



Studying hadronization at LHCb

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on behalf of the **LHCb** collaboration

XXVIII International Workshop on DIS and related subjects

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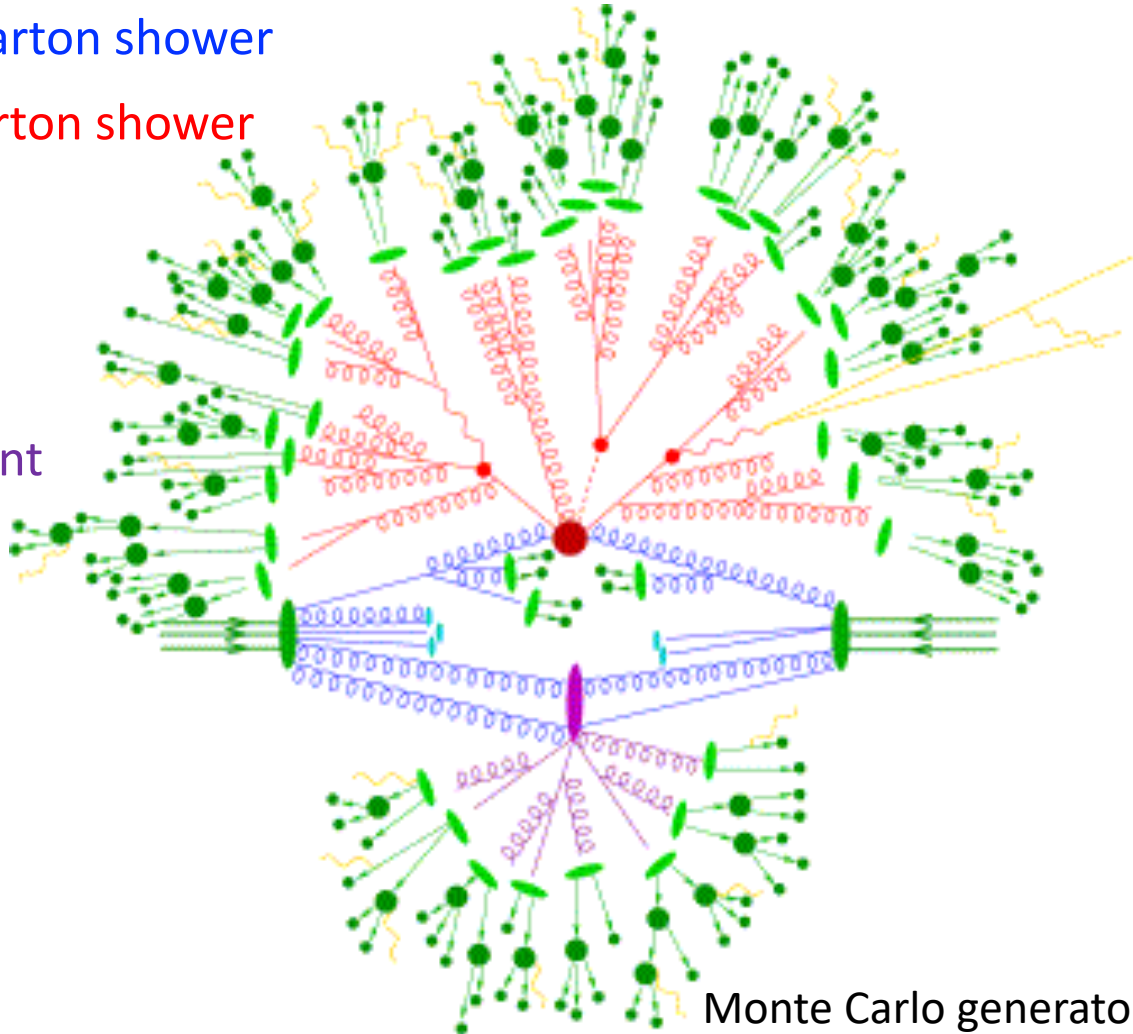


Hadronization program at LHCb

- Fragmentation functions
 - Light quark initiated jets (u, d, s)
 - Heavy quark initiated jets (b, c)
 - Flavor dependence in final state hadrons
- Multiparticle correlations within jets
- Transverse-momentum-dependent (TMD) fragmentation functions via spontaneous hyperon polarization
- Quarkonia formation
 - J/ψ , Υ family
 - Production and polarization
 - Distributions within jets

A proton + proton collision

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

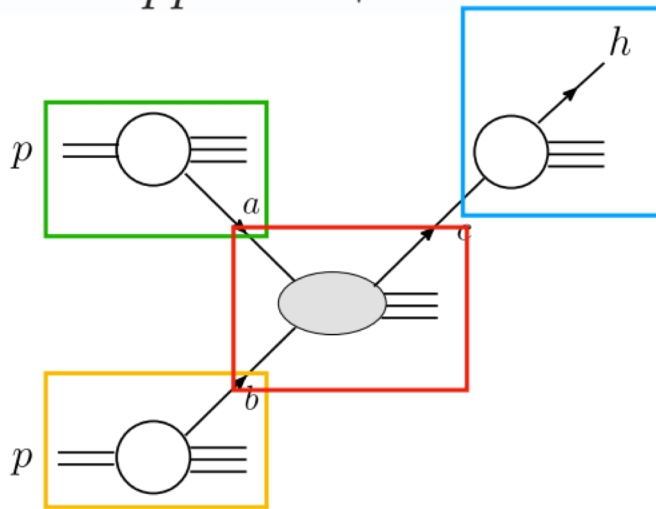


Monte Carlo generator representation

[Prog. Part. Nucl. Phys. 53, 329 \(2004\)](#) ²

pQCD factorization

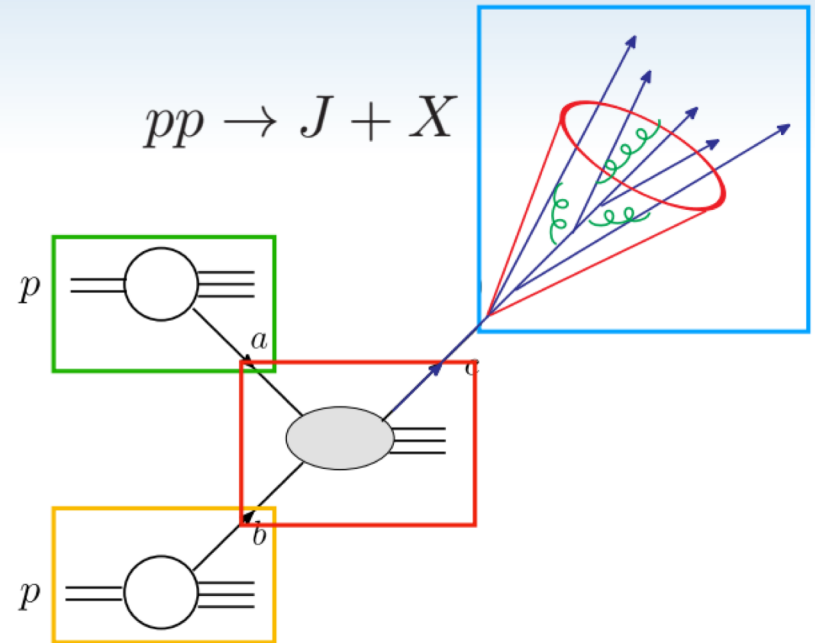
$$pp \rightarrow h + X$$



$$\frac{d\sigma^{pp \rightarrow hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_c^h$$

Fragmentation function
: non-perturbative, universal

$$pp \rightarrow J + X$$



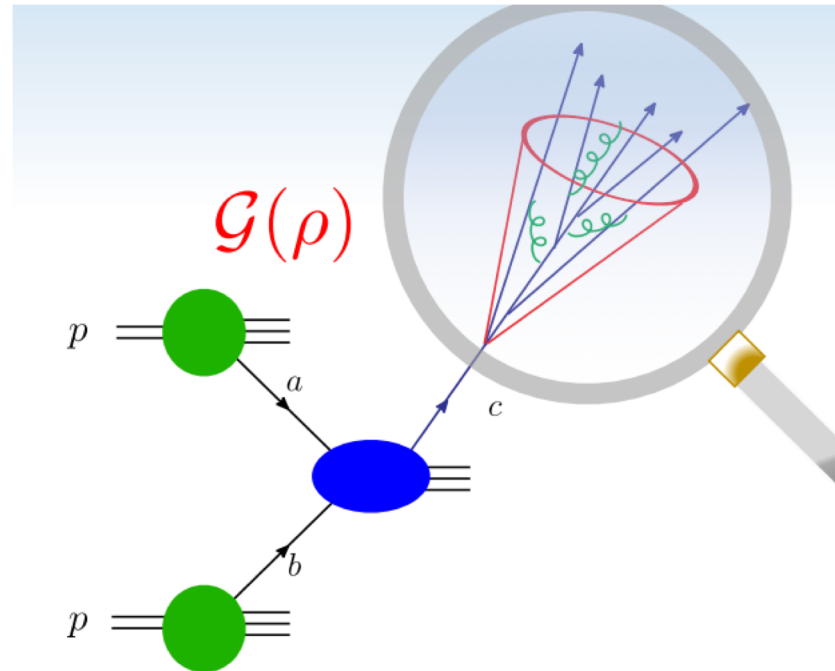
$$\frac{d\sigma^{pp \rightarrow JX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

Jet function
: perturbatively calculable

Jet substructure factorization

Jet substructure ρ

- Jet angularity
- fragmenting jet function (FJF)
- TMD FJF
- ...



$$\frac{d\sigma^{pp \rightarrow \text{jet}(\rho)X}}{dp_T d\eta d\rho} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c(\rho)$$

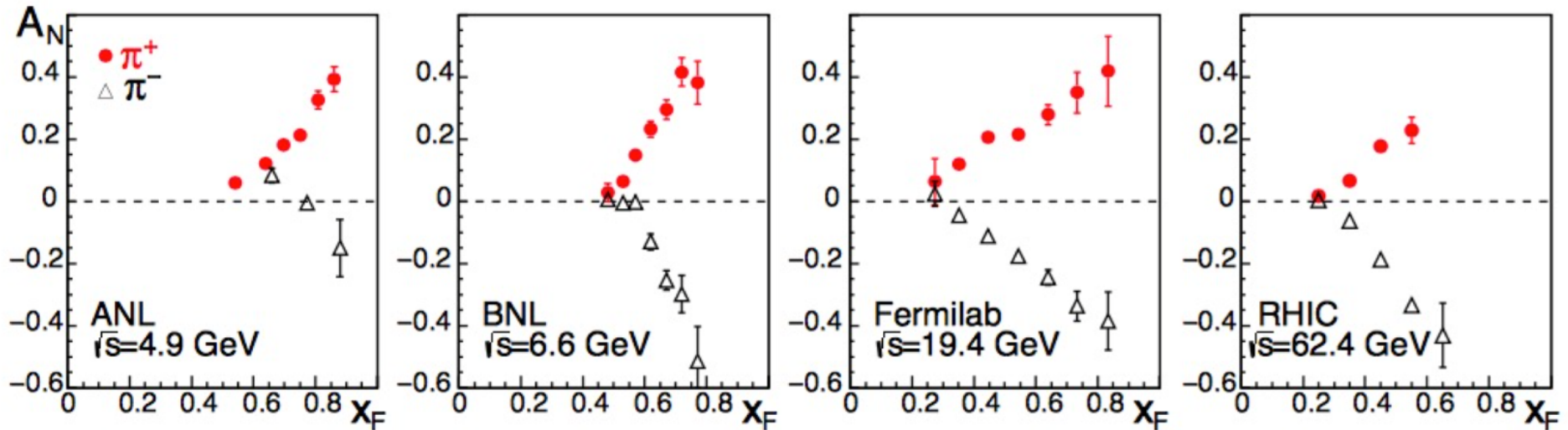
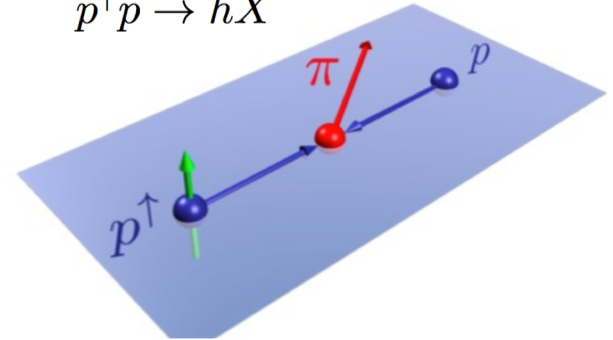
Beginning of TMD physics

A_N

: Transverse Single Spin Asymmetry

: Predicted to be small $\sim m_q \alpha_s / Q$

$$p^\uparrow p \rightarrow hX$$



1976 →

$$x_F = \frac{2p_z}{\sqrt{s}}$$

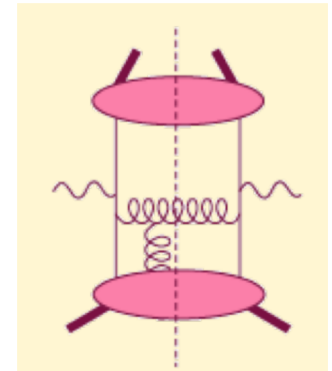
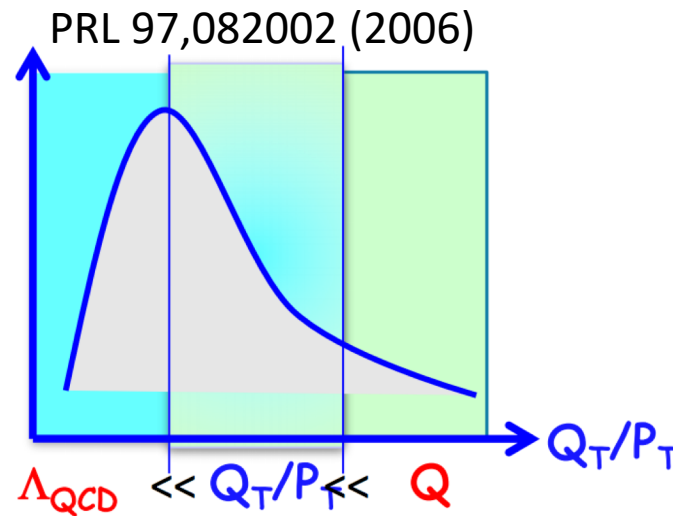
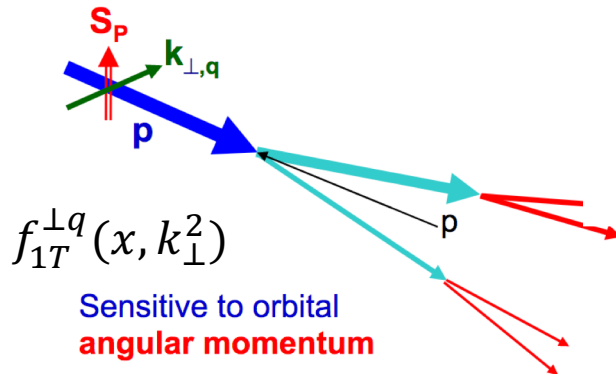
TMD

- Requires 2 scales:
 - Hard scale Q
 - Soft scale p_T
- Suitable for
 - SIDIS, DY, W/Z and **hadrons in jets**

Collinear Twist-3

- Only require single scale
 - Hard scale: p_T
- Suitable for
 - Inclusive π^0 , jet, γ and Λ

e.g. **Sivers Fn:**



See **Jordan Roth's** talk (tomorrow 10:52AM)
on **Test of TMD factorization breaking!**

Efremov, Teryaev;
Sterman, Qiu

Leading twist TMD PDFs

Boer-Mulders Fn

: quark spin-momentum correlation
: can be measured via DY angular distribution at low pT ($\cos 2\varphi$ modulation) at LHCb.

Nucleon Quark			
	Unpol.	Long.	Trans.
Unpol.	$f_1 = \text{circle with dot}$		$f_{1T}^\perp = \text{circle with up arrow} - \text{circle with down arrow}$ Sivers
Long.		Helicity $g_{1L} = \text{circle with right arrow} - \text{circle with left arrow}$	$g_{1T} = \text{circle with up arrow} - \text{circle with right arrow}$ Worm-gear
Trans.	$h_1^\perp = \text{circle with dot} - \text{circle with dot}$	Worm-gear $h_{1L}^\perp = \text{circle with right arrow} - \text{circle with left arrow}$	Transversity $h_{1T}^\perp = \text{circle with up arrow} - \text{circle with up arrow}$ Pretzelosity $h_{1T}^\perp = \text{circle with up arrow} - \text{circle with up arrow}$

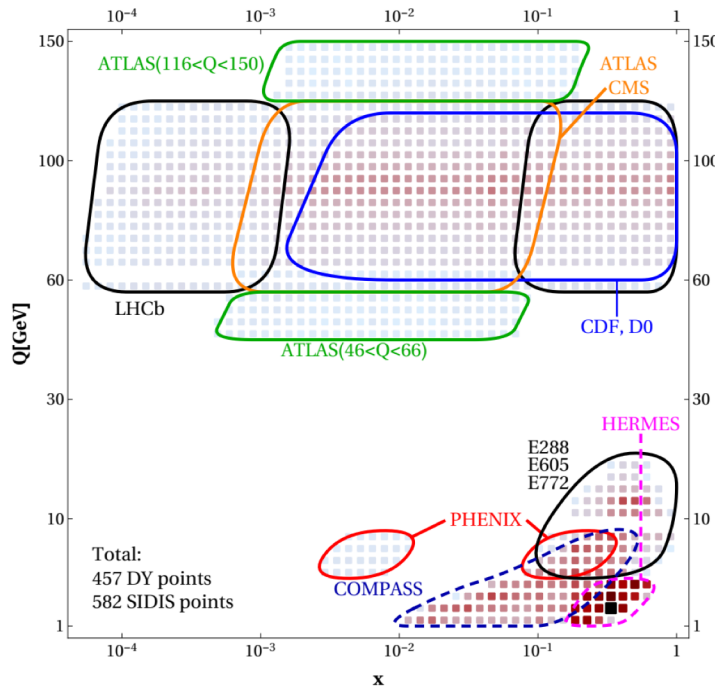


$$h_1^\perp = P \left[\text{diagram 1} \right] - P \left[\text{diagram 2} \right]$$

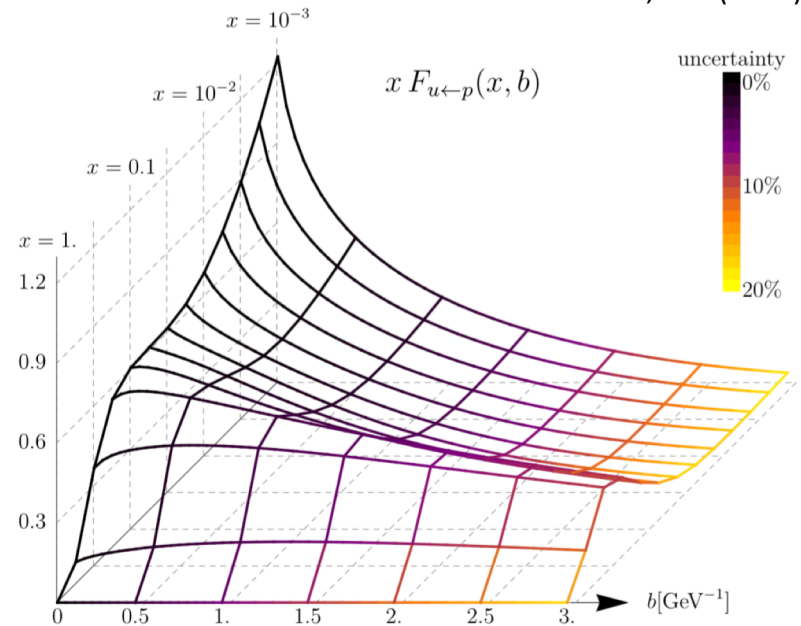
Diagram 1: A yellow rectangle with a black arrow pointing right. A blue vector k_T points up from the center. A red vector q points up and to the right from the top-left corner. A red vector S_T points up and to the right from the top-right corner.

Diagram 2: A yellow rectangle with a black arrow pointing right. A blue vector k_T points up from the center. A red vector q points up and to the right from the top-left corner. A red vector S_T points up and to the right from the top-right corner.

Unpolarized quark TMD PDF



JHEP 06, 137 (2020)

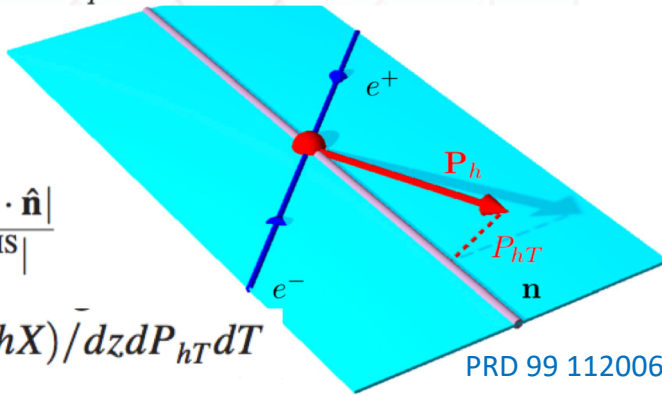


- Z production measured at LHCb reaches small x region of TMD PDF; sensitive to unpolarized quark TMD PDF
- Results for 7 TeV, 8 TeV and 13 TeV have been used for recent global fit of TMD PDF.

TMD fragmentation function

- e^+e^- annihilation:

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



$$T^{\max} \equiv \frac{\sum_h |\mathbf{P}_h^{\text{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\text{CMS}}|}$$

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

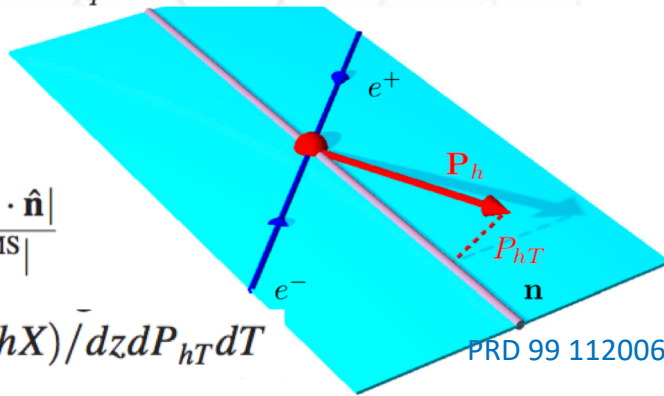
PRD 99 112006 (2019)

- BELLE thrust measurements can provide access to **unpolarized transverse momentum dependent (TMD) FF's**

TMD fragmentation function

- e^+e^- annihilation:

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

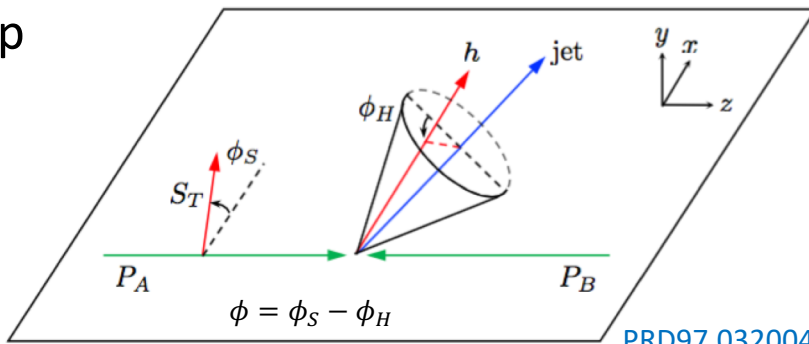


$$T^{\max} = \frac{\sum_h |\mathbf{P}_h^{\text{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\text{CMS}}|}$$

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

PRD 99 112006 (2019)

- pp



PRD97,032004 (2018)

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

: Transverse Single Spin Asymmetry (TSSA)

- BELLE thrust measurements can provide access to **unpolarized transverse momentum dependent (TMD) FF's**
- STAR TSSA measurements 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!**

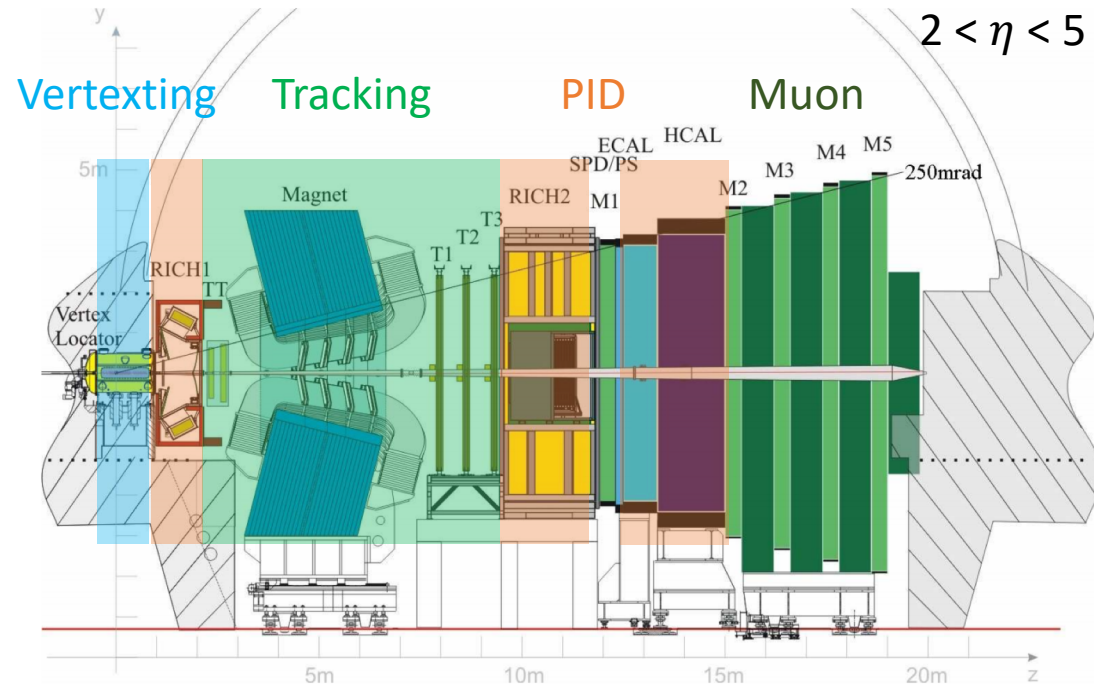
The LHCb Detector

[JINST 3 \(2008\) S08005](#)

[Int. J. Mod. Phys. A 30 \(2015\) 1530022](#)

Features attractive for hadronization studies:

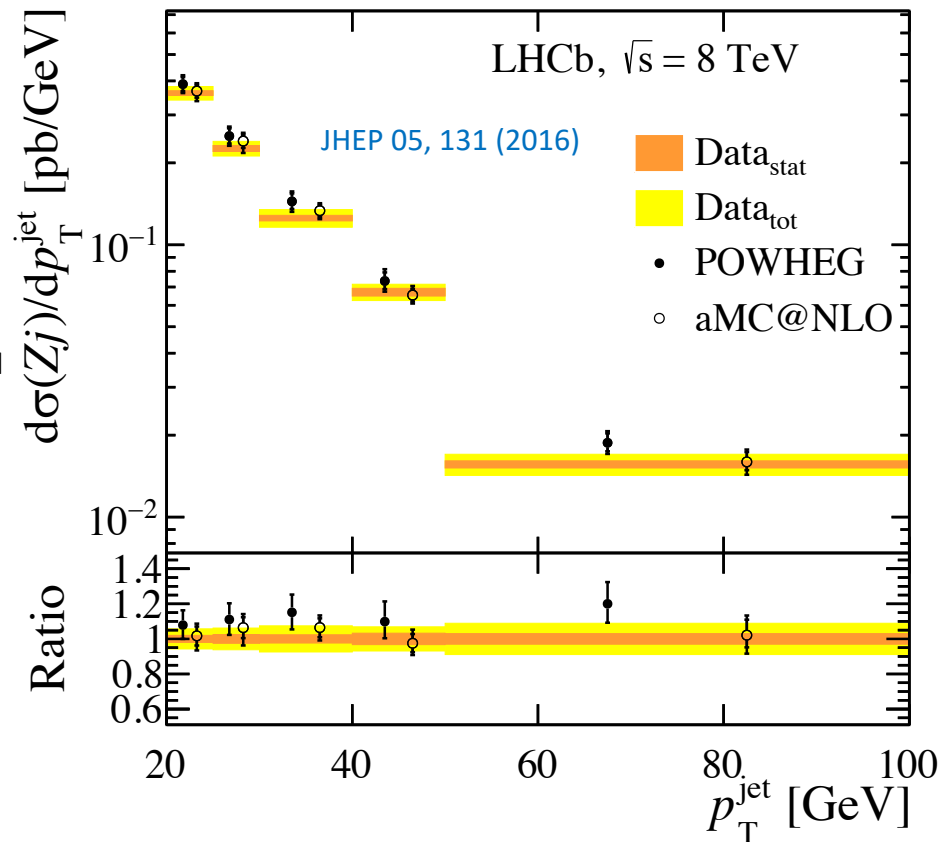
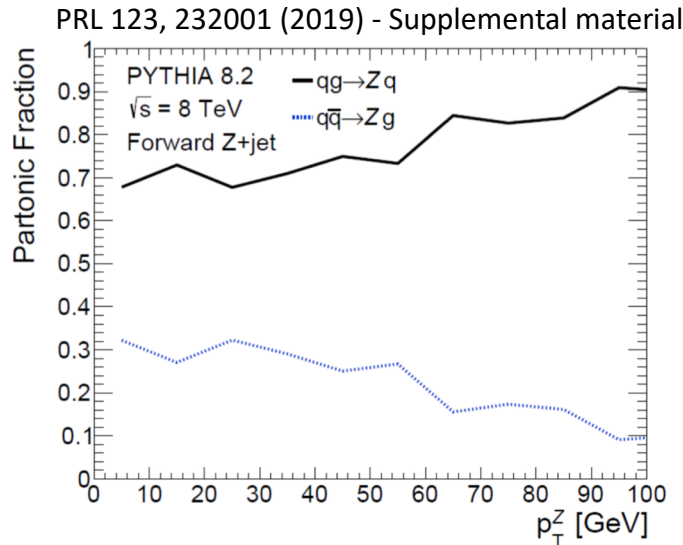
- Full jet reconstruction with tracking, ECAL and HCAL
- Tagging of jets from light-quark, c- and b-quark
- Charged hadron identification from $2 < p < 100 \text{ GeV}/c$
- Muon reconstruction for resonance states
- Large pp datasets available from Run I (3.23/fb at $\sqrt{s} = 7\text{-}8 \text{ TeV}$)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



Can study identified hadron distributions within jets!

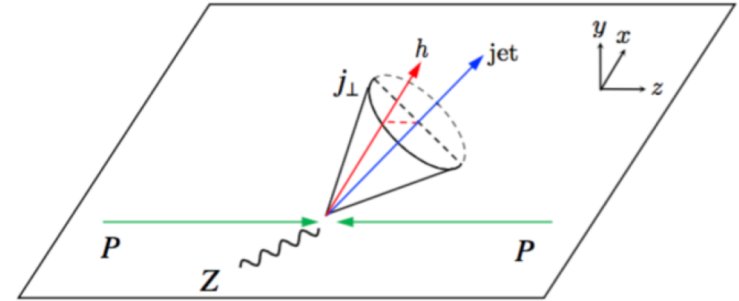
Quark-initiated jets

- 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.



Charged hadrons in jets : Observables

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



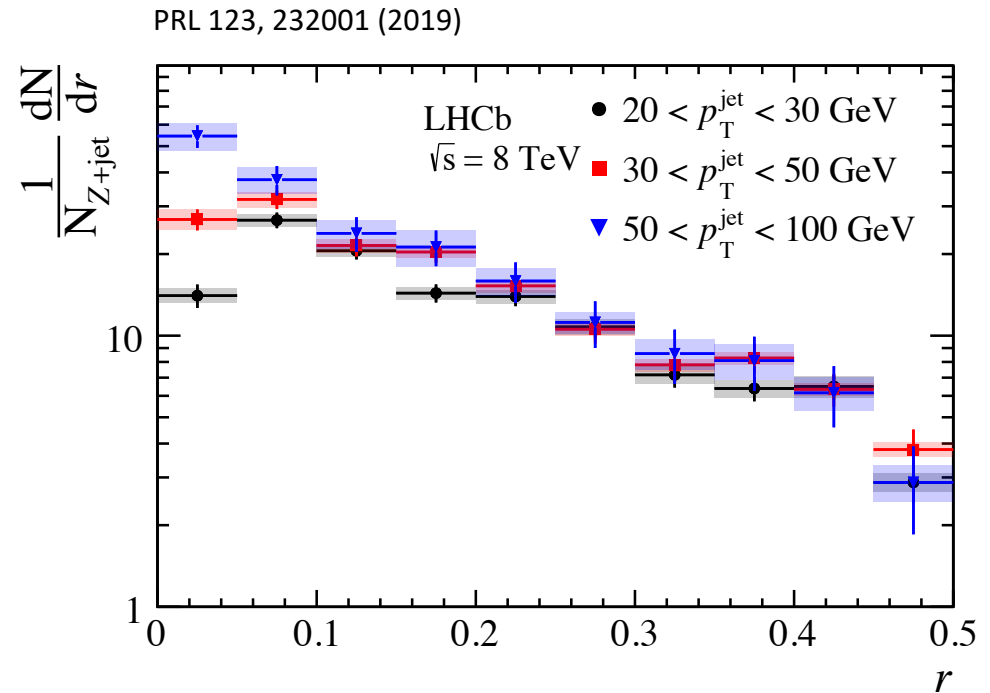
$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

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

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

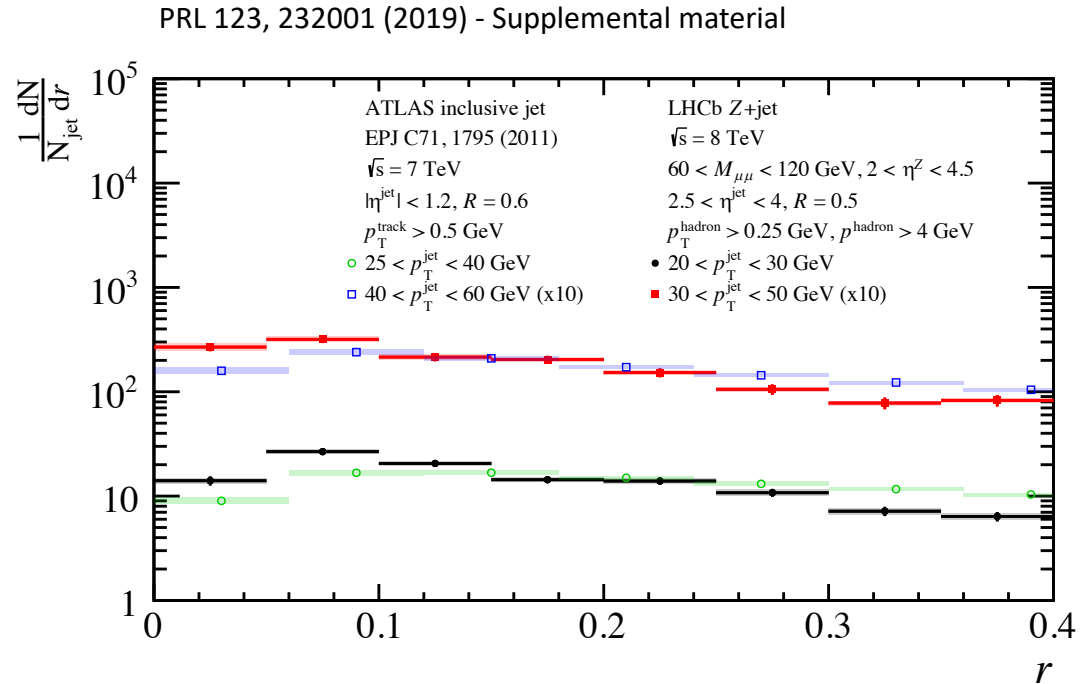
Hadronization in quark-initiated jets

- Greater energy available in higher transverse momentum jets leads to more hadrons produced, mainly close to the jet axis

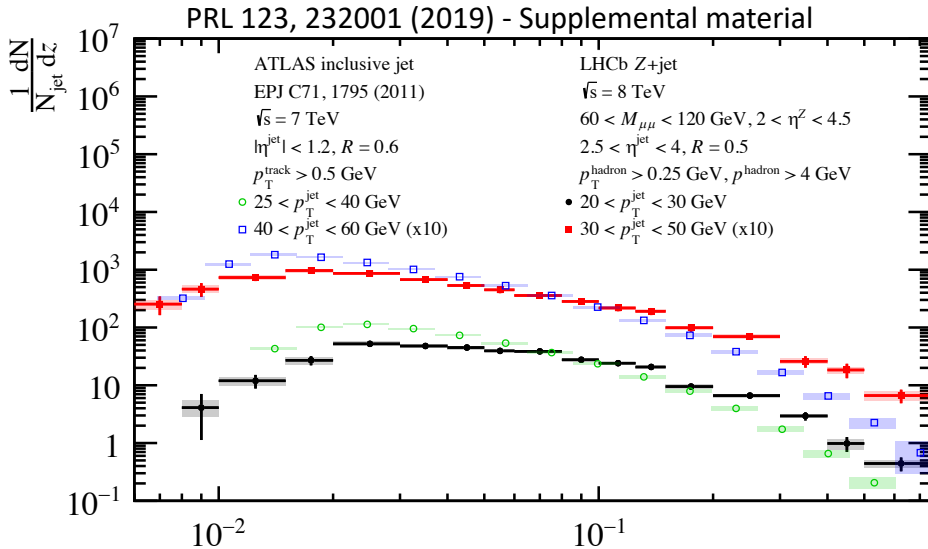


Quark- vs. gluon-initiated jets

- Greater energy available in higher transverse momentum jets leads to more hadrons produced, mainly close to the jet axis
- Quark-initiated jets narrower (more collimated) than gluon-initiated jets measured by ATLAS.

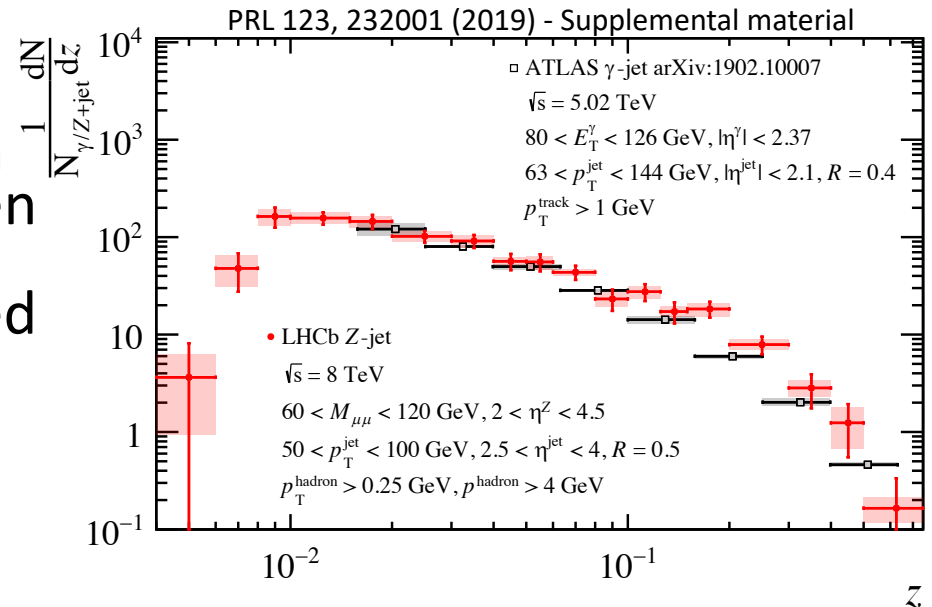


Quark- vs. gluon-initiated jets



- Similar longitudinal momentum distributions are shown between ATLAS midrapidity γ +jet and LHCb Z+jet; differences observed between LHCb and inclusive ATLAS results are due to differences in quark and gluon hadronization

- Quark-initiated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-initiated jets



Identified charged hadron distributions in jets

- $j_{\perp}$ vs z :

Access to unpolarized
Transverse-momentum-
dependent Fragmentation
Functions (TMD FF)

$$\frac{d\sigma^{pp \rightarrow \text{jet}(h)X}}{dp_T d\eta dz_h d^2 j_{\perp}} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H_{ab}^c \otimes \mathcal{G}_c^h(z_h, j_{\perp})$$

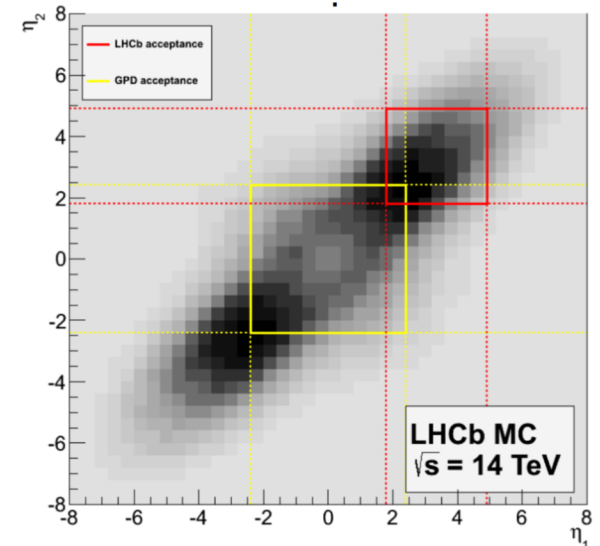
$\sim \widehat{D}_{h/c}(z_h, j_{\perp}, \mu_J)$
: **TMD FF**

- **Identified charged hadron distributions in jets & charge ratio thereof:**

Statistical sensitivity to flavor of quarks that initiate jets

- Light quark-initiated (Z-associated) jets
- Heavy quark-initiated (b- and c-tagged) jets

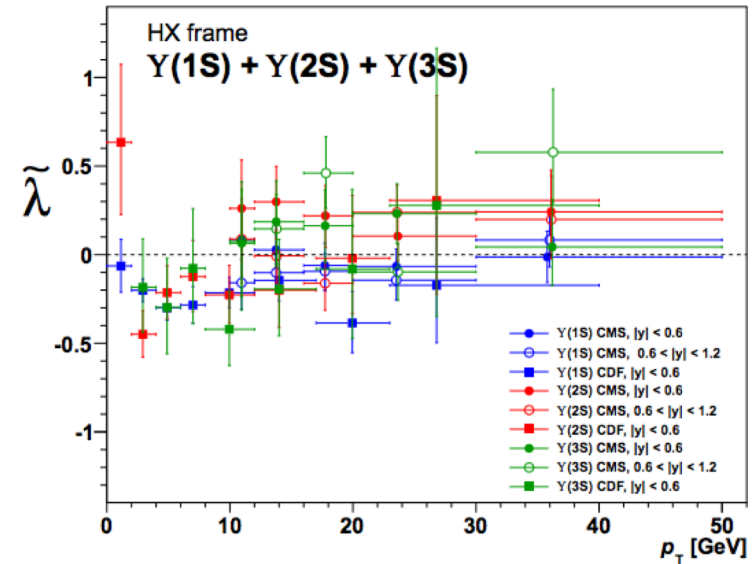
$\sim 40\%$ of all produced $c\bar{c}$ and $b\bar{b}$ pairs are in LHCb acceptance.



Quarkonia formation

[10.22323/1.216.0012]

- Hadronization mechanisms of energetic heavy quark into $Q\bar{Q}$ bound states not well understood
- NRQCD has seen success in describing world data on quarkonia production, while no theory exists so far simultaneously describing their polarization

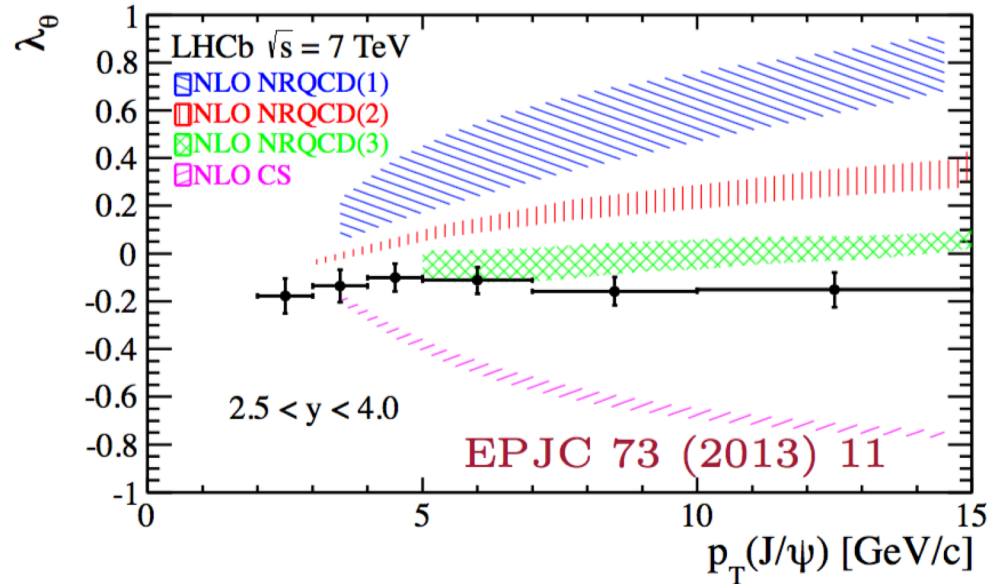
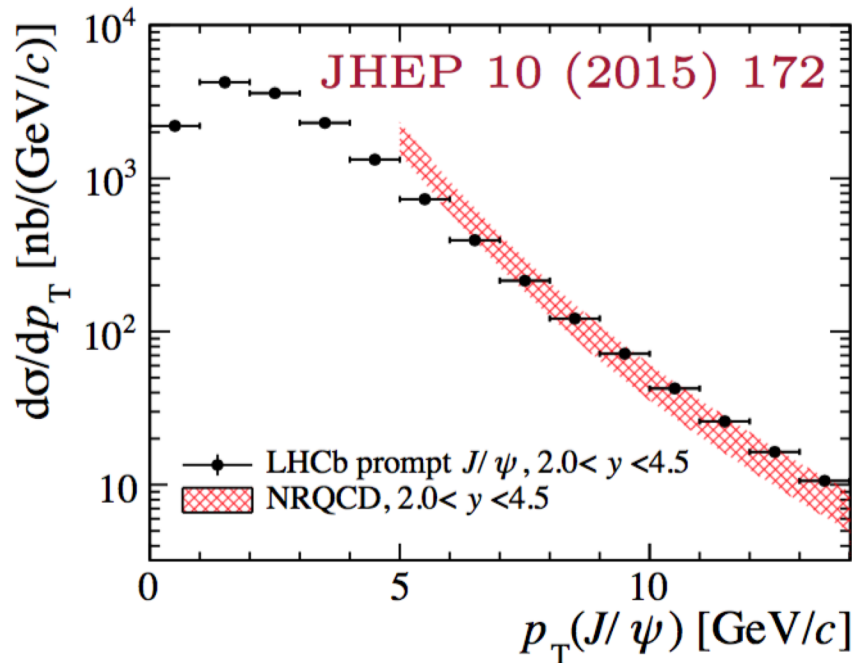
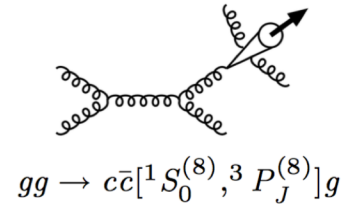
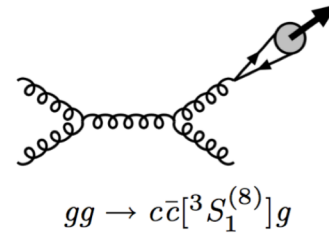
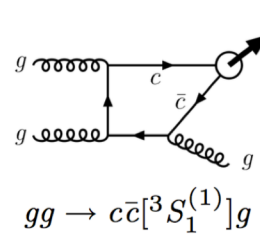


NRQCD

$$d\sigma(pp \rightarrow H + X)$$

$$= \sum_{s,L,J} d\hat{\sigma}(pp \rightarrow Q\bar{Q}[^{2s+1}L_J] + X) \langle \mathcal{O}^H[^{2s+1}L_J] \rangle$$

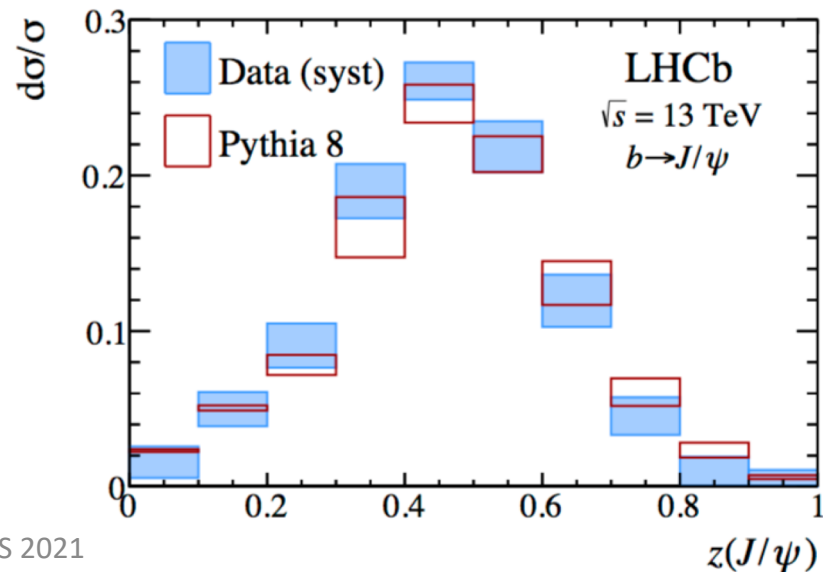
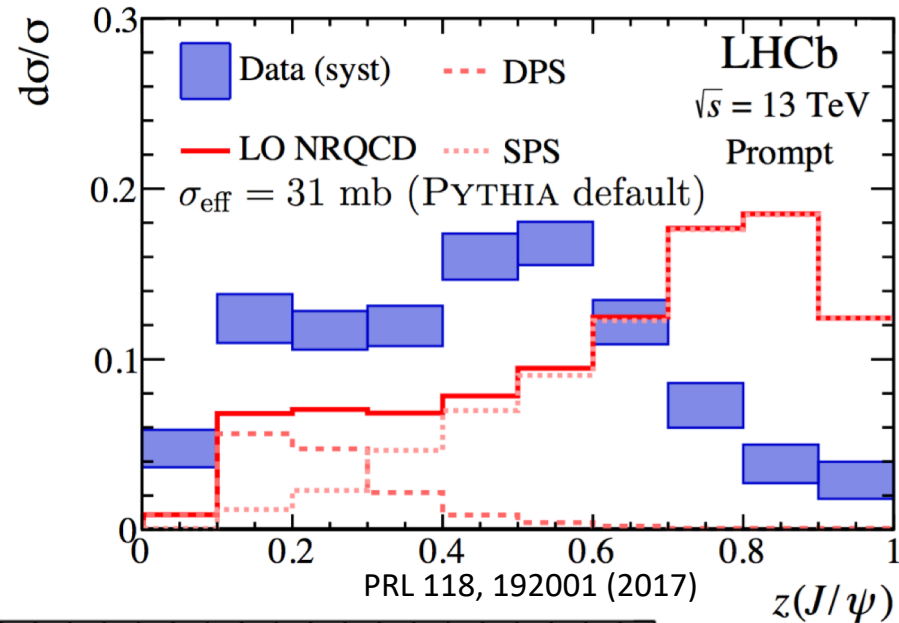
Charmonium formation



- LHCb J/ψ production and polarization

Charmonium formation in jets

- New approaches: look at quarkonia inside jets
- Collinear fragmentation along jet axis has been measured and polarization within jets ongoing



Summary

- LHCb initiated a wide ranging hadronization program.
- Kinematic coverage allows for sensitivity to small x unpolarized TMD PDF (Z production) as well as unpolarized TMD FF (Z-tagged jets).
- Hadron distributions within Z-tagged jets give sensitivity to unpolarized quark-jet TMD FF.
- Non-identified hadron distribution results confirm quantitatively difference between quark-jet and gluon-jet.
- Identified hadron distributions are expected to provide statistical sensitivity to flavor of quarks that initiate jets.
- Heavy flavor tagged jets can probe quark mass effects when compared to light-quark jet results.
- Quarkonium production mechanisms have been explored with production, polarization and collinear fragmentation within jets.

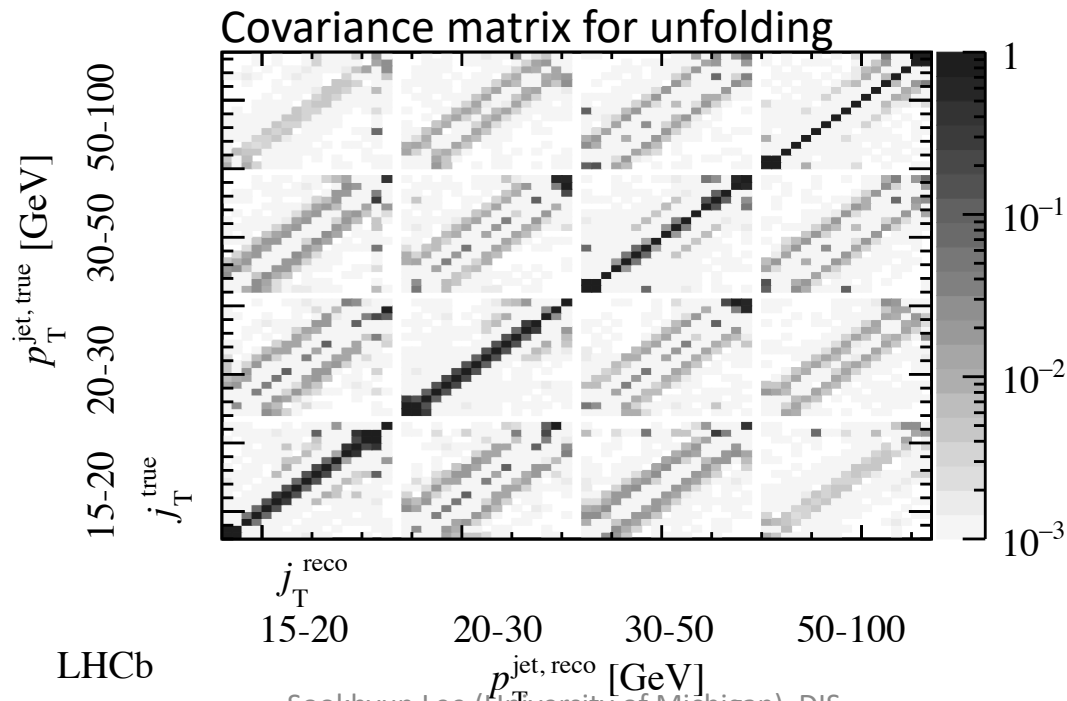
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Analysis

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)



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2021

- Excellent separation in wide momentum range

