Jet measurements in pp collisions from LHCb

DAVIDE ZULIANI, ON BEHALF OF LHCb COLLABORATION
UNIVERSITY AND INFN OF PADOVA

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Overview

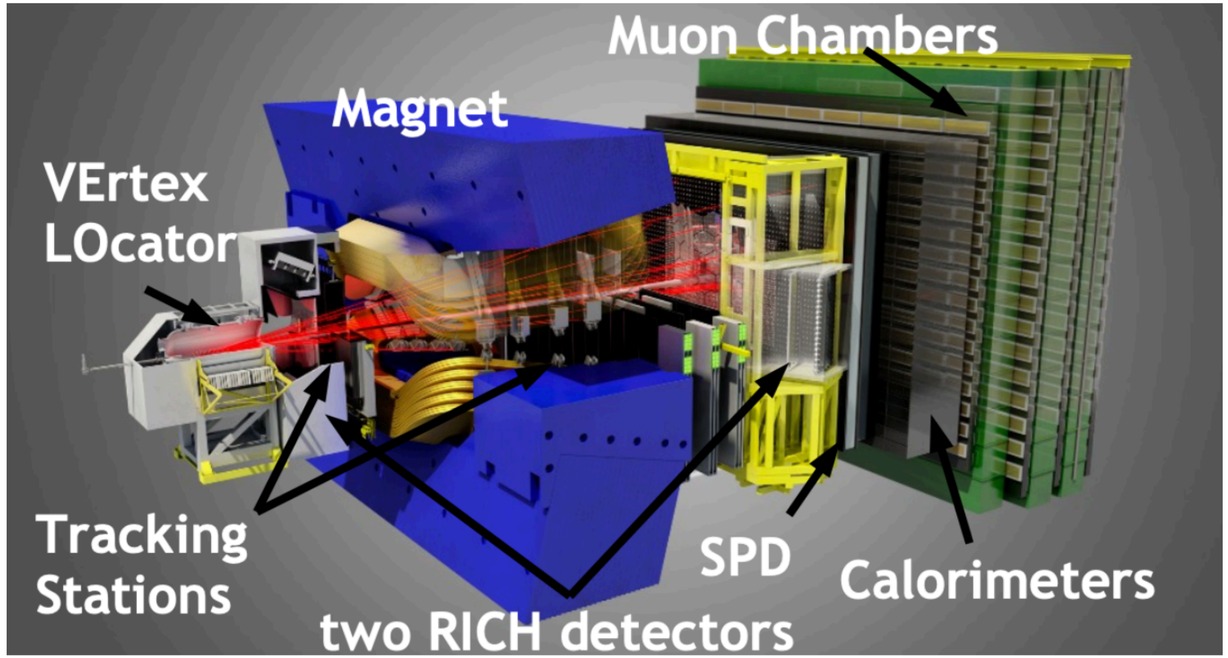
- **The LHCb detector**
- **Latest jet measurements**
  - Multidifferential study of identified charged hadron distributions in Z-tagged jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

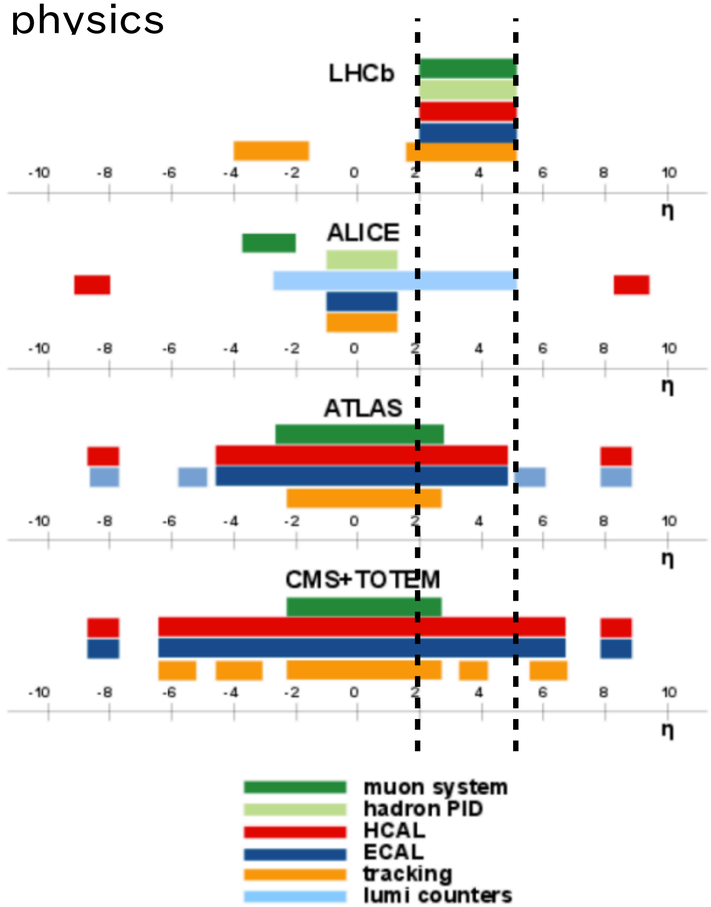
  - Study of Z bosons produced in association with charm in the forward region
  - Measurement of $b\bar{b}$- and $c\bar{c}$-dijet differential cross-sections in the forward region of pp collisions at $\sqrt{s} = 13$ TeV
- **Conclusions**

JINST 3 (2008) S08005, INT. J. MOD: PHYS. A 30, 1530022 (2015), CERN-LPCC-2018-04

The LHCb detector

- LHCb is a forward spectrometer originally designed to study b- and c-hadron physics
- Unique phase space region $(2 < \eta < 5)$ **complementary** to ATLAS & CMS





- **Excellent track momentum resolution**: 0.4% at 5 GeV to 1.0% at 200 GeV
- Impact Parameter resolution $\sigma_{IP} = (15 + 29/p_{\mathrm{T}})\ \mu$m, lifetime resolution of $\sigma_\tau = 0.2$ ps
- Muon ID efficiency: 97% with 1-3% $\mu \to \pi$ misidentification
- Electron ID efficiency: 90% with 5% $h \to e$ misidentification

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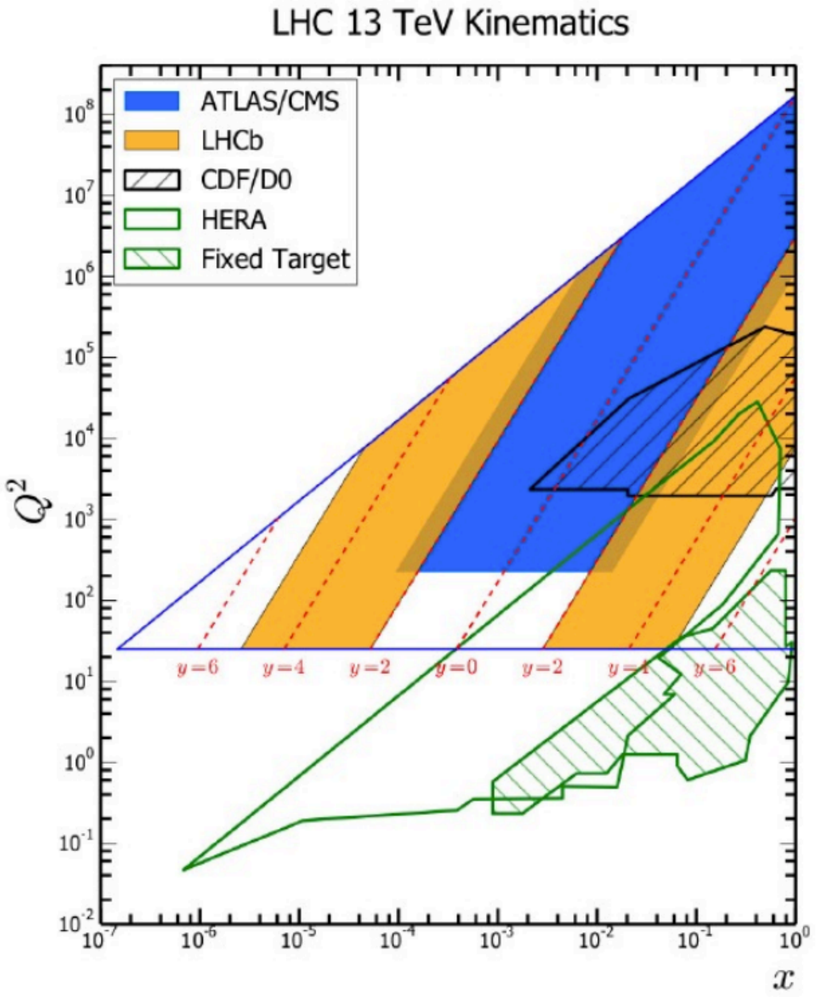
The LHCb detector and QCD



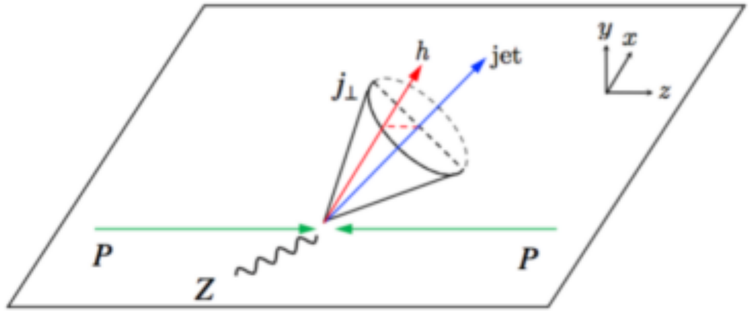
- Parton Distribution Functions (PDFs) are a fundamental input for LHC experiments
  - Must be determined from experiments!
- LHCb allows to test perturbative QCD (pQCD) predictions in a phase space $(2 < \eta < 5)$ **complementary** to other experiments
- PDFs and proton structure can be studied in two different kinematic regions:
  - At high x values, comparison with other experiments
  - At low x values and high Q^2, **unexplored by other experiments**
- Also, at LHCb both pp **collisions** and **heavy ions**!

PHYS. REV. LETT. 123.232001, LHCB-PAPER-2022-013

Charged hadron distributions in Z-tagged jets

- Several motivations:
  - Extending the previous measurement of non-identified charged hadron
  - Excellent hadron identification performance for LHCb
  - Access Transverse Momentum Dependent Fragmentation Functions (TMD FF) for hadrons
  - Access flavour dependent hadron production mechanisms
- Approximately $1.6\ \mathrm{fb}^{-1}$ of data

	old (published)	new (this analysis)
$\sqrt{s}$	8 TeV	13 TeV
j_T and z distributions	1D	1D and 2D
PID	non-identified $h^{\pm}$	non-identified and identified $\pi^{\pm}$, $K^{\pm}$ $p^{\pm}$



$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

$$j_T = \frac{|p_{jet} \times p_h|}{|p_{jet}|}$$

$$r = \sqrt{(\phi_{jet} - \phi_h)^2 + (y_{jet} - y_h)^2}$$

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Charged hadron distributions in Z-tagged jets

- Distributions are measured for pions, kaons and protons
- Standard selection requirements for Z boson and jets

Muons	$Z^0 \to$ ZMuMuLine	Jet $\to$ StdJets
$p_T > 20$ GeV	$60 < M_{\mu\mu} < 120$ GeV	$p_T^{reco} > 15$ GeV
$2 < \eta < 4.5$	Num PVs == 1	$\to p_T^{true} > 20$ GeV
$\sqrt{PERR2}/P < 0.1$		$2.5 < \eta < 4$
TRPCHI2 > 0.01		$\Delta R_{jet-\mu^\pm} > 0.5$
ISMUON		
L0Muon Trigger		
Hlt1SingleMuon Trigger		
Hlt2SingleMuon Trigger		

$$f(z, j_T) = \frac{d\sigma}{d\mathcal{PS}\, dz\, dj_T} \Big/ \frac{d\sigma}{d\mathcal{PS}},$$

$$F(z) = \int dj_T\, f(z, j_T) = \frac{d\sigma}{d\mathcal{PS}\, dz} \Big/ \frac{d\sigma}{d\mathcal{PS}}$$

$$F(j_T) = \int dz\, f(z, j_T) = \frac{d\sigma}{d\mathcal{PS}\, dj_T} \Big/ \frac{d\sigma}{d\mathcal{PS}}$$

- Additional requirement: $\Delta\phi_{Z+\text{jet}} > 7\pi/8$ to select away-side jets
- Jet Fragmentation Functions (JFF) measured differentially

$$f(z, j_T) = \frac{1}{N_{Z+\text{jet}}} \frac{dN_{\text{had}}(z, j_T)}{dz\, dj_T},\ F(z) = \frac{1}{N_{Z+\text{jet}}} \frac{dN_{\text{had}}(z)}{dz},\ F(j_T) = \frac{1}{N_{Z+\text{jet}}} \frac{dN_{\text{had}}(j_T)}{dj_T}$$

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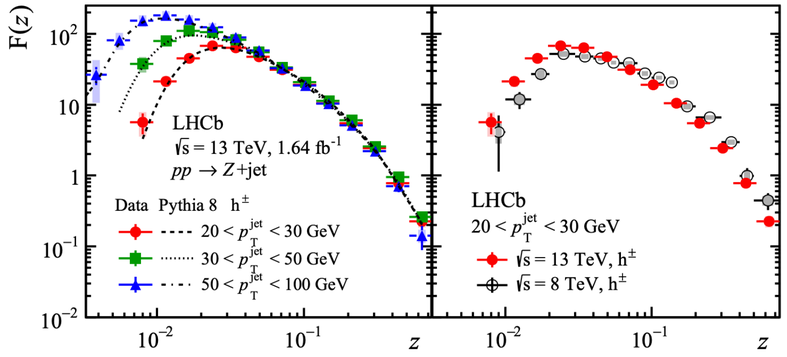
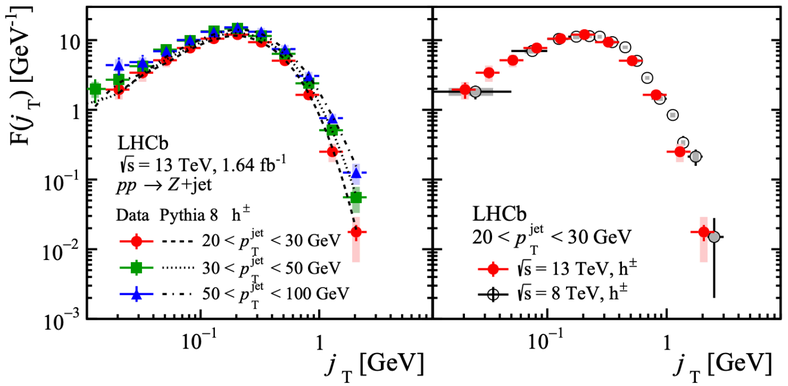
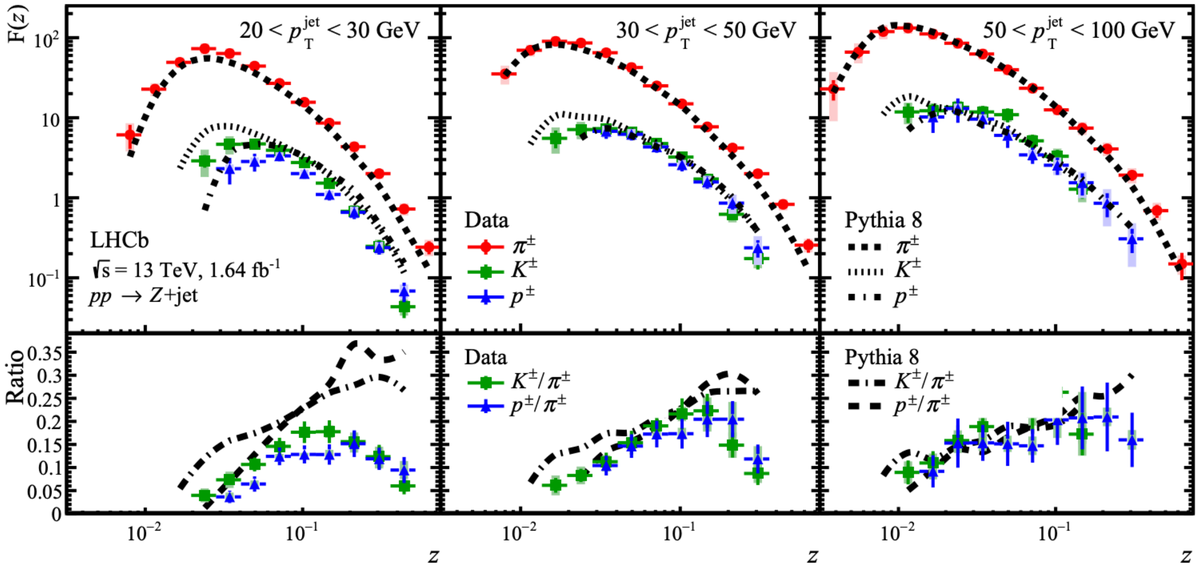
Charged hadron distributions in Z-tagged jets

- z and j_{T} distributions for non-identified hadrons
  - z distributions show a humpbacked structure due to both color coherence and kinematic requirements
  - Overall increase in particle production in all regions of j_{T}
  - Comparisons with $\sqrt{s} = 8$ TeV show a general similarity in shape



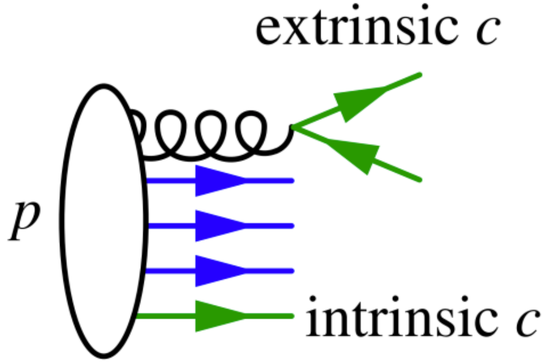




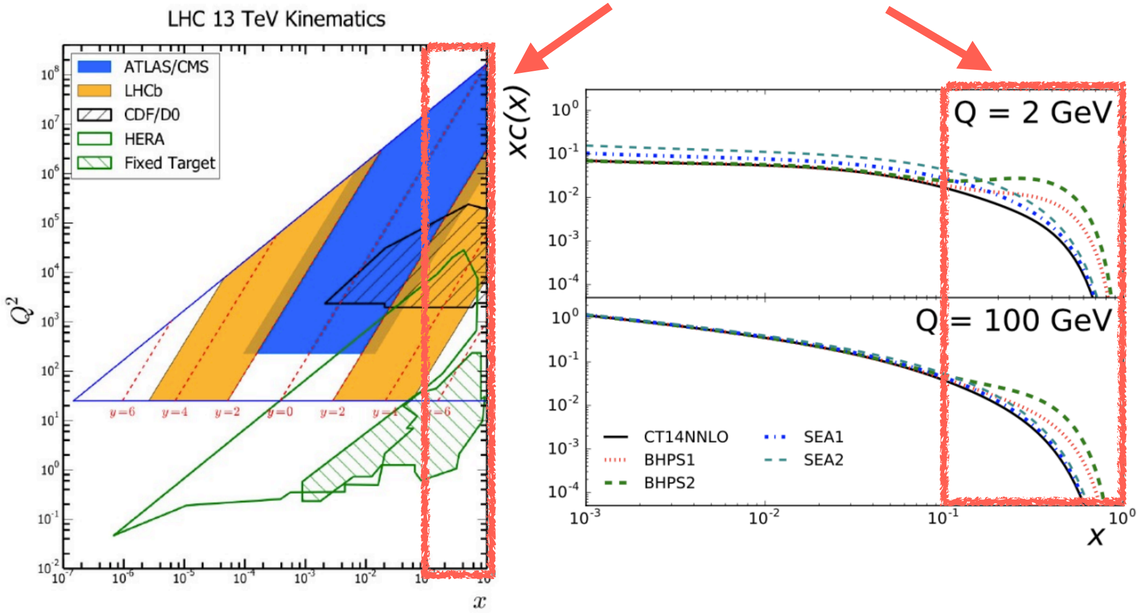
- z and j_{T} distributions for JFFs and ratios shown for different hadrons
- Underestimation (overestimation) of charged pions (kaons and protons) by PYTHIA8
- An analysis is ongoing also tagging jets

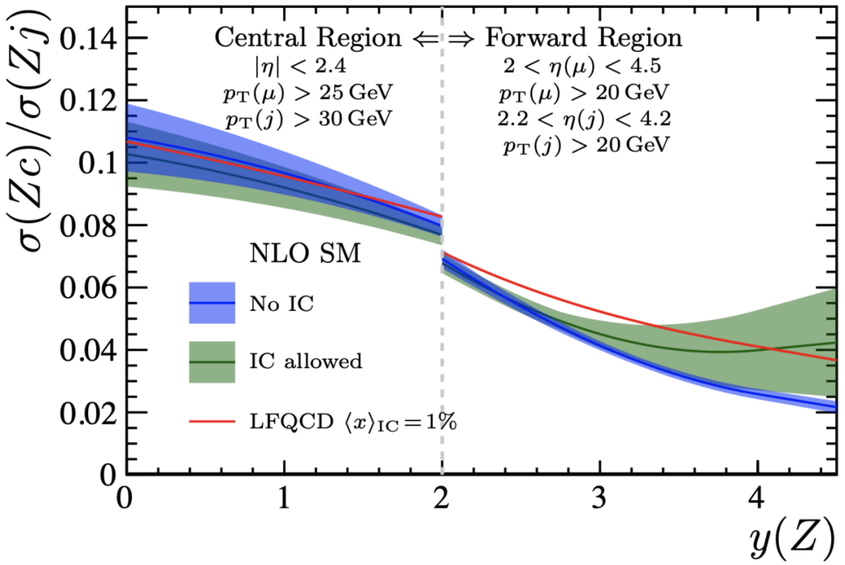
PHYS. REV. LETT. 128, 082001

Z+c-jet production



- Proton charm content can be:
  - **extrinsic,** produced by gluon splitting $g \to c\bar{c}$
  - **intrinsic (IC),** a $|uudc\bar{c}>$ component bound to valence quarks
- The existence of an IC component would affect many processes studied at LHC
- So far, IC component in the proton has not been excluded
- Particularly, an IC component would manifest itself for $x > 0.1$





- Therefore, the idea is to study high-x charm quarks to search for IC
- The $Z + c$-jet production in the forward region is sensitive to the high x and high Q^2 intrinsic charm component → **feasible at LHCb!**

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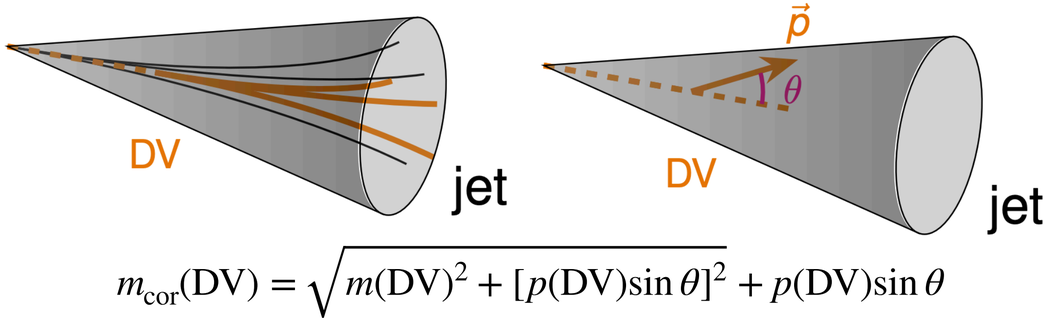
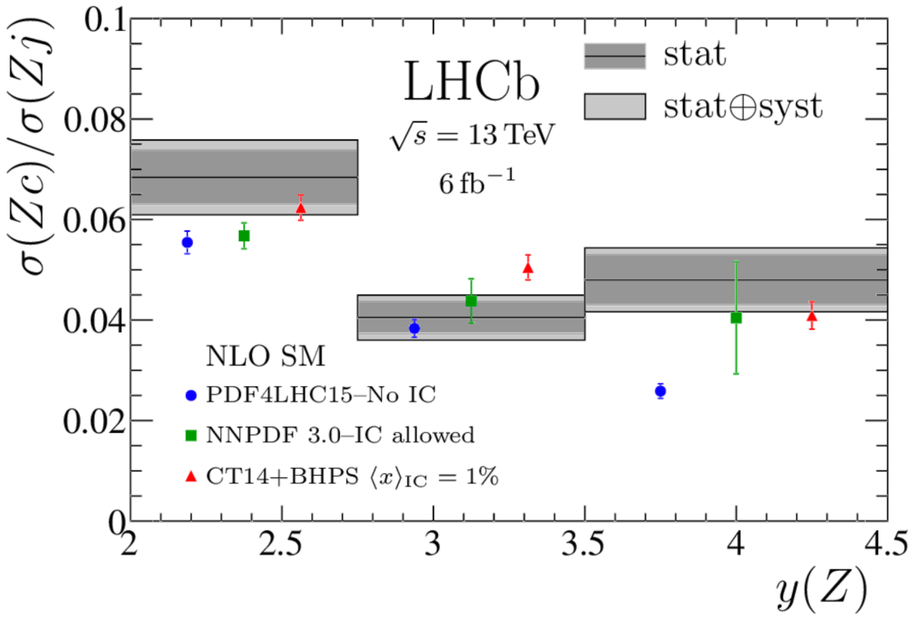
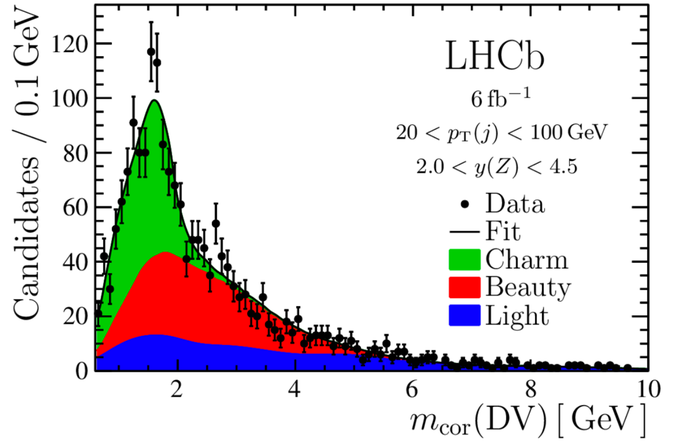
Z+c-jet production

- The 13 TeV dataset is used, for a total integrated luminosity of 6 fb^{-1} (Run II condition), requiring a $Z \to \mu\mu$ with at least one jet
- Heavy flavour jets are tagged with a Displaced Vertex (DV) technique
- The corrected DV-mass $m_{\text{cor}}(\text{DV})$ and the number of tracks in the DV are fitted to obtain the flavour components



$$m_{\text{cor}}(\text{DV}) = \sqrt{m(\text{DV})^2 + [p(\text{DV})\sin\theta]^2} + p(\text{DV})\sin\theta$$





- **Hint of the intrinsic charm component in the high rapidity interval** $(3.5 < y(Z) < 4.5)$
- No-IC hypothesis inconsistent at $\sim 3\sigma$
- Result is statistically limited → **more data is needed!**

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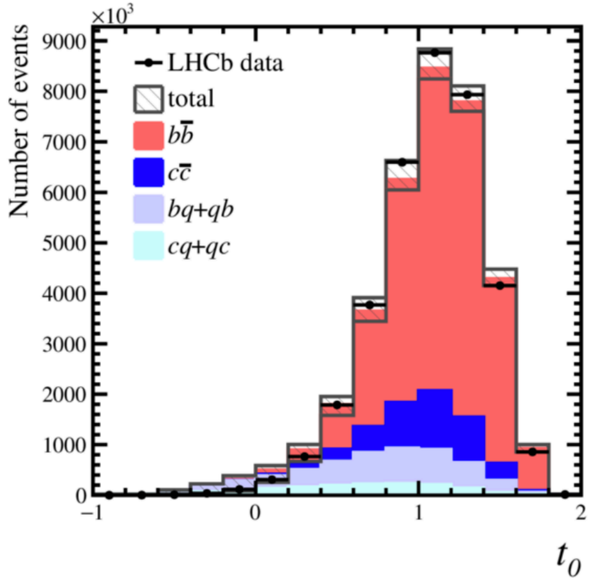
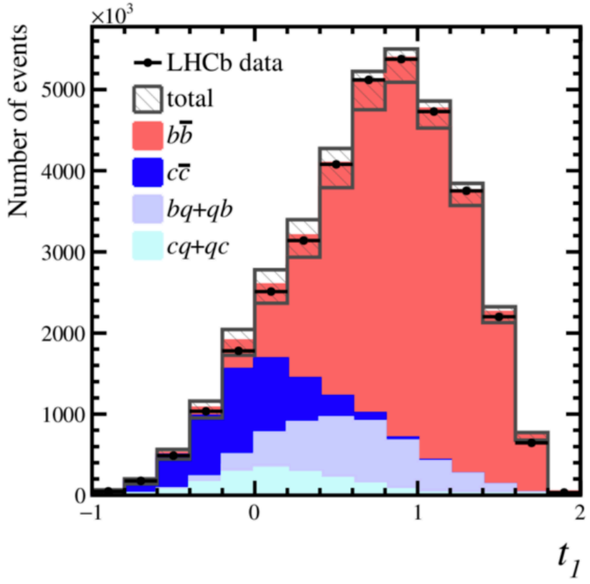
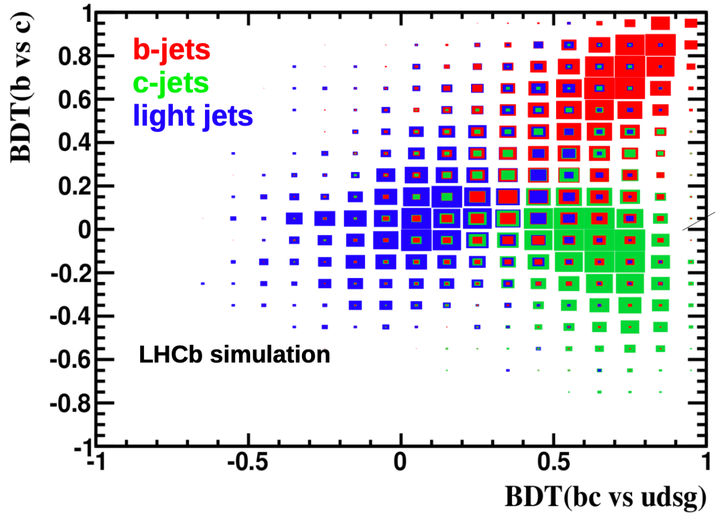
$b\bar{b}$ and $c\bar{c}$ differential cross-section

- The main idea is to study the inclusive decay of high mass resonances in $b\bar{b}$ and $c\bar{c}$ jet pairs
- It is possible to study lower invariant masses w.r.t. ATLAS & CMS
- QCD background has an important role in this analysis
- Background from $Z \to b\bar{b}$ $(c\bar{c})$ is also considered
- Directly trigger on di-jets
- Exploit good LHCb jet tagging performances







- A first study has been performed to measure $b\bar{b}$ and $c\bar{c}$ differential cross sections with 2016 data
- Fit to combination of two MVA discriminators (BDTs) t_0 and t_1 to get flavour composition:

$$t_0 = \mathrm{BDT}_{bc|q}(j_0) + \mathrm{BDT}_{bc|q}(j_1)$$
$$t_1 = \mathrm{BDT}_{b|c}(j_0) + \mathrm{BDT}_{b|c}(j_1)$$

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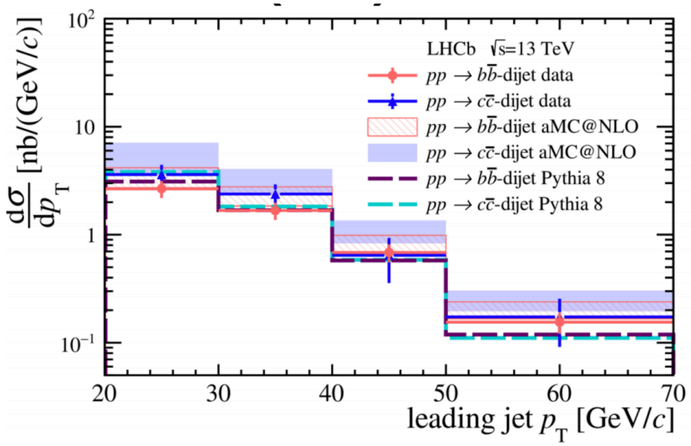
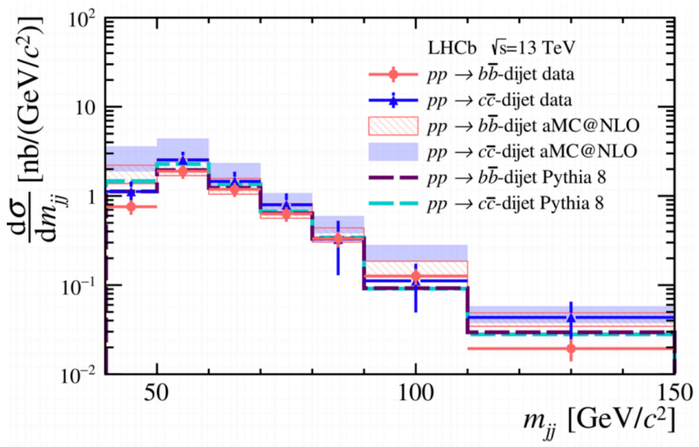
$b\bar{b}$ and $c\bar{c}$ differential cross-section

- Differential cross sections are measured and compared with simulations from Pythia and aMC@NLO
- Results are computed for different di-jets kinematic variables:

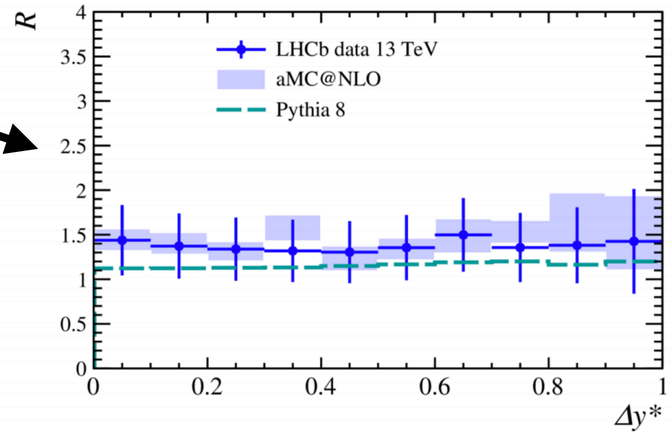
leading jet p_T | leading jet η

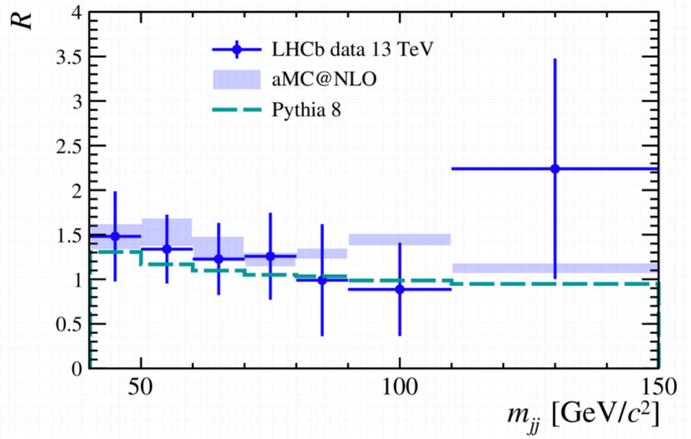
di-jet invariant mass m_{jj} | $\Delta y^* = 1/2\,|y_0 - y_1|$





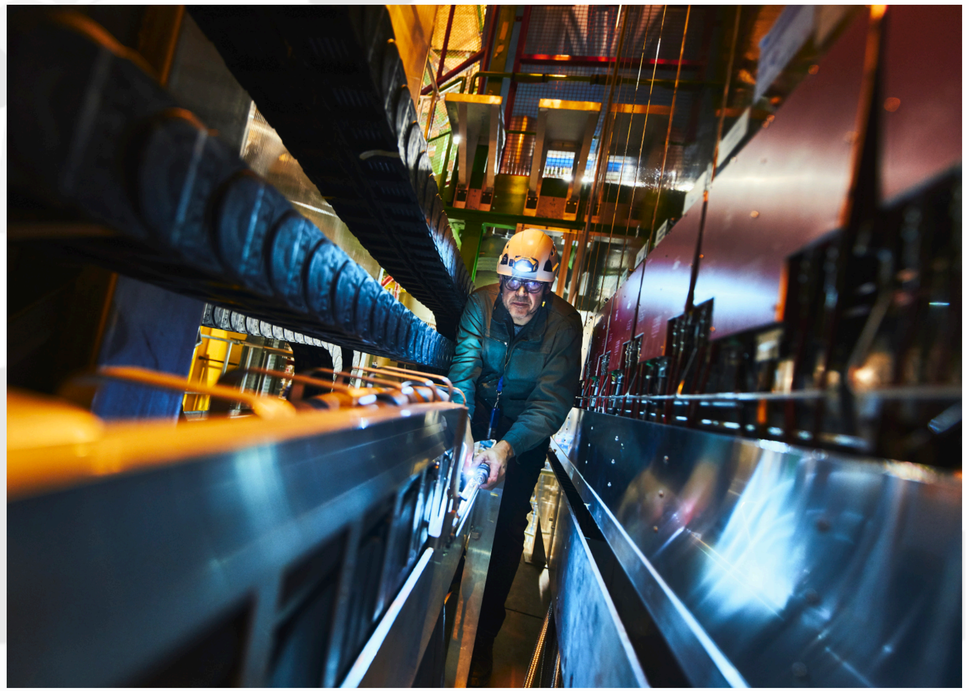
- The cross section ratios $R = \sigma_{b\bar{b}}/\sigma_{c\bar{c}}$ are also computed as functions of kinematic variables
- Results are compatible with expectations
- **This is the first inclusive, direct measurement of $c\bar{c}$ differential cross section at a hadron collider**
- A similar approach will include high mass resonances (such as the Higgs boson) decaying to $b\bar{b}$ and $c\bar{c}$ di-jets





Conclusions

- **LHCb can be considered as a General Purpose Forward Detector**
  - Not only flavour physics, QCD and pQCD are tested in a region complementary to ATLAS and CMS
  - Interesting environment to test PDFs and proton structure
- **A lot of interesting results (these are just the latest!!)**
  - Identified charged hadron distributions in Z-tagged jets events
  - Intrinsic charm component in proton content at high rapidities using $Z + c-$jet events
  - Measurement of differential heavy flavour di-jets cross sections



Waiting for the next run(s) to come, stay tuned!

Thank you for your attention

Belgrade, 22 - 26 May 2023