QCD physics measurements at the LHCb experiment

BOOST 2021

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on behalf of the LHCb collaboration

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Overview

- Introduction

Hadronisation & jet fragmentation

- Charged hadrons in jets
- J/ψ in jets

Dijet cross sections

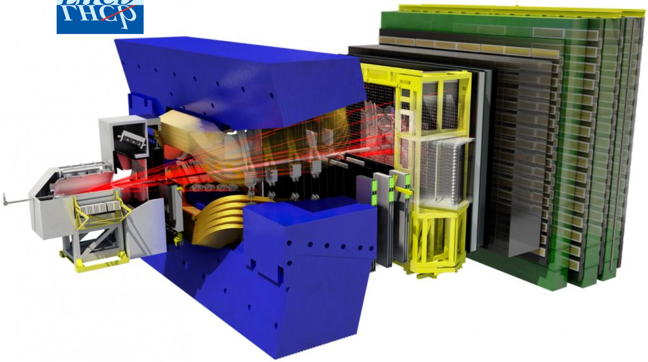
- $c\bar{c}$
- $b\bar{b}$

Intrinsic charm

- $Z + c$ NEW!

Covering a selection of recent jet-physics analyses but will focus on new $Z + c$ results

The LHCb Detector

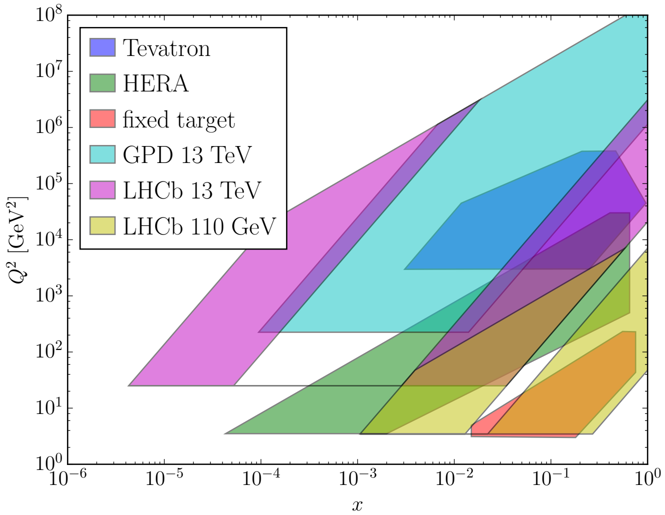


JINST **3** (2008) S08005

Int. J. Mod. Phys. A **30** (2015) 1530022

- Forward detector optimised for *b*- and *c*-physics
- Precise vertexing and charged particle ID information
- Complementary angular acceptance to GPDs: 0.6° to $\sim 15^\circ$

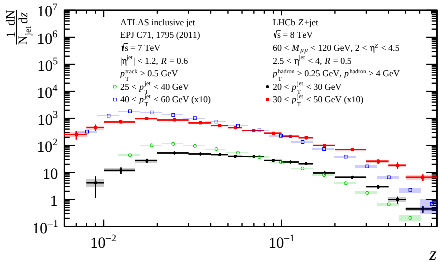
The LHCb Detector: Kinematics

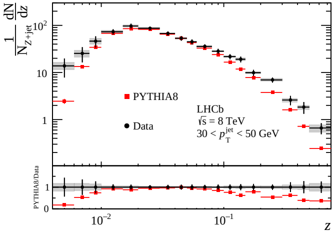


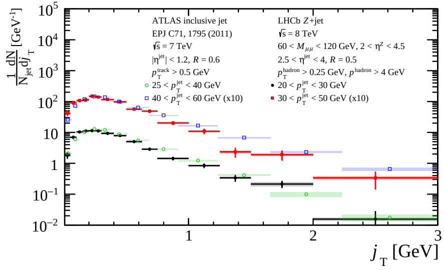
- LHCb coverage sensitive to large and small x
- Increasingly functioning as a general purpose detector in the forward region

Hadronisation & jet fragmentation

- Study hadronisation in Z-tagged jets at LHCb
- First measurements at forward rapidities
- Dominated by light-quark jets *cf.* gluon jets for mid-rapidities
- Hadrons found to more longitudinally and transversely collimated
- Simulation underestimates number of high-p hadrons

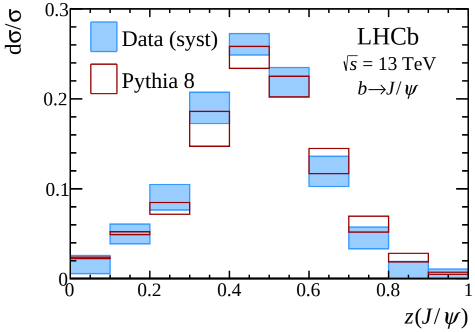


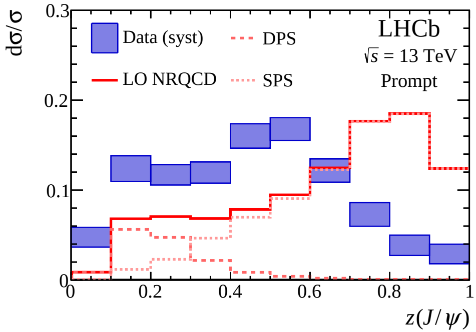




Phys. Rev. Lett. **118** (2017) 192001

- Study production of quarkonium in jets
- Identify prompt vs from-*b* using pseudo-lifetime fits
- Measure fraction of jet p_{T} carried by J/ψ



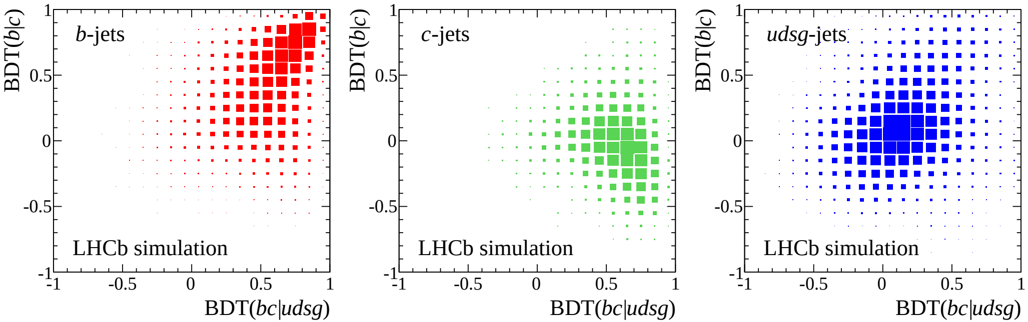


- From-*b* distribution well described
- Data disagree with fixed-order NRQCD for prompt J/ψ
- Lower than expected isolation may be related to quarkonimum polarisation puzzle

Dijet cross sections

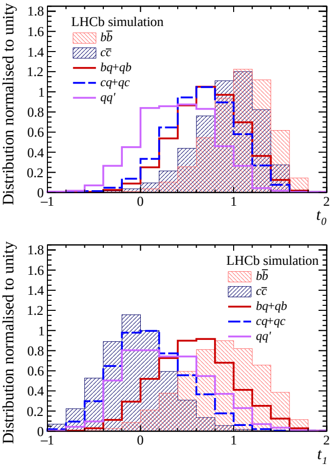
Heavy flavour: tagging

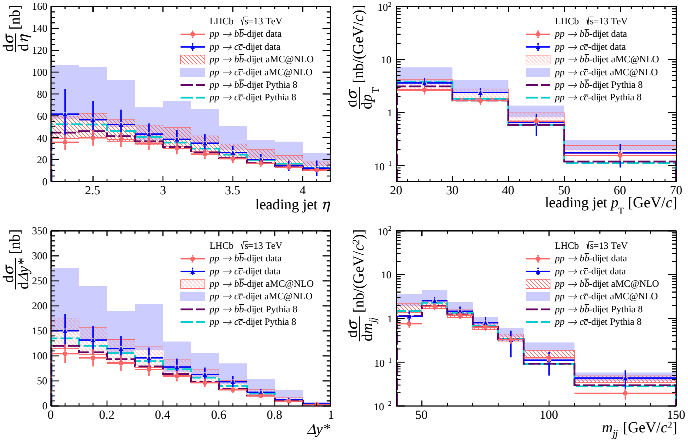
JINST **10** (2015) P06013



- Distinguish between flavours of jet based on properties of displaced secondary vertices
- Run 1 studies used BDTs trained to distinguish between light- and heavy-flavour jets, and between beauty and charm
- *c* (*b*) jets tagged with $\sim 25\,\%$ ($\sim 65\,\%$) efficiency, with a $0.3\,\%$ light jet mis-tag rate

- Heavy-flavour quarks typically produced in pairs at LHC through flavour creation or annihilation, or gluon splitting
- Distinguish dijet flavours using fit to the sums of single-jet BDT outputs (templates shown right)

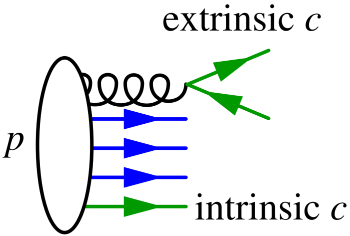




- Differential cross sections measured in η and p_T of the leading jet as well as the rapidity gap and invariant mass of the dijet
- $c\bar{c}$ and $b\bar{b}$ cross sections consistent with predictions
- Ratio also found to be consistent

Intrinsic charm

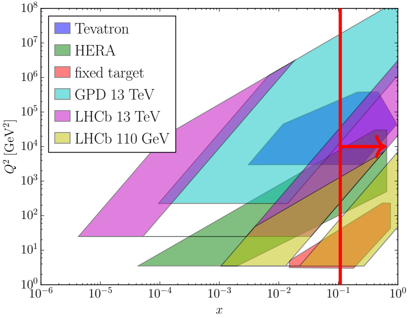
Intrinsic charm

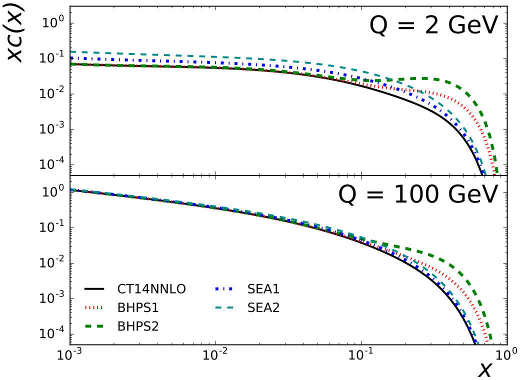


- *Extrinsic* charm content of the proton arises from soft gluon splitting
- Proton may also have an *intrinsic* charm content bound to valance quarks
- Current limits do not rule out a percent-level IC component in the proton
- Previous results have been claimed as evidence both for and against IC
- Important for understanding other processes
  - *e.g.* percent-level IC would lead to percent-level corrections to relative rates of Higgs production mechanisms

Intrinsic charm

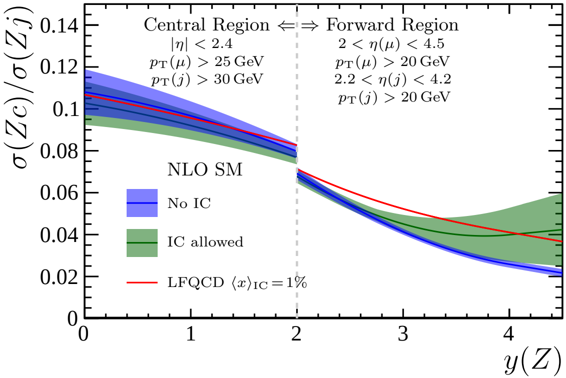
- PDF of IC may be valance-quark-like or sea-quark-like
- In particular, valance-like IC would produce a clear signature at $x > 0.1$
- Probe high-x charm to search for IC

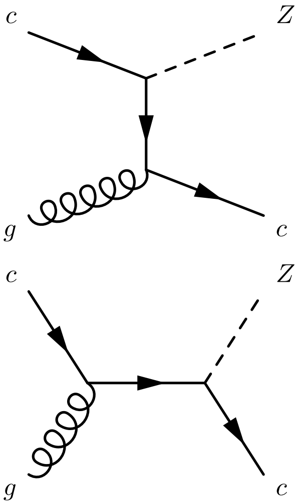


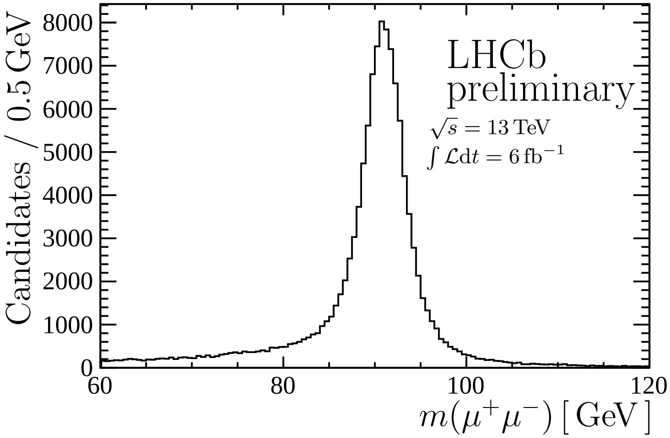


Phys. Rev. **D 93** (2016) 074008

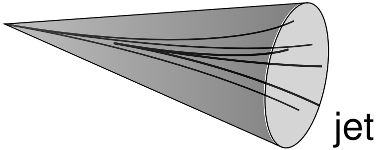
- Study production of c-jets in association with a Z
- Forward region sensitive to high-x, high-Q^2 charm content of the proton





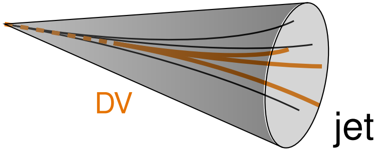


- Analysis based on Run 2 dataset
- Select events with $Z \to \mu^+\mu^-$ and at least one jet with $p_\mathrm{T} > 15\,\mathrm{GeV}/c$
- Identify c-jets using displaced-vertex tagger in bins of jet p_T and Z rapidity
- Unfold jet p_T to obtain results in fiducial volume, $p_\mathrm{T} > 20\,\mathrm{GeV}$
- Tagger must distinguish charm jets from beauty and mis-tagged light jets . . .



- Reconstruct displaced vertices within jets

$Z + c$: displaced-vertex c-tagger



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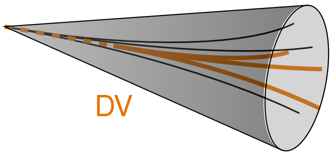
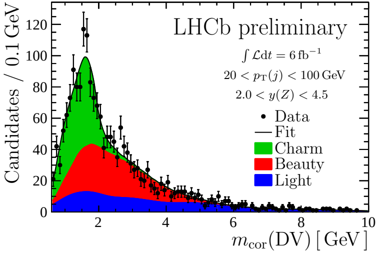
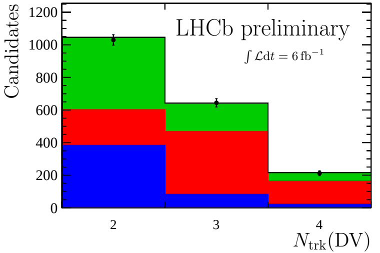
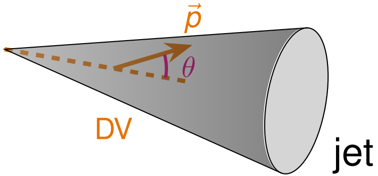


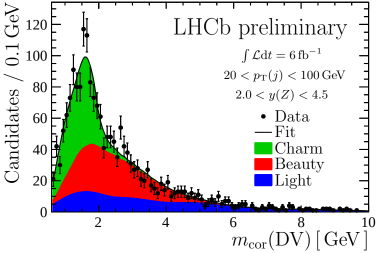
- Reconstruct displaced vertices within jets
- Use 2D fit to corrected mass and number of tracks to distinguish charm jets from beauty and light

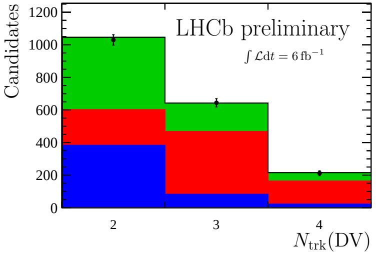




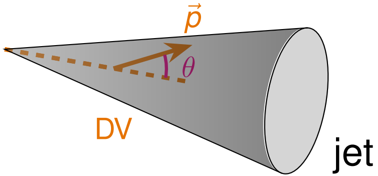
$Z + c$: displaced-vertex c-tagger

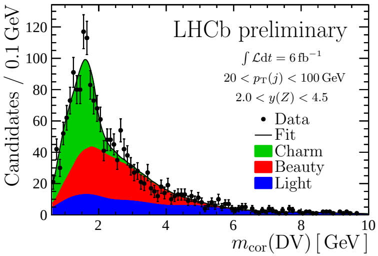


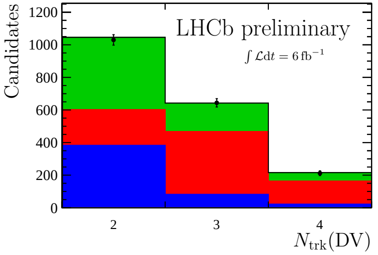




- Reconstruct displaced vertices within jets
- Use 2D fit to corrected mass and number of tracks to distinguish charm jets from beauty and light
- $m_\mathrm{cor}(\mathrm{DV}) \equiv \sqrt{m(\mathrm{DV})^2 + [p(\mathrm{DV})\sin\theta]^2} + p(\mathrm{DV})\sin\theta$



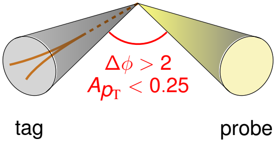




- Reconstruct displaced vertices within jets
- Use 2D fit to corrected mass and number of tracks to distinguish charm jets from beauty and light
- $m_{\text{cor}}(\text{DV}) \equiv \sqrt{m(\text{DV})^2 + [p(\text{DV}) \sin\theta]^2} + p(\text{DV}) \sin\theta$
- Templates from flavour-enhanced calibration samples
- Determine tagger efficiency using dijet events . . .

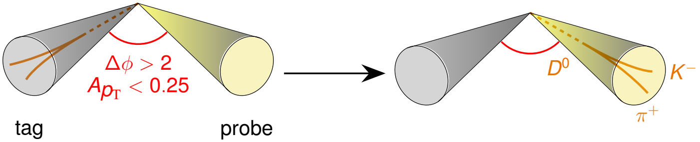
$Z+c$: c-tagger calibration

- Trigger on DV in "other" jet



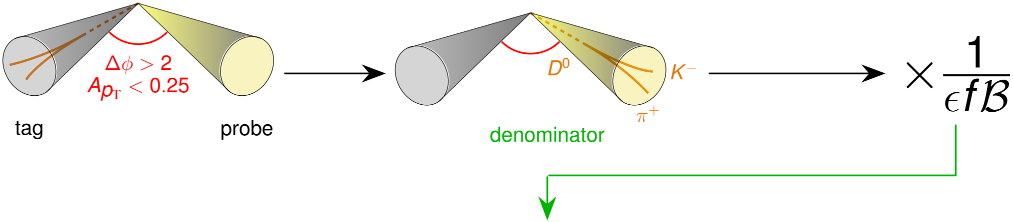
$Z + c$: c-tagger calibration

- Trigger on DV in "other" jet
- Tag prompt $D^0 \to K^- \pi^+$, $D^+ \to K^- 2\pi^+$



$Z + c$: c-tagger calibration

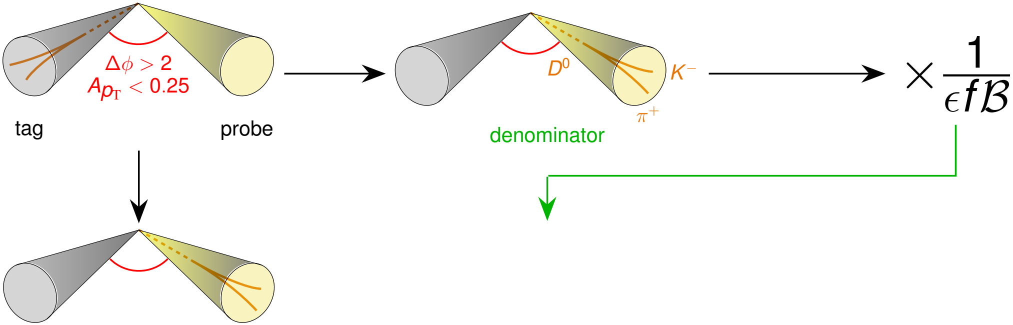
- Trigger on DV in "other" jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$
- Correct for eff, FF and BF



$Z + c$: c-tagger calibration

LHCb-PAPER-2021-029 NEW!

- Trigger on DV in “other” jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$
- Correct for eff, FF and BF

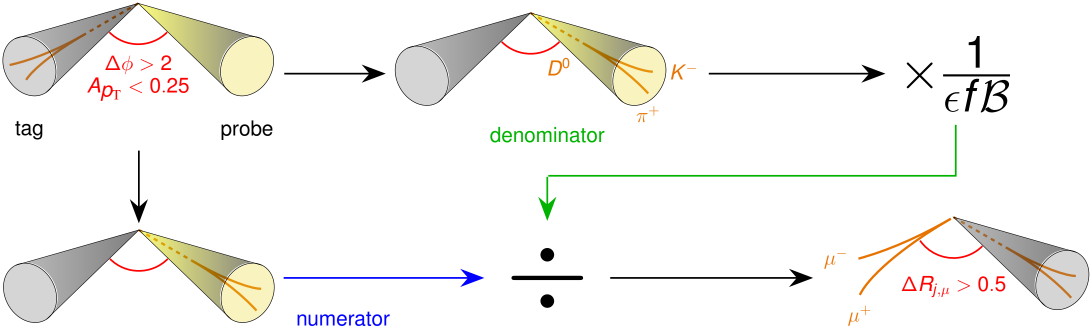


- Tag DV candidates

$Z + c$: c-tagger calibration

LHCb-PAPER-2021-029 NEW!

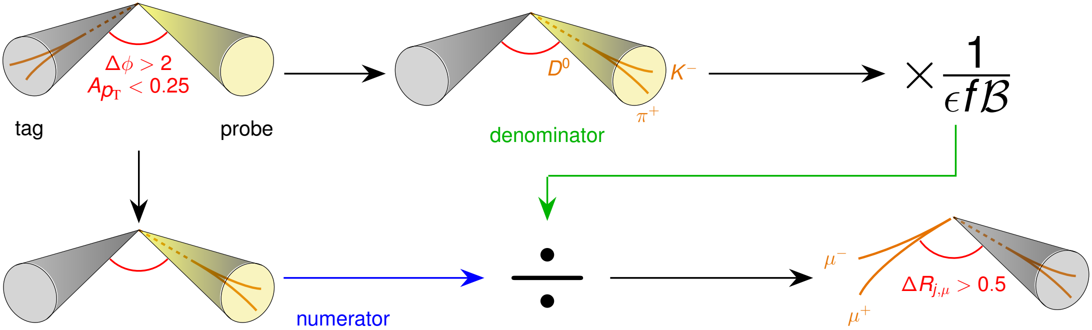
- Trigger on DV in “other” jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$
- Correct for eff, FF and BF



- Tag DV candidates
- Divide to get tag efficiency
- Use for DV-tagged $Z + c$

$Z + c$: c-tagger calibration

- Trigger on DV in "other" jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$
- Correct for eff, FF and BF



- Tag DV candidates
- Divide to get tag efficiency
- Use for DV-tagged $Z + c$

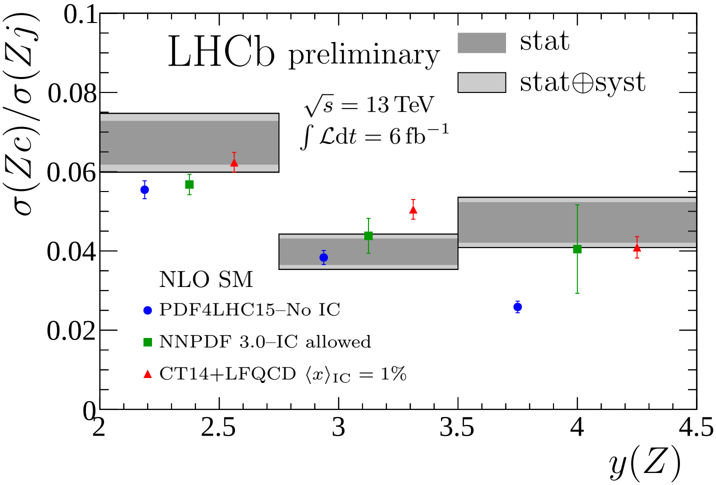
- Efficiency determined as function of jet p_T:

$23.9 \pm 1.4\,\%$, $24.4 \pm 1.9\,\%$ and $23.6 \pm 4.1\,\%$ for $p_T \in (20, 30), (30, 50)$ and $(50, 100)\,\mathrm{GeV}/c$

Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%

- Leading systematic uncertainty due to *c*-tagging calibration
- Systematics almost all cancel between $y(Z)$ bins so double ratios have good potential for future precision measurements
- However, current results are statistically limited

$Z + c$: results



- Clear enhancement in highest-y bin
- Consistent with expected effect from $|uudc\bar{c}\rangle$ component predicted by LFQCD
- Inconsistent with No-IC theory at ~ 3 standard deviations
- Global PDF analysis required to determine true significance

Summary

- Wide range of QCD results
- $Z + c$ in forward region provides first direct probe of IC
- Clear enhancement in highest-y bin
- May give first unambiguous evidence for IC in the proton but global PDF analyses required
- Statistically limited but Run 3 dataset should give definitive answer

Stay tuned!