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

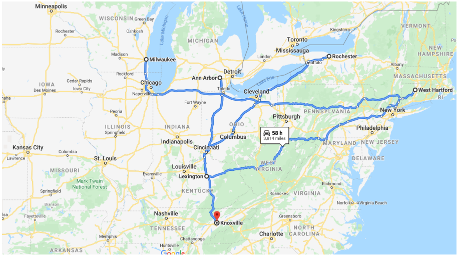
Joe Osborn

Oak Ridge National Laboratory, University of Michigan

February 3, 2020

About Me

- Born in Milwaukee, WI
- Moved several times as a child
- Lived in WI, Sweden, CT, NY, KY



About Me

- Born in Milwaukee, WI
- Moved several times as a child
- Lived in WI, Sweden, CT, NY, KY
- Received B.S. in Physics and B.S. in mathematics from University of Kentucky (2013)
- Received M.S. and Ph.D in physics from University of Michigan (2018)
- Worked 1 year as a postdoc at UM
- Now a postdoc at ORNL

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    - Hydrodynamic supernovae simulations

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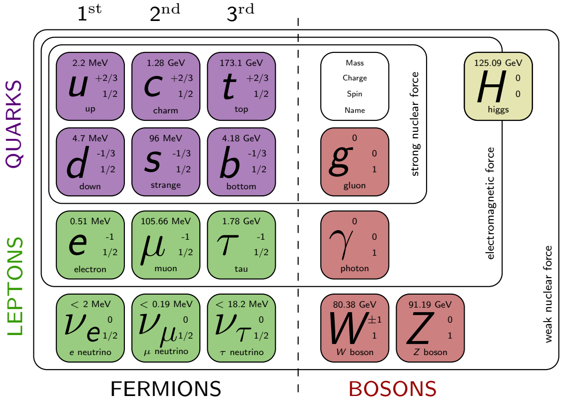
- Postdoctoral
    - LHCb at CERN (today!)
    - Various software initiatives

The Standard Model

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



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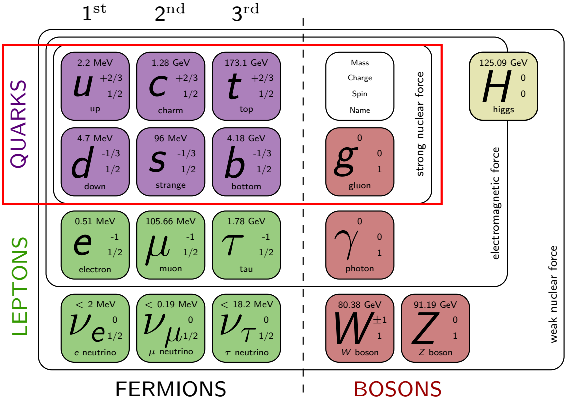
- Two main "sectors"
  - Strong force
  - Electroweak force



The Standard Model

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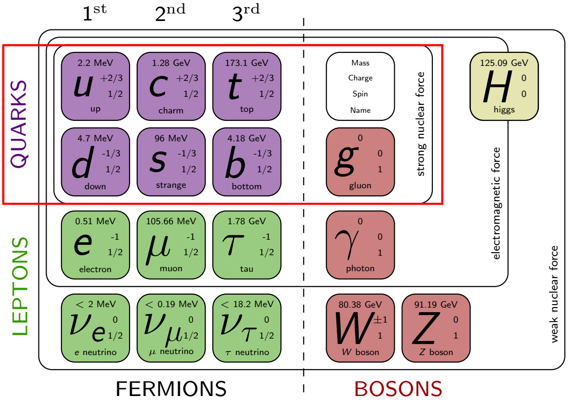
- Two main "sectors"
  - Strong force
  - Electroweak force
- Strong force particularly not well understood due to confinement - quarks and gluons cannot be observed freely!



Quantum Chromodynamics

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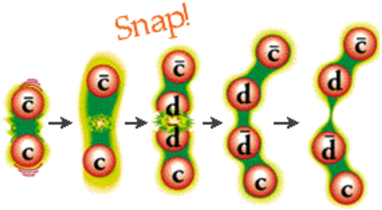
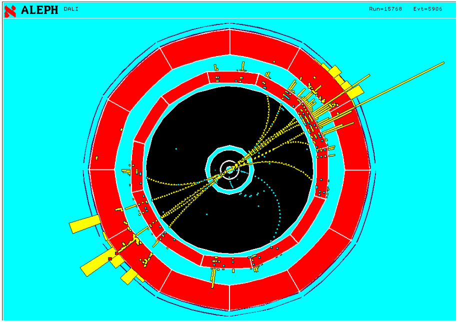
- Theoretical description in hand since the 1970's
- However, connecting the field theory degrees of freedom (quarks and gluons) to the observables (hadrons) remains a challenge!
  - Perturbative and nonperturbative QCD



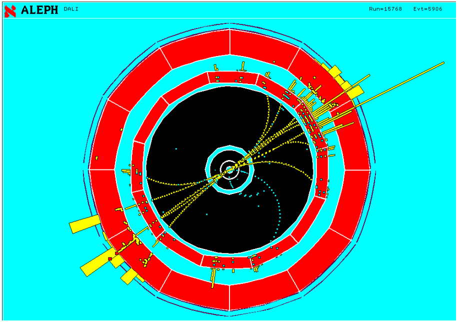
particleadventure.org

- Quarks and gluons are color confined within hadrons!



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

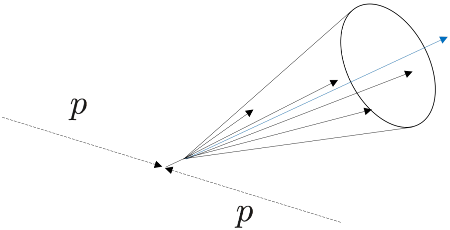
Observing Quarks and Gluons



- To "observe" quarks and gluons (partons), we must produce them via scattering processes
- 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

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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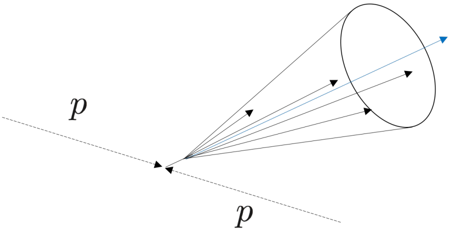
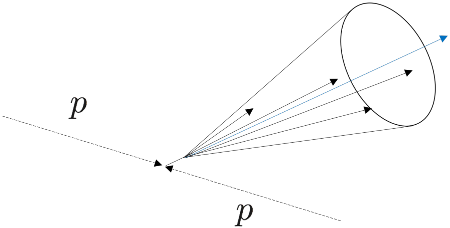
- Jets are a proxy for partons, and thus provide sensitivity to the underlying partonic dynamics

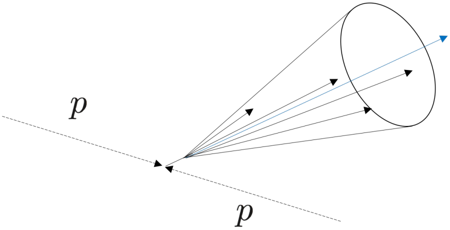


Jet Hadronization

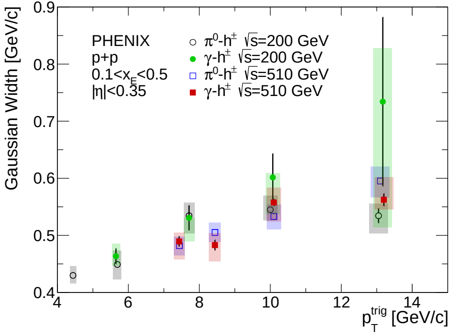
- BUT - jets are still formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jets



- BUT - jets are still formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jets
- We can use a field theory DOF (jet/parton) to learn about the observable DOF (bound-state hadron formation)

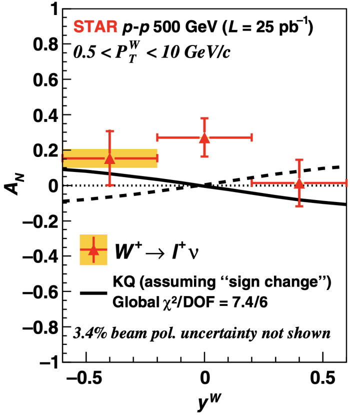


Examples: Perturbing the nonperturbative



Phys. Rev. C 99, 044912 (2019)
Phys. Rev. D 98, 072004 (2018)
Phys. Rev. D 95, 072002 (2017)

- Using large energy-scale measurements to look for effects from QCD color



Phys. Rev. Lett. 116, 32301 (2016)

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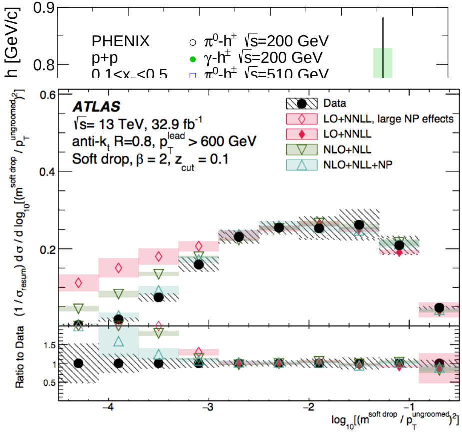

Phys. Rev. Lett. 121, 092001 (2018)

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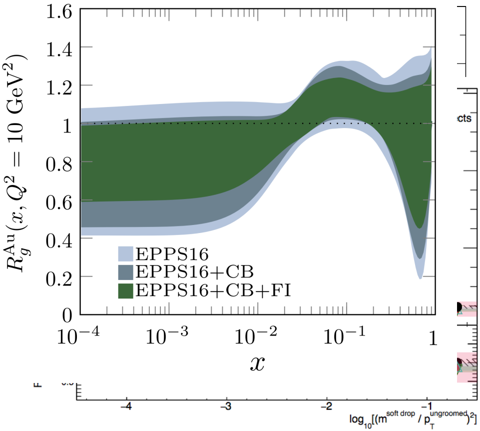
Examples: Perturbing the nonperturbative

Helenius, Lajoie, JO, Paakkinen, Paukkenen
Phys. Rev. D 100, 014004 (2019)



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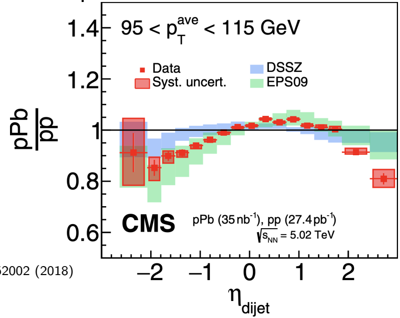

Phys. Rev. Lett. 121, 062002 (2018)

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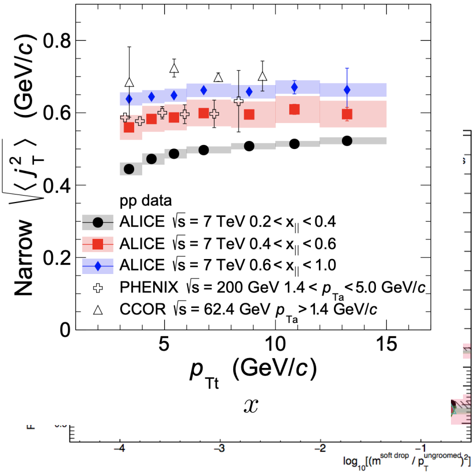
JHEP 1903, 169 (2019)



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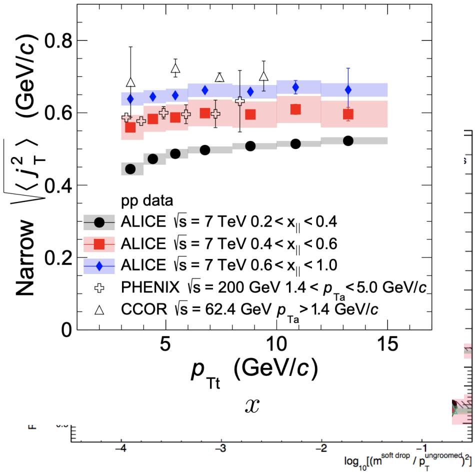

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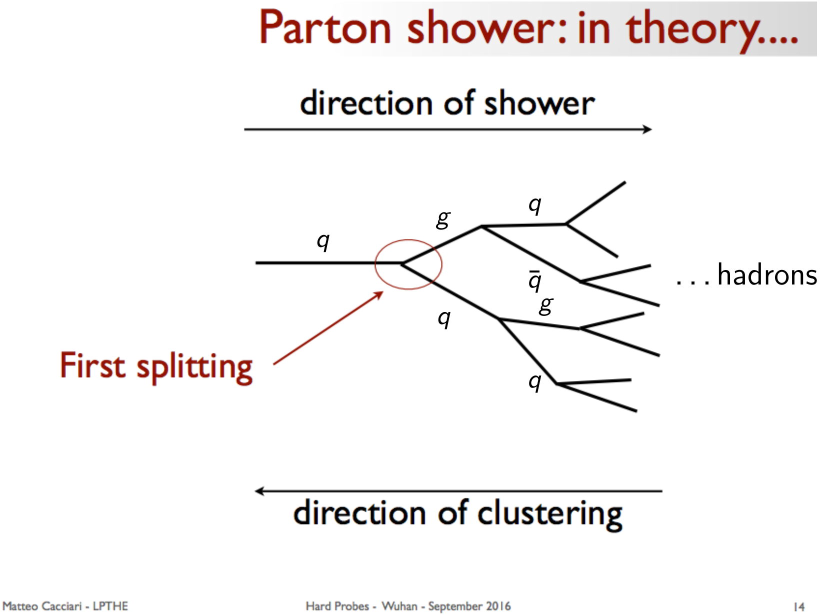
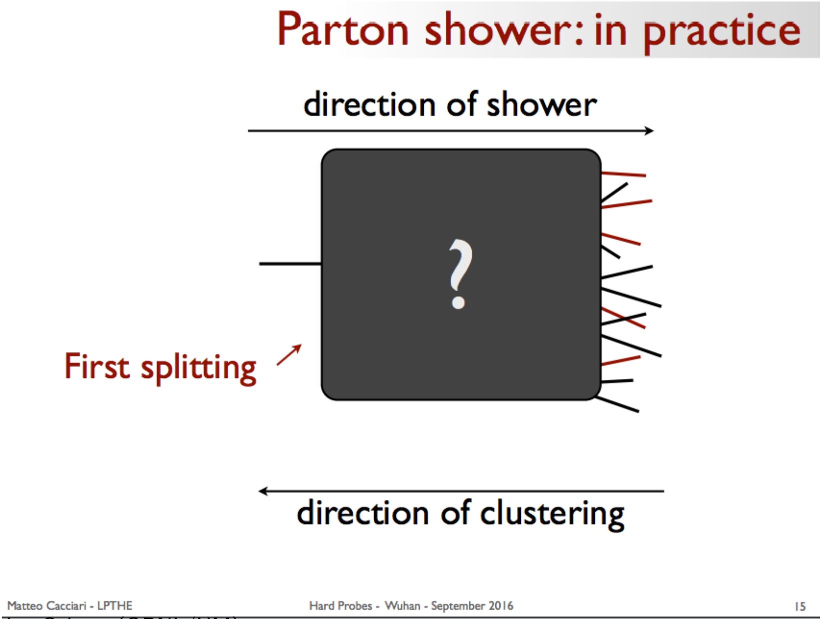
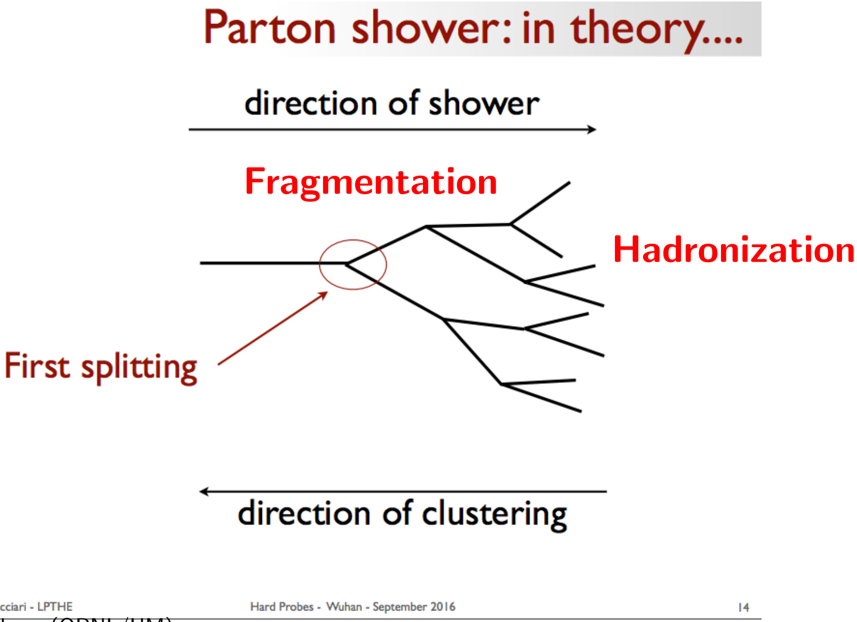
How do jets really form?

Jet Formation

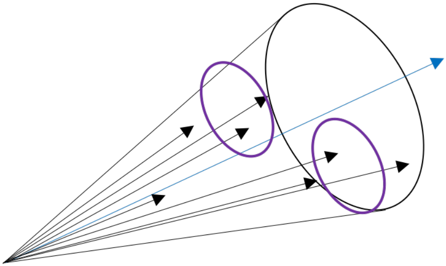


Jet Formation




Parton shower: in theory....
direction of shower
Fragmentation
Hadronization
First splitting
direction of clustering
Matteo Cacciari - LPTHE
Hard Probes - Wuhan - September 2016
14

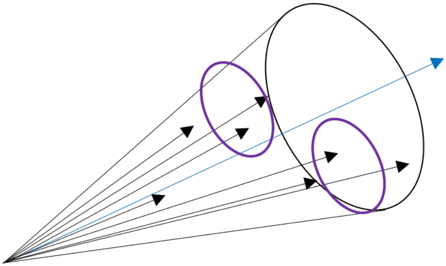
Fragmentation



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

Fragmentation vs. Hadronization

Fragmentation



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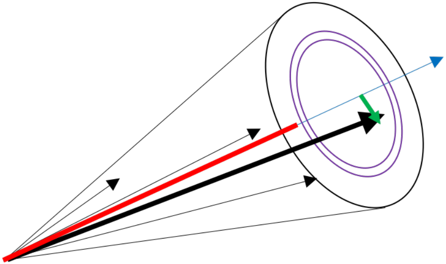
Hadronization



- Use individual hadrons to study correlations with jet axis

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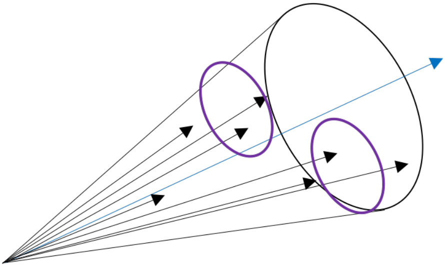

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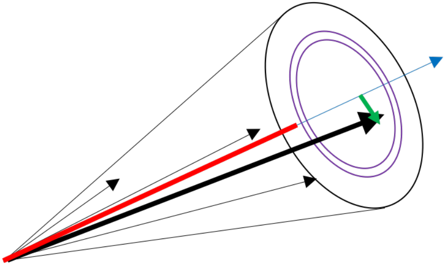
  Emphasis on parton shower (perturbative QCD)

Hadronization



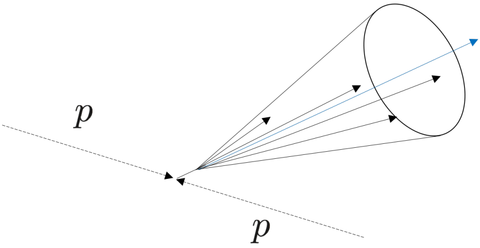
- Use individual hadrons to study correlations with jet axis

  Emphasis on hadron formation (NONperturbative QCD)

Jet substructure at LHCb

$\rightarrow$ focus on hadronization

Hadronization: What do we want?



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

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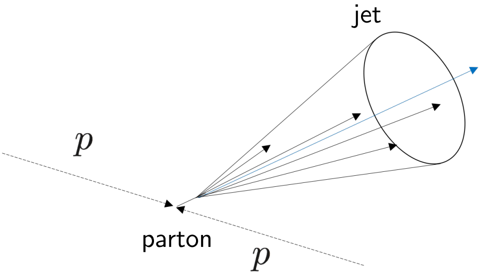

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  1. A way to connect the initial-state parton to the final-state hadrons
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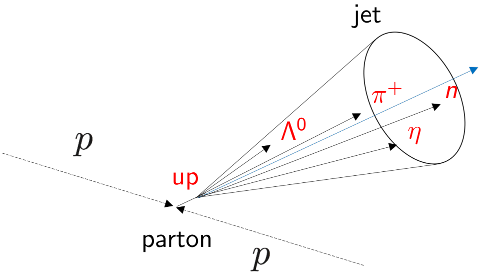

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     - Would allow for complete characterization of parton $\rightarrow$ hadron

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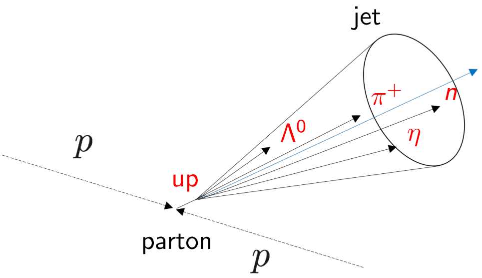

- Baryon vs. meson (3 quark vs. 2 quark states)
- Correlations (e.g. strange, heavy flavor quarks. . .)
- Resonance production ($\phi(s\bar{s})$, $J/\psi(c\bar{c})$, $\Upsilon(b\bar{b})$)
- . . .

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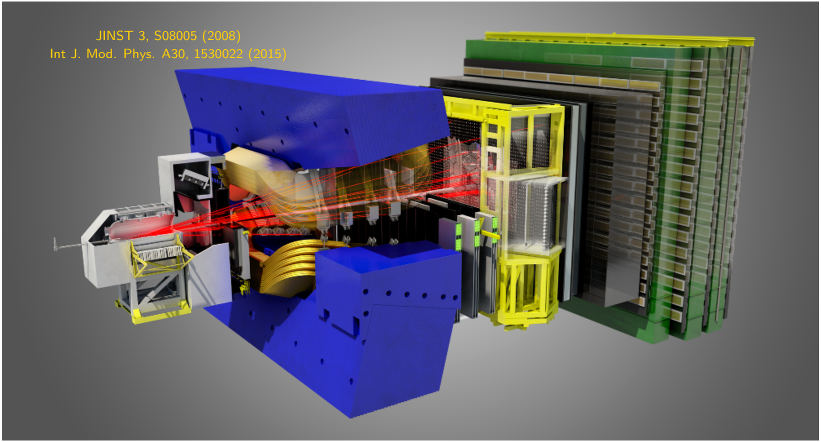
LHC

LHCb Experiment



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

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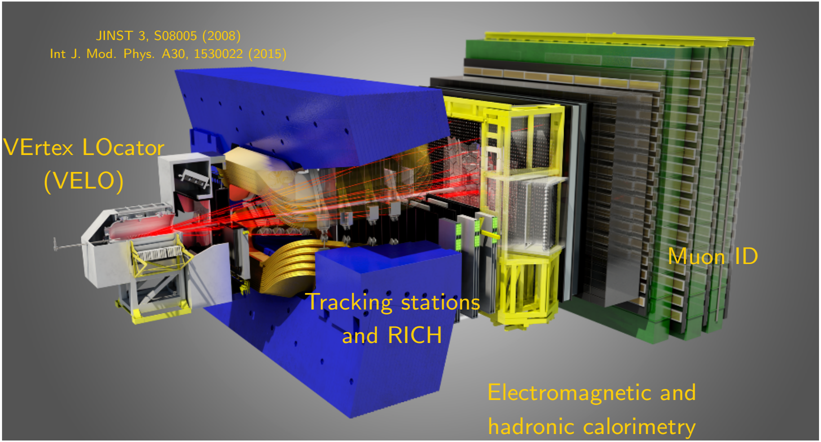

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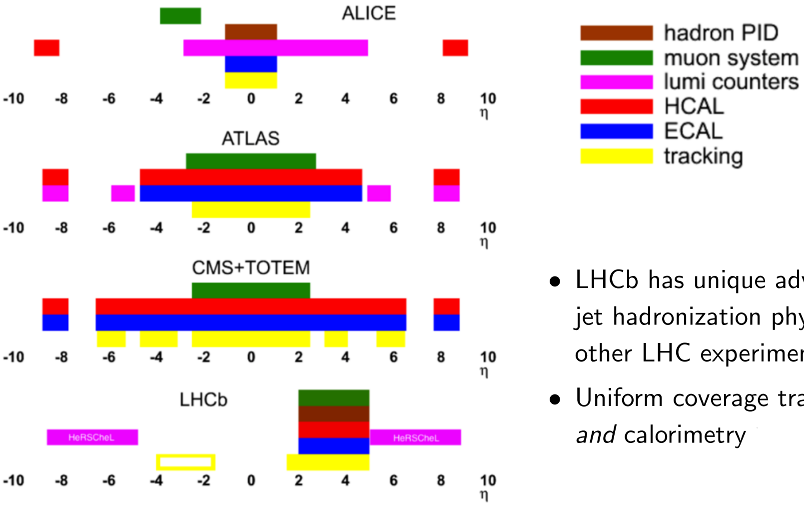
Why LHCb?



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- Uniform coverage tracking, PID, *and* calorimetry

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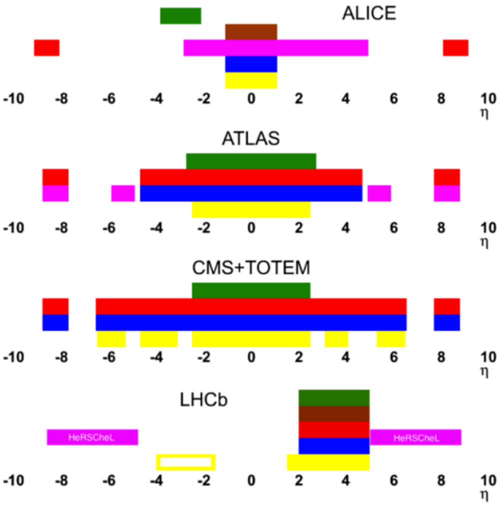

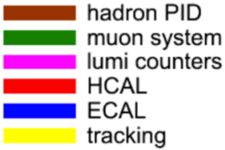

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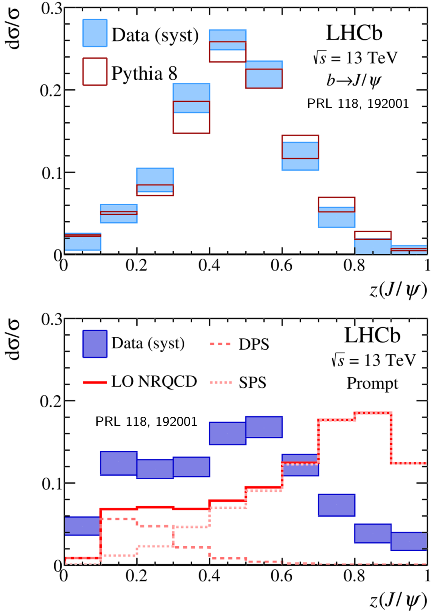
- Uniform coverage tracking, PID, *and* calorimetry
- Can identify nearly all particles within a high p_T jet

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 was J/ψ-in-jet production



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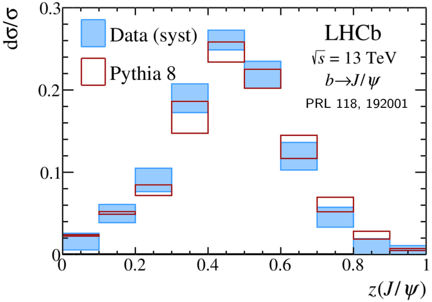
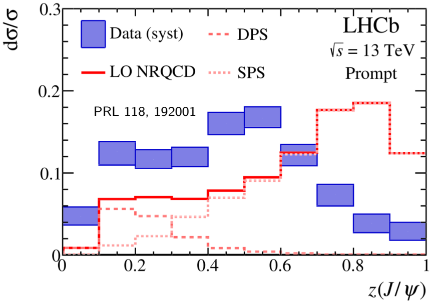
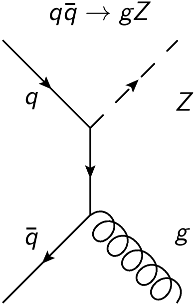
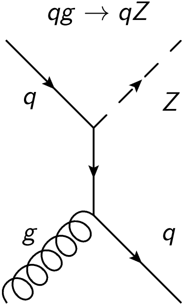




Why Z+jet?





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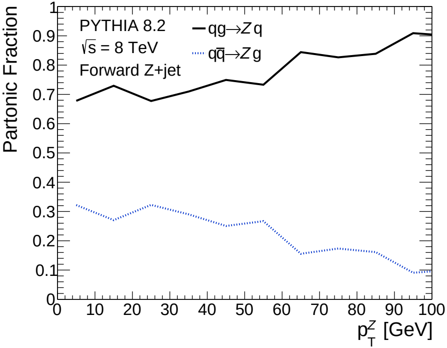

- Z+jet is predominantly sensitive to light quark jets

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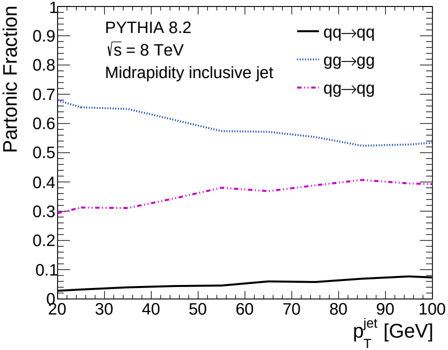

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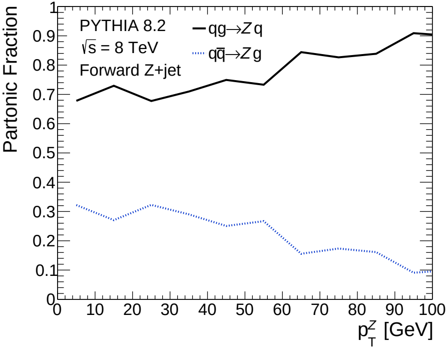

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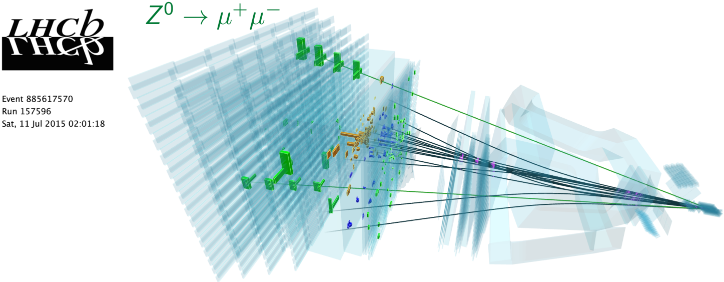
- Opportunity to study light quark vs. gluon:
    - Hadronization dynamics
    - Jet properties

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



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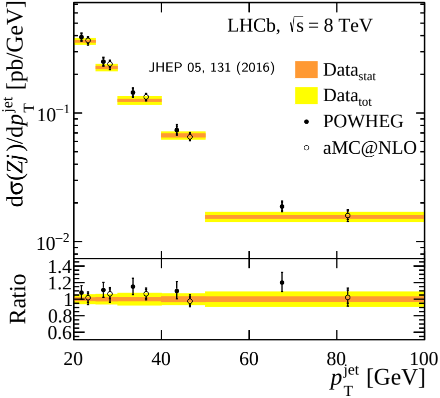

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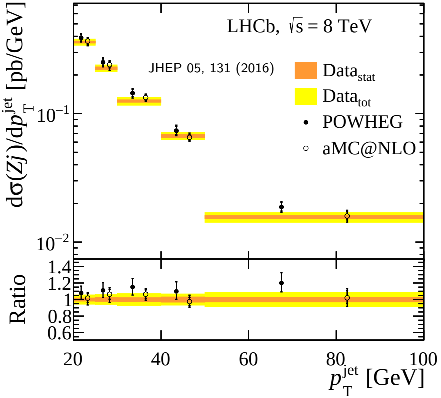

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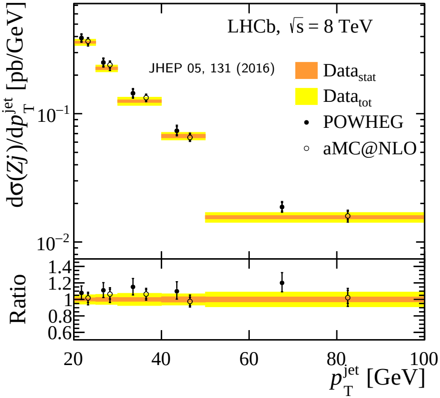
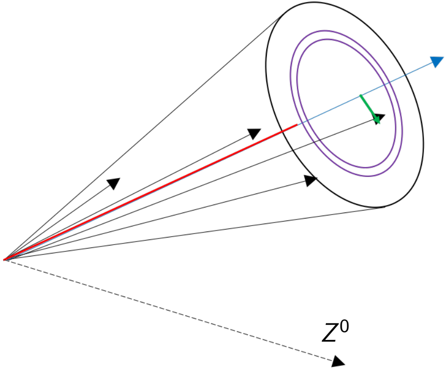


- **First measurement of charged hadrons within Z tagged jets**
- **First measurement of charged hadrons-in-jets at forward rapidity**



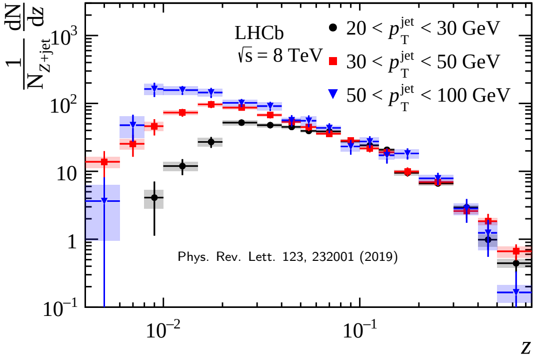
$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

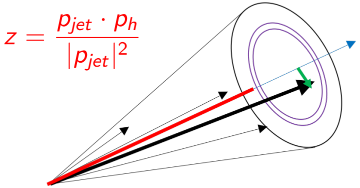
$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$

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

- 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

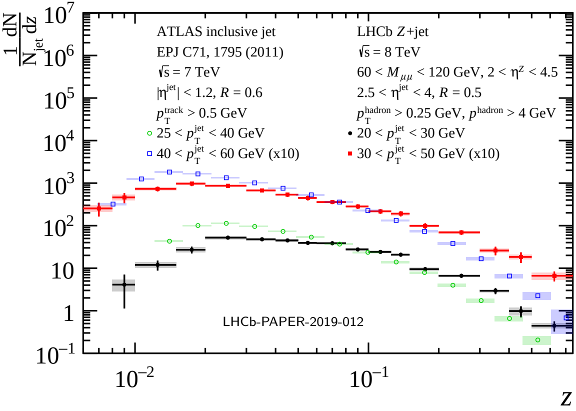
- Measurements in three jet transverse momentum (p_T^{jet}) bins, integrated over Z kinematics
- Longitudinal hadron-in-jet distributions independent of jet p_T at high z
- Distributions diverge at low z due to kinematic phase space available





ATLAS and LHCb Comparisons

- Compare ATLAS gluon dominated to LHCb light quark dominated

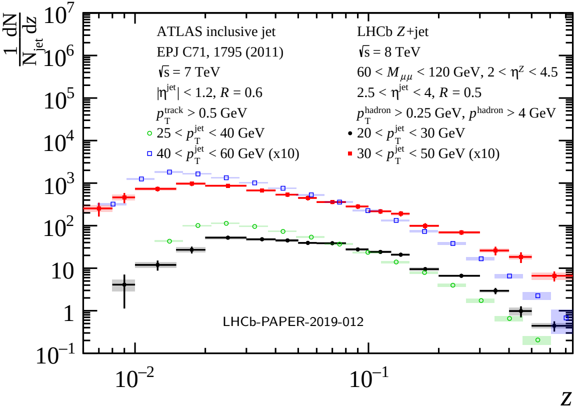


LHCb quark jet (filled) - red and black

ATLAS gluon jet (open) - blue and green

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



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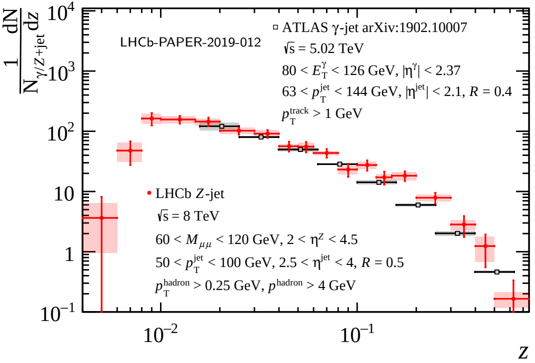
- ATLAS midrapidity γ-jet and LHCb forward rapidity Z-jet distributions are very similar



LHCb quark jet (filled) - red
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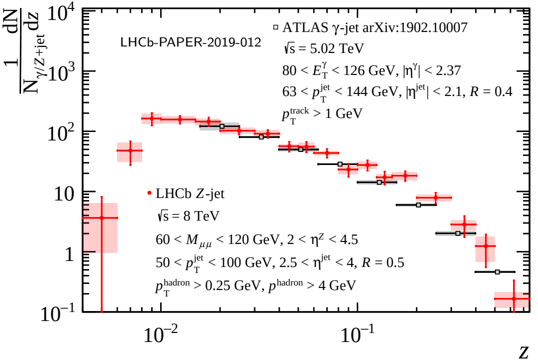
Comparison to ATLAS γ-jet

- ATLAS midrapidity γ-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



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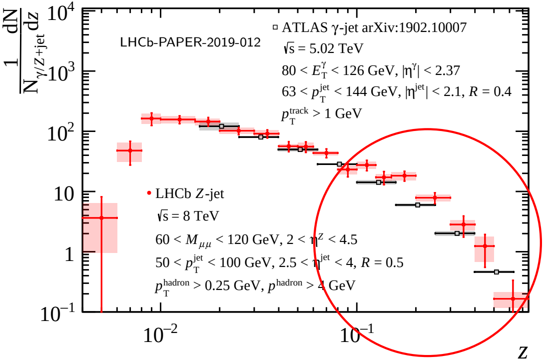
Comparison to ATLAS γ-jet

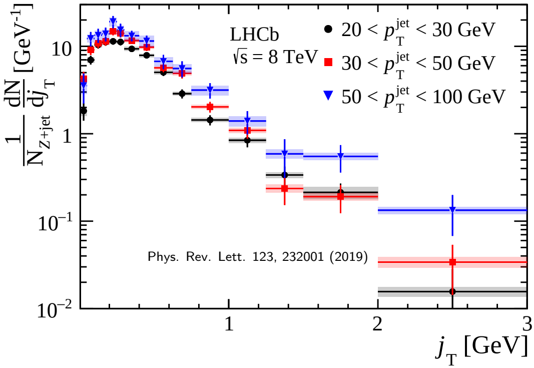
- ATLAS midrapidity γ-jet and LHCb forward rapidity Z-jet distributions are very similar
- Both processes light quark jet dominated
- Light quark jet structure shows little rapidity dependence
- Hint of more collimated jets in Z+jet
    - Massive Z vs. massless γ?



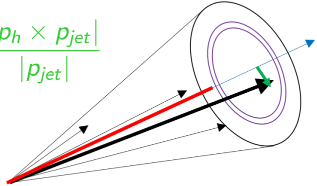
LHCb quark jet (filled) - red
ATLAS quark jet (open) - black

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}

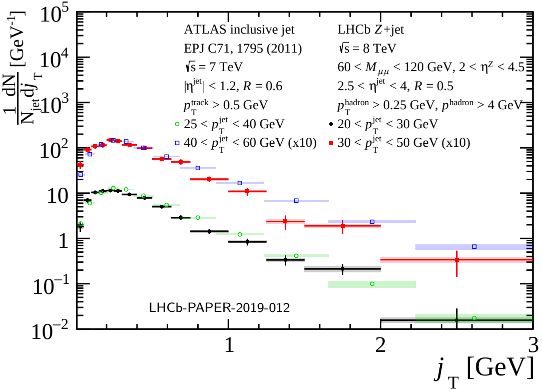


$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$



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



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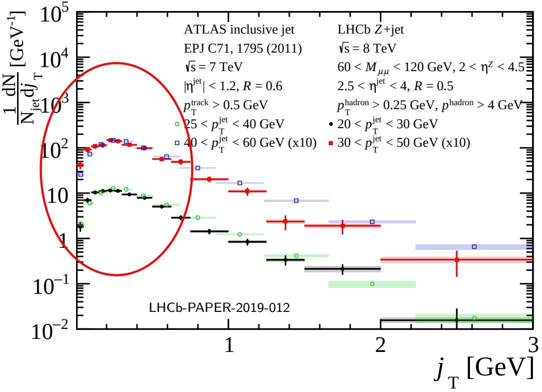

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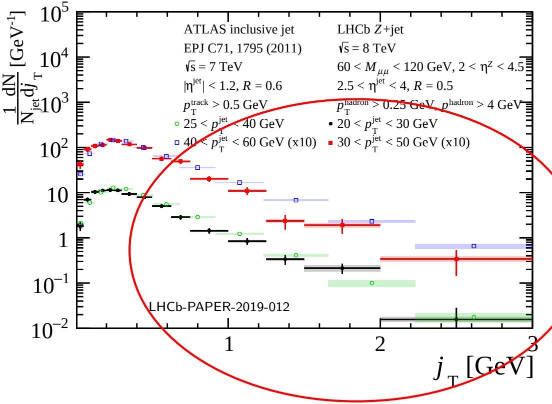
ATLAS and LHCb Comparisons

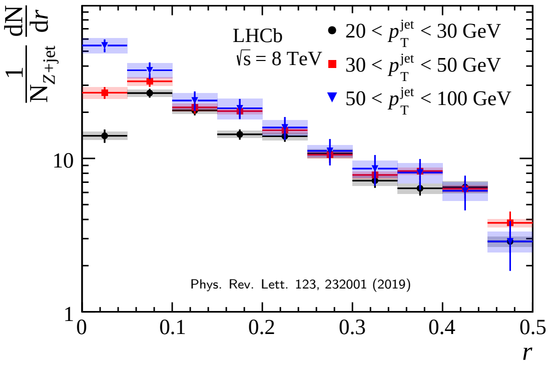
- Transverse momentum distributions show smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T
  - Consistent with more collimated light quark vs. gluon jets
- Perturbative region quite similar between quark and gluon jets



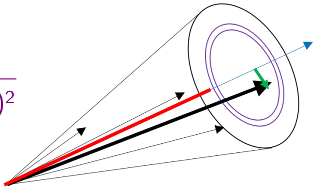
LHCb quark jet (filled) - red and black
ATLAS gluon jet (open) - blue and green

Results

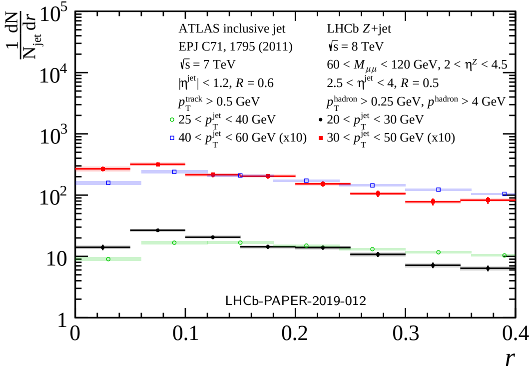
- Radial profiles largely independent of jet p_T away from jet axis
  - Large angle hadron formation independent of jet p_T or scale of process
- Multiplicity of hadrons along jet axis rises sharply with jet p_T



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



- 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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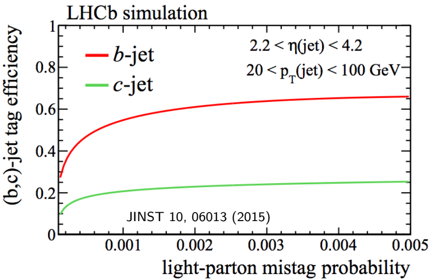
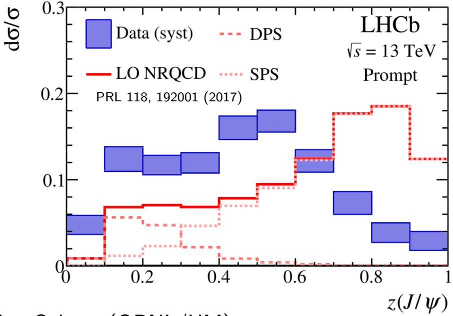
Future Jet Hadronization Measurements

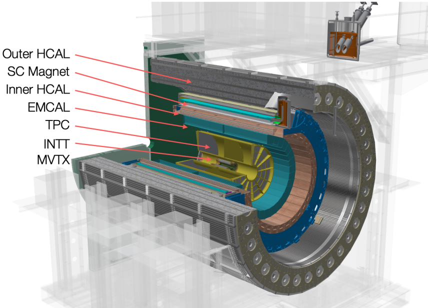




- Intended to lay the foundation for a broader hadronization program at LHCb utilizing
  - Particle ID (tracking, RICH, calorimetry)
  - Heavy flavor jet tagging
  - Resonance production within jets (ϕ, J/ψ, Υ)
  - Correlations with flavor ID
  - Change in target size (e.g. use proton-nucleus collisions)

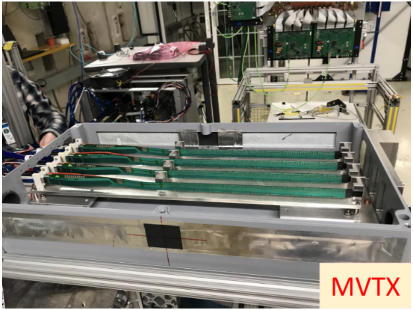
Future Jet Hadronization Measurements

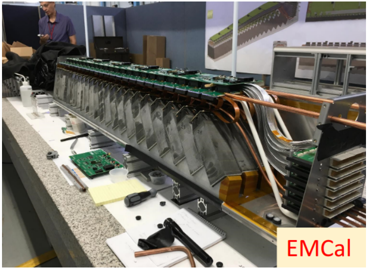
- sPHENIX is a dedicated jet detector being constructed at RHIC



Future Jet Hadronization Measurements

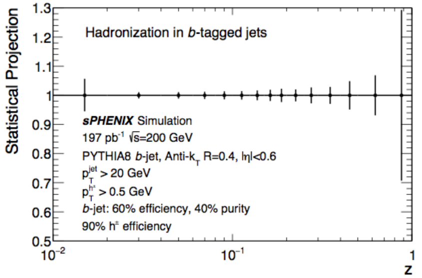
- sPHENIX is a dedicated jet detector being constructed at RHIC
- CD3 recently approved, construction is moving forward for installation in 2022

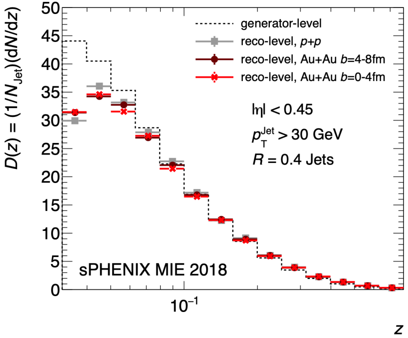




Future Jet Hadronization Measurements

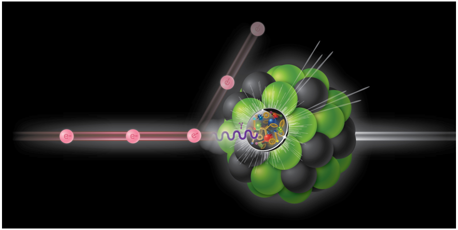
- sPHENIX is a dedicated jet detector being constructed at RHIC
- CD3 recently approved, construction is moving forward for installation in 2022
- Jet substructure and hadronization a major component of science case





Hadronization at an Electron Ion Collider

- Electron Ion Collider (EIC) is the next major accelerator facility planned in the US
- CD0 recently approved by DOE for construction at Brookhaven National Laboratory



Hadronization at an Electron Ion Collider

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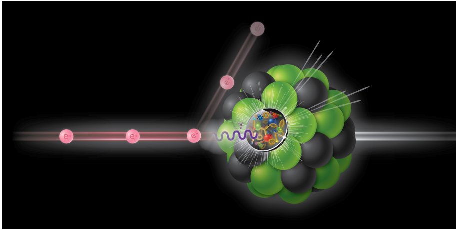
- CD0 recently approved by DOE for construction at Brookhaven National Laboratory
- Hadronization is a major pillar of EIC physics case
- Developing ideas in the next decade before EIC will be crucial to maximize science output of this unique QCD machine!



Conclusions

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- Preferentially selects light quark jets vs. gluon jets
  - Opportunity for understanding nonperturbative hadronization dynamics
  - Opportunity for understanding boosted gluon vs. light quark jets

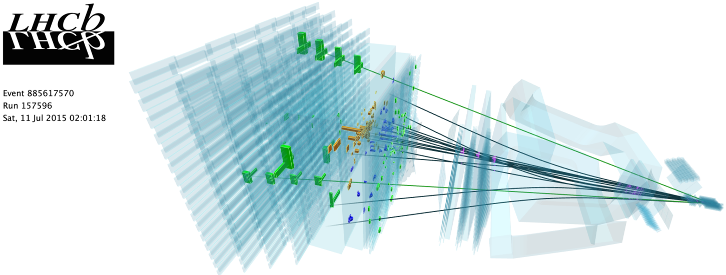
Conclusions

- Jet substructure has exploded onto the high energy and nuclear physics scene, with wide ranging physics interests
- New results on hadronization and jet substructure in Z +jet events at LHCb
- Preferentially selects light quark jets vs. gluon jets
  - Opportunity for understanding nonperturbative hadronization dynamics
  - Opportunity for understanding boosted gluon vs. light quark jets
- Ideas behind hadronization are relatively undeveloped, but there will be significant growth with current and future experiments!

Back Up

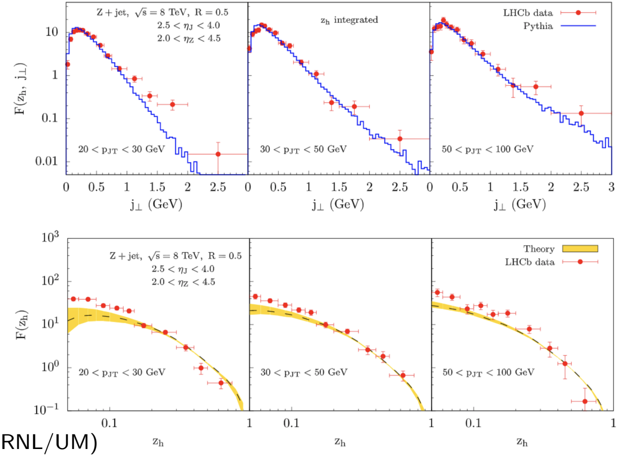
Analysis Details

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



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

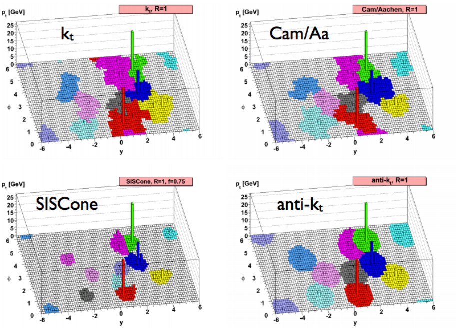


Anti-k$_T$ Algorithm

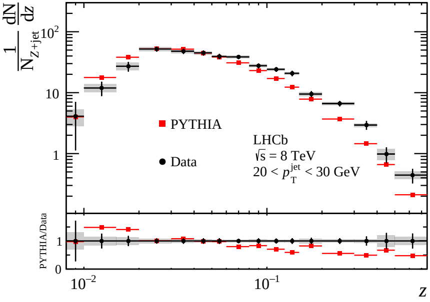
- Sequential recombination algorithm which clusters particles into jets based on their p_T
- Widely used as it is both infrared and collinear safe in calculations
- Clusters particles around highest p_T particle in a conical shape

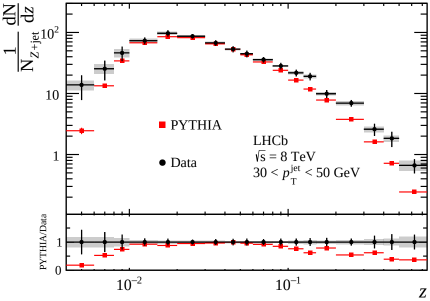
$$d_{ij} = min(p_{T_i}^{-2}, p_{T_j}^{-2})\frac{\Delta_{ij}^2}{R^2}$$

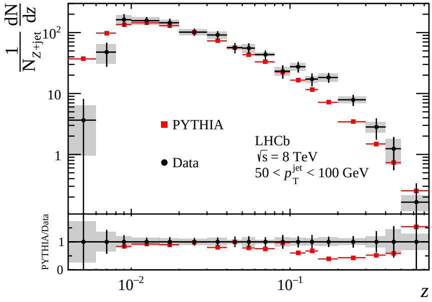
$$d_{iB} = p_{T_i}^{-2}$$



Comparisons with PYTHIA (z)

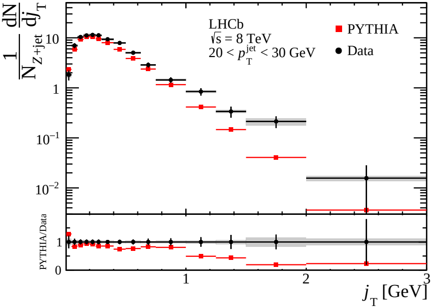


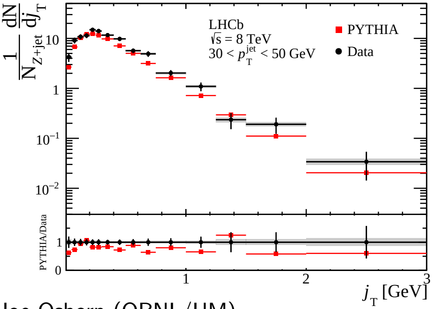


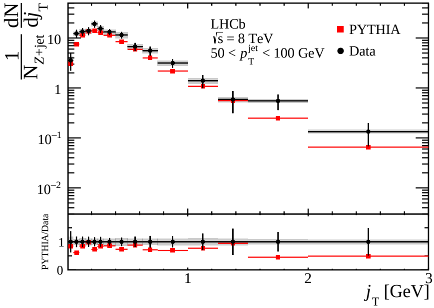


- PYTHIA generally underpredicts the number of high z hadrons

Comparisons with PYTHIA (j_T)

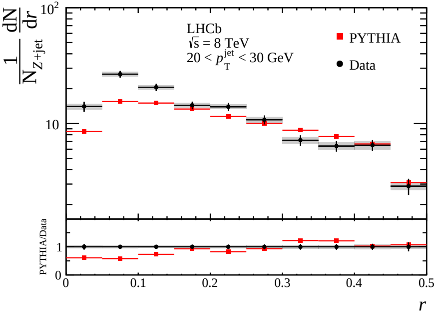


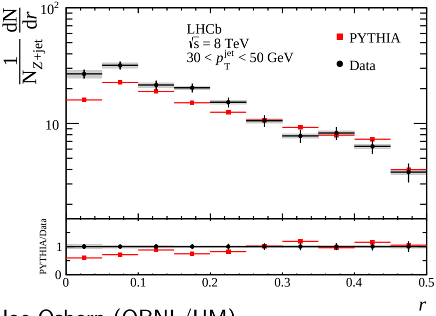


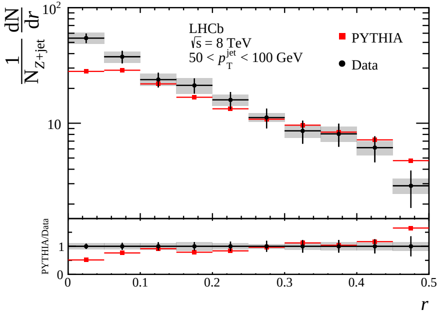


- PYTHIA generally gets j_T shape, with about a 20% difference in normalization

Comparisons with PYTHIA (r)

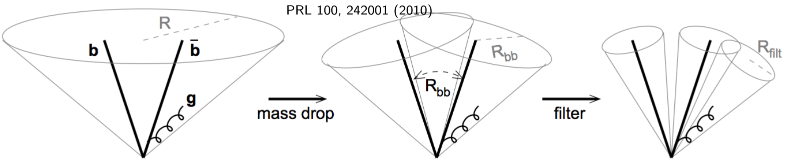






- PYTHIA generally underpredicts the number of small r hadrons

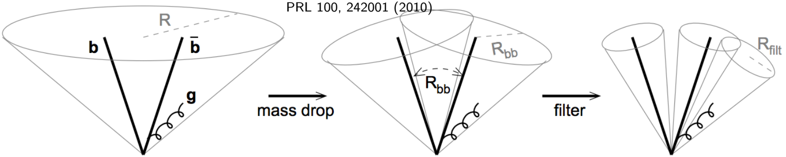
Symbolic Beginning



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

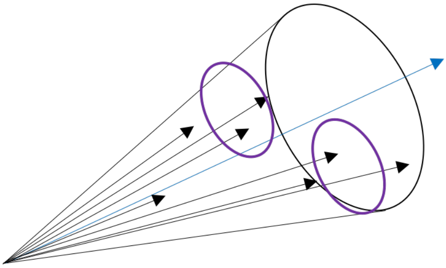
Symbolic Beginning

PRL 100, 242001 (2010)



- 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

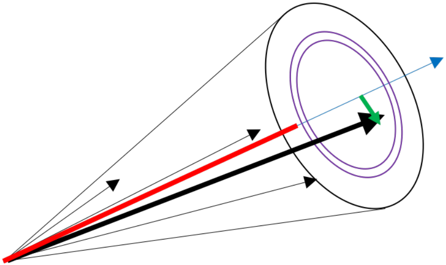
Fragmentation



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

LEFT

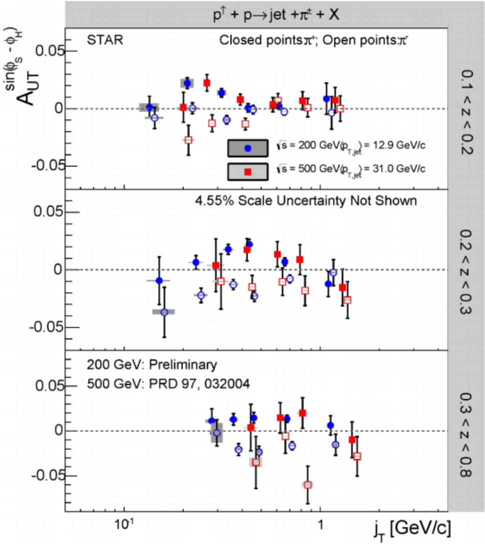
Hadronization



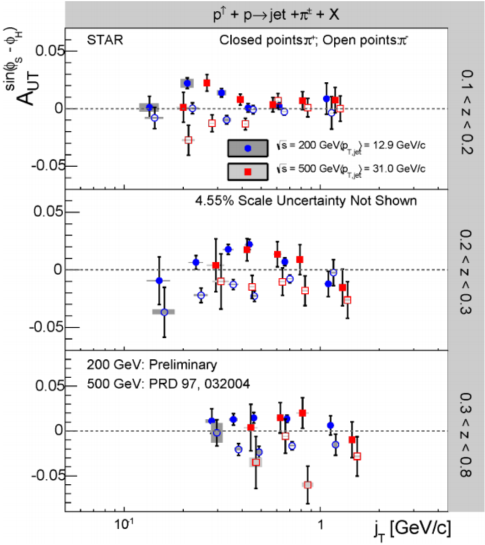
- Use individual hadrons to study correlations with jet axis

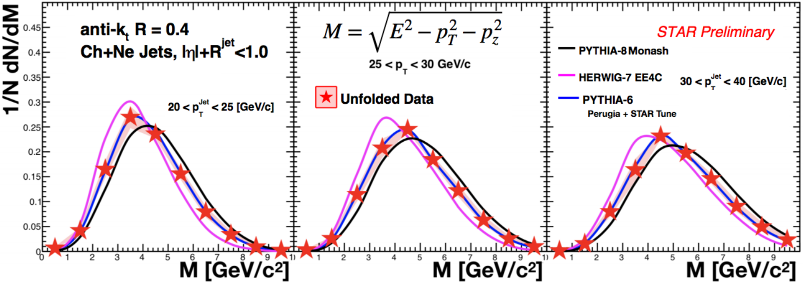
RIGHT

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



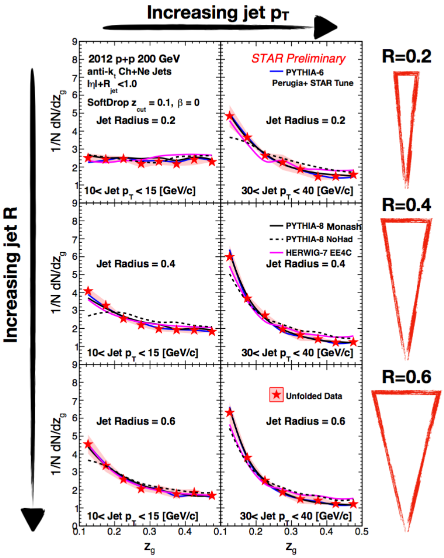
- STAR has measured hadrons in jets produced in transversely polarized *pp* collisions
- Sensitive to 3D distributions of hadrons within jets
- Sensitive to quark-hadron spin-momentum correlations





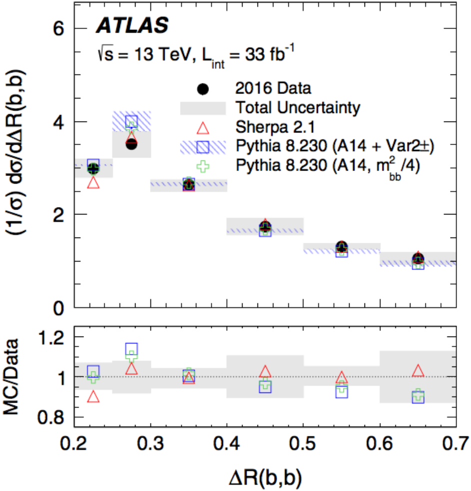
- Measurement of jet mass sensitive to both fragmentation and hadronization aspects of jet substructure!
- Can study the interplay and connections between both

Jet Substructure Physics at RHIC



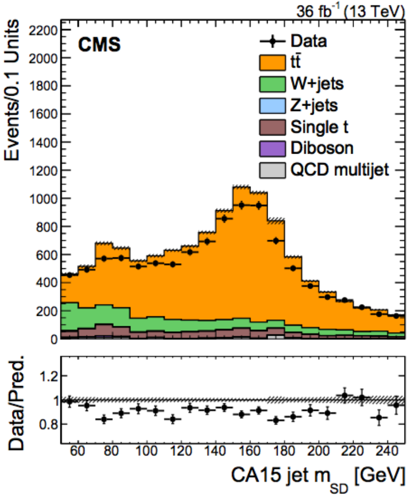
- Measurements of momentum sharing between subjets within jets
- Sensitive to QCD splitting function
    - How is energy shared between partons?
- Multidifferential as a function of jet radius and jet transverse momentum

Jet Substructure at the LHC



Phys. Rev. D 99, 052004 (2019)

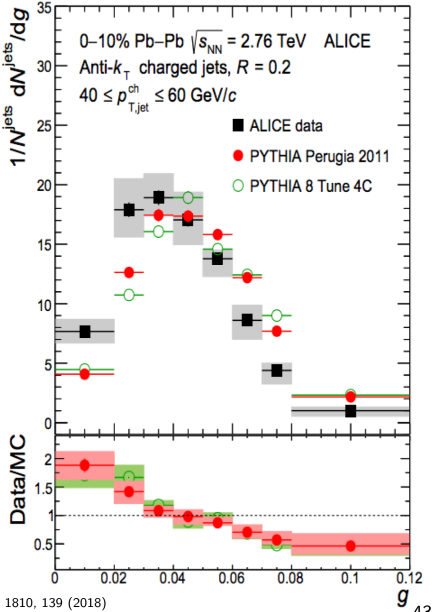
- Measurement of $b\bar{b}$ jets from gluon splitting
- Improve understanding of boosted $H \to b\bar{b}$ decays
- Improve understanding of $b\bar{b}$ fragmentation



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 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)

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
- 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
    - ...