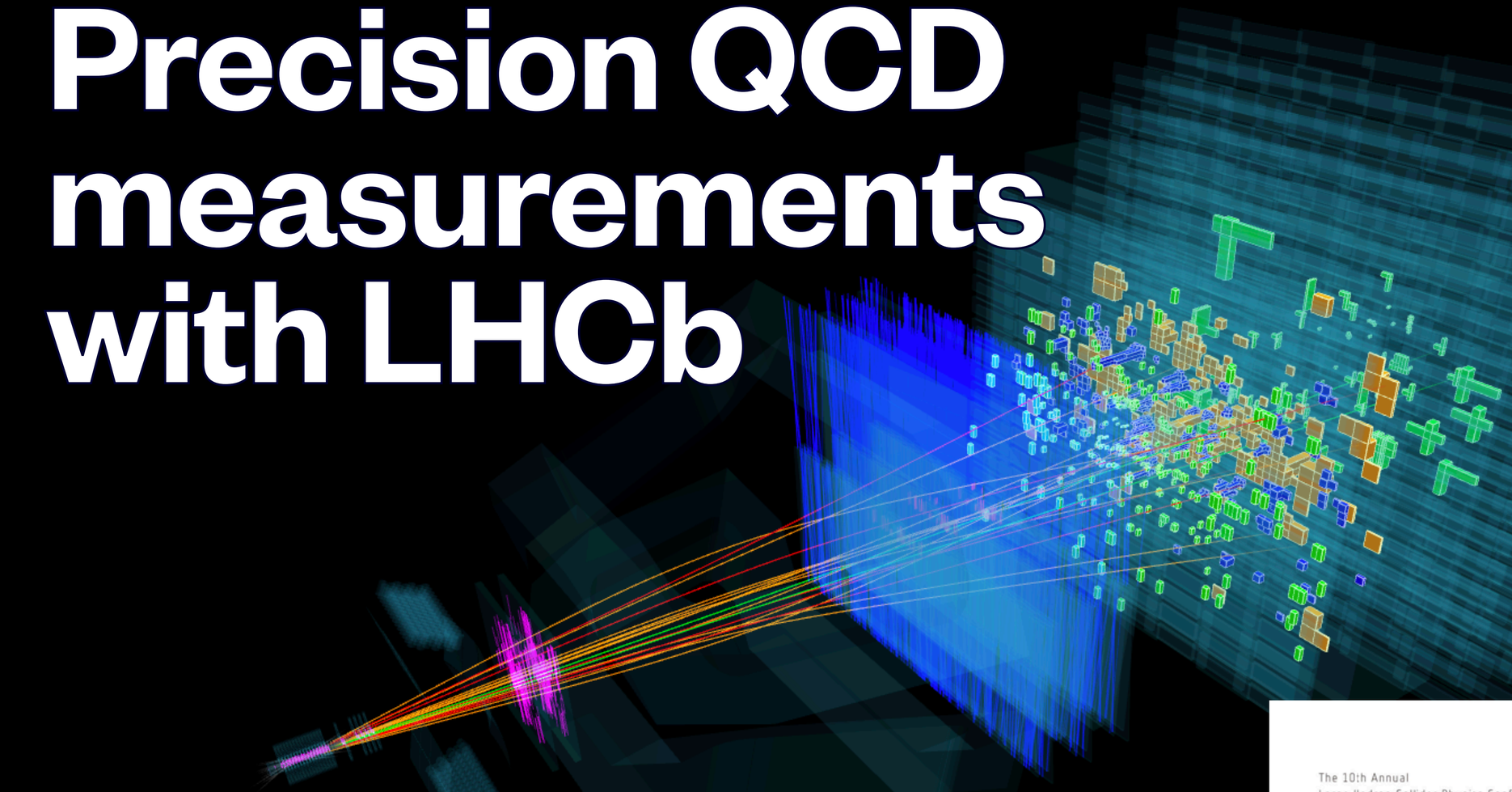
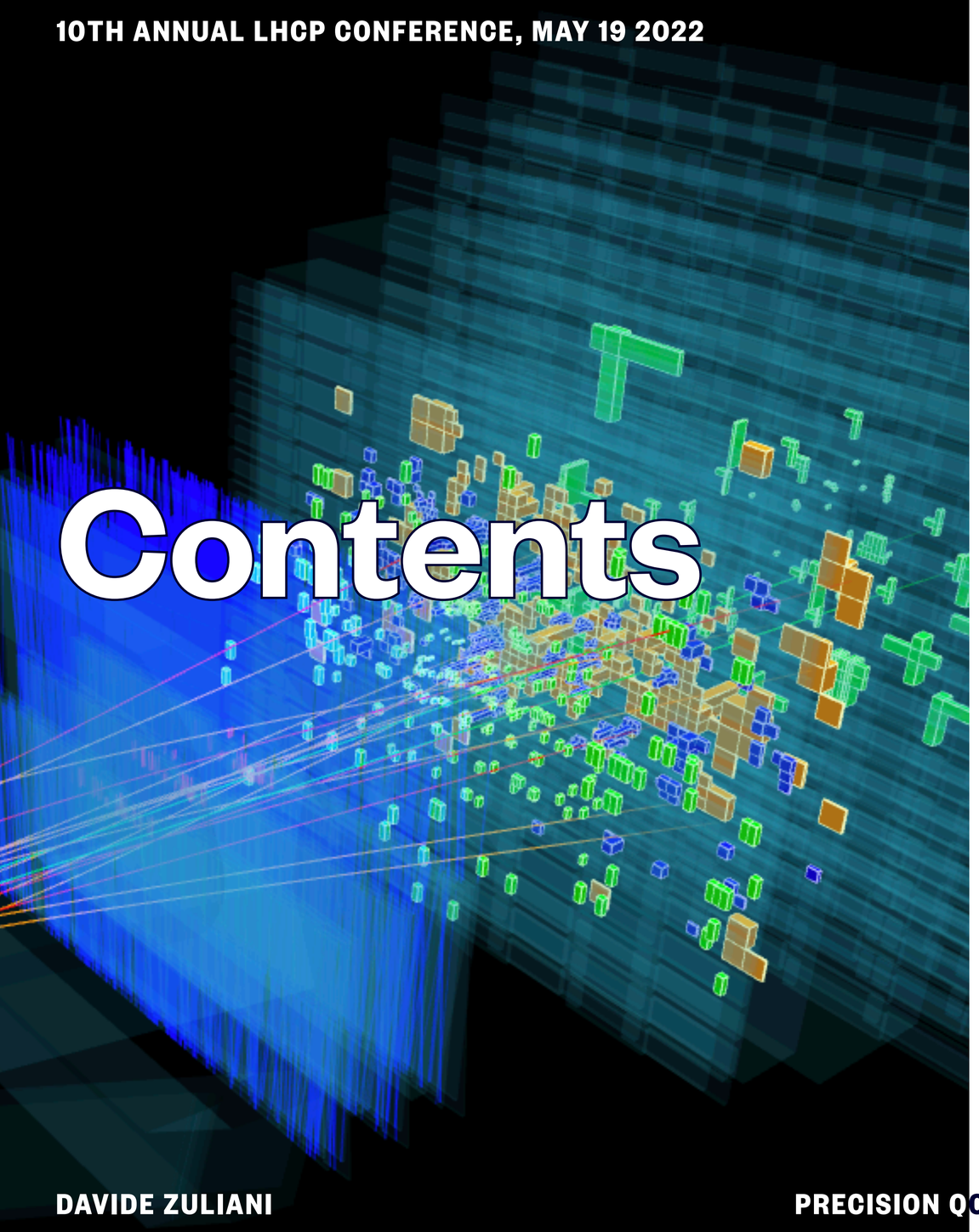
Precision QCD measurements with LHCb



Davide Zuliani
University and INFN of Padova

On behalf of the LHCb Collaboration

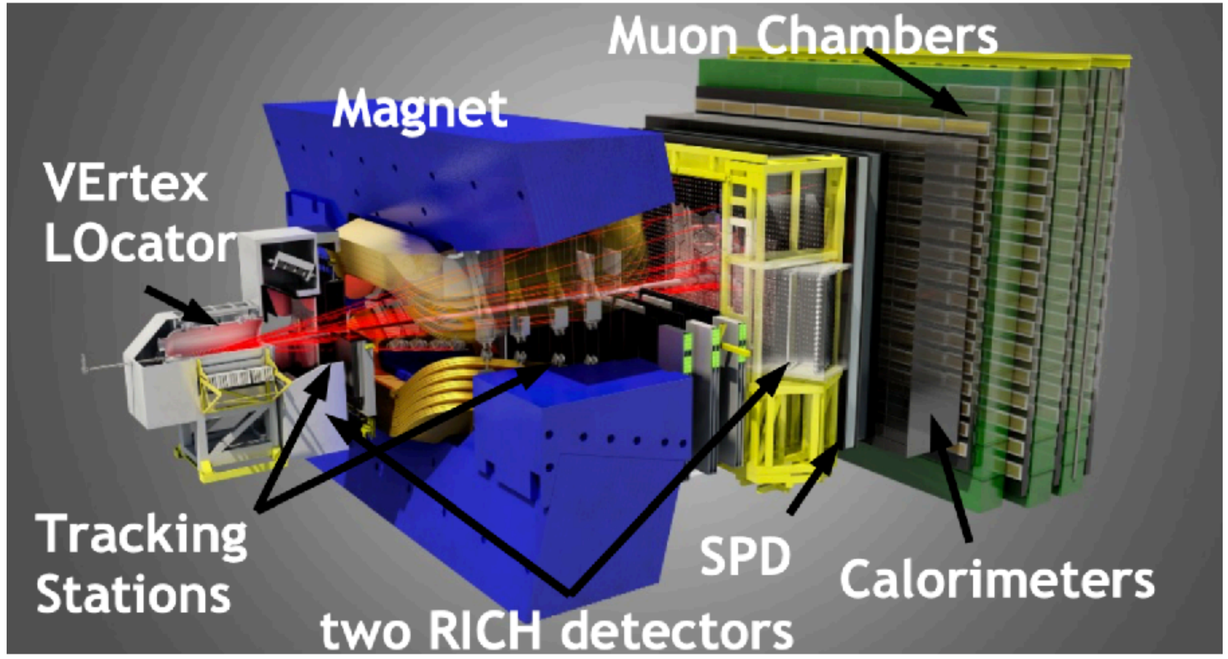


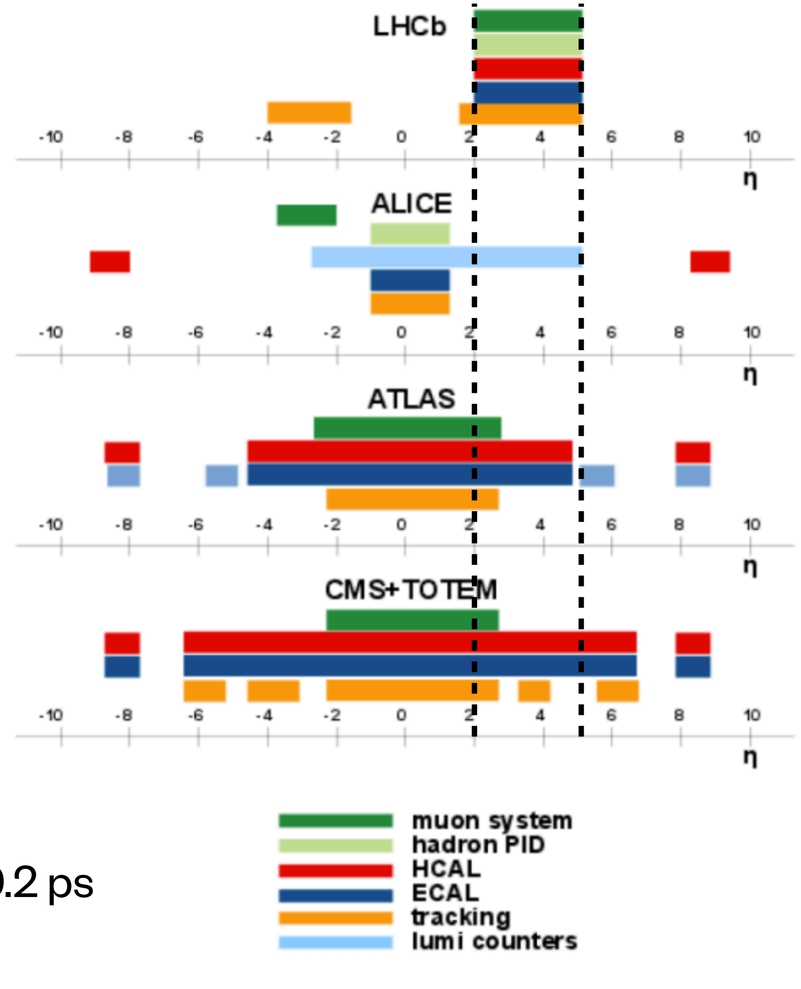
Contents

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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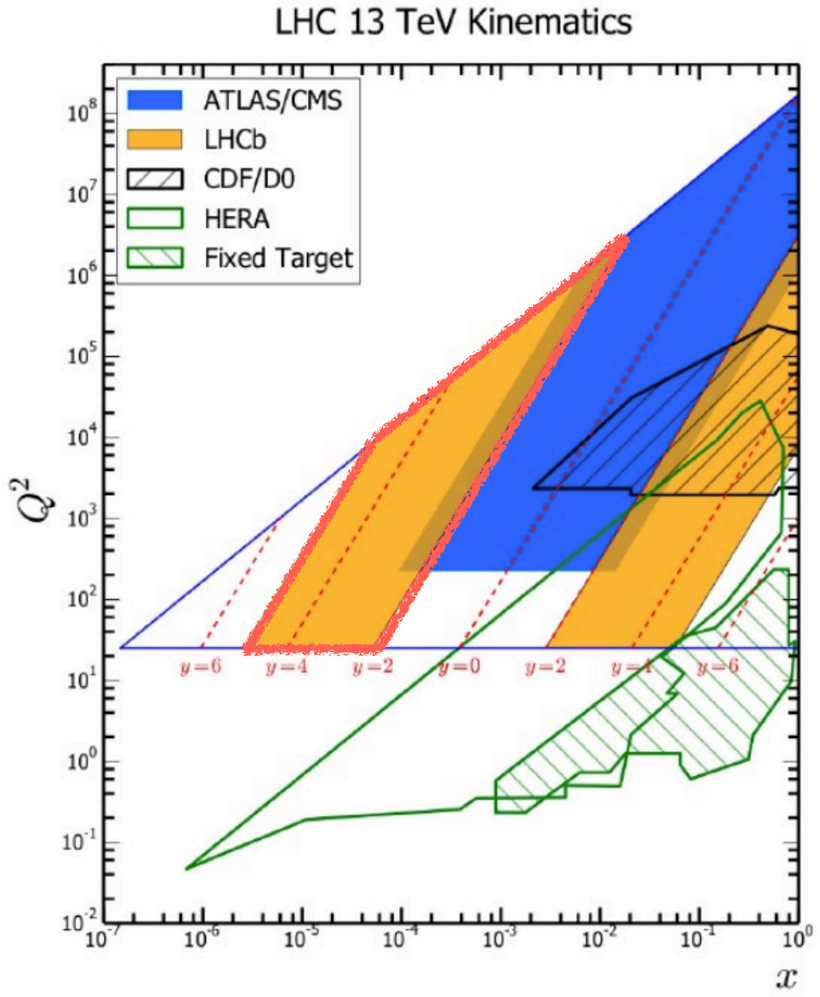
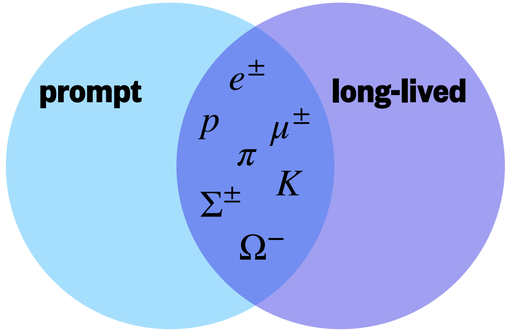
The LHCb detector and QCD

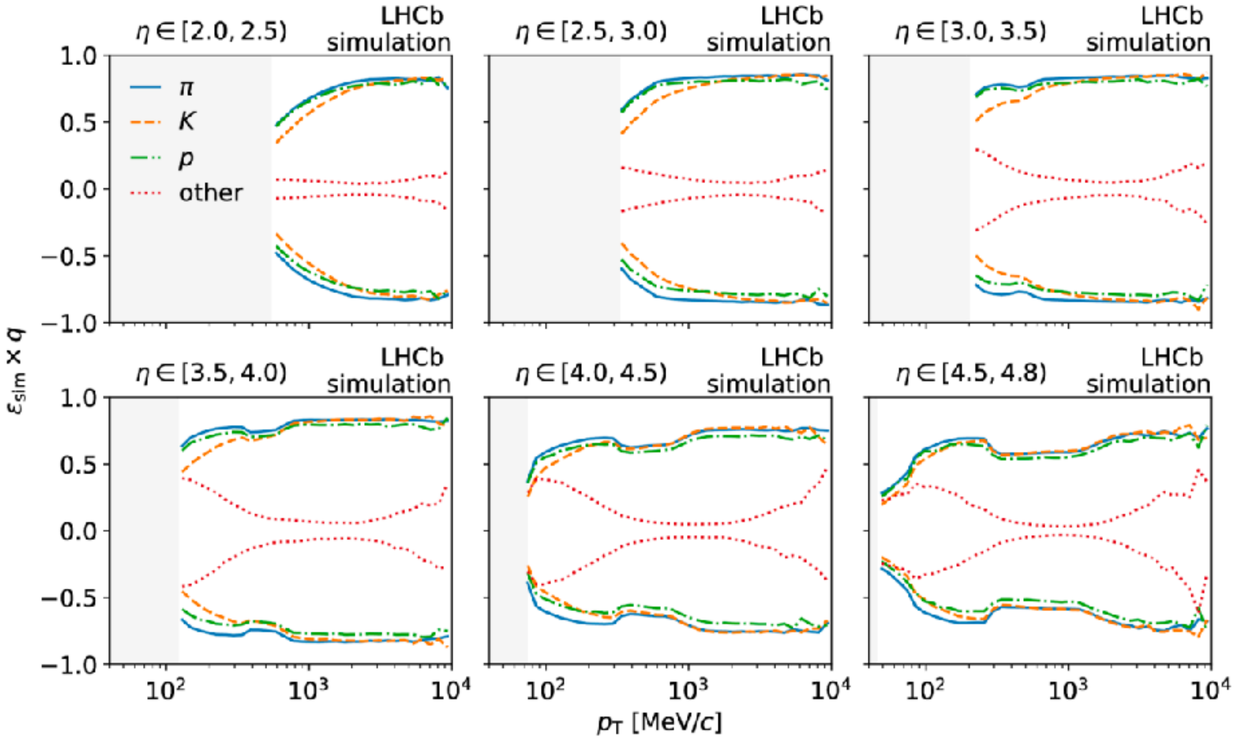


- Parton Distribution Functions (PDFs) are a fundamental input for LHC experiments
  - Must be determined from experiments!
- LHCb allows to test perturbative QCD (pQCD) predictions in a phase space $(2 < \eta < 5)$ **complementary** to other experiments
- PDFs and proton structure can be studied in 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**!

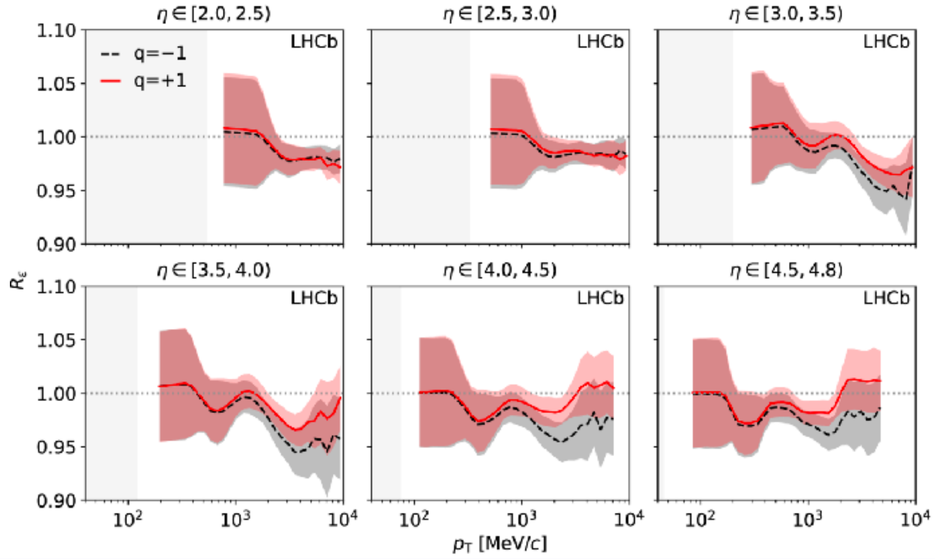
Prompt-charged particles production

- Soft QCD processes description is based of phenomenological models
- Model parameters determination relies on experiments at particle accelerators
- Prompt long-lived charged particles are a suitable proxy for light hadrons production
- In this analysis a double-differential cross section measurement is performed





- $\sqrt{s} = 13$ TeV data from 2015 ($\mathscr{L} = 5.4\ \text{nb}^{-1}$)
- $p_{\text{T}} \in [80,10000)$ MeV/c and $\eta \in [2.0,4.8)$
- Important to access efficiencies and correction to match data



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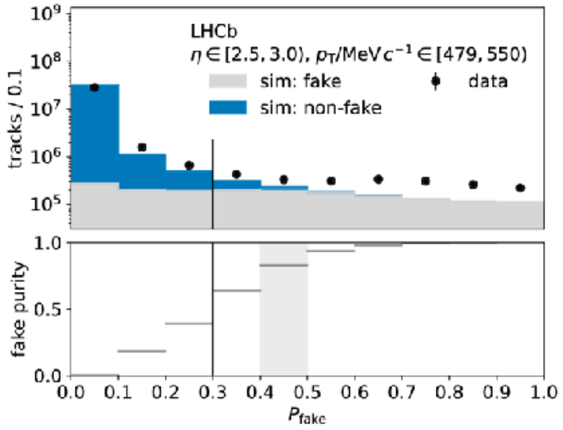
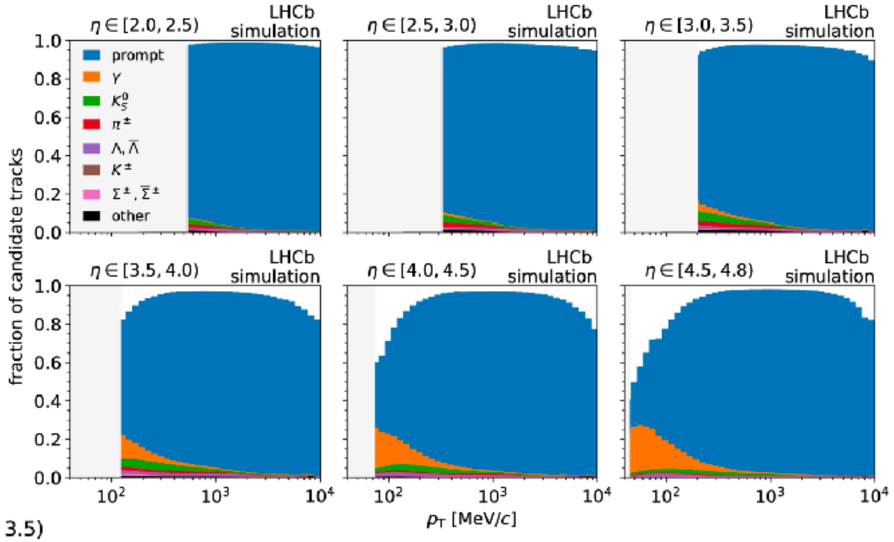
Prompt-charged particles production

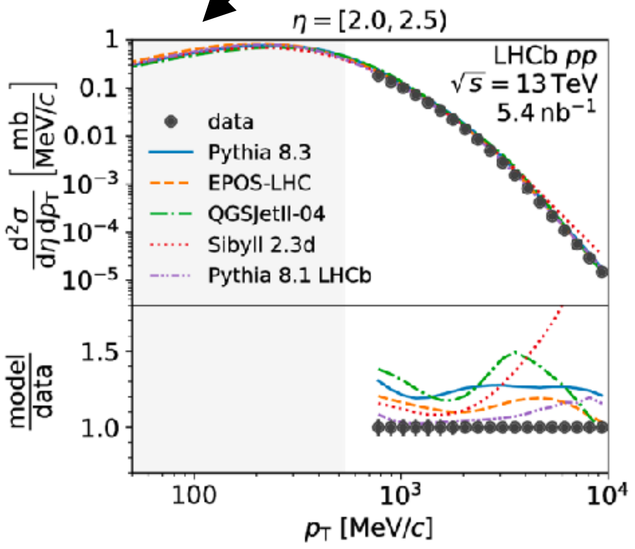
- Several background contributions:
  - Non-prompt particles
  - Beam-gas interactions
  - Fake tracks
  - Material interactions

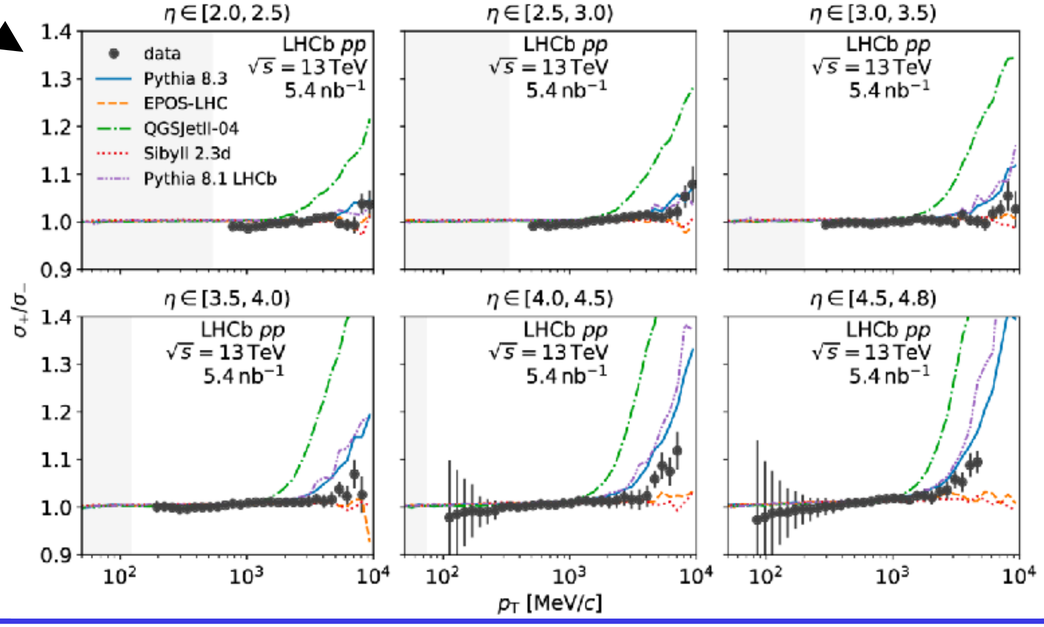
TOTAL UNCERTAINTY: 2.3% – 15%





- Results are compared with several models
  - **Differential** and **cross-section ratios** as function of p_T and η

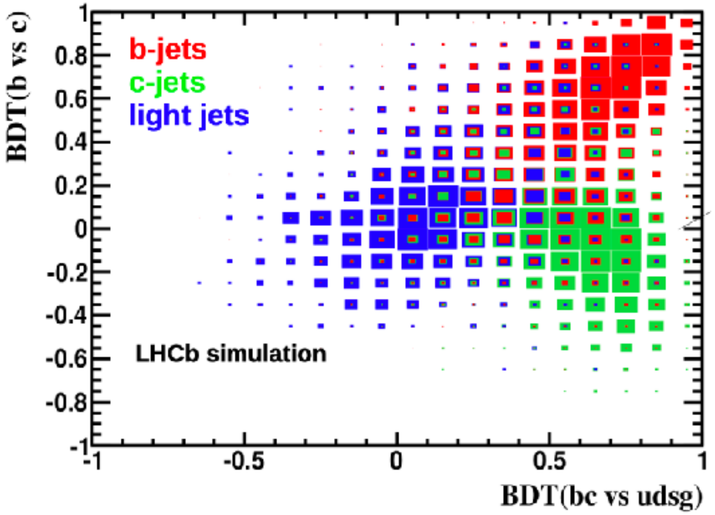


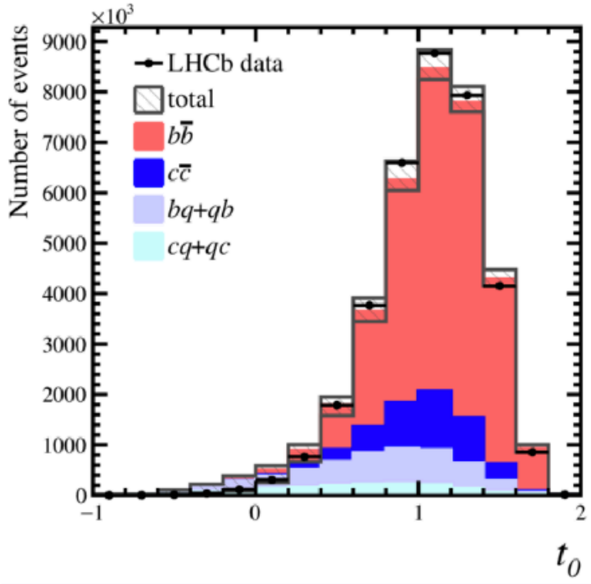


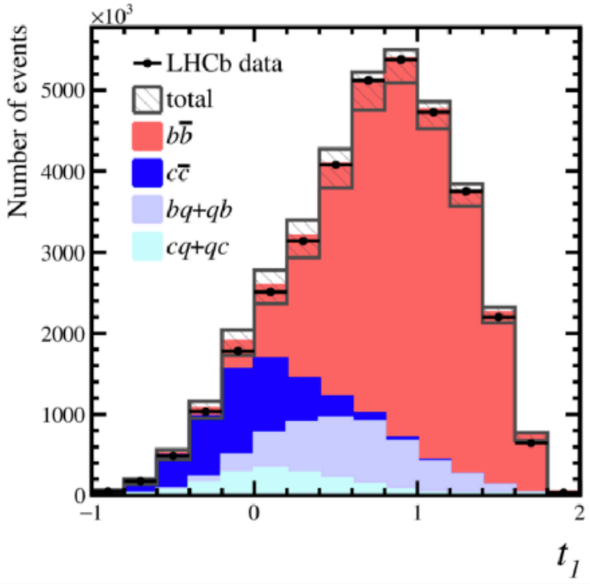
- Comparisons show that models overestimate the differential cross sections
- Best agreement with:
  - EPOS-LHC and Pythia 8.1 (LHCb tuned) for particle density
  - Pythia 8.3 for charged ratio

$b\bar{b}$- and $c\bar{c}$-dijet differential cross-sections

- 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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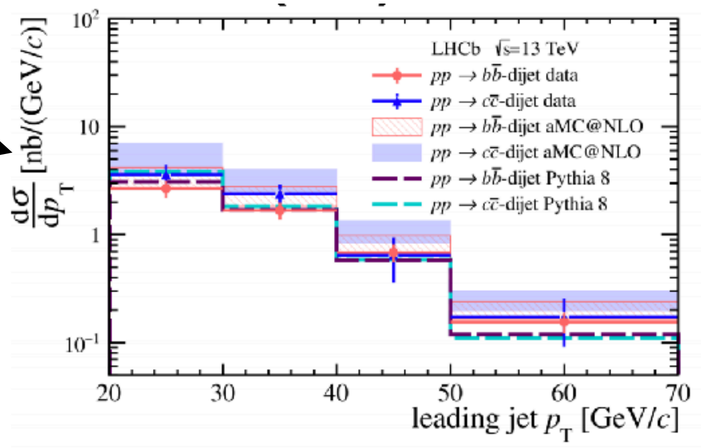
$b\bar{b}$- and $c\bar{c}$-dijet differential cross-sections

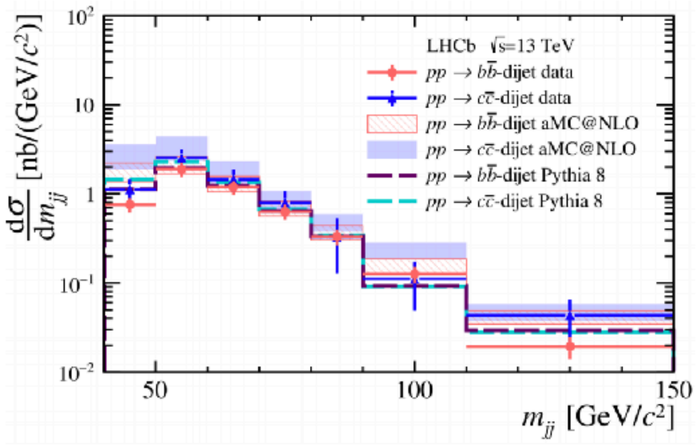
- Differential cross sections are measured and compared with simulations from Pythia and aMC@NLO
- Results are computed for different di-jets kinematic variables:

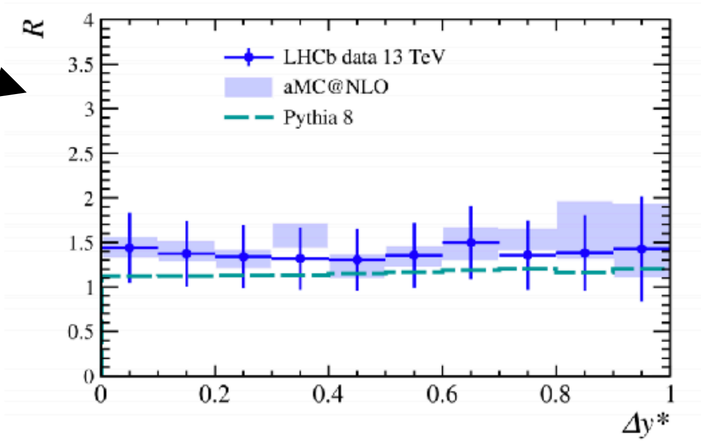
leading jet p_T leading jet η

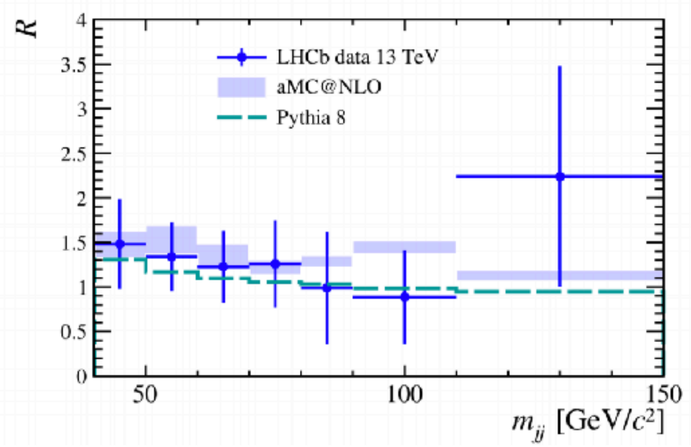
di-jet invariant mass m_{jj} $\Delta y^* = 1/2\,|y_0 - y_1|$

- 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

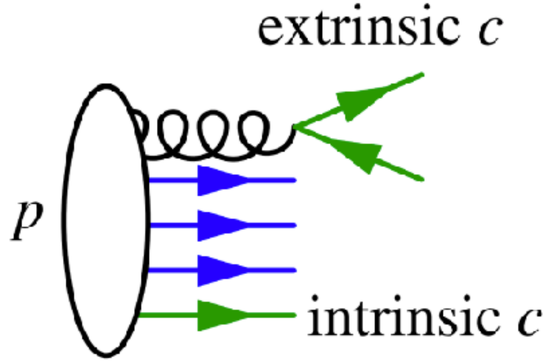




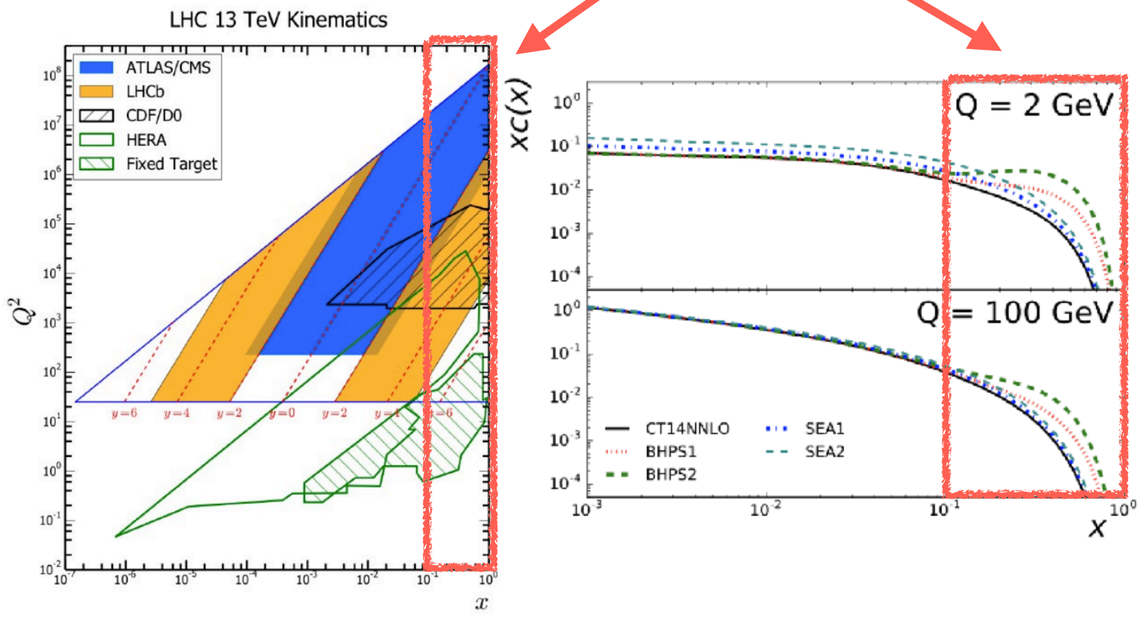


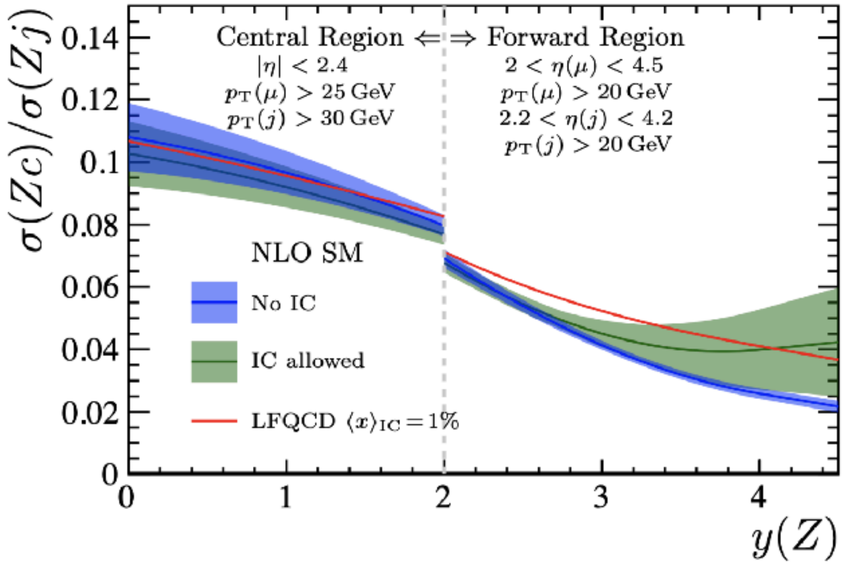


Z+c-jet production



- 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 $x > 0.1$

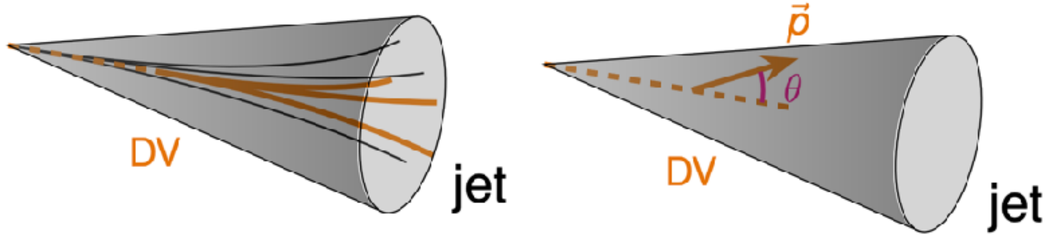




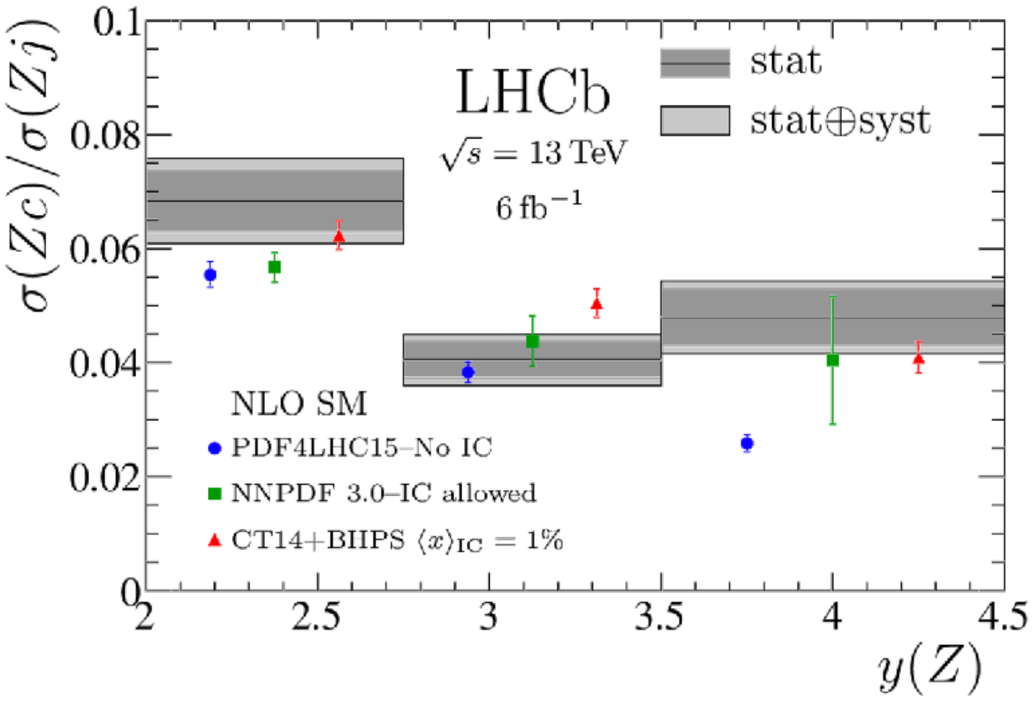
- Therefore, the idea is to study high-x charm quarks to search for IC
- The $Z + c$-jet production in the forward region is sensitive to the high x and high Q^2 intrinsic charm component → **feasible at LHCb!**

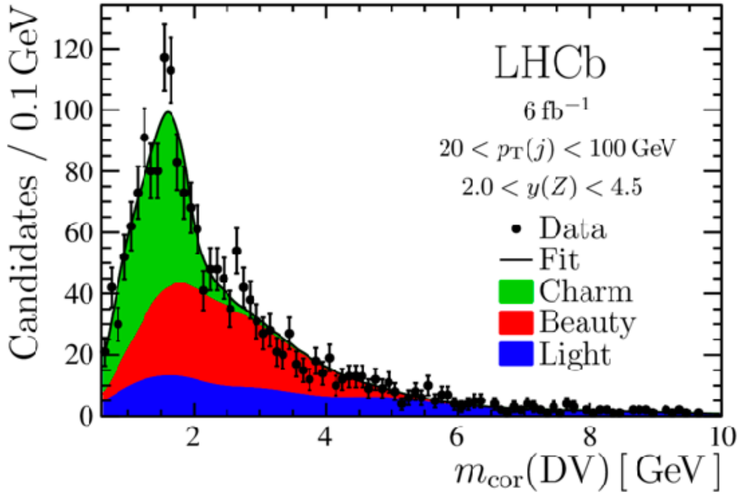
Z+c-jet production

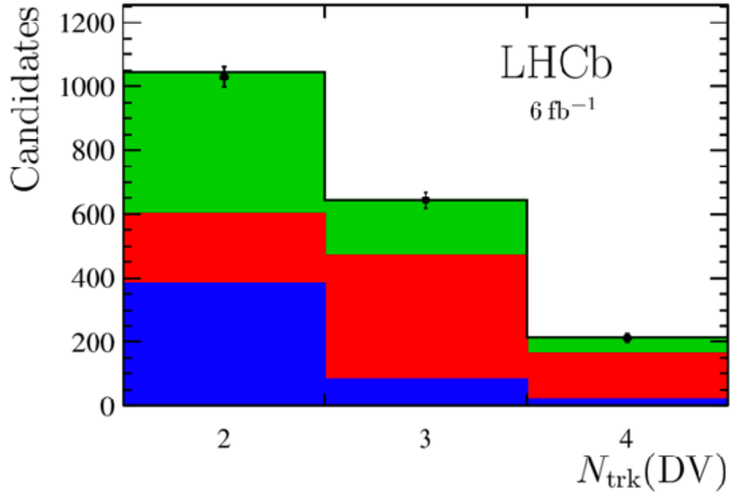
- The 13 TeV dataset is used, for a total integrated luminosity of $6\ \text{fb}^{-1}$ (Run II condition), requiring a $Z \to \mu\mu$ with at least one jet
- Heavy flavour jets are tagged with a Displaced Vertex (DV) technique
- The corrected DV-mass $m_{\text{cor}}(\text{DV})$ and the number of tracks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



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



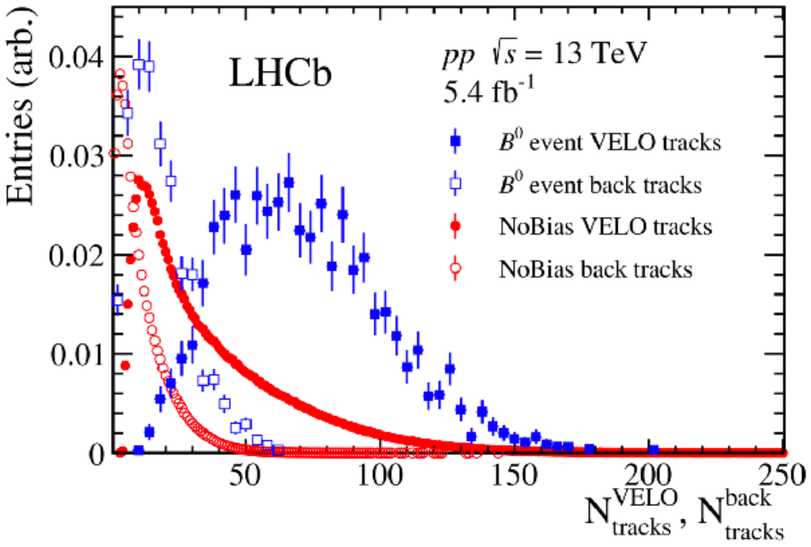


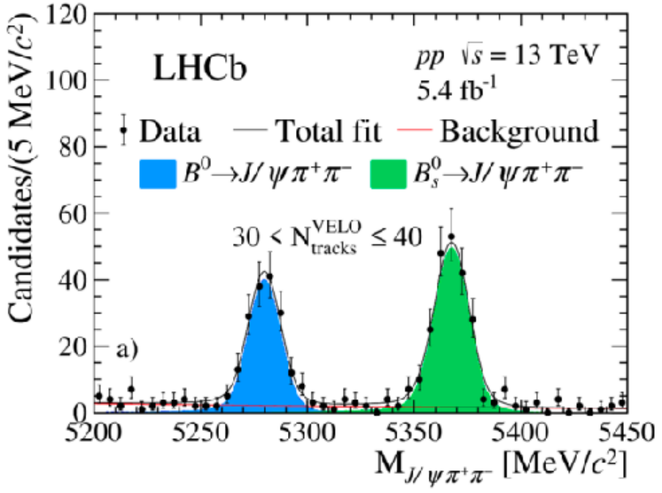


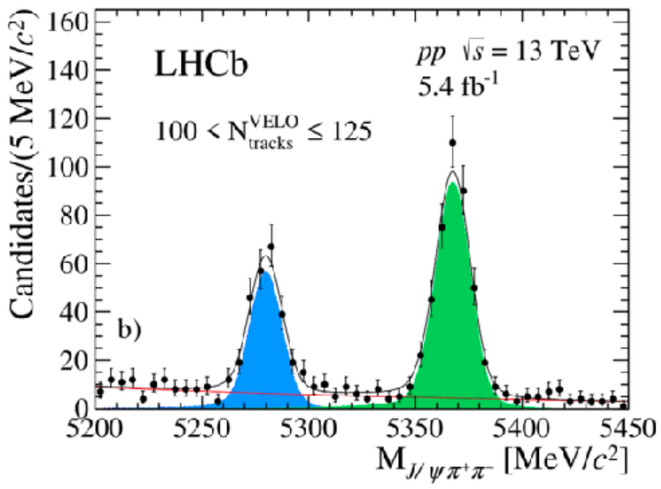
- **Hint of the intrinsic charm component in the high rapidity interval** $(3.5 < y(Z) < 4.5)$
- No-IC hypothesis inconsistent at $\sim 3\sigma$
- Result is statistically limited → **more data is needed!**

Modification of b quark hadronization

- Measurements of B mesons at colliders offer unique probes of the hadronization process by which single quarks evolve into color-neutral hadrons
- The ratio f_s/f_d has a dependence on the collision center-of-mass energy and on the B meson p_{T}
- Different hadronization mechanisms can occur (e.g. “quark coalescence”), not just fragmentation
- At LHCb this is studied by measuring the ratio of B_s^0 to B^0 cross sections, using Run 2 data
- The multiplicity metrics used in this analysis are the total number of charged tracks reconstructed in the VELO detector
  - The high-multiplicity data samples recall the environment of heavy-ions collisions
- A fit to the invariant mass of $J/\psi\pi^+\pi^-$ is performed to extract the ratio of B_s^0 to B^0 yields

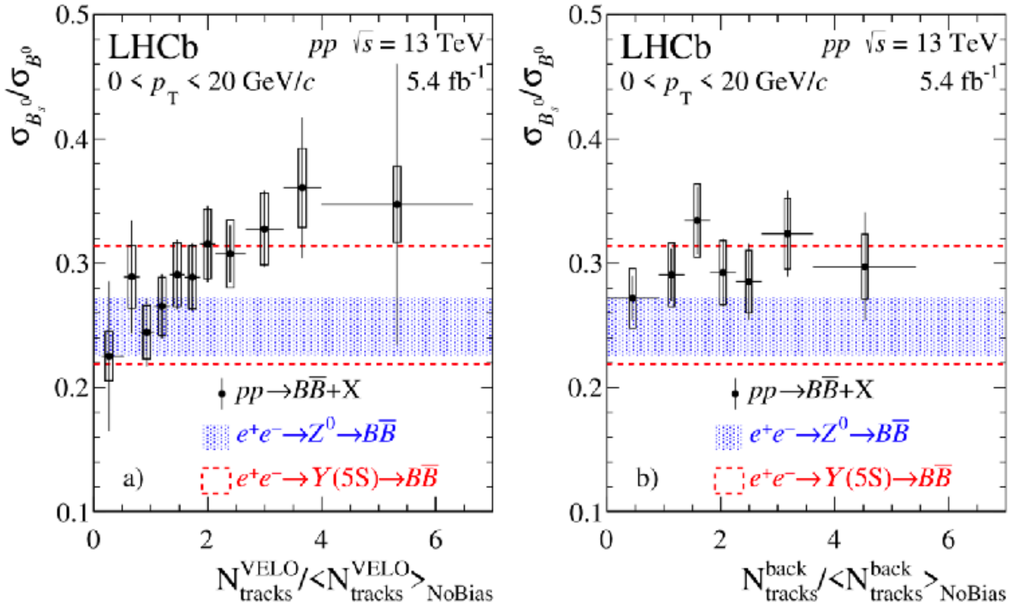






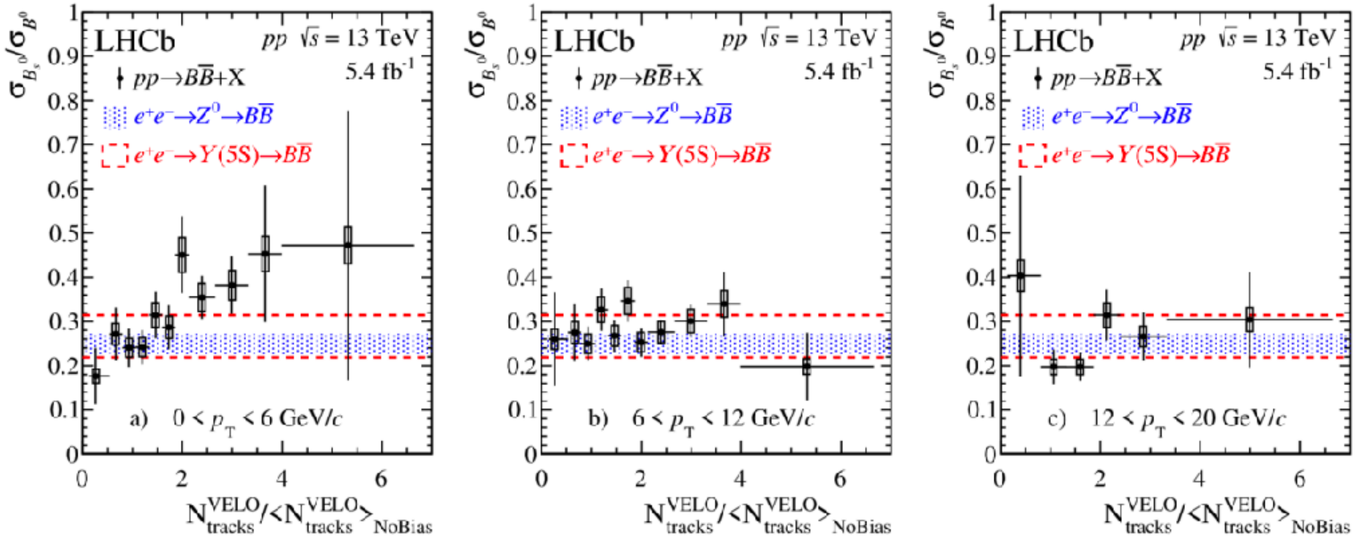
Modification of b quark hadronization

- The measurement is performed with respect to multiplicity and transverse momentum p_{T}
- LHCb results are compared with cross sections ratios measured at e^+e^- collisions



- This behaviors is expected in a scenario where low-p_{T} b quarks recombine with s quarks produced in high-multiplicity collisions
- Measurements are qualitatively consistent with quark coalescence as and additional hadronization mechanism

- Good agreement with data is found at low multiplicity
- For high multiplicity, B_s^0 mesons productions is enhanced relative to B^0 mesons
- No significant dependence is observed in the backward region

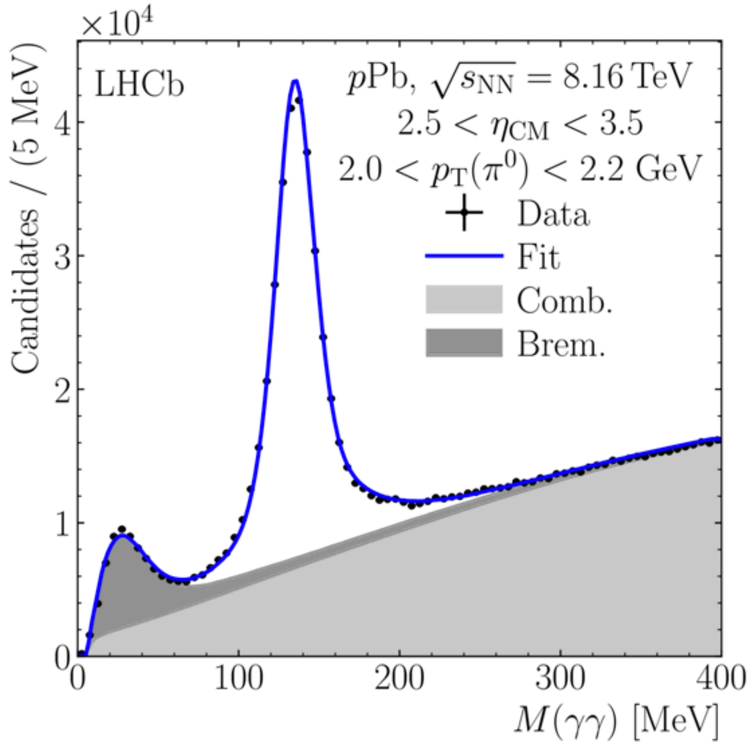


Nuclear modification factor of neutral pions

- Neutral pion production is an important probe of nuclear effects in heavy ion collisions
- In proton-lead (pPb) collisions, π^0 production is particularly sensitive to cold nuclear matter (CNM) effects on the initial state of the bound nucleons in the colliding nucleus
- This analysis measures the nuclear modification factor of π^0 meson production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

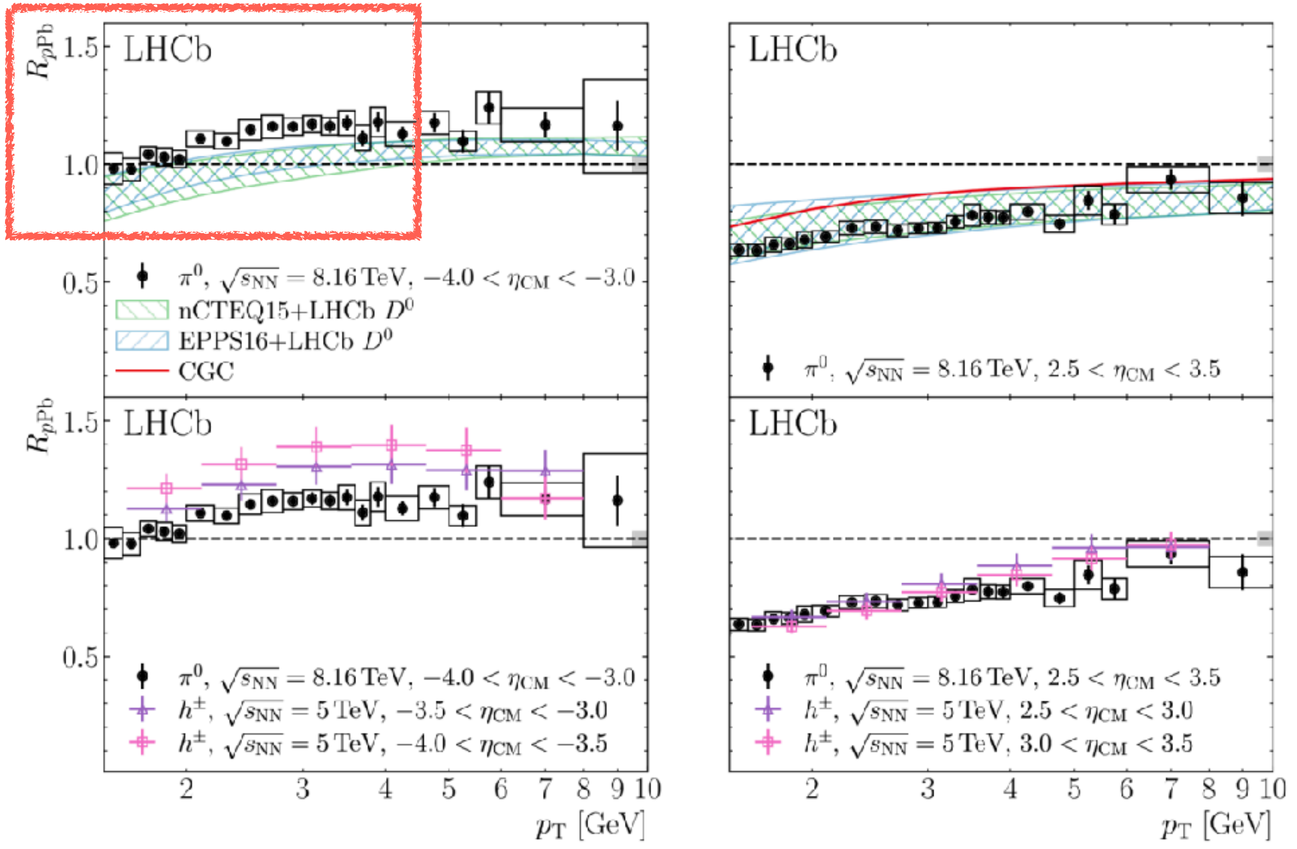
$$R_{p\mathrm{Pb}} \equiv \frac{1}{A} \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

- Measurements of π^0 production in pPb collisions at forward and backward rapidities with the LHCb detector can provide constraints on nuclear PDFs
  - Typical x between 10^{-6} and 10^{-1}
- The measurement is performed for
  - $1.5 < p_{\mathrm{T}} < 10$ GeV
  - $2.5 < \eta_{\mathrm{CM}} < 3.5$ and $-4.0 < \eta_{\mathrm{CM}} < -3.0$
- At least 1 track in VELO and π^0 reconstructed as pairs of photons



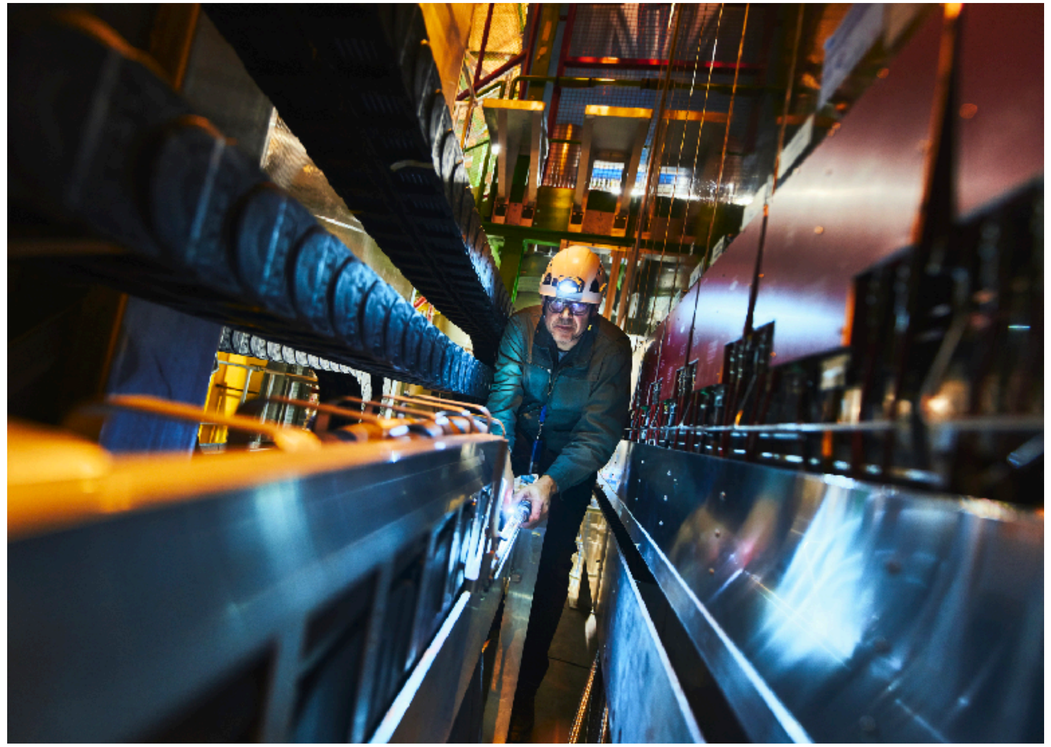
Nuclear modification factor of neutral pions

- The main systematic error comes from the interpolation between pp cross-sections and the π^0 fit model
  - Total uncertainty: 1.4 % - 9.1 %
- The backward measurement shows the first evidence of enhanced π^0 production in proton-ion collisions at LHC
- **Enhanced production for backward rapidities for** $2 < p_{\mathrm{T}} < 4$ GeV
- Results are compatible with charged-particle nuclear modification factor at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV
  - Lower enhancement for backward rapidities
  - Studies of proton and heavier unflavored mesons could help in finding an explanation!



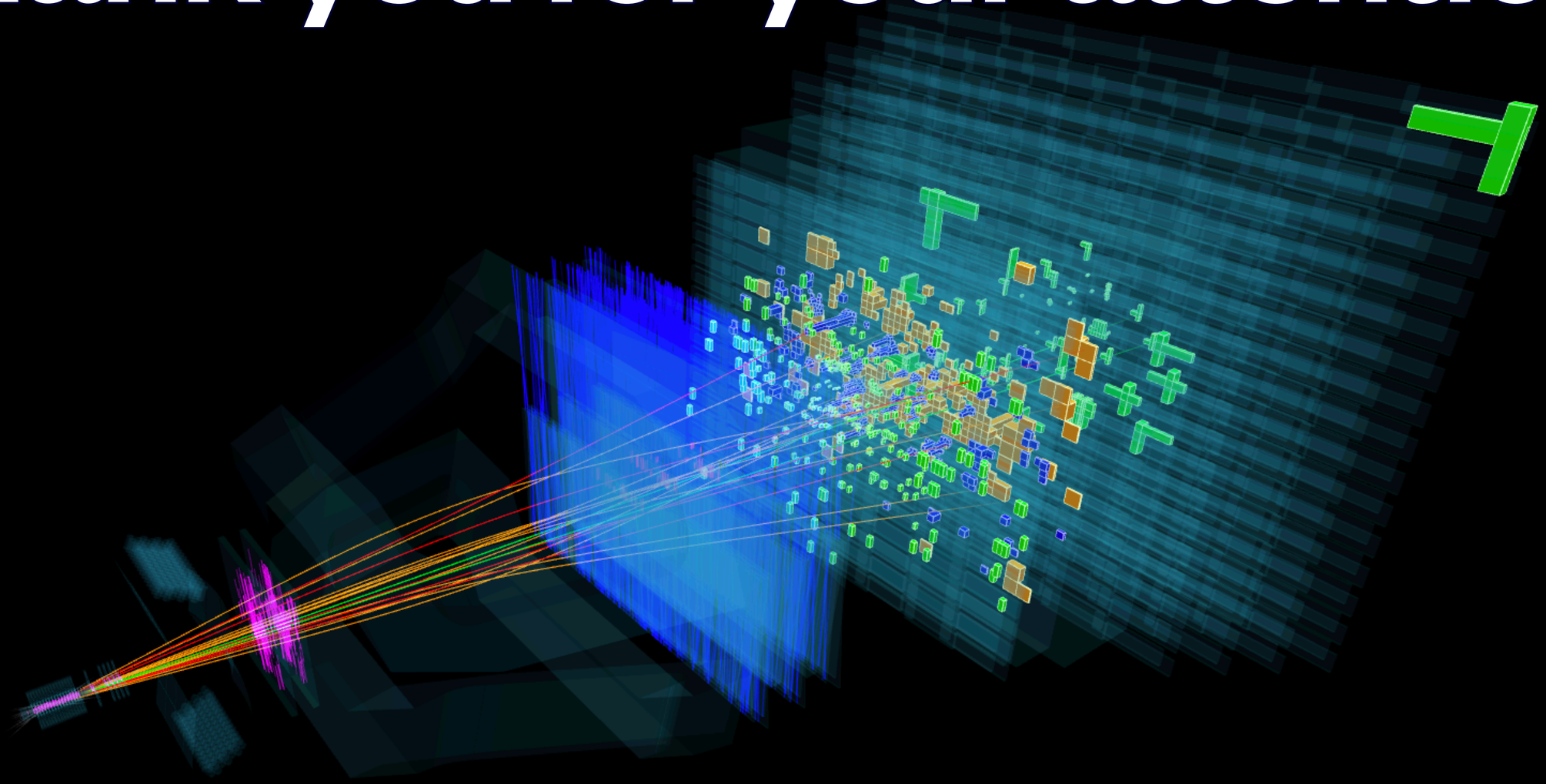
Conclusions

- **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!!)**
  - Checks on light hadron production using prompt-charged particles production
  - Measurement of differential heavy flavour di-jets cross sections
  - Intrinsic charm component in proton content at high rapidities using $Z + c-$jet events
  - Possible different hadronization process in b quark production
  - Study of nuclear modification factor for π^0



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

Thank you for your attention!



Questions?