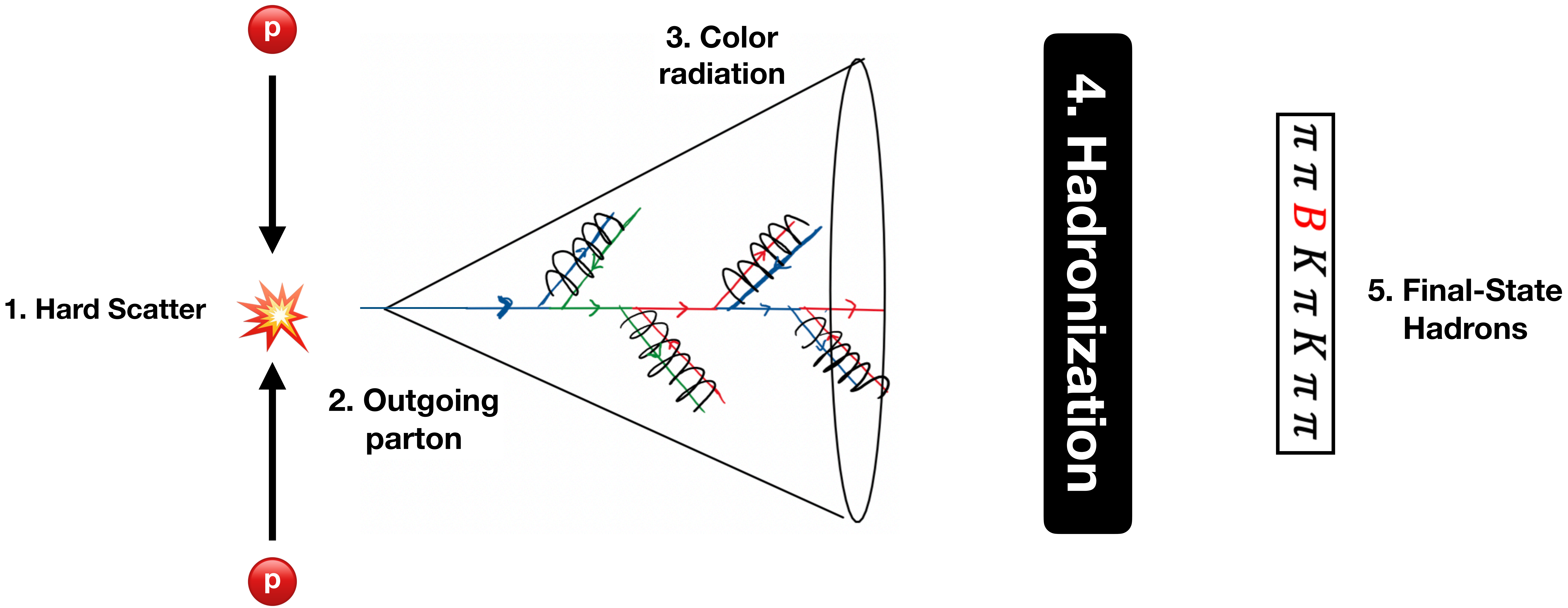
Heavy Flavor Fragmentation and Lund Jet Plane Measurements at LHCb

Heavy Flavours at High pT 2023
Nov 29 - Dec 01, 2023

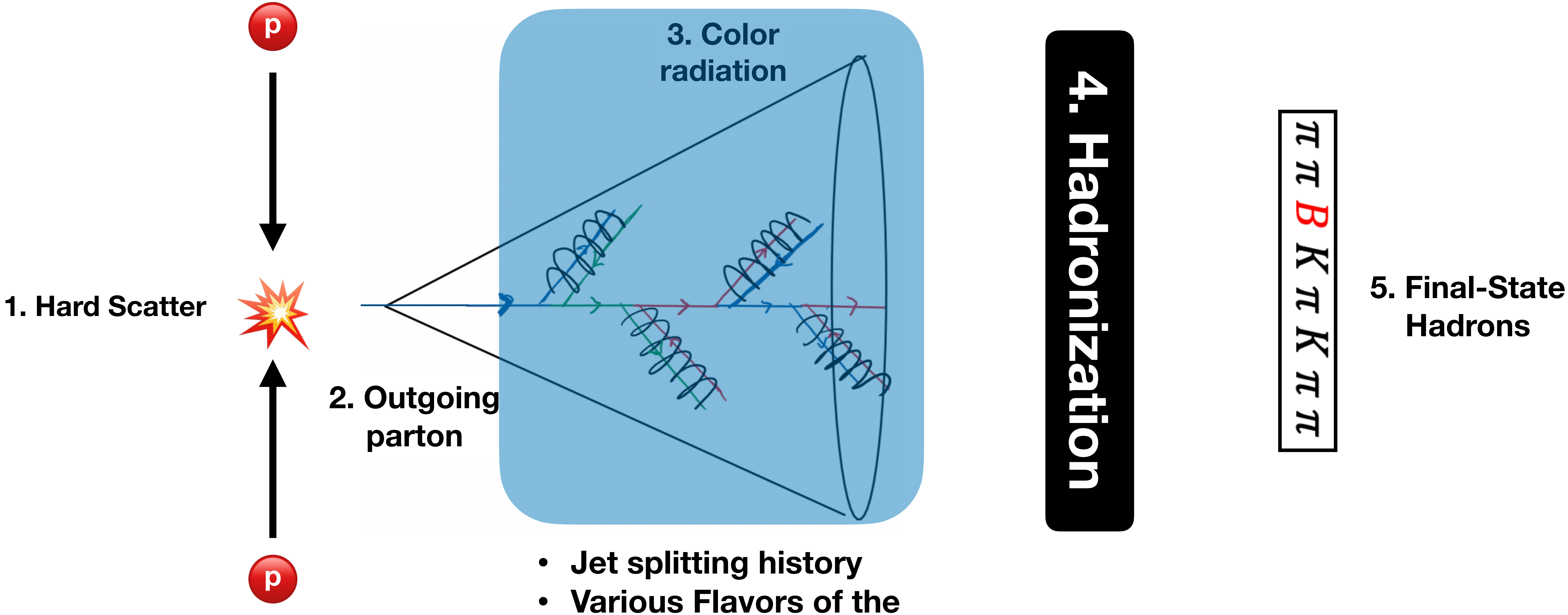
Ibrahim Chahrour, on behalf of the LHCb collaboration.
PhD Candidate, University of Michigan, Ann Arbor

A typical hard-scattering event at the LHC



*Not to scale

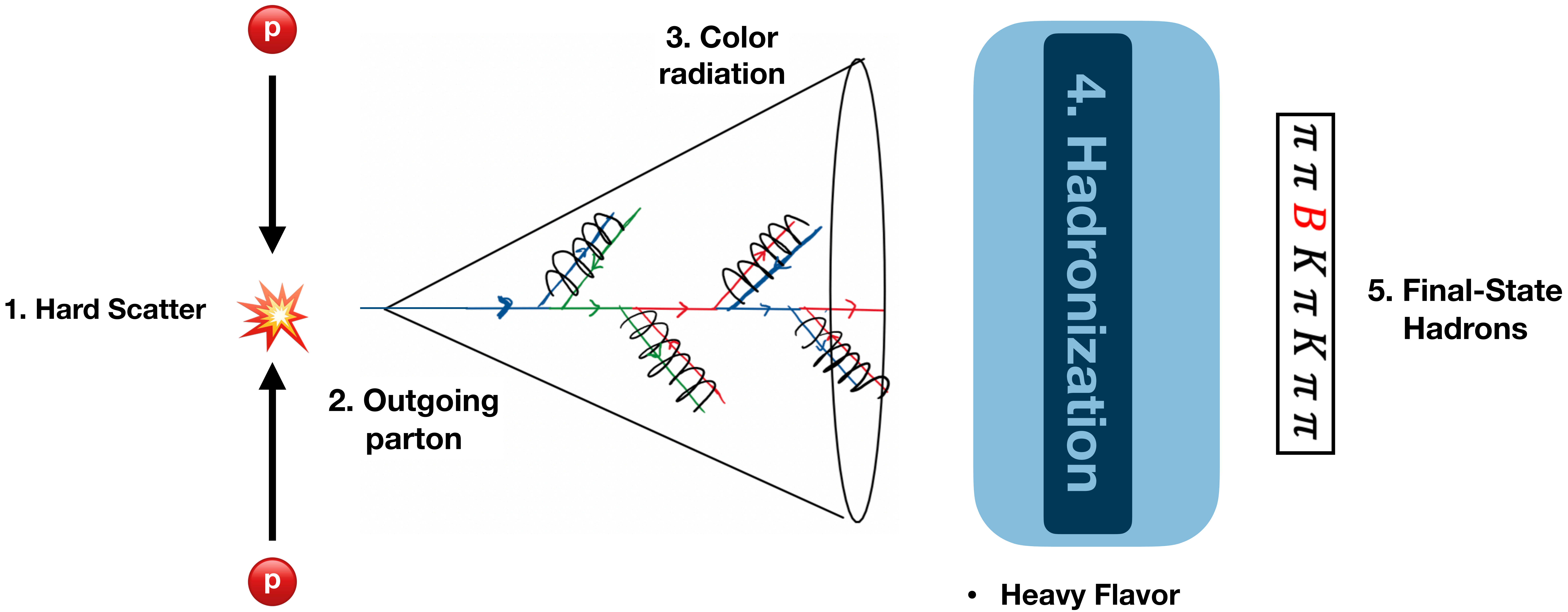
A typical hard-scattering event at the LHC



- Jet splitting history
- Various Flavors of the Lund Jet Plane
- Dead-cone effect

*Not to scale

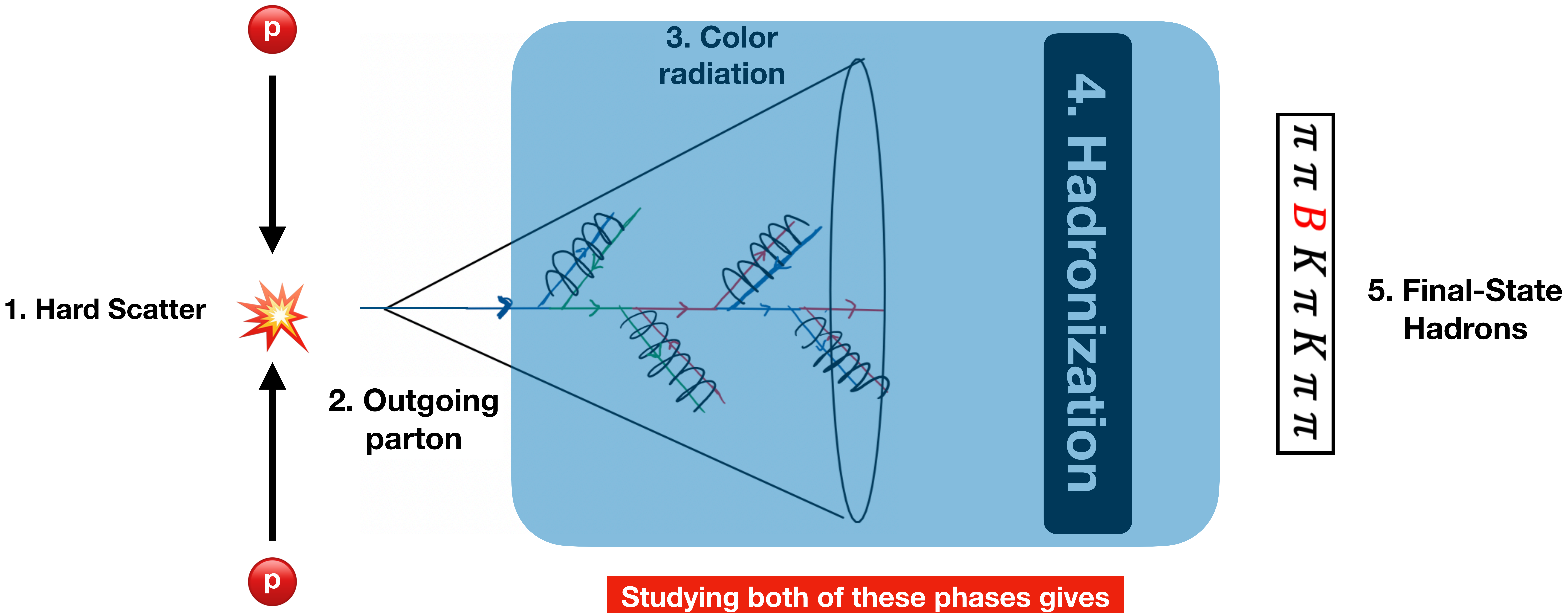
A typical hard-scattering event at the LHC



- **Heavy Flavor Fragmentation**

*Not to scale

A typical hard-scattering event at the LHC

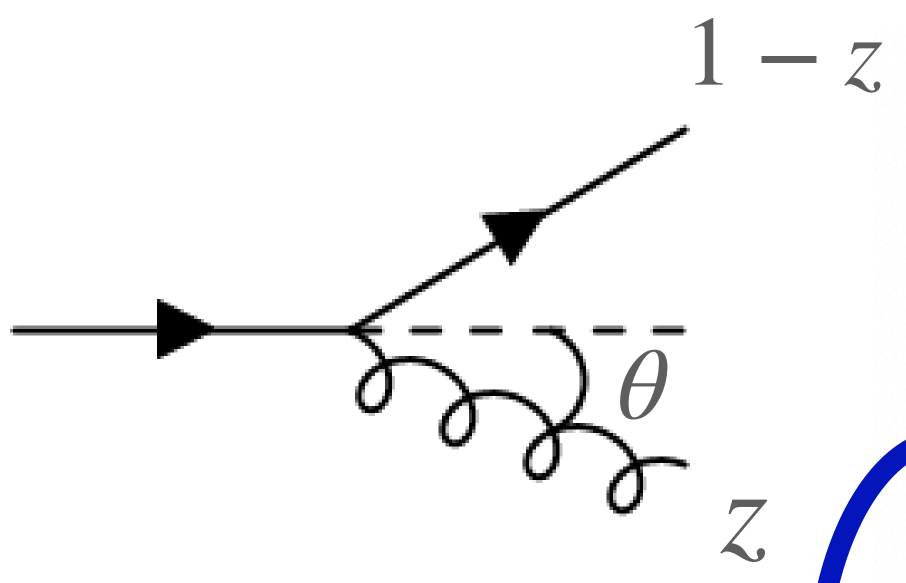


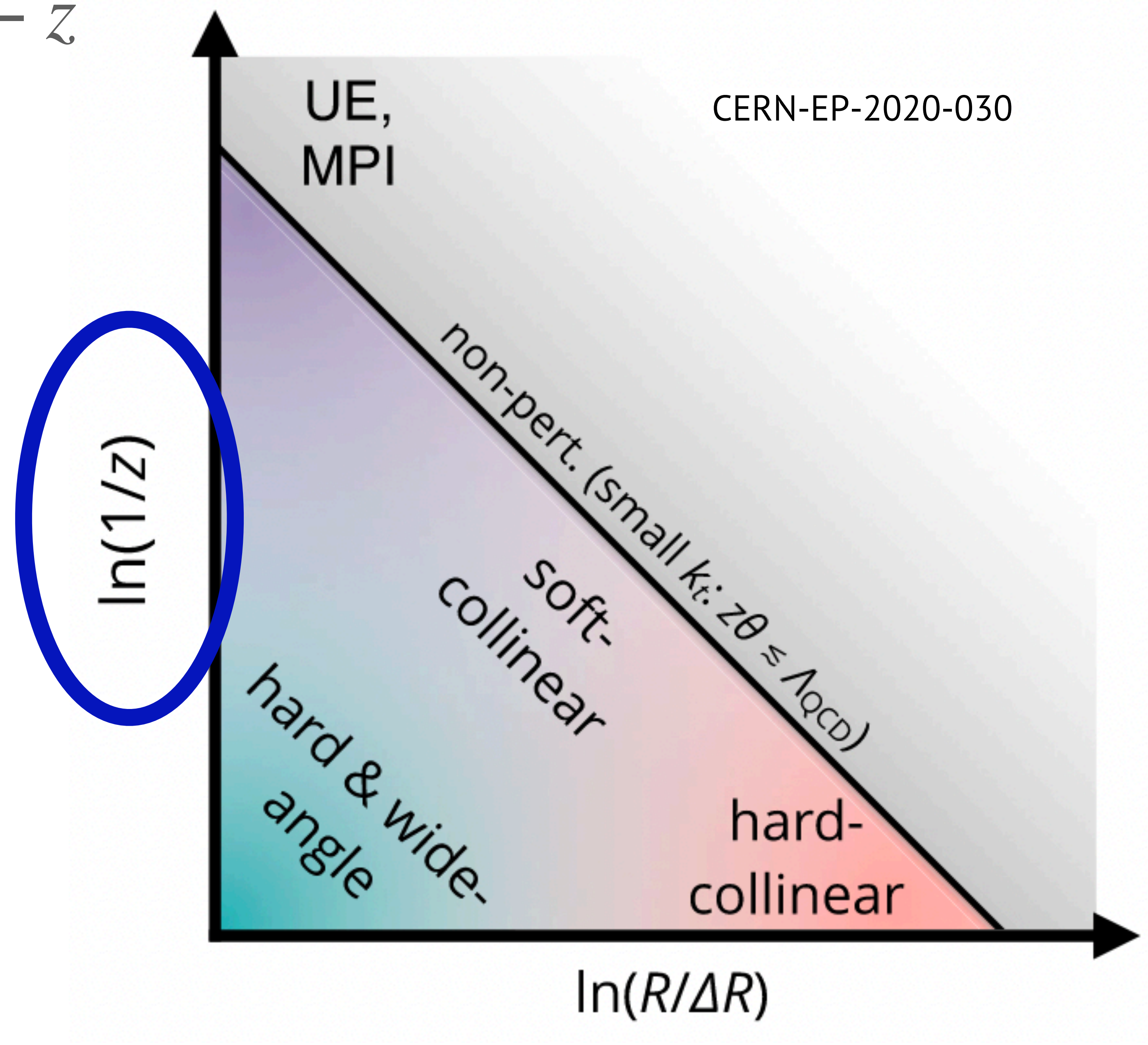
Studying both of these phases gives us a more complete picture of jets

*Not to scale

Heavy Flavor Lund Jet Plane

The Lund jet plane



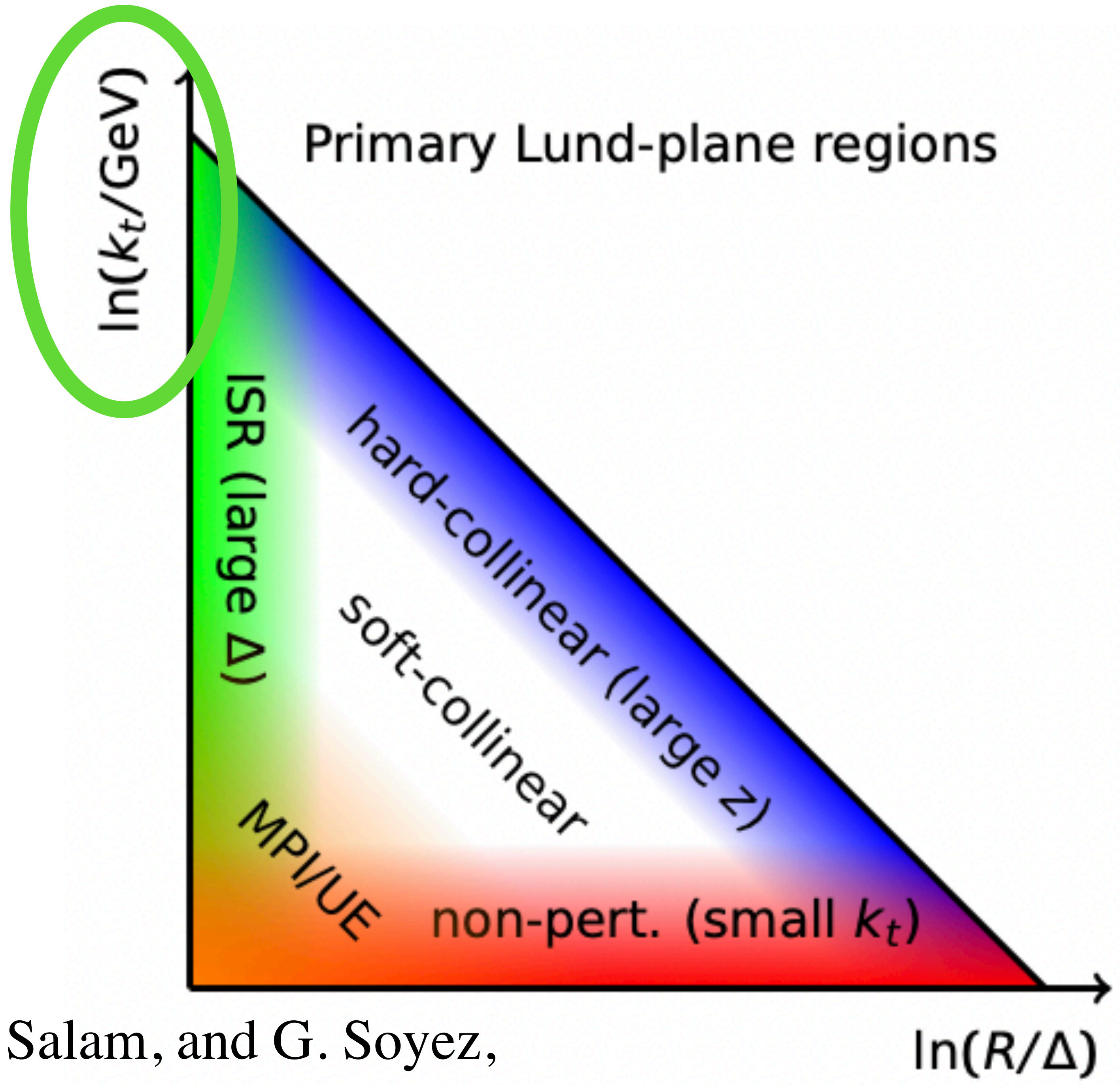


- The Lund jet plane (LJP) is a 2D "image" of parton emissions in jets
- Different representations of the LJP are possible, e.g. $[\ln(1/z), \ln(R/\Delta R)]$ or $[\ln(k_t), \ln(R/\Delta R)]$
- The LJP separates various types of emissions into different regions
- The plane is populated uniformly for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

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

$$k_T = p_T^{soft}\sin(\Delta R),$$

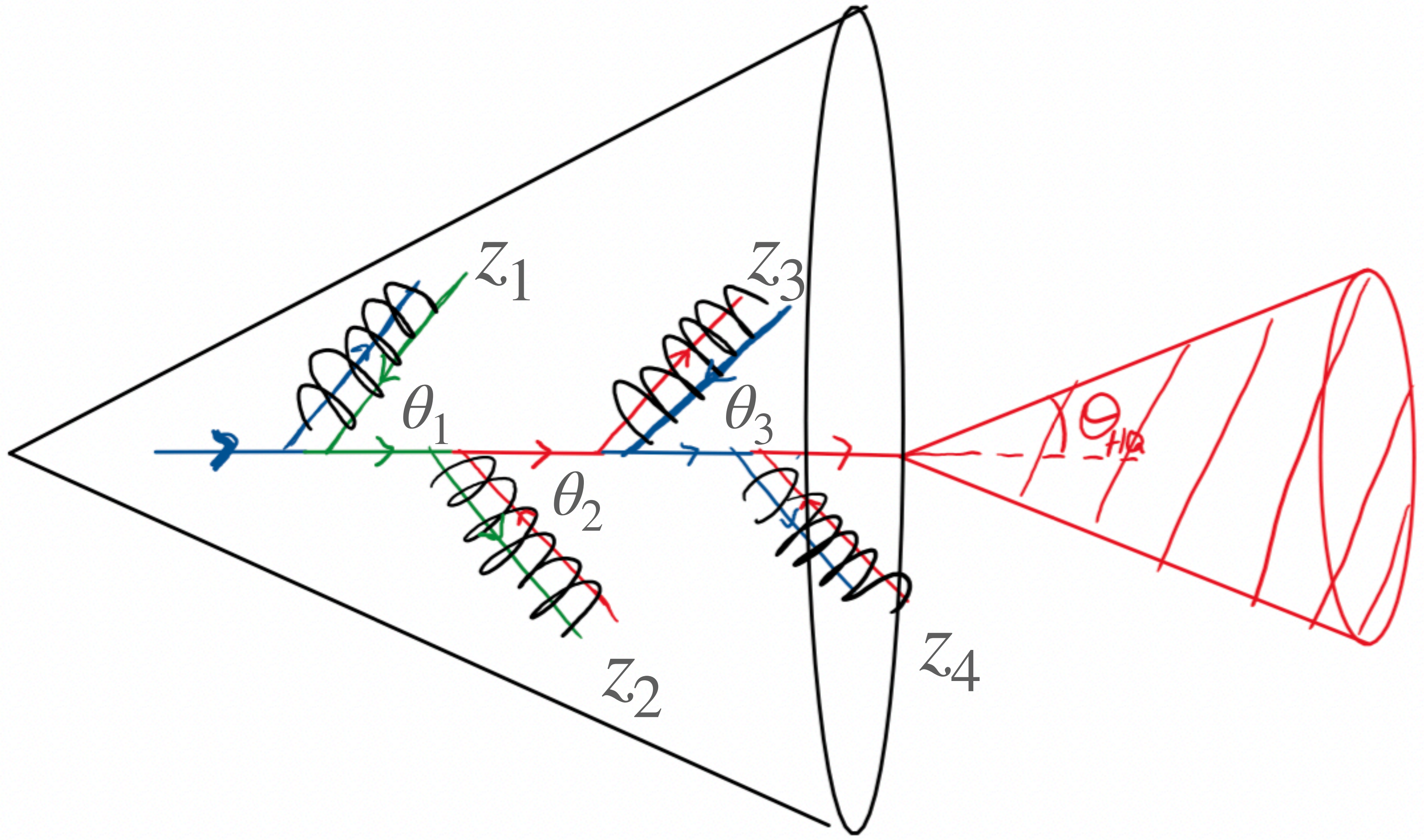
$$z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$$



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

The Dead Cone Effect

Suppression of collinear radiation off of massive quarks



- 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

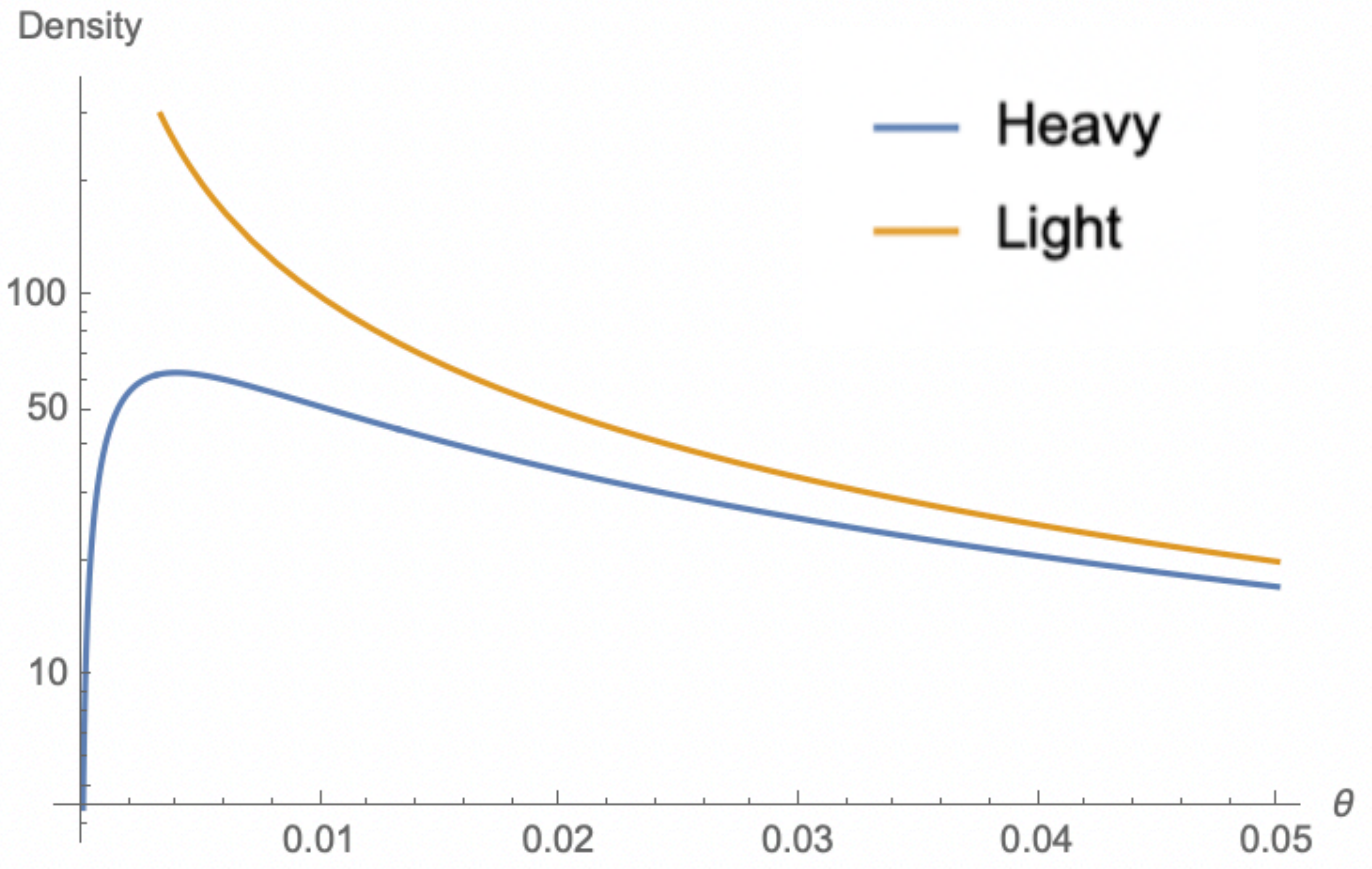
θ : Splitting angle

C_i : Color factor

- For heavy quarks (HQ), 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.

The Dead Cone Effect

Bremsstrahlung off moving charges

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

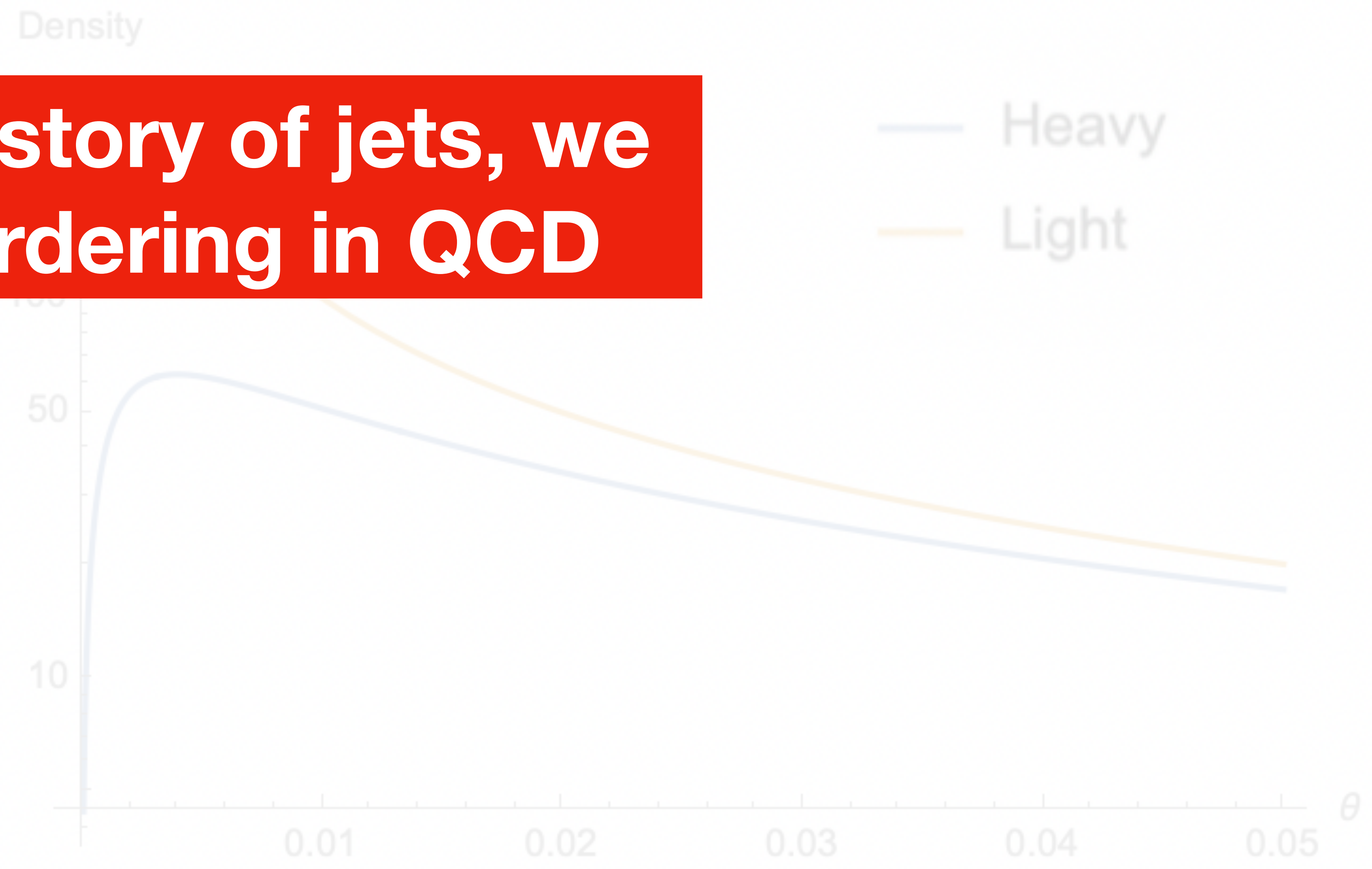
$$dP_{i\to ig} =$$

z : Energy Fraction

To reconstruct the splitting history of jets, we take advantage of angular ordering in QCD

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

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



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

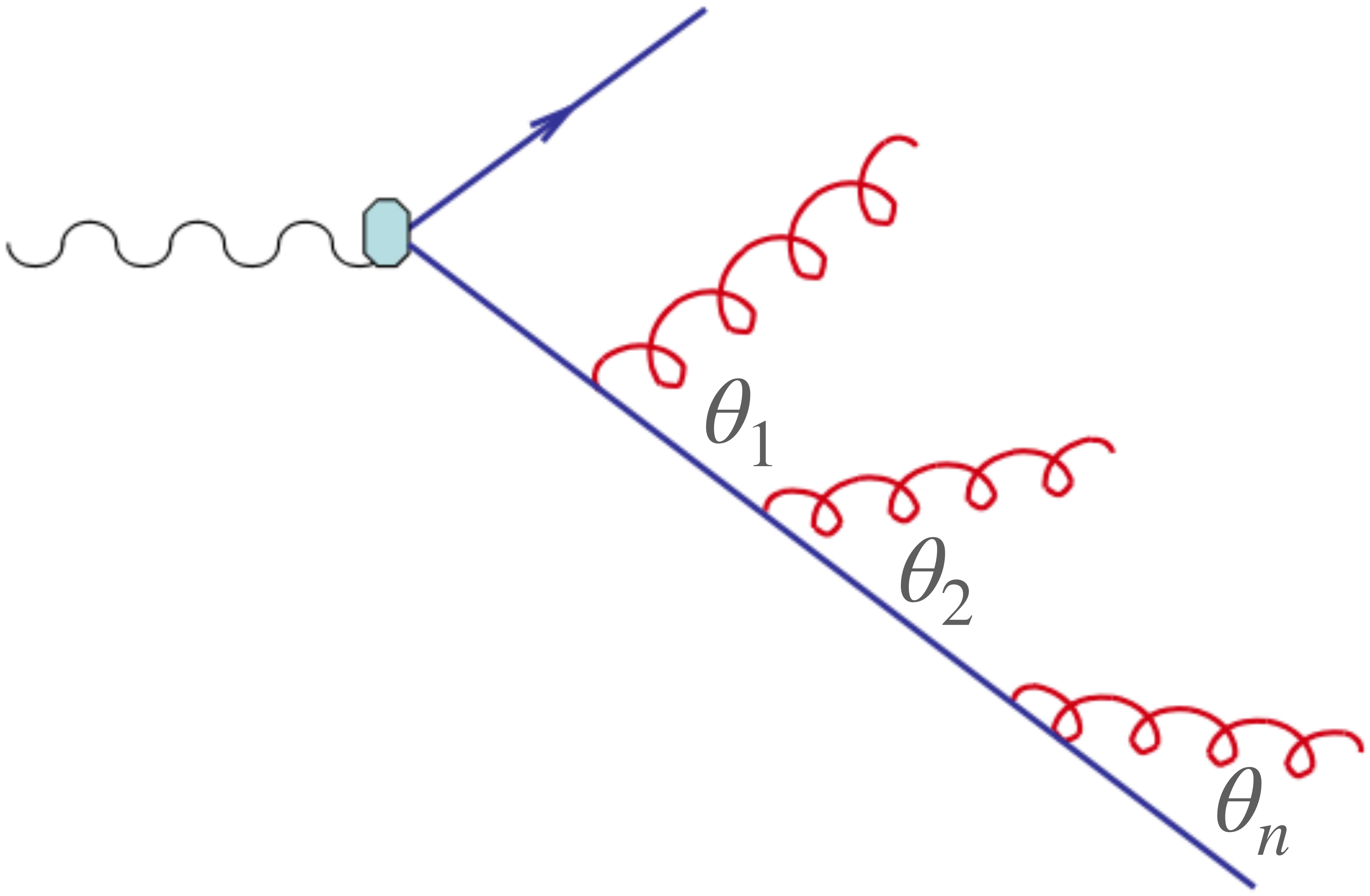
Angular Ordering

Accessing the splitting history

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

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

- The Cambridge/Aachen (C/A) algorithm clusters jets based on smallest angles first = respects angular ordering!

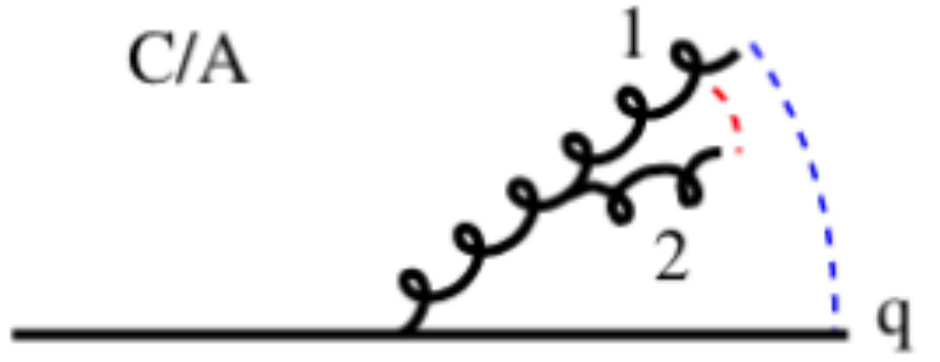


C/A gives us access to the splitting history of the jet

Image: Mangano-Lect3

Iterative Declustering

Cunqueiro, Leticia, and Mateusz Płoskoń. Physical Review D 99.7 (2019): 074027



Recluster = combine most collinear particles according to C/A

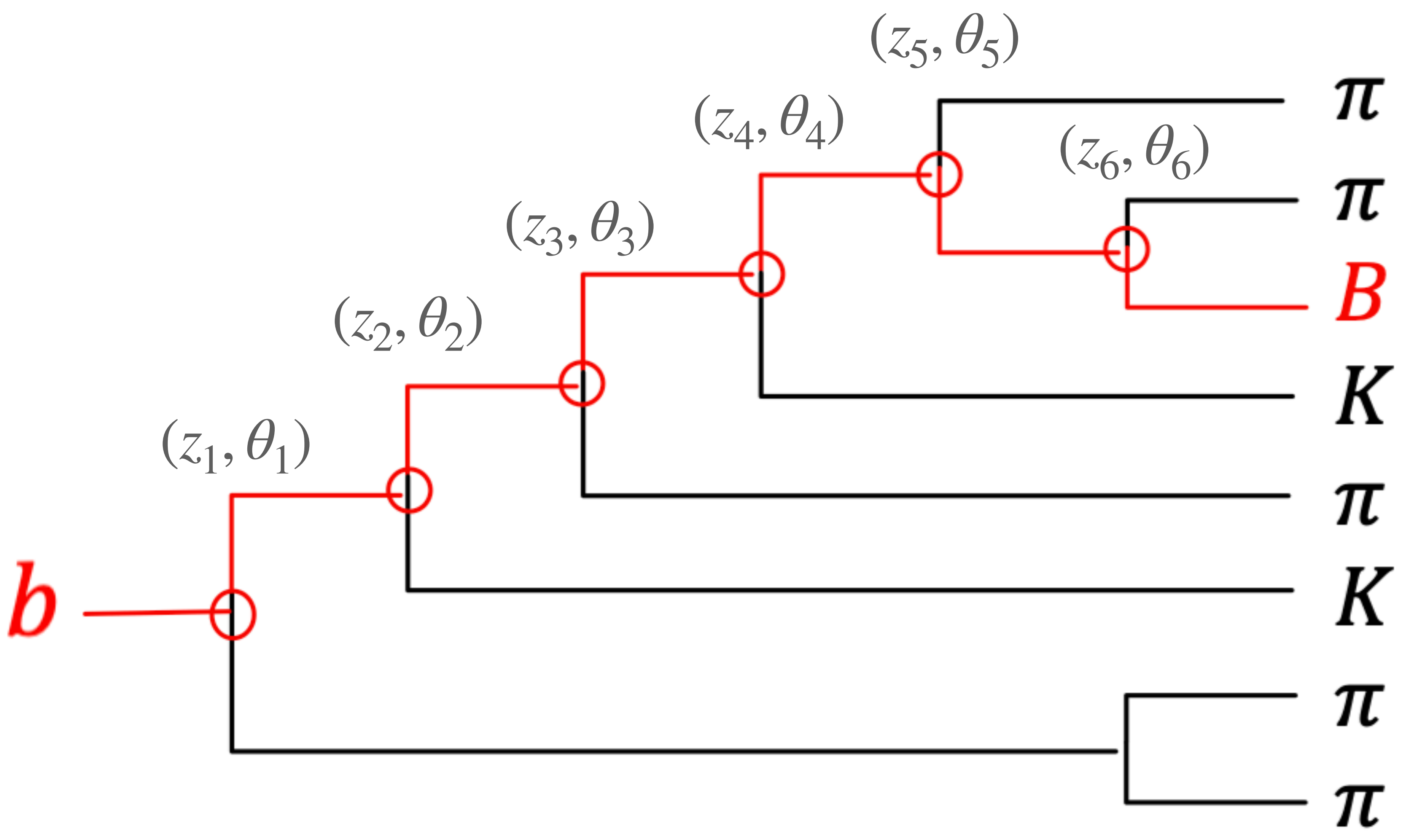
Anti-k_T Jet

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

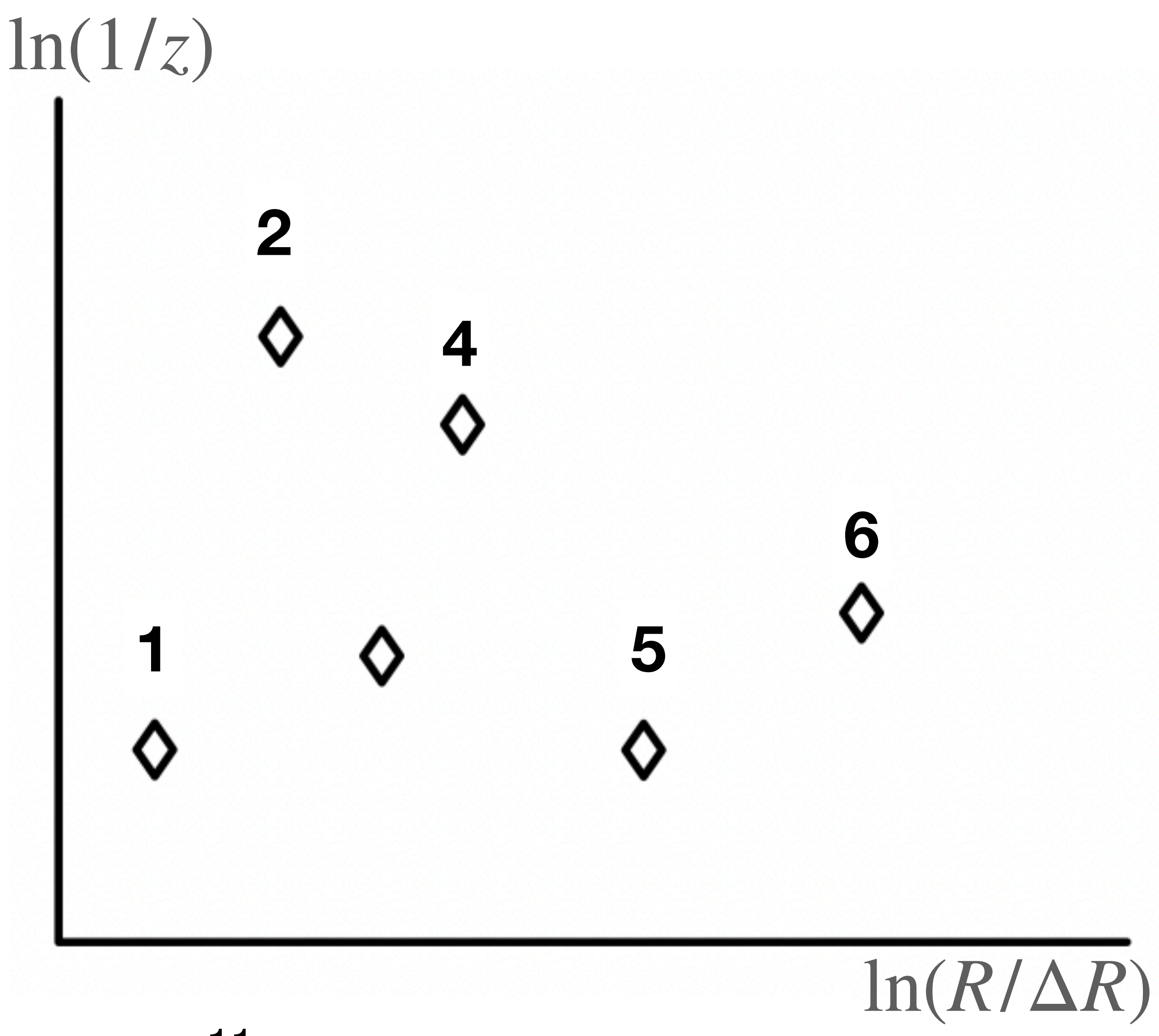
- **Infrared and collinear safe**
- **Conical**

Recluster with C/A

Angular Ordered Tree



1. Using the FastJet algorithm, cluster jets with the anti-k_T algorithm ("AK5" for R = 0.5)
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: $k_T, z, \Delta R, \theta, E_{rad}$



Eur. Phys. J. C 72 (2012) 1896

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 plane

ATLAS, ALICE, and CMS

arXiv:2111.00020v1

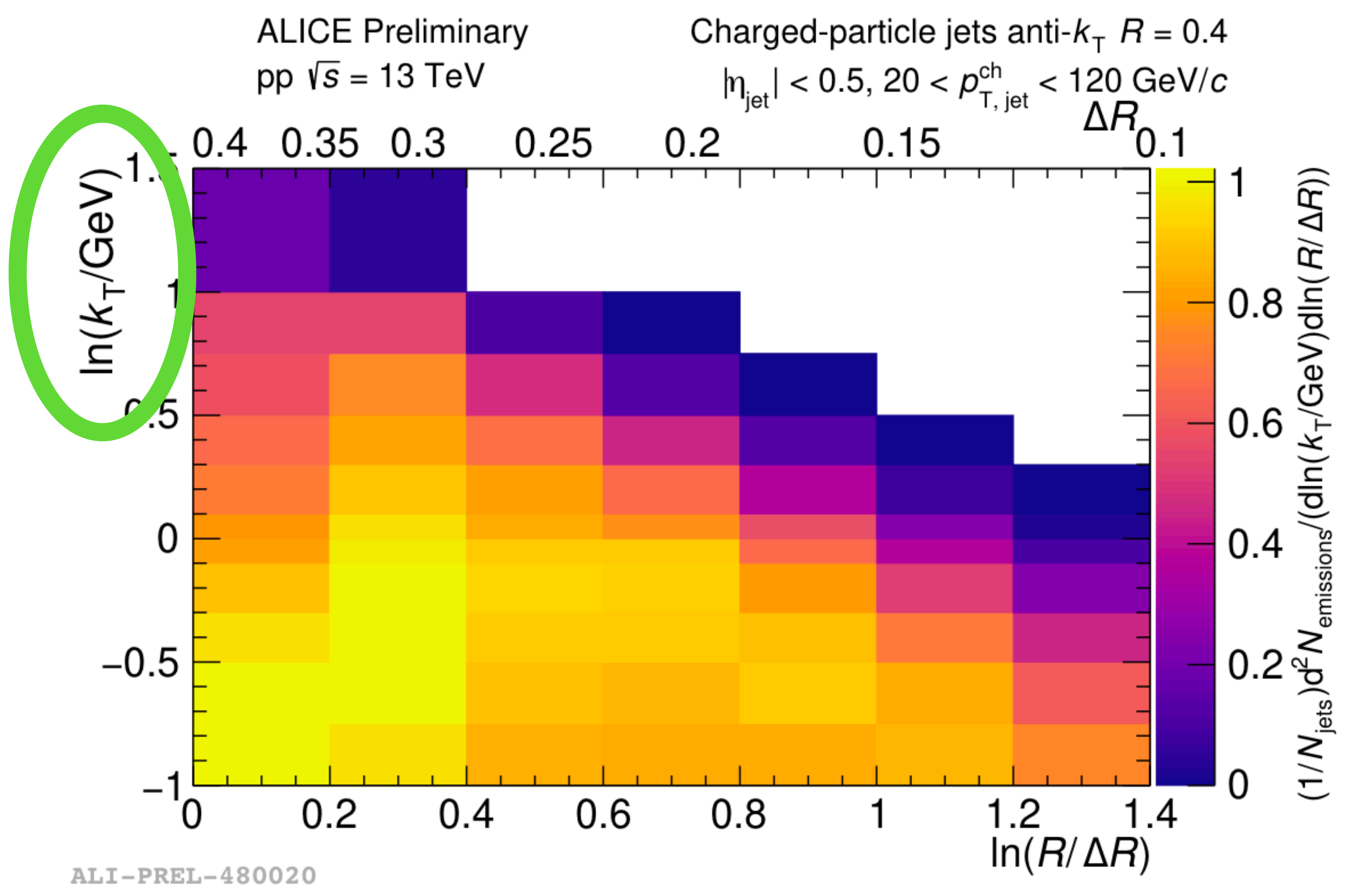
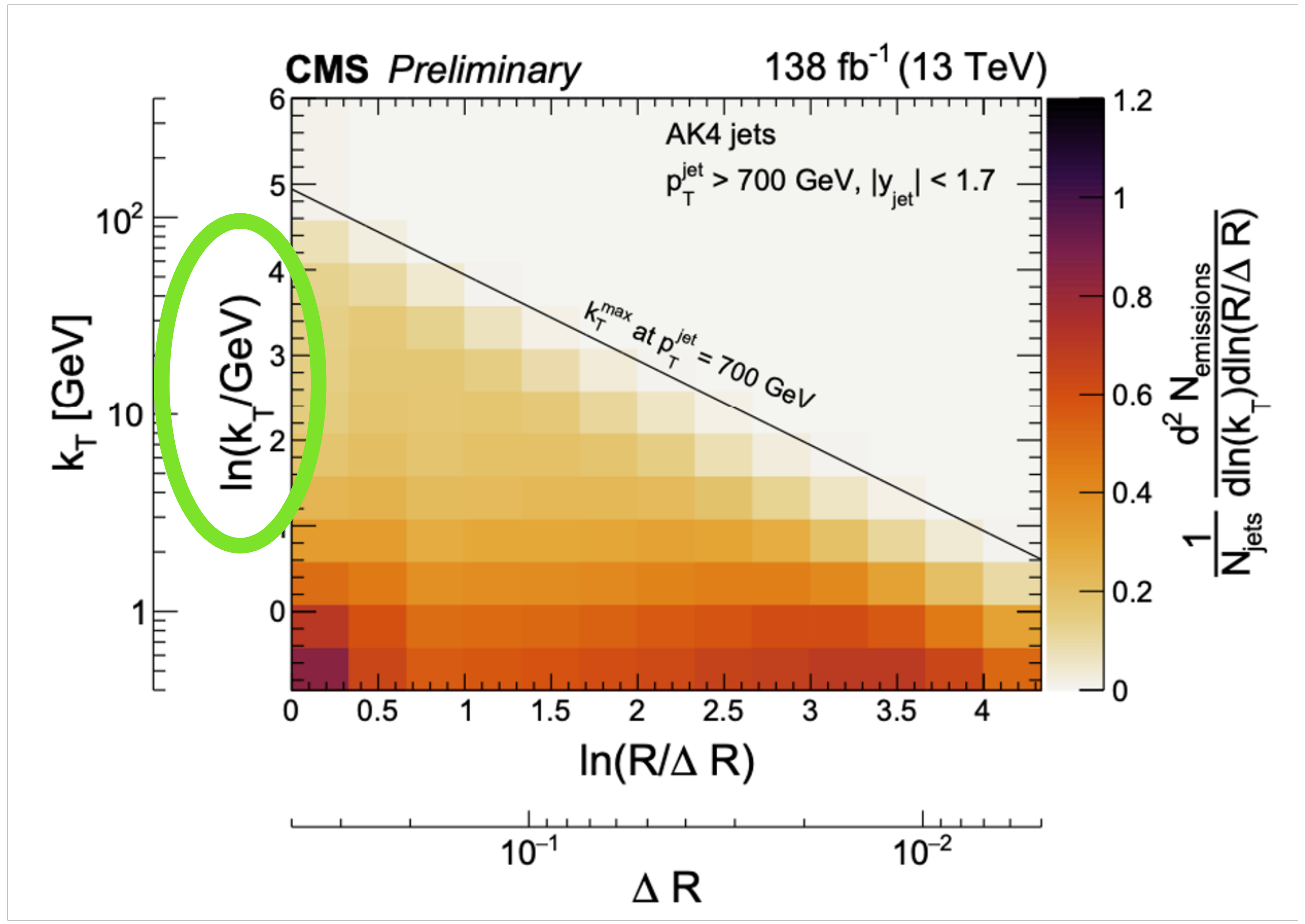


Figure 3: Fully corrected primary Lund plane density.

CMS PAS SMP-22-007



PRL 124.22 (2020): 222002

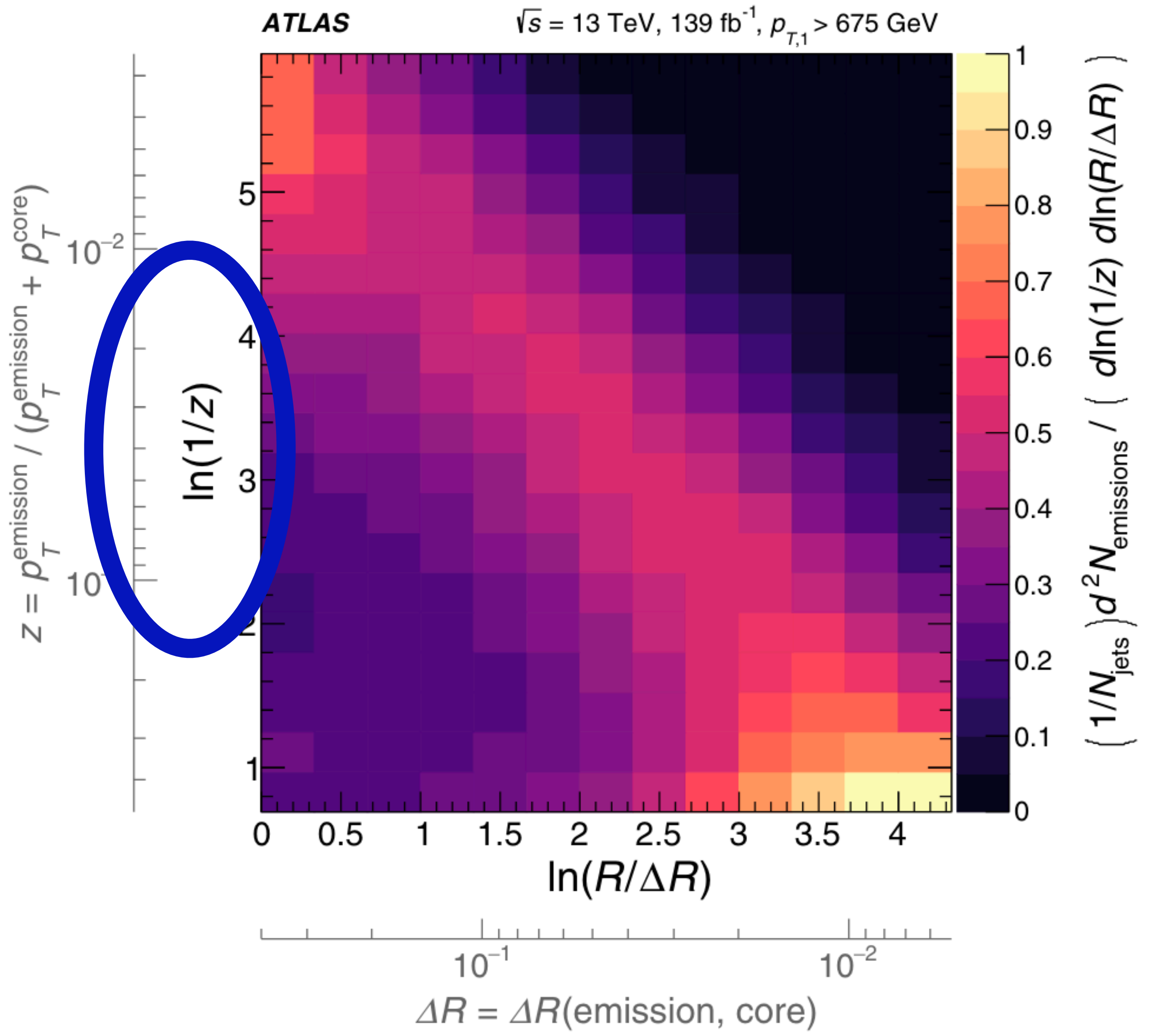


FIG. 2. The LJP measured using jets in 13 TeV pp collision data, corrected to particle level. The inner set of axes indicates the coordinates of the LJP itself, while the outer set indicates corresponding values of z and ΔR.

Flavor-inclusive Lund jet planes

Dead cone measurement by ALICE

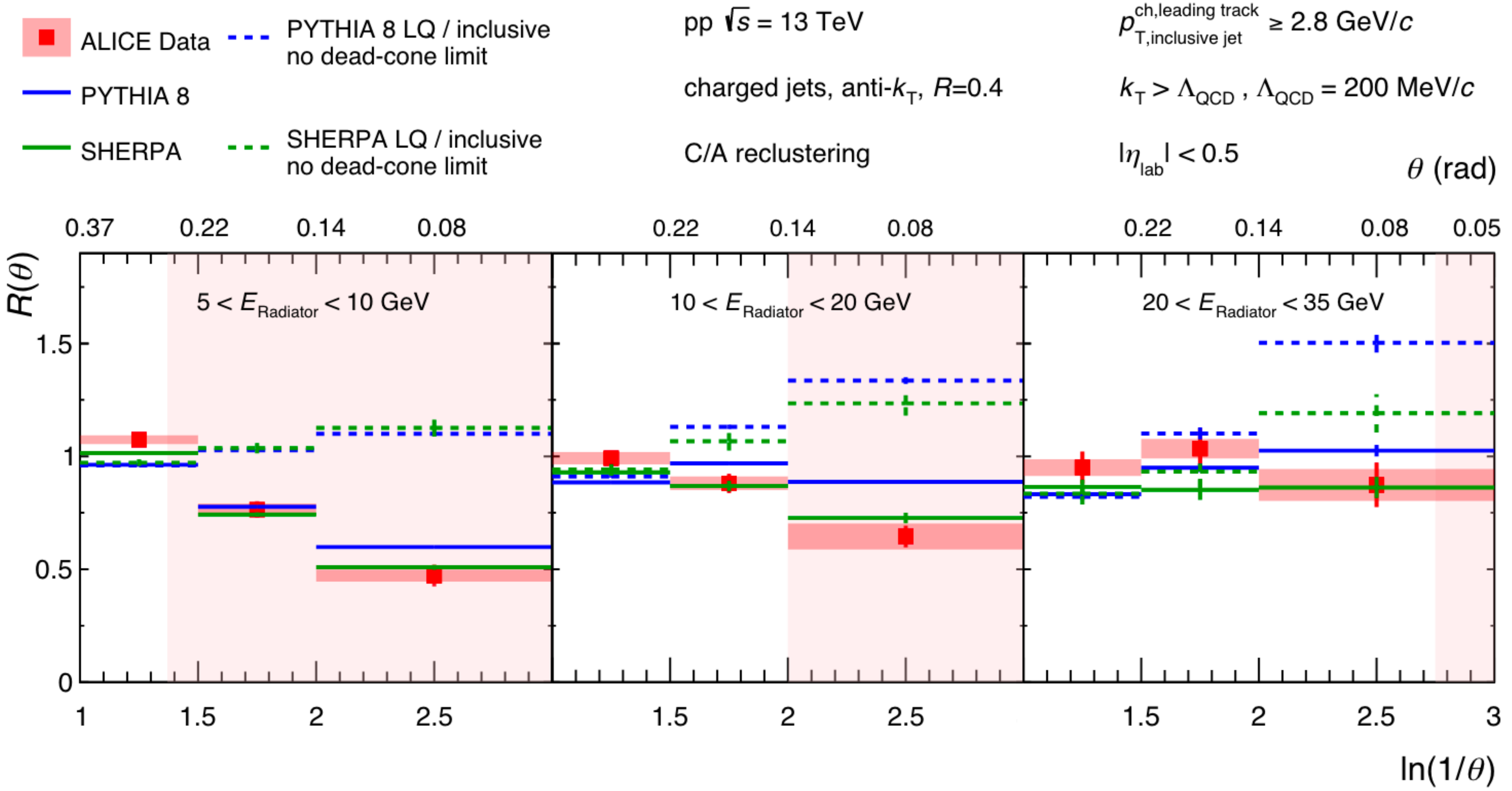
Ratio of charm to inclusive jets

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

ALICE

Nature 605, no. 7910 (2022): 440-446

- **ALICE has observed the dead cone in charm jets relative to inclusive jets**

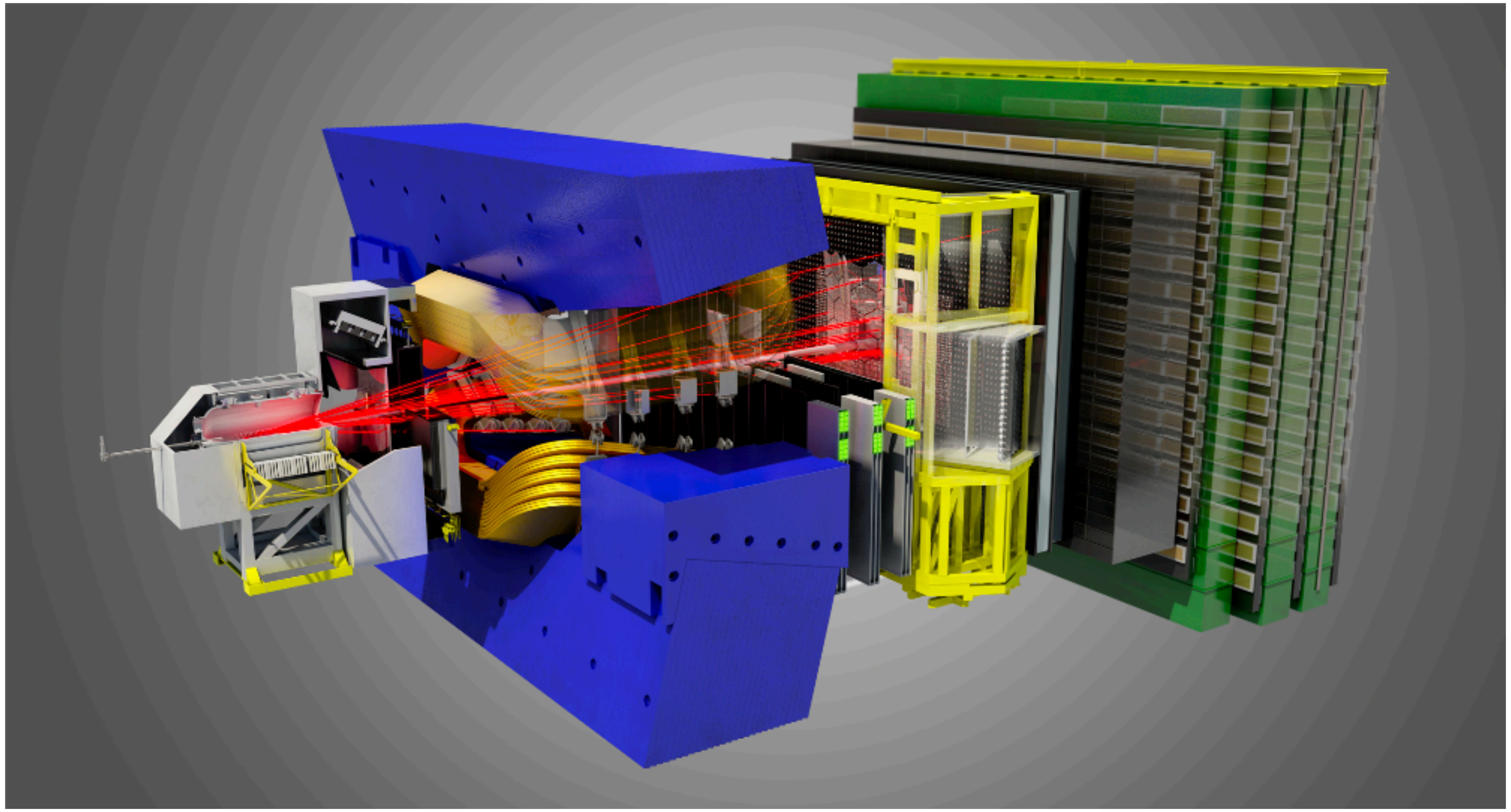


Prospects for the LJP at LHCb

The LHCb Detector

Forward-arm spectrometer

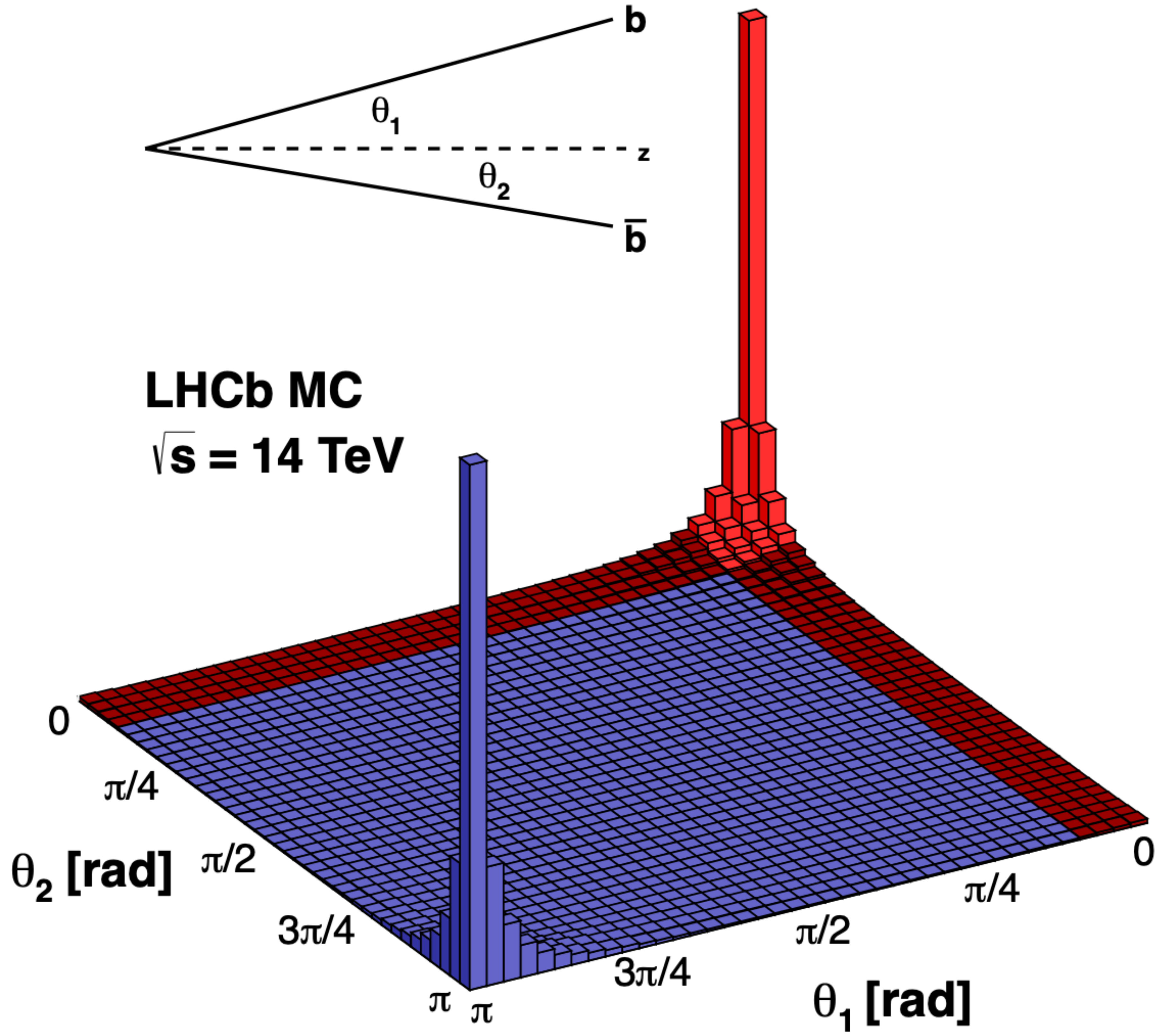
- Forward rapidities:
  $2 < \eta < 5$
- Excellent vertex resolution
- Tracking and particle identification
- Hadronic and electromagnetic calorimetry
- Muon system

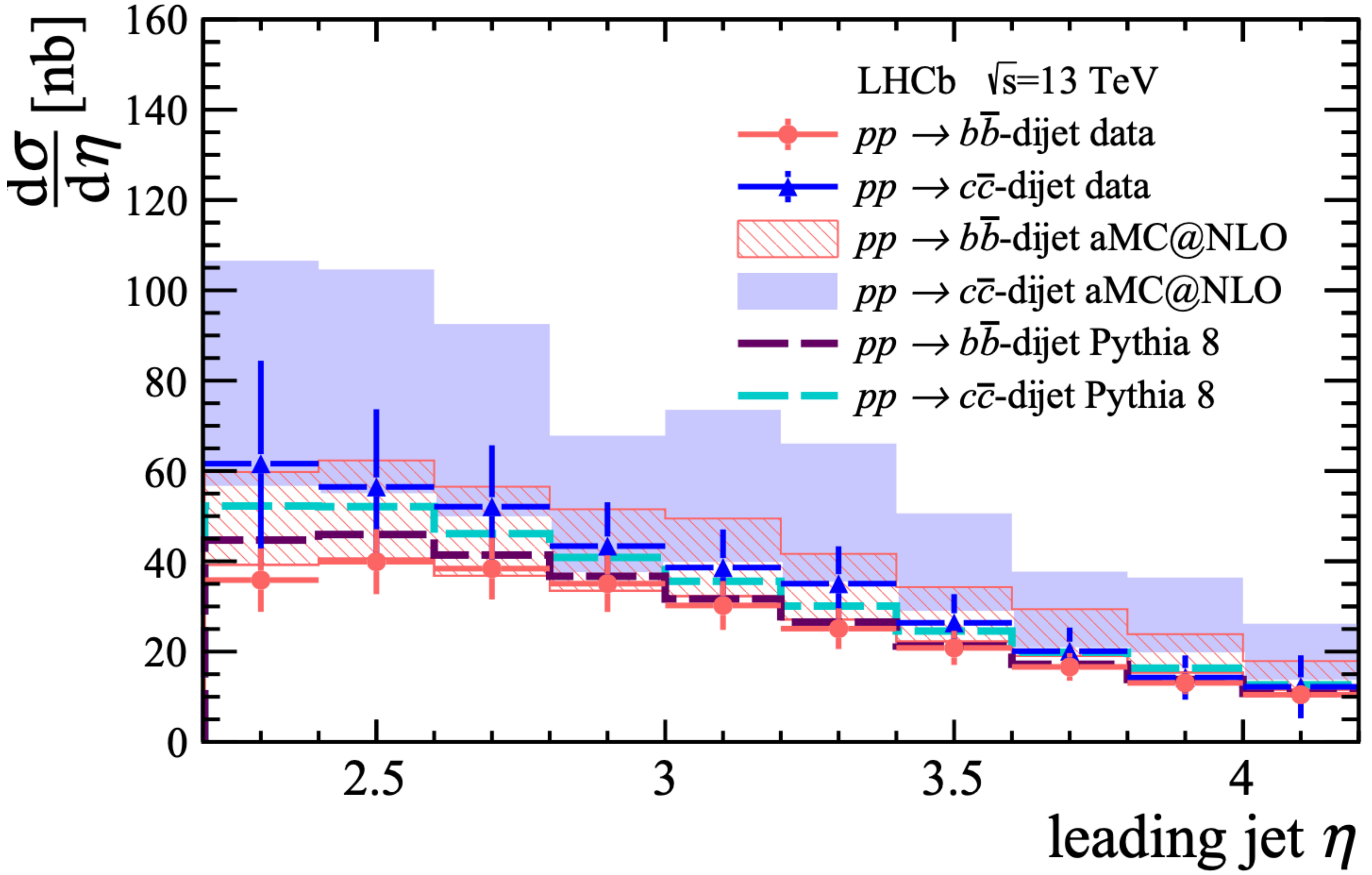


Large Heavy Flavor Cross-sections

JHEP 2021.2 (2021): 1-37

Lots of HF jets!

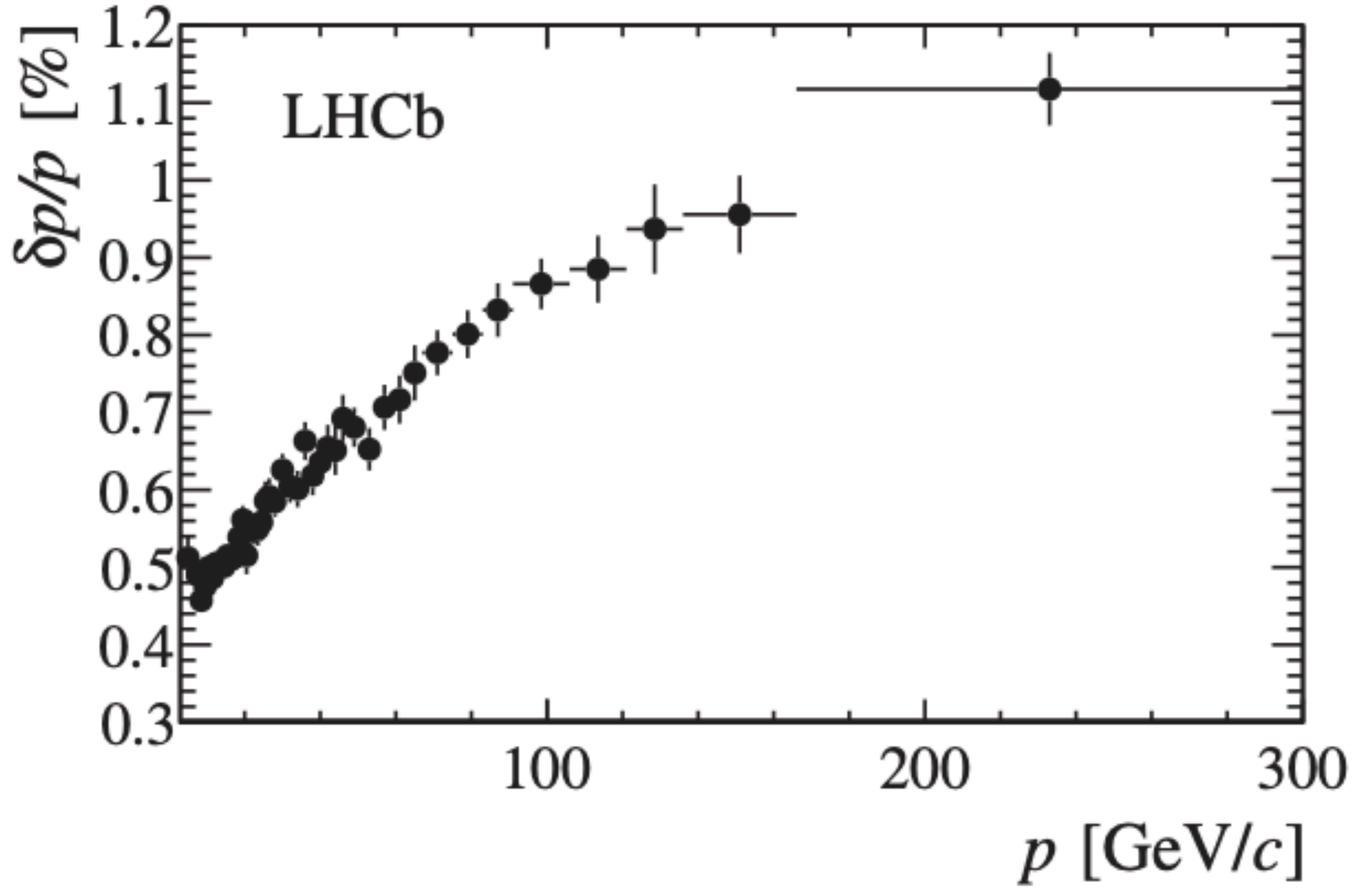




- HF dijet cross-section is large at forward rapidities!
- For each 1fb^{-1} of integrated luminosity, millions of heavy flavor jets are created!

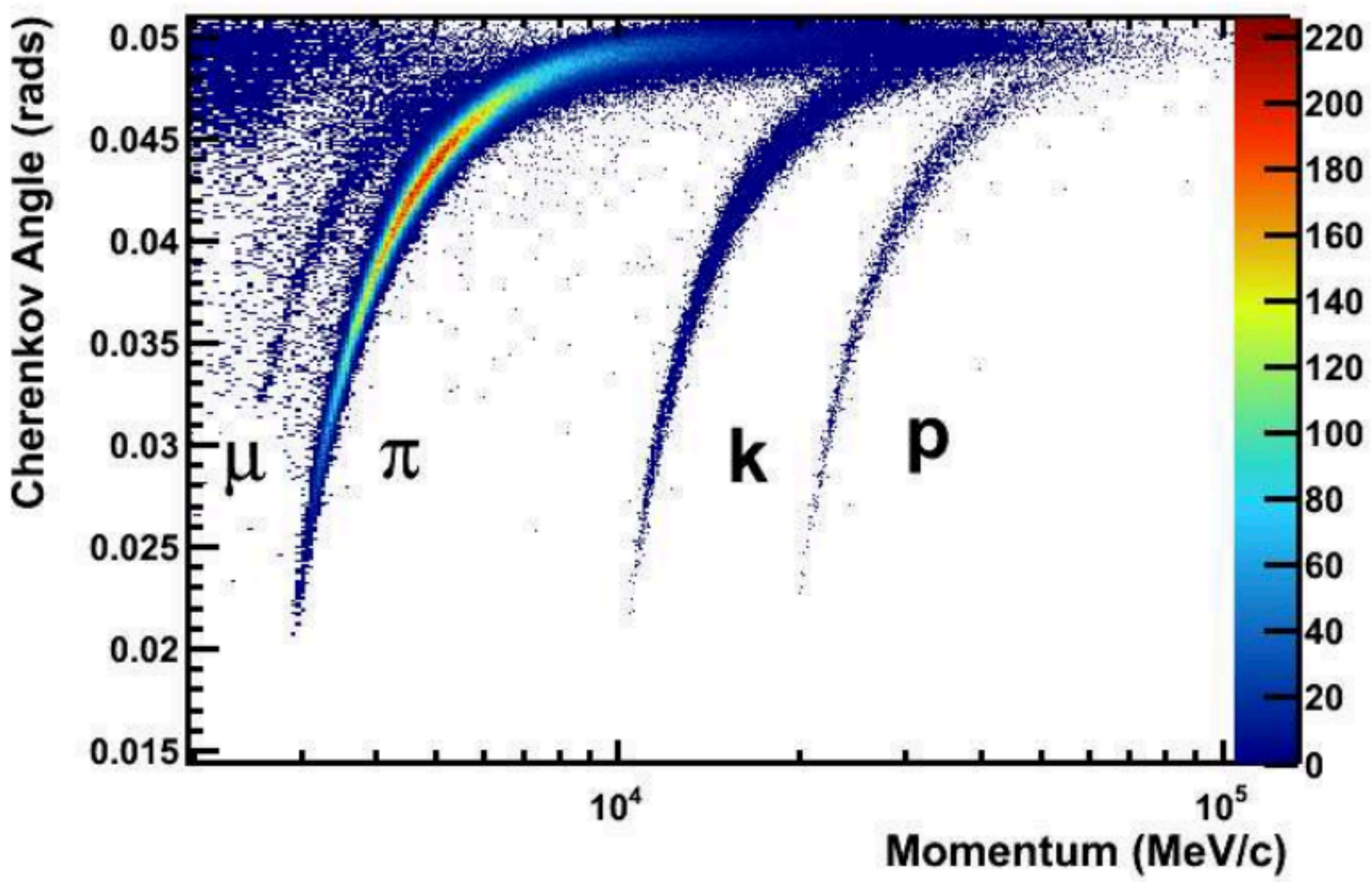
Tracking and PID

Excellent momentum resolution and particle identification



Resolution <1% up to 200 GeV

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

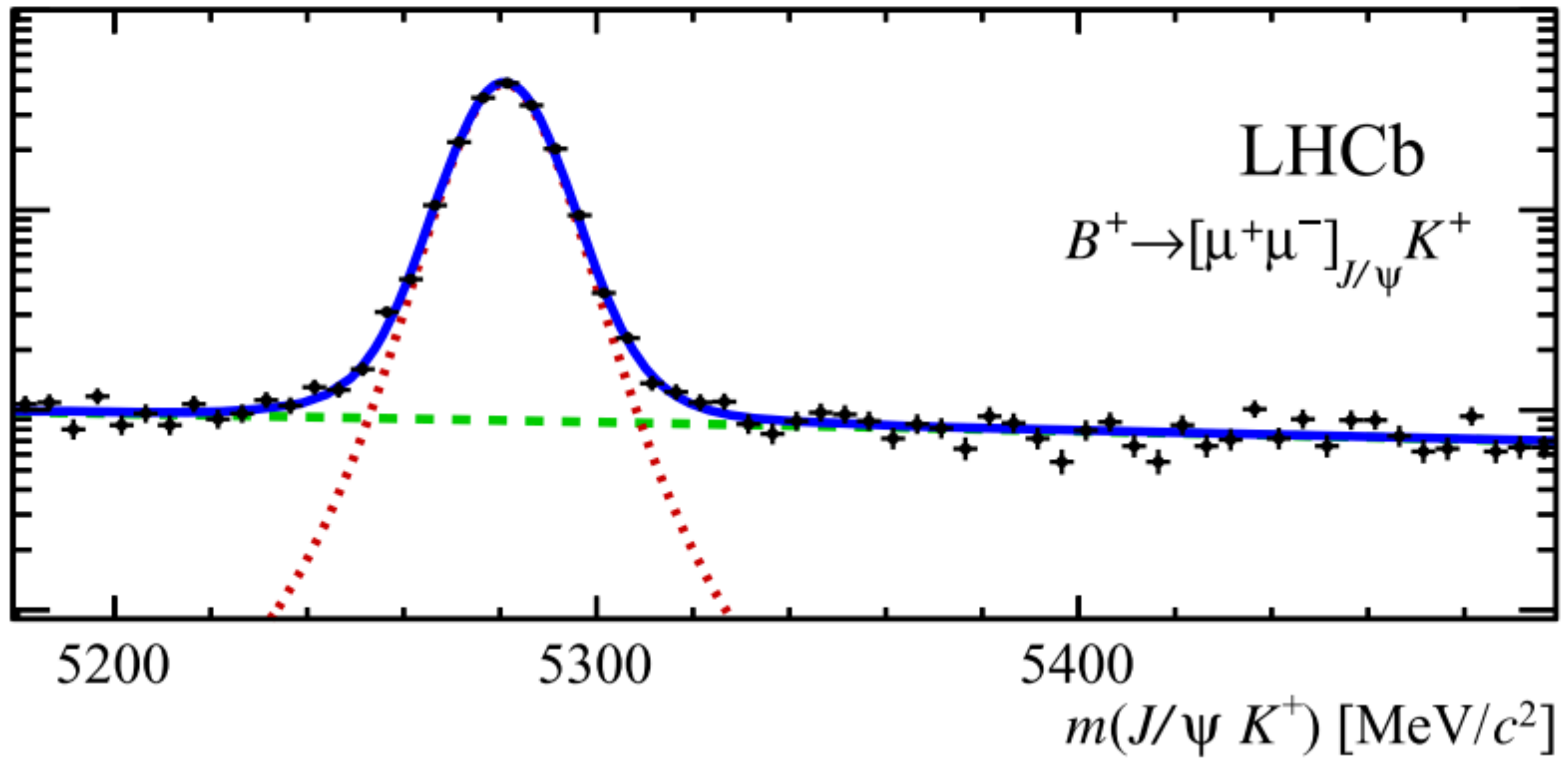


Capability of selecting exclusive decays!

The European Physical Journal C 73.5 (2013): 1-17

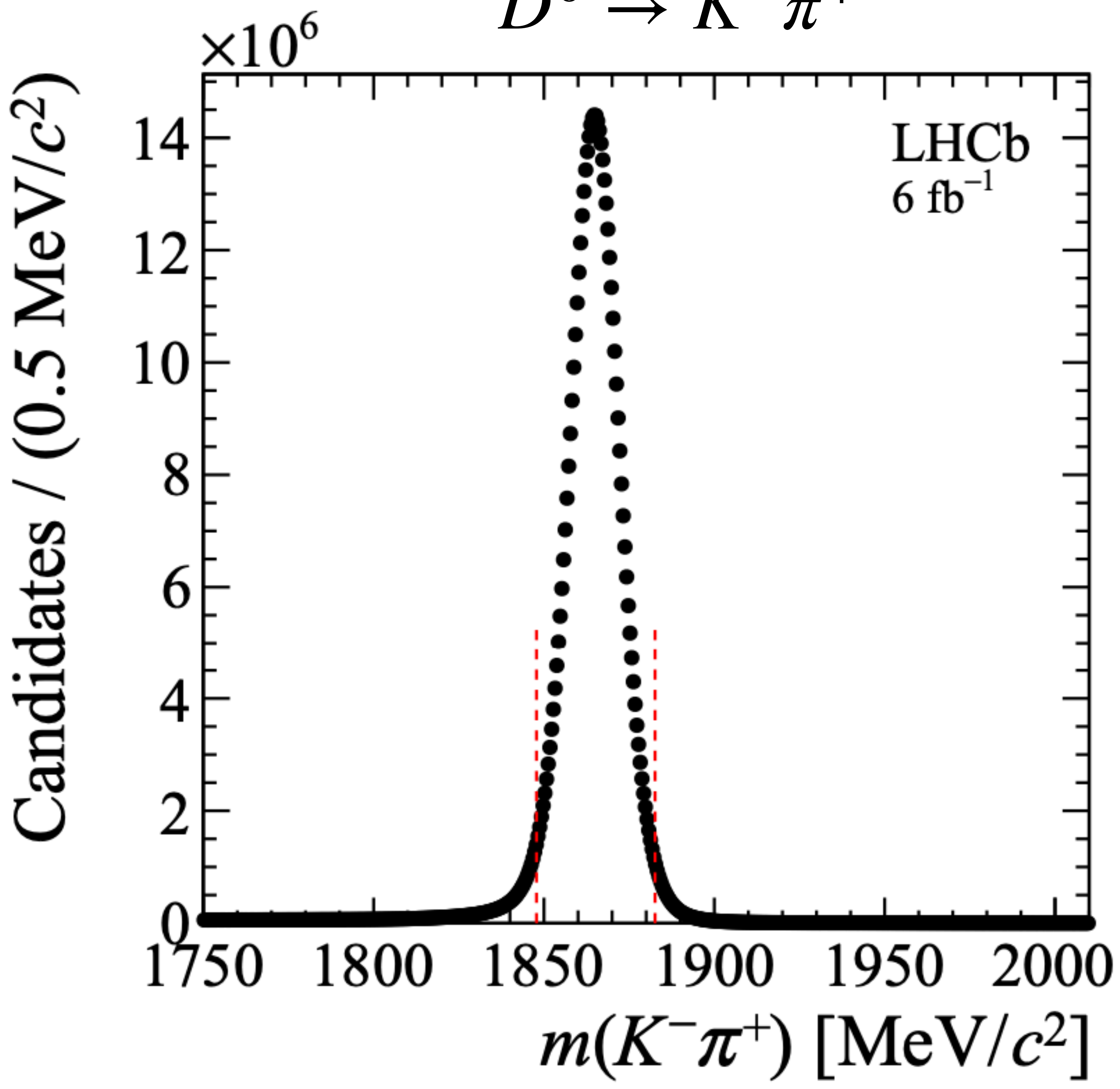
Powerful reconstruction of exclusive decays

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



PRD 95, 052005 (2017)

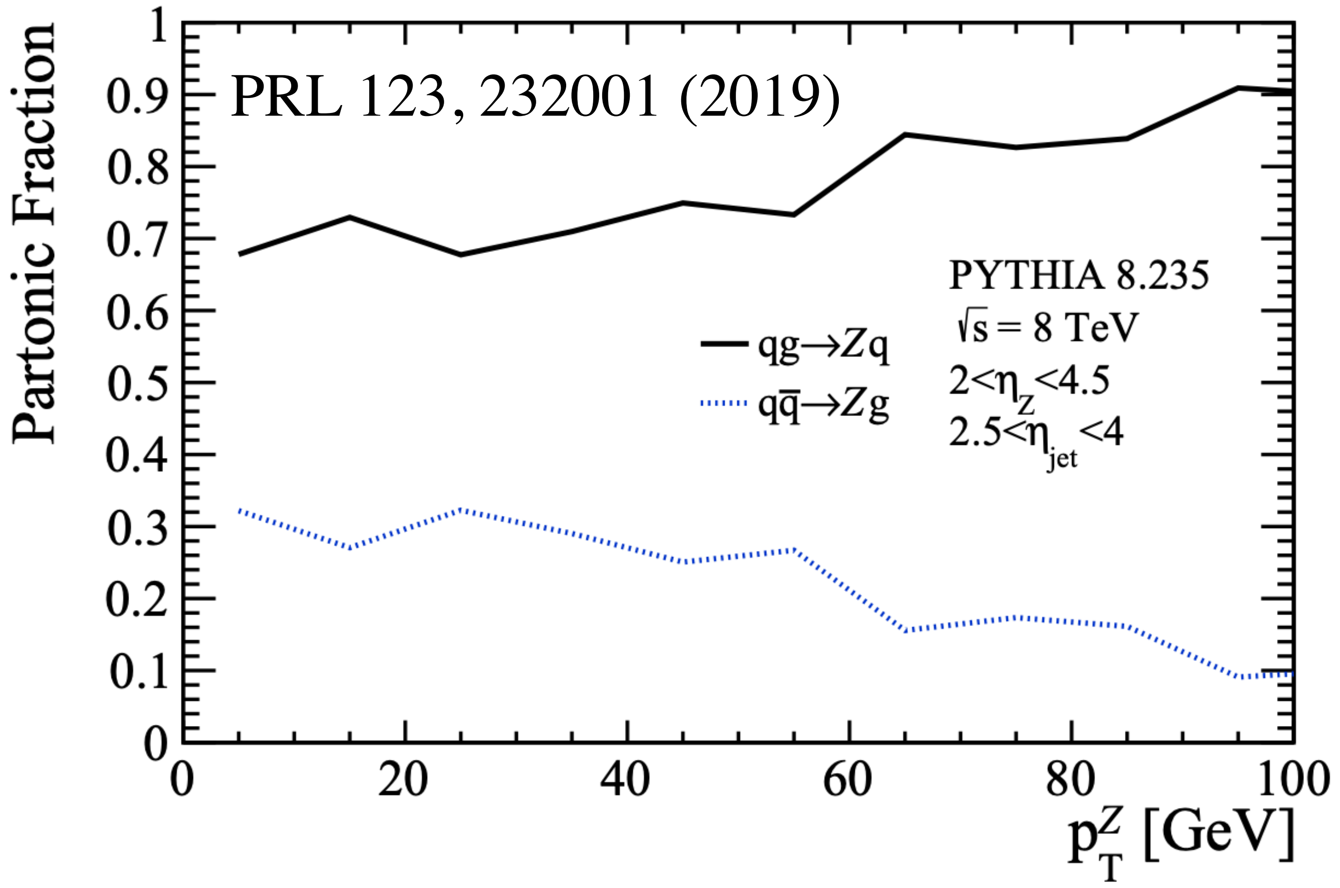
$D^0 \to K^-\pi^+$



Phys. Rev. D 104 (2021) 072010

Looking ahead: Jet Samples

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



- We use Run 2 p+p collisions at $\sqrt{s} = 13$ TeV data during the years 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 $D^0/\bar{D}^0$ 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 Dijet Simulations

Pythia8 settings:
pp collisions

$\sqrt{s} = 13$ **TeV**

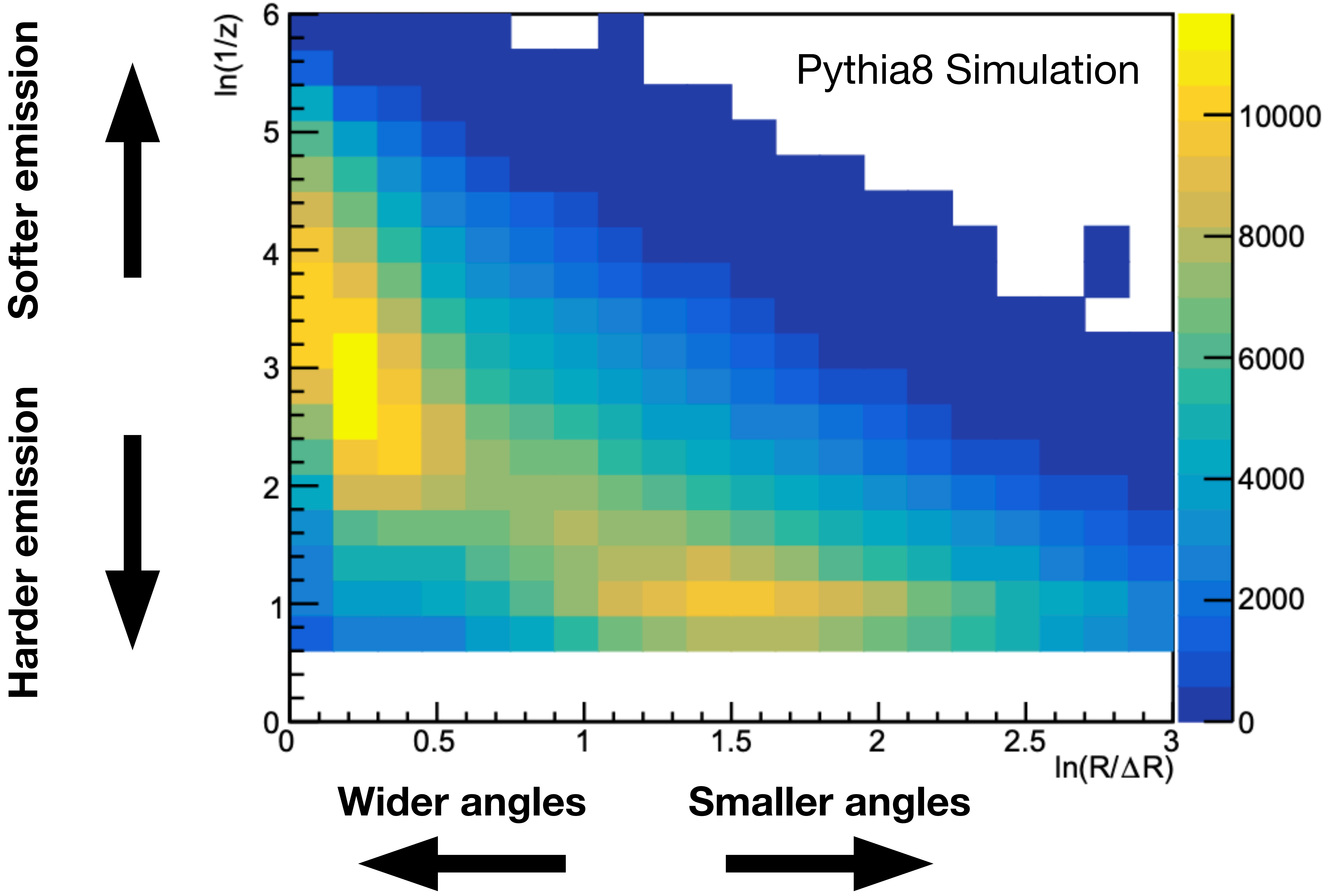
$2.5 < \eta_{jet} < 4$

$p_{T,jet} > 20$ **GeV**

$R = 0.5$

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

Light quark jets



Note: Pythia8 simulations were produced privately and NOT by LHCb

Various Emission Regions

Pythia8 Simulations/ATLAS result

Pythia8 settings:
pp collisions
$\sqrt{s} = 13$ **TeV**
$2.5 < \eta_{jet} < 4$
$p_{T,jet} > 20$ **GeV**
$R = 0.5$

PRL 124.22 (2020): 222002

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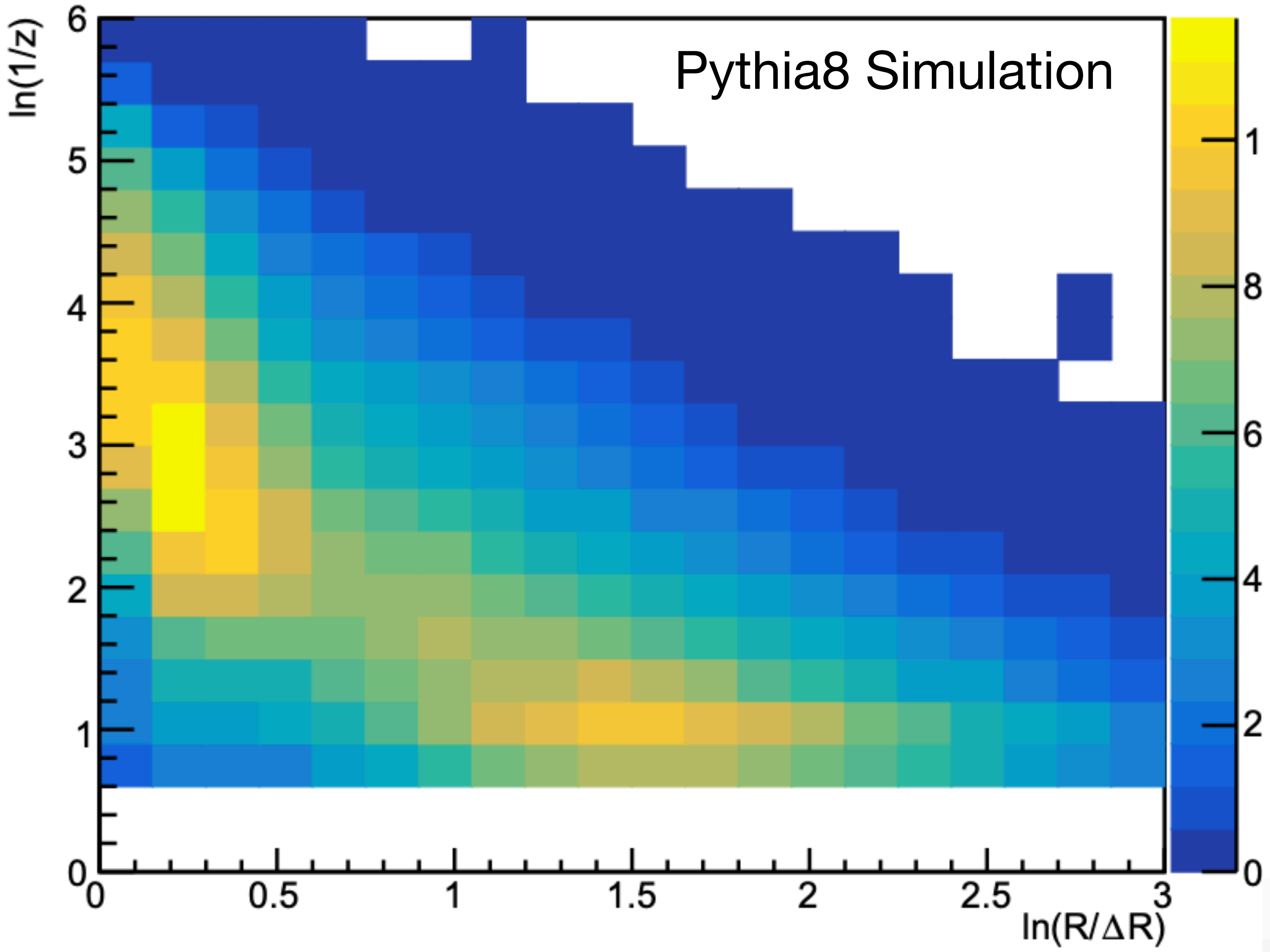
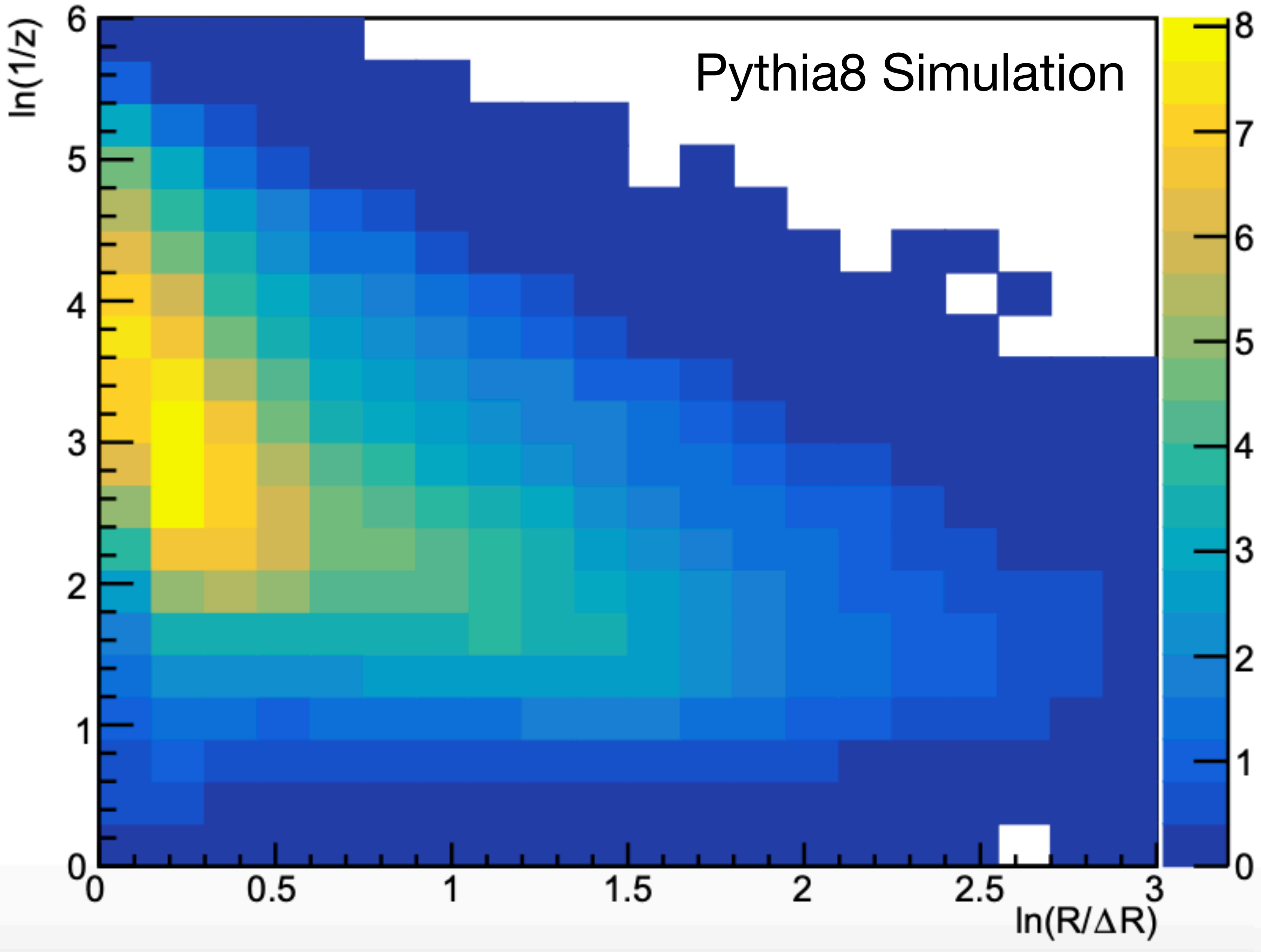
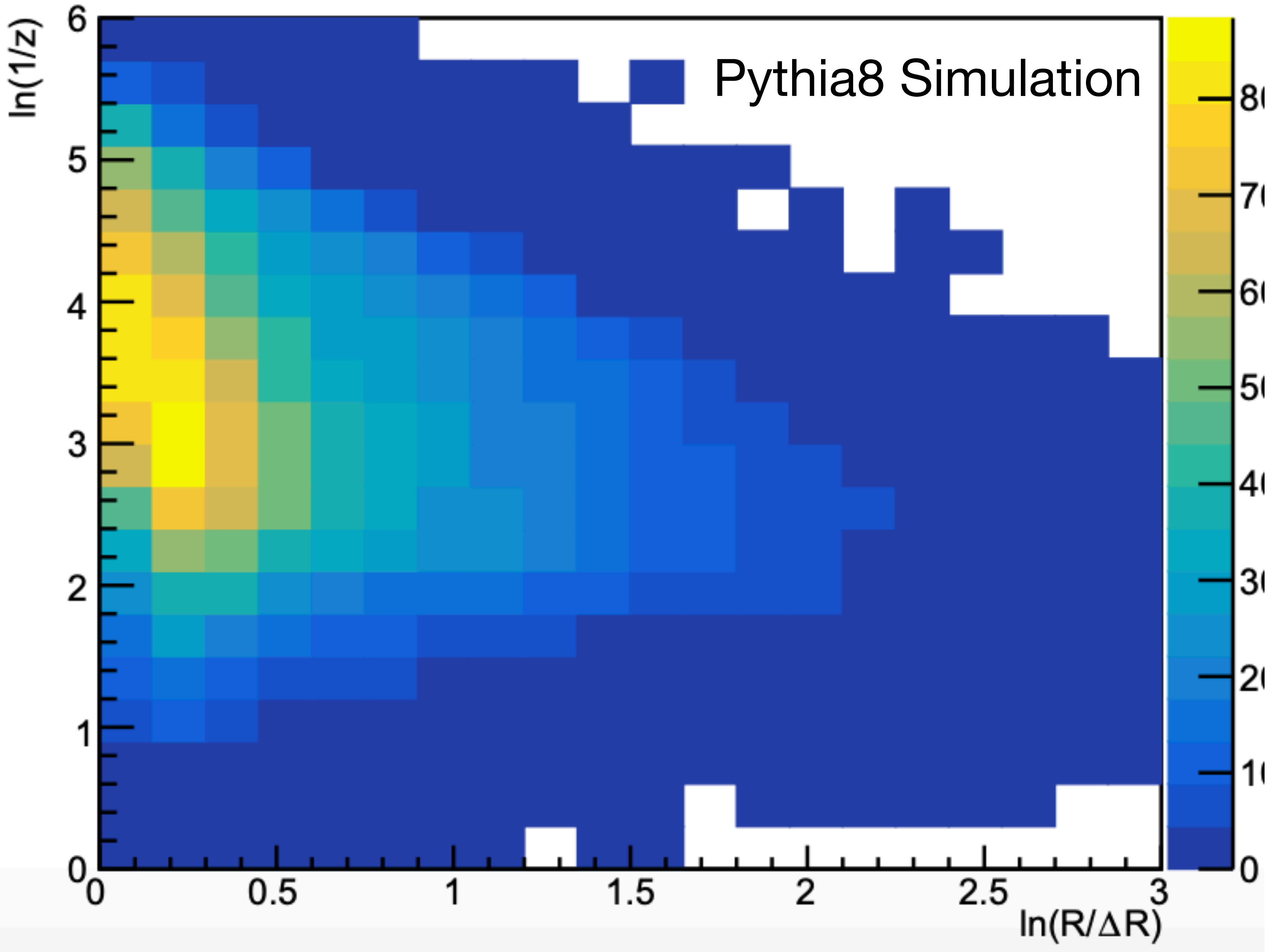
Light quark jets



Charm jets



Beauty jets



LJP at forward rapidities

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Pythia8 settings:
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$2.5 < \eta_{jet} < 4$
$p_{T,jet} > 20$ **GeV**
$R = 0.5$

Light quark jets **Charm jets** **Beauty jets**

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

LJP at forward rapidities

Pythia8 Dijet Simulations

Pythia8 settings:
pp collisions
$\sqrt{s} = 13$ **TeV**
$2.5 < \eta_{jet} < 4$
$p_{T,jet} > 20$ **GeV**
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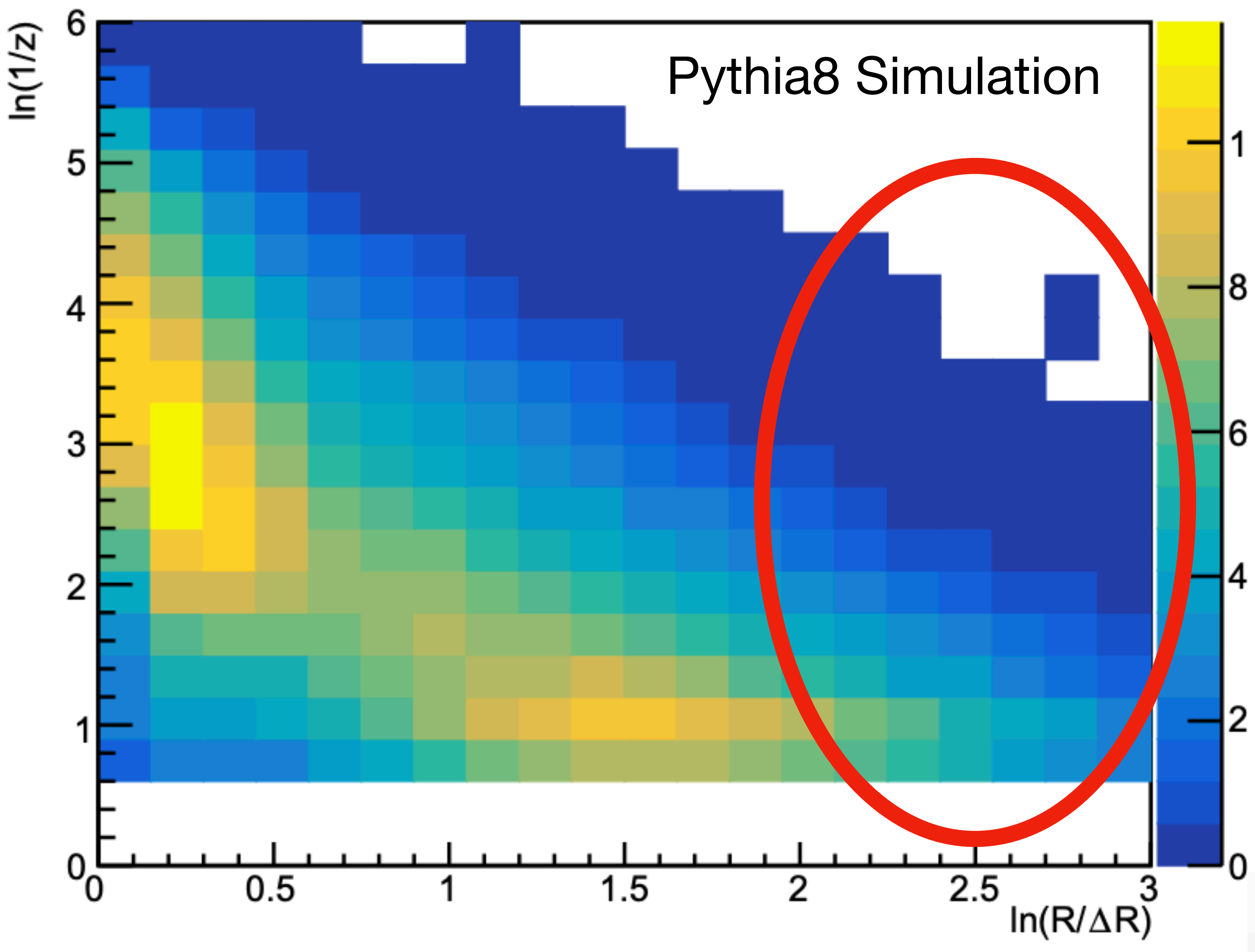
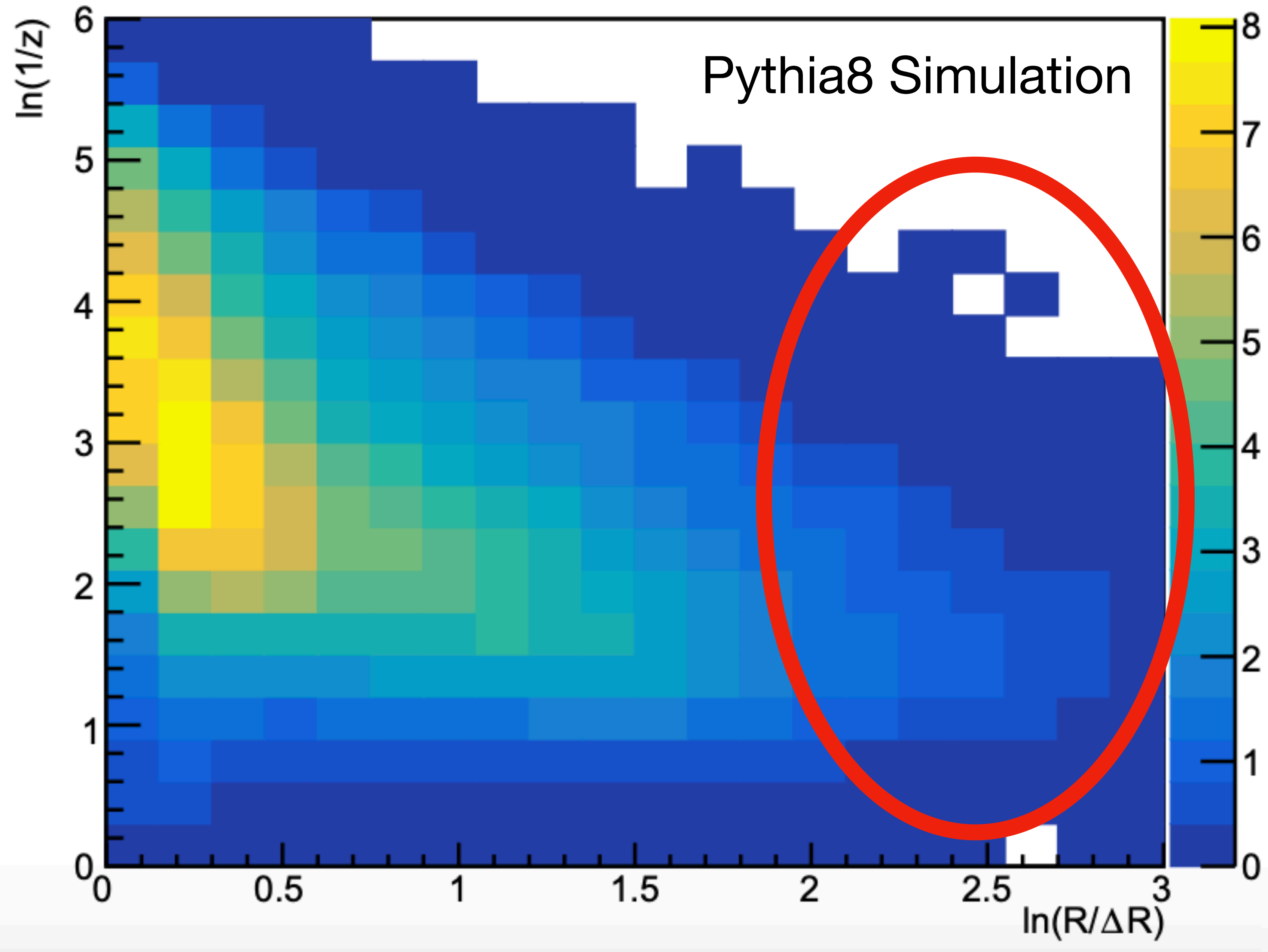
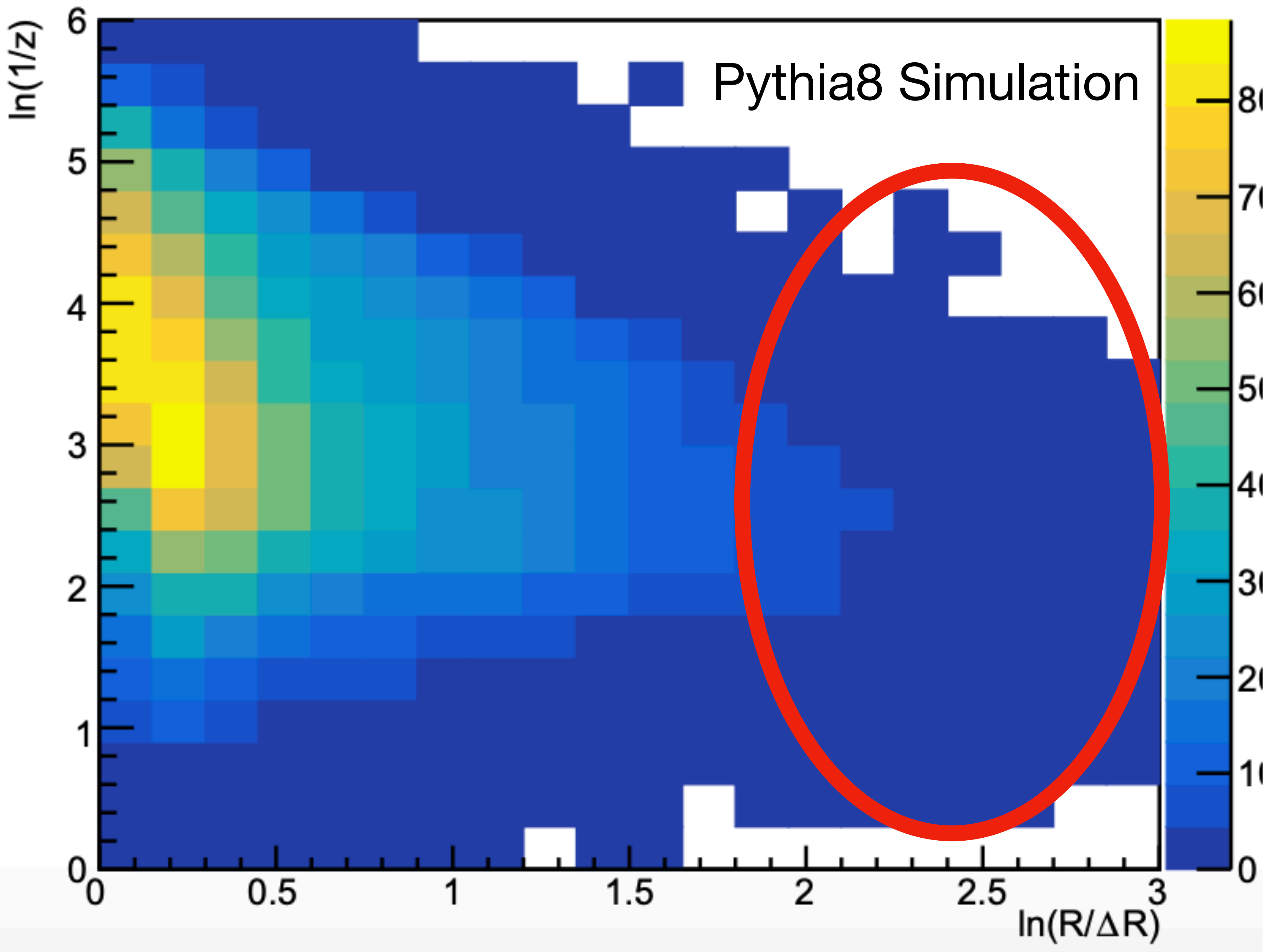
Light quark jets



Charm jets



Beauty jets



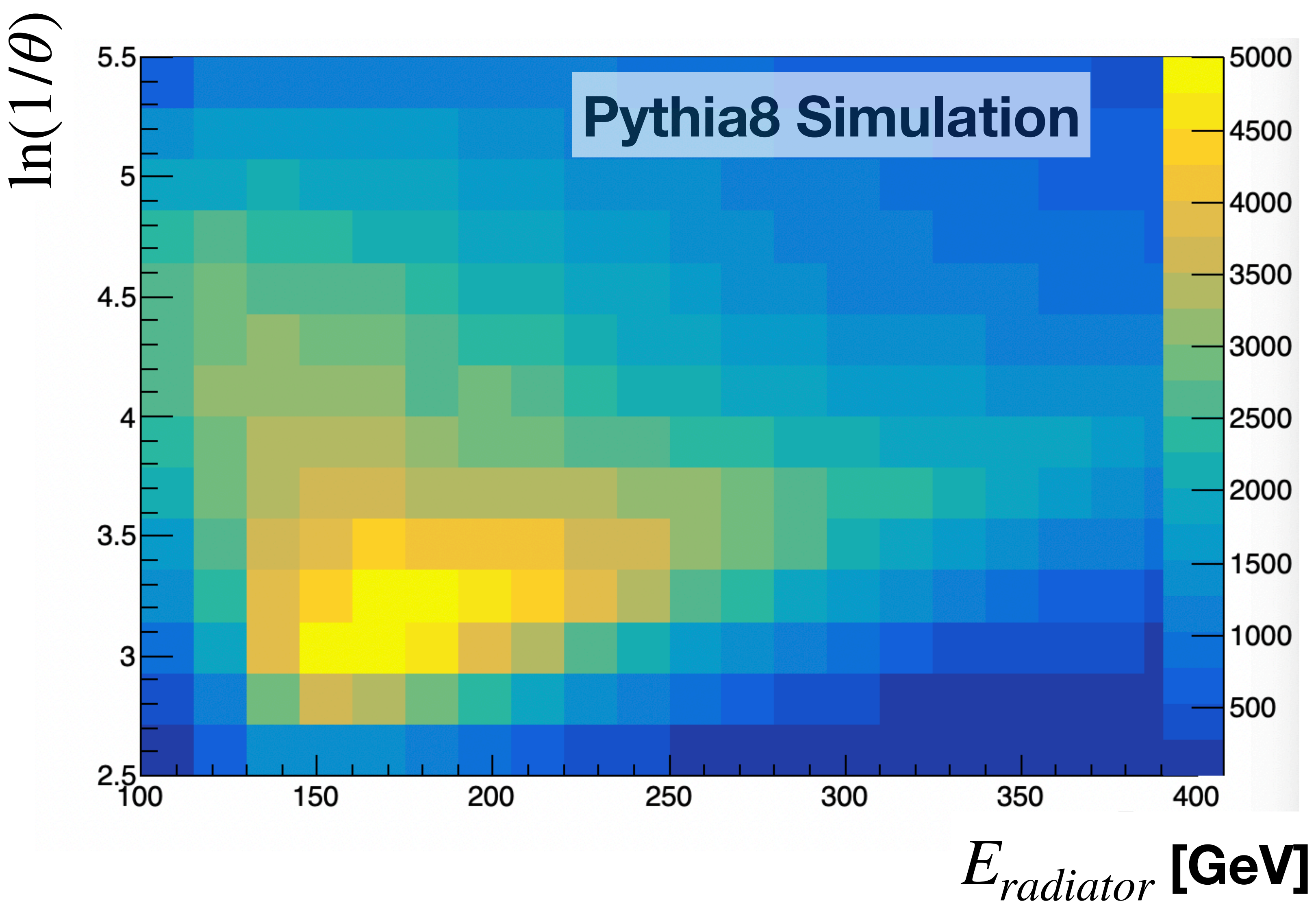
Suppressed collinear radiation = dead cone effect!

Dead cone at forward rapidities

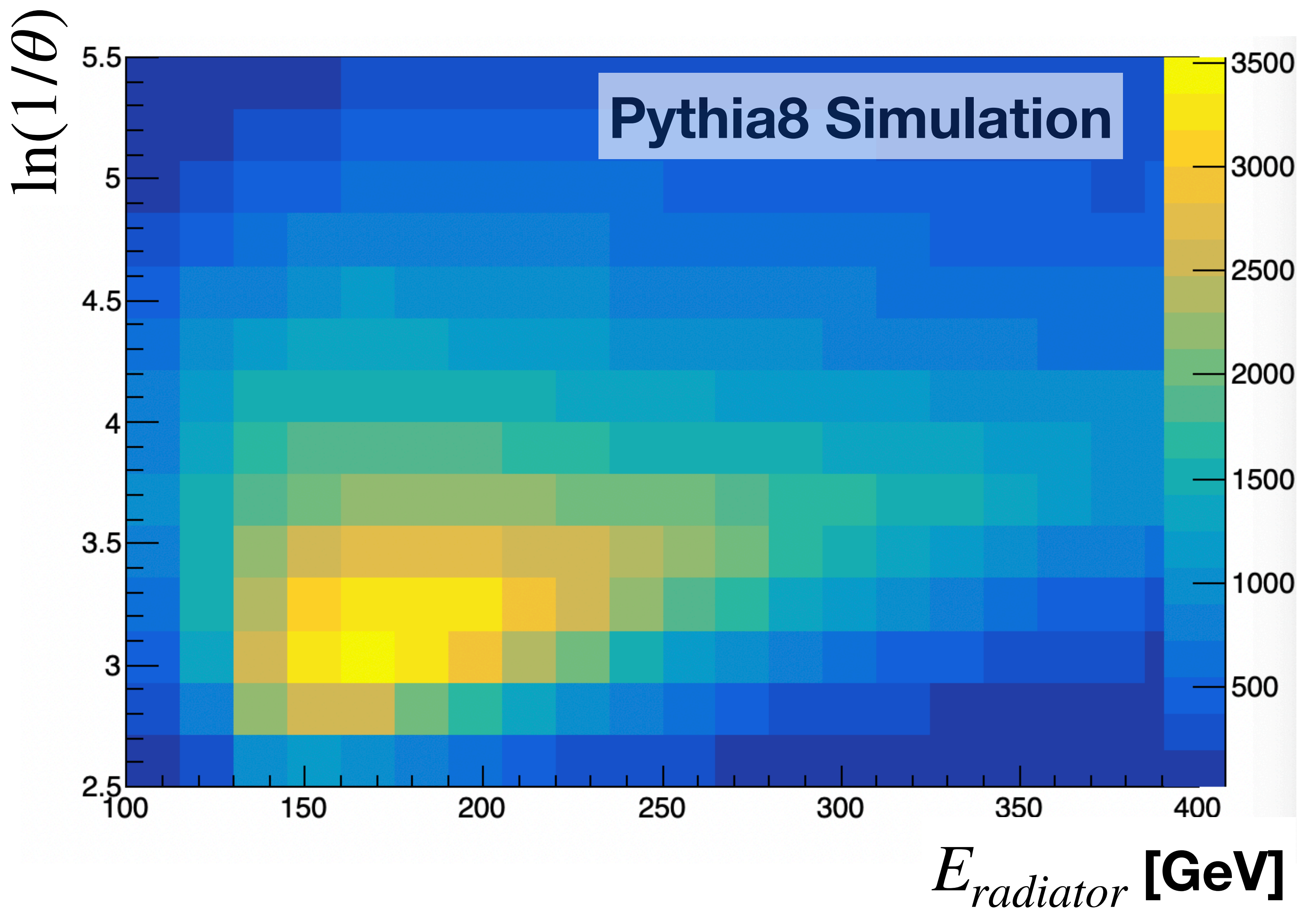
Pythia8 Dijet Simulations

Pythia8 settings:
pp collisions
$\sqrt{s} = 13$ **TeV**
$2.5 < \eta_{jet} < 4$
$p_{T,jet} > 20$ **GeV**
$R = 0.5$

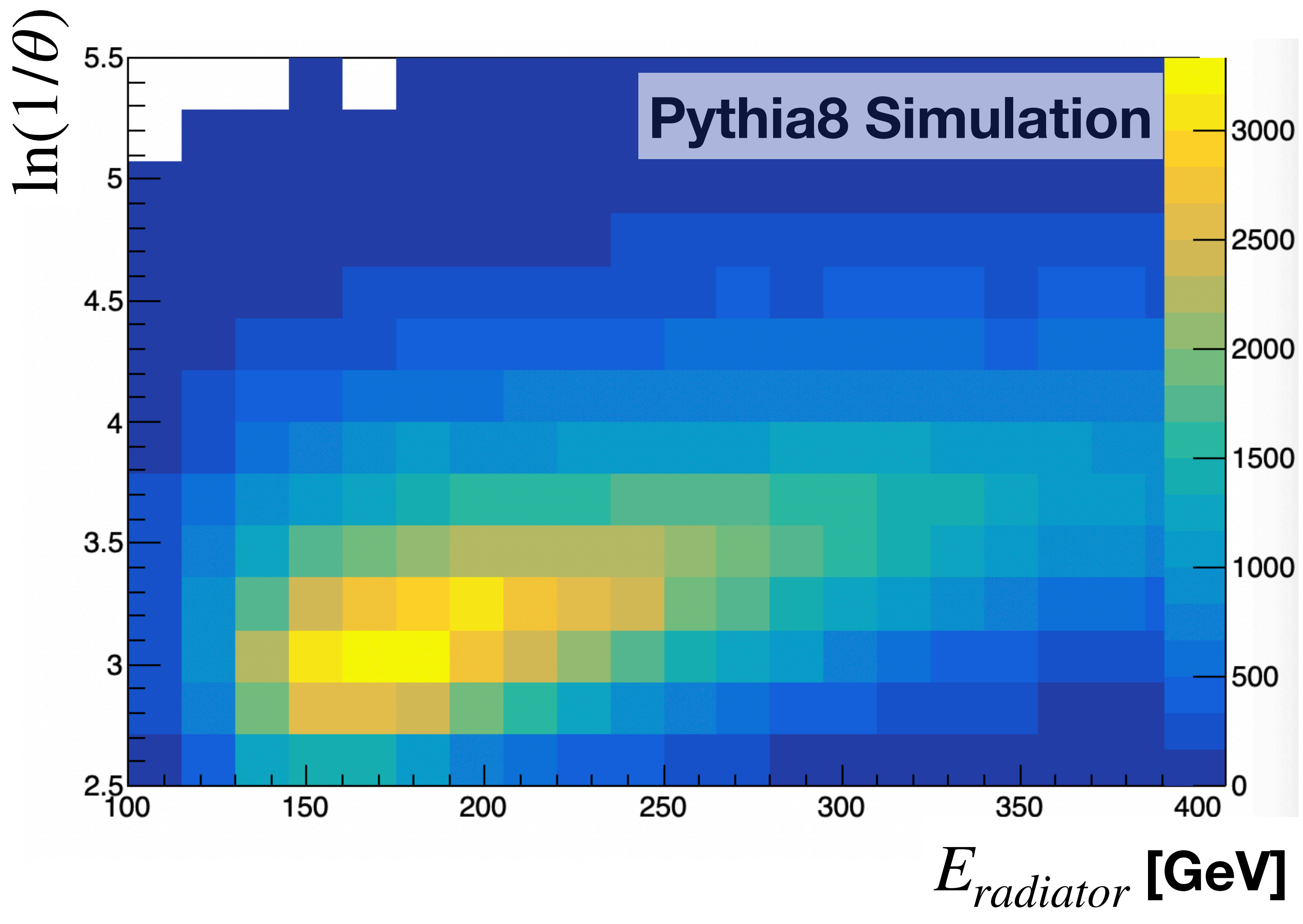
Light jets



Charm jets



Beauty jets



Dead cone at forward rapidities

Pythia8 Dijet Simulations

Pythia8 settings:
pp collisions
$\sqrt{s} = 13$ **TeV**
$2.5 < \eta_{jet} < 4$
$p_{T,jet} > 20$ **GeV**
$R = 0.5$

Charm/Light **Beauty/Charm** **Beauty/Light**

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

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

Dead cone at forward rapidities

Pythia8 Dijet Simulations

Pythia8 settings:
pp collisions
$\sqrt{s} = 13$ **TeV**
$2.5 < \eta_{jet} < 4$
$p_{T,jet} > 20$ **GeV**
$R = 0.5$

Dead cone effect is most prominent for Beauty/Light ratio

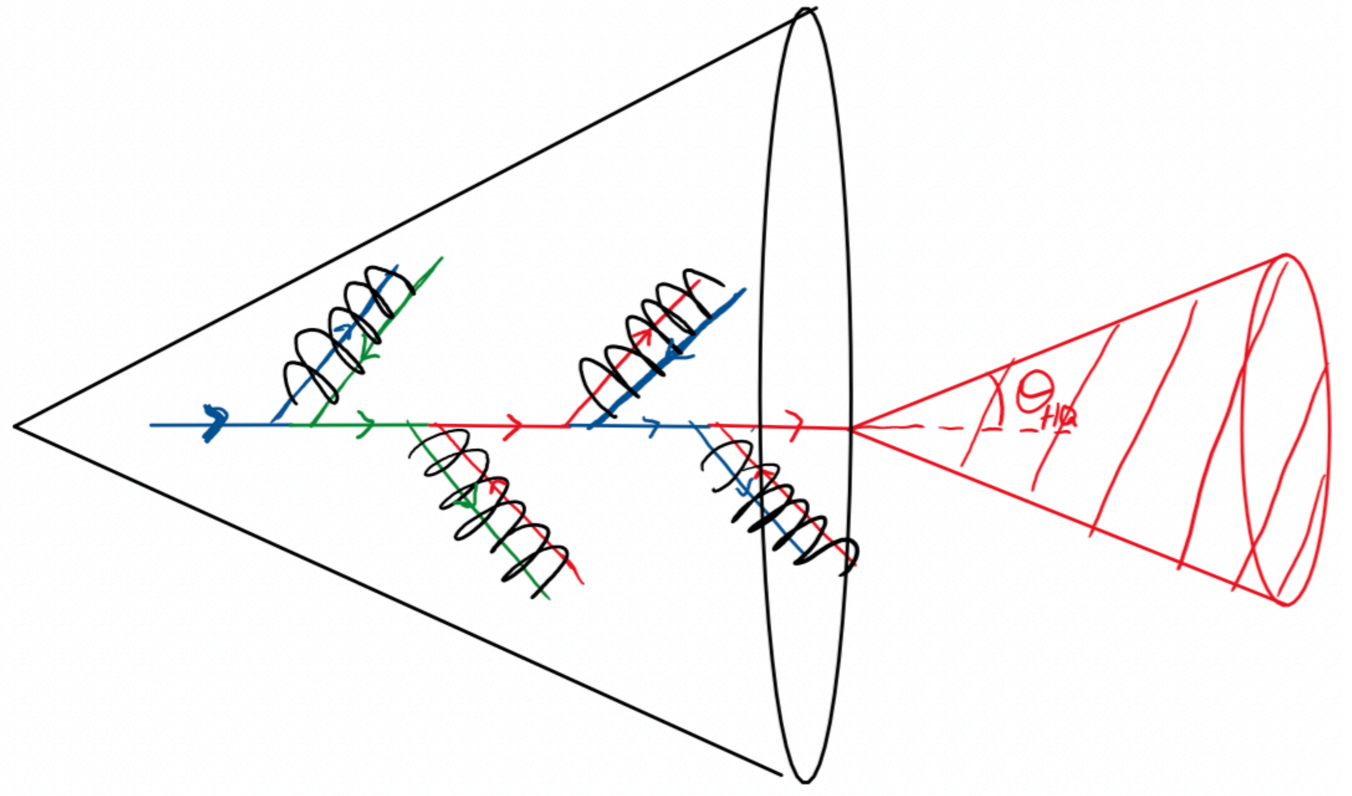
Summary: Lund plane at LHCb

- We're in the process of:
  - measuring the LJP for **light**, **charm**, and **beauty** jets,
  - measuring the LJP for **tracks** as well as **tracks + neutrals,**
  - measuring the **dead-cone** effect in b/c, $b/(q,g)$, and $c/(q,g)$.

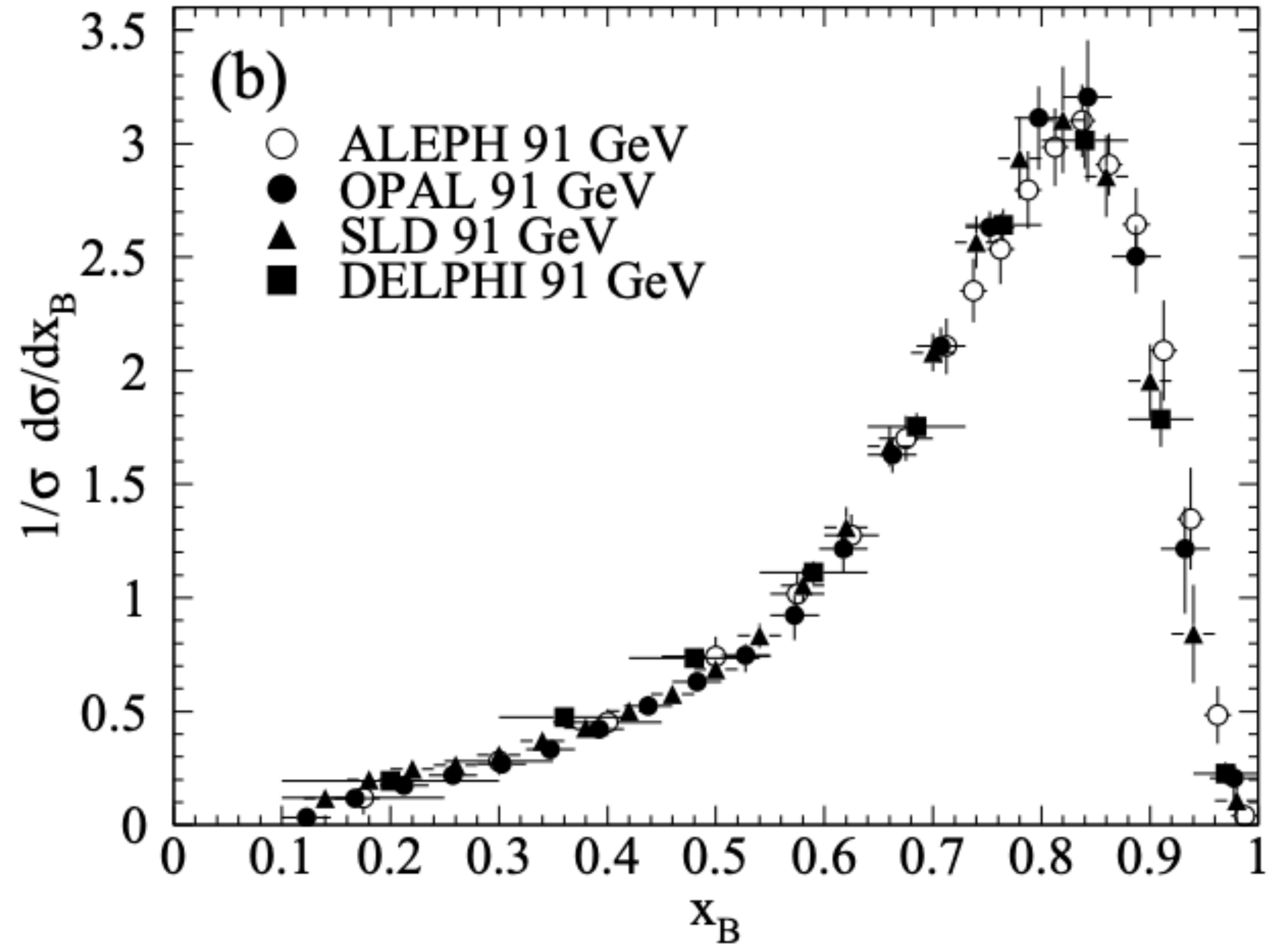
Heavy Flavor Fragmentation

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!
- 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),

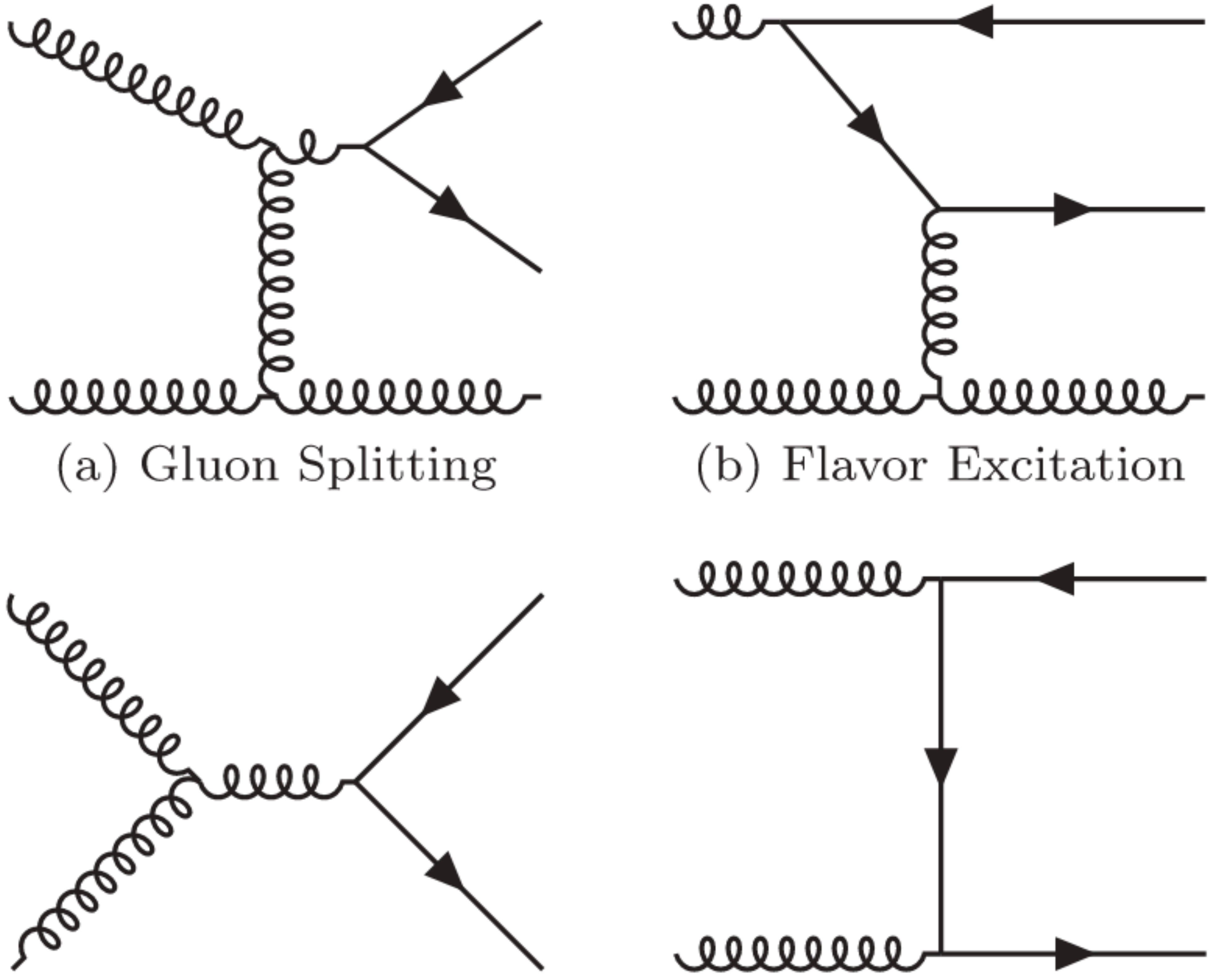
(SLD), Phys. Rev. D65

(Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

Heavy Flavor Production Mechanisms

QCD leading order diagrams

- At e^+e^- colliders, main production of heavy flavor is through $Z/\gamma*$
- At pp colliders, gluon splitting is an important production mechanism of heavy flavor
- Rate of gluon splitting increases with higher jet p_T

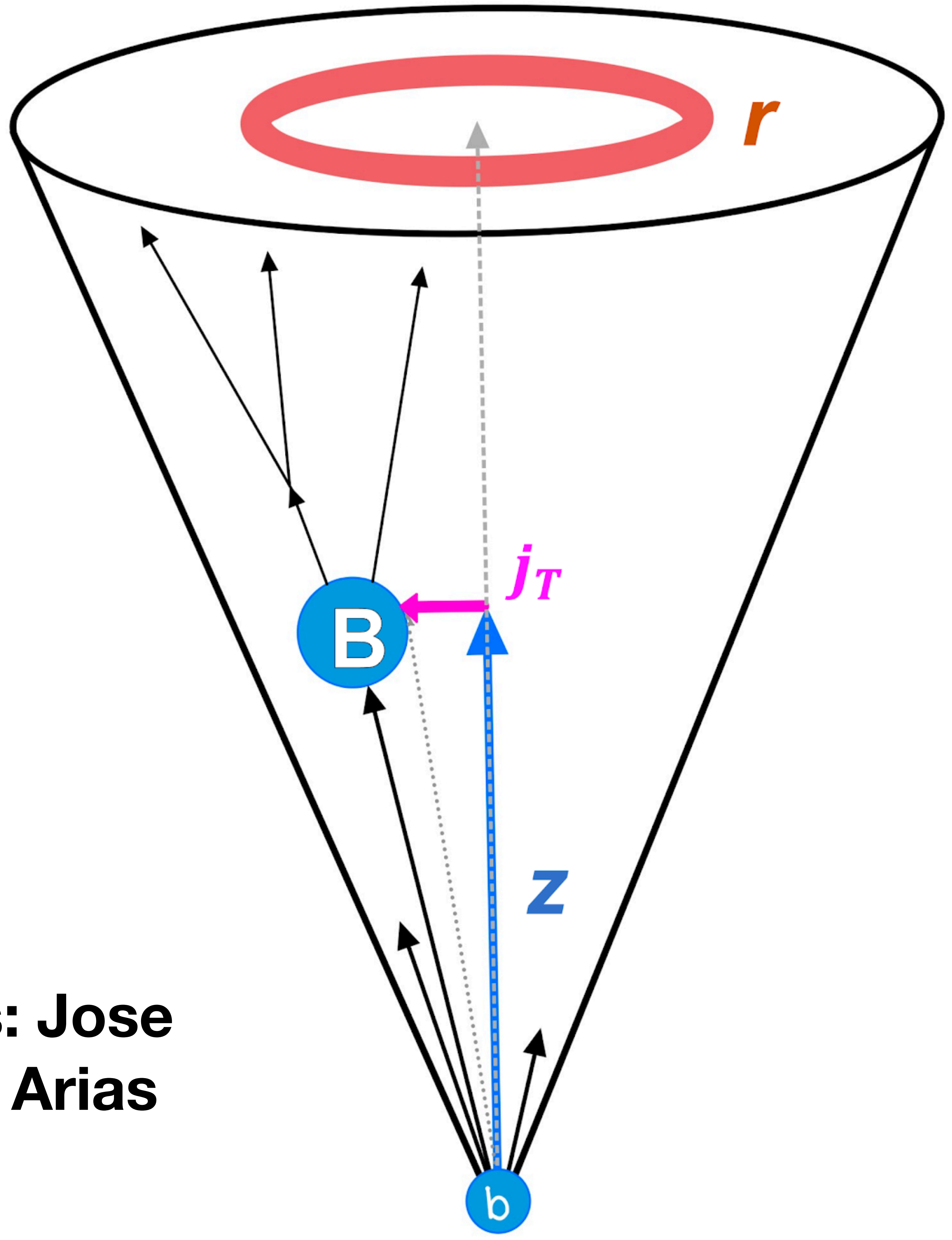


(a) Gluon Splitting (b) Flavor Excitation (c) s-channel Flavor Creation (d) t-channel Flavor Creation

PHYSICAL REVIEW D 96, 054019 (2017)

ILTEN, RODD, THALER, and WILLIAMS

Heavy Flavor Kinematic Observables in Jets



Credits: Jose Marco Arias

Longitudinal Momentum Fraction

$$z = \frac{\mathbf{p_{HF}} \cdot \mathbf{p_{jet}}}{\left|\mathbf{p_{jet}}\right|^2}$$

Transverse Momentum

$$j_T = \frac{\left|\mathbf{p_{HF}} \times \mathbf{p_{jet}}\right|}{\left|\mathbf{p_{jet}}\right|}$$

Angular Distance

$$\Delta R = \sqrt{\left(y_{HF} - y_{jet}\right)^2 + \left(\phi_{HF} - \phi_{jet}\right)^2}$$

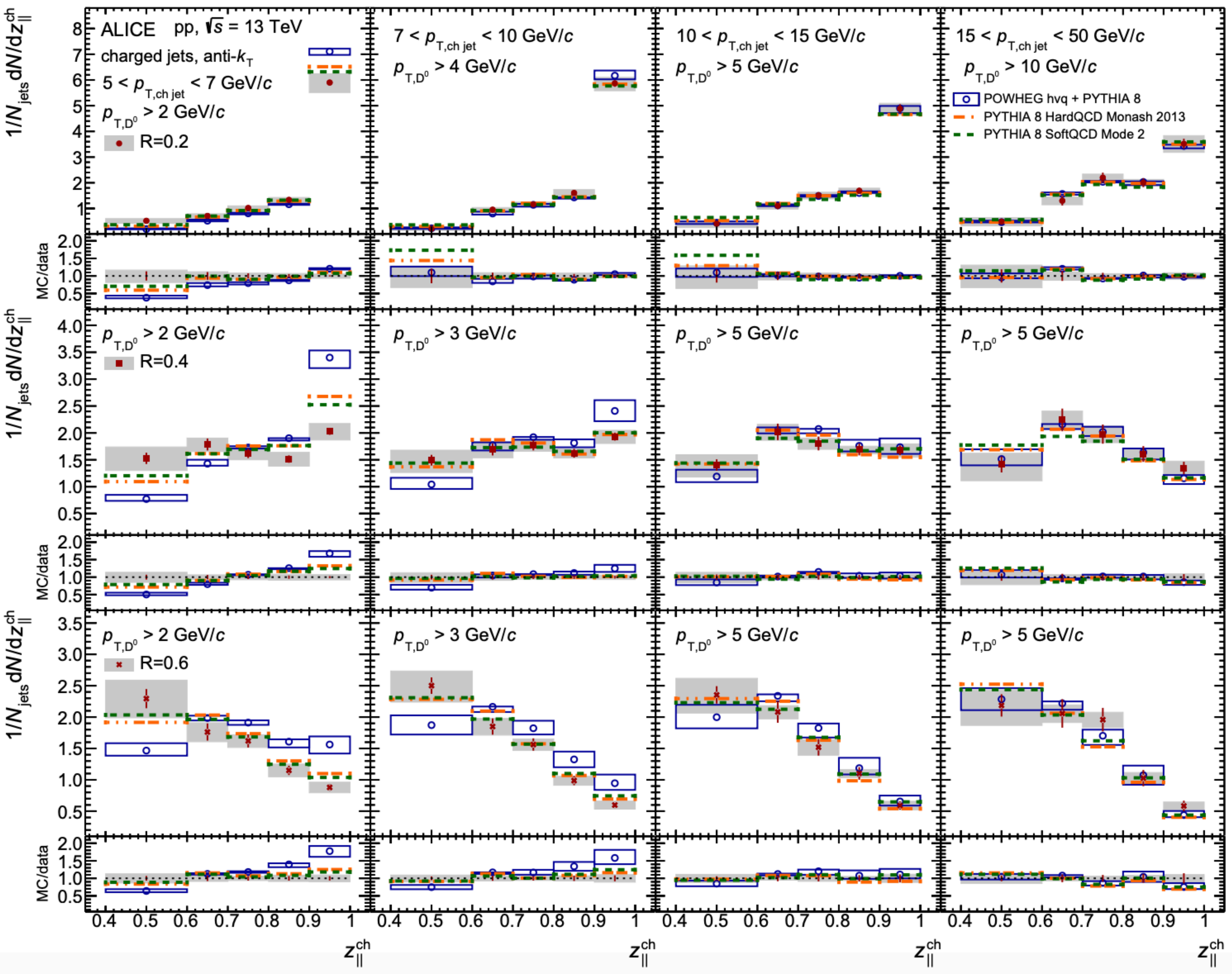
Credits: Kara Mattioli

Previous Measurements

ALICE D^0 Heavy Flavor Production in Jets

- Rows: $p_T^{D^0}$ increases to the right
- Columns: R increases downward
- Wider jets lead to lower momentum fraction (softer fragmentation) of the D^0 meson in jet

JHEP06(2023)133

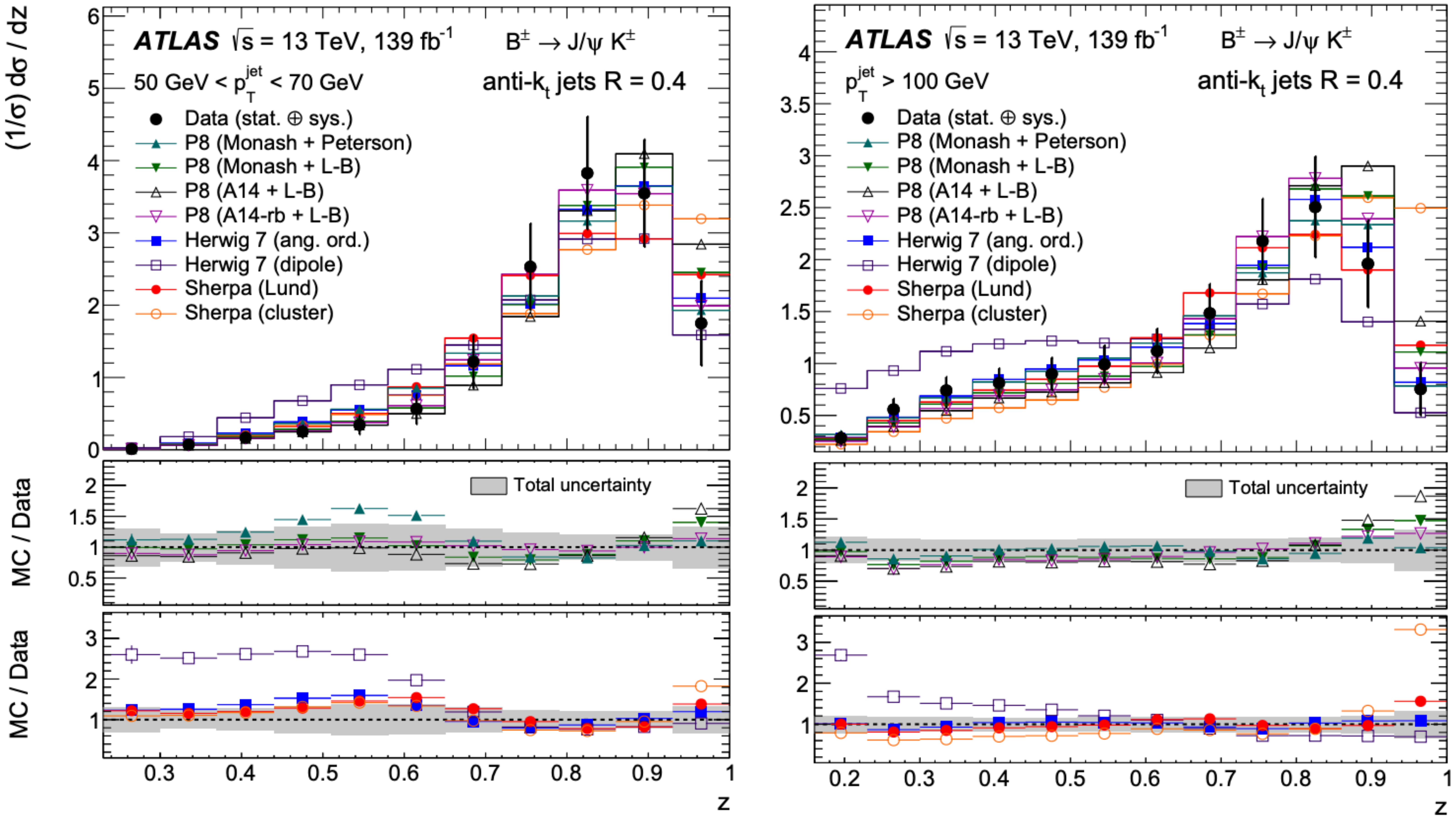


Previous Measurements

ATLAS $B^{\pm}$ Heavy Flavor Production in Jets

JHEP 12 (2021) 131

- Left panel: Longitudinal momentum fraction z with $50 < p_T^{jet} < 70$ GeV
- Right panel: $p_T^{jet} > 100$ GeV
- Hard fragmentation of $B^{\pm}$ (peaks around 0.85)
- Larger fraction of gluon splitting events leads to increased low-z fragmentation events for $p_T^{jet} > 100$ GeV

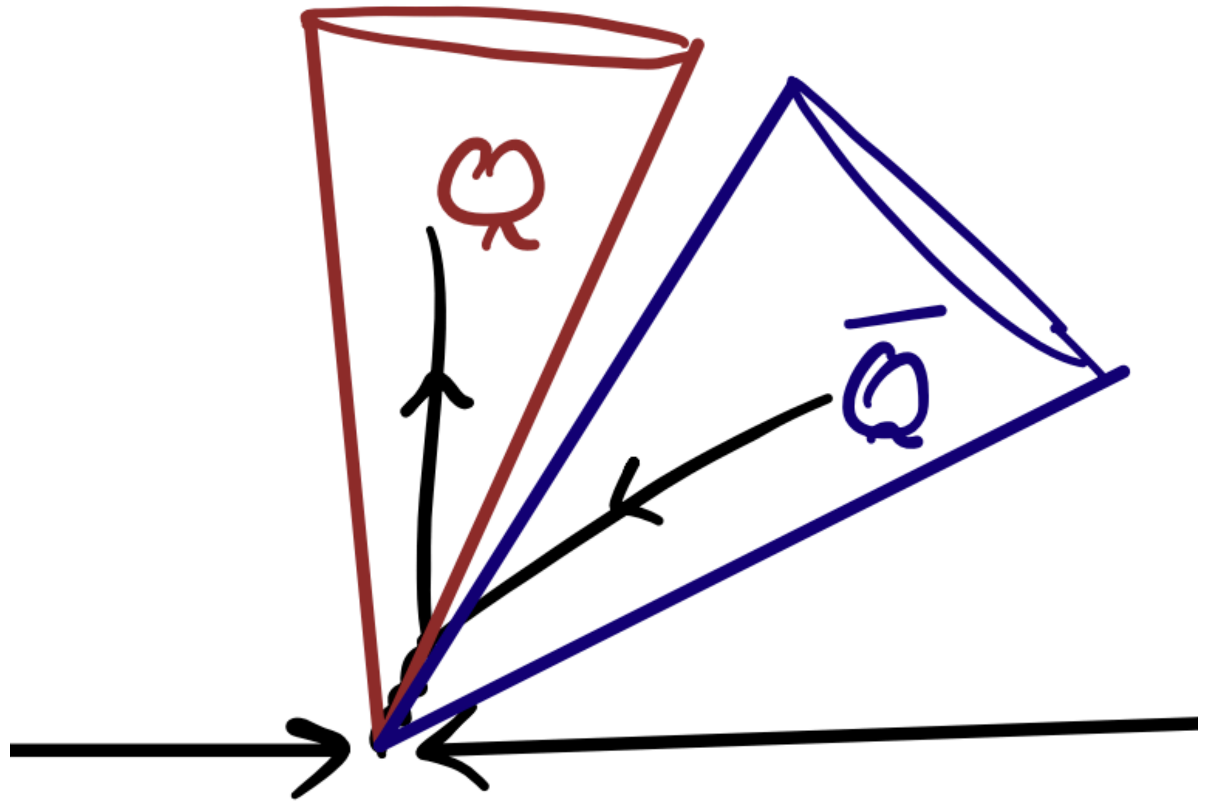


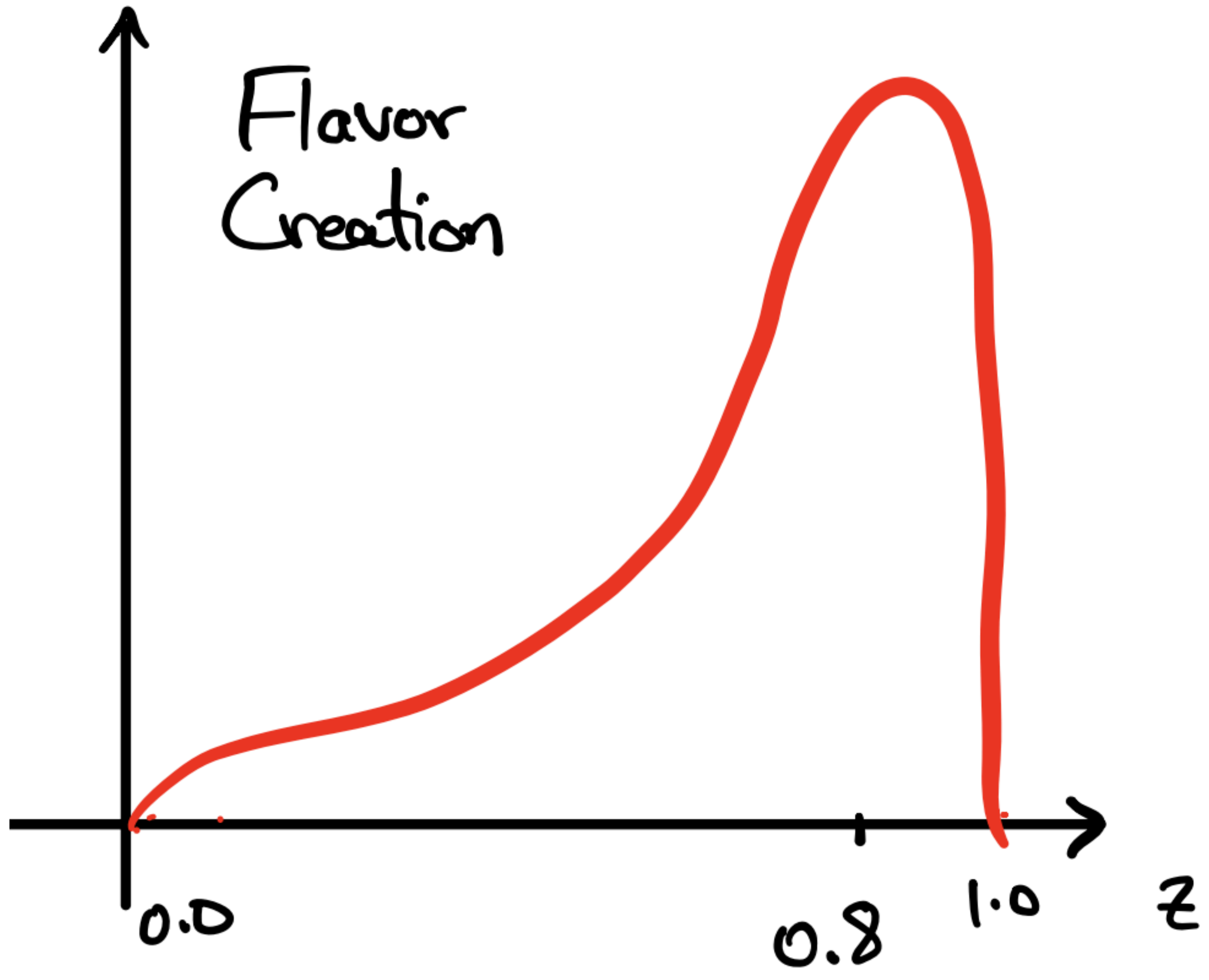
Heavy Flavor Fragmentation in Jets

$$z = \frac{\vec{p}_{HF} \cdot \vec{p}_{jet}}{\left|\vec{p}_{jet}\right|^2}$$

Gluon splitting vs. Flavor Creation

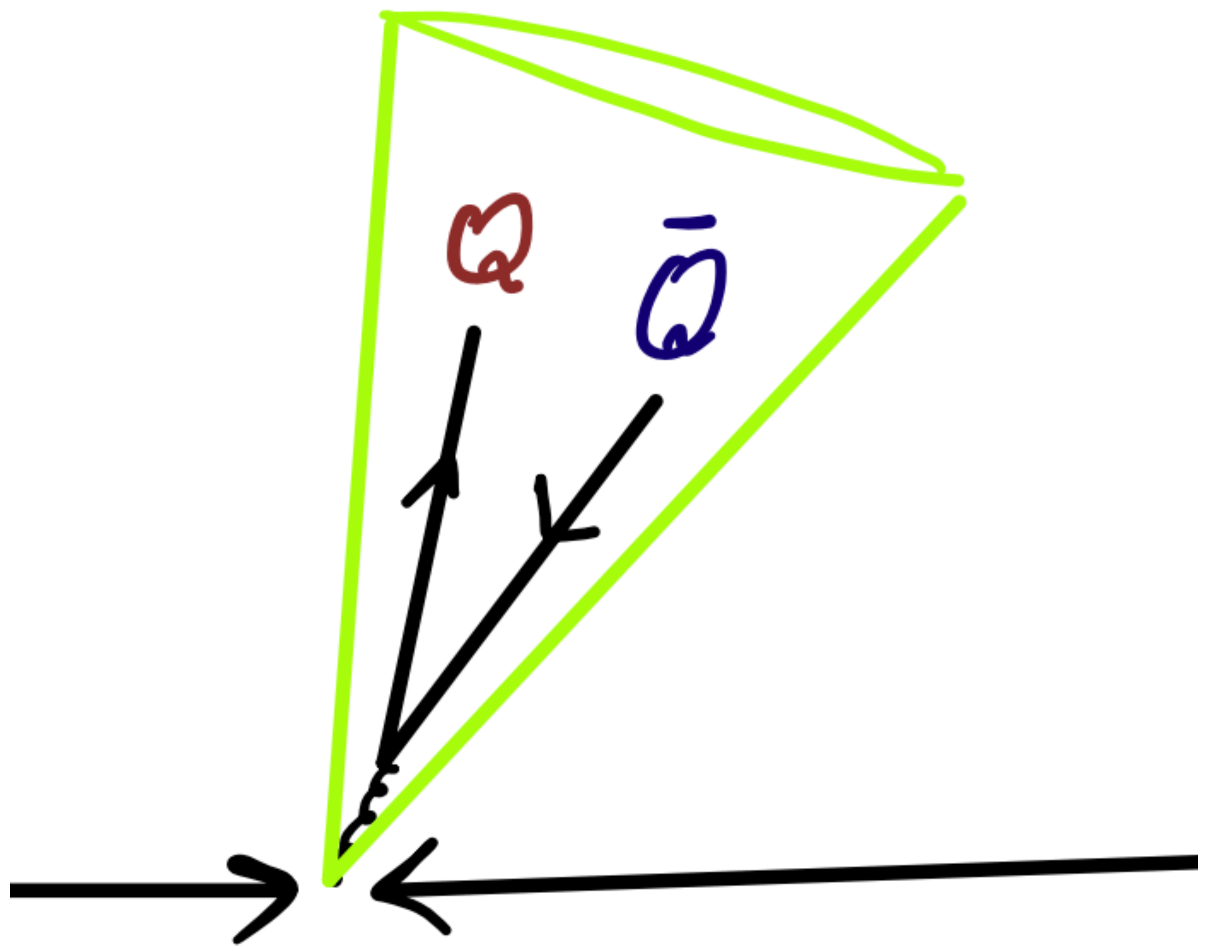
Flavor Creation dominated





B hadron carries most of the energy in the jet

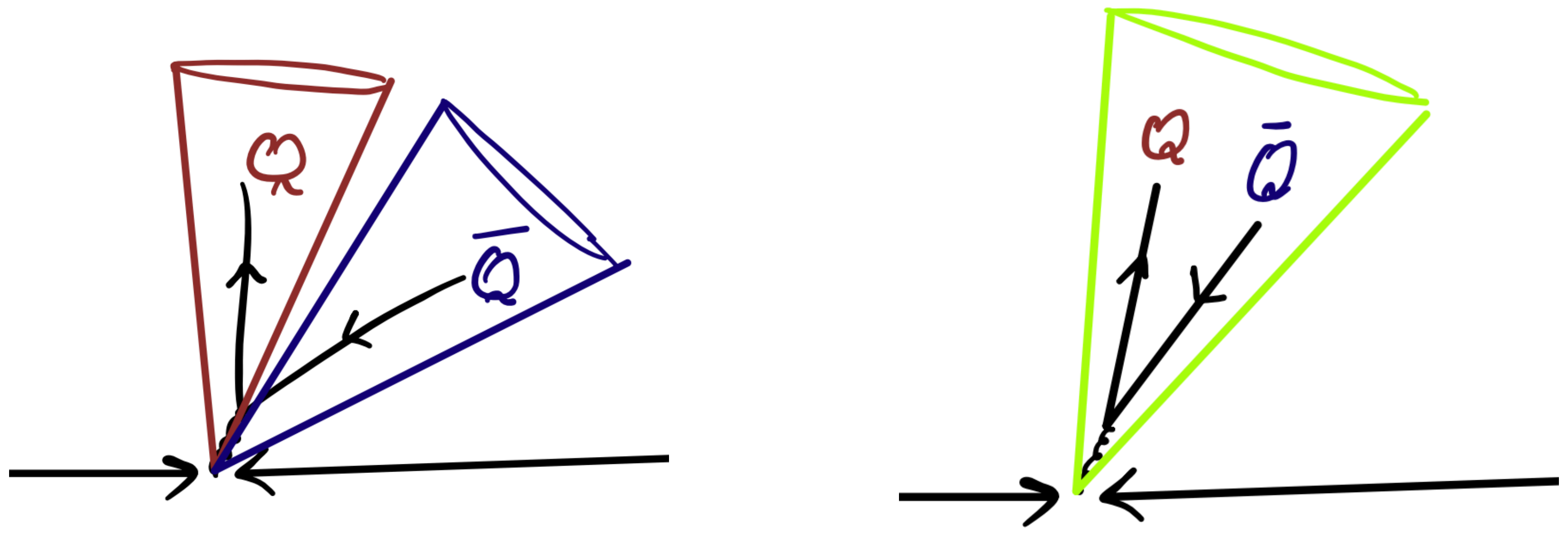
Gluon-splitting dominated



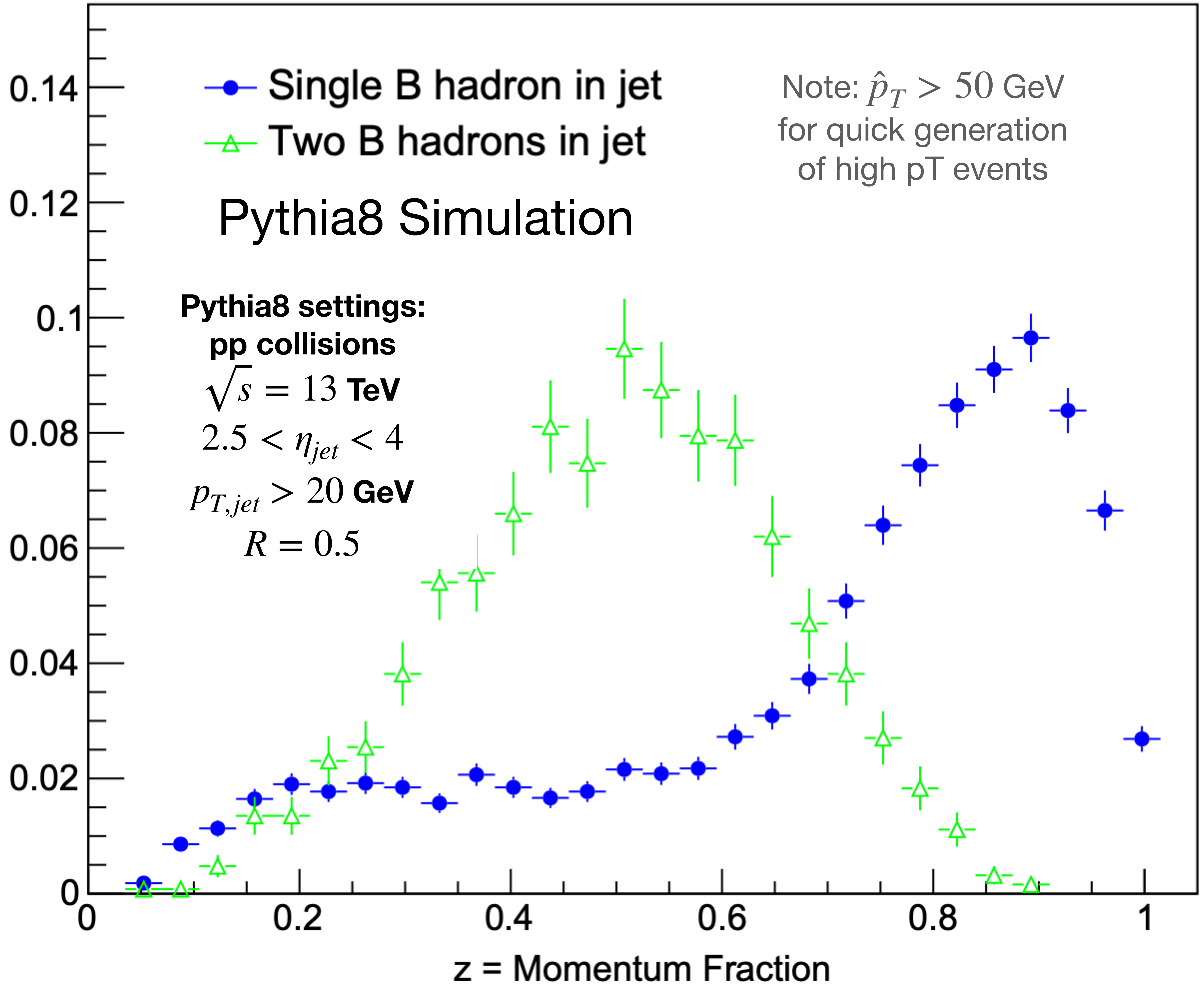
B hadron carries about half the energy of the jet.

Pythia Simulation

Illustration with simulated jets

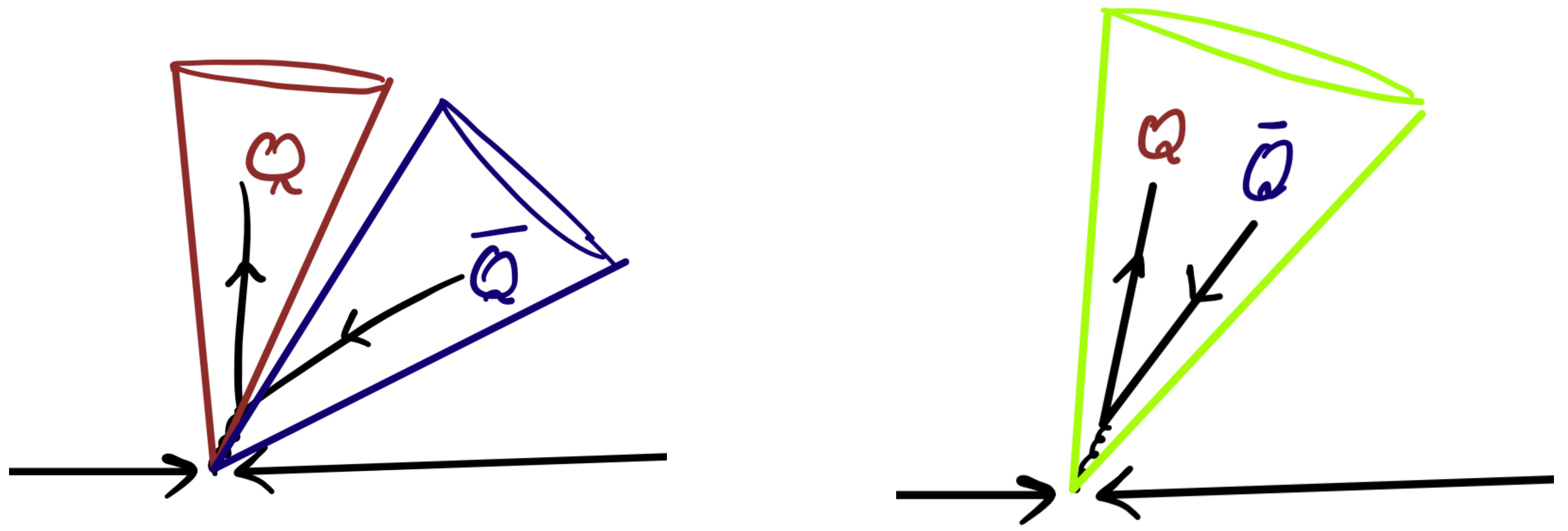


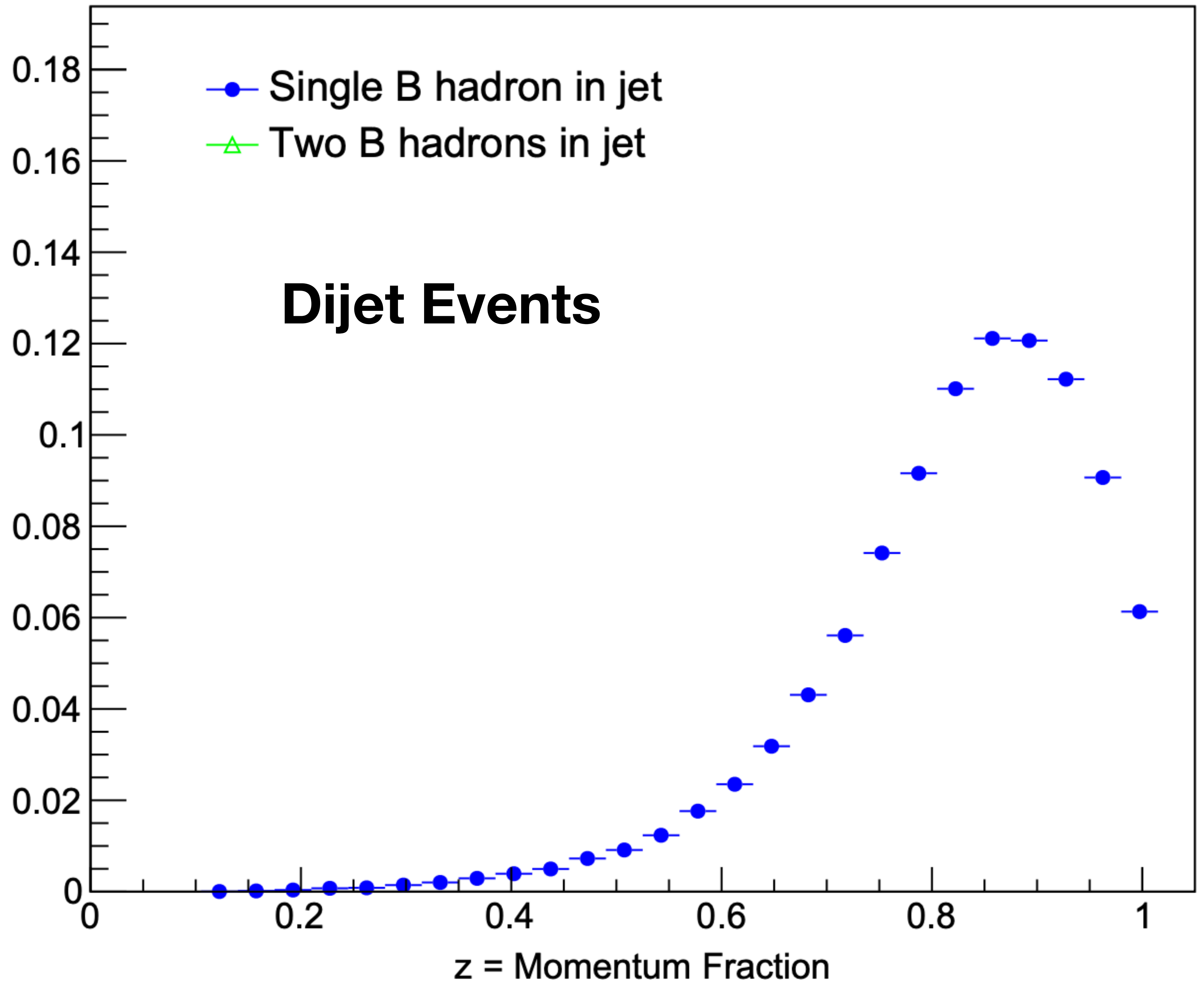
- Local Pythia (not produced by LHCb) simulations of $g \to b\bar{b}$ jets
- Fragmentation depends on whether two B hadrons are clustered together or separately
- B hadrons from gluon splitting clustered into separate jets behave differently than flavor creation
- Overall fragmentation is some linear combination of the two processes

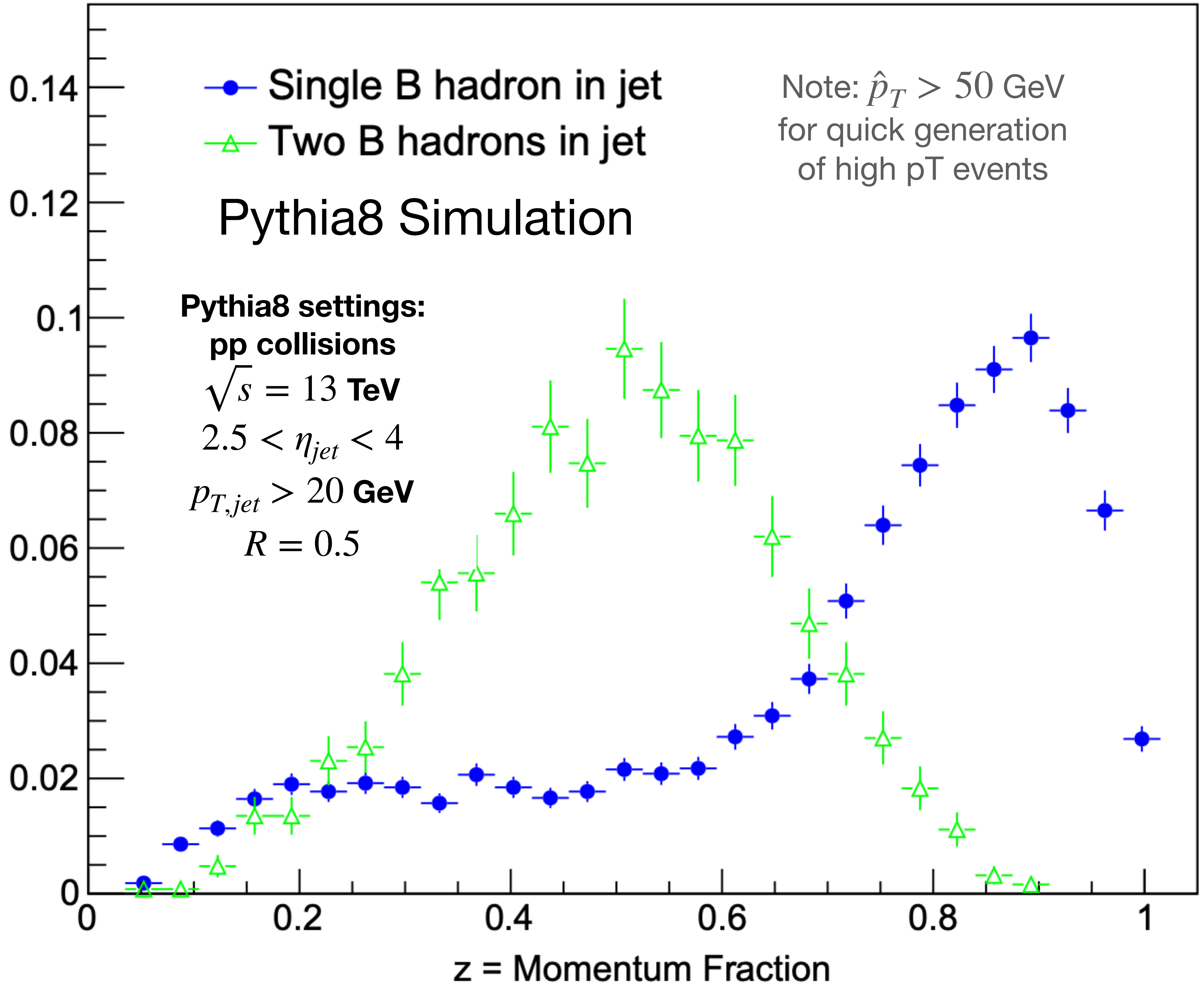


Pythia Simulation

Illustration with simulated jets





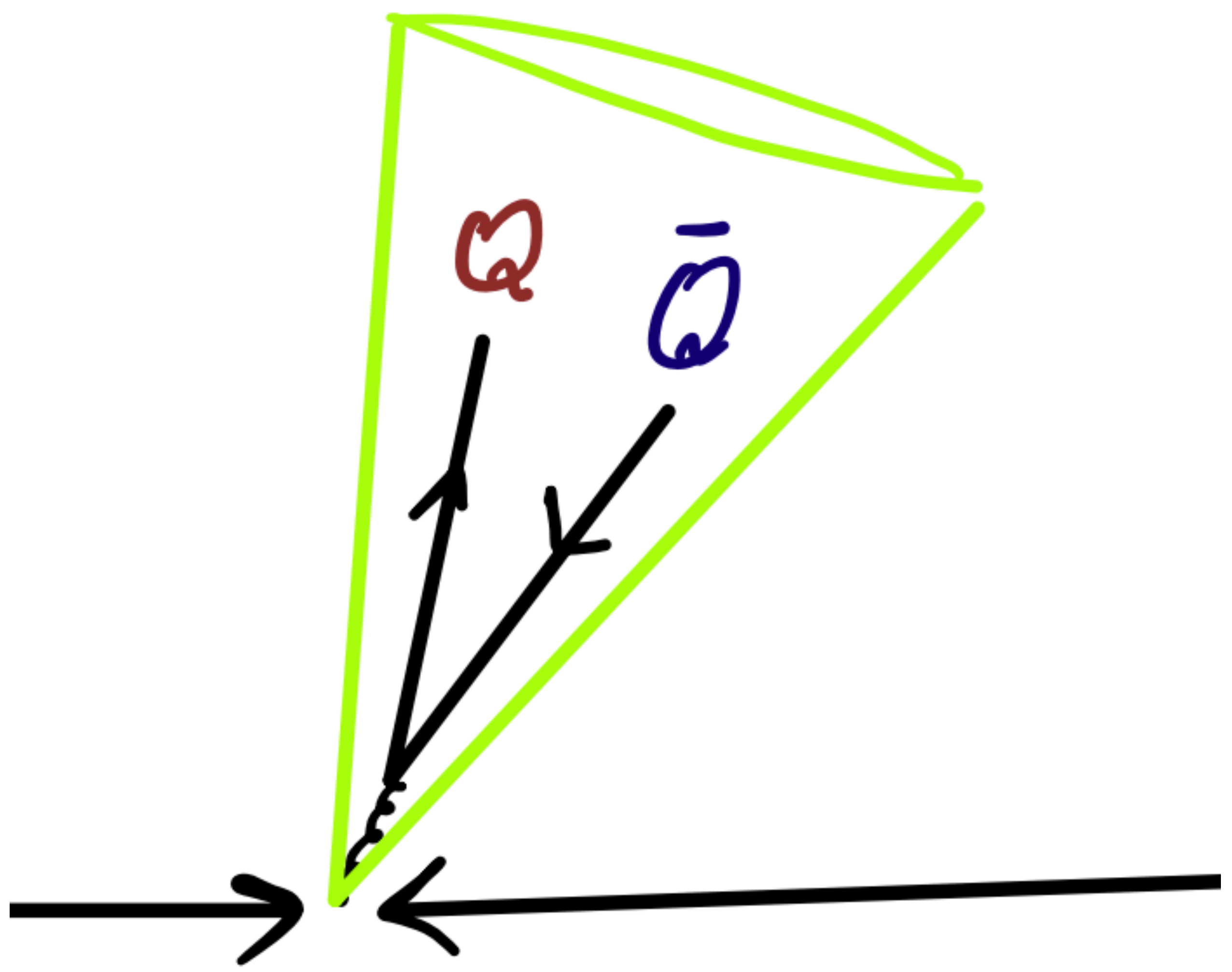


Identifying Gluon Splitting Events at LHCb

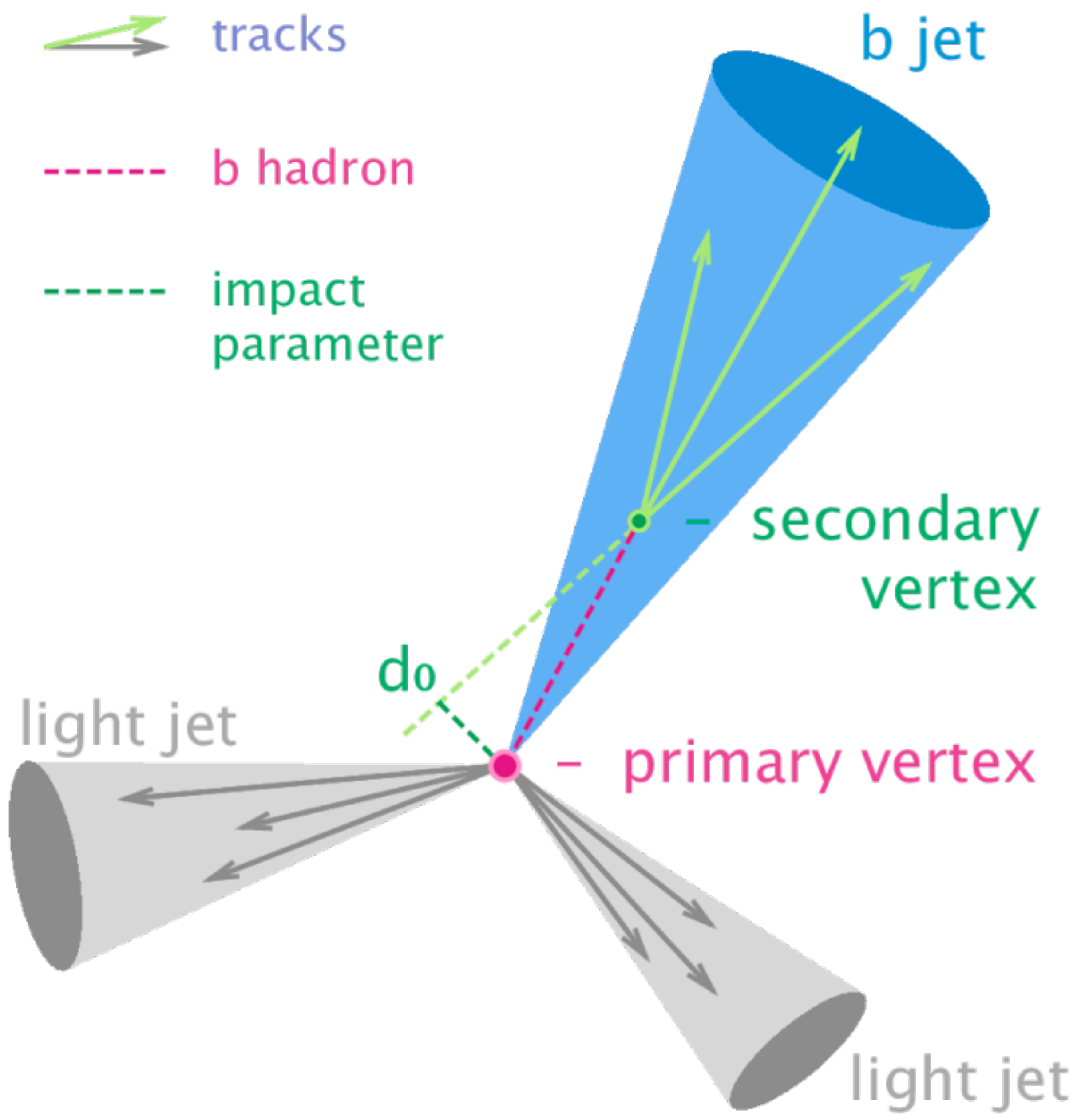
Secondary Vertex tagging

Credits: https://www.particlebites.com/?p=4007

- Reconstructing both hadrons is highly inefficient
- Instead look for secondary vertices (SV)
- Events with a fully reconstructed B hadron + SV are proxies for gluon splitting events



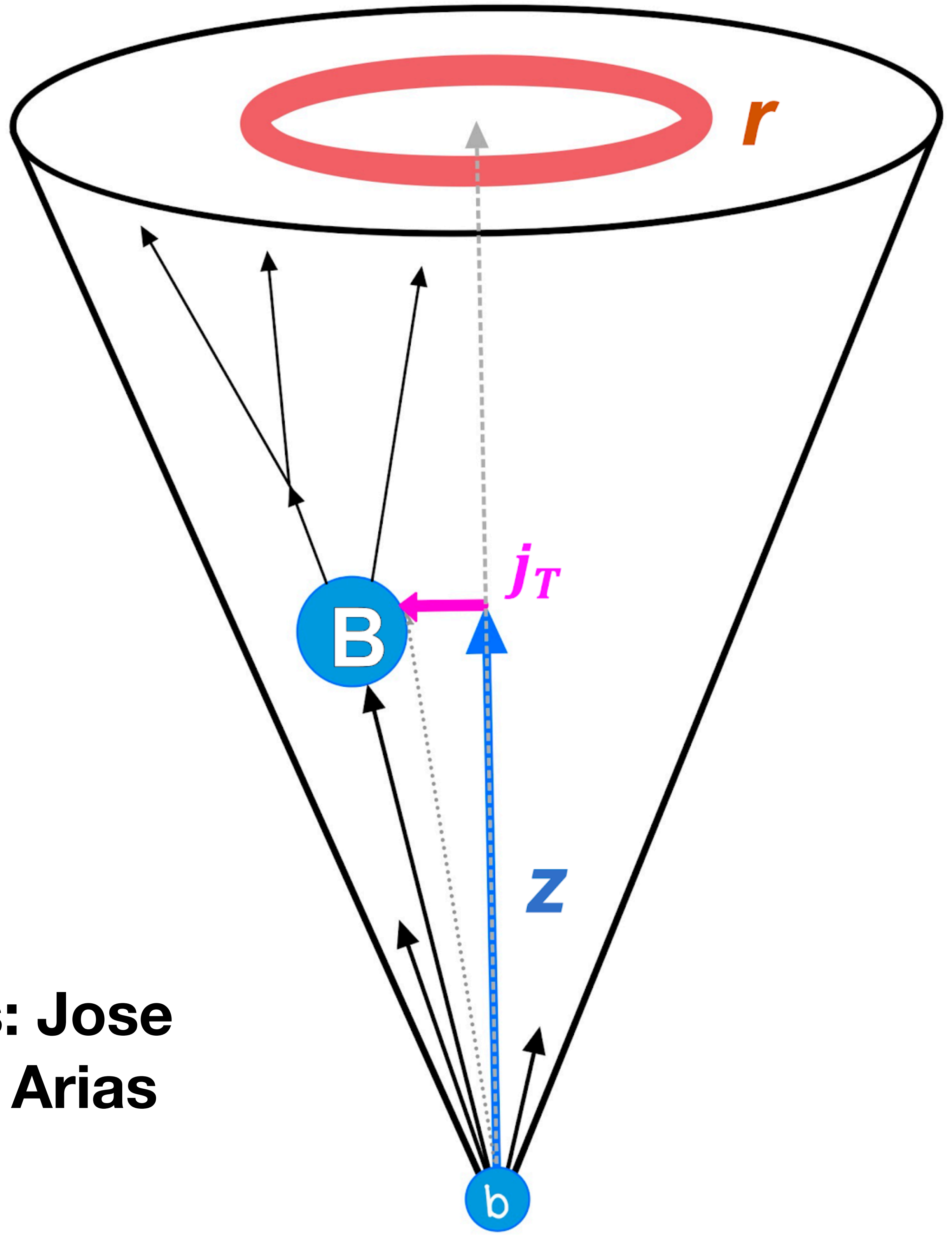
Gluon-splitting Event



Secondary Vertex Tagging

Current LHCb HF Fragmentation Measurements

- LHCb is currently measuring the fragmentation of $B^{\pm}$ and D^{0} in jets for Run II data
- Measurement of hadronization variables will be differential in p_T^{jet}
- Currently, the SV-tagger is being studied for potential measurements of gluon splitting rate and fragmentation functions



Credits: Jose Marco Arias

Summary

Ongoing Heavy Flavor Jet Measurements at LHCb

- The LJP has been measured in inclusive jets at ATLAS, ALICE, and CMS, but no such measurement has been done for heavy flavor jets. At LHCb, we are currently measuring the LJP for $B^{\pm}$ and D^0 jets using the full Run II data from 2016 - 2018.

- In addition, we are working on the dead cone measurement in beauty and charm jets relative to light quark-enriched jets.

- LHCb is also measuring the fragmentation properties of $B^{\pm}$ and D^0 mesons in jets, with interesting capabilities of exposing events with heavy quarks originating from gluon splitting.

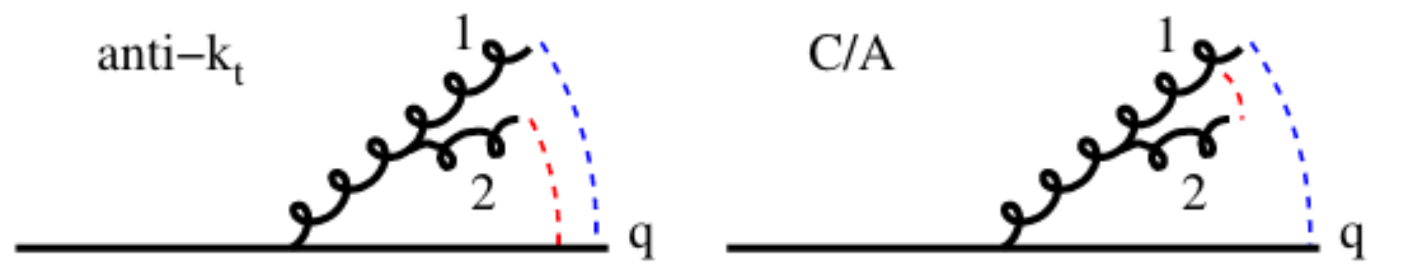
Backup slides

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

R : Jet Radius

Jets and Clustering Algorithms

Anti-k_T, Cambridge/Aachen



- Given a collection of particles, define a distance between two particles as:

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

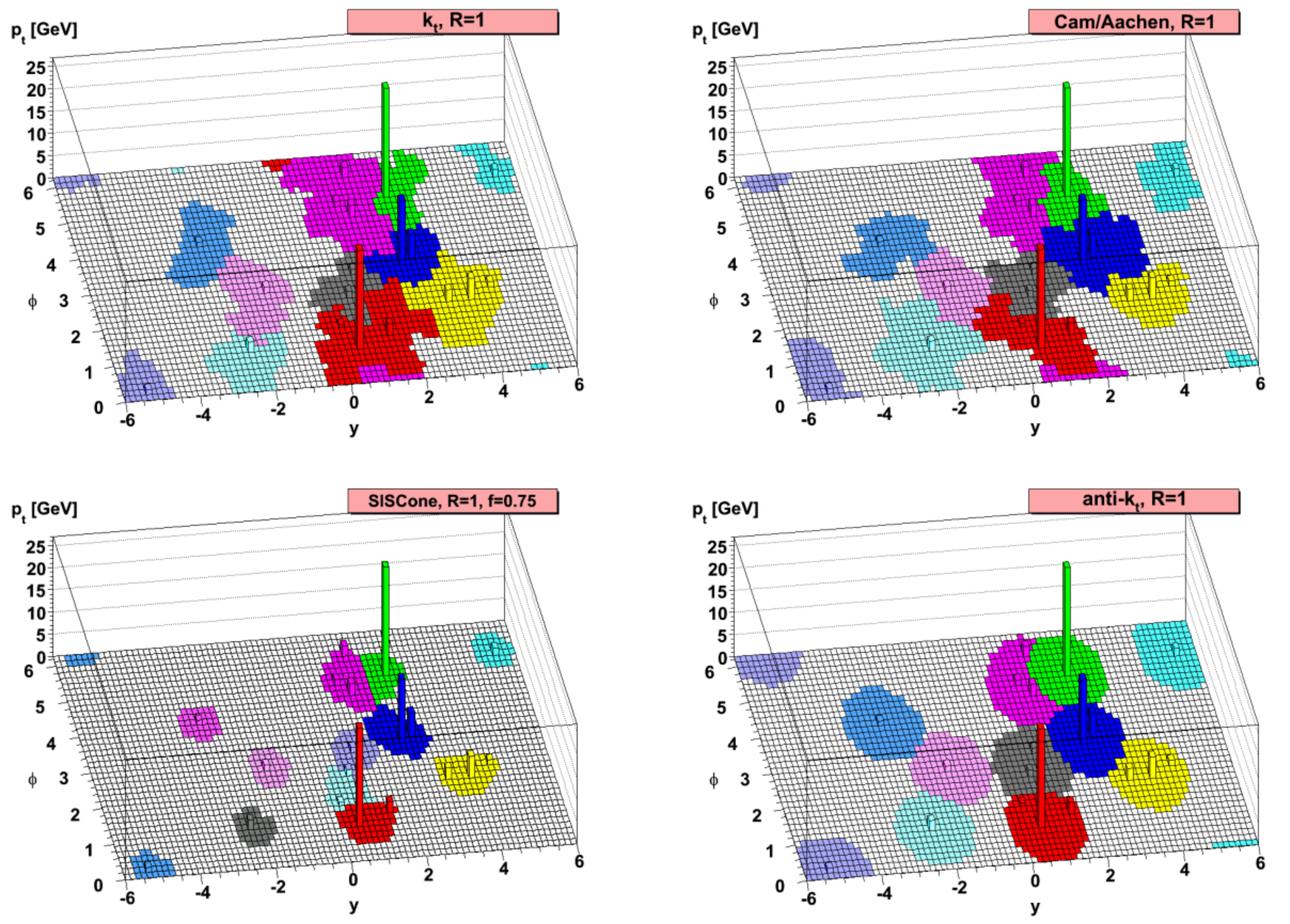
$p = 1$: k_T

$p = 0$: 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

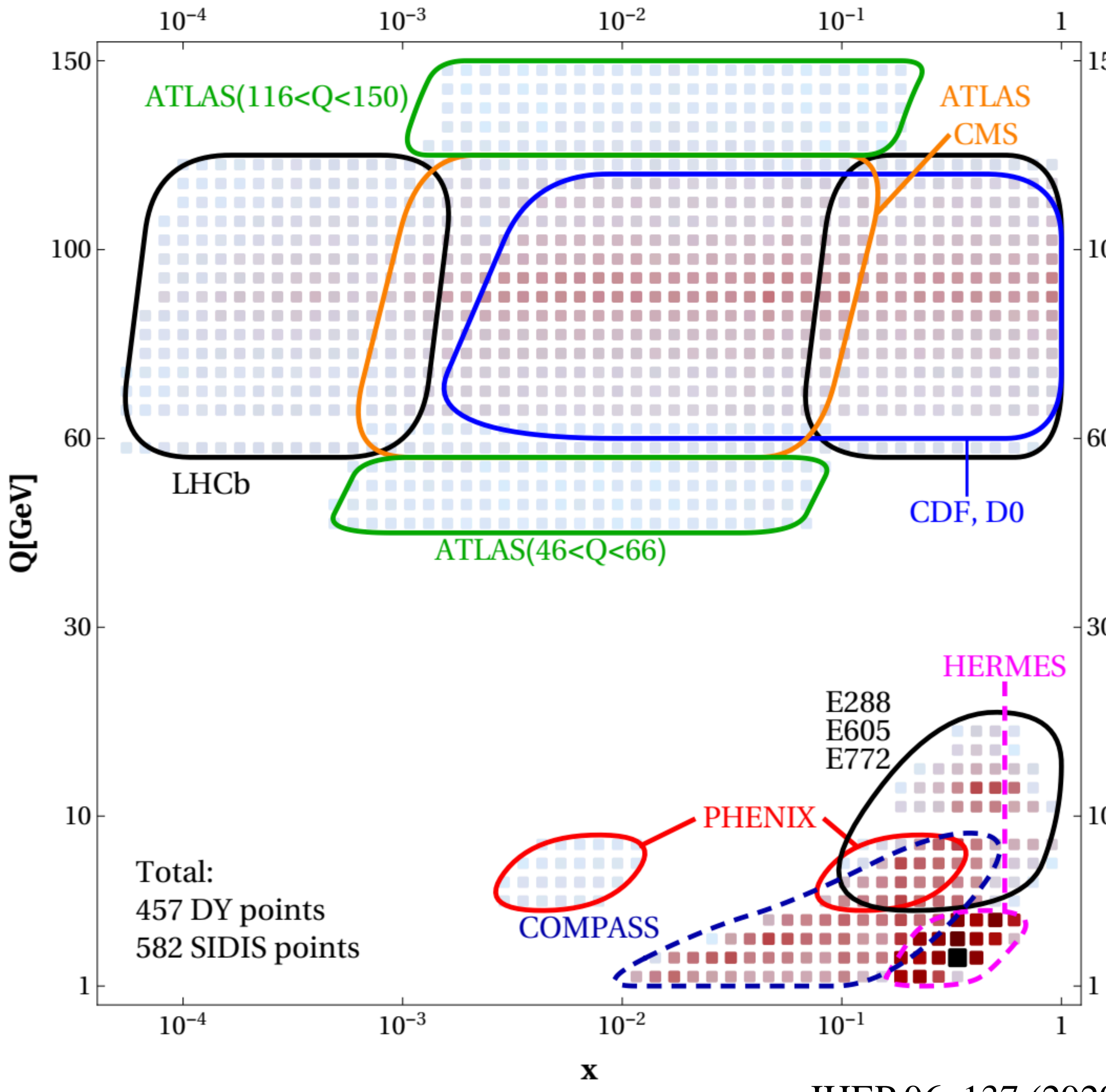
- **Anti-k_T is infrared and collinear safe (IRC), and produces conical jets!**



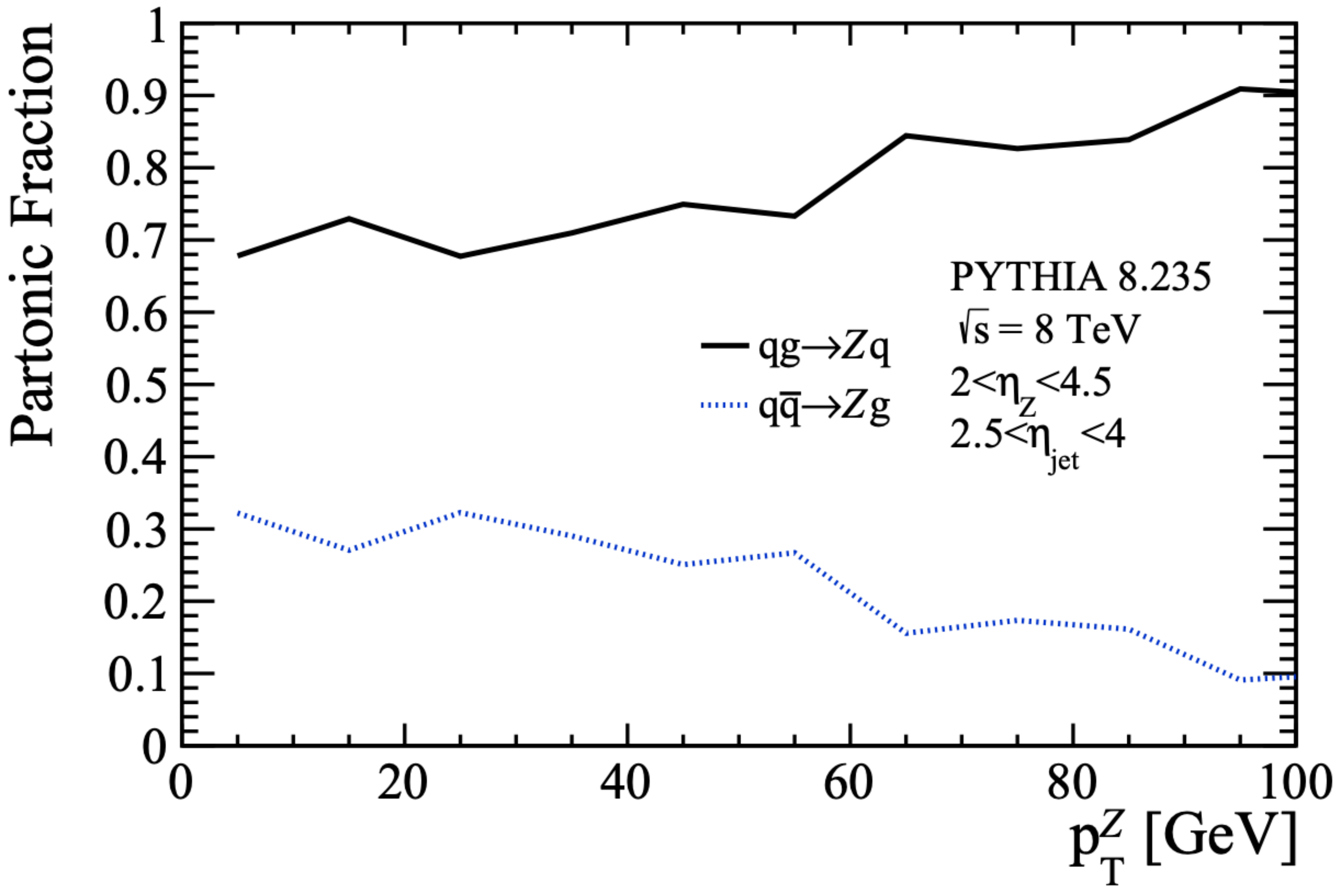
Cacciari, Matteo, Gavin P. Salam, and Gregory Soyez. JHEP 2008.04 (2008): 063.

Partonic fractions at forward rapidity

High-x enhances the light-quark jet fraction



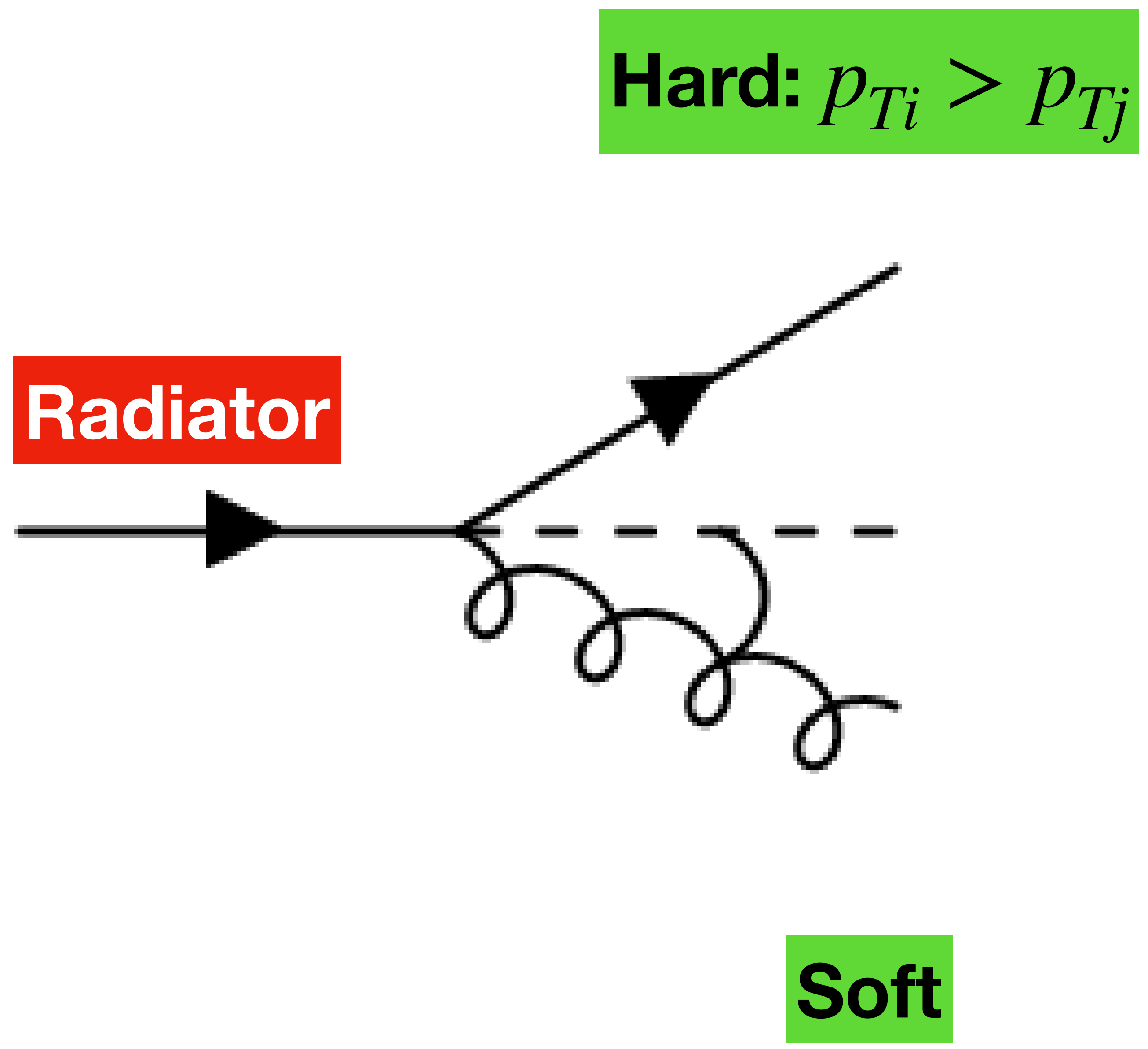
JHEP 06, 137 (2020)



PRL 123, 232001 (2019)

Splitting Variables

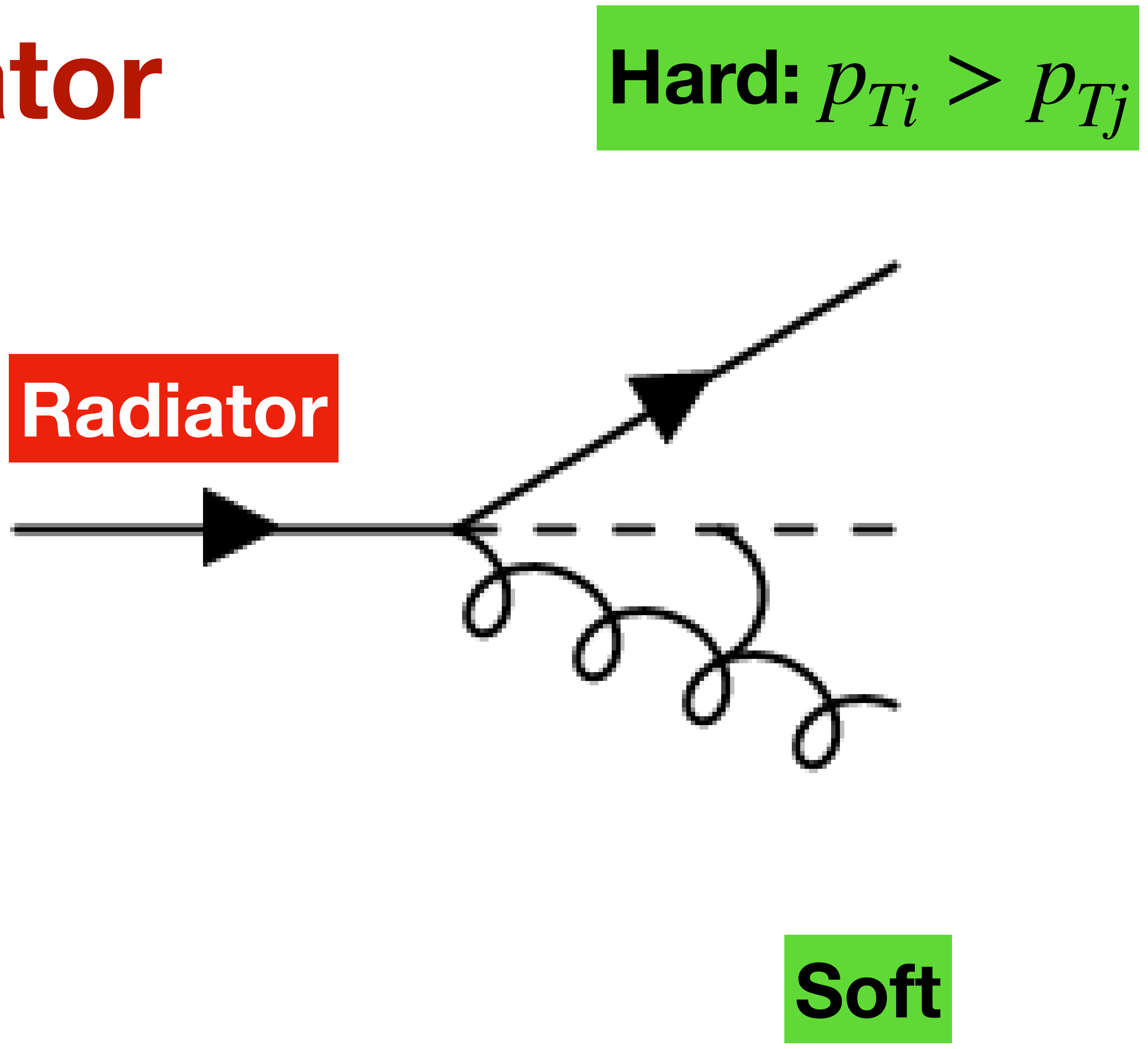
- We adopt the following definitions for the Lund jet plane variables:
  - θ_{ij} : the angle between the soft daughter and radiator
  - E_{rad} : the energy of the radiator
  - $\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ - angular distance
  - $k_T = p_T^{soft} \sin(\Delta R)$ - relative transverse momentum
  - $z = \dfrac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$ - transverse momentum fraction



Splitting Variables

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

- Focusing on these variables:
  - θ_{ij} **: the angle between the soft daughter and radiator**
  - E_{rad} **: the energy of the radiator**



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

Dead cone plane in E_{rad} and θ

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

Splitting Variables

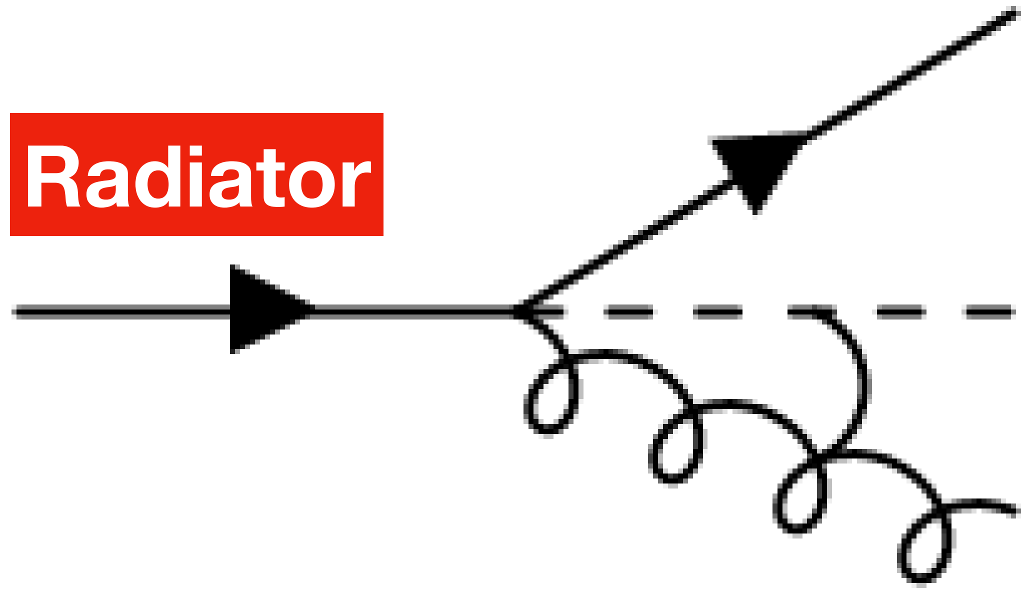
$$\rho(\Delta R, z) = \frac{1}{N_{emissions}} \frac{d^2 n}{d\ln(R/\Delta R) d\ln(1/z)}$$

- Focusing on these variables:
  - $\Delta R = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$
  - $k_T = p_T^{soft} \sin(\Delta R)$
  - $z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$

Lund jet plane

Hard: $p_{Ti} > p_{Tj}$

Radiator



Soft