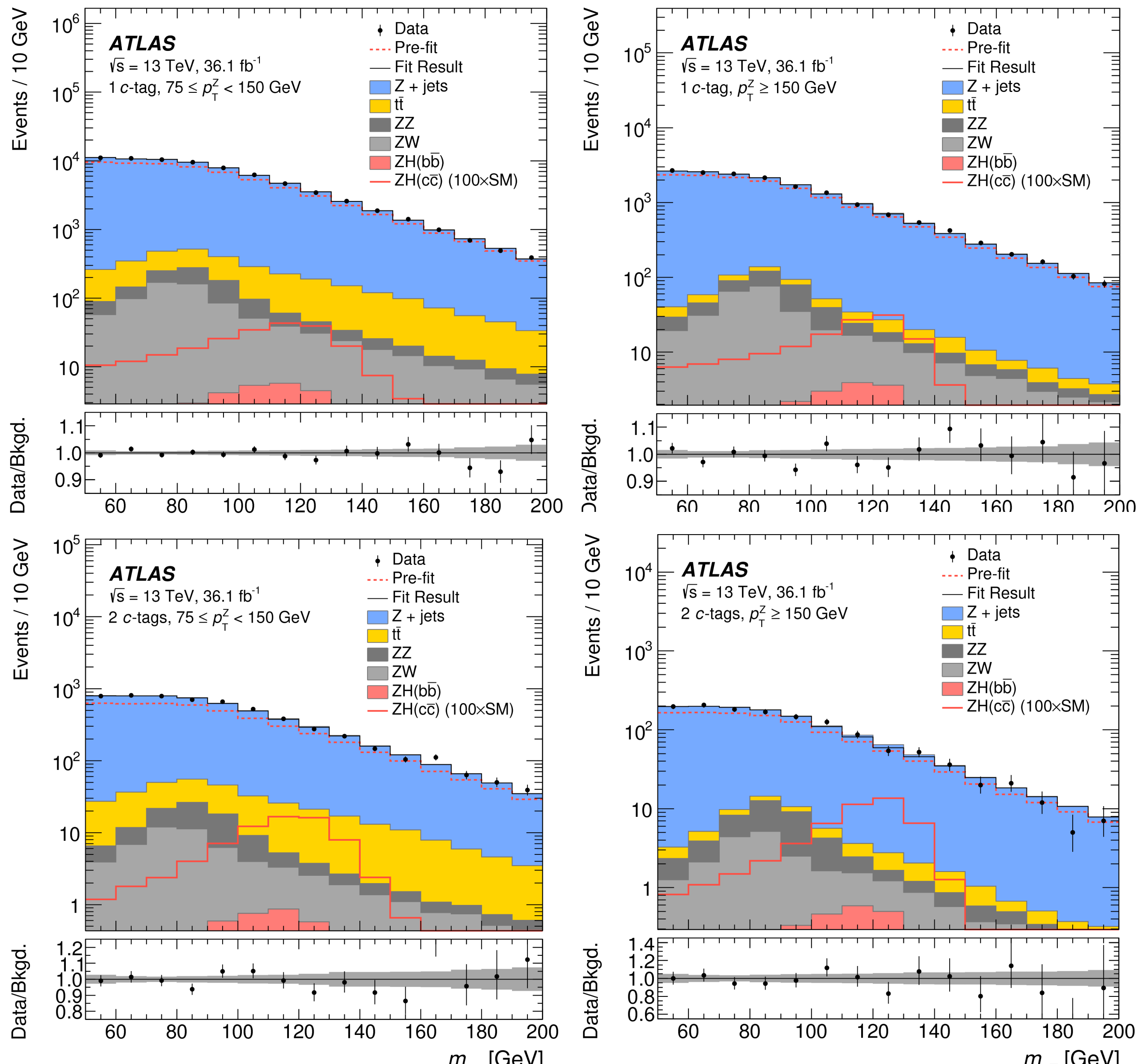

Uncertainties of the ZH→$\ell\ell$cc Analysis

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Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

High correlations between groups → sum > 100%

ZH→ℓℓcc Analysis Prospects

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- Estimate for end of Run 3 (300 fb^{-1} at 13 TeV) with same analysis strategy as Run 2 and systematic uncertainties:

$$\mu_{Z(H\rightarrow cc)} < 38^{+18}_{-10} \text{ (w.r.t SM exp.)}$$

- Impact of systematic uncertainties on HL-LHC prospects (3000 fb^{-1} at 14 TeV) assuming Run 2 uncertainties

Source of uncertainty	Change in limit
Background shape	+36%
Jet energy scale and resolution	+17%
Lepton reconstruction and identification	+12%
c-jet tagging efficiency	+11%