UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN PADOVA

Jet physics at LHCb

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GENOVA - JULY 30, 2024

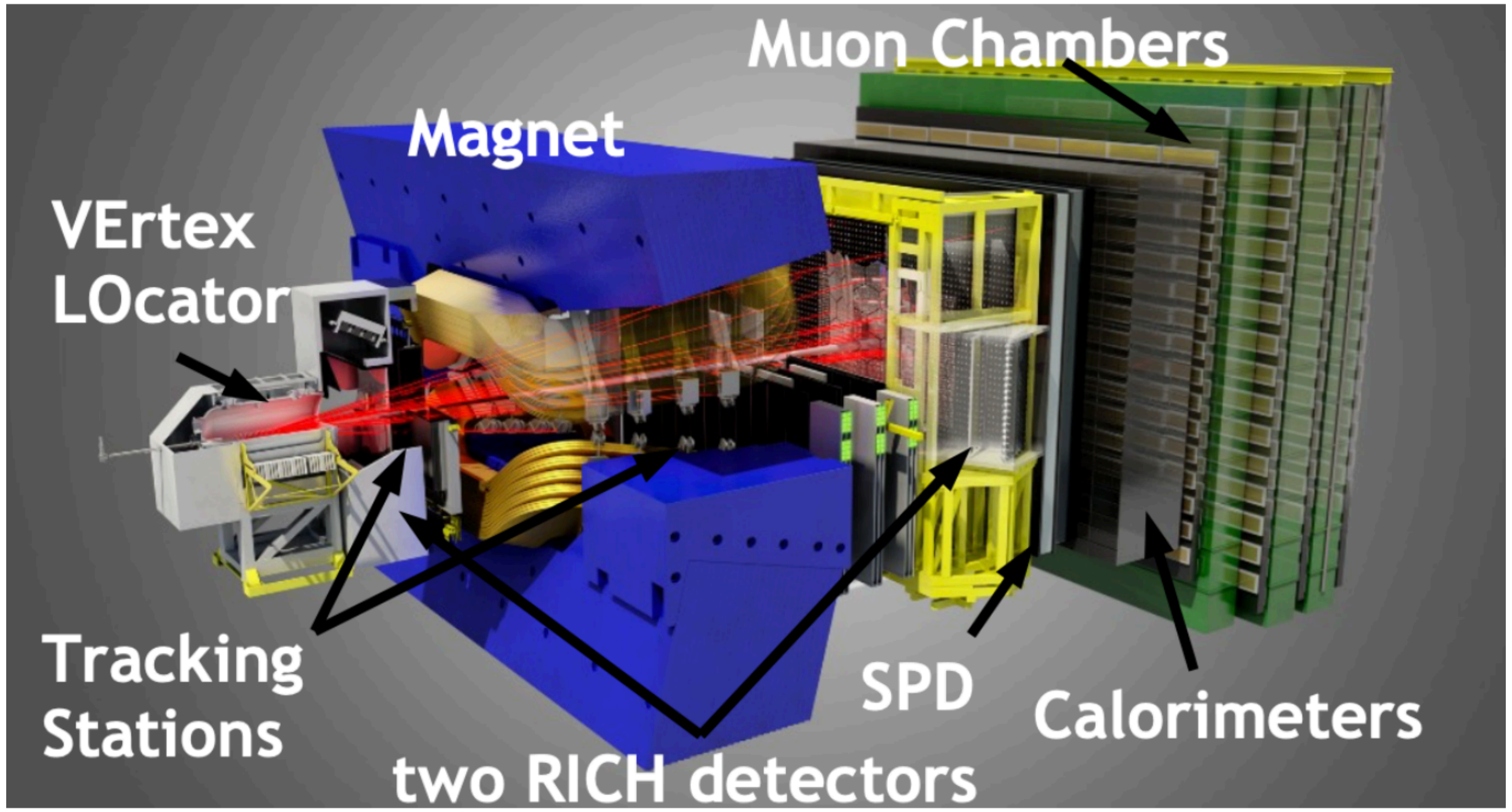
Overview

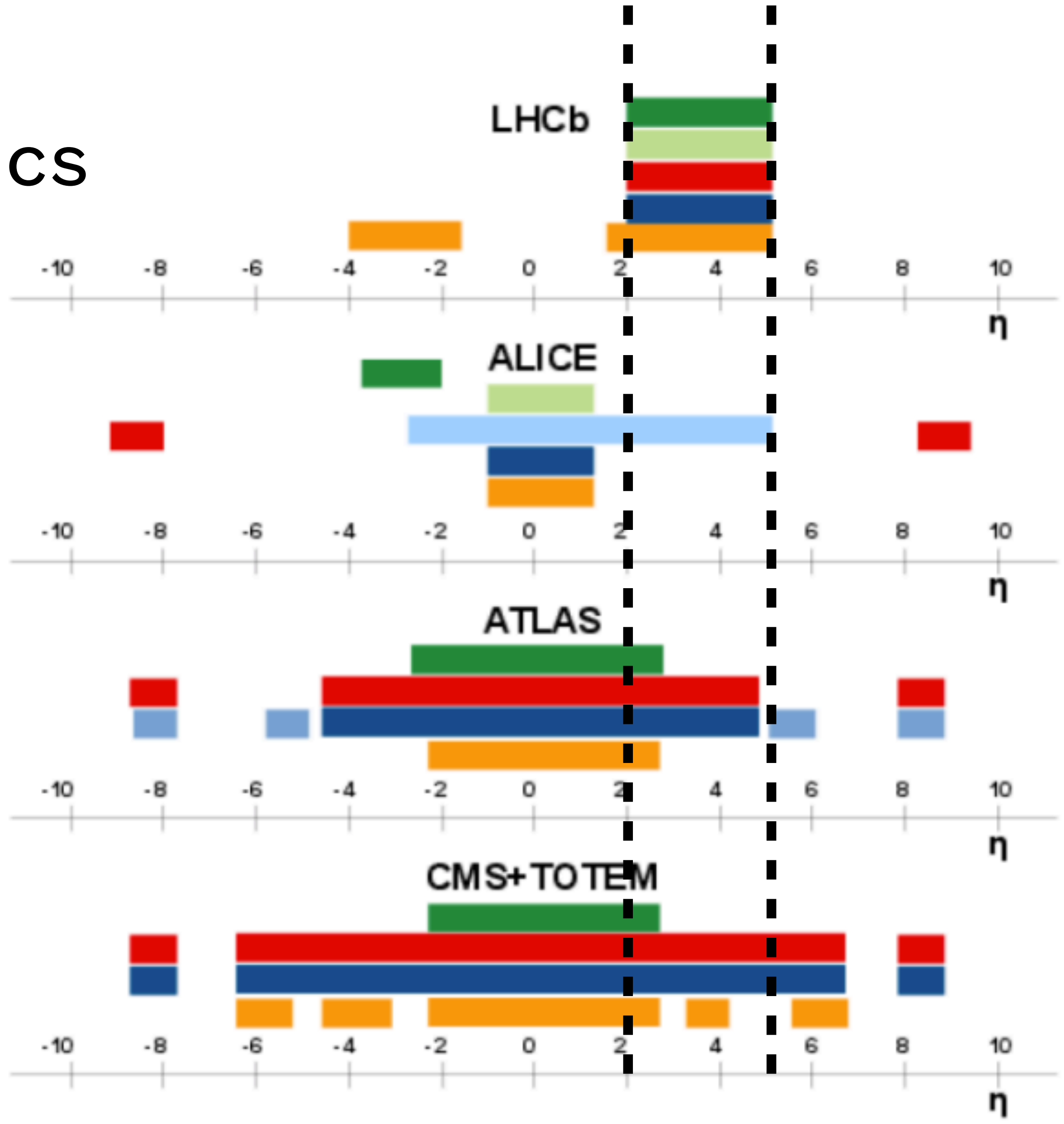
- **The LHCb detector**
- **Latest jet physics measurements**
  - Multidifferential study of identified charged hadron distributions in Z-tagged jets in proton-proton collisions at $\sqrt{s} = 13$ TeV
  - Study of Z bosons produced in association with charm in the forward region
  - Measurement of $b\bar{b}$- and $c\bar{c}$-dijet differential cross-sections in the forward region of pp collisions at $\sqrt{s} = 13$ TeV
- **New tools for jet reconstruction**
- **Conclusions**

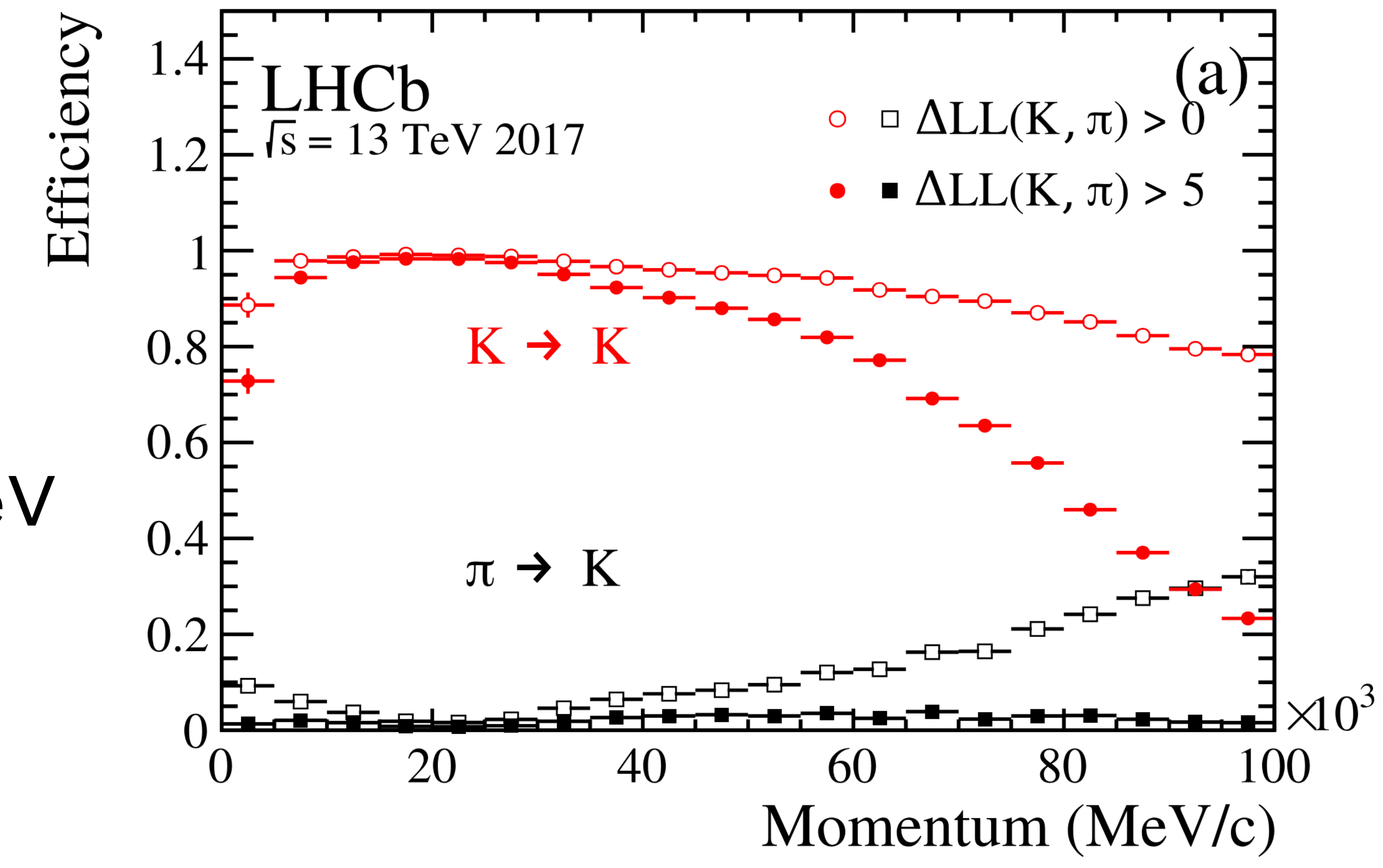
JINST 3 (2008) S08005, INT. J. MOD: PHYS. A 30, 1530022 (2015), CERN-LPCC-2018-04

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
- Excellent IP resolution, important for PV and SV reconstruction
- Excellent muon and electron ID efficiency, with low misidentification
- **Good hadron PID**, thanks to RICH detectors

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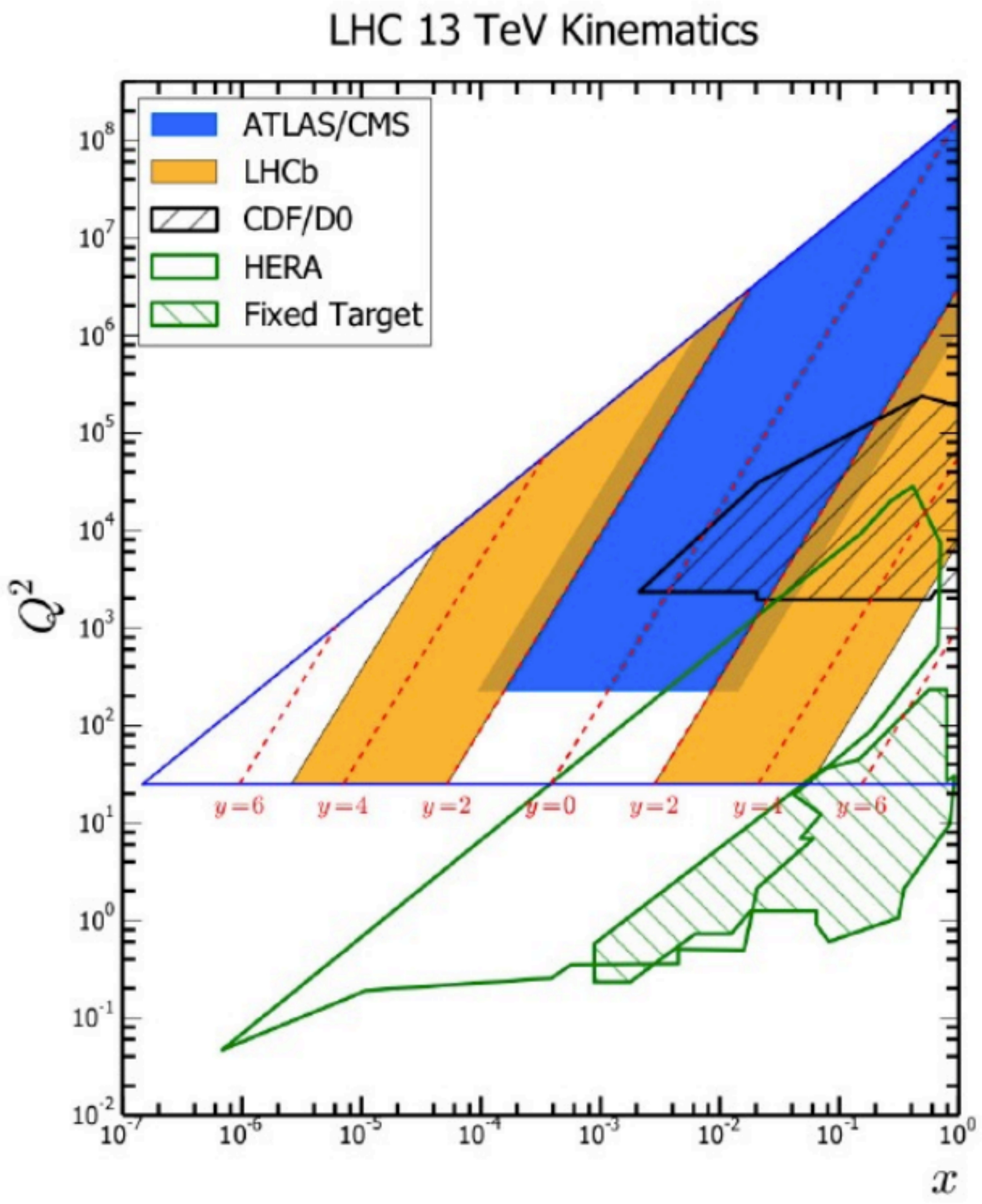
The LHCb detector and QCD



- 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**!

Latest jet physics measurements

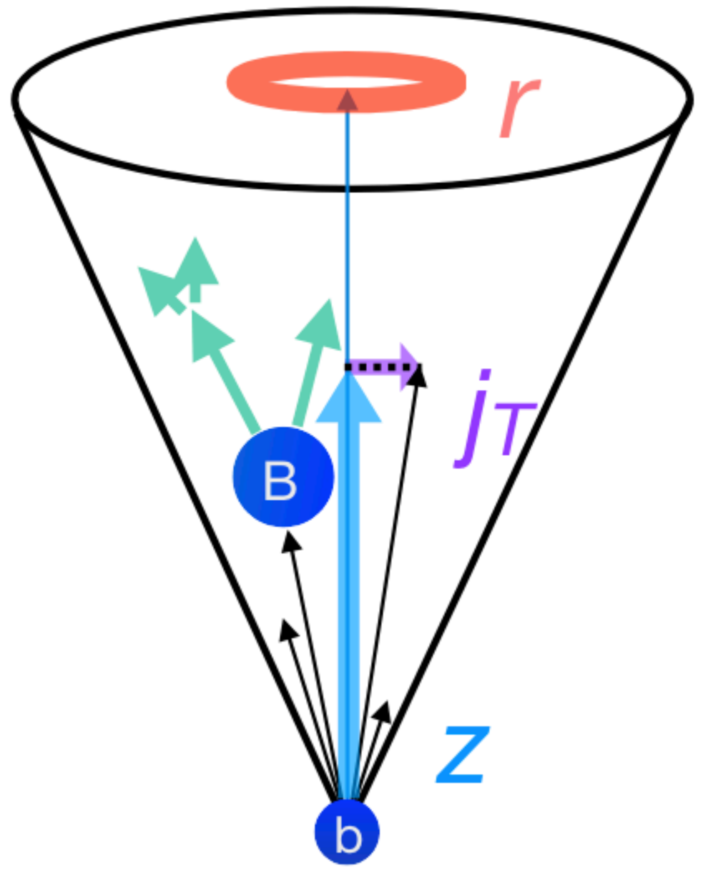
PHYS. REV. LETT. 123.232001, PHYS. REV. D 108, L031103

Charged hadron distributions in Z-tagged jets

- Several motivations:
  - Extending the previous measurement of **non-identified** charged hadron
  - Access Transverse Momentum Dependent Jet Fragmentation Functions (TMD JFF) for hadrons
  - Access flavour dependent hadron production mechanisms
- This analysis targets 2016 data, $\mathscr{L} \sim 1.6\ \mathrm{fb}^{-1}$
- Measure Jet Fragmentation Functions (JFF) **differentially**

$$f(z, j_\mathrm{T}) = \frac{1}{N_{Z+\mathrm{jet}}} \frac{\mathrm{d}N_\mathrm{had}(z, j_\mathrm{T})}{\mathrm{d}z\,\mathrm{d}j_\mathrm{T}}, \quad F(z) = \frac{1}{N_{Z+\mathrm{jet}}} \frac{\mathrm{d}N_\mathrm{had}(z)}{\mathrm{d}z}, \quad F(j_\mathrm{T}) = \frac{1}{N_{Z+\mathrm{jet}}} \frac{\mathrm{d}N_\mathrm{had}(j_\mathrm{T})}{\mathrm{d}j_\mathrm{T}}$$

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



$$r = \sqrt{(\phi_{jet} - \phi_{hadron})^2 + (\eta_{jet} - \eta_{hadron})^2}$$

$$j_T = \frac{|\mathbf{p}_\mathbf{jet} \times \mathbf{p}_\mathbf{hadron}|}{|\mathbf{p}_\mathbf{jet}|}$$

$$z = \frac{\mathbf{p}_\mathbf{jet} \cdot \mathbf{p}_\mathbf{hadron}}{|\mathbf{p}_\mathbf{jet}|^2}$$

$$f(z, j_\mathrm{T}) = \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}\,\mathrm{d}z\,\mathrm{d}j_\mathrm{T}} \Big/ \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}},$$

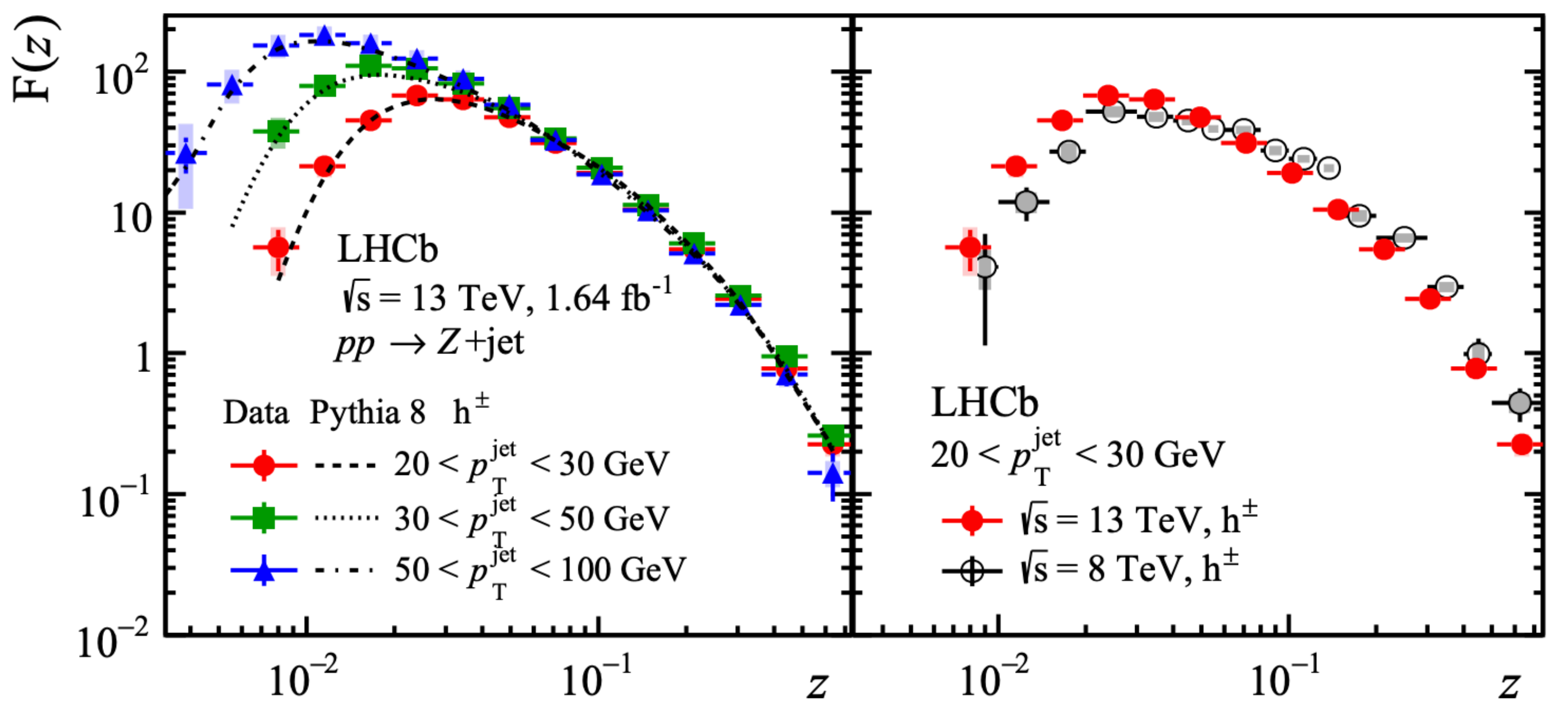
$$F(z) = \int \mathrm{d}j_\mathrm{T}\ f(z, j_\mathrm{T}) = \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}\,\mathrm{d}z} \Big/ \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}}$$

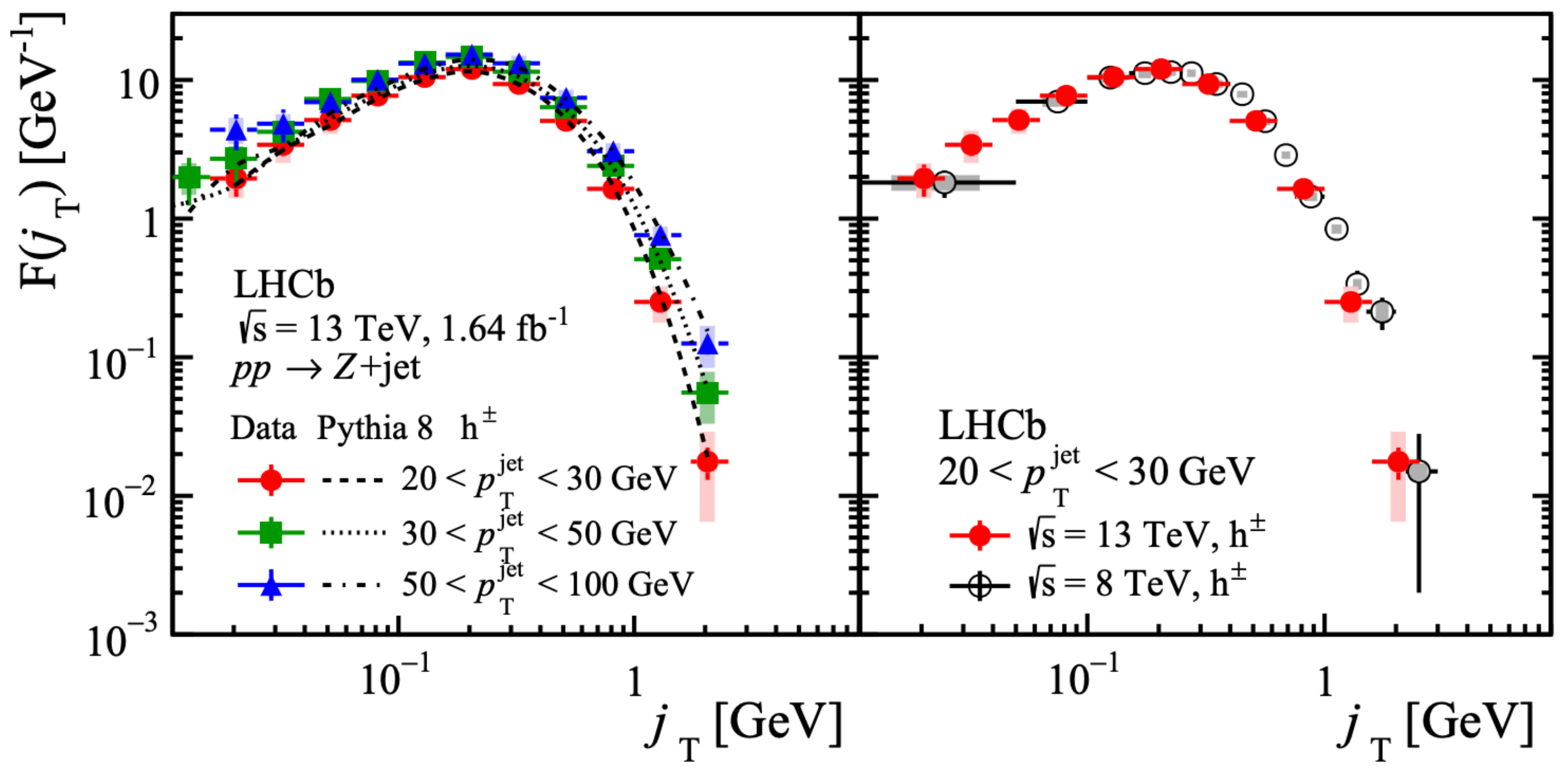
$$F(j_\mathrm{T}) = \int \mathrm{d}z\ f(z, j_\mathrm{T}) = \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}\,\mathrm{d}j_\mathrm{T}} \Big/ \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}}$$

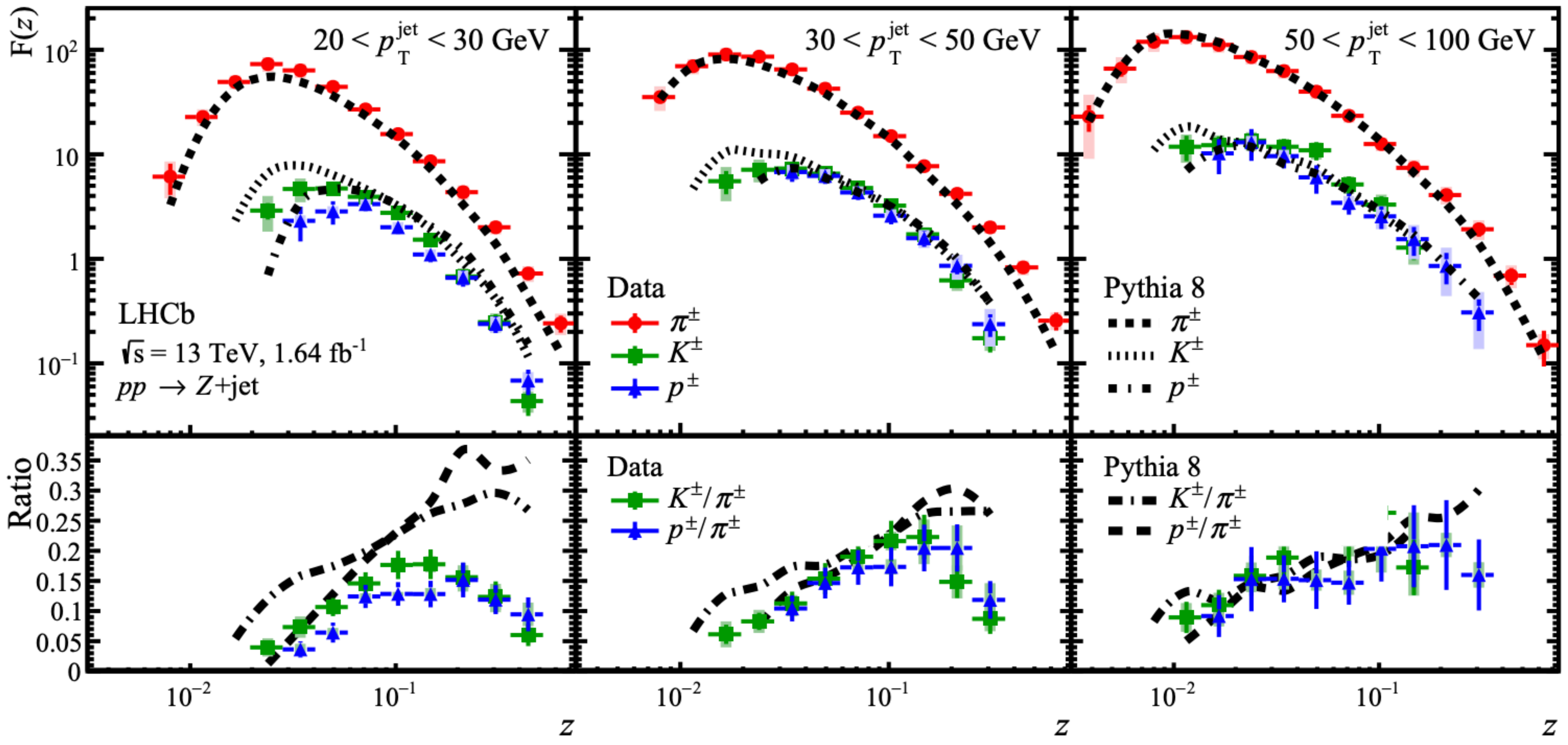
PHYS. REV. LETT. 123.232001, PHYS. REV. D 108, L031103

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 for jets with higher p_T
  - Comparisons with $\sqrt{s} = 8$ TeV show **similarity in shape**





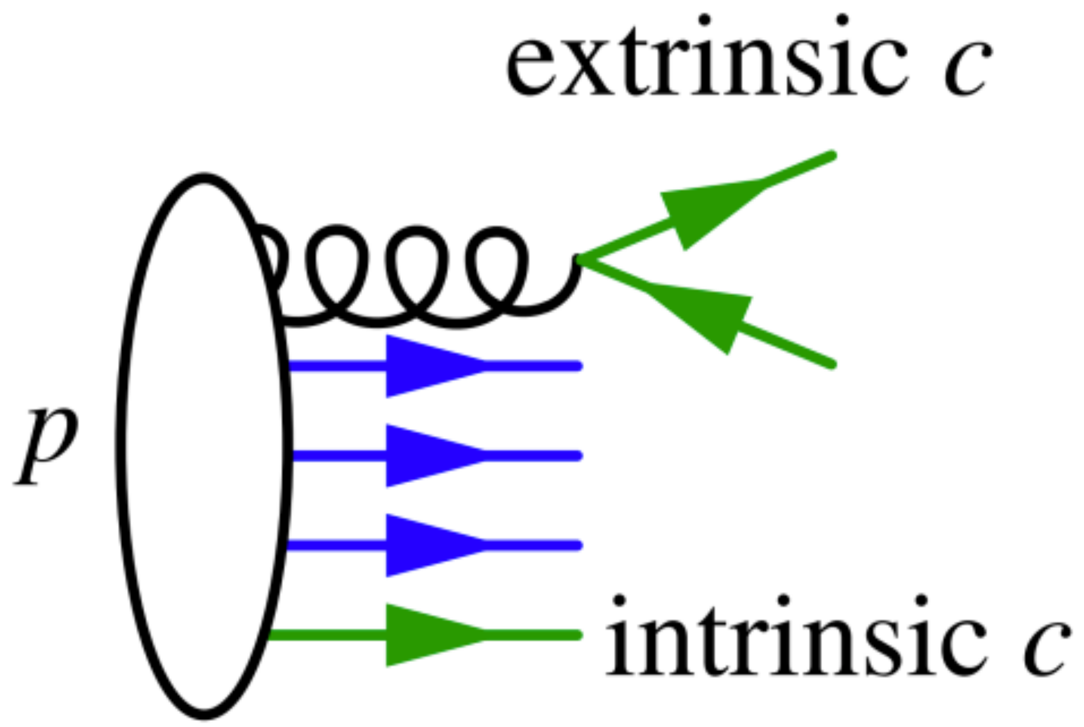


- z and j_T distributions for JFFs and ratios shown for different hadrons (for CT09MCS PDF)
- Relevant underestimation (overestimation) of charged pions (kaons and protons) by PYTHIA8
- An analysis is ongoing also with tagged jets

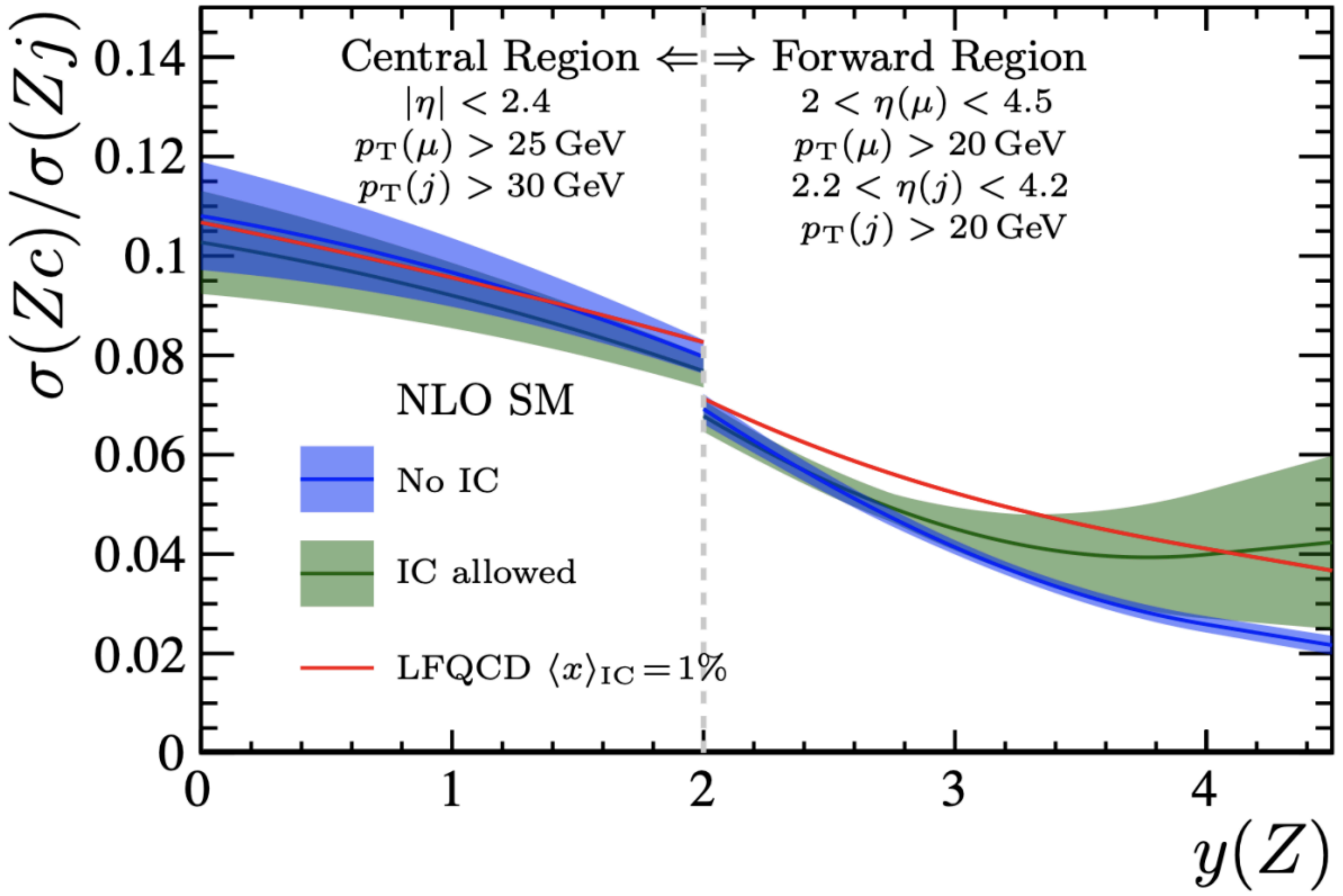
PHYS. REV. LETT. 128, 082001

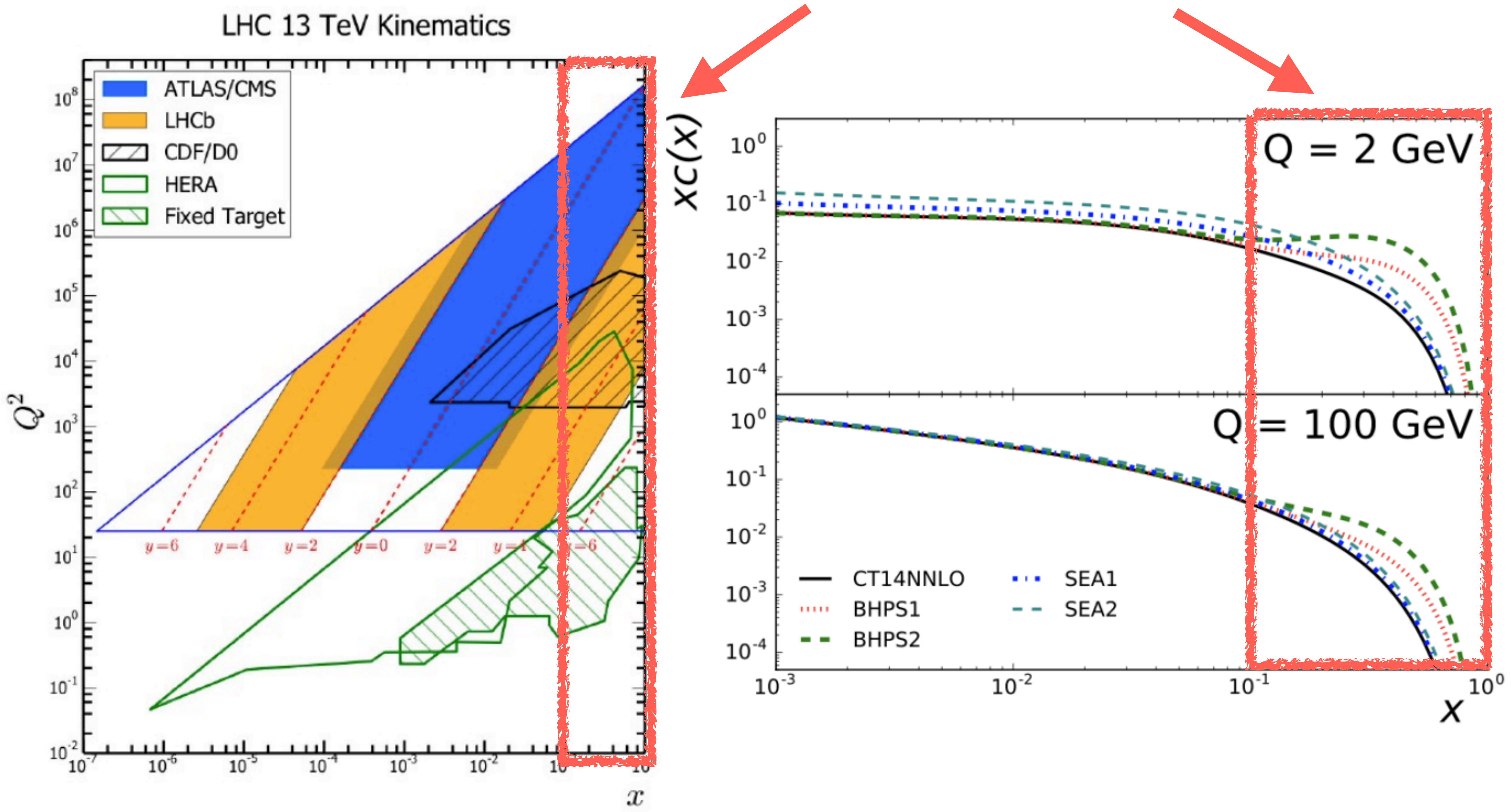
Z+c-jet production

- 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



- IC component in the proton has not been excluded
- In some model, IC component would manifest itself for $x > 0.1$



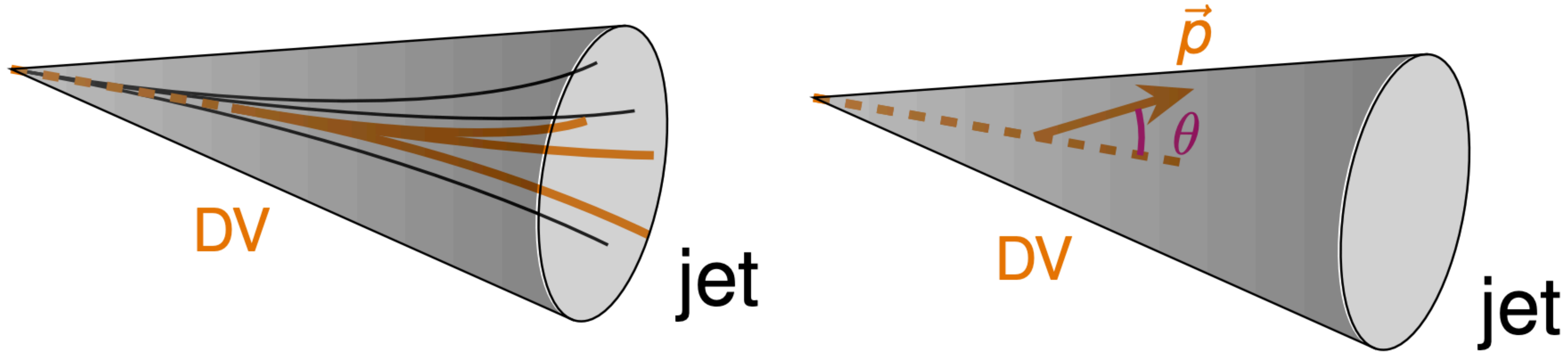


- Idea: study high-x charm quarks to search for IC
- $Z + c$-jet production in forward region is sensitive to the high x and high Q^2 intrinsic charm component
  → **feasible at LHCb!**

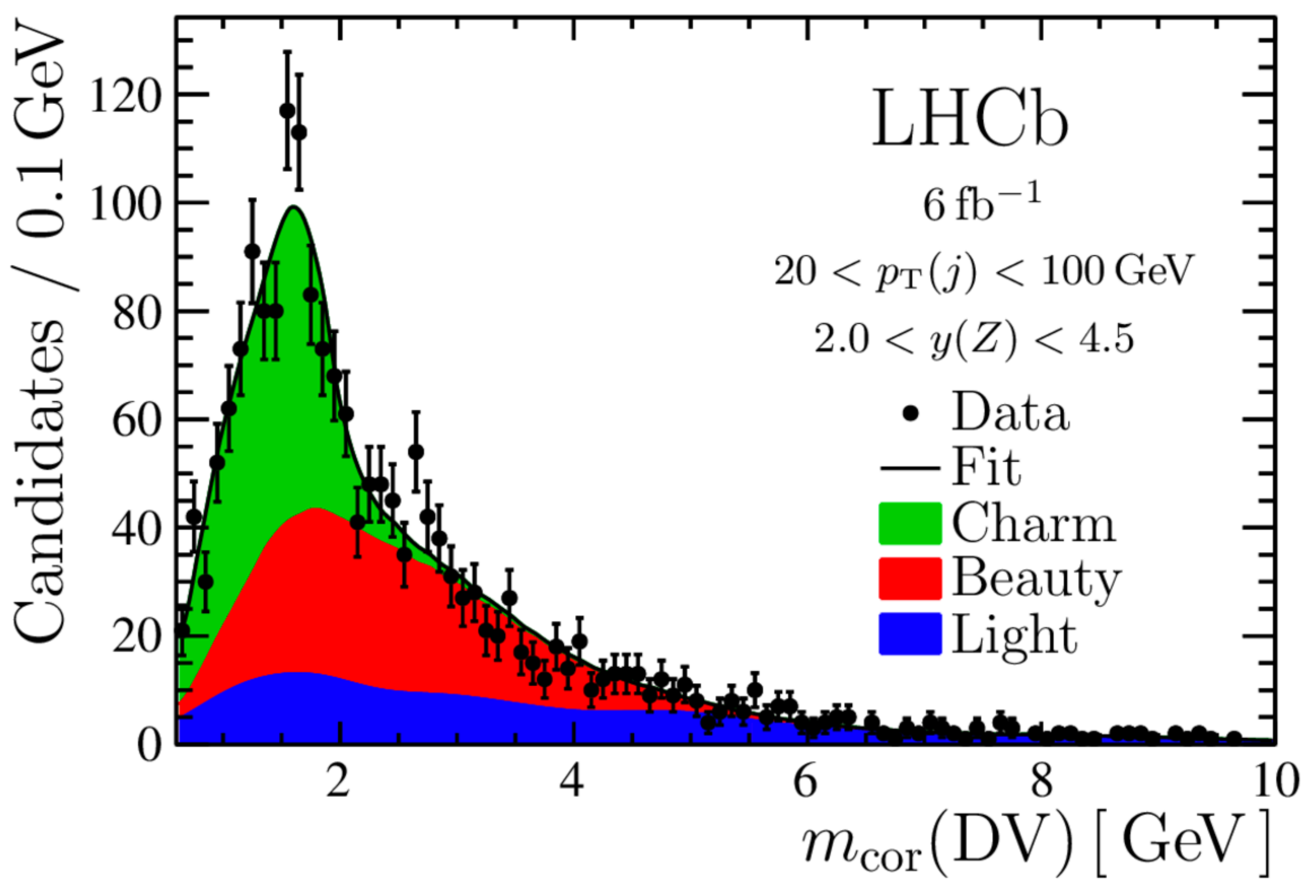
PHYS. REV. LETT. 128, 082001

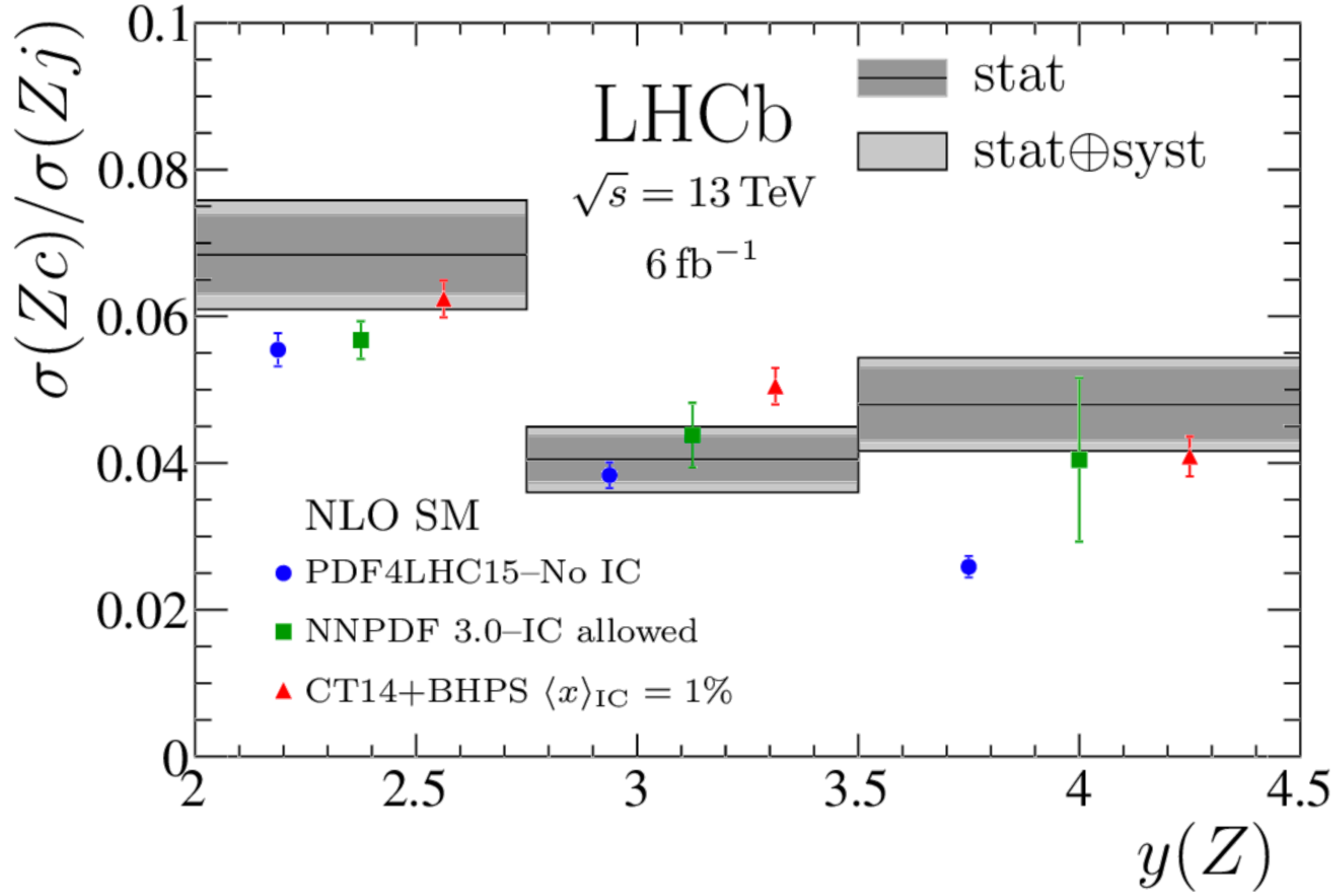
Z+c-jet production

- The 13 TeV dataset is used, $\mathscr{L} \sim 6\ \text{fb}^{-1}$ (Run 2 condition)
- Triggering on $Z \to \mu\mu$, requiring 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



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



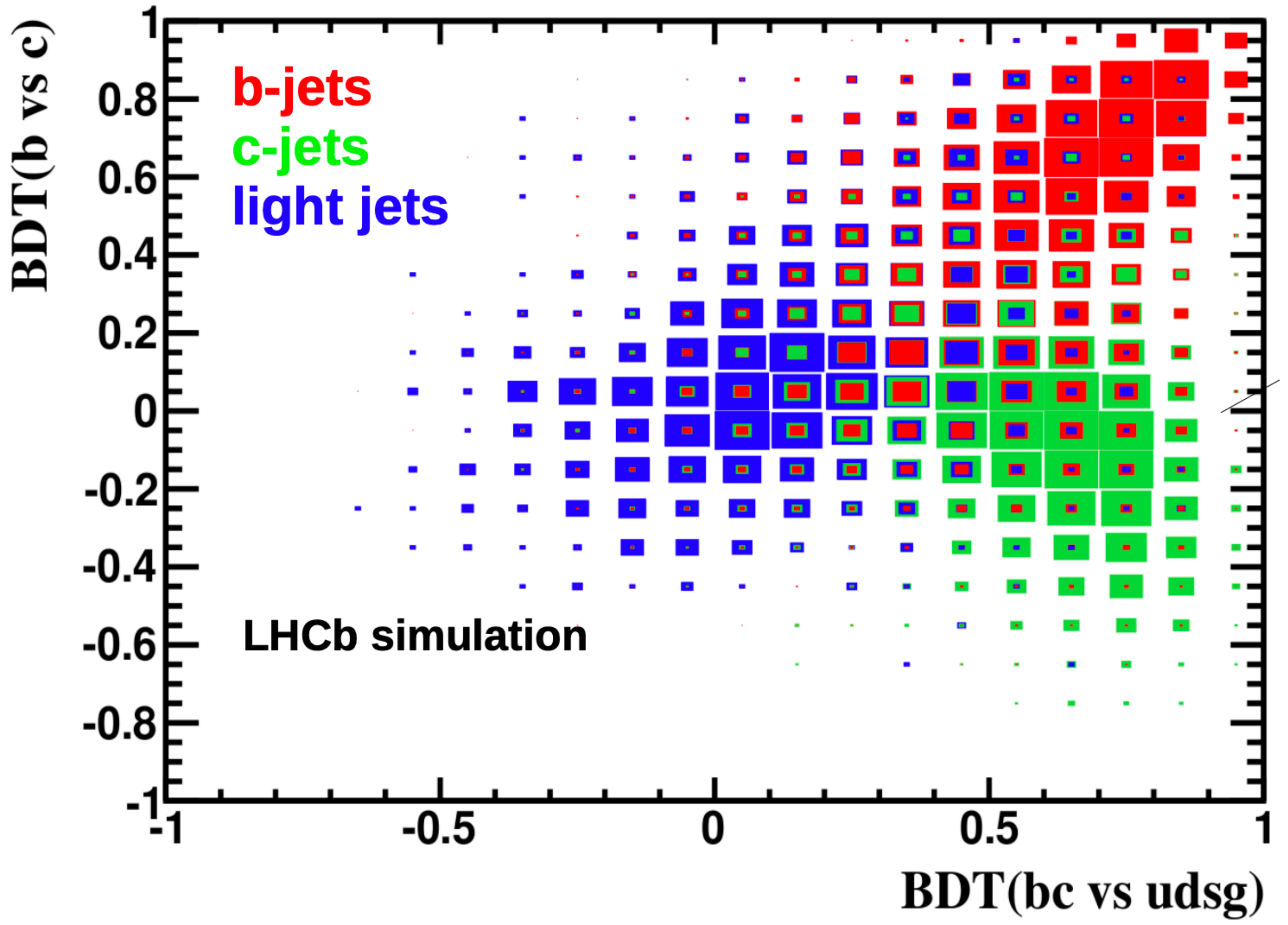


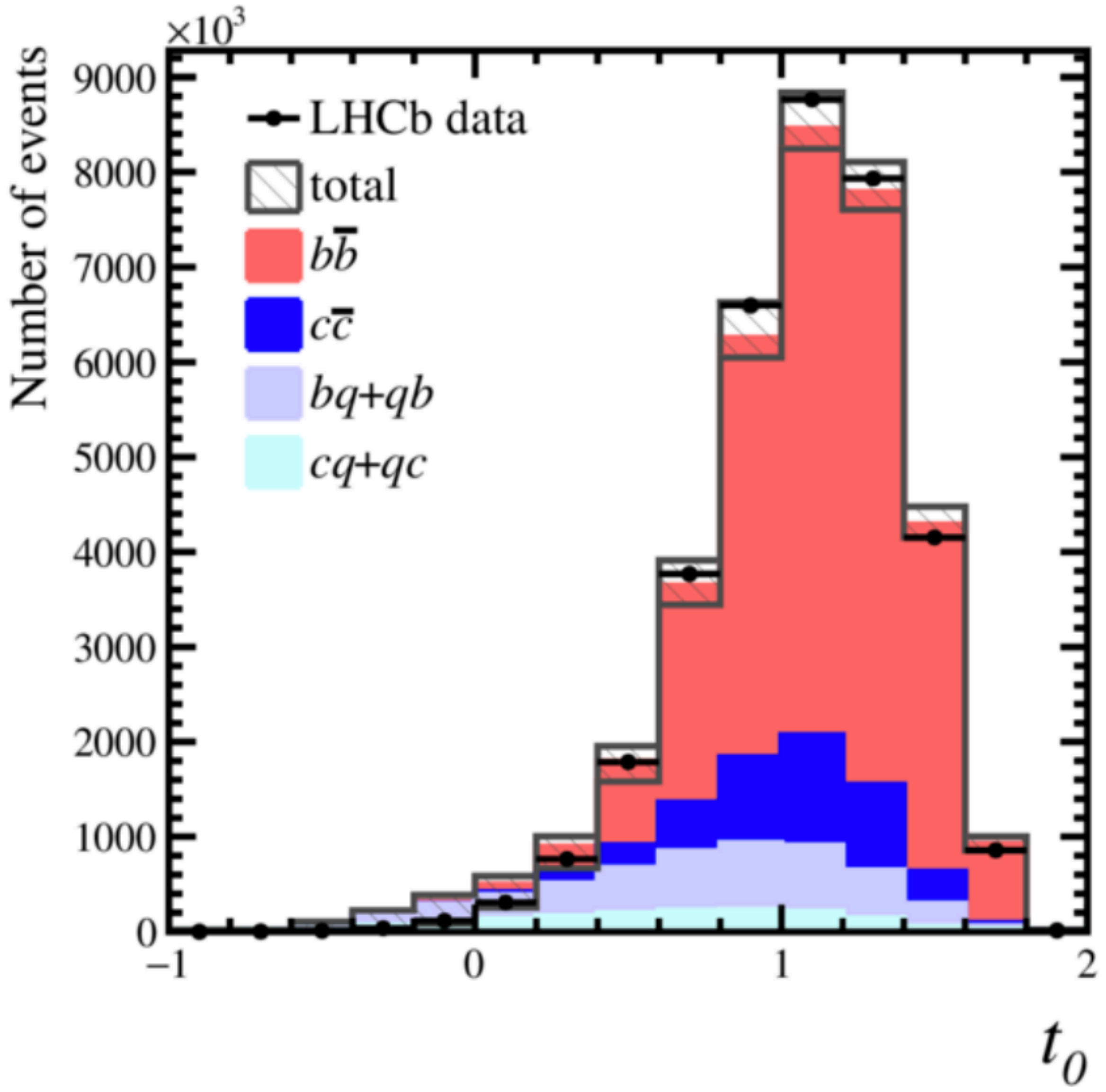
- **Hint of the intrinsic charm component in the high rapidity interval** $(3.5 < y(Z) < 4.5)$
- No-IC hypothesis inconsistent at $\sim 3\sigma$
- Result is statistically limited → **more data is needed!**

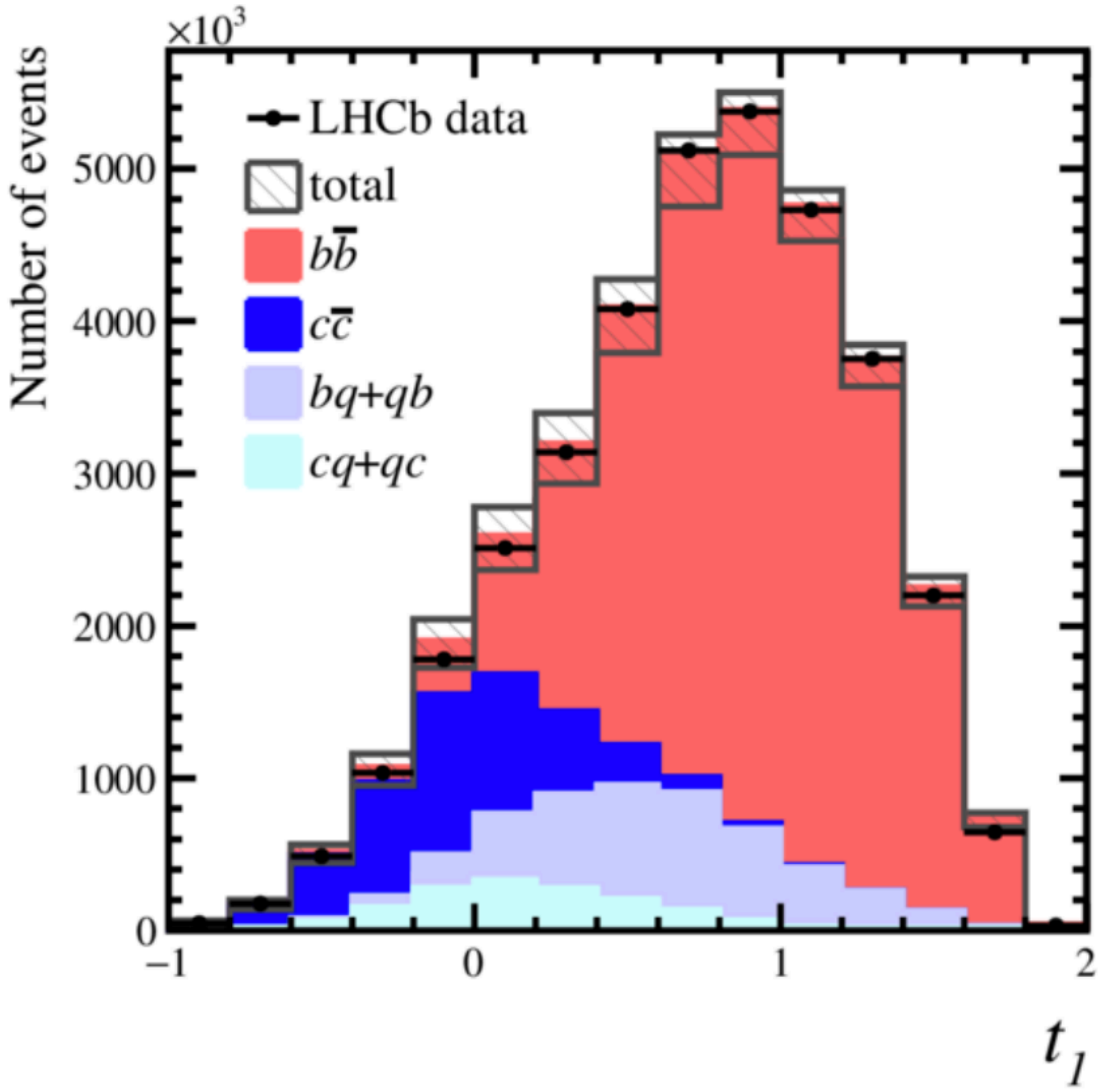
JHEP 02 (2021) 023

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

- The main idea is to study the decay of high mass resonances in $b\bar{b}$ and $c\bar{c}$ jet pairs (search for $H \to c\bar{c}$)
- QCD background has an important role in these analyses
  - Therefore, understand the handles on this kind of background
- A first study has been performed to measure $b\bar{b}$ and $c\bar{c}$ differential cross sections with 2016 data
- Directly trigger on di-jets **with SV reconstructed**







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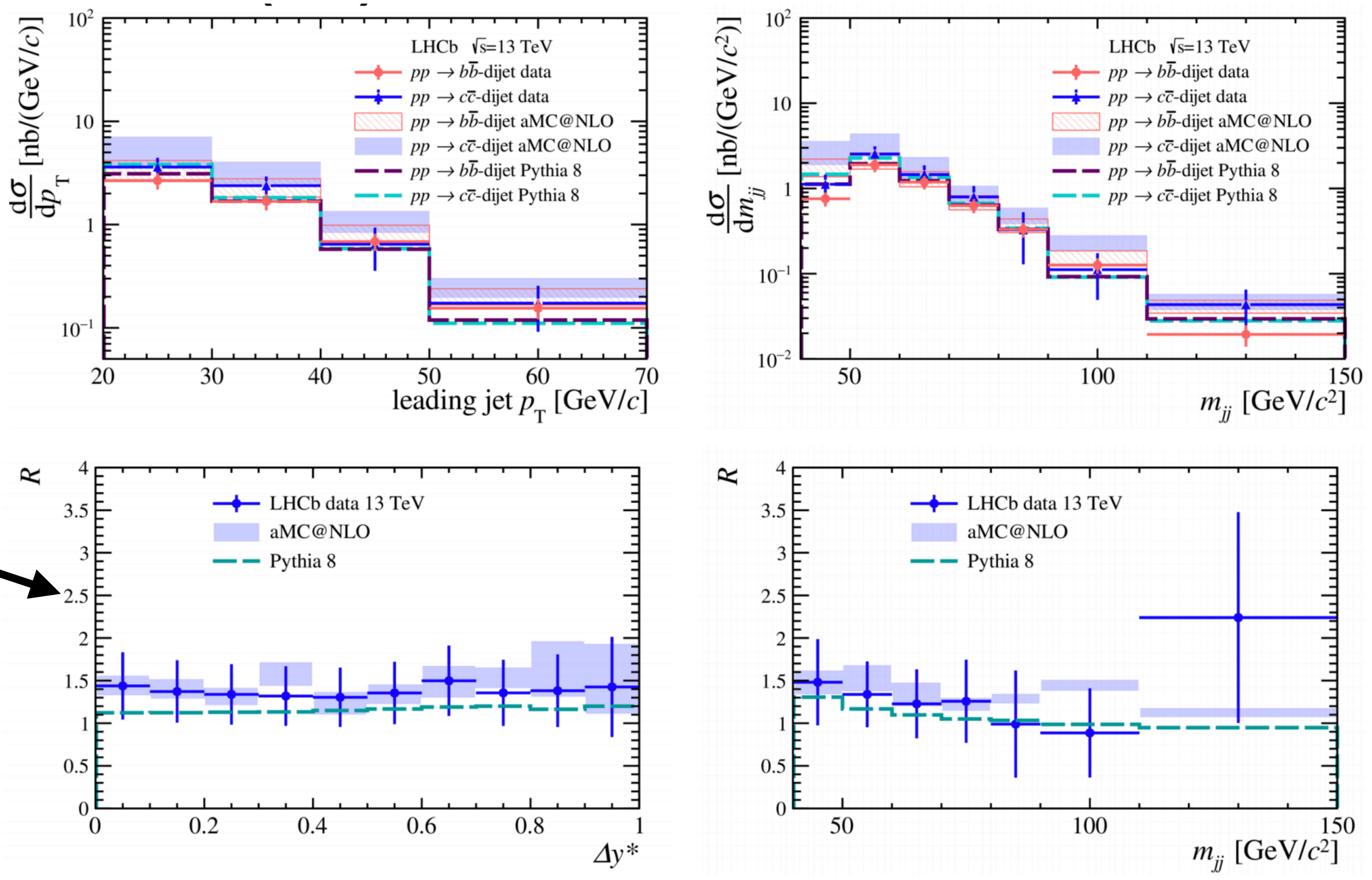
$b\bar{b}$ and $c\bar{c}$ differential cross-section

- 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 has been the first inclusive, direct measurement of $c\bar{c}$ differential cross section at a hadron collider**

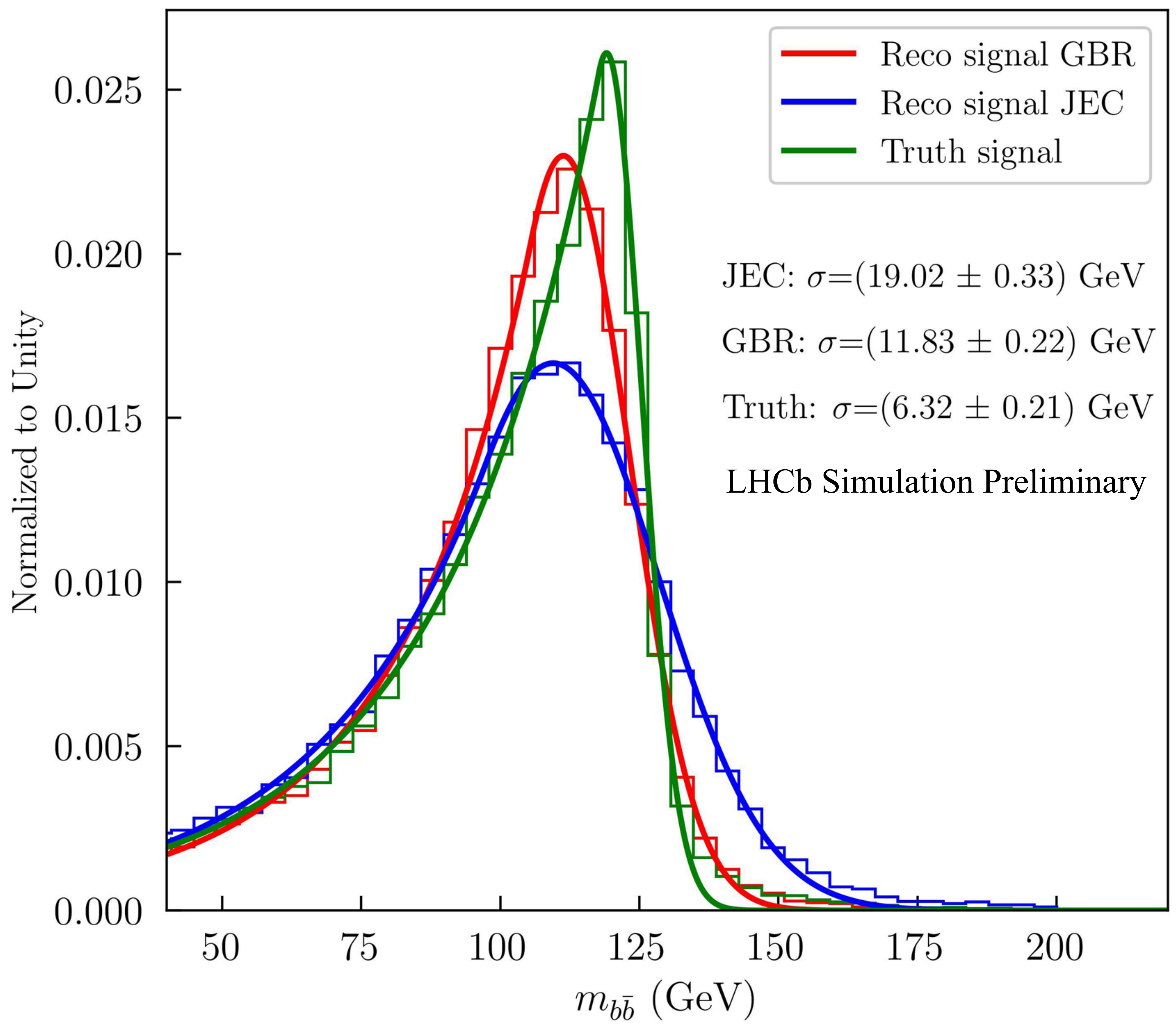


New tools for jet reconstruction

LHCB-FIGURE-2023-029

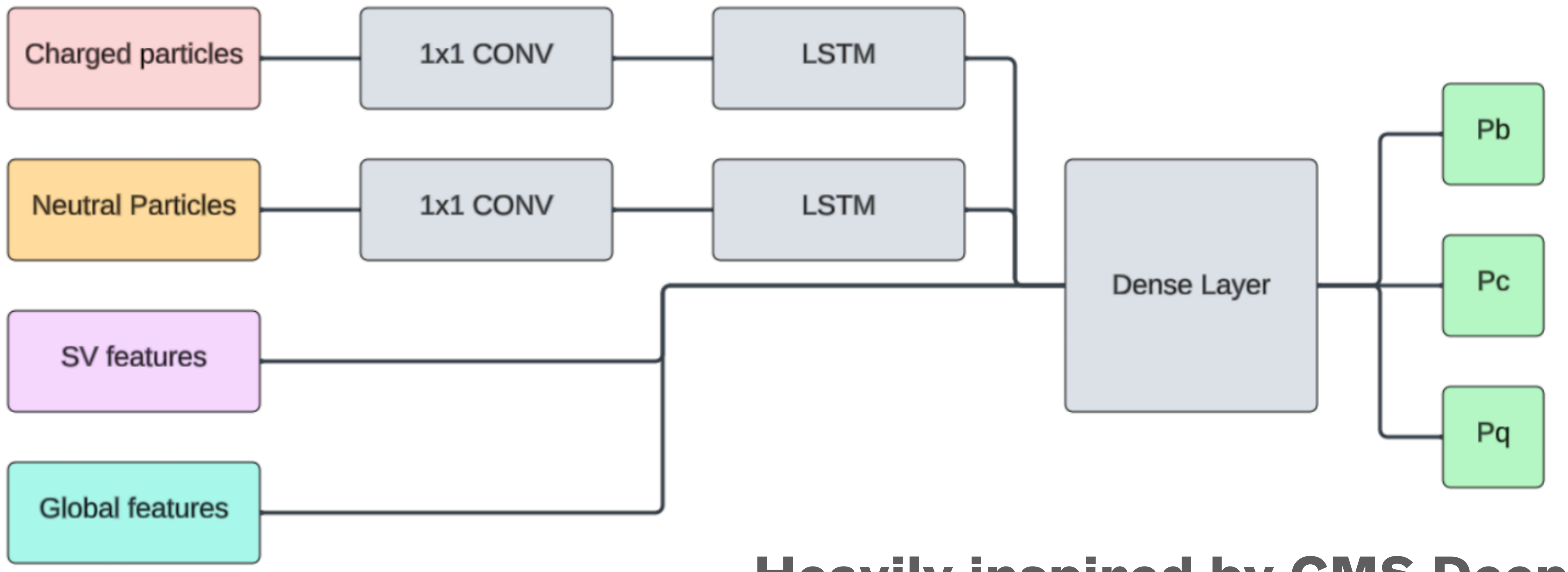
Regression technique for di-jet invariant mass

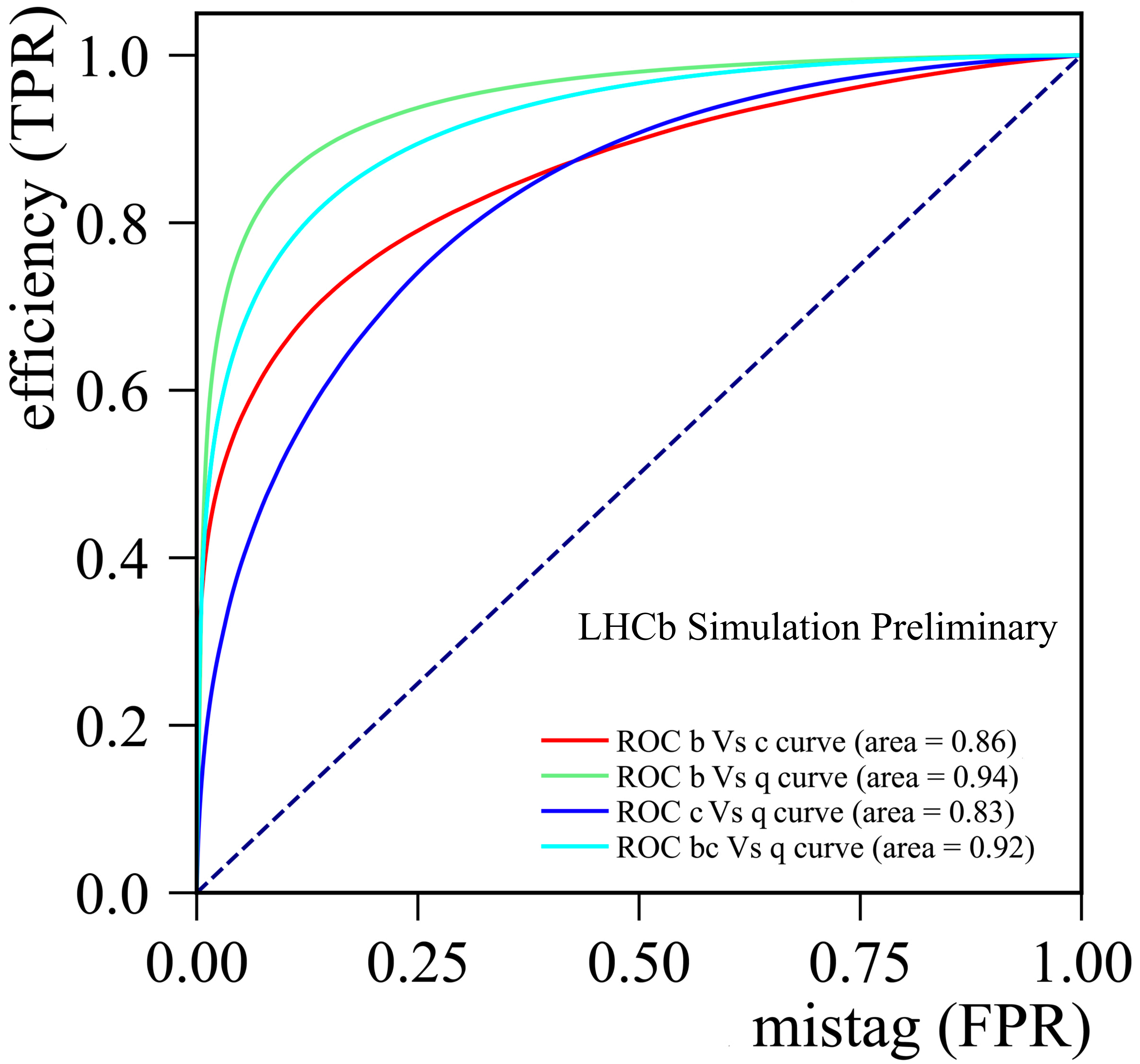
- Fundamental to have precise calibration and reconstruction of jets
  - Search for $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$ based on fit to invariant mass
- A new reconstruction tool has been implemented, based on a **regression technique**
- A **Gradient Boosted Regressor** (GBR) is used to reconstruct the reconstructed invariant mass
- 51 observables from the **jet kinematics** and **substructure** are used
- Up to now, this technique specifically targets **Higgs reconstruction**
- Compared to standard Jet Energy Correction (JEC) tools, a 50% **improvement** on the Higgs invariant mass is found



DNN for jet tagging

- Currently, jet tagging relies on **Secondary Vertex** (SV) identification and BDTs to distinguish between bc vs. q and b vs. c
  - This is **limited** by the **SV reconstruction efficiency**
- "New" approach: Deep Neural Network (DNN)
  - 400 jet observables are used (**not necessarily requiring SV**)
  - Features related to **jet constituents** and **sub-structure**
  - 3 output probabilities: P_b, P_c and P_q



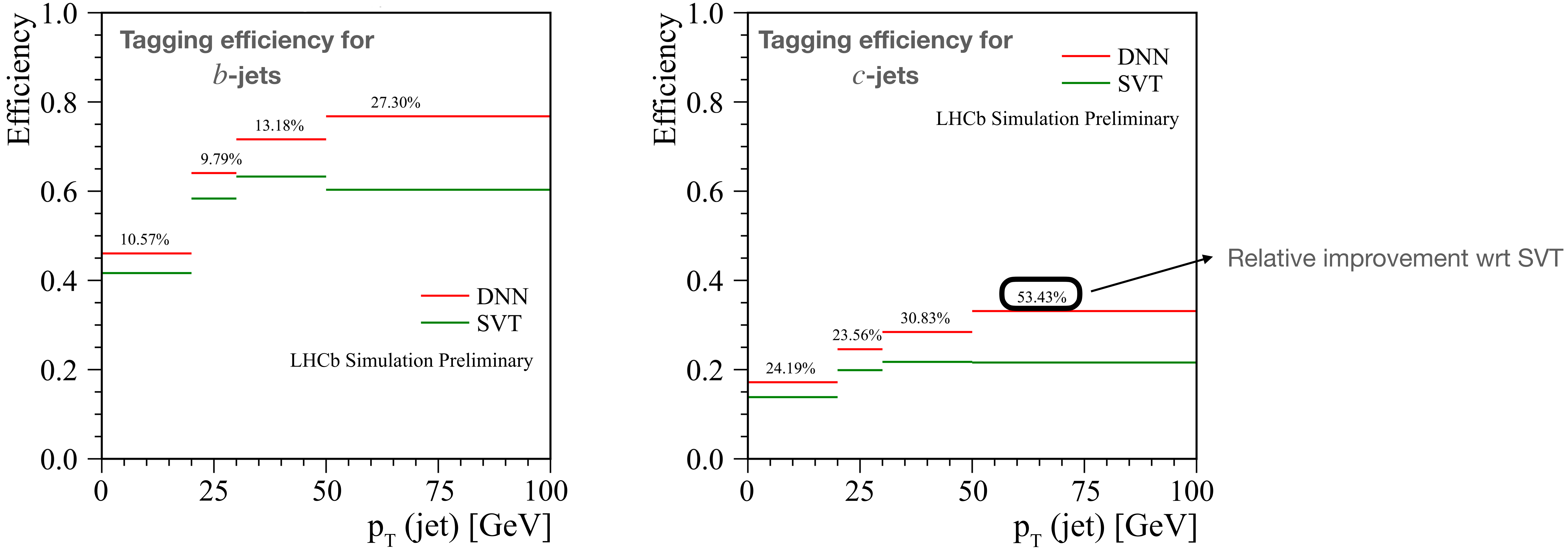


Heavily inspired by CMS DeepJet!

LHCB-FIGURE-2023-029

DNN for jet tagging

- The DNN is trained using $b\bar{b}$, $c\bar{c}$ and $q\bar{q}$ di-jets simulation
    - **SV is not strictly required** (very important for future runs of LHCb)
- Performance with respect to standard SV tagging (SVT) algorithm show **good improvement** ($> 20\,\%$ for c-jet tagging)
    - These plots are obtained requiring the DNN to have the **same light jet mis-identification** as SVT ($\sim 1\,\%$)



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
- **New tools to reconstruct and identify jets**

Thank you for your attention