Vector Boson Production with Heavy Flavours

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on behalf of the ATLAS, CMS, and LHCb collaborations

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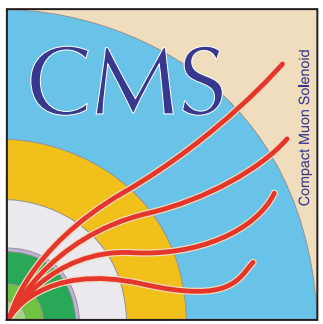
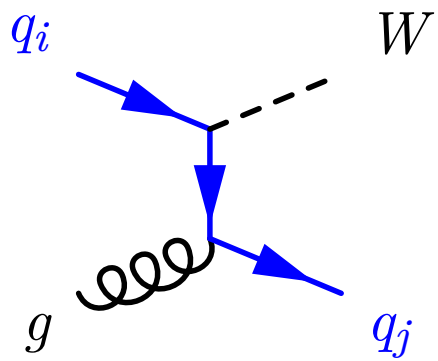
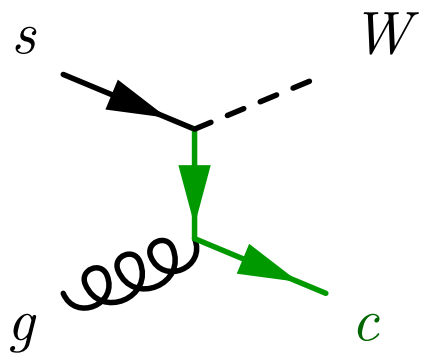
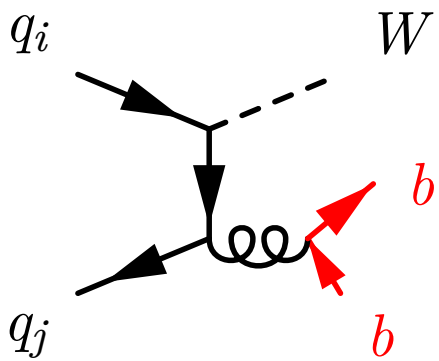


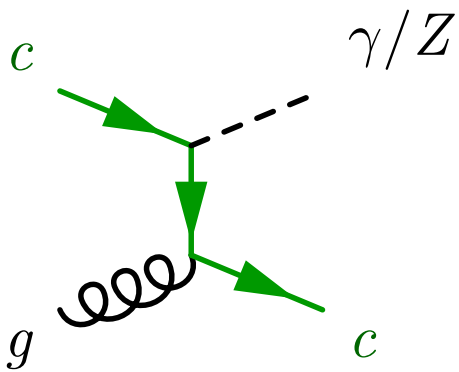
LHC Electroweak Working Group

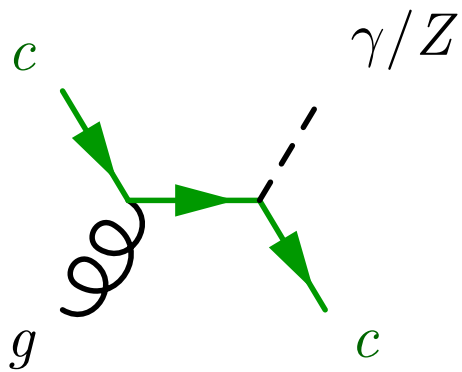
Signatures





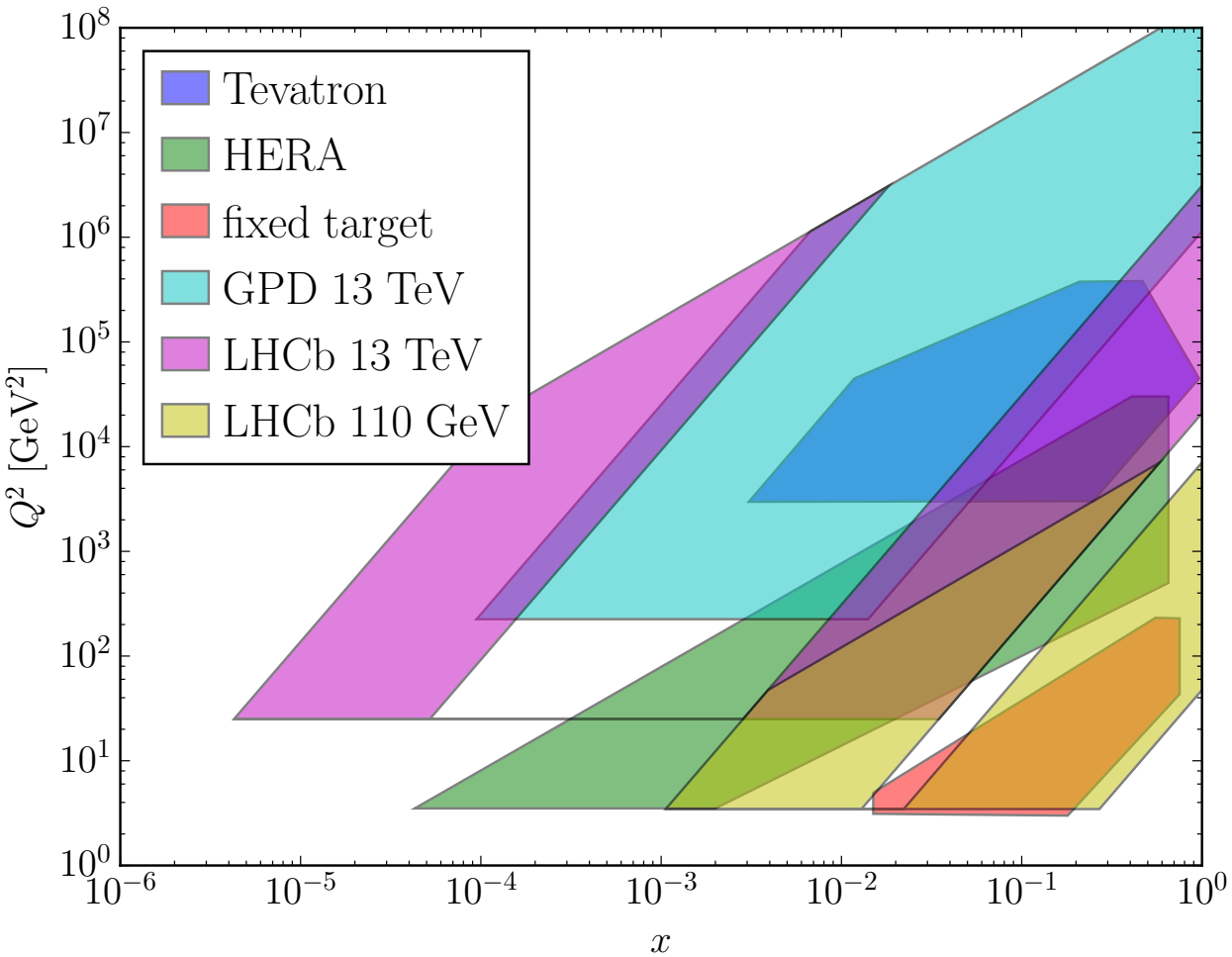






PDF Kinematics

$$\sigma = \int xfx(f_1, x_1, Q^2) xfx(f_2, x_2, Q^2) \hat{\sigma}\, \mathrm{d}x_1 \mathrm{d}x_2, \quad Q^2(x) = e^{\pm 2y} x^2 s$$

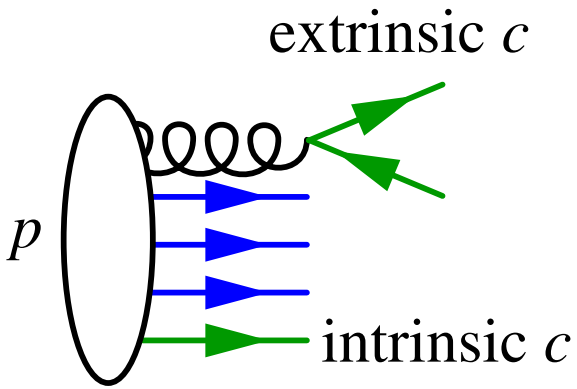


Intrinsic Heavy Flavour

- *extrinsic* heavy-flavor content from soft gluon splitting

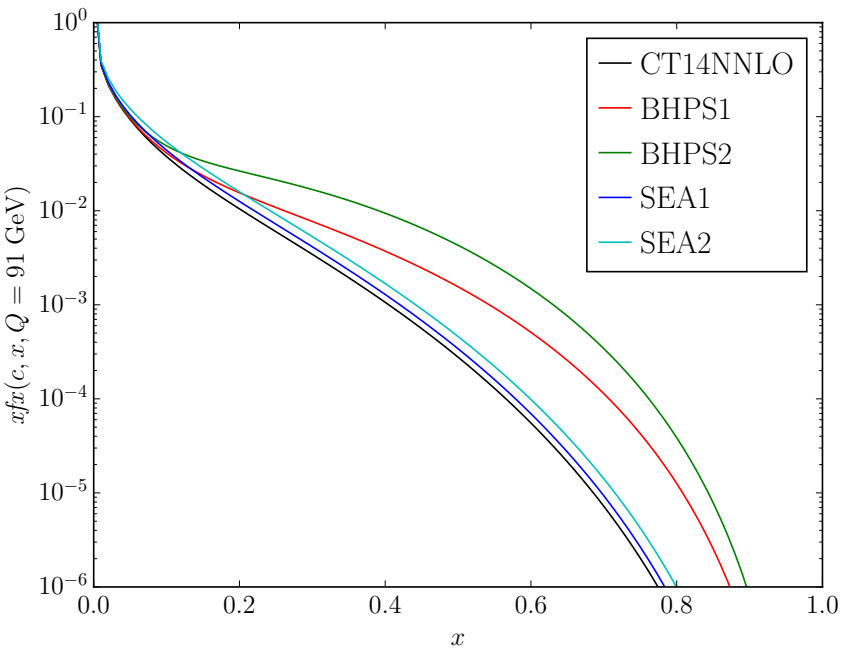
$$xfx(c, x, Q^2) \approx (1 - x)xfx(g, x, Q^2)$$

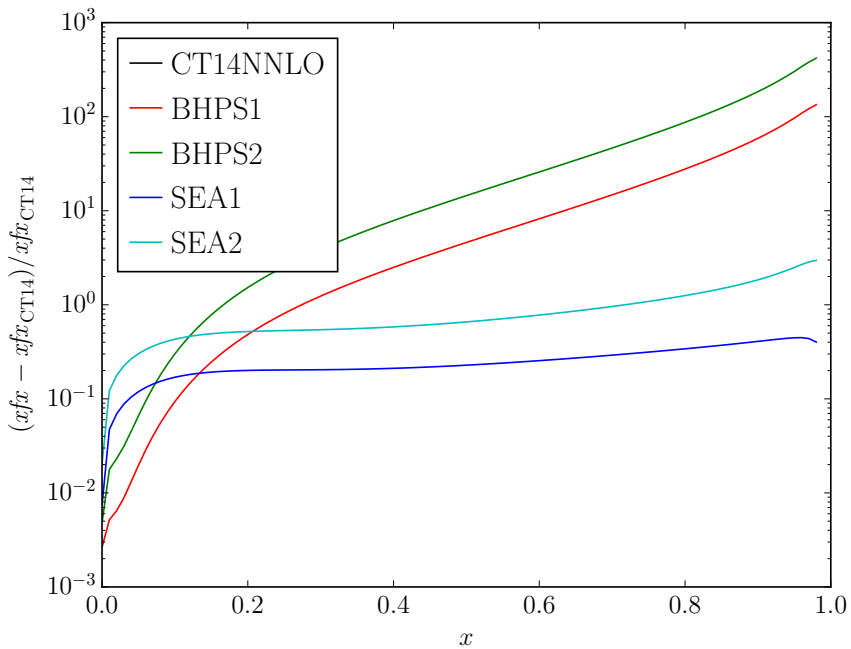
- *intrinsic* content also possible, bound to valence quarks
  - see AHEP 2015 (2015)
  - percent-level charm content possibly seen in DIS
  - $Q \approx 1 - 10$ GeV, high-x
  - excluded from some global PDF fits



Intrinsic Charm PDFs

- consider two models from CT14 (PRD 93 (2016))
  - BHPS: valence-like via the light-cone picture of nucleon structure
  - SEA: sea-like assuming IC $\propto [\bar{u}(x, Q_0) + \bar{d}(x, Q_0)]$ for $Q_0 < m_c$
- two normalization points, $\langle x \rangle_{\rm IC} \equiv \int_0^1 x{\rm IC}(x, m_c){\rm d}x$
  - 1: $\langle x \rangle_{\rm IC} = 0.6\%$
  - 2: $\langle x \rangle_{\rm IC} \approx 2\%$ (maximally allowed from global fit)





Measurements

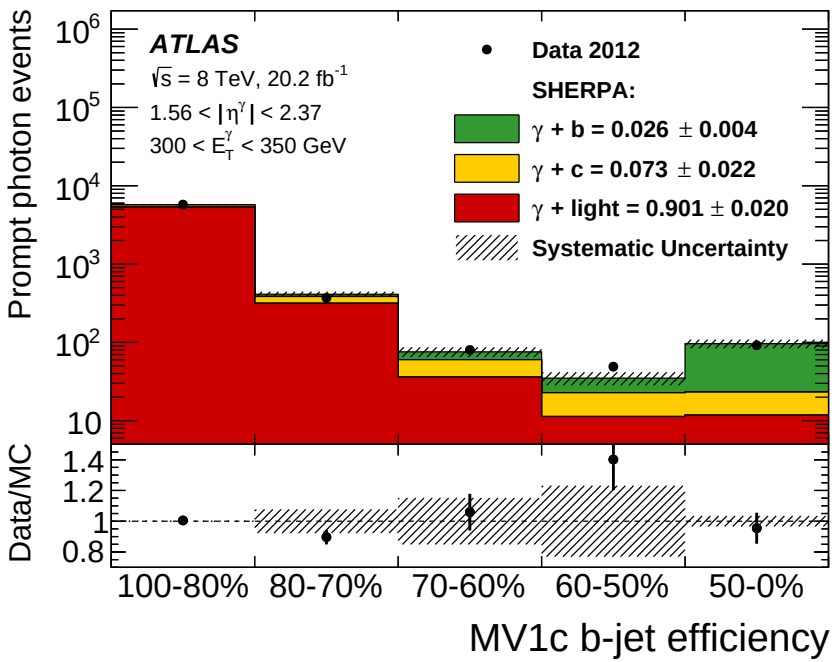
experiment	final state	year	$\sqrt{s}$ TeV	reference
ATLAS	$\gamma + c/b$	2017	8	arXiv:1710.09560
	$Z + b(b)$	2014	7	JHEP 10 (2014) 141
	$W + c$	2014	7	JHEP 05 (2014) 068
	$W + b$	2013	7	JHEP 06 (2013) 084
	$W + b$	2011	7	PLB 707 (2012) 418
	$Z + b$	2011	7	PLB 706 (2012) 295
CMS	$Z + c$	2017	8	arXiv:1711.02143
	$Z + b(b)$	2016	8	EPJC 77 (2017) 751
	$W + bb$	2016	8	EPJC 77 (2017) 92
	$Z + b(b)$	2014	7	JHEP 06 (2014) 120
	$W + bb$	2013	7	PLB 735 (2014) 204
	$W + c$	2013	7	JHEP 02 (2014) 013
	$Z + b$	2013	7	JHEP 12 (2013) 039
	$Z + b$	2012	7	JHEP 06 (2012) 126
LHCb	tt, $W + cc/bb$	2016	8	PLB 767 (2017) 110
	$W + c/b/j$	2015	7/8	PRD 92 (2015) 052
	$Z + b$	2014	7	JHEP 01 (2015) 064
	$Z + D$	2014	7	JHEP 04 (2014) 091

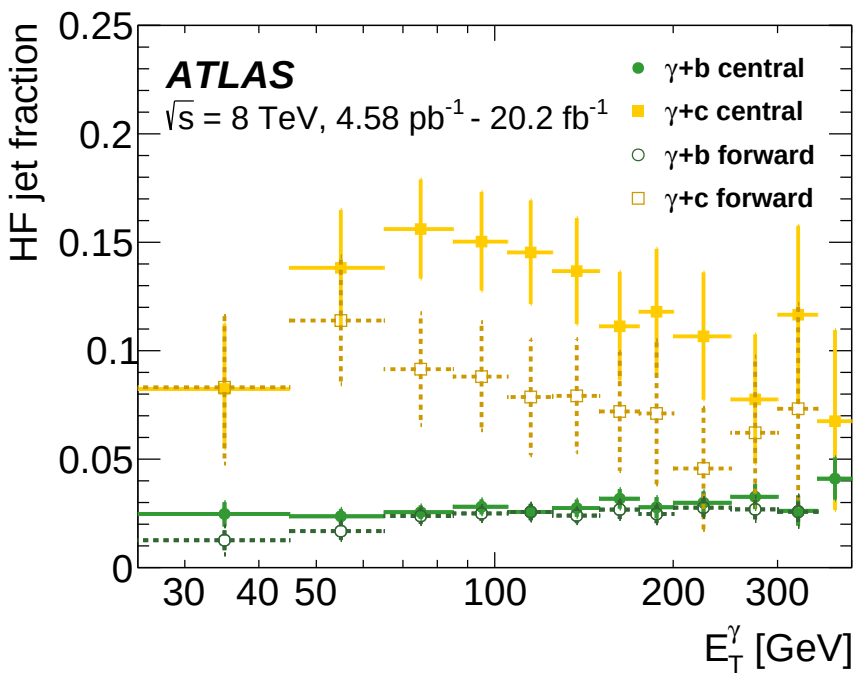
ATLAS $\gamma + c/b$

arXiv:1710.09560

Signal Determination

- measured differentially in $E_{\mathrm{T}}(\gamma)$ and $\eta(\gamma)$
- *central*: $|\eta(\gamma)| < 1.37$, *forward*: $1.56 < |\eta(\gamma)| < 2.37$
- photon signal determined from sidebands
- flavour determined from discriminator fit



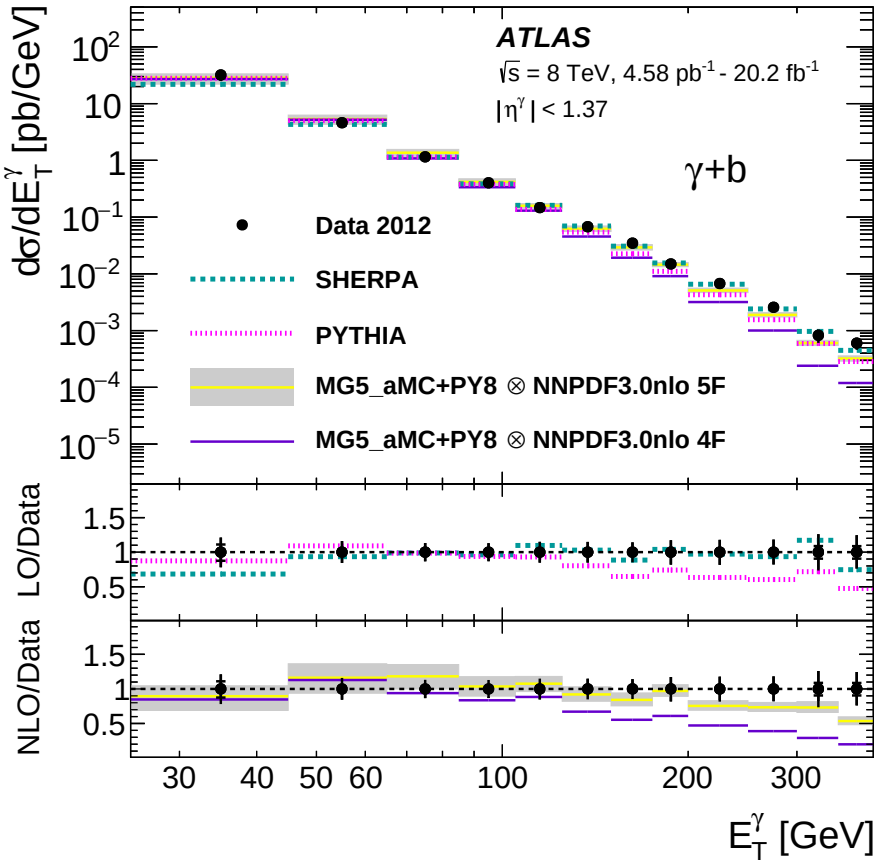


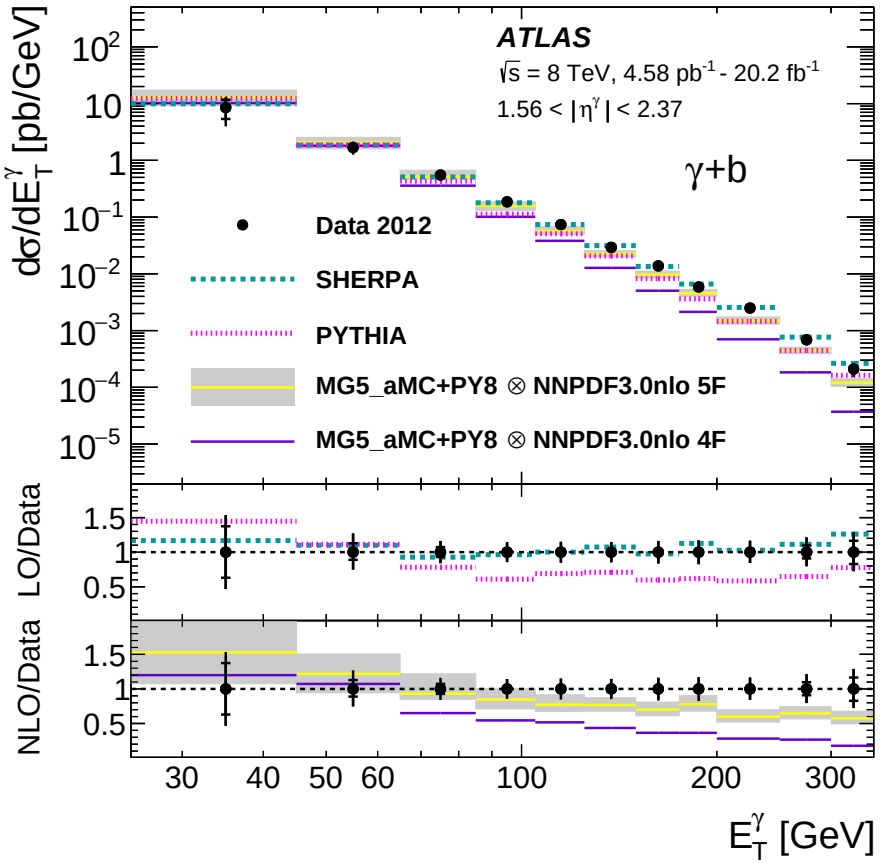
Systematics

	$\gamma + b$ central	$\gamma + b$ forward	$\gamma + b$ ratio
MC statistical	1.9 - 6.4	3.1 - 14	3.6 - 17
b-tagging	2.4 - 17	2.5 - 15	0.1 - 0.6
c-tagging	5.7 - 18	5.3 - 11	2.3 - 6.9
light-tagging	4.9 - 15	6.1 - 31	1.6 - 8.3
	$\gamma + c$ central	$\gamma + c$ forward	$\gamma + c$ ratio
MC statistical	2.5 - 24	6.0 - 33	6.1 - 39
b-tagging	0.4 - 12	0.5 - 8.3	0.2 - 2.3
c-tagging	6.0 - 18	6.4 - 18	0.4 - 2.7
light-tagging	12 - 46	21 - 57	8.4 - 28

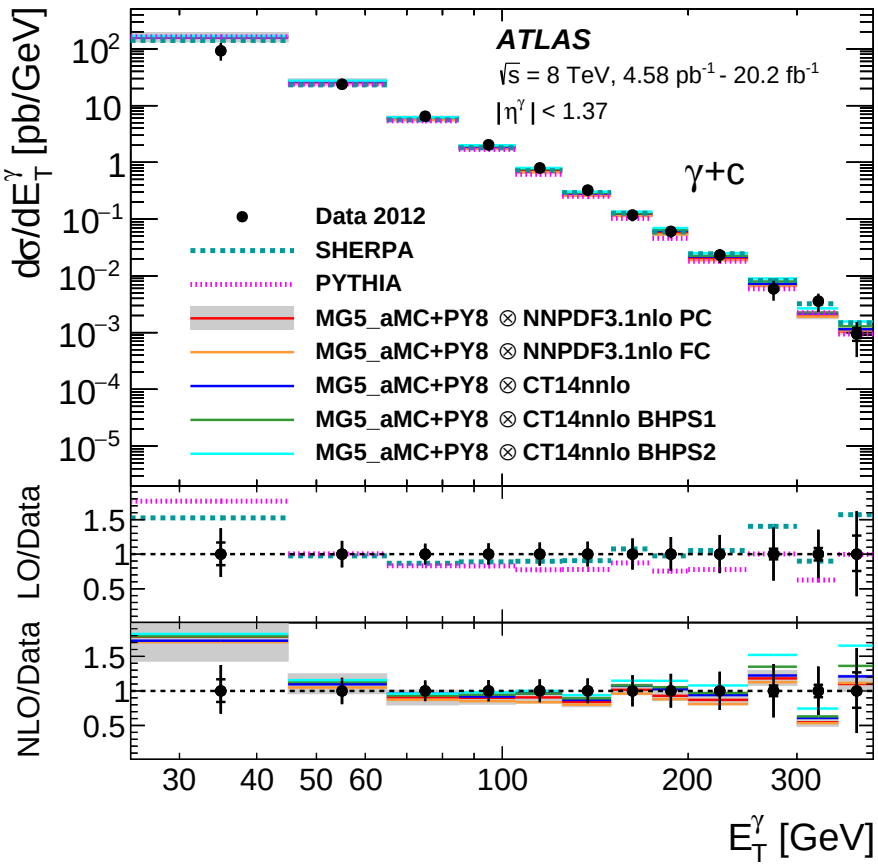
- tagging efficiencies dominate uncertainties

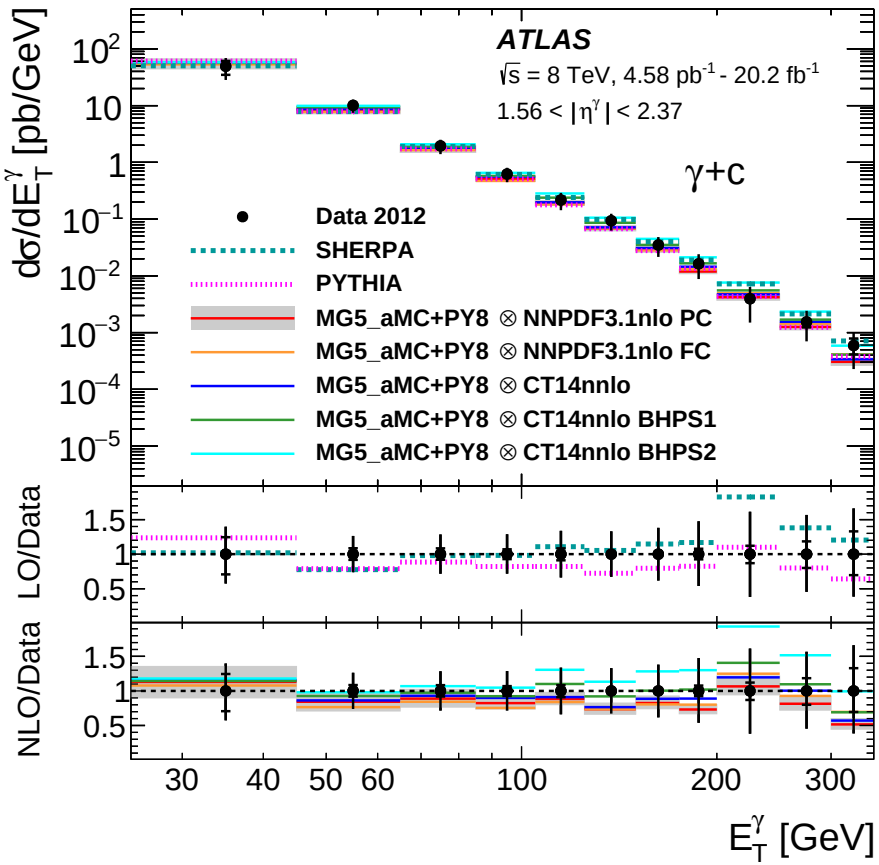
$\gamma + b$ Results



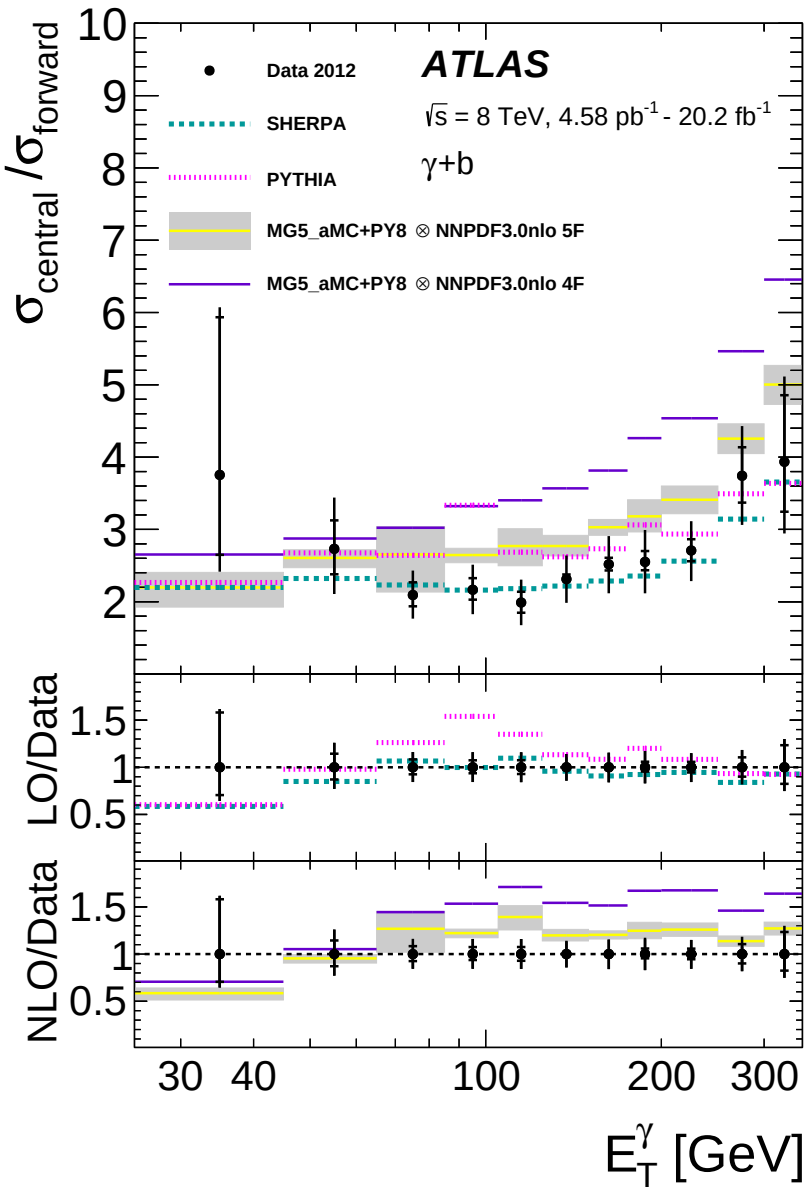


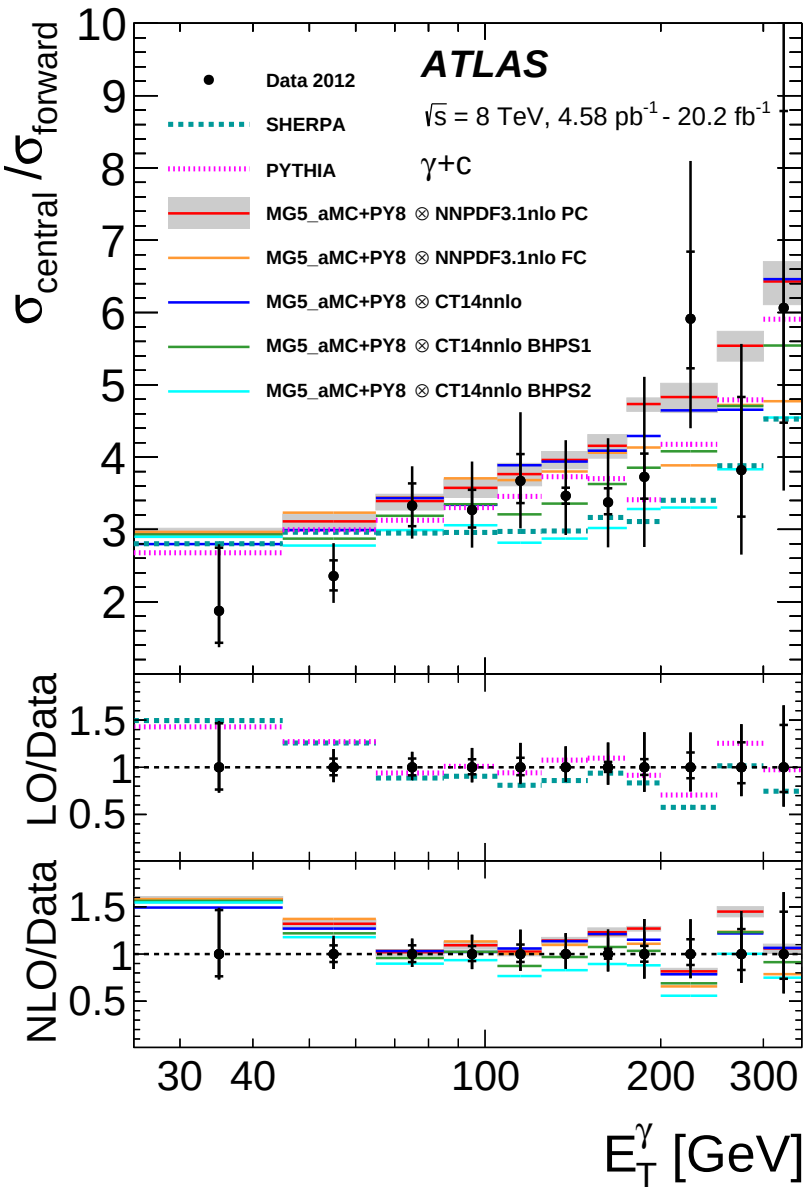
$\gamma + c$ Results





Ratios


Data 2012
SHERPA
PYTHIA
MG5_aMC+PY8 ⊗ NNPDF3.0nlo 5F
MG5_aMC+PY8 ⊗ NNPDF3.0nlo 4F
ATLAS
√s = 8 TeV, 4.58 pb-1 - 20.2 fb-1
γ+b
σcentral /σforward
LO/Data
NLO/Data
E_T^γ [GeV]

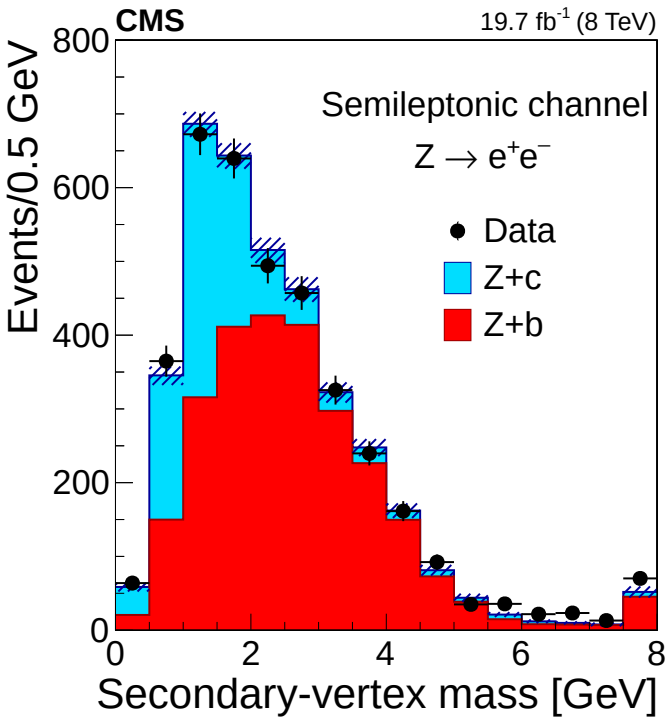

Data 2012
SHERPA
PYTHIA
MG5_aMC+PY8 ⊗ NNPDF3.1nlo PC
MG5_aMC+PY8 ⊗ NNPDF3.1nlo FC
MG5_aMC+PY8 ⊗ CT14nnlo
MG5_aMC+PY8 ⊗ CT14nnlo BHPS1
MG5_aMC+PY8 ⊗ CT14nnlo BHPS2
ATLAS
√s = 8 TeV, 4.58 pb-1 - 20.2 fb-1
γ+c
σcentral /σforward
LO/Data
NLO/Data
E_T^γ [GeV]

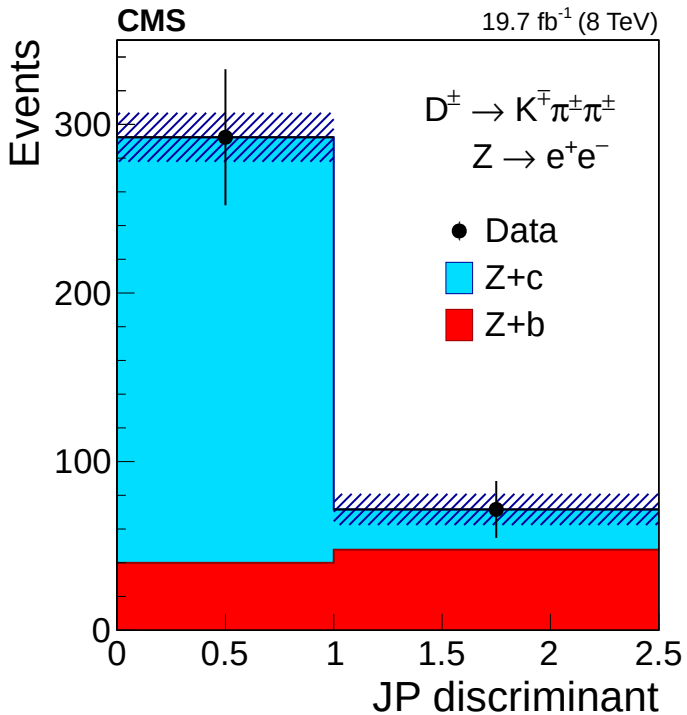
CMS $Z + c$

arXiv:1711.02143

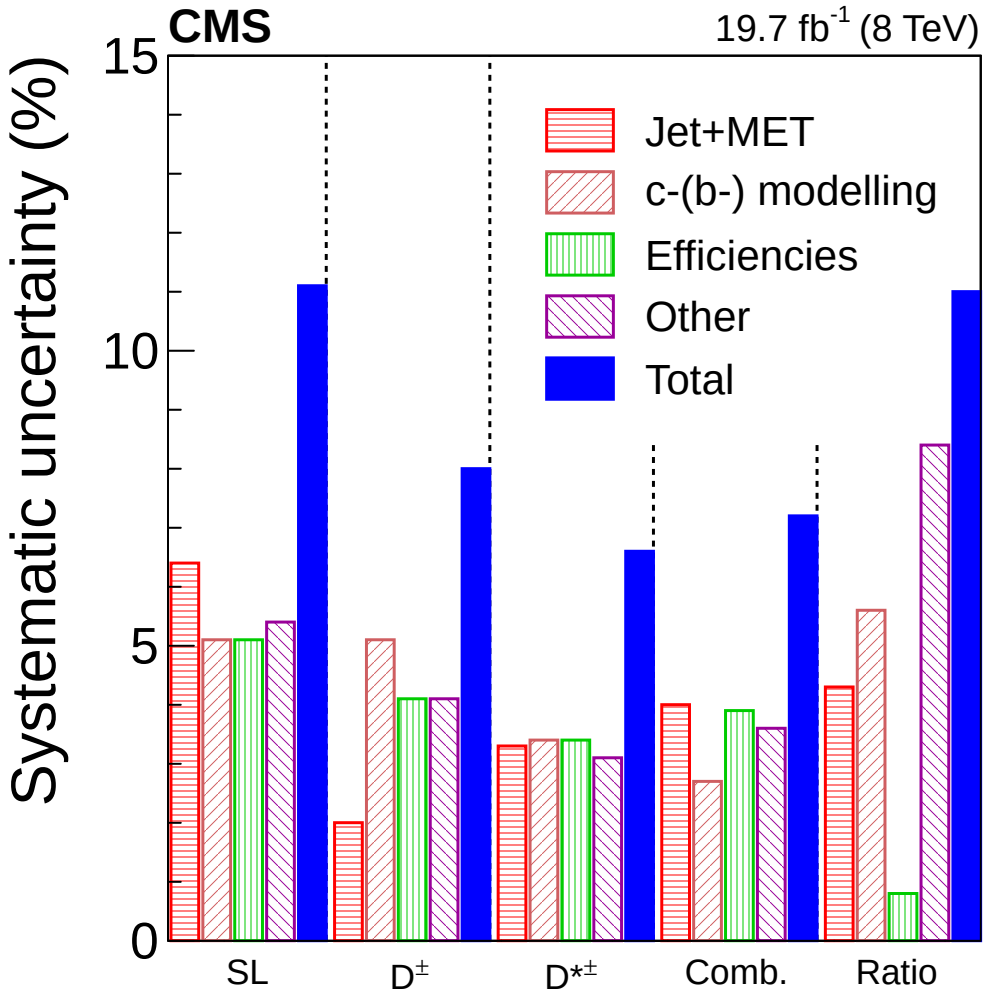
Signal Determination

- three tagging methods are used
  - semi-leptonic decay associated with a secondary vertex
  - an exclusive $D^+ \to K^-\pi^+\pi^+$ secondary vertex
  - an exclusive $D^{*+} \to D^0(K^-\pi^+)\pi^+$ secondary vertex
- measured differentially in $p_{\mathrm{T}}(Z)$ and $p_{\mathrm{T}}(j)$
- flavour determination from corrected mass and jet probability



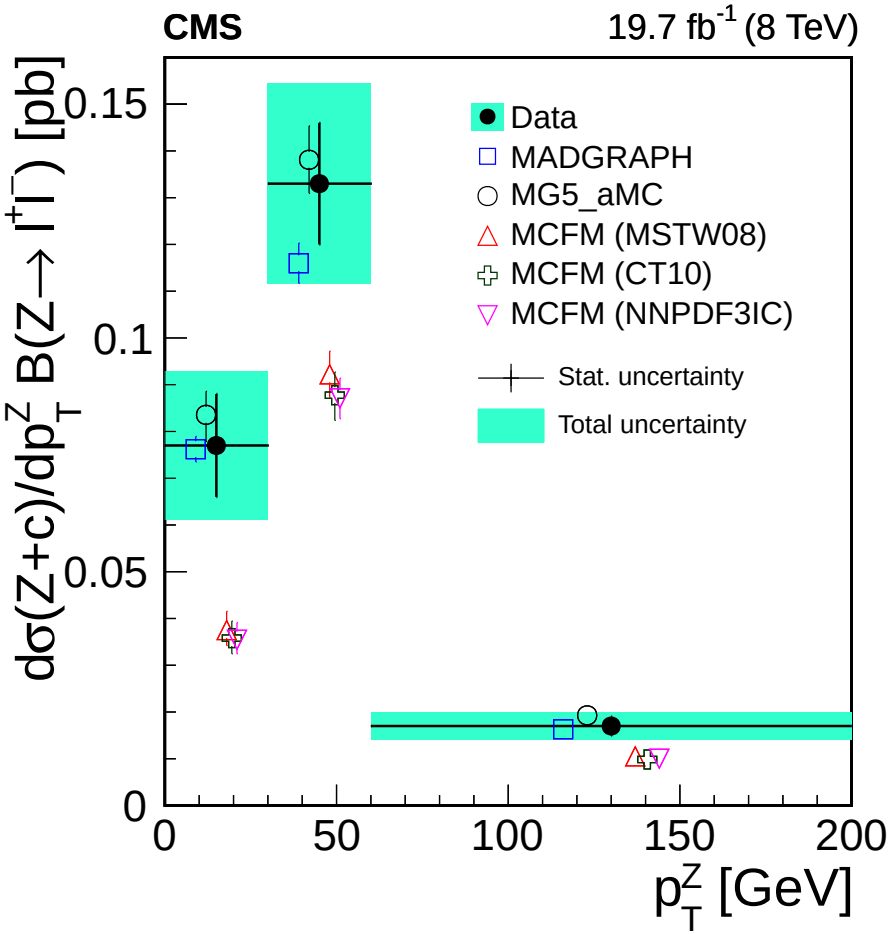


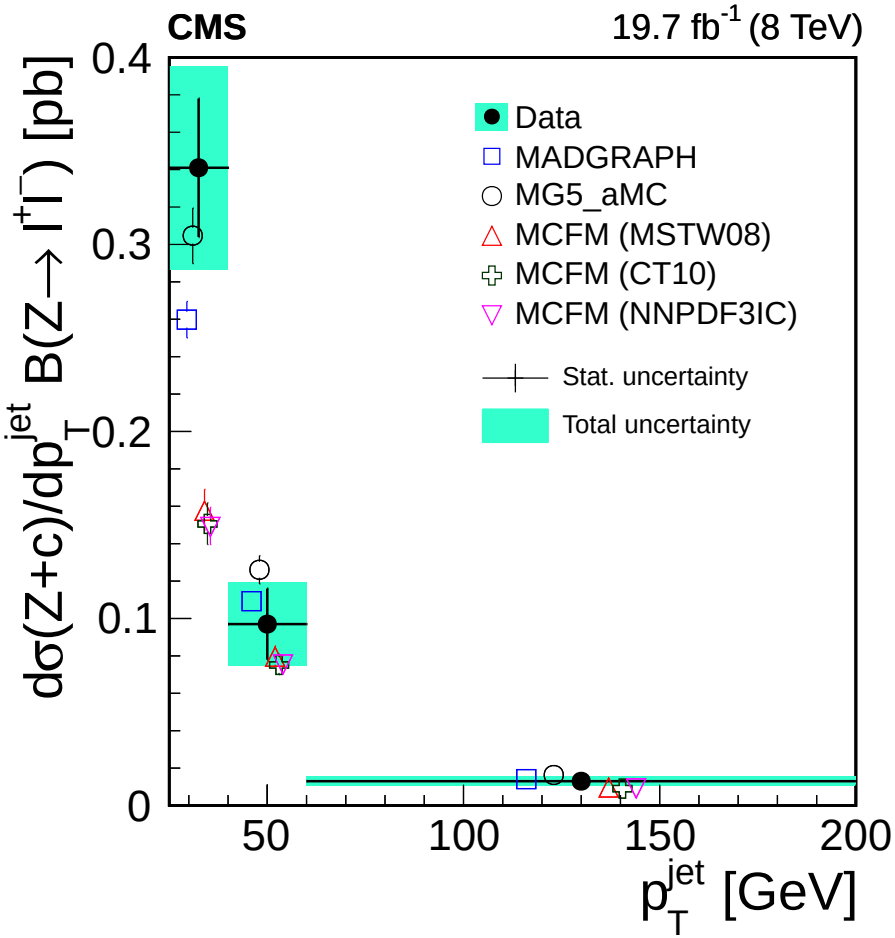
Systematics



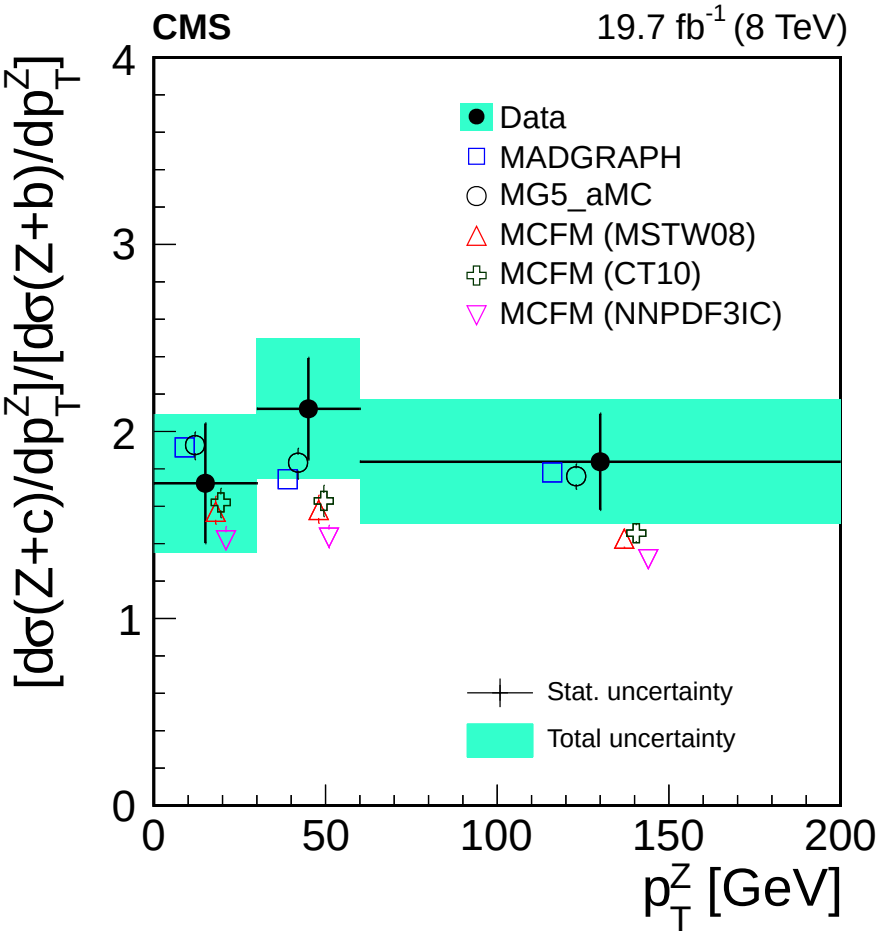
- modeling of c-fragmentation and decays and b-jet correction from top dominant systematics

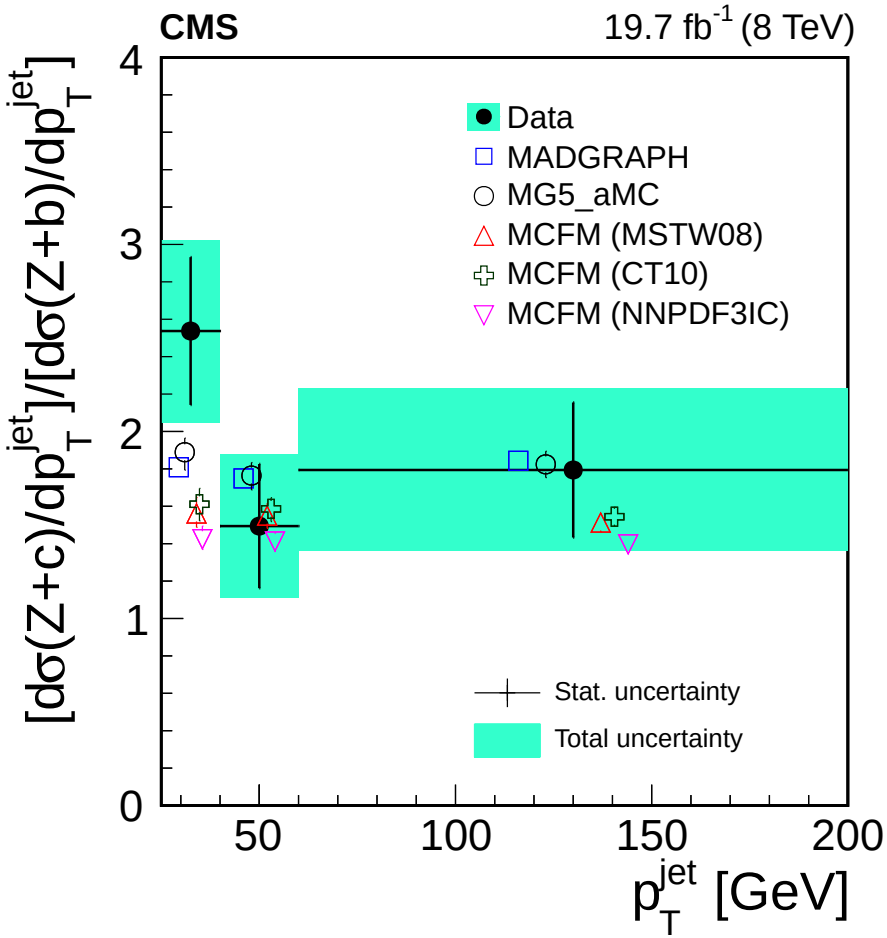
Results


CMS
19.7 fb-1 (8 TeV)
Data
MADGRAPH
MG5_aMC
MCFM (MSTW08)
MCFM (CT10)
MCFM (NNPDF3IC)
Stat. uncertainty
Total uncertainty
dσ(Z+c)/dpTZ B(Z→l+l−) [pb]
pTZ [GeV]
0
0.05
0.1
0.15
0
50
100
150
200


CMS
19.7 fb-1 (8 TeV)
Data
MADGRAPH
MG5_aMC
MCFM (MSTW08)
MCFM (CT10)
MCFM (NNPDF3IC)
Stat. uncertainty
Total uncertainty
dσ(Z+c)/dpTjet B(Z→l+l−) [pb]
pTjet [GeV]
0
0.1
0.2
0.3
0.4
50
100
150
200

Ratios


CMS
19.7 fb-1 (8 TeV)
Data
MADGRAPH
MG5_aMC
MCFM (MSTW08)
MCFM (CT10)
MCFM (NNPDF3IC)
Stat. uncertainty
Total uncertainty
[dσ(Z+c)/dpTZ]/[dσ(Z+b)/dpTZ]
pTZ [GeV]

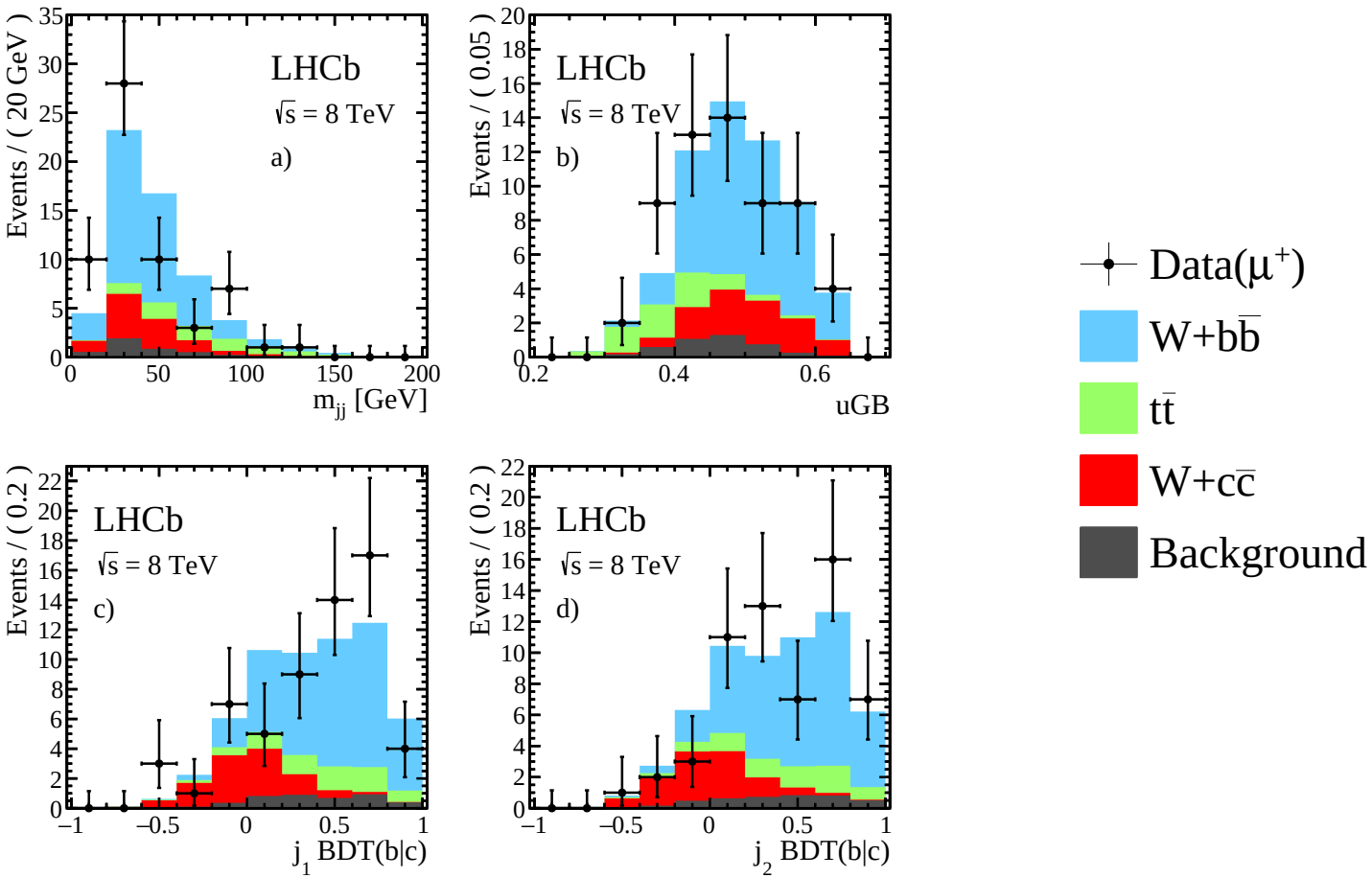

CMS
19.7 fb-1 (8 TeV)
Data
MADGRAPH
MG5_aMC
MCFM (MSTW08)
MCFM (CT10)
MCFM (NNPDF3IC)
Stat. uncertainty
Total uncertainty
[dσ(Z+c)/dpTjet]/[dσ(Z+b)/dpTjet]
pTjet [GeV]

LHCb tt, $W + cc/bb$

PLB 767 (2017) 110

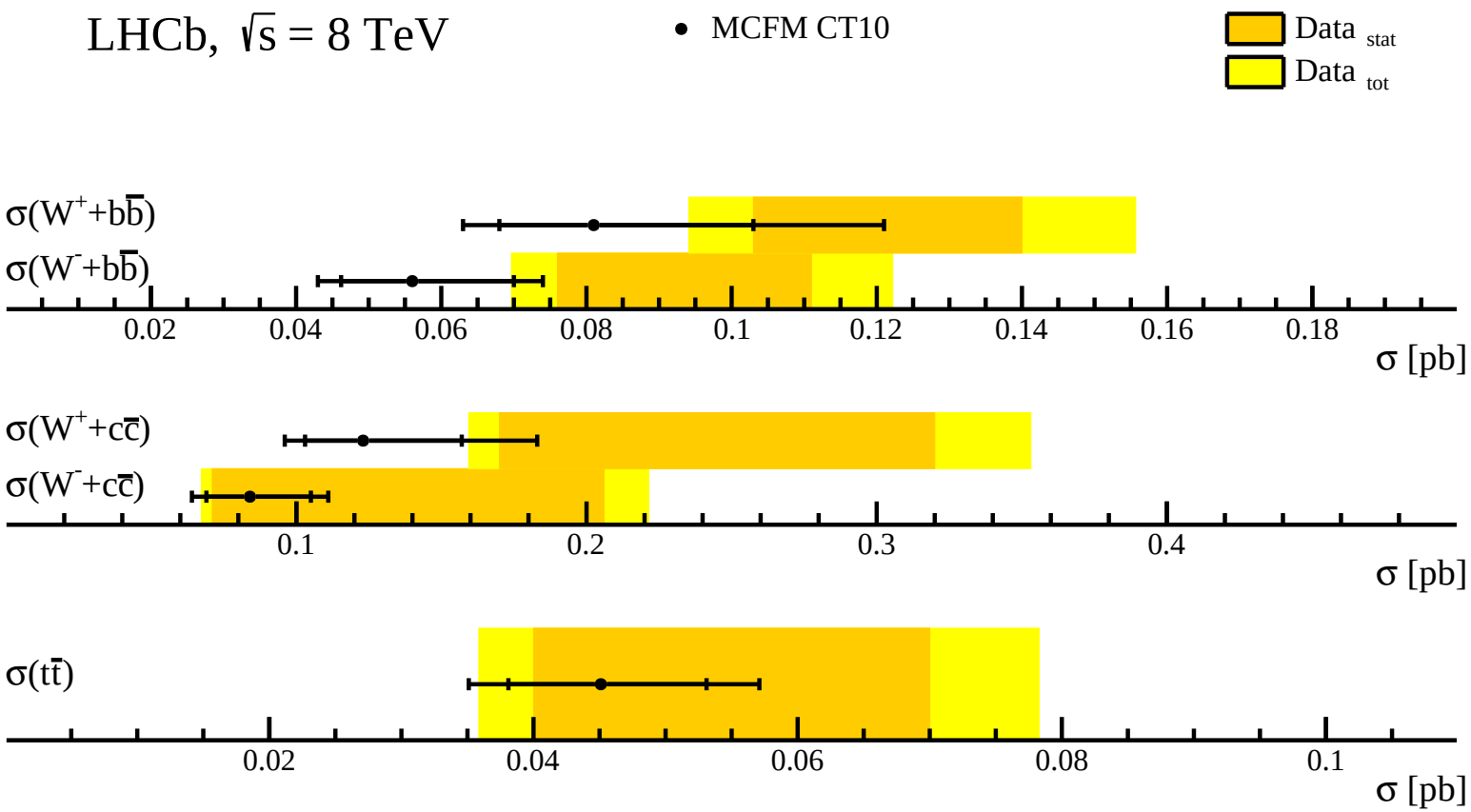
Signal Determination

- tag jets with secondary vertex
- limited statistics allow only integrated cross-sections
- processes determined from four-variable fit



Results

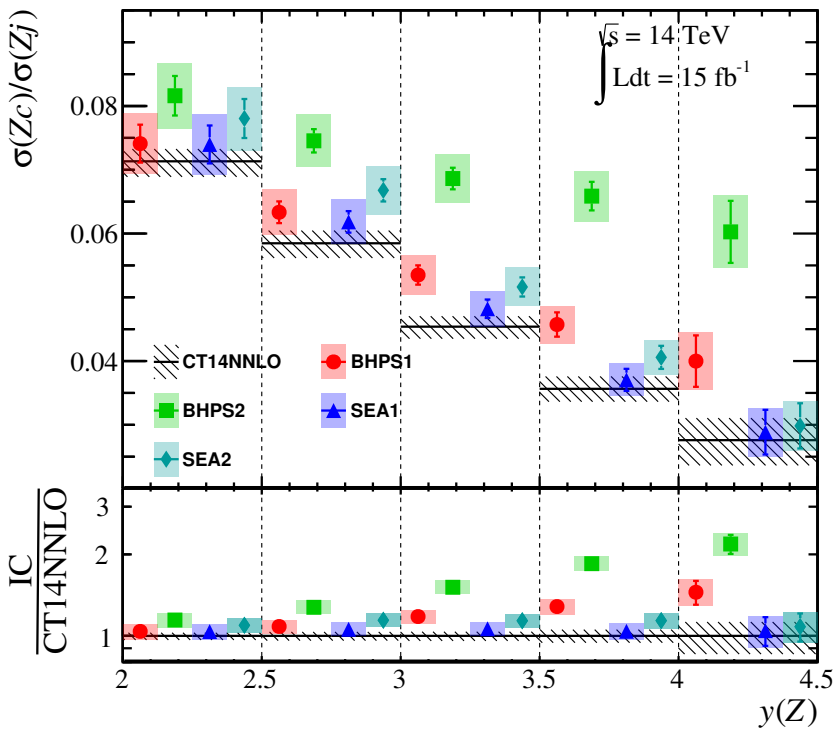
- dominate uncertainty from tagging efficiencies at 5 - 10%

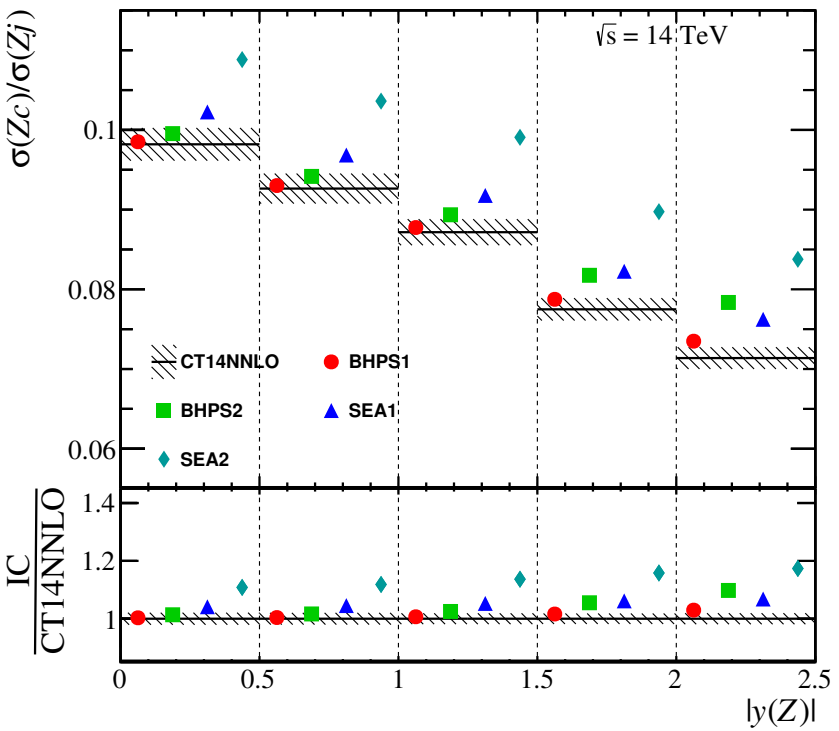


Outlook

Future Intrinsic Charm

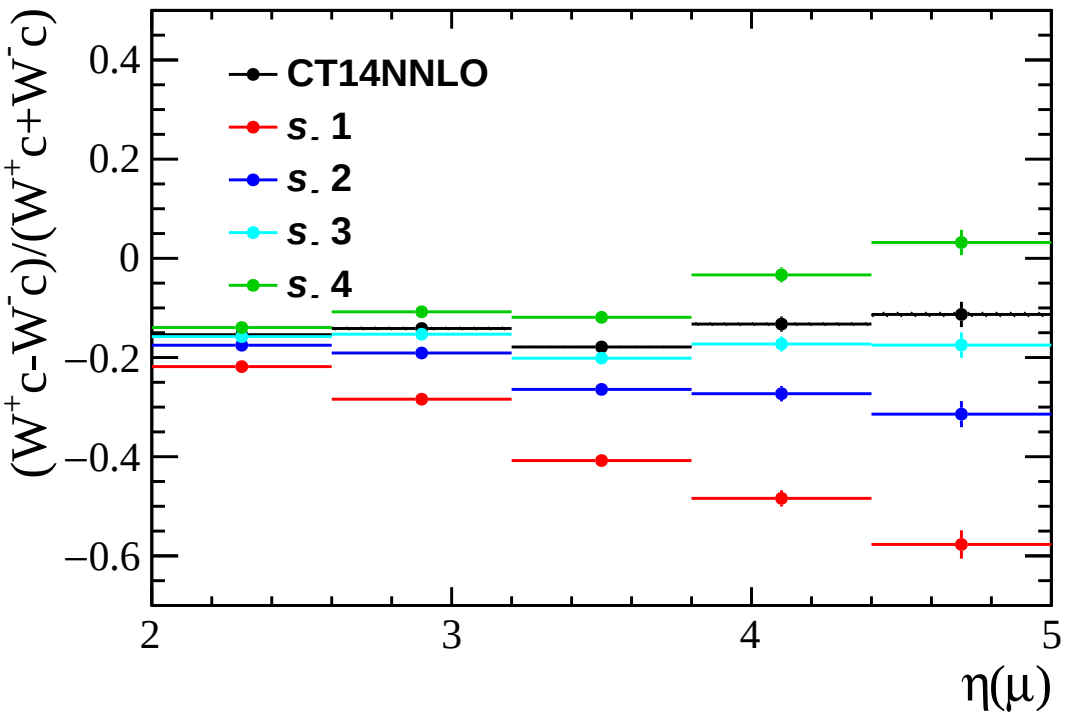
- phenomenology study in PRD 93 (2016)
- LHCb sensitive to valence $\langle x \rangle_{\mathrm{IC}} > 0.3\%$ and sea $\langle x \rangle_{\mathrm{IC}} > 1\%$
- ATLAS/CMS sensitivity dependent on tagging uncertainties

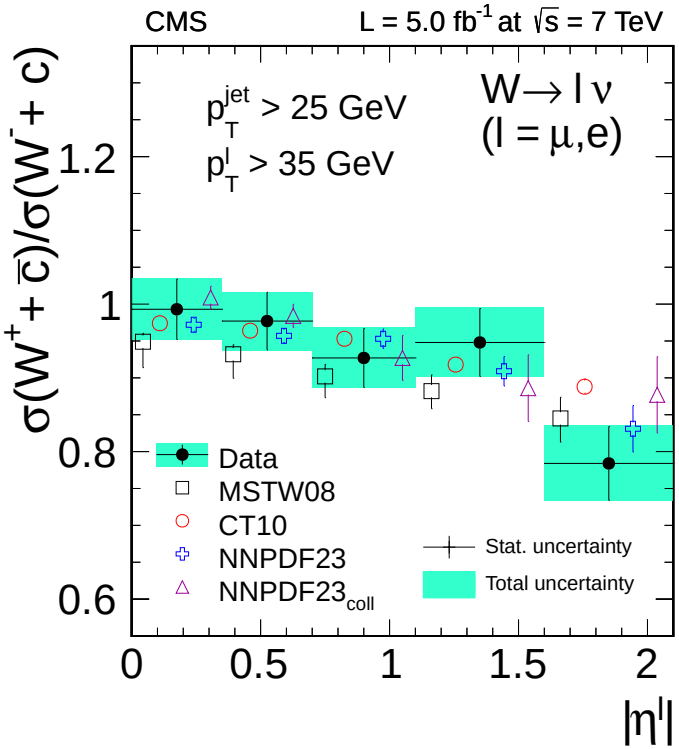




Strange Asymmetries

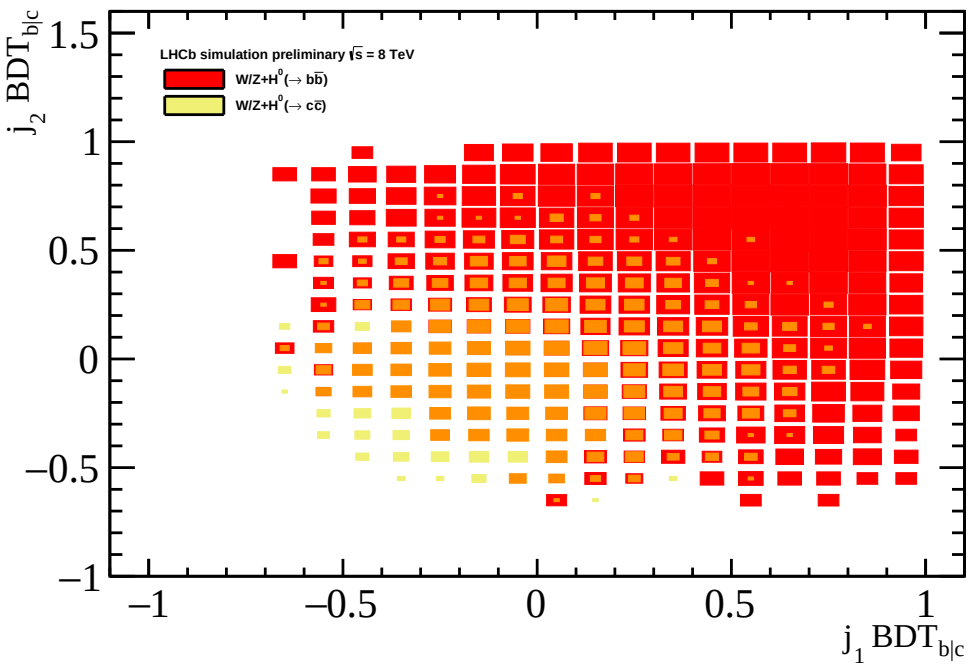
- proton strangeness higher than expected, $\approx 1\%$
- precision inclusive W and Z measurements primary constraint
- $W + c$ asymmetry can constrain strange asymmetry
- four scenarios from CTEQ fit, JHEP 0704 (2007)

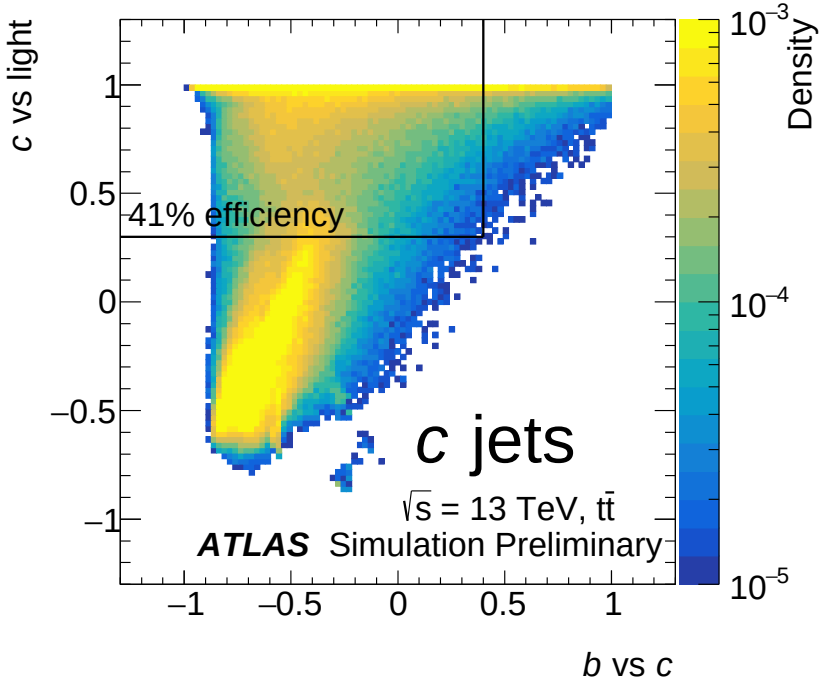




Charm Yukawa

- recent $V + H(c\bar{c}$ result from ATLAS (ATLAS-CONF-2017-078) and LHCb (LHCb-CONF-2016-006)
- highlight $V + Q(Q)$ importance for calibration and background





Conclusions

- recent developments in heavy flavour tagging
- in many cases statistics still a limiting factor
- tagging efficiency and c/b separation will remain as dominant systematics
- need for updated measurements, energy ratios, *etc.* clear

Thank you!