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

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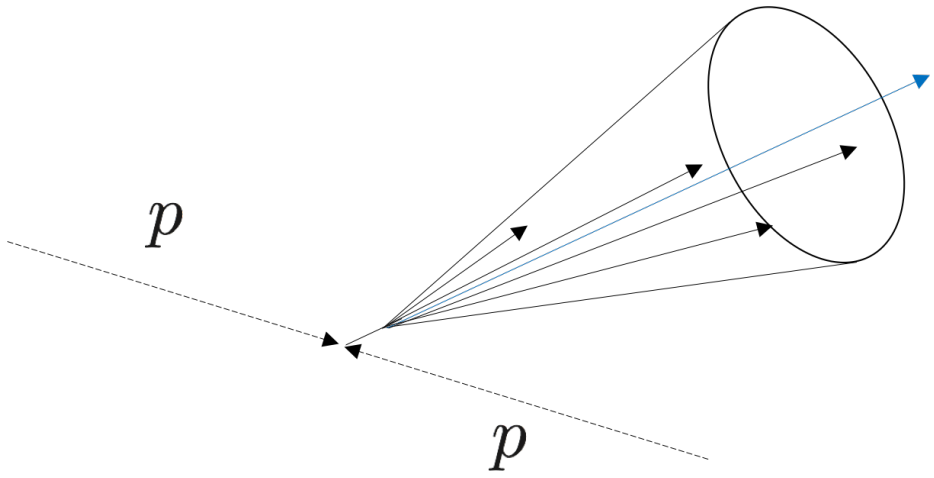
# Jets

- Jet physics is a broad experimental endeavor at RHIC and the LHC
- Enabled by more robust comparisons that can be made between theory and experiment with recent jet finding algorithms



# Jets

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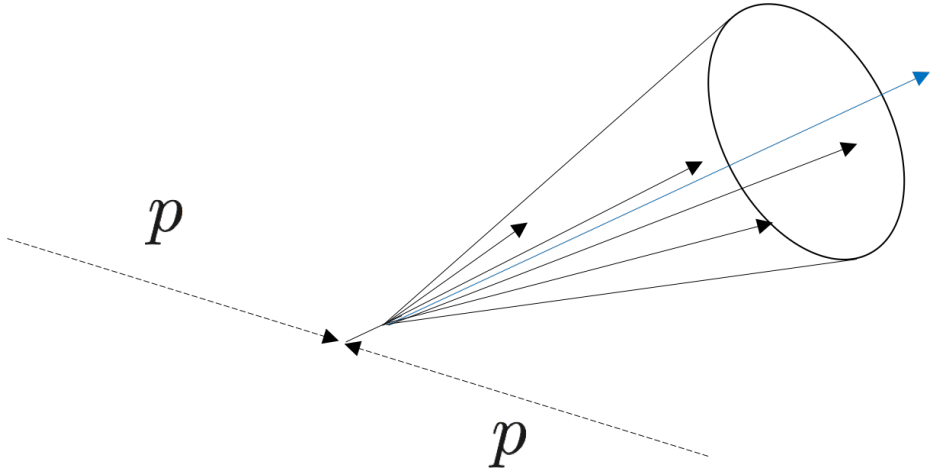
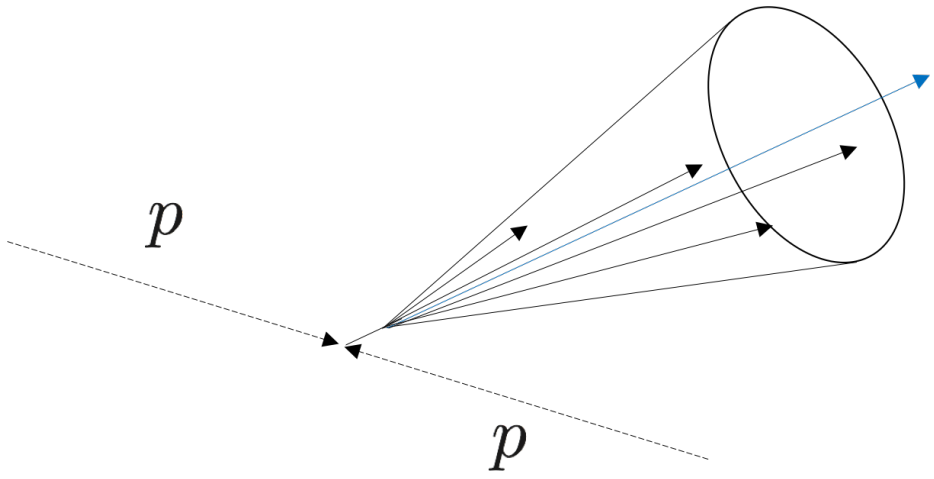
- Enabled by more robust comparisons that can be made between theory and experiment with recent jet finding algorithms
- Jets are a proxy for partons, and thus provide sensitivity to the underlying partonic dynamics



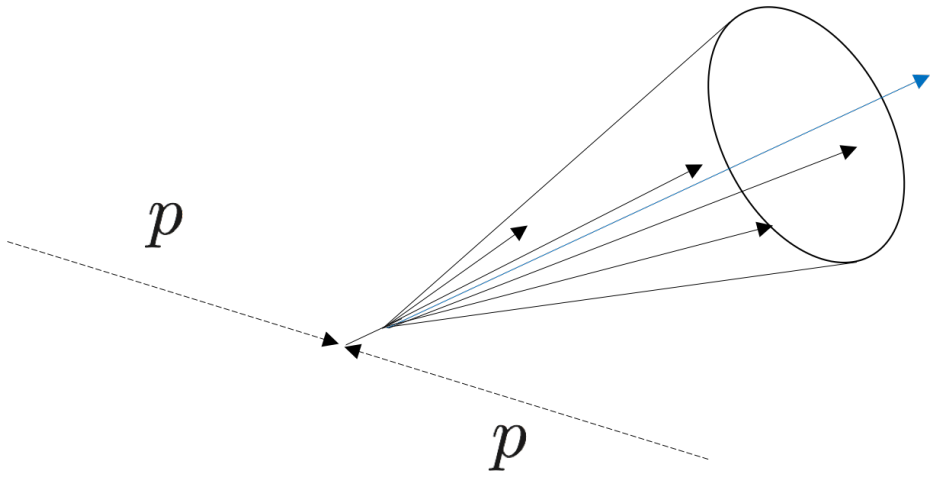
# Jet Hadronization

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



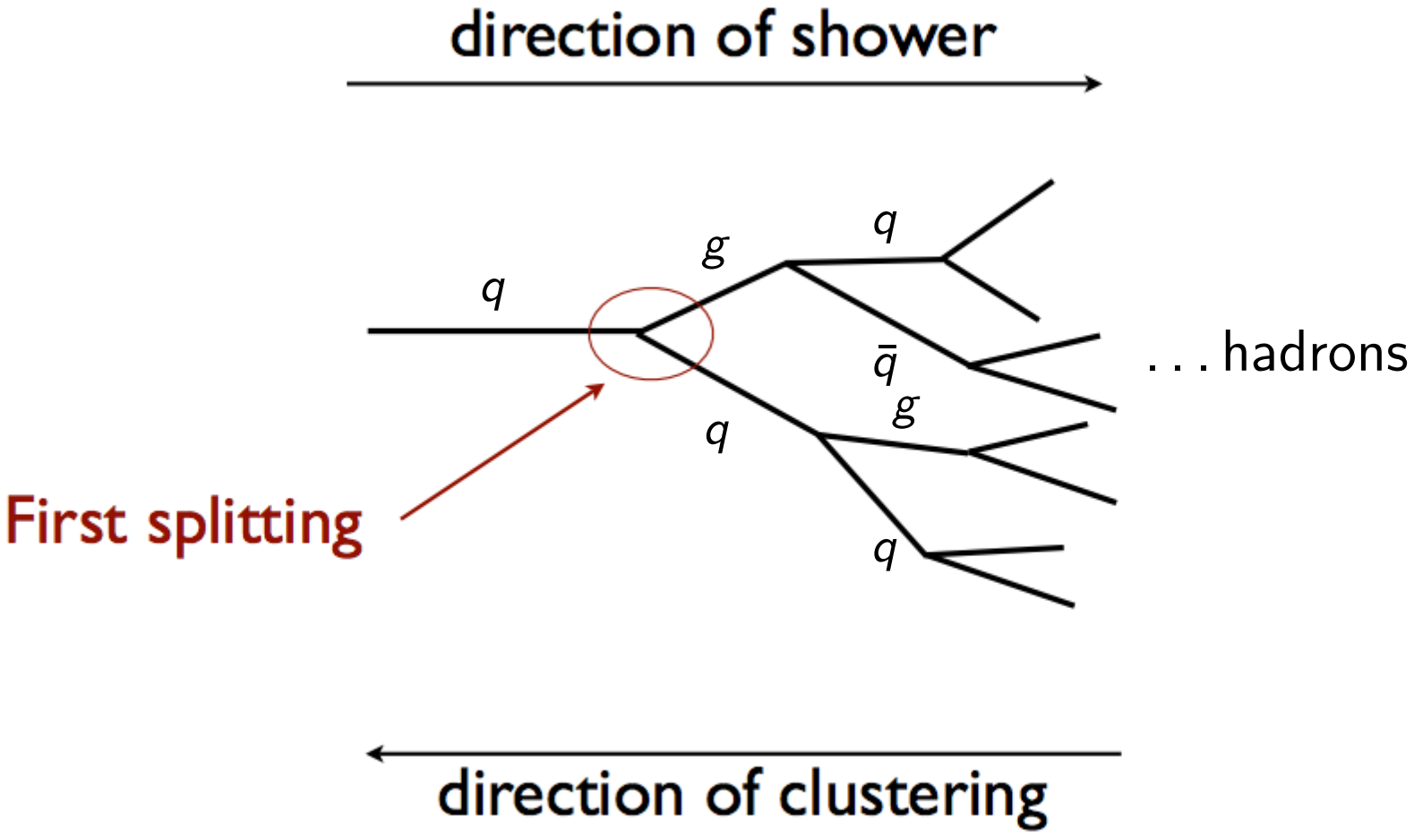
# Jet Hadronization

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

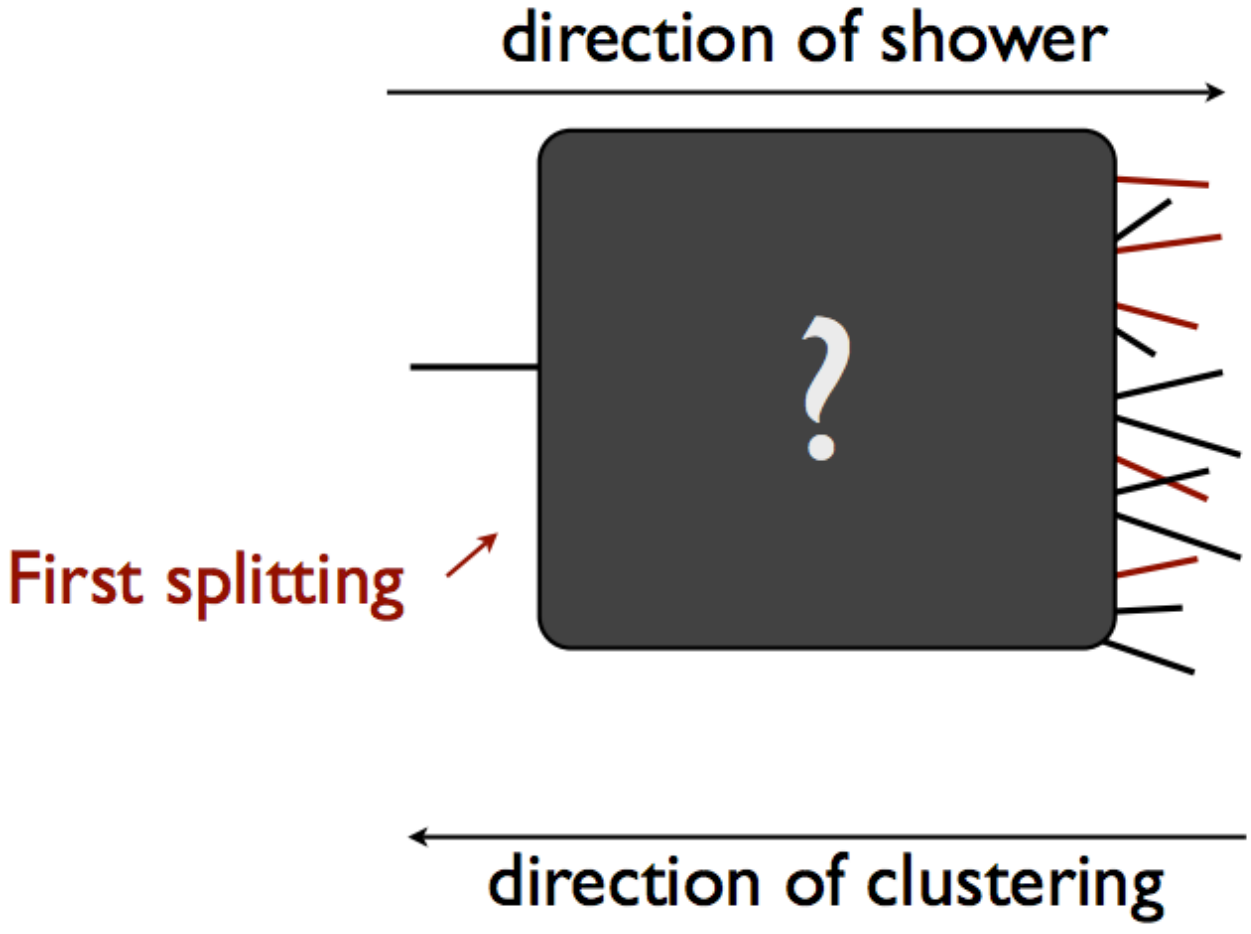


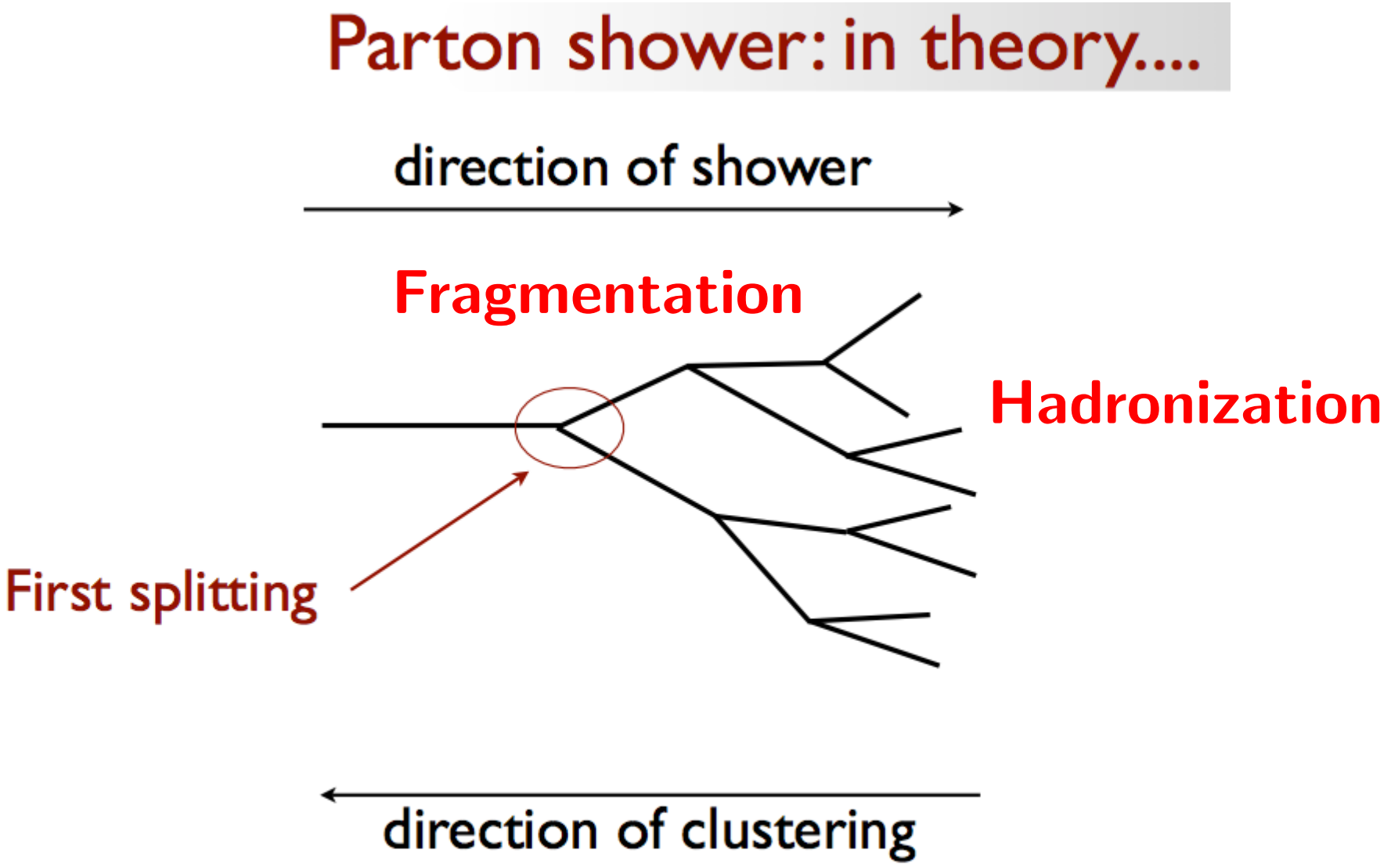
# How do jets really form?

# Parton shower: in theory....



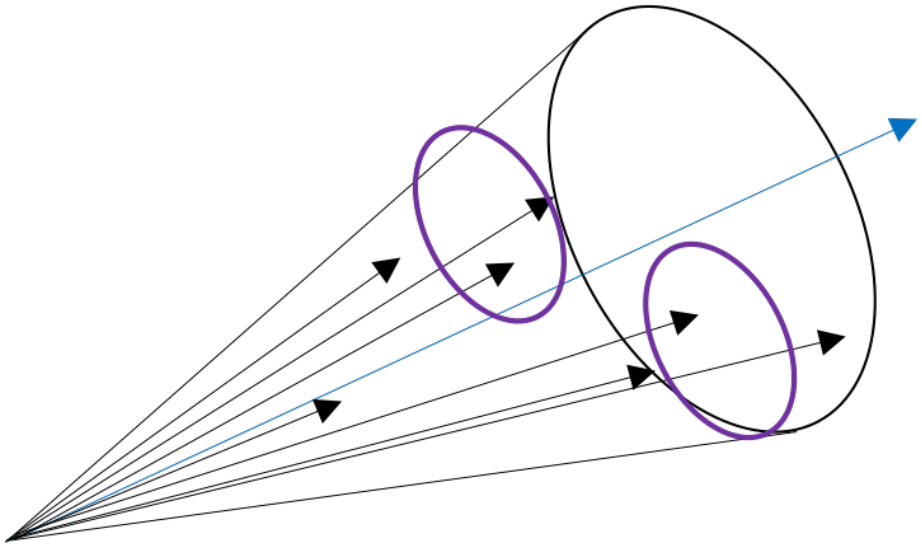
# Parton shower: in practice




Parton shower: in theory....
direction of shower
Fragmentation
Hadronization
First splitting
direction of clustering

# Fragmentation vs. Hadronization

## Fragmentation



- Use jet grooming algorithms to identify "prongs" of jet, as a proxy for partonic splittings

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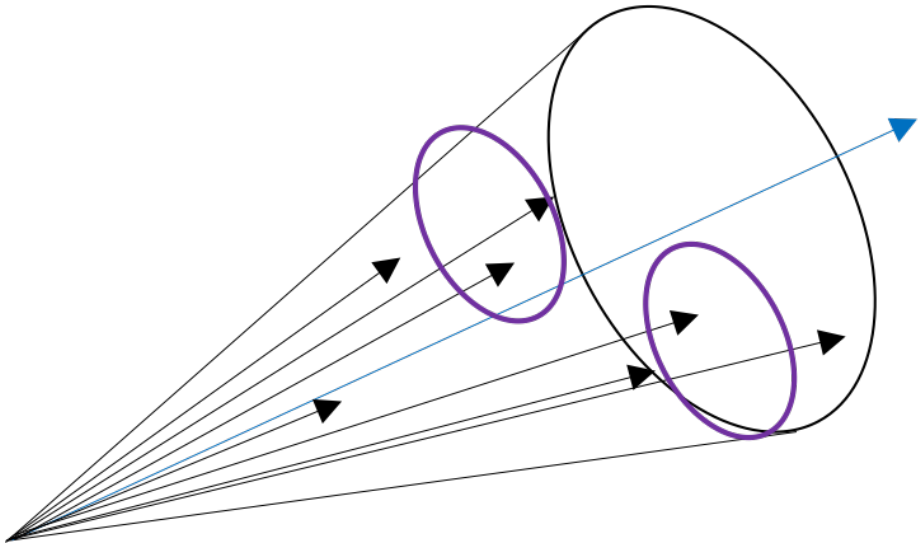

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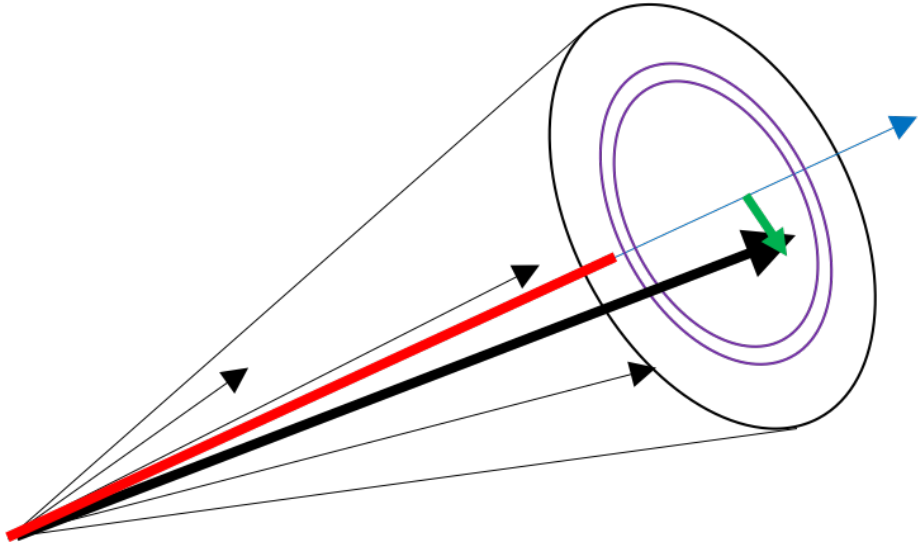

- Use individual hadrons to study correlations with jet axis

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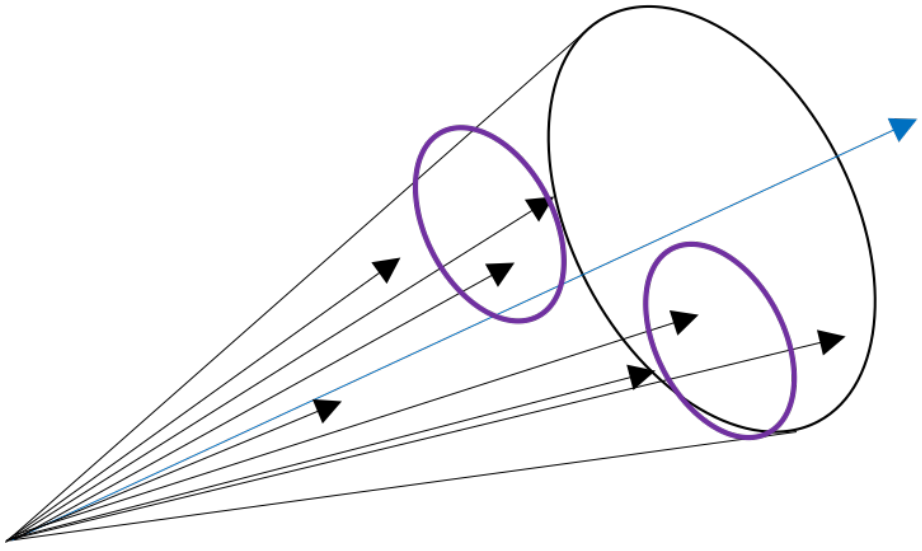

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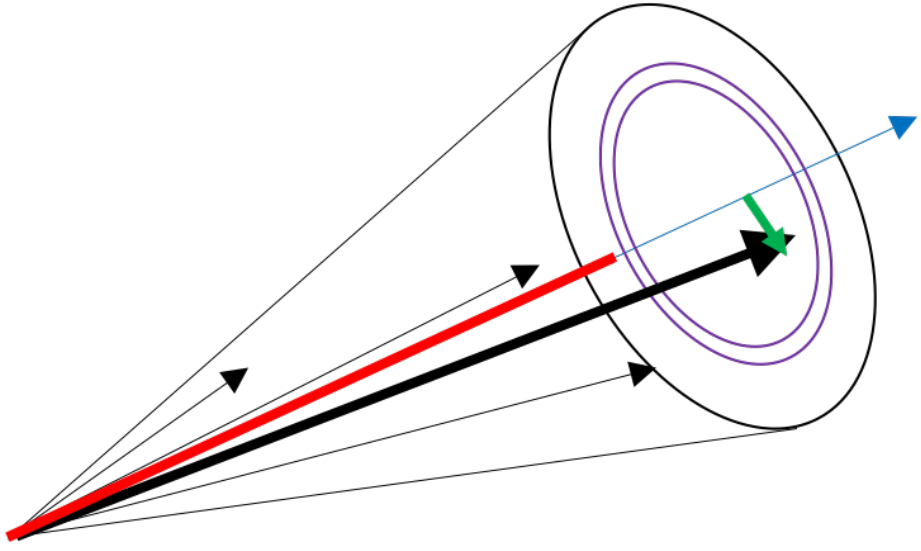

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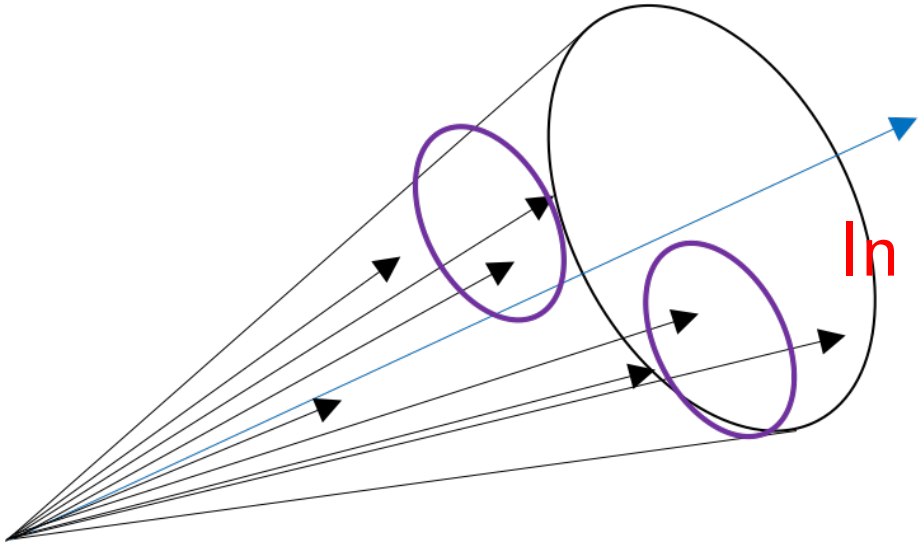

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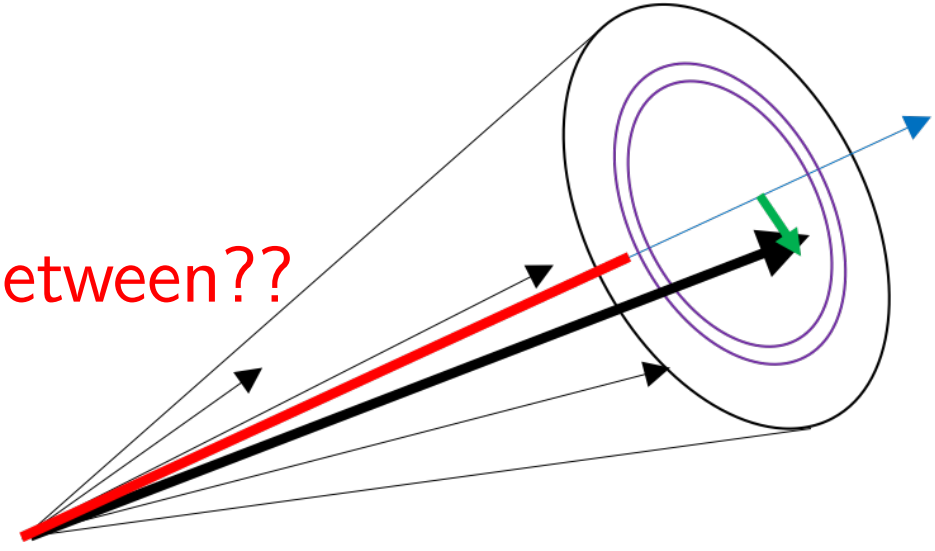

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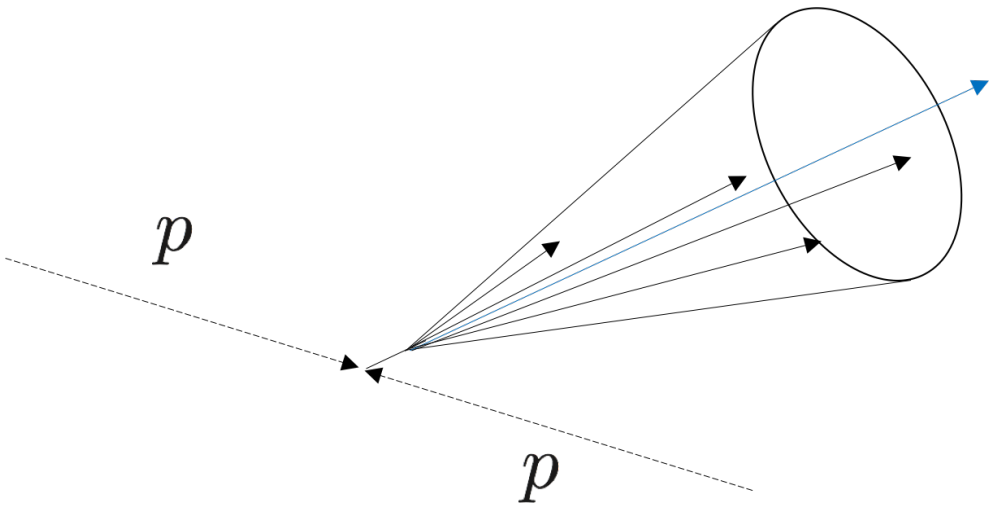
Emphasis on NONperturbative QCD

In between??

# Hadronization: What do we want?




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

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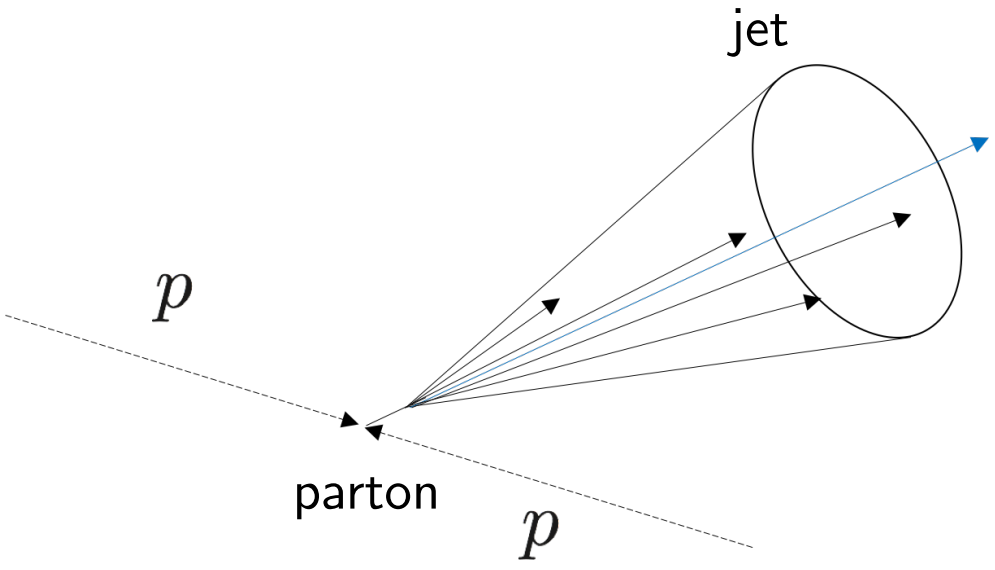


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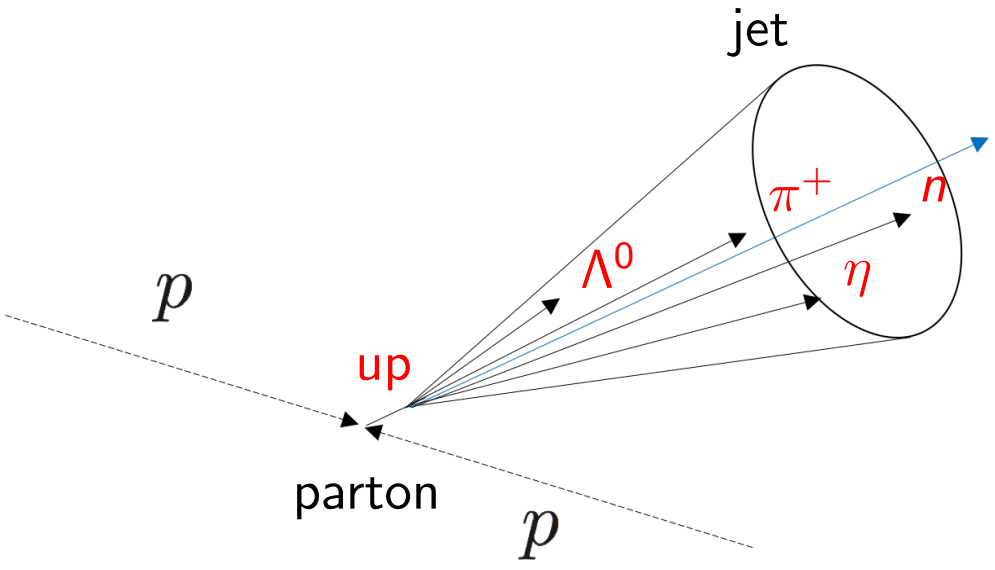


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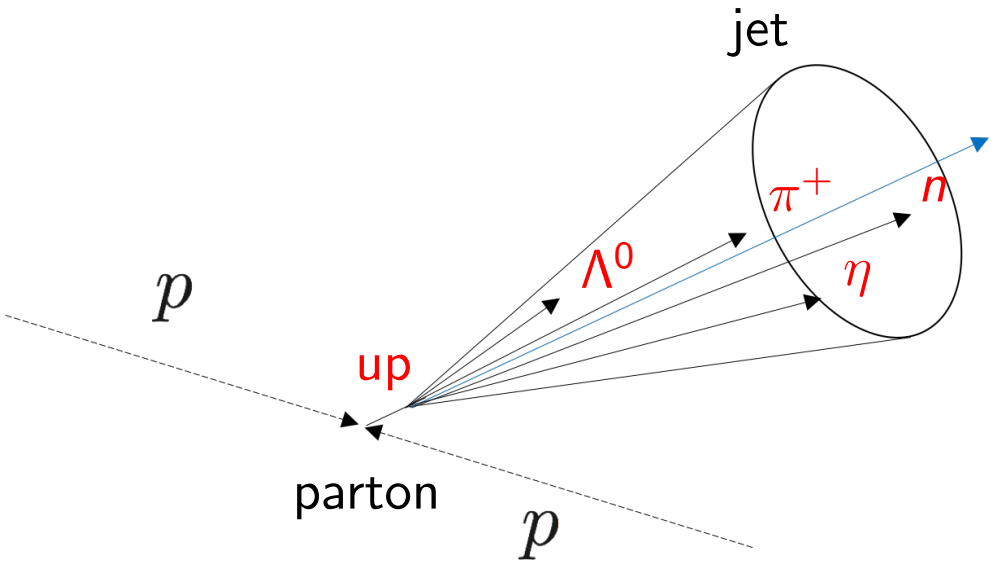


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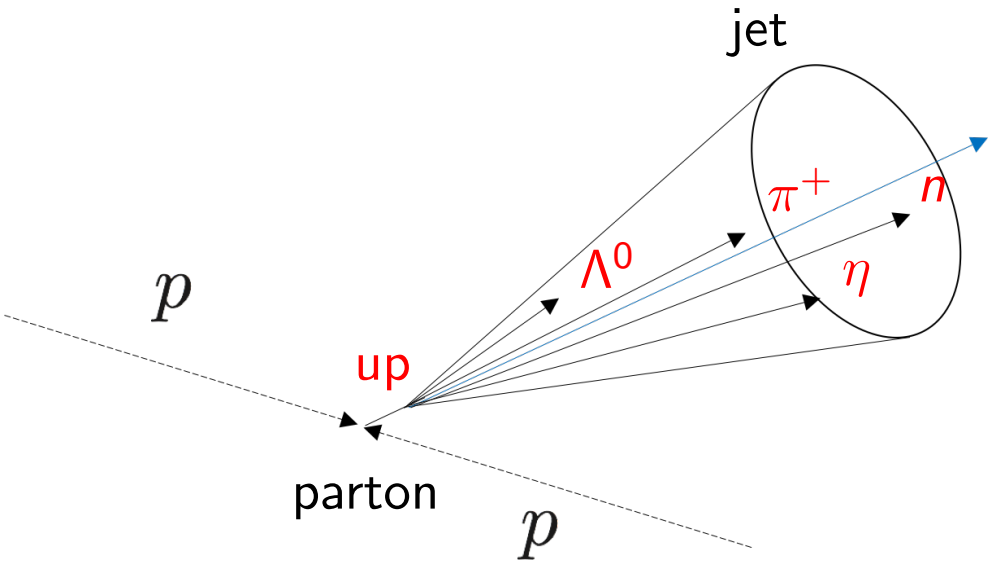


- Baryon vs. meson
- Resonance production ($\phi$, $J/\psi$, $\Upsilon$)
- Correlations (e.g. kinematic, PIDed. . . )
- . . .

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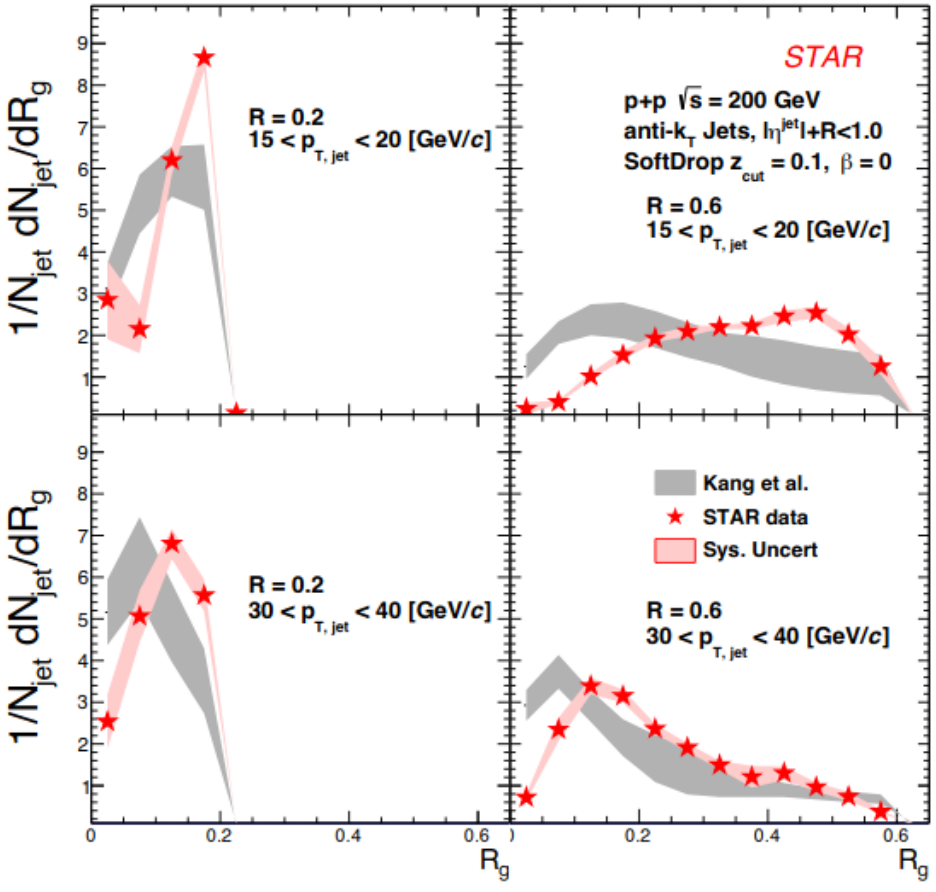
# STAR Soft Drop

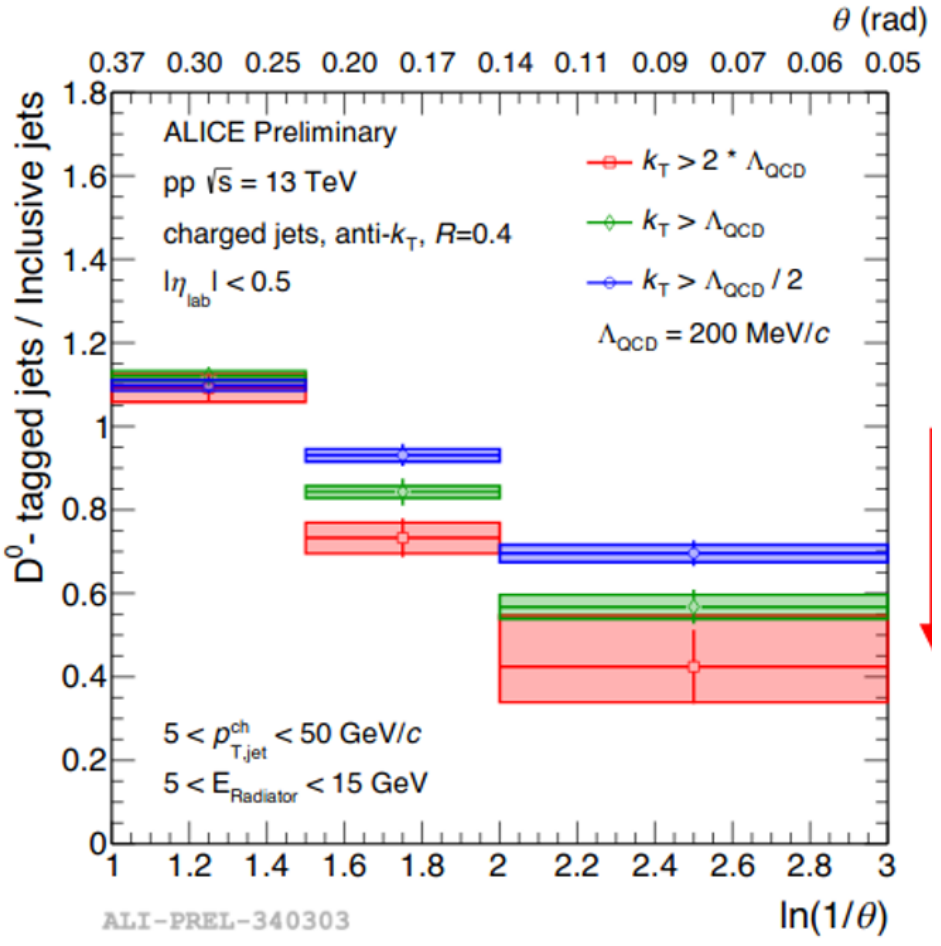



arXiv:2003.02114

- New STAR results are first study at RHIC of Soft Drop splittings
- Highlight $R_G$, which shows need for more robust theory calculations relating fragmentation and hadronization effects

# Flavor Dependence - Heavy Quarks

- First study trying to observe the dead cone effect
- Suppression of splittings at small angles comparing $D^0$ to inclusive jets



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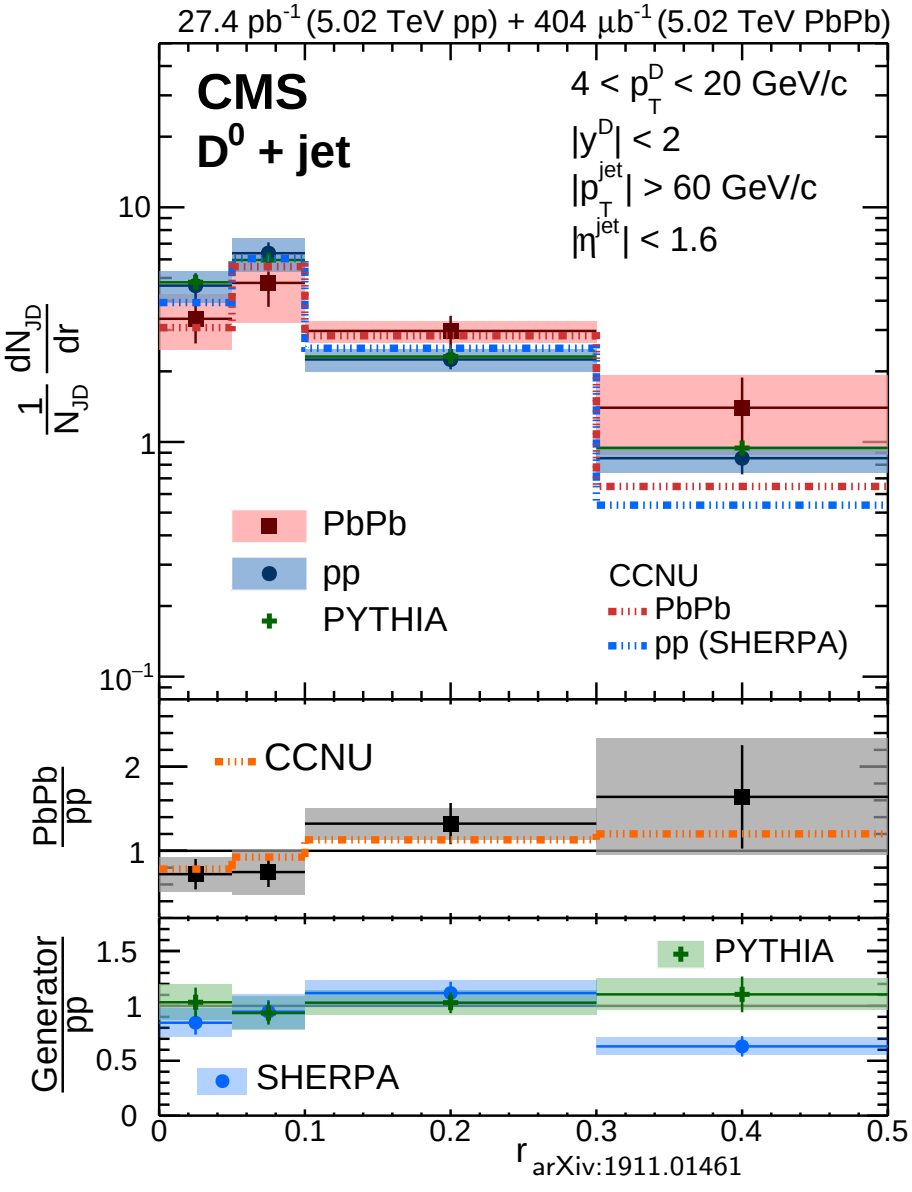

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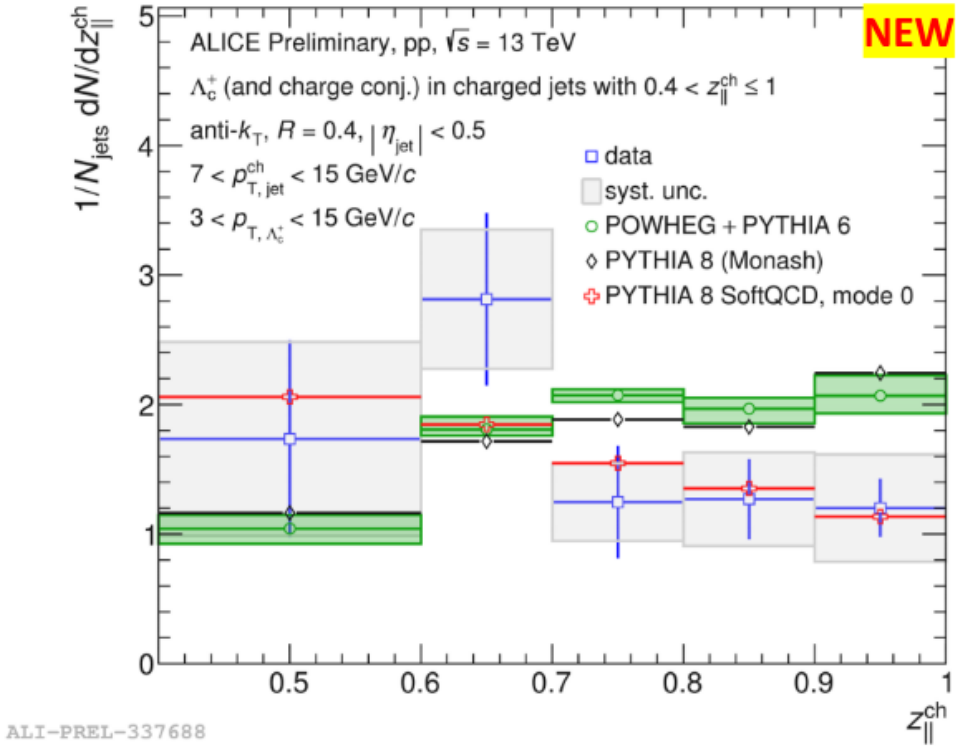
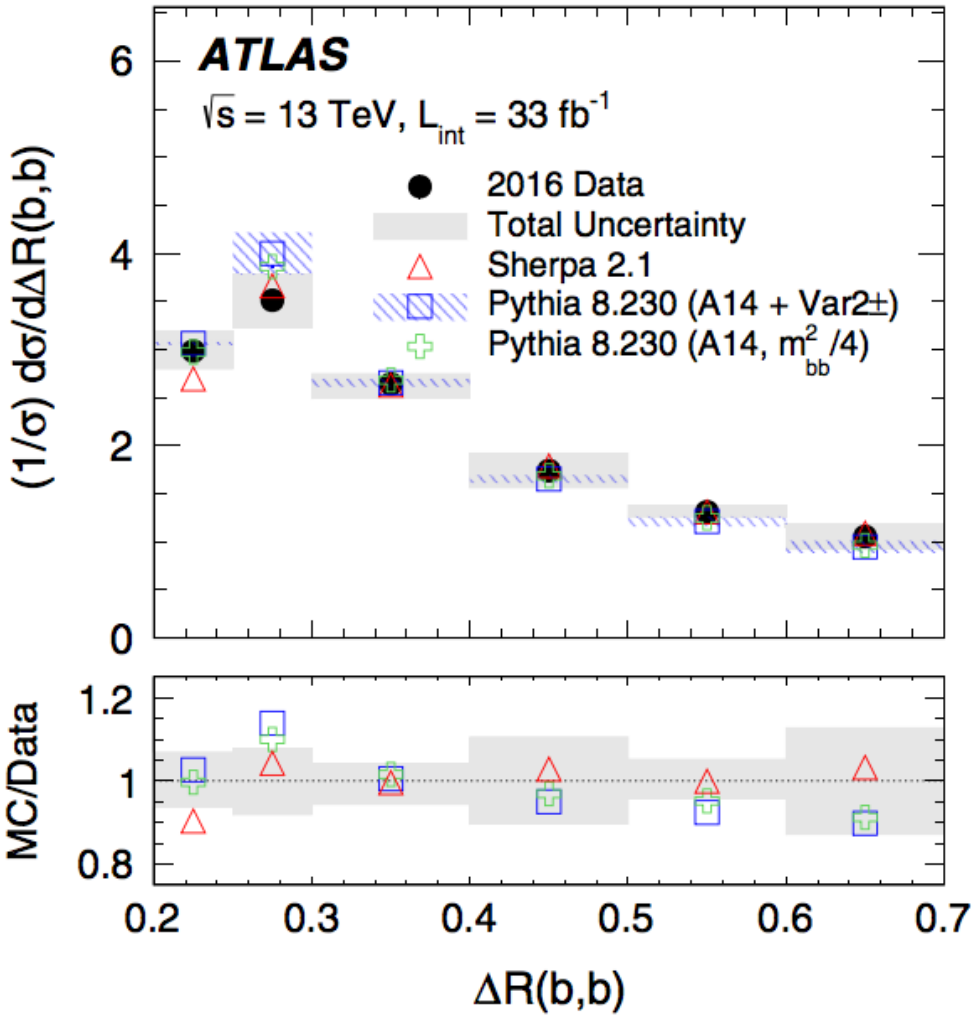
- Measurement of $D^0$ production as a function of radial dimension
- More exotic $\Lambda_c^+$ hadronization studies



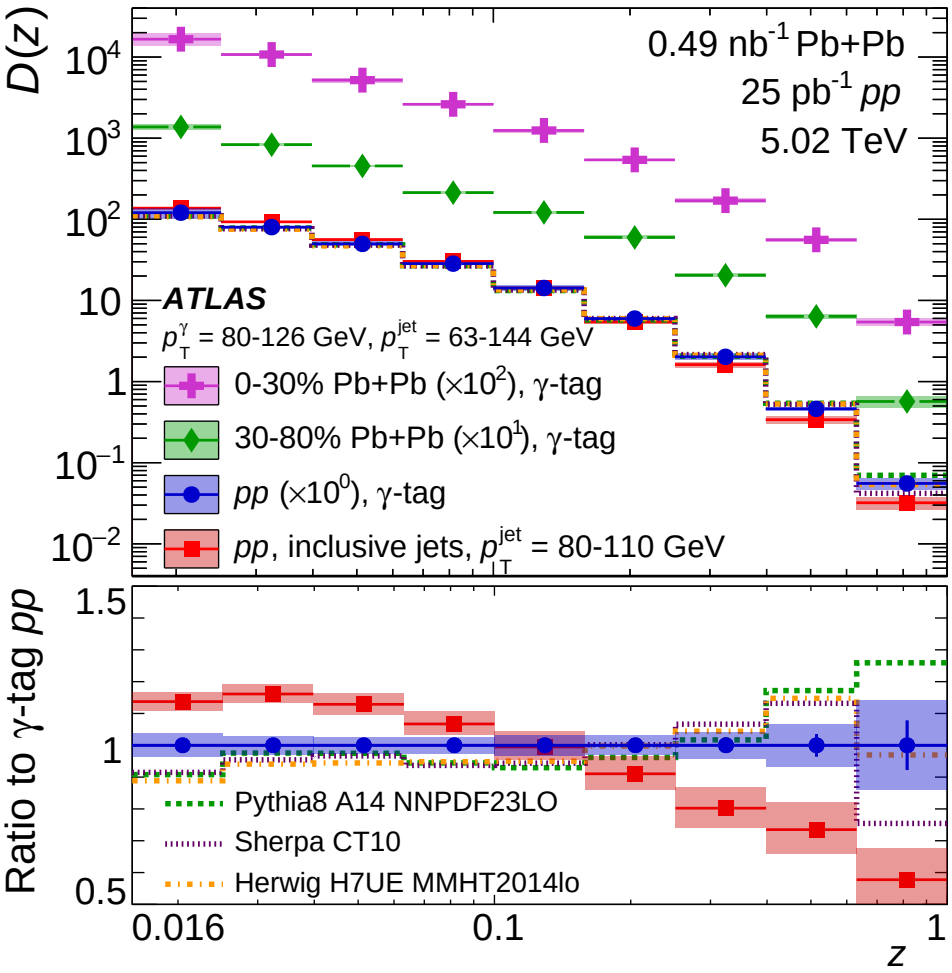
# Flavor Dependence - $g \to b\bar{b}$




Phys. Rev. D 99, 052004 (2019)

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

# Flavor Dependence - Quark vs. Gluon




Phys. Rev. Lett. 123, 042001 (2019)

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- Use direct photon tags to preferentially select light quarks vs. gluons

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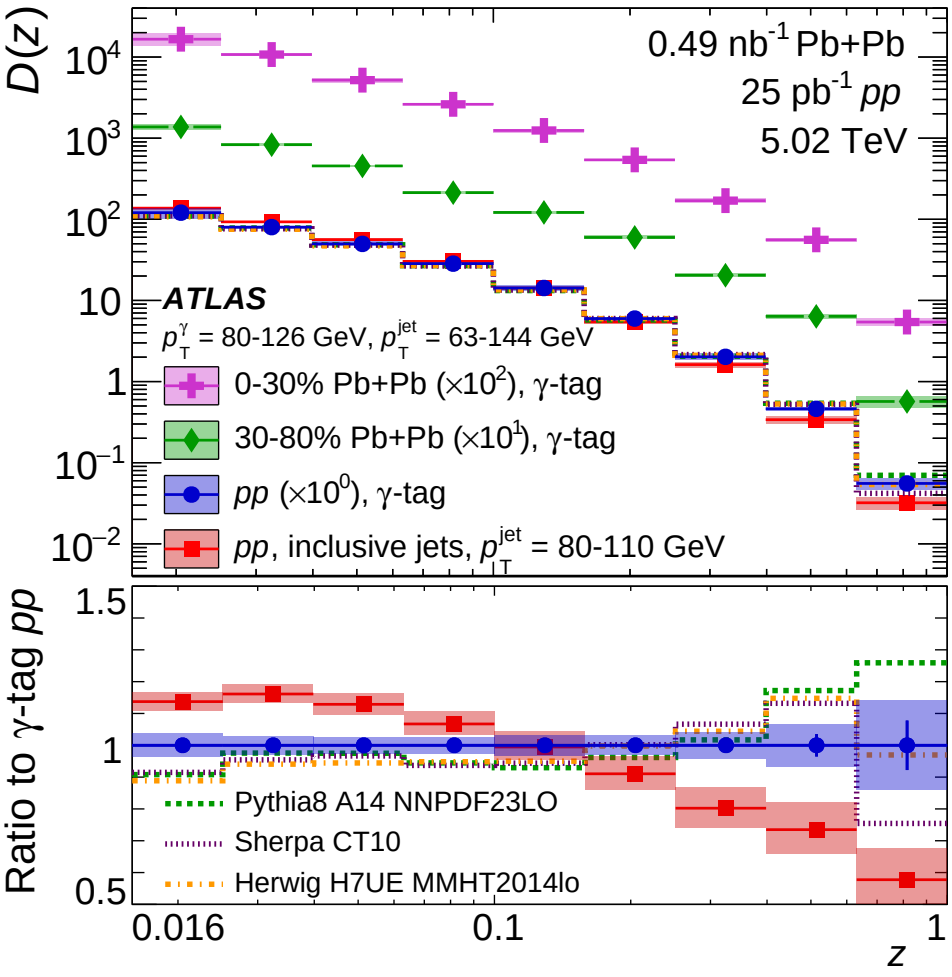


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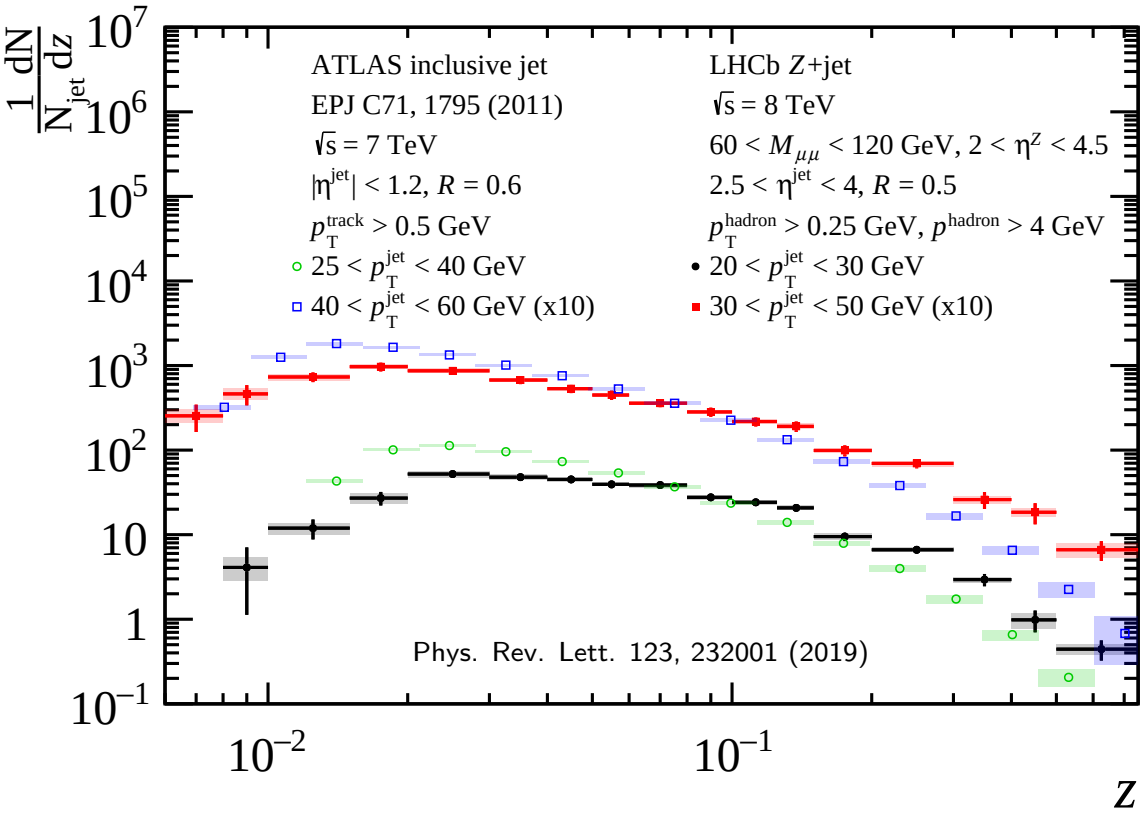
- Starting to move towards flavor dependence
- Use direct photon tags to preferentially select light quarks vs. gluons
- On average, light quark jets produce higher momentum particles than gluon jets

# ATLAS Inclusive and LHCb $Z$+jet

- Compare ATLAS inclusive jet to LHCb $Z$+jet

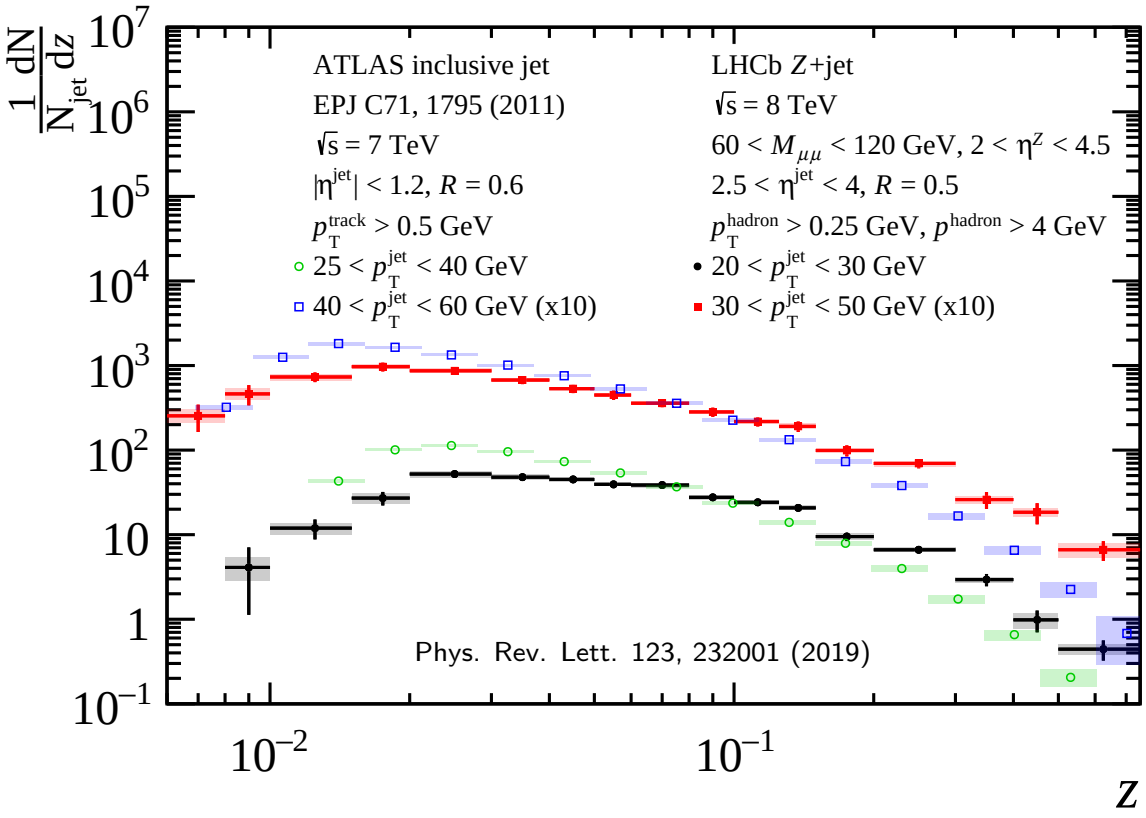



LHCb quark jet (filled) - red and black

ATLAS gluon jet (open) - blue and green

# ATLAS Inclusive and LHCb $Z$+jet

- Compare ATLAS inclusive jet to LHCb $Z$+jet
- Light quark jets produce higher momentum particles than gluon jets
- Light quark jets are more collimated than gluon jets

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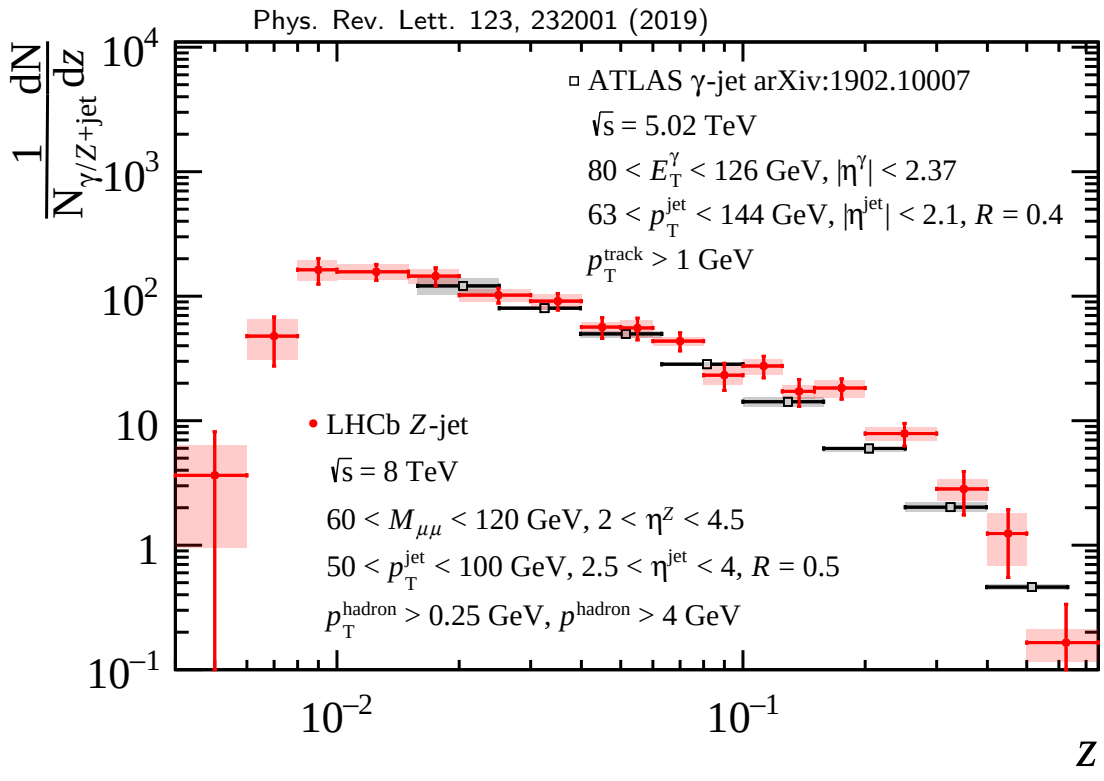
- ATLAS midrapidity $\gamma$-jet and LHCb forward rapidity $Z$-jet distributions are very similar

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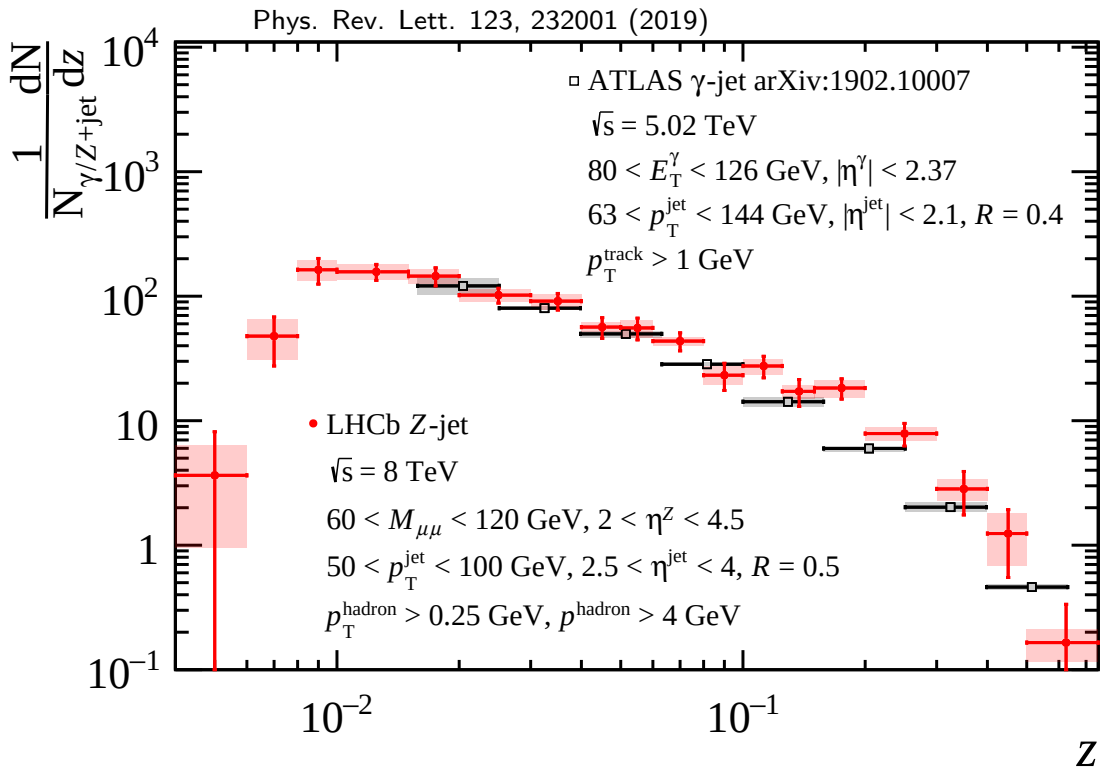
- Light quark jet structure shows little rapidity dependence

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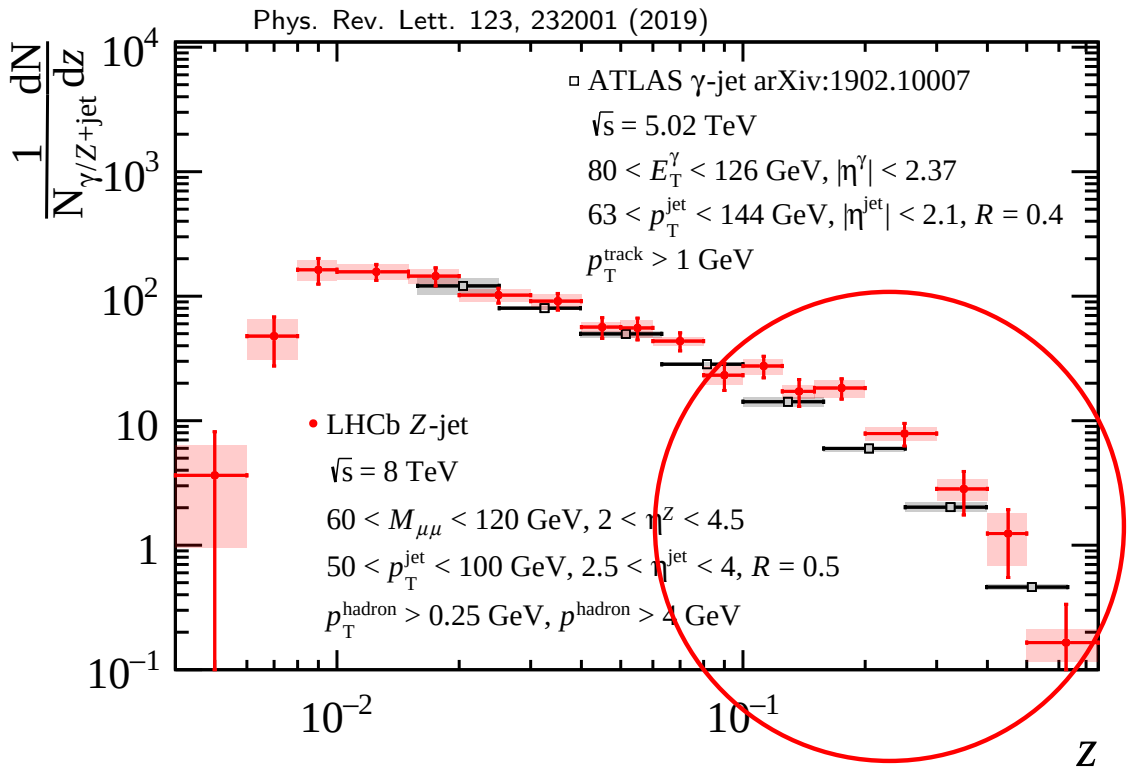
- Hint of more collimated jets in $Z$+jet
  - Massive $Z$ vs. massless $\gamma$?

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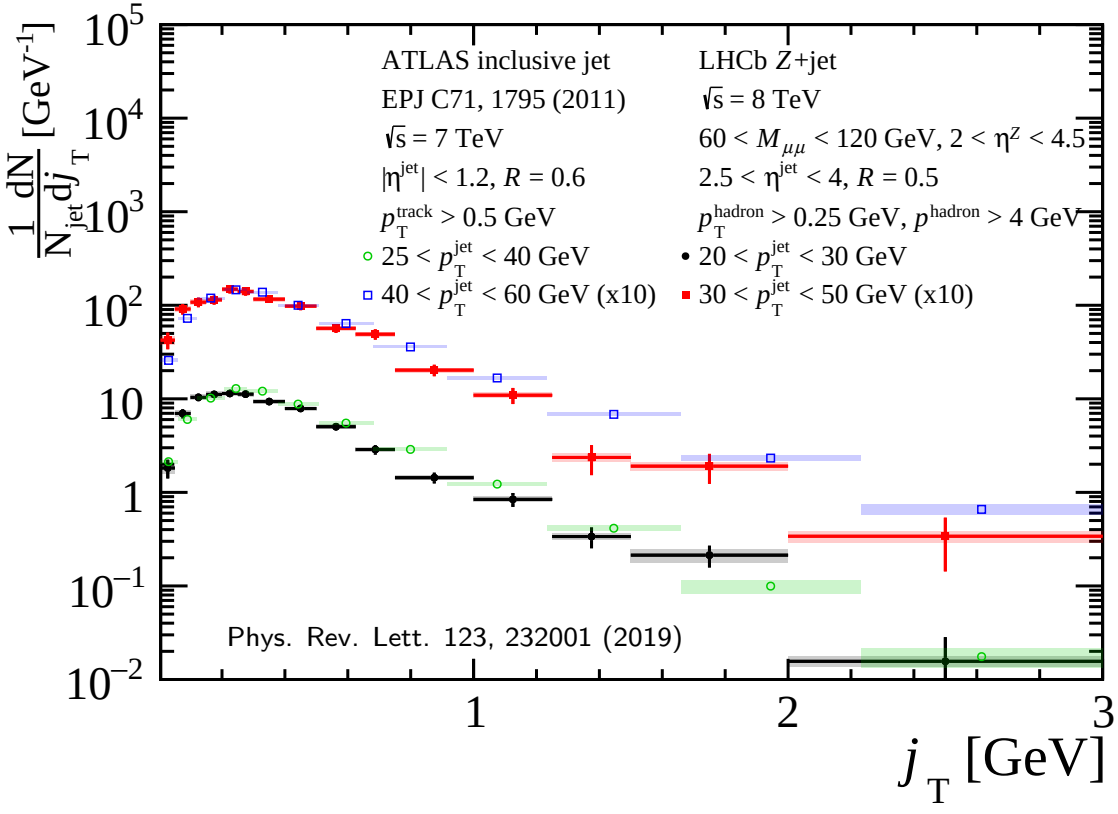
  - Consistent with more collimated light quark vs. gluon jets

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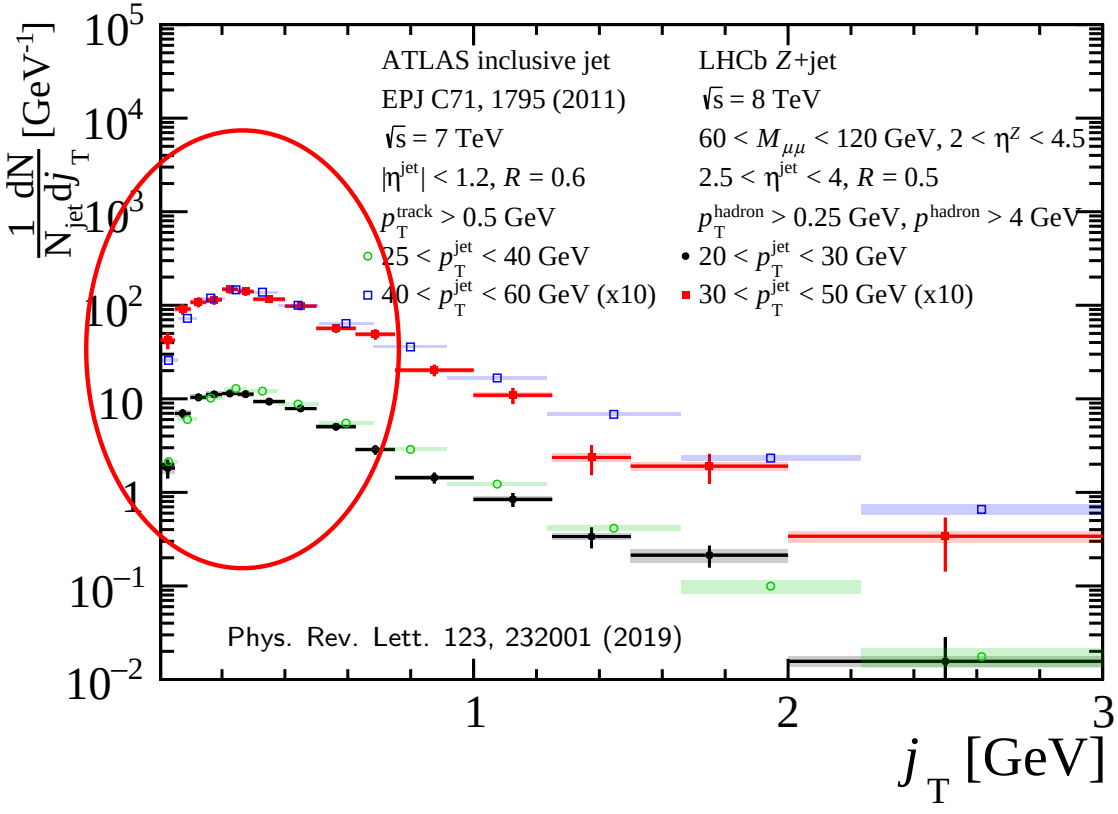


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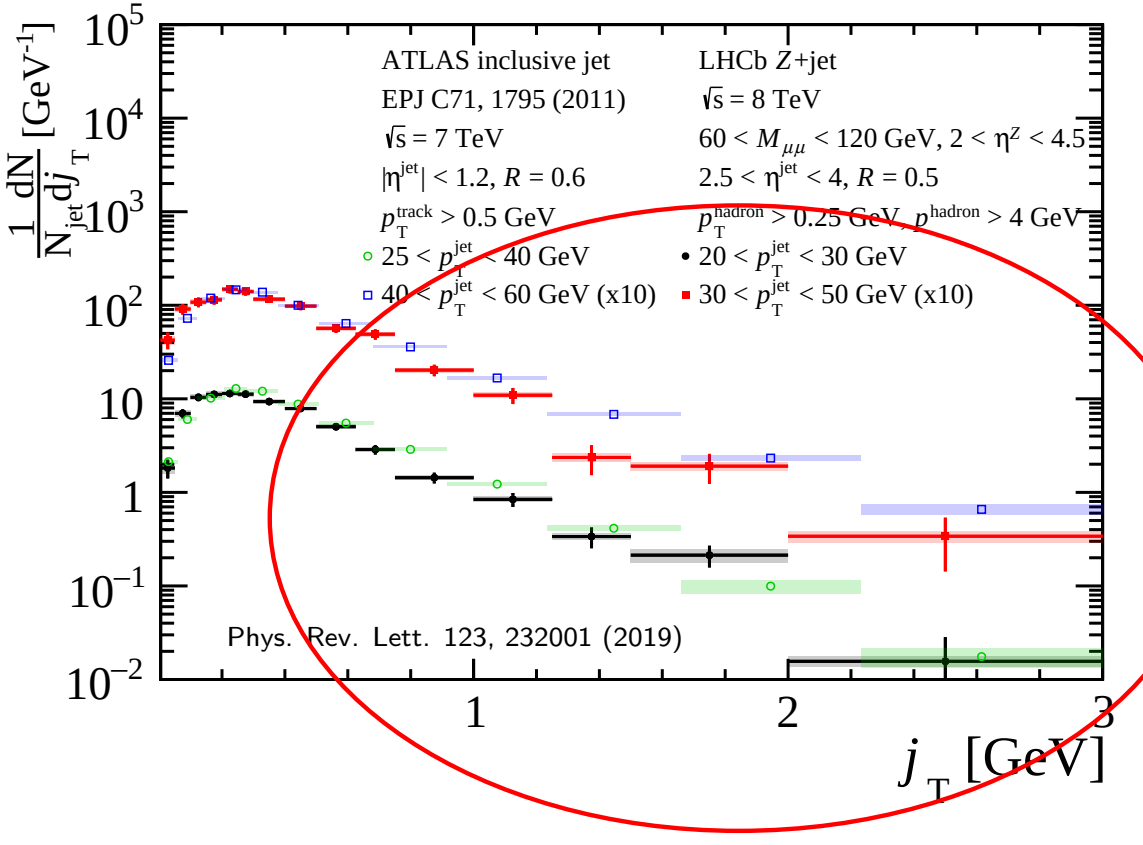
- Perturbative region quite similar between quark and gluon jets

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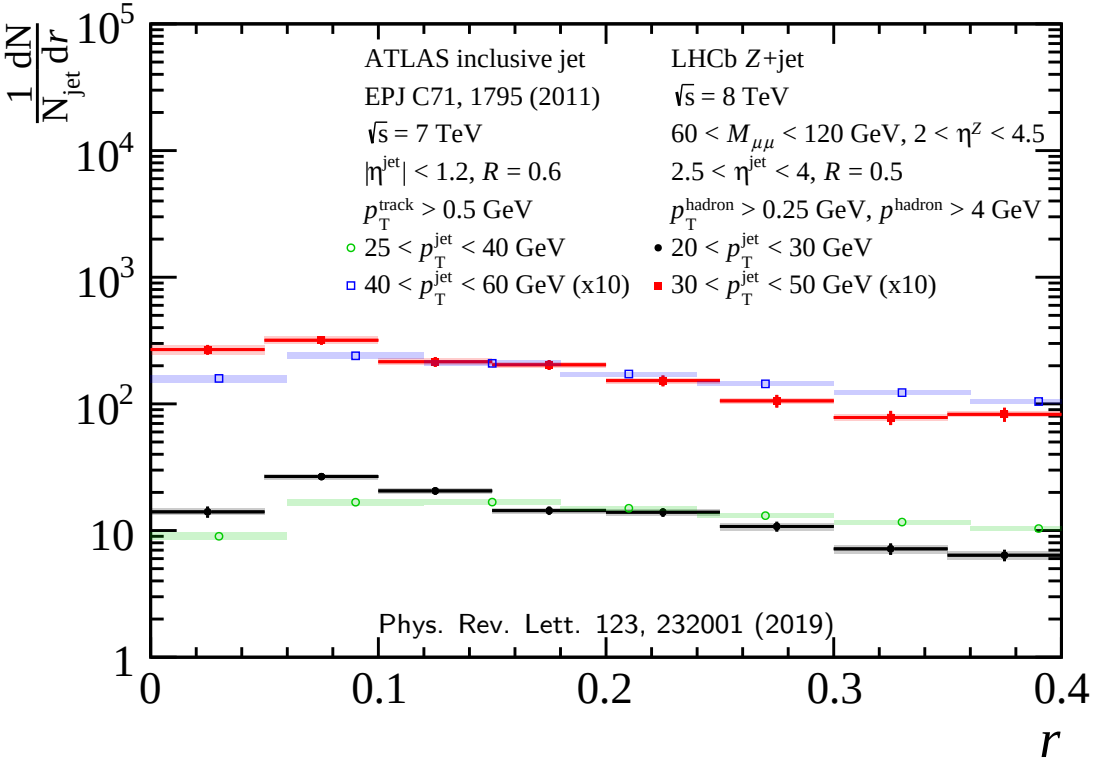
# ATLAS Inclusive and LHCb $Z$+jet

- 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"

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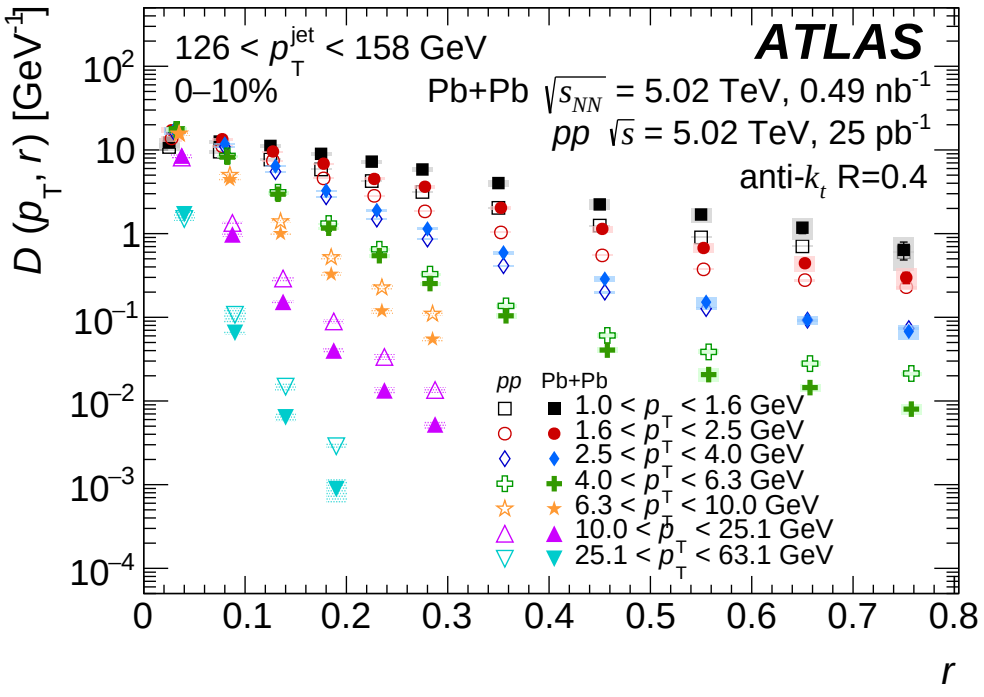


Phys. Rev. C 100, 064901 (2019)

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  - Provide more information and deeper understanding than inclusive measurements
- Correlations between $p_T$ and $r$ of hadrons within jets

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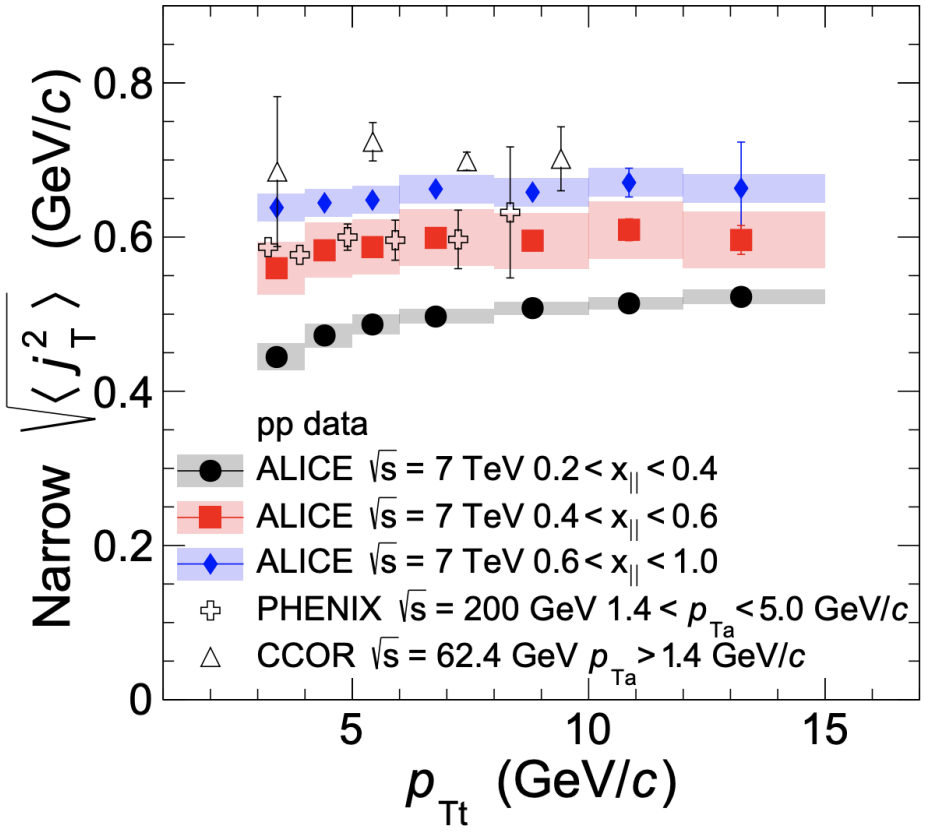


JHEP 1903, 169 (2019)

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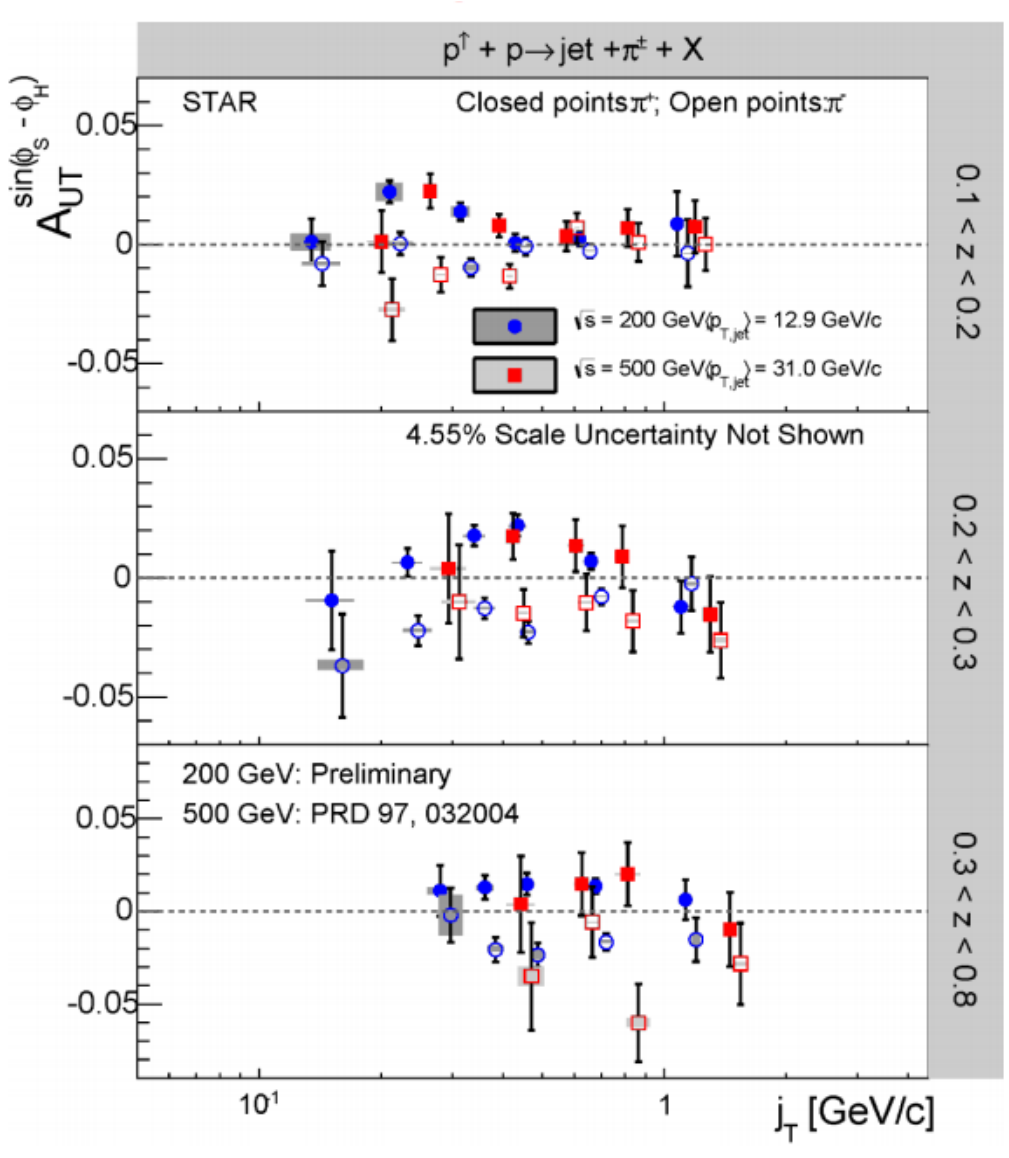


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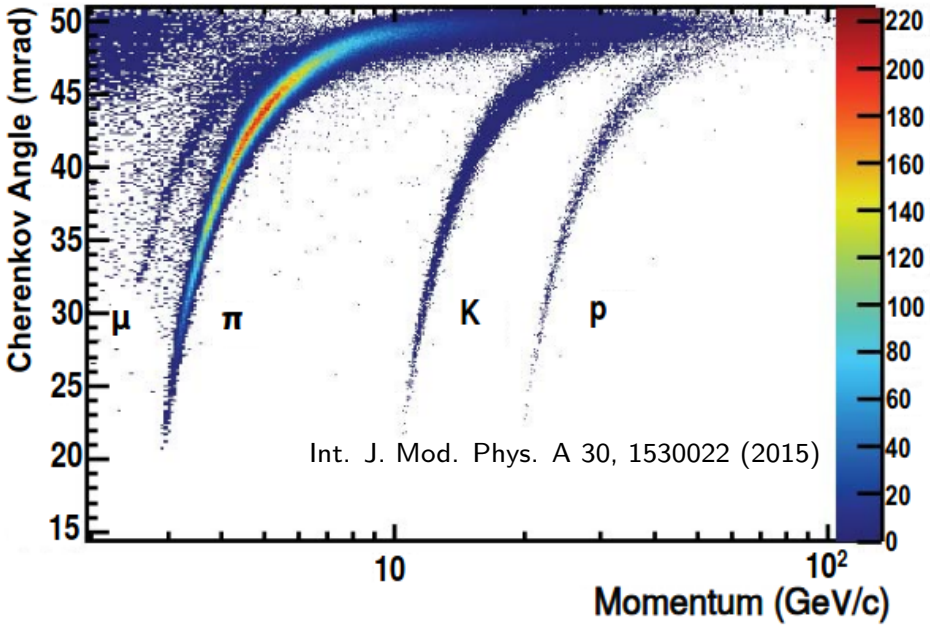
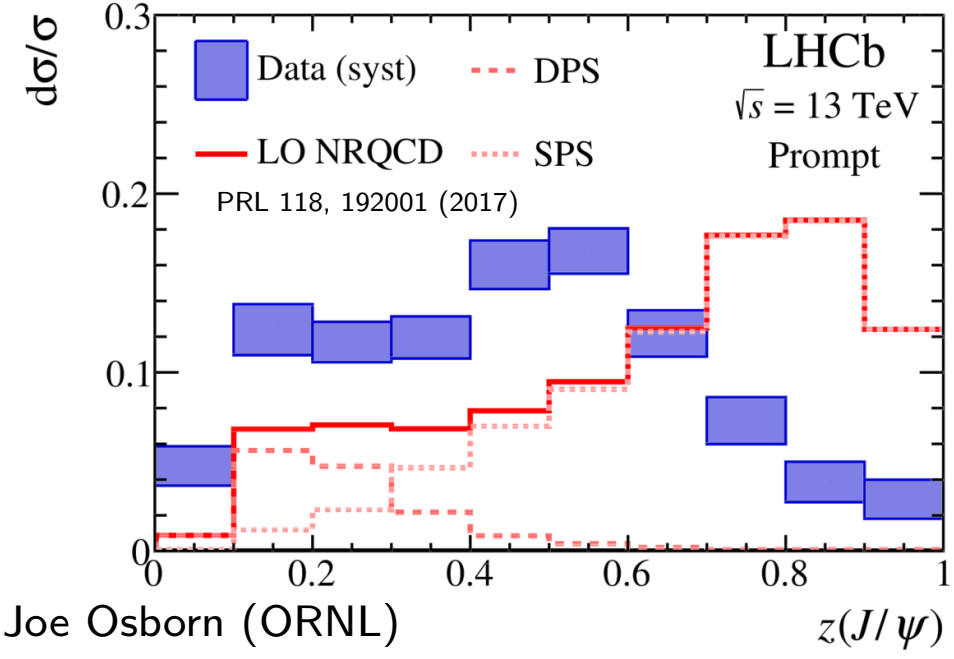
- Correlations between $p_T$ and $r$ of hadrons within jets
- Correlations between $x_E$ (proxy for $z$) and $j_T$
- Correlations between $z$, $j_T$, and angular production sensitive to 3D polarized FFs

# Future Jet Hadronization Measurements




- Where are we headed, and what don't we have?
  - Particle ID (tracking, RICH, calorimetry)
  - Heavy flavor jet tagging
  - Resonance production within jets ($\phi$, $J/\psi$, $\Upsilon$)
  - Correlations with flavor ID

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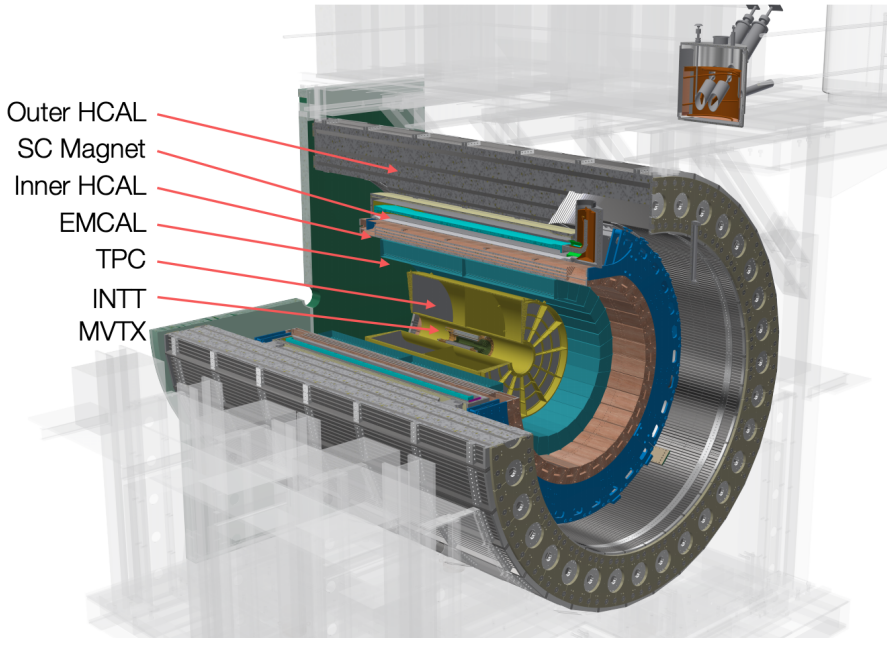
- CD3 recently approved, construction is moving forward for installation in 2022



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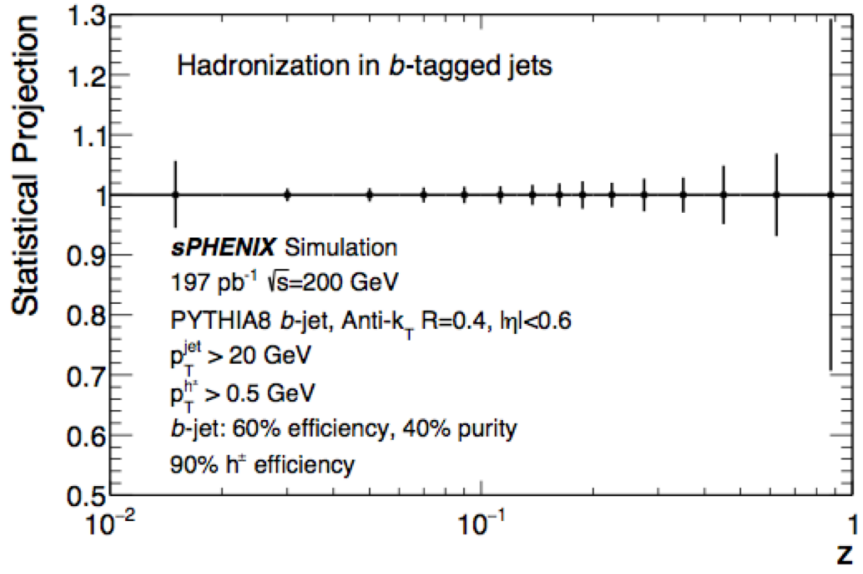
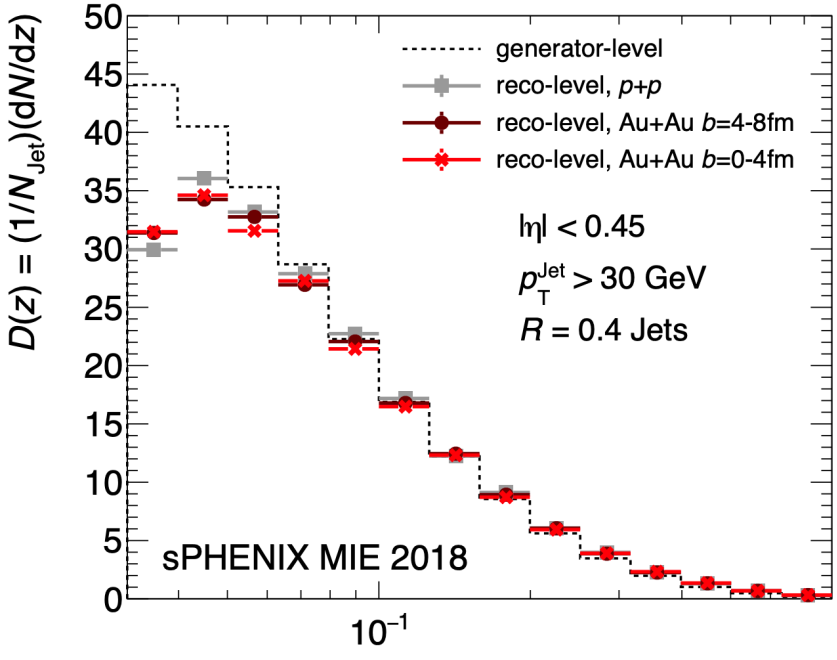
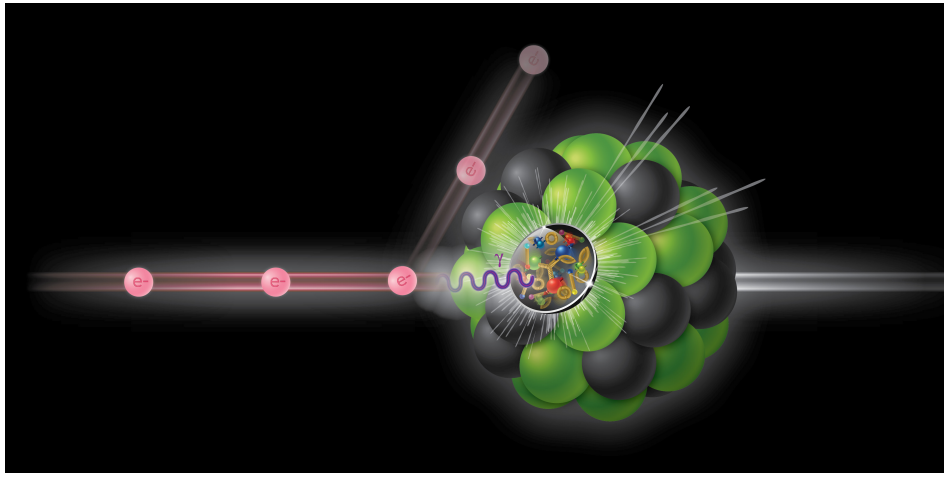
- CD3 recently approved, construction is moving forward for installation in 2022
- Jet substructure and hadronization a major component of science case



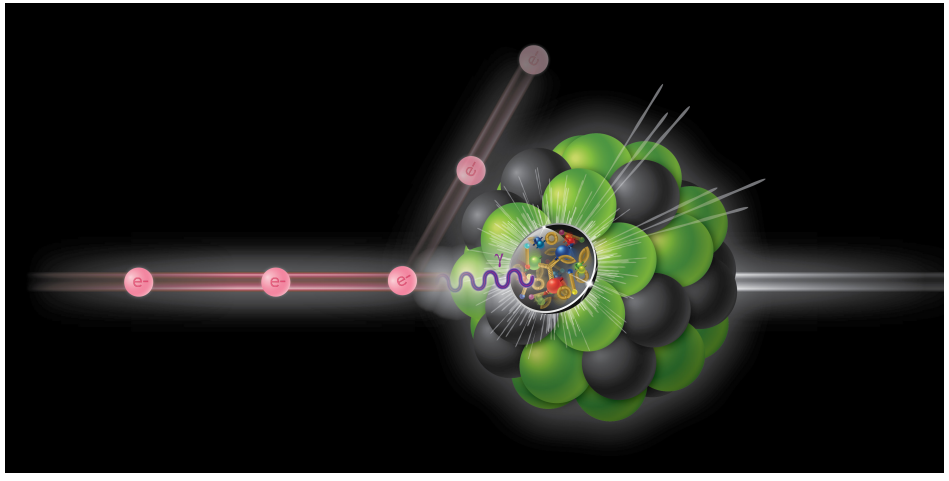
# Hadronization at an Electron Ion Collider

- Electron Ion Collider (EIC) will be a QCD physics machine



# Hadronization at an Electron Ion Collider

- Electron Ion Collider (EIC) will be a QCD physics machine
- Hadronization is a major pillar of EIC physics case
- Developing ideas in the next decade before EIC will be crucial to maximize science output of this unique QCD machine!



# Conclusions

- Jet substructure and hadronization has exploded onto the high energy and nuclear physics scene, with wide ranging physics interests

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  - Heavy quark jet substructure

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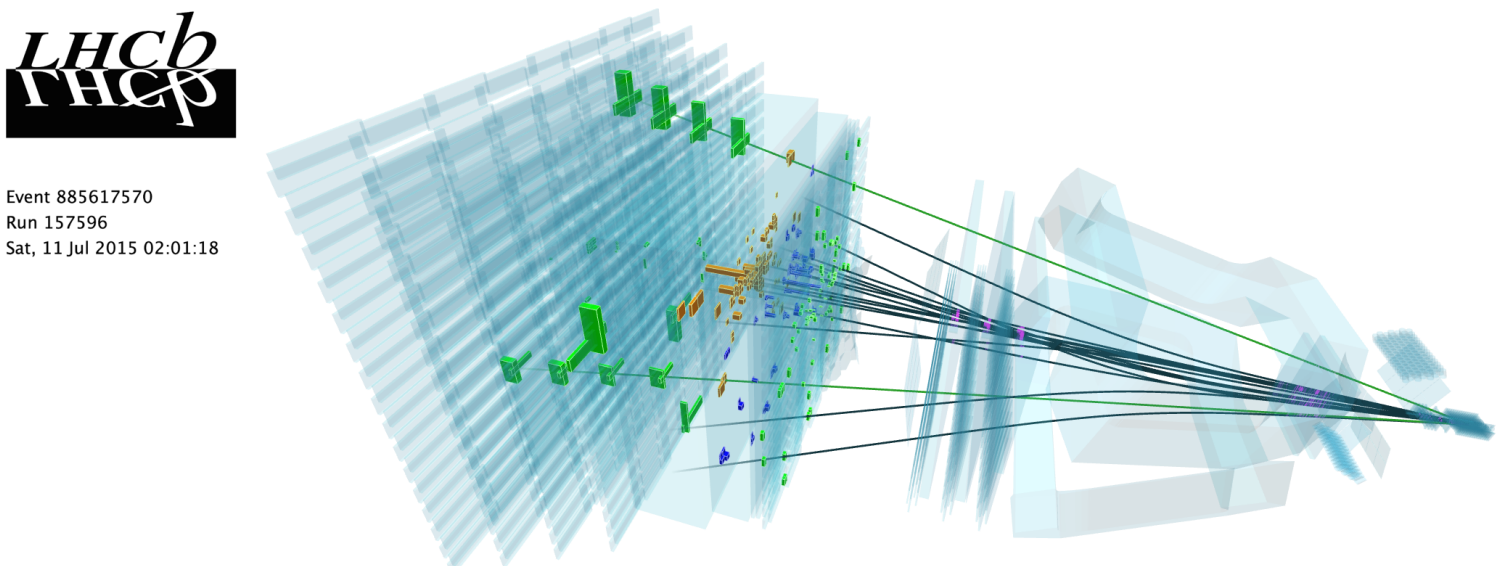
- Entering phase of synthesizing information and asking more fundamental questions
  - Kinematic correlations between hadrons in jets
  - Light quark vs. gluon jet hadronization
  - Heavy quark jet substructure
- Many opportunities moving forward, beginning to utilize PID, multidifferential measurements, etc.
- Ideas behind hadronization are relatively undeveloped, but there will be significant growth with current and future experiments!

# Back Up

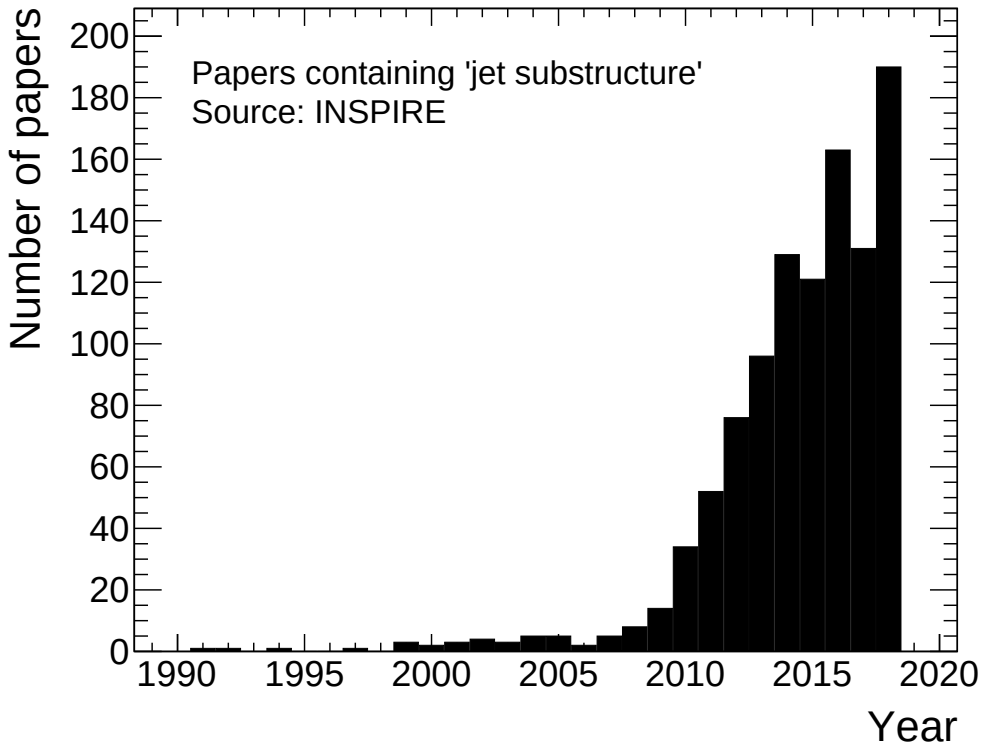
# Analysis Details

- Follow similar analysis strategy to ATLAS (EPJC 71, 1795 (2011), NPA 978, 65 (2018)) and LHCb (PRL 118, 192001 (2017))
- $Z \to \mu^+\mu^-$ 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 $2 \to 2$ topology
- Charged hadrons identified with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta R < 0.5$
- Results efficiency corrected and 2D Bayesian unfolded



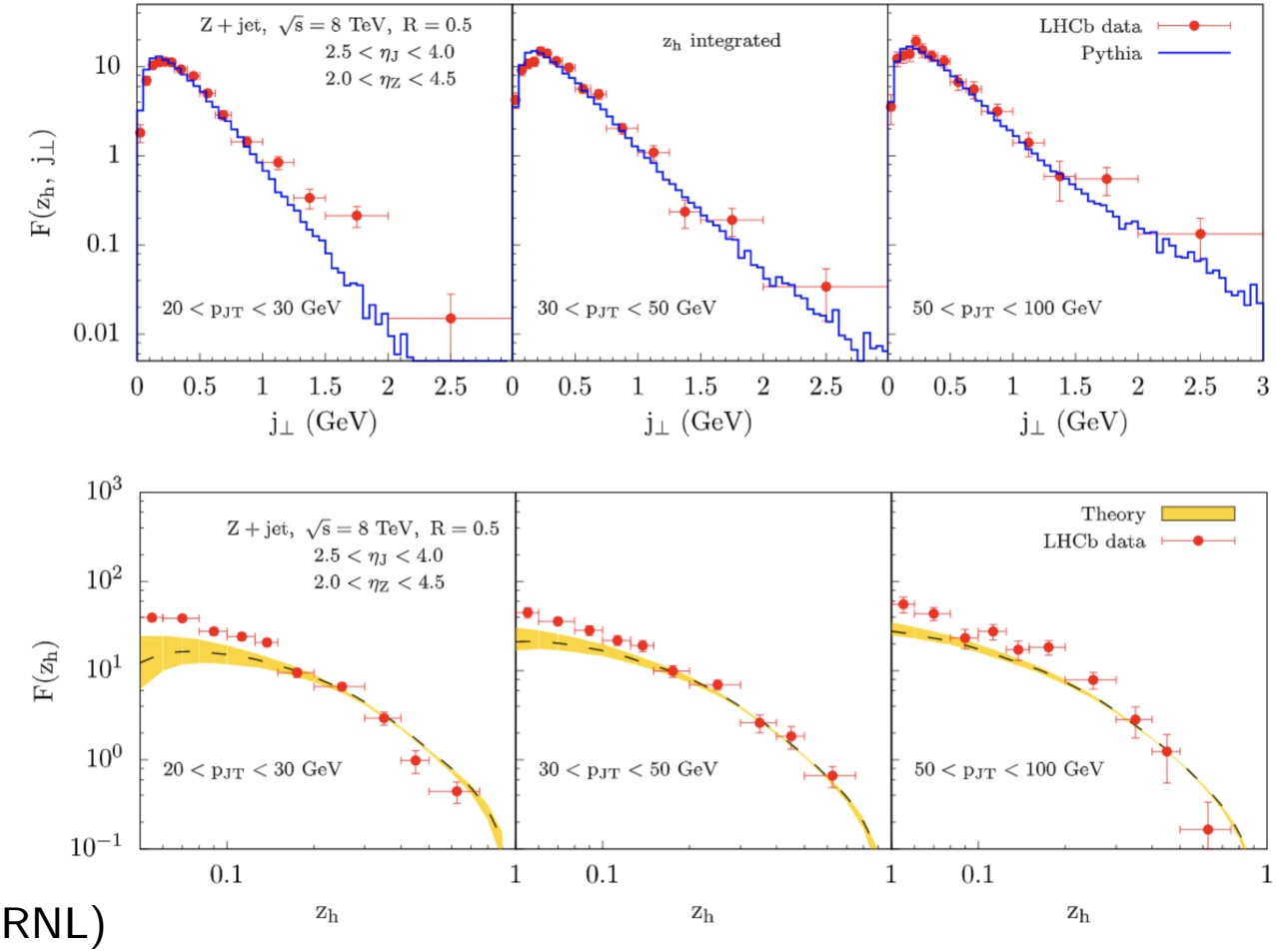
# Jet Substructure

- 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
  - ...



# Theory Comparisons

- Theory colleagues have already published comparisons to data
- Reasonable description of data
- However, LHCb data has started a discussion on best (theoretically) tractable ways to study hadronization

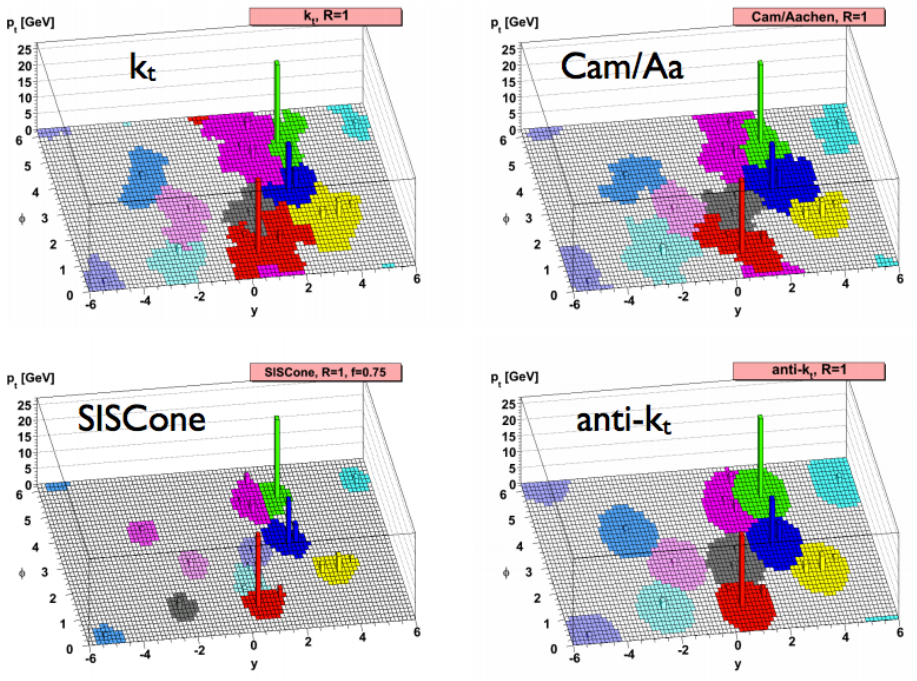


# Anti-$k_T$ Algorithm

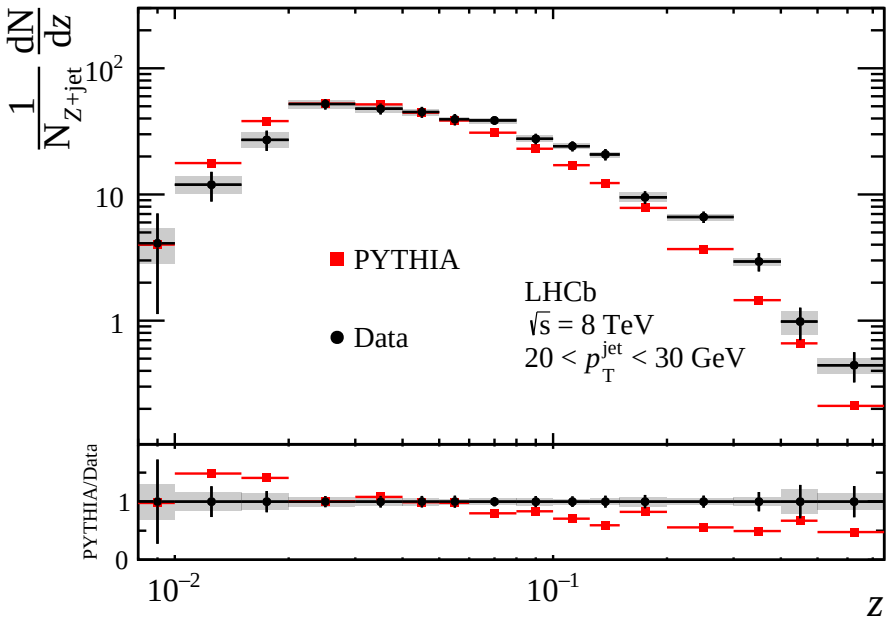
- Sequential recombination algorithm which clusters particles into jets based on their $p_T$
- Widely used as it is both infrared and collinear safe in calculations
- Clusters particles around highest $p_T$ particle in a conical shape

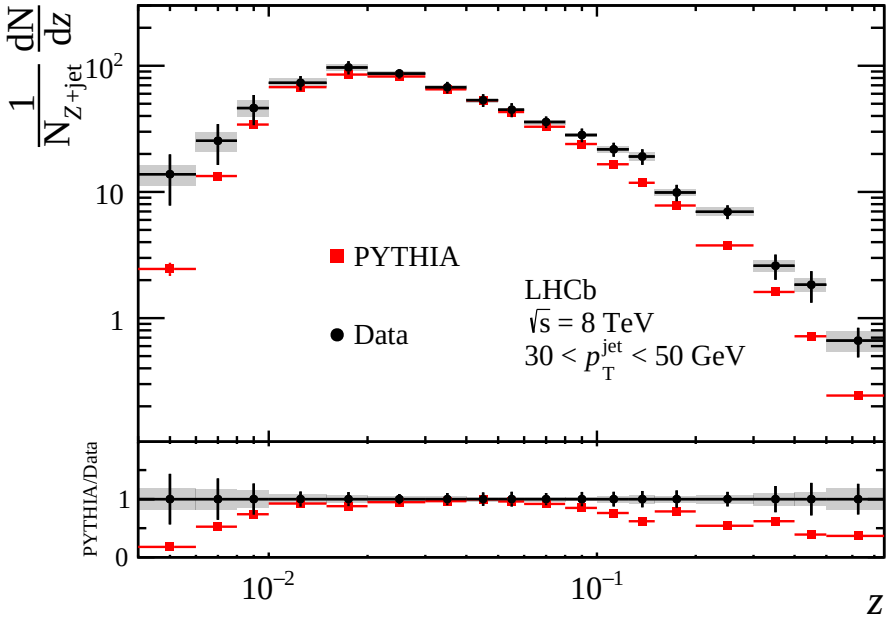
$$d_{ij} = min(p_{T_i}^{-2}, p_{T_j}^{-2}) \frac{\Delta_{ij}^2}{R^2}$$

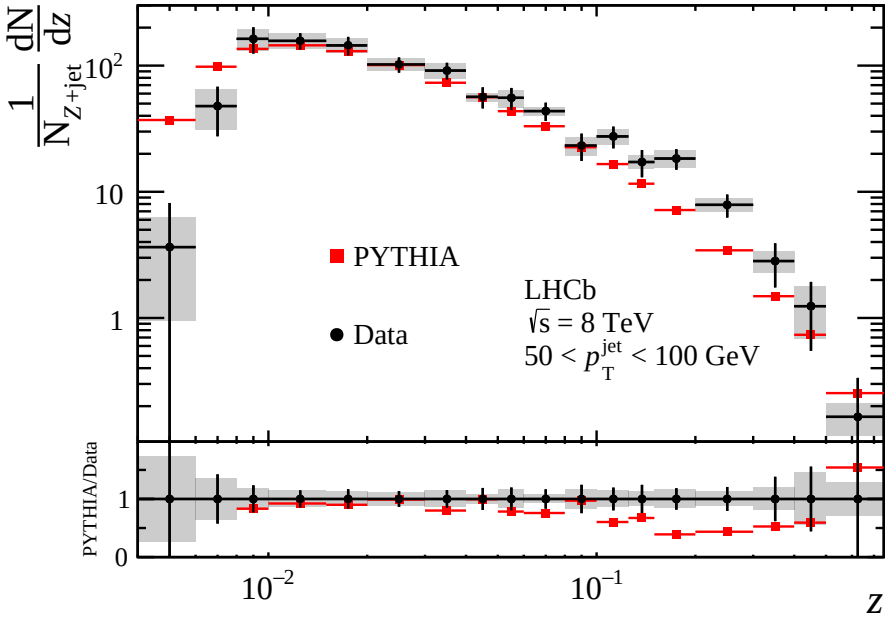
$$d_{iB} = p_{T_i}^{-2}$$



# Comparisons with PYTHIA ($z$)

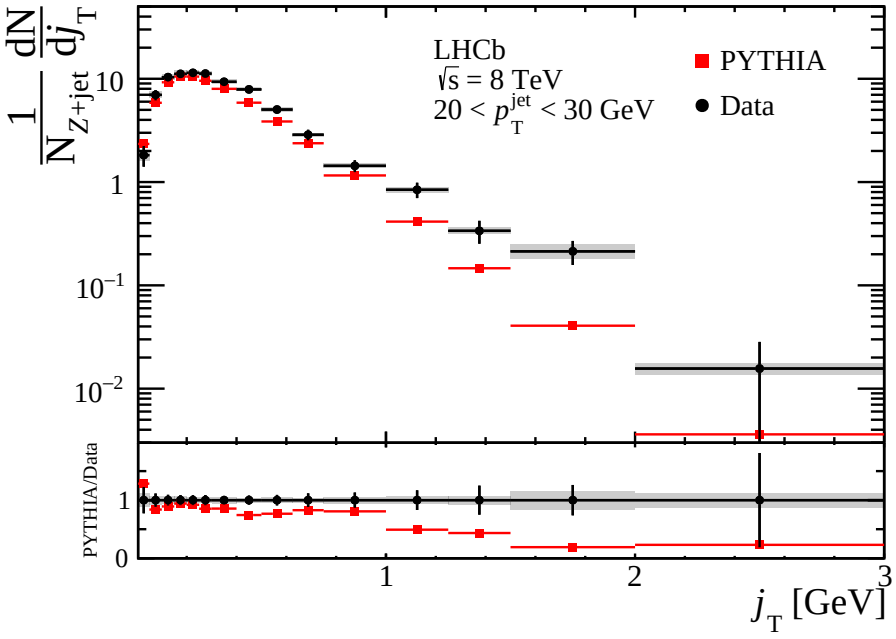


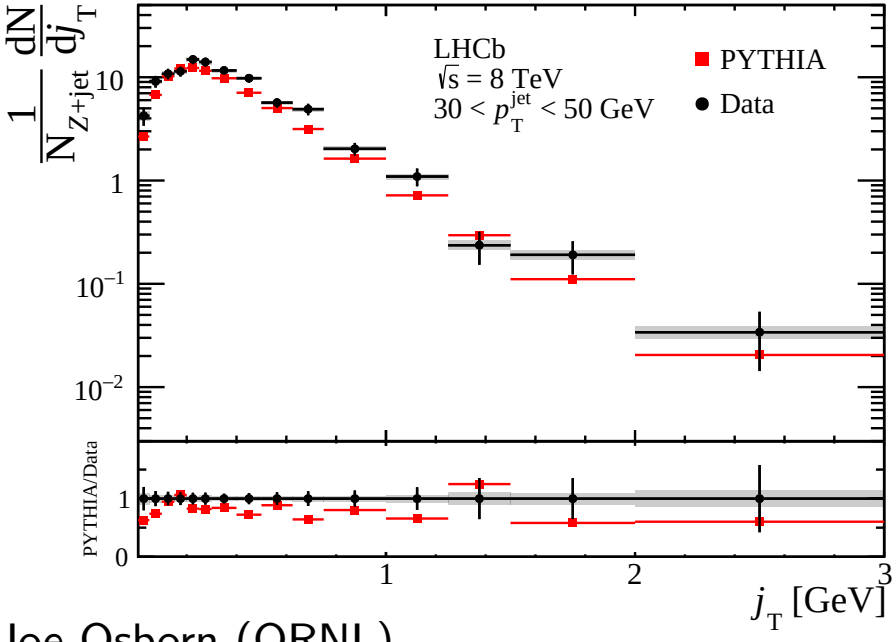



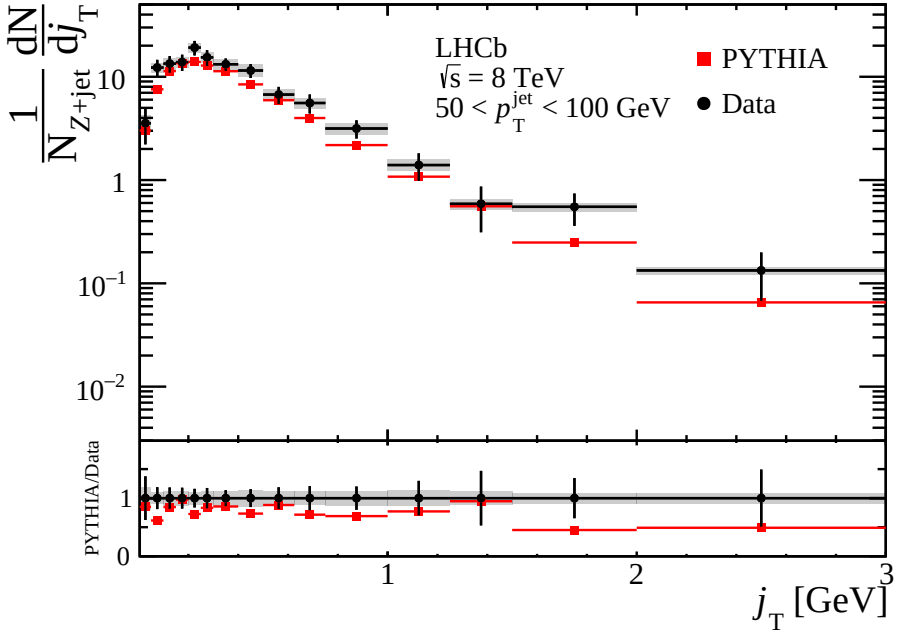




- PYTHIA generally underpredicts the number of high $z$ hadrons

# Comparisons with PYTHIA ($j_T$)

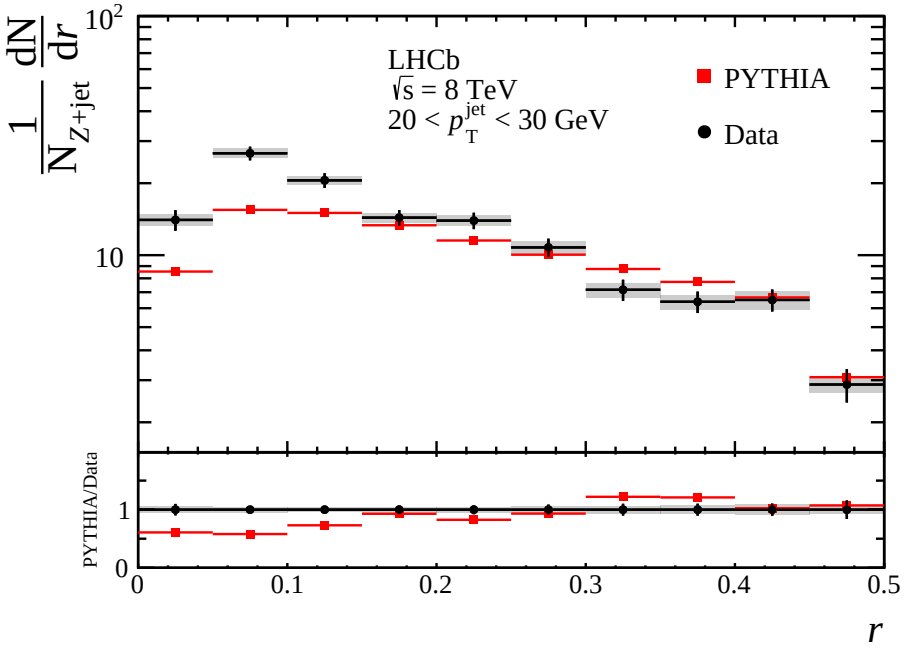


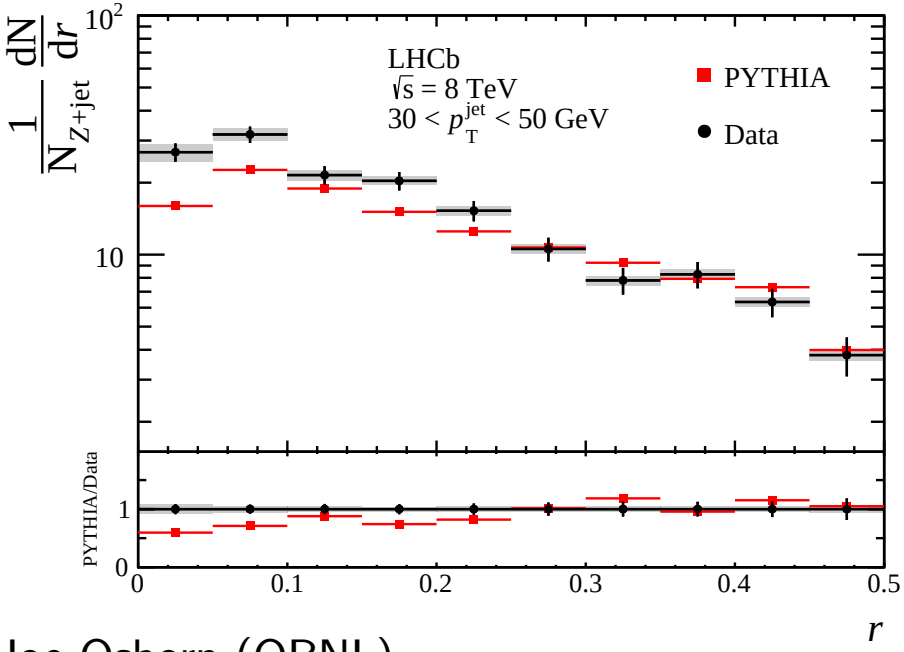



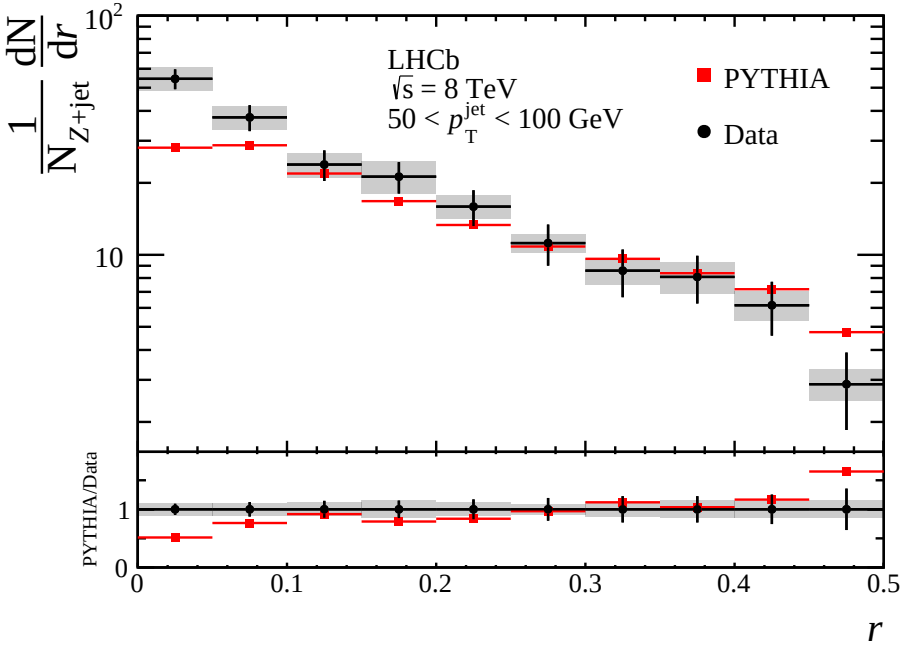




- PYTHIA generally gets $j_T$ shape, with about a 20% difference in normalization

# Comparisons with PYTHIA ($r$)

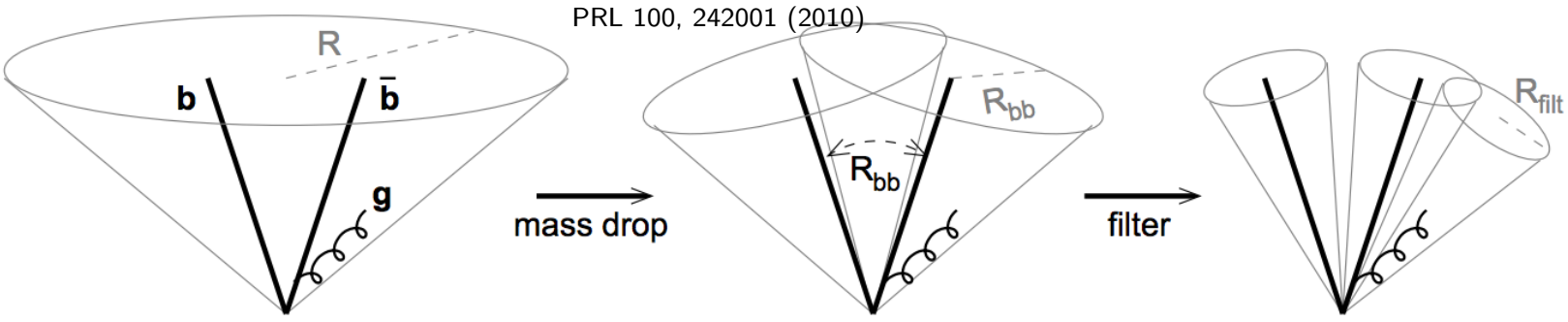



- PYTHIA generally underpredicts the number of small $r$ hadrons

# Symbolic Beginning




- Substructure revolution symbolically initiated by 2010 Butterworth *et al* PRL
- Motivated by searching for highly boosted $VH \to \ell^{\pm} b\bar{b}$ production

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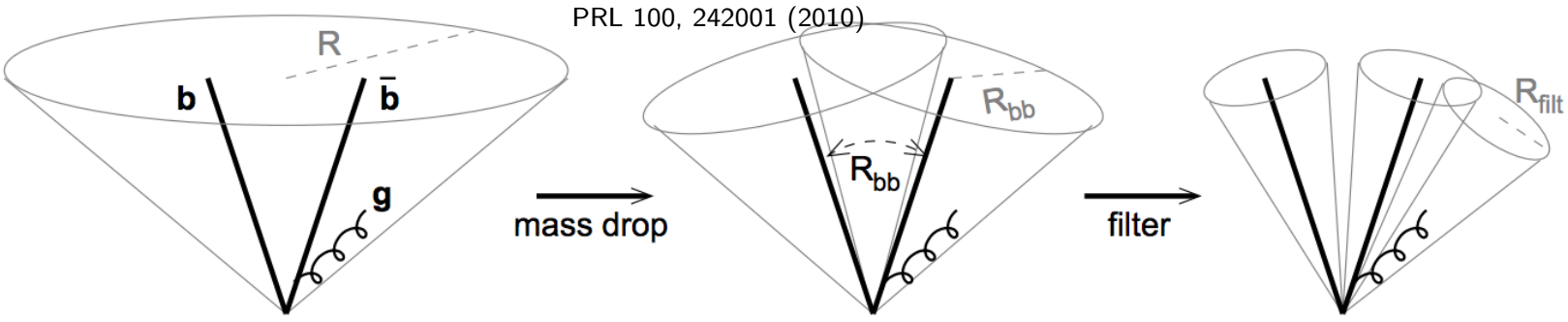
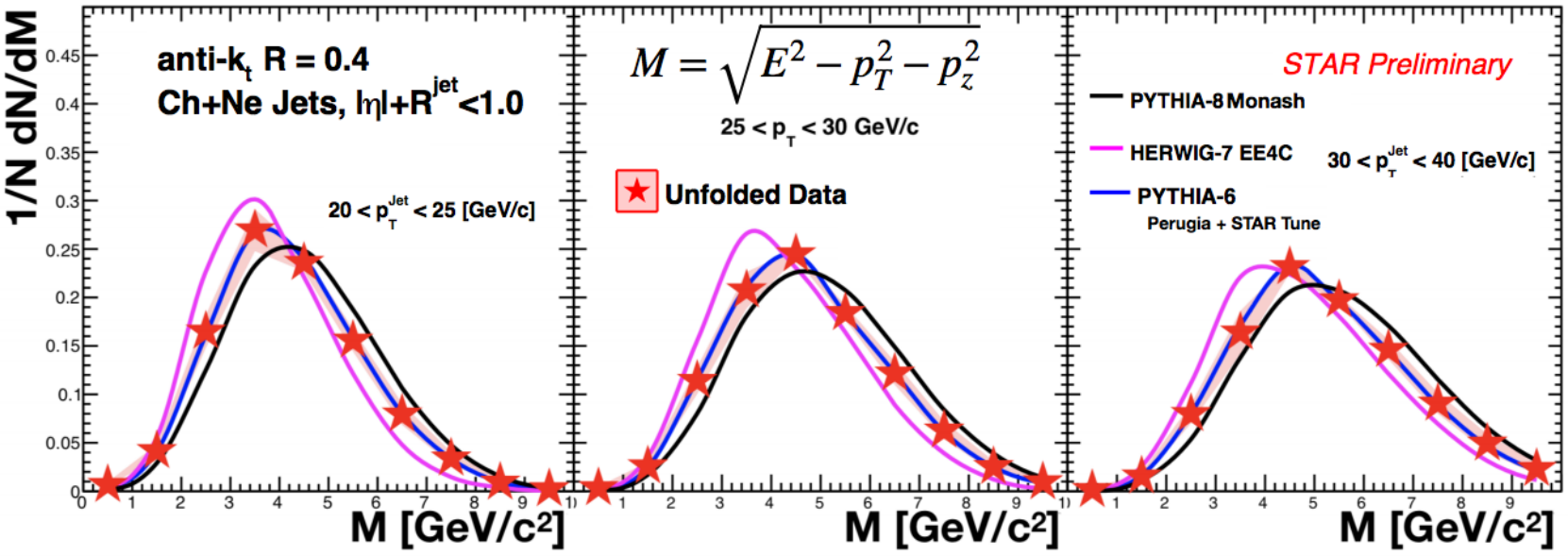


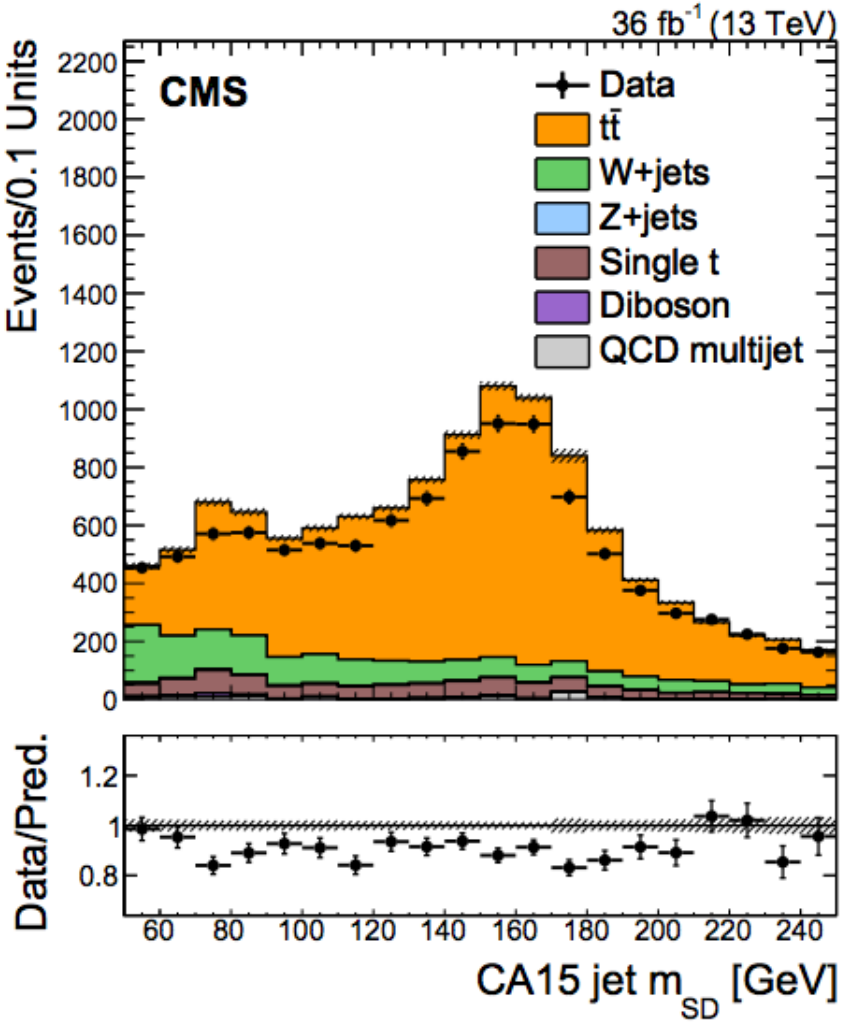

- Substructure revolution symbolically initiated by 2010 Butterworth *et al* PRL
- Motivated by searching for highly boosted $VH \to \ell^{\pm} b\bar{b}$ production
- Jet substructure was motivated by new particle searches
- However, many fields of physics at collider facilities quickly realized the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

# 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

# Jet Substructure at the LHC

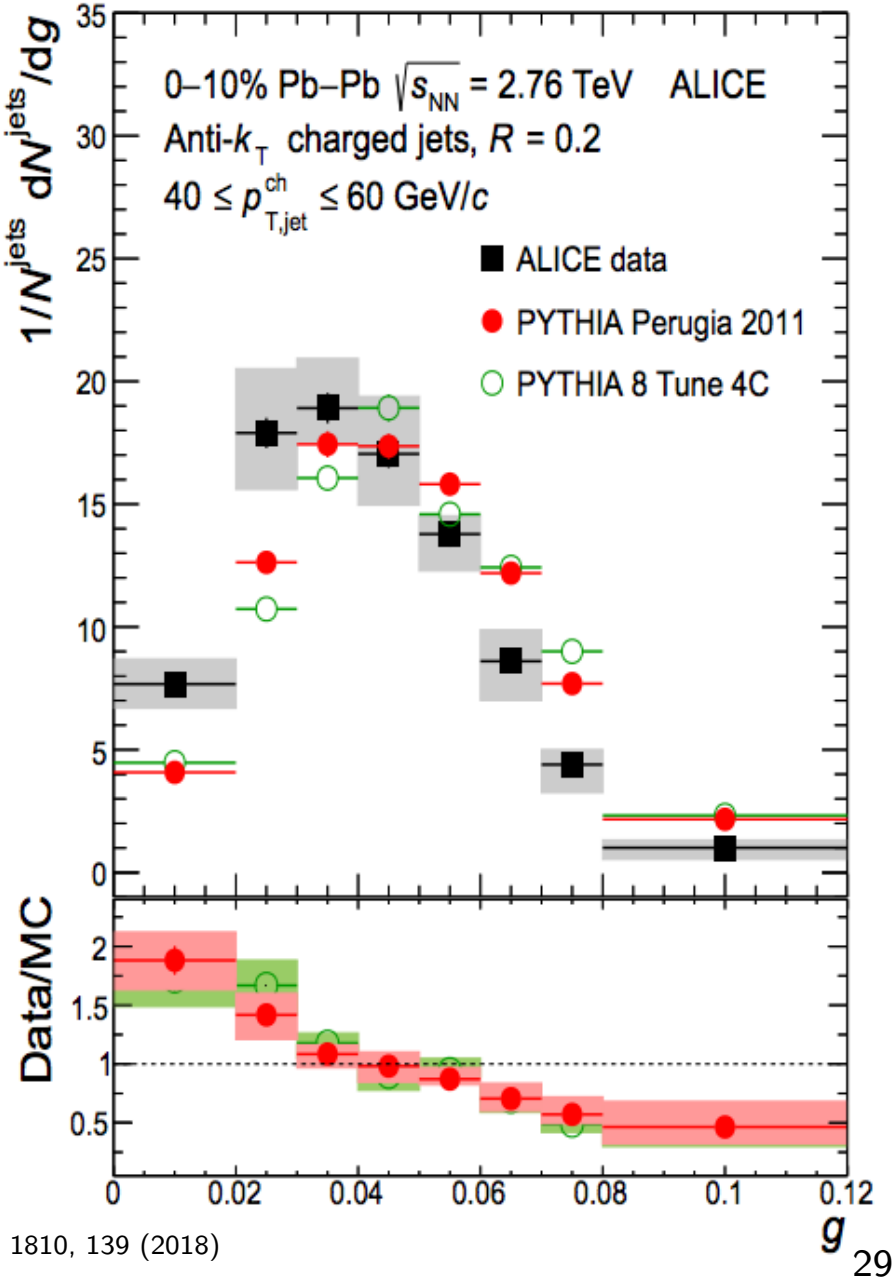



JHEP 1806, 027 (2018)

- 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

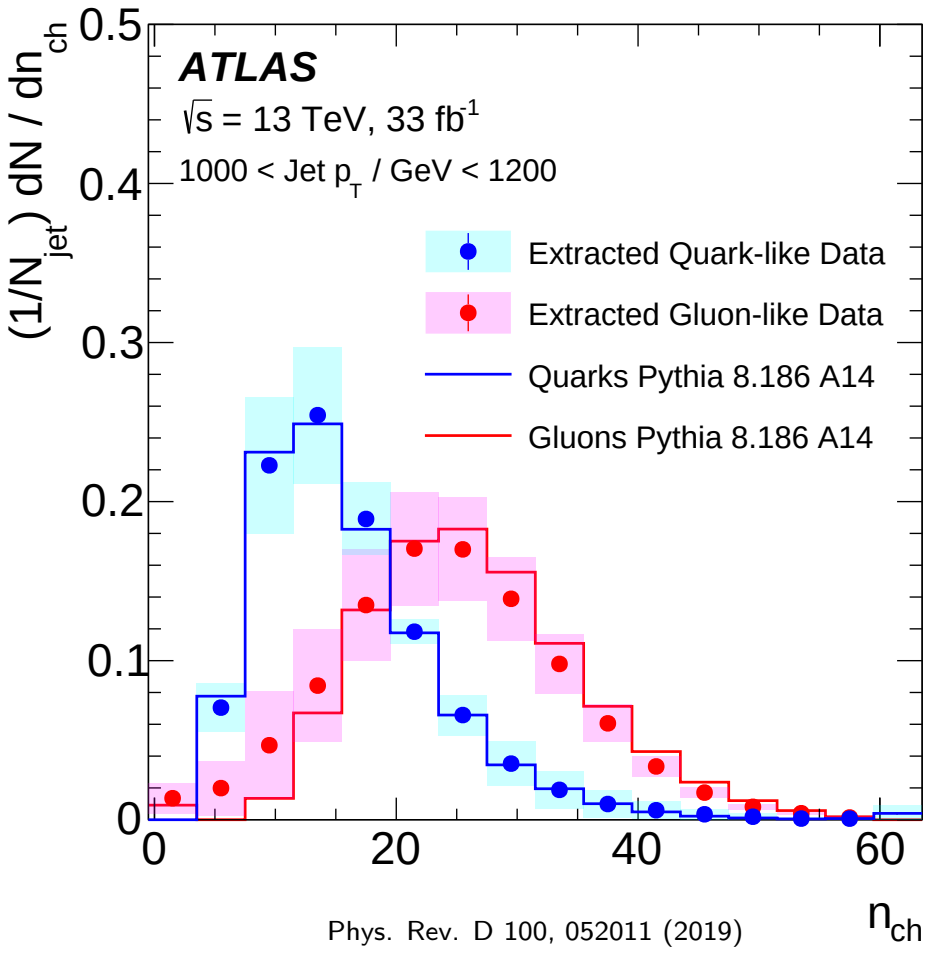
# Jet Substructure at the LHC

- 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)

# Central vs. Forward Jets

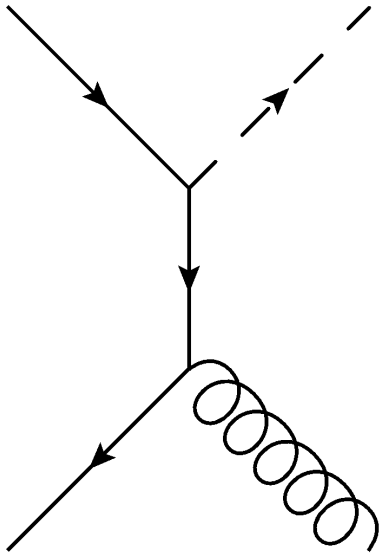


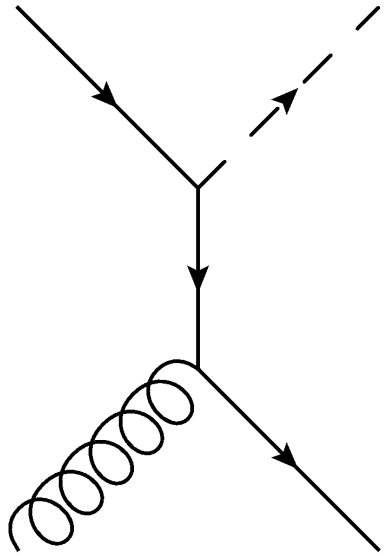

Phys. Rev. D 100, 052011 (2019)

- Leverage different rapidity regions to extract quark-like and gluon-like data
- Investigate radiation pattern differences between light quarks and gluons

# $Z$+jet

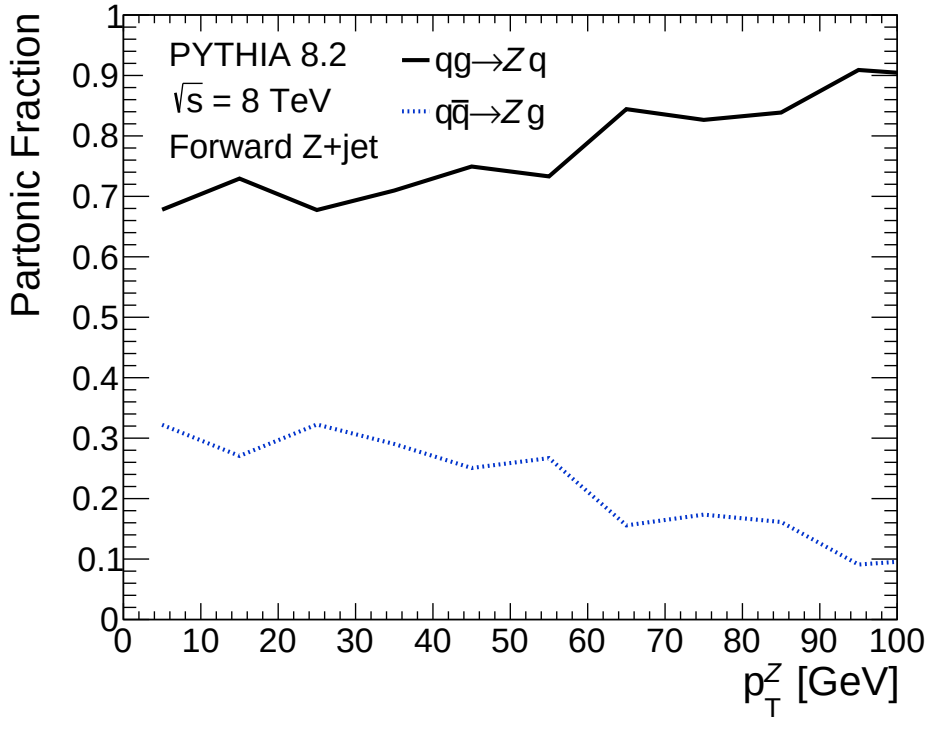
- Why $Z$+jet?





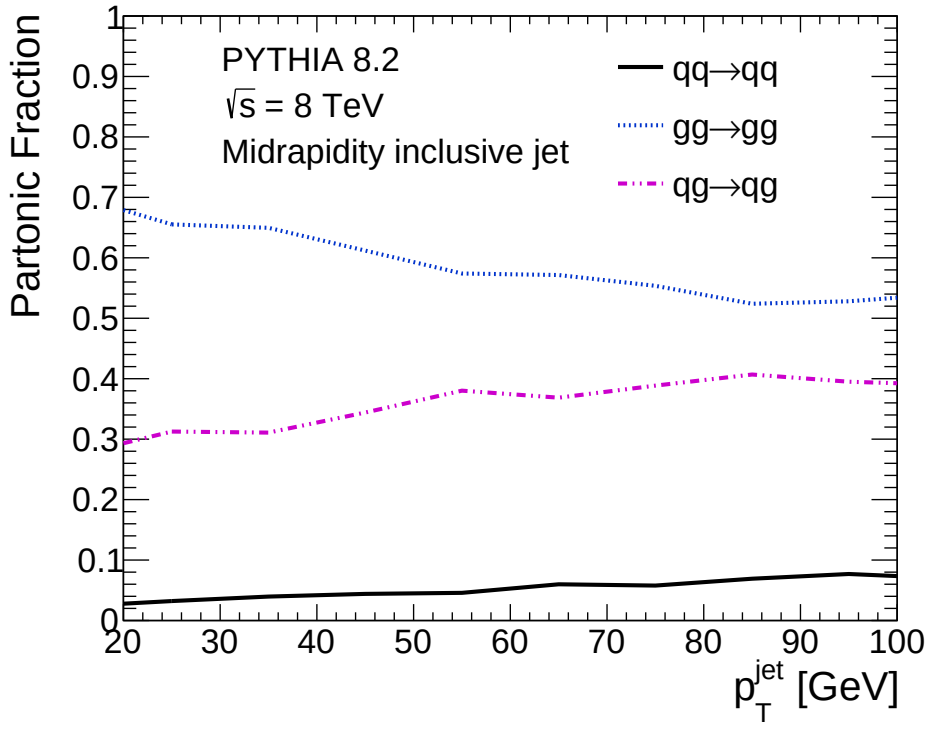
# $Z$+jet

- Why $Z$+jet?
- $Z$+jet is predominantly sensitive to light quark jets



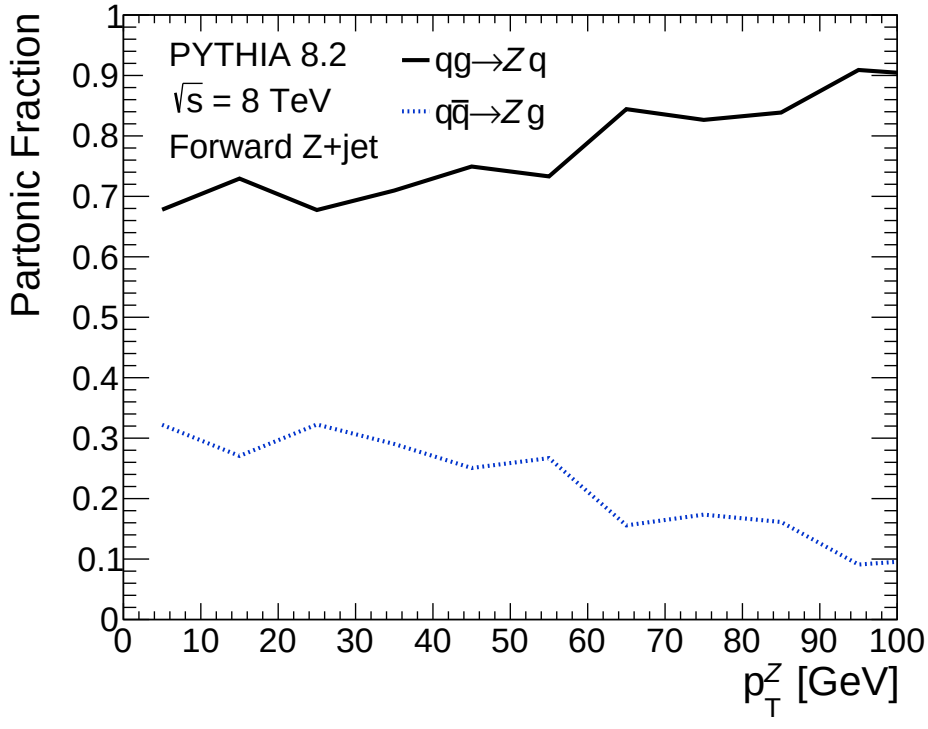
# $Z$+jet

- Why $Z$+jet?
- $Z$+jet is predominantly sensitive to light quark jets
- Nearly all other hadronization studies at LHC measure inclusive jets, which are sensitive to predominantly gluon jets

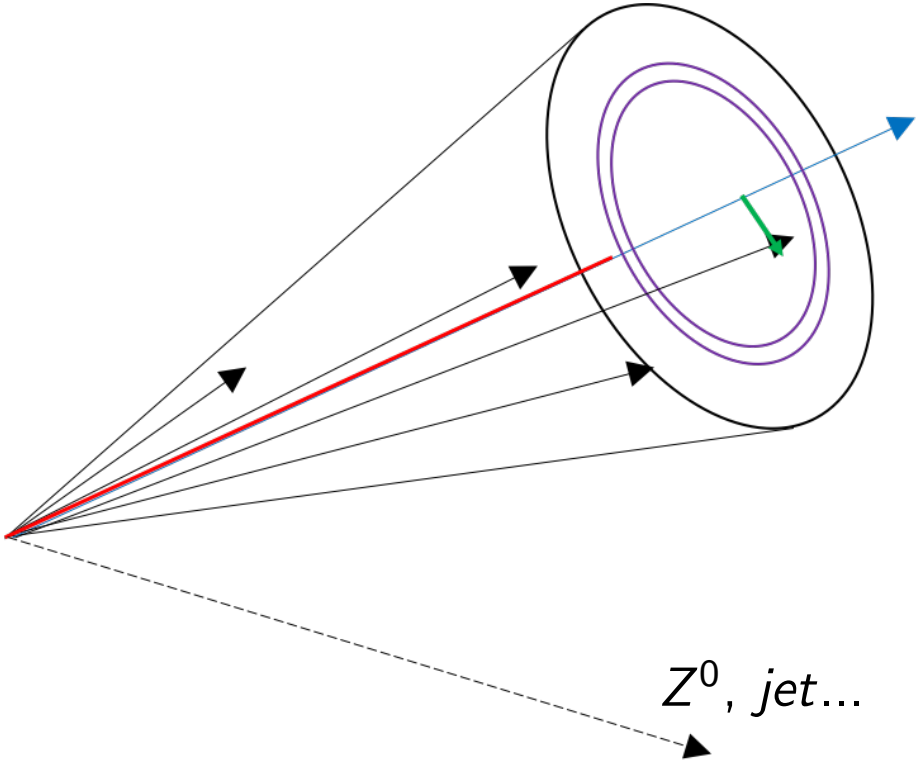


# $Z$+jet

- Why $Z$+jet?
- $Z$+jet is predominantly sensitive to light quark jets
- 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



# 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
- $x_E$ defined as $\frac{p_T^{trig} \cdot p_T^{assoc}}{|p_T^{trig}|^2}$