Jet hadronization at LHCb

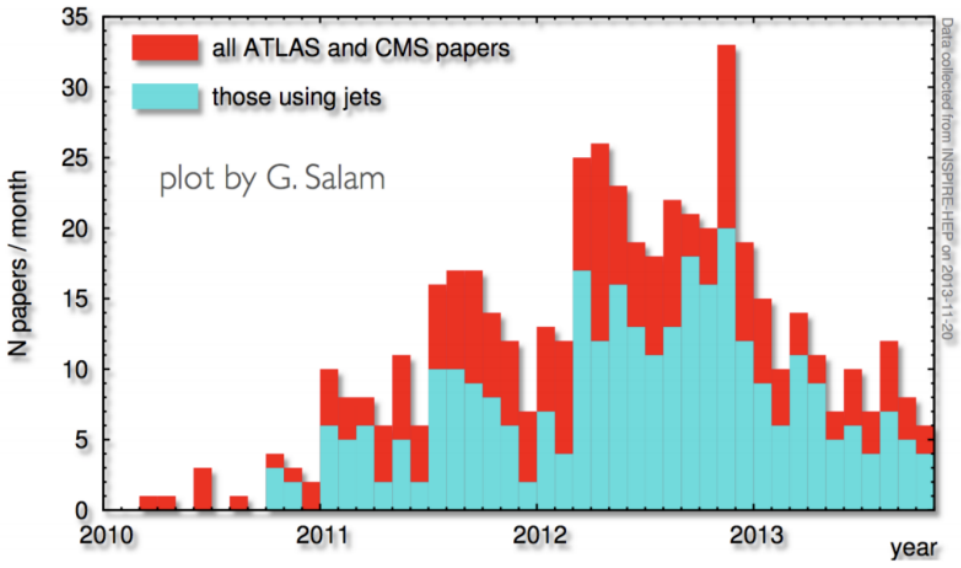
Joe Osborn
on behalf of the LHCb collaboration

University of Michigan

March 20, 2019

Jet Hadronization

- Jet physics is a broad experimental endeavor at LHC
- Enabled by more robust comparisons that can be made between theory and experiment with e.g. anti-k_T algorithm



Jet Hadronization

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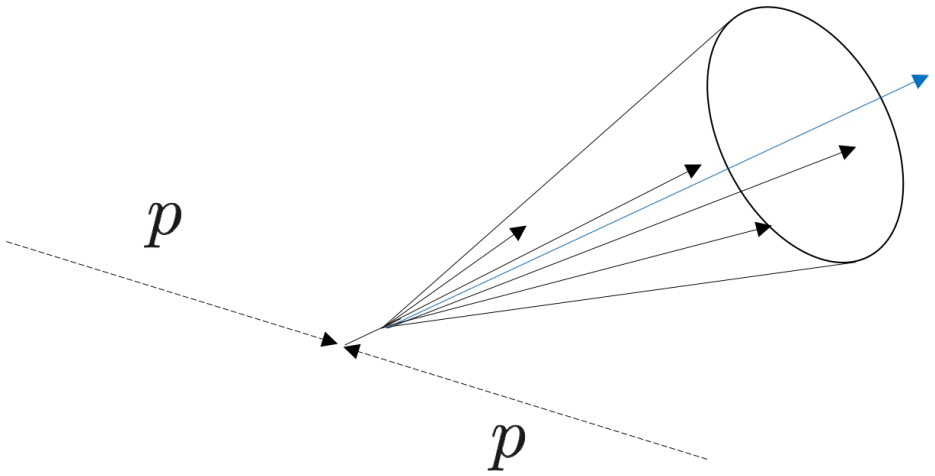
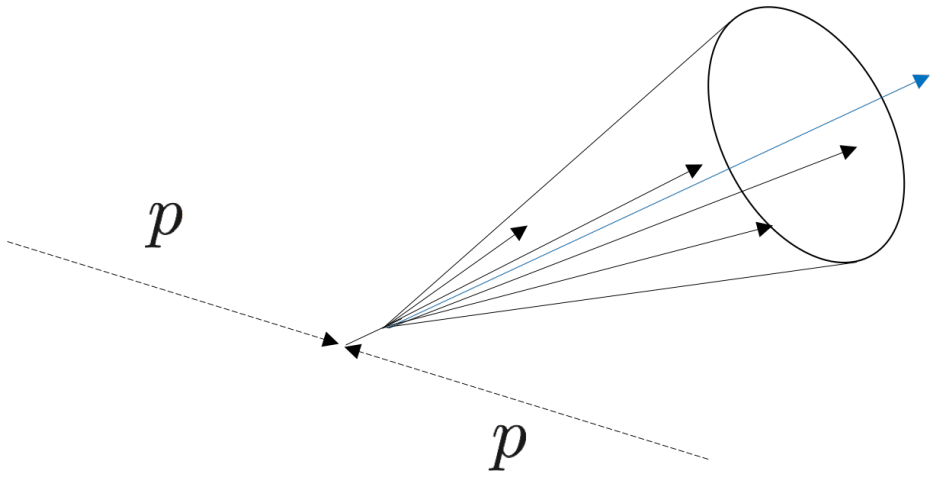
- Enabled by more robust comparisons that can be made between theory and experiment with e.g. anti-k_T algorithm
- Jets are a proxy for partons, and thus provide sensitivity to the underlying partonic dynamics



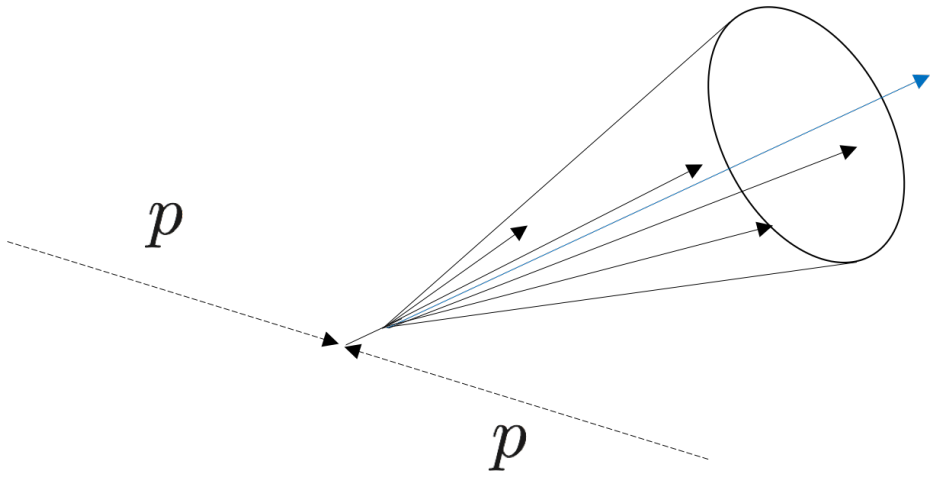
Jet Hadronization

- BUT - jets are still formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jet formation



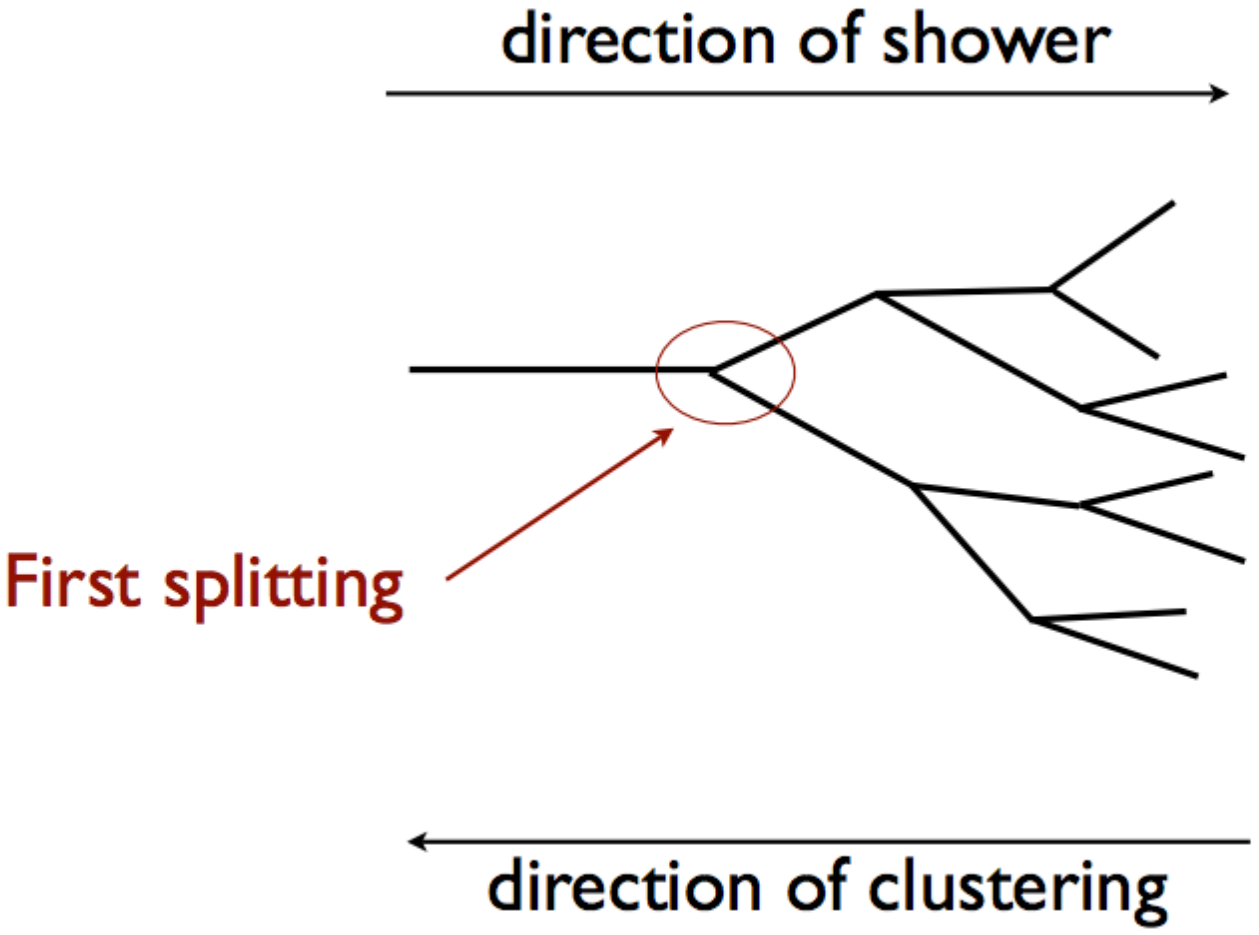
Jet Hadronization

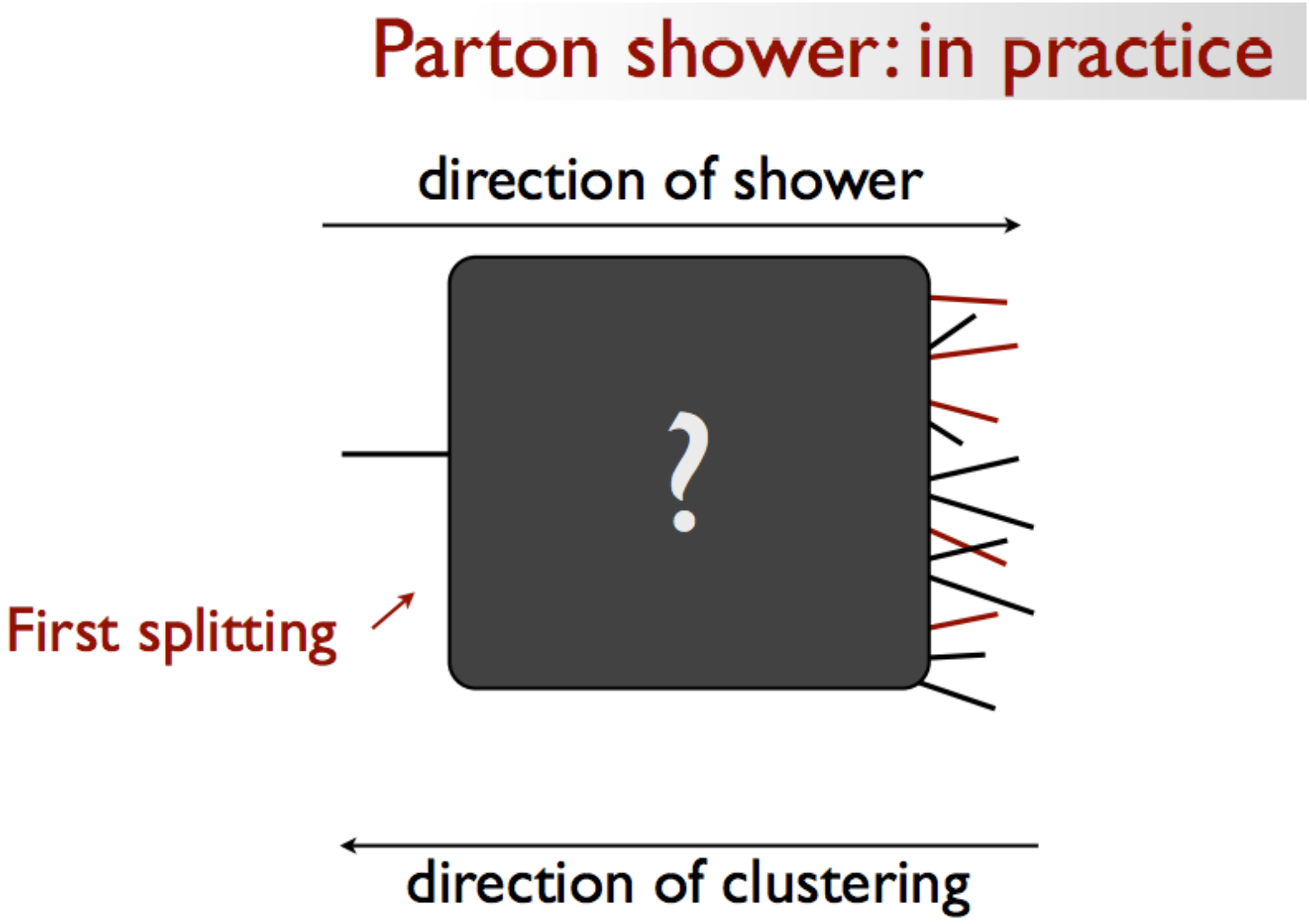
- BUT - jets are still formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jet formation
- We can use a perturbative object to learn about nonperturbative physics



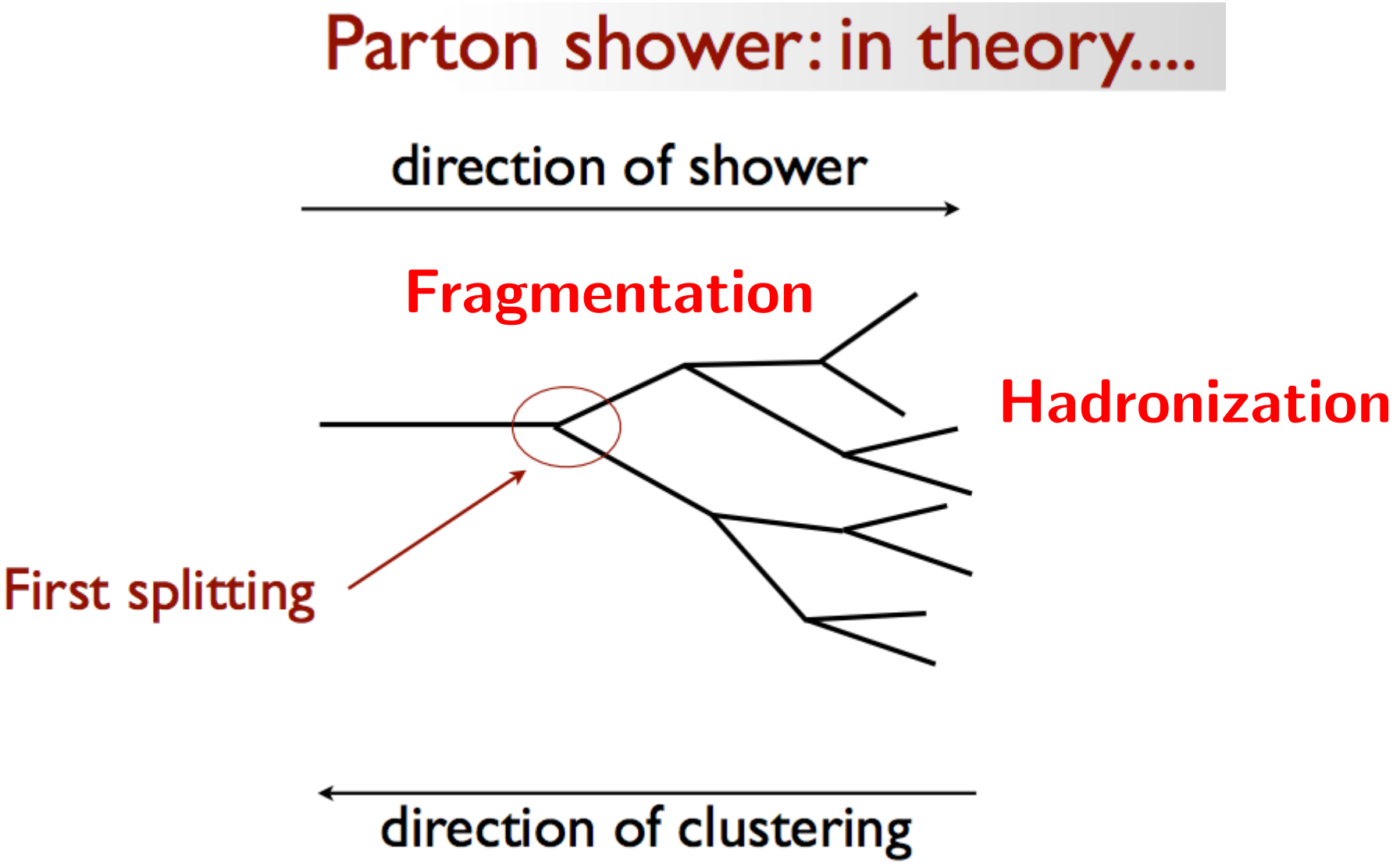
Jet Formation

Parton shower: in theory....



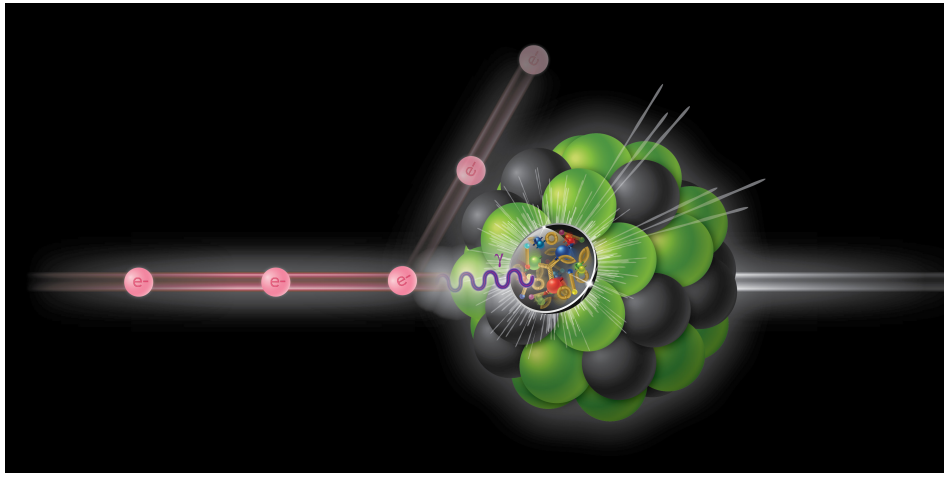

Parton shower: in practice
direction of shower
?
First splitting
direction of clustering

Jet Formation



Hadronization at an Electron Ion Collider

- Physical ideas behind hadronization significantly behind those in the initial state (e.g. PDFs)
- Crucial to begin developing (nuclear modification of) hadronization program before EIC



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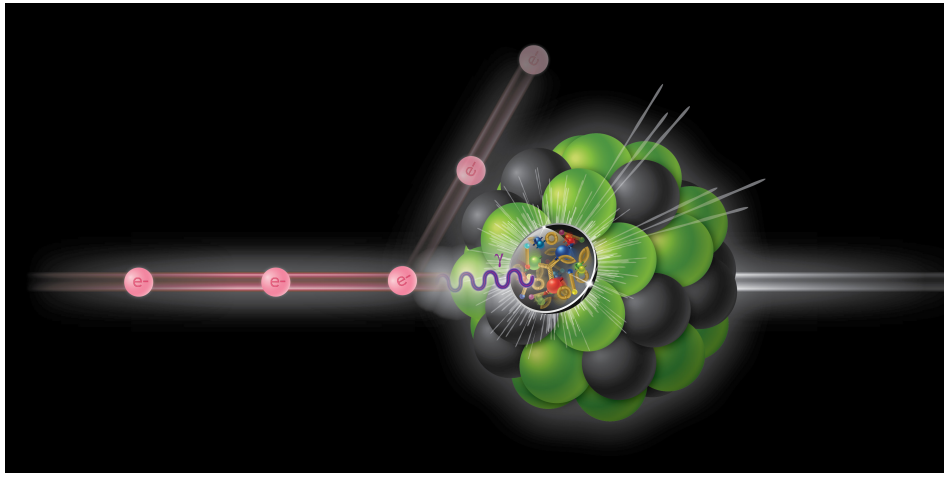
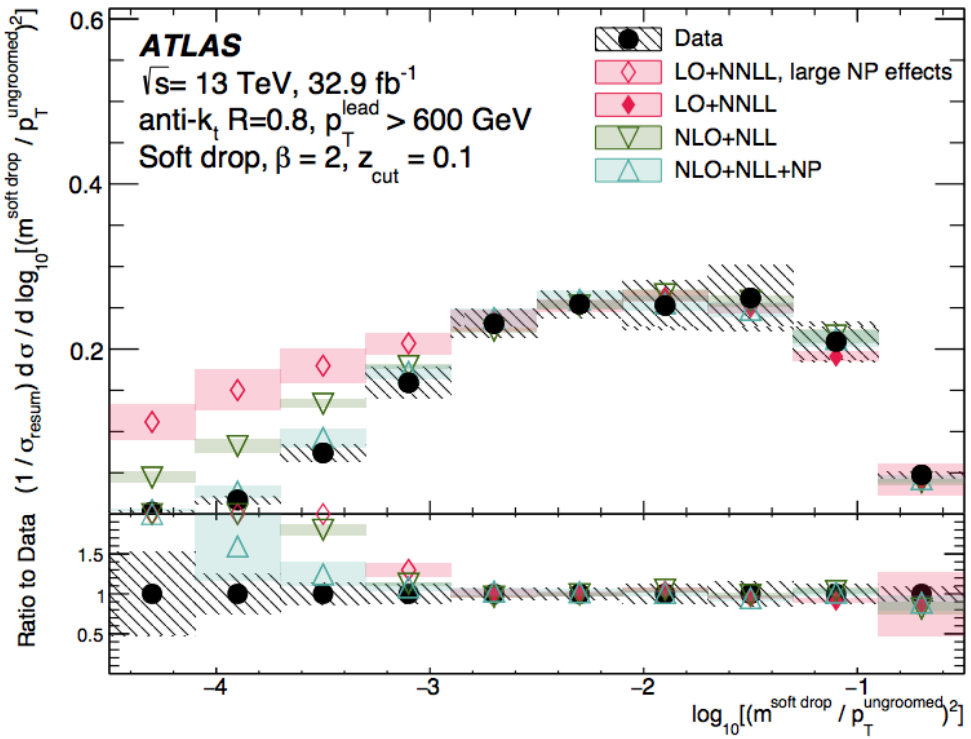
- Crucial to begin developing (nuclear modification of) hadronization program before EIC
- We should not begin the EIC era with limited ideas on how to pursue one of its major physics programs



Jet Substructure Studies at the LHC

- Several measurements of jet substructure at midrapidity from ATLAS, CMS, ALICE
- Wide range of physics interests and effects probed



PRL 121, 092001 (2018)

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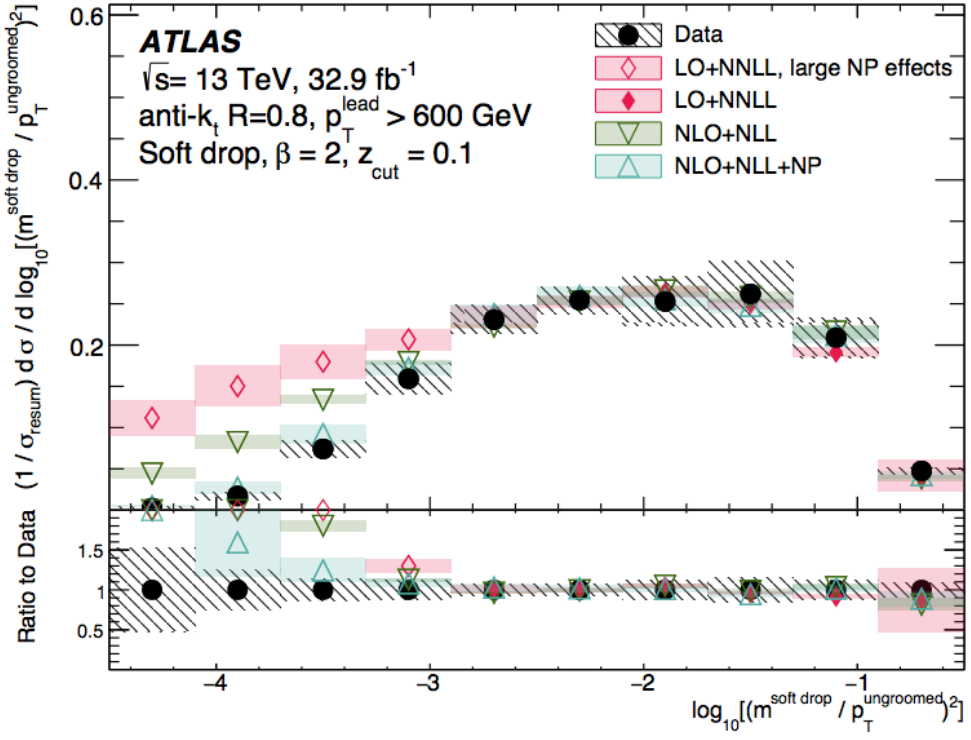

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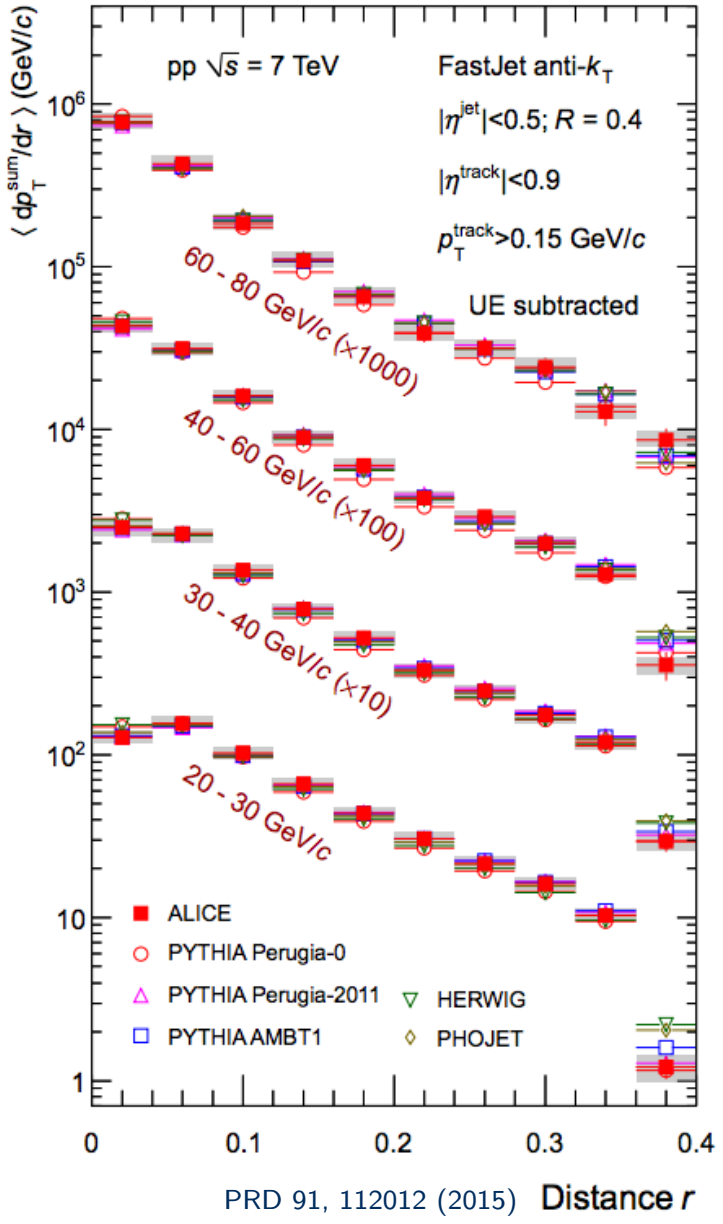

PRD 91, 112012 (2015)

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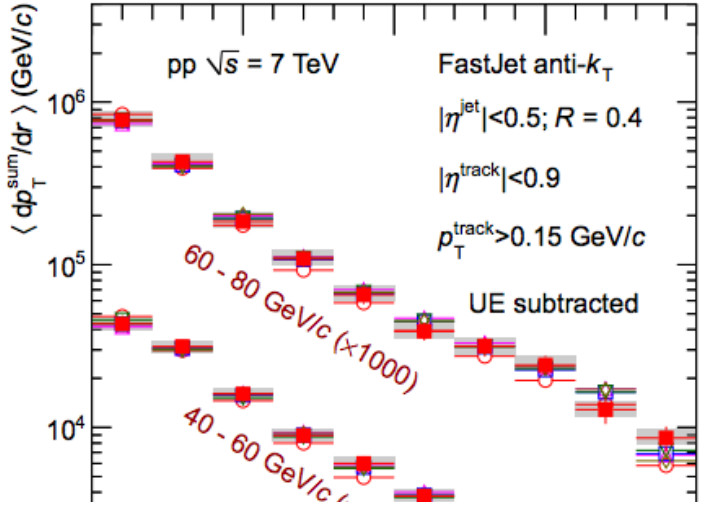
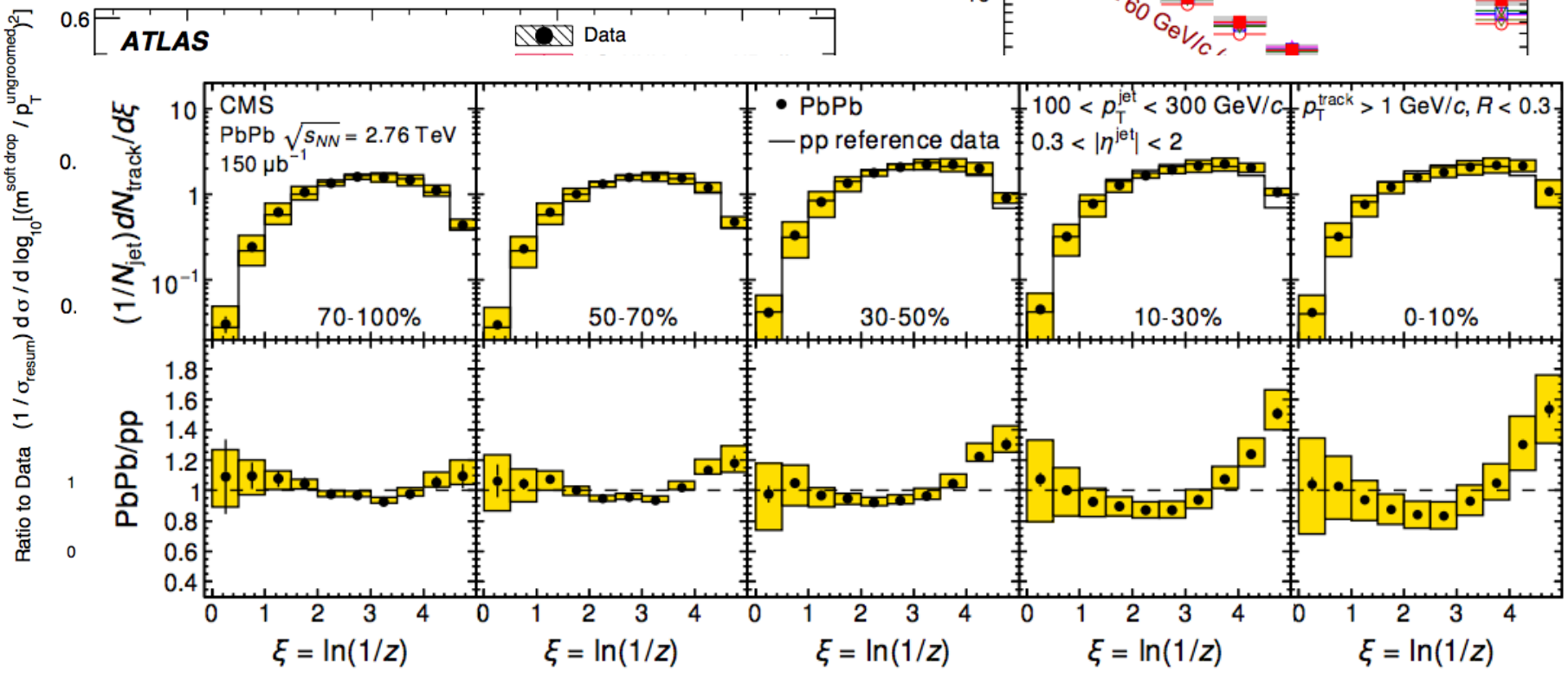
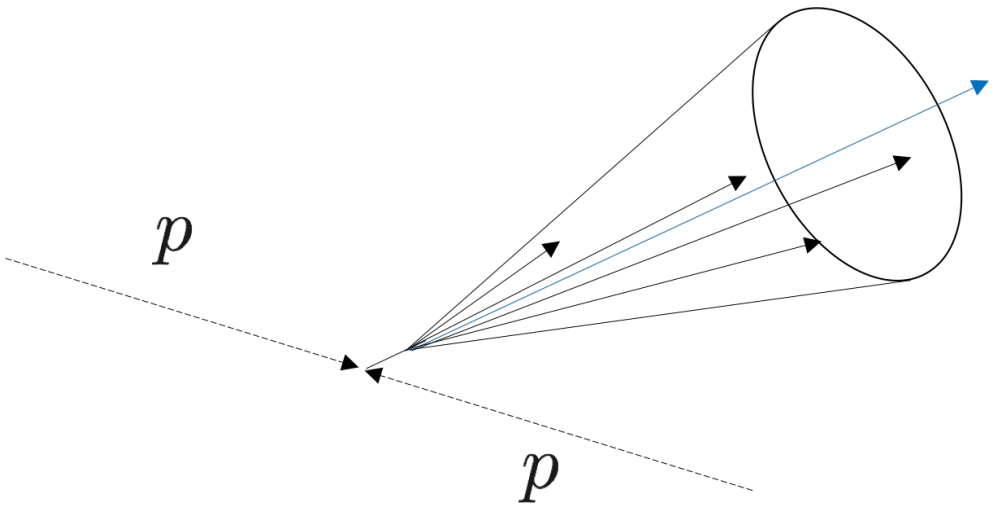




PRC 90, 024908 (2014)

Hadronization: What do we want?



- What is on our wish list to *robustly* study hadronization?

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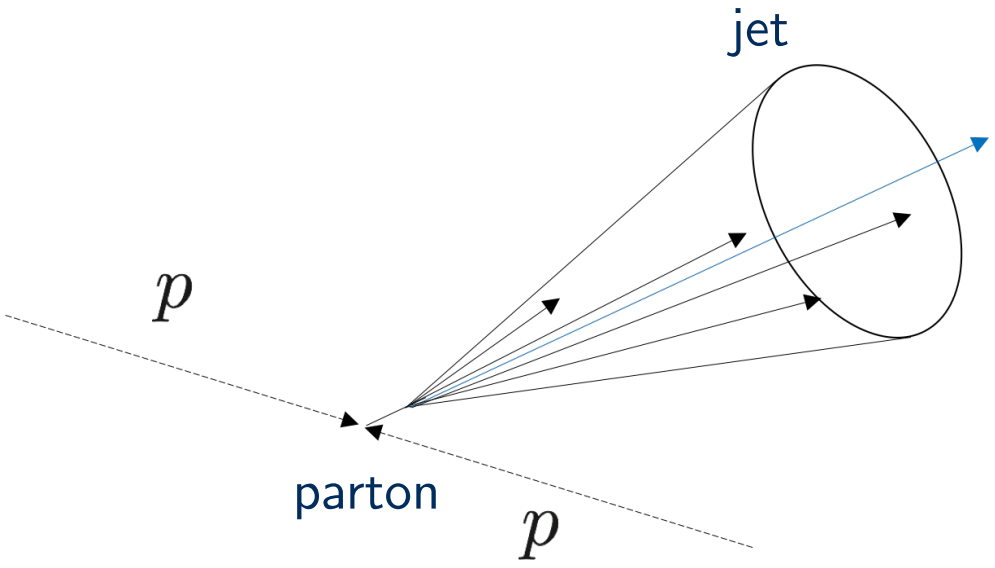

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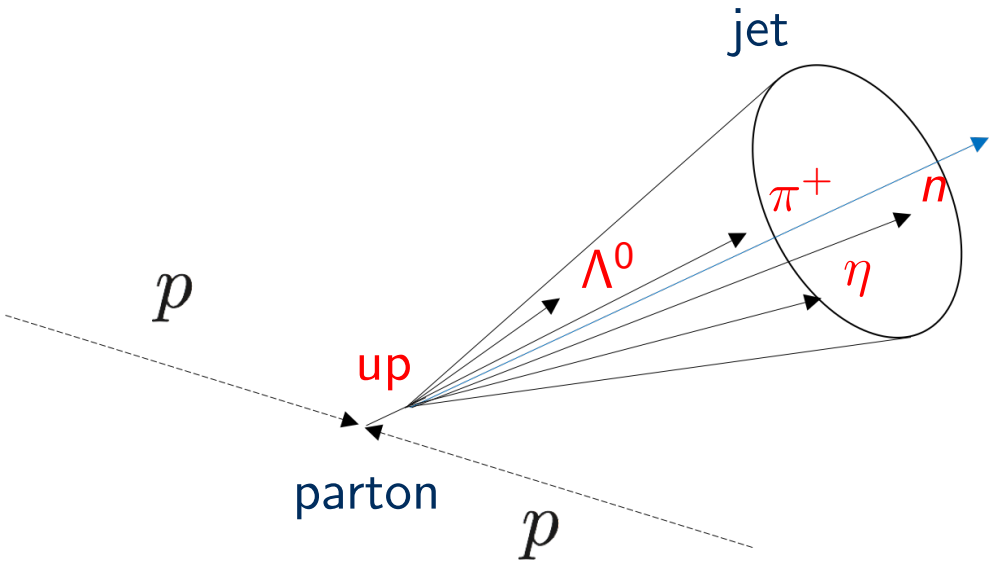

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     - Would allow for complete characterization of parton $\rightarrow$ hadron

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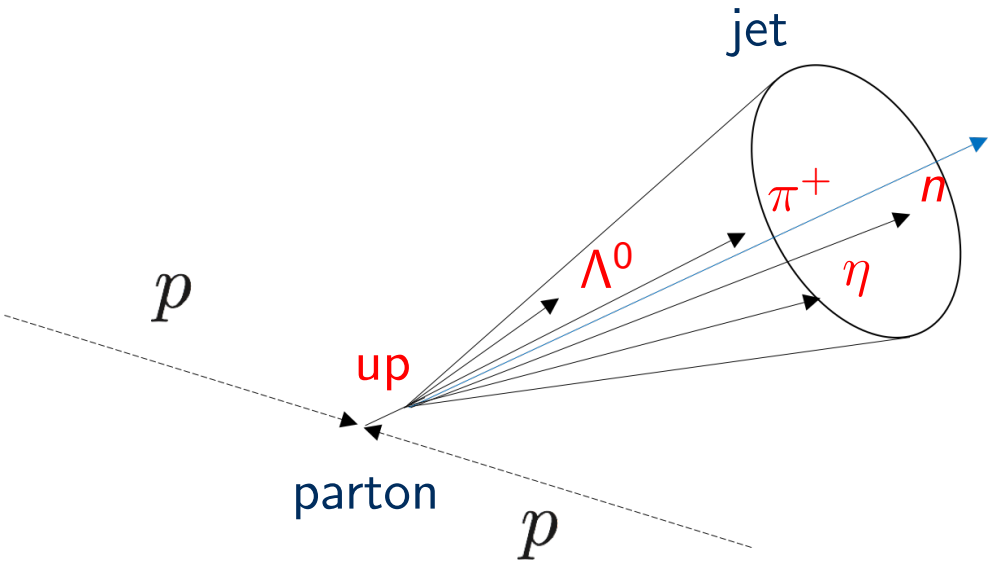

- Baryon vs. meson
- Correlations (e.g. strangeness, heavy flavor...)
- Resonance production (ϕ, J/ψ, Υ)
- Increase projectile/target size
- ...

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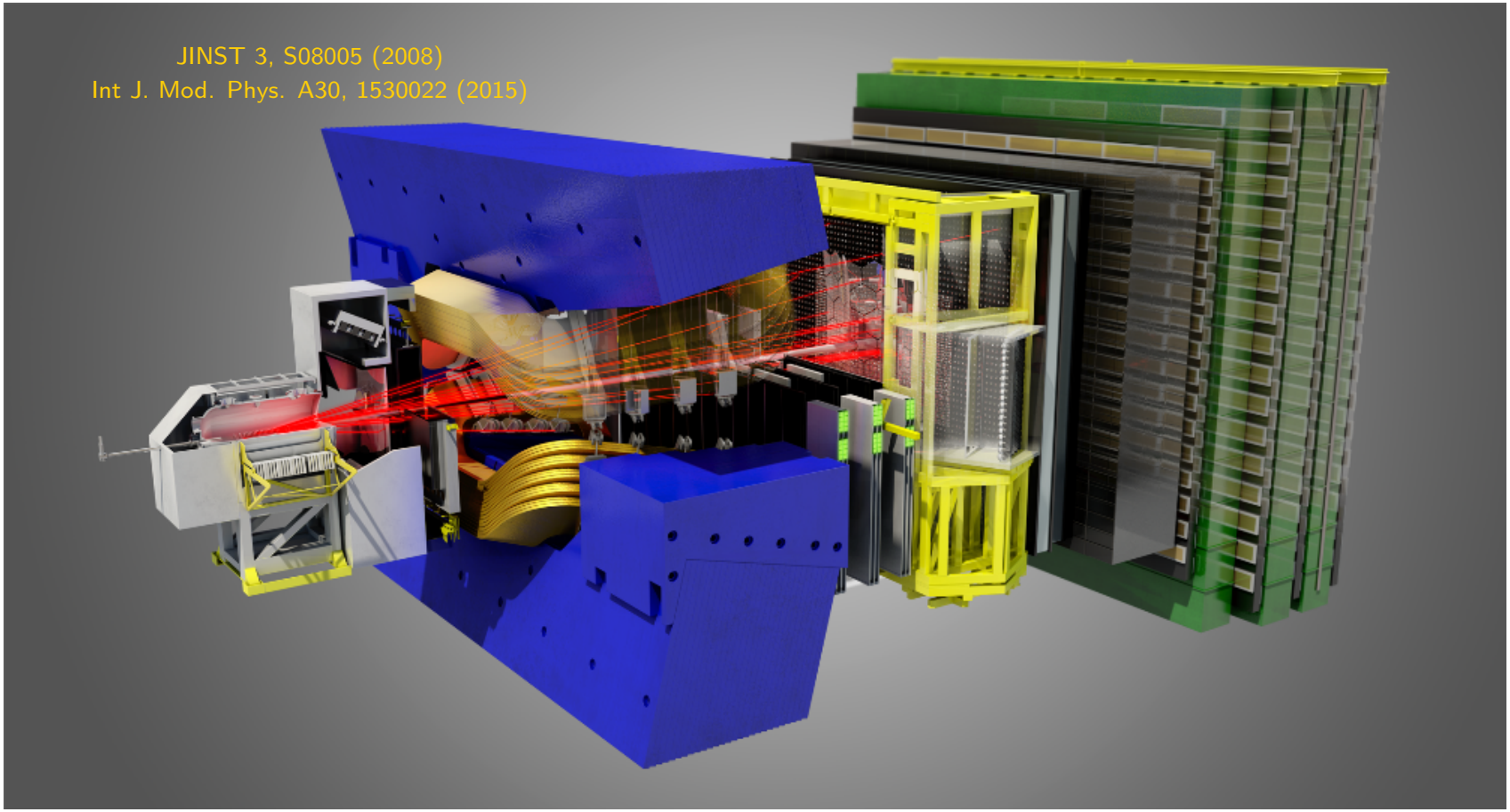
LHCb Experiment



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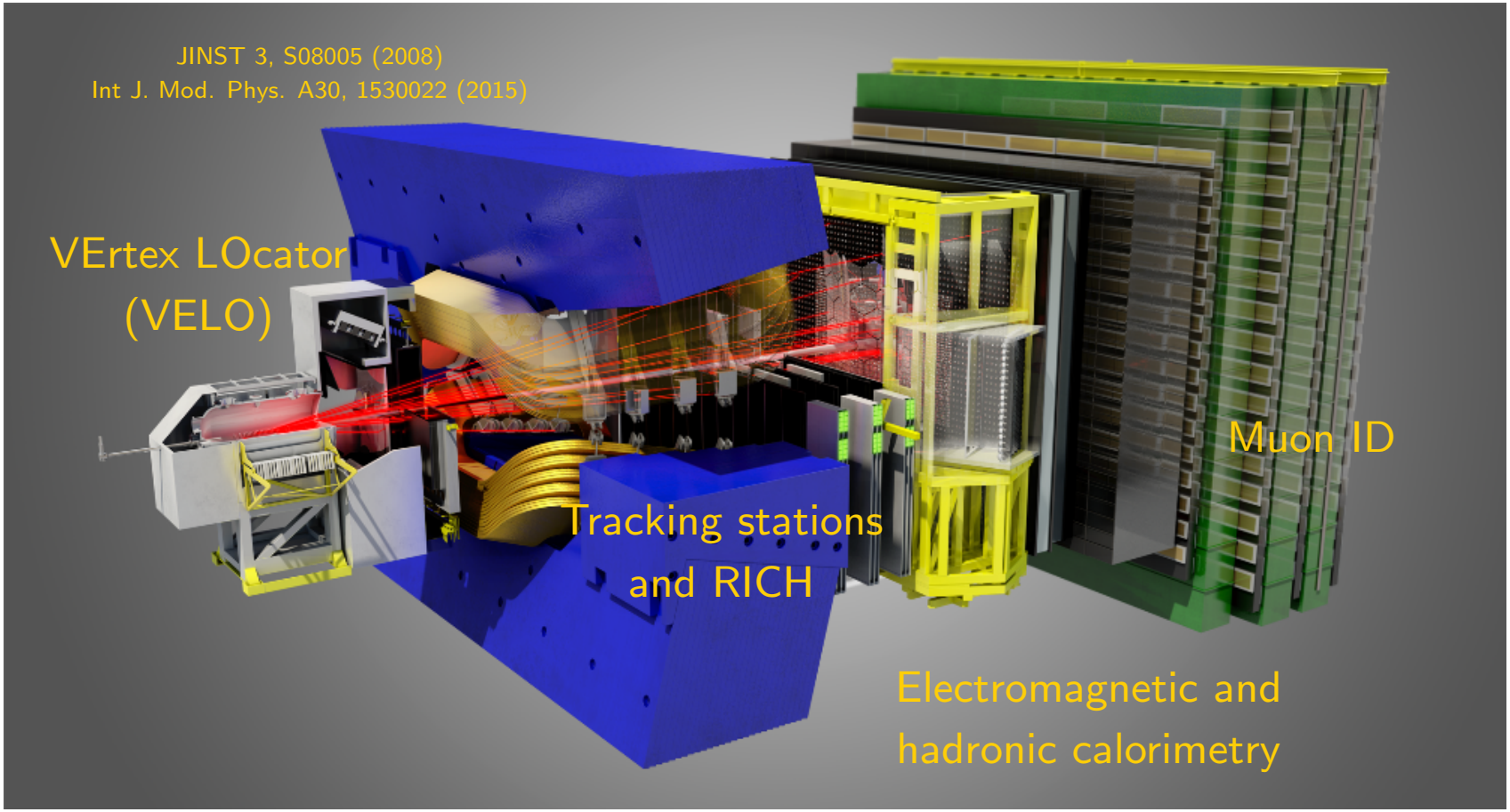

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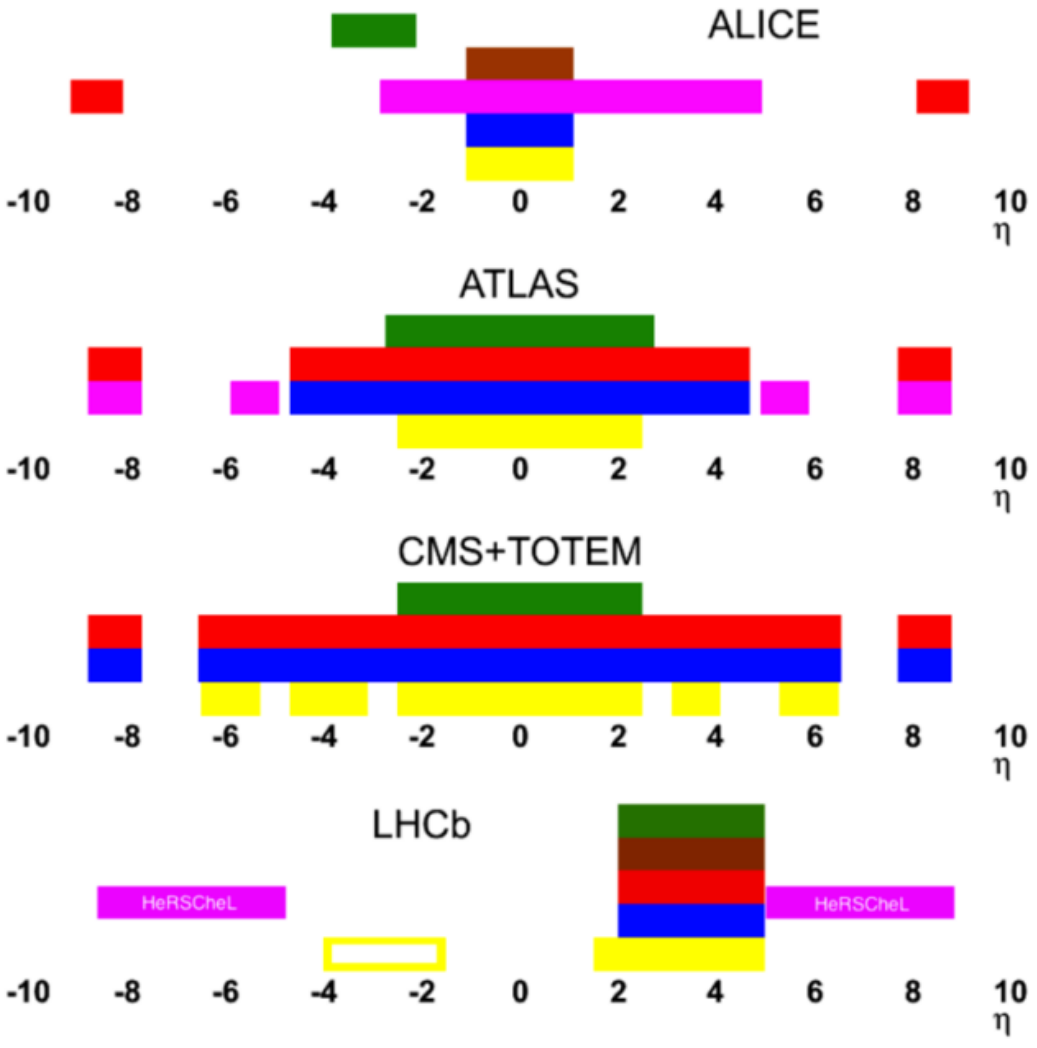

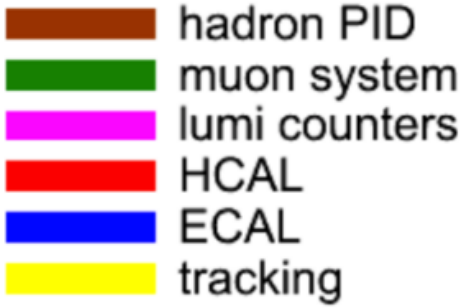

- LHCb has unique advantages for jet hadronization physics over other LHC experiments
- Uniform coverage tracking, PID, *and* calorimetry

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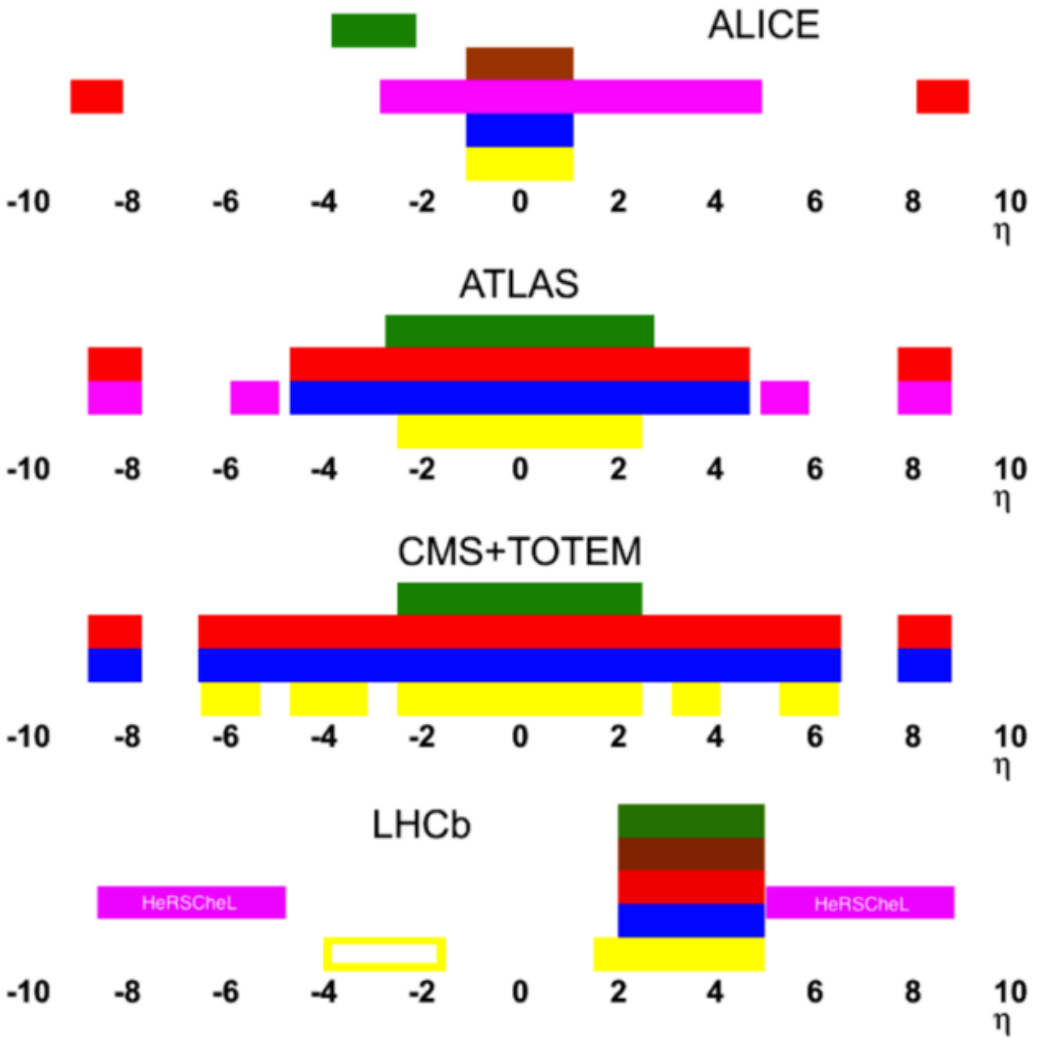

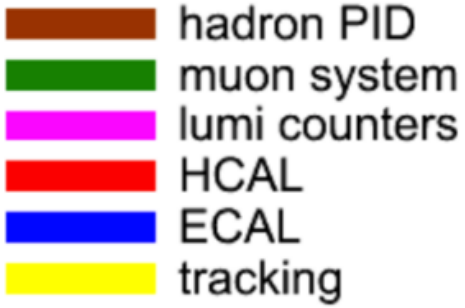

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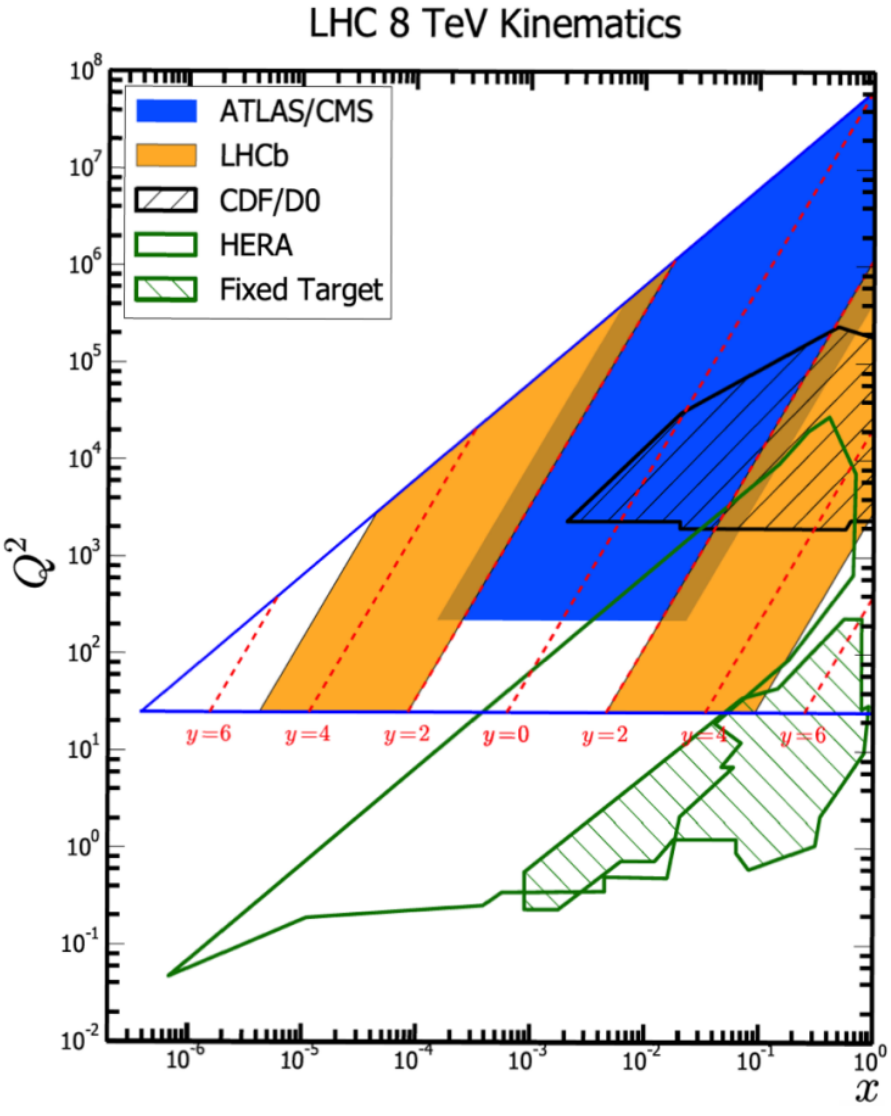
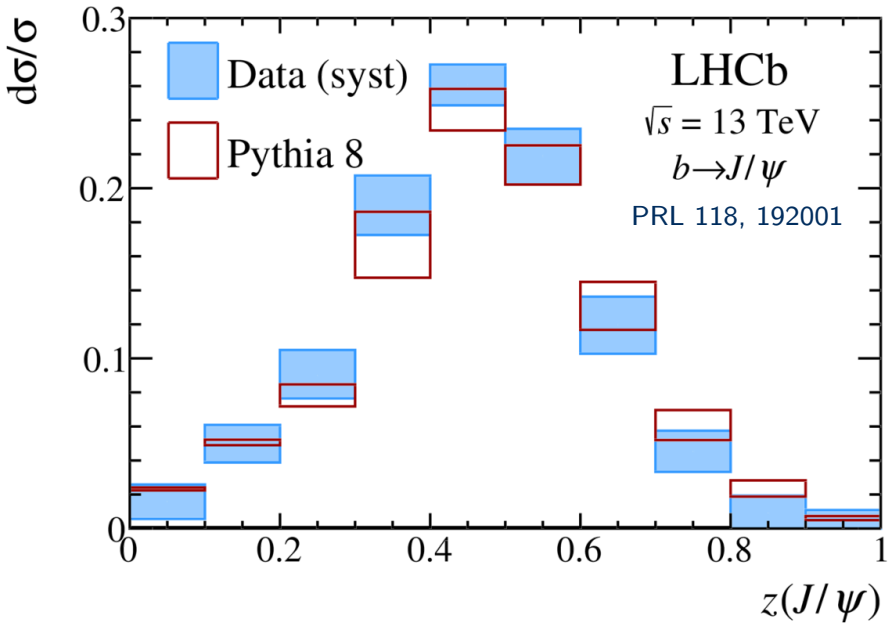
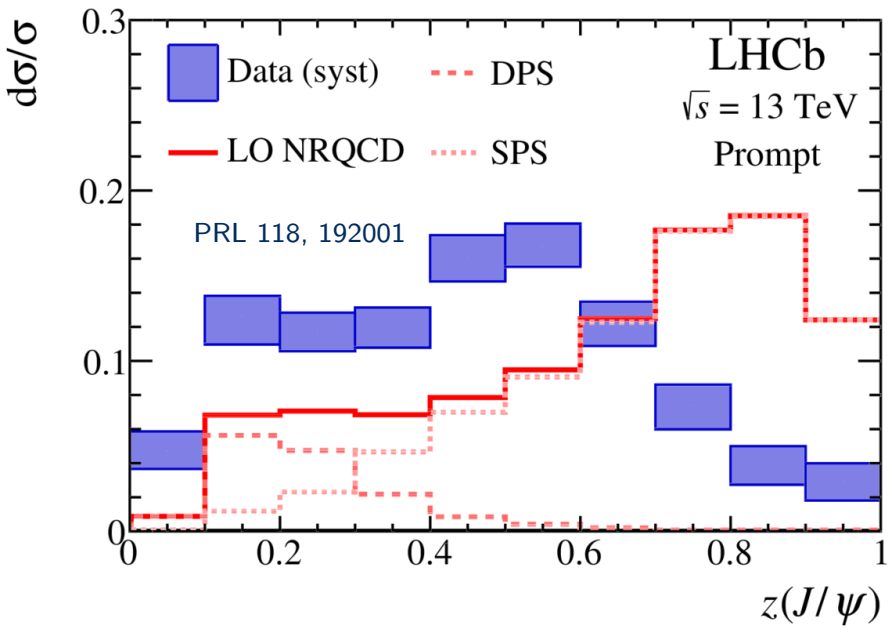


- LHCb has unique advantages for jet hadronization physics over other LHC experiments
- Uniform coverage tracking, PID, *and* calorimetry
- Can identify nearly all particles within a high p_T jet
- Also occupy a unique region in (x, Q^2)

Jets at LHCb

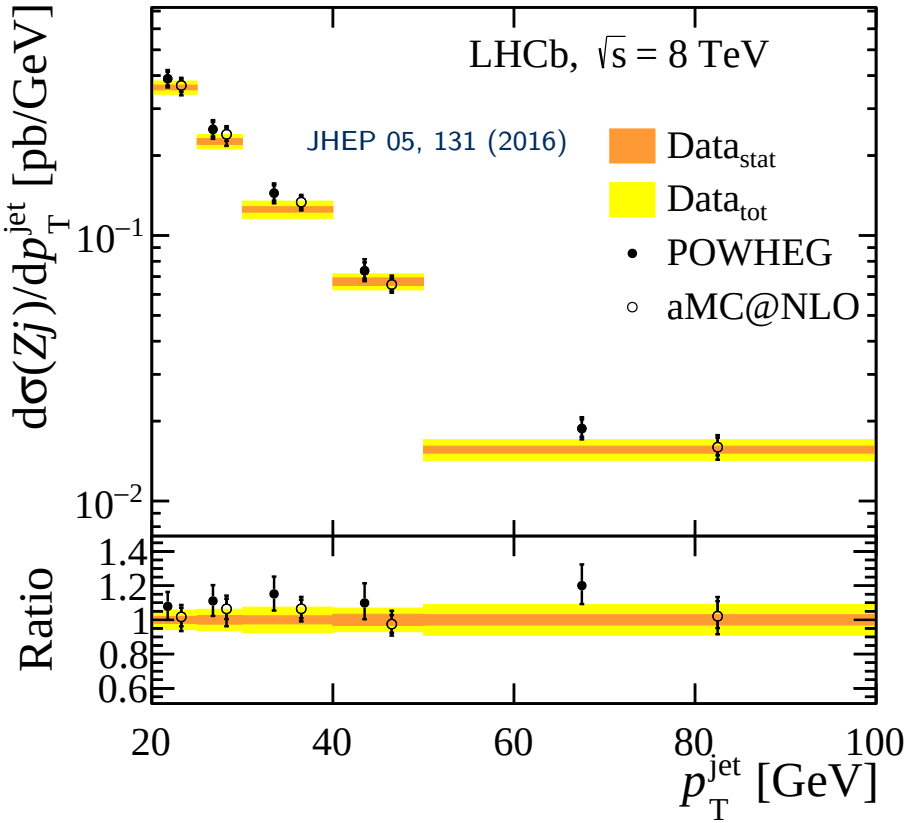
- Jet production has been studied in a variety of ways at LHCb
  - W/Z+jet cross sections
    - JHEP 05, 131 (2016)
    - JHEP 01, 064 (2015)
    - JHEP 01, 33 (2014)
  - Heavy flavor jets
    - PRL 118, 192001 (2017)
    - JINST 10, P06013 (2015)
- First LHCb jet substructure measurement is J/ψ-in-jet production





Z+jet at LHCb

- Z+jet cross section published at $\sqrt{s} = 7$ and 8 TeV
- High signal-to-background, established analysis techniques



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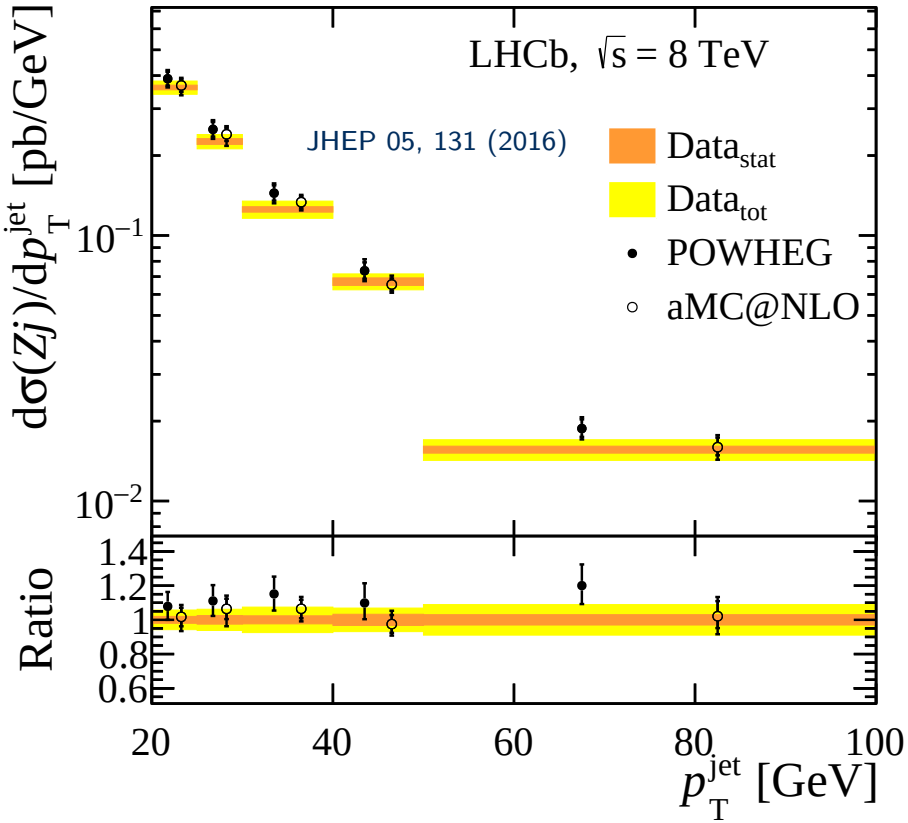
- Z+jet cross section published at $\sqrt{s} = 7$ and 8 TeV
- High signal-to-background, established analysis techniques
- Preferentially selects light quarks (!)
- Starkly in contrast from midrapidity inclusive jet results at LHC which are gluon dominated until very high p_T ($p_T > \mathcal{O}(400)$ GeV)
- Recent ATLAS/CMS $\gamma-$tagged jets complementary



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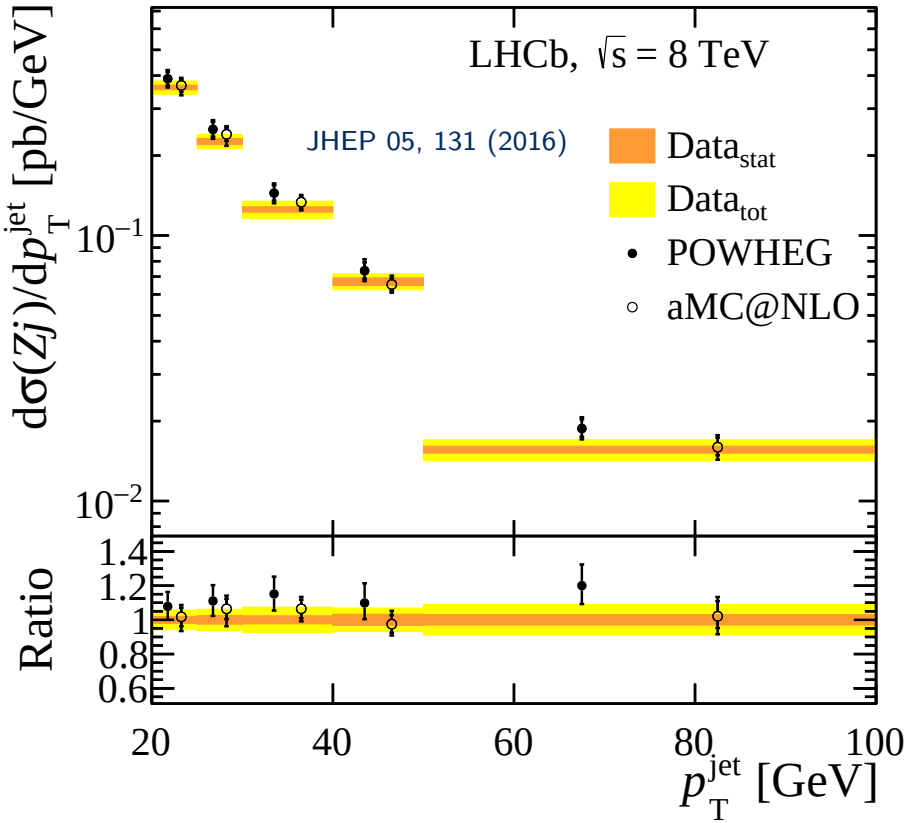
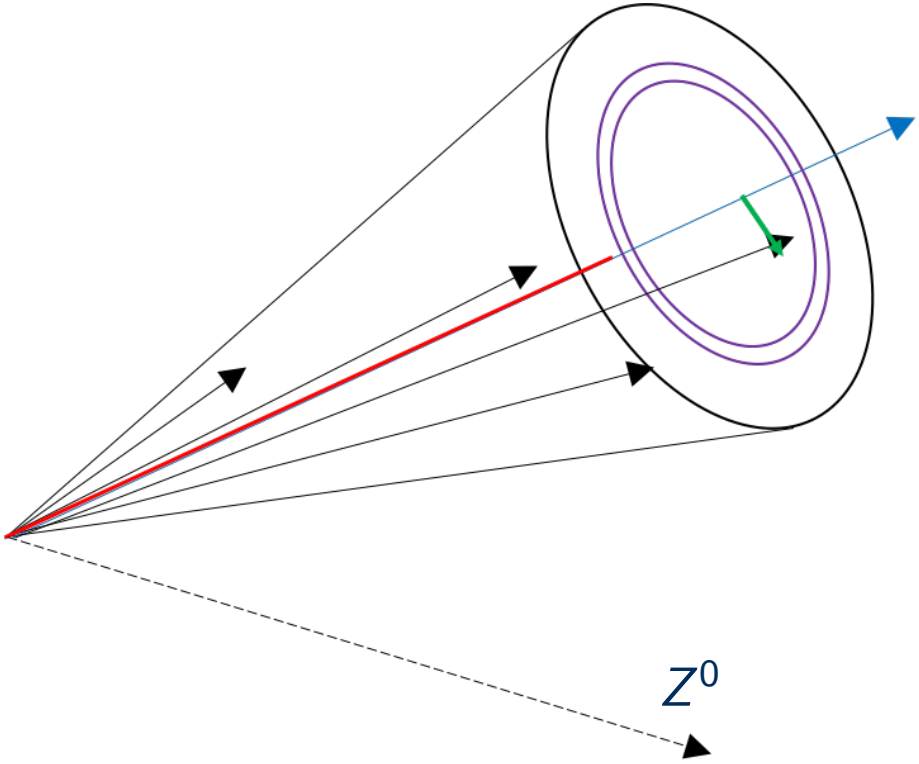


- **First LHC measurement of charged hadrons within Z tagged jets**
- **First LHC measurement of charged hadrons-in-jets at forward rapidity**

Observables



- Measure hadronization observables in two dimensions
  - Longitudinal momentum fraction z
  - Transverse momentum j_T
  - Radial profile r

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

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

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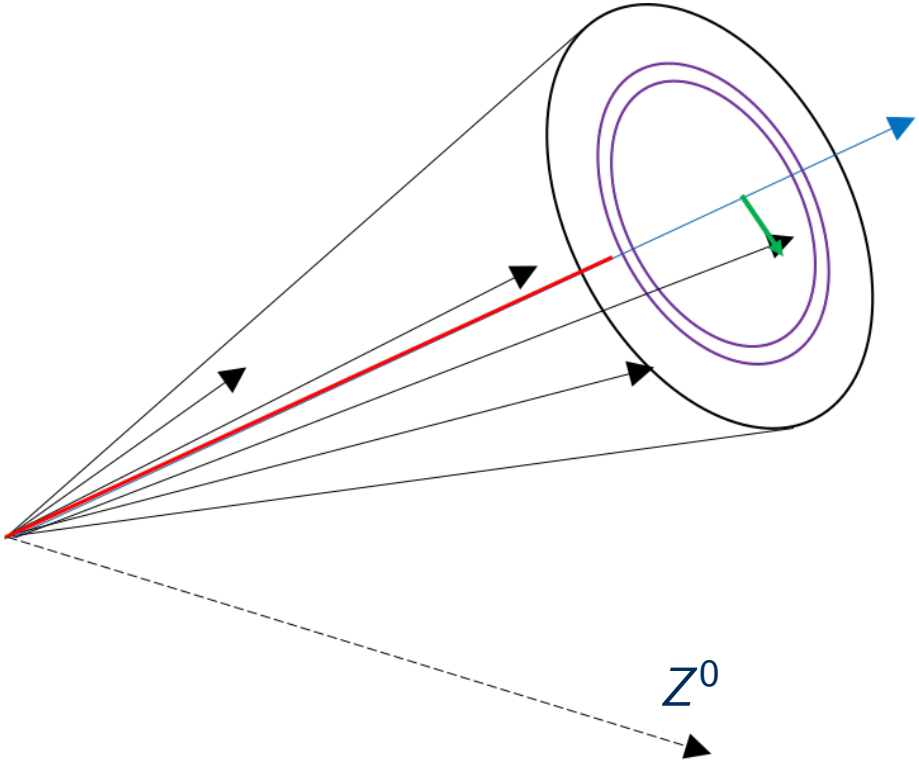

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- Measure hadronization observables in two dimensions
  - Longitudinal momentum fraction z
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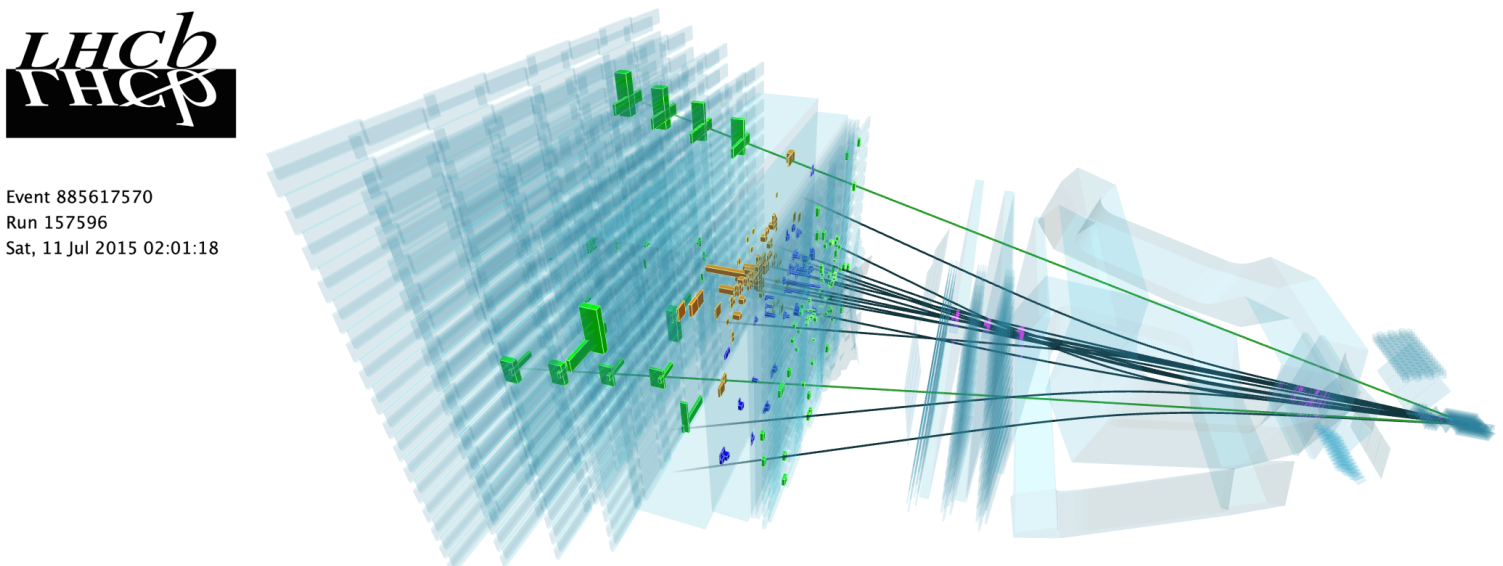
- Intended to lay the foundation for a broader hadronization program at LHCb utilizing
  - Particle ID (tracking, RICH, calorimetry)
  - Heavy flavor jet tagging
  - Resonance production within jets (ϕ, J/ψ, Υ)
  - Correlations with flavor ID

Analysis Details

- Follow similar analysis strategy to ATLAS (EPJC 71, 1795 (2011), NPA 978, 65 (2018)) and LHCb (PRL 118, 192001 (2017))



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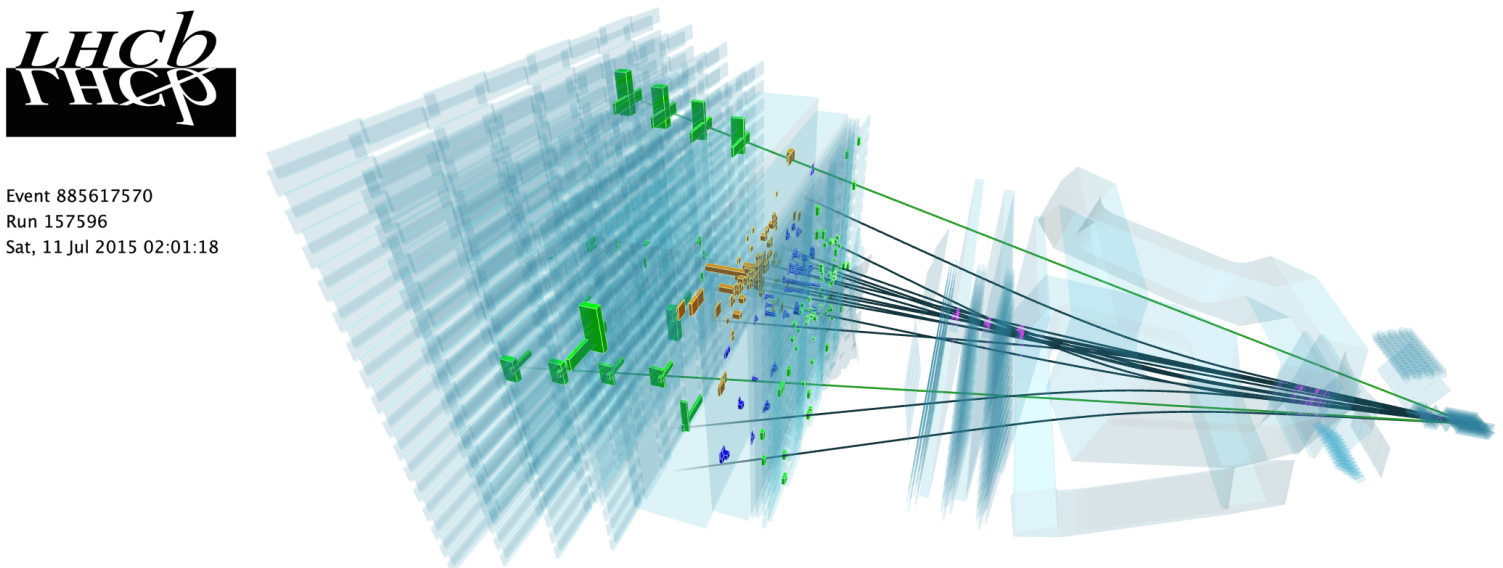
- Anti-k$_T$ jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2.5 < \eta < 4$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects $2 \to 2$ event topology



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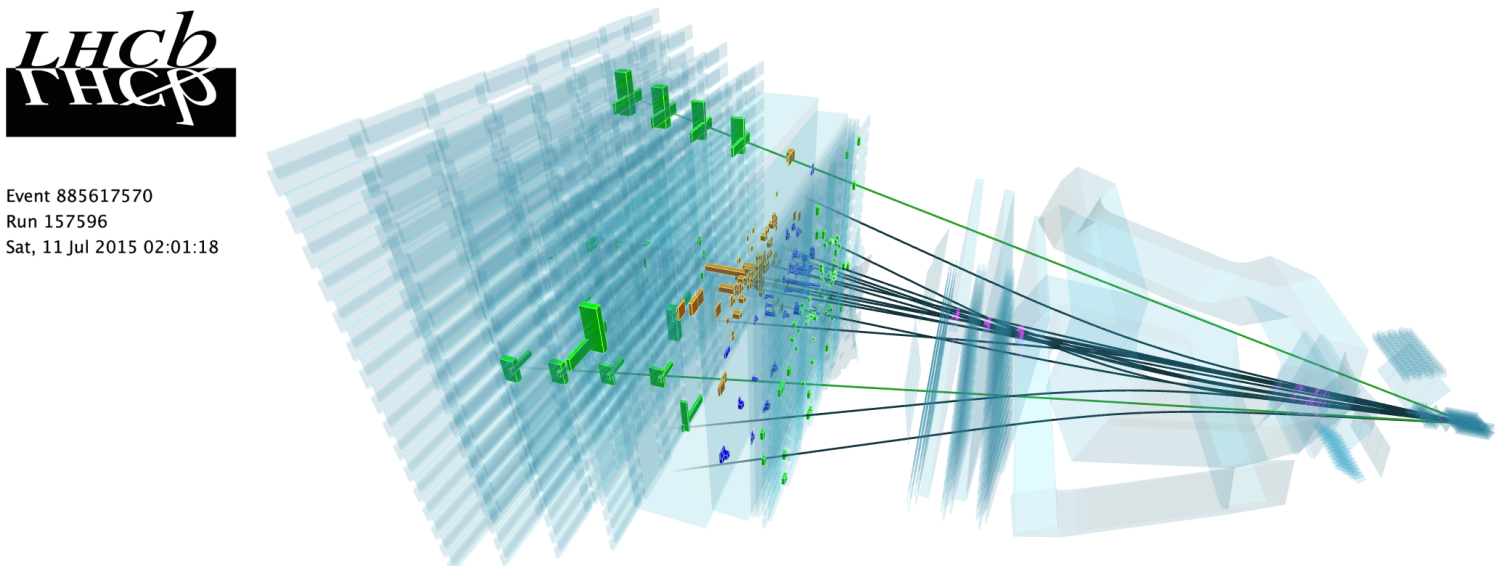

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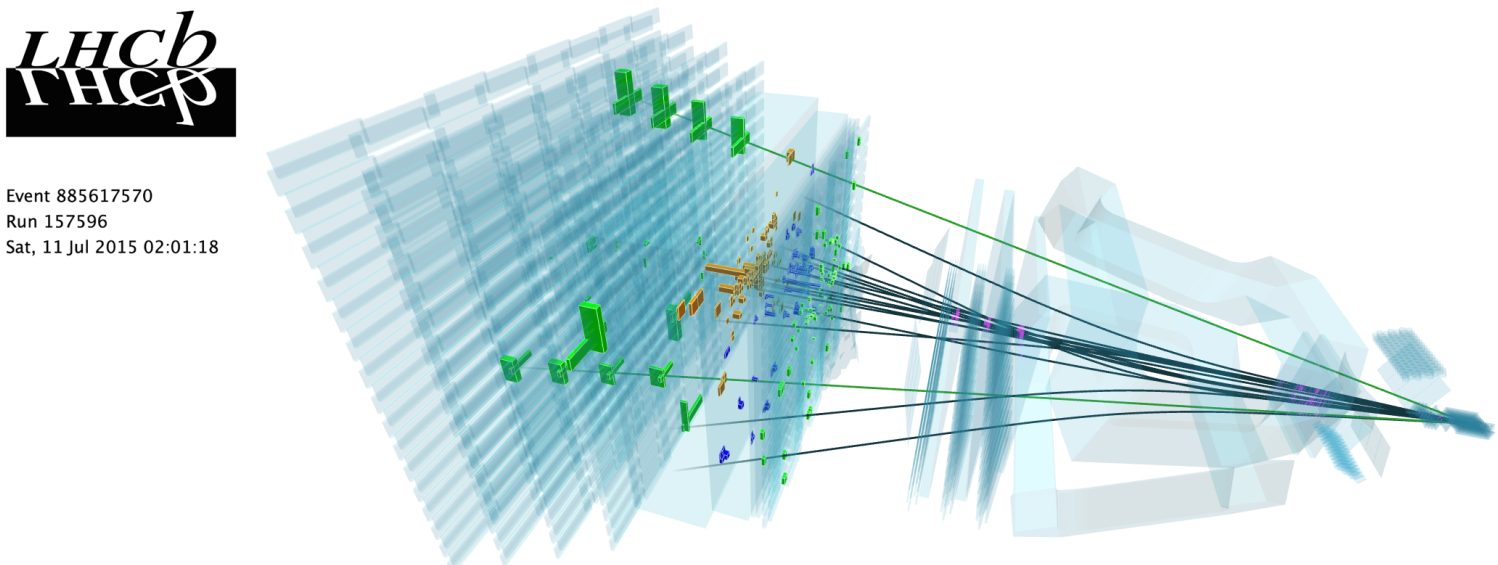
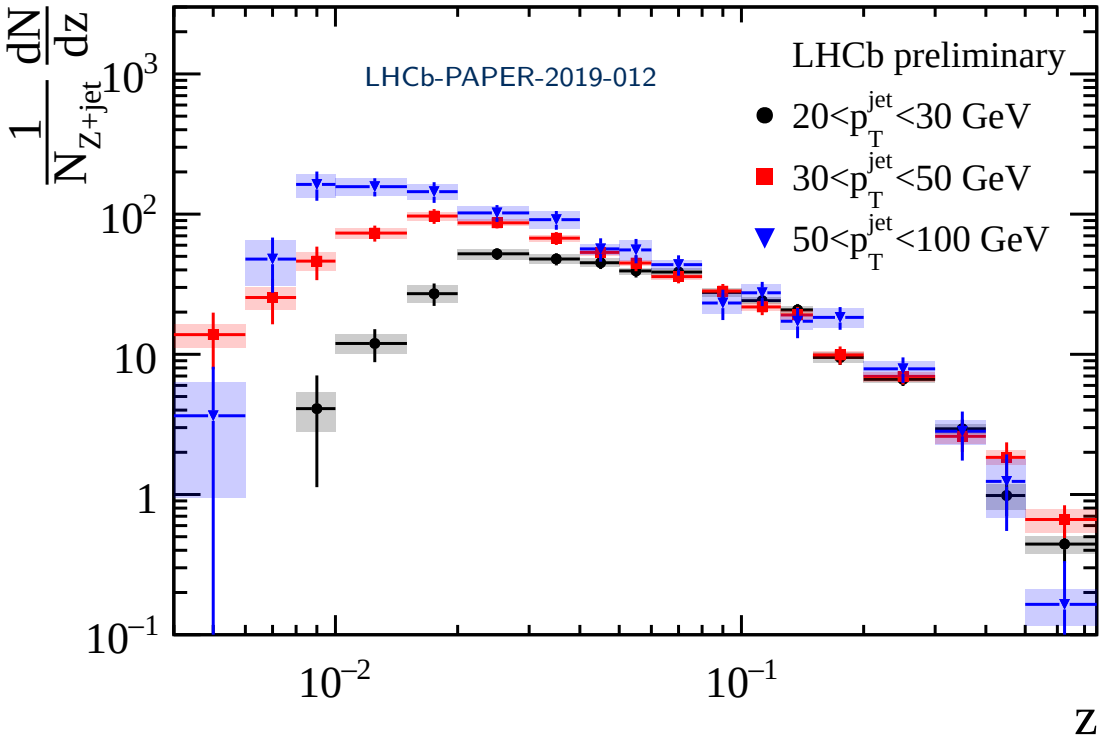
- Results efficiency corrected and 2D Bayesian unfolded

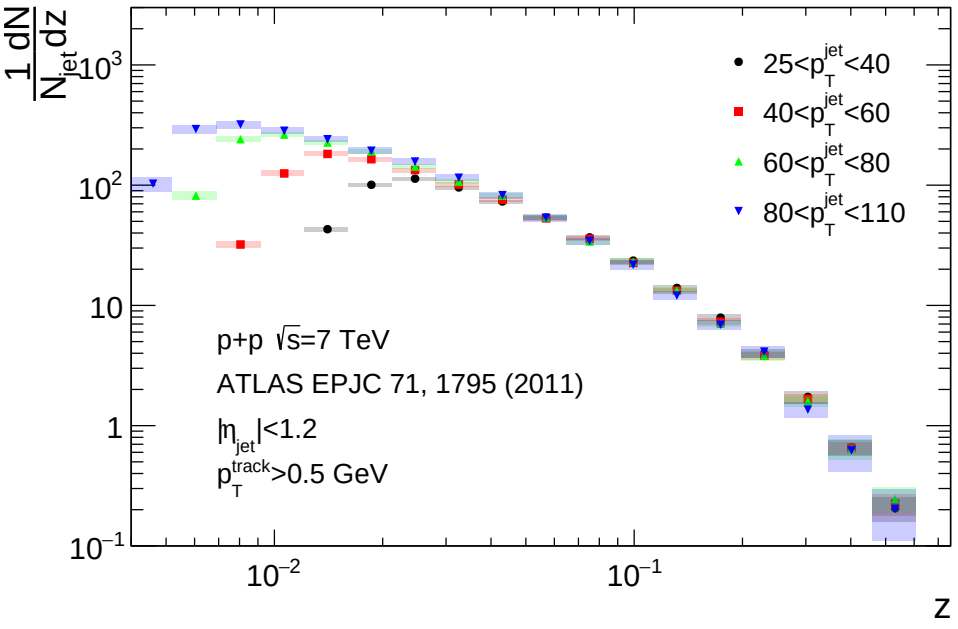


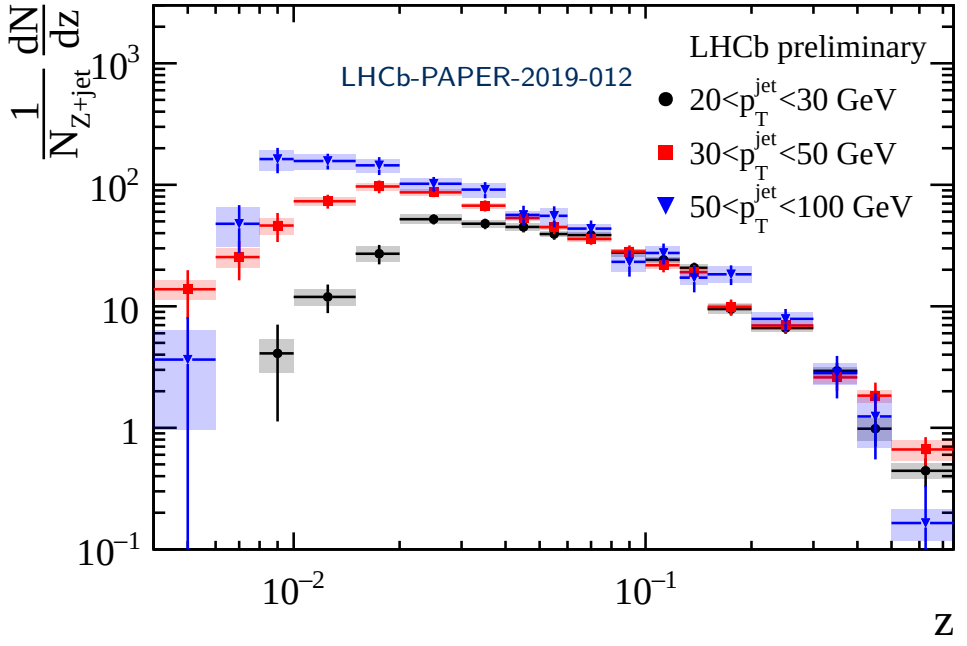
Results

- Measurements in three p_T^{jet} bins, integrated over Z kinematics
- Longitudinal hadron-in-jet distributions independent of jet p_T at high z
- Distributions diverge at low z due to kinematic phase space available



ATLAS and LHCb Comparisons





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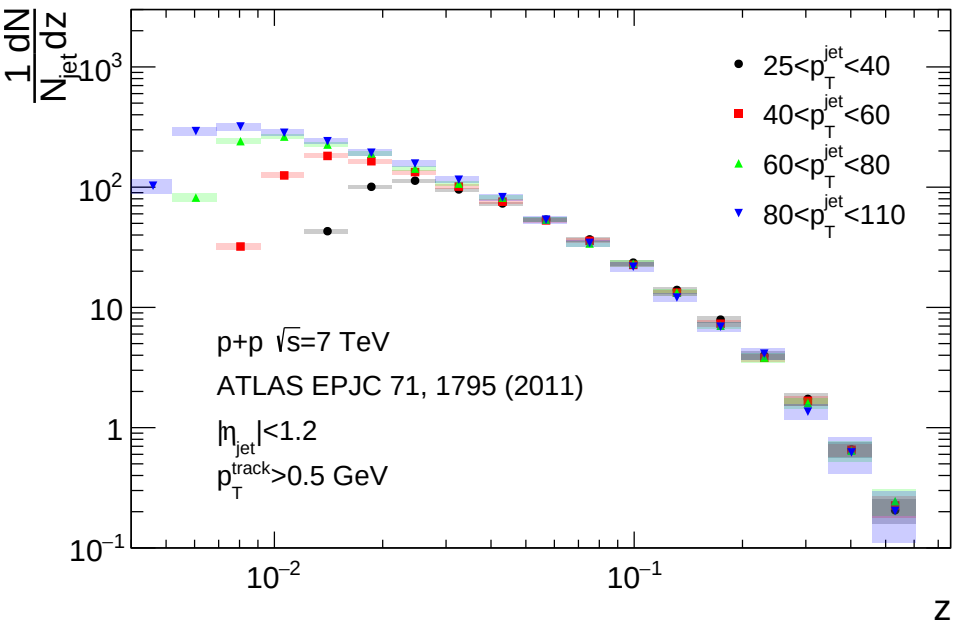
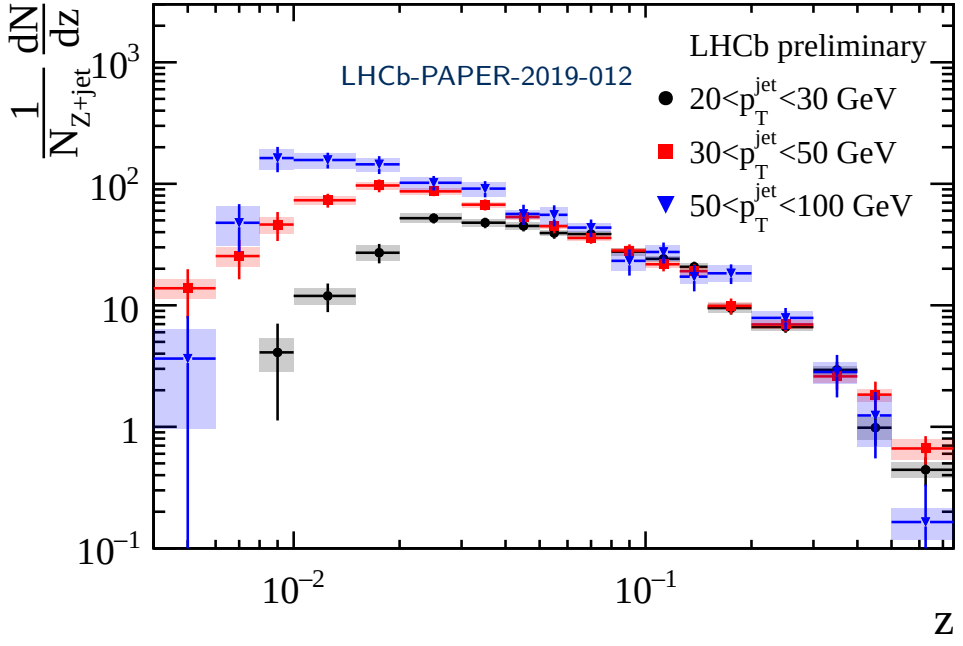
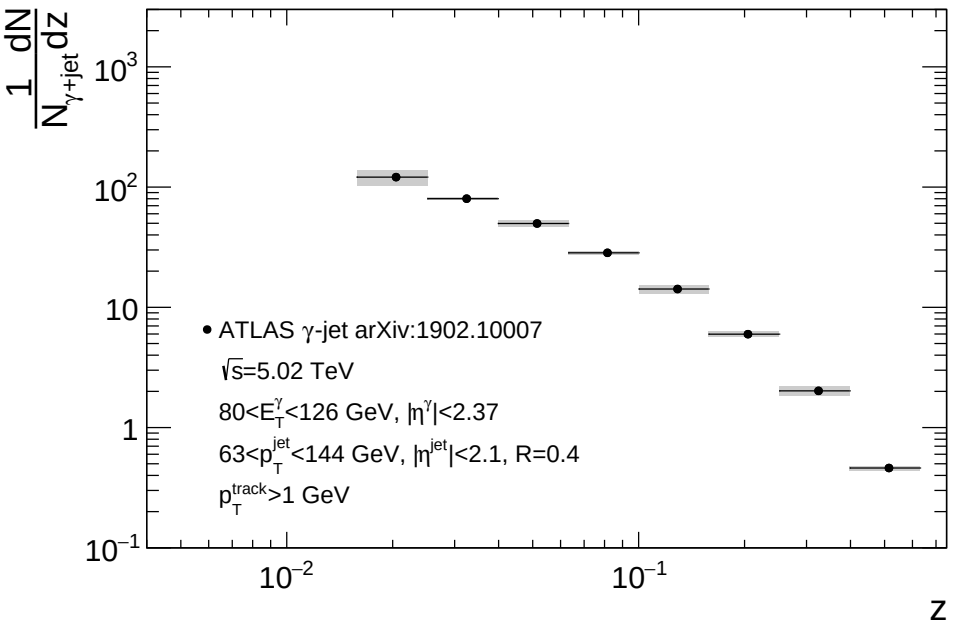
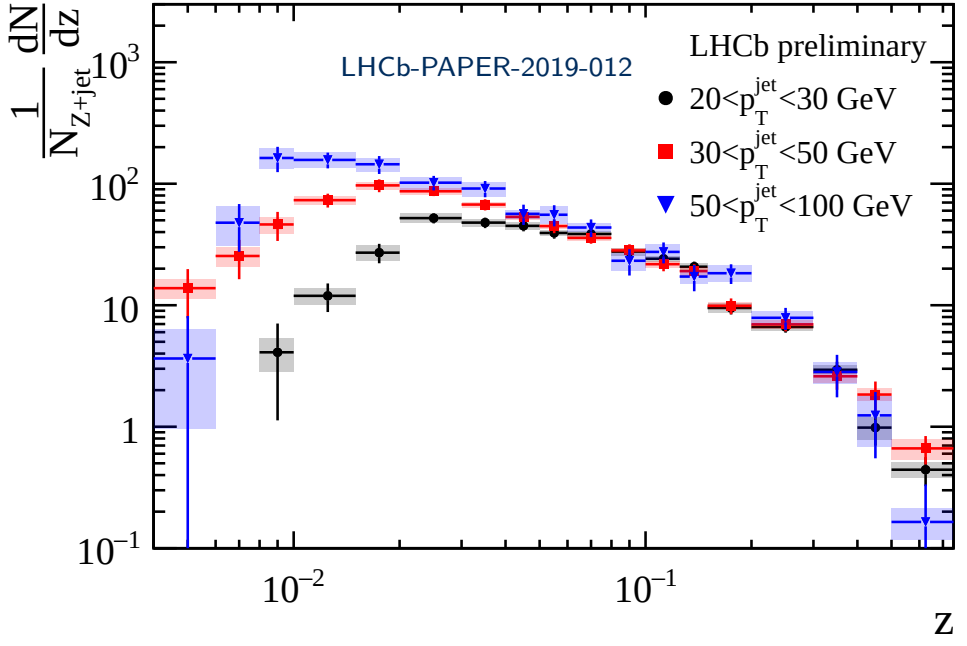




- Comparing ATLAS midrapidity inclusive jets to LHCb forward Z+jet shows longitudinal distributions "flatter" as a function of z
- Caveats - ATLAS/LHCb measurements can only be compared qualitatively due to different kinematics

Comparison to ATLAS γ-jet

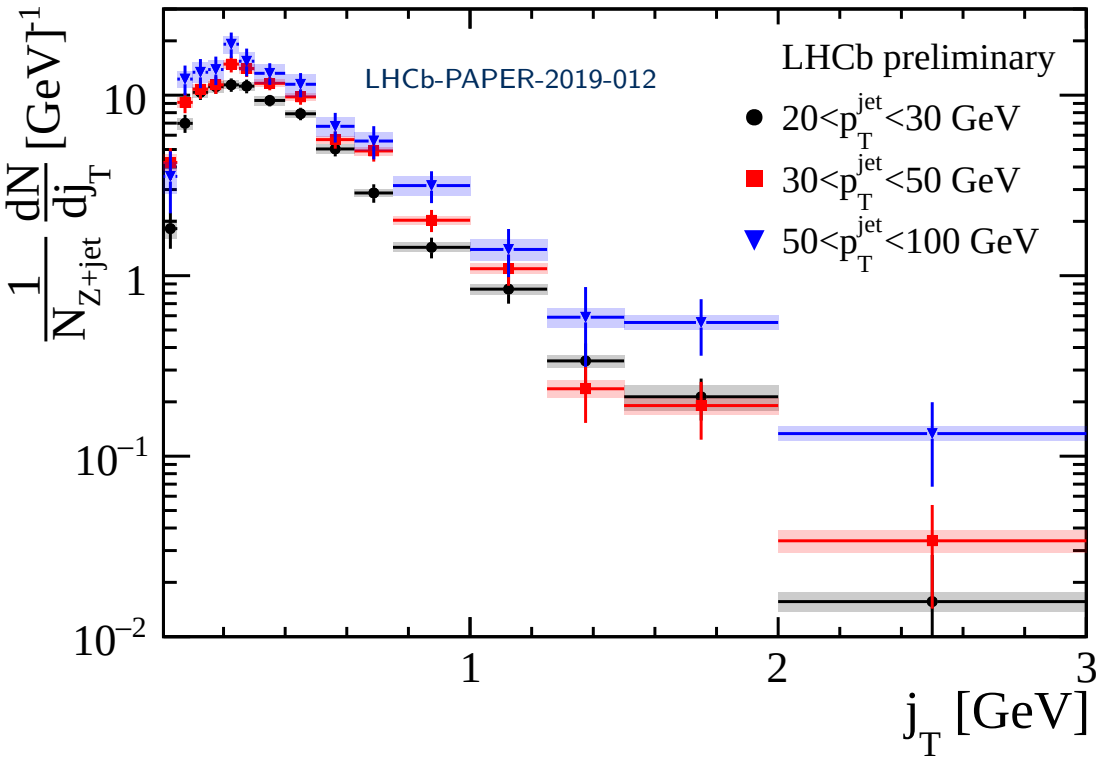




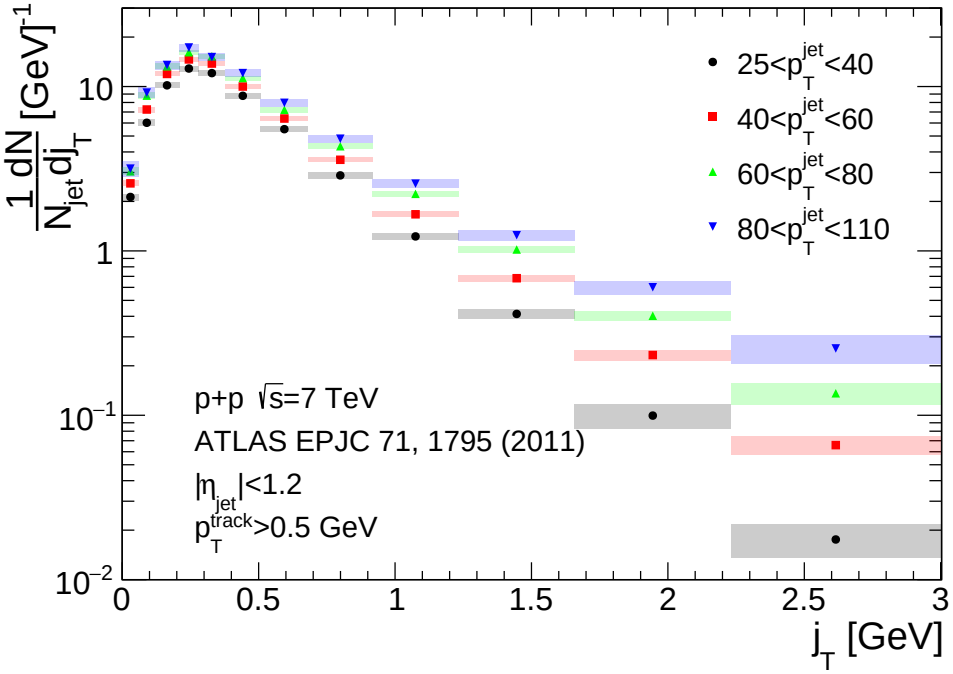
- ATLAS midrapidity γ-jet and LHCb Z-jet longitudinal distributions are very similar in the comparable jet p_T bin
- Kinematic fiducial space similar but not exactly the same

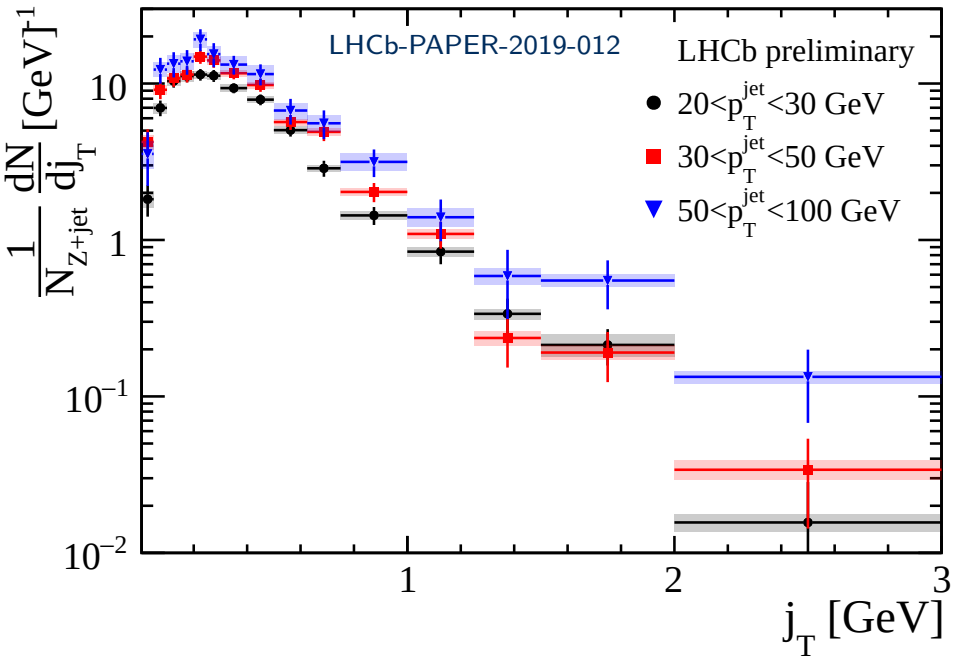
Results

- Transverse momentum shows nonperturbative to perturbative transition
- Shapes very similar as a function of p_T^{jet} - slight increase of $\langle j_T \rangle$ with p_T^{jet}



ATLAS and LHCb Comparisons

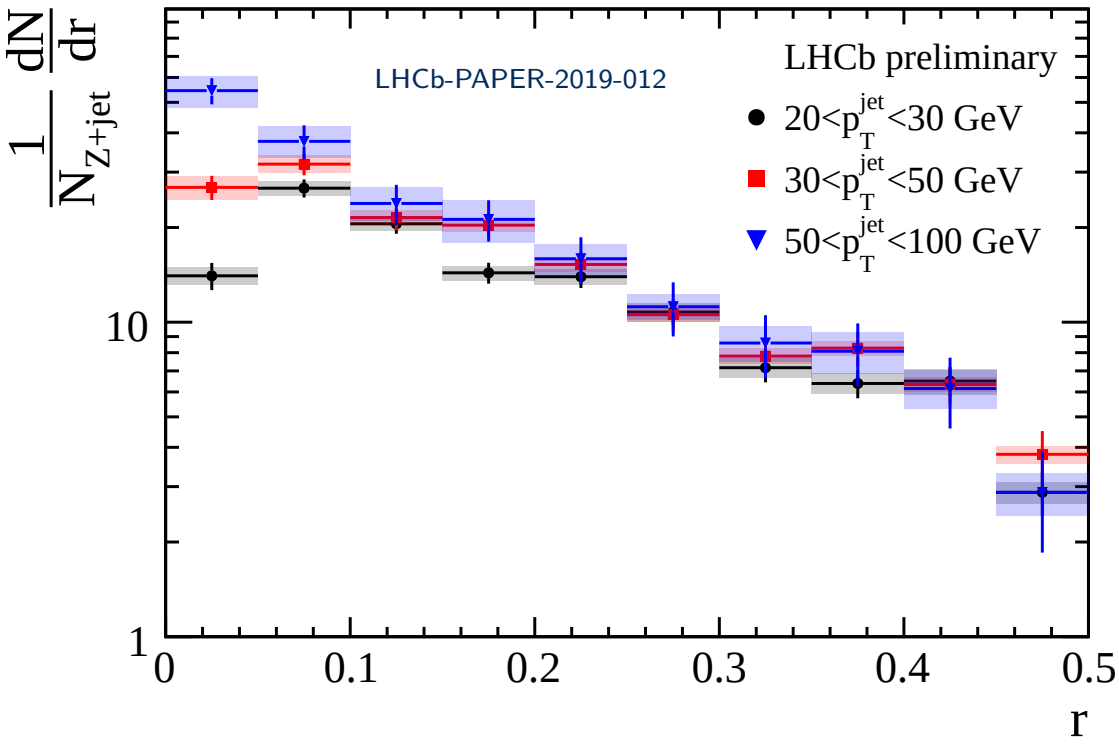




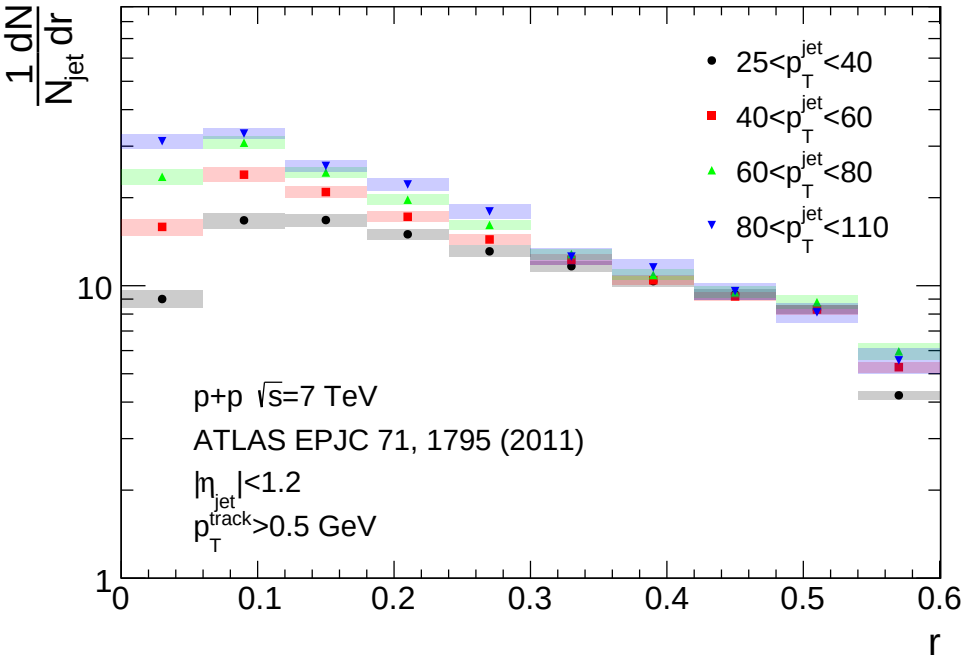
- Transverse momentum distributions show smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T

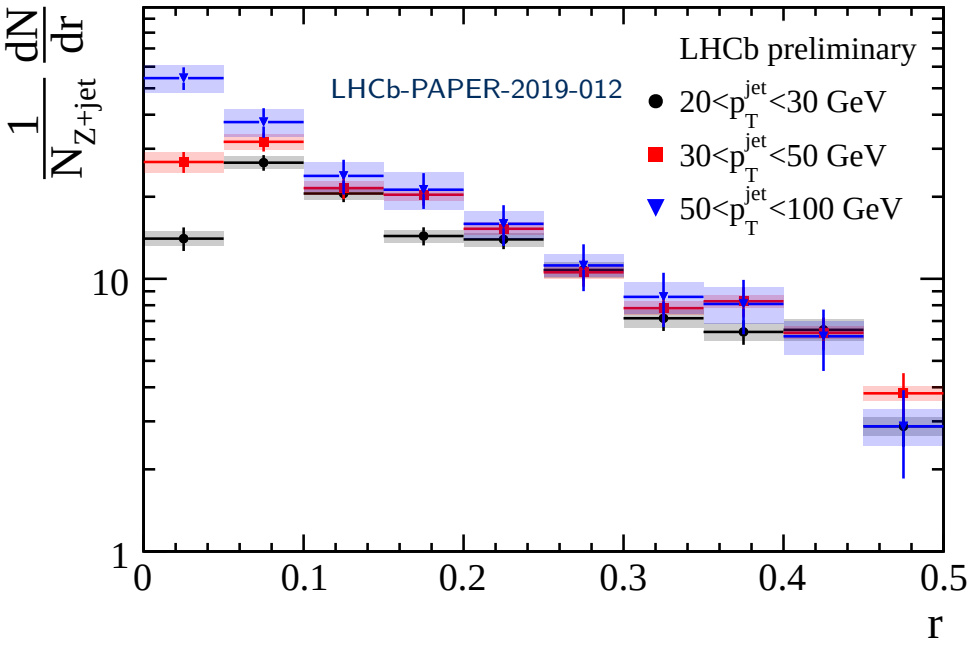
Results

- Radial profiles largely independent of jet p_T away from jet axis
  - Indication of independence of nonperturbative contributions?
- Multiplicity of hadrons along jet axis rises sharply with jet p_T



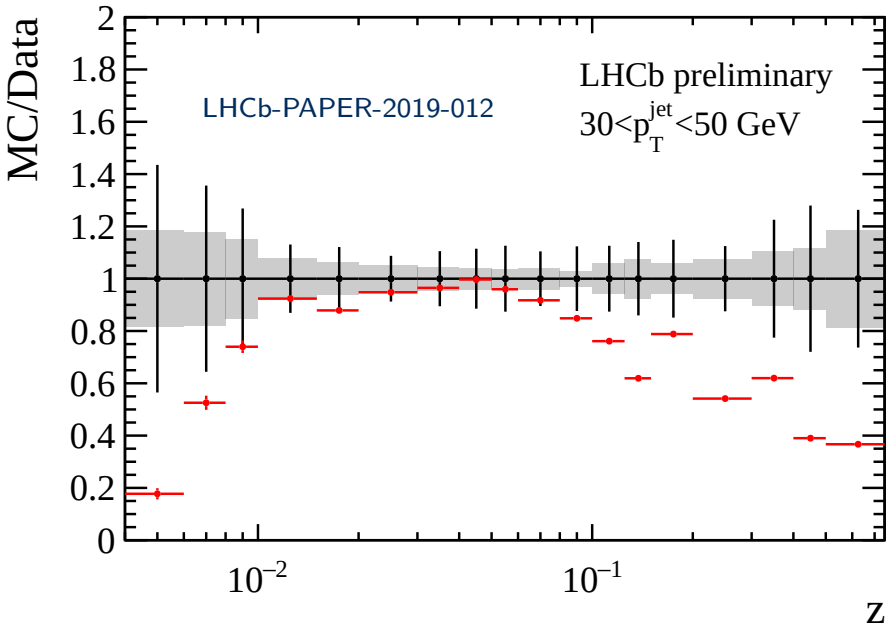
ATLAS and LHCb Comparisons

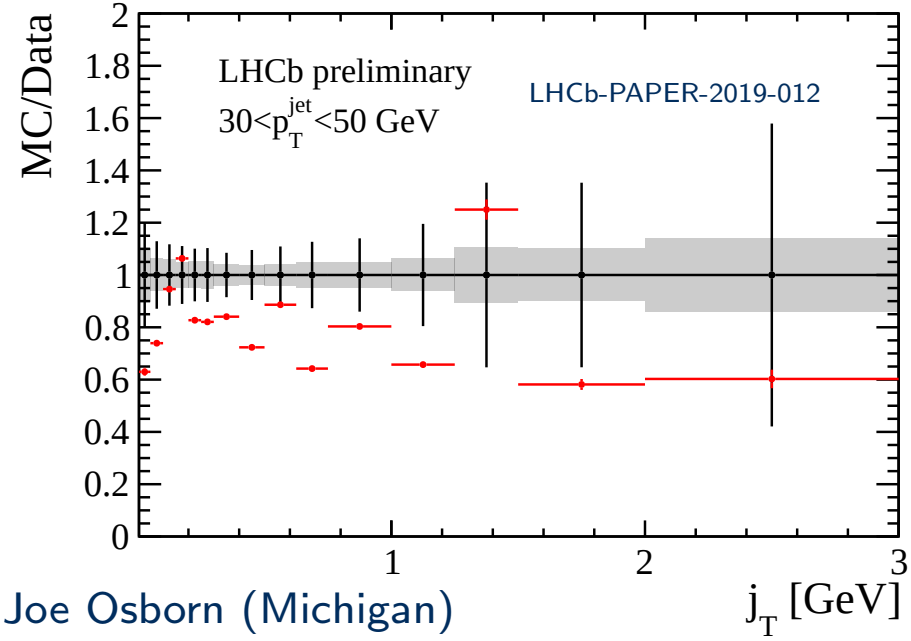


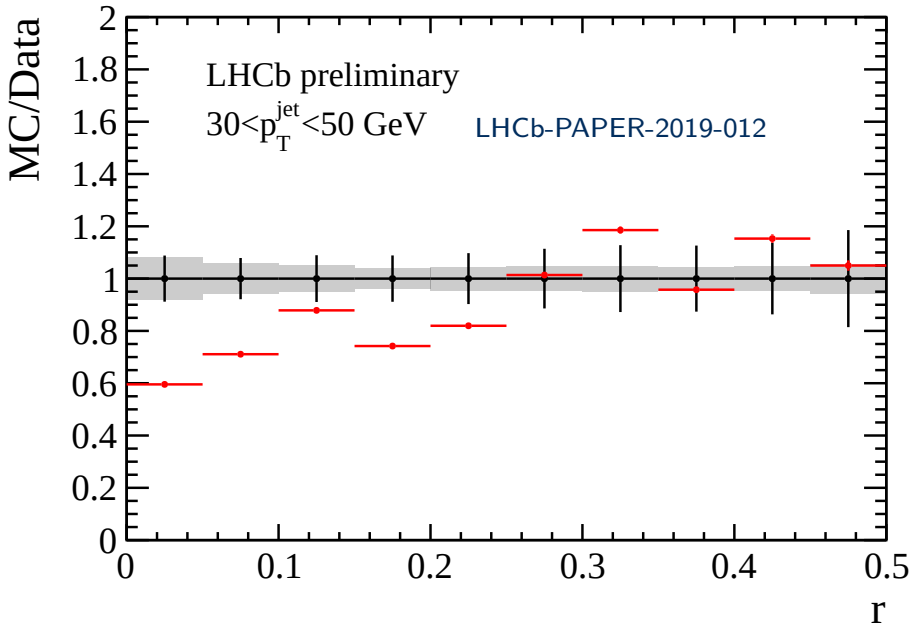


- Comparing ATLAS midrapidity inclusive jets to LHCb forward Z+jet shows jets are more collimated when tagged with a Z

Comparisons with PYTHIA







- Comparisons with PYTHIA show that PYTHIA generally underpredicts the number of high momentum charged hadrons within Z-tagged jets

Conclusions

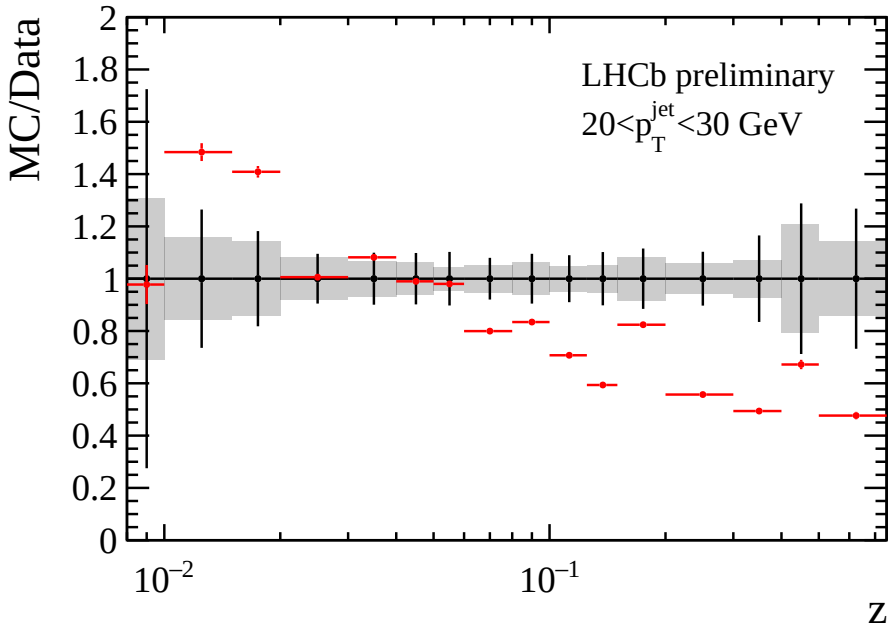
- New results on hadronization and jet substructure in Z-tagged jets at LHCb
- Select events that better correspond to a $2 \rightarrow 2$ hard scattering
- Measure longitudinal and transverse charged hadron-in-jet observables with respect to anti-k$_T$ jet axis
- Preferentially selects light quark jets vs. gluon jets - opportunity for understanding nonperturbative hadronization differences

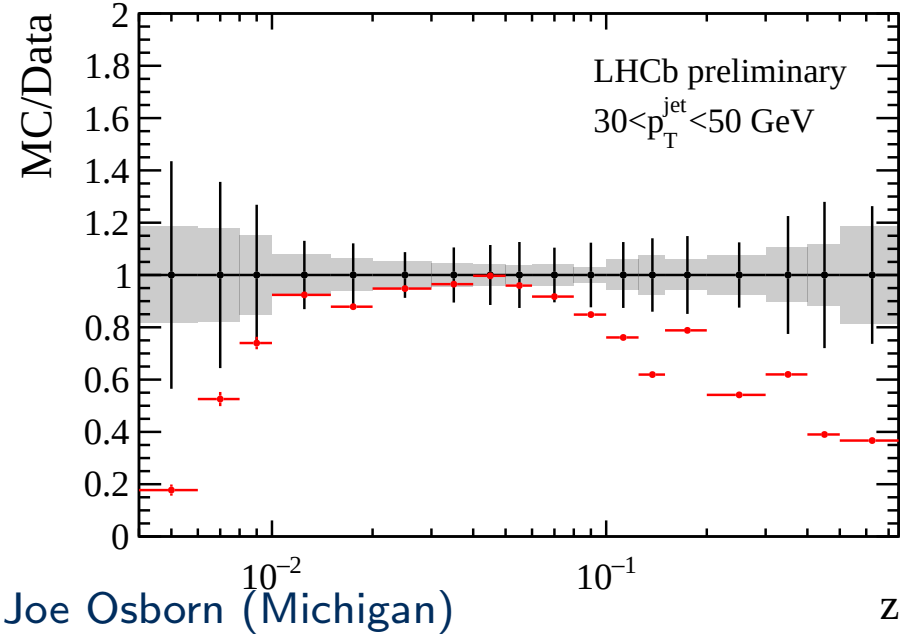
Conclusions

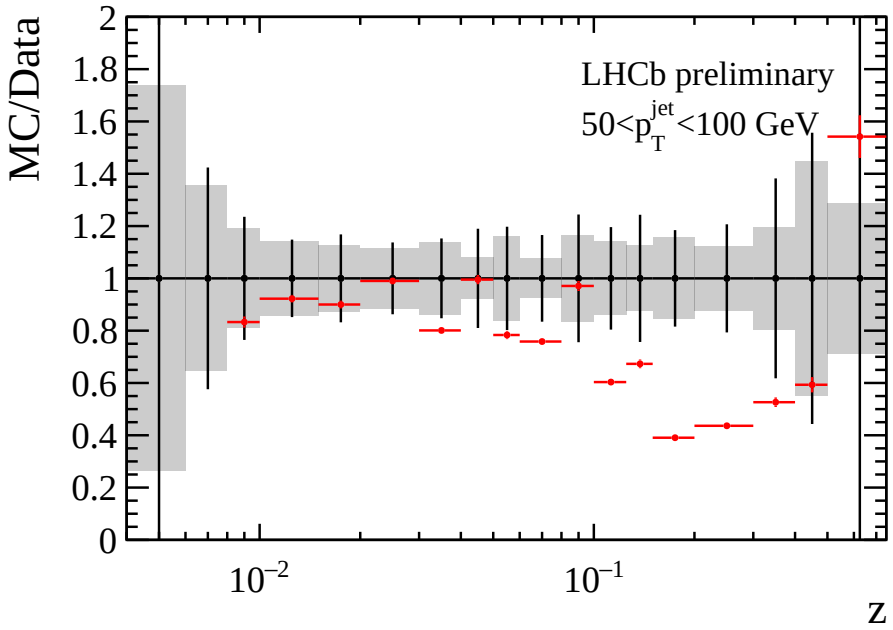
- New results on hadronization and jet substructure in Z-tagged jets at LHCb
- Select events that better correspond to a $2 \rightarrow 2$ hard scattering
- Measure longitudinal and transverse charged hadron-in-jet observables with respect to anti-k$_T$ jet axis
- Preferentially selects light quark jets vs. gluon jets - opportunity for understanding nonperturbative hadronization differences
- More hadronization results to come from LHCb utilizing PID, heavy flavor ID, and calorimetry

Back Up

Comparisons with PYTHIA (z)

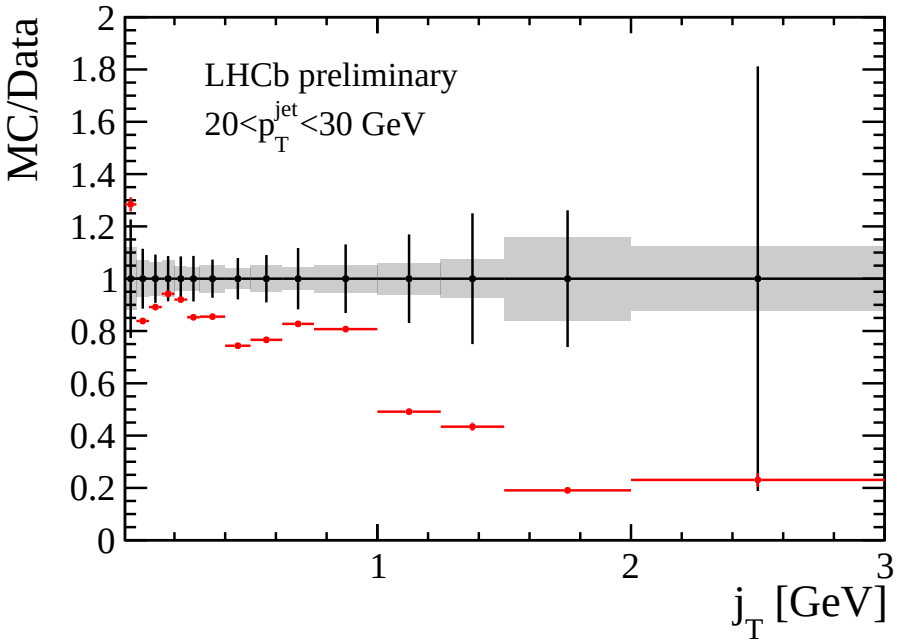


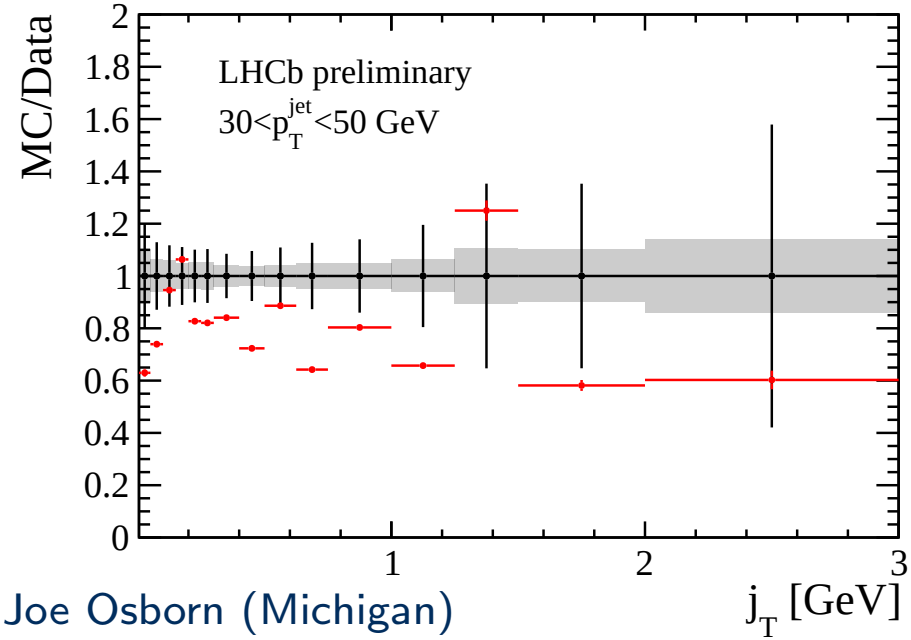


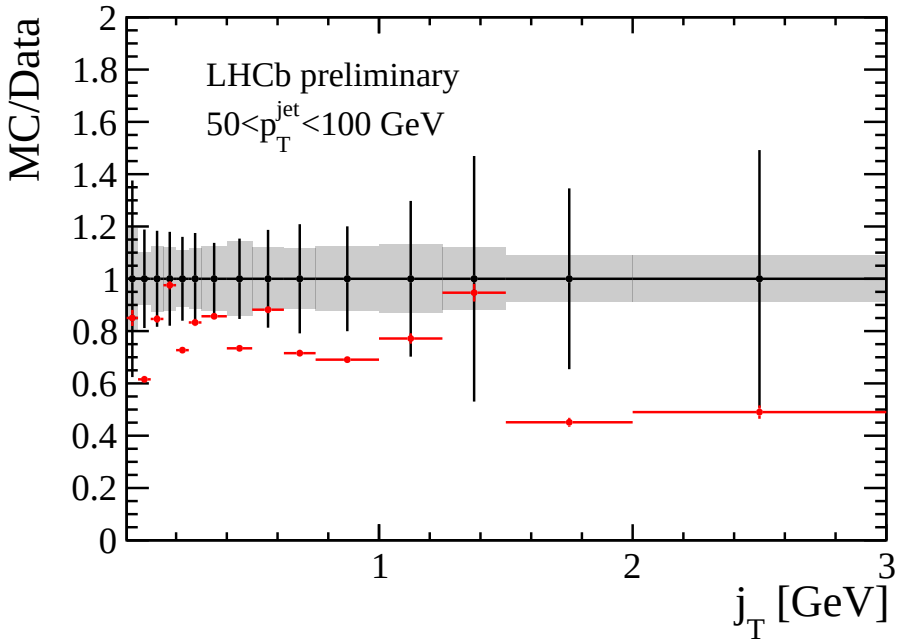


- PYTHIA generally underpredicts the number of high z hadrons

Comparisons with PYTHIA (j_T)

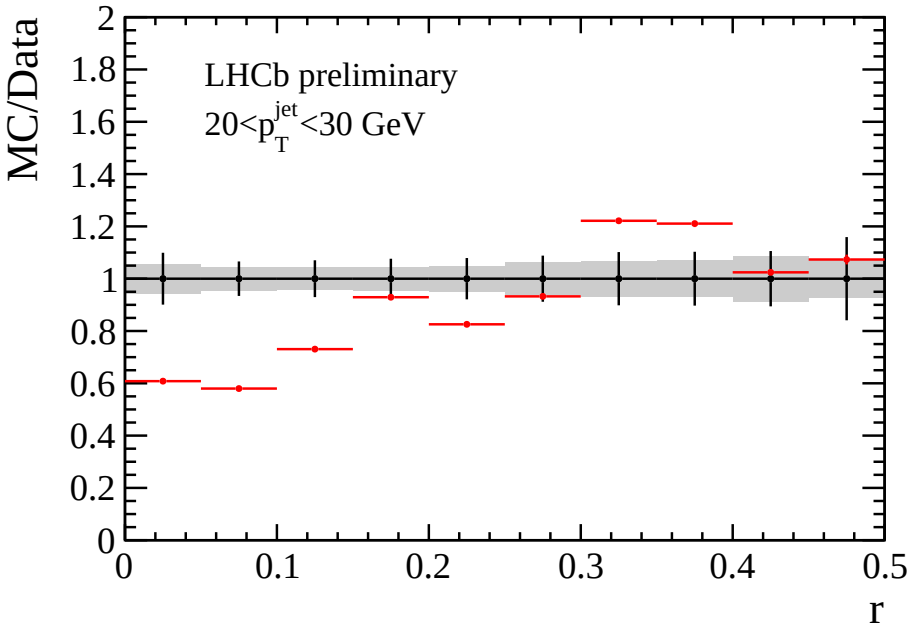


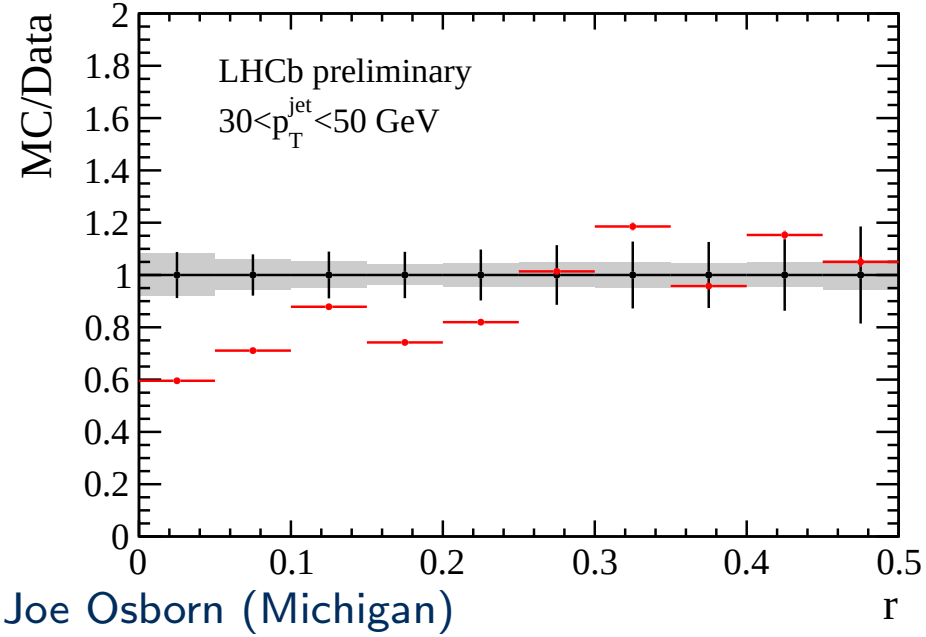


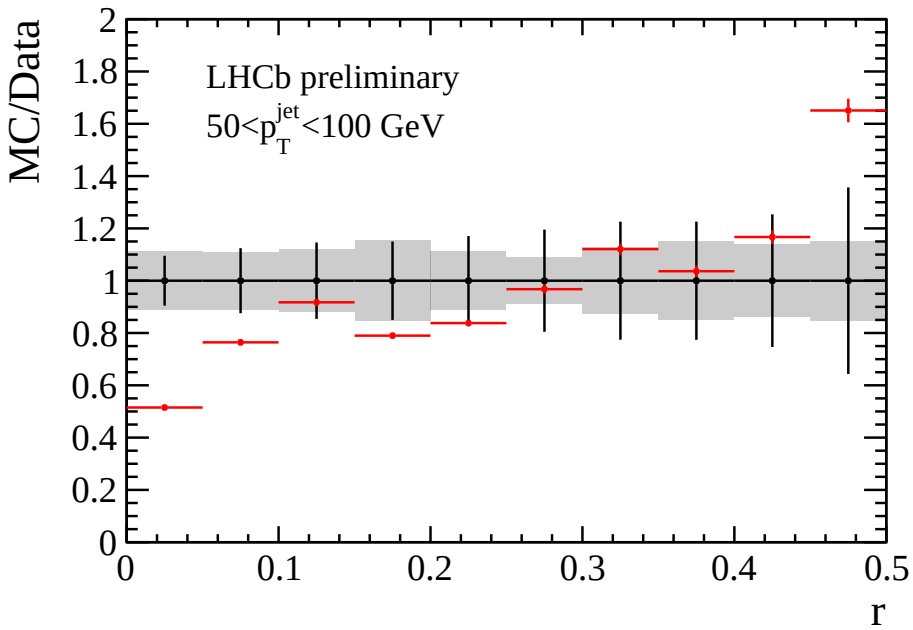


- PYTHIA generally gets j_T shape, with about a 20% difference in normalization

Comparisons with PYTHIA (r)







- PYTHIA generally underpredicts the number of small r hadrons