Opportunities for Hadronization Measurements with Heavy-Flavor-Tagged Jets at LHCb

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On behalf of the LHCb Collaboration

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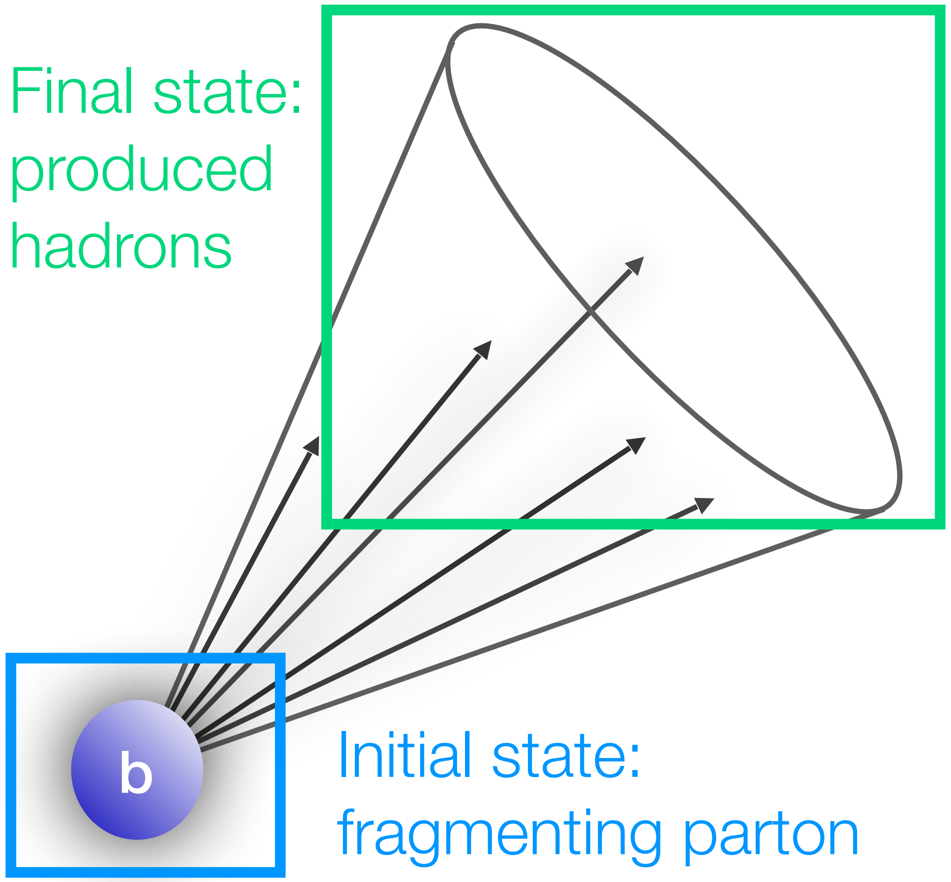
Heavy-Flavor-Tagged Jets: Ideal Systems for Hadronization Studies



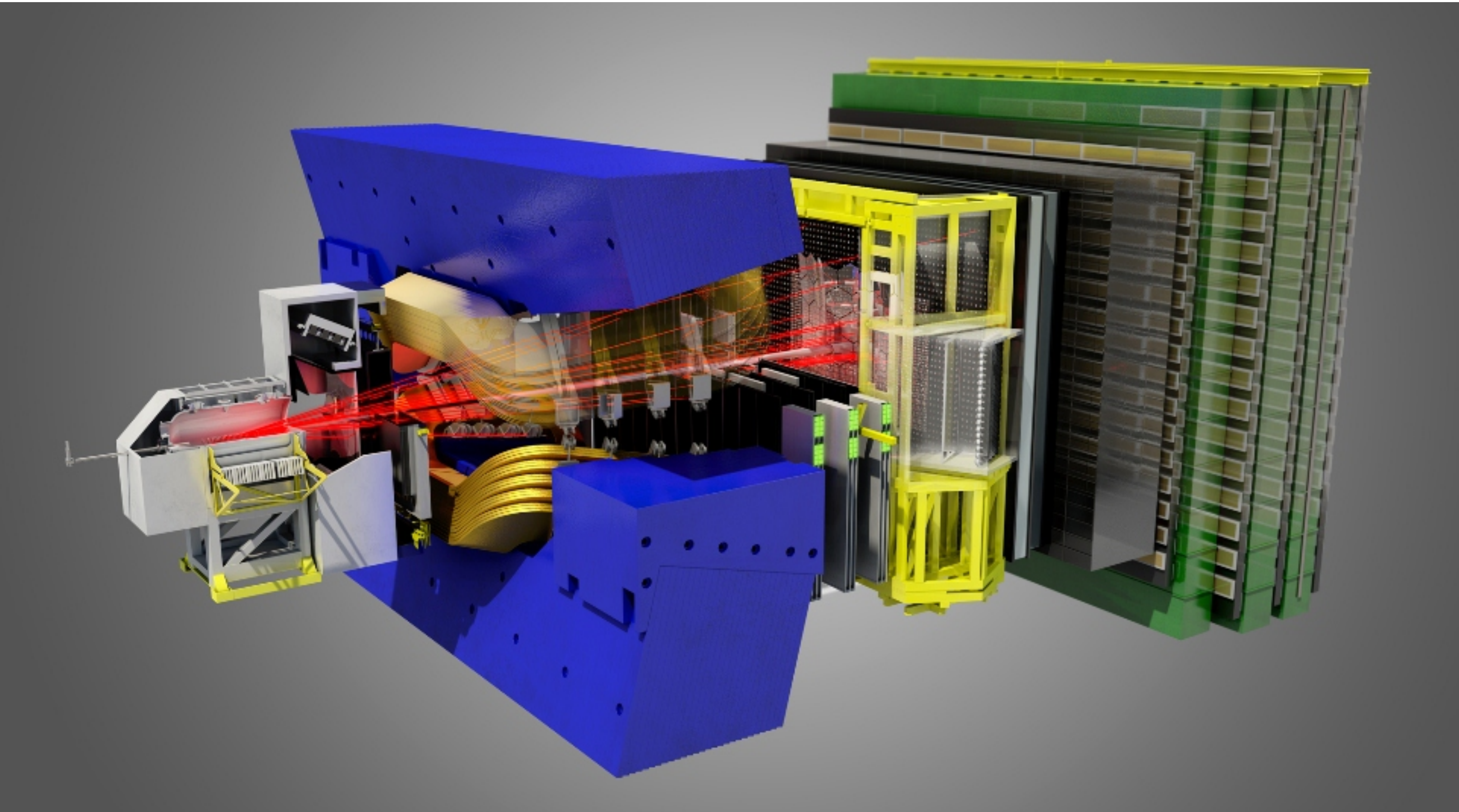
- Flavor tagging provides information about ***both*** the initial and final states of the hadronization process - information we have never had experimental access to in jets before!
- Unprecedented opportunities for hadronization measurements exist at LHCb, which has excellent heavy-flavor jet tagging and particle ID capabilities

In this talk:

- LHCb's advantage for hadronization studies
- Possible measurements
- Implications for our understanding of hadronization

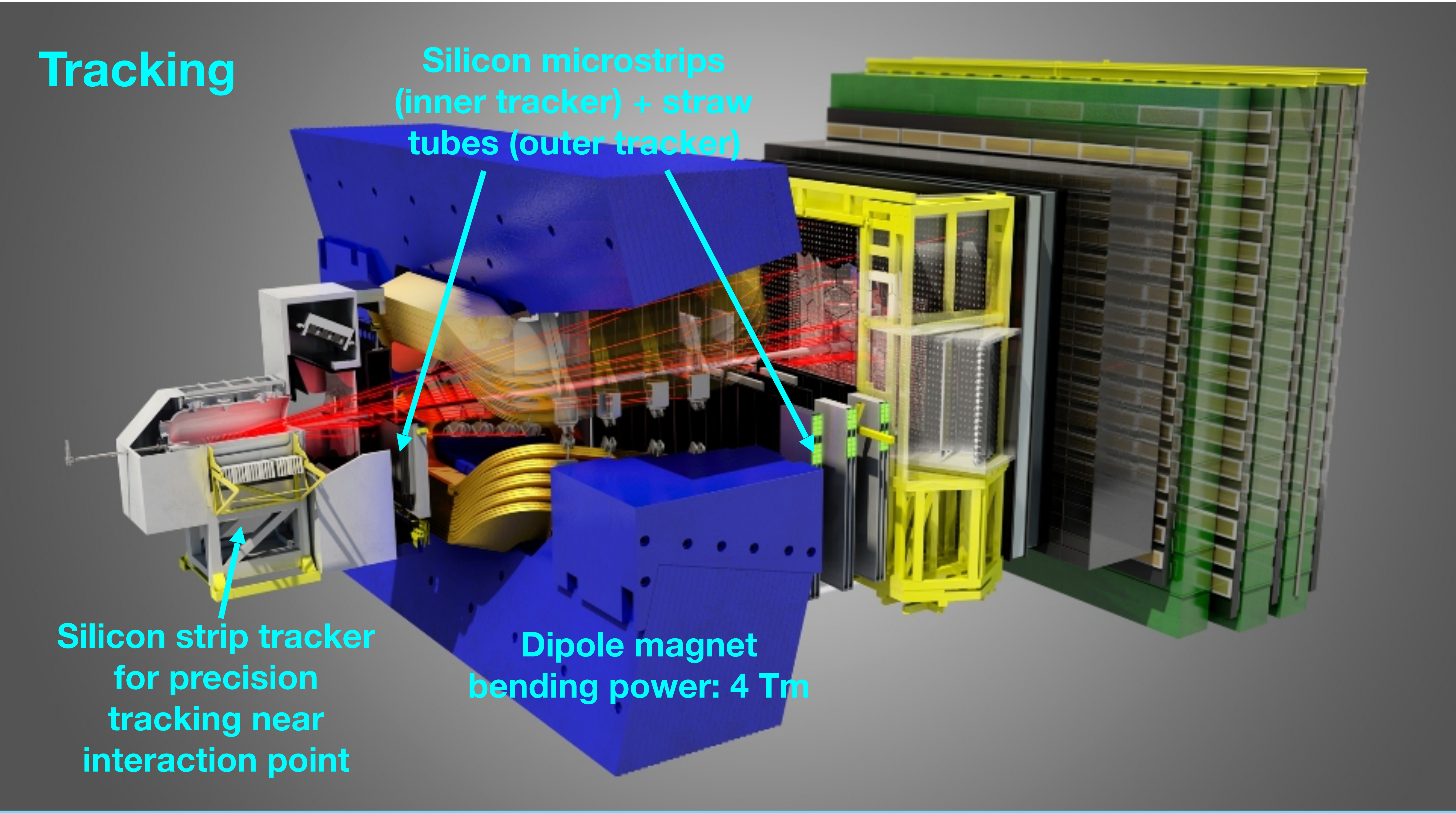
The Large Hadron Collider beauty (LHCb) Experiment

- Forward detector ($2 < \eta < 5$) designed to study decays of beauty and charm hadrons



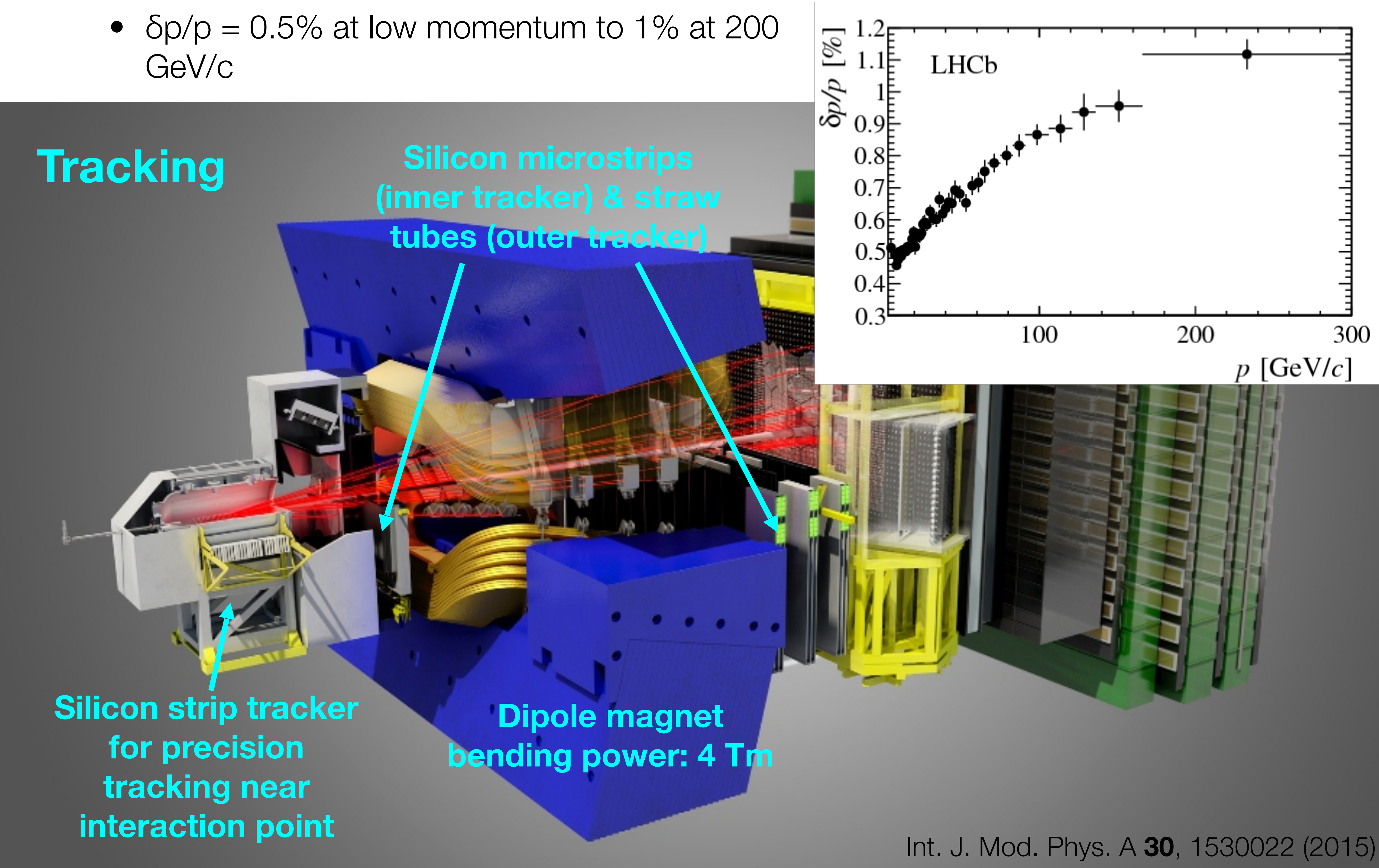
LHCb Tracking

- Precision tracking achieved with silicon microstrip and straw tube detectors



LHCb Tracking

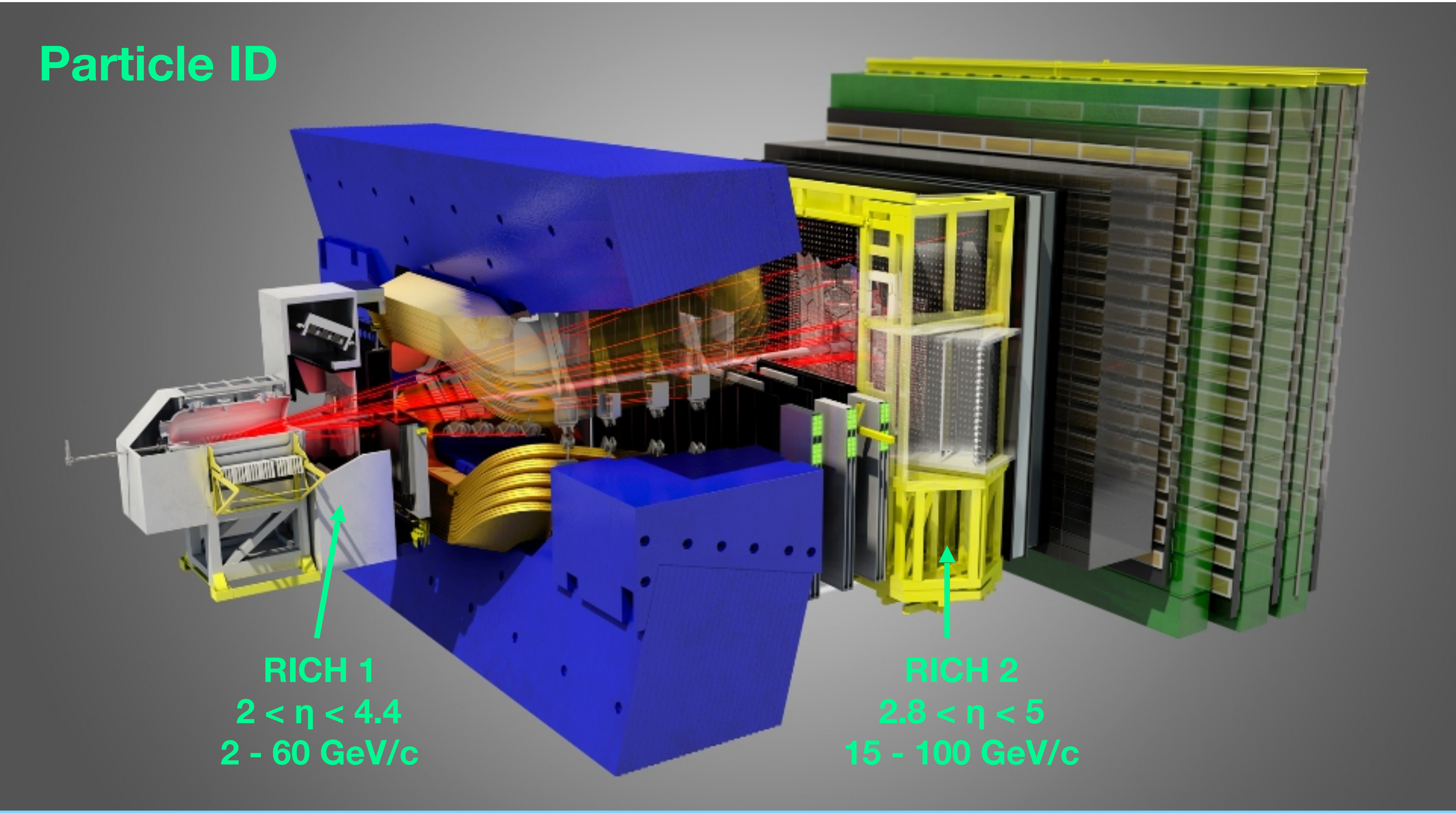
- δp/p = 0.5% at low momentum to 1% at 200 GeV/c



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

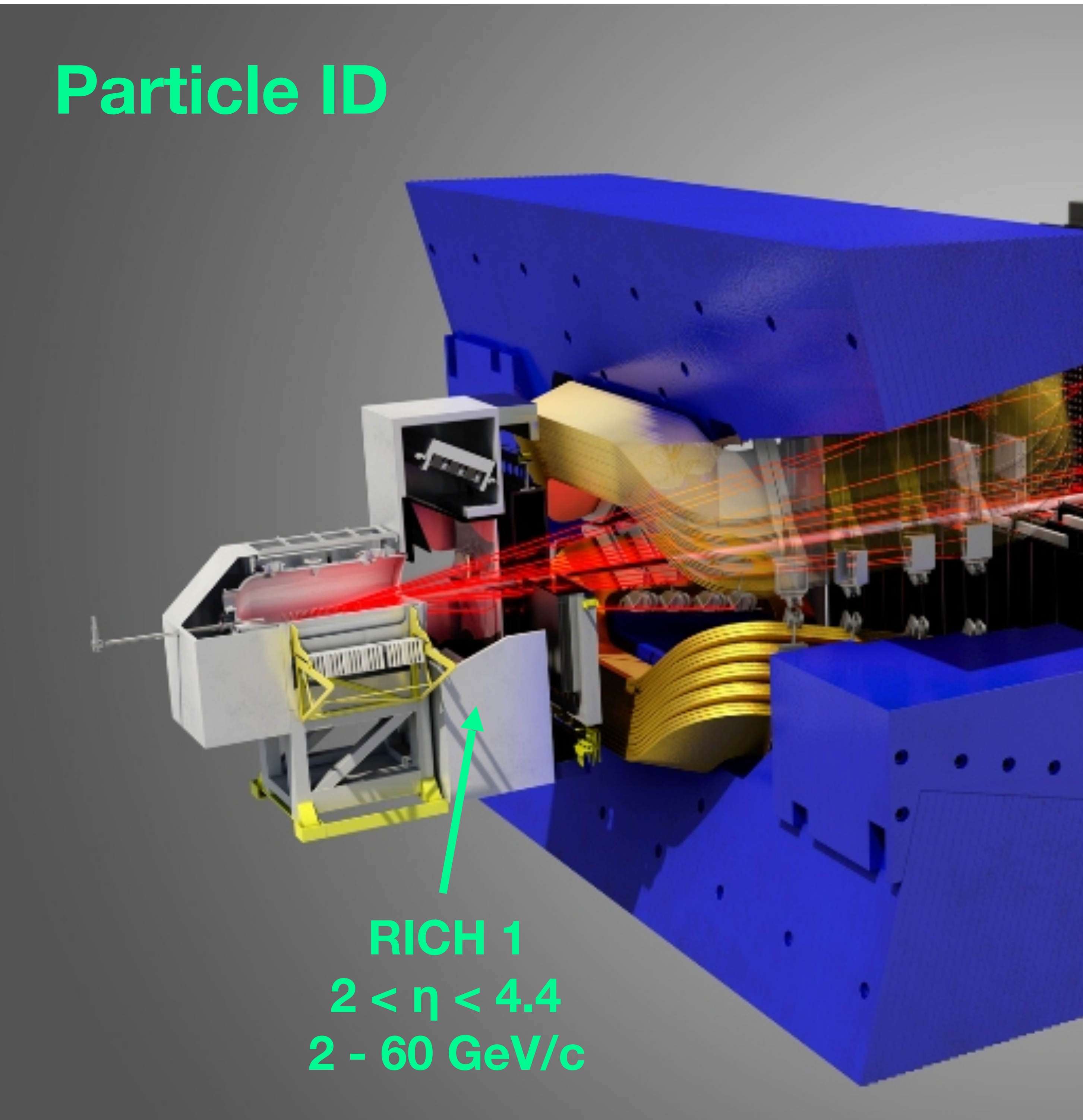
LHCb Particle Identification

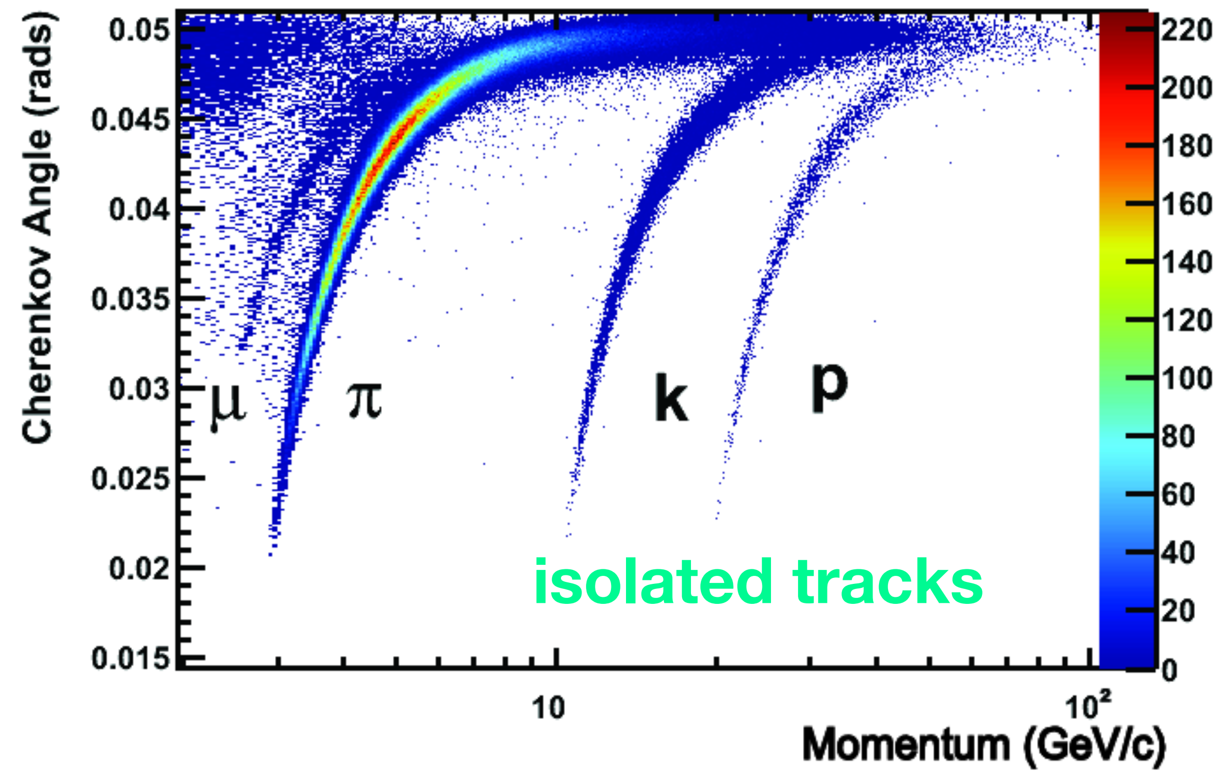
- Excellent Particle ID achieved with two Ring Imaging Cherenkov (RICH) detectors

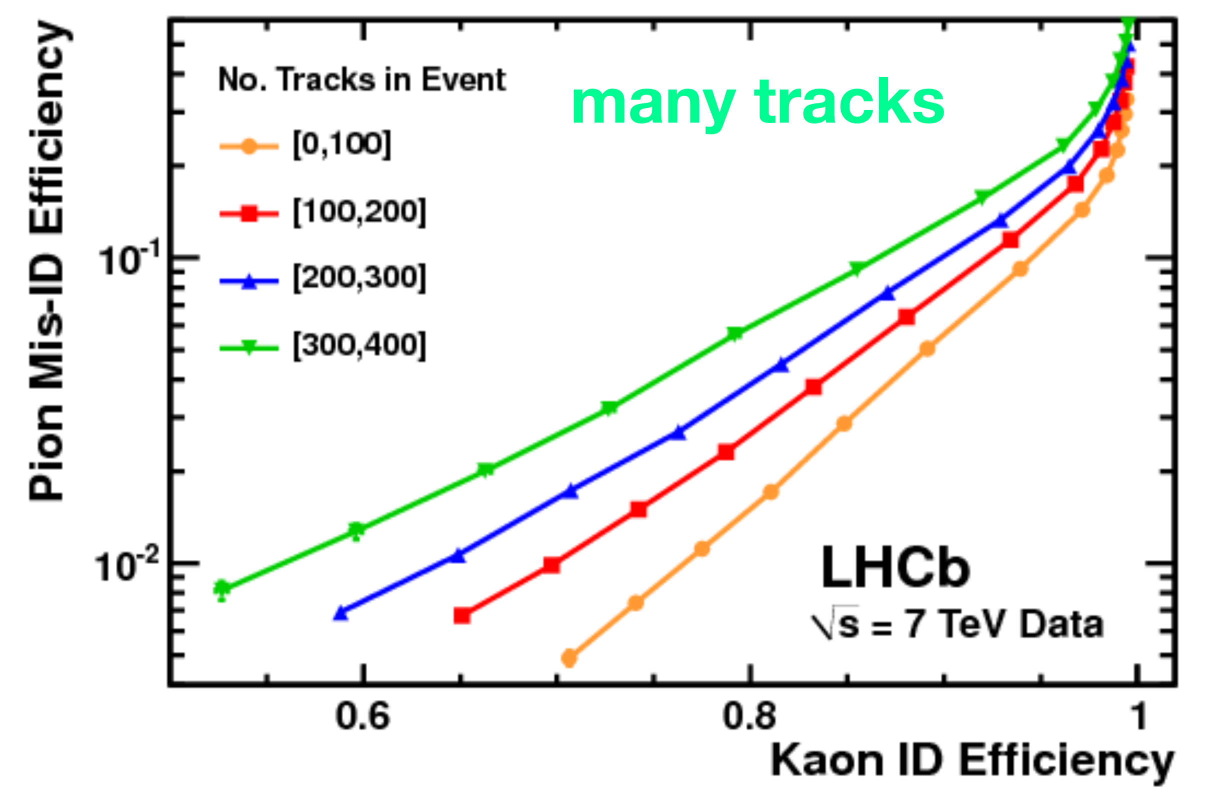


LHCb Particle Identification

- Particle ID performance remains excellent even in high-multiplicity events



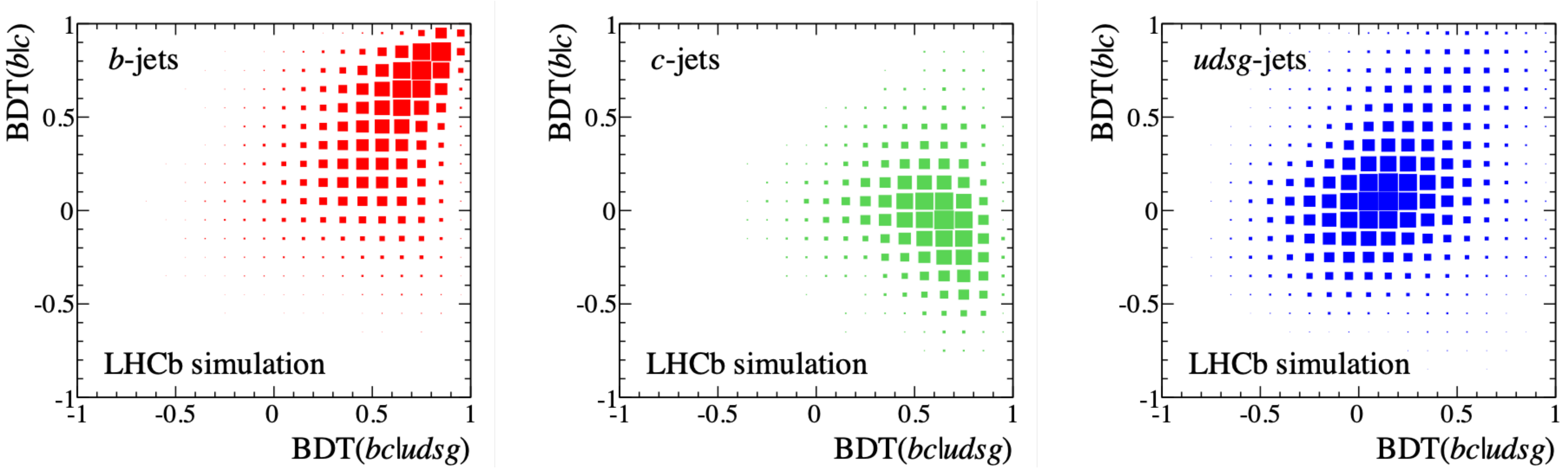




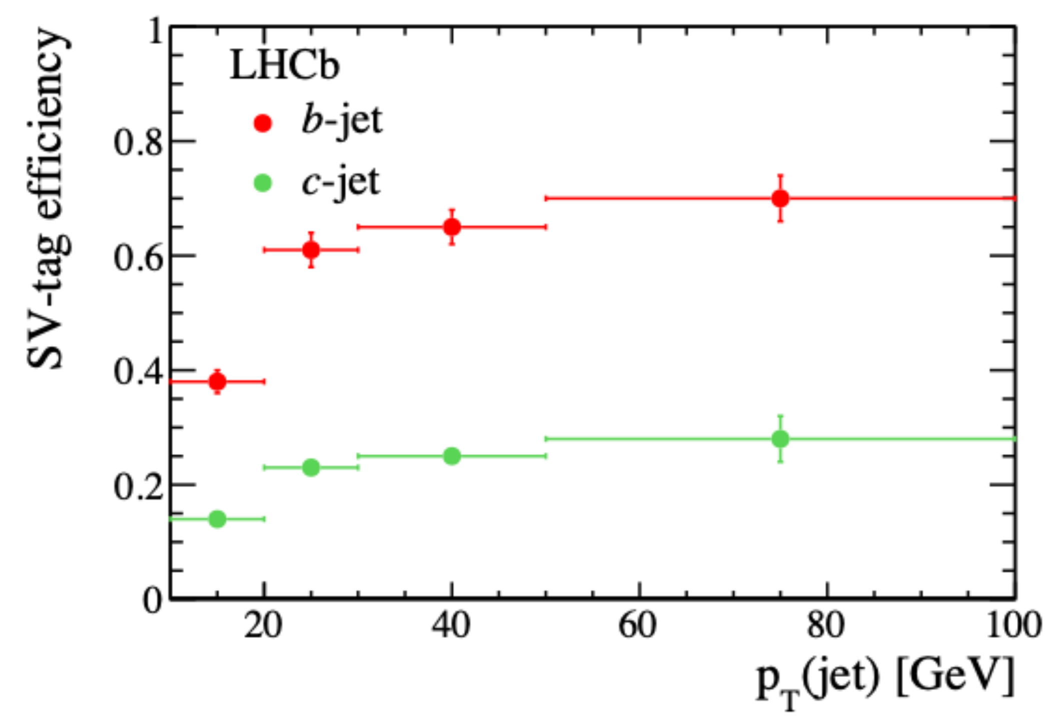
Eur. Phys. J. C **73**, 2431 (2013)

Heavy Flavor Jet Tagging at LHCb

- The Secondary Vertex tagging (SV-tagger) algorithm finds secondary vertices within a jet cone and uses two boosted decision trees (BDTs) for flavor discrimination
- BDT(bc|udsg) discriminates between heavy and light flavor jets, while BDT(b|c) discriminates between beauty and charm jets:



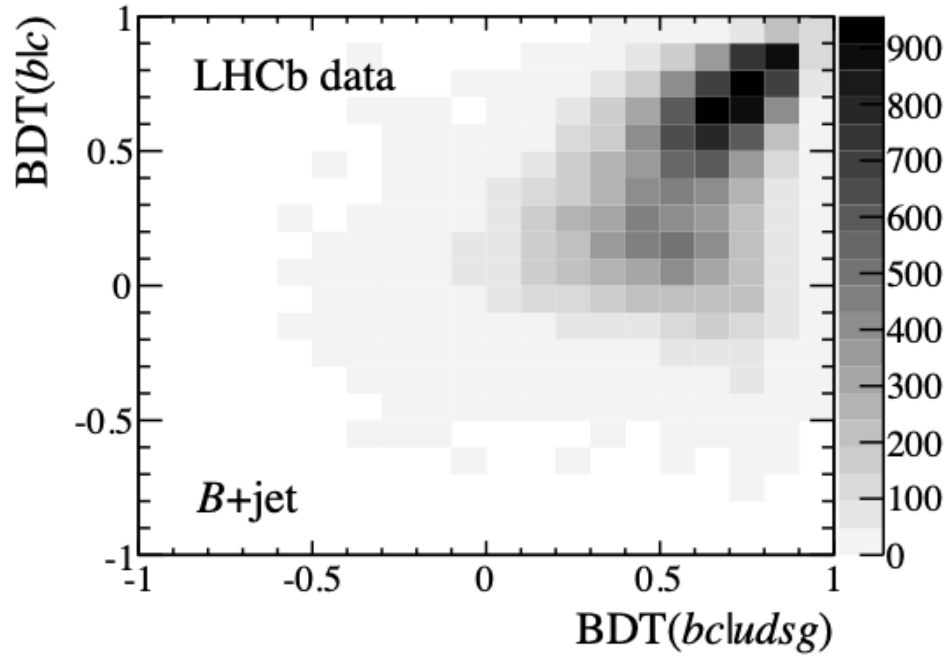
- Simulation shows clearly distinguishable BDT distributions for each jet tag
- Tagging efficiencies measured in data: for jets with $p_T > 20$ GeV and $2.2 < \eta < 4.2$, $\varepsilon_{b\text{-jet}}$ is ~ 65% and $\varepsilon_{c\text{-jet}}$ is ~ 25%, with a light-parton jet misidentification probability of 0.3%



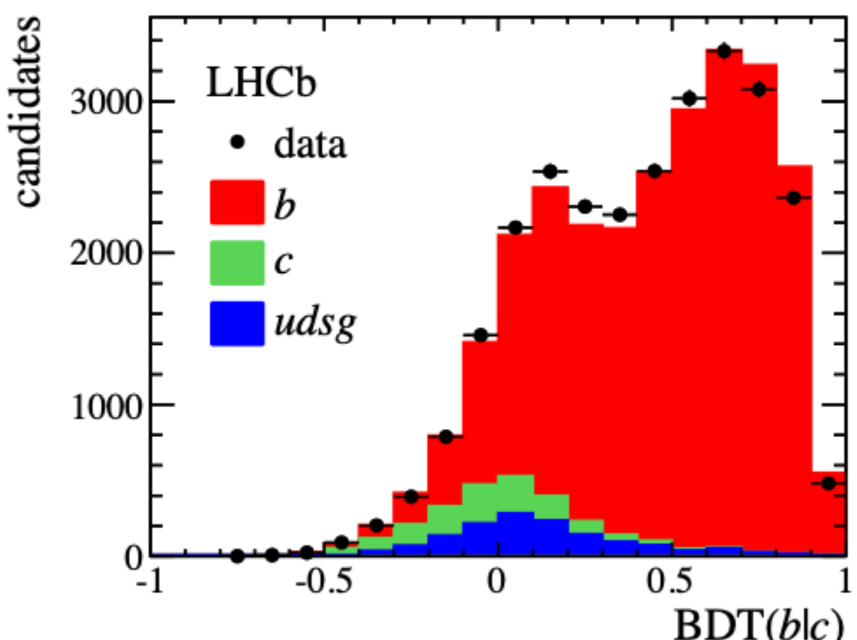
JINST **10**, P06013 (2015)

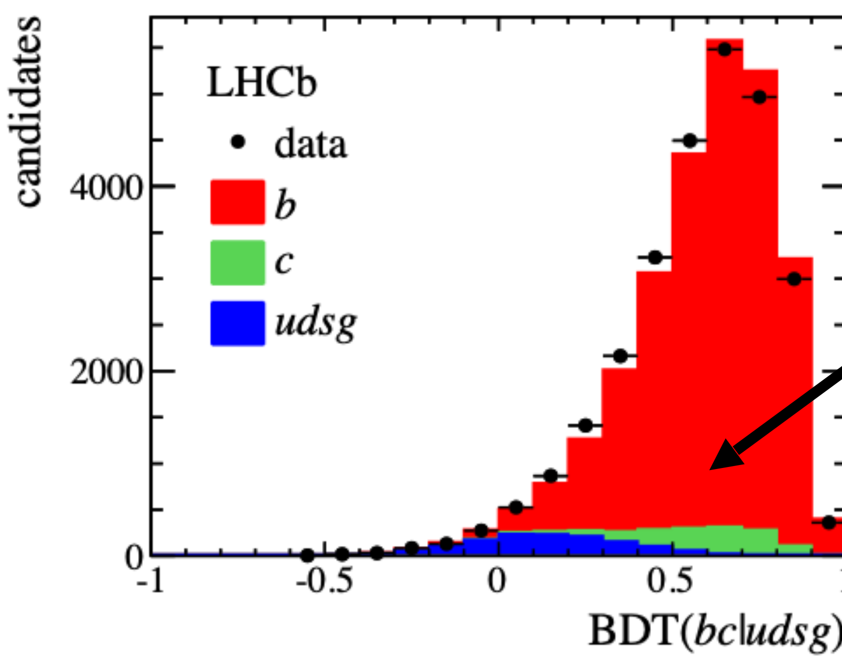
Heavy Flavor Jet Tagging at LHCb: An Example in Data

BDT distribution from data for
LHCb B + jet events



Projected 1D BDT distributions from 2D fit to data



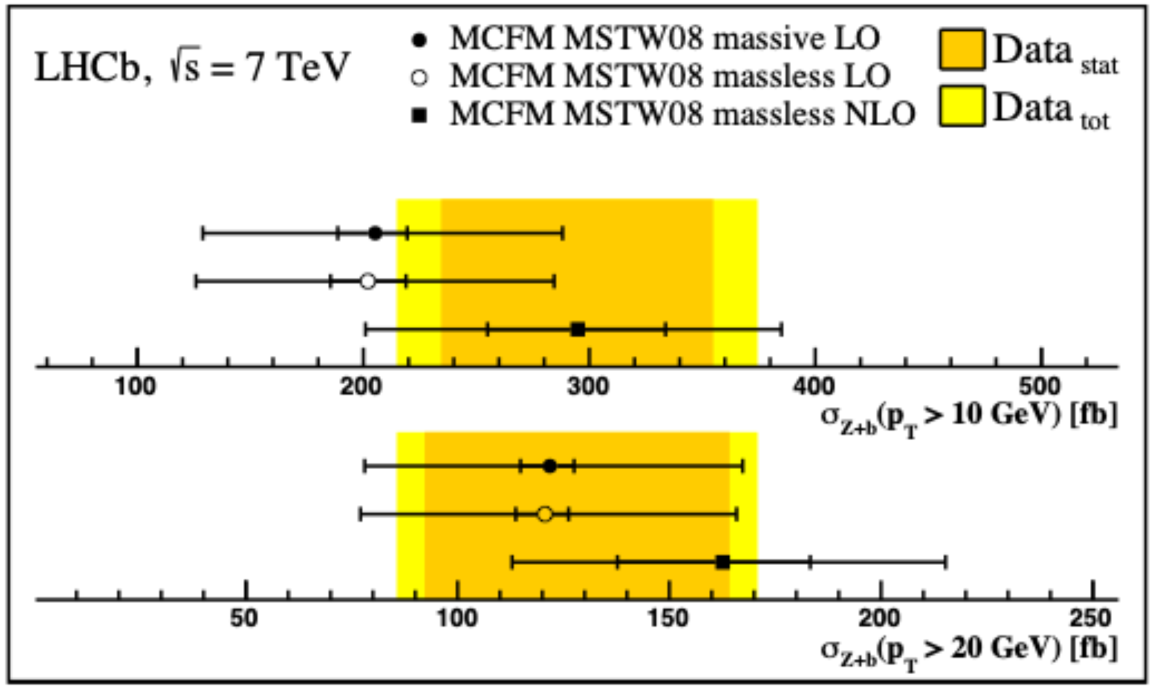


Obtain yields of flavor-tagged jets

JINST **10**, P06013 (2015)

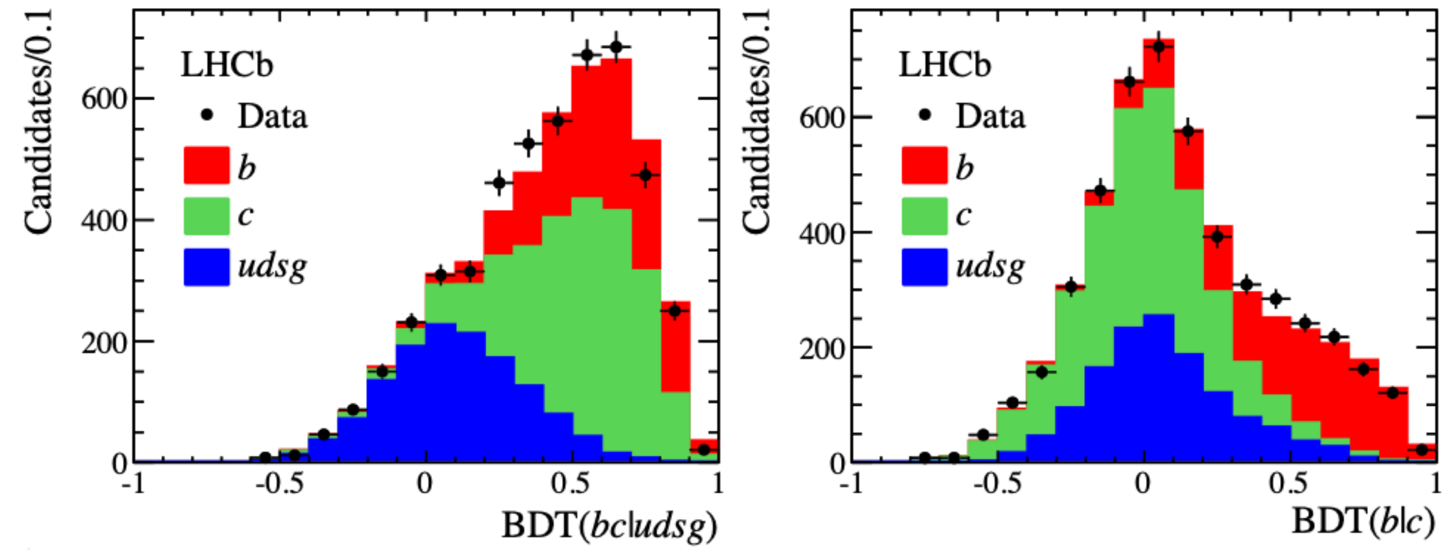
Selected Heavy-Flavor-Tagged Jet Results from LHCb

Z+b-jet cross section



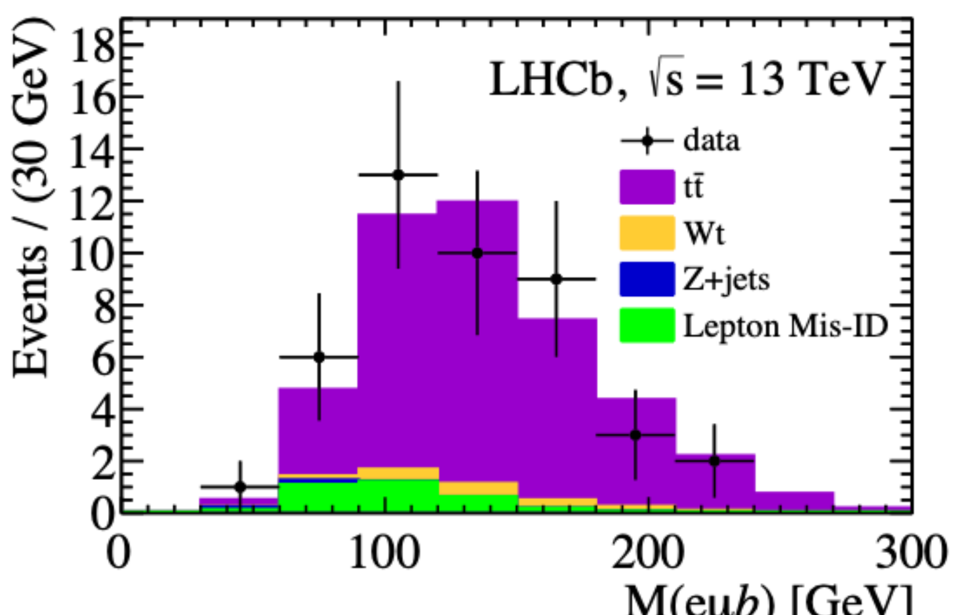
JHEP **01**, 064 (2015)

Simultaneous extraction of W+b-jet and W+c-jet yields



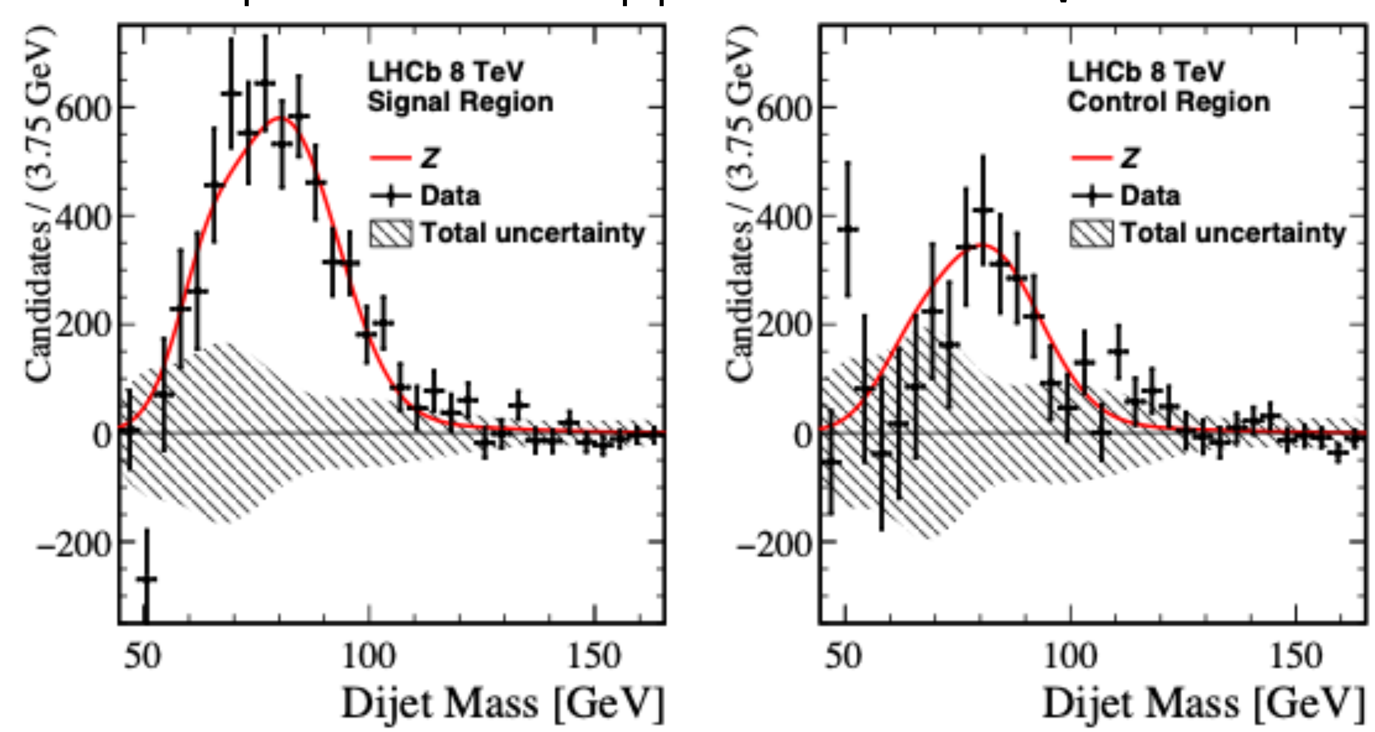
PRD **92**, 052001 (2015)

Forward top pair production in the dilepton channel in pp collisions at √s = 13 TeV



JHEP **08**, 174 (2018)

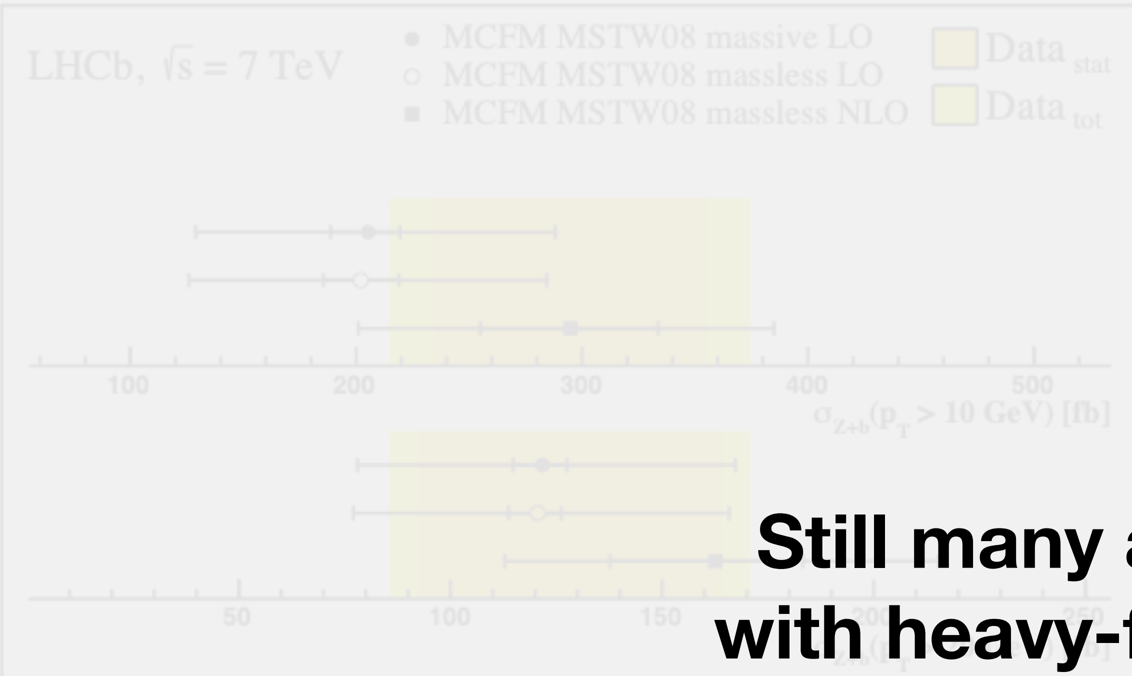
First observation of forward Z->bb̄ production in pp collisions at √s = 8 TeV



PLB **776**, 430-439 (2018)

Selected Heavy-Flavor-Tagged Jet Results from LHCb

Z+b-jet cross section



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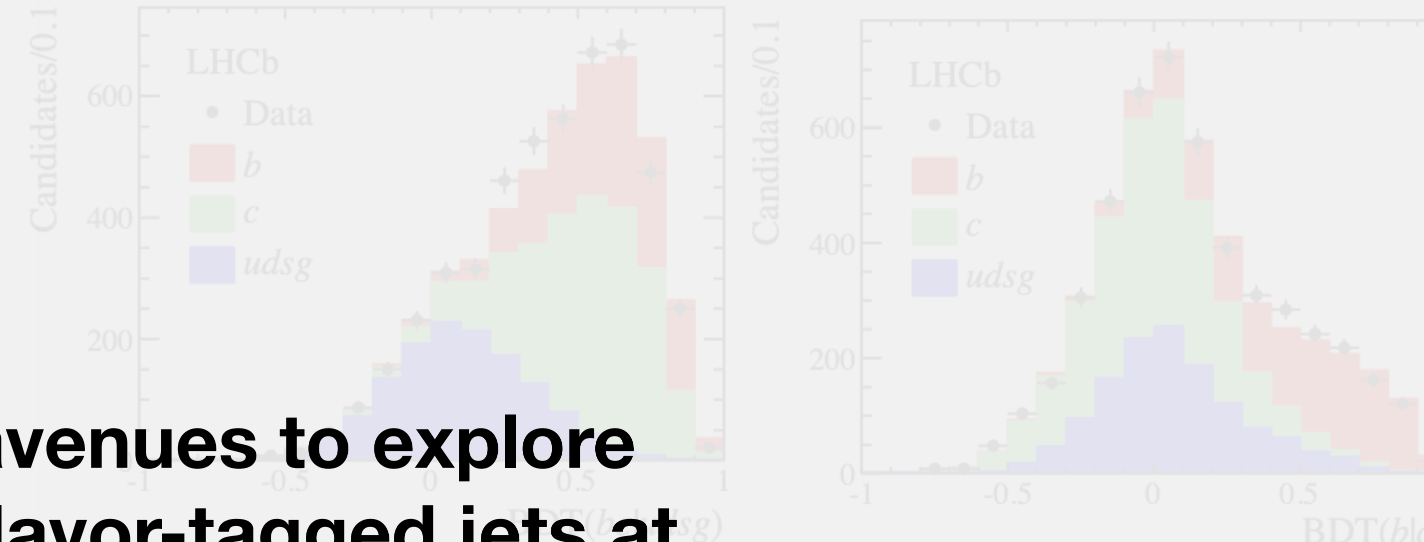
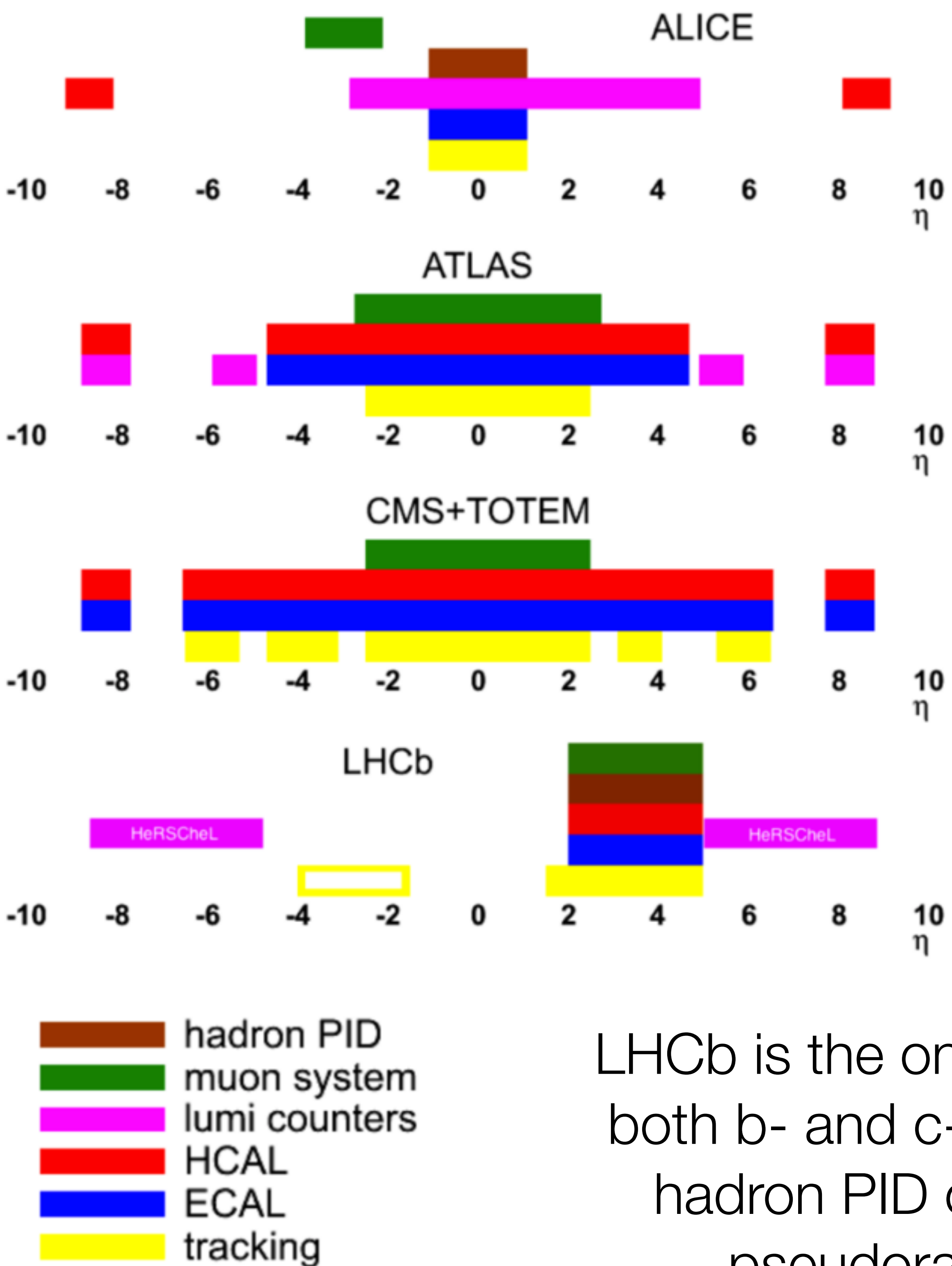


Still many avenues to explore with heavy-flavor-tagged jets at LHCb, including hadronization!

Forward top pair production in the dilepton channel in pp collisions at √s = 13 TeV

First observation of forward Z->bb production in pp collisions at √s = 8 TeV

Heavy Flavor Jet Tagging at the LHC



LHC Run 1 ($\sqrt{s}$ = 7, 8 TeV) Heavy-Flavor Jet Tagging for Jets with p_T > 20 GeV/c

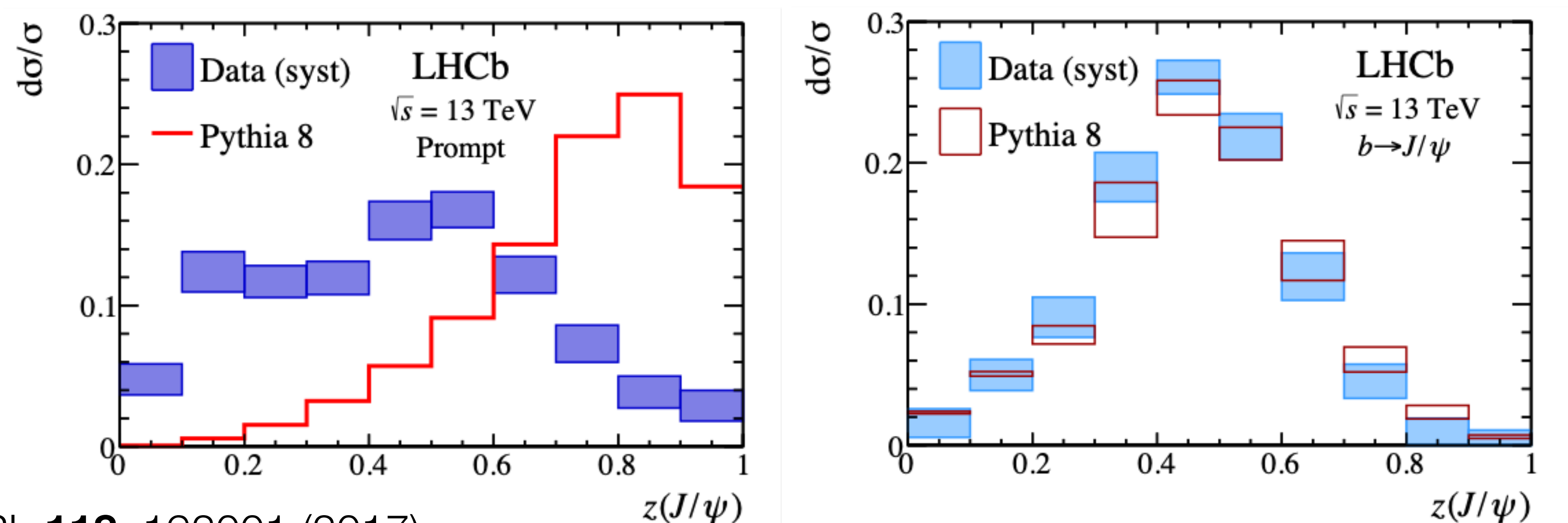
	ATLAS[1]	CMS[2]	ALICE[3]	LHCb[4]
$\varepsilon_{b\text{-jet}}$	70%	70%	None	65%
$\varepsilon_{c\text{-jet}}$	25-40%	None	None	25%
Mis-ID as light parton	1%	1.5%	N/A	0.3%
Hadron PID	None	None	$\lvert\eta\rvert < 1$, 0.1 -100 GeV/c	$2 < \eta < 5$ 2 -100 GeV/c

[1] JINST **11** P04008 (2016)
[2] JINST **8** P04013 (2013)
[3] JINST **3** S08002 (2008)
[4] JINST **10** P06013 (2015)

LHCb is the only LHC experiment that has both b- and c-jet tagging capabilities *and* hadron PID over a large range in both pseudorapidity and momentum

LHCb's Advantage for Hadronization Studies

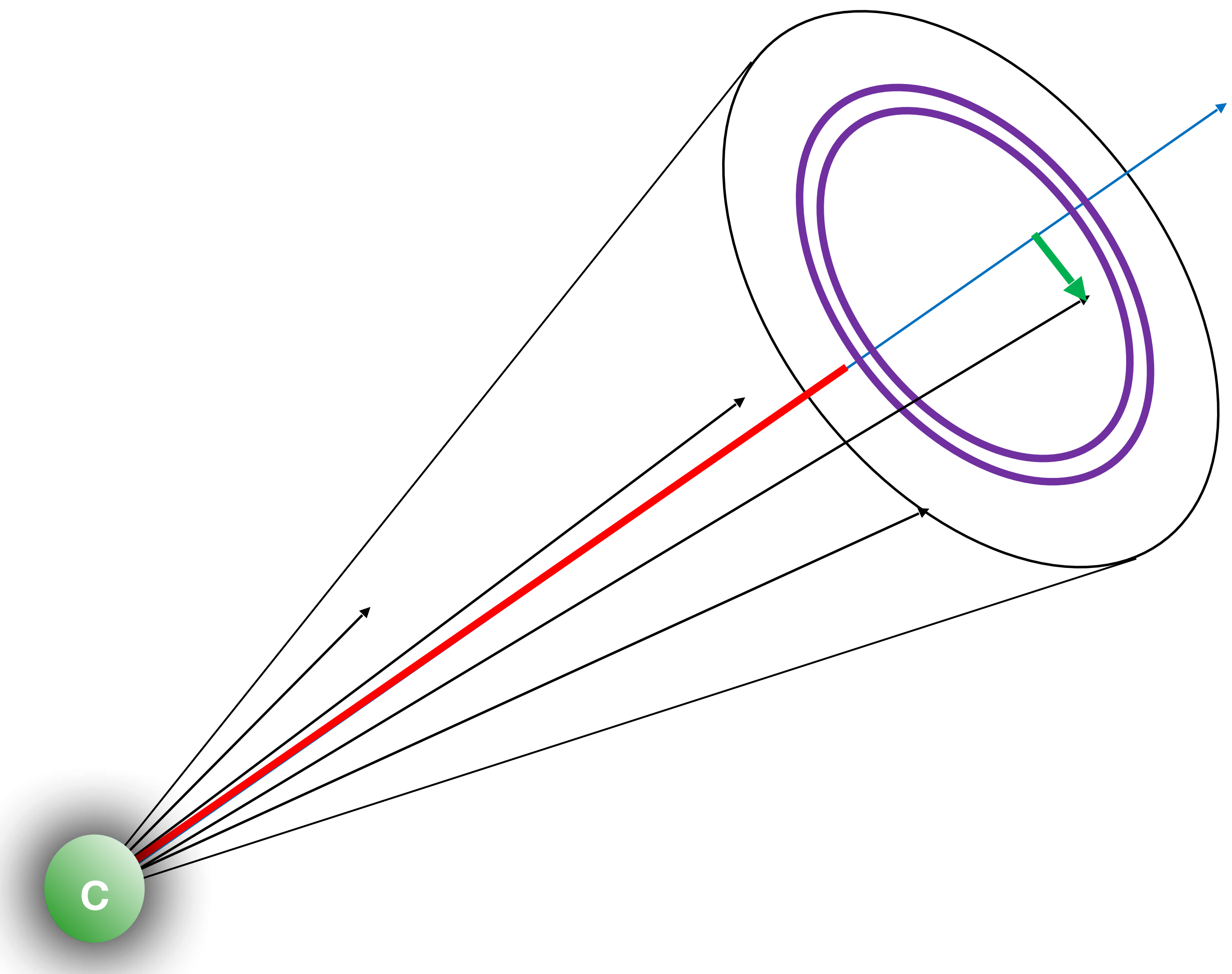
- Excellent tracking and particle ID detectors allow for the identification of final-state hadrons in a fully reconstructed jet
- Forward acceptance gives access to a mix of quark and gluon jets
- Established techniques exist for tagging heavy-flavor jets with high purity
- Emphasis in studying the production and decays of heavy flavor hadrons makes it an ideal experiment to study how beauty and charm quarks hadronize
- Hadronization studies in heavy-flavor-tagged jets at LHCb would expand on recent work done at LHCb to study J/Ψ production in jets:



PRL **118**, 192001 (2017)

- A heavy-flavor-tagged jet hadronization study would be complementary to the LHCb Z + jet hadronization study currently in progress, which preferentially selects light-quark jets

Hadronization Measurements Accessible at LHCb



- Longitudinal momentum distribution of hadrons in a heavy-flavor-tagged jet

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

- Transverse momentum distribution of hadrons in a heavy-flavor-tagged jet

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

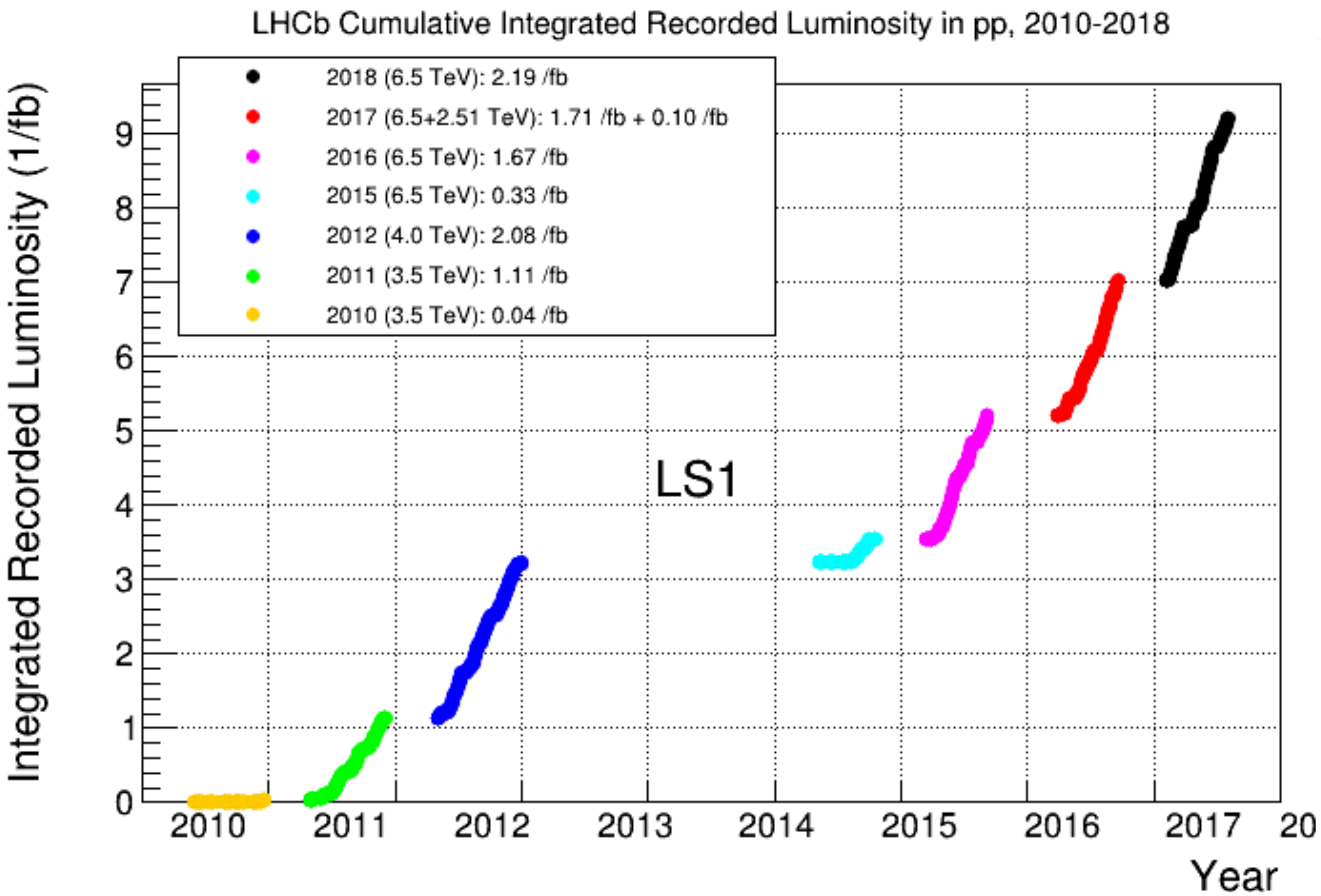
- Radial profile of hadrons in a heavy-flavor-tagged jet

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

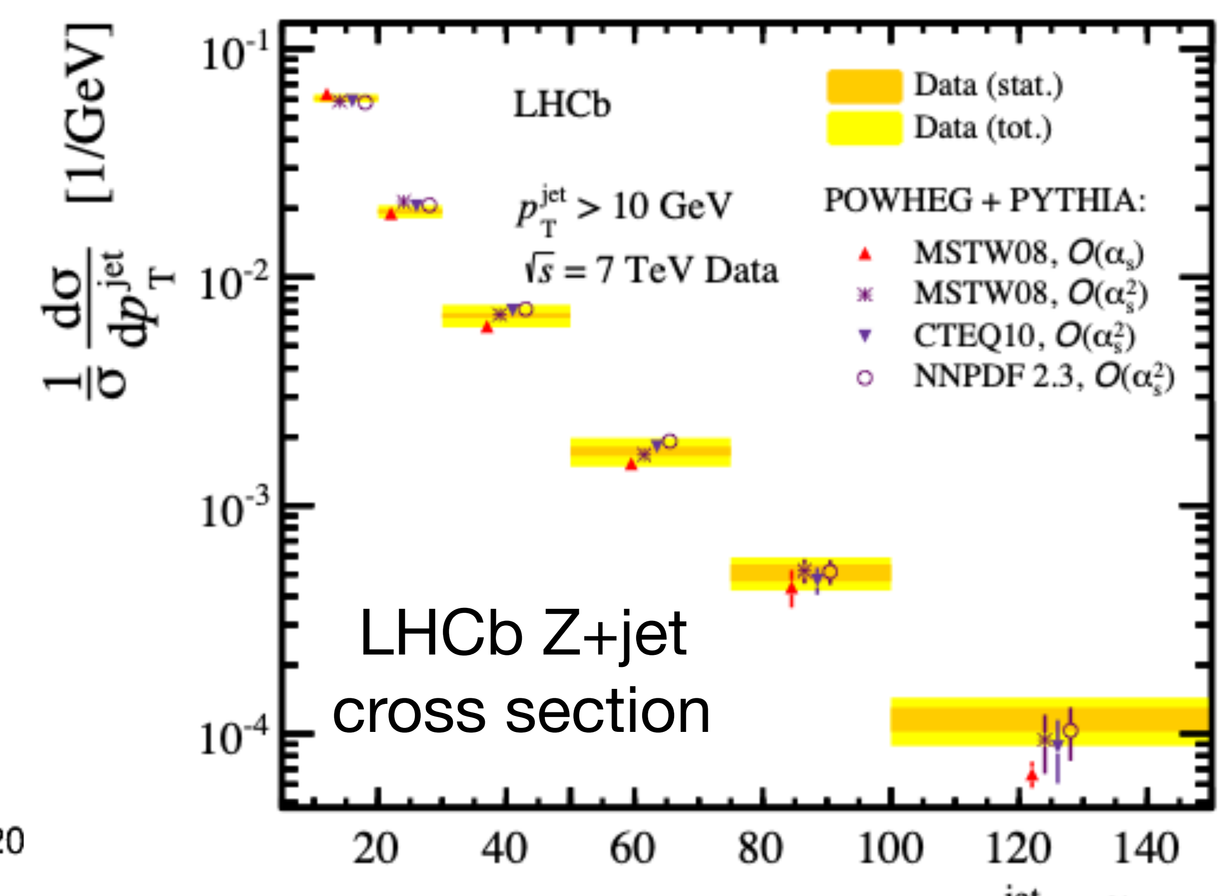
- Number of heavy-flavor and light-flavor hadrons in the jet and their flavor composition
- Number of baryons and mesons in the jet
- Comparison of these observables between beauty and charm jets
- *Suggestions for more observables are very welcome!*

Measurement Uncertainty Projections for LHCb Data

- LHCb has collected 9.23 fb^{-1} of data since 2010:



- Range of jet p_T for multidifferential studies:



JHEP **01**, 033 (2014)

- Subsets of Run 1 and Run 2 data indicate a lower bound of several million for the heavy-flavor-tagged jet yield
  - Yields likely to increase with improved tagging techniques

Implications of Hadronization Studies with Heavy-Flavor-Tagged Jets

- Identifying final-state hadrons in fully-reconstructed, flavor-tagged jets will offer new insights into mechanisms of color neutralization in hadronization
- All of the proposed studies in this talk can be done at LHCb with existing data within the next few years
- We hope that the capability to measure identified final-state hadrons in a fully-reconstructed, flavor-tagged jet will encourage the theoretical community to calculate distributions for multiple hadrons in a jet
  - Wealth of 1D and multi-dimensional projections possible to facilitate theoretical comparisons
  - Suggestions for additional observables within b- and c-tagged jets are very welcome!
- Hadronization will be a major component of the Electron-Ion Collider physics program. Learning more about hadronization now will help the community refine its goals for hadronization measurements at a future Electron-Ion Collider

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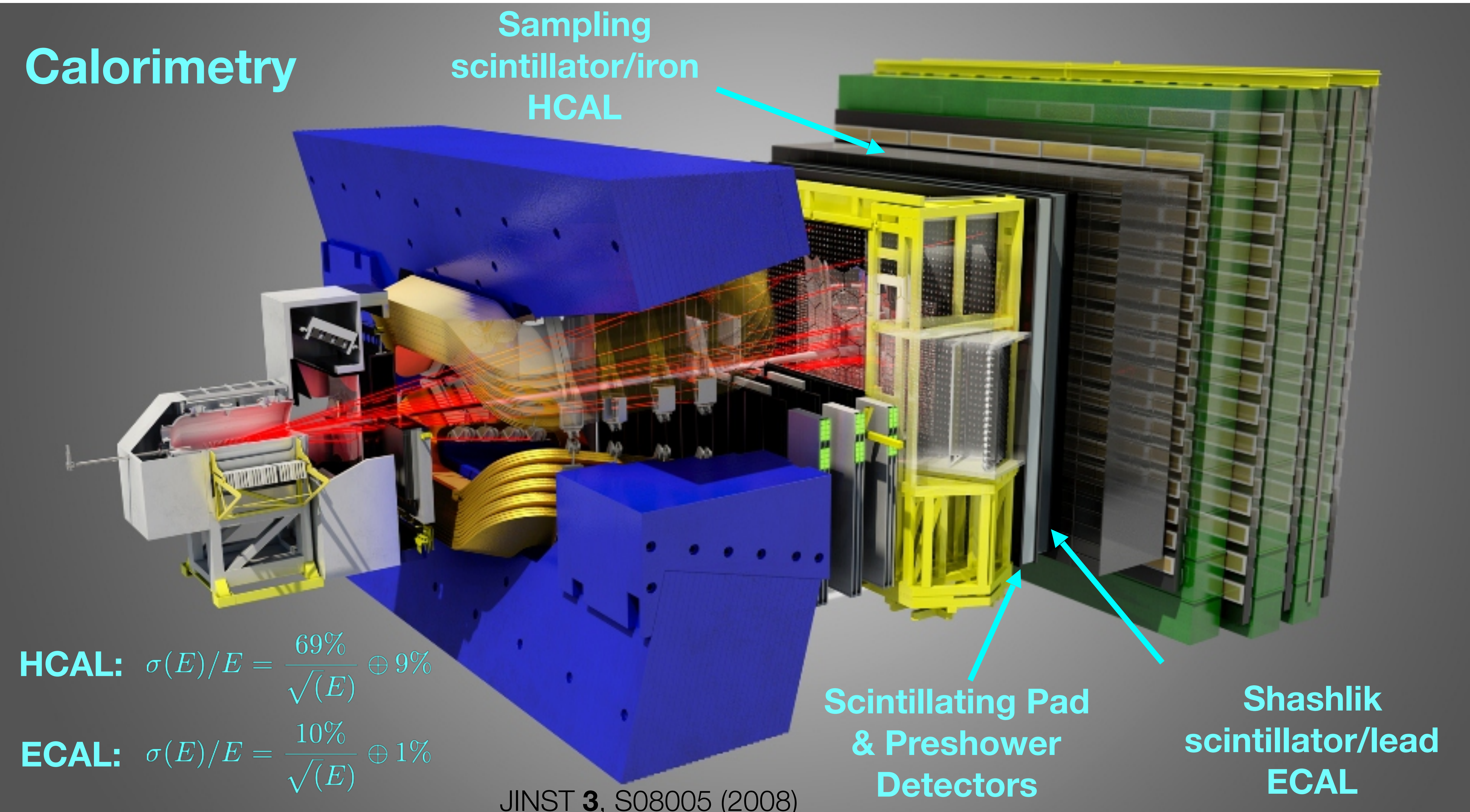
Backup

LHCb Calorimetry

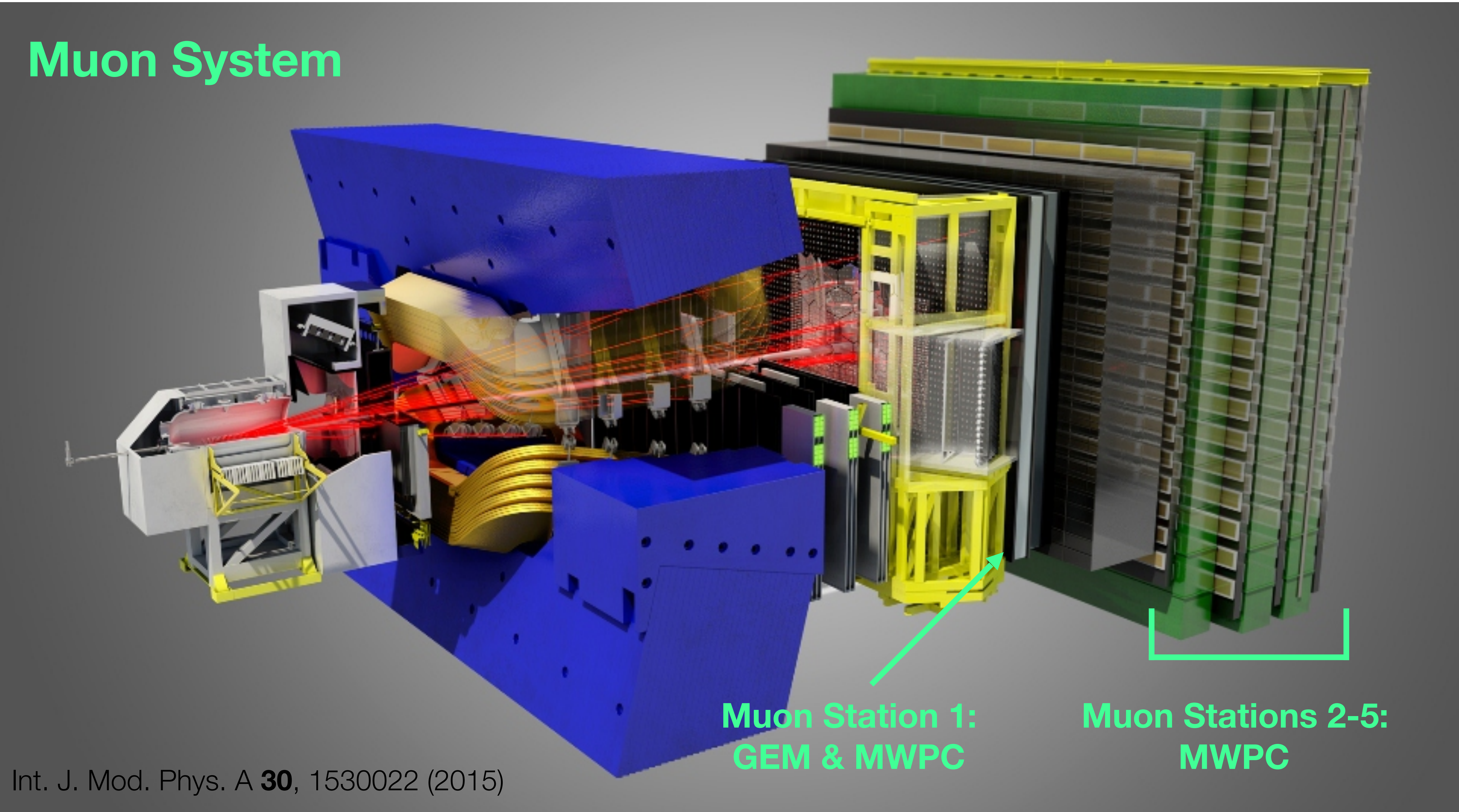
- Calorimeter system includes a Scintillating Pad Detector, a Preshower Detector, an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)



JINST **3**, S08005 (2008)

LHCb Muon System

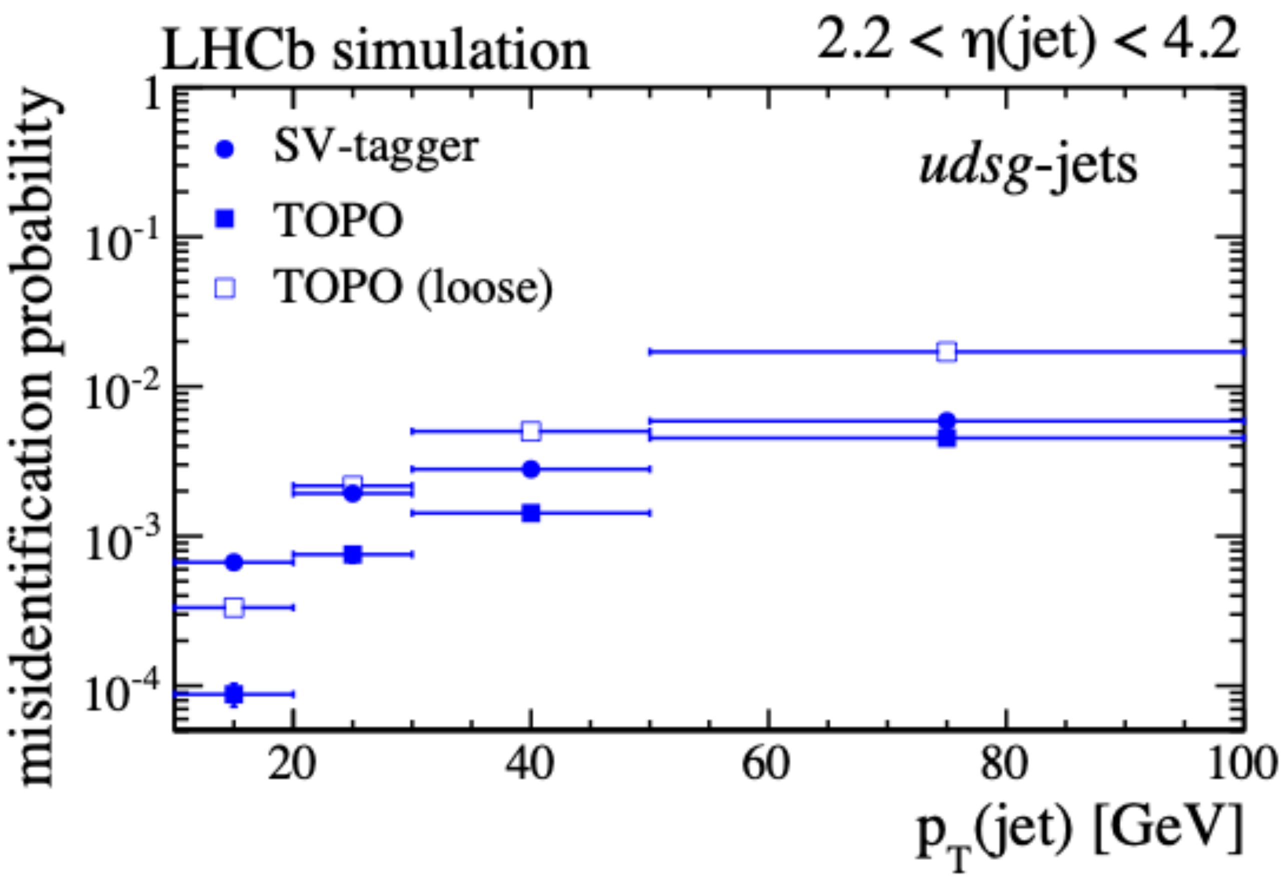
- Muon ID achieved with five muon stations consisting of Gas Electron Multiplier (GEM) and 1380 Multi-Wire Proportional Chambers (MWPC) interleaved with iron absorbers

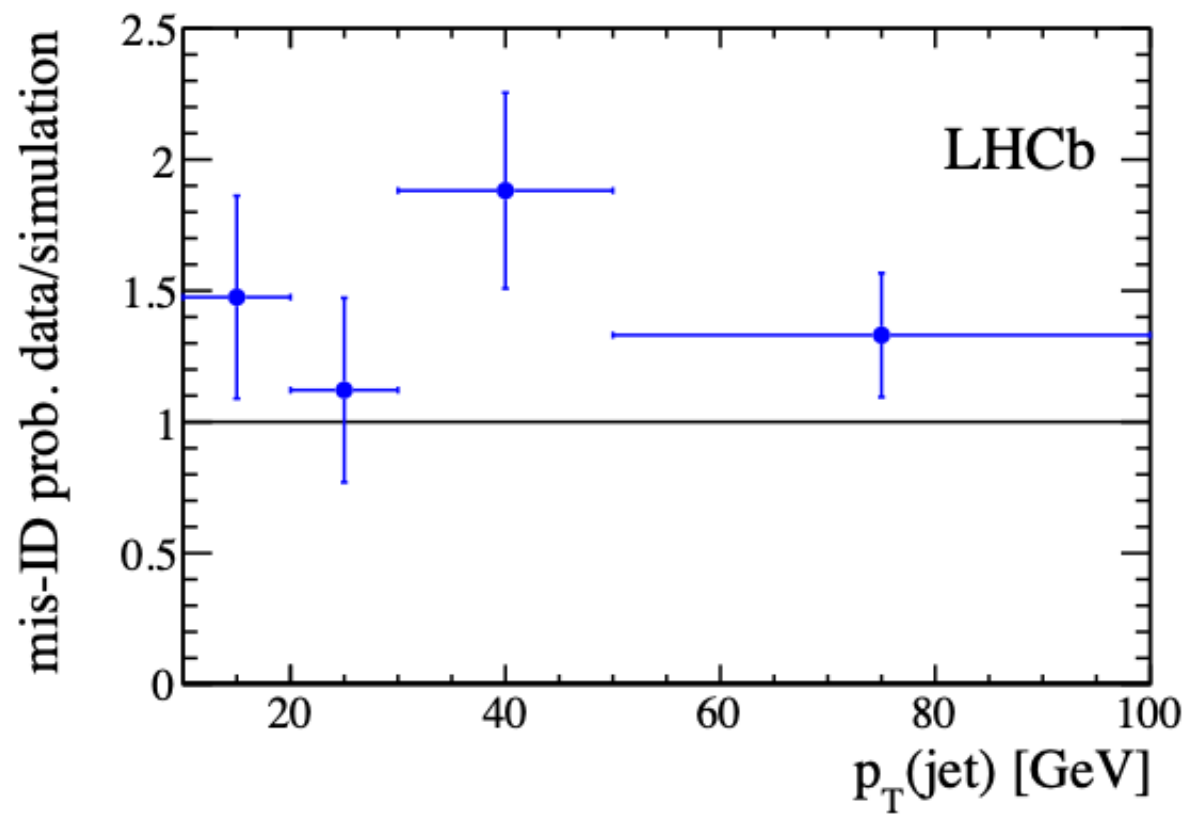


Int. J. Mod. Phys. A **30**, 1530022 (2015)

Light-parton Jet Mis-ID with the SV-Tagger Algorithm

- Light-parton mis-ID probability studied in simulation and measured in data



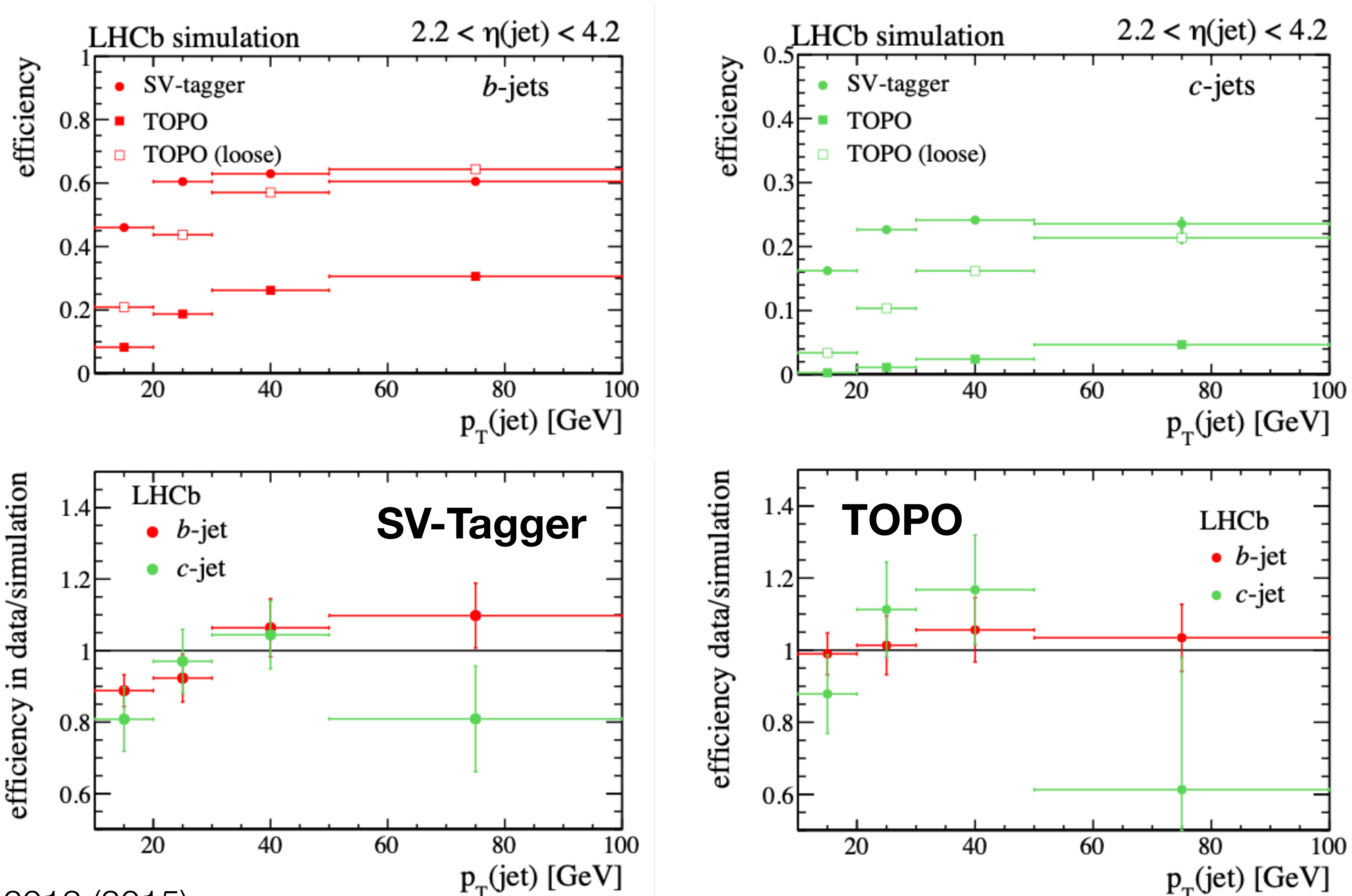


- Mis-identification of a heavy-flavor jet as a light-parton jet is predominantly due to prompt tracks mis-reconstructed as displaced tracks to form a fake secondary vertex

JINST **10**, P06013 (2015)

Heavy Flavor Jet Tagging with the Topological Trigger

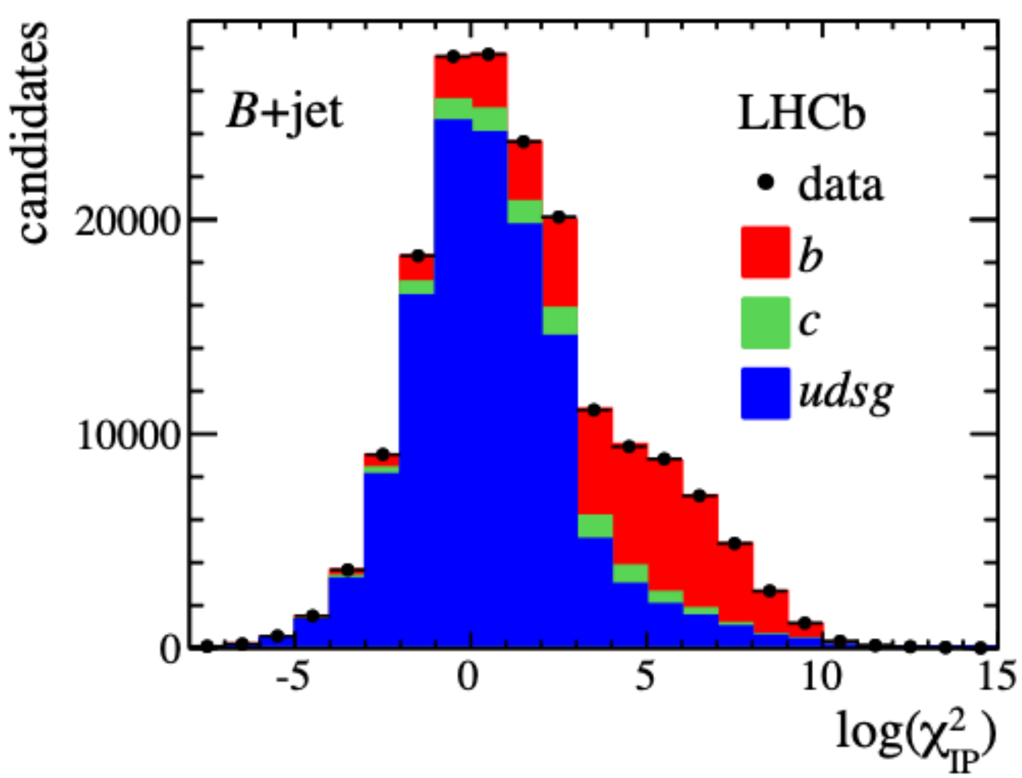
- Software trigger designed to identify decays of beauty hadrons
- Has been used as a b-jet tagger by requiring the tagged b-hadron to be inside a jet
- Jet tagging performance studied in both data and simulation:



JINST **10**, P06013 (2015)

Calculation of SV-Tagger Efficiency

- Efficiency is calculated as the number of SV-tagged beauty and charm jets divided by the total number of beauty and charm jets
- Number of SV-tagged beauty and charm jets is determined by fitting the 2D BDT distribution from data (see slide 8)
- Total number of beauty and charm jets is determined by fitting χ^2_{IP}: the difference in χ^2 of a primary interaction vertex reconstructed with and without the highest-pT track in the jet
- The highest-pT track in light-parton jets usually originates from the primary vertex, while the highest-pT track in heavy-flavor jets usually originates from the beauty or charm hadron decay
- Fit templates obtained from simulation and calibrated by comparison to data from W + jet events (primarily light-parton jet dominated) to determine detector resolution effects



JINST **10**, P06013 (2015)

The Secondary Vertex (SV)-Tagger Algorithm

- Requires that either a high-p_T muon or a beauty or charm hadron passes trigger requirement:
  - Muon candidate must have $p_T > 10$ GeV
  - Beauty or charm hadron candidate must have $p_T > 1.7$ GeV, and the difference in χ^2 of a primary vertex reconstructed with and without the considered track greater than 16
- For events with a candidate passing the trigger requirement, jets are clustered with the anti-k_T algorithm
- Tracks for secondary vertex reconstruction within the jet are required to have $p_T > 0.5$ GeV and a difference in χ^2 of a primary vertex reconstructed with and without the considered track greater than 16
  - No hadron PID is used - all particles are assigned a pion mass
  - Tracks are not required to be in the jet cone
- All possible two-track secondary vertices are reconstructed subject to the following cuts:
  - Distance of closest approach between tracks is less than 2mm
  - χ^2 of vertex fit < 10
  - Two-body mass is in the range 0.4 GeV < M < M(B), where M(B) is the nominal B^0 mass

JINST **10**, P06013 (2015)

The Secondary Vertex (SV)-Tagger Algorithm

- All two-track secondary vertices with $\Delta R < 0.5$ relative to the jet axis are merged until none of the secondary vertices share tracks.
- The weighted average of the two-body secondary vertices is calculated with the inverse of the vertex χ^2 values as the weights. The weighted average is taken to be the position of the secondary vertex in the jet
- The merged and weighted secondary vertices are required to satisfy the following:
  - $p_T > 2$ GeV
  - Significant spatial separation from primary vertex
  - Contain at most one track with $\Delta R > 0.5$ relative to jet axis
  - Pass quality cuts to suppress strange-hadron decays
- Information about secondary vertices is passed to two BDTs for flavor discrimination: BDT (bc|udsg) and BDT (b|c)

JINST **10**, P06013 (2015)

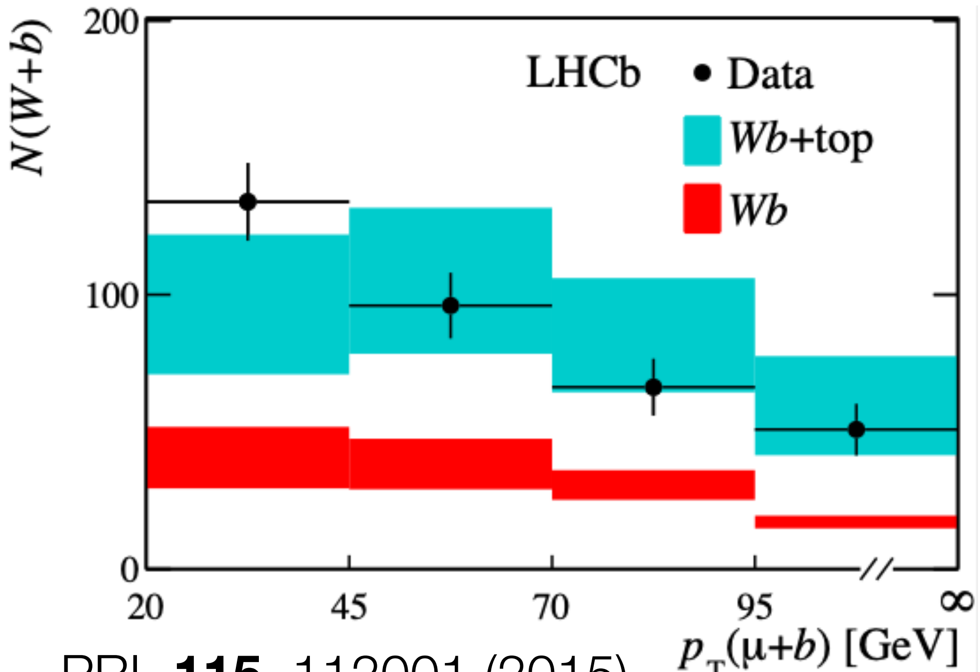
Input to SV-Tagger BDTs

- Secondary vertex mass
- Secondary vertex corrected mass: $M_{cor} = \sqrt{M^2 + p^2 sin^2\theta} + psin\theta$
  - M is the invariant mass of the particles that form the secondary vertex, p is the momentum of the particles that form the secondary vertex, θ is the angle between the momentum and direction of flight of the secondary vertex
- Transverse flight distance of the two-track secondary vertex closest to the primary vertex
- Fraction of the jet p_T carried by the secondary vertex
- ΔR between the secondary vertex flight direction and the jet
- Number of tracks in the secondary vertex
- Number of secondary vertex tracks with $\Delta R < 0.5$ relative to the jet axis
- Net charge of the tracks that form the secondary vertex
- Flight distance χ^2
- Sum of all secondary vertex track $(\chi_{IP})^2$: the difference in χ^2 of a primary vertex reconstructed with and without a considered track

JINST **10**, P06013 (2015)

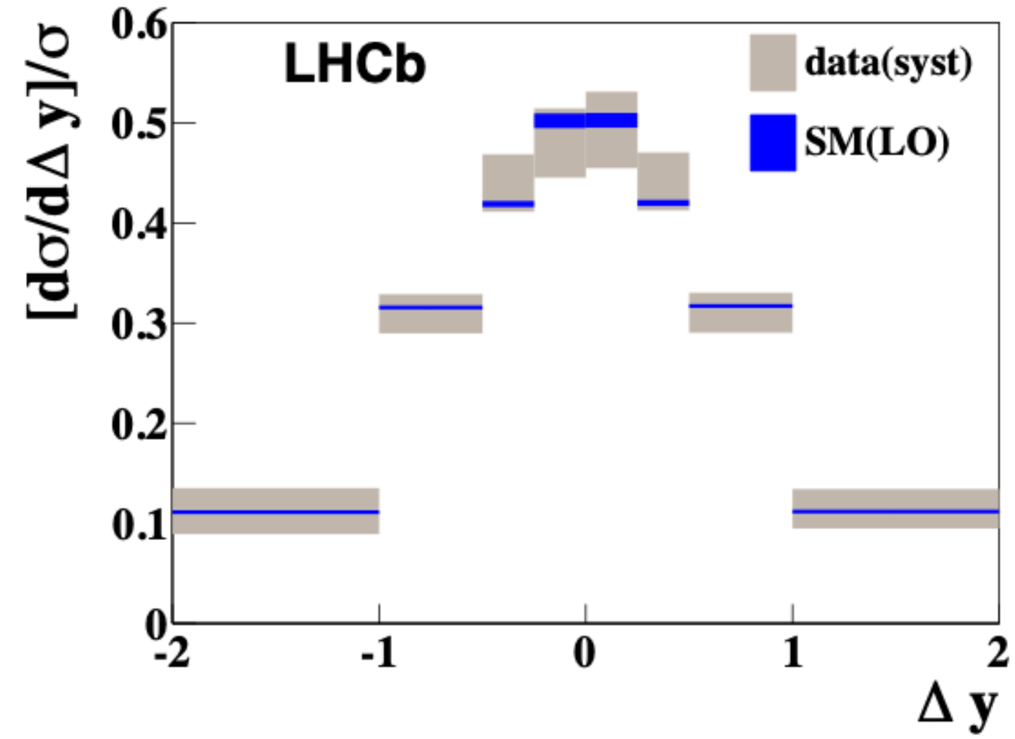
Additional Heavy-Flavor-Tagged Jet Results from LHCb

First observation of top quark production in the forward region



PRL **115**, 112001 (2015)

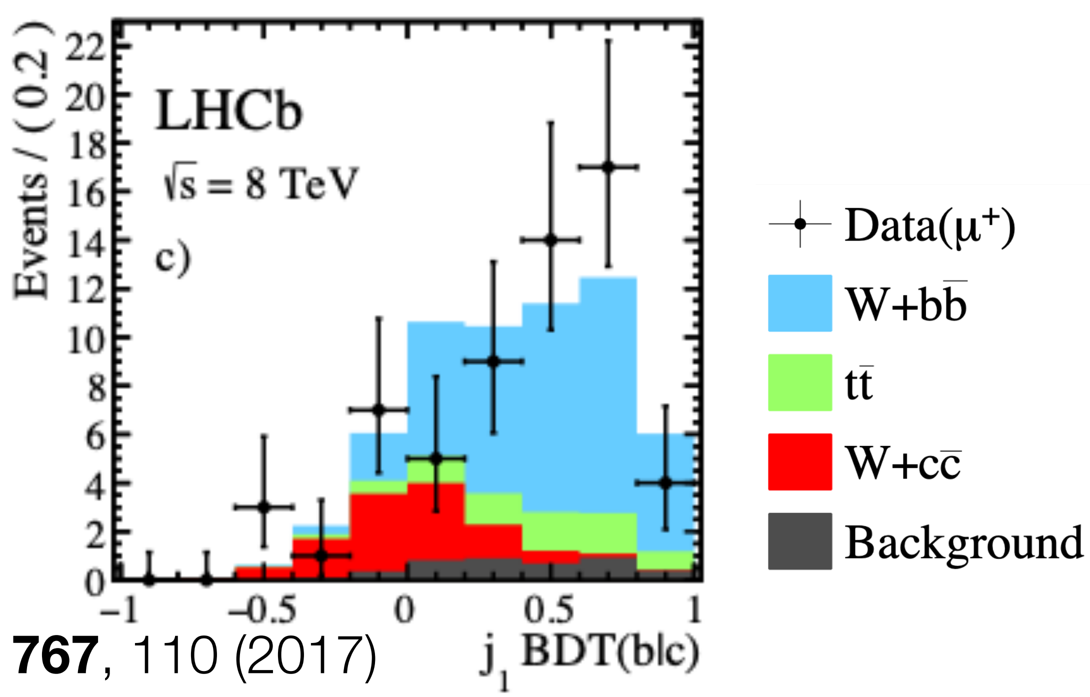
First measurement of the charge asymmetry in $b\bar{b}$ production



$$A_C^{b\bar{b}} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

PRL **113**, 082003 (2014)

Forward $t\bar{t}$, W+$b\bar{b}$, and W+$c\bar{c}$ production



PLB **767**, 110 (2017)

Advances in Theoretical Approaches to Hadronization

Early 1970s	Fragmentation functions introduced to describe the probability for a parton to fragment into a specific hadron as a function of z PRD **4**, 3388 (1971)
Late 1970s	Dihadron fragmentation functions introduced to describe the probability of a single parton fragmenting into two specific hadrons PLB **78**, 243 (1978), Nuc. Phys. B **157**, 45 (1979)
Early 1980s	Transverse-momentum-dependent fragmentation functions introduced, adding a dependence on the transverse momentum of the produced hadron in addition to z Nuc. Phys. B **193**, 381 (1981), Nuc. Phys. B **194**, 445 (1982)
1990s	Dihadron interference fragmentation function introduced J. C. Collins and G. A. Ladinsky (1994), hep-ph/9411444 , PRL **80**, 1166 (1998)
2010s	Theoretical predictions for distributions of hadron-in-jet observables introduced PRD **81**, 074009 (2010), JHEP **1404**, 147 (2014)