Hadron Production at LHCb Experiment

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on behalf of LHCb Collaboration

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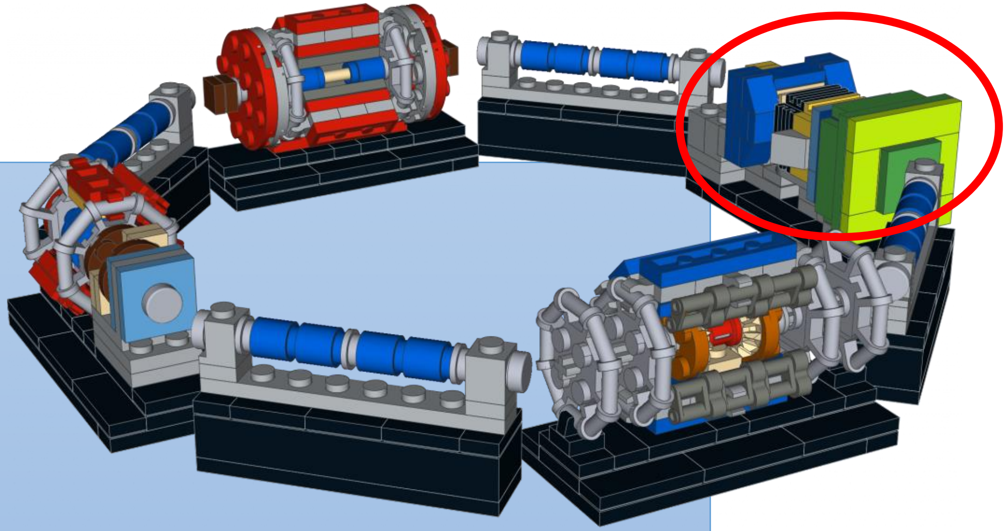
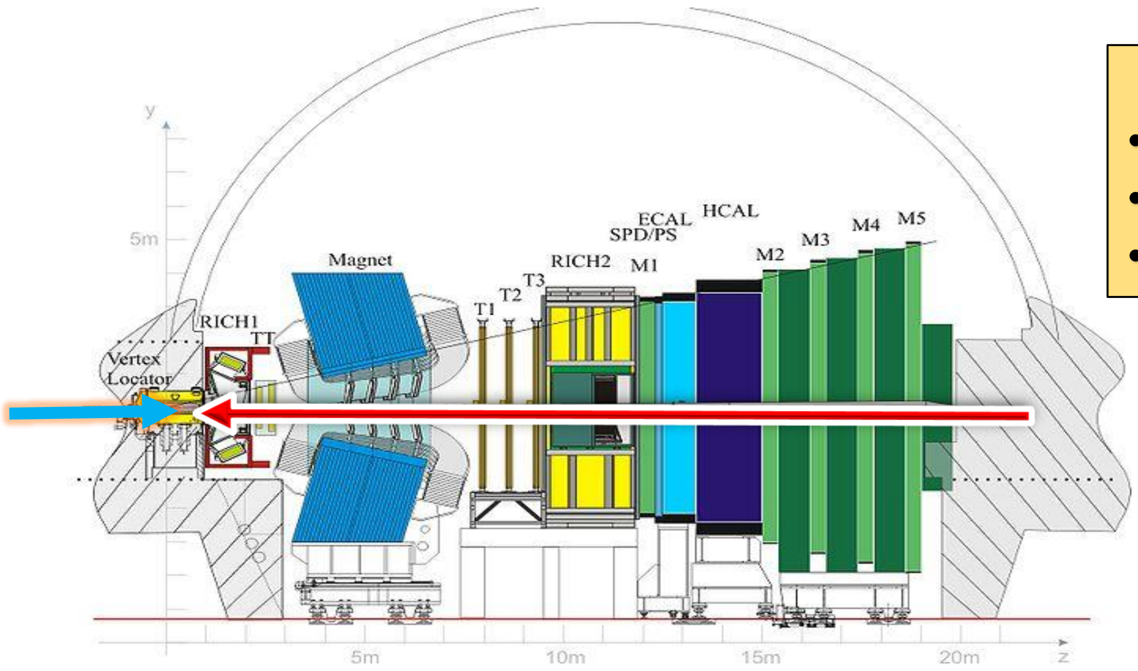
Outline



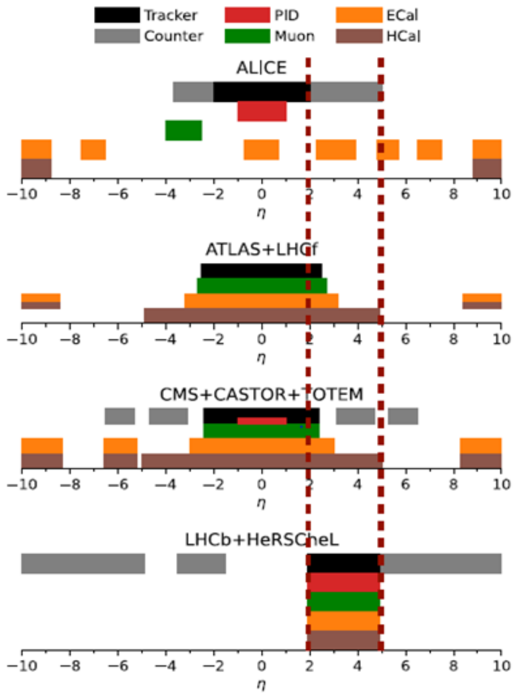
- The LHCb Detector
- Cold Nuclear Matter
- QCD at LHCb
- Latest QCD Analyses
  - Measurement of $b\bar{b}$- and $c\bar{c}$ -dijet differential cross-sections in the forward region of collisions at $\sqrt{s}$ =13 TeV. (JHEP 2102 (2021) 023)
  - Nuclear modification factor of neutral pions in the forward and backward regions of *pPb* collisions. (Phys.Rev.Lett. 131 (2023) 4, 042302)
- Conclusions

The LHCb Detector



Physics at LHCb

- Matter-antimatter asymmetry
- CP Violation and rare decays of beauty and charm meson
- QCD, electroweak, exotica …



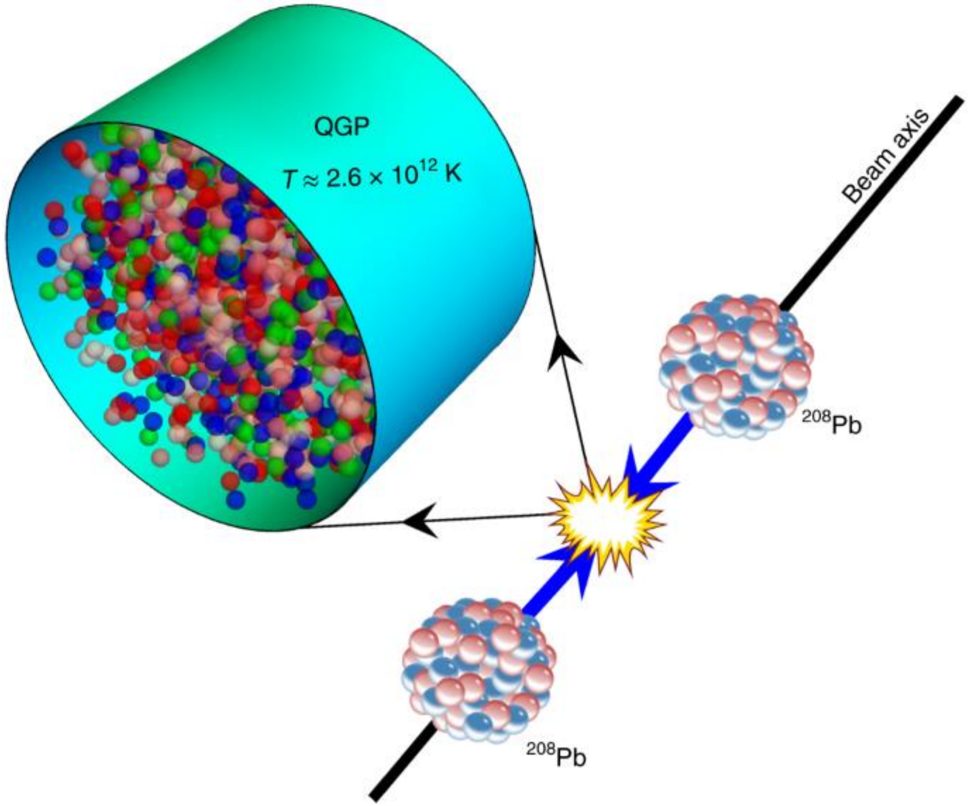
- Rapidity range 2< η < 5 : ~40% of heavy quarks produced hits the detector acceptance
- VELO : Decay time resolution ~45 fs
- Data Taking Efficiency : 90%
- Relative Track Momentum Resolution : 0.5% at low momentum, 1.0% at 200 GeV/c
- Track Reconstruction Efficiency : ~ 96 % for long tracks
- Calorimeters : ECAL, HCAL, $\Delta E/E$= 1% + 10 / $\sqrt{E}[GeV]$ for ECAL
- High Quality Particle Identification

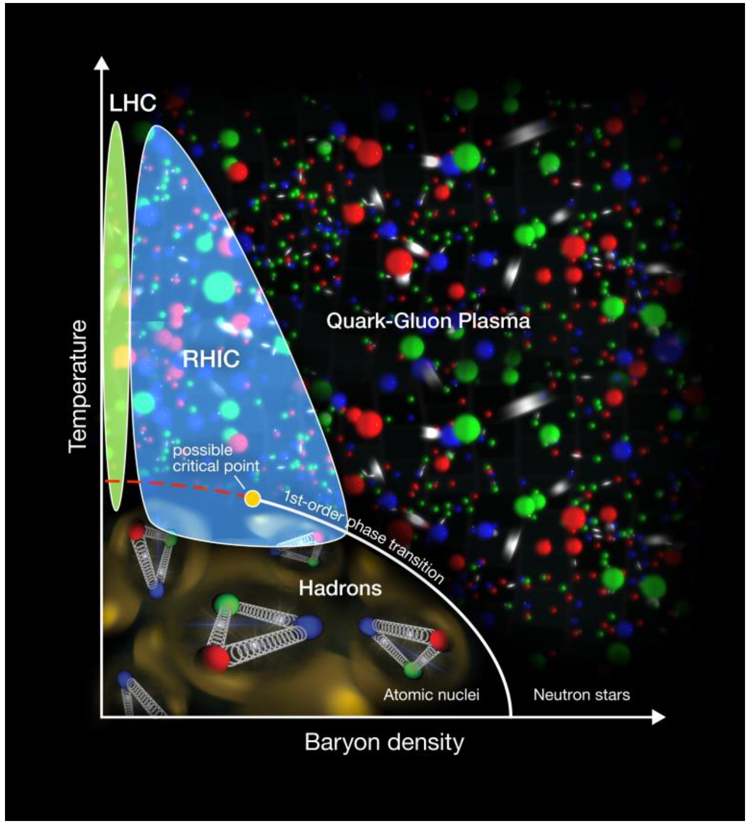
https://lhcb.web.cern.ch/speakersbureau/html/PerformanceNumbers.html

LHCb JINST 3 (2008) S08005

Cold Nuclear Matter

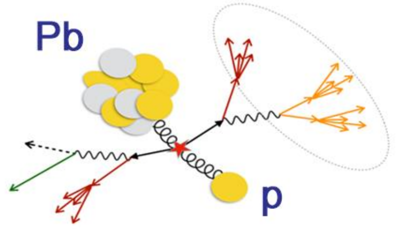
- The experiments at high energy, especially those at collider energies at RHIC and the LHC at are designed to search for phase transitions from normal matter to a deconfined quark-gluon plasma.



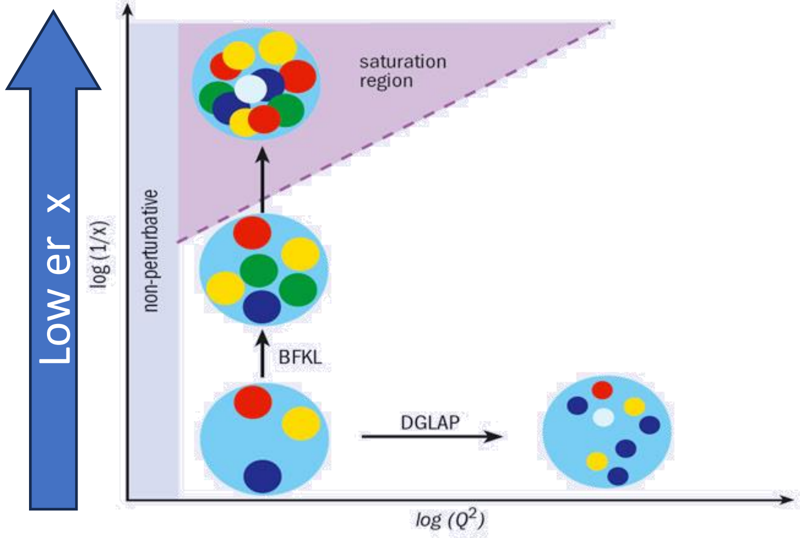


Cold Nuclear Matter

- There are other mechanisms that can mimic some of the effects of the deconfinement phase transition that do not involve quark-gluon plasma production.
- The way to separate these ’cold nuclear matter’ effects from those of the deconfined media is to study other, smaller collision systems.
- Deviations from the pp baseline in p+Pb and Pb+Pb collisions have been typically been quantified by ratios of observables in the heavy systems to the light system, such as the nuclear modification factor:
- At low-x gluon density becomes very large and a non-linear evolution regime with 2-> 1 gluon processes sets in at saturation scale Q
    - CGC is an effective theory for that regime
- More saturation at Lower x
- Lower x → forward rapidity
- Forward rapidity →



$$R = \frac{\frac{d\sigma_{pPb}\,(y,p_T)}{dy\,dp_T}}{T_{pp}\frac{d\sigma_{pp}\,(y,p_T)}{dy\,dp_T}}$$



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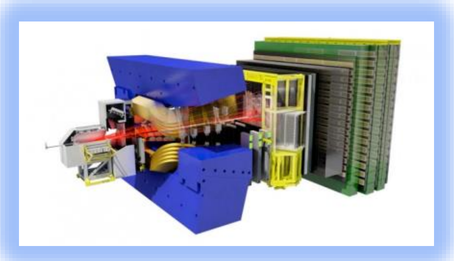
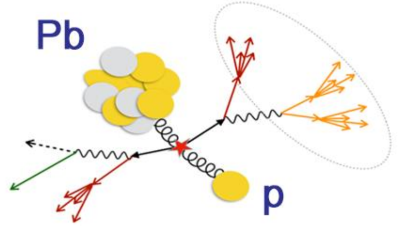
    - CGC is an effective theory for that regime
- More saturation at Lower x
- Lower x ⟶ forward rapidity
- Forward rapidity ⟶ LHCb





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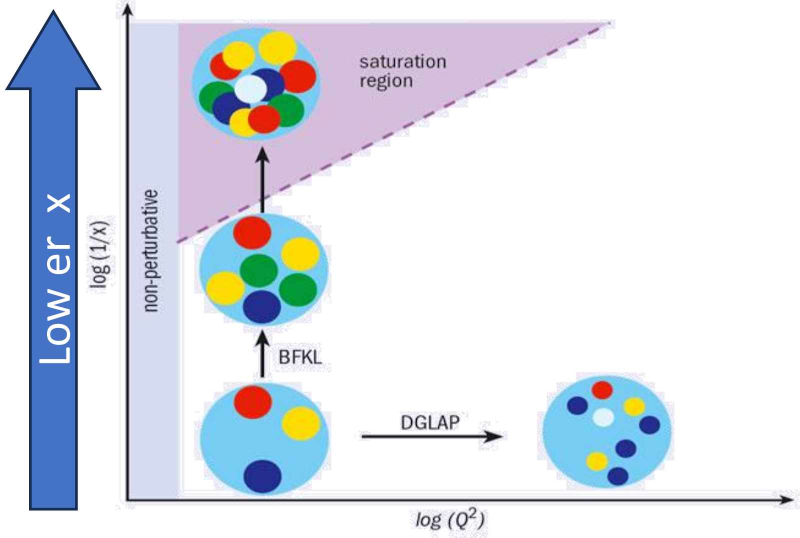
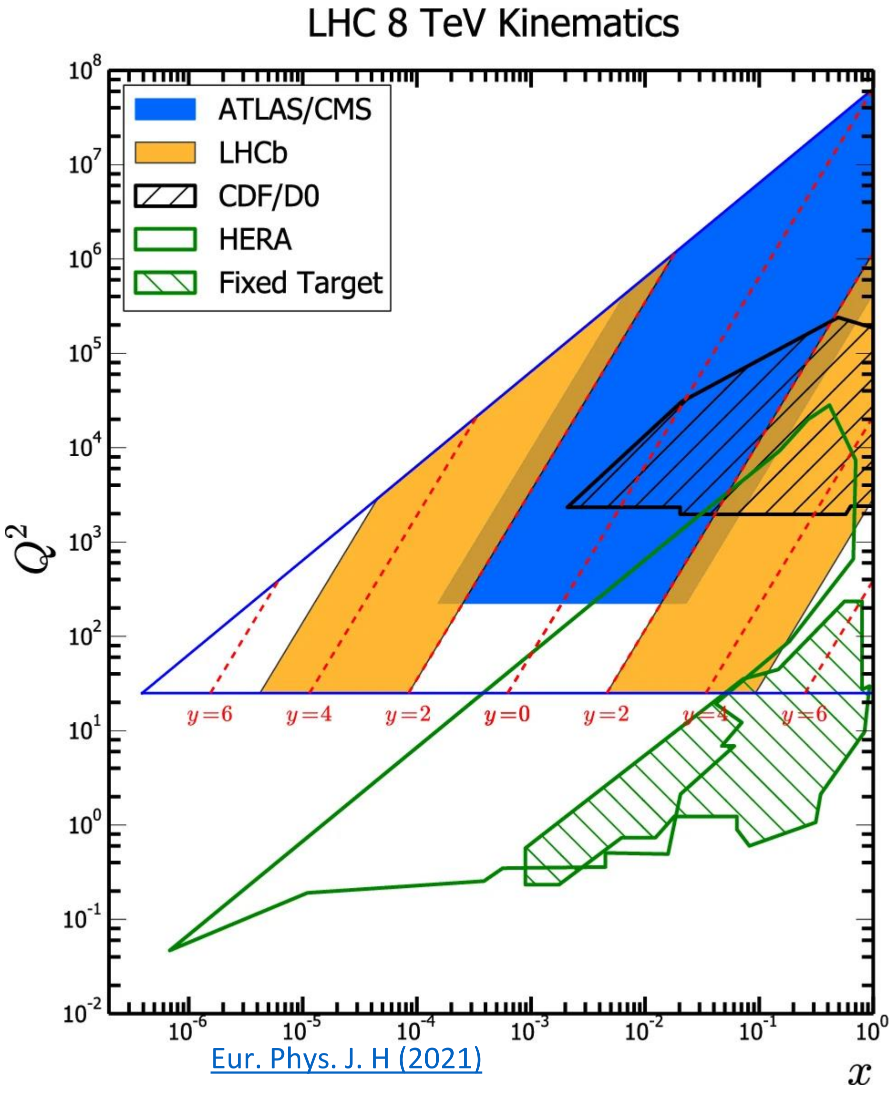


LHCb Detector and QCD



Eur. Phys. J. H (2021)

You can study QCD in the LHCb acceptance:

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

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

$b\bar{b}$- and $c\bar{c}$ -dijet: Motivation and selection criteria

JHEP 02 (2021) 023

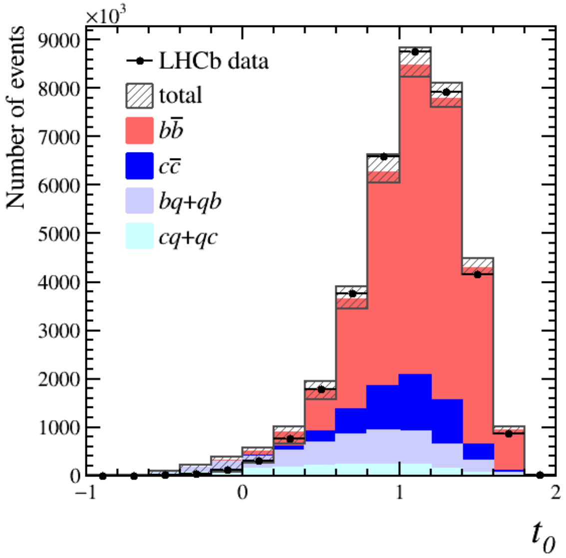
Motivation

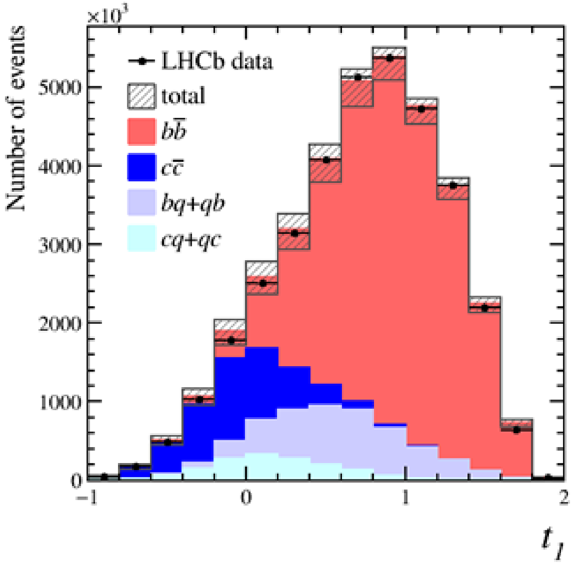
- In collisions at LHC, bottom and charm quarks are mostly produced in pairs.
- As $b\bar{b}$- and $c\bar{c}$ dijet differential cross-sections can be calculated in perturbative QCD (pQCD) as a function of the dijet kinematics, comparisons between data and predictions provide a critical test of next-to-leading-order (NLO) pQCD calculations.
- **This is the first inclusive, direct measurement of $c\bar{c}$ differential cross section at a hadron collider**

- The jet tagging system takes advantage of the LHCb features (precise vertex reconstruction)
- A jet is identified to be generated from a b or a c quark(b-jet or c-jet).
- Two Boosted Decision Trees are used to identify b and c jets.
  - BDT(bc|q): to separate heavy flavor jets from light jets
  - BDT(b|c): to separate b-jets from c-jets

Fit to combination of two MVA discriminators (BDTs) t_0 and t_1 to get flavor composition:

$$t_0 = BDT_{bc|q}(j_0) + BDT_{bc|q}(j_1)$$
$$t_1 = BDT_{b|c}(j_0) + BDT_{b|c}(j_1)$$





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

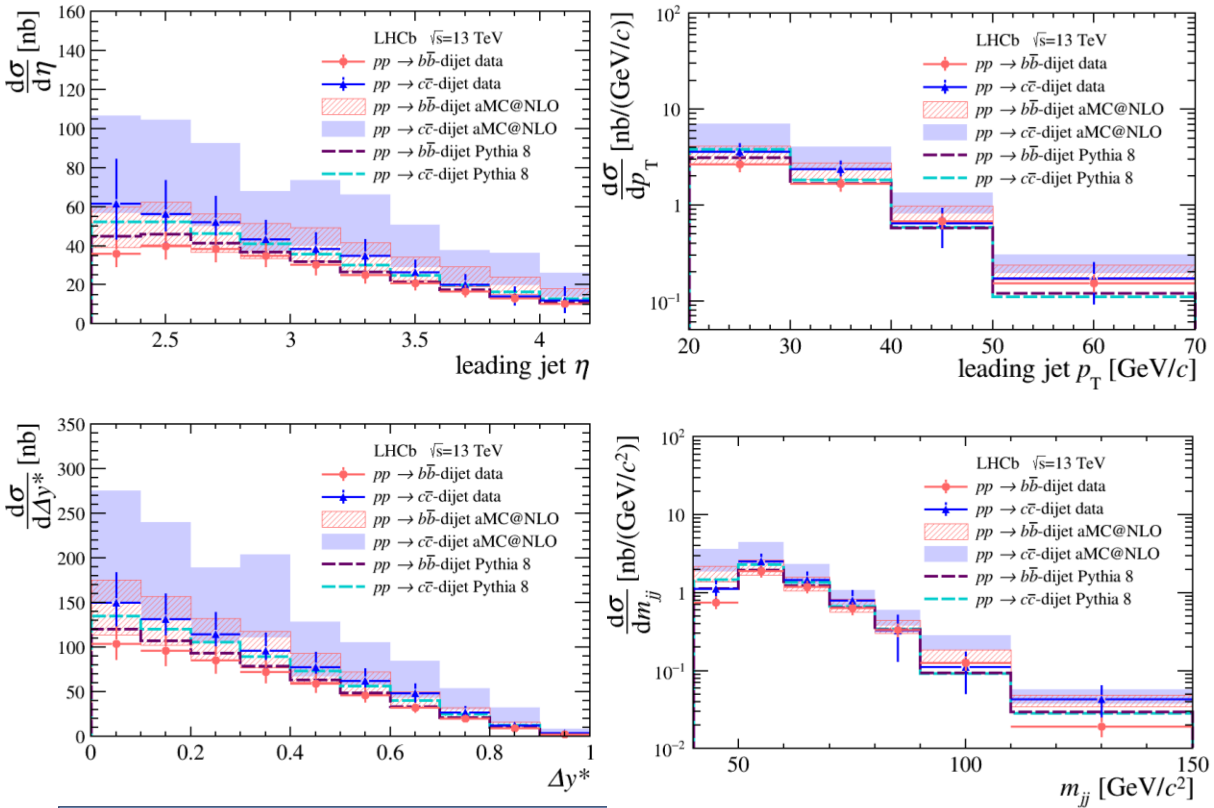
- The cross-section is evaluated using:

$$\frac{d\sigma}{dz} = \frac{1}{\mathcal{L}}\frac{1}{2\Delta z(i)}\frac{1}{A(i).\epsilon(i)}\sum_{j=1}^{n} U_{ij}.N(j)$$

where,

  - z is the variable under study at generator level
  - $\mathcal{L}$ is the integrated luminosity
  - $2\Delta z(i)$ is the width of the bin
  - i is the index of the bin
  - A(i) is the acceptance factor for the bin
  - $\epsilon(i)$ is the efficiency of the bin ($\epsilon_{tot} = \epsilon_{reco}.\epsilon_{tag}.\epsilon_{trig}$)
  - U_{ij} is the unfolding matrix that maps reconstructed to generator level variables
  - N(j) is the number of the fitted events in the bin

- $b\bar{b}$ and $c\bar{c}$ differential cross-sections measured with 2016 data.
- The differential cross-section as a function of leading jet η, p_T, Δy^* and m_{jj} is presented.
- The measurements are slightly below the predictions, with uncertainties within 1-2 σ.
- The measurements are also compared with simulations from Pythia and a MC@NLO.



σ(pp → $b\bar{b}$ -dijet X) = 53.0 ± 9.5 ± 2.1 nb
σ(pp → $c\bar{c}$ -dijet X) = 72.6 ± 16.1 ± 2.9 nb

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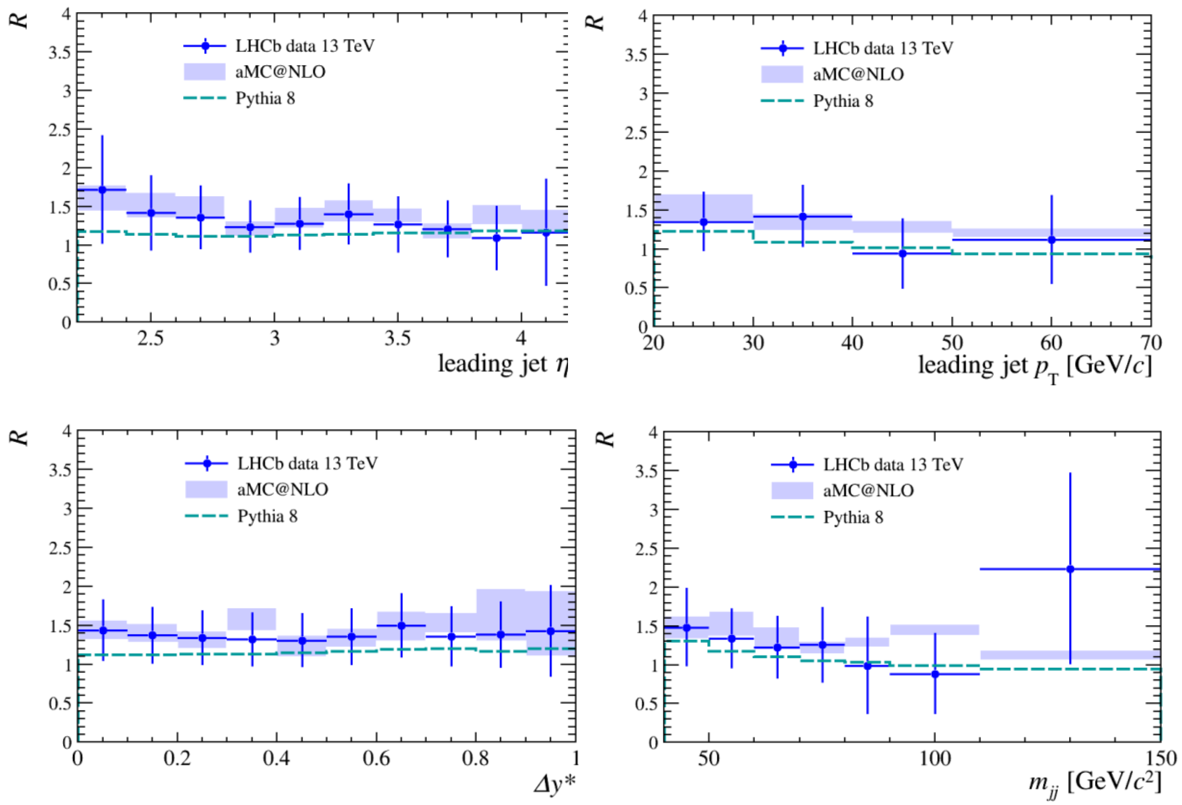
$b\bar{b}$- and $c\bar{c}$:Differential cross-sections ratios

- The total $b\bar{b}$ -dijet and $c\bar{c}$-dijet cross-sections and their ratio in the fiducial region, compared with the NLO predictions.
- The R measurements are compatible with the prediction within its uncertainties.
- The total cross-sections and R are compatible with the prediction from Madgraph5 aMC@NLO + Pythia within its uncertainty.

$$R = \frac{\sigma(pp \rightarrow c\bar{c} - dijet\ X)}{\sigma(pp \rightarrow b\bar{b} - dijet\ X)} = 1.37\ \pm 0.27$$



Pythia: arXiv:2203.11601 [hep-ph]
Madgraph: arXiv:1106.0522 [hep-ph]

JHEP 02 (2021) 023

Nuclear Modification Factor of π^0

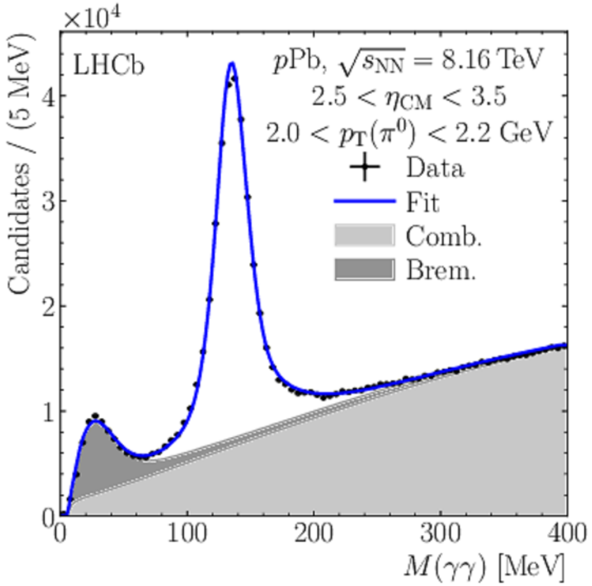
Motivation

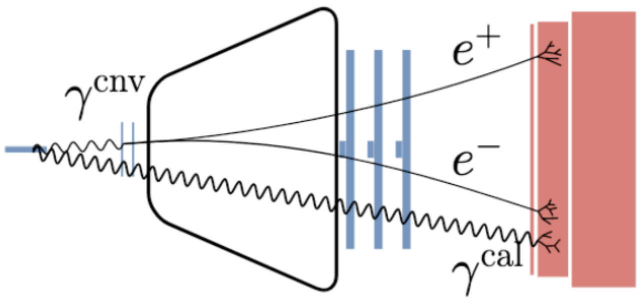
- Neutral pion production is an important probe of nuclear effects in heavy ion collisions.
- In proton-lead (*pPb*) collisions, π^0production is particularly sensitive to cold nuclear matter (CNM) effects.
- First π^0 result in forward rapidity at LHC.
- Measurements of π^0 production in pPb collisions at forward and backward rapidities with the LHCb detector can provide constraints on nuclear PDFs helping identify the parton saturation effects
  - Typical *x* between 10^{-6} and 10^{-1}

$$R_{pPb} = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

Selection Criteria

- π^0 candidates are obtained from decays to pair of photons
$$\pi^0 \rightarrow \gamma^{cnv}\gamma^{cal}$$
- This analysis measures the nuclear modification factor of π^0 meson production in *pPb at* $\sqrt{s} = 8.16\, TeV$.
- The measurement is performed for:
  - $1.5 < p_T < 10\ GeV$
  - $2.5 < \eta_{CM} < 3.5\ and\ -4.0 < \eta_{CM} < -3.0$
- At least 1 track in VELO and π^0 reconstructed as pairs of photons



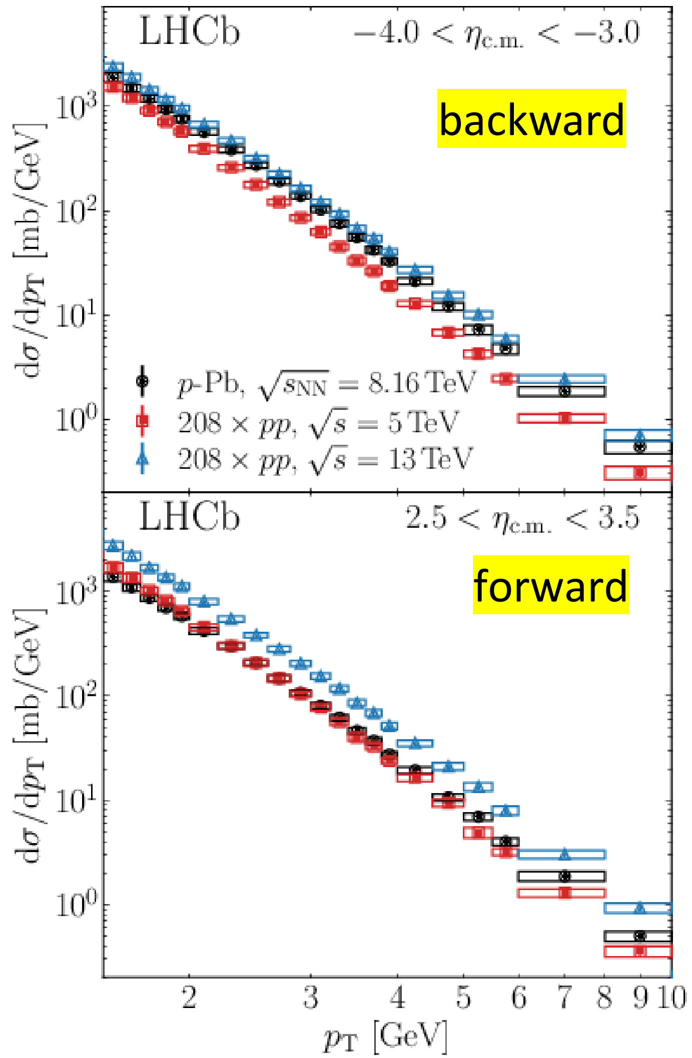


Phys.Rev.Lett. 131 (2023) 4, 042302

Nuclear Modification Factor of π^0:Interpolation

- The main systematic error comes from the interpolation between *pp* cross-sections and the π^0fit model.
- Statistical uncertainties are shown by error bars, while systematic uncertainties are shown by boxes. The pp cross sections are scaled by the atomic mass of the lead ion, A =208.

- The nuclear modification factor shows a Cronin like **enhancement at backward pseudorapidity** and a strong **suppression in the forward pseudorapidity.**
- These measurements are compared to next-to-leading order pQCD calculations
- The enhancement in the backward direction between 2 and 4 GeV is larger than predicted by the pQCD calculation, suggesting that effects not described by NPDFs contribute to the enhancement



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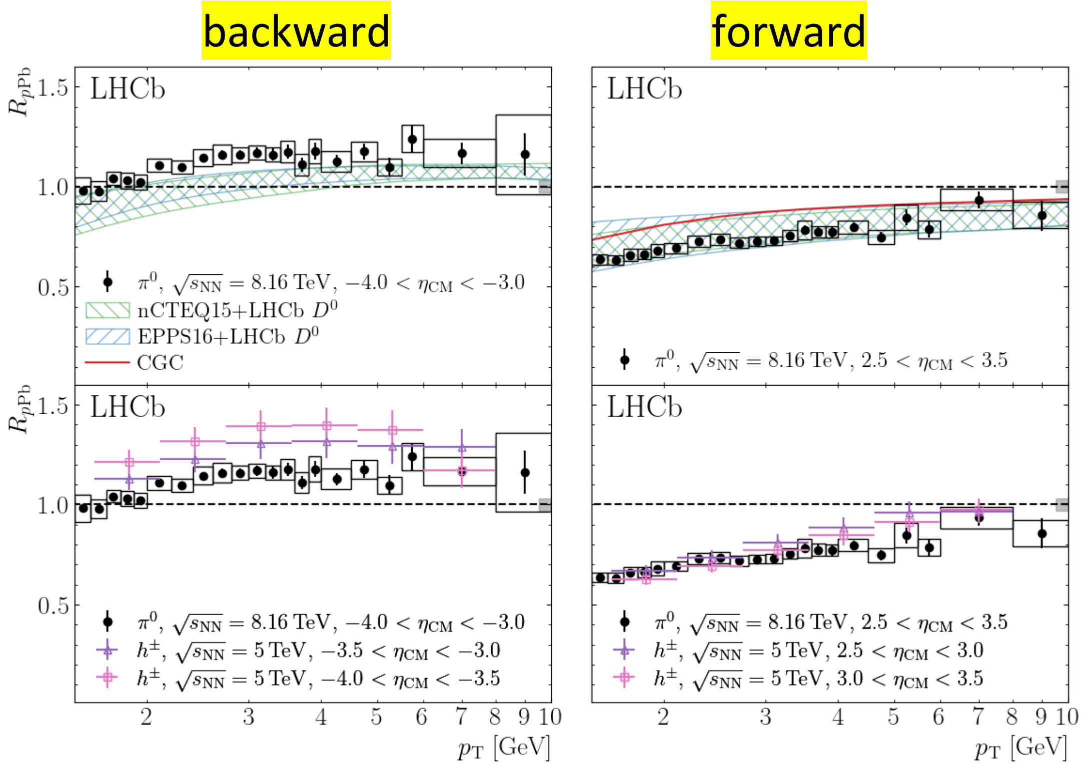

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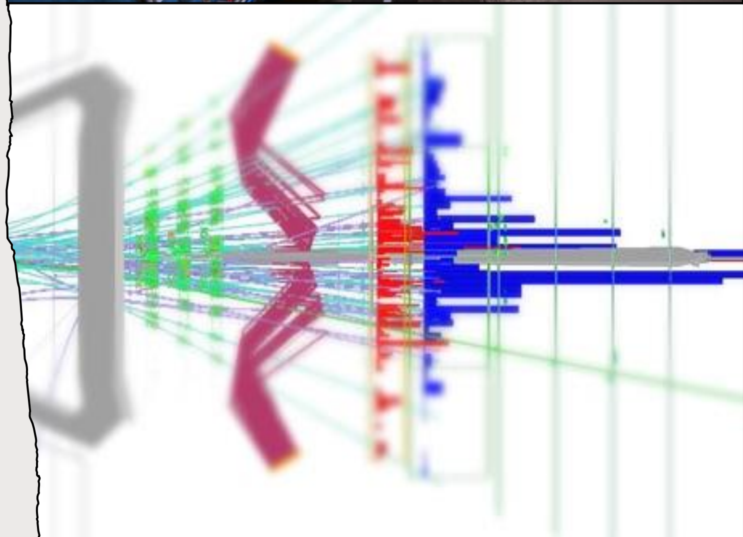
Conclusions

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.
- The exploration of cold nuclear matter effects advances our understanding of nuclear matter and its behavior under different conditions.

A lot of interesting results (these are just the latest!!)

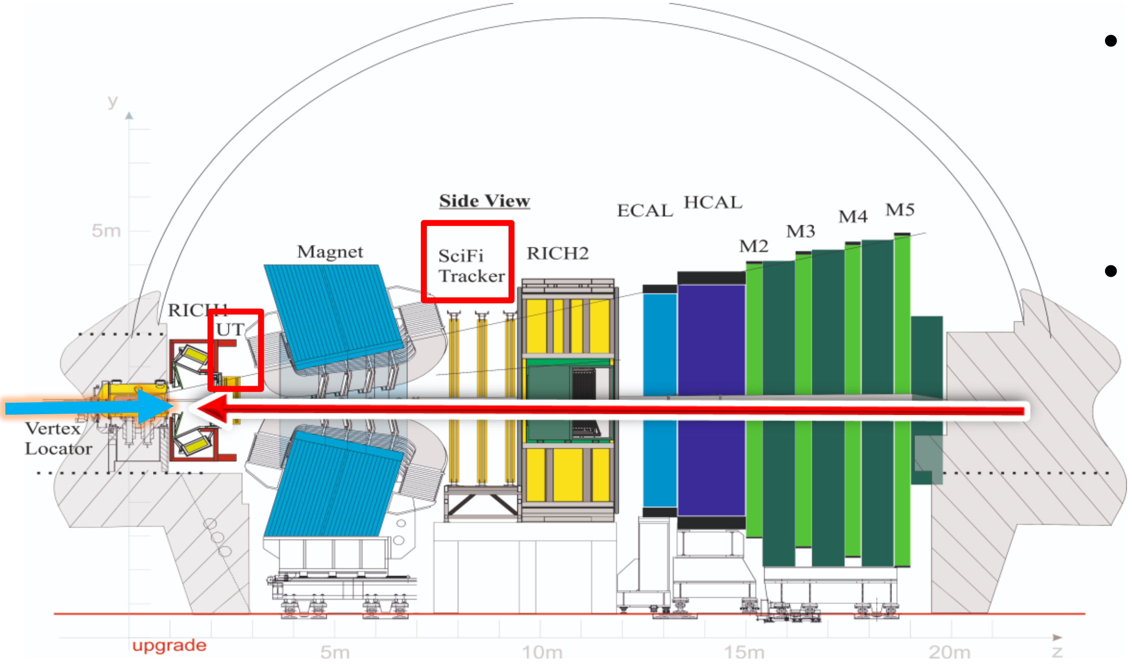
- Measurement of differential heavy flavour di-jets cross- sections.
- Study of nuclear modification factor for π^0.
- The measurements of dijet and neutral pion production provide complementary information on the PDFs and nuclear structure, which are important for understanding QCD dynamics in high-energy nuclear collisions and for further improving the theoretical models.



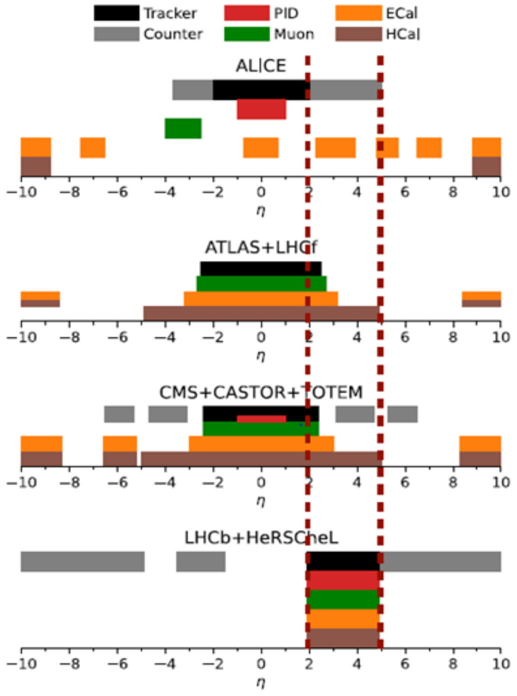
Thank You

for your attention

The LHCb Detector - Upgraded



- New Installation: from subdetectors technologies to the data acquisition domain, from the timing and fast controls distribution to a full-software trigger architecture.
- Five-fold increase in the instantaneous luminosity and pile-up to improve precision in flavour physics observables.



- **Rapidity range 2< η < 5 : ~40% of heavy quarks produced hits the detector acceptance**
- **VELO : Decay time resolution ~45 fs**
- **Data Taking Efficiency : 90%**
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- **Calorimeters : ECAL, HCAL, $\Delta E/E$= 1% + 10 / $\sqrt{E}[GeV]$ for ECAL**
- **High Quality Particle Identification**

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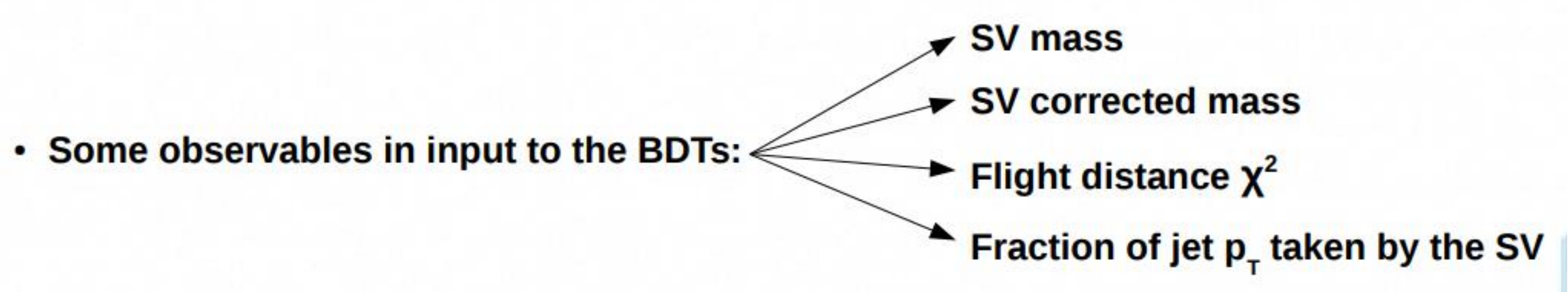
LHCb JINST 3 (2008) S08005

SV-Tagging Algorithm

- The SV-tagging algorithm reconstructs secondary vertices (SVs) using tracks inside and outside of the jet
- In this algorithm tracks that have a significant pT and displacement from every PV are combined to form two-body SVs.
- Then good quality two-body SVs are linked together if they share one track, in order to form n-body SVs.
- If a SV is found inside the cone of the jet, the jet is tagged as likely to be originating from b- or c-quark fragmentation

Boosted Decision Tree Classifiers (BDT)

- To further distinguish light-flavour jets from heavy-flavour jets and b-jets from c-jets multivariate analysis algorithms are used.
- Two boosted decision tree (BDT) classifiers that use as inputs variables related to the SV, are employed: one for heavy-/light-jet separation ($BDT_{bc|q}$) and the other for b-/c-jet separation ($BDT_{b|c}$).



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Jet Reconstruction Algorithm

Particle flow

- Long tracks, calorimeter clusters and metastable particles are selected as an Inputs

Anti K_T clustering

- Inputs are used to form jets of a given cone radius R =0.5

Jet Four-momentum

- $E_{jet} = \sum_i E_i \vec{p}_{jet} = \sum_i \vec{p_i}$

Jet Energy correction

- The jet energy is corrected for detector efficiencies