25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM

The Lund jet plane in light and heavy quarks at LHCb

SPIN 2023
Sep 25-29, 2023

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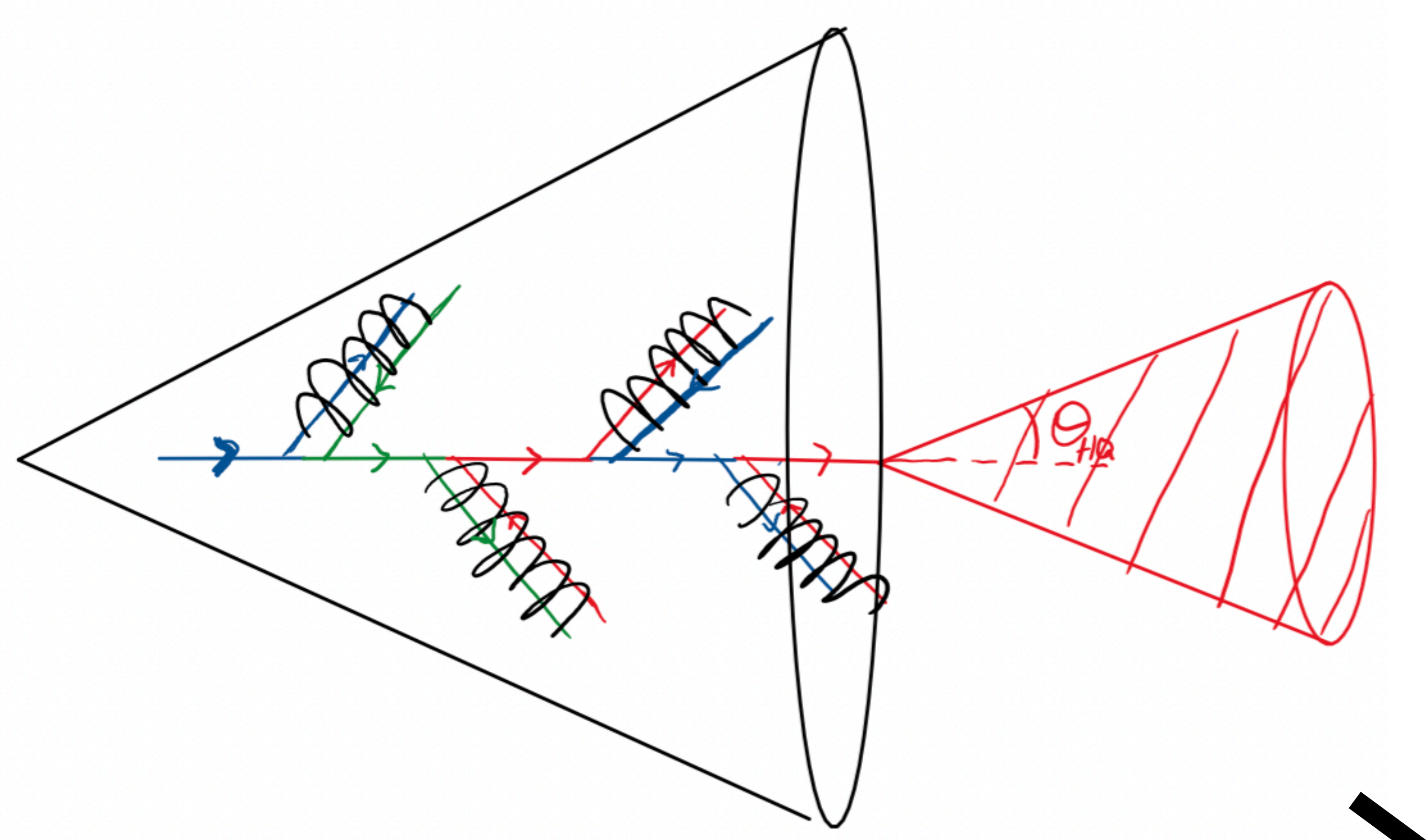
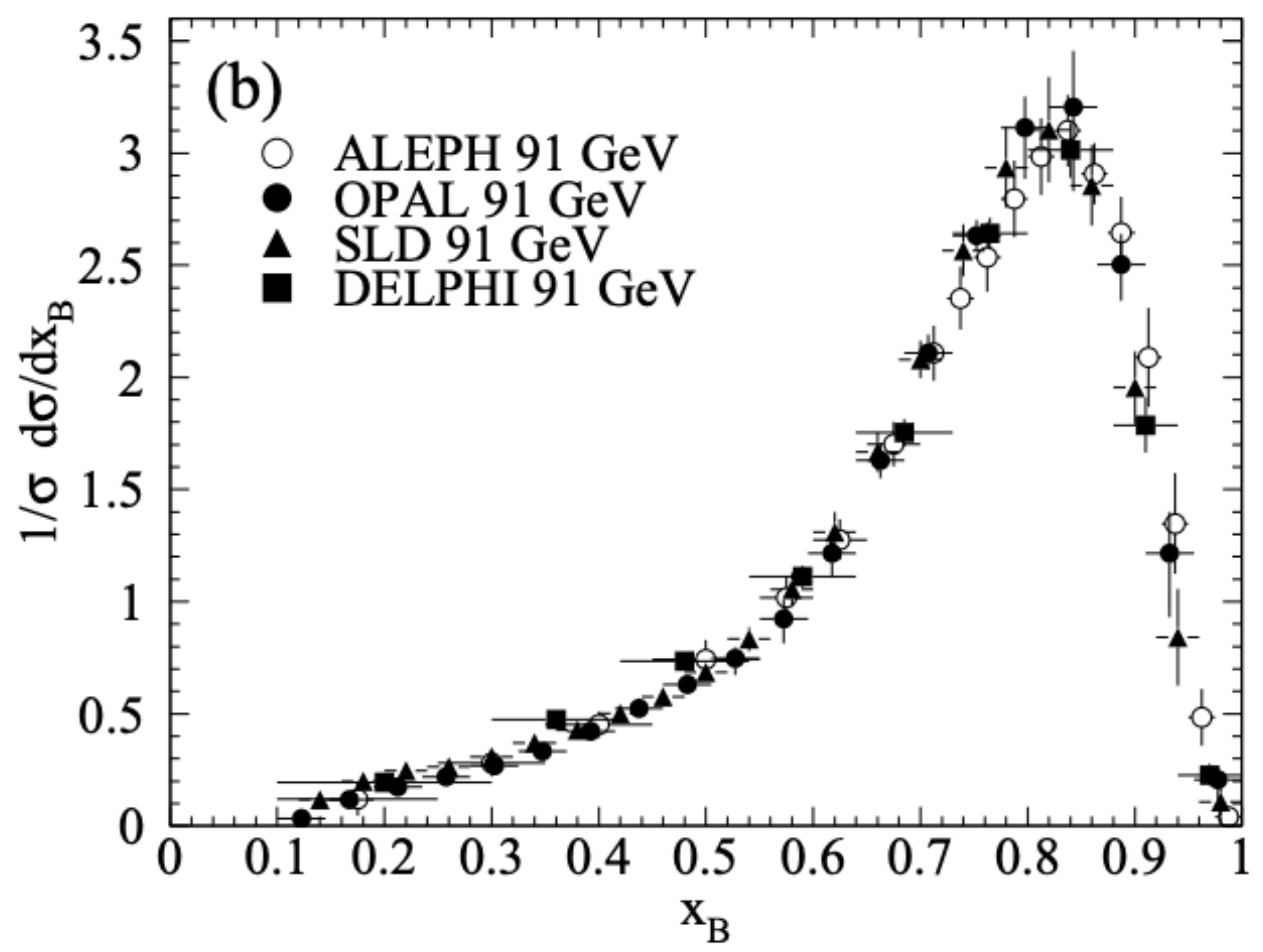
PhD Candidate, University of Michigan, Ann Arbor

Heavy Quark Showering and Fragmentation

1. The Dead Cone Effect



2. The Leading Particle Effect



Lund Jet Plane

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

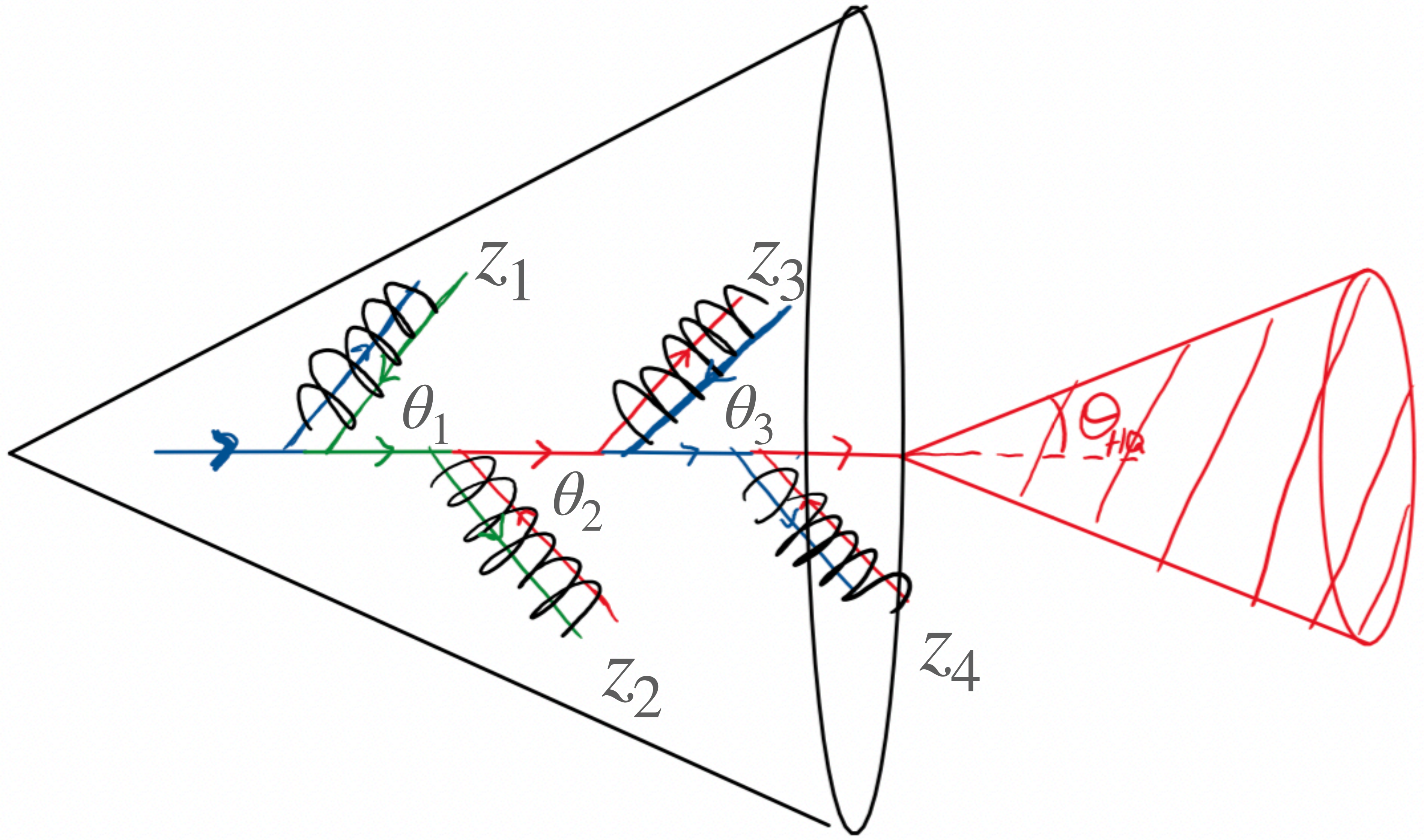
C_i : Color factor

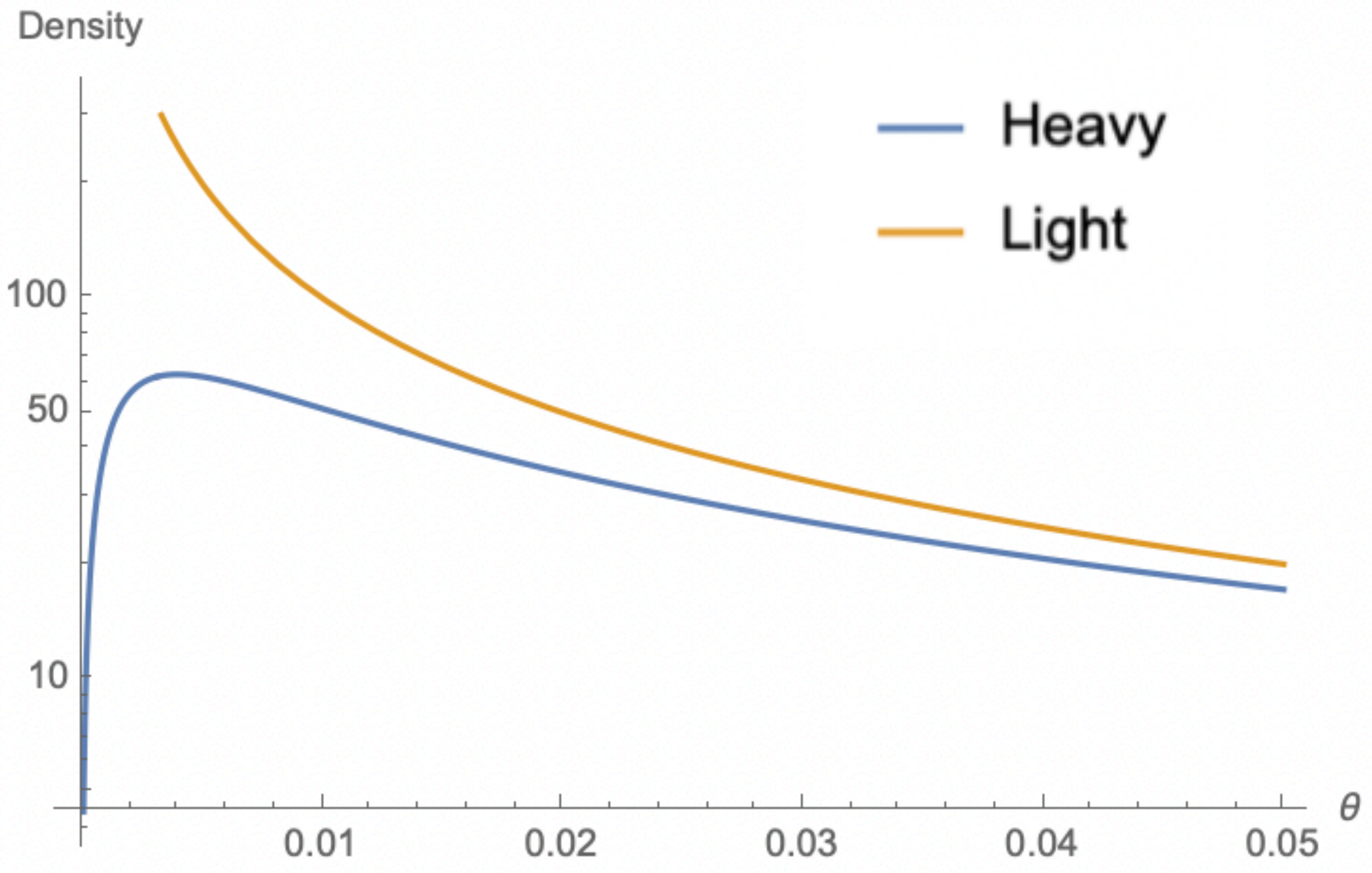
- For heavy quarks (HQ), a characteristic angle appears in the equation

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

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

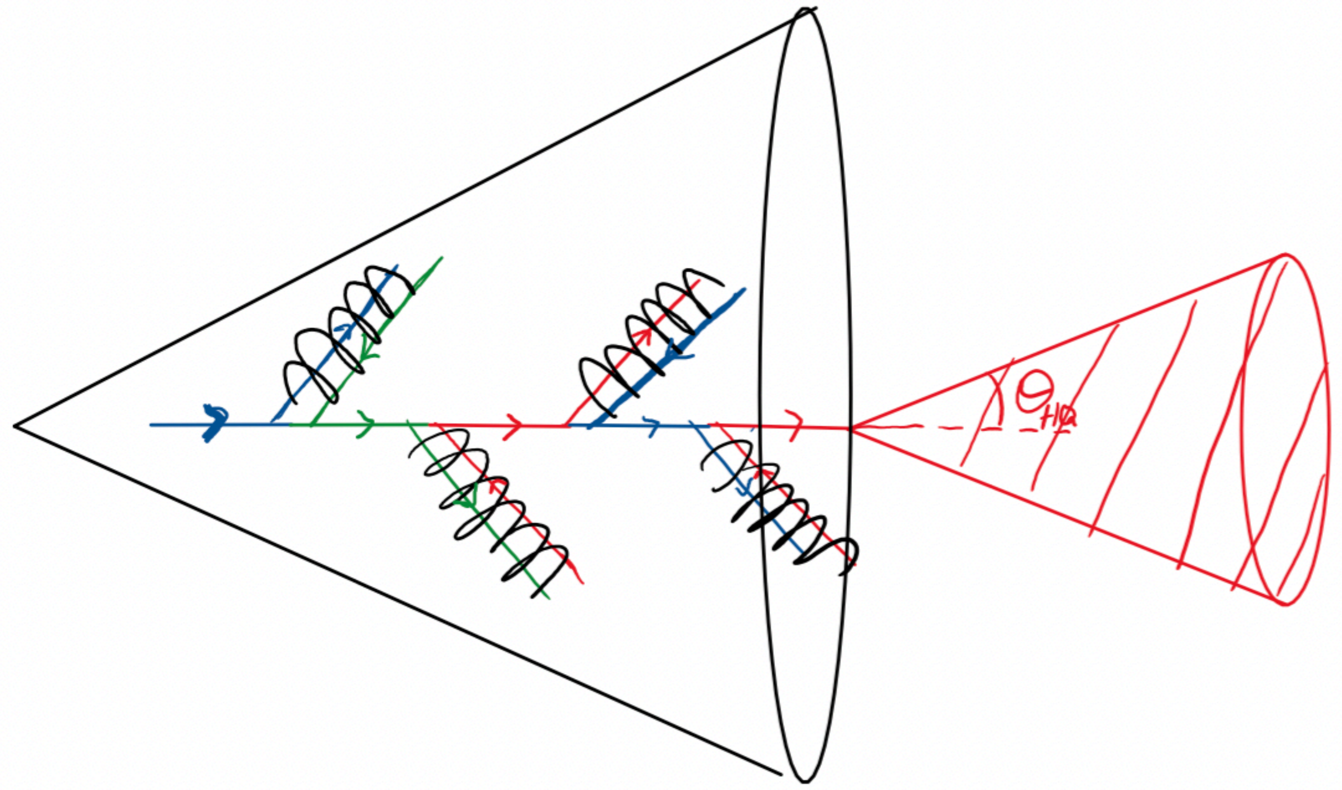
Dokshitzer, Y.L., Khoze, V.A. and Troyan, S.I., 1991.
Journal of Physics G: Nuclear and Particle Physics, *17*(10), p.1602.



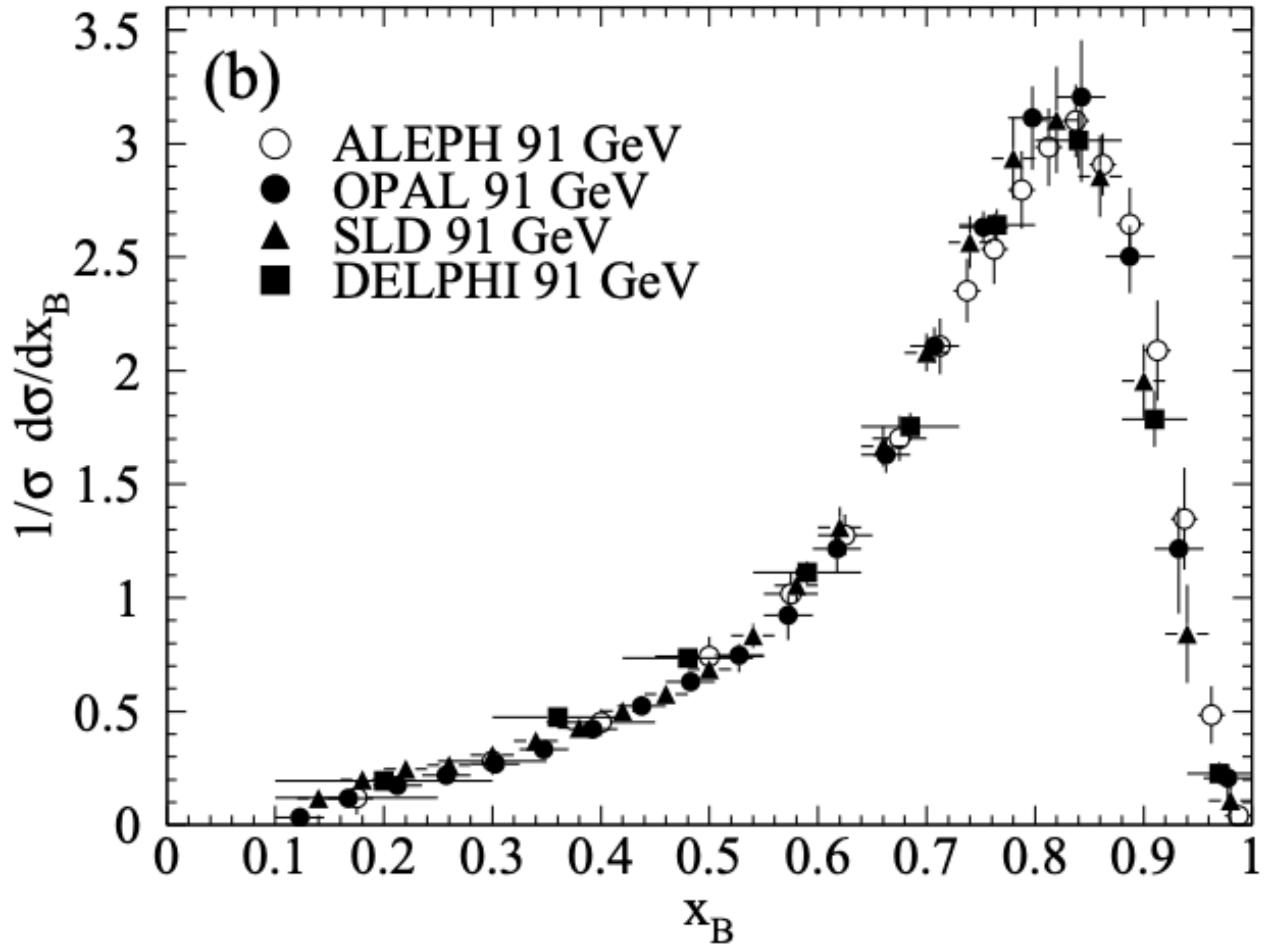


Heavy Quark Fragmentation

Heavy quarks maintain most of their energy



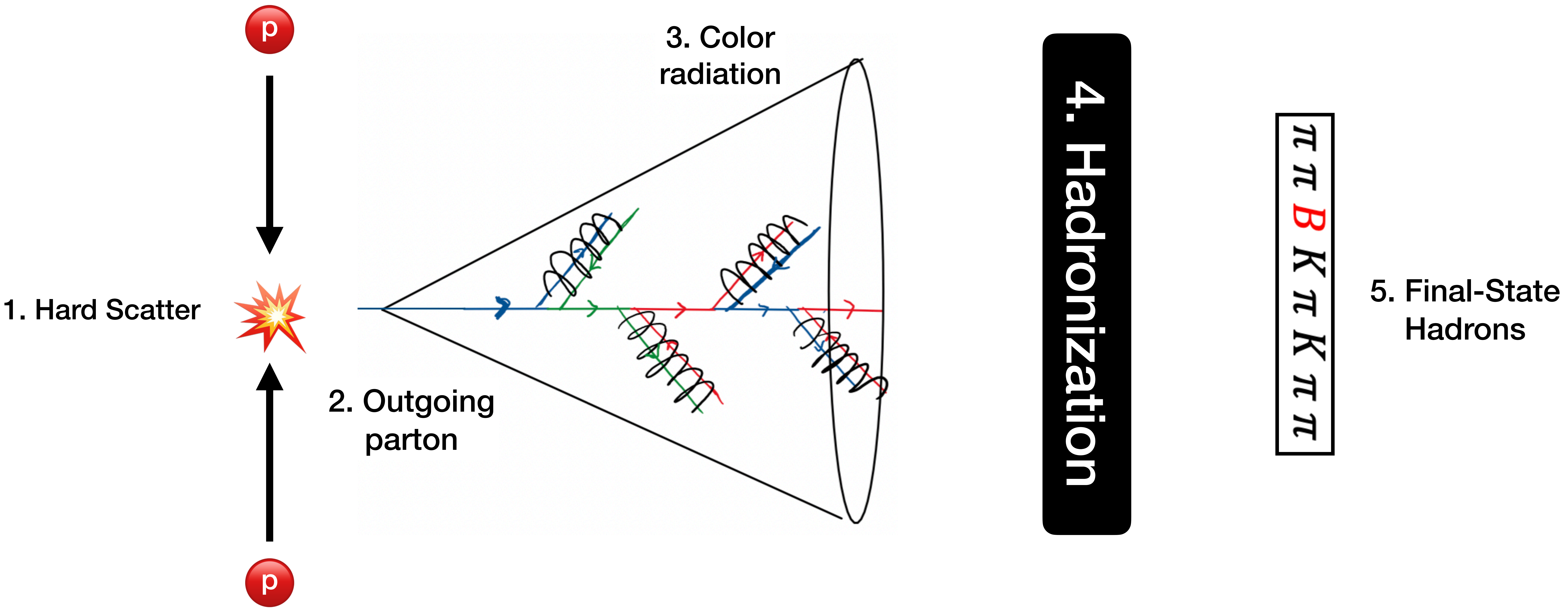
- Light partons lose most of their energy in hard collinear radiation
- The dead cone effect in heavy quarks prevents collinear radiation —> very few hard and collinear bremsstrahlung!
- Thus, the heavy quark maintains most of its energy



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)

Single partons are inaccessible!
Only access to collimated cone of hadrons a.k.a *Jets.*



*Not to scale

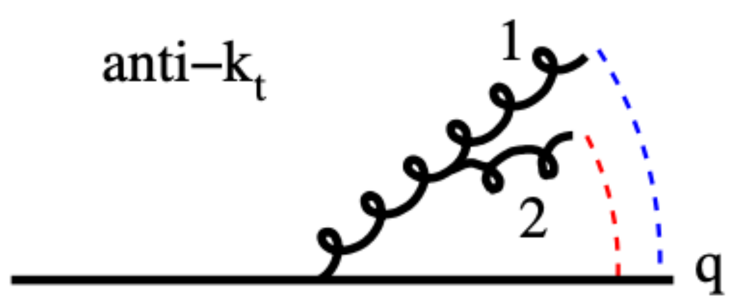
Cacciari, Matteo, Gavin P. Salam, and Gregory Soyez. JHEP 2008.04 (2008): 063.

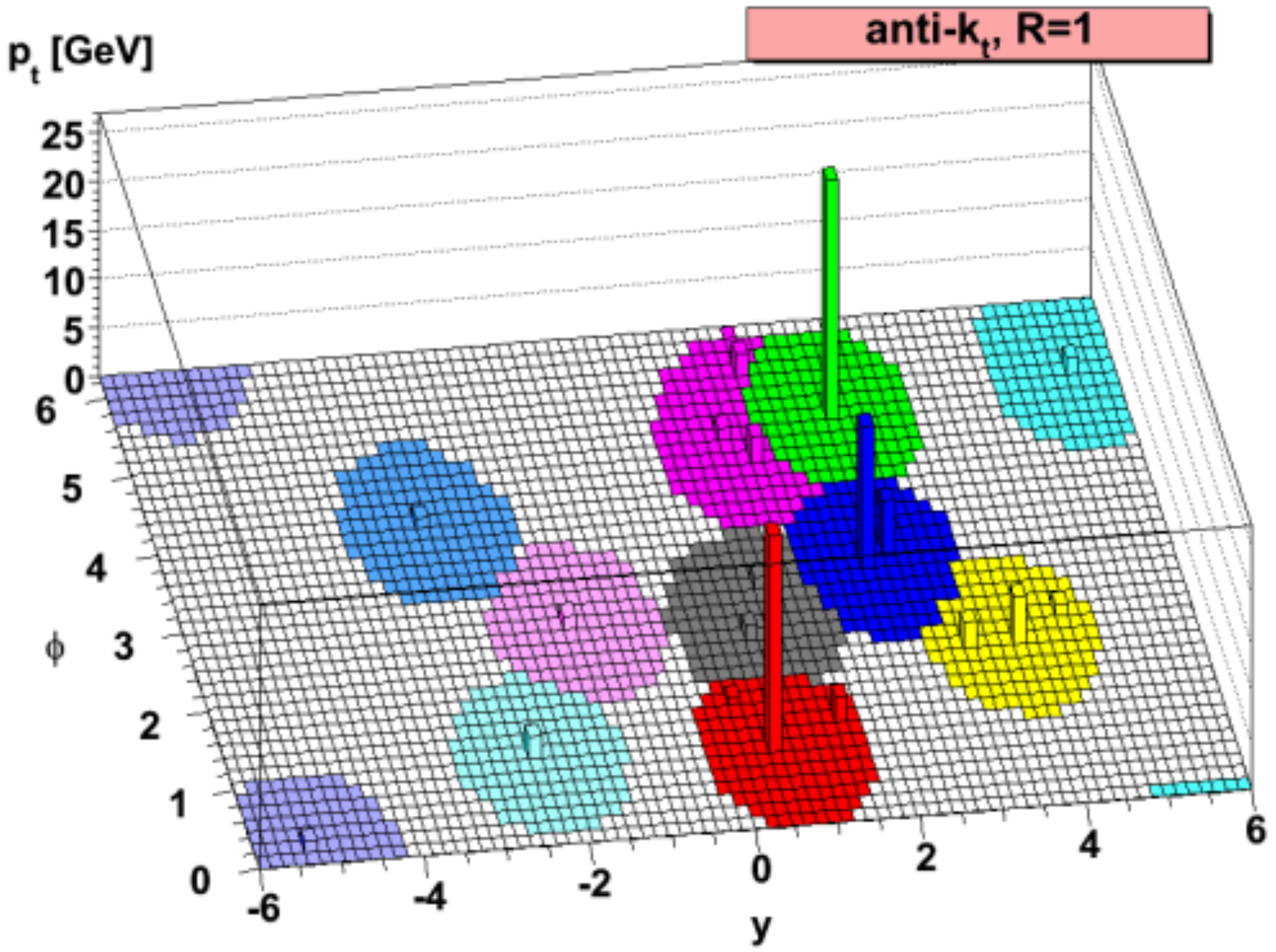
F. A. Dreyer, G. P. Salam, and G. Soyez, The Lund jet plane, J. High Energy Phys. 12 (2018) 064

Jet Clustering Algorithms

Anti-k_T

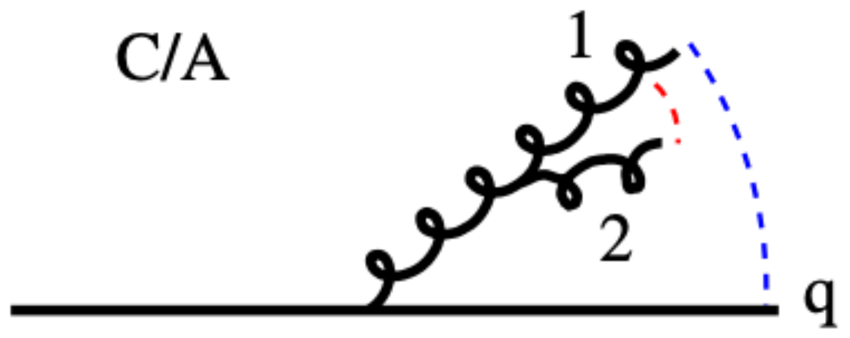
- Infrared and Collinear safe
- Conical jets
- Standard jet clustering algorithm

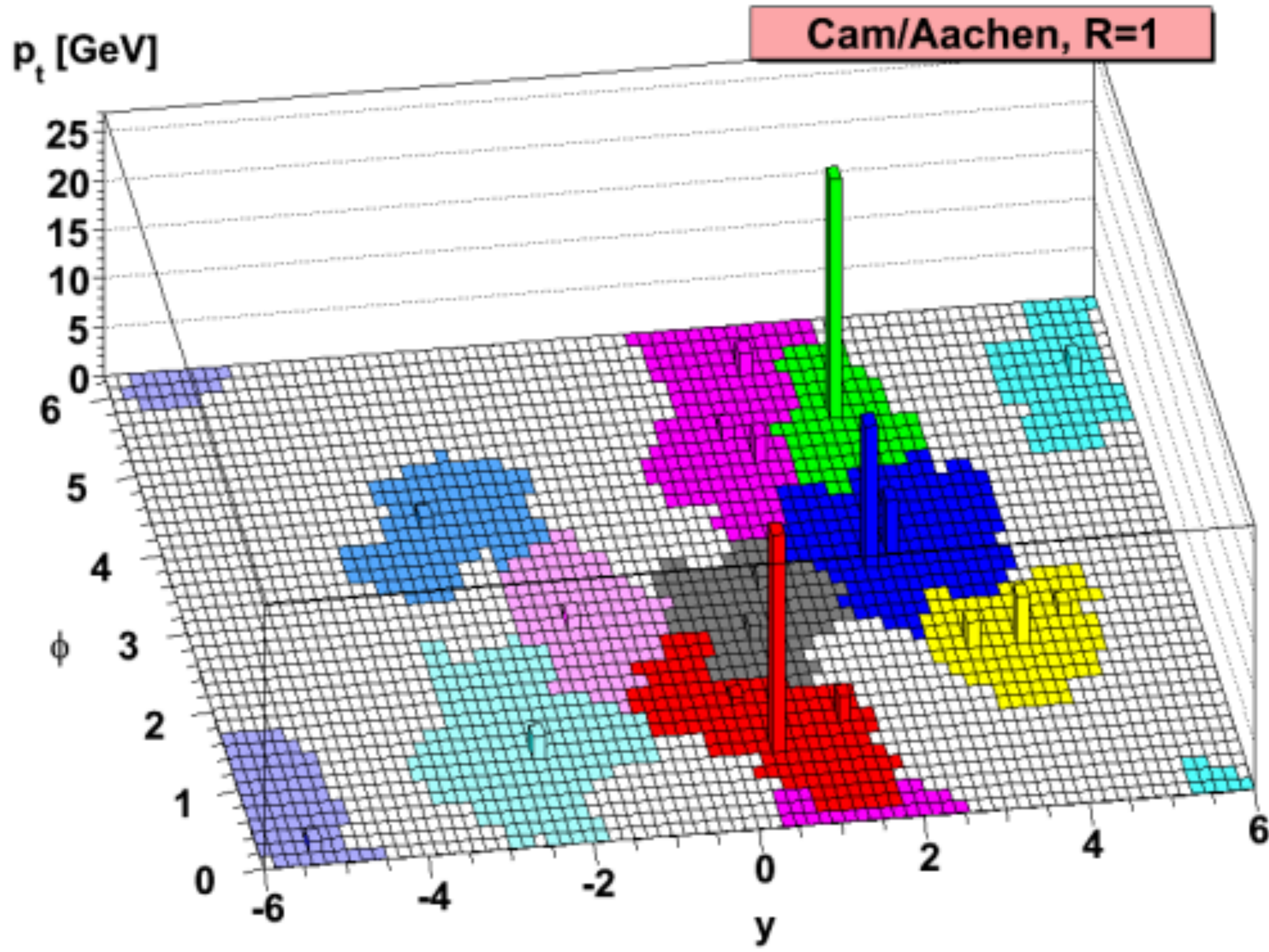




Cambridge/Aachen

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





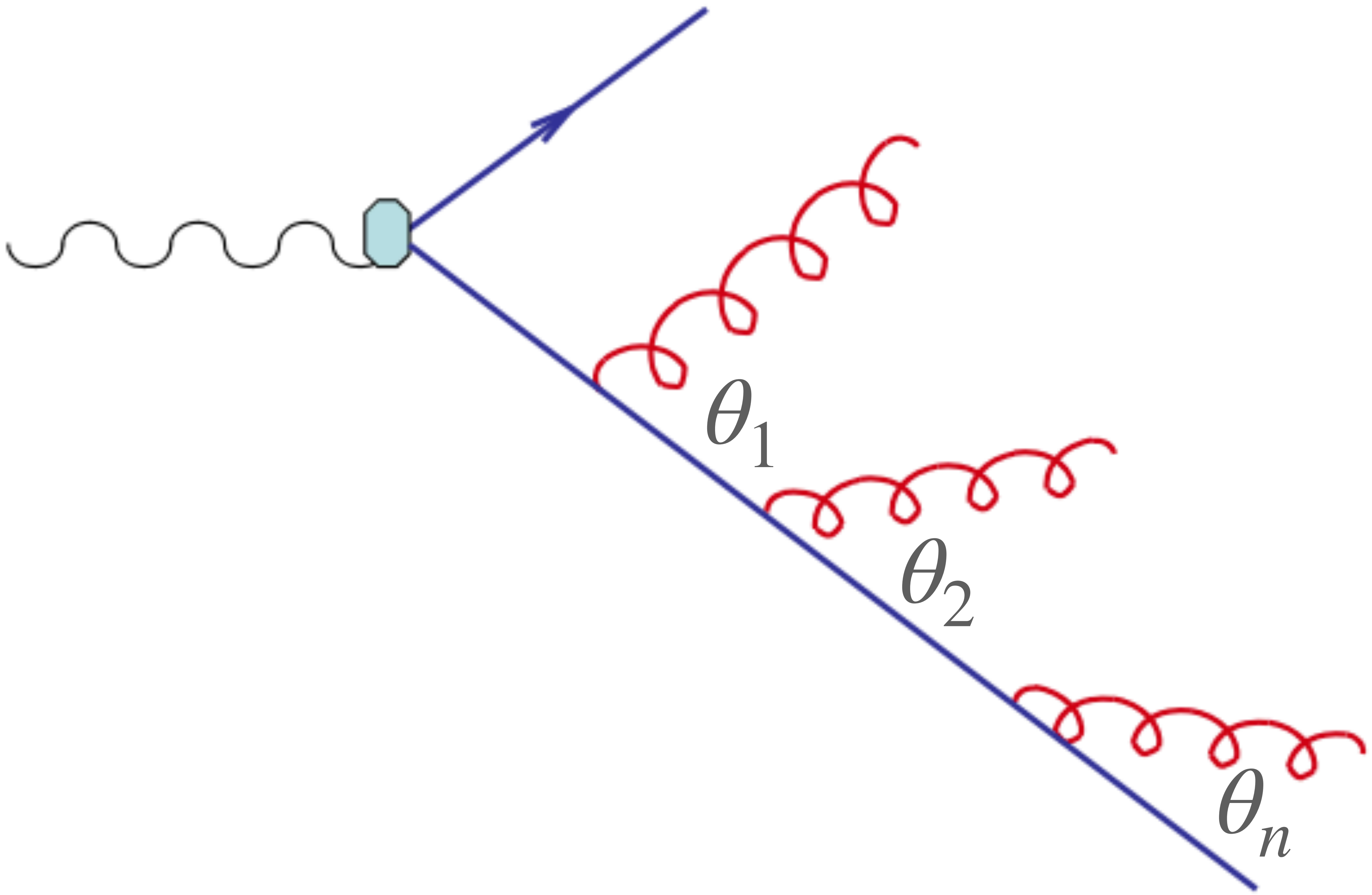
Angular Ordering

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!

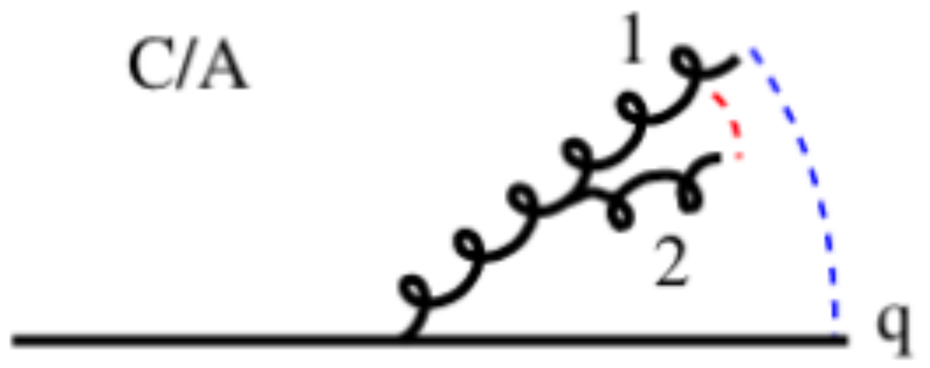


C/A gives us access to the splitting history of the jet

Image: Mangano-Lect3

Iterative Declustering

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

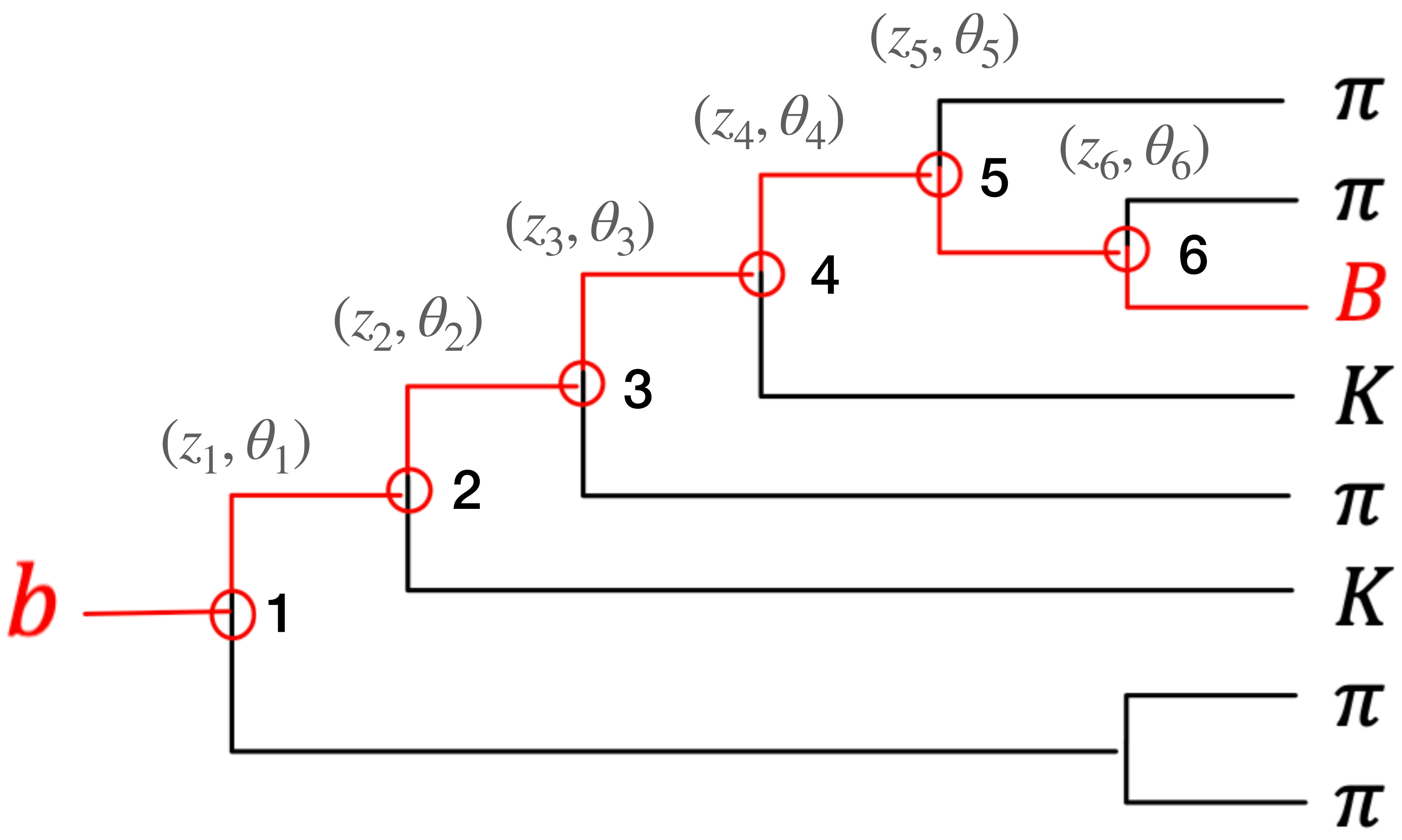
$\pi\ \pi\ B\ K\ \pi\ K\ \pi\ \pi$

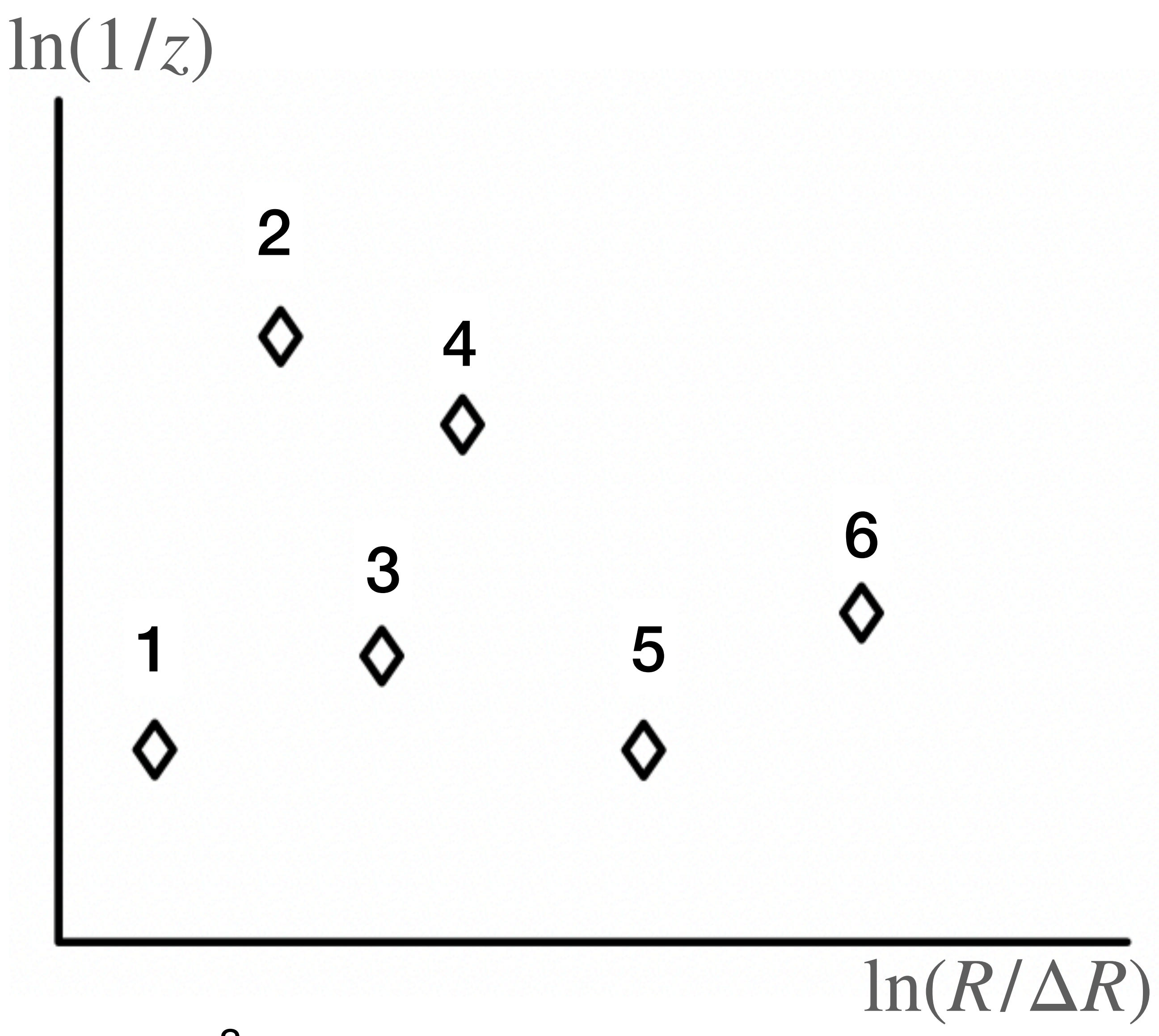
- Infrared and collinear safe
- Conical

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: $k_T, z, \Delta R, \theta, E_{rad}$



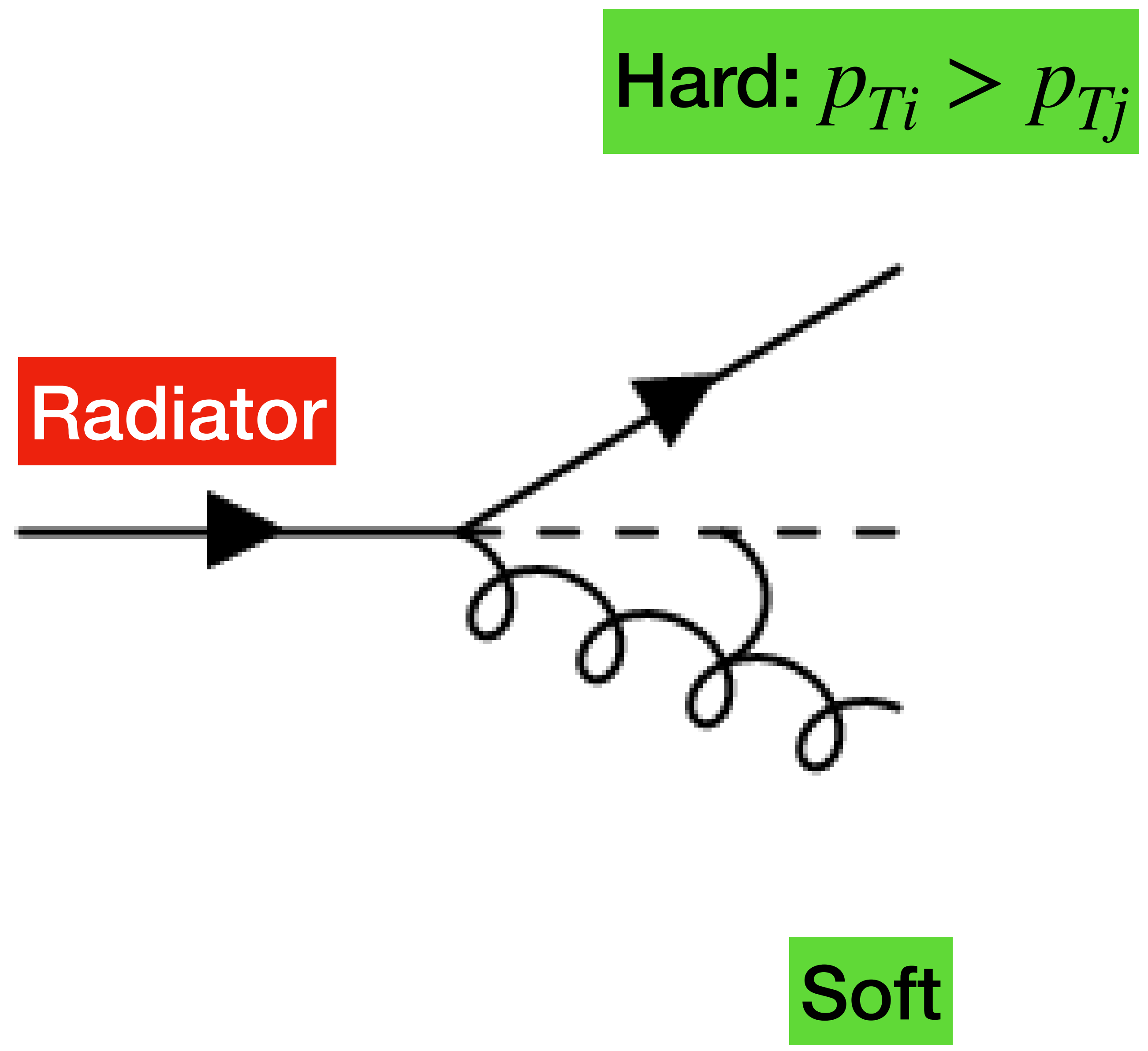


Eur. Phys. J. C 72 (2012) 1896

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

Splitting Variables

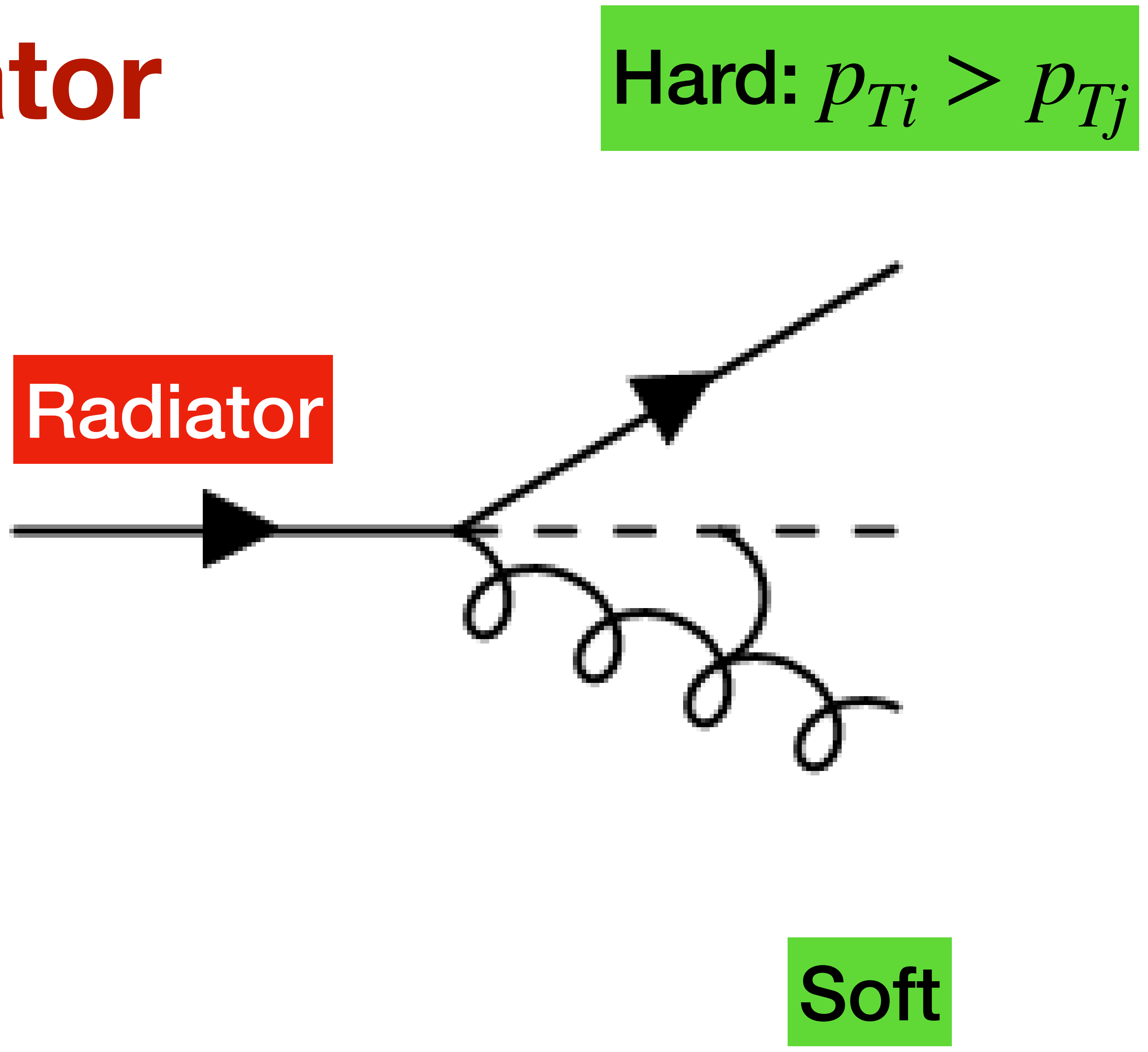
- We adopt the following definitions for the Lund jet plane variables:
    - θ_{ij} : the angle between the soft daughter and radiator
    - E_{rad} : the energy of the radiator
    - $\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ - angular distance
    - $k_T = p_T^{soft} \sin(\Delta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

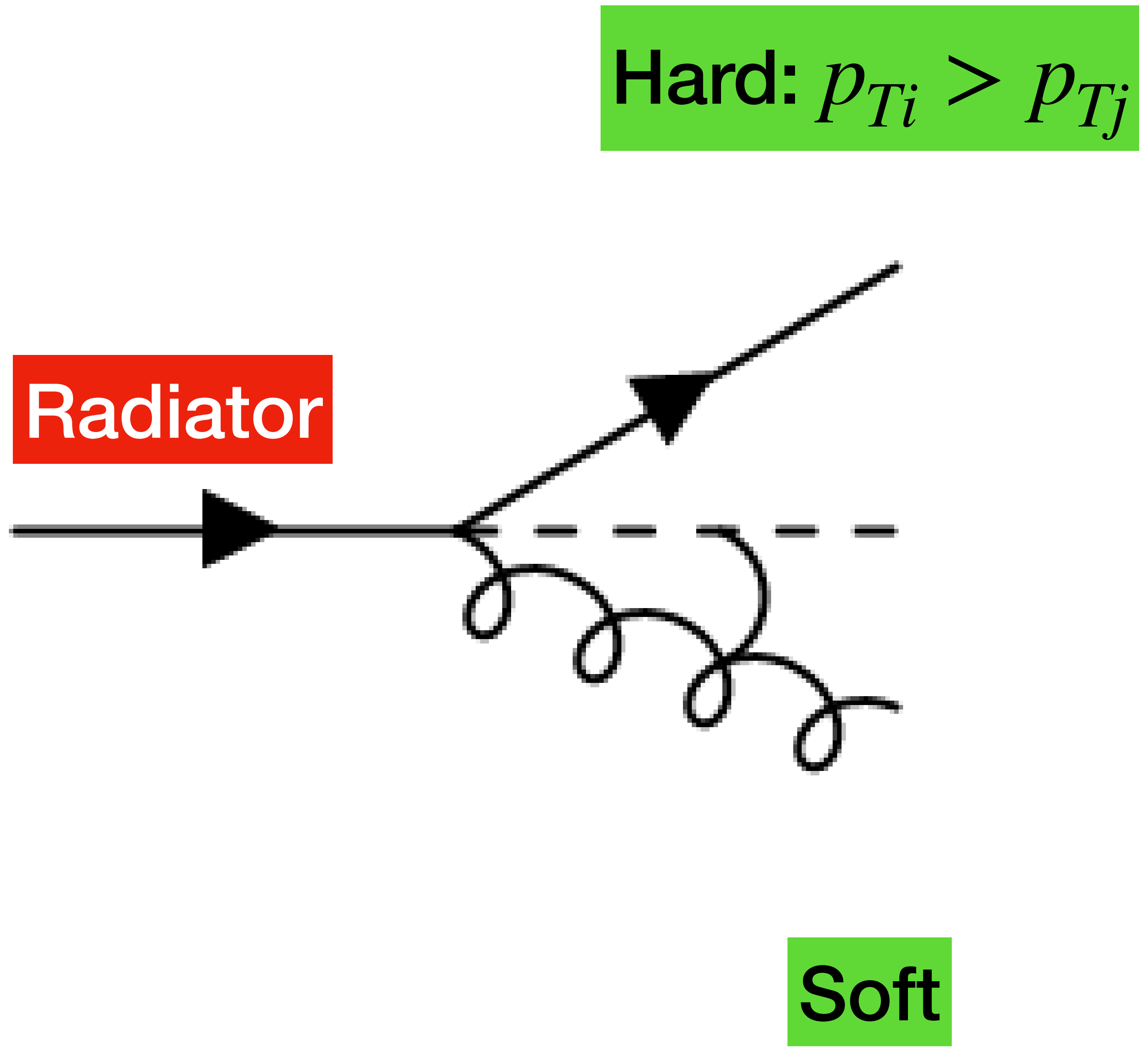
Splitting Variables

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

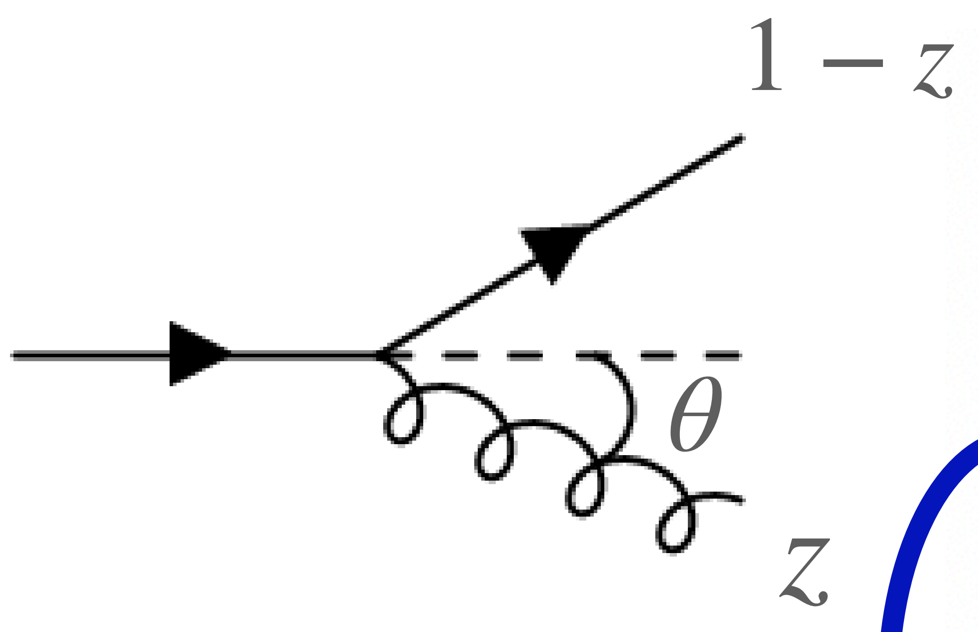
$$\rho(\Delta R, z) = \frac{1}{N_{emissions}} \frac{d^2 n}{d\ln(R/\Delta R)\, d\ln(1/z)}$$

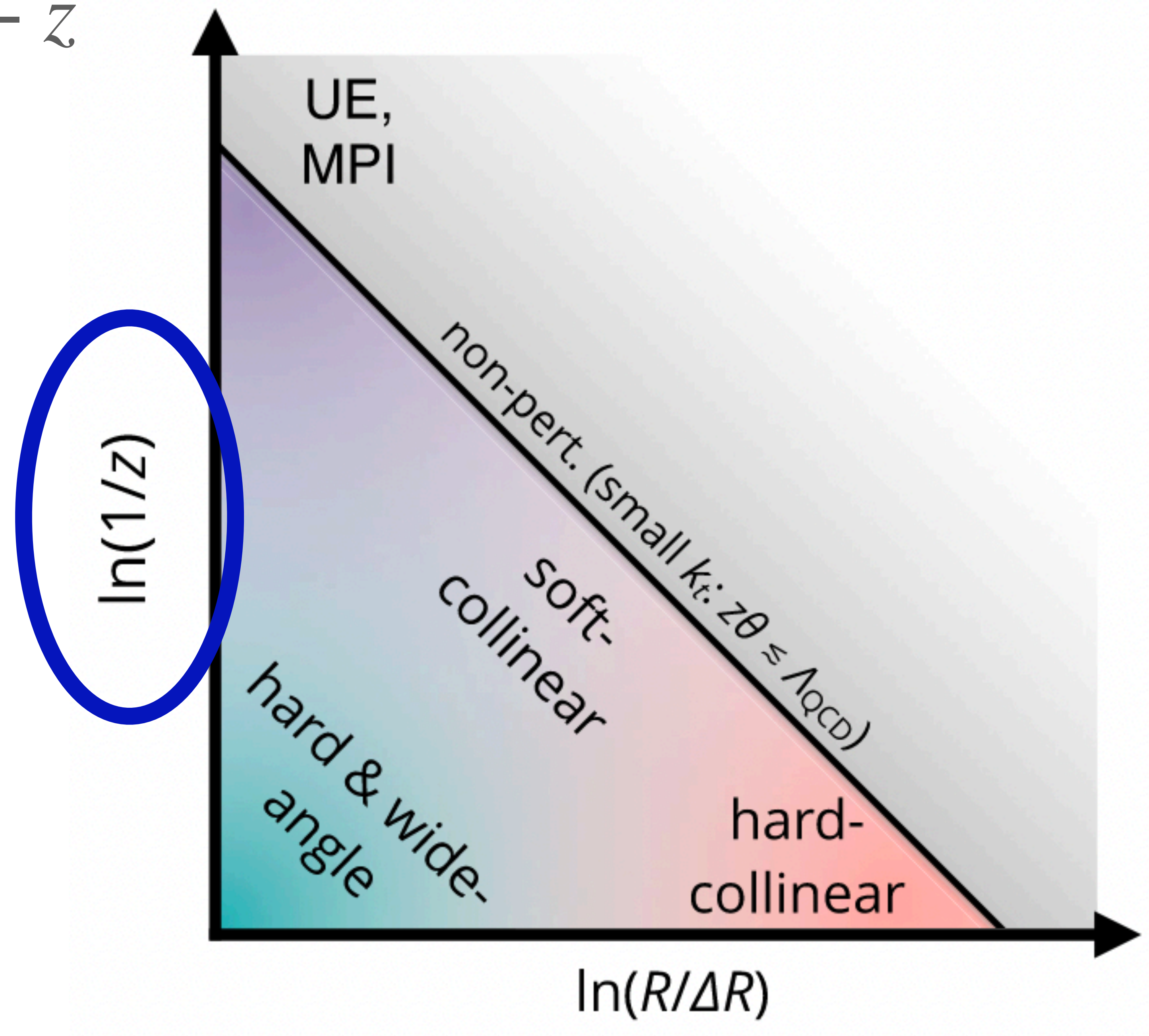
- Focusing on these variables:
  - $\Delta R = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$
  - $k_T = p_T^{soft} \sin(\Delta R)$
  - $z = \dfrac{p_T^{soft}}{p_T^{hard} + p_T^{soft}}$

Lund jet plane



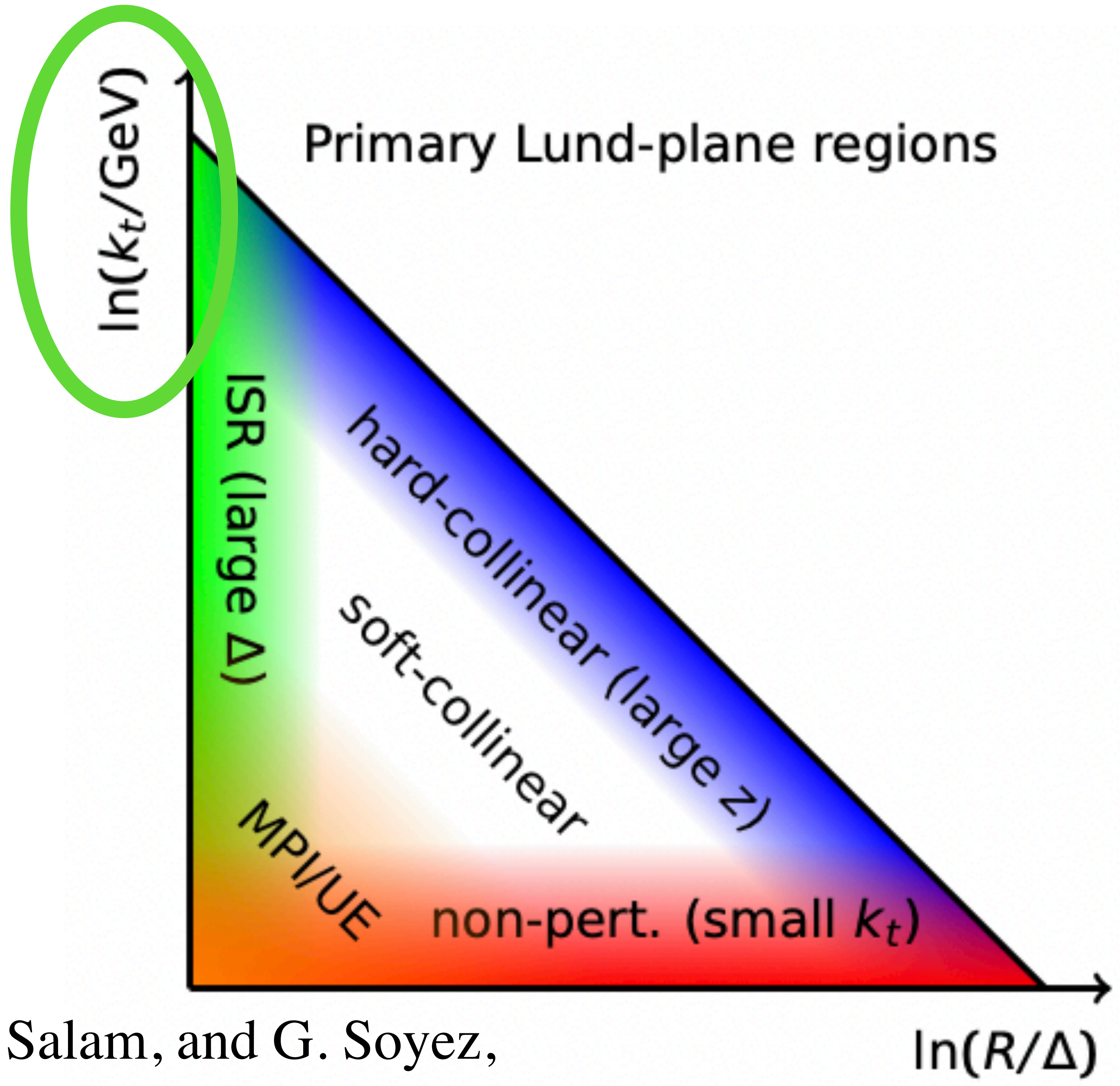
The Lund jet plane





- 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

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



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

Studying the Lund jet plane gives us access to many interesting phenomena in QCD such as the parton shower, hadronization, the dead cone effect, and jet flavor discrimination all in one!

Previous measurements of the Lund plane

ATLAS, ALICE, and CMS

arXiv:2111.00020v1

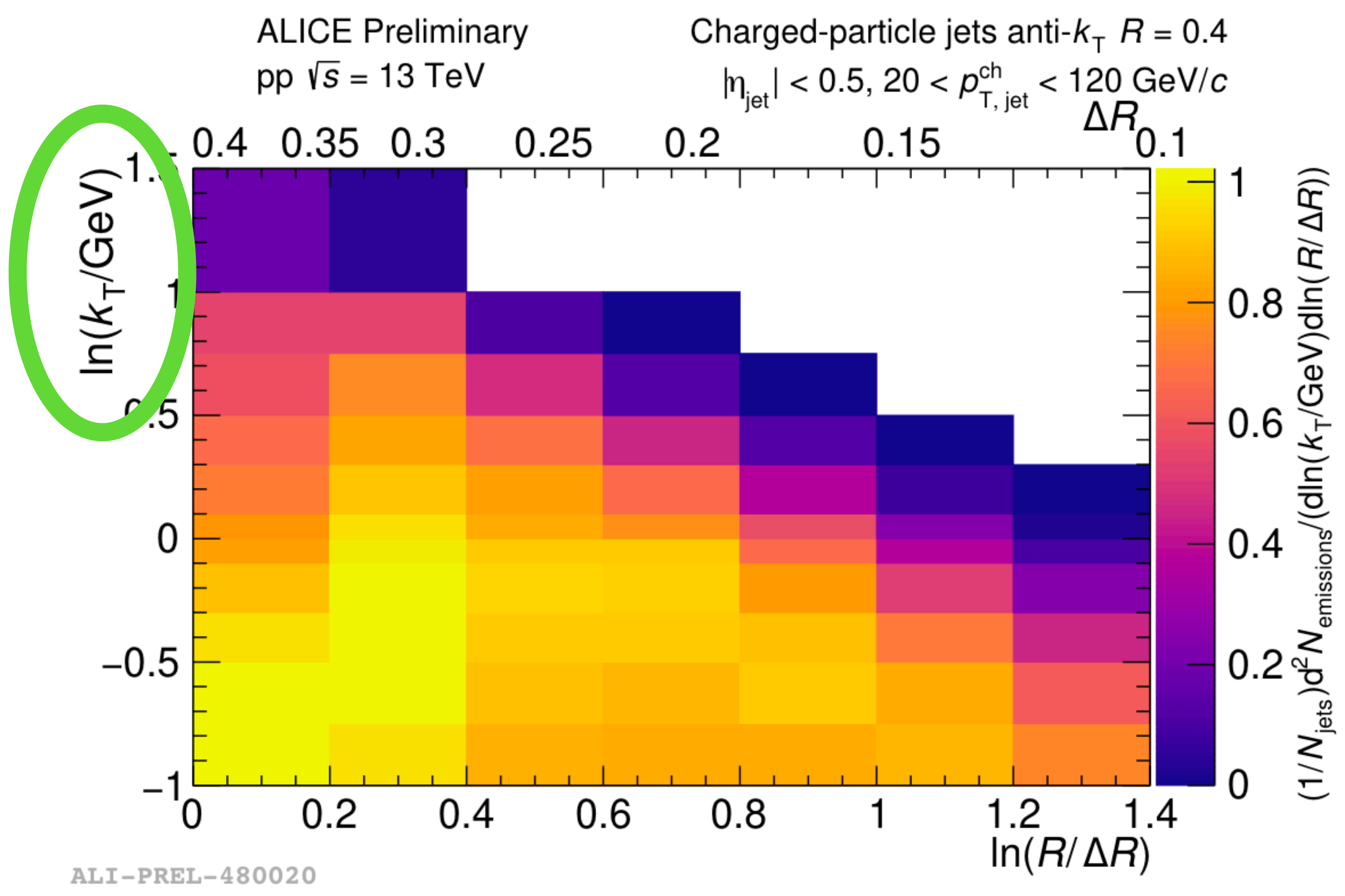
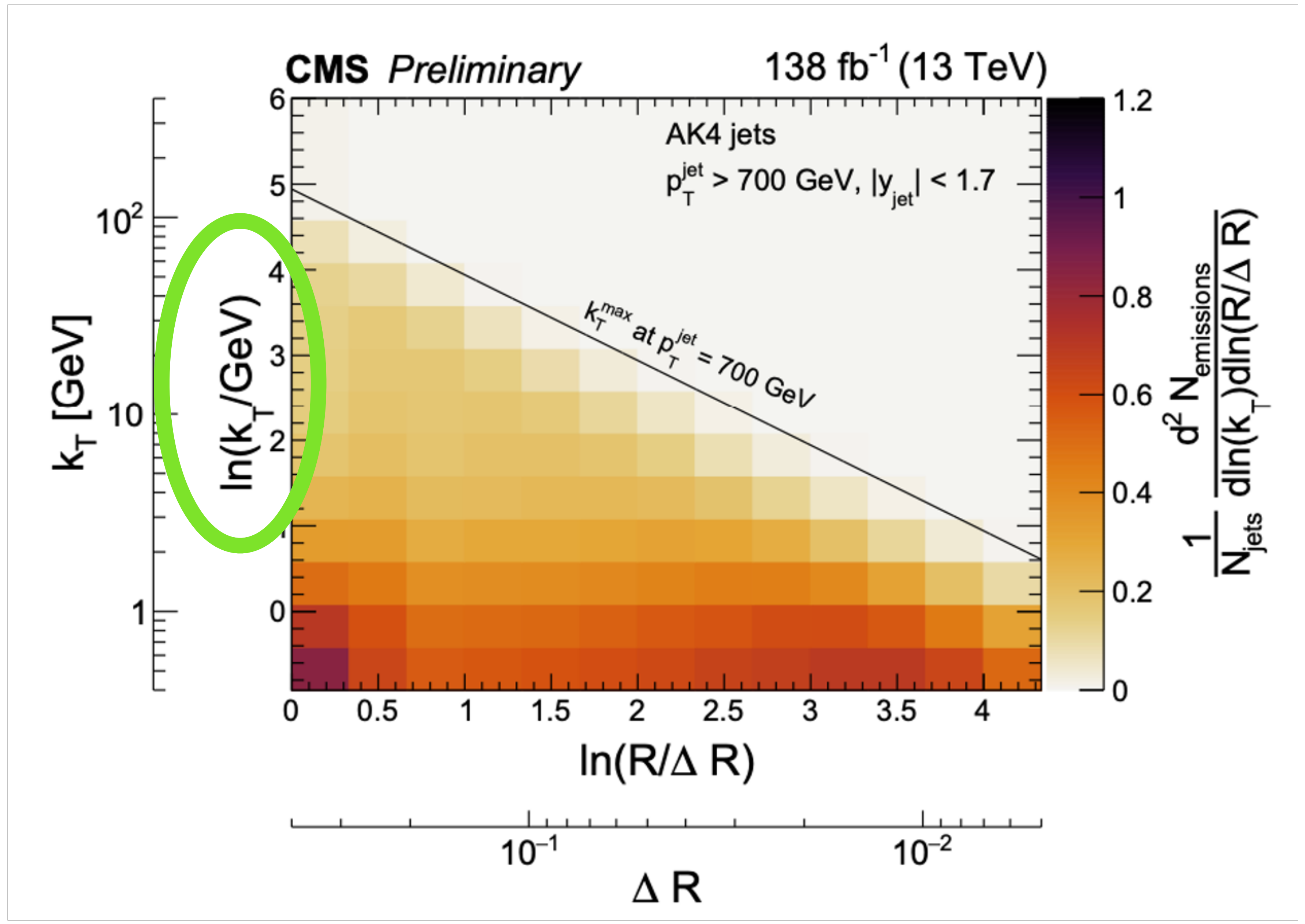


Figure 3: Fully corrected primary Lund plane density.

CMS PAS SMP-22-007



PRL 124.22 (2020): 222002

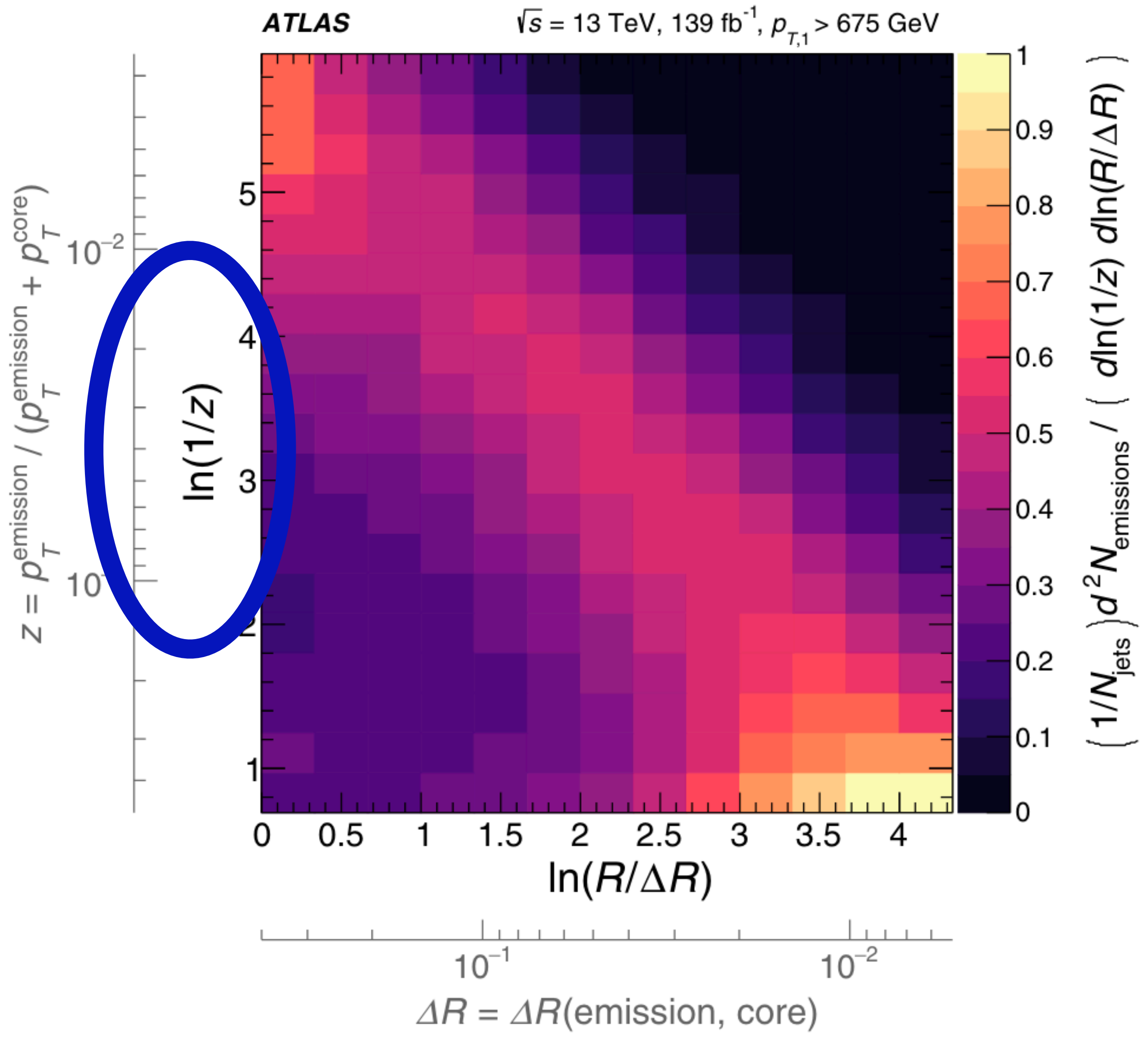


FIG. 2. The LJP measured using jets in 13 TeV pp collision data, corrected to particle level. The inner set of axes indicates the coordinates of the LJP itself, while the outer set indicates corresponding values of z and ΔR.

Flavor-inclusive Lund jet planes

Dead cone measurement by ALICE

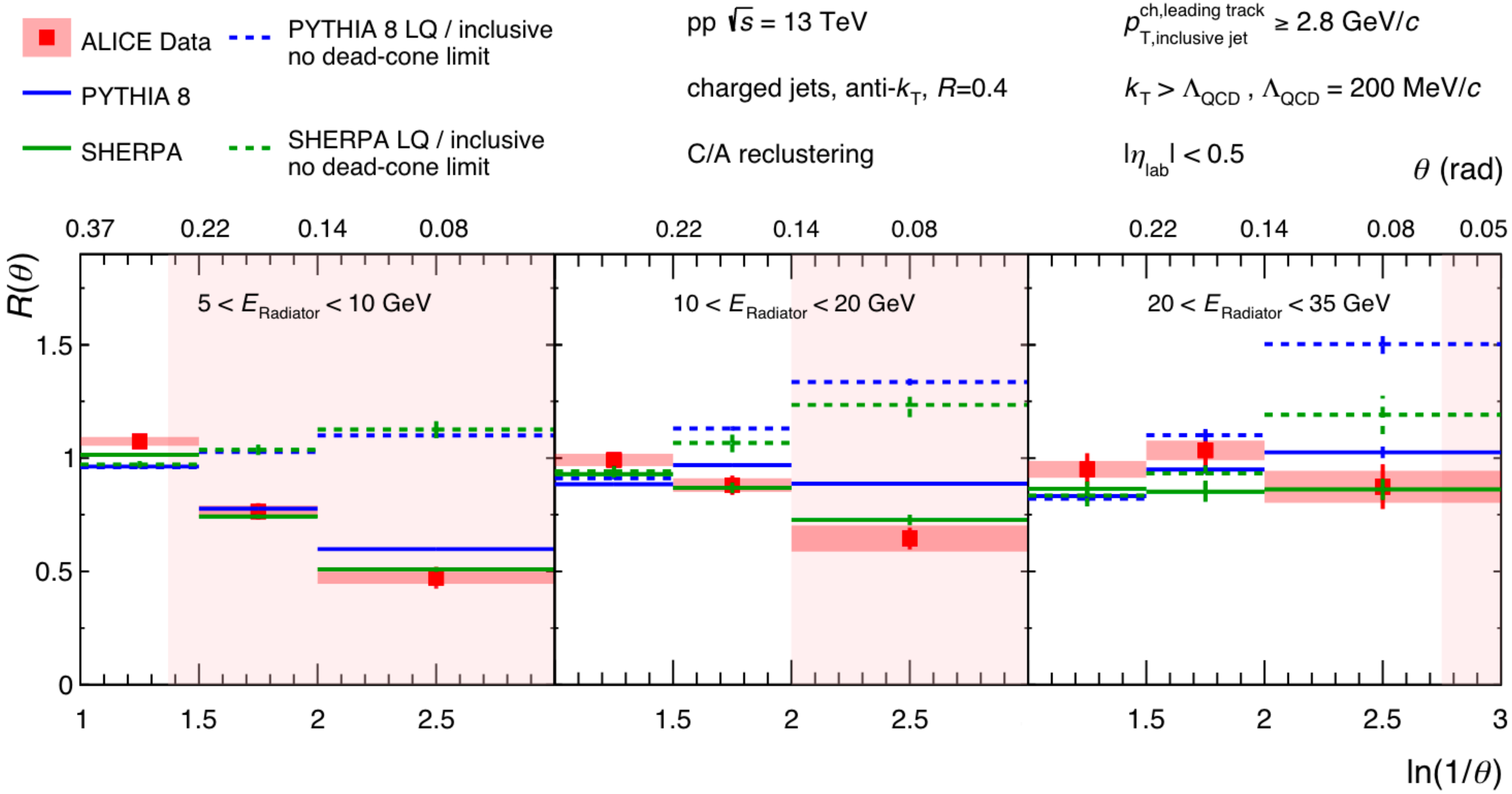
Ratio of charm to inclusive jets

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

ALICE

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

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

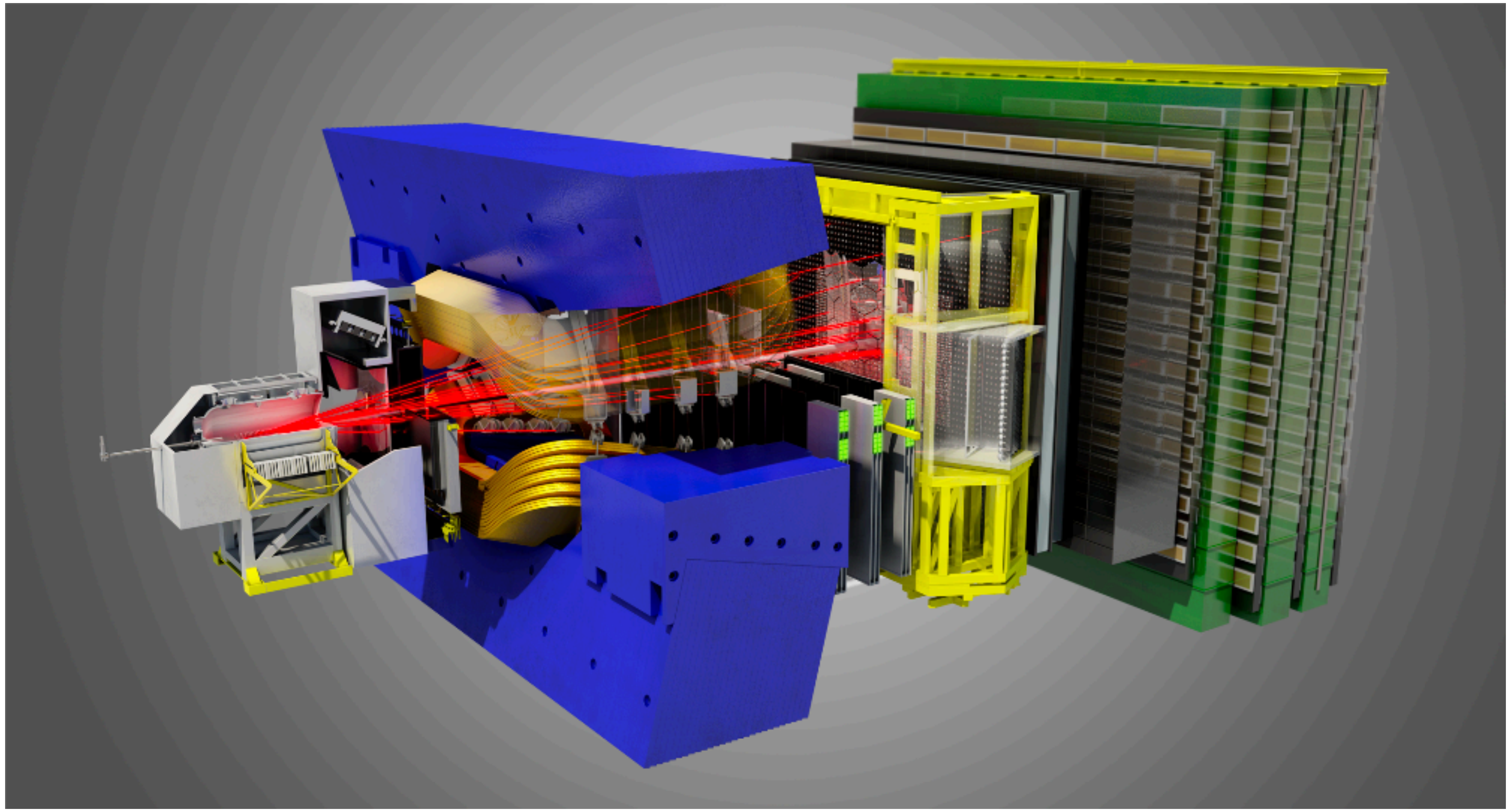


Prospects for the LJP at LHCb

The LHCb Detector

Forward-arm spectrometer

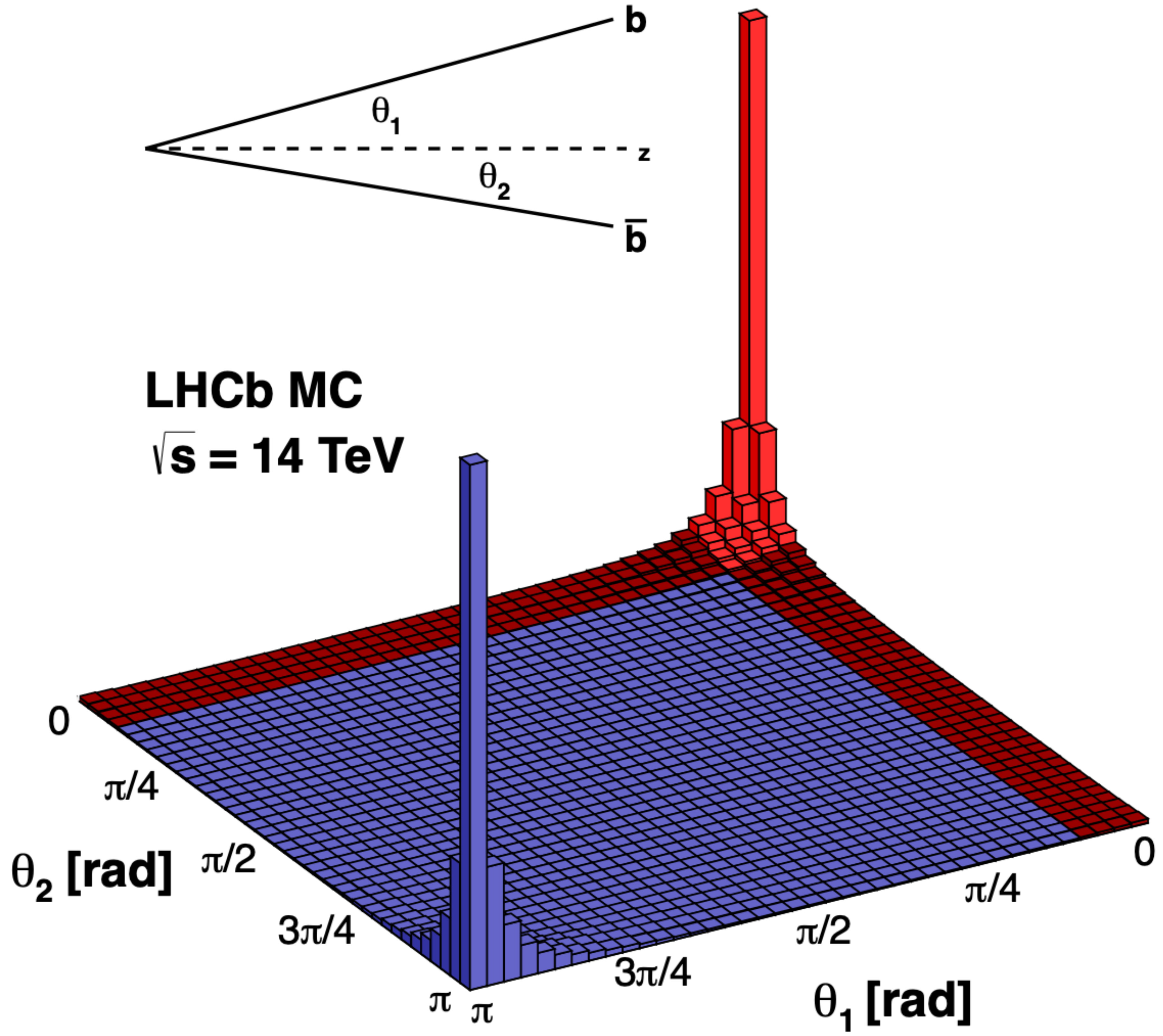
- Forward rapidities: $2 < \eta < 5$
- Excellent vertex resolution
- Tracking and particle identification
- Hadronic and electromagnetic calorimetry
- Muon system

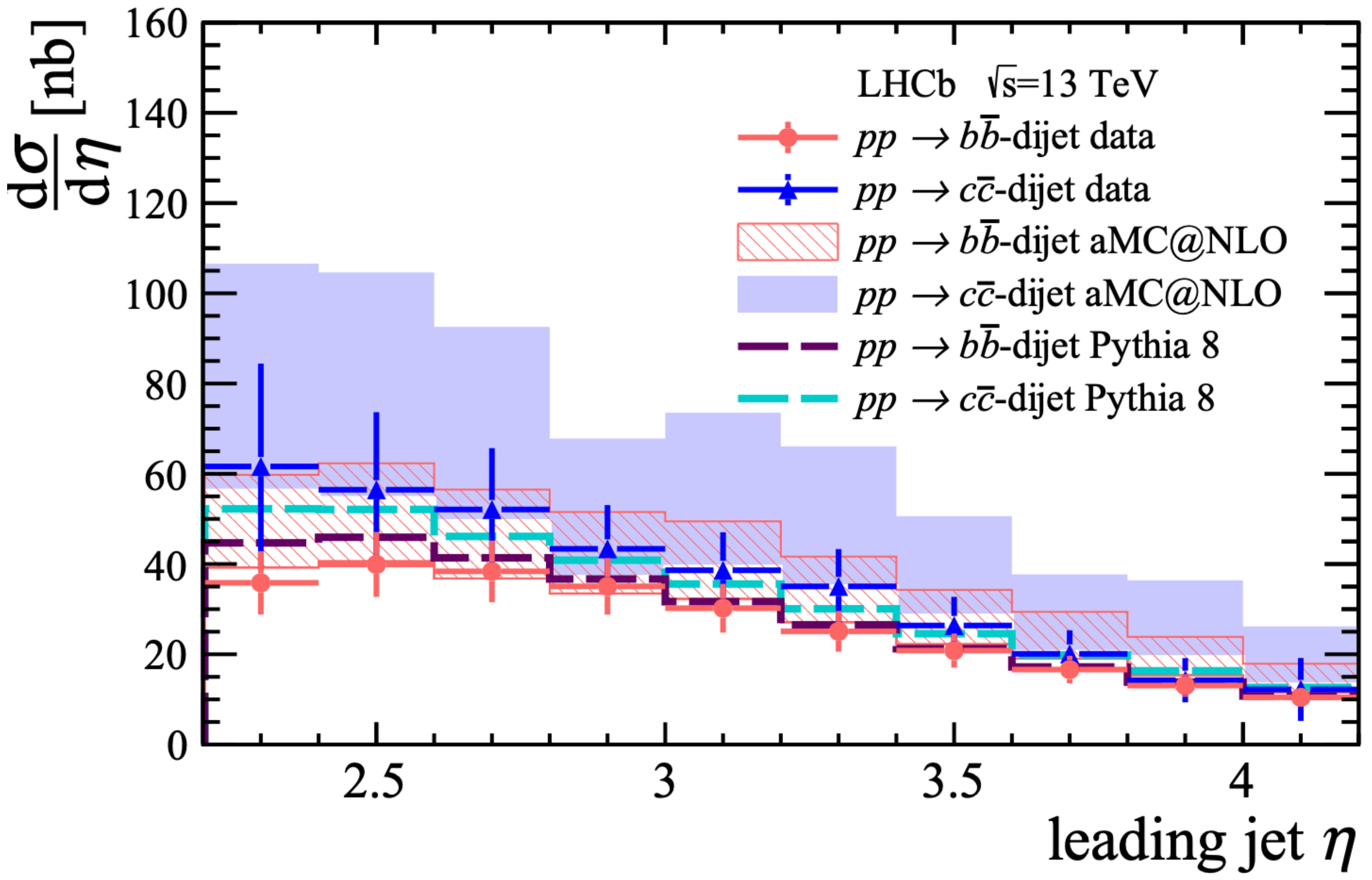


Large Heavy Flavor Cross-sections

JHEP 2021.2 (2021): 1-37

Lots of HF jets!

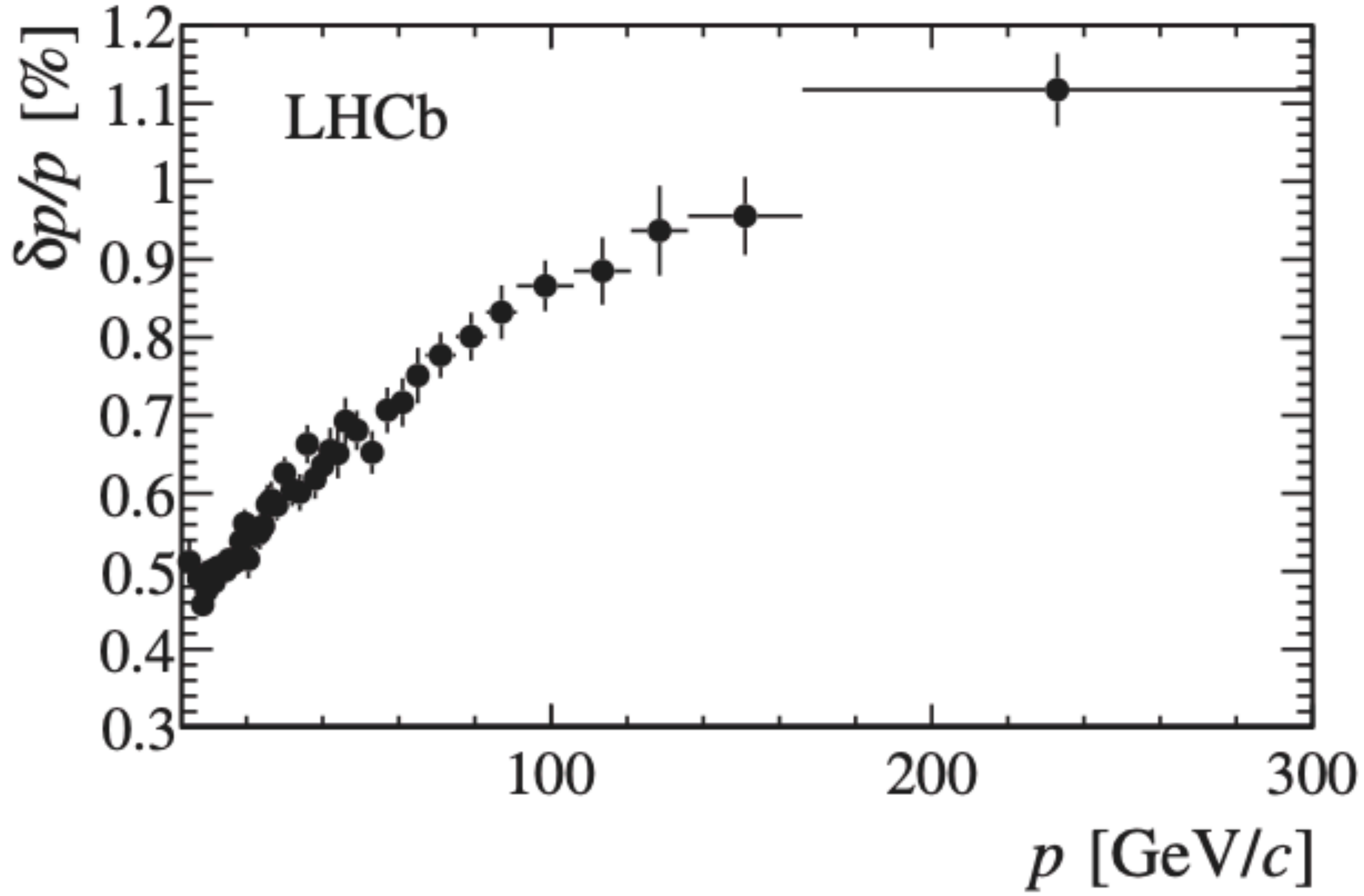




- HF dijet cross-section is large at forward rapidities!
- For an integrated luminosity of 1.6fb^{-1}, millions of heavy flavor jets are created!

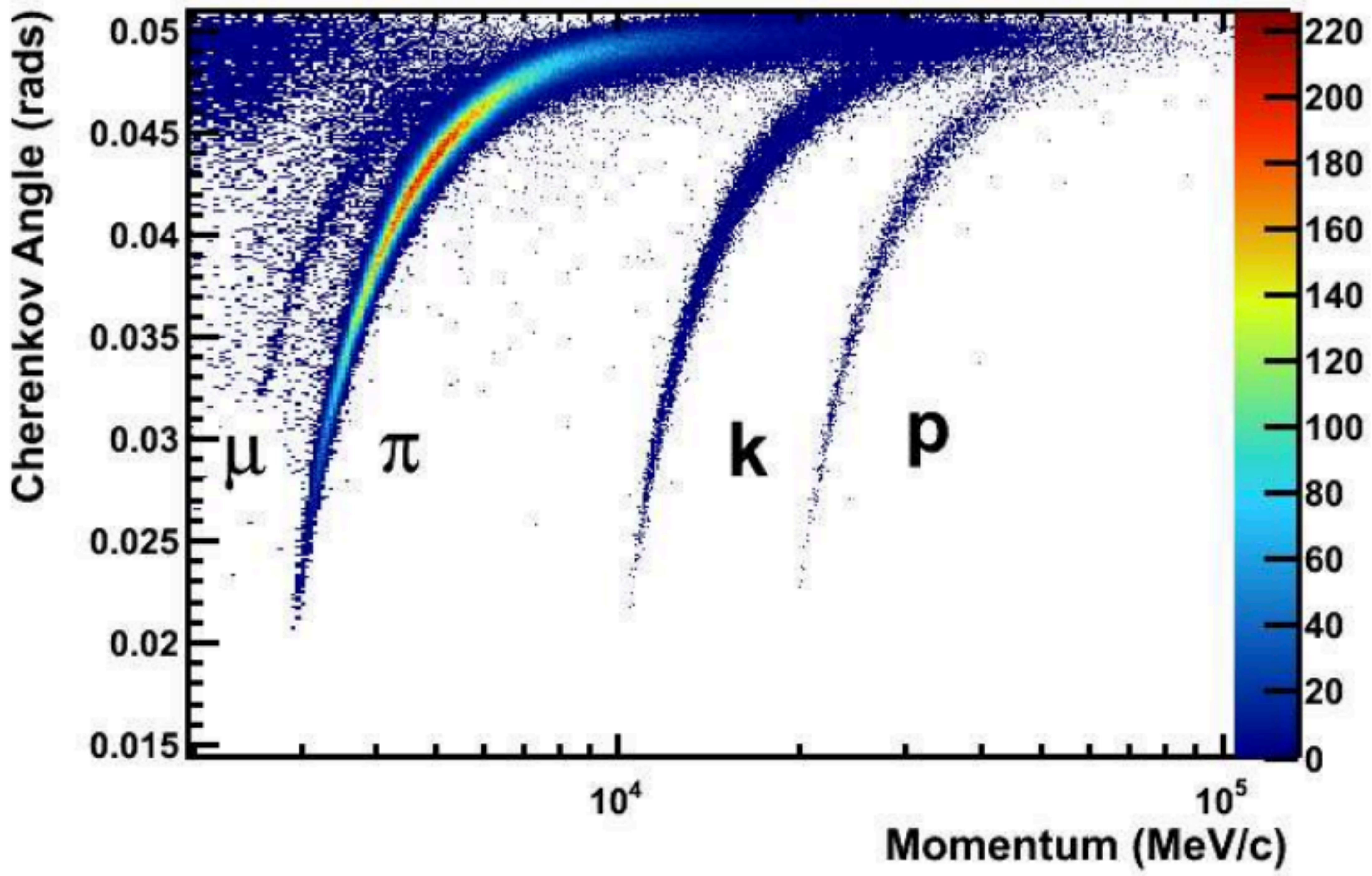
Tracking and PID

Excellent momentum resolution and particle identification



Resolution <1% up to 200 GeV

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

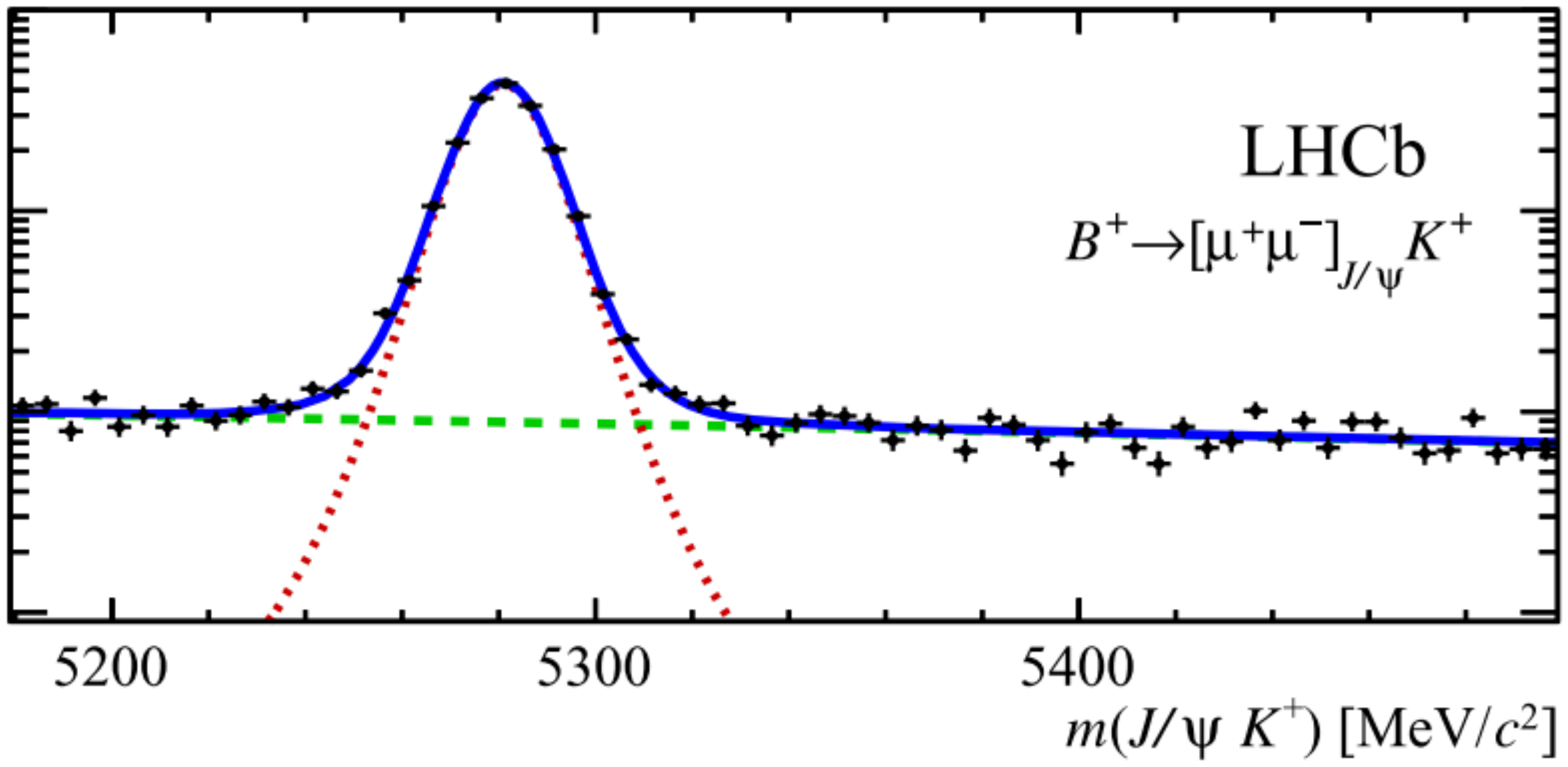


Capability of selecting exclusive decays!

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

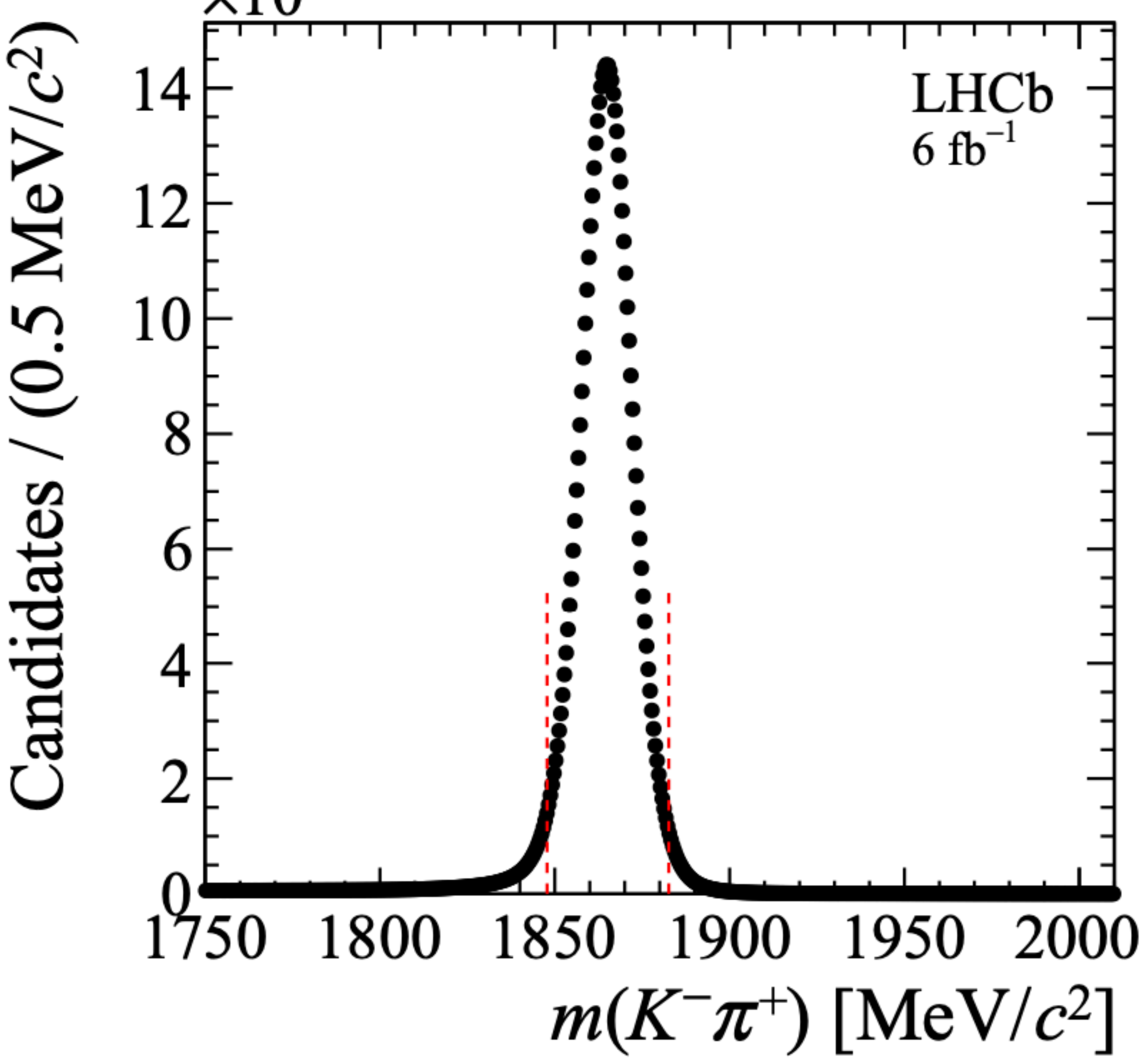
Powerful reconstruction of exclusive decays

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



PRD 95, 052005 (2017)

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



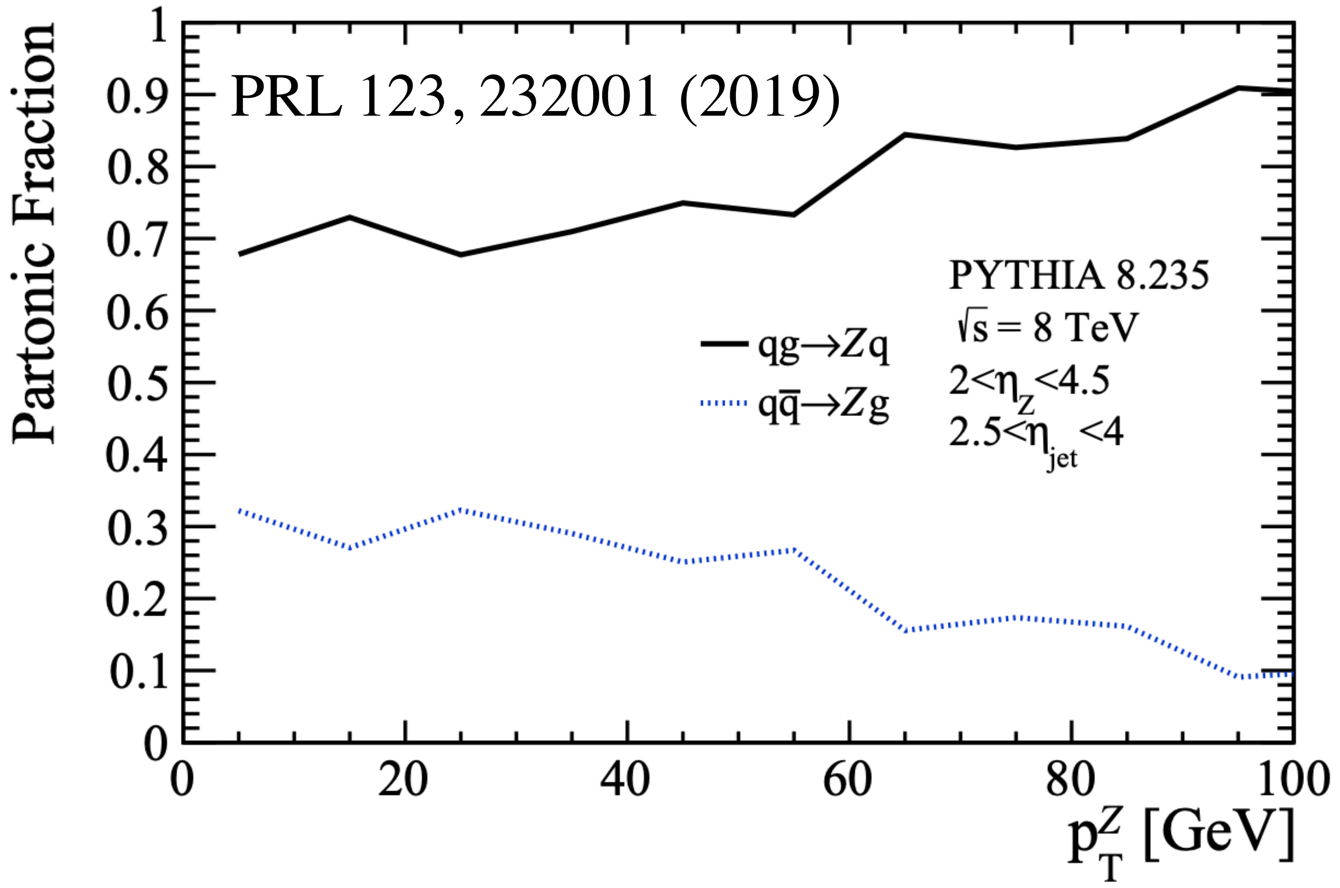
Phys. Rev. D 104 (2021) 072010

Lund plane at LHCb

- We plan on:
  - measuring the LJP for **light**, **charm**, and **beauty** jets,
  - measuring the LJP for **tracks** as well as **tracks + neutrals,**
  - and measuring the **dead-cone** and **leading-particle** effects from the various LJP parametrization.

Planning 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. $pp \to Z(\to \mu\mu) + q(g)$

- For charm-initiated jets, we reconstruct $D^0 \to K^-\pi^+$ candidates and find jets that contain the $D^0/\bar{D}^0$ within the jet radius.

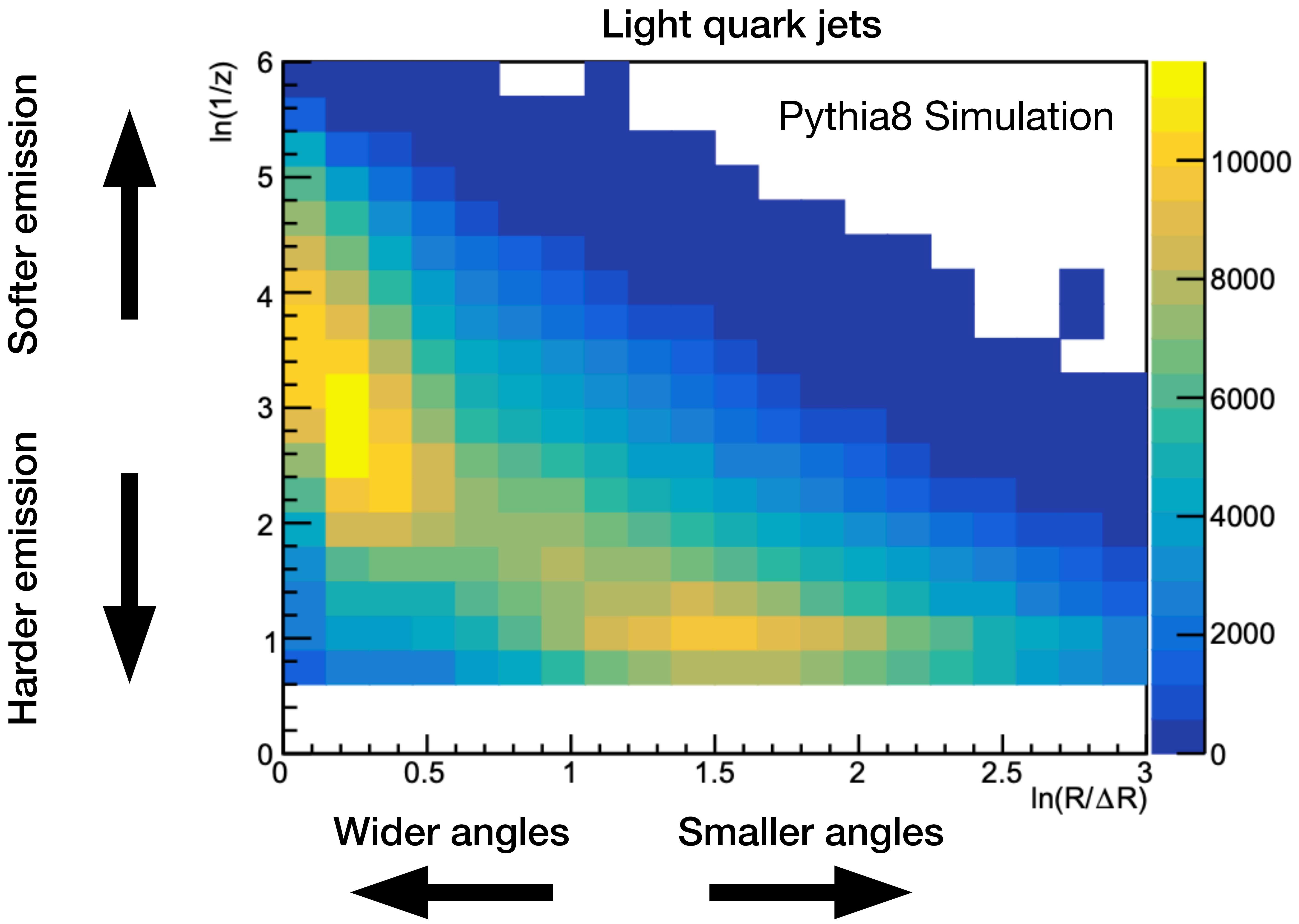
- For beauty-initiated jets, we reconstruct $B^+ \to J/\psi(\to \mu\mu)K^+$ candidates and find jets that contain the $B^{\pm}$ within the jet radius.

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
$R = 0.5$

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



Note: Pythia8 simulations were produced privately and NOT by LHCb

Various Emission Regions

Pythia8 Simulations/ATLAS result

Pythia8 settings:
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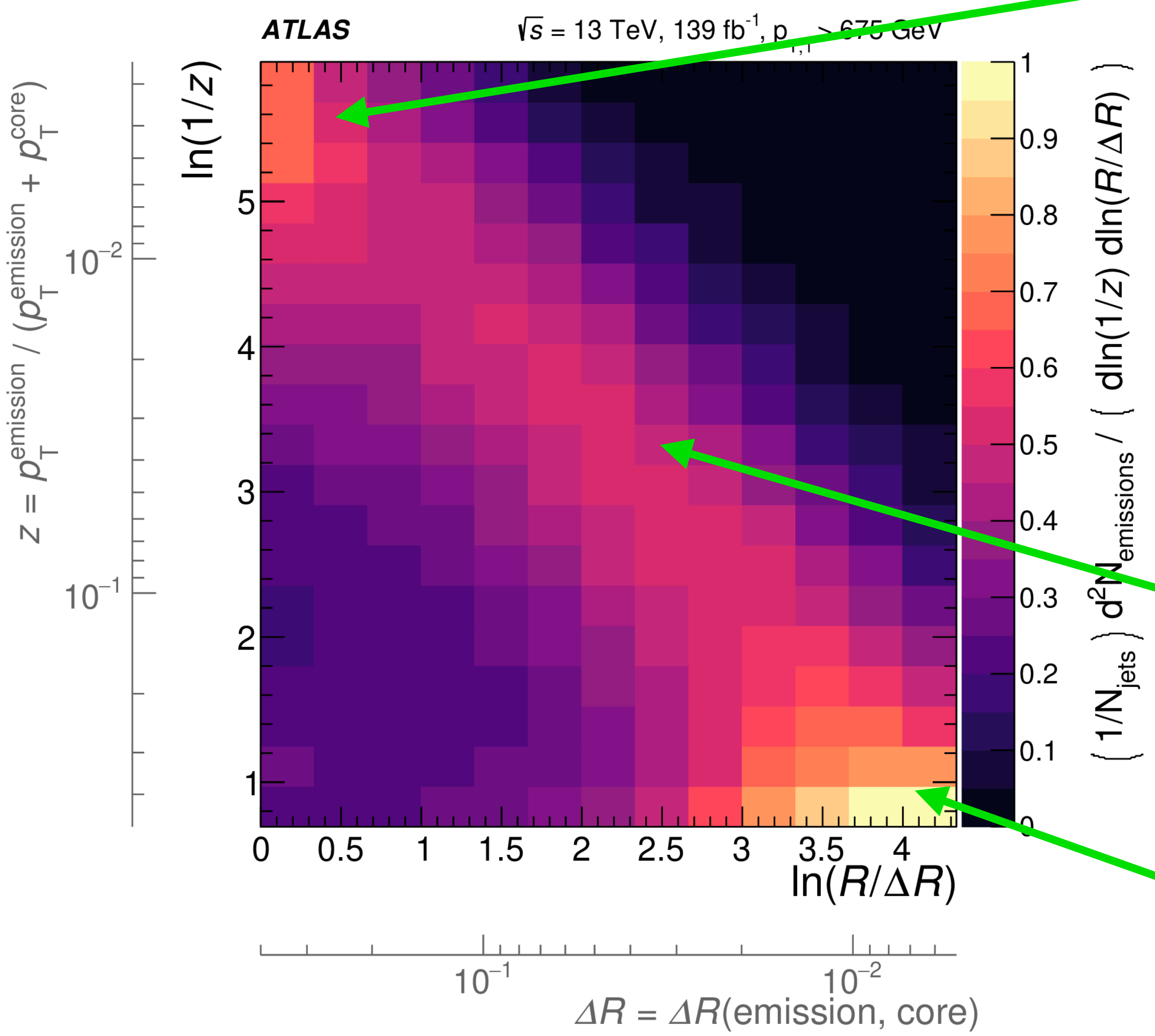
$p_{T,jet} > 20$ GeV
$R = 0.5$

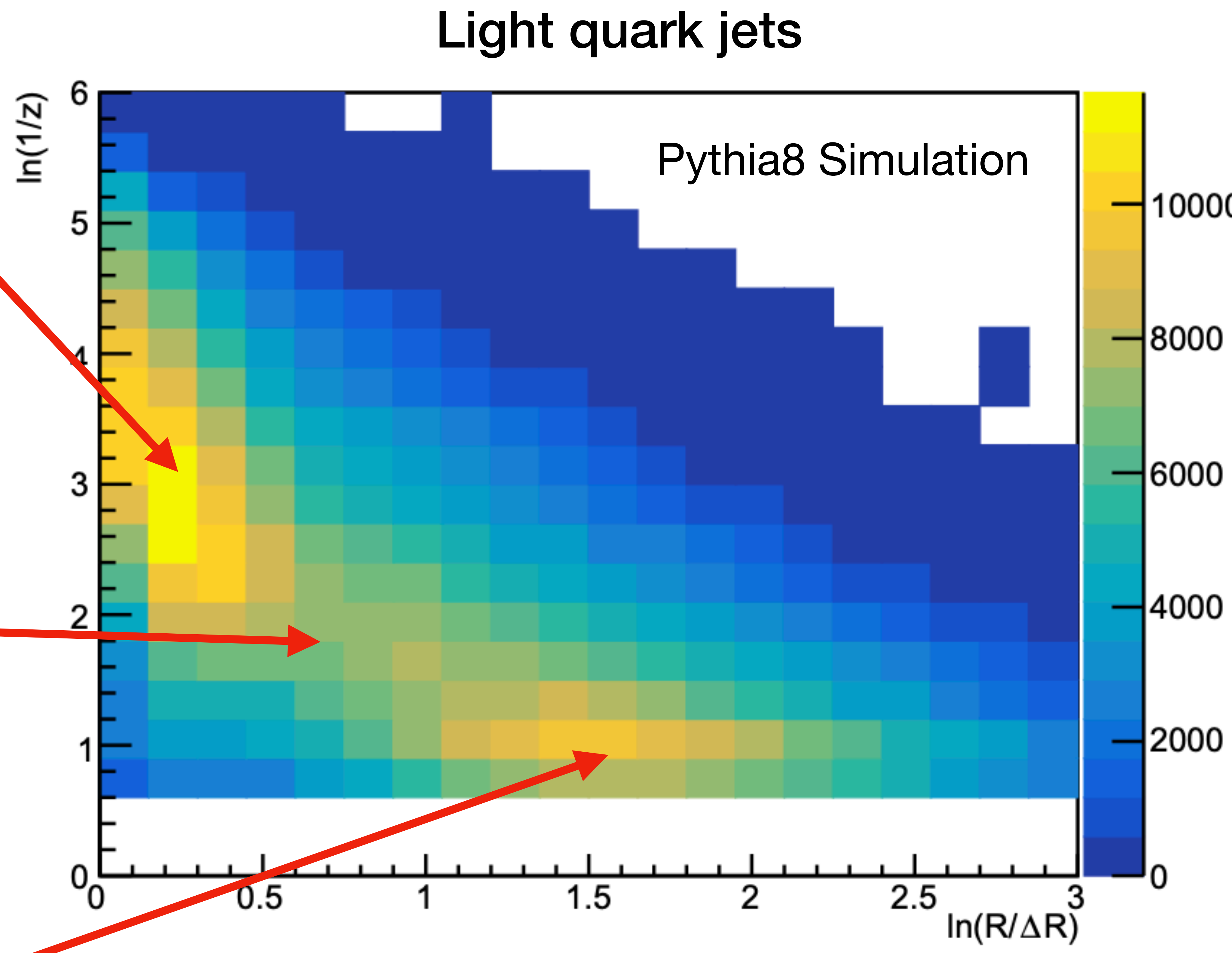
PRL 124.22 (2020): 222002



Soft and wide

Soft and collinear

Hard and collinear



LJP at forward rapidities

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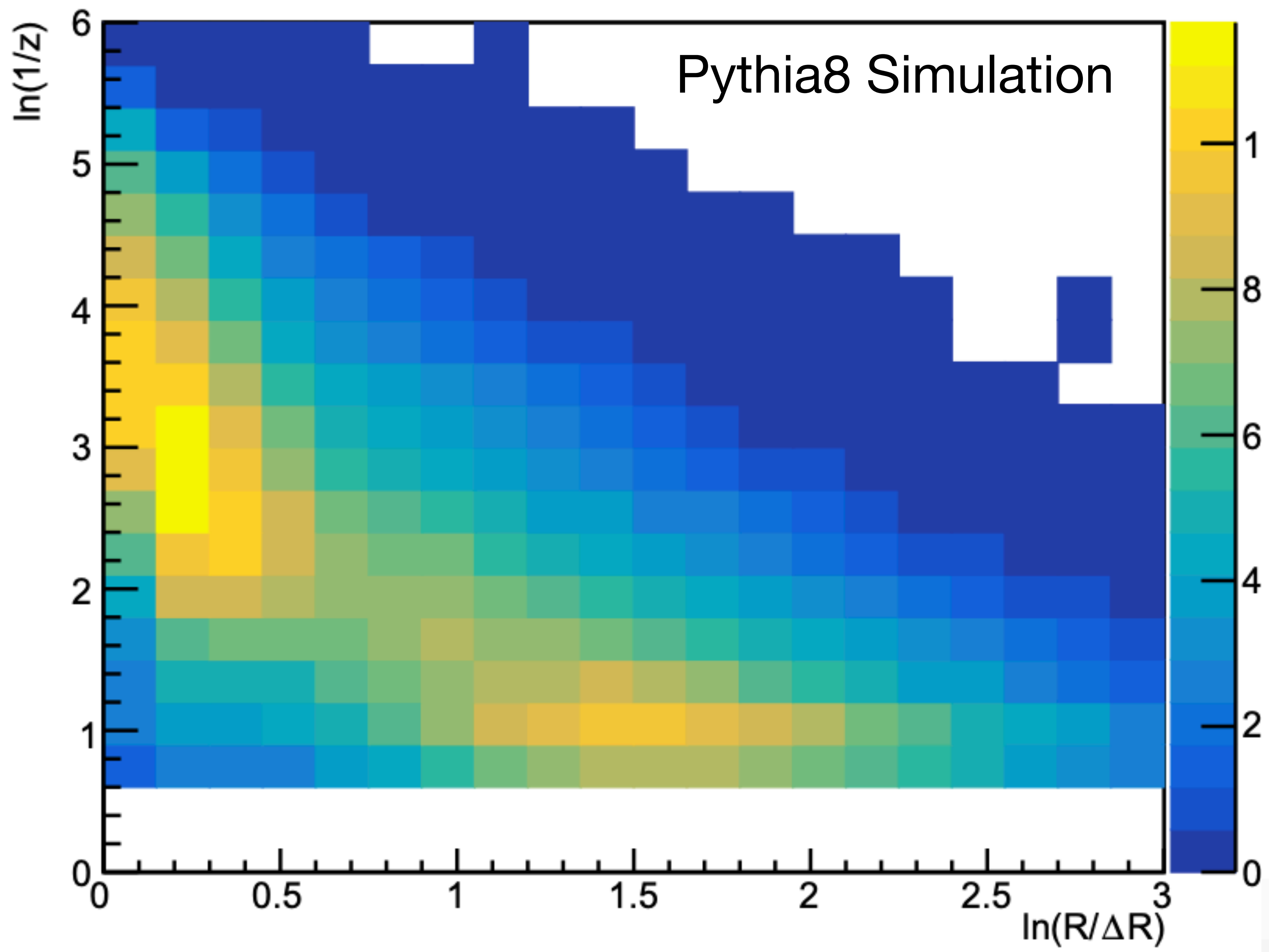
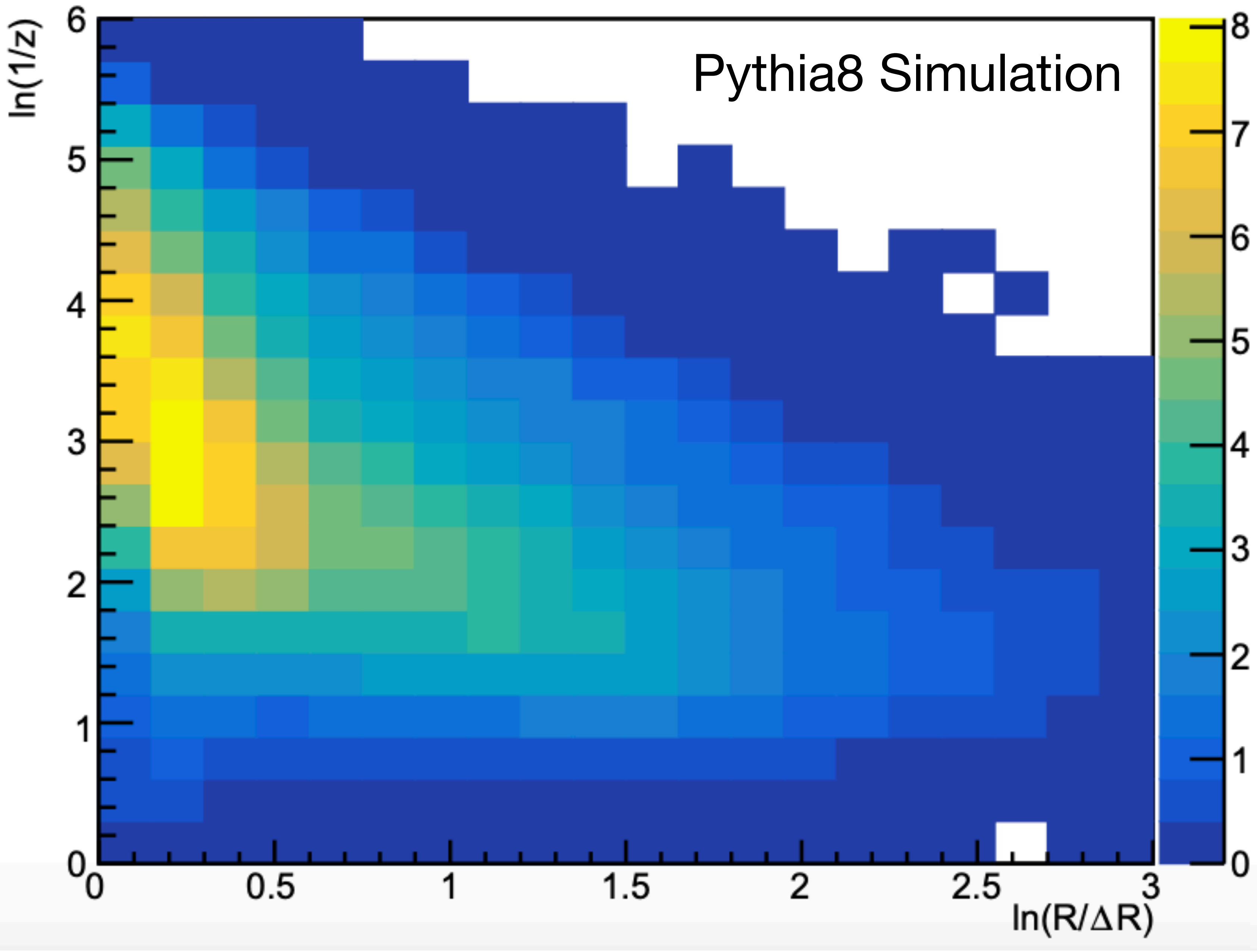
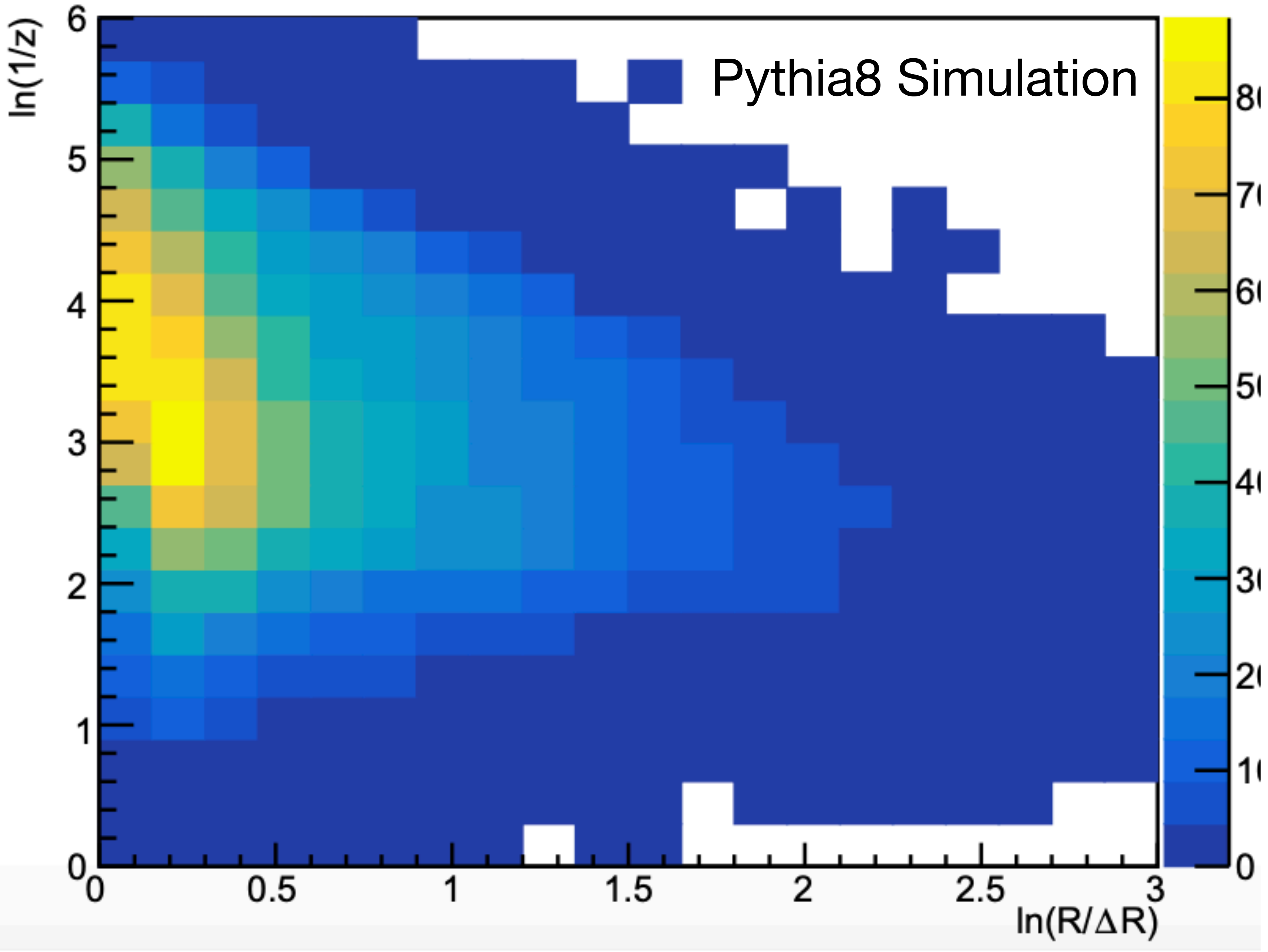
Light quark jets



Charm jets



Beauty jets



LJP at forward rapidities

Pythia8 Dijet Simulations

Pythia8 settings:
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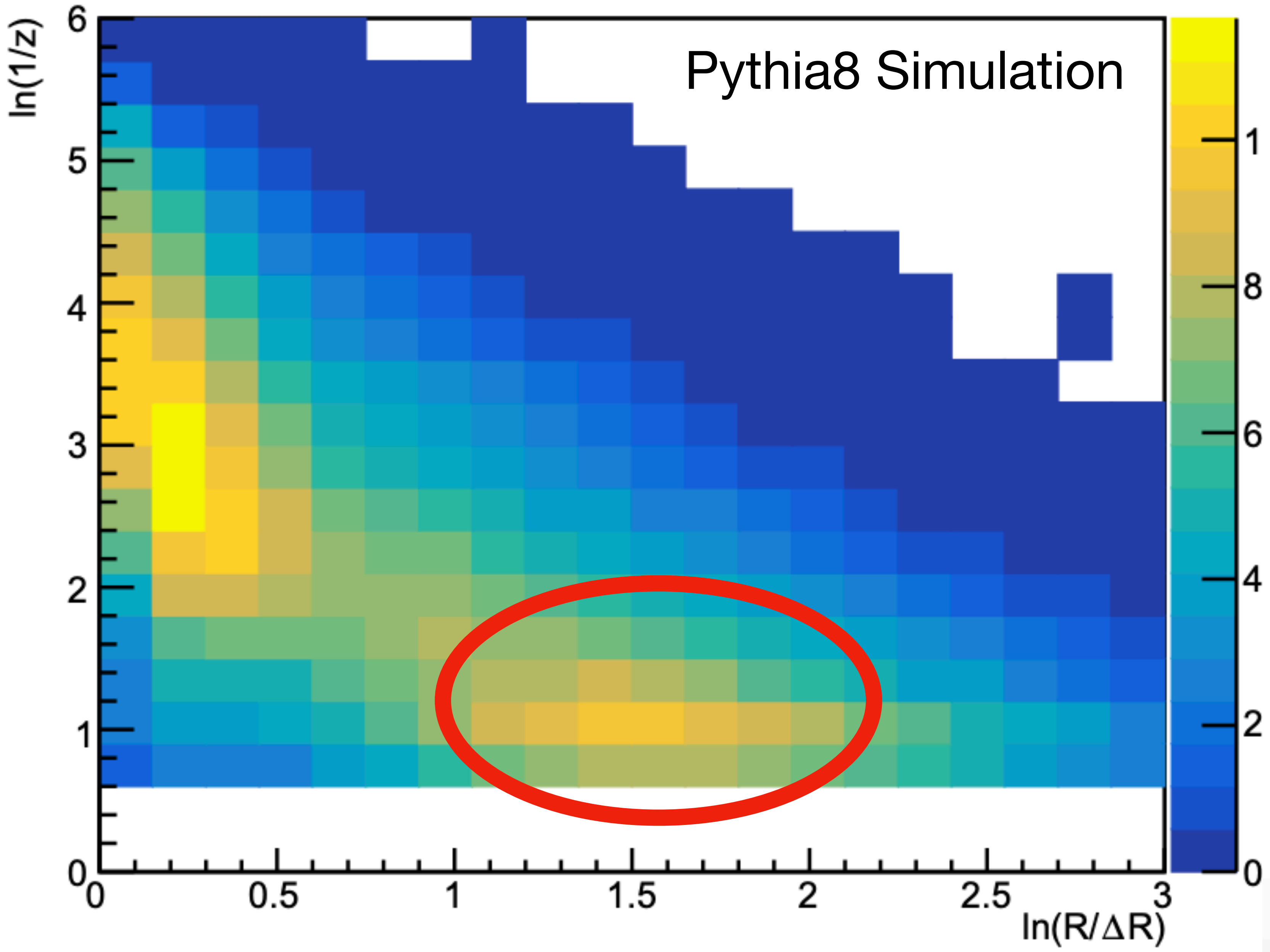
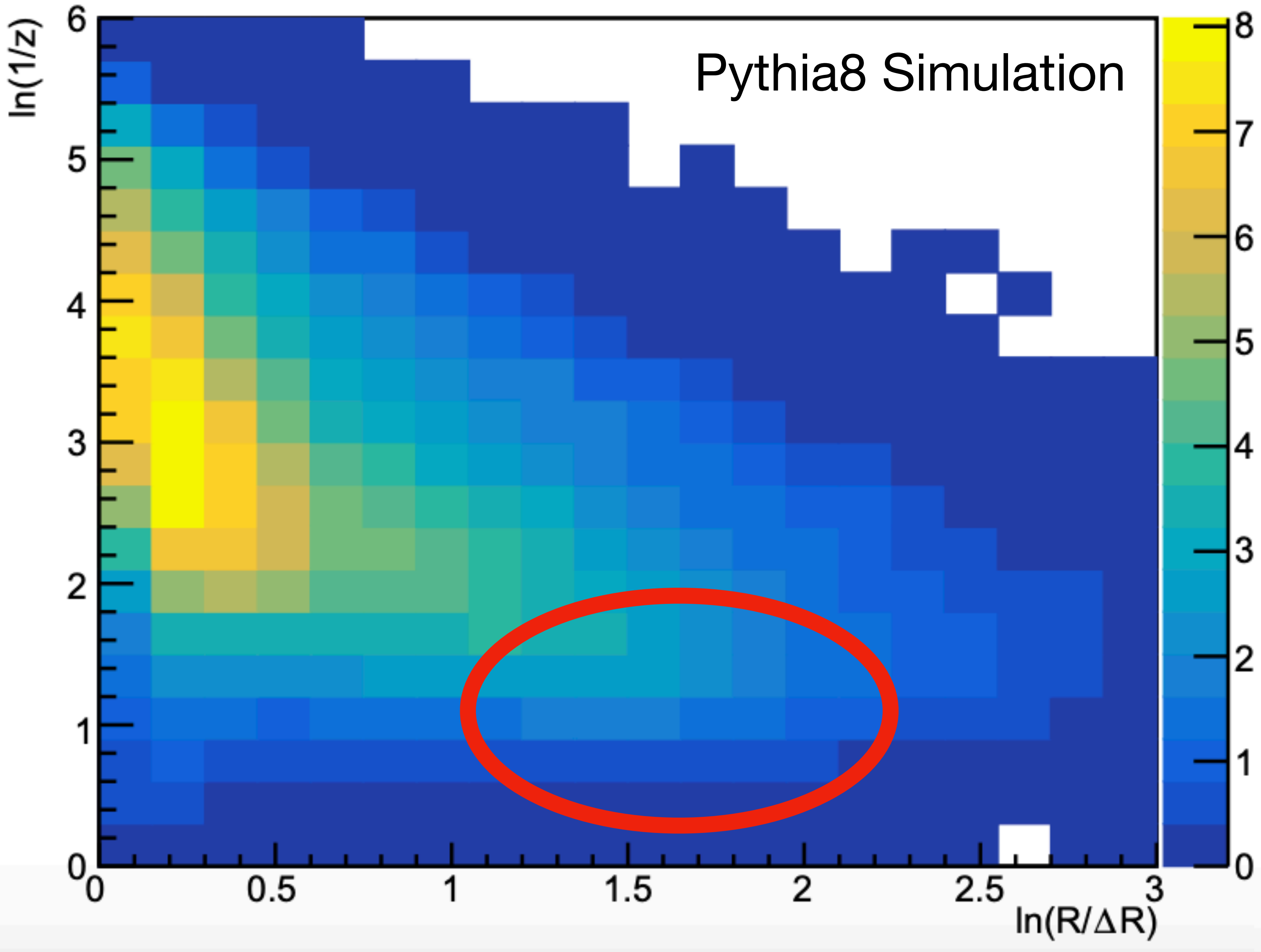
$p_{T,jet} > 20$ GeV
$R = 0.5$

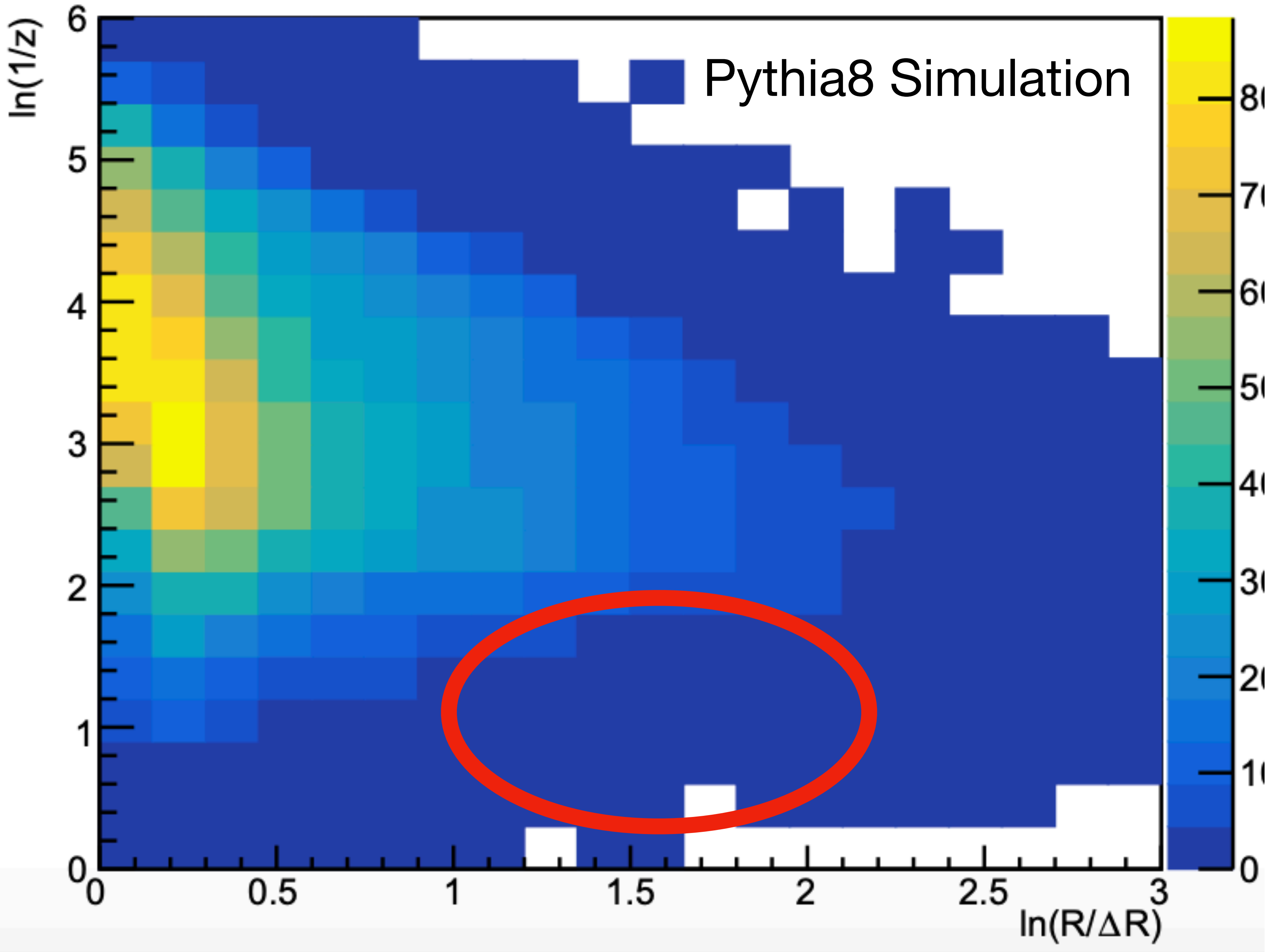
Light quark jets



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
$2.5 < \eta_{jet} < 4$
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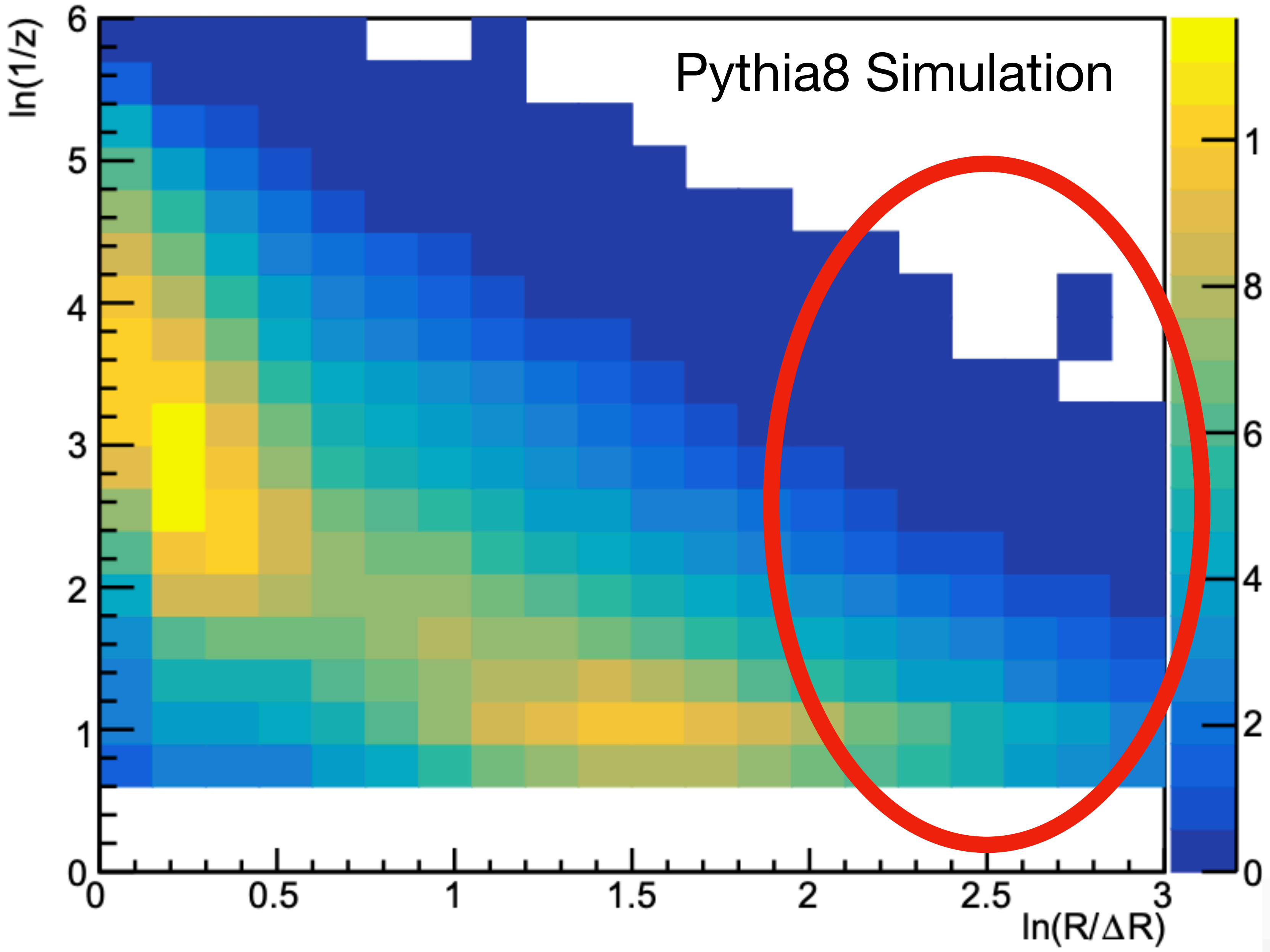
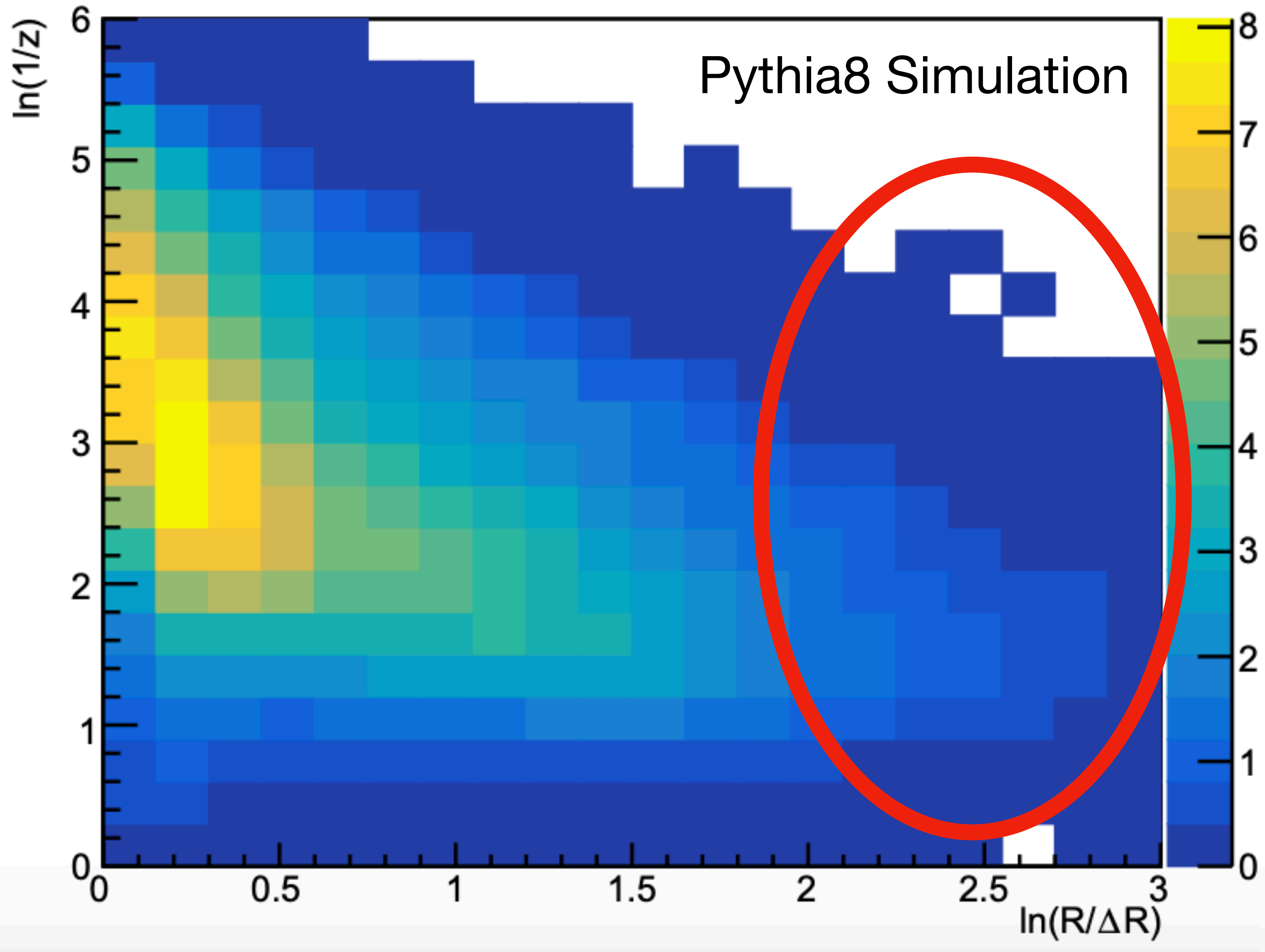
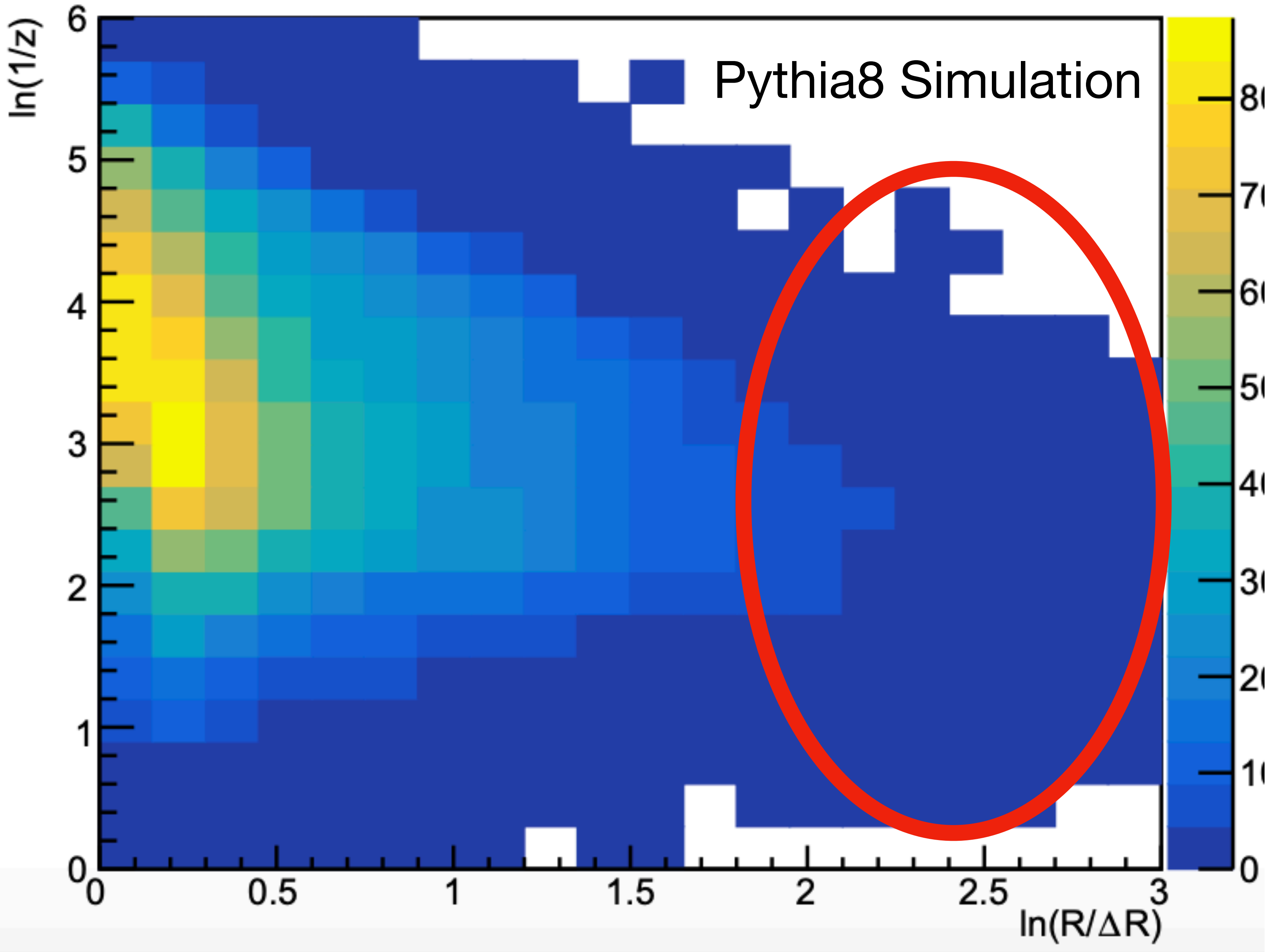
Light quark jets



Charm jets



Beauty jets



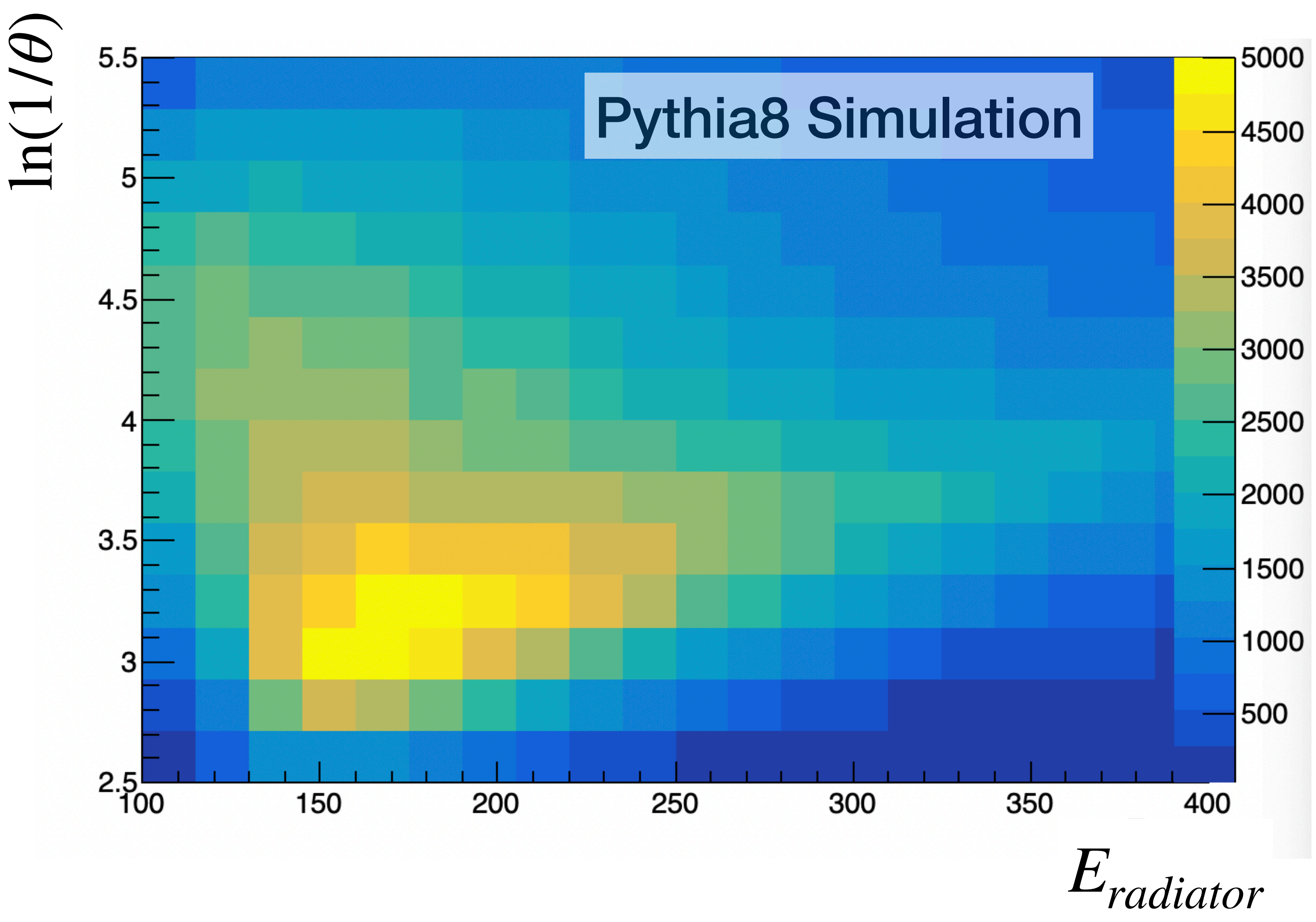
Suppressed collinear radiation = dead cone effect!

Dead cone at forward rapidities

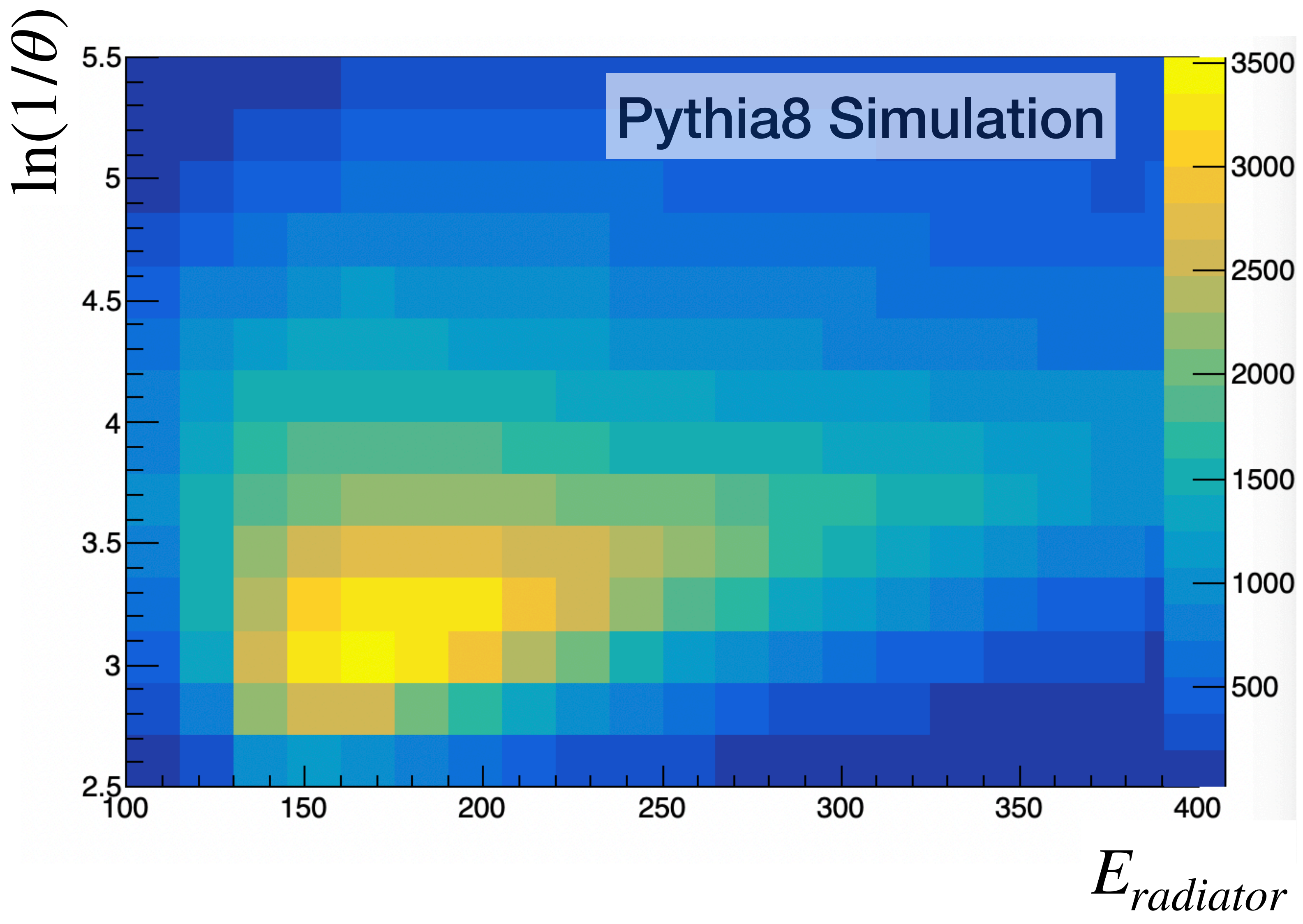
Pythia8 Dijet Simulations

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

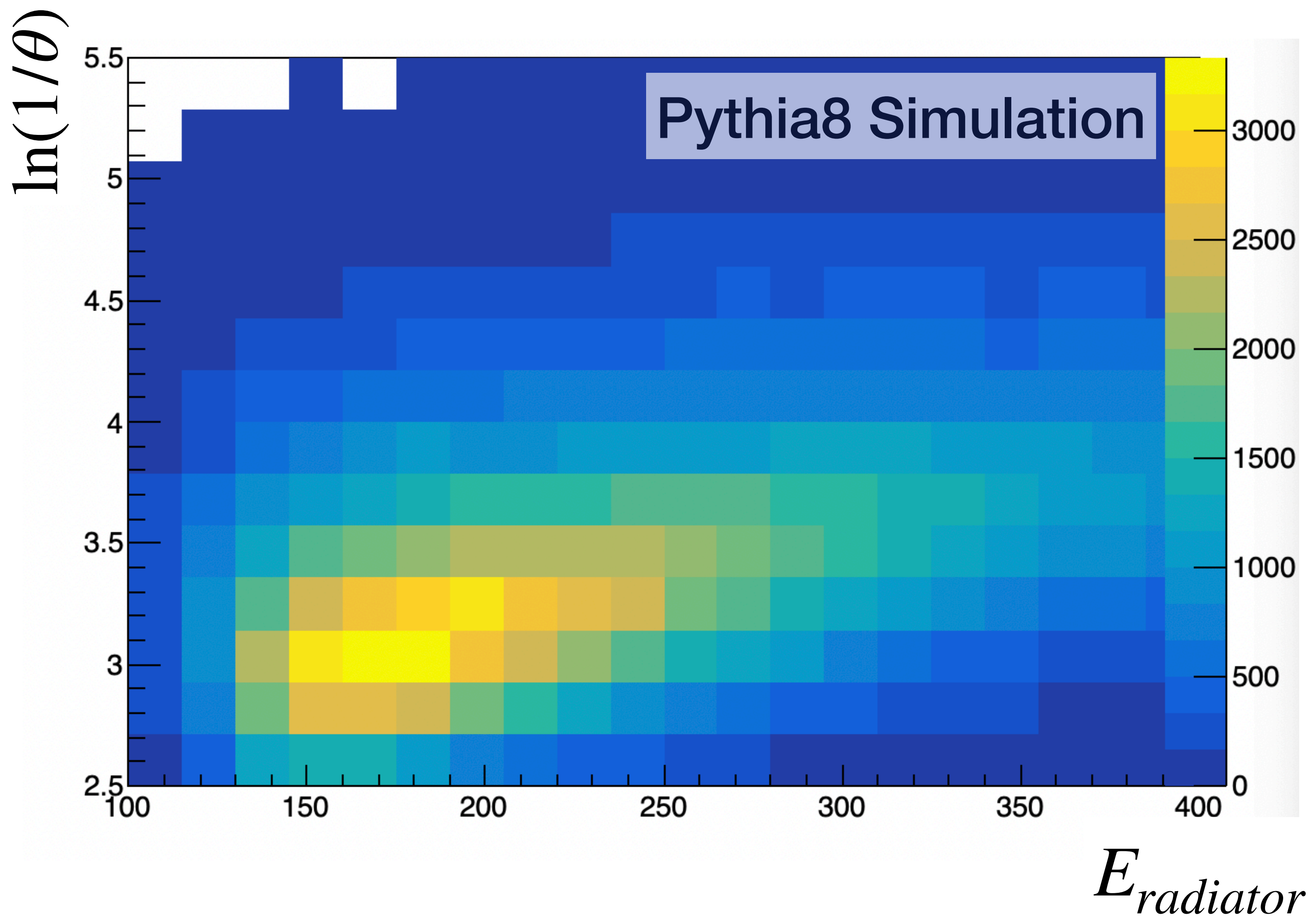
Light jets



Charm jets



Beauty jets

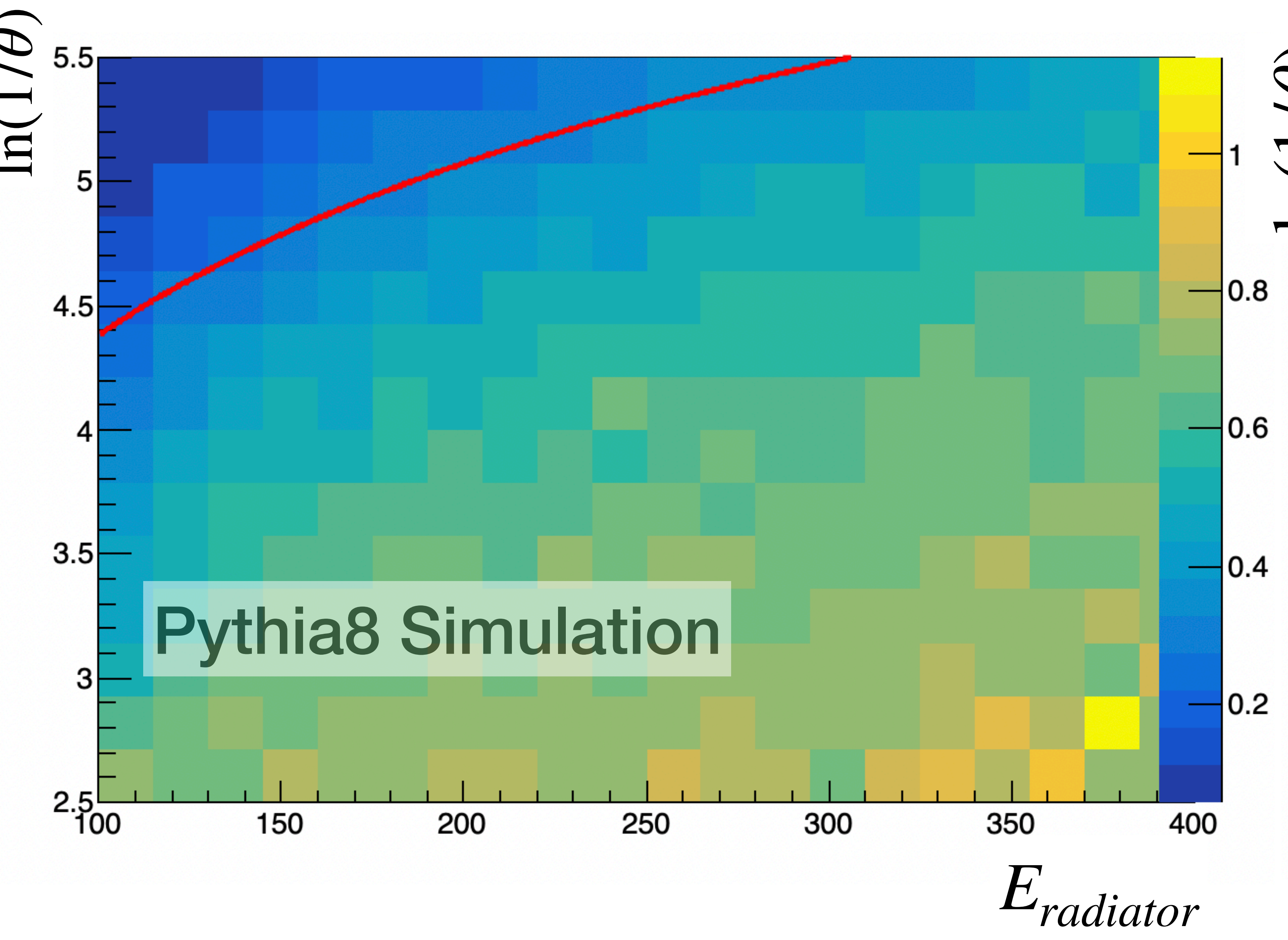


Dead cone at forward rapidities

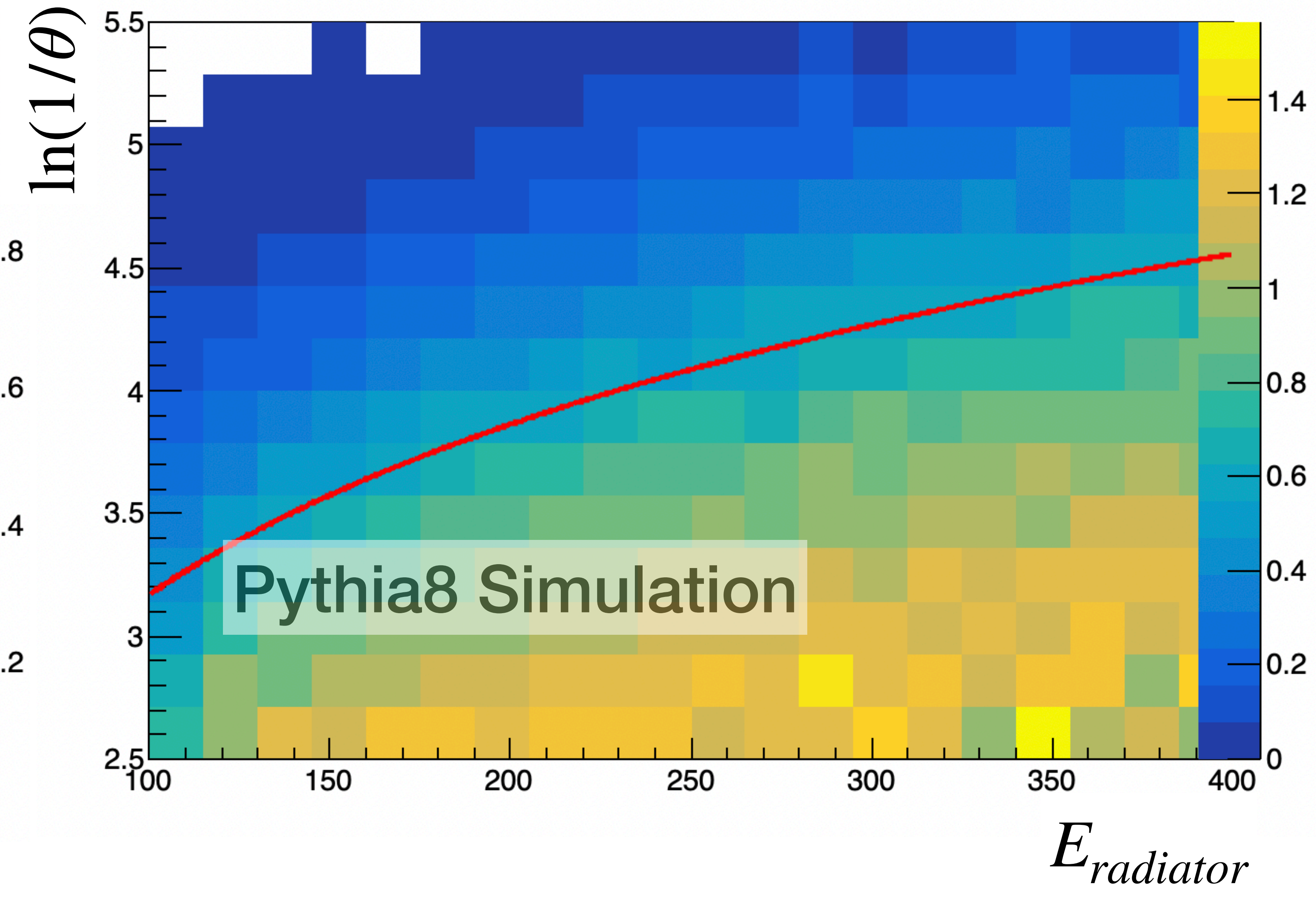
Pythia8 Dijet Simulations

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

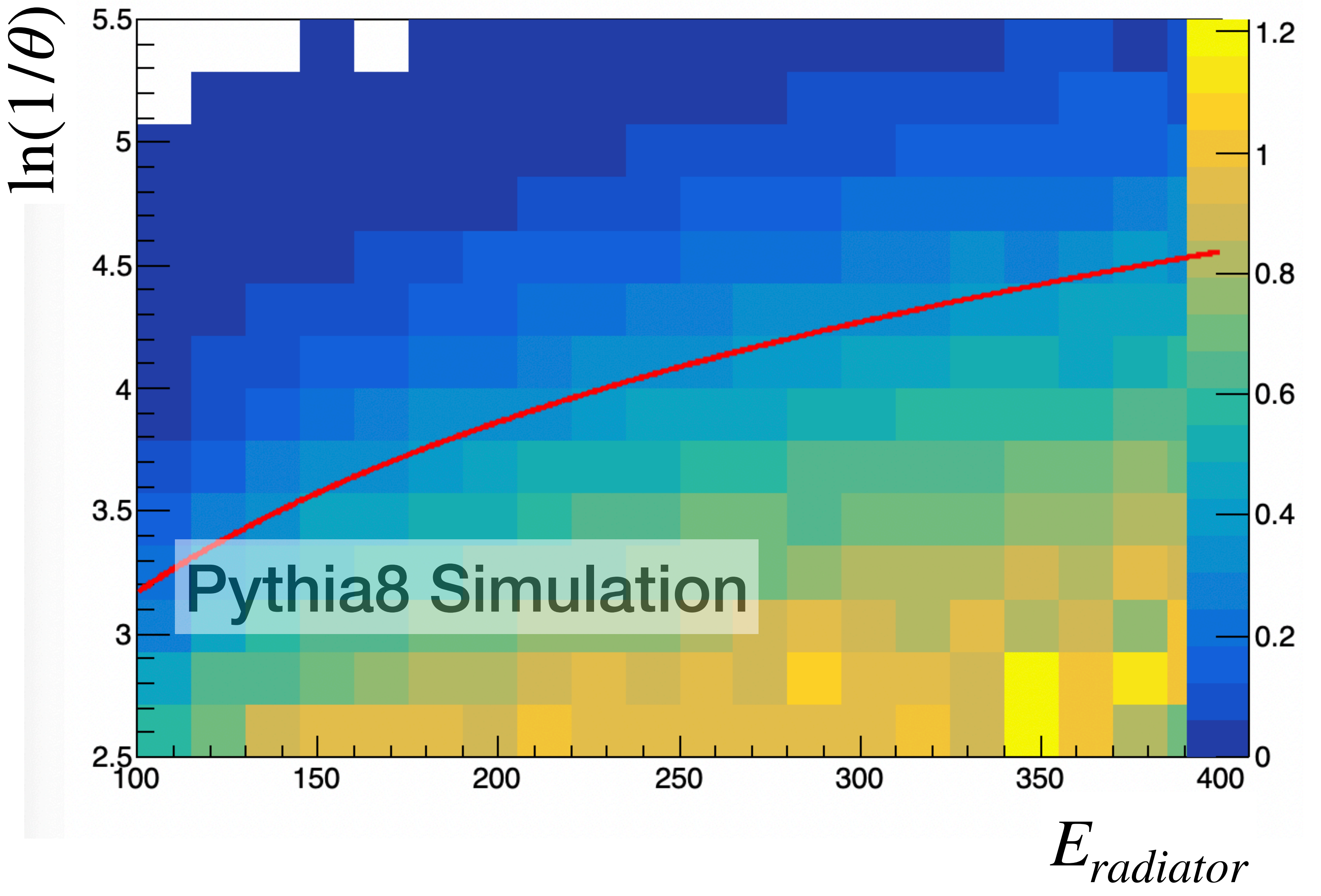
Charm/Light



Beauty/Charm



Beauty/Light



Red line: Dead cone angle as a function of Eradiator

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

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
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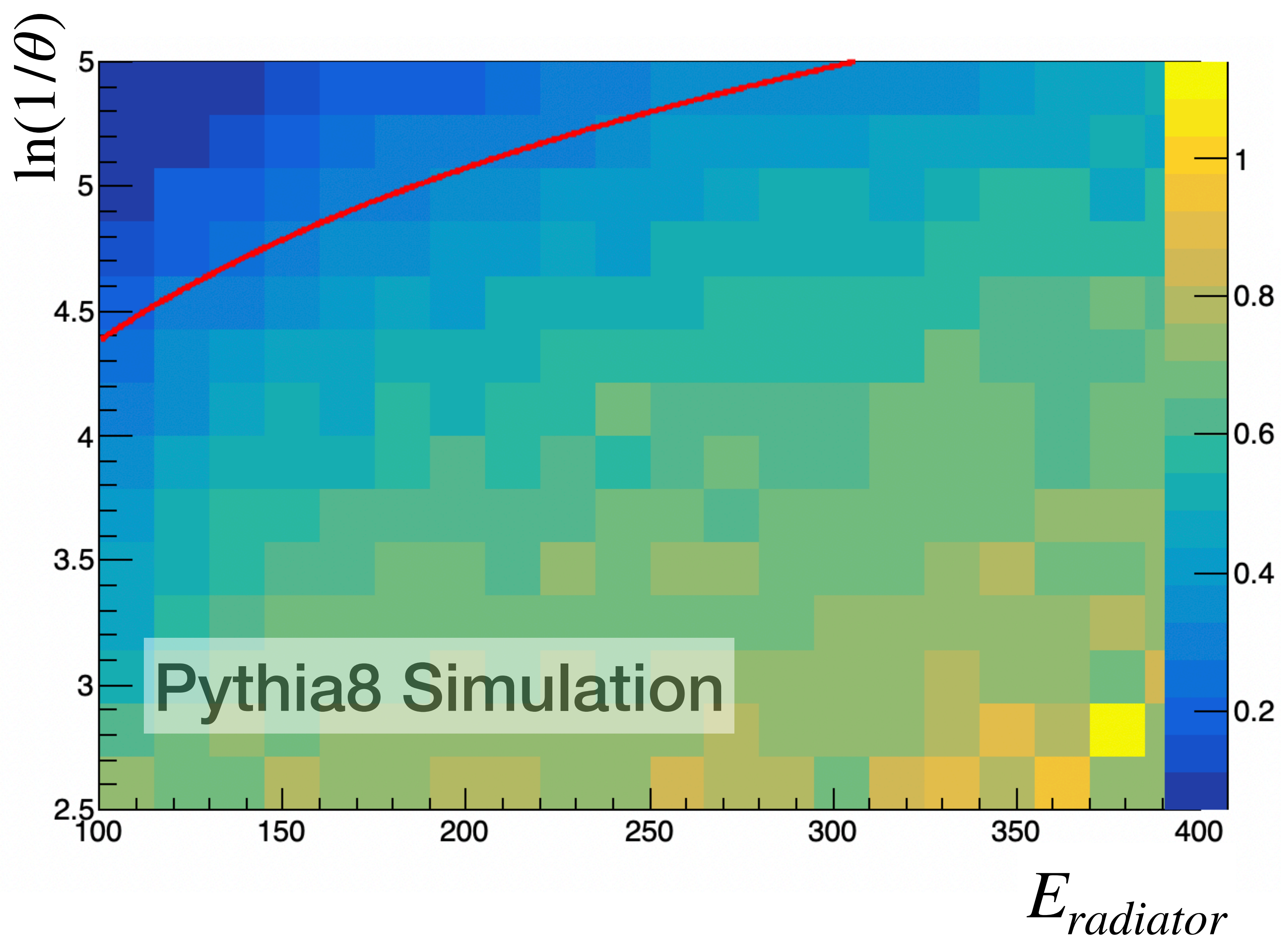
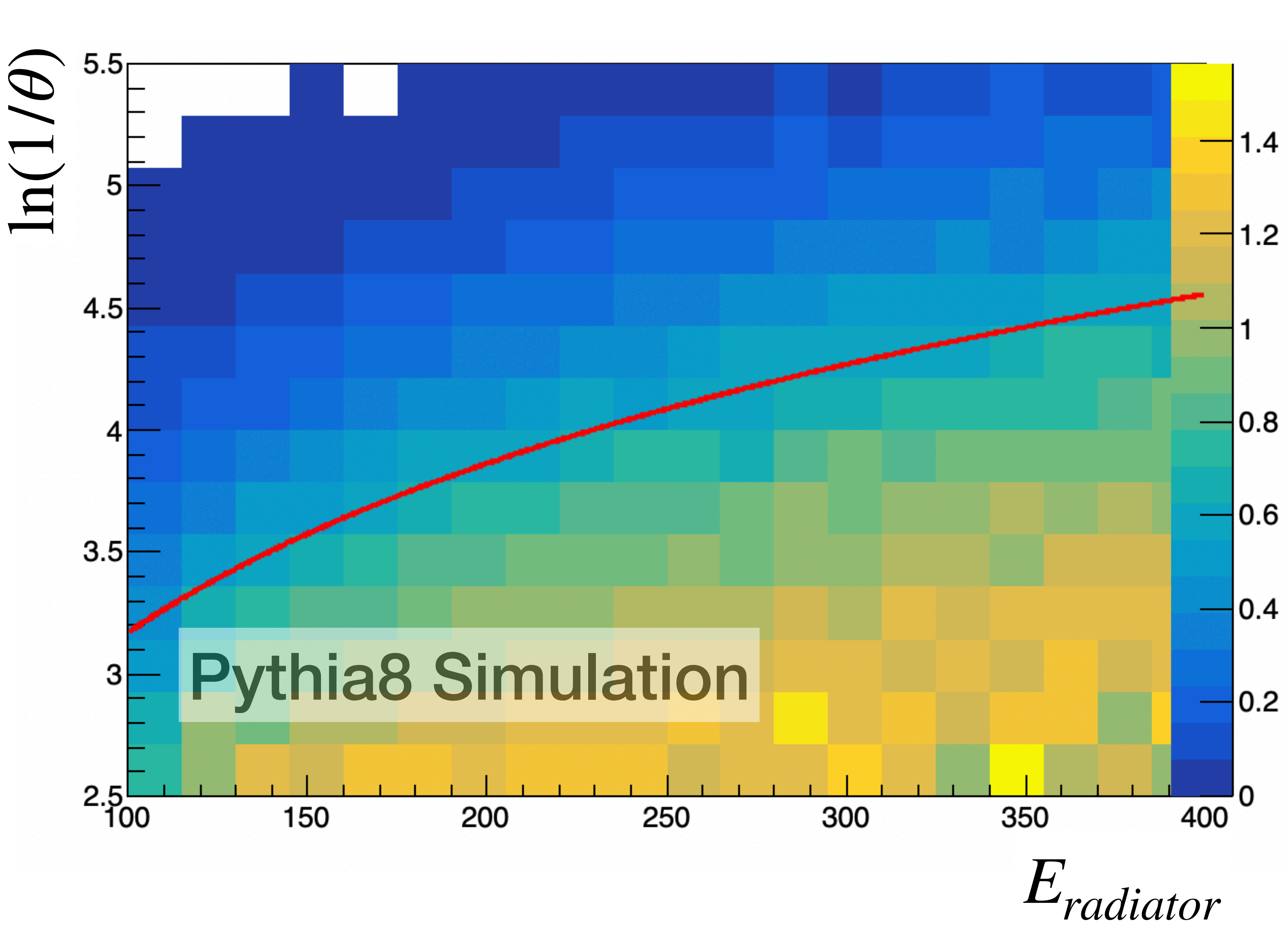
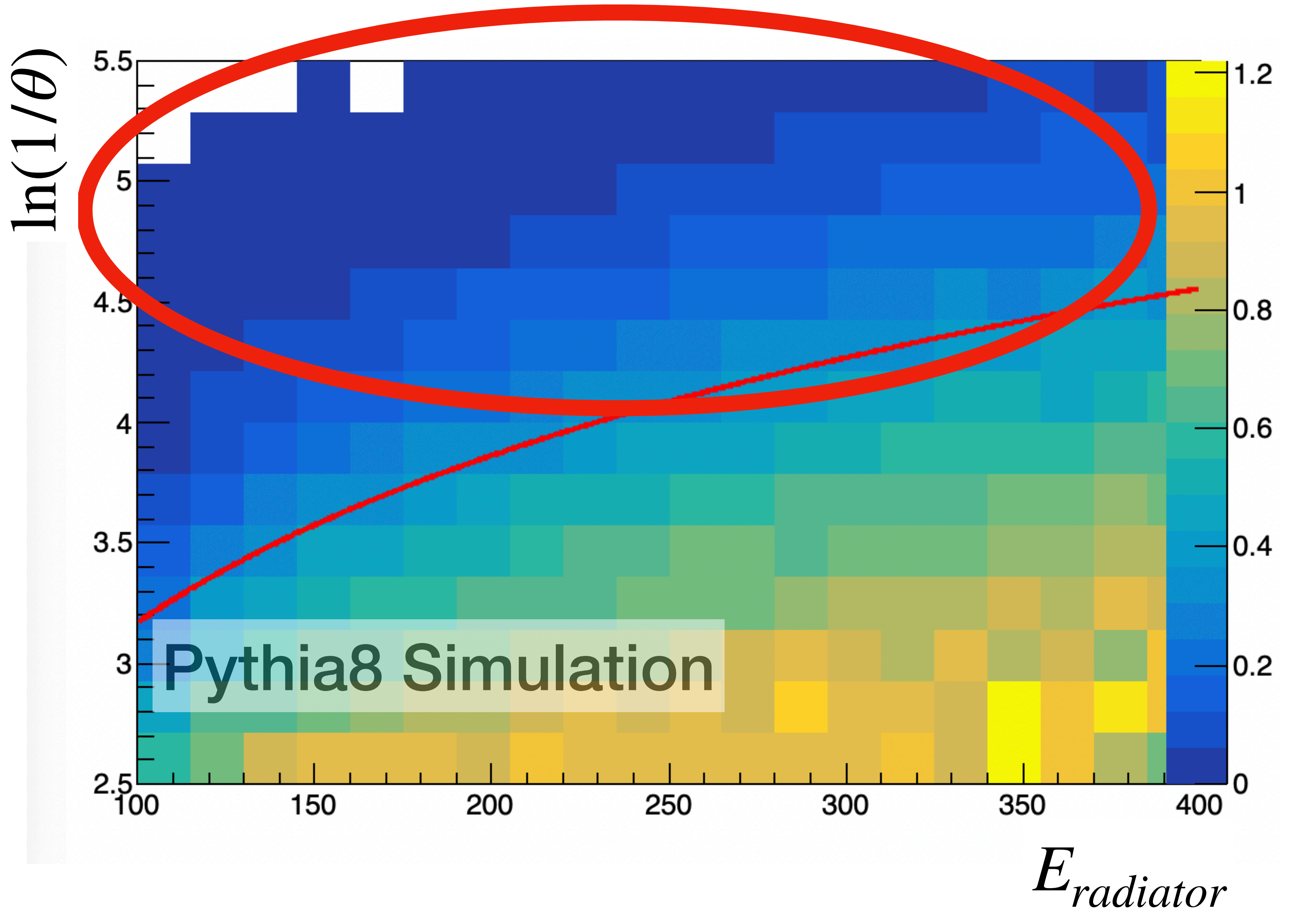
Charm/Light



Beauty/Charm



Beauty/Light



Dead cone effect is most prominent for Beauty/Light ratio

Recap: Lund plane at LHCb

- We plan on:
  - measuring the LJP for **light**, **charm**, and **beauty** jets,
  - measuring the LJP for **tracks** as well as **tracks + neutrals,**
  - and measuring the **dead-cone** and **leading-particle** effects from the various LJP parametrization.

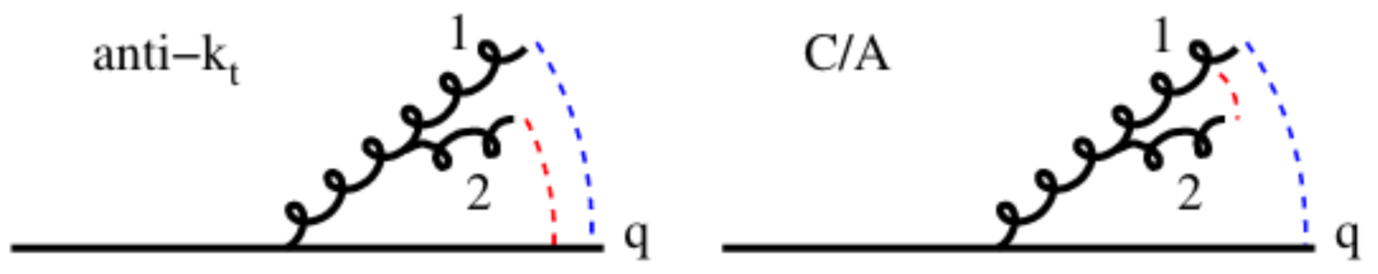
Backup slides

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

R : Jet Radius

Jets and Clustering Algorithms

Anti-k_T, Cambridge/Aachen



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

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

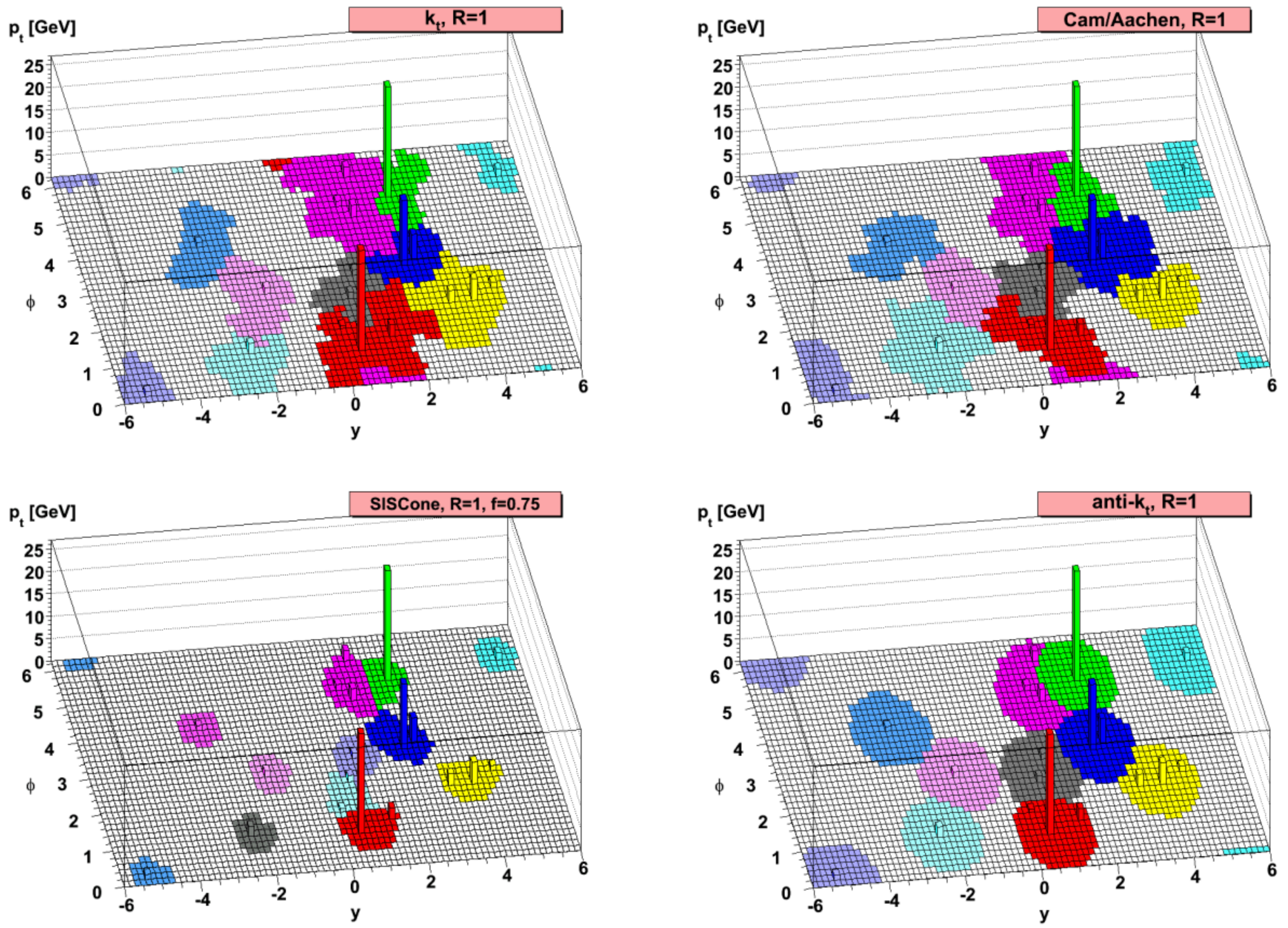
$p = 1$: k_T

$p = 0$: 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

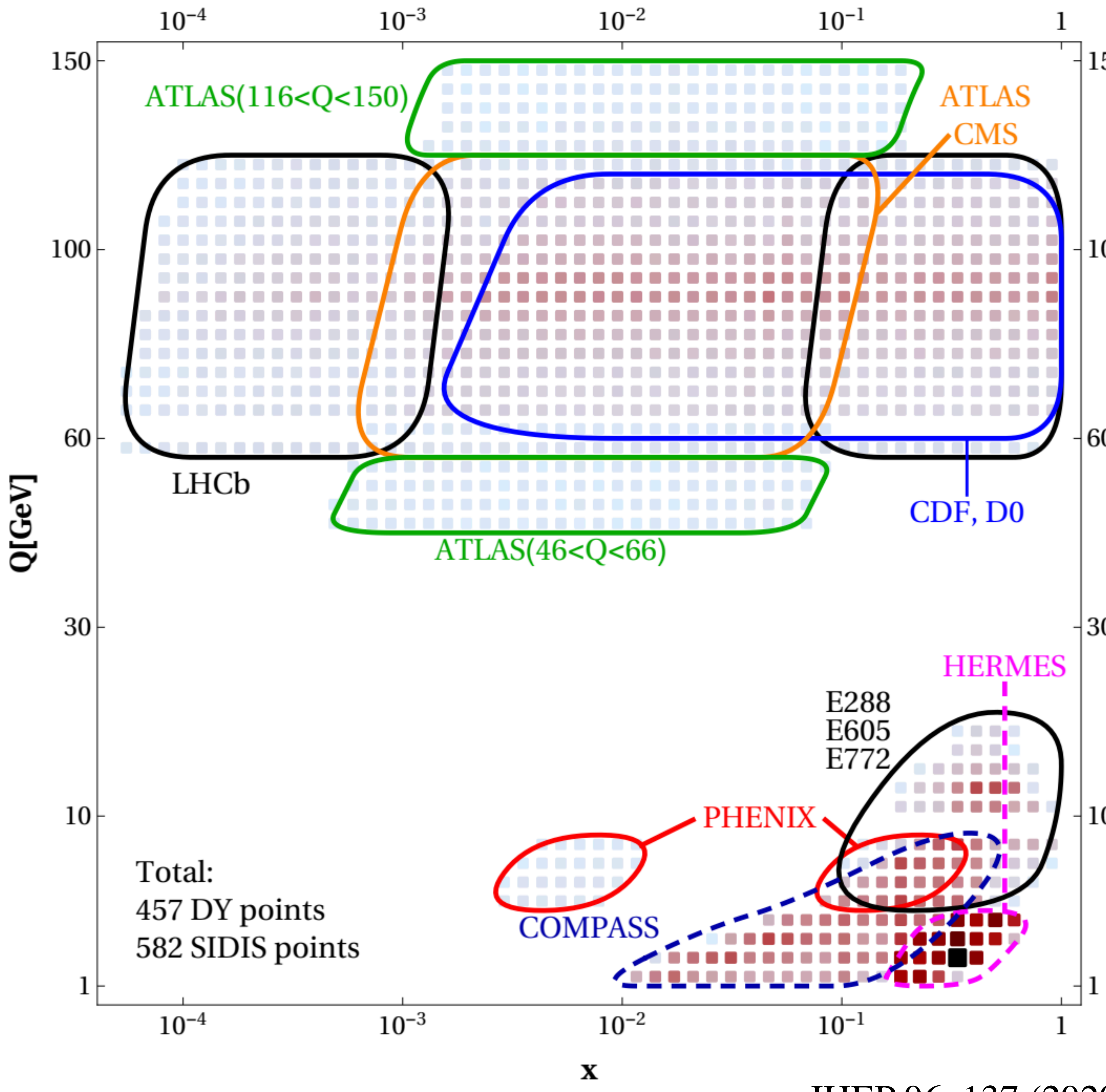
- **Anti-k_T is infrared and collinear safe (IRC), and produces conical jets!**



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



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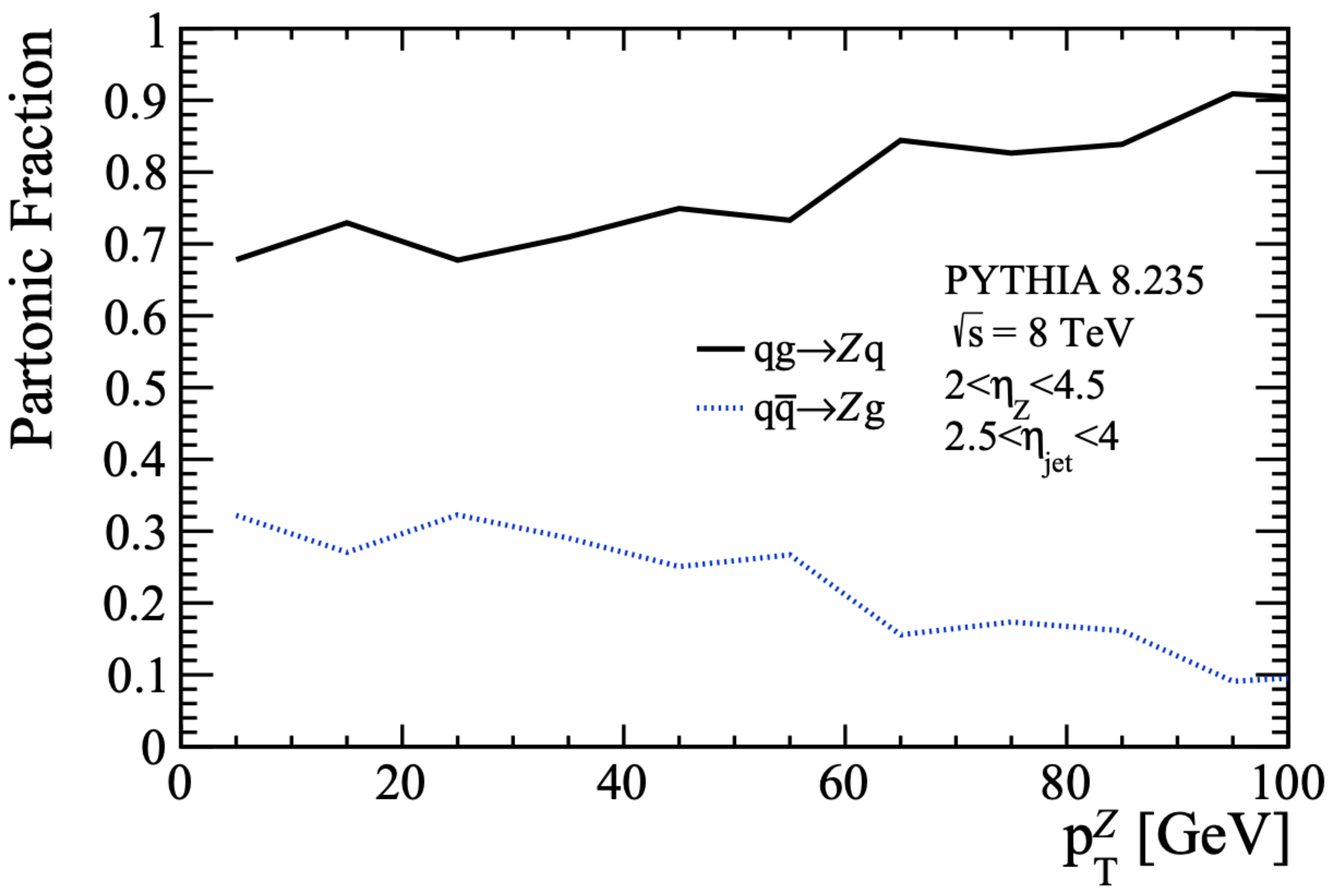

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