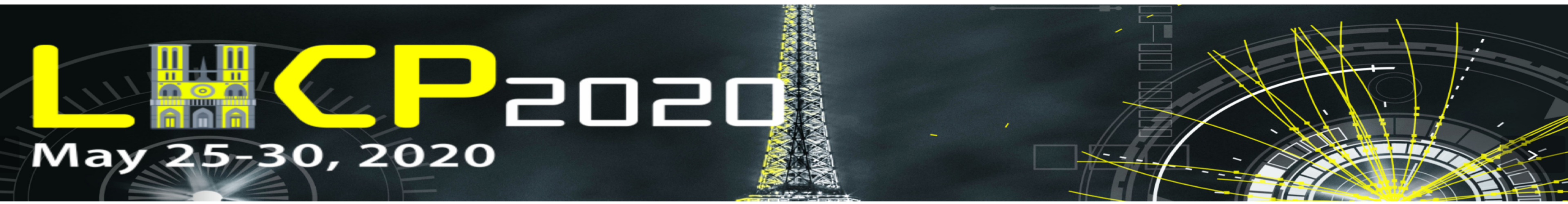

Charged hadron distributions in Z-tagged jets

Sookhyun Lee on behalf of the **LHCb** collaboration

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LHCP 2020, Paris

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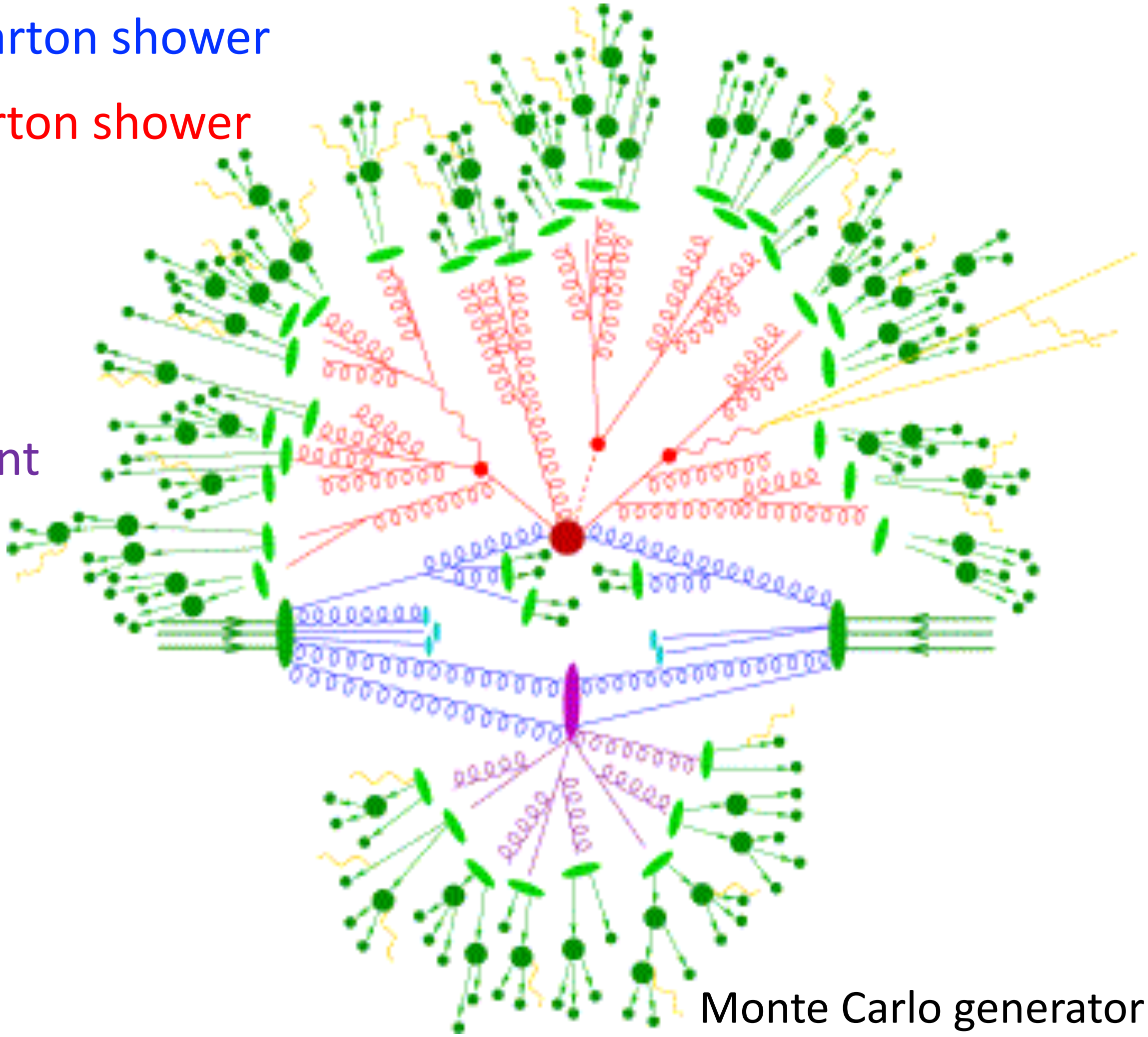
May 27, 2020

A proton + proton collision

- (Initial state) Parton shower
- (Final state) Parton shower
- **Hadronization**
- Hadron decays
- Beam remnant
- Underlying event

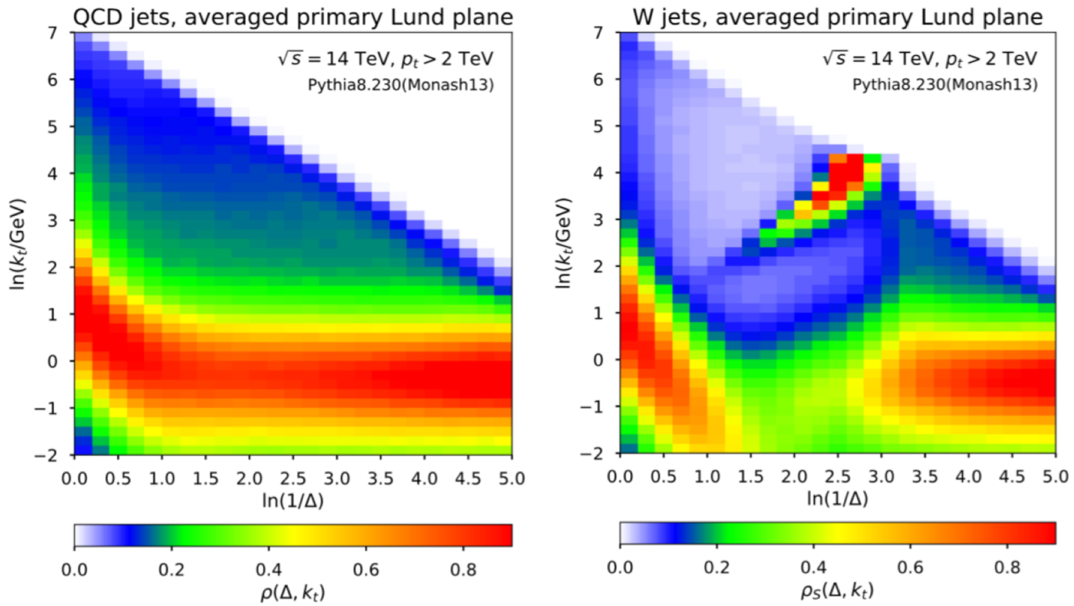


Monte Carlo generator representation
Prog. Part. Nucl. Phys. **53**, 329 (2004)

Jet substructure/event shape

- Motivated mostly by search for new particles and BSM physics
- Within QCD, emphasis is on perturbative part of process, e.g.
  - Splitting functions,
  - Constraining α_s
- Theory revolutionized & experimental techniques developed in past decade, e.g.
  - Soft Collinear Effective Field Theory,
  - Sophisticated jet grooming algorithms
- Great opportunity to study hadronization processes!

JHEP12, 064 (2018)



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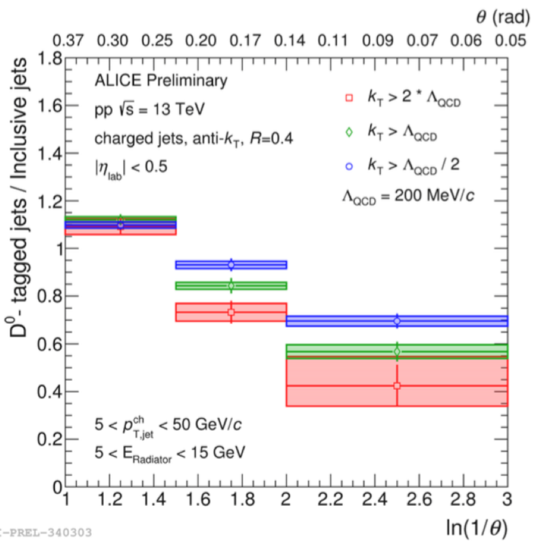

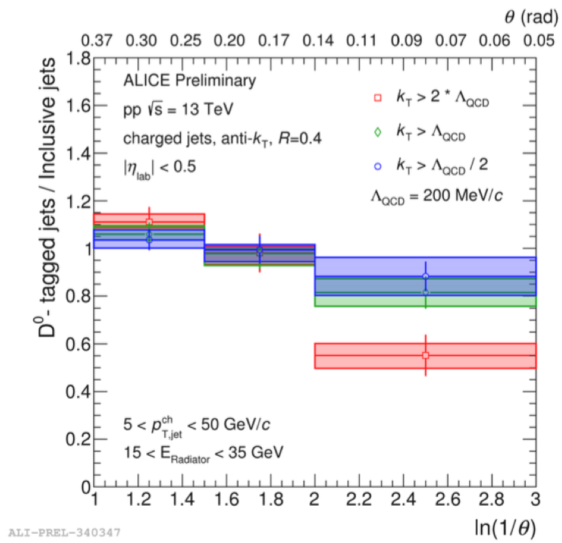

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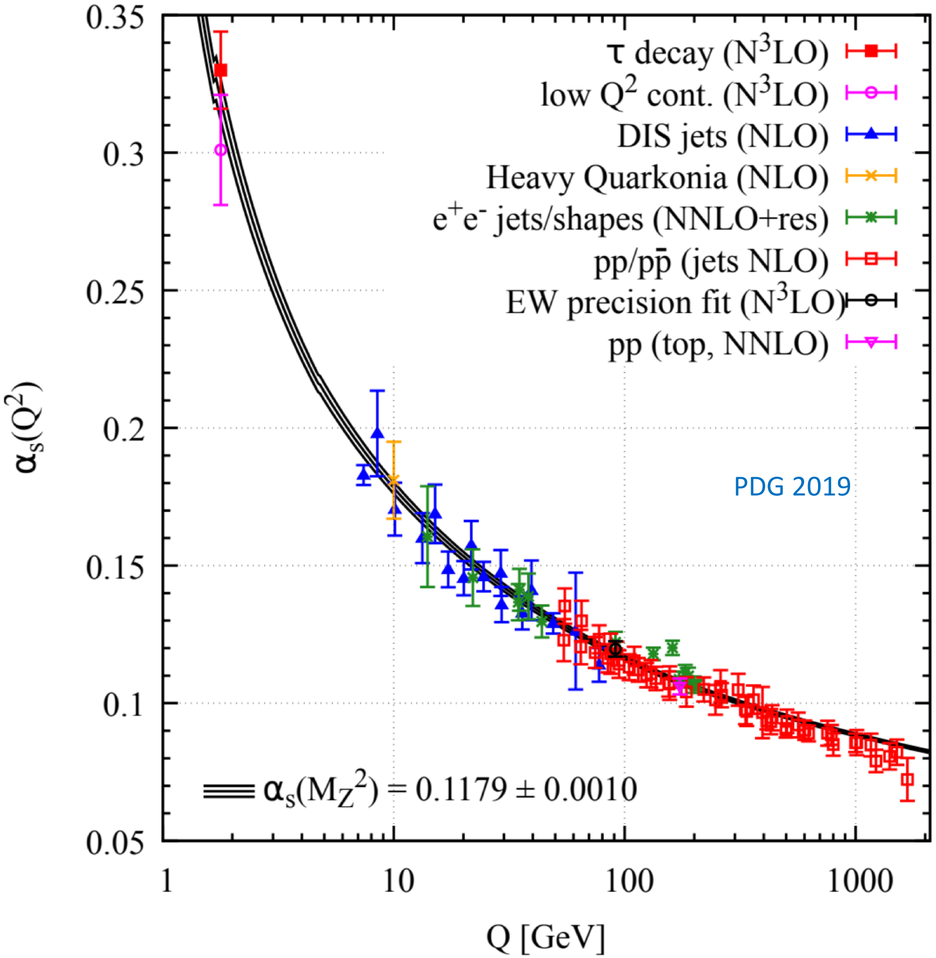
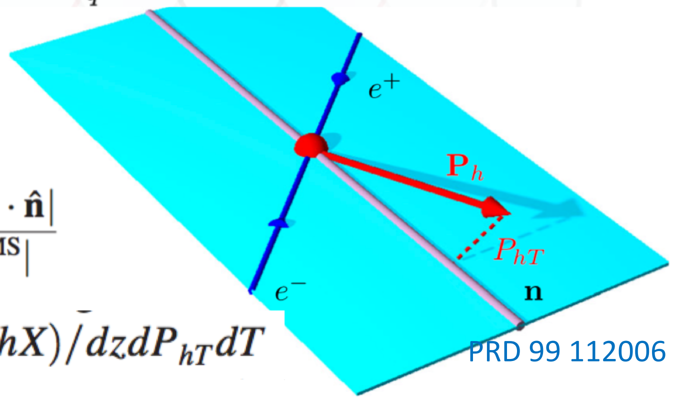


Fragmentation functions (FF)

- e^+e^- annihilation:

$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(\underline{D_{1,q}^h(z, k_t, Q^2)} + D_{1,\bar{q}}^h(z, k_t, Q^2)\right)$$



$$T \stackrel{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

$$d^3\sigma(e^+e^- \rightarrow hX)/dz dP_{hT} dT$$

PRD 99 112006 (2019)

- Initially constructed in e+e-, where no parton distribution function (PDF) is needed, as a function of z, longitudinal momentum fraction of outgoing parton carried by final state hadrons : **collinear FF**
- More recently, BELLE made measurements that can provide access to **unpolarized transverse momentum dependent (TMD) FF's**

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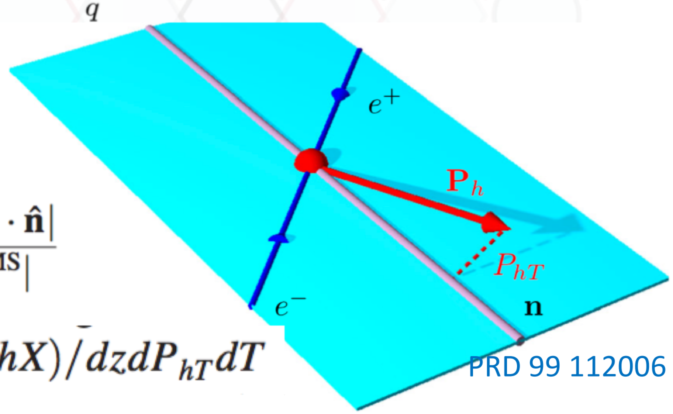

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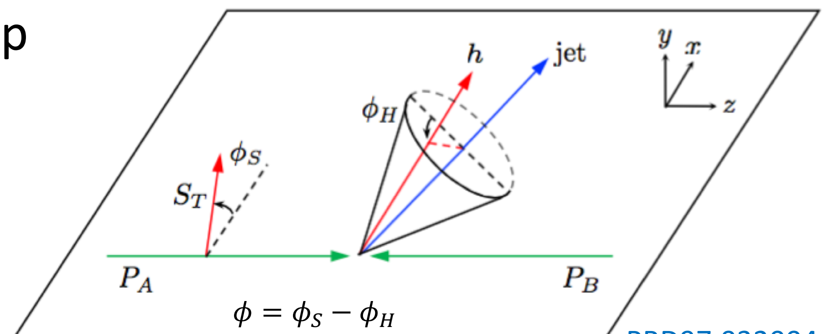
PRD 99 112006 (2019)

- pp



PRD97,032004 (2018)

$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)} \propto \underline{H^\perp_{1\,h/c}(z_h, j_\perp^2; Q)}$$

: Transverse Single Spin Asymmetry (TSSA)

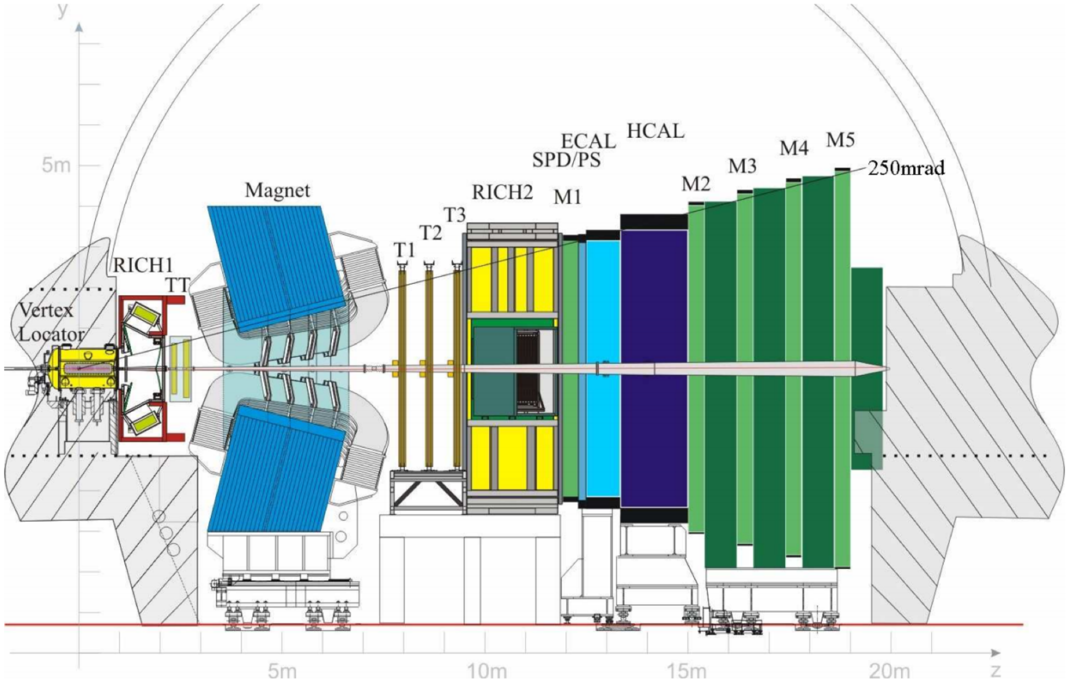
- Initially constructed in e+e-, where no parton distribution function (PDF) is needed, as a function of z, longitudinal momentum fraction of outgoing parton carried by final state hadrons : **collinear FF**
- More recently, BELLE made measurements that can provide access to **unpolarized transverse momentum dependent (TMD) FF's**
- Also, STAR measured TSSA of hadrons within a jet that enables access to Collins (polarized TMD) FF's; new approach.
- We can access **collinear FF**'s as well as **unpolarized TMD FF**'s by measuring **hadron distributions within Z tagged jets at LHCb**!

The LHCb Detector

Detector design:

- Forward geometry to optimize acceptance for $c\bar{c}$ and $b\bar{b}$ pairs : $2 < \eta < 5$
- VErtex LOcator (VELO): vertex position, lifetime and impact parameter.
- Tracking stations TT, T1-T3 and dipole magnet: momentum of charged particles.
- PID system (RICH, calorimeters): π/K/p separation, triggering on high p_T hadrons and $e^{\pm}$, γ energy.
- Muon stations M1-M5: triggering on muons, tracking stations for muon identification.

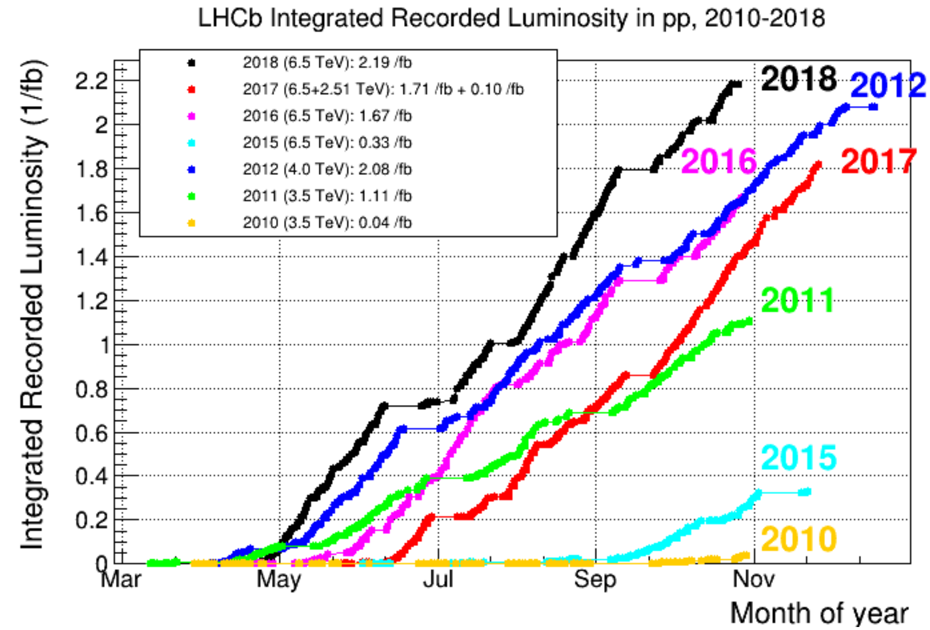
[JINST 3 (2008) S08005]
[Int. J. Mod. Phys. A 30 (2015) 1530022]



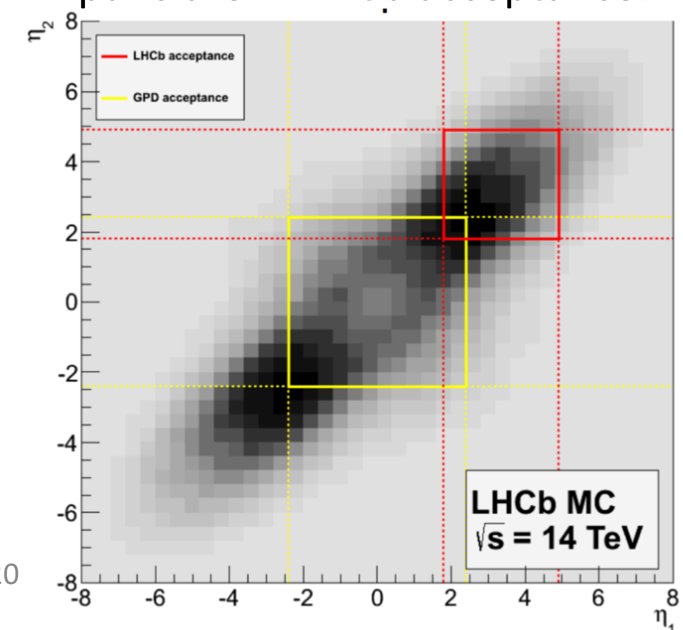
Features attractive for hadronization studies:

- Full jet reconstruction with tracking, ECAL and HCAL
- Tagging of jets from light-quark, c- and b-quark
- Charged hadron identification from 2 < p < 100 GeV/c
- Large pp datasets available from Run I (3.23/fb at √s = 7-8 TeV) and Run II (5.9 /fb at √s = 13 TeV)

Can study identified hadron distributions within jets!

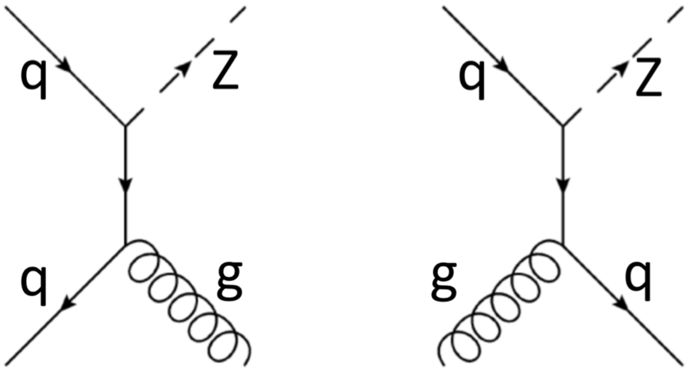


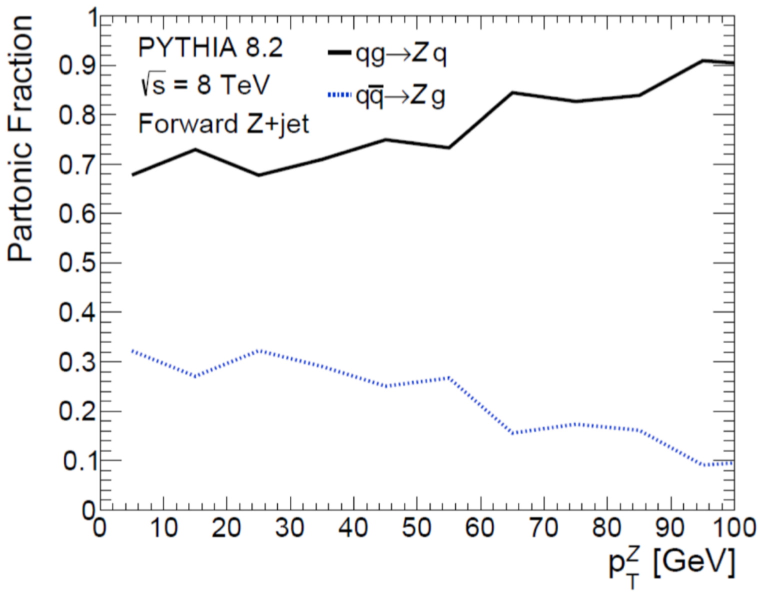
~40% of all produced $c\bar{c}$ and $b\bar{b}$ pairs are in LHCb acceptance.



Studying hadronization in jets: Z^0 tagged jets at LHCb

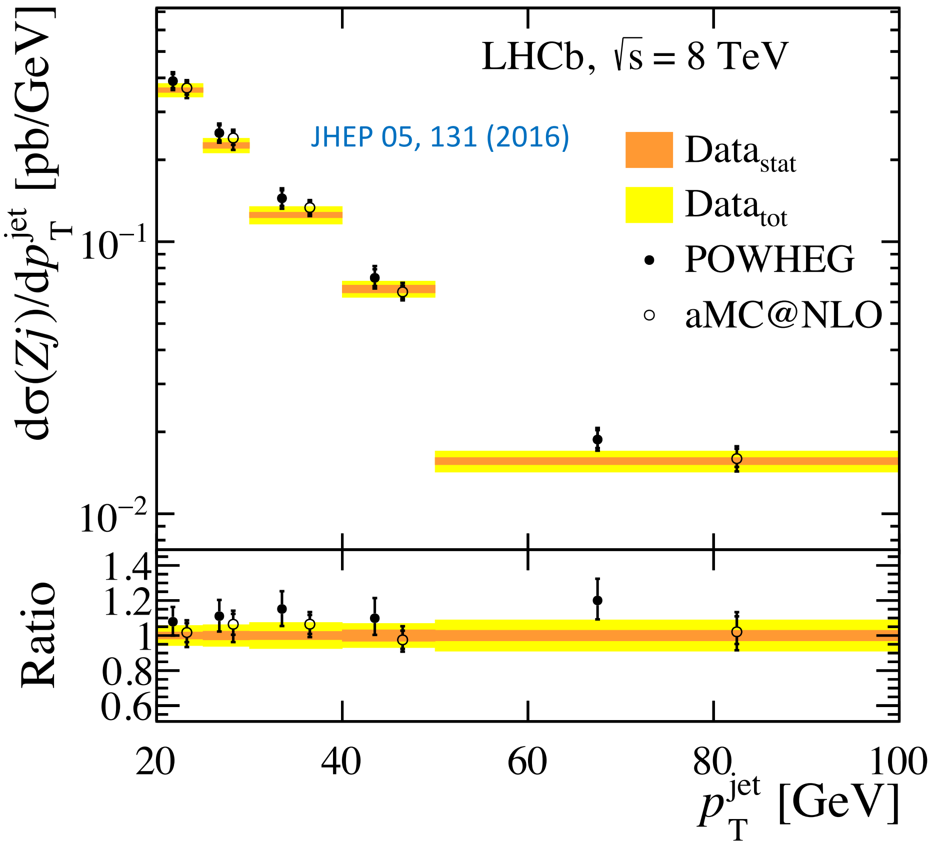
- Z boson + jet production is predominantly sensitive to quark initiated jets.
- Forward kinematics further increases fraction of light quark jets, in particular up and down flavored quarks
- Events are selected such that there is a back-to-back ($\Delta\varphi > 7/8\,\pi$) Z + leading jet pair present per event.





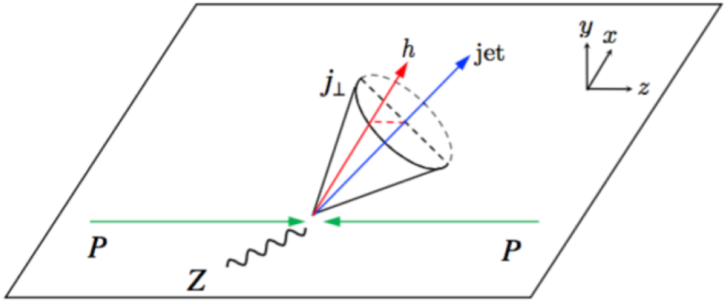
Studying hadronization in jets: Z^0 tagged jets at LHCb

- LHCb previously measured Z0 + jet cross section
  - JHEP 05, 131 (2016)
- Now have measured unidentified charged hadron distributions within the jet in the same dataset.
  - PRL 123, 232001 (2019)
- First measurement at the LHC of charged hadrons within Z^0-tagged jets and also at forward rapidity.
- Measurement of identified hadron distributions within the jet under way.



Charged hadrons in jets : Observables

- Longitudinal momentum fraction z
- Transverse momentum with respect to jet axis j_T
- Radial profile r



Lays the foundation for a broader hadronization program at LHCb utilizing

- Full particle identification
- Charm- and beauty-initiated jets
- Multiparticle correlations within jets
- Hadron distributions in correlated jet pairs

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

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

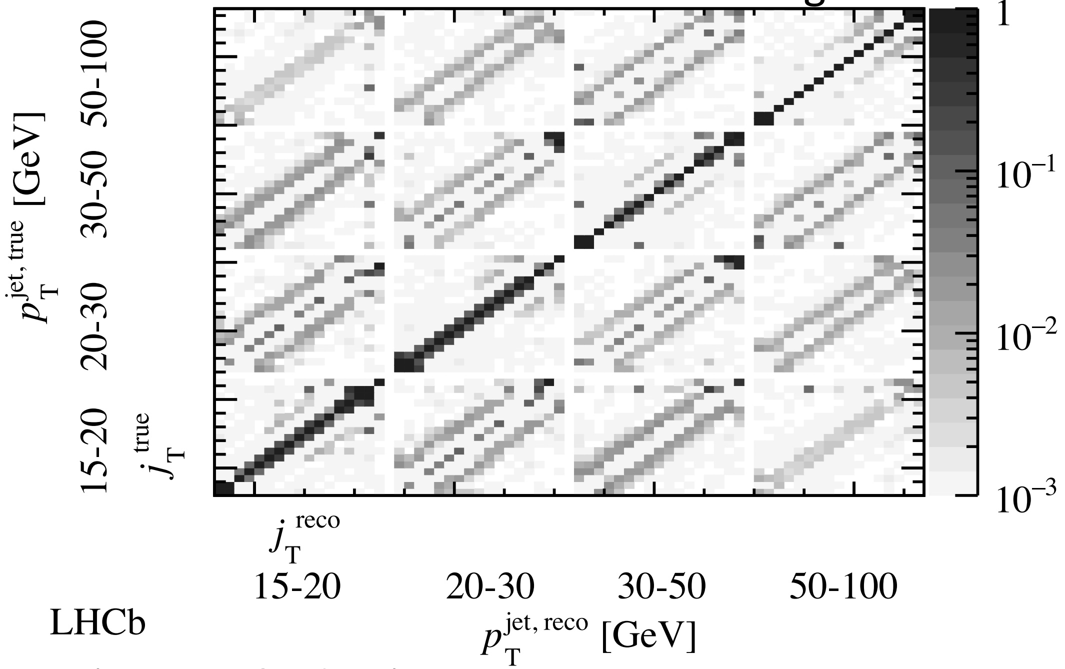
$$r = \sqrt{(\phi_{jet} - \phi_h)^2 + (y_{jet} - y_h)^2}$$

Analysis

PRL 123, 232001 (2019)
LHCb-PAPER-2019-012

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

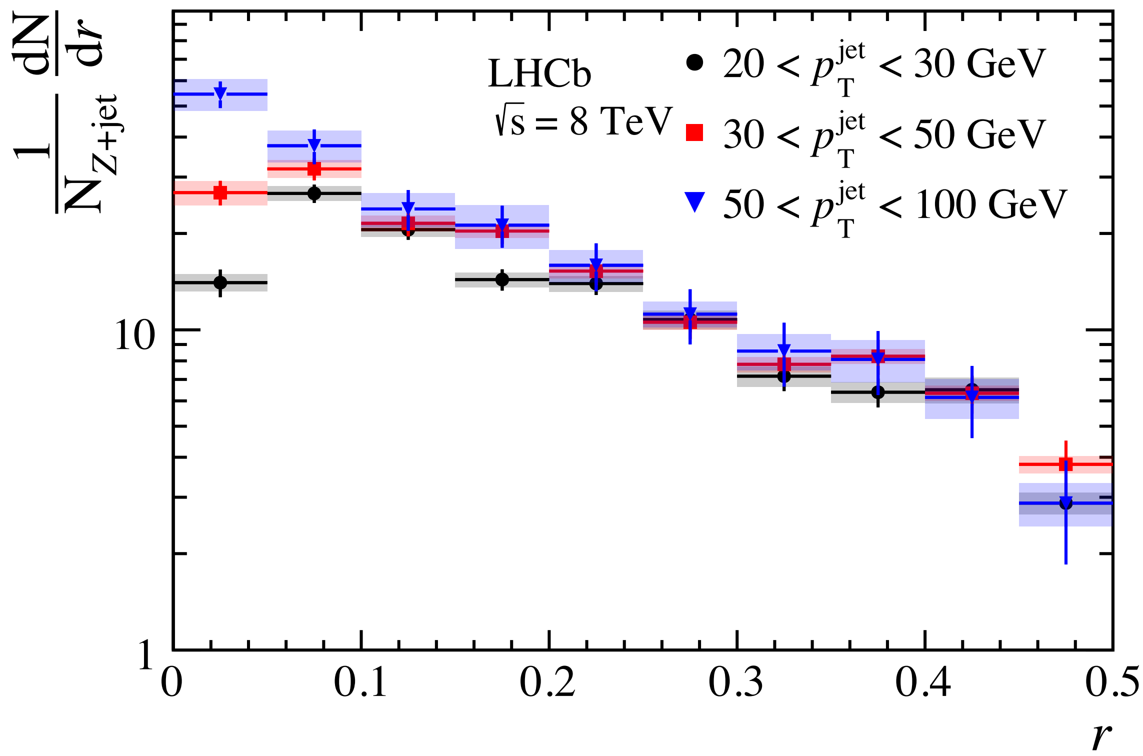
Covariance matrix for unfolding



Results: Radial profile

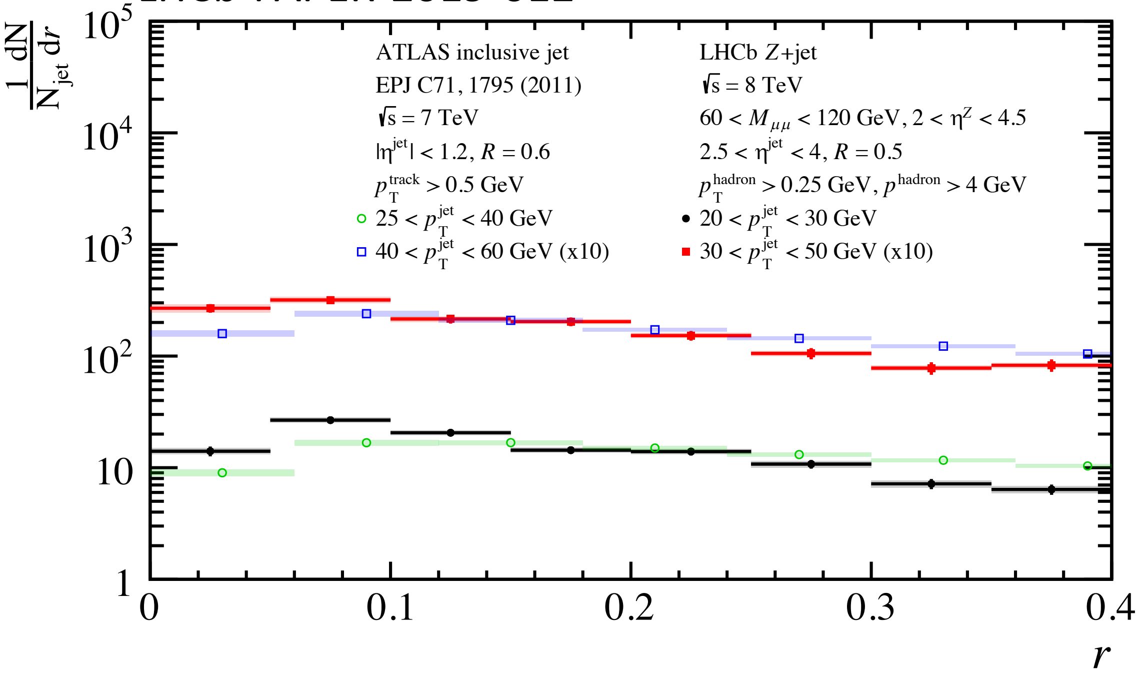
PRL 123, 232001 (2019)
LHCb-PAPER-2019-012

- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced
- Almost all of the additional particles are produced close to the jet axis, and go from a depletion to an excess



Quark- vs. gluon-initiated jets : Radial profile

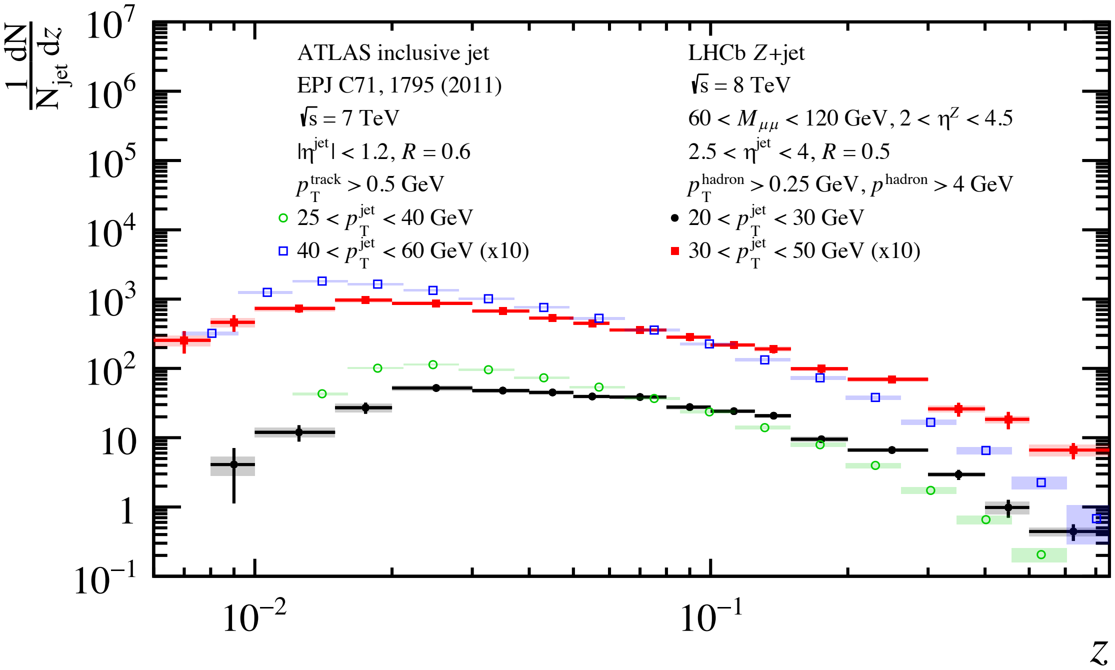
PRL 123, 232001 (2019)
LHCb-PAPER-2019-012



- Quark-initiated jets narrower (more collimated) than gluon-initiated jets measured by ATLAS.
- i.e. more charged hadrons at small radii, fewer at large radii.
- Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data.

Quark- vs. gluon-initiated jets : Longitudinal profile

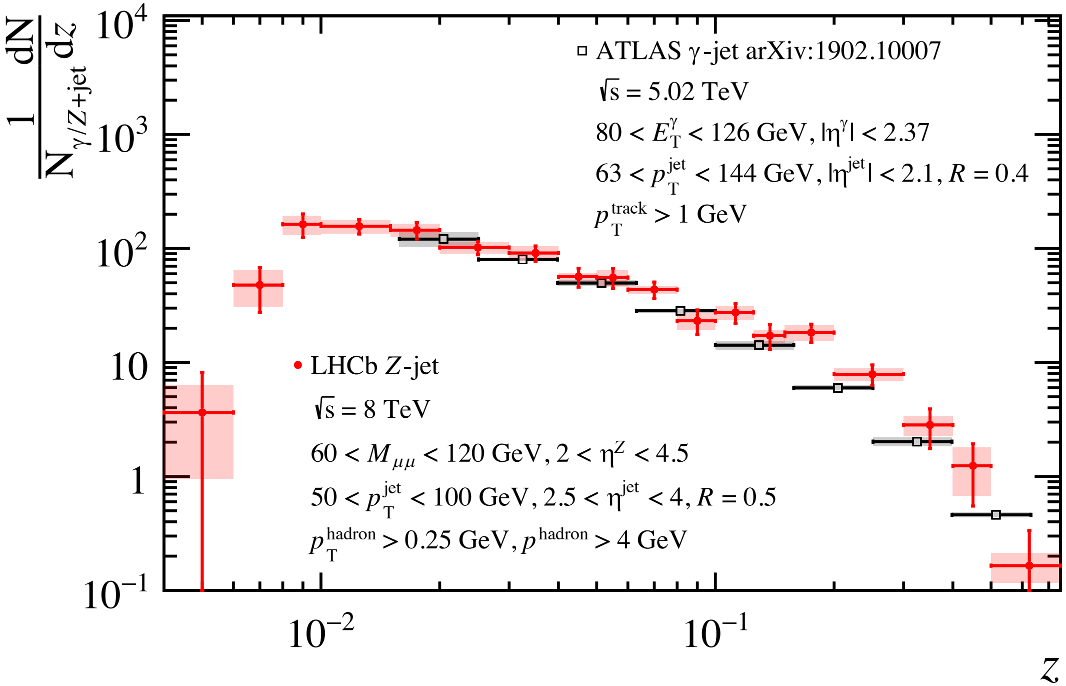
PRL 123, 232001 (2019)
LHCb-PAPER-2019-012



- Quark-initiated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-initiated jets
- Measuring identified charged hadron distributions will be sensitive to the quark flavor transition between hard scattering and formation of a hadron at high z.

Quark- vs. gluon-initiated jets : Longitudinal profile

PRL 123, 232001 (2019)
LHCb-PAPER-2019-012



- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal momentum distributions are more similar
- γ+ jet, like Z+jet, enhances quark jet fraction
- Further evidence that differences observed between LHCb and ATLAS results are due to differences in quark and gluon hadronization

Future work

PLB 798, 134978 (2019)

$$\frac{d\sigma^h}{d\mathcal{PS}\,dz_h\,d^2\boldsymbol{j}_\perp} = \sum_{a,b,c}\int d\phi_J \int \prod_{i=1}^{4} d^2\boldsymbol{k}_{iT}\,\delta^2\Big(\boldsymbol{q}_T - \sum_i^4 \boldsymbol{k}_{iT}\Big) f_a(x_a, k_{1T}^2, \mu, \nu) f_b(x_b, k_{2T}^2, \mu, \nu)$$
$$\times S^{\text{global}}_{n\bar{n}n_J}(\boldsymbol{k}_{3T}, \mu, \nu) S^{cs}_{n_J}(\boldsymbol{k}_{4T}, R, \mu) H_{ab\to cZ}(p_T, m_Z, \mu)\, \mathcal{G}_c^h(z_h, p_{JT}R, \boldsymbol{j}_\perp, \mu)\,,$$

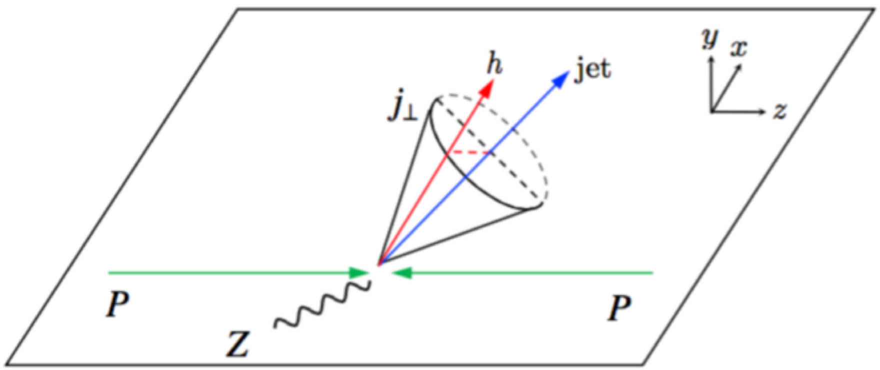
$\sim\widehat{D}_{h/c}(z_h, j_\perp, \mu_J)$ **: TMD FF**

Two-dimensional analysis of hadron distributions

- $j_\perp$ vs z : Access to unpolarized Transverse-momentum-dependent Fragmentation Functions (TMD FF)

Identified charged hadron distributions in jets & charge ratio thereof

- Statistical sensitivity to flavor of quarks that initiate jets



Conclusion

- Jet substructure/event shape research advanced in past decade improved our knowledge of QCD.
- TMD observables have gained much interest in nuclear physics community and unpolarized TMD fragmentation functions are poorly constrained.
- LHCb has full potential of measuring identified hadron distributions within a jet in order to access unpolarized TMD fragmentation functions.
- First measurement of unidentified hadron distributions within a jet has been recently published, showing results that are
  - in contrast to inclusive jets results from ATLAS.
  - similar to photon+jet results from ATLAS.
- Lays the foundation for a variety of future measurements related to hadronization in jets.