Experimental perspectives on factorization breaking and color entanglement

Part 2 - New LHCb jet hadronization results

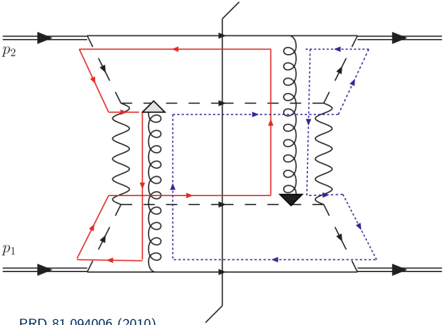
on behalf of the LHCb collaboration

Joe Osborn

University of Michigan

FF2019, March 16, 2019

Example 1: Color Entanglement



PRD 81,094006 (2010)

- Many recent examples within QCD of processes sensitive to color flow
- In a transverse-momentum-dependent (TMD) framework, color entanglement predicted in $p + p \rightarrow$ dihadrons

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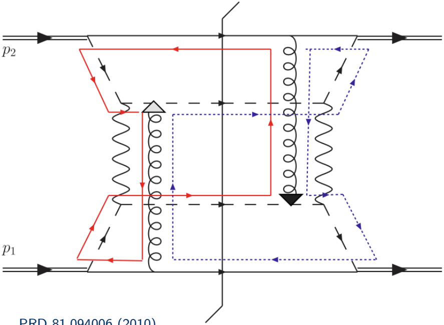

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- Corresponds to break down of factorization in a TMD framework

$$\sigma = f_1(x, k_T) \otimes f_2(x, k_T) \otimes \frac{d\hat{\sigma}}{dt} \otimes D_1(z, j_t) \otimes D_2(z, j_T)$$

$$\downarrow$$

$$\sigma \overset{?}{=} CF(x_1, x_2, k_{T_1}, k_{T_2}, z_1, z_2, j_{T_1}, j_{T_2}) \otimes \frac{d\hat{\sigma}}{dt}$$

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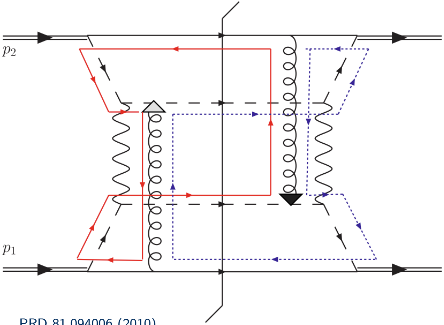
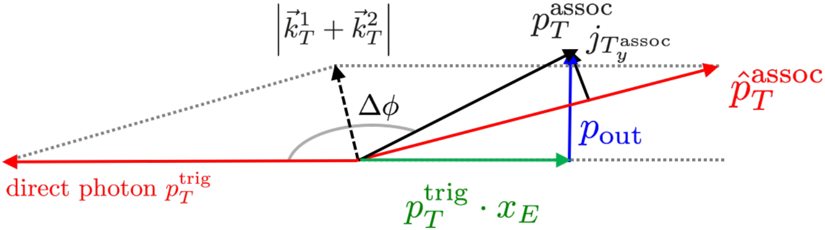


PRD 81,094006 (2010)

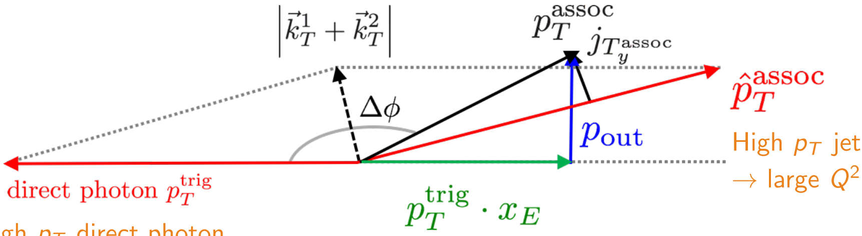
- Many recent examples within QCD of processes sensitive to color flow
- In a transverse-momentum-dependent (TMD) framework, color entanglement predicted in $p + p \rightarrow$ dihadrons
- Corresponds to break down of factorization in a TMD framework
- Specifically a non-Abelian effect

Observables To Probe Entanglement



- To probe TMD physics, an observable must be sensitive to two scales: $\Lambda_{QCD} \lesssim k_T \ll Q$

Observables To Probe Entanglement



High p_T direct photon
→ large Q^2

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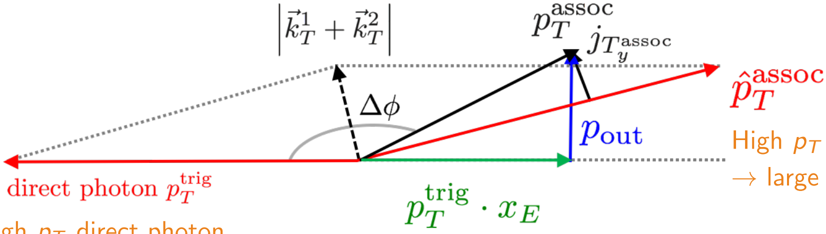
Observables To Probe Entanglement



High p_T jet
$\rightarrow$ large Q^2

High p_T direct photon
$\rightarrow$ large Q^2

Nearly back-to-back
$\Delta\phi \sim \pi \rightarrow$ small p_{out}

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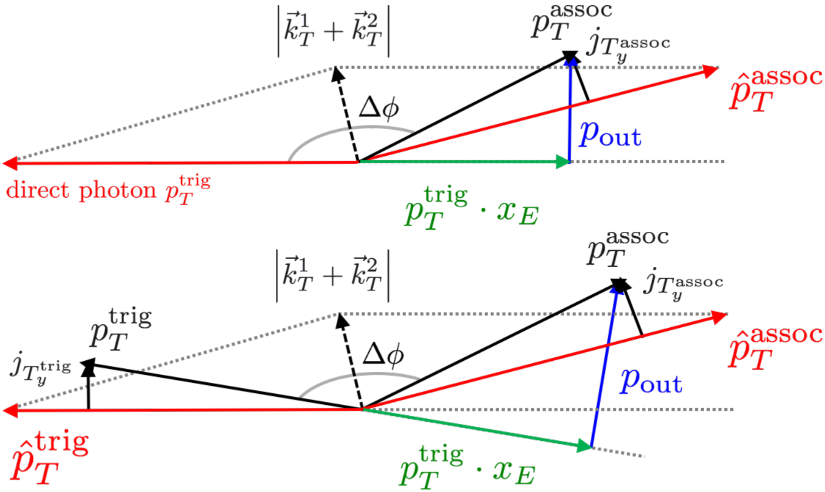
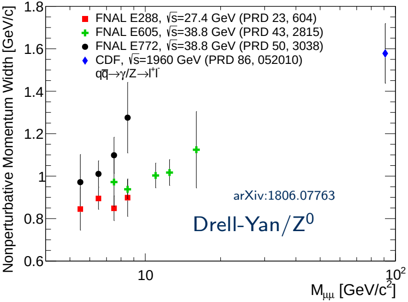
Observables To Probe Entanglement



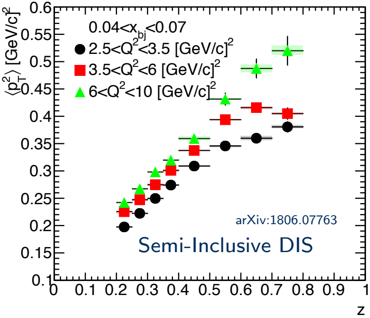
Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow qualitative expectations from CSS evolution



arXiv:1806.07763

Drell-Yan/Z^0



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Semi-Inclusive DIS

Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

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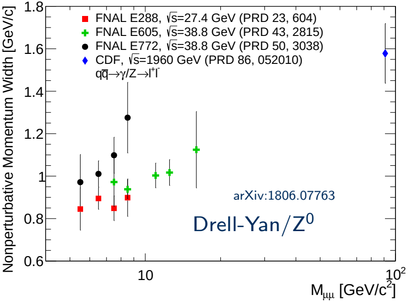
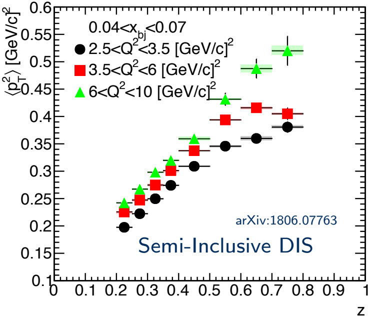
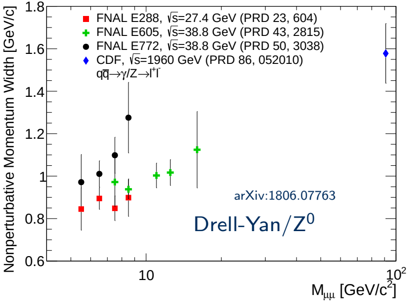
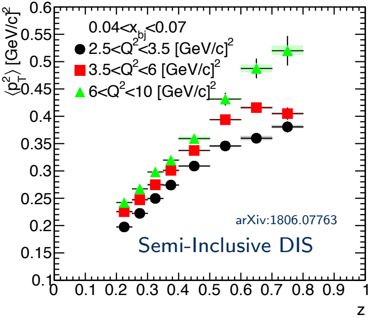




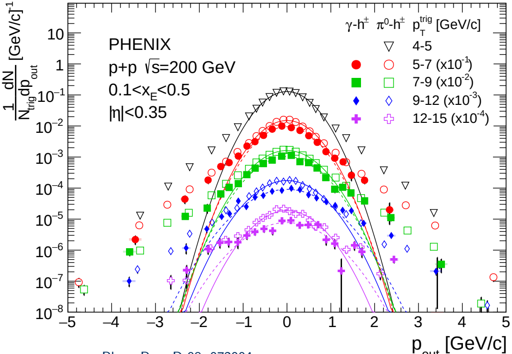
Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow qualitative expectations from CSS evolution
- The evolution prediction comes directly out of the derivation for TMD factorization
    - If TMD factorization, then CSS evolution. If not CSS evolution, then not TMD factorization!





Measurements of p_{out} Distributions in $p{+}p \to$ hadrons



Phys. Rev. D 98, 072004

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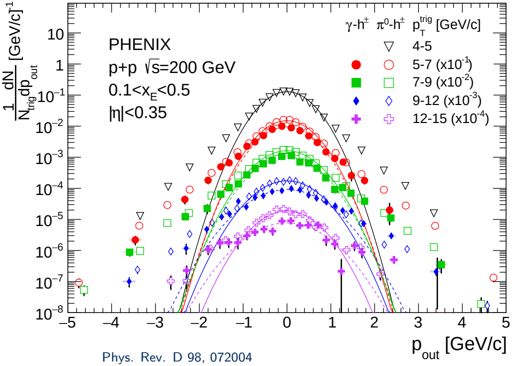

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- Two distinct regions:
  - Gaussian at small p_{out}
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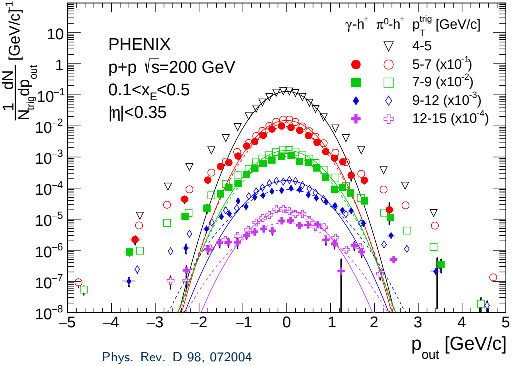

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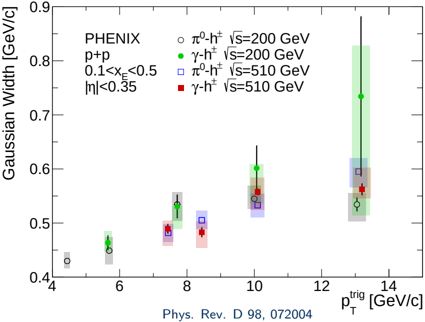
- Two distinct regions:
  - Gaussian at small p_{out}
  - Power law at large p_{out}
- Indicates TMD observable - $\Lambda_{QCD} \lesssim p_{out} \ll p_T^{\mathrm{trig}}$
- Can characterize any potential differences from CSS by studying width evolution

Gaussian Width of p_{out} Evolution in $p+p \to$ hadrons

- Away-side Gaussian widths shown as a function of p_T^{trig} (top) and x_T (bottom) at $\sqrt{s} = 200$ and 510 GeV



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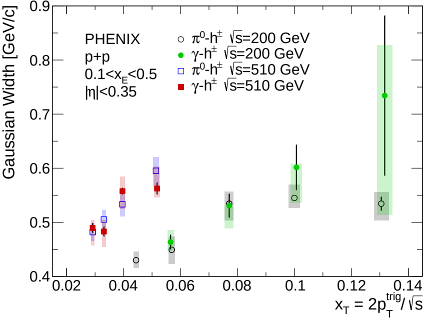
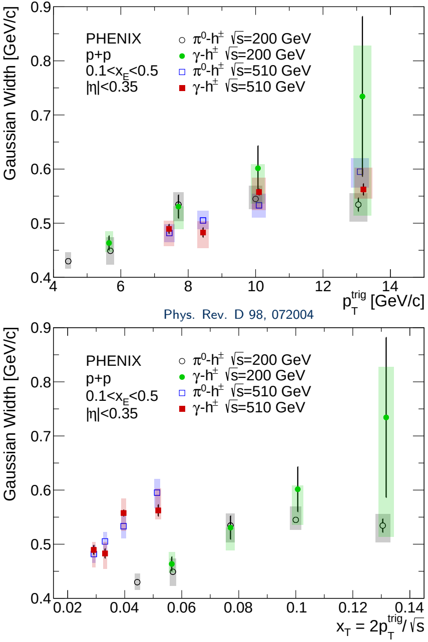


Gaussian Width of p_{out} Evolution in $p+p \to$ hadrons

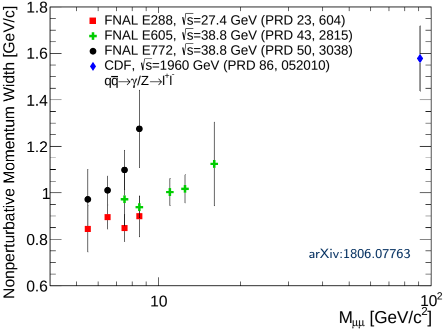
- Away-side Gaussian widths shown as a function of p_T^{trig} (top) and x_T (bottom) at $\sqrt{s} = 200$ and 510 GeV
- Qualitatively similar behavior to Drell-Yan and semi-inclusive DIS interactions where color entanglement is not predicted



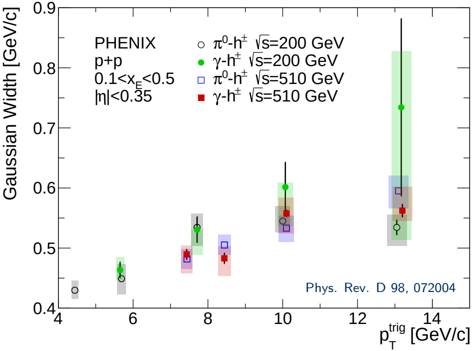
Phys. Rev. D 98, 072004

Comparing Drell-Yan and p+p → hadrons

Drell-Yan

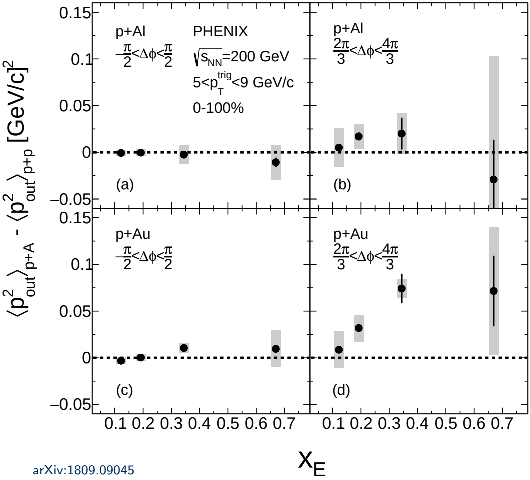


p+p → hadrons



- Since qualitative behavior is similar, calculations needed to compare TMD evolution rates in different processes
- Drell-Yan (no color entanglement predicted) and p+p → hadrons (color entanglement predicted) may exhibit different magnitudes, evolution rates, etc.

Nonperturbative Transverse Momentum Broadening in *p*+A



arXiv:1809.09045

- Can also extend Gaussian width studies to compare between *p*+A and *p*+*p*

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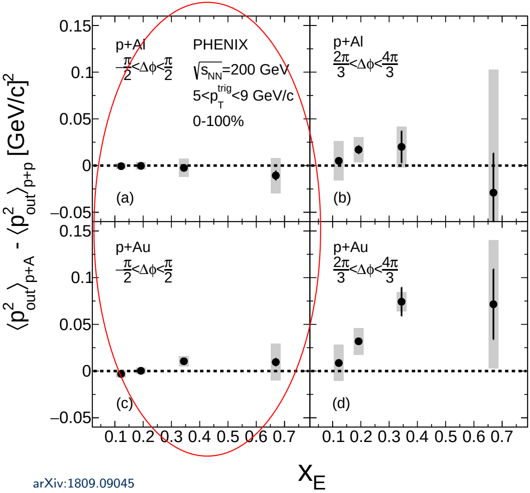

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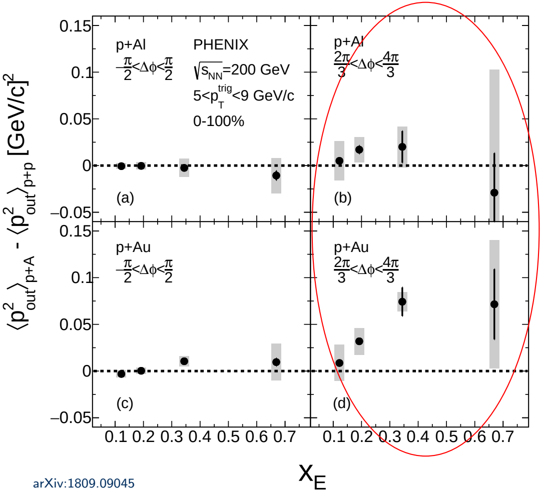

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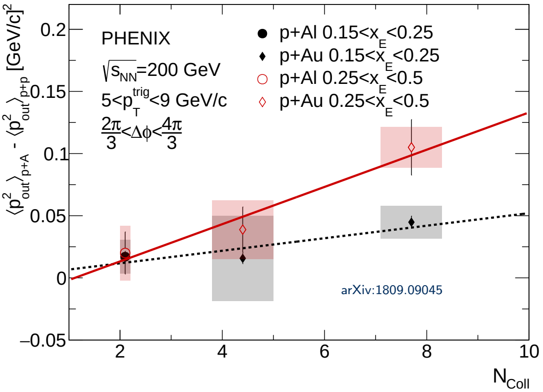
- Can also extend Gaussian width studies to compare between *p*+A and *p*+*p*
- No significant near-side transverse momentum broadening
- Nonzero away-side nonperturbative transverse momentum broadening in *p*+A

Broadening as a Function of N_{coll}



- Away-side transverse momentum broadening is clearly a function of N_{coll} (event multiplicity) for two x_E bins

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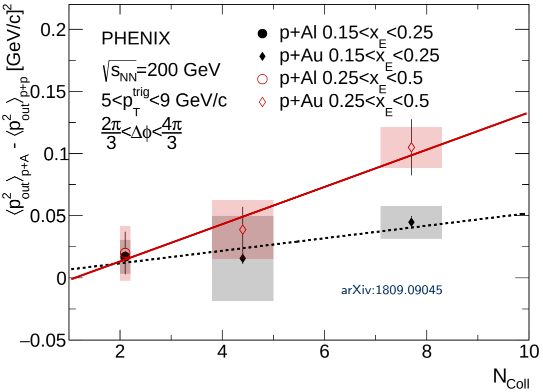

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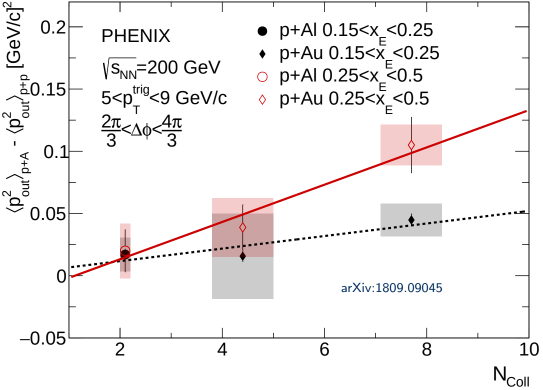

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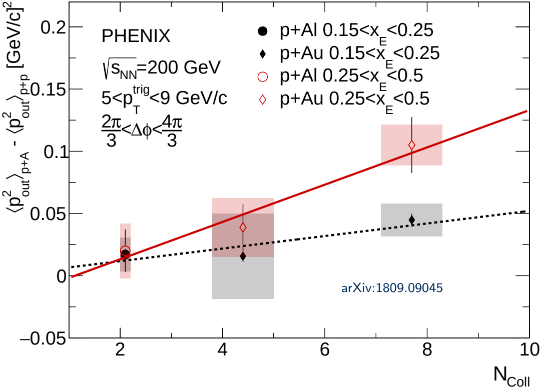
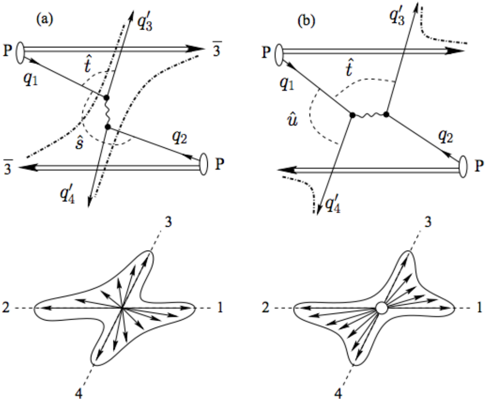


- Away-side transverse momentum broadening is clearly a function of N_{coll} (event multiplicity) for two x_E bins
- Physical effects that contribute?
  - Stronger color fields in nuclear interactions?
  - Additional initial-state k_T in nucleus?
  - Energy loss?
  - Physical effects behind “Cronin” mechanisms?
  - . . .

Example 2: Color Coherence

- Another example: color coherence
- Color flow through hard processes leads to certain regions of particle production in hadronic collisions



Y. Dokshitzer. Basics of Perturbative QCD, 1991

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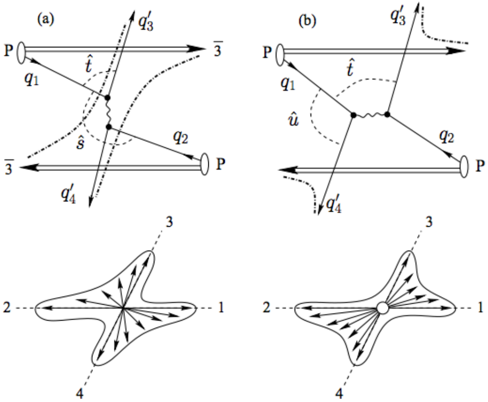
- Color connects hard scattered partons with remnants of other proton



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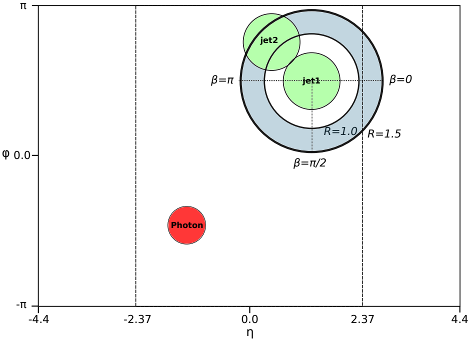
Color Coherence Measurements

$p + p \rightarrow \text{dijet} + \text{jet} + \text{X}$

$p + p \rightarrow \gamma + \text{jet} + \text{jet} + \text{X}$



Nucl. Phys. B 918, 257 (2017)

- β is angle in (ϕ, η) space between sub-leading hard-scattered jet and third jet

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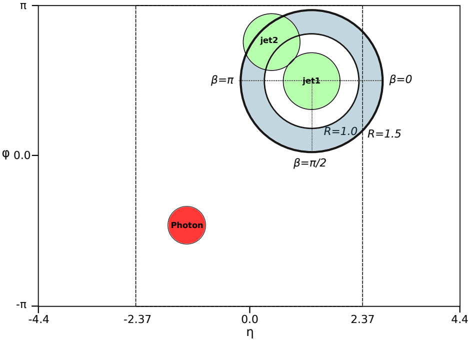

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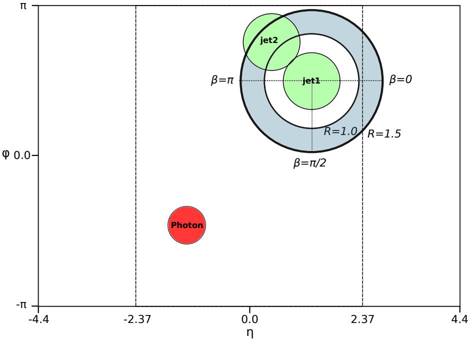
$p + p \rightarrow$ dijet + jet + X

$p + p \rightarrow \gamma$ + jet + jet + X



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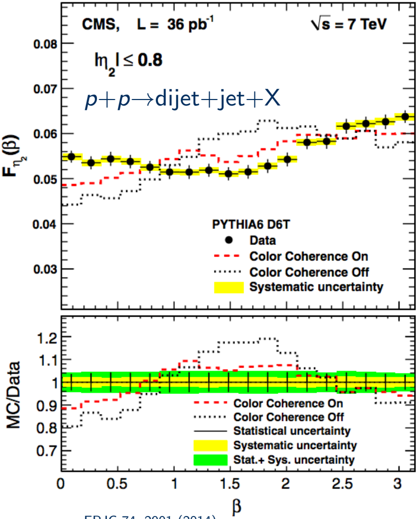

EPJC 74, 2901 (2014)

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- $\beta = 0$ points to the beam closer to sub-leading jet in (ϕ, η) space
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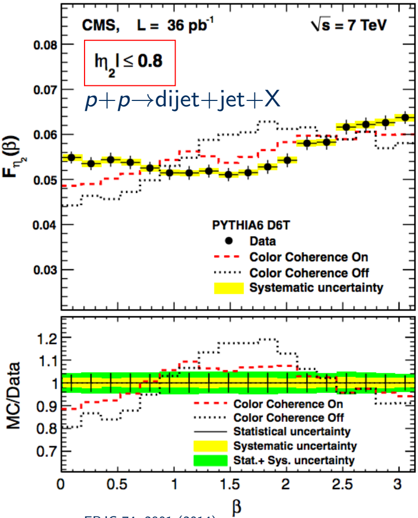
- Third jet more likely to be found at $\beta = 0$, $\beta = \pi$, i.e. similar ϕ but large η gap

Color Coherence Measurements



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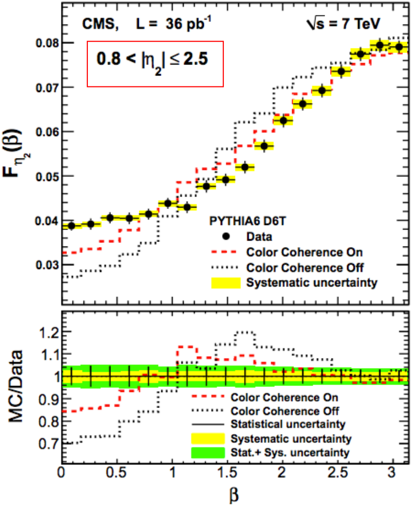
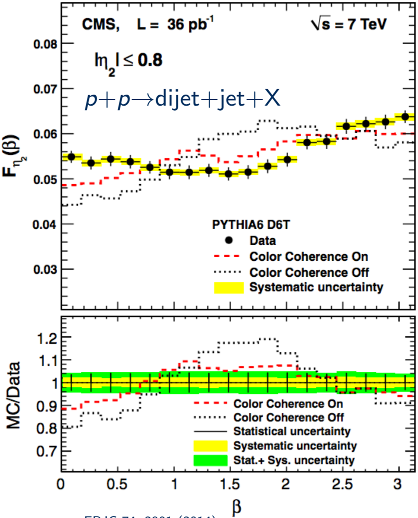


EPJC 74, 2901 (2014)

- Even stronger correlation to opposite beam at forward rapidities!

Color Coherence Measurements



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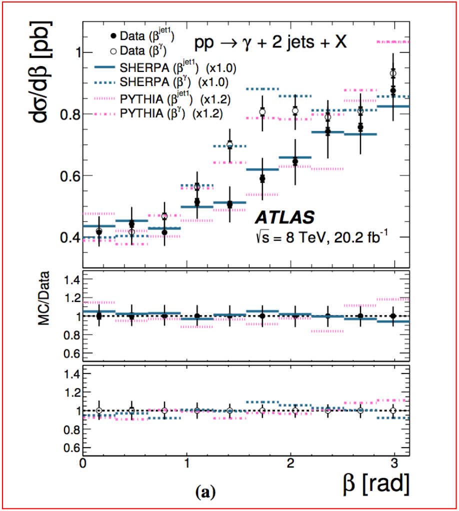


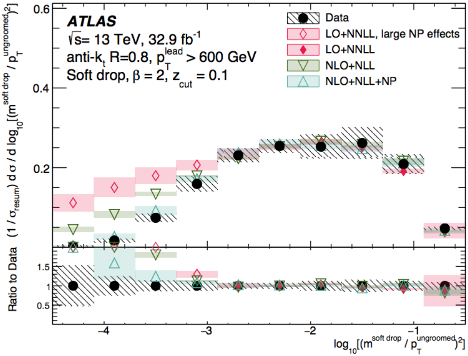
Nucl. Phys. B 918, 257 (2017)

- Even stronger correlation to opposite beam when using $\gamma-$jet!

Z-tagged jet hadronization at LHCb

Hadronization Studies at the LHC

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



PRL 121, 092001 (2018)

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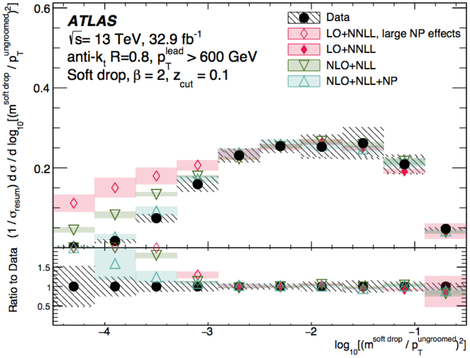

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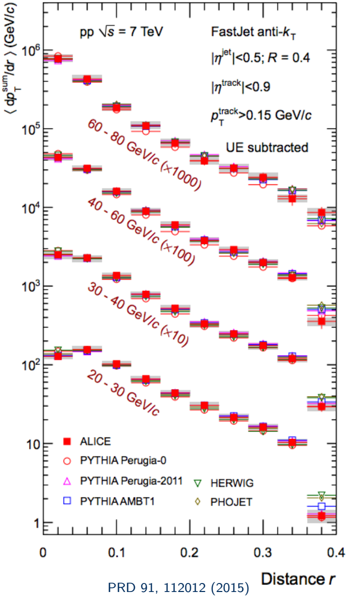

PRD 91, 112012 (2015)

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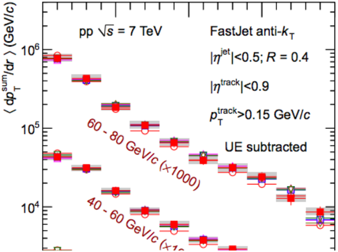
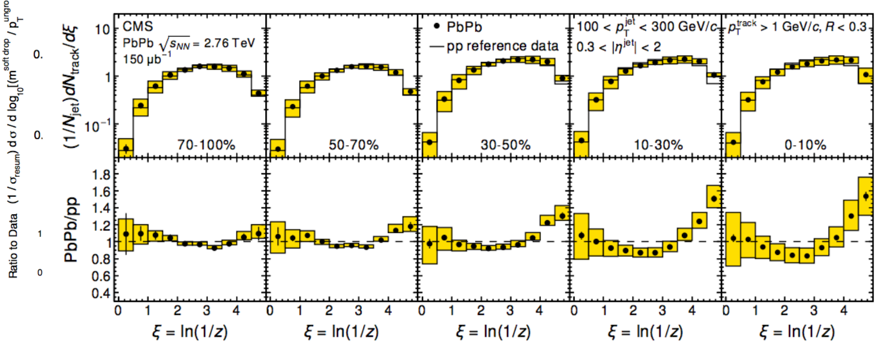
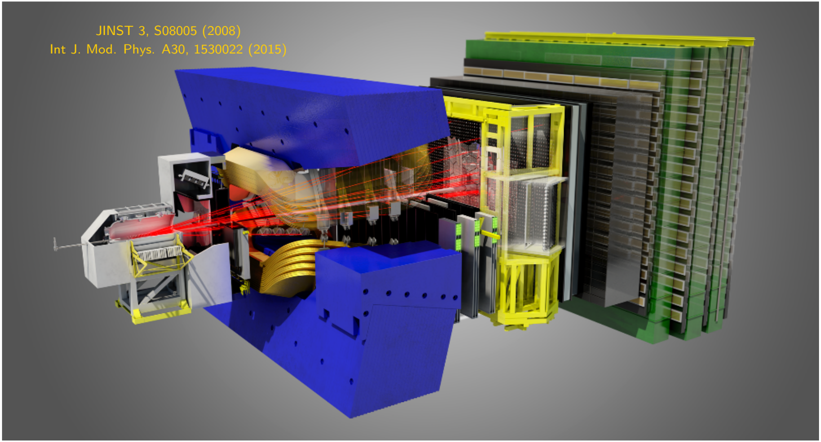




PRC 90, 024908 (2014)

LHCb Experiment


JINST 3, S08005 (2008)
Int J. Mod. Phys. A30, 1530022 (2015)

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

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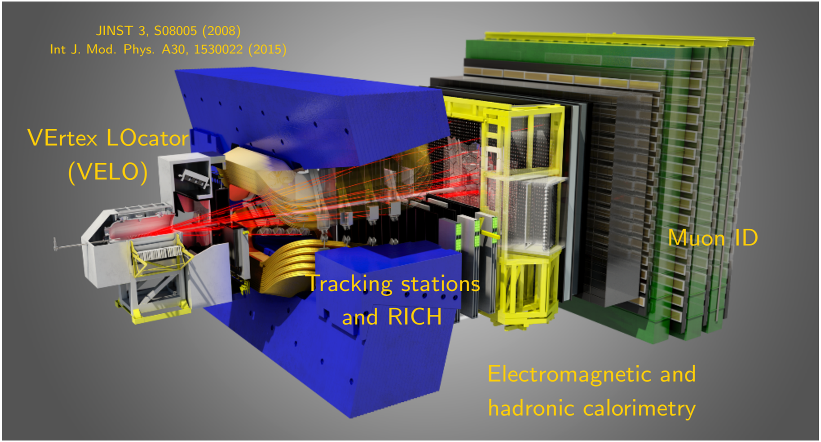
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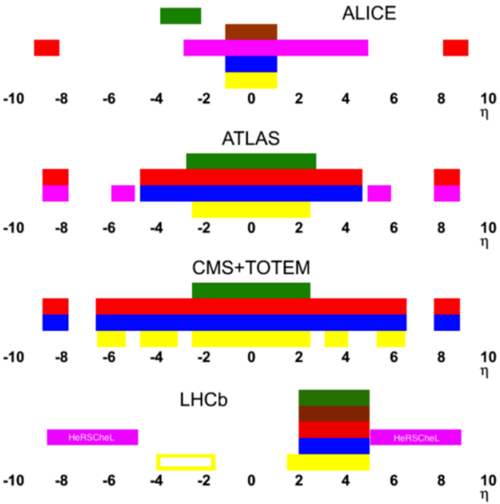
Why LHCb?



🟫 hadron PID
🟩 muon system
🟪 lumi counters
🟥 HCAL
🟦 ECAL
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- LHCb has unique advantages for jet physics over other LHC experiments
- Uniform coverage tracking, PID, *and* calorimetry

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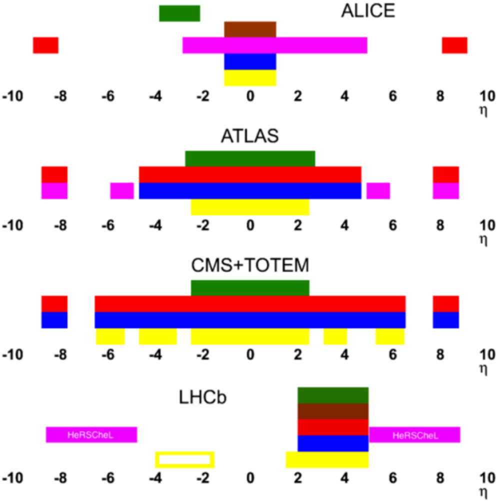

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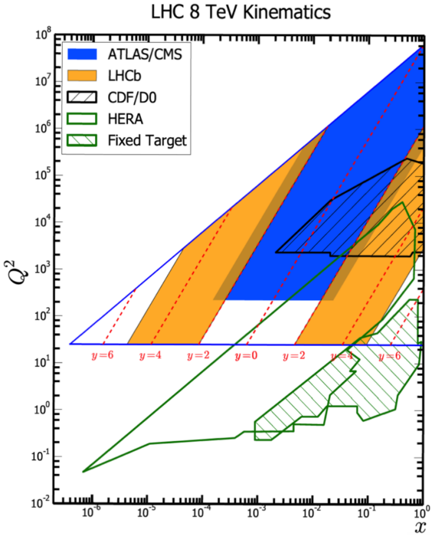

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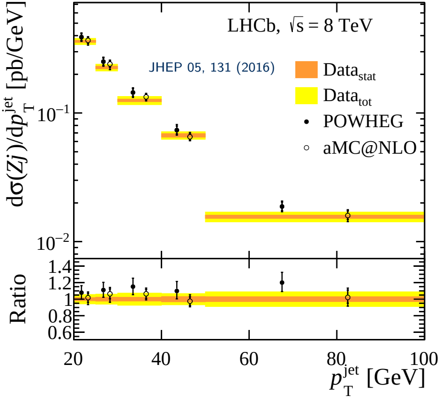
- Uniform coverage tracking, PID, *and* calorimetry
- Can identify nearly all particles within a high p_T jet
- Also occupy a unique region in (x, Q^2)

Z+jet at LHCb

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



Z+jet at LHCb

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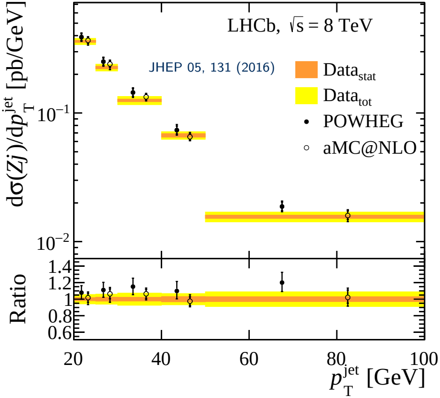
- Preferentially selects light quarks (!)
- Starkly in contrast from midrapidity inclusive jet results from CMS/ATLAS/ALICE which are gluon dominated until very high p_T ($p_T > \mathcal{O}(400)$ GeV)
- Very recent ATLAS $\gamma-$tagged jets complementary (arXiv:1902.10007)



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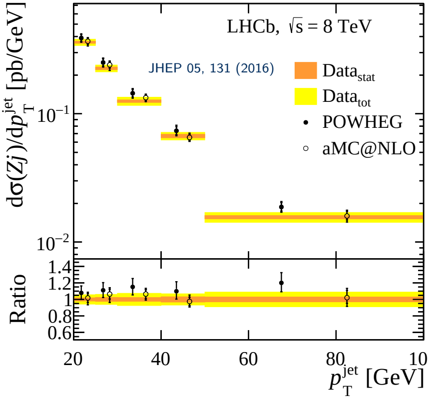
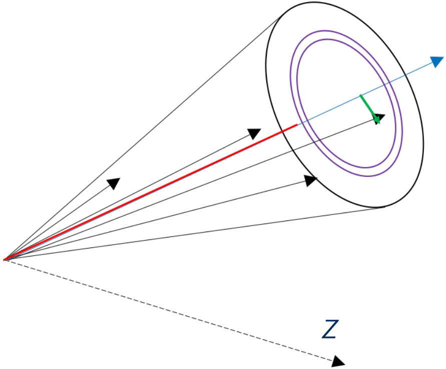


- **First LHC measurement of charged hadrons within Z tagged jets**
- **First LHC measurement of charged hadrons-in-jets at forward rapidity**

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

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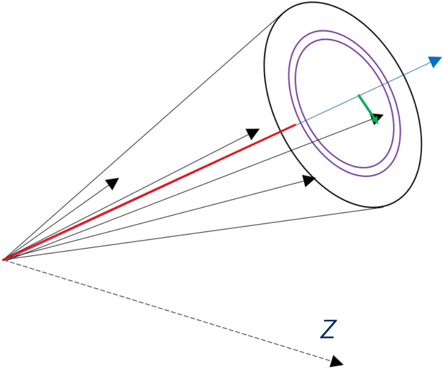

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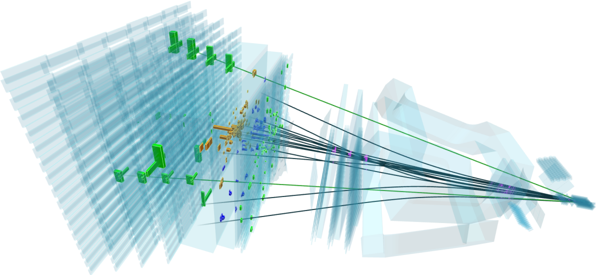
- Measure hadronization observables in two dimensions
    - Longitudinal momentum fraction z
    - Transverse momentum j_T
    - Radial profile r
- Intended to lay the foundation for a broader hadronization program at LHCb utilizing
    - Particle ID (tracking, RICH, calorimetry)
    - Heavy flavor jet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

Analysis Details

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



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

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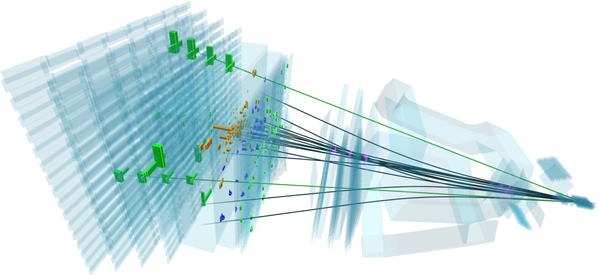
- $Z \rightarrow \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-k$_T$ jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2.5 < \eta < 4$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects $2 \rightarrow 2$ event topology



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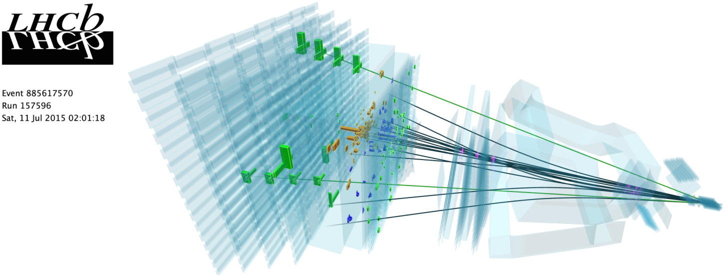

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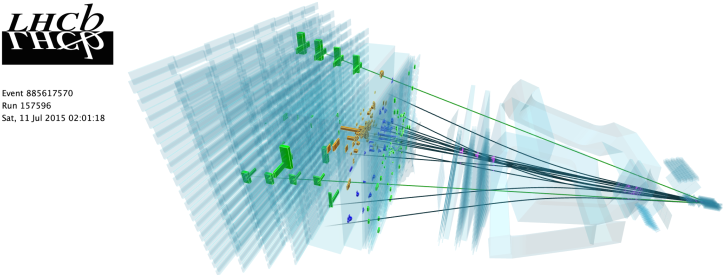
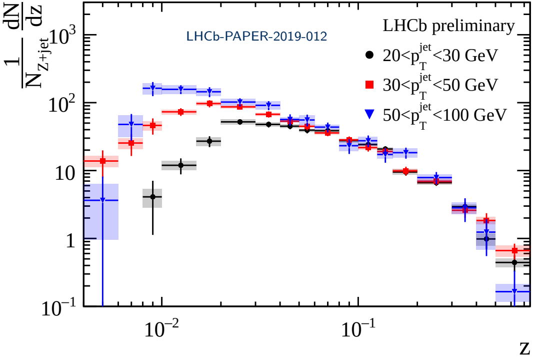
- Results efficiency corrected and 2D Bayesian unfolded

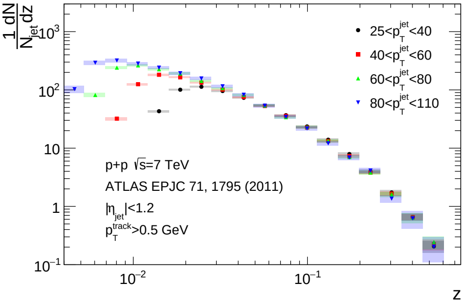


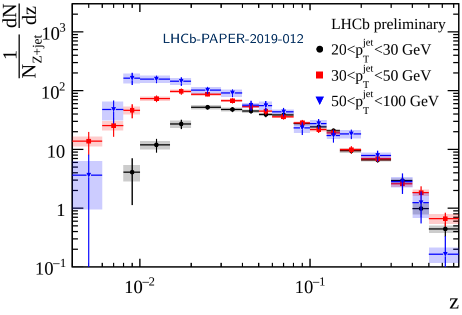
Results

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



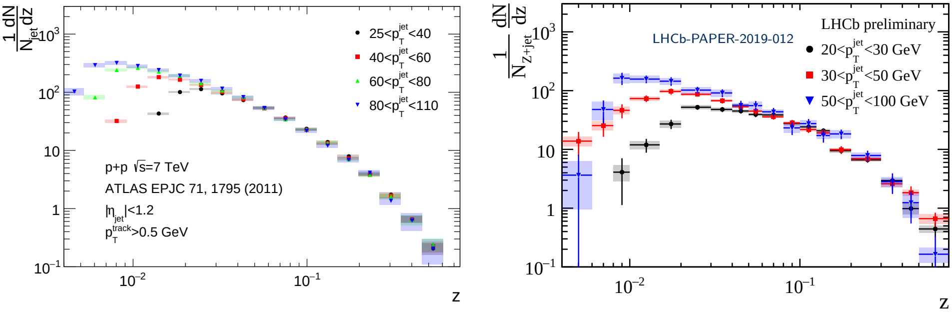
ATLAS and LHCb Comparisons





- Comparing ATLAS midrapidity inclusive jets to LHCb forward Z+jet shows longitudinal FFs “flatter” as a function of z

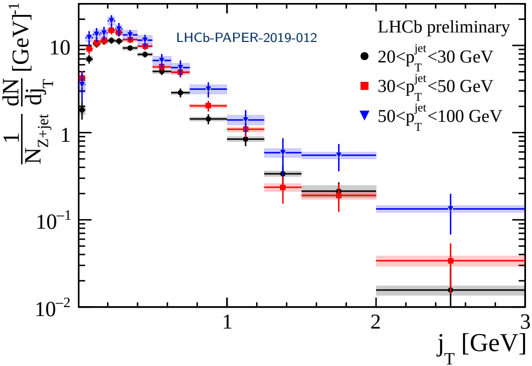
ATLAS and LHCb Comparisons



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

Results

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



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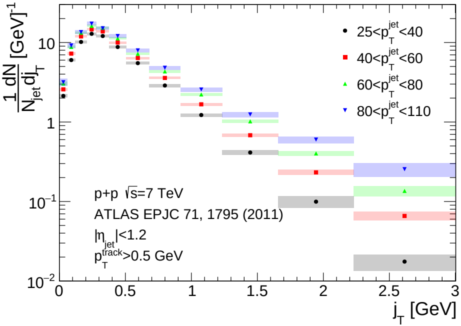
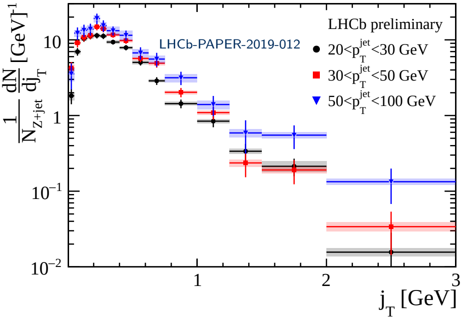
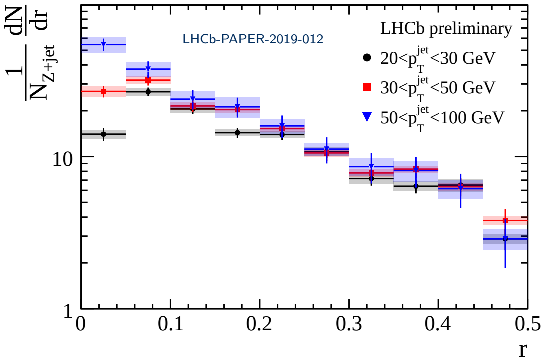




- Transverse momentum distributions show slightly smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T

Results

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



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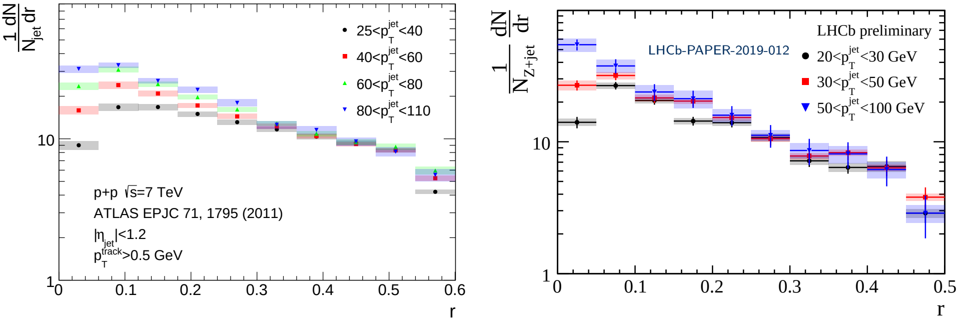

- Comparing ATLAS midrapidity inclusive jets to LHCb forward Z+jet shows jets are more collimated when tagged with a Z

Conclusions

- Color entanglement and TMD factorization breaking
    - Results from PHENIX experiment comparing evolution of TMD observables to expectations from CSS
    - Recent LHC results studying color coherence
    - Other measurements I haven't touched on sensitive to color flow (e.g. jet substructure observables)
    - A large amount of data now exists, perhaps not with enough TMD sensitivity, but is worth looking into (e.g. arXiv:1902.04374)

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- More results to come from LHCb utilizing PID, heavy flavor ID, and calorimetry

Discussions and/or ideas about observables of interest are more than welcome!

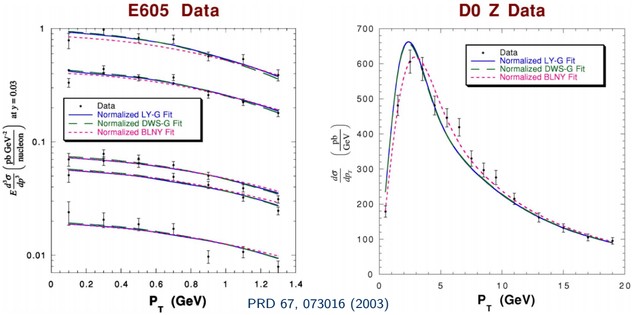
Back Up

Color in QCD

- QCD is a non-Abelian quantum field theory
- Fermions and bosons in QCD have color charge
- Color has always been an integral part of the theory
- However the last several decades have illuminated some of the specific consequences that color can have within QCD!

Collins-Soper-Sterman (CSS) Evolution with Q^2

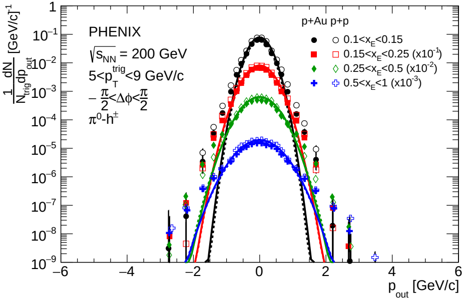
- CSS evolution first published in 1985. Similar to DGLAP evolution equation, but includes small transverse momentum scale
- Has been used to successfully describe global Drell-Yan and Tevatron Z^0 cross sections
- Clear qualitative prediction - momentum widths sensitive to nonperturbative transverse momentum increase with increasing hard scale
- Due to increased phase space for gluon radiation



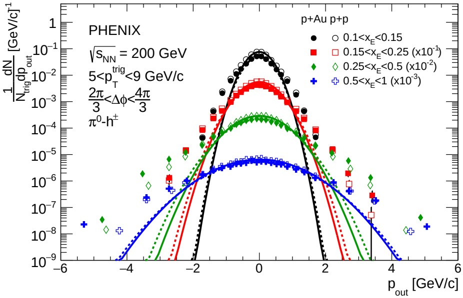
PRD 67, 073016 (2003)

Extending Color Studies to p+A

- Dihadrons give additional QCD interactions in p+A collisions compared to direct photon-hadrons
- Measure the p_{out} distributions on both the near-side and away-side in p+p and p+A to compare



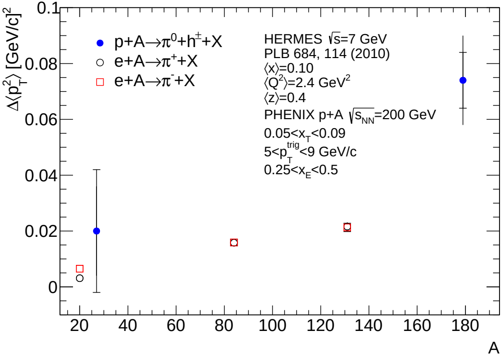
Near-side



Far-side

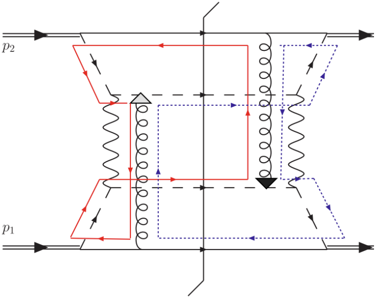
Broadening as a Function of Nucleus Size

- Interesting to compare to other collision systems, e.g. HERMES $e + A$ data
- Caveats - kinematics. . .



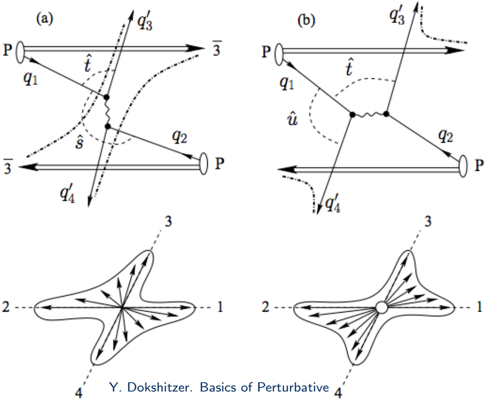
Example 2: Color Coherence

Color entanglement



PRD 81, 094006 (2010)

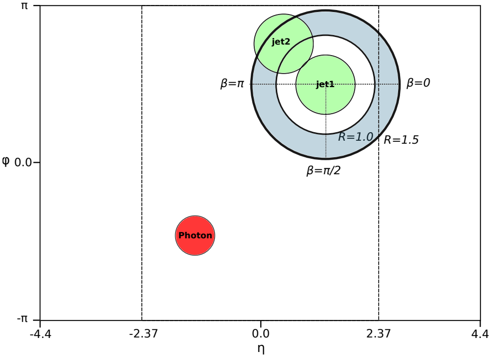
Color coherence



Y. Dokshitzer. Basics of Perturbative QCD, 1991

- The same underlying QCD phenomena at play - color leads to nonperturbative consequences

Color Coherence Measurements



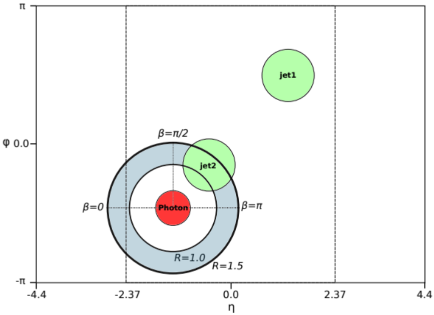
Nucl. Phys. B 918, 257 (2017)

- Color coherence measurements study:

$$\beta = \tan^{-1}\frac{\Delta\phi_{21}}{\mathrm{sign}(\eta_1)\Delta\eta_{21}}$$

- Angle in $(\phi,\ \eta)$ space between sub-leading hard-scattered jet and gluon initiated jet
- $\beta = 0$ points to the beam closer to jet 1 in (ϕ, η) space
- $\beta = \pi$ points to the beam farther from jet 1 in (ϕ, η) space

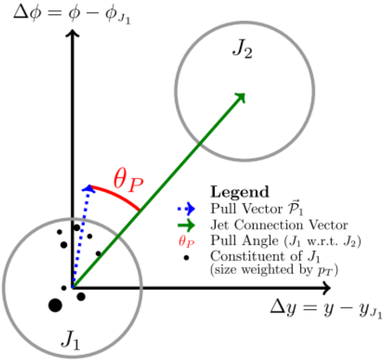
β_γ Definition



- ATLAS collaboration also measures β_γ, defined in a similar way to β_{jet}

$$\beta^\gamma = \tan^{-1}\frac{|\phi^{jet2}-\phi^\gamma|}{\mathrm{sign}(\eta^\gamma)\cdot(\eta^{jet2}-\eta^\gamma)}$$

Example 3: Jet Substructure

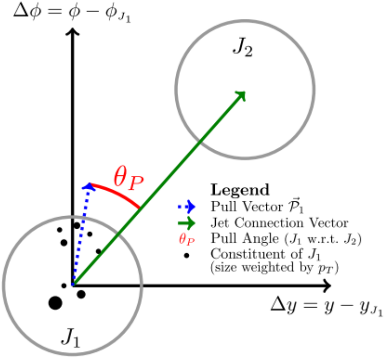


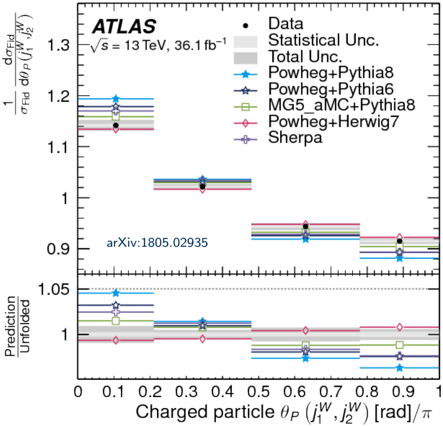
Jet-pull vector predicted to be sensitive to color connections (PRL 105, 022001 (2010))

$$\vec{\mathcal{P}}(j) = \sum_{i\epsilon j} \frac{\left|\vec{\Delta r}_i\right| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i$$

- Absence of color connection - θ_p expected to be distributed uniformly
- Color connection - θ_p expected to preferentially lie along jet connection vector $\theta_p \sim 0$

Example 3: Jet Substructure

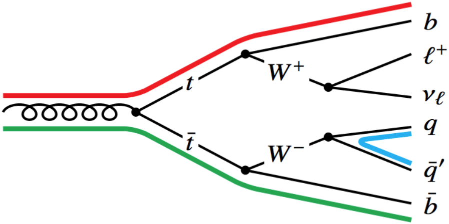




- Jet pull angle preferentially $\sim 0 \rightarrow$ color connections
- Color affects radiation patterns within jets

$t\bar{t}$ Color Topology

- Example $t\bar{t}$ color topology
- $t\bar{t}$ are color connected via gluon splitting
- Hadronizing quarks from W decays can also be color connected



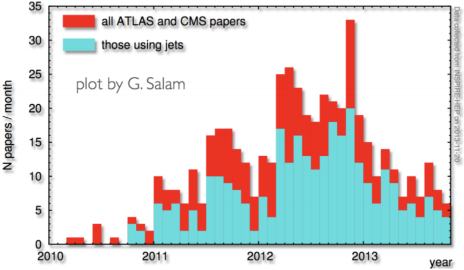
“Global Fits”??

- A wealth of data that should be sensitive to TMD color entanglement effects now exists from RHIC and the LHC
- At least $\Delta\phi$ correlations exist in all of these publications
- Are “phenomenological” studies now possible? Need to also encourage experimental colleagues to measure additional observables (not only $\Delta\phi$)

- Dihadron/γ-hadron
    - Phys. Rev. D 82, 072001 (2010)
    - Phys. Lett. B 760, 689 (2016)
    - Phys. Rev. D 95, 072002 (2017)
    - Phys. Rev. D 98, 072004 (2018)
    - arXiv:1809.09045
- Dijet/$\gamma(W^{\pm}, Z)$-jet
    - Phys. Rev. Lett. 106, 172002 (2011)
    - Nucl. Phys. B 875, 483 (2013)
    - Phys. Lett. B 722, 238 (2013)
    - Phys. Lett. B 741, 12 (2015)
    - JHEP 1704, 022 (2017)
    - Nucl. Phys. B 918, 257 (2017)
    - Phys. Rev. D 96, 072005 (2017)
    - Phys. Rev. D 95, 052002 (2017)
    - arXiv:1901.10440
    - arXiv:1902.04374
    - . . .

Jet Hadronization

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



Jet Hadronization

- Jet physics is a broad experimental endeavor at LHC
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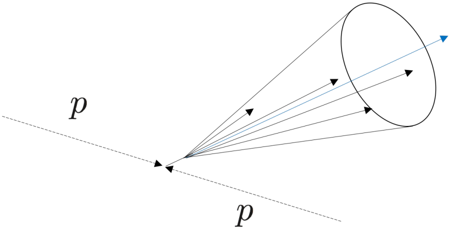
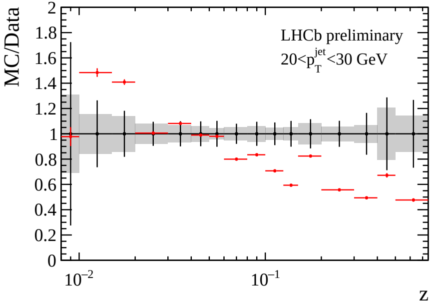
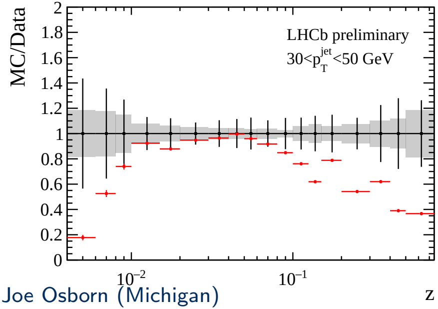
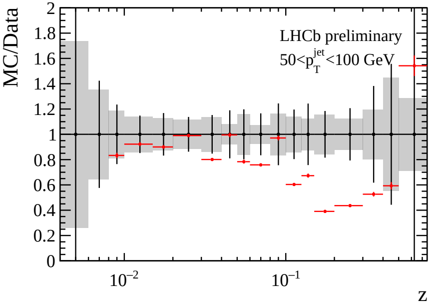
- Jets are a proxy for partons, and thus provide a way to have sensitivity to the underlying partonic dynamics



Comparisons with PYTHIA (z)

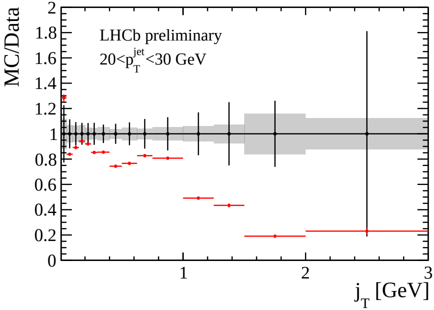


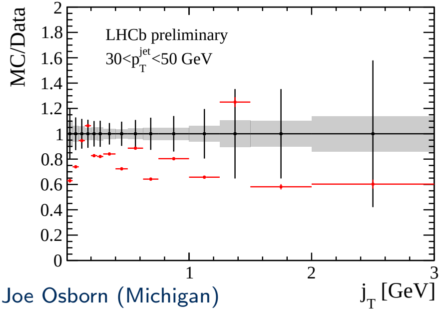


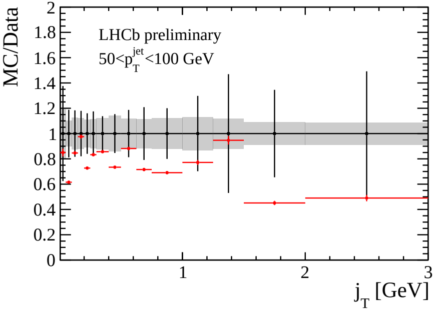


- PYTHIA generally underpredicts the number of high z hadrons

Comparisons with PYTHIA (j_T)

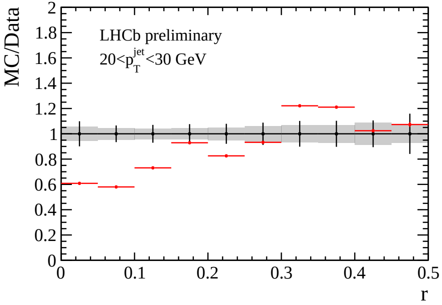


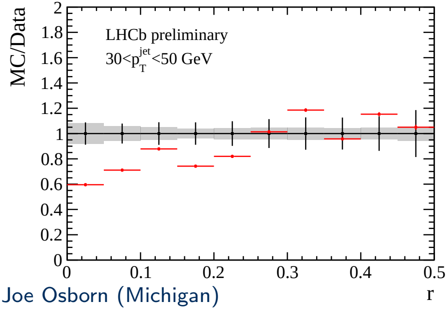


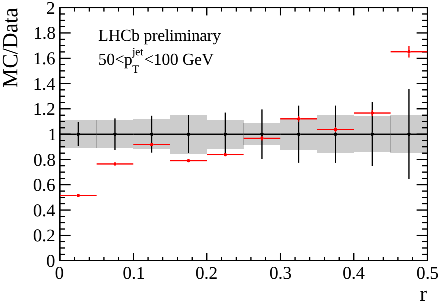


- PYTHIA generally gets j_T shape, with about a 20% difference in normalization

Comparisons with PYTHIA (r)

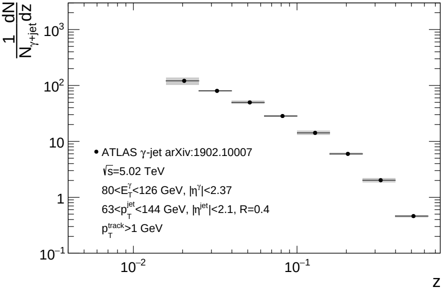


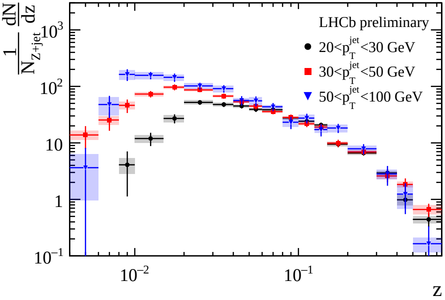




- PYTHIA generally underpredicts the number of small r hadrons

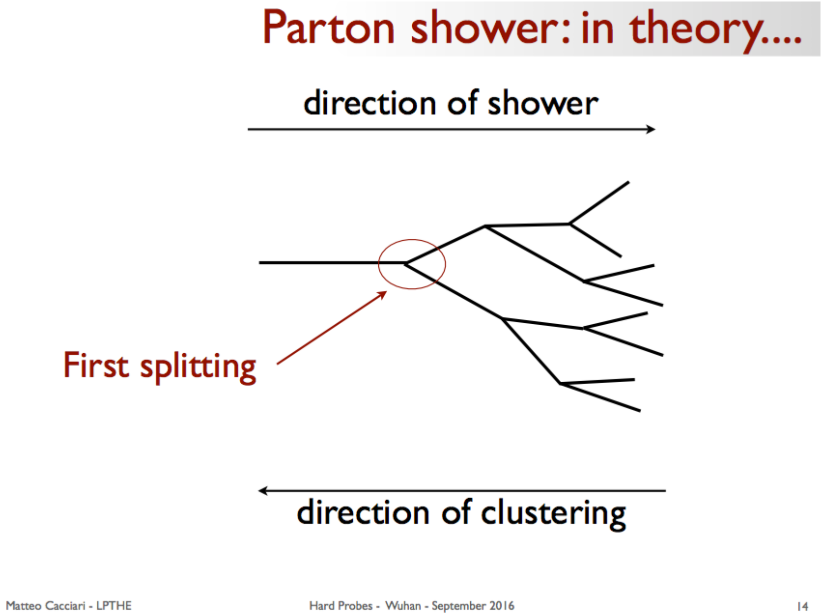
Comparison to ATLAS γ-jet





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

Jet Formation



Parton shower: in theory....

direction of shower

First splitting

direction of clustering

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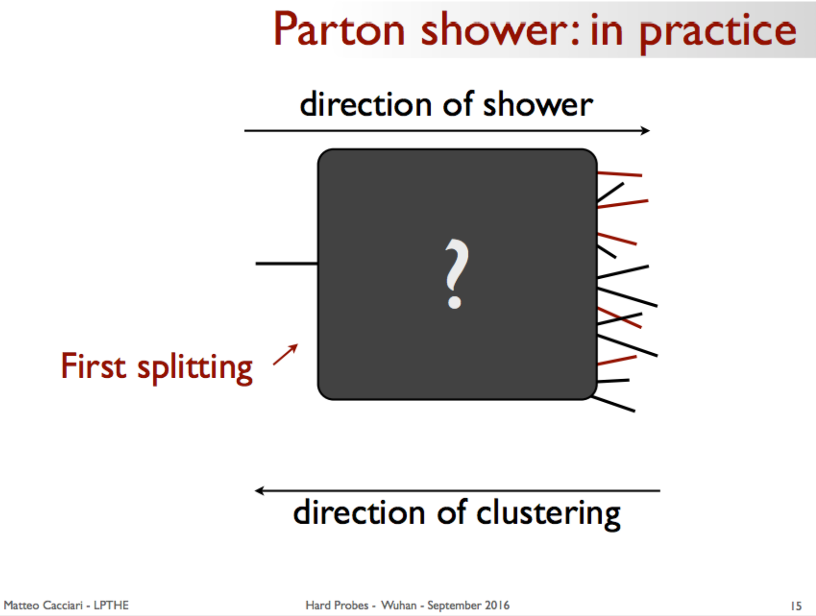
Jet Formation



Parton shower: in practice

direction of shower

First splitting

direction of clustering

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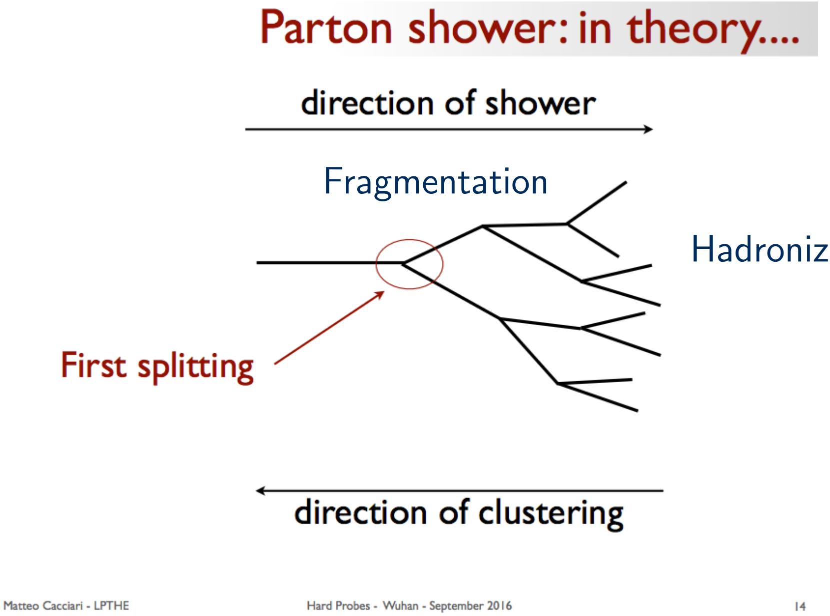
Jet Formation



Parton shower: in theory....

direction of shower

First splitting

direction of clustering

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Fragmentation

Hadronization