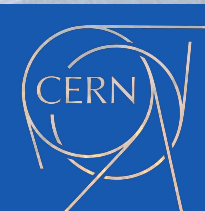




Hadronization studies in jets at LHCb

Esteban Felipe Molina Cárdenas
on behalf of the LHCb Collaboration
QCD@LHC26, University of Oxford
September 28th, 2026



Physics motivation

Physics motivation

**Formation of QCD jets is given
by a complex interplay
between perturbative and
non-perturbative physics**



**In this context, jets
are good for ...**

Physics motivation

Formation of QCD jets is given by a complex interplay between perturbative and non-perturbative physics



In this context, jets are good for ...



measuring and refining non-perturbative QCD objects

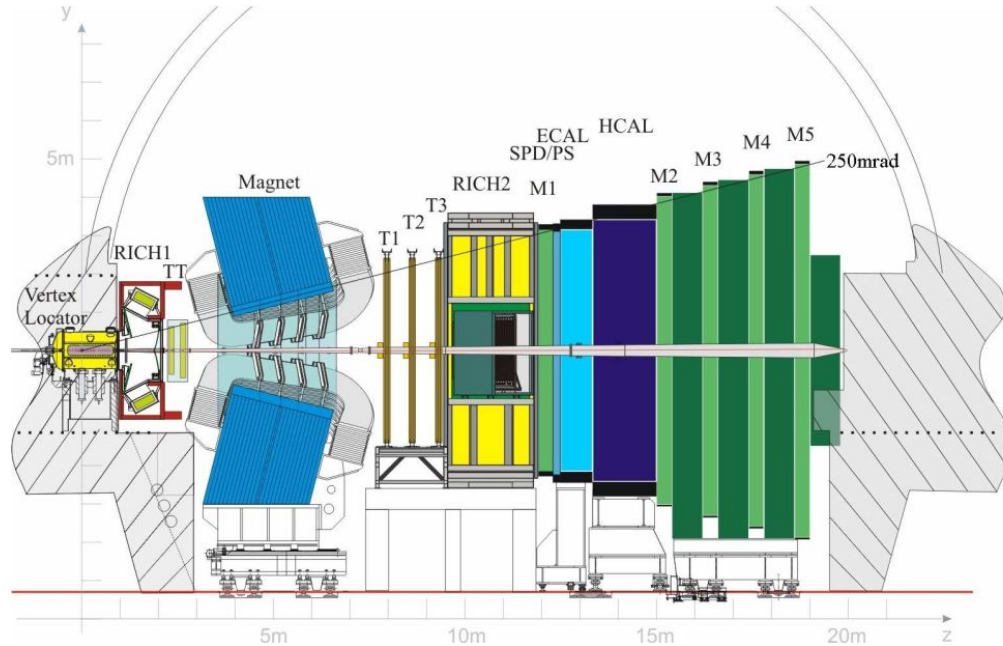


testing and developing techniques in perturbative QCD



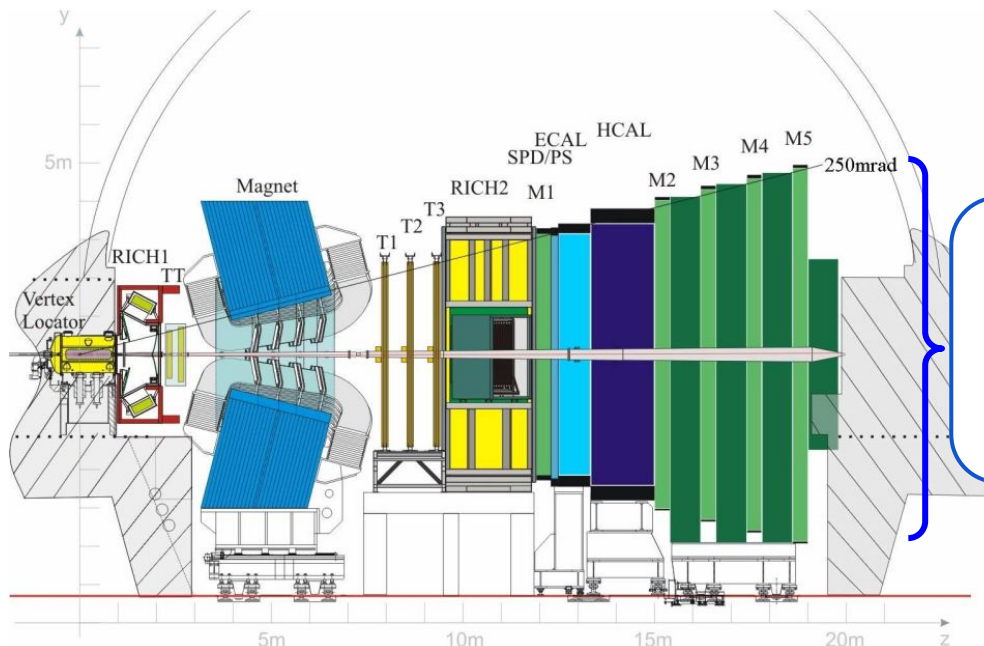
gaining insights on the space-time development of partons and radiation

Physics motivation



LHCb is great at measuring jets!

The LHCb experiment in Run 2

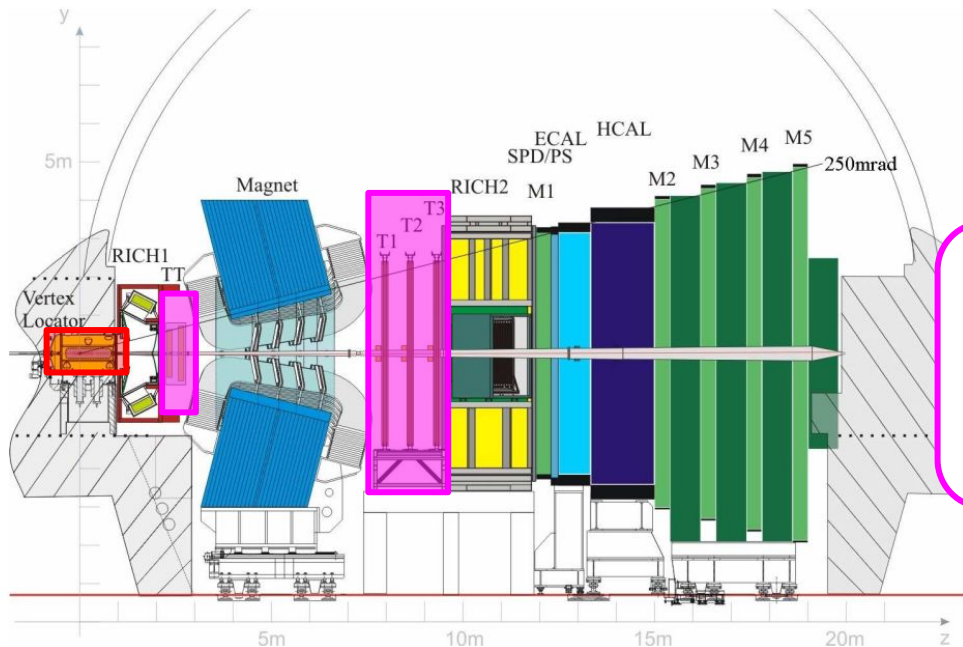


**Forward coverage
favours HF cross
sections and
light-quark enhanced
jet samples**

**Small pile-up to cleanly reconstruct
HF mesons and jets**

The LHCb experiment in Run 2

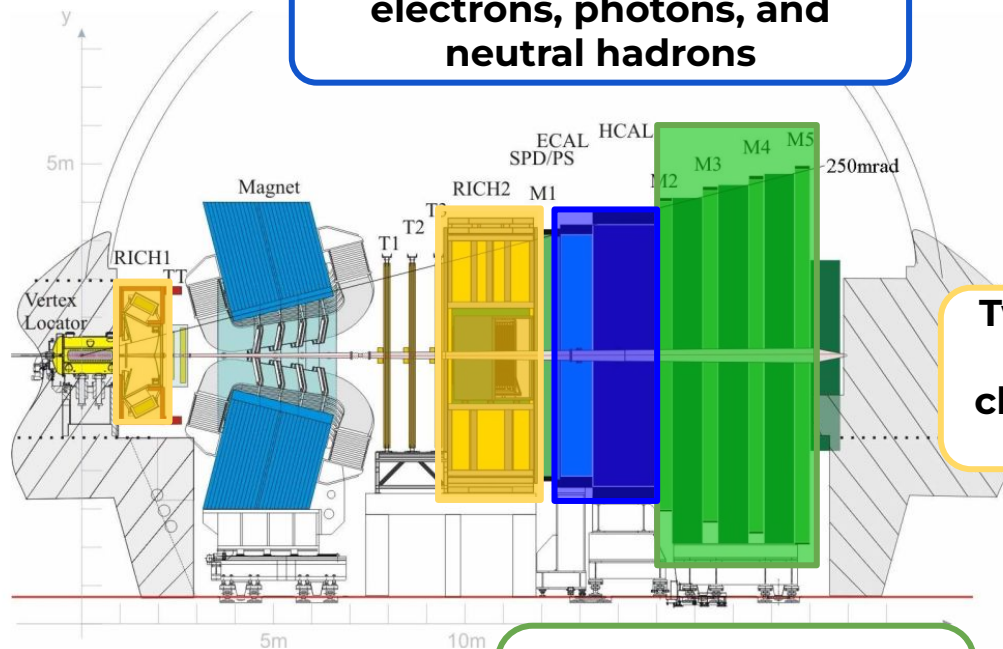
Dedicated vertex locator to clearly distinguish PVs and SVs



Tracking system before and after magnets to precisely track momentum

Small pile-up to cleanly reconstruct HF mesons and jets

The LHCb experiment in Run 2



**ECal and HCal to measure
electrons, photons, and
neutral hadrons**

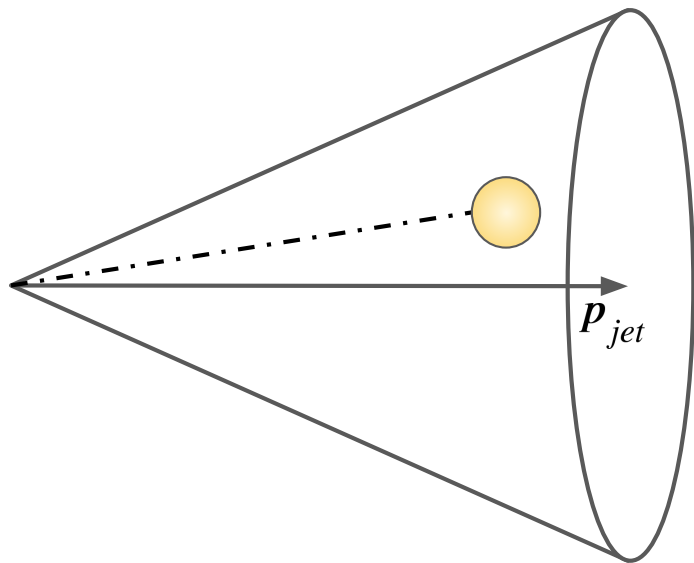
**Two RICH detectors to
clearly identify
charged hadrons up to
100 GeV**

**Five-station muon
system interleaved
by iron absorbers**

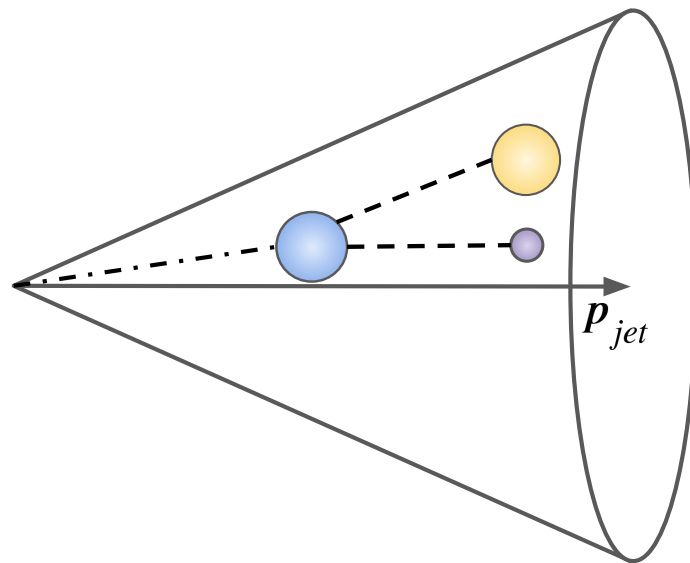
Recent Results

$\psi(2S)$ and χ_{c1} (3872) production in jets (2025)

Prompt

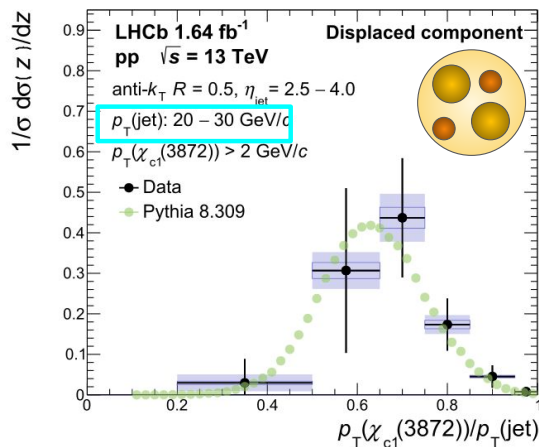
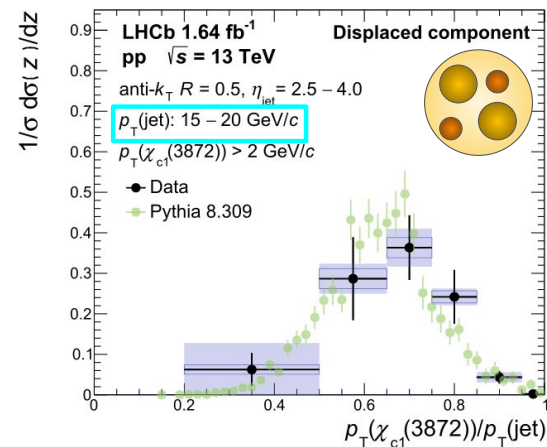
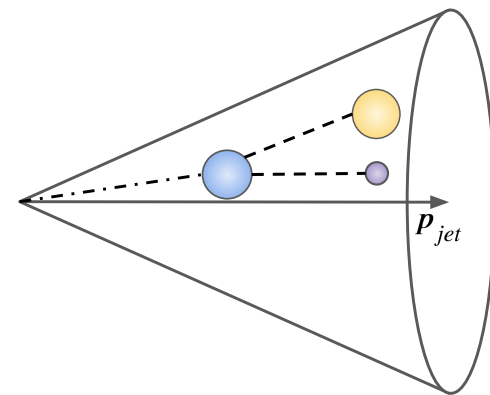
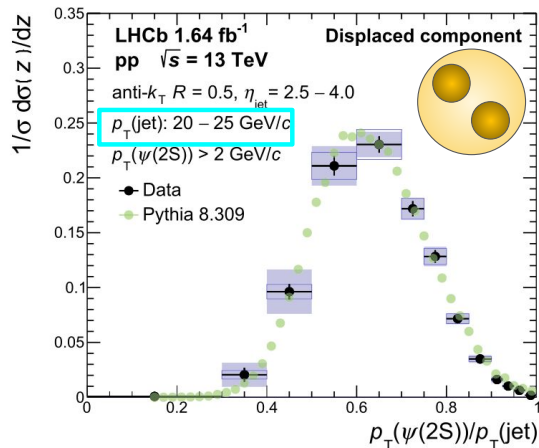
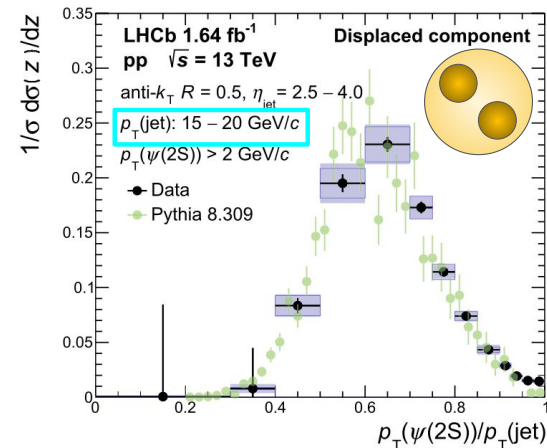


Displaced



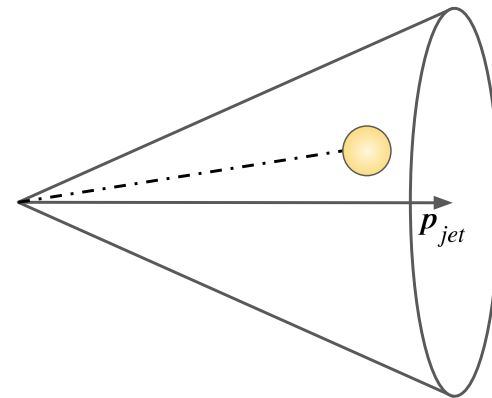
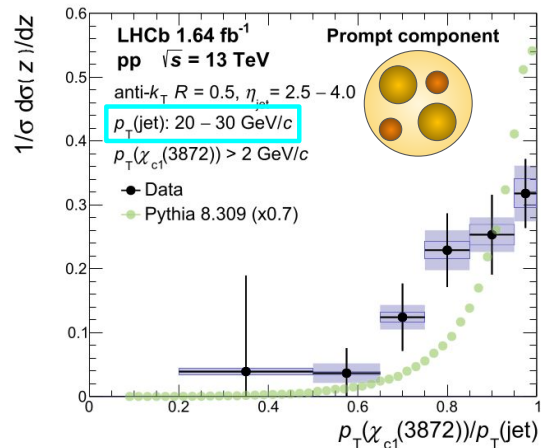
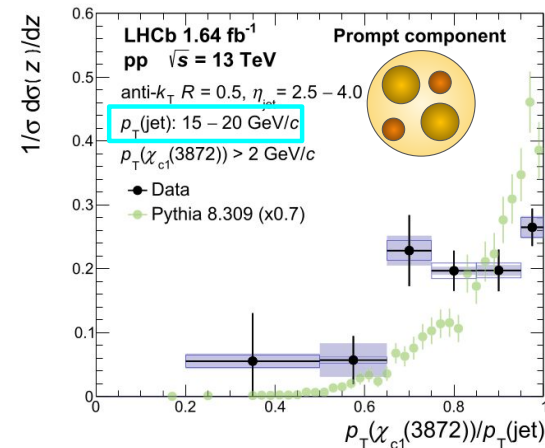
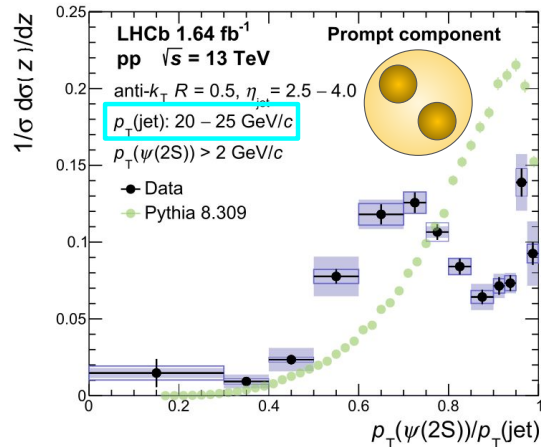
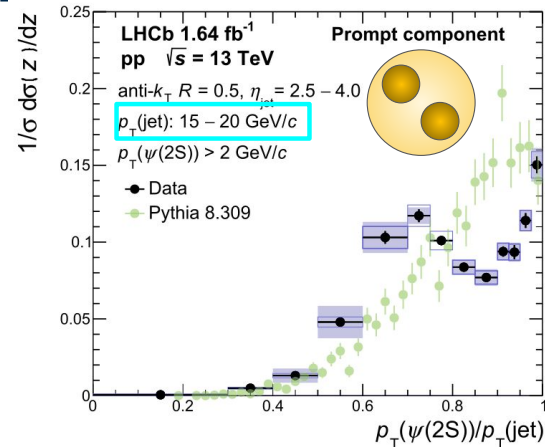
How does the production mechanism affect charmonium distributions in jets?

$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets (2025)



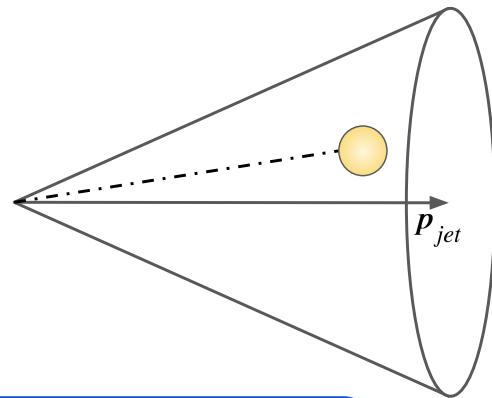
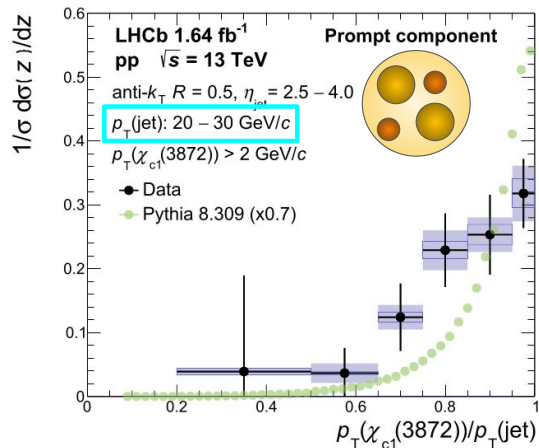
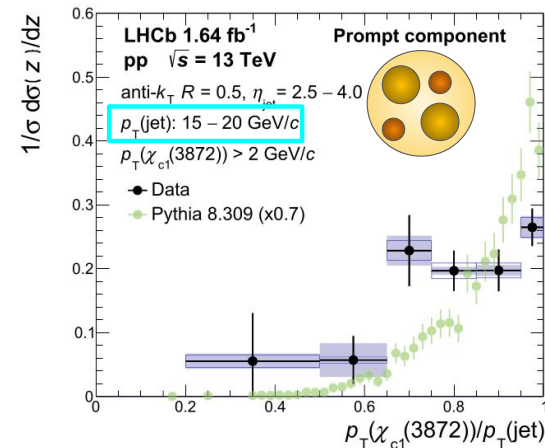
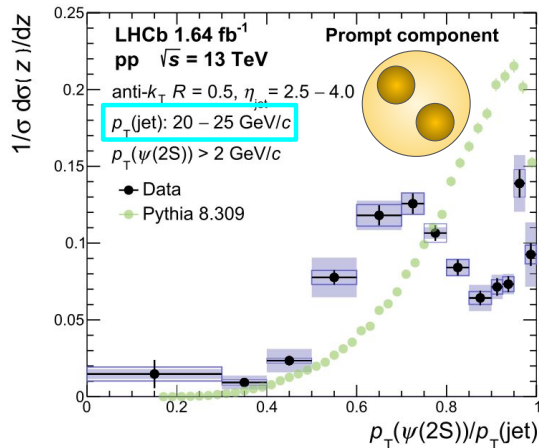
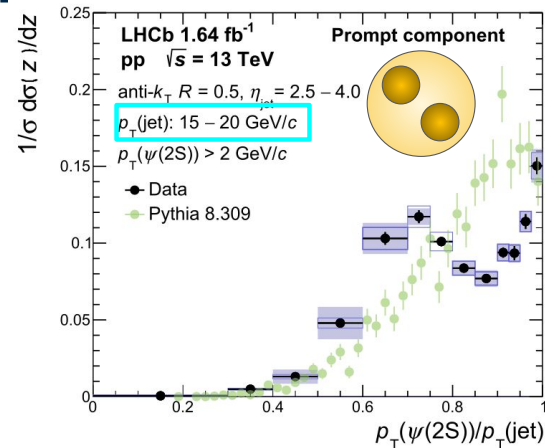
Production by decays
is well described by
PYTHIA

$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets (2025)



Bimodal shape not seen in simulations

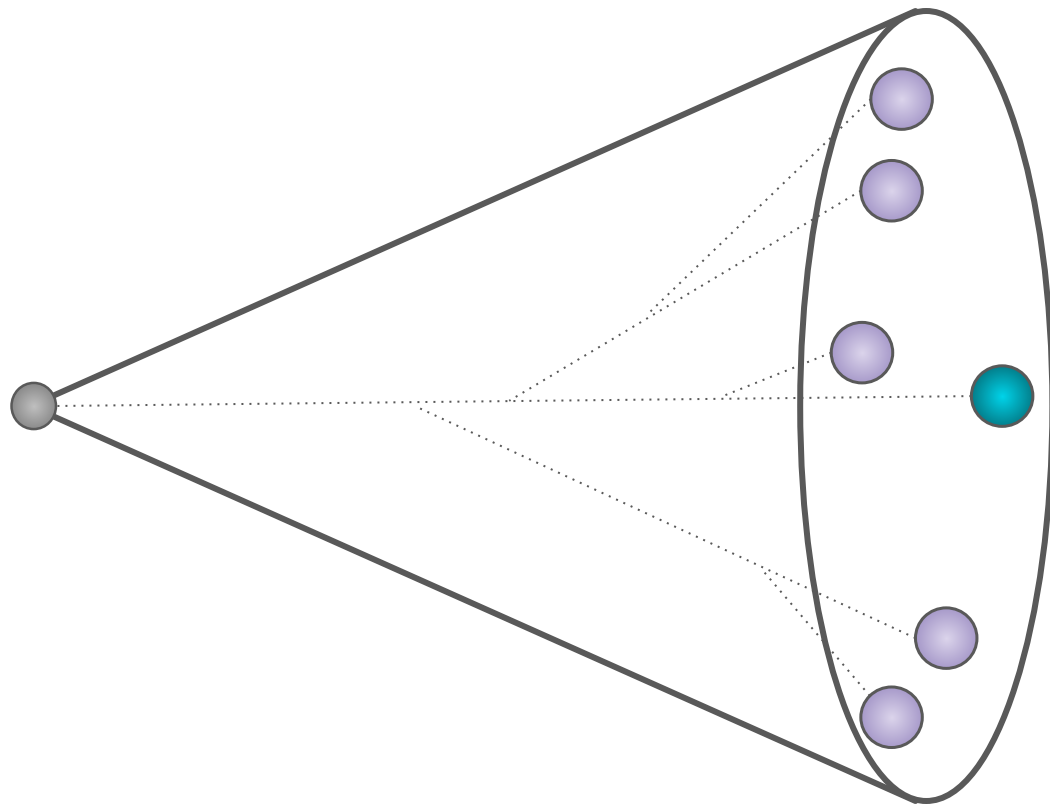
$\psi(2S)$ and $\chi_{c1}(3872)$ production in jets (2025)



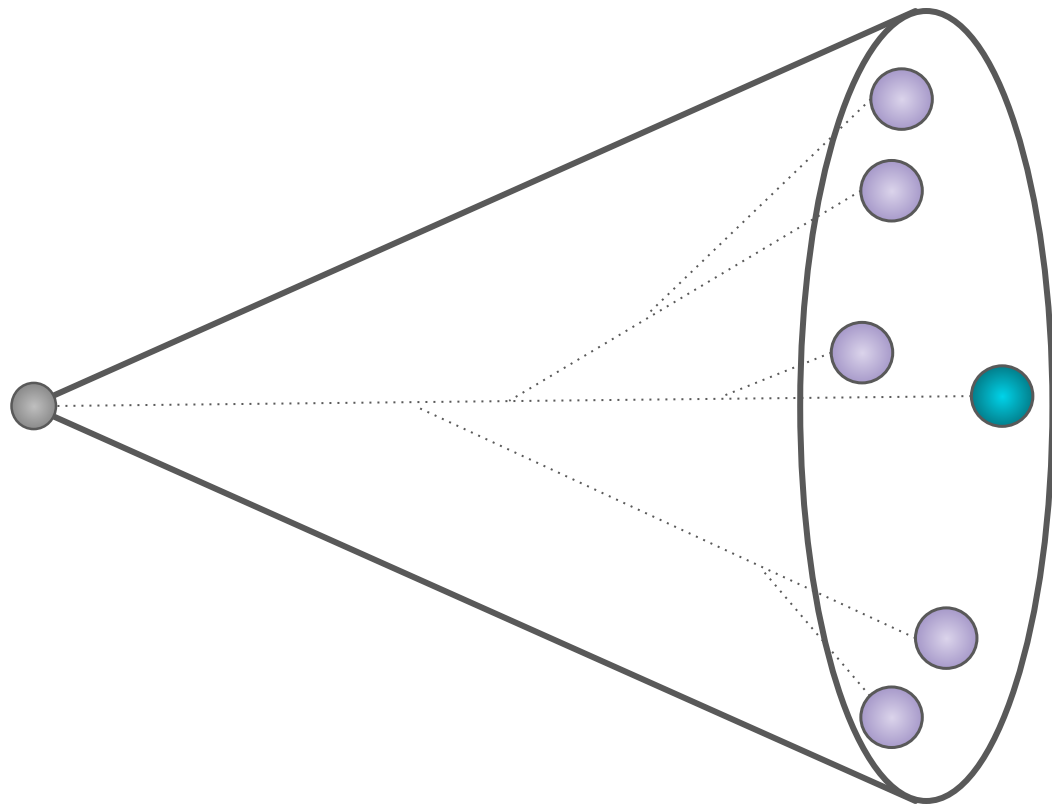
Two hadronization mechanisms at play?

Underestimation of the in-shower production of $c\bar{c}$?

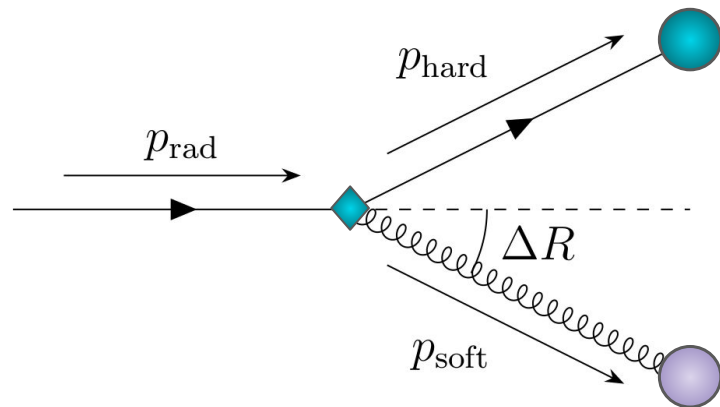
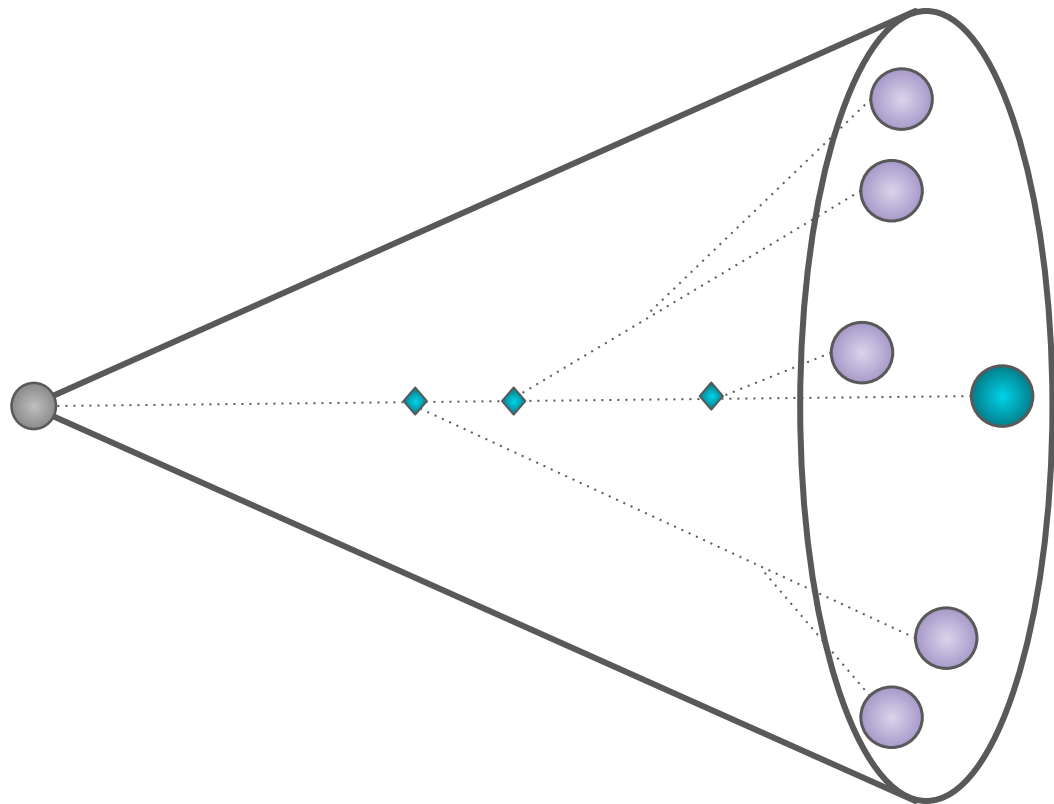
More studies needed!



What radiation patterns are observed in jets initiated by different partons?



Follow the radiation history of
the hardest particle  in the
jet

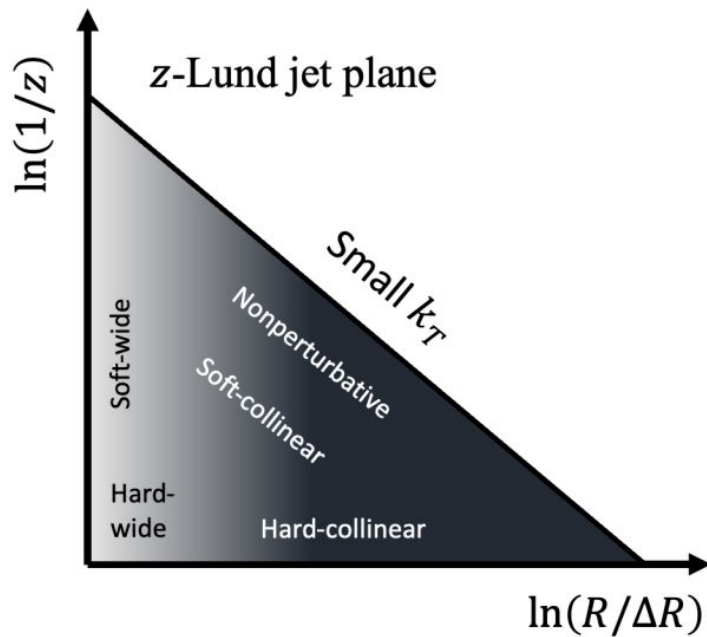


$$z \equiv \frac{p_{T,\text{soft}}}{p_{T,\text{soft}} + p_{T,\text{hard}}},$$

$$k_T \equiv p_{T,\text{soft}} \Delta R,$$

$$\Delta R \equiv \sqrt{(y_{\text{soft}} - y_{\text{rad}})^2 + (\phi_{\text{soft}} - \phi_{\text{rad}})^2}$$

$$z \equiv \frac{p_{T,\text{soft}}}{p_{T,\text{soft}} + p_{T,\text{hard}}}$$

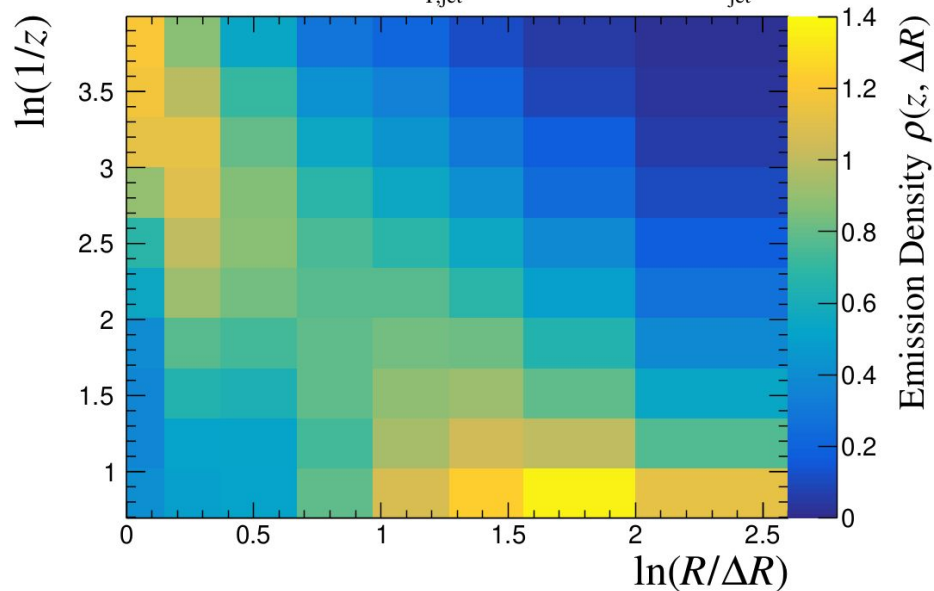


$$\Delta R \equiv \sqrt{(y_{\text{soft}} - y_{\text{rad}})^2 + (\phi_{\text{soft}} - \phi_{\text{rad}})^2}$$

LHCb, pp $\sqrt{s} = 13$ TeV

Z+jets

Anti- k_T jets, $R = 0.5$, $p_{T,\text{jet}} > 20$ GeV/c, $2.5 < y_{\text{jet}} < 4.0$

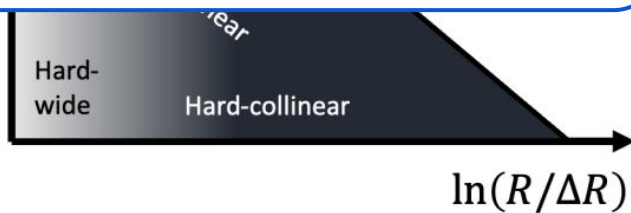


Lund plane for light- and beauty-quark jets (2025)

$$z \equiv \frac{p_{T,\text{soft}}}{p_{T,\text{soft}} + p_{T,\text{hard}}}$$

$(1/z)$
z-Lund jet plane

Hard- collinear and soft-wide contributions dominate the emissions in Z-tagged jets

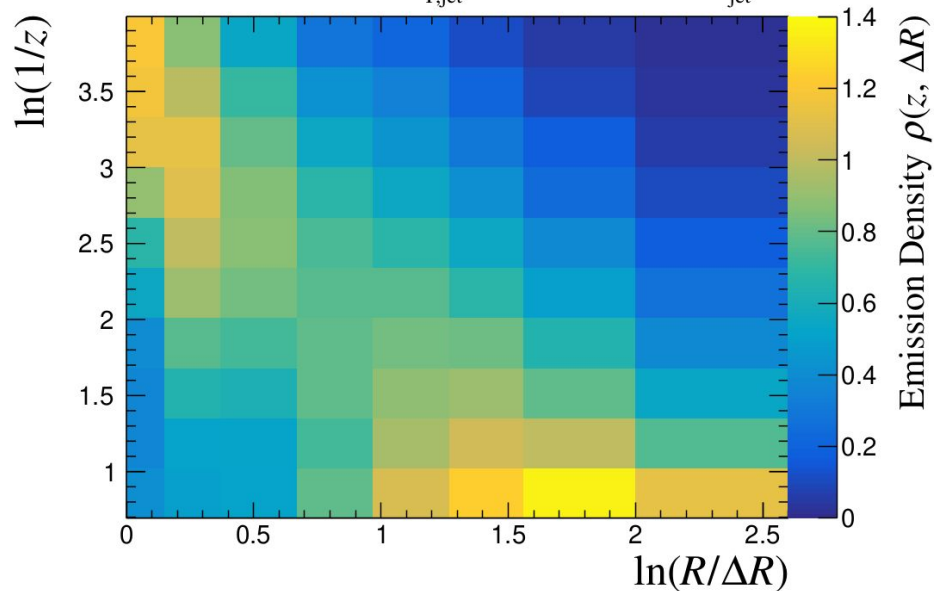


$$\Delta R \equiv \sqrt{(y_{\text{soft}} - y_{\text{rad}})^2 + (\phi_{\text{soft}} - \phi_{\text{rad}})^2}$$

LHCb, $pp \sqrt{s} = 13 \text{ TeV}$

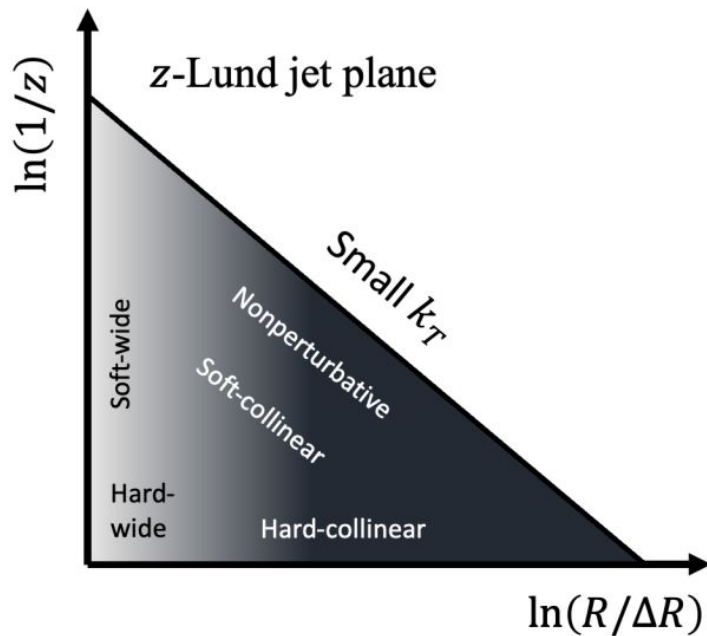
Z+jets

Anti- k_T jets, $R = 0.5$, $p_{T,\text{jet}} > 20 \text{ GeV}/c$, $2.5 < y_{\text{jet}} < 4.0$



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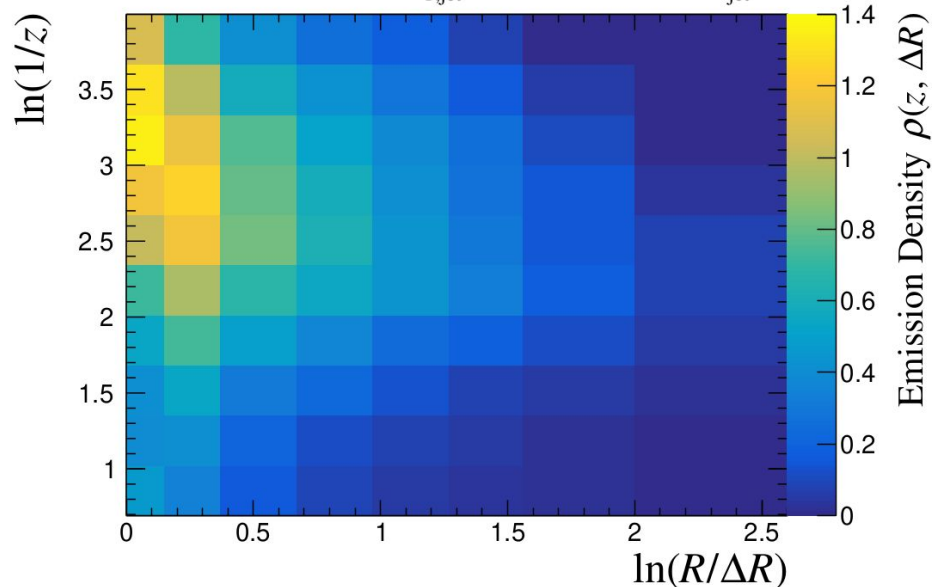


$$\Delta R \equiv \sqrt{(y_{\text{soft}} - y_{\text{rad}})^2 + (\phi_{\text{soft}} - \phi_{\text{rad}})^2}$$

LHCb, pp $\sqrt{s} = 13$ TeV

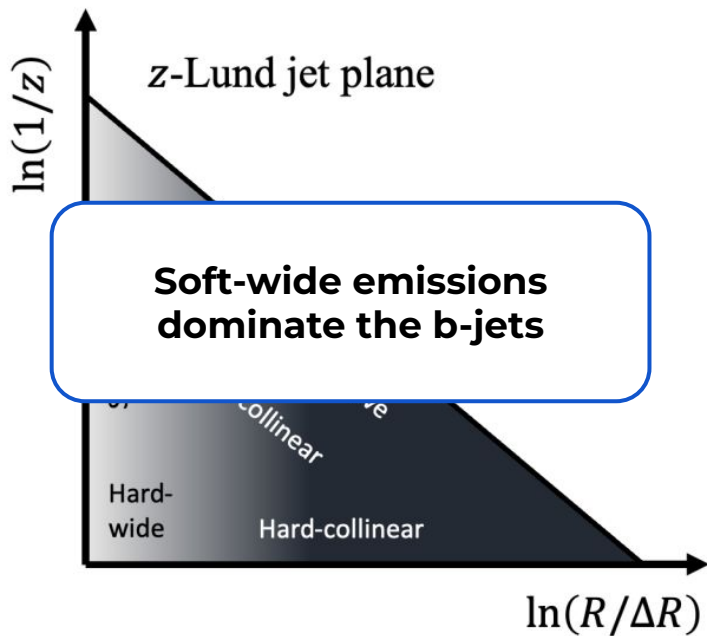
$B^\pm$ -tagged jets + WTA

Anti- k_T jets, $R = 0.5$, $p_{T,\text{jet}} > 20$ GeV/c, $2.5 < y_{\text{jet}} < 4.0$



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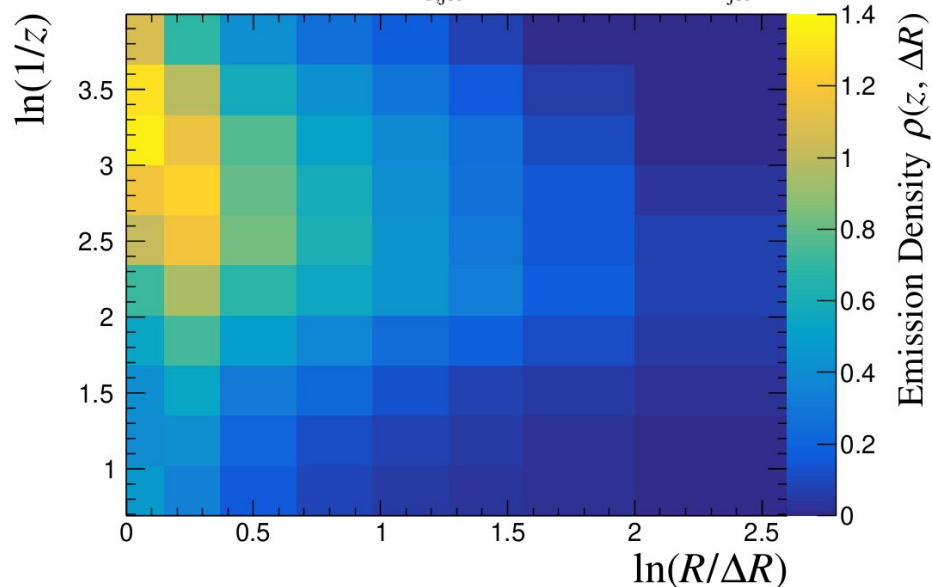


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LHCb, $pp \sqrt{s} = 13 \text{ TeV}$

$B^\pm$ -tagged jets + WTA

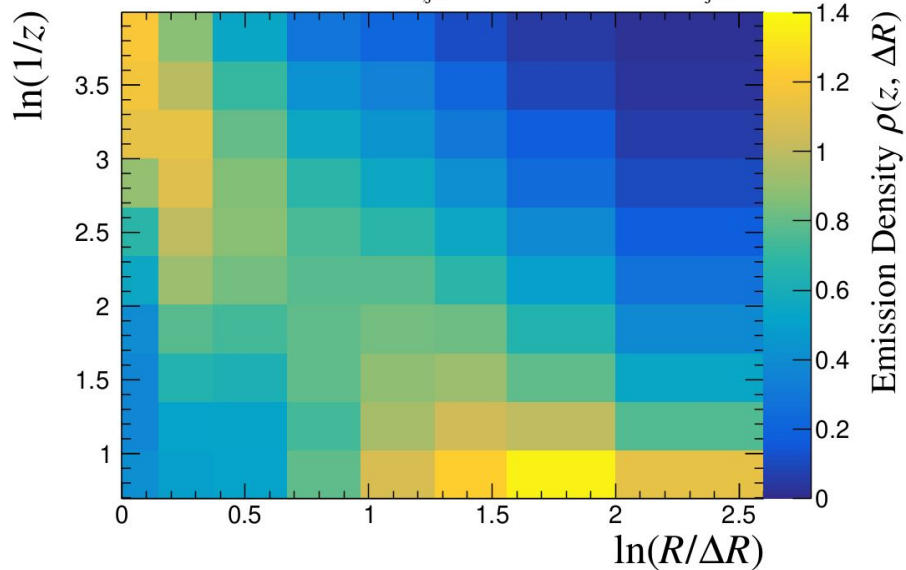
Anti- k_T jets, $R = 0.5$, $p_{T,\text{jet}} > 20 \text{ GeV}/c$, $2.5 < y_{\text{jet}} < 4.0$



LHCb, pp $\sqrt{s} = 13$ TeV

Z+jets

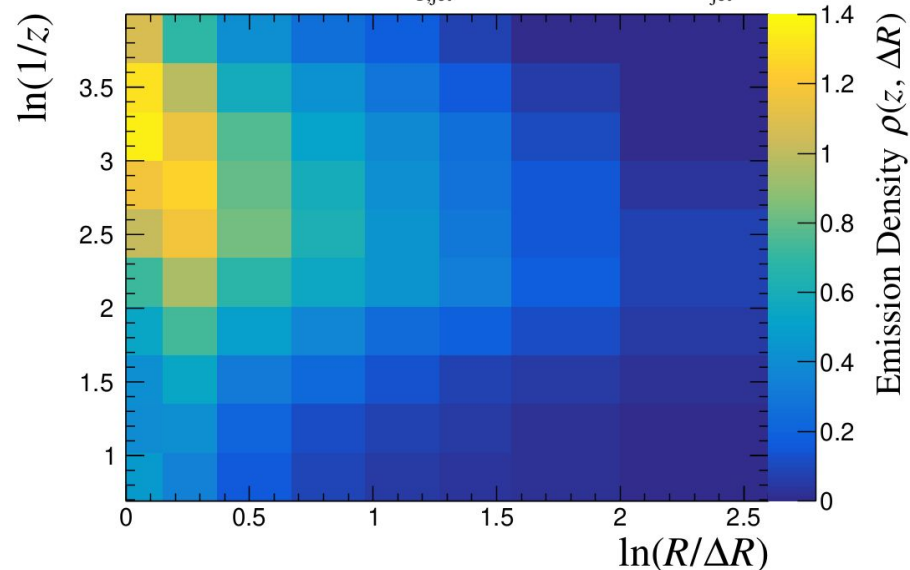
Anti- k_T jets, $R = 0.5$, $p_{T,\text{jet}} > 20$ GeV/c, $2.5 < y_{\text{jet}} < 4.0$



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Z+jets

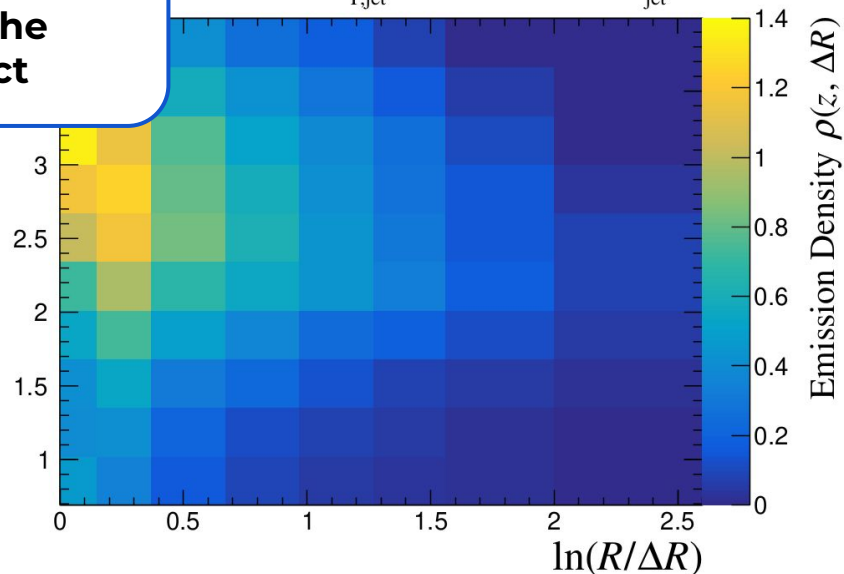
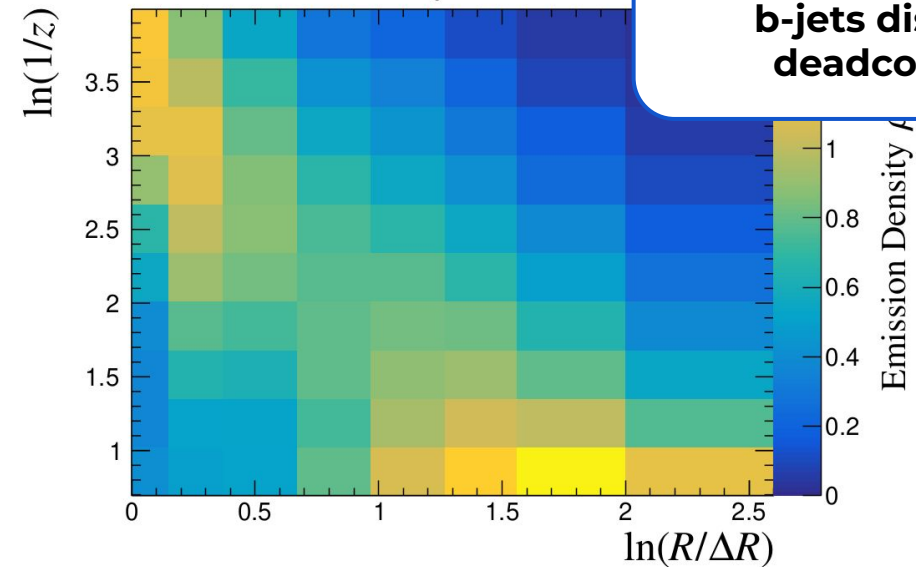
Anti- k_T jets, $R = 0.5$, $p_{T,jet} > 20$ GeV/c,

LHCb, pp $\sqrt{s} = 13$ TeV

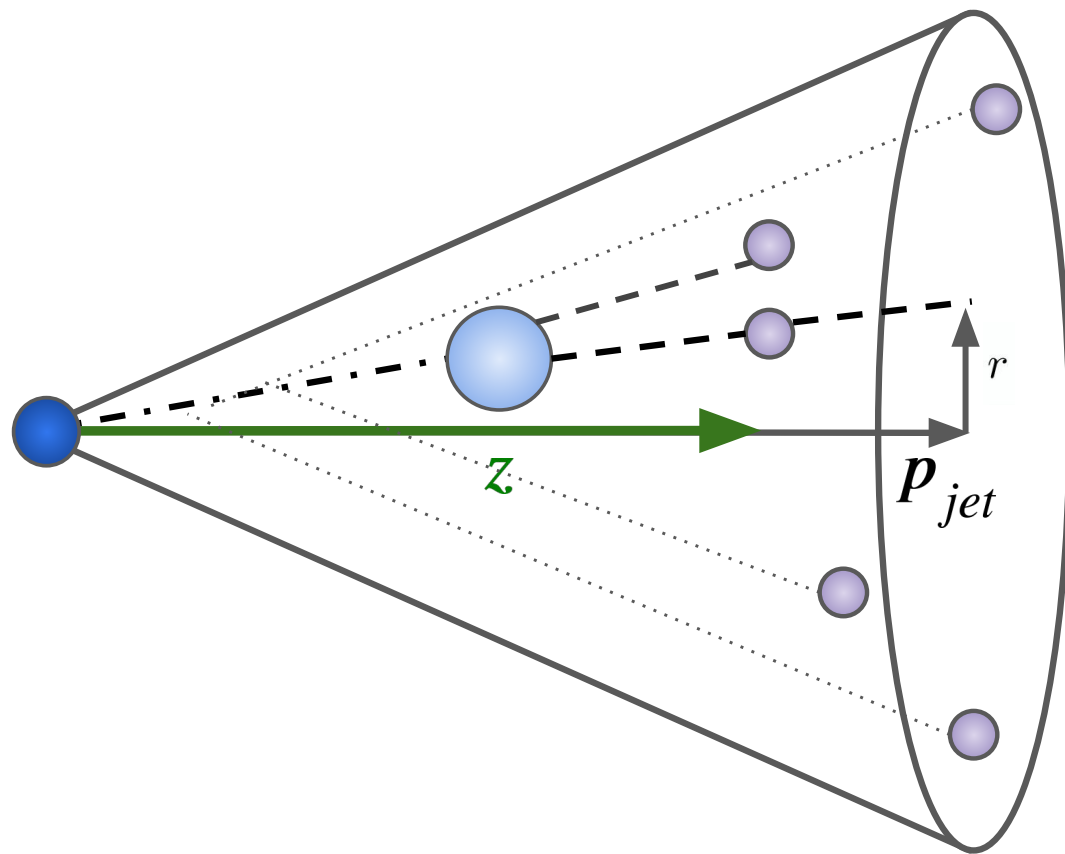
g jets + WTA

jets, $R = 0.5$, $p_{T,jet} > 20$ GeV/c, $2.5 < y_{jet} < 4.0$

**The absence of
hard-collinear emissions in
b-jets displays the
deadcone effect**



Charged hadron production in c and b jets (2025)

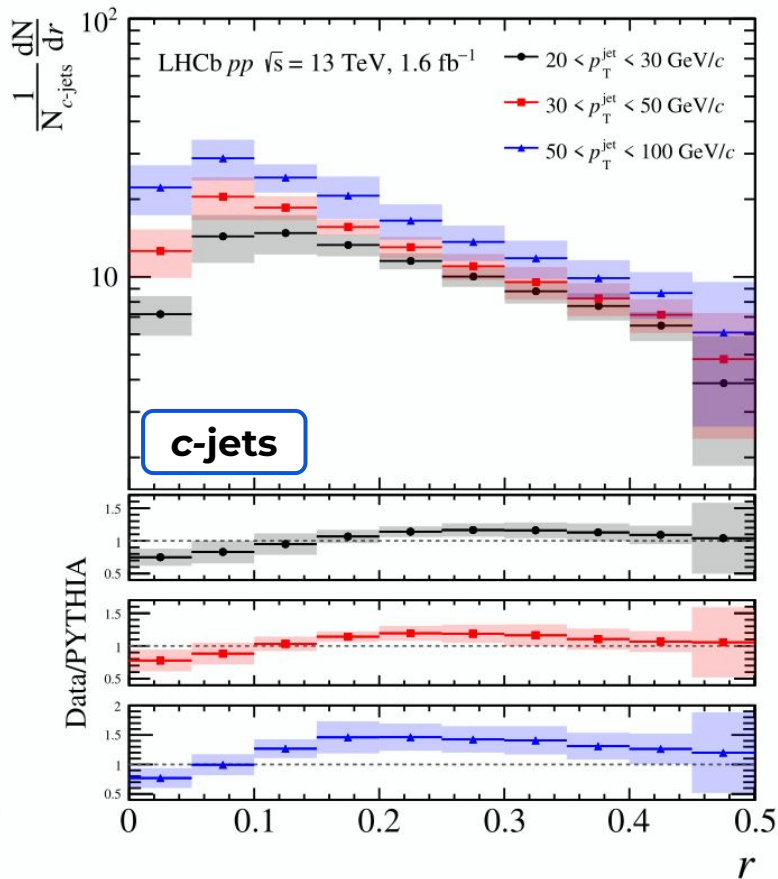
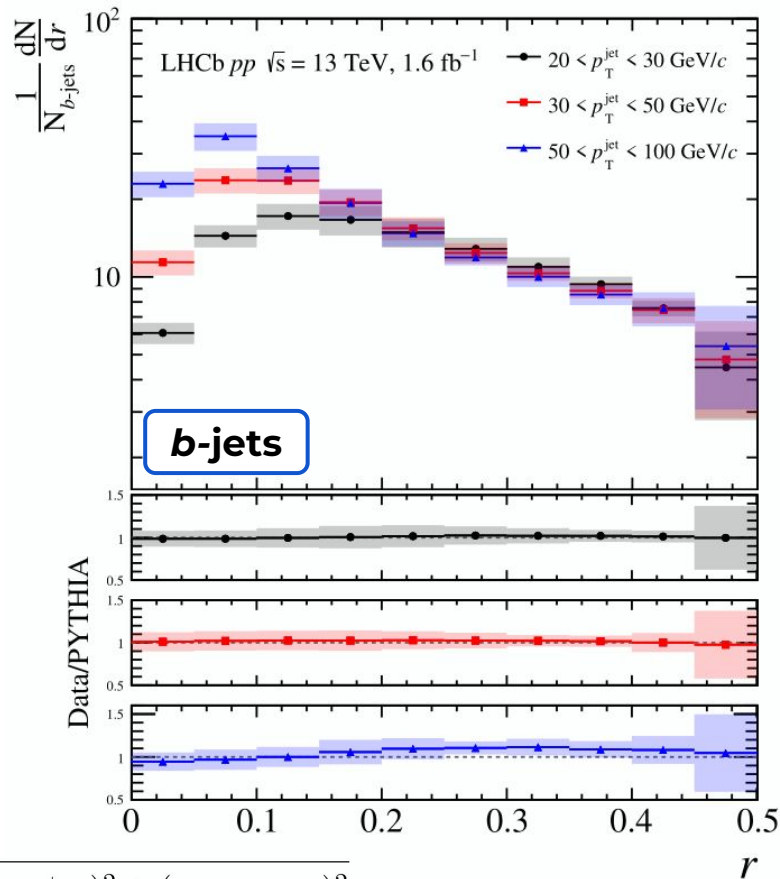


How do mass effects govern the production of charged hadrons?

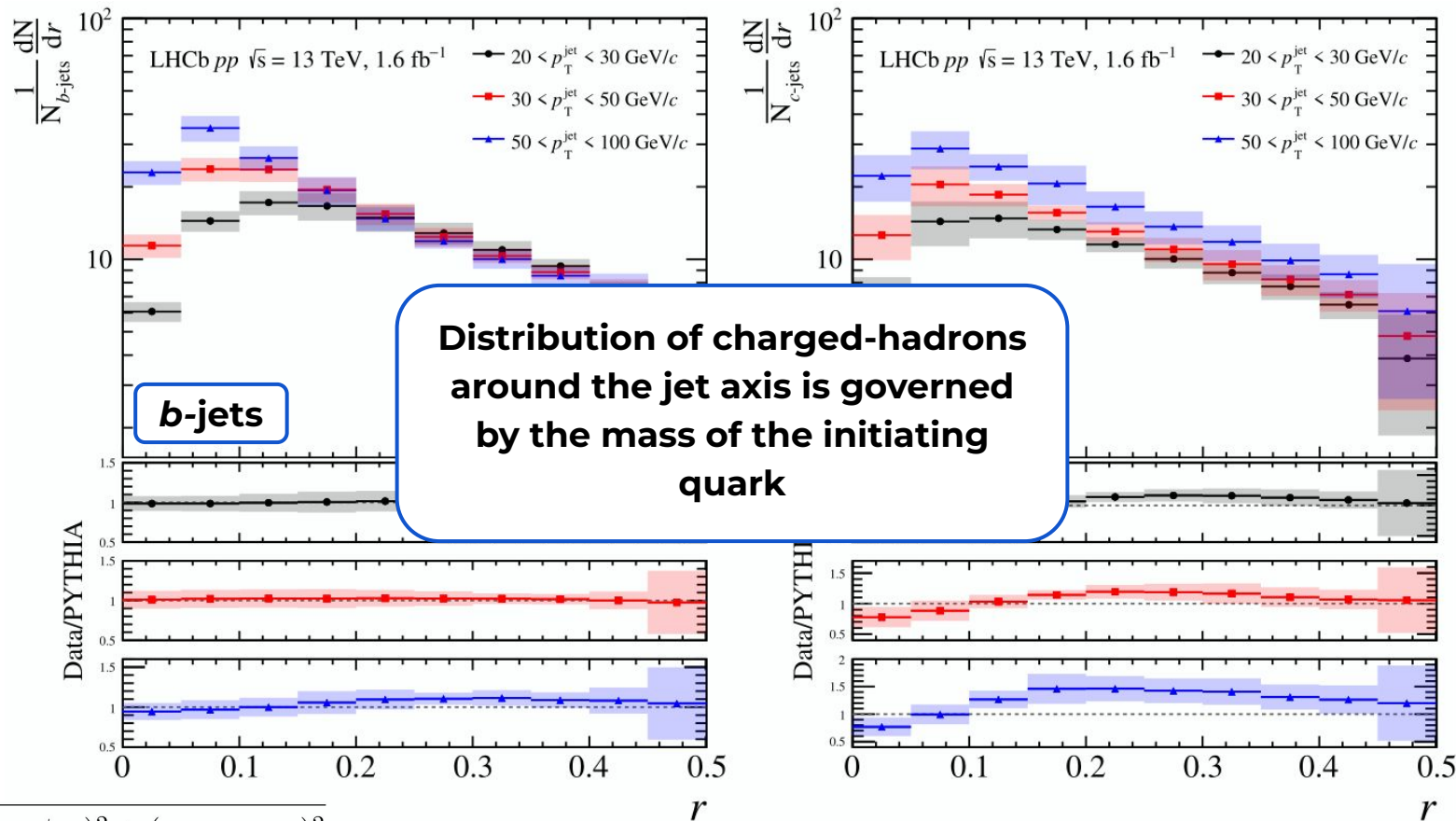
$$z = \frac{p_h \cdot p_{jet}}{|p_{jet}|^2}$$

$$r \equiv \sqrt{(\phi_{had} - \phi_{jet})^2 + (\eta_{had} - \eta_{jet})^2}$$

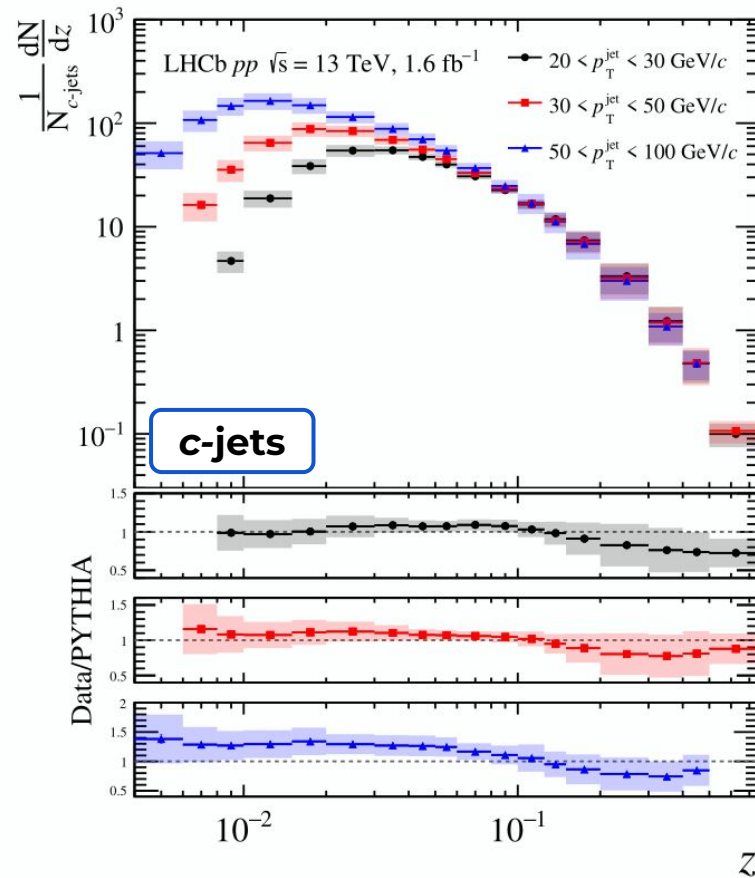
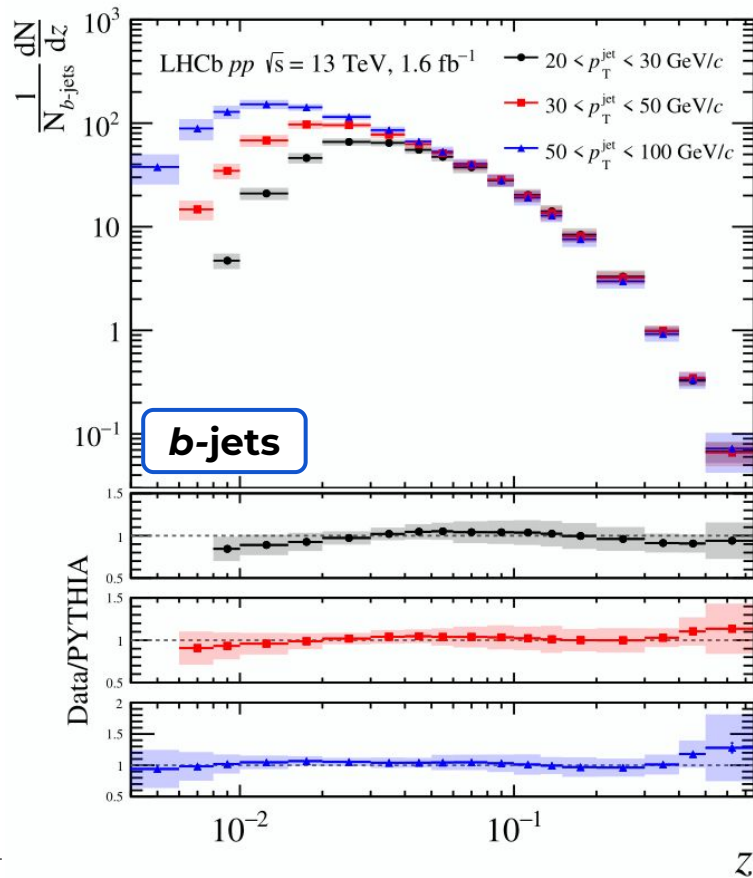
Charged hadron production in c and b jets (2025)



Charged hadron production in c and b jets (2025)

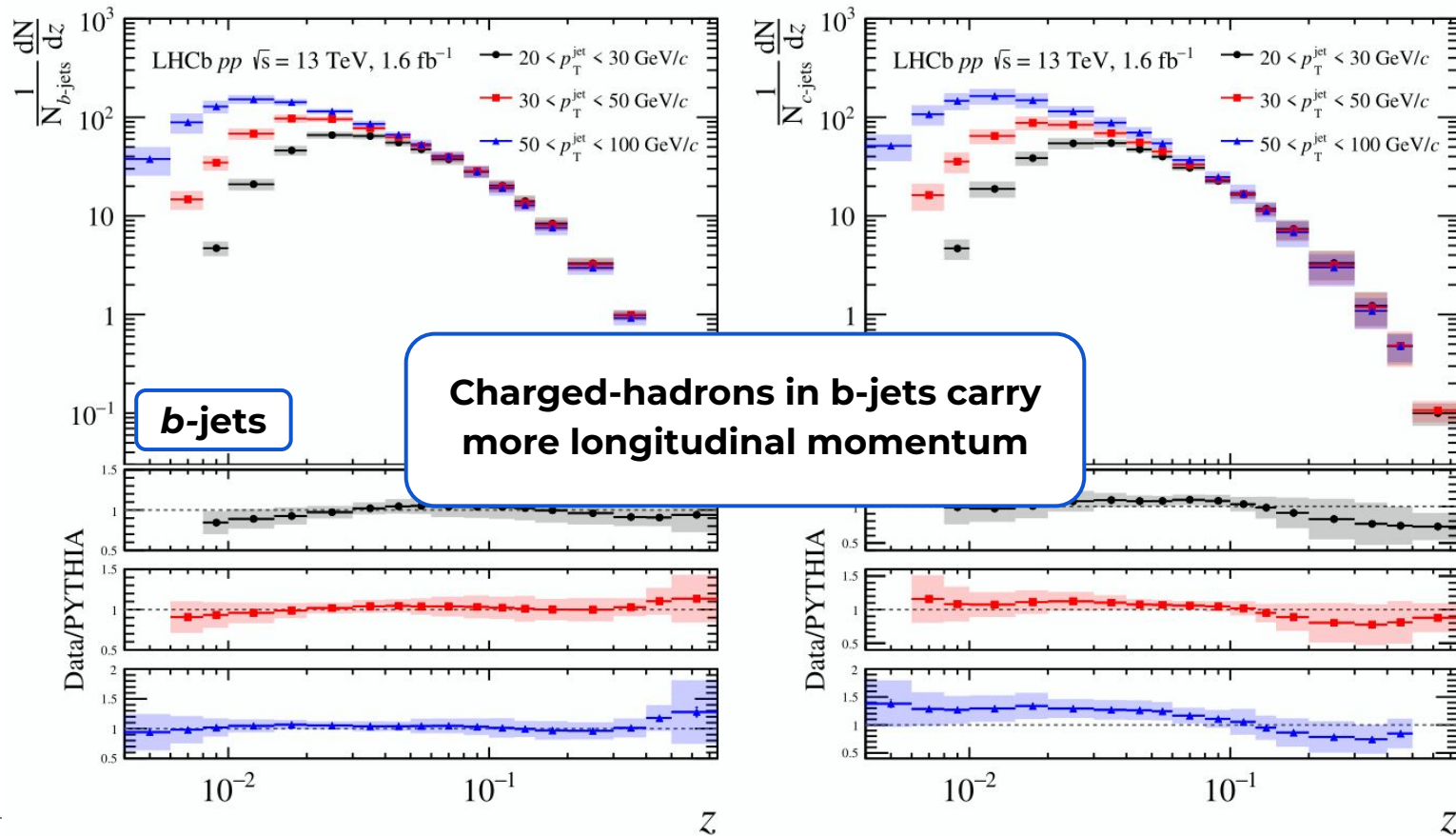


Charged hadron production in c and b jets (2025)

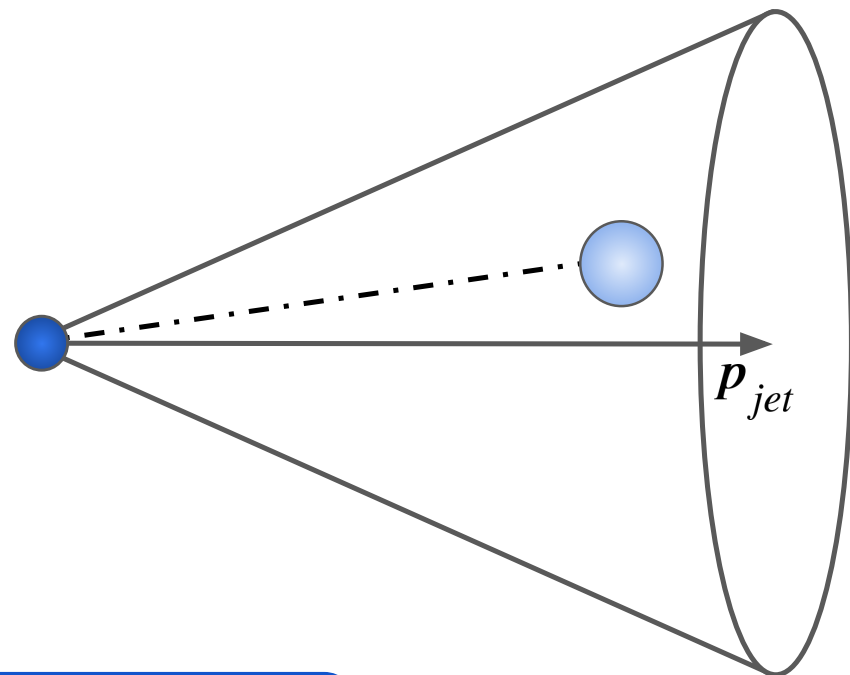
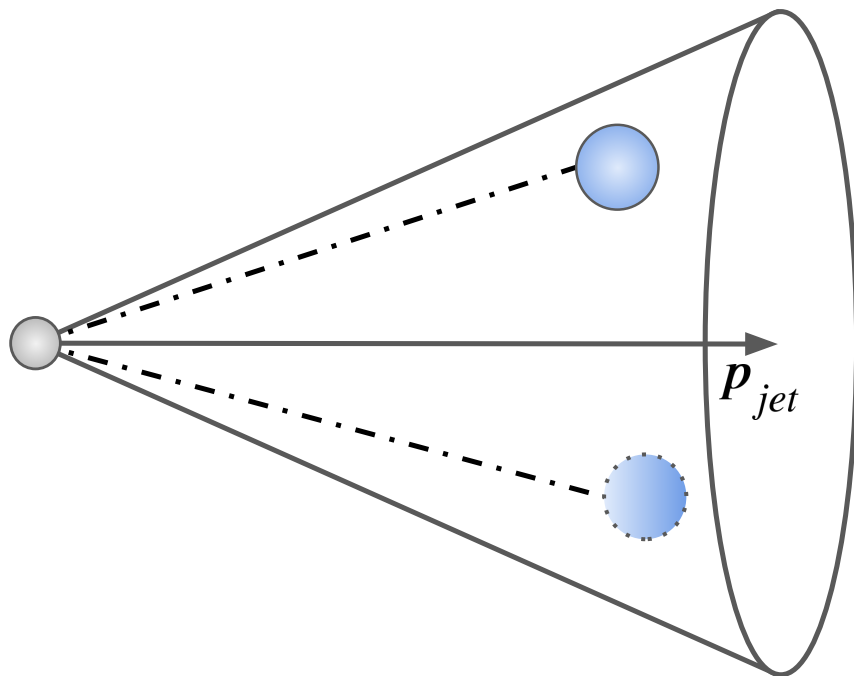


$$z = \frac{p_h \cdot p_{\text{jet}}}{|p_{\text{jet}}|^2}$$

Charged hadron production in c and b jets (2025)

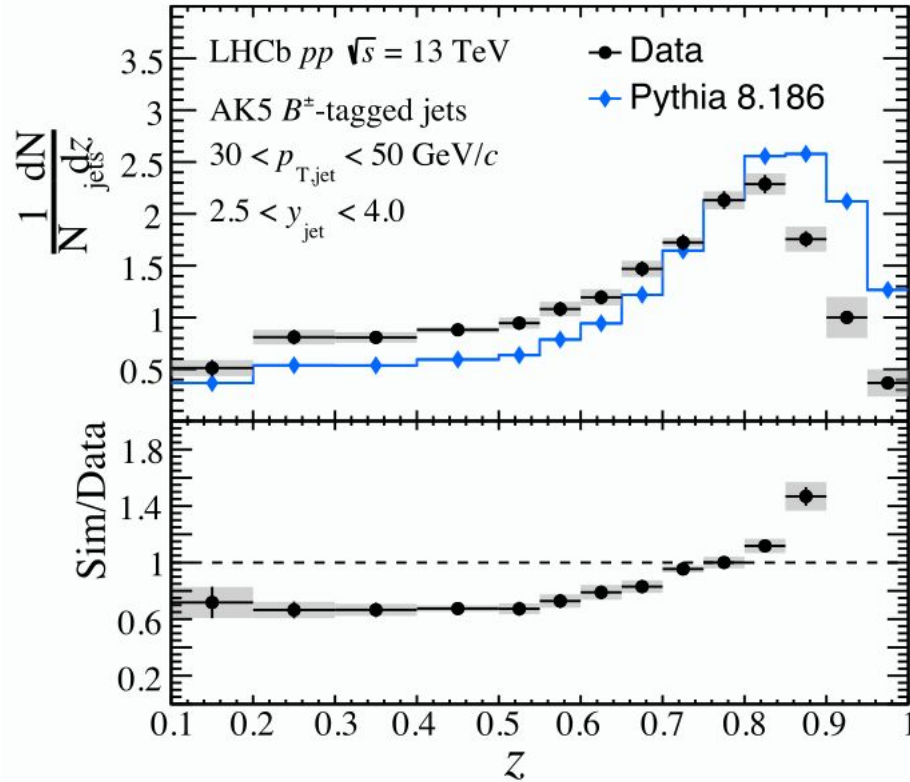


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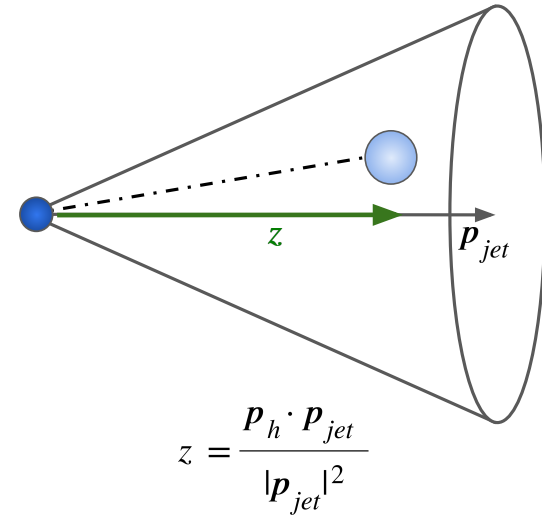


What dynamics are observed in b quarks fragmenting in a jet?

B-jet fragmentation with $B^\pm \rightarrow J/\psi K^\pm$ (2026)

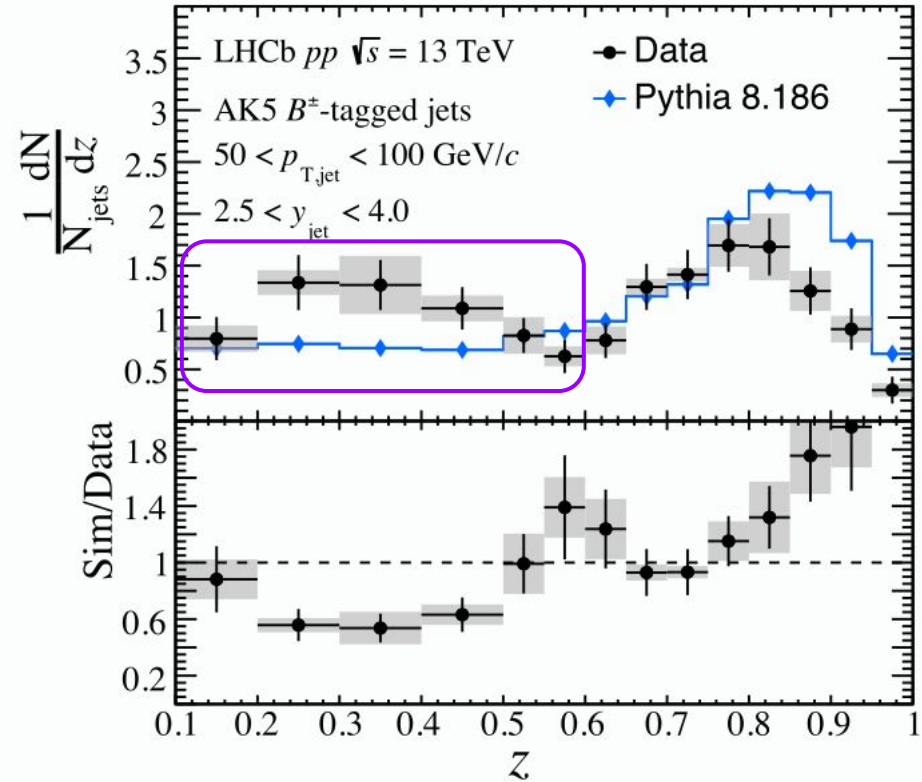
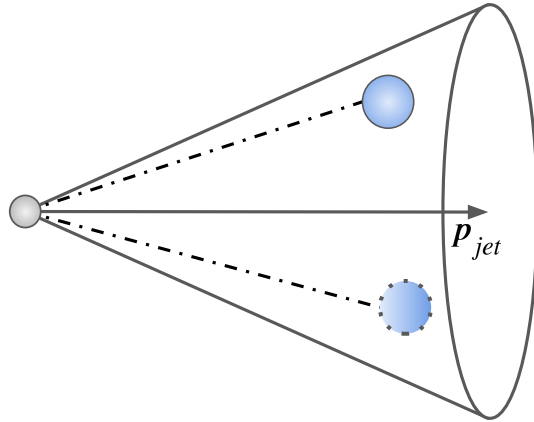


B meson carries most of the jet momentum at low jet pt



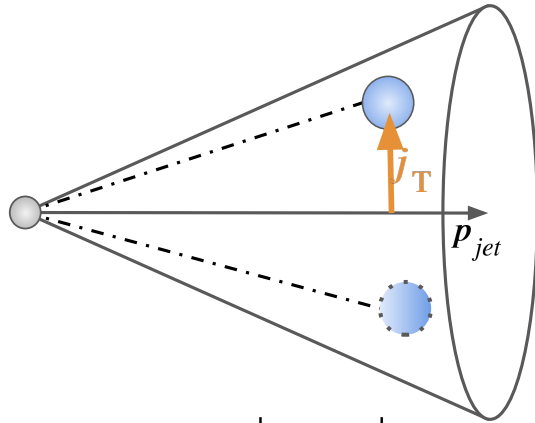
B-jet fragmentation with $B^\pm \rightarrow J/\psi K^\pm$ (2026)

**Contribution of
gluon-splitting becomes
significant at high jet pt**

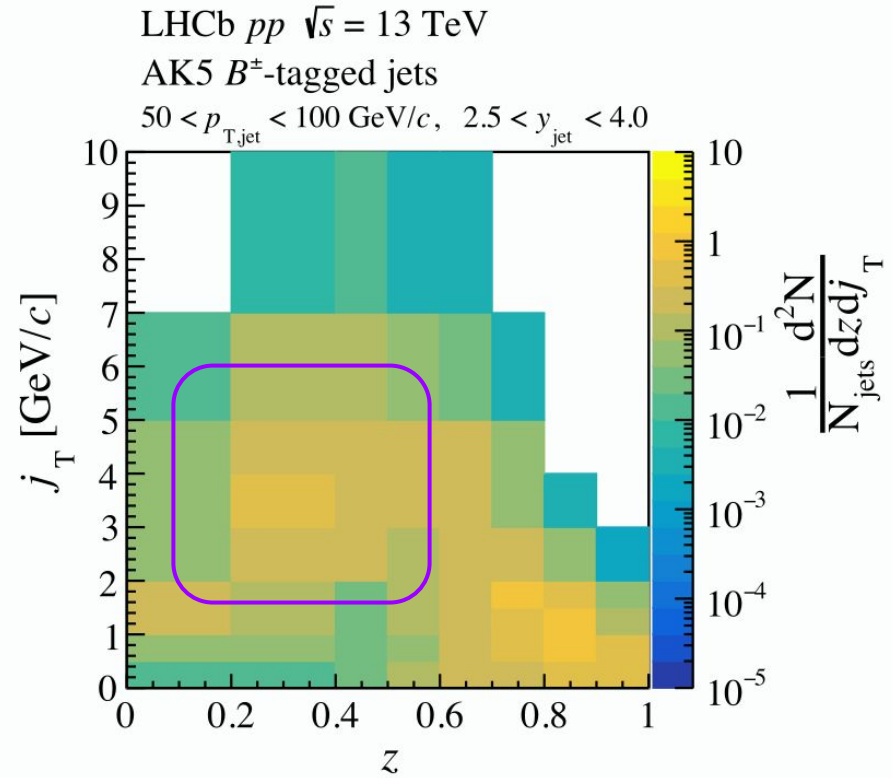


B-jet fragmentation with $B^\pm \rightarrow J/\psi K^\pm$ (2026)

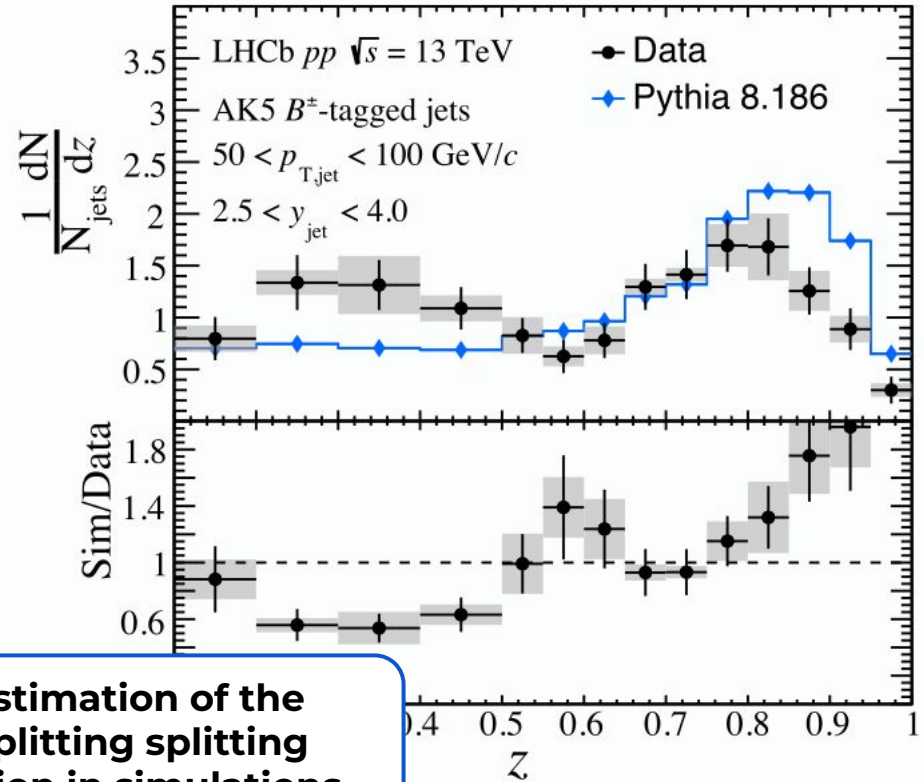
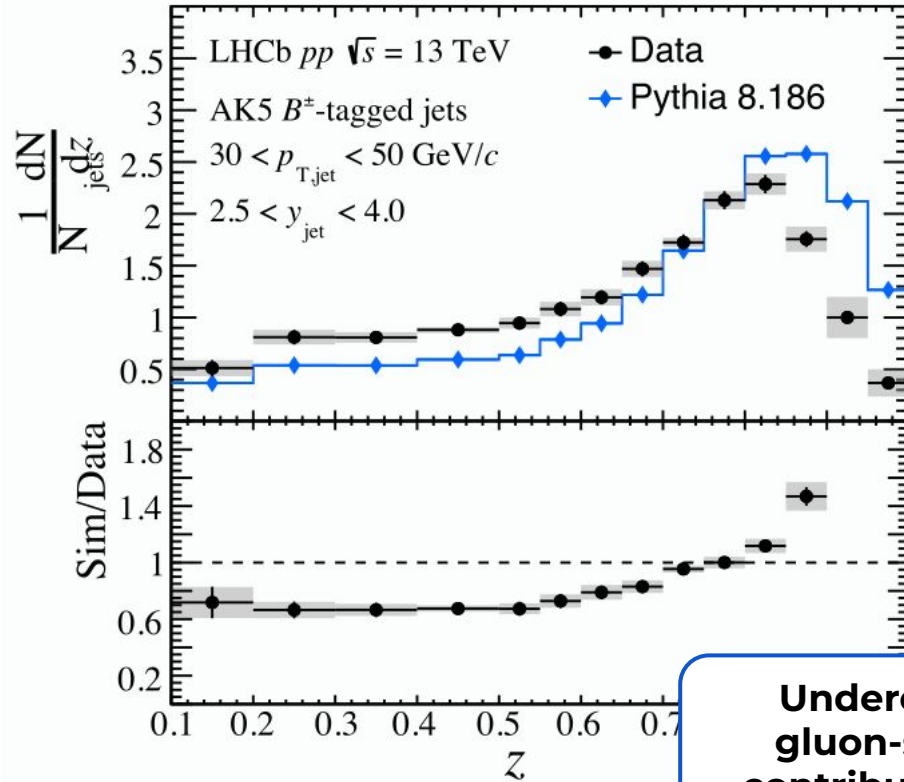
Another perspective
corroborates the
contribution of gluon
splitting



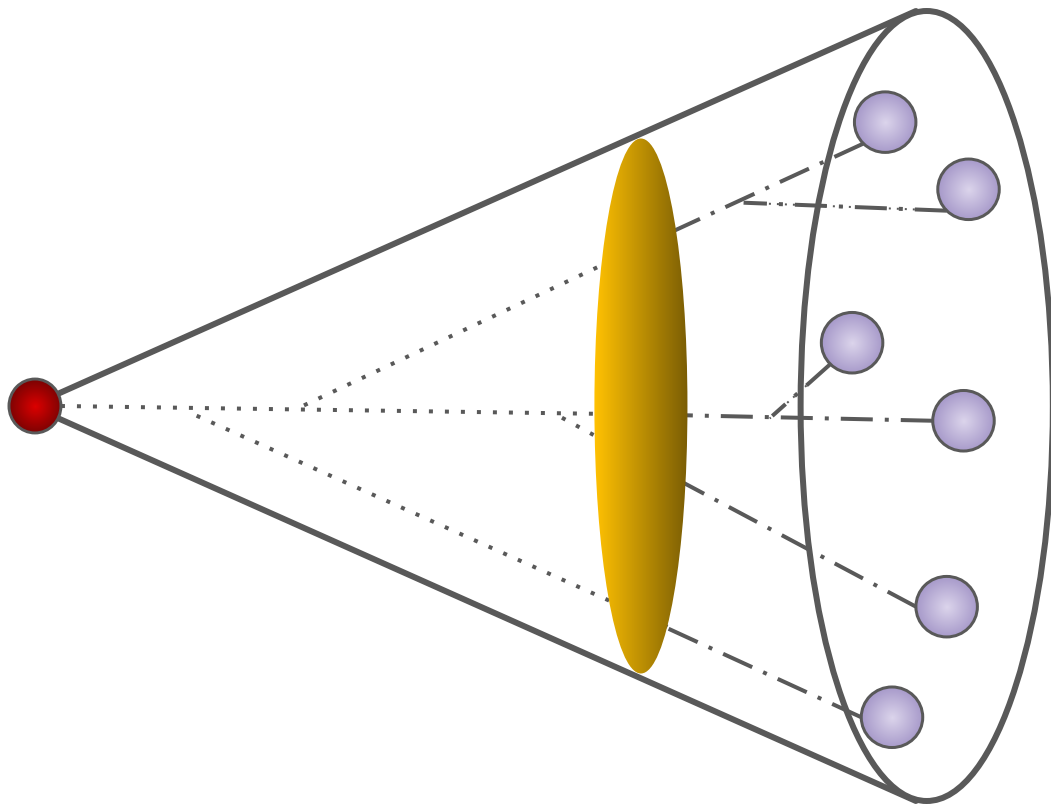
$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$



B-jet fragmentation with $B^\pm \rightarrow J/\psi K^\pm$ (2026)



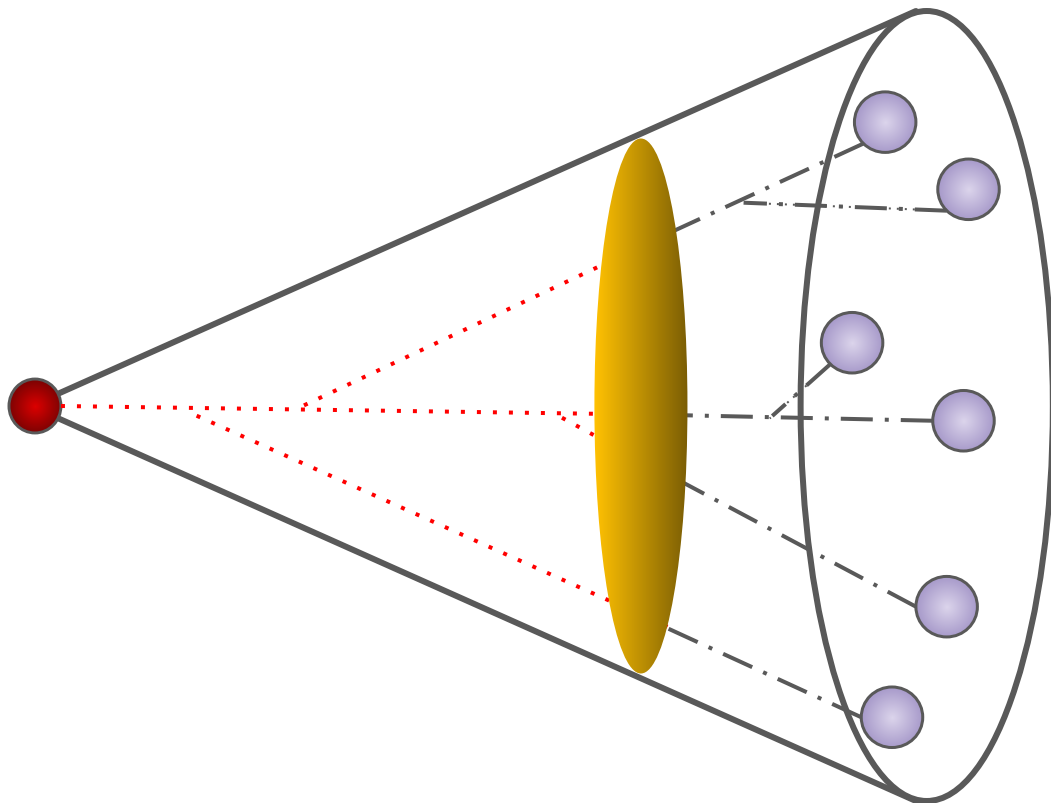
**Underestimation of the
gluon-splitting splitting
contribution in simulations**



**Accessing QCD's
perturbative and
non-perturbative regimes
through
momentum-weighted
angular correlations**

$$w_{p_T}^{ij} = \frac{p_T^i p_T^j}{(p_{T,\text{jet}})^2}$$

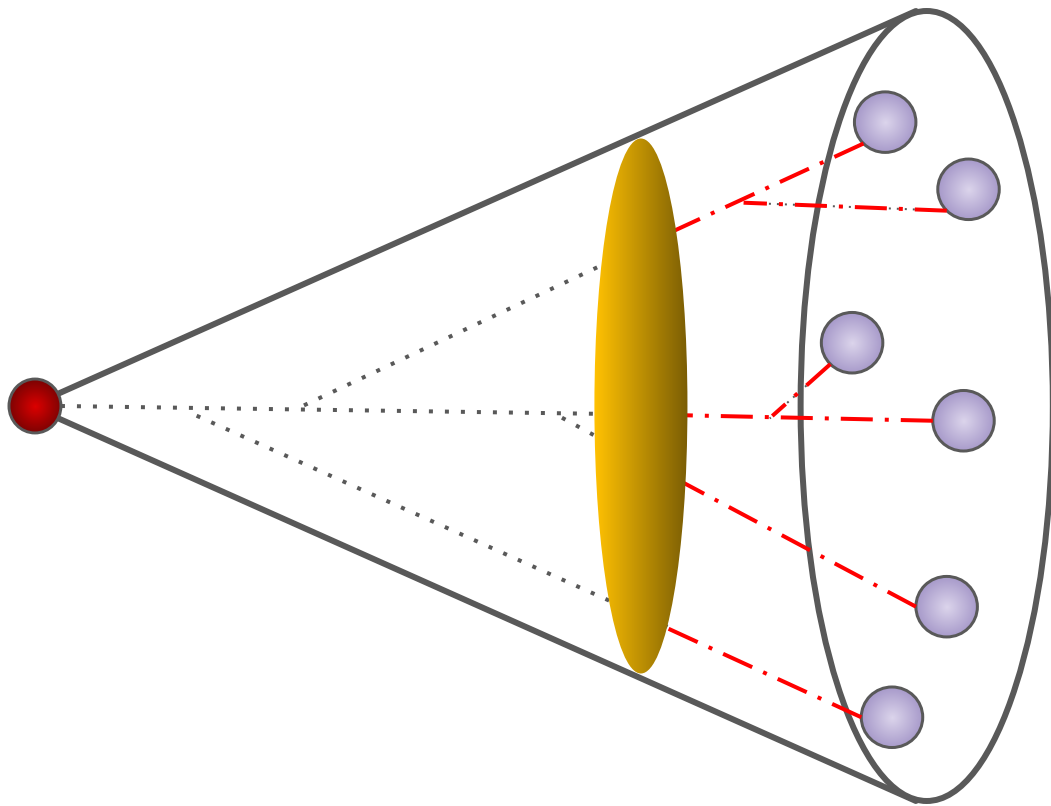
$$R_L = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$$



Accessing QCD's
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non-perturbative regimes
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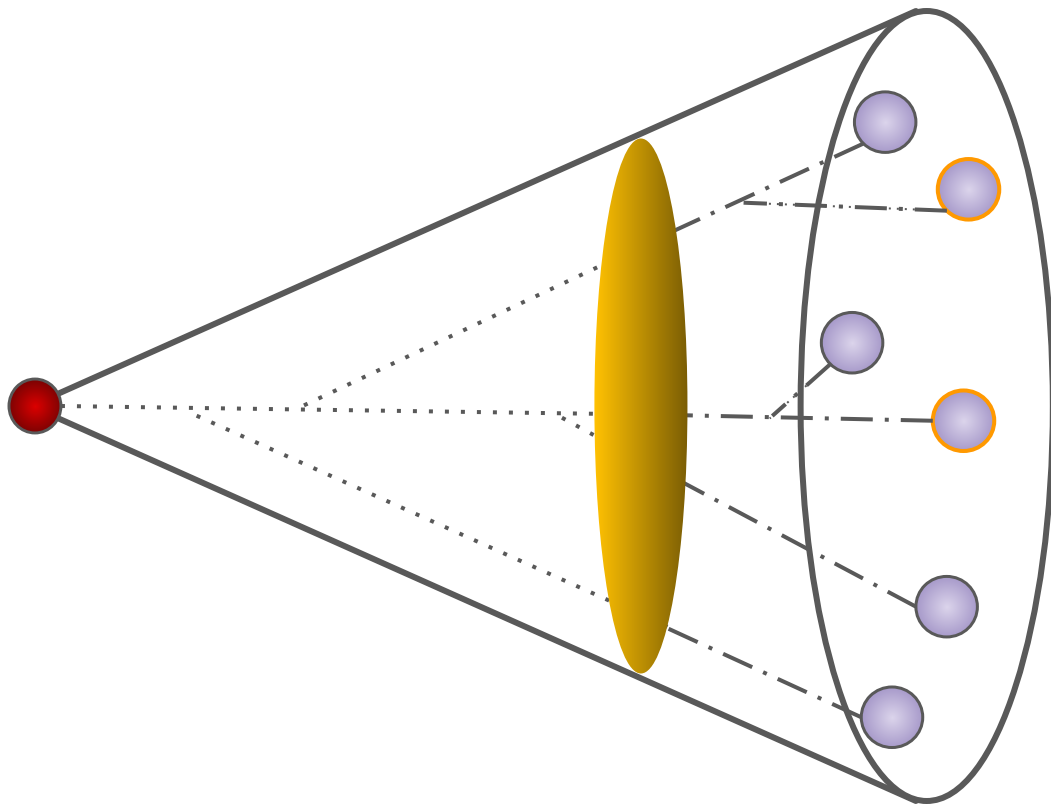
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Accessing QCD's
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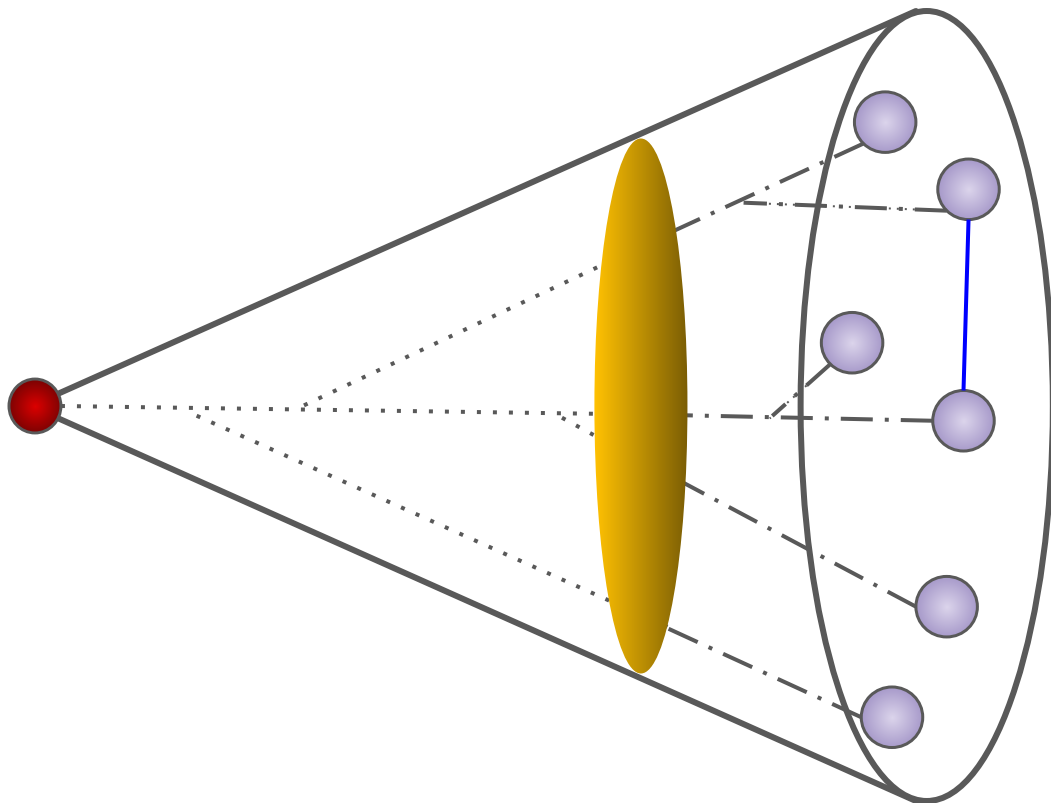
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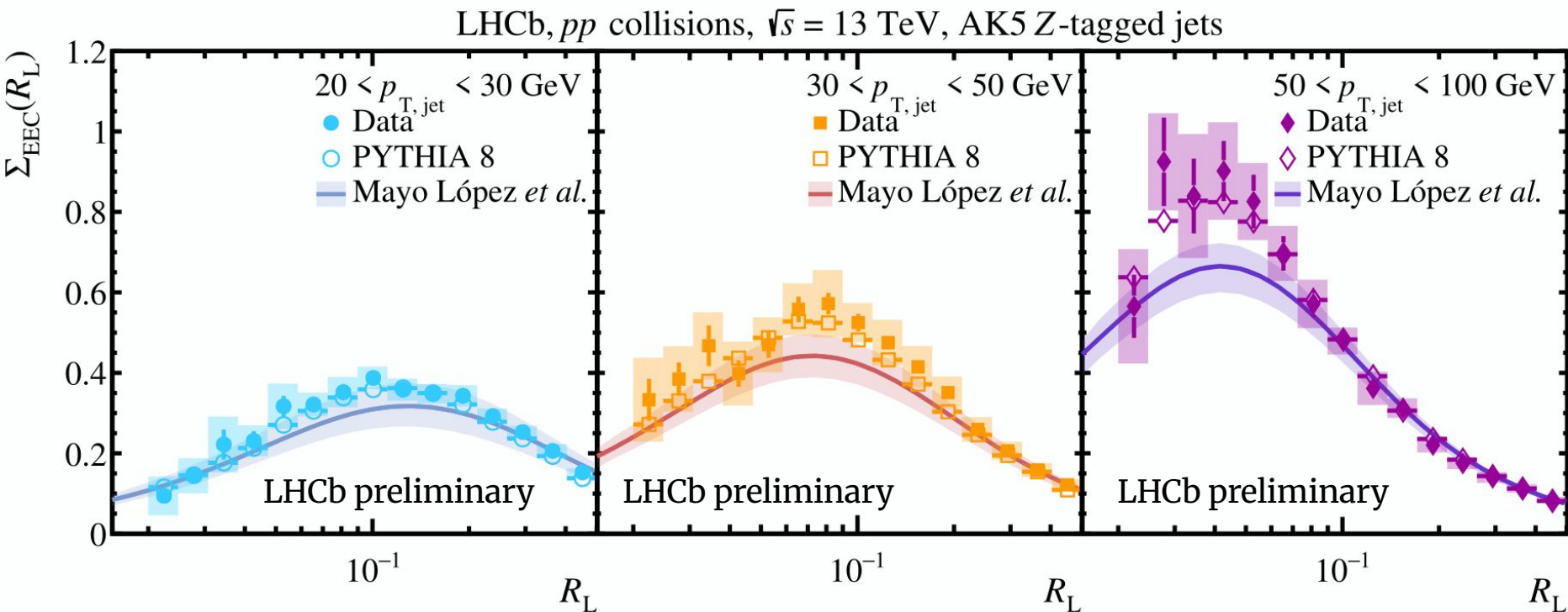


Accessing QCD's
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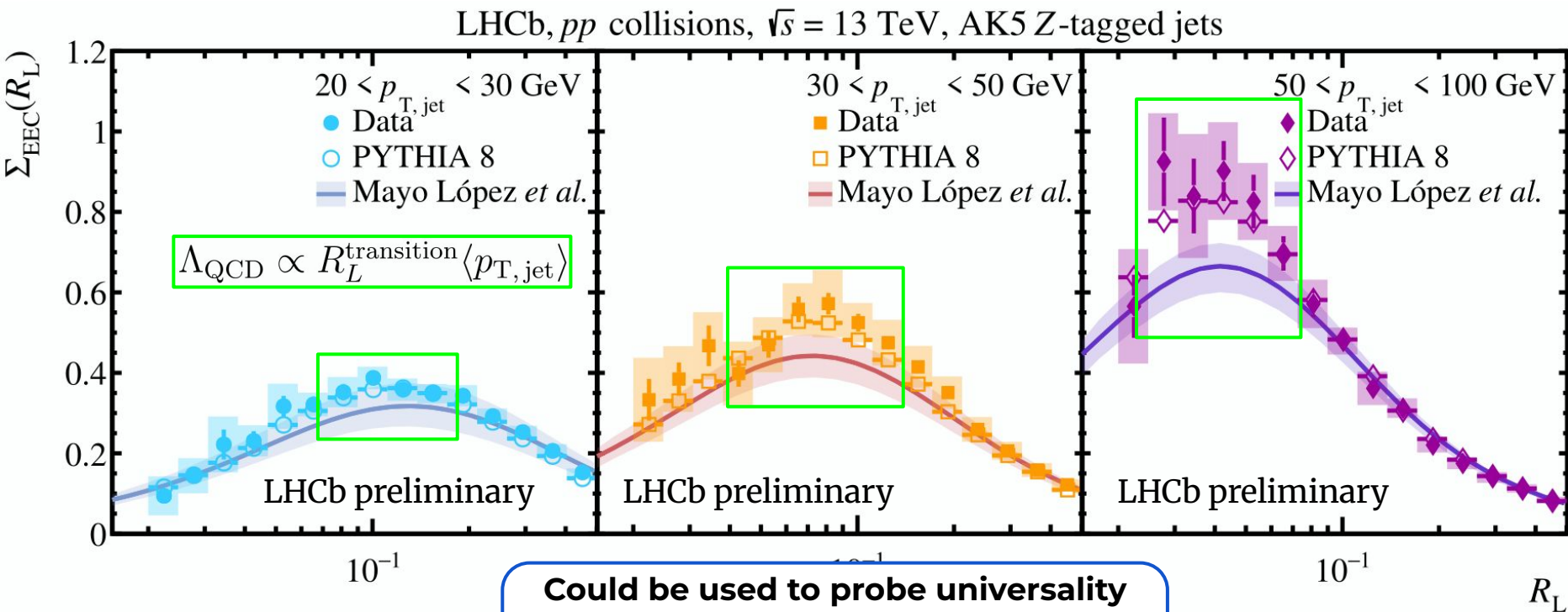
$$R_L = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$$

Energy-energy correlators in Z-tagged jets



$$R_L = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$$

Energy-energy correlators in Z-tagged jets

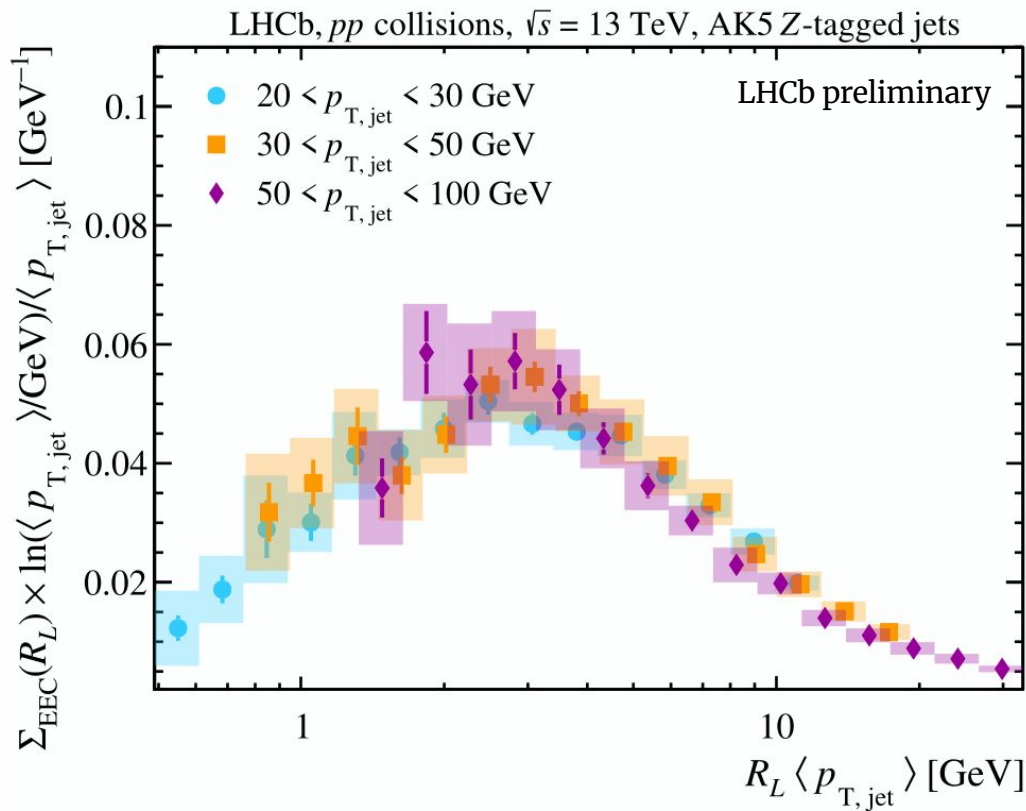


Could be used to probe universality
of confinement transition across
hadronization environments

[arXiv:2609.03072 \[hep-ph\]](https://arxiv.org/abs/2609.03072)

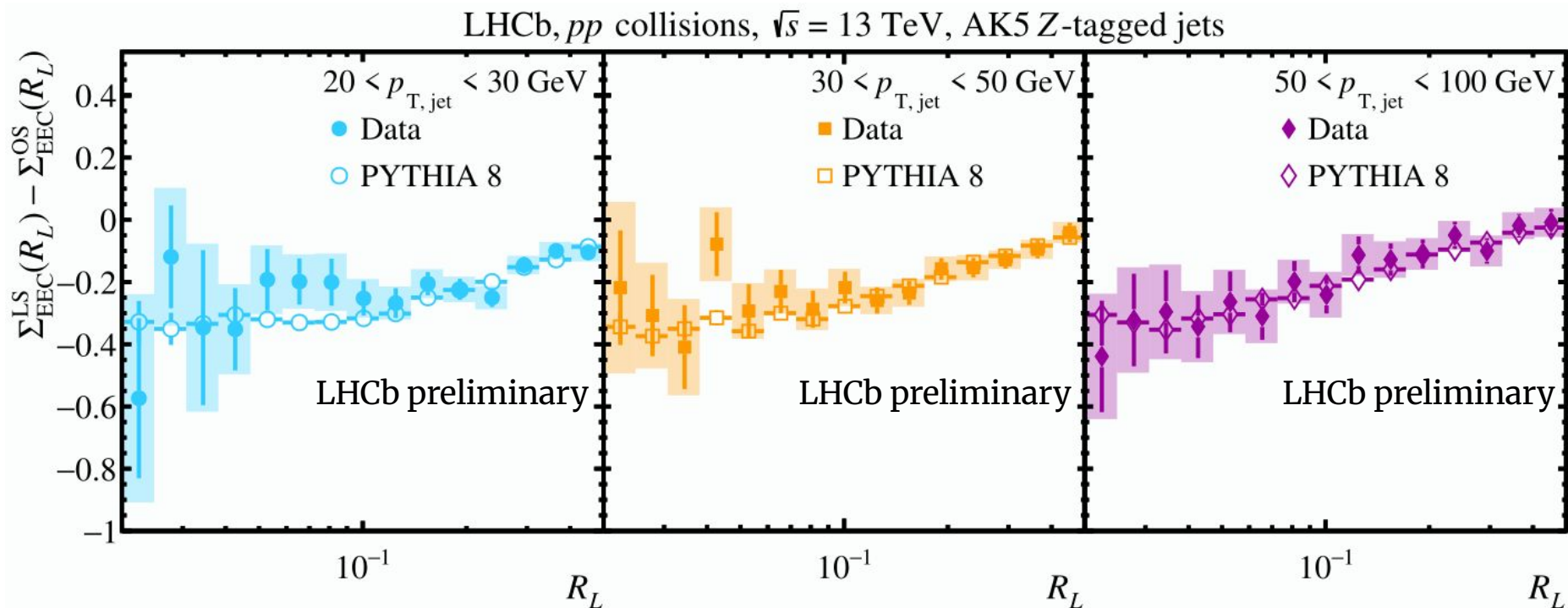
$$R_L = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$$

Energy-energy correlators in Z-tagged jets (2026)

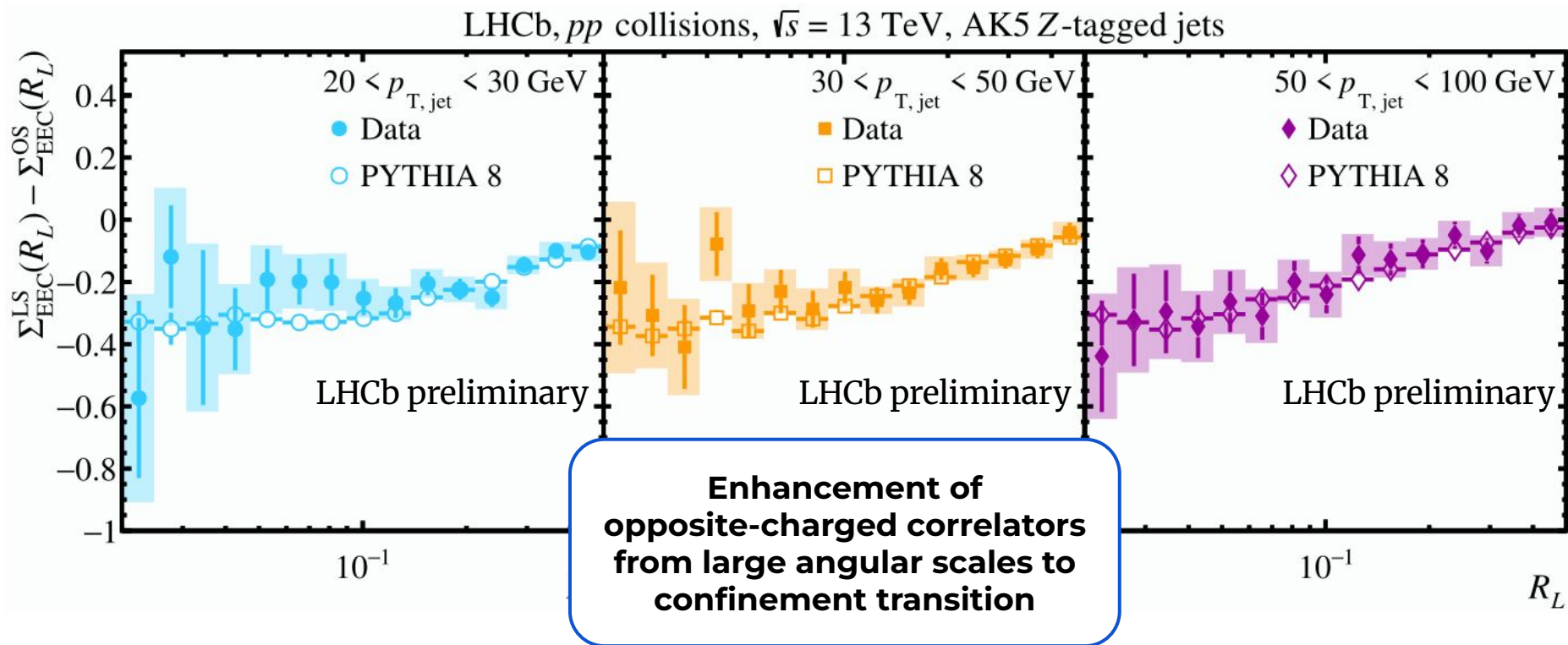


**Rescaling of x-axis displays
the alignment of the
transition regions**

**Could be used to probe
universality of confinement
transition across jet
transverse momentum**



$$R_L = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$$



$$R_L = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$$

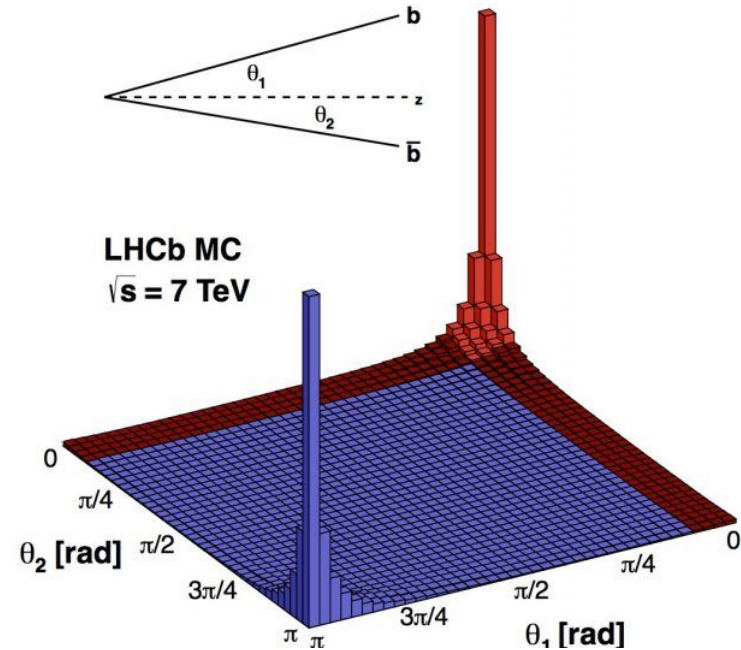
Summary

- LHCb provides the appropriate conditions for clean measurements of HF-flavored and light-quark jets.
- Results displays different dynamics of jet formation at different jet p_t ranges.
- More results on jets at LHCb will come up in the following months!

Thank you!

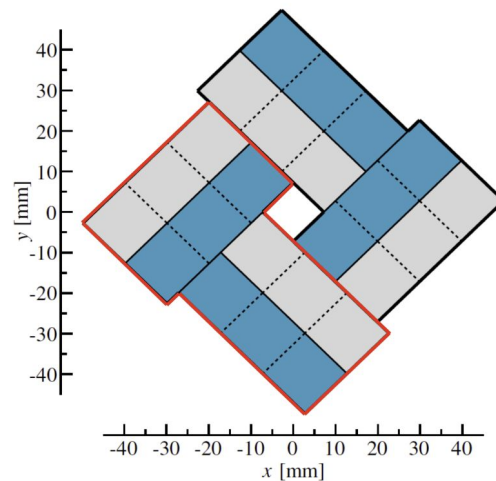
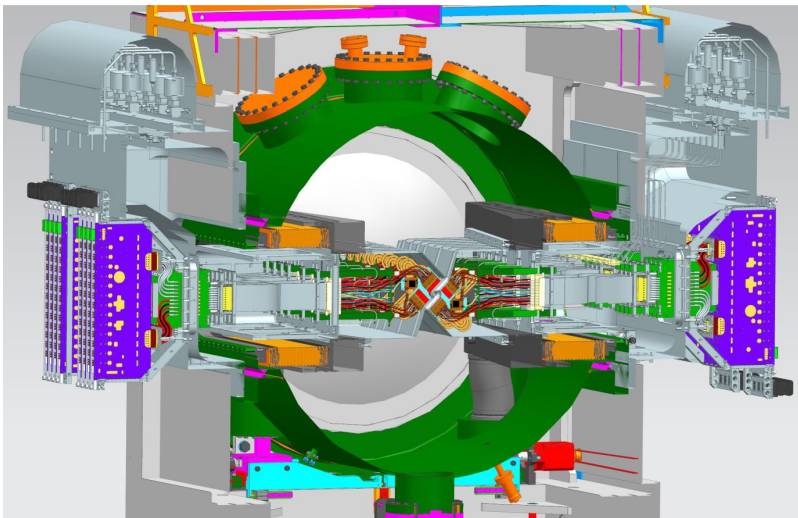
Backup Slides

The forward region coverage by LHCb is especially convenient for the measurement of heavy quark physics.



The LHCb Experiment : VELO (Run 3)

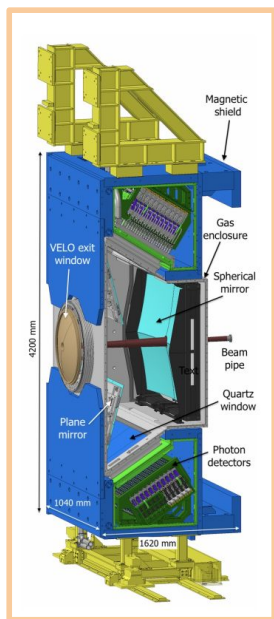
- Designed to handle higher luminosities.
- Use of pixelated hybrid silicon detectors.
- Upgraded VELO can be positioned as close as 5mm to the beamline.



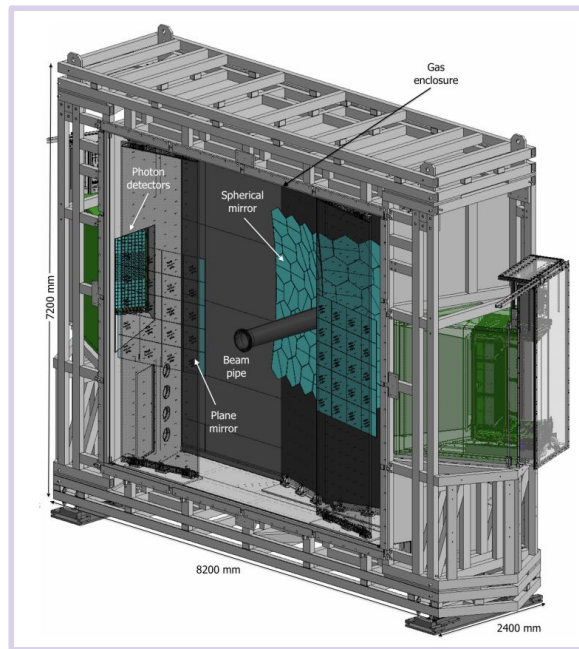
The LHCb Experiment : RICH

- **Main goal** : provide accurate PID for charged hadrons.
- Two RICH stations to cover different momentum ranges.
- Layout and design of the RICH has not changed between Run 1-2 and Run 3

RICH 1
 $2.6 < p(\text{GeV}) < 60$

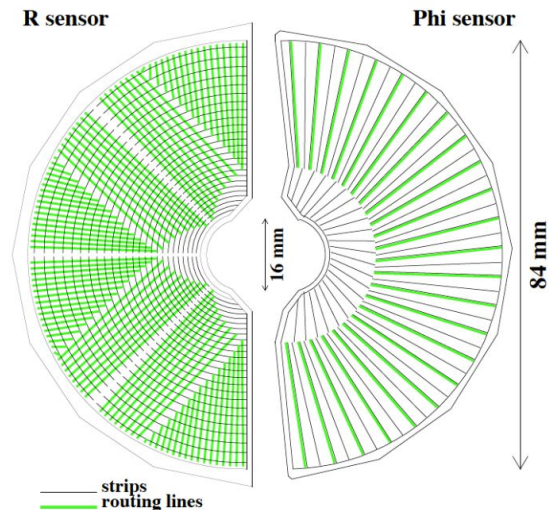


RICH 2
 $15 < p(\text{GeV}) < 100$



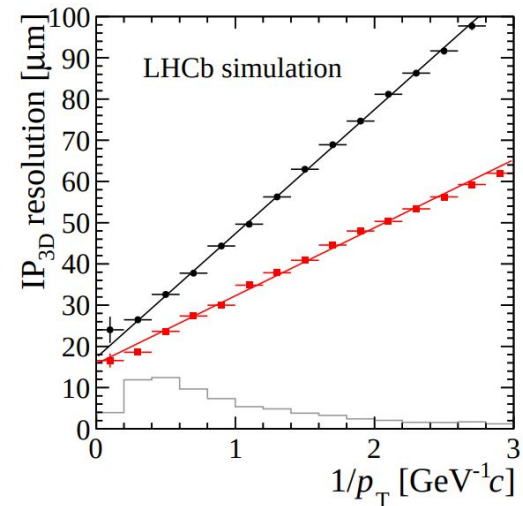
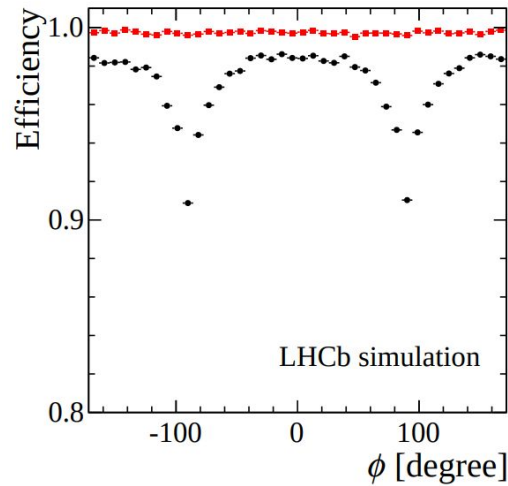
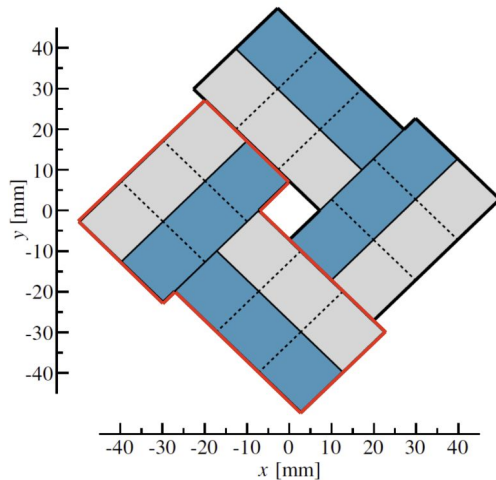
The LHCb Experiment : VELO (Run 1 and 2)

- **Main goal:** identify the location of displaced secondary vertices (indication of heavy flavour jets)
- The Vertex Locator (VELO) is the detector in charge of taking precise information about the tracks near to the collision point.
- VELO can be positioned as close as 7mm to the beamline.

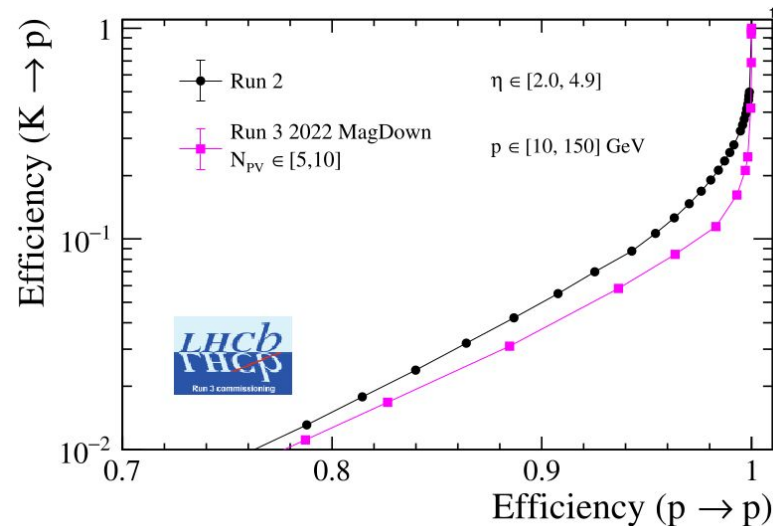
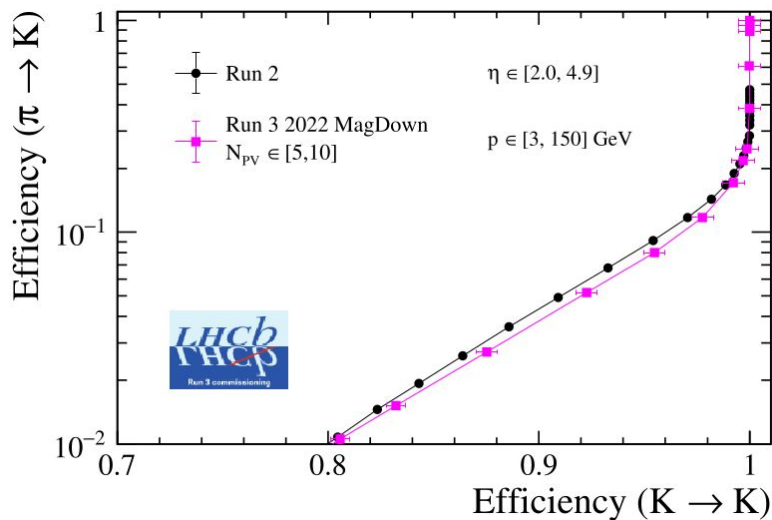


The LHCb Experiment : VELO (Run 3)

- The performance of the Run 3 VELO is given by the red points.
- Uniform efficiency across ϕ .
- Better resolution in comparison to Run 1-2 VELO.

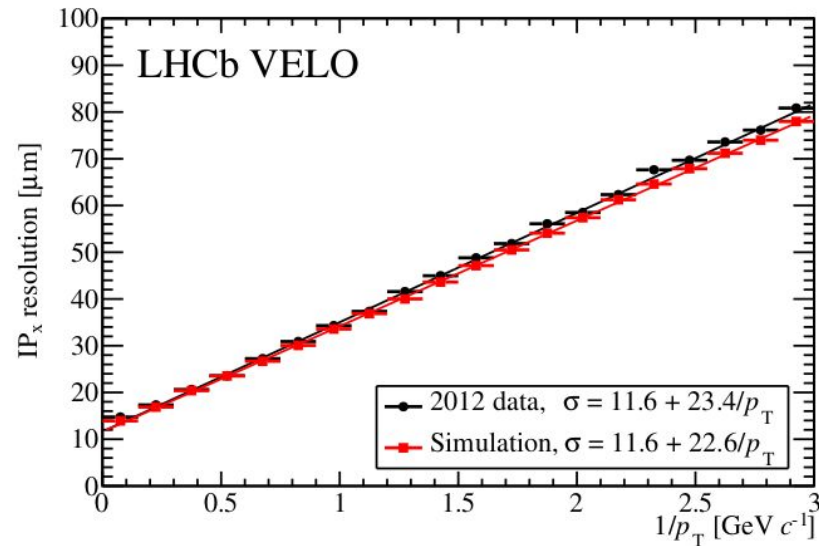
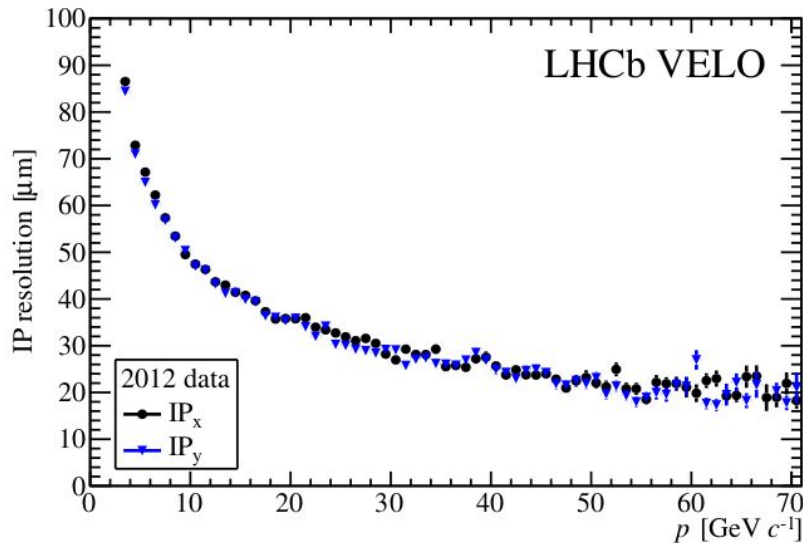


- Run 3 performance of the RICH shows a better performance in terms of reducing the mis-ID efficiency (vertical axis)

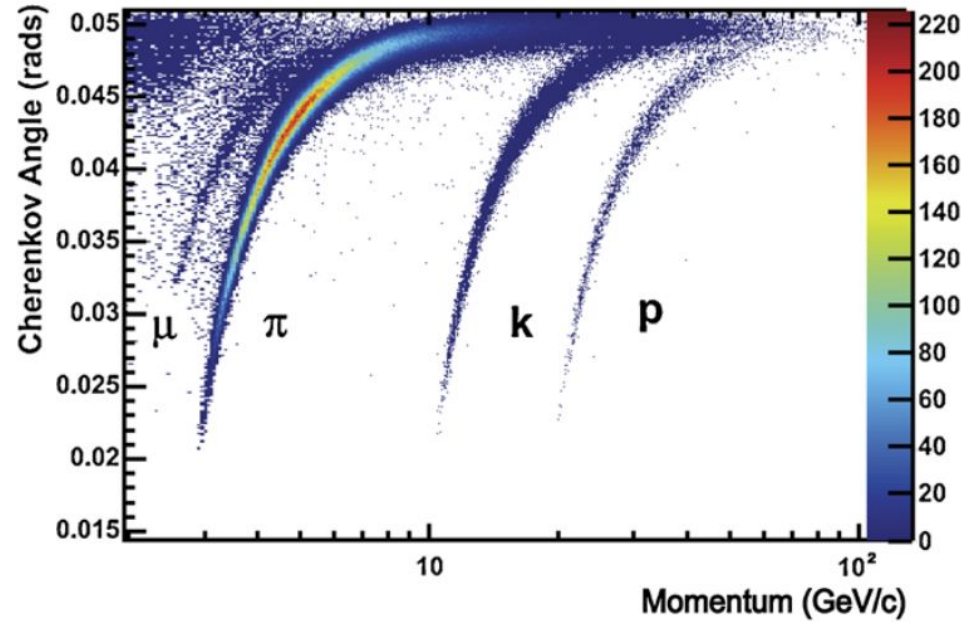


The LHCb Experiment : VELO (Run 1 and 2)

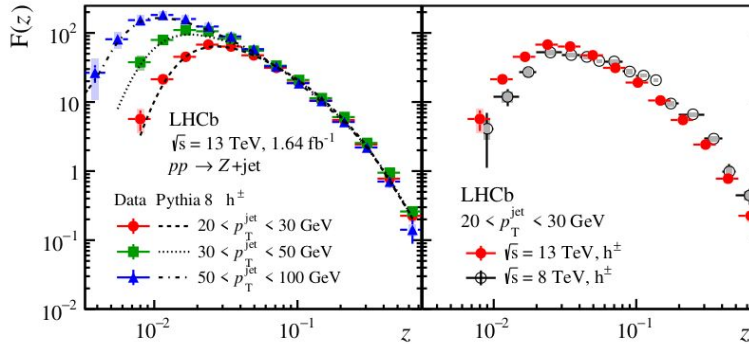
- IP is the minimum distance between the primary vertex and the trajectory of a displaced track.
- The performance of the VELO is the same for x and y coordinates.



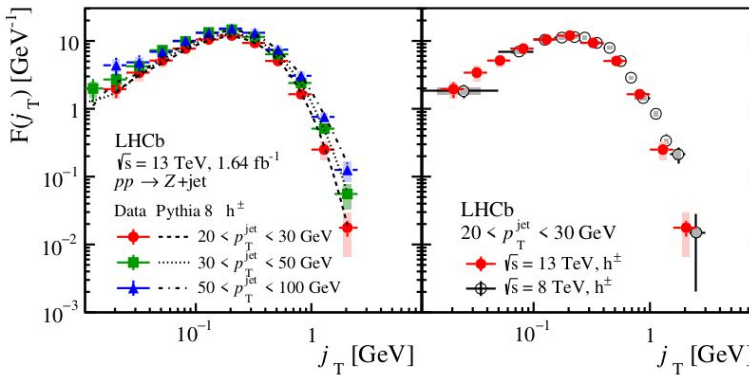
RICH (Run 1) PID capabilities



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



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



- Distributions are shown for all the hadrons combined.
- Increasing jet pt shows a shift of the distributions towards low z regions which are associated with a vast production of soft particles.
- Comparison between results with different $\sqrt{s}$ shows an enhancement of the soft radiation region.

Algorithm to determine the flavour of the Jet. Given a jet clustered with any algorithm follow the steps:

1. For all pairs of particles in the jet calculate a metric d_{ij}
2. Take the pair with the smallest d_{ij} and combine the two particles into one with:
 - a. Total pt equal to the sum of p_{ti} and p_{tj}
 - b. Direction and mass equal to the particle with highest pt.
3. Replace the aforementioned pair with the ij combination in the jet.
4. Repeat until there is one particle. The direction of that final particle is defined as the WTA jet axis.
5. The flavour of the jet is determined by the sum of flavours of the particles that lie exactly along the WTA axis.

- Normalization
 - JEC approx 3%
 - Z boson mis-reconstruction approx 1.4%
 - Unfolding 1%
- Charged hadrons
 - PID between 1 and 3%
 - Unfolding 0.8%

Lund plane for light- and beauty-quark jets

Source	k_T -LJP uncertainty (%)	z -LJP uncertainty (%)
Tracking efficiency	< 1	< 1
PID efficiency	< 1	< 1
Trigger efficiency	< 1	< 1
Jet energy scale	$0 - 10$	$0 - 10$
Jet energy resolution	$0 - 10$	$0 - 5$
Jet identification	$0 - 2$	$0 - 2$
Unfolding prior	$0 - 13$	$0 - 15$
Unfolding nonclosure	$2 - 10$	$2 - 20$
Unfolding iterations	$0 - 5$	$0 - 5$
Jet-constituent-reconstruction efficiency	$0 - 14$	$0 - 10$
Total	$0 - 23$	$0 - 25$

Z tagged jets

Lund plane for light- and beauty-quark jets

Source	k_T -LJP uncertainty (%)	z -LJP uncertainty (%)
Background subtraction	0 – 10	0 – 11
Tracking efficiency	< 1	< 1
PID efficiency	< 1	< 1
Trigger efficiency	< 1	< 1
Jet energy scale	0 – 8	0 – 6
Jet energy resolution	0 – 14	0 – 10
Jet identification	0 – 5	0 – 7
Unfolding prior	0 – 25	0 – 50
Unfolding nonclosure	3 – 50	3 – 55
Unfolding iterations	0 – 6	0 – 9
Reconstruction and selection	0 – 10	0 – 10
Jet-constituent-reconstruction efficiency	0 – 6	0 – 6
Total	0 – 60	0 – 65

b jets

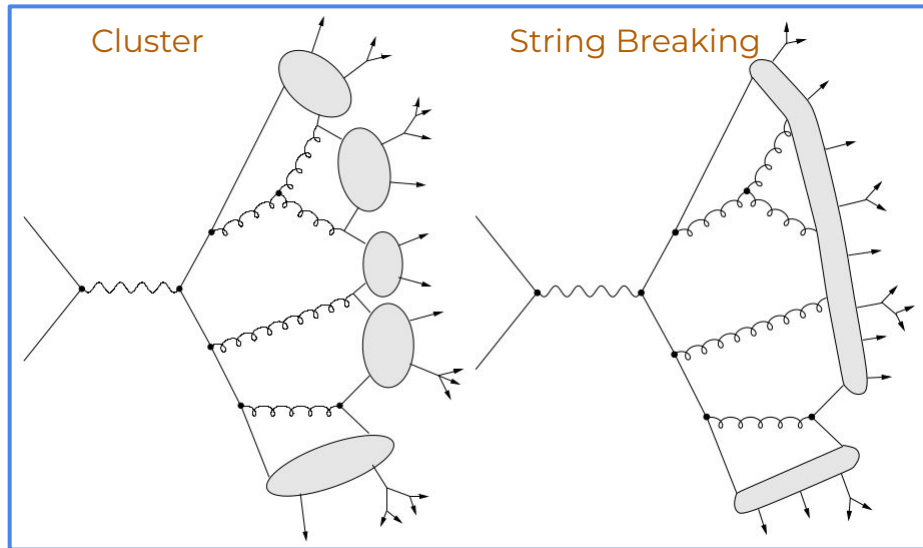
There are two main sources of systematic uncertainties: those from the efficiency determination and those from the unfolding procedure (systematic uncertainties from the signal fits are negligible).

b quark hadronization

“NoBias events are selected based on the Large Hadron Collider beam clock, which indicates that a bunch crossing has occurred, without any other trigger requirements.”

Charged hadron production in c and b jets

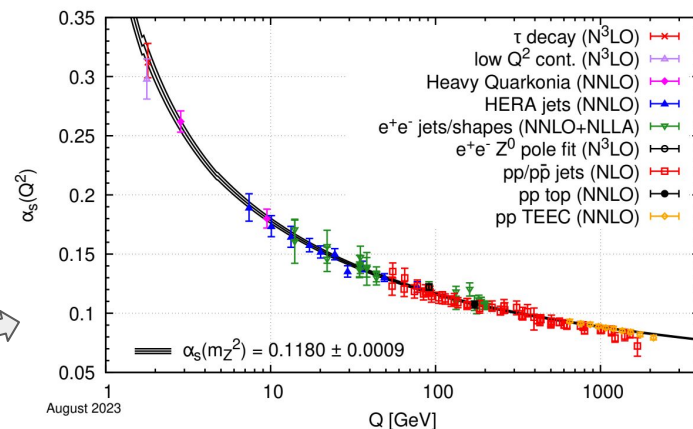
Source	Beauty jets			Charm jets		
	z (%)	j_T (%)	r (%)	z (%)	j_T (%)	r (%)
Jet identification	0–13	0–6	0–3	0–8	0–6	0–5
Track purity	2–7	1–7	2–4	1–10	1–10	3–7
Track-in-jet reconstruction efficiency	4–8	4–5	4–42	4–10	4–6	4–54
Particle misidentification	1–3	1–2	0–2	0–2	0–2	0–1
Jet energy scale	0–20	1–10	1–3	0–19	0–13	0–8
Jet energy resolution	0–16	0–6	0–4	0–10	0–10	0–9
SV+BDT _{<i>b c</i>} tag bias	1–30	1–15	1–12	1–38	1–21	1–20
Unfolding	0–17	0–19	0–10	0–7	0–23	0–10
Nonclosure	0–25	0–20	0–7	0–14	0–14	0–5
Total (excl. 2% sys. on normalization)	6–42	6–40	6–43	6–39	7–34	7–57



- Hadronization is the process where a *quasi-free* quark transform into a hadron.
- Different mechanisms of hadronization have been proposed.
- Studies of hadronization can be performed by analyzing the properties of hadronic final states from a hard interactions.

Non-Perturbative QCD

- Regime in which pQCD is no longer reliable due to the behavior of the strong coupling.
 - Hadronization happens at this energy scale.
- Need factorization for separation of the **non-perturbative physics** from partonic hard scattering.

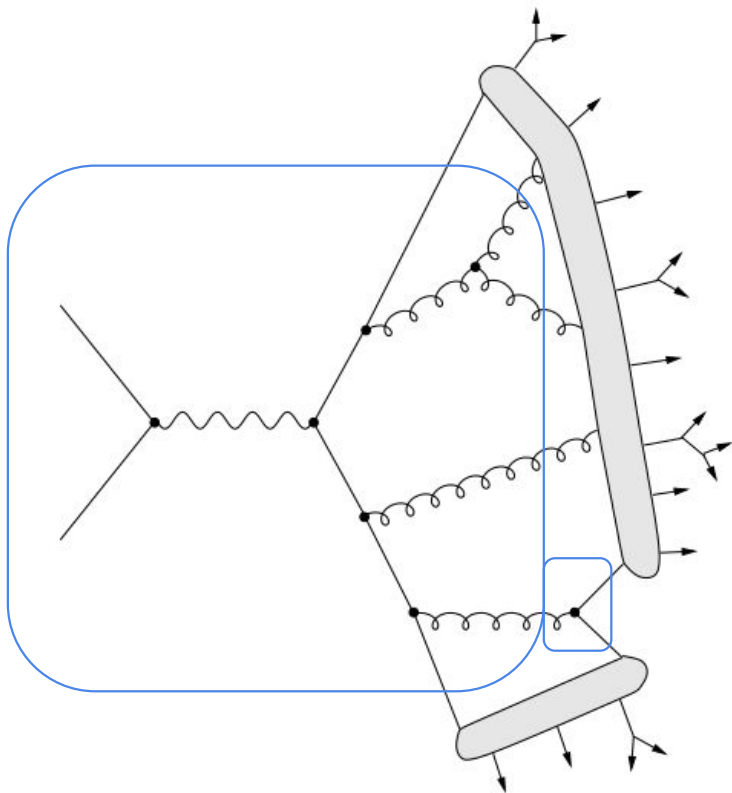


Partonic interaction

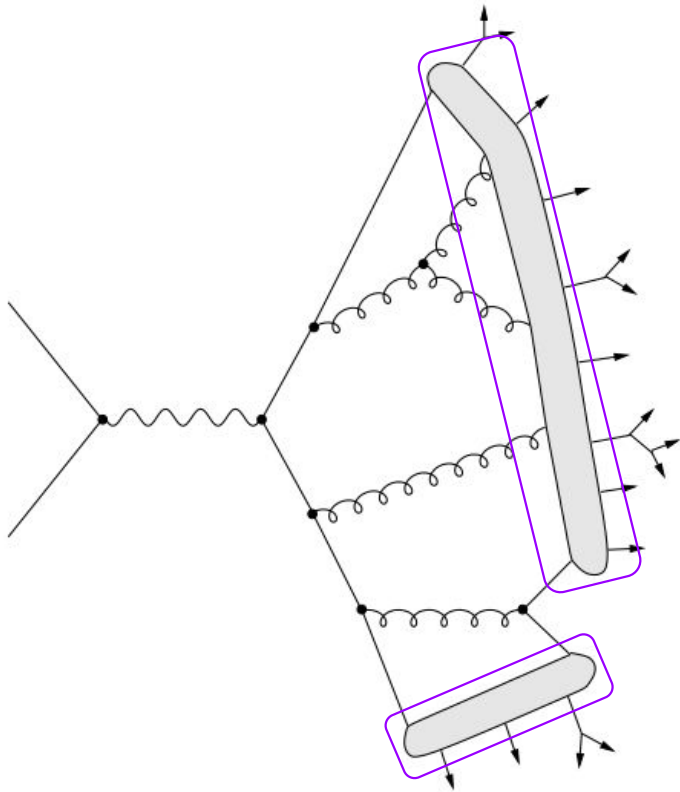
Fragmentation Function

$$d\sigma = d\hat{\sigma} \otimes f_q(x, \mu) \otimes D_{h/q}(z, \mu)$$

Parton Dist. Function

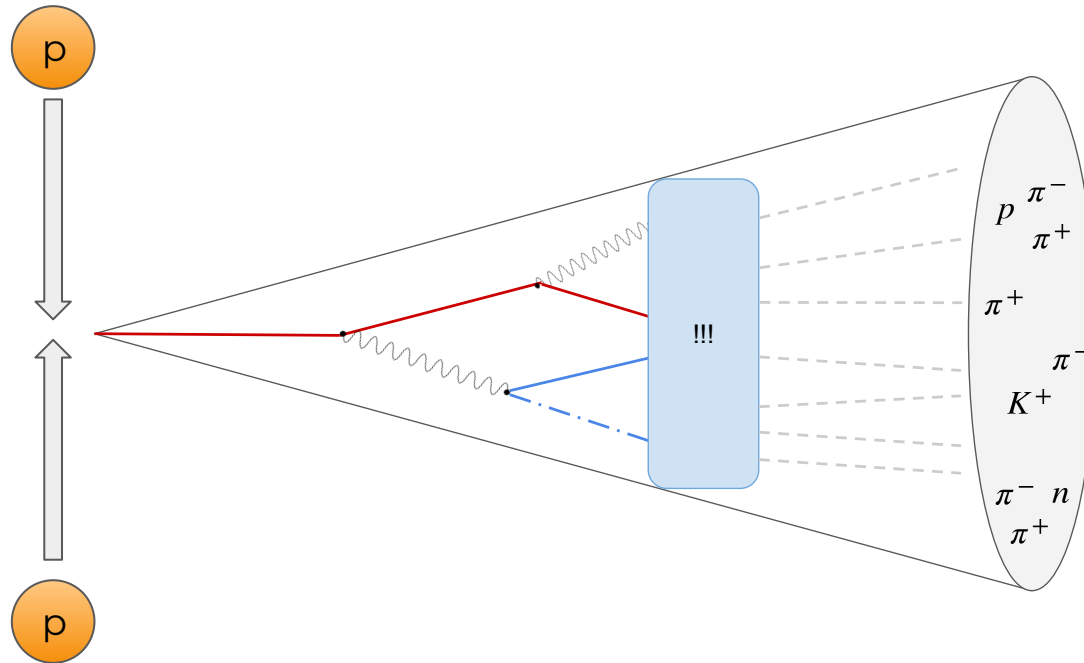


- Can be *mostly* explained by perturbative QCD.
 - There could also be soft interactions after the hard scattering.



- Realm of non-perturbative QCD
 - What hadron species are more favoured in hadronization?
 - What are the space/time patterns of hadron production?
 - What are the time hierarchies in the hadronization process?
 - How does the environment affect the hadronization process?
 - And more!

- At LHC/LHCb, studying hadronization in jets provides a proxy of the outgoing parton's kinematics.



Previously shown results

What is the hadron species dependence on the in-jet hadronization process?

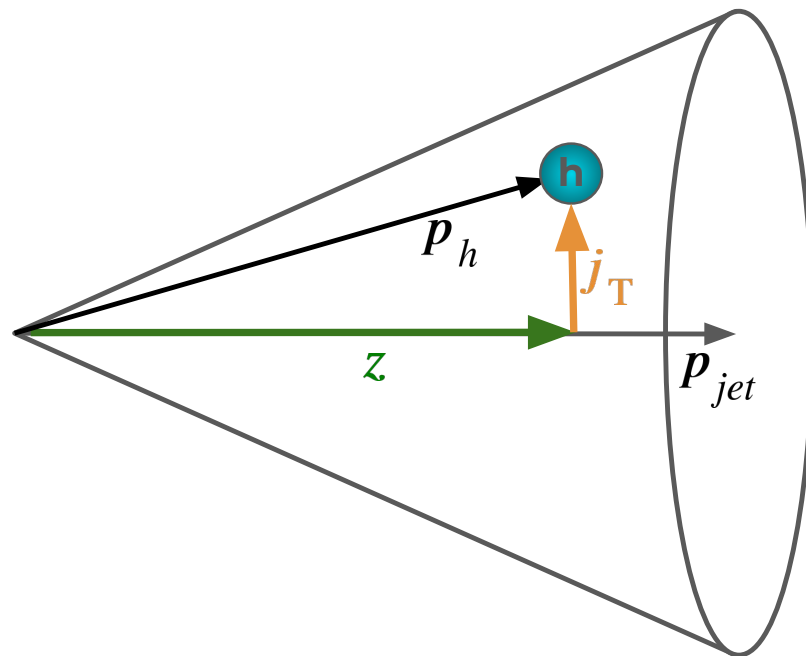
Jet Fragmentation Functions are shown as a function of:

- The longitudinal momentum fraction of the hadron w.r.t. the momentum of the jet.

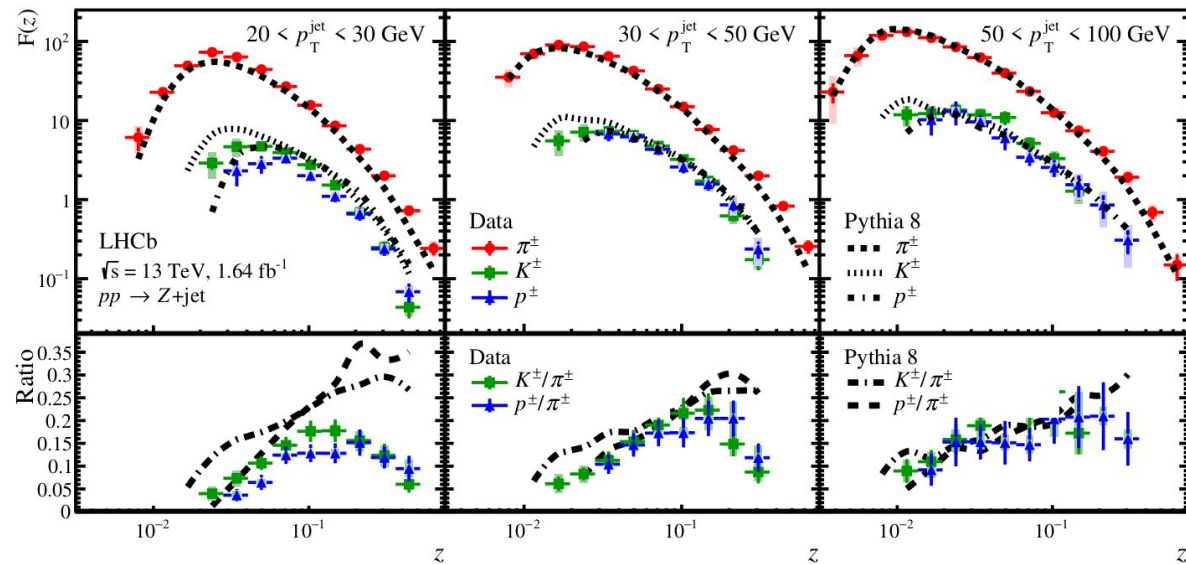
$$z = \frac{\mathbf{p}_h \cdot \mathbf{p}_{jet}}{|\mathbf{p}_{jet}|^2}$$

- The transverse momentum profile of the hadron w.r.t. the jet axis.

$$j_T = \frac{|\mathbf{p}_h \times \mathbf{p}_{jet}|}{|\mathbf{p}_{jet}|}$$

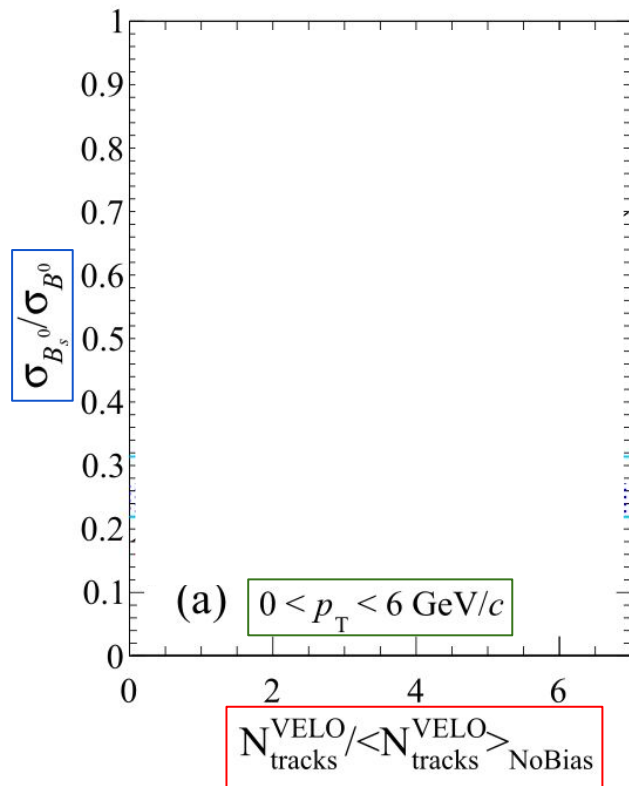


- Collinear Jet Fragmentation functions are shown for different species of hadrons.
- Heavier hadrons require a bigger energy threshold to be produced; hence, they *start* at higher z .
- Pythia overestimates the K and p ratios w.r.t. pions at low jet pT.
- **Clear hierarchy between the overall scales of the fragmentation functions of the different hadron species.**

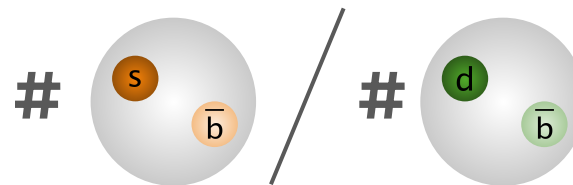


How does the collision environment affect the hadronization of a b quark?

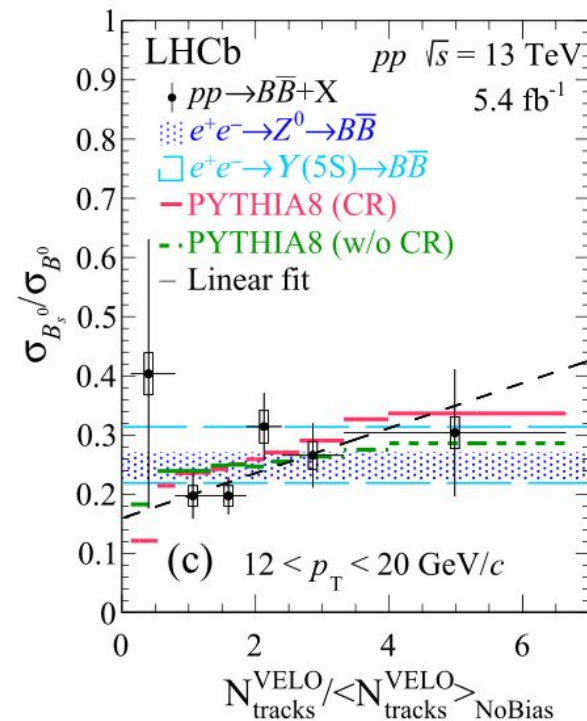
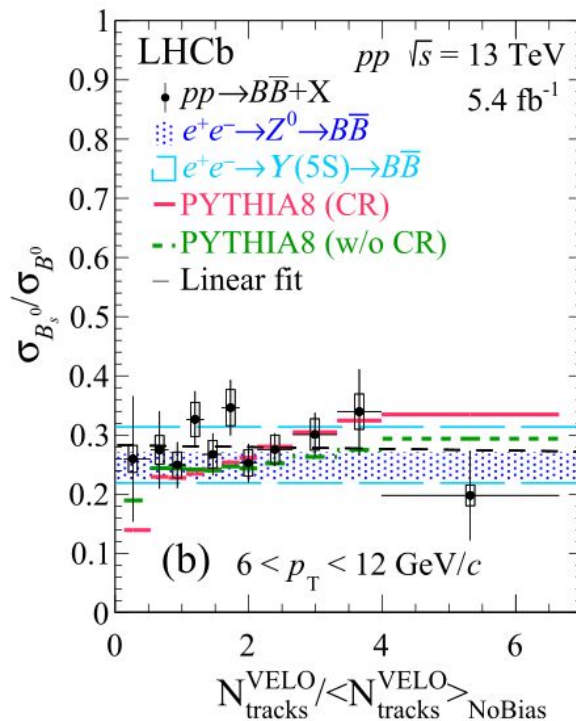
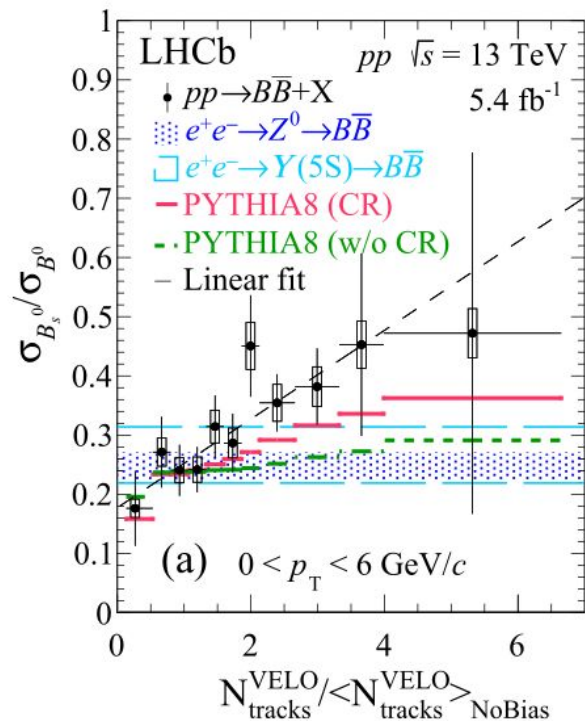
No jets on this one!



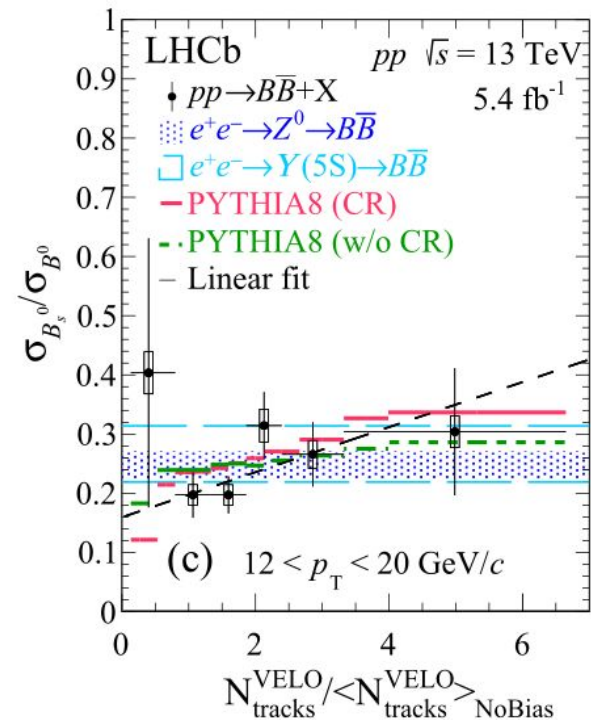
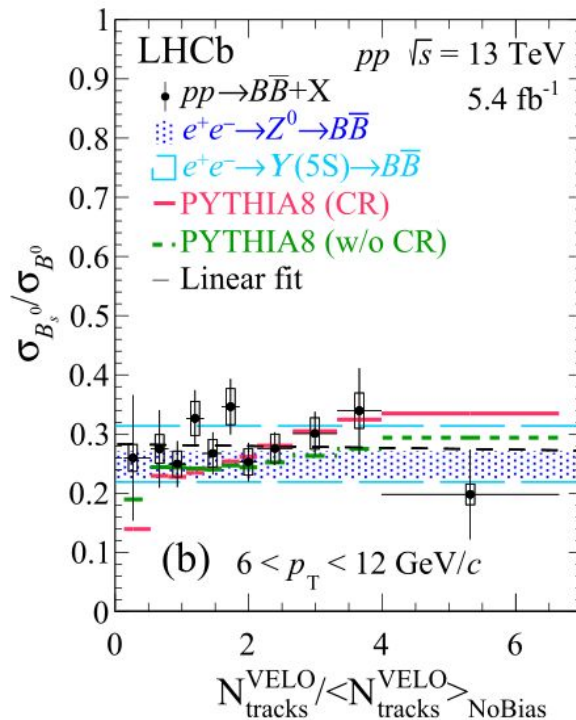
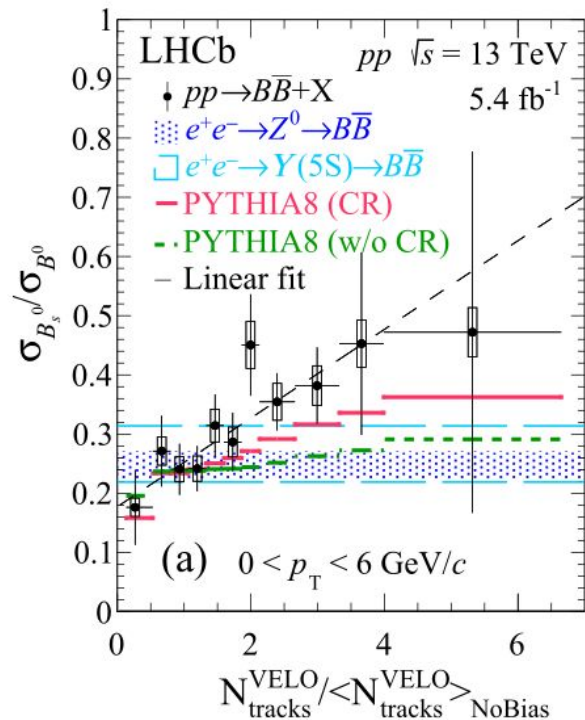
- Normalized number of charged tracks reconstructed on the **VELO** for the B meson event.
- Transverse momentum of the B meson.
- Ratio between the number of B_s^0 and the number of B^0 .



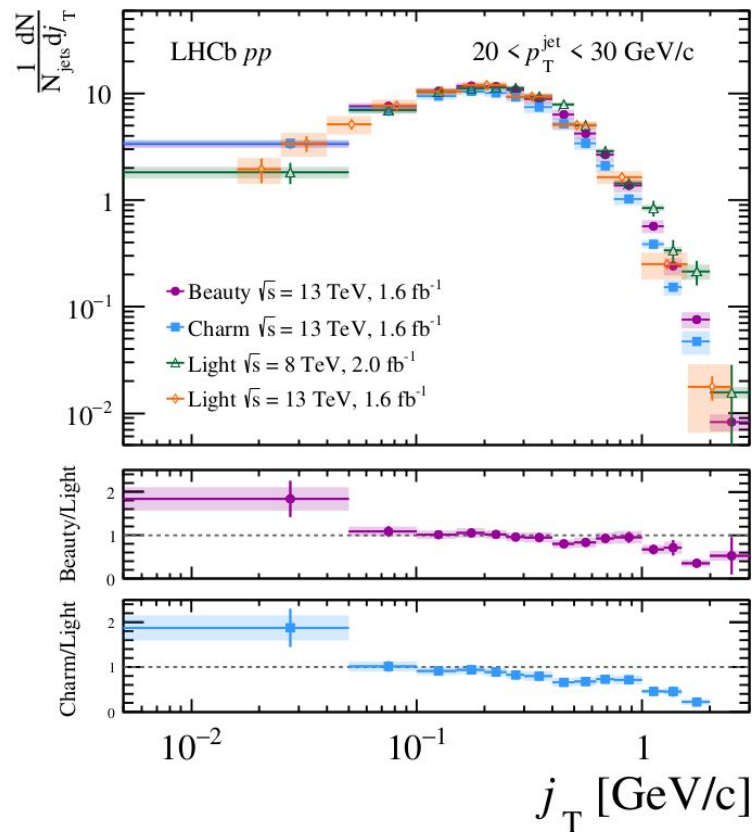
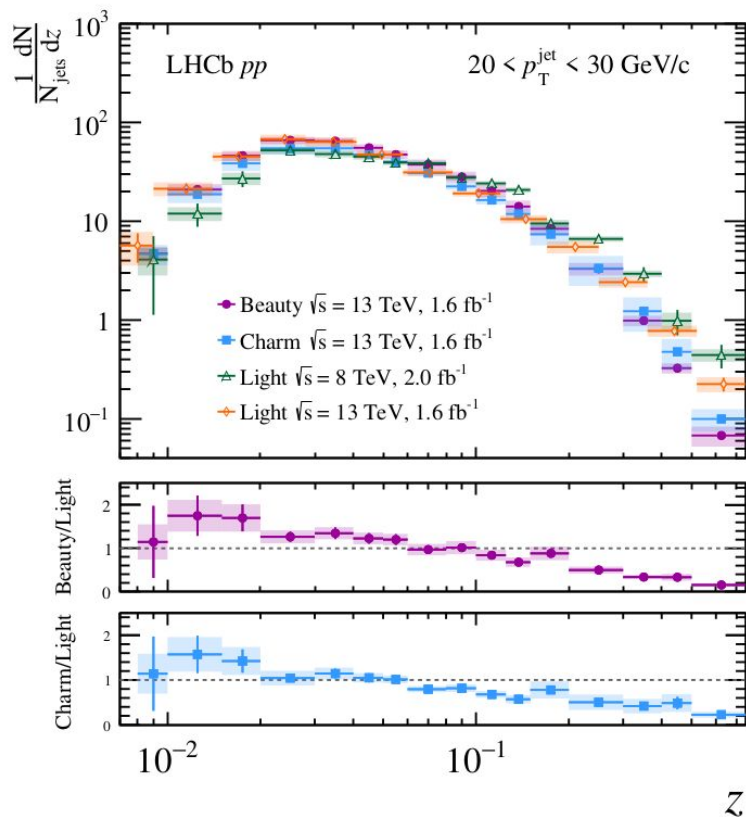
- In more populated environments there is an enhancement on the strangeness of the B meson.

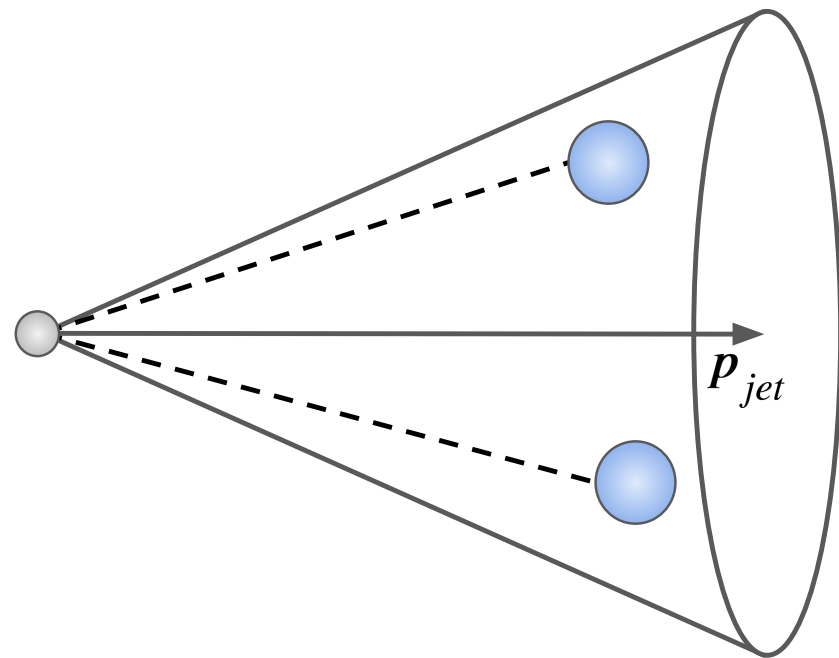
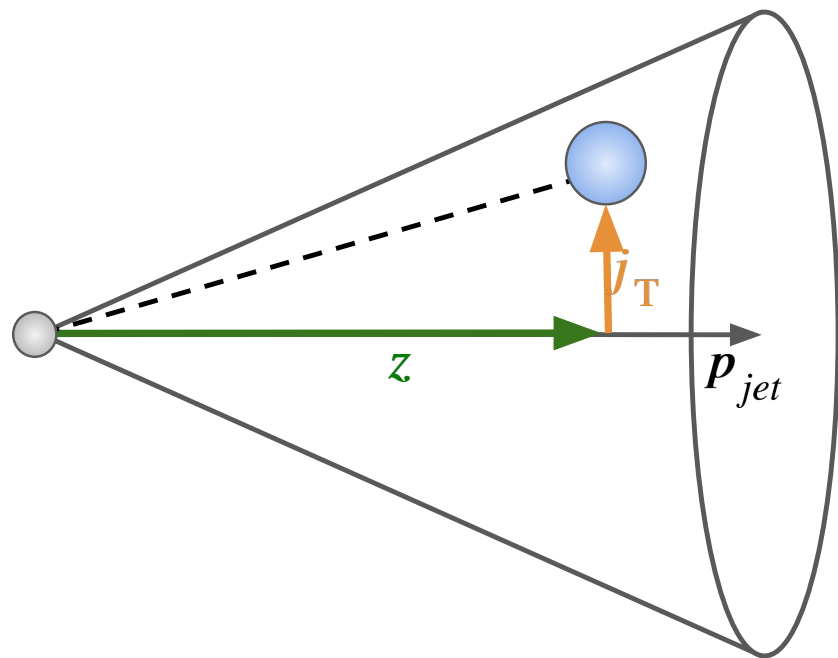


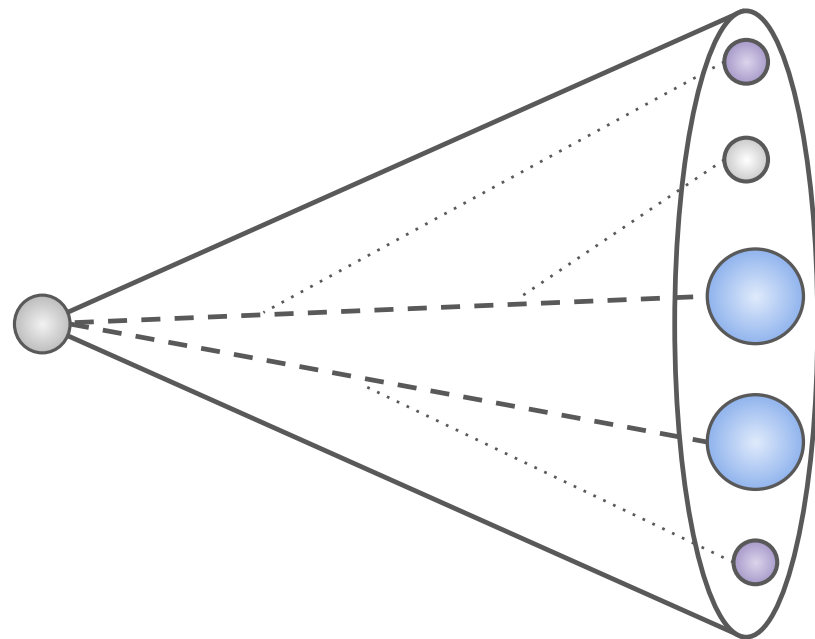
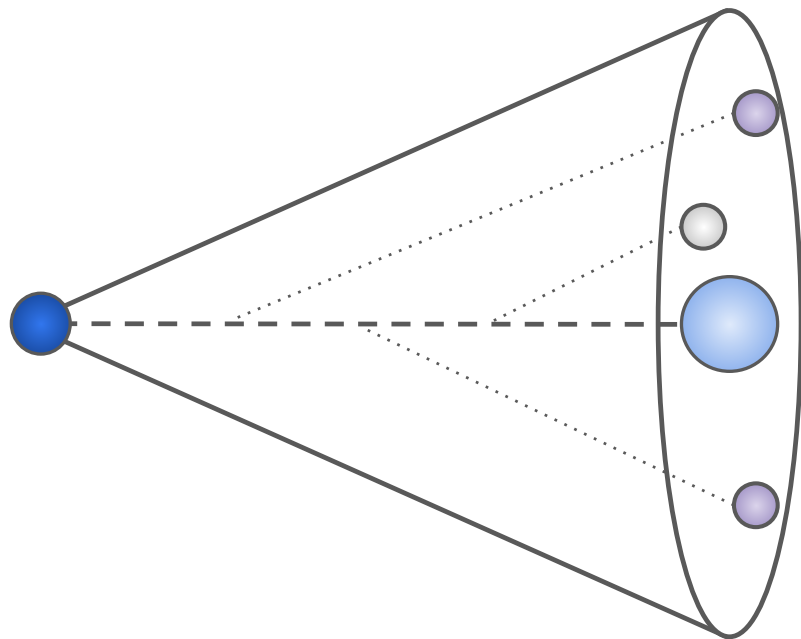
- The strangeness enhancement seems to attenuate when looking at higher transverse momentum B mesons.
 - "This behavior is expected in a scenario where low- p_T b quarks with relatively low velocity recombine with s quarks produced in high-multiplicity collisions"*



Charged hadron production in c and b jets (2025)



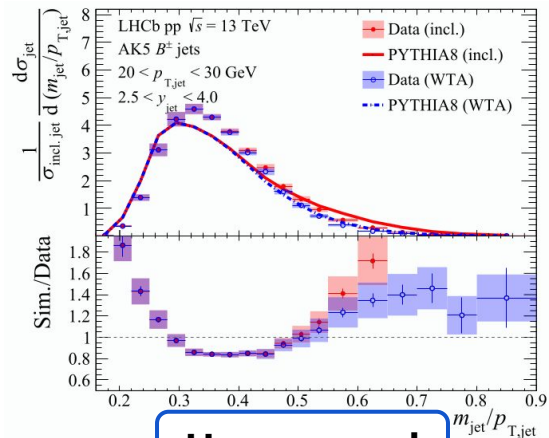




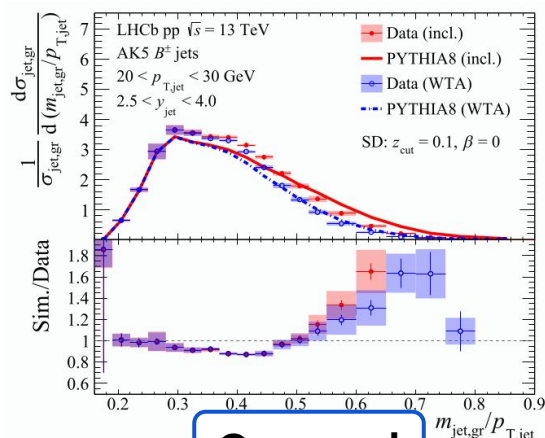
What the jet mass tells us about the overall radiation of the b-jet?

$$m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2}$$

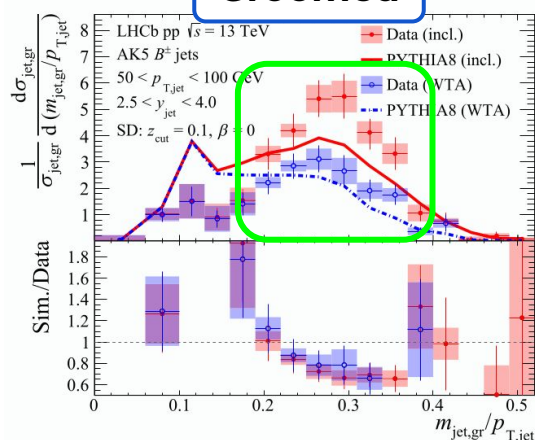
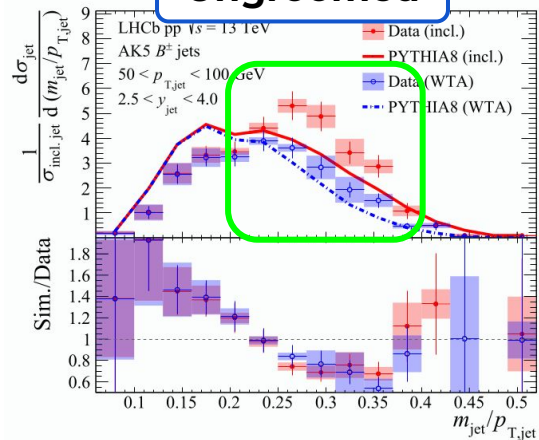
First measurement of b-jet mass with and without grooming



Un groomed

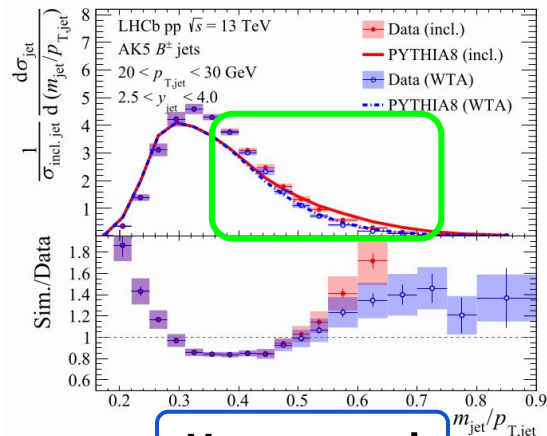


Groomed

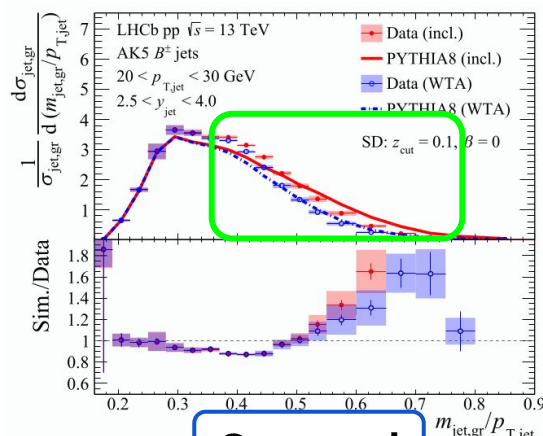


**Gluon splitting
produces more
massive jets**

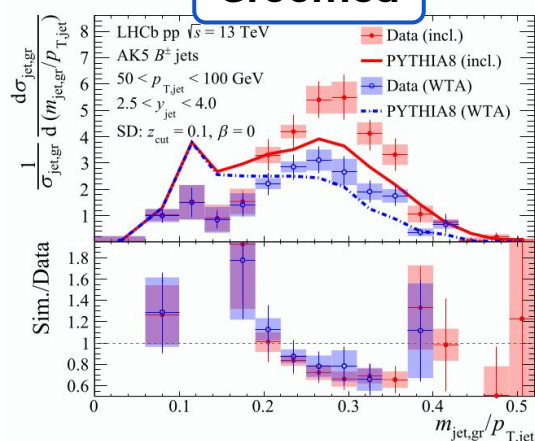
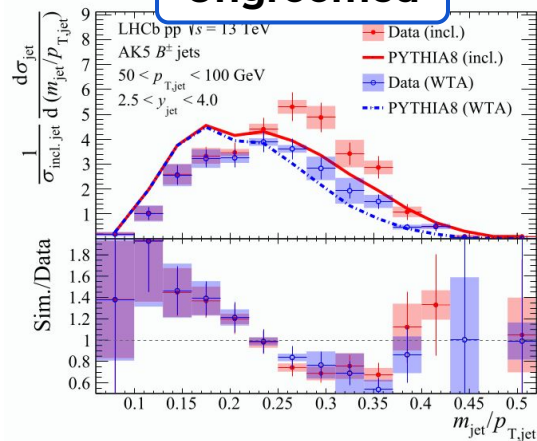
First measurement of b-jet mass with and without grooming



Un groomed

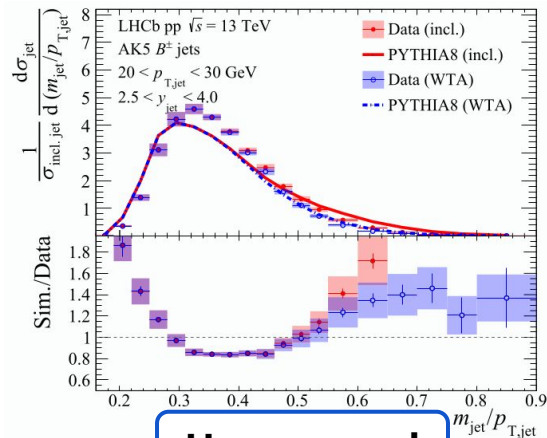


Groomed

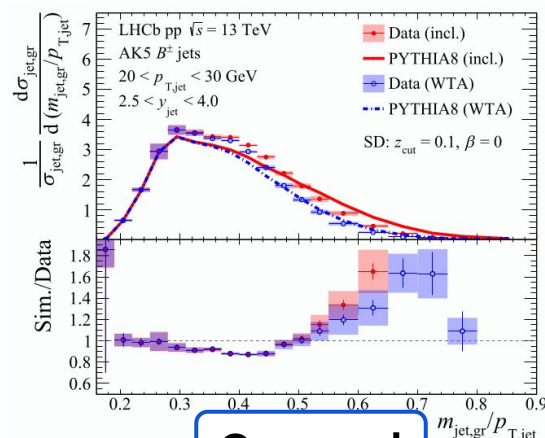


More soft, wide-angle radiation in massive jets at low jet pt

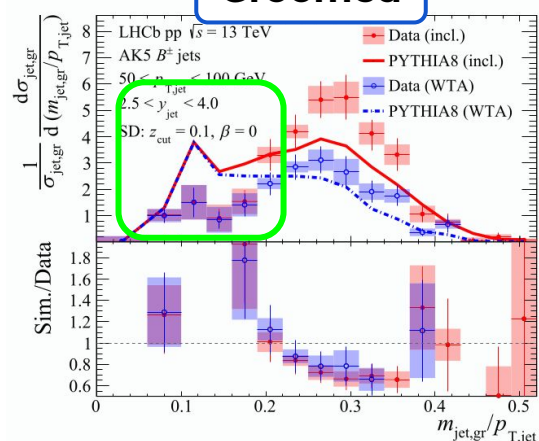
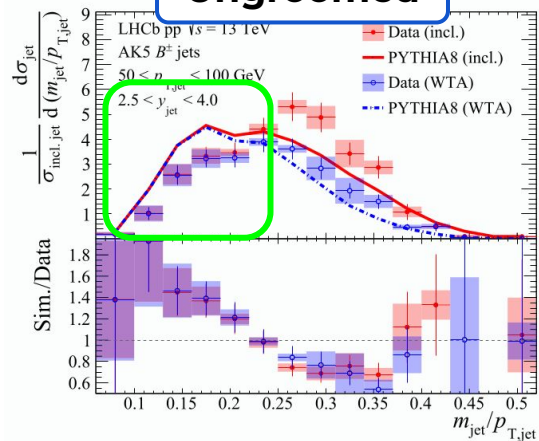
First measurement of b-jet mass with and without grooming



Ungroomed



Groomed



More soft, wide-angle radiation in lighters jets at low jet pt