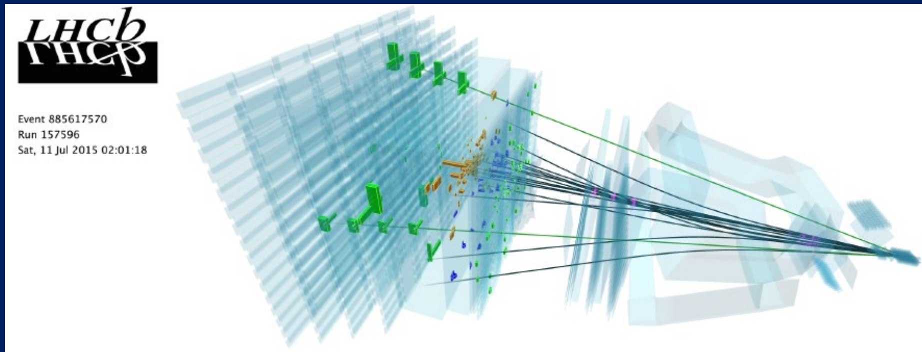
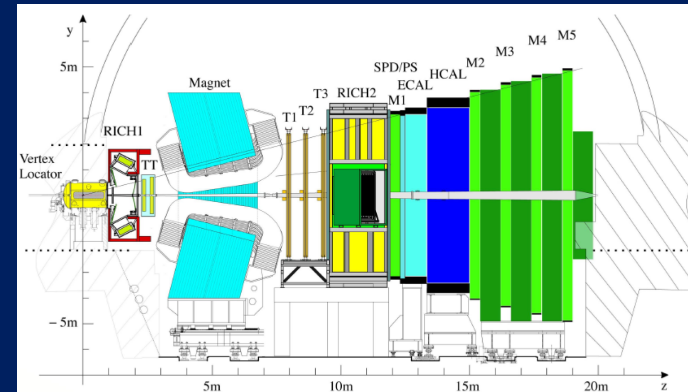
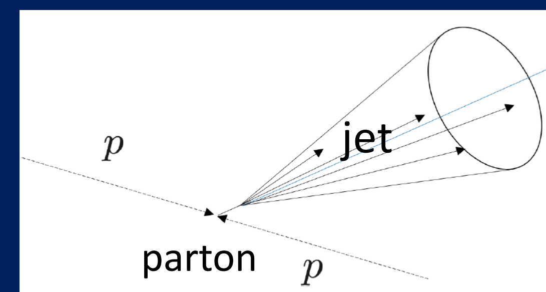




JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

Jets and Lund plane studies at LHCb

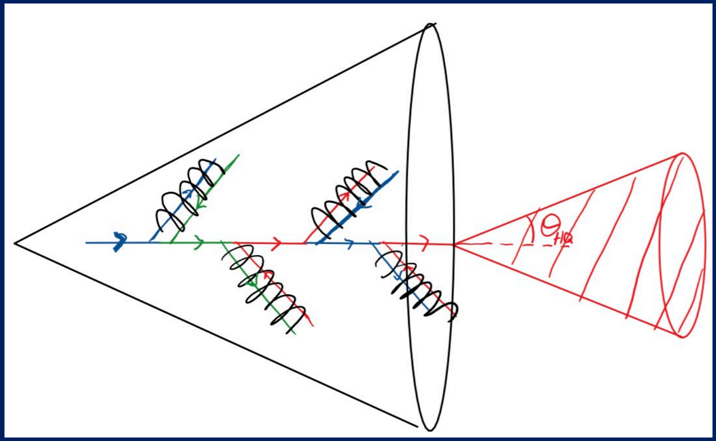


Christine A. Aidala
University of Michigan
On behalf of the LHCb Collaboration

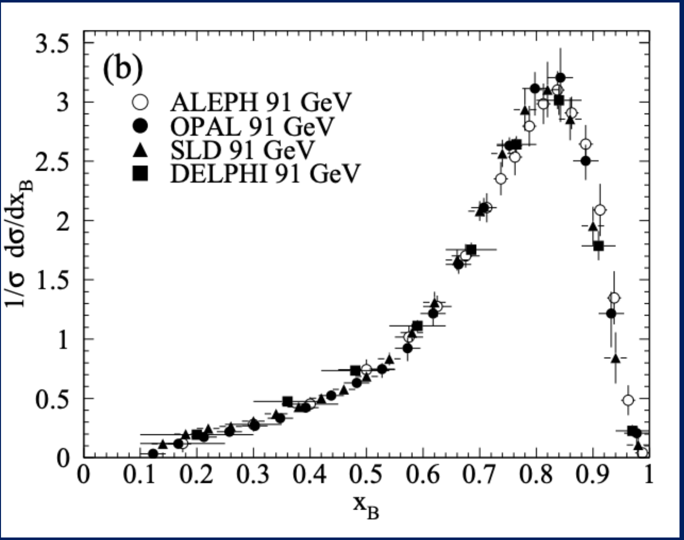
1st Lund Jet Plane Institute
July 3, 2023

Heavy quark showering and fragmentation

1. The Dead Cone Effect

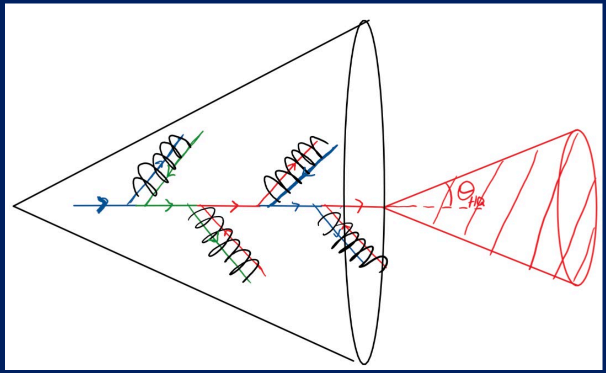


2. The Leading Particle Effect



Lund Jet Plane

Dead cone effect



Bremsstrahlung off moving charges

- The relativistic and massless splitting probability in pQCD is given by

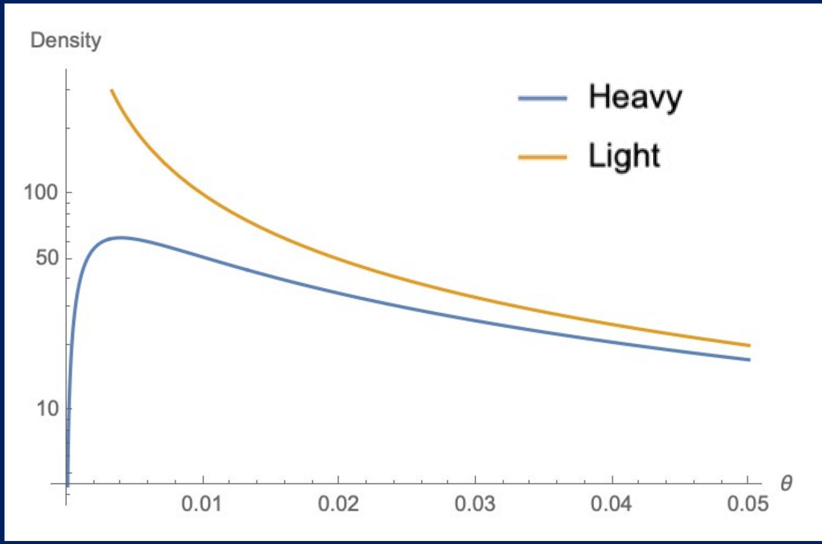
$$dP_{i\to ig} = \frac{\alpha_s C_i}{\pi}\frac{d\theta^2}{\theta^2}\frac{dz}{z}$$

z : Energy Fraction
θ : Splitting angle
C_i : Color factor

- For heavy quarks (HQs), a characteristic angle appears in the equation

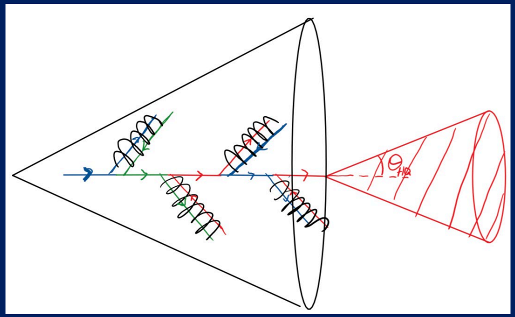
$$dP_{i\to ig} = \frac{\alpha_s C_i}{\pi}\frac{\theta^2 d\theta^2}{(\theta^2+\theta_{\mathrm{HQ}}^2)^2}\frac{dz}{z}$$

$$\theta_{\mathrm{HQ}} = \frac{m_{\mathrm{HQ}}}{E}$$



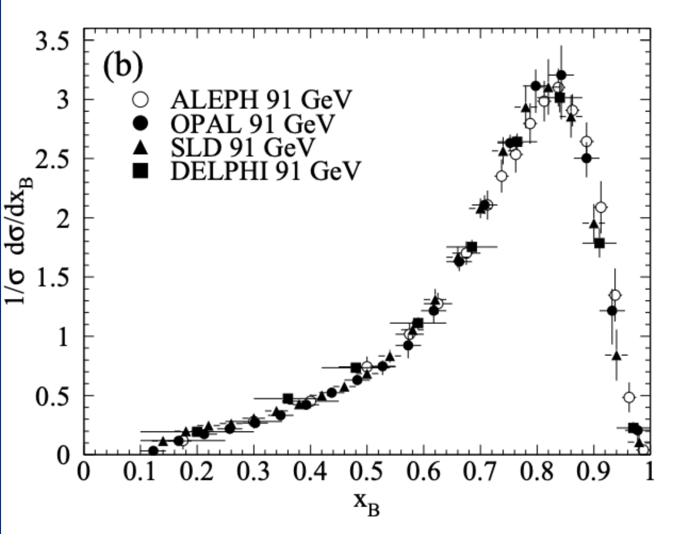
Dokshitzer, Y.L., Khoze, V.A. and Troyan, S.I., 1991.
Journal of Physics G: Nuclear and Particle Physics, *17*(10), p.1602.

Heavy quark fragmentation



Heavy quarks maintain most of their energy

- Light partons lose most of their energy in hard collinear radiation
- The dead cone effect in heavy quarks prevents collinear radiation → very few hard and collinear bremsstrahlung emissions
- Thus, the heavy quark maintains most of its energy



Energy fraction of the jet carried by the b-hadron

(ALEPH), Phys. Lett. B357, 699 (1995)
(ALEPH), Phys. Lett. B512, 30 (2001)
(DELPHI), Eur. Phys. J. C71, 1557 (2011)
(OPAL) Eur. Phys. J. C29, 463 (2003)
(SLD), Phys. Rev. D65
(Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

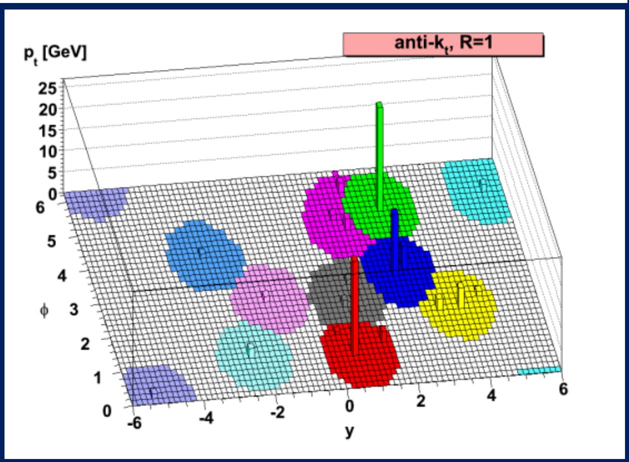
Jet clustering algorithms

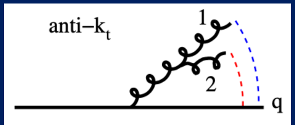
Cacciari, Matteo, Gavin P. Salam, and Gregory Soyez.
JHEP 2008.04 (2008): 063.

F. A. Dreyer, G. P. Salam, and G. Soyez,
The Lund jet plane, J. High Energy Phys. 12 (2018) 064

Anti-k_T

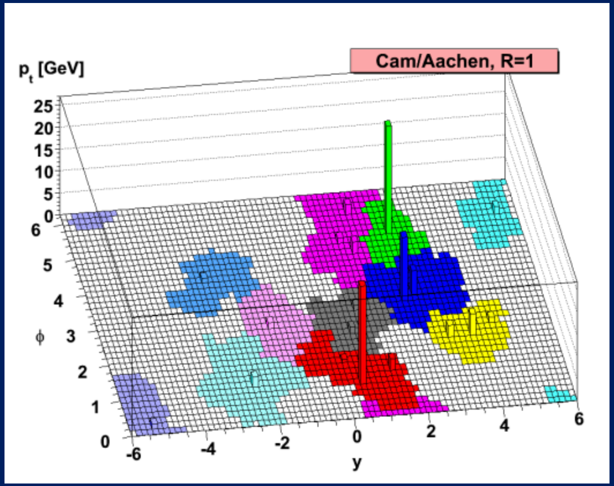
- Infrared and Collinear safe
- Conical jets
- Standard jet clustering algorithm

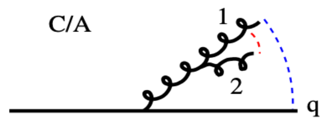




Cambridge/Aachen

- Respects angular ordering
- Reconstructs splitting history
- *Not* infrared safe





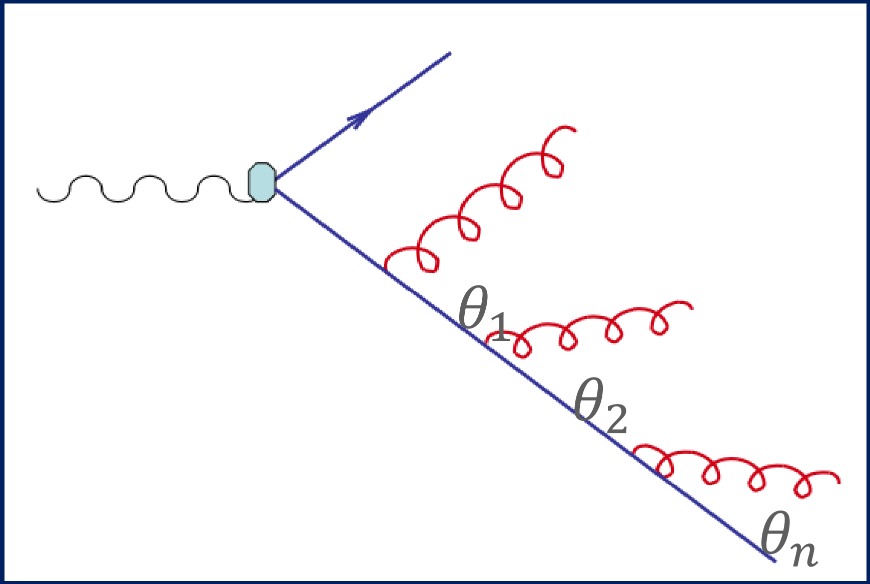
Angular ordering

Accessing the splitting history

- Gluon radiation is ordered from larger to smaller angles throughout the showering

$$\theta_1 > \theta_2 > \ldots > \theta_n$$

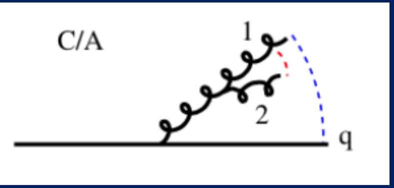
- The C/A algorithm clusters jets based on smallest angles first = respects angular ordering



C/A gives us access to the splitting history of the jet

Image: Mangano-Lect3

Iterative declustering



Recluster = combine most collinear particles according to C/A

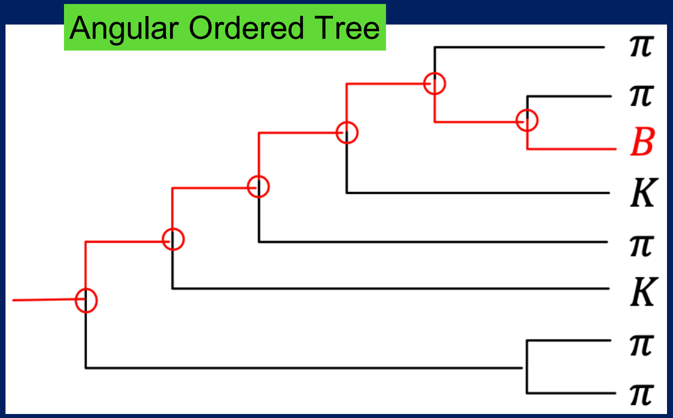
Cunqueiro, Leticia, and Mateusz Płoskoń. PRD 99.7 (2019): 074027

Anti-k_T Jet

$\pi\ \pi\ B\ K\ \pi\ K\ \pi\ \pi$

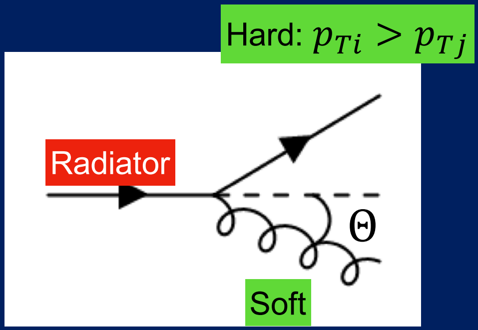
IRC and Conical

Recluster with C/A



1. Using the FastJet algorithm, cluster jets with the anti-k_T algorithm ("AK5" for R = 0.5) [*EPJC* 72:1 (2012)]
2. Recluster jets passing the selection criteria using C/A
3. Following the hardest/heavy-flavor branch, at each splitting point record the variables of interest: $k_T, z, \Delta R, \theta, E_{rad}$

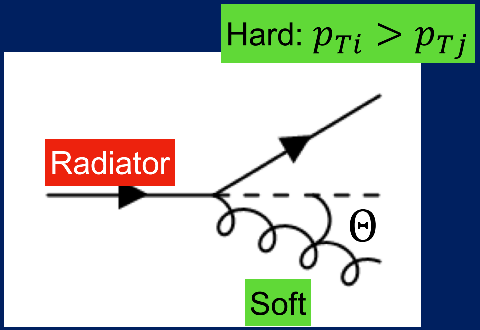
Splitting variables



We adopt the following definitions for the Lund jet plane variables:

- θ_{ij} : the angle between the soft daughter and radiator
- E_{rad} : the energy of the radiator
- $\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ - angular distance
- $k_T = p_T^{soft} \sin(\Delta R)$ - relative transverse momentum
- $z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$ - transverse momentum fraction

Splitting variables



Focusing on these variables:

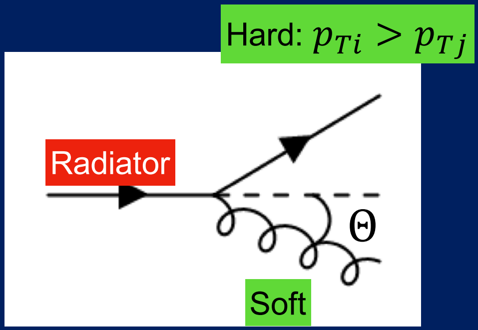
- θ_{ij} : the angle between the soft daughter and radiator
- E_{rad} : the energy of the radiator

Obtain "dead cone plane" in E_{rad} and θ

$$\rho(E_{rad}, \theta) = \frac{1}{N_{emissions}} \frac{d^2 n}{dE_{rad}\ d\ln(1/\theta)}$$

$$\theta_{HQ} = \frac{m_{HQ}}{E}$$

Splitting variables



Focusing instead on these variables:

- $\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ - angular distance
- $k_T = p_T^{soft} \sin(\Delta R)$ - relative transverse momentum
- $z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$ - transverse momentum fraction

Obtain "standard" versions of Lund jet plane

$$\rho(\Delta R, k_T) = \frac{1}{N_{emissions}} \frac{d^2 n}{d\ln(R/\Delta R) d\ln(k_T)}$$

$$\rho(\Delta R, z) = \frac{1}{N_{emissions}} \frac{d^2 n}{d\ln(R/\Delta R) d\ln(1/z)}$$

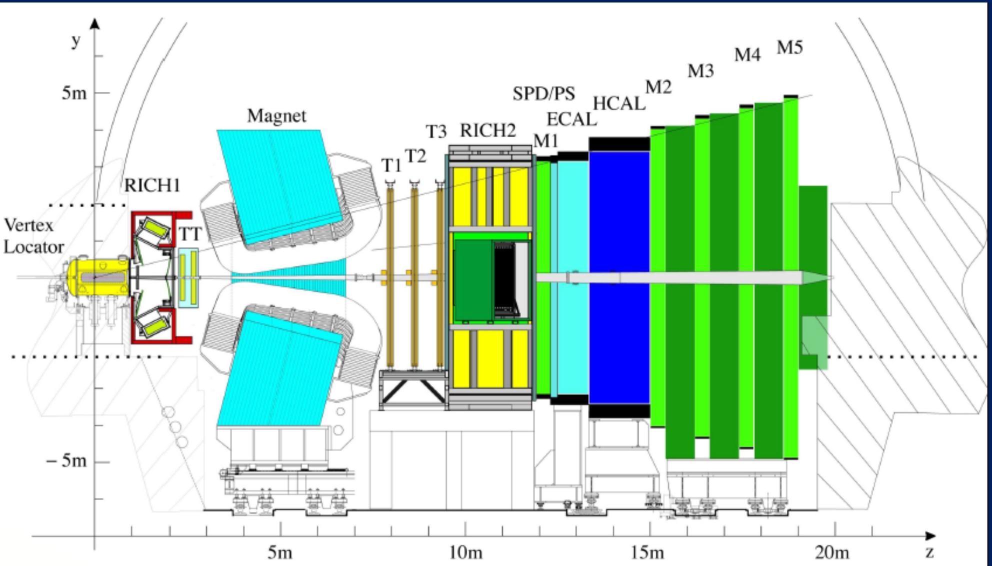
Prospects for the LJP at LHCb

LHCb: Opportunities for measuring hadron distributions in jets

LHCb is the experiment devoted to flavor physics at the LHC.

Detector design:

- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for $p < 200$ GeV/c
- Particle ID: Excellent capabilities to select exclusive decays



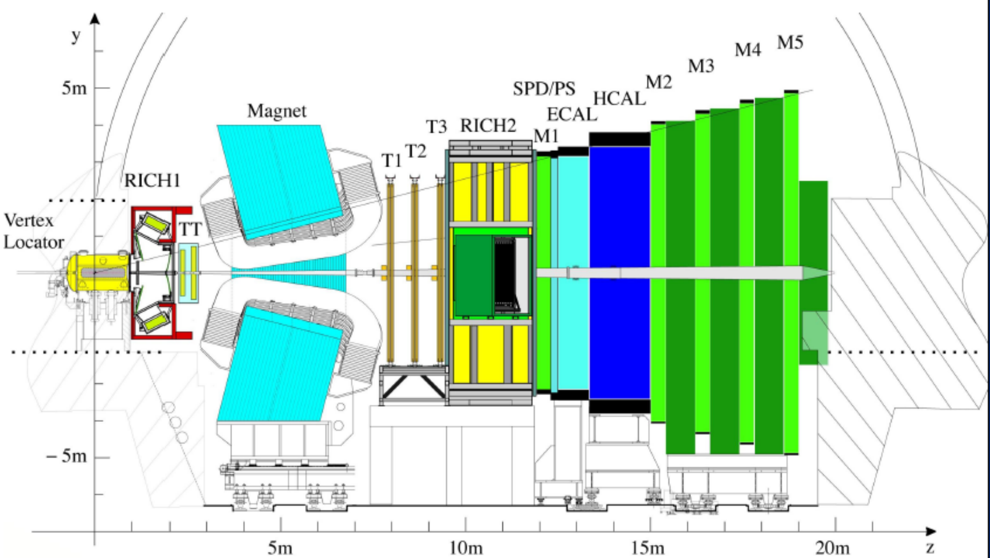
JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

LHCb: Opportunities for measuring hadron distributions in jets

LHCb is the experiment devoted to flavor physics at the LHC.

Detector design:

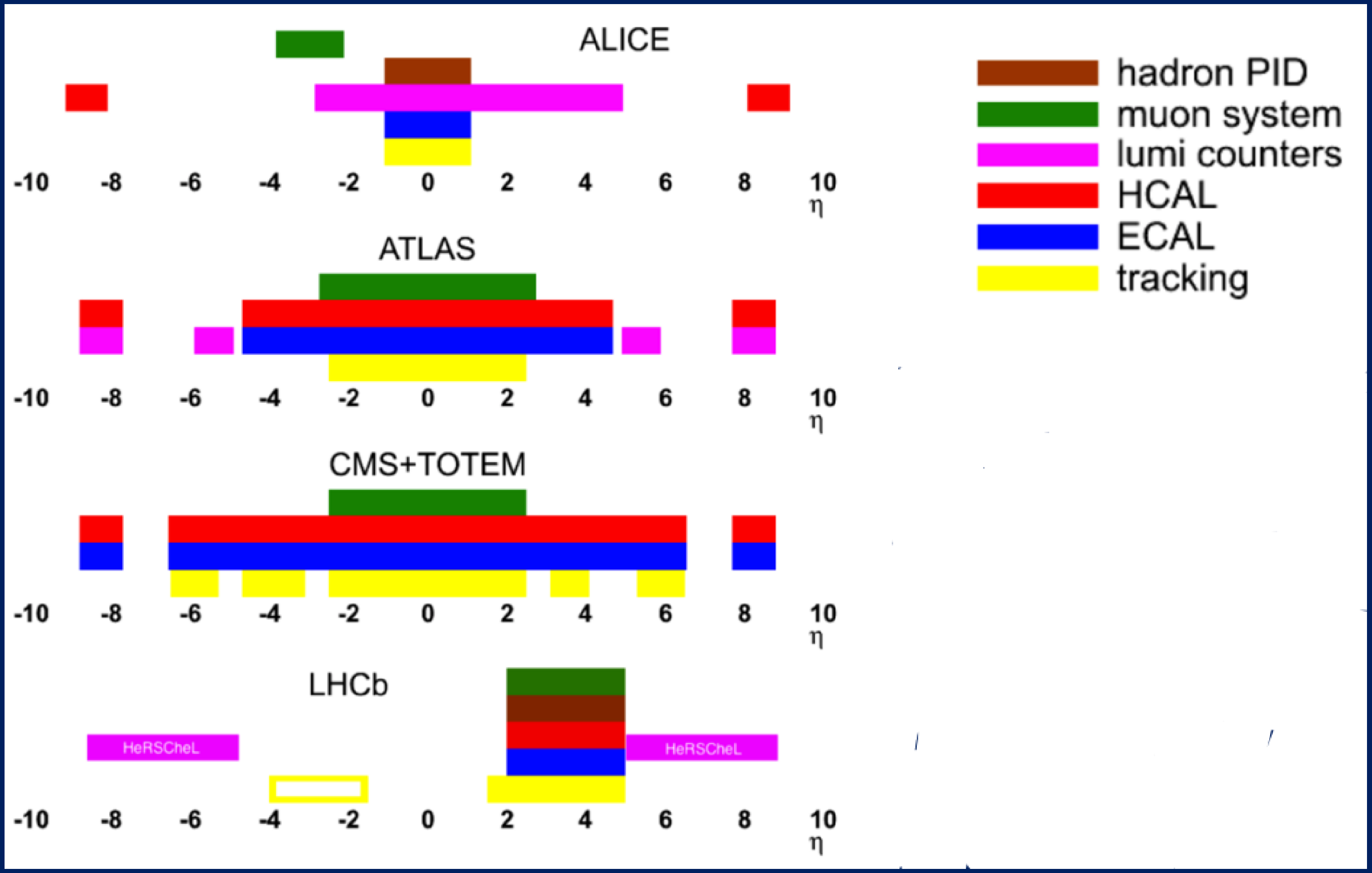
- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for $p < 200$ GeV/c
- Particle ID: Excellent capabilities to select exclusive decays



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

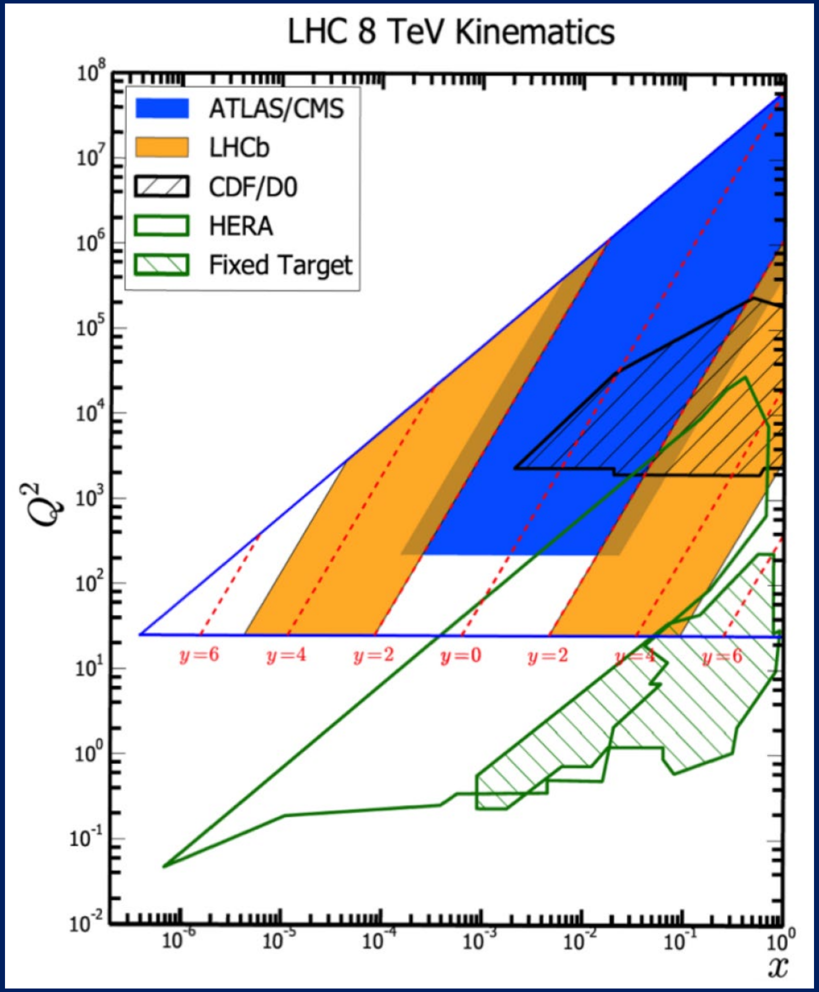
- Full jet reconstruction with tracking, ECAL, HCAL
- Heavy flavor tagging of jets
- Charged hadron PID from $2 < p < 100$ GeV
  - Can study identified particle distributions within jets
- Muon detection

Pseudorapidity coverage comparison



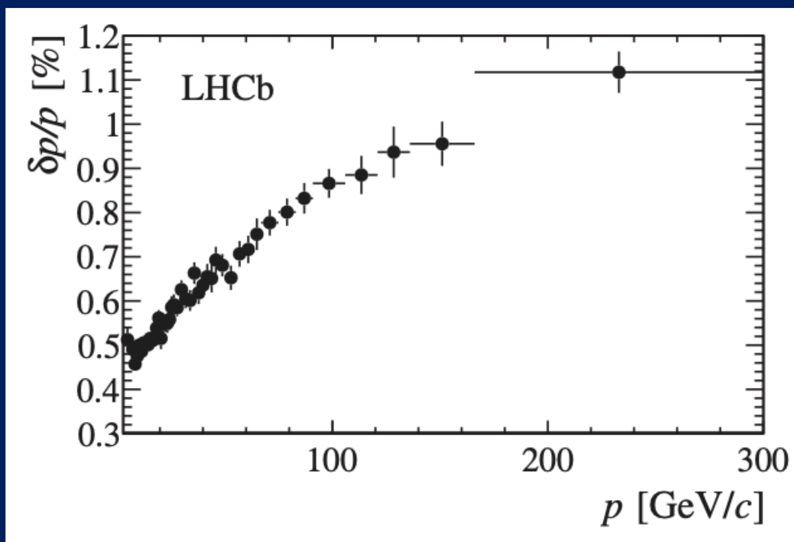
x-Q² coverage affects parton mix

- LHCb also has unique x-Q^2 coverage
  - Enhanced light quark jet fraction in forward region



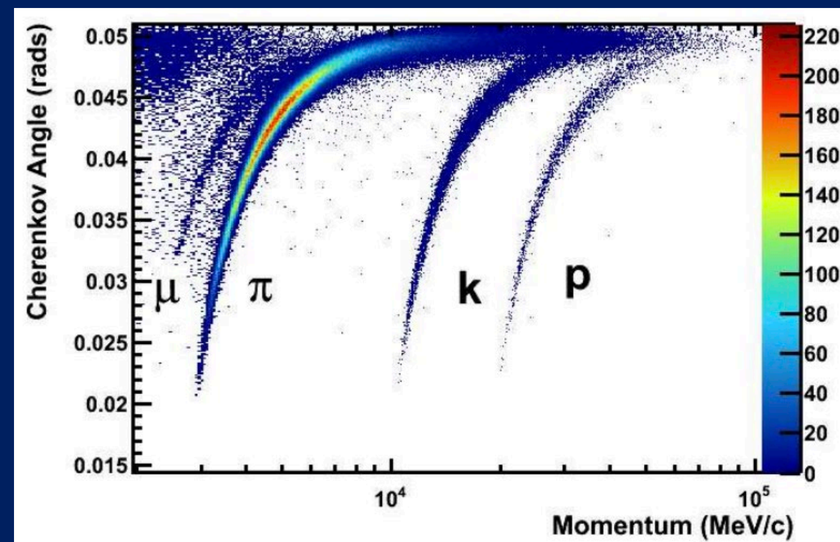
Tracking and PID

Excellent momentum resolution and hadron PID



Resolution <1% up to 200 GeV

Int. J. Mod. Phys. A 30, 1530022 (2015)



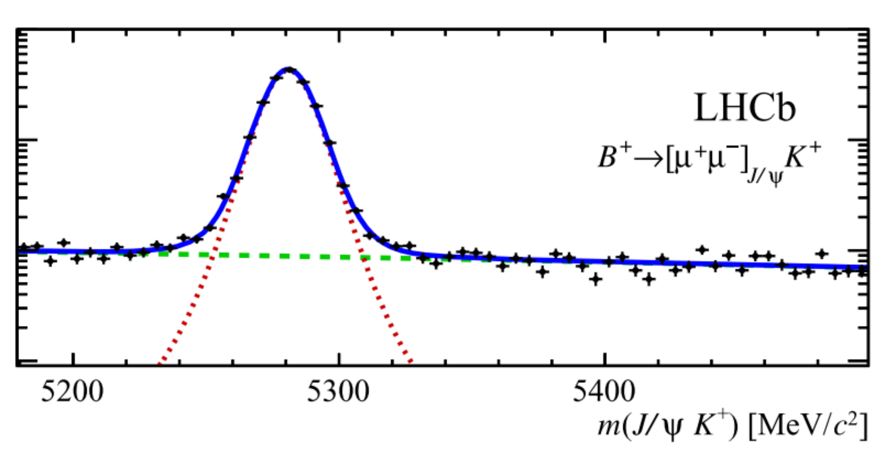
Capability of selecting exclusive decays

EPJC 73.5 (2013): 1-17

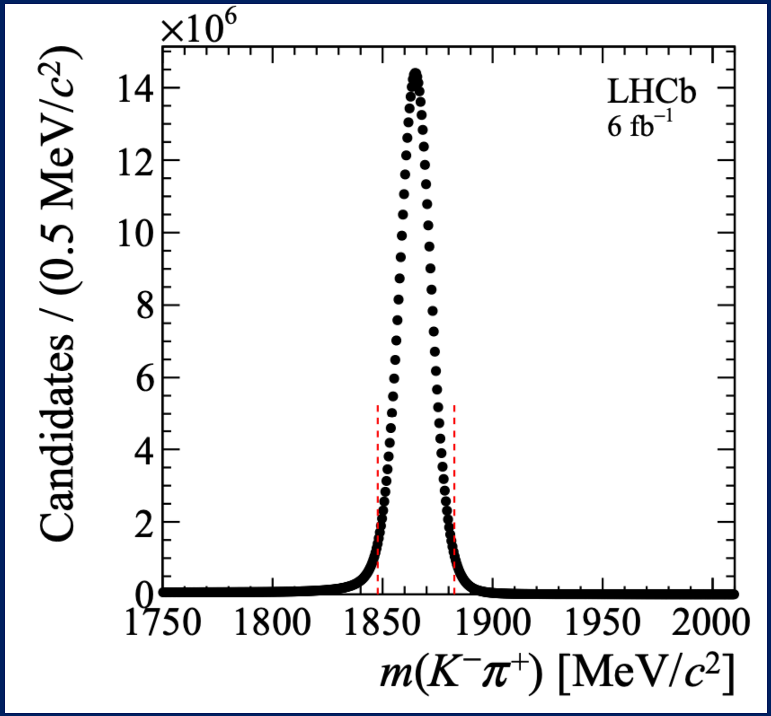
Excellent reconstruction of exclusive decays

$D^0 \to K^-\pi^+$

$B^+ \to J/\psi(\to \mu\mu)K^+$



PRD 95, 052005 (2017)



Phys. Rev. D 104 (2021) 072010

Lund plane at LHCb

We plan on

- measuring the LJP for ***light***, ***charm***, and ***beauty*** jets,
- measuring the LJP for ***track*** jets as well as ***track*** + ***neutral*** jets,
- and measuring the ***dead-cone*** effect from the various LJP parametrizations.

Jet samples

Z-tagged jets, jets around D^0 ,jets around $B^{\pm}$

- Run 2 pp collisions at $\sqrt{s} = 13$ TeV data, 2016-2018.
- For light partons (u/d/s/g), jets recoiling off a Z-boson are used to obtain a quark-enriched jet sample. $pp \rightarrow Z(\rightarrow \mu\mu) + q(g)$
- For charm-initiated jets, we reconstruct $D^0 \rightarrow K^-\pi^+$ candidates and find jets that contain the $D^0/\overline{D}^0$ within the jet radius.
- For beauty-initiated jets, we reconstruct $B^+ \rightarrow J/\psi(\rightarrow \mu\mu)K^+$ candidates and find jets that contain the $B^{\pm}$ within the jet radius.

LJP at forward rapidities

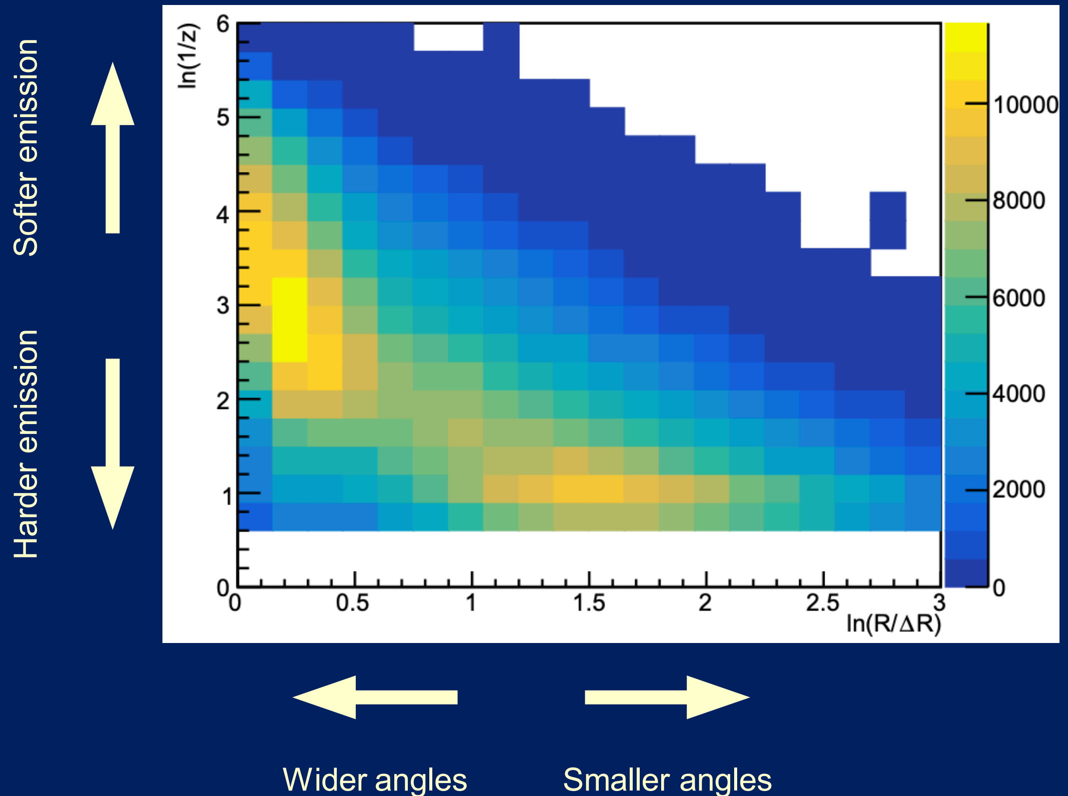
Pythia8 simulations

pp collisions

$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV

$$z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$$

Light quark jets



LJP at forward rapidities

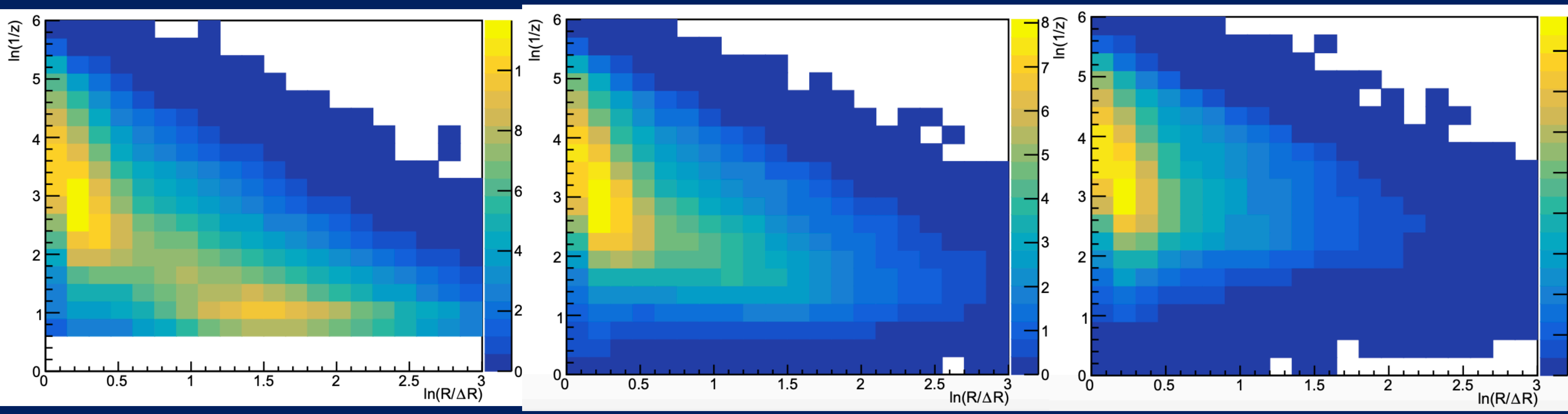
Pythia8 simulations

pp collisions

$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV

$$z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$$

Light quark jets | Charm jets | Beauty jets



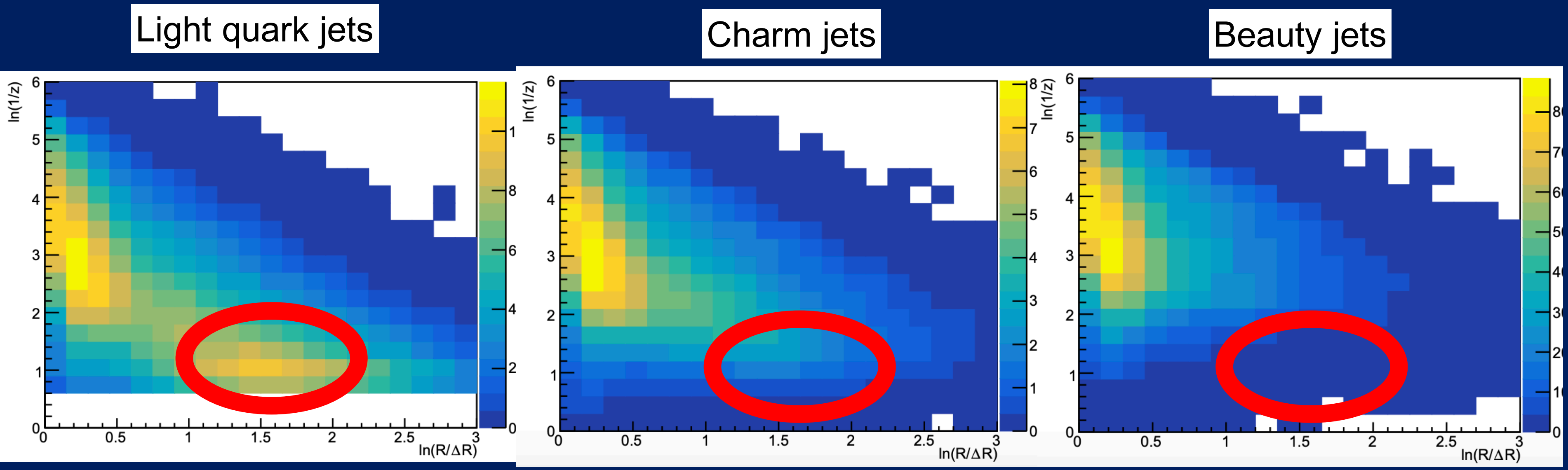
LJP at forward rapidities

Pythia8 simulations

pp collisions

$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV

$$z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$$



Suppression of hard collinear radiation = Heavy quarks maintain most of their energy

LJP at forward rapidities

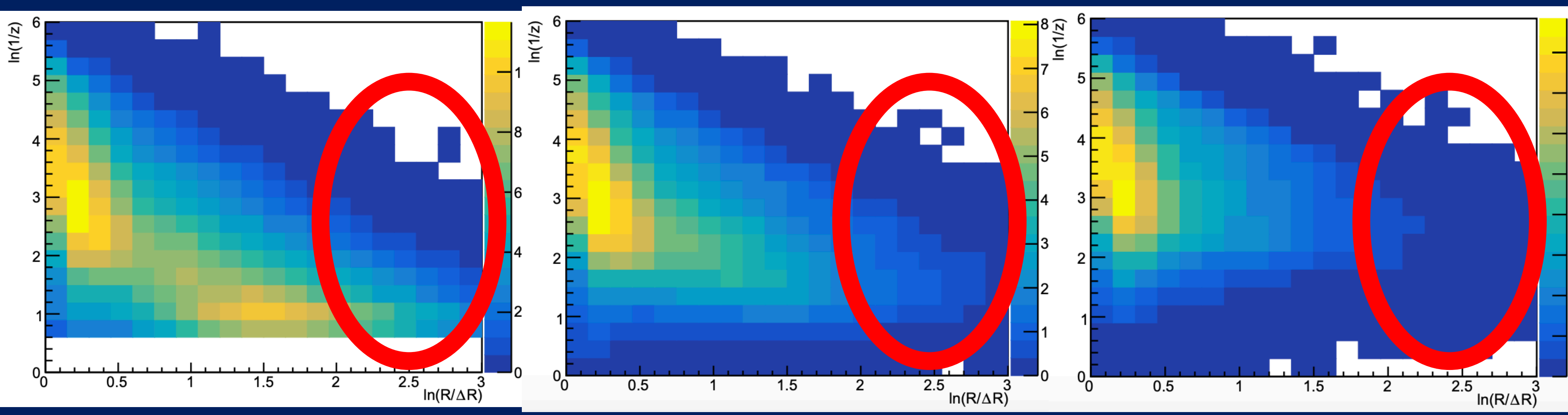
Pythia8 simulations

pp collisions

$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV

$$z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$$

Light quark jets | Charm jets | Beauty jets



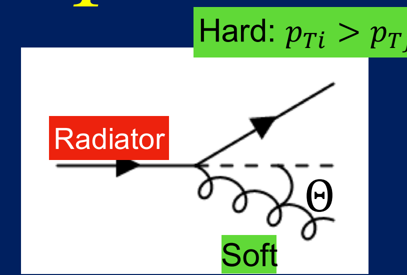
Suppressed collinear radiation = dead cone effect

"Dead cone plane" at forward rapidities

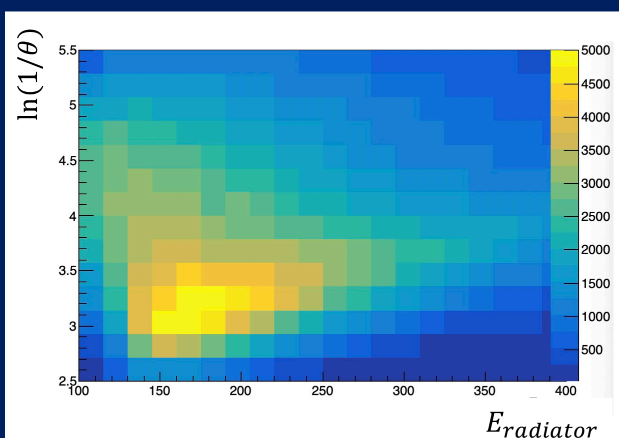
Pythia8 simulations

pp collisions

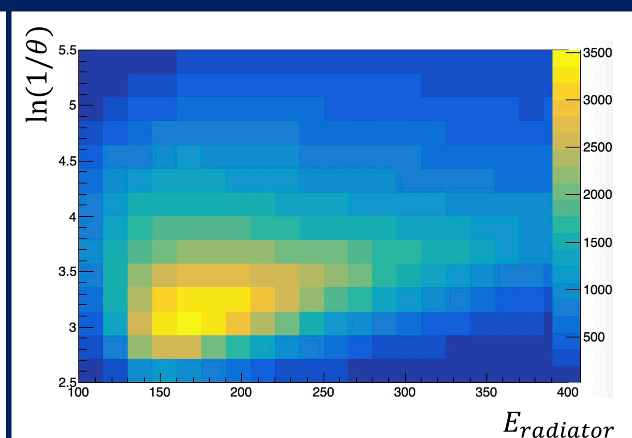
$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV



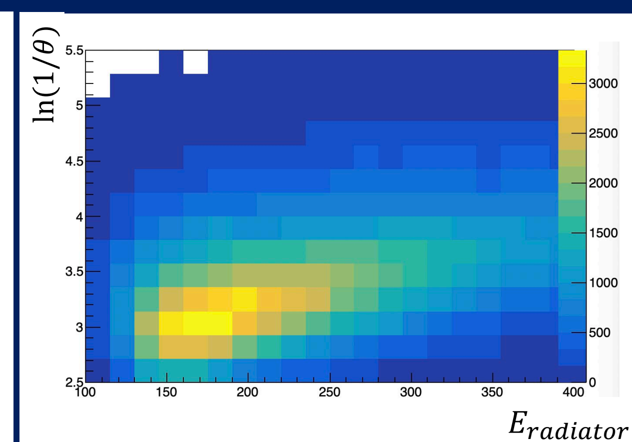
Light quark jets



Charm jets



Beauty jets

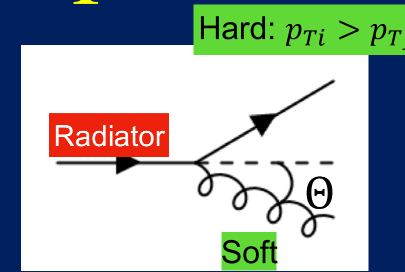


"Dead cone plane" at forward rapidities

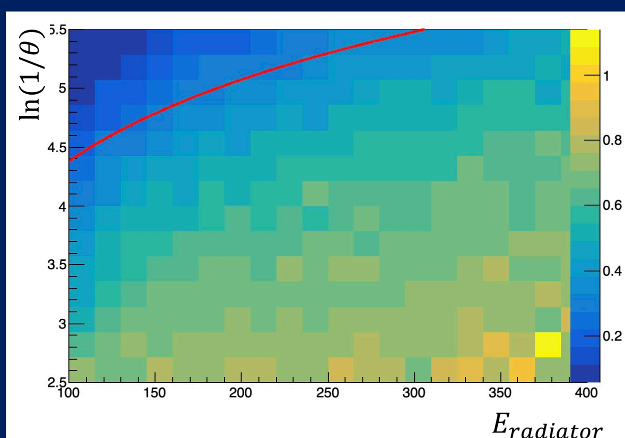
Pythia8 simulations - ratios

pp collisions

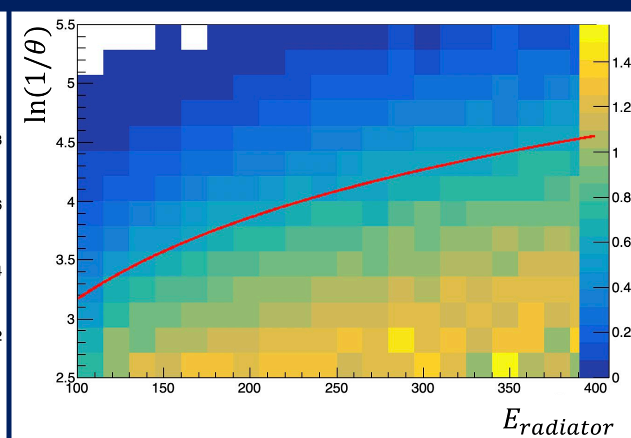
$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV



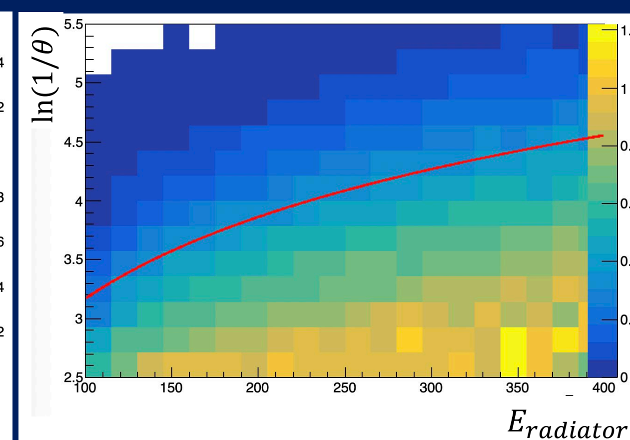
Charm/Light



Beauty/Charm



Beauty/Light



Red line: Dead cone angle as a function of $E_{radiator}$

$$\theta_{\mathrm{HQ}} = \frac{m_{\mathrm{HQ}}}{E}$$

“Dead cone plane” at forward rapidities

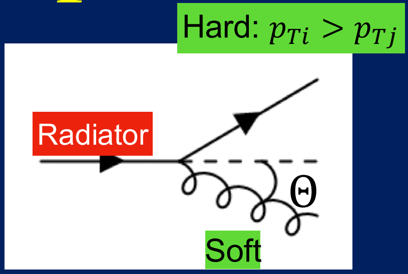
Pythia8 simulations - ratios

pp collisions

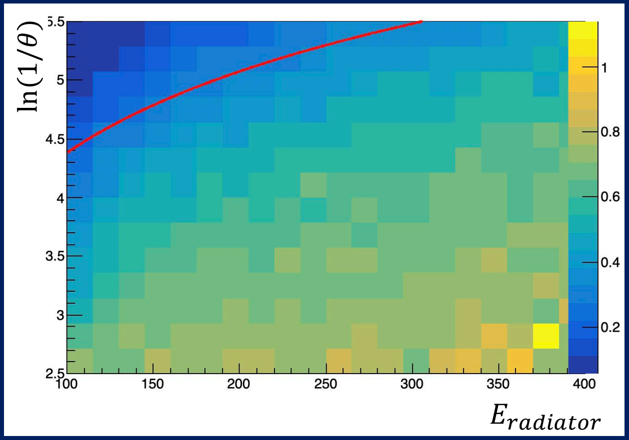
$\sqrt{s} = 13$ TeV

$2.5 < \eta_j < 4$

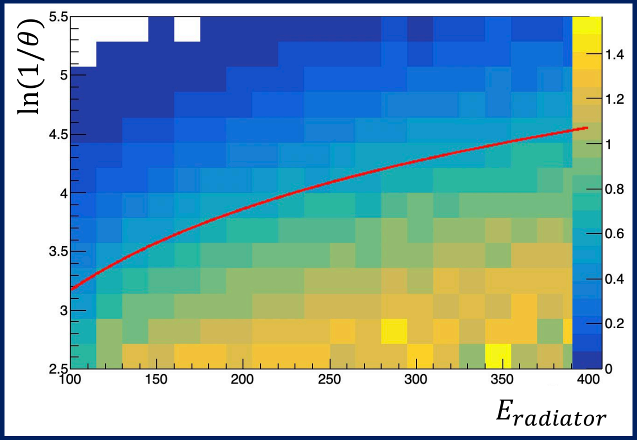
$p_{T,jet} > 20$ GeV



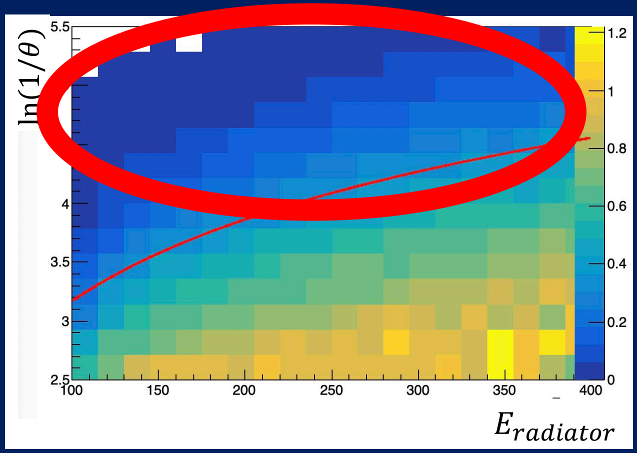
Charm/Light



Beauty/Charm



Beauty/Light



Dead cone effect is most prominent for Beauty/Light ratio

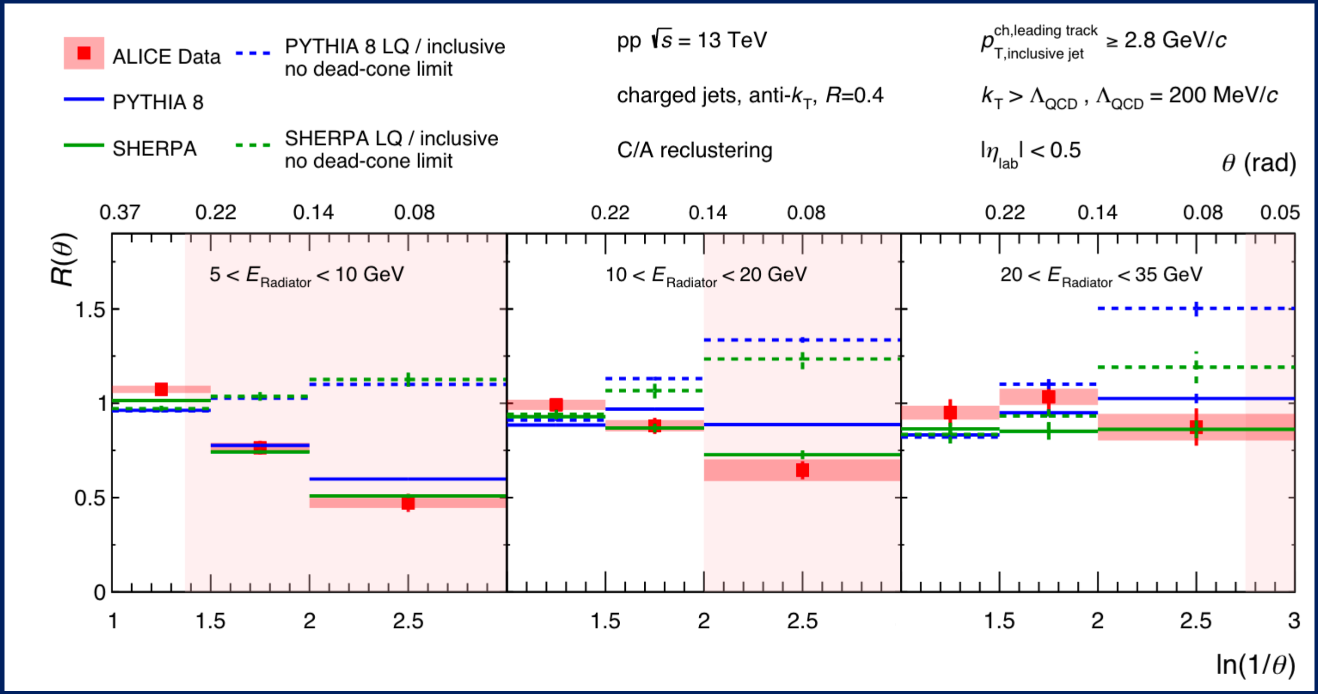
$$\theta_{\mathrm{HQ}} = \frac{m_{\mathrm{HQ}}}{E}$$

Dead cone measurement by ALICE

Ratio of charm to inclusive jets

Nature 605, 440 (2022)

- ALICE has observed the dead cone in charm jets relative to inclusive jets
- We would like to measure beauty/light, charm/light, and beauty/charm



Recap: Lund jet plane at LHCb

We plan on measuring

- the LJP for ***light***, ***charm***, and ***beauty*** jets
- the LJP for ***track-based*** and ***track+neutral*** jets
- the ***dead cone effect*** from the various LJP measurements

Questions for the community (I)

- Our definition of a heavy flavor jet (anti-k_T containing a HF hadron) is not IRC safe beyond NLO. Would theorists advise using a different definition?
- Our HF LJPs contain gluon splitting events. Would trying to isolate these events also be of interest?
- For HF LJPs, some emissions have $z > 0.5$ (emission has more energy than the heavy quark). Should we discard these to maintain strict comparison with the light-quark case?

Questions for the community (II)

- For track-based jets, one does not reconstruct the true kinematics of the radiator and the emission. Does this not lead to a large uncertainty on the LJP?
- Normalizing the dead cone ratio: ALICE measures their significance relative to the "no-dead-cone limit" at R = 1. The ratio of heavy/light emissions can be scaled by a multiplicative factor depending on how one chooses to normalize it. Would the choice of normalization affect the "no-dead-cone limit"? The average number of splittings per jet is different for heavy vs. light quark jets.
  - We tentatively plan to normalize by the number of emissions

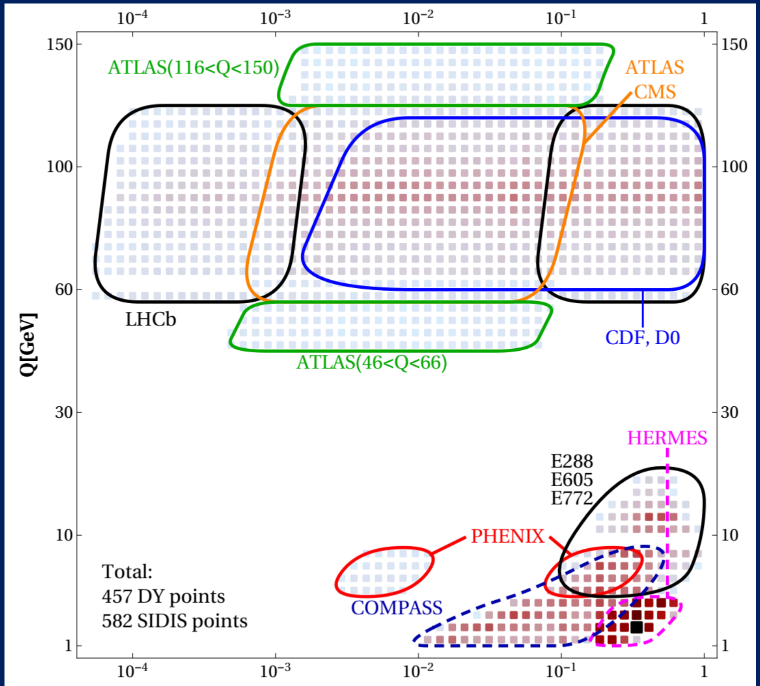
Backup

Bibliography

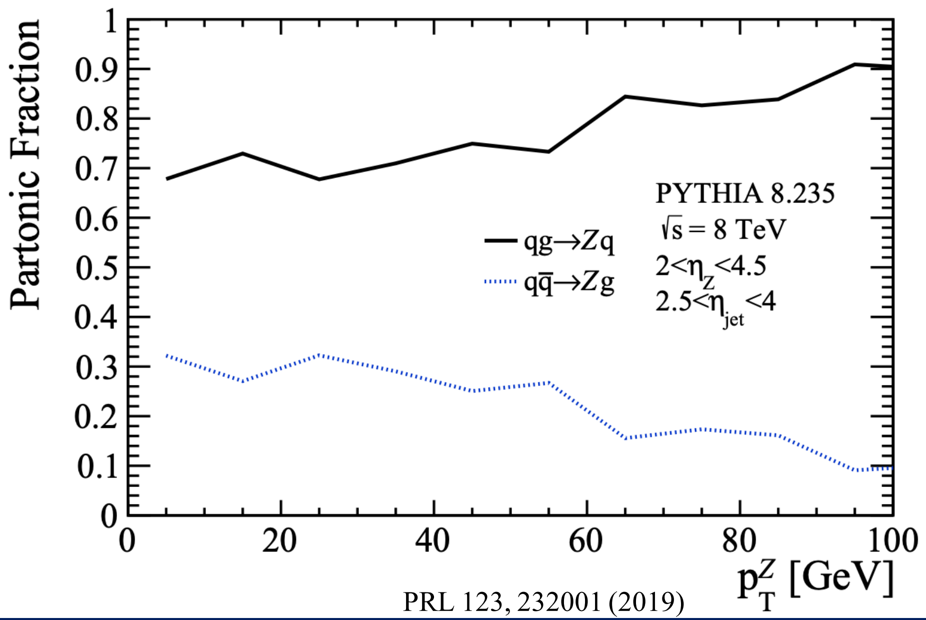
- Dokshitzer, Y.L., Khoze, V.A. and Troyan, S.I., 1991. *Journal of Physics G: Nuclear and Particle Physics*, *17*(10), p.1602. [Intro to the dead cone effect and the leading particle effect]
- (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022) [Fragmentation functions of heavy quarks]
- Cacciari, Matteo, Gavin P. Salam, and Gregory Soyez. JHEP 2008.04 (2008): 063. [anti-kT algorithm]
- F. A. Dreyer, G. P. Salam, and G. Soyez, The Lund jet plane, J. High Energy Phys. 12 (2018) 064 [All the details on the Lund Jet Plane, with theoretical calculations + simulations]
- Cunqueiro, Leticia, and Mateusz Płoskoń. "Searching for the dead cone effects with iterative declustering of heavy-flavor jets." *Physical Review D* 99.7 (2019): 074027. [Exposing the dead cone effect using the Iterative Declustering technique]
- PRL 124.22 (2020): 222002 [ATLAS LJP measurement]
- arXiv:2111.00020v1 [ALICE preliminary measurement]
- *Nature* 605, no. 7910 (2022): 440-446 [ALICE Dead cone measurement]
- https://cds.cern.ch/record/2853467/files/SMP-22-007-pas.pdf [CMS LJP Analysis Summary]
- https://indico.cern.ch/event/575526/contributions/2368491/attachments/1426116/2187895/Mangano-Lect3-print.pdf [Image and explanation of Angular Ordering]

Partonic fractions at forward rapidity

High-x enhances the light-quark jet fraction

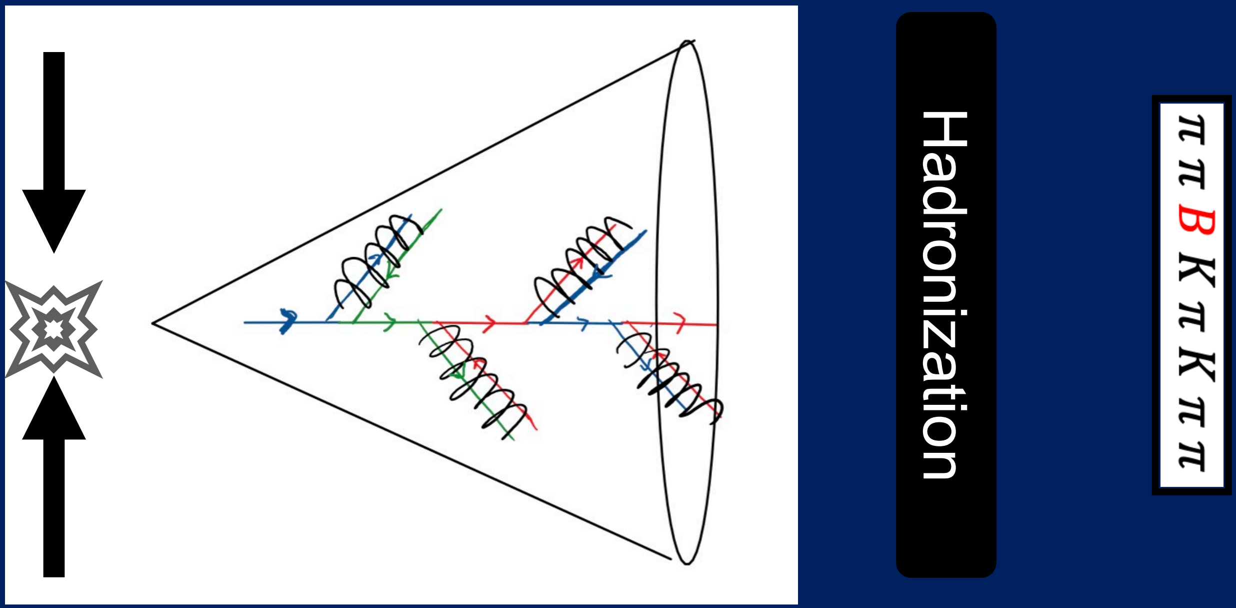


JHEP 06, 137 (2020)



PRL 123, 232001 (2019)

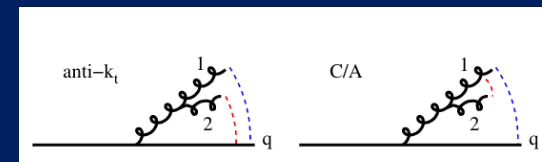
Single partons are inaccessible! Only access is to collimated cone of hadrons, i.e. *jets*



Jets and clustering algorithms

$\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$

R: *Jet Radius*

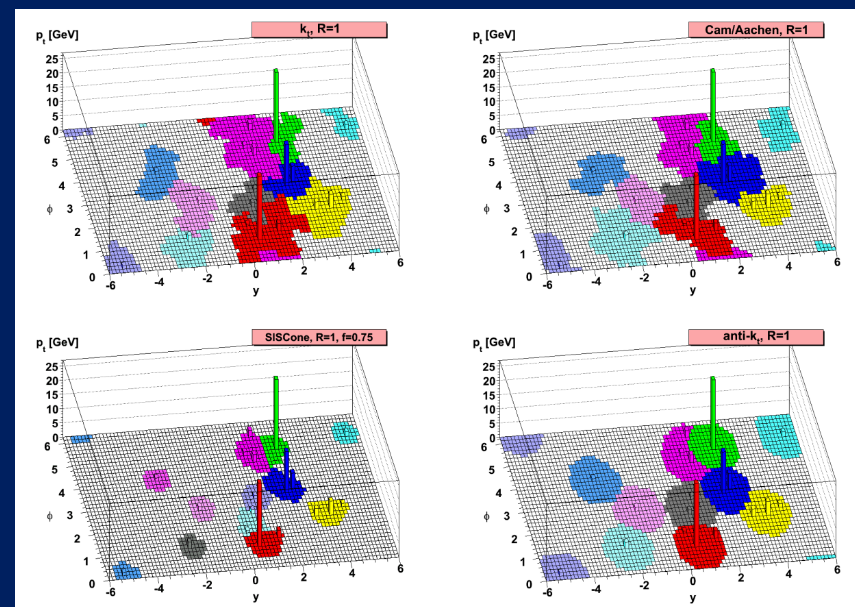


- Given a collection of particles, define a distance as

$$d_{ij} = min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right) \Delta R_{ij}^2 / R^2$$

  - $p = 1$: k_T
  - $p = 0$: Cambridge/Aachen (C/A)
  - $p = -1$: Anti-k_T

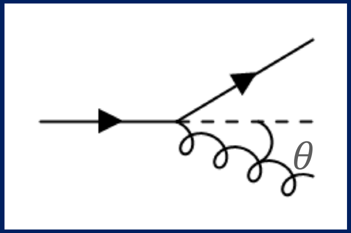
- Merge the two particles with the lowest distance first, repeat until all particles have been merged/clustered
- Anti-k_T is infrared and collinear (IRC) safe, and produces conical jets



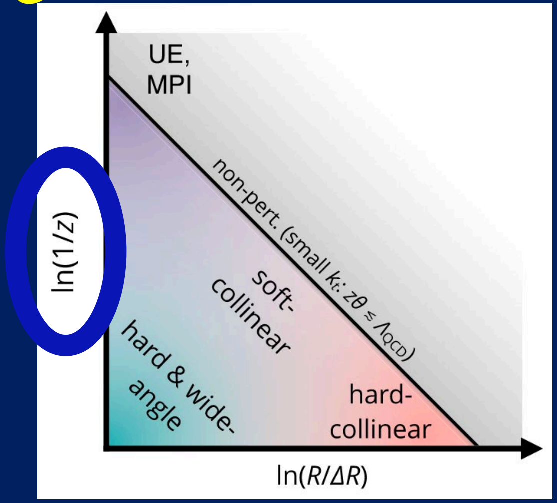
Cacciari, Matteo, Gavin P. Salam, and Gregory Soyez.
JHEP 2008.04 (2008): 063.

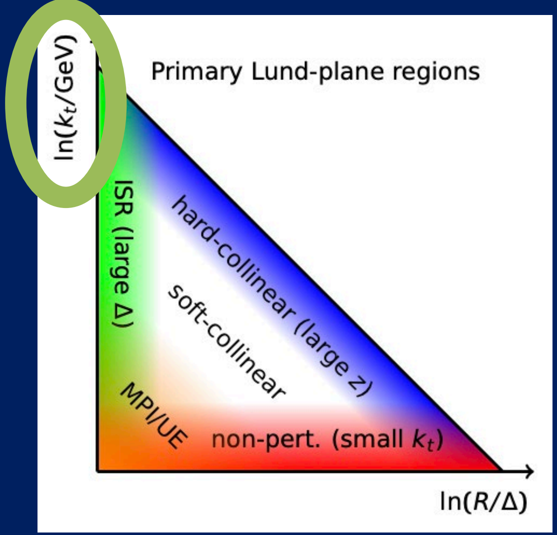
The Lund jet plane

- The Lund jet plane (LJP) is a 2D "image" of parton emissions in jets
- Different representations of the LJP are possible, e.g. $[\ln(1/z), \ln(R/\Delta R)]$ or $[\ln(k_t), \ln(R/\Delta R)]$
- The LJP separates various types of emissions into different regions
- The plane is populated uniformly for soft and collinear emissions



$$dP_{i\to ig} = \frac{\alpha_s C_i}{\pi}\frac{d\theta^2}{\theta^2}\frac{dz}{z}$$





F. A. Dreyer, G. P. Salam, and G. Soyez,
The Lund jet plane, J. High Energy Phys. 12 (2018) 064

Previous measurements of the Lund jet plane

arXiv:2111.00020v1

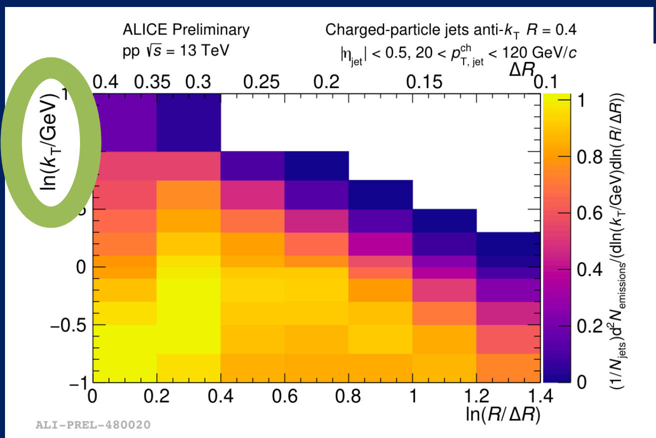
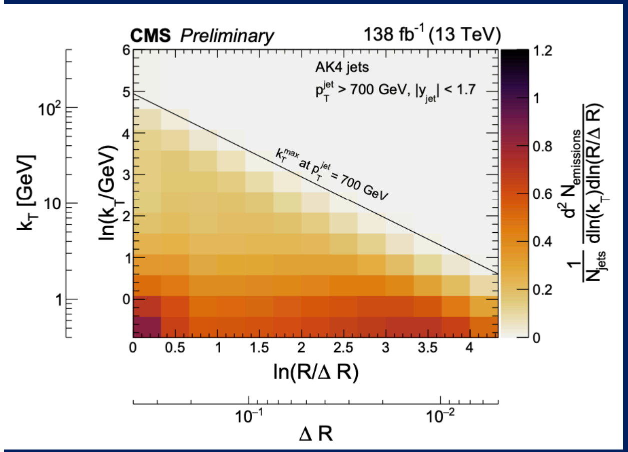


Figure 3: Fully corrected primary Lund plane density.

ALICE



CMS

PRL 124.22 (2020): 222002

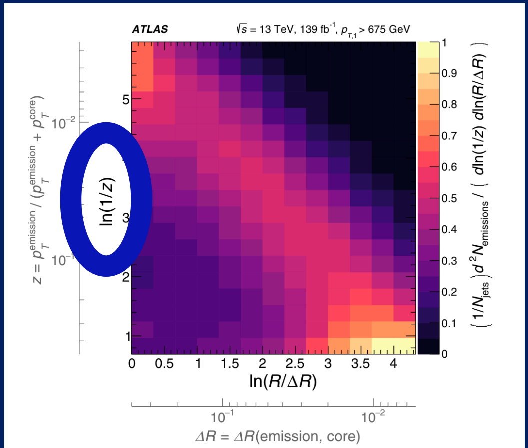


FIG. 2. The LJP measured using jets in 13 TeV pp collision data, corrected to particle level. The inner set of axes indicates the coordinates of the LJP itself, while the outer set indicates corresponding values of z and ΔR.

ATLAS

LJP at forward rapidities

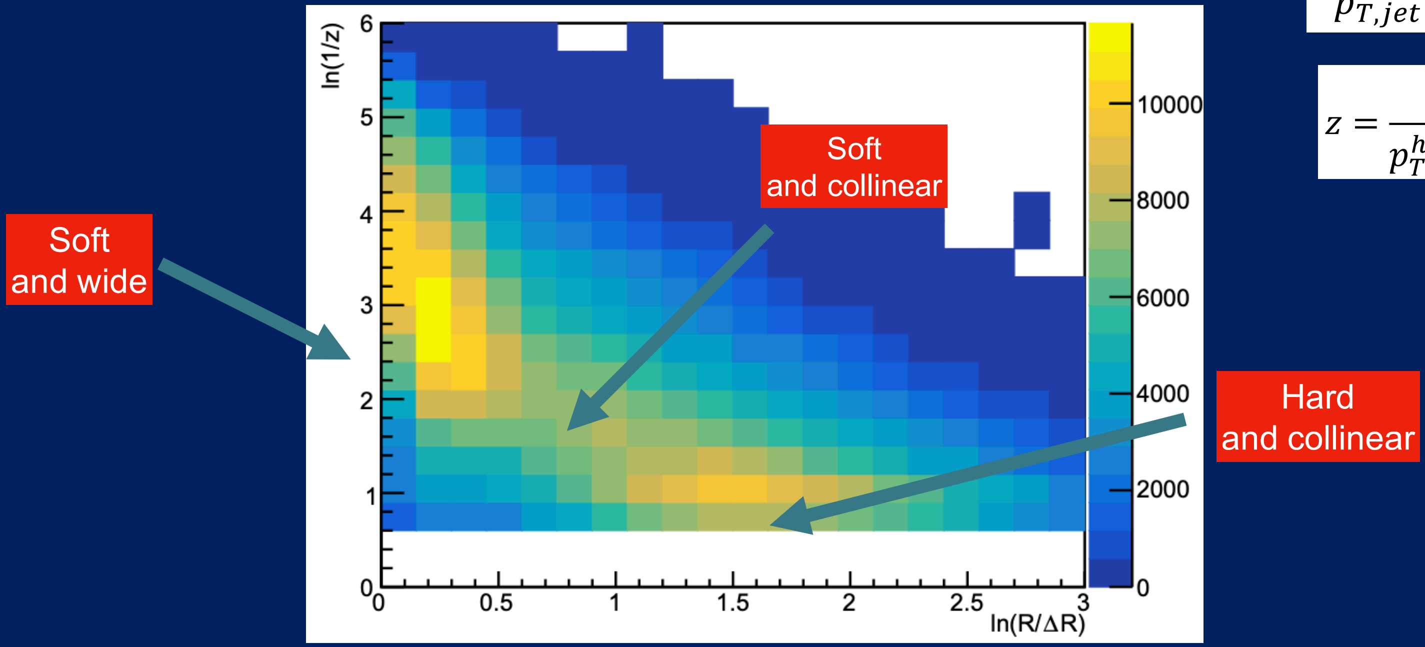
Pythia8 simulations

pp collisions

$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV

$$z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$$

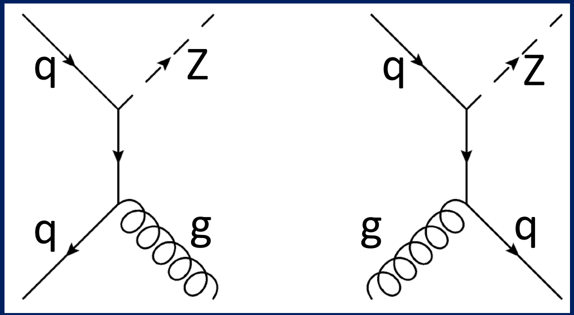
Light quark jets

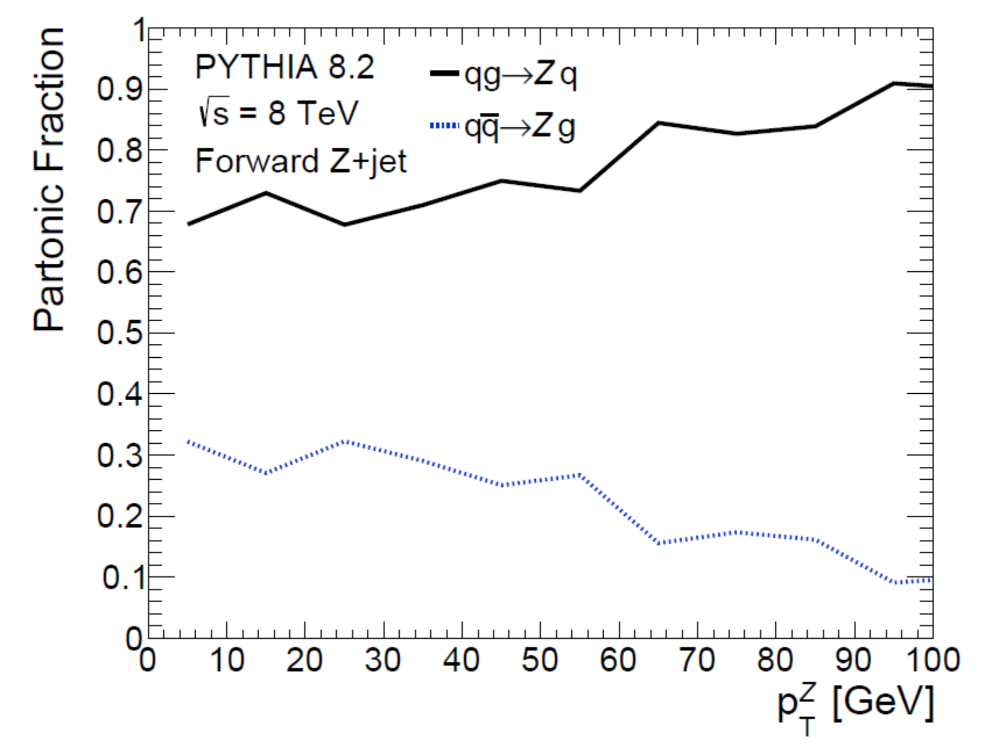


Forward Z+jet

- Z+jet is predominantly sensitive to quark jets

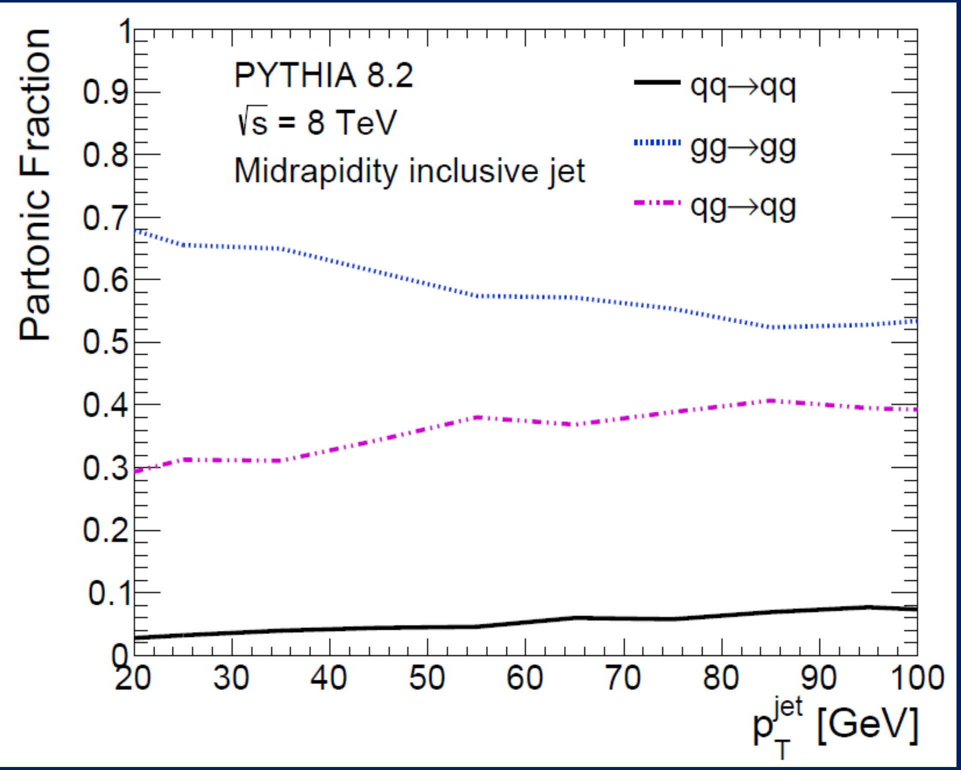
- Forward kinematics increases fraction of light quark jets





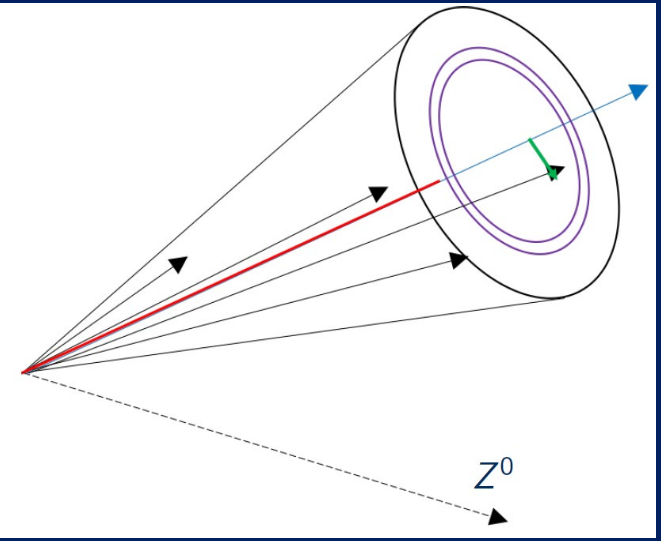
Forward Z+jet

- In contrast to midrapidity inclusive jets, dominated by gluons
- Opportunity to study light quark vs. gluon jets
  - Hadronization dynamics
  - Jet properties



Charged hadrons in forward Z+jet: Observables measured

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



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

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

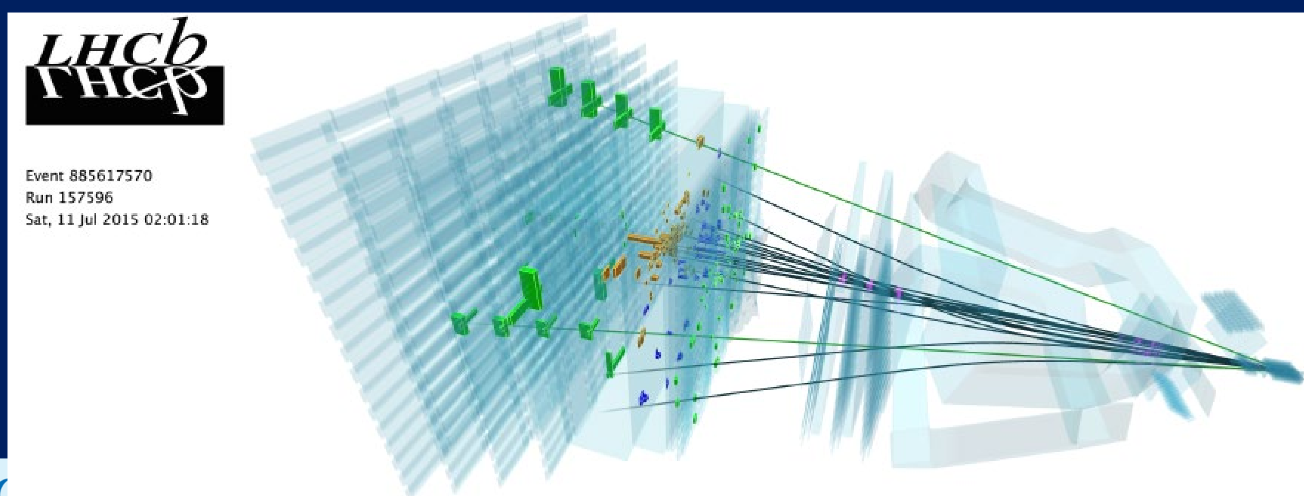
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$

PRL 123, 232001 (2019)

Analysis details

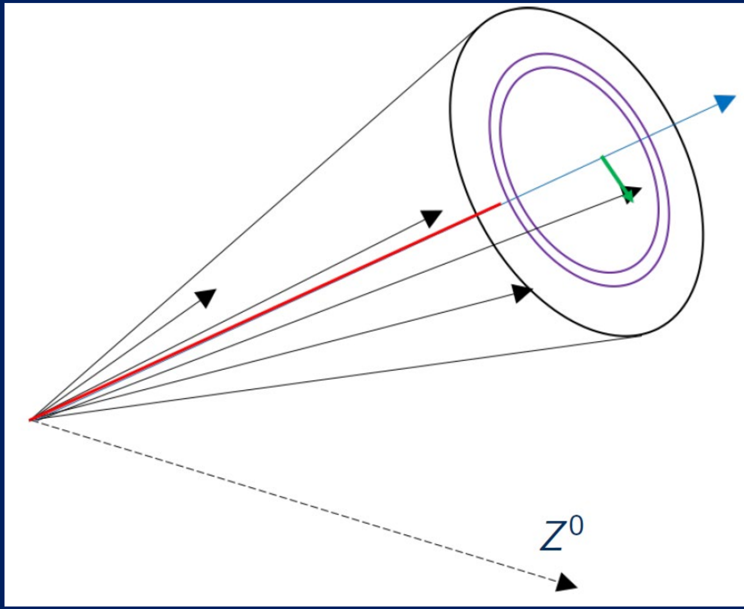
- Follow similar analysis strategy to ATLAS and previous LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

- $Z \to \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-k_T jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2 < \eta < 4.5$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects 2→2 event topology
- Charged hadrons selected with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta R < 0.5$



Charged hadrons in forward Z+jet: Observables

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

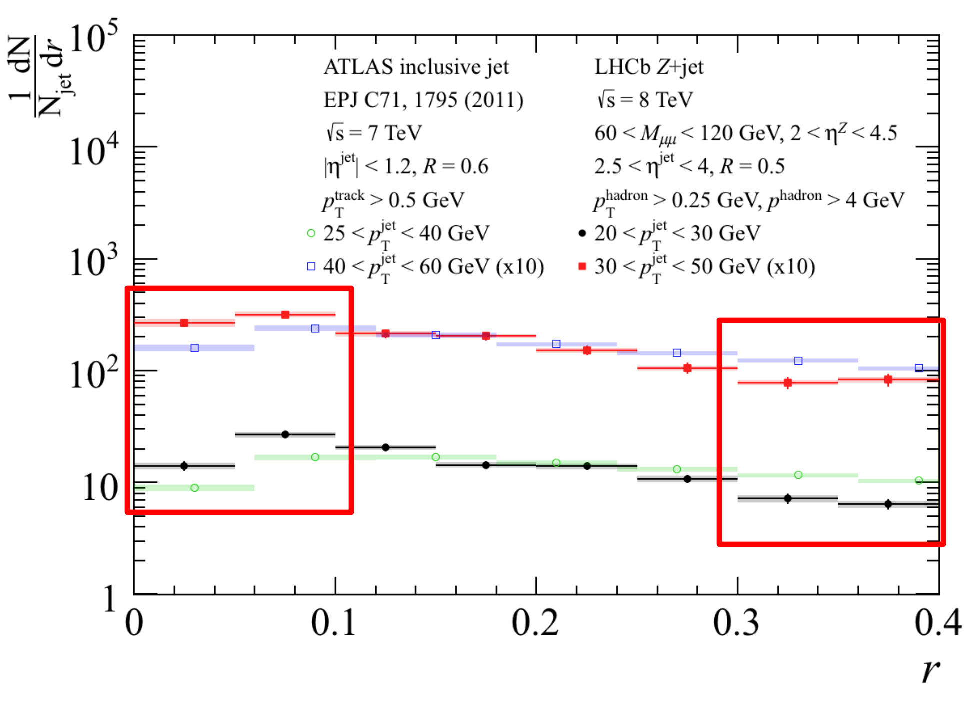


$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

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

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

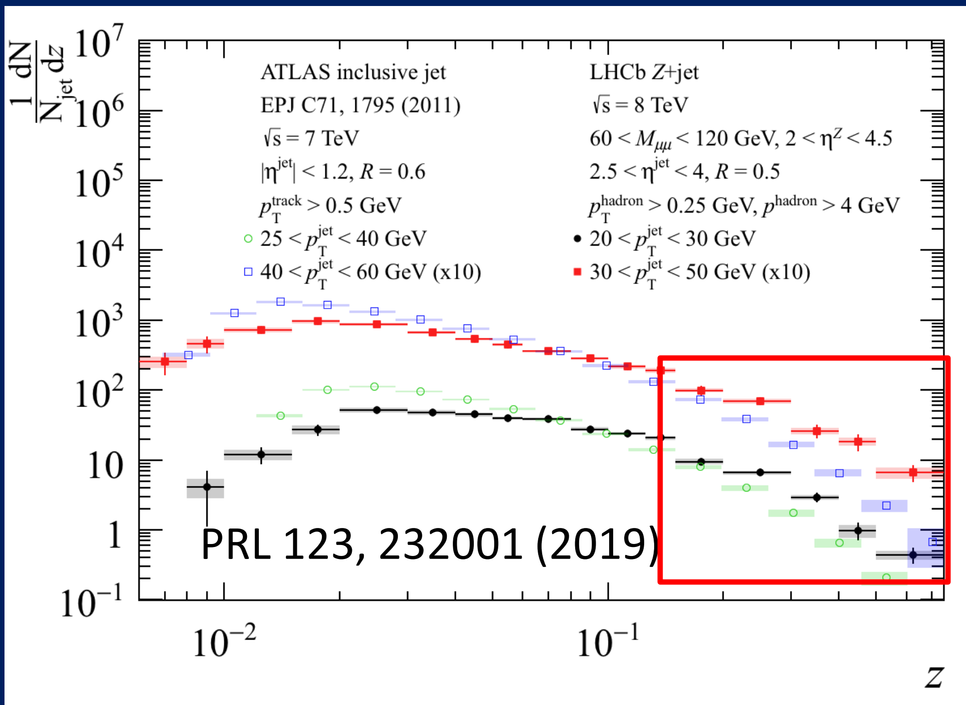
Differences between quark- and gluon-dominated jet samples: Radial profile



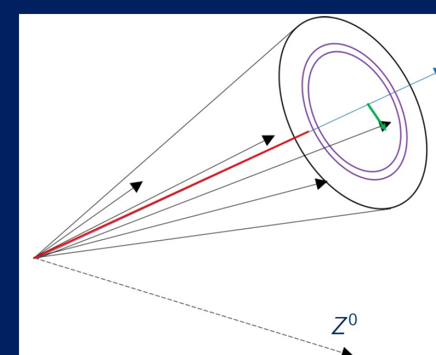
PRL 123, 232001 (2019)

- Quark-dominated jets more collimated than gluon-dominated 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

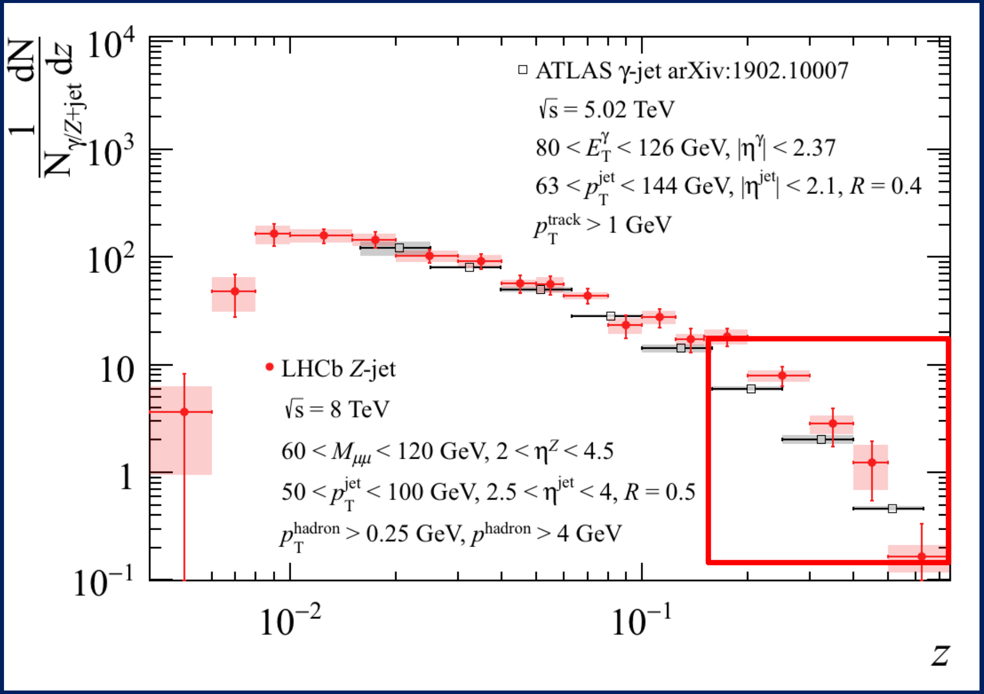
Differences between quark- and gluon-dominated jet samples: Longitudinal profile



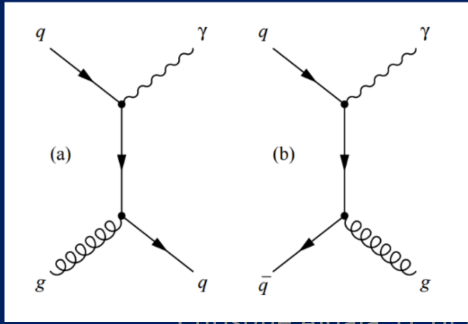
- Quark-dominated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-dominated jets



Differences between quark- and gluon-dominated jet samples: Longitudinal profile



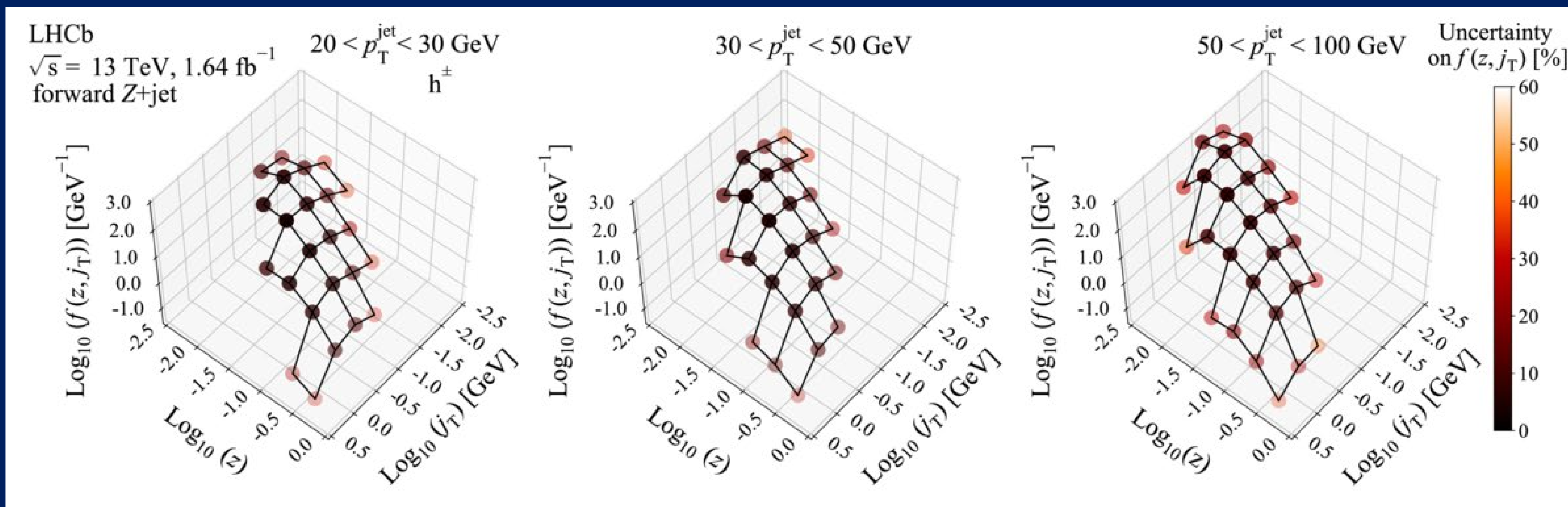
PRL 123, 232001 (2019)



- 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 results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

First <u>multidifferential</u> z-j_T distributions

arXiv:2208.11691 (accepted by PRD Lett.)

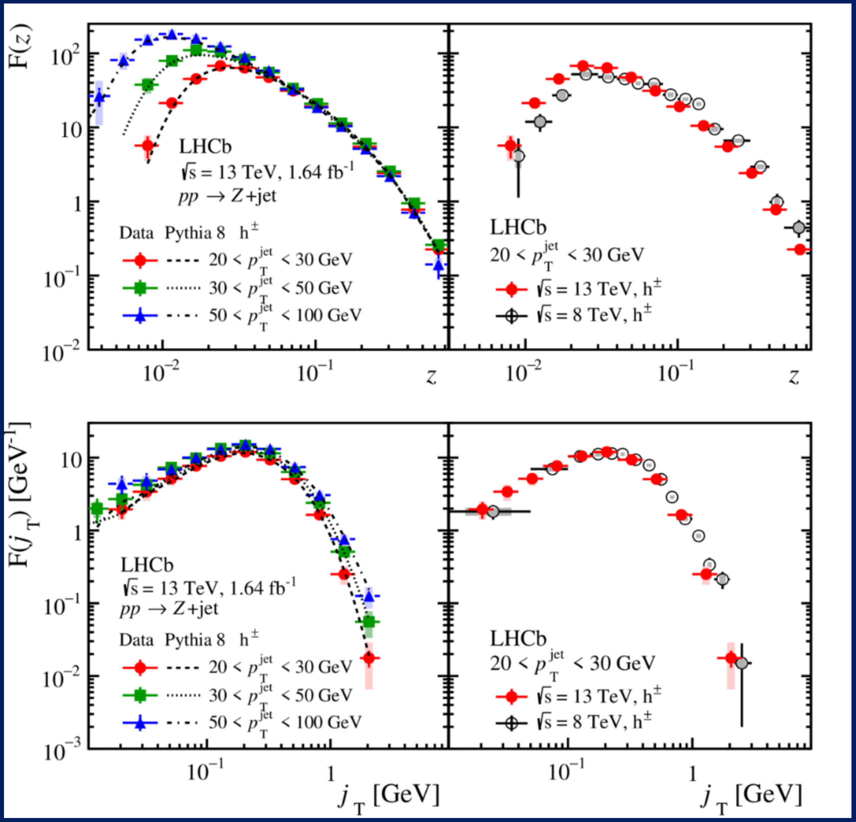


- Larger longitudinal momentum fraction z correlated with larger transverse momentum w.r.t. jet axis j_T - differs from typical phenomenological assumption that they're uncorrelated!

- Larger j_T for given z in jets with higher p_T; consistent with Markov chain fragmentation models, e.g. string or cluster models

1D distributions in Z+jet at 8 and 13 TeV

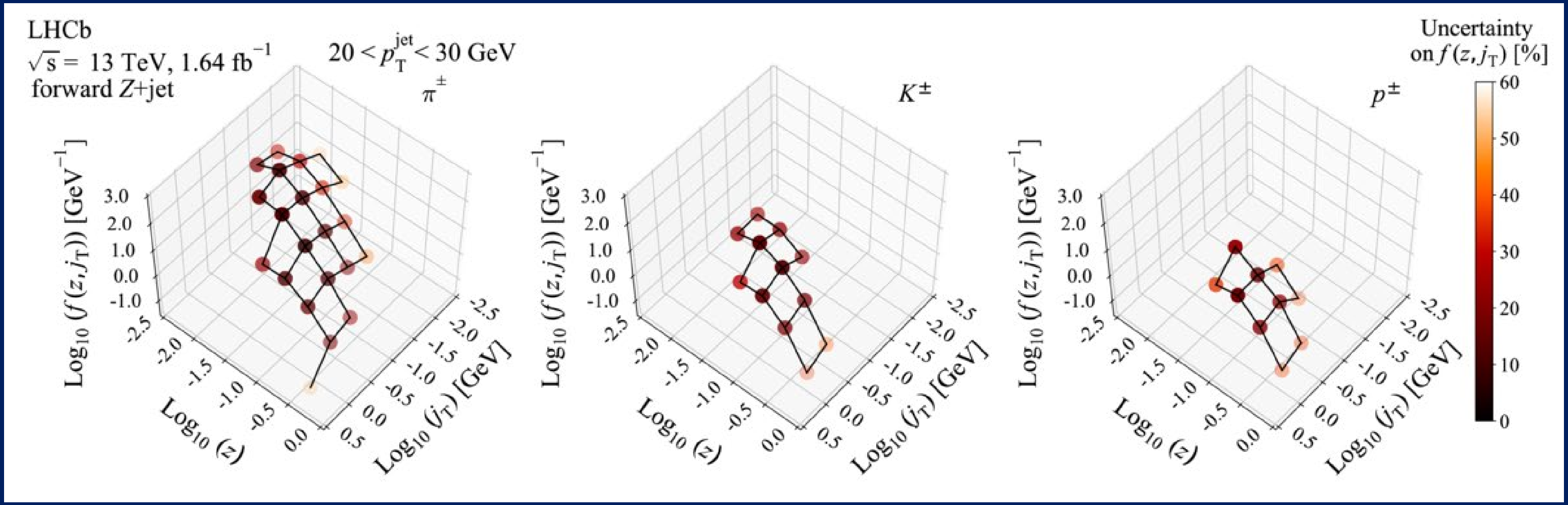
arXiv:2208.11691 (accepted by PRD Lett.)



- At small $z < 0.02$, effects of color coherence as well as kinematic cuts manifest as a humped-back structure
- Harder jets, higher p_T or higher $\sqrt{s}$, produce an excess of soft particles per jet; access smaller z
- Scaling behavior at $z > 0.04$
- Similar pattern in j_T between $\sqrt{s}$ = 8 and 13 TeV

Multidifferential distributions for <u>identified</u> $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$

arXiv:2208.11691 (accepted by PRD Lett.)

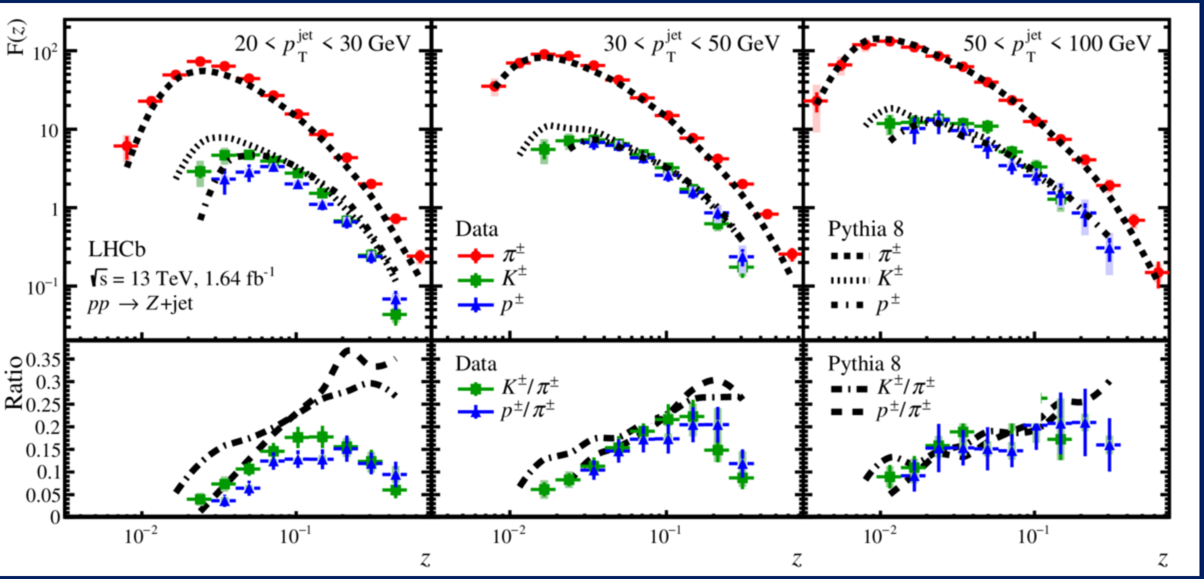


- Multidifferential distributions for pions, kaons, and protons at $20 < p_T^{jet} < 30$ GeV/c
- Heavier hadrons produced at larger j_T and z

1D distributions and ratios for $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$

arXiv:2208.11691 (accepted by PRD Lett.)

- Charged hadron formation within jets predominantly $\pi^{\pm}$ due to its low mass and flavor content of initial-state protons
- Hadrons with higher mass require a larger z threshold for their formation



In lowest jet p_T interval

- Proton production relative to kaons clearly suppressed at lower z
- Pythia 8 overestimates kaon and proton production relative to pions

13 TeV identified hadron-in-jet analysis

Dataset & Selections

- MC : Reco16 Sim09j
  - Generation Code : 42112001
  - Generator level cuts : $p_T(\mu)$ > 4 GeV/c, $\eta(\mu)$> 1.6 and $m_{\mu\mu}$>40 GeV/c^2
- Data: Run II 2016 p+p data
- Stripping line : 'Z02MuMuLine' in Stripping28r2
- Trigger :
  - L0MuonEWDecision & Hlt1SingleMuonHighPTDecision & Hlt2EWSingleMuonVHighPtDecision
- Event requirement :
  - nPV=1

- Z selection:
  - $p_T(\mu)$ > 20 GeV/c, 2 < $\eta(\mu)$ < 4.5
  - $\frac{\sigma_p}{p}$ < 0.1, P(χ^2) > 0.1%, isMuon
  - 60 < $m_{\mu\mu}$ < 120 GeV/c^2
- Jet selection:
  - StdJets, p_T(jet) > 20 [15] GeV/c, 2.5 < η(jet) <4.0, deltaR(jet)=0.5
  - $\Delta\phi$(jet-μ) > 0.4
  - $\Delta\phi$ (Z-jet)> $\frac{7}{8}\pi$
- Track selection
  - Track χ^2/ndf < 3
  - 4 < p < 1000 GeV/c
  - p_T > 0.25 GeV/c