Probing proton PDFs at high-x with LHCb

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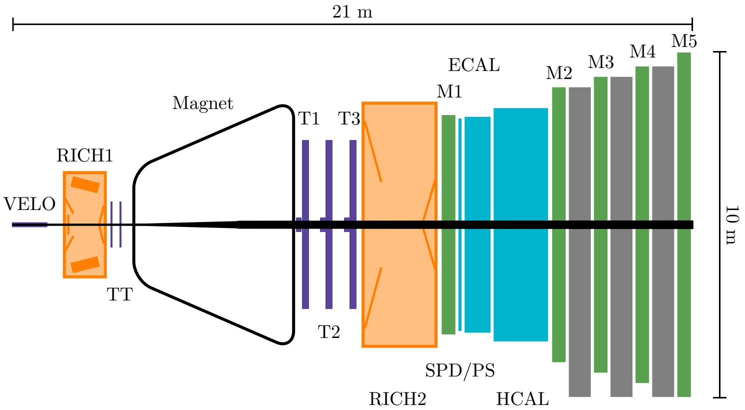
Outline

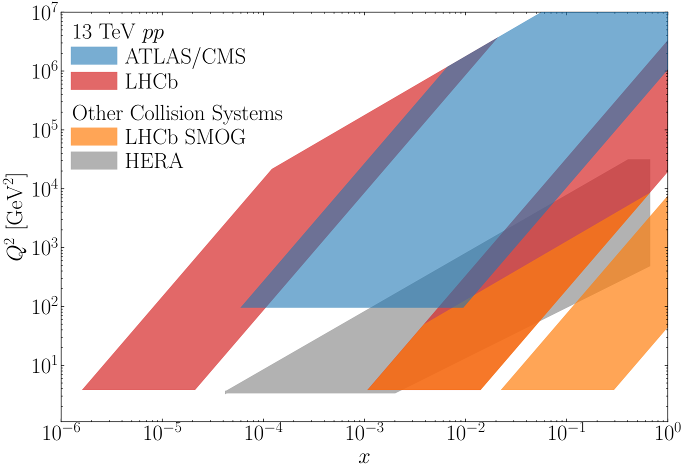
- How LHCb measurements are used in PDF fits and other LHCb measurements with sensitivity to high-x PDFs
- Studying PDFs with heavy flavor jets
- Searching for intrinsic charm at LHCb

The LHCb detector (Int. J. Mod. Phys. A 30, 1530022 (2015))

- Forward spectrometer: $2 < \eta < 5$
- **tracking**, **calorimetry**, **RICH**, **muon** systems
- Excellent vertex resolution ($10 - 50\ \mu m$ in x and y)
- Track $\sigma(p)/p \sim 0.5 - 1.0\%$
- Fixed-target mode with the SMOG system



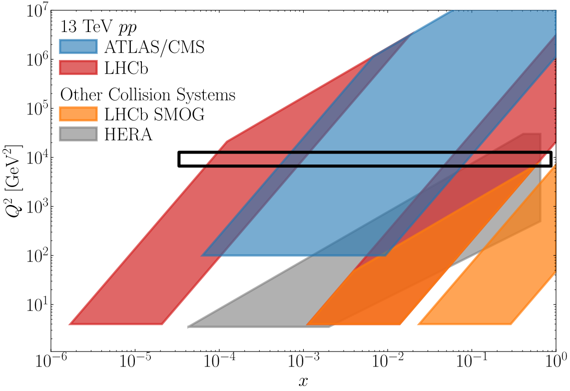
LHCb kinematics

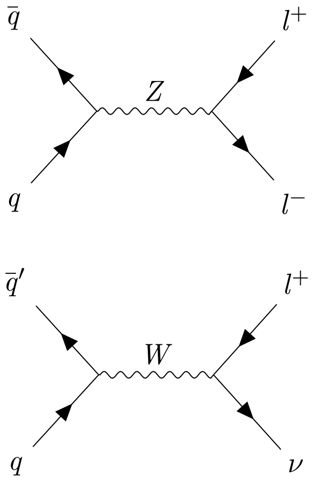


This talk will focus on the high-x, high-Q^2 regime

LHCb data in PDF fits

LHCb measurements in PDF fits: W and Z



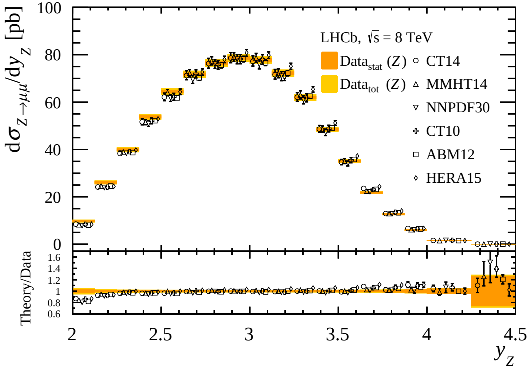


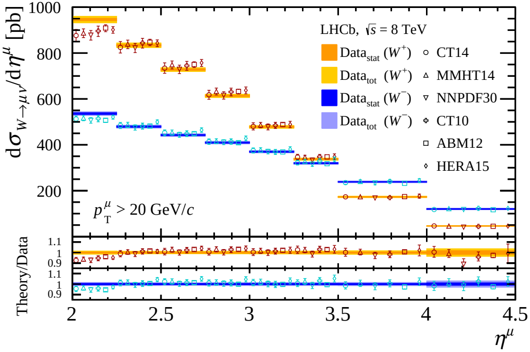
Recent PDF fits using LHCb data

- CT18 (PRD 103, 014013 (2021))
- NNPDF3.1 (EPJC 77, 663 (2017))
- MSHT20 (arXiv:2012.04684)

LHCb measurements in PDF fits: W and Z production

$Z \to \mu\mu$ and $W \to \mu\nu$ at 8 TeV, JHEP 01 (2016) 155

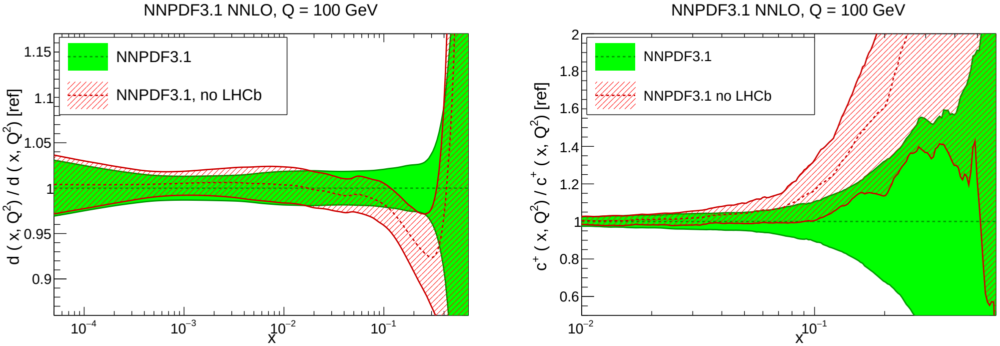




- $Z \to \mu\mu$ at 7 TeV (JHEP 08 (2015) 039)
- $Z \to ee$ at 7 TeV (JHEP 02 (2013) 106)
- $Z \to ee$ at 8 TeV (JHEP 05 (2015) 109)
- $W \to \mu\nu$ at 7 TeV (JHEP 12 (2014) 079)
- $W \to e\nu$ at 8 TeV (JHEP 10 (2016) 030)

LHCb's impact

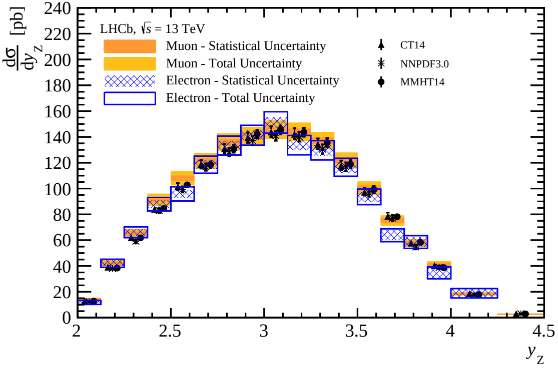
EPJC 77, 663 (2017)



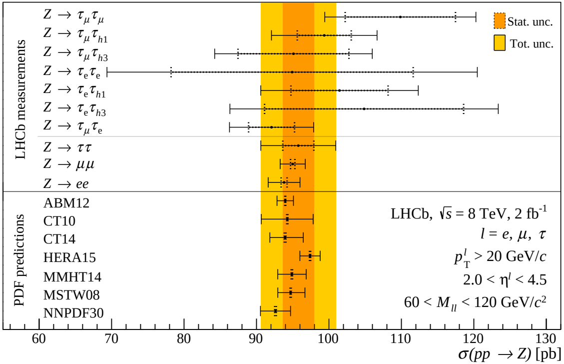
Current LHCb data provides powerful constraints on the quark PDFs at high-x

Additional measurements: More Z production

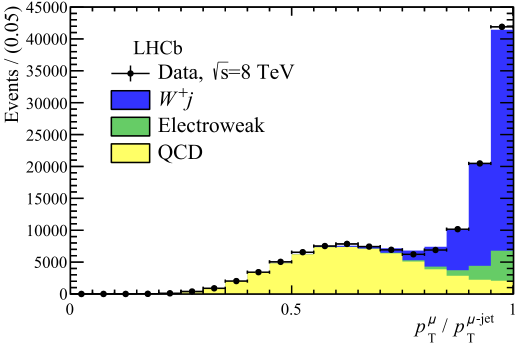
$Z \to \mu\mu/ee$ at 13 TeV
(JHEP 09 (2016) 136)

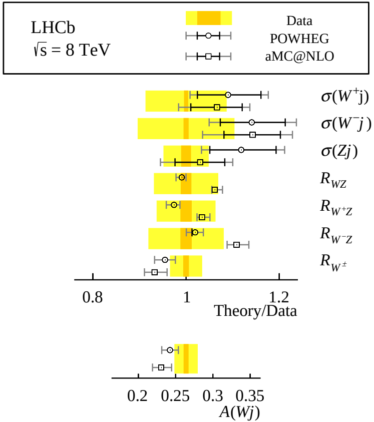


$Z \to \tau\tau$ at 8 TeV
(JHEP 1809 (2018) 159)



Additional measurements: $W + j$ and $Z + j$ (JHEP 05 (2016) 131)





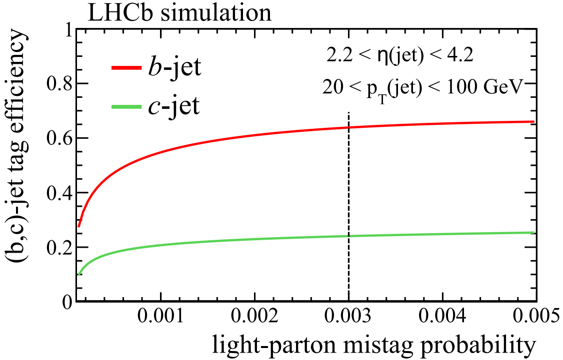
$$A(Wj) = \frac{\sigma(W^+j) - \sigma(W^-j)}{\sigma(W^+j) + \sigma(W^-j)}, \; R_{XY} = \sigma(Xj)/\sigma(Yj)$$

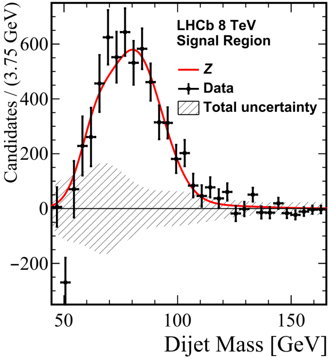
- Asymmetries and ratios minimize scale uncertainties → greater PDF sensitivity
- Sensitive to quark PDFs above $x \sim 0.5$ (see *e.g.* PRD 93, 014008 (2016))

Studying PDFs with Heavy Flavor Jets at LHCb

Heavy flavor jet tagging at LHCb (JINST 10 P06013)

$Z \to b\bar{b}$ (Phys. Lett. B776 (2018) 430)

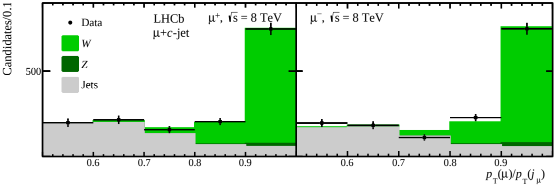




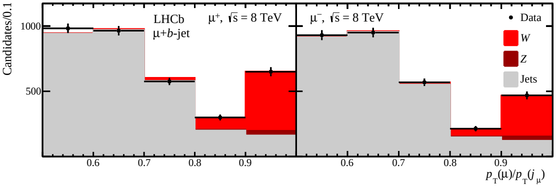
- Jets are using displaced secondary vertices and two BDTs: $BDT_{bc|udsg}$ and $BDT_{b|c}$
- b (c) jets tagged with 65% (25%) efficiency with 0.3% mistag probability

$W + (c, b)$ (PRD 92 (2015) 052001)

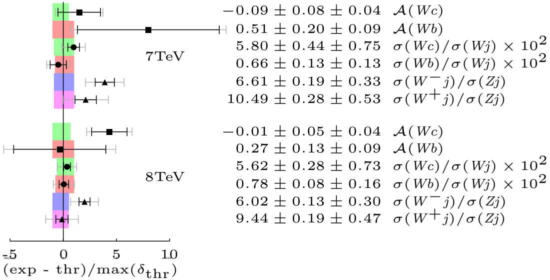
Probes $s/\bar{s}$ PDFs via $gs \to Wc$



Probes $b/\bar{b}$ PDFs via $qb \to Wbq'$

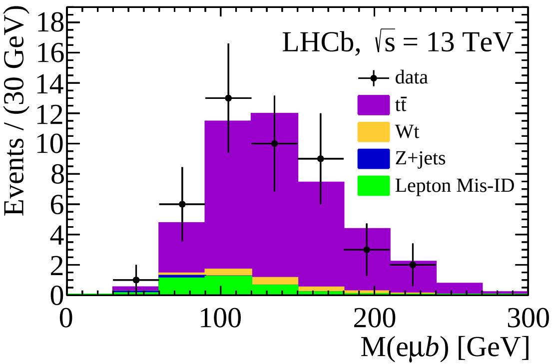


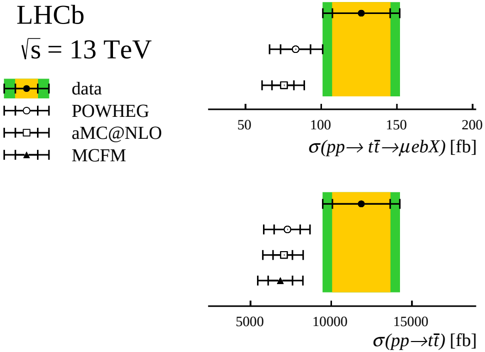
Wc, Wb, W^-j, W^+j



$\sim 2\sigma$ tension in $\mathcal{A}(Wc)$ could point to an asymmetry between s and $\bar{s}$ PDFs

$t\bar{t}$ at 13 TeV (JHEP 08 (2018) 174)



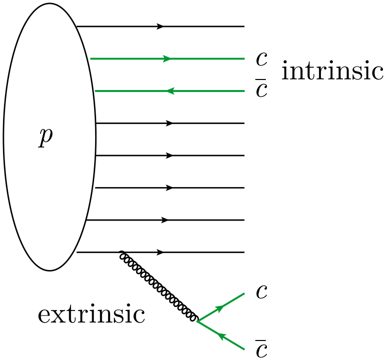


- Measured in the $\mu + e + b$ final state
- Probes the gluon PDF at high-x

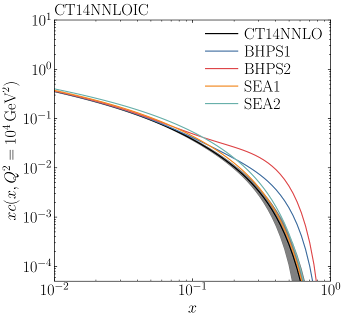
- Syst. and stat. uncertainties are similar
- Syst. uncertainties dominated by b-tagging efficiency

Searching for Intrinsic Charm at LHCb

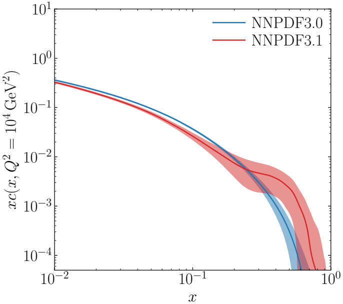
Intrinsic charm in the proton



arXiv:1810.00264

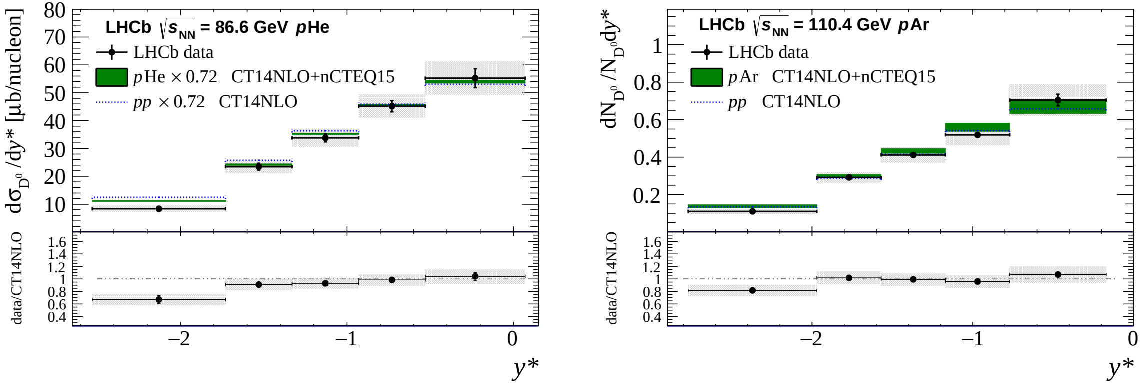


EPJC 77, 663 (2017)



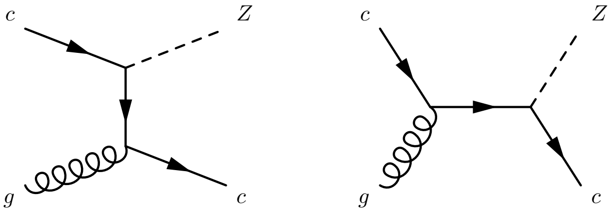
- Most PDF fits assume charm is generated perturbatively for $Q^2 > m_c^2$
- Intrinsic charm (IC) implies $\langle x \rangle_{\mathrm{IC}} \equiv \int_0^1 xc(x, Q^2 = m_c^2)dx > 0$
- See e.g. AHEP 2015 (2015) 231547 for a review
- NNPDF3.1 fits c PDF independently: $\langle x \rangle_{\mathrm{IC}} = (0.4 \pm 0.4)\%$

Fixed target charm production (PRL 122 (2019) 132002)



- **S**ystem for **M**easuring **O**verlap with **G**as (SMOG)
- Fixed target D^0 production probes the charm PDF at low-Q^2 and high-x
- No evidence for significant IC
- Low-Q^2 fixed target charm production data is difficult to interpret and usually omitted from PDF fits

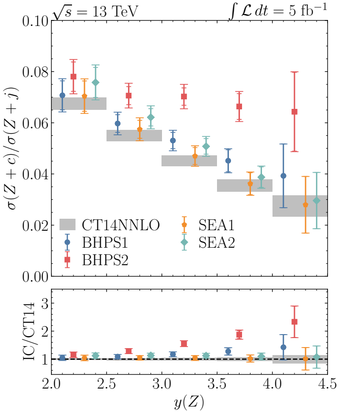
Probing IC with $Z + c$



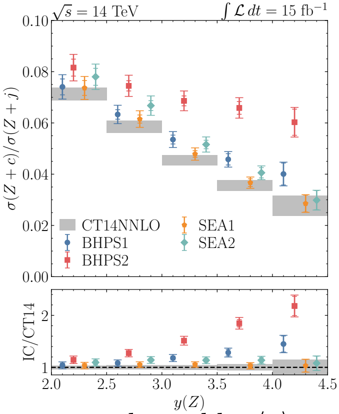
- An ideal probe of IC should be sensitive to the c PDF at high-x AND high-Q^2
- $Z + c$ production at LHCb probes the c PDF in the valence region at $Q^2 \sim m_Z^2$

Outlook (Phys. Rev. D 93, 074008 (2016))

Run 2 projection



Run 3 projection



- Run 2 measurement in progress
- Sensitive to valence-like IC down to about $\langle x \rangle_{\text{IC}} \sim 1\%$

- Sensitive to valence-like $\langle x \rangle_{\text{IC}} \sim 0.3\%$ by the end of Run 3
- Sensitive to IC favored by NNPDF3.1

Conclusions

- LHCb data provides significant constraints on the quark PDFs at high-x in state-of-the-art PDF fits

- Measurements using heavy flavor tagged jets provide additional information
  - $W + c(b)$ probes the $s(b)$ PDF
  - $t\bar{t}$ probes the g PDF

- LHCb has performed IC studies in fixed target mode, and studies of $Z + c$ production at 13 TeV are in progress.

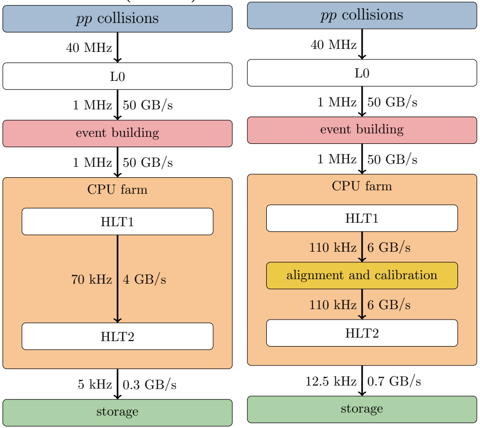
- Expect to rule out or observe valence-like IC at the level of $\langle x \rangle_{\text{IC}} \sim 1\%$ in Run 2 and 0.3% in Run 3

Thank You!

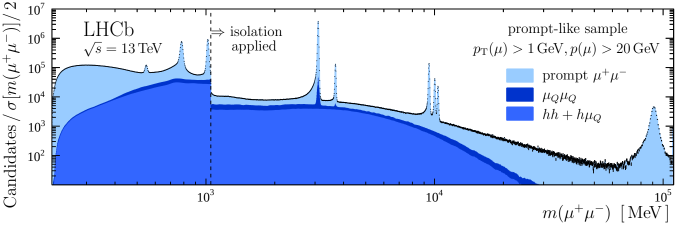
Backup

LHCb Trigger

Run 1 (2012) | Run 2

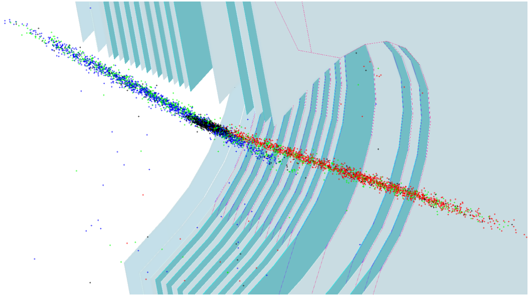


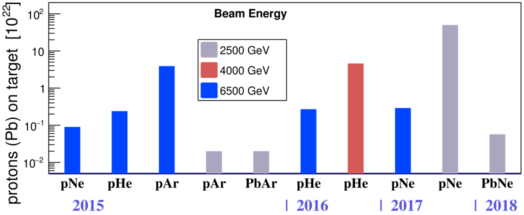
PRL 120 (2018) 061801



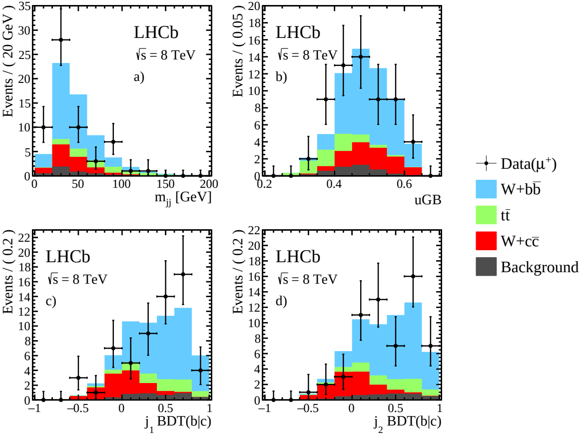
- Flexible software trigger
- Realtime alignment and calibration in Run 2 → offline-quality reconstruction

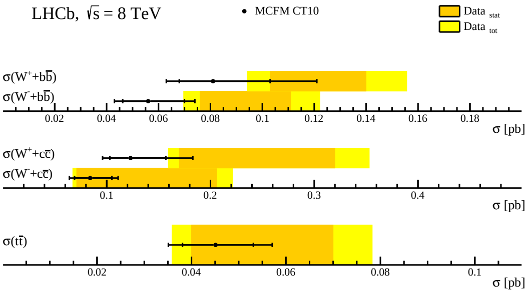
SMOG (JINST 9 (2014) 12, P12005)





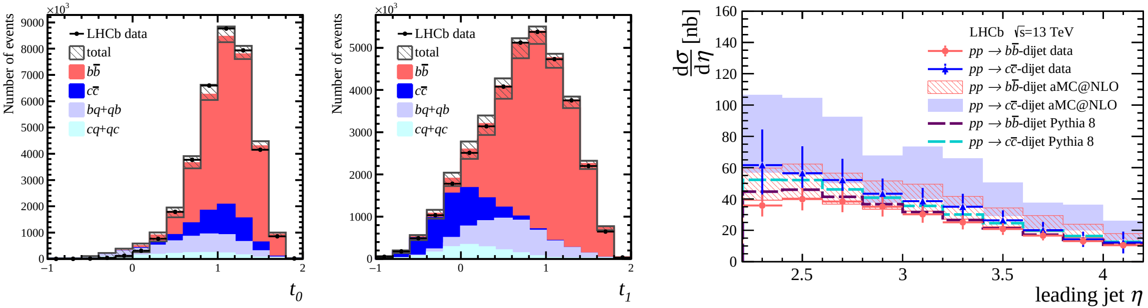
$t\bar{t}$, $W + c\bar{c}$, and $W + b\bar{b}$ (Phys. Lett. B767 (2017) 110)





First ever measurement of $W + c\bar{c}$ cross-section

$c\bar{c}$ and $b\bar{b}$ at 13 TeV (JHEP 02 (2021) 023)



- Yields determined using template fits to jet tagging BDT outputs:

$$t_0 = BDT_{bc|udsg}(j_0) + BDT_{bc|udsg}(j_1)$$
$$t_1 = BDT_{b|c}(j_0) + BDT_{b|c}(j_1)$$

- Theoretical uncertainties dominated by scale uncertainties