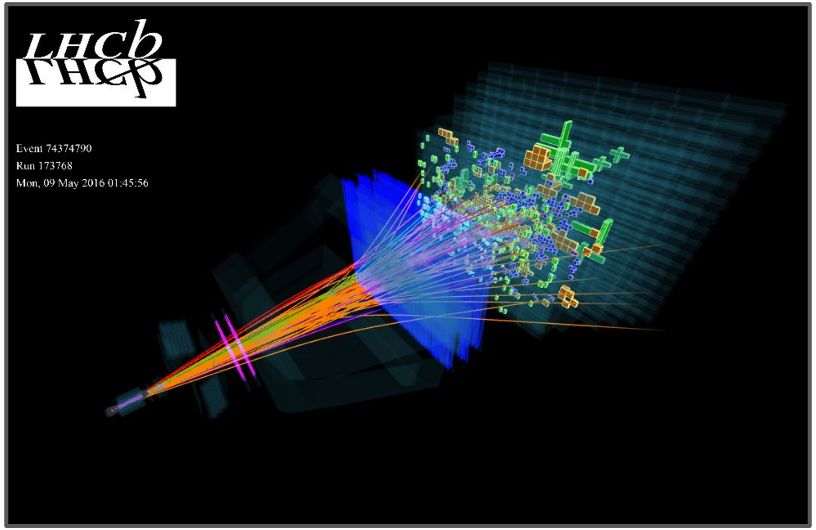


Jet Substructure at LHCb

01/09/2025

Dillon Fitzgerald on behalf of the LHCb Collaboration

Jets: QCD in Action

Jets are ideal tools to study many aspects of QCD (e.g. radiation patterns, bound state formation, medium interaction)

- They are laboratories for understanding fragmentation and hadronization (substructure)
  - Correlations with particles and the jet axis
  - Correlations between particles within a jet
  - Decluster jet to study splitting history
- They are probes of the QGP
- The best of both worlds!
  - One can study how substructure is modified in the presence of QGP

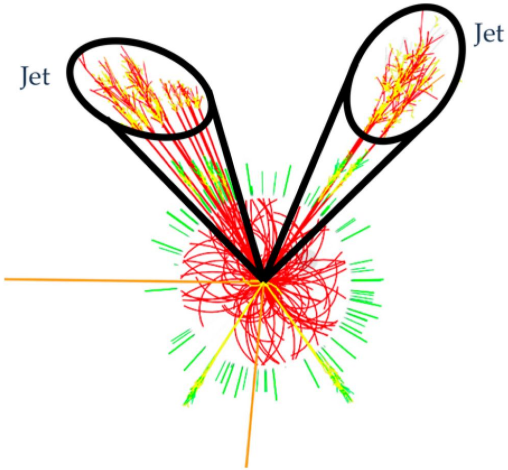


Image credit: *Universe* **2019**, *5*(5), 114; https://doi.org/10.3390/universe5050114

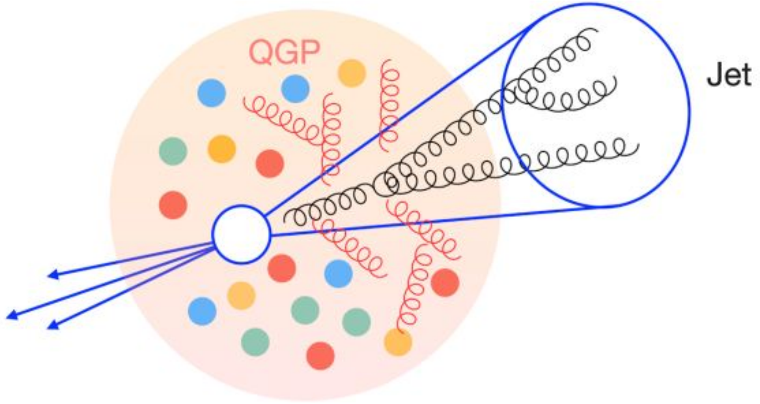


Image credit: https://www.int.washington.edu/programs-and-workshops/21r-2b

Jet Substructure Studies: A Wishlist

What information would we like to make the most of jet substructure studies?

- Full jet reconstruction with good momentum and energy resolution
  - LHCb has high precision tracking with electromagnetic and hadronic calorimetery
- Identified species of particles in the jet
  - LHCb has excellent hadron PID with p/K/π separation up to p ~ 100 GeV/c
- Flavor of the parton initiating the jet
  - LHCb can fairly efficiently tag HF jets
    - Generally SV tagged, so often missing energy from the SV (semileptonics)
  - Jets can be built around a fully reconstructed HF hadron
    - Other production mechanisms beyond leading order (e.g. splitting of gluon initiated jet)

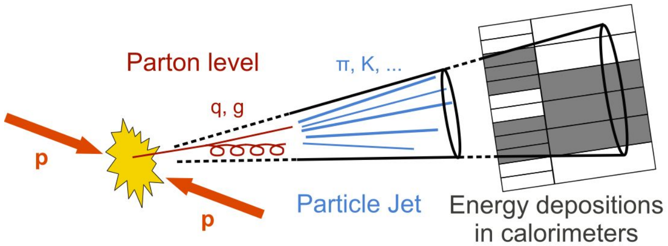


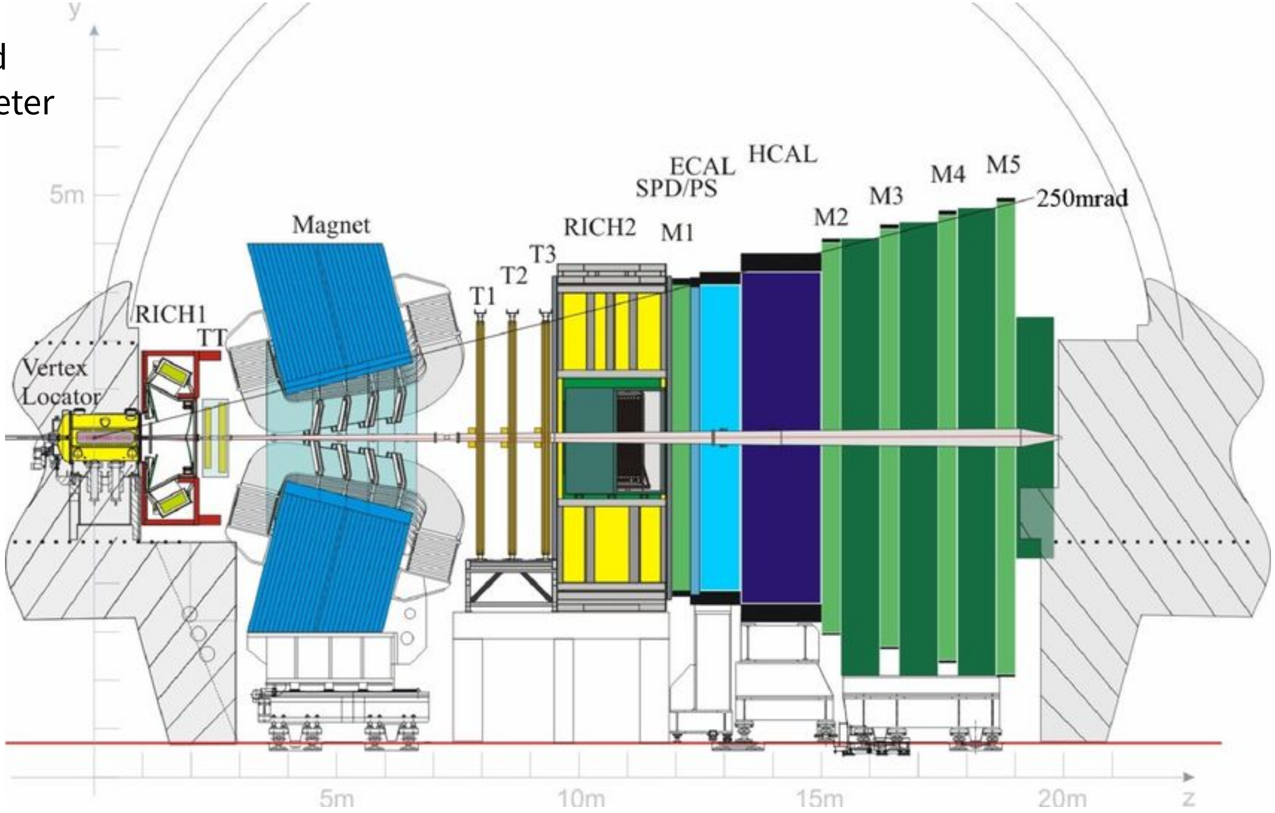
Image credit:
https://cms.cern/news/jets-cms-and-determination-their-energy-scale

The LHCb Detector (Run 1-2)

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

Fully instrumented forward spectrometer

- 2 < η < 5



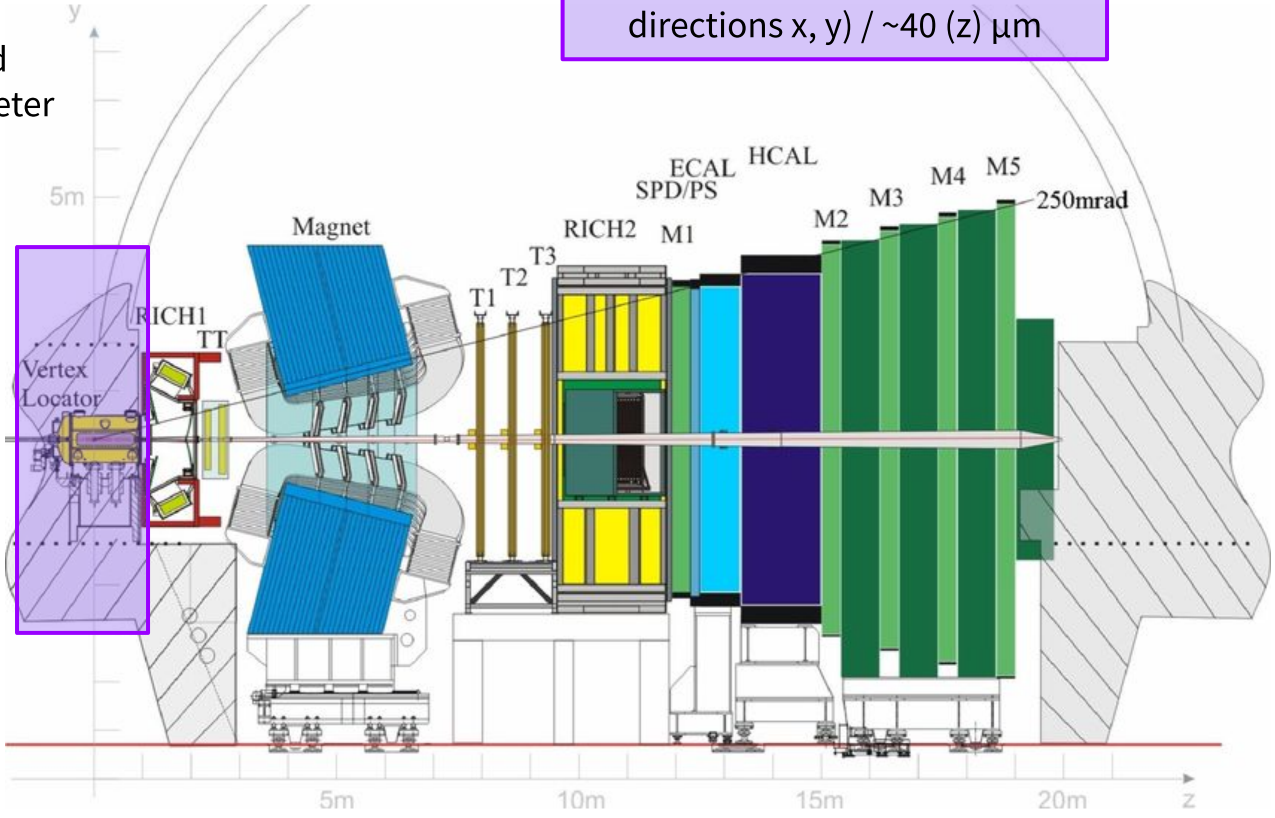
The LHCb Detector (Run 1-2)

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

Vertex Locator
Excellent primary vertex resolution of ~10 (transverse directions x, y) / ~40 (z) µm

Fully instrumented forward spectrometer

- $2 < \eta < 5$



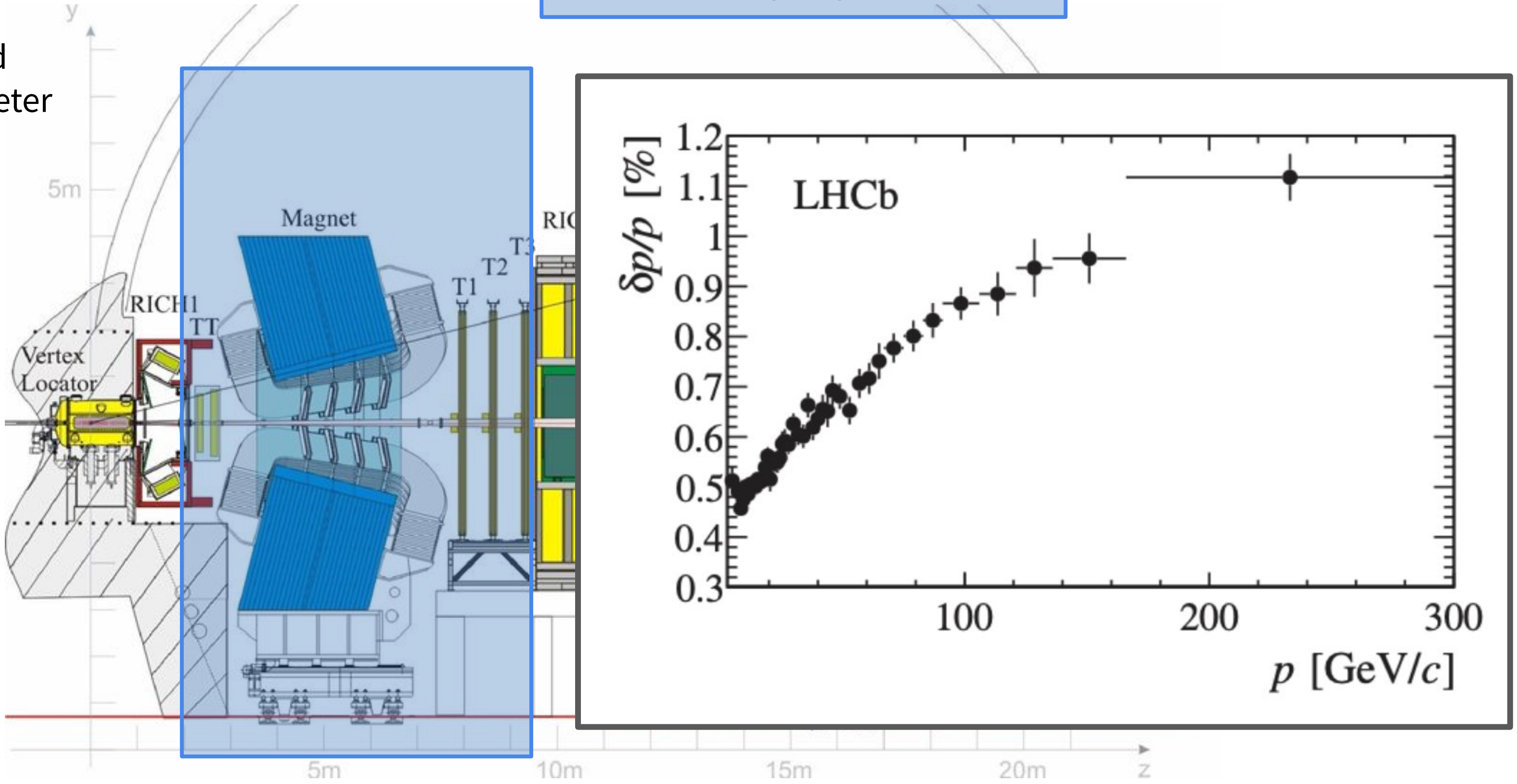
The LHCb Detector (Run 1-2)

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

Tracking Stations
Sub-percent momentum resolution up to p~200 GeV/c

Fully instrumented forward spectrometer

- $2 < \eta < 5$



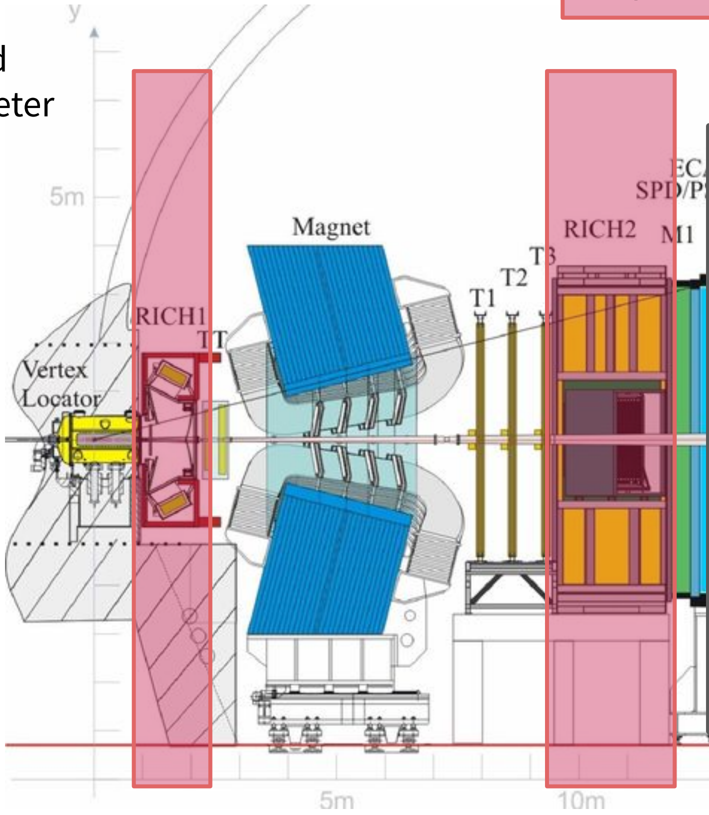
The LHCb Detector (Run 1-2)

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

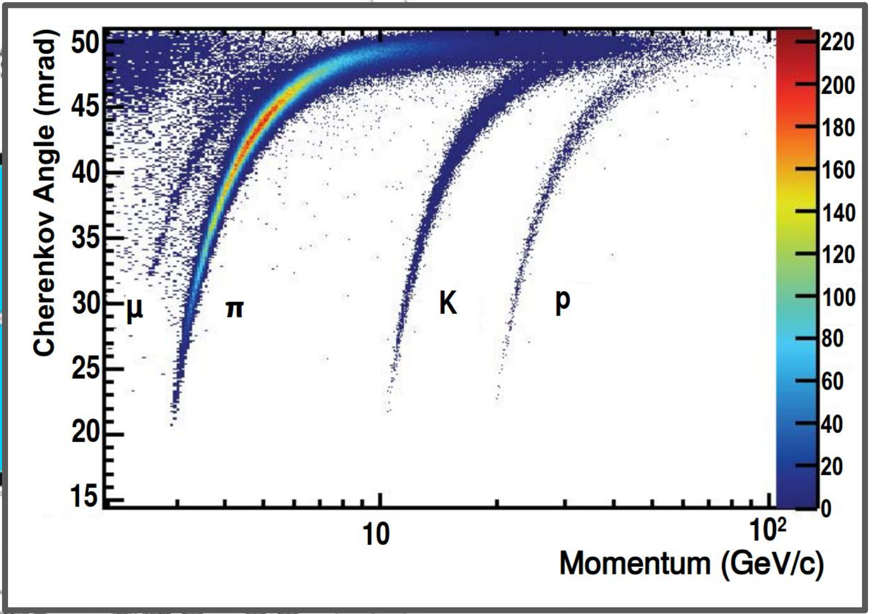
RICH Systems
Excellent hadron PID wit p/K/π separation from p~2-100 GeV/c

Fully instrumented forward spectrometer

- $2 < \eta < 5$



https://twiki.cern.ch/twiki/bin/view/LHCb/PIDConferencePlots



The LHCb Detector (Run 1-2)

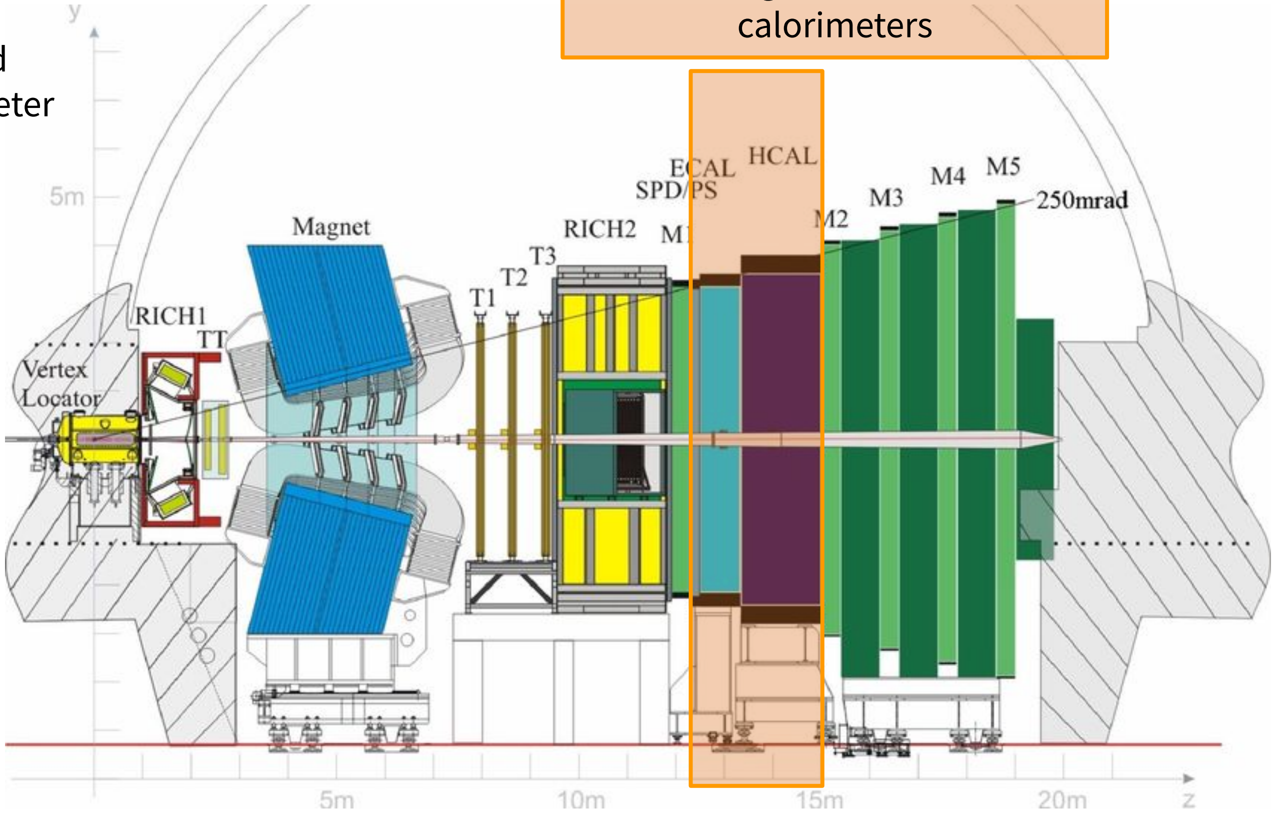
Int. J. Mod. Phys. A 30, 1530022 (2015)

Fully instrumented forward spectrometer

- 2 < η < 5

Calorimeters

Full calorimetry with both electromagnetic and hadronic calorimeters



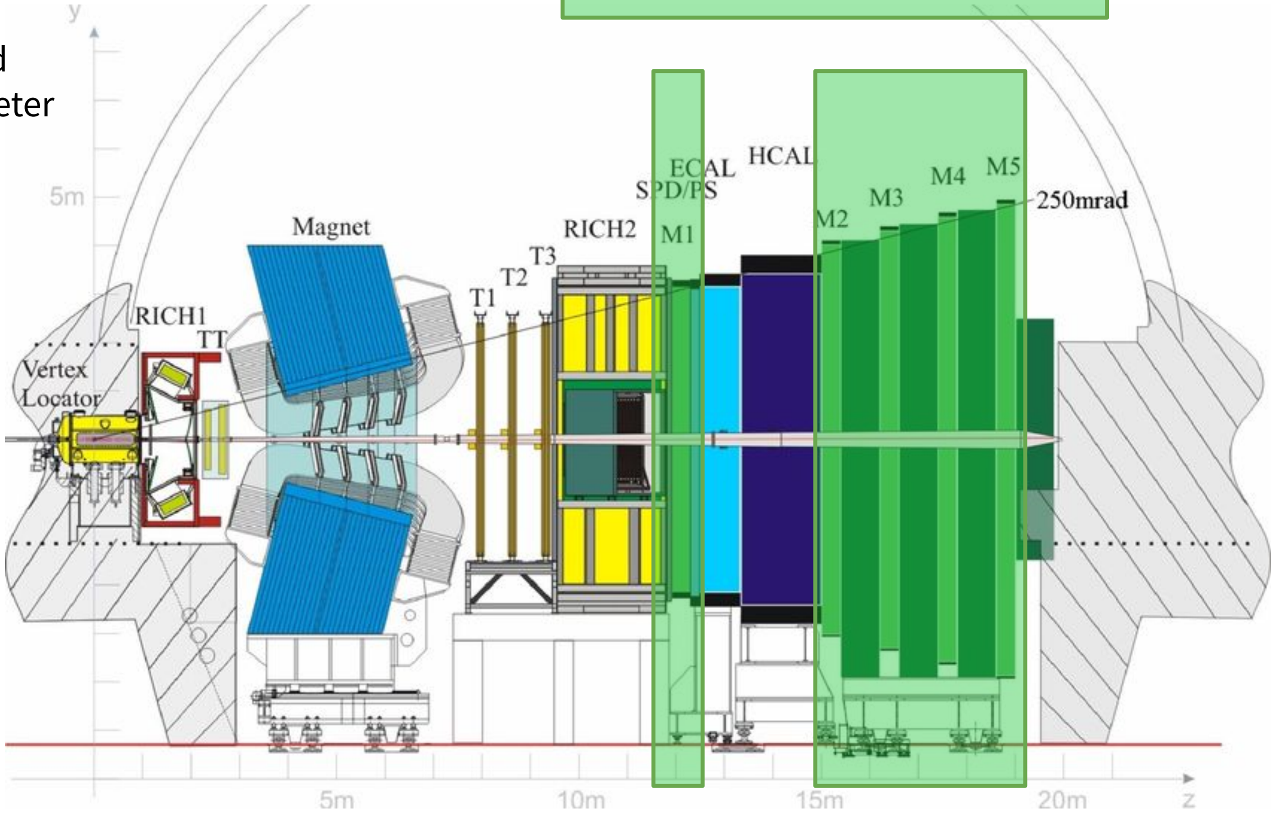
The LHCb Detector (Run 1-2)

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

Muon Systems
Reconstruction efficiency well above 95%

Fully instrumented forward spectrometer

- $2 < \eta < 5$

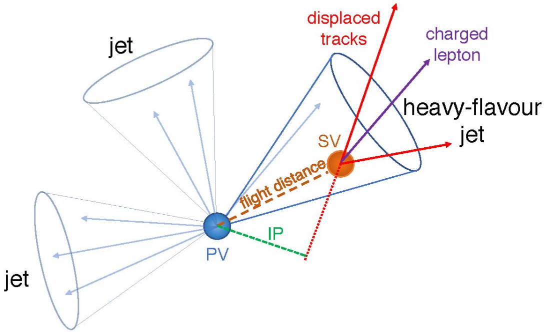


b-quark Production at the LHC

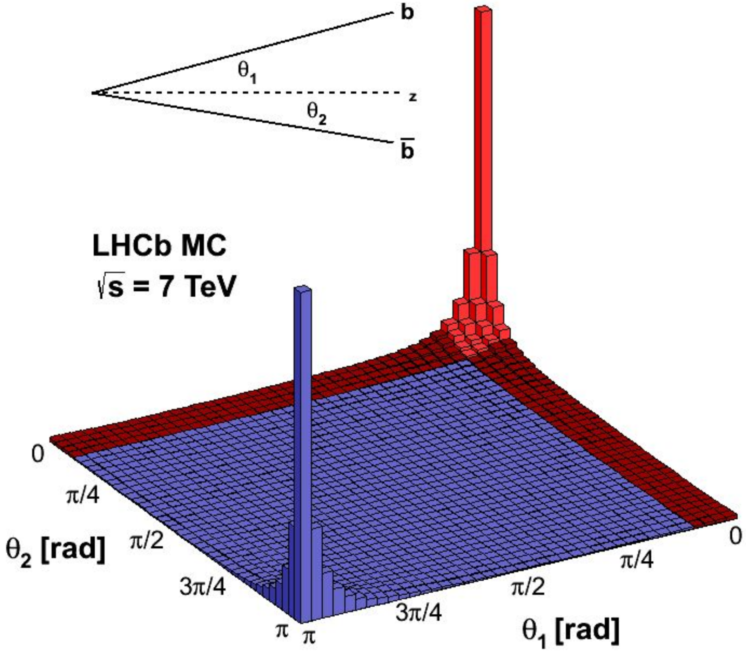
Forward geometry is optimal for measuring b-quark production

VELO detector allows for fine pointing resolution and secondary vertex reconstruction

⇒ Access to heavy flavor jets!

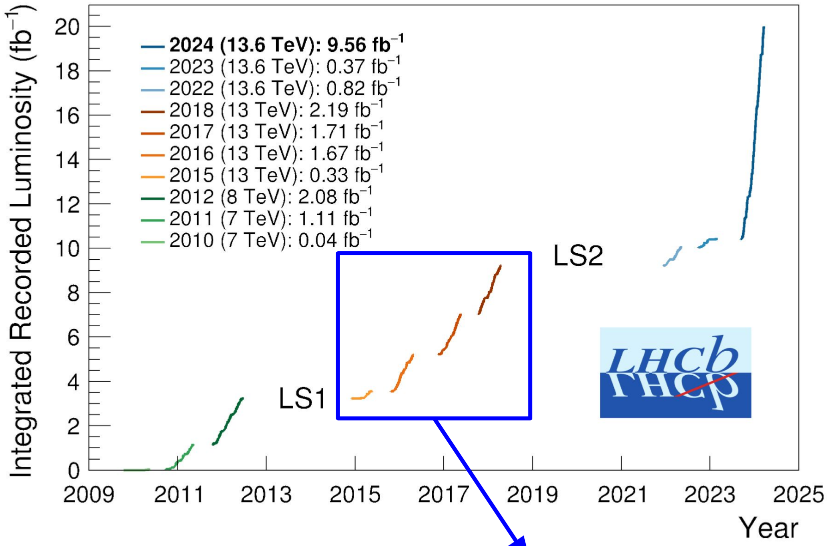


[Figure link](#)

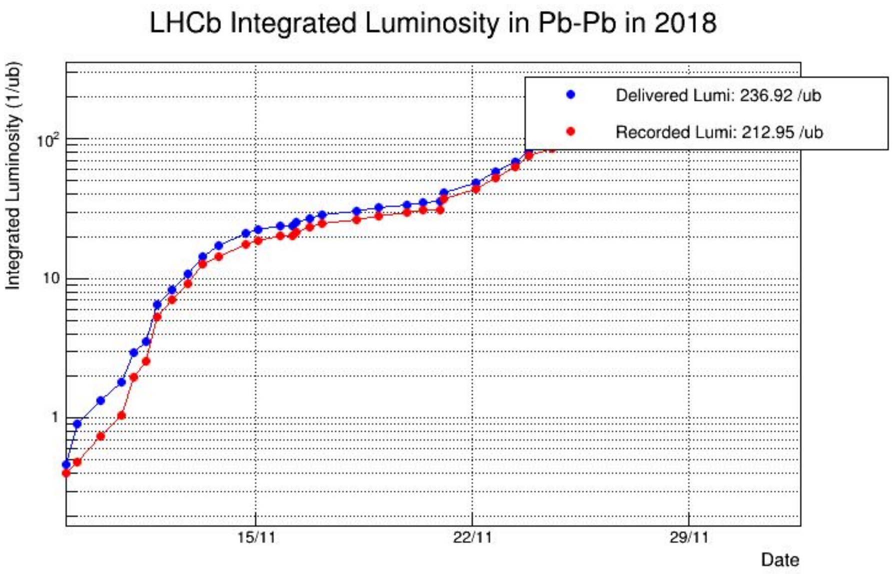


LHCb Datasets

https://lhcb-outreach.web.cern.ch/2024/10/18/end-of-successful-proton-proton-collision-data-taking-period/



https://lbgroups.cern.ch/online/OperationsPlots/2018PlotsPb.htm

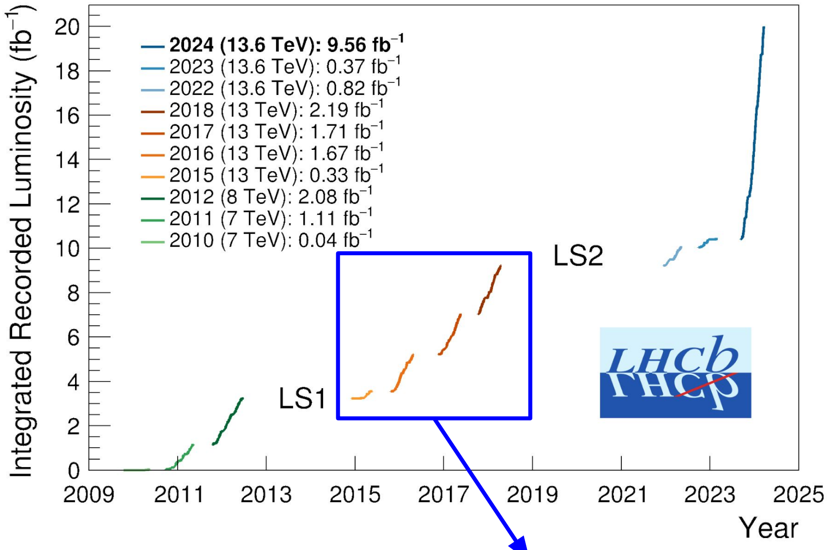


μ: The average number of visible interactions per bunch crossing **~1-2**

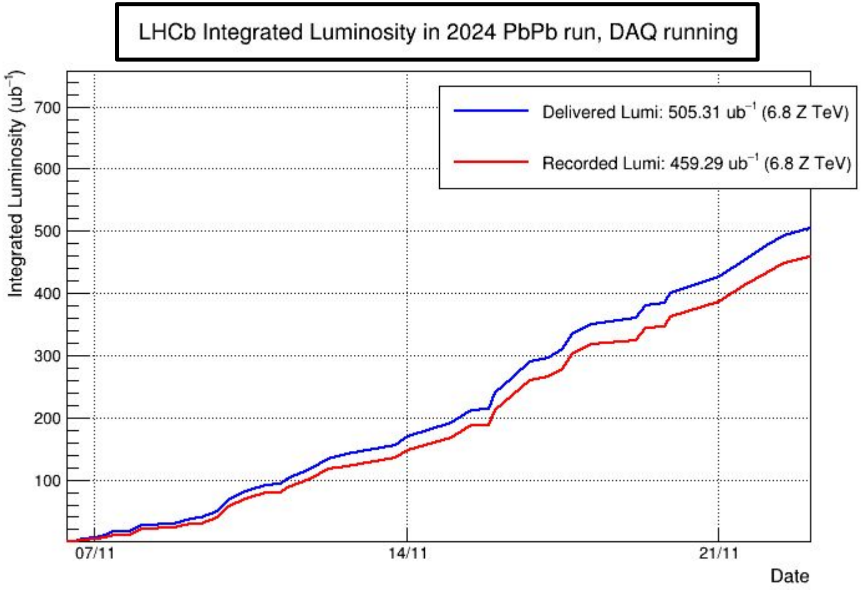
- Low level of pileup allows for clean substructure studies!

LHCb Datasets

https://lhcb-outreach.web.cern.ch/2024/10/18/end-of-successful-proton-proton-collision-data-taking-period/



https://lbgroups.cern.ch/online/OperationsPlots/2018PlotsPb.htm



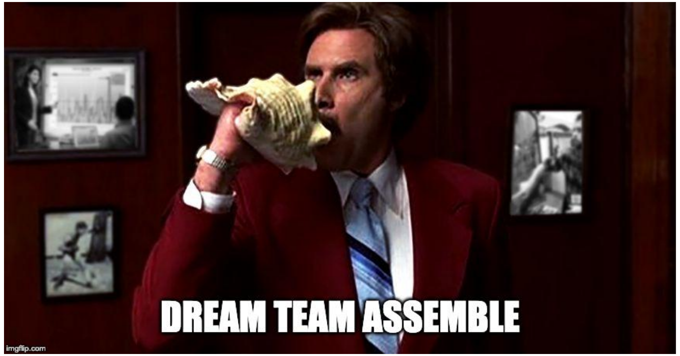
μ: The average number of visible interactions per bunch crossing **~1-2**

- Low level of pileup allows for clean substructure studies!

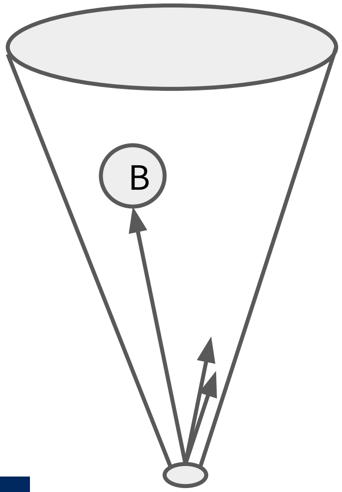
Jet Substructure Analysis Efforts at LHCb

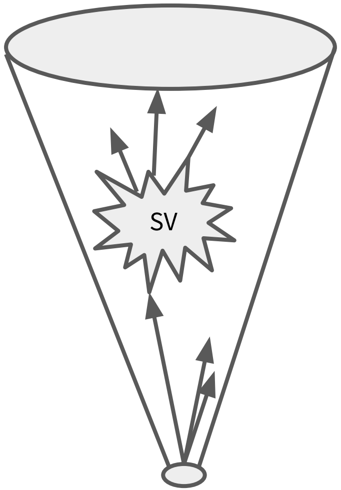
There has been a growing effort for jet substructure measurements on LHCb

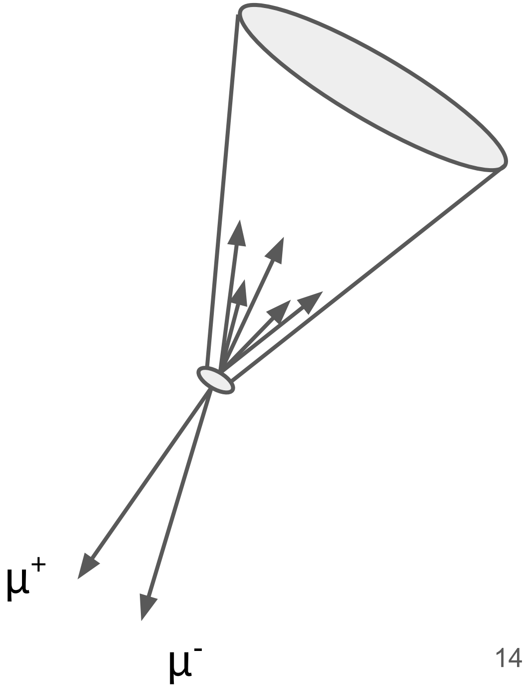
- Historically, not a lot of people working with jets
- This is changing, with various collaborators beginning to centralize efforts across measurements
- Lots of measurements on the horizon relevant for this conference! I will only be able to show a few that have been published to date
    - First, focus on exploring flavor and hadron mass dependence of jet substructure observables in pp collisions
    - Then, can investigate similar measurements in PbPb and pPb collisions to see how the substructure is affected



Physics Channels Under Investigation

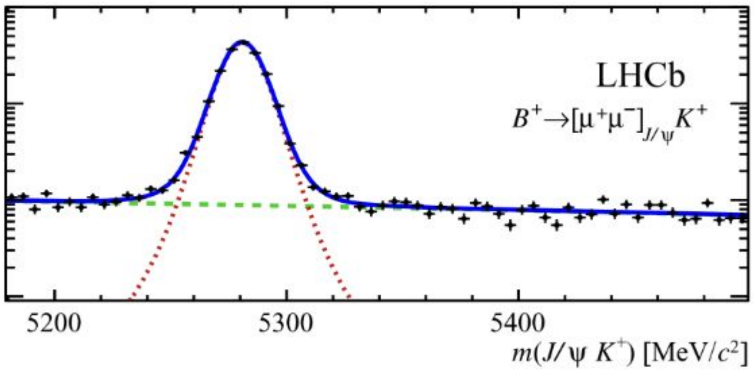




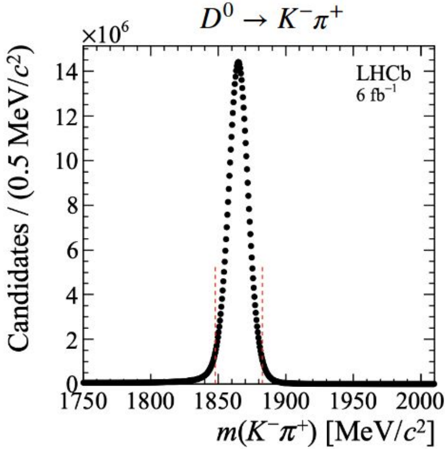


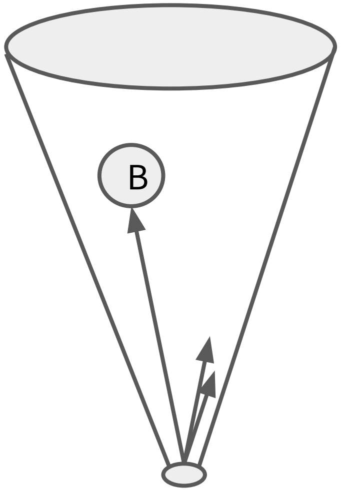
Fully reconstructed HF hadron in jet

PRD 95, 052005 (2017)



Phys. Rev. D 104, 072010 (2021)

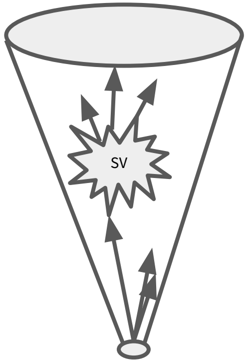


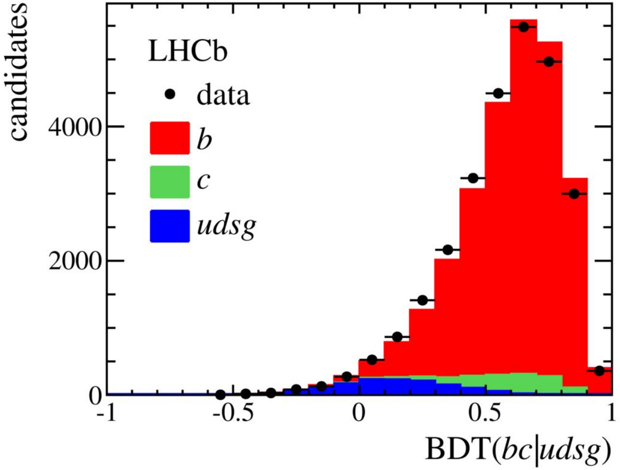


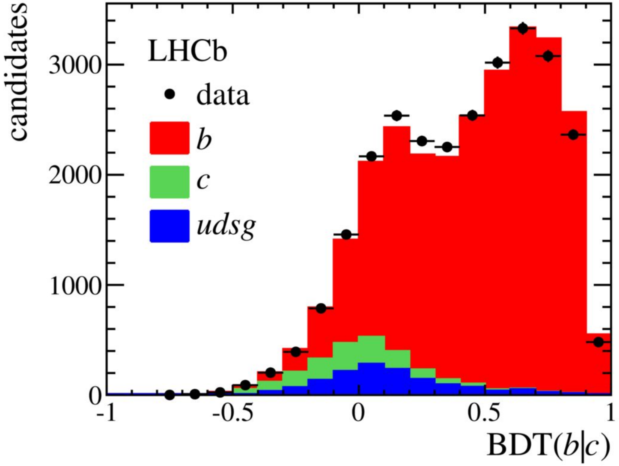
- Excellent mass resolution for HF hadrons
- Build jets including fully reconstructed HF hadron (e.g. B^+, D^0, Λ_c^+)
  - Explore mass and flavor dependence of jet fragmentation and hadronization process

SV tagged jets

LHCb efficiently tags b-jets!
[JINST 10 (2015) P06013]





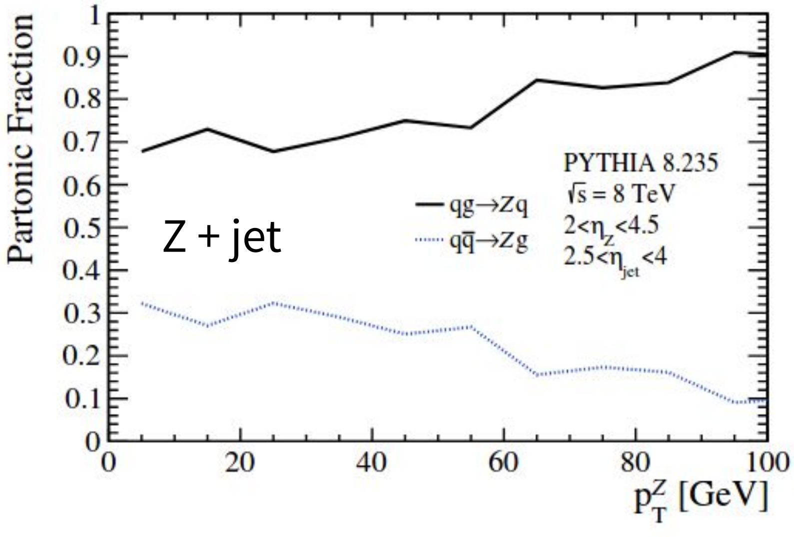


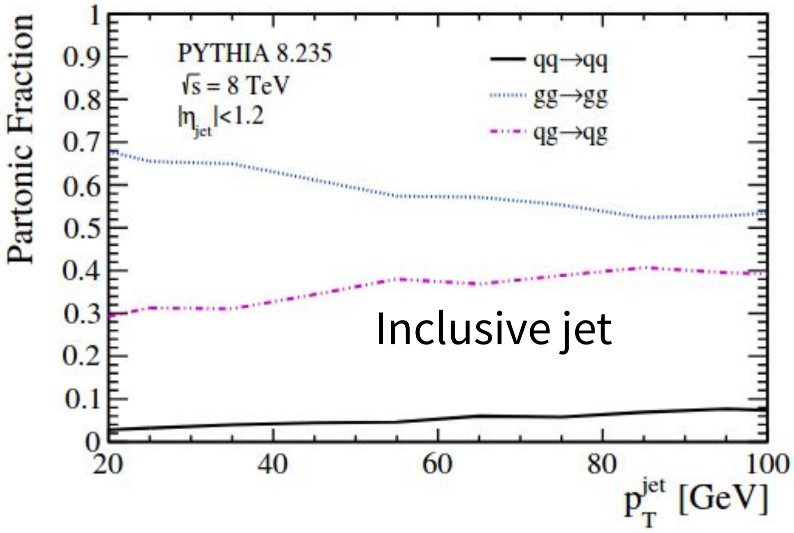
Boosted decision tree (BDT) used to evaluate probability of jet being initiated by partons of certain flavor

- One is used to separate heavy flavor (*cb*) jets from light (*udsg*) jets
- One is used to separate *c* and *b* jets

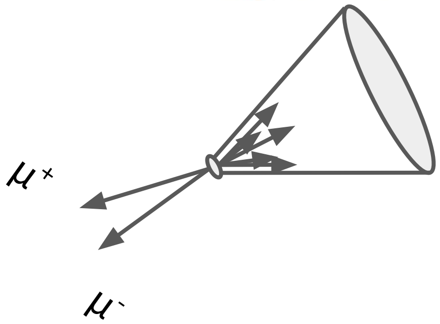
Z + jet

[Phys. Rev. Lett. **123**, 232001 (2019) - Supplemental Material]



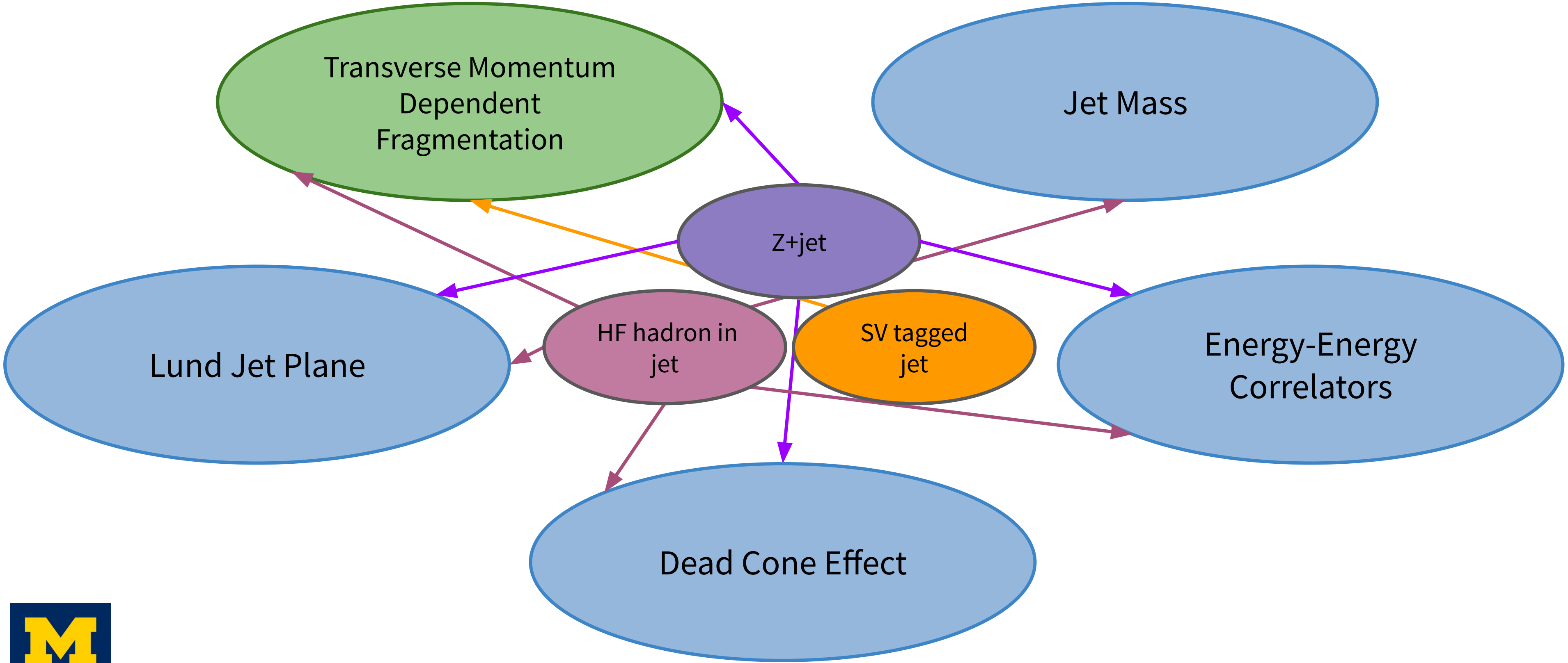


- Forward rapidities lead to an enhanced production Z bosons with a light quark from the quark-gluon Compton scattering process
  - Forward rapidity → asymmetry in x; gluon often sampled with low x → quark often sampled in the valence region
  - Further explore mass and flavor dependence!

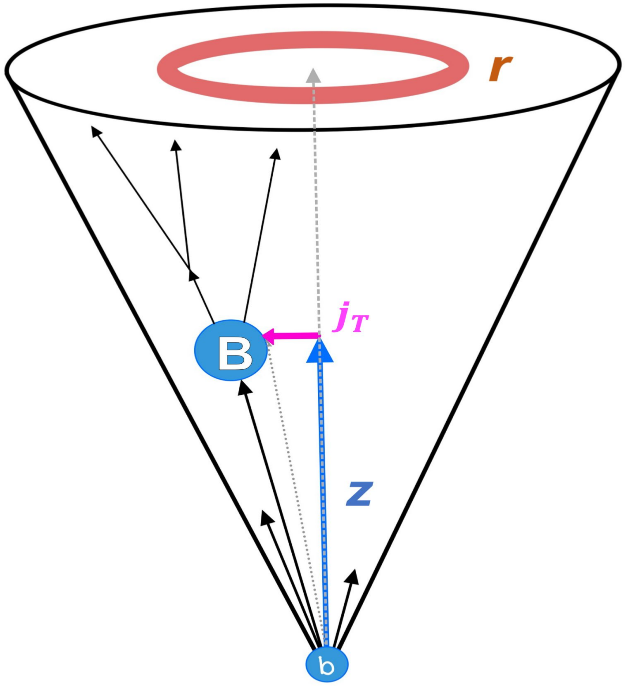


Observables of Interest

Green: Focus for today
Blue: Work in Progress



TMD Fragmentation Observables



Collinear momentum fraction **or** transverse momentum fraction (z)

$$z = \frac{\vec{p}_{hadron} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2} \quad \textbf{or} \quad z = \frac{p_{T,hadron}}{p_{T,jet}}$$

Transverse momentum w.r.t. Jet axis (j_T)

$$j_T = \frac{|\vec{p}_{hadron} \times \vec{p}_{jet}|}{|\vec{p}_{jet}|}$$

Radial profile (r = ΔR(hadron, jet))

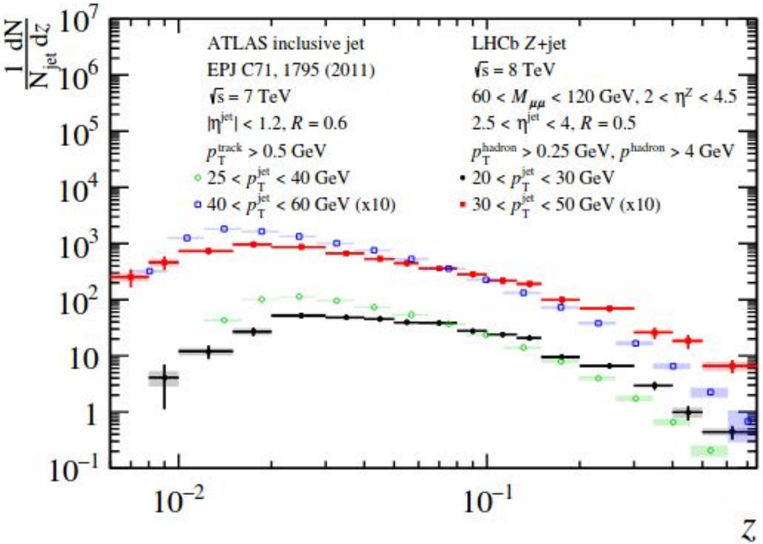
$$r = \sqrt{(\eta_{hadron} - \eta_{jet})^2 + (\phi_{hadron} - \phi_{jet})^2} \; *$$

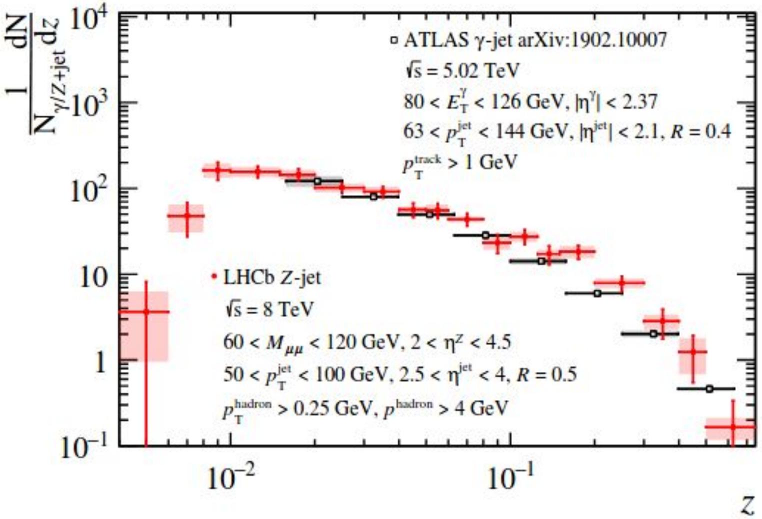
*Replace η with rapidity (y) if mass is known (fully reconstructed or identified hadron)

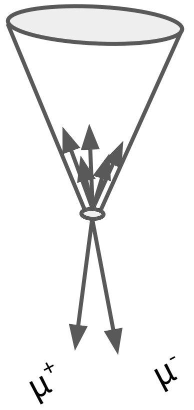
Z+jet $\sqrt{s}$ = 8 TeV pp

$$z = \frac{\vec{p}_{hadron} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2}$$

Phys. Rev. Lett. **123**, 232001 (2019) - Supplemental Material





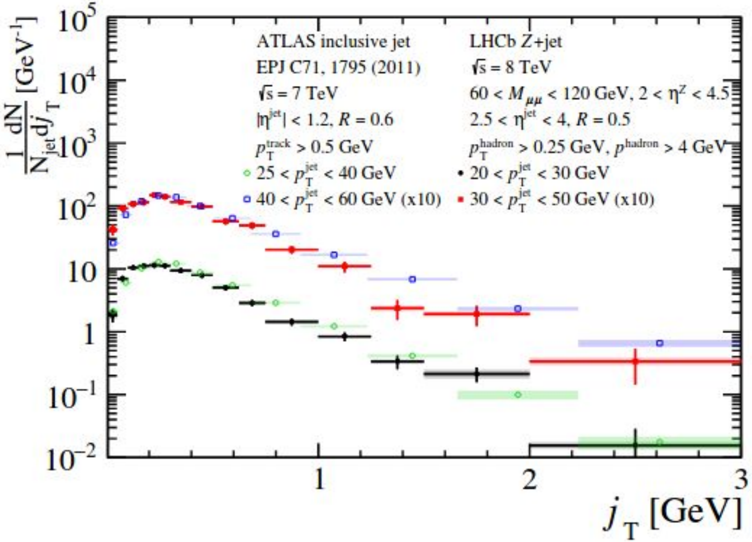


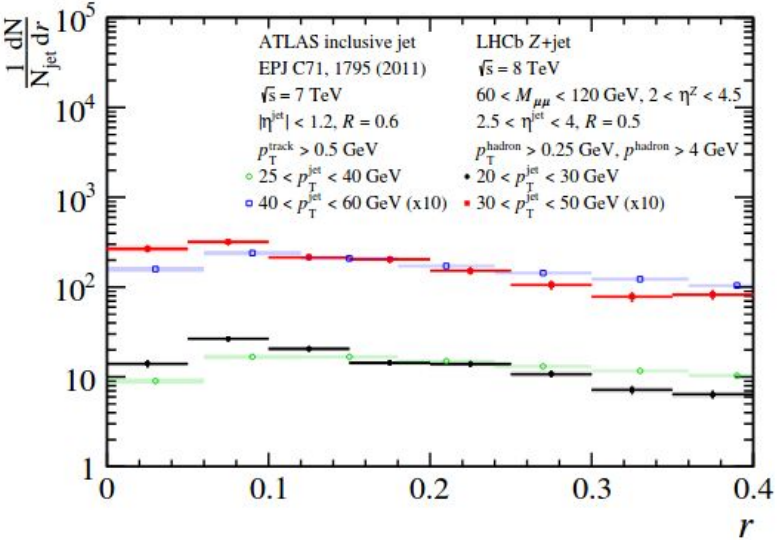
- Slightly different kinematic bins and jet resolution parameters (R)
- (Left) Predominantly light quark initiated jets (LHCb Z+jet) compared with predominantly gluon initiated jets (ATLAS inclusive jet)
  - Gluon initiated jets tend to peak at lower z values and decrease more rapidly as z increases
- (Right) LHCb Z+jet compared with ATLAS γ+jet -- similar LO production mechanisms
  - Distributions are much more similar

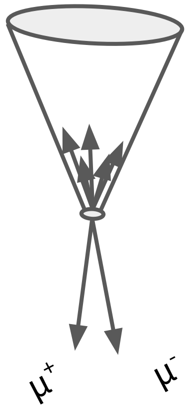
Z+jet √s = 8 TeV pp

$$j_T = \frac{|\vec{p}_{hadron} \times \vec{p}_{jet}|}{|\vec{p}_{jet}|} \qquad r = \sqrt{(\eta_{hadron} - \eta_{jet})^2 + (\phi_{hadron} - \phi_{jet})^2}$$

Phys. Rev. Lett. **123**, 232001 (2019) - Supplemental Material







Comparison of predominantly light quark initiated jets (LHCb Z+jet) and predominantly gluon initiated jets (ATLAS inclusive jet) with slightly different kinematic bins and jet resolution parameters (R)

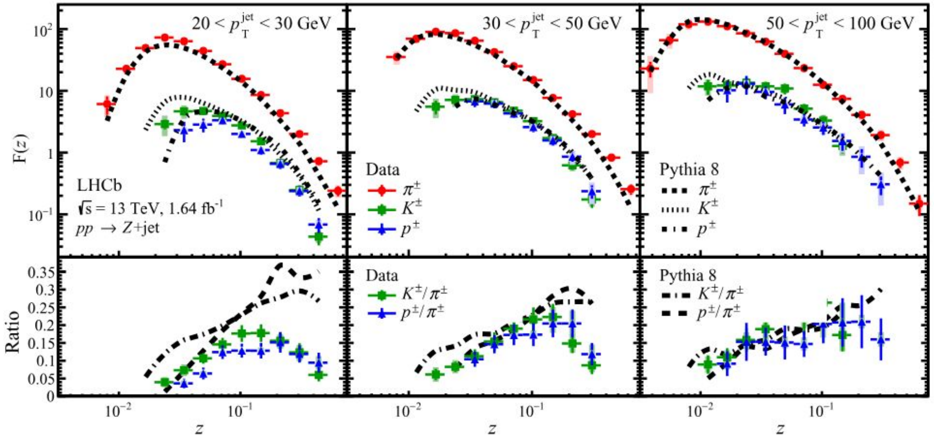
- **(Left) j_T distribution:** tends to have a less pronounced peak for gluon initiated jets that decreases less rapidly than light quark initiated jets
- **(Right) r distribution:** jets in predominantly light quark initiated sample tend to be more collimated

Z+jet $\sqrt{s}$ = 13 TeV pp

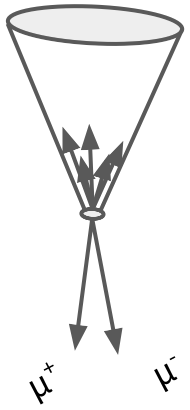
$$z = \frac{\vec{p}_{hadron} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2} \qquad j_T = \frac{|\vec{p}_{hadron} \times \vec{p}_{jet}|}{|\vec{p}_{jet}|}$$

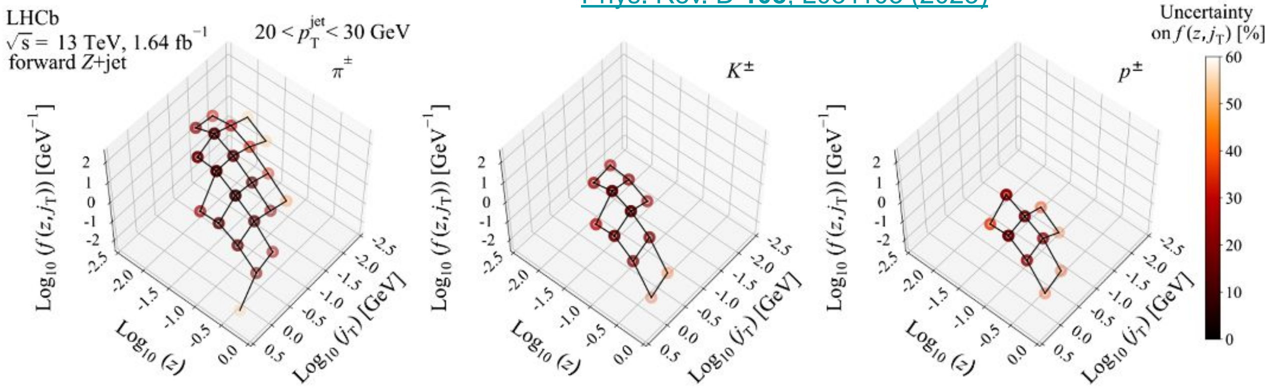
Flavor dependent fragmentation observed for predominantly light quark initiated jets (Z+jet)

- Mass dependence of z distribution can be observed via shift in peak position and change in slope
- Relevant for extracting transverse momentum and flavor dependent jet fragmentation functions

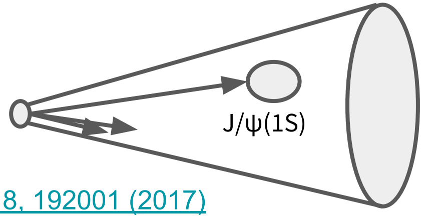


[Phys. Rev. D **108**, L031103 (2023)](#)



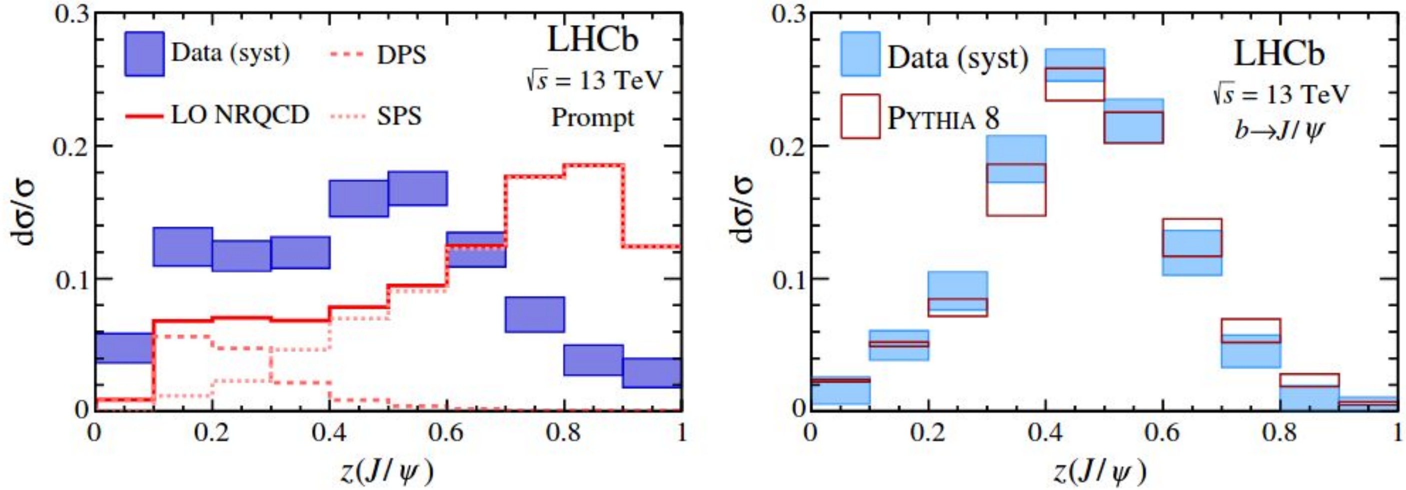


J/ψ(1S) in jet √s = 13 TeV pp



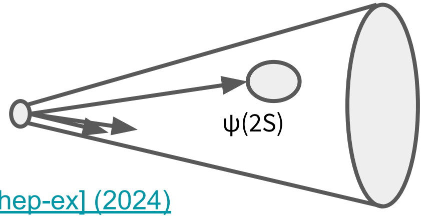
$$z = \frac{p_{T,hadron}}{p_{T,jet}}$$

Phys. Rev. Lett. 118, 192001 (2017)

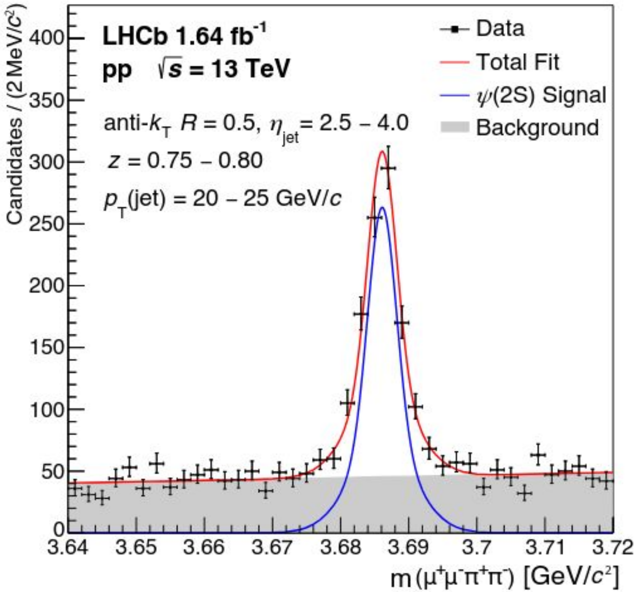


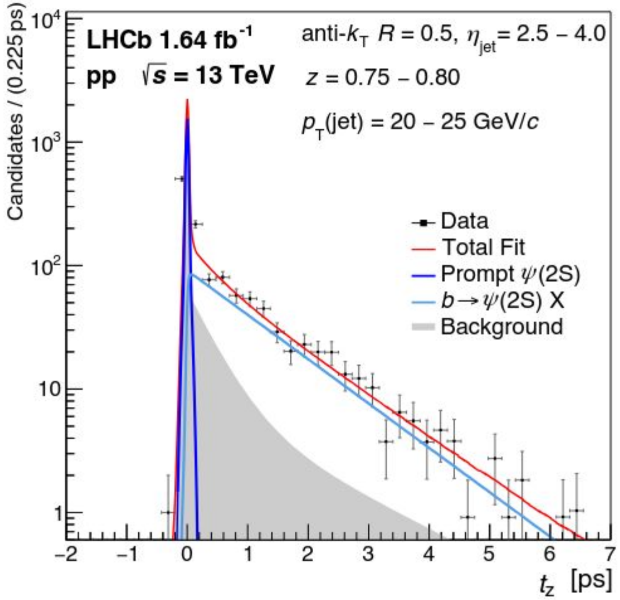
- **(Left) Prompt production:** J/ψ mesons produced in the hard scattering or parton shower
  - LO NRQCD overpredicts at high z and underpredicts at low z
  - **Prediction of isolated J/ψ production is higher than seen in data**
    - Better agreement with NRQCD calculations using fragmenting jet function (FJF) formalism (Phys. Rev. Lett. 119, 032002 (2017))
- **(Right) Non-prompt production:** J/ψ mesons produced via B hadron decays
  - On average, J/ψ from b decays tends to carry about 50% of the jet p_T
  - Good agreement between data and PYTHIA 8

ψ(2S) in jet √s = 13 TeV pp



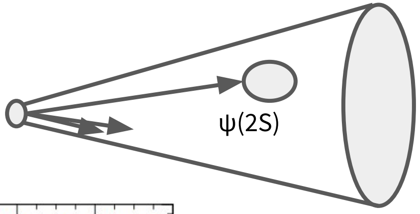
2410.18018 [hep-ex] (2024)





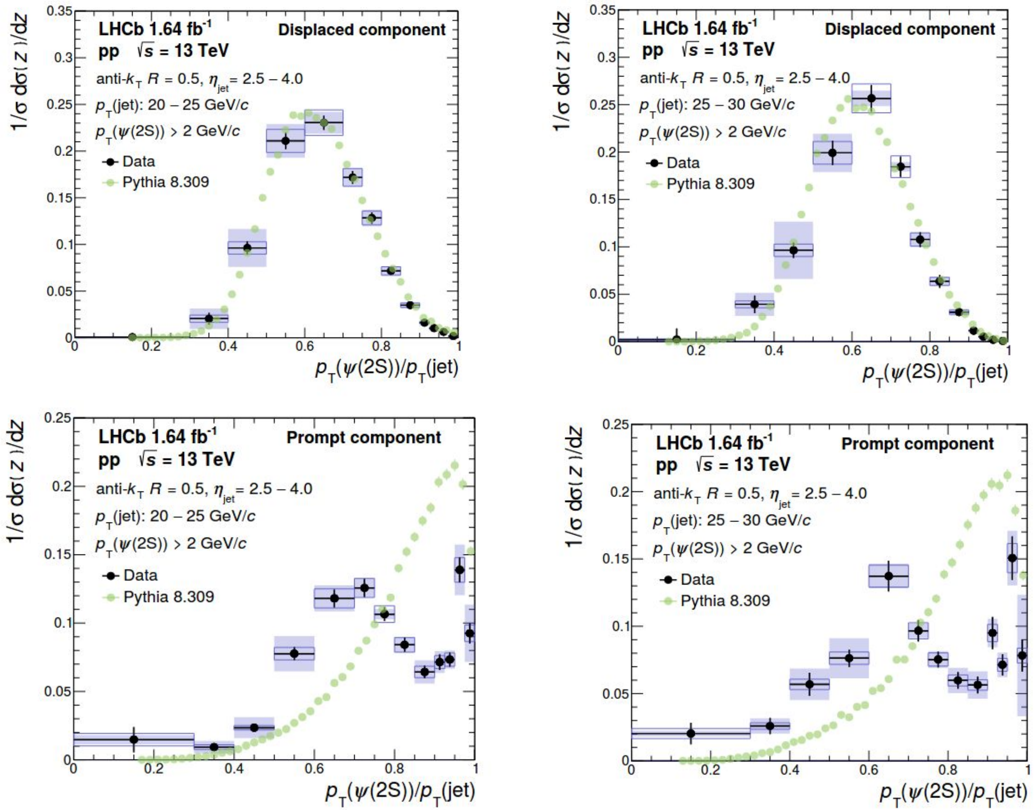
- Clean signal of ψ(2S) observed in the m(μ$^+$μ$^-$π$^+$π$^-$) spectrum
- Pseudo-decay time $t_z = \lambda\, m/p_z$ where λ is the flight distance projected along the beam axis between reconstructed ψ(2S) and primary vertex
  - Distribution used to determine the prompt vs non-prompt contribution

ψ(2S) in jet $\sqrt{s}$ = 13 TeV pp



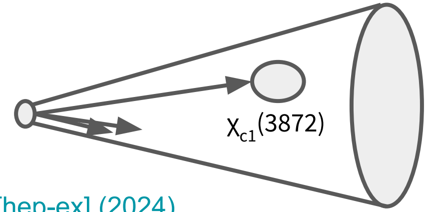
$$z = \frac{p_{T,hadron}}{p_{T,jet}}$$

2410.18018 [hep-ex] (2024)

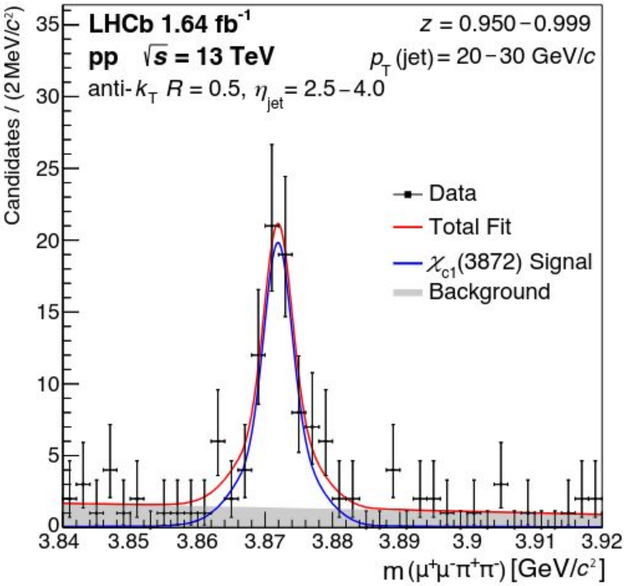


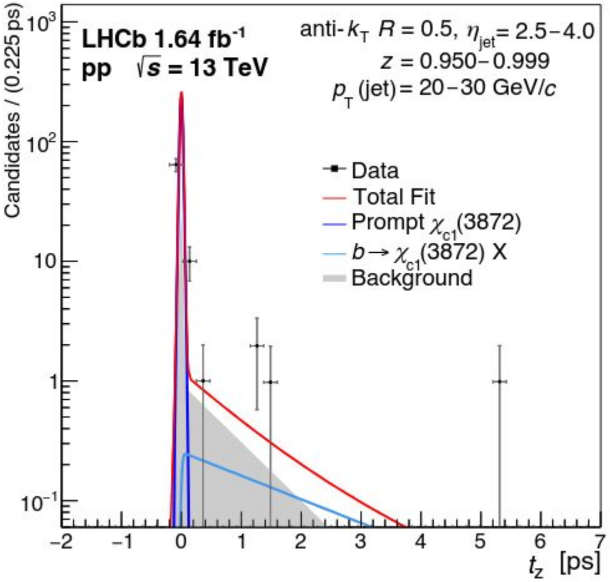
- **(Top) displaced (non-prompt) production:** Good agreement between data and PYTHIA 8
- **(Bottom) prompt production:** Poor agreement between data and PYTHIA 8, **isolated production of ψ(2S) overpredicted, similar to J/ψ result**

χ(3872) in jet √s = 13 TeV pp



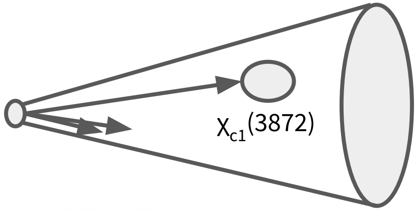
2410.18018 [hep-ex] (2024)





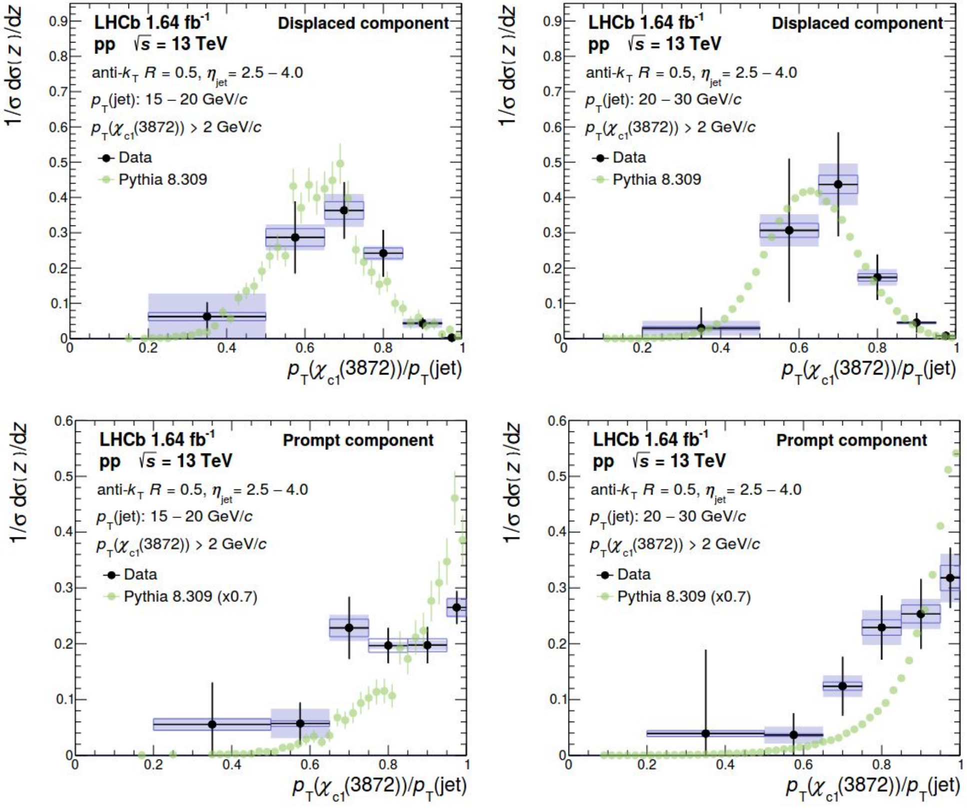
- Clear signal of χ_{c1}(3872) observed in the m($\mu^+\mu^-\pi^+\pi^-$) spectrum
- Pseudo-decay time $t_z = \lambda\, m/p_z$ where λ is the flight distance projected along the beam axis between reconstructed χ_{c1}(3872) and primary vertex
  - Distribution used to determine the prompt vs non-prompt contribution

χ(3872) in jet √s = 13 TeV pp



$$z = \frac{p_{T,hadron}}{p_{T,jet}}$$

2410.18018 [hep-ex] (2024)



- **(Top) displaced (non-prompt) production:** Good agreement between data and PYTHIA 8
- **(Bottom) prompt production:** Poor agreement between data and PYTHIA 8, **isolated production of $\chi_{c1}(3872)$ overpredicted, similar to J/ψ and ψ(2S) result**

Observations

- Light quark initiated jets tend to have harder fragmentation than gluon initiated jets
- Momentum fraction z tends to increase on average with the mass of the hadron in consideration
- Isolated production of charmonium is overpredicted by PYTHIA and NRQCD
  - Similar results have been observed by the other LHC experiments for the J/ψ
    - **CMS:** **PLB 825 (2021) 136842**
    - **ATLAS:** **JHEP 12 (2021) 131**
    - **ALICE:** **preliminary**
  - Adjusting the formalism can account for some of the differences
    - Better agreement with NRQCD calculations using fragmenting jet function (FJF) formalism for z(J/ψ) (Phys. Rev. Lett. 119, 032002 (2017))
  - **What does this imply?**
    - Significant contribution of charm quark-antiquark pairs produced in the parton shower rather than from initial hard scattering?
      - New calculations on NRQCD production of charmonia in timelike parton showers (EPJ C84 432 (2024))
        - Implemented in Pythia 8.310
      - **Could call into question effectiveness of charmonium states as a clean probe of the QGP**
    - Or significant radiative energy loss of charm quark-antiquark pairs produced in the initial hard scattering?

Measurements in Progress

- Heavy flavor jet mass ($\sqrt{s}$ = 13 TeV pp)
  - $B^+ \rightarrow (J/\psi(1S) \rightarrow \mu^+\mu^-)K^+$
- Heavy flavor TMD jet fragmentation ($\sqrt{s}$ = 13 TeV pp)
  - $B^+ \rightarrow (J/\psi(1S) \rightarrow \mu^+\mu^-)K^+$ in jet
  - $D^0 \rightarrow K^-\pi^+\pi^0$ in jet
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ in jet
  - SV tagged dijets
- Z+jet energy-energy correlators ($\sqrt{s}$ = 13 TeV pp)
- Heavy flavor jet and Z+jet Lund Jet Plane and Dead Cone ($\sqrt{s}$ = 13 TeV pp)
  - $Z^0 \rightarrow \mu^+\mu^-$ plus jet
  - $B^+ \rightarrow (J/\psi(1S) \rightarrow \mu^+\mu^-)K^+$ in jet
  - $D^0 \rightarrow K^-\pi^+\pi^0$ in jet
- Heavy flavor QCD splitting functions

Looking Forward

The physics channels and observables we are currently investigating lend themselves nicely to future measurements in heavy ion collisions!

- Heavy flavor used as a probe of the QGP, believed to be produced during the initial hard scattering and perturbed during the lifetime of the QGP
  - **Beauty is a better probe than charm!**
- Z+jet used to measure energy loss and modification of the jet, given that the Z^0 does not interact with the QGP
- Investigating modification to jet substructure in these channels in PbPb collisions vs pp collisions would be very interesting!

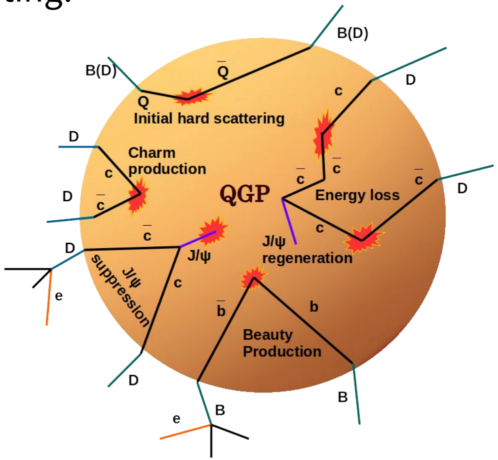


Image credit: https://indico.cern.ch/event/760884/

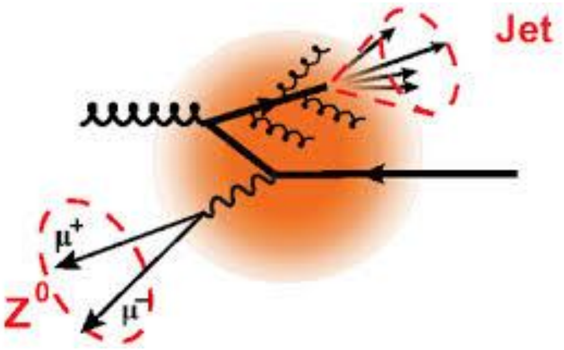


Image credit: https://physics.aps.org/articles/v10/s93

Conclusions

- LHCb is an excellent detector with unique capabilities amongst other experiments
  - Excellent tracking resolution with full calorimetry (full jets)
  - Excellent hadron PID (identified hadron in jet)
  - Excellent pointing resolution (allows for clean reconstruction of HF hadrons)

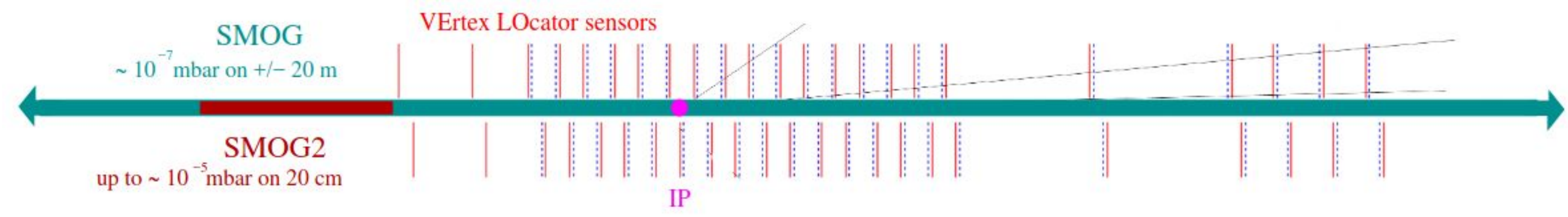
- Efforts for jet substructure measurements at LHCb are slowly growing
  - Lots of measurements on the horizon, with even more opportunities to do unique and timely QCD measurements

- Current and ongoing measurements analyze mass and flavor dependence of jet fragmentation
  - Light quark initiated jets tend to have harder fragmentation than gluon initiated jets
  - Momentum fraction z tends to increase on average with the mass of the hadron in consideration
  - Isolated production of charmonium is overpredicted by PYTHIA and NRQCD

- Future measurements in heavy ion collisions could shed light on how jet fragmentation and substructure are modified by interactions with the QGP

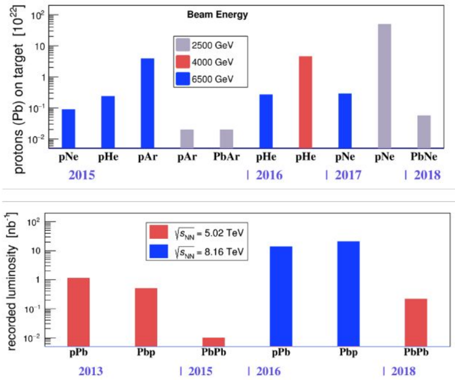
Backup

Fixed Target Physics with the System for Measuring Overlap with Gas (SMOG)

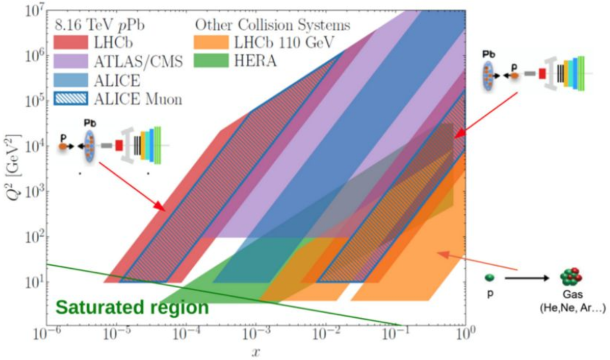


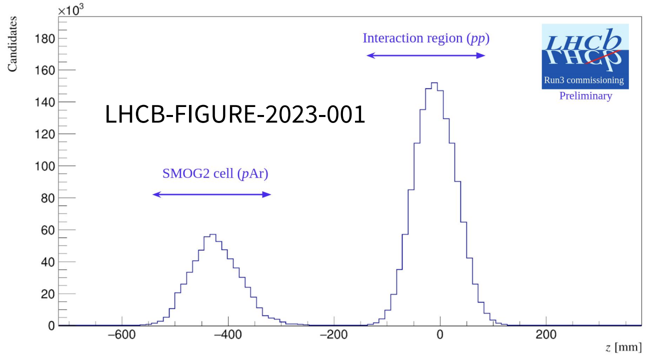
Upgraded to a gas cell for Run 3 → increase in luminosity and clean separation of PVs of fixed target and collider data

- Can take data for both simultaneously in Run 3 and beyond!



http://dx.doi.org/10.22323/1.387.0176





LHCB-FIGURE-2023-001

https://lhcb-outreach.web.cern.ch/detector/smog-more-info/

The LHCb Detector (Run 3)

Eur. Phys. J. C 84, 608 (2024)

Instrumented for higher rate of data taking and higher occupancies!
→ Increase in luminosity and extended reach from 60% centrality in PbPb (Run 2) to 30% (Run 3)

Fully instrumented forward spectrometer

- $2 < \eta < 5$