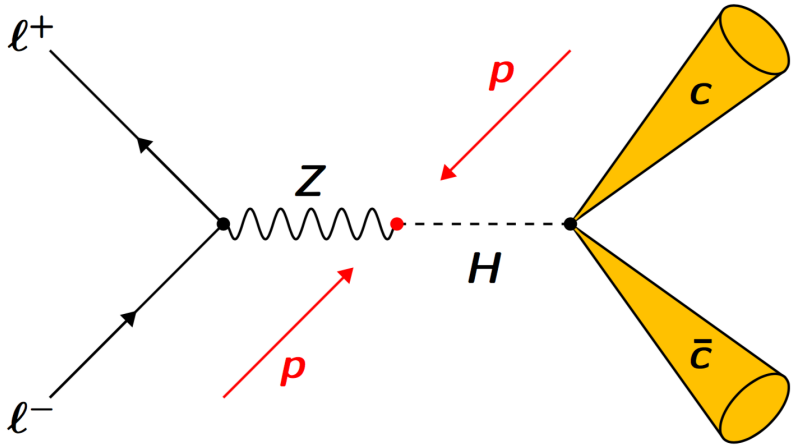
HL-LHC $Z(\ell^+\ell^-)H(c\bar{c})$ Search Prospects

Elliot Reynolds for the ATLAS Collaboration

CERN HE/HL-LHC Workshop, 19/6/18



ATLAS EXPERIMENT

UNIVERSITY OF BIRMINGHAM

Run 2 $ZH(c\bar{c})$ Analysis

Phys. Rev. Lett. 120, 211802

Run 2 Analysis Overview

Motivation

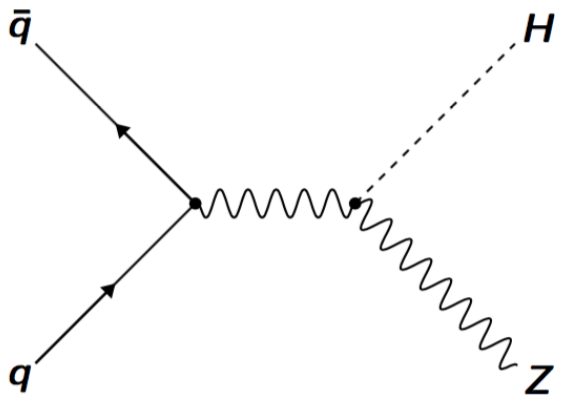
- $H \to c\bar{c}$ is SM process with largest Yukawa coupling to lack experimental evidence
- Smallness of y_c^{SM} makes potential new physics more pronounced over small SM rate

Aims

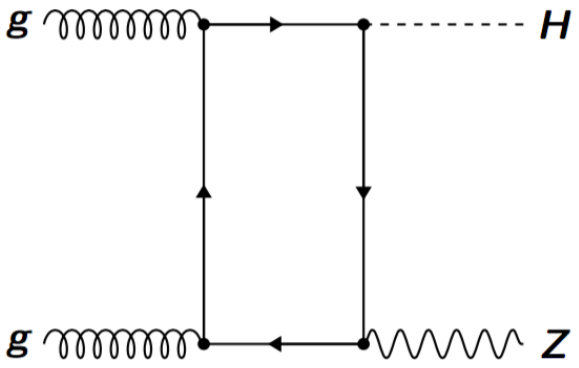
- Use **2015+16** data (**36.1 fb^{-1}**) to set direct limit on $\boldsymbol{Z(\ell\ell)H(c\bar{c})}$
- Focus on associated production with $Z(\ell\ell)$
- Analysis strategy very similar to cut-based 2-lepton $VH(b\bar{b})$ analysis
- Pioneer use of new Run 2 c-tagging algorithm

Present Constraints

- Global fits impose $BR(H \to c\bar{c}) < 20\%^{\dagger}$
- $H \to J/\psi\gamma$ sets limit of $220 \times y_c^{SM}$ ‡



$pp \to ZH$ dominated $q\bar{q} \to ZH$ processes, $\sigma \approx 0.76$ pb at $\sqrt{s} = 13$ TeV



Smaller contributions from $gg \to ZH$, but harder p_T^H, $\sigma \approx 0.12$ pb at $\sqrt{s} = 13$ TeV

†Phys. Rev. D 89, 033014

‡Phys. Rev. Lett. 114, 121801

Data, Selection and Categorisation

Data and Trigger

36.1 fb^{-1} of **13 TeV** data, collected in 2015 and 2016 using **single electron/muon triggers**

$Z \to \ell^+\ell^-$ Selection

- Exactly **2 same flavour leptons** (e or μ), passing loose identification, impact parameter and isolation requirements
- Require **opposite charges** (μ only)
- Both leptons $\boldsymbol{p_T} > \mathbf{7\ GeV}$, with at least one $\boldsymbol{p_T} > \mathbf{27\ GeV}$ and $|\boldsymbol{\eta}| < \mathbf{2.5}$
- $\mathbf{81\ GeV} < \boldsymbol{m_{\ell\ell}} < \mathbf{101\ GeV}$
- $\boldsymbol{p_T^Z} > \mathbf{75\ GeV}$

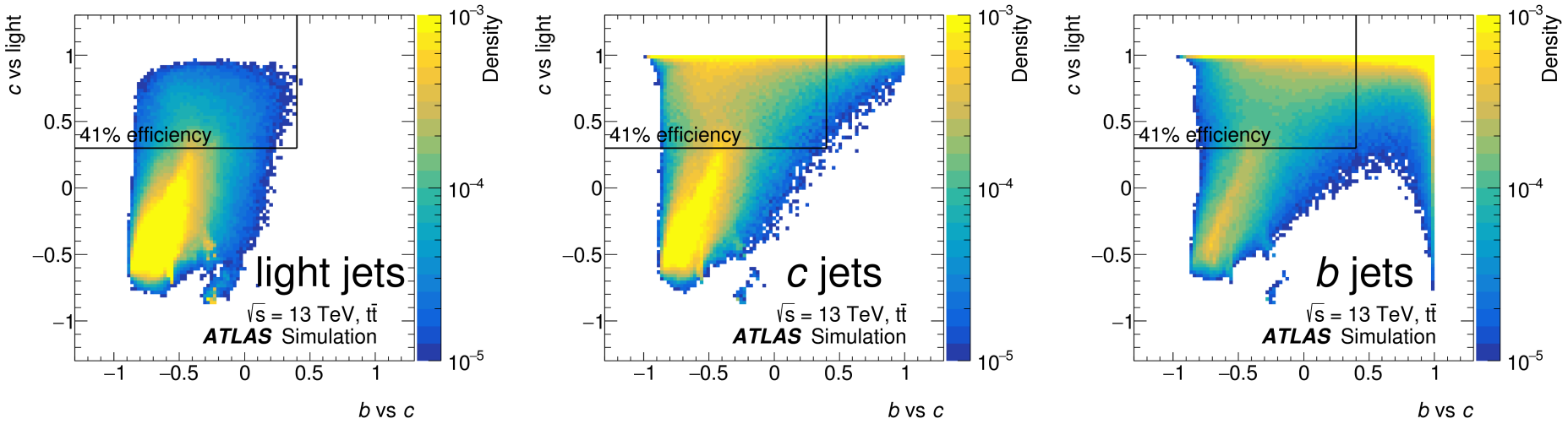
$H \to c\bar{c}$ Selection

- At least **2 jets** with $|\boldsymbol{\eta}| < \mathbf{2.5}$ and $\boldsymbol{p_T} > \mathbf{20\ GeV}$
- Leading jet $\boldsymbol{p_T} > \mathbf{45\ GeV}$
- $H \to c\bar{c}$ candidate formed from two highest p_T jets
- Dijet $\Delta R_{c\bar{c}}$ requirement on $H \to c\bar{c}$ jets which varies with p_T^H
- At least **one $\boldsymbol{H \to c\bar{c}}$ jet $\boldsymbol{c}$-tagged**

Event Categorisation

Events divided into **4 categories**, each with $H \to c\bar{c}$ candidates from 1 or 2 c-tagged jets, and p_T^Z above or below 150 GeV

c-Tagging



light-jets **c-jets** **b-jets**

Figure: Phys. Rev. Lett. 120, 211802

- BDT-based discriminant built using low-level b-tagging variables
- BDTs trained to separate c-jets from b-jets (x-axes), and from light-jets (y-axes)
- Rectangular cuts in 2D discriminant space optimised for analysis
- c-jet efficiency of **41%** for a b-jet rejection of **4** and a light-jet rejection of **10**
- Efficiency calibrated in data
- Uncertainties of 5% for b-jets, 20% for light-jets, and 25% for c-jets
- 'Truth-tagging', parameterised in p_T and $|\eta|$, applied to simulated events to preserve statistics

Backgrounds and Simulation

Backgrounds

- Background dominated by $\boldsymbol{Z + \text{jets}}$ (esp. HF)
- Smaller contributions from ZZ, ZW and $t\bar{t}$
- $W + \text{jets}$, WW, single-top and multi-jet shown to be negligible ($< 0.5\%$)
- $ZH(b\bar{b})$ treated as a background, and constrained to SM expectation: $\mathbf{1 \pm 0.04}$

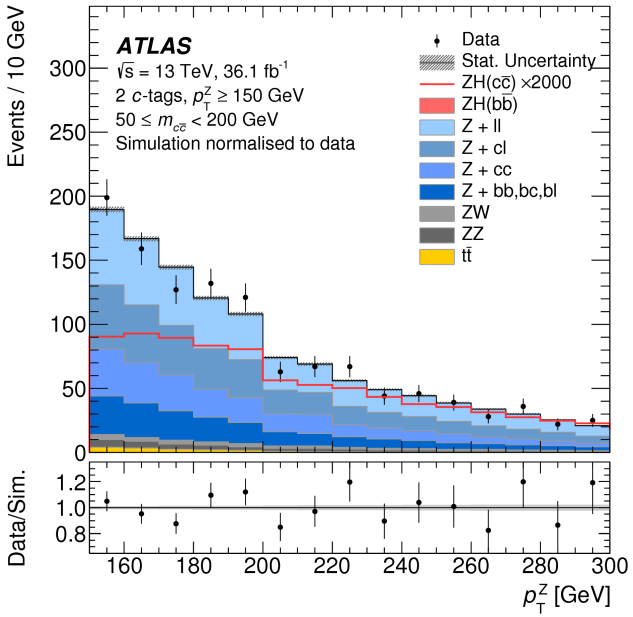


Figure: Phys. Rev. Lett. 120, 211802

Simulation

Process	Generator	Parton Shower	Cross-section (QCD)
$q\bar{q} \to ZH$	Powheg-BOX v2	Pythia 8	NNLO
$gg \to ZH$	Powheg-BOX v2	Pythia 8	NLO+NLL
$Z + \text{jets}$	Sherpa 2.2.1	Sherpa	NNLO
ZW, ZZ	Sherpa 2.2.1	Sherpa	NLO
$t\bar{t}$	Powheg-BOX v2	Pythia 8	NNLO+NNLL

Quantifying the Search Results

Statistical Model Overview

- Simultaneous likelihood fit performed in all 4 event categories
- $m_{c\bar{c}}$ used as observable
- **Signal yield** used as parameter of interest
- $Z + \text{jets}$ background normalisation free in fit
- All other background yields constrained to theory expectations
- The ZV production rate was measured to cross-check the analysis methods

Implementation of Systematic Uncertainties

- Uncertainties modelled as nuisance parameters in fit, constrained using auxiliary measurements
- Impact of categories of uncertainty evaluated

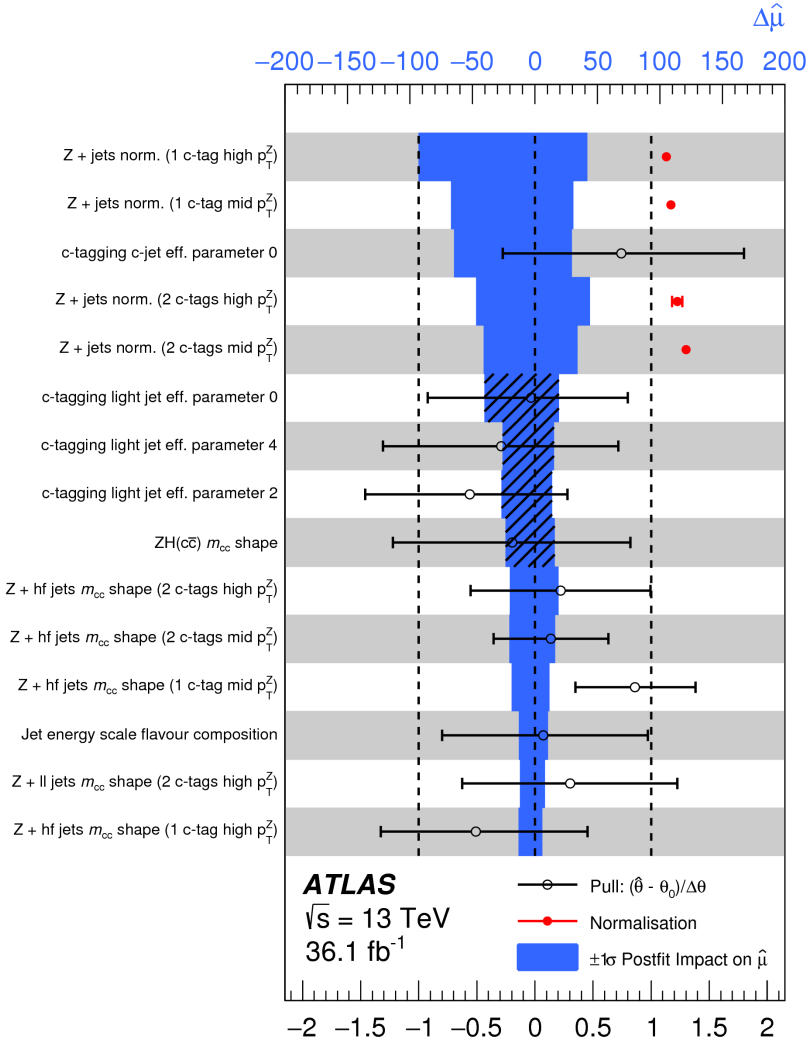


Figure: Phys. Rev. Lett. 120, 211802

Systematic Uncertainties

Signal and Background Modelling

- $ZH(c\bar{c}/b\bar{b})$ cross-section uncertainties from YR4[†]
- Signal $m_{c\bar{c}}$ shape and acceptance uncertainties from alternative parton shower model
- Background cross-section, acceptance and $m_{c\bar{c}}$ shape uncertainties from MC generator comparisons

Table: Phys. Rev. Lett. 120, 211802

Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
$Z+$ jets Normalisation	31%
Systematic	**87%**
Flavour Tagging	73%
Background Modelling	47%
Lepton, Jet and Lumi.	28%
Signal Modelling	28%
MC statistical	6%

Experimental Uncertainties

- **Leptons:** Trigger, reconstruction, identification, track to vertex association (μ-only) and isolation scale factor uncertainties; with energy/momentum scale and resolution uncertainties
- **Jets:** Energy scale, resolution, and jet vertex tagging scale factor uncertainties
- **Flavour-Tagging:** Eigen-vector reduction, resulting in 11 NPs for fit
- **Miscellaneous:** Luminosity and pileup reweighting uncertainties

[†] arXiv:1610.07922

Results of Run 2 Analysis

- $\hat{\mu}_{ZV(c\bar{c})} = 0.6^{+0.5}_{-0.4}$
- $\hat{\mu}_{ZH(c\bar{c})} = -69 \pm 101$
- 95% CL_s upper limit on $\mu_{ZH(c\bar{c})}$ of **110** (Expected: 150), or **2.7 pb** (Expected: 3.9 pb)
- Worlds tightest direct constraint on $H \to c\bar{c}$!

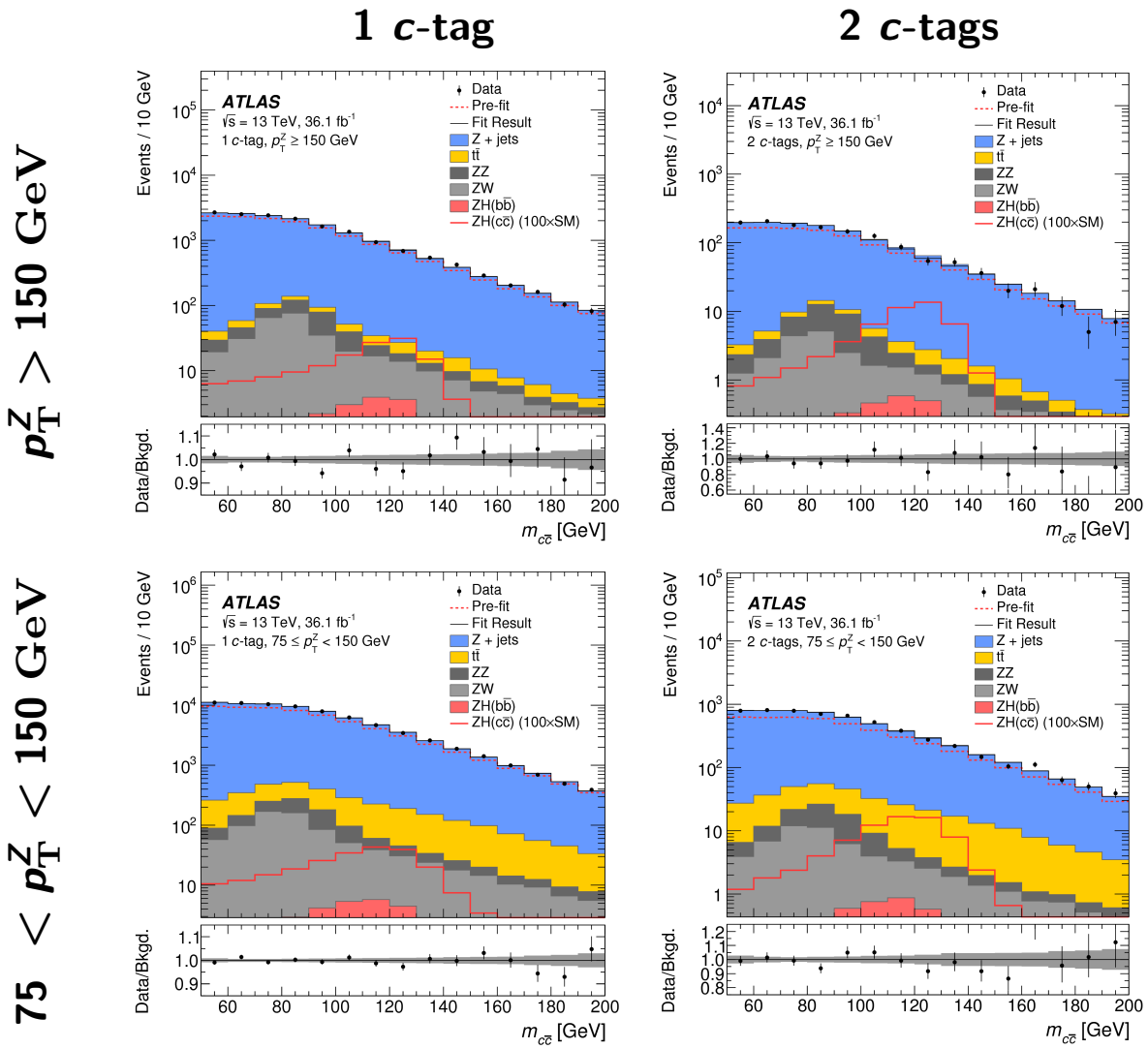


Figure: Phys. Rev. Lett. 120, 211802

HL-LHC Extrapolation

ATL-PHYS-PUB-2018-XYZ (in preparation)

General Strategy

- Expected limit calculated using pre-fit Asimov dataset and stat-only fit from Run 2 analysis
- Expected limit recalculated after scaling all histograms up to expected **3000** $\mathbf{fb^{-1}}$
- Energy increase to **14 TeV** accounted for

14 TeV Energy Increase

- Effect of 13 $\mathrm{TeV} \rightarrow$ 14 TeV energy increase estimated by scaling inputs
- Higgs process cross sections scaled up by **11%**[†]
- Acceptance corrections applied separately for each p_T^Z category
- $Z+$jets background cross sections scaled by $\Sigma q\bar{q}$ parton luminosity ratio of **9%**[†]

[†] arXiv:1610.07922

Tight Flavour Tagging

- Loose FT WP used for Run-2 analysis due to low signal expectation
- Tight FT WP reconsidered due to:
  - Greater signal statistics
  - Increased sensitivity to kinematically irreducible $ZH(b\bar{b})$ background
- Tight FT WP evaluated by scaling Loose WP processes and categories by relative normalisation SF: $\frac{n_{Tight}(Sample,\ Category)}{n_{Loose}(Sample,\ Category)}$
- Method assumes any shape effects due to different FT WPs negligible
- Tight FT WP has *c*-jet efficiency of **24%** for *b*-jet and light-jet rejections of **17** and **100**, respectively
- Tight FT WP has **46%** signal event efficiency wrt Loose WP for a factor **5.3** better light-jet rejection
- Tight FT WP improved expected limit by **6%**

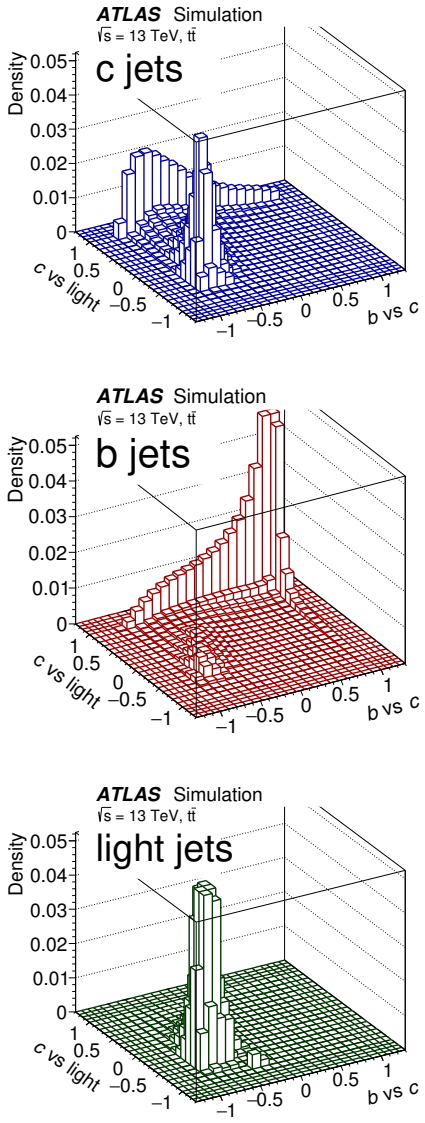


Figure: Phys. Rev. Lett. 120, 211802

Background Yields

- Z+jets normalisation free in fit (as per Run 2)
- ZHbb allowed to vary within expected HL-LHC ATLAS measurement uncertainty of 14%†
- Diboson and $t\bar{t}$ backgrounds fixed to SM expectation

Table: ATL-PHYS-PUB-2018-XYZ (in preparation)

Sample	Yield			
	1 c-tag		2 c-tags	
	$75 \leq p_T^Z < 150$ GeV	$p_T^Z > 150$ GeV	$75 \leq p_T^Z < 150$ GeV	$p_T^Z > 150$ GeV
Z + jets	271 000 ± 3200	59 300 ± 690	4350 ± 51	892 ± 10
WZ	3750 ± 190	1570 ± 78	44.5 ± 2.2	27.2 ± 1.4
ZZ	2360 ± 120	934 ± 47	87.9 ± 4.4	86.4 ± 4.3
$t\bar{t}$	14 200 ± 92	766 ± 5.0	214 ± 1.4	23.3 ± 0.15
$ZH(b\bar{b})$	441 ± 17	327 ± 12	10.7 ± 0.41	9.38 ± 0.36
$ZH(c\bar{c})$	74.4 ± 2.8	52.6 ± 2.0	8.54 ± 0.32	6.89 ± 0.26
Total	291 000 ± 3200	63 000 ± 700	4710 ± 51	1040 ± 11

ATL-PHYS-PUB-2014-016†

Results of HL-LHC Extrapolated Analysis

- Expected stat-only upper limit of: $\mu_{ZH(c\bar{c})} < 6.3^{+2.5}_{-1.8}$
- Run 2 stat+sys expected upper limit of: $\mu_{ZH(c\bar{c})} < 150$
- Expected best fit value of: $\hat{\mu}_{ZH(c\bar{c})} = 1 \pm 3.2$

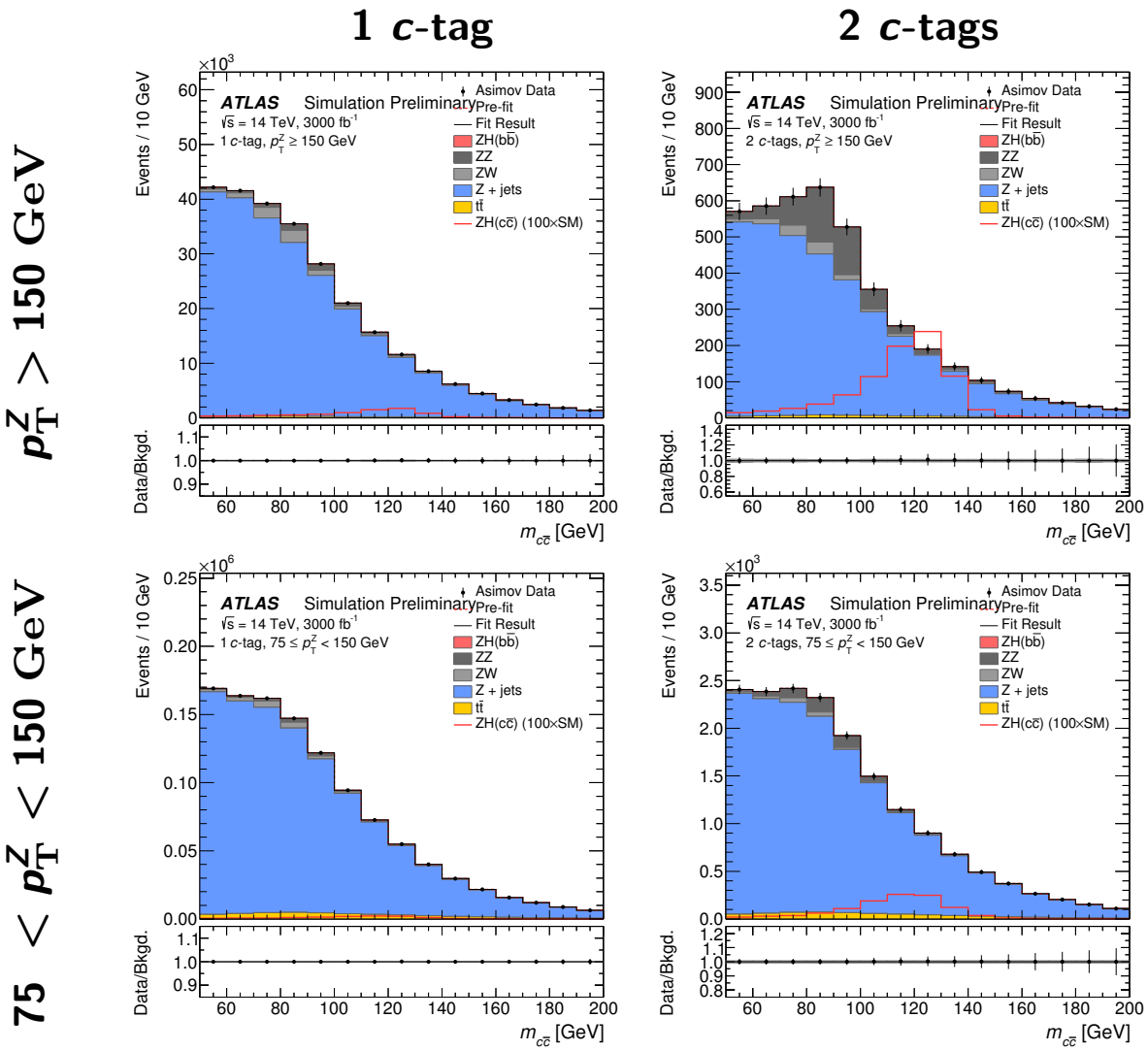


Figure: ATL-PHYS-PUB-2018-XYZ (in preparation)

Systematic Uncertainties

- All uncertainties based on Run 2 performance

Table: ATL-PHYS-PUB-2018-XYZ (in preparation)

Source of uncertainty	Change in limit
Background shape	+37%
c-tagging efficiency	+34%
Jet energy scale and resolution	+18%
Lepton reconstruction and identification	+12%

- HL-LHC analysis may use a data-driven background model, removing dominant background modelling uncertainty
- c-tagging is dominant component of flavour tagging uncertainty
- ITk is expected to offer improved flavour tagging performance, despite higher pileup
- Jet energy scale and smaller resolution uncertainties will be changed by reduced material in the ITk and increased pileup

ITk Light-Jet Rejection

- Studies into the *b*-tagging performance of the ITk show better light-jet rejection capabilities, despite the higher pileup
- These suggest an improvement of a factor of $\sim$**2.5** light-jet rejection
- Scaling light-jet rejection by a factor of 2.5 improves expected limit by **10%**
- The extended coverage will also enable ***c*-tagging in the forward region**
- Room for improvement in *c*-tagging algorithms

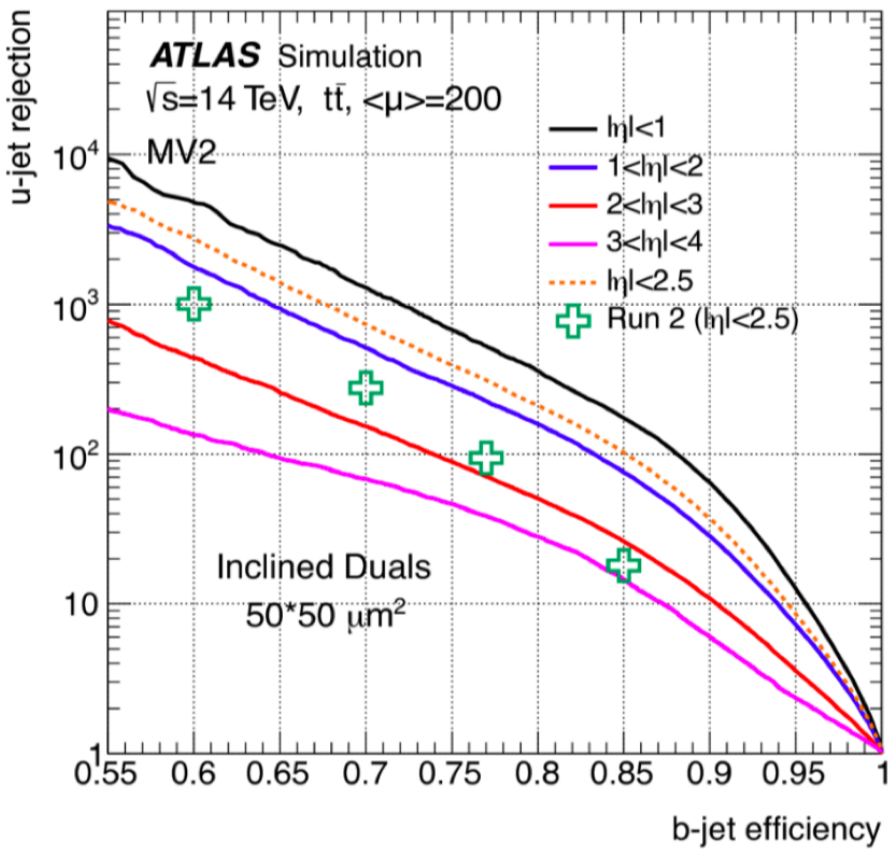


Figure: ATLAS Flavour-Tagging Public Plots

Summary

- Largest Yukawa coupling of any SM decay yet to be measured makes $H \to c\bar{c}$ a promising Higgs decay channel
- Using **36.1 fb^{-1}** of data, ATLAS has already set world's tightest limit at $\mu_{ZH(c\bar{c})} <$**110**
- **300 fb^{-1}** expected limit (**with systematics**): $\mu_{ZH(c\bar{c})} <$**31^{+16}_{-9}**
- **3000 fb^{-1}** stat-only expected limit: $\mu_{ZH(c\bar{c})} <$**6.3**
- Potential **10%** improvement in expected limit due to improved flavour tagging performance due to ITk
- Potential for further gains through use of:
  - Other associated production channels ($Z(\nu\nu)H$ and $W(\ell\nu)H$)
  - MVA-based analysis strategy
  - Search expected to gain substantially from advances in c-tagging algorithms

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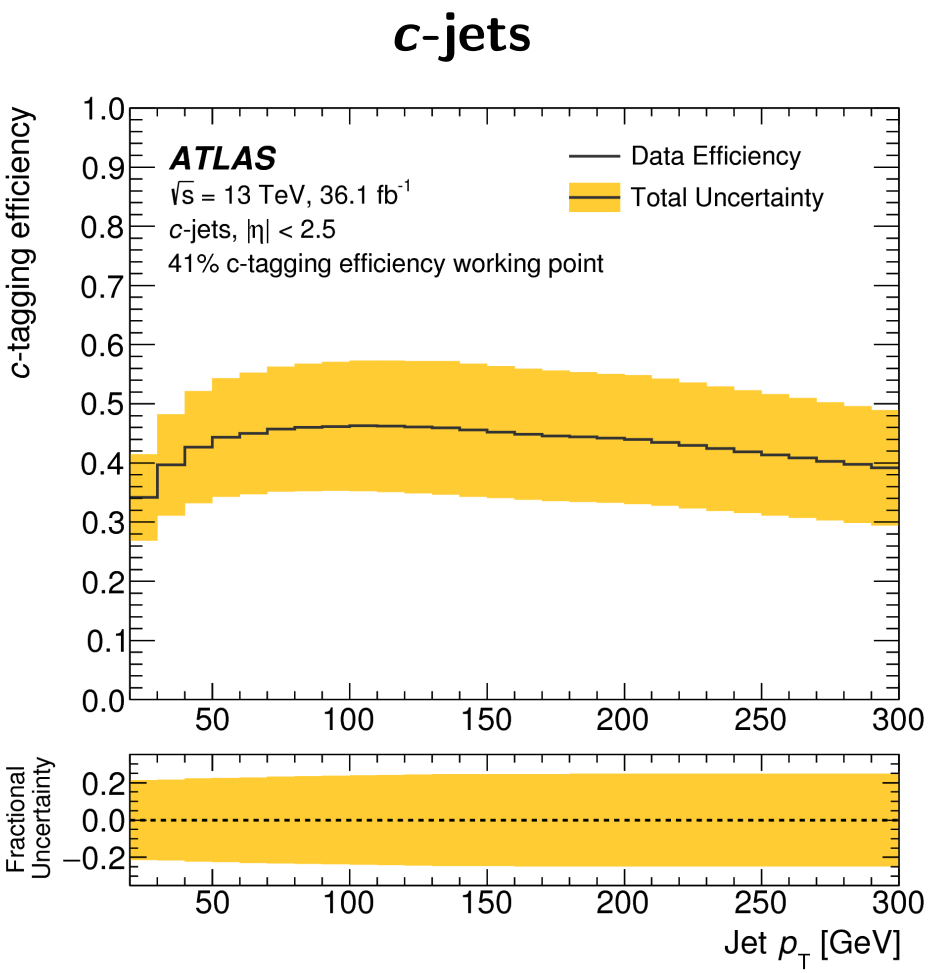
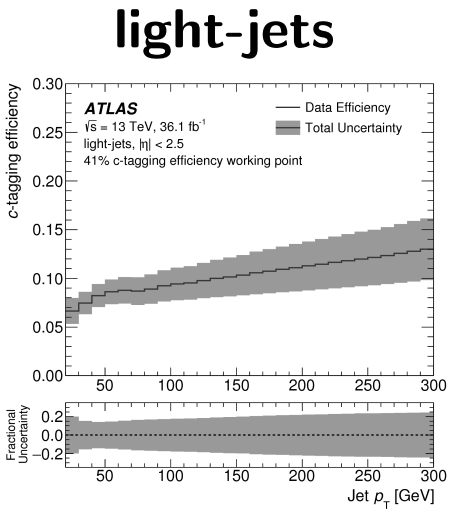
Thank you for listening!

Backup Slides

- c-tagging efficiencies (Run 2)
- Linear post-fit $m_{c\bar{c}}$ distributions (Run 2)
- Background flavour compositions (Run 2):
  1. $Z + \mathrm{jets}$
  2. Diboson
- Post-fit control distributions (Run 2):
  1. p_T^Z
  2. $p_T^{lead\ \ jet}$
  3. $p_T^{sublead\ \ jet}$

c-Tagging Efficiencies (Run 2)





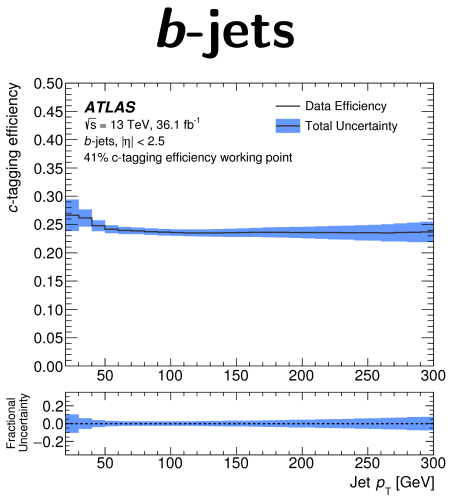


Figure: Phys. Rev. Lett. 120, 211802

Post-Fit $m_{c\bar{c}}$ Distributions (Linear) (Run 2)

- Data consistent with background-only hypothesis
- Best fit signal strength value: $\hat{\mu} = -69^{+73}_{-129}$
- Data used to set 95% CL CL_s upper limit on signal strength
- Post-fit $Z + \text{jets}$ normalisation parameters between 1.1 and 1.3

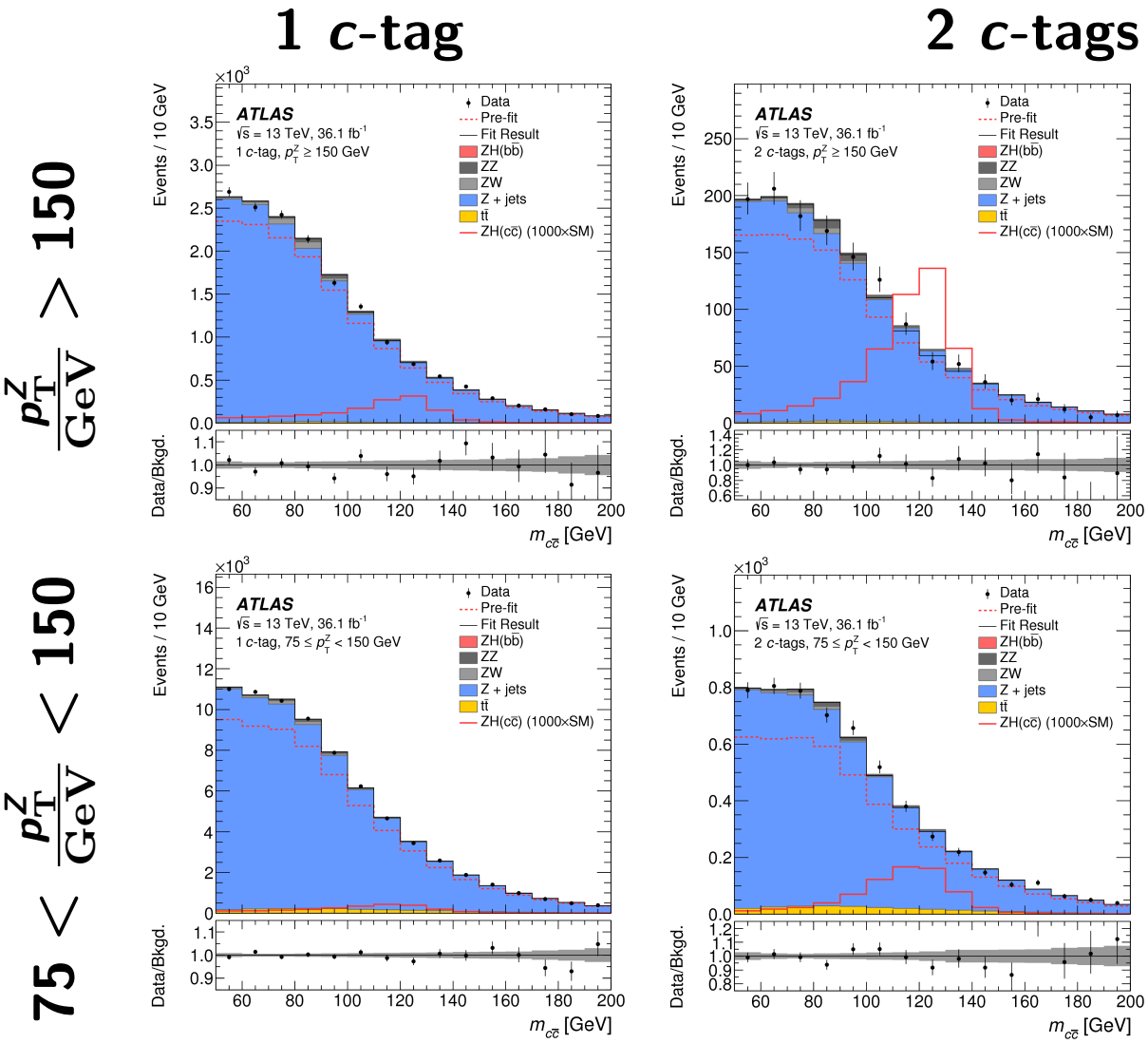
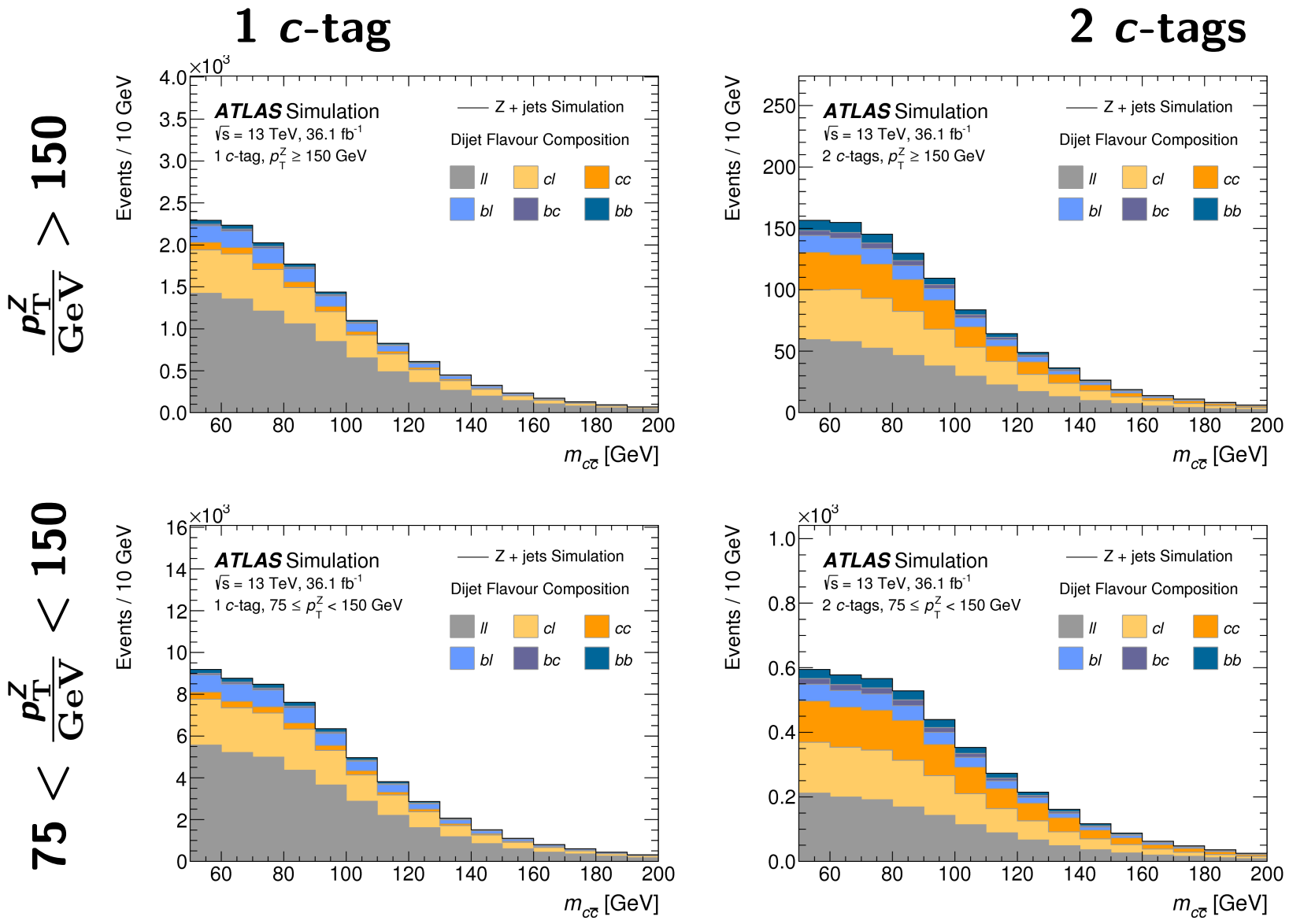


Figure: Phys. Rev. Lett. 120, 211802

$Z + \text{jets}$ Flavour Composition (Run 2)



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Diboson Flavour Composition (Run 2)

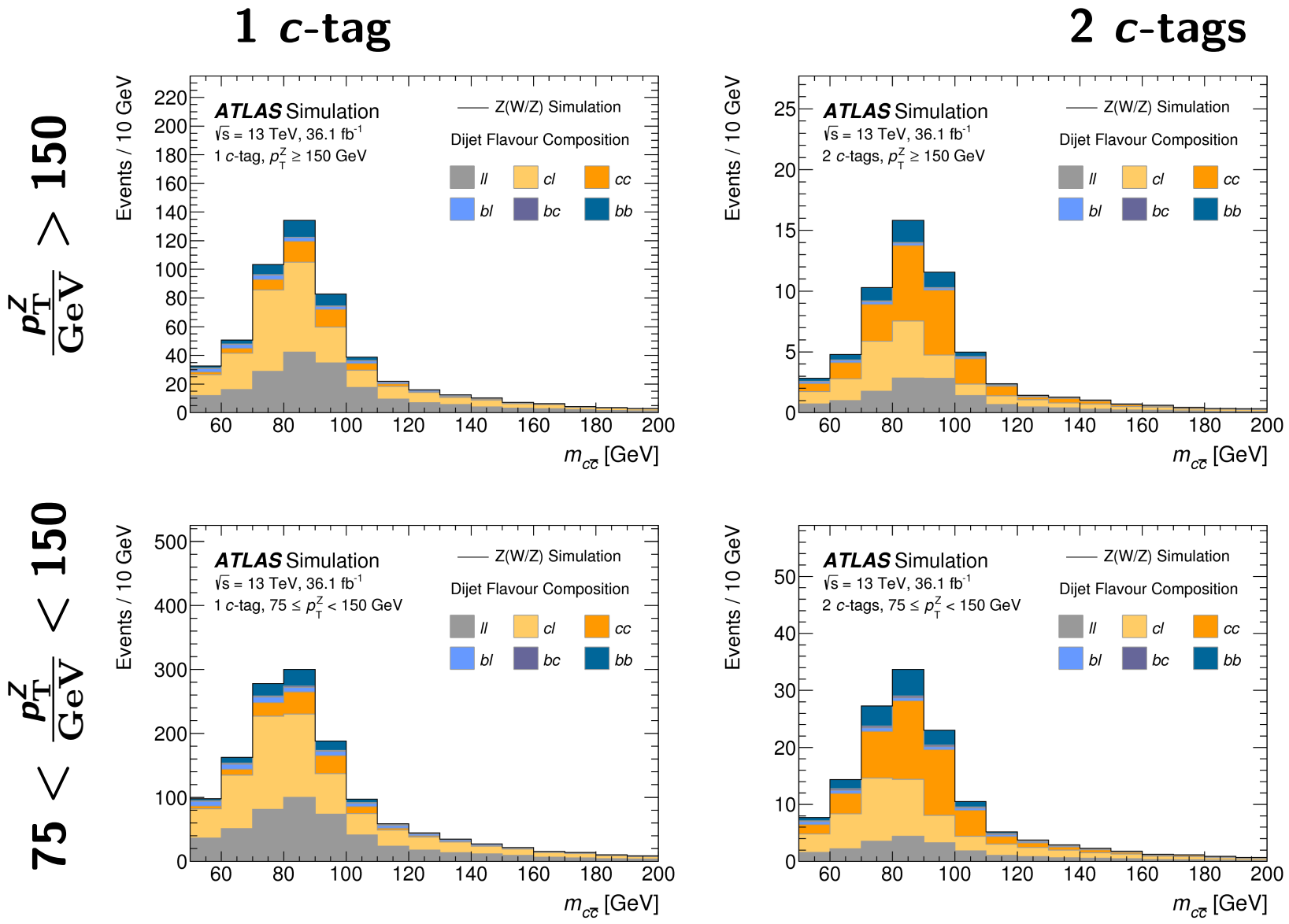


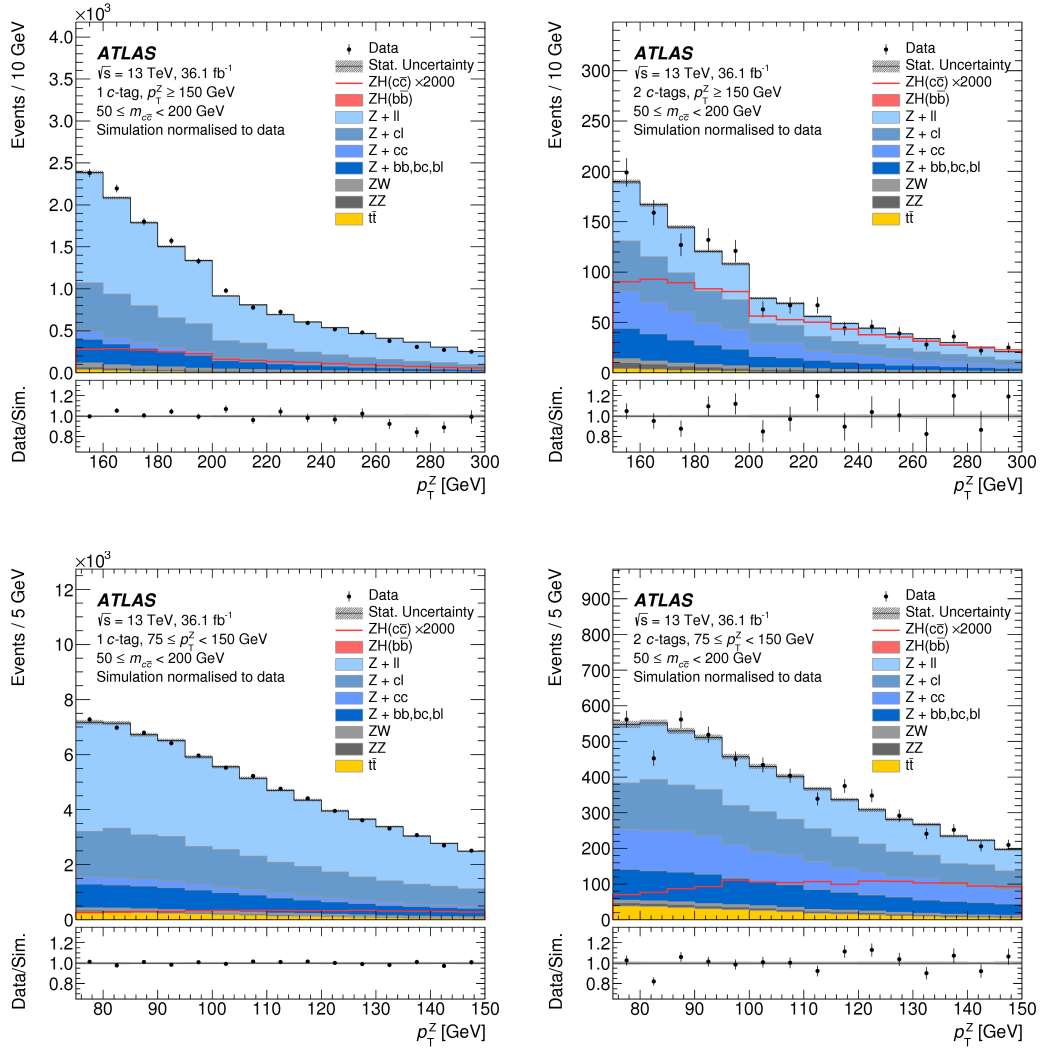
Figure: Phys. Rev. Lett. 120, 211802

p_T^Z Distributions (Run 2)

1 c-tag **2 c-tags**

$\frac{p_T^Z}{\text{GeV}} > 150$

$75 < \frac{p_T^Z}{\text{GeV}} < 150$



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$p_T^{lead\ jet}$ Distributions (Run 2)

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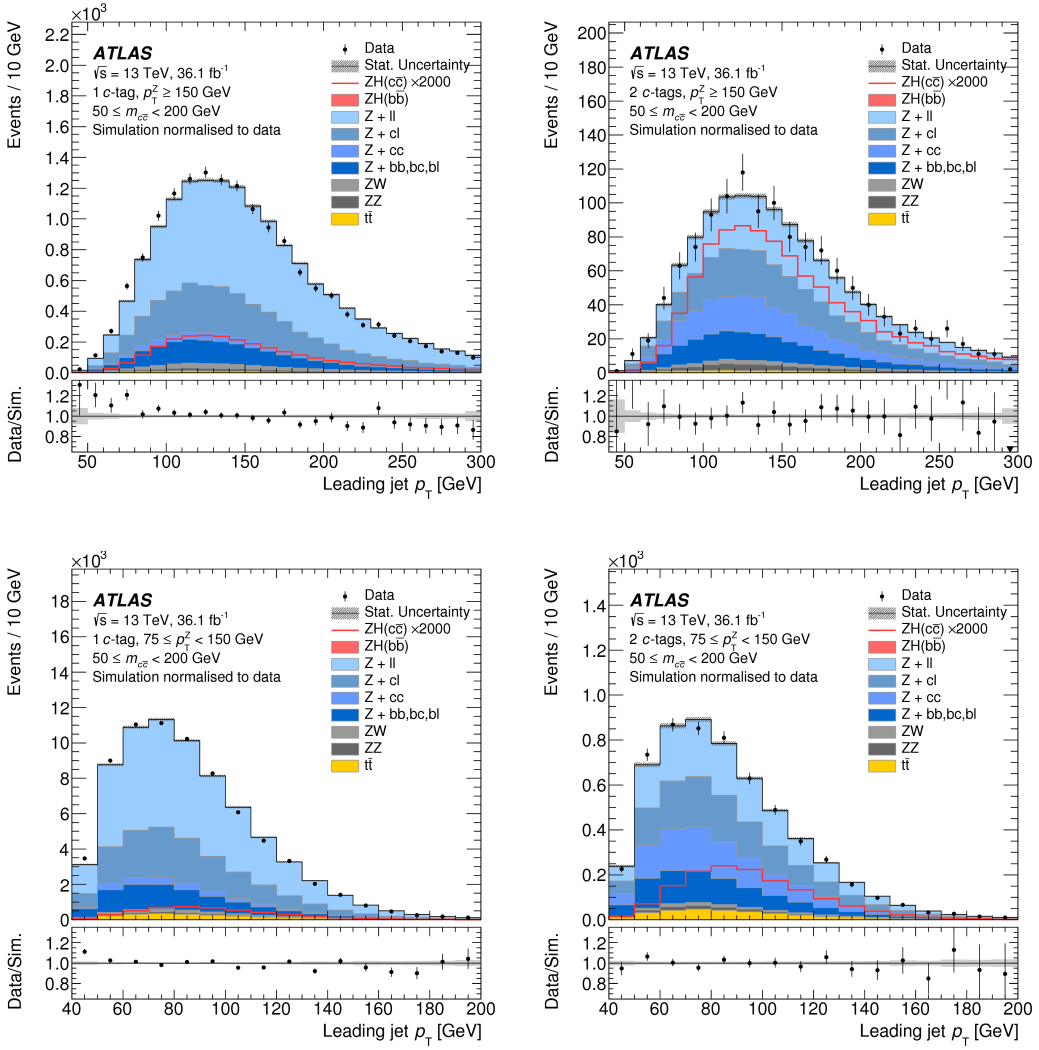

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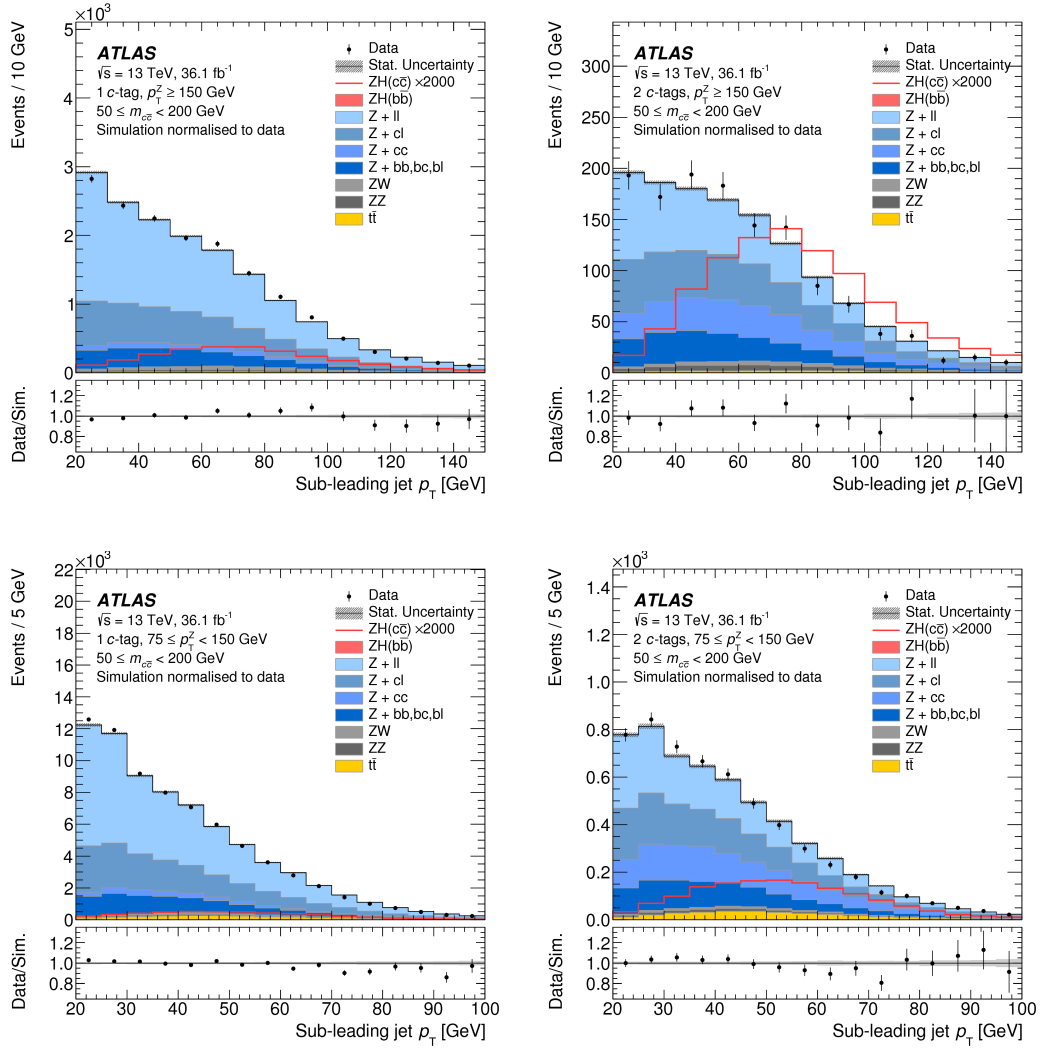
$p_T^{sublead\ jet}$ Distributions (Run 2)

1 c-tag | **2 c-tags**

$\frac{p_T^Z}{\text{GeV}} > 150$

$75 < \frac{p_T^Z}{\text{GeV}} < 150$



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