# Jet substructure at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC)

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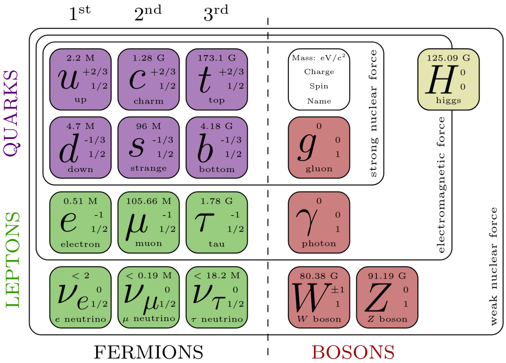
University of Michigan

April 8, 2019

# The Standard Model

- The Standard Model of particle physics is one of the most successful descriptions of fundamental interactions



# The Standard Model

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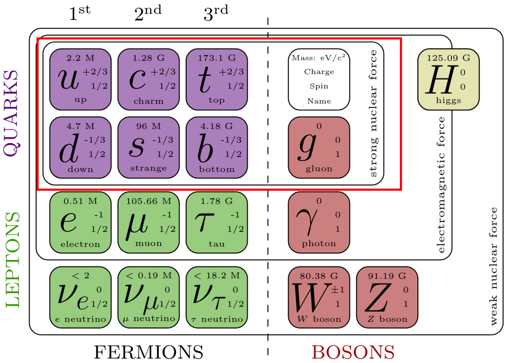
- Two main "sectors"
  - Strong force
  - Electroweak force



# The Standard Model

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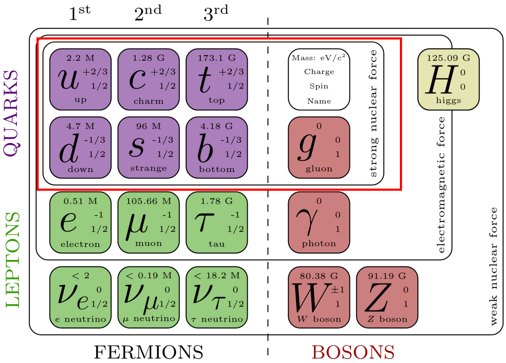
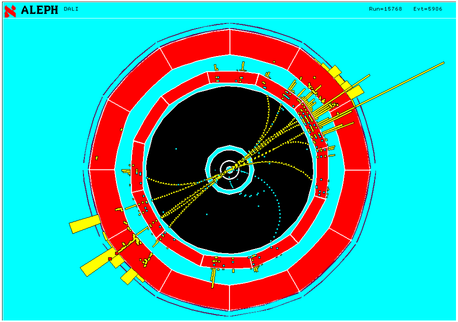
- Two main "sectors"
  - Strong force
  - Electroweak force
- Strong force particularly not well understood due to confinement - quarks and gluons cannot be observed freely!



# Observing Quarks and Gluons

- To "observe" quarks and gluons (partons), we must produce them via scattering processes
- Can use $e^+e^- \rightarrow q\bar{q}$, $e^-p \rightarrow e^-q + X$, or $pp \rightarrow q/g + X$



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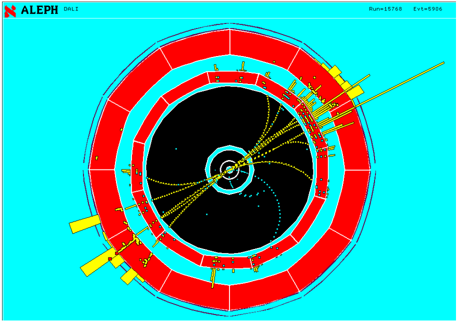
- Can use $e^+e^- \to q\bar{q}$, $e^-p \to e^-q + X$, or $pp \to q/g + X$
- After producing a parton, it nonperturbatively becomes bound state hadron(s)
- The collimated spray of particles that results is called a jet



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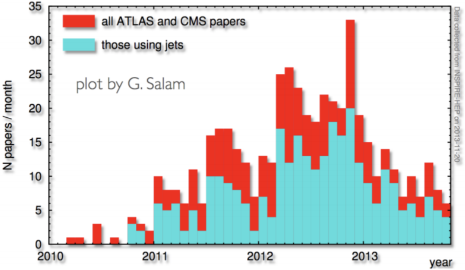
- Enabled by more robust comparisons that can be made between theory and experiment with recent jet finding algorithms



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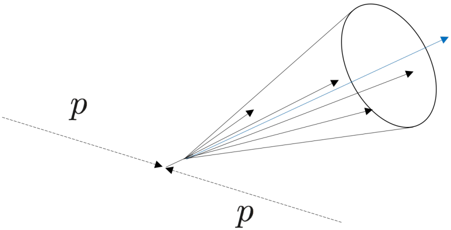
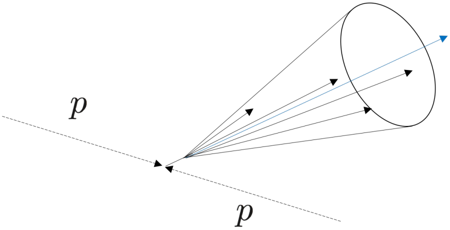
- Enabled by more robust comparisons that can be made between theory and experiment with recent jet finding algorithms
- Jets are a proxy for partons, and thus provide sensitivity to the underlying partonic dynamics



# Jet Hadronization

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



# Jet Hadronization

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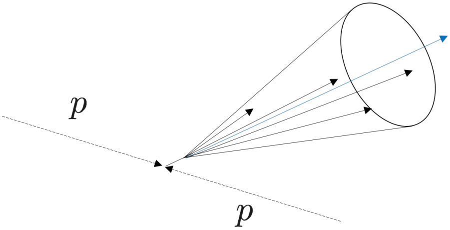
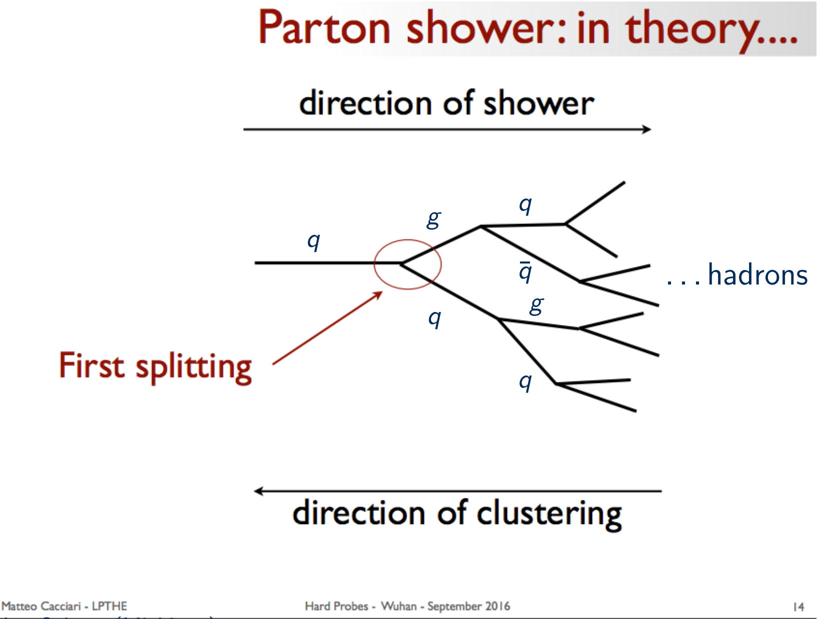
- Nonperturbative elements of QCD still important in understanding perturbative jets
- We can use a perturbative object to learn about nonperturbative physics

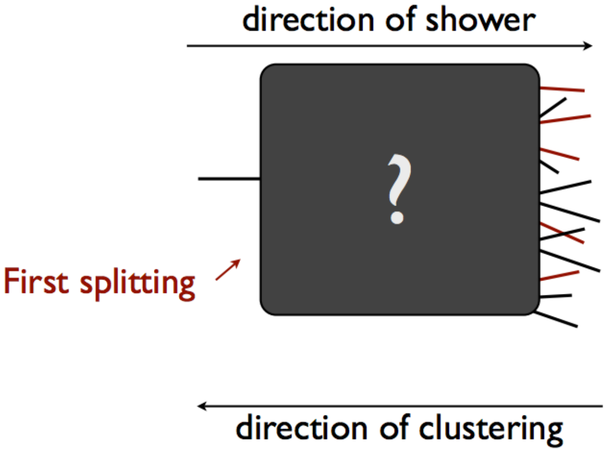


# Jet Formation



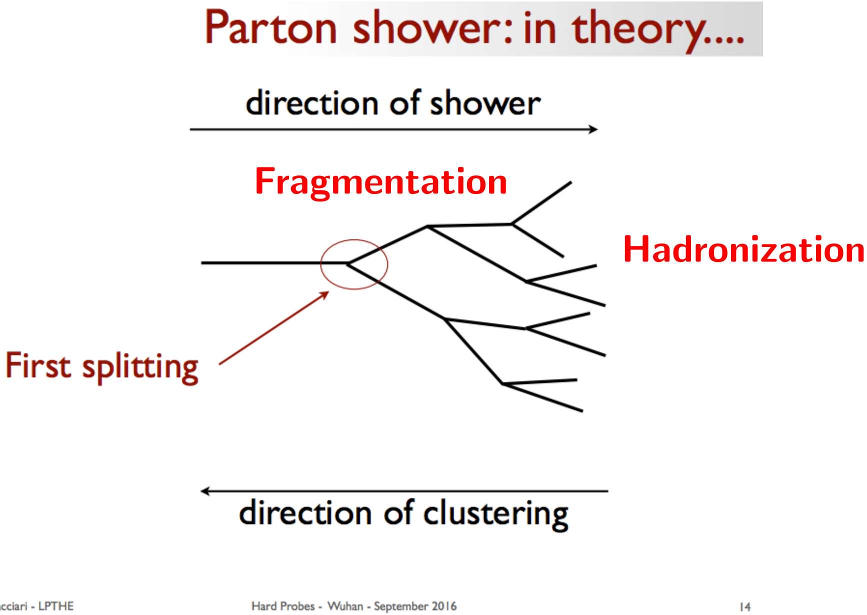
# Jet Formation

## Parton shower: in practice




Matteo Cacciari - LPTHE    Hard Probes - Wuhan - September 2016    15

# Jet Formation



# Fragmentation vs. Hadronization

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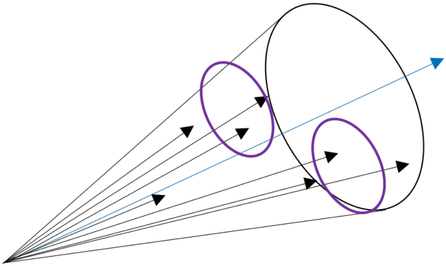

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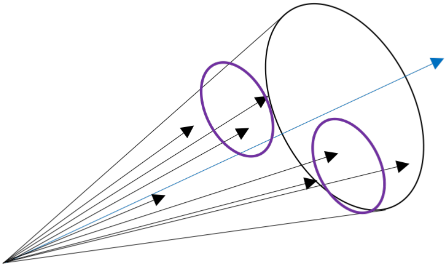

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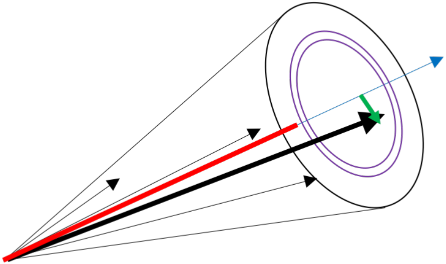
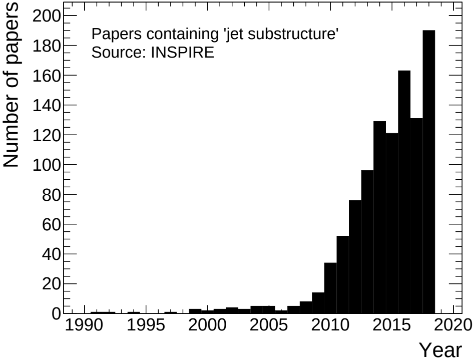


- Use individual hadrons to study correlations with jet axis

# What physics can jet substructure access?

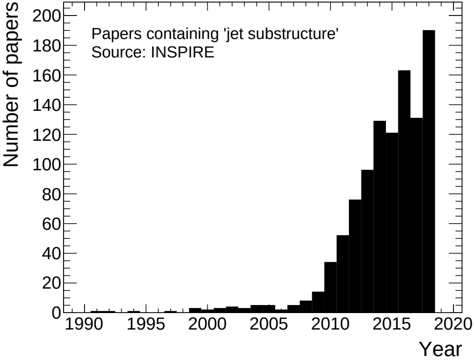
# Jet Substructure

- Searching “find fulltext 'jet substructure' and tc p” on INSPIRE yields number of published papers
- Number of papers per year has exploded in last decade



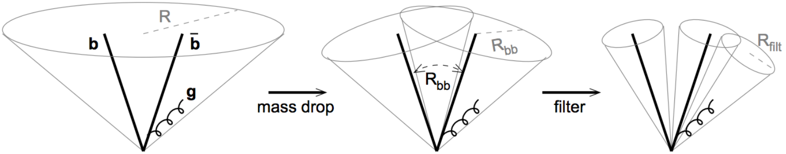
# Jet Substructure

- Searching "find fulltext 'jet substructure' and tc p" on INSPIRE yields number of published papers
- Number of papers per year has exploded in last decade
- Papers discuss wide range of physics interests
  - Searches for new particles
  - Heavy flavor jet tagging
  - BSM searches (e.g. dark matter)
  - Heavy ion collisions
  - Machine learning
  - QCD color connections
  - ...



# Symbolic Beginning

PRL 100, 242001 (2010)

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- Motivated by searching for highly boosted $VH \rightarrow \ell^{\pm} b\bar{b}$ production

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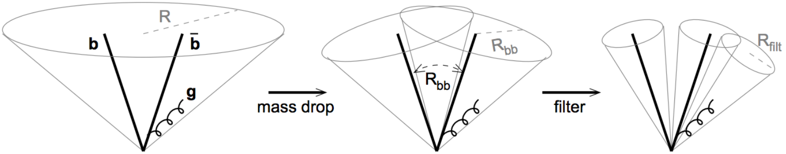
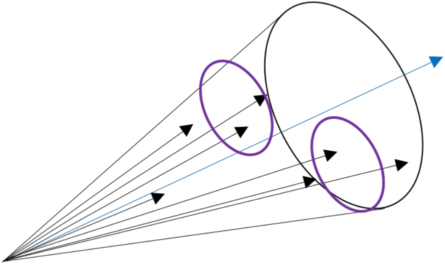



- Substructure revolution symbolically initiated by 2010 Butterworth *et al* PRL
- Motivated by searching for highly boosted $VH \rightarrow \ell^{\pm} b\bar{b}$ production
- Jet substructure was motivated by new particle searches
- However, many fields of physics at collider facilities quickly realized the potential of these techniques

# Fragmentation vs. Hadronization

## Fragmentation



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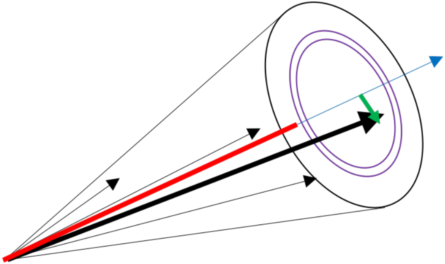
**LEFT**

## Hadronization

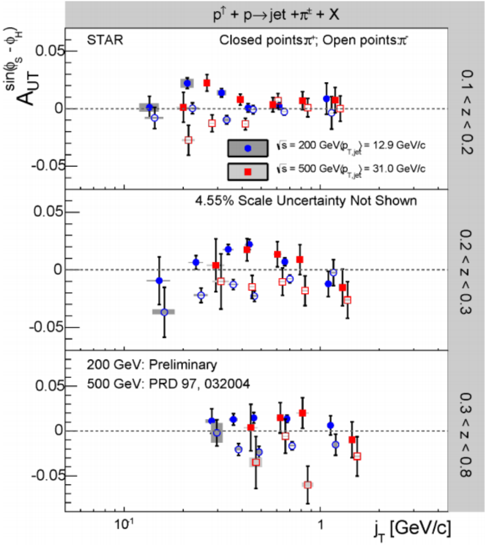


- Use individual hadrons to study correlations with jet axis

**RIGHT**

# Jet Substructure Physics at RHIC

- STAR has measured hadrons in jets produced in transversely polarized *pp* collisions
- Sensitive to 3D distributions of hadrons within jets



# Jet Substructure Physics at RHIC

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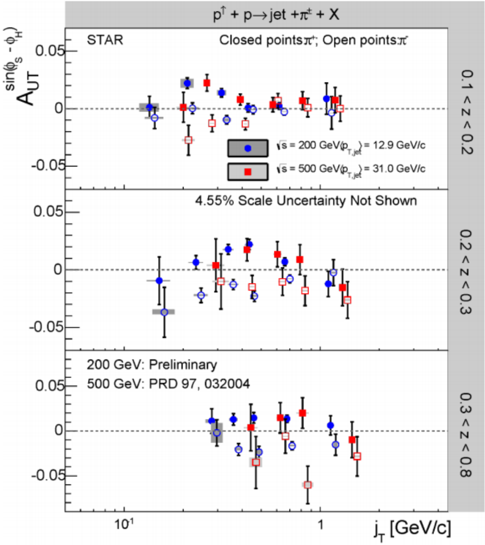
- Sensitive to quark-hadron spin-momentum correlations



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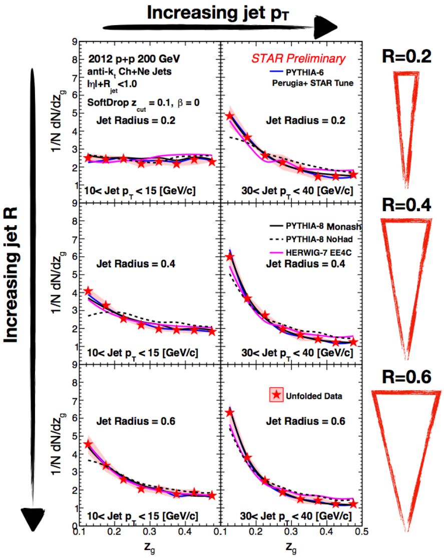
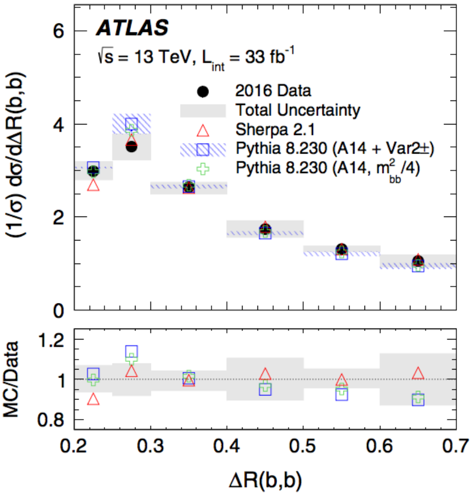


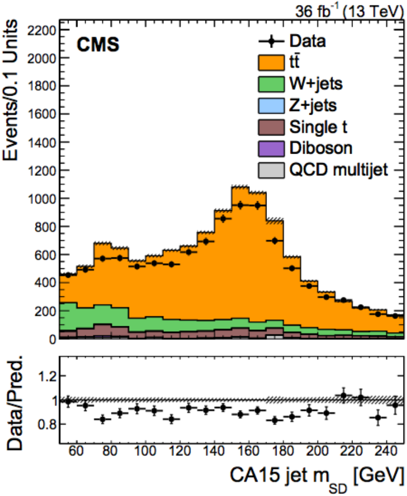

- Measurements of momentum sharing between subjets within jets
- Sensitive to QCD splitting function
  - How is energy shared between partons?
- Multidifferential as a function of jet radius and jet transverse momentum

# Jet Substructure at the LHC




Phys. Rev. D 99, 052004 (2019)

- Measurement of $b\bar{b}$ jets from gluon splitting
- Improve understanding of boosted $H \rightarrow b\bar{b}$ decays
- Improve understanding of $b\bar{b}$ fragmentation

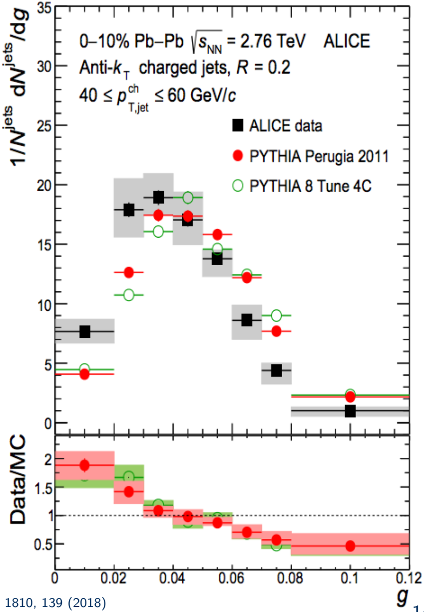



JHEP 1806, 027 (2018)

- Searches for dark matter particles using jet substructure techniques
- Soft drop algorithm recursively removes soft, wide angle radiation to better identify $t\bar{t}$ candidates
  - Improves searches for new particles

# Jet Substructure at the LHC

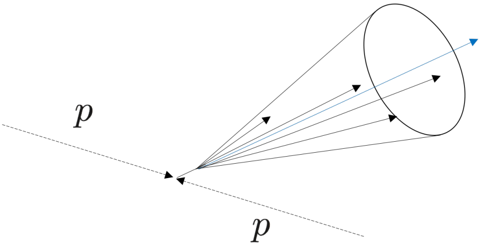
- Jet girth shows transverse momentum weighted width
- Indication of how "wide" jets are based on their hadronic constituents
- Improves understanding of nonperturbative hadronization dynamics




JHEP 1810, 139 (2018)

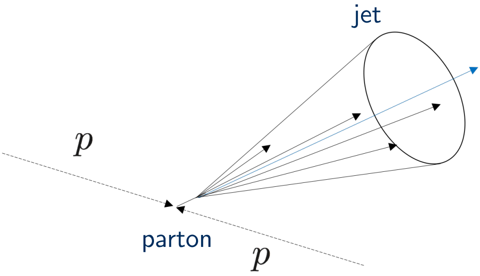
# Jet substructure at LHCb
# $\rightarrow$ focus on hadronization

# Hadronization: What do we want?




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

# Hadronization: What do we want?




- What is on our wish list to *robustly* study hadronization?
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     - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

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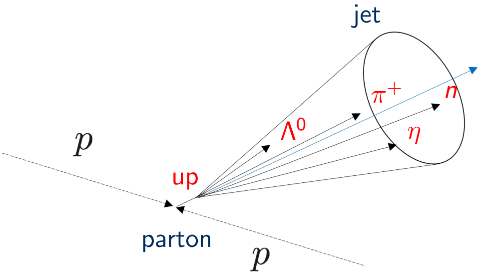


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     - Would allow for complete characterization of parton $\rightarrow$ hadron

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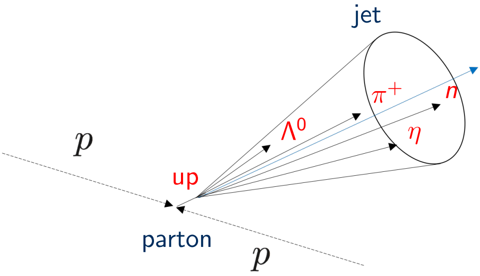


- Baryon vs. meson
- Correlations (e.g. strangeness, heavy flavor...)
- Resonance production ($\phi$, $J/\psi$, $\Upsilon$)
- ...

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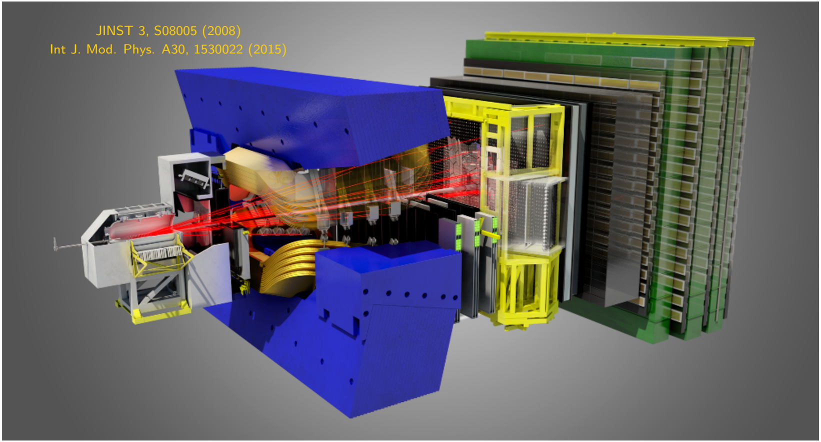
Large Hadron Collider
CMS
p
p
LHCb
ATLAS
ALICE

# LHCb Experiment




- Precision tracking and particle identification spectrometer at forward rapidities $(2 < \eta < 5)$

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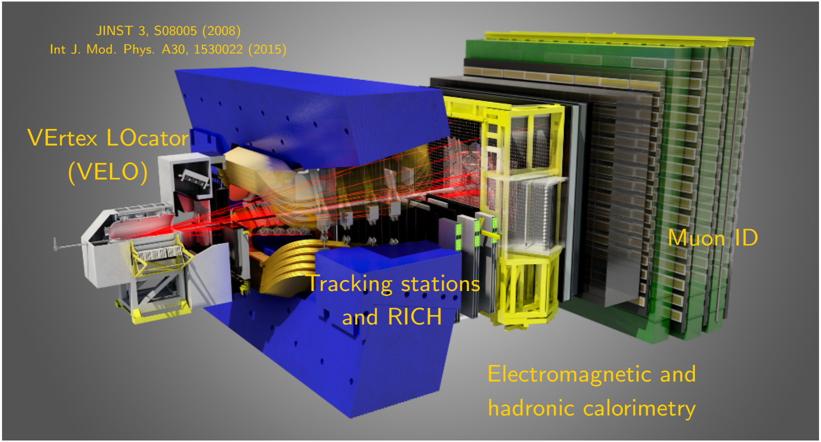


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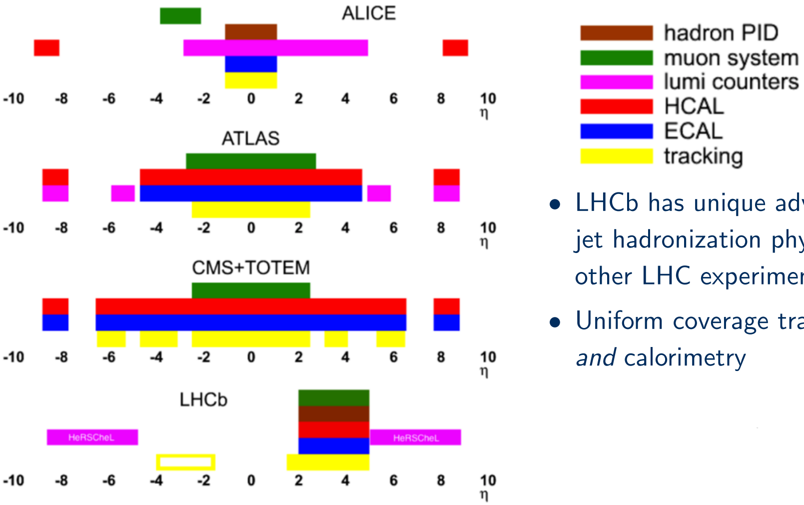


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- Uniform coverage tracking, PID, *and* calorimetry

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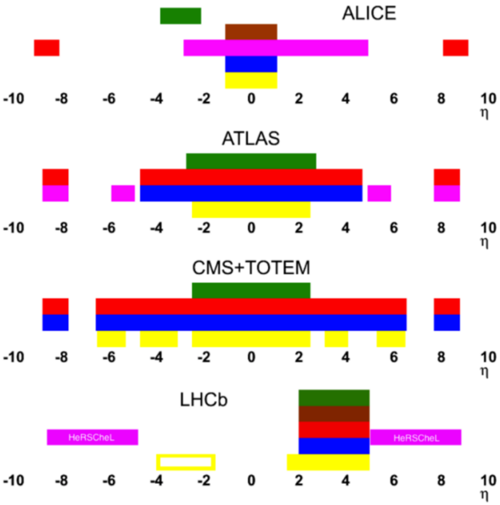


- hadron PID
- muon system
- lumi counters
- HCAL
- ECAL
- tracking

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- Can identify nearly all particles within a high $p_T$ jet

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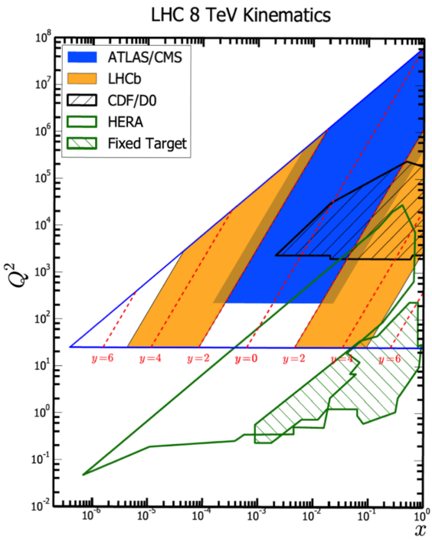
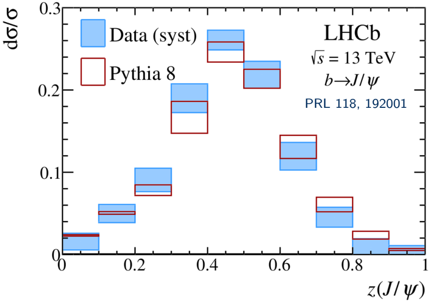
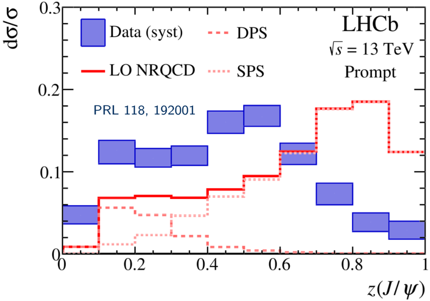



- LHCb has unique advantages for jet hadronization physics over other LHC experiments
- Uniform coverage tracking, PID, *and* calorimetry
- Can identify nearly all particles within a high $p_T$ jet
- Also occupy a unique region in $(x, Q^2)$

# 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 $J/\psi$-in-jet production



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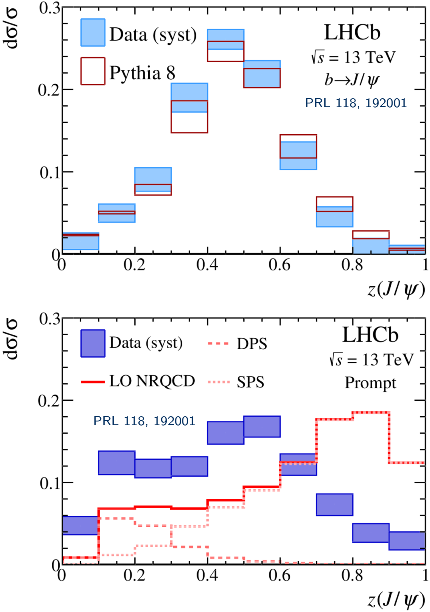

# $Z$+jet

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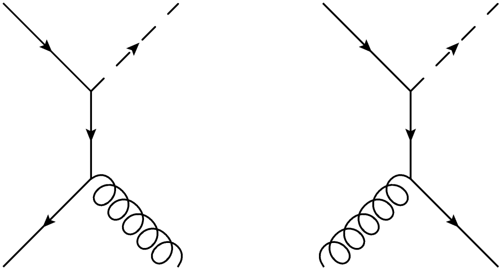

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- Why $Z$+jet?
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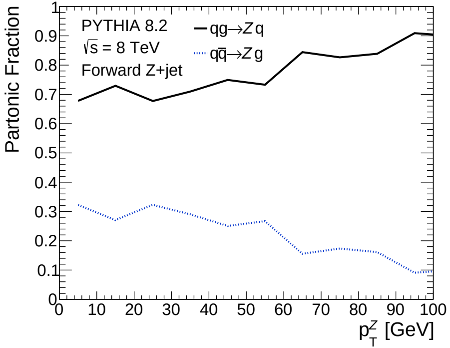

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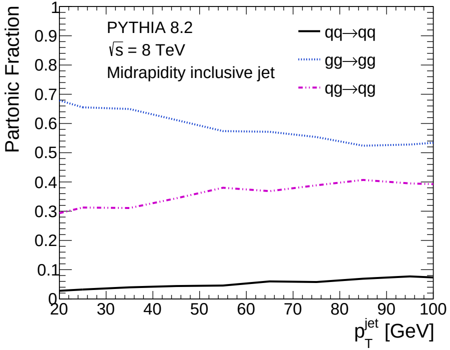

# $Z$+jet

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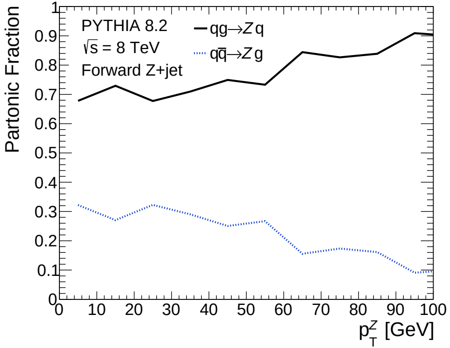
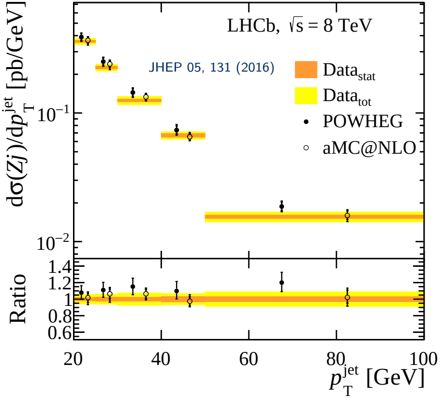
- Nearly all other hadronization studies at LHC measure inclusive jets, which are sensitive to predominantly gluon jets
- Opportunity to study light quark vs. gluon:
  - Hadronization dynamics
  - Jet properties



# $Z$+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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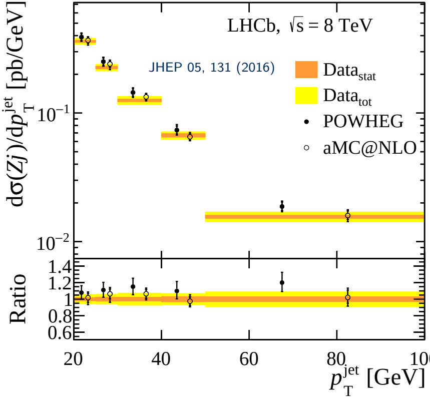

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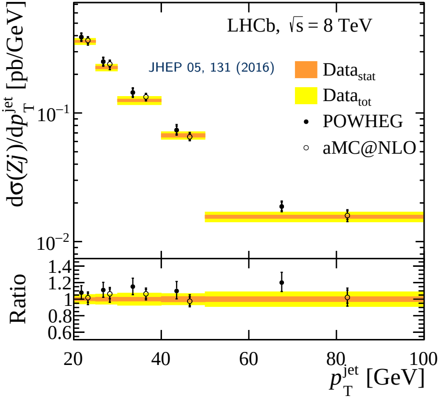
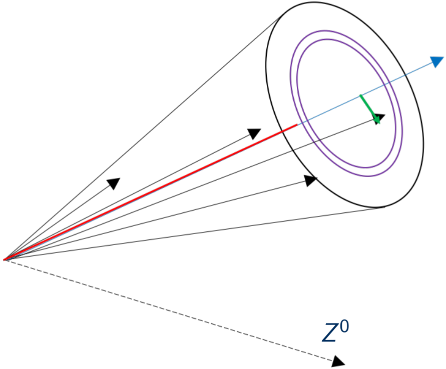



- **First LHC measurement of charged hadrons within $Z$ tagged jets**
- **First LHC measurement of charged hadrons-in-jets at forward rapidity**

# Observables




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

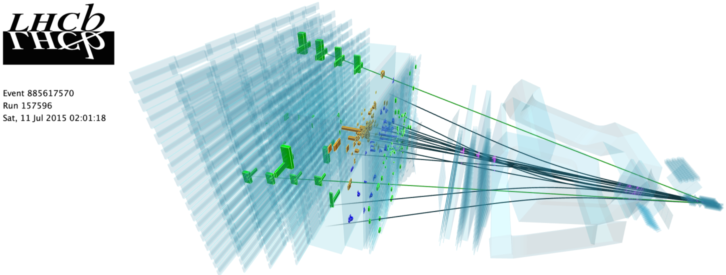
$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$

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

- Measure hadronization observables in two dimensions
  - Longitudinal momentum fraction $z$
  - Transverse momentum $j_T$
  - Radial profile $r$ (transverse)
- Reminder - each of these observables is for a single hadron within the jet

# Analysis Details

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



# Analysis Details

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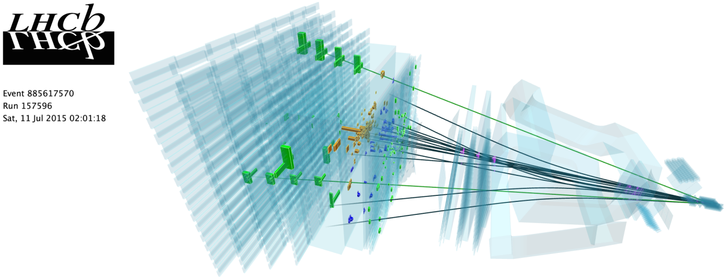
- $Z \rightarrow \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-$k_T$ jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2.5 < \eta < 4$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ and single primary vertex selects $2 \rightarrow 2$ topology



# Analysis Details

- Follow similar analysis strategy to ATLAS (EPJC 71, 1795 (2011), NPA 978, 65 (2018)) and LHCb (PRL 118, 192001 (2017))
- $Z \rightarrow \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
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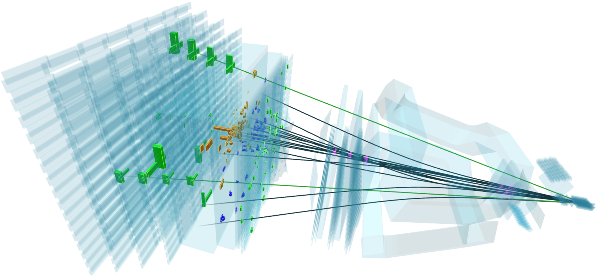
LHCb

Event 885617570
Run 157596
Sat, 11 Jul 2015 02:01:18



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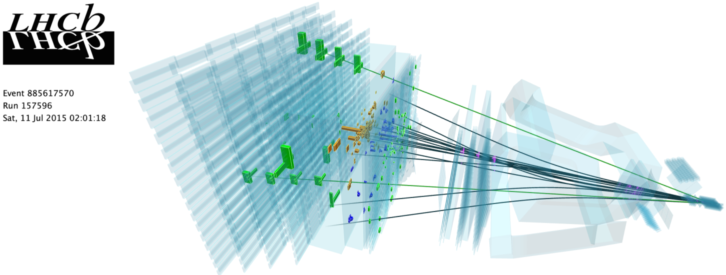
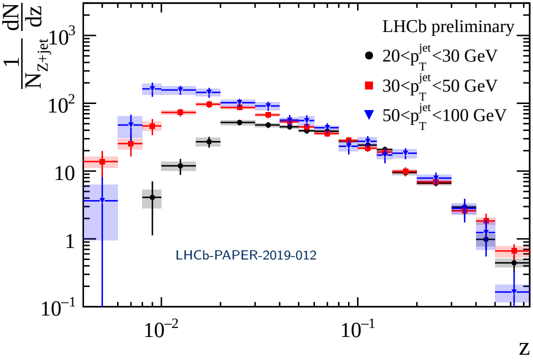
- Results efficiency corrected and 2D Bayesian unfolded

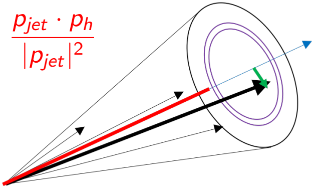


# Results

- 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

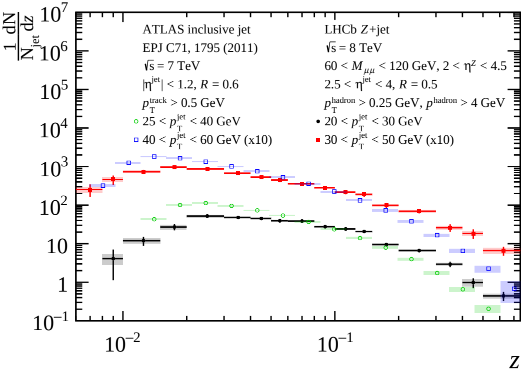



$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$



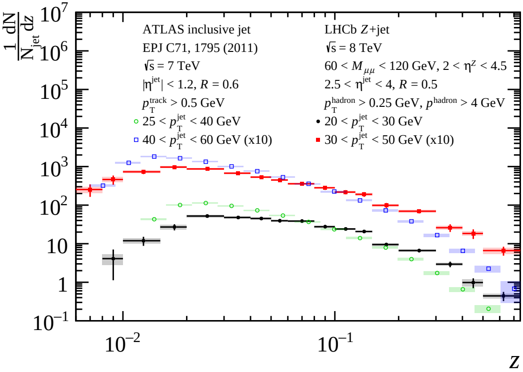
# ATLAS and LHCb Comparisons

- Compare ATLAS gluon dominated to LHCb light quark dominated



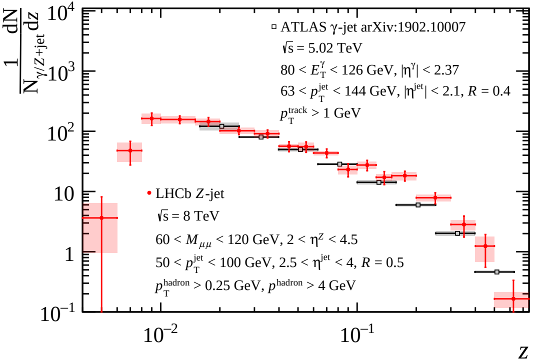
# ATLAS and LHCb Comparisons

- Compare ATLAS gluon dominated to LHCb light quark dominated
- Light quark jets produce higher momentum particles than gluon jets
- Light quark jets are more collimated than gluon jets



# Comparison to ATLAS $\gamma$-jet

- ATLAS midrapidity $\gamma$-jet and LHCb forward rapidity $Z$-jet distributions are very similar
- Both processes light quark jet dominated
- Light quark jet structure shows little rapidity dependence



# Comparison to ATLAS $\gamma$-jet

- ATLAS midrapidity $\gamma$-jet and LHCb forward rapidity $Z$-jet distributions are very similar
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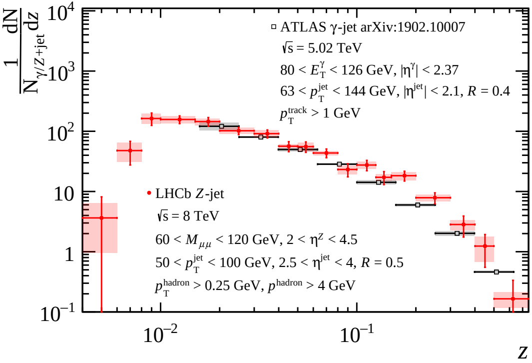
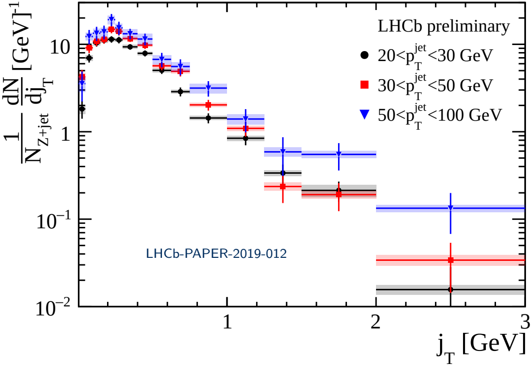
- Hint of more collimated jets in $Z$+jet
  - Massive $Z$ vs. massless $\gamma$?

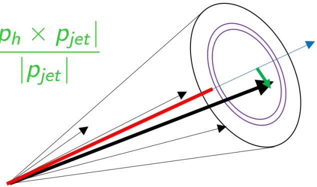


# Results

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

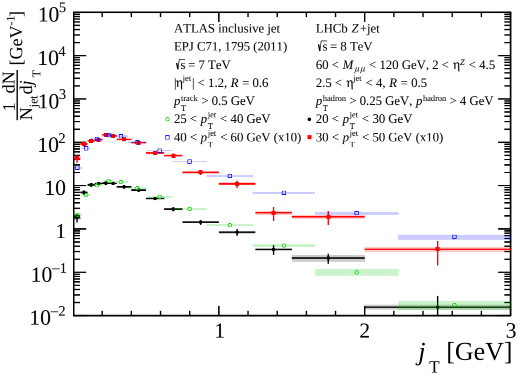



$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$



# ATLAS and LHCb Comparisons

- Transverse momentum distributions show smaller $\langle j_T \rangle$ in $Z$+jet vs. inclusive jet at small $j_T$
  - Consistent with more collimated light quark vs. gluon jets
- Perturbative region quite similar between quark and gluon jets



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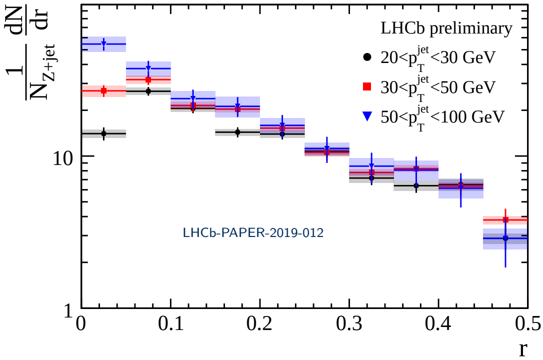
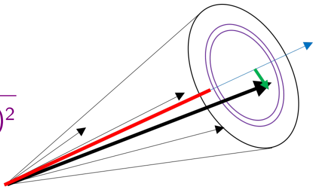


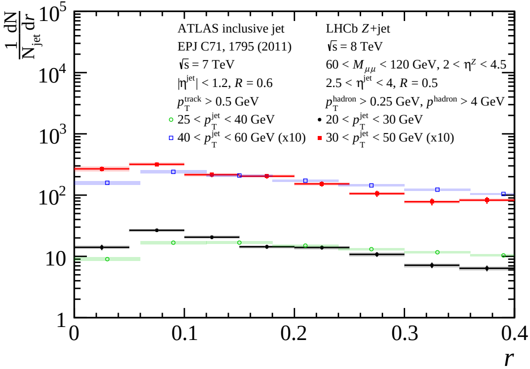

- Radial profiles largely independent of jet $p_T$ away from jet axis
  - Indication of independence of nonperturbative contributions?
- Multiplicity of hadrons along jet axis rises sharply with jet $p_T$

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

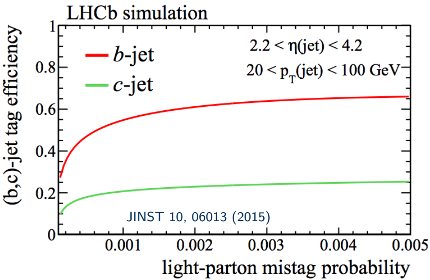


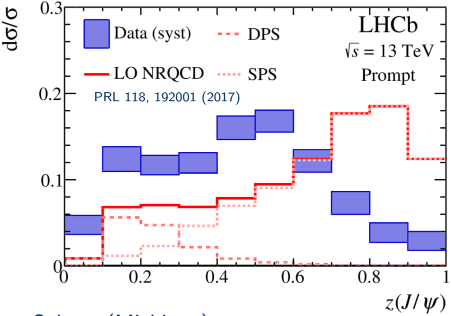
# ATLAS and LHCb Comparisons

- Comparing ATLAS midrapidity inclusive jets to LHCb forward $Z$+jet shows jets are more collimated when tagged with a $Z$
- Gluon jets "flatter" in radius, while light quark jets are "steeper"



# Future LHCb Jet Hadronization




- 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 ($\phi$, $J/\psi$, $\Upsilon$)
  - Correlations with flavor ID
  - Change in target size (e.g. use proton-nucleus collisions)

# Conclusions

- Jet substructure has exploded onto the HEP scene, with wide ranging physics interests

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  - Opportunity for understanding nonperturbative hadronization dynamics
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  - Data potentially of interest to wide range of collider physics
  - Opportunity for understanding nonperturbative hadronization dynamics
  - Opportunity for understanding boosted gluon vs. light quark jets
- More hadronization results to come from LHCb utilizing PID, heavy flavor ID, and calorimetry

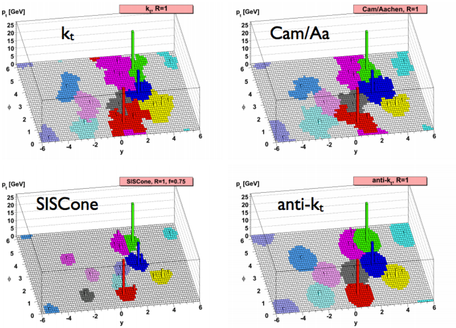
# Back Up

# Anti-$k_T$ Algorithm

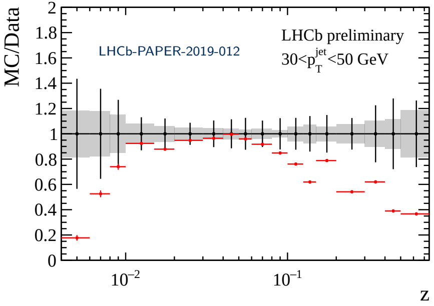
- Sequential recombination algorithm which clusters particles into jets based on their $p_T$
- Widely used as it is both infrared and collinear safe in calculations
- Clusters particles around highest $p_T$ particle in a conical shape

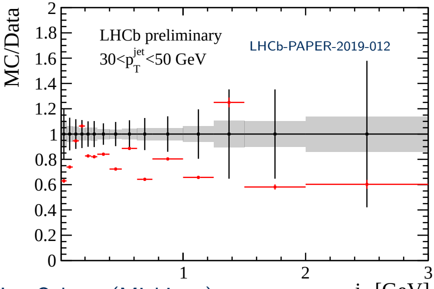
$$d_{ij} = min(p_{T_i}^{-2}, p_{T_j}^{-2}) \frac{\Delta_{ij}^2}{R^2}$$

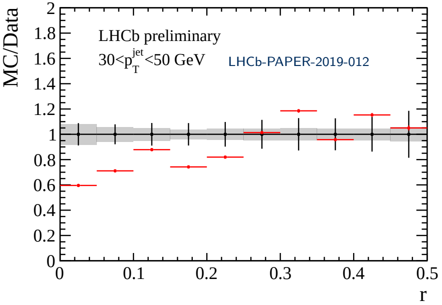
$$d_{iB} = p_{T_i}^{-2}$$



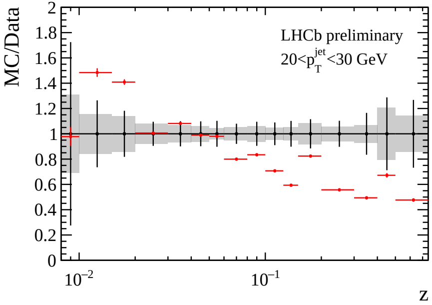
# Comparisons with PYTHIA

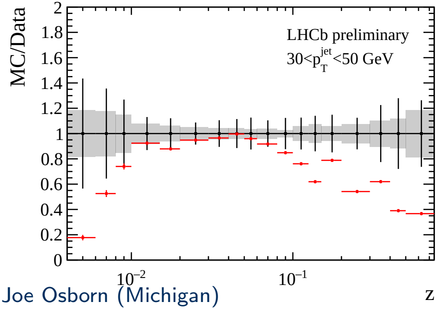


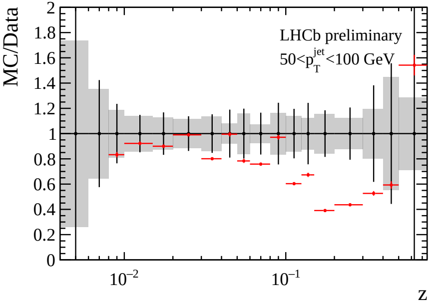




- Comparisons with PYTHIA show that PYTHIA generally underpredicts the number of high momentum charged hadrons within $Z$-tagged jets

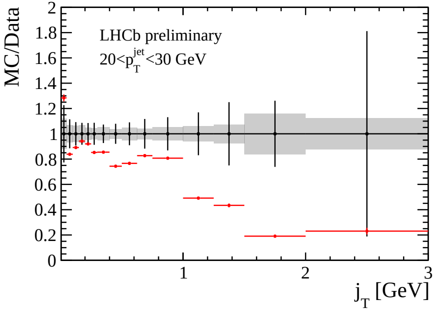


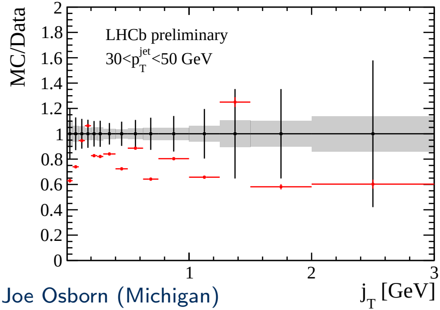



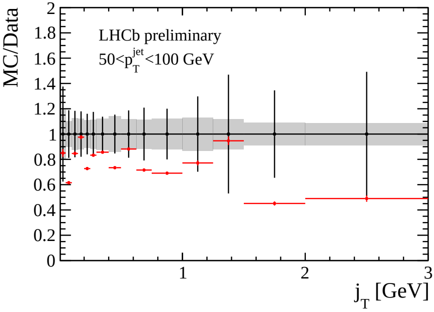




- PYTHIA generally underpredicts the number of high $z$ hadrons

# Comparisons with PYTHIA ($j_T$)

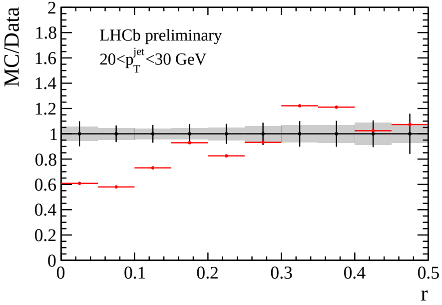


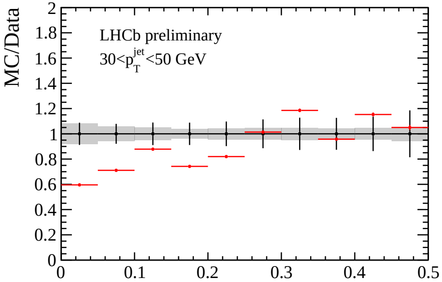



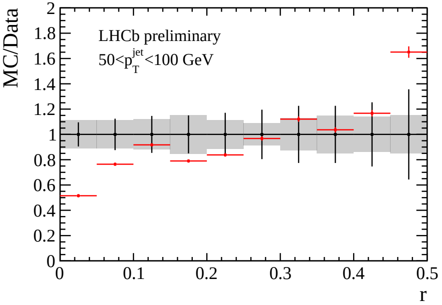




- PYTHIA generally gets $j_T$ shape, with about a 20% difference in normalization

# Comparisons with PYTHIA (*r*)

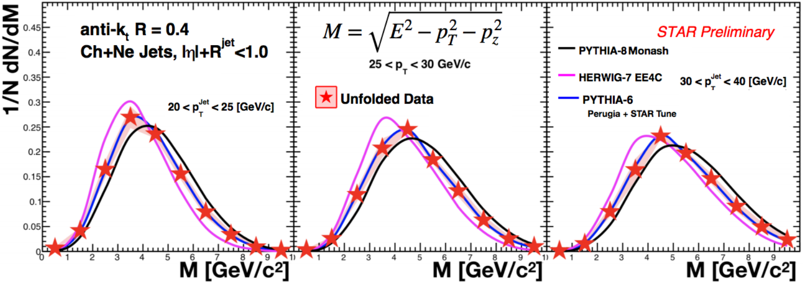



- PYTHIA generally underpredicts the number of small *r* hadrons

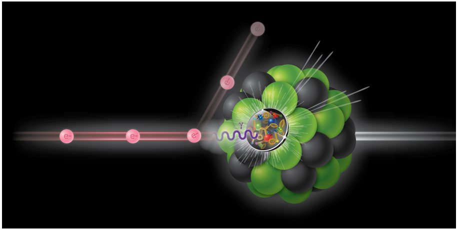
# Jet Substructure Physics at RHIC




- Measurement of jet mass sensitive to both fragmentation and hadronization aspects of jet substructure!
- Can study the interplay and connections between both

# 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