Physics with $W/Z/\gamma$ + Jets at the LHCb and ALICE Experiments

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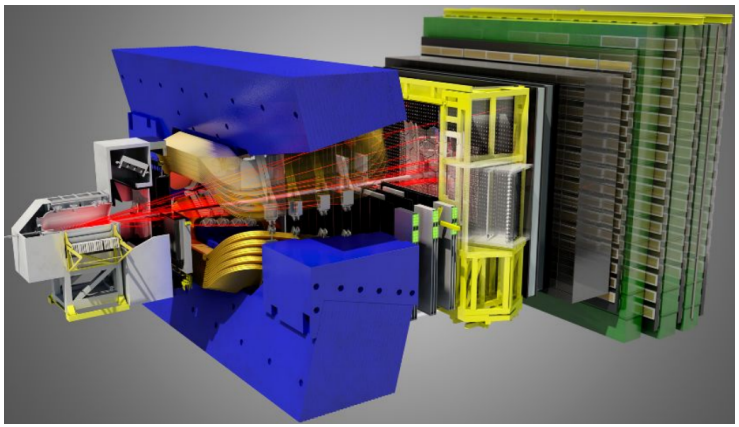
Introduction and Overview

JINST 3 (2008) S08005

→ LHCb Strengths of Design:

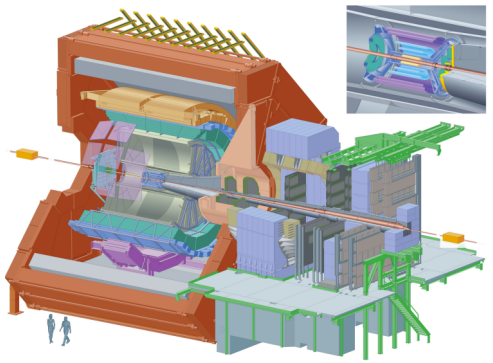
- Long tracking distances for improved flavour physics
- Ring-Imaging Cherynkov (RICH) detectors for particle identification (PID)



PRD 93, 074008 (2016)

→ ALICE Strengths of Design:

- Designed for ion physics focus
- Excellent calorimetry for photon and jet measurements



CERN-LHCC-2012-012

- Isolated photon-jet correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in ALICE arXiv 2208.08523
- Study of Z Bosons Produced in Association with Charm in the Forward Region PRL 128, 082001 (2022)
- Multidifferential study of identified charged hadron distributions in Z-tagged jets in proton-proton collisions at $\sqrt{s} = 13$ TeV PRD 108, L031103 (2023)

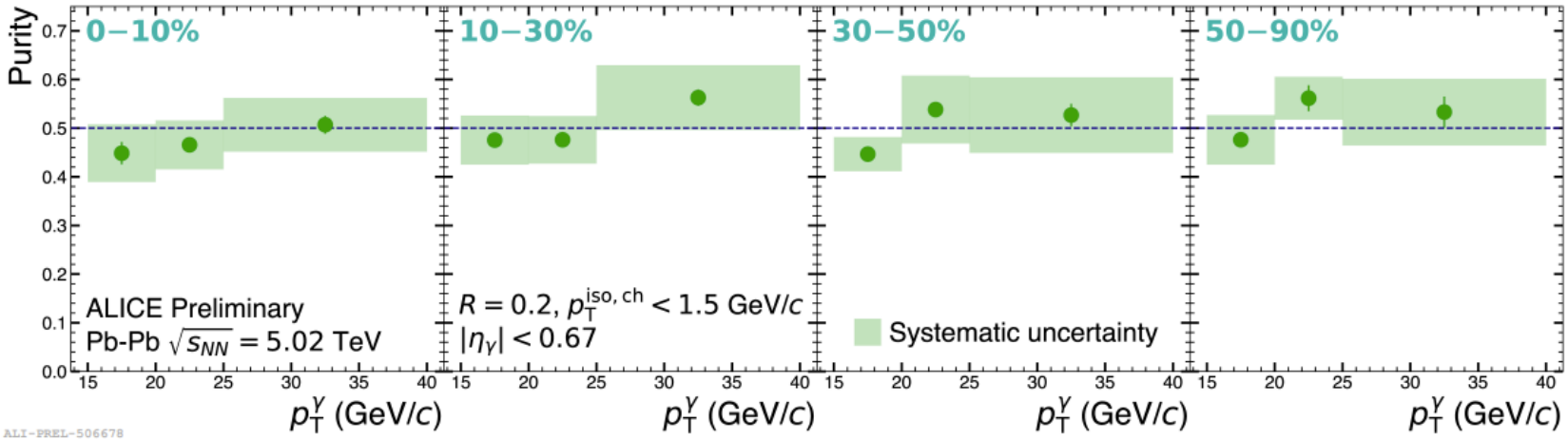
Pipeline of Future results:

- W + jets production cross section (Run 2 LHCb)
- Z + bb production cross section (Run 2 LHCb)
- W/Z + charm jets (Run 3 LHCb)
- γ + jets (Run 3 ALICE)

γ+jets Correlations

(ALICE Preliminary) arXiv 2208.08523

Motivation: Jets interact strongly with the QGP, photons interact weakly
$\rightarrow$ Study partonic energy loss in QGP

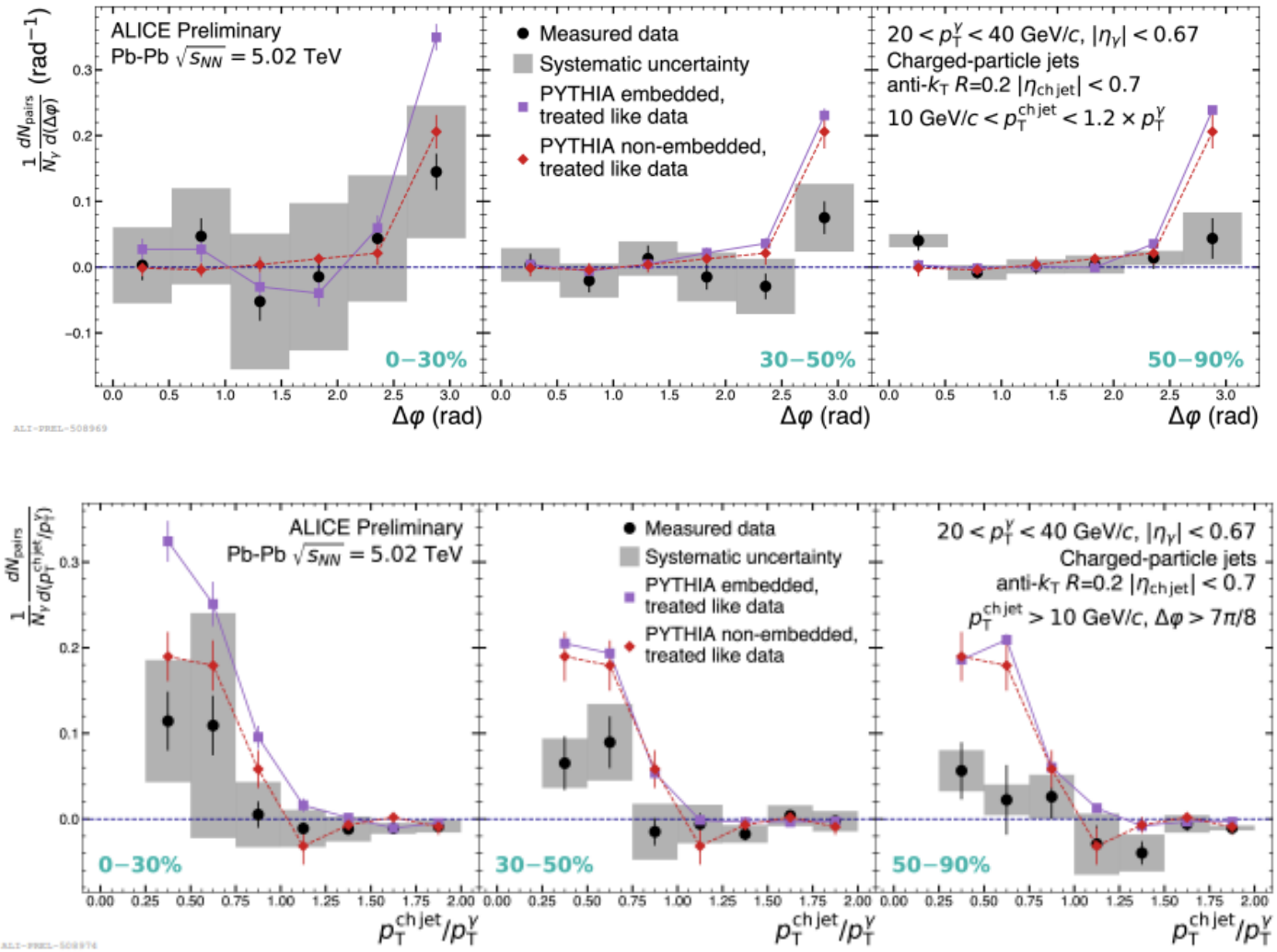


Photon isolation is used to select prompt photons, suppressing photons from meson decays

$\rightarrow$ Additional measurement of shower shapes is used to characterize further background contributions

γ+jets Correlations

(ALICE Preliminary) arXiv 2208.08523



→ No centrality-dependent medium modification for the photon-jet angular correlation

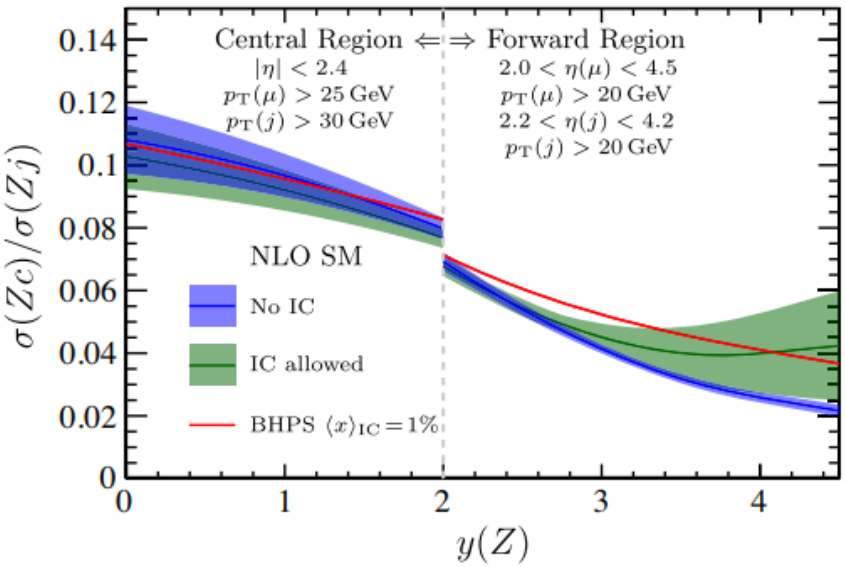
→ Averaged p_T imbalance shows no centrality dependence

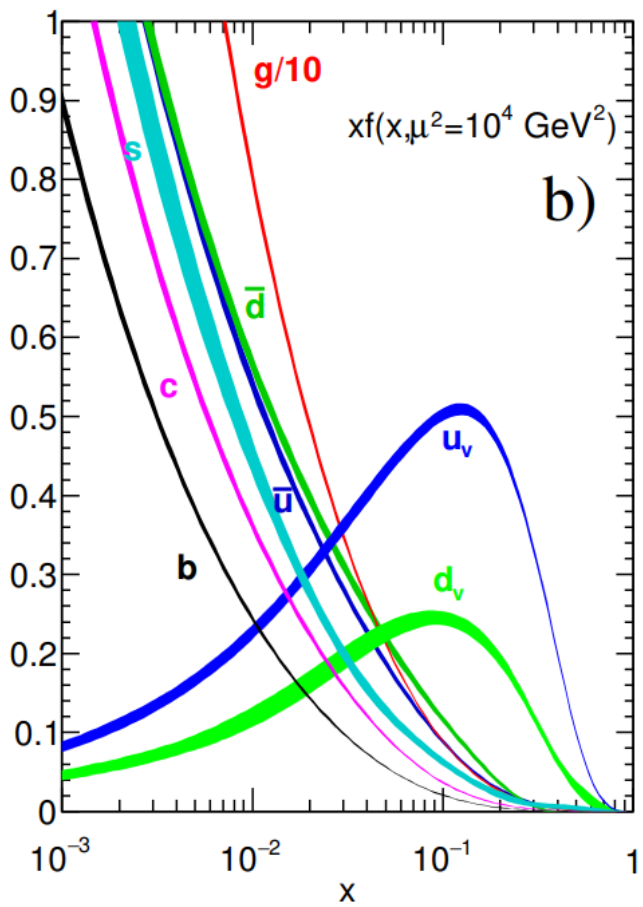
Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Study of the proton wave function has been a topic for discussion for many years $\rightarrow$ Does the proton wave function contain a a valence-like charm contribution beyond the $g \rightarrow c\bar{c}$ perturbative gluon radiation?

1. Intrinsic charm (IC) will manifest in the proton wave function as $|uudc\bar{c}\rangle$
2. Forward coverage of LHCb detector provides unique probe to proton pdf

$\downarrow$

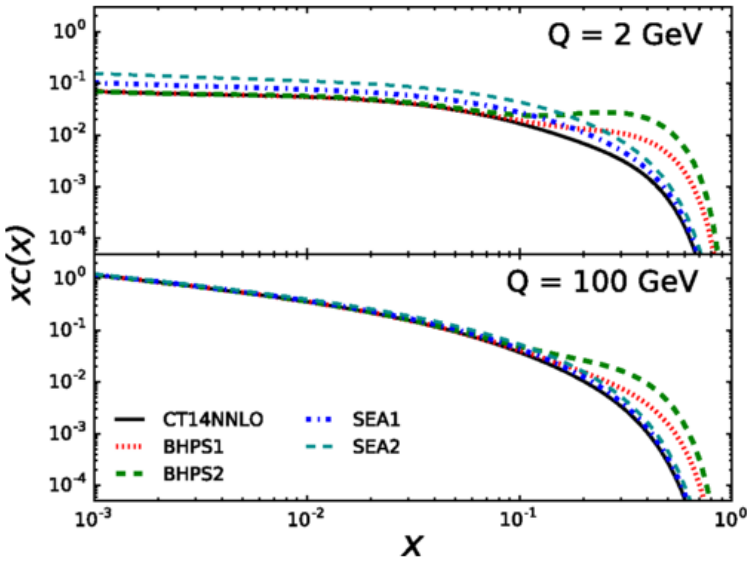


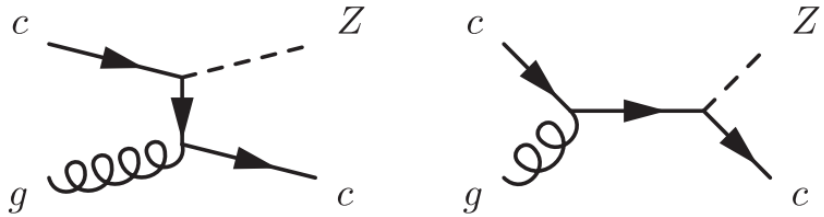


Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Analysis Strategy: Use jets produced in association of a Z boson to study the intrinsic charm production

Forward production of Zc allows to specifically probe high-x of the proton PDF ↓





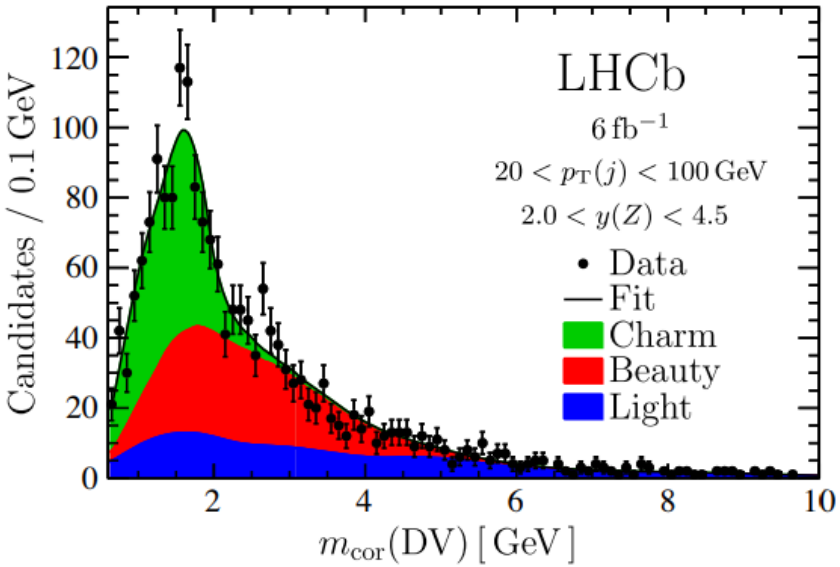
Analysis is made differentially in y_Z bins, with charm-jet yields caclulated in p_T^j bins

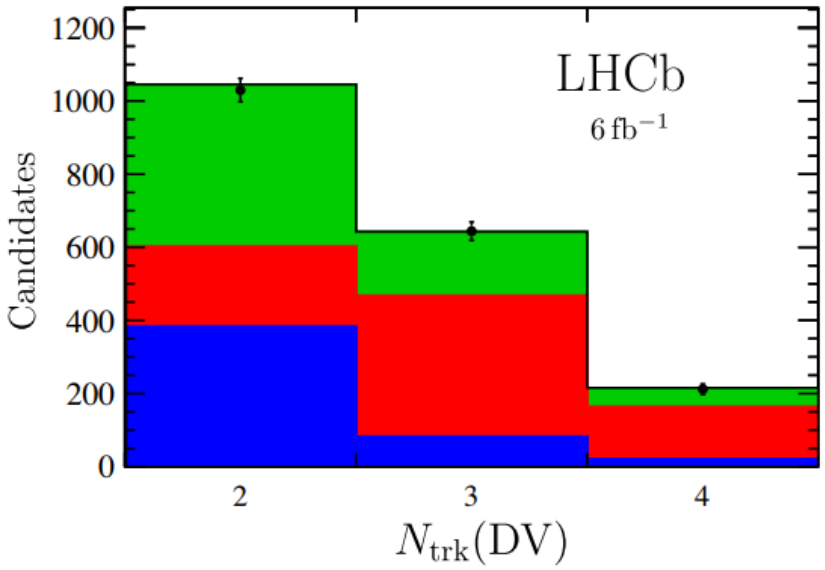
Result is given as the ratio of yields of Zc to total Zj yield:

$$R_c^j \equiv \frac{N(c-tag)}{\epsilon(c-tag)N(j)}$$

Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Charm Tagging: c-jets defined as jets containing long-lived c hadron with $p_T^h > 5$ GeV





Displaced Vertex (DV) jet properties are used to extract c-jet yields

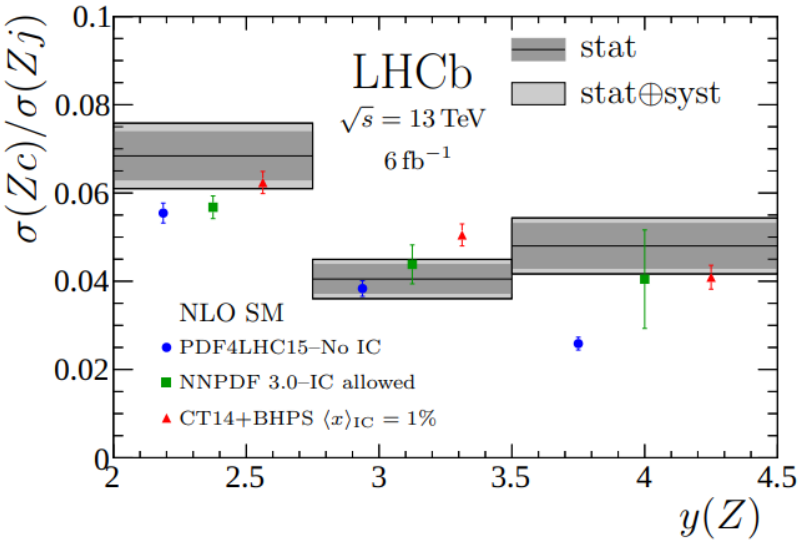
$\rightarrow$ Efficiencies vary as function of $p_T^{c-\text{jet}}$, roughly around 25%

Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Results: R_c^j measurements show consistency with valence-like intrinsic charm theory
Conclusions on the p wave function can be drawn with inclusion in global PDF analyses

- Systematics dominated by c-tag procedure, arising from tag-and-probe method scale factor calculations
  - c-tagging efficiency and $Z + c$ yield are highly correlated $\rightarrow$ taken into account in the systematic calculation
- Theoretical predictions allowing IC are limited due to very little data available to constrain the charm PDF in this region
  - Fixed values of IC contribution reduces this uncertainty and has strong agreement with R_c^j measurement

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



Charged Hadron Distributions in Z-tagged Jets

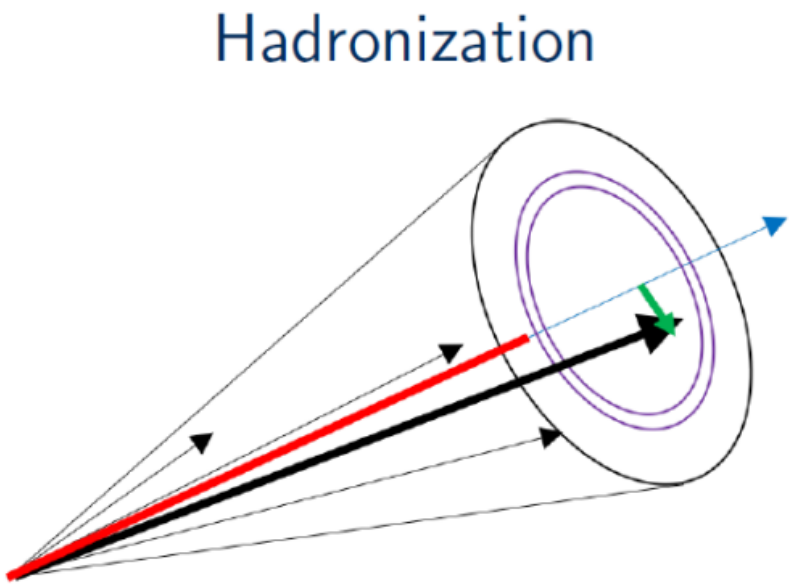
PRD 108, L031103 (2023)

Observing quarks and gluons in isolation is impossible $\rightarrow$ Must relate quark-gluon degrees of freedom to observables of bound state hadrons

1. Parton Distribution Function (PDF) – The nucleus hard-scatter part, The momentum the partons carry
2. Fragmentation Functions (FF) – The long-range hadronization part, The momentum the hadrons carry

FF and PDFs must be constrained by experimental measurements, used to tune MC generators

1. Jet Fragmentation Functions (JFFs) – Provide probe of FFs using jet substructure



Motivation: Set constraints on fragmentation functions and parton distribution functions of pp hard-scatter factorization, providing tuneable feedback to MC generators

Charged Hadron Distributions in Z-tagged Jets

PRD 108, L031103 (2023)

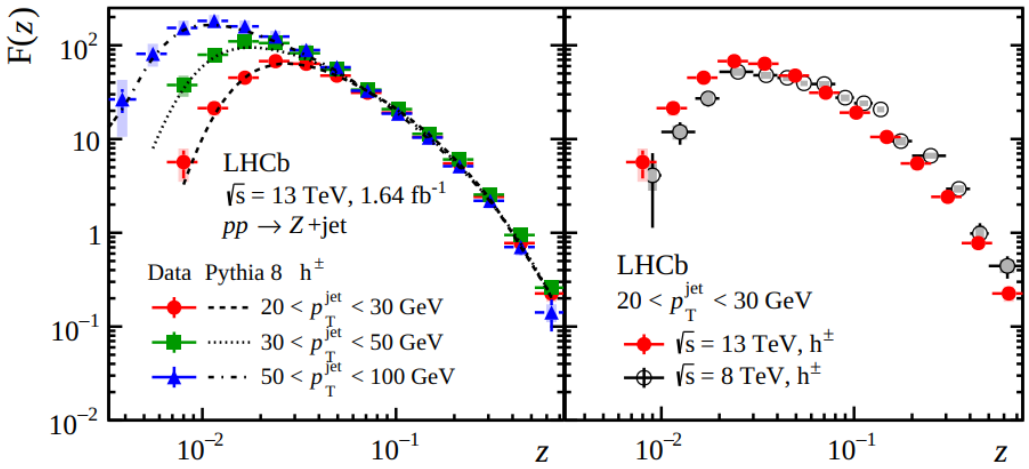
Analysis Strategy: Use jets produced in association with Z boson to study JFF parameters $\rightarrow$ Jets contain identified charged hadrons

Two observables employed to study the longitudinal and transverse contributions:

1. $z = \frac{\mathbf{p}_{\rm had} \cdot \mathbf{p}_{\rm jet}}{|\mathbf{p}_{\rm jet}|^2}$
2. $j_T = \frac{|\mathbf{p}_{\rm had} \times \mathbf{p}_{\rm jet}|}{|\mathbf{p}_{\rm jet}|}$

Event selection follows closely the Z-production measurement

1. m_Z window:
   $60 < m_{\mu^+\mu^-} < 120$ GeV
2. $\mu^\pm$ acceptance:
   $p_T^\mu > 20$ GeV ; $2.0 < \eta^\mu < 4.5$
3. Jet acceptance:
   $20 < p_T^{\rm jet} < 100$ GeV ; $2.5 < \eta^{\rm jet} < 4.0$



Inclusive measurement of the observable yields in differential $p_T^{\rm jet}$ bins shows agreement with theory and previous 8 TeV LHCb analysis

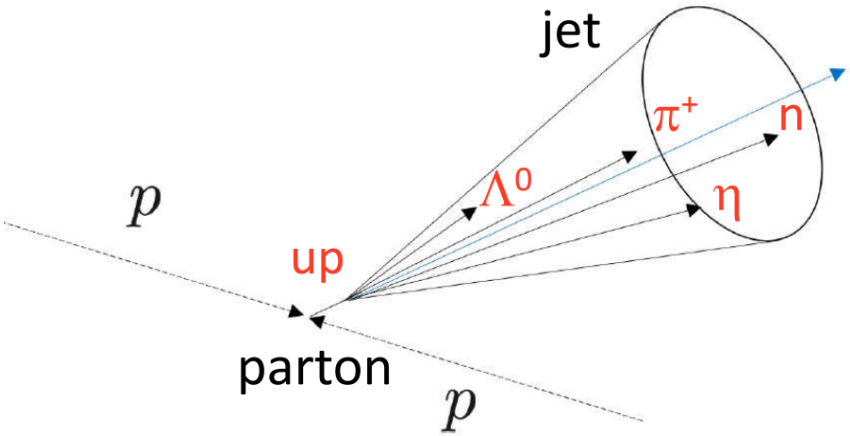
Yields are defined as:

$$f(z, j_T) = \frac{1}{N_{\rm Z+jet}} \frac{{\rm d}N_{\rm had}(z, j_T)}{{\rm d}z{\rm d}j_T}$$

Charged Hadron Distributions in Z-tagged Jets

PRD 108, L031103 (2023)

Identifying the Hadrons: Identification of the charged hadrons is performed using the RICH systems

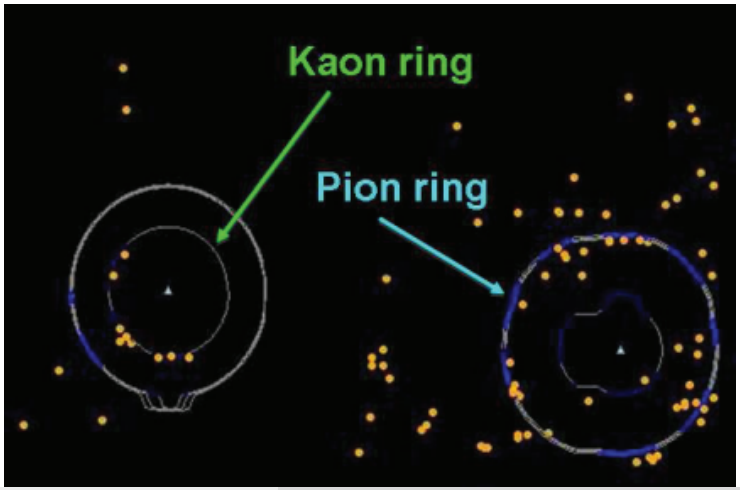


Connecting the dots:

1. Connect initial state (parton) to final state (hadron) using jets
2. Connecting initial flavor (parton) to final flavor (hadron)

The speed of the particle can be calculated from the angle of emission of the photon:

- $cos\theta_c = \frac{c}{nv}$
- The radius then gives an accurate measurement of θ_c: $r = f\theta_c$

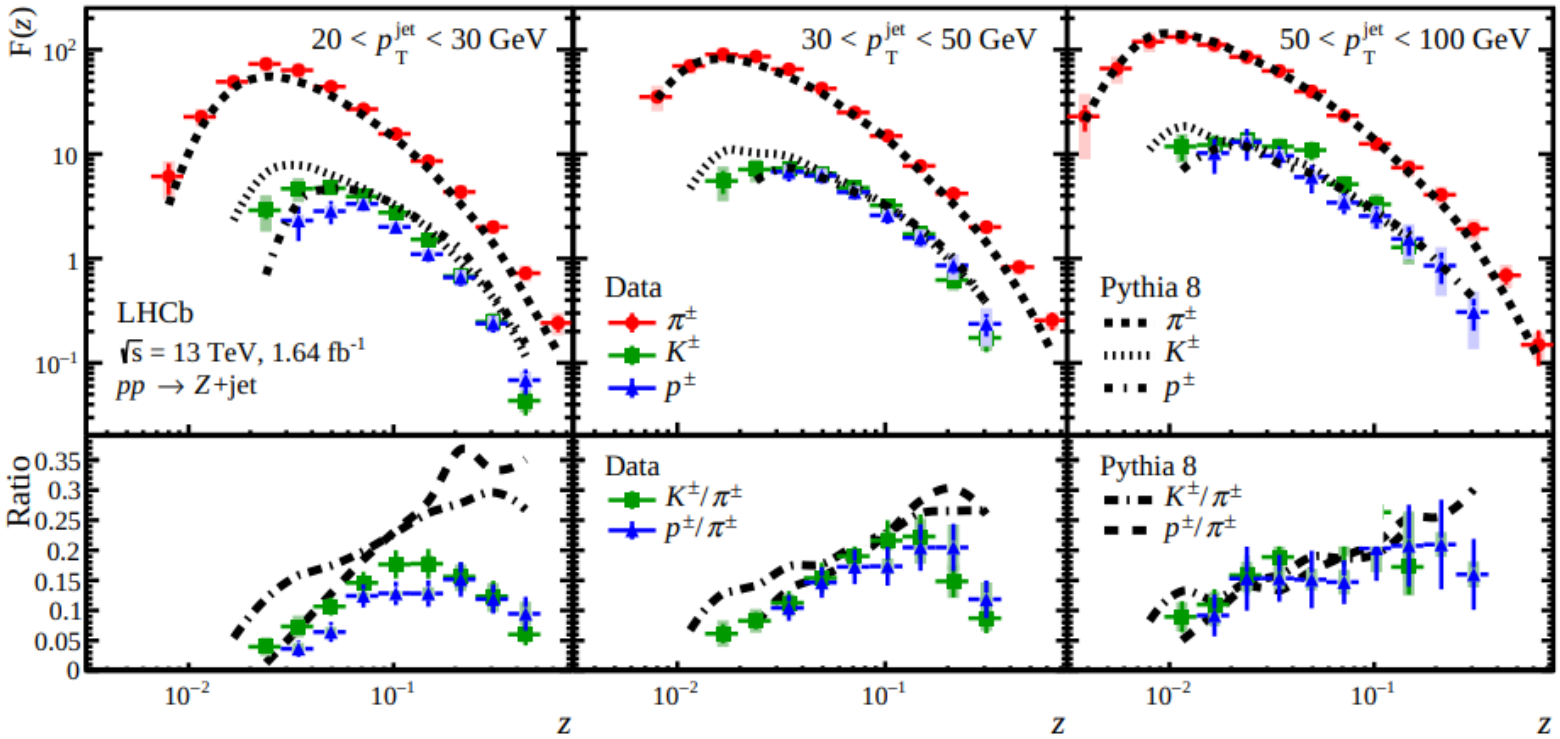


Charged Hadron Distributions in Z-tagged Jets

PRD 108, L031103 (2023)

Results: Integrated differential distributions for both z and j_T show similar behavior between the two consider centre-of-mass energies

Significant overestimation of heavier charged particles (kaons and protons) relative to pions is shown in low jet p_T

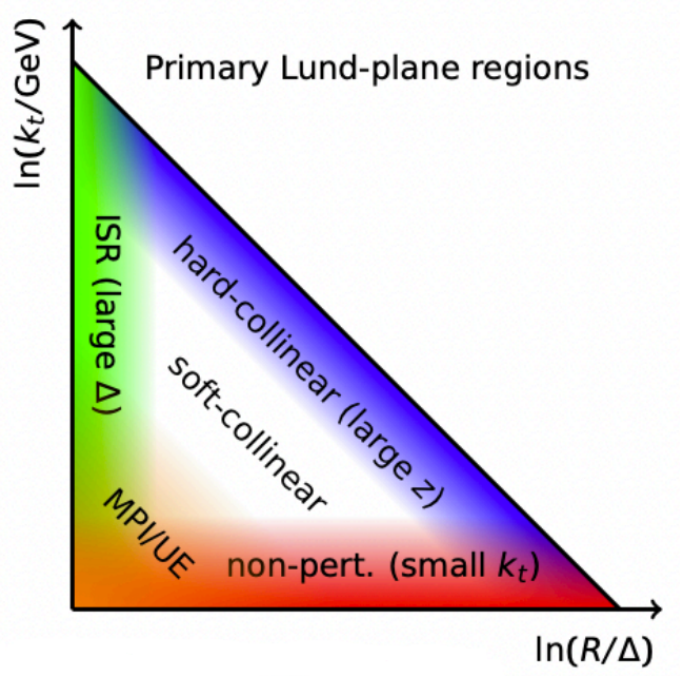


→ Information can be used to tune MC generation of identified charged particles

Run 2 Pipelines – Physics with V + Jets

Upcoming Measurements: Numerous V+jets measurements are in late-stage of the analysis life-cycle, and will be public in the near future

→ Measurement of $Z + bb$ production cross section: Test 4FS vs. 5FS
→ Measurement of the Lund Jet Plane: Probe of pQCD



LHCb

Data set	NNPDF4.0	NNPDF3.1	ABMP16	CT18	MSHT20
LHCb Z 940 pb	✓	✓	✗	✗	✓
LHCb $Z \to ee$ 2 fb	✓	✓	✓	✓	✓
LHCb $W, Z \to \mu$ 7 TeV	✓	✓	✓	✓	✓
LHCb $W, Z \to \mu$ 8 TeV	✓	✓	✓	✓	✓
LHCb $Z \to \mu\mu, ee$ 13 TeV	✓	✗	✗	✗	✗

ATLAS

Data set	NNPDF4.0	NNPDF3.1	ABMP16	CT18	MSHT20
ATLAS W, Z 7 TeV (2010)	✓	✓	✓	✓	✓
ATLAS W, Z 7 TeV (2011)	✓	✓	✗	✓	✓
ATLAS low-mass DY 7 TeV	✓	✓	✗	✗	✗
ATLAS high-mass DY 7 TeV	✓	✓	✗	✗	✓
ATLAS W 8 TeV	✓	✗	✗	✗	✓
ATLAS DY 2D 8 TeV	✓	✗	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	✓	✗	✗	✗	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	✓	✗	✓	✗	✗
ATLAS W^++jet 8 TeV	✓	✗	✗	✗	✓
ATLAS Z p_T 8 TeV	✓	✓	✗	✓	✓
ATLAS σ_{tt}^{tot} 7, 8 TeV	✓	✓	✓	✗	✗
ATLAS σ_{tt}^{tot} 13 TeV	✓	✓	✓	✗	✗
ATLAS $t\bar{t}$ lepton+jets 8 TeV	✓	✓	✗	✓	✓
ATLAS $t\bar{t}$ dilepton 8 TeV	✓	✗	✗	✗	✓
ATLAS single-inclusive jets 7 TeV, R=0.6	✗	✓	✗	✓	✓
ATLAS single-inclusive jets 8 TeV, R=0.6	✓	✗	✗	✗	✗
ATLAS dijets 7 TeV, R=0.6	✓	✗	✗	✗	✗
ATLAS direct photon production 13 TeV	✓	✗	✗	✗	✗
ATLAS single top R_t 7, 8, 13 TeV	✓	✗	✓	✗	✗
ATLAS single top diff. 7, 8 TeV	✓	✗	✗	✗	✗
ATLAS single top diff. 8 TeV	✓	✗	✗	✗	✗

→ Measurement of W+jets production cross section: PDF fit contributions

Run 3 Outlook

arXiv:1808.08865

A significant increase in luminosity will help to explore less common modes.

→ What is envisioned:

- Differential Z boson production, along with V + heavy flavour measurements
  → Set important constraints on out-of-reach x–Q^2 phase-space
- γ+ charm and beauty associated productions
  → Further probe the intrinsic charm and beauty contributions providing access to the high-x portion of PDFs
- γ+ jet correlations at ALICE
  → Study the interactions of photons and jets in dense medium, probing behavior of QGP
- Z+jets provides a very clean environment for studying jets at the LHC, combining with low μ at LHCb
  → Continuing to study jet substructure to understand further QCD observables

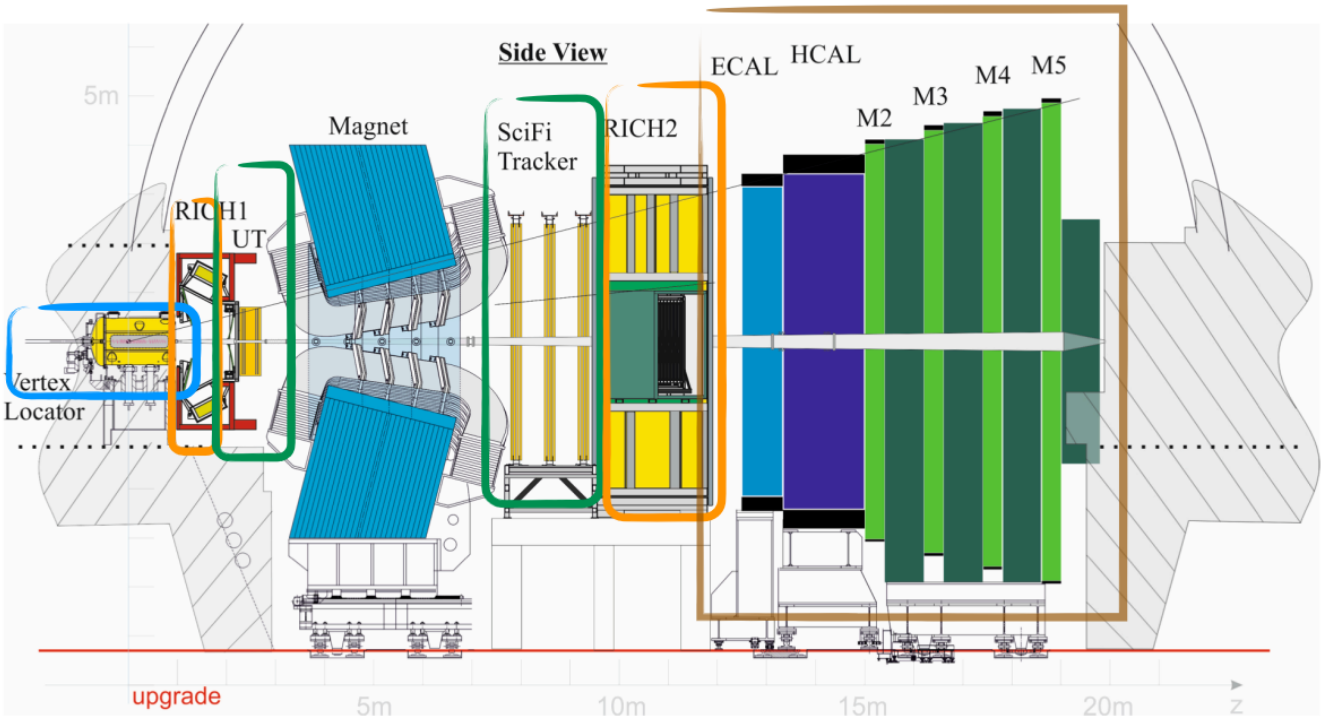
Stayed tuned!

BACKUP

LHCb Upgrade I

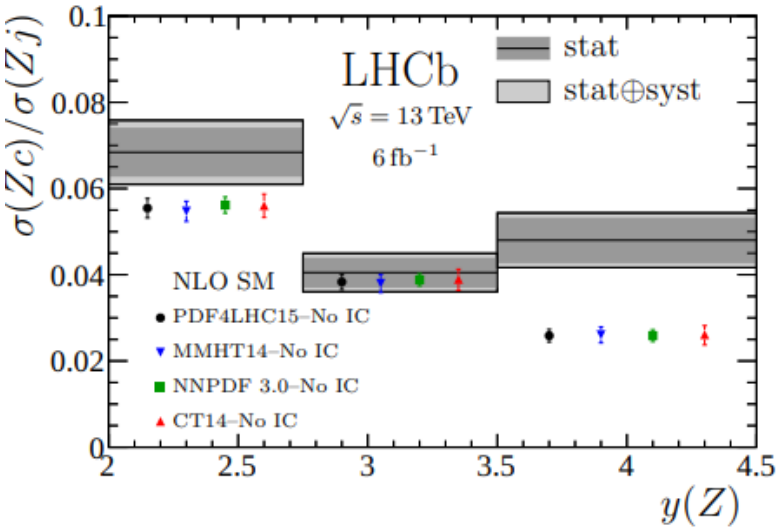
arXiv:2305.10515

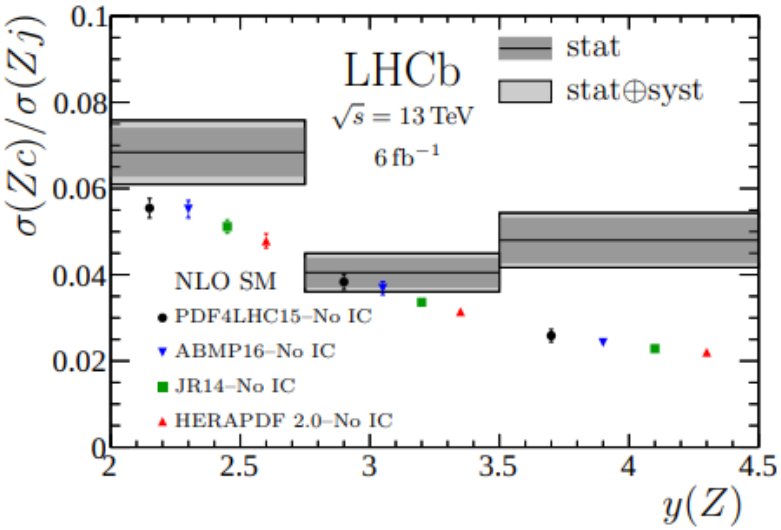
Significant upgrades to the LHCb detector were made during the recent LHC LS2

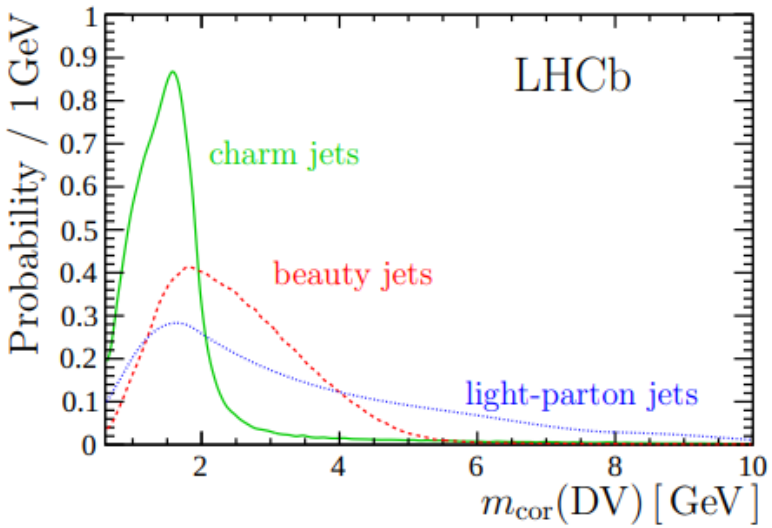


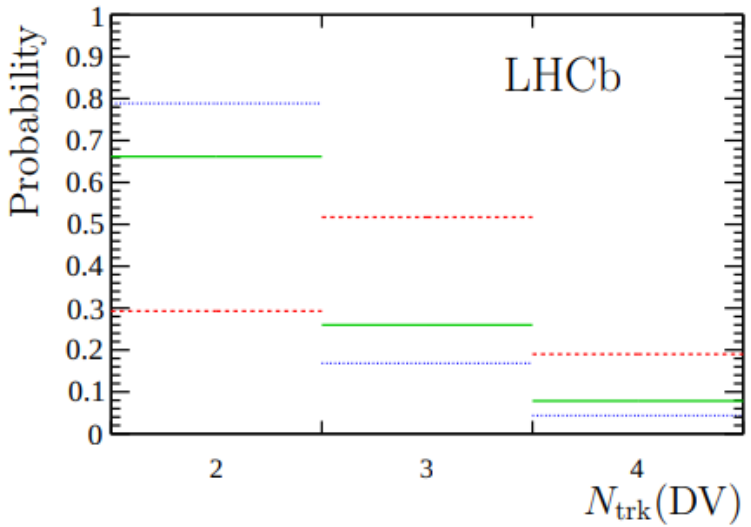
- New Vertexing Detector → Closer to beam; Silicon pixels improve IP resolution
- New PID detector → New photon detectors and improved readout
- New tracking system → Silicon strip UT for improved tracking granularity; Fibre tracking for high particle density momentum resolution
- New Readout Systems
- *BONUS* : New GPU-based trigger

Z Bosons in Association with Charm BU Plots PRL 128, 082001 (2022)









Charged Hadron in Z-tagged Jets BU Plots PRD 108, L031103 (2023)