The charm of the proton

Using forward $Z + c$ production to study intrinsic charm at LHCb

Daniel Craik

2022-03-10

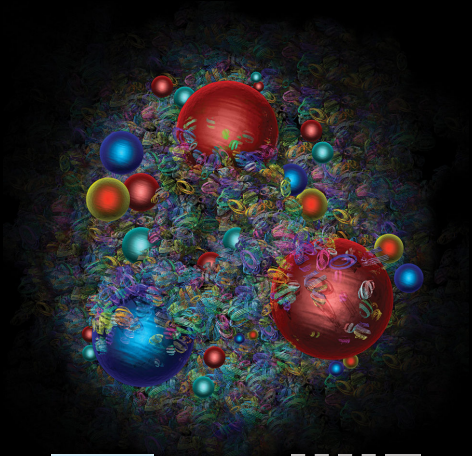


Image: Daniel Dominguez/CERN

Outline

- What is intrinsic charm?
- A very brief recap of a long history
- A direct probe
- Charm-jet tagging at LHCb
- Probing intrinsic charm at LHCb

Intrinsic charm

$$|\text{proton}\rangle = |uud\rangle$$

Intrinsic charm

$$|\text{proton}\rangle = |uud\rangle \; + \epsilon \, |uudc\bar{c}\rangle \, ?$$

$$\epsilon \lesssim \mathcal{O}(\%)$$

Why should I care about intrinsic charm?

- Production cross sections affected
  The proton is one of our main probes of the universe. The LHC collides them so LHC cross sections depend on the proton's composition. Even processes that don't involve charm are affected due to the PDF sum rules assumed when determining the content of the proton.

Why should I care about intrinsic charm?

- Production cross sections affected
  The proton is one of our main probes of the universe. The LHC collides them so LHC cross sections depend on the proton's composition. Even processes that don't involve charm are affected due to the PDF sum rules assumed when determining the content of the proton.

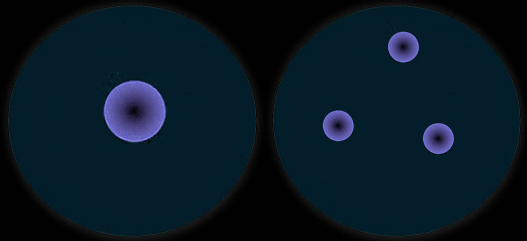
- Backgrounds affected
  Charmed hadrons produced in the upper atmosphere by the interactions of cosmic-ray protons may decay semi-leptonically forming a significant background to astrophysical neutrinos.

Why should I care about intrinsic charm?

- Production cross sections affected
  The proton is one of our main probes of the universe. The LHC collides them so LHC cross sections depend on the proton's composition. Even processes that don't involve charm are affected due to the PDF sum rules assumed when determining the content of the proton.
- Backgrounds affected
  Charmed hadrons produced in the upper atmosphere by the interactions of cosmic-ray protons may decay semi-leptonically forming a significant background to astrophysical neutrinos.
- "How charming am I?"
  As one of the main ingredients of the world around us, the proton's structure is interesting in its own right.

Proton structure

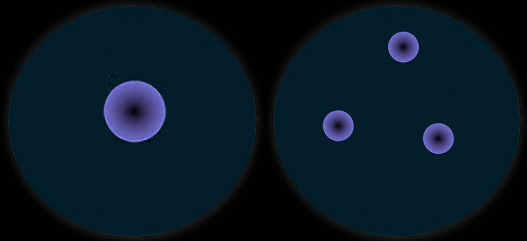
Probe wavelength



Probe energy

Proton structure

Probe wavelength

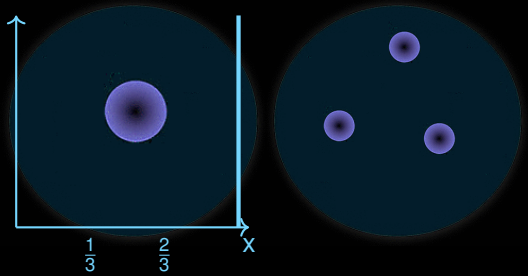


Probe energy

Momentum transfer (Q)

Proton structure

Probe wavelength



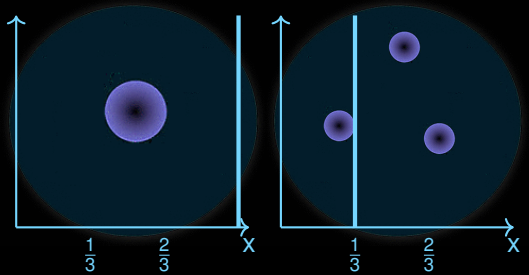
Probe energy

Momentum transfer (Q)

x = momentum fraction

Proton structure

Probe wavelength

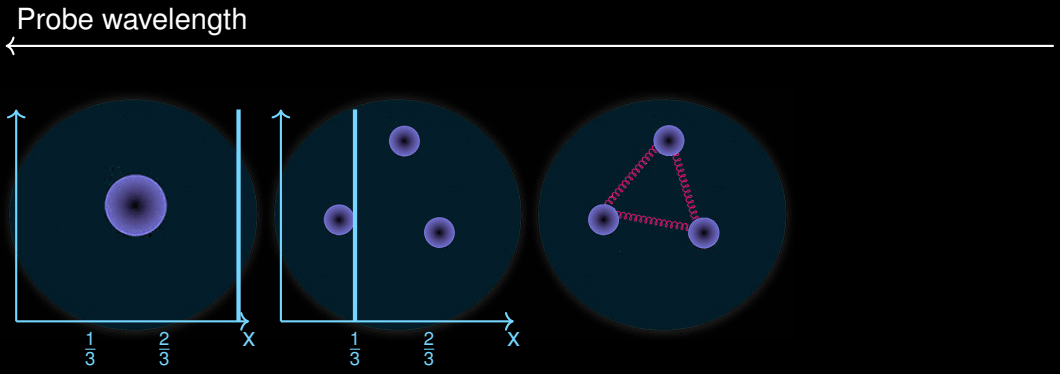


Probe energy

Momentum transfer (Q)

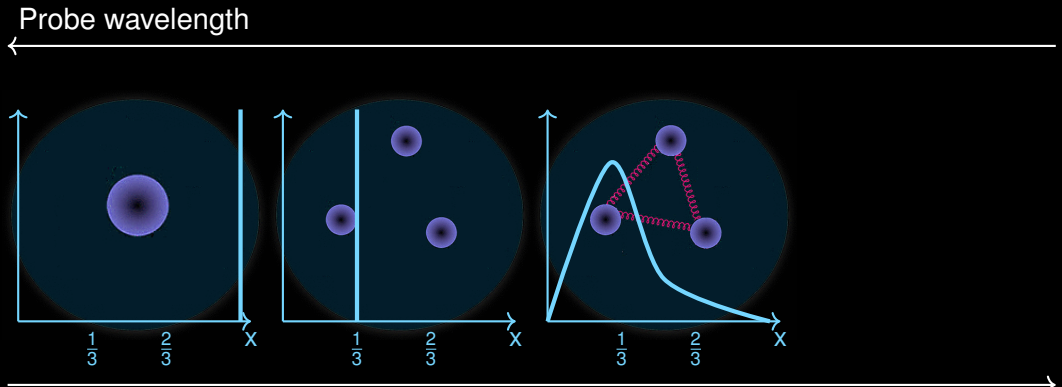
x = momentum fraction

Proton structure



x = momentum fraction

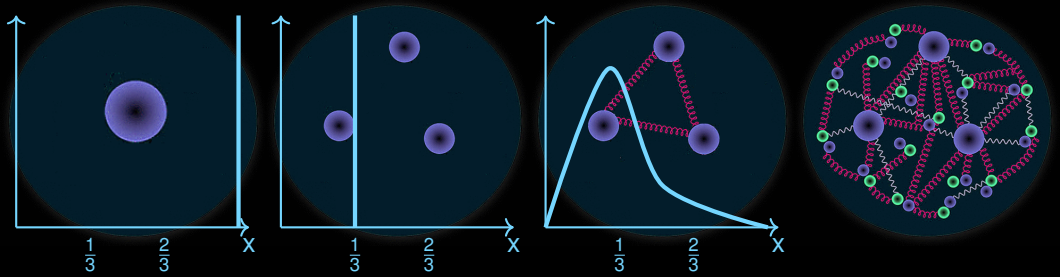
Proton structure



x = momentum fraction

Proton structure

Probe wavelength

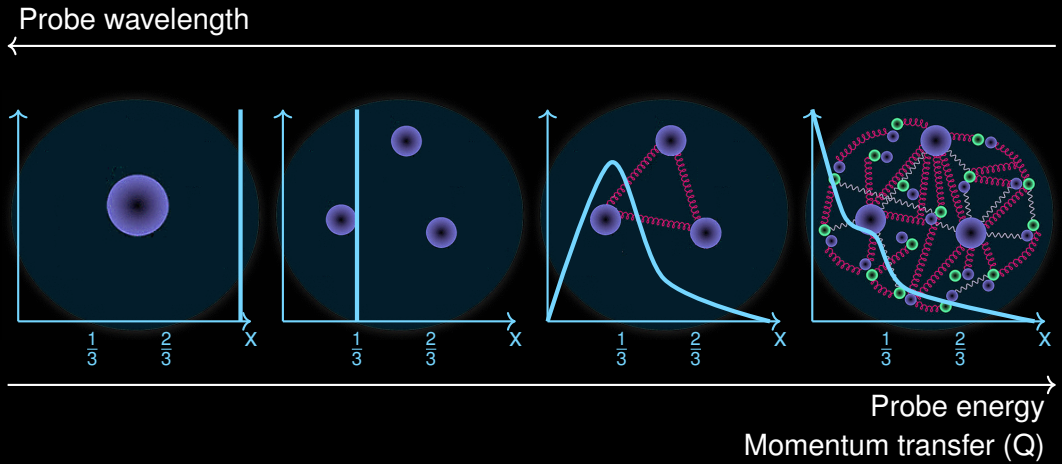


Probe energy

Momentum transfer (Q)

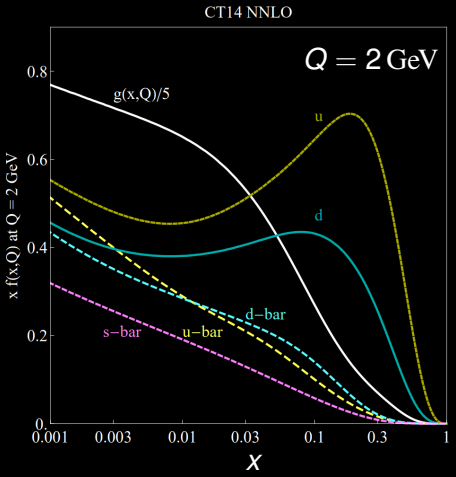
x = momentum fraction

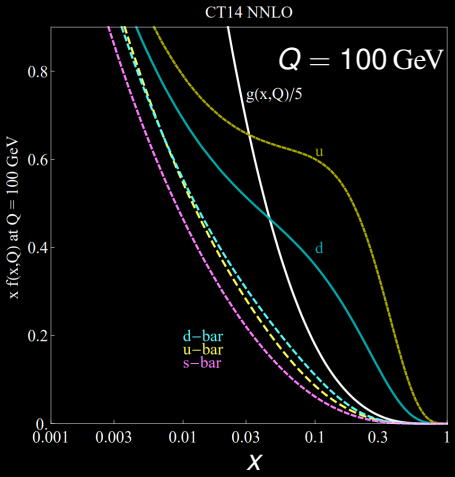
Proton structure



x = momentum fraction

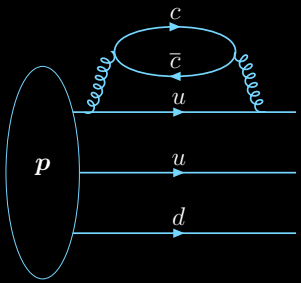
Proton structure





Charm in the proton

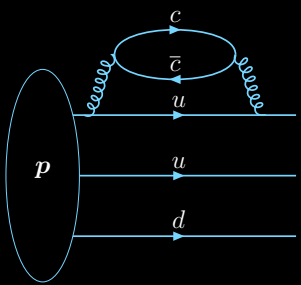
Extrinsic Charm



- Perturbative
- Short time scales

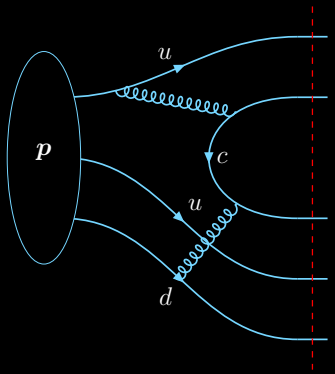
Charm in the proton

Extrinsic Charm



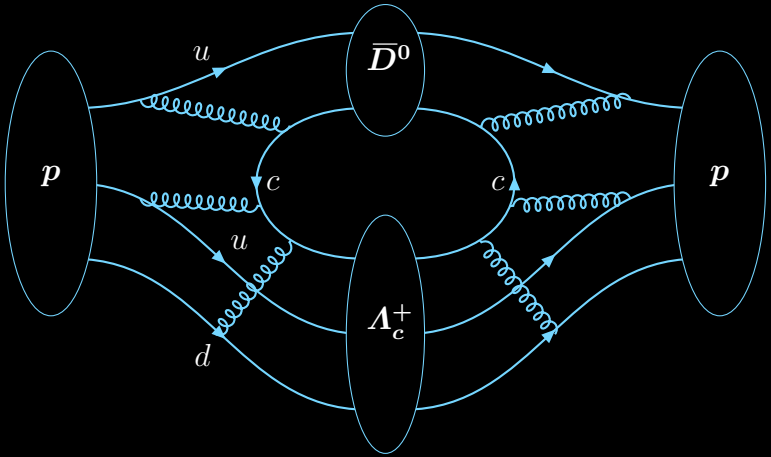
- Perturbative
- Short time scales

Intrinsic Charm



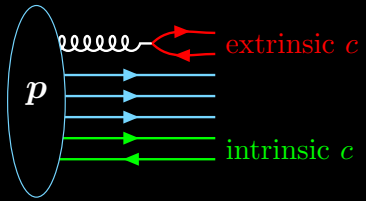
- Bound to multiple valance quarks
- Longer time scales

Intrinsic charm: a hadronic picture



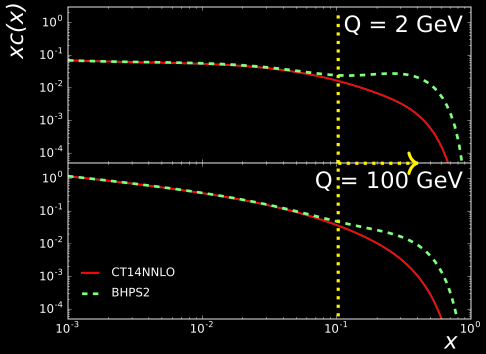
Intrinsic charm

- *Extrinsic* charm from gluon splitting
- *Intrinsic* charm bound to valance quarks

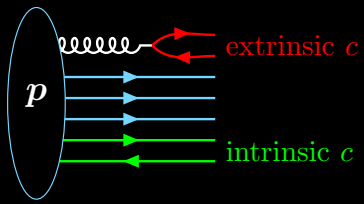


Intrinsic charm

- *Extrinsic* charm from gluon splitting
- *Intrinsic* charm bound to valance quarks



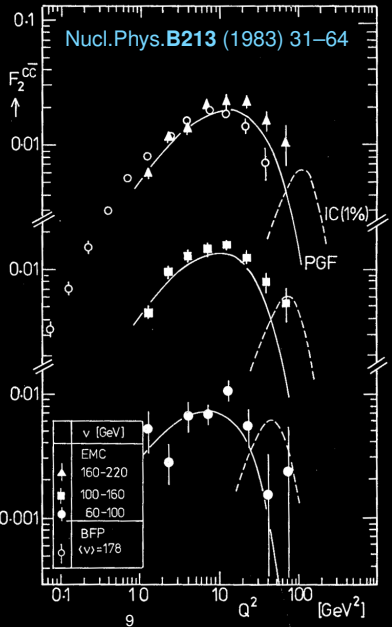
Phys. Rev. **D 93** (2016) 074008



- Valance-quark-like IC would produce a clear signature at $x > 0.1$
- IC could also have a sea-like PDF but this would simply be an enhancement of EC
- Probe high-x charm to search for IC

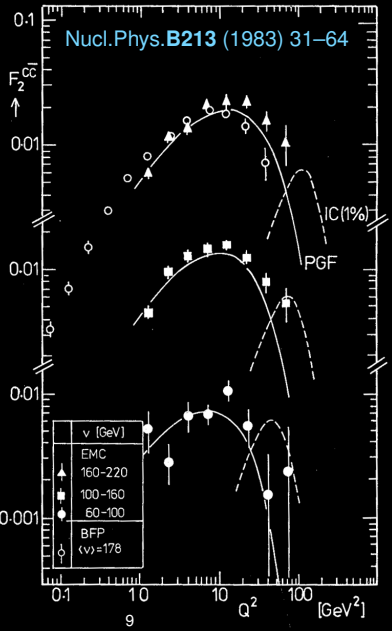
Previously. . .

- First evidence of IC from EMC in 1982
- Charm production in $\mu^+ - \mathrm{Fe}$ DIS
- Typical $Q \approx 10\,\mathrm{GeV}$



Previously...

- First evidence of IC from EMC in 1982
- Charm production in $\mu^+ - \mathrm{Fe}$ DIS
- Typical $Q \approx 10\,\mathrm{GeV}$
- Evidence *for* IC...

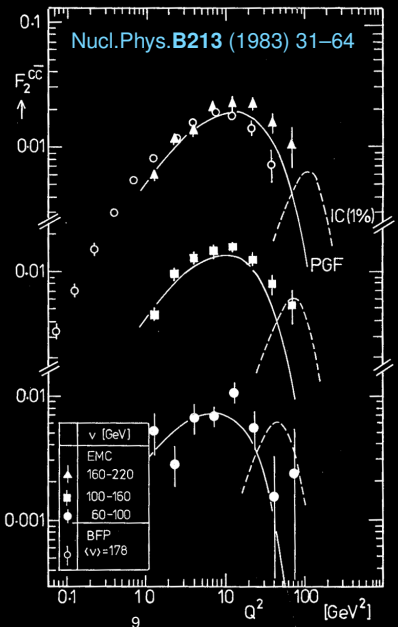


"*The results of this analysis are compared with the EMC DIS charm quark data and evidence for an intrinsic charm component in the proton is found.*"

Nucl.Phys.**B461** (1996) 181–196

Previously...

- First evidence of IC from EMC in 1982
- Charm production in $\mu^+ - \mathrm{Fe}$ DIS
- Typical $Q \approx 10\,\mathrm{GeV}$
- Evidence *for* IC...
- Or *no* IC?



"*The results of this analysis are compared with the EMC DIS charm quark data and evidence for an intrinsic charm component in the proton is found.*"

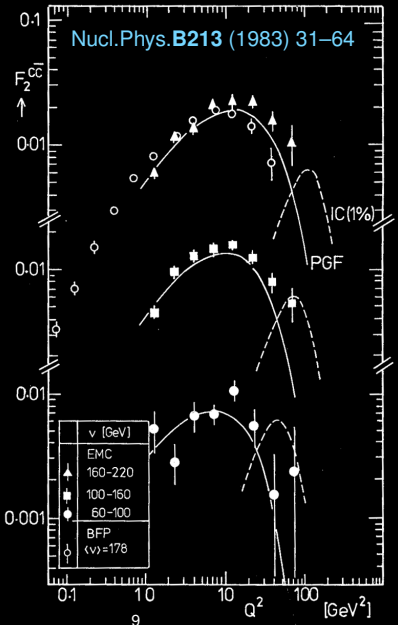
Nucl.Phys.**B461** (1996) 181–196

"*We find no conclusive evidence in favor of an intrinsic charm component in the nucleon*"

Eur.Phys.J.**C11** (1999) 673–683

Previously...

- First evidence of IC from EMC in 1982
- Charm production in $\mu^+ - \mathrm{Fe}$ DIS
- Typical $Q \approx 10\,\mathrm{GeV}$
- Evidence *for* IC...
- Or *no* IC?
- low-Q data hard to interpret due to hadronic uncertainties
- Need to study at higher Q^2 for theoretically unambiguous result...



"*The results of this analysis are compared with the EMC DIS charm quark data and evidence for an intrinsic charm component in the proton is found.*"

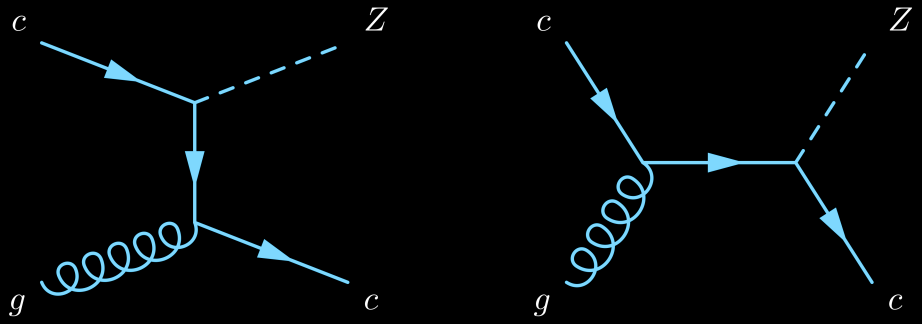
Nucl.Phys.**B461** (1996) 181–196

"*We find no conclusive evidence in favor of an intrinsic charm component in the nucleon*"

Eur.Phys.J.**C11** (1999) 673–683

$gc \to Zc$

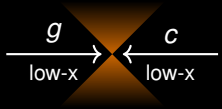
Proposed in: Phys. Rev. **D 93** (2016) 074008

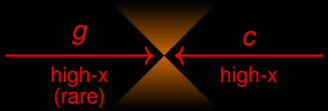


- Production of Z boson in association with a charm quark
- Typical $Q \approx m_Z$
- Proposed to measure relative to total Z+jet as many uncertainties cancel
- Theoretically: cleaner
- Experimentally: need to identify charm jets

$gc \to Zc$: seeking high x

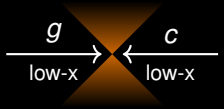
Central

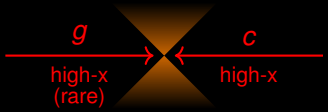




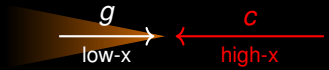
$gc \to Zc$: seeking high x

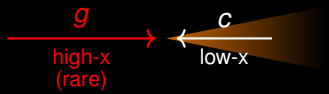
Central





Forward

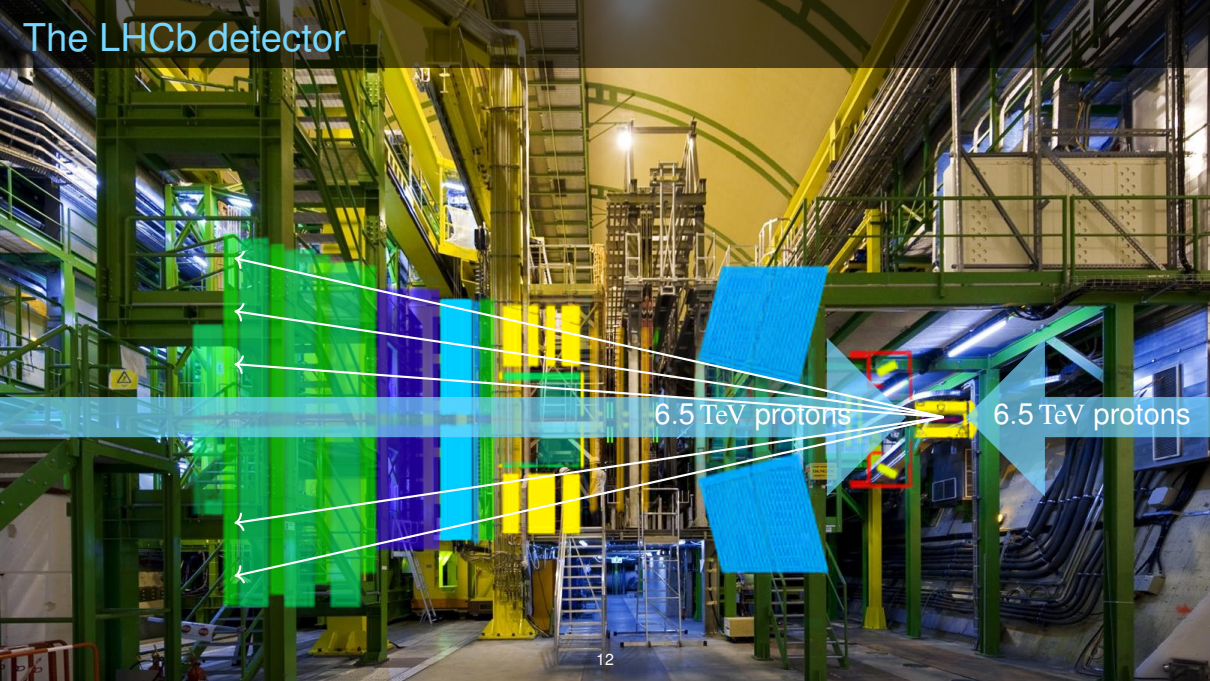




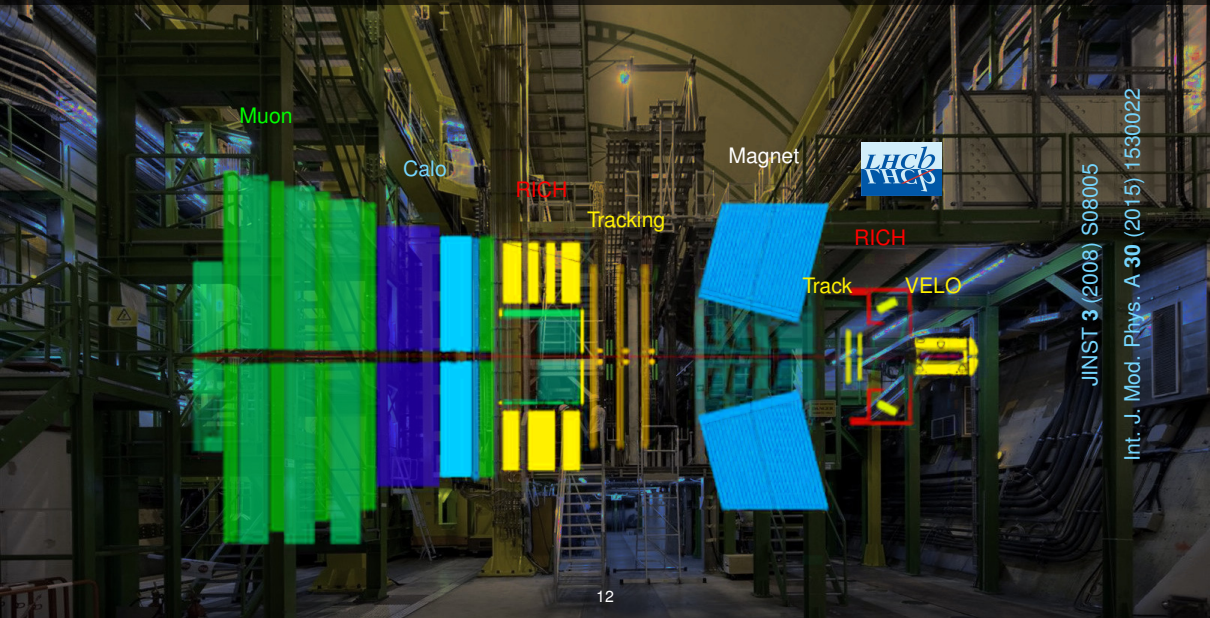
- Most gluons have low x so high-x charm interactions typically populate the forward region...

The LHCb detector

The LHCb detector



The LHCb detector



JINST **3** (2008) S08005

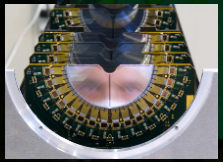
Int. J. Mod. Phys. A **30** (2015) 1530022

The LHCb detector

Vertex Locator

Silicon tracker 7 mm from beams

Detect displaced decays



JINST **3** (2008) S08005

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

The LHCb detector

RICH detectors

Cherenkov detectors → particle velocity

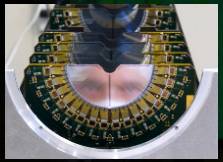
Combine with tracking momentum

Mass → charged particle ID

Vertex Locator

Silicon tracker 7 mm from beams

Detect displaced decays

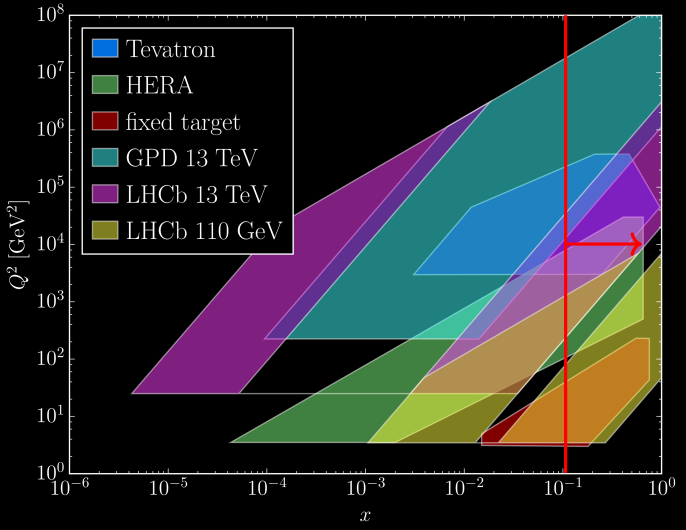


JINST **3** (2008) S08

Int. J. Mod. Phys. A **30** (20

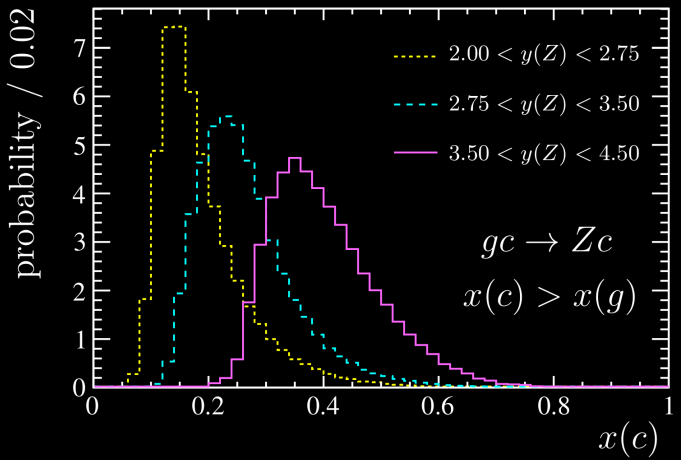
5) 153

The LHCb detector: high x coverage



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

$gc \to Zc$: $x(c)$



PRL **128** (2022) 082001

- Rapidity: $y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$
- Bins in Z rapidity an effective proxy for bins in $x(c)$

$gc \to Zc$: models

- No IC J. Phys. **G43** (2016) 023001

  PDF4LHC15 – combination of PDF sets assuming no intrinsic charm
  - Purely extrinsic
  - Zero below charm mass

$gc \to Zc$: models

- **No IC** J. Phys. **G43** (2016) 023001

  PDF4LHC15 – combination of PDF sets assuming no intrinsic charm
  - Purely extrinsic
  - Zero below charm mass

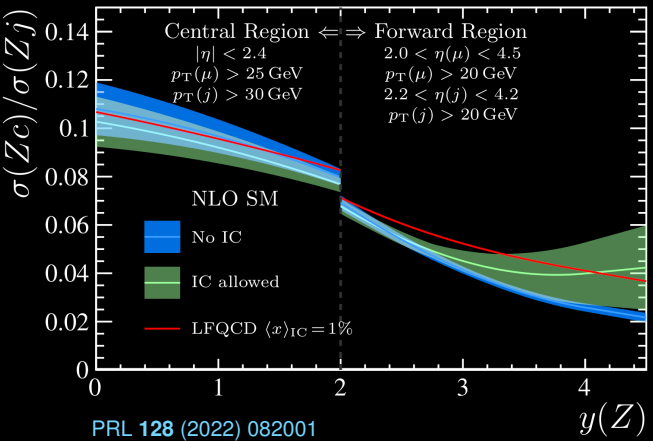
- **IC allowed** Eur. Phys. J. **C76** (2016) 647, JHEP **04** (2015) 040

  NNPDF3.0 IC – allows global fit to include intrinsic charm where not excluded by existing measurements
  - Uncertainties reflect current experimental limits

$gc \to Zc$: models

- **No IC** J. Phys. **G43** (2016) 023001
  PDF4LHC15 – combination of PDF sets assuming no intrinsic charm
  - Purely extrinsic
  - Zero below charm mass
- **IC allowed** Eur. Phys. J. **C76** (2016) 647, JHEP **04** (2015) 040
  NNPDF3.0 IC – allows global fit to include intrinsic charm where not excluded by existing measurements
  - Uncertainties reflect current experimental limits
- **LFQCD $\langle x \rangle_{\mathrm{IC}} = 1\%$** JHEP **02** (2018) 059
  BHPS3 – PDF set based on LFQCD calculations with a fixed intrinsic charm contribution
  - Uncertainties reflect model assumptions

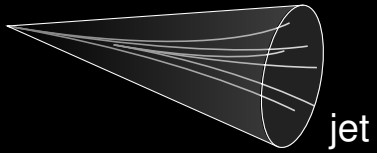
$gc \to Zc$: $y(Z)$



PRL **128** (2022) 082001

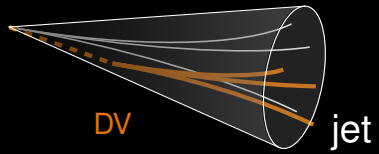
- Measure ratio of $Z + c$ production to total Z+jet
- IC would give significant enhancement over no-IC at high $y(Z)$
- IC-allowed model at high $y(Z)$ largely unconstrained by previous experimental results
- Many jet-related systematics cancel in the ratio but charm-jet-tagging efficiency important...

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



- Reconstruct displaced vertices within jets

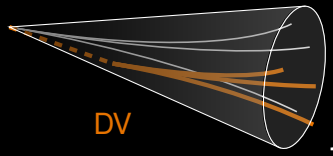
$Z + c$: displaced-vertex c-tagger



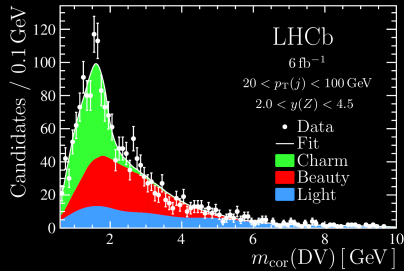
- Reconstruct displaced vertices within jets

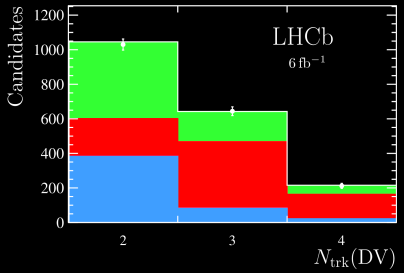
$Z + c$: displaced-vertex c-tagger

PRL **128** (2022) 082001

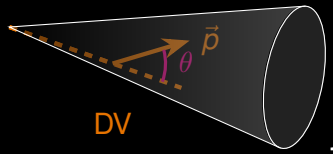


- Reconstruct displaced vertices within jets
- Use 2D fit to corrected mass and number of tracks to distinguish charm jets from beauty and light



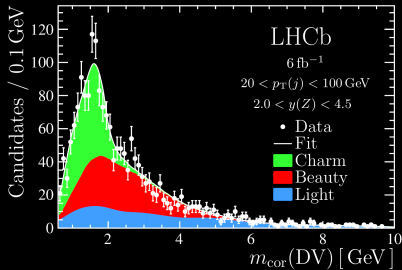


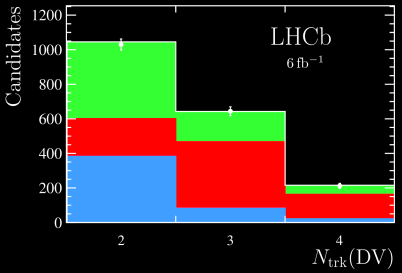
$Z + c$: displaced-vertex c-tagger



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

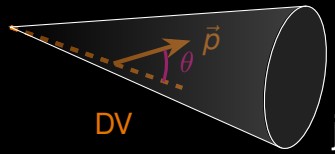
PRL **128** (2022) 082001



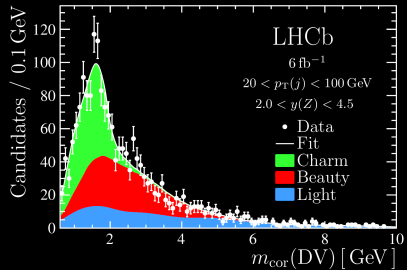


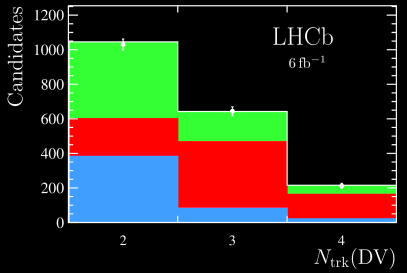
$Z + c$: displaced-vertex c-tagger

PRL **128** (2022) 082001

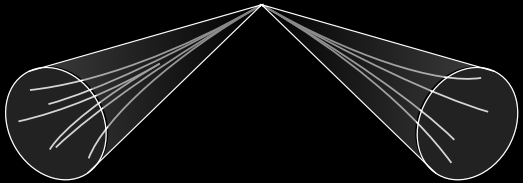


- Reconstruct displaced vertices within jets
- Use 2D fit to corrected mass and number of tracks to distinguish charm jets from beauty and light
- $m_{\text{cor}}(\text{DV}) \equiv \sqrt{m(\text{DV})^2 + [p(\text{DV}) \sin\theta]^2} + p(\text{DV}) \sin\theta$
- Templates from flavour-enhanced calibration samples
- Fit in bins of jet p_{T} and $y(Z)$
- Determine tagger efficiency using 2016 dijet events

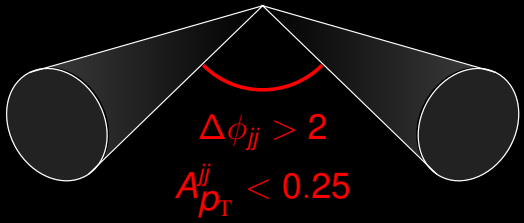




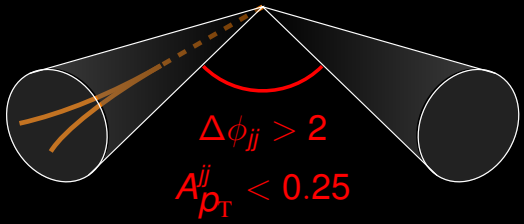
$Z + c$: c-tagger calibration



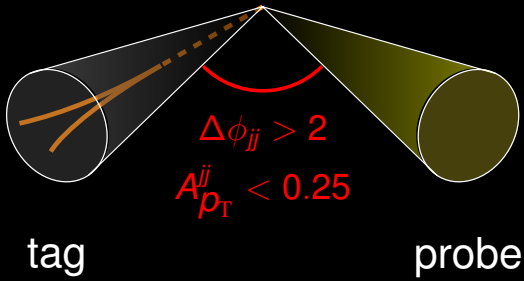
$Z + c$: c-tagger calibration



$Z + c$: c-tagger calibration

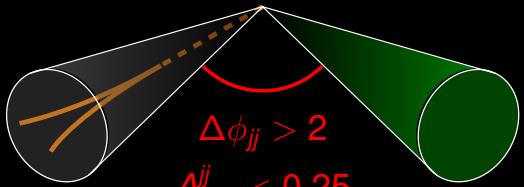


$Z + c$: c-tagger calibration



HF-enriched

$Z + c$: c-tagger calibration



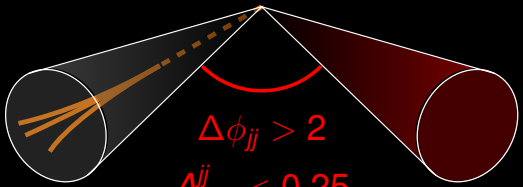
$m_{\mathrm{cor}}(DV) < 2\,\mathrm{GeV}$

$N_{\mathrm{trk}}(DV) = 2$

c-enriched

$30 - 40\%$ pure

$Z + c$: c-tagger calibration



$\Delta\phi_{jj} > 2$

$A^{jj}_{p_T} < 0.25$

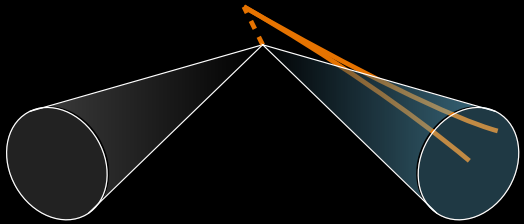
$m_{\mathrm{cor}}(DV) > 2\,\mathrm{GeV}$

$N_{\mathrm{trk}}(DV) > 2$

b-enriched

$60 - 70\%$ pure

$Z + c$: c-tagger calibration

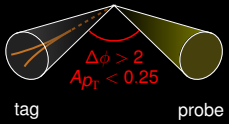


$z(DV) < z(PV)$

light-quark-enriched

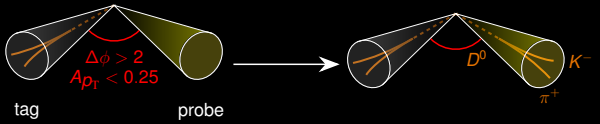
$Z + c$: c-tagger calibration

- Trigger on DV in “other” jet



$Z + c$: c-tagger calibration

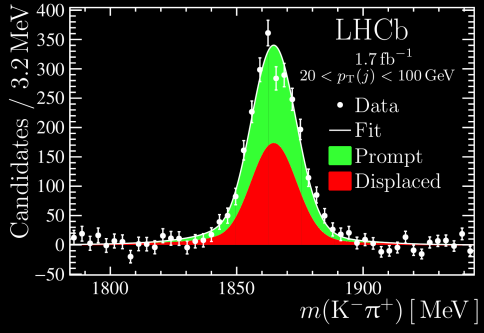
- Trigger on DV in "other" jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$

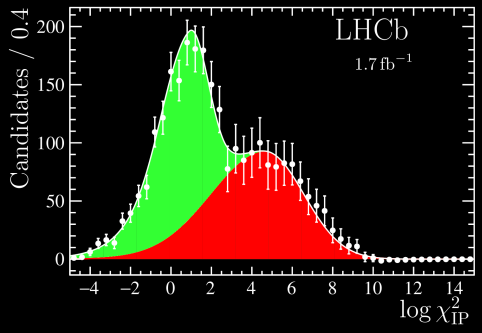


$Z + c$: c-tagger calibration

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

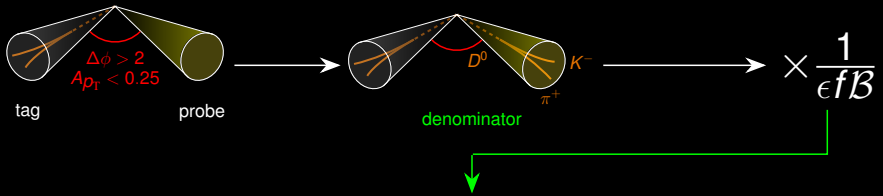
JINST **17** (2022) P02028





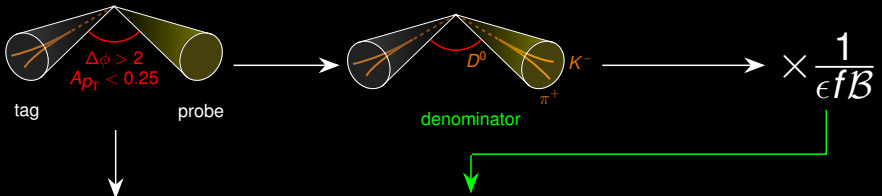
$Z + c$: c-tagger calibration

- 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

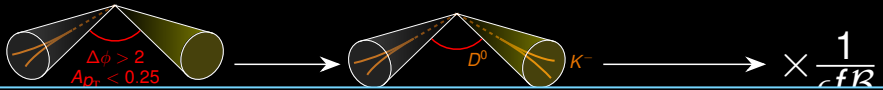
- Trigger on DV in "other" jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$
- Correct for eff, FF and BF



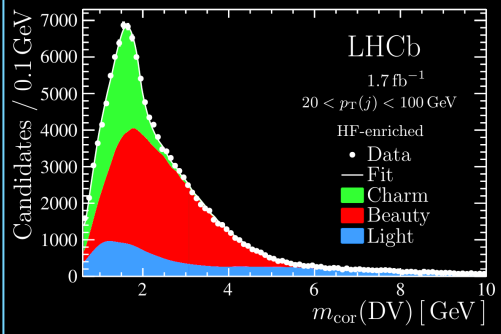
- Tag DV candidates

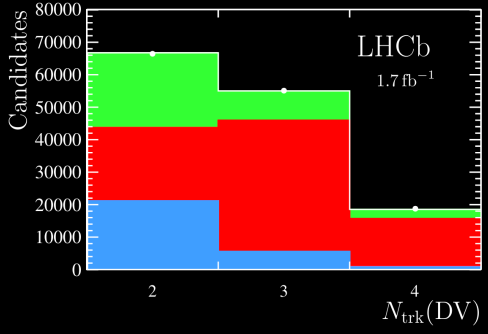
$Z + c$: c-tagger calibration

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



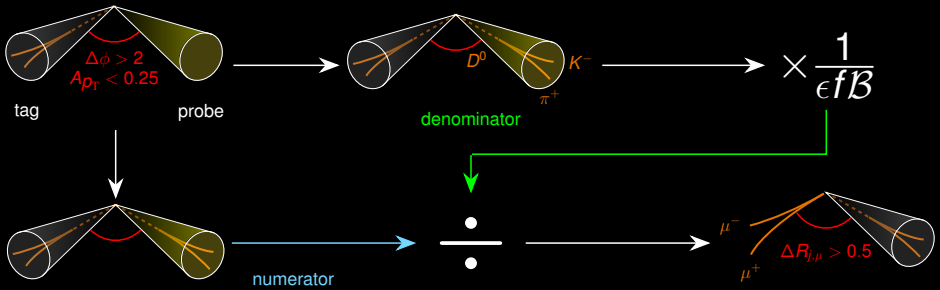
JINST **17** (2022) P02028





$Z + c$: c-tagger calibration

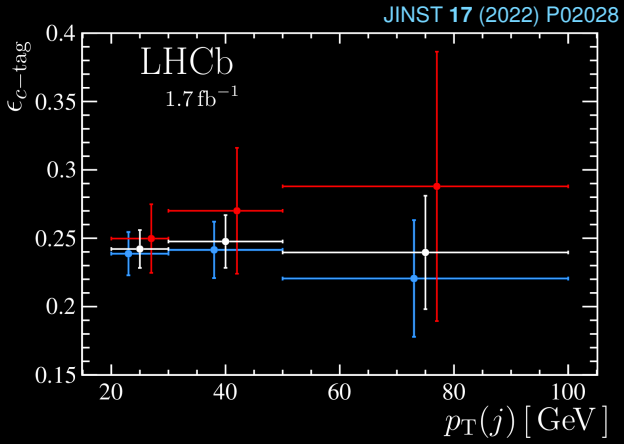
- Trigger on DV in "other" jet
- Tag prompt $D^0 \to K^-\pi^+$, $D^+ \to K^-2\pi^+$
- Correct for eff, FF and BF



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

- p_T detector resolution of numerator and denominator unfolded separately

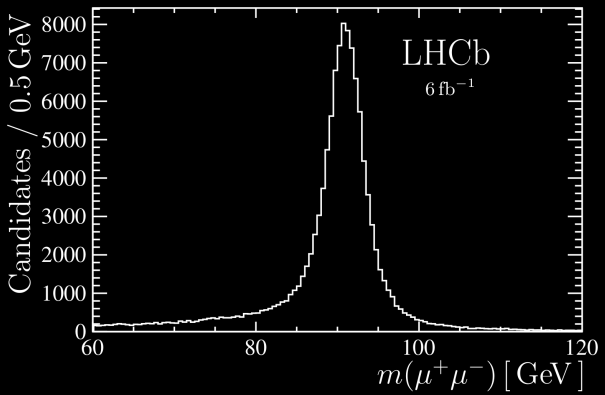
$Z + c$: c-tagger calibration



- Efficiency determined as function of jet p_{T} using D^0, D^+ and the combination:

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

$Z + c$

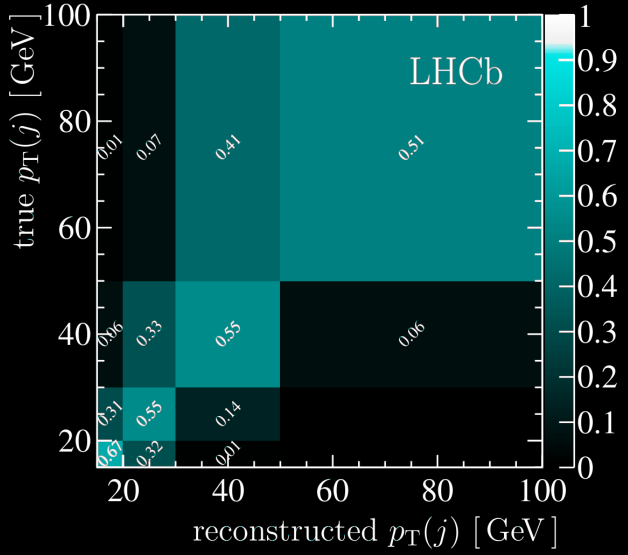


PRL **128** (2022) 082001

- 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} of Zc and Zj to obtain results in fiducial volume, $p_{\mathrm{T}} > 20\,\mathrm{GeV}$

$Z + c$

PRL **128** (2022) 082001

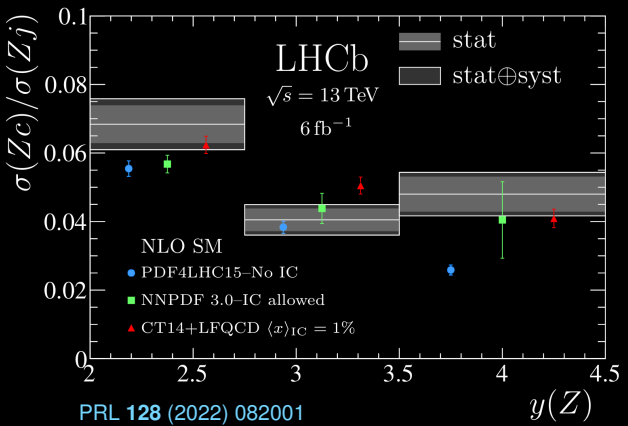


$Z + c$: systematics

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



PRL **128** (2022) 082001

- 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 $> 3\sigma$
- More consistent with IC-allowed NNPDF predictions – harder charm-x spectrum than simple LFQCD model

Summary & outlook

- $Z + c$ gives compelling evidence for IC
- Inconsistent with No-IC model at $> 3\sigma$
- Good agreement with both IC models
- Global PDF analysis required to determine true significance
- Run 3 dataset will allow for finer binning in $y(Z)$
- Results highlighted in Nov/Dec issue of CERN Courier

Alternative summary

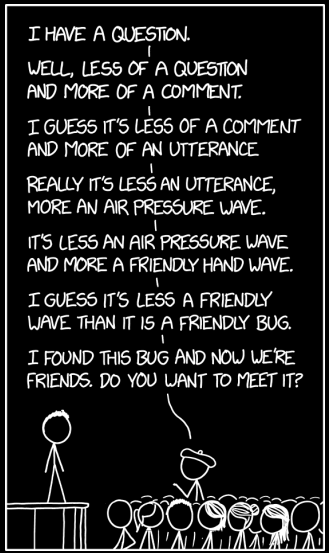
Miguel Albaladejo
@AlbaladejoMigue

Replying to @LHCbExperiment

Geez, guys, another pentaquark! 😂😂
😂

13:46 · 27 Jul 21 · Twitter for Android

Questions, utterances or friendly bugs?



xkcd/2191